Difficulties with Simulating Cosmological Ionizing Radiative Transfer

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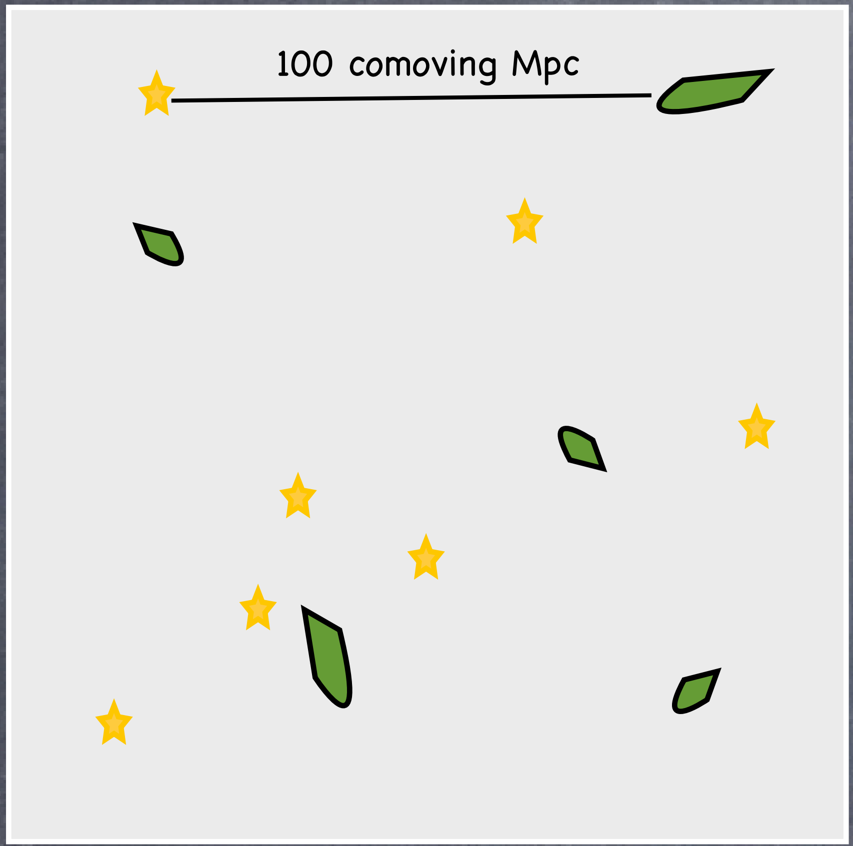
Outline

- the impact of Lyman-limit systems on reionization
- towards better source models

★ the impact of photoionization feedback

The importance of Lyman-limit systems (LLSs)

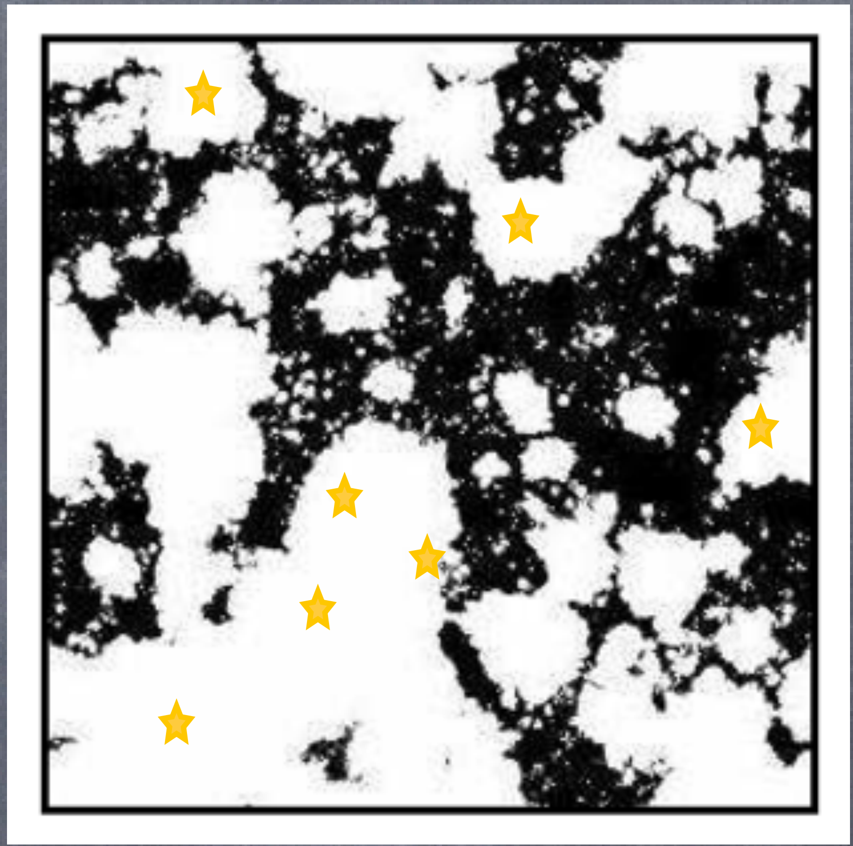
After Reionization



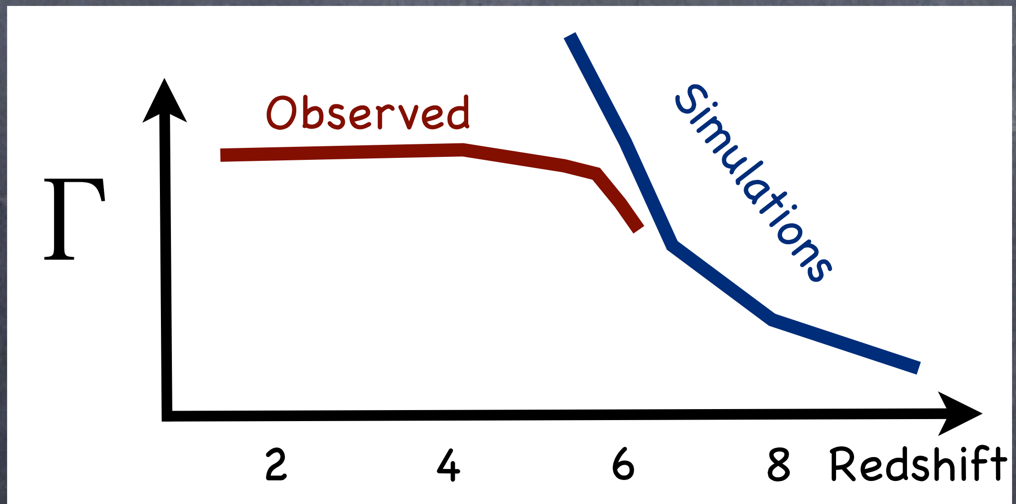
Mean free path limited by dense systems w/ δ =10-1000

Are they capturing this transition?

During Reionization

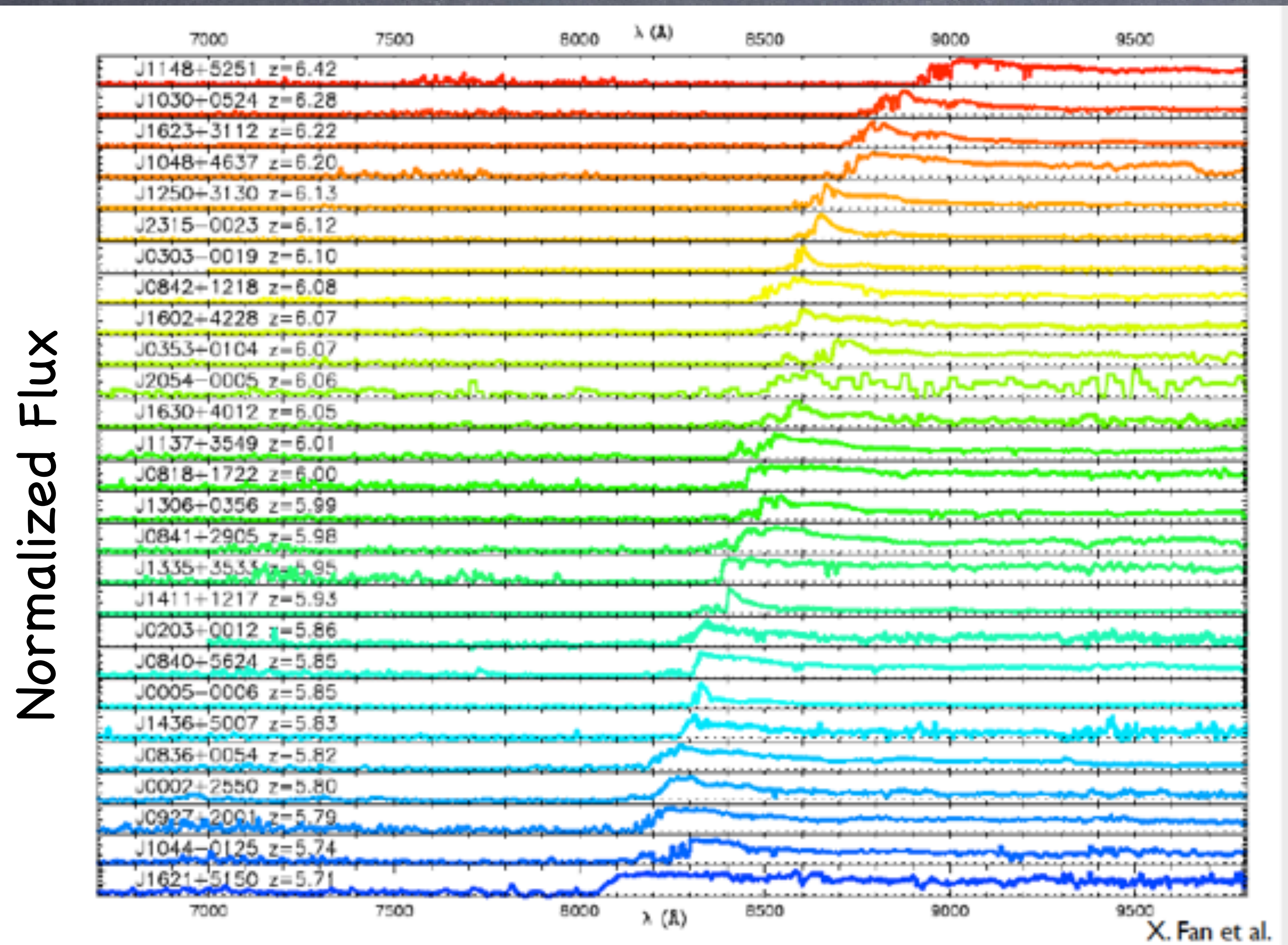


Mean free path limited by bubbles



Intensity of Ionizing Background = (mean free path) x (source emissivity)

Capturing LLSs is crucial for understanding z=6 Hydrogen Ly α forest



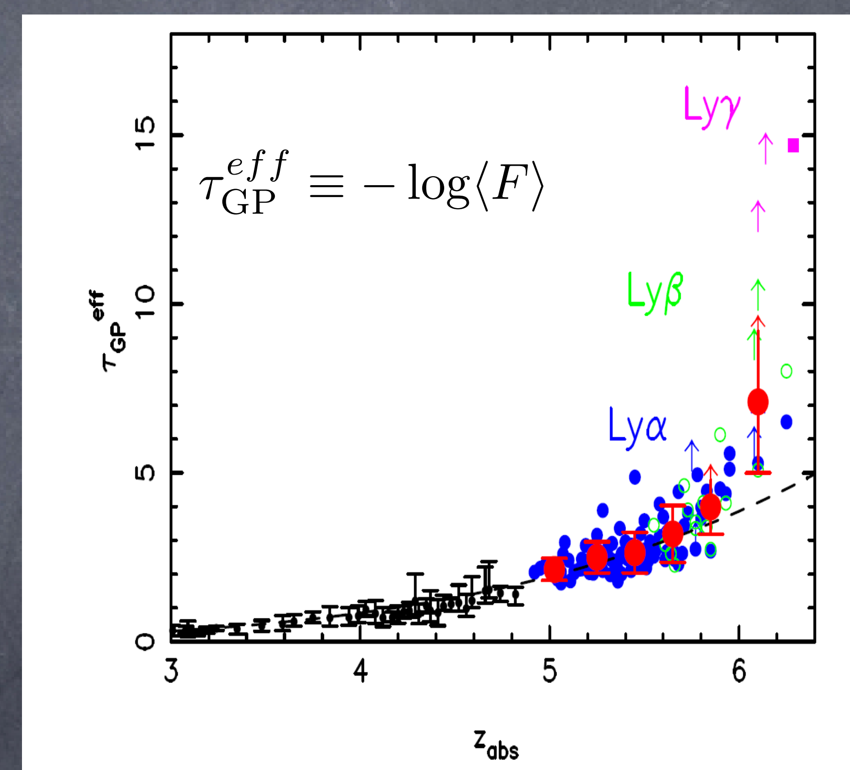
Currently ≥47 z > 5.7 QSOs known (many faint)

Neutral region:

$$\tau_{\rm GP} = 3\times 10^5\, x_{\rm HI}\,(1+\delta)\left(\frac{1+z}{7}\right)^{3/2}$$

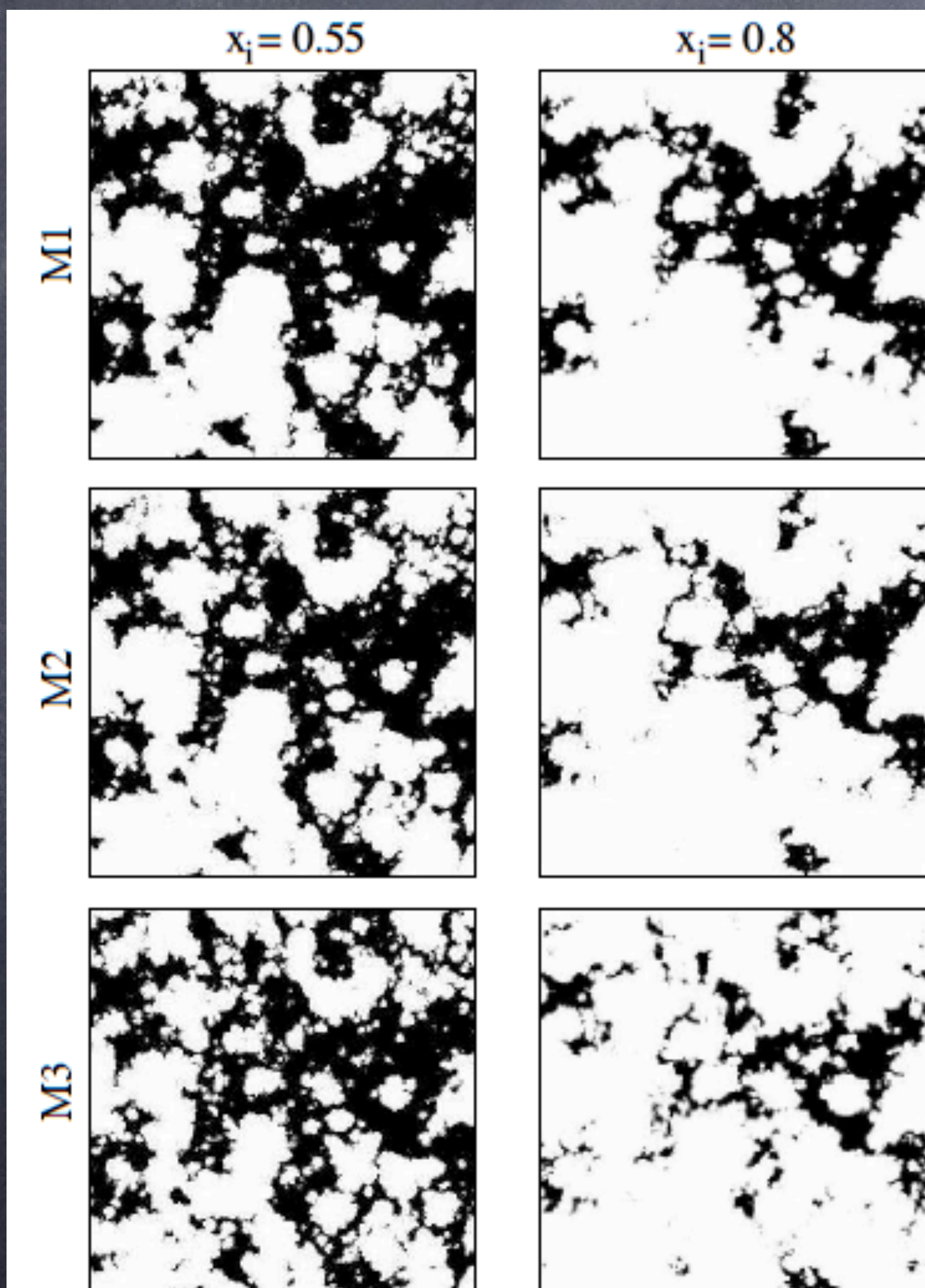
Photoionized region:

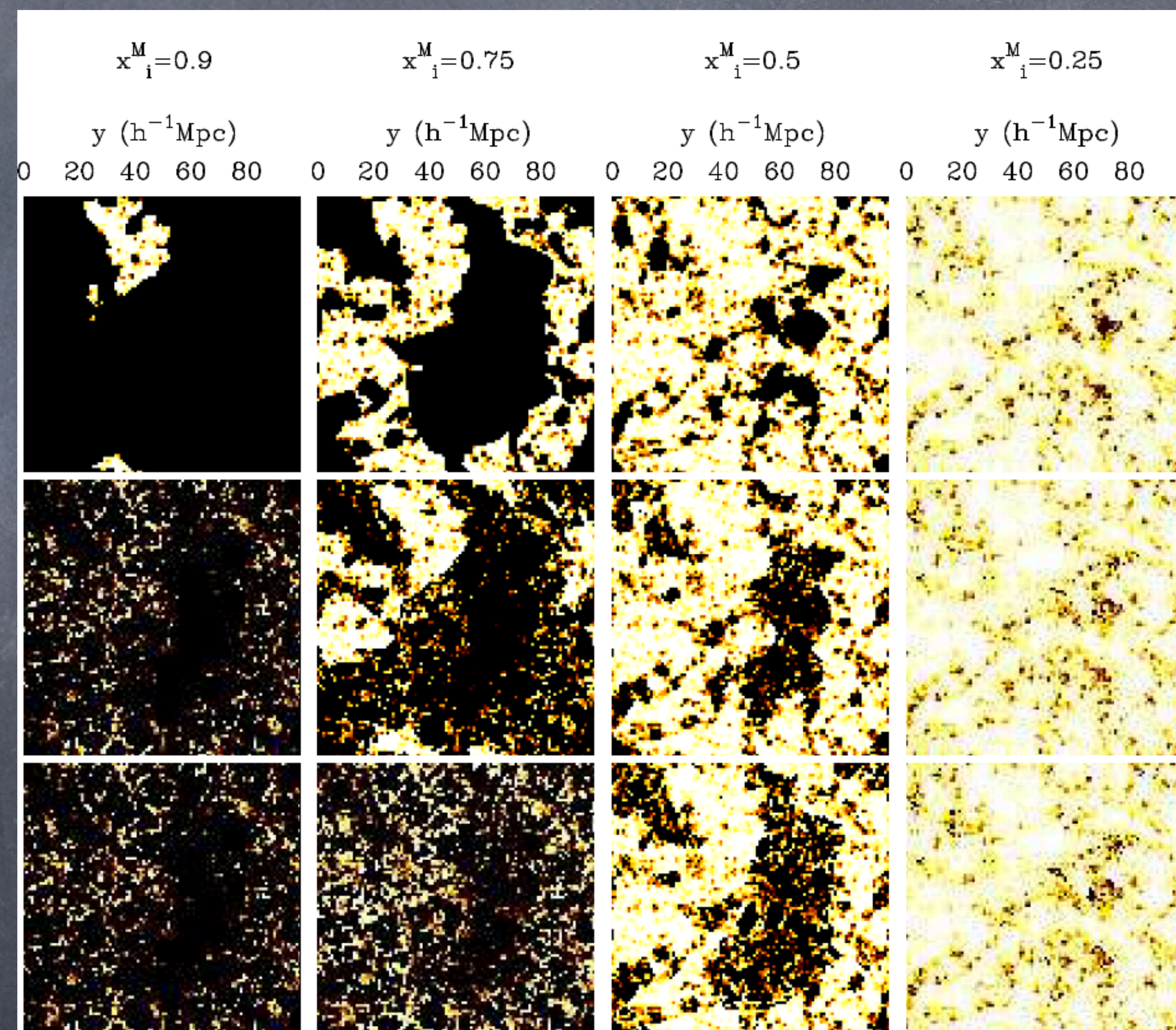
$$\tau_{GP} = 9\;(1+\delta)^2\left(\frac{10^{-12}\ {\rm s}^{-1}}{\Gamma_{\rm HI}}\right)\left(\frac{1+z}{7}\right)^{9/2}$$



Difficult to explain fast evolution with reionization because occurs in 0.1 $H(z)^{-1}$

Other reason: could change structure of reionization



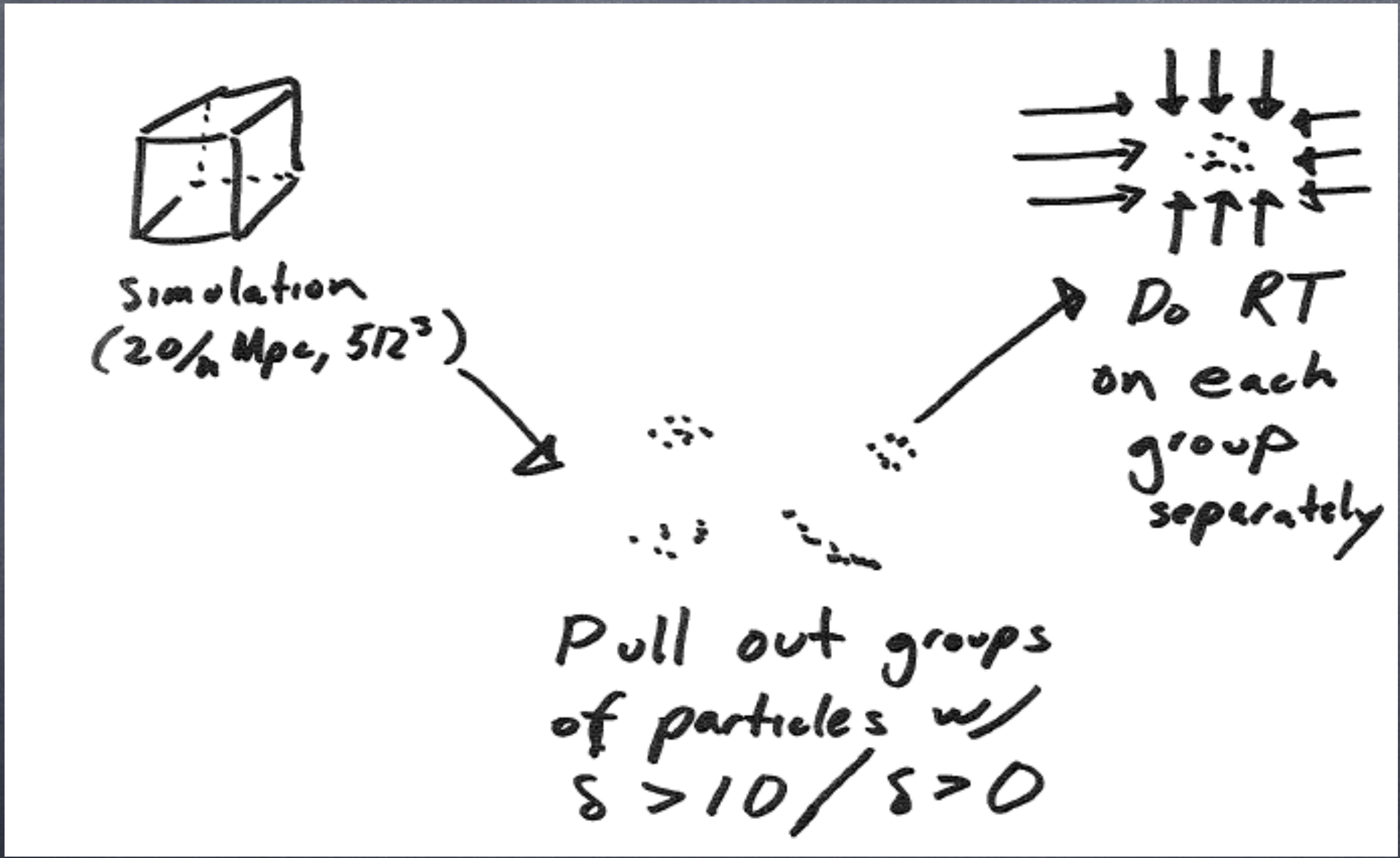


Choudhury et al (2009)

McQuinn et al 2007 (see also Furlanetto & Oh '05)

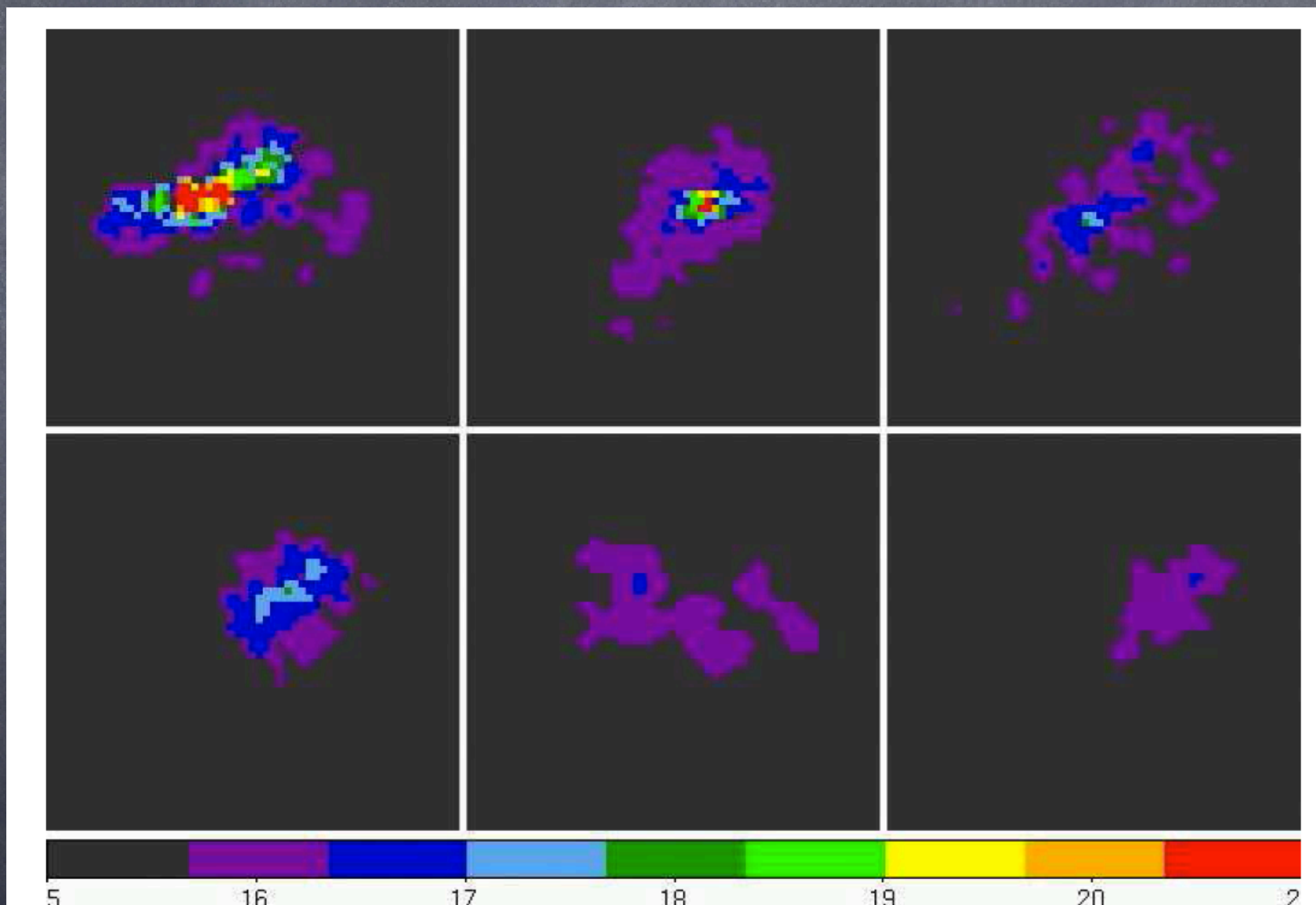
Project: Study Lyman-limit systems (dense self-shielding systems)

Goal: Understand properties at end and after reionization



Do this for a few tens of thousands of groups.

What self-shielding systems look like (z=4)

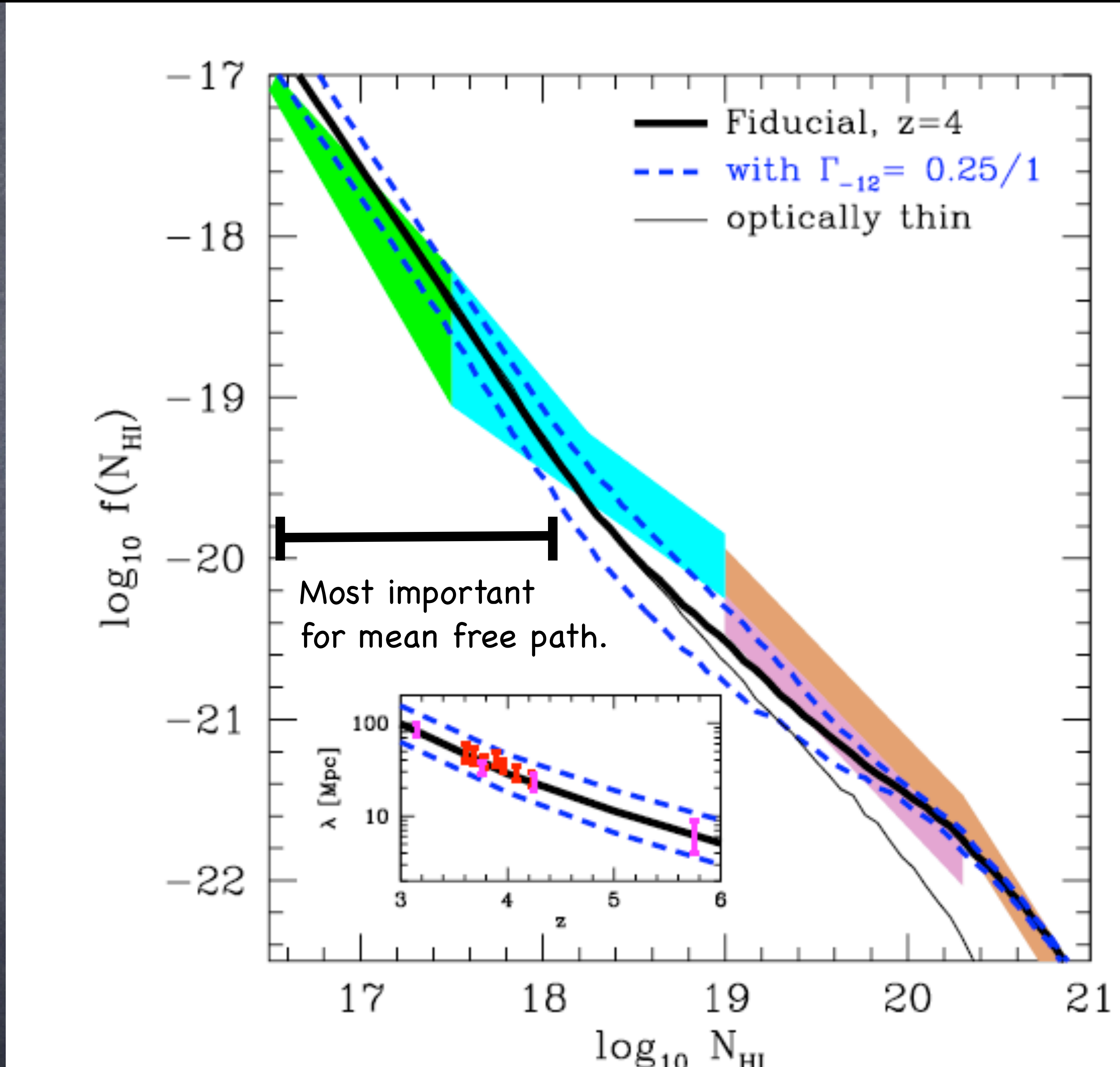


0.5 Mpc

N_{HI}

Comparison w/ Observations at z=4

HI Column density distribution



Highlighted regions are observational constraints derived/ compiled in Prochaska, Omeara, Worseck (2010)

McQuinn, Oh, Faucher-giguere, '11 (also see Altay et al '11)

Simulations able to (approximately) reproduce gas at outskirts of galactic halos. They should do better with increasing redshift.

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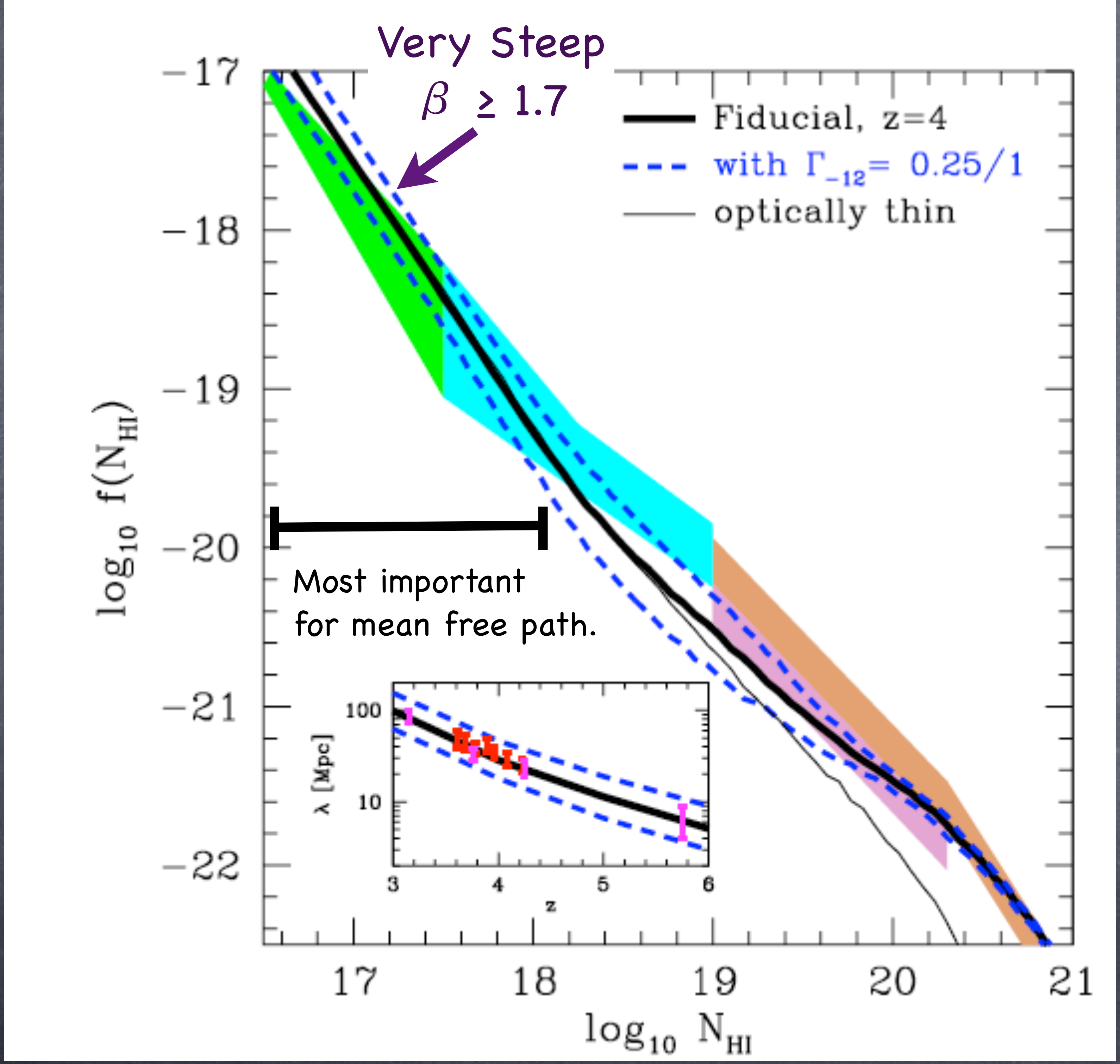

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Measured from Ly α Forest

Distance between dense self-shielding systems

↓

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$\approx$ emissivity$^{1/(2-\beta)}$

(assumes power-law profile for systems)

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- At z=4, simulations predict a 10% change in emissivity can result in 30% change in Γ.
- At z=6, simulations predict a 10% change in emissivity can result in factor of 2 change in Γ.

  Possible explanation for evolution seen in Fan et al (2006).
- Strong scaling related to result that IGM clumping factor $<(1+\delta)^2>$ is << 10 (e.g., Pawlik et al '08)

Implications for reionization simulations

- ionizing background and Lyman-limit systems strongly coupled
  - we aren't making it any easier on ourselves by having sources that are too emissive!
- You cannot barely resolve these systems to capture their impact. The mfp is also not just one number during reionization.

LL density:

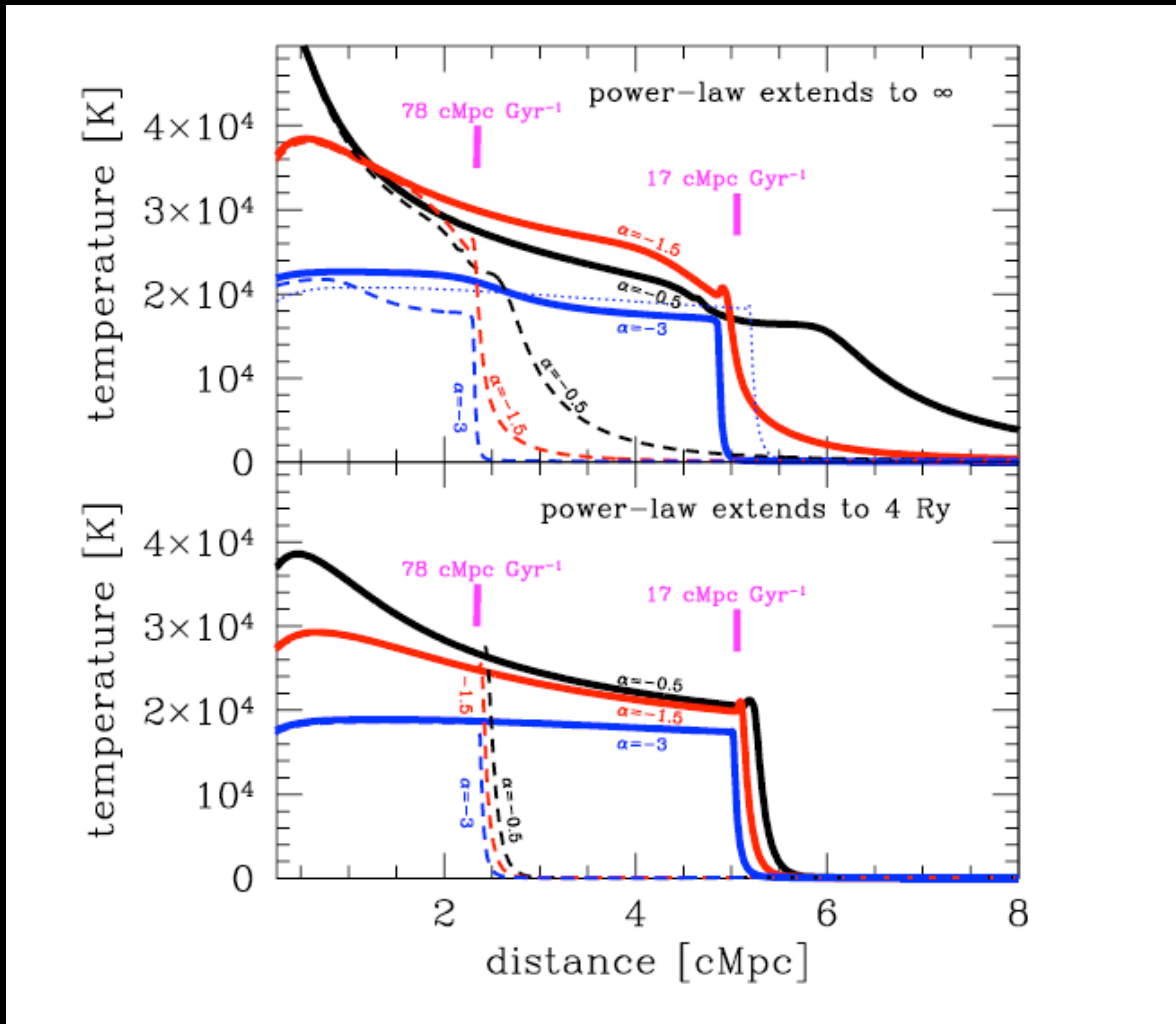
$$\delta_b = 13 \left(\frac{1+z}{10}\right)^{-3} \left(\frac{N_{\rm HI}}{10^{17}\ {\rm cm}^{-2}} \frac{\Gamma_{\rm HI}}{10^{-12}\ {\rm s}^{-1}}\right)^{2/3} \left(\frac{T}{10^4\ K}\right)^{0.17}$$

LL size:

$$\ell = 0.11 \left(\frac{1+z}{10}\right) \left(\frac{N_{\rm HI}}{10^{17}\ {\rm cm}^{-2}} \frac{\Gamma_{\rm HI}}{10^{-12}\ {\rm s}^{-1}}\right)^{-1/3} \left(\frac{T}{10^4\ K}\right)^{0.41} \quad \text{comoving Mpc}$$

Above numbers are from model of Schaye '01

Temperature



dashed and solid curves are at 10 and 100 Myr respectively (McQuinn '12)

Conclusions

- Simulations need to capture Lyman-limit systems!
- There is an intuitive picture that describes the halo masses that can accrete gas after reionization.