Cosmological simulations of X-ray heating during the Universe's "Dark Ages"

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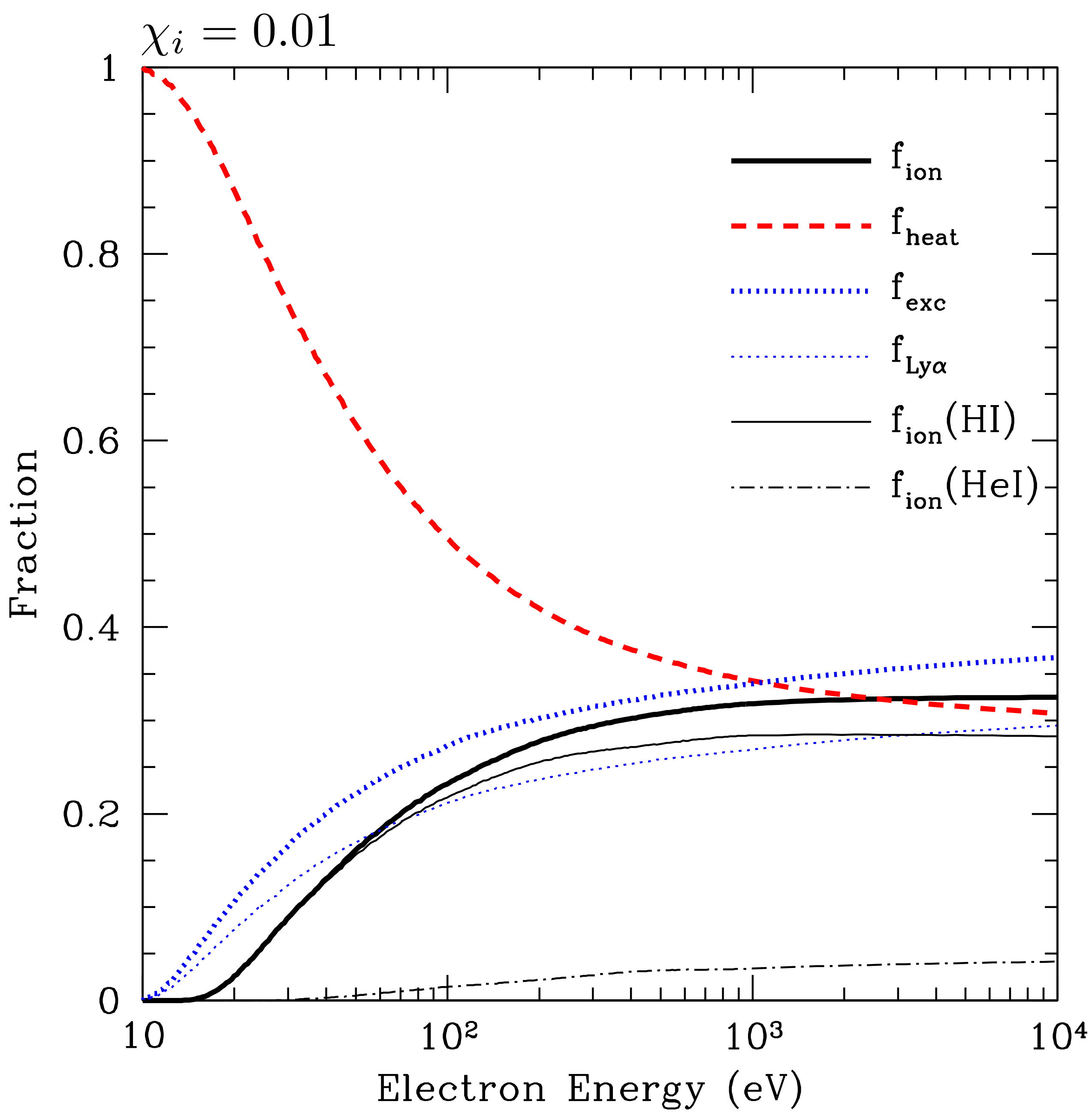
Outline

- Introduction: Dark Ages, X-ray heating
- Methods
- Preliminary results
- Future work

Dark Ages/Reionization

Loeb, 2006

X-ray heating



Energy deposition fractions for secondary electrons as a function of energy. From Furlanetto & Stoever, 2010.

- Due to their long mean free paths, X-rays (SN, BH-accretion, PopIII) are expected to be the dominant heating mechanism at high redshift.
- Likely to ionize He, producing fast electrons, E > 10eV.

The 21cm Signal

- Fundamental quantity - the HI differential brightness temperature:

$$\delta T_b = 27 x_{HI} (1+\delta) \left(\frac{\Omega_b h^2}{0.023} \right) \left(\frac{0.15}{\Omega_m h^2} \frac{1+z}{10} \right)^{1/2} \left[1 - \frac{T_\gamma(z)}{T_S} \right] \ \mathrm{mK}$$

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-T_\star / T_S}$$

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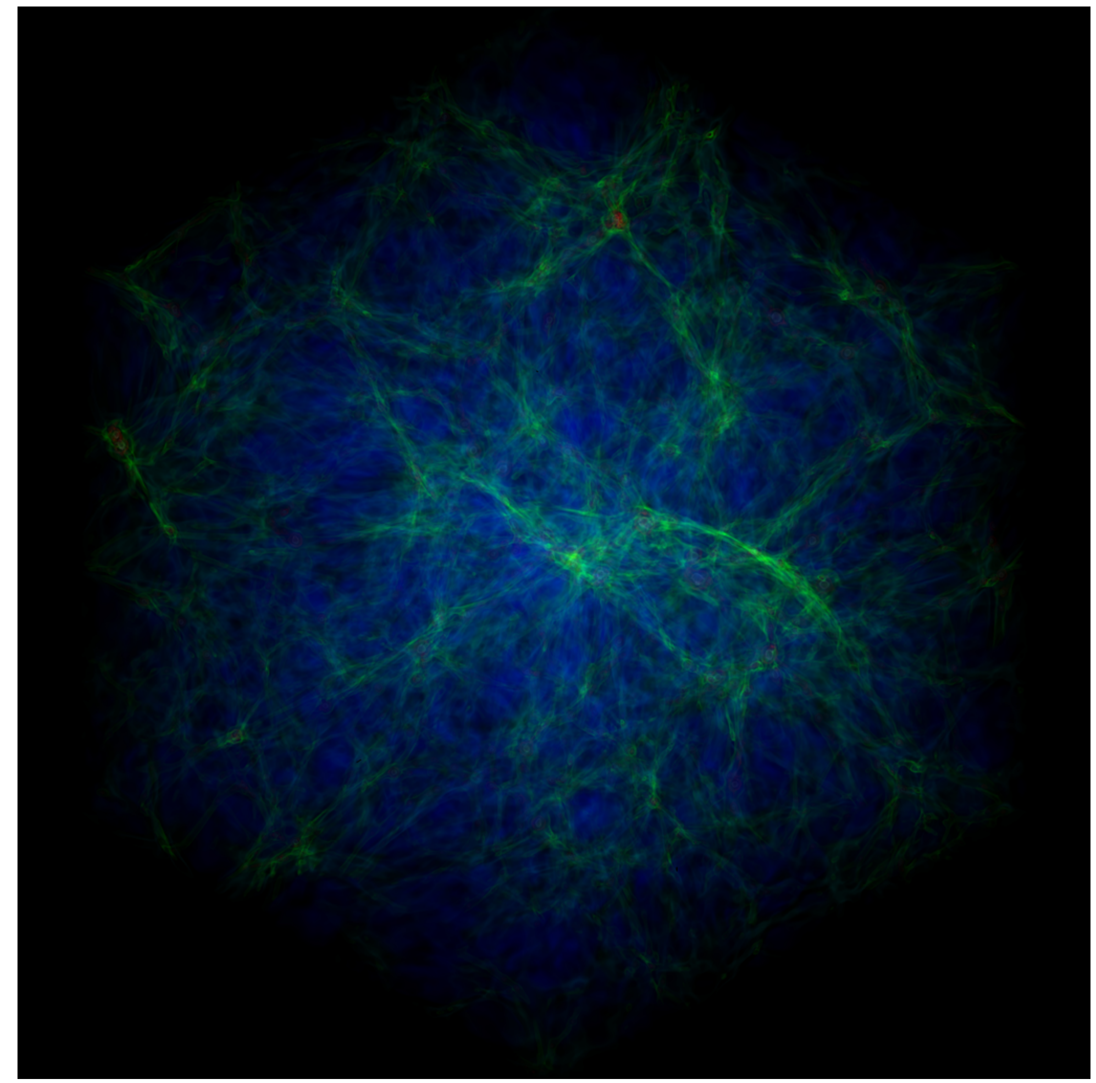
enzo

- Cosmological, hydrodynamics (Eulerian) + N-body, adaptive-mesh-refinement (AMR).
- Adaptive ray-tracing radiative transfer method (Abel & Wandelt 2002)
- Secondary ionizations calculated via Shull & van Steenberg 1985 formulae.



Volume rendering of a cosmological simulation performed with Enzo. Created by Sam Skillman with the AMR analysis toolkit yt, which we also use in this work.

Preliminary Simulations

Cells	Box Size
1024^3	60 Mpc/h

$\downarrow$

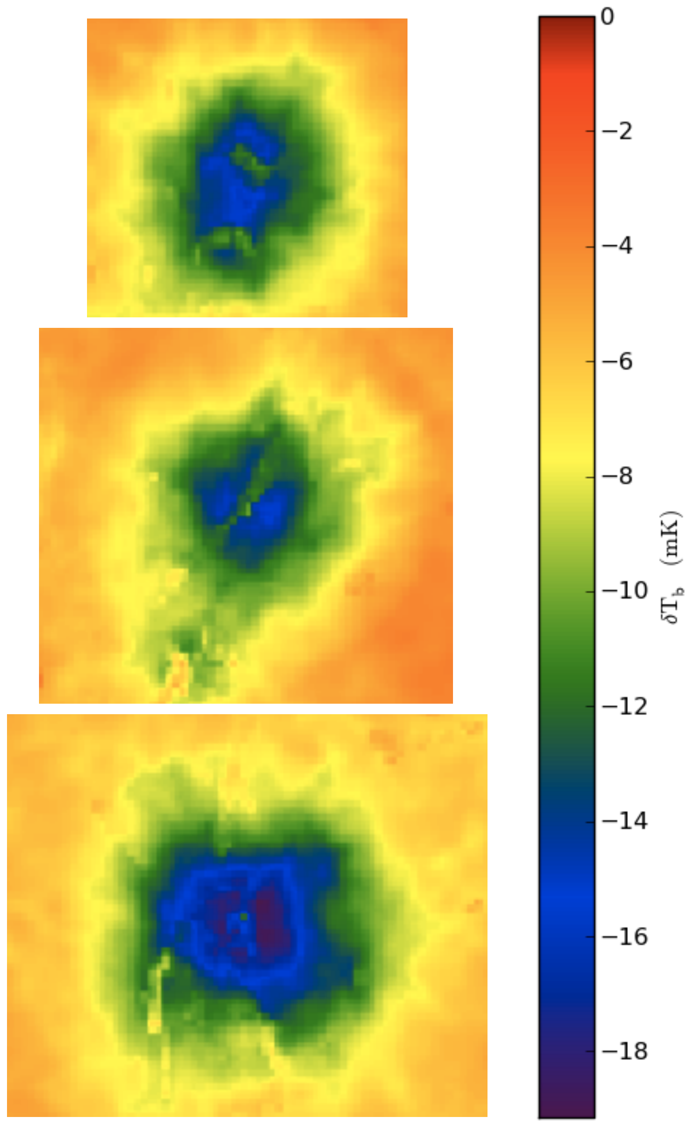
Mass Resolution

$\sim 1.8 \times 10^7 M_\odot$

- Use friends-of-friends (FOF) halo finder inline with Enzo to populate halos with radiative particles.
- These "MBH" particles are inserted in all halos above threshold mass of $2 \times 10^9 M_\odot$ (so they are resolved with > 100 particles).

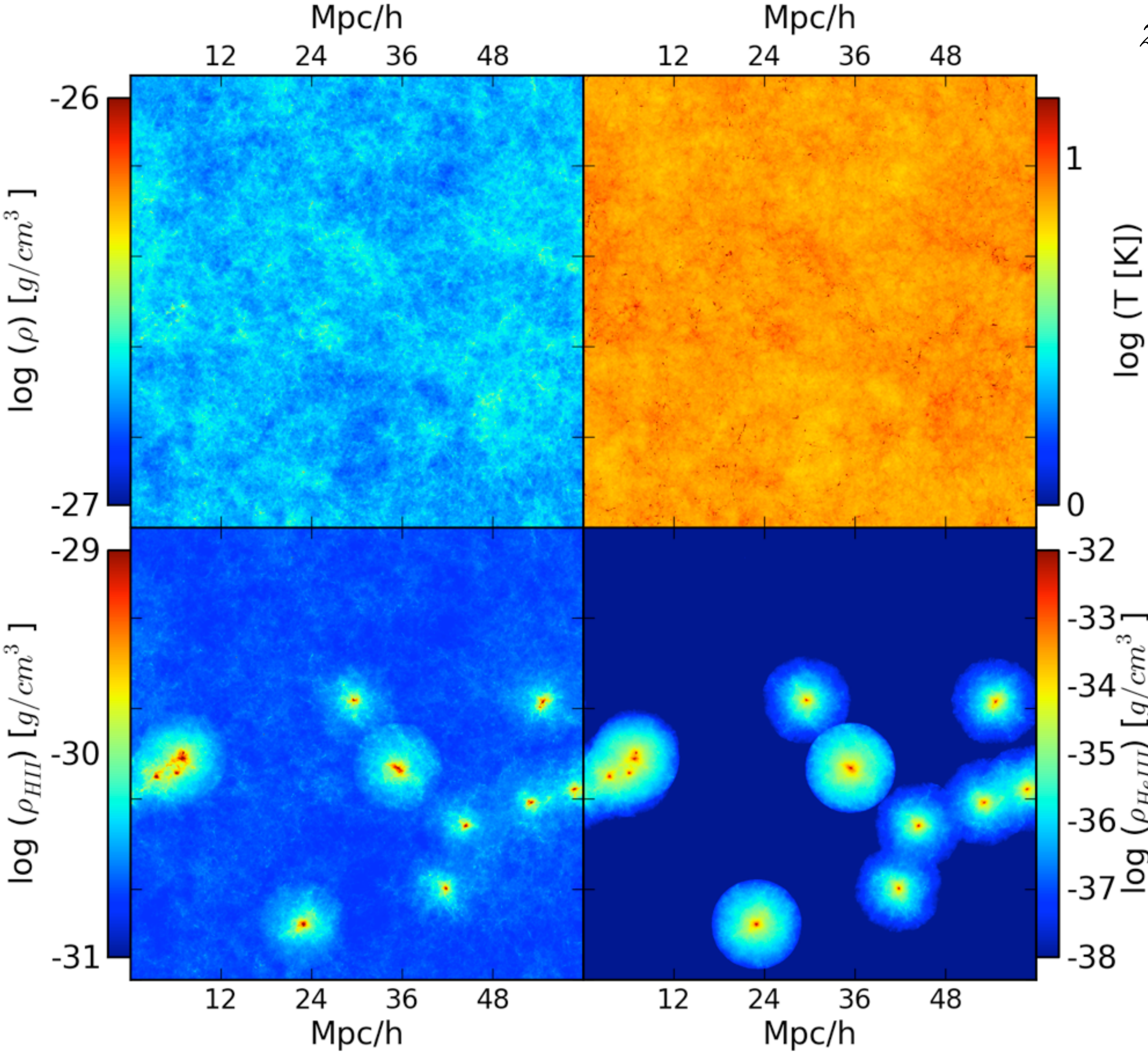
Preliminary Simulations

- Assuming 10^5 M_{sun} black holes undergoing Eddington accretion with a radiative efficiency of 10%.
- Currently using single energy bin spectrum, with 10% of the total luminosity emitted at 0.5 keV.

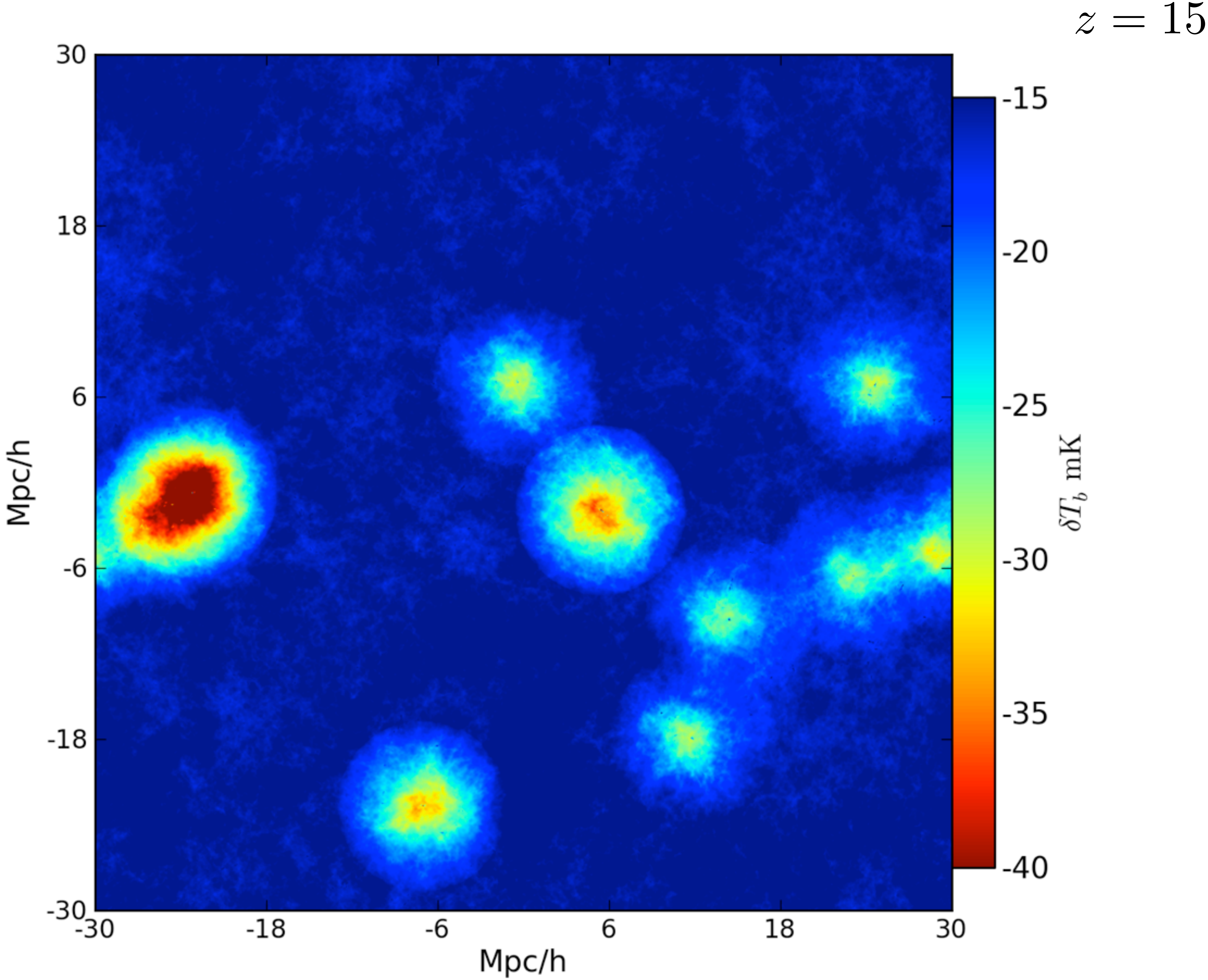


Projections of the differential brightness temperature around individual sources with softer specra (0.1 - 0.2 keV) from a 256^3, 20 Mpc/h box test simulation.

$z = 15$

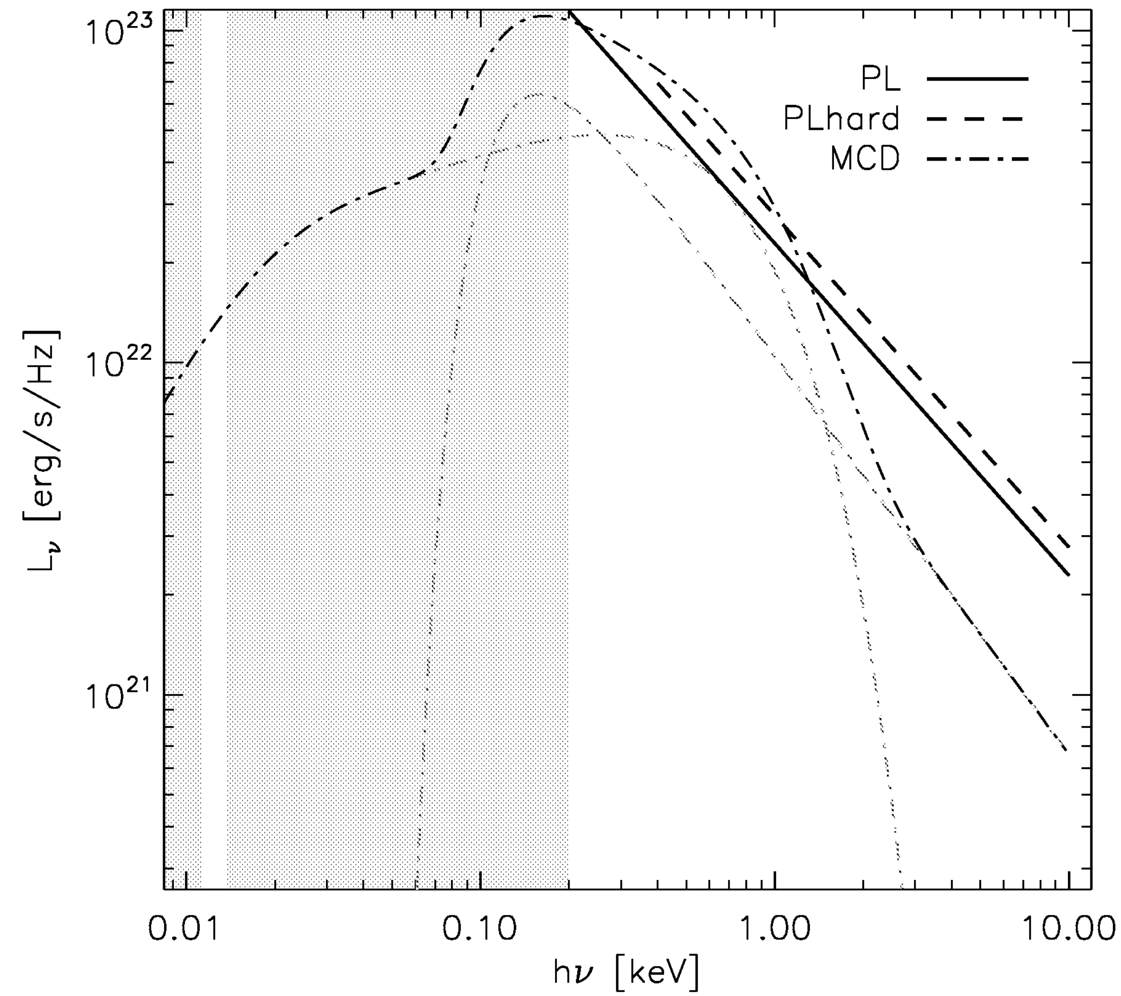


Mpc/h
12
24
36
48
Mpc/h
12
24
36
48
log (ρ) [g/cm^3]
-26
-27
log (T [K])
1
0
log (ρ_{HII}) [g/cm^3]
-29
-30
-31
log (ρ_{HeIII}) [g/cm^3]
-32
-33
-34
-35
-36
-37
-38
12
24
36
48
Mpc/h
12
24
36
48
Mpc/h


$z = 15$
Mpc/h
Mpc/h
30
18
6
-6
-18
-30
-30
-18
-6
6
18
30
δT_b mK
-15
-20
-25
-30
-35
-40

Upcoming Work

- Future work will implement a more complex, multi-energy bin spectrum.
- Average quasar spectrum of Sazonov et al. 2004 may not be appropriate for high-z. Perhaps adopt 'miniquasar' spectrum of Kuhlen & Madau 2005?



Three different spectral templates used to simulate intermediate mass black hole accretion in Kuhlen & Madau, 2005.

Upcoming Work

- Prepare two simulations - one with an abundance of less luminous X-ray sources, another with rare, very luminous sources.
    - Can the global HI signal or angular power spectrum tell them apart reliably?
- Larger volume to improve statistical sampling of the halo mass function more grid cells to maintain (or enhance) mass resolution.

Acknowledgements

- Special thanks to John Wise and Tom Abel for guidance using the adaptive ray tracing scheme in Enzo.
- Additional thanks to Britton Smith and Stephen Skory for their insights on simulating the universe at high redshift.

References

Abel, T. & Wandelt, B. D. 2002, MNRAS, 330, L53

Furlanetto, S. R. & Stoever, S. J. 2010, MNRAS, 404, 1869

Kuhlen, M. & Madau, P. 2005, MNRAS, 363, 1069

Shull, J. M. & van Steenberg, M. E. 1985, ApJ, 298, 268

Wise, J. H. & Abel, T. 2008, ApJ, 685, 40

Radiative Transfer

- Method: Adaptive Ray Tracing (Abel & Wandelt 2002, Wise & Abel 2008)
- Conserve photon flux along rays, branching only when necessary to maintain accuracy of integration.

$$\frac{1}{c}\frac{\partial N_p}{\partial t} + \frac{\partial N_p}{\partial r} = -\kappa N_p$$

R.T.E. for the photon number flux, N_p, and absorption coefficient, κ.

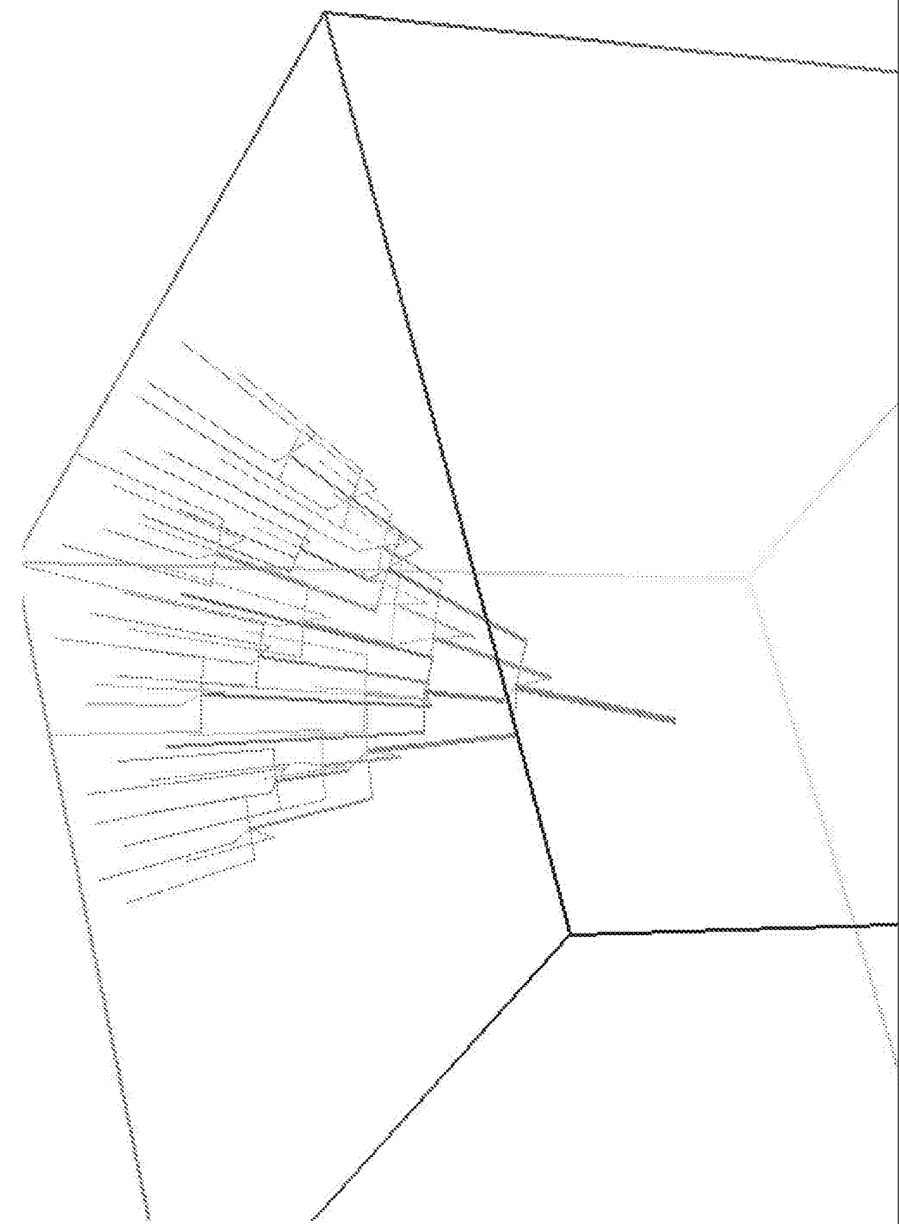
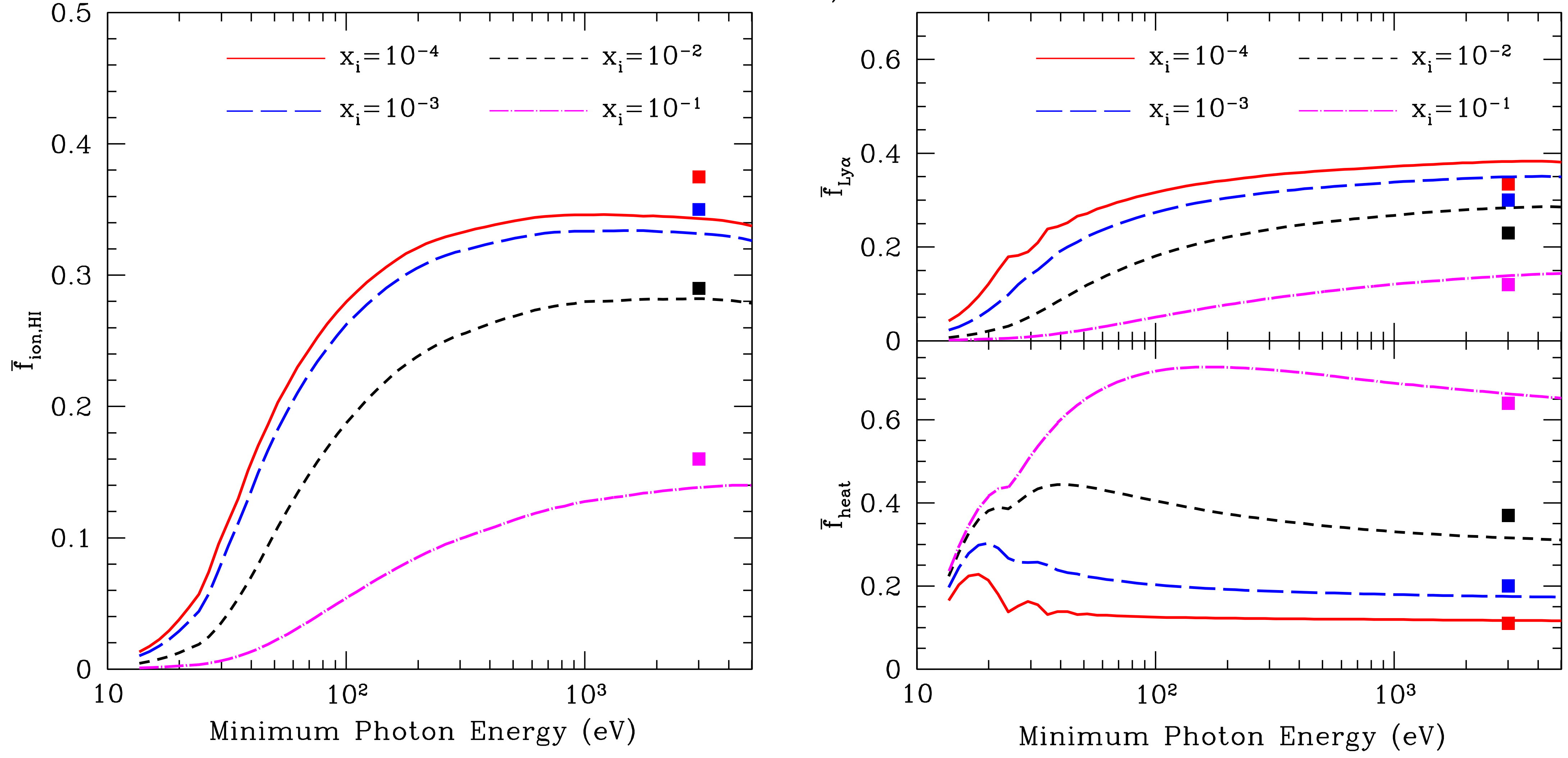


Illustration of a single parent ray spawning many child rays to sample the underlying grid. From Abel & Wandelt, 2002.

X-ray heating

$$L_\nu \propto \nu^{-\alpha}; \alpha = 1.5$$



Energy deposition fractions in ionization, Lyman-alpha, and heat for secondary electrons integrated over sample power law UV/X-ray spectrum. From Furlanetto & Stoever, 2010.

Calculating T_S

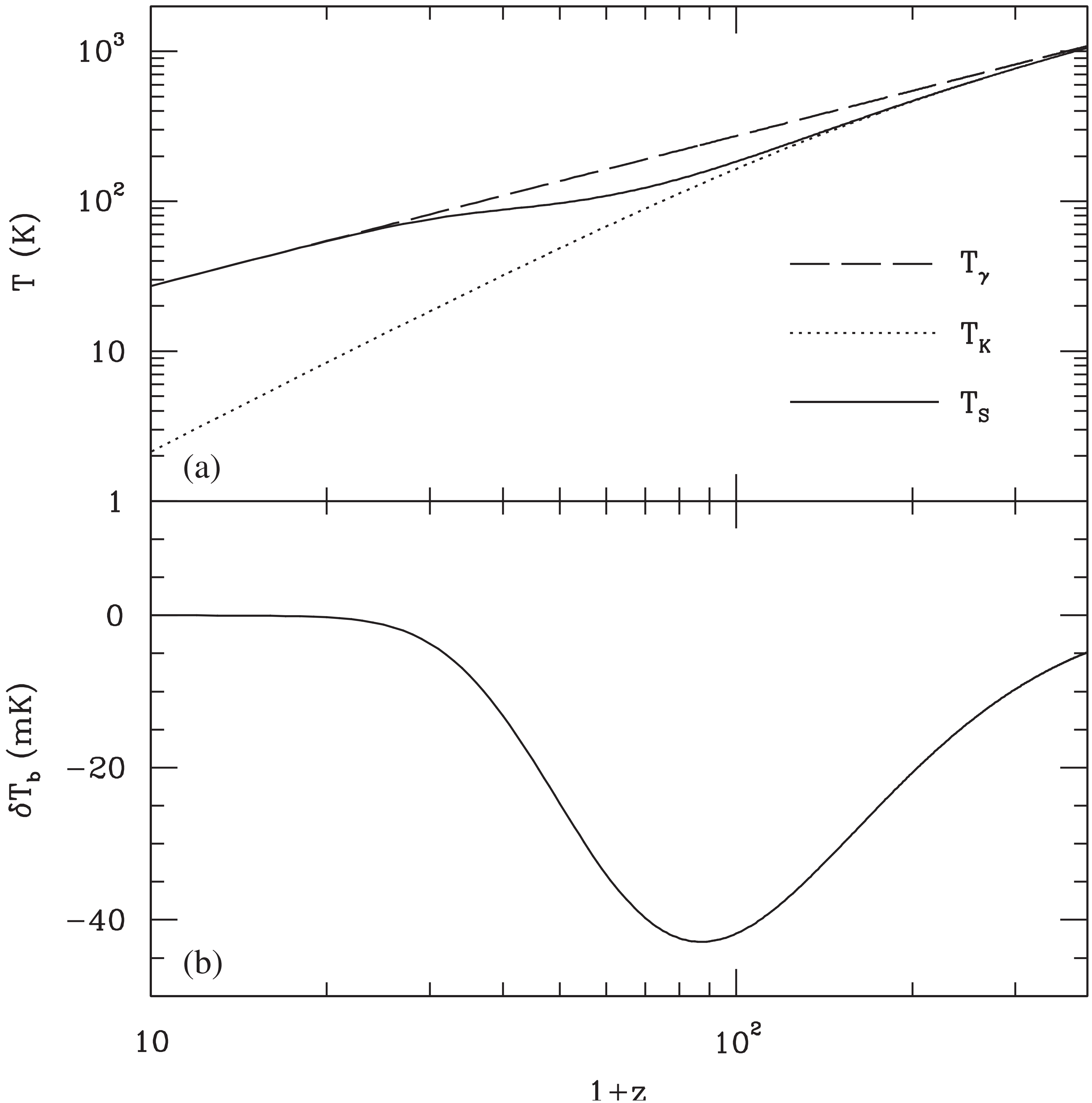
- Enzo is able to track e^-, HI, HII, HeI, HeII, and HeIII abundances in each grid cell.
- Vital in calculating T_S, since H-e^- and H-H collisions are the dominant means of mixing hyperfine levels.

$$T_S^{-1} \approx \frac{T_\gamma^{-1} + x_c T_K^{-1}}{1 + x_c}$$

T_S also depends on x_α, a coupling coefficient for UV scattering, and T_C, the UV color temperature. We neglect them now since sources emit at 0.5 keV only.

$$x_c^i = \frac{n_i \kappa_{10}^i}{A_{10}} \frac{T_\star}{T_\gamma}$$

Coupling coefficient for species i, x_c^i, where κ_{10}^i is the rate coefficient for spin de-excitation for species i (Furlanetto, 2006).



T (K)
10^3
10^2
10
1
T_γ
T_K
T_S
(a)
δT_b (mK)
0
−20
−40
(b)
10
10^2
1+z

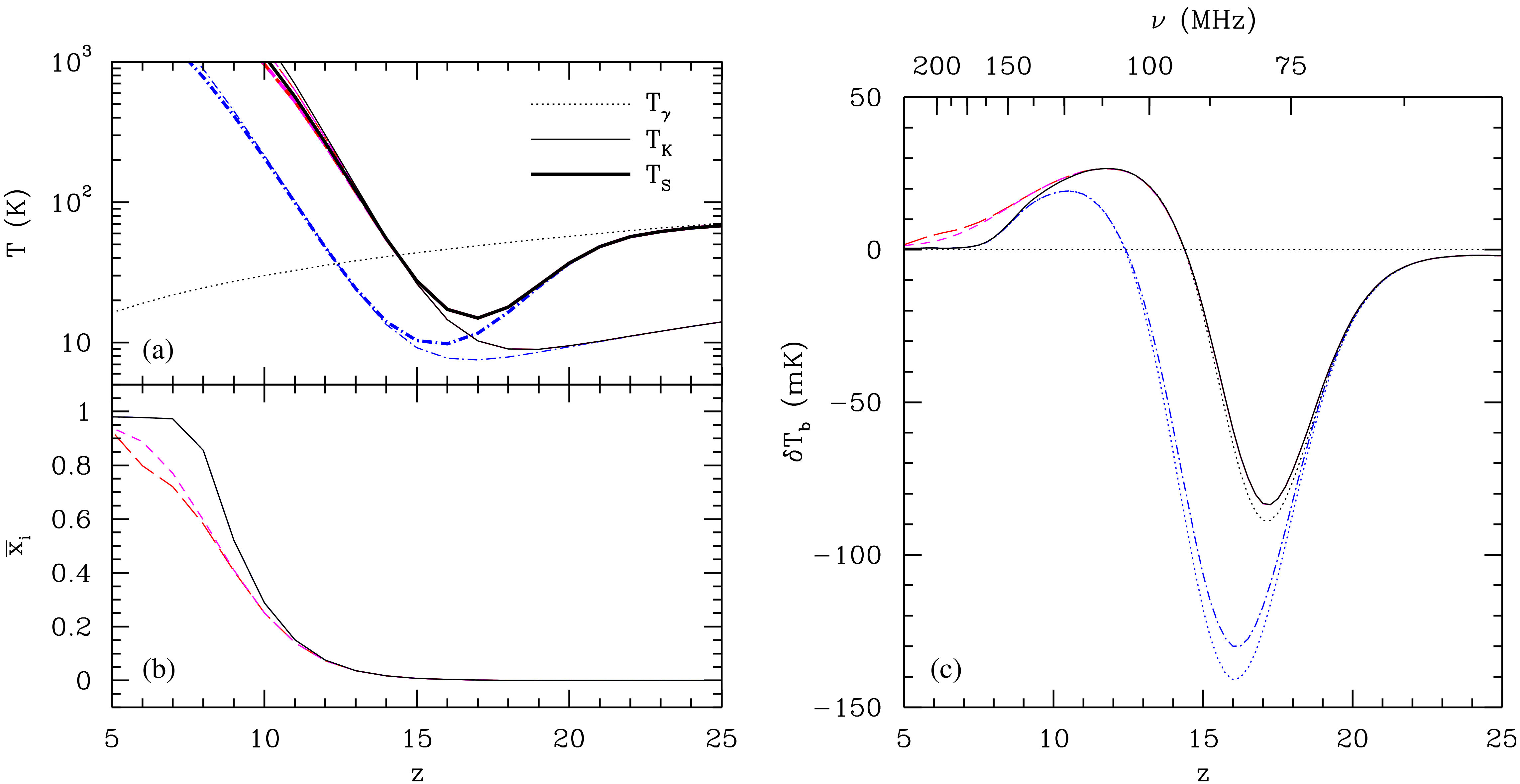


Fig. 7. Global IGM histories for Pop II stars. The solid curves take our fiducial parameters without feedback. The dot–dashed curve takes $f_X = 0.2$. The short- and long-dashed curves include strong photoheating feedback: (a) thermal properties; (b) ionized fraction; (c) differential brightness temperature against the CMB. In this panel, the two dotted lines show δT_b without including shock heating. From [270].