Reionization, CMB and small-scale structure

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20th IAP colloquium on CMB physics and observation

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Outline

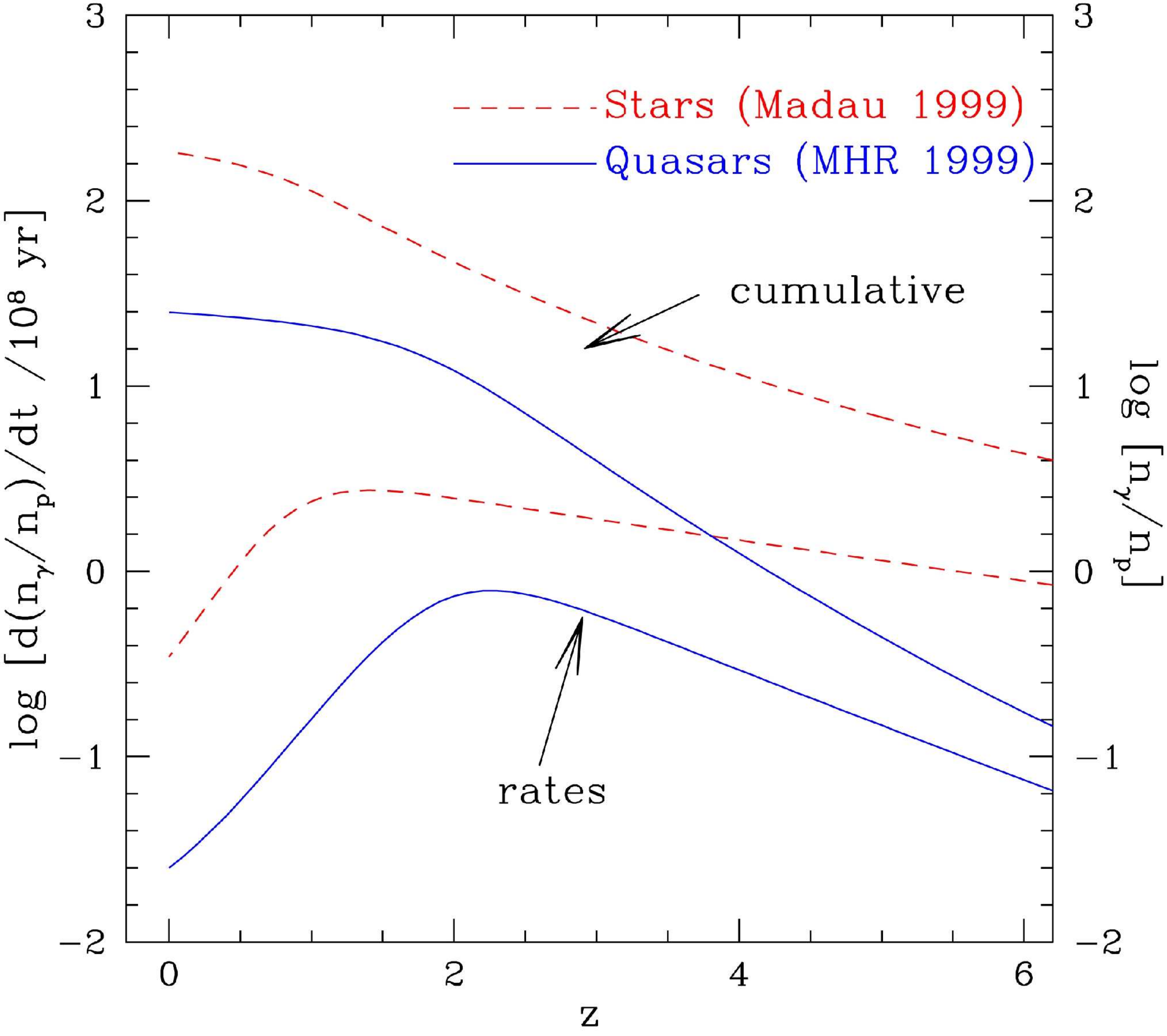
- Introduction: The Epoch of Reionization
- Cosmological I-Fronts and the Photoevaporation of Minihalos During Reionization
- Effects of small-scale structures on global reionization and CMB electron-scattering optical depth

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 ~ 6-7.
- 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 ~ 6-7.

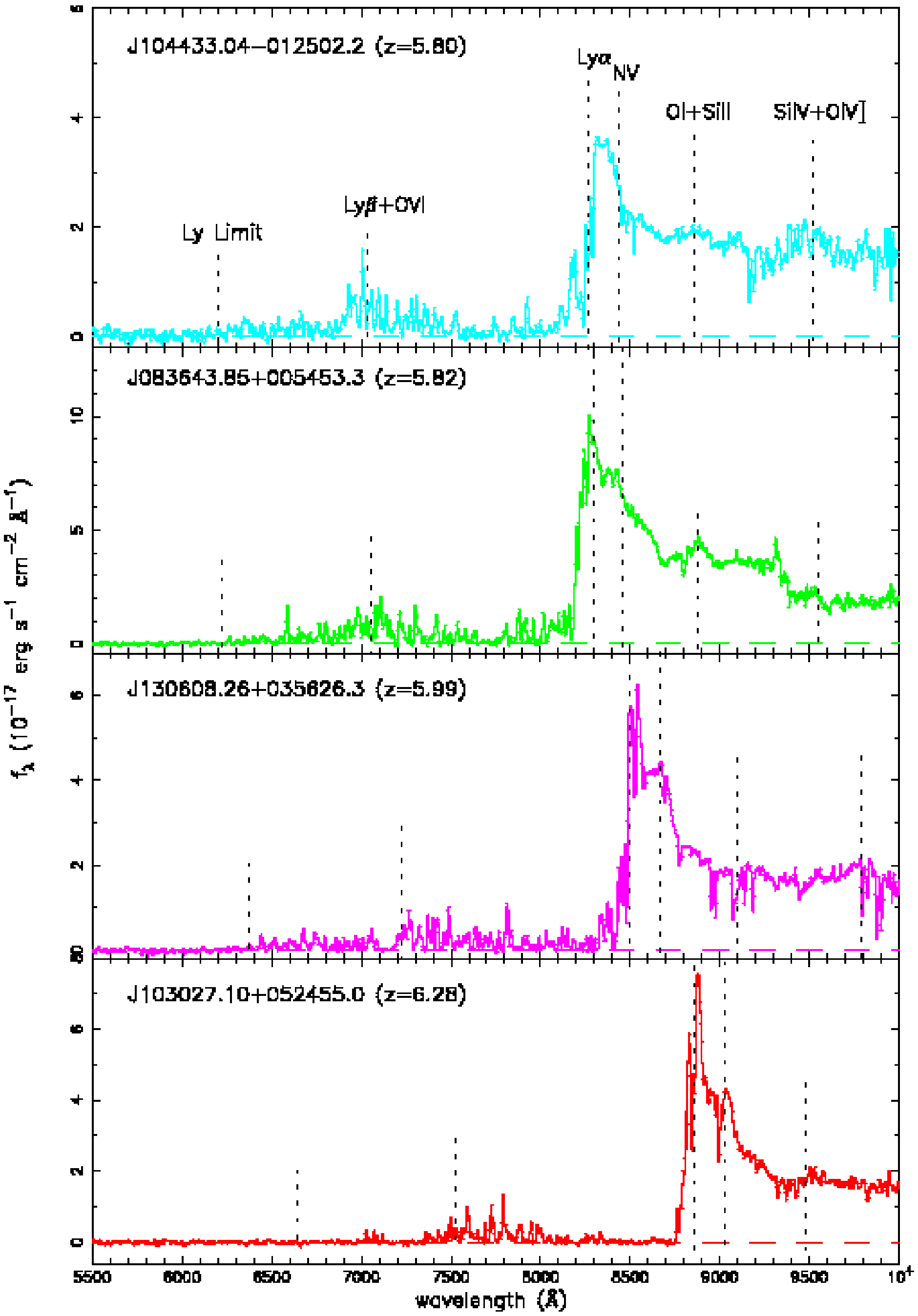
Q : Which sources ionized the IGM?

A : Probably starlight from massive stars



Haiman et al. (2000)

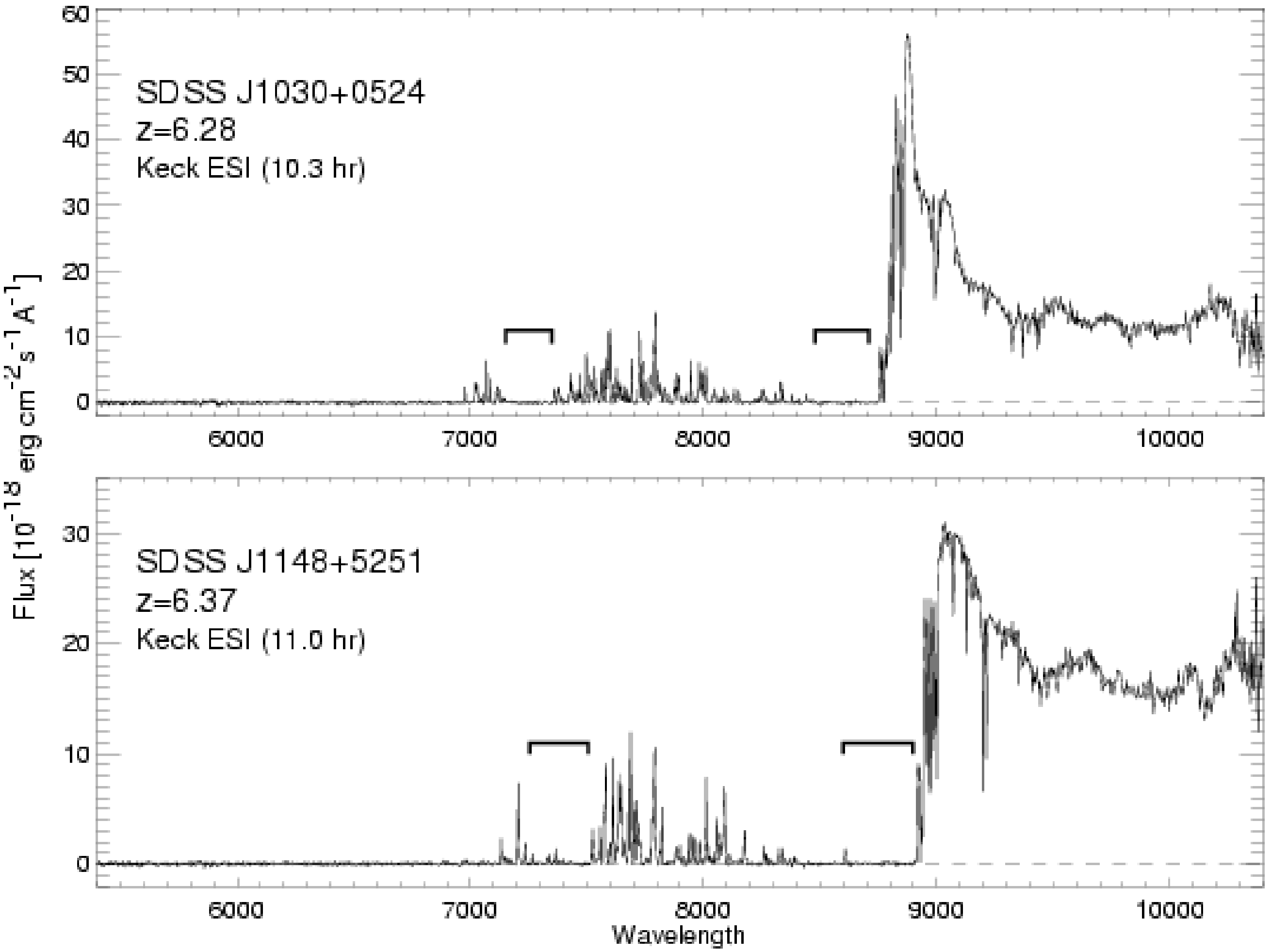
GP troughs, both Ly α and Ly β, finally detected in spectrum of quasar SDSS J1030+0524 at z=6.28 (Becker et al. 2001).



- Latest observations by White et al. (2003) find $\tau > 22.8$ (1σ) at $z=6$

$$\frac{n_{HI}}{n_H}(z=6) \leq 7 \times 10^{-5}$$

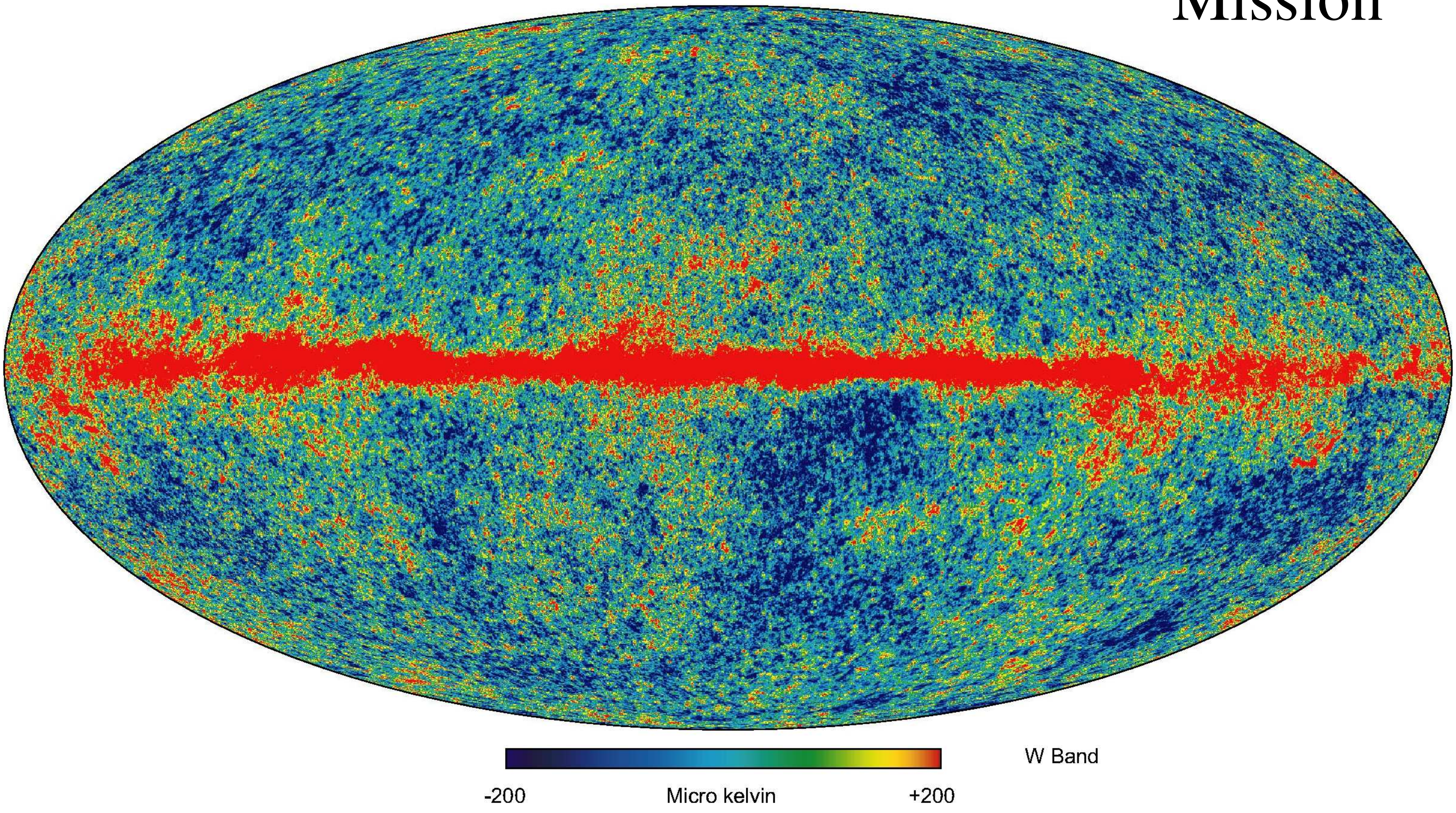
$\Rightarrow$ $n_{HI}/n_H(z=6)<7x10^{-5}$



CMB Polarization Detects the Ionized IGM at High z

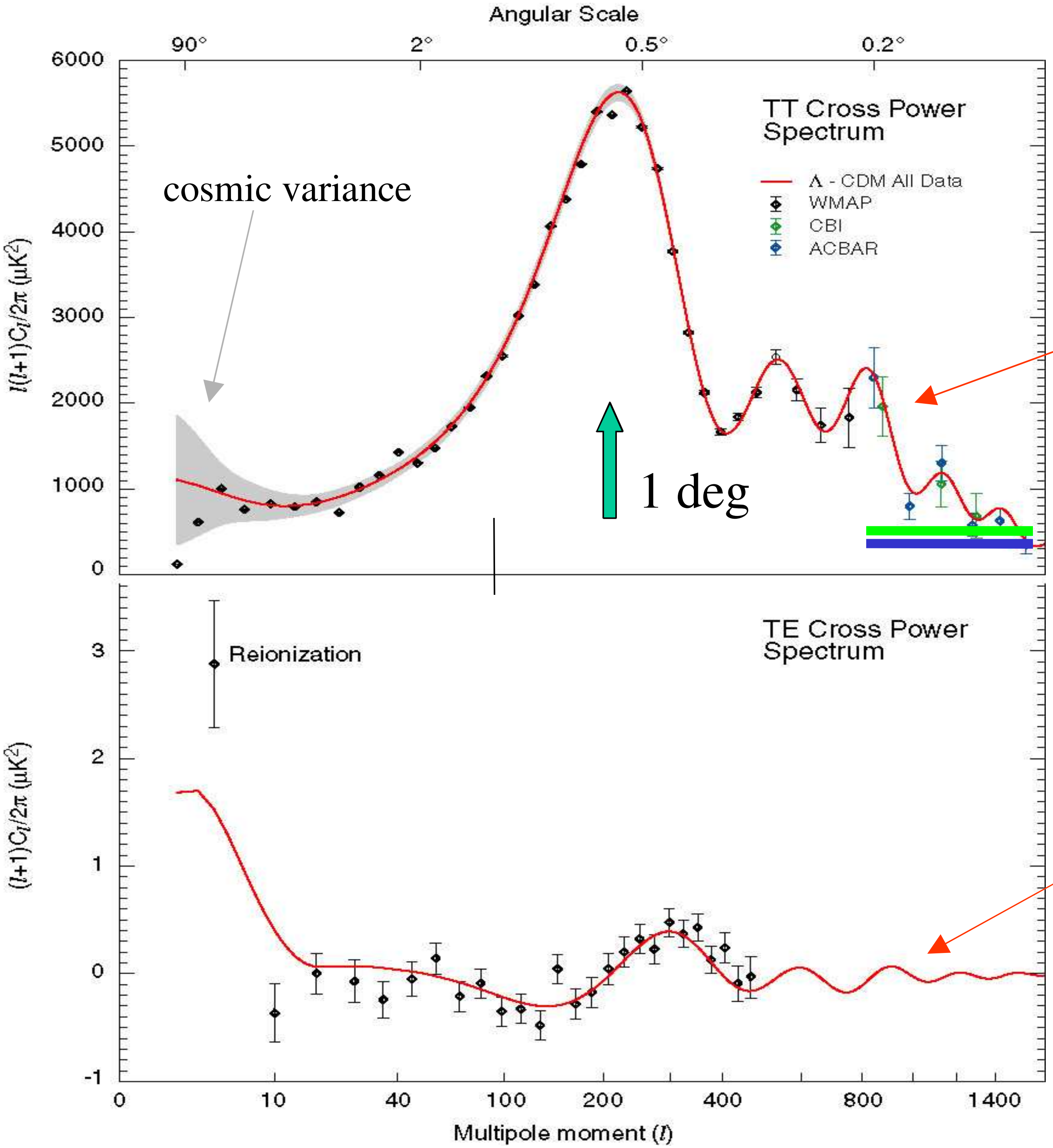
- Linear polarization of CMB results from Thomson scattering of anisotropic CMB (i.e. quadrupole).
- Horizon at $z < 50$ is large angular scale today, $\theta > 5^{o}$ polarization fluctuates on large angular scales if IGM reionized at $z < 50$.
- τ_{es} optical depth to electron scattering due to free electrons in IGM out to redshift z

The
WILKINSON MICROWAVE ANISOTROPY PROBE
Mission



Temperature

85% of sky



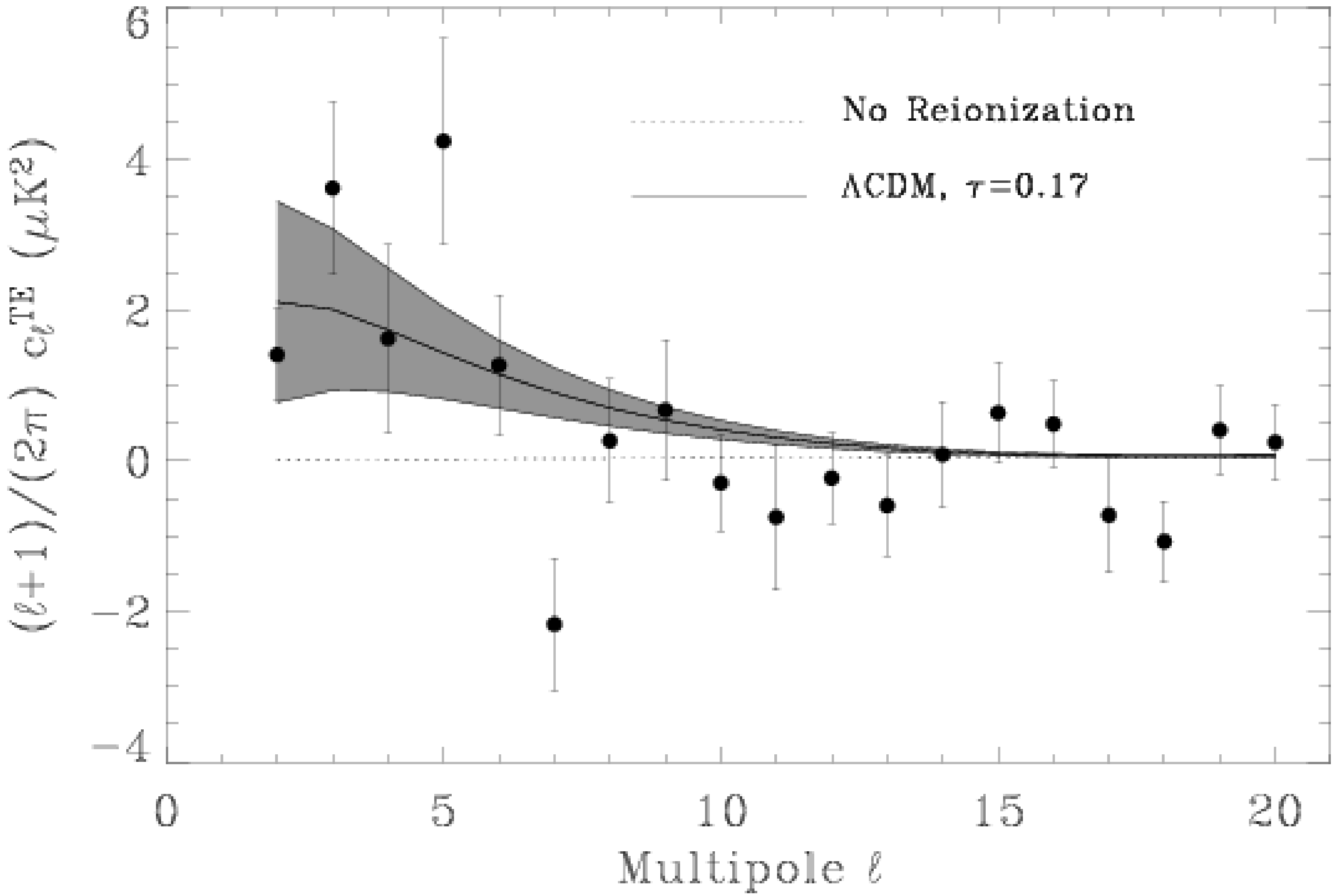
cosmic variance

1 deg

Best fit model

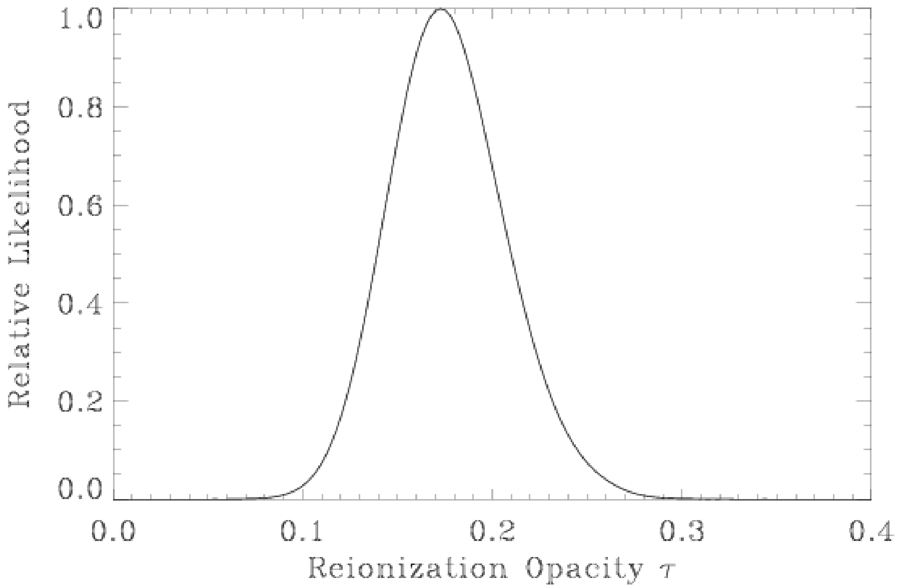
Temperature-polarization

Prediction
based on TT,
no free params.



Kogut et al. (2003)

- WMAP detected correlations between CMB temperature and polarization fluctuations at $\theta > 10^o$, in excess of that expected from adiabatic perturbations alone.



$$\Rightarrow \tau_{es} = 0.17 \pm 0.04$$

(68% confidence)

$$\Rightarrow z_r = 17 \pm 3$$

Summary
GP Effect vs. CMB Polarization

- GP upper limits at $z < 6 \Rightarrow$ Universe already reionized.
- GP lower limit at $z = 6 \Rightarrow$ IGM neutral fraction increased rapidly from $z < 6 \Rightarrow$ reionization just ended at $z = 6$.
- WMAP polarization $\Rightarrow$ reionization started earlier, $z_r = 17 \pm 3$.
- Reionization by radiation from massive stars or miniquasars, probably stars.

Ionization fronts in the IGM

- The first sources of ionizing radiation to condense out of the dark, neutral, opaque IGM heated and ionized it between z~30 and z~6.
- Weak, R-type ionization fronts surrounding each source swept outward through the IGM, overtaking other condensations and photoevaporating them.
- High-redshift sources of ionizing photons may have found the sky covered by these minihalos. If so, then minihalos blocked the path of reionization until they photoevaporated.
- Results are presented of the first gas dynamical simulations of this process, including radiative transfer, along with some observational diagnostics.

COSMOLOGICAL H II REGIONS

(Shapiro and Giroux 1987, ApJ, 321, L107)

Cosmological Stromgren Spheres

$S(r,t)$ = number of ionizing photons emitted by source which pass thru sphere of comoving radius r per second.

$a(t)$ = cosmic scale factor = $(1+z_i)/(1+z)$

$$\frac{\partial S}{\partial r} = -4\pi r^2 a^{-3} n_{H,i}^2 c_\ell \chi^2 \alpha_2$$

$$\begin{aligned} n_H &= n_{H,i} a^{-3} \\ c_\ell &= \langle n_H^2 \rangle / \langle n_H \rangle^2 = \text{clumping factor} \\ \chi &= \text{ionized fraction} \\ \alpha_2 &= \text{recombination coeff. to } n \geq 2 \end{aligned}$$

$$\begin{aligned} \Rightarrow r_S(t) &= \left[3N_{ph}/(4\pi \chi_{eff} \alpha_2 c_\ell n_{H,i}^2) \right]^{1/3} a(t) \\ &\equiv r_{S,i} a(t), \qquad N_{ph} \equiv S(0) \end{aligned}$$

Cosmological Ionization Fronts

Jump Condition: $n_{H,1} u_1 = \beta_i^{-1} J$

$$\begin{aligned} u_1 &= v_{I,pec} = a(dr_I/dt) = \text{I-front peculiar velocity} \\ n_{H,1} &= \text{H atom density ahead of I-front} \\ J &= S(r_I)/(4\pi r_I^2 a^2) = \text{photon number flux} \\ \beta_i &= \text{\# of positive ions created per H ionization} \\ &= \chi_{eff} = 1 + pA(He) \end{aligned}$$

($p = 0, 1$, or 2 if H only, HeI, or HeII ionized)

Evolution of $r_I(t)$: $dy/dx = \lambda(1 - y/a^3)$

$y \equiv (r_I/r_{S,i})^3, \qquad x \equiv t/t_i,$

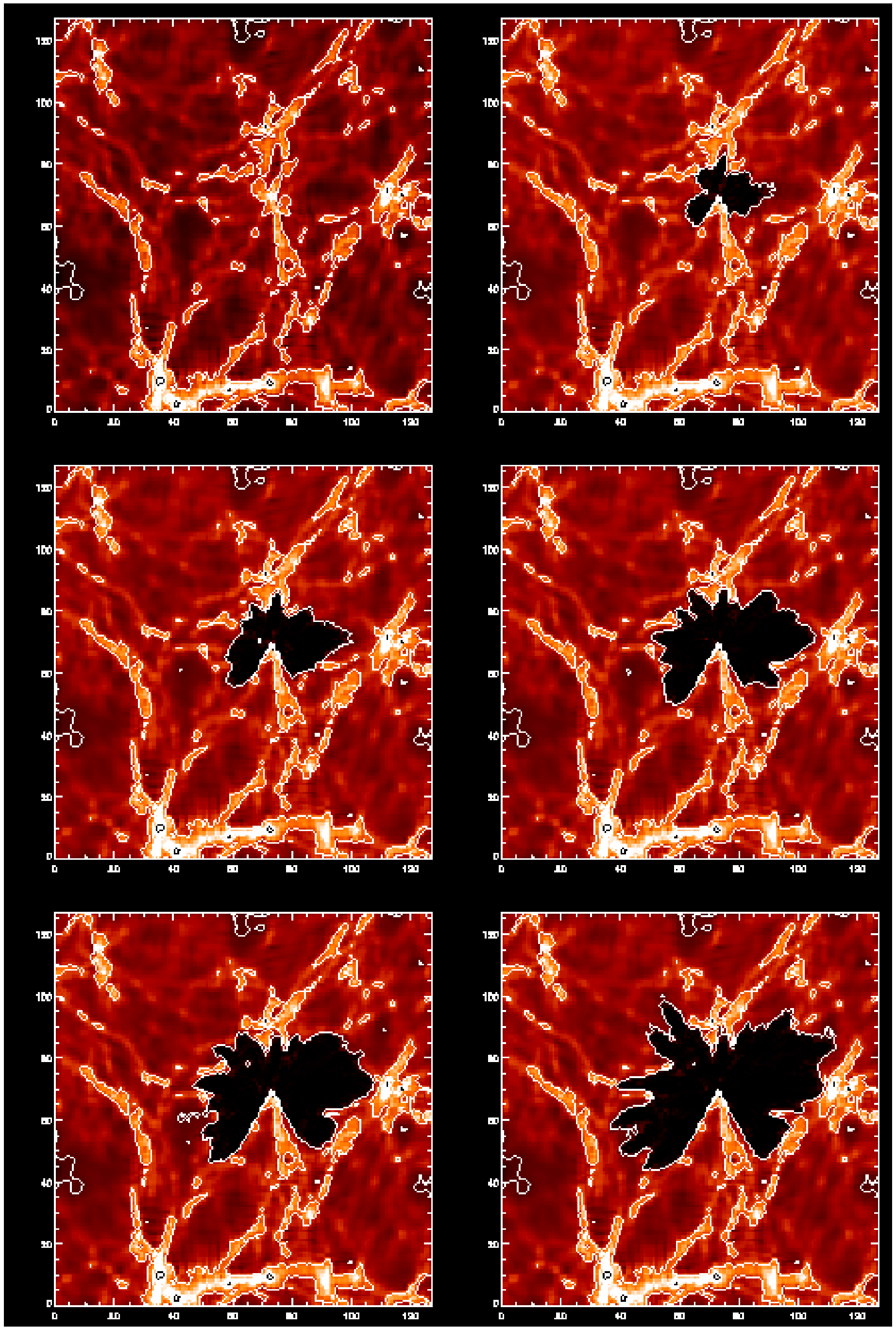
$\lambda \equiv \chi_{eff}\alpha_2 c_\ell n_{H,i} t_i = \dfrac{\text{age of universe at turn-on}}{\text{recomb. time at turn-on}}$

Result

- Analytical solution $= fcn(q_0, z_i, c_\ell \Omega_b h)$
  [i.e. $\alpha_2 = \alpha(10^4\,K)$ and $\chi_{eff} = 1 - 1.2$]
- $r_I(t) <$ Strömgren radius, except for very large z_i
- $v_{I,pec}(t) >> c_{sound}$

$\Rightarrow$ weak, R-type front at all times.

Inhomogeneous Reionization: Static Limit



Ciardi et al. (2000)

ΛCDM, Boxsize=160 kpc

Z_{on}=12, metal-free stars

t=0,10,20,40,60,100 Myrs

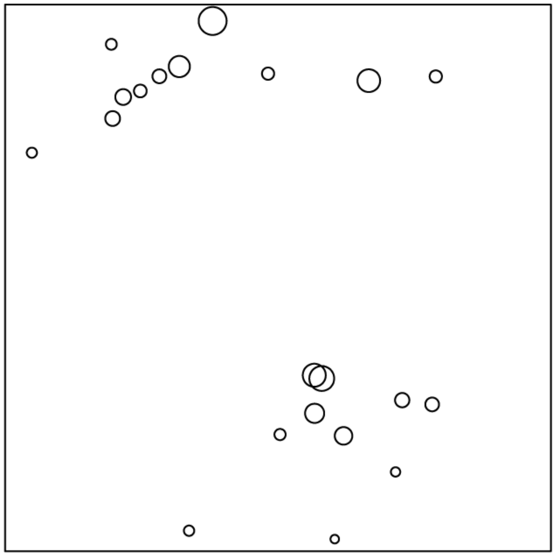
H I density
(Black = 99% ionized H)

DWARF GALAXY MINIHALOS AT HIGH REDSHIFT

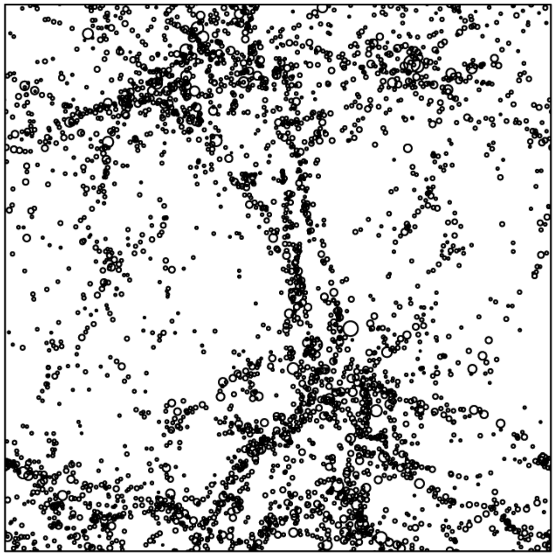
(w/Paul Shapiro and Hugo Martel)

- For ΛCDM, the universe at $z > 6$ was already filled with dwarf galaxies capable of trapping a piece of the global, intergalactic I-fronts which reionized the universe and photoevaporating their gaseous baryons back into the IGM.

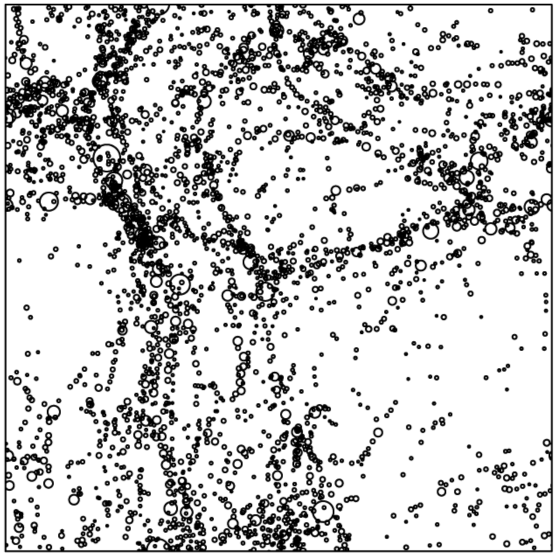
100 kpc box, $T_{vir} > 10^4$K



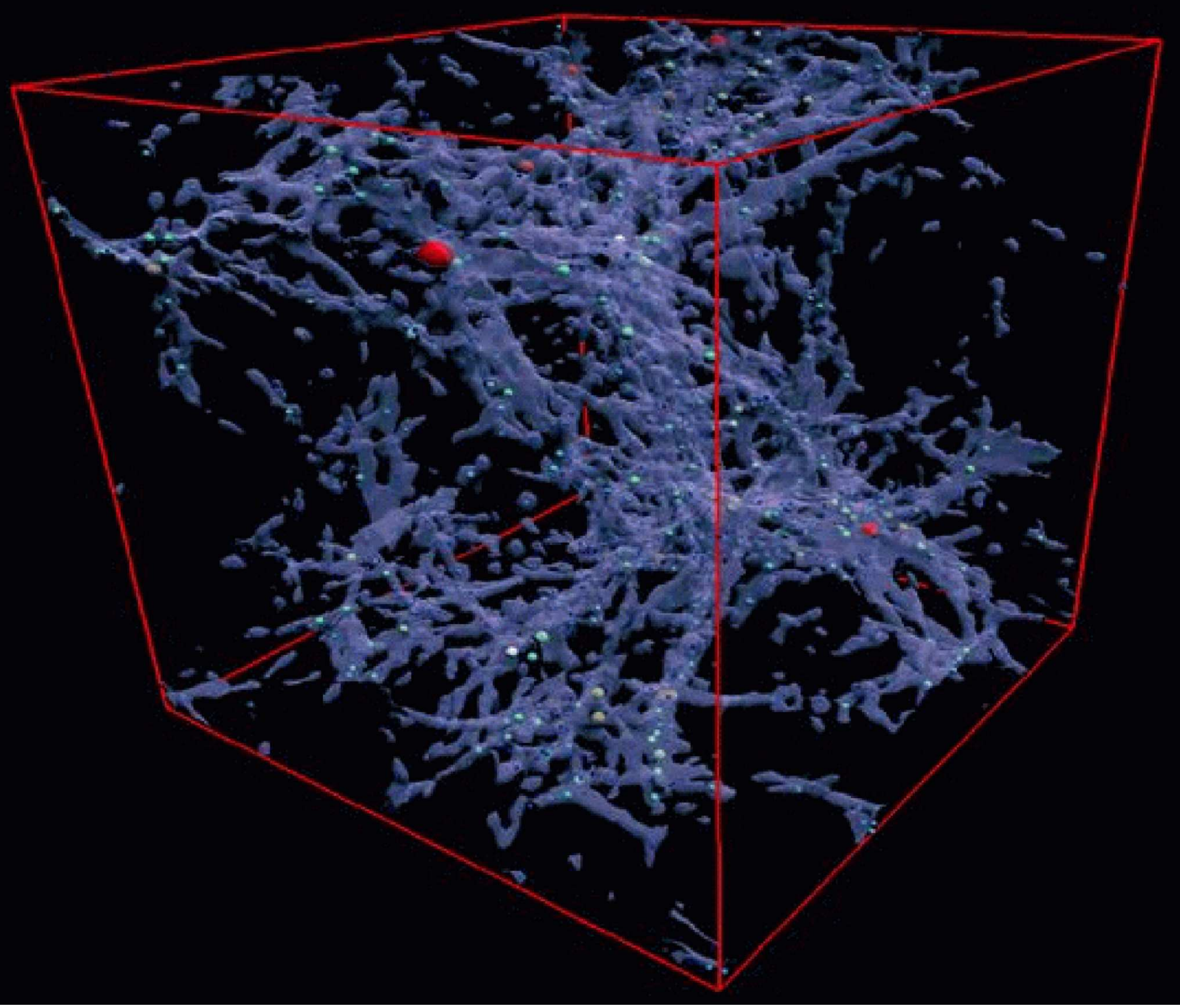
100 kpc box, $T_{vir} < 10^4$K



50 kpc box, $T_{vir} < 10^4$K

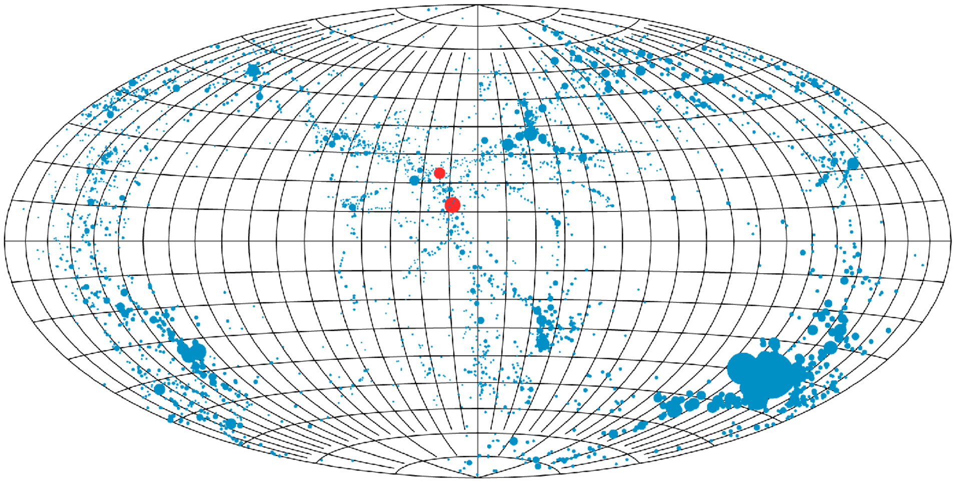


Universe at Redshift z = 9



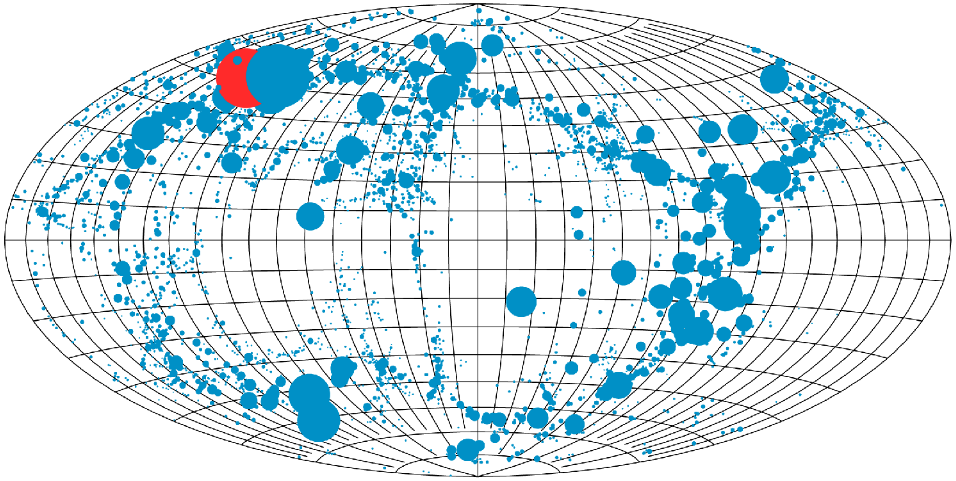
- Minihalos with $T_{vir} < 10^4$ K were common enough to cover the sky around source halos with $T_{vir} > 10^4$ K during reionization.

ΛCDM HALOS WITHIN 25 KPC AT Z = 9



Sky as seen from a random location

Covering fraction : 10.7%



Sky as seen from a 1.1×10^8 $M_\odot$ source

Covering fraction : 23.6%

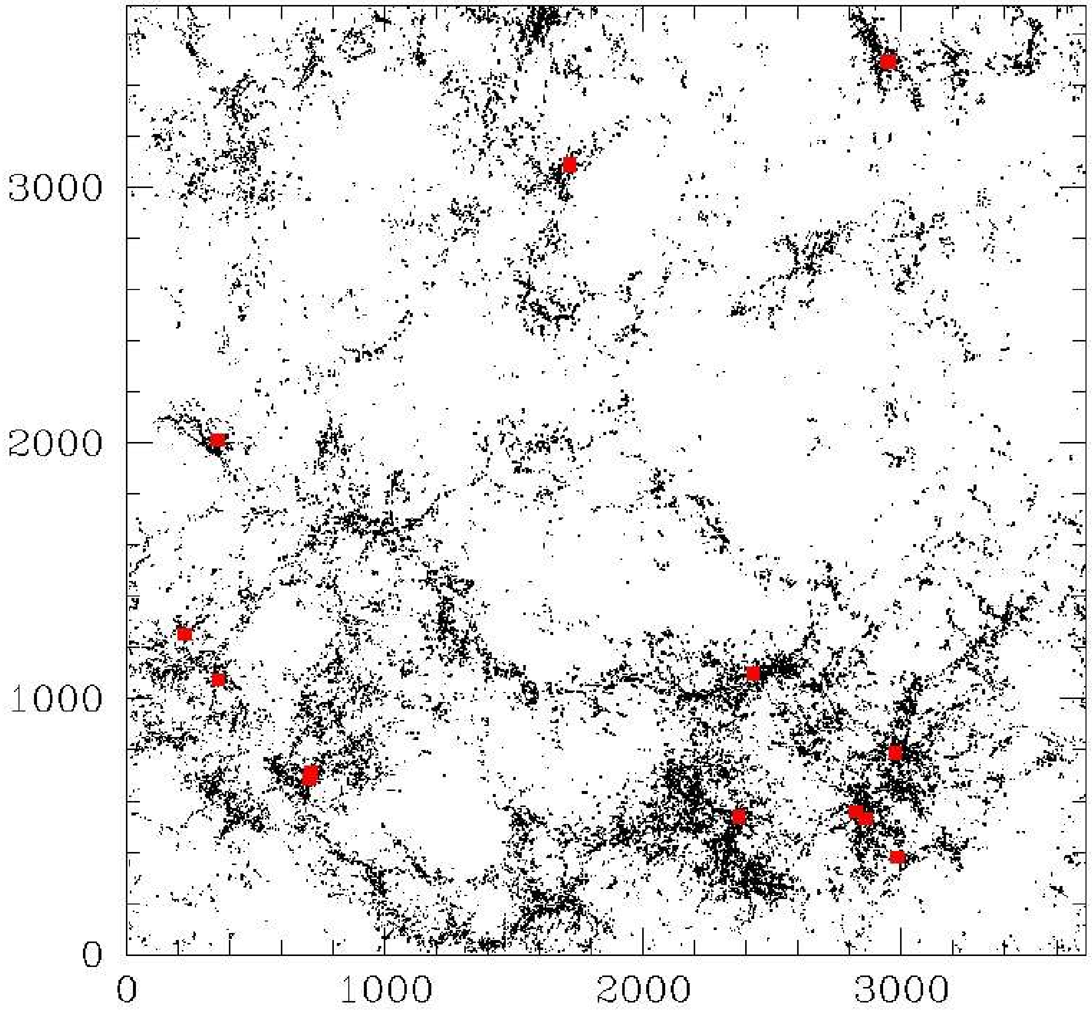
High-resolution N-body simulations

(w/Ue-Li Pen, Hy Trac, Hugh Merz and Mirza Ahmic)

- We performed high-resolution N-body simulations of structure formation at high-z using PMFAST code developed at CITA (Merz, Pen & Trac 2004)
- 10/h Mpc box (3/h Mpc box currently running)
- 1856^3 particles (6.4 billion)
- 3712^3 cells
- Identified between 544,000 halos (z=17.2) to 2.3 million halos (z=6) (>100 particles/halo)

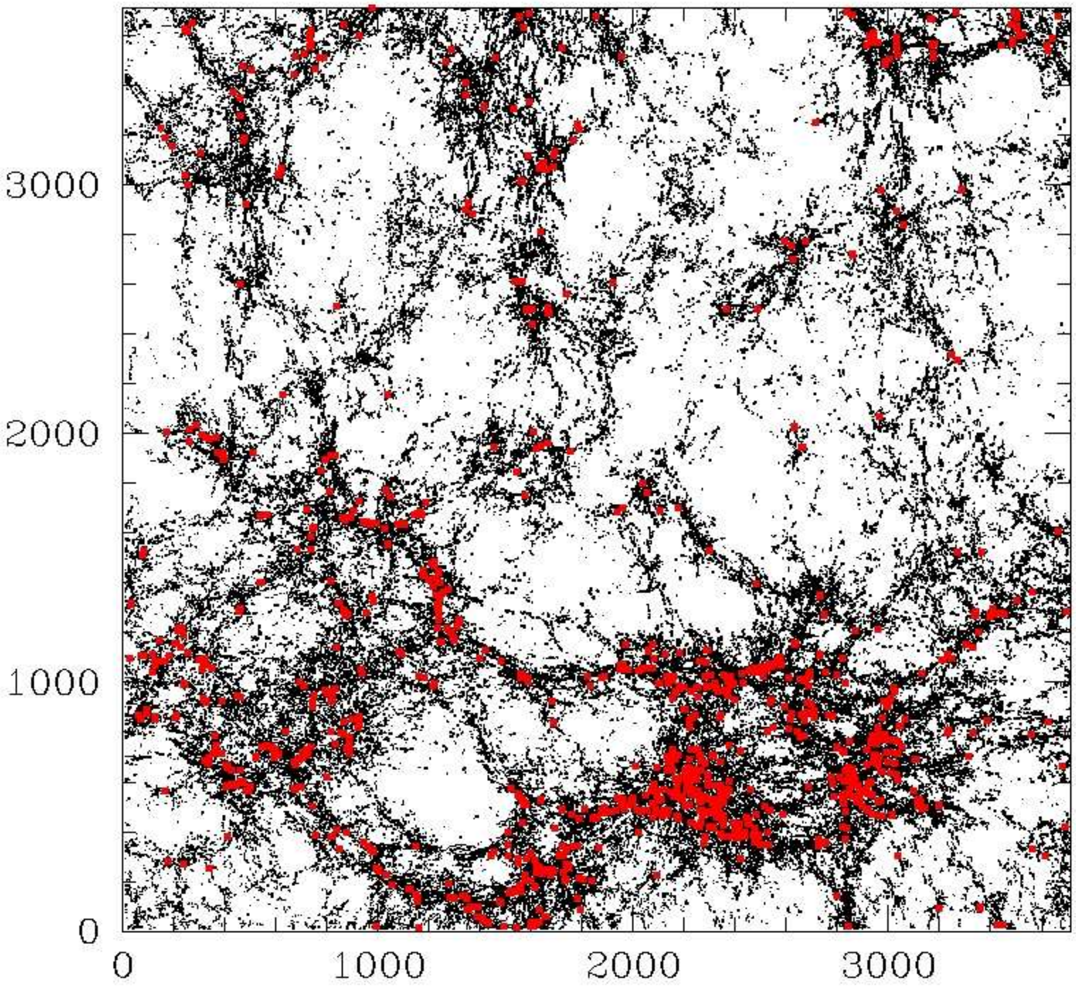
High-resolution N-body simulations

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



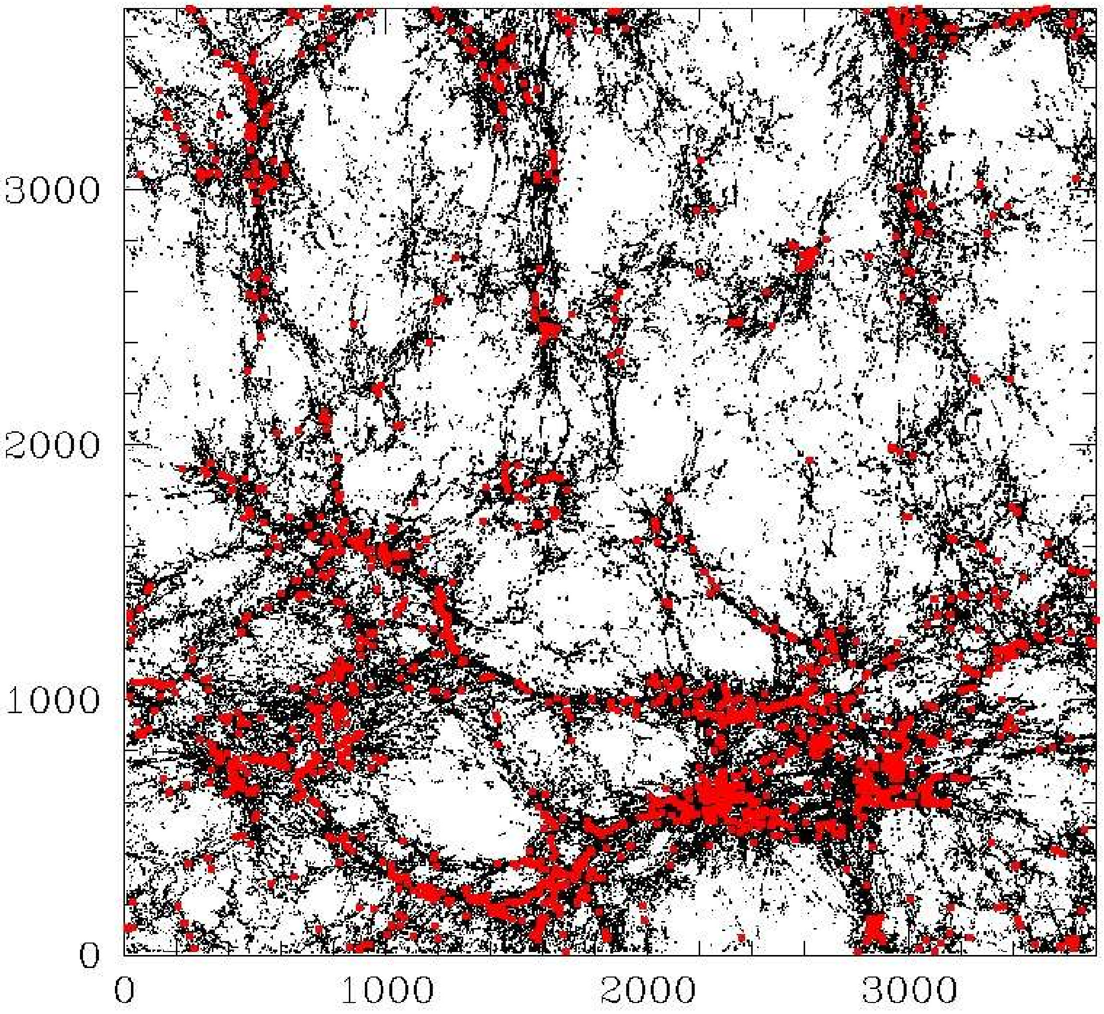
High-resolution N-body simulations

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



High-resolution N-body simulations

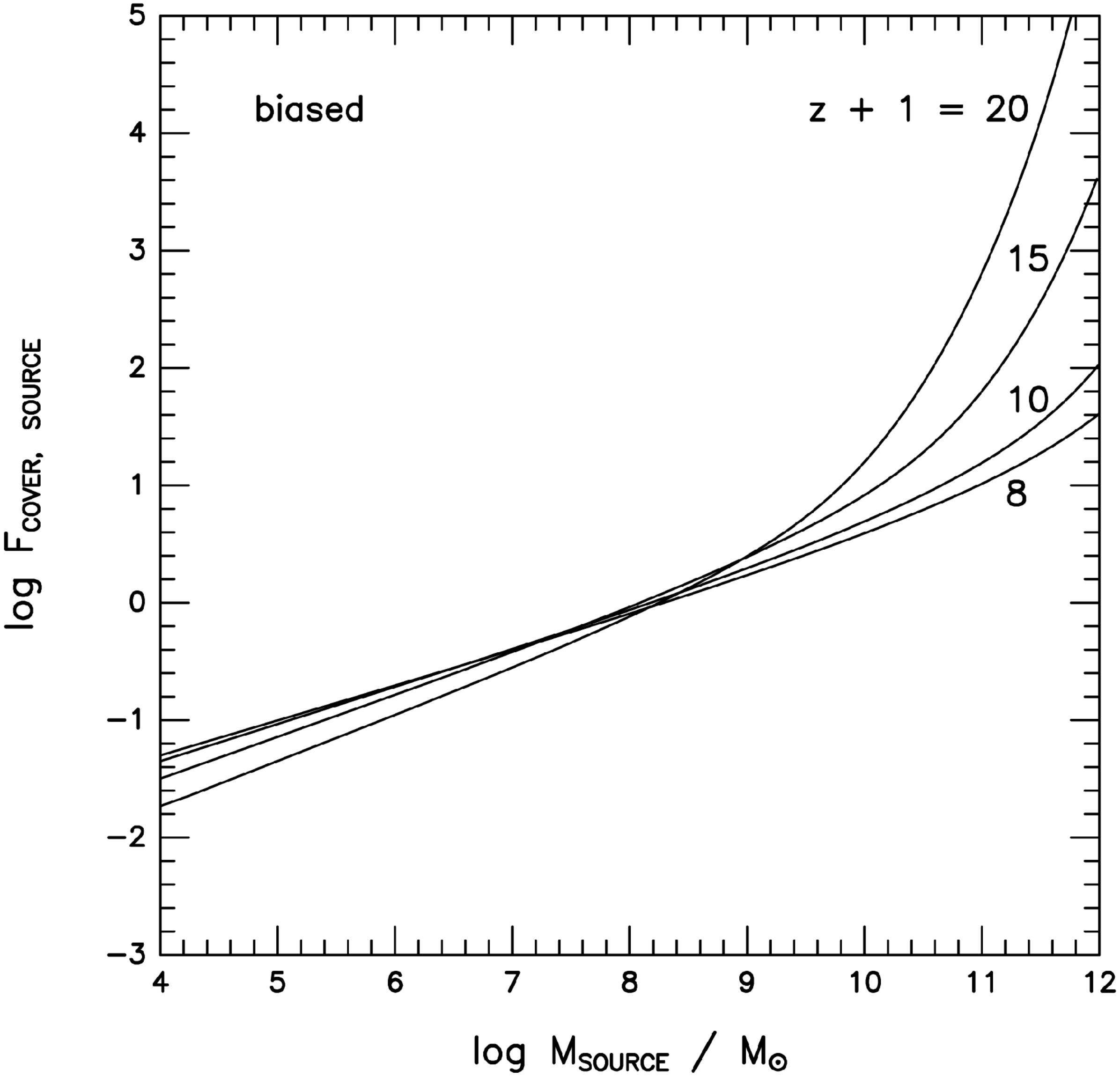
- 1 Mpc slice
- z=6
- red=sources (1672 halos)
- black=minihalos (142,260 halos)



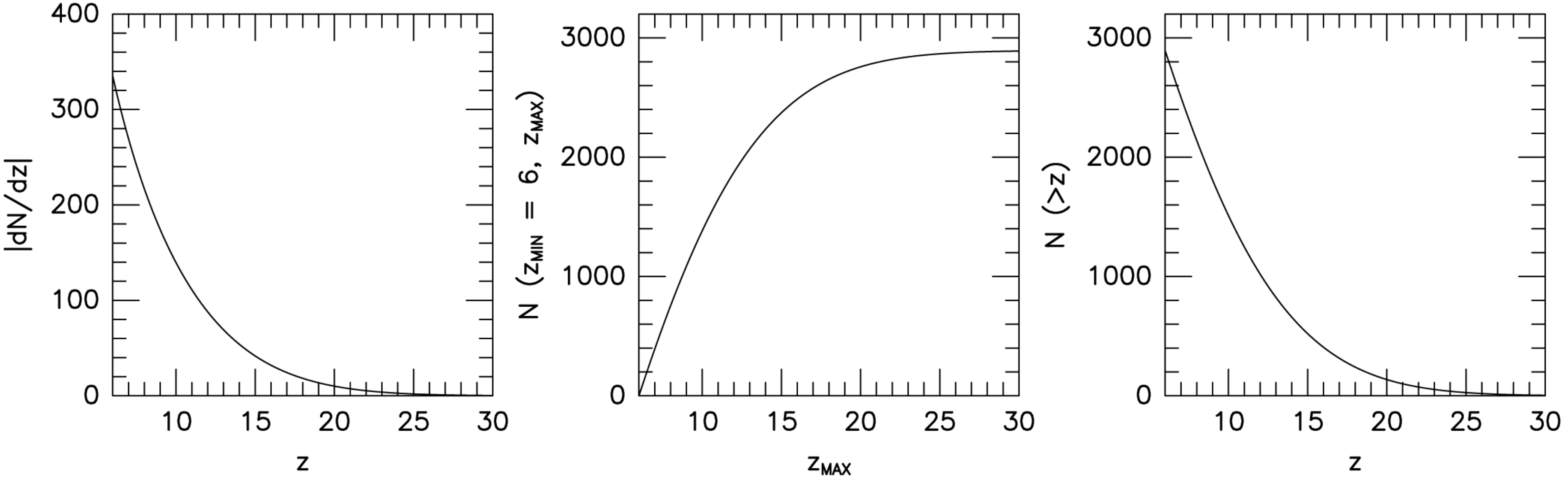
How common were minihalos at high redshift?

Fraction of sky covered by minihalos located within the mean volume per source halo, corrected for bias.

- If $M_{source} > 10^8 M_{sun}$, $F_{cover,source} > 1$.

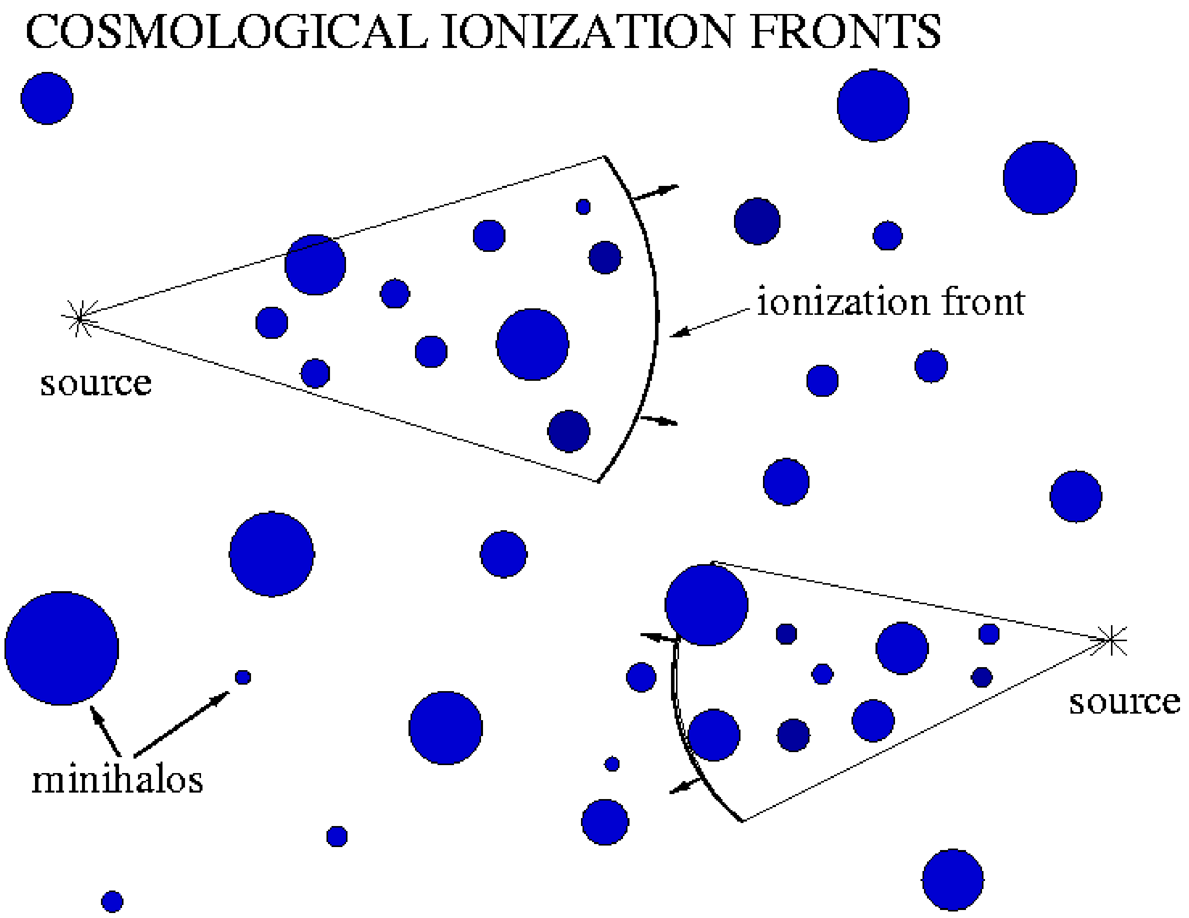


- Photons emitted by any high z source before or during reionization will typically encounter large numbers of photoevaporating minihalos at z > 6.



3. THE PHOTOEVAPORATION OF MINIHALOS OVERTAKEN BY COSMOLOGICAL I-FRONTS

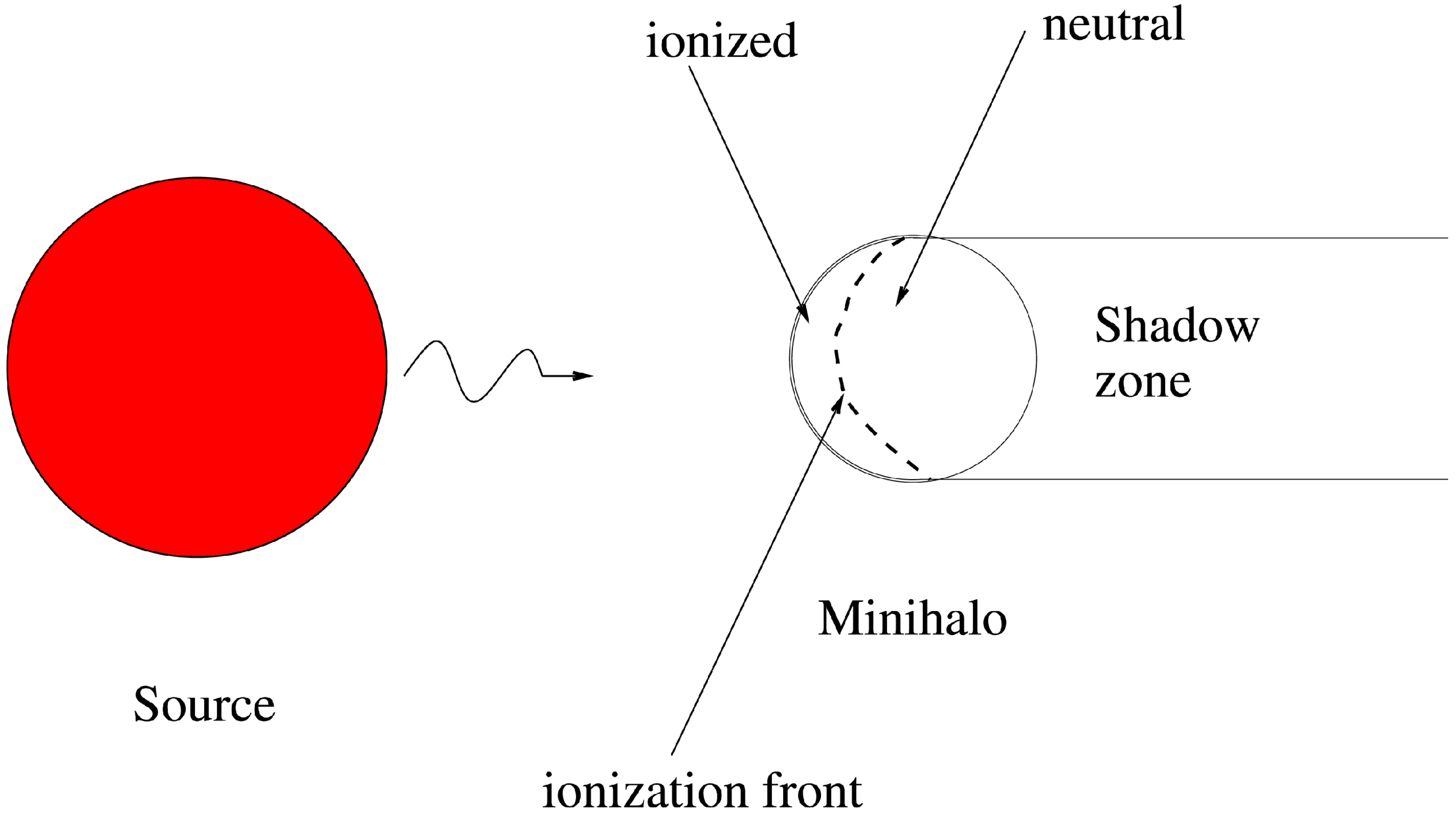
- We have performed radiation-hydrodynamical simulations of the photoevaporation of a cosmological minihalo overrun by a weak, R-type I-front in the surrounding IGM, created by an external source of radiation.



PHOTOEVAPORATION SIMULATIONS

- Minihalo model: Truncated, nonsingular, isothermal sphere (“TIS”) of CDM + baryons + self-similar, spherical, cosmological infall. e.g. $M_{tot} = 10^7 M_{sun}$, $T_{vir} = 4000$ K, $\sigma_V = 5.2$ km/s, $r_t = 0.75$ kpc, if $z_{collapse} = 9$.
- Halo masses: $M_0 = 10^4 - 4 \times 10^7 M_{sun}$ ($10^4 M_{sun}$ is roughly the Jeans mass, $4 \times 10^7 M_{sun}$ corresponds to $T_{vir} = 10^4$ K for $z_{coll} = 9$).
- Three Source Spectra:
  (1) QSO-like: $F_\nu \propto \nu^{-1.8} (\nu > \nu_H)$
  (2) Stellar (Pop II): Blackbody $T_{eff} = 50{,}000$ K
  (3) “No Metals” Stellar (Pop III): $T_{eff} = 100{,}000$ K.
- Source turn-ons at $1+z_{initial} = 7\text{-}20$.
- Flux levels: $F_0 = N_{ph,56}(\nu > \nu_H)/r_{Mpc}^2 = (0.01\text{-}10^3)$.
- 2D, axisymmetric, Eulerian hydro code with Adaptive Mesh Refinement and the van Leer flux-splitting algorithm, including radiative transfer (H, He bound-free opacity) (Raga et al. 1995, Mellema et al. 1998).
- Nonequilibrium ionization rate equations: H, He + (C, N, O, Ne, S) @ 10^{-3} solar abundance

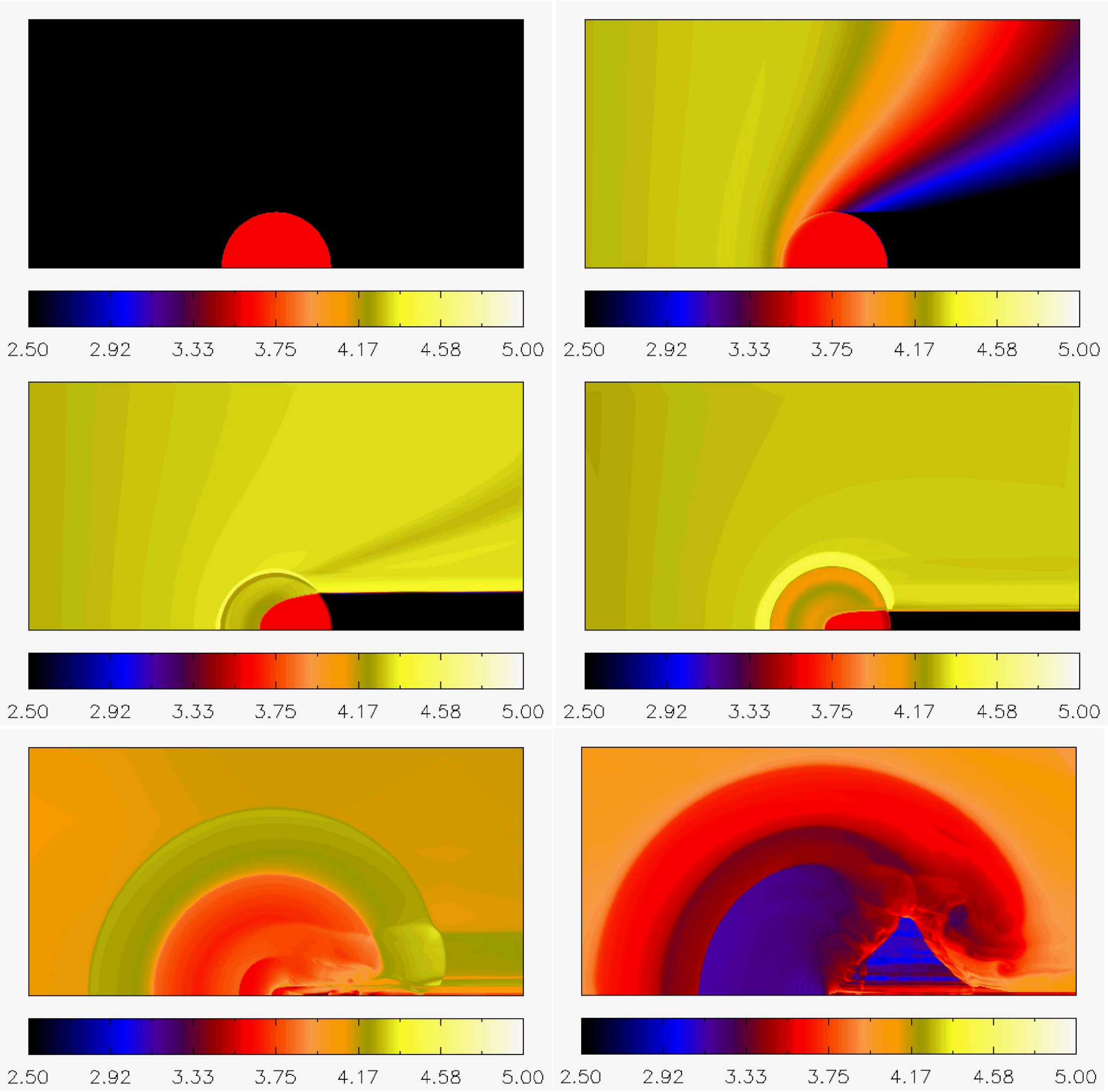
PHOTOEVAPORATION OF MINIHALO DURING COSMOLOGICAL REIONIZATION

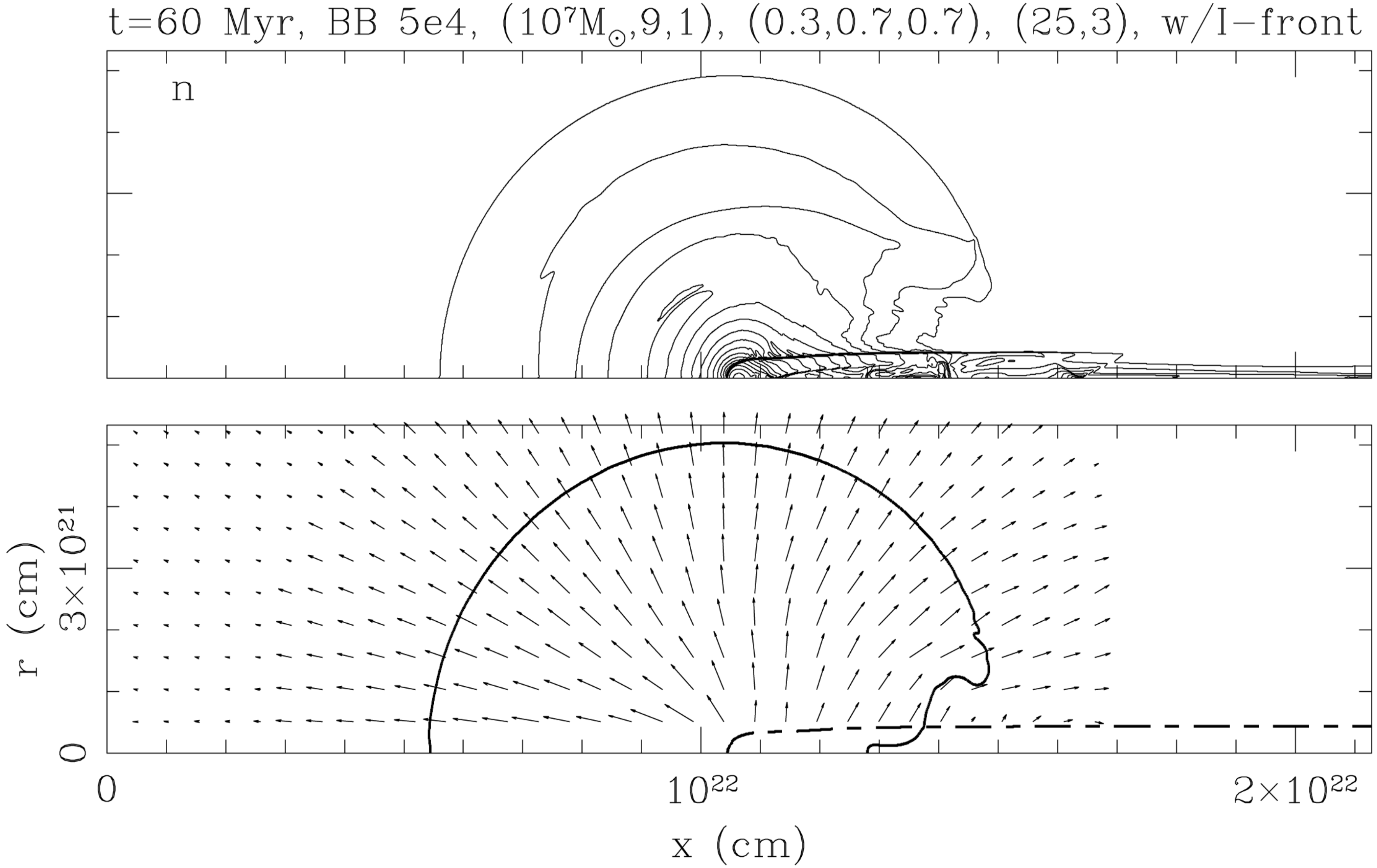


Temperature at times t = 0.0, 0.2, 2.5, 10, 60, 150 Myrs.

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

Pop II source.




t=60 Myr, BB 5e4, ($10^7 M_\odot$,9,1), (0.3,0.7,0.7), (25,3), w/I–front
n
r (cm)
0
3×10^{21}
0
10^{22}
2×10^{22}
x (cm)

1 = IGM shock.

2 = contact discontinuity which separates shocked halo wind (between 2 and 3) from swept-up IGM (between 1 and 2).

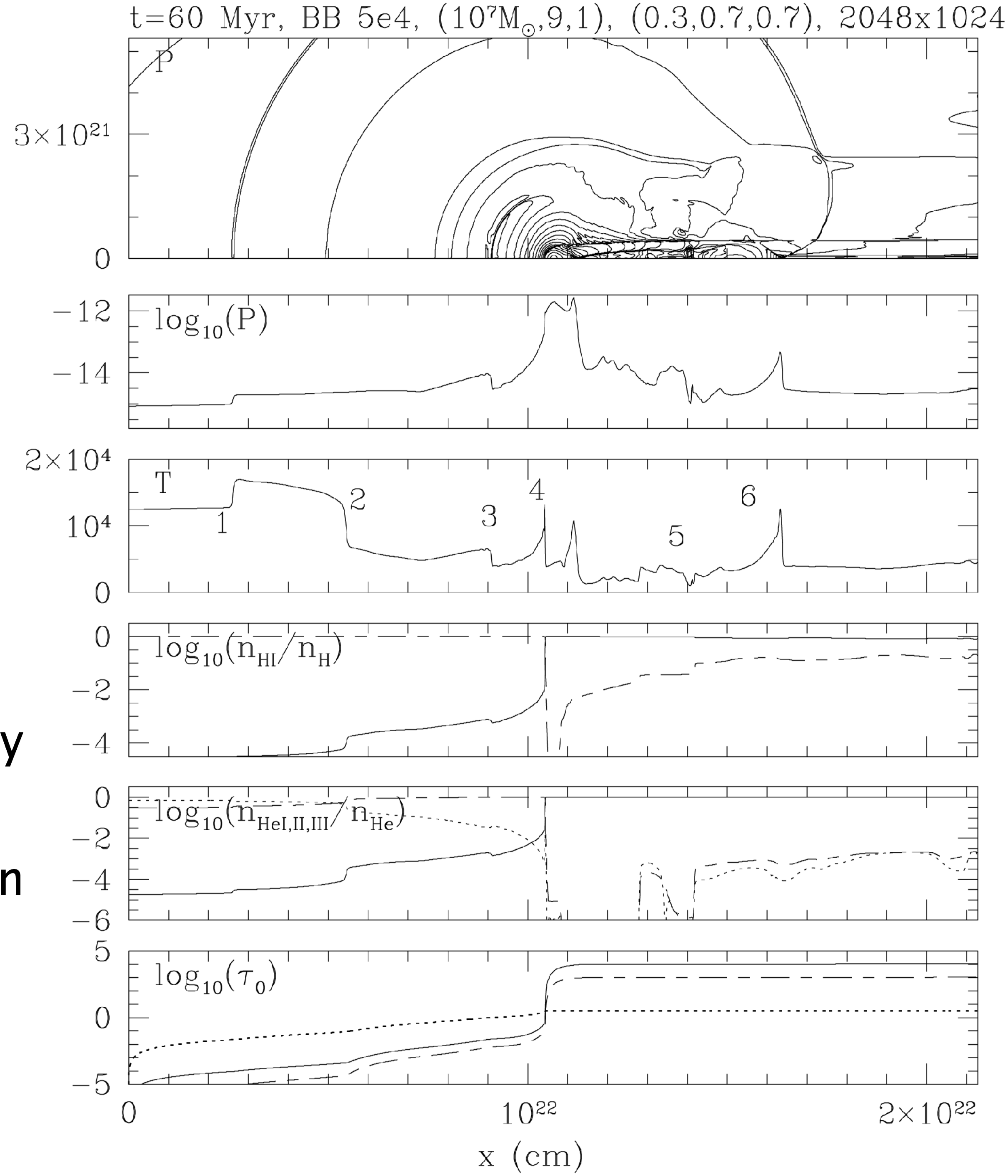
3 = wind shock.

between 3 and 4 = supersonic wind.

4 = I-front.

5 = boundary of gas initially inside minihalo at z = 9.

6 = shock in shadow region caused by compression of shadow gas by shock-heated gas outside shadow.



ANIMATIONS

(available also at galileo.as.utexas.edu)

Pop II

- **TEMPERATURE**
- **DENSITY**
- **H I**
- **He II**
- **C IV**

Pop III

- **TEMPERATURE**
- **DENSITY**
- **H I**
- **He II**
- **C IV**

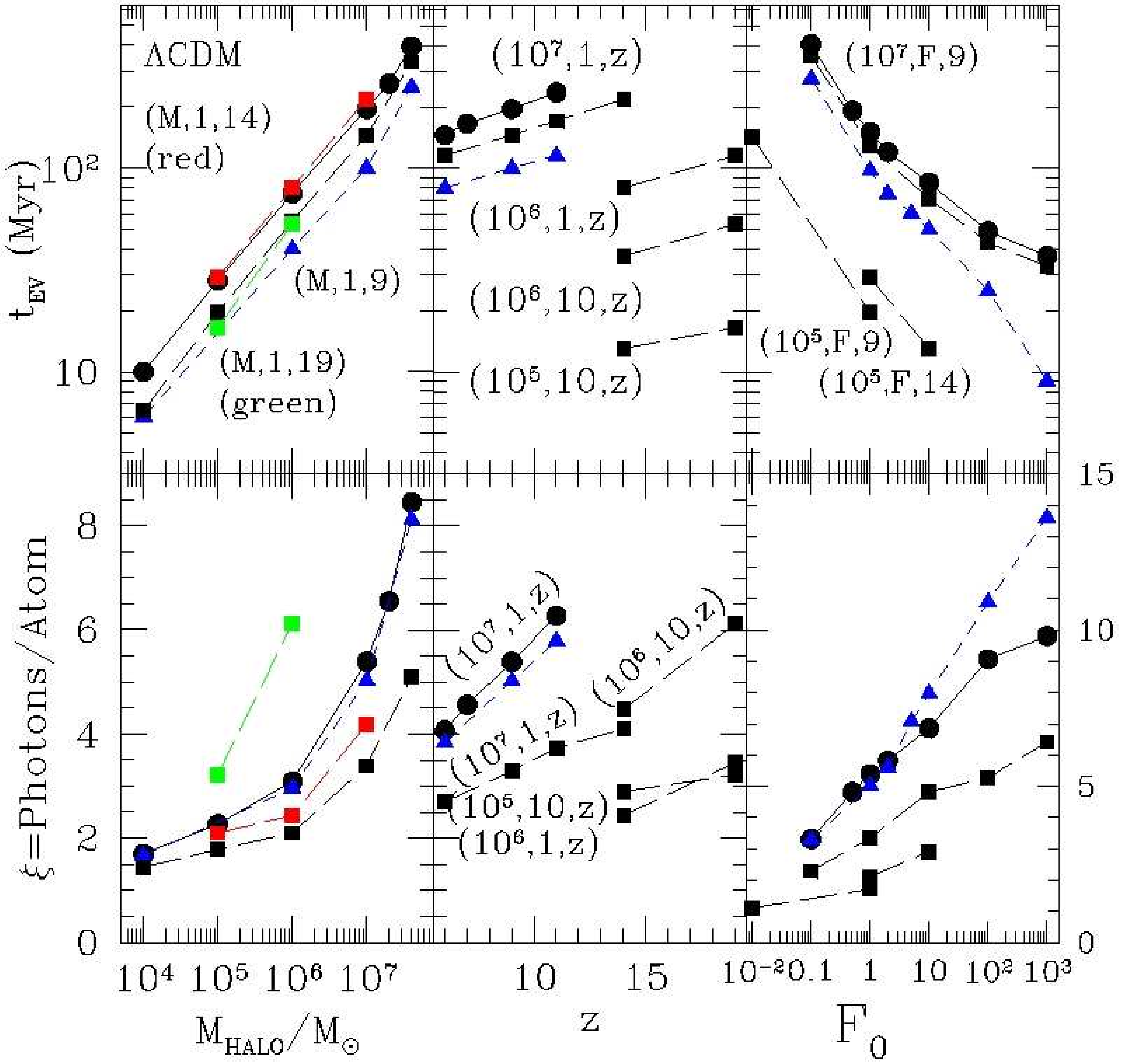
Ionizing Photons Consumed Per Minihalo Atom

(Shapiro, Iliev and Raga 2004; Iliev, Shapiro and Raga 2004)

- $\xi(t)$ = # 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

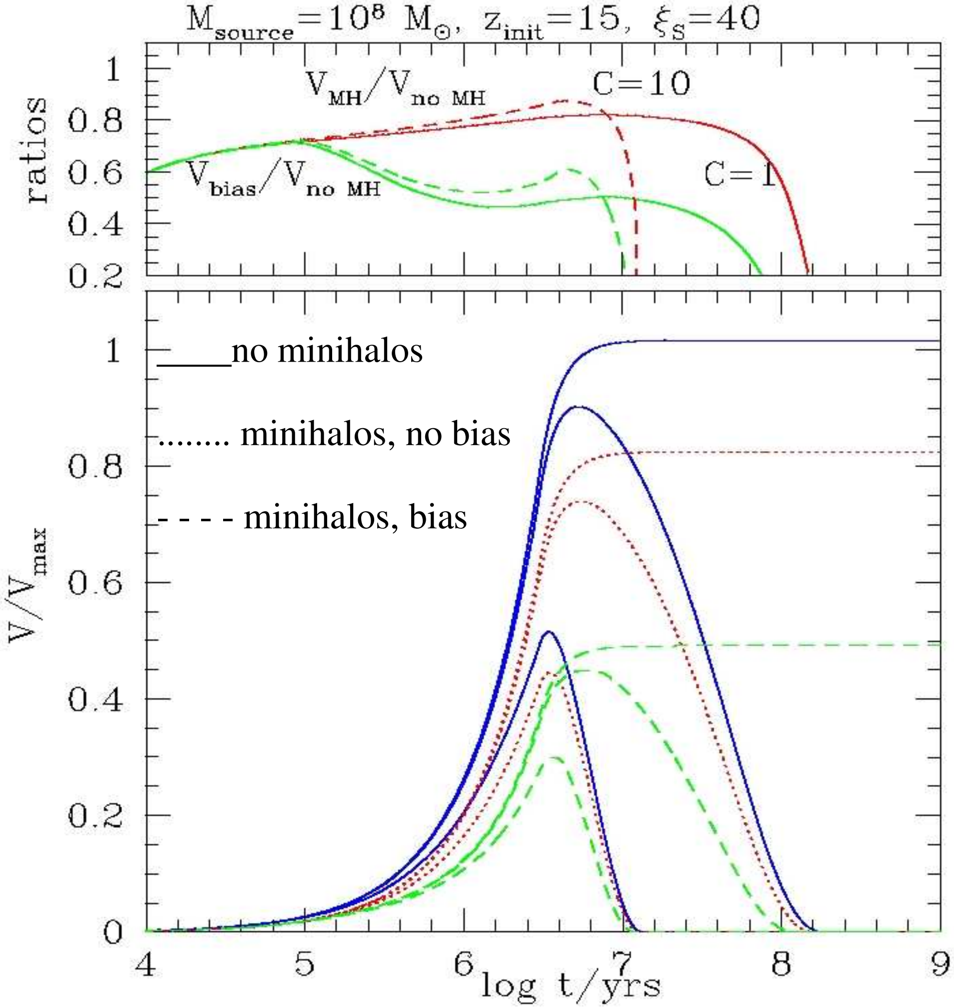


Effect of minihalos on the propagation of a cosmological I-front

(Iliev, Scannapieco and Shapiro 2004)

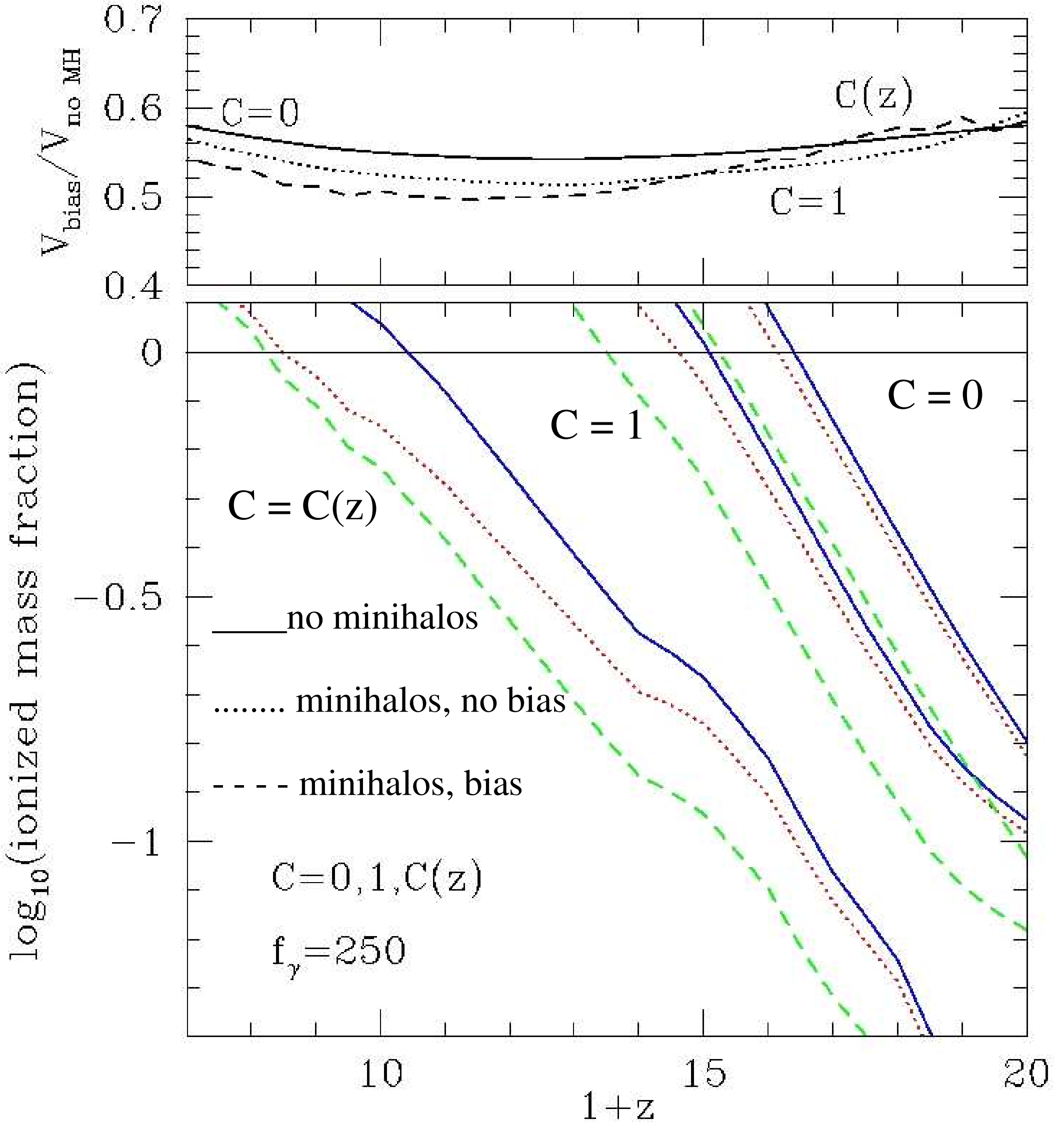
Propagation of an I-front about an individual source:

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



Effect of Minihalos and IGM Clumping on Reionization

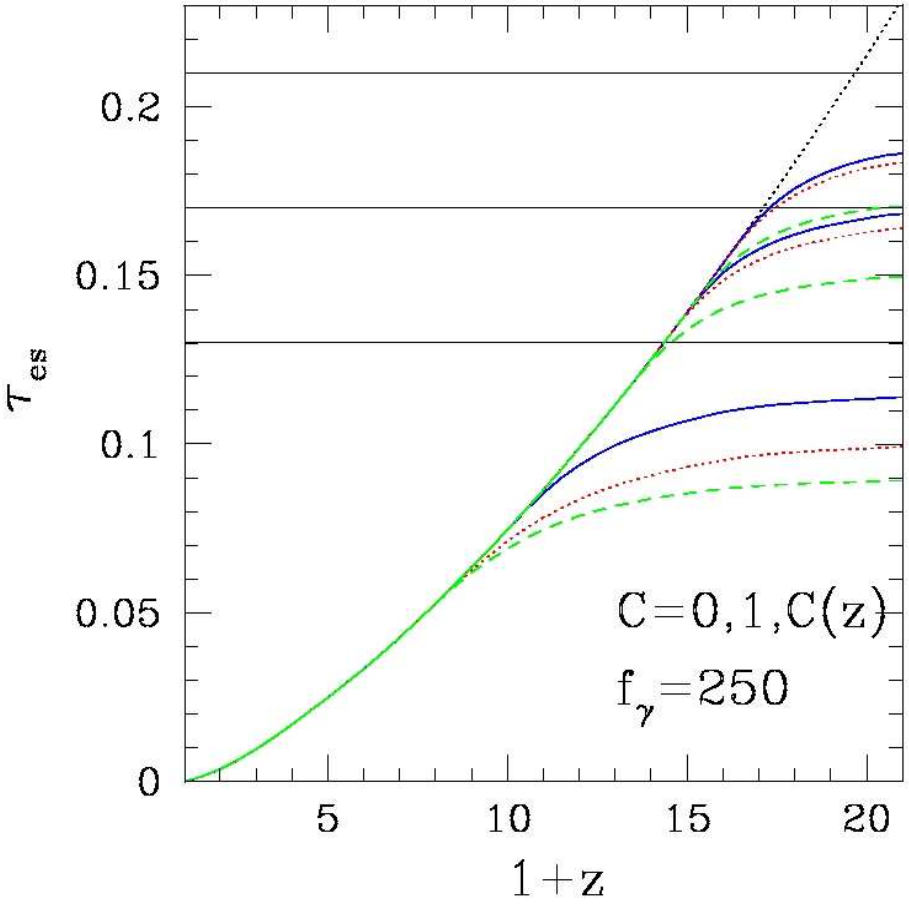
- Let each source halo create its own expanding spherical H II region.
- I-front speed is slowed by minihalo trapping and evaporation and recombinations in IGM.
- Integrate over statistical distribution of source halo masses and turn-on epochs until neighboring H II regions overlap => reionization finished.
- Minihalos increase photon consumption by factor of ~2, delaying reionization by $\Delta z \sim 2$.



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

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 too low optical depth for realistic evolving IGM clumping C=C(z)



A FEW SUMMARY POINTS

- Reionization of IGM by radiation sources involved weak, R-type ionization fronts which expanded and eventually overlapped.
- Dwarf galaxy minihalos with velocity dispersion $\sigma_V \leq 10$ km s^{-1} trapped these I-fronts and converted them to D-type, expelling their gaseous baryonic content into the surrounding IGM.
- These minihalos blocked the path of the I-fronts which reionized the universe, until their photoevaporation was complete.
- Photoevaporation of minihalos was an important sink of ionizing photons during reionization which may have delayed the overlap epoch and raised the output of ionizing photons required to reionize the universe.
- Photoevaporating minihalos may be observable via absorption lines once high z sources are detected, allowing diagnostics of reionization source and epoch and metallicity of expelled gas.

A FEW MORE SUMMARY POINTS

- Dwarf galaxy minihalos significantly increase (by factor of ~2) the demand for ionizing photons needed to complete reionization
- The minihalos also delay reionization by $\Delta z{\sim}2$
- Realistic, evolving small-scale clumping of the IGM gas delays reionization significantly, by $\Delta z{\sim}5$, and increases the global photon consumption by factor of ~10 or more
- Presence of small-scale structure helps significantly in reconciling the early start of reionization predicted by WMAP with the late end suggested by SDSS quasars
- No stellar population with a fixed ionizing photon output efficiency is completely consistent with both constraints – need evolving efficiencies (starting high, consistent with Pop. III properties and ending lower, according to Pop. II properties)