Self-Regulated Reionization and the Fluctuating H_2 Dissociating UV Background

Paul R. Shapiro

University of Texas at Austin

"The Third Cosmological Radiative Transfer Comparison Project Workshop,"

The University of Texas at Austin

December 8, 2008

Self-Regulated Reionization and the Fluctuating H_2 Dissociating UV Background

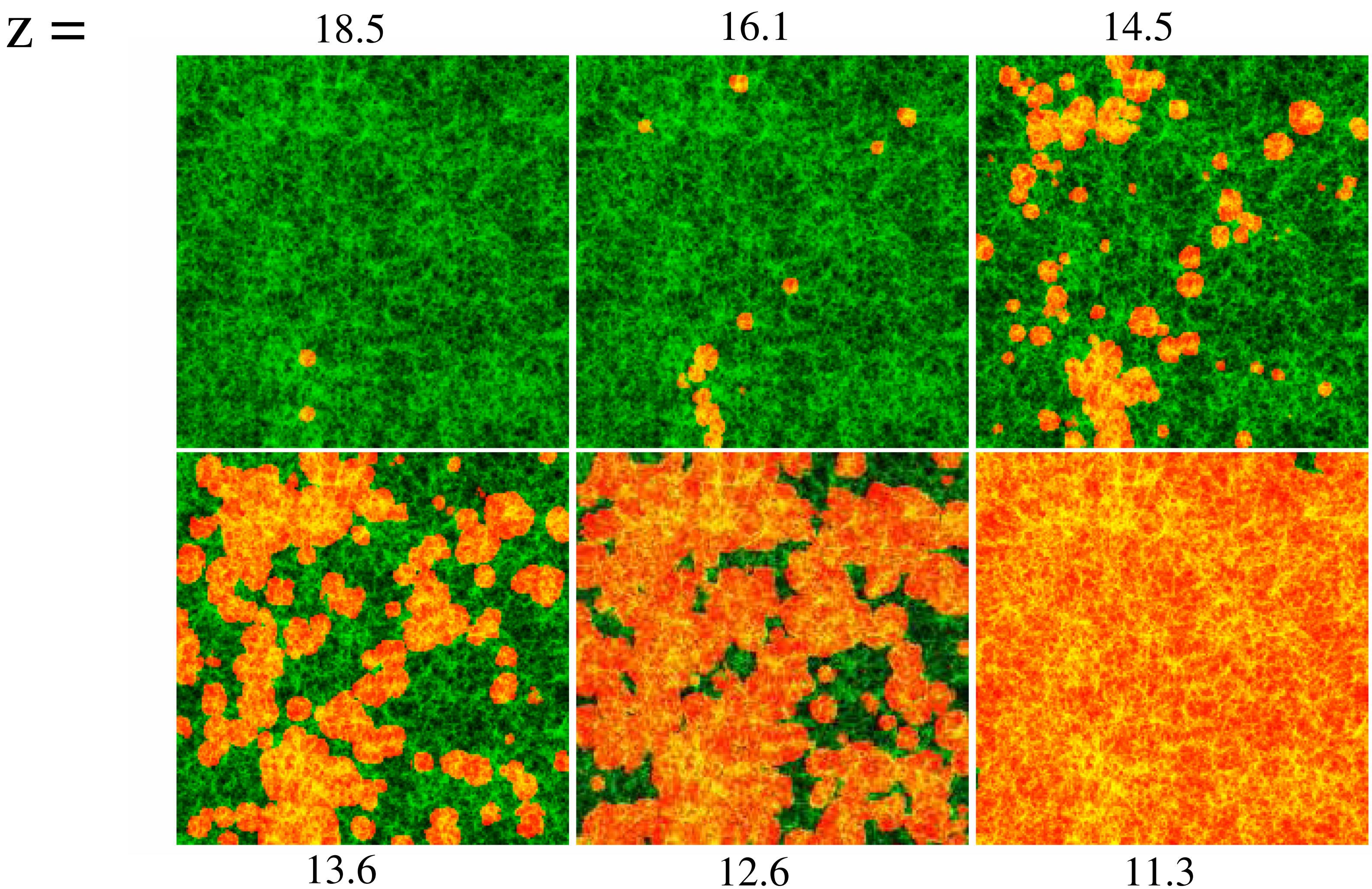
Paul R. Shapiro

University of Texas at Austin

Collaborators:
Ilian Iliev (U. Zurich)
Ue-Li Pen, J. Richard Bond, Patrick McDonald (CITA/U.Toronto)
Garrelt Mellema (Stockholm U.), Hugh Merz (U. Waterloo)
Kyungjin Ahn (Chosun U./Korea), Leonid Chuzhoy (U.Chicago)
Marcelo Alvarez (KIPAC/Stanford), Benedetta Ciardi (MPA),
Eiichiro Komatsu, Jun Koda, Elizabeth Fernandez, Yi Mao (U. Texas)

Simulating Cosmic Reionization at Large Scales I. : The Geometry of Reionization

Iliev, Mellema, Pen, Merz, Shapiro & Alvarez (2006)
MNRAS, 369, 1625 (astro-ph/0512187)



N-body + Radiative Transfer → Reionization simulation

- N-body simulation yields the density field and sources of ionizing radiation

  - PMFAST code (Merz, et al. 2005) with

    1624^3 = 4.28 billion particles, 3248^3 cells,

    particle mass = 2.5 x 10^7 M_{sun} (100 h^{-1}Mpc box),

  - Halo finder "on-the-fly" yields location, mass, other properties of all galaxies,

    $M \geq 2.5 \times 10^9$ M_{sun} (100 h^{-1}Mpc box),

e.g. N_{halo} ~ 4 x 10^5 by z ~ 8 (WMAP1)

~ 3 x 10^5 by z ~ 6 (WMAP3)

N-body + Radiative Transfer ➔ Reionization simulation

- Radiative transfer simulations evolve the radiation field and nonequilibrium ionization state of the gas

  - New, fast, efficient C^2-Ray code (Conservative, Causal Ray-Tracing) (Mellema, Iliev, Alvarez, & Shapiro 2006, *New Astronomy*, 11, 374) uses short-characteristics to propagate radiation throughout the evolving gas density field provided by the N-body results, re-gridded to $(203)^3$ and $(406)^3$ cells, for different resolution runs, from each and every galaxy halo source in the box.

e.g. N_{halo} ~ 4 x 10^5 by z ~ 8 (WMAP1)

~ 3 x 10^5 by z ~ 6 (WMAP3)

Every galaxy in the simulation volume emits ionizing radiation

- We assume a constant mass-to-light ratio for simplicity:

f_γ = # ionizing photons released by each galaxy per halo baryon

$= f_* \; f_{esc} \; N_i$,

where f_* = star-forming fraction of halo baryons,

f_{esc} = ionizing photon escape fraction,

N_i = # ionizing photons emitted per stellar baryon over stellar lifetime

e.g. $N_i = 50{,}000$ (top-heavy IMF), $f_* = 0.2$, $f_{esc} = 0.2$ ➔ $f_\gamma = 2000$

Every galaxy in the simulation volume emits ionizing radiation

- We assume a constant mass-to-light ratio for simplicity:

f_γ = # ionizing photons released by each galaxy per halo baryon

$= f_* \; f_{esc} \; N_i$,

where f_* = star-forming fraction of halo baryons,

f_{esc} = ionizing photon escape fraction,

N_i = # ionizing photons emitted per stellar baryon over stellar lifetime

e.g. $N_i = 50{,}000$ (top-heavy IMF), $f_* = 0.2$, $f_{esc} = 0.2$ ➔ $f_\gamma = 2000$

- This yields source luminosity: $dN_\gamma/dt = f_\gamma \, M_{bary} /(\mu \, m_H \, t_*)$,

t_* = source lifetime (e.g. 2×10^7 yrs),

M_{bary} = halo baryonic mass

Self-Regulated Reionization

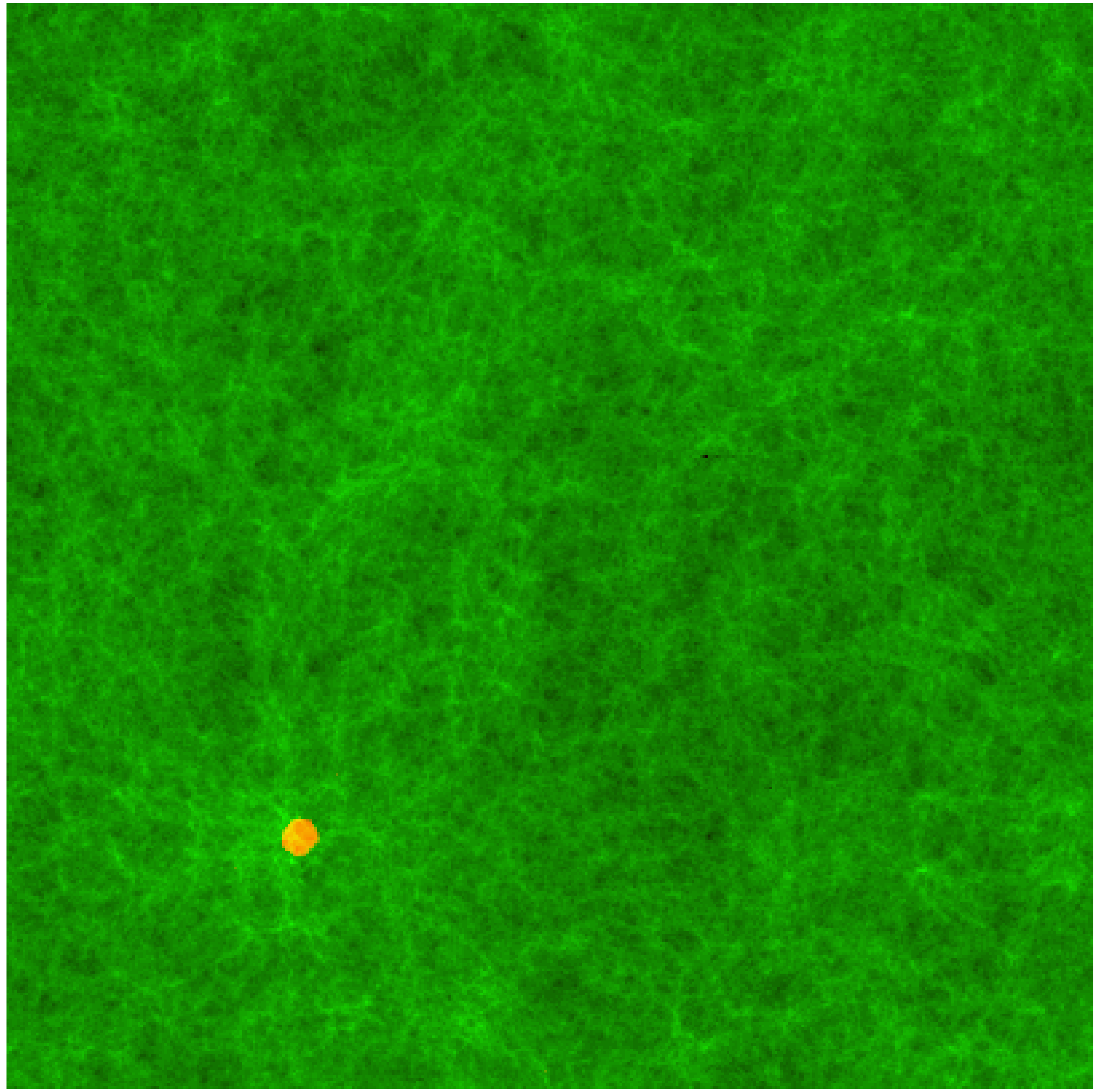
Iliev, Mellema, Shapiro, & Pen (2007), MNRAS, 376, 534; (astro-ph/0607517)

•Jeans-mass filtering ➔ low-mass source halos ($M < 10^9 M_{solar}$) cannot form inside H II regions ;

•35/h Mpc box, 406^3 radiative transfer simulation, WMAP3, $f_\gamma = 250$;

•resolved all halos with $M > 10^8 M_{solar}$ (i.e. all atomically-cooling halos), (blue dots = source cells);

• Evolution: z=21 to z_{ov} = 7.5.



Extended reionization: Jeans-mass filtering, halo-mass-dependent emissivity

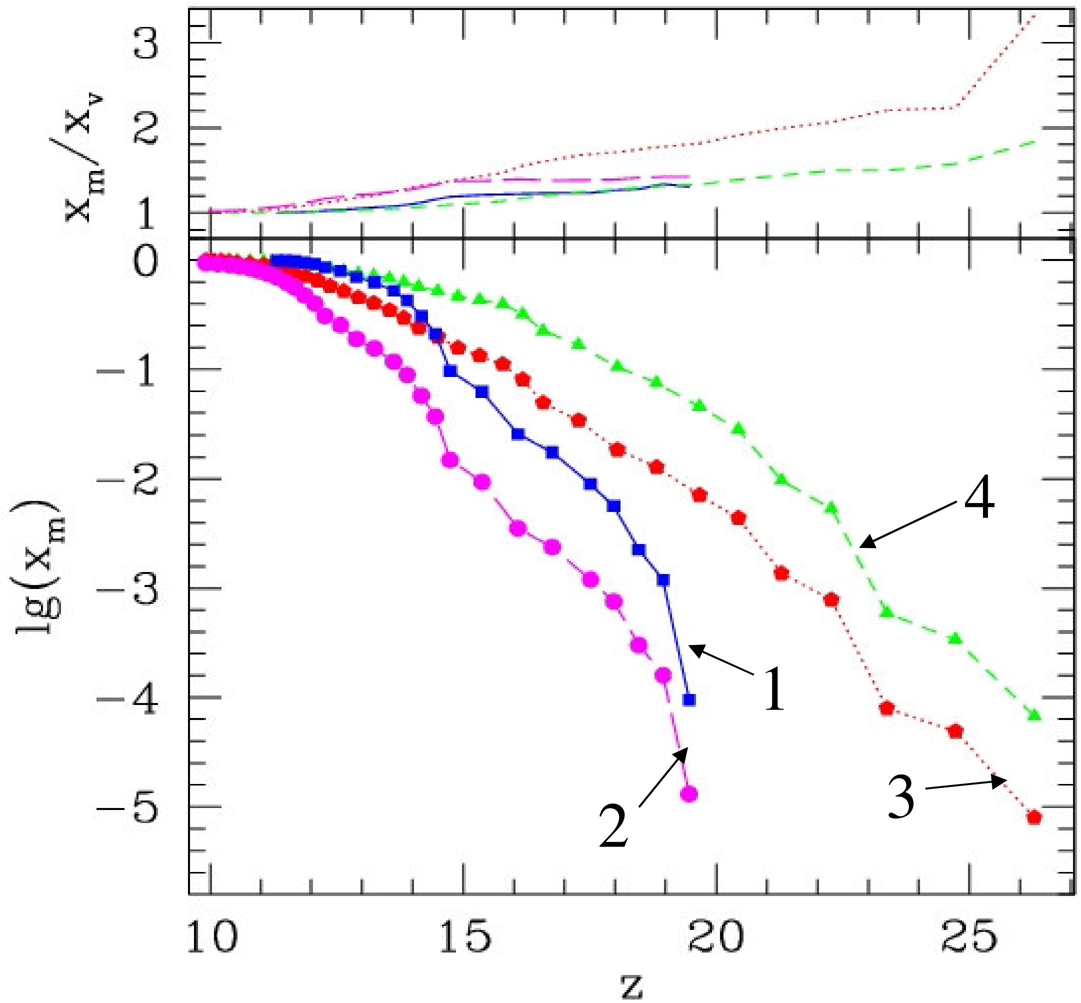
<u>Cases</u>

1. Halo masses $M_{solar} > 10^9$
   $f_\gamma = 2000$ (e.g. Pop III);

2. Halo masses $M_{solar} > 10^9$
   $f_\gamma = 250$ (e.g. Pop II);

3. Halo masses $M_{solar} > 10^8$
   $f_\gamma = 250$ (e.g. Pop II),
   lower-mass halos
   suppressed inside H II regions
   (Jeans-mass filtering) ;

4. Same as 3., but
   $f_\gamma = 2000$ ($M_{solar} < 10^9$)
   $f_\gamma = 250$ ($M_{solar} > 10^9$)

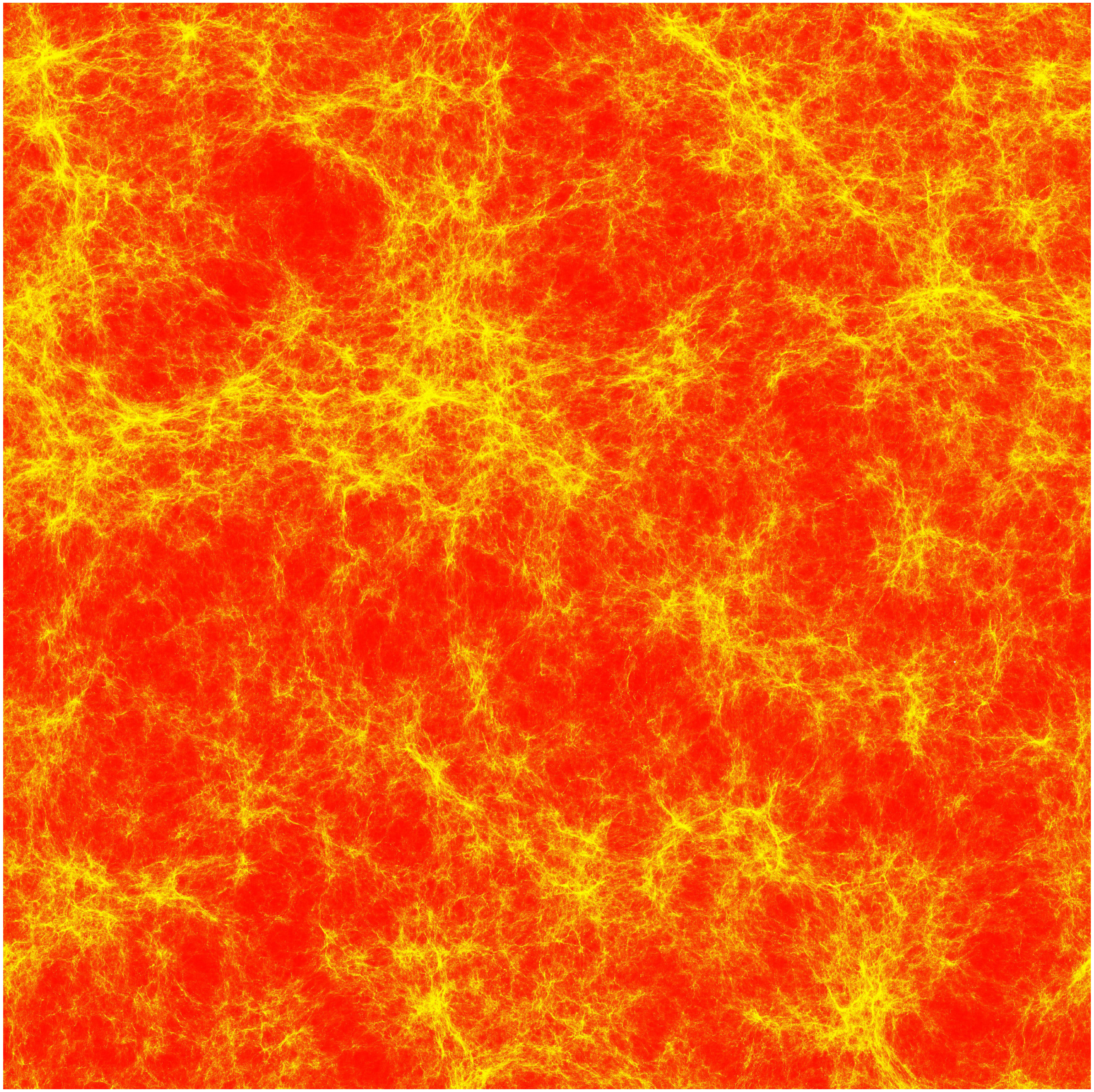


New, Large-Scale Simulations of Self-Regulated Reionization

Iliev, Mellema, Pen, Shapiro, and Merz (2008), in press (astro-ph/0806.2887);

Shapiro, Iliev, Mellema, Pen, & Merz (2008), AIPC, 1035, 68 (astro-ph/0806.3091)

CubeP^{3}M N-body ΛCDM sim with
3072^3 (29 billion) particles,
6144^3 cells,
box size = 160 Mpc;
particle mass = 5 million solar masses



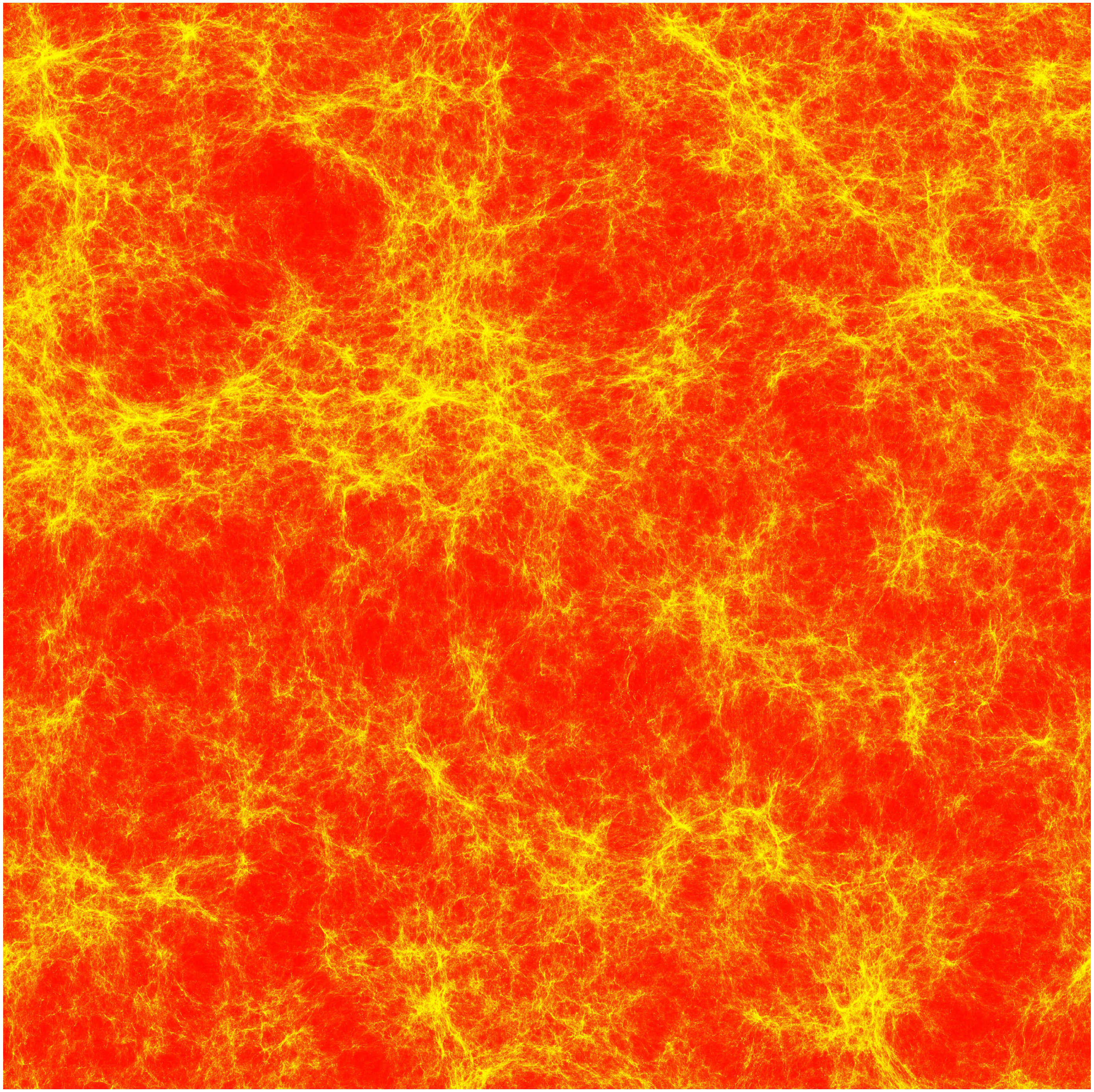
New, Large-Scale Simulations of Self-Regulated Reionization

Iliev, Mellema, Pen, Shapiro, and Merz (2008), in press (astro-ph/0806.2887);

Shapiro, Iliev, Mellema, Pen, & Merz (2008), AIPC, 1035, 68 (astro-ph/0806.3091)

CubeP^{3}M N-body ΛCDM sim with 3072^3 (29 billion) particles,

resolves halos above 10^8 solar masses



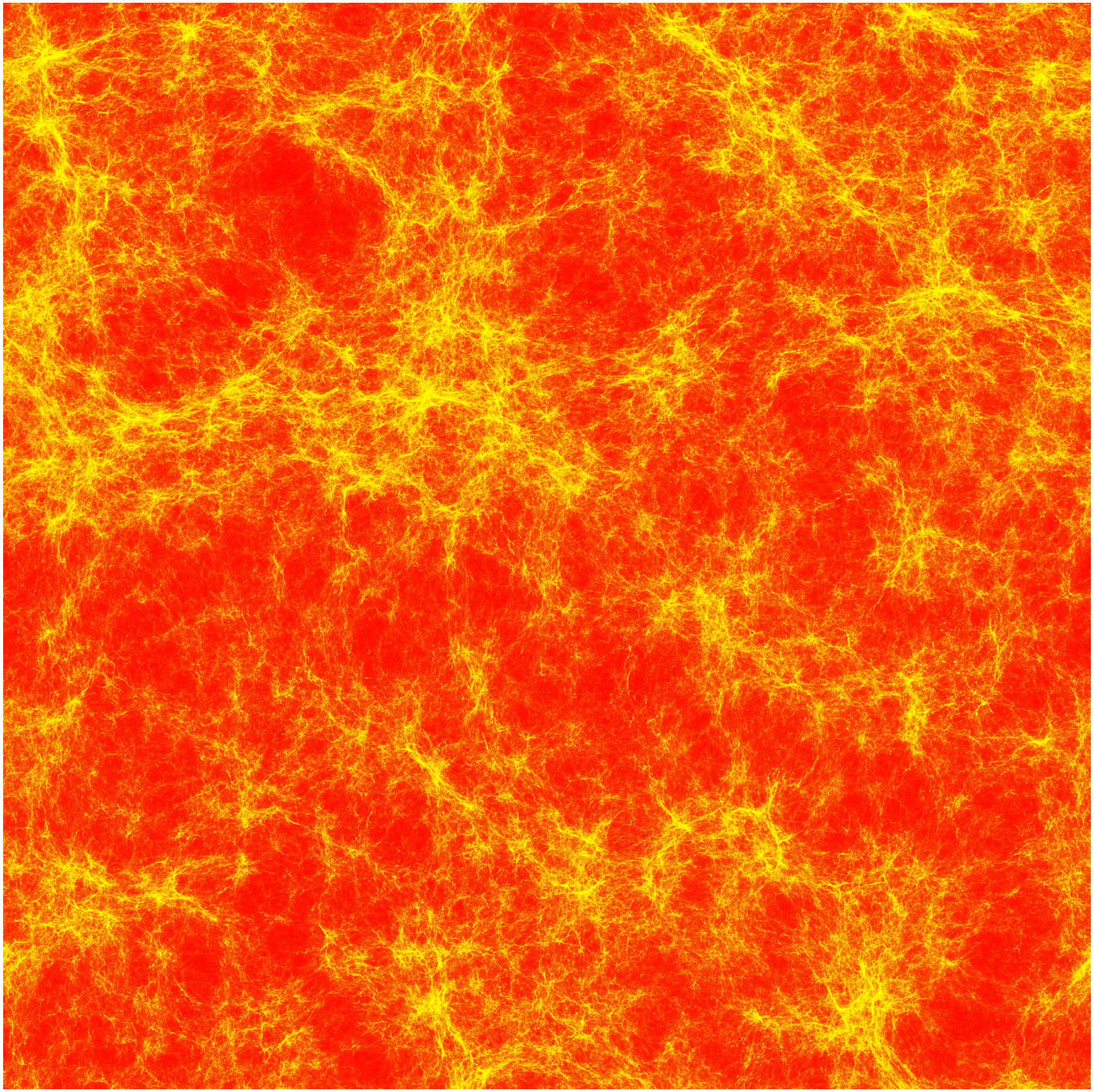
New, Large-Scale Simulations of Self-Regulated Reionization

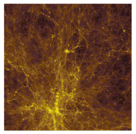
Iliev, Mellema, Pen, Shapiro, and Merz (2008), in press (astro-ph/0806.2887);

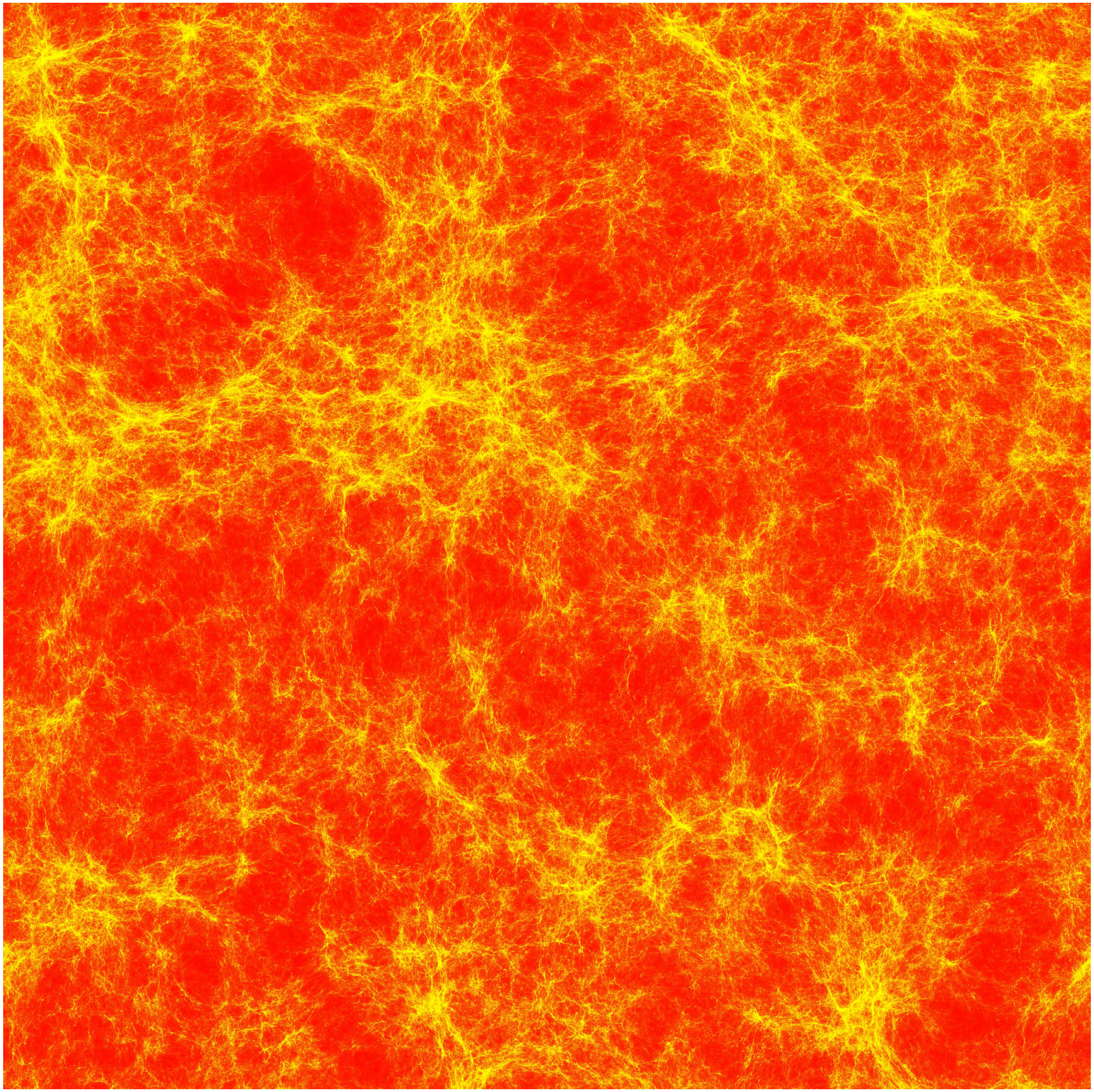
Shapiro, Iliev, Mellema, Pen, & Merz (2008), AIPC, 1035, 68 (astro-ph/0806.3091)

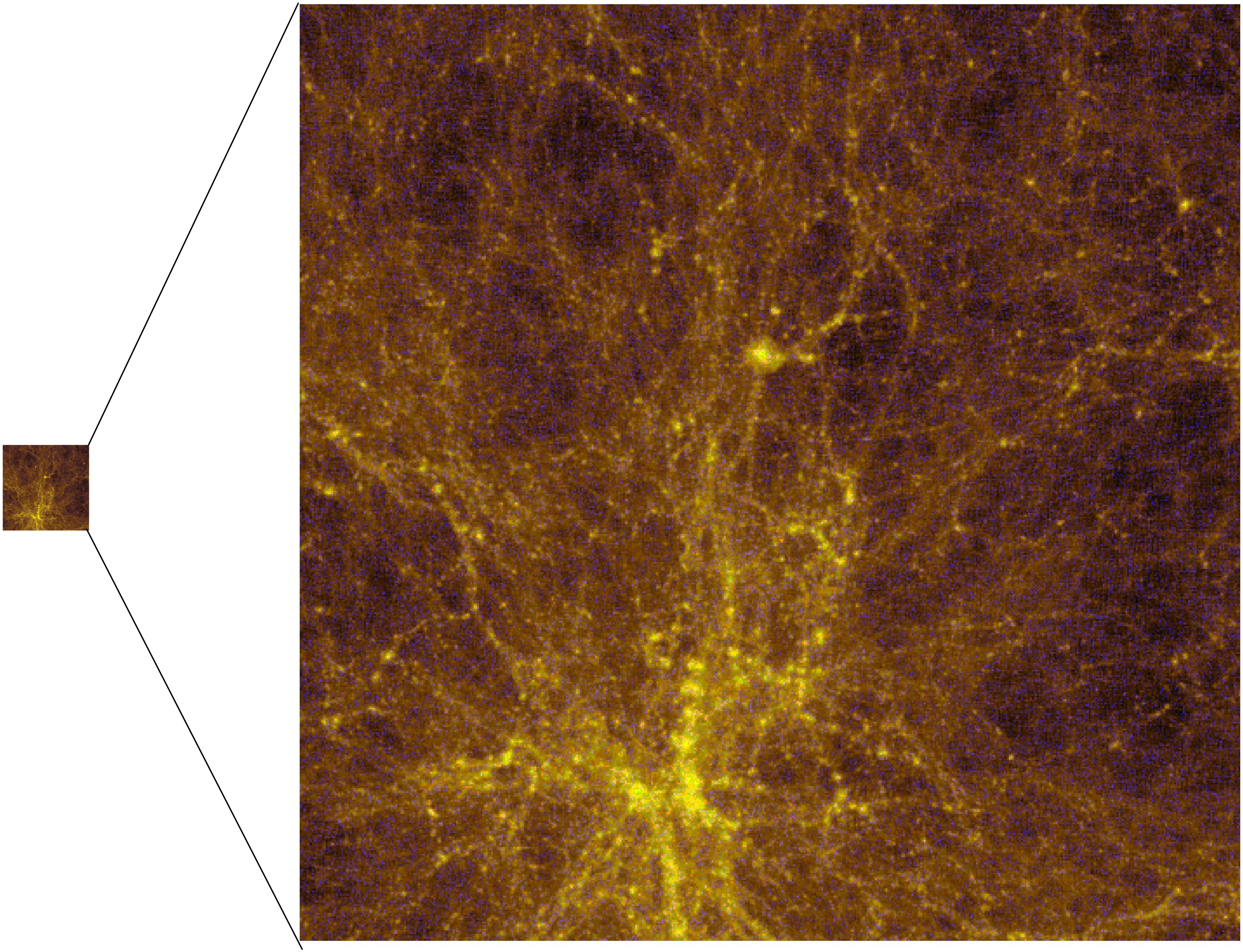
CubeP^{3}M N-body

- new Texas Sun Constellation Linux Cluster, *Ranger*, 2048 cores, 159,000 SUs (cores x hours)



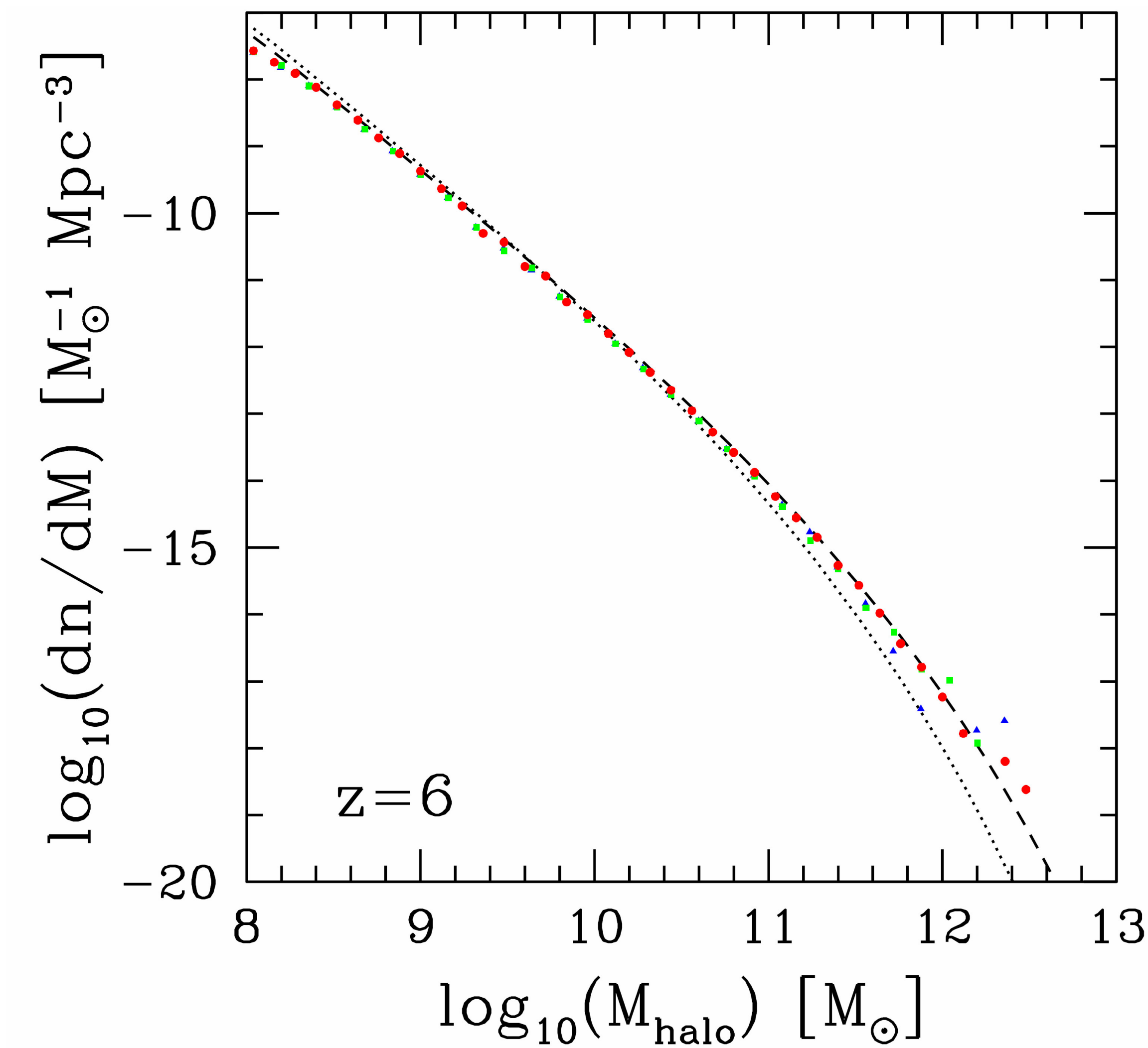






ΛCDM Halo Mass Function (M > 10^8 Solar Masses)

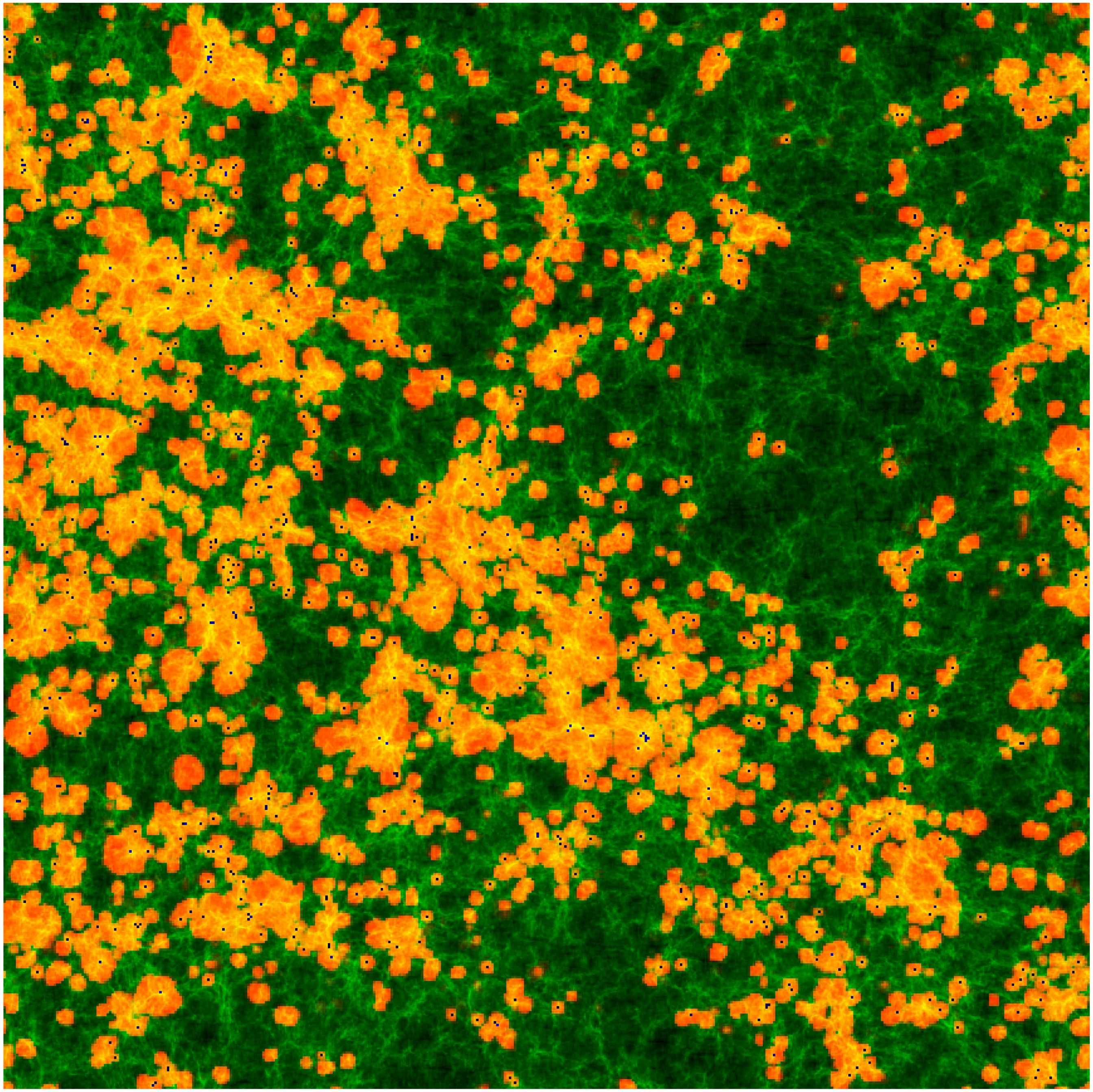
from CubeP^{3}M N-body Simulations



simulation box sizes 91 Mpc, 103 Mpc, 163 Mpc

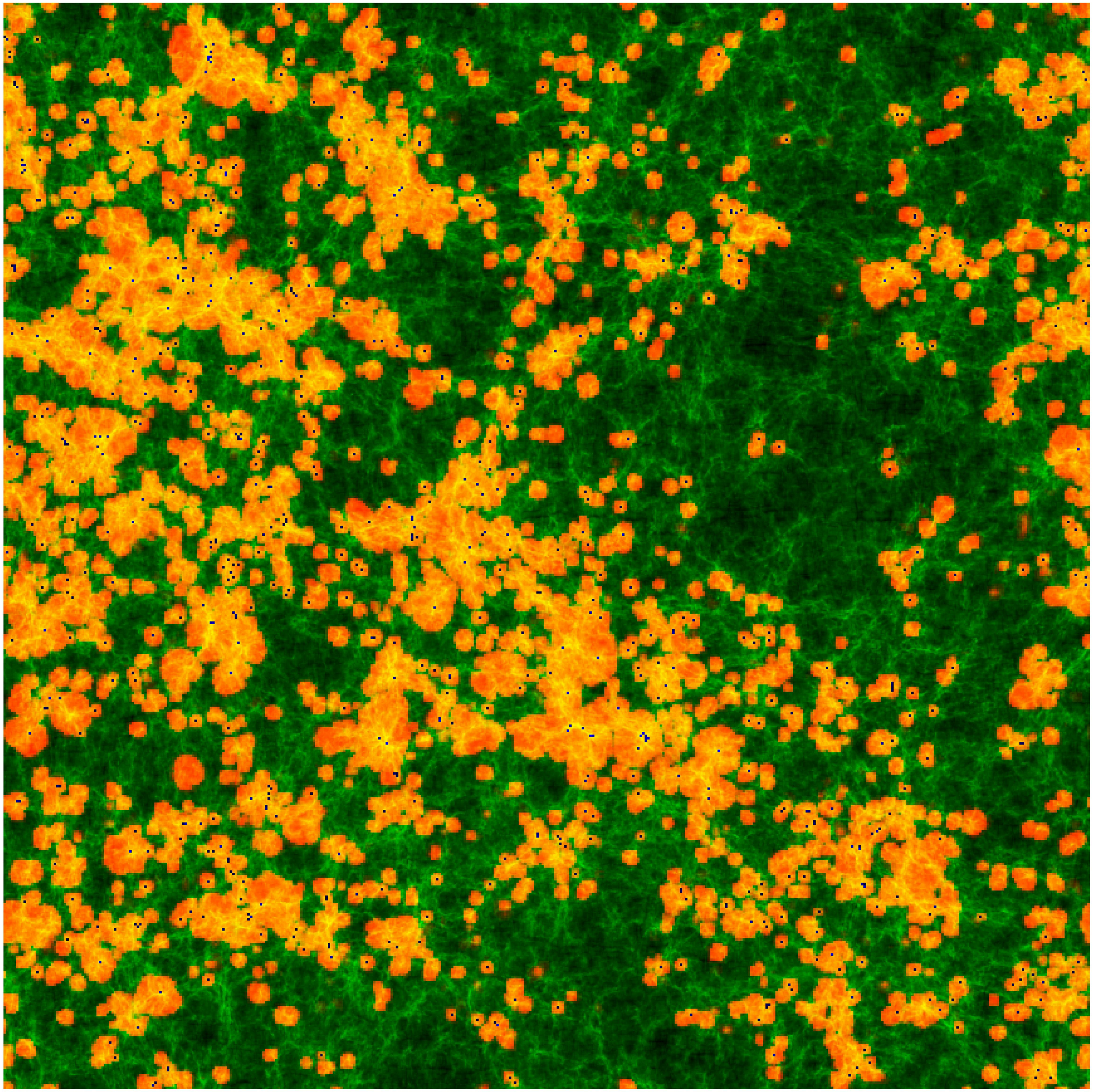
C^2Ray radiative transfer

- RT grid 432^3 cells
- box size = 90 Mpc

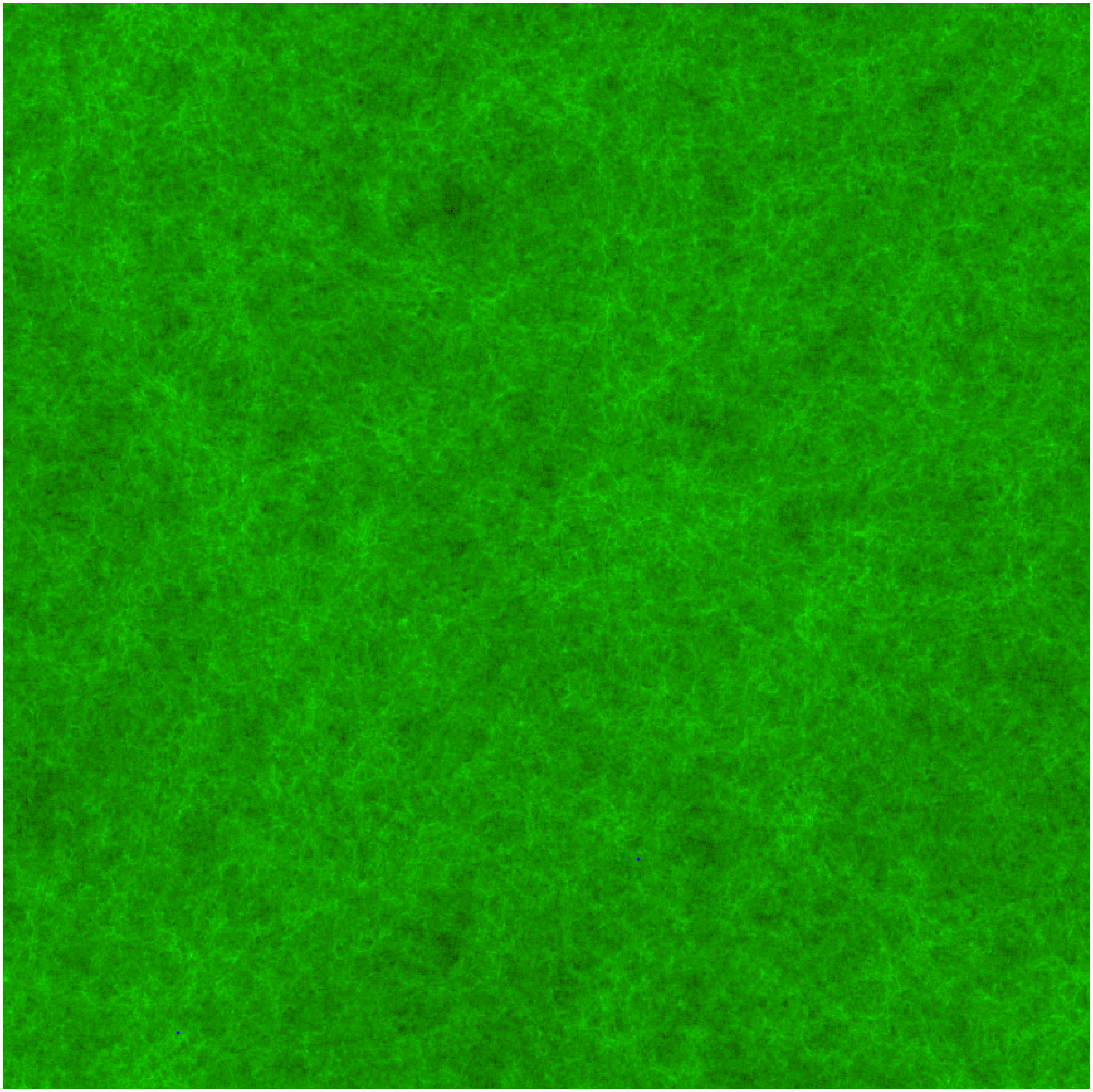


C^2Ray radiative transfer

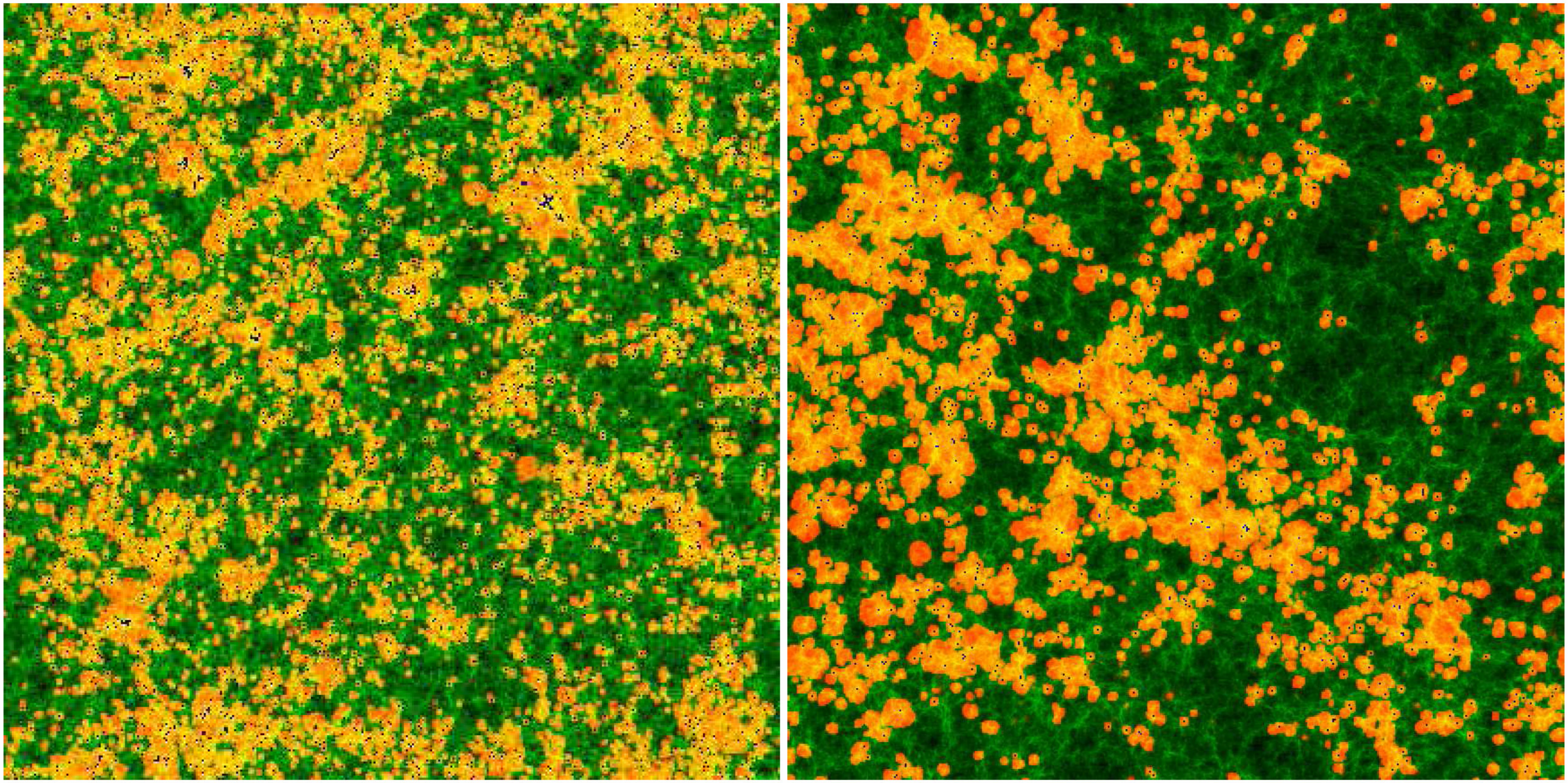
- RT grid 432^3 cells
- box size = 90 Mpc
- *Ranger*, Texas Sun Constellation Linux Cluster, 700,000 SUs (cores x hours), up to 10,000 cores



Self-Regulated Reionization in ΛCDM



- 90 Mpc box



160 Mpc box | 90 Mpc box

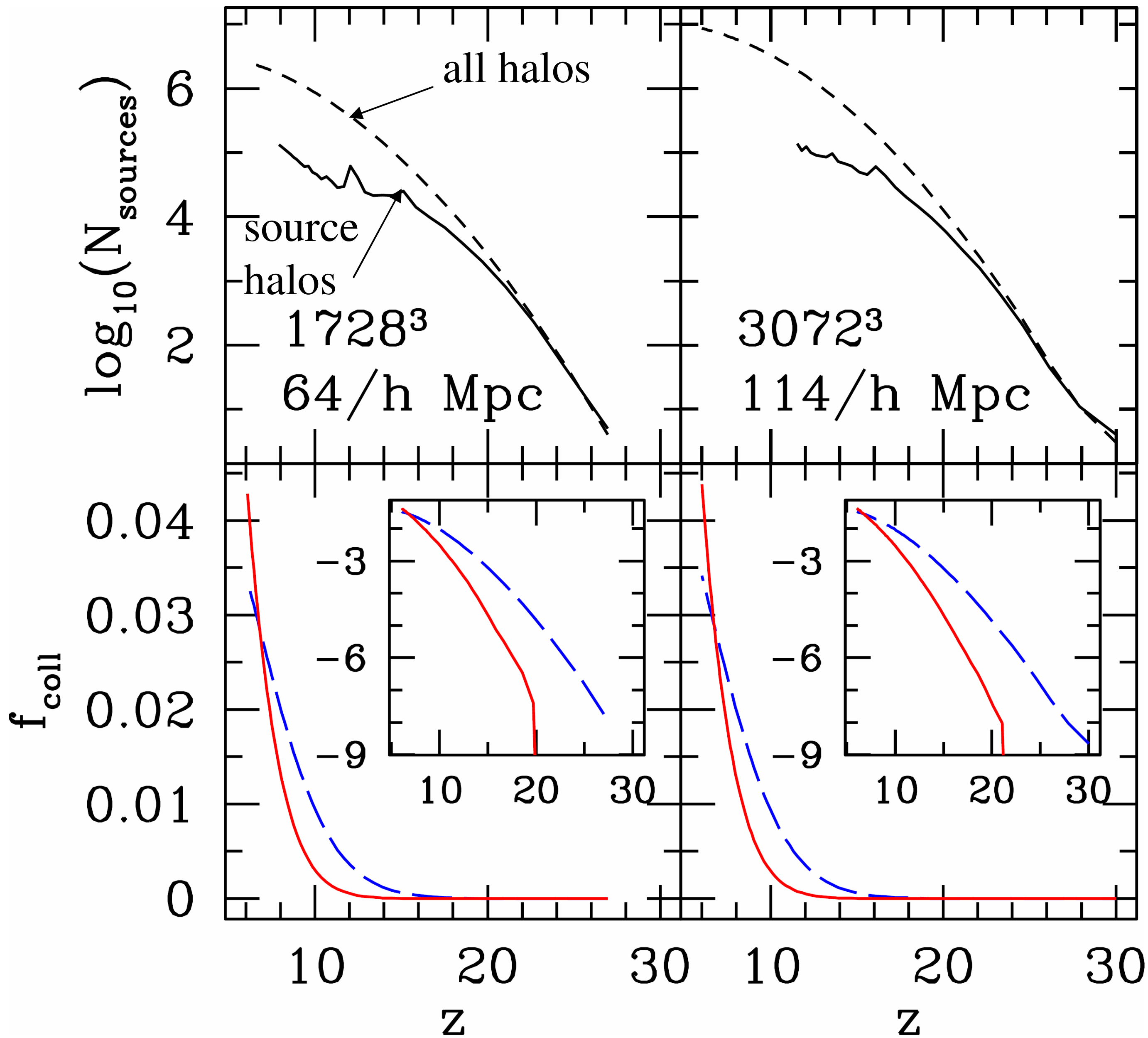
$z = 11.6$ | $z = 11.9$

when mass-weighted mean ionized fraction of universe $x_m = 0.3$

Self-regulated halo mass function

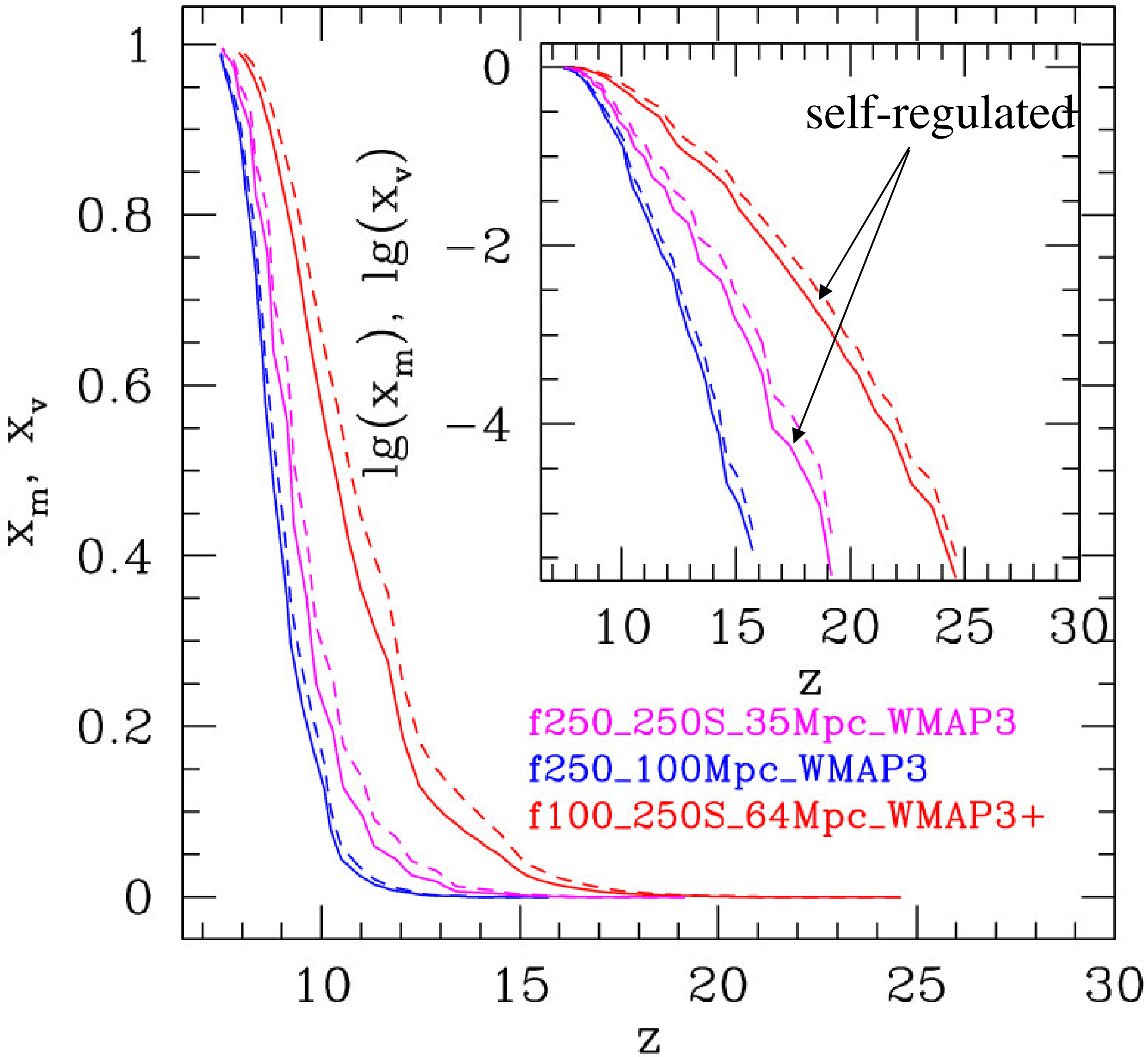
- Jeans-mass filtering suppresses formation of sources in small-mass halos which form inside H II regions
- clustering of small-mass halos around density peaks enhances this effect ➔

suppression is strongly biased



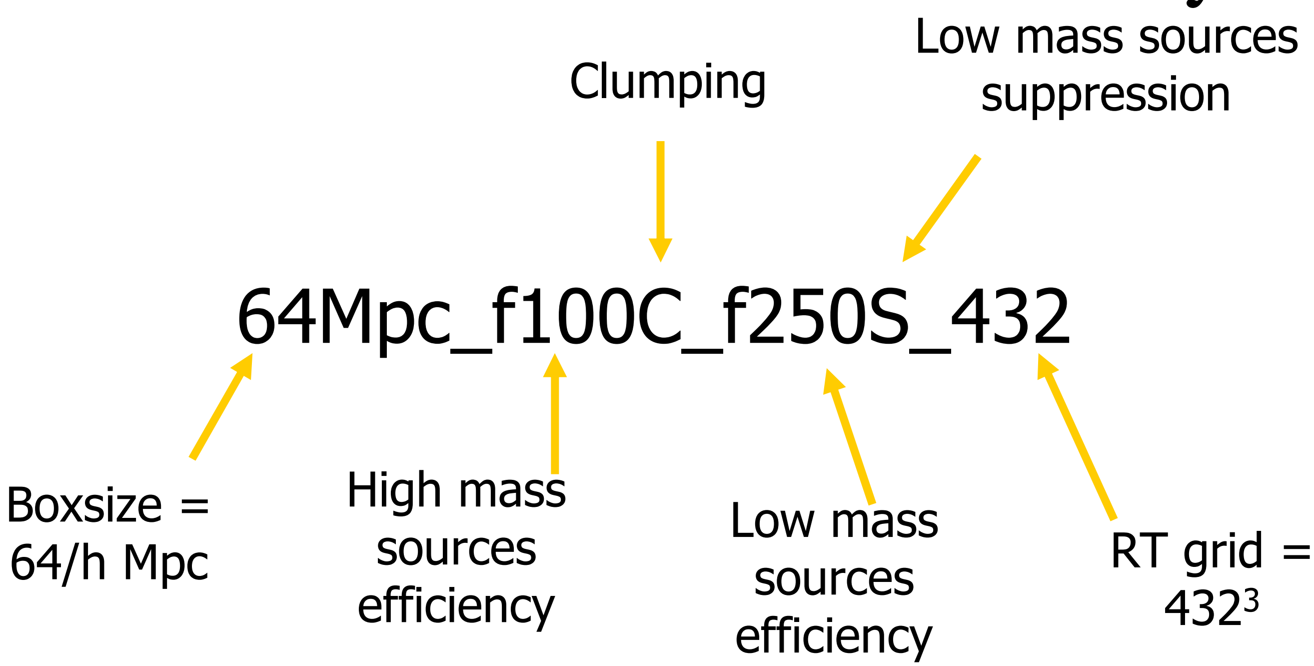
Evolution of the Mean Ionized Fraction of the Universe

- self-regulated reion. (i.e. small-mass halos resolved) starts earlier, but ends about the same time ➔
- high-mass halos dominate the end of EOR



Notation

- Our simulations are characterized by



The Fluctuating H_2 Dissociating Background During Reionization

Ahn, Shapiro, Iliev, Mellema, & Pen 2008, ApJ, submitted (astro-ph/0807.2254; 0807.0920)

• Simulations suggest first stars formed inside minihalos of mass ~ 10^{5-6} solar masses at redshift z >~ 20, when H_2 molecules cooled the primordial, metal-free gas and gravitational collapse ensued.

• **But** H_2 Lyman-Werner ("LW") band photons (11.2 – 13.6 eV) dissociate H_2, so too much LW background intensity (i.e. $J_{LW} > (J_{LW})_{threshold}$)

➔ star formation inside minihalos suppressed

The Fluctuating H_2 Dissociating Background During Reionization

Ahn, Shapiro, Iliev, Mellema, & Pen 2008, ApJ, submitted (astro-ph/0807.2254; 0807.0920)

- Simulations suggest first stars formed inside minihalos of mass ~ 10^{5-6} solar masses at redshift z >~ 20, when H_2 molecules cooled the primordial, metal-free gas and gravitational collapse ensued.

- **But** H_2 Lyman-Werner ("LW") band photons (11.2 – 13.6 eV) dissociate H_2, so too much LW background intensity (i.e. $J_{LW} > (J_{LW})_{threshold}$)

  ➔ star formation inside minihalos suppressed

Q: How much is too much?

The Fluctuating H_2 Dissociating Background During Reionization

Ahn, Shapiro, Iliev, Mellema, & Pen 2008, ApJ, submitted (astro-ph/0807.2254; 0807.0920)

• Simulations suggest first stars formed inside minihalos of mass ~ 10^{5-6} solar masses at redshift z >~ 20, when H_2 molecules cooled the primordial, metal-free gas and gravitational collapse ensued.

• **But** H_2 Lyman-Werner ("LW") band photons (11.2 – 13.6 eV) dissociate H_2, so too much LW background intensity (i.e. $J_{LW} > (J_{LW})_{threshold}$)

➔ star formation inside minihalos suppressed

Q: How much is too much?
A: Early estimates (e.g. Haiman, Abel, and Rees 2000) suggested it depended on minihalo mass and redshift, and to suppress *all* minihalos, $\mathbf{(J_{LW,21})_{threshold} \sim 0.01 \text{ to } 1}$, as z varies from 10 to 50, respectively. Later estimates with more realistic, cosmological initial conditions, 3D, numerical gas dynamics found similar range (e.g. Ricotti et al. 2002; Yoshida et al. 2003; Yoshida et al. 2007; O'Shea and Norman 2007).

The Fluctuating H_2 Dissociating Background During Reionization

Ahn, Shapiro, Iliev, Mellema, & Pen 2008, ApJ, submitted (astro-ph/0807.2254; 0807.0920)

• Simulations suggest first stars formed inside minihalos of mass ~ 10^{5-6} solar masses at redshift z >~ 20, when H_2 molecules cooled the primordial, metal-free gas and gravitational collapse ensued.

• **But** H_2 Lyman-Werner ("LW") band photons (11.2 – 13.6 eV) dissociate H_2, so too much LW background intensity (i.e. $J_{LW} > (J_{LW})_{threshold}$)

➔ star formation inside minihalos suppressed

Q: How much is too much?
A: Early estimates (e.g. Haiman, Abel, and Rees 2000) suggested it depended on minihalo mass and redshift, and to suppress *all* minihalos, $\mathbf{(J_{LW,21})_{threshold} \sim 0.01\ to\ 1}$, as z varies from 10 to 50, respectively. Later estimates with more realistic, cosmological initial conditions, 3D, numerical gas dynamics found similar range (e.g. Ricotti et al. 2002; Yoshida et al. 2003; Yoshida et al. 2007; O'Shea and Norman 2007).

• **But** during EOR, sources of reionization also emit continuum below 13.6 eV Lyman limit, in the H_2 LW bands ➔ *rising LW background inevitable!*

The Fluctuating H_2 Dissociating Background During Reionization

Ahn, Shapiro, Iliev, Mellema, & Pen 2008, ApJ, submitted (astro-ph/0807.2254; 0807.0920)

• Simulations suggest first stars formed inside minihalos of mass ~ 10^{5-6} solar masses at redshift z >~ 20, when H_2 molecules cooled the primordial, metal-free gas and gravitational collapse ensued.

• **But** H_2 Lyman-Werner ("LW") band photons (11.2 – 13.6 eV) dissociate H_2, so too much LW background intensity (i.e. $J_{LW} > (J_{LW})_{threshold}$)

➔ star formation inside minihalos suppressed

Q: How much is too much?
A: Early estimates (e.g. Haiman, Abel, and Rees 2000) suggested it depended on minihalo mass and redshift, and to suppress *all* minihalos, $\mathbf{(J_{LW,21})_{threshold} \sim 0.01}$ **to 1**, as z varies from 10 to 50, respectively. Later estimates with more realistic, cosmological initial conditions, 3D, numerical gas dynamics found similar range (e.g. Ricotti et al. 2002; Yoshida et al. 2003; Yoshida et al. 2007; O'Shea and Norman).

• **But** during EOR, sources of reionization also emit continuum below 13.6 eV Lyman limit, in the H_2 LW bands ➔ *rising LW background inevitable!*

• **How high does it get?**

The Fluctuating H_2 Dissociating Background During Reionization

Ahn, Shapiro, Iliev, Mellema, & Pen 2008, ApJ, submitted (astro-ph/0807.2254; 0807.0920)

- Ionization sources also emit continuum below Lyman limit, in the H_2 Lyman-Werner bands

  (11.2 – 13.6 eV).
- In IGM, this radiation is attenuated by scattering in H Lyman series lines and downgrading to lower energy photons.
- By transfering this radiation from each source halo thru the IGM, we compute the inhomogeneous LW band intensity field durng reionization.
- e.g. Pop II sources,

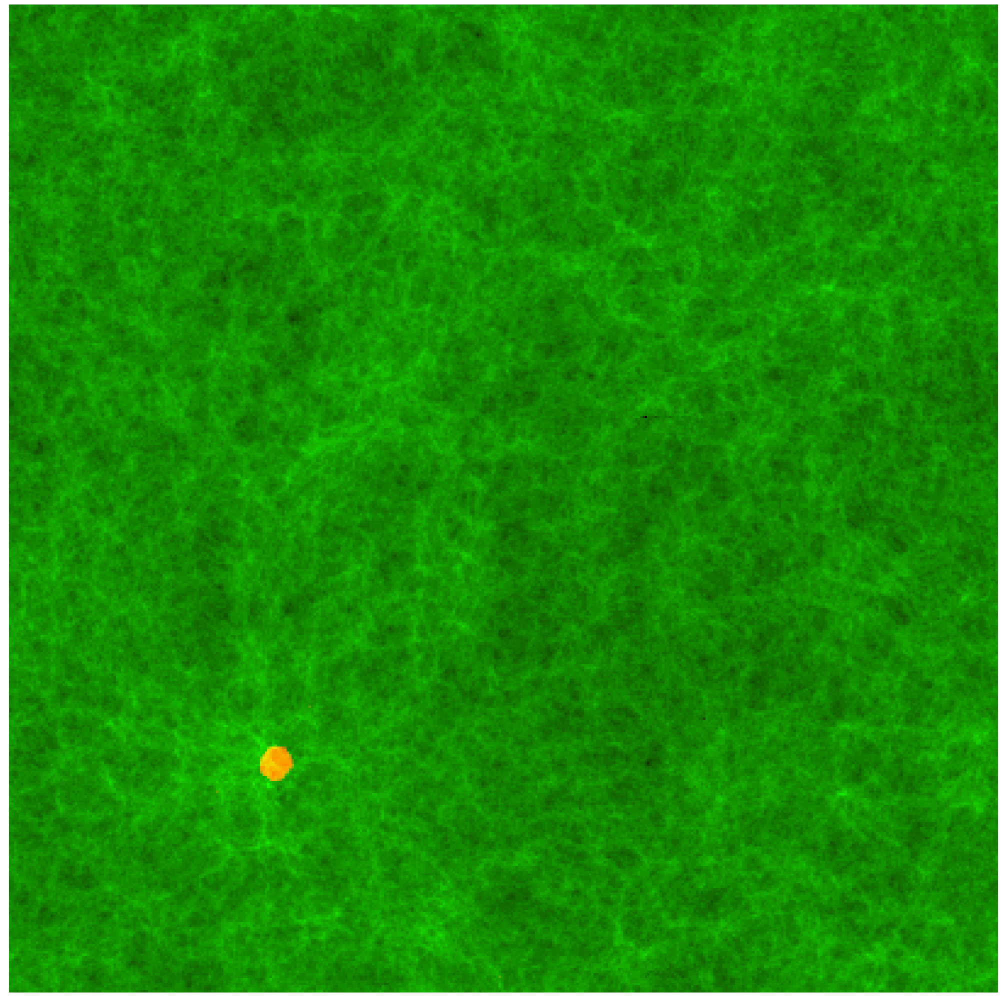
  $f_{esc} = 0.2$, $f_* = 0.2$,

  $f_\gamma = 250$.

The Fluctuating H_2 Dissociating Background During Reionization

Ahn, Shapiro, Iliev, Mellema, & Pen 2008, ApJ, submitted (astro-ph/0807.2254; 0807.0920)

- Ionization sources also emit continuum below Lyman limit, in the H_2 Lyman-Werner bands
  (11.2 – 13.6 eV).
- In IGM, this radiation is attenuated by scattering in H Lyman series lines and downgrading to lower energy photons.
- By transfering this radiation from each source halo thru the IGM, we compute the inhomogeneous LW band intensity field durng reionization.
- e.g. Pop II sources,
  $f_{esc} = 0.2$, $f_* = 0.2$,
  $f_\gamma = 250$.



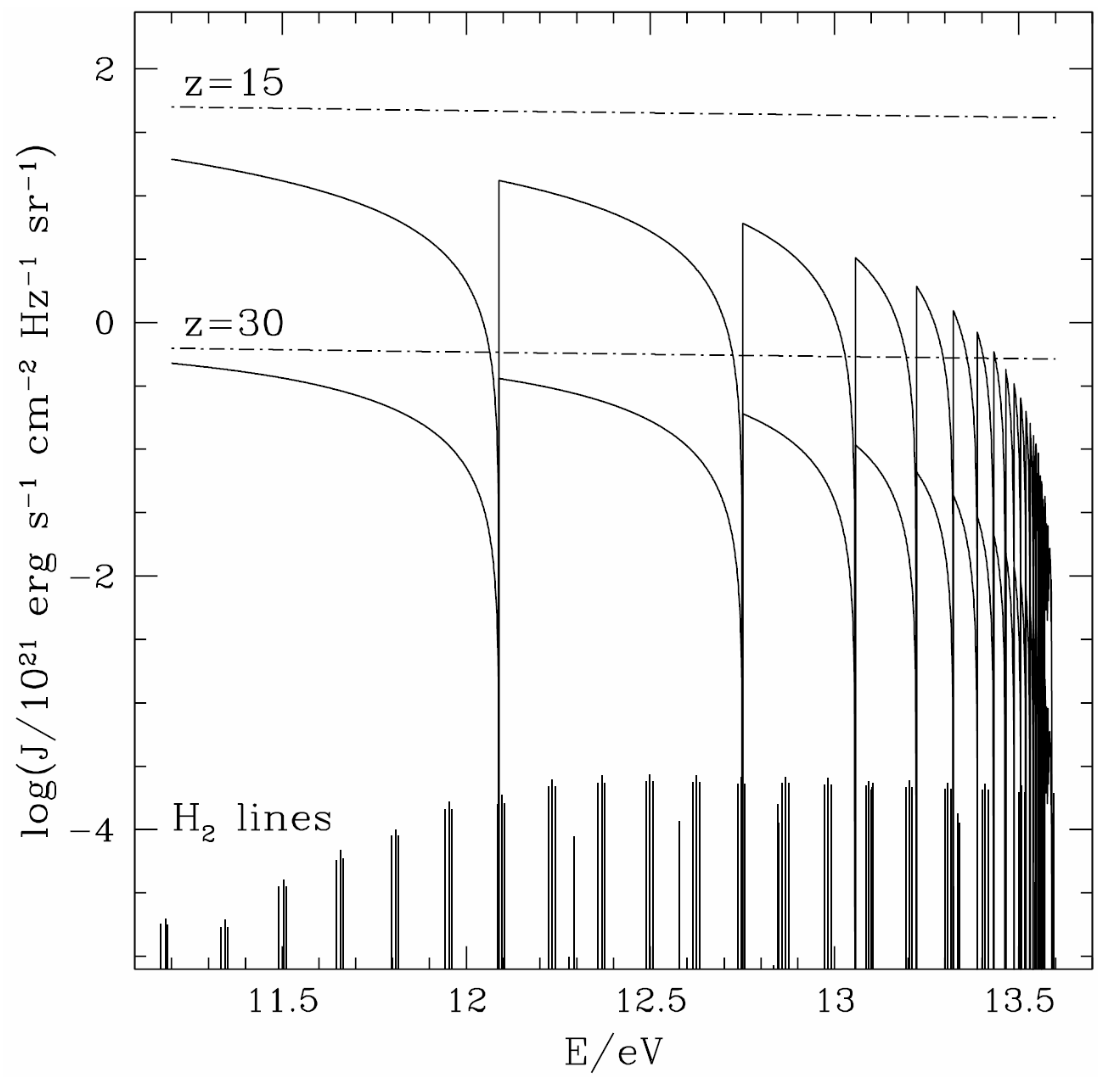
35/h Mpc box

Previous approximation for cosmic mean LW Background during EOR: homogeneous universe ➔ "saw-tooth" modulation

- assume sources of UV emissivity *uniformly* distributed in space (e.g. Haiman et al. 2000; Ricotti et al. 2002; Yoshida et al. 2003)

- assume H_2 dissociating photons, emitted below H Lyman limit, are removed whenever they redshift into an H Lyman series line and are resonantly scattered by the IGM, down-converting them out of LW bands

- uniform IGM opacity filters uniformly distributed LW emitters by "saw-tooth" modulation.

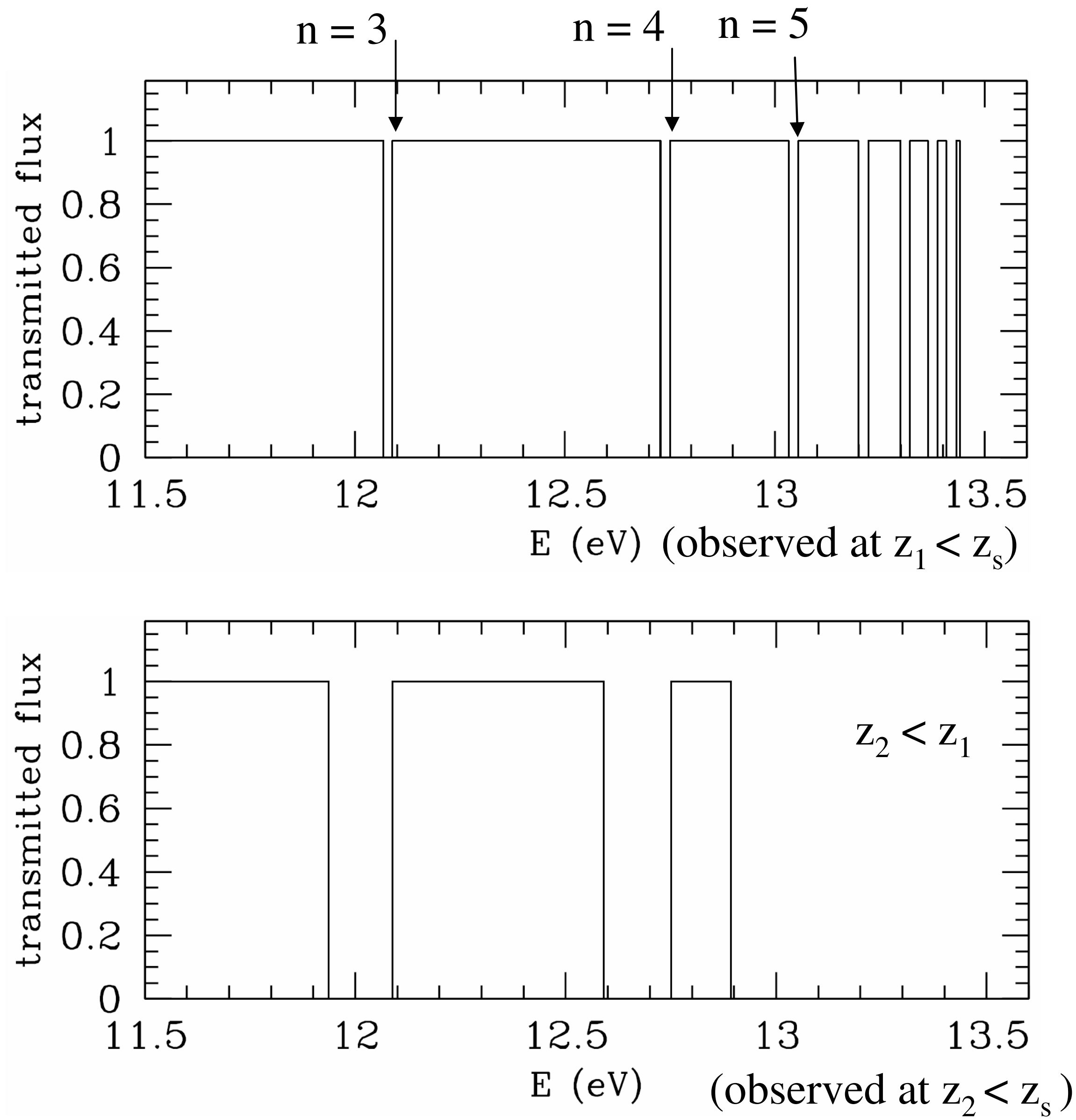


(Haiman, Abel, and Rees 2000)

Attenuation of LW photons from a single source: "picket-fence" modulation

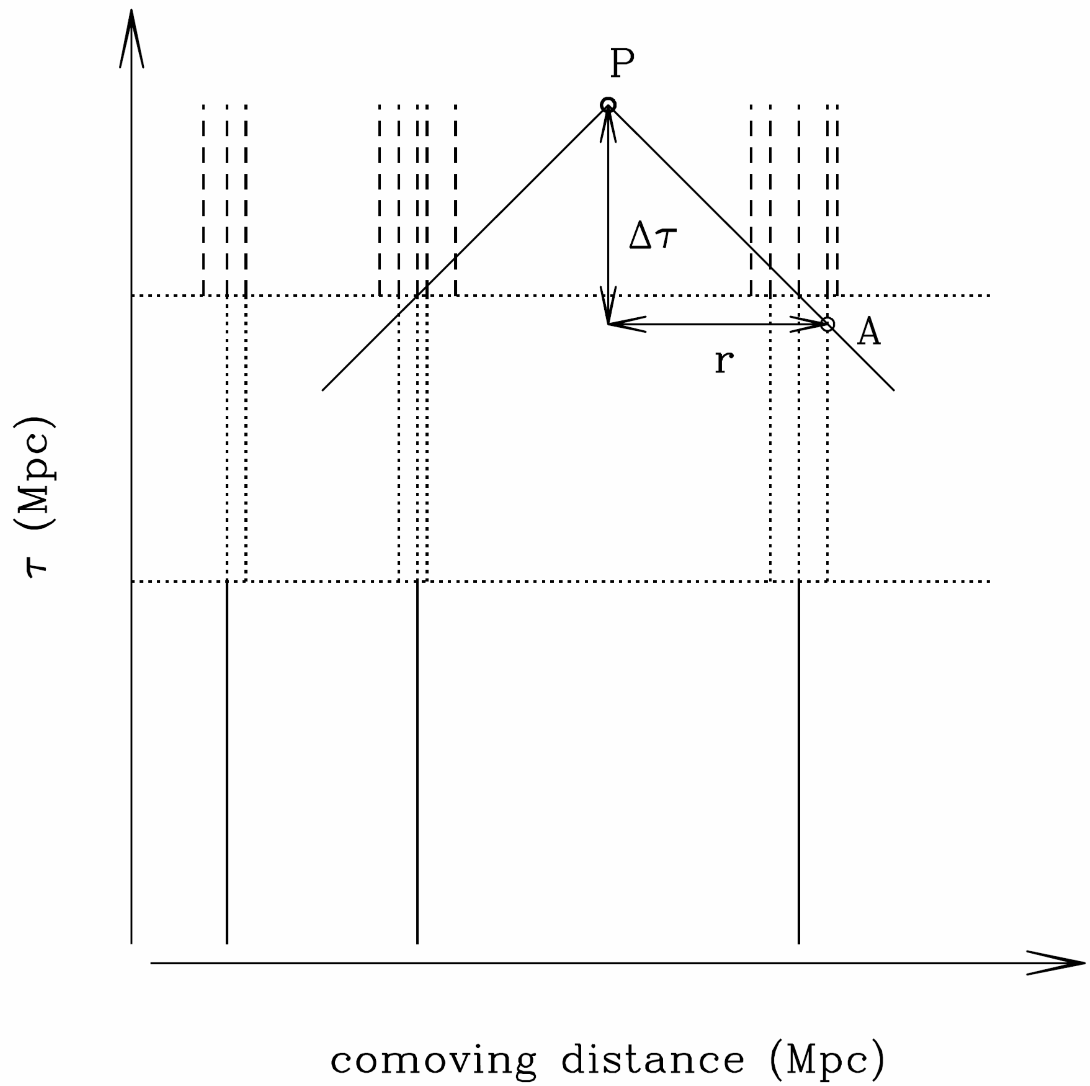
- A source at redshift z_s observed at different distances suffers different amounts of attenuation, dilution, and redshift
- When LW photon redshifts into the nearest lower H Lyman series line, it is scattered and destroyed (converted to lower energy photon).
- Source is completely attenuated at comoving distance

$r_{cMpc} = 97\ [(1 + z)/21]^{-0.5}$



LW background radiative transfer is intrinsically cosmological : sources along the "past light-cone" of every point in space

- Space-time diagram of radiation sources and observer at point P at conformal time τ
- luminosity of each halo source is constant during finite time-step
- observer at point P will see sources whose world lines intersect the past light-cone
- must determine the attenuation, dilution, and redshift of the LW photons emitted at A and received at P



Computational Challenge

$J_\nu(\mathbf{x}_{\rm obs}, z_{\rm obs}, \nu_{\rm obs})$ at observed frequency $\nu_{\rm obs}$ at some comoving position $\mathbf{x}_{\rm obs}$ at redshift $z_{\rm obs}$ is given by

$$J_\nu(\mathbf{x}_{\rm obs}, z_{\rm obs}, \nu_{\rm obs}) = \frac{1}{4\pi} \sum_{\rm s} F_{\nu,\,\rm s}(\mathbf{x}_{\rm obs}, z_{\rm obs}, \nu_{\rm obs}), \tag{5}$$

where $F_{\nu,\,\rm s}$ is the flux received at $(\mathbf{x}_{\rm obs}, z_{\rm obs}, \nu_{\rm obs})$ that was emitted at $(\mathbf{x}_{\rm s}, z_{\rm s}, \nu_{\rm s})$ by a source (denoted by subscript s), where

$$\frac{\nu_{\rm s}}{\nu_{\rm obs}} = \frac{1 + z_{\rm s}}{1 + z_{\rm obs}}. \tag{6}$$

Computational Challenge

The position and redshift, $(\mathbf{x}_{\rm s}, z_{\rm s})$, of a source are related to those of the observer at $(\mathbf{x}_{\rm obs}, z_{\rm obs})$ by the fact that the signal emitted at the epoch $z_{\rm s}$ must reach the position $\mathbf{x}_{\rm obs}$ at the epoch $z_{\rm obs}$, travelling at the speed of light while the universe expands. We express this implicitly by writing the comoving separation, $r_{\rm os}$, of the source and observer as follows:

$$r_{\rm os} = |\mathbf{x}_{\rm obs} - \mathbf{x}_{\rm s}| = \int_{t(z_{\rm s})}^{t(z_{\rm obs})} \frac{c dt}{a(t)} = - \int_{z_{\rm obs}}^{z_{\rm s}} c \frac{dz}{H(z)}. \qquad (7)$$

Computational Challenge

The differential flux, $F_{\nu,s}$, received at $(\mathbf{x}_{\rm obs}, z_{\rm obs}, \nu_{\rm obs})$ from a source of differential luminosity L_ν emitted at $(\mathbf{x}_{\rm s}, z_{\rm s}, \nu_{\rm s})$ is given by

$$F_{\nu,s}(\mathbf{x}_{\rm obs}, z_{\rm obs}, \nu_{\rm obs}) = \frac{L_\nu\,(\nu = \nu_{\rm s})}{4\pi D_L^2(z_{\rm obs}, z_{\rm s})} \cdot \left(\frac{1+z_{\rm s}}{1+z_{\rm obs}}\right) \cdot \exp\left[-\tau_{\nu_{\rm obs}}\right], \tag{9}$$

Here $D_L(z_{\rm obs}, z_{\rm s})$ is

the luminosity distance given by

$$D_L(z_{\rm obs}, z_{\rm s}) \equiv \left(\frac{r_{\rm os}}{1+z_{\rm obs}}\right)\left(\frac{1+z_{\rm s}}{1+z_{\rm obs}}\right), \tag{10}$$

Computational Challenge

The differential flux, $F_{\nu,s}$, received at $(\mathbf{x}_{\rm obs}, z_{\rm obs}, \nu_{\rm obs})$ from a source of differential luminosity L_ν emitted at $(\mathbf{x}_{\rm s}, z_{\rm s}, \nu_{\rm s})$ is given by

$$F_{\nu,s}(\mathbf{x}_{\rm obs}, z_{\rm obs}, \nu_{\rm obs}) = \frac{L_\nu\left(\nu = \nu_{\rm s}\right)}{4\pi D_L^2(z_{\rm obs}, z_{\rm s})} \cdot \left(\frac{1+z_{\rm s}}{1+z_{\rm obs}}\right) \cdot \exp\left[-\tau_{\nu_{\rm obs}}\right], \tag{9}$$

Here $D_L(z_{\rm obs}, z_{\rm s})$ is

the luminosity distance given by

$$D_L(z_{\rm obs}, z_{\rm s}) \equiv \left(\frac{r_{\rm os}}{1+z_{\rm obs}}\right)\left(\frac{1+z_{\rm s}}{1+z_{\rm obs}}\right), \tag{10}$$

- Expected number of computational operations : ~ $N_{\rm sources} * N_{\rm cells} * N_{\rm frequencies}$
  where $N_{\rm sources}$ >~ 10^7 within the LW horizon of $r_{\rm LW}$ ~ 100 cMpc
  $N_{\rm cells}$ >~ 10^6 grid cells for sufficient resolution and statistical accuracy
  $N_{\rm frequencies}$ >> 1 for multi-frequency transfer of optically thick Lyman series lines

➔ *full 3D, multi-frequency radiative transfer would be prohibitive!!*

Computational Challenge

The differential flux, $F_{\nu,s}$, received at $(\mathbf{x}_{\rm obs}, z_{\rm obs}, \nu_{\rm obs})$ from a source of differential luminosity L_ν emitted at $(\mathbf{x}_{\rm s}, z_{\rm s}, \nu_{\rm s})$ is given by

$$F_{\nu,s}(\mathbf{x}_{\rm obs}, z_{\rm obs}, \nu_{\rm obs}) = \frac{L_\nu\,(\nu=\nu_{\rm s})}{4\pi D_L^2(z_{\rm obs}, z_{\rm s})} \cdot \left(\frac{1+z_{\rm s}}{1+z_{\rm obs}}\right) \cdot \exp\left[-\tau_{\nu_{\rm obs}}\right], \tag{9}$$

Here $D_L(z_{\rm obs}, z_{\rm s})$ is

the luminosity distance given by

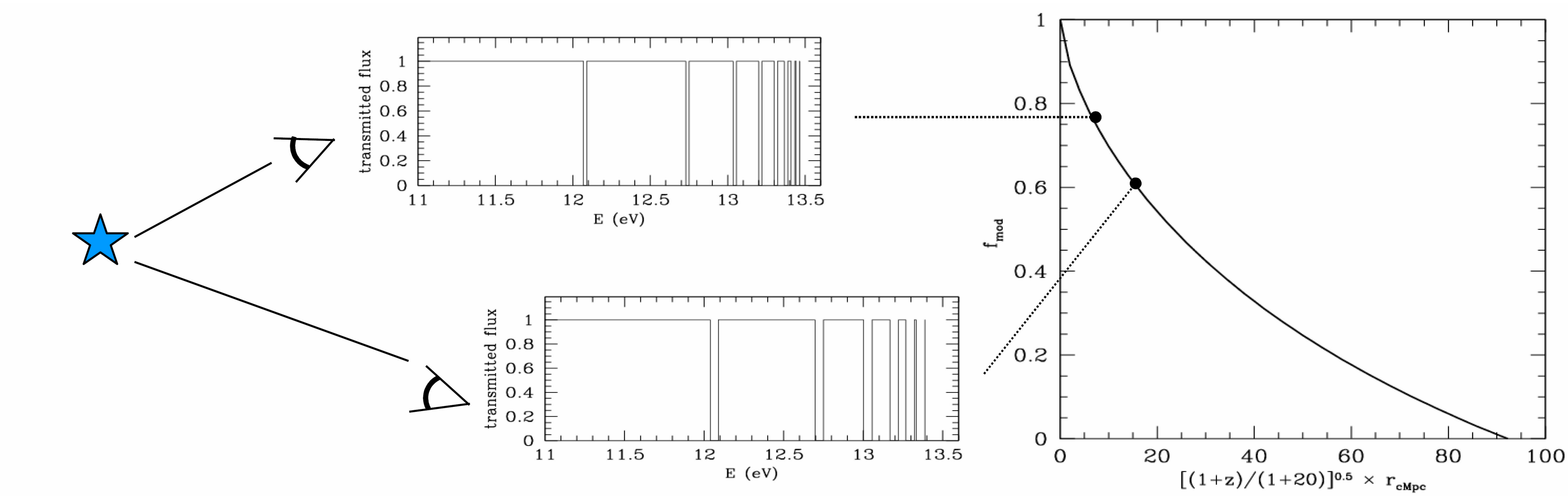
$$D_L(z_{\rm obs}, z_{\rm s}) \equiv \left(\frac{r_{\rm os}}{1+z_{\rm obs}}\right)\left(\frac{1+z_{\rm s}}{1+z_{\rm obs}}\right), \tag{10}$$

- Expected number of computational operations : ~ $N_{sources}$ * N_{cells} * $N_{frequencies}$
  where $N_{sources}$ >~ 10^7 within the LW horizon of r_{LW} ~ 100 cMpc
  N_{cells} >~ 10^6 grid cells for sufficient resolution and statistical accuracy
  $N_{frequencies}$ >> 1 for multi-frequency transfer of optically thick Lyman series lines

➔ *full 3D, multi-frequency radiative transfer would be prohibitive!!*

➔ **We solve this by making a grey opacity approximation equivalent to multi-freqency…**

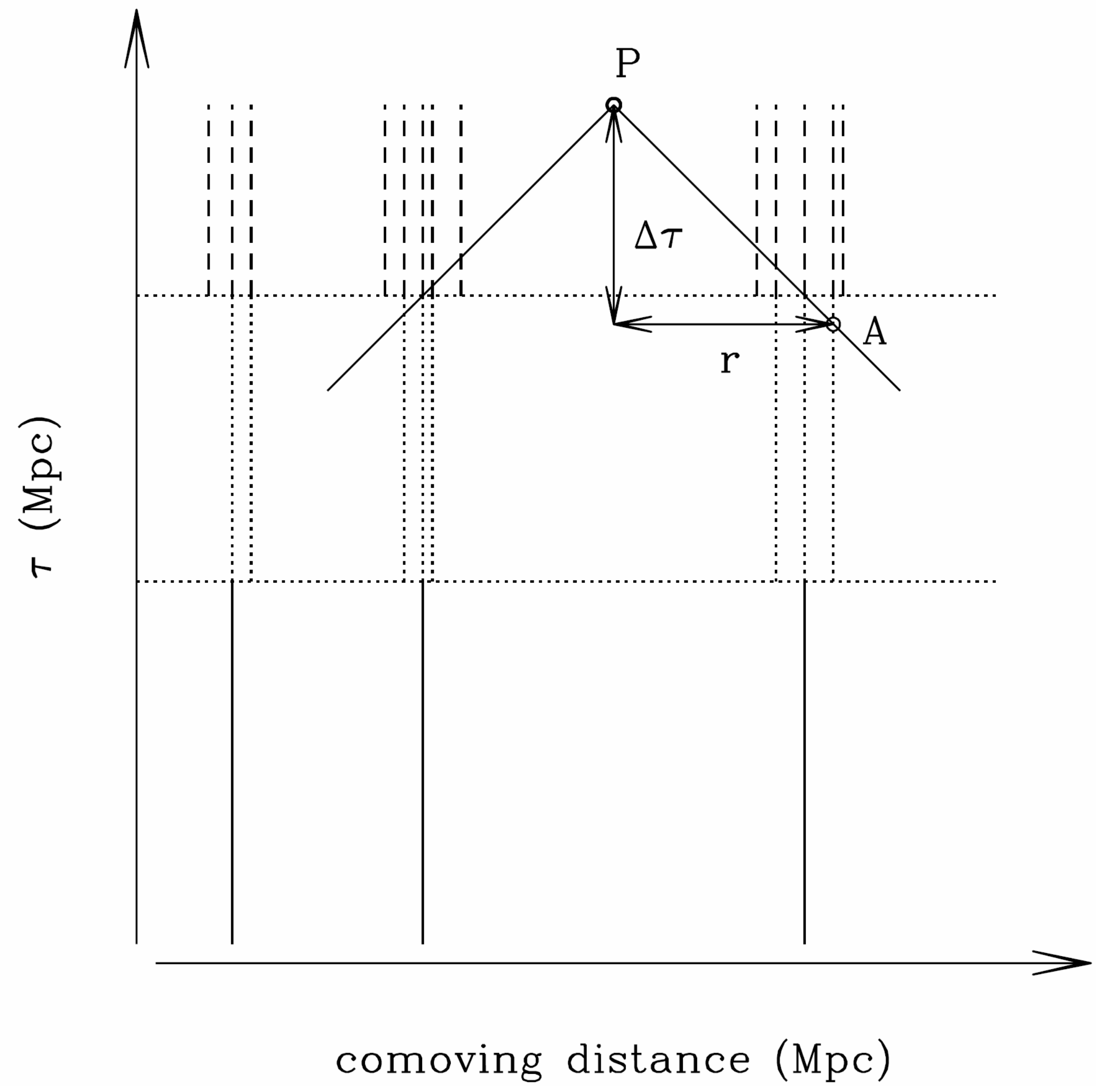
Attenuation of LW photons from a single source: "picket-fence" modulation factor



Modulation Factor

LW background radiative transfer is intrinsically cosmological : sources along the "past light-cone" of every point in space

- Space-time diagram of radiation sources and observer at point P at conformal time τ
- luminosity of each halo source is constant during finite time-step
- observer at point P will see sources whose world lines intersect the past light-cone
- must determine the attenuation, dilution, and redshift of the LW photons emitted at A and received at P



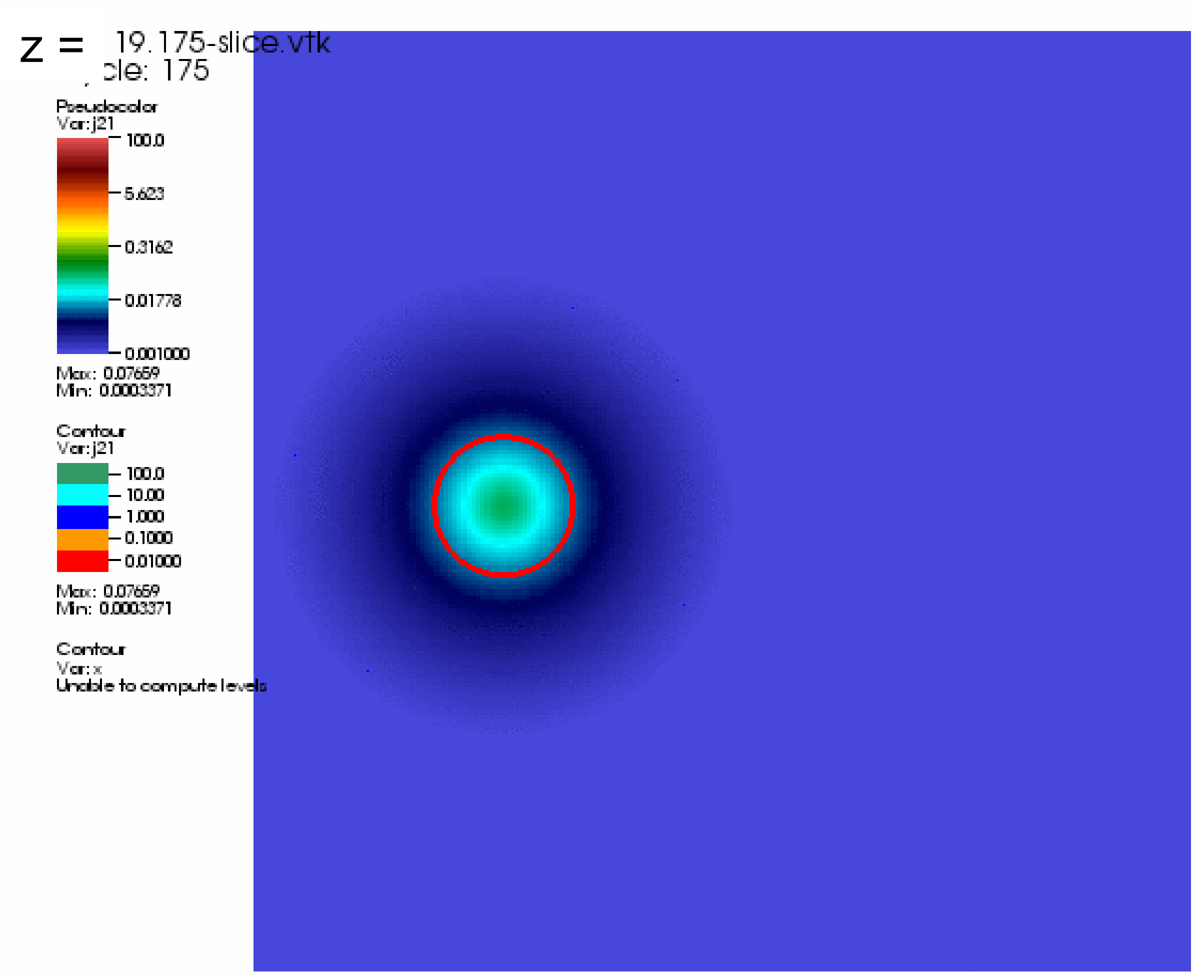
The Fluctuating H_2 Dissociating Background During Reionization

Ahn, Shapiro, Iliev, Mellema, & Pen 2008, MNRAS, submitted (astro-ph/0807.0920)

- LW background radiative transfer code parallelized using MPI for distributed-memory parallel computers;

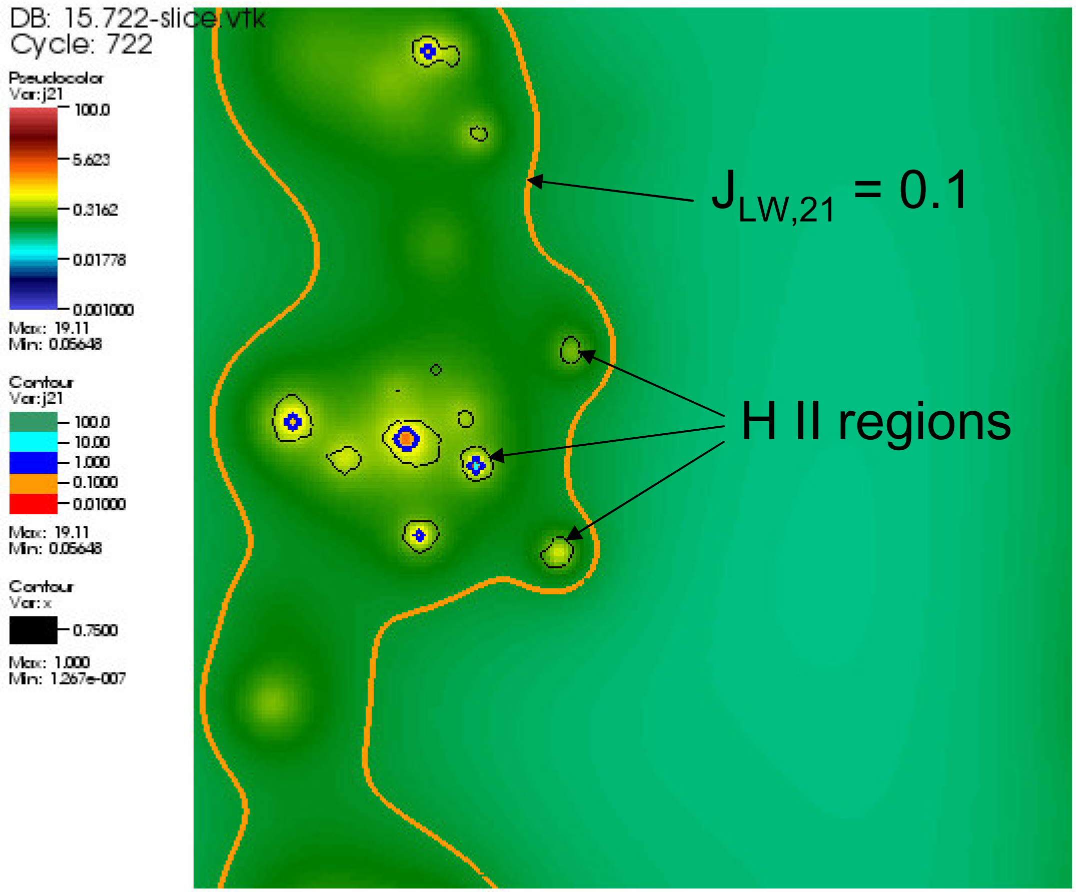
- e.g. 35/h Mpc reionization simulation has $(203)^3$ cells, $N_{sources}$ = 200,000 by z = 8, but must do LW transfer in 5^3 boxes stacked around the central box to fill 100 Mpc LW horizon ➔ $N_{sources}$, total > 20 million!

- Ran for 22 hours, on 320 computing cores, 1.5 GB memory per core, Texas supercomputer *Lonestar* (5200 cores of dual-core Intel Xeon processors, with 11.6 TB aggregate memory).

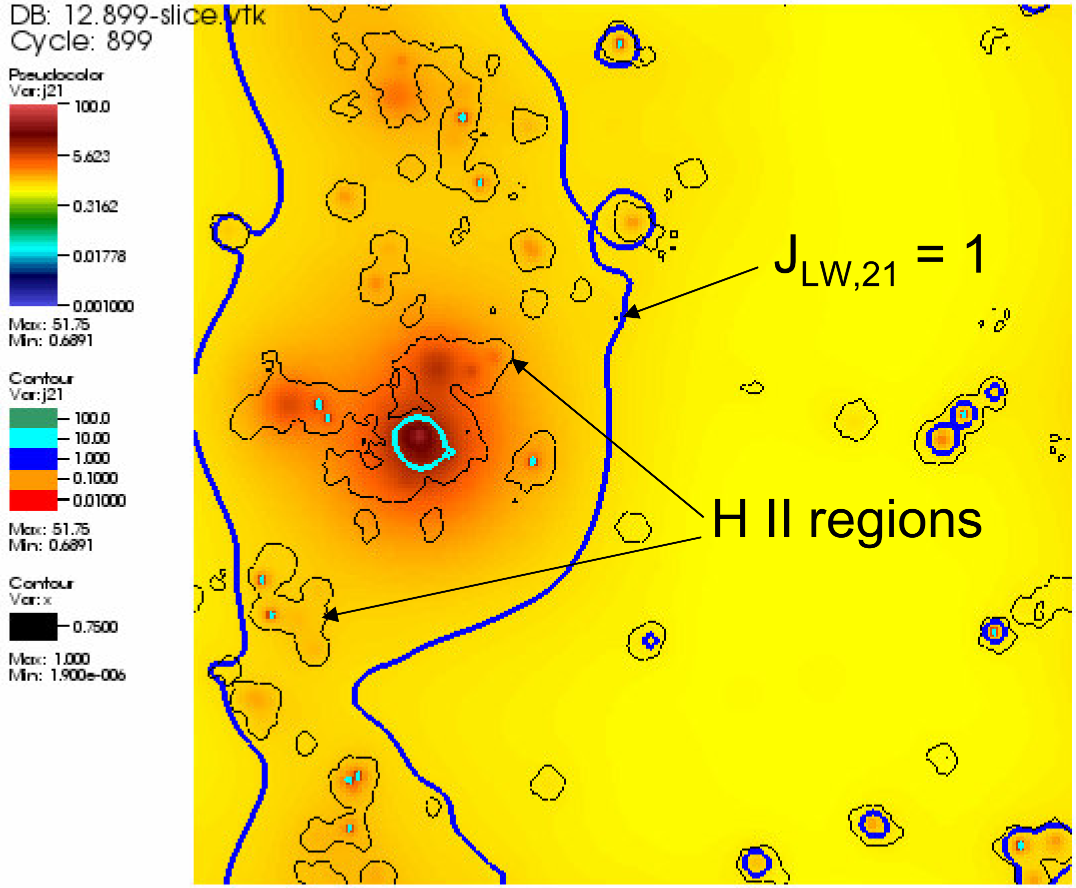


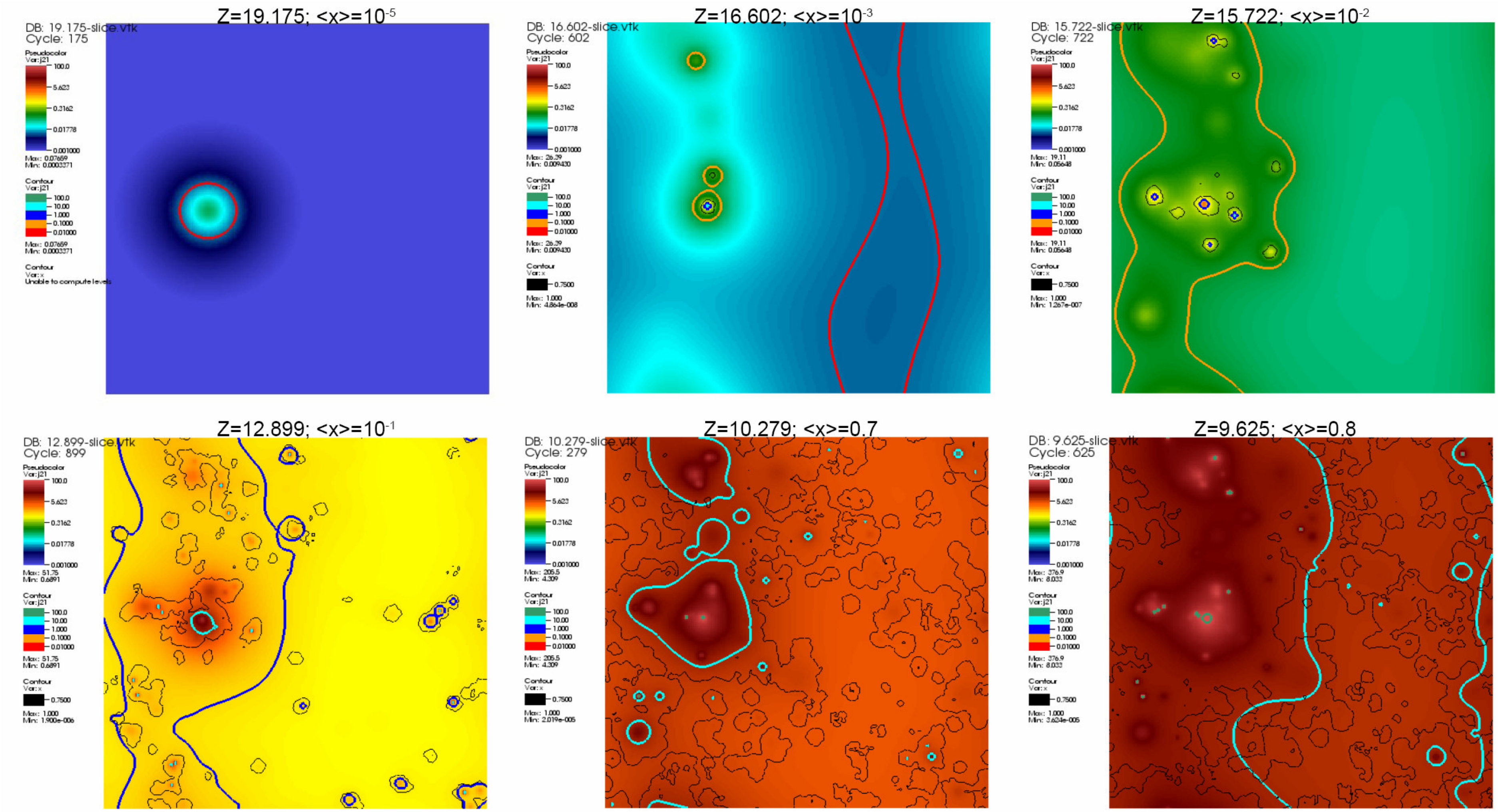
35/h Mpc box

H_2 Dissociating Background during EOR

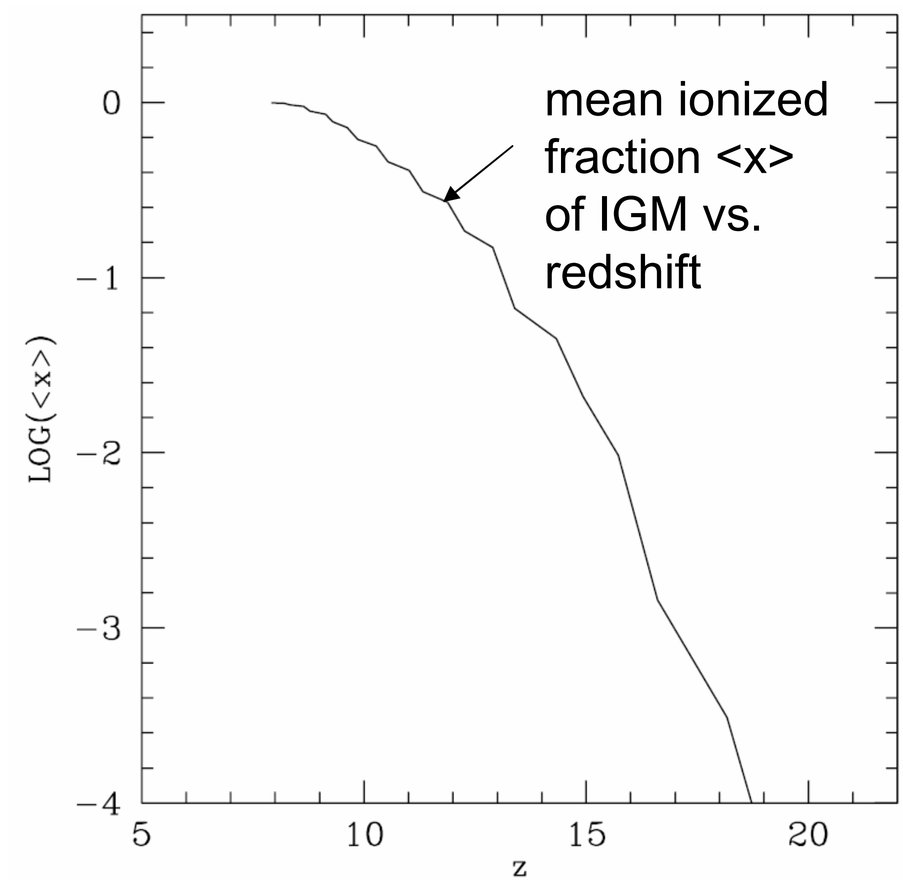


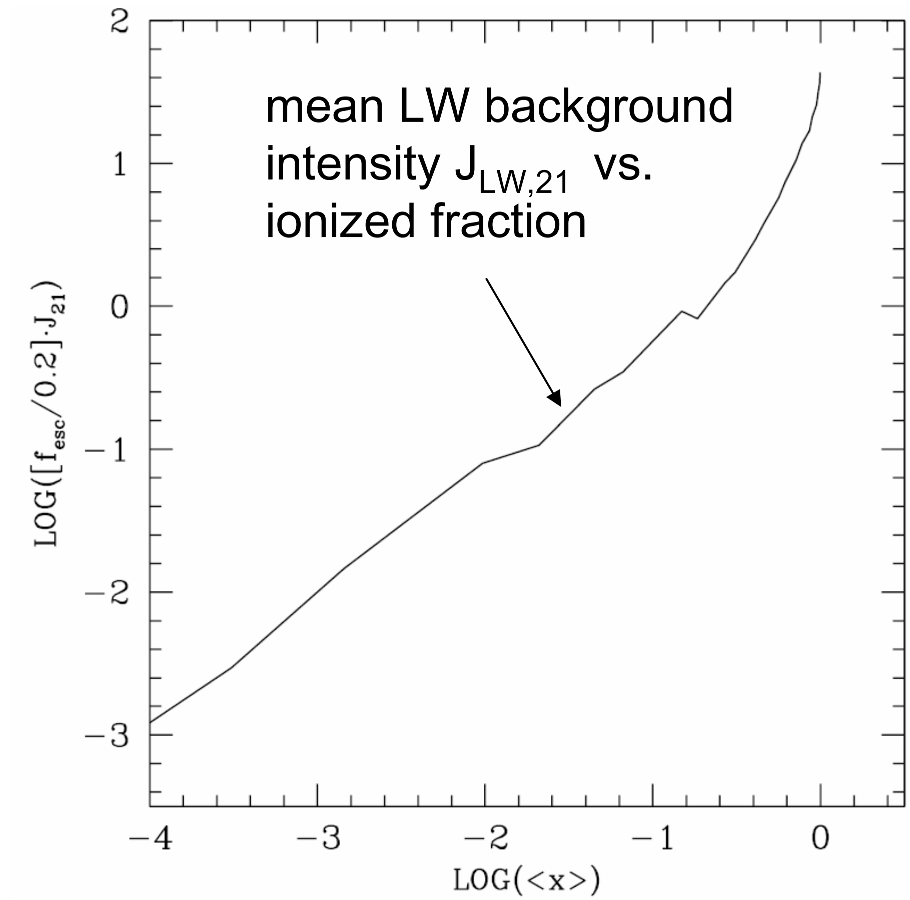
H_2 Dissociating Background during EOR




Z=19.175; <x>=10^-5
DB: 19.175-slice.vtk
Cycle: 175
Z=16.602; <x>=10^-3
DB: 16.602-slice.vtk
Cycle: 602
Z=15.722; <x>=10^-2
DB: 15.722-slice.vtk
Cycle: 722
Z=12.899; <x>=10^-1
DB: 12.899-slice.vtk
Cycle: 899
Z=10.279; <x>=0.7
DB: 10.279-slice.vtk
Cycle: 279
Z=9.625; <x>=0.8
DB: 9.625-slice.vtk
Cycle: 625

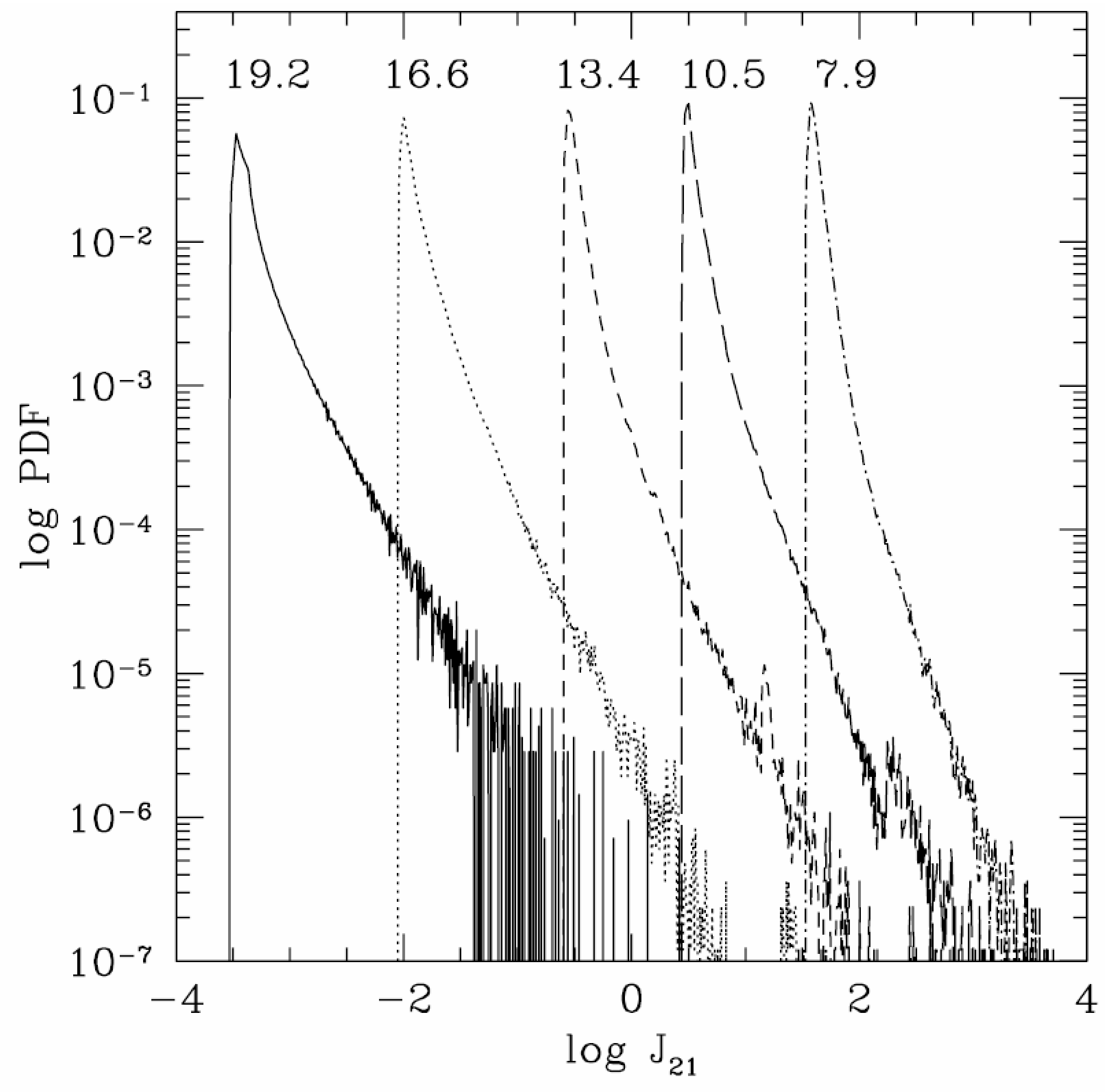
The Mean H_2 Dissociating UV Background During EOR





$J_{LW,\,21} = J/(10^{-21}\ \mathrm{erg\ s^{-1} cm^{-2}\ Hz^{-1}\ ster^{-1}})$

Distribution of Intensity Fluctuations for the LW Background During Reionization



(35/h Mpc box)

What are the dominant sources of the LW background during the EOR?

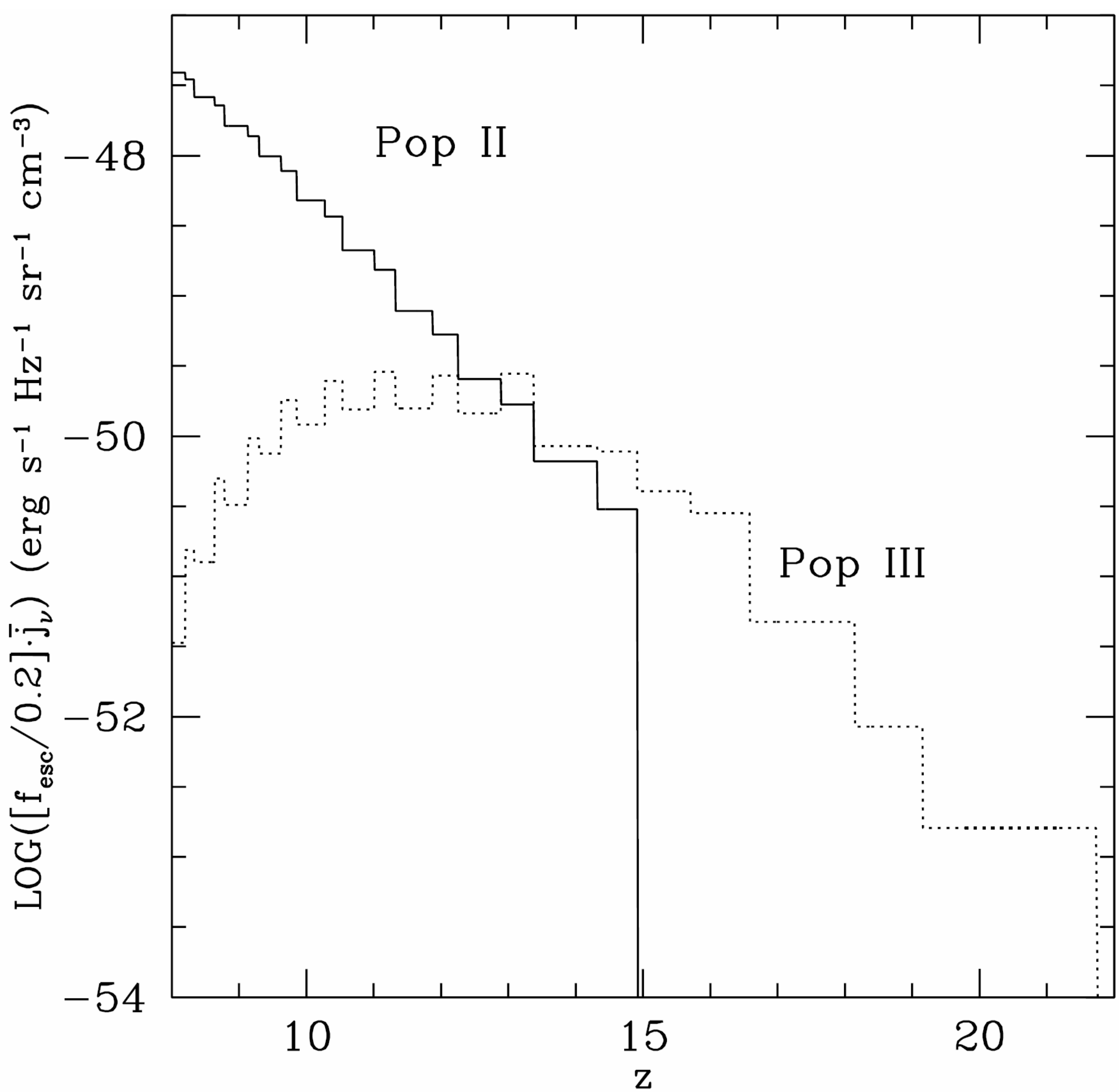
- Self-regulation of reionization

  ➔ early LW background is dominated by low-mass sources that are suppressed if they form inside H II regions,

  BUT the rise of the small-mass sources saturates long before end of EOR

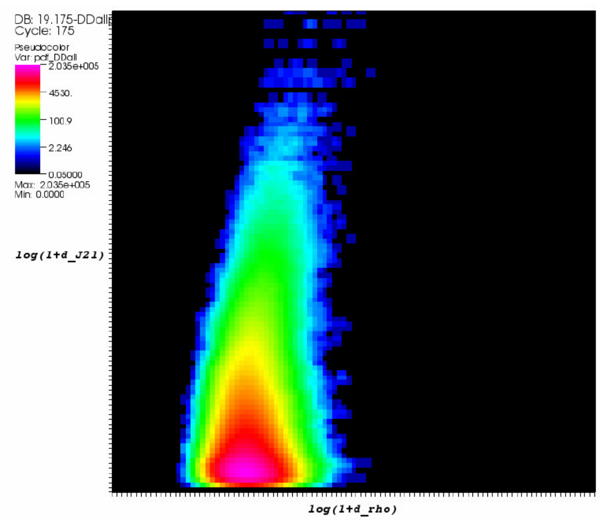
  ➔

  the high-mass sources eventually dominate the LW background

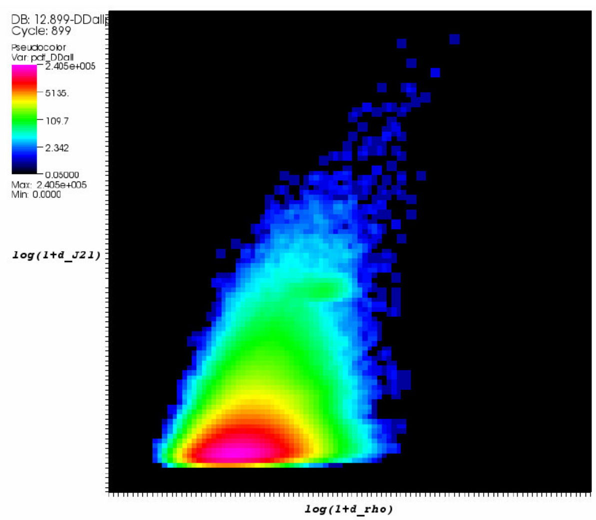


LW background intensity fluctuations in space are correlated with matter density fluctuations

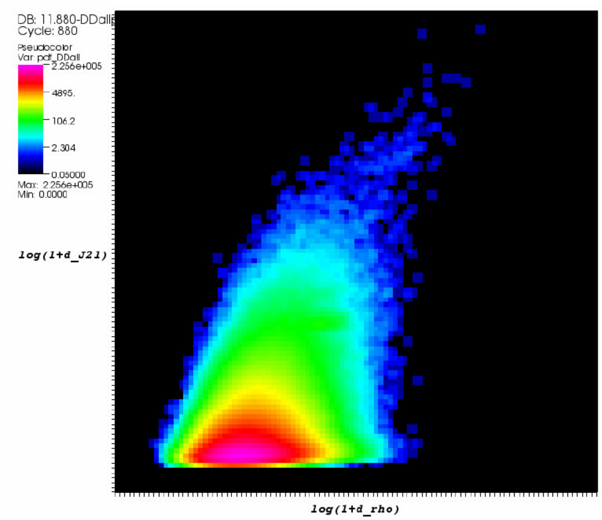
z = 19



z = 13



z = 12



LW Background Conclusions

- Picket-fence modulation of LW background photons
  - makes computation of inhomogeneous LW background tractable

- LW rises above the threshold for suppressing star formation in minihalos long before end of the EOR➔ supports the idea that MHs, on average, not significant reionization source, but

- LW intensity fluctuates significantly in space ➔may be “safe spots” early on, to form Pop III stars in minihalos where LW background minima occur, far from the large-scale H II regions made by clustered dwarf galaxies.

- Fluctuation in LW background comes from source clustering, at a scale of ~10 comoving Mpc

- May contribute to NIR background fluctuations

- Understanding radiative feedback on Pop III star formation in minihalos may be important to complete the theory of reionization

More Feedback From First Radiation Sources: H^- Photodissociation

Chuzhoy, Kuhlen, & Shapiro (2007), ApJL, 665, L85 (astro-ph/0704.0426)

- Rate for H_2 formation in primordial gas,

$$H^- + H \rightarrow H_2 + e^-$$

is proportional to abundance of H^- ===> destroying H^- will reduce H_2 formation rate;

- Photodissociation can destroy H^-,

$$H^- + \gamma \rightarrow H + e^- \qquad (\nu \geq 0.755 \text{ eV});$$

- **During reionization, as sources release ionizing radiation, they also cause a background of H^- dissociating radiation to build up, which reduces the H_2 formation rate by factor F_s,**

$$\mathbf{F_s \sim 1 + 1000\, k_s\, x / (f_{esc}\, \delta)},$$

where x = cosmic mean ionized fraction, δ = local baryon gas overdensity, and k_s = a constant of order unity which depends on type of radiation source (e.g. recombination radiation, direct stellar or quasar emission, or secondary emission by nonthermal electrons following X-ray background ionization) ;

- **Hence, by the time $x \gtrsim 0.1$, H^- photodissociation may significantly reduce H_2 abundance and cooling, and the rate of primordial star formation.**