The Inhomogeneous Rise of Metallicity During the Epoch of Reionization in the CoDa III Simulation

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Background
& Previous Works

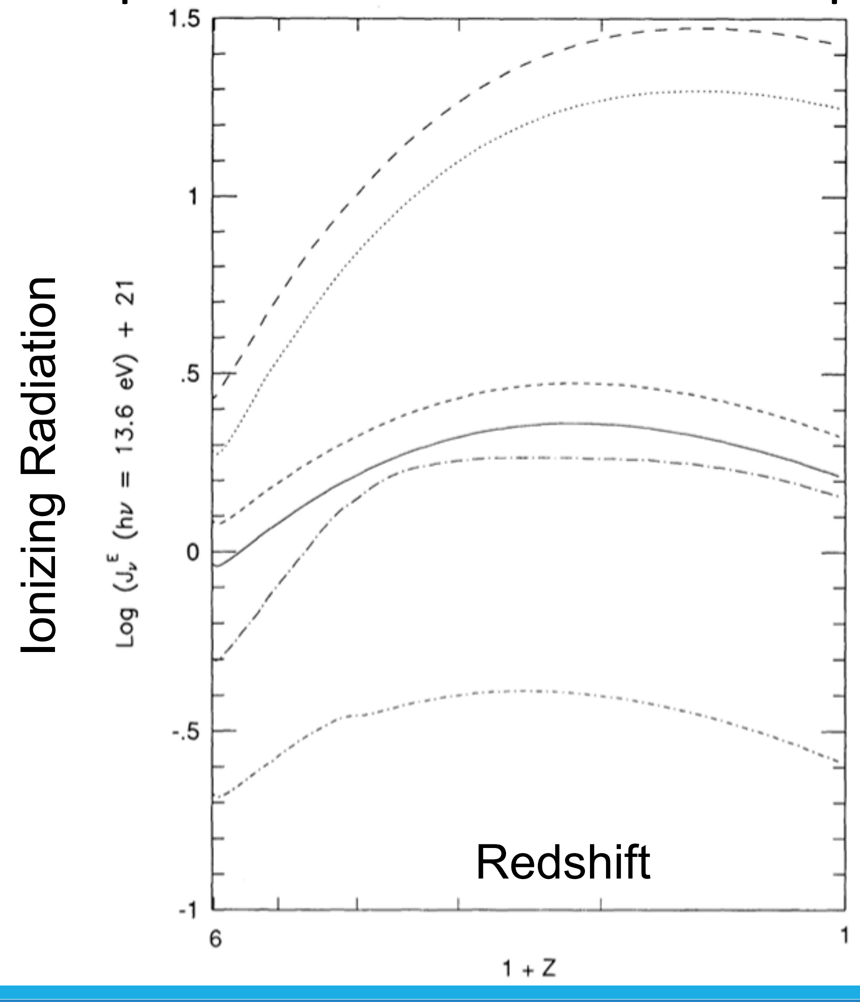
Massive Stars: Sources of Ionizing Photons & Metals

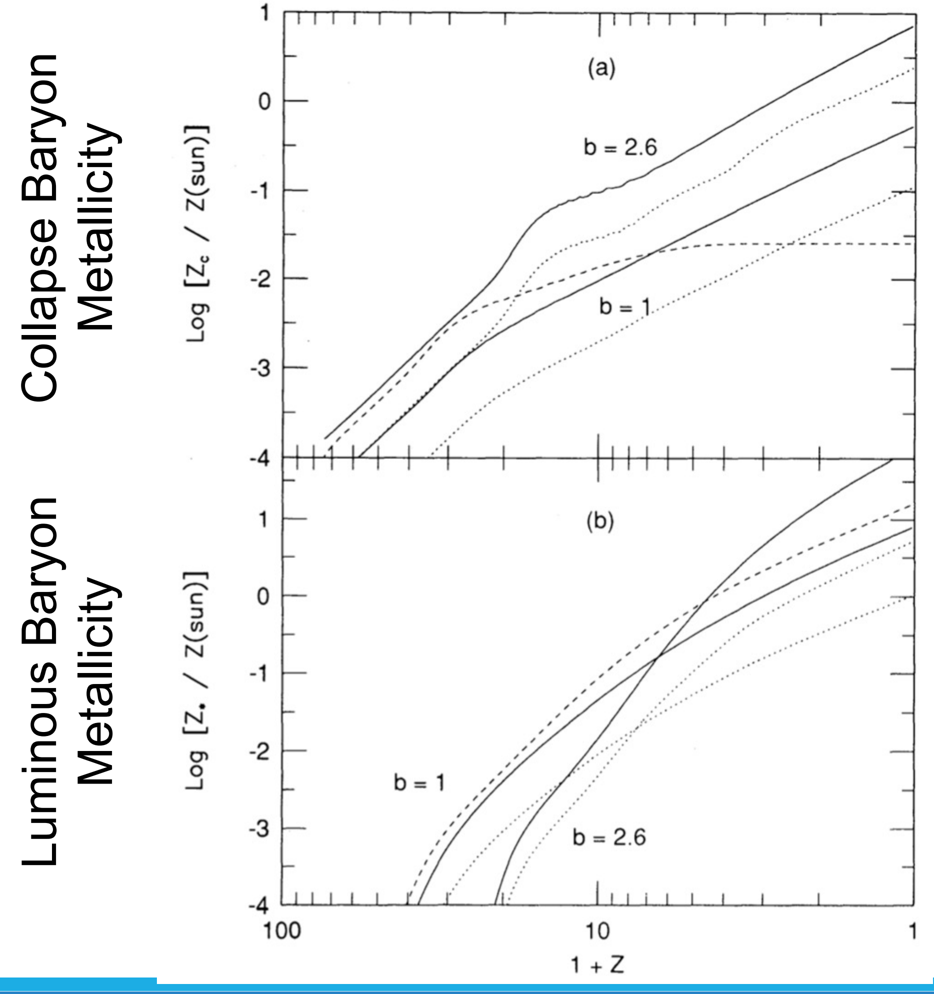
- ***Reionization and metal enrichment are directly correlated!***
- ***The same massive stars*** that released the ionizing photons also released the metals that enriched the universe when they exploded as SNe
(Shapiro, Giroux & Babul 1994, Giroux & Shapiro 1996)

$$\rightarrow \dot{n}_\gamma \propto \dot{\rho}_Z$$

Direct Correspondence Between Reionization and Metal Enrichment

- Shapiro, Giroux & Babul (1994) and Giroux & Shapiro (1996) pointed out one-to-one correspondence between cosmic production of ionizing radiation and metals





Shapiro, Giroux & Babul 1994

Same Massive Stars in IMF Release the H-Ionizing Photons and Metals

- **Metals ejected in SNe per ionizing photon released over stellar lifetimes**

For a Salpeter IMF, Shapiro and Giroux (1996) showed:

η **= metal mass (in $M_{\odot}$) ejected per H ionizing photon** $\sim 10^{-62}$

- **# of ionizing photons per H atom required to finish reionization ➔ corresponding metallicity**

If

$N_{\gamma,\mathrm{H}}$ = # of H-ionizing photons per H atom required to finish reionization,

Then a metallicity build-up was required to finish reionization, too, given by:

$$\left(Z/Z_{\odot}\right)_{\mathrm{reion}} = (\eta M_{\odot} N_{\gamma,\mathrm{H}})/(m_{\mathrm{H}} Z_{\odot})$$

And, if so,

$$Z_{\odot} \sim 0.01 + \text{ Salpeter IMF} \quad ➔ \quad \left(Z/Z_{\odot}\right)_{reion} \sim 10^{-5} \times N_{\gamma,H}$$

Reionization and Metal Enrichment in the CoDa III Simulation

Cosmic Dawn (CoDa) III Simulation

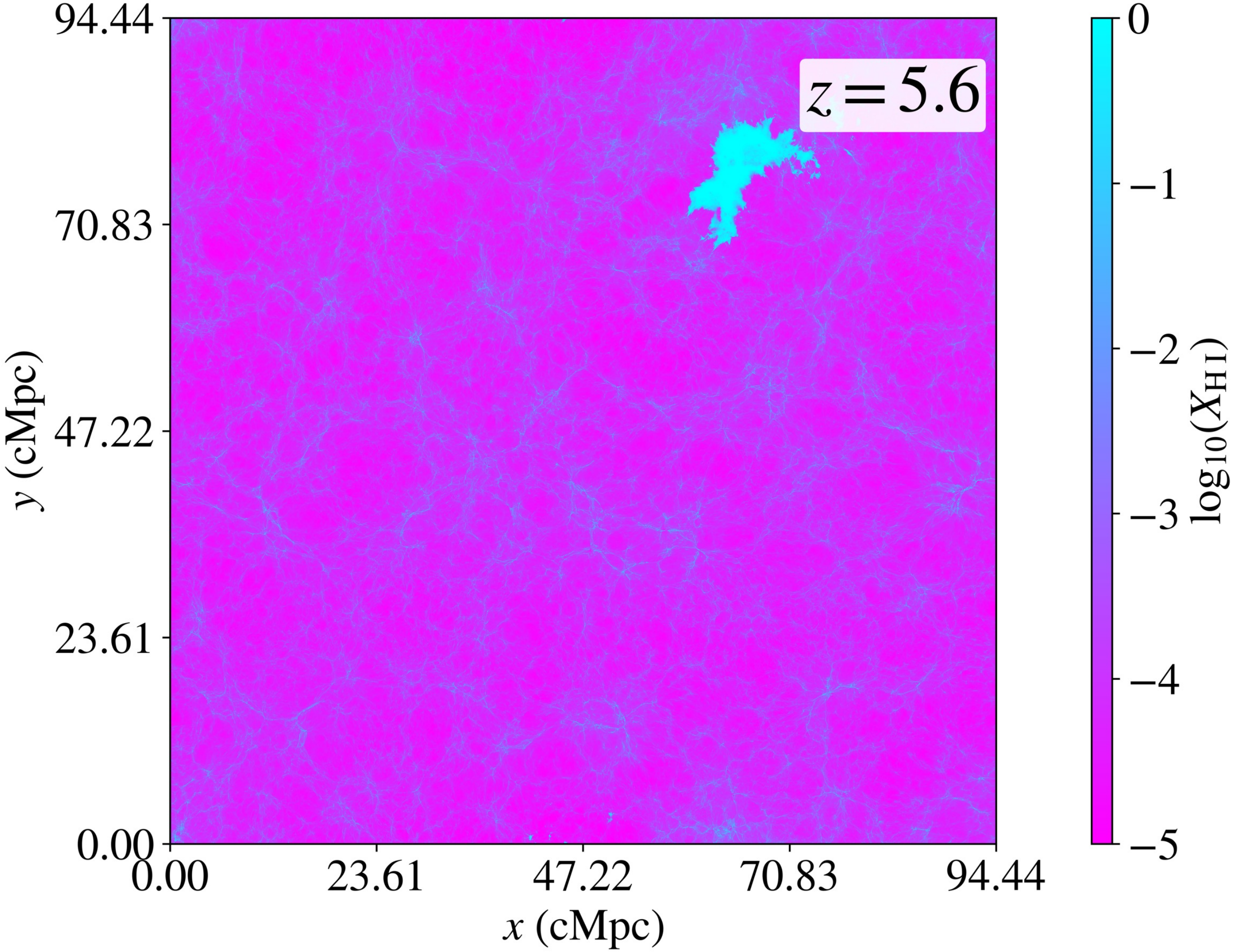
- 8192^3 particles and cells, uni-grid rad-hydro (RHD) simulation by RAMSES-CUDATON
  - ➔ First trillion-element computer simulation of fully-coupled galaxy formation and reionization
  - ➔ *Advantage*: High mass res + Eulerian retains length/mass resolution in CGM/IGM, unlike Lagrangian SPH and moving mesh codes, or zoom-in's (cf. AGORA VI CGM comparison paper; Strawn+ 2022)
- First CoDa simulation with self-consistent evolution of metals and dust, including dust opacity in radiative transfer
- Massive stars (20% of stars) eject 5% of their mass as metals by SN

The Cosmic Dawn ("CoDa") Project

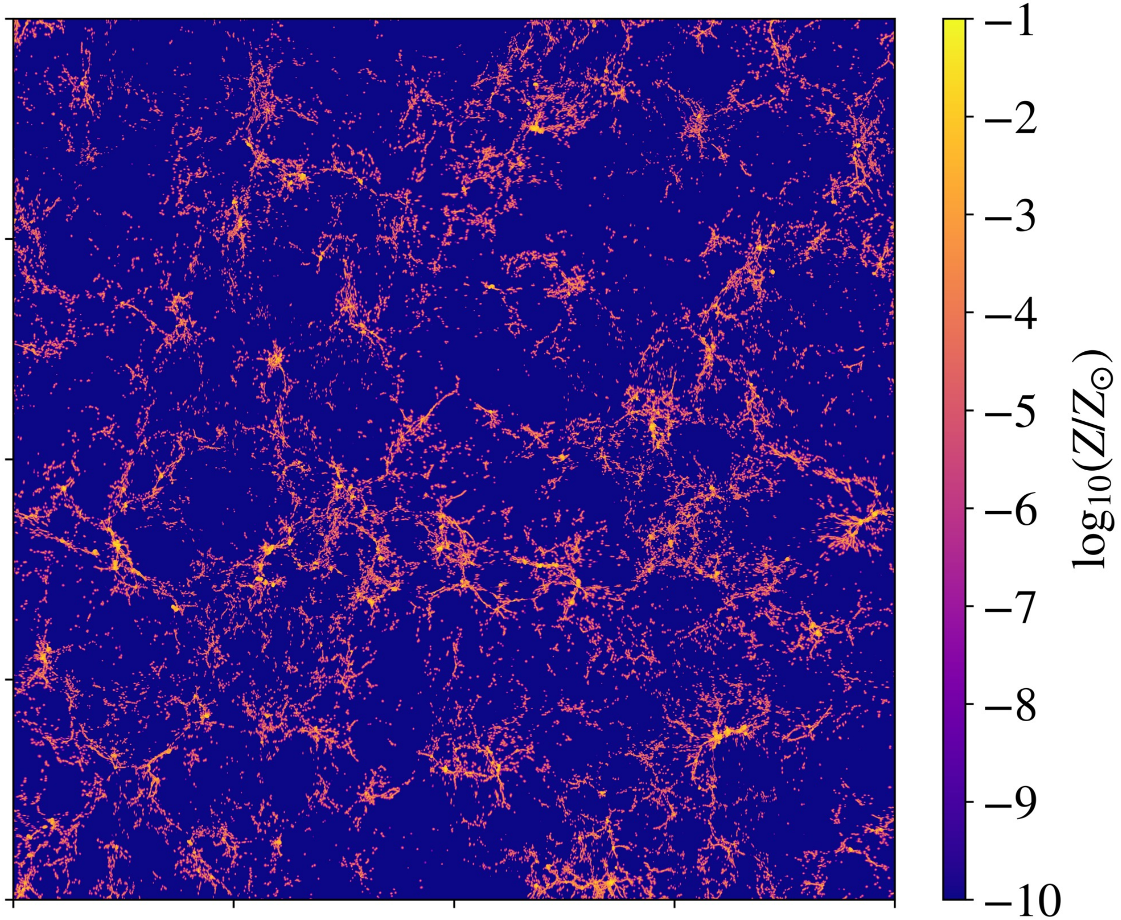
Lewis+2022

Reionization and Metal Enrichment in CoDa III

Ionized Fraction

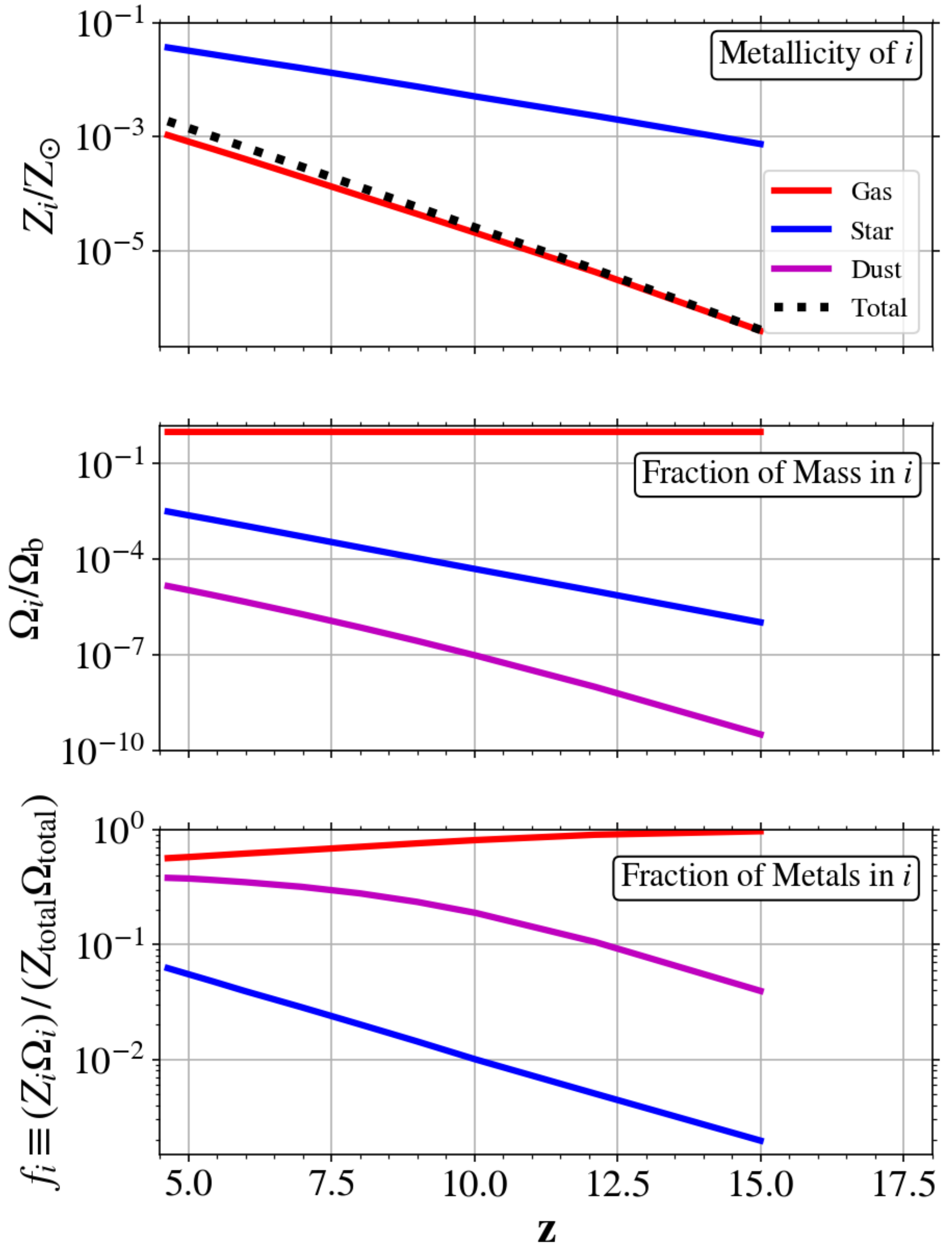


Metallicity



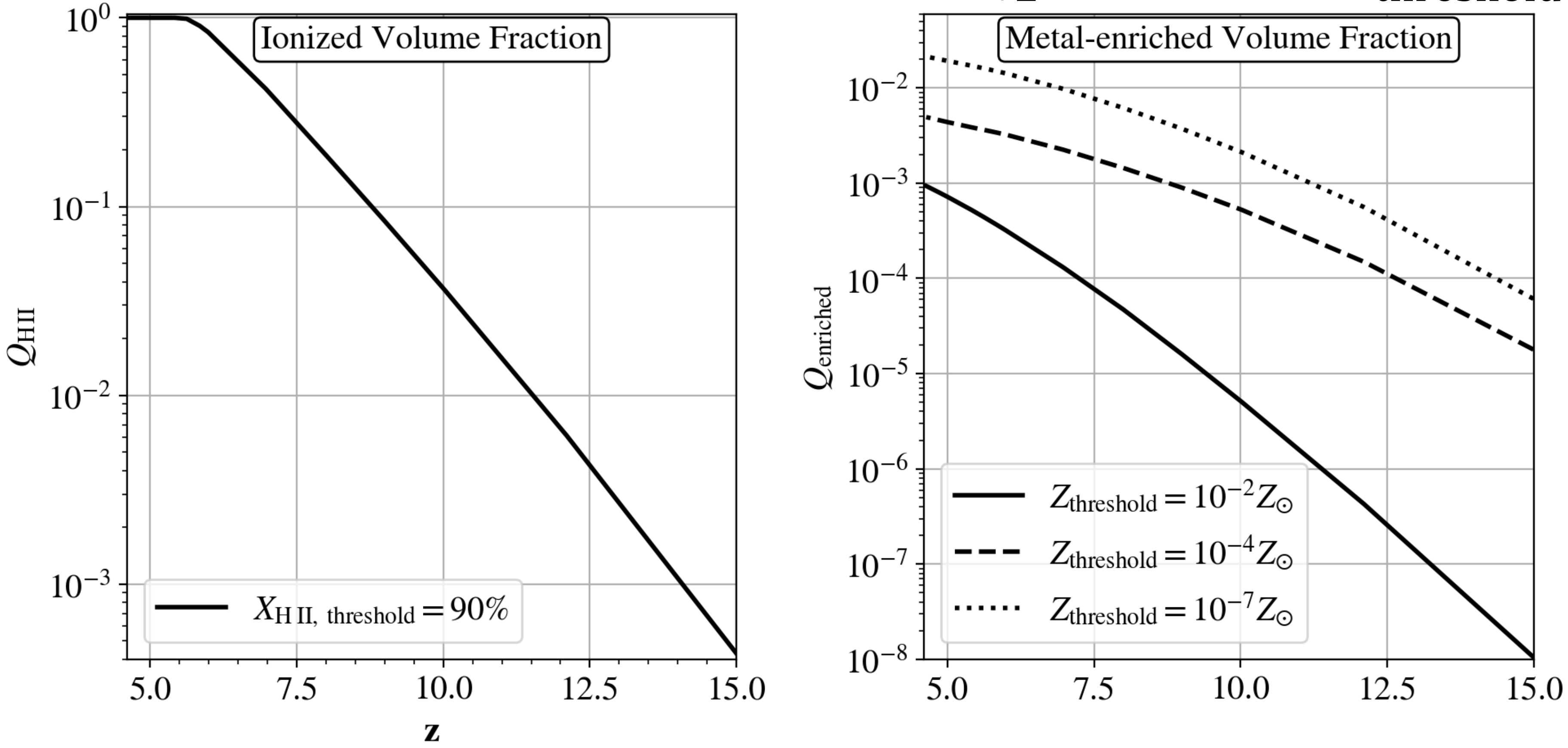
Global Metal Enrichment in CoDa III

- Indeed, $Z_{\rm baryon} / Z_{\odot} \sim 1{\times}10^{-3}$ when EoR ends at $z_{\rm re} = 5.53$ in CoDa III (@ $x_{\rm H\,II} = 99.99\%$)
- Simple model correlating *reionization* and *metal enrichment* (c.f. Shapiro, Giroux & Babul 94, Giroux & Shapiro 96) works well!
- Stellar metallicity is higher than gas-phase metallicity
- Most metals are in gas-phase during the EoR, while metals in dust gradually increase

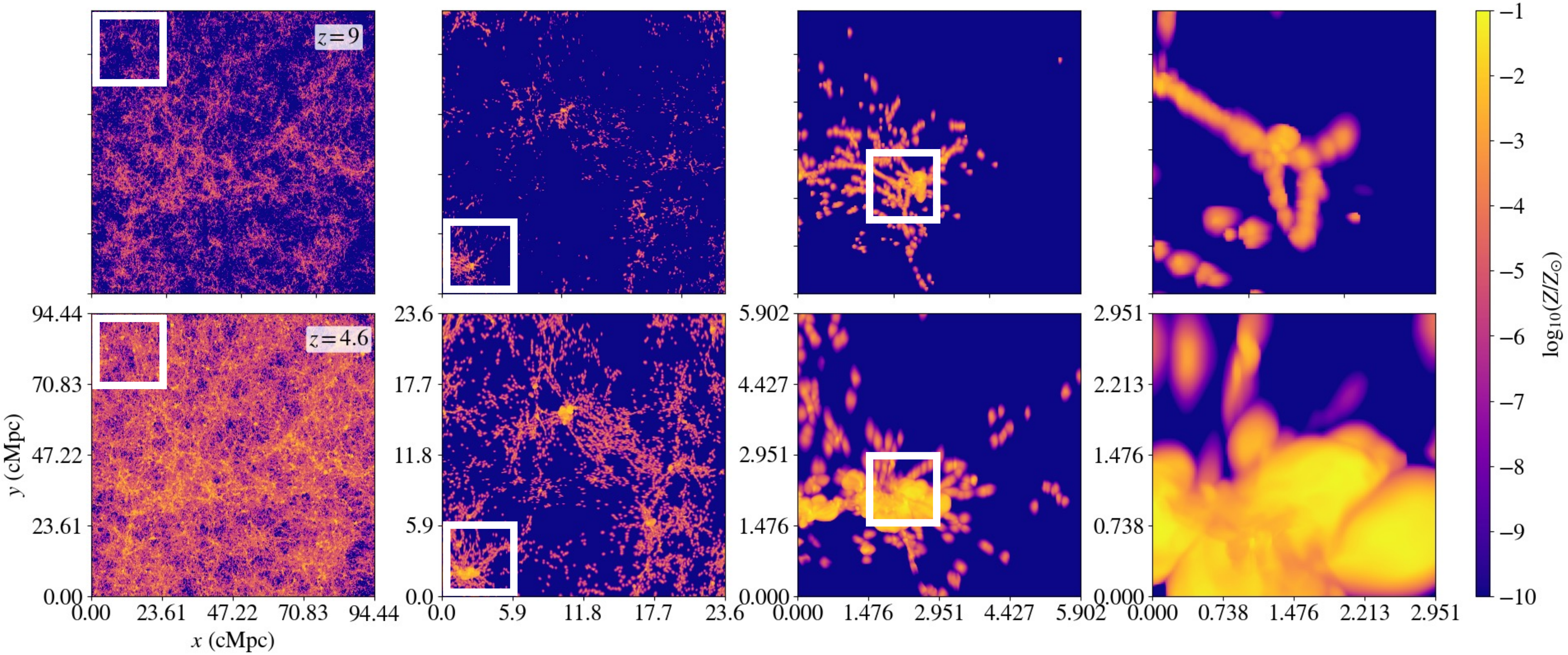


Global Reionization vs. Metal Enrichment

- Reionization ionization-fronts (I-fronts) travel farther, faster than metal enrichment ("Z-fronts"; i.e. SN-driven galactic winds) ➔ if Q = volume filling fractions, then $Q_{\mathrm{H\,II}} > Q_Z$
- When reionization ends, most of IGM still metal-free: $Q_Z < 2\ \%$ $(Z > Z_{\mathrm{threshold}} = 10^{-7} Z_{\odot})$

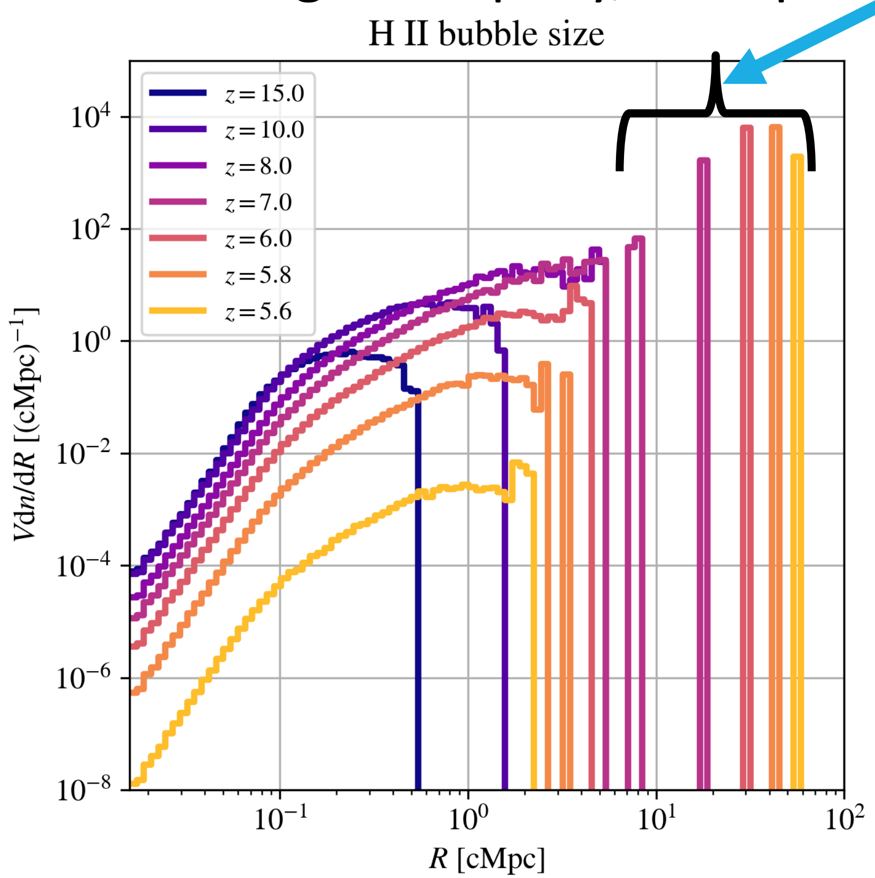


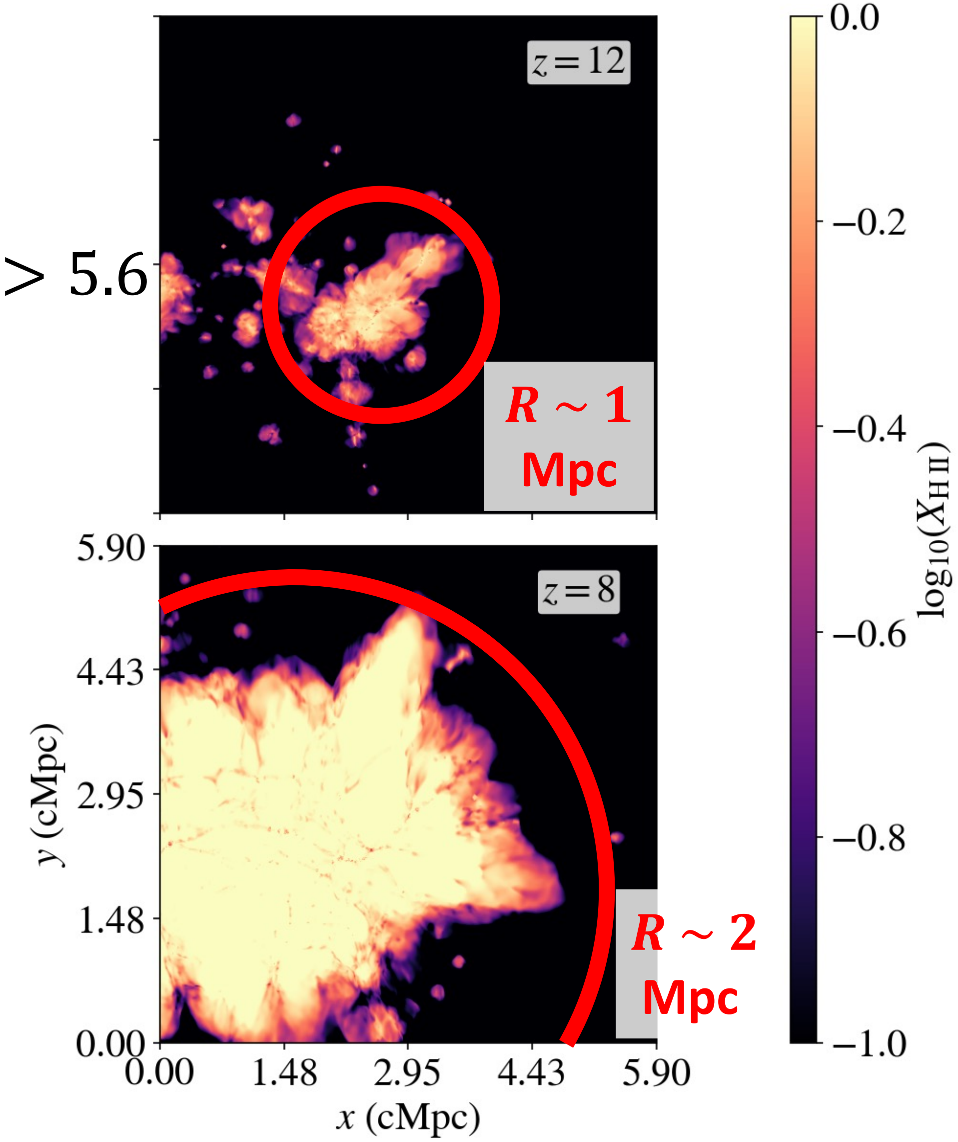
Inhomogeneous! **Metal Enrichment in CoDa III**



Growth of Ionized Bubbles—Friends-of-Friends (FoF)

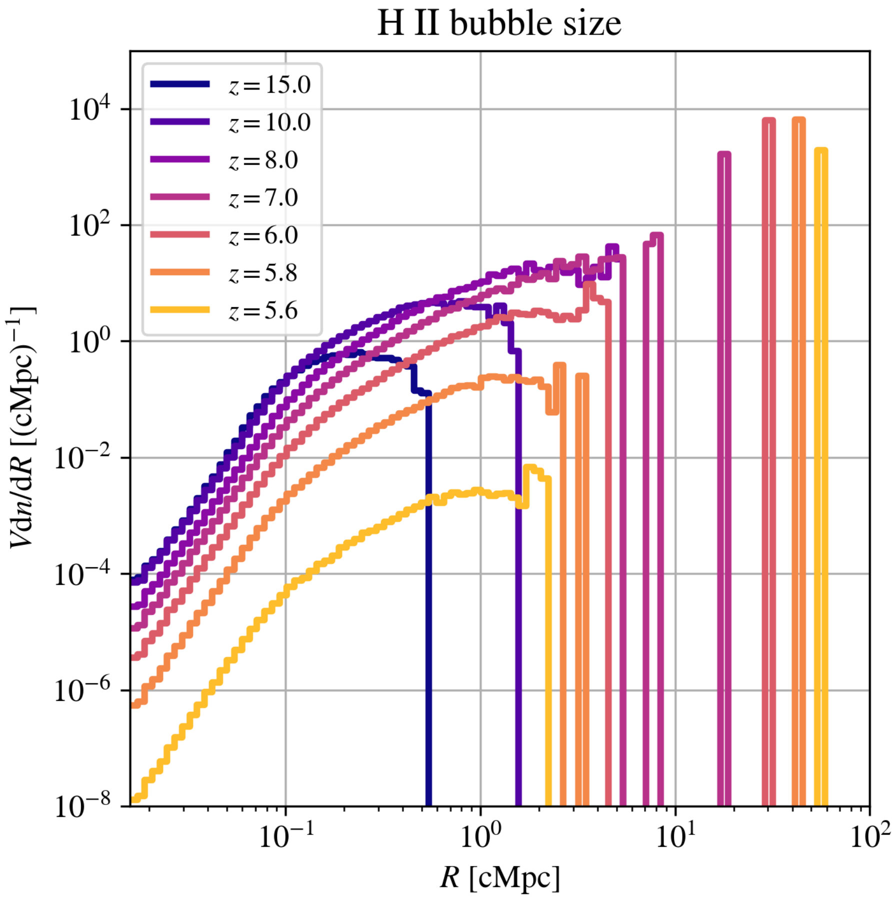
- Friends-of-Friends algorithm (FoF; Iliev+ 2006) used to detect ionized bubbles and their size distribution
- Size and number grow rapidly, until percolation at $7 > z > 5.6$

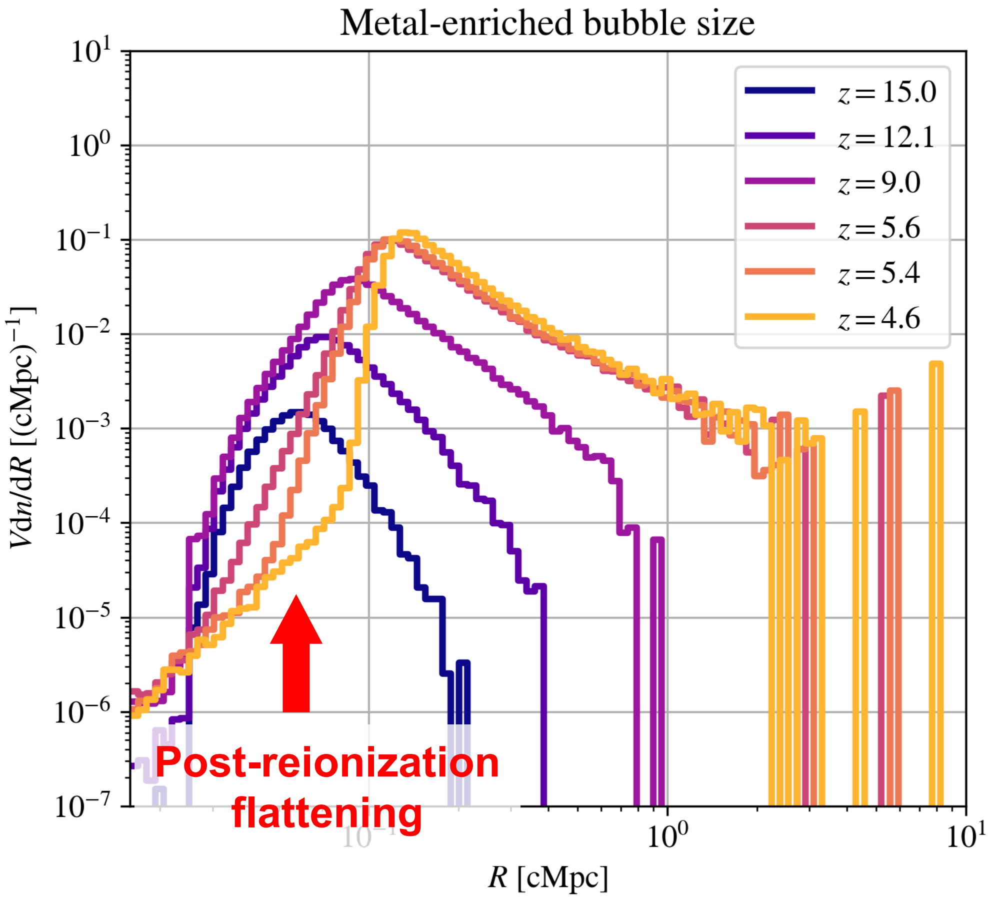




Growth of Metal Enriched Bubbles—FoF

- Metal enriched bubbles
  - 1. grow much more slowly than ionized H bubbles   2. have less percolated bubbles
  - 3. show post-reionization flattening in slope on small radius end

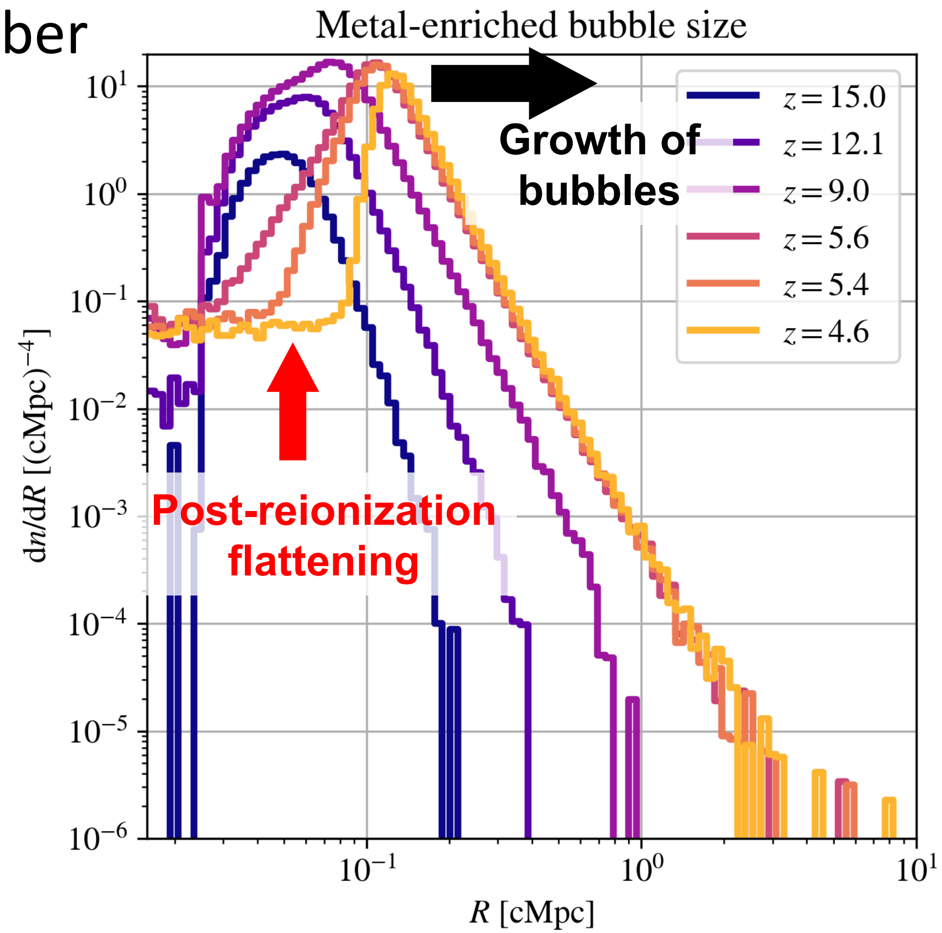


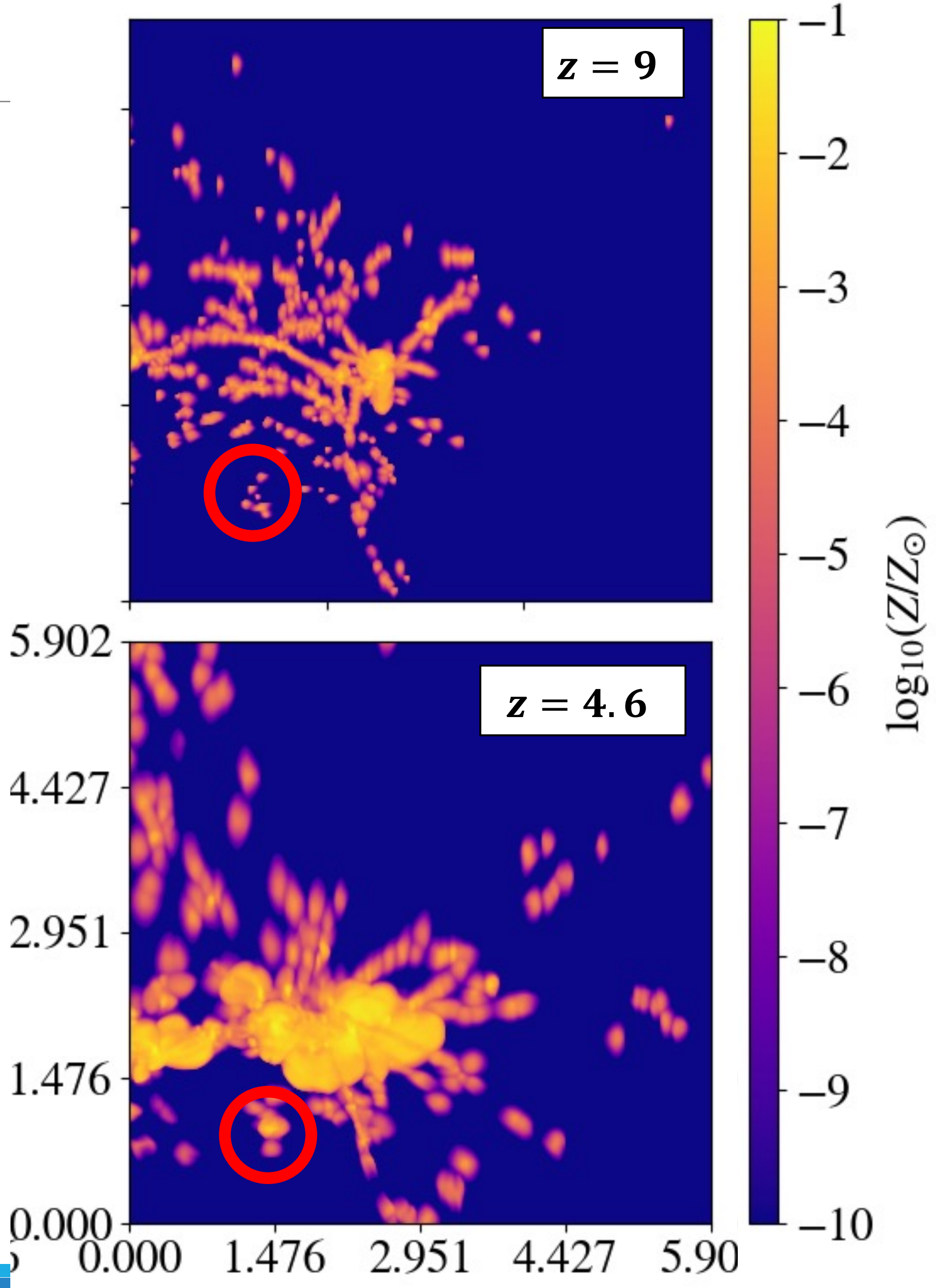


Growth of Metal Enriched Bubbles—FoF

- Characteristic size ~100 ckpc
- Again, sharp reduction of small bubble number after reionization

➔ Signature of reionization end!!

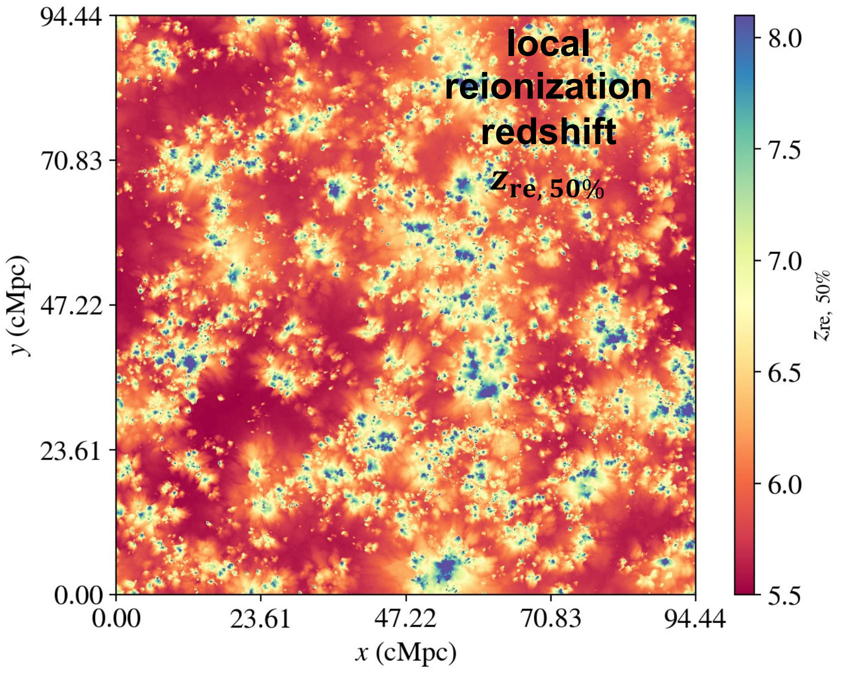


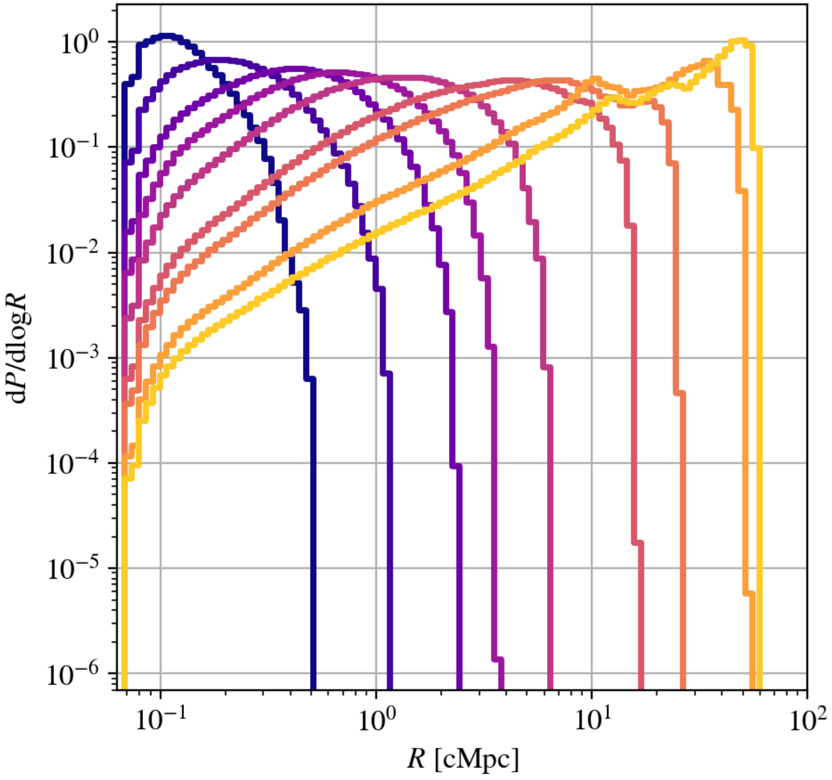


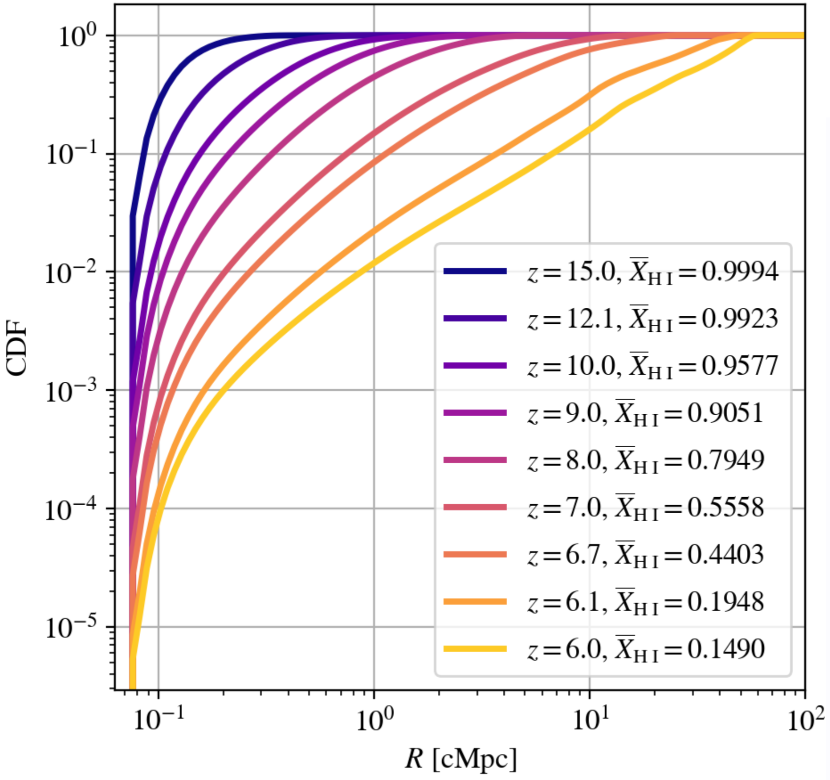
Growth of Ionized Bubbles—Mean Free Path

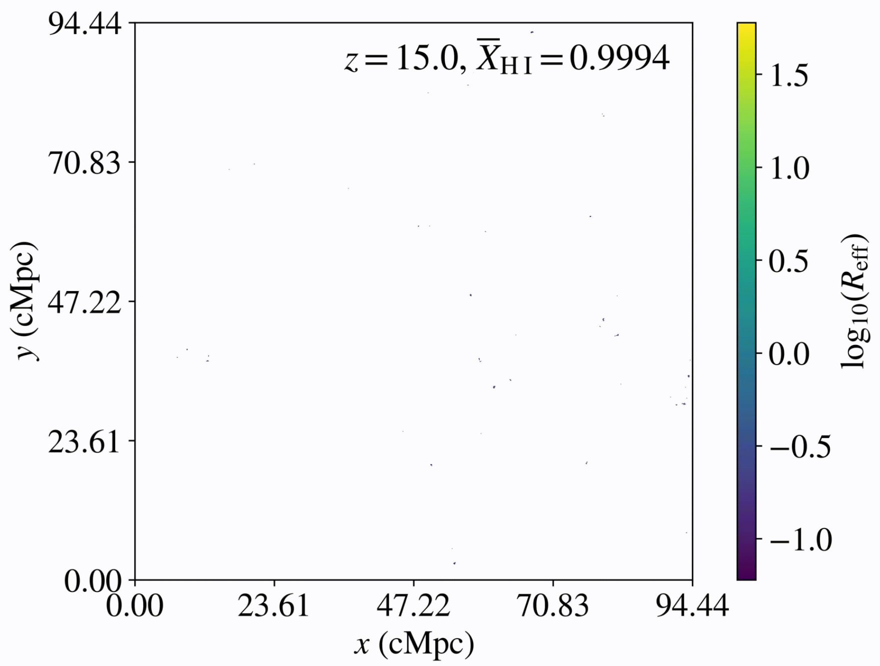
- Mean free path method (MFP; Mesinger & Furlanetto 2007) to measure "locally-defined" H II bubble sizes on 1024^3 grid
  = angle-averaged distance to nearest neutral cell

- Even at > 85% reionized, MFP bubble size is < 60 cMpc









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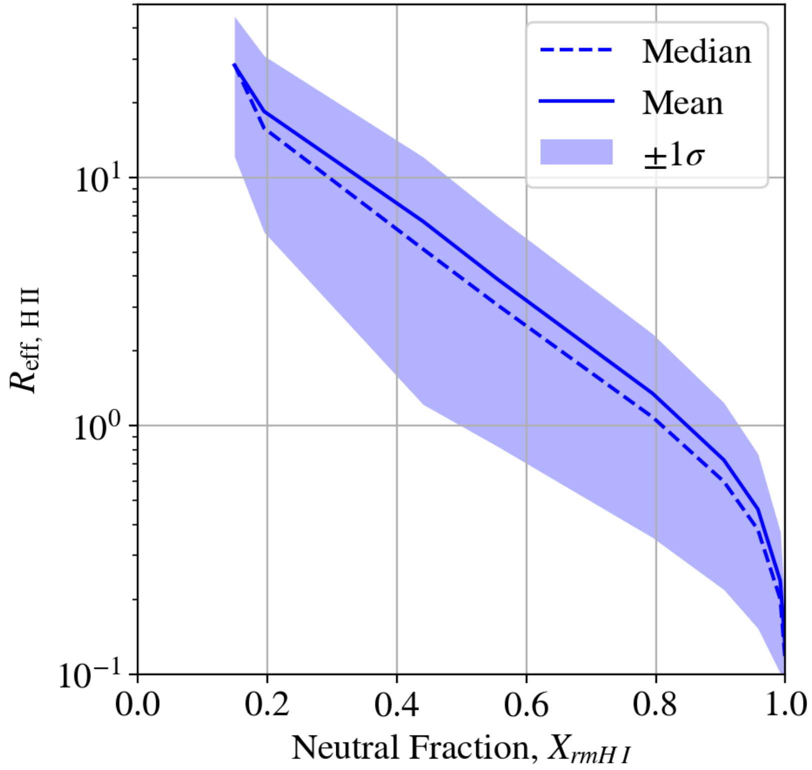
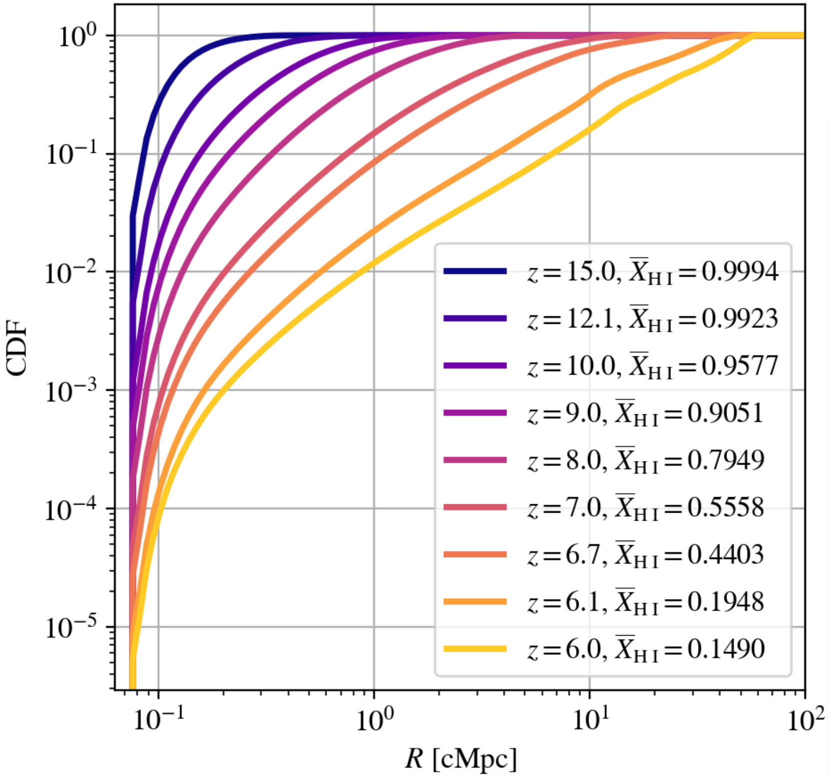
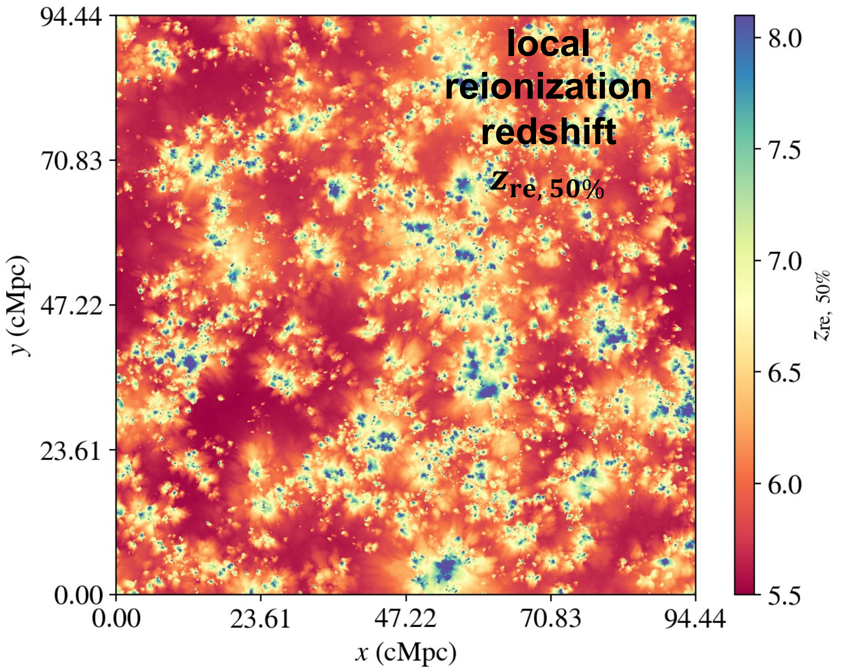
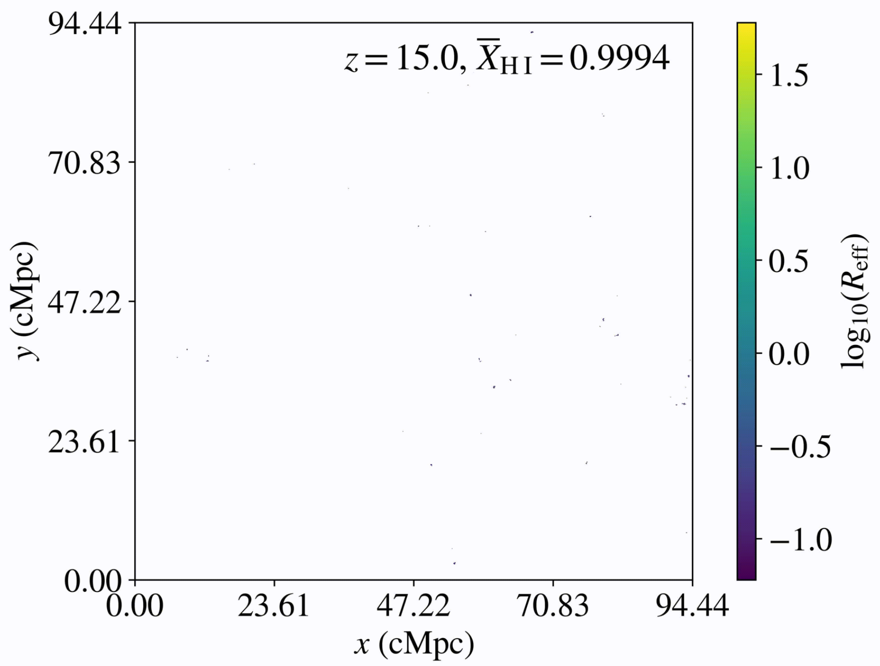








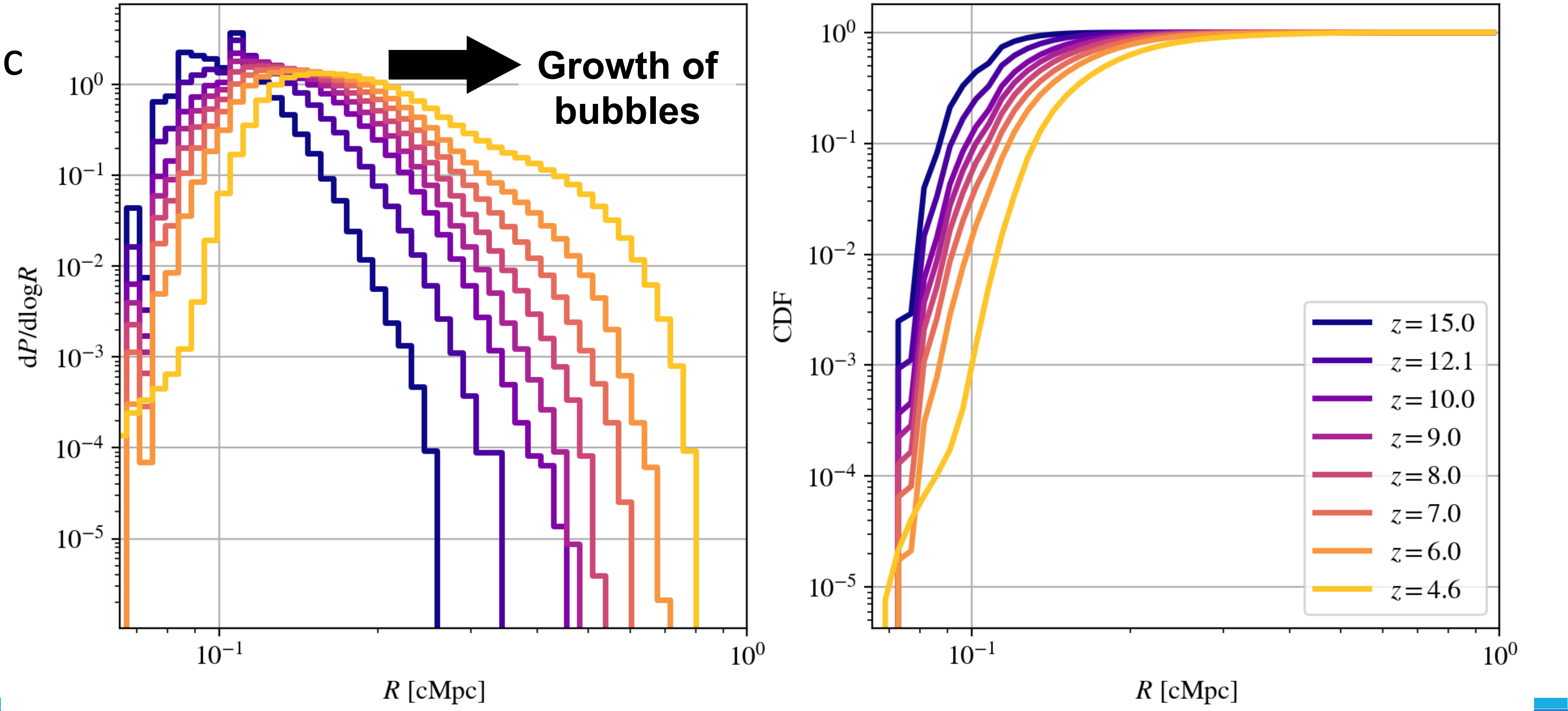
Growth of Metal Enriched Bubbles—Mean Free Path

- MFP method: "locally-defined" metal enriched bubble sizes

  = angle-averaged distance from metal-enriched cell to nearest metal-free cell

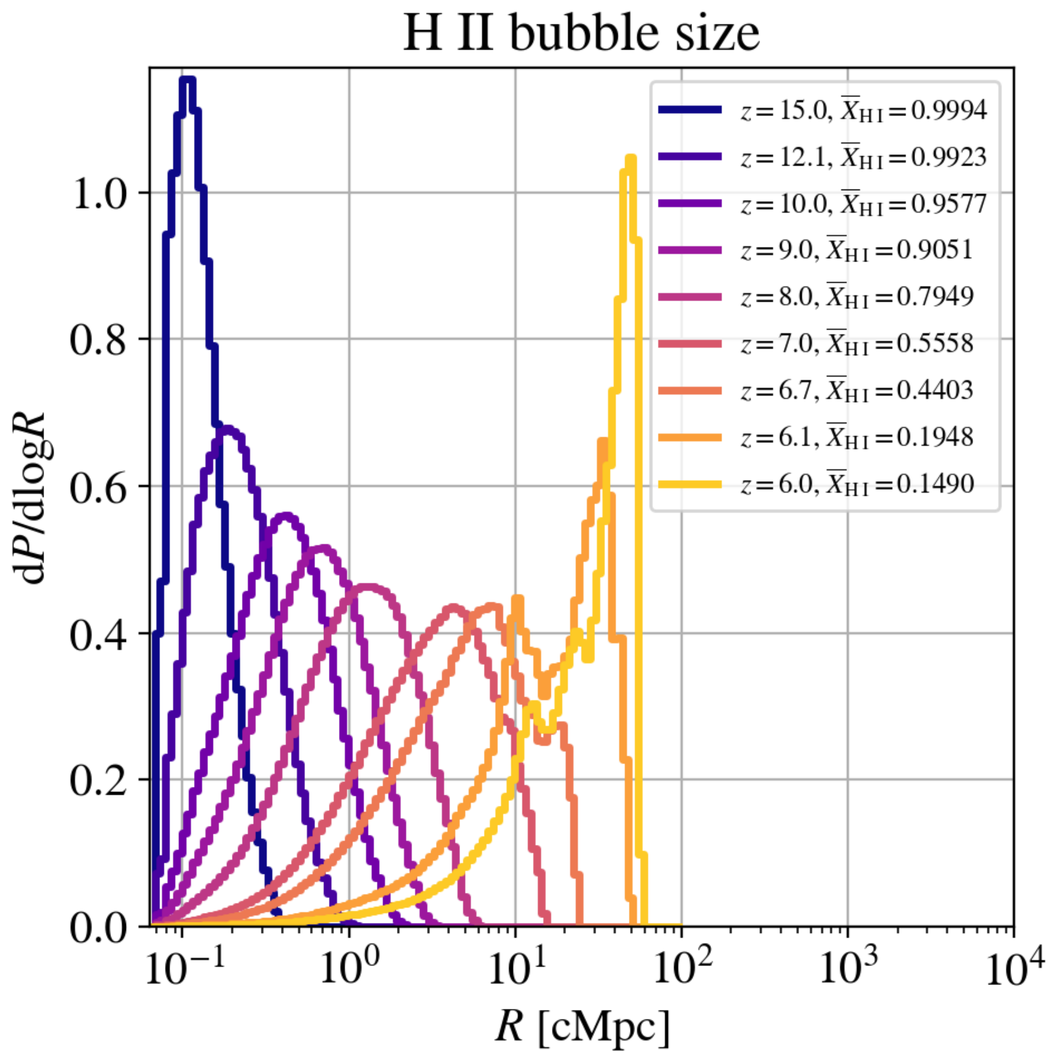
  $(Z < Z_{\text{threshold}} = 10^{-7} Z_{\odot})$

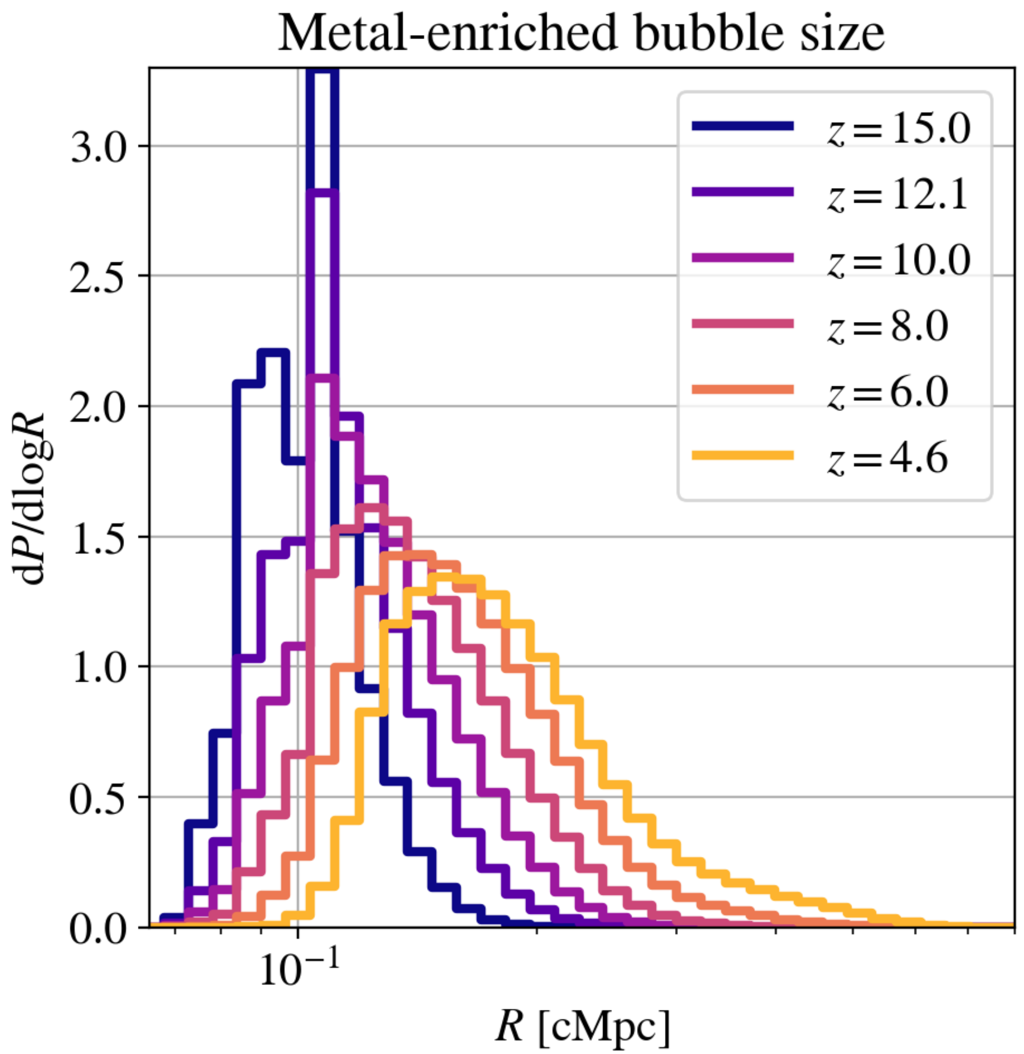
- Peaks at $\sim$100 ckpc



Growth of H II & Metal Enriched Bubbles—Mean Free Path

- Again, metal enriched bubbles grow much more slowly than ionized hydrogen bubbles

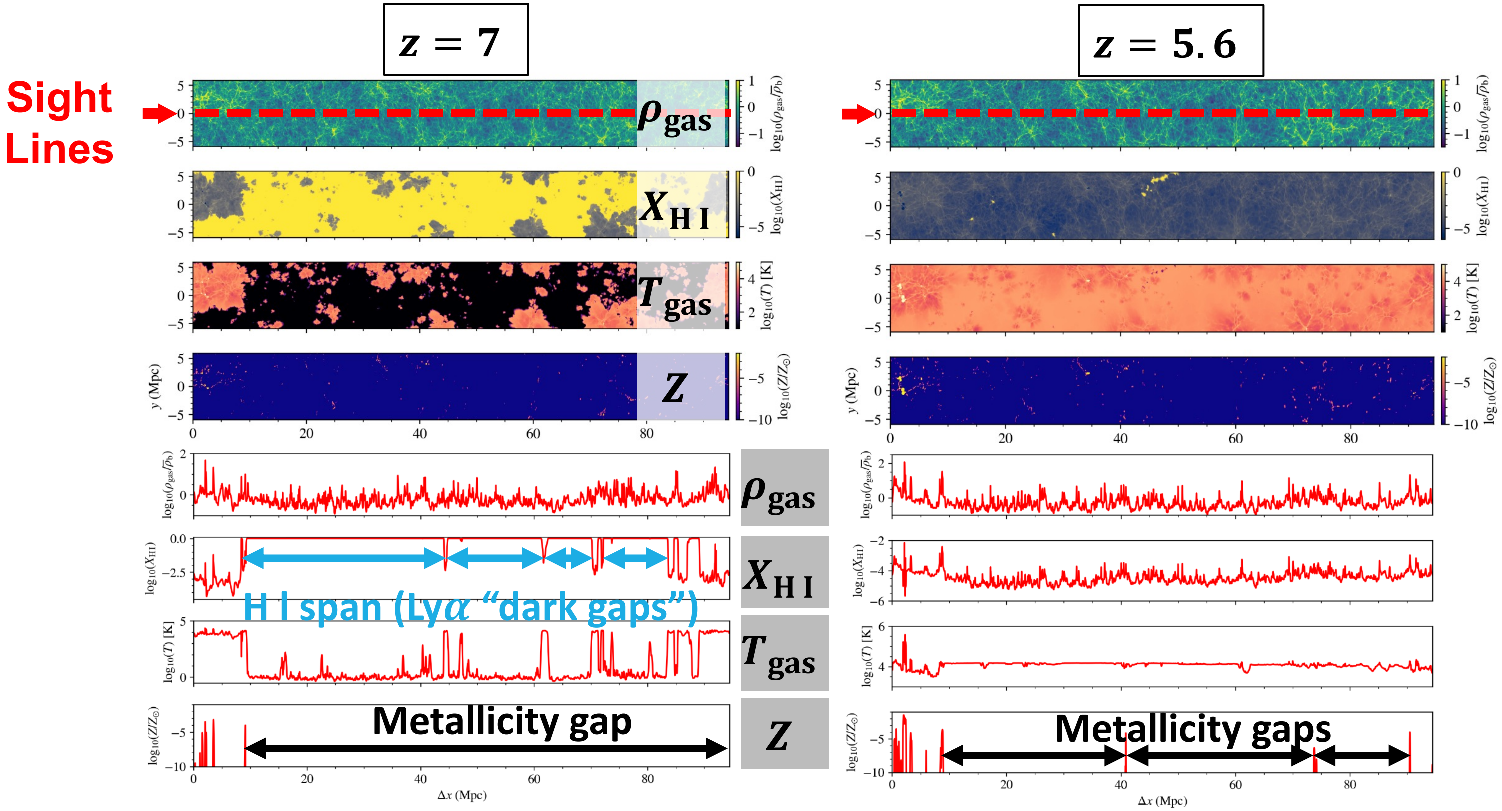


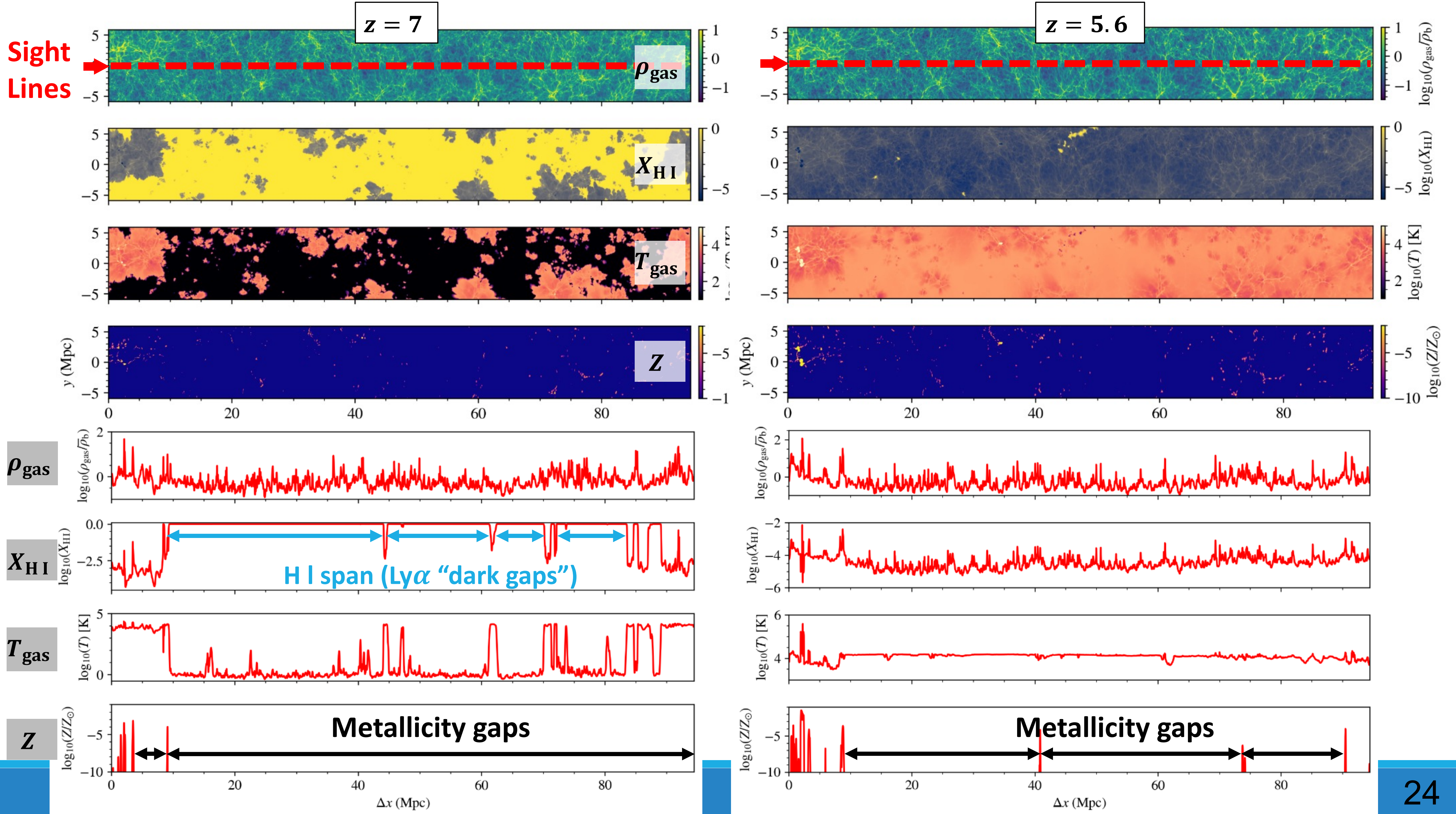


Introducing Metallicity Gaps

“Metallicity Gap”—Analogue of Lyα “Dark Gap”

- IGM patches optically thick to Lyα (or Lyβ) ←→ ***“Dark gaps”*** in Lyα (or Lyβ) forest
- Metal-free patches ←→ ***“Metallicity gaps”*** observable as long distances between metal absorbers (e.g., Si IV, C IV) in QSO spectra

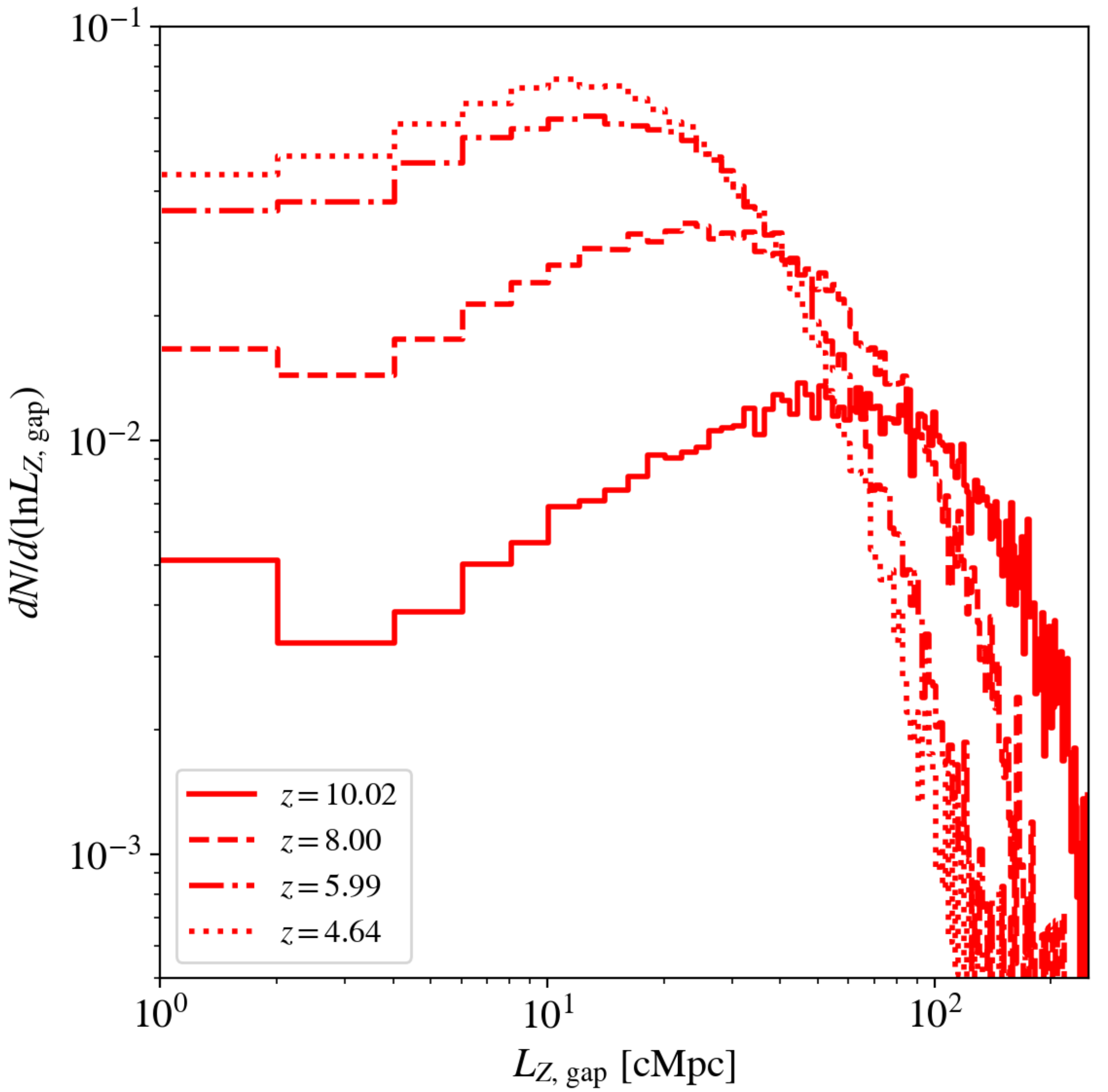




z = 7
z = 5.6
Sight Lines
ρgas
XH I
Tgas
Z
y (Mpc)
log10(ρgas/ρ̄b)
log10(XHI)
log10(T) [K]
log10(Z/Z⊙)
H I span (Lyα "dark gaps")
Metallicity gaps
Δx (Mpc)

Metallicity Gap Statistics

- Distributions of metallicity gap length ($L_{Z,\,gap}$) along 4000 random sight lines at each snapshot
- The gap length decreases as the cosmic metal enrichment process proceed

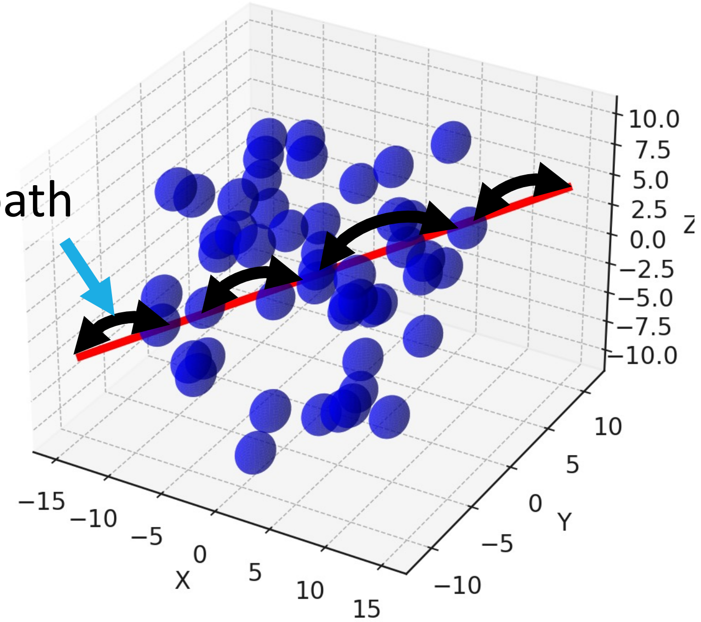


Metallicity Gap Statistics

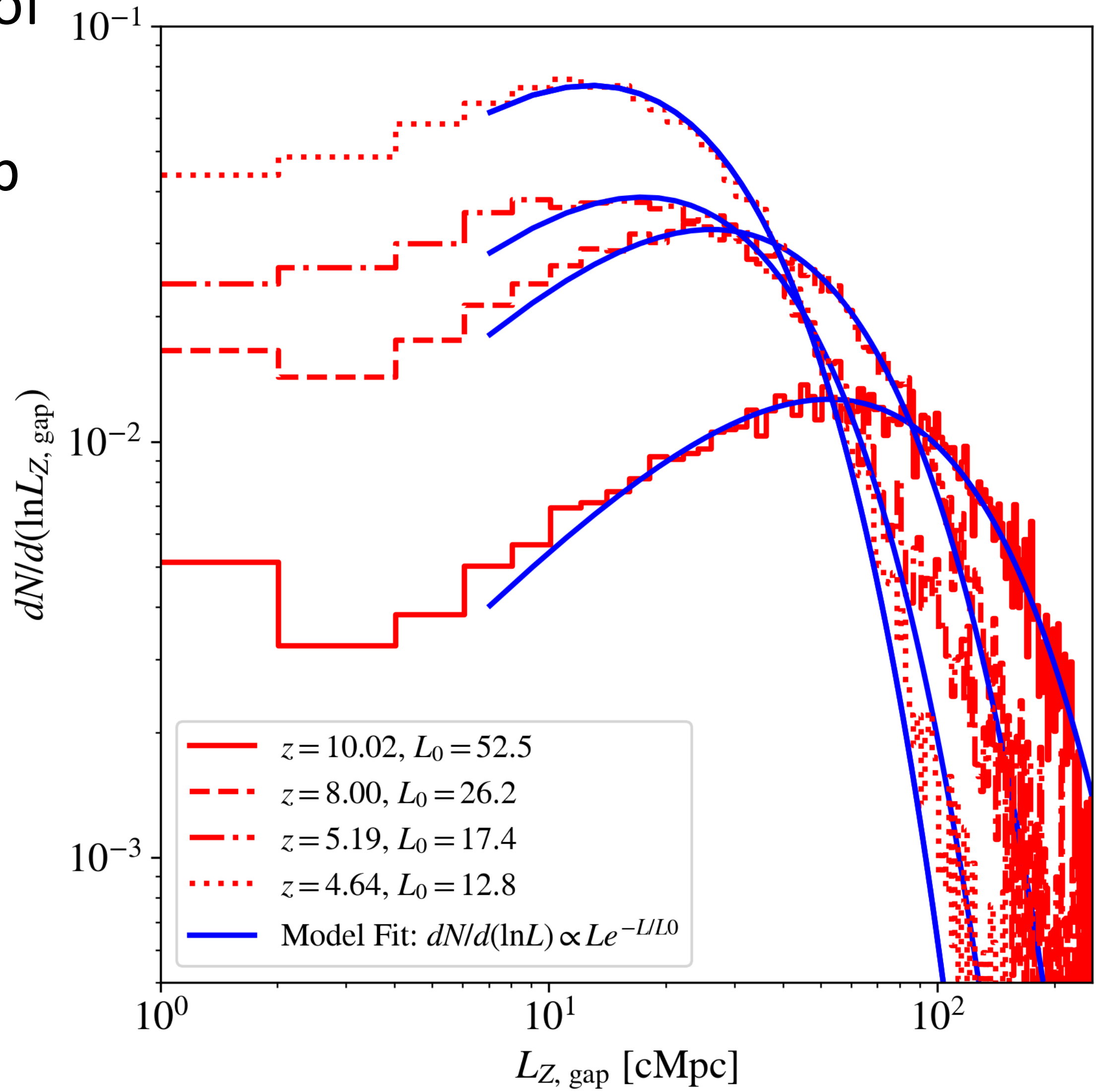
- A simple mathematical toy model as a distribution of LOS distances between spherical metal bubbles located randomly in empty space fits metallicity gap distribution well:

$$dN/dL \propto e^{-L/L_0}, \text{ where } L_0 = 1/(\pi R^2 n) = \lambda_{\text{mfp}}$$

λ_{mfp}
Mean-free path

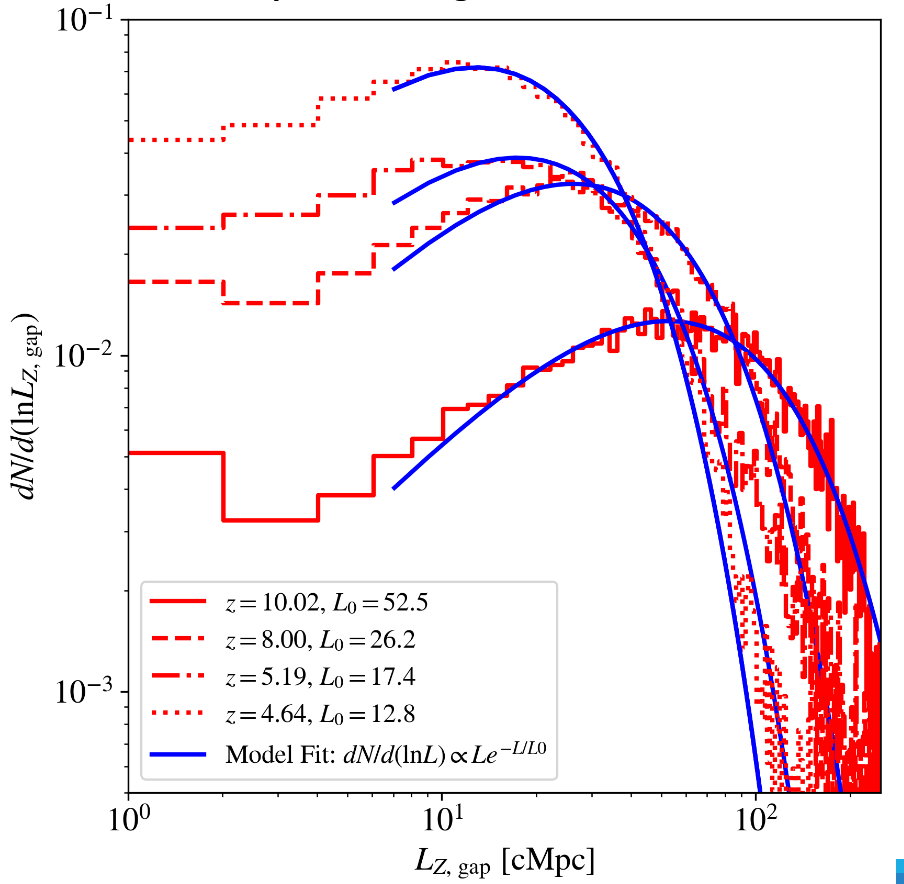


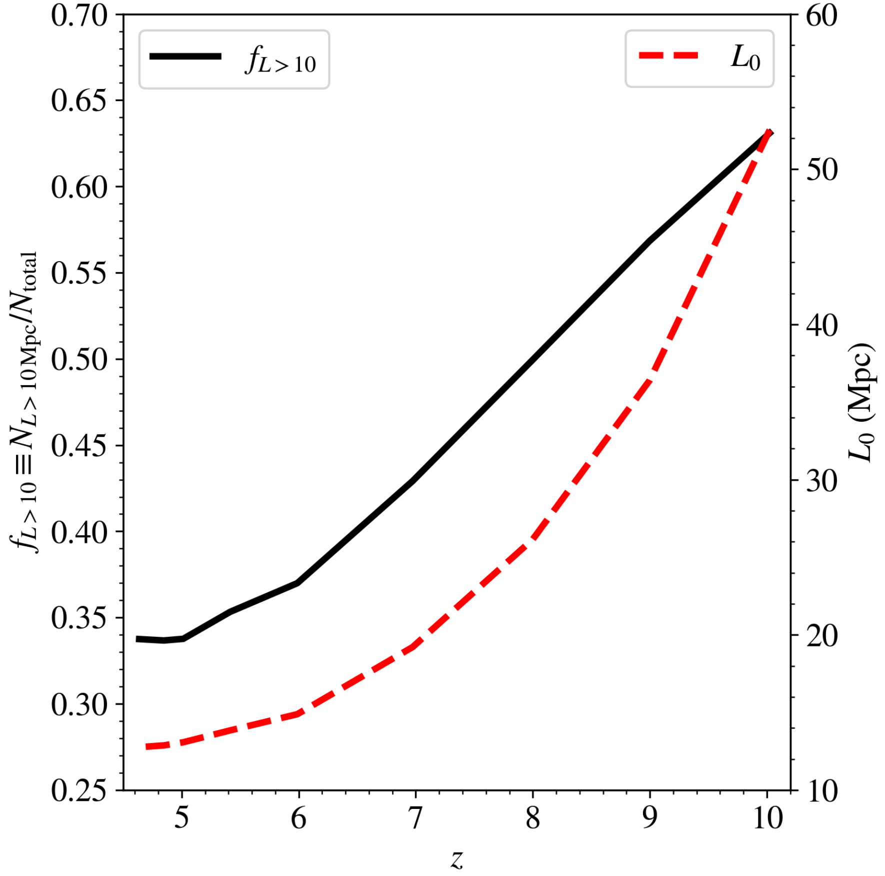
Randomly distributed metal-filled spheres with radii R



Metallicity Gap Statistics

- The model fits long gap distribution well ($L \geq 10$ Mpc);
  but undershoots short gap distribution: "**non-random clustering" on small scales**
- L_0 drops dramatically during EoR: @z=10 ~ 50 Mpc, @z=5: ~ 10 Mpc





Conclusions

1. Stellar nucleosynthesis and SNe by the same massive stars that reionized the universe enriched the universe to $\bar{Z}/Z_{\odot} = 10^{-3}$ by the end of the EoR, $z_{\mathrm{re}} = 5.53$ (99.99% ionized).
2. The metal-enriched volume fraction of the universe was tiny, at all times during the EoR and well beyond it ($Q_Z < 2\%$ with $Z > Z_{\mathrm{threshold}} = 10^{-7} Z_{\odot}$ at $z_{\mathrm{re}} = 5.53$).
3. Metal-enriched zones are well-characterized as "metal-enriched bubbles" arranged along the filaments and nodes of the cosmic web.
4. Friends-of-Friends and mean free path methods characterize size distributions of metal-enriched bubbles and ionized H bubbles
   ←→ Ionized bubbles grow bigger and faster than metal bubbles.
5. Metal bubble size distribution peaks at ~ 100 ckpc, with slope evolving below the peak, a possible indicator of when reionization ended.
6. "Metallicity gaps" offer a new observational diagnostic of the inhomogeneous rise of metallicity and reionization, both!