21CMFAST

[Installing on a workstation]

[Running coeval cubes and lightcones]

ASTROPHYSICAL PARAMETERS

- INHOMO_RECO (*bool, optional*) – Whether inhomogeneous recombinations are being calculated. This is not a part of the astro parameters structure, but is required by this class to set some default behaviour.
- **R_BUBBLE_MAX** (*float, optional*) – Mean free path in Mpc of ionizing photons within ionizing regions. The propagation of ionizing photons through the IGM strongly depends on the abundances and properties of absorption systems (Lyman limit as well as more diffuse systems), which are below the resolution limits of EoR simulations. These systems act as photon sinks, roughly dictating the maximum scales to which H II bubbles can grow around ionizing galaxies. Default is 50 if INHOMO_RECO is True, or 15.0 if not. $5 \le R_{\rm mfp}/{\rm Mpc} \le 20$.
- **HII_EFF_FACTOR** (*float, optional*) – The ionizing efficiency of high-z galaxies. Higher values tend to speed up reionization. It describes the conversion of mass into ionising photons:

$$\zeta = 30 \left(\frac{f_{\rm esc}}{0.3}\right) \left(\frac{f_\star}{0.05}\right) \left(\frac{N_\gamma}{4000}\right) \left(\frac{2}{1 + n_{\rm rec}}\right)$$

where, $f_{\rm esc}$ is the fraction of ionizing photons escaping into the IGM, $f_\star$ is the fraction of galactic gas in stars, N_γ is the number of ionizing photons produced per baryon in stars and $n_{\rm rec}$ is the typical number of times a hydrogen atom recombines. Usually vary between 5 and 100 (corresponding to $0.05 \le f_{\rm esc} \le 1$). Default is 30.

- **ION_Tvir_MIN** (*float, optional*) – Minimum virial temperature of star-forming haloes. Given in log10 units. $10^4\ \mathrm{K} \leq T_{\mathrm{vir}} \leq 2 \times 10^5\ \mathrm{K}$. Default is 4.69897.

Define the minimum threshold for a halo hosting a star-forming galaxy to be in terms of its virial temperature, which regulates processes important for star formation: gas accretion, cooling and retainment of supernovae outflows:

$$M_{\min} = 10^8 h^{-1} \left(\frac{\mu}{0.6}\right)^{-3/2} \left(\frac{\Omega_{\mathrm{m}}}{\Omega_{\mathrm{m}}^z} \frac{\Delta_{\mathrm{c}}}{18\pi^2}\right)^{-1/2} \times \left(\frac{T_{\mathrm{vir}}}{1.98 \times 10^4 \mathrm{K}}\right)^{3/2} \left(\frac{1+z}{10}\right)^{-3/2} \mathrm{M}\odot$$

where μ is the mean molecular weight, $\Omega_{\mathrm{m}}^z = \Omega_{\mathrm{m}}(1+z)^3 / \left[\Omega_{\mathrm{m}}(1+z)^3 + \Omega_\Lambda\right]$ and $\Delta_c = 18\pi^2 + 82d - 39d^2$ where $d = \Omega_{\mathrm{m}}^z - 1$. Typically, $T_{\mathrm{vir}} = 10^4\ \mathrm{K}$ has been adopted in the literature as the minimum temperature when efficient atomic cooling occurs, corresponding to a DM halo mass of $\sim 10^8 M_\odot$ at z ~ 10.

- L_X (*float, optional*) – The specific X-ray luminosity per unit star formation escaping host galaxies. Given in log10 units. Default is 40.0.

$$L_{\mathrm{X}<2\mathrm{keV}}/\mathrm{SFR} = \int_{E_0}^{2\mathrm{keV}} \mathrm{d}E_e L_{\mathrm{X}}/\mathrm{SFR}$$

- X_RAY_Tvir_MIN (*float, optional*) – Minimum halo virial temperature in which X-rays are produced. Given in log10 units. Default is ION_Tvir_MIN.
- NU_X_THRESH (*float, optional*) – X-ray energy threshold for self-absorption by host galaxies (in eV). Also called E_0. Typical range is (100, 1500). The interstellar medium (ISM) of high-z galaxies can absorb soft X-ray photons, attenuating the emergent X-ray profile, and limiting IGM heating. Das et al. (2017) find that the emergent X-ray spectrum from simulated high-z galaxies can be well fitted by a step- function attenuation below E0 ~ 0.5 keV (corresponding to a metal-free ISM with an H I column density of log10(NH I/cm2) = 21.5). At a fixed soft-band luminosity, increasing E0 hardens the emerging spectrum. Since the mean free path is a strong function of photon energy, the resulting EoH is more uniform. Here, we take a flat prior over E0 ∈ [0.1, 1.5] keV which corresponds approximately to an optical depth of unity through a metal-free ISM with log10(NH I/cm2) ∈ [19.3, 23.0]. Default is 500.0.
- X_RAY_SPEC_INDEX (*float, optional*) – X-ray spectral energy index. Typical range is (-1, 3). This depends on the dominant physical process producing the X-ray photons. Increasing/decreasing αX results in more numerous soft/hardX-ray photons (when the soft-band luminosity is fixed), resulting in similar qualitative behaviour to that for decreasing/increasing E0. We adopt a flat prior of αX ∈ [– 1.0, 3.0], which

encompasses a wide range of plausible X-ray spectral energy distributions that describe high-z galaxies. Default is 1.0.

- N_RSD_STEPS (*int*, *optional*) – Number of steps used in redshift-space-distortion algorithm. NOT A PHYSICAL PARAMETER. Default is 20.

If USE_MASS_DEPENDENT_ZETA =True in FlagOptions

The stellar mass of a galaxy M∗ can be related to the mass of the host halo Mh (Park+2018):

$$M_*\left(M_{\mathrm{h}}\right)=f_*\left(\frac{\Omega_{\mathrm{b}}}{\Omega_{\mathrm{m}}}\right) M_{\mathrm{h}}$$

where f∗ is the fraction of galactic gas in stars such that:

$$f_*\left(M_{\mathrm{h}}\right)=f_{*, 10}\left(\frac{M_{\mathrm{h}}}{10^{10} \mathrm{M}_{\odot}}\right)^{\alpha_*}$$

where is the fraction of galactic gas in stars normalized to the value in haloes of mass $10^{10} M_{\odot}$ and $\alpha_{\star}$ is the power-law index. We impose a physical upper limit of $f_{\star} \leq 1$.

- **ALPHA_STAR** (*float*, *optional*) – Power-law index of fraction of galactic gas in stars as a function of halo mass. Default is 0.5.
- **F_STAR10** (*float*, *optional*) – The fraction of galactic gas in stars for 10^10 solar mass haloes. Used along with F_ESC10 to determine HII_EFF_FACTOR (which is then unused). Given in log10 units. Default is -1.3.

$$f_{\mathrm{esc}}\left(M_{\mathrm{h}}\right)=f_{\mathrm{esc}, 10}\left(\frac{M_{\mathrm{h}}}{10^{10} \mathrm{M}_{\odot}}\right)^{\alpha_{\mathrm{esc}}}$$

- **ALPHA_ESC** (*float*, *optional*) – Power-law index of escape fraction as a function of halo mass. Default is -0.5.
- **F_ESC10** (*float*, *optional*) – The escape fraction for 10^10 solar mass haloes. Used along with F_STAR10 to determine HII_EFF_FACTOR(which is then unused). Default is -1.0.

Star formation in small galaxies is expected to be quenched due to SNe feedback, photoheating feedback, or inefficient gas accretion. We account for this suppression with a redshift-independent duty cycle:

$$f_{\rm duty}\ (M_{\rm h}) = \exp\left(-\frac{M_{\rm turn}}{M_{\rm h}}\right)$$

- **M_TURN** (*float*, *optional*) – Turnover mass (in log10 solar mass units) for quenching of star formation in halos, due to SNe or photo-heating feedback, or inefficient gas accretion. Default is 8.7.

The SFR can be expressed on average as the total stellar mass divided by a characteristic time-scale $t_\star$:

$$\dot{M}_*\left(M_{\rm h}, z\right) = \frac{M_*}{t_* H(z)^{-1}}$$

- **t_STAR** (*float*, *optional*) – Fractional characteristic time-scale (fraction of hubble time) defining the star-formation rate of galaxies. Default is 0.5.

If USE_MASS_MINI_HALOS =True in FlagOptions

Since star formation can proceed differently in molecularly-cooled galaxies (MCGs) compared to atomic-cooled galaxies (ACGs), we allow them to have a different stellar to halo mass normalization

$$M_*^{\rm mol} = \min\left[1, f_{*,7}^{\rm mol}\left(\frac{M_{\rm vir}}{10^7 {\rm M}_\odot}\right)^{\alpha_*}\right]\frac{\Omega_{\rm b}}{\Omega_{\rm m}} M_{\rm vir}$$

- **F_STAR7_MINI** (*float*, *optional*) – The fraction of galactic gas in stars for 10^7 solar mass minihaloes. Used along with F_ESC7_MINI to determine HII_EFF_FACTOR_MINI (which is then unused). See Eq. 8 of Qin+2020. Given in log10 units. Default is -2.0.

We adopt a power-law relation for the escape fraction to halo mass, allowing both the normalization and scaling to be different between MCGs and ACGs

$$f_{\rm esc}^{\rm atom\ (mol)} = \min\left[1, f_{\rm esc\ ,\ atom\ (mol)}^{10(7)}\left(\frac{M_{\rm vir}}{10^{10(7)}{\rm M}_\odot}\right)^{\alpha_{\rm esc}^{\rm atom\ (mol)}}\right]$$

- **F_ESC7_MINI** (*float*, *optional*) – The "escape fraction for minihalos", i.e. the fraction of ionizing photons escaping into the IGM, for 10^7 solar mass minihaloes. Used along with F_STAR7_MINI to determine HII_EFF_FACTOR_MINI (which is then unused). Given in log10 units. Default is -2.0.

Tthe X-ray emission from all galaxies (MCG and ACG) follows a power law with an energy index of αX and a specific luminosity of

$$\frac{\mathrm{d}L^i_{\mathrm{X}/\dot{\odot}}}{\mathrm{d}E}(E) = L^i_{\mathrm{X}<2\mathrm{keV}/\odot}\left(\int_{E_0}^{2\mathrm{keV}}\mathrm{d}EE^{-\alpha_\mathrm{X}}\right)^{-1}E^{-\alpha_\mathrm{X}}$$

where E_0 represents the minimum energy that a X-ray photon needs to escape from the host galaxy into the IGM while $L^i_{\mathrm{X}<2\mathrm{keV}/\odot}$ is the total luminosity between E0 and 2keV.

- **L_X_MINI** (*float*, *optional*) – The specific X-ray luminosity per unit star formation escaping host galaxies for minihalos. Given in log10 units. Default is 40.0.

See Eq. 12 Qin+2020

$$J^{21}_{\mathrm{LW,eff}} = \frac{J_\mathrm{LW}}{10^{-21}\mathrm{ergs}^{-1}\mathrm{Hz}^{-1}\mathrm{cm}^{-2}\mathrm{sr}^{-1}}\left(1 - f^{\mathrm{shield}}_{\mathrm{H}_2}\right)$$

- **F_H2_SHIELD** (*float*, *optional*) – Self-shielding factor of molecular hydrogen when experiencing LW suppression.

FLAG OPTIONS

Default value is False for all the below options.

- **USE_HALO_FIELD** : Set to True if intending to find and use the halo field. If False, uses the mean collapse fraction (which is considerably faster).
- **USE_MINI_HALOS** : Set to True if using mini-halos parameterization. If True, USE_MASS_DEPENDENT_ZETA and INHOMO_RECO must be True.
- **USE_MASS_DEPENDENT_ZETA** : Set to True if using new parameterization. Setting to True will automatically set `M_MIN_in_Mass` to True.
- **SUBCELL_RSD** : Add sub-cell redshift-space-distortions (cf Sec 2.2 of Greig+2018). Will only be effective if `USE_TS_FLUCT` is True.
- **INHOMO_RECO** : Whether to perform inhomogeneous recombinations. Increases the computation time.
- **USE_TS_FLUCT** : Whether to perform IGM spin temperature fluctuations (i.e. X-ray heating). Dramatically increases the computation time.
- **M_MIN_in_Mass** : Whether the minimum halo mass (for ionization) is defined by mass or virial temperature. Automatically True if `USE_MASS_DEPENDENT_ZETA` is True.

- **PHOTON_CONS** : bool, optional Whether to perform a small correction to account for the inherent photon non-conservation.

GLOBAL PARAMETERS

Non-exhaustive list (see link)

- **FIND_BUBBLE_ALGORITHM** (int, {1,2}) – Choose which algorithm used to find HII bubbles. Options are: (1) Mesinger & Furlanetto 2007 method of overlapping spheres: paint an ionized sphere with radius R, centered on pixel where R is filter radius. This method, while somewhat more accurate, is slower than (2), especially in mostly ionized universes, so only use for lower resolution boxes (HII_DIM<~400). (2) Center pixel only method (Zahn et al. 2007). This is faster.
- Cosmological parameters: **OMn** for neutrinos, **OMk** for curvature, **OMr** for radiation, **OMtot** for fractional density of the universe with respect to critical density (1 for a flat universe).
- **Zreion_HeII** (float) – Redshift of helium reionization, currently only used for tau_e

To compute the brightness temperature

- **T_USE_VELOCITIES** (*bool, default is 1*) – Whether to use velocity corrections in 21-cm fields. The approximation used to include peculiar velocity effects works only in the linear regime, so be careful using this (see Mesinger+2010)
- **MAX_DVDR** *(float, default is 0.2)* Maximum velocity gradient along the line of sight in units of the Hubble parameter at z. This is only used in computing the 21cm fields.
- **VELOCITY_COMPONENT** (int) – Component of the velocity to be used in 21-cm temperature maps (1=x, 2=y, 3=z)

To compute the spin temperature of the gas

- **Z_HEAT_MAX** *(float, default 35.0)* Maximum redshift used in the Tk and x_e evolution equations. Temperature and x_e are assumed to be homogeneous at higher redshifts. Lower values will increase performance.
- **TK_at_Z_HEAT_MAX** *(float, default -1.0)* Kinetic temperature of the gas at boundary conditions (ie at Z_HEAT_MAX). If positive, then overwrite default boundary conditions for the evolution equations with this value. The default is to use the value obtained from RECFAST `T_RECFAST(global_params.Z_HEAT_MAX,0)`.
- **XION_at_Z_HEAT_MAX** *float, default -1.0)* If positive, then overwrite default boundary conditions for the evolution equations with this value. The default is to use the value

obtained from RECFAST `xion_RECFAST(global_params.Z_HEAT_MAX,0)`.

USER PARAMETERS

- **USE_INTERPOLATION_TABLES** (bool, optional, default False) – If True, calculates and evaluates quantities using interpolation tables, which is considerably faster than when performing integrals explicitly.
- **PERTURB_ON_HIGH_RES** (bool, optional) – Whether to perform the Zel'Dovich or 2LPT perturbation on the low or high resolution grid.
- **DIM** (int,optional) – Number of cells for the high-res box (sampling ICs) along a principal axis. To avoid sampling issues, DIM should be at least 3 or 4 times HII_DIM, and an integer multiple. By default, it is set to 3*HII_DIM.
- **USE_FFTW_WISDOM** (bool, optional) – Whether or not to use stored FFTW_WISDOMs for improving performance of FFTs