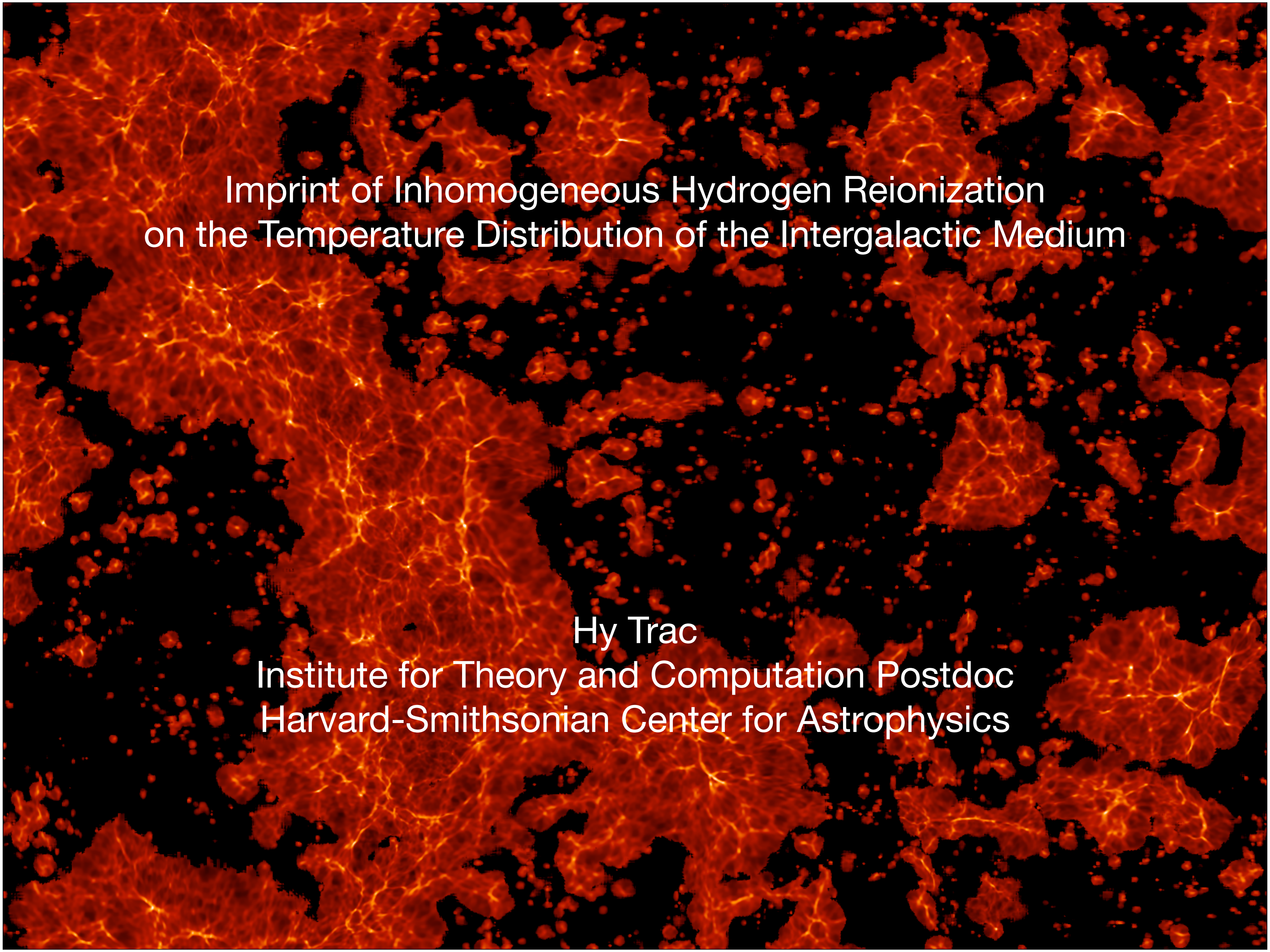
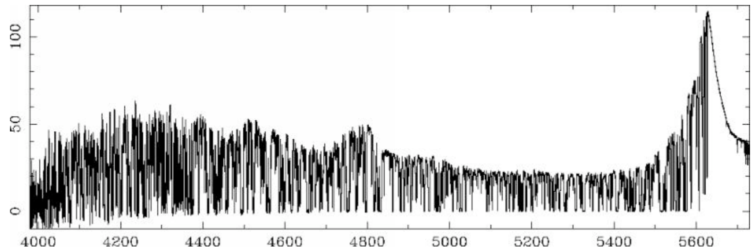


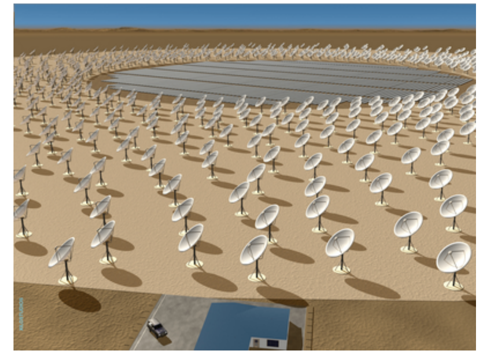
Imprint of Inhomogeneous Hydrogen Reionization on the Temperature Distribution of the Intergalactic Medium

Hy Trac
Institute for Theory and Computation Postdoc
Harvard-Smithsonian Center for Astrophysics

Lyman alpha absorption in quasar spectra

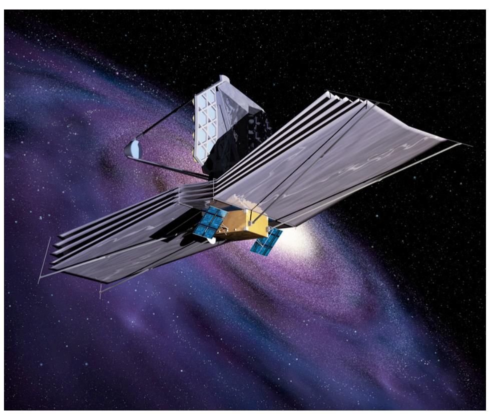


21 cm signal with radio telescopes

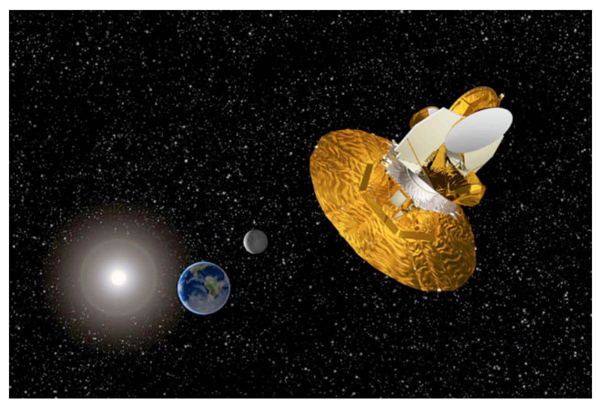


hydrogen + radiation ↔ proton + electron + heat

Young, star-forming galaxies
Rare, but luminous quasars



Thomson scattering with the CMB
Kinetic Sunyaev-Zel'dovich effect



THERMAL EVOLUTION after UNIFORM REIONIZATION

Hui & Gnedin (1997)

Instantaneous and uniform reionization models

a) $z_{RE} = 5$

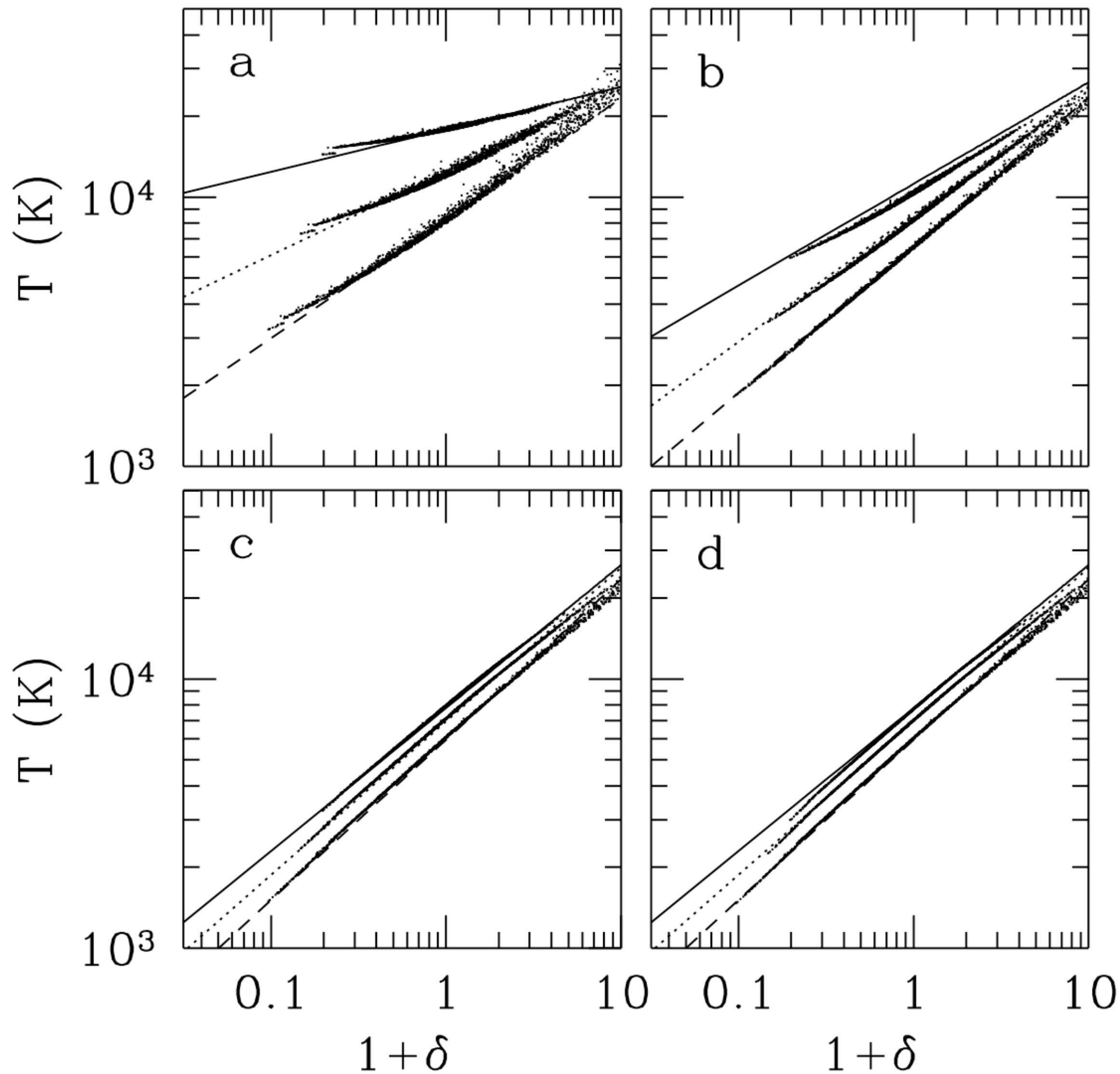
b) $z_{RE} = 7$

c) $z_{RE} = 10$

d) $z_{RE} = 19$

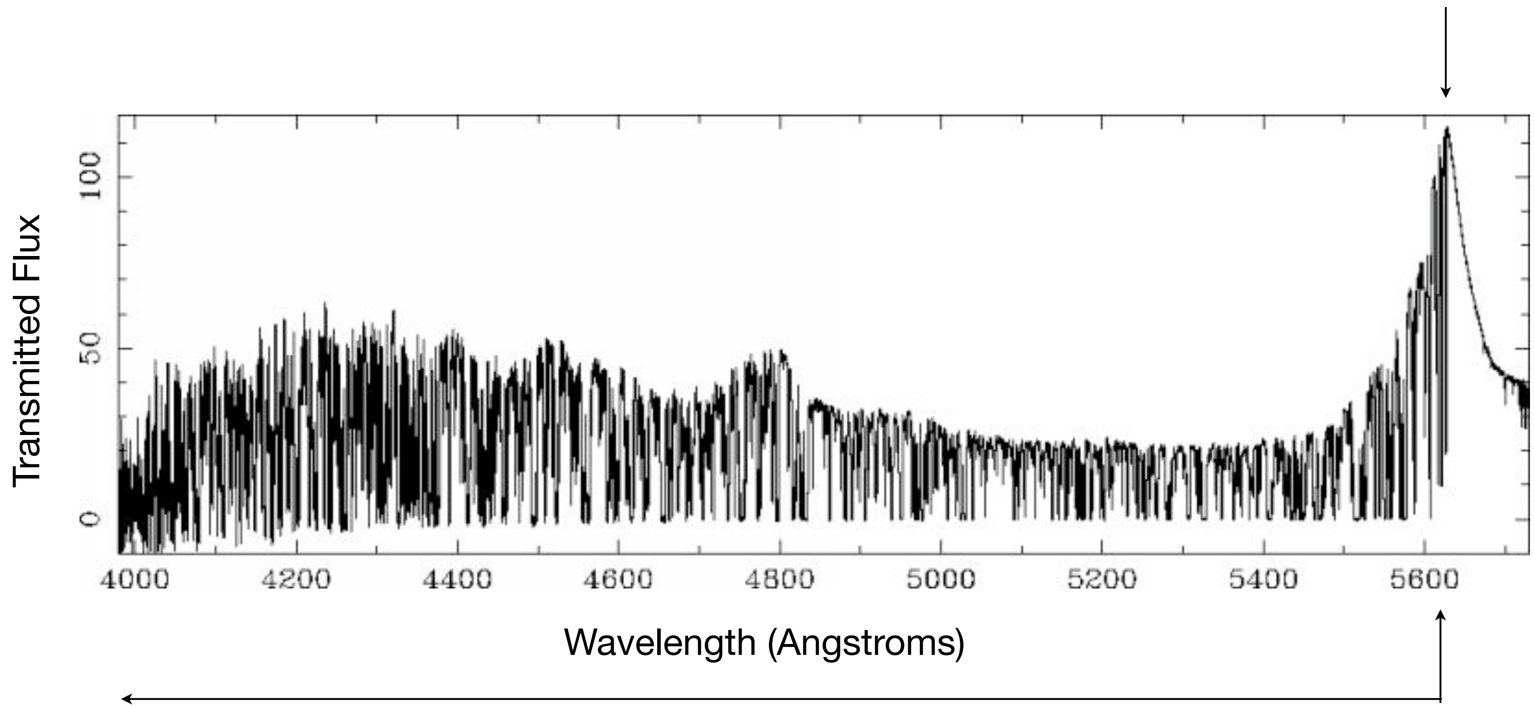
Temperature-density relations

- z = 4, 3, 2 from top to bottom
- Approximately power-laws with little scatter



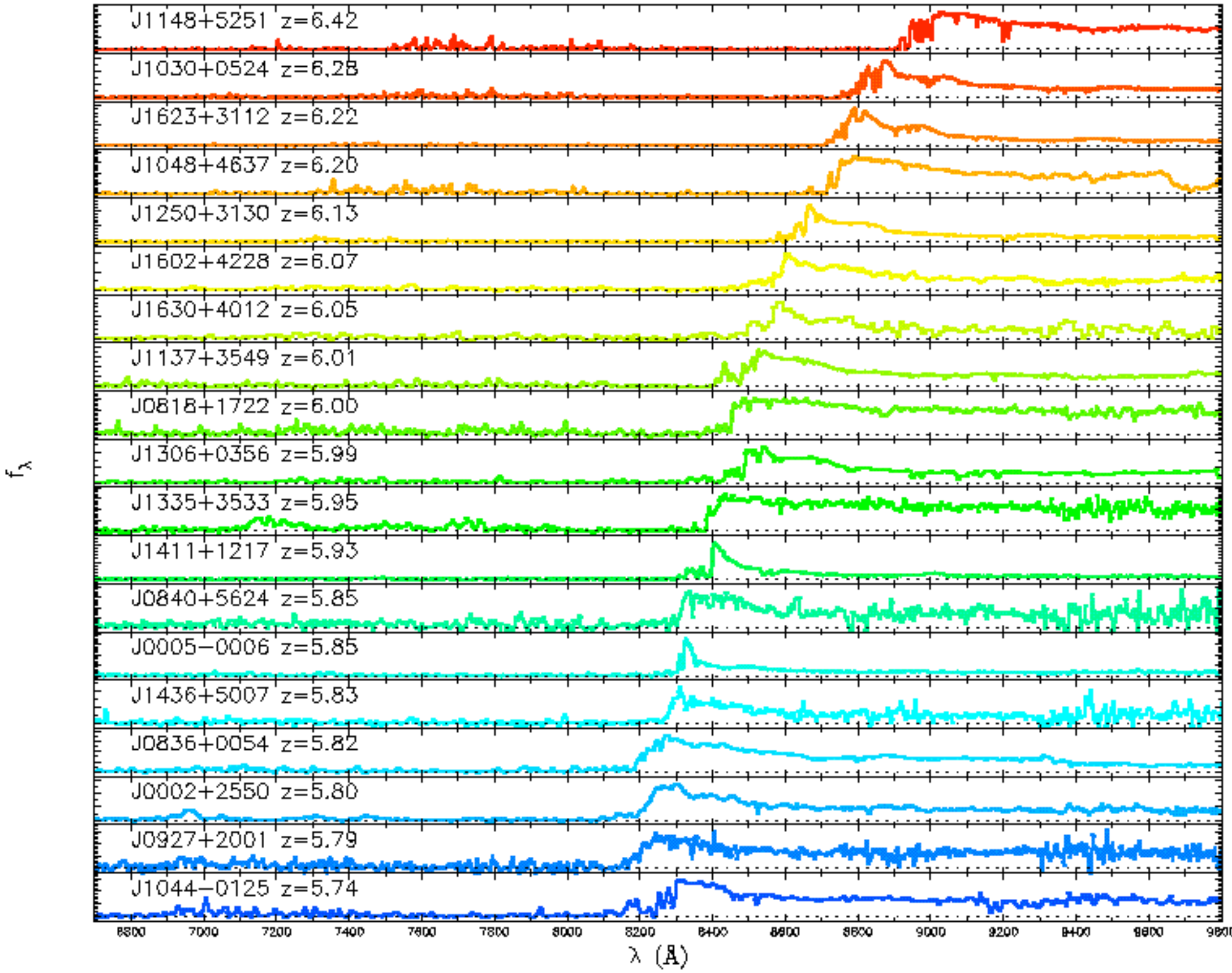
THE LYMAN ALPHA FOREST in QUASAR SPECTRA

Quasar's Lyman alpha emission
Rest wavelength 1216 Angstroms



Lyman alpha absorption/scattering by neutral hydrogen

LYMAN ALPHA ABSORPTION in HIGH-REDSHIFT QUASARS



(Fan et al 2006)

PHYSICAL SCALES & NUMERICAL REQUIREMENTS

Mass resolution

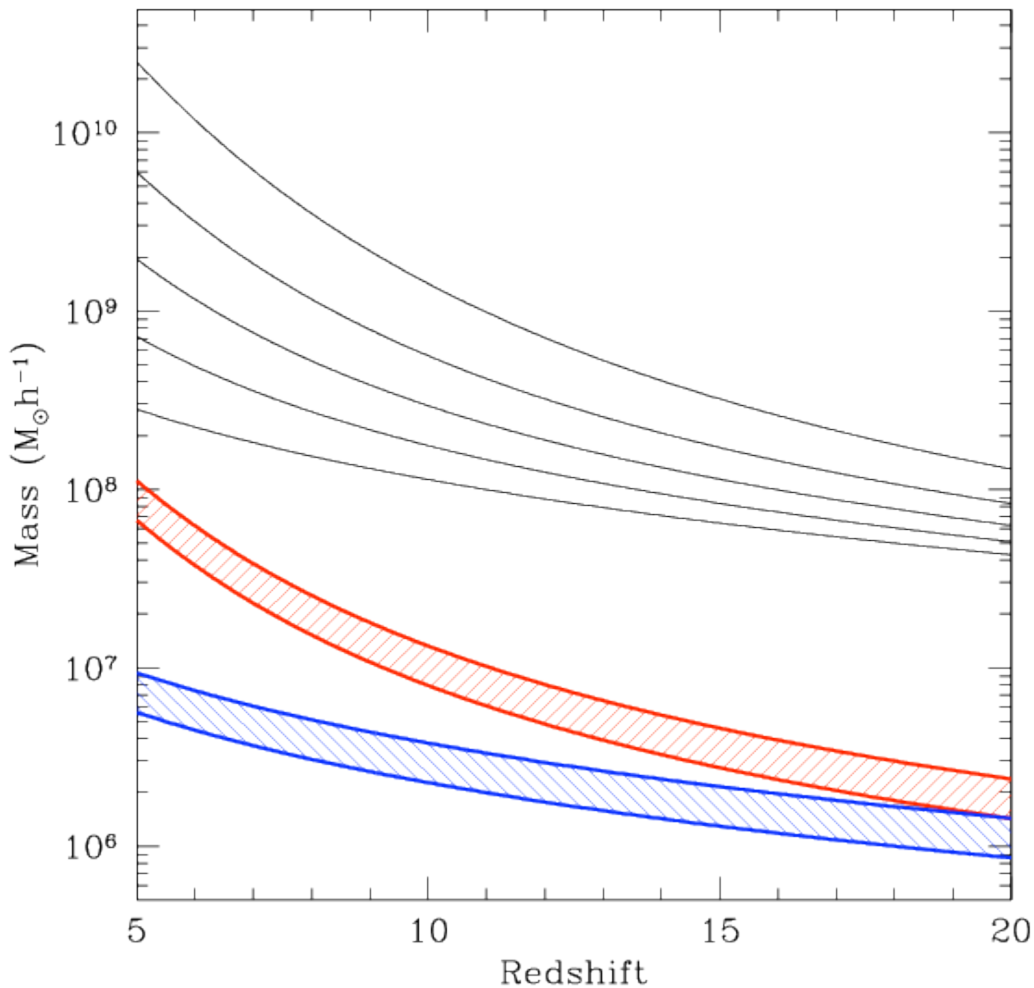
- Identify dark matter halos with mass ~ 10^8 Msun/h in order to model galaxy formation

Simulation volume

- A box size ~ 100 Mpc/h is required to have a fair sample of galaxies

Conclusions

- N-body simulations must have 20 to 35 billion particles



N-BODY

- The dark matter distribution is represented by collisionless particles influenced only by gravity
- Identify collapsed dark matter halos on the fly to model sources and sinks
- Particle-multi-mesh N-body code (Trac & Pen 2006)

1

SOURCES

2

- Stars form within cooling radius of dark matter halos with temperatures > 10^4 K
- Star formation rate modeled using empirical relations (e.g. Schmidt-Kennicutt law)
- Source spectra modeled from population synthesis (e.g. Bruzual & Charlot, Schaerer)

3

HYDRODYNAMICS

- Fluid conservation equations for gas mass, momentum, and total energy are solved on an Eulerian grid.
- Eulerian moving-frame hydro + particle-mesh N-body code (Trac & Pen 2004)
- Includes non-equilibrium ionization, non-uniform photoheating, atomic cooling, metal transport

4

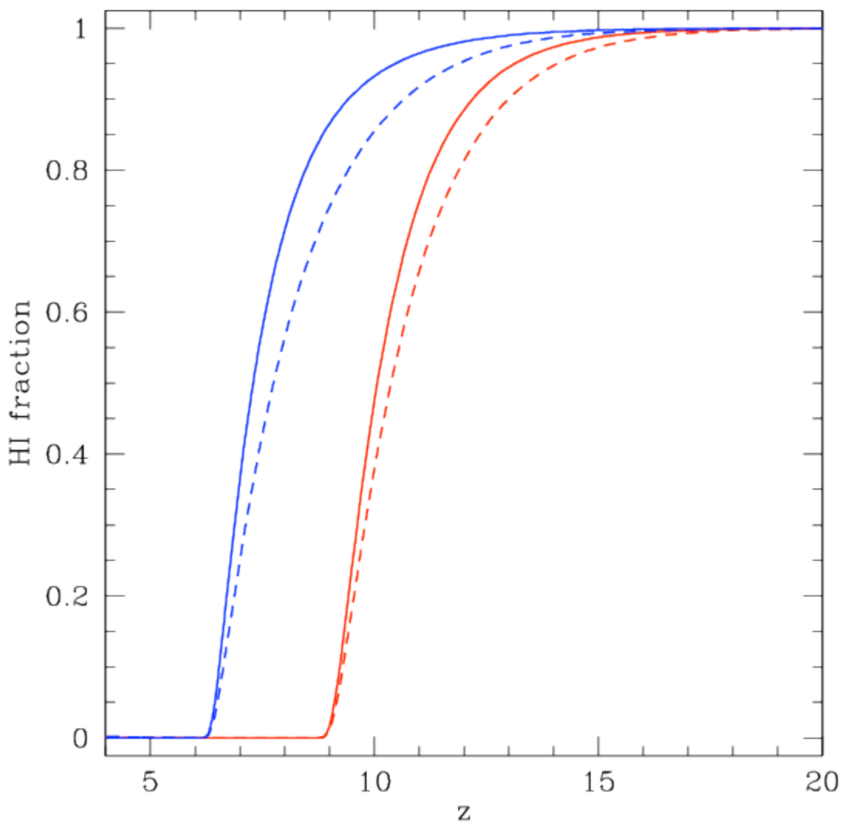
RADIATIVE TRANSFER

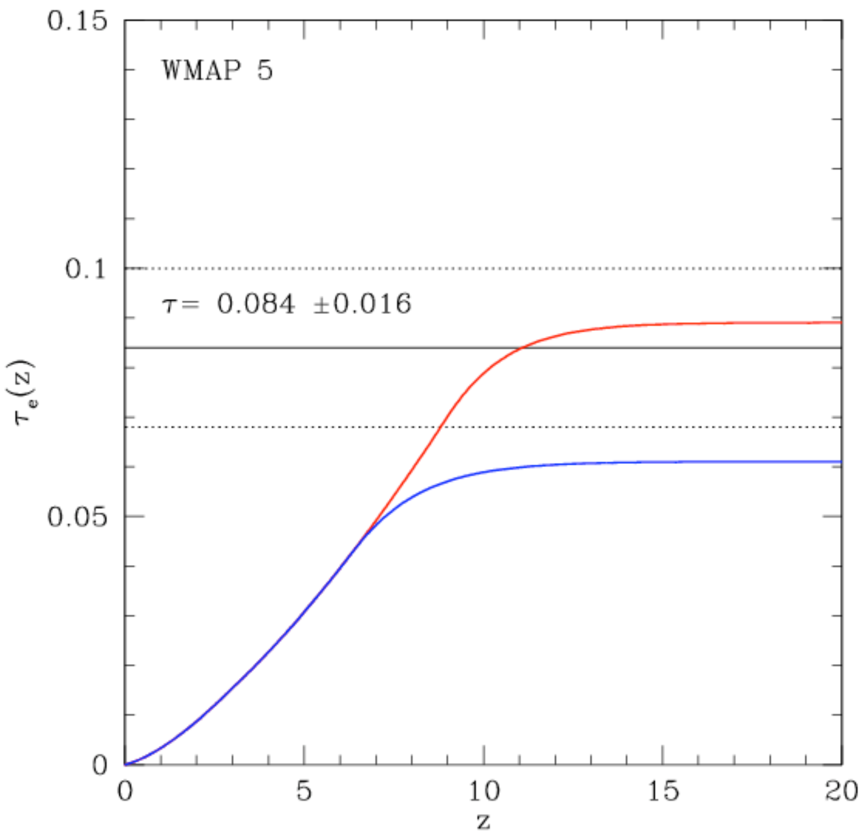
- Adaptive raytracing to track the propagation of ionizing photons
- With ray splitting to improve angular resolution (Abel & Wandelt 2001)
- With ray merging to improve scaling with sources (Trac & Cen 2007)

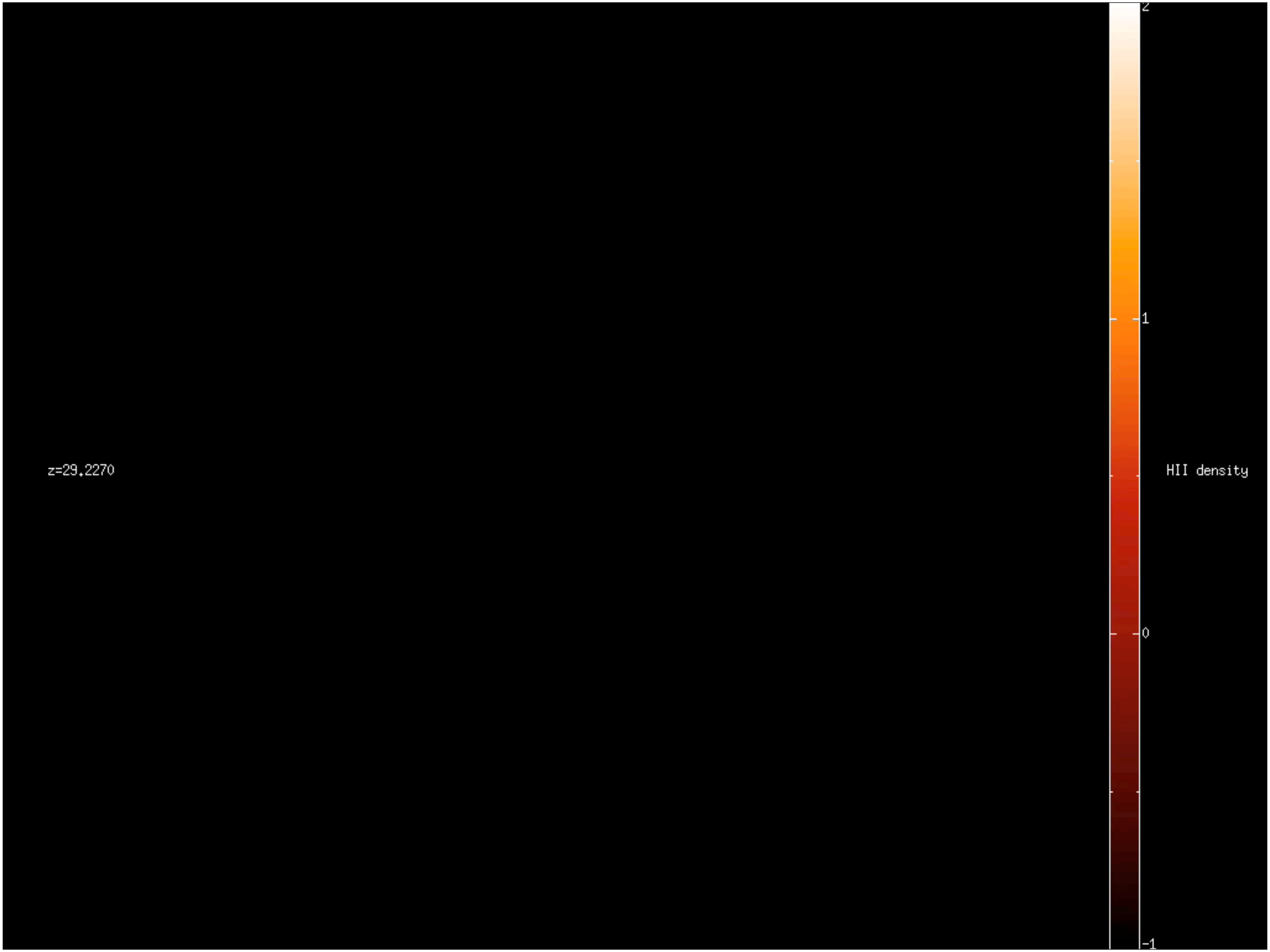
COSMOLOGICAL SIMULATIONS

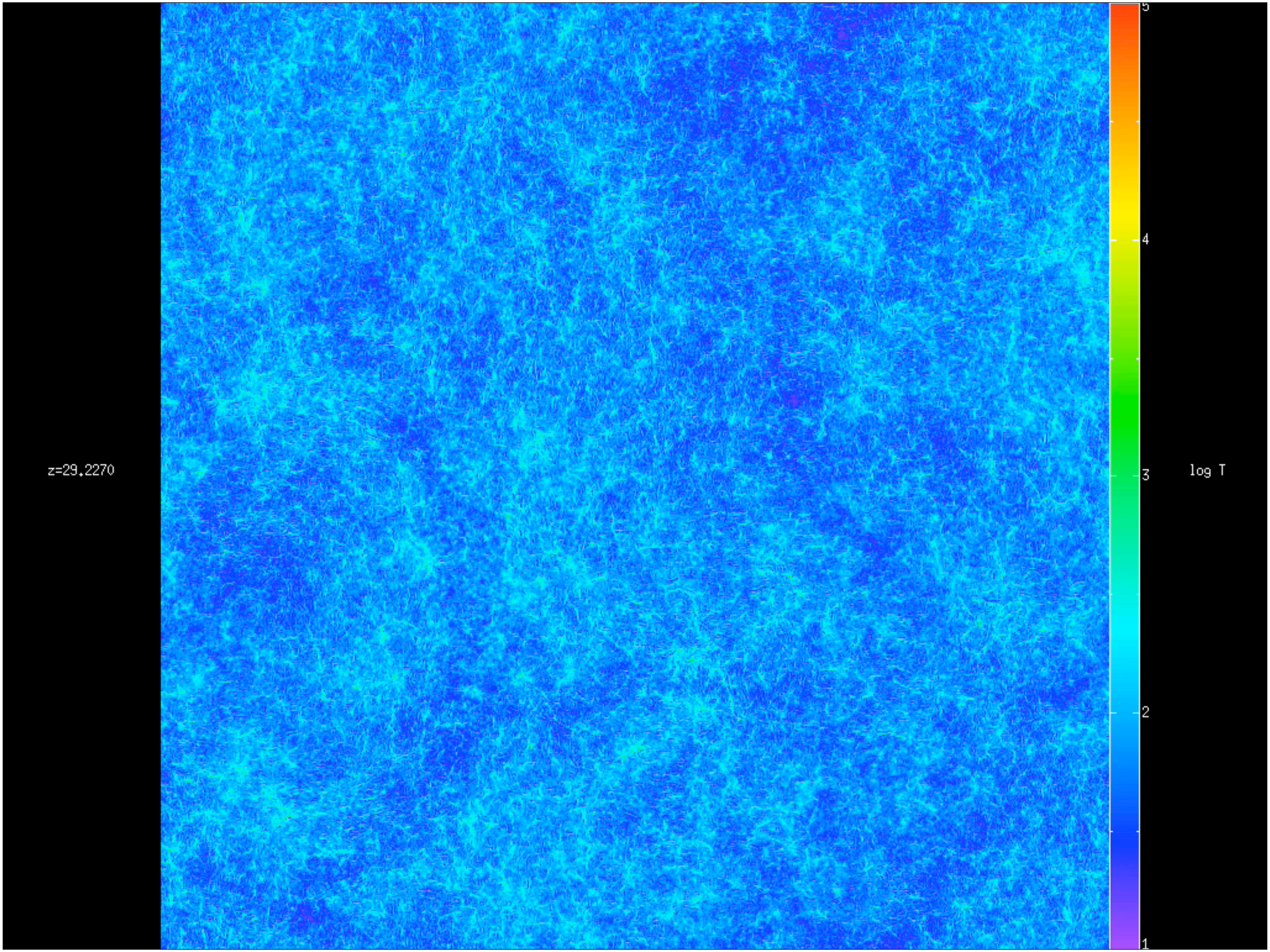
Model	L (Mpc/h)	N_{DM}	N_{Gas}, N_{Ray}	M_{DM} (Msun/h)	Comments
L100N	100	29 Billion		2.7×10^6	N-body only
L100A	100	1536^3	1536^3	2.1×10^7	Late reionization $z_{END} \sim 6$
L100B	100	1536^3	1536^3	2.1×10^7	Early reionization $z_{END} \sim 9$
L100	100	24 Billion		3.0×10^6	N-body & radiative transfer
L50A	50	3 Billion	400 Million rays	3.0×10^6	Pop II stars
L50B	50	3 Billion	400 Million rays	3.0×10^6	Pop II & III stars

MODEL	$z_{50\%}$ by volume (solid)	$z_{50\%}$ by mass (dashed)	z_{END}	$\tau_{THOMSON}$
EARLY	10.0	10.4	~ 9	0.098
LATE	7.3	7.7	~ 6	0.062

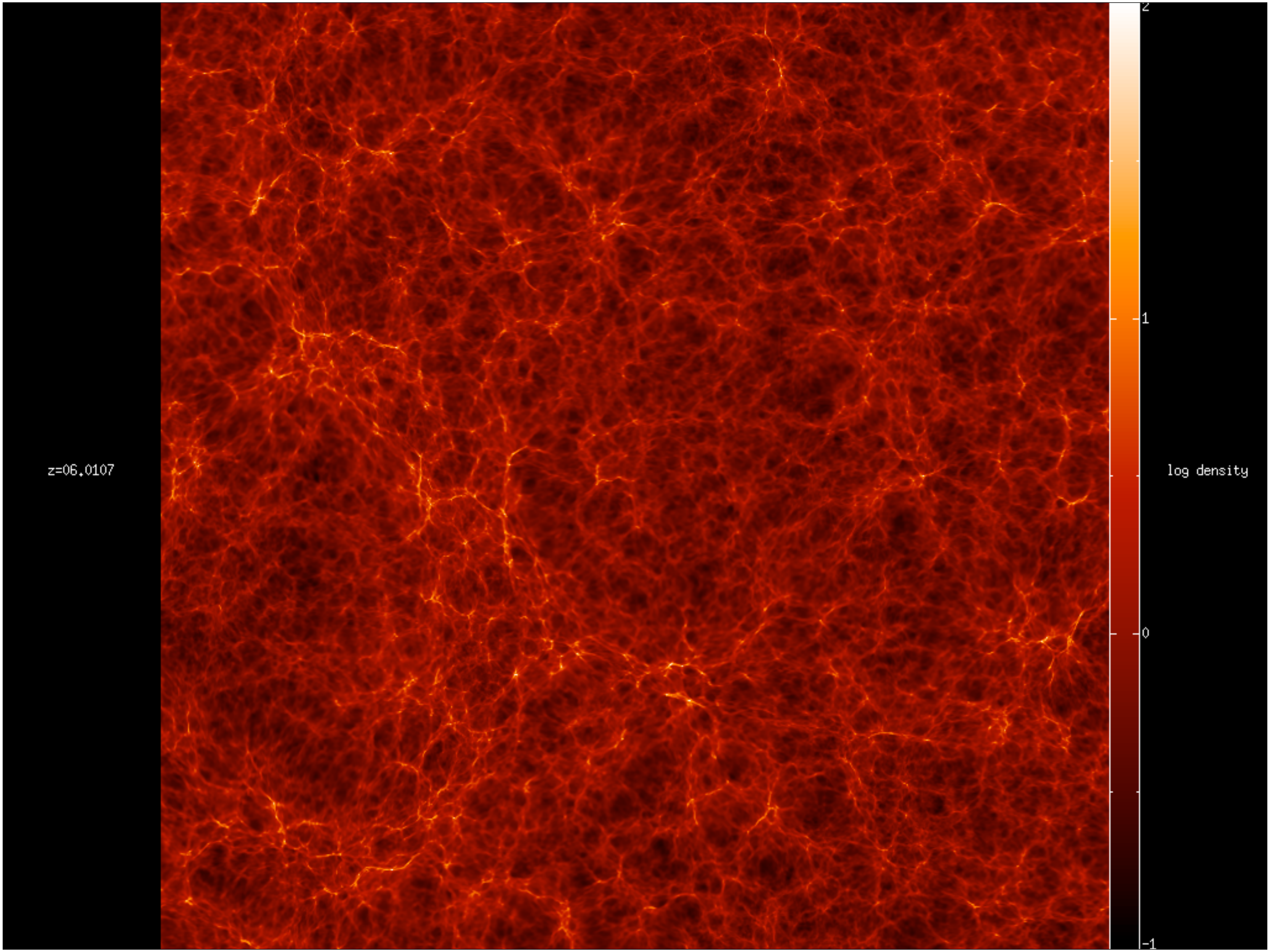


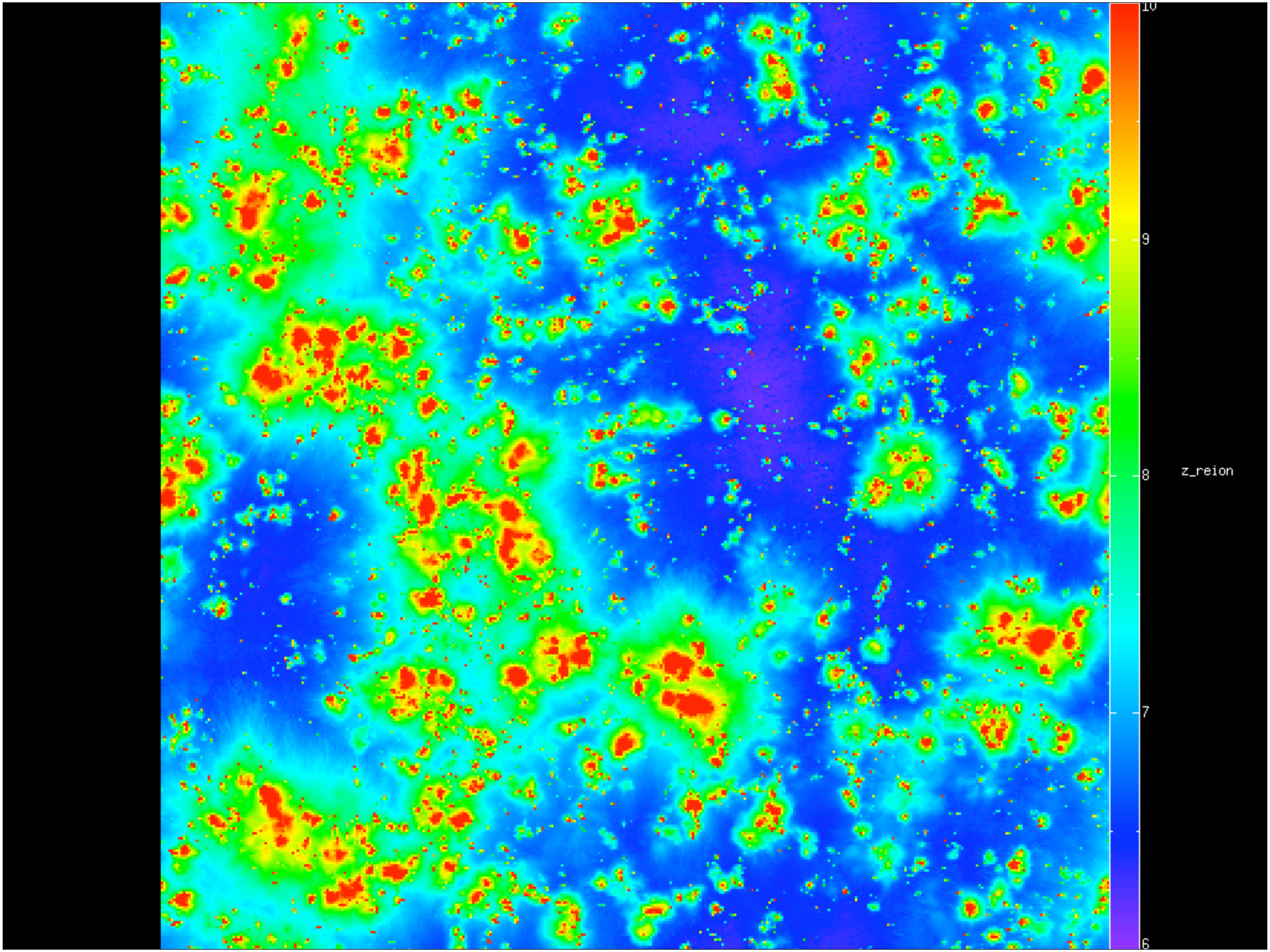


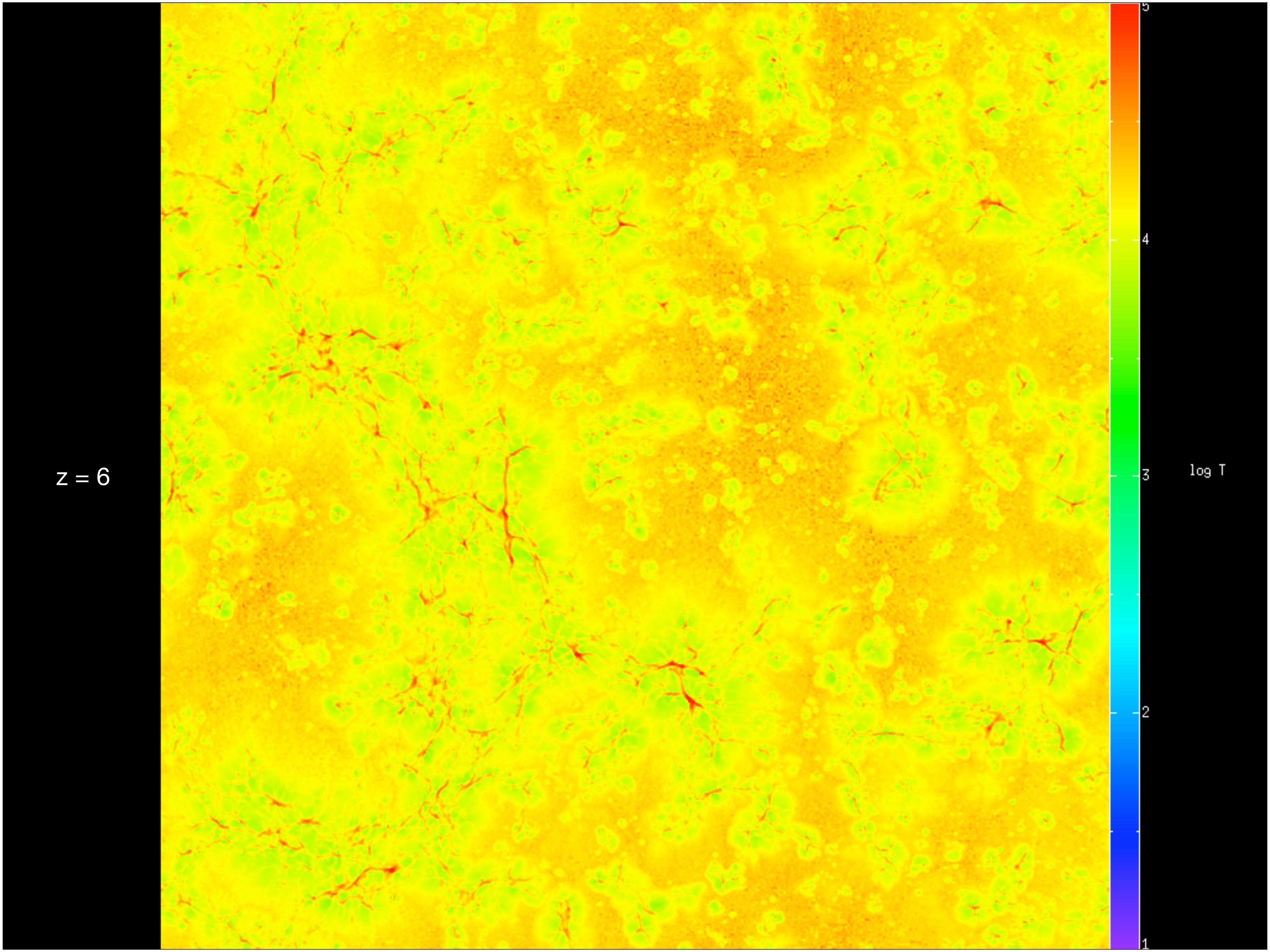

z=29.2270
HII density
2
1
0
-1



z=29.2270
5
4
3
2
1
log T

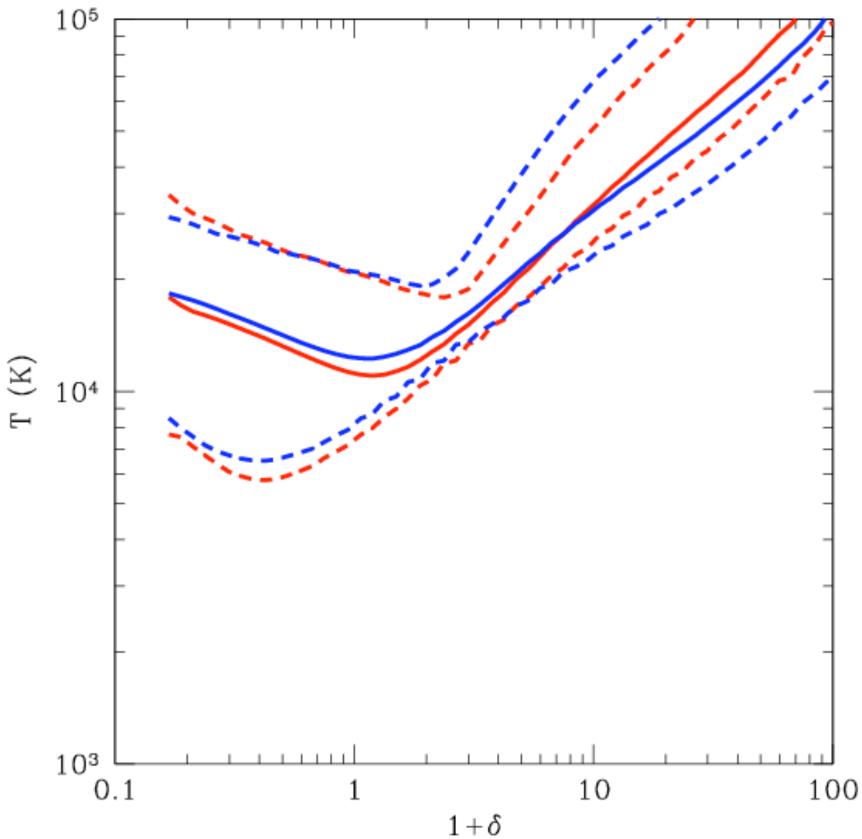

z=06.0107
2
1
0
-1
log density

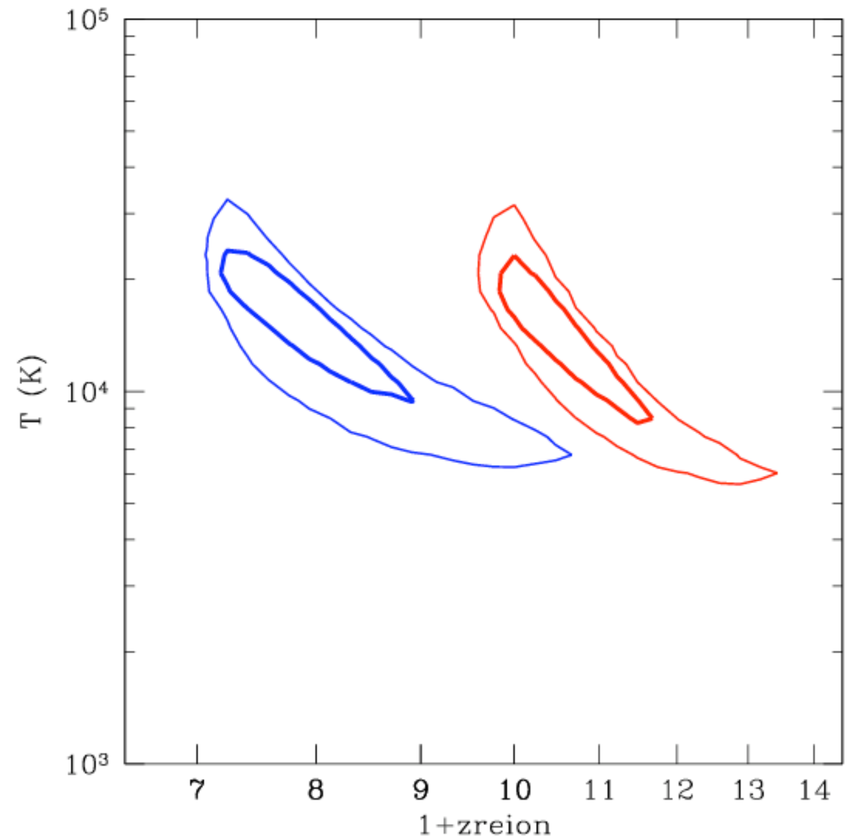

10
9
8
7
6
z_reion



z = 6
5
4
3
2
1
log T

TEMPERATURE DISTRIBUTION at the END of REIONIZATION



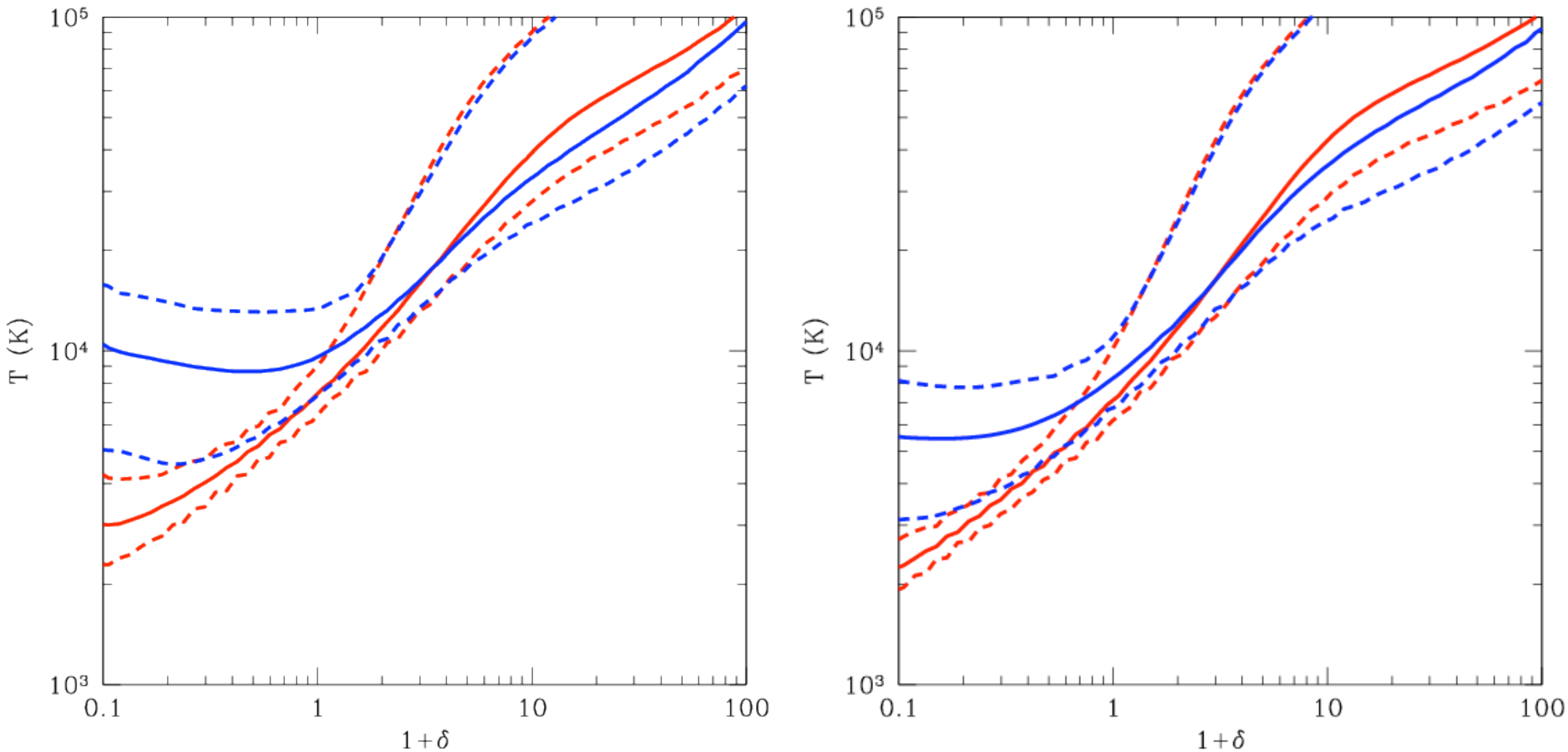


Inverted powerlaw relations with slope -0.2 for the early (z ~ 9) and late (z ~ 6) models

End-of-reionization temperature as a function of reionization-redshift for low-density gas δ ~ -0.5

(Trac, Cen, & Loeb 2008)

TEMPERATURE DISTRIBUTION after REIONIZATION



z = 5

z = 4

(Trac, Cen, & Loeb 2008)

SUMMARY

Photoheating of the IGM

- The signature of inhomogeneous reionization is imprinted in the temperature distribution of the intergalactic medium
- The temperature-density relation at low densities is inverted just at the completion of reionization and there is order unity spread at a fixed density

Radiative transfer algorithm

- Adaptive ray splitting and merging
- Time stepping based on the light-crossing time
- Scales as O(N) and effectively independent of the number of sources when the radiation filling factor approaches unity