Sterrewacht Leiden

Non-Equilibrium Interstellar Chemistry in Simulations of Galaxy Formation

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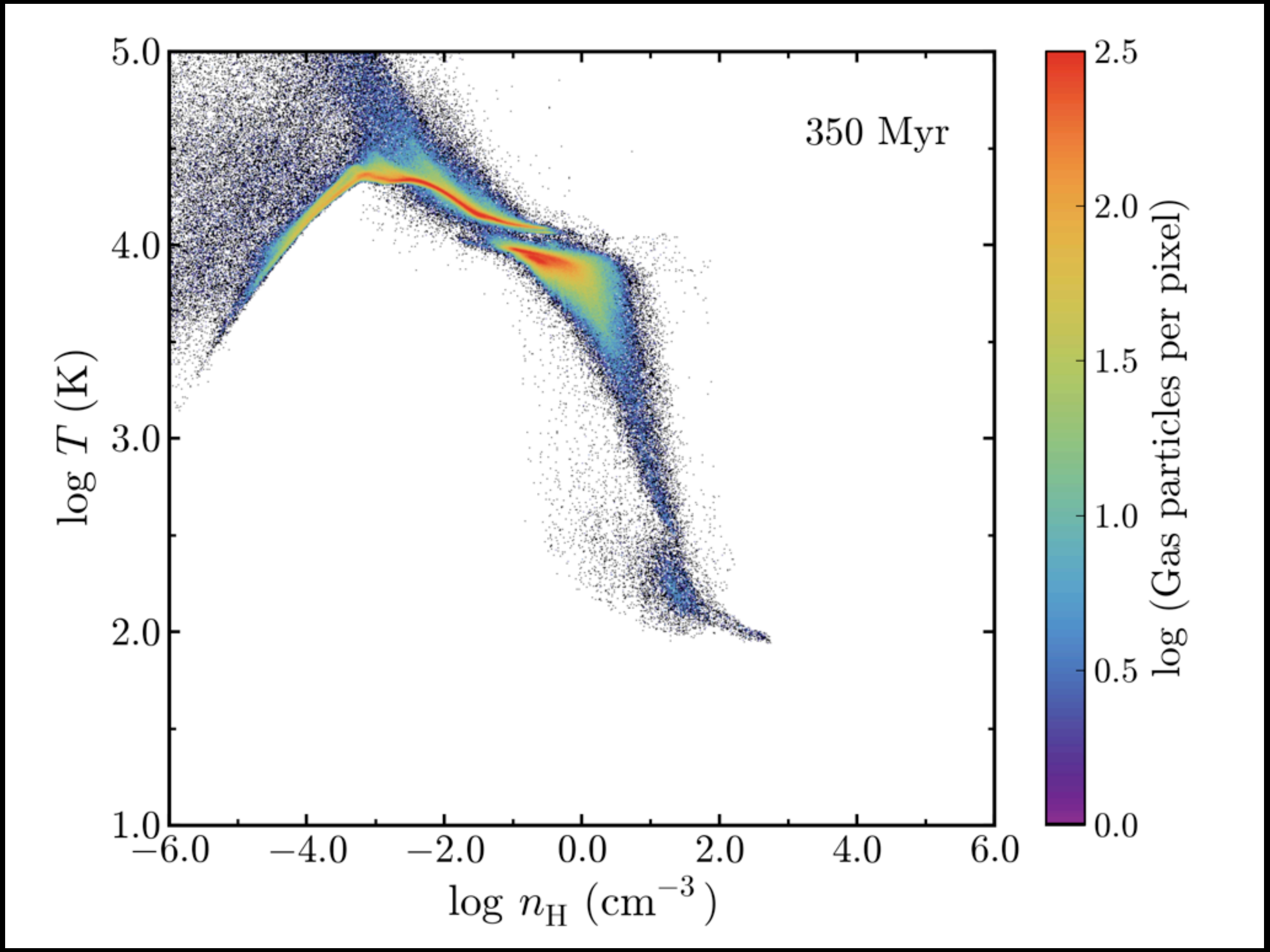
Introduction

- We are interested in the transition from the warm ISM (10^4 K) to the cold ISM (100 K).

- Thermal instability between these phases leads to short cooling times. Chemical non-equilibrium could potentially be important.



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I: Chemical Model

Chemical Network

Species:

- Ions - H, He, N, C, O, Ne, Mg, Si, S, Ca, Fe (137 in total)
- Molecules - H_2, CO & intermediate species (20 in total)

Chemical Network

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Cooling:

- Metal line cooling
- Molecular hydrogen
- Recombination cooling
- Free-free emission

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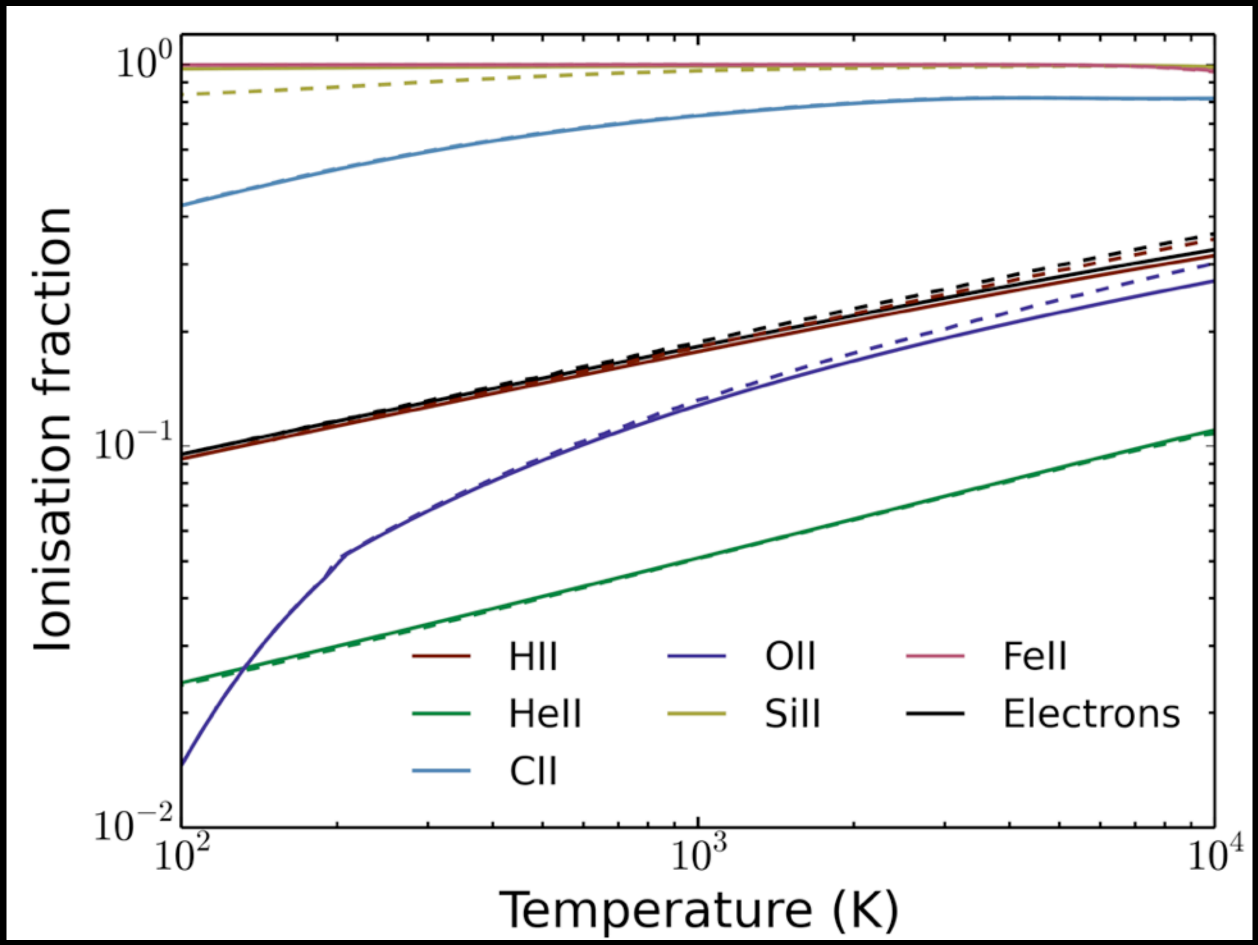
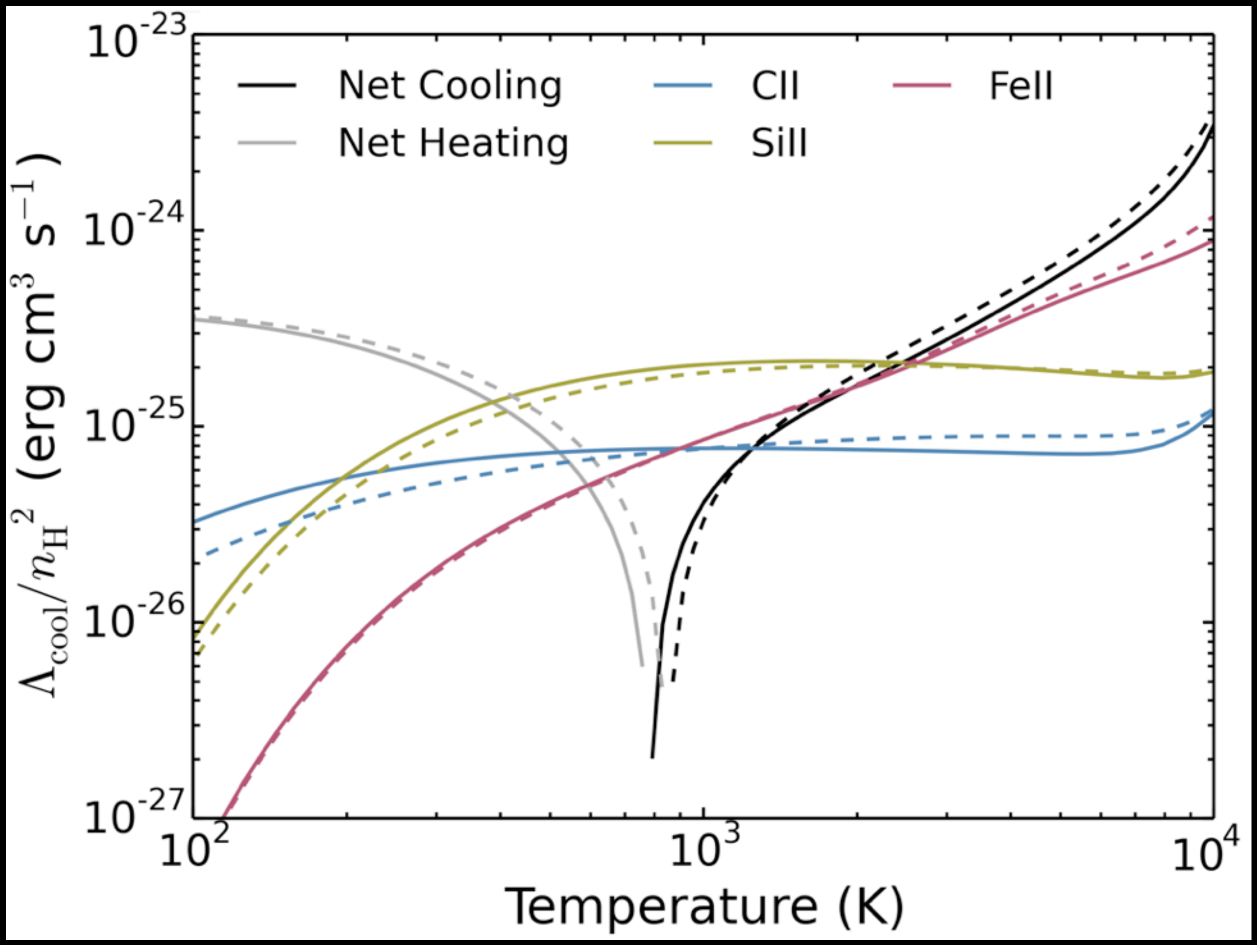
Heating:

- Photoheating
- Photoelectric dust heating
- Cosmic Rays

Equilibrium Cooling

Haardt & Madau (2001) extragalactic UVB; n_H = 1 cm^{-3}





Non-Equilibrium Cooling

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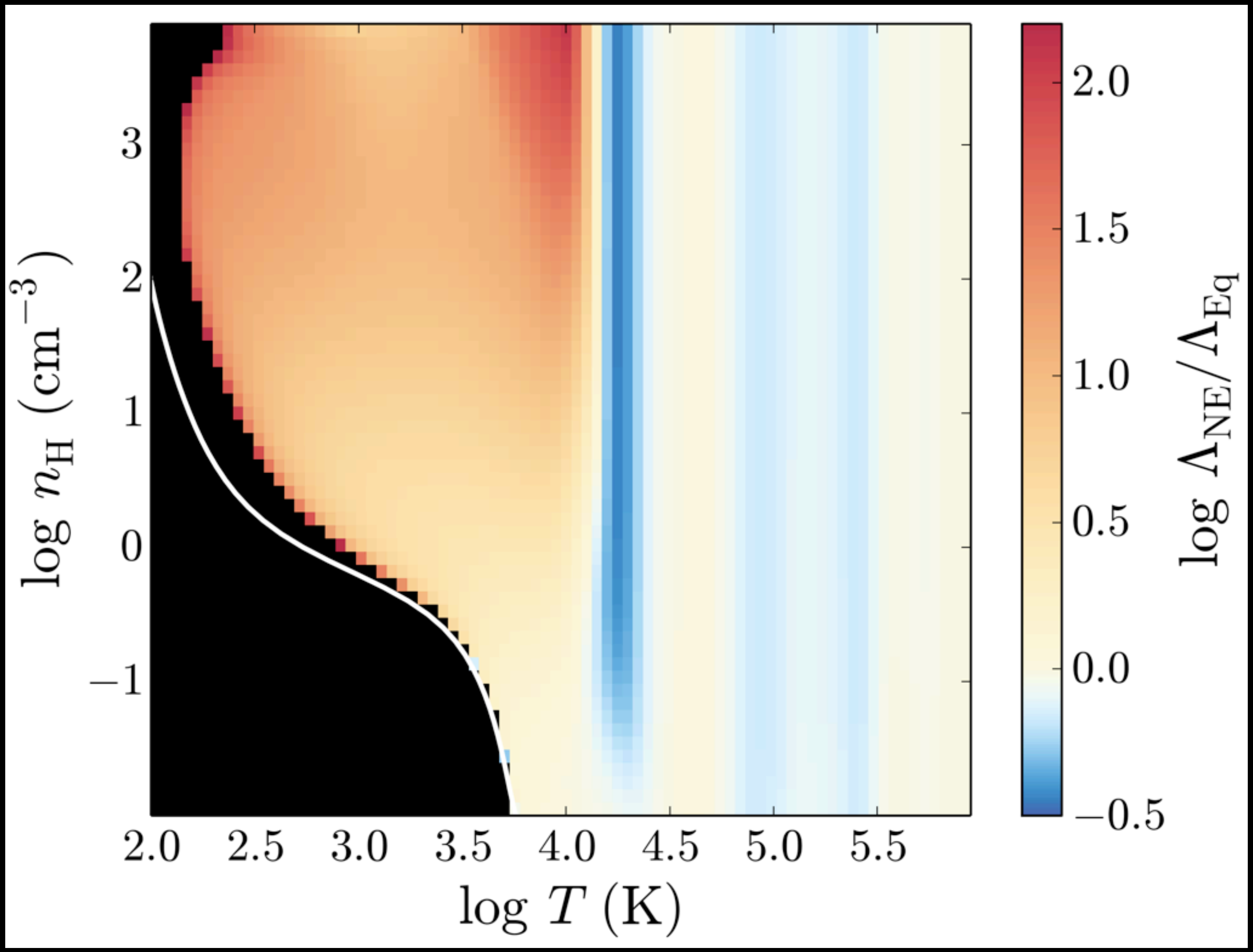
Gas cooling isochorically from T = 10⁶ K

- Solar metallicity
- Haardt & Madau (2001) UV background



Richings et al. (2014)

Shielded Gas

- Photoionisation rates attenuated by:
  - HI, H_2, HeI and HeII.
  - Dust.
- Photodissociation rates attenuated by:
  - H_2 self-shielding.
  - CO self-shielding and CO shielding by H_2.
  - Dust.
- $N_i = n_i L$
- $L = \rho / |2\nabla\rho|$

Chemical Abundances in Shielded Gas

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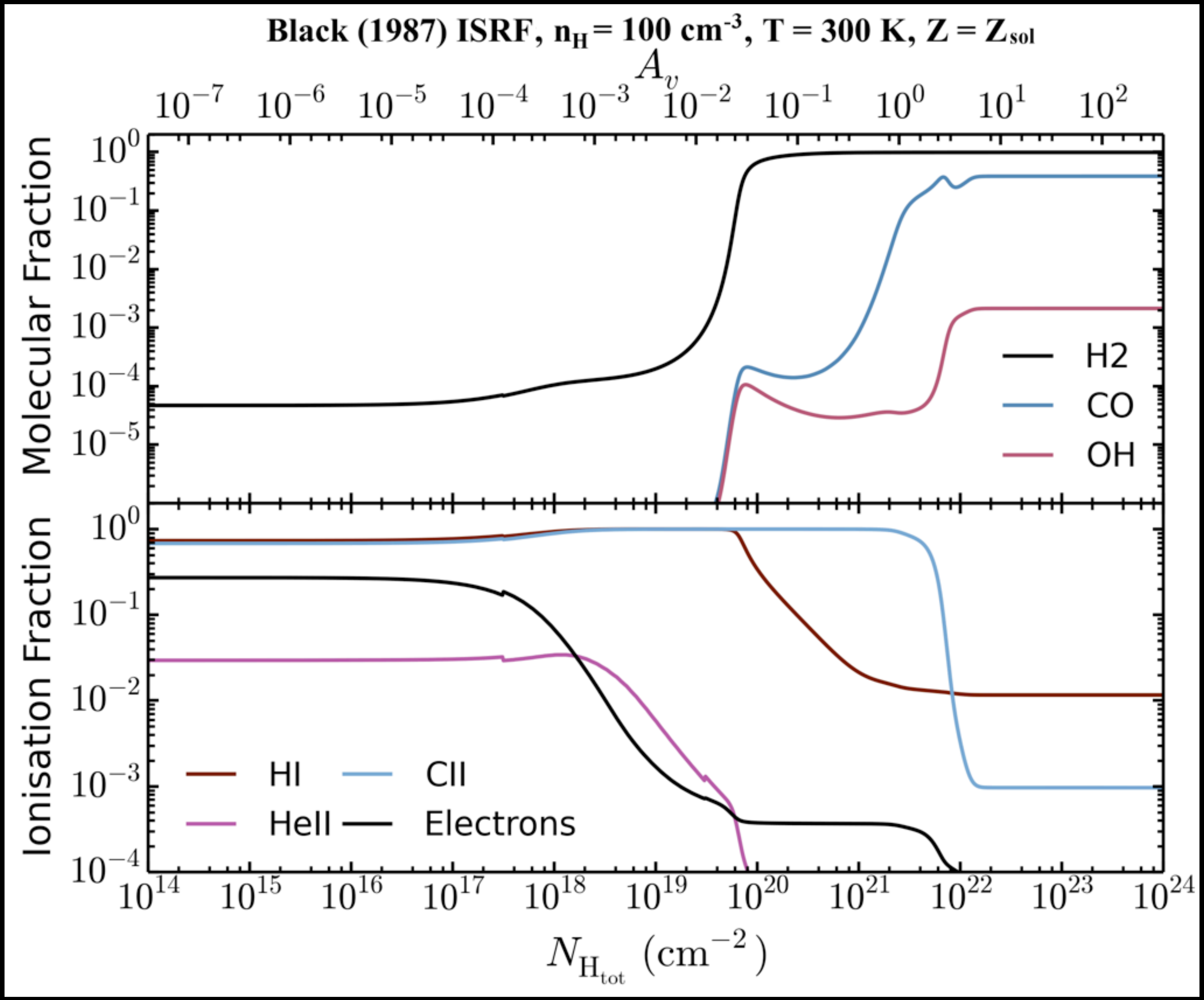

Chemical Abundances in Shielded Gas

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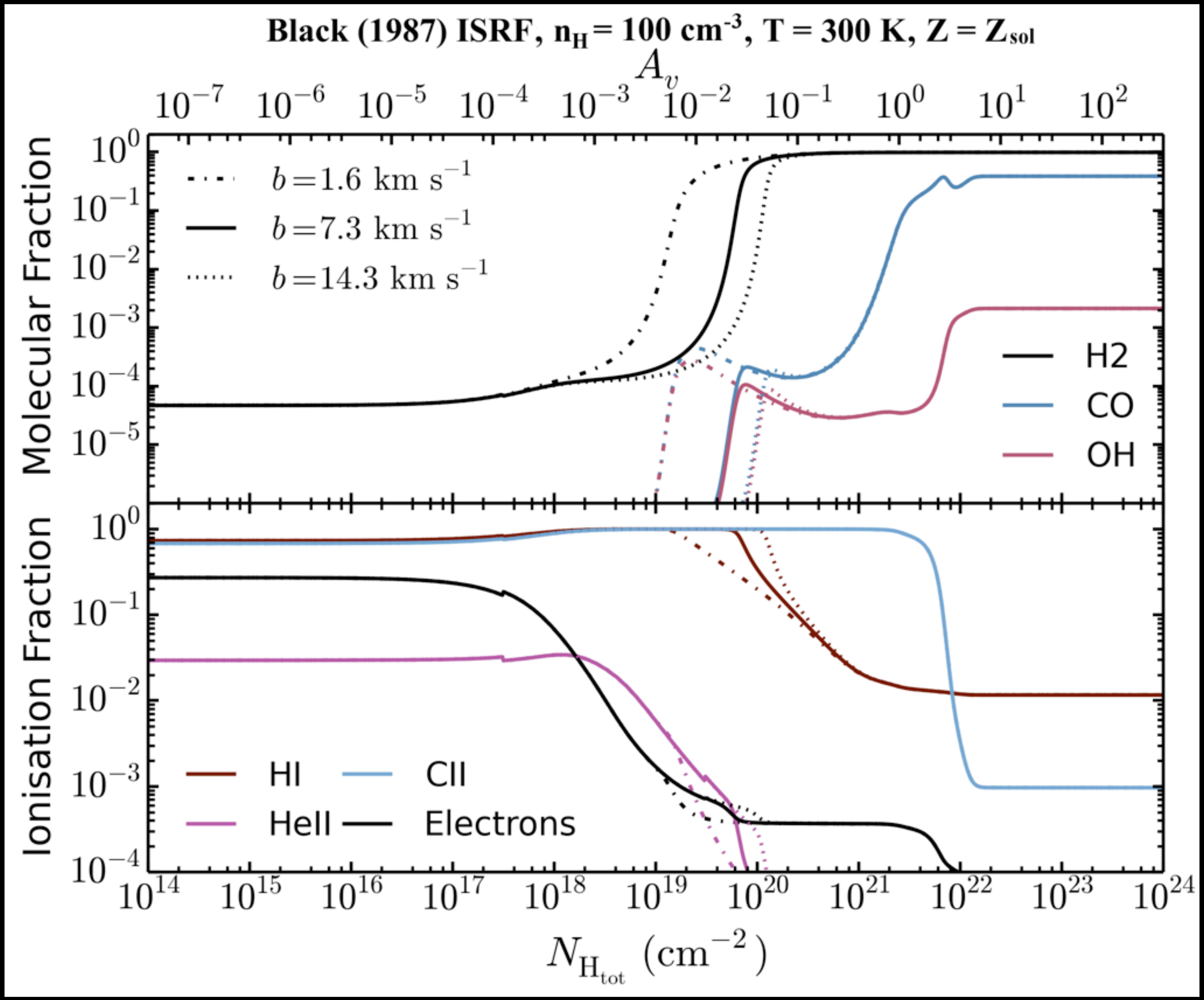
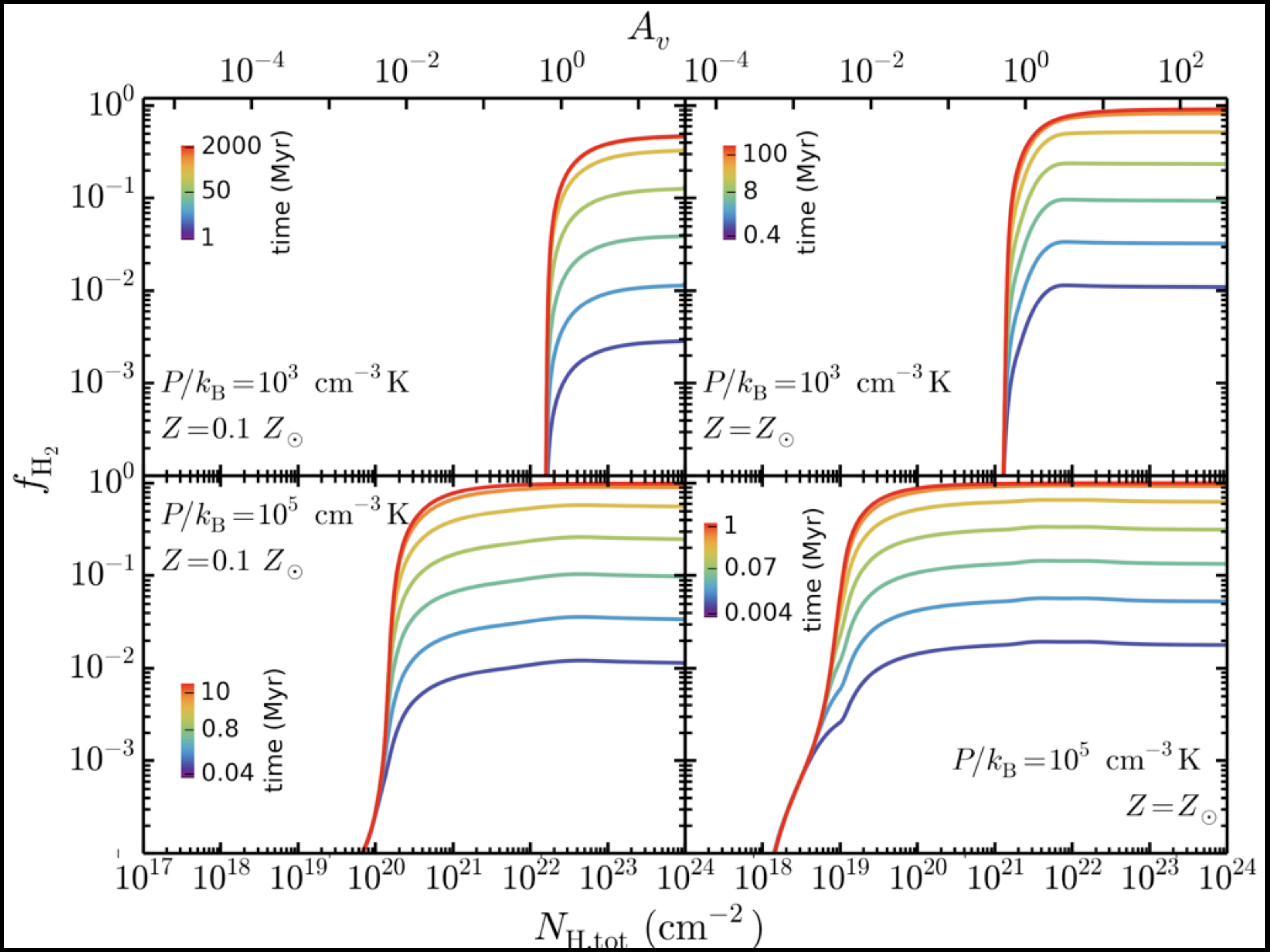


Molecular Hydrogen

Solid Coloured Lines:

- Our model



Molecular Hydrogen

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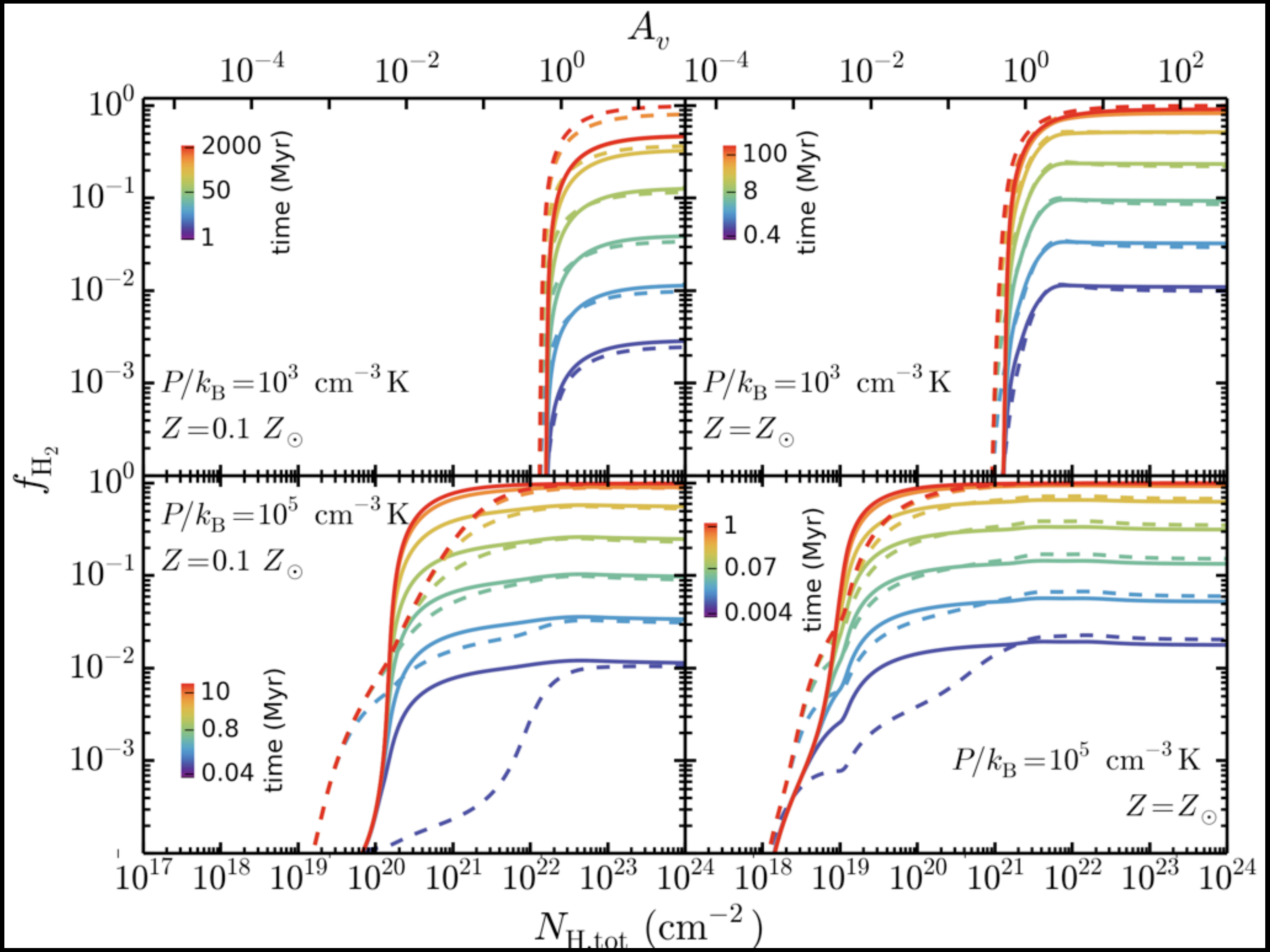
Solid Coloured Lines:

- Our model

Dashed Coloured Lines:

- Gnedin et al. (2009)



Molecular Hydrogen

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Solid Coloured Lines:

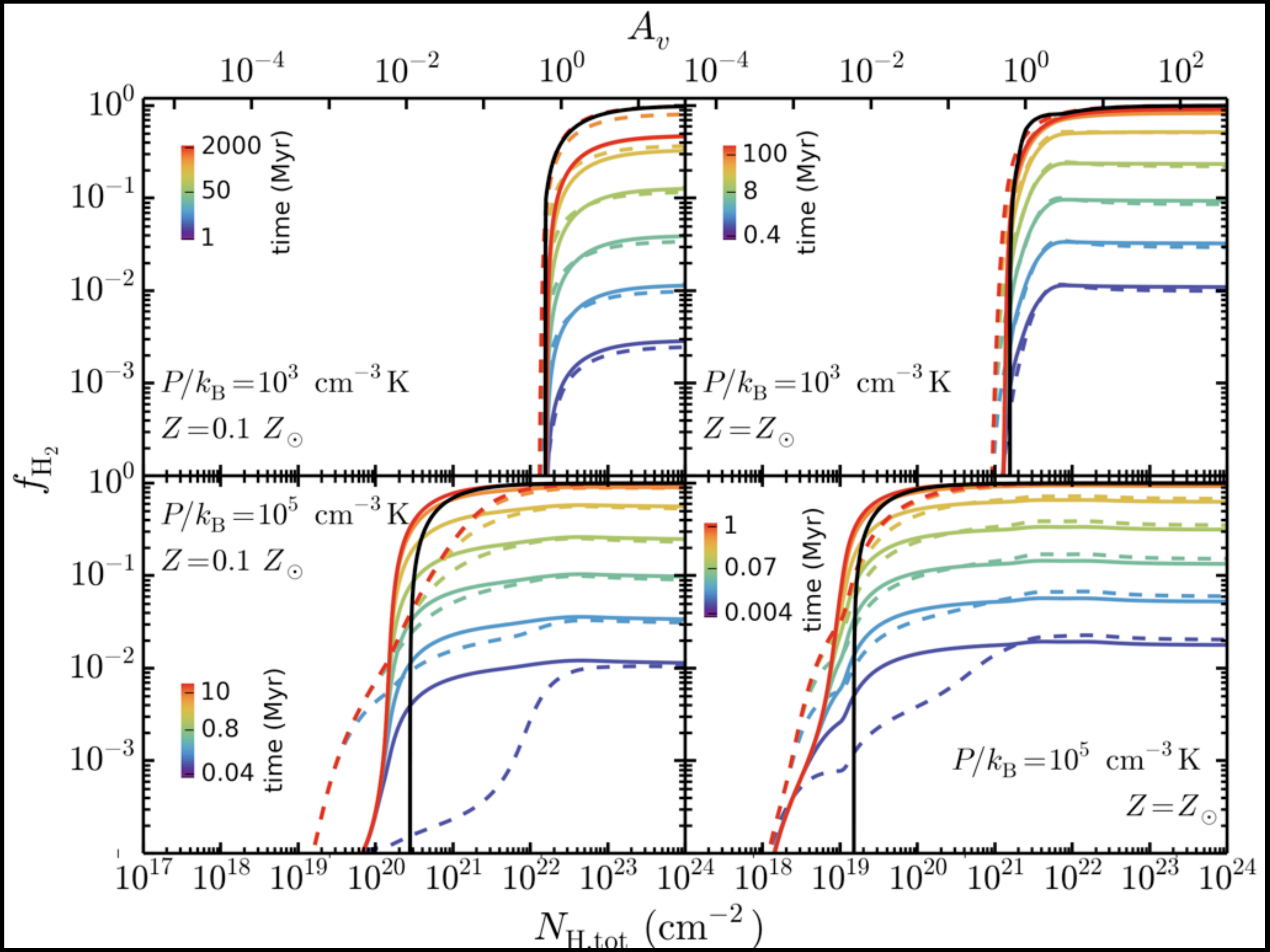
- Our model

Dashed Coloured Lines:

- Gnedin et al. (2009)

Solid Black Lines:

- Krumholz et al. (2008, 2009, 2010)



II: Isolated Galaxies

Isolated Disc Galaxies

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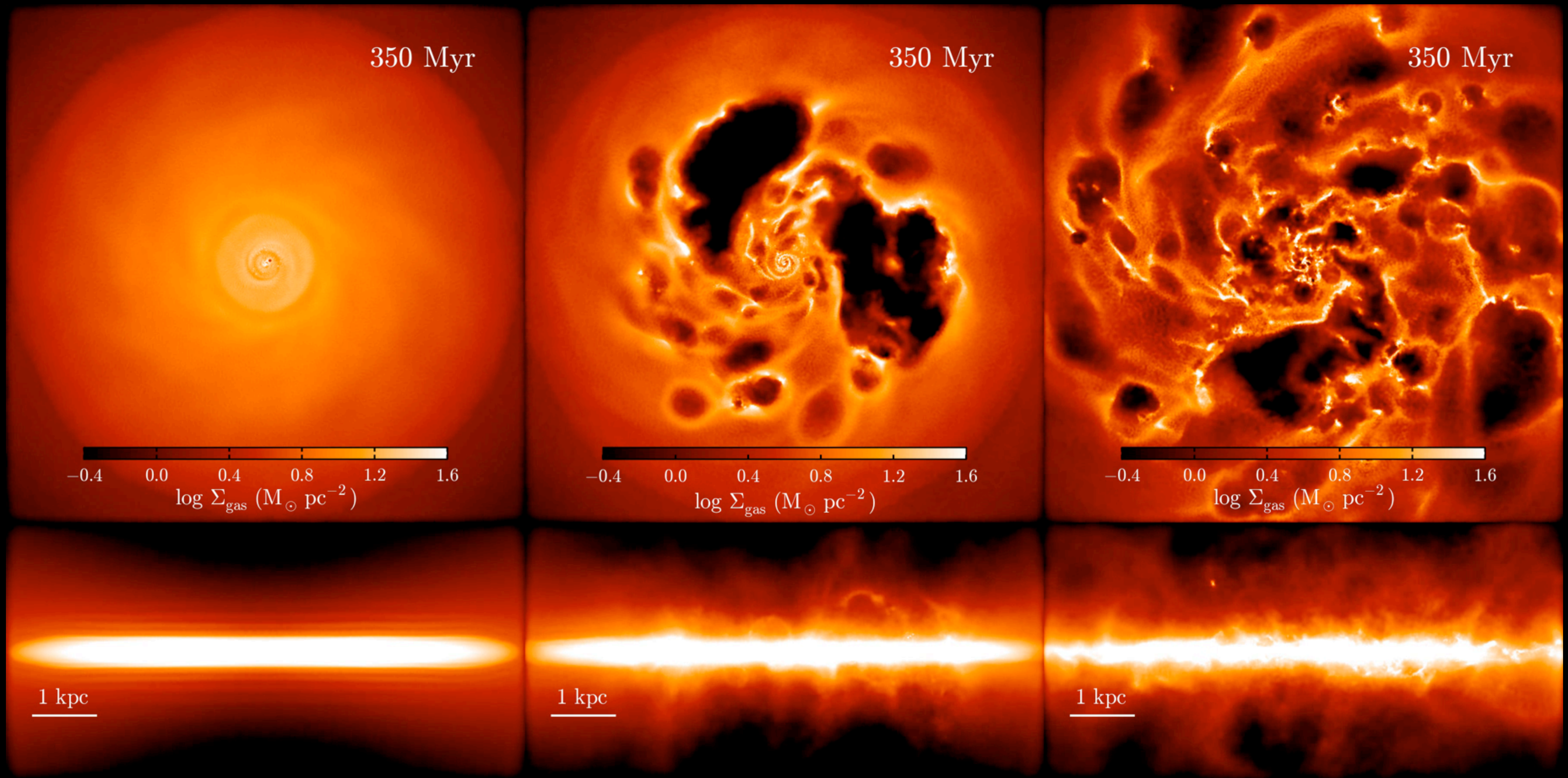
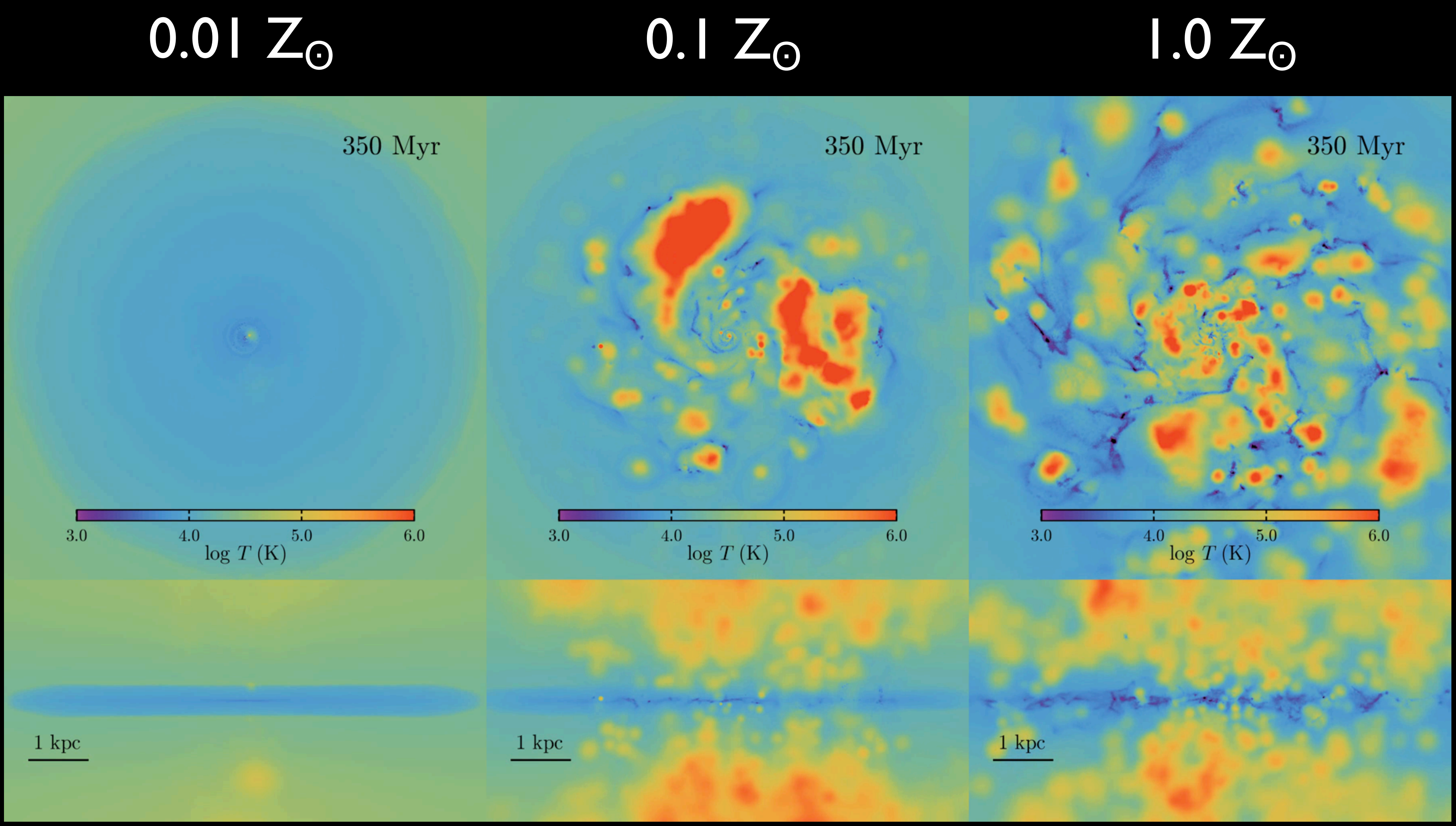
- Tree/SPH code Gadget3 (Springel 2005).
- Star formation:
  - $n_H > 1$ cm^{-3}; $T < 1000$ K; $\varepsilon_{SF} = 0.005$.
- $M_{200} = 10^{11}\ M_{\odot}$.
- $M_{star} = 1.4 \times 10^{9}\ M_{\odot}$.
- $M_{gas} = 4.8 \times 10^{8}\ M_{\odot}$.
- $m_{SPH} = 750\ M_{\odot}$.

Gas Surface Density

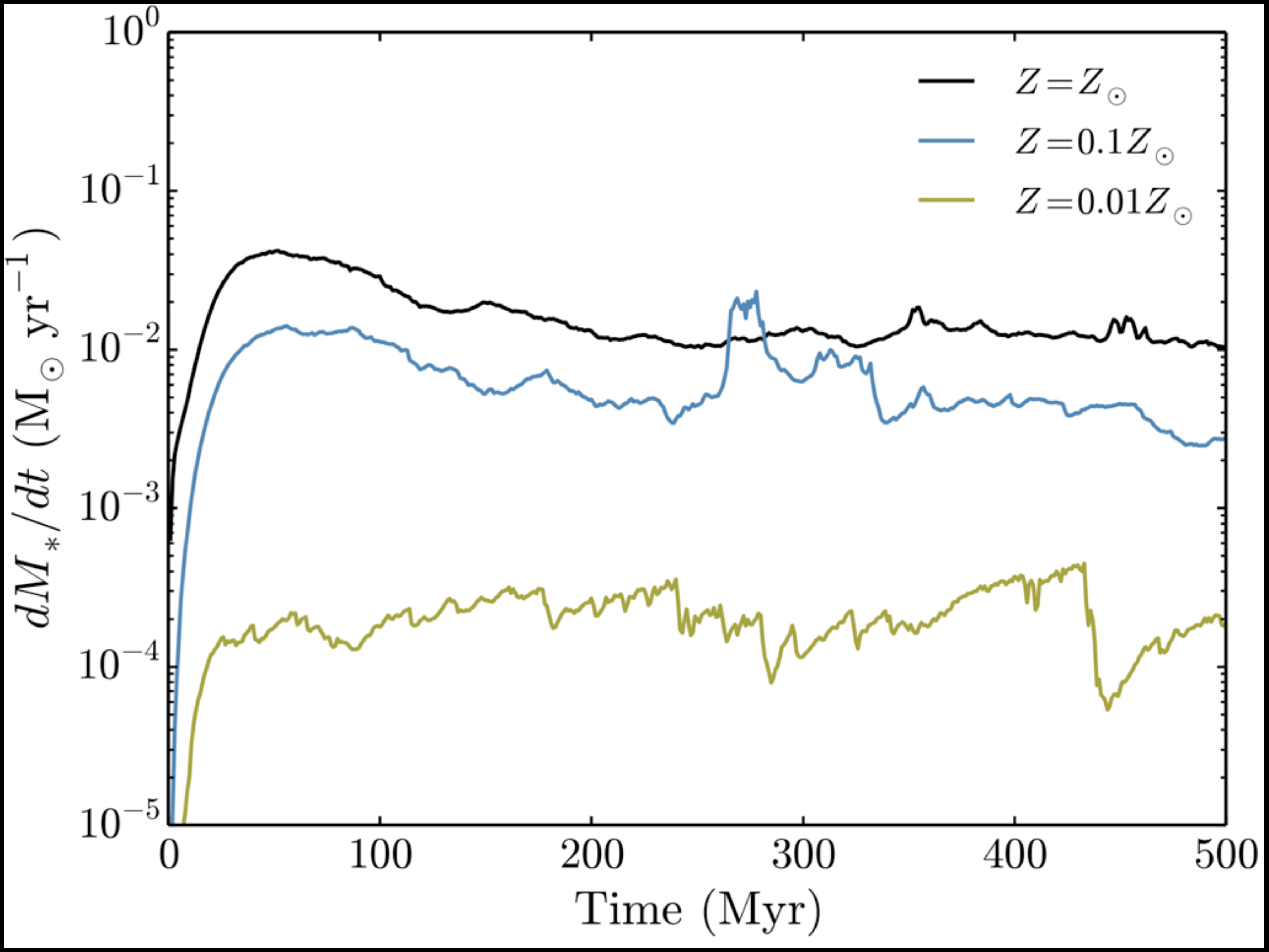
0.01 $Z_\odot$ | 0.1 $Z_\odot$ | 1.0 $Z_\odot$



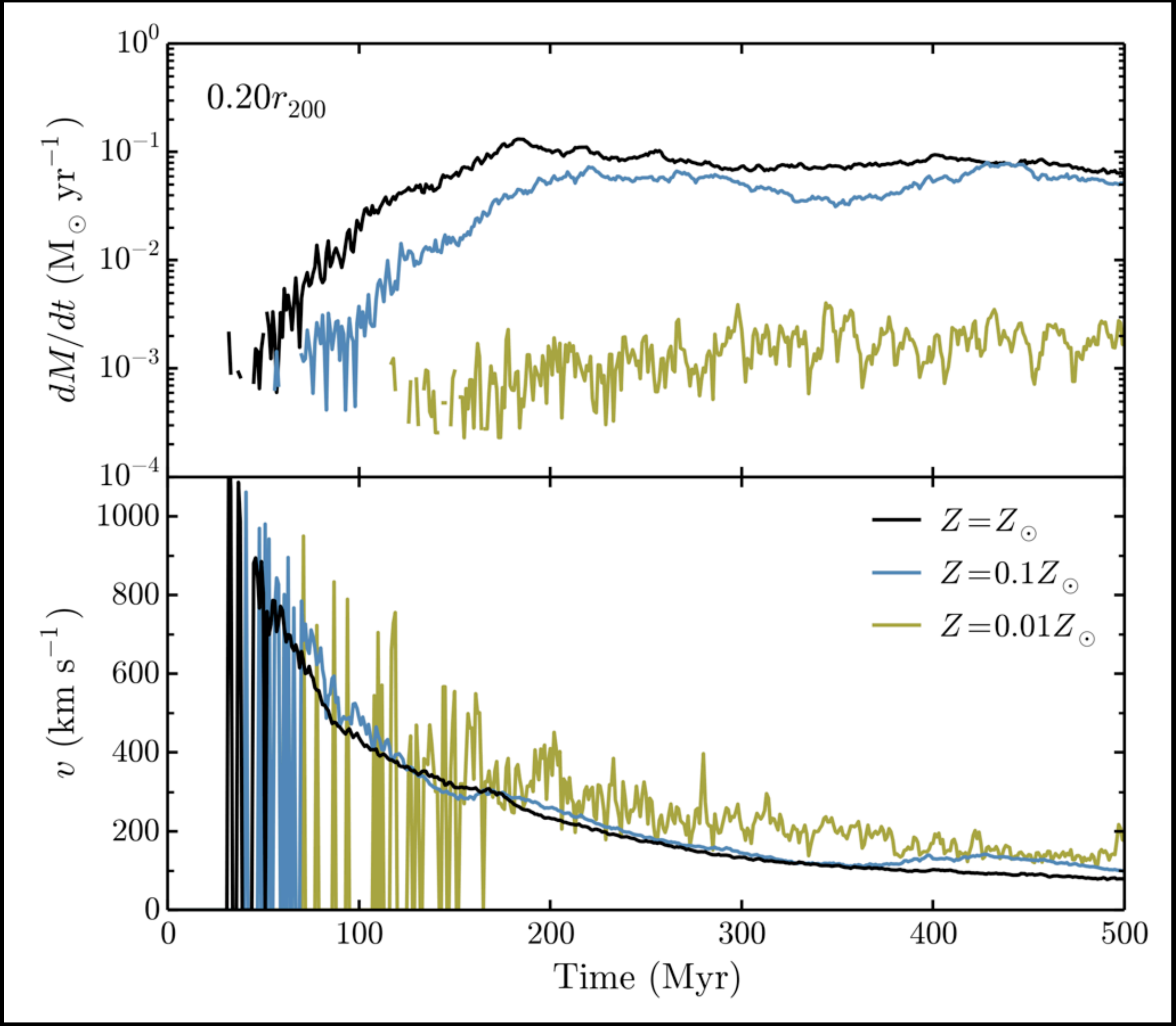
Gas Temperature



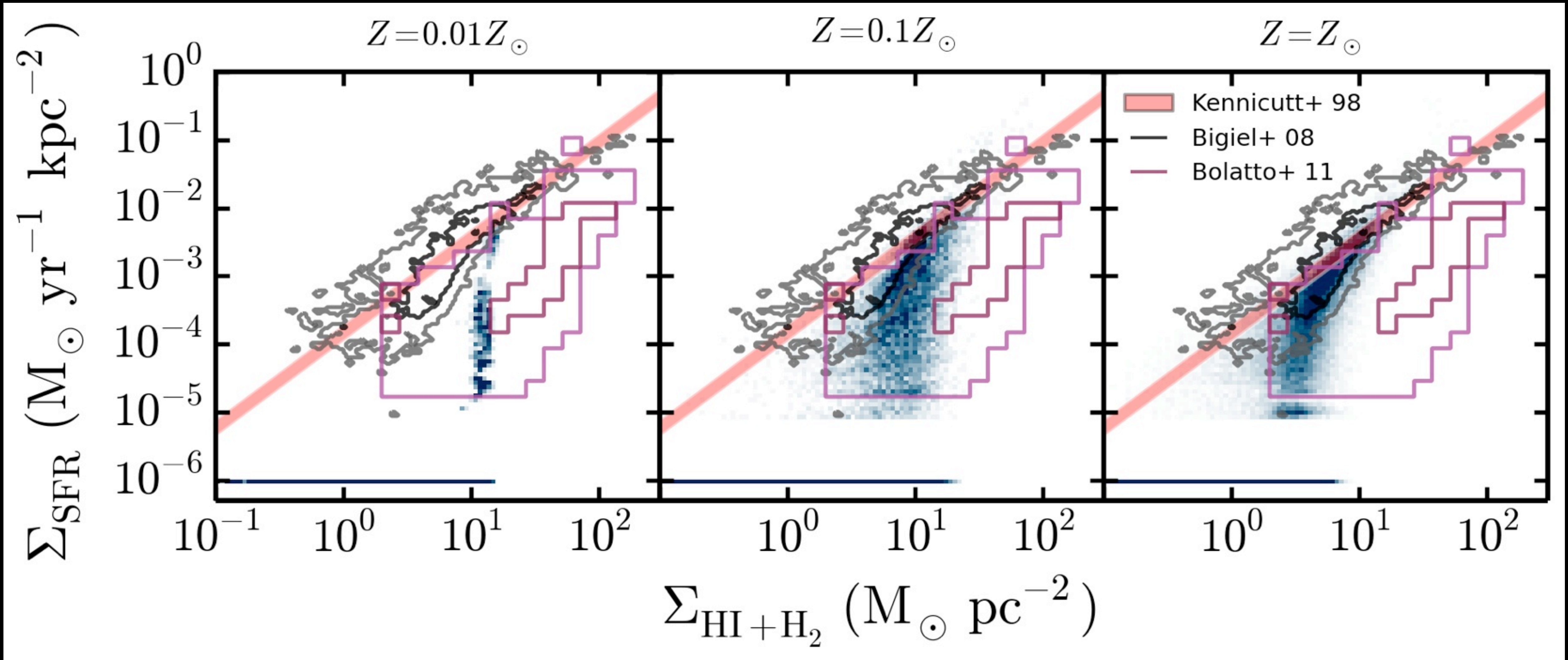
Star Formation Histories



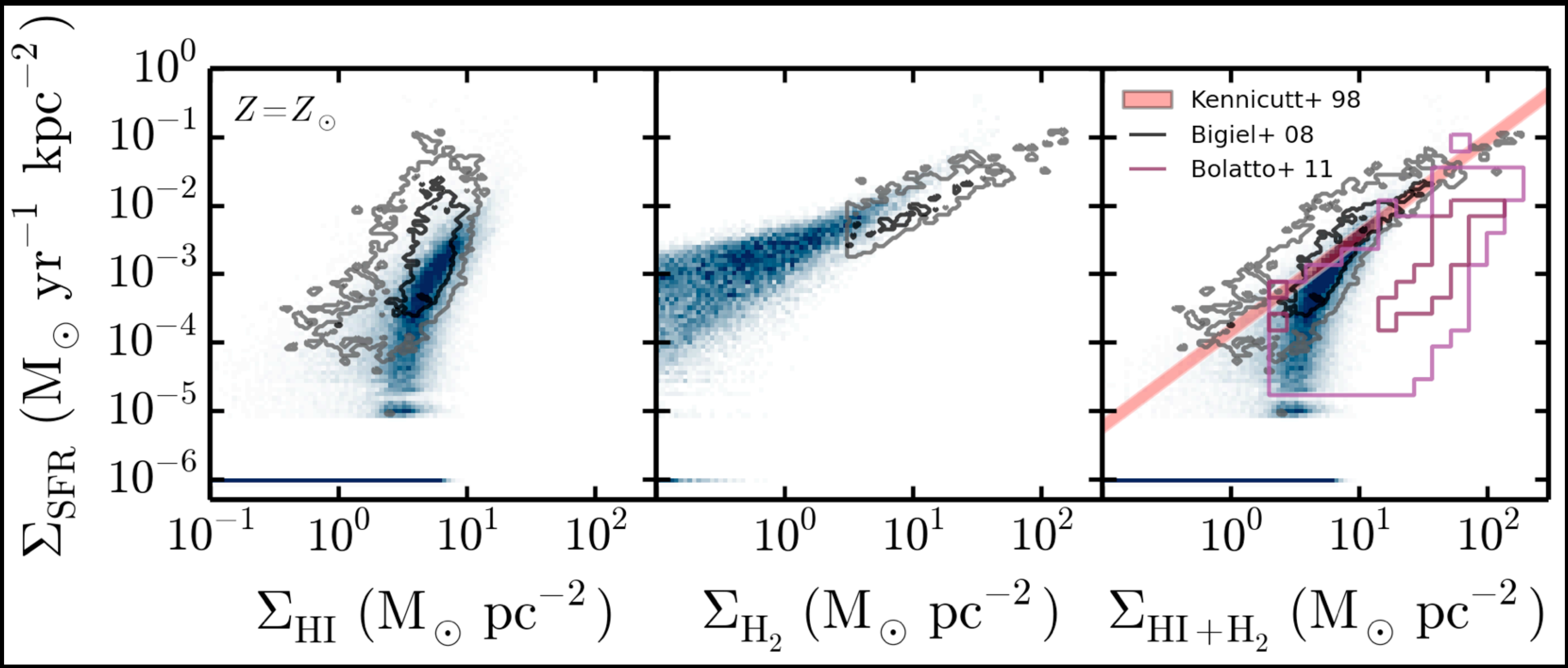
Outflows


$0.20r_{200}$
dM/dt ($M_\odot$ yr^{-1})
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
v (km s^{-1})
1000
800
600
400
200
0
$Z = Z_\odot$
$Z = 0.1Z_\odot$
$Z = 0.01Z_\odot$
0
100
200
300
400
500
Time (Myr)

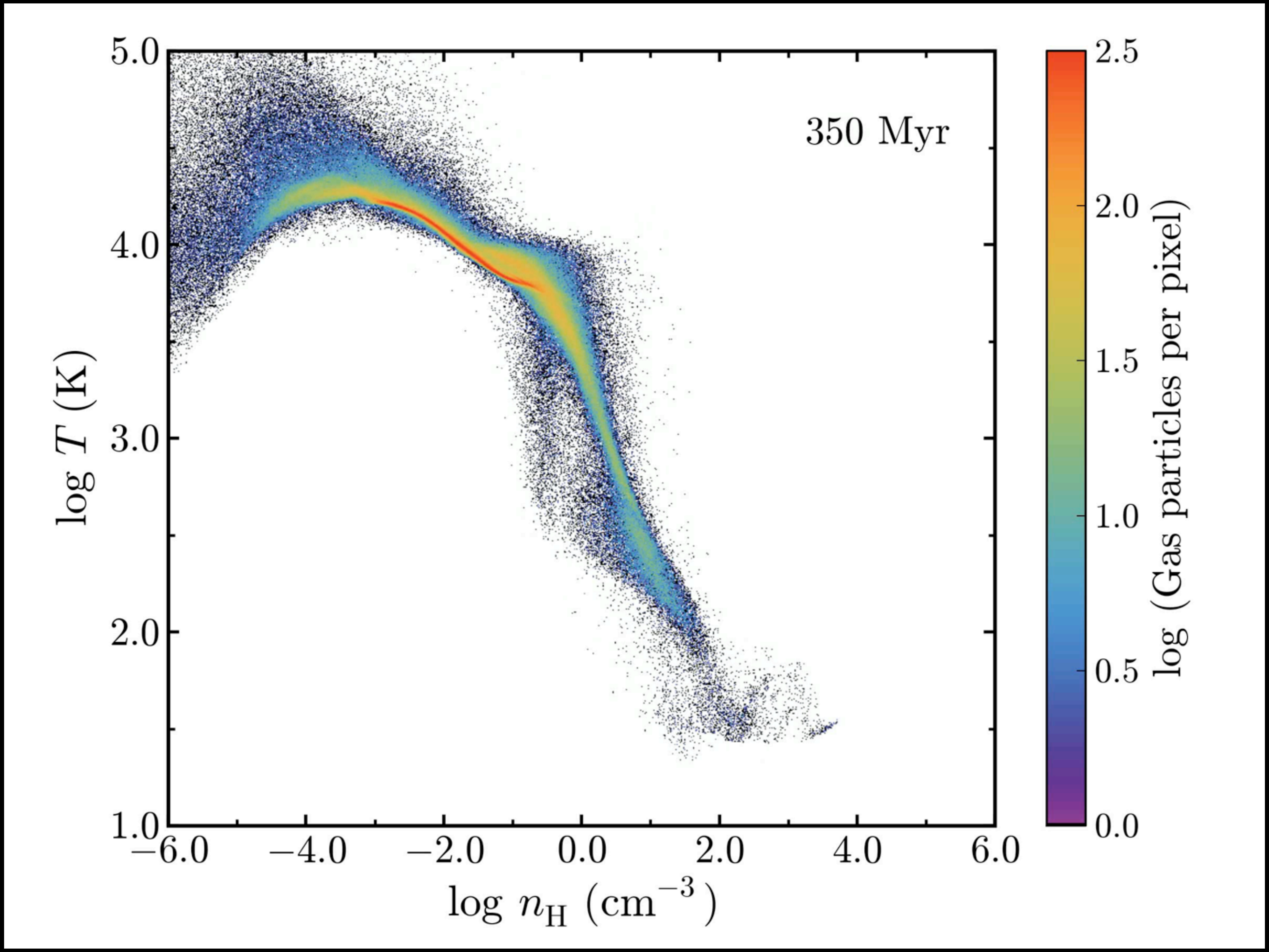
Kennicutt-Schmidt Relation



Kennicutt-Schmidt Relation

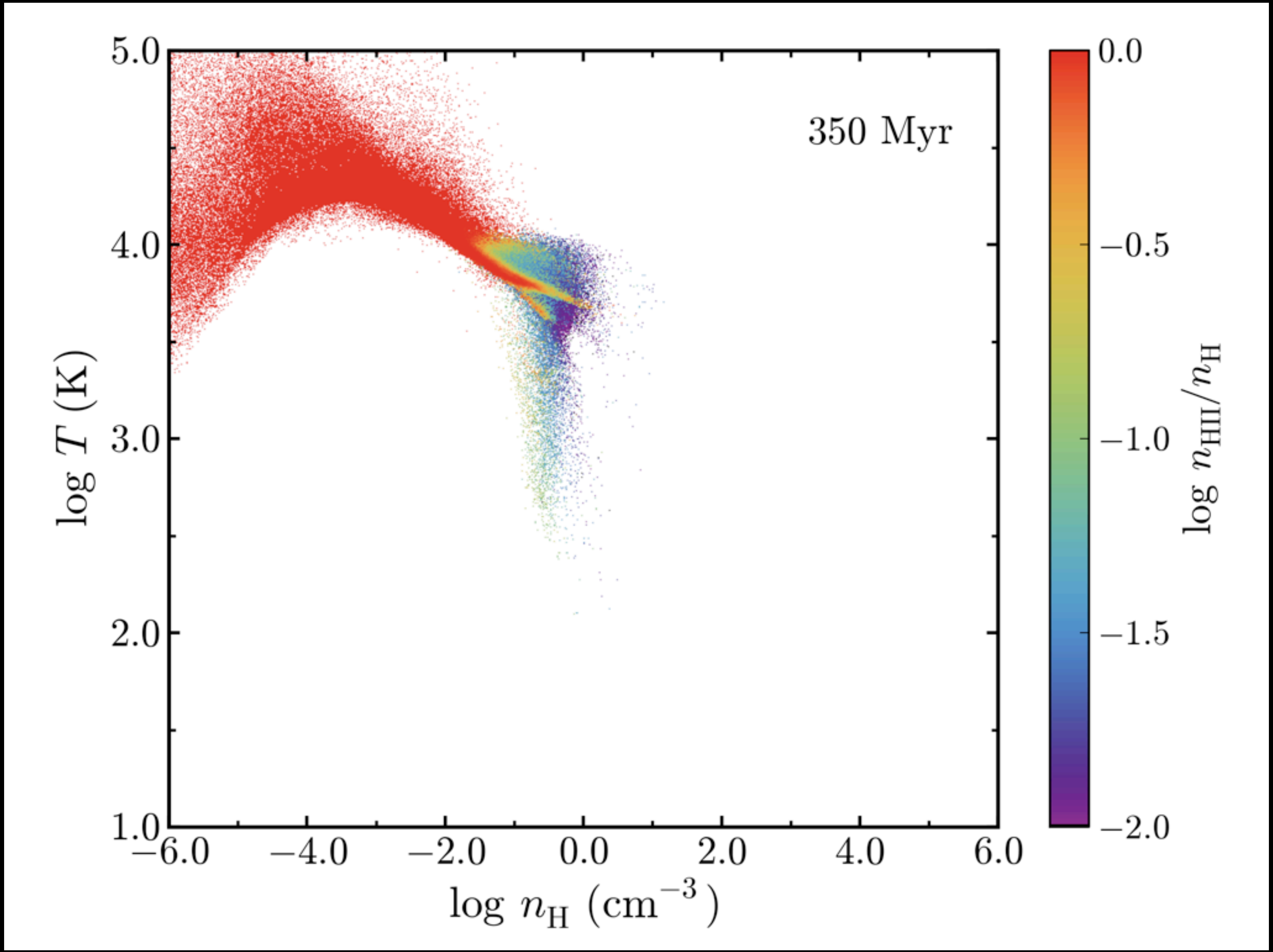


Temperature-Density



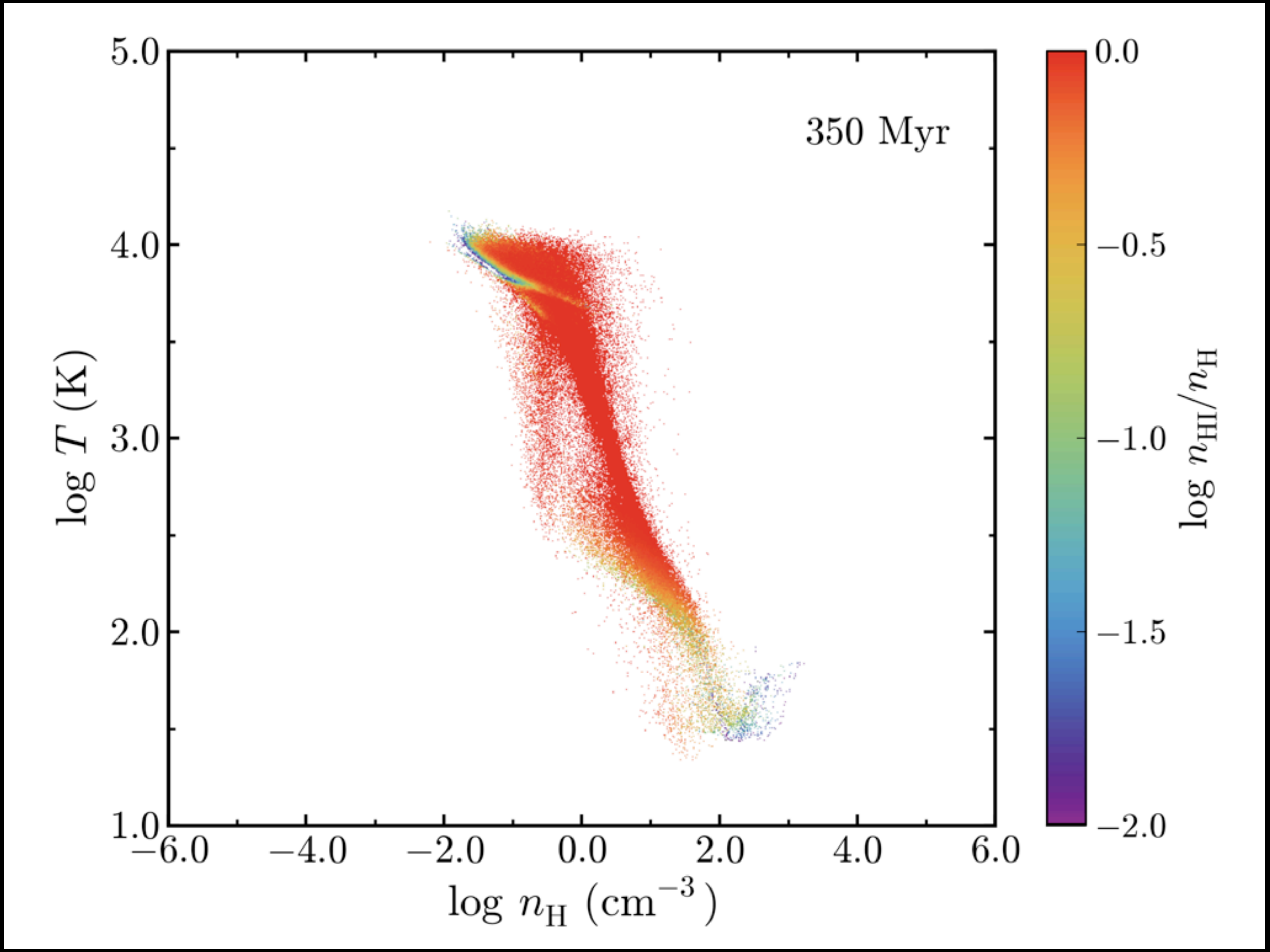
Temperature-Density

HII



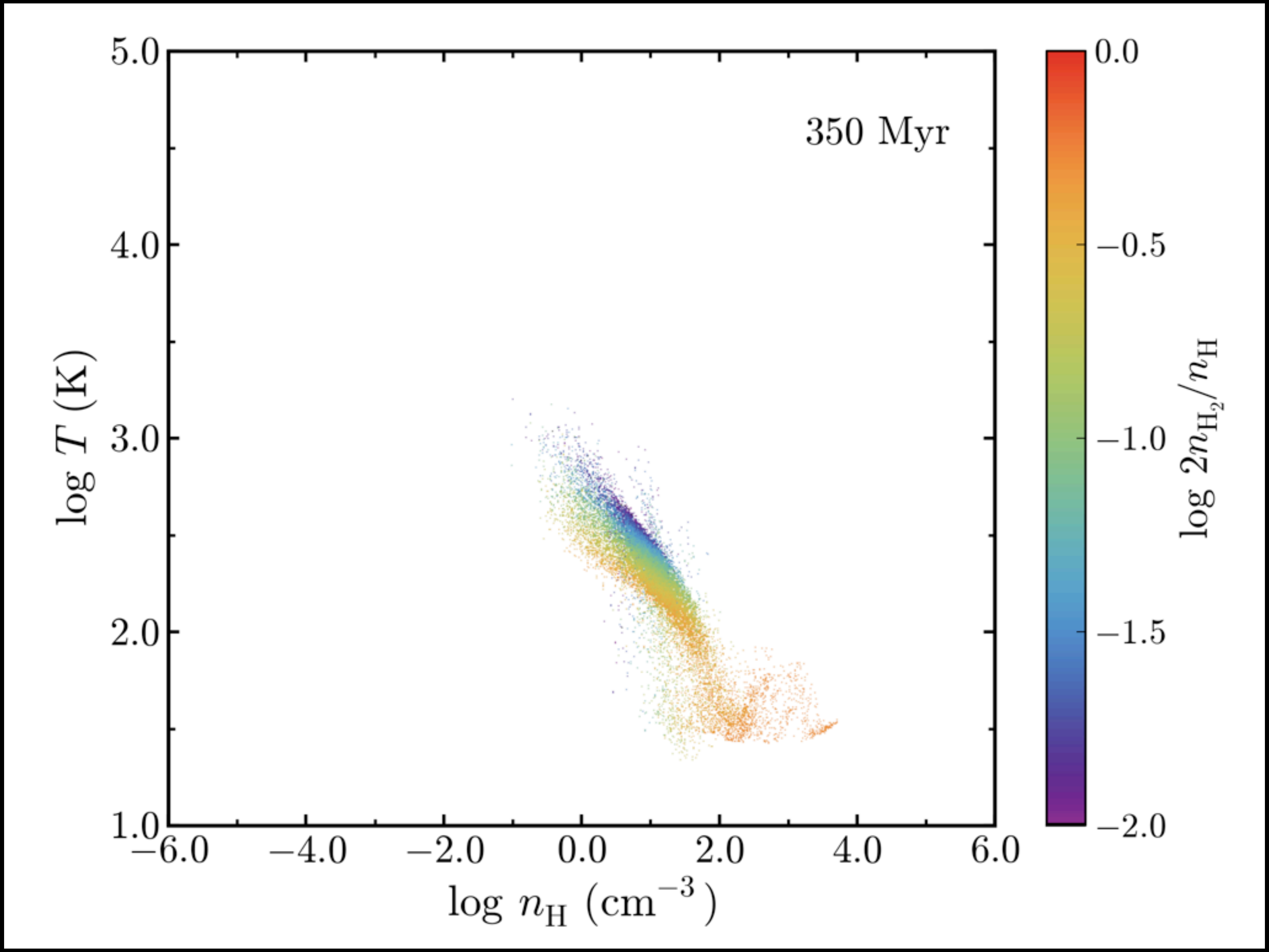
Temperature-Density

HI



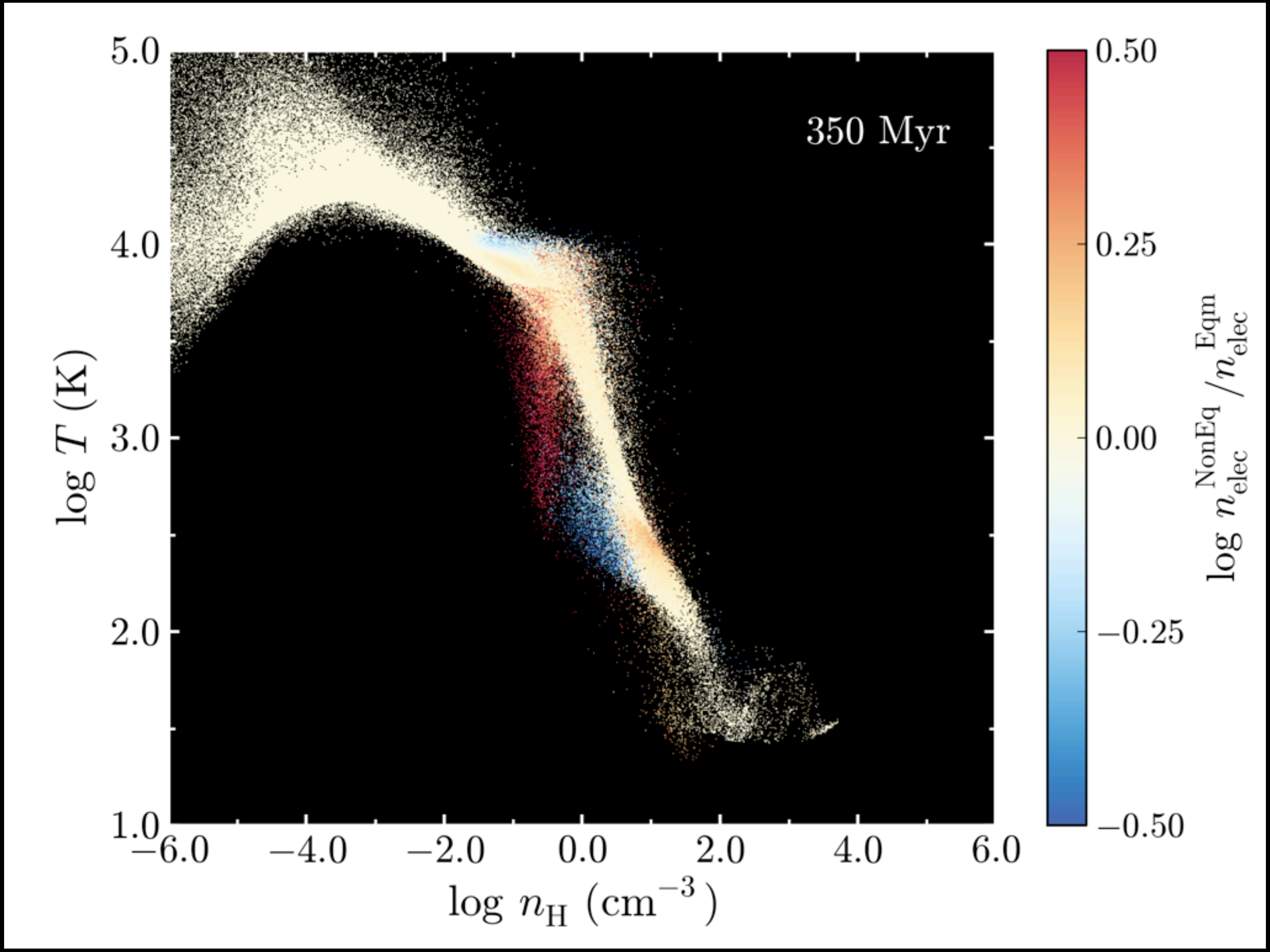
Temperature-Density

H_2



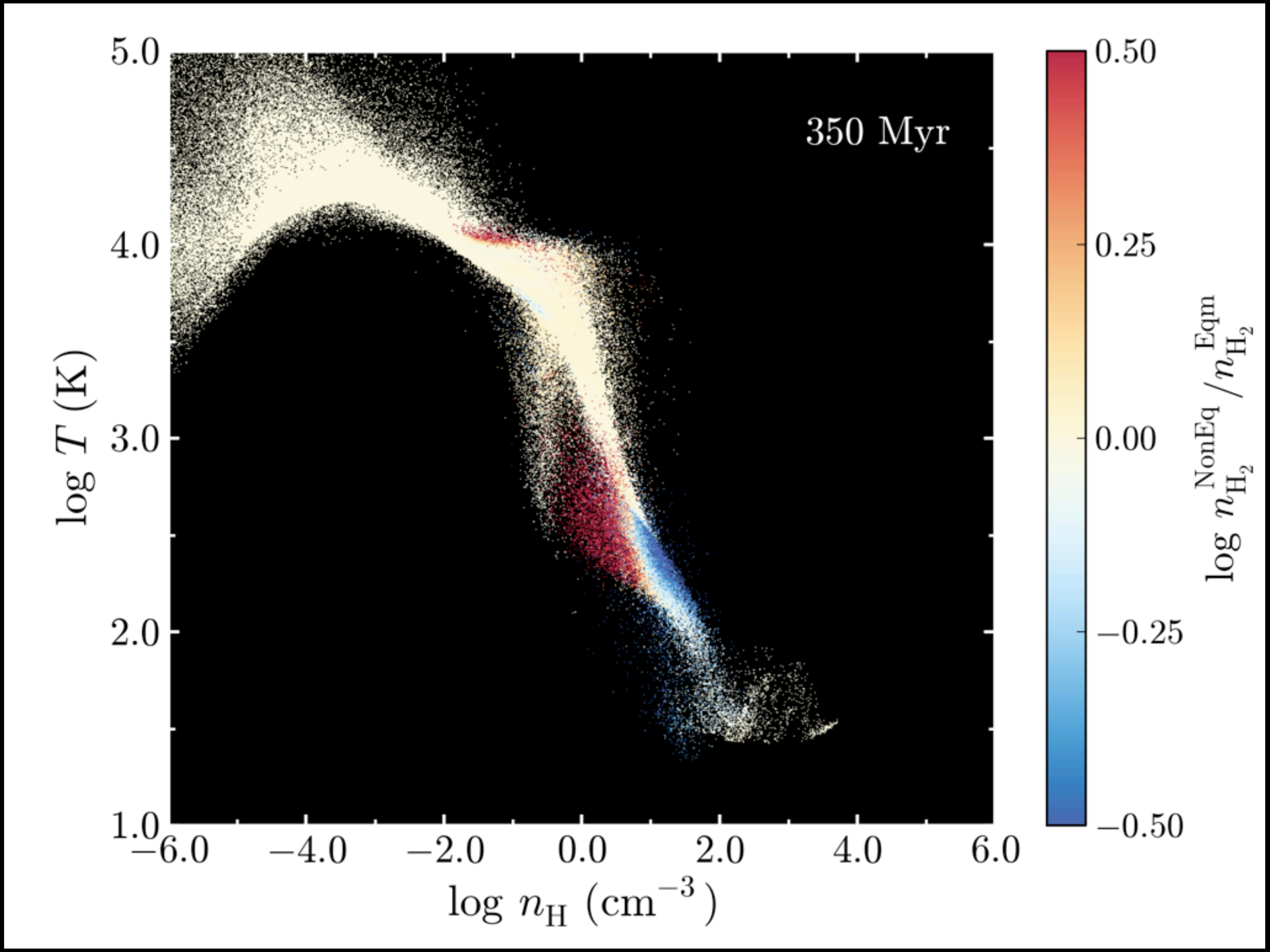
Temperature-Density

Non-equilibrium abundances: electrons



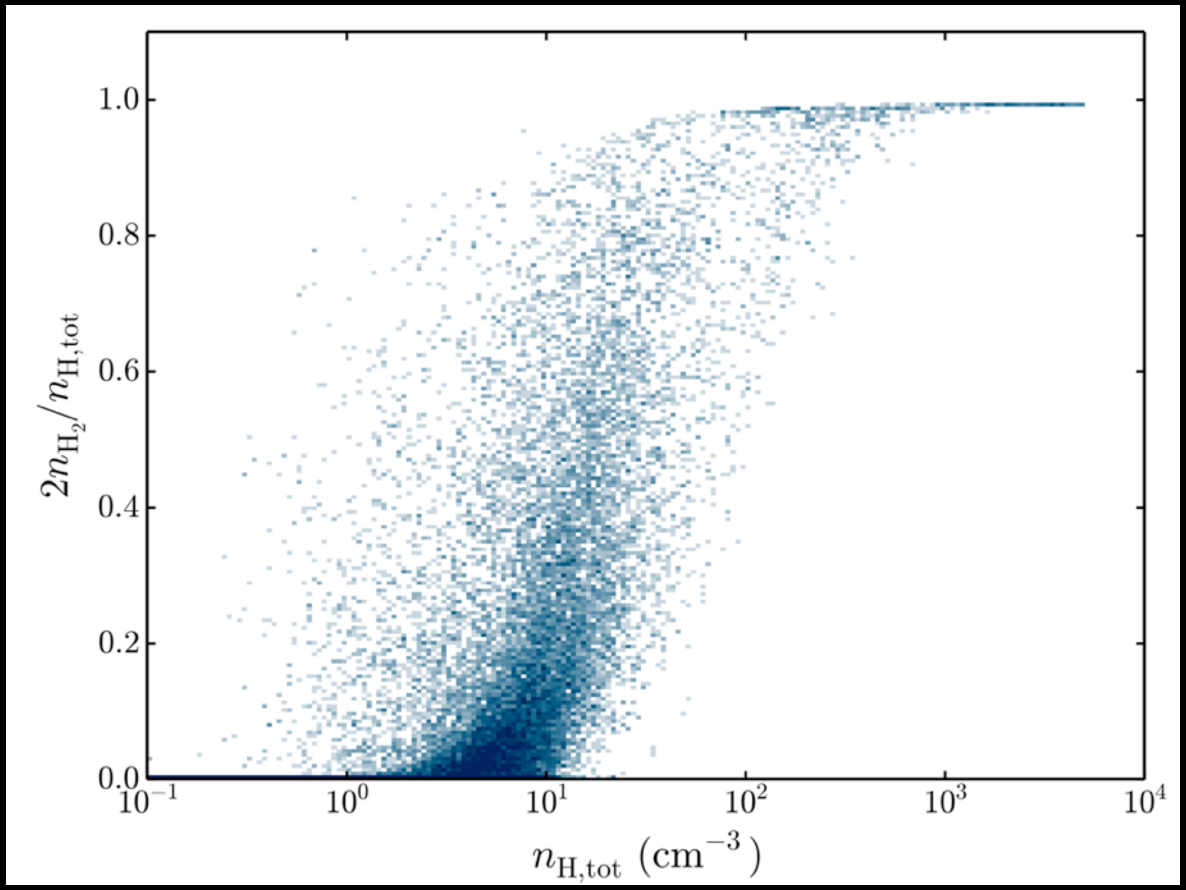
Temperature-Density

Non-equilibrium abundances: H_2

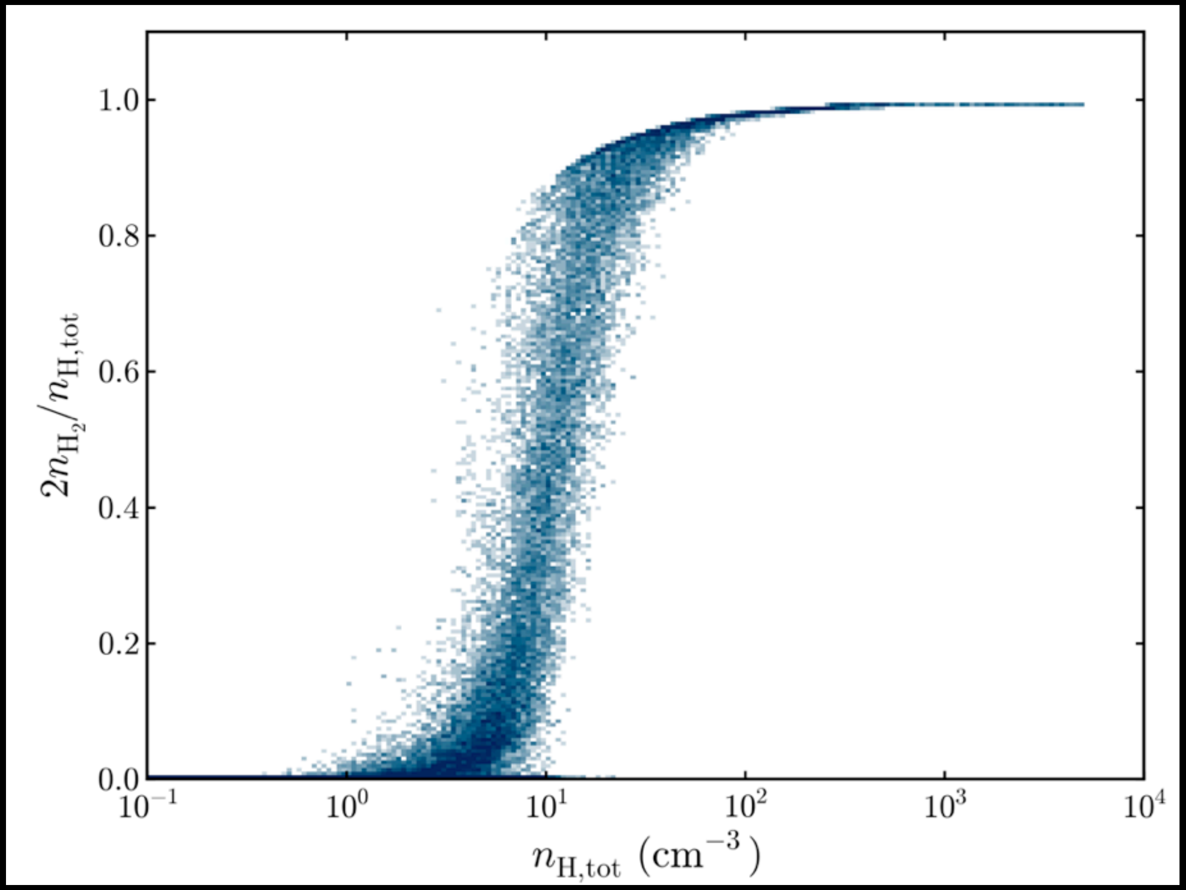


Molecular Gas

Non-Equilibrium



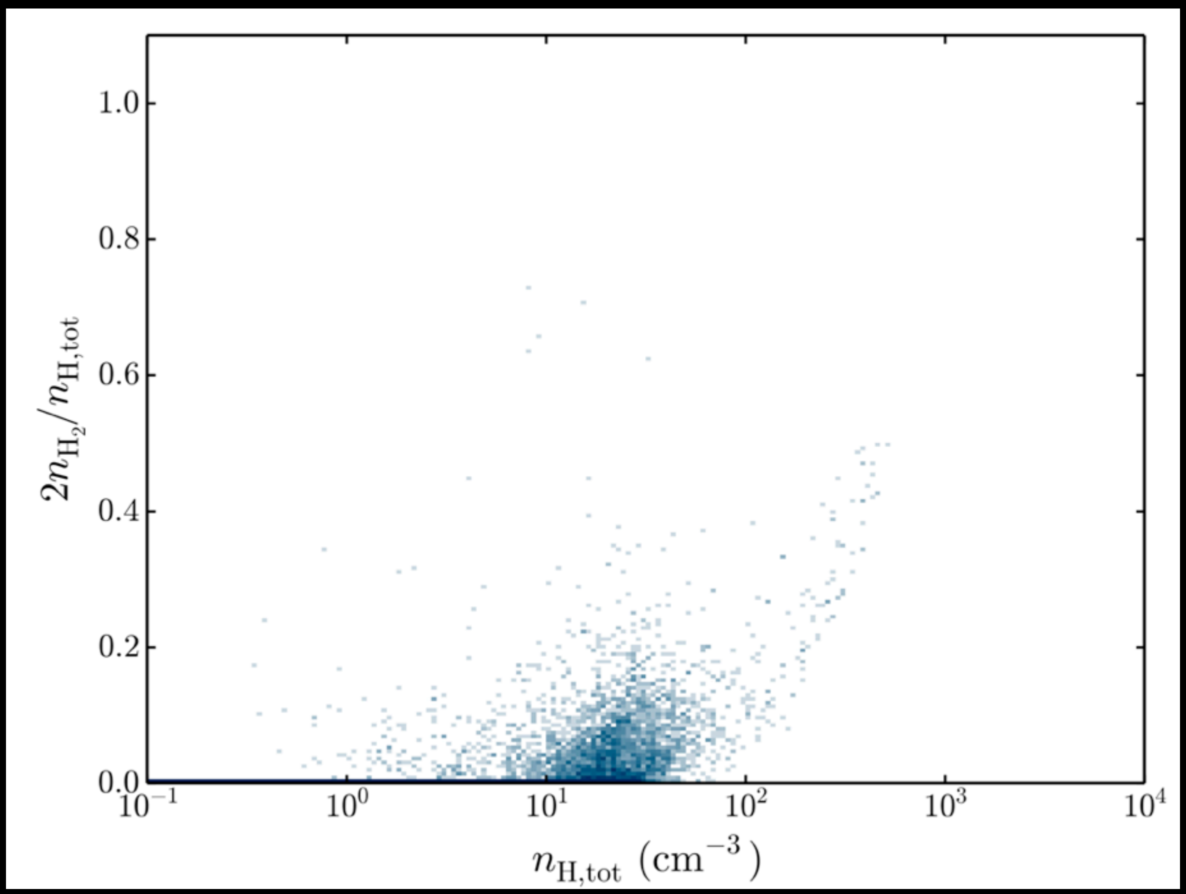
Equilibrium



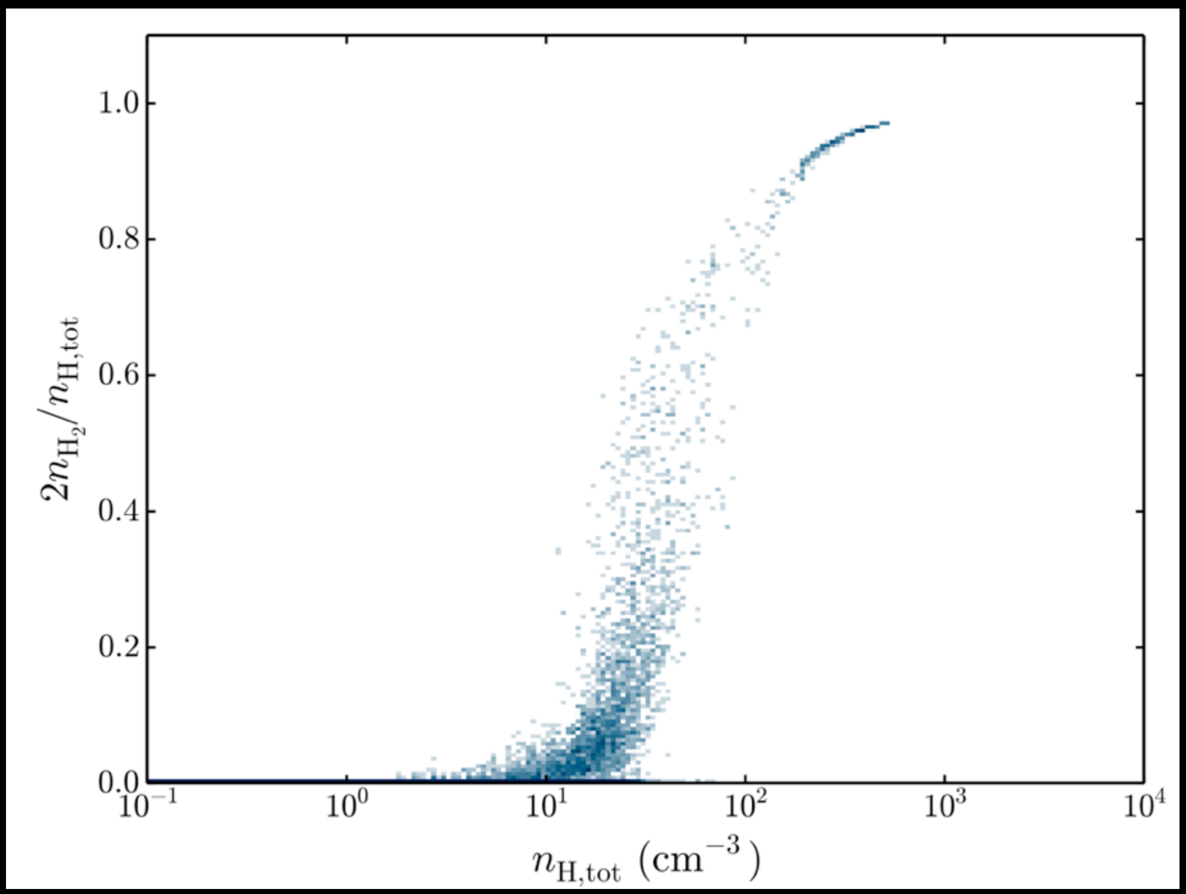
1.0 $Z_{\odot}$

Molecular Gas

Non-Equilibrium

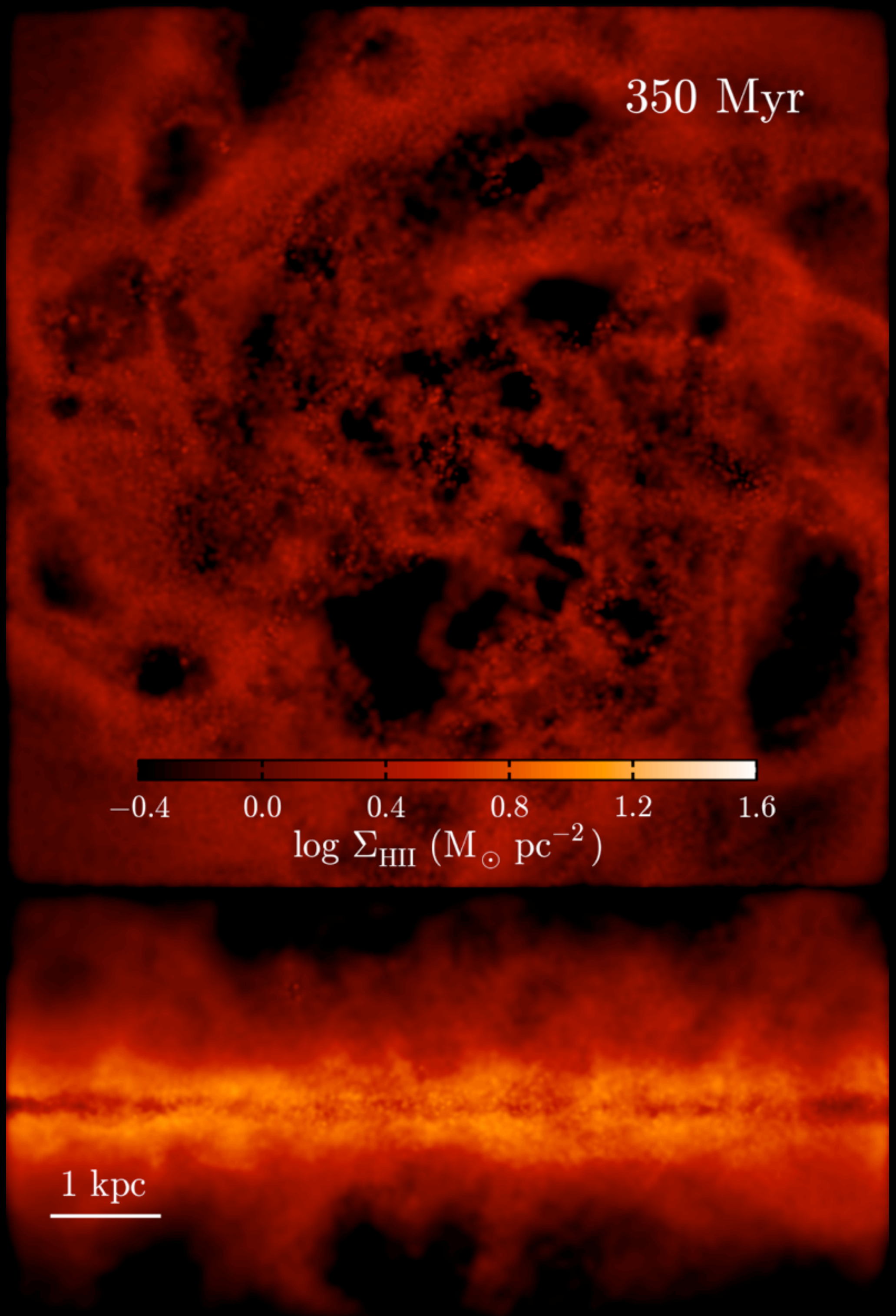


Equilibrium



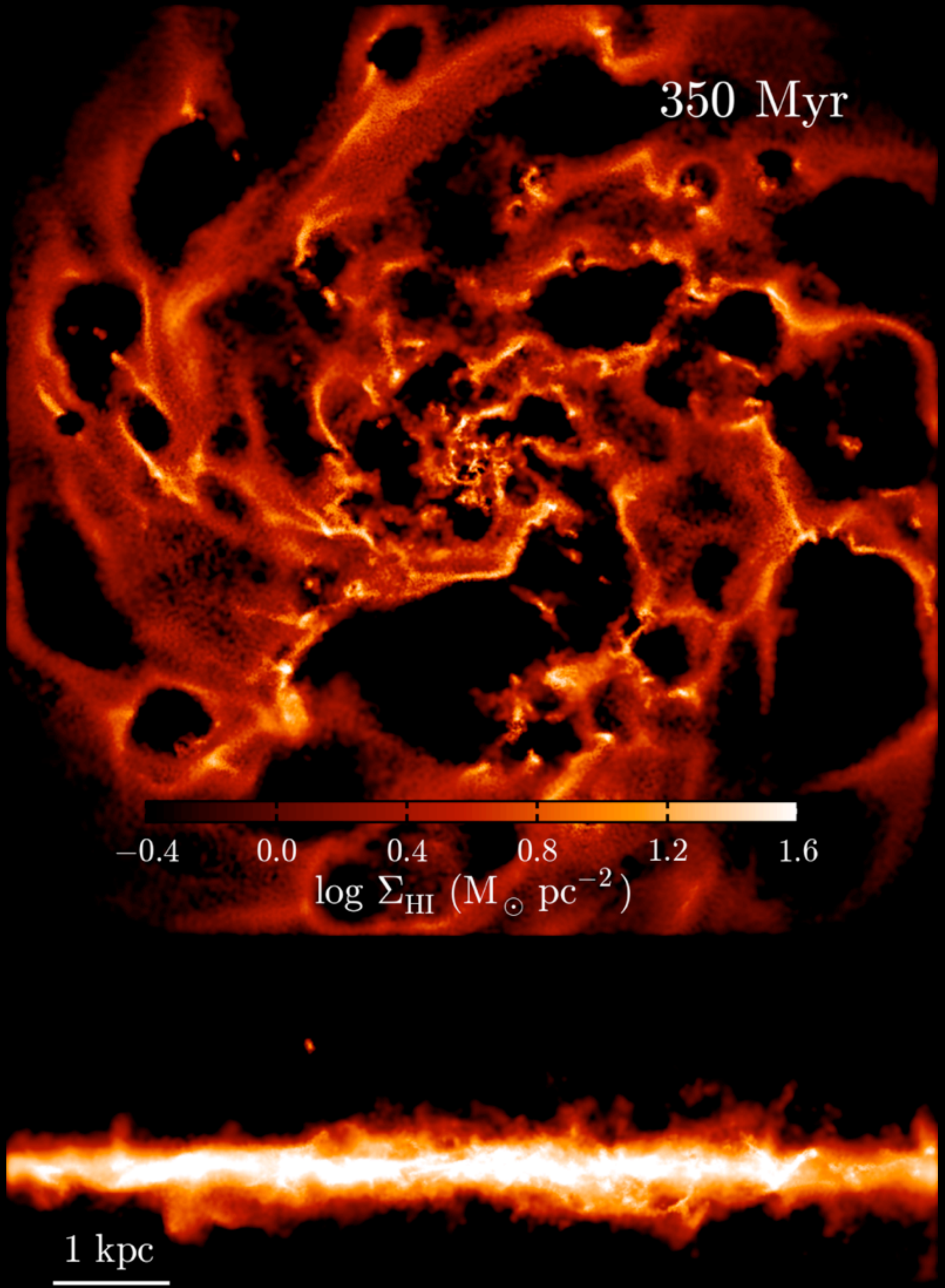
0.1 $Z_{\odot}$

HII Surface Density



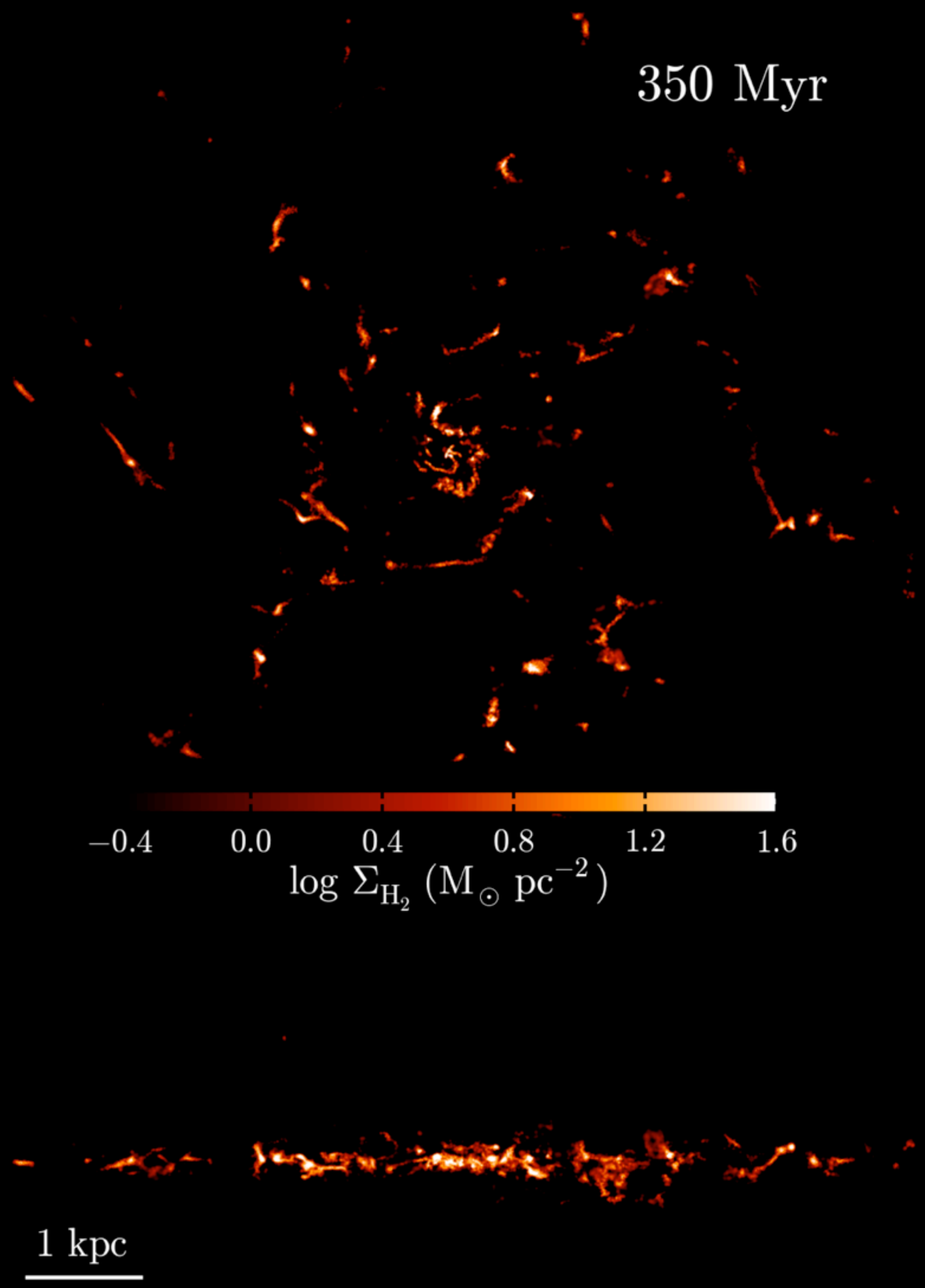
1.0 $Z_{\odot}$

HI Surface Density



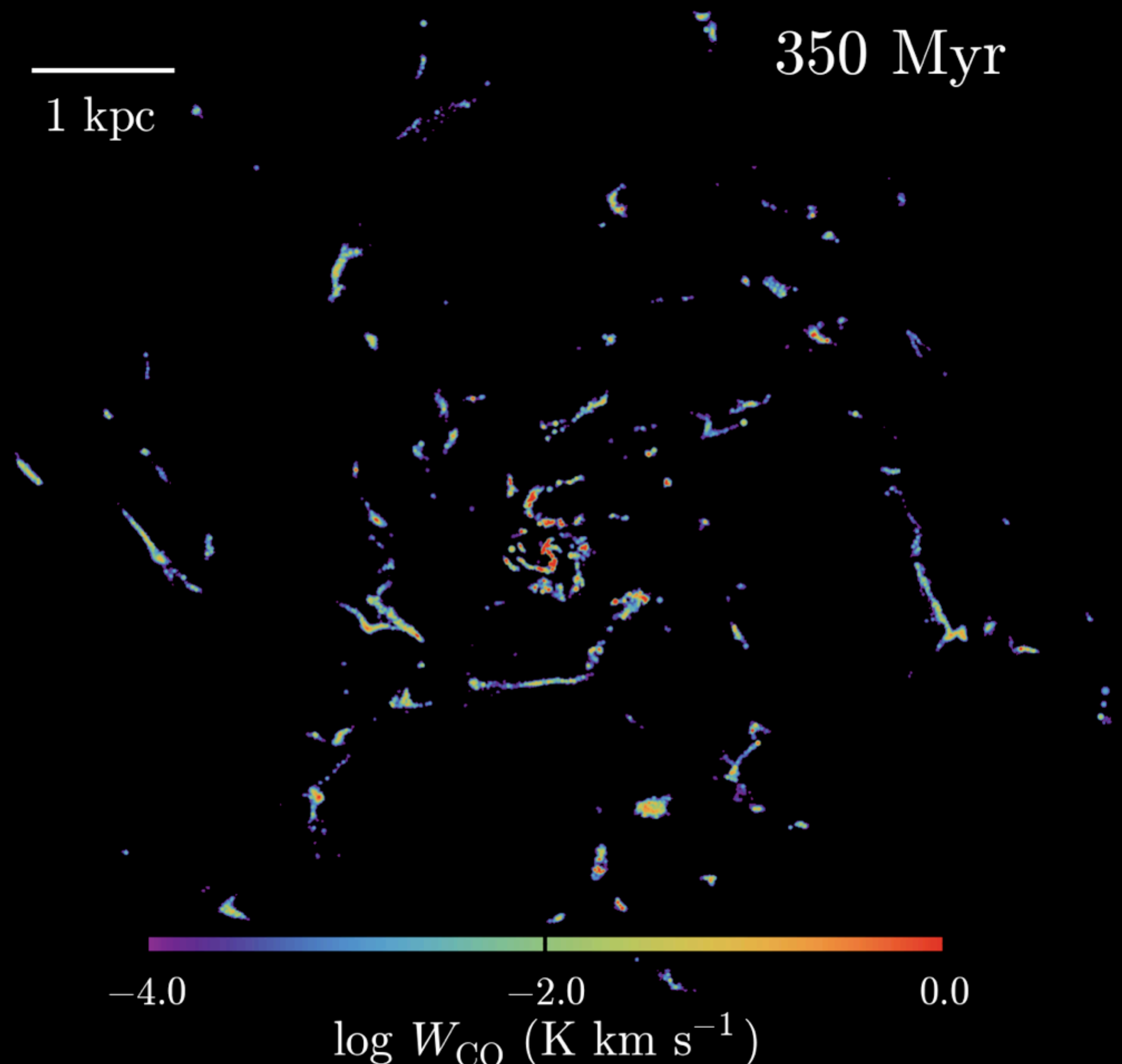
1.0 $Z_\odot$

H_2 Surface Density



1.0 $Z_\odot$

CO Emission



$1.0\ Z_{\odot}$

CO Emission

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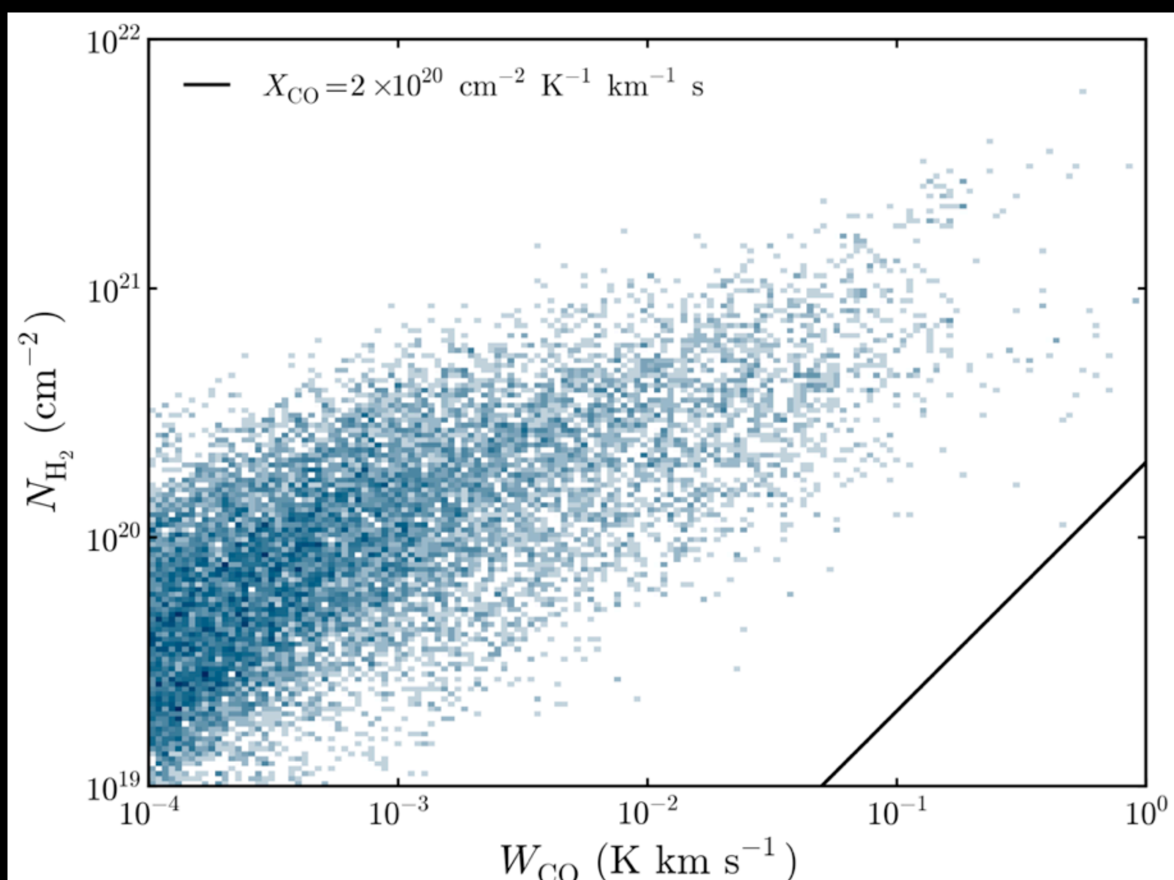
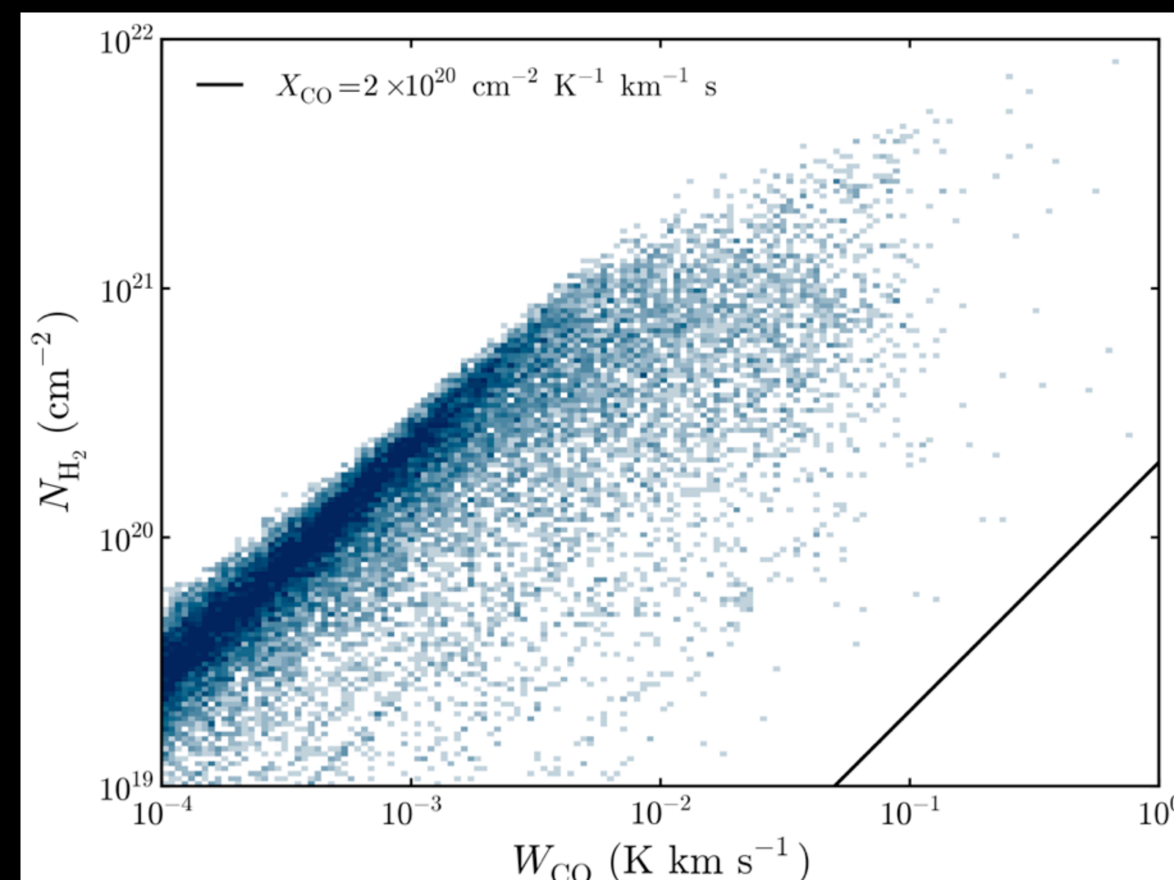
Non-Equilibrium

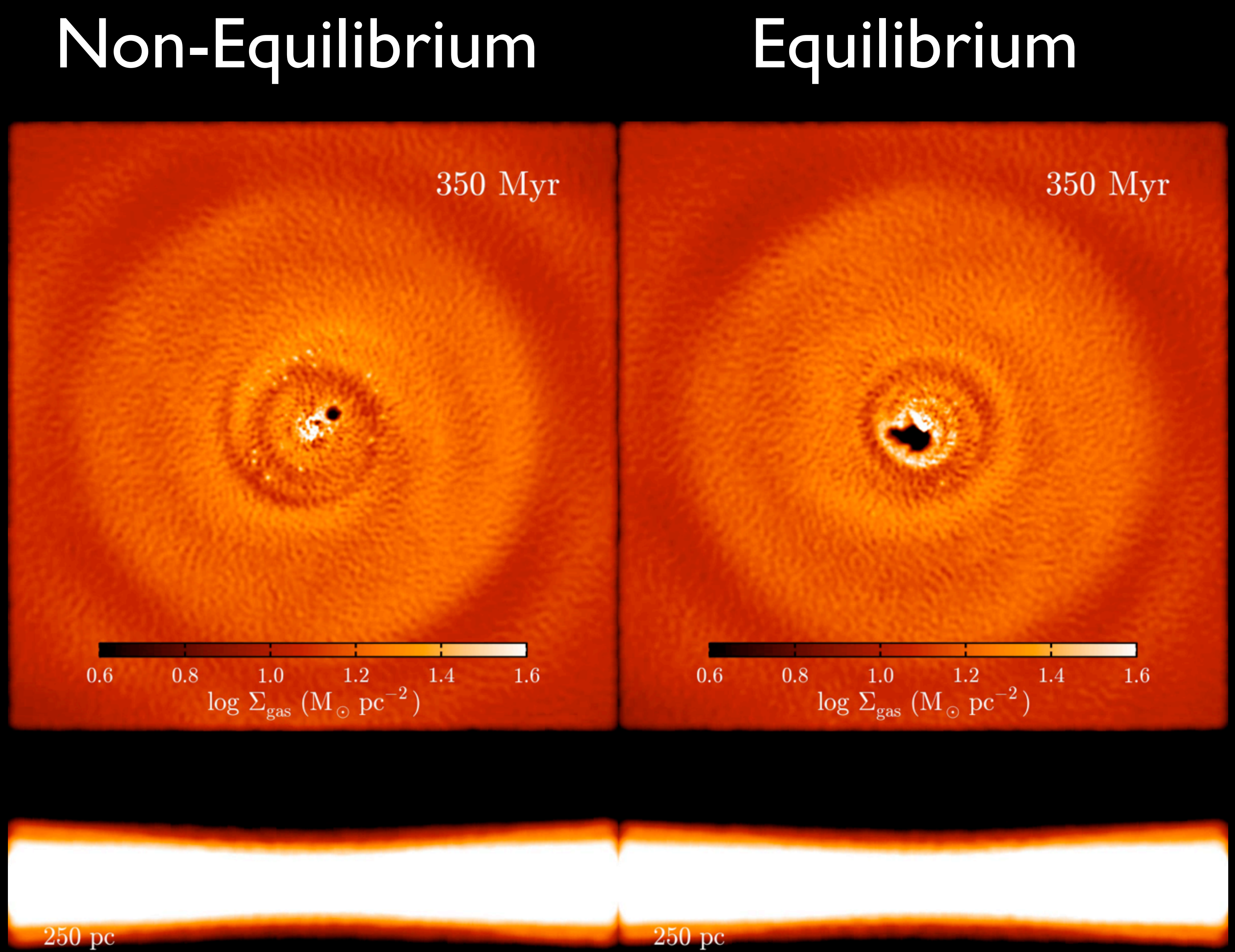


Equilibrium



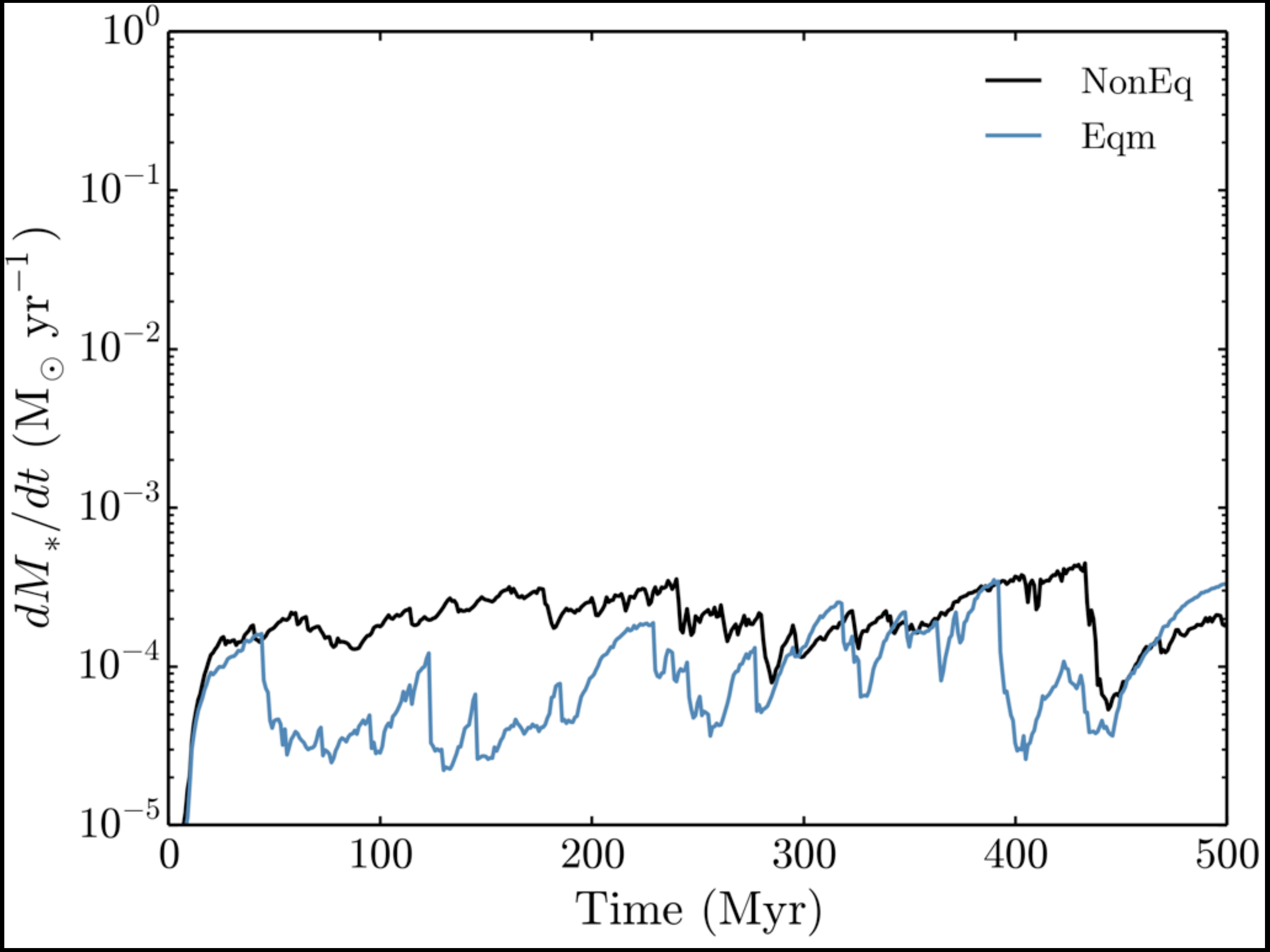
1.0 $Z_{\odot}$

Impact of Non-Equilibrium Cooling

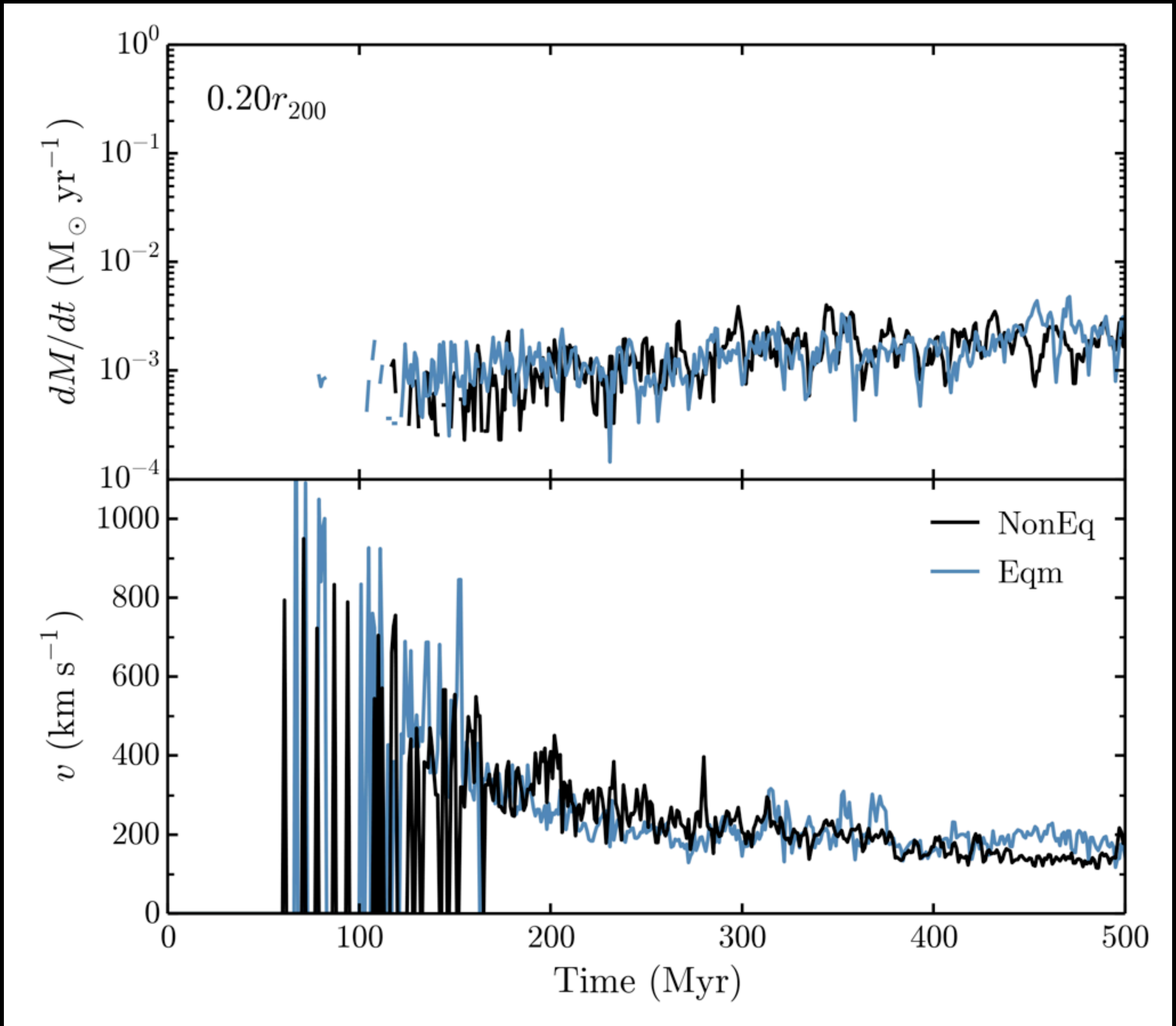


0.01 $Z_\odot$

Impact of Non-Equilibrium Cooling



Impact of Non-Equilibrium Cooling



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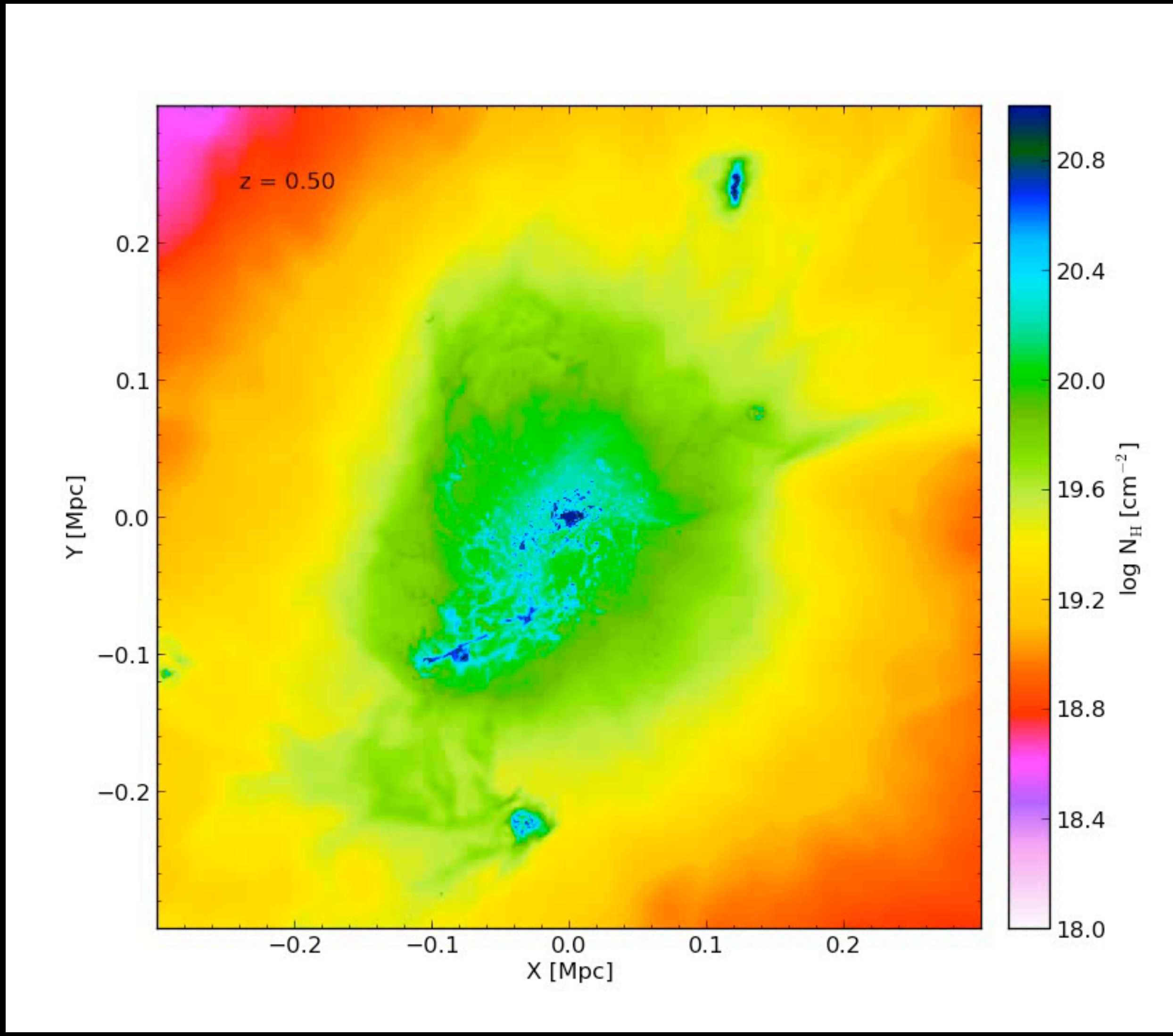
III: Cosmological Zoom-In Simulations

Zoom-In Simulations

- Haloes taken from the EAGLE simulations (Schaye et al. 2015).
- $M_{200} = 10^{12.3}\ M_{\odot}$.
- $m_{SPH} = 3 \times 10^{4}\ M_{\odot}$ in the high resolution region.
- Evolve with non-equilibrium chemistry from z = 0.5 to 0.



Ben Oppenheimer

Zoom-In Simulations

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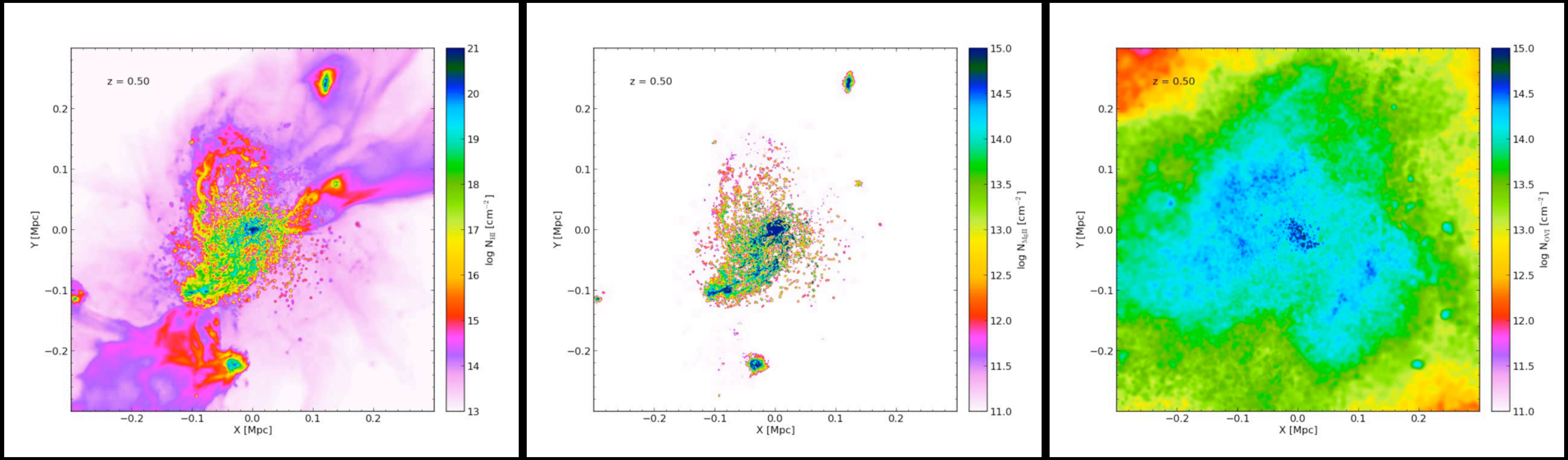
HI | MgII | OVI



Ben Oppenheimer

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Summary

I: Chemical Model

- Important coolants include CII, FeII, SiII, OI & H2.
- Recombination lags can enhance the cooling rate below 10^4 K by up to two orders of magnitude.

II: Isolated Galaxies

- H_2 abundances are further from equilibrium at low metallicities.
- There is more scatter in the N_{H2} - W_{CO} relation when we use non-equilibrium abundances.

III: Cosmological Simulations

- We can predict column densities of ions in the CGM.