Semi-Numerical Tools Applied to Lyα Emitter and Lyα Damping Wing Constraints on Reionization

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Outline

- Efficient "semi-numerical" simulations of structure and reionization

- Recent applications of simulations:
  - High-z LAEs: abundance and counts-in-cell statistics
  - Lyα damping wing in non-homogeneous reionization

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Modeling High-z and Reionization

Improvements in the interpretation of high-z spectra should take advantage of improved modeling (density and velocity biases, realistic ionization topology, etc.)

The major difficulty lies in the enormous dynamical range required…

Even with modest halo resolution (Springel & Hernquist 2003) of tens of dark matter particles per halo, current simulations are limited to box sizes of ≤ tens of Mpc --> not enough to model highly-non linear processes such as reionization!

Hybrid schemes extending the resolution (McQuinn et al. 2007), rely on merger trees and are not self-consistent.

Enter "pseudo" or "semi-numerical" simulations …
Fast! (e.g. PTHalos and Pinocchio model halo fields)

Procedure

Halo fields

(updated form of the independently developed "peak-patch" formalism of Bond & Myers 1996)

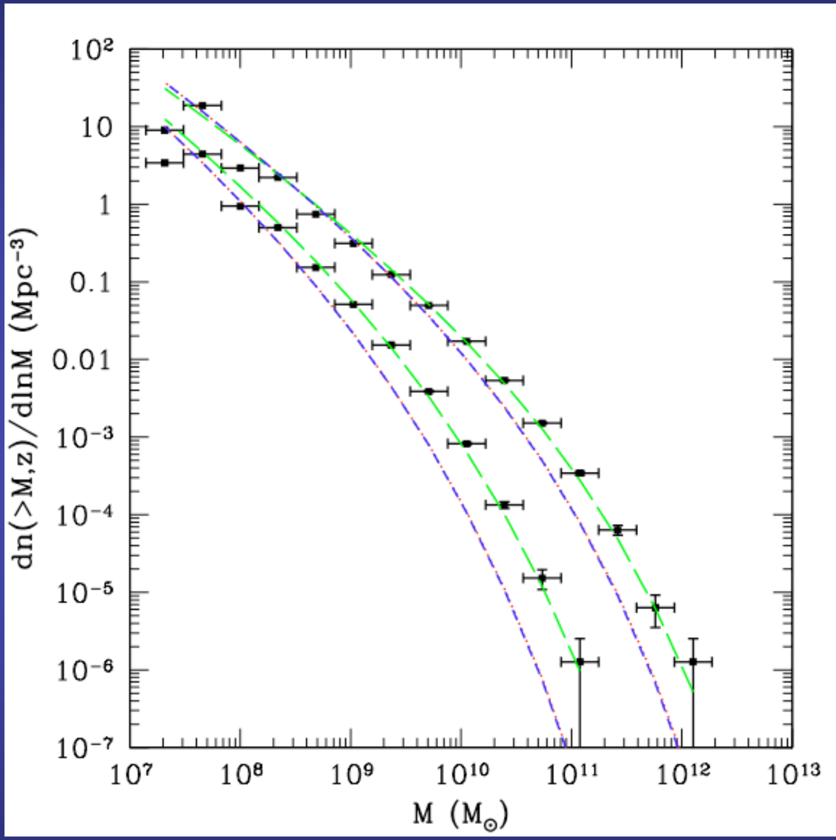
1. create linear density and velocity fields
2. filter halos from the linear density field using excursion-set formalism (e.g. Bond et al. 1991)
3. adjust halo locations using linear-order displacements (Zel'Dovich 1970)

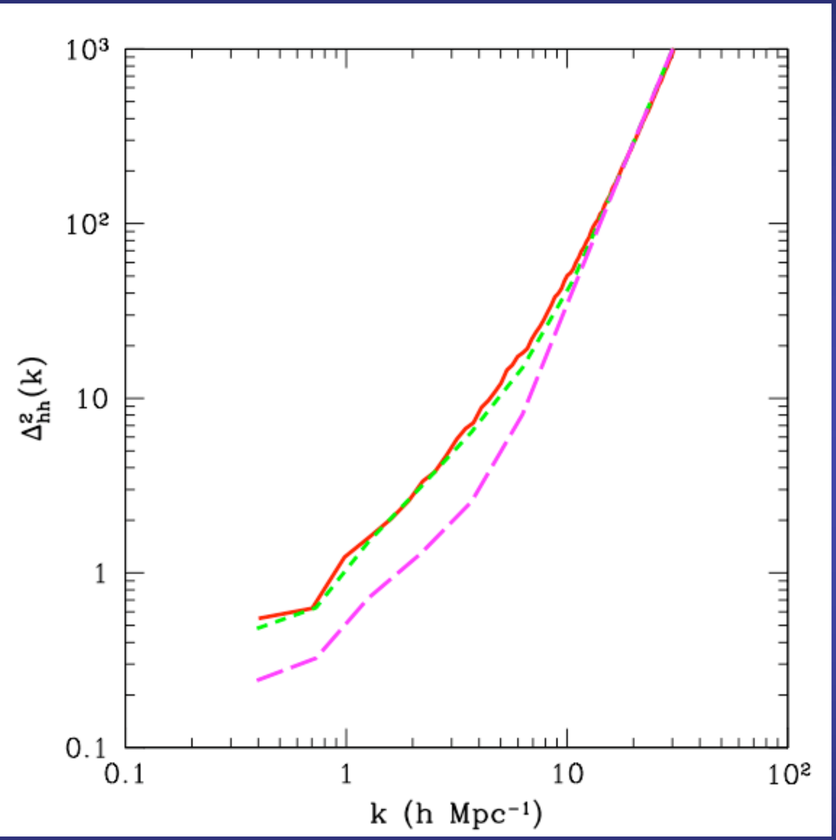
Ionization fields

4. perturb linear density field using linear-order displacements (Zel'Dovich 1970)
5. filter ionized regions from the halo and perturbed density fields using excursion-set formalism (e.g. Furlanetto et al. 2004)

Halo Filtering

Mesinger & Furlanetto (2007a)

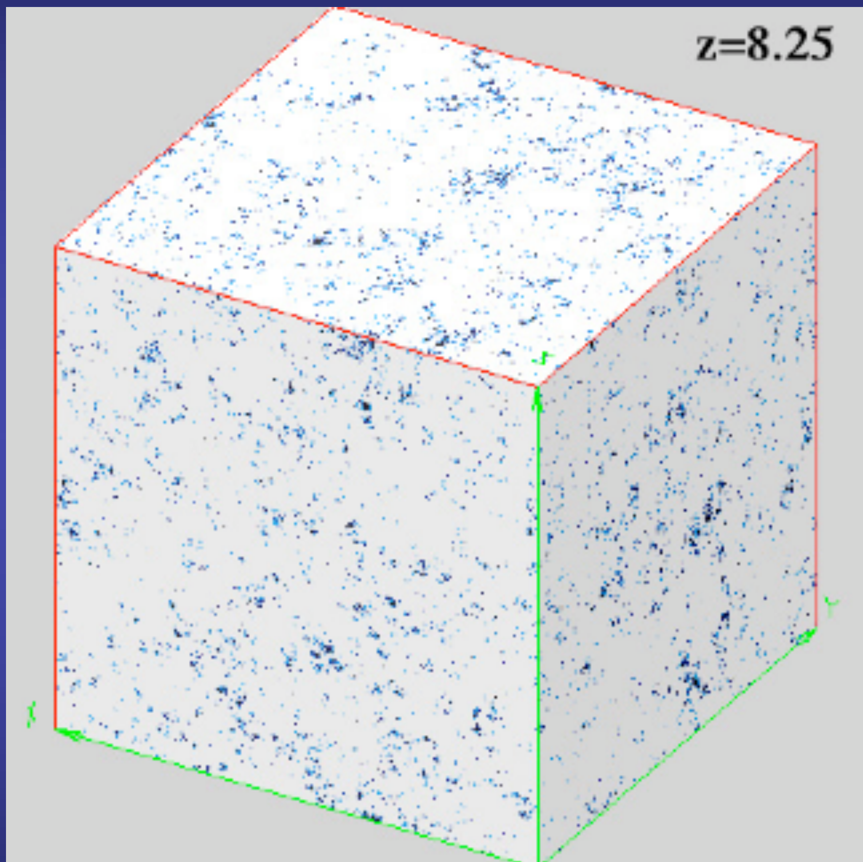




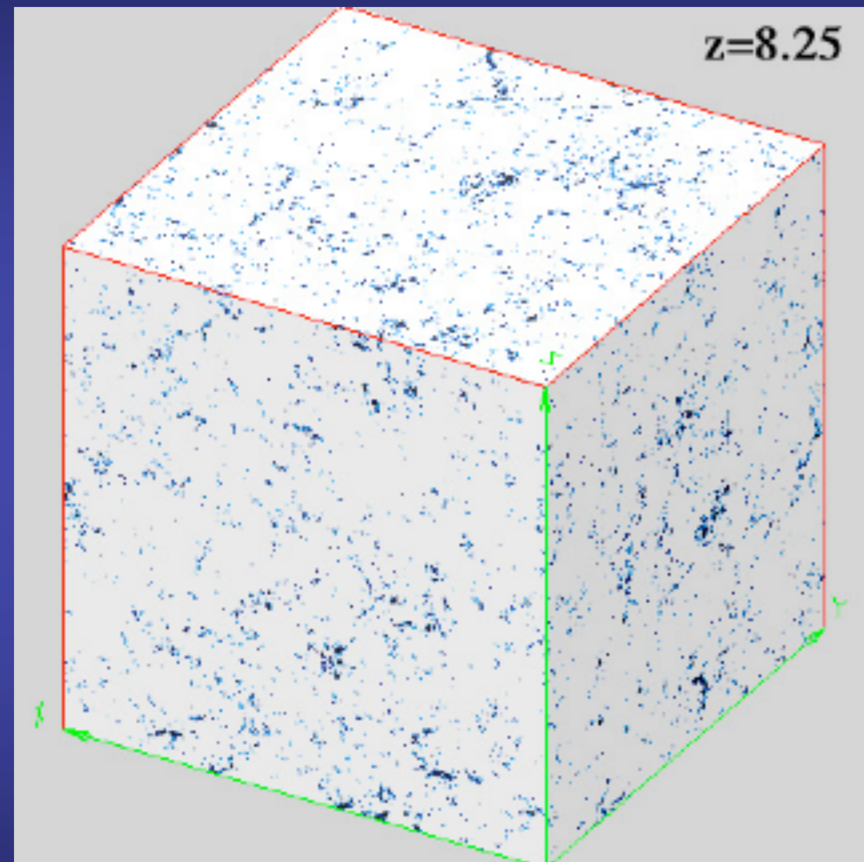
z=8.7 N-body halo field from McQuinn et al. (2007)

Halo Filtering

Mesinger & Furlanetto (2007a)



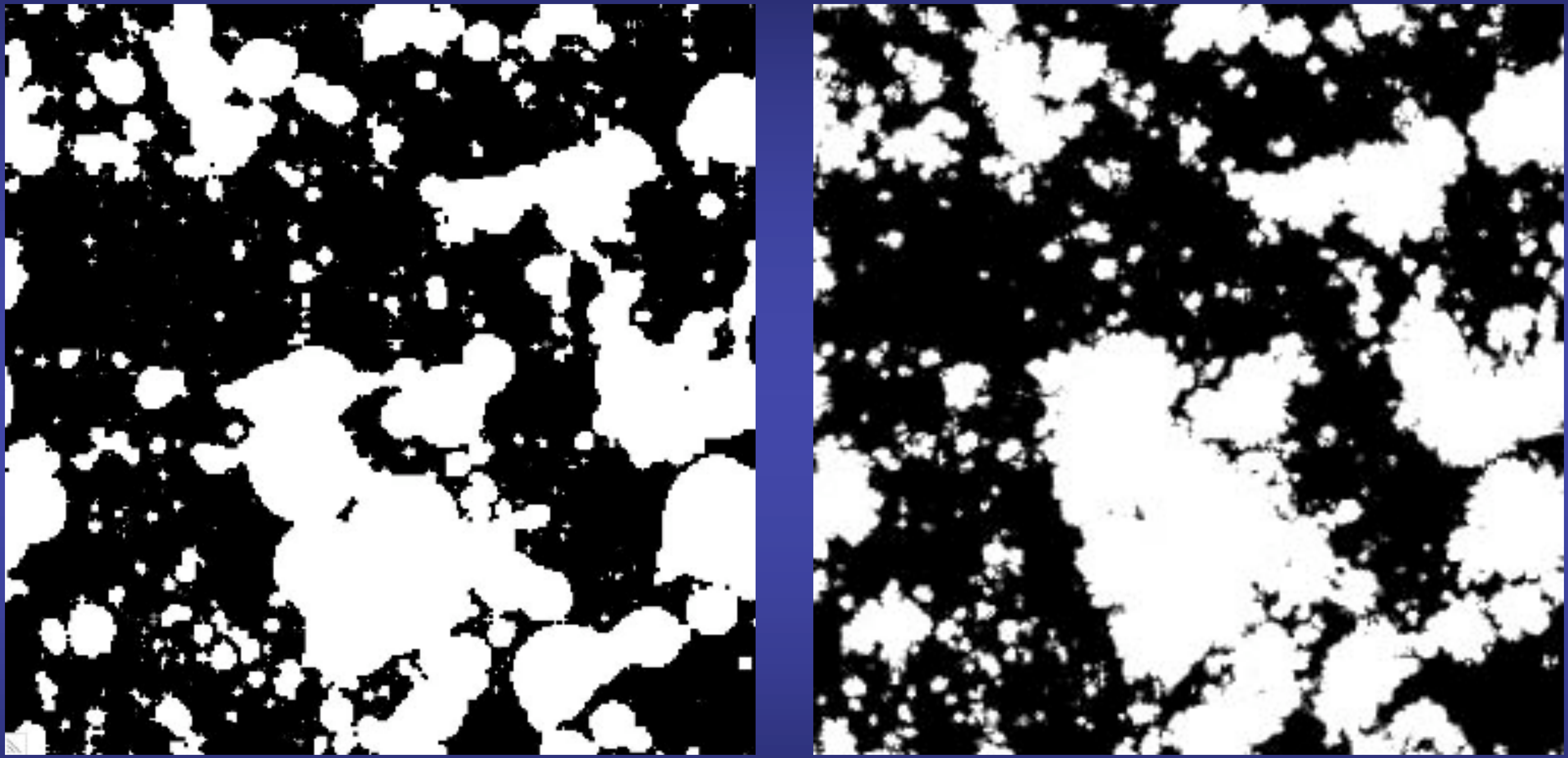
without adjusting halo locations



with adjusting halo locations

HII Bubble Filtering

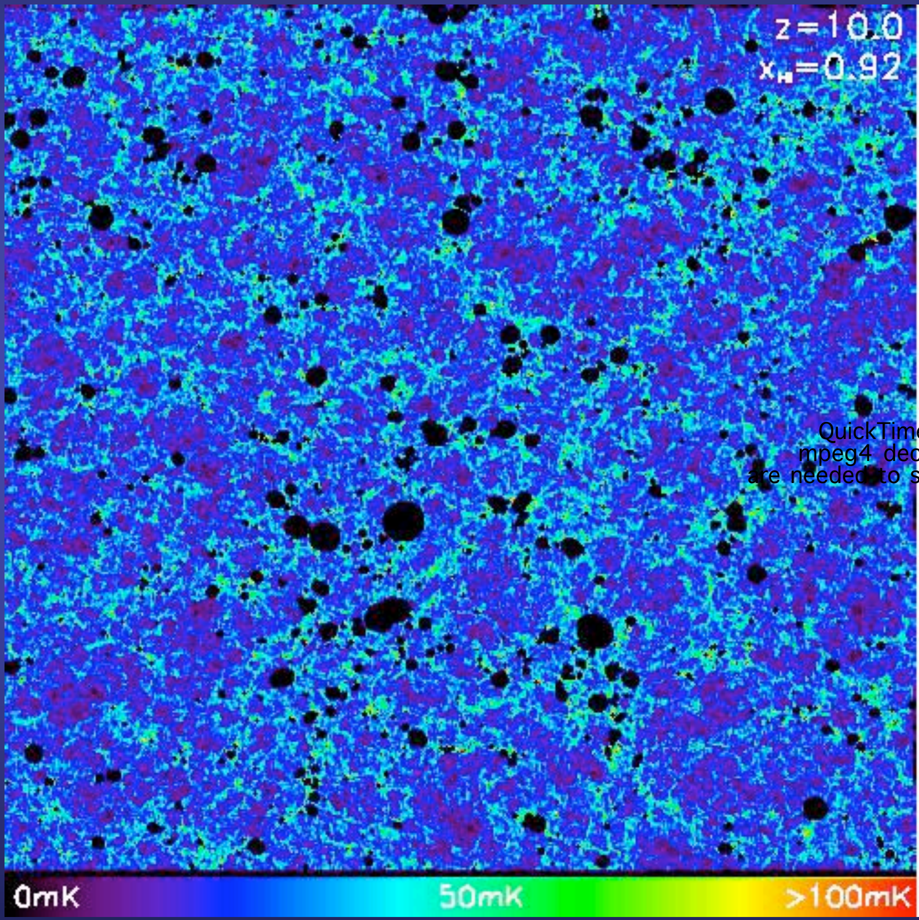
Mesinger & Furlanetto (2007a)



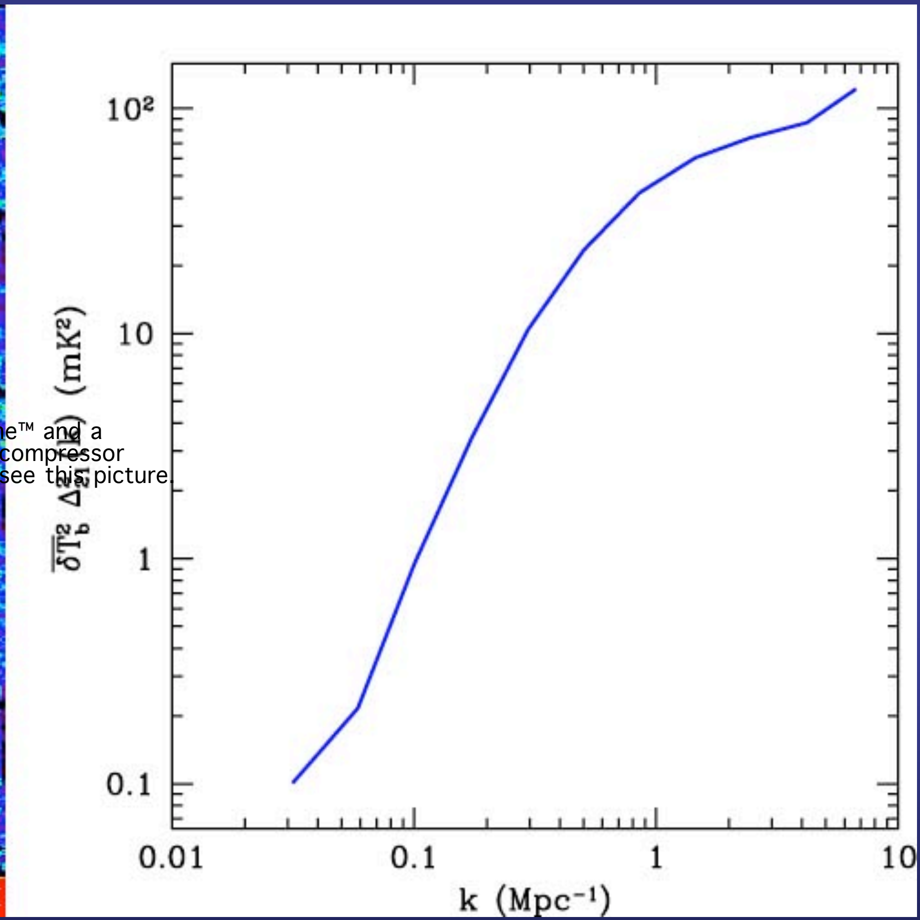
RT ionization field from
Zahn et al. (2007)

Cool PR Movie

available at http://pantheon.yale.edu/~am834/Sim



QuickTime™ and a
mpeg4 decompressor
are needed to see this picture.



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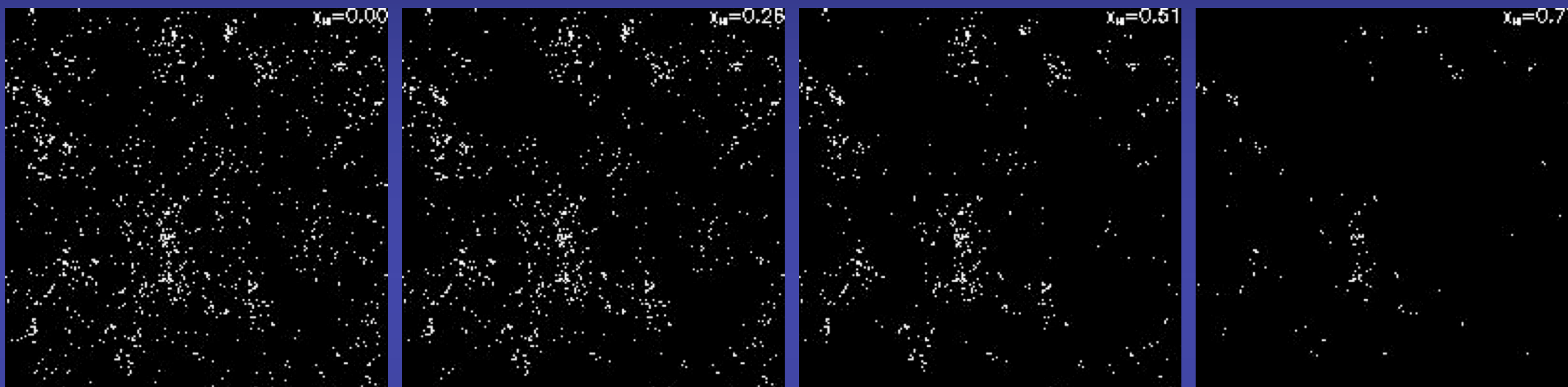
Lyα Emitter Observability

Reionization modulates the observed LAE maps

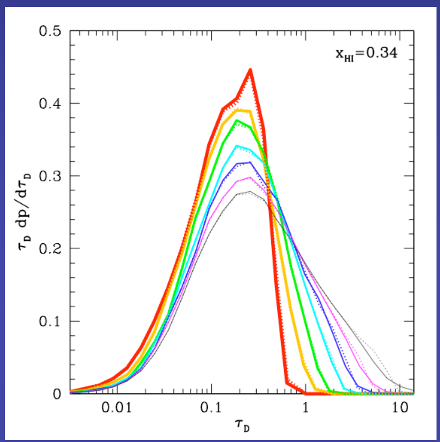
$x_{HI} \sim 0$ | $x_{HI} = 0.26$ | $x_{HI} = 0.51$ | $x_{HI} = 0.77$



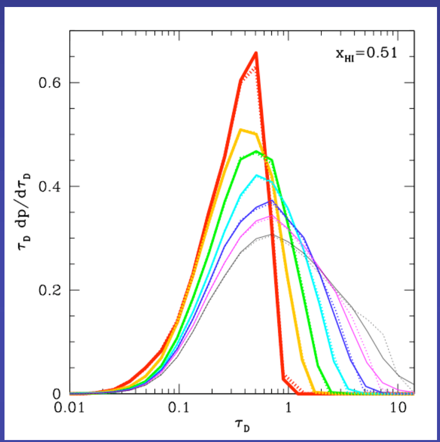
$M > 1.67\text{x}10^{10}\, e^{-\tau}\, M_{SUN}$

τ_D Distributions

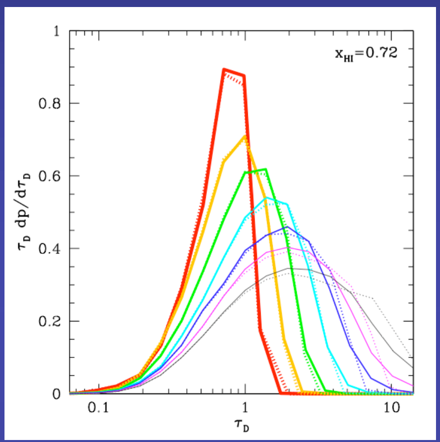
$x_{HI} = 0.34$



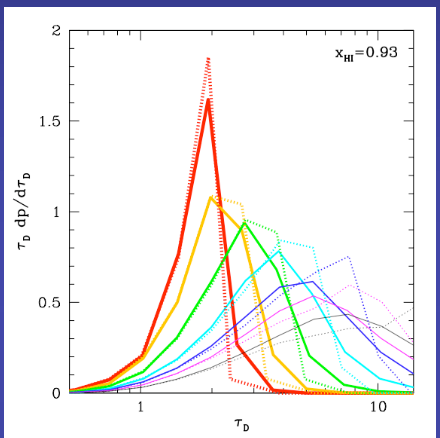
$x_{HI} = 0.51$



$x_{HI} = 0.72$



$x_{HI} = 0.93$



$2 \times 10^9 M_{SUN} < M < 3 \times 10^{11} M_{SUN}$

Massive halos reside close to the cores of large HII regions

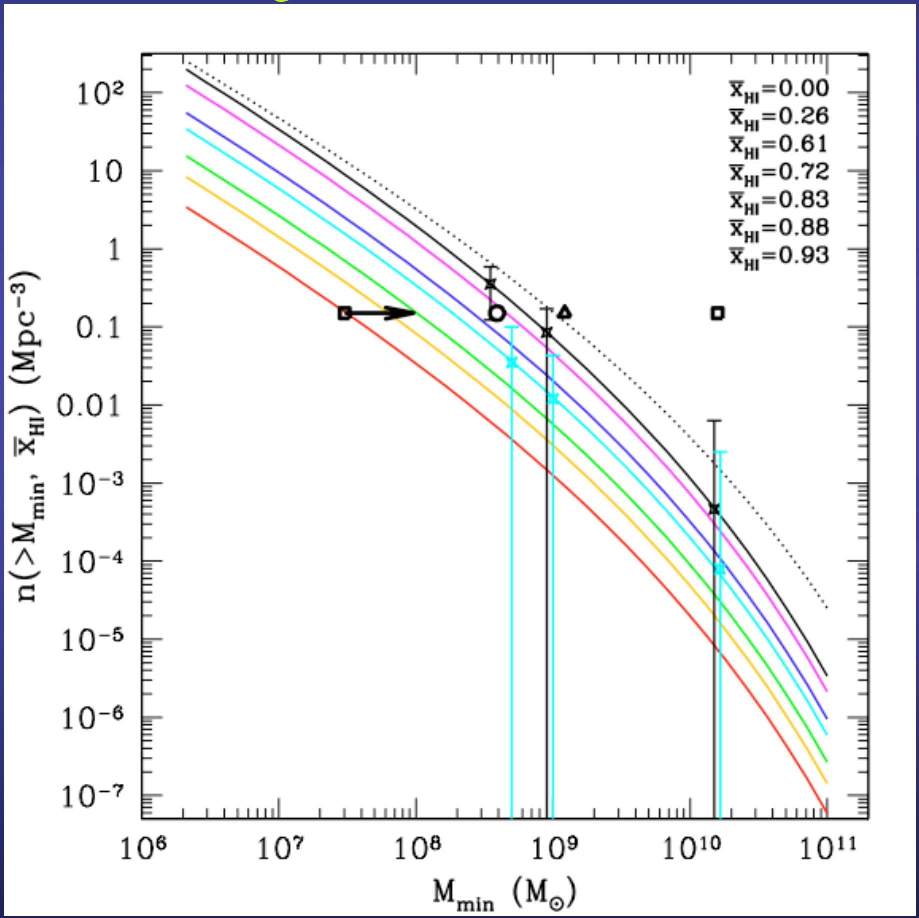
Stark et al. 2007 z~9! LAEs

- Lensing survey of 9 clusters found 6 candidate (>5σ) LAEs at z~9 with L= $10^{41.2}$-$10^{42.7}$ ergs s^{-1}
- No evidence any are low-redshift interlopers
- Constraints from derived number density? Must assume M <--> L
  - Span allowed range…

z=9 Luminosity Functions

$L = 1.88 \times 10^{-12}$ *erg* $(\epsilon_\gamma f_* T_{\gamma,res} / t_*) M$

Mesinger & Furlanetto (2007b)



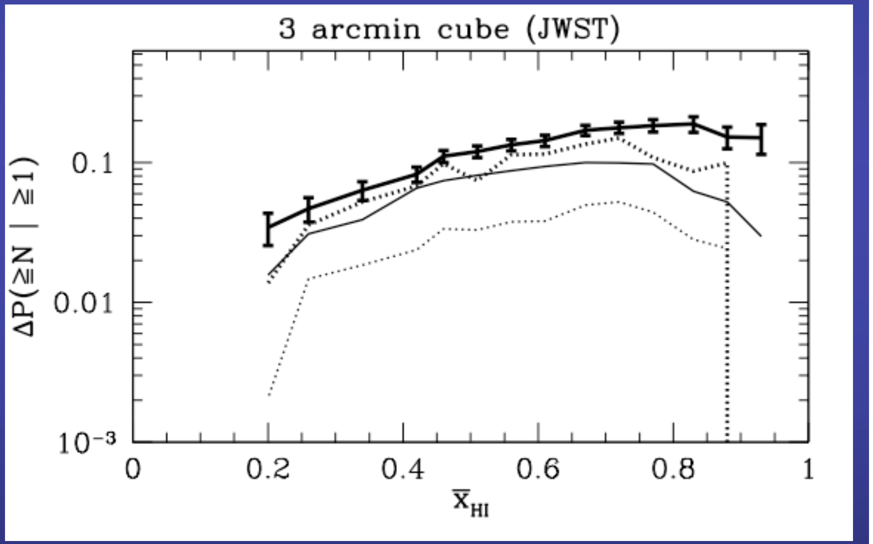
Four M<-->L relations:

1. z~6 with Pop II stars
   -> 0.24 (f_{esc}/0.02) ion ph/H atom
2. z~6 with Pop III stars
   -> 3.1 (f_{esc}/0.02) ion ph/H atom
3. max conservative with Pop II stars
   -> 2.4 (f_{esc}/0.02) ion ph/H atom
4. max conservative with Pop III stars
   -> 31--140 (f_{esc}/0.02) ion ph/H atom

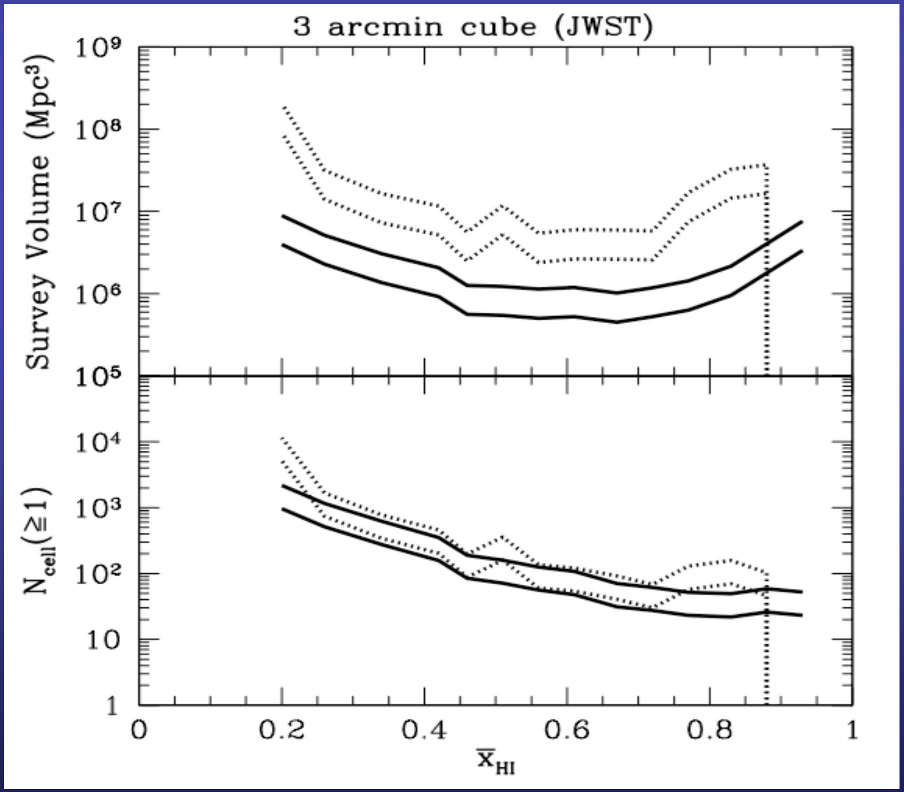
- x_{HI} (z~9) < 0.7
- requires star formation in $<10^9$ M_{SUN} objects

Counts-in-Cell Statistics

- Includes higher-order, non-Gaussian corrections to clustering, unlike the commonly studied power spectrum (e.g. McQuinn et al. 2007; Iliev et al. 2007)
- Not very model dependent; reionization signal is separable from the evolution in structure, especially in higher-order (see Mesinger & Furlanetto 2007b for details)
- Few constraints on survey geometry; useful for follow-up



Reionization detectable with < 100 fields



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Patchy Reionization

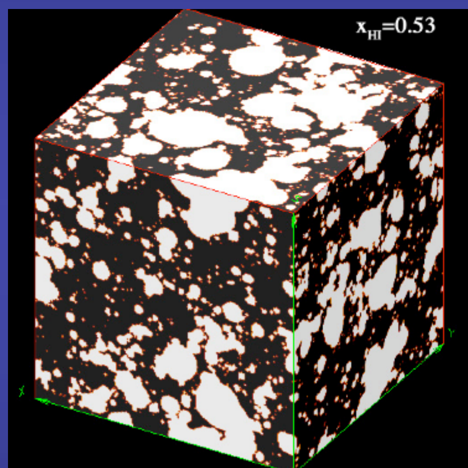
- Almost all reionization constraints are derived assuming a homogeneous x_{HI} or J_{UV} -> wrong!

QuickTime™ and a
mpeg4 decompressor
are needed to see this picture.

- How wrong? Lets focus on damping wing studies:
  - QSOs proximity region (Mesinger & Haiman 2004; 2007)
  - GRB after disentangling DLA (Totani et al. 2006)

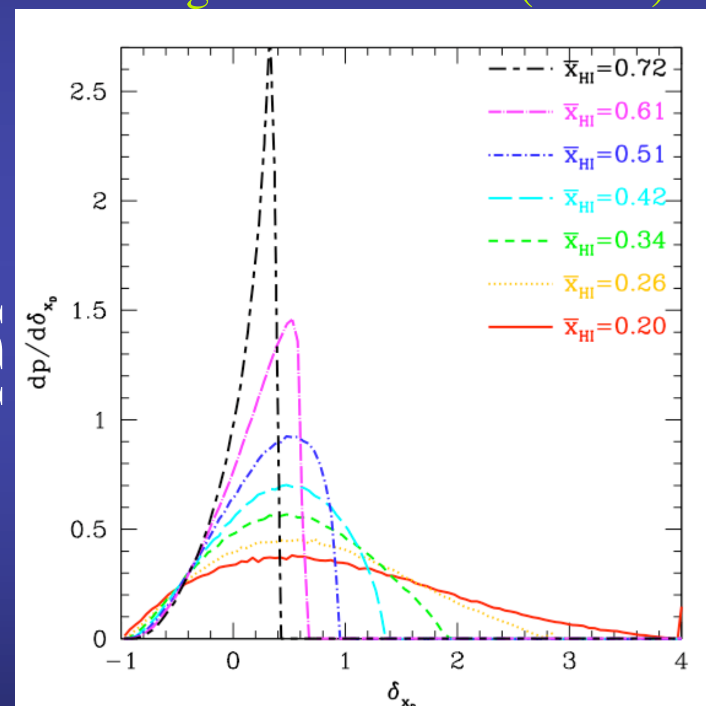
Bias

- Common reasoning: absorption cross-section is flat in the wings and so is sensitive to a large path length in the IGM, so clumpiness is averaged-over
- Not flat enough! -> bias + scatter



Mesinger & Furlanetto (2007c)

PDF



x_D/x_{HI} - 1

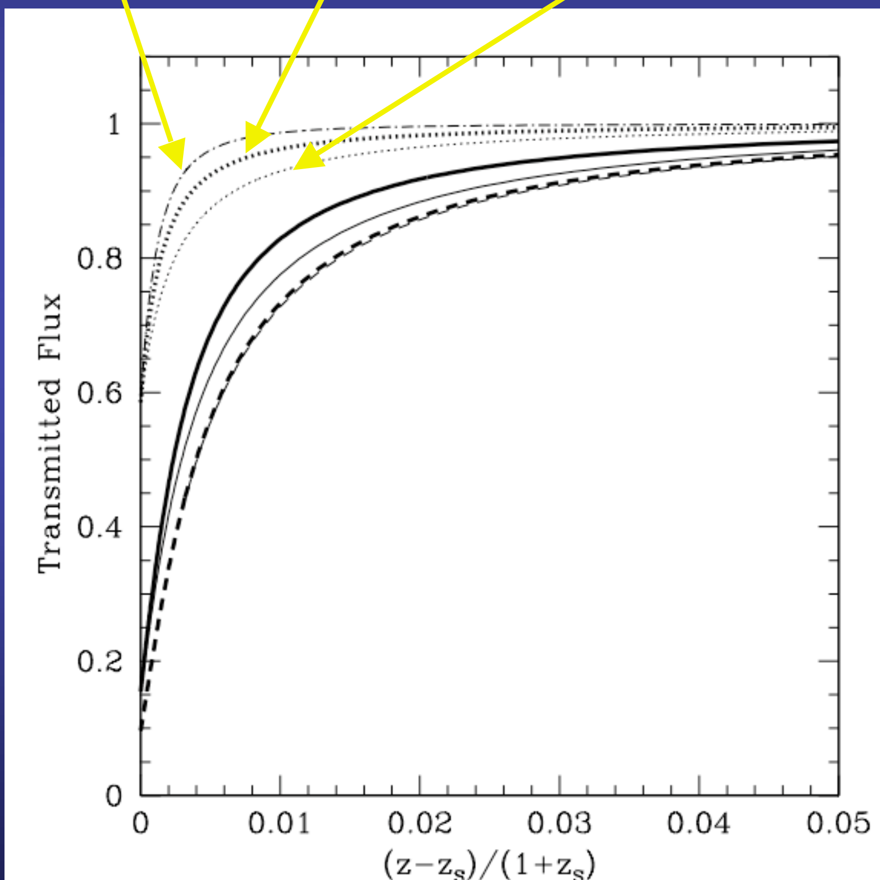
• constrain x_{HI} with scatter? Noise --> Signal

• bias and scatter are reduced if one probes subset (e.g. Rs>40)

Absorption Profile

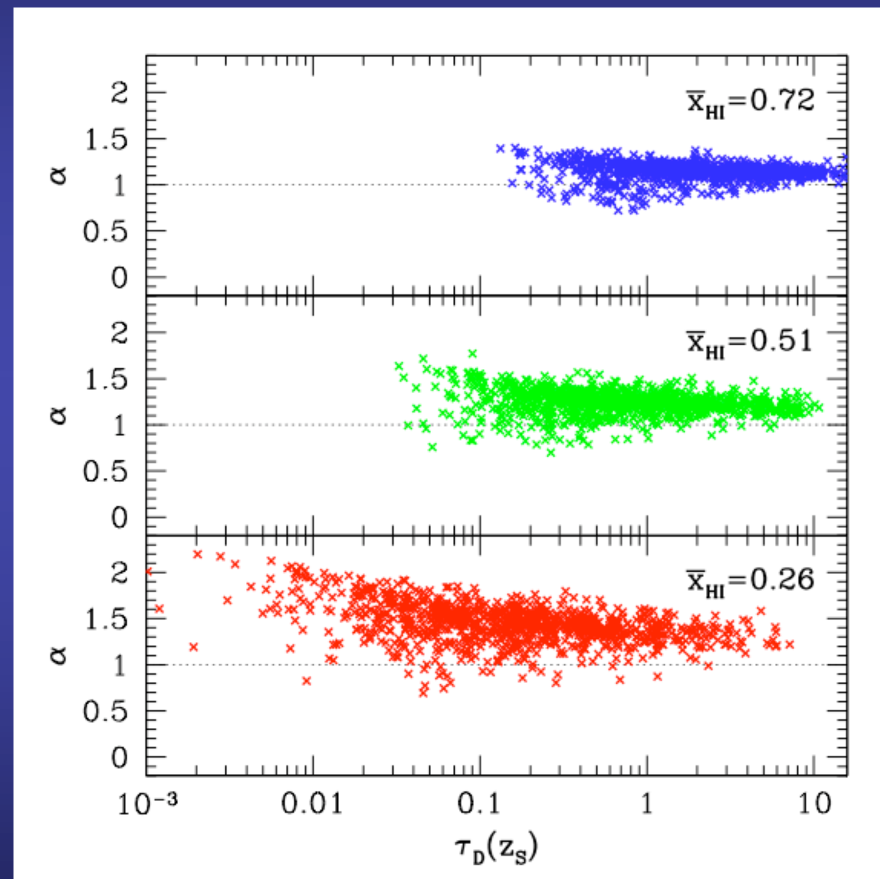
x_{HI}=0.1

DLA patchy homogeneous



$\tau_D(z) \propto R_{b1}^{-\alpha}$

α



$\tau_D(z)$

Impact on Present Damping Wing Studies

- Not clear, however profile is more important than bias: steeper profile -> harder detection

  --> weakens upper limit from Totani et al. 2006

  --> strengthens lower limits from Mesinger & Haiman 2004, 2007

- Scatter likely causes confidence contours to degrade for all studies

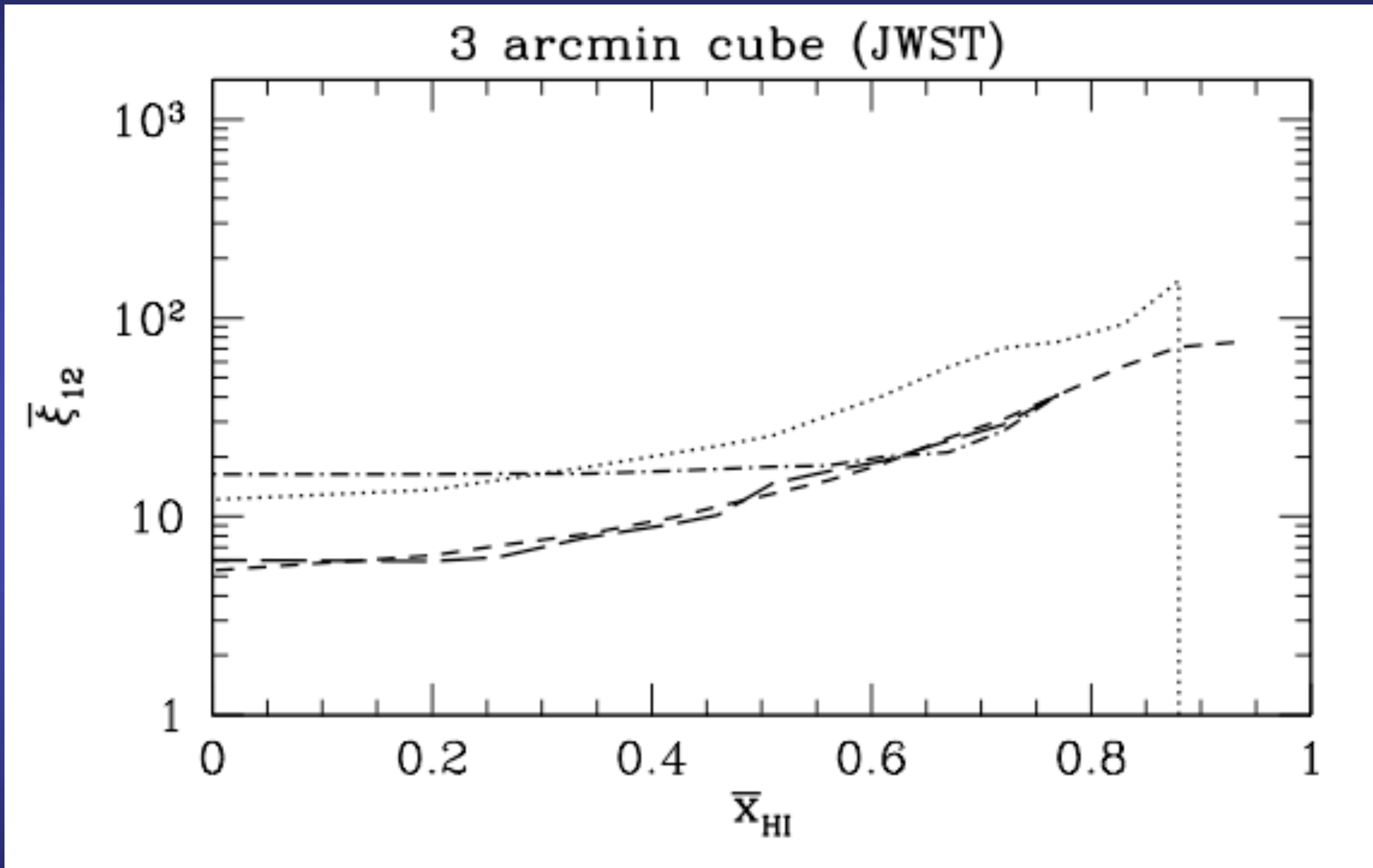
- Should be redone! More sources would be nice

Conclusions

- Our semi-numeric simulation can be a very useful scientific tool:
  - density and velocity biases, ionization topology, but also radiative and chemical feedback, LAE studies, deterministic merger trees, training ground for bubble detection algorithms and other 21-cm software, allows for wide parameter studies…
  - Fairly easy to fold-in smaller scale physics calibrated from numerical simulations.

Conclusions, *cont.*

- If Stark et al. 2007 z~9 LAEs are genuine… (burden of proof on observers)
  - $x_{HI}(z\sim9) < 0.7$
  - significant star formation in extremely low mass halos, $< 10^9$ M_{SUN}
- Counts-in-cells is a very powerful statistic for detecting reionization-induced clustering
  - Fewer than 100 JWST-esque narrowband fields should be needed at $x_{HI}>0.5$
- Inhomogeneous reionization induces a bias and scatter in damping wing estimates of x_{HI}, when compared to homogeneous reionization. Absorption profile is on average steeper.
- Observations of reionization MUST be interpreted by comparison to models of inhomogeneous reionization


3 arcmin cube (JWST)
10^3
10^2
10
1
$\bar{\xi}_{12}$
0
0.2
0.4
0.6
0.8
1
$\bar{x}_{HI}$