holodeck

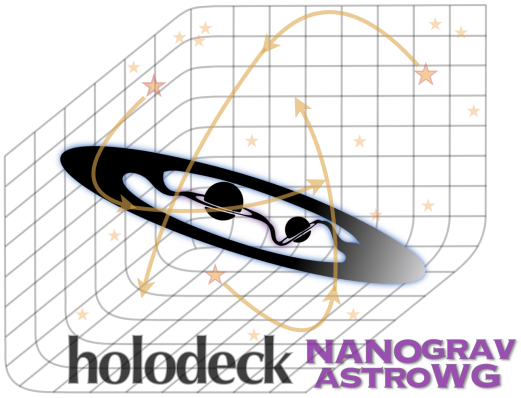
Release 1.2

NANOGrav

Apr 13, 2024

GETTING STARTED GUIDE

Massive Black-Hole Binary Population Synthesis for Gravitational Wave Calculations



holodeck on github

This package provides a comprehensive framework for MBH binary population synthesis. The framework includes modules to perform population synthesis using a variety of methodologies from semi-analytic models, to cosmological hydrodynamic simulations, and even observationally-derived galaxy merger catalogs.

This File:

CHAPTER

ONE

GETTING STARTED: INTRODUCTION

This File:

1.1 Overview

The `holodeck` framework simulates populations of MBH binaries, and calculates their GW signals. In general, the calculation proceeds in three stages:

(1) *Populations*: Construct an initial population of MBH 'binaries'. This is typically done for pairs of MBHs when their galaxies merge (i.e. long before the two MBHs are actually a gravitationally-bound binary). The initial populations must specify, for each binary:

   (a) both MBH masses (typically as total-mass M and mass-ratio q),

   (b) the redshift (z) at which the pair of MBHs form,

   (c) the initial separation (a_{init}) of the MBHs at their formation time.

   Additional information can be very useful. In particular, information about the host galaxy of the MBH pair can be used in the binary evolution calculation.

(2) *Binary Evolution*: Evolve the binary population from their initial conditions (i.e. large separations) until they reach the regime of interest (i.e. small separations). In the simplest models, binaries are assumed to coalesce instantaneously, and are assumed to evolve purely due to GW emission. Note that these two assumptions are contradictory. More complex, self-consistent evolution models are recommended. These models typically involve interactions between MBH binaries and their host galaxies ('environmental' interactions). Note that the effects of binary evolution can be broken up into two distinct effects:

   (a) The redshift at which binaries reach the given frequencies (or separations) of interest, and similarly which binaries are able to reach those frequencies before redshift zero, and

   (b) The rate of binary evolution at the given frequencies of interest.

Cases which treat (a) and (b) consistently, we refer to as 'self-consistent' binary evolution models. Often this is not the case, for example assuming that (a) the redshift at which binaries reach all frequencies is identical and equal to the formation redshift (i.e. binaries merge 'instantaneously'); but also assuming that (b) binaries evolve due to GW emission alone.

(3) *Gravitational Waves*: From the population of MBH binaries at the separations (or frequencies) of interest, calculate the resulting GW signals. GW calculations can be done in many different ways, depending on what assumptions are made regarding:

(a) Discretization: whether binaries are treated as discrete objects, i.e. there can only be an integer number of binaries in a given frequency bin (this often relates to whether the number-density, or total-number of binaries is used in the calculation). One can also consider the effects of cosmic variance in this category as well.

(b) Evolution: whether self-consistent models of binary evolution are considered, or if purely GW-driven evolution is assumed (see *Binary Evolution*).

(c) Eccentricity: whether binaries are restricted to circular orbits, or allowed to have eccentric evolution. Eccentricity has multiple effects on binary evolution, mostly (i) by changing the rate of binary hardening, and (ii) by changing the GW frequencies corresponding to each orbital frequency. Circular binaries emit GWs at only the $n = 2$ harmonic of the orbital frequency, while eccentric binaries emit at all integer harmonics.

1.2 Populations

1.2.1 Semi-Analytic Models (SAMs)

`holodeck` SAMs are handled in the `holodeck.sams` module. The core of the module is the `Semi_Analytic_Model` class, in the: `holodeck.sams.sam` file.

The SAMs use simple, analytic components to calculate populations of binaries. The `Semi_Analytic_Model` handles and stores these components which themselves are defined in the `holodeck.sams.components` file. Holodeck calculates the number-density of MBH binaries, by calculating a number-density of galaxy-galaxy mergers, and then converting from galaxy properties to MBH properties by using an MBH-host relationship.

The SAMs are initialized over a 3-dimensional parameter space of total MBH mass ($M = m_1 + m_2$), MBH mass ratio ($q = m_2/m_1 \leq 1$), and redshift (z). The `holodeck` code typically refers to the number of bins in each of these dimensions as `M`, `Q`, and `Z`; for example, the shape of the number-density of galaxy mergers will be `(M, Q, Z)`. Most calculations retrieve the number of binaries in the Universe at a given set of frequencies (or sometimes binary separations), so the returned values will be 4-dimensional with an additional axis with `F` frequency bins added. For example, the number of binaries at a given set of frequencies will typically be arrays of shape `(M, Q, Z, F)`.

Galaxy Mergers

`holodeck` SAMs always start with a Galaxy Stellar-Mass Function (GSMF) that determines how many galaxies there are as a function of stellar mass, $\psi(m_\star) \equiv \partial n_\star / \partial \log_{10} m_\star$, where $n_\star$ is the comoving number density of galaxies. We then have to add a galaxy merger rate (GMR), $R_\star(M_\star, q_\star) \equiv (1/n_\star)\partial^2 n_{\star\star}/\partial q_\star\, \partial t$, to find the number density of galaxy-pairs:

$$\frac{\partial^3 n_{\star\star}(M_\star, q_\star, z)}{\partial \log_{10} M_\star\, \partial q_\star\, \partial z} = \psi(m_{1,\star})\, R_\star(M_\star, q_\star).$$

Here, $M_\star = m_{1,\star} + m_{2,\star}$ is the total stellar mass of both galaxies, and $q_\star = m_{2,\star}/m_{1,\star} \leq 1$ is the stellar mass ratio. Often in the literature, the GMR is estimated as a galaxy pair fraction (GPF; $P_\star$) divided by a galaxy merger timescale (GMT; $T_\star$), i.e. $R_\star \approx P_\star / T_\star$. The GPF is typically an observationally-derived component, defined roughly as, $P_\star(m_{1,\star}, q_\star) \equiv N_{\star\star}(m_{1,\star}, q_\star)/N_\star(m_{1,\star})$, i.e. the number of galaxy pairs in a given survey divided by the number of all galaxies in the parent sample. Note that there are significant selection effects in determining the number of

galaxy pairs, including cuts on galaxy brightness/mass, and especially on the separations a_0 and a_1 between which pairs can be identified robustly. The GMT is typically derived from numerical simulations, and defined roughly as, $T_\star(M_\star, q_\star) \equiv \int_{a_0}^{a_1} [da/dt]^{-1}_{\star\star}\, da$, i.e. the total time that the galaxy pair spends at separations between a_0 and a_1. So we can also write:

$$\frac{\partial^3 n_{\star\star}(M_\star, q_\star, z)}{\partial \log_{10} M_\star\, \partial q_\star\, \partial z} = \psi(m_{1,\star})\, \frac{P_\star(m_{1,\star}, q_\star)}{T_\star(M_\star, q_\star)}.$$

Implementation: Each component (GSMF, GMR, GPF, GMT) is implemented by constructing a class that inherits from the appropriate base classes:

- GSMF: *_Galaxy_Stellar_Mass_Function*, for example the *GSMF_Schechter* class.
- GMR: *_Galaxy_Merger_Rate*, for example the *GMR_Illustris* class.
- GPF: *_Galaxy_Pair_Fraction*, for example the *GPF_Power_Law* class.
- GMT: *_Galaxy_Merger_Time*, for example the *GMT_Power_Law* class.

The classes need to expose a `__call__` method (i.e. the class instances themselves are callable) which accepts the appropriate arguments and returns the particular distribution.

MBH Populations and MBH-Host Relations

We now have a galaxy-galaxy merger rate, and we need to populate these galaxies with MBHs. To do this, we need an MBH-host relationship, typically in the form of M-MBulge ($m_{\rm BH} = M_\mu(m_{\rm bulge}, z)$; mass of the MBH, relative to the stellar-bulge mass of the host galaxy), and possibly a relationship between bulge mass and overall stellar-mass (i.e. $m_{\rm bulge} = m_{\rm bulge}(m_\star)$). Given this relationship, we can convert to MBH mergers as,

$$\frac{\partial^3 n(M, q, z)}{\partial \log_{10} M\, \partial q\, \partial z} = \frac{\partial^3 n_{\star\star}(M_\star, q_\star, z)}{\partial \log_{10} M_\star\, \partial q_\star\, \partial z} \left[\frac{\partial M_\star}{\partial M}\right] \left[\frac{\partial q_\star}{\partial q}\right],$$

where the masses must be evaluated at the appropriate locations: $m_1 = M_\mu(m_{1,\star})\,\&\, m_2 = M_\mu(m_{2,\star})$.

Implementation: M-MBulge relationships are implemented as subclasses inheriting from the *holodeck.host_relations._MMBulge_Relation* class (defined in the *holodeck.host_relations* file), for example the *holodeck.host_relations.MMBulge_KH2013* class. Subclasses must implement a number of methods to allow for conversion between stellar bulge-mass and MBH mass.

1.2.2 'Discrete' Populations from cosmological hydrodynamic simulations (e.g. illustris)

1.3 Binary Evolution

1.4 Gravitational Waves

CHAPTER

TWO

GENERATING AND USING HOLODECK LIBRARIES

File Contents

2.1 Libraries Overview

holodeck 'libraries' are collections of simulations in which a certain set of parameters are varied, producing different populations and/or GW signatures at each sampled parameter value. Libraries are run from the same parameter-space and using the same hyper parameters (for example, the functional form that is assumed for the galaxy stellar-mass function). Libraries are constructed using the *librarian* module, with a 'parameter space' class that organizes the different simulations. The base-class is called *_Param_Space* (defined in the *holodeck.librarian.libraries* file), and all parameter space classes inherit from this, and should typically be prefixed by `PS_` to denote that they are parameter spaces. The parameter-space subclasses implement a number of parameters that are varied. Each parameter is implemented as a subclass of *_Param_Dist*, for example the *PD_Uniform* class that implements a uniform distribution.

As an example, the fiducial library and parameter space for *the 15yr astrophysics analysis* was the 'phenomenological uniform' library, implemented as *PS_Classic_Phenom_Uniform* (at the time, it was internally called `PS_Uniform_09B`). This library spanned a 6D parameter space using a 'phenomenological' binary evolution model, and assuming a uniform distribution in sampling from the parameter priors. Two parameters from the galaxy stellar-mass function were varied, along with two parameters from the M-MBulge relationship, and two parameters from the hardening model.

2.2 Parameter Spaces and Distributions

NOTE: currently parameter-spaces are only designed for use with SAMs.

Parameter spaces are implemented as subclasses of the *_Param_Space* class, and are generally named with a `PS_` prefix. Each class generates a certain number of samples using a latin hypercube to efficiently sample the parameter space. Each parameter being varied in the parameter space corresponds to parameter distribution, implemented as a *_Param_Dist* subclass. Each subclass is generally named with a `PD_` prefix. These parameter distributions convert from uniform random variables (uniform samples in $[0.0, 1.0]$ in the latin hypercube) to the desired distributions. For example, the `PD_Normal(mean, stdev)` class draws from a normal (Gaussian) distribution, and the `PD_Normal(min, max)` class draws from a uniform distribution.

2.2.1 Parameter Distributions

New parameter distributions should subclass *_Param_Dist*, and must provide a method with signature: `_dist_func(self, xx)` which accepts a float value `xx` in $[0.0, 1.0]$ and maps it to a value in the desired distribution, and returns a float value. Typically an `__init__` function will also be provided to set any required parameters. See the *PD_Uniform* class for a simple example that maps from $[0.0, 1.0]$ to another uniform variable with a different minimum (`lo`) and maximum (`hi`) value.

How the parameter distributions are used in parameter spaces is described below, but in summary, each *_Param_Space* subclass will build a list of *_Param_Dist* subclass instances which are used to specify the domain of the parameter space. The construct for each *_Param_Dist* subclass must accept first the variable name, and then any additional required arguments, for example: `PD_Normal("gsmf_phi0", -2.56, 0.4)`. The name of the variable **must match the name used in the |pspace_class|**, i.e. for the previous example, the *_Param_Space* will be expecting a variable named `gsmf_phi0`. All *_Param_Dist* subclasses optionally accept a `default=` keyword-argument, for example, `PD_Uniform("hard_time", 0.1, 11.0, default=3.0)`. The 'default' values are provided so that *_Param_Space*'s can construct a model using default parameters (see: *holodeck.librarian.libraries._Param_Space.default_params()*), typically as a fiducial model. In the preceding example, the default 'hard_time' parameter would be 3.0. If a `default` is not specified in the instance constructor, then the value produced by an input of `0.5` is used. In the preceding example, if no `default` was specified, then the middle value of $(11.0 + 0.1)/2 = 5.55$ would be used.

2.2.2 Parameter Spaces

As an example, consider the *PS_Test* class which is included as a test-case and usage example.

Parameter spaces must subclass *_Param_Space*, and provide 4 elements:

(0) OPTIONAL/Recommended: A class attribute called `DEFAULTS` which is a `dict` of default parameter values for all of the parameters needed by the initialization methods. **This is strongly recommended to ensure that parameters are set consistently, by setting them explicitly.**

- |*ps_test_class*| *Example:* while this example construct a 3-dimensional parameter space (over "hard_time", "hard_gamma_inner", "mmb_mamp"), there are `DEFAULTS` specified for all of the parameters used to construct the GSMF, GMR, M-MBulge, and hardening models.

(1) An `__init__()` method that passes all required parameter distributions (*_Param_Dist* subclasses) to the superclass `__init__()` method. The list of *_Param_Dist* instances is where the actual parameter-space being explored is defined. Adding or removing a new element to this list of instances is all that it takes to increase or decrease the parameter space.

- |*ps_test_class*| *Example:* in this case, a 3-dimensional parameter space is constructed, using uniform distributions (*PD_Uniform*) for "hard_time" and "hard_gamma_inner", and a normal (i.e. Gaussian, *PD_Normal*) distribution for "hard_time".

(2) An `_init_sam()` function that takes the input parameters, and then constructs and returns a *Semi_Analytic_Model* instance.

(3) An `_init_hard()` function that takes the input parameters, and then constructs and returns a `_Hardening` instance.

Public parameter spaces should also be 'registered' to the *holodeck.librarian.param_spaces_dict* dictionary. See *holodeck.librarian*.

2.3 Generating Libraries

holodeck libraries are generated by running a number of simulations (i.e. SAM models) at different points in a parameter space (i.e. *_Param_Space* subclass). The module *holodeck.librarian.gen_lib* is designed to do this. It provides a command-line interface to run many simulations in parallel (using MPI), or its functions can be used as API methods. For detailed usage information, see: *holodeck.librarian.gen_lib*.

Once a *_Param_Space* is defined, and is registered in the *holodeck.librarian.param_spaces_dict* dictionary, then it can be accessed using the *holodeck.librarian.gen_lib* script. A typical usage example is:

```
mpirun -np 16  python -m holodeck.librarian.gen_lib PS_Classic_Phenom_Uniform ./output/
↪ps-classic-phenom -n 512 -f 40
```

This command starts an mpi job with 16 processors, and runs the *holodeck.librarian.gen_lib* module. There are two required positional arguments: first, the name of the parameter-space class (this much match exactly the class definition), and the desired output directory for simulation files. A number of optional arguments can also be specified, in the above example for instance, the number of sample points in this library (i.e. in the latin hypercube) is set to 512, and the number of frequency bins is set to 40. The command-line usage can be seen by running:

```
python -m holodeck.librarian.gen_lib --help
```

The holodeck installer also makes available the command line alias `holodeck_lib_gen` which is equivalent to running `python -m holodeck.librarian.gen_lib`.

In the preceding example, a *PS_Classic_Phenom_Uniform* parameter space instance is constructed which defines a 5-dimensional parameter space. 512 points are sampled using a latin hypercube, and $512/16 = 32$ sets of parameters are given to each processor. Each set of parameters is then run as an individual simulation, and the resulting files are saved to a `sims/` subdirectory in the specified output path. Once all of the jobs are completed, the results from all 512 simulations are combined into a single 'library' file called `sam_lib.hdf5` in the output path. Once the `sam_lib.hdf5` file is created, typically the individual simulation output files in the `sims/` subdirectory can safely be deleted, but **note that this is not done automatically**, and thus almost twice as much space is used up as is required.

A copy of the parameter-space instance itself (in this case an instance of *PS_Classic_Phenom_Uniform*) is saved as a numpy npz file to output directory also. This allows for the library generation to be resumed if it is halted (or fails) part way through, and also ensures that the specifications for the parameter space are easily accessible.

A more complicated job execution script which works for the SLURM job scheduler, is included in the file: *scripts/run_holodeck_lib_gen.sh <https://github.com/nanograv/holodeck/blob/dev/scripts/run_holodeck_lib_gen.sh>*.

2.4 Analytic GWB Fits to Libraries

It is often useful to fit analytic functions to the GWB spectra in a library. This can be done using the *holodeck.librarian.fit_spectra* script/submodule, which is also parallelized using MPI. This script can be run as, for example:

```
mpirun -np 16  python -m holodeck.librarian.fit_spectra ./output/ps-classic-phenom
```

This will find the library file (`sam_lib.hdf5`) in the given directory, and fit all of the included spectra. For more information, see: *holodeck.librarian.fit_spectra*. For command-line usage information, run:

```
python -m holodeck.librarian.fit_spectra --help
```

2.5 Using holodeck libraries

2.5.1 Loading a saved parameter-space instance

TLDR: Use the *load_pspace_from_path()* function, passing in the path to the directory containing the save file (a `.pspace.npz` file).

Typically all that is needed for using/analyzing a holodeck library is the combined library output file `sam_lib.hdf5`. A saved instance of the parameter-space class which generated the library is also saved to the output directory (as a `.pspace.npz` file), and can be useful for some use cases, for example if new simulations/realizations are desired from the same parameter space. The *_Param_Space* provides a method to load saved instances, see the *from_save()* method. Typically, the best way to load a saved parameter-space instance is to use the *load_pspace_from_path()* function.

2.5.2 The combined holodeck library file `sam_lib.hdf5`

In general, it is recommended to use the h5py python package for handling HDF5 files. The HDF5 standard provides a hierarchical dictionary-like structure to store data sets (including very large ones). It also provides structures for storing simple header/metadata (with strings, primitive types, etc), including metadata to document all datasets. In general, every level of an hdf5 file can contains either data or 'groups' (a deeper, dictionary-like level), which are accessed as if they were dictionary elements. Each level also has a set of metadata called *attrs* which are also accessed if they were dictionary elements.

Example:

```
# Open the HDF5 file using the `h5py` package
library = h5py.File("./sam_lib.hdf5", "r")
# Load the parameter-space parameter names from the file metadata
param_names = library.attrs["param_names"]
# Load the parameter values for each simulation in the library
sample_params = library["sample_params"]
```

Metadata

Metadata is included in the top-level `attrs` of the `sam_lib.hdf5` file.

- `holodeck_git_hash`: string. The git hash code for the current repository commit. *NEW in librarian v1.1.*
- `holodeck_librarian_version`: string. The version number of holodeck.librarian module specifically. *NEW in librarian v1.1.*
- `holodeck_version`: string. The version number of the holodeck package as a whole. *NEW in librarian v1.1.*
- `parameter_space_class_name`: string. The name of the parameter-space class used to generate the library. *NEW in librarian v1.1.*
- `param_names`: an array of bytes (strings). The names (and ordering) of the parameter-space parameters. To convert to strings, use `library.attrs['param_names'].astype(str)`.

Data

- `fobs_edges`: ndarray (F+1,). Units of [Hz]. Frequency bin edges at which GW properties are evaluated. There are one more bin-edges than bins.
- `fobs_cents`: ndarray (F,). Units of [Hz]. Frequency bin centers at which GW properties are evaluated. We use *F* to designate the number of frequency bins.
- `sample_params`: ndarray (S, P). Units vary. The parameter values used to construct each simulation. The number of simulations (sample points) is *S* and the number of parameters (dimensions of the parameter space) is *P*. Each of the *P* parameters corresponds to the parameter names in the *param_names* metadata attribute.

If the `gwb` flag was used when generating the library:

- `gwb`: ndarray (S, F, R). Unitless (characteristic strain). The GW background characteristic strain amplitude for each simulation *S*, frequency bin *F*, and realization *R*.

If the `ss` flag was used when generating the library:

- `hc_bg`: ndarray (S, F, R). The characteristic strain of the GW background **minus** the *L* loudest individual sources in each frequency bin (given in *hc_ss*). This is evaluated at each simulation *S*, frequency bin *F*, and realization *R*.
- `hc_ss`: ndarray (S, F, R, L). The characteristic strain of the *L* loudest individual binaries in each frequency bin. This is evaluated at each simulation *S*, frequency bin *F*, and realization *R*.

If the `params` flag was used when generating the library:

- `bgpar`: ndarray (S, X, F, R). The GWB-amplitude weighted parameters of simulated binaries for *S* simulations, *F* frequency bins, and *R* realizations. The *X* values are the different weighted parameters. Currently these are:
  - [0]: total mass, in units of [gram]
  - [1]: mass ratio
  - [2]: formation redshift
  - [3]: redshift to binary at emission
  - [4]: comoving distance to binary at emission, in units of [cm]
  - [5]: binary physical separation at emission, in units of [cm]
  - [6]: binary angular separation at emission, in units of [radian]
- `sspar`: ndarray (). (S, X, F, R, L). The parameters of the *L* loudest binaries for *S* simulations, *F* frequency bins, and *R* realizations. The *Y* values are the different parameters. Currently these are:

- [0]: total mass, in units of [gram]
- [1]: mass ratio
- [2]: formation redshift
- [3]: redshift to binary at emission

CHAPTER

THREE

THE NANOGRAV 15YR ASTROPHYSICS ANALYSIS

Holodeck was used to perform the 'Astrophysical Interpretation' of the 15yr NANOGrav dataset, by the NANOGrav Astrophysics Working Group. The publication can be found here: Agazie+2023 (for the NANOGrav Collaboration) - The NANOGrav 15 yr Data Set: Constraints on Supermassive Black Hole Binaries from the Gravitational-wave Background. The astrophysics datasets can be found here: LINK. The analysis notebooks can be found here: LINK.

The initial set of **NANOGrav 15yr papers** are:

- The 15yr Dataset [N15data]
- Detector and Noise Characterization [N15detchar]
- Measuring a Gravitational Wave Background [N15GWB]
- Astrophysical Interpretation [N15astro]
- Constraints on New Physics [N15NP]
- Search for Anisotropy [N15anisotropy]
- Search for Individual Sources (CWs) [N15CWs]

The use of **holodeck in the 15yr astrophysics interpretation**:

CHAPTER

FOUR

DEFINITIONS AND ABBREVIATIONS

4.1 Abbreviations

- **AGN**: Active Galactic Nucleus, an accreting massive black hole that produced observable EM emission (radio, optical, X-ray, etc). Generally used synonymously with "Quasar" which is traditionally a very bright AGN, produced by an MBH accreting at a very high rate.
- **BH**: Black Hole
- **CBD**: Circum-Binary Disk, an accretion disk surrounding both components of a binary system.
- **CSD**: Circum-Single Disk, an accretion disk surrounding a single component of a binary system.
- **CW**: Continuous Wave, as in Continuous Wave GW source
- **DF**: Dynamical Friction, the drag force experienced by a massive object moving in a gravitating background.
- **EM**: Electromagnetic, traditional radiation produced by moving charges (from the radio to optical to gamma-ray).
- **GR**: General relativity.
- **GPF**: Galaxy Pair Fraction, the fraction of galaxies in galaxy pairs.
- **GMR**: Galaxy Merger Rate, the specific rate of galaxy mergers (i.e. the rate of mergers per galaxy).
- **GMT**: Galaxy Merger Time, the characteristic duration that a galaxy merger takes. This is typically defined observationally, i.e. the duration of time over which a galaxy merger could be identified in an imaging survey.
- **GSMF**: Galaxy Stellar-Mass Function, the number-density of galaxies as a function of their stellar mass.
- **GW/GWB**: Gravitational Waves / Gravitational Wave Background
- **ISCO**: Inner-most Stable Circular Orbit, the radius or location within which no object can maintain a stable orbit around a black hole. The radius is dependent on the spin of the black hole, but equal to 3 times the Schwarzschild radius for a non-spinning ($a = 0$) black hole.
- **LISA**: Laser Interferometer Space Antenna, future space-based GW detector
- **MBH**: Massive Black-Hole, usually treated interchangeably with 'SMBH' (super-massive black-hole)
- **MBHB**: Massive Black-Hole Binary, also referred to as BSMBH, SMBHB, ...

- **NFW**: Navarro-Frenk-White dark matter radial-density profile for a dark-matter halo.
- **PTA**: Pulsar Timing Array.
- **QLF**: Quasar Luminosity Function. The number-density of quasars/AGN as a function of their brightness.
- **SAM**: Semi-Analytic Models. (Grey area relative to SEMs).
- **SEM**: Semi-Empirical Models. (Grey area relative to SAMs).
- **TOA**: Time of Arrival, the specific measured time at which a pulsar's radio bursts are measured by the observer.

4.2 Symbols

- a**:**
  - (1) binary orbital semi-major axis (i.e. separation).
  - (2) the scale-factor of the universe at a given redshift, $a = 1/(1+z)$.
- d_c: Comoving Distance, the distance to a location in the Universe that, for zero relative velocity, remains invariant as a function of redshift. Related to luminosity distance as, $d_c = d_L/(1+z)$.
- d_L: Luminosity Distance, the effective distance to a source in the Universe determining its EM brightness or GW amplitude. Related to comoving distance as, $d_L = d_c\,(1+z)$.
- $\mathcal{M}$': Chirp-mass
- M: Mass, or total-mass ($M = m_1 + M_2$) in the context of a binary.
- q: Mass-ratio of a binary, defined to be less-than or equal to unity, $q \equiv m_2/m_1$, where the more massive primary is m_1.
- z: (Cosmological) redshift, a proxy for the distance to a source/location in the Universe, and also a proxy for the age of the Universe at that time. Related to the scale-factor as $z = (1/a) - 1$.

4.3 Terminology

- **AGN/Quasar**: There is a long and convoluted history of terms for different types of EM-bright astronomical sources that are now all believed to be produced by accreting massive black holes. 'Active galactic nuclei' is perhaps the most generic term for any accreting MBH which is then producing EM emission. Formally 'quasars' are relatively massive MBHs that are accreting at very high rates, and are thus very bright. Often 'quasar' is used relatively interchangeably with AGN (for instance in 'Quasar Luminosity Function').
- **Hardening**: the shrinking of the semi-major axis of a binary system by extracting energy and angular momentum. This term is also often used to simply mean the process of bringing two bodies (i.e. MBHs) closer together, even if they are not formally a gravitational-bound binary. 'Hardening' is typically due to either GW emission, or interactions between the binary and the surrounding environment. More generally, the "hardness" of a binary refers to how its binding energy compares to the kinetic energy of the surrounding environment (typically stars). If the binding energy is larger, then the binary is said to be 'hard'; if the binding energy is less, it is said to be 'soft'. The "Heggie Law" or the "Heggie-Hills Law" states that hard binaries tend to harden further, and soft binaries tend to soften further, both based on interactions with the surrounding medium. This is based on a pair of papers: [Heggie1975] and [Hills1975].
- **M-Mbulge**: the $M_{bh} - M_{\rm bulge}$ relation, whereby the mass of MBHs is closely correlated with the mass of the stellar bulge of their host galaxy.
- **Stellar Bulge**

CHAPTER

FIVE

BIBLIOGRAPHY

5.1 Annotated Bibliography

- **Begelman, Blandford & Rees 1980**, [BBR1980] - Massive black hole binaries in active galactic nuclei
  - The definitive early discussion of massive black-hole binary evolution, outlining the different stages of environmental interaction (dynamical friction, stellar scattering, etc) and mentioning the possibility of stalling in the parsec regime.
  - Includes simplistic, but useful prescriptions for calculating timescales for each regime of evolution.
- **Genel et al. 2014**, [Genel2014] - Introducing the Illustris project: the evolution of galaxy populations across cosmic time
  - One of the standard references for the original Illustris simulations written by the Illustris team.
  - Focuses on the redshift evolution of simulated galaxies.
- **Hogg 1999**, [Hogg1999] - Distance measures in cosmology.
  - This is the go-to reference/cheat-sheet for basic cosmological calculations such as distances (comoving, luminosity), volume of the universe, lookback times, etc.
- **Kelley, Blecha, and Hernquist 2017**, [Kelley2017a] - Massive black hole binary mergers in dynamical galactic environments
  - Describes the MBH-MBH mergers from the Illustris cosmological hydrodynamic simulations.
  - Results include comprehensive semi-analytic models for post-processing the binary mergers at sub-grid scales.
- **Kelley et al. 2017**, [Kelley2017b] - The gravitational wave background from massive black hole binaries in Illustris: spectral features and time to detection with pulsar timing arrays
  - Uses the MBH-MBH merger catalogs from Illustris, along with comprehensive semi-analytic models of the unresolved binary evolution process, to calculate the expected properties of the GWB and PTA detection prospects.
- **Kelley et al. 2018**, [Kelley2018] - Single sources in the low-frequency gravitational wave sky: properties and time to detection by pulsar timing arrays
  - Uses the MBH-MBH merger catalogs from Illustris, along with comprehensive semi-analytic models of the unresolved binary evolution process, to calculate the expected properties of individual continuous wave (CW) GW sources and PTA detection prospects.
- **Nelson et al. 2015**, [Nelson2015] - The illustris simulation: Public data release
  - One of the standard references for the original Illustris simulations written by the Illustris team.
  - Summarizes the Illustris public data and API.

- **Phinney 2001**, [Phinney2001] - A Practical Theorem on Gravitational Wave Backgrounds
  - Pioneering analytic calculation of the GWB by integrating the GW emission of binaries over the history of the universe.
- **Rodriguez-Gomez et al. 2015**, [Rodriguez-Gomez2015] - The merger rate of galaxies in the Illustris simulation: a comparison with observations and semi-empirical models
  - Methods and results for galaxy-galaxy merger rates from the Illustris simulations.
  - These rates are used to prescribe merger rates in the observational-populations *holodeck* catalogs.
- **Sesana et al. 2008** [Sesana2008] - The stochastic gravitational-wave background from massive black hole binary systems: implications for observations with Pulsar Timing Arrays.
  - Thorough description of how to calculate the GWB, with a discussion on some of the nuances.
  - Particular attention is given to the difference between the analytic formalism of [Phinney2001] and numerical / semi-analytic approaches, i.e. the effects of discreteness of binary sources which produces a turnover in the GWB spectrum at high frequencies.
- **Sijacki et al. 2015**, [Sijacki2015] - The Illustris simulation: the evolving population of black holes across cosmic time
  - One of the standard references for the original Illustris simulations written by the Illustris team.
  - Describes the MBH/AGN population derived from the simulations.
- **Siwek, Weinberger, and Hernquist 2023**, [Siwek2023] - Orbital evolution of binaries in circumbinary discs
- **Springel 2010**, [Springel2010] - E pur si muove: Galilean-invariant cosmological hydrodynamical simulations on a moving mesh
  - Methods paper for the arepo hydrodynamics code, used in the Illustris simulations.
- **Vogelsberger et al. 2014**, [Vogelsberger2014] - Introducing the Illustris Project: simulating the coevolution of dark and visible matter in the Universe
  - One of the standard references for the original Illustris simulations written by the Illustris team.
  - Gives a summary of the simulation methodology and results.

5.2 Quick References

These are provided here for easy copy-and-paste usage in other files.

5.3 NASA/ADS Quick-Reference

Generating references on NASA ADS:

- For short references (e.g. in code files):

```
* [%1.1h%Y]_ %3.1M (%Y).
```

- For the *Annotated Bibliography* section:

```
* **%3.1M %Y**, [%1.1h%Y]_ - `%T <%u>`_\n
```

- For full references (e.g. in the *Quick References* section above):

```
.. [%1.1h%Y] %3.1M (%Y), %q, %V, %S.\n   %T\n   %u\n
```

CHAPTER

SIX

DEVELOPMENT & CONTRIBUTIONS

This File:

This project is being led by the NANOGrav Astrophysics Working Group. Details on contributions and the mandatory code of conduct can be found in CONTRIBUTING.md.

Contributions are welcome and encouraged, anywhere from new modules/customizations, to bug-fixes, to improved documentation and usage examples. The git workflow is based around a `main` branch which is intended to be (relatively) stable and operational, and an actively developed `dev` branch. New development should be performed in "feature" branches (made off of the `dev` branch), and then incorporated via pull-request (back into the `dev` branch).

For active developers, please install the additional development package requirements:

```
pip install -r requirements-dev.txt
```

6.1 Formatting

New code should generally abide by PEP8 formatting, with numpy-style docstrings. Exceptions are:

- lines may be broken at either 100 or 120 columns

6.2 Notebooks

Please strip all notebook outputs before commiting notebook changes. The nbstripout package is an excellent option to automatically strip all notebook output only in git commits (i.e. it doesn't change your notebooks in-place). You can also use `nbconvert` to strip output in place:

```
jupyter nbconvert --clear-output --inplace <NOTEBOOK-NAME>.ipynb
```

To install `nbstripout` for the `holodeck` git repository, make sure you're in the `holodeck` root directory and run:

```
pip install --upgrade nbstripout    # install nbstripout
nbstripout --install                # install git hook in current repo only
```

6.3 Test Suite

Before submitting a pull request, please run the test suite on your local machine.

Tests can be run by using `$ pytest` in the root holodeck directory. Tests can also be run against all supported python versions and system configurations by using `$ tox`. `tox` creates anaconda environments for each supported python version, sets up the package and test suite, and then runs `pytest` to execute tests.

Two types of unit-tests are generally used in `holodeck`.

(1) Simple functions and behaviors are included as normal unit-tests, e.g. in "holodeck/tests" and similar directories. These are automatically run by `pytest` and `tox`.

(2) More complex functionality should be tested in notebooks (in "notebooks/") where they can also be used as demonstrations/tutorials for that behavior. Certain notebooks are also converted into unit-test modules to be automatically run by `pytest` and `tox`. The python script scripts/convert_notebook_tests.py converts target notebooks into python scripts in the `holodeck/tests/converted_notebooks` directory, which are then run by `pytest`. The script scripts/holotest.sh will run the conversion script and then run `pytest`. For help and usage information, run `$ scripts/holotest.sh -h`.

CHAPTER

SEVEN

HOLODECK API REFERENCE

holodeck: Massive Black-Hole Binary Population Synthesis & Gravitational Wave Calculations

This package is aimed at providing a comprehensive framework for MBH binary population synthesis. The framework includes modules to perform pop synth using a variety of methodologies to get a handle on both statistical and systematic uncertainties. Currently, binary populations can be synthesis based on: cosmological hydrodynamic simulations (Illustris), semi-analytic/semi-empirical models, and observational catalogs of local galaxies and/or quasars.

See the *README.md* file for more information. The github repository is: https://github.com/nanograv/holodeck. Additional documentation can be found at: holodeck-gw.readthedocs.io/en/docs/index.html. Note that the readthedocs documentation can also be built locally from the *holodeck/docs* folder. A methods paper for *holodeck* is currently in preparation.

In general, *holodeck* calculations proceed in three stages:

(1) **Population**: Construct an initial population of MBH 'binaries'. This is typically done for pairs of MBHs when their galaxies merge (i.e. long before the two MBHs are actually a gravitationally-bound binary). Constructing the initial binary population may occur in a single step: e.g. gathering MBH-MBH encounters from cosmological hydrodynamic simulations; or it may occur over two steps: (i) gathering galaxy-galaxy encounters, and (ii) prescribing MBH properties for each galaxy.

(2) **Evolution**: Evolve the binary population from their initial conditions (i.e. large separations) until coalescence (i.e. small separations). The complexity of this evolutionary stage can range tremendously in complexity. In the simplest models, binaries are assumed to coalesce instantaneously (in that the age of the universe is the same at formation and coalescence), and are assumed to evolve purely due to GW emission (in that the time spent in any range of orbital frequencies can be calculated from the GW hardening timescale). Note that these two assumptions are contradictory.

(3) **Gravitational Waves**: Calculate the resulting GW signals based on the binaries and their evolution. Note that GWs can only be calculated based on some sort of model for binary evolution. The model may be extremely simple, in which case it is sometimes glanced over.

`holodeck.log = <Logger holodeck (DEBUG)>`

global root logger from *holodeck.logger*

CHAPTER

EIGHT

HOLODECK.DISCRETE MODULE

Discrete populations module, for binaries from cosmological simulations.

This module handles generating MBH binary populations using discrete samples of MBH binaries.

8.1 holodeck.discrete.evolution

Module for binary evolution from the time of formation/galaxy-merger until BH coalescence.

#!NOTE: much of this documentation needs to be updated to reflect that much of the material in this #! file was moved to *holodeck.hardening*.

In *holodeck*, initial binary populations are typically defined near the time of galaxy-galaxy merger, when two MBHs come together at roughly kiloparsec scales. Environmental 'hardening' mechanisms are required to dissipate orbital energy and angular momentum, allowing the binary separation to shrink ('harden'). Typically *dynamical friction (DF)* is most important at large scales ($\sim$ kpc). Near where the pair of MBHs become a gravitationally-bound binary, the DF approximations break down, and individual *stellar scattering* events (from stars in the 'loss cone' of parameter space) need to be considered. In the presence of significant gas (i.e. from accretion), a circumbinary accretion disk (CBD) may form, and gravitational *circumbinary disk torques* from the gas distribution (typically spiral waves) may become important. Finally, at the smaller separations, *GW emission* takes over. The classic work describing the overall process of binary evolution in its different stages is [BBR1980]. [Kelley2017a] goes into significant detail on implementations and properties of each component of binary evolution also. Triple MBH interactions, and perturbations from other massive objects (e.g. molecular clouds) can also be important.

The `holodeck.evolution` submodule provides tools for modeling the binary evolution from the time of binary 'formation' (i.e. galaxy merger) until coalescence. Models for binary evolutionary can range tremendously in complexity. In the simplest models, binaries are assumed to coalesce instantaneously (in that the age of the universe is the same at formation and coalescence), and are also assumed to evolve purely due to GW emission (in that the time spent in any range of orbital frequencies can be calculated from the GW hardening timescale). Note that these two assumptions are contradictory, but commonly employed in the literature. The ideal, self-consistent approach, is to model binary evolution using self-consistently derived environments (e.g. gas and stellar mass distributions), and applying the same time-evolution prescription to both the redshift evolution of each binary, and also the GW calculation. Note that GWs can only be calculated based on some sort of model for binary evolution. The model may be extremely simple, in which case it is sometimes glanced over.

The core component of the evolution module is the *Evolution* class. This class combines a population of initial binary parameters (i.e. from the `holodeck.population.Pop_Illustris` class), along with a specific binary hardening model (`_Hardening` subclass), and performs the numerical integration of each binary over time - from large separations to coalescence. The *Evolution* class also acts to store the binary evolution histories ('trajectories' or 'tracks'), which are then used to calculate GW signals (e.g. the GWB). To facilitate GW and similar calculations, *Evolution* also provides interpolation functionality along binary trajectories.

8.1.1 To-Do

- General
  - evolution modifiers should act at each step, instead of after all steps? This would be a way to implement a changing accretion rate, for example; or set a max/min hardening rate.
  - re-implement "magic" hardening models that coalesce in zero change-of-redshift or fixed amounts of time.
- Evolution
  - *_sample_universe()* : sample in comoving-volume instead of redshift

References

- [BBR1980] Begelman, Blandford & Rees 1980.
- [Chen2017] Chen, Sesana, & Del Pozzo 2017.
- [Kelley2017a] Kelley, Blecha & Hernquist 2017.
- [Quinlan1996] Quinlan 1996.
- [Sesana2006] Sesana, Haardt & Madau et al. 2006.
- [Sesana2010] Sesana 2010.

class holodeck.discrete.evolution.**Evolution**(*pop*, *hard*, *nsteps: int = 100*, *mods=None*, *debug: bool = False*, *acc=None*)

Bases: `object`

Base class to evolve discrete binary populations forward in time.

NOTE: This class is primary built to be used with `holodeck.population.Pop_Illustris`.

The *Evolution* class is instantiated with a `holodeck.population._Population_Discrete` instance, and a particular binary hardening model (subclass of `_Hardening`). It then numerically integrates each binary from their initial separation to coalescence, determining how much time that process takes, and thus the rate of redshift/time evolution. NOTE: at initialization, a regular range of binary separations are chosen for each binary being evolved, and the integration calculates the time it takes for each step to complete. This is unlike most types of dynamical integration in which there is a prescribed time-step, and the amount of distance (etc) traveled over that time is then calculated.

Initialization: all attributes are set to empty arrays of the appropriate size. NOTE: the 0th step is *not* initialized at this time, it happens in *Evolution.evolve()*.

Evolution: binary evolution is performed by running the *Evolution.evolve()* function. This function first calls *Evolution._init_step_zero()*, which sets the 0th step values, and then iterates over each subsequent step, calling *Evolution._take_next_step()*. Once all steps are taken (integration is completed), then *Evolution._finalize()* is called, at which points any stored modifiers (`utils._Modifier` subclasses, in the *Evolution._mods* attribute) are applied.

NOTE: whenever *frequencies* are used (rest-frame or observer-frame), they refer to **orbital** frequencies, not GW frequencies. For circular binaries, GW-freq = 2 * orb-freq.

8.1.2 Additional Notes

acc: Instance of accretion class. This supplies the method by which total accretion
rates are divided into individual accretion rates for each BH. By default, accretion rates are calculated at every step as a fraction of the Eddington limit. If acc contains a path to an accretion rate file which already stores total accretion rates at every timestep, then we omit the step where we calculate mdot_total as a fraction of the Eddington limit. This gives the flexibility to include accretion rates motivated by e.g. Illustris or other cosmological simulations.

`_EVO_PARS = ['mass', 'sepa', 'eccen', 'scafa', 'tlook', 'dadt', 'dedt']`

`_LIN_INTERP_PARS = ['eccen', 'scafa', 'tlook', 'dadt', 'dedt']`

`_SELF_CONSISTENT = None`

`_STORE_FROM_POP = ['_sample_volume']`

`_pop`
: initial binary population instance

`_debug`
: debug flag for performing extra diagnostics and output

`_nsteps`
: number of integration steps for each binary

`_mods`
: modifiers to be applied after evolution is completed

`scafa`
: scale-factor of the universe, set to 1.0 after z=0

`tlook`
: negative after redshift zero

Type
lookback time [sec], NOTE

`sepa`
: semi-major axis (separation) [cm]

`mass`
: mass of BHs [g], 0-primary, 1-secondary

`mdot`
: accretion rate onto each component of binary [g/s]

`dadt`
: hardening rate in separation [cm/s]

`eccen`
: eccentricity [], *None* if not being evolved

`dedt`
: eccen evolution rate [1/s], *None* if not evolved

evolve(*progress=False*)

Evolve binary population from initial separation until coalescence in discrete steps.

Each binary has a fixed number of 'steps' from initial separation until coalescence. The role of the *evolve()* method is to determine the amount of time each step takes, based on the 'hardening rate' (in separation and possible eccentricity i.e. da/dt and de/dt). The hardening rate is calculated from the stored `_Hardening` instances in the iterable `Evolution._hard` attribute.

When *Evolution.evolve()* is called, the 0th step is initialized separately, using the *Evolution._init_step_zero()* method, and then each step is integrated by calling the *Evolution._take_next_step()* method. Once all steps are completed, the *Evolution._finalize()* method is called, where any stored modifiers are applied.

Parameters

progress (*bool,*) – Show progress-bar using *tqdm* package.

modify(*mods=None*)

Apply and modifiers after evolution has been completed.

at(*xpar*, *targets*, *params=None*, *coal=False*, *lin_interp=None*)

Interpolate evolution to the given target locations in either separation or frequency.

The variable of interpolation is specified with the *xpar* argument. The evolutionary tracks are interpolated in that variable, to the new target locations given by *targets*. We use 'x' to refer to the independent variable, and 'y' to refer to the dependent variable that is being interpolated. Which values are interpolated are specified with the *params* argument.

The behavior of this function is broken into three sub-functions, that are only used here:

- *Evolution._at__inputs()* : parse the input arguments.
- *Evolution._at__index_frac()* : find the indices in the evolutionary tracks bounding the target interpolation locations, and also the fractional distance to interpolate between them.
- *Evolution._at__interpolate_array()* : actually interpolate each parameter to a the target location.

Parameters

- **xpar** (*str, in ['fobs', 'sepa']*) – String specifying the variable of interpolation.
- **targets** (*array_like,*) – Locations to interpolate to:
  - if `xpar == sepa` : binary separation, units of [cm],
  - if `xpar == fobs` : binary orbital freq, observer-frame, units of [1/sec],
- **params** (*None or (list of str)*) – Names of the parameters that should be interpolated. If *None*, defaults to *Evolution._EVO_PARS* attribute.
- **coal** (*bool,*) – Only store evolution values for binaries coalescing before redshift zero. Interpolated values for other binaries are set to *np.nan*.
- **lin_interp** (*None or bool,*) – Interpolate parameters in linear space.
  - True : all parameters interpolated in lin-lin space.
  - False: all parameters interpolated in log-log space.
  - None : parameters are interpolated in log-log space, unless they're included in the *Evolution._LIN_INTERP_PARS* attribute.

Returns

vals – Dictionary of arrays for each interpolated parameter. The returned shape is (N, T), where T is the number of target locations to interpolate to, and N is the total number of binaries. Each data array is filled with *np.nan* values if the targets are outside of its evolution track. If `coal=True`, then binaries that do *not* coalesce before redshift zero also have their data array values fillwed with *np.nan*.

Return type

dict,

Notes

- Out of bounds values are set to *np.nan*.
- Interpolation is 1st-order in log-log space in general, but properties which are in the *_LIN_INTERP_PARS* array are interpolated at 1st-order in lin-lin space. Parameters which can be negative should be interpolated in linear space. Passing a boolean for the *lin_interp* parameter will override the behavior (see *Parameters* above).

_at__inputs(*xpar*, *targets*, *params*, *lin_interp*)

Parse/sanitize the inputs of the *Evolution.at()* method.

Parameters

- **xpar** (*str, in ['fobs', 'sepa']*) – String specifying the variable of interpolation.
- **targets** (*array_like,*) – Locations to interpolate to. One of: * if `xpar == sepa` : binary separation, units of [cm], * if `xpar == fobs` : binary orbital-frequency, observer-frame, units of [1/sec].
- **params** (*None or list[str]*) – Names of parameters that should be interpolated. If *None*, defaults to *Evolution._EVO_PARS* attribute.

Returns

- **xnew** (*np.ndarray*) – (T,) Log10 of the target locations to interpolate to, i.e. `log10(targets)`.
- **xold** (*np.ndarray*) – (N, M) Log10 of the x-values at which to evaluate the target interpolation points. Either `log10(sepa)` or `log10(freq_orb_obs)`. NOTE: these values will be returned in *increasing* order. If they have been reversed, then `rev=True`.
- **params** (*list[str]*) – Names of parameters that should be interpolated.
- **rev** (*bool*) – Whether or not the *xold* array has been reversed.
- **squeeze** (*bool*) – Whether or not the *targets* were a single scalar value (i.e. `T=1`, as opposed to an iterable). If *targets* were a scalar, then the data returned from *Evolution.at()* will be shaped as (N,) instead of (N,T); since in this case, T=1.

_at__index_frac(*xnew*, *xold*)

Find indices bounding target locations, and the fractional distance to go between them.

Parameters

- **xnew** (*np.ndarray*) – Target locations to interplate to. Shape (T,).
- **xold** (*np.ndarray*) – Values of the x-coordinate between which to interpolate. Shape (N, M). These are the x-values of either *sepa* or *fobs* from the evolutionary tracks of each binary.

Returns

- **cut_idx** (*np.ndarray*) – For each binary, the step-number indices between which to interpolate, for each target interpolation point. shape (2, N, T); where the 0th dimension, the 0th value is the low/before index, and the 1th value is the high/after index. i.e. for binary 'i' and target 'j', we need to interpolate between indices given by [0, i, j] and [1, i, j].
- **interp_frac** (*np.ndarray*) – The fractional distance between the low value and the high value, to interpolate to. Shape (2, N, M). For binary 'i' and target 'j', *interp_frac[i, j]* is how the fraction of the way, from index *cut_idx[0, i, j]* to *cut_idx[1, i, j]* to interpolate to, in the *data* array.
- **valid** (*np.ndarray*) – Array of boolean values, giving whether or not the target interpolation points are within the bounds of each binary's evolution track. Shape (N, T).

`_at__interpolate_array`(*yold*, *cut_idx*, *interp_frac*, *lin_interp_flag*)

Interpolate a parameter to a fraction between integration steps.

Parameters

- **yold** (*np.ndarray*) – The data to be interpolated. This is the raw evolution data, for each binary and each step. Shaped either as (N, M) or (N, M, 2) if parameter is mass.
- **cut_idx** (*np.ndarray*) – For each binary, the step-number indices between which to interpolate, for each target interpolation point. shape (2, N, T); where the 0th dimension, the 0th value is the low/before index, and the 1th value is the high/after index. i.e. for binary 'i' and target 'j', we need to interpolate between indices given by [0, i, j] and [1, i, j].
- **interp_frac** (*np.ndarray*) – The fractional distance between the low value and the high value, to interpolate to. Shape (2, N, M). For binary 'i' and target 'j', *interp_frac[i, j]* is how the fraction of the way, from index *cut_idx[0, i, j]* to *cut_idx[1, i, j]* to interpolate to, in the *data* array.
- **lin_interp_flag** (*bool,*) – Whether data should be interpolated in lin-lin space (True), or log-log space (False).

Returns

ynew – The input *data* interpolated to the new target locations. Shape is (N, T) or (N, T, 2) for N-binaries, T-target points. A third dimension is present if the input *data* was 3D.

Return type

np.ndarray

sample_universe(*fobs_orb_edges*, *down_sample=None*)

Construct a full universe of binaries based on resampling this population.

Parameters

- **fobs** (*array_like,*) – Observer-frame *orbital*-frequencies at which to sample population. Units of [1/sec].
- **down_sample** (*None or float,*) – Factor by which to downsample the resulting population. For example, *10.0* will produce 10x fewer output binaries.

Returns

- **names** (*(4,) list of str,*) – Names of the returned binary parameters (i.e. each array in *samples* and *vals*).
- **samples** (*(4, S) ndarray,*) – Sampled binary data. For each binary samples S, 4 parameters are returned: ['mtot', 'mrat', 'redz', 'fobs'] (these are listed in the *names* returned value.) NOTE: *fobs* is *observer*-frame *orbital*-frequencies. These values correspond to all of the

binaries in an observer's Universe (i.e. light-cone), within the given frequency bins. The number of samples *S* is roughly the sum of the *weights* — but the specific number is drawn from a Poisson distribution around the sum of the *weights*.

- **vals** (*((4,) list of (V,) ndarrays or float)*) – Binary parameters (log10 of parameters specified in the *names* return values) at each frequency bin. Binaries not reaching the target frequency bins before redshift zero, or before coalescing, are not returned. Thus the number of values *V* may be less than F*N for F frequency bins and N binaries.
- **weights** (*((V,) ndarray of float)*) – The weight of each binary-frequency sample. i.e. number of observer-universe binaries corresponding to this binary in the simulation, at the target frequency.
- *To-Do*
- —
- * This should sample in volume instead of *redz*, see how it's done in sam module.

_sample_universe__at_values_weights(*fobs_orb_edges*)

Interpolate binary histories to target frequency bins, obtaining parameters and weights.

The *weights* correspond to the number of binaries in an observer's Universe (light-cone) corresponding to each simulated binary sample.

Parameters

fobs_orb_edges (*(F+1,) arraylike*) – Edges of target frequency bins to sample population. These are observer-frame orbital frequencies. Binaries are interpolated to frequency bin centers, calculated from the midpoints of the provided bin edges.

Returns

- **names** (*((4,) list of str,)*) – Names of the returned binary parameters (i.e. each array in *vals*).
- **vals** (*((4,) list of (V,) ndarrays or float)*) – Binary parameters (log10 of parameters specified in the *names* return values) at each frequency bin. Binaries not reaching the target frequency bins before redshift zero, or before coalescing, are not returned. Thus the number of values *V* may be less than F*N for F frequency bins and N binaries.
- **weights** (*((V,) ndarray of float)*) – The weight of each binary-frequency sample. i.e. number of observer-universe binaries corresponding to this binary in the simulation, at the target frequency.

_sample_universe__resample(*fobs_orb_edges*, *vals*, *weights*, *down_sample*)

_init_step_zero()

Set the initial conditions of the binaries at the 0th step.

Transfers attributes from the stored `holodeck.population._Population_Discrete` instance to the 0th index of the evolution arrays. The attributes are [*sepa*, *scafa*, *mass*, and optionally *eccen*]. The hardening model is also used to calculate the 0th hardening rates *dadt* and *dedt*. The initial lookback time, *tlook* is also set.

_take_next_step(*step*)

Integrate the binary population forward (to smaller separations) by one step.

For an integration step *s*, we are moving from index *s-1* to index *s*. These correspond to the 'left' and 'right' edges of the step. The evolutionary trajectory values have already been calculated on the left edges (during either the previous time step, or the initial time step). Each subsequent integration step then proceeds as follows:

(1) The hardening rate is calculated at the right edge of the step.

(2) The time it takes to move from the left to right edge is calculated using a trapezoid rule in log-log space.

(3) The right edge evolution values are stored and updated.

Parameters
step (*int*) – The destination integration step number, i.e. *step=1* means integrate from 0 to 1.

_hardening_rate(*step*, *store_debug=True*)

Calculate the net hardening rate for the given integration step.

The hardening rates (_Hardening subclasses) stored in the Evolution._hard attribute are called in sequence, their _Hardening.dadt_dedt() methods are called, and the da/dt and de/dt hardening rates are added together. NOTE: the da/dt and de/dt values are added together to get the net rate, this is an approximation.

Parameters
step (*int*) – Current step number (the destination of the current step, i.e. step=1 is for integrating from 0 to 1.)

Returns

- **dadt** (*np.ndarray*) – The hardening rate in separation, da/dt, in units of [cm/s]. The shape is (N,) where N is the number of binaries.
- **dedt** (*np.ndarray or None*) – If eccentricity is not being evolved, this is *None*. If eccentricity is being evolved, this is the hardening rate in eccentricity, de/dt, in units of [1/s]. In this case, the shape is (N,) where N is the number of binaries.

_check()

Perform basic diagnostics on parameter validity after evolution.

_finalize()

Perform any actions after completing all of the integration steps.

_update_derived()

Update any derived quantities after modifiers are applied.

property shape

The number of binaries and number of steps (N, S).

property size

The number of binaries

property steps

The number of evolution steps

property coal

Indices of binaries that coalesce before redshift zero.

property tage

Age of the universe [sec] for each binary-step.

Derived from *Evolution.tlook*.

Returns
ta – (B, S). Age of the universe.

Return type
np.ndarray,

property mtmr

Total-mass and mass-ratio.

Returns

- **mt** (*np.ndarray*) – Total mass ($M = m_1 + m_2$) in [gram].
- **mr** (*np.ndarray*) – Mass ratio ($q = m_2/m_1 \leq 1.0$).

property freq_orb_rest

Rest-frame orbital frequency. [1/s]

property freq_orb_obs

Observer-frame orbital frequency. [1/s]

_check_evolved()

Raise an error if this instance has not yet been evolved.

8.2 holodeck.discrete.population

Discrete MBH Binary Populations (from cosmological hydrodynamic simulations) and related tools.

Cosmological hydrodynamic simulations model the universe by coevolving gas along with particles that represent dark matter (DM), stars, and often BHs. These simulations strive to model physical processes at the most fundamental level allowed by resolution constraints / computational limitations. For example, BH accretion will typically be calculated by measuring the local density (and thermal properties) of gas, which may also be subjected to 'feedback' processes from the accreting BH itself, thereby producing a 'self-consistent' model. However, no cosmological simulations are able to fully resolve either the accretion or the feedback process, such that 'sub-grid models' (simplified prescriptions) must be adopted to model the physics at sub-resolution scales.

The numerical methods and subgrid modeling details of cosmological hydrodynamic simulations vary significantly from one code-base and simulation suite to another. This *holodeck* submodule generates populations of MBH binaries using processed data files derived what whatever cosmo-hydro simulations are used. To get to MBHBs, data must be provided either on the encounter ('merger') rate of MBHs from the cosmological simulations directly, or based on the galaxy-galaxy encounters and then prescribing MBH-MBH pairs onto those.

This submodule provides a generalized base-class, *_Population_Discrete*, that is subclassed to implement populations from particular cosmological simulations. At the time of this writing, an Illustris-based implementation is included, *Pop_Illustris*. Additionally, a set of classes are also provided that can make 'modifications' to these populations based on subclasses of the *_Population_Modifier* base class. Examples of currently implemented modifiers are: adding eccentricity to otherwise circular binaries (*PM_Eccentricity*), or changing the MBH masses to match prescribed scaling relations (*PM_Mass_Reset*).

The implementation for binary evolution (e.g. environmental hardening processes), as a function of separation or frequency, are included in the `holodeck.evolution` module. The population classes describe the 'initial conditions' of binaries. The initial conditions, or 'formation', of the binary can be defined arbitrarily. In practice, due to cosmologcal-simulation resolution constraints, this is at/during the galaxy merger when the two MBHs are at separations of roughly a kiloparsec, and not gravitational bound, or even interacting. Depending on what evolution model is used along with the initial population, all or only some fraction of 'binaries' (MBH pairs) will actually reach the small separations to become a true, gravitationally-bound binary.

The fundamental, required attributes for all population classes are:

- *sepa* the initial binary separation in [cm]. This should be shaped as (N,) for N binaries.
- *mass* the mass of each component in the binary in [gram]. This should be shaped as (N, 2) for N binaries, and the two components of the binary. The 0th index should refer to the more massive primary, while the 1th component refers to the less massive secondary.

- *scafa* the scale-factor defining the age of the universe for formation of this binary. This should be shaped as (N,).

Notes

- **Populations (subclasses of *_Population_Discrete*)**
  - The *_init()* method is used to set the basic attributes of the binary population (i.e. *sepa*, *mass*, and *scafa*).
  - The *_update_derived()* method is used to set quantities that are derived from the basic attributes. For example, the *size* attribute should be set here, based on the length of the attribute arrays.
- **Modifiers (subclasses of *_Population_Modifier*)**
  - The *modify()* method must be overridden to change the attributes of a population instance. The changes should be made in-place (i.e. without returning a new copy of the population instance).

References

- [Genel2014] Genel et al. (2014)
- [Kelley2017a] Kelley, Blecha, and Hernquist (2017a).
- [Kelley2017b] Kelley et al. (2017b).
- [Kelley2018] Kelley et al. (2018).
- [Nelson2015] Nelson et al. (2015)
- [Rodriguez-Gomez2015] Rodriguez-Gomez et al. (2015)
- [Sijacki2015] Sijacki et al. (2015)
- [Springel2010] Springel (2010)
- [Vogelsberger2014] Vogelsberger et al. (2014)

class holodeck.discrete.population.**_Population_Discrete**(**args*, *mods=None*, *check=True*, ***kwargs*)

Bases: ABC

Base class for representing discrete binaries, e.g. from cosmo hydrodynamic simulations.

This class must be subclasses for specific implementations (i.e. for specific cosmo sims).

mass

blackhole masses (N, 2)

sepa

binary separation *a* (N,)

scafa

scale factor of the universe (N,)

eccen

binary eccentricities (N,) [optional]

weight

weight of each binary as a sample point (N,) [optional]

_size

number of binaries

_sample_volume

comoving volume containing the binary population [cm^3]

abstract _init()

Initialize basic binary parameters.

This function should typically be overridden in subclasses.

_update_derived()

Set or reset any derived quantities.

property size

Number of binaries in descrete population.

Returns
Number of binaries.

Return type
int

property mtmr

Total mass and mass-ratio of each binary.

Returns
The total-mass (0) and mass-ratio (1) of each binary.

Return type
ndarray (2, N)

property redz

Redshift at formation of each binary.

Returns
Redshift.

Return type
ndarray (N,)

modify(*mods=None*)

Apply any population modifiers to this population.

Process: 1) Each modifier is applied to the population and *_update_derived()* is called. 2) After all modifiers are applied, *_finalize()* is called. 3) If the *_check_flag* attribute is true, then the *_check()* method is called.

Parameters
mods (None or (list of *Population_Modifer*)) – Population modifiers to apply to this population.

_finalize()

Method called after all population modifers have been applied, in the *modify()* method.

_check()

Perform diagnostic/sanity checks on the binary population.

_abc_impl = <_abc._abc_data object>

class holodeck.discrete.population.**Pop_Illustris**(*fname=None*, ***kwargs*)

Bases: *_Population_Discrete*

Discrete population derived from the Illustris cosmological hydrodynamic simulations.

Illustris are a suite of cosmological simulations that co-evolve gas, stars, dark-matter, and BHs from the early universe until redshift zero. The simulations are based on the moving-mesh hydrodynamics code arepo [Springel2010]. The basic results of the simulations are presented in [Vogelsberger2014] & [Genel2014], which emphasize the simulations' accuracy in reproducing the properties and evolution of galaxies across cosmic time. [Sijacki2015] goes into more depth about the MBH implementation, their results, and comparisons with observational measuremens of MBHs and AGN. The Illustris data, including MBH binary catalogs, are available online, described in [Nelson2015]. Catalogs of galaxy-galaxy mergers have also been calculated and released publically, described in [Rodriguez-Gomez2015].

Takes as input a data file that includes BH and subhalo data for BH and/or galaxy mergers.

Notes

- **Parameters required in input hdf5 file:**
  - *box_volume_mpc*:
  - *part_names*:
  - *time*:
  - *SubhaloHalfmassRadType*:
  - *SubhaloMassInRadType*:
  - *SubhaloVelDisp*:
  - *SubhaloBHMass*:

_fname

Filename for binary data

_init()

Set the population parameters using an input simulation file.

_abc_impl = <_abc._abc_data object>

class holodeck.discrete.population.**_Population_Modifier**

Bases: *_Modifier*

Base class for constructing Modifiers that are applied to *_Discrete_Population* instances.

_abc_impl = <_abc._abc_data object>

class holodeck.discrete.population.**PM_Eccentricity**(*eccen_dist: Tuple[float, float] = (1.0, 0.2)*)

Bases: *_Population_Modifier*

Population Modifier to implement eccentricity in the binary population.

eccen_dist

Two parameter specification for eccentricity distribution

modify(*pop*)

Add eccentricity to the given population.

Passes the *self.eccen_dist* attribute to the *holodeck.utils.eccen_func* function.

Parameters
pop (instance of *_Population_Discrete* or subclass,) – Binary population to be modified.

_random_eccentricities(*size*) → ndarray

Draw random eccentricities from the standard distribution.

Parameters
size (*scalar,*) – The number of eccentricity values to draw. Cast to *int*.

Returns
Eccentricities, with shape (N,) such that N is the parameter *size* cast to *int* type.

Return type
ndarray

_abc_impl = <_abc._abc_data object>

class holodeck.discrete.population.**PM_Resample**(*resample=10.0*, *plot=False*, *additional_keys=True*)

Bases: *_Population_Modifier*

Population Modifier to resample a population instance to a new number of binaries.

Uses *kalepy* kernel density estimation (KDE) to resample the original population into a new one, changing the total number of binaries by some factor (usually increasing the population).

Notes

Resampled Parameters: By default, four or five parameters are resampled: 1) *mtot*: total mass; 2) *mrat*: mass ratio; 3) *redz*: redshift; and 4) *sepa*: separation; and if the *eccen* attrbute of the population is not *None*, then it is also resampled. Additional parameters can be specified using the *_DEF_ADDITIONAL_KEYS* attribute which is a list of str giving the parameter names, which must then be accessible attributes of the population instance being resampled. **Sample Volume**: *_Discrete_Population* instances refer to some finite (comoving) volume of the Universe, which is given in the population's *_sample_volume* attribute. When resampling is performed, this volume is also multiplied by the same resampling factor. For example, if the population is resampled 10x (i.e. `resample==10.0`), then the *_sample_volume* attribute is also multiplied by 10x.

_DEF_ADDITIONAL_KEYS = ['vdisp', 'mbulge']

_old_data

Version of the previous population stored for plotting purposes

_new_data

Version of the updated population stored for plotting purposes

_additional_keys

Additional parameter names to be resampled

modify(*pop*)

Resample the binaries from the given population to achieve a new number of binaries.

Parameters
pop (instance of *_Population_Discrete* or subclass,) – Binary population to be modified.

plot()

Plot a comparison of the old and new data, before and after resampling.

A *kalepy.Corner* plot is generated.

Returns
The figure object containing the plot.

Return type
mpl.figure.Figure instance,

_abc_impl = <_abc._abc_data object>

class holodeck.discrete.population.**PM_Mass_Reset**(*mhost*, *scatter=True*)

Bases: *_Population_Modifier*

Reset the masses of a target population based on a given M-Host relation.

mhost

Scaling relationship between host and MBH (*holo.host_relations._BH_Host_Relation*)

_scatter

Bool determining whether resampled masses should include statistical scatter

modify(*pop*)

Reset the BH masses of the given population.

Parameters
pop (instance of *_Population_Discrete* or subclass,) – Binary population to be modified.

_abc_impl = <_abc._abc_data object>

class holodeck.discrete.population.**PM_Density**(*factor*)

Bases: *_Population_Modifier*

modify(*pop*)

Perform an in-place modification on the passed object instance.

Parameters
base (*object*) – The object instance to be modified.

_abc_impl = <_abc._abc_data object>

CHAPTER

NINE

HOLODECK.SAMS (SEMI-ANALYTIC MODELS) MODULE

holodeck - Semi-Analytic Models (SAMs)

The *holodeck* SAMs construct MBH binary populations using simple semi-analytic and/or semi-empirical relationships. For more information, see the *SAMs getting-started guide*.

The core element of holodeck SAMs is the `Semi_Analytic_Model` class. Instances of this class piece together the different components of the model (defined in `holodeck.sams.components`) to construct a population. The population is evolved with a binary evolution model, implemented as a subclass of the `_Hardening`, typically in the `holodeck.hardening` module.

9.1 holodeck.sams.components

Semi-Analytic Model - Components

This module provides the key building blocks for the holodeck SAMs. In particular, the:

- Galaxy Stellar-Mass Function (GSMF) : number-density of galaxies as a function of stellar mass;
- Galaxy Merger Rate (GMR) : rate of galaxy mergers per galaxy;
- Galaxy Pair Fraction (GPF) : fraction of galaxy pairs, relative to all galaxies;
- Galaxy Merger Time (GMT) : duration over which galaxy pairs are observable as pairs.

For more information see the `holodeck.sams` module, or the *SAMs getting-started guide*.

References

- [Sesana2008] Sesana, Vecchio, Colacino 2008.
- **[Rodriguez-Gomez2015] Rodriguez-Gomez, Genel, Vogelsberger, et al. 2015**
  The merger rate of galaxies in the Illustris simulation: a comparison with observations and semi-empirical models https://ui.adsabs.harvard.edu/abs/2015MNRAS.449...49R/abstract
- [Chen2019] Chen, Sesana, Conselice 2019.
- **[Leja2020] Leja, Speagle, Johnson, et al. 2020.**
  A New Census of the 0.2 < z < 3.0 Universe. I. The Stellar Mass Function https://ui.adsabs.harvard.edu/abs/2020ApJ...893..111L/abstract

class holodeck.sams.components.**_Galaxy_Stellar_Mass_Function**(**args*, ***kwargs*)

Bases: ABC

Galaxy Stellar-Mass Function base-class. Used to calculate number-density of galaxies.

mbh_mass_func(*mbh*, *redz*, *mmbulge*, *scatter=None*)

Convert from the GSMF to a MBH mass function (number density), using a given Mbh-Mbulge relation.

Parameters

- **mbh** (*array_like*) – Blackhole masses at which to evaluate the mass function.
- **redz** (*array_like*) – Redshift(s) at which to evaluate the mass function.
- **mmbulge** (*relations._MMBulge_Relation* subclass instance) – Scaling relation between galaxy and MBH masses.
- **scatter** (*None, bool, or float*) – Introduce scatter in masses. * *None* or *True* : use the value from *mmbulge._scatter_dex* * *False* : do not introduce scatter * float : introduce scatter with this amplitude (in dex)

Returns

ndens – Number density of MBHs, in units of [Mpc^-3]

Return type

array_like

_abc_impl = <_abc._abc_data object>

class holodeck.sams.components.**GSMF_Schechter**(*phi0=-2.77*, *phiz=-0.27*, *mchar0_log10=11.24*, *mchar0=None*, *mcharz=0.0*, *alpha0=-1.24*, *alphaz=-0.03*)

Bases: *_Galaxy_Stellar_Mass_Function*

Single Schechter Function - Galaxy Stellar Mass Function.

This is density per unit log10-interval of stellar mass, i.e. $\Phi = dn/d\log_{10}(M)$

See: [Chen2019] Eq.9 and enclosing section.

_phi_func(*redz*)

See: [Chen2019] Eq.9

_mchar_func(*redz*)

See: [Chen2019] Eq.10 - NOTE: added *redz* term

_alpha_func(*redz*)

See: [Chen2019] Eq.11

_abc_impl = <_abc._abc_data object>

class holodeck.sams.components.**_GSMF_Single_Schechter**(*log10_phi_terms*, *log10_mstar_terms*, *alpha*)

Bases: *_Galaxy_Stellar_Mass_Function*

Schechter function, with parameters as quadratics with respect to redshift.

Parameterization follows [Leja2020] and is primarily for use in the *GSMF_Double_Schechter* class. From [Leja2020] Eq.14:

$$\frac{\partial n}{\partial \log_{10} M} = \ln(10)\phi \left(\frac{M}{M_\star}\right)^{\alpha+1} \exp[-M/M_\star].$$

The power-law index α is a scalar value, while the reference mass $M_\star$, and the normalization ϕ are defined as quadratics with respect to redshift:

$$\log_{10}(\phi) = a_0 + a_1 z + a_2 z^2,$$
$$\log_{10}(M_\star) = b_0 + b_1 z + b_2 z^2.$$

Class instances are callable, see `__call__()`, and return galaxy number densities in units of $[\mathrm{Mpc}^{-3}\,\mathrm{dex}^{-1}]$.

_log10_phi_terms

these are the a_i terms in the defintion.

_log10_mstar_terms

these are the b_i terms.

_alpha

power-law index

_phi_func(*redz*)

Evaluate the GSMF normalization (phi) at the given redshift(s).

Parameters
redz (*array_like of float,*) – Redshift(s) at which to calculate the GSMF normalization.

Returns
phi – Number density normalization.

Return type
array_like of float, [Mpc^-3 dex^-1]

_mstar_func(*redz*)

Evaluate the GSMF characteristic mass ($M_\star$) at the given redshift(s).

_abc_impl = <_abc._abc_data object>

class holodeck.sams.components.**GSMF_Double_Schechter**(*log10_phi1=[-2.383, -0.264, -0.107]*, *log10_phi2=[-2.818, -0.368, 0.046]*, *log10_mstar=[10.767, 0.124, -0.033]*, *alpha1=-0.28*, *alpha2=-1.48*)

Bases: *_Galaxy_Stellar_Mass_Function*

Sum of two Schechter functions, each parameterized as quadratics in redshift.

For each Schechter Function (*_GSMF_Single_Schechter*), the normalizations (ϕ) and characteristic masses ($M_\star$) are parameterized as quadratics with respect to redshift.

Each Schechter function is parameterized as,

$$\frac{\partial n}{\partial \log_{10} M} = \ln(10)\,\phi \cdot \left(\frac{M}{M_\star}\right)^{\alpha+1} \exp[-M/M_\star],$$
$$\log_{10}(\phi) = a_0 + a_1 z + a_2 z^2,$$
$$\log_{10}(M_\star) = b_0 + b_1 z + b_2 z^2.$$

The parameters for ϕ and α are different for the two functions, while the parameters for $M_\star$ are shared (i.e. the same characteristic mass is used for both). Default parameters are the best fits from [Leja2020]. With uncertainties, these are:

```
log10(phi_1):  [ -2.383 ± 0.027,  -0.264 ± 0.071,  -0.107 ± 0.030],
log10(phi_2):  [ -2.818 ± 0.050,  -0.368 ± 0.070,  +0.046 ± 0.020],
log10(M_star): [+10.767 ± 0.026,  +0.124 ± 0.045,  -0.033 ± 0.015].
```

_abc_impl = <_abc._abc_data object>

class holodeck.sams.components._Galaxy_Merger_Rate(*args, **kwargs)

Bases: ABC

Galaxy Merger Rate base class, used to model merger rates of galaxy pairs.

NOTE: the definition of mass is ambiguous, i.e. whether it is the primary mass, the combined system mass, the descendent mass, etc.

_Galaxy_Merger_Rate instances are callable, returning the specific galaxy merger-rate (i.e. the rate per galaxy), per unit mass-ratio, i.e.

$$R = \frac{\partial N_{\rm mergers}(M_\star, q_\star, z)}{\partial q_\star \, \partial t}.$$

Typically the mass $M_\star$ is taken to be that of the descendent (roughly the combined mass of the two galaxies), and the mass ratio is $q_\star \equiv M_{2,\star}/M_{1,\star} \leq 1.0$.

_abc_impl = <_abc._abc_data object>

class holodeck.sams.components.GMR_Illustris(*norm0_log10=None*, *normz=None*, *malpha0=None*, *malphaz=None*, *mdelta0=None*, *mdeltaz=None*, *qgamma0=None*, *qgammaz=None*, *qgammam=None*)

Bases: _Galaxy_Merger_Rate

Galaxy Merger Rate - based on multiple power-laws.

See [Rodriguez-Gomez2015], Table 1. "merger rate as a function of descendant stellar mass M_star, progenitor stellar mass ratio mu_star"

_get_norm(*redz*)

_get_malpha(*redz*)

_get_mdelta(*redz*)

_get_qgamma(*redz*, *mtot*)

_abc_impl = <_abc._abc_data object>

class holodeck.sams.components._Galaxy_Pair_Fraction(*args, **kwargs)

Bases: ABC

Galaxy Pair Fraction base class, used to describe the fraction of galaxies in mergers/pairs.

_abc_impl = <_abc._abc_data object>

class holodeck.sams.components.GPF_Power_Law(*frac_norm_allq=0.025*, *frac_norm=None*, *mref=None*, *mref_log10=11.0*, *malpha=0.0*, *zbeta=0.8*, *qgamma=0.0*, *obs_conv_qlo=0.25*, *max_frac=1.0*)

Bases: _Galaxy_Pair_Fraction

Galaxy Pair Fraction - Single Power-Law

_abc_impl = <_abc._abc_data object>

class holodeck.sams.components._Galaxy_Merger_Time(*args, **kwargs)

Bases: ABC

Galaxy Merger Time base class, used to model merger timescale of galaxy pairs.

zprime(*mass*, *mrat*, *redz*, ***kwargs*)

Return the redshift after merger (i.e. input *redz* delayed by merger time).

_abc_impl = <_abc._abc_data object>

class holodeck.sams.components.**GMT_Power_Law**(*time_norm=1.7356680000000002e+16*, *mref0=1.9884098706980508e+44*, *malpha=0.0*, *zbeta=-0.5*, *qgamma=0.0*)

Bases: *_Galaxy_Merger_Time*

Galaxy Merger Time - simple power law prescription

_abc_impl = <_abc._abc_data object>

9.2 holodeck.sams.sam

Semi Analytic Modeling (SAM) submodule.

The core element of the SAM module is the *Semi_Analytic_Model* class. This class requires four components as arguments:

(1) Galaxy Stellar Mass Function (GSMF): gives the comoving number-density of galaxies as a function of stellar mass. This is implemented as subclasses of the `_Galaxy_Stellar_Mass_Function` base class.

(2) Galaxy Pair Fraction (GPF): gives the fraction of galaxies that are in a 'pair' with a given mass ratio (and typically a function of redshift and primary-galaxy mass). Implemented as subclasses of the `_Galaxy_Pair_Fraction` subclass.

(3) Galaxy Merger Time (GMT): gives the characteristic time duration for galaxy 'mergers' to occur. Implemented as subclasses of the `_Galaxy_Merger_Time` subclass.

(4) M_bh - M_bulge Relation (mmbulge): gives MBH properties for a given galaxy stellar-bulge mass. Implemented as subcalsses of the *holodeck.host_relations._MMBulge_Relation* subclass.

The *Semi_Analytic_Model* class defines a grid in parameter space of total MBH mass ($M = M_1 + M_2$), MBH mass ratio (q
$equiv M_1/M_2$), redshift (z), and at times binary separation (semi-major axis a) or binary rest-frame orbital-frequency (f_r). Over this grid, the distribution of comoving number-density of MBH binaries in the Universe is calculated. Methods are also provided that interface with the *kalepy* package to draw 'samples' (discretized binaries) from the distribution, and to calculate GW signatures.

The step of going from a number-density of binaries in (M, q, z) space, to also the distribution in a or f is subtle, as it requires modeling the binary evolution (i.e. hardening rate).

9.2.1 To-Do (sam.py)

- Allow SAM class to take M-sigma in addition to M-Mbulge.

References

- [Sesana2008] Sesana, Vecchio, Colacino 2008.
- [Chen2019] Chen, Sesana, Conselice 2019.

holodeck.sams.sam.**REDZ_SAMPLE_VOLUME = True**

get redshifts by sampling uniformly in 3D spatial volume, and converting

holodeck.sams.sam.**GSMF_USES_MTOT = False**

the mass used in the GSMF is interpretted as M=m1+m2, otherwise use primary m1

holodeck.sams.sam.**GPF_USES_MTOT = False**

the mass used in the GPF is interpretted as M=m1+m2, otherwise use primary m1

holodeck.sams.sam.**GMT_USES_MTOT = False**

the mass used in the GMT is interpretted as M=m1+m2, otherwise use primary m1

class holodeck.sams.sam.**Semi_Analytic_Model**(*mtot=(1.988409870698051e+37, 1.988409870698051e+45, 91), mrat=(0.001, 1.0, 81), redz=(0.001, 10.0, 101), shape=None, log=None, gsmf=<class 'holodeck.sams.components.GSMF_Schechter'>, gpf=None, gmt=None, gmr=None, mmbulge=<class 'holodeck.host_relations.MMBulge_KH2013'>, **kwargs*)

Bases: `object`

Semi-Analytic Model (SAM) of MBH Binary populations.

This class produces simulated MBH binary populations using idealized (semi-)analytic functions starting from galaxy populations, to massive black holes, to merger rates. Using SAMs, MBH binary populations are calculated over a fixed, rectilinear grid of 3 or 4 dimensional parameter-space. The starting parameter space is total mass, mass ratio, and redshift; but often the distribution of binaries are desired at particular orbital frequencies or separations, which adds a dimension. Some parameters are calculated at grid edges (e.g. binary number densities), while others are calculated at grid centers (e.g. number of binaries in a universe). Ultimately, what the SAM calculates in the number (or number-density) of binaries at each point in this 3-4 dimensional parameter space.

Conceptually, three components are required to build SAMs.

(1) Galaxies and stellar-masses (i.e. how many galaxies there are as a function of stellar mass and redshift). This component is provided by the Galaxy Stellar-Mass Function (GSMF), which are implemented as subclasses of the *holodeck.sams.components._Galaxy_Stellar_Mass_Function* base-class.

(2) Galaxy merger rates (GMRs; i.e. how often galaxies merge as a function of stellar mass, mass ratio, and redshift.) This component can be provided in two ways:

- Subclasses of *holodeck.sams.components._Galaxy_Merger_Rate*, which provide merger rates directly.
- Both a galaxy pair fraction (GPF; subclasses of *holodeck.sams.components._Galaxy_Pair_Fraction*) which give the fraction of galaxies in the process of merger, and a galaxy merger time (GMT; subclasses of *holodeck.sams.components._Galaxy_Merger_Time*) which gives the duration of time that galaxies spend in the merger process.

(3) MBH-Host relationships which determine MBH properties for a given host galaxy. Currently these relationships are only fully implemented as Mbh-MBulge (MMBulge) relationships, which are subclasses of *holodeck.host_relations._MMBulge_Relation*.

__init__(*mtot=(1.988409870698051e+37, 1.988409870698051e+45, 91), mrat=(0.001, 1.0, 81), redz=(0.001, 10.0, 101), shape=None, log=None, gsmf=<class 'holodeck.sams.components.GSMF_Schechter'>, gpf=None, gmt=None, gmr=None, mmbulge=<class 'holodeck.host_relations.MMBulge_KH2013'>, **kwargs*)

Construct a new `Semi_Analytic_Model` instance.

Parameters

- **mtot** (*(3,) tuple*) – Specification for the domain of the grid in total-mass. Three arguments must be included, the 0th giving the lower-limit [grams], the 1th giving the upper-limit [grams], and the 2th giving the number of bin-edges (i.e. the number-of-bins plus one).
- **mrat** (*(3,) tuple*) – Specification for the domain of the grid in mass-ratio. Three arguments must be included, the 0th giving the lower-limit, the 1th giving the upper-limit, and the 2th giving the number of bin-edges (i.e. the number-of-bins plus one).
- **redz** (*(3,) tuple*) – Specification for the domain of the grid in redshift. Three arguments must be included, the 0th giving the lower-limit, the 1th giving the upper-limit, and the 2th giving the number of bin-edges (i.e. the number-of-bins plus one).
- **shape** (*int or (3,) tuple*) – The shape of the grid in total-mass, mass-ratio, and redshift. This argument specifies the number of grid-edges in each dimension, and overrides the shape arguments of `mtot`, `mrat`, and `redz`.
  - If a single *int* is given, then this is the number of edges for all dimensions.
  - If a (3,) iterable of values is given, then each value specifies the size of the grid in the corresponding dimension. *None* values can be provided which indicate to use the default sizes (provided by the `mtot`, `mrat`, and `redz` arguments.) For example, `shape=(12, None, 14)` would produce 12 grid edges in total mass, the default number of grid edges in mass ratio, and 14 grid edges in redshit.
- **gsmf** (None or `_Galaxy_Stellar_Mass_Function` subclass instance) –
- **gpf** (None or `_Galaxy_Pair_Fraction` subclass instance) –
- **gmt** (None or `_Galaxy_Merger_Time` subclass instance) –
- **gmr** (None or `_Galaxy_Merger_Rate` subclass instance) –
- **mmbulge** (None or `_MMBulge_Relation` subclass instance) –

_gsmf

Galaxy Stellar-Mass Function (*_Galaxy_Stellar_Mass_Function* instance)

_gmr

Galaxy Merger Rate (*_Galaxy_Merger_Rate* instance)

_gpf

Galaxy Pair Fraction (*_Galaxy_Pair_Fraction* instance)

_gmt

Galaxy Merger Time (*_Galaxy_Merger_Time* instance)

_mmbulge

Mbh-Mbulge relation (*host_relations._MMBulge_Relation* instance)

_density

Binary comoving number-density

_shape

Shape of the parameter-space domain (mtot, mrat, redz)

_redz_prime

redshift following galaxy merger process

_gmt_time

GMT timescale of galaxy mergers [sec], set in *static_binary_density*

property edges

[*mtot*, *mrat*, *redz*])

Type
The grid edges defining the domain (list of

property shape

Shape of the parameter space domain (number of edges in each dimension), (3,) tuple

mass_stellar()

Calculate stellar masses for each MBH based on the M-MBulge relation.

Returns
masses – Galaxy total stellar masses for all MBH. [0, :] is primary, [1, :] is secondary [grams].

Return type
(2, N) ndarray of scalar,

property static_binary_density

The number-density of binaries at the edges of the grid in mtot, mrat, redz.

The 'number density' is a density both in terms of volume (i.e. number of binaries per unit comoving-volume, $n = dN/dV_c$), and in terms of binary parameters (e.g. binaries per unit of log10 mass, $dn/d\log_{10} M$). Specifically, the values returned are:

$$d^3n/[d\log_{10} M dq dz]$$

For each *Semi_Analytic_Model* instance, this value is calculated once and cached.

Returns
density – Number density of binaries, per unit redshift, mass-ratio, and log10 of mass. The values are in units of inverse cubic, comoving-Mpc.

Return type
(M, Q, Z) ndarray [$cMpc^{-3}$]

Notes

- This function effectively calculates Eq.21 & 5 of [Chen2019]; or equivalently, Eq. 6 of [Sesana2008].
- Bins which 'merge' after redshift zero are set to zero density (using the *self._gmt* instance).

dynamic_binary_number_at_fobs(*hard*, *fobs_orb*, *use_cython=True*, ***kwargs*)

Calculate the differential number of binaries in at each grid point, at each frequency.

The number of binaries is a differential over binary parameters (e.g. number of binaries per unit of log10 mass, $dN/d\log_{10} M$). Specifically, the values returned are:

$$d^4N/[d\log_{10} M dq dz d\ln f_{obs}]$$

The calculated number of binaries is obtained by converting the number-density (calculated in *Semi_Analytic_Model.static_binary_density()*) using the given binary hardening model (*hard*) to evolve the binaries to the frequencies of interest.

To convert to the number of binaries (non-differential number), use the method `holodeck.utils.integrate_differential_number_3dx1d()`.

Parameters

- **hard** (`holodeck.hardening._Hardening` subclass instance,) – Binary evolution model used to evolve binaries to the target frequencies.
- **fobs_orb** (*(F,) array_like [1/s]*) – Observer-frame orbital frequencies at which to evaluate the differential number of binaries, in units of inverse seconds. Note that the number of binaries are evaluated *at* these frequencies (not between them), so they act as bin centers, not bin edges.
- **use_cython** (*bool*) –

Returns

- **grid** (*(4,) list of ndarray*) – The locations of the parameter-space grid at which the differential number of binaries is evaluated. The elements are: {total mass, mass ratio, redshift, frequency}. The total mass, mass ratio, and redshfit arrays correspond to grid edges, while the frequency array is bin centers. The frequency values are exactly the same as those that are passed in with the `fobs_orb` variable. The first three edges are the same as the grid edges stored within the *Semi_Analytic_Model* instance, i.e. the attributes: `Semi_Analytic_Model.mtot`, `Semi_Analytic_Model.mrat`, and `Semi_Analytic_Model.redz`.
- **dnum** (*(M, Q, Z, F) ndarray []*) – The differential number of binaries per unit 4-D parameter-space volume. Unitless.
- **redz_final** (*(M, Q, Z, F) ndarray []*) – The redshift at which each grid point reaches the target frequencies. This is distinct from the `Semi_Analytic_Model.redz` parameter which gives the redshift at the time of galaxy merger. Unitless.

_dynamic_binary_number_at_fobs_consistent(*hard*, *fobs_orb*, *steps=200*, *details=False*)

Calculate the differential number of binaries in at each grid point, at each frequency.

See *dynamic_binary_number_at_fobs()* for general information.

This is the python implementation for binary evolution (hardening) that is self-consistent, i.e. evolution models that are able to evolve binaries from galaxy merger until the target frequencies.

This function should produce the same results as the new cython implementation in: *holodeck.sams.sam_cyutils.dynamic_binary_number_at_fobs()*, which is more than 10x faster. This python implementation is maintained for diagnostic purposes, and for functionality when cython is not available.

BUG doesn't work for Fixed_Time_2PL

_dynamic_binary_number_at_fobs_inconsistent(*hard*, *fobs_orb*)

_dynamic_binary_number_at_sepa_consistent(*hard*, *target_sepa*, *steps=200*, *details=False*)

Get correct redshifts for full binary-number calculation.

Slower but more correct than old *dynamic_binary_number*. Same as new cython implementation *sam_cyutils.dynamic_binary_number_at_fobs*, which is more than 10x faster. LZK 2023-05-11

gwb_new(*fobs_gw_edges*, *hard=<holodeck.hardening.Hard_GW object>*, *realize=100*)

Calculate GWB using new cython implementation, 10x faster!

gwb_old(*fobs_gw_edges*, *hard=<class 'holodeck.hardening.Hard_GW'>*, *realize=100*)

Calculate GWB using new *dynamic_binary_number_at_fobs* method, better, but slower.

gwb_ideal(*fobs_gw*, *sum=True*, *redz_prime=None*)

Calculate the idealized, continuous GWB amplitude.

Calculation follows [Phinney2001] (Eq.5) or equivalently [Enoki+Nagashima-2007] (Eq.3.6). This calculation assumes a smooth, continuous population of binaries that are purely GW driven. * There are no finite-number effects. * There are no environmental or non-GW driven evolution effects. * There is no coalescence of binaries cutting them off at high-frequencies.

gwb(*fobs_gw_edges*, *hard=<holodeck.hardening.Hard_GW object>*, *realize=100*, *loudest=1*, *params=False*)

Calculate the (smooth/semi-analytic) GWB and CWs at the given observed GW-frequencies.

Parameters

- **fobs_gw_edges** (*(F,) array_like of scalar,*) – Observer-frame GW-frequencies. [1/sec] These are the frequency bin edges, which are integrated across to get the number of binaries in each frequency bin.
- **hard** (*holodeck.evolution._Hardening class or instance*) – Hardening mechanism to apply over the range of *fobs_gw*.
- **realize** (*int*) – Specification of how many discrete realizations to construct. Realizations approximate the finite-source effects of a realistic population.
- **loudest** (*int*) – Number of loudest single sources to distinguish from the background.
- **params** (*Boolean*) – Whether or not to return astrophysical parameters of the binaries.

Returns

- **hc_ss** (*(F, R, L) NDarray of scalars*) – The characteristic strain of the L loudest single sources at each frequency.
- **hc_bg** (*(F, R) NDarray of scalars*) – Characteristic strain of the GWB.
- **sspar** (*(4, F, R, L) NDarray of scalars*) – Astrophysical parametes (total mass, mass ratio, initial redshift, final redshift) of each loud single sources, for each frequency and realization. Returned only if params = True.
- **bgpar** (*(7, F, R) NDarray of scalars*) – Average effective binary astrophysical parameters (total mass, mass ratio, initial redshift, final redshift, final comoving distance, final separation, final angular separation) for background sources at each frequency and realization, Returned only if params = True.

rate_chirps(*hard=None*, *integrate=True*)

Find the event rate of binary coalescences ('chirps').

Get the number of coalescence events per unit time, in units of [1/sec].

Parameters

- **hard** (None or *_Hardening* subclass instance) –
- **integrate** (*bool*) –

Returns

- **redz_final** (*(M, Q, Z)*) – Redshift of binary coalescence. Binaries stalling before *z=0*, have values set to *-1.0*.
- **rate** (*ndarray*) – Rate of coalescence events in each bin, in units of [1/sec]. The shape and meaning depends on the value of the *integrate* flag:

- if *integrate* == *True*, then the returned values is `dN/dt`, with shape (M-1, Q-1, Z-1)
- if *integrate* == *False*, then the returned values is `dN/[dlog10M dq dz dt]`, with shape (M, Q, Z)

_integrate_event_rate(*rate*)

_ndens_gal(*mass_gal*, *mrat_gal*, *redz*)

_ndens_mbh(*mass_gal*, *mrat_gal*, *redz*)

_integrated_binary_density(*ndens=None*, *sum=True*)

holodeck.sams.sam.**sample_sam_with_hardening**(*sam*, *hard*, *fobs_orb=None*, *sepa=None*, *sample_threshold=10.0*, *cut_below_mass=None*, *limit_merger_time=None*, ***sample_kwargs*)

Discretize Semi-Analytic Model into sampled binaries assuming the given binary hardening rate.

Parameters

- **sam** (*Semi_Analytic_Model*) – Instance of an initialized semi-analytic model.
- **hard** (*holodeck.evolution._Hardening*) – Binary hardening model for calculating binary hardening rates (dadt or dfdt).
- **fobs_orb** (*ArrayLike*) – Observer-frame orbital-frequencies. Units of [1/sec]. NOTE: Either *fobs_orb* or *sepa* must be provided, and not both.
- **sepa** (*ArrayLike*) – Binary orbital separation. Units of [cm]. NOTE: Either *fobs_orb* or *sepa* must be provided, and not both.

Returns

- **vals** (*(4, S) ndarray of scalar*) – Parameters of sampled binaries. Four parameters are: * mtot : total mass of binary (m1+m2) in [grams] * mrat : mass ratio of binary (m2/m1 <= 1) * redz : redshift of binary * fobs_orb / sepa : observer-frame orbital-frequency [1/s] or binary separation [cm]
- **weights** (*(S,) ndarray of scalar*) – Weights of each sample point.
- **edges** (*(4,) of list of scalars*) – Edges of parameter-space grid for each of above parameters (mtot, mrat, redz, fobs_orb) The lengths of each list will be [(M,), (Q,), (Z,), (F,)]
- **dnum** (*(M, Q, Z, F) ndarray of scalar*) – Number-density of binaries over grid specified by *edges*.

holodeck.sams.sam.**evolve_eccen_uniform_single**(*sam*, *eccen_init*, *sepa_init*, *nsteps*)

Evolve binary eccentricity from an initial value along a range of separations.

Parameters

- **sam** (*holodeck.sam.Semi_Analytic_Model* instance) – The input semi-analytic model. All this does is provide the range of total-masses to determine the minimum ISCO radius, which then determines the smallest separations to evolve until.
- **eccen_init** (*float,*) – Initial eccentricity of binaries at the given initial separation *sepa_init*. Must be between [0.0, 1.0).
- **sepa_init** (*float,*) – Initial binary separation at which evolution begins. Units of [cm].
- **nsteps** (*int,*) – Number of (log-spaced) steps in separation between the initial separation *sepa_init*, and the final separation which is determined as the minimum ISCO radius based on the smallest total-mass of binaries in the *sam* instance.

Returns

- **sepa** (*(E,) ndarray of float*) – The separations at which the eccentricity evolution is defined over. This is the independent variable of the evolution. The shape *E* is the value of the *nsteps* parameter.
- **eccen** (*(E,)*) – The eccentricity of the binaries at each location in separation given by *sepa*. The shape *E* is the value of the *nsteps* parameter.

holodeck.sams.sam.**add_scatter_to_masses**(*mtot*, *mrat*, *dens*, *scatter*, *refine=4*, *log=None*)

Add the given scatter to masses m1 and m2, for the given distribution of binaries.

The procedure is as follows (see *dev-notebooks/sam-ndens-scatter.ipynb*):

- (1) The density is first interpolated to a uniform, regular grid in (m1, m2) space. A 2nd order interpolant is used first. A 0th-order interpolant is used to fill-in bad values. In-between, a 1st-order interpolant is used if *linear_interp_backup* is True.
- (2) The density distribution is convolved with a smoothing function along each axis (m1, m2) to account for scatter.
- (3) The new density distribution is interpolated back to the original (mtot, mrat) grid.

Parameters

- **mtot** (*(M,) ndarray*) – Total masses in grams.
- **mrat** (*(Q,) ndarray*) – Mass ratios.
- **dens** (*(M, Q) ndarray*) – Density of binaries over the given mtot and mrat domain.
- **scatter** (*float*) – Amount of scatter in the M-MBulge relationship, in dex (i.e. over log10 of masses).
- **refine** (*int,*) – The increased density of grid-points used in the intermediate (m1, m2) domain, in step (1).
- **linear_interp_backup** (*bool,*) – Whether a linear interpolant is used to fill-in bad values after the 2nd order interpolant. This generally doesn't seem to fix any values.
- **logspace_interp** (*bool,*) – Whether interpolation should be performed in the log-space of masses. NOTE: strongly recommended.

Returns
m1m2_dens – Binary density with scatter introduced.

Return type
(M, Q) ndarray,

9.3 holodeck.sams.sam_cyutils

$ python setup.py build_ext -i

$ python setup.py develop

holodeck.sams.sam_cyutils.**dynamic_binary_number_at_fobs**()

Calculate the differential number of binaries at the given frequencies.

This function converts from differential binary volume-density to differential number of binaries. The differential binary volume-density is:

$$d^3n/[d\log_{10} M dq dz]$$

Where the number density is $n = dN/dV_c$ for a comoving volume V_c. The differential binary number is:

$$d^4N/[d\log_{10} M dq dz d\ln f]$$

Parameters

- **fobs_orb** (*(F,) array of float, [1/s]*) – The observer-frame orbital frequencies of interest, in units of inverse seconds.
- **sam** (*holodeck.sams.sam.Semi_Analytic_Model* instance) – The semi-analytic model population.
- **hard** (holodeck.hardening._Hardening subclass instance,) – The binary evolution model to evolve binaries from galaxy merger to the given frequencies.
- **cosmo** (astropy.cosmology.core.Cosmology instance) – Cosmology object used for calculating cosmological measurements.

Returns

- **redz_final** (*(M, Q, Z, F) array of float, []*) – The redshifts at which binaries at each grid point reach the frequencies of interest. Unitless.
- **diff_num** (*(M, Q, Z, F) array of float, []*) – The differential number of binaries at each grid point. Unitless.

holodeck.sams.sam_cyutils.**find_2pwl_hardening_norm**()

holodeck.sams.sam_cyutils.**hard_func_2pwl_gw**()

NOTE: this function will be somewhat slow, because of the explicit broadcasting!

holodeck.sams.sam_cyutils.**hard_gw**()

holodeck.sams.sam_cyutils.**integrate_binary_evolution_2pwl**()

holodeck.sams.sam_cyutils.**integrate_differential_number_3dx1d**()

Integrate the differential number of binaries over each grid bin into total numbers of binaries.

Trapezoid used over first 3 dims (mtot, mrat, redz), and Riemann over 4th (freq). (Riemann seemed empirically to be more accurate for freq, but this should be revisited.) mtot is integrated over *log10(mtot)* and frequency is integrated over *ln(f)*.

Note on array shapes:

- input *dnum* is shaped (M, Q, Z, F)
- input *edges* must be (4,) of array_like of lengths: M, Q, Z, F+1
- output *numb* is shaped (M-1, Q-1, Z-1, F)

Parameters

- **edges** (*(4,) array_like w/ lengths M, Q, Z, F+1*) – Grid edges of *mtot*, *mrat*, *redz*, and *freq*. NOTE:
  - *mtot* should be passed as regular *mtot*, NOT log10(mtot)
  - *freq* should be passed as regular *freq*, NOT ln(freq)
- **dnum** (*(M, Q, Z, F)*) – Differential number of binaries, dN/[dlog10M dq qz dlnf] where 'N' is in units of dimensionless number.

Returns

numb

Return type
(M-1, Q-1, Z-1, F)

CHAPTER

TEN

HOLODECK.LIBRARIAN MODULE

Module to generate and manage holodeck libraries.

Holodeck 'libraries' are collections of simulations in which a certain set of parameters are varied, producing different populations and/or GW signatures at each sampled parameter value. Libraries are run from the same parameter-space and using the same hyper parameters. Libraries are constructed using a 'parameter space' class that organizes the different simulations. The base-class is *_Param_Space* (defined in the *holodeck.librarian.libraries* file). The parameter-space subclasses are given a number of different parameters to be varied. Each parameter is implemented as a subclass of *_Param_Dist*, for example the *PD_Uniform* class that implements a uniform distribution.

For more information, see the *'libraries' page in the getting-started guide*.

Notes

The `librarian` module is composed of the following elements:

- The core components of the holodeck libraries are defined in *libraries*. Constructing simulations from parameter spaces can be performed using the relevant parameter spaces themselves (subclasses of *_Param_Space*).
- Parameter spaces are defined in the 'param_spaces' files, particularly:
  - 'Classic' parameter spaces from the 15yr NANOGrav astrophysics analysis are in *param_spaces_classic*.
  - More recent parameter are in *param_spaces*.
- Library generation functionality is in the *gen_lib* module.
- Analytic fits to libraries can be performed using *fit_spectra*.
- Drawing samples (sample populations) from libraries fit to particular constraints (for example, the NANOGrav 15yr observations) is performed using the module *posterior_populations*.

`holodeck.librarian.DEF_NUM_REALS = 100`

Default number of realizations to construct in libraries.

`holodeck.librarian.DEF_NUM_FBINS = 40`

Default number of frequency bins at which to calculate GW signals.

`holodeck.librarian.DEF_NUM_LOUDEST = 5`

Default number of loudest binaries to calculate in each frequency bin.

`holodeck.librarian.DEF_PTA_DUR = 16.03`

Default PTA duration which determines Nyquist frequency bins [yrs].

holodeck.librarian.**param_spaces_dict = {'PS_Astro_Strong_All': <class 'holodeck.librarian.param_spaces.PS_Astro_Strong_All'>, 'PS_Astro_Strong_GMR': <class 'holodeck.librarian.param_spaces.PS_Astro_Strong_GMR'>, 'PS_Astro_Strong_GSMF': <class 'holodeck.librarian.param_spaces.PS_Astro_Strong_GSMF'>, 'PS_Astro_Strong_Hard': <class 'holodeck.librarian.param_spaces.PS_Astro_Strong_Hard'>, 'PS_Astro_Strong_MMBulge': <class 'holodeck.librarian.param_spaces.PS_Astro_Strong_MMBulge'>, 'PS_Classic_GWOnly_Astro_Extended': <class 'holodeck.librarian.param_spaces_classic.PS_Classic_GWOnly_Astro_Extended'>, 'PS_Classic_GWOnly_Uniform': <class 'holodeck.librarian.param_spaces_classic.PS_Classic_GWOnly_Uniform'>, 'PS_Classic_Phenom_Astro_Extended': <class 'holodeck.librarian.param_spaces_classic.PS_Classic_Phenom_Astro_Extended'>, 'PS_Classic_Phenom_Uniform': <class 'holodeck.librarian.param_spaces_classic.PS_Classic_Phenom_Uniform'>, 'PS_Test': <class 'holodeck.librarian.param_spaces_classic.PS_Test'>}**

Registry of standard parameter-spaces

10.1 holodeck.librarian.combine

Combine output files from individual simulation runs into a single library hdf5 file.

This file can be executed as a script (see the *main()* function), and also provides an API method (*sam_lib_combine()*) for programatically combining libraries.

holodeck.librarian.combine.**main**()

Command-line interface executable method for combining holodeck simulation files.

holodeck.librarian.combine.**sam_lib_combine**(*path_output*, *log*, *path_pspace=None*, *recreate=False*, *gwb_only=False*)

Combine individual simulation files into a single library (hdf5) file.

Parameters

- **path_output** (*str or Path,*) – Path to output directory where combined library will be saved.
- **log** (*logging.Logger*) – Logging instance.
- **path_sims** (*str or None,*) – Path to output directory containing simulation files. If *None* this is set to be the same as *path_output*.
- **path_pspace** (*str or None,*) – Path to file containing _Param_Space subclass instance. If *None* then *path_output* is searched for a *_Param_Space* save file.

Returns

lib_path – Path to library output filename (typically ending with 'sam_lib.hdf5').

Return type

Path,

10.2 holodeck.librarian.fit_spectra

Script and methods to fit simulated GWB spectra with analytic functions.

10.2.1 Usage

For usage information, run the script with the `-h` or `--help` arguments, i.e.:

```
python -m holodeck.librarian.fit_spectra -h
```

Typically, the only argument required is the path to the folder containing the combined library file (`sam_lib.hdf5`).

Notes

As a script, this submodule runs in parallel, with the main processor loading a holodeck library (from a single, combined HDF5 file), and distributes simulations to the secondary processors. The secondary processors then perform analytic fits to the GWB spectra. What functional forms are fit, and using how many frequency bins, is easily adjustable. Currently, the implemented functions are:

- A power-law, with two parameters (amplitude and spectral index),
- A power-law with turnover model, using four parameters: the normal amplitude and spectral index, in addition to a break frequency, and a spectral index below the break frequency.

A variety of numbers-of-frequency-bins are also fit, which are specified in the `FITS_NBINS_PLAW` and `FITS_NBINS_TURN` variables.

The methods used in this submodule are easily adaptable as API methods.

`holodeck.librarian.fit_spectra.`**`fit_all_libraries_in_path`**(*path*, *log*, *pattern=None*, *recreate=False*)

Recursively find all *sam_lib.hdf5* files in the given path, and construct spectra fits for them.

`holodeck.librarian.fit_spectra.`**`fit_library_spectra`**(*library_path*, *log*, *recreate=False*)

Calculate analytic fits to library spectra using MPI.

10.3 holodeck.librarian.gen_lib

Library generation interface.

This file can be run from the command-line to generate holodeck libraries, and also provides some API methods for quick/easy generation of simulations. In general, these methods are designed to run simulations for populations constructed from parameter-spaces (i.e. *_Param_Space* subclasses).

This script can be run by executing:

```
python -m holodeck.librarian.gen_lib <ARGS>
```

Run `python -m holodeck.librarian.gen_lib -h` for usage information.

`holodeck.librarian.gen_lib.`**`main`**()

Parent method for generating libraries from the command-line.

This function requires `mpi4py` for parallelization.

This method does the following:

(1) Loads arguments from the command-line (`args`, via *_setup_argparse()*).

   (a) The `output` directory is created as needed, along with the `sims/` and `logs/` subdirectories in which the simulation datafiles and log output files are saved.

(2) Sets up a `logging.Logger` instance for each processor.

(3) Constructs the parameter space specified by `args.param_space`. If this run is being resumed, then the param-space is loaded from an existing save file in the output directory.

(4) Samples from the parameter space are allocated to all processors.

(5) Each processor iterates over it's allocated parameters, calculates populations, saves them to files in the output directories. This is handled in *run_sam_at_pspace_num()*.

(6) All of the individual simulation files are combined using *holodeck.librarian.combine.sam_lib_combine()*.

Parameters
None –

Return type
None

holodeck.librarian.gen_lib.**run_sam_at_pspace_num**(*args*, *space*, *pnum*)

Run a given simulation (index number `pnum`) in the `space` parameter-space.

This function performs the following:

(1) Constructs the appropriate filename for this simulation, and checks if it already exist. If the file exists and the `args.recreate` option is not specified, the function returns `True`, otherwise the function runs this simulation.

(2) Calls `space.model_for_sample_number` to generate the semi-analytic model and hardening instances; see the function *holodeck.librarian.libraries._Param_Space.model_for_sample_number()*.

(3) Calculates populations and GW signatures from the SAM and hardening model using *holodeck.librarian.libraries.run_model()*, and saves the results to an output file.

(4) Optionally: some diagnostic plots are created in the *make_plots()* function.

Parameters

- **args** (`argparse.ArgumentParser` instance) – Arguments from the *gen_lib_sams.py* script. NOTE: this should be improved.
- **space** (`holodeck.librarian.libraries._Param_space` instance) – Parameter space from which to construct populations.
- **pnum** (*int*) – Which parameter-sample from `space` should be run.

Returns

- **rv** (*bool*) – `True` if this simulation was successfully run, `False` otherwise.
- **sim_fname** (`pathlib.Path` instance) – Path of the simulation save file.

holodeck.librarian.gen_lib.**_setup_argparse**(**args*, ***kwargs*)

Setup the argument-parser for command-line usage.

Parameters

- ***args** (*arguments*) –

- ****kwargs** (*keyword arguments*) –

holodeck.librarian.gen_lib.**_setup_log**(*comm*, *args*)

Setup up the logging module logger for output messaging.

10.3.1 Arguemnts

comm args

returns
log

rtype
logging.Logger instance

holodeck.librarian.gen_lib.**make_plots**(*args*, *data*, *sim_fname*)

Generate diagnostic plots from the given simulation data and save to file.

holodeck.librarian.gen_lib.**make_gwb_plot**(*fobs*, *gwb*, *fit_data*)

Generate a GWB plot from the given data.

holodeck.librarian.gen_lib.**make_ss_plot**(*fobs*, *hc_ss*, *hc_bg*, *fit_data*)

holodeck.librarian.gen_lib.**make_pars_plot**(*fobs*, *hc_ss*, *hc_bg*, *sspar*, *bgpar*)

Plot total mass, mass ratio, initial d_c, final d_c

10.4 holodeck.librarian.libraries

Parameters and parameter spaces for holodeck libraries.

class holodeck.librarian.libraries.**_Param_Space**(*parameters*, *log=None*, *nsamples=None*, *sam_shape=None*, *seed=None*, *random_state=None*)

Bases: ABC

Base class for generating holodeck libraries. Defines the parameter space and settings.

Libraries are generated over some parameter space defined by which parameters are being varied.

_SAVED_ATTRIBUTES = ['sam_shape', 'param_names', '_uniform_samples', 'param_samples', '_nsamples', '_nparameters']

DEFAULTS = {}

model_for_params(*params*, *sam_shape=None*)

Construct a model (SAM and hardening instances) from the given parameters.

Parameters

- **params** (*dict*) – Key-value pairs for sam/hardening parameters. Each item much match expected parameters that are set in the *defaults* dictionary.
- **sam_shape** (*None or int or (3,) int*) –

Returns

- **sam** (holodeck.sam.Semi_Analytic_Model instance)
- **hard** (holodeck.hardening._Hardening instance)

abstract classmethod _init_sam(*sam_shape*, *params*)

abstract classmethod _init_hard(*sam*, *params*)

save(*path_output*)

Save the generated samples and parameter-space info from this instance to an output file.

This data can then be loaded using the `_Param_Space.from_save` method. NOTE: existing save files with the same name will be overwritten!

Parameters
path_output (*str*) – Path in which to save file. This must be an existing directory.

Returns
fname – Output path including filename in which this parameter-space was saved.

Return type
`pathlib.Path` object

classmethod from_save(*fname*, *log=None*)

Create a new _Param_Space instance loaded from the given save file.

Parameters
fname (*str*) – Filename containing parameter-space save information, generated form *_Param_Space.save*.

Returns
space

Return type
_Param_Space subclass instance

param_dict(*samp_num*)

property extrema

property name

property lib_shape

property nsamples

property nparameters

model_for_sample_number(*samp_num*, *sam_shape=None*)

normalized_params(*vals*)

Convert input values (uniform/linear) into parameters from the stored distributions.

For example, if this parameter space has 2 dimensions, where the distributions are:

0. 'value_a' is a uniform parameter from [-1.0, 1.0], and
1. 'value_b' normal with mean 10.0 and stdev 1.0

Then input values of `[0.75, 0.5]` are mapped to parameters `[0.5, 10.0]`, which will be returned as `{value_a: 0.5, value_b: 10.0}`.

Parameters
vals (*(P,) iterable of float,*) – A list/iterable of *P* float values, matching the number of parameters (i.e. dimensions) in this parameter space. Each value is passed to the corresponding distribution for that parameter.

Returns
params – The resulting parameters in the form of key-value pairs where the keys are the parameter names, and the values are drawn from the correspinding distributions.

Return type
dict,

default_params()

Return a parameter dictionary with default values for each parameter.

Returns
params – Key-value pairs where each key is the parameter name, and the value is the default value returned from the *_Param_Dist* subclass.

Return type
dict,

_abc_impl = <_abc._abc_data object>

class holodeck.librarian.libraries.**_Param_Dist**(*name*, *default=None*, *clip=None*)

Bases: ABC

Parameter Distribution base-class for use in Latin HyperCube sampling.

These classes are passed uniform random variables between [0.0, 1.0], and return parameters from the desired distribution.

Subclasses are required to implement the `_dist_func()` function which accepts a float value from [0.0, 1.0] and returns the appropriate corresponding parameter, drawn from the desired distribution. In practice, `_dist_func()` is usually the inverse cumulative-distribution for the desired distribution function.

abstract _dist_func(**args*, ***kwargs*)

property extrema

property name

property default

Return the default parameter value.

If a fixed value was set, it will be returned. Otherwise the parameter value for a random uniform input value of 0.5 will be returned.

_abc_impl = <_abc._abc_data object>

class holodeck.librarian.libraries.**PD_Uniform**(*name*, *lo*, *hi*, ***kwargs*)

Bases: *_Param_Dist*

_dist_func(*xx*)

_abc_impl = <_abc._abc_data object>

class holodeck.librarian.libraries.**PD_Uniform_Log**(*name*, *lo*, *hi*, ***kwargs*)

Bases: *_Param_Dist*

_dist_func(*xx*)

_abc_impl = <_abc._abc_data object>

class holodeck.librarian.libraries.**PD_Normal**(*name*, *mean*, *stdev*, *clip=None*, ***kwargs*)

Bases: *_Param_Dist*

Normal/Gaussian parameter distribution with given mean and standard-deviation.

NOTE: use *clip* parameter to avoid extreme values.

_dist_func(*xx*)

_abc_impl = <_abc._abc_data object>

class holodeck.librarian.libraries.**PD_Lin_Log**(*name*, *lo*, *hi*, *crit*, *lofrac*, ***kwargs*)

Bases: *_Param_Dist*

_dist_func(*xx*)

_abc_impl = <_abc._abc_data object>

class holodeck.librarian.libraries.**PD_Log_Lin**(*name*, *lo*, *hi*, *crit*, *lofrac*, ***kwargs*)

Bases: *_Param_Dist*

_dist_func(*xx*)

_abc_impl = <_abc._abc_data object>

class holodeck.librarian.libraries.**PD_Piecewise_Uniform_Mass**(*name*, *edges*, *weights*, ***kwargs*)

Bases: *_Param_Dist*

_dist_func(*xx*)

_abc_impl = <_abc._abc_data object>

class holodeck.librarian.libraries.**PD_Piecewise_Uniform_Density**(*name*, *edges*, *densities*, ***kwargs*)

Bases: *PD_Piecewise_Uniform_Mass*

_abc_impl = <_abc._abc_data object>

holodeck.librarian.libraries.**run_model**(*sam*, *hard*, *pta_dur=16.03*, *nfreqs=40*, *nreals=100*, *nloudest=5*, *gwb_flag=True*, *singles_flag=True*, *details_flag=False*, *params_flag=False*, *log=None*)

Run the given SAM and hardening model to construct a binary population and GW signatures.

Parameters

- **sam** (*holodeck.sams.sam.Semi_Analytic_Model* instance,) –
- **hard** (holodeck.hardening._Hardening subclass instance,) –
- **pta_dur** (*float, [seconds]*) – Duration of PTA observations in seconds, used to determine Nyquist frequency basis at which GW signatures are calculated.
- **nfreqs** (*int*) – Number of Nyquist frequency bins at which to calculate GW signatures.
- **nreals** (*int*) – Number of 'realizations' (populations drawn from Poisson distributions) to construct.
- **nloudest** (*int*) – Number of loudest binaries to consider in each frequency bin. These are the highest GW strain binaries in each frequency bin, for which the individual source strains are calculated.
- **gwb_flag** –

- **details_flag** –
- **singles_flag** –
- **params_flag** –
- **log** (logging.Logger instance) –

Returns

data – The population and GW data calculated from the simulation. The dictionary elements are:

- fobs_cents : Nyquist frequency bin centers, in units of [seconds].
- fobs_edges : Nyquist frequency bin edgeds, in units of [seconds].
- If details_flag == True:
  - static_binary_density :
  - number :
  - redz_final :
  - gwb_params :
  - num_params :
  - gwb_mtot_redz_final :
  - num_mtot_redz_final :
- If params_flag == True:
  - sspar :
  - bgpar :
- If singles_flag == True:
  - hc_ss :
  - hc_bg :
- If gwb_flag == True:
  - gwb :

Return type
dict

holodeck.librarian.libraries.**_calc_model_details**(*edges*, *redz_final*, *number*)

Calculate derived properties from the given populations.

Parameters

- **edges** (*(4,) list of 1darrays*) – [mtot, mrat, redz, fobs_orb_edges] with shapes (M, Q, Z, F+1)
- **redz_final** (*(M,Q,Z,F)*) – Redshift final (redshift at the given frequencies).
- **number** (*(M-1, Q-1, Z-1, F)*) – Absolute number of binaries in the given bin (dimensionless).

Returns

- *gwb_pars*
- *num_pars*

- *gwb_mtot_redz_final*
- *num_mtot_redz_final*

holodeck.librarian.libraries.**load_pspace_from_path**(*path*, *space_class=None*, *log=None*)

Load a *_Param_Space* subclass instance from the saved file in the given directory.

This function tries to determine the correct class based on the save file name, then uses that class to load the save itself.

Parameters

- **path** (*str or pathlib.Path*) – Path to directory containing save file. A single file matching **.pspace.npz* is required in that directory. NOTE: the specific glob pattern is specified by *holodeck.librarian.PSPACE_FILE_SUFFIX* e.g. '.pspace.npz'
- **space_class** (*_Param_Space* subclass or *None*) – Class with which to call the *from_save()* method to load a new *_Param_Space* instance. If *None* is given, then the filename is used to try to determine the appropriate class.
- **log** (*logging.Logger*) –

Returns

- **space** (*_Param_Space* subclass instance) – An instance of the *space_class* class.
- **space_fname** (*pathlib.Path*) – File that *space* was loaded from.

holodeck.librarian.libraries.**_get_space_class_from_space_fname**(*space_fname*)

holodeck.librarian.libraries.**_get_sim_fname**(*path*, *pnum*)

holodeck.librarian.libraries.**get_sam_lib_fname**(*path*, *gwb_only*)

holodeck.librarian.libraries.**get_fits_path**(*library_path*)

Get the name of the spectral fits file, given a library file path.

holodeck.librarian.libraries.**log_mem_usage**(*log*)

10.5 holodeck.librarian.param_spaces

Parameter-Space definitions for holodeck libraries.

class holodeck.librarian.param_spaces.**PS_Astro_Strong_All**(*log=None*, *nsamples=None*, *sam_shape=None*, *seed=None*)

class holodeck.librarian.param_spaces.**PS_Astro_Strong_GMR**(*log=None*, *nsamples=None*, *sam_shape=None*, *seed=None*)

class holodeck.librarian.param_spaces.**PS_Astro_Strong_GSMF**(*log=None*, *nsamples=None*, *sam_shape=None*, *seed=None*)

class holodeck.librarian.param_spaces.**PS_Astro_Strong_Hard**(*log=None*, *nsamples=None*, *sam_shape=None*, *seed=None*)

class holodeck.librarian.param_spaces.**PS_Astro_Strong_MMBulge**(*log=None*, *nsamples=None*, *sam_shape=None*, *seed=None*)

class holodeck.librarian.param_spaces.**PS_Test**(*log=None*, *nsamples=None*, *sam_shape=None*, *seed=None*, ***kwargs*)

Simple Test Parameter Space: SAM with strongly astrophysically-motivated parameters.

This model uses a double-Schechter GSMF, an Illustris-derived galaxy merger rate, a Kormendy+Ho M-MBulge relationship, and a phenomenology binary evolution model.

10.6 holodeck.librarian.param_spaces_classic

'Classic' parameter spaces used in the NANOGrav 15yr analysis.

class holodeck.librarian.param_spaces_classic.**PS_Classic_GWOnly_Astro_Extended**(*log=None*, *nsamples=None*, *sam_shape=None*, *seed=None*)

Classic 10D GW-Only, uniform parameter space used in 15yr analysis.

Previously called the *PS_New_Astro_02_GW* parameter space, or 'gw-only+extended'.

class holodeck.librarian.param_spaces_classic.**PS_Classic_GWOnly_Uniform**(*log=None*, *nsamples=None*, *sam_shape=None*, *seed=None*)

Classic 4D GW-Only, uniform parameter space used in 15yr analysis.

Previously called the *PS_Uniform_07_GW* parameter space, or 'gw-only'.

class holodeck.librarian.param_spaces_classic.**PS_Classic_Phenom_Astro_Extended**(*log=None*, *nsamples=None*, *sam_shape=None*, *seed=None*)

Classic 12D phenomenological, uniform parameter space used in 15yr analysis.

Previously called the *PS_New_Astro_02B* parameter space, or 'phenom-astro+extended'.

class holodeck.librarian.param_spaces_classic.**PS_Classic_Phenom_Uniform**(*log=None*, *nsamples=None*, *sam_shape=None*, *seed=None*)

Classic 5D phenomenological, uniform parameter space used in 15yr analysis.

Previously called the *PS_Uniform_09B* parameter space, or 'phenom-uniform'.

class holodeck.librarian.param_spaces_classic.**PS_Test**(*log=None*, *nsamples=None*, *sam_shape=None*, *seed=None*)

Simple test parameter space in 2D.

10.7 holodeck.librarian.posterior_populations

Script to generate Holodeck populations, drawing from the 15yr analysis constraints.

See *holodeck-pops.ipynb* for example usage of this data.

10.7.1 Usage (posterior_populations.py)

See *python gen_holodeck_pop.py -h* for usage information.

Example:

```
python gen_holodeck_pops.py -t 20 -f 30 -r 100 -l 10 -m
                                |     |     |      |   |--> use maxmimum-likelihood values
                                |     |     |      |------> 10 loudest binaries in each␣
↪frequency bin
                                |     |     |--------------> 100 realizations of␣
↪populations
                                |     |--------------------> 30 frequency bins
                                |--------------------------> 20 years observing baseline =␣
↪1/(20yr) lowest frequency
```

10.7.2 To-Do (posterior_populations.py)

- Improve handling of data path.
- **Improve handling/specification of parameter space.**
  - Allow changes to be passed in through API and or CL
  - Make each particular 15yr dataset specify its own parameter space (these need to match up anyway!)

holodeck.librarian.posterior_populations.**get_maxlike_pars_from_chains**(*chains=None*)

Load the maximum-likelihood (ML) parameters from the given chains (i.e. parameter posteriors).

KDEs from *kalepy* are used to construct the ML parameters.

Parameters

chains (*dict*) – The MCMC parameter values for each of the parameters in this holodeck parameter-space. These chains should typically be loaded using the *load_chains* function.

Returns

pars – Maximum likelihood parameters drawn from the *chains*. This will be a single float value for each of the parameters in the holodeck parameter-space, for example:

```
['hard_time', 'gsmf_phi0', 'gsmf_mchar0_log10',
'mmb_mamp_log10', 'mmb_scatter_dex', 'hard_gamma_inner']
```

Return type

dict

holodeck.librarian.posterior_populations.**load_chains**(*path_data*)

Load the MCMC chains from the given path.

The path must contain the expected files resulting from fitting with *ceffyl*.

Parameters

path_data (*str* or *pathlib.Path*) – Path to directory containing the *pars.txt* and *chain_1.0.txt* files.

Returns

data – The values at each step of the MCMC chains for each parameters. For example, the parameters may be:

```
['hard_time', 'gsmf_phi0', 'gsmf_mchar0_log10',
'mmb_mamp_log10', 'mmb_scatter_dex', 'hard_gamma_inner']
```

in which case each of these will be an entry in the dictionary, where the values are an array of the steps in each of these parameters.

Return type

dict

holodeck.librarian.posterior_populations.**load_population_for_pars**(*pars*, *pta_dur=16.0*, *nfreqs=60*, *nreals=103*, *nloudest=10*)

Construct a holodeck population.

Parameters

- **pars** (*dict*) – Binary population parameters for the appropriate parameter space *PSPACE*. Typically the *pars* should be loaded using either the *sample_pars_from_chains* or the *get_maxlike_pars_from_chains* function.
- **pta_dur** (*scalar [seconds]*) – Duration of PTA observations, used to determine Fourier frequency bins. Bin centers are at frequencies `f_i = (i+1) / pta_dur`
- **nfreqs** (*int*) – Number of frequency bins.
- **nreals** (*int*) – Number of realizations to construct.
- **nloudest** (*int*) – Number of loudest binaries to calculate, per frequency bin.

Returns

data – Binary population and derived properties. Entries:

- *number* : ndarray (M, Q, Z, F) Number of binaries in the Universe in each bin. The bins are total mass (M), mass ratio (Q), redshift (Z), and frequency (F).
- *hc_ss* : ndarray (F, R, L) GW characteristic strain of the loudest L binaries in each frequency bin (F) and realization (R). The GW frequencies are assumed to be 2x the orbital frequencies (i.e. circular orbits).
- *hc_bg* : ndarray (F, R) GW characteristic strain of all binaries besides the L loudest in each frequency bin, for frequency bins *F* and realizations *R*. The GW frequencies are assumed to be 2x the orbital frequencies (i.e. circular orbits).
- *sspar* : ndarray (P, F, R, L) Binary parameters of the loudest *L* binaries in each frequency bin *F* for realizations *R*. The P=4 parameters included are {total mass [grams], mass ratio, initial redshift, final redshift}, where initial redshift is at the time of galaxy merger, and final redshift is when reaching the frequency bin.
- *mtot_edges* : ndarray (M+1,) The edges of the total-mass dimension of the SAM grid, in units of [grams]. Note that there are *M+1* bin edges for *M* bins.
- *mrat_edges* : ndarray (Q+1,) The edges of the mass-ratio dimension of the SAM grid. Note that there are *Q+1* bin edges for *Q* bins.

- *redz_edges* : ndarray (Z+1,) The edges of the redshfit dimension of the SAM grid. Note that there are *Z+1* bin edges for *Z* bins.
- *fobs_orb_edges* : ndarray (F+1,) The edges of the orbital-frequency dimension of the SAM grid. Note that there are *F+1* bin edges for *F* bins.

Return type
dict

holodeck.librarian.posterior_populations.**main**(*args=None*)

Top level function that does all the work.

holodeck.librarian.posterior_populations.**sample_pars_from_chains**(*chains=None*)

Sample randomly from the given chains (i.e. parameter posteriors).

Parameters
chains (*dict*) – The MCMC parameter values for each of the parameters in this holodeck parameter-space. These chains should typically be loaded using the *load_chains* function.

Returns

pars – Randomly selected parameters drawn from the *chains*. This will be a single float value for each of the parameters in the holodeck parameter-space, for example:

```
['hard_time', 'gsmf_phi0', 'gsmf_mchar0_log10',
'mmb_mamp_log10', 'mmb_scatter_dex', 'hard_gamma_inner'],
```

Return type
dict

holodeck.librarian.posterior_populations.**setup_argparse**(**args*, ***kwargs*)

Setup parameters/arguments.

Note that this can be used to set parameters NOT from command-line usage, but in this case the *args* argument must be set to empty. For example:

This will load of all the default arguments (NOTE the empty string argument is typically needed):
`args = gen_holodeck_pops.setup_argparse("")`

This will set the desired parameters, and otherwise load the defaults:
`args = gen_holodeck_pops.setup_argparse("", nloudest=12, nreals=6, maxlike=True)`

CHAPTER

ELEVEN

HOLODECK.ACCRETION

Massive Black Hole Binary (MBHB) accretion models to evolve individual Massive Black Hole (MBH) masses using the illustris accretion rates.

11.1 Authors

Magdalena Siwek

class holodeck.accretion.**Accretion**(*accmod='Basic'*, *f_edd=0.01*, *mdot_ext=None*, *eccen=0.0*, *subpc=True*, ***kwargs*)

Preferential Accretion prescription

accmod

Type
{'Basic', 'Proportional', 'Primary', 'Secondary', 'Siwek22', 'Duffell'}, optional

f_edd

Type
double, optional

mdot_ext

Type
Any, optional

eccen

Type
float, optional

subpc

Type
boolean, optional

:meth:`mdot_eddington(mass)`

Calculate the total accretion rate based on masses and a fraction of the Eddington limit.

:meth:`pref_acc(mdot, evol, step)`

Contains a variety of accretion models to choose from to calculate primary vs secondary accretion rates.

mdot_eddington(*mass*, *eps=0.1*)

Calculate the total accretion rate based on masses and a fraction of the Eddington limit.

mass : float eps : float, optional

Radiative efficiency epsilon. Defaults to 0.1.

medd : float

holodeck.constants : constants used for calculation of the accretion rate.

The limiting Eddington accretion rate is defined as: .. math:: `dot{M}_{mathsf{Edd}} = rac{4 pi GM m_p}{epsilon c sigma_{mathsf{T}}}`

```
>>> acc = Accretion()
>>> mass =
>>> print(acc.mdot_eddington(mass))
```

pref_acc(*mdot*, *evol*, *step*)

Contains a variety of accretion models to choose from to calculate primary vs secondary accretion rates.

The accretion models are as follows: * Basic * Primary * Secondary * Proportional * Siwek22 * Duffell

Parameters

- **mdot** – Gas inflow rate in solar masses. Units of [M/year]
- **evol** – evolution class instance which contains the eccentricities of the current evolution
- **step** (*int*) – current timestep

Returns

mdot_arr – Array of accretion rates for each binary in the timestep.

Return type

ndarray

See also:

`Evolution._take_next_step()` : Relationship

Notes

The instance of the evolution class must also be suppled in case eccentricities need to be accessed.

CHAPTER

TWELVE

HOLODECK.CONSTANTS

Numerical Constants

All constants are used in CGS units, as raw floats. Most of the holodeck package works in CGS units whenever possible. Constants and units should only be added when they are frequently used (i.e. in multiple files/submodules).

Notes

- [cm] = centimeter
- [g] = gram
- [s] = second
- [erg] = cm^2 * g / s^2
- [Jy] = jansky = [erg/s/cm^2/Hz]
- [fr] franklin = statcoulomb = electro-static unit [esu]
- [K] Kelvin

holodeck.constants.**ARCSEC = 4.84813681109536e-06**
arcsecond in radians []

holodeck.constants.**AU = 14959787070000.0**
Astronomical Unit [cm]

holodeck.constants.**DAY = 86400.0**
Day [s]

holodeck.constants.**EDDT = 63219.620781981204**
Eddington Luminosity prefactor factor [erg/s/g]

holodeck.constants.**EVOLT = 1.6021766339999997e-12**
Electronvolt in ergs

holodeck.constants.**GPC = 3.085677581491367e+27**
Giga-parsec [cm]

holodeck.constants.**GYR = 3.15576e+16**
Giga-year [s]

holodeck.constants.**HPLANCK = 6.62607015e-27**
Planck constant [erg/s]

holodeck.constants.**JY = 1e-23**
Jansky [erg/s/cm^2/Hz]

holodeck.constants.**KBOLTZ = 1.380649e-16**
Boltzmann constant [erg/K]

holodeck.constants.**KMPERSEC = 100000.0**
km/s [cm/s]

holodeck.constants.**KPC = 3.0856775814913673e+21**
Kilo-parsec [cm]

holodeck.constants.**LSOL = 3.828e+33**
Solar Luminosity [erg/s]

holodeck.constants.**MELC = 9.1093837015e-28**
Electron Mass [g]

holodeck.constants.**MPC = 3.0856775814913676e+24**
Mega-parsec [cm]

holodeck.constants.**MPRT = 1.67262192369e-24**
Proton Mass [g]

holodeck.constants.**MSOL = 1.988409870698051e+33**
Solar Mass [g]

holodeck.constants.**MYR = 31557600000000.0**
Mega-year [s]

holodeck.constants.**NWTG = 6.674299999999999e-08**
Newton's Gravitational Constant [cm^3/g/s^2]

holodeck.constants.**PC = 3.085677581491367e+18**
Parsec [cm]

holodeck.constants.**QELC = 4.803204712570263e-10**
Fundamental unit of charge (electron charge) [fr]

holodeck.constants.**RSOL = 69570000000.0**
Solar Radius [cm]

holodeck.constants.**SCHW = 1.4852320538237328e-28**
Schwarzschild Constant (2*G/c^2) [cm]

holodeck.constants.**SIGMA_SB = 5.6703744191844314e-05**
Stefan-Boltzmann constant [erg/cm^2/s/K^4]

holodeck.constants.**SIGMA_T = 6.6524587321000005e-25**
Thomson/Electron -Scattering cross-section [cm^2]

holodeck.constants.**SPLC = 29979245800.0**
Speed of light [cm/s]

holodeck.constants.**YR = 31557600.0**
year [s]

CHAPTER

THIRTEEN

HOLODECK.CYUTILS

Module for methods implemented in cython.

To use and load this module, you will need to build the cython extension using:

$ python setup.py build_ext -i

from the holodeck root directory (containing the *setup.py* file).

And you still need to install holodeck in develop mode, using:

$ python setup.py develop

holodeck.cyutils.**Sh_rest**()

Calculate the noise from all the single sources except the source in question and the next N_excl loudest sources.

Parameters

- **hc_ss** (*(F,R,L) NDarray*) – Characteristic strain from all loud single sources.
- **hc_bg** (*(F,R) NDarray*) – Characteristic strain from all but loudest source at each frequency.
- **freqs** (*(F,) 1Darray*) – Frequency bin centers.
- **nexcl** (*int*) – Number of loudest single sources to exclude from hc_rest noise, in addition to the source in question.

Returns

Sh_rest – The noise in a single pulsar from other GW sources for detecting each single source.

Return type

(F,R,L) NDarray of scalars

holodeck.cyutils.**gamma_of_rho_interp**()

rho

[1Darray of scalars] SNR of single sources, in flat array

rsort

[1Darray] order of flat rho values smallest to largest

rho_interp_grid

[1Darray] rho values corresponding to each gamma

gamma_interp_grid

[1Darray] gamma values corresponding to each rho

holodeck.cyutils.**loudest_hc_and_par_from_sorted**()

Calculates the characteristic strain from loud single sources and a background of all other sources.

Parameters

- **number** (*[M, Q, Z, F] NDarray*) – number in each bin
- **h2fdf** (*[M, Q, Z, F] NDarray*) – Strain amplitude squared x frequency / frequency bin width for each bin.
- **nreals** – Number of realizations.
- **nloudest** – Number of loudest sources to separate in each frequency bin.
- **mt** (*(M,) 1Darray of scalars*) – Total masses, M, of each bin center.
- **mr** (*(Q,) 1Darray of scalars*) – Mass ratios, q, of each bin center.
- **rz** (*(Z,) 1Darray of scalars*) – Redshifts, z, of each bin center.
- **msort** (*(M*Q*Z,) 1Darray*) – M indices of each bin, sorted from largest to smallest h2fdf.
- **qsort** (*(M*Q*Z,) 1Darray*) – q indices of each bin, sorted from largest to smallest h2fdf.
- **zsort** (*(M*Q*Z,) 1Darray*) – z indices of each bin, sorted from largest to smallest h2fdf.
- **normal_threshold** (*float*) – Threshold for approximating poisson sampling as normal.

Returns

- **hc2ss** (*(F, R, L) Ndarray of scalars*) – Char strain squared of the loudest single sources.
- **hc2bg** (*(F, R) Ndarray of scalars*) – Char strain squared of the background.
- **lspar** (*(3, F, R) NDarray of scalars*) – Average effective M, q, z parameters of the loudest L sources.
- **bgpar** (*(3, F, R) NDarray of scalars*) – Average effective M, q, z parameters of the background.
- **ssidx** (*(3, F, R, L) NDarray of ints*) – Indices of the loudest single sources.

holodeck.cyutils.**loudest_hc_and_par_from_sorted_redz**()

Calculates the characteristic strain and binary parameters from loud single sources and a background of all other sources.

Parameters

- **number** (*[M, Q, Z, F] NDarray*) – number in each bin
- **h2fdf** (*[M, Q, Z, F] NDarray*) – Strain amplitude squared x frequency / frequency bin width for each bin.
- **nreals** – Number of realizations.
- **nloudest** – Number of loudest sources to separate in each frequency bin.
- **mt** (*(M,) 1Darray of scalars*) – Total masses, M, of each bin center.
- **mr** (*(Q,) 1Darray of scalars*) – Mass ratios, q, of each bin center.
- **rz** (*(Z,) 1Darray of scalars*) – Redshifts, z, of each bin center.
- **redz_final** (*(M,Q,Z,F) NDarray of scalars*) – Final redshifts of each bin.
- **dcom_final** (*(M,Q,Z,F) NDarray of scalars*) – Final comoving distances of each bin.

- **sepa** (*(M,Q,Z,F) NDarray of scalars*) – Final separations of each mass and frequency combination.
- **angs** (*(M,Q,Z,F)*) – Final angular separations of each bin.
- **msort** (*(M*Q*Z,) 1Darray*) – M indices of each bin, sorted from largest to smallest h2fdf.
- **qsort** (*(M*Q*Z,) 1Darray*) – q indices of each bin, sorted from largest to smallest h2fdf.
- **zsort** (*(M*Q*Z,) 1Darray*) – z indices of each bin, sorted from largest to smallest h2fdf.
- **normal_threshold** (*float*) – Threshold for approximating poisson sampling as normal.

Returns

- **hc2ss** (*(F, R, L) Ndarray of scalars*) – Char strain squared of the loudest single sources.
- **hc2bg** (*(F, R) Ndarray of scalars*) – Char strain squared of the background.
- **sspar** (*(4, F, R) NDarray of scalars*) – Effective M, q, z parameters of the loudest L sources. mass, ratio, redshift, redshift_final
- **bgpar** (*(4, F, R) NDarray of scalars*) – Average effective M, q, z parameters of the background. mass, ratio, redshift, redshift_final

holodeck.cyutils.**loudest_hc_from_sorted**()

Calculates the characteristic strain from loud single sources and a background of all other sources.

Parameters

- **number** (*[M, Q, Z, F] NDarray*) – number in each bin
- **h2fdf** (*[M, Q, Z, F] NDarray*) – Strain amplitude squared x frequency / frequency bin width for each bin.
- **nreals** – Number of realizations.
- **nloudest** – Number of loudest sources to separate in each frequency bin.
- **msort** (*(M*Q*Z,) 1Darray*) – M indices of each bin, sorted from largest to smallest h2fdf.
- **qsort** (*(M*Q*Z,) 1Darray*) – q indices of each bin, sorted from largest to smallest h2fdf.
- **zsort** (*(M*Q*Z,) 1Darray*) – z indices of each bin, sorted from largest to smallest h2fdf.
- **normal_threshold** (*float*) – Threshold for approximating poisson sampling as normal.

Returns

- **hc2ss** (*(F, R, L) Ndarray of scalars*) – Char strain squared of the loudest single sources.
- **hc2bg** (*(F, R) Ndarray of scalars*) – Char strain squared of the background.

holodeck.cyutils.**sam_calc_gwb_single_eccen**()

Pure-python wrapper for the SAM eccentric GWB calculation method. See: *_sam_calc_gwb_single_eccen()*.

holodeck.cyutils.**sam_calc_gwb_single_eccen_discrete**()

Pure-python wrapper for the SAM eccentric GWB calculation method. See: *_sam_calc_gwb_single_eccen()*.

holodeck.cyutils.**snr_ss**()

Calculate single source SNR.

Parameters

- **amp** (*(F,R,L) NDarray*) – Dimensionless strain amplitude of loudest single sources
- **F_iplus** (*(P,F,S,L) NDarray*) – Antenna pattern function for each pulsar.

- **F_icross** (*(P,F,S,L) NDarray*) – Antenna pattern function for each pulsar.
- **iotas** (*(F,S,L) NDarray*) – Inclination, used to calculate: $a_pol = 1 + np.cos(iotas)^2$ $b_pol = -2np.cos(iotas)$
- **dur** (*scalar*) – Duration of observations.
- **Phi_0** (*(F,S,L) NDarray*) – Initial GW phase
- **S_i** (*(P,F,R,L) NDarray*) – Total noise of each pulsar wrt detection of each single source, in s^3.
- **freqs** (*(F,) 1Darray*) – Observed frequency bin centers.

Returns

snr_ss – SNR from the whole PTA for each single source with each realized sky position (S) and realized strain (R)

Return type

(F,R,S,L) NDarray

holodeck.cyutils.**sort_h2fdf**()

Get indices of sorted h2fdf. :param h2fdf: h_s^2 * f / df of a source in each bin. :type h2fdf: (M,Q,Z) NDarray

Returns

indices

Return type

?

holodeck.cyutils.**ss_bg_hc**()

Calculates the characteristic strain from loud single sources and a background of all other sources.

Parameters

- **number** (*[M, Q, Z, F] ndarray*) – number in each bin
- **h2fdf** (*[M, Q, Z, F] ndarray*) – strain squared x frequency / frequency bin width for each bin
- **nreals** – number of realizations

Returns

- **hc2ss** (*(F, R) Ndarray of scalars*)
- **hc2bg** (*(F, R) Ndarray of scalars*)
- **ssidx** (*(3, F, R) Ndarray of ints*) – Index of the loudest single source, -1 if there are none at the frequency/realization.

holodeck.cyutils.**ss_bg_hc_and_par**()

Calculates the characteristic strain from loud single sources and a background of all other sources.

Parameters

- **number** (*[M, Q, Z, F] NDarray*) – number in each bin
- **h2fdf** (*[M, Q, Z, F] NDarray*) – Strain amplitude squared x frequency / frequency bin width for each bin.
- **nreals** – Number of realizations.
- **mt** (*(M,) 1Darray of scalars*) – Total masses, M, of each bin center.
- **mr** (*(Q,) 1Darray of scalars*) – Mass ratios, q, of each bin center.

- **rz** (*(Z,) 1Darray of scalars*) – Redshifts, z, of each bin center.

Returns

- **hc2ss** (*(F, R) Ndarray of scalars*) – Char strain squared of the loudest single sources.
- **hc2bg** (*(F, R) Ndarray of scalars*) – Char strain squared of the background.
- **ssidx** (*(3, F, R) NDarray of ints*) – Indices of the loudest single sources. -1 if there are no single sources at that frequency/realization.
- **bgpar** (*(3, F, R) NDarray of scalars*) – Average effective M, q, z parameters of the background.
- **sspar** (*(3, F, R) NDarray of scalars*) – M, q, z parameters of the loudest single sources.

CHAPTER

FOURTEEN

HOLODECK.GALAXY_PROFILES

Galaxy/Halo structure profiles (e.g. density and velocity).

References

- [Behroozi2013] : Behroozi, Wechsler & Conroy 2013.
- [Guo2010] Guo, White, Li & Boylan-Kolchin 2010.
- [Klypin2016] Klypin et al. 2016.
- [KH2013] Kormendy & Ho 2013.
- [MM2013] McConnell & Ma 2013.
- [NFW1997] Navarro, Frenk & White 1997.

class holodeck.galaxy_profiles.**Klypin_2016**

Bases: object

Class to calculate dark matter halo 'concentration' parameters based on [Klypin2016].

This class does not need to be instantiated, all methods are class methods, simply call `Klypin_2016.concentration()`.

Interpolate between redshifts and masses to find DM halo concentrations. [Klypin2016] Eq. 24 & Table 2.

_redz = [0.0, 0.35, 0.5, 1.0, 1.44, 2.15, 2.5, 2.9, 4.1, 5.4]

_interp(*yy*)

_zz = array([0. , 0.13033377, 0.17609126, 0.30103 , 0.38738983, 0.49831055, 0.54406804, 0.59106461, 0.70757018, 0.80617997])

_lin_interp_c0 = <scipy.interpolate._interpolate.interp1d object>

_lin_interp_gamma = <scipy.interpolate._interpolate.interp1d object>

_lin_interp_mass0 = <scipy.interpolate._interpolate.interp1d object>

classmethod _c0(*redz*)

classmethod _gamma(*redz*)

classmethod _mass0(*redz*)

classmethod concentration(*mhalo: _SupportsArray[dtype[Any]] | _NestedSequence[_SupportsArray[dtype[Any]]] | bool | int | float | complex | str | bytes | _NestedSequence[bool | int | float | complex | str | bytes]*, *redz: _SupportsArray[dtype[Any]] | _NestedSequence[_SupportsArray[dtype[Any]]] | bool | int | float | complex | str | bytes | _NestedSequence[bool | int | float | complex | str | bytes]*) → _SupportsArray[dtype[Any]] | _NestedSequence[_SupportsArray[dtype[Any]]] | bool | int | float | complex | str | bytes | _NestedSequence[bool | int | float | complex | str | bytes]

Return the halo concentration for the given halo mass and redshift.

Parameters

- **mhalo** (*ArrayLike*) – Halo mass. [grams]
- **redz** (*ArrayLike*) – Redshift.

Returns

conc – Halo concentration parameters. []

Return type

ArrayLike

class holodeck.galaxy_profiles.**NFW**

Bases: _Density_Profile

Navarro, Frank & White dark-matter density profile from [NFW1997].

static density(*rads: _SupportsArray[dtype[Any]] | _NestedSequence[_SupportsArray[dtype[Any]]] | bool | int | float | complex | str | bytes | _NestedSequence[bool | int | float | complex | str | bytes]*, *mhalo: _SupportsArray[dtype[Any]] | _NestedSequence[_SupportsArray[dtype[Any]]] | bool | int | float | complex | str | bytes | _NestedSequence[bool | int | float | complex | str | bytes]*, *redz: _SupportsArray[dtype[Any]] | _NestedSequence[_SupportsArray[dtype[Any]]] | bool | int | float | complex | str | bytes | _NestedSequence[bool | int | float | complex | str | bytes]*) → _SupportsArray[dtype[Any]] | _NestedSequence[_SupportsArray[dtype[Any]]] | bool | int | float | complex | str | bytes | _NestedSequence[bool | int | float | complex | str | bytes]

NFW DM Density profile.

Parameters

- **rads** (*ArrayLike*) – Target radial distances. [cm]
- **mhalo** (*ArrayLike*) – Halo mass. [grams]
- **redz** (*ArrayLike*) – Redshift. []

Returns

dens – Densities at the given radii. [g/cm^3]

Return type

ArrayLike

static mass(*rads: _SupportsArray[dtype[Any]] | _NestedSequence[_SupportsArray[dtype[Any]]] | bool | int | float | complex | str | bytes | _NestedSequence[bool | int | float | complex | str | bytes]*, *mhalo: _SupportsArray[dtype[Any]] | _NestedSequence[_SupportsArray[dtype[Any]]] | bool | int | float | complex | str | bytes | _NestedSequence[bool | int | float | complex | str | bytes]*, *redz: _SupportsArray[dtype[Any]] | _NestedSequence[_SupportsArray[dtype[Any]]] | bool | int | float | complex | str | bytes | _NestedSequence[bool | int | float | complex | str | bytes]*) → _SupportsArray[dtype[Any]] | _NestedSequence[_SupportsArray[dtype[Any]]] | bool | int | float | complex | str | bytes | _NestedSequence[bool | int | float | complex | str | bytes]

DM mass enclosed at the given radii from an NFW profile.

Parameters

- **rads** (*ArrayLike*) – Target radial distances. [cm]
- **mhalo** (*ArrayLike*) – Halo mass. [gram]
- **redz** (*ArrayLike*) – Redshift. []

Returns

mass – Mass enclosed within the given radii. [gram]

Return type

ArrayLike

static _concentration(*mhalo*, *redz*)

_abc_impl = <_abc._abc_data object>

static _nfw_rho_rad(*mhalo*, *redz*)

Return the DM halo parameters for characteristic density and halo scale radius.

Parameters

- **mhalo** (*ArrayLike*) – Halo mass. [grams]
- **redz** (*ArrayLike*) – Redshift.

Returns

- **rho_s** (*ArrayLike*) – DM halo characteristic density. [g/cm^3]
- **rs** (*ArrayLike*) – Scale radius of the DM halo. [cm]

static radius_scale(*mhalo: _SupportsArray[dtype[Any]] | _NestedSequence[_SupportsArray[dtype[Any]]] | bool | int | float | complex | str | bytes | _NestedSequence[bool | int | float | complex | str | bytes]*, *redz: _SupportsArray[dtype[Any]] | _NestedSequence[_SupportsArray[dtype[Any]]] | bool | int | float | complex | str | bytes | _NestedSequence[bool | int | float | complex | str | bytes]*) → _SupportsArray[dtype[Any]] | _NestedSequence[_SupportsArray[dtype[Any]]] | bool | int | float | complex | str | bytes | _NestedSequence[bool | int | float | complex | str | bytes]

Return the DM-halo scale radius.

Parameters

- **mhalo** (*ArrayLike*) – Halo mass. [grams]
- **redz** (*ArrayLike*) – Redshift.

Returns

rs – Scale radius of the DM halo. [cm]

Return type

ArrayLike

static density_characteristic(*mhalo: _SupportsArray[dtype[Any]] | _NestedSequence[_SupportsArray[dtype[Any]]] | bool | int | float | complex | str | bytes | _NestedSequence[bool | int | float | complex | str | bytes]*, *redz: _SupportsArray[dtype[Any]] | _NestedSequence[_SupportsArray[dtype[Any]]] | bool | int | float | complex | str | bytes | _NestedSequence[bool | int | float | complex | str | bytes]*) → _SupportsArray[dtype[Any]] | _NestedSequence[_SupportsArray[dtype[Any]]] | bool | int | float | complex | str | bytes | _NestedSequence[bool | int | float | complex | str | bytes]

Return the DM halo parameters for characteristic density.

Parameters

- **mhalo** (*ArrayLike*) – Halo mass. [grams]
- **redz** (*ArrayLike*) – Redshift.

Returns

rho_s – DM halo characteristic density. [g/cm^3]

Return type

ArrayLike

CHAPTER

FIFTEEN

HOLODECK.GRAVWAVES

Gravitational Wave (GW) calculations module.

This module provides tools for calculating GW signals from MBH binaries. Currently the components here are used with the 'discrete' / 'illustris' population of binaries, and not the semi-analytic or observational population models.

class holodeck.gravwaves.**Grav_Waves**(*bin_evo*, *fobs_gw*, *nharms=103*, *nreals=100*)

Bases: object

property freqs

class holodeck.gravwaves.**GW_Discrete**(**args*, ***kwargs*)

Bases: *Grav_Waves*

emit(*eccen=None*, *stats=False*, *progress=True*, *nloudest=5*)

class holodeck.gravwaves.**LISA**(*mission_duration_yrs=5.0*, *fobs=(1e-07, 1.0, 1000)*)

Bases: object

property sensitivity

is_above_hc_curve(*ff*, *hc*)

Determine which frequencies and strains are above the LISA sensitivity curve.

Parameters

- **ff** (*array_like of float*) – Frequencies of binaries. Units of [Hz]
- **hc** (*array_like of float*) – Characterstic-strains of binaries.

Returns

sel – Whether or not the corresponding binary is detectable. Matches the shape of *ff*.

Return type

array_like of bool

holodeck.gravwaves.**_gws_harmonics_at_evo_fobs**(*fobs_gw*, *dlnf*, *evo*, *harm_range*, *nreals*, *box_vol*, *loudest=5*)

Calculate GW signal at range of frequency harmonics for a single observer-frame GW frequency.

Parameters

- **fobs_gw** (*float*) – Observer-frame GW-frequency in units of [1/sec]. This is a single, float value.
- **dlnf** (*float*) – Log-width of observered-frequency bin, i.e. $\Delta \ln f$. This is width of observed GW frequency bins.

- **evo** (*holodeck.evolution.Evolution*) – Initialized and evolved binary evolution instance, storing the binary evolution histories of each binary.
- **harm_range** (*list[int]*) – Harmonics of the orbital-frequency at which to calculate GW emission. For circular orbits, only [2] is needed, as the GW frequency is twice the orbital frequency. For eccentric orbital, GW emission is produced both at harmonic 1 and higher harmonics. The higher the eccentricity the more GW energy is emitted at higher and higher harmonics.
- **nreals** (*int*) – Number of realizations to calculate in Poisson sampling.
- **box_vol** (*float*) – Volume of the simulation box that the binary population is derived from. Units of [cm^3].
- **loudest** (*int*) – Number of 'loudest' (highest amplitude) strain values to calculate and return separately.

Returns

- **mc_ecc_both** (*(R,) ndarray,*) – Combined (background + foreground) GW Strain at this frequency, for *R* realizations.
- **mc_ecc_fore** (*(R,) ndarray,*) – GW foreground strain (i.e. loudest single source) at this frequency, for *R* realizations.
- **mc_ecc_back** (*(R,) ndarray,*) – GW background strain (i.e. all sources except for the loudest) at this frequency, for *R* realizations.
- **loud** (*(L, R) ndarray,*) – Strains of the *L* loudest binaries (L=`loudest` input parameter) for each realization.
- **gwb_harms** (*(H,)*)

holodeck.gravwaves.**_gws_from_samples**(*vals*, *weights*, *fobs_gw_edges*)

Calculate GW signals at the given frequencies, from weighted samples of a binary population.

Parameters

- **vals** (*(4, N) ndarray of scalar,*) – Arrays of binary parameters. * vals[0] : mtot [grams] * vals[1] : mrat [] * vals[2] : redz [] * vals[3] : *observer*-frame *orbital*-frequency of binaries [1/sec]
- **weights** (*(N,) array of scalar,*) –
- **fobs_gw_edges** (*(F,) array of scalar,*) – Target observer-frame GW-frequencies to calculate GWs at. Units of [1/sec].

Returns

- **gff** (*(F,) ndarray,*) – Observer-frame GW-frequencies of the loudest binary in each bin [1/sec].
- **gwf** (*(F,) ndarray,*) – GW Foreground: the characteristic strain of the loudest binary in each frequency bin.
- **gwb** (*(F,) ndarray,*) – GW Background: the characteristic strain of the GWB in each frequency bin. Does not include the strain from the loudest binary in each bin (*gwf*).

holodeck.gravwaves.**_strains_from_samples**(*vals*)

From a sampled binary population, calculate the GW strains.

Parameters

vals (*(4,) array_like of array_like,*) – Each element of *vals* is an array of binary parameters, the elements must be: * 0) total binary mass [grams] * 1) binary mass-ratio [], * 2) redshift at this frequency [], * 3) *observer*-frame *orbital*-frequency [1/sec].

Returns

- **hs** (*(N,) ndarray,*) – Source strains (i.e. not characteristic strains) of each binary.
- **fobs_gw** (*(N,) ndarray,*) – Observer-frame GW-frequencies of each sampled binary. [1/sec].

holodeck.gravwaves.**gws_from_sampled_strains**(*fobs_gw_edges*, *fo*, *hs*, *weights*)

Calculate GW background/foreground from sampled GW strains.

Parameters

- **fobs_gw_edges** (*(F,) array_like of scalar*) – Observer-frame GW-frequency bin edges.
- **fo** (*(S,) array_like of scalar*) – Observer-frame GW-frequency of each binary sample. Units of [1/sec]
- **hs** (*(S,) array_like of scalar*) – GW source strain (*not characteristic strain*) of each binary sample.
- **weights** (*(S,) array_like of int*) – Weighting factor for each binary. NOTE: the GW calculation is ill-defined if weights have fractional values (i.e. float values, instead of integral values; but the type itself doesn't matter)

Returns

- **gwf_freqs** (*(F,) ndarray of scalar*) – Observer-frame GW frequency of foreground sources in each frequency bin. Units of [1/sec].
- **gwfore** (*(F,) ndarray of scalar*) – Strain amplitude of foreground sources in each frequency bin.
- **gwback** (*(F,) ndarray of scalar*) – Strain amplitude of the background in each frequency bin.

holodeck.gravwaves.**sampled_gws_from_sam**(*sam*, *fobs_gw*, *hard=<class 'holodeck.hardening.Hard_GW'>*, ***kwargs*)

Sample the given binary population between the target frequencies, and calculate GW signals.

NOTE: the input *fobs* are interpretted as bin edges, and GW signals are calculate within the corresponding bins.

Parameters

- **sam** (*Semi_Analytic_Model* instance,) – Binary population to sample.
- **fobs_gw** (*(F+1,) array_like,*) – Target observer-frame GW-frequencies of interest in units of [1/sec]
- **hard** (*holodeck.evolution._Hardening* instance,) – Binary hardening model used to calculate binary residence time at each frequency.
- **kwargs** (*dict,*) – Additional keyword-arguments passed to *sample_sam_with_hardening()*

Returns

- **gff** (*(F,) ndarry,*) – Observer-frame GW-frequencies of the loudest binary in each bin [1/sec].
- **gwf** (*(F,) ndarry,*) – GW Foreground: the characteristic strain of the loudest binary in each frequency bin.

- **gwb** (*(F,) ndarry,*) – GW Background: the characteristic strain of the GWB in each frequency bin. Does not include the strain from the loudest binary in each bin (*gwf*).

holodeck.gravwaves.**_gws_from_number_grid_integrated_redz**(*edges*, *redz*, *number*, *realize*, *sum=True*)

Parameters

- **edges** (*(4,) list of 1darrays*) – A list containing the edges along each dimension. The four dimensions correspond to total mass, mass ratio, redshift, and observer-frame orbital frequency. The length of each of the four arrays is M, Q, Z, F.
- **redz** –
- **number** (*(M-1, Q-1, Z-1, F-1) ndarray*) – The number of binaries in each bin of parameter space. This is calculated by integrating *dnum* over each bin.
- **realize** (*bool or int,*) – Specification of how to construct one or more discrete realizations. If a *bool* value, then whether or not to construct a realization. If an *int* value, then how many discrete realizations to construct.
- **sum** (*bool,*) – Whether or not to sum over axes {0, 1, 2}.

Returns

hc – Characteristic strain of the GWB. The shape depends on whether *sum* is true or false. sum = True: shape is (F-1,) sum = False: shape is (M-1, Q-1, Z-1, F-1)

Return type

ndarray

holodeck.gravwaves.**_gws_from_number_grid_integrated**(*edges*, *number*, *realize*, *sum=True*)

Parameters

- **edges** (*(4,) list of 1darrays*) – A list containing the edges along each dimension. The four dimensions correspond to total mass, mass ratio, redshift, and observer-frame orbital frequency. The length of each of the four arrays is M, Q, Z, F.
- **number** (*(M-1, Q-1, Z-1, F-1) ndarray*) – The number of binaries in each bin of parameter space. This is calculated by integrating *dnum* over each bin.
- **realize** (*bool or int,*) – Specification of how to construct one or more discrete realizations. If a *bool* value, then whether or not to construct a realization. If an *int* value, then how many discrete realizations to construct.
- **sum** (*bool,*) – Whether or not to sum over axes {0, 1, 2}.

Returns

hc – Characteristic strain of the GWB. The shape depends on whether *sum* is true or false. sum = True: shape is (F-1,) sum = False: shape is (M-1, Q-1, Z-1, F-1)

Return type

ndarray

holodeck.gravwaves.**gwb_ideal**(*fobs_gw*, *ndens*, *mtot*, *mrat*, *redz*, *dlog10*, *sum=True*)

holodeck.gravwaves.**poisson_as_needed**(*values*, *thresh=10000000000.0*)

Calculate Poisson distribution when values are below threshold, otherwise approximate with normal distribution.

Parameters

- **values** (*ndarray*) – Expectation values for poisson distribution.
- **thresh** (*float*) – Expectation value above which to use Normal distribution approximation.

Returns
output – (Approximately) Poisson distributed values. Same shape as input *values*.

Return type
ndarray

holodeck.gravwaves.**char_strain_sq_from_bin_edges_redz**(*edges*, *redz*)

holodeck.gravwaves.**strain_amp_from_bin_edges_redz**(*edges*, *redz*)

holodeck.gravwaves.**char_strain_sq_from_bin_edges**(*edges*)

holodeck.gravwaves.**_python_sam_calc_gwb_single_eccen**(*gwfobs*, *sam*, *sepa_evo*, *eccen_evo*, *nharms=100*)

Parameters

- **gwfobs** (*(F,) array_like*) – Observer-frame frequencies at which to calculate GWB.
- **sam** (*Semi_Analytic_Model* instance) –
- **forb_rst_evo** (*(M, E) array_like*) – Rest-frame orbital frequencies of binaries, for each total-mass M and evolution step E.
- **eccen_evo** (*(E,) array_like*) – Eccentricities at each evolution step. The same for all binaries, corresponding to fixed binary separations for all binaries.
- **nharms** (*int*) – Number of harmonics to use in calculating GWB.

Returns

- **gwfobs_harms** (*Observer-frame GW harmonic frequencies.*)
- **gwb** (*(F,) ndarray*) – GW Background: the ideal characteristic strain of the GWB in each frequency bin. Does not include the strain from the loudest binary in each bin (*gwf*).
- *ecc_out*
- *tau_out*

holodeck.gravwaves.**sam_calc_gwb_single_eccen**(*gwfobs*, *sam*, *sepa_evo*, *eccen_evo*, *nharms=100*)

holodeck.gravwaves.**sam_calc_gwb_single_eccen_discrete**(*gwfobs*, *sam*, *sepa_evo*, *eccen_evo*, *nharms=100*, *nreals=None*)

Parameters

- **gwfobs** (*(F,) array_like*) – Observer-frame frequencies at which to calculate GWB.
- **sam** (*Semi_Analytic_Model* instance) – Binary population to sample. See *holodeck.simple_sam* or 'holodeck.sam`
- **sepa_evo** – Separation at each evolution step.
- **eccen_evo** (*(E,) array_like*) – Eccentricities at each evolution step. The same for all binaries, corresponding to fixed binary separations for all binaries.
- **nharms** (*int, optional*) – Number of harmonics to use in calculating GWB.
- **nreals** (*int or None, optional*) – Number of realizations to calculate in Poisson sampling.

Returns
gwb – GW Background: the characteristic strain of the GWB in each frequency bin. Does not include the strain from the loudest binary in each bin (*gwf*).

Return type
(F,) ndarray,

holodeck.gravwaves.**_calc_mc_at_fobs**(**args*, ***kwargs*)

holodeck.gravwaves.**_gws_from_number_grid_centroids**(*edges*, *dnum*, *number*, *realize*)

Calculate GWs based on a grid of number-of-binaries.

! BUG: THIS ASSUMES THAT FREQUENCIES ARE NYQUIST SAMPLED ! # ! otherwise the conversion from hs to hc doesnt work !

NOTE: *_gws_from_number_grid_integrated()* should be more accurate, but this method better matches GWB from sampled (*kale.sample_*) populations!!

The input number of binaries is *N* s.t.

$$N = (d^4N/[dlog10(M)dqdzdlogf]) * dlog10(M)dqdzdlogf$$

The number *N* is evaluated on a 4d grid, specified by *edges*, i.e.

$$N = N(M, q, z, f_r)$$

NOTE: the provided *number* must also summed/integrated over dlogf. To calculate characteristic strain, this function divides again by the dlogf term.

Parameters

- **edges** (*(4,) iterable of array_like,*) – The edges of each dimension of the parameter space. The edges should be, in order: [mtot, mrat, redz, fobs], In units of [grams], [], [], [1/sec].
- **dnum** (*(M, Q, Z, F) ndarray,*) – Differential comoving number-density of binaries in each bin.
- **number** (*(M, Q, Z, F) ndarray,*) – Volumetric comoving number-density of binaries in each bin.
- **realize** (*bool or int,*) – Whether or not to calculate one or multiple realizations of the population. BUG: explain more.

Returns
hc – Total characteristic GW strain from each bin of parameter space. NOTE: to get total strain from all bins, must sum in quarature! e.g. `gwb = np.sqrt(np.square(hc).sum())`

Return type
(M',Q',Z',F) ndarray,

CHAPTER

SIXTEEN

HOLODECK.HARDENING

Binary evolution hardening submodules.

16.1 To-Do (Hardening)

- **Dynamical_Friction_NFW**
  - Allow stellar-density profiles to also be specified (instead of using a hard-coded Dehnen profile)
  - Generalize calculation of stellar characteristic radius. Make self-consistent with stellar-profile, and user-specifiable.
- **Evolution**
  - *_sample_universe()* : sample in comoving-volume instead of redshift
- **Sesana_Scattering**
  - Allow stellar-density profile (or otherwise the binding-radius) to be user-specified and flexible. Currently hard-coded to Dehnen profile estimate.
- **_SHM06**
  - Interpolants of hardening parameters return 1D arrays.
- **Fixed_Time_2PL**
  - Handle *rchar* better with respect to interpolation. Currently not an interpolation variable, which restricts it's usage.
  - This class should be separated into a generic *_Fixed_Time* class that can use any functional form, and then a 2-power-law functional form that requires a specified normalization. When they're combined, it will produce the same effect. Another good functional form to implement would be GW + log-uniform hardening time, the same as the current phenomenological model but with both power-laws set to 0.

References

- [BBR1980] Begelman, Blandford & Rees 1980.
- [Chen2017] Chen, Sesana, & Del Pozzo 2017.
- [Kelley2017a] Kelley, Blecha & Hernquist 2017.
- [Quinlan1996] Quinlan 1996.
- [Sesana2006] Sesana, Haardt & Madau et al. 2006.

- [Sesana2010] Sesana 2010.
- [Siwek2023] Siwek+2023

class holodeck.hardening.**CBD_Torques**(*f_edd=0.1*, *subpc=True*)

Binary Orbital Evolution based on Hydrodynamic Simulations by Siwek+23.

This module uses data from Siwek+23, which supplies rates of change of binary semi-major axis a_b and binary eccentricity e_b. The calculation of a_b and e_b versus time requires accretion rates (for scale).

dadt_dedt(*evo*, *step*)

Circumbinary Disk Torque hardening rate.

Parameters

- **evo** (*Evolution*) – Evolution instance providing binary parameters at the given intergration step.
- **step** (*int*) – Integration step at which to calculate hardening rates.

Returns

- **dadt** (*array_like*) – Binary hardening rates in units of [cm/s], defined to be negative.
- **dedt** (*array_like*) – Binary rate-of-change of eccentricity in units of [1/sec].

class holodeck.hardening.**Dynamical_Friction_NFW**(*mmbulge=None*, *msigma=None*, *smhm=None*, *coulomb=10.0*, *attenuate=True*, *rbound_from_density=True*)

Dynamical Friction (DF) hardening module assuming an NFW dark-matter density profile.

This class calculates densities and orbital velocities based on a NFW profile with parameters based on those of each MBH binary. The *holodeck.observations.NFW* class is used for profile calculations, and the halo parameters are calculated from Stellar-mass–Halo-mass relations (see 'arguments' below). The 'effective-mass' of the inspiralling secondary is modeled as a power-law decreasing from the sum of secondary MBH and its stellar-bulge (calculated using the *mmbulge* - Mbh-Mbulge relation), down to just the bare secondary MBH after 10 dynamical times. This is to model tidal-stripping of the secondary host galaxy.

Attenuation of the DF hardening rate is typically also included, to account for the inefficiency of DF once the binary enters the hardened regime. This is calculated using the prescription from [BBR1980]. The different characteristic radii, needed for the attenuation calculation, currently use a fixed Dehnen stellar-density profile as in [Chen2017], and a fixed scaling relationship to find the characteristic stellar-radius.

Notes

- This module does not evolve eccentricity.
- The hardening rate (da/dt) is not allowed to be larger than the orbital/virial velocity of the halo (as a function of radius).

dadt_dedt(*evo*, *step*, *attenuate=None*)

Calculate DF hardening rate given *Evolution* instance, and an integration *step*.

Parameters

- **evo** (*Evolution* instance) – The evolutionary tracks of the binary population, providing binary parameters.
- **step** (*int,*) – Integration step at which to calculate hardening rates.

Returns

- **dadt** (*(N,) np.ndarray of scalar,*) – Binary hardening rates in units of [cm/s].
- **dedt** (*(N,) np.ndarray or None*) – Rate-of-change of eccentricity, which is not included in this calculation, it is zero. *None* is returned if the input *eccen* is None.

class holodeck.hardening.**Fixed_Time_2PL**(*time*, *mtot*, *mrat*, *redz*, *sepa_init*, *rchar=3.0856775814913674e+20*, *gamma_inner=-1.0*, *gamma_outer=1.5*, *progress=False*, *interpolate_norm=False*)

Provide a binary hardening rate such that the total lifetime matches a given value.

This class uses a phenomenological functional form (defined in *Fixed_Time_2PL.function()*) to model the hardening rate (da/dt) of binaries. The functional form is,

$$\dot{a} = -A * (1.0 + x)^{-g_2 - 1} / x^{g_1 - 1},$$

where $x \equiv a/r_{\rm char}$ is the binary separation scaled to a characteristic transition radius ($r_{\rm char}$) between two power-law indices g_1 and g_2. There is also an overall normalization A that is calculated to yield the desired binary lifetimes.

The normalization for each binary, to produce the desired lifetime, is calculated as follows:

(1) A set of random test binary parameters are chosen.

(2) The normalization constants are determined, using least-squares optimization, to yield the desired lifetime.

(3) Interpolants are constructed to interpolate between the test binary parameters.

(4) The interpolants are called on the provided binary parameters, to calculate the interpolated normalization constants to reach the desired lifetimes.

Construction/Initialization: note that in addition to the standard `Fixed_Time_2PL.__init__()` constructor, there are two additional constructors are provided:

- *Fixed_Time_2PL.from_pop()* - accept a `holodeck.population._Discrete_Population`,
- *Fixed_Time_2PL.from_sam()* - accept a `holodeck.sam.Semi_Analytic_Model`.

#! Using a callable for *rchar* probably doesnt work - *_calculate_norm_interpolant* looks like #! it only accepts a scalar value.

dadt_dedt(*evo*, *step*)

Calculate hardening rate at the given integration *step*, for the given population.

Parameters

- **evo** (*Evolution* instance) – The evolutionary tracks of the binary population, providing binary parameters.
- **step** (*int,*) – Integration step at which to calculate hardening rates.

Returns

- **dadt** (*(N,) np.ndarray*) – Binary hardening rates in units of [cm/s].
- **dedt** (*(N,) np.ndarray or None*) – Rate-of-change of eccentricity, which is not included in this calculation, it is zero. *None* is returned if the input *eccen* is None.

classmethod from_pop(*pop*, *time*, ***kwargs*)

Initialize a *Fixed_Time_2PL* instance using a provided *_Discrete_Population* instance.

Parameters

- **pop** (*_Discrete_Population*) – Input population, from which to use masses, redshifts and separations.

- **time** (*float, callable or array_like*) – Total merger time of binaries, units of [sec], specifiable in the following ways:
  - float : uniform merger time for all binaries
  - callable : function *time(mtot, mrat, redz)* which returns the total merger time
  - array_like : (N,) matching the shape of *mtot* (etc) giving the merger time for each binary
- ****kwargs** (*dict*) – Additional keyword-argument pairs passed to the *Fixed_Time_2PL* initialization method.

Returns
Instance configured for the given binary population.

Return type
Fixed_Time_2PL

classmethod from_sam(*sam*, *time*, *sepa_init=3.0856775814913676e+22*, ***kwargs*)

Initialize a *Fixed_Time_2PL* instance using a provided *Semi_Analytic_Model* instance.

Parameters

- **sam** (*holodeck.sam.Semi_Analytic_Model*) – Input population, from which to use masses, redshifts and separations.
- **time** (*float, callable or array_like*) – Total merger time of binaries, units of [sec], specifiable in the following ways:
  - float : uniform merger time for all binaries
  - callable : function *time(mtot, mrat, redz)* which returns the total merger time
  - array_like : (N,) matching the shape of *mtot* (etc) giving the merger time for each binary
- **sepa_init** (*float or array_like*) – Initial binary separation. Units of [cm].
  - float : initial separation applied to all binaries,
  - array_like : initial separations for all binaries, shaped (N,) matching the number binaries.
- ****kwargs** (*dict*) – Additional keyword-argument pairs passed to the *Fixed_Time_2PL* initialization method.

Returns
Instance configured for the given binary population.

Return type
Fixed_Time_2PL

classmethod function(*norm*, *xx*, *gamma_inner*, *gamma_outer*)

Hardening rate given the parameters for this hardening model.

The functional form is,

$$\dot{a} = -A * (1.0 + x)^{-g_o ut + g_i n} / x^{g_i n - 1},$$

Where A is an overall normalization, and $x = a/r_{\rm char}$ is the binary separation scaled to a characteristic transition radius ($r_{\rm char}$) between two power-law indices $g_i nner$ and $g_o uter$.

Parameters

- **norm** (*array_like*) – Hardening rate normalization, units of [cm/s].
- **xx** (*array_like*) – Dimensionless binary separation, the semi-major axis in units of the characteristic (i.e. transition) radius of the model *rchar*.

- **gamma_inner** (*scalar*) – Power-law of hardening timescale in the inner regime (small separations: r < rchar).
- **gamma_outer** (*scalar*) – Power-law of hardening timescale in the outer regime (large separations: r > rchar).

class holodeck.hardening.**Fixed_Time_2PL_SAM**(*sam*, *time*, *sepa_init=3.0856775814913673e+21*, *rchar=3.0856775814913675e+19*, *gamma_inner=-1.0*, *gamma_outer=1.5*, *num_steps=300*)

SAM-Optimized version of *Fixed_Time_2PL*: binary evolution for a fixed total lifetime.

class holodeck.hardening.**Hard_GW**

Gravitational-wave driven binary hardening.

static **dadt**(*mtot*, *mrat*, *sepa*, *eccen=None*)

Calculate GW Hardening rate of semi-major-axis vs. time.

See [Peters1964], Eq. 5.6

Parameters

- **mtot** (*array_like*) – Total mass of each binary system. Units of [gram].
- **mrat** (*array_like*) – Mass ratio of each binary, defined as $q \equiv m_1/m_2 \leq 1.0$.
- **sepa** (*array_like*) – Binary semi-major axis (separation), in units of [cm].
- **eccen** (*array_like or None*) – Binary eccentricity, *None* is the same as zero eccentricity (circular orbit).

Returns

dadt – Hardening rate in semi-major-axis, result is negative, units [cm/s].

Return type

np.ndarray

static **dadt_dedt**(*evo*, *step*)

Calculate GW binary evolution (hardening rate) in semi-major-axis and eccentricity.

Parameters

- **evo** (*Evolution*) – Evolution instance providing the binary parameters for calculating hardening rates.
- **step** (*int*) – Evolution integration step index from which to load binary parameters. e.g. separations are loaded as `evo.sepa[:, step]`.

Returns

- **dadt** (*np.ndarray*) – Hardening rate in semi-major-axis, returns negative value, units [cm/s].
- **dedt** (*np.ndarray*) – Hardening rate in eccentricity, returns negative value, units [1/s].

static **deda**(*sepa*, *eccen*)

Rate of eccentricity change versus separation change.

See [Peters1964], Eq. 5.8

Parameters

- **sepa** (*array_like,*) – Binary semi-major axis (i.e. separation) [cm].
- **eccen** (*array_like,*) – Binary orbital eccentricity.

Returns
rv – Binary deda rate [1/cm] due to GW emission. Values are always positive.

Return type
array_like,

`static dedt(mtot, mrat, sepa, eccen=None)`

Calculate GW Hardening rate of eccentricity vs. time.

See [Peters1964], Eq. 5.7

If *eccen* is *None*, zeros are returned.

Parameters

- **mtot** (*array_like*) – Total mass of each binary system. Units of [gram].
- **mrat** (*array_like*) – Mass ratio of each binary, defined as $q \equiv m_1/m_2 \leq 1.0$.
- **sepa** (*array_like*) – Binary semi-major axis (separation), in units of [cm].
- **eccen** (*array_like or None*) – Binary eccentricity, *None* is the same as zero eccentricity (circular orbit).

Returns
dedt – Hardening rate in eccentricity, result is <= 0.0, units [1/s]. Zero values if *eccen* is *None*.

Return type
np.ndarray

`class holodeck.hardening.Sesana_Scattering(gamma_dehnen=1.0, mmbulge=None, msigma=None)`

Binary-Hardening Rates calculated based on the Sesana stellar-scattering model.

This module uses the stellar-scattering rate constants from the fits in [Sesana2006] using the *_SHM06* class. Scattering is assumed to only be effective once the binary is bound. An exponential cutoff is imposed at larger radii.

`dadt_dedt(evo, step)`

Stellar scattering hardening rate.

Parameters

- **evo** (*Evolution*) – Evolution instance providing binary parameters at the given intergration step.
- **step** (*int*) – Integration step at which to calculate hardening rates.

Returns

- **dadt** (*array_like*) – Binary hardening rates in units of [cm/s], defined to be negative.
- **dedt** (*array_like*) – Binary rate-of-change of eccentricity in units of [1/sec].

CHAPTER

SEVENTEEN

HOLODECK.LOGGER

Logging module.

This module produces a *logging.Logger* instance that can log both to stdout (i.e. using print) and also to an output file. This is especially useful for long or parallelized calculations where more significant diagnostic outputs are required for debugging and/or record-keeping.

holodeck.logger.**get_logger**(*name='holodeck'*, *level_stream=30*, *tostr=<_io.TextIOWrapper name='<stdout>' mode='w' encoding='utf-8'>*, *tofile=None*, *level_file=10*)

Create a standard logger object which logs to file and or stdout stream.

Parameters

- **name** (*str,*) – Handle for this logger, must be distinct for a distinct logger.
- **level_stream** (*int,*) – Logging level for stream.
- **tostr** (*bool,*) – Log to stdout stream.
- **tofile** (str or *None*,) – Filename to log to (turned off if *None*).
- **level_file** (*int,*) – Logging level for file.

Returns

logger – Logger object to use for logging.

Return type

logging.Logger object,

CHAPTER

EIGHTEEN

HOLODECK.PLOT

Plotting module.

Provides convenience methods for generating standard plots and components using *matplotlib*.

class holodeck.plot.**MidpointLogNormalize**(*vmin=None*, *vmax=None*, *midpoint=0.0*, *clip=False*)

class holodeck.plot.**MidpointNormalize**(*vmin=None*, *vmax=None*, *midpoint=0.0*, *clip=False*)

Normalise the colorbar so that diverging bars work there way either side from a prescribed midpoint value)

e.g. im=ax1.imshow(array, norm=MidpointNormalize(midpoint=0.,vmin=-100, vmax=100))

holodeck.plot.**figax**(*figsize=[7, 5]*, *ncols=1*, *nrows=1*, *sharex=False*, *sharey=False*, *squeeze=True*, *scale=None*, *xscale='log'*, *xlabel=''*, *xlim=None*, *yscale='log'*, *ylabel=''*, *ylim=None*, *left=None*, *bottom=None*, *right=None*, *top=None*, *hspace=None*, *wspace=None*, *widths=None*, *heights=None*, *grid=True*, ***kwargs*)

Create matplotlib figure and axes instances.

Convenience function to create fig/axes using *plt.subplots*, and quickly modify standard parameters.

Parameters

- **figsize** (*(2,) list, optional*) – Figure size in inches.
- **ncols** (*int, optional*) – Number of columns of axes.
- **nrows** (*int, optional*) – Number of rows of axes.
- **sharex** (*bool, optional*) – Share xaxes configuration between axes.
- **sharey** (*bool, optional*) – Share yaxes configuration between axes.
- **squeeze** (*bool, optional*) – Remove dimensions of length (1,) in the *axes* object.
- **scale** (*[type], optional*) – Axes scaling to be applied to all x/y axes. One of [‘log’, ‘lin’].
- **xscale** (*str, optional*) – Axes scaling for xaxes [‘log’, ‘lin’].
- **xlabel** (*str, optional*) – Label for xaxes.
- **xlim** (*[type], optional*) – Limits for xaxes.
- **yscale** (*str, optional*) – Axes scaling for yaxes [‘log’, ‘lin’].
- **ylabel** (*str, optional*) – Label for yaxes.
- **ylim** (*[type], optional*) – Limits for yaxes.
- **left** (*[type], optional*) – Left edge of axes space, set using *plt.subplots_adjust()*, as a fraction of figure.

- **bottom** (*[type], optional*) – Bottom edge of axes space, set using *plt.subplots_adjust()*, as a fraction of figure.
- **right** (*[type], optional*) – Right edge of axes space, set using *plt.subplots_adjust()*, as a fraction of figure.
- **top** (*[type], optional*) – Top edge of axes space, set using *plt.subplots_adjust()*, as a fraction of figure.
- **hspace** (*[type], optional*) – Height space between axes if multiple rows are being used.
- **wspace** (*[type], optional*) – Width space between axes if multiple columns are being used.
- **widths** (*[type], optional*) –
- **heights** (*[type], optional*) –
- **grid** (*bool, optional*) – Add grid lines to axes.

Returns

- **fig** (*matplotlib.figure.Figure*) – New matplotlib figure instance containing axes.
- **axes** ([ndarray] *matplotlib.axes.Axes*) – New matplotlib axes, either a single instance or an ndarray of axes.

holodeck.plot.**plot_bg_ss**(*fobs*, *bg*, *ss=None*, *bglabel=None*, *sslabel=None*, *xlabel='GW Frequency $[\\mathrm{yr}^{-1}]$'*, *ylabel='GW Characteristic Strain'*, ***kwargs*)

Can plot strain or power spectral density, just need to set ylabel accordingly

holodeck.plot.**scientific_notation**(*val*, *man=1*, *exp=0*, *dollar=True*)

Convert a scalar into a string with scientific notation (latex formatted).

Parameters

- **val** (*scalar*) – Numerical value to convert.
- **man** (int or *None*) – Precision of the mantissa (decimal points); or *None* for omit mantissa.
- **exp** (int or *None*) – Precision of the exponent (decimal points); or *None* for omit exponent.
- **dollar** (*bool*) – Include dollar-signs ('$') around returned expression.

Returns

rv_str – Scientific notation string using latex formatting.

Return type

str

holodeck.plot.**smap**(*args=[0.0, 1.0]*, *cmap=None*, *log=False*, *norm=None*, *midpoint=None*, *under='0.8'*, *over='0.8'*, *left=None*, *right=None*)

Create a colormap from a scalar range to a set of colors.

Parameters

- **args** (*scalar or array_like of scalar*) – Range of valid scalar values to normalize with
- **cmap** (None, str, or `matplotlib.colors.Colormap` object) – Colormap to use.
- **log** (*bool*) – Logarithmic scaling
- **norm** (None or *matplotlib.colors.Normalize*) – Normalization to use.
- **under** (str or *None*) – Color specification for values below range.

- **over** (str or *None*) – Color specification for values above range.
- **left** (float {0.0, 1.0} or *None*) – Truncate the left edge of the colormap to this value. If *None*, 0.0 used (if *right* is provided).
- **right** (float {0.0, 1.0} or *None*) – Truncate the right edge of the colormap to this value If *None*, 1.0 used (if *left* is provided).

Returns

smap – Scalar mappable object which contains the members: *norm*, *cmap*, and the function *to_rgba*.

Return type

`matplotlib.cm.ScalarMappable`

`holodeck.plot.truncate_colormap(`*cmap*, *minval=0.0*, *maxval=1.0*, *n=100*`)`

https://stackoverflow.com/a/18926541

CHAPTER

NINETEEN

HOLODECK.HOST_RELATIONS

Empirical and phenomenological scaling relationships.

This module defines numerous classes and accessor methods to implement scaling relationships between different empirical quantities, for example BH–Galaxy relations, or Stellar-Mass vs Halo-Mass relations. `abc` base classes are used to implement generic functionality, and define APIs while subclasses are left to perform specific implementations. In general most classes implement both the forward and reverse versions of relationships (e.g. stellar-mass to halo-mass, and also halo-mass to stellar-mass). Reverse relationships are often interpolated over a grid.

Detailed information about the different types of relationships that are implemented can be found in the documentation for the base-classes. Most of the relationships currently implemented are among two groups (and corresponding base classes):

- **BH-Host Relations** (subclasses of *_BH_Host_Relation*): These produce mappings between host galaxy properties (e.g. bulge mass) and the mass of their black holes. Currently, generally only the M-Mbulge relationships should be used for assigning MBH masses (see below).
  - **Mbh-Mbulge relations** ("M-Mbulge"; subclasses of *_MMBulge_Relation*): mapping from host galaxy stellar-bulge mass to black-hole mass. MMBulge relationships must be able to calculate black hole masses given total stellar-masses, not just stellar-bulge masses. This requires the usage of bulge-fractions (the fraction of total stellar-mass in the bulge). These bulge fractions are implemented using subclasses of the `_Bulge_Frac`, in the simplest case a constant bulge fraction using `BF_Constant`.
  - **Mbh-Sigma relations** ("M-Sigma"; subclasses of *_MSigma_Relation*): mapping from host galaxy velocity dispersion (sigma) to black-hole mass. NOTE: as of writing this (2024-03-29) the M-Sigma relationships are not fully supported in semi-analytic models in that the initial galaxy populations do not have stellar velocity-dispersions set.
- **Stellar-Mass vs. Halo-Mass Relations** (subclasses of `_StellarMass_HaloMass`): mapping from dark matter halo-mass to stellar-mass.

19.1 Mbh-MBulge (M-Mbulge)

M-Mbulge relationships, implemented as subclasses of *_MMBulge_Relation*, map from stellar-bulge masses to black-hole masses. These classes also use a bulge-fraction, implemented as subclasses of `_Bulge_Frac`, instance to map from total stellar-masses to bulge masses internally, so that often the *_MMBulge_Relation.mbh_from_mstar()* method will be the primary API interface. The *_MMBulge_Relation* subclasses also provide partial derivative terms, in particular the *_MMBulge_Relation.dmstar_dmbh()* method, which is used by SAMs to convert from galaxy-galaxy mergers to MBH-MBH mergers. See the class docstrings for more information.

Note that redshift-dependent versions of M-Mbulge relationships are also provided, but note that these are still under development and testing (2024-03-28).

It is very easy to implement new M-Mbulge relationships by creating new subclasses of *_MMBulge_Relation*. See the class documentation for more information.

19.2 Relations: To-Do

- Pass concentration-relation (or other method to calculate) to NFW classes on instantiation

References

- [Behroozi2013] : Behroozi, Wechsler & Conroy 2013.
- [Guo2010] Guo, White, Li & Boylan-Kolchin 2010.
- [KH2013] Kormendy & Ho 2013.
- [MM2013] McConnell & Ma 2013.

class holodeck.host_relations.**_BH_Host_Relation**(**args*, ***kwargs*)

Bases: ABC

Base class for general relationships between MBHs and their host galaxies.

This base-class is mostly organizational. For **discrete** populations, it specifies the API method `get_host_properties` which is a generic interface to derive BH masses from arbitrary properties of host galaxies (e.g. velocity dispersion, bulge mass, etc). This must be implemented by the subclasses. For **SAMs**, this base class provides no functionality.

_PROPERTIES = []

list of property names to retrieve from population instances.

get_host_properties(*pop*, *copy=True*) → dict

Get the host properties specified in the *_PROPERTIES* list of variable names.

NOTE: if the *copy* flag is False, then values are returned by reference and the original values may be modified accidentally. Use *copy=True* to avoid modifying values in place. Use *copy=False* carefully, when trying to avoid unnecessary memory duplication.

Parameters

- **pop** (*holodeck.population.Population* instance) – Binary population including necessary host properties.
- **copy** (*bool, optional*) – Copy the *pop* data into new arrays instead of returning references to original values.

Returns

vals – Values loaded from *pop*. Names/keys correspond to *_PROPERTIES* strings.

Return type

dict

abstract mbh_from_host(*pop*, **args*, ***kwargs*) → ndarray

Convert from abstract host galaxy properties to blackhole mass.

This method is intended for discrete (e.g. illustris) based populations.

The pop instance must contain the attributes required for this class's scaling relations. The required properties are stored in this class's _PROPERTIES attribute.

Parameters
pop (_Discrete_Population,) – Population instance having the attributes required by this particular scaling relation.

Returns
mbh – Black hole mass. [grams]

Return type
array_like [g]

_abc_impl = <_abc._abc_data object>

class holodeck.host_relations._MMBulge_Relation(*bulge_frac=None*, *bulge_mfrac=None*)

Bases: _BH_Host_Relation

Base class for implementing Mbh–Mbulge relationships, between MBH and their host galaxies.

Typically there is an intermediate step of converting from the galaxy total stellar-mass into a bulge mass, so these relations would more accurately be called Mbh-Mstar relationships. For **discrete** populations, derived classes must provide a BH mass for a given stellar/bulge mass. For **SAMs** derived classes must additionally provide the partial derivatives of the black hole mass (so that galaxy-galaxy number densities can be converted to MBH-MBH number densities).

19.3 API / Subclass Implementation

Provided - Functions provided directly by this base-class (_MMBulge_Relation).

- dmstar_dmbh : uses dmstar_dmbulge from the bulge-fraction instance, and the dmbulge_dmbh method which must be provided by subclass implementations.
- mbh_from_mstar: requires mbulge_from_mstar in the bulge-fraction instance.

Required - for core functionality, all _MMBulge_Relation subclasses are required to implement the following methods:

- mbh_from_mbulge : the core purpose/functionality of all subclasses.
- dmbulge_dmbh : required for calculating semi-analytic model populations. More specifically, the dmstar_dmbh method is required for SAMs, and that method in turn requires dmbulge_dmbh to be implemented.

Optional - For extended functionality, _MMBulge_Relation subclasses may implement additional functions, but it is not guaranteed/required. Specifically the following methods:

- mbulge_from_mbh: the inverse relationship. Not necessarily calculable analytically.

Dependent - Implemented functionality that depends on 'Optional' API methods.

- mstar_from_mbh: requires the mbulge_from_mbh method to be implemented.

_PROPERTIES = ['mbulge']

list of property names to retrieve from population instances.

_bulge_frac

_Bulge_Frac subclass instance to obtain bulge masses

dmstar_dmbh(*mstar*, *redz=None*, ***bfkwargs*)

Calculate the partial derivative of stellar mass versus BH mass dM_star/dM_bh.

$$dM_star/dM_bh = [dM_star/dM_bulge] * [dM_bulge/dM_bh]$$

The dMbulge/dMbh component is calculated explicitly using `self.ddmbulge_dmbh`, while the dMstar/dMbulge component is obtained from the `bulge_frac` instance.

Parameters

- **mstar** (*array_like, [g]*) – Total stellar mass of galaxy in units of grams.
- **redz** (array_like or *None*) – Redshifts of the galaxies under consideration.
- **bfkwargs** (*dict*) – Additional arguments passed to the bulge-fraction isntance (`self._bulge_frac`).

Returns
dmstar_dmbh – Jacobian term: partial derivative of stellar mass w.r.t. black-hole mass. This quantity is unitless.

Return type
array_like []

mbh_from_mstar(*mstar*, *redz=None*, *scatter=None*)

Calculate a black-hole mass from the given total stellar-mass.

NOTE: this function requires the `mbulge_from_mstar` function to be implemented by the bulge-fraction instance (`self._bulge_frac`) that's being used. This is not guaranteed!

Parameters

- **mstar** (*array_like, [g]*) – Total stellar mass of host galaxy in units of grams.
- **redz** (array_like or *None*) – Redshifts of the galaxies under consideration.
- **scatter** (*bool,*) – Whether or not to include scatter when converting to BH masses.

Returns
mbh – Black hole masses in units of grams.

Return type
array_like [g]

abstract mbh_from_mbulge(*mbulge*, *redz=None*, *scatter=None*, ***kwargs*)

Convert from stellar-bulge mass to black-hole mass.

Returns

- **mbh** (*array_like [g]*) – Mass of black hole in units of grams.
- **redz** (array_like or *None*) – Redshifts of the galaxies under consideration.
- **scatter** (*bool,*) – Whether or not to include scatter when converting to BH masses.
- **kwargs** (*dict,*) – Additional keyword-arguments.

Returns
mbh – Black-hole masses in units of grams.

Return type
array_like [g]

abstract dmbulge_dmbh(*mbulge*, *redz=None*)

The partial derivative of stellar mass versus black-hole mass.

Parameters
mbulge (*array_like, [g]*) – Mass of the host galaxy stellar bulges in units of grams.

Returns
dmbulge_dmbh – Jacobian term: partial derivative of stellar-bulge mass w.r.t. black-hole mass. This quantity is unitless.

Return type
array_like, []

`mbulge_from_mbh`(**args*, ***kwargs*)

Convert from black-hole mass to stellar-bulge mass.

Returns
mbulge – Mass of stellar bulge. [grams]

Return type
array_like,

`mstar_from_mbh`(*mbh*, *redz=None*)

Calculate a total stellar-mass from the given BH mass.

NOTE: this function requires the `mbulge_from_mbh` function to be implemented by the particular `_MMBulge_Relation` subclass, and additionally that the `mstar_from_mbulge` function is implemented by the bulge-fraction instance (`self._bulge_frac`) that's being used. Neither is guaranteed!

Parameters

- **mbh** (*array_like [g]*) – Mass of black hole in units of grams.
- **redz** (array_like or *None*) – Redshifts of the galaxies under consideration.

Returns
mstar – Total stellar-mass of galaxies in units of grams.

Return type
array_like [g]

`_abc_impl = <_abc._abc_data object>`

class holodeck.host_relations.**MMBulge_Standard**(*mamp_log10=None*, *mplaw=None*, *mref=None*, *scatter_dex=None*, *bulge_frac=None*, *bulge_mfrac=None*, ***kwargs*)

Bases: *_MMBulge_Relation*

Simple Mbh-Mbulge relation as a single power-law.

This Mbh-Mbulge relation implements a single power-law relationship between BH mass and stellar-bulge mass:

$$M_{bh} = M_0 * (M_{bulge}/M_{ref})^{\gamma} * 10^{N} ormal(0, \epsilon)$$

See documemtation for *_MMBulge_Relation* for more information.

MASS_AMP_LOG10 = 8.17

MASS_PLAW = 1.01

MASS_REF = 1.9884098706980508e+44

SCATTER_DEX = 0.3

BULGE_MASS_FRAC = 0.615

Default bulge mass as fraction of total stellar mass

_mamp

Mass-Amplitude [grams]

_mplaw

Mass Power-law index

_mref

Reference Mass (argument normalization)

mbh_from_host(*pop*, *scatter=None*)

Convert from abstract host galaxy properties to blackhole mass.

This method is intended for discrete (e.g. illustris) based populations.

The pop instance must contain the attributes required for this class's scaling relations. The required properties are stored in this class's _PROPERTIES attribute.

Parameters
pop (_Discrete_Population,) – Population instance having the attributes required by this particular scaling relation.

Returns
mbh – Black hole mass. [grams]

Return type
array_like [g]

mbh_from_mbulge(*mbulge*, *redz=None*, *scatter=None*)

Convert from stellar-bulge mass to black-hole mass.

Returns

- **mbh** (*array_like [g]*) – Mass of black hole in units of grams.
- **redz** (array_like or *None*) – Redshifts of the galaxies under consideration.
- **scatter** (*bool,*) – Whether or not to include scatter when converting to BH masses.
- **kwargs** (*dict,*) – Additional keyword-arguments.

Returns
mbh – Black-hole masses in units of grams.

Return type
array_like [g]

dmbulge_dmbh(*mbulge*, *redz=None*, ***bfkwargs*)

Calculate the partial derivative of bulge mass versus BH mass dM_bulge/dM_bh.

$$[dM_bulge/dM_bh] = [M_bulge/(plaw * M_bh)]$$

Parameters

- **mbulge** (*array_like, [g]*) – Bulge stellar mass of galaxy in units of grams.
- **redz** (array_like or *None*) – Redshifts of the galaxies under consideration.

Returns
deriv – Jacobian term: partial derivative of stellar mass w.r.t. black-hole mass. This quantity is unitless.

Return type
array_like, []

mbulge_from_mbh(*mbh*, *redz=None*, *scatter=None*)

Convert from black-hole mass to stellar-bulge mass.

Parameters

- **mbh** (*array_like, [g]*) – Mass of black holes in units of grams.
- **redz** (array_like or *None*) – Redshifts of the galaxies under consideration.
- **scatter** (*bool,*) – Whether or not to include scatter in scaling relationship. Uses *self._scatter_dex* attribute.

Returns

mbulge – Mass of stellar bulge in units of grams.

Return type

array_like, [g]

mstar_from_mbh(*mbh*, *redz=None*, *scatter=None*, ***kwargs*)

Calculate a total stellar-mass from the given BH mass.

NOTE: this function requires the `mbulge_from_mbh` function to be implemented by the particular `_MMBulge_Relation` subclass, and additionally that the `mstar_from_mbulge` function is implemented by the bulge-fraction instance (`self._bulge_frac`) that's being used. Neither is guaranteed!

Parameters

- **mbh** (*array_like [g]*) – Mass of black hole in units of grams.
- **redz** (array_like or *None*) – Redshifts of the galaxies under consideration.

Returns

mstar – Total stellar-mass of galaxies in units of grams.

Return type

array_like [g]

_abc_impl = <_abc._abc_data object>

class holodeck.host_relations.**MMBulge_KH2013**(*mamp_log10=None*, *mplaw=None*, *mref=None*, *scatter_dex=None*, *bulge_frac=None*, *bulge_mfrac=None*, ***kwargs*)

Bases: *MMBulge_Standard*

Mbh-MBulge Relation, single power-law, from Kormendy & Ho 2013.

Values taken from [KH2013] Eq.10.

MASS_AMP_LOG10 = 8.69

MASS_REF = 1.9884098706980508e+44

MASS_PLAW = 1.17

SCATTER_DEX = 0.28

_abc_impl = <_abc._abc_data object>

class holodeck.host_relations.**MMBulge_MM2013**(*mamp_log10=None*, *mplaw=None*, *mref=None*, *scatter_dex=None*, *bulge_frac=None*, *bulge_mfrac=None*, ***kwargs*)

Bases: *MMBulge_Standard*

Mbh-MBulge Relation from McConnell & Ma 2013

[MM2013] Eq. 2, with values taken from Table 2 ("Dynamical masses", first row, "MPFITEXY")

MASS_AMP_LOG10 = 8.46

MASS_REF = 1.9884098706980508e+44

MASS_PLAW = 1.05

SCATTER_DEX = 0.34

_abc_impl = <_abc._abc_data object>

class holodeck.host_relations.**MMBulge_Redshift**(**args*, *zplaw=None*, ***kwargs*)

Bases: *MMBulge_Standard*

Mbh-Mbulge relation with an additional redshift power-law dependence.

Provides black hole mass as a function of galaxy bulge mass and redshift with a normalization that depends on redshift. `zplaw=0` (default) is identical to MMBulge_Standard. `mamp = mamp0 * (1 + z)**zplaw`.

TODO: make sure all of the inherited methods from *MMBulge_Standard* are appropriate for redshift dependencies!! In particular, check *dmstar_dmbh* check which redshifts need to be passed into this function. does not pass all cases as is

MASS_AMP_LOG10 = 8.17

MASS_PLAW = 1.0

MASS_REF = 1.9884098706980508e+44

SCATTER_DEX = 0.0

Z_PLAW = 0.0

_PROPERTIES = ['mbulge', 'redz']

list of property names to retrieve from population instances.

mbh_from_host(*pop*, *scatter*)

Convert from abstract host galaxy properties to blackhole mass.

This method is intended for discrete (e.g. illustris) based populations.

The `pop` instance must contain the attributes required for this class's scaling relations. The required properties are stored in this class's `_PROPERTIES` attribute.

Parameters
pop (`_Discrete_Population`,) – Population instance having the attributes required by this particular scaling relation.

Returns
mbh – Black hole mass. [grams]

Return type
array_like [g]

mbh_from_mbulge(*mbulge*, *redz*, *scatter*)

Convert from stellar-bulge mass to black-hole mass.

Returns

- **mbh** (*array_like [g]*) – Mass of black hole in units of grams.
- **redz** (array_like or *None*) – Redshifts of the galaxies under consideration.
- **scatter** (*bool,*) – Whether or not to include scatter when converting to BH masses.
- **kwargs** (*dict,*) – Additional keyword-arguments.

Returns
mbh – Black-hole masses in units of grams.

Return type
array_like [g]

mbulge_from_mbh(*mbh*, *redz*, *scatter*)

Convert from black-hole mass to stellar-bulge mass.

Parameters

- **mbh** (*array_like, [g]*) – Mass of black holes in units of grams.
- **redz** (array_like or *None*) – Redshifts of the galaxies under consideration.
- **scatter** (*bool,*) – Whether or not to include scatter in scaling relationship. Uses *self._scatter_dex* attribute.

Returns
mbulge – Mass of stellar bulge in units of grams.

Return type
array_like, [g]

_abc_impl = <_abc._abc_data object>

class holodeck.host_relations.**MMBulge_Redshift_MM2013**(**args*, *zplaw=None*, ***kwargs*)

Bases: *MMBulge_Redshift*

Mbh-MBulge Relation from McConnell & Ma 2013 for z=0 plus redshift evolution of the normalization

BUG/FIX: use multiple-inheritance for this

[MM2013] Eq. 2, with values taken from Table 2 (“Dynamical masses”, first row, “MPFITEXY”)

MASS_AMP_LOG10 = 8.46

MASS_REF = 1.9884098706980508e+44

MASS_PLAW = 1.05

SCATTER_DEX = 0.34

Z_PLAW = 0.0

_abc_impl = <_abc._abc_data object>

class holodeck.host_relations.**MMBulge_Redshift_KH2013**(**args*, *zplaw=None*, ***kwargs*)

Bases: *MMBulge_Redshift*

Mbh-MBulge Relation from Kormendy & Ho 2013, w/ optional redshift evolution of normalization.

BUG/FIX: use multiple-inheritance for this

Values taken from [KH2013] Eq.10 (pg. 61 of PDF, "571" of ARAA)

MASS_AMP_LOG10 = 8.69

MASS_REF = 1.9884098706980508e+44

MASS_PLAW = 1.17

SCATTER_DEX = 0.28

Z_PLAW = 0.0

_abc_impl = <_abc._abc_data object>

holodeck.host_relations.**get_mmbulge_relation**(*mmbulge:* _MMBulge_Relation | *Type[*_MMBulge_Relation*]* | *None = None*) → *_MMBulge_Relation*

Return a valid Mbh-Mbulge instance.

Parameters

mmbulge (None or (type or instance of *_MMBulge_Relation*),) – If *None*, then a default M-Mbulge relation is returned. Otherwise, the type is checked to make sure it is a valid instance of an *_MMBulge_Relation*.

Returns

Instance of an Mbh-Mbulge relationship.

Return type

_MMBulge_Relation

class holodeck.host_relations.**_MSigma_Relation**(**args*, ***kwargs*)

Bases: *_BH_Host_Relation*

Base class for 'M-Sigma relations' between BH mass and host velocity dispersion.

_PROPERTIES = ['vdisp']

list of property names to retrieve from population instances.

abstract mbh_from_vdisp(*vdisp*, *scatter*)

abstract vdisp_from_mbh(*mbh*, *scatter*)

_abc_impl = <_abc._abc_data object>

class holodeck.host_relations.**MSigma_Standard**(*mamp=None*, *sigma_plaw=None*, *sigma_ref=None*, *scatter_dex=None*)

Bases: *_MSigma_Relation*

Simple M-sigma relation (BH mass vs. host velocity dispersion) as a single power-law.

Notes

- Single power-law relationship between BH mass and Stellar-bulge mass. $Mbh = M0 * (sigma/sigma_ref)^plaw * 10^Normal(0, eps)$

MASS_AMP = 1.988409870698051e+41

SIGMA_PLAW = 4.24

SIGMA_REF = 20000000.0

SCATTER_DEX = 0.0

mbh_from_host(*pop*, *scatter*)

Convert from abstract host galaxy properties to blackhole mass.

This method is intended for discrete (e.g. illustris) based populations.

The pop instance must contain the attributes required for this class's scaling relations. The required properties are stored in this class's _PROPERTIES attribute.

Parameters
pop (_Discrete_Population,) – Population instance having the attributes required by this particular scaling relation.

Returns
mbh – Black hole mass. [grams]

Return type
array_like [g]

mbh_from_vdisp(*vdisp*, *scatter*)

Convert from host galaxy stellar velocity dispersion to black-hole mass.

Parameters

- **vdisp** (*array_like,*) – Host-galaxy velocity dispersion. [cm/s].
- **scatter** (*bool,*) – Whether or not to include scatter in scaling relationship. Uses *self._scatter_dex* attribute.

Returns
mbh – Mass of black hole. [grams]

Return type
array_like,

vdisp_from_mbh(*mbh*, *scatter*)

Convert from black-hole mass to host galaxy stellar velocity dispersion.

Parameters

- **mbh** (*array_like,*) – Mass of black hole. [grams]
- **scatter** (*bool,*) – Whether or not to include scatter in scaling relationship. Uses *self._scatter_dex* attribute.

Returns
vdisp – Host-galaxy velocity dispersion. [cm/s].

Return type
array_like,

_abc_impl = <_abc._abc_data object>

class holodeck.host_relations.**MSigma_MM2013**(*mamp=None*, *sigma_plaw=None*, *sigma_ref=None*, *scatter_dex=None*)

Bases: *MSigma_Standard*

Mbh-Sigma Relation from McConnell & Ma 2013.

[MM2013] Eq. 2, with values taken from Table 2 ("M-sigma all galaxies", first row, "MPFITEXY")

MASS_AMP = 4.1543770494014215e+41

SIGMA_REF = 20000000.0

MASS_PLAW = 5.64

SCATTER_DEX = 0.38

_abc_impl = <_abc._abc_data object>

class holodeck.host_relations.**MSigma_KH2013**(*mamp=None*, *sigma_plaw=None*, *sigma_ref=None*, *scatter_dex=None*)

Bases: *MSigma_Standard*

Mbh-Sigma Relation from Kormendy & Ho 2013.

[KH2013] Eq. 10, (pg. 65 of PDF, "575" of ARAA)

MASS_AMP = 5.734636708221092e+41

SIGMA_REF = 20000000.0

MASS_PLAW = 4.26

SCATTER_DEX = 0.3

_abc_impl = <_abc._abc_data object>

holodeck.host_relations.**get_msigma_relation**(*msigma: _MSigma_Relation | Type[_MSigma_Relation] | None = None*) → *_MSigma_Relation*

Return a valid M-sigma (BH Mass vs. host galaxy velocity dispersion) instance.

Parameters

msigma (None or (class or instance of *_MSigma_Relation*),) – If *None*, then a default M-sigma relation is returned. Otherwise, the type is checked to make sure it is a valid instance of an *_MSigma_Relation*.

Returns

Instance of an Mbh-sigma relationship.

Return type

_MSigma_Relation

class holodeck.host_relations.**Guo_2010**

Bases: _StellarMass_HaloMass

Stellar-Mass - Halo-Mass relation from Guo et al. 2010.

[Guo2010] Eq.3

_NORM = 0.129

_M0 = 4.994659774486157e+44

_ALPHA = 0.926

_BETA = 0.261

_GAMMA = 2.44

classmethod stellar_mass(*mhalo*)

Calculate the stellar-mass for the given halo mass.

Parameters
mhalo (*ArrayLike*) – Halo mass. [gram]

Returns
mstar – Stellar mass. [gram]

Return type
ArrayLike

_abc_impl = <_abc._abc_data object>

class holodeck.host_relations.**Behroozi_2013**(**args*, ***kwargs*)

Bases: _StellarMass_HaloMass_Redshift

Redshift-dependent Stellar-Mass - Halo-Mass relation based on Behroozi et al. 2013.

[Behroozi2013] best fit values are at the beginning of Section 5 (pg.9), uncertainties are 1-sigma.

stellar_mass(*mhalo*, *redz*)

This is [Behroozi2013] Eq.3 (upper)

_nu_func()

[Behroozi2013] Eq. 4

classmethod _param_func(*redz*, *v0*, *va*, *vz*, *va2=None*)

[Behroozi2013] Eq. 4

classmethod _eps(*redz=0.0*)

classmethod _m1(*redz=0.0*)

classmethod _alpha(*redz=0.0*)

classmethod _delta(*redz=0.0*)

classmethod _gamma(*redz=0.0*)

classmethod _xsi(*redz=0.0*)

[Behroozi+2013] Eq.5

classmethod _f_func(*xx*, *redz=0.0*)

[Behroozi+2013] Eq.3 (lower)

_abc_impl = <_abc._abc_data object>

CHAPTER

TWENTY

HOLODECK.UTILS

Utility functions and tools.

References

- [Peters1964] Peters 1964
- [Enoki2004] Enoki, Inoue, Nagashima, & Sugiyama 2004
- [Sesana2004] Sesana, Haardt, Madau, & Volonteri 2004
- [EN2007] Enoki & Nagashima 2007

class holodeck.utils.**_Modifier**

Bases: ABC

Base class for all types of post-processing modifiers.

Notes

- Must be subclassed for use.
- `__call__(base)` ==> `modify(base)`

abstract modify(*base: object*)

Perform an in-place modification on the passed object instance.

Parameters

base (*object*) – The object instance to be modified.

_abc_impl = <_abc._abc_data object>

holodeck.utils.**deprecated_warn**(*msg*, *exc_info=True*)

Decorator for functions that will be deprecated, add warning, but still execute function.

holodeck.utils.**deprecated_pass**(*new_func*, *msg=''*, *exc_info=True*)

Decorator for functions that have been deprecated, warn and pass arguments to new function.

holodeck.utils.**deprecated_fail**(*new_func*, *msg=''*, *exc_info=True*)

Decorator for functions that have been deprecated, warn and raise error.

holodeck.utils.**load_hdf5**(*fname*, *keys=None*)

Load data and header information from HDF5 files into dictionaries.

Parameters

- **fname** (*str*) – Filename to load (must be an *hdf5* file).
- **keys** (*None or (list of str)*) – Specific keys to load from the top-level of the HDF5 file. *None*: load all top-level keys.

Returns

- **header** (*dict,*) – All entries from *hdf5.File.attrs*, typically used for meta-data.
- **data** (*dict,*) – All top level datasets from the hdf5 file, specifically everything returned from *hdf5.File.keys()*.

holodeck.utils.**mpi_print**(**args*, ***kwargs*)

holodeck.utils.**python_environment**()

Tries to determine the current python environment, one of: 'jupyter', 'ipython', 'terminal'.

Returns
Description of the current python environment, one of ['jupter', 'ipython', 'terminal'].

Return type
str

holodeck.utils.**tqdm**(**args*, ***kwargs*)

Construct a progress bar appropriately based on the current environment (script vs. notebook)

Parameters

- ***args** (All arguments are passed directory to the *tqdm* constructor.) –
- ****kwargs** (All arguments are passed directory to the *tqdm* constructor.) –

Returns
Decorated iterator that shows a progress bar.

Return type
tqdm.tqdm_gui

holodeck.utils.**get_file_size**(*fnames*, *precision=1*)

Return a human-readable size of a file or set of files.

Parameters

- **fnames** (*str or list*) – Paths to target file(s)
- **precisions** (*int,*) – Sesired decimal precision of output

Returns
byte_str – Human-readable size of file(s)

Return type
str

holodeck.utils.**path_name_ending**(*path*, *ending*)

holodeck.utils.**get_subclass_instance**(*value*, *default*, *superclass*, *allow_none=False*)

Convert the given *value* into a subclass instance.

None ==> instance from *default* class Class ==> instance from that class instance ==> check that this is an instance of a subclass of *superclass*, error if not

Parameters

- **value** (*object,*) – Object to convert into a class instance.
- **default** (*class,*) – Default class constructor to use if *value* is None.

- **superclass** (*class,*) – Super/parent class to compare against the class instance from *value* or *default*. If the class instance is not a subclass of *superclass*, a ValueError is raised.

Returns
value – Class instance that is a subclass of *superclass*.

Return type
object,

:raises ValueError : if the class instance is not a subclass of *superclass*.:

holodeck.utils.**get_git_hash**(*short=True*) → str

holodeck.utils.**roll_rows**(*arr*, *roll_num*)

Roll each row (axis=0) of the given array by an amount specified.

Parameters

- **arr** (*(R, D) ndarray*) – Input data to be rolled.
- **roll_num** (*(R,) ndarray of int*) – Amount to roll each row. Must match the number of rows (axis=0) in *arr*.

Returns
result – Rolled version of the input data.

Return type
(R, D) ndarray

Example

```
>>> a = np.arange(12).reshape(3, 4); b = [1, -1, 2]; utils.roll_rows(a, b)
array([[ 3,  0,  1,  2],
       [ 5,  6,  7,  4],
       [10, 11,  8,  9]])
```

holodeck.utils.**get_scatter_weights**(*uniform_cents*, *dist*)

Get the weights (fractional mass) that should be transferred to each bin to introduce the given scatter.

Parameters

- **uniform_cents** (*(N,) ndarray*) – Uniformly spaced bin-centers specifying distances in the parameter of interest (e.g. mass).
- **dist** (*scipy.stats._distn_infrastructure.rv_continuous_frozen* instance) – Object providing a CDF function *cdf(x)* determining the weights for each bin. e.g. `dist = sp.stats.norm(loc=0.0, scale=0.1)`

Returns
dm – Array of weights for bins with the given distances. [-N+1, -N+2, …, -2, -1, 0, +1, +2, …, +N-2, +N-1]

Return type
(2*N - 1,) ndarray

holodeck.utils.**_scatter_with_weights**(*dens*, *weights*, *axis=0*)

holodeck.utils.**_get_rolled_weights**(*log_cents*, *dist*)

holodeck.utils.**scatter_redistribute_densities**(*cents*, *dens*, *dist=None*, *scatter=None*, *axis=0*)

Redistribute *dens* across the target axis to account for scatter/variance.

Parameters

- **cents** (*(N,) ndarray*) – Locations of bin centers in the parameter of interest.
- **dist** (*scipy.stats._distn_infrastructure.rv_continuous_frozen* instance) – Object providing a CDF function *cdf(x)* determining the weights for each bin. e.g. `dist = sp.stats.norm(loc=0.0, scale=0.1)`
- **dens** (*ndarray*) – Input values to be redistributed. Must match the size of *cents* along axis *axis*.

Returns

dens_new – Array with resitributed values. Same shape as input *dens*.

Return type

ndarray

holodeck.utils.**eccen_func**(*cent: float*, *width: float*, *size: int*) → ndarray

Draw random values between [0.0, 1.0] with a given center and width.

This function is a bit contrived, but the *norm* defines the center-point of the distribution, and the *std* parameter determines the width of the distribution. In all cases the resulting values are only between [0.0, 1.0]. This function is typically used to draw initial random eccentricities.

Parameters

- **cent** (*float,*) – Specification of the center-point of the distribution. Range: positive numbers. Values *norm << 1* correspond to small eccentricities, while *norm >> 1* are large eccentricities, with the distribution symmetric around *norm=1.0* (and eccens of 0.5).
- **width** (*float,*) – Specification of the width of the distribution. Specifically how near or far values tend to be from the given central value (*norm*). Range: positive numbers. Note that the 'width' of the distribution depends on the *norm* value, in addition to *std*. Smaller values (typically *std << 1*) produce narrower distributions.
- **size** (*int,*) – Number of samples to draw.

Returns

eccen – Values between [0.0, 1.0] with shape given by the *size* parameter.

Return type

ndarray,

holodeck.utils.**frac_str**(*vals*, *prec=2*)

Return a string with the fraction and decimal of non-zero elements of the given array.

e.g. [0, 1, 2, 0, 0] ==> "2/5 = 4.0e-1"

Parameters

- **vals** (*(N,) array_like,*) – Input array to find non-zero elements of.
- **prec** (*int*) – Decimal precision in scientific notation string.

Returns

rv – Fraction string.

Return type

str,

holodeck.utils.**interp**(*xnew*, *xold*, *yold*, *left=nan*, *right=nan*, *xlog=True*, *ylog=True*)

Linear interpolation of the given arguments in log/lin-log/lin space.

Parameters

- **xnew** (*npt.ArrayLike*) – New locations (independent variable) to interpolate to.
- **xold** (*npt.ArrayLike*) – Old locations of independent variable.
- **yold** (*npt.ArrayLike*) – Old locations of dependent variable.
- **left** (*float, optional*) – Fill value for locations below the domain *xold*.
- **right** (*float, optional*) – Fill value for locations above the domain *xold*.
- **xlog** (*bool, optional*) – Linear interpolation in the log of x values.
- **ylog** (*bool, optional*) – Linear interpolation in the log of y values.

Returns

y1 – Interpolated output values of the dependent variable.

Return type

npt.ArrayLike

holodeck.utils.**isnumeric**(*val: object*) → bool

Test if the input value can successfully be cast to a float.

Parameters

val (*object*) – Value to test.

Returns

True if the input value can be cast to a float.

Return type

bool

holodeck.utils.**isinteger**(*val: object*) → bool

Test if the input value is an integral (integer) number.

Parameters

val (*object*) – Value to test.

Returns

True if the input value is an integer number.

Return type

bool

holodeck.utils.**log_normal_base_10**(*mu: float*, *sigma: float*, *size: int | List[int] | None = None*, *shift: float = 0.0*) → ndarray

Draw from a log-normal distribution using base-10 standard-deviation.

i.e. the *sigma* argument is in "dex", or powers of ten.

Parameters

- **mu** (*float*) – Mean value of the distribution.
- **sigma** (*float*) – Standard deviation in dex (i.e. powers of ten). *sigma=1.0* means a standard deviation of one order of magnitude around mu.
- **size** (*Union[int, list[int]], optional*) – Number of values to draw. Either a single integer, or a tuple of integers describing a shape.

- **shift** (*float, optional*) –

Returns
dist – Resulting distribution values.

Return type
npt.ArrayLike

holodeck.utils.**midpoints**(*vals*, *axis=-1*, *log=False*)

holodeck.utils.**midpoints_multiax**(*vals*, *axis*, *log=False*)

holodeck.utils.**minmax**(*vals: _SupportsArray[dtype[Any]] | _NestedSequence[_SupportsArray[dtype[Any]]] | bool | int | float | complex | str | bytes | _NestedSequence[bool | int | float | complex | str | bytes]*, *filter: bool = False*) → ndarray

Find the minimum and maximum values in the given array.

Parameters

- **vals** (*npt.ArrayLike*) – Input values in which to find extrema.
- **filter** (*bool, optional*) – Select only finite values from the input array.

Returns
extr – Minimum and maximum values.

Return type
(2,) np.ndarray

holodeck.utils.**ndinterp**(*xx*, *xvals*, *yvals*, *xlog=False*, *ylog=False*)

Interpolate 2D data to an array of points.

xvals and *yvals* are (N, M) where the interpolation is done along the 1th (*M*) axis (i.e. interpolation is done independently for each *N* row. Should be generalizeable to higher dim.

Parameters

- **xx** (*(T,) or (N, T) ndarray*) – Target x-values to interpolate to.
- **xvals** (*(N, M) ndarray*) – Evaluation points (x-values) of the functions to be interpolated. Interpolation is performed over the 1th (last) axis. NOTE: values *must* be monotonically increasing along axis=1 !
- **yvals** (*(N, M) ndarray*) – Function values (y-values) of the function to be interpolated. Interpolation is performed over the 1th (last) axis.

Returns
ynew – Interpolated function values, for each of N functions and T evaluation points.

Return type
(N, T) ndarray

holodeck.utils.**pta_freqs**(*dur=505868328.00000006*, *num=40*, *cad=None*)

Get Fourier frequency bin specifications for the given parameters.

Parameters

- **dur** (*float,*) – Total observing duration, which determines the minimum sensitive frequency, `1/dur`. Typically *dur* should be given in units of [sec], such that the returned frequencies are in units of [1/sec] = [Hz]
- **num** (*int,*) – Number of frequency bins. If *cad* is not None, then the number of frequency bins is determined by *cad* and the *num* value is disregarded.

- **cad** (float or *None*,) – Cadence of observations, which determines the maximum sensitive frequency (i.e. the Nyquist frequency). If *cad* is not given, then *num* frequency bins are constructed.

Returns

- **cents** (*(F,) ndarray*) – Bin-center frequencies for *F* bins. The frequency bin centers are at: `F_i = (i + 1.5) / dur` for i between 0 and *num-1*. The number of frequency bins, *F* is the argument *num*, or determined by *cad* if it is given.
- **edges** (*(F+1,) ndarray*) – Bin-edge frequencies for *F* bins, i.e. *F+1* bin edges. The frequency bin edges are at: `F_i = (i + 1) / dur` for i between 0 and *num*. The number of frequency bins, *F* is the argument *num*, or determined by *cad* if it is given.

holodeck.utils.**print_stats**(*stack=True*, *print_func=<built-in function print>*, ***kwargs*)

Print out basic properties and statistics on the input key-value array_like values.

Parameters

- **stack** (*bool,*) – Whether or not to print a backtrace to stdout.
- **print_func** (*callable,*) – Function to use for returning/printing output.
- **kwargs** (*dict,*) – Key-value pairs where values are array_like for the shape/stats to be printed.

holodeck.utils.**quantile_filtered**(*values*, *percs*, *axis*, *func=<ufunc 'isfinite'>*)

holodeck.utils.**quantiles**(*values*, *percs=None*, *sigmas=None*, *weights=None*, *axis=None*, *values_sorted=False*, *filter=None*)

Compute weighted percentiles.

NOTE: if *values* is a masked array, then only unmasked values are used!

Parameters

- **values** (*(N,)*) – input data
- **percs** (*(M,) scalar*) – Desired quantiles of the data. Within range of [0.0, 1.0].
- **weights** ((N,) or *None*) – Weights for each input data point in *values*.
- **axis** (int or *None*,) – Axis over which to calculate quantiles.
- **values_sorted** (*bool*) – If True, then input values are assumed to already be sorted. Otherwise they are sorted before calculating quantiles (for efficiency).

Returns
percs – Array of quantiles of the input data.

Return type
(M,) float

holodeck.utils.**random_power**(*extr*, *pdf_index*, *size=1*)

Draw from power-law PDF with the given extrema and index.

FIX/BUG : negative *extr* values break *pdf_index=-1* !!

Parameters

- **extr** (*array_like scalar*) – The minimum and maximum value of this array are used as extrema.

- **pdf_index** (*scalar*) – The power-law index of the PDF distribution to be drawn from. Any real number is valid, positive or negative. NOTE: the *numpy.random.power* function uses the power-law index of the CDF, i.e. *g+1*
- **size** (*scalar*) – The number of points to draw (cast to int).
- ****kwags** (*dict pairs*) – Additional arguments passed to *zcode.math_core.minmax* with *extr*.

Returns
rv – Array of random variables with N=`size` (default, size=1).

Return type
(N,) scalar

holodeck.utils.**rk4_step**(*func*, *x0*, *y0*, *dx*, *args=None*, *check_nan=0*, *check_nan_max=5*)

Perform a single 4th-order Runge-Kutta integration step.

holodeck.utils.**stats**(*vals*, *percs=None*, *prec=2*, *weights=None*) → str

Return a string giving quantiles of the given input data.

Parameters

- **vals** (*npt.ArrayLike,*) – Input values to get quantiles of.
- **percs** (*npt.ArrayLike, optional*) – Quantiles to calculate.
- **prec** (*int, optional*) – Precision in scientific notation of output.

Returns
rv – Quantiles of input formatted as a string of scientific notation values.

Return type
str

Raises
TypeError – raised if input data is not iterable.:

holodeck.utils.**std**(*vals*, *weights*)

Weighted standard deviation (stdev).

See: https://www.itl.nist.gov/div898/software/dataplot/refman2/ch2/weightsd.pdf

holodeck.utils.**trapz**(*yy: _SupportsArray[dtype[Any]] | _NestedSequence[_SupportsArray[dtype[Any]]] | bool | int | float | complex | str | bytes | _NestedSequence[bool | int | float | complex | str | bytes]*, *xx: _SupportsArray[dtype[Any]] | _NestedSequence[_SupportsArray[dtype[Any]]] | bool | int | float | complex | str | bytes | _NestedSequence[bool | int | float | complex | str | bytes]*, *axis: int = -1*, *cumsum: bool = True*)

Perform a cumulative integration along the given axis.

Parameters

- **yy** (*ArrayLike of scalar,*) – Input to be integrated.
- **xx** (*ArrayLike of scalar,*) – The sample points corresponding to the *yy* values. This must either be shaped as * the same number of dimensions as *yy*, with the same length along the *axis* dimension, or * 1D with length matching *yy[axis]*
- **axis** (*int,*) – The axis over which to integrate.

Returns
ct – Cumulative trapezoid rule integration.

Return type
ndarray of scalar,

holodeck.utils.**trapz_loglog**(*yy: _SupportsArray[dtype[Any]] | _NestedSequence[_SupportsArray[dtype[Any]]] | bool | int | float | complex | str | bytes | _NestedSequence[bool | int | float | complex | str | bytes]*, *xx: _SupportsArray[dtype[Any]] | _NestedSequence[_SupportsArray[dtype[Any]]] | bool | int | float | complex | str | bytes | _NestedSequence[bool | int | float | complex | str | bytes]*, *bounds: Tuple[float, float] | None = None*, *axis: int = -1*, *dlogx: float | None = None*, *lntol: float = 0.01*, *cumsum: bool = True*) → _SupportsArray[dtype[Any]] | _NestedSequence[_SupportsArray[dtype[Any]]] | bool | int | float | complex | str | bytes | _NestedSequence[bool | int | float | complex | str | bytes]

Calculate integral, given $y = dA/dx$ or $y = dA/d\log x$ w/ trapezoid rule in log-log space.

We are calculating the integral A given sets of values for y and x. To associate yy with dA/dx then $dlogx = None$ [default], otherwise, to associate yy with $dA/d\log x$ then $dlogx = True$ for natural-logarithm, or $dlogx = b$ for a logarithm of base b.

For each interval (x[i+1], x[i]), calculate the integral assuming that y is of the form,
$y = a * x^{gamma}$

Parameters

- **yy** (*ndarray*) –
- **xx** (*(X,) array_like of scalar,*) –
- **bounds** (*(2,) array_like of scalar,*) –
- **axis** (*int,*) –
- **dlogx** (*scalar or None,*) –
- **lntol** (*scalar,*) –

Return type
integ

Notes

- When bounds are given that are not identical to input *xx* values, then interpolation must be performed. This can be done on the resulting cumsum'd values, or on the input integrand values. The cumsum values are *not necessarily a power-law* (for negative indices), and thus the interpolation is better performed on the input *yy* values.
- Interpolating the cumulative-integral works very badly, instead interpolate the x/y values initially to obtain the integral at the appropriate locations.

holodeck.utils.**_parse_log_norm_pars**(*vals*, *size*, *default=None*)

Parse/Sanitize the parameters for a log-normal distribution.

- () ==> (N,)
- (2,) ==> (N,) log_normal(vals)
- (N,) ==> (N,)

BUG: this function should probably be deprecated / removed !

Parameters
vals (*object,*) –

Input can be a single value, (2,) array_like, of array_like of size *size*:

- scalar : this value is broadcast to an ndarray of size *size*
- (2,) array_like : these two arguments are passed to *log_normal_base_10* and *size* samples are drawn
- (N,) array_like : if *N* matches *size*, these values are returned.

Returns
vals – Returned values.

Return type
ndarray

holodeck.utils.**_parse_val_log10_val_pars**(*val*, *val_log10*, *val_units=1.0*, *name='value'*, *only_one=True*)

Given either a parameter value, or the log10 of the value, ensure that both are set.

Parameters

- **val** (*array_like or None,*) – The parameter value itself in the desired units (specified by *val_units*).
- **val_log10** (*array_like or None,*) – The log10 of the parameter value in natural units.
- **val_units** (*array_like,*) – The conversion factor from natural units (used in *val_log10*) to the desired units (used in *val*).
- **name** (*str,*) – The name of the variable for use in error messages.
- **only_one** (*bool,*) – Whether one, and only one, of *val* and *val_log10* should be provided (i.e. not *None*).

Returns

- **val** (*array_like,*) – The parameter value itself in desired units. e.g. mass in grams, s.t. mass = Msol * 10^{mass_log10}
- **val_log10** (*array_like,*) – The log10 of the parameter value in natural units. e.g. log10 of mass in solar-masses, s.t. mass = Msol * 10^{mass_log10}

holodeck.utils.**_integrate_grid_differential_number**(*edges*, *dnum*, *freq=False*)

Integrate the differential number-density of binaries over the given grid (edges).

NOTE: the *edges* provided MUST all be in linear space, mass is converted to `log10(M)` and frequency is converted to `ln(f)`. NOTE: the density *dnum* MUST correspond to *d^3 n / [dlog10(M) dq dz dln(f)]*

Parameters

- **edges** (*(4,) iterable of ArrayLike*) –
- **dnum** (*ndarray*) –
- **freq** (*bool*) – Whether or not to also integrate the frequency dimension.

Returns
number – Number of binaries in each bin of mass, mass-ratio, redshift, frequency. NOTE: if *freq=False*, then *number* corresponds to *dN/dln(f)*, the number of binaries per log-interval of frequency.

Return type
ndarray

holodeck.utils.**_func_gaussian**(*xx*, *aa*, *mm*, *ss*)

holodeck.utils.**fit_gaussian**(*xx*, *yy*, *guess=None*)

Fit a Gaussian/Normal distribution with the given initial guess of parameters.

Parameters

- **xx** (*array, (N,)*) –
- **yy** (*array, (N,)*) –
- **guess** (*None or (3,) array of float*) – Initial parameter values as starting point of fit. The values correspond to: [amplitude, mean, stdev]. If `guess` is None, then the maximum, mean, and stdev of the given values are used as a starting point.

Returns

- **popt** (*(3,) array of float*) – Best fit parameters: [amplitude, mean, stdev]
- **pcov** (*(3, 3) array of float*) – Covariance matrix of best fit parameters.

holodeck.utils.**_func_line**(*xx*, *amp*, *slope*)

holodeck.utils.**fit_powerlaw**(*xx*, *yy*, *init=[-15.0, -0.6666666666666666]*)

Fit the given data with a power-law.

Returns

- *log10_amp*
- *plaw*

holodeck.utils.**_func_powerlaw_psd**(*freqs*, *fref*, *amp*, *index*)

holodeck.utils.**fit_powerlaw_psd**(*xx*, *yy*, *fref*, *init=[-15.0, -4.333333333333333]*)

holodeck.utils.**fit_powerlaw_fixed_index**(*xx*, *yy*, *index=-0.6666666666666666*, *init=[-15.0]*)

Returns

- *log10_amp*
- *plaw*

holodeck.utils.**_func_turnover_psd**(*freqs*, *fref*, *amp*, *gamma*, *fbreak*, *kappa*)

holodeck.utils.**fit_turnover_psd**(*xx*, *yy*, *fref*, *init=[-16, -4.333333333333333, 9.506426344208685e-09, 2.5]*)

Parameters

- **xx** (*(F,)*) – Frequencies in units of reference-frequency (e.g. 1/yr)
- **yy** (*(F,)*) – GWB PSD

holodeck.utils.**dfdt_from_dadt**(*dadt*, *sepa*, *mtot=None*, *frst_orb=None*)

Convert from hardening rate in separation to hardening rate in frequency.

Parameters

- **dadt** (*array_like*) – Hardening rate in terms of binary separation.
- **sepa** (*array_like*) – Binary separations.
- **mtot** (*None or array_like*) – Binary total-mass in units of [gram]. Either *mtot* or *frst_orb* must be provided.

- **frst_orb** (*None or array_like*) – Binary rest-frame orbital-frequency in units of [1/sec]. Either *mtot* or *frst_orb* must be provided.

Returns

- *dfdt* – Hardening rate in terms of rest-frame frequency. [1/sec^2] NOTE: Has the opposite sign as *dadt*.
- *frst_orb* – Orbital frequency, in the rest-frame. [1/sec]

holodeck.utils.**mtmr_from_m1m2**(*m1*, *m2=None*)

Convert from primary and secondary masses into total-mass and mass-ratio.

NOTE: it doesn't matter if *m1* or *m2* is the primary or secondary.

Parameters

- **m1** (*array_like,*) – Mass. If this is a single value, or a 1D array, it denotes the mass of one component of a binary. It can also be shaped, (N,2) where the two elements are the two component masses.
- **m2** (*None or array_like,*) – If array_like, it must match the shape of *m1*, and corresponds to the companion mass.

Returns

Total mass and mass-ratio. If the input values are floats, this is just shaped (2,).

Return type

(2,N) ndarray

holodeck.utils.**m1m2_from_mtmr**(*mt: _SupportsArray[dtype[Any]] | _NestedSequence[_SupportsArray[dtype[Any]]] | bool | int | float | complex | str | bytes | _NestedSequence[bool | int | float | complex | str | bytes]*, *mr: _SupportsArray[dtype[Any]] | _NestedSequence[_SupportsArray[dtype[Any]]] | bool | int | float | complex | str | bytes | _NestedSequence[bool | int | float | complex | str | bytes]*) → _SupportsArray[dtype[Any]] | _NestedSequence[_SupportsArray[dtype[Any]]] | bool | int | float | complex | str | bytes | _NestedSequence[bool | int | float | complex | str | bytes]

Convert from total-mass and mass-ratio to individual masses.

Parameters

- **mt** (*array_like*) – Total mass of the binary.
- **mr** (*array_like*) – Mass ratio of the binary.

Returns

Primary and secondary masses respectively. 0-primary (more massive component), 1-secondary (less massive component)

Return type

(2,N) ndarray

holodeck.utils.**frst_from_fobs**(*fobs*, *redz*)

Calculate rest-frame frequency from observed frequency and redshift.

Parameters

- **fobs** (*array_like*) – Observer-frame frequencies.
- **redz** (*array_like*) – Redshifts.

Returns
fobs – Rest-frame frequencies.

Return type
array_like

holodeck.utils.**fobs_from_frst**(*frst*, *redz*)

Calculate observed frequency from rest-frame frequency and redshift.

Parameters

- **frst** (*array_like*) – Rest-frame frequencies.
- **redz** (*array_like*) – Redshifts.

Returns
fobs – Observer-frame frequencies.

Return type
array_like

holodeck.utils.**kepler_freq_from_sepa**(*mass*, *sepa*)

Calculate binary orbital frequency using Kepler's law.

Parameters

- **mass** (*array_like*) – Binary total mass [grams].
- **sepa** (*array_like*) – Binary semi-major axis or separation [cm].

Returns
freq – Binary orbital frequency [1/s].

Return type
array_like

holodeck.utils.**kepler_sepa_from_freq**(*mass*, *freq*)

Calculate binary separation using Kepler's law.

Parameters

- **mass** (*array_like*) – Binary total mass [grams]
- **freq** (*array_like*) – Binary orbital frequency [1/s].

Returns
sepa – Binary semi-major axis (i.e. separation) [cm].

Return type
array_like

holodeck.utils.**rad_isco**(*m1*, *m2=0.0*, *factor=3.0*)

Inner-most Stable Circular Orbit, radius at which binaries 'merge'.

ENH: allow single (total) mass argument. ENH: add function to calculate factor as a function of BH spin.

Parameters

- **m1** (*array_like,*) – Mass of first (either) component of binary [grams].
- **m2** (*array_like,*) – Mass of second (other) component of binary [grams].
- **factor** (*float,*) – Factor by which to multiple the Schwarzschild radius to define the ISCO. 3.0 for a non-spinning black-hole.

Returns
rs – Radius of the inner-most stable circular orbit [cm].

Return type
array_like,

holodeck.utils.**frst_isco**(*m1*, *m2=0.0*, ***kwargs*)

Get rest-frame orbital frequency of ISCO orbit.

Parameters

- **m1** (*array_like, units of [gram]*) – Total mass, or mass of the primary. Added together with *m2* to get total mass.
- **m2** (*array_like, units of [gram] or None*) – Mass of secondary, or None if *m1* is already total mass.

Returns
fisco

Return type
array_like, units of [Hz]

holodeck.utils.**redz_after**(*time*, *redz=None*, *age=None*)

Calculate the redshift after the given amount of time has passed.

Parameters

- **time** (*array_like, [s]*) – Amount of time to pass, in units of seconds.
- **redz** (*None or array_like, []*) – Redshift of starting point after which *time* is added. Unitless.
- **age** (*None or array_like, [s]*) – Age of the Universe at the starting point, after which *time* is added. Units of seconds.

Returns
new_redz – Redshift of the Universe after the given amount of time. Unitless

Return type
array_like, []

holodeck.utils.**schwarzschild_radius**(*mass*)

Return the Schwarschild radius [cm] for the given mass [grams].

Parameters
m1 (*array_like*) – Mass [grams]

Returns
rs – Schwzrschild radius for this mass.

Return type
array_like,

holodeck.utils.**velocity_orbital**(*mt*, *mr*, *per=None*, *sepa=None*)

holodeck.utils.**_get_sepa_freq**(*mt*, *sepa*, *freq*)

holodeck.utils.**lambda_factor_dlnf**(*frst*, *dfdt*, *redz*, *dcom=None*)

Account for the universe's differential space-time volume for a given hardening rate.

For each binary, calculate the factor:

$$\Lambda \equiv (dVc/dz) * (dz/dt) * [dt/dln(f)]$$

, which has units of [Mpc^3]. When multiplied by a number-density [Mpc^-3], it gives the number of binaries in the Universe *per log-frequency interval*. This value must still be multiplied by $\Delta \ln(f)$ to get a number of binaries across a frequency in.

Parameters

- **frst** (*ArrayLike*) – Binary frequency (typically rest-frame orbital frequency; but it just needs to match what's provided in the *dfdt* term. Units of [1/sec].
- **dfdt** (*ArrayLike*) – Binary hardening rate in terms of frequency (typically rest-frame orbital frequency, but it just needs to match what's provided in *frst*). Units of [1/sec^2].
- **redz** (*ArrayLike*) – Binary redshift. Dimensionless.
- **dcom** (*ArrayLike*) – Comoving distance to binaries (for the corresponding redshift, *redz*). Units of [cm]. If not provided, calculated from given *redz*.

Returns

lambda_fact – The differential comoving volume of the universe per log interval of binary frequency.

Return type

ArrayLike

holodeck.utils.**angs_from_sepa**(*sepa*, *dcom*, *redz*)

Calculate angular separation

Parameters

- **sepa** (*ArrayLike*) – Binary separation, in cm
- **dcom** (*ArrayLike*) – Binary comoving distance, in cm
- **redz** (*ArrayLike*) – Binary redshift

Returns

angs – Angular separation

Return type

ArrayLike

holodeck.utils.**eddington_accretion**(*mass*, *eps=0.1*)

Eddington Accretion rate, $\dot{M}_{Edd} = L_{Edd}/\epsilon c^2$.

Parameters

- **mass** (*array_like of scalar*) – BH Mass.
- **eps** (*array_like of scalar*) – Efficiency parameter.

Returns

mdot – Eddington accretion rate.

Return type

array_like of scalar

holodeck.utils.**eddington_luminosity**(*mass*)

holodeck.utils.**chirp_mass**(*m1*, *m2=None*)

Calculate the chirp-mass of a binary.

Parameters

- **m1** (*array_like,*) – Mass [grams] This can either be the mass of the primary component, if scalar or 1D array_like, or the mass of both components, if 2D array_like, shaped (N, 2).

- **m2** (*None or array_like,*) – Mass [grams] of the other component of the binary. If given, the shape must be broadcastable against *m1*.

Returns
mc – Chirp mass [grams] of the binary.

Return type
array_like,

holodeck.utils.**chirp_mass_mtmr**(*mt*, *mr*)

Calculate the chirp-mass of a binary.

Parameters

- **mt** (*array_like,*) – Total mass [grams]. This is `M = m1+m2`.
- **mr** (*array_like,*) – Mass ratio. `q = m2/m1 <= 1`. This is defined as the secondary (smaller) divided by the primary (larger) mass.

Returns
mc – Chirp mass [grams] of the binary.

Return type
array_like,

holodeck.utils.**gw_char_strain_nyquist**(*dur_obs*, *hs*, *frst_orb*, *redz*, *dfdt_rst*)

GW Characteristic Strain assuming frequency bins are Nyquist sampled.

Nyquist assumption: the bin-width is equal to 1/T, for T the total observing duration.

See, e.g., [Sesana2004], Eq.35, and surrounding text. NOTE: make sure this is the correct definition of "characteristic" strain for your application!

! THIS FUNCTION MAY NOT BE CORRECT [LZK:2022-08-25] !

Parameters

- **dur_obs** (*array_like,*) – Duration of observations, in the observer frame, in units of [sec]. Typically this is a single float value.
- **hs** (*array_like,*) – Strain amplitude of the source. Dimensionless.
- **frst_orb** (*array_like,*) – Observer-frame orbital frequency, units of [1/sec].
- **redz** (*array_like,*) – Redshift of the binary. Dimensionless.
- **dfdt_rst** (*array_like,*) – Rate of orbital-frequency evolution of the binary, in the rest-frame. Units of [1/sec^2].

Returns
hc – Characteristic strain of the binary.

Return type
array_like,

holodeck.utils.**gw_dedt**(*m1*, *m2*, *sepa*, *eccen*)

GW Eccentricity Evolution rate (de/dt) due to GW emission.

NOTE: returned value is negative.

See [Peters1964], Eq. 5.8

Parameters

- **m1** (*array_like,*) – Mass of one component of the binary [grams].

- **m2** (*array_like,*) – Mass of other component of the binary [grams].
- **sepa** (*array_like,*) – Binary semi-major axis (i.e. separation) [cm].
- **eccen** (*array_like,*) – Binary orbital eccentricity.

Returns
dedt – Rate of eccentricity change of the binary. NOTE: returned value is negative or zero.

Return type
array_like

holodeck.utils.**gw_dade**(*sepa*, *eccen*)

Rate of semi-major axis evolution versus eccentricity, due to GW emission (da/de).

NOTE: returned value is positive (e and a go in same direction). See [Peters1964], Eq. 5.7

Parameters

- **sepa** (*array_like*) – Binary semi-major axis (separation) [grams].
- **eccen** (*array_like*) – Binary eccentricity [grams].

Returns
dade – Rate of change of semi-major axis versus eccentricity [cm]. NOTE: returned value is positive.

Return type
array_like

holodeck.utils.**gw_freq_dist_func**(*nn*, *ee=0.0*, *recursive=True*)

GW frequency distribution function.

See [EN2007] Eq. 2.4; this function gives g(n,e).

NOTE: recursive relation fails for zero eccentricities! TODO: could choose to use non-recursive when zero eccentricities are found?

TODO: replace *ee* variable with *eccen*

Parameters

- **nn** (*int,*) – Number of frequency harmonic to calculate.
- **ee** (*array_like,*) – Binary eccentricity.

Returns
gg – GW Frequency distribution function g(n,e).

Return type
array_like,

holodeck.utils.**gw_hardening_rate_dadt**(*m1*, *m2*, *sepa*, *eccen=None*)

GW Hardening rate in separation (da/dt).

NOTE: returned value is negative.

See [Peters1964], Eq. 5.6

Parameters

- **m1** (*array_like,*) – Mass of one component of the binary [grams].
- **m2** (*array_like,*) – Mass of other component of the binary [grams].
- **sepa** (*array_like,*) – Binary semi-major axis (i.e. separation) [cm].

- **eccen** (*None or array_like,*) – Binary orbital eccentricity. Treated as zero if *None*.

Returns
dadt – Binary hardening rate [cm/s] due to GW emission.

Return type
array_like,

holodeck.utils.**gw_hardening_rate_dfdt**(*m1*, *m2*, *frst_orb*, *eccen=None*)

GW Hardening rate in frequency (df/dt).

Parameters

- **m1** (*array_like*) – Mass of one component of each binary [grams].
- **m2** (*array_like*) – Mass of other component of each binary [grams].
- **freq_orb** (*array_like*) – Rest frame orbital frequency of each binary [1/s].
- **eccen** (*array_like, optional*) – Eccentricity of each binary.

Returns
dfdt – Hardening rate in terms of frequency for each binary [1/s^2].

Return type
array_like,

holodeck.utils.**gw_hardening_timescale_freq**(*mchirp*, *frst*)

GW Hardening timescale in terms of frequency (not separation).

`tau = f_r / (df_r / dt)`, e.g. [EN2007] Eq.2.9

Parameters

- **mchirp** (*array_like,*) – Chirp mass in [grams]
- **frst** (*array_like,*) – Rest-frame orbital frequency [1/s].

Returns
tau – GW hardening timescale defined w.r.t. orbital frequency [sec].

Return type
array_like,

holodeck.utils.**gw_lum_circ**(*mchirp*, *freq_orb_rest*)

Calculate the GW luminosity of a circular binary.

[EN2007] Eq. 2.2

Parameters

- **mchirp** (*array_like,*) – Binary chirp mass [grams].
- **freq_orb_rest** (*array_like,*) – Rest-frame binary orbital frequency [1/s].

Returns
lgw_circ – GW Luminosity [erg/s].

Return type
array_like,

holodeck.utils.**gw_strain_source**(*mchirp*, *dcom*, *freq_rest_orb*)

GW Strain from a single source in a circular orbit.

For reference, see: * [Sesana2004] Eq.36 : they use *f_r* to denote rest-frame GW-frequency. * [Enoki2004] Eq.5.

Parameters

- **mchirp** (*array_like,*) – Binary chirp mass [grams].
- **dcom** (*array_like,*) – Comoving distance to source [cm].
- **freq_orb_rest** (*array_like,*) – Rest-frame binary orbital frequency [1/s].

Returns
hs – GW Strain (*not* characteristic strain).

Return type
array_like,

holodeck.utils.**sep_to_merge_in_time**(*m1*, *m2*, *time*)

The initial separation required to merge within the given time.

See: [Peters1964]

Parameters

- **m1** (*array_like,*) – Mass of one component of the binary [grams].
- **m2** (*array_like,*) – Mass of other component of the binary [grams].
- **time** (*array_like,*) – The duration of time of interest [sec].

Returns
Initial binary separation [cm].

Return type
array_like

holodeck.utils.**time_to_merge_at_sep**(*m1*, *m2*, *sepa*)

The time required to merge starting from the given initial separation.

See: [Peters1964].

Parameters

- **m1** (*array_like,*) – Mass of one component of the binary [grams].
- **m2** (*array_like,*) – Mass of other component of the binary [grams].
- **sepa** (*array_like,*) – Binary semi-major axis (i.e. separation) [cm].

Returns
Duration of time for binary to coalesce [sec].

Return type
array_like

holodeck.utils.**gamma_psd_to_strain**(*gamma_psd*)

holodeck.utils.**gamma_strain_to_psd**(*gamma_strain*)

holodeck.utils.**gamma_strain_to_omega**(*gamma_strain*)

holodeck.utils.**char_strain_to_psd**(*freqs*, *hc*)

Parameters

- **freqs** (*array_like*) – Frequencies of interest in [1/sec]. Note: these should NOT be in units of reference frequency, but in units of [Hz] = [1/sec].
- **hc** (*array_like*) – Characteristic strain.

Returns
psd – Power spectral density of gravitational waves.

Return type
array_like

holodeck.utils.**psd_to_char_strain**(*freqs*, *psd*)

holodeck.utils.**char_strain_to_rho**(*freqs*, *hc*, *tspan*)

holodeck.utils.**rho_to_char_strain**(*freqs*, *rho*, *tspan*)

holodeck.utils.**char_strain_to_strain_amp**(*hc*, *fc*, *df*)

Calculate the strain amplitude of single sources given their characteristic strains.

Parameters

- **hc** (*array_like*) – Characteristic strain of the single sources.
- **fc** (*array_like*) – Observed orbital frequency bin centers.
- **df** (*array_like*) – Observed orbital frequency bin widths.

Returns
hs – Strain amplitude of the single sources.

Return type
(F,R,L)

holodeck.utils.**_gw_ecc_func**(*eccen*)

GW Hardening rate eccentricitiy dependence F(e).

See [Peters1964] Eq. 5.6, or [EN2007] Eq. 2.3

Parameters
eccen (*array_like,*) – Binary orbital eccentricity [].

Returns
fe – Eccentricity-dependence term of GW emission [].

Return type
array_like

holodeck.utils.**_array_args**(**args*)

holodeck.utils.**scatter_redistribute**(*cents*, *dist*, *dens*, *axis=0*)

holodeck.utils.**nyquist_freqs**(*dur*, *cad*)

DEPRECATED. Use *holodeck.utils.pta_freqs* instead.

CHAPTER

TWENTYONE

GETTING STARTED

(1) Read the *getting started* guide.

(2) Install `holodeck` following the *installation* instructions below.

(3) Explore the package demonstration notebooks.

CHAPTER

TWENTYTWO

INSTALLATION

The *holodeck* framework is currently under substantial, active development. Stable versions are now available with `pip install holodeck-gw` (see holodeck on pypi). However, recent versions and many development tools will not generally be available with `pip` or `conda` install.

holodeck requires `python >= 3.9` (with support for: `3.9, 3.10, 3.11`). The recommended installation is:

0) OPTIONAL & recommended: create and activate a new **anaconda** environment to isolate your build:

```
conda create --name holo311 python=3.11; conda activate holo311
```

Note that you will need to activate this environment every time you want to use holodeck. If you're not familiar with **anaconda**, take a look at their official Getting started guide. To use your anaconda environment with jupyter notebooks, make sure to add this environment to your ipython kernels:

```
conda install -c conda-forge ipykernel
python -m ipykernel install --user --name=holo311
```

1) Clone the `holodeck` repository, and move into the repo directory:

```
git clone https://github.com/nanograv/holodeck.git; cd holodeck
```

2) Install the required external packages specified in the requirements file:

```
pip install -r requirements.txt
```

OPTIONAL: install development requirements:

```
pip install -r requirements-dev.txt
```

3) Build the required c libraries from `holodeck` `cython` code:

```
python setup.py build_ext -i
```

4) Perform a development/editable local installation:

```
python setup.py develop
```

The 'editable' installation allows the code base to be modified, and have those changes take effect when using the `holodeck` module without having to rebuild/reinstall it. Note that any changes to the `cython` library files do still require a rebuild by running steps (3) and (4) above.

22.1 MPI

For some scripts (particularly for generating libraries), an MPI implementation is required (e.g. `openmpi`), along with the mpi4py package. This is not included as a requirement in the `requirements.txt` file as it significantly increases the installation complexity, and is not needed for many `holodeck` use cases. If you already have an MPI implementation installed on your system, you should be able to install `mpi4py` with anaconda: `conda install mpi4py`. To see if you have `mpi4py` installed, run `python -c 'import mpi4py; print(mpi4py.__version__)'` from a terminal.

macos users: if you are using homebrew on macos, you should be able to simply run: `brew install mpi4py` which will include the required openmpi implementation.

CHAPTER

TWENTYTHREE

ATTRIBUTION & REFERENCING

The `holodeck` package uses an MIT license.

A dedicated paper on `holodeck` is currently in preparation, but the package is also described in the recent astrophysics analysis from the NANOGrav 15yr dataset.

```
@ARTICLE{2023ApJ...952L..37A,
      author = {{Agazie}, Gabriella and {et al} and {Nanograv Collaboration}},
      title = "{The NANOGrav 15 yr Data Set: Constraints on Supermassive Black Hole␣
↪Binaries from the Gravitational-wave Background}",
      journal = {\apjl},
         year = 2023,
      month = aug,
      volume = {952},
      number = {2},
         eid = {L37},
      pages = {L37},
         doi = {10.3847/2041-8213/ace18b},
archivePrefix = {arXiv},
      eprint = {2306.16220},
primaryClass = {astro-ph.HE},
      adsurl = {https://ui.adsabs.harvard.edu/abs/2023ApJ...952L..37A},
}
```

CHAPTER

TWENTYFOUR

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