# Cosmological Reionization by the First Stars under the Hydrogen-Molecule Dissociating Background

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We present the first results of a large-scale simulation of cosmic reionization which includes the combined feedback effects from ionization of hydrogen atoms and dissociation of hydrogen molecules by sources in full dynamic range, from minihalos to atomic-cooling halos. The inhomogeneous growth of ionizing and dissociating UV backgrounds is calculated self-consistently. Our results imply that cosmic reionization is commenced by the first stars, followed by an era of self-regulation of first star formation, and finally finished by sources in atomically cooling halos.

• Pop III Star Formation: ***local*** and ***cosmological*** problem at the same time!

– $H_2$ : crucial coolant for Pop III star formation in primordial environment

– Easily dissociated by UV photons in range 11 - 13.6 eV (LW bands)

– $H_2$ dissociating photons travel cosmological distances (~100 cMpc)

– Pop III star formation is thus affected by sources at cosmological distances, and source clustering means inhomogeneous background.

– Need to calculate the rise of the ***inhomogeneous*** LW background.

• Inhomogeneous $H_2$ Dissociating Background during the EOR (Ahn, Shapiro, Iliev, Mellema, Pen 2009, ApJ, 695, 1430)

– Computational Challenge: Need to calculate multi-frequency radiative transfer in cosmological volume, computationally VERY expensive.

– Adopted a pre-computed gray opacity → Reduces to a single-frequency radiative transfer

– Picket-fence modulation factor for inhomogeneous universe (Fig. 2)

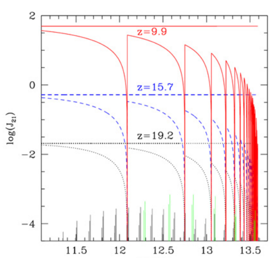


Fig 1. **Homogeneous Universe.** Illustrative spectrum of the UV background at redshifts z=19.2, 15.7 and 9.9 in the cosmological model with high-efficiency emitters (Ahn et al. 2009: ApJ, 695, 1430). Horizontal lines are unattenuated flat spectra, while saw-tooth shaped curves are spectra after attenuation by Lyman resonance lines. For reference, at the bottom of the figure the location of the LW lines of $H_2$ is shown. The length of each line indicates its relative contribution to dissociations of $H_2$.

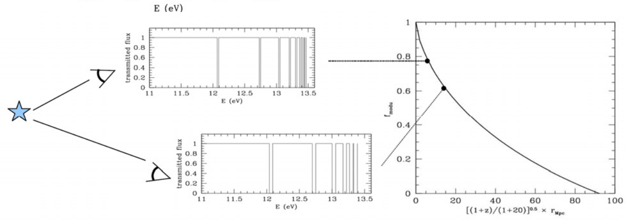


Fig 2. **"Picket-fence" modulation**: attenuation of LW photons from a single source. As a Lyman continuum photon travels, when its frequency redshifts to an H resonance line, it is absorbed, resonantly scatters, reabsorbed, until all resonant photons turn into low frequency photons below LW bands. For *homogeneous* universe, this gives "saw-tooth" modulation of the spectrum. But in *inhomogeneous* universe, each source is attenuated by its own "picket-fence" modulation factor ($f_{mod}$) , which is a function of $r_{Mpc}$ (comoving distance from source to observer).

– LW Background by sources inside atomically-cooling halos ($M$>~$10^8 M_\odot$), in units of $J_{21}$ (=$10^{-21}$ erg /cm² /s /Hz /sr).

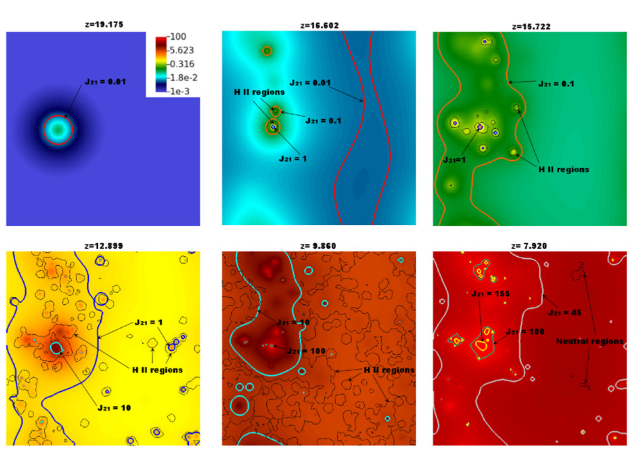


Fig 3. LW Background ONLY by sources inside atomically cooling halos ($M$>~$10^8 M_\odot$) at different redshifts. Expressed in terms of J21 (=$10^{-21}$ erg /cm2 /s /Hz /sr). The size of simulation box is 35/h Mpc, for this simulation of self-regulated reionization.

• Large-Scale Cosmological Simulation of Reionization

– Virtues of Reionization Simulation (N-body + Radiative Transfer)

• Simulates inhomogeneous history of reionization at large scales

• Generates mock data for observables, e.g. high-redshift 21cm observation.

– Limitations of Reionization Simulation (so far)

• Big simulation box (> ~100 Mpc) needed for correct statistics

• Numerical resolution → ONLY atomically-cooling halos resolved; minihalos not resolved in big simulation box and so neglected

• Justification: Easy $H_2$ dissociation → Self-regulation of Pop III star formation → Reionization dominated by sources inside atomically cooling halos

• Self-Consistent Simulation of Cosmic Reionization with First Stars → Minihalo Sources Included

– Earliest reionization governed by first stars inside minihalos anyway

– Requirements: (1) Populate minihalos inside simulation box, (2) Calculate LW background, (3) Suppress Pop III sources where minihalos form inside H II regions or where LW background is too high

– (1) Populating minihalos inside big simulation box

• Simulate small-box (a few Mpc) structure-formation first, to resolve minihalos

• Obtain the empirical bias factor → correlation between mesh cell density ~ minihalo population (Fig 4)

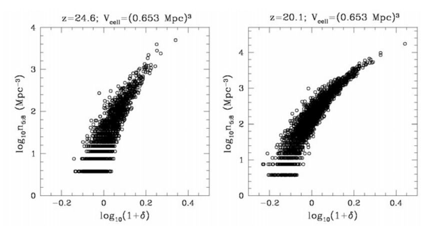


Fig 4. **Biased minihalo formation**. Number of minihalos ($n_{5:8}$) is strongly correlated with cell density (1+δ). Data points compiled from high-res 6.3 Mpc box, averaged over 0.653 Mpc cells. This empirical relation is used to populate minihalos in each radiative transfer cell in much bigger box (114/h Mpc) of reionization simulation.

– (2) & (3) Calculating LW background and suppressing Pop III formation inside minihalos

• Calculate LW background contributed by all minihalos (subgrid) and atomic cooling halos (all the individually identified halos in big-box N-body results)

• Apply suppression criterion → Impose $J_{21,\,crit}$: If $J_{21}$(cell) > $J_{21,\,crit}$ or cell is ionized or both, Pop III formation inside minihalos there is suppressed.

– Perform ionization calculation with (1), (2), (3) simultaneously.

• First Results: Early Phase of Reionization at High z (z>~20)

– H II bubble distribution: rich, small-scale bubbles; many regions partially ionized below simulation resolution → also indicating existence of very small-scale H II bubbles; small-scale clustering observed. (Fig 5)

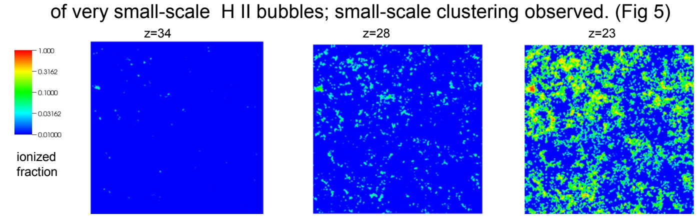


Fig 6. **Patchy reionization at high redshift, dominated by first stars**. Big-box simulation with size 114/h Mpc, accounting for both minihalos and atomic-cooling halos and self-consistently calculating LW background and its feedback effect.

– With $J_{21,\,crit}$~0.1, global ionized fraction <x> ~ 1 – a few % achieved by Pop III stars. We expect <x> to rise again as atomically cooling halos emerge and dominate (z<~16).

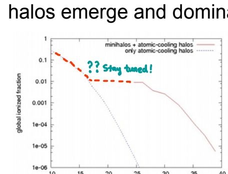


Fig 5. **Patchy reionization at high redshift, dominated by first stars**. Big-box simulation with size 114/h Mpc, accounting for both minihalos and atomic-cooling halos and self-consistently calculating LW background and its feedback effect. Minihalos self-regulate long before reionization is complete →atomic cooling halos have to finish the job → simulation still running →stay tuned!

• Different $J_{21,\,crit}$, different star formation being tested; Observable properties (e.g. high-z 21cm signal) being re-calculated. Stay tuned!!