



The user guide

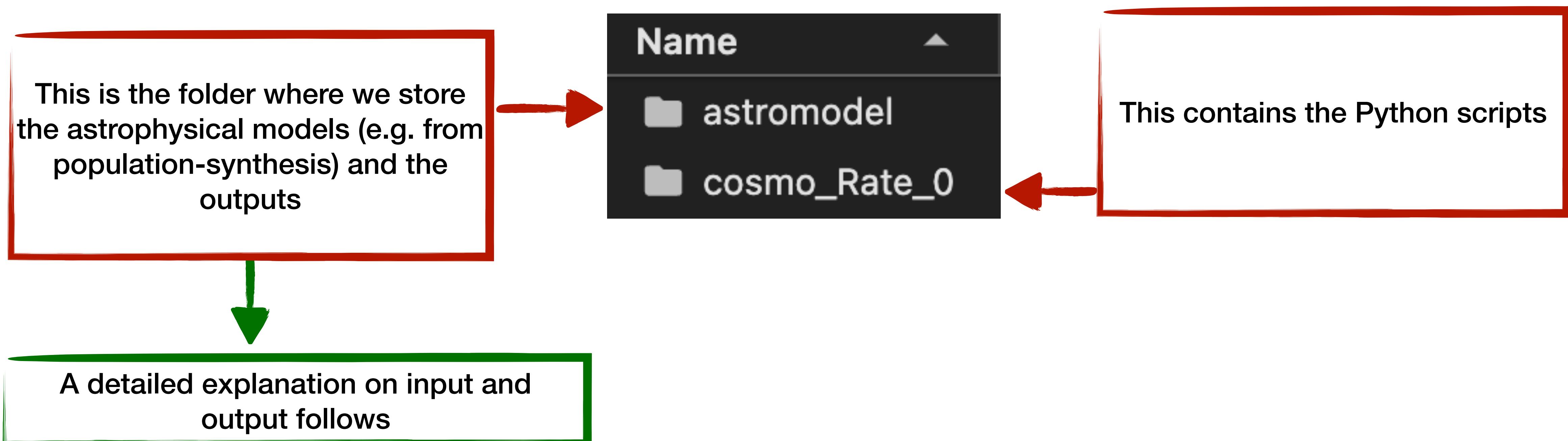
download

- cosmoRate:
 - https://gitlab.com/Filippo.santoliquido/cosmo_rate_public

Installation

- To be sure cosmoRate works on your laptop, we need to create a conda environment including all the necessary libraries:
 - `conda env create -f environment.yml`
 - `conda activate cosmo_env`
- The following command installs the conda environment on Jupyter lab as well:
 - `python -m ipykernel install --user --name=cosmo_env --display-name “cosmo_env”`

What you get with cosmoRate



- **cosmoRate** is made of three Python scripts
- Here we focus on learning how to use **cosmo_params.py**



How to run **cosmoRate**



Modify input parameters in
cosmo_params.py



Modify the file
cosmo_rate_notebook.ipynb



Modify the file **cosmo_functions.py**



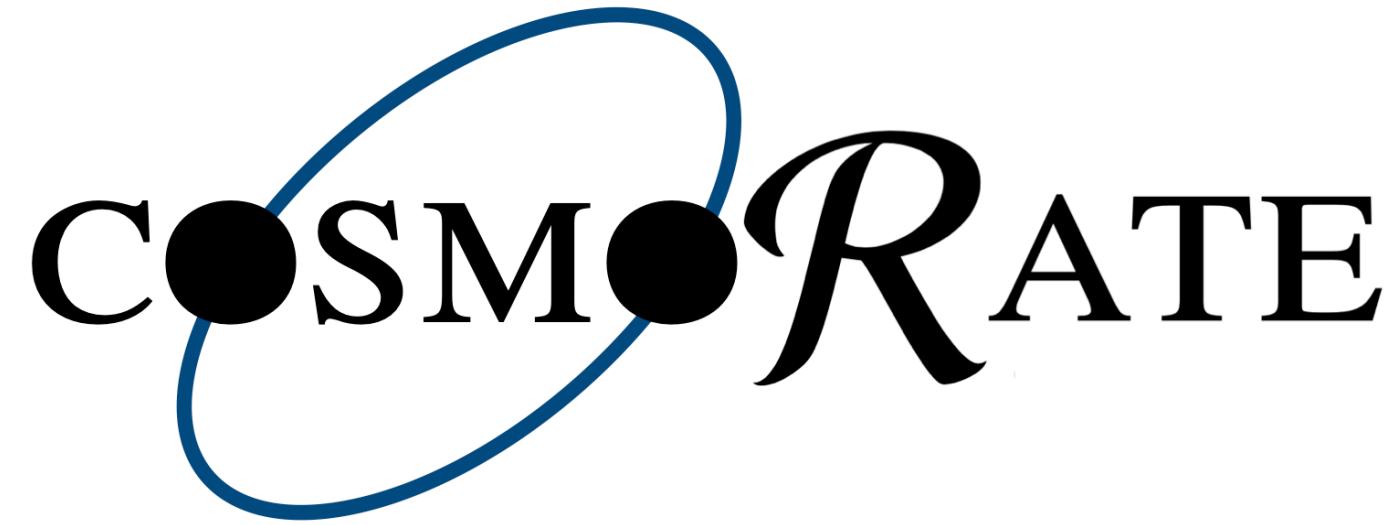
Get new ideas?!

Level 1: How to run cosmoRate

- Two ways:
 - directly from the jupyter notebook **cosmo_rate_notebook.ipynb**
 - or by launching “**ipython cosmo_rate_notebook.py**” from the shell

Level 2: How to modify `cosmo_params.py`

- Long list of parameters... most of them might not immediately clear to you
- That's why we need to have a look at **WHAT** `cosmoRate` does



Santoliquido et al. 2020:
<https://arxiv.org/pdf/2004.09533.pdf>

$$\mathcal{R}(z) = \int_{z_{\min}}^z \left[\int_{Z_{\min}}^{Z_{\max}} \text{SFRD}(z', Z) \mathcal{F}(z', z, Z) dZ \right] \frac{dt(z')}{dz'} dz'$$



cosmoRate evaluates this equation, which is implemented in `cosmo_functions.py`

- cosmoRate evaluates the merger rate density by solving the above Equation. It basically counts how many compact objects merge at a given redshift
- You may ask yourself: how does the population of compact objects look like at a given redshift? cosmoRate also prints catalogs of merging compact objects
- These are the two main output of cosmoRate



$$\mathcal{R}(z) = \int_{z_{\min}}^z \left[\int_{Z_{\min}}^{Z_{\max}} \text{SFRD}(z', Z) \mathcal{F}(z', z, Z) dZ \right] \frac{dt(z')}{dz'} dz'$$

/ ... / A1.0 / all_channels /	
Name	Last Modified
output_cosmo_Rate	a month ago
data_BBH_0.0001.dat	3 months ago
data_BBH_0.0002.dat	3 months ago
data_BBH_0.0004.dat	3 months ago
data_BBH_0.0006.dat	3 months ago
data_BBH_0.0008.dat	3 months ago
data_BBH_0.001.dat	3 months ago
data_BBH_0.002.dat	3 months ago
data_BBH_0.004.dat	3 months ago
data_BBH_0.006.dat	3 months ago
data_BBH_0.008.dat	3 months ago
data_BBH_0.01.dat	3 months ago
data_BBH_0.014.dat	3 months ago
data_BBH_0.017.dat	3 months ago
data_BBH_0.02.dat	3 months ago
data_BBH_0.03.dat	3 months ago

This factor here is evaluated starting from the input catalogs you inject in cosmoRate.

These catalogs comes from population-synthesis (M0BSE, SEVN), dynamical formation channel, or others (e.g. FASTCLUSTER).

This is an example of how the input folder and the names of input files look like



Santoliquido et al. 2020:
<https://arxiv.org/pdf/2004.09533.pdf>

First row, first column: Total simulated mass in Msun

Each following row is a compact object merger, defined by
 Column 0: delay time in years [WARNING: this is mandatory!]
 Column 1- n: any other intrinsic parameter
 (in the example here,
 Column 1: primary mass m_1 in Msun
 Column 2: secondary mass m_2 in Msun)

$$\mathcal{R}(z) = \int_{z_{\min}}^z \left[\int_{Z_{\min}}^{Z_{\max}} \text{SFRD}(z', Z) \mathcal{F}(z', z, Z) dZ \right] \frac{dt(z')}{dz'} dz'$$

- This factor here is evaluated starting from the input catalogs you inject in cosmoRate.
- These catalogs comes from population-synthesis (M0BSE, SEVN) or dynamical formation channel, or others (e.g. FASTCLUSTER).

	data_BBHs_0.0002.txt
1	215180664.01669434
2	2.7591700000000000e+07 2.5552600000000000176e+01 3.2588900000000000242e+01
3	1.0283900000000000e+07 1.681370000000000076e+01 2.140279999999999916e+01
4	2.5212700000000000e+07 8.191700000000000870e+00 8.944000000000000838e+00
5	9.9759000000000000e+06 1.6782499999999886e+01 2.3093099999999974e+01
6	3.2837500000000000e+07 7.5438999999999828e+00 8.2096000000000009e+00
7	1.2522100000000000e+07 1.8600899999999932e+01 2.93505000000000026e+01
8	3.4051900000000000e+07 7.7885999999999746e+00 1.3495300000000030e+01
9	2.8093230000000000e+08 7.6943999999999906e+00 6.9394000000000013e+00
10	1.3280700000000000e+07 2.06685000000000165e+01 2.6877099999999866e+01



$$\mathcal{R}(z) = \int_{z_{\min}}^z \left[\int_{Z_{\min}}^{Z_{\max}} \text{SFRD}(z', Z) \mathcal{F}(z', z, Z) dZ \right] \frac{dt(z')}{dz'} dz'$$

```

# Compact objects specificities (PopSynth / N-body)
# list of compact objects type
cb_class = ['BBH'] # it can be either 'BBHs', 'BHNS', 'BNSs' sys.argv[2] within the parentheses
# list of metallicity used from simulations, as float type, ascending order
# uncomment what you need!
#Z_simulated = [0.0002, 0.0004, 0.0008, 0.0012, 0.0016, 0.002, 0.004, 0.006, 0.008, 0.012, 0.016, 0.02]
Z_simulated = [0.0001, 0.0002, 0.0004, 0.0006, 0.0008, 0.001, 0.002, 0.004, 0.006, 0.008, 0.01, 0.014,
 0.017, 0.02, 0.03]
#Z_simulated = [1e-11]

formation_channel = 'iso' # formation channel type (iso, dyn, popIII)

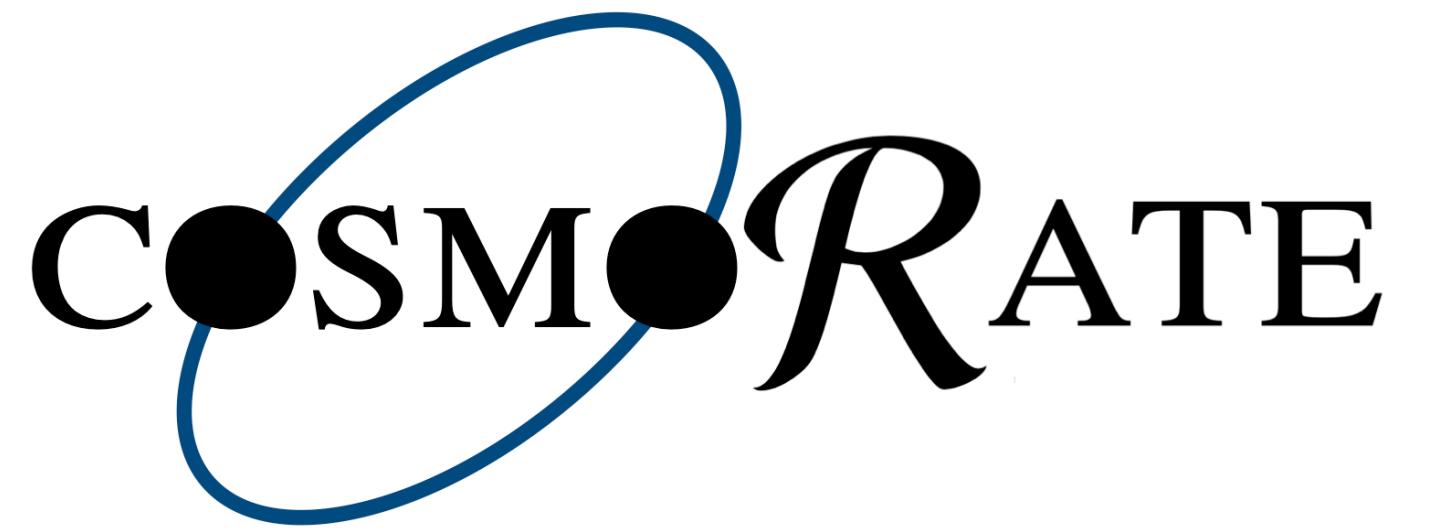
# this parameter is used to select your astrophysical model and
# in naming the output catalog files (i.e values of alpha, SN model type...)
#sim = 'popI_II/popII_I_for_comp/fiducial_Hrad_5M/A1.0'
#      'popI_II/popII_I_for_comp/fiducial_Hrad_5M_channels/A1.0/all_channels'
sim = sys.argv[1]

#it can be either sys.argv[1] or a string ( e.g. 'A5', 'popI_II/popII_I_for_comp/fiducial_pisnfarmer19/A1.0' ,
'')

sim_name = 'MandF2017_met' # it can be equal to sim or selected by the user
                           # WARNING: if sim is a path, sim_name must be not a path!
extension = '.dat' # also include the dot

```

- In the first part of `cosmo_params.py` you set all the parameters that refer to the input catalogs.
- For instance, the compact object type, the list of progenitor metallicity, the specific simulations



$$\mathcal{R}(z) = \int_{z_{\min}}^z \left[\int_{Z_{\min}}^{Z_{\max}} \text{SFRD}(z', Z) \mathcal{F}(z', z, Z) dZ \right] \frac{dt(z')}{dz'} dz'$$

```
# Compact objects specificities (PopSynth / N-body)
# list of compact objects type
cb_class = ['BBH'] # it can be either 'BBHs', 'BHNS', 'BNSs' sys.argv[2] within the parentheses
# list of metallicity used from simulations, as float type, ascending order
# uncomment what you need!
#Z_simulated = [0.0002, 0.0004, 0.0008, 0.0012, 0.0016, 0.002, 0.004, 0.006, 0.008, 0.012, 0.016, 0.02]
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 0.017, 0.02, 0.03]
#Z_simulated = [1e-11]

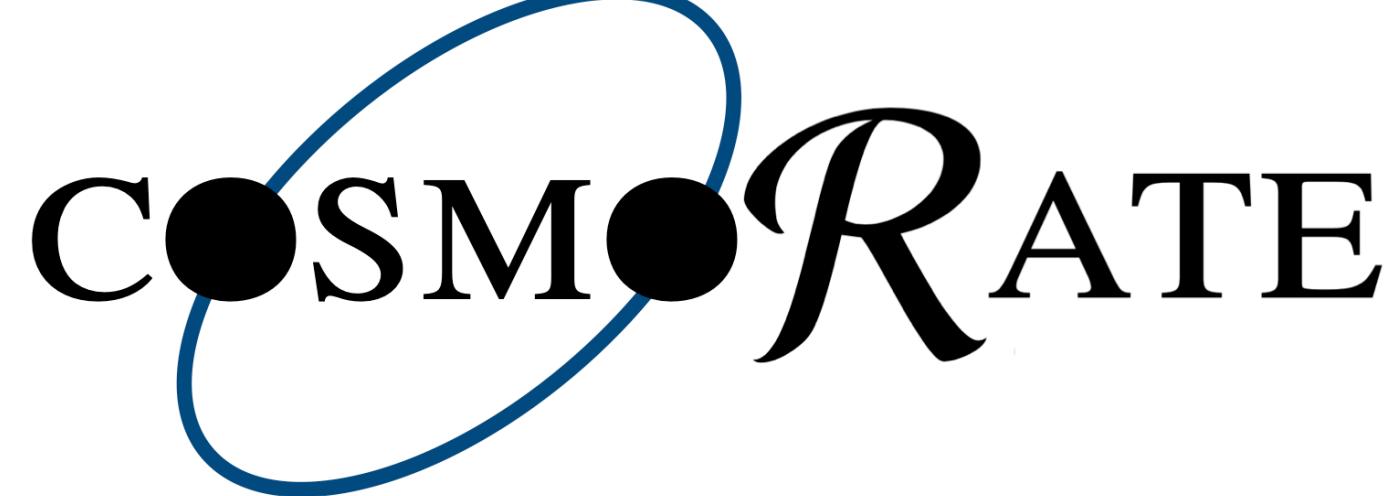
formation_channel = 'iso' # formation channel type (iso, dyn, popIII) ←

# this parameter is used to select your astrophysical model and
# in naming the output catalog files (i.e values of alpha, SN model type...)
#sim = 'popI_II/popII_I_for_comp/fiducial_Hrad_5M/A1.0'
#      'popI_II/popII_I_for_comp/fiducial_Hrad_5M_channels/A1.0/all_channels'
sim = sys.argv[1]

#it can be either sys.argv[1] or a string ( e.g. 'A5', 'popI_II/popII_I_for_comp/fiducial_pisnfarmer19/A1.0' ,
'')

sim_name = 'MandF2017_met' # it can be equal to sim or selected by the user
                           # WARNING: if sim is a path, sim_name must be not a path!
extension = '.dat' # also include the dot
```

The `formation_channel` variable sets two quantities. 1) The fraction of star-formation rate happening in binary systems 2) the correction due to not sampled initial mass function (IMF). For example, channel '`iso`' sets the binary fraction to 50%, while channel '`popIII`' does not apply any correction for IMF. Details on this are provided in the main Jupyter notebook



Santoliquido et al. 2020:
<https://arxiv.org/pdf/2004.09533.pdf>

$$\mathcal{R}(z) = \int_{z_{\min}}^z \left[\int_{Z_{\min}}^{Z_{\max}} \text{SFRD}(z', Z) \mathcal{F}(z', z, Z) dZ \right] \frac{dt(z')}{dz'} dz'$$

SFRD(z', Z) $\mathcal{F}(z', z, Z)$

Injected catalogs

$$\text{SFRD}(z, Z) = \psi(z) p(Z|z)$$



- cosmoRate couples these **injected catalogs with a distribution of star-formation rate density (SFRD)** as function of redshift and metallicity.
- The second part of `cosmo_params.py` refers to the parameters setting this distribution of SFRD

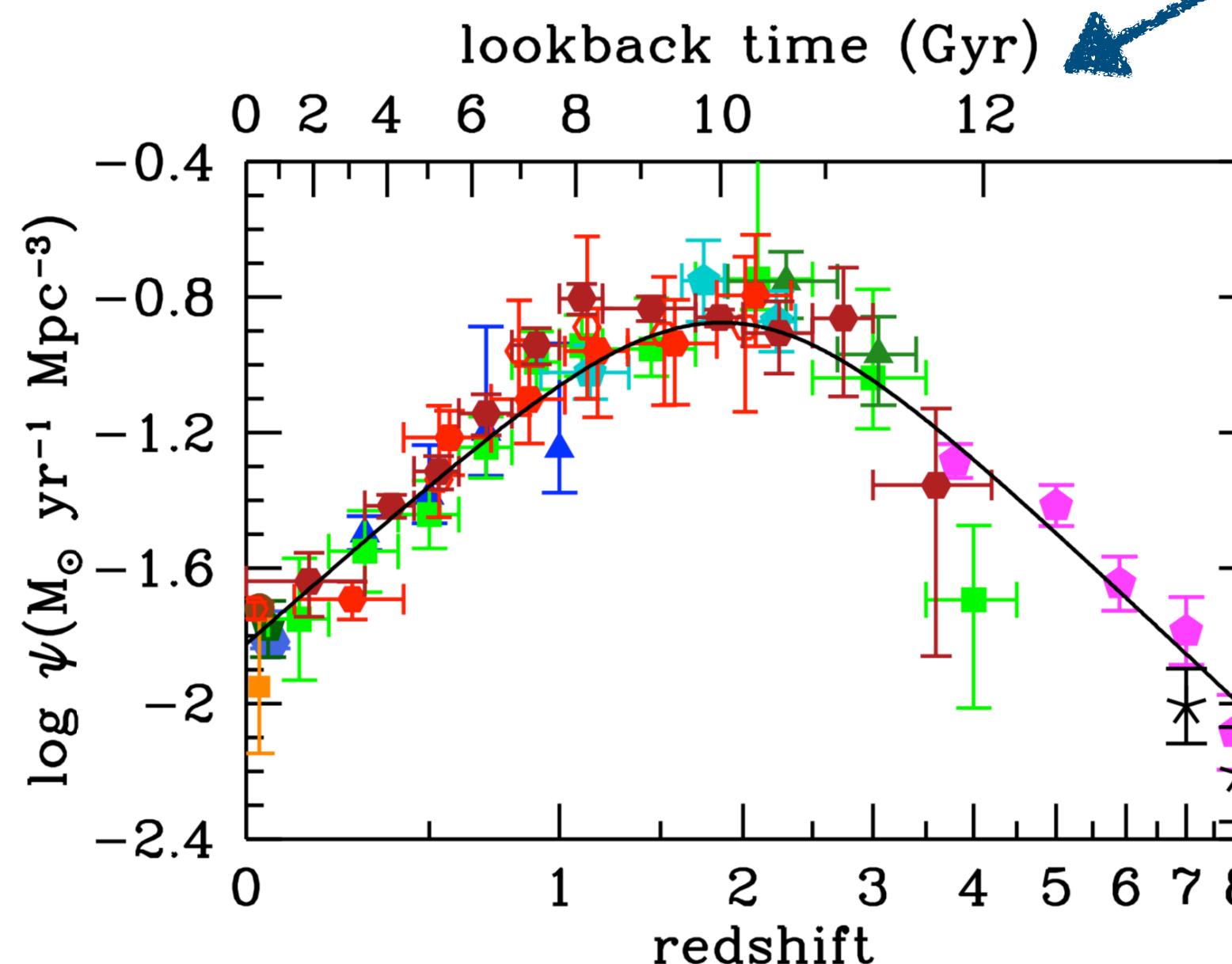
COSMORATE

Santoliquido et al. 2020:
<https://arxiv.org/pdf/2004.09533.pdf>

$$\mathcal{R}(z) = \int_{z_{\min}}^z \left[\int_{Z_{\min}}^{Z_{\max}} \text{SFRD}(z', Z) \mathcal{F}(z', z, Z) dZ \right] \frac{dt(z')}{dz'} dz'$$

Injected catalogs

$$\text{SFRD}(z, Z) = \psi(z) p(Z|z)$$



[Madau & Dickinson 2014](#), [Madau & Fargas 2017](#)

```
#####
# select the population of stars
pop = 'I-II' # it can be 'III' or 'I-II'

# for popI-II star, 'MandF2017' is the only option available
# for popIII you can choose from many options:
# 1. 'A-sloth_smooth_off'
# 2. 'Hartwig16'
# 3. 'DeSouza_smooth_off'
# 4. 'Jaacks'
# 5. 'LiuBromm'
# for other options see cosmo_rate_notebook.ipynb
# or sys.argv[2]
SFRD_model = 'MandF2017'
```

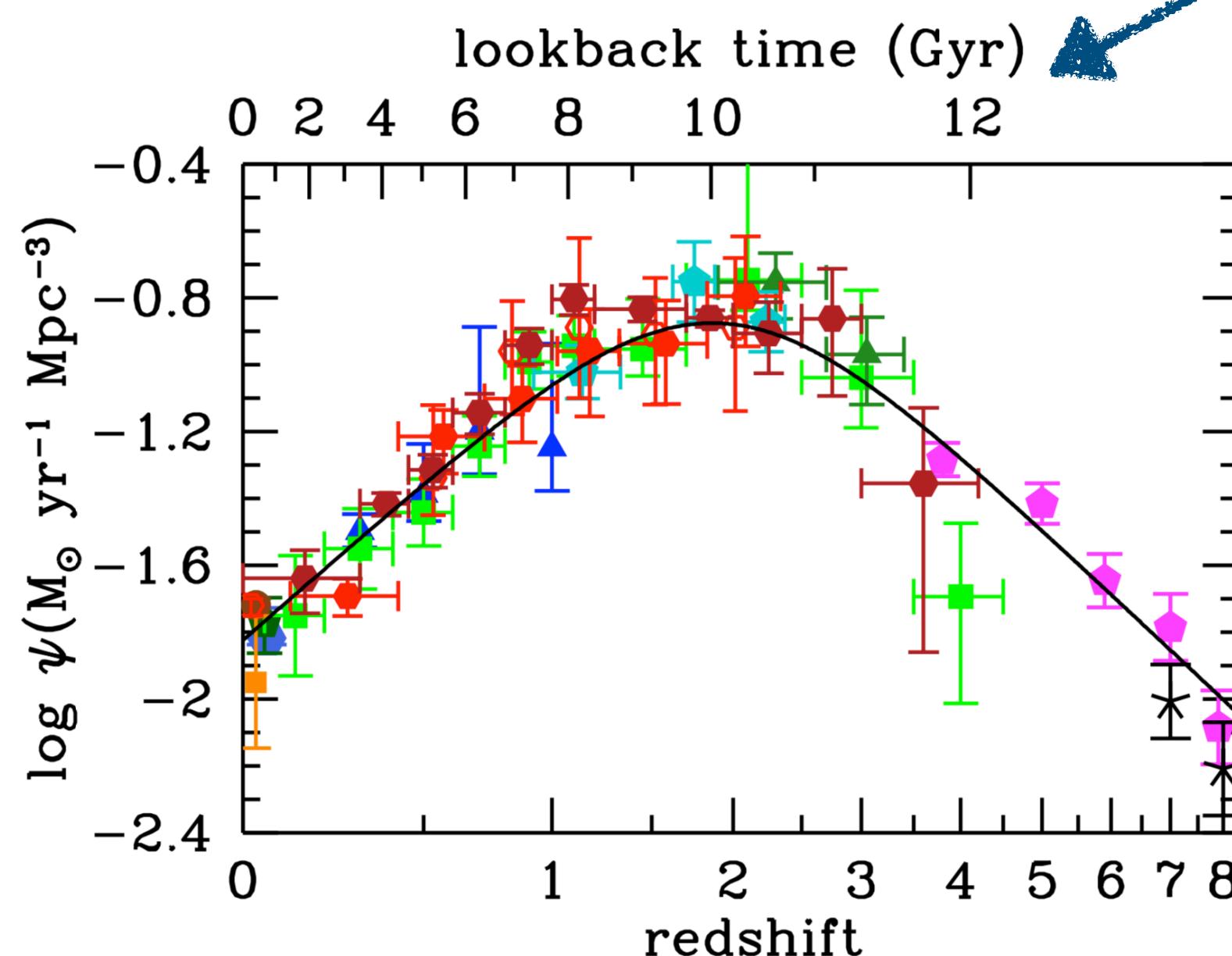
COSMORATE

Santoliquido et al. 2020:
<https://arxiv.org/pdf/2004.09533.pdf>

$$\mathcal{R}(z) = \int_{z_{\min}}^z \left[\int_{Z_{\min}}^{Z_{\max}} \text{SFRD}(z', Z) \mathcal{F}(z', z, Z) dZ \right] \frac{dt(z')}{dz'} dz'$$

Injected catalogs

$$\text{SFRD}(z, Z) = \psi(z) p(Z|z)$$



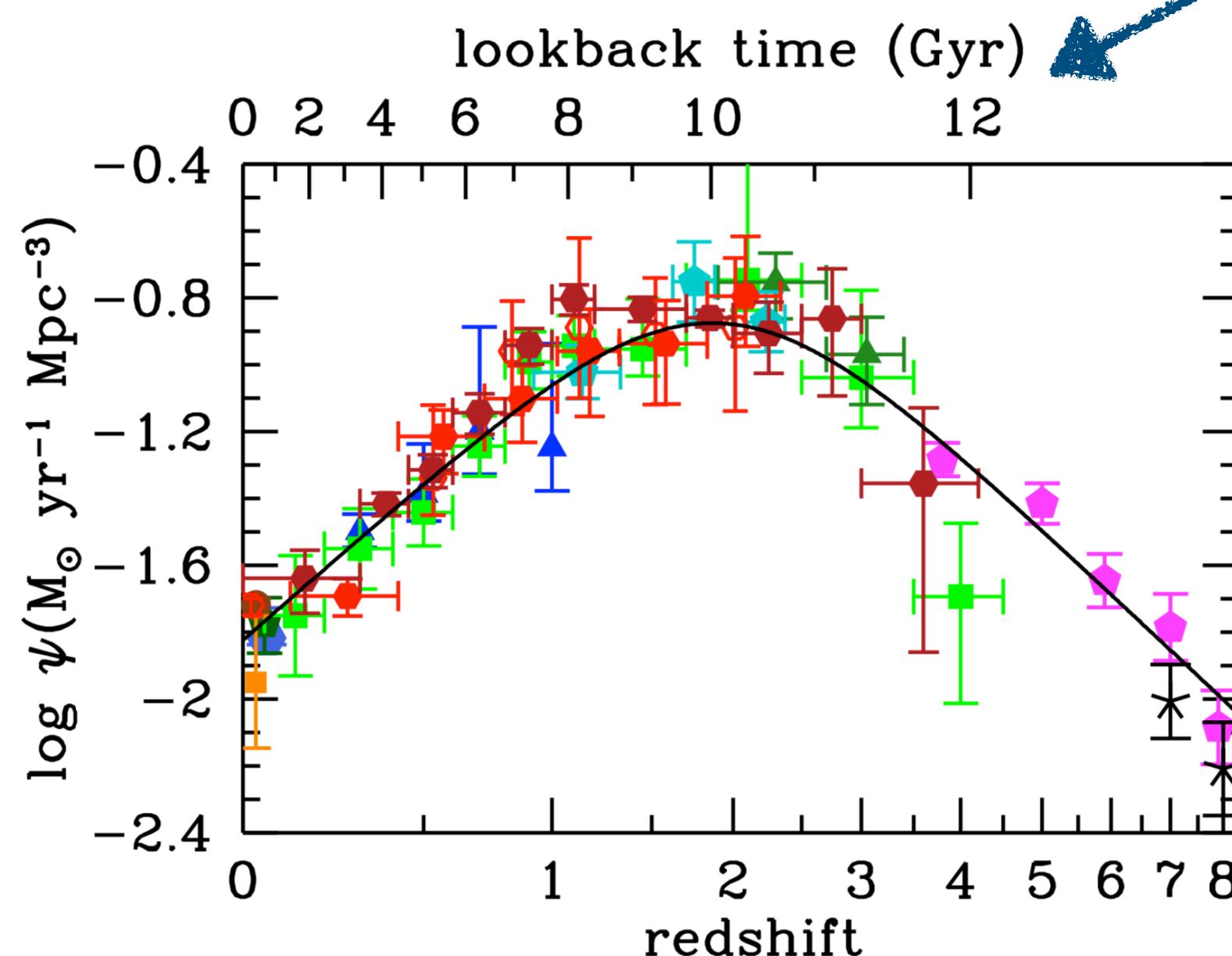
$$p(Z|z) = \frac{1}{\sqrt{2\pi \sigma_Z^2}} \exp \left\{ - \frac{[\log(Z/Z_\odot) - \mu(z)]^2}{2\sigma_Z^2} \right\}.$$

The **distribution of metallicities at fixed redshift** is by default a **gaussian** distribution. Here we can change the mean and the spread. The mean $\mu(z)$ is a function of redshift and for the model ‘linear’ we also know the uncertainty

[Madau & Dickinson 2014](#), [Madau & Fargas 2017](#)

COSMORATE

Santoliquido et al. 2020:
<https://arxiv.org/pdf/2004.09533.pdf>



$$\mathcal{R}(z) = \int_{z_{\min}}^z \left[\int_{Z_{\min}}^{Z_{\max}} \text{SFRD}(z', Z) \mathcal{F}(z', z, Z) dZ \right] \frac{dt(z')}{dz'} dz'$$

Injected catalogs

$$\text{SFRD}(z, Z) = \psi(z) p(Z|z)$$

$$p(Z|z) = \frac{1}{\sqrt{2\pi \sigma_Z^2}} \exp \left\{ - \frac{[\log(Z/Z_\odot) - \mu(z)]^2}{2\sigma_Z^2} \right\}.$$

```
# Choose the model for average metallicity fit type
metmod_type = 'MandF2017' # it can be 'linear' or 'MandF2017'
sigma_met = 0.20 # value of the metallicity spread in log-sun-scale
# it can be 0.10, 0.20, 0.30 or sys.argv[3]

# Definition of Solar metallicity
Z_sun = 0.019 # 0.0153 from Cauffau et al. 2011
# 0.019 from Gallazzi et al. 2008
```

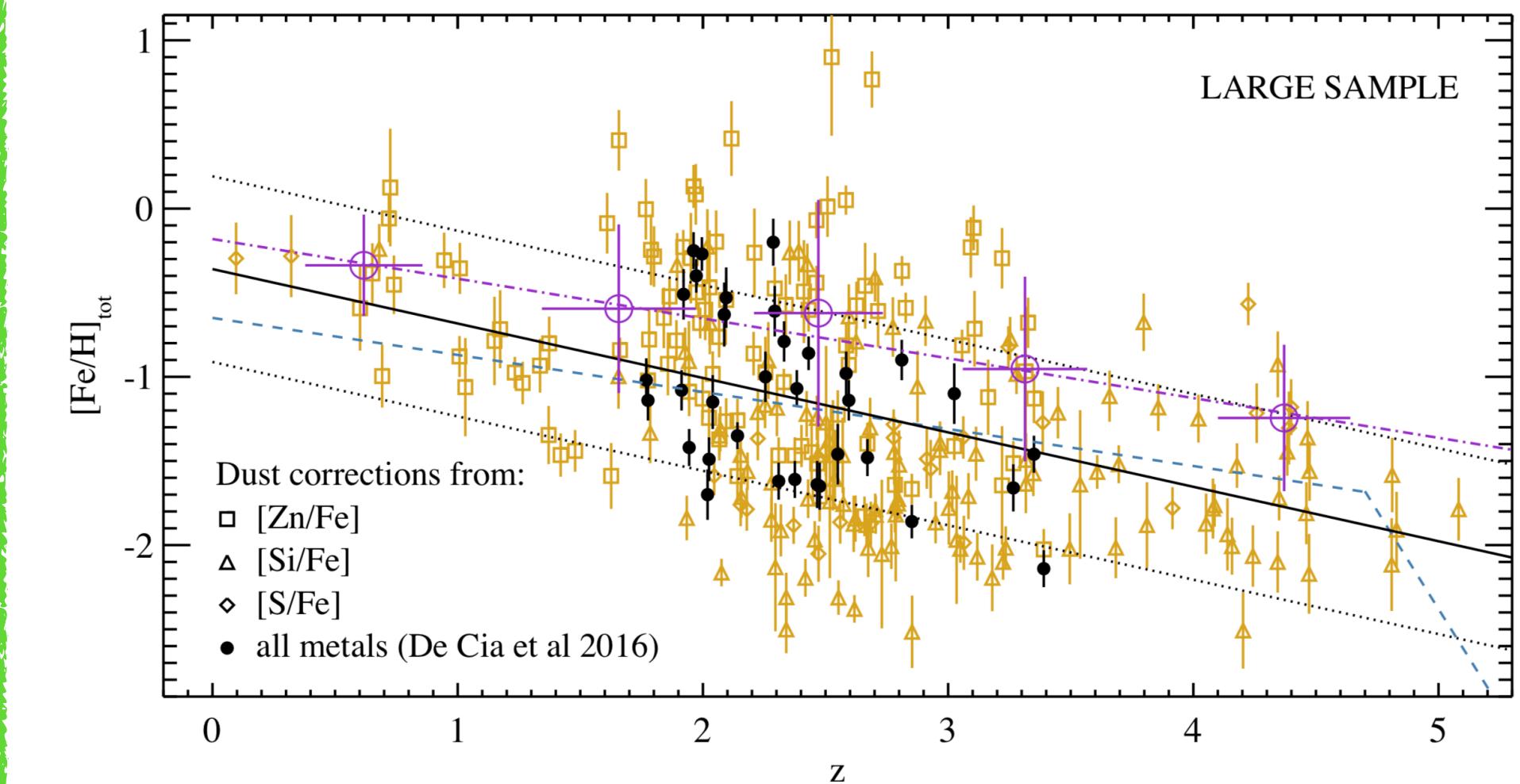
[Madau & Dickinson 2014](#), [Madau & Fragos 2017](#)

[De Cia et al. 2018](#), [Gallazzi et al. 2008](#), [Madau & Fragos 2017](#)

Level 2: How to modify `cosmo_params.py`

- `cosmoRate` has other useful features:
 - Propagate known sources of uncertainty on the merger rate density

For example, the ‘linear’ model is extracted from the metallicity evolution of neutral hydrogen ([De Cia et al. 2018](#)). The model we implemented is the purple line in the figure, which is a linear fit. `cosmoRate` can propagate the uncertainty of slope and intercept on the merger rate density via a Monte Carlo approach. Each time it samples a value of slope and intercept forms a gaussian distribution. How to switch on this features is explained in the next slide.



Level 2: How to modify cosmo_params.py

- cosmoRate has other useful features:
 - Propagate known sources of uncertainty on the merger rate density

```
# Here you set if cosmo_Rate evaluates also the uncertainty through a Monte Carlo approach
N_iter = 1 # number of iteration to be done for evaluating the uncertainty. In any case, it must be at least one!
# 1000 iterations are enough to perform a robust estimation of the uncertainties

# metallicity
met_uncertainty = 'No' # if 'Yes' the uncertainty due to metallicity will be computed
met_slope_sprd = 0.014 # 0.14 for linear metallicity model or 0.014 from 'MandF2017'
met_inter_sprd = 0.14 # from Gallazzi et al. 2008

# star formation rate option
sfr_uncertainty = 'No' # if 'Yes' the uncertainty due to sfr will be computed,
# spread over the normalisation value
sfr_sprd = 0.2 # from Madau & Dickinson 2017
```

Level 2: How to modify cosmo_params.py

- Creating catalogs of merging compact objects at some given redshift bins

```
catalogues_c = 'Yes' # if 'Yes' merging compact object per redshift bin are produced
mrd_eval = 'Yes' # this option is to skip the evaluation of the merger rate density in case
# it has been already done in previous runs

# specify the redshift bins of which you want to have the catalogs printed
# WARNING: The code will search for the closest available redshift bin!
z_vect_cat_op = False
#[30, 25, 20, 17, 15, 14, 13, 12, 11, 10, 9, 8, 7, 6, 5, 4, 3, 2, 1, 0.1]
# some other options:
#[14, 13, 12, 11, 10, 9, 8, 7, 6, 5, 4, 3, 2, 1, 0.1]
#[20, 11, 5, 0.1]
# if this option is set to False the catalogs will be printed at every merger redshift
#[30, 25, 20, 17, 15, 14, 13, 12, 11, 10, 9, 8, 7, 6, 5, 4, 3, 2, 1, 0.1]

# Specify what parameters cosmoRate will sample. The order of the parameter names must be exactly
# the same as the order of the corresponding column in input_catalogs/
# delay time is sampled by default.
# The number of parameters can be smaller than the total number of paramters given as input.
# Leave parameters = [] if in your catalogs you want just time-delay related parameters,
# i.e. merging redshift, formation redshift, delay time and progenitor star metallicity
parameters = ['ID', 'M1[Msun]', 'M2[Msun]']
```

Level 2: How to modify cosmo_params.py

- Creating catalogs of merging compact objects at some given redshift bins

```
catalogues_c = 'Yes' # if 'Yes' merging compact object per redshift bin are produced
mrd_eval = 'Yes' # this option is to skip the evaluation of the merger rate density in case
# it has been already done in previous runs

# specify the redshift bins of which you want to have the catalogs printed
# WARNING: The code will search for the closest available redshift bin!
z_vect_cat_op = False
#[30, 25, 20, 17, 15, 14, 13, 12, 11, 10, 9, 8, 7, 6, 5, 4, 3, 2, 1, 0.1]
# some other options:
#[14, 13, 12, 11, 10, 9, 8, 7, 6, 5, 4, 3, 2, 1, 0.1]
#[20, 11, 5, 0.1]
# if this option is set to False the catalogs will be printed at every merger redshift
```

WARNING: the order of parameter names in the array parameters must be exactly the same as in your input catalogs!

```
# i.e. merging_reasnlc, formation_reasnlc, decay_time and progenitor_star_metallicity
parameters = ['ID', 'M1[Msun]', 'M2[Msun]']
```

cosmoRate output

/ ... / output_cosmo_Rate / sigma0.2 /	
Name	Last Modified
BBH	3 months ago
SFRD_plot_MandF2017_met_MandF2017.pdf	a month ago

1. One folder per each compact object type
2. A plot of the adopted SFRD model

BBH_MandF2017_met_MandF2017_z9.62_50_SFR_pw.dat	a month ago
BBH_MandF2017_met_MandF2017_z9.77_50_SFR_pw.dat	a month ago
BBH_MandF2017_met_MandF2017_z9.92_50_SFR_pw.dat	a month ago
m1_dist_MandF2017_met_BBH_MandF2017_SFR_pw.pdf	a month ago
MRD_plot_MandF2017_met_BBH_MandF2017_SFR_pw.pdf	a month ago
MRD_spread_15Z_50_No_MandF2017_0.2_No_No_False_MandF2017_0.dat	a month ago
Sampled_parameters_15Z_50_No_MandF2017_0.2_No_No_False_MandF2017_0.dat	a month ago
z_form_dist_MandF2017_met_BBH_MandF2017_SFR_pw.pdf	a month ago
Zperc_z_15Z_50_No_MandF2017_0.2_No_No_False_MandF2017_50_0_SFR_pw.dat	a month ago

Catalogs of merging compact objects at a given redshift (e.g. 9.92, 9.77, 9.62)

This contains the merger rate density at a given redshift

cosmoRate output

```
≡ MRD_spread_15Z_50_No_M ×  
1 #Redshift Merger_Rate_Density[Gpc^-3yr^-1]  
2 7.5757575757524620e-02 9.999916614617394117e+00  
3 2.2727272727266268e-01 1.162545328129738387e+01  
4 3.7878787878780074e-01 1.393256901156849281e+01  
5 5.3030303030293879e-01 1.645152655180917023e+01  
6 6.818181818181816567e-01 1.797975387254746948e+01  
7 8.33333333333330373e-01 1.855869690584141551e+01  
8 9.8484848484844179e-01 1.904926877060518819e+01  
9 1.136363636363635798e+00 1.997089741730858137e+01
```

```
≡ BBH_MandF2017_met_Mar ×  
1 #ID M1[Msun] M2[Msun] z_merg z_form time_delay[yr] Z_progenitor  
2 3304345.00000 30.32970 26.32721 0.07576 14.92424 13186997527.04119 0.00010  
3 3566223.00000 31.37294 24.66961 0.07576 14.92424 13008058858.42008 0.00010  
4 4949627.00000 22.47323 17.41708 0.07576 14.92424 13467649911.29968 0.00010  
5 220280.00000 39.08434 32.70891 0.07576 14.92424 11612581593.33620 0.00010  
6 4085742.00000 37.72191 27.38235 0.07576 14.92424 13304820193.02670 0.00010  
7 2277682.00000 43.57659 40.35687 0.07576 14.92424 13455617795.50724 0.00010  
8 3276481.00000 27.34489 21.45434 0.07576 14.92424 13237437606.31335 0.00010  
9 3682468.00000 38.62225 30.58141 0.07576 14.92424 12471478414.62328 0.00010
```

Merger rate density file
First column: middle of the redshift bin
Merger rate density in Gpc⁻³ yr⁻¹

- 1.
- 2.

Catalog of merging compact objects

WARNING: storage usage may be very high!

Homework

- **cosmoRate:**
 - Create a figure where you compare the primary mass distribution m_1 at different redshifts ($z = 0, z = 2, z = 8$) of binary black holes (BBHs) evaluated with two different values of $\sigma_Z = 0.1, 0.6$. Use the astrophysical model provided. *SUGGESTION:* you need to update also the variable `sim_name`
 - Do the same for BHNSs