Ionization fronts and their interactions with density fluctuations: implications for reionization

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Outline

- Cosmological I-Fronts
- New cosmological radiative transfer code
- Structure formation at high-z
- Photoevaporation of cosmological minihalos
- Effects of small-scale structure on I-front propagation
- Source clustering and small-source suppression

Propagating ionization fronts

- Whenever a source of ionizing radiation turns on in a neutral medium, it creates a propagating I-front
- General theory and classification of I-fronts exists (e.g. Spitzer).
- I-fronts start as weak, fast R-type fronts, propagating faster than gasdynamic response until slowing down due to recombinations and geometric dilution, or increased local density, converting to slower, D-type I-front, often preceded by a shock, in which case hydrodynamics becomes important.
- The I-front propagation is described by “jump condition”, v=F/n, which expresses the balance at the front of ionizing photon flux and opposite neutral atoms flux (assuming a sharp transition).
- First cosmological I-front solutions derived in Shapiro & Giroux 87

Relativistic I-fronts

(Iliev et al. 2005, in prep.)

- Fast I-fronts often propagate with speeds $v_I \sim c$.
- This problem was first discussed in White et al. 03 (ignoring recombinations) and Yu 2005.
- In a recent paper we show how the I-front jump condition can be generalized to account for the finite speed of light, as well as for gas peculiar motions, recombinations in the ionized volume, gas clumping and presence of helium.
- We derived general analytical families of solutions in both static (1-parameter) and expanding backgrounds (2-parameter). and showed that relativistic effects are important for individual luminous cosmological sources, but not for overall reionization.
- Relativistic effects are generally unimportant for compact HII regions due to finite source raise time, which is much longer than the relativistic phase of the I-front.

Analytical vs. Numerical I-front solutions

Analytical:

- fast and efficient
- large dynamic range
- can handle only simple situations (symmetric, constant clumping and temperature, sharp I-fronts, etc.)

Numerical:

- general
- can include complex physics and chemistry
- works for any density field
- limited dynamic range

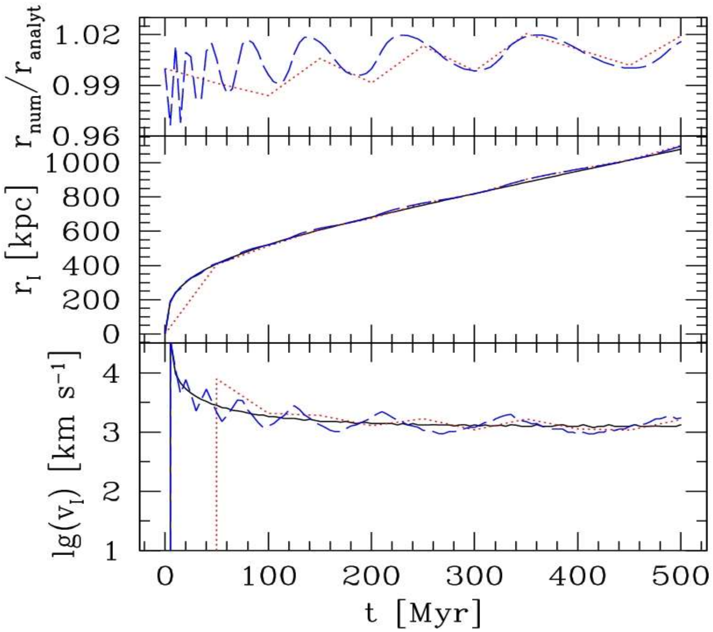
Photon-Conserving Transport of Ionizing Radiation

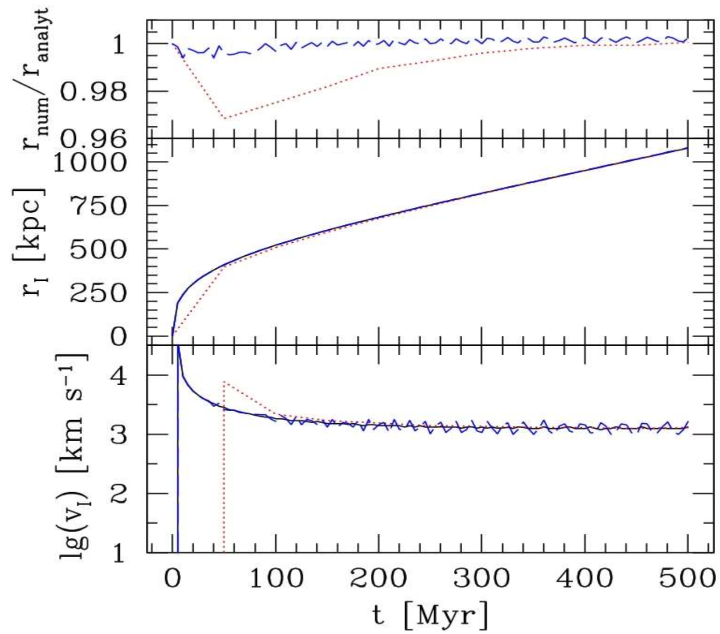
(Mellema, Iliev, Alvarez & Shapiro, in prep.)

We have developed a new radiative transfer method:

- explicitly photon-conserving. Rates calculated as in Abel, Norman & Madau 00 + averaging in time following non-equilibrium chemistry => much faster, does not require small time-steps to follow fast I-fronts)
- Tested in detail (multiple tests with exact analytical solutions performed, samples on next slides):
  - correctly evolves I-fronts even at very low spatial and time resolutions
  - non-equilibrium chemistry, finds correct temperature
- fast and efficient, easily coupled to hydro and N-body dynamics
- applicable in either cosmological or non-cosmological situations

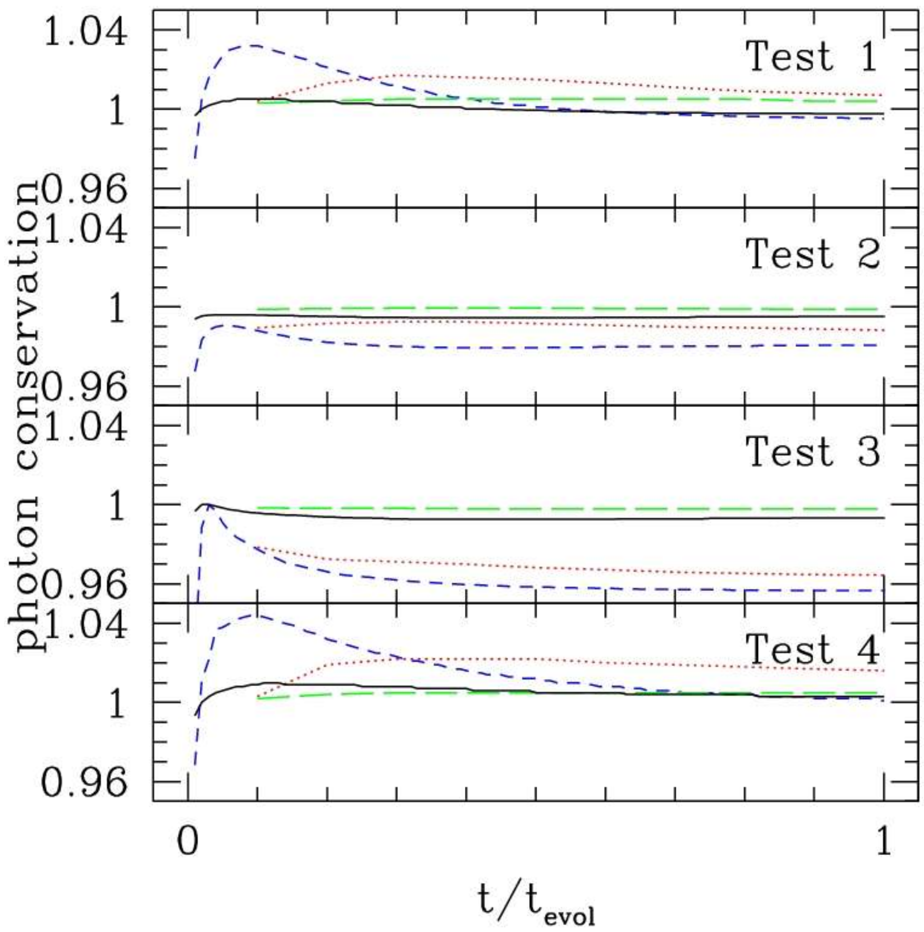
Tests: I-front propagation in 3-D
(sample)





Example: Cosmological I-front propagation, starting at z=9, expanding, uniform IGM with mean clumping and fixed temperature (analytical solution exists: Shapiro & Giroux 1987)

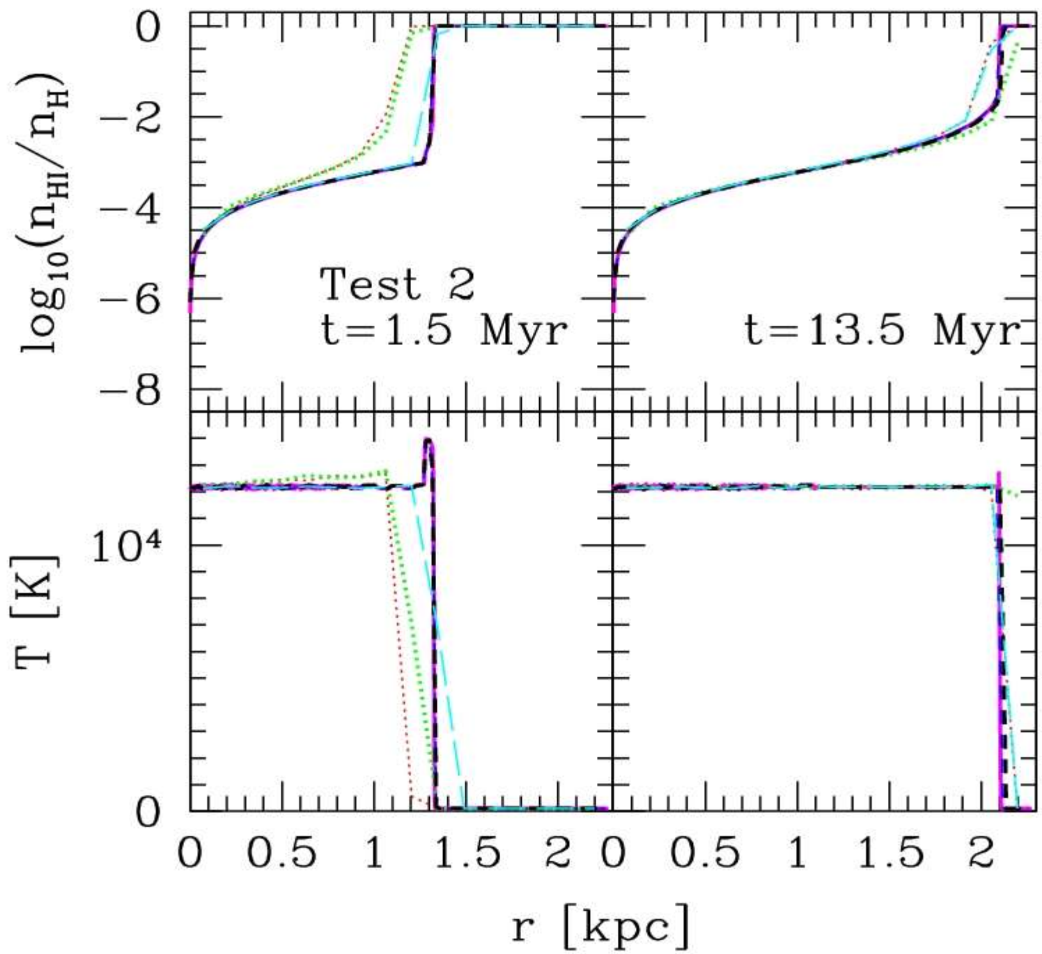
Photon Conservation



Photons are conserved to within few percent at very low resolution and small fraction of 1% at higher resolution

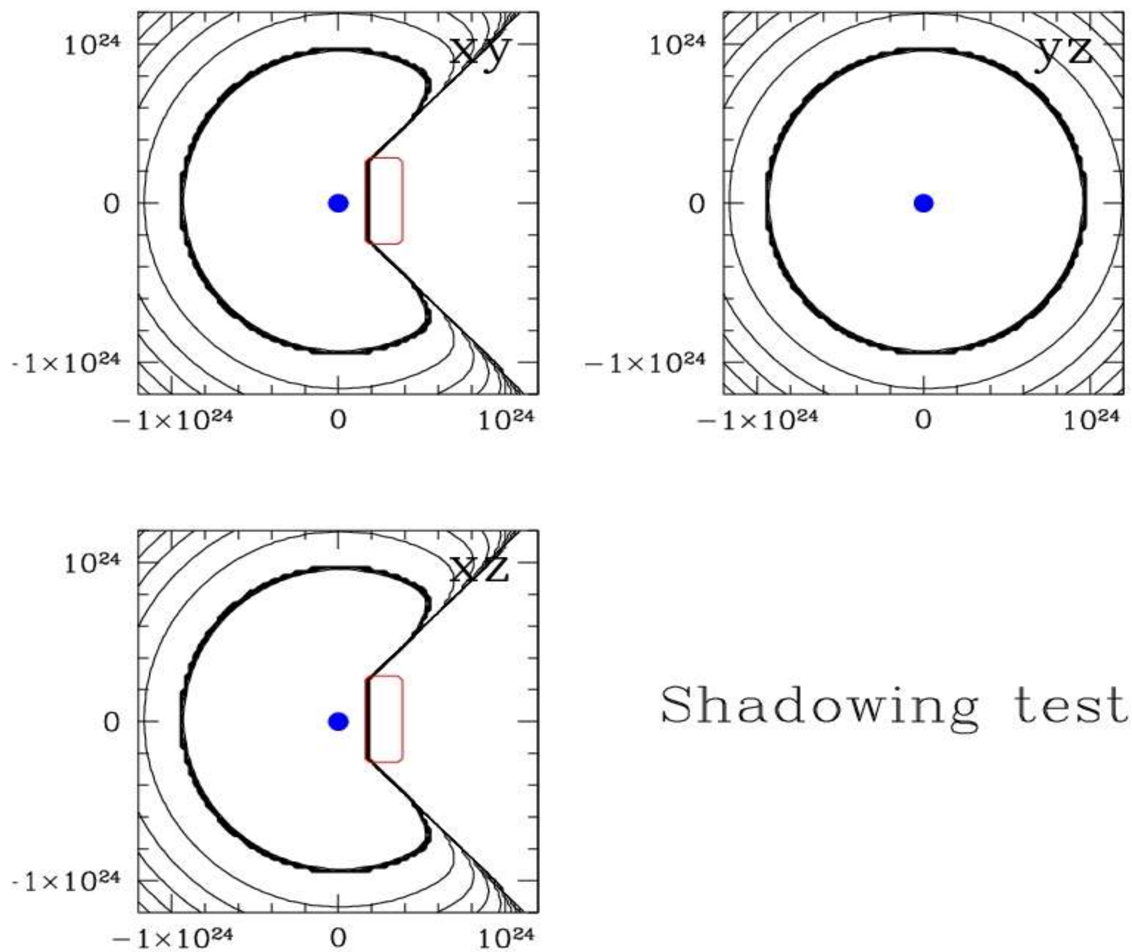
Temperature tests (sample)

- 1/r density profile (NFW-like)
- Stromgren sphere reached
- 1-D, 3-D and "analytical" agree, regardless of space/time resolution

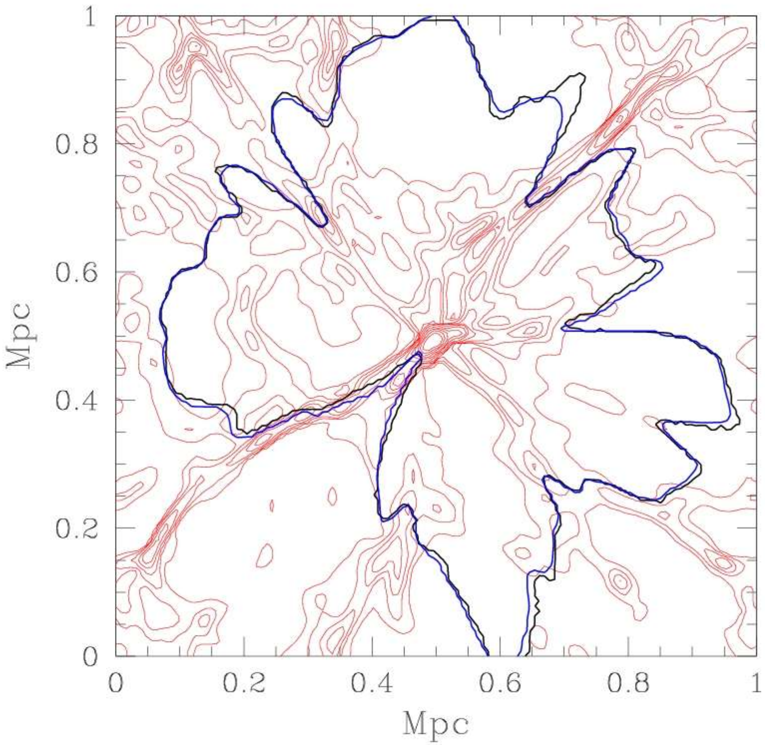


Shadowing Test

- ionizing source (blue)
- dense obstacle (red)
- 256^3 cells
- contours: time-sequence of 50% ionized fraction, every 20 Myr
- I-front is spherical, shadows are at the correct place, there is slight diffusion around the shadow's edges

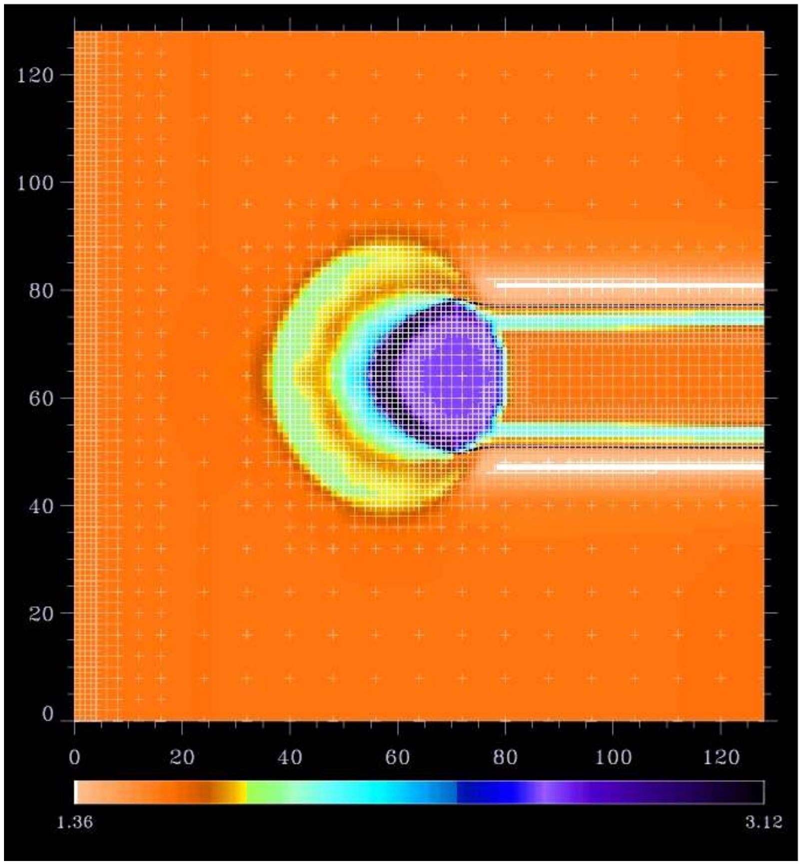


Long- vs. Short-characteristics



- Long-characteristics is more precise, but often slower and more difficult to implement for multiple sources
- Short-characteristics is faster and with appropriately chosen weightings gives same results as LC

Coupling to AMR Hydrodynamics



Code is now coupled to adaptive mesh refinement (AMR) hydrodynamics code yguasu (by A. Raga).

Example: plane-parallel I-front encounters a dense clump and starts photoevaporating it

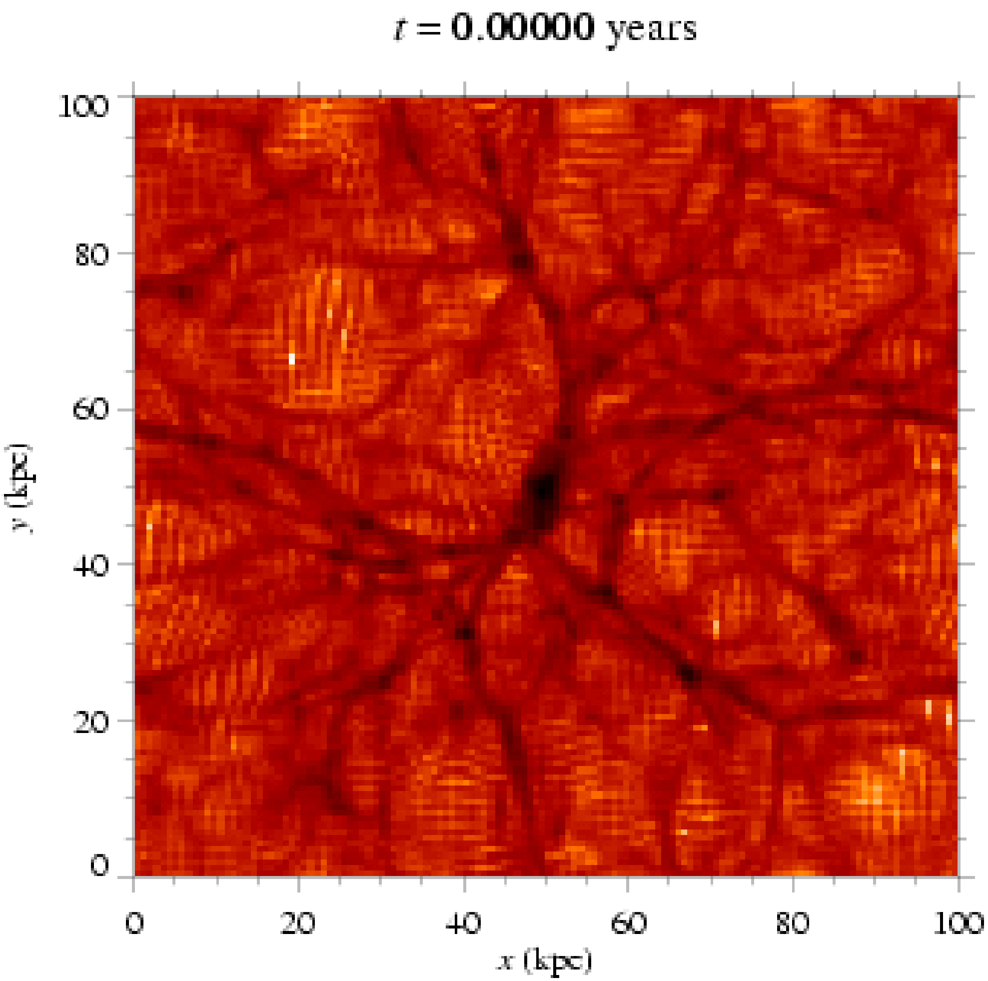
Cosmological I-front Evolution

1 Mpc box

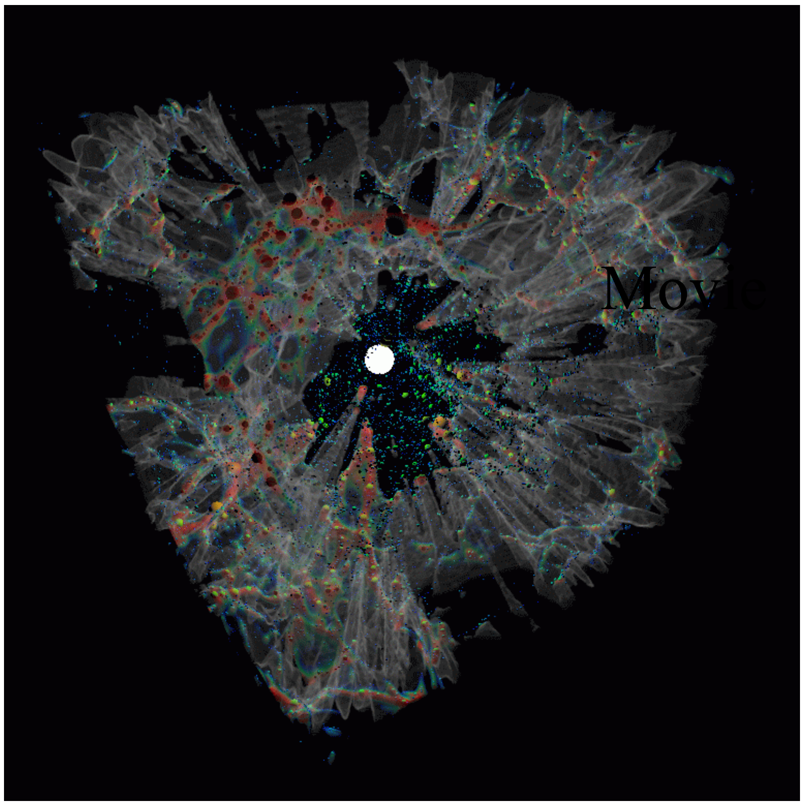
1 source

x-y cross-section

The evolution is complex (neither low-density first, not high-density first) dense filaments and halos cast long shadows



I-front propagation in a cosmological density field with minihalos



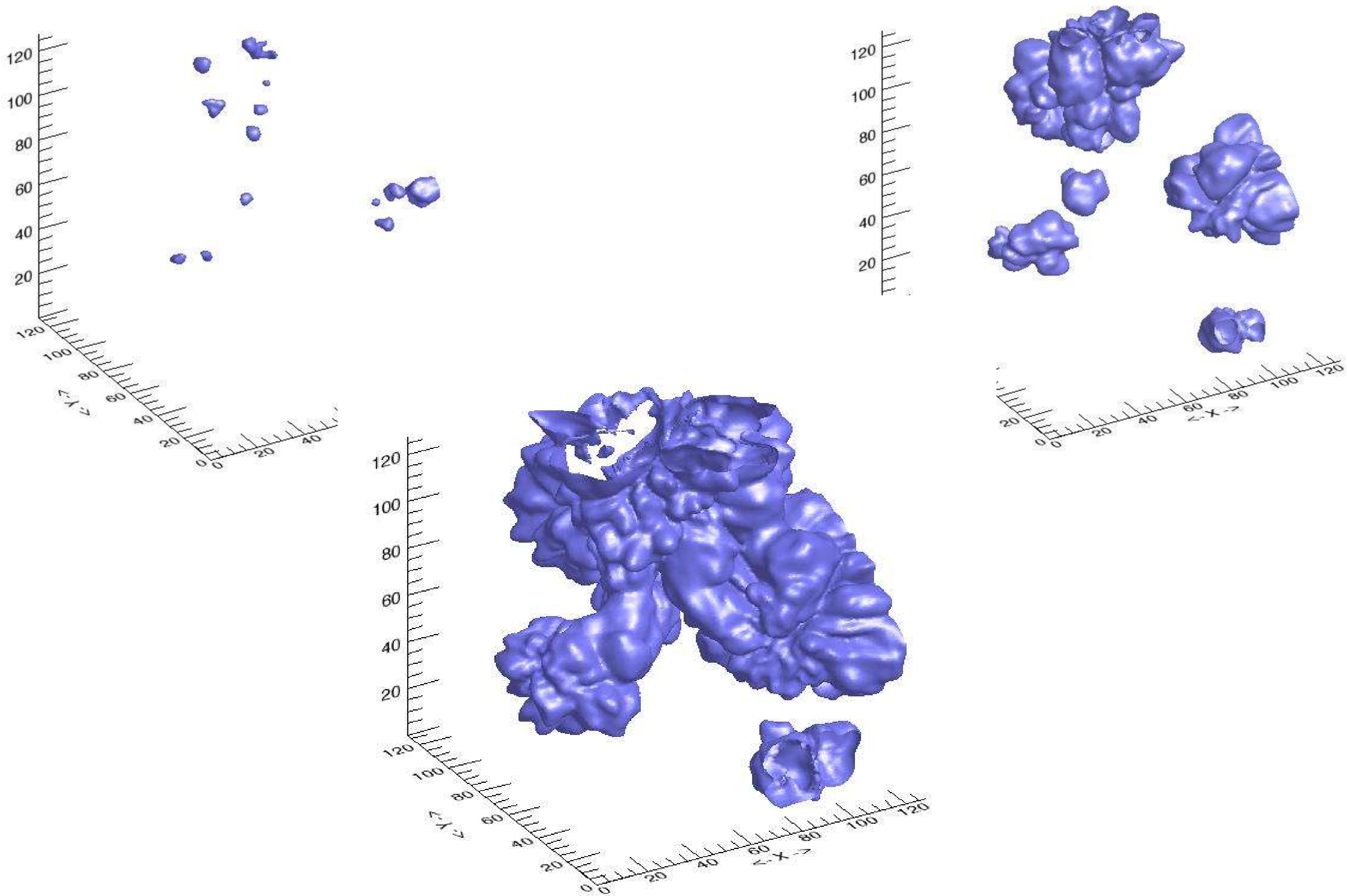
Visualization of an I-front propagation in a cosmological density field (LCDM)

box : 0.5/h Mpc

redshift: z=9

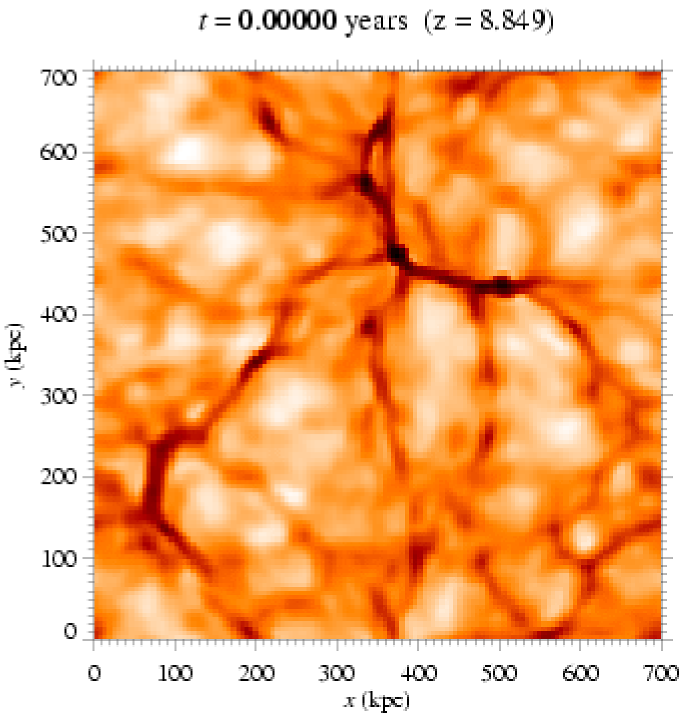
Movie

Multiple-source run

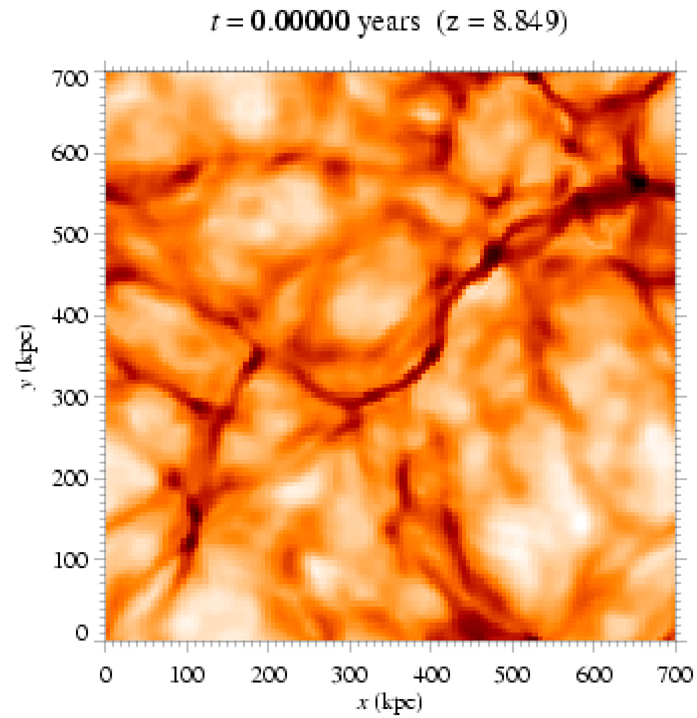


Multiple-source run

x-y slice



y-z slice



The Epoch of Reionization

- GP troughs detected in spectra of SDSS quasars at $z > 6$ ==> IGM H I density high enough to suggest reionization only just ended at $z \sim 6$.
- WMAP detection of CMB polarization fluctuations on large angular scale ==> foreground electron scattering optical depth high enough to suggest IGM mostly ionized by $z > 12$.
- Plausible explanation: reionization began by $z > 15$ but was extended in time, with final “overlap” of ionized zones at $z \sim 6$.
- Can small-scale structure forming at high-z help?

Structure Formation at High-z

(Iliev, et al., in prep.)

We performed very high-resolution N-body simulations of structure formation at high-z using PMFAST code developed at CITA

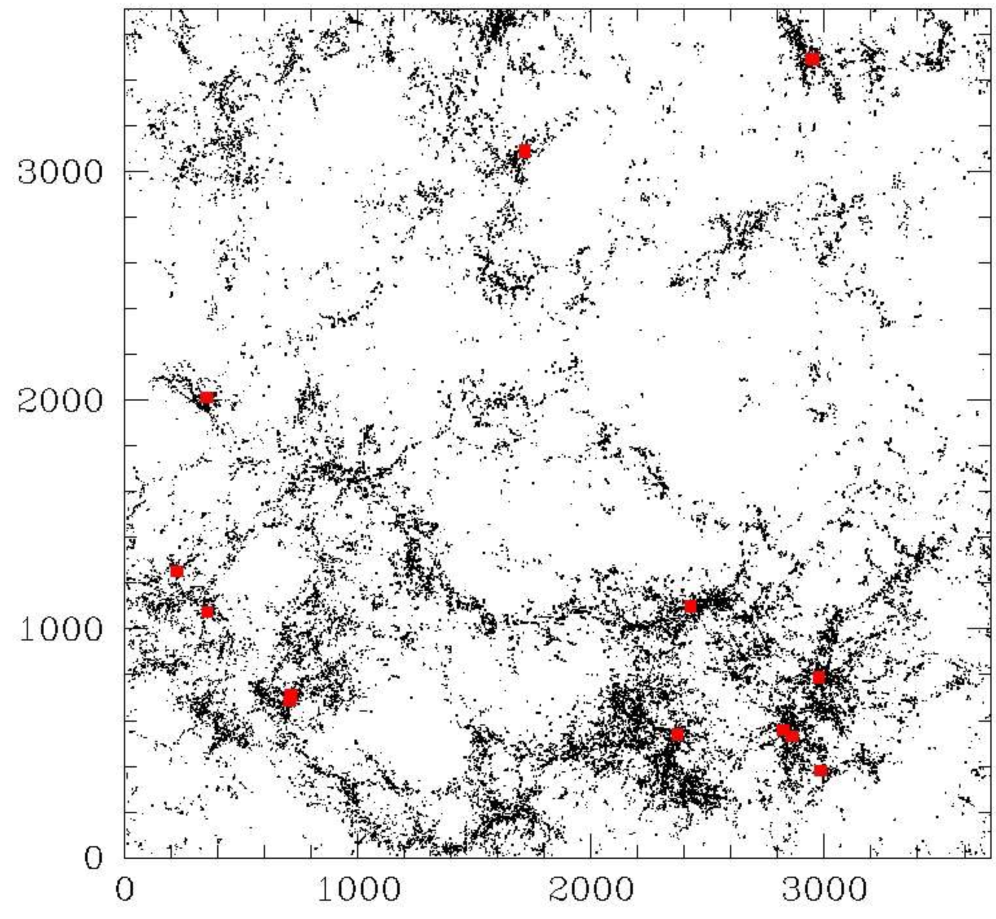
(Merz, Pen & Trac 2004)

Simulation parameters:

- 10/h Mpc box (other box sizes in progress)
- 1856^3 particles (6.4 billion)
- 3712^3 cells
- Identified between 544,000 halos (at z=17.2) and 2.3 million halos (at z=6) (>100 particles/halo)

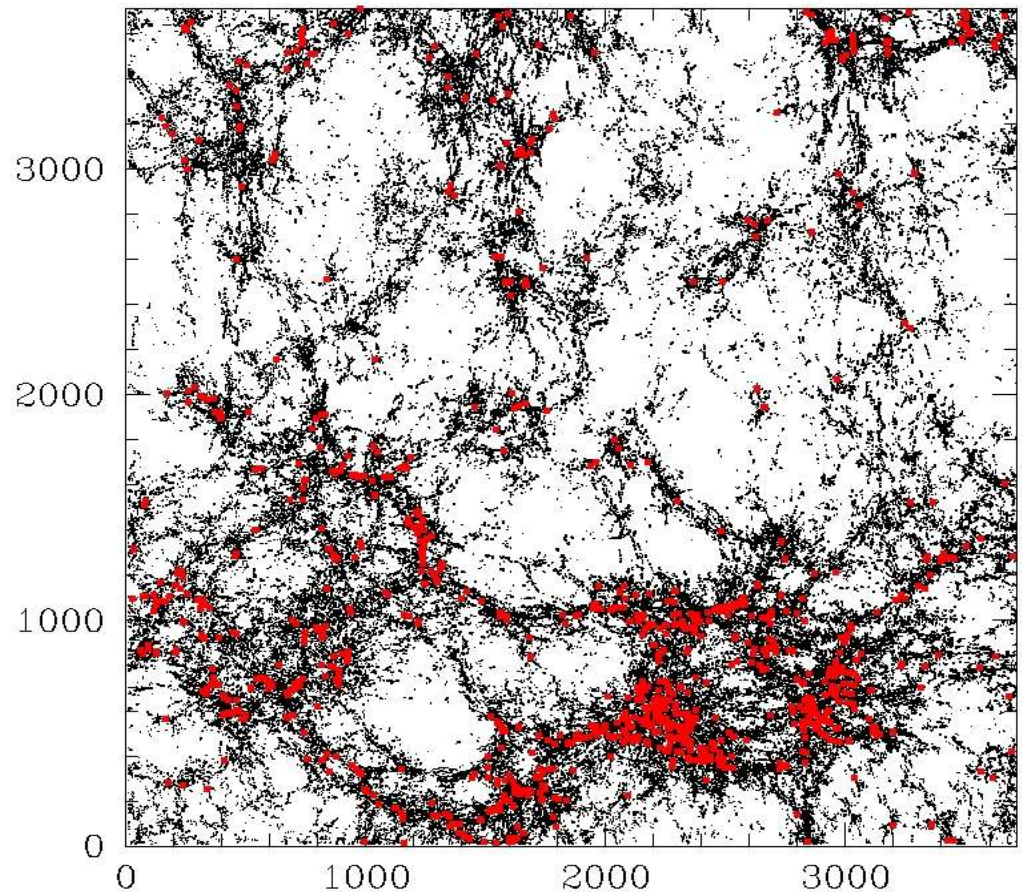
High-resolution N-body simulations

- 1 Mpc slice (1/14th of the box)
- z=17.2
- red=sources (16 halos)
- black=minihalos (32,627 halos)



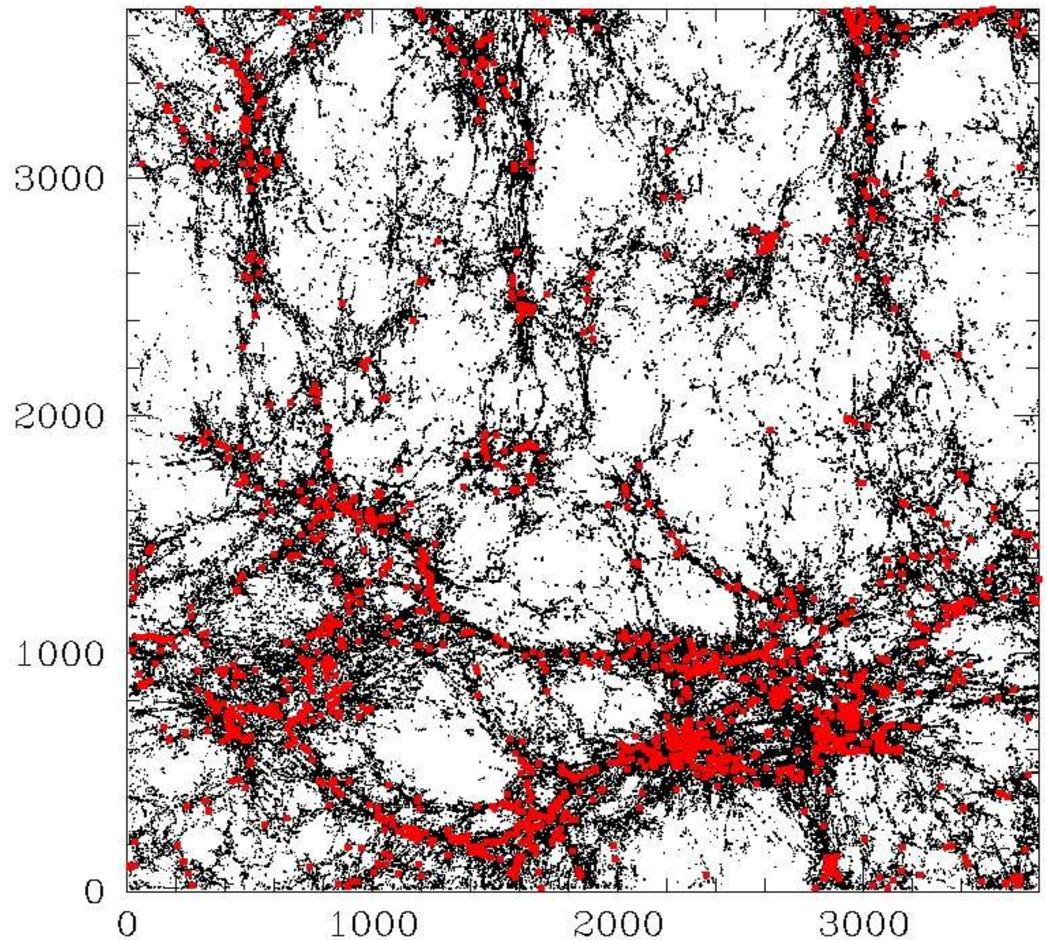
High-resolution N-body simulations

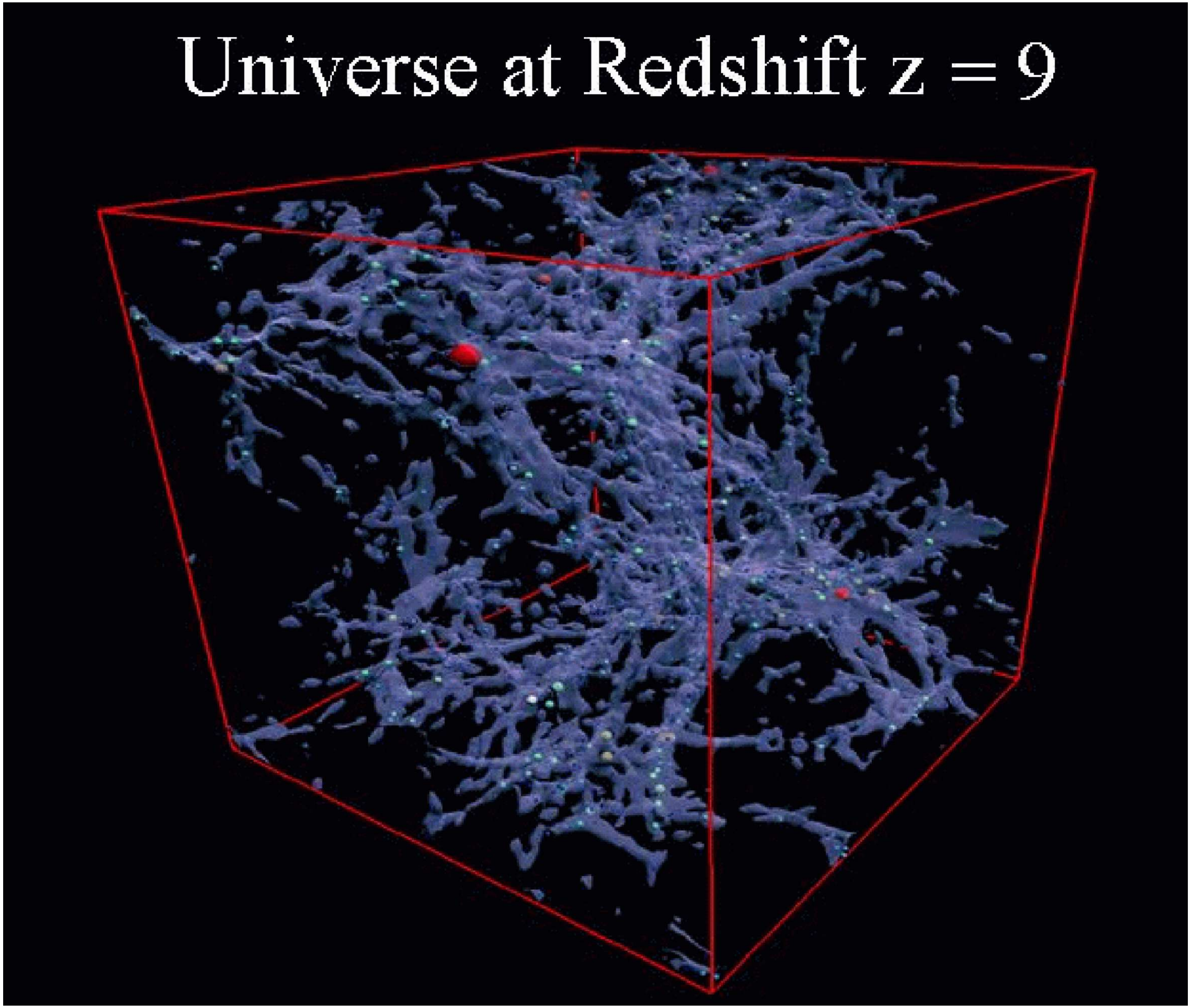
- 1 Mpc slice
- z=9.42
- red=sources (1077 halos)
- black=minihalos (124,121 halos)



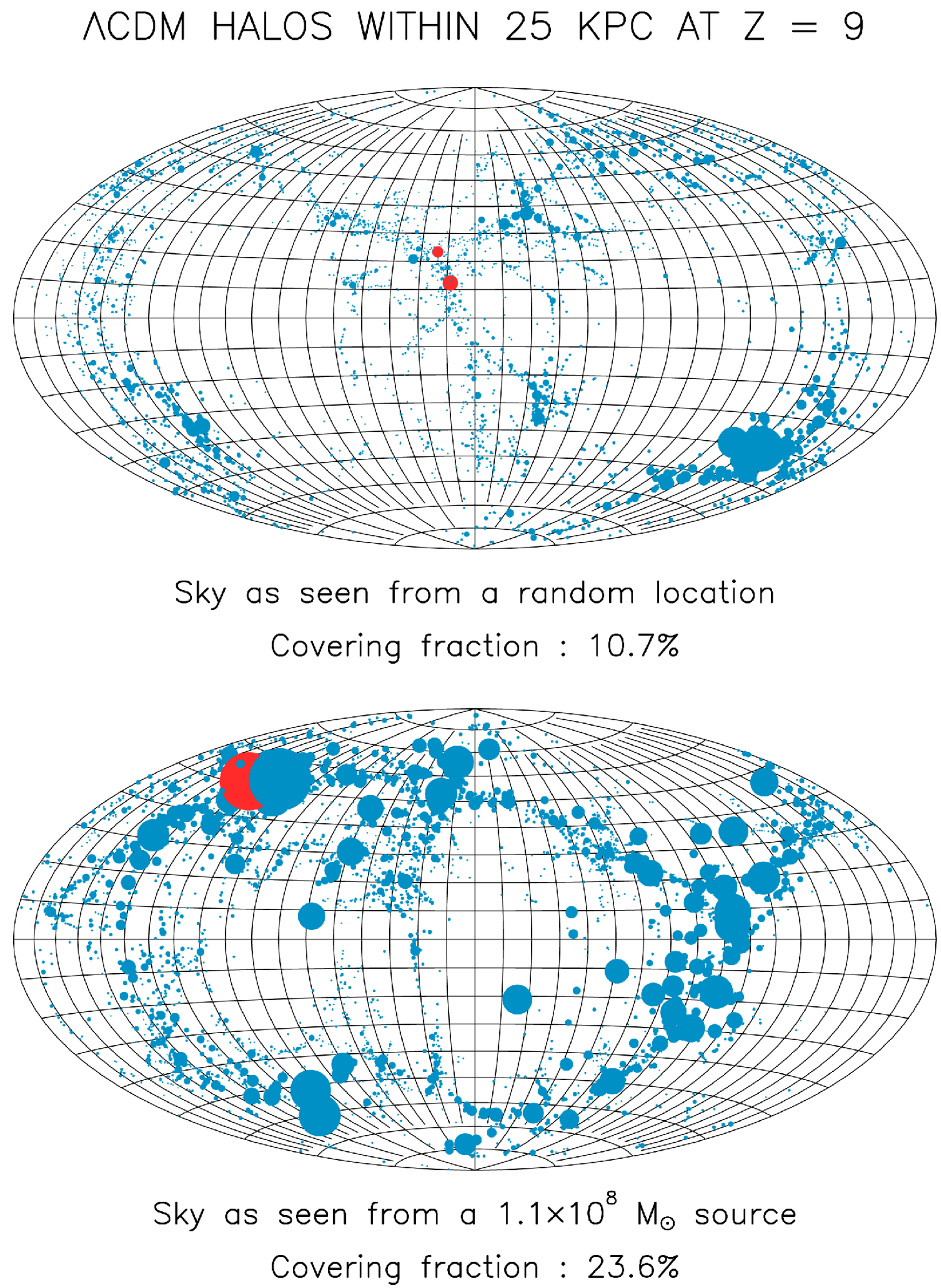
High-resolution N-body simulations

- 1 Mpc slice
- z=6
- red=sources (1672 halos)
- black=minihalos (142,260 halos)




Universe at Redshift z = 9

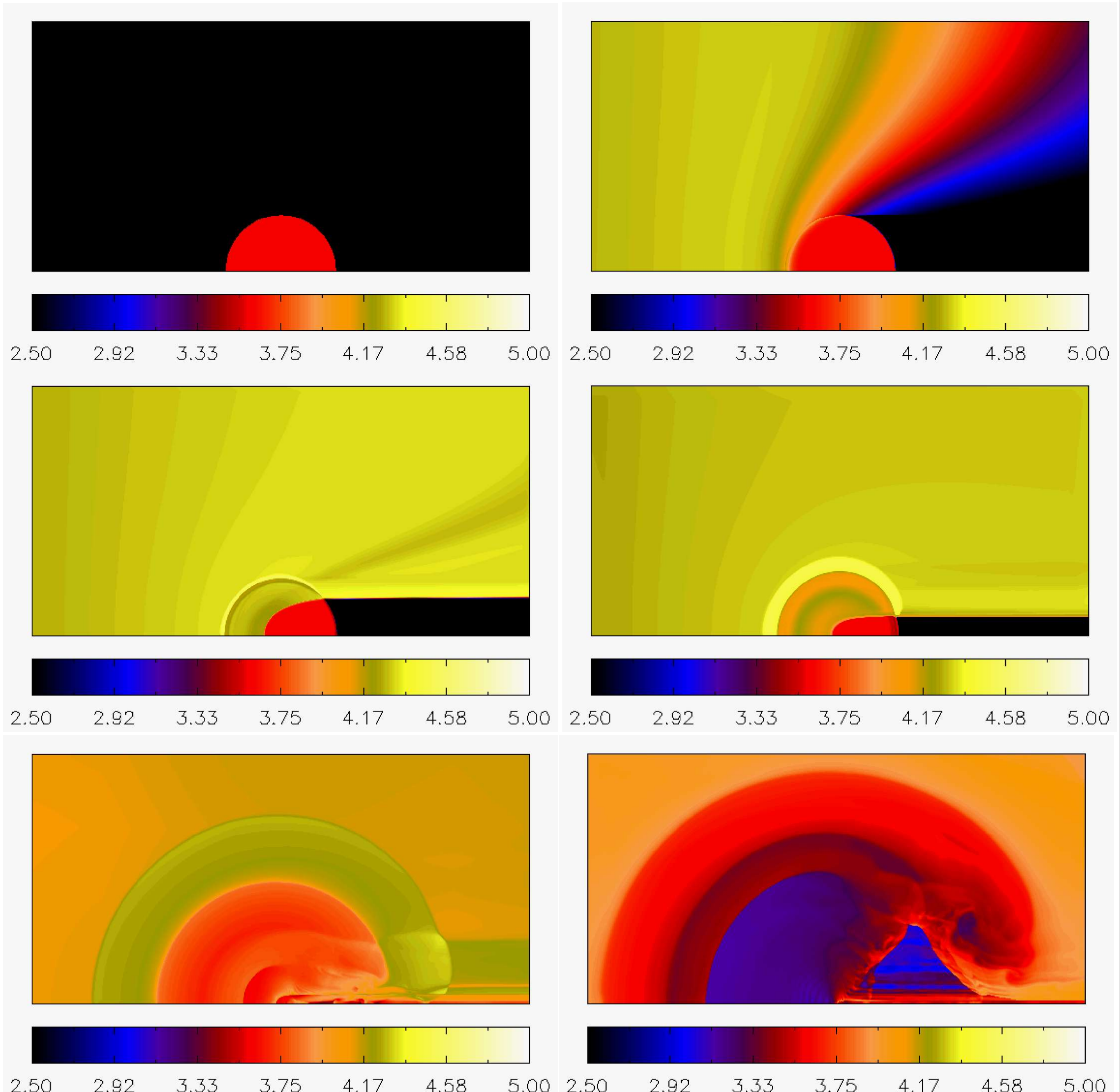
- Minihalos with $T_{vir} < 10^4$ K were common enough to cover the sky around source halos with $T_{vir} > 10^4$ K during reionization.



Temperature at times t = 0.0, 0.2, 2.5, 10, 60, 150 Myrs.

$(M_{halo}, z_{initial}, F_0)$ = $(10^7 M_{sun}, 9, 1)$.

Pop II source.

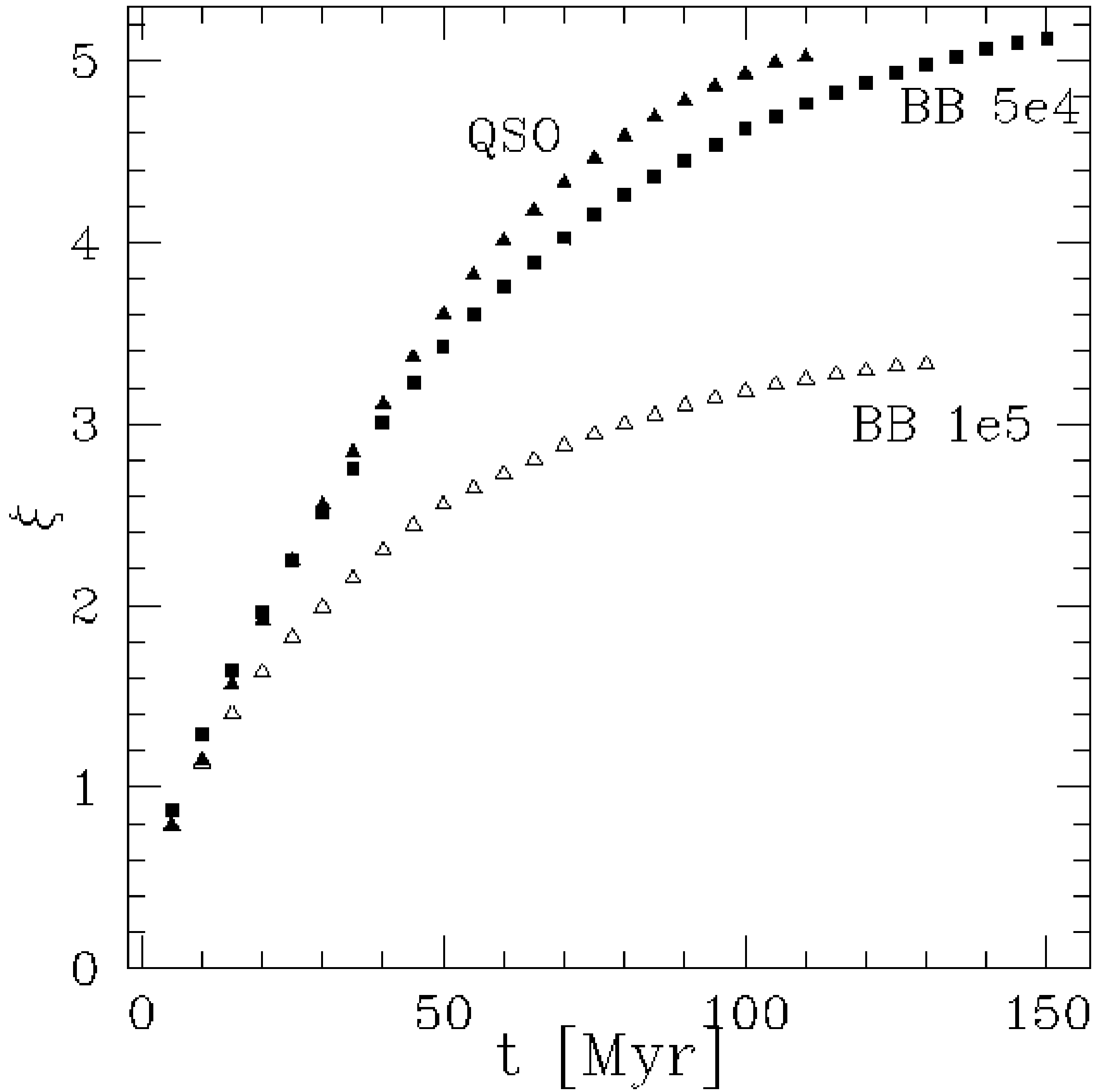


Minihalo Photoevaporation Movies

Pop. II stars	Pop. III stars
temperature	temperature
gas number density	gas number density
H I fraction	H I fraction

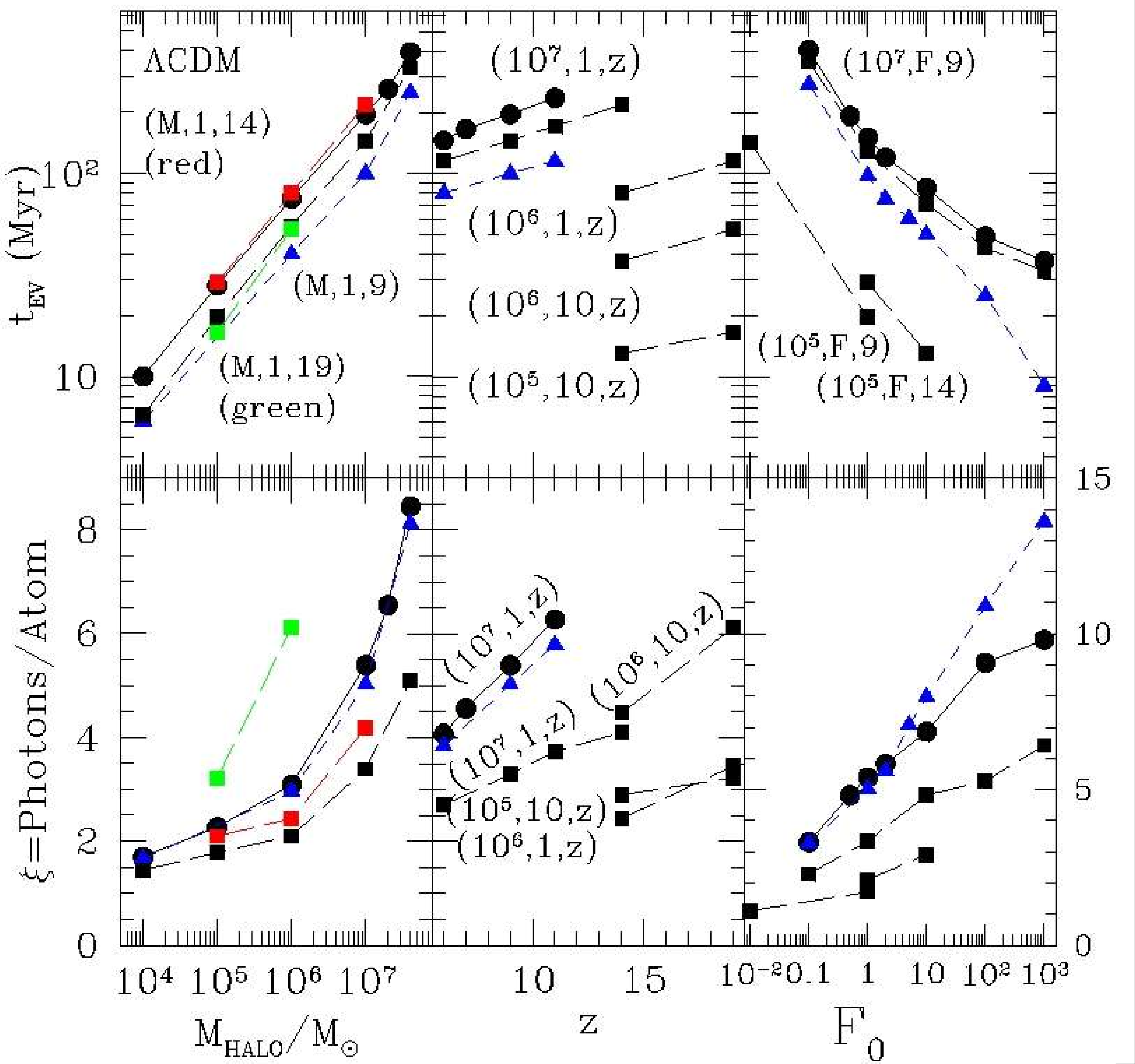
Ionizing Photons Consumed Per Minihalo Atom

- $\xi(t)$ = # photons consumed per H atom after time t.
- $(M_{halo}, z_{initial}, F_0)$ = $(10^7 M_{sun}, 9, 1)$.



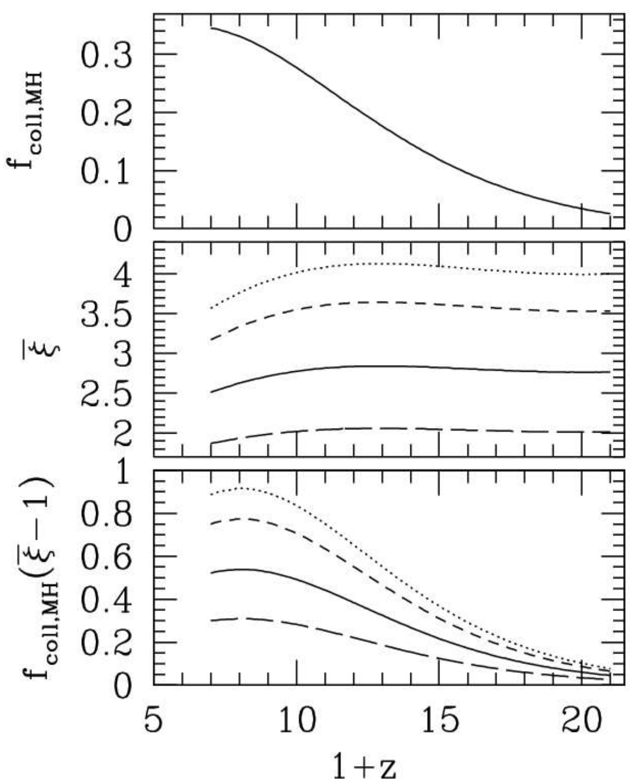
Evaporation times

Ionizing photon consumption

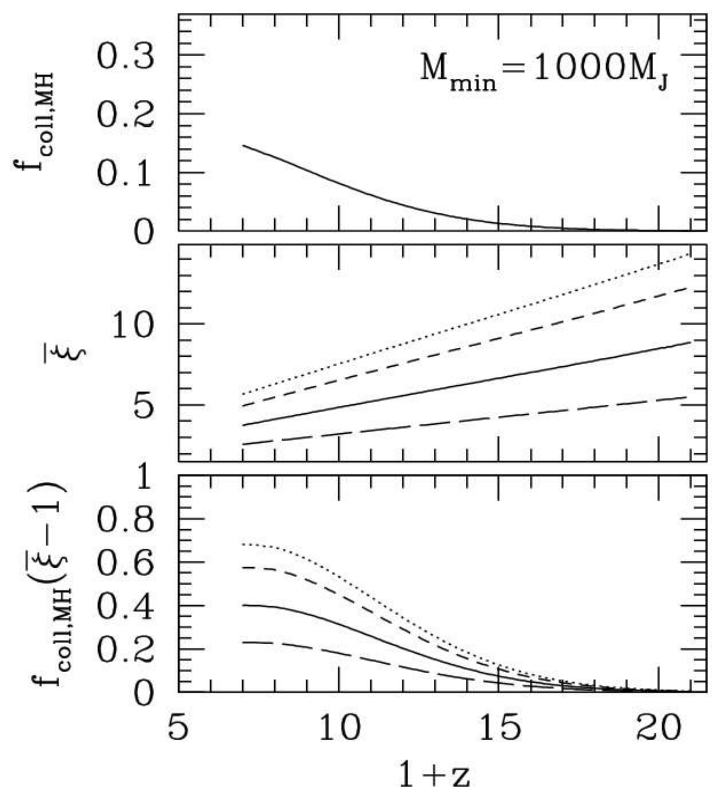


Effect of Minihalos on Global Ionizing Photon Consumption: A Rough Estimate

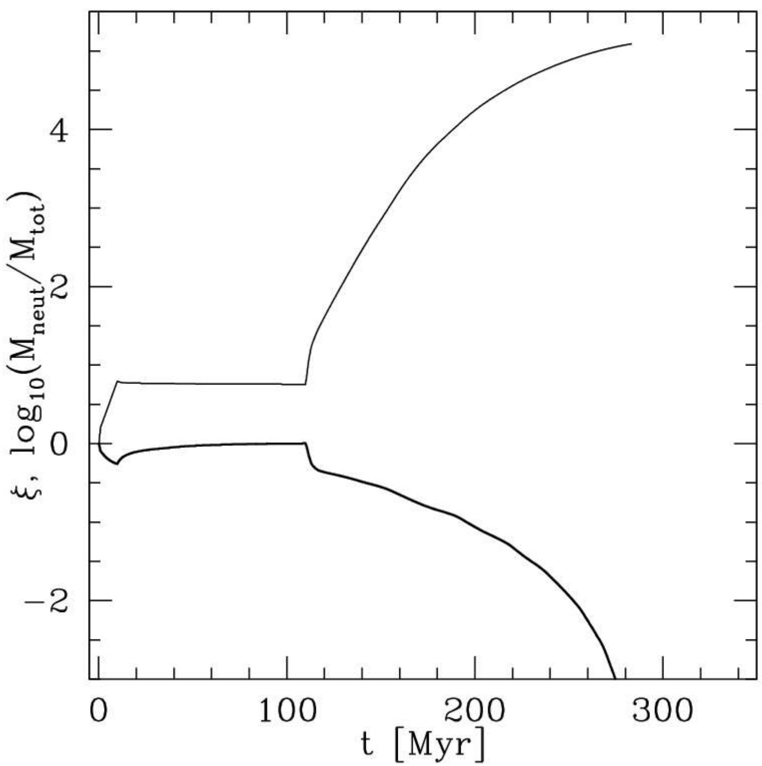
No reheating



With reheating



Case of Intermittent Ionizing Sources



Ionizing source on for 10 Myr, off for 100 Myr and on again.

Results:

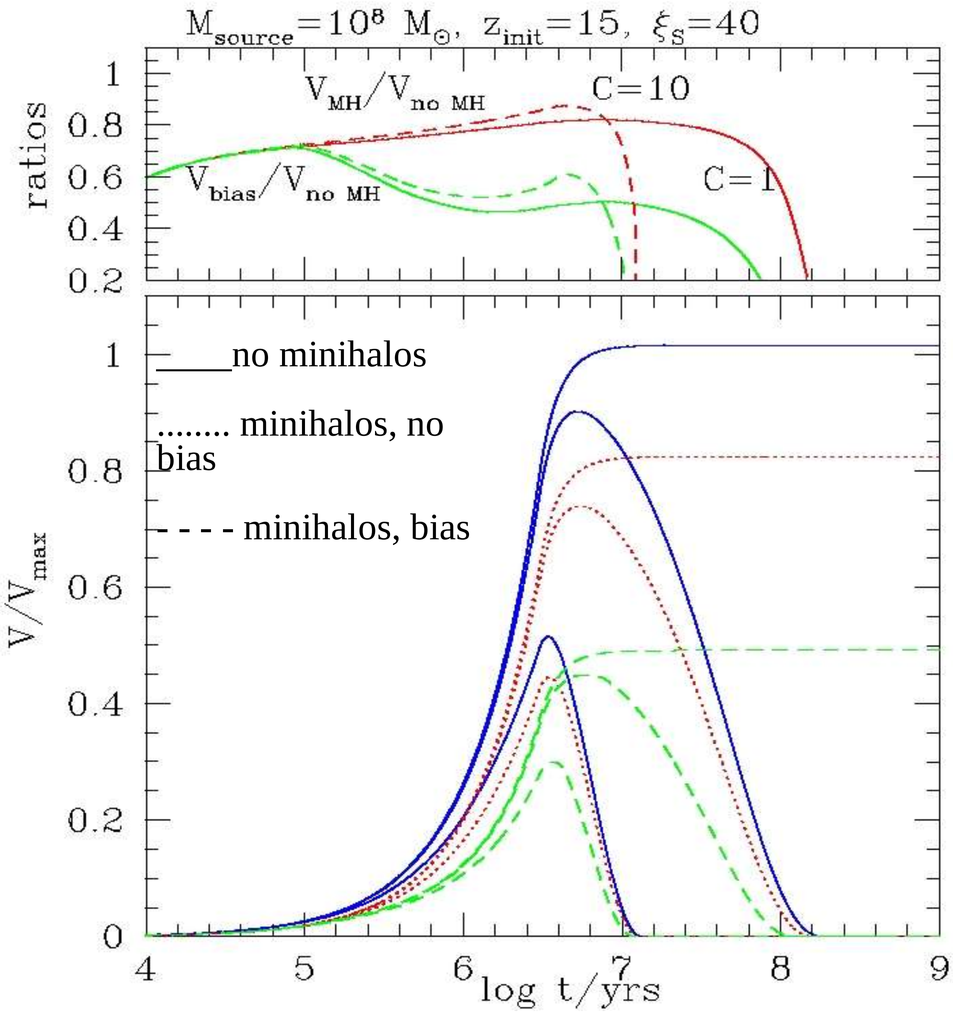
evaporation time is longer by about 80 Myr, while photon consumption is very similar to case of uninterrupted source with same flux.

Effect of minihalos on the propagation of a cosmological I-front

(Iliev, Scannapieco & Shapiro 2005)

Propagation of an I-front about an individual source:

10^8 M_{solar} source forming at z=15 producing 40 photons/atom during its lifetime



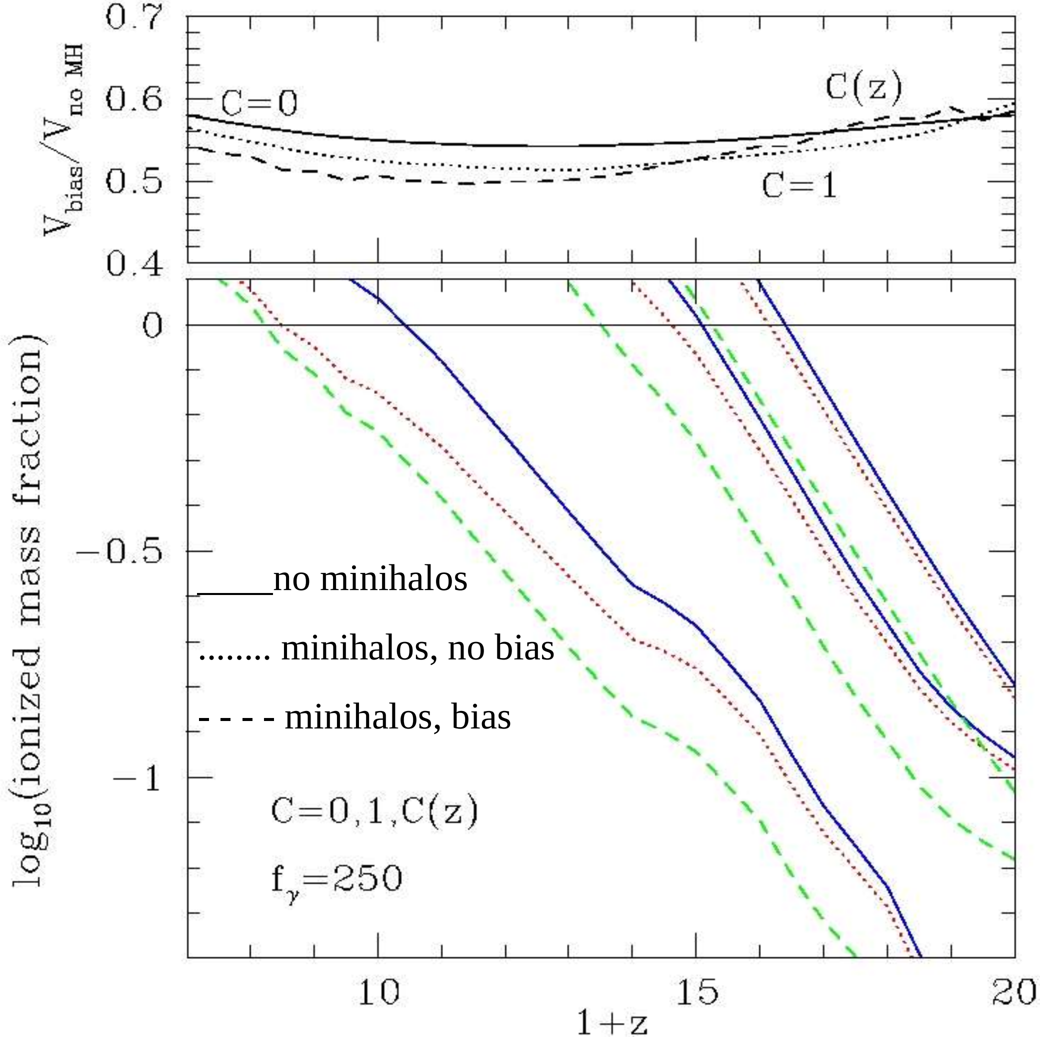
Effect of Minihalos and IGM Clumping on Reionization

Let each source halo create its own expanding spherical H II region.

I-front speed is slowed by minihalo trapping and evaporation and recombinations in IGM.

Integrate over statistical distribution of source halo masses and turn-on epochs until neighboring H II regions overlap => reionization finished.

Minihalos can increase photon consumption by factor of ~2, delaying reionization by z~2.

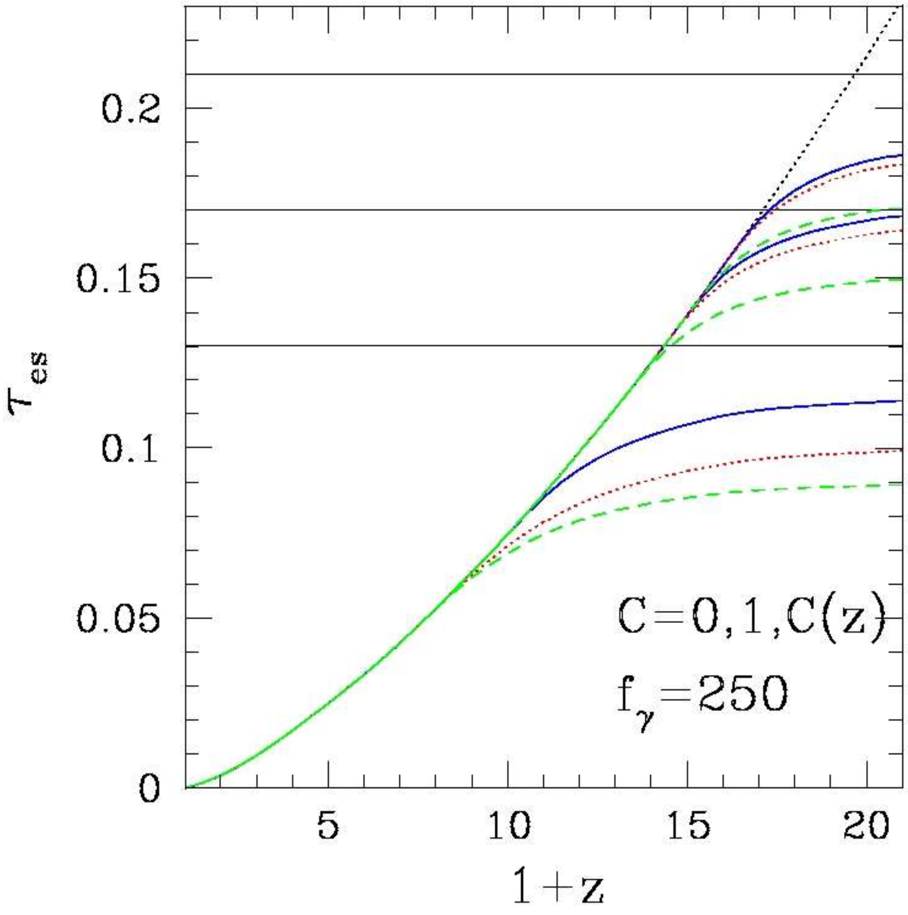


Effect of Minihalos and IGM Clumping on Reionization II: Electron Scattering Optical Depth

Multiple models studied (see paper for details)

For sources producing a total of 250 photons per baryon during their lifetime:

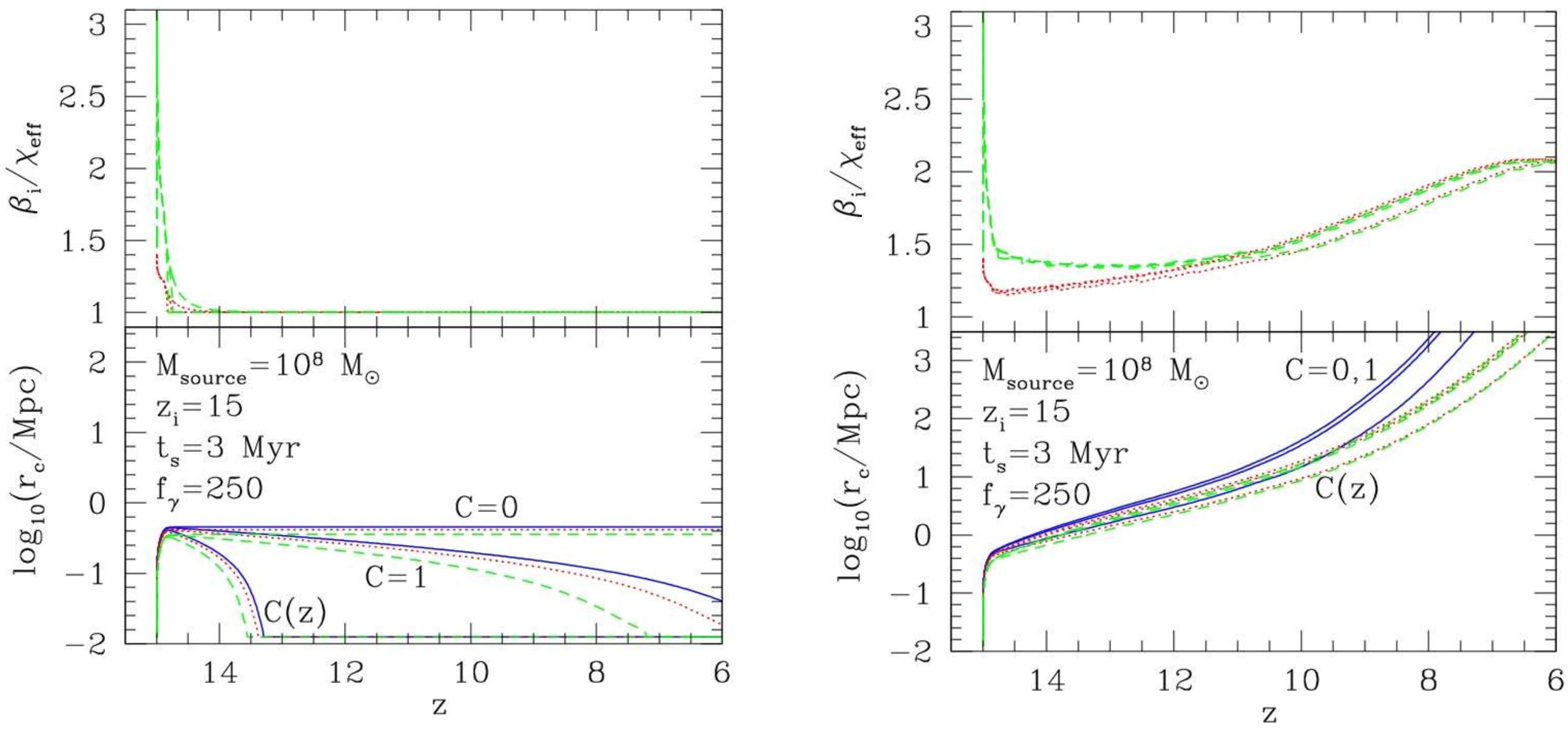
- Consistent with WMAP constraint for low or no clumping of IGM
- Produces somewhat low optical depth for cosmologically-evolving IGM clumping



Ionizing sources clustering effects:

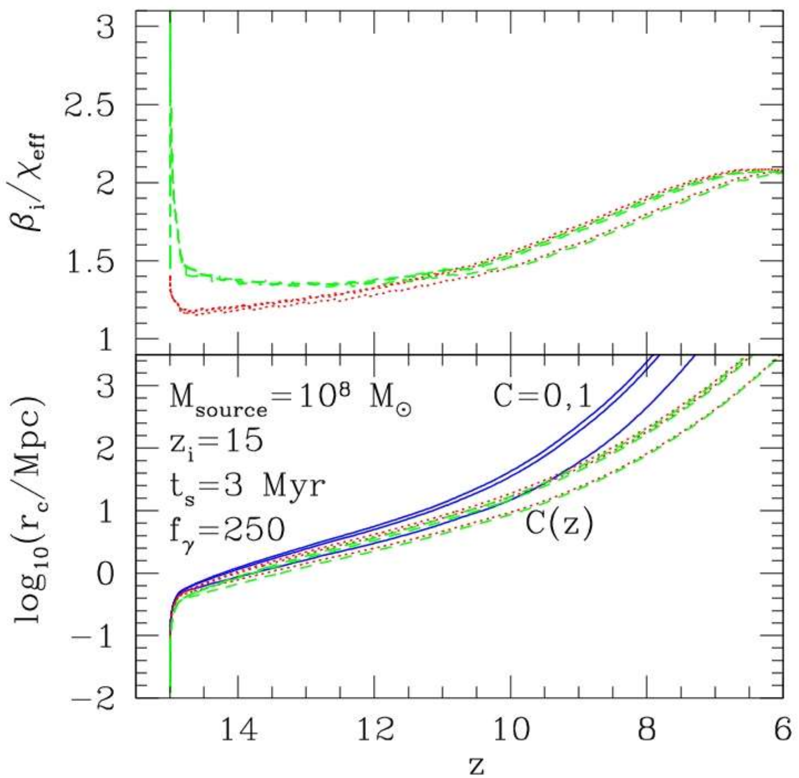
single source vs. biased multiple sources

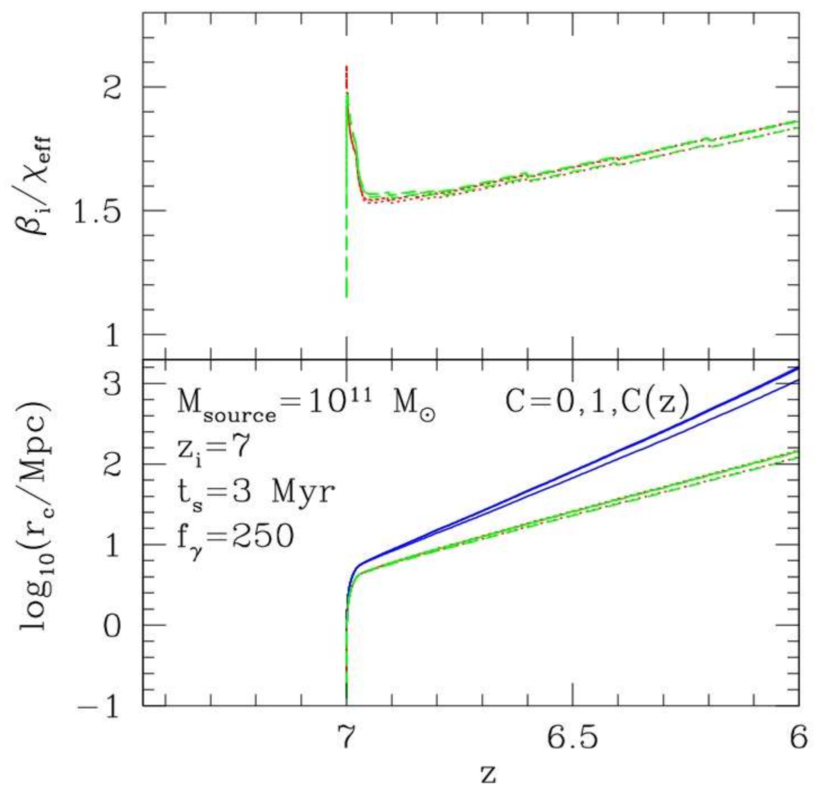
(with E. Scannapieco and P. Shapiro)



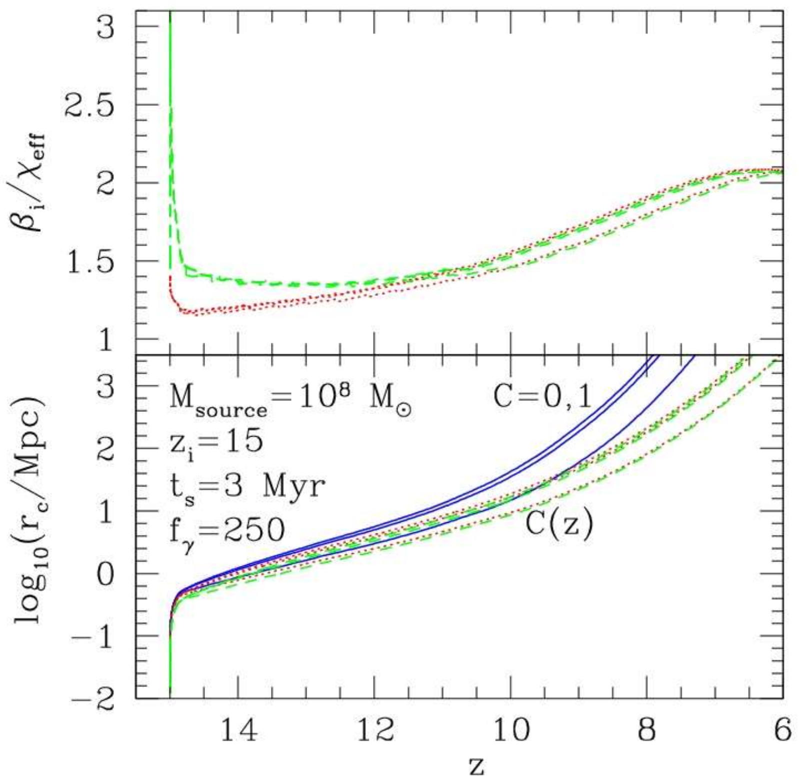
Ionizing sources clustering effects:

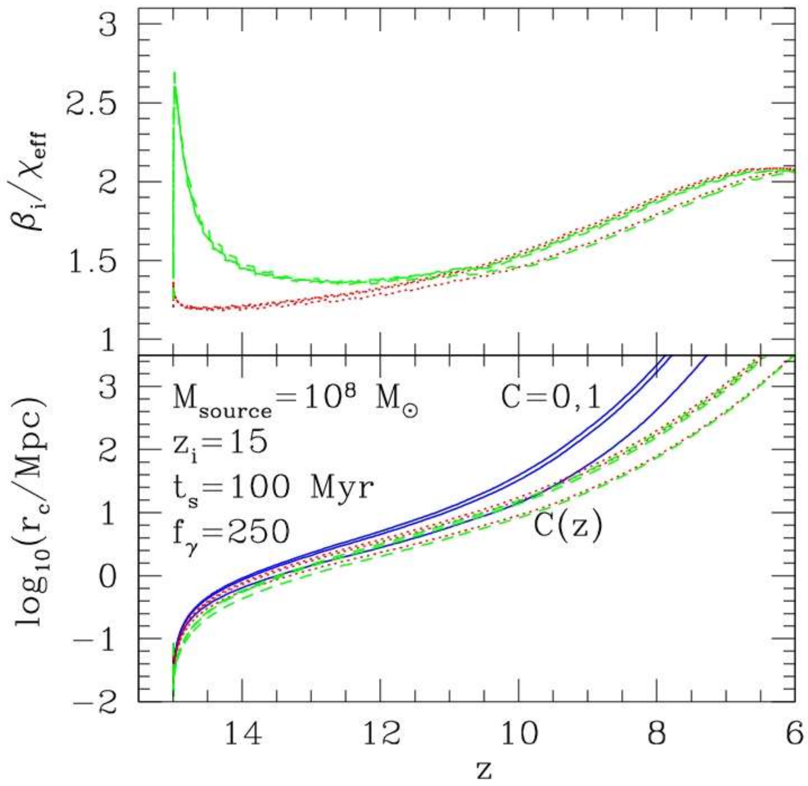
3-σ density fluctuations at z=15 and 7



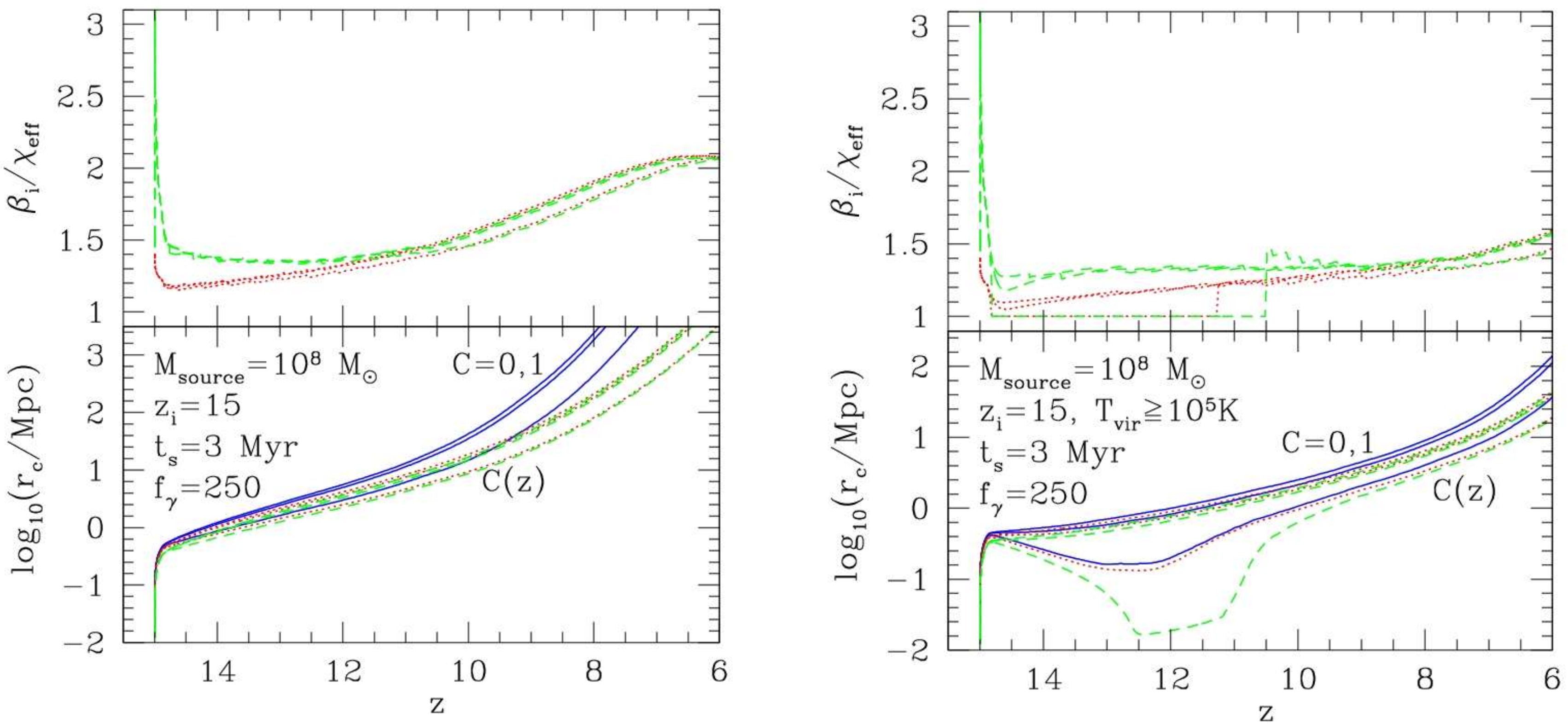


Ionizing sources clustering effects: short- vs. long-lived sources





Ionizing sources clustering effects: small source suppression



Summary

- We have studied how I-fronts propagate in inhomogeneous density fields and the implications of this for reionization.
- CDM model predicts that significant small-scale structure form at high-z. The ionizing sources are highly clustered and surrounded by enhanced density and minihalos.
- Minihalos are self-shielded and trap the global reionization I-fronts. We performed the first realistic simulations of this process, showing that minihalos consume significantly more ionizing photons than the minimum of one per atom.
- We modified the I-front propagation equations to include self-shielded structures as well as relativistic effects, and incorporated the results from these simulations into semi-analytical reionization models, which also include the effects of bias, infall, evolving IGM clumping and sources with different ionizing photon production efficiencies and spectra.
- We found that the small-scale structures, might have had significant effect on the progress and duration of reionization, slowing it down and extending it in time, in agreement with early, but extended reionization epoch.
- Correct modelling of the clustering of the high-z ionizing sources and bias of matter and minihalos around these high-density peaks is crucial for understanding the progress and topology of reionization, and its observational signatures at e.g. 21-cm line and imprint on the CMB anisotropies.
- Finally, we have developed a new fast and efficient method for radiative transfer with which we can accurately follow both fast and slow I-fronts with arbitrary time-steps. I have presented some of the tests and first results from this code, including coupling it to AMR gas-dynamics.
- As simple application, we simulated locally the cosmological reionization and showed that the process is complex and does not follow any simple scenarios (e.g. “low density regions first”, or “high-density regions first”). Much more is to follow soon!