Semi-Numerical Tools Applied to UV Radiative Feedback and Lyα Damping Wing Constraints on Reionization

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in collaboration with Steven Furlanetto and Mark Dijkstra

Outline

- Efficient “semi-numerical” simulations of structure and reionization

- Recent applications of simulations:
  - UV Radiative Feedback and M_{min}
  - Lyα damping wing in non-homogeneous reionization

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Deus ex Machina (DexM)?

Halo fields

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

1. create linear density and velocity fields (like N-body)
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)

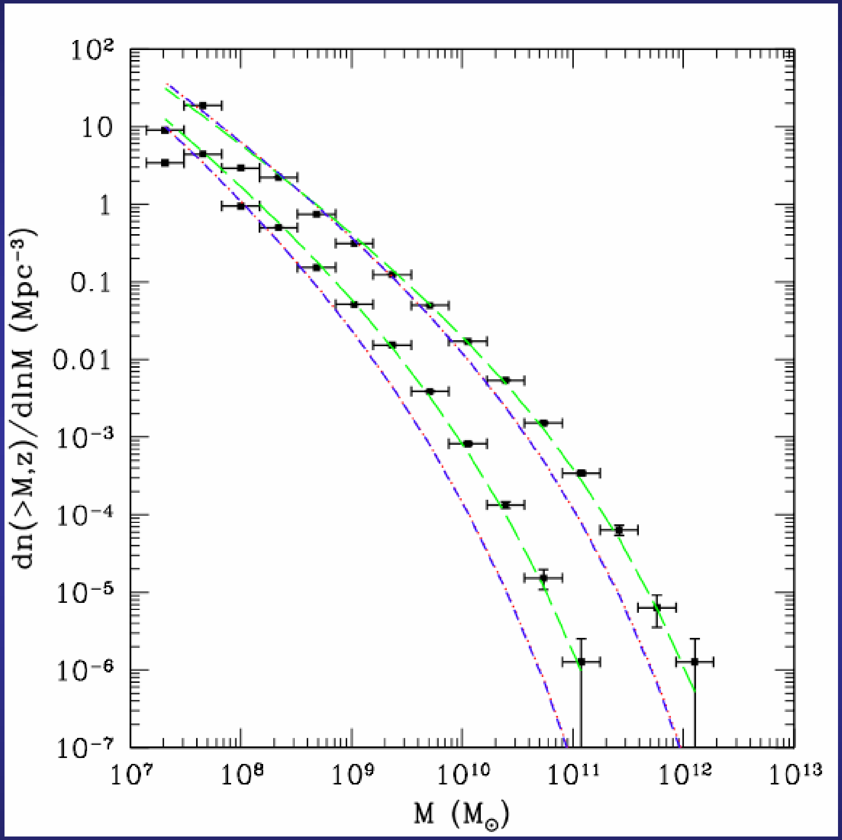
Ionization fields

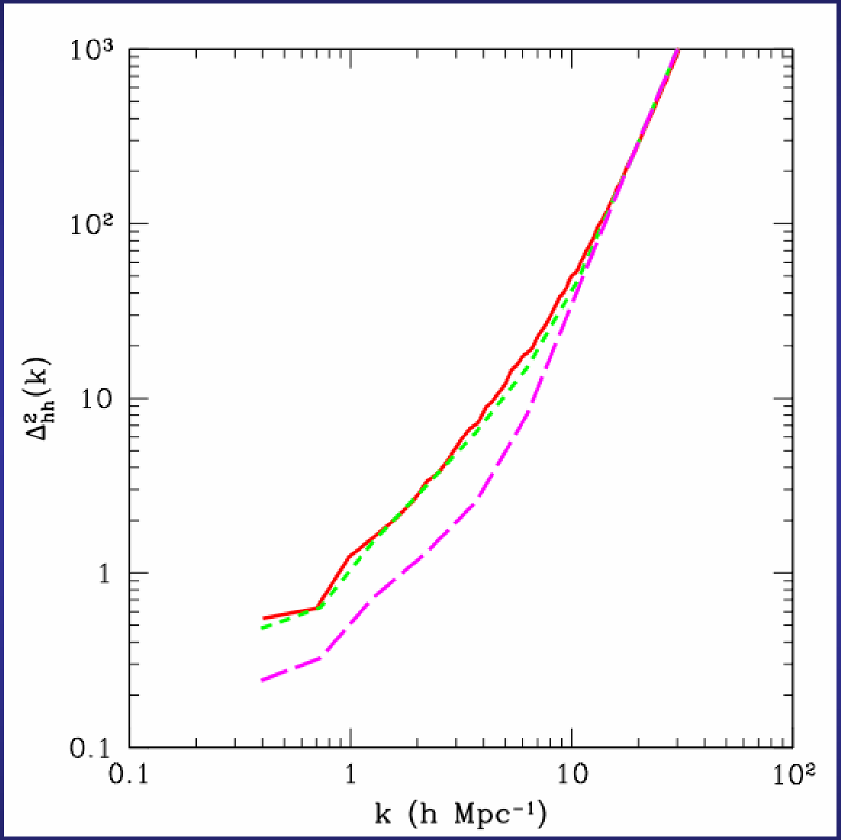
(similar to Zahn et al. 2007)

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 (2007)

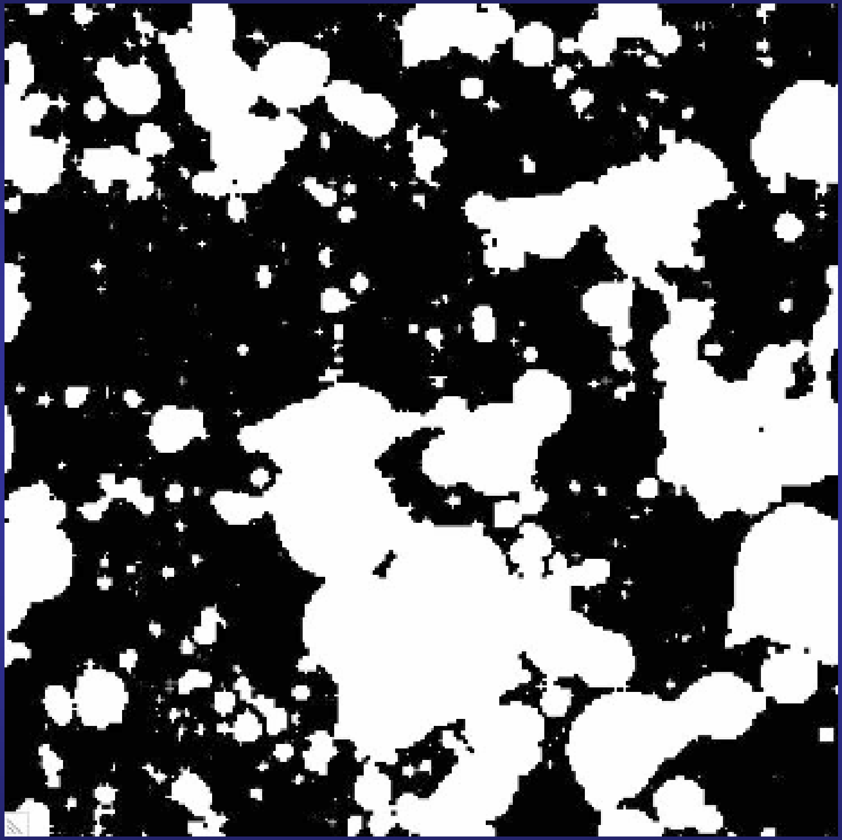


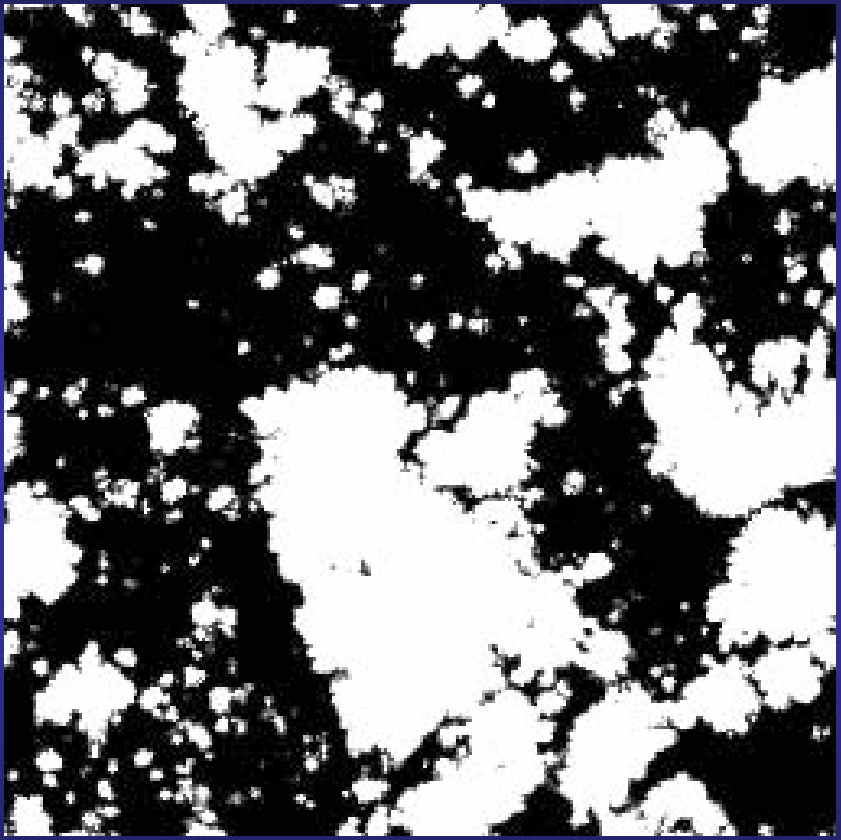


z=8.7 N-body halo field from McQuinn et al. (2007)

HII Bubble Filtering

Mesinger & Furlanetto (2007)

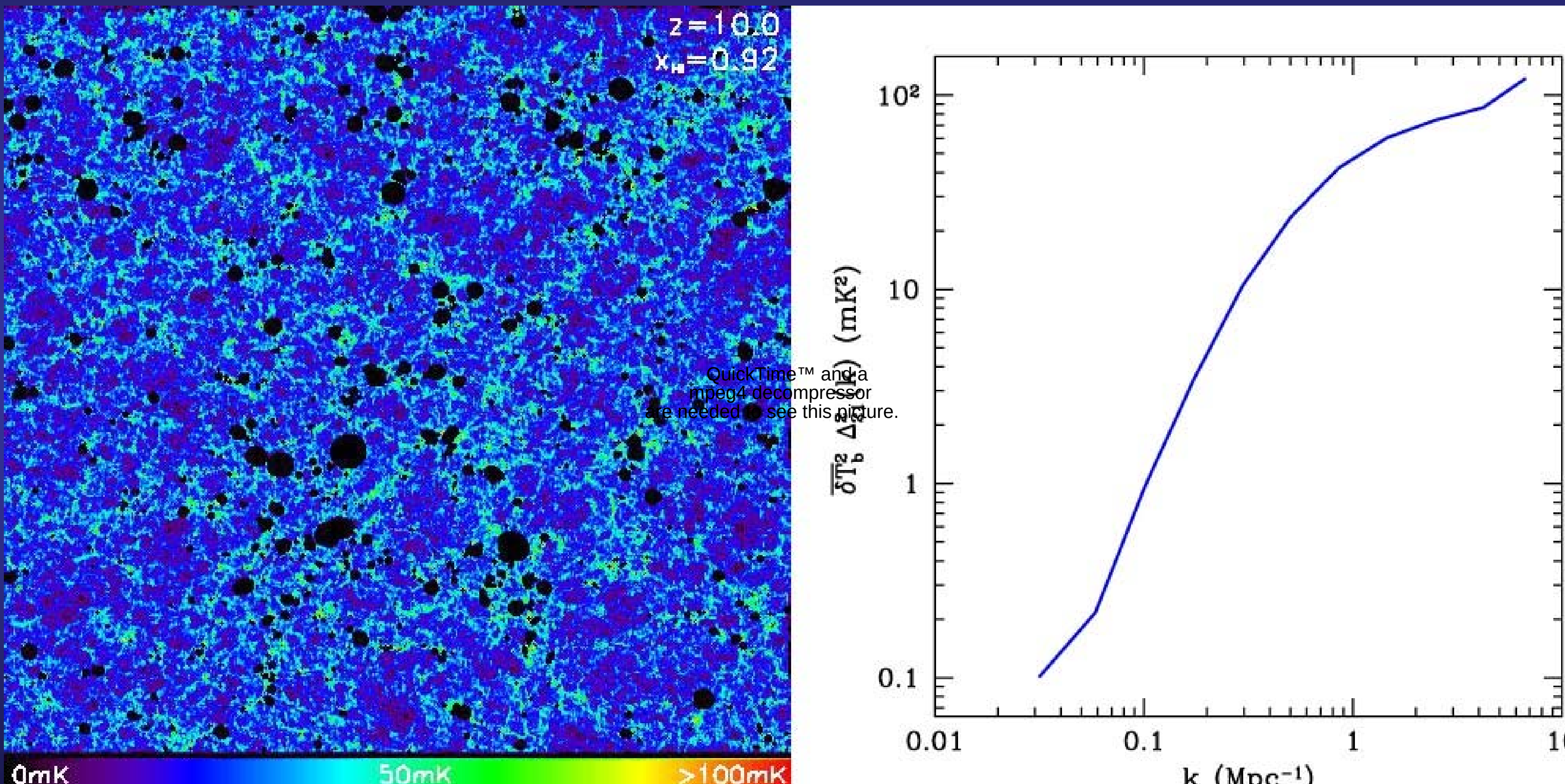




RT ionization field from Zahn et al. (2007)

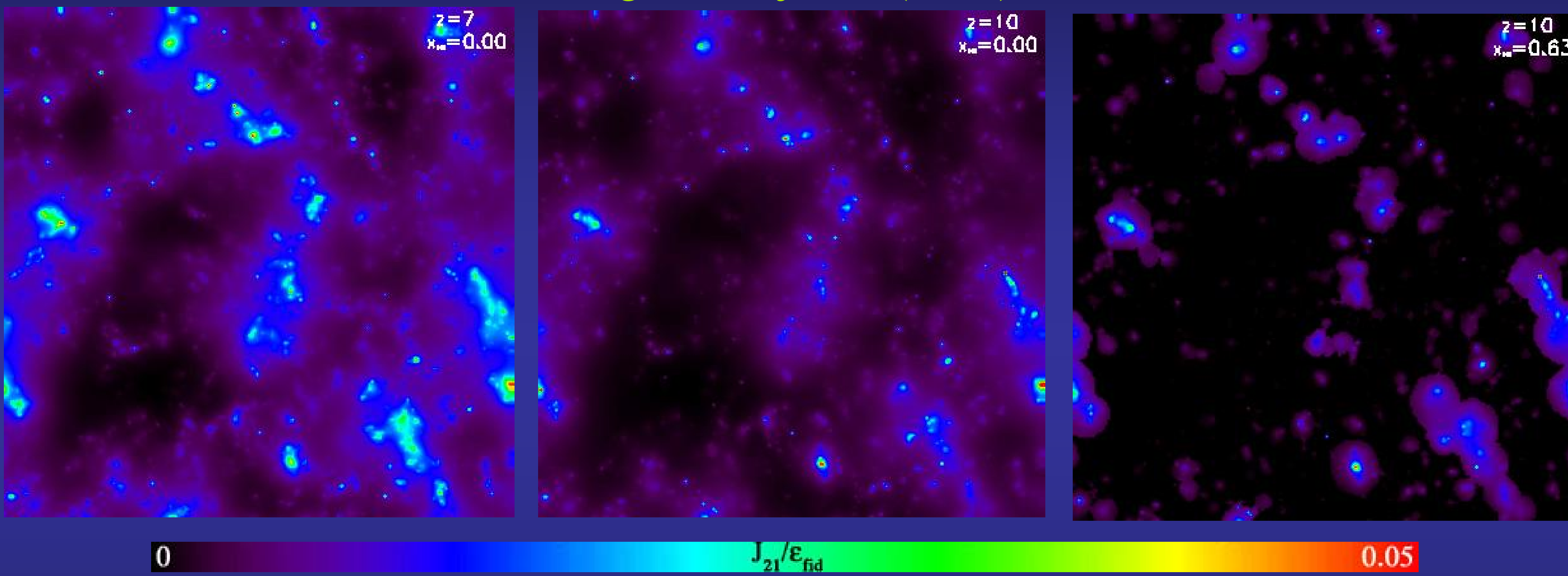
Cool PR Movie

available at http://www.astro.ucla.edu/~mesinger



Ionizing UV Flux Fields

Mesinger & Dijkstra (2008)



$$\text{flux} \propto \sum L(M_{halo})/r^2 \, e^{-r/\lambda_{mfp}}$$

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M_{min}?

- Ionizing UVB suppresses gas content of low-mass galaxies (e.g. Efstathiou 1992; Shapiro+1994; Thoul & Weinberg 1996; Hui & Gnedin 1997; Gnedin 2000)
- How important is this negative feedback during reionization? (we focus on atomically-cooled halos, $T_{vir}>10^4$ K)
  - can extend reionization
  - early work, z=2 halos with $v_{cir}<35$km/s completely suppressed; $v_{cir} < 100$km/s partially suppressed
  - NOT THIS SIMPLE! Not instantaneous; high-z mediated by more compact profiles, increased cooling efficiencies, shorter exposure times (Kitayama & Ikeuchi 2000; Dijkstra+ 2004)
- Can we draw any general conclusions about this exceedingly complex problem?

Systematic approach -> Minimize Assumptions

Does UV radiative feedback impact the advanced stages of reionization? Does/How M_{min} effectively increase in ionized regions?

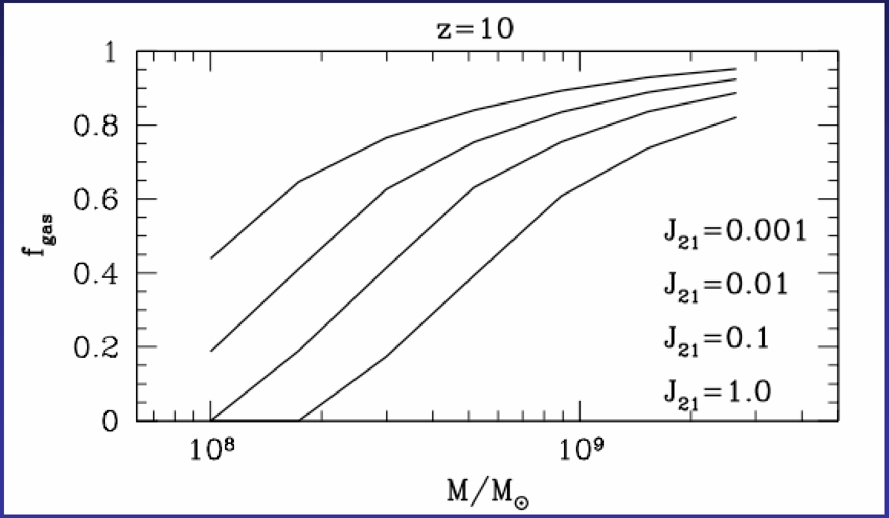
- We do NOT attempt to self-consistently model reionization (we are humble mortals..)
- LARGE parameter space (small knowledge at high-z):
  - z = 7, 10, 13
  - $<x_{HI}>$
  - ionization efficiency, ε_{fid} (=1 to match z=6 LAE and LBG LFs)

Two Tier Approach

Mesinger & Dijkstra (2008)

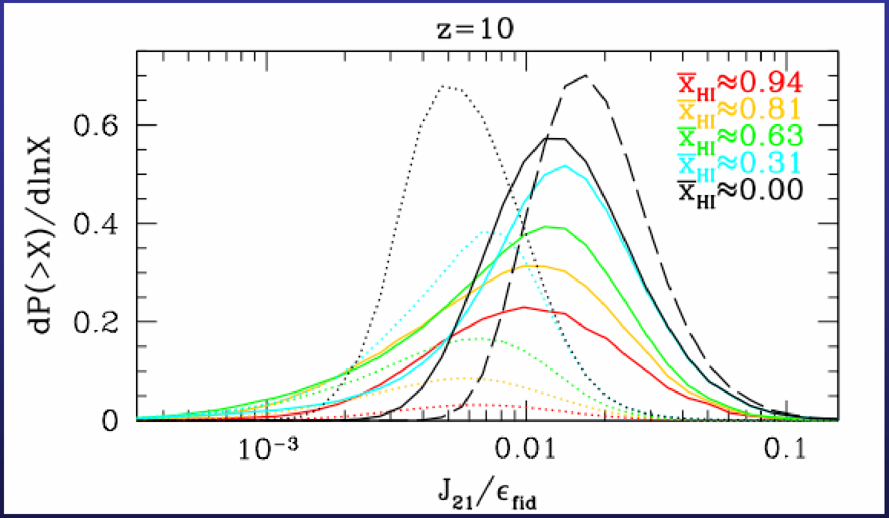
- 1D hydro simulations to model collapse of gas + dark matter under UVB:

  $f_g(M_{halo}, z, J_{21}, z_{on}=14)$



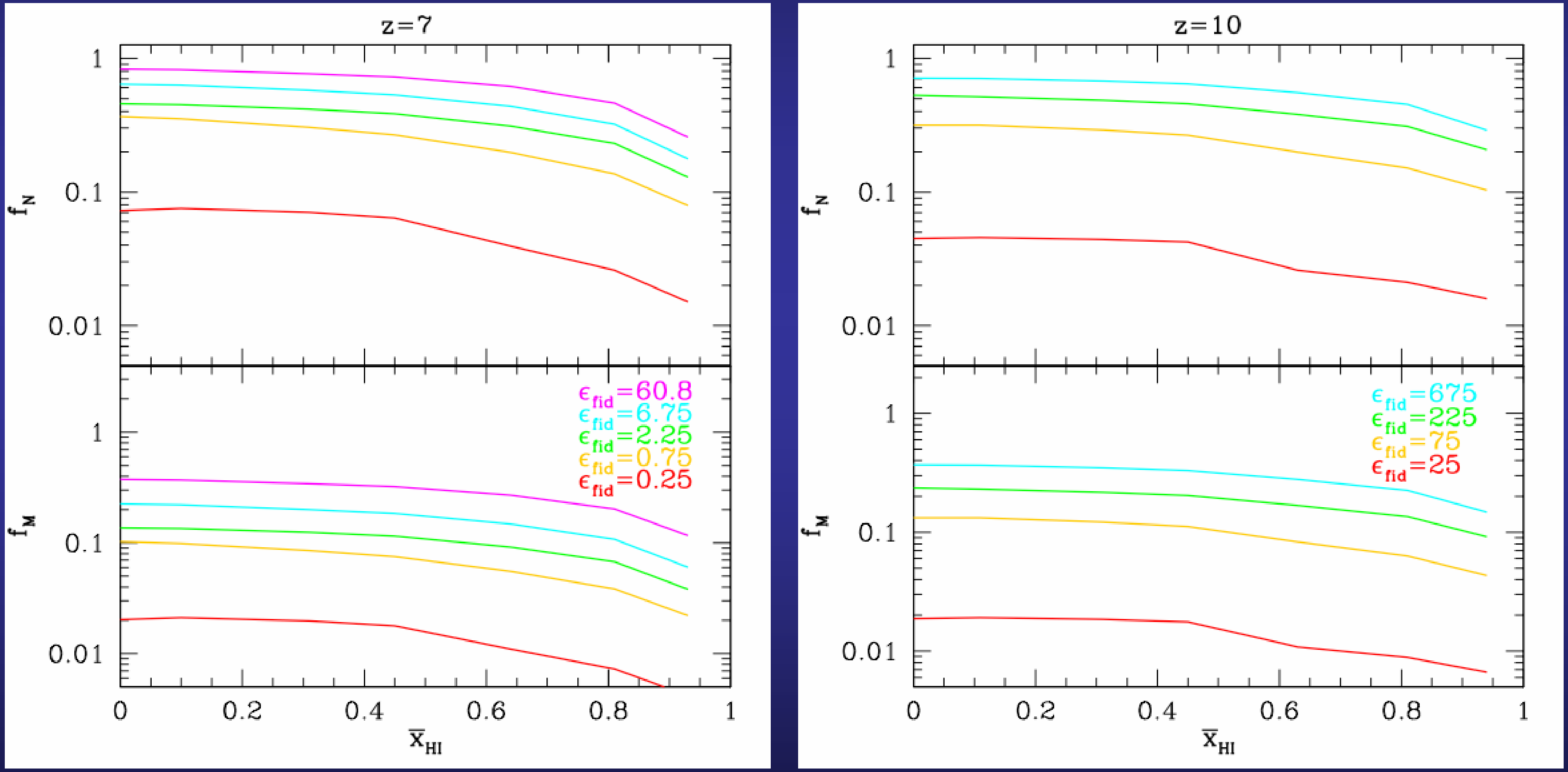
- Semi-numerical code to model halo, density, ionization and *inhomogeneous* flux fields:

  $J_{21}(\mathbf{x}, z, <x_H>, \varepsilon_{fid})$

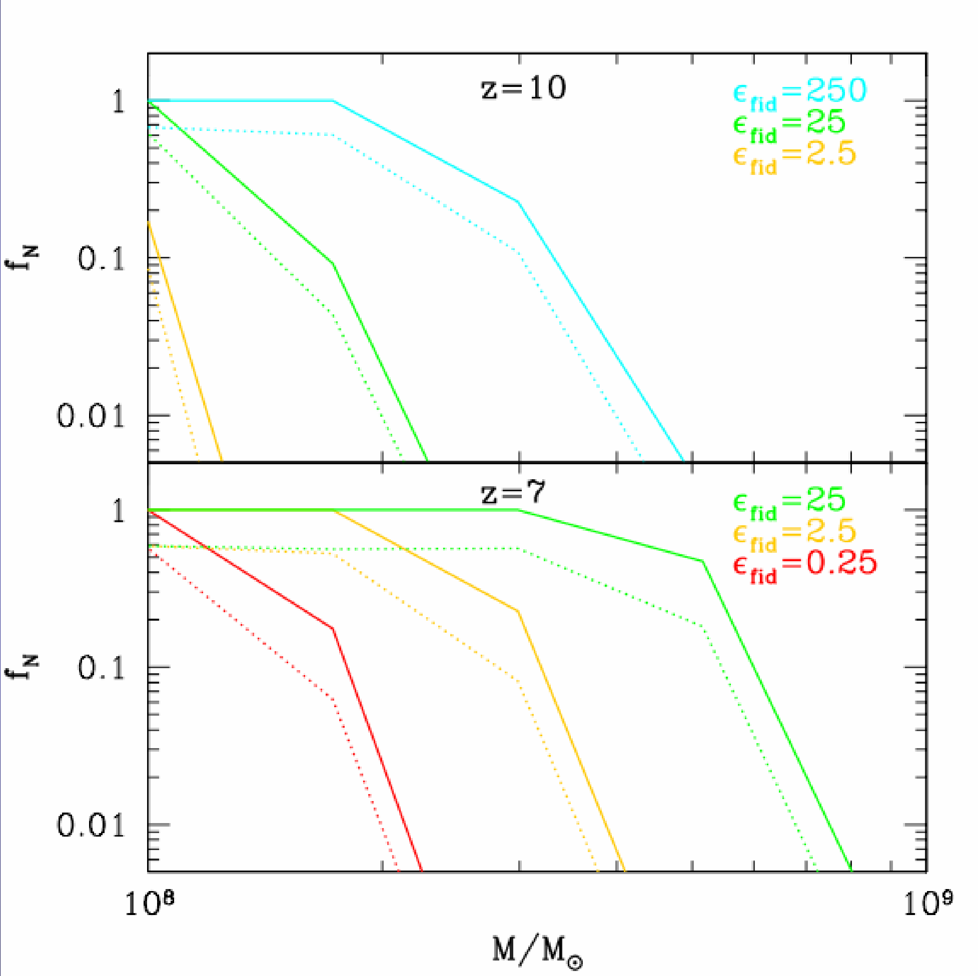


Global impact

Mesinger & Dijkstra (2008)



M_{min}



- Factor of 10 increase in ionizing efficiency is required to extend suppression by only factor of 2 in mass.

Being Conservative…

- Assumed hard, QSO-like spectra. Galactic spectra effectively mean $\varepsilon_{fid}=0.2$
- No self-shielding
- $\lambda_{mfp} = 20$ Mpc (the high-end of z<4 LLS extrapolations; Storrie-Lombardi+ 1994)
- $z_{on} = 14$ ($z_{re} = 11.0 \pm 1.4$; Dunkley+ 2008)
  – biased halo formation
- No redshift evolution of J_{21} over z_{on} --> z

UV Feedback Conclusions / Implications

- UV feedback on $T>10^4$ K halos NOT strong enough to notably affect bulk of reionization (requires factor of ~100 increase in ionizing efficiencies)
- Effectively $M_{min} \sim 10^8 M_{sun}$ throughout most of reionization when minihalos go away (consistent with claims that faint galaxies dominate photon budget at z>6; Yan & Windhorst 2004a,b; Bouwens+ 2006)
- Natural timescale for bulk of reionization is the growth of the collapsed fraction in $T>10^4$ K halos, with small filling factor tail extending to higher z due to $T<10^4$ K halos
- Dynamic range is important in modeling reionization!

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Patchy Reionization

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

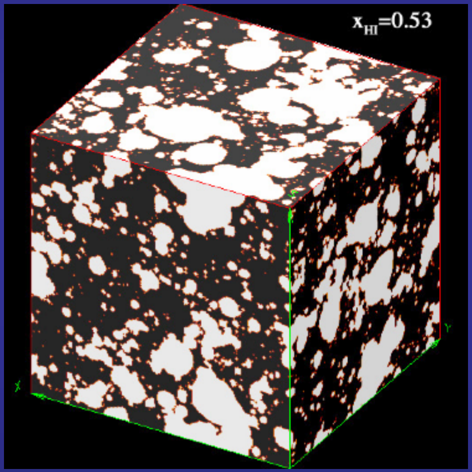
QuickTime™ and a
mpeg4 decompressor
are needed to see this picture.

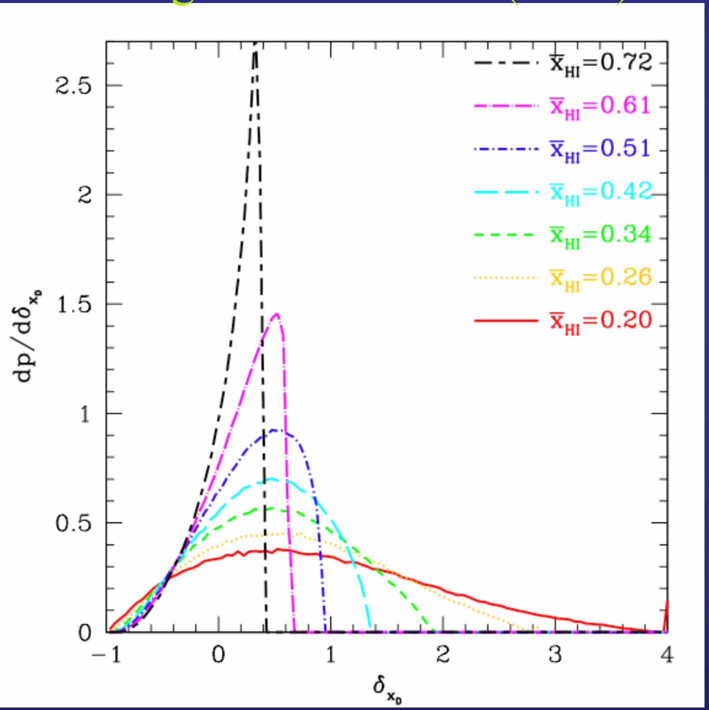
- How wrong? Lets focus on damping wing studies:
  - QSOs proximity region (Mesinger & Haiman 2004; 2007)
  - GRB after disentangling DLA (Totani et al. 2006)

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 (2008)





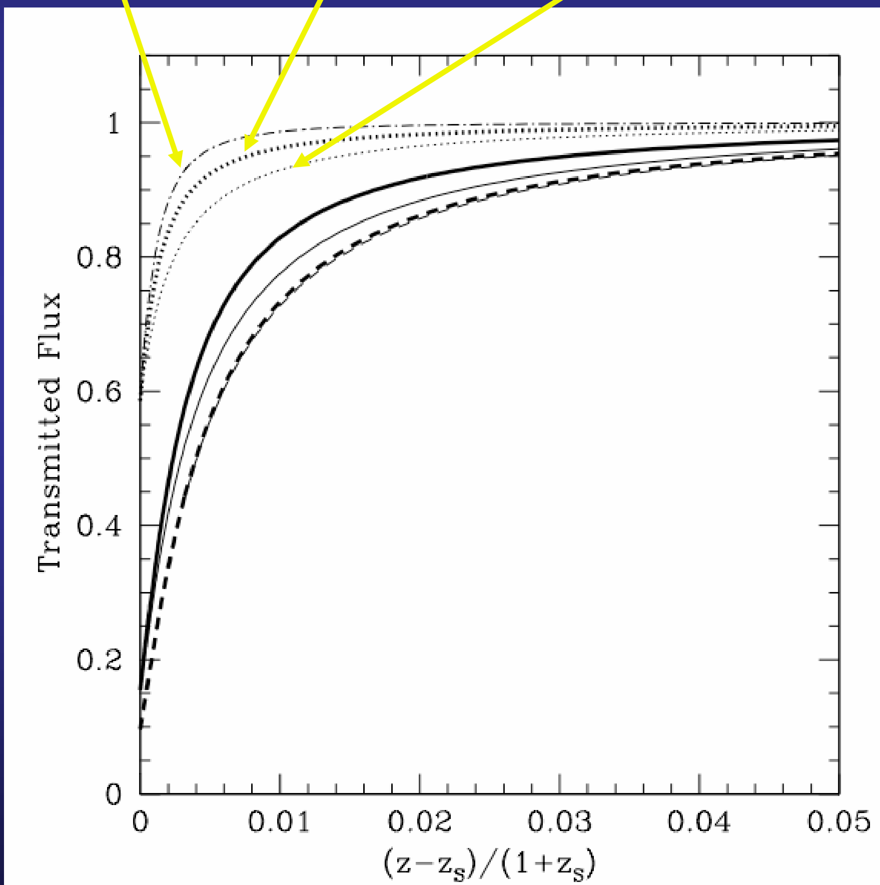
x_D/x_{HI} - 1

- *constrain x_{HI} with scatter? Noise --> Signal*
- *bias and scatter are reduced if one probes subset (e.g. R_s>40 Mpc)*

Absorption Profile

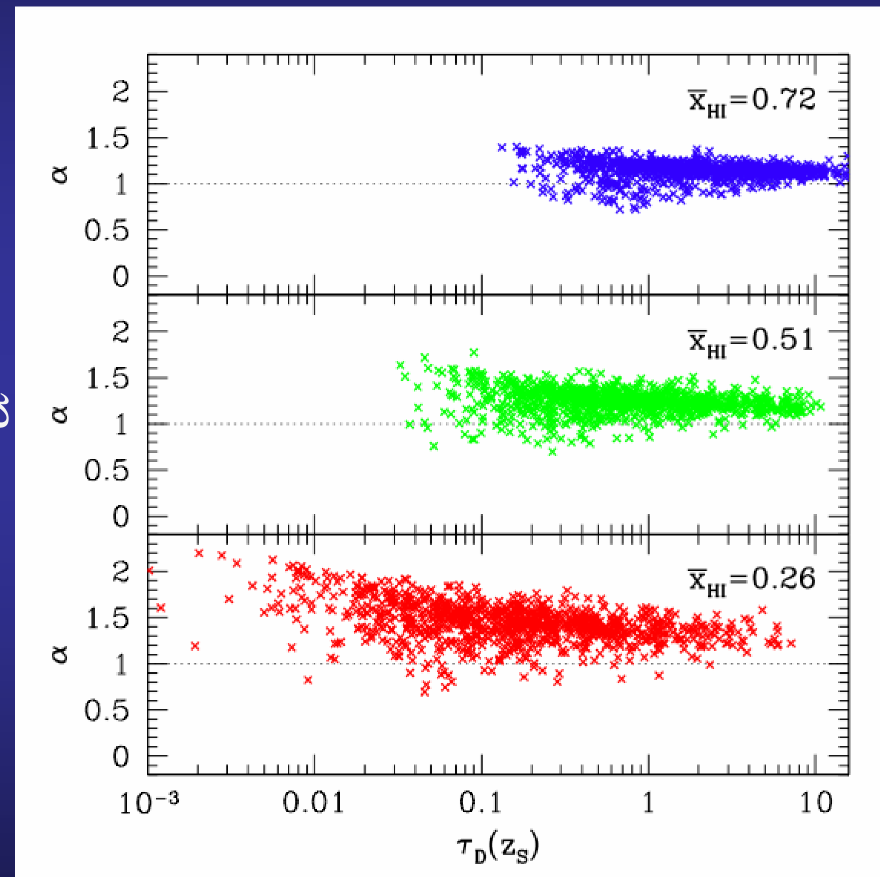
x_{HI}=0.1

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, 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.*

- UV feedback on $>10^4$ K halos NOT strong enough to notably delay bulk of reionization.
- $\sim 10^8$ M_{sun} halos must be taken into account during reionization even in ionized regions
- 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