BEoRN: a Python package to simulate the 21cm signal during cosmic dawn

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cosmic-reionization/BEoRN

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Introduction

Motivation:

- The 21cm signal will help us understand the formation of the first galaxies, and constrain cosmological parameters and properties of dark matter.
- *SKA-low* will measure sky maps of the 21cm signal during cosmic dawn.

Challenge:

Constructing the signal involves modelling small-scale hydrodynamical feedback processes for galaxies, and propagating radiation across cosmological scales while solving their interaction processes with gas particles of the IGM.

BEoRN...

...is designed to efficiently generate 3D maps of the 21cm signal.

The observable

Radio interferometers measure the 21cm ***differential brightness temperature:*** $dT_{\rm b} = T_{\rm b} - T_{\rm cmb}$

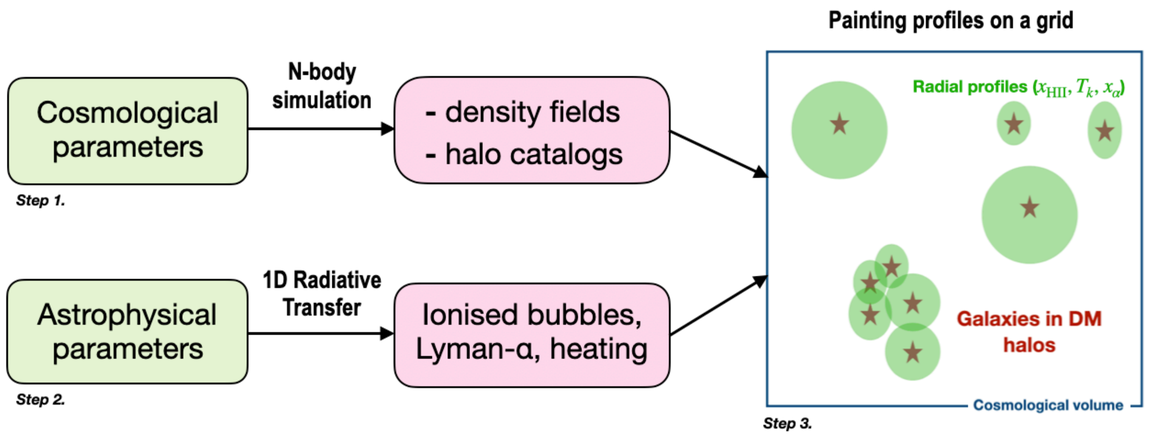
$$dT_b(\mathbf{x}, z) \propto (1 - x_{\rm HII}) \times \frac{x_\alpha}{1 + x_\alpha} \times \left[1 - \frac{T_{\rm cmb}}{T_k}\right]$$

hydrogen ionisation fraction — *Lyman–α coupling coefficient* — *gas kinetic temperature*

Methodology

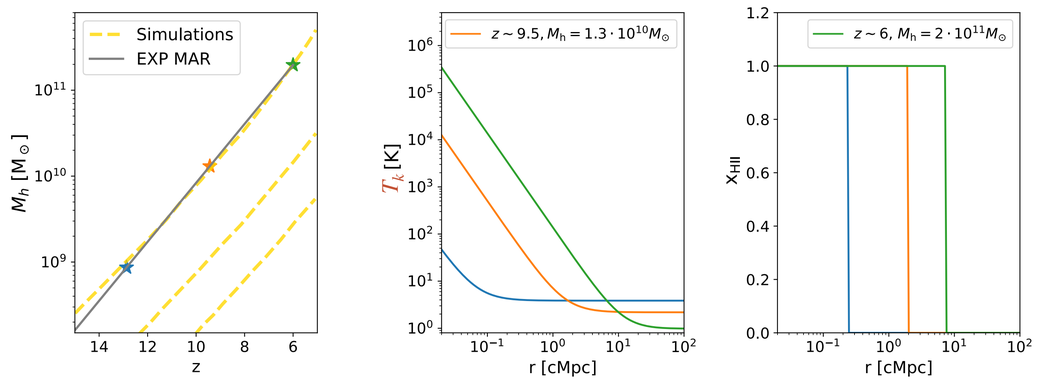
From individual sources to $dT_{\rm b}$ maps

The code paints 1D profiles of $x_{\rm HII}$, x_α , and T_k on 3D grids, centred on DM haloes, to produce 21cm brightness temperature maps.



Spherical profiles around DM halos

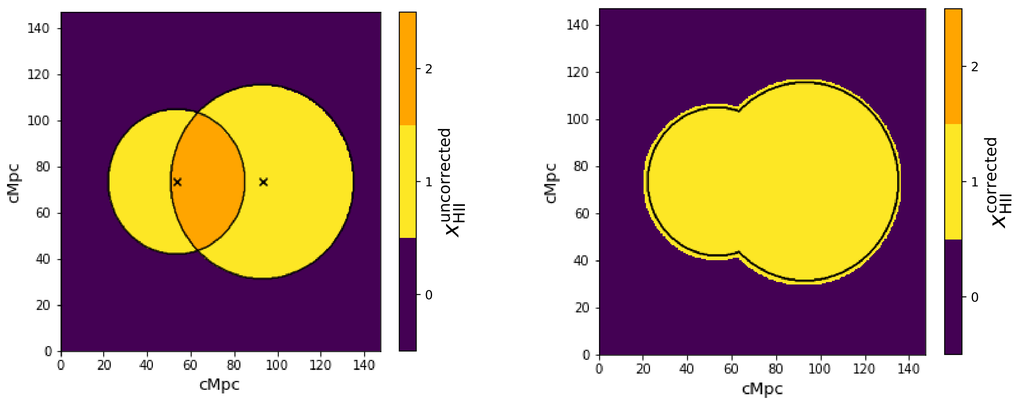
We generate 1D profiles of $x_{\rm HII}$, x_α , and T_k following the *mass accretion rate* of halos, and the subsequent increase in luminosity of their central source.



Halo mass growth and profiles for different masses and redshifts

Overlap of ionised bubbles

Ionising bubbles are *not additive!* We redistribute the *excess ionisation fraction* to the set of pixels closest to the boundary of the ionised region.



A toy example to illustrate how we correct for the overlap of ionised bubbles

BEoRN offers flexibility

The user can choose among various options for the gravity calculation, the modelling of sources and the radiative transfer.

Cosmology
- external N-body
- embedded *LPT* solver
- embedded *FOF* halo finder
- neural network for halo catalogs

Source modelling
- stellar feedback: heterogeneous or global
- flexible semi-analytical model
- halo growth: merger trees or universal MAR

Radiative transfer
- uncoupled $(T_{\rm gas}, x_{\rm HII})$ equations, **HI** only
- fully coupled equations using **pyC²Ray**

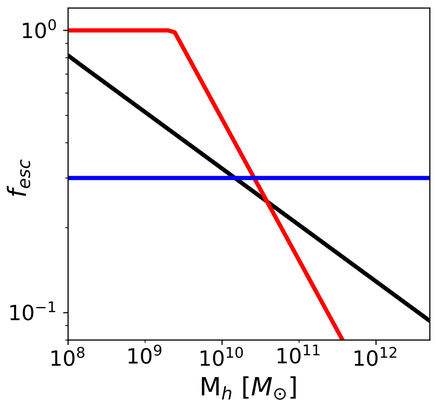
Results

Simulations of the cosmic dawn 21cm signal

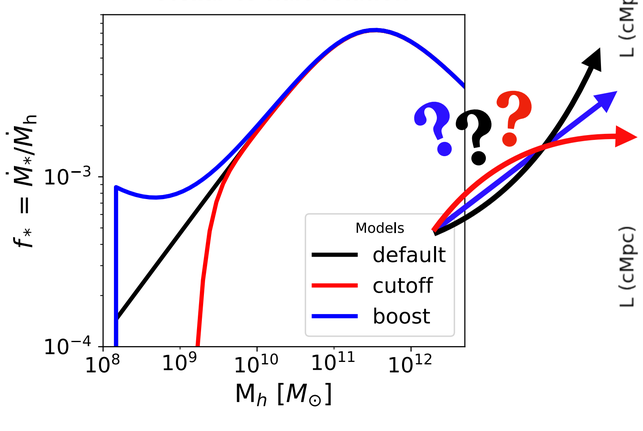
We ran **BEoRN** for 3 different source models, calibrated on high-redshift observations...

...can you guess which model corresponds to each 21cm signal?

Ionising photons escape fraction



Stellar-to-halo relation



Light-cone evolution of the 21cm brightness temperature $d\overline{T}_{\rm b}$ for the 3 models