Understanding the Role of Early Stars in the Formation and Evolution of Galaxies

A step towards understanding cosmic reionization

19-08-2024

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Agenda

1. Research Background and Motivation
2. Problem under study
3. Methodology
4. Results
5. How is it relevant in the bigger picture?

Research background & motivation

JWST is opening up new frontiers of cosmology by looking further than HST!

JWST Sees More Galaxies than Expected

February 9, 2024 • *Physics* 17, 23

The new JWST observatory is revealing far more bright galaxies in the early Universe than anyone predicted, and astrophysicists have more than one explanation for the puzzle.

James Webb Space Telescope sees early galaxies defying 'cosmic rulebook' of star formation

News By Robert Lea published September 25, 2023

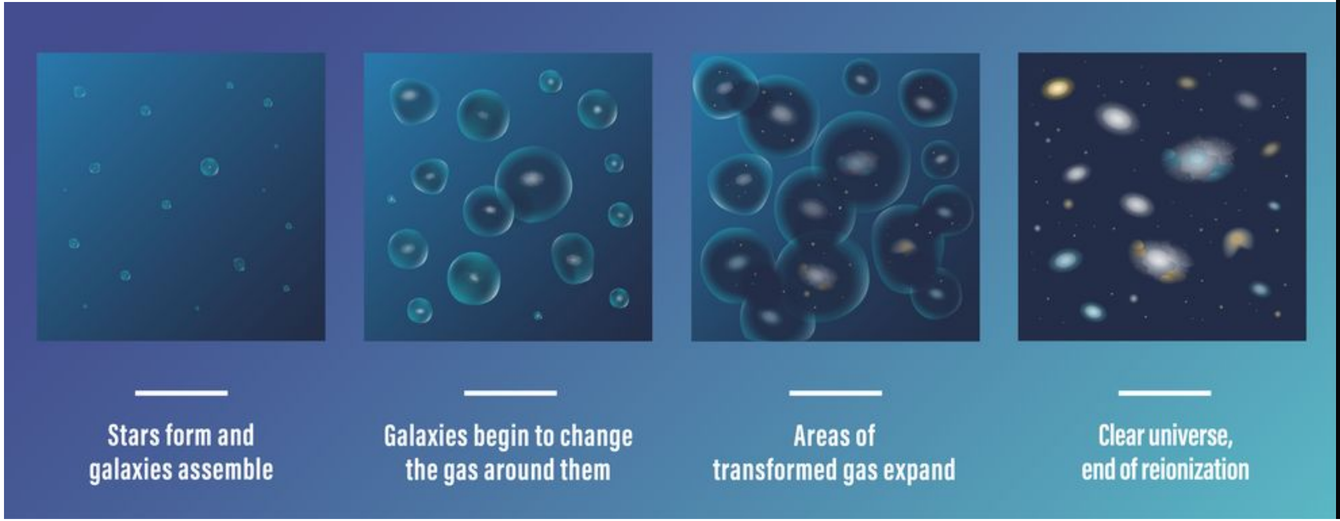
"It was like the galaxies had a rulebook that they followed — but astonishingly, this cosmic rulebook appears to have undergone a dramatic rewrite during the universe's infancy."

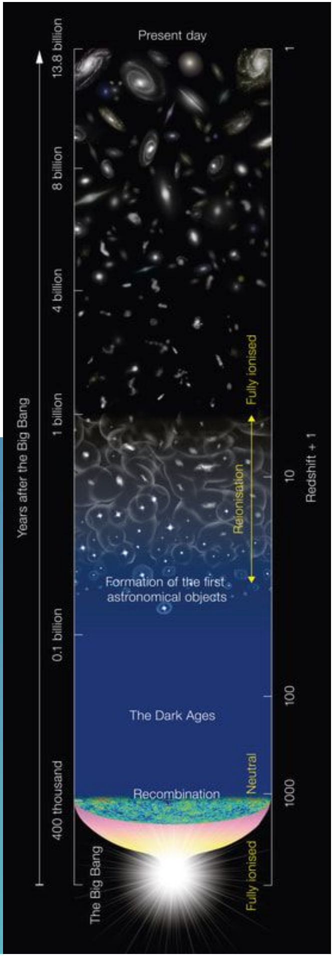
- ↳ C. T. Donnan *et al.*, "The evolution of the galaxy UV luminosity function at redshifts $z \sim 8$–15 from deep JWST and ground-based near-infrared imaging," arXiv:2207.12356.
- ↳ I. Labbé *et al.*, "A population of red candidate massive galaxies ~600 Myr after the Big Bang," Nature 616 (2023).
- ↳ P. Arrabal Haro *et al.*, "Confirmation and refutation of very luminous galaxies in the early Universe," Nature 622 (2023).
- ↳ S. L. Finkelstein *et al.*, "The complete CEERS early Universe galaxy sample: A surprisingly slow evolution of the space density of bright galaxies at $z \sim 8.5$–14.5," arXiv:2311.04279.
- ↳ G. Sun *et al.*, "Bursty star formation naturally explains the abundance of bright galaxies at cosmic dawn," Astrophys. J., Lett. 955 (2023).
- ↳ A. Ferrara, "Super-early JWST galaxies, outflows and Lyman alpha visibility in the EoR," arXiv:2310.12197.
- ↳ A. Ferrara *et al.*, "On the stunning abundance of super-early, luminous galaxies revealed by JWST," Mon. Not. R. Astron. Soc. 522 (2023).

Research background & motivation

JWST is opening up new frontiers of cosmology by looking further than HST!

One of the key problem on which JWST would be very useful is the problem of *reionization*.





Problem Under Study

Problem:

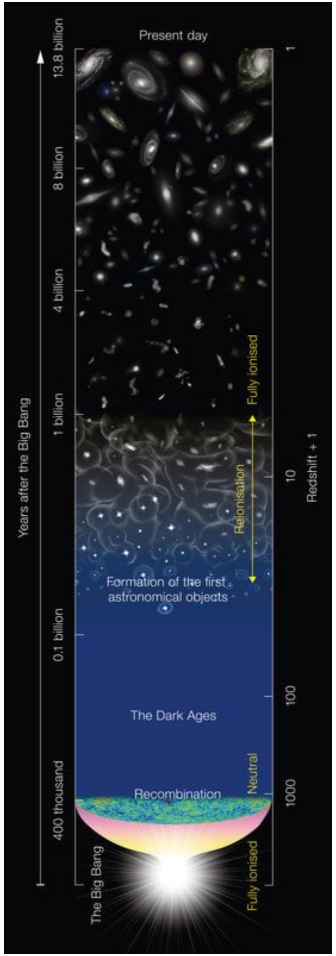
- ? We don’t know what happens during reionization !
- ? We don’t have predictions for JWST !!

Currently Accepted Hypothesis:

Early Galaxies and accretion of matter into the black holes released enough energy to re-ionize the universe.

Problem to Investigate:

- ➠ How the early stars shaped the evolution of early galaxies?
- ➠ How much do PopIII stars contribute to reionization?



Methods

Methods

No observations available for the primordial universe.

Use High Resolution N-Body simulations in Cosmological settings to understand the role of the early stars in galaxy formation and evolution!

Methods - Setting the background

Methods - Setting the background

Cosmology :

$$H = H_0 \left[\Omega_0 a^{-3} + (1 - \Omega_0 - \Omega_\Lambda) a^{-2} + \Omega_\Lambda\right]^{1/2}$$

Vogelsberger et. al 2020

Methods - Setting the background

Cosmology :

$$H = H_0 \left[\Omega_0 a^{-3} + (1 - \Omega_0 - \Omega_\Lambda) a^{-2} + \Omega_\Lambda\right]^{1/2}$$

Hydrodynamics

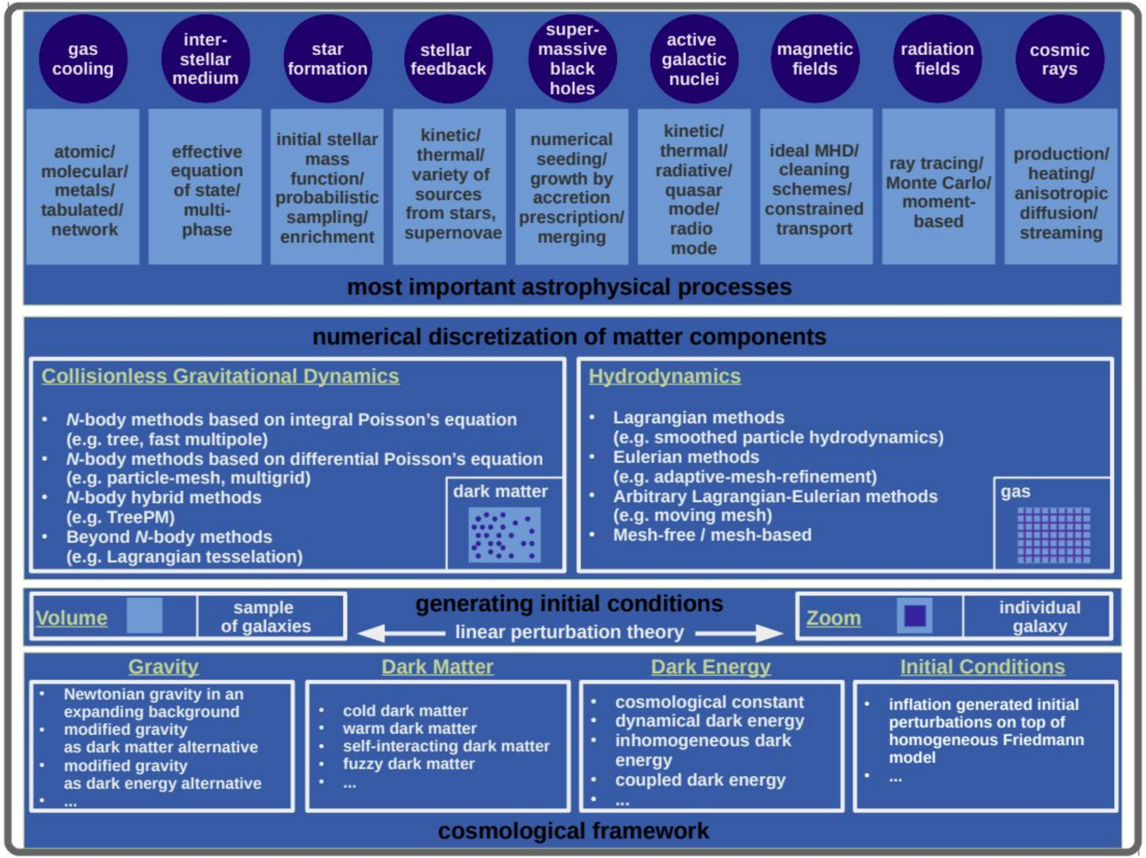
$$\dot{\boldsymbol{x}} = \boldsymbol{v}/a,$$

$$\nabla^2 \Phi = 4\pi G(\rho_{\mathrm{total}} - \rho_{\mathrm{mean}}), \qquad \dot{\boldsymbol{v}} = -\frac{\nabla\Phi}{a^2} - \frac{\dot{a}}{a}\boldsymbol{v},$$

$$\frac{D\rho}{Dt} = -\rho\nabla\cdot\vec{v}\ ;\ \frac{D\vec{v}}{Dt} = -\frac{1}{\rho}\nabla P\ ;\ \frac{De}{Dt} = -\frac{1}{\rho}\nabla\cdot P\vec{v}$$

Vogelsberger et. al 2020

Methods - Setting the background



gas cooling: atomic/ molecular/ metals/ tabulated/ network

inter-stellar medium: effective equation of state/ multi-phase

star formation: initial stellar mass function/ probabilistic sampling/ enrichment

stellar feedback: kinetic/ thermal/ variety of sources from stars, supernovae

super-massive black holes: numerical seeding/ growth by accretion prescription/ merging

active galactic nuclei: kinetic/ thermal/ radiative/ quasar mode/ radio mode

magnetic fields: ideal MHD/ cleaning schemes/ constrained transport

radiation fields: ray tracing/ Monte Carlo/ moment-based

cosmic rays: production/ heating/ anisotropic diffusion/ streaming

most important astrophysical processes

numerical discretization of matter components

Collisionless Gravitational Dynamics

- *N*-body methods based on integral Poisson's equation (e.g. tree, fast multipole)
- *N*-body methods based on differential Poisson's equation (e.g. particle-mesh, multigrid)
- *N*-body hybrid methods (e.g. TreePM)
- Beyond *N*-body methods (e.g. Lagrangian tesselation)

dark matter

Hydrodynamics

- Lagrangian methods (e.g. smoothed particle hydrodynamics)
- Eulerian methods (e.g. adaptive-mesh-refinement)
- Arbitrary Lagrangian-Eulerian methods (e.g. moving mesh)
- Mesh-free / mesh-based

gas

Volume: sample of galaxies

generating initial conditions

← linear perturbation theory →

Zoom: individual galaxy

Gravity

- Newtonian gravity in an expanding background
- modified gravity as dark matter alternative
- modified gravity as dark energy alternative
- ...

Dark Matter

- cold dark matter
- warm dark matter
- self-interacting dark matter
- fuzzy dark matter
- ...

Dark Energy

- cosmological constant
- dynamical dark energy
- inhomogeneous dark energy
- coupled dark energy
- ...

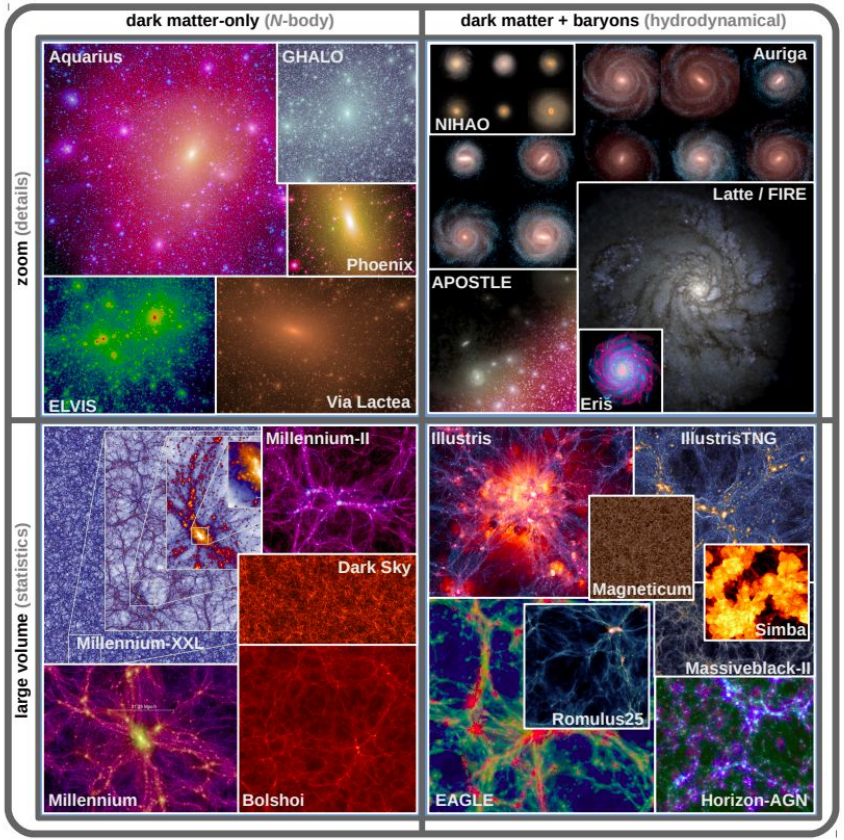
Initial Conditions

- inflation generated initial perturbations on top of homogeneous Friedmann model
- ...

cosmological framework

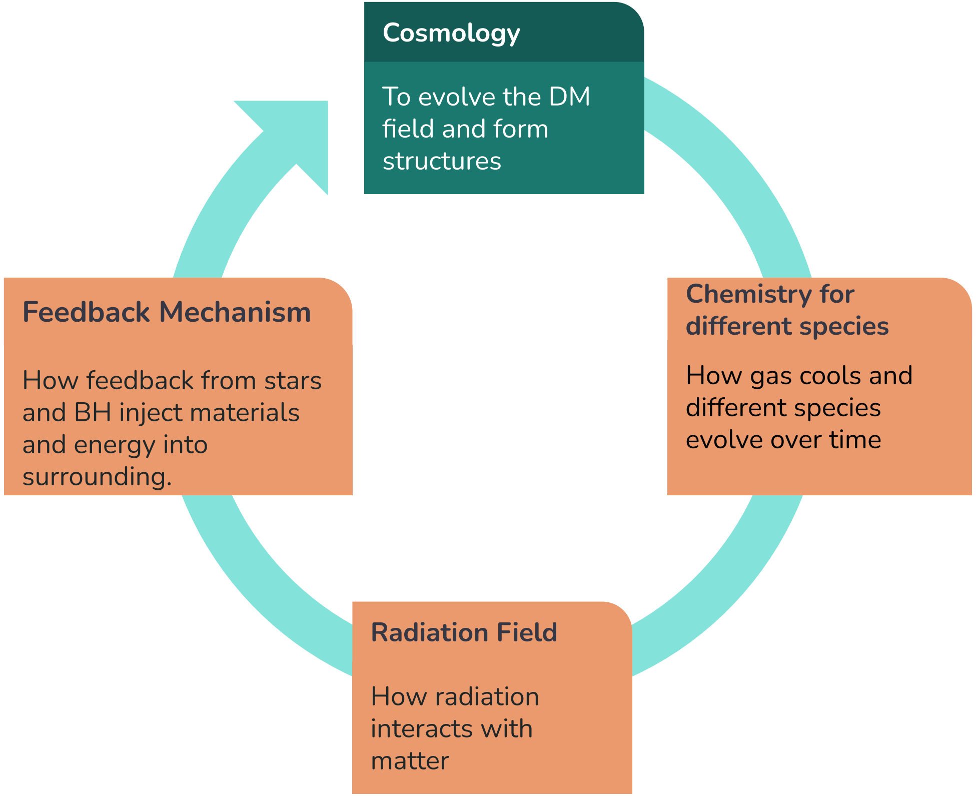
Vogelsberger et. al 2020

Methods - Setting the background



Vogelsberger et. al 2020

Methods: *What is needed for simulating a realistic galaxy?*



Cosmology

To evolve the DM field and form structures

Chemistry for different species

How gas cools and different species evolve over time

Radiation Field

How radiation interacts with matter

Feedback Mechanism

How feedback from stars and BH inject materials and energy into surrounding.

Broad Goals of this project:

- ✓ Track the formation of PopIII stars
- ✓ Develop Thermochemistry for low metallicity regime
- ✓ Develop Feedback Mechanisms for the PopIII stars.

Methods

Thermochemistry: AREPO - RT (Kannan et.al 2019)

We are interested in single scattering regime: a particular photon interacts with the surrounding medium only once. We discretize the frequency into different bins *i*

$$\frac{\partial N^i_\gamma}{\partial t} = -\tilde{c}\, N^i_\gamma \left(\sum_j n_j\, \bar{\sigma}_{ij} + \kappa_i\, \rho \right) + \sum_j s_{ij}$$

$$\frac{\partial \mathbf{F}^i_\gamma}{\partial t} = -\tilde{c}\, \mathbf{F}^i_\gamma \left(\sum_j n_j\, \bar{\sigma}_{ij} + \kappa_i\, \rho \right)$$

$$\{\tilde{c}N^i_\gamma, \boldsymbol{F}^i_\gamma, \mathbb{P}^i_\gamma\} = \int_{\nu_{i1}}^{\nu_{i2}} \frac{1}{h\nu} d\nu \int_{4\pi} \{1, \boldsymbol{n}, \boldsymbol{n} \otimes \boldsymbol{n}\}\, I_\nu d\Omega$$

$\bar{\sigma}_{ij}$ = Mean Ionization Cross Section

s_{ij} = Recombination Radiation

The species are coupled with this recombination radiation term!

Methods

Thermochemistry (Kannan et.al 2019, Kannan et. al 2020, Gnedin et. al 2011)

For early stars, the species that we are interested in tracking are

$$[\mathrm{HI}, \mathrm{HII}, \mathrm{H}_2, \mathrm{H}_2^+, \mathrm{H}^-, \mathrm{HeI}, \mathrm{HeII}, \mathrm{HeIII}]$$

$$\mathrm{H} + \mathrm{H}^+ \rightarrow \mathrm{H}_2^+ + \gamma$$

$$\mathrm{H} + \mathrm{H}_2^+ \rightarrow \mathrm{H}_2 + \mathrm{H}^+$$

$$\mathrm{H} + \mathrm{e} \rightarrow \mathrm{H}^- + \gamma$$

$$\mathrm{H} + \mathrm{H}^- \rightarrow \mathrm{H}_2 + \mathrm{e}^-$$

- ➢ Current cosmological simulations don’t consider primordial universe H2 thermochemistry which becomes extremely relevant for PopIII stars.

Methods

Thermochemistry (Kannan et.al 2019, Kannan et. al 2020, Gnedin et. al 2011)

For early stars, the species that we are interested in tracking are

$$[\mathrm{HI}, \mathrm{HII}, \mathrm{H_2}, \mathrm{H_2^+}, \mathrm{H^-}, \mathrm{HeI}, \mathrm{HeII}, \mathrm{HeIII}]$$

- ➢ Current cosmological simulations don't consider primordial universe H2 thermochemistry which becomes extremely relevant for PopIII stars.
- ✓ We are develop a more accurate thermochemistry module by adding additional gas phase reaction to the existing Thermochemistry module.
  - The evolution of ionic species can be written as:

$$\frac{\partial x}{\partial t} = C - Dx$$

Methods

Thermochemistry (Kannan et.al 2019, Kannan et. al 2020, Gnedin et. al 2011)

The evolution of ionic species can be written as: $\frac{\partial x}{\partial t} = C - Dx$

$$\begin{aligned}
\dot{\mathcal{M}}_{\mathrm{H}_2^+} = & -\Gamma_{\mathrm{B}} n_{\mathrm{H}_2^+} - \Gamma_{\mathrm{C}} n_{\mathrm{H}_2^+} + \Gamma_{\mathrm{D}} n_{\mathrm{H}_2} - k_4 n_{\mathrm{H_I}} n_{\mathrm{H}_2^+} - k_6 n_e n_{\mathrm{H}_2^+} - k_{21} n_{\mathrm{H}^-} n_{\mathrm{H}_2^+} - k_{22} n_{\mathrm{H}^-} n_{\mathrm{H}_2^+} \\
& + k_3 n_{\mathrm{HI}} n_{\mathrm{HII}} + k_7 n_{\mathrm{H}_2} n_{\mathrm{HII}} + k_{16} n_{\mathrm{HII}} n_{\mathrm{H}^-} + k_{25} n_{\mathrm{H}_2} n_{\mathrm{HeII}} \ , \\
\dot{\mathcal{M}}_{\mathrm{H}^-} = & -\Gamma_{\mathrm{A}} n_{\mathrm{H}^-} - k_2 n_{\mathrm{HI}} n_{\mathrm{H}^-} - k_5 n_{\mathrm{H}} n_{\mathrm{H}^-} - k_{14} n_e n_{\mathrm{H}^-} - k_{15} n_{\mathrm{H_I}} n_{\mathrm{H}^-} - k_{16} n_{\mathrm{H_{II}}} n_{\mathrm{H}^-} \\
& - k_{21} n_{\mathrm{H}_2^+} n_{\mathrm{H}^-} - k_{22} n_{\mathrm{H}_2^+} n_{\mathrm{H}^-} - k_{28} n_{\mathrm{He}} n_{\mathrm{H}^-} - k_{29} n_{\mathrm{He}} n_{\mathrm{H}^-} + k_1 n_e n_{\mathrm{HI_I}} + k_{23} n_e n_{\mathrm{H}_2} \ ,
\end{aligned}$$

Methods

Thermochemistry (Kannan et.al 2019, Kannan et. al 2020, Gnedin et. al 2011)

The evolution of ionic species can be written as: $\frac{\partial x}{\partial t} = C - Dx$

$$\begin{aligned}
\dot{\mathscr{M}}_{\mathrm{HI}} =& \Gamma_{\mathrm{A}} n_{\mathrm{H}^-} + \Gamma_{\mathrm{B}} n_{\mathrm{H}_2^+} + 2\Gamma_{\mathrm{E}} n_{\mathrm{H}_2} + 2\Gamma_{\mathrm{LW}} n_{\mathrm{H}_2} - k_1 n_e n_{\mathrm{H}_\mathrm{I}} - k_2 n_{\mathrm{H}^-} n_{\mathrm{HI}} - k_3 n_{\mathrm{HII}} n_{\mathrm{HI}} \\
& - k_4 n_{\mathrm{H}_2^+} n_{\mathrm{H}_\mathrm{I}} - k_{26} n_{\mathrm{He}} n_{\mathrm{HI}} - 2k_{30} n_{\mathrm{HI}}^3 - 2k_{31} n_{\mathrm{HI}}^2 n_{\mathrm{H}_2} - 2k_{32} n_{\mathrm{HI}}^2 n_{\mathrm{HeI}} + 2k_5 n_{\mathrm{HII}} n_{\mathrm{H}^-} \\
& + 2k_6 n_e n_{\mathrm{H}_2^+} + k_7 n_{\mathrm{H}_2} n_{\mathrm{HII}} + 2k_8 n_e n_{\mathrm{H}_2} + 2k_9 n_{\mathrm{HI}} n_{\mathrm{H}_2} + 2k_{10} n_{\mathrm{H}_2} n_{\mathrm{H}_2} + 2k_{11} n_{\mathrm{HeI}} n_{\mathrm{H}_2} \\
& + k_{14} n_e n_{\mathrm{H}^-} + k_{15} n_{\mathrm{HI}} n_{\mathrm{H}^-} + k_{21} n_{\mathrm{H}_2^+} n_{\mathrm{H}^-} + 3k_{22} n_{\mathrm{H}^-} n_{\mathrm{H}_2^+} + k_{23} n_e n_{\mathrm{H}_2} + k_{24} n_{\mathrm{HeII}} n_{\mathrm{H}_2} \\
& + k_{27} n_{\mathrm{He}} n_{\mathrm{HII}} + k_{28} n_{\mathrm{HeII}} n_{\mathrm{H}^-} + k_{29} n_{\mathrm{HeI}} n_{\mathrm{H}^-} + \alpha_{\mathrm{HII}} n_{\mathrm{HII}} n_e - \sigma_{e\mathrm{HI}} n_{\mathrm{HI}} n_e - \Gamma_{\mathrm{HI}} n_{\mathrm{HI}} \ , \\
\dot{\mathscr{M}}_{\mathrm{HII}} =& \Gamma_{\mathrm{B}} n_{\mathrm{H}_2^+} + 2\Gamma_{\mathrm{C}} n_{\mathrm{H}_2^+} - k_3 n_{\mathrm{HI}} n_{\mathrm{HII}} - k_5 n_{\mathrm{H}^-} n_{\mathrm{HII}} - k_7 n_{\mathrm{H}_2} n_{\mathrm{HII}} - k_{16} n_{\mathrm{H}^-} n_{\mathrm{HII}} - k_{27} n_{\mathrm{HeI}} n_{\mathrm{HII}} \\
& + k_4 n_{\mathrm{H}_2^+} n_{\mathrm{HI}} + k_{24} n_{\mathrm{He}} n_{\mathrm{H}_2} + k_{26} n_{\mathrm{H}_\mathrm{I}} n_{\mathrm{HeII}} - \alpha_{\mathrm{HII}} n_{\mathrm{HII}} n_e + \sigma_{e\mathrm{HI}} n_{\mathrm{HI}} n_e + \Gamma_{\mathrm{HI}} n_{\mathrm{HI}} \ , \\
\dot{\mathscr{M}}_{\mathrm{H}_2} =& - \Gamma_{\mathrm{D}} n_{\mathrm{H}_2} - \Gamma_{\mathrm{E}} n_{\mathrm{H}_2} - \Gamma_{\mathrm{LW}} n_{\mathrm{H}_2} - k_7 n_{\mathrm{H}_2} n_{\mathrm{HII}} - k_8 n_e n_{\mathrm{H}_2} - k_9 n_{\mathrm{H}_1} n_{\mathrm{H}_2} - k_{10} n_{\mathrm{H}_2} n_{\mathrm{H}_2} \\
& - k_{11} n_{\mathrm{He}_\mathrm{I}} n_{\mathrm{H}_2} - k_{23} n_e n_{\mathrm{H}_2} - k_{24} n_{\mathrm{He}_\mathrm{II}} n_{\mathrm{H}_2} - k_{25} n_{\mathrm{He}_\mathrm{II}} n_{\mathrm{H}_2} + k_2 n_{\mathrm{H}^-} n_{\mathrm{HI}_\mathrm{I}} \\
& + k_4 n_{\mathrm{H}_2^+} n_{\mathrm{H}_\mathrm{I}} + k_{21} n_{\mathrm{H}_2^+} n_{\mathrm{H}^-} + k_{30} n_{\mathrm{HI}}^3 + k_{31} n_{\mathrm{HI}}^2 n_{\mathrm{H}_2} + k_{32} n_{\mathrm{HI}}^2 n_{\mathrm{He}} + \alpha_{\mathrm{H}_2}^{\mathrm{D}} \left(\frac{D}{D_{\mathrm{MW}}} \right) n_{\mathrm{H}} n_{\mathrm{HI}}
\end{aligned}$$

Methods : Thermochemistry (Kannan et.al 2019, Kannan et. al 2020, Gnedin et. al 2011)

Simplification:

- ➢ Abundances of H_2^+ and H^- are always extremely small in cosmological settings, so that they can always be assumed to be in the kinetic equilibrium
- ➢ Neglecting terms involving k_{21}, k_{22} as it is $\propto n_{H-}\, n_{H2+}$
- ➢ Ignore inter-species terms i.e reactions between H and He
- ➢ Use closure relations

$$x_{\rm HI} = 1 - x_{\rm HII} - 2x_{\rm H_2} \ ,$$

$$x_{\rm HeI} = 1 - x_{\rm HeII} - x_{\rm HeIII} \ ,$$

Methods : Thermochemistry (Kannan et.al 2019, Kannan et. al 2020, Gnedin et. al 2011)

Internal Energy:

$$\Lambda_{\rm tot} = \Lambda_p\left(n_j, N_\gamma^i, T\right) + \frac{Z}{Z_\odot}\Lambda_M(T,\rho,z) + \Lambda_{\rm PE}\left(D, T, N_\gamma^{\rm FUV}\right) + \Lambda_D\left(\rho, T, D, N_\gamma^{\rm IR}\right)$$

$$\begin{aligned}
\dot{\mathscr{M}}_{\rm Internal\ energy} =& \,\mathfrak{h}_{\rm HI} n_{\rm HI} + \mathfrak{h}_{\rm HeI} n_{\rm HeI} + \mathfrak{h}_{\rm HeII} n_{\rm HeII} + \mathfrak{h}_{\rm H_2} n_{\rm H_2} - \mathscr{C}_M + \mathscr{C}_{\rm PE} \\
& - \mathscr{C}_D - \Lambda(n \rightarrow 0)_{\rm H_2HI} n_{\rm H_2} n_{\rm HI} - \Lambda(n \rightarrow 0)_{\rm H_2H_2} n_{\rm H_2}^2 \\
& - \Lambda_{\rm H_2^+e} n_{\rm H_2^+} n_e - \Lambda_{\rm H_2^+HI} n_{\rm H_2^+} n_{\rm HI} - \Lambda_{\rm Inverse\ Compton\ Cooling} n_e
\end{aligned}$$

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Internal Energy:

$$\Lambda_{\mathrm{tot}} = \Lambda_p\left(n_j, N_\gamma^i, T\right) + \frac{Z}{Z_\odot}\Lambda_M(T, \rho, z) + \Lambda_{\mathrm{PE}}\left(D, T, N_\gamma^{\mathrm{FUV}}\right) + \Lambda_D\left(\rho, T, D, N_\gamma^{\mathrm{IR}}\right)$$

$$\begin{aligned} \dot{\mathscr{M}}_{\text{Internal energy}} =& \mathfrak{h}_{\mathrm{HI}} n_{\mathrm{HI}} + \mathfrak{h}_{\mathrm{HeI}} n_{\mathrm{HeI}} + \mathfrak{h}_{\mathrm{HeII}} n_{\mathrm{HeII}} + \mathfrak{h}_{\mathrm{H_2}} n_{\mathrm{H_2}} - \mathscr{C}_M + \mathscr{C}_{\mathrm{PE}} \\ & - \mathscr{C}_D - \Lambda(n \to 0)_{\mathrm{H_2 HI}} n_{\mathrm{H_2}} n_{\mathrm{HI}} - \Lambda(n \to 0)_{\mathrm{H_2 H_2}} n_{\mathrm{H_2}}^2 \\ & - \boxed{\Lambda_{\mathrm{H_2^+ e}} n_{\mathrm{H_2^+}} n_e - \Lambda_{\mathrm{H_2^+ HI}} n_{\mathrm{H_2^+}} n_{\mathrm{HI}}} - \Lambda_{\text{Inverse Compton Cooling}} n_e \end{aligned}$$

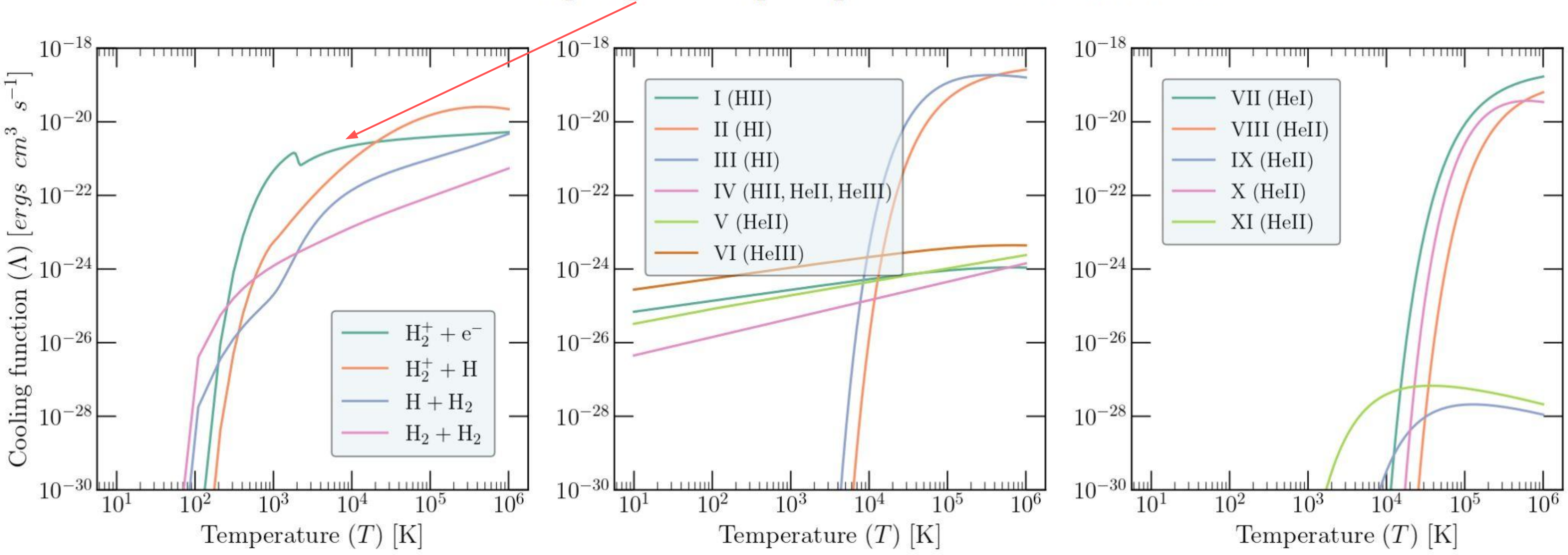
Additional cooling at low temperatures that becomes very important for the primordial metal free gas

See: Glover & Abel (2008)

Methods : Thermochemistry (Kannan et.al 2019, Kannan et. al 2020, Gnedin et. al 2011)

Internal Energy:

$$\begin{aligned}\dot{\mathscr{M}}_{\text{Internal energy}} =\,& \mathfrak{h}_{\mathrm{HI}} n_{\mathrm{HI}} + \mathfrak{h}_{\mathrm{HeI}} n_{\mathrm{HeI}} + \mathfrak{h}_{\mathrm{HeII}} n_{\mathrm{HeII}} + \mathfrak{h}_{\mathrm{H_2}} n_{\mathrm{H_2}} - \mathscr{C}_M + \mathscr{C}_{\mathrm{PE}} \\ & - \mathscr{C}_D - \Lambda(n \rightarrow 0)_{\mathrm{H_2HI}} n_{\mathrm{H_2}} n_{\mathrm{HI}} - \Lambda(n \rightarrow 0)_{\mathrm{H_2H_2}} n_{\mathrm{H_2}}^2 \\ & - \Lambda_{\mathrm{H_2^+e}} n_{\mathrm{H_2^+}} n_e - \Lambda_{\mathrm{H_2^+HI}} n_{\mathrm{H_2^+}} n_{\mathrm{HI}} - \Lambda_{\text{Inverse Compton Cooling}} n_e\end{aligned}$$



Methods : Thermochemistry (Kannan et.al 2019, Kannan et. al 2020, Gnedin et. al 2011)

Overview of Thermochemistry network:

Solve the thermochemistry network using closure relations and update the species fractions, internal energy and photon density and flux: we use a *semi - implicit* scheme when change in Temperature or ionic species density is less than 10% otherwise we numerically solve the differential equation using **SUNDIALS CVODE** solver.

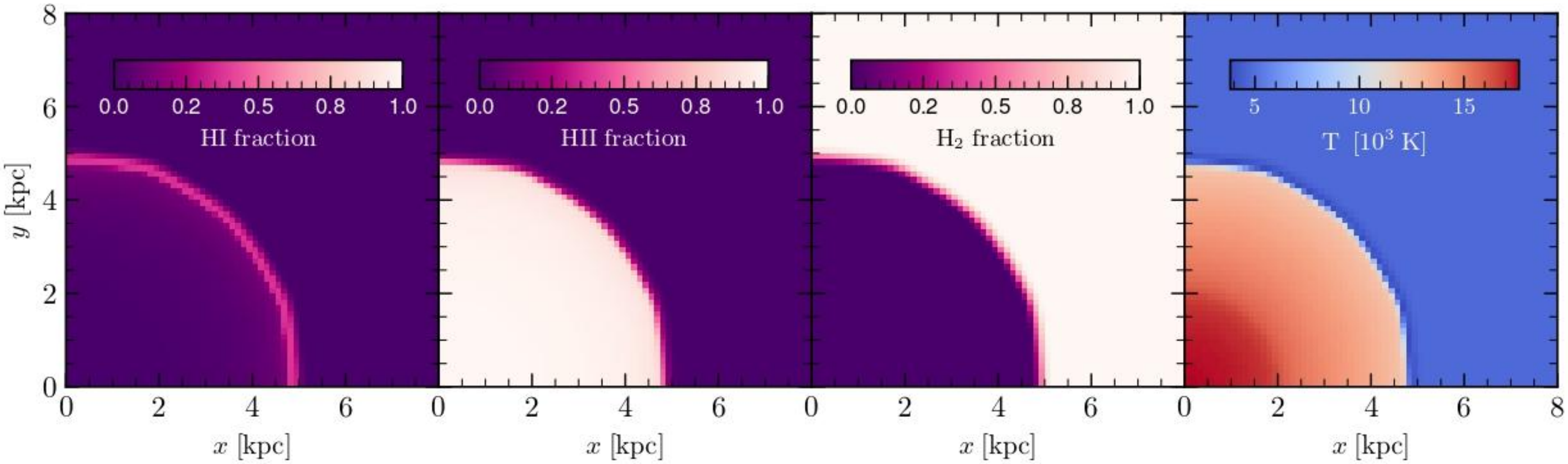
In addition to changing ionization state of different species, photons can also heat the surrounding through photo-heating - we account for photo-heating.

Additionally there will be momentum injection due to photon absorption and here also we see coupling of the radiation and matter fields through source terms in hydrodynamic equations.

Methods : Thermochemistry (Kannan et.al 2019, Kannan et. al 2020, Gnedin et. al 2011)

Testing the thermochemistry network:

O star ($T = 4.3 \times 10^3$ K) at the centre of a box in a pure molecular medium.



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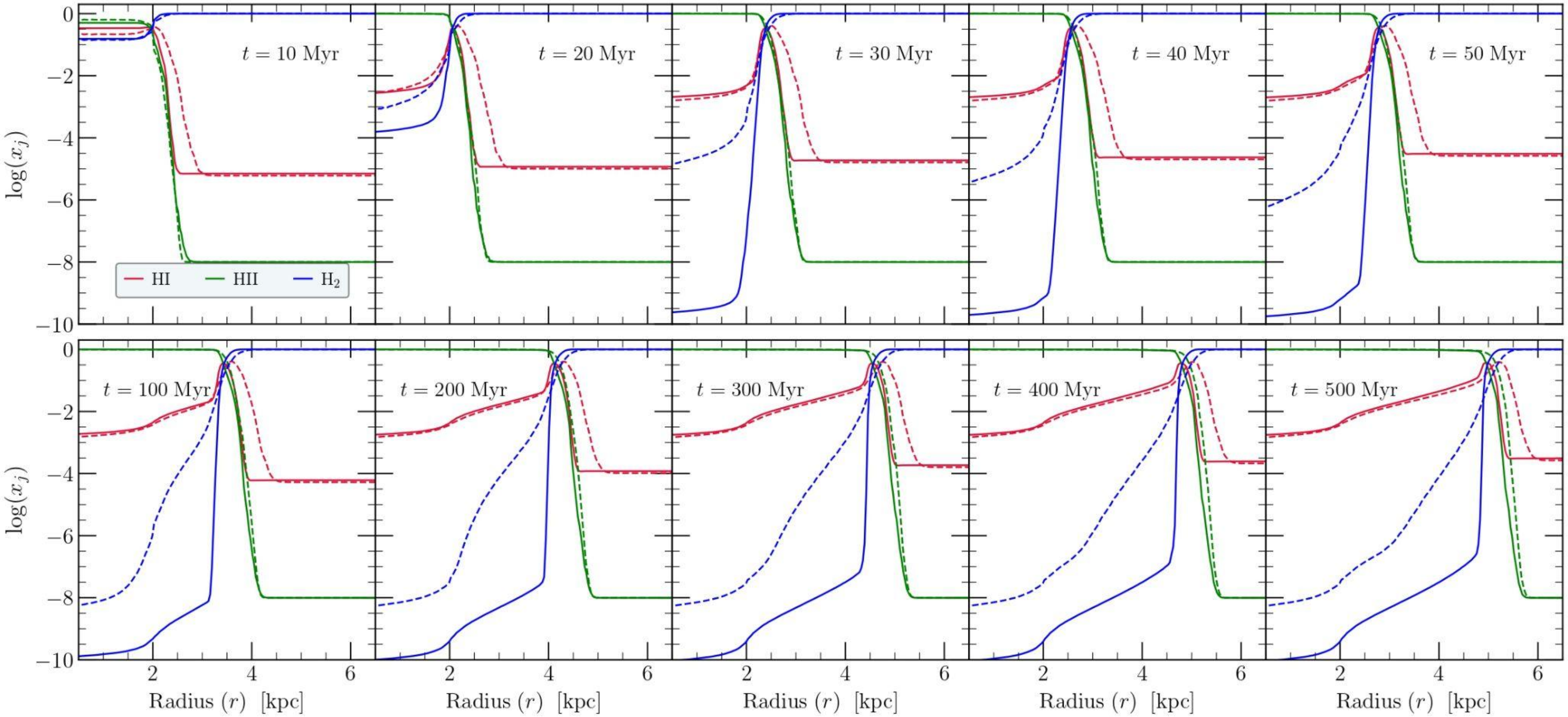

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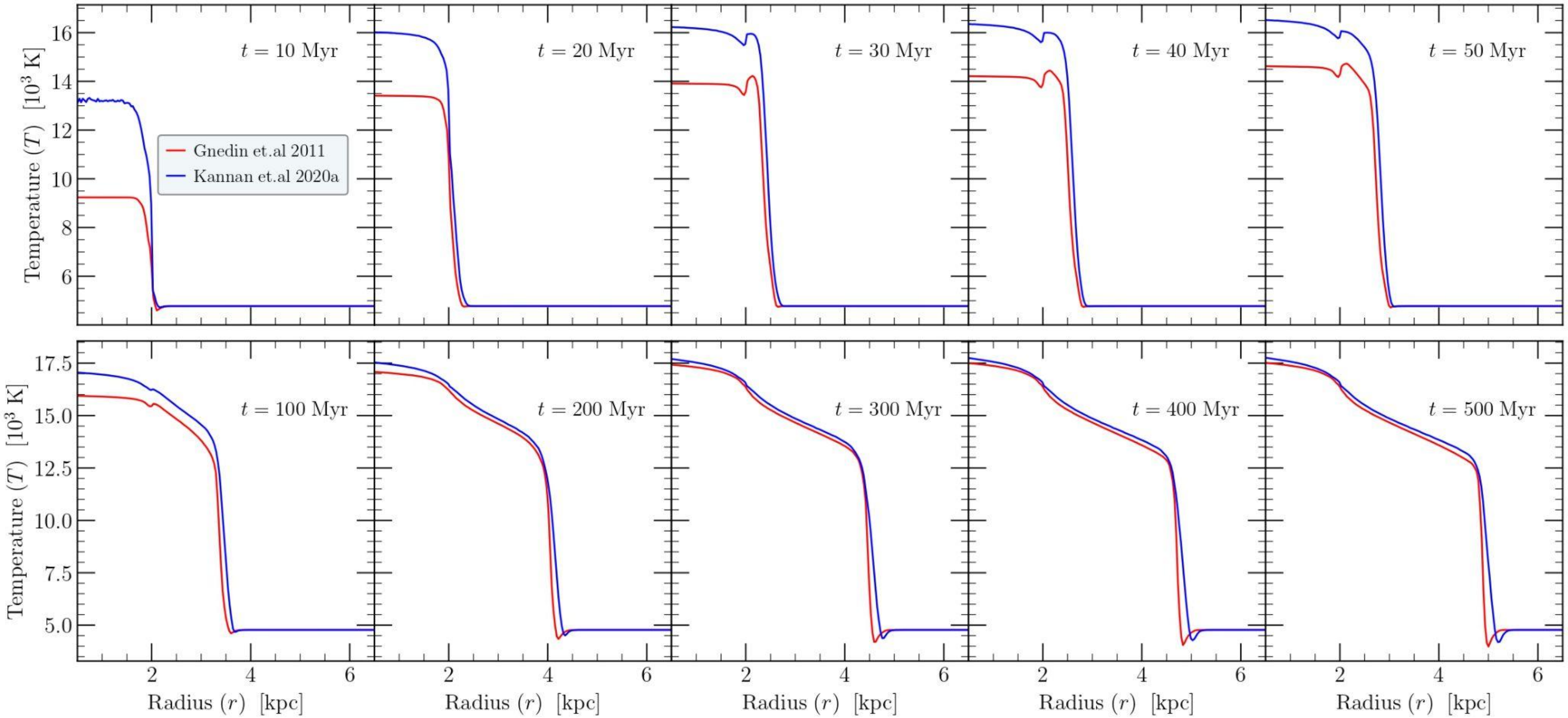
Testing the thermochemistry network:



Methods

Radiation field of PopIII stars : (Mirouh et. al 2023, Jones et. al 2022)

PopIII stars are purely made up of Hydrogen and Helium, and have short lifetimes compared to metal rich counterparts.

The radiation field of a star depends on two important factors: T_{eff} and $log(g)$.

Traditionally there are two approaches to get the radiation field

- Model the spectrum as black body
- Explicitly solve the radiative transfer of the stellar atmosphere

Methods

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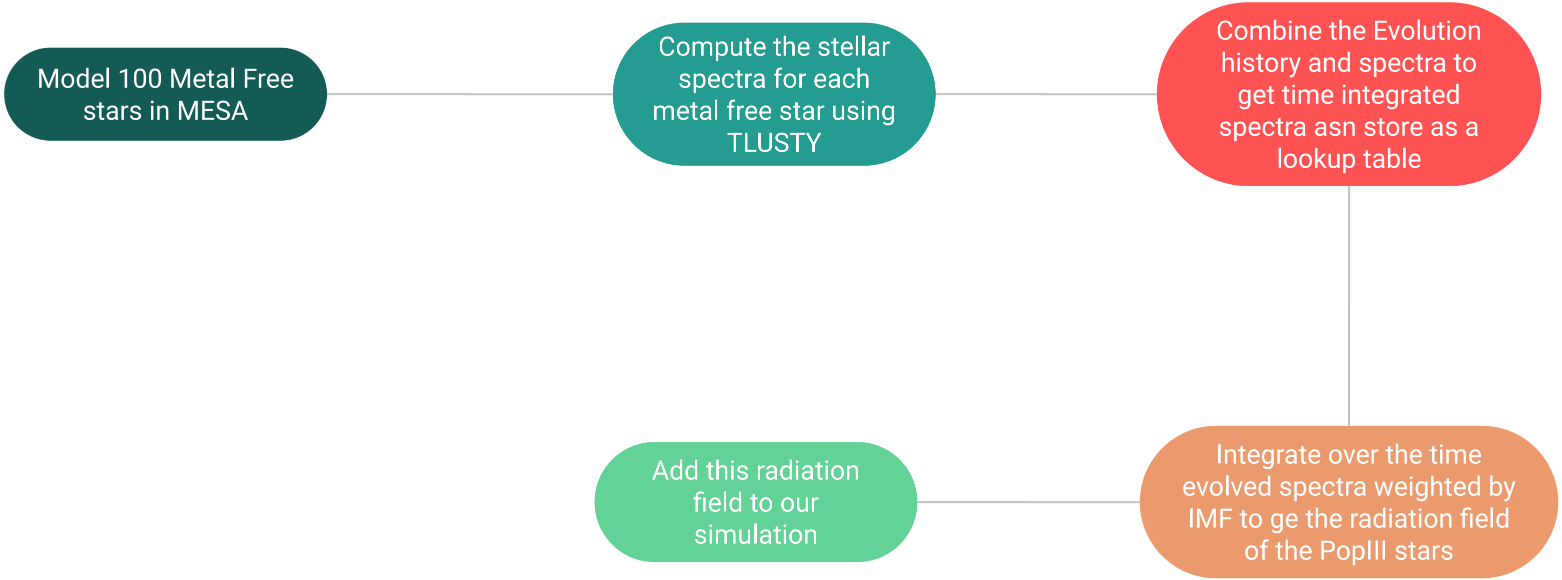
- Model the spectrum as black body
- ✓ Explicitly solve the radiative transfer of the stellar atmosphere

We use the **Tlusty** (Hubney and Lanz) and **MESA** (Paxton et. al 2011)

Methods: Radiation field of PopIII stars : (Mirouh et. al 2023, Jones et. al 2022)

Overview



Model 100 Metal Free stars in MESA

Compute the stellar spectra for each metal free star using TLUSTY

Combine the Evolution history and spectra to get time integrated spectra asn store as a lookup table

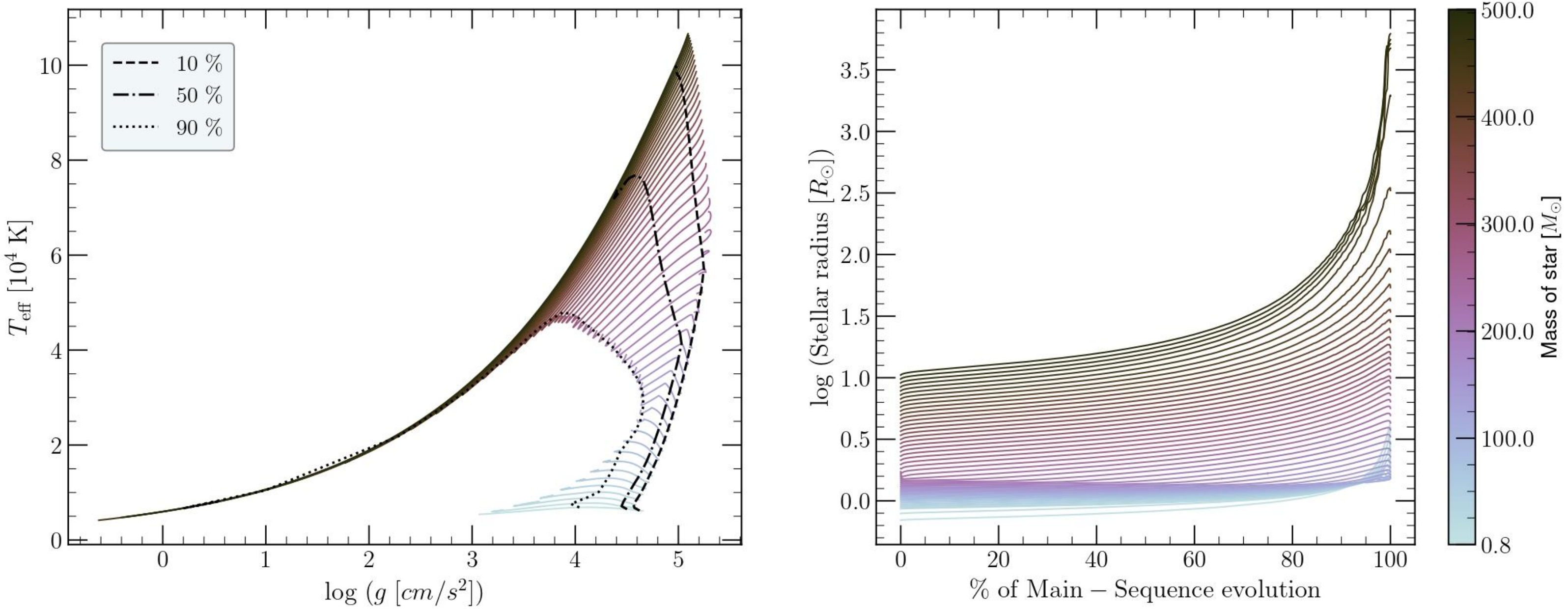
Integrate over the time evolved spectra weighted by IMF to ge the radiation field of the PopIII stars

Add this radiation field to our simulation

Methods: Radiation field of PopIII stars : (Mirouh et. al 2023, Jones et. al 2022)

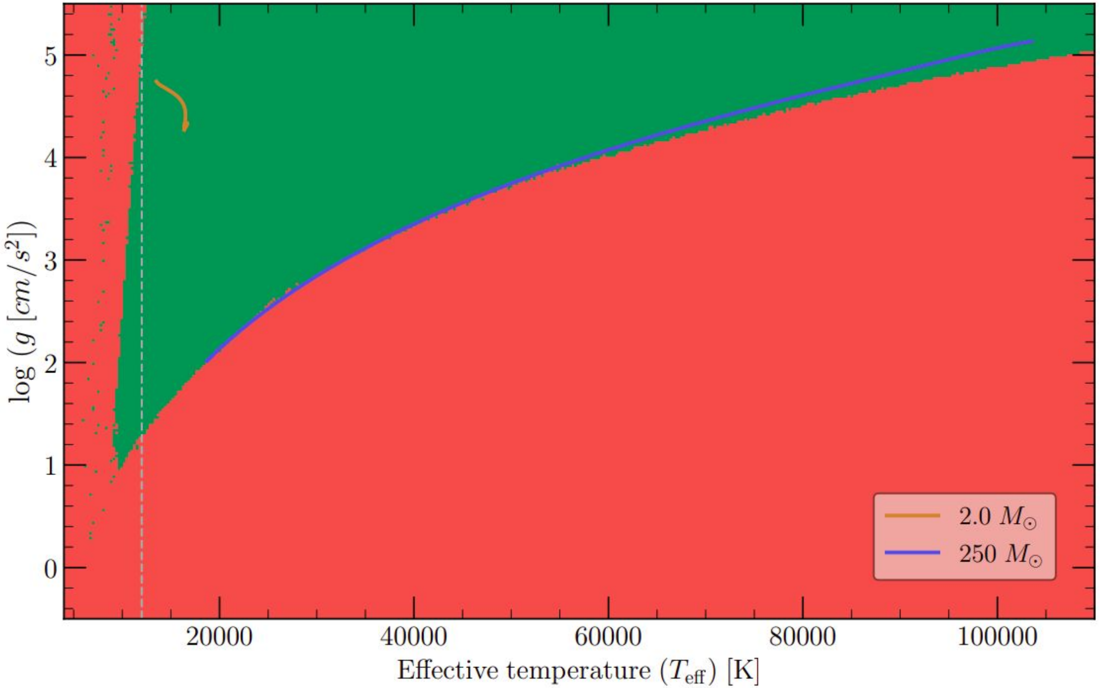
Model 100 Metal Free stars in MESA

Stars are irrotational and non-convective stars & initialized with BBN proportions of H, He



Methods: Radiation field of PopIII stars : (Mirouh et. al 2023, Jones et. al 2022)

Compute stellar spectrum on a grid for the metal free stars



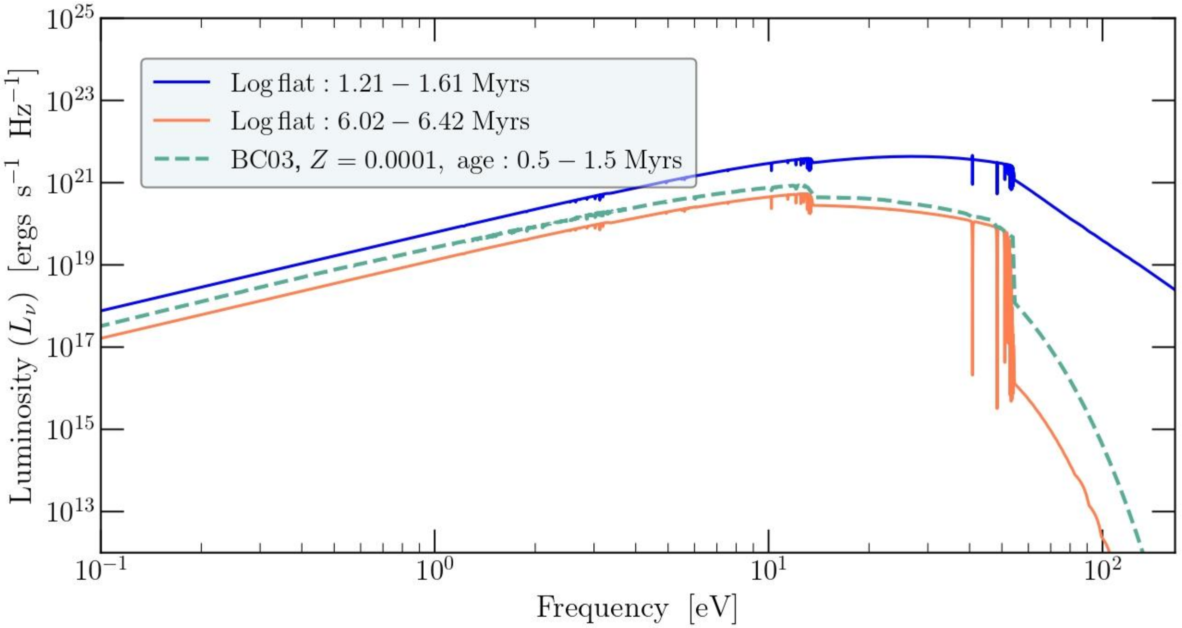
Methods: Radiation field of PopIII stars : (Mirouh et. al 2023, Jones et. al 2022)

Combine evolutionary history to obtain IMF averaged spectra

$$\overline{L}_\nu(t_i, M) = \frac{\int_{t_i-\Delta t}^{t_i+\Delta t} L_\nu(t, M, T_{\rm eff}, \log(g))\mathrm{d}t}{2\Delta t}$$

$$\downarrow$$

$$L_{\nu,\rm IMF}(\nu, t_i) = \frac{\int_{M_{\min}}^{M_{\max}} \overline{L}_\nu(t_i, M)\Phi(M)\mathrm{d}M}{\int_{M_{\min}}^{M_{\max}} M\Phi(M)\mathrm{d}M}$$



Standard spectra: Bruzual G., Charlot S., 2003,

Methods: Radiation field of PopIII stars : (Mirouh et. al 2023, Jones et. al 2022)

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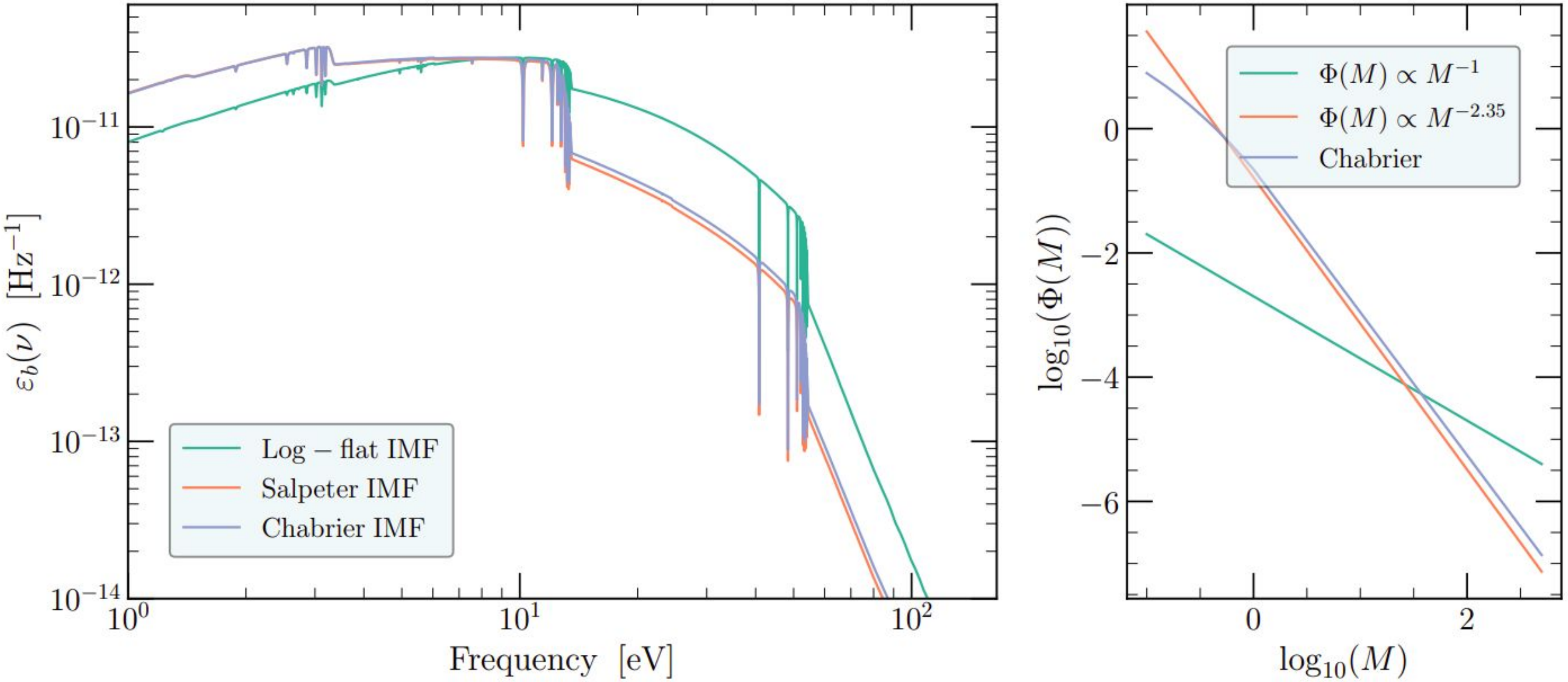

Methods

Feedback from PopIII stars : (Heger & Woosley 2002, Heger & Woosley 2010)

PopIII stars can die as supernova or black holes, and they inject large amount of energy into the interstellar medium

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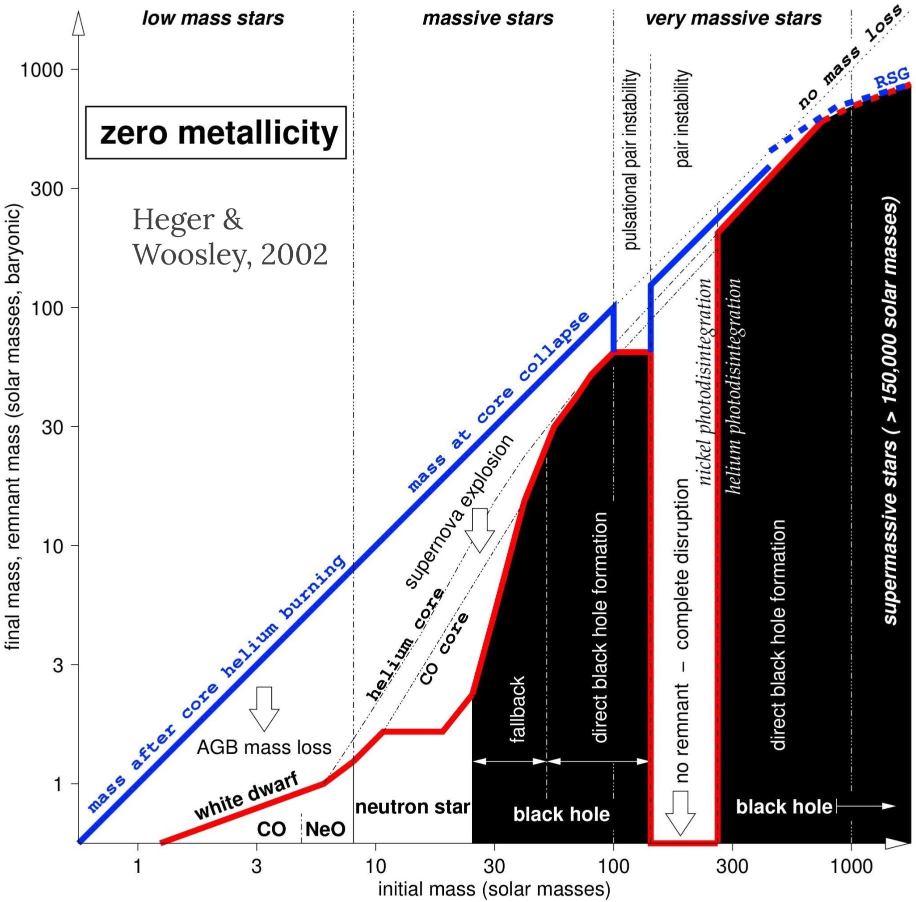

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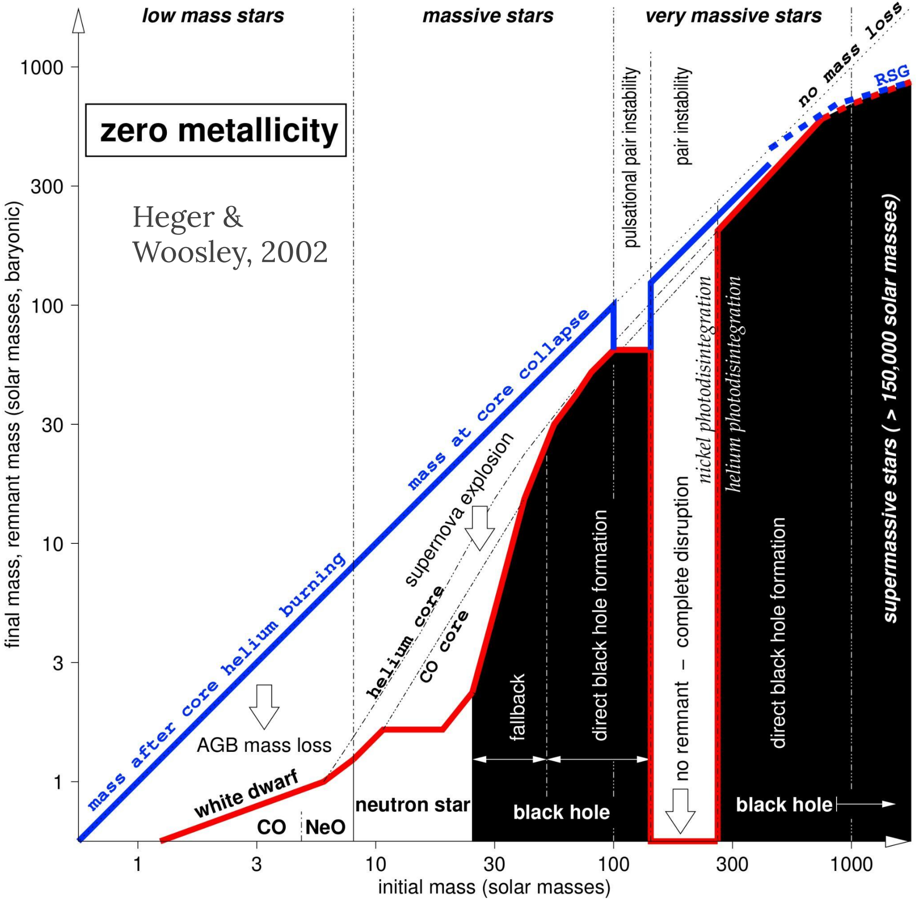
$$\Delta M_i(t,\Delta t) = \int_{\mathscr{M}(t+\Delta t)}^{\mathscr{M}(t)} \chi_{i,\mathrm{enrich}}(M)\Phi(M)\mathrm{d}M$$

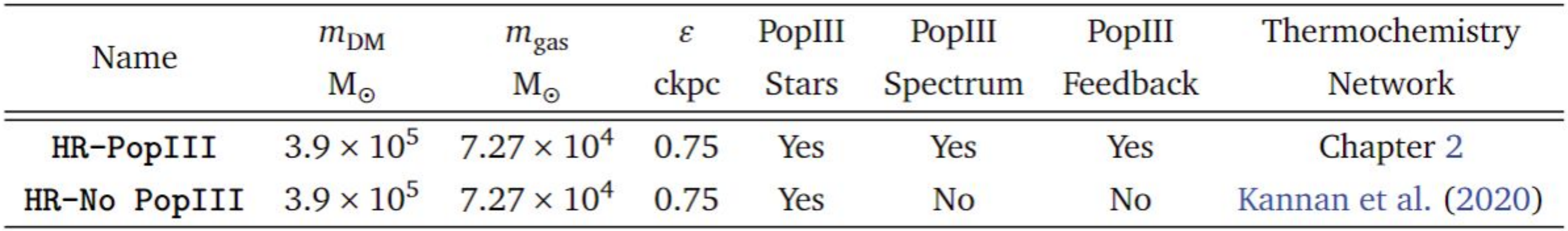


Cosmological simulation of galaxy

Cosmological simulation of galaxy

Now, we run cosmological zoom-in simulations of galaxies with(out) the PopIII physics

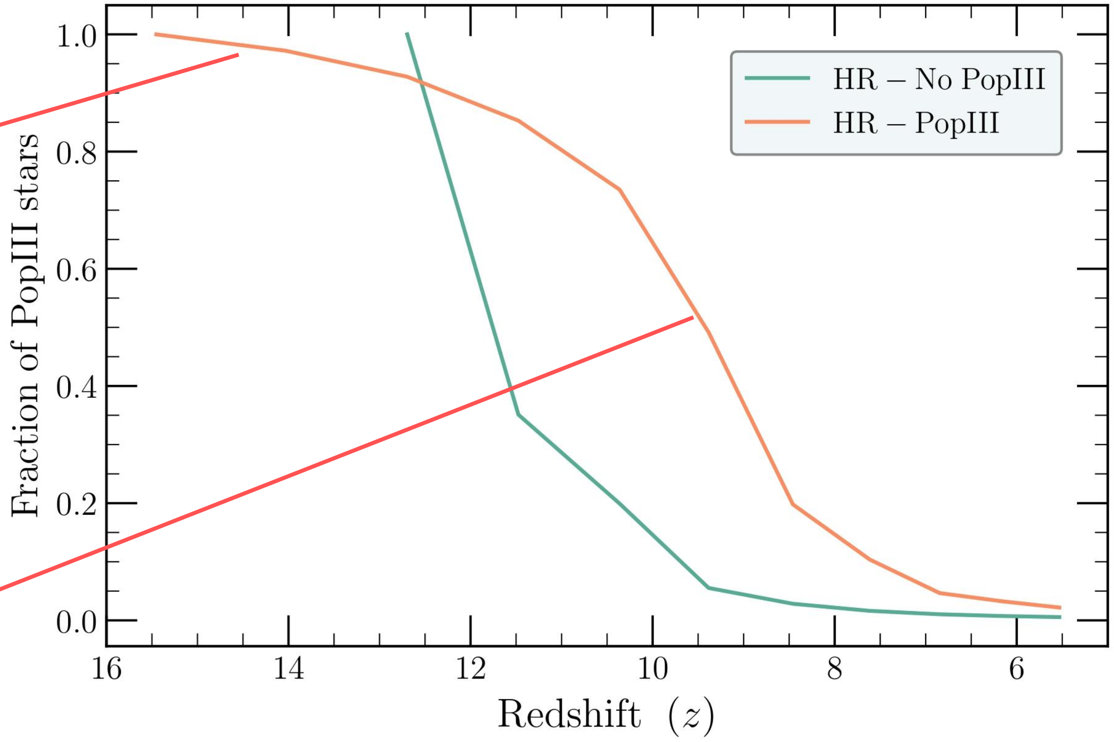
- AREPO-RT Kannan et. al, 2019, Springel et. al, 2010 for Gravity and RHD.
- IC from Thesan box (Kannan et. al, in Prep)
- Cosmology from Planck 2018
- Galaxy formation - Marinacci et. al, 2019, Kannan et. al, 2020



Name	m_{DM} $\mathrm{M}_\odot$	m_{gas} $\mathrm{M}_\odot$	ε ckpc	PopIII Stars	PopIII Spectrum	PopIII Feedback	Thermochemistry Network
`HR-PopIII`	3.9×10^5	7.27×10^4	0.75	Yes	Yes	Yes	Chapter 2
`HR-No PopIII`	3.9×10^5	7.27×10^4	0.75	Yes	No	No	Kannan et al. (2020)

Cosmological simulation of galaxy

Properties of the central halo:

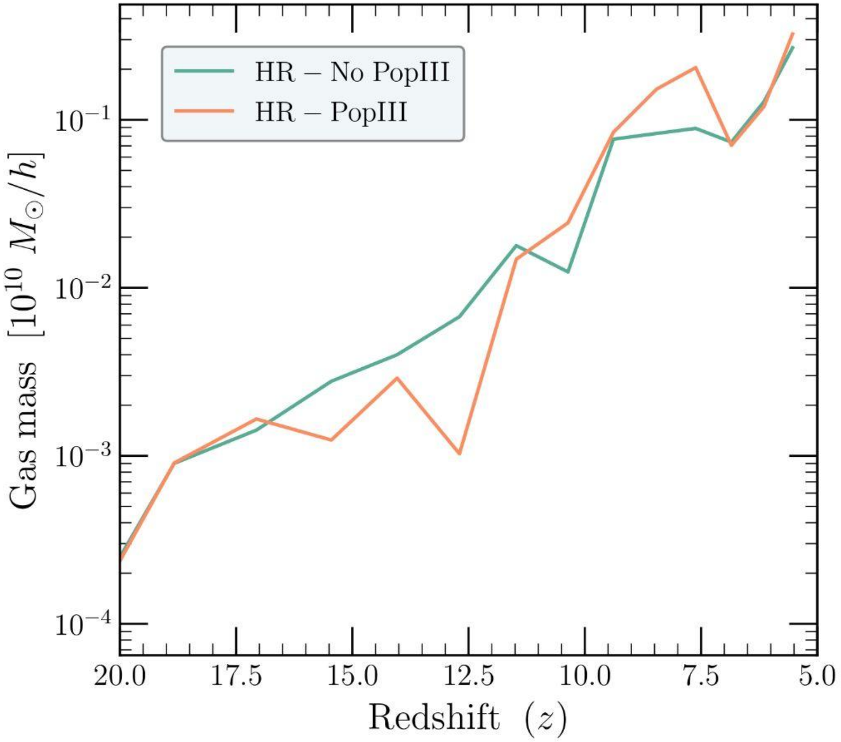


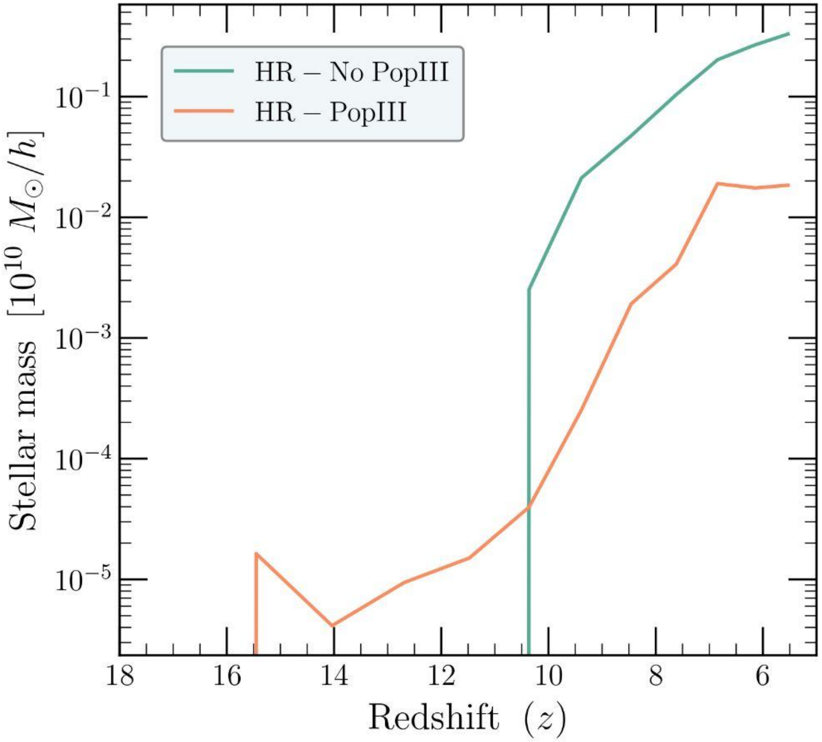
Early star formation
additional cooling from H_2^+

Slower cooling at late times
due to PopIII SNe

Cosmological simulation of galaxy

Properties of the central halo:





Cosmological simulation of galaxy

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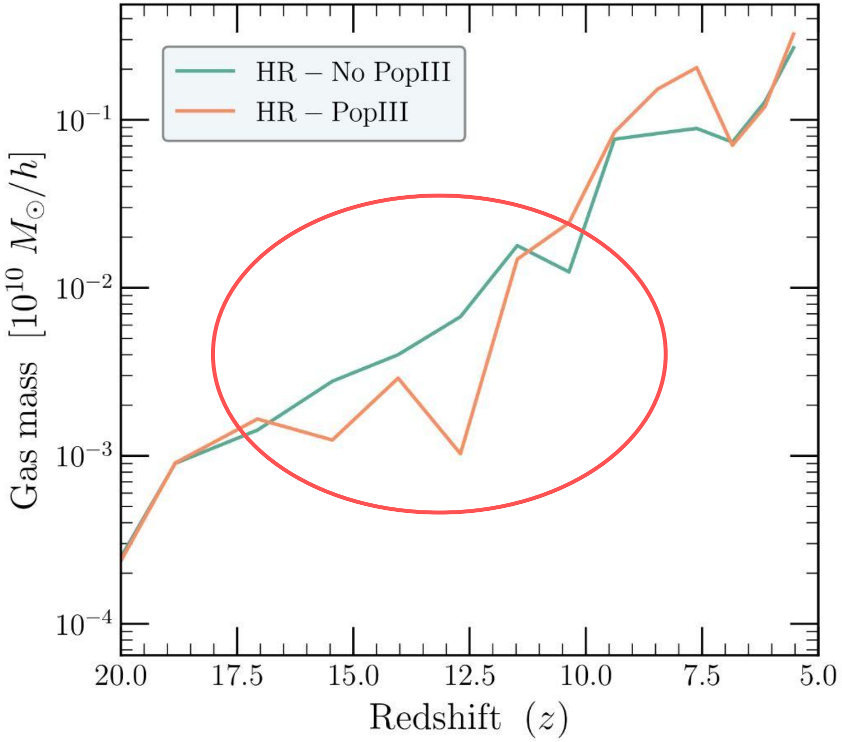
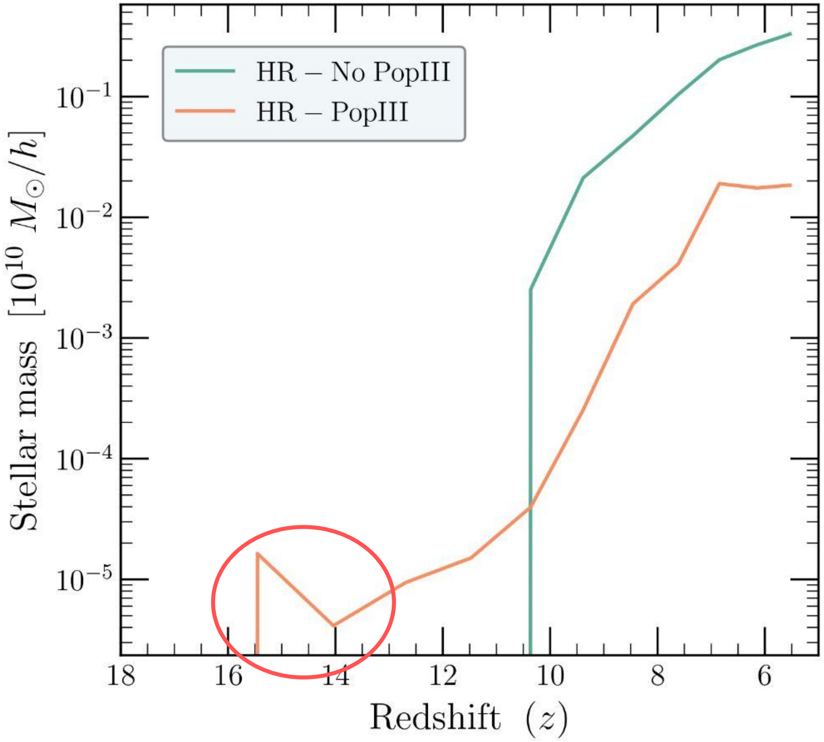
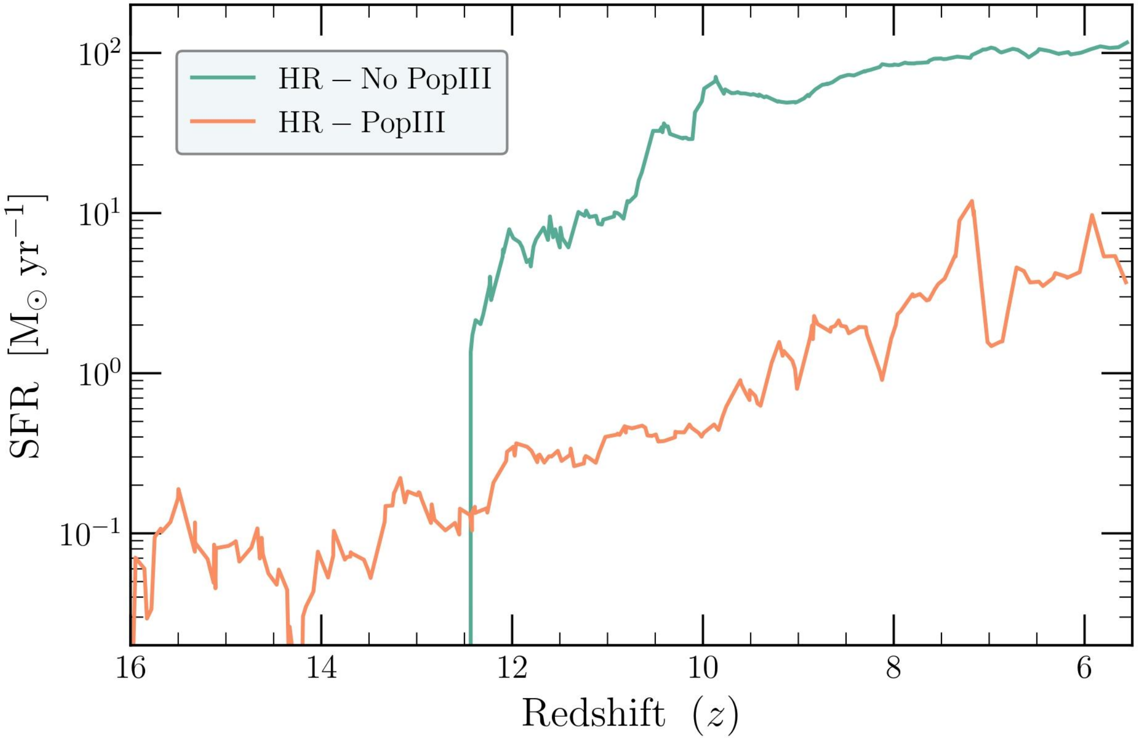




Cosmological simulation of galaxy

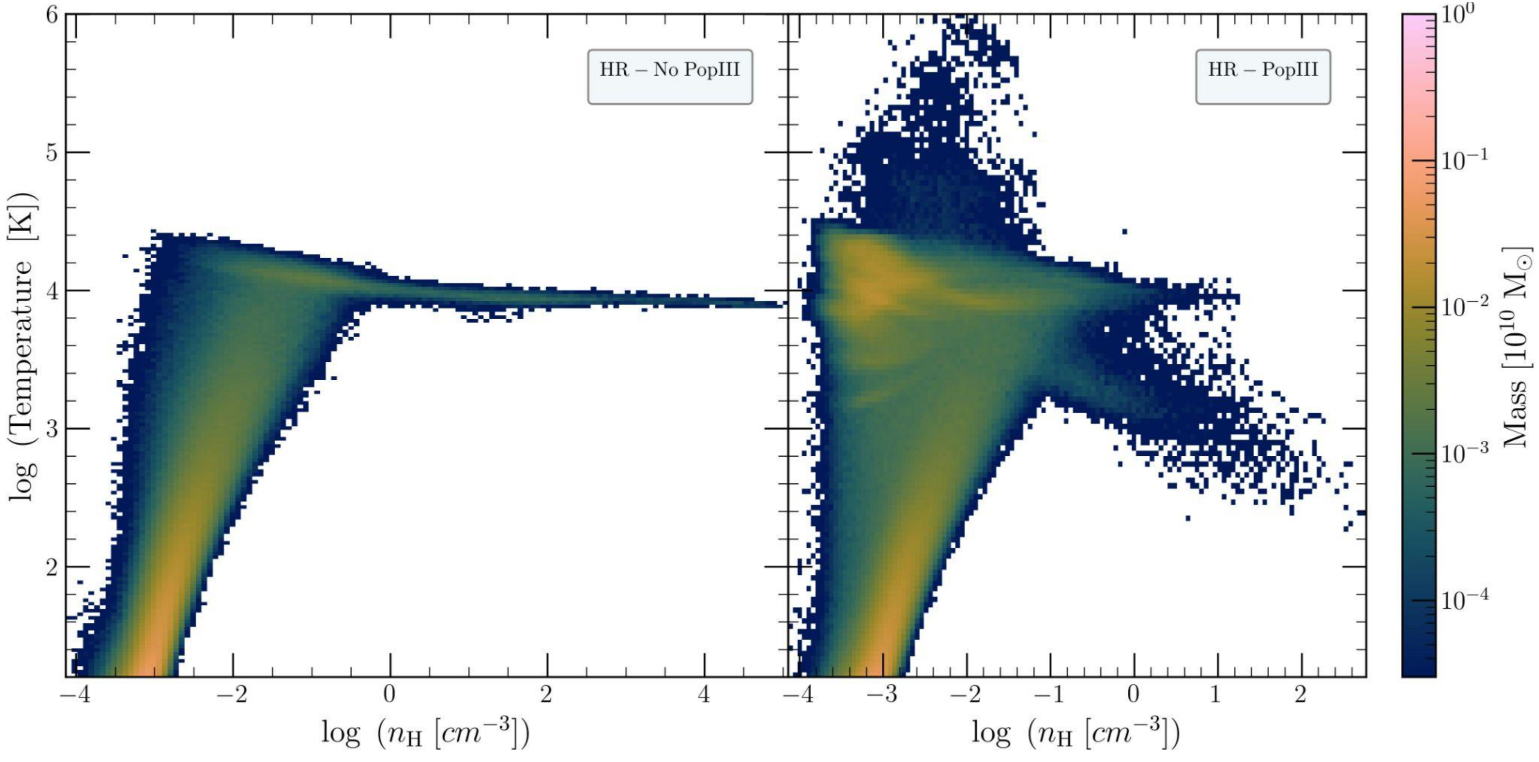
Properties of the central halo:

Energetic PopIII SNe results in stronger feedback that delays star formation and slower enrichment of gas



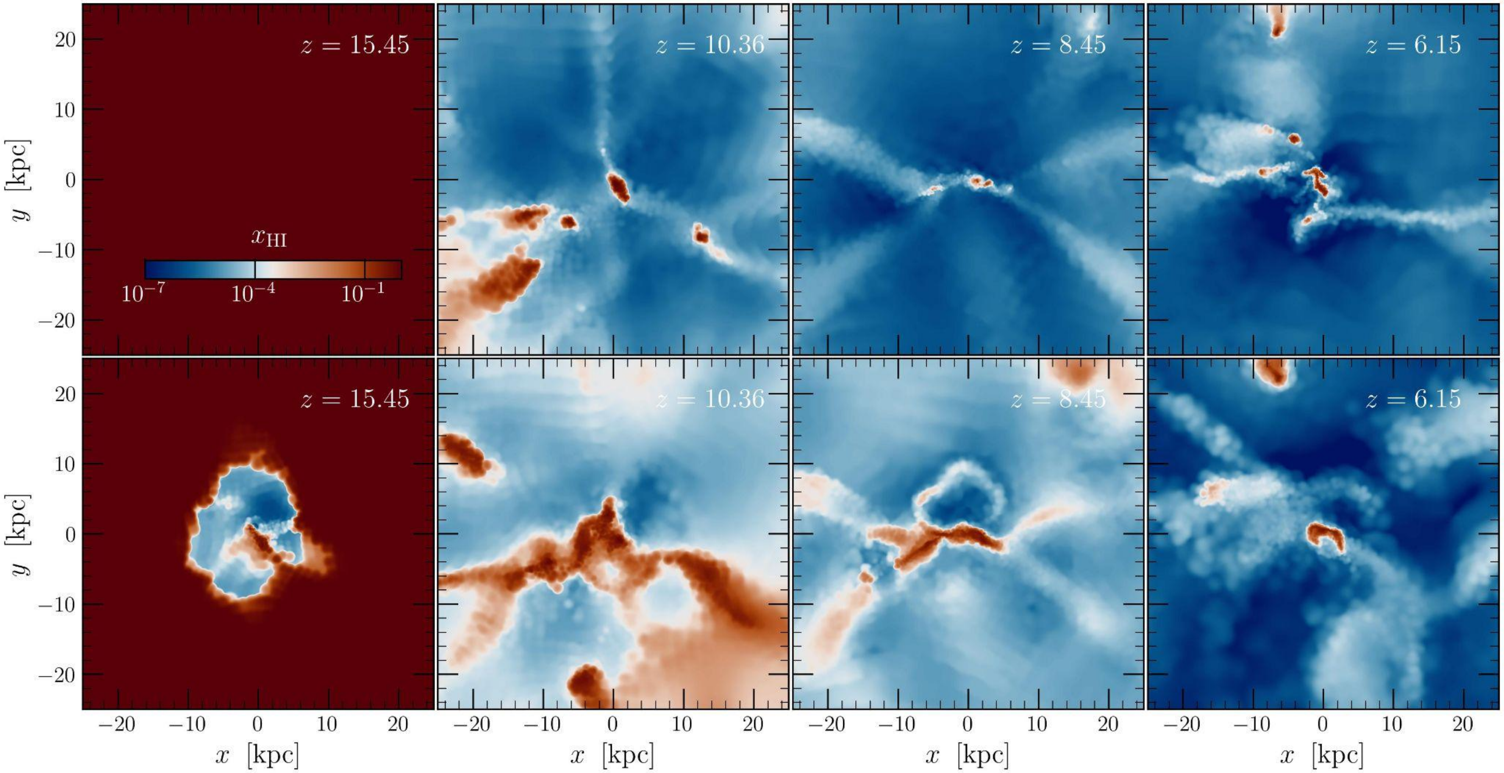
Cosmological simulation of galaxy

<u>Properties of the central halo:</u> phase space diagram (z ~ 12)



Cosmological simulation of galaxy

Ionization properties:



Cosmological simulation of galaxy

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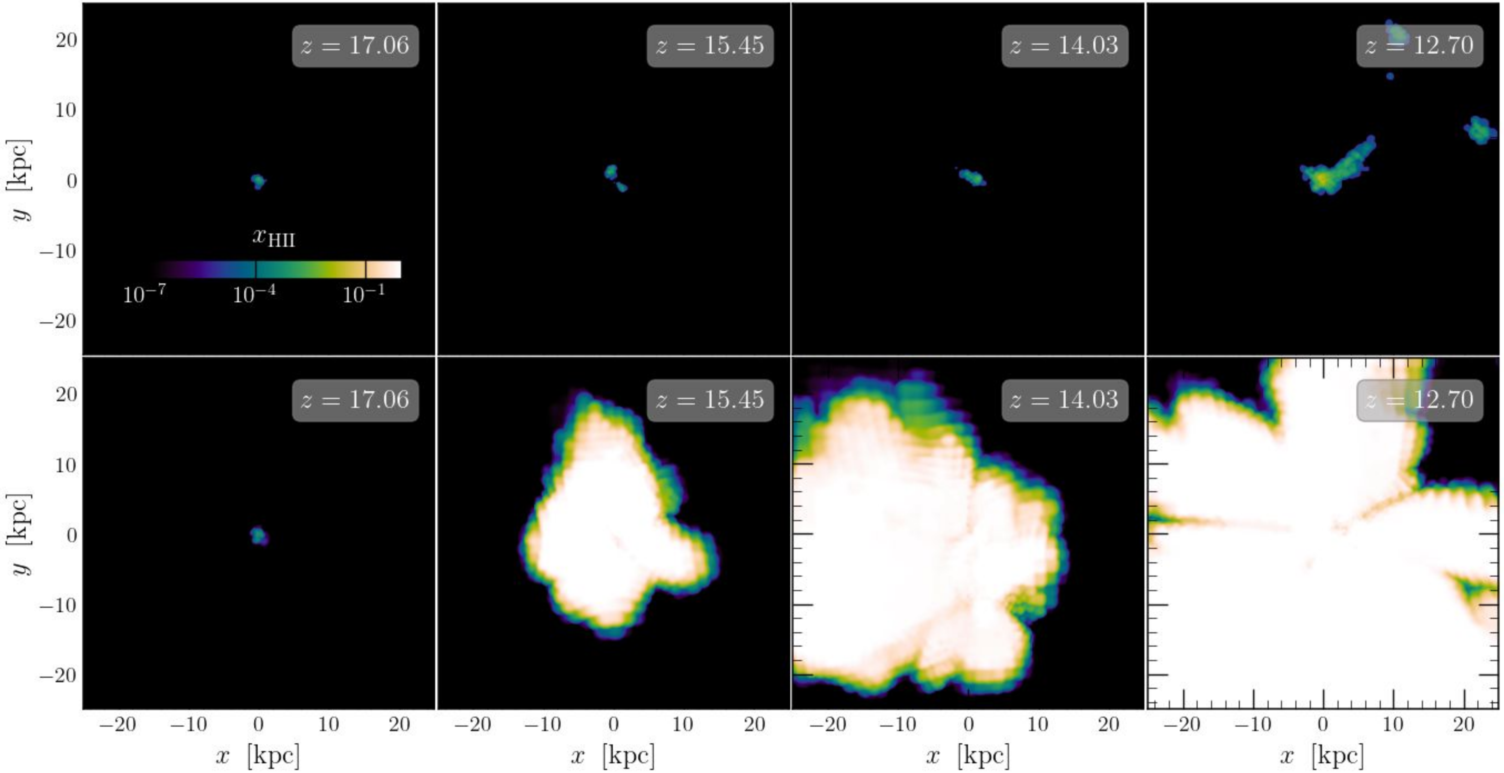

Conclusion

- Developed an accurate Molecular Hydrogen Thermochemistry network very relevant for the early universe
- Created IMF averaged stellar spectra for PopIII stars with high fidelity
- Developed metal enrichment and feedback prescription for PopIII stars.

- Found that PopIII stars can form at z ~ 15.45
- PopIII stars decreases SFR in Halos, Reduces Gas Metallicity in CGM
- Found strong evidence that PopIII stars ***can*** affect the onset of reionization !

Thank you 🤗

Acknowledgement

- Dr. Rahul Kannan (PI)

- Dr. Giovanni Mirrouh, for useful discussion on stellar evolution.
- Mr. Thomas Gessey Jones, for insightful discussions on PopIII spectra.
- This research was enabled in part by support provided by ACENET, Calcul Québec, Compute Ontario, and the Digital Research Alliance of Canada (alliancecan.ca)
- My parents and friends, for always supporting me !

Methods : Thermochemistry (Kannan et.al 2019, Kannan et. al 2020, Gnedin et. al 2011)

Photo heating:
Photons in addition to changing the ionization state, they also heat the gas.
The excess energy is taken away by the photoelectrons.

$$\mathcal{H} = \sum_j n_j \Gamma_j .$$

(Total photo-heating rate)

$$\Gamma_j = \sum_i \int_{\nu_{i1}}^{\nu_{i2}} \frac{4\pi J_\nu}{h\nu} \sigma_{j_\nu} \left(h\nu - h\nu_{tj}\right) \mathrm{d}\nu$$

Methods : Thermochemistry (Kannan et.al 2019, Kannan et. al 2020, Gnedin et. al 2011)

Change of momentum:

The radiation pressure term due to photon absorption is added as a source term in the momentum conservation equation of hydrodynamics and is given by

$$\frac{\partial \rho v}{\partial t} = \frac{1}{c} \sum_{i} \boldsymbol{F}_{\gamma}^{i} \left(\sum_{j} n_j \, \bar{\sigma}_{ij} \, p_{ij} + \kappa_i \, \rho \, e_i \right)$$

$$p_{ij} = \frac{\displaystyle\int_{\nu_{i1}}^{\nu_{i2}} 4\pi J_\nu \sigma_{j_\nu} \, \mathrm{d}\nu}{\displaystyle\int_{\nu_{i1}}^{\nu_{i2}} \frac{4\pi J_\nu}{h\nu} \sigma_{j_\nu} \, \mathrm{d}\nu} .$$

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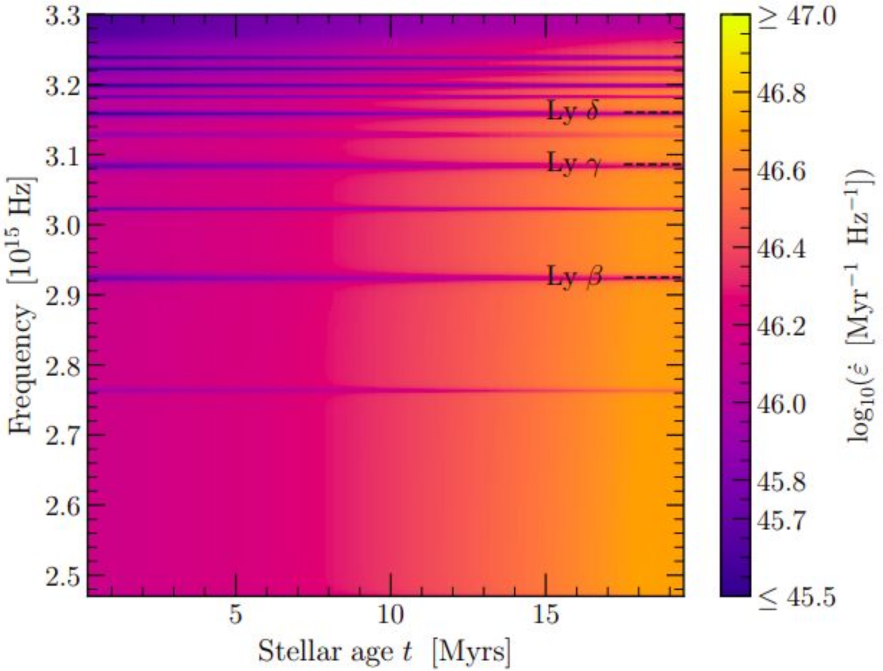
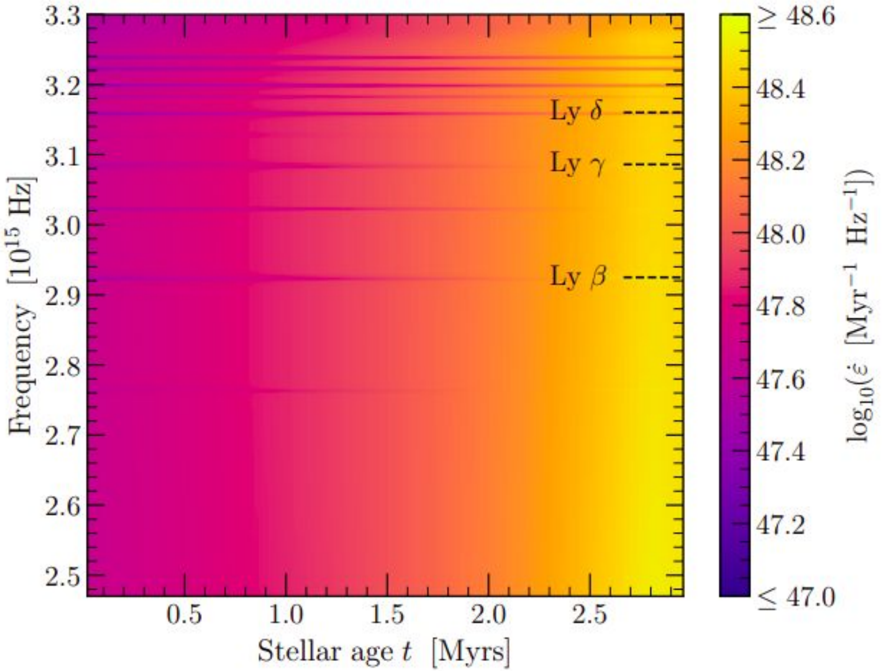


(a) Lifetime emission of 10 $M_{\odot}$ star.



(b) Lifetime emission of 100 $M_{\odot}$ star.