The Inhomogeneous Background of H_2 Dissociating Radiation During Cosmic Reionization

w/ P. R. Shapiro (Texas)
I. T. Iliev (Zurich)
G. Mellema (Stockholm)
U.-L. Pen (CITA)

Kyungjin Ahn
Chosun University

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Simulation of Cosmic Reionization – 1. N-body simulation

- Iliev et al. (2005 – 2007)
- Other groups: Harvard, Princeton, Paris, …
- Perform a pure N-body simulation in a big box (> ~ 50 Mpc)
- Create a density field
- Paint hydrogen(HI) with cosmic abundace

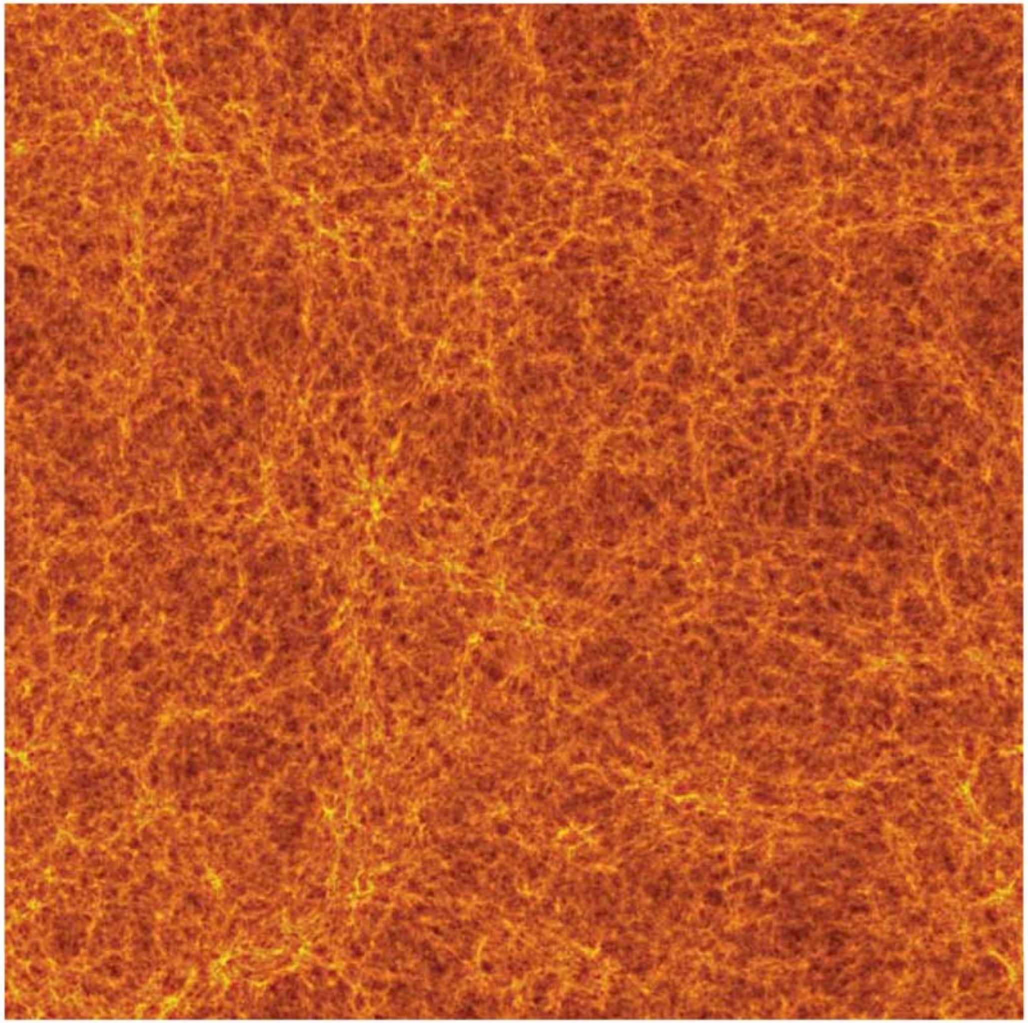
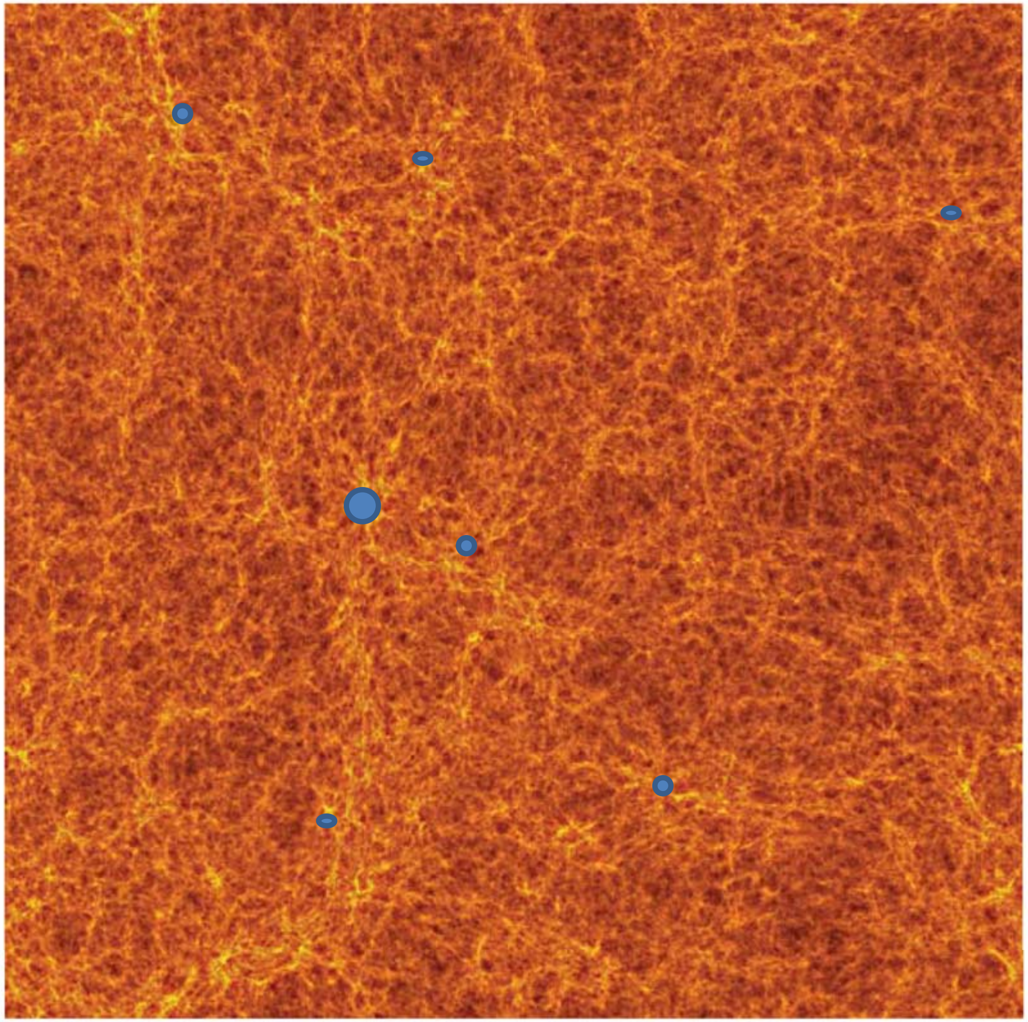


Figure 1. Early structure formation in ΛCDM, at $z = 10$, from our *N*-body simulation: projection of the cloud-in-cell densities on the fine simulation grid (3248 × 3248 pixel) in a 20 comoving Mpc slice ($\sim 6 \times 10^8$ particles in the slice) of the $(100\,h^{-1})^3\,\mathrm{Mpc}^3$ simulation volume. (See http://www.cita.utoronto.ca/~iliev/research.html for the full-resolution images and some movies of our simulations.)

Simulation of Cosmic Reionization – 2. Halo Identification

- Identify halos
- halo mass → stellar mass → ionizing photon luminosity (“parametrizing our ignorance”)



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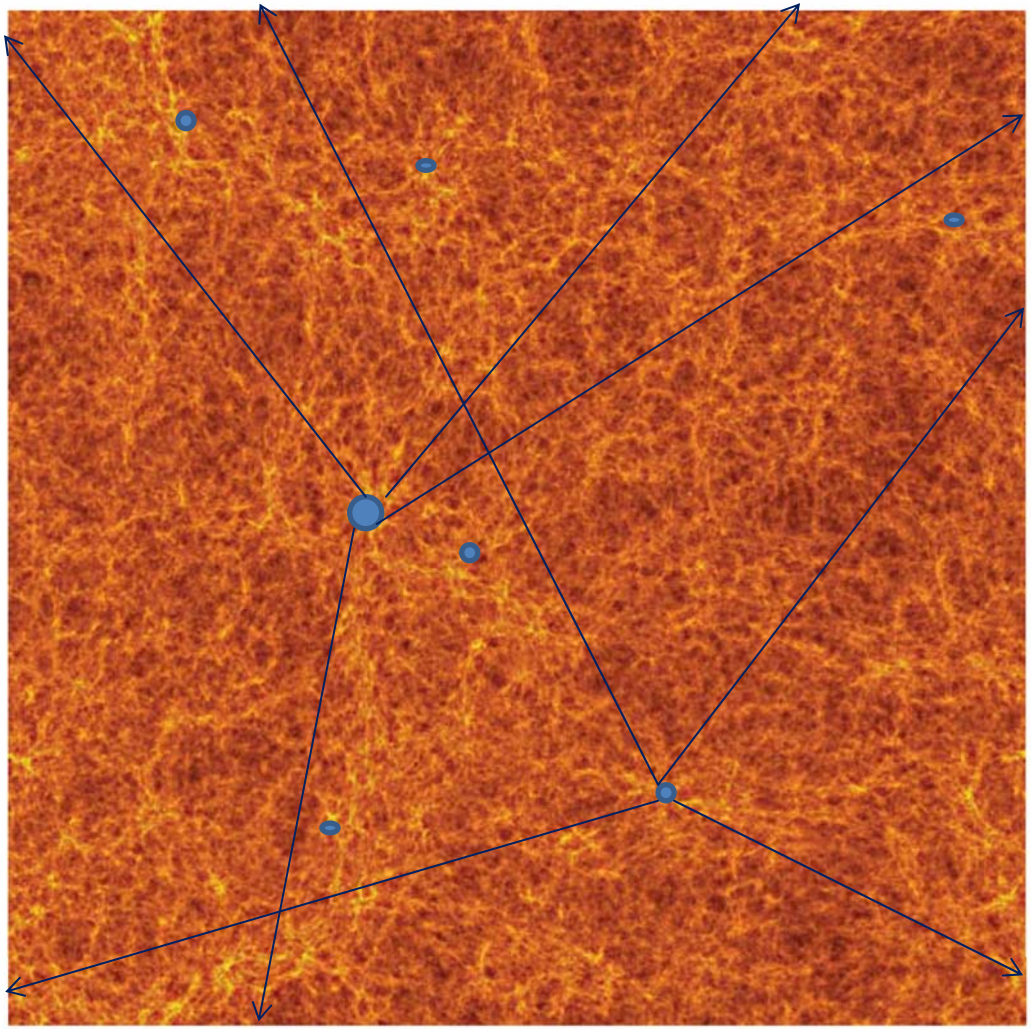
Simulation of Cosmic Reionization – 3. Ray tracing

- Draw rays
- Along each ray, perform radiative transfer calculation



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Simulation of Cosmic Reionization – 4. Evolve in time

- Get ionized fraction at each cell, solving rate equations for ~ 20 million year
- Update source population
- Iterate

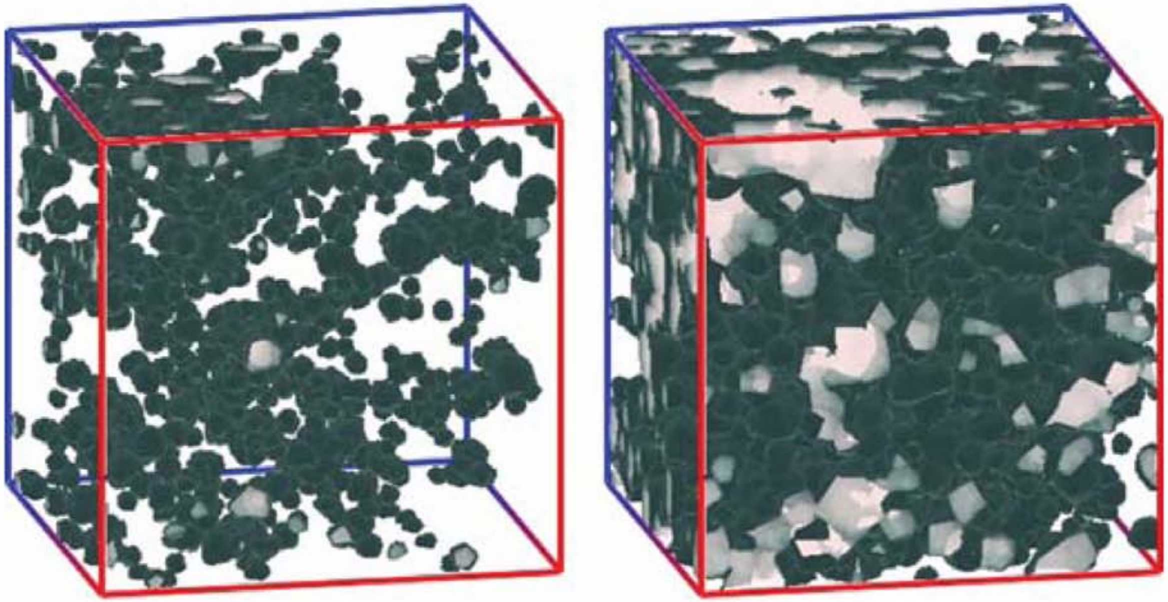


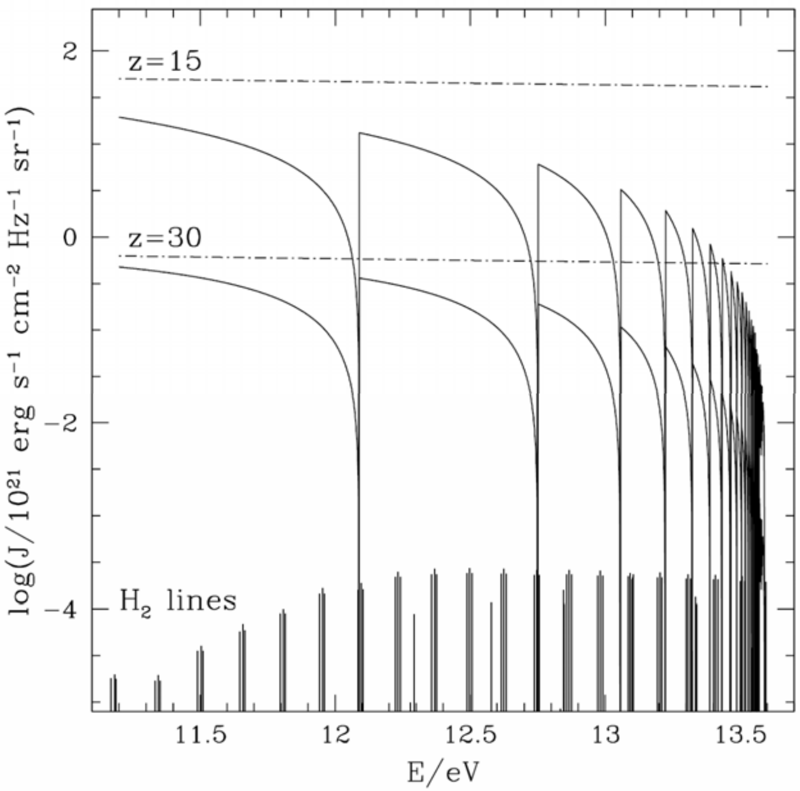
Figure 10. Volume rendering of the H II regions at redshifts $z = 14.74$ (left-hand panel) and $z = 13.62$ (right-hand panel). The 50 per cent ionization iso-surfaces are shown in dark colour, while the light colour volume renders the ionized gas density. (Images produced using the IFRIT visualization package of N. Gnedin)

Motivation

- Persistent UV background exists before ionizing radiation arrives
  - LW horizon (~ 100 Mpc comoving) is much larger than Stromgren radii
  - mostly negative feedback
- One needs to calculate UV background, especially in the H_2 Lyman-Werner (LW) band (dissociating H_2), and **fluctuating**
  - Usually done with parameterized J_{21}
  - Self-consistent calculations are from uniformly distributed sources (Haiman, Abel, Rees 2000), or averaged over a small box, which is even worse since it is too small to account for source-clustering (Ricotti, Gnedin, Shull 2001; Yoshida, Abel, Hernquist, Sugiyama 2003)
- LW band photons contributed by stars in minihalos (T_{vir}<~10^4K) AND stars in atomic cooling halos (T_{vir}>~10^4K), which are responsible for reionizing the Universe
- At least, atomic cooling halos are highly clustered (e.g. Iliev et al. 2006, 2007) with mean separation of clusters about a few - ~10 comoving Mpc

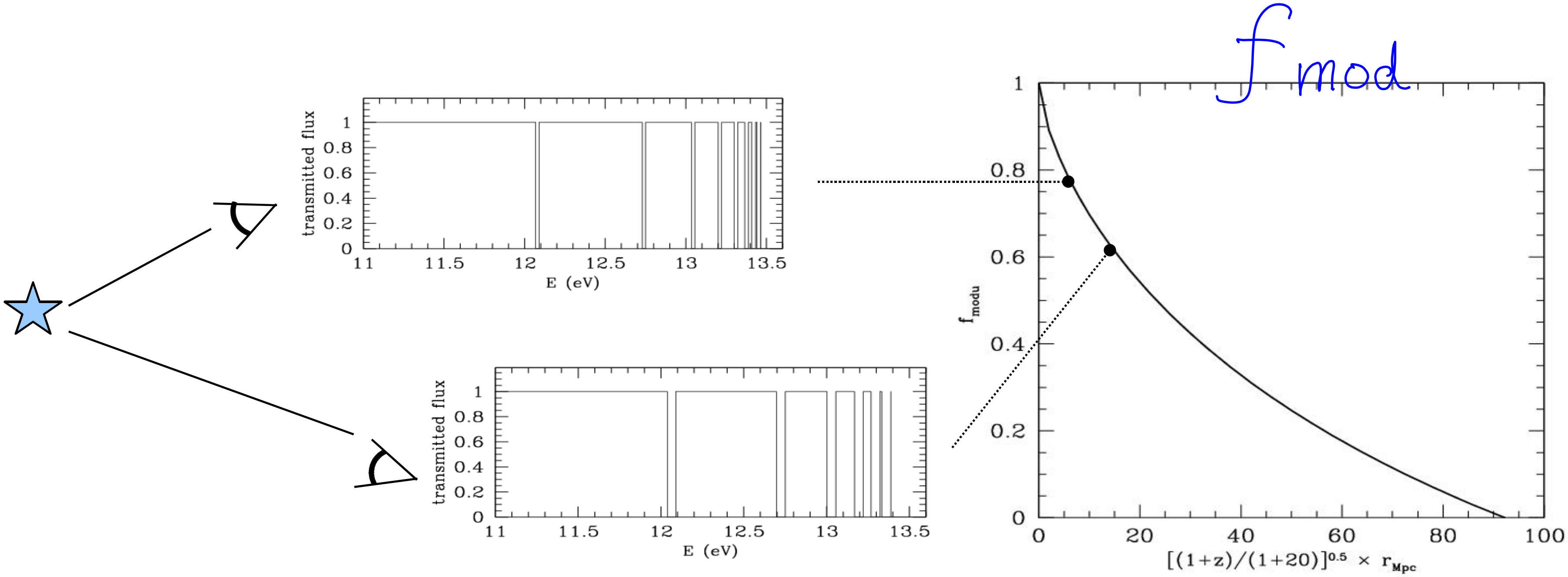
Attenuation of LW band photons by HI Lyman Series

- LW band photons attenuated by HI Lyman resonance lines
- Assume infinite opacity for every HI Lyman resonance line
- Sawtooth-modulation (Haiman, Abel, Rees 2000)
  - Based upon **uniformly distributed sources: no fluctuation**
  - Different horizon for different Lyman resonance lines



Picket-Fence Modulation

- Sources distributed inhomogeneously: Need to sum individual contribution
- One single source is observed as a picket-fence in spectrum
- Obtain “picket-fence modulation” factor
  - Relative flux averaged over E=[11.5 – 13.6] eV
  - Can effectively follow attenuation by multi-frequency phenomenon by pre-calculated modulation factor -> Huge alleviation computationally.



Picket-Fence Modulation

- Optically thin (ot) limit: Geometrical dilution only

$$F_{\nu,\,\mathrm{ot}}(\nu_{\mathrm{obs}}) = \frac{L_\nu\left(\frac{[1+z_{\mathrm{s}}]}{[1+z_{\mathrm{obs}}]}\nu_{\mathrm{obs}}\right)}{4\pi\left(\frac{r_{\mathrm{os}}}{1+z_{\mathrm{obs}}}\right)^2} \cdot \left(\frac{1+z_{\mathrm{obs}}}{1+z_{\mathrm{s}}}\right)$$

- Real situation: Geometrical dilution + Attenuation by H Lyman series

$$\langle F_\nu \rangle = \frac{\langle L_\nu \rangle}{4\pi\left(\frac{r_{\mathrm{os}}}{1+z_{\mathrm{obs}}}\right)^2} \cdot \left(\frac{1+z_{\mathrm{obs}}}{1+z_{\mathrm{s}}}\right) \cdot f_{\mathrm{mod}}\cdot$$

Procedure

- Use the N-body halo catalogue in 50 Mpc box
- Mimic larger volume by attaching the same box periodically (caveat)
- Sum fluxes from individual sources, multiplying by picket-fence modulation factor
- When finding sources, follow the past light cone
- Use "Self-Regulated Reionization" simulation (Iliev et al. 2007): Sources categorized by (1) Jeans-mass filtering, and (2) atomic-cooling.
  - Large-mass halos ($M >\sim 10^9 M_\odot$): Stars form even if photoionized. Stars do NOT only under $J_{21}>>1$. Possibly Pop II.
  - Intermediate-mass halos ($10^8 \sim< M/M_\odot <\sim 10^9$): Stars do NOT form if photoionized or under $J_{21}>\sim 1$. Possibly Pop III.
  - Mini-halos ($M <\sim 10^8 M_\odot$): Stars do NOT form even if photoionized or under $J_{21} > (J_{21})_{\mathrm{threshold}} \sim 10^{-2}\text{-}10^{-1}$ ← NOT resolved yet...

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↑ unfiltered

↓ JM filtered

- Large-mass halos ($M >\sim 10^9\ M_\odot$): Stars form even if photoionized. Stars do NOT only under $J_{21} >> 1$. Possibly Pop II.

↑ atomic-cooling

↓ molecular cooling

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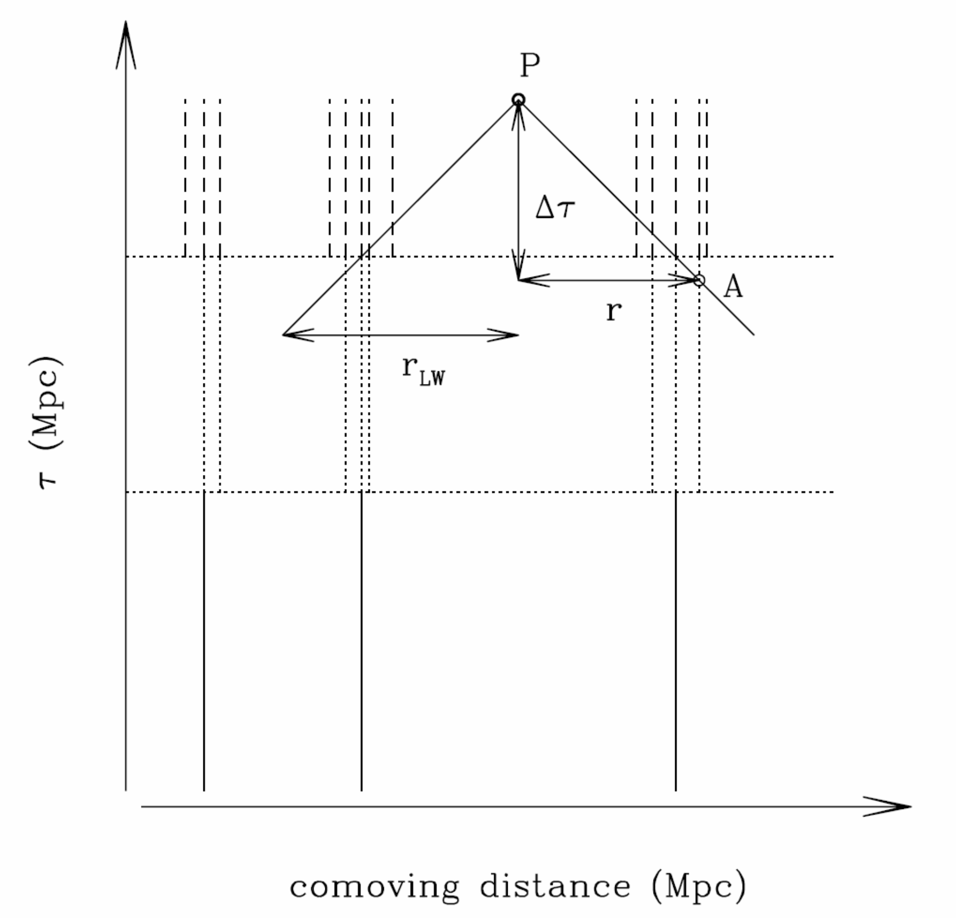
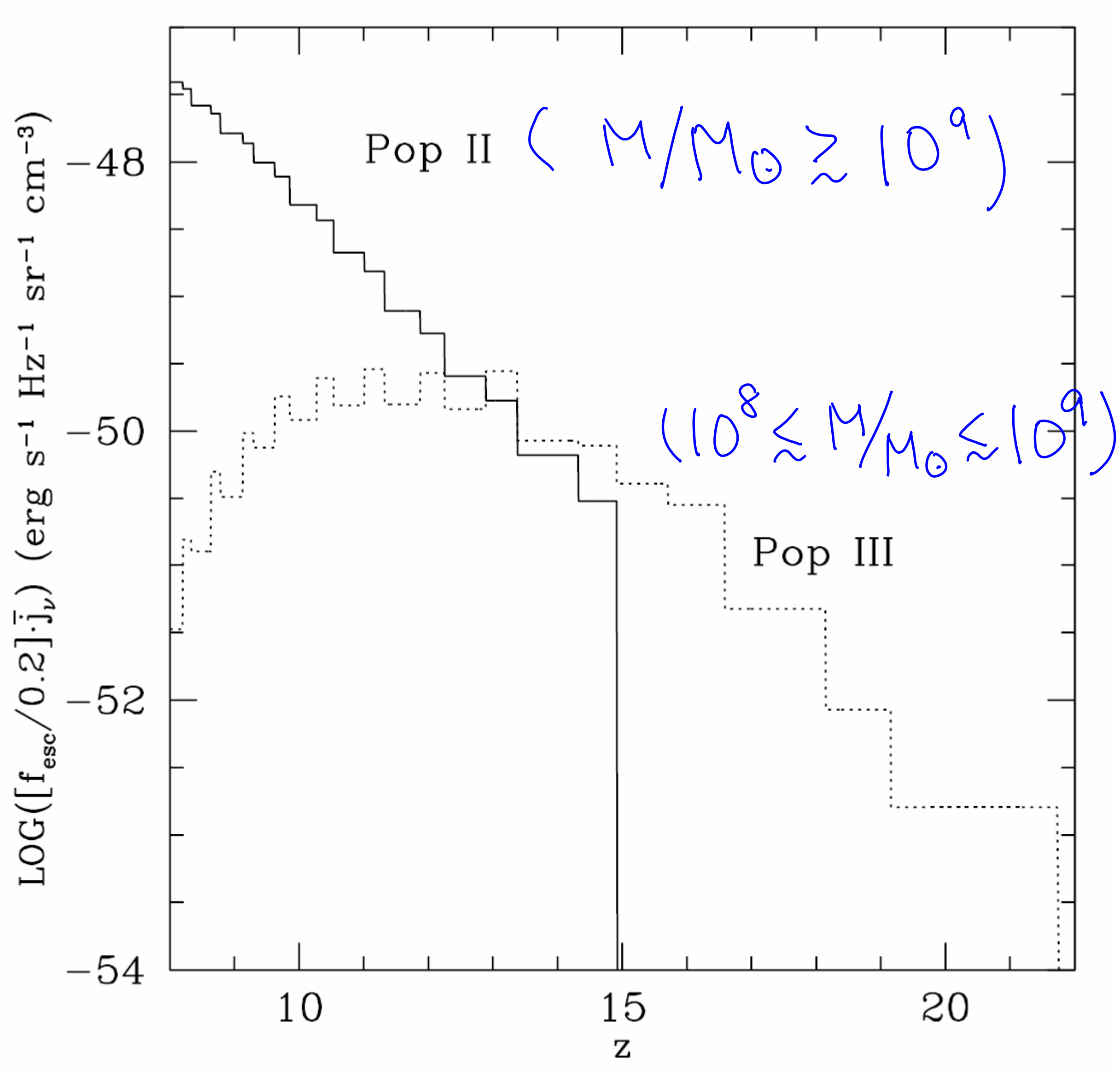
Retarded time emissivity

- Sources form in hierarchy.
- Horizon for LW background is large (~100 comoving Mpc)
- Construct spacetime diagram and draw past line cone at a given space-time to account for LW



Emission Coefficient of Pop II and Pop III sources

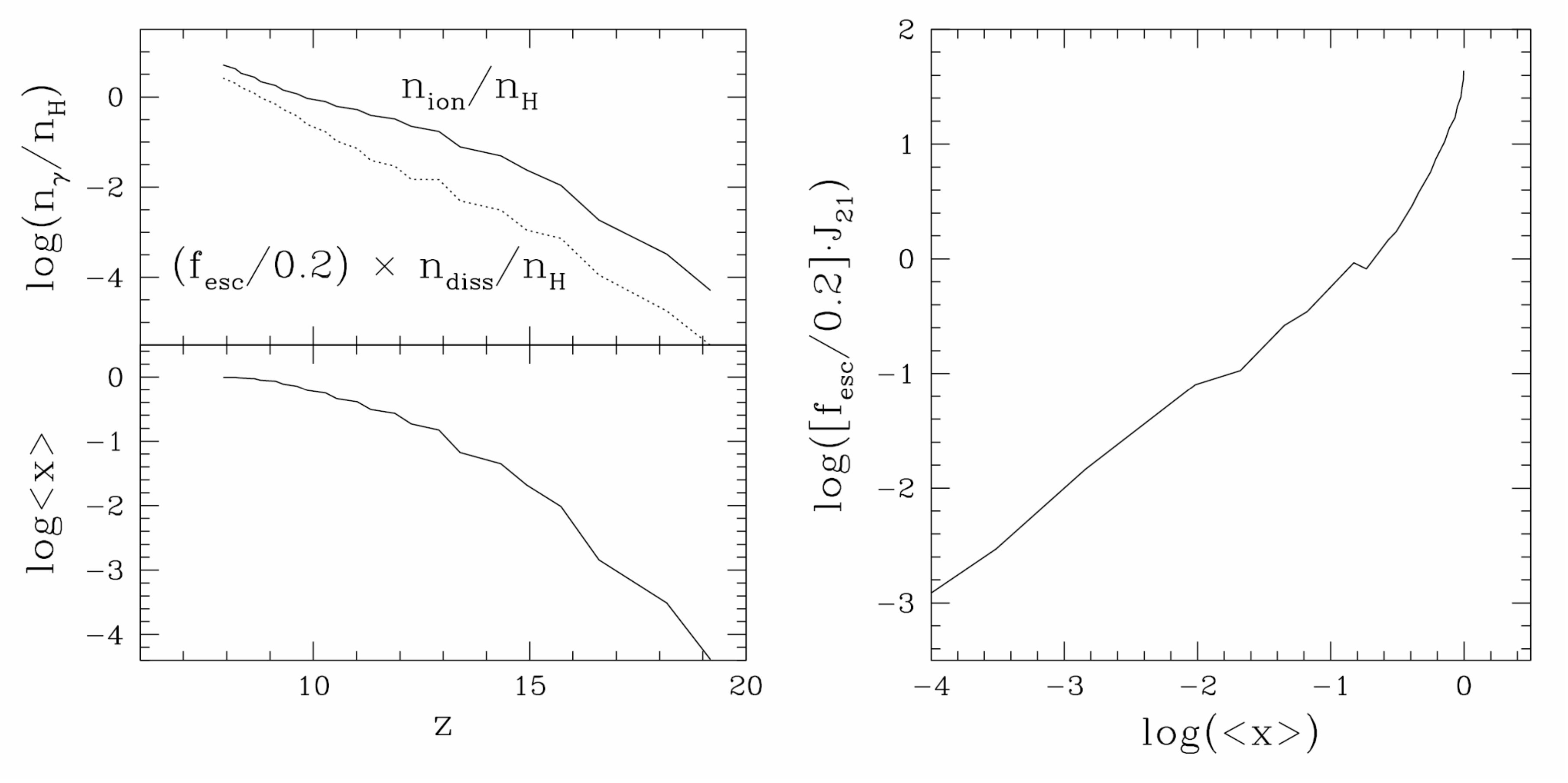


$(M/M_\odot \gtrsim 10^9)$

$(10^8 \lesssim M/M_\odot \lesssim 10^9)$

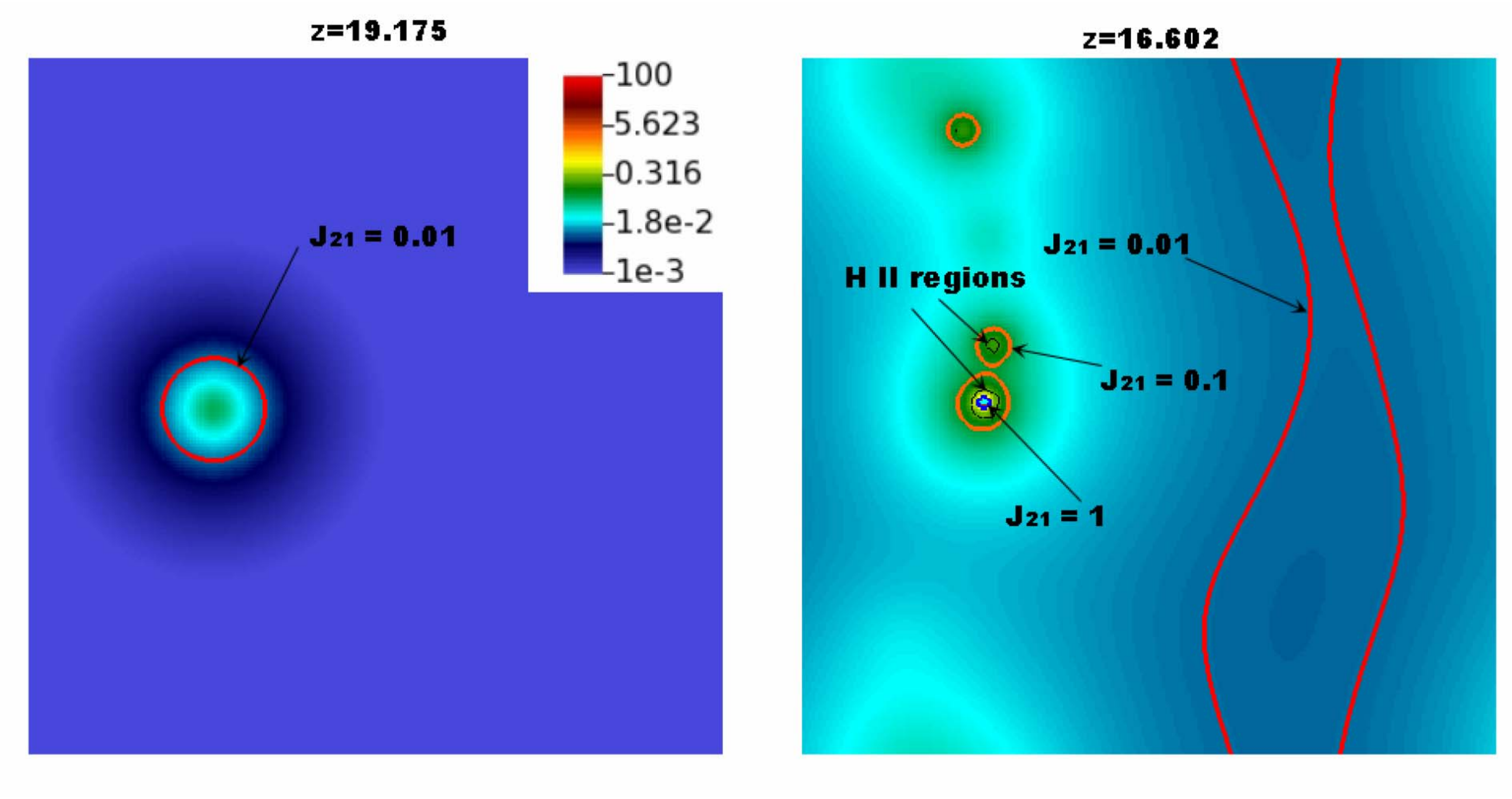
Dissociating background: Global evolution

- $(J_{21})_{\text{threshold}}$ reached long before reionization finished
- Minihalo sources do not contribute significantly to reionization



Dissociating background: Fluctuation in evolution

- Huge fluctuation exists
- Inside-out evolution of J_{21}



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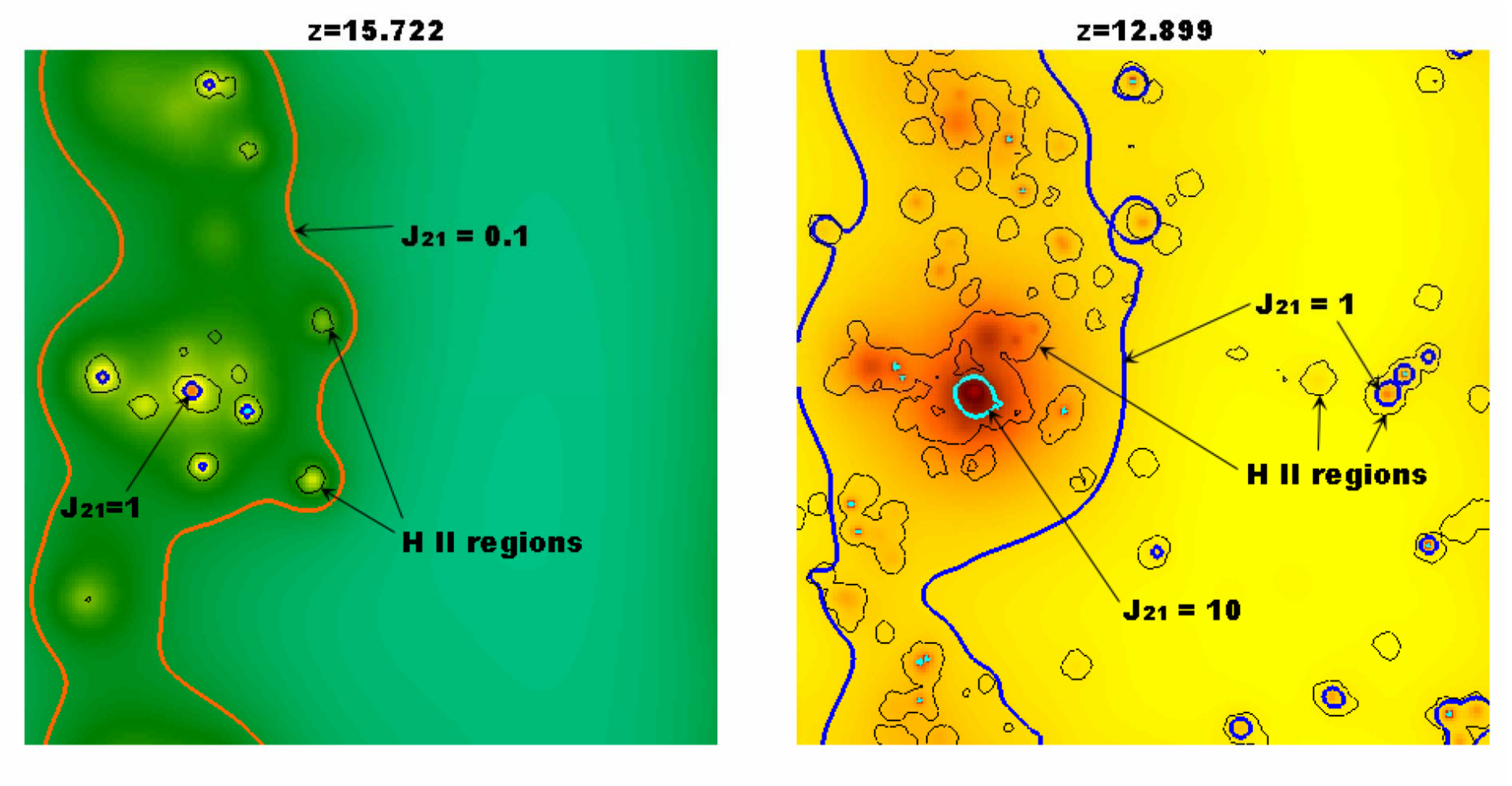

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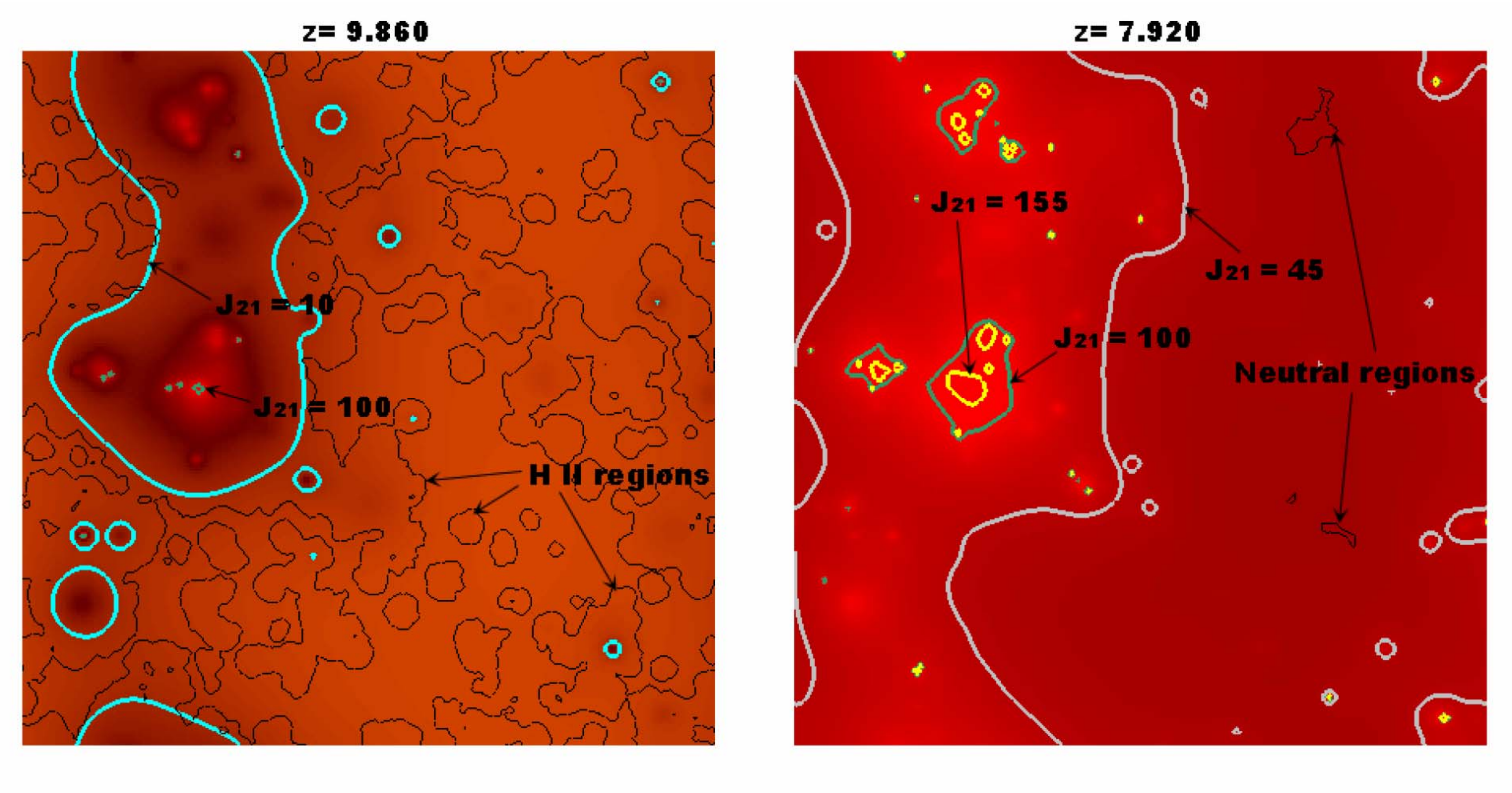


Dissociating background: Fluctuation in evolution

- Huge fluctuation exists
- Fluctuation decreases in time

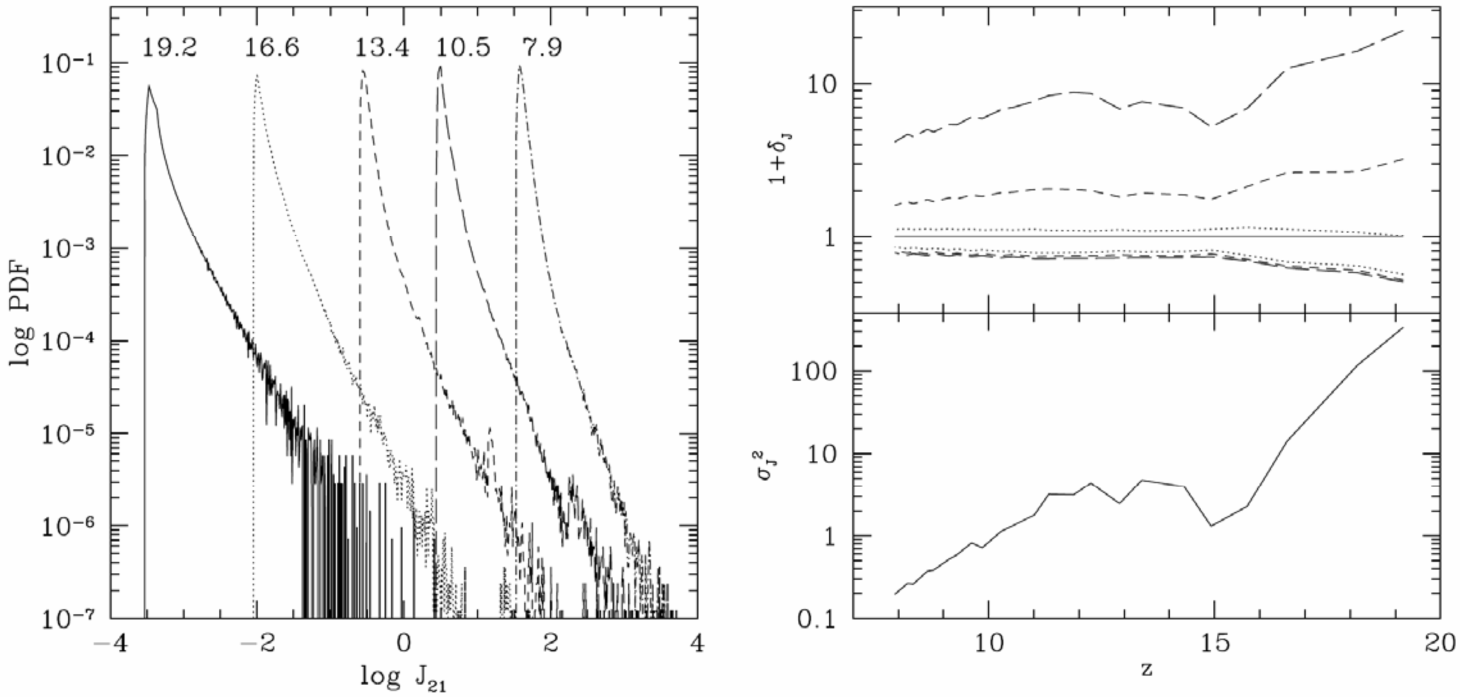
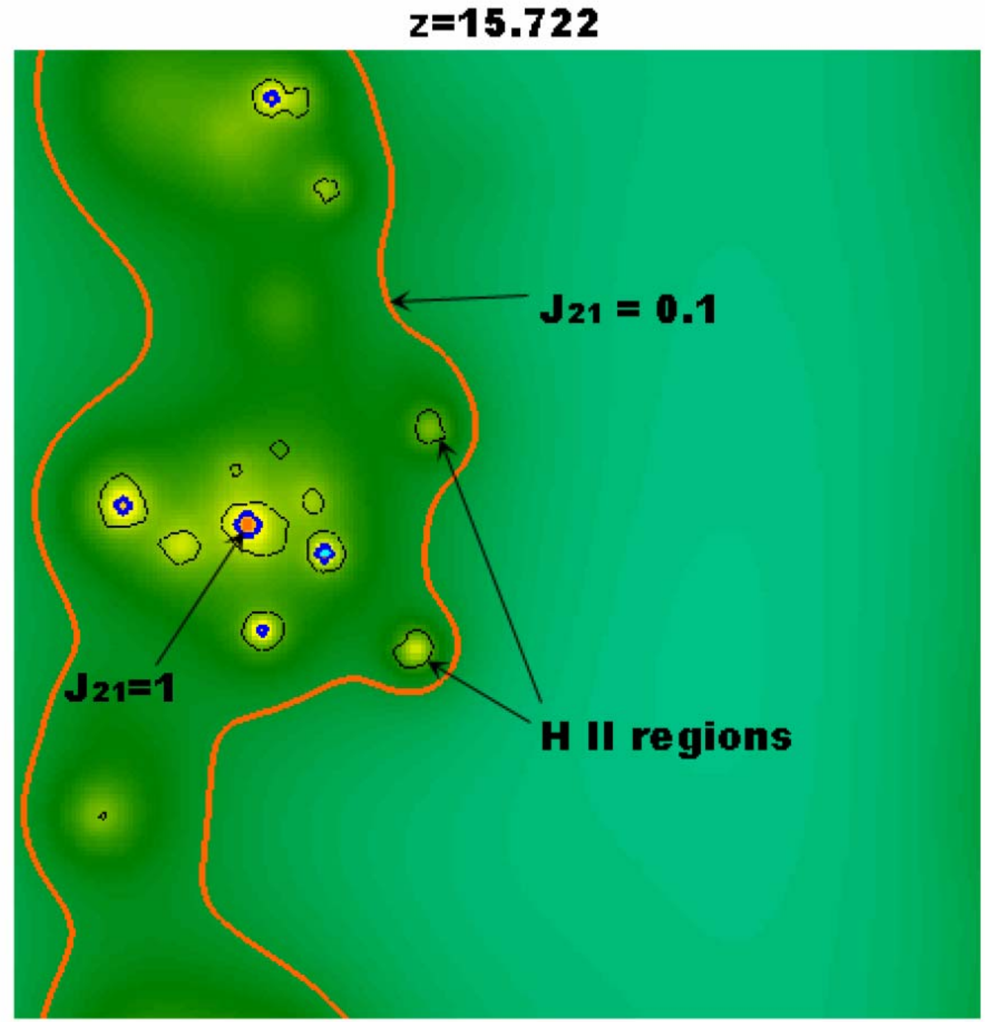


Fig. 11.— (*left*) Probability distribution of $J_{\mathrm{LW},21}$ inside a box of comoving size 35 h^{-1} Mpc at different redshifts. Numbers on individual curves represent corresponding redshifts. (*right*) The top panel shows deviation of $J_{\mathrm{LW},21}$ from the average $\langle J_{\mathrm{LW},21}\rangle$, expressed in terms of $1+\delta_J$. Around $\langle J_{\mathrm{LW},21}\rangle$ (solid), 68.27% (dotted), 95.45% (short dashed), and 99.73% (long dashed) of $J_{\mathrm{LW},21}$ populations are shown. Variance of $J_{\mathrm{LW},21}$, σ_J^2, is plotted in the bottom panel.

Where to look at for most pristine Pop III star forming regions?

- Inhomogeneous Radiative Feedback!!
    - Highly clustered ionizing sources
- Degeneracy broken for different source properties
    - escape fraction of ionizing radiation
    - dissociating/ionizing photon # ratio
- Contribution to NIR background fluctuation by Pop III objects -> Need to understand inhomogeneous feedback.



Conclusion

- Picket-fence modulation of LW background photons
    - Ease of LW background calculaiton
- Fluctuation in LW background comes from source clustering, at a scale of ~10 comoving Mpc
- Inhomogeneous feedback + Inhomogeneous structure formation = Inhomogeneous Pop III source formation
- Minihalo sources, globally, are suppressed long before reionization is complete
- Slight chance that reionization history be affected, if molecules are dissociated under very strong UV even inside atomic cooling halos: only near the end of reionization.
- Stay tuned
    - Radiative feedback coupled, bigger box, cosmic reionization simulation !!
    - Cosmic reionization simulation with minihalo prescription: Statistics of Pop III objects
    - Observables from the epoch of reionization