21cmFAST

A Fast, Semi-Numerical Simulation of the High-Redshift 21cm Signal

Mesinger, Furlanetto, & Cen (2010)

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Motivation

- Dynamic range required is enormous: single star --> Universe
- 21cm observations are on LARGE (Gpc) scales
- We know next to nothing about high-z --> ENORMOUS parameter space to explore
- Cosmological numerical simulations are computationally expensive (not good for parameter studies) and don't even approach the scales of 21cm observations
- Most relevant scales are in the linear to quasi-linear regime

Philosophy

Semi-numerical and Analytic Estimates

Semi-numerical Simulations

(*independent* 3D realizations; *FAST!*)

Hydrodynamical Numerical Simulations (+RT)

scale

21cmFAST

- Portable and FAST! (if it's in the name, it must be true…)
  - A realization can be obtained in ~ minutes on a single CPU
  - Does not require lots of RAM (unlike DexM; Mesinger & Furlanetto 2007)
- Run on arbitrarily large scales
- Optimized for the 21cm signal
- Vary many independent free parameters; cover wide swaths of parameter space
- Calibrated to hydrodynamic cosmological simulations
- Publically available!

21cmFAST: 3D realizations

$$\delta T_b(\nu) \approx 27 \boxed{x_{\rm HI}} \boxed{(1+\delta_{\rm nl})} \boxed{\left(\frac{H}{dv_r/dr + H}\right)} \boxed{\left(1-\frac{T_\gamma}{T_S}\right)} \left(\frac{1+z}{10}\,\frac{0.15}{\Omega_M h^2}\right)^{1/2} \left(\frac{\Omega_b h^2}{0.023}\right) \mathrm{mK}$$

spin temperature

LOS velocity gradient

neutral fraction

gas density

21cmFAST: 3D realizations

$$\delta T_b(\nu) \approx 27 \underbrace{\boxed{x_{\rm HI}}}_{\text{neutral fraction}} \underbrace{\boxed{(1+\delta_{\rm nl})}}_{\text{gas density}} \underbrace{\boxed{\left(\frac{H}{dv_r/dr + H}\right)}}_{\text{LOS velocity gradient}} \underbrace{\boxed{\left(1-\frac{T_\gamma}{T_S}\right)}}_{\text{spin temperature}} \left(\frac{1+z}{10}\frac{0.15}{\Omega_M h^2}\right)^{1/2} \left(\frac{\Omega_b h^2}{0.023}\right) \mathrm{mK}$$

Compare with hydro sims of Trac & Cen (2007); Trac+ (2008)

- coupled hydro, DM, 5 freq. RT, M_{min}~$10^8 M_{sun}$, L=143 Mpc

Density Fields

1. create linear density and velocity fields (like N-body)
2. perturb linear density field using first-order displacement vectors (Zel'Dovich 1970)
3. recreate evolved velocity field corresponding to the evolved density field

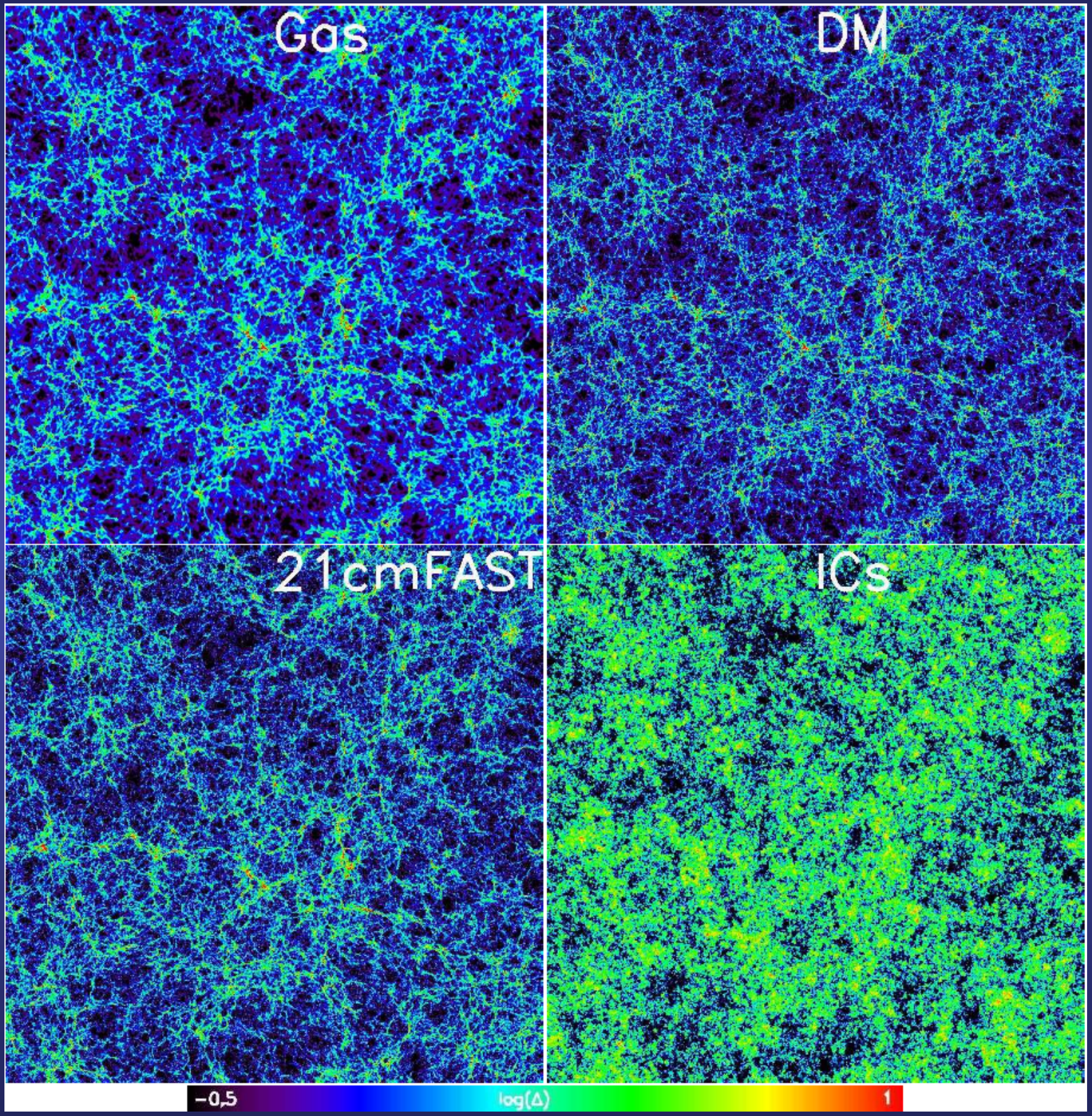
OR

1. scale ICs using linear growth factor

Density Fields, Pics

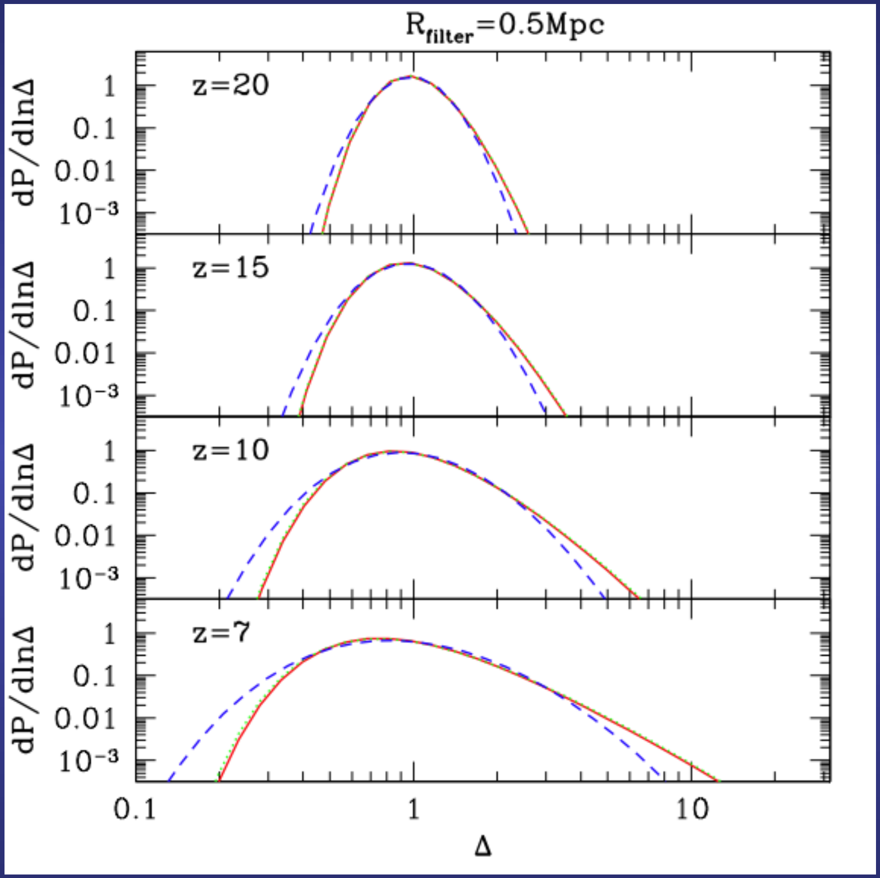
z=7

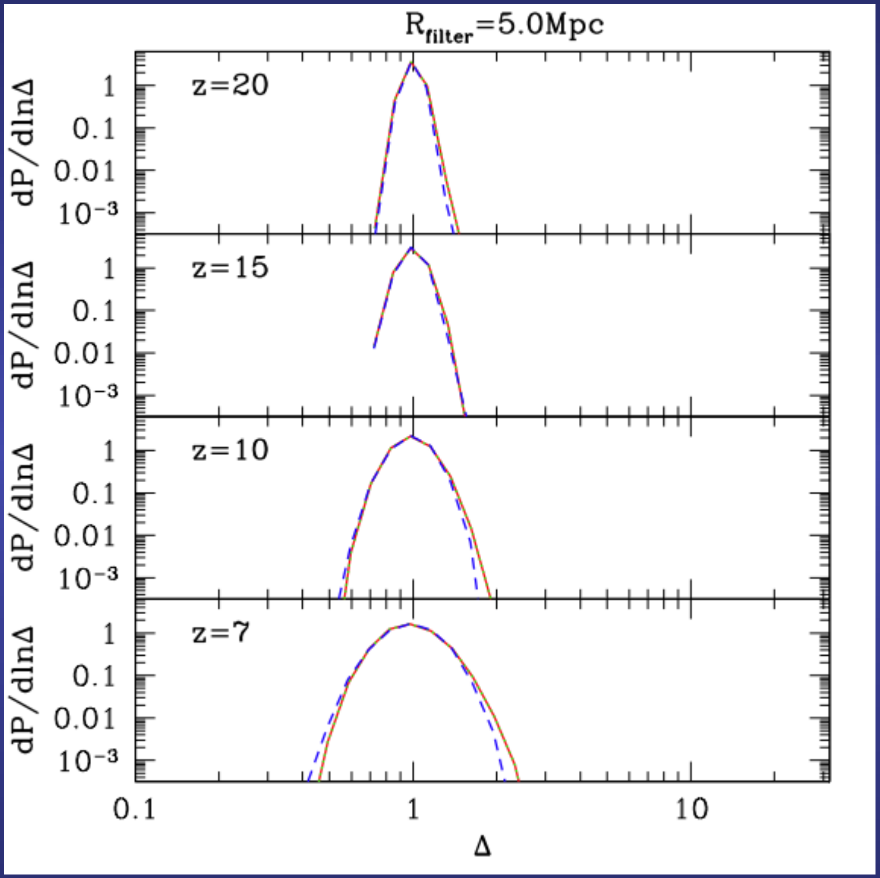
0.19 Mpc cells



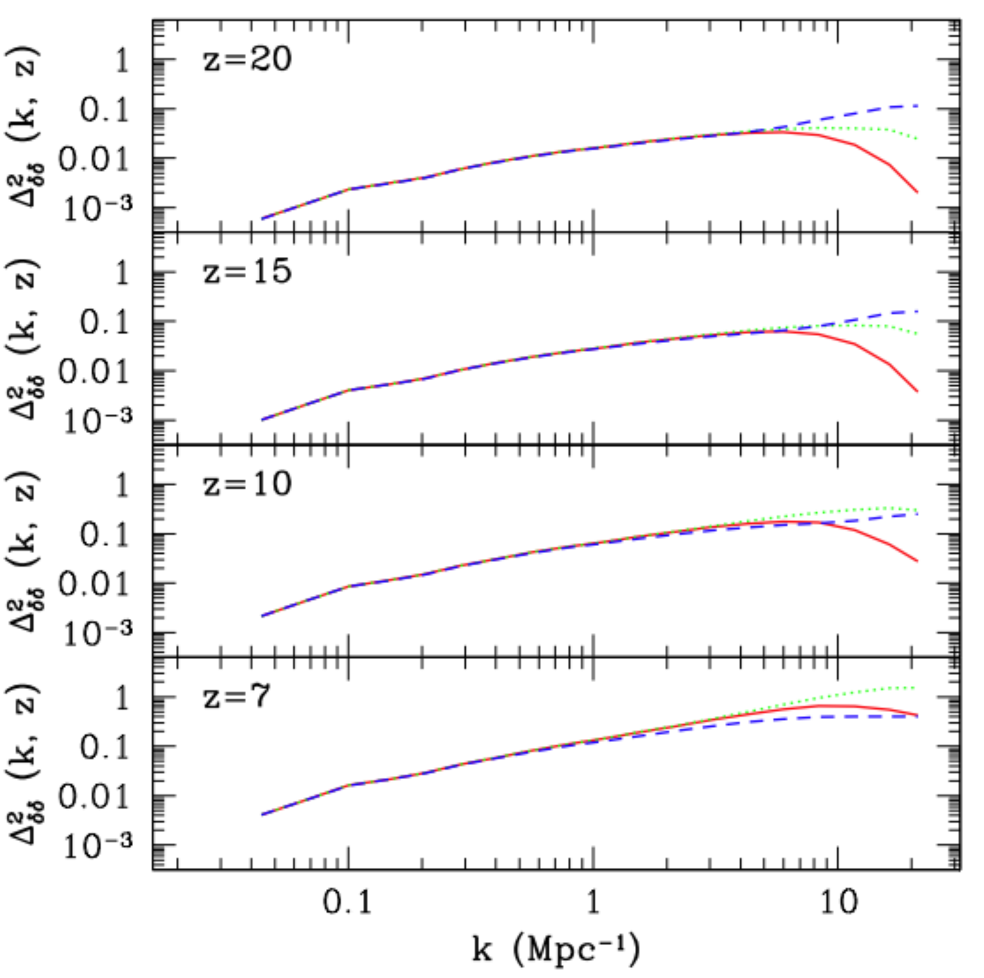
143 Mpc

Density Fields, PDFs





Density Field, power spectra



-Collapse of gas is delayed with respect to DM

-Jeans smoothing, which depends on uncertain ionization + heating history

Note scales

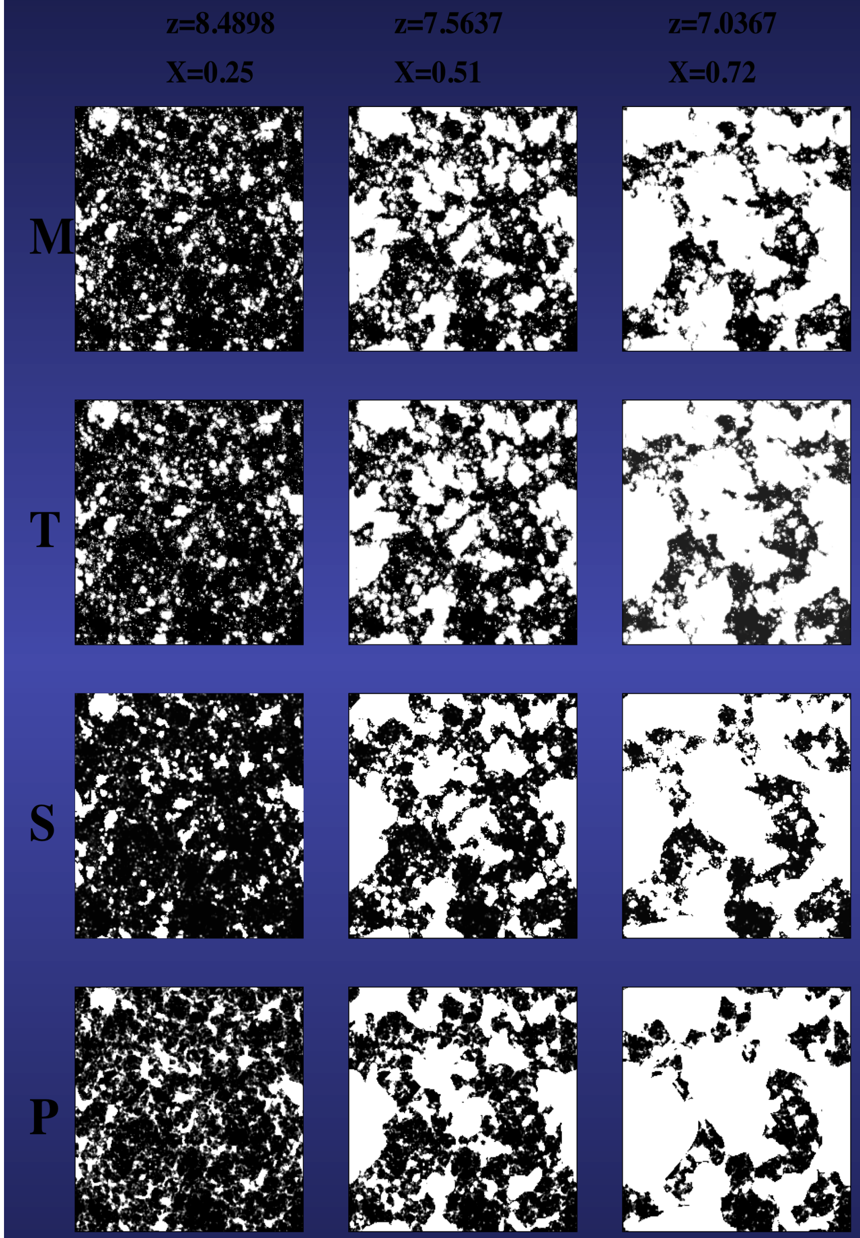
Ionization Fields

(look Ma, no halos…)

- Use excursion-set formalism (e.g. Furlanetto et al. 2004), and check if $f_{coll}(R_{filter}, x, z) > 1/\zeta$, starting from some R_{max} --> R_{cell}
- Use evolved density field to compute f_{coll}
- Set fractional ionization at last filter step from subgrid sources
- If desired, include Poisson fluctuations in halo number when computing f_{coll}

(see Zahn+ 2010)

Pics



McQuinn+ (2007)

Trac & Cen (2007)

FFRT-S

see Zahn+ (2010)

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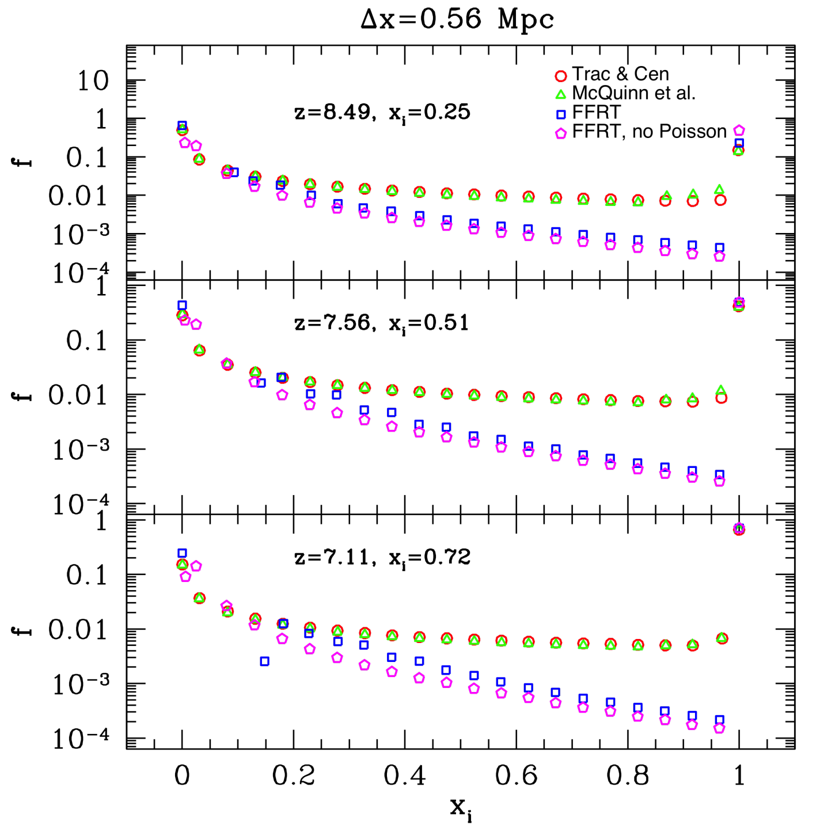
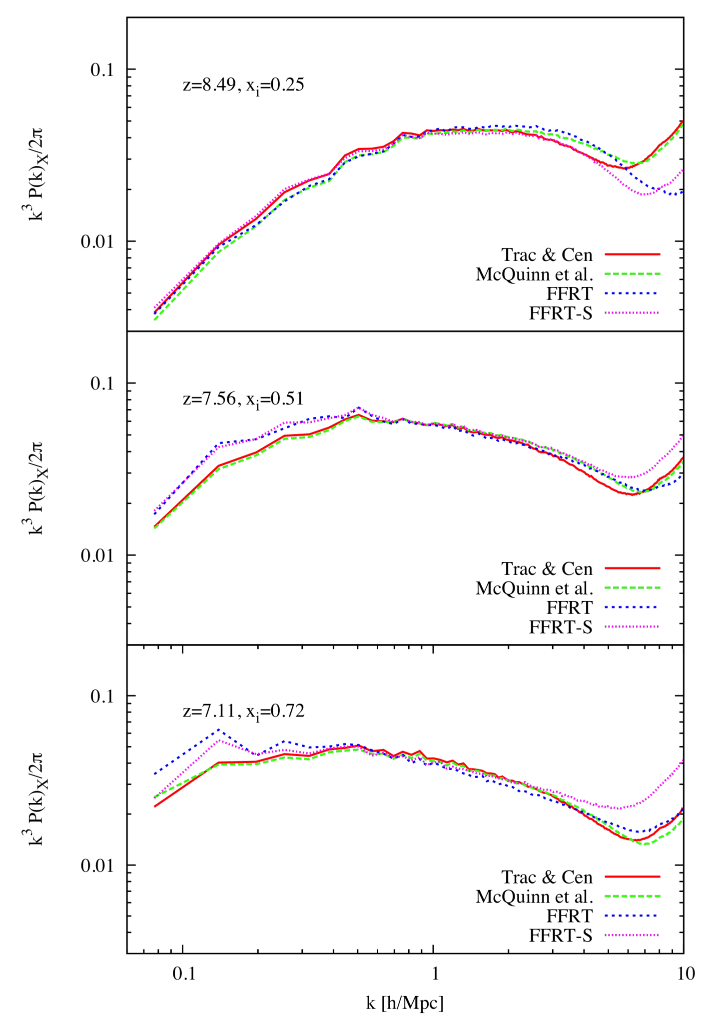
Ionization Fields, PDFs

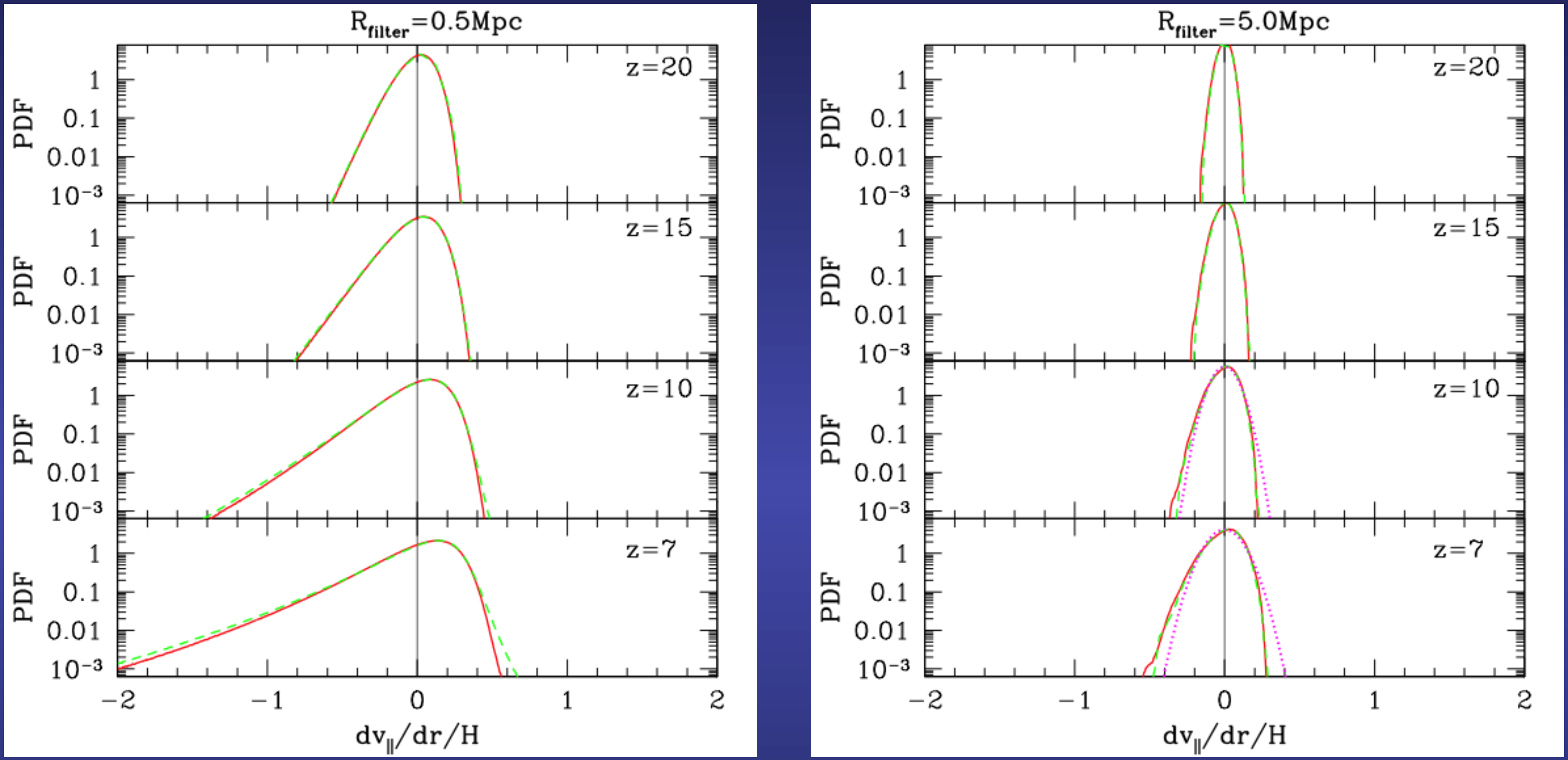


0.56 Mpc cells

Ionization Fields, power spectra



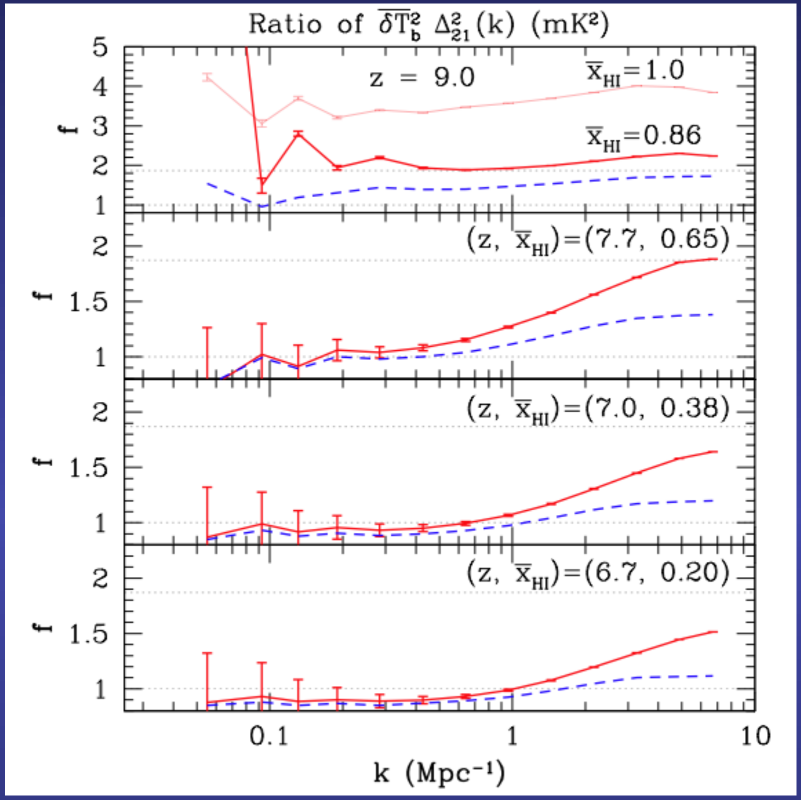
Velocity Gradients, PDFs



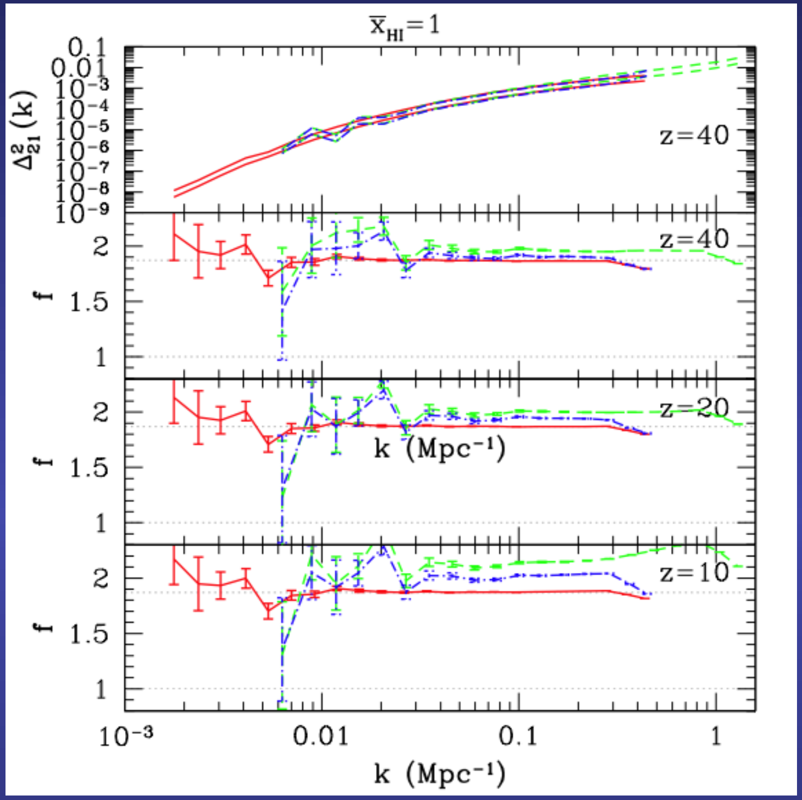
-nonlinear structure formation creates an asymmetric velocity gradient distribution!

How does this impact 21cm power spectra?

dimensional ratio

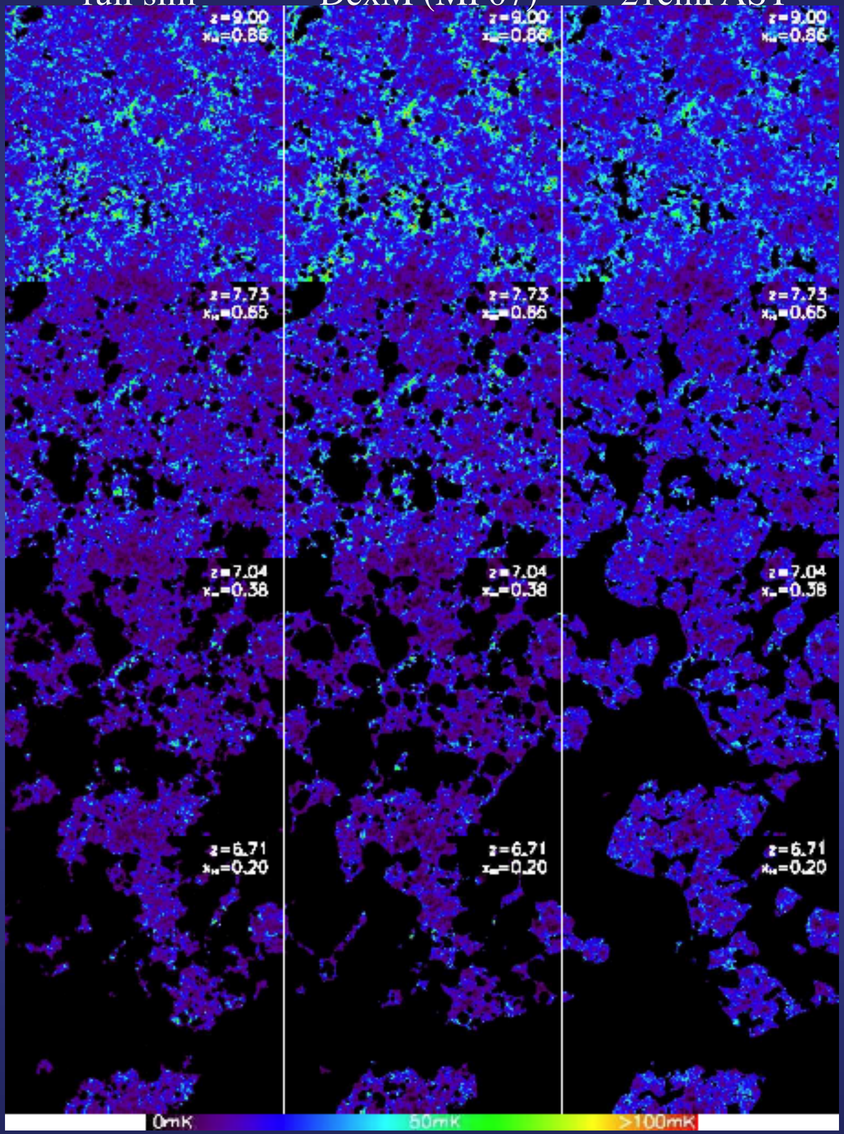


dimensionless ratio

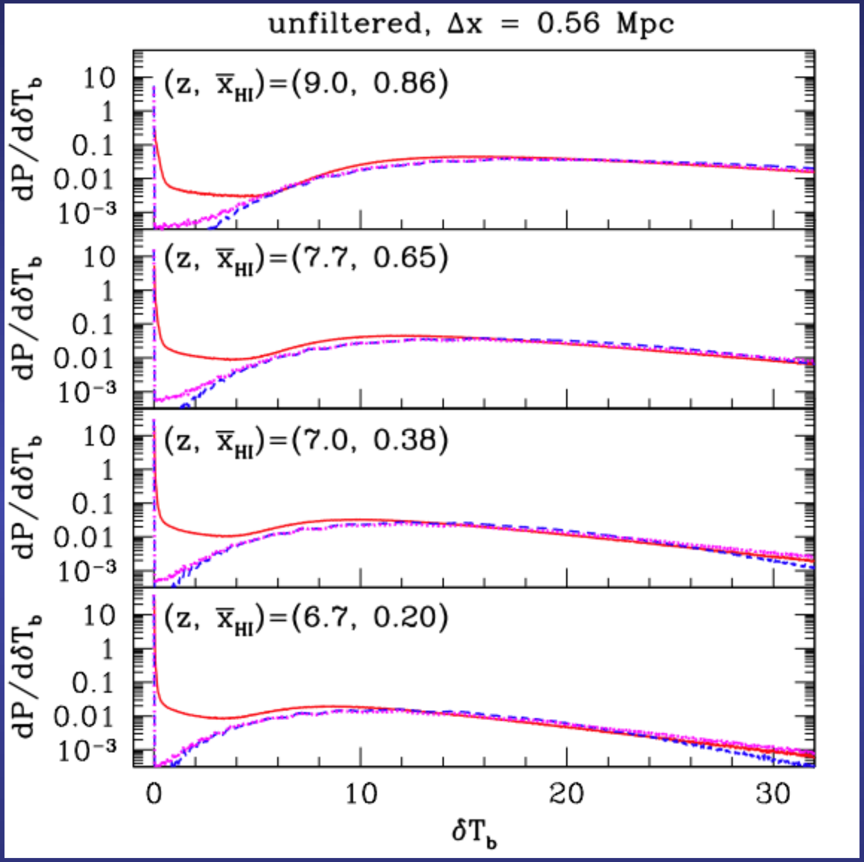


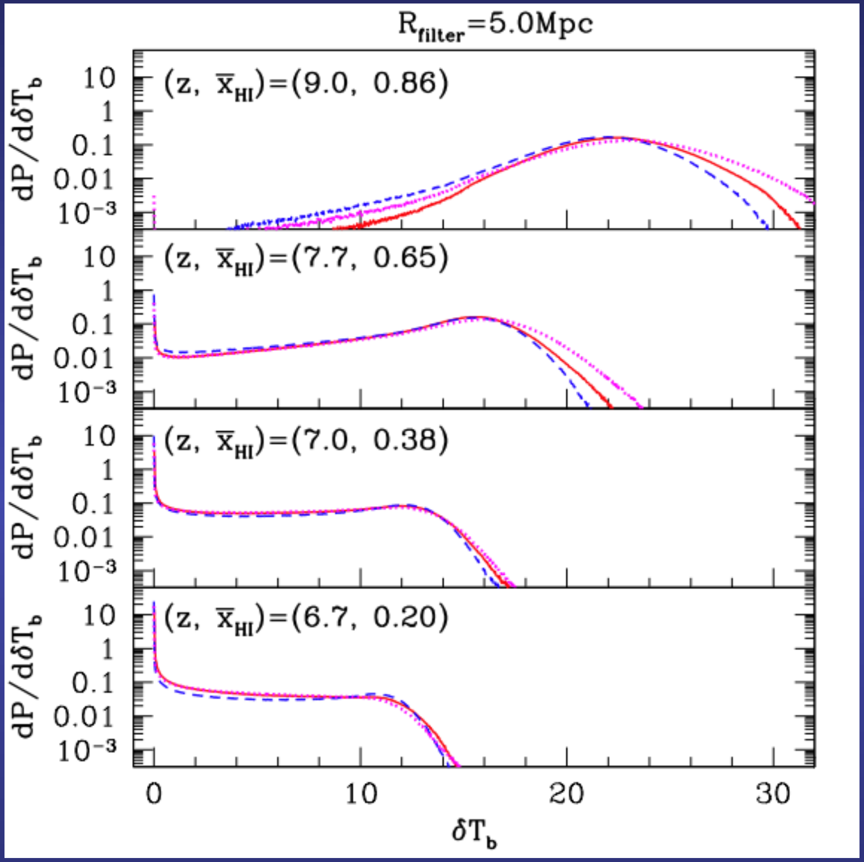
- enhanced power in excess of the geometric (Kaiser) effect (e.g. Barkana & Loeb 2005)
- Ionized bubbles quickly erase the boosts from velocity gradients on moderate to large scales
- Mean signal is *smaller* due to velocity gradients late in reionization:
    - inside-out reionization

Full comparison post heating ($T_s >> T_\gamma$)

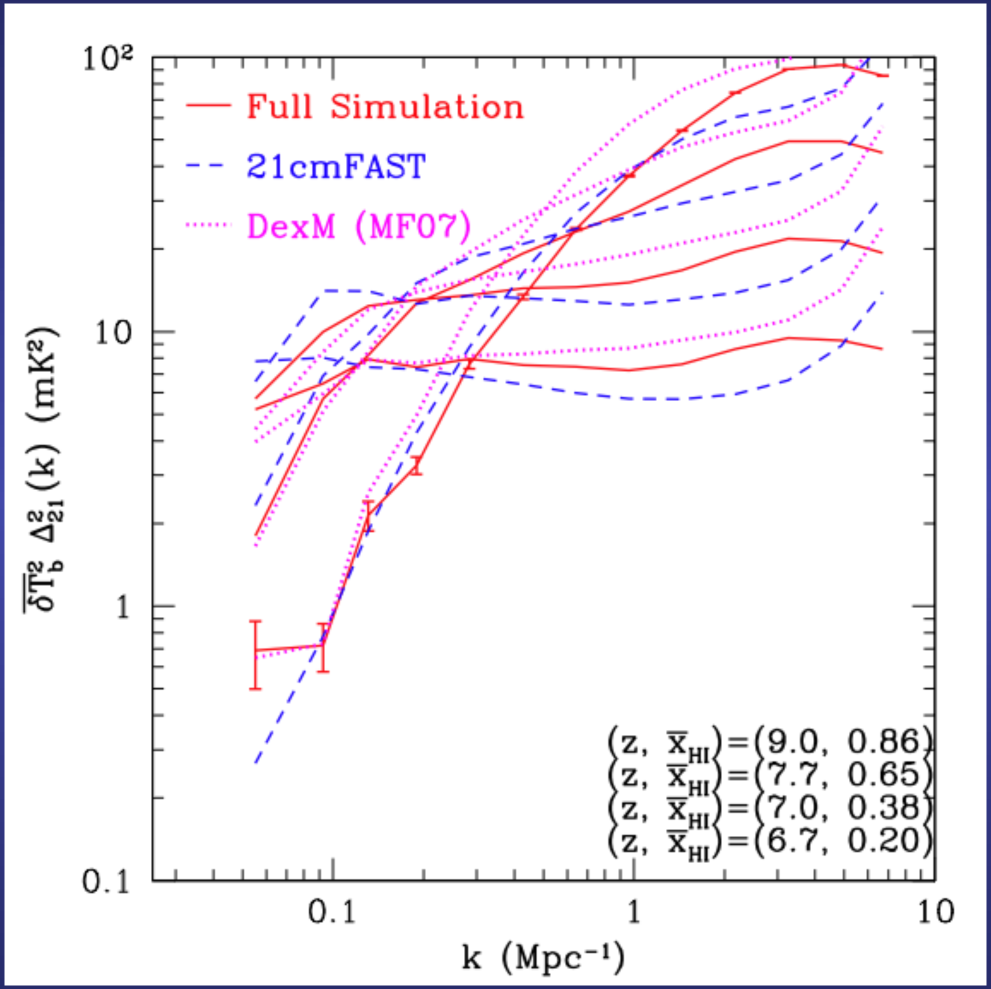

full sim
DexM (MF07)
21cmFAST

Full comparison post heating ($T_s>>T_\gamma$)





Full comparison post heating ($T_s \gg T_\gamma$)



Now the full power of the Moon!

$$\delta T_b(\nu) \approx 27 x_{HI}(1+\delta_{nl}) \left(\frac{H}{dv_r/dr + H}\right) \boxed{\left(1 - \frac{T_\gamma}{T_S}\right)} \left(\frac{1+z}{10}\,\frac{0.15}{\Omega_M h^2}\right)^{1/2} \left(\frac{\Omega_b h^2}{0.023}\right) \mathrm{mK}$$

spin temperature

defined in terms of the ratio of the number densities of electrons occupying the two hyperfine levels:

$$n_1/n_0 = 3\, e^{-0.068\ \mathrm{K}/T_s}$$

Now the full power of the Moon!

$$\delta T_b(\nu) \approx 27 x_{\mathrm{HI}}(1+\delta_{\mathrm{nl}}) \left(\frac{H}{dv_r/dr + H}\right) \boxed{\left(1 - \frac{T_\gamma}{T_S}\right)} \left(\frac{1+z}{10}\,\frac{0.15}{\Omega_M h^2}\right)^{1/2} \left(\frac{\Omega_b h^2}{0.023}\right) \mathrm{mK}$$

spin temperature:

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

T_γ – *temperature of the CMB*

T_K – *gas kinetic temperature*

T_α – *color temperature* ~ T_K

the spin temperature interpolates between T_γ *and* T_K

The spin temperature interpolates between T$_\gamma$ and T$_\mathrm{K}$

$$T_\mathrm{S}^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_\mathrm{K}^{-1}}{1 + x_\alpha + x_c}$$

two coupling coefficients:

$$x_c = \frac{0.0628\ \mathrm{K}}{A_{10} T_\gamma}\left[n_\mathrm{HI}\kappa_{1-0}^\mathrm{HH}(T_\mathrm{K}) + n_e \kappa_{1-0}^\mathrm{eH}(T_\mathrm{K}) + n_\mathrm{p}\kappa_{1-0}^\mathrm{pH}(T_\mathrm{K})\right]$$

collisional coupling

requires high densities
effective in the IGM at z>40

$$x_\alpha = 1.7 \times 10^{11} (1+z)^{-1} S_\alpha J_\alpha$$

Wouthuysen-Field (WF)

uses the Lyα background
effective soon after the first sources ignite

The spin temperature approaches the kinetic temperature if either coefficient is high. Otherwise, the spin temperature approaches the CMB temperature: NO SIGNAL!

What do the temperatures do?

T_γ – CMB temperature decreases as (1+z)

T_K – coupled to the CMB at high z ~>250. Then after decoupling adiabatically cools as $\sim(1+z)^2$. When first astrophysical sources ignite, they heat the IGM through their X-rays.

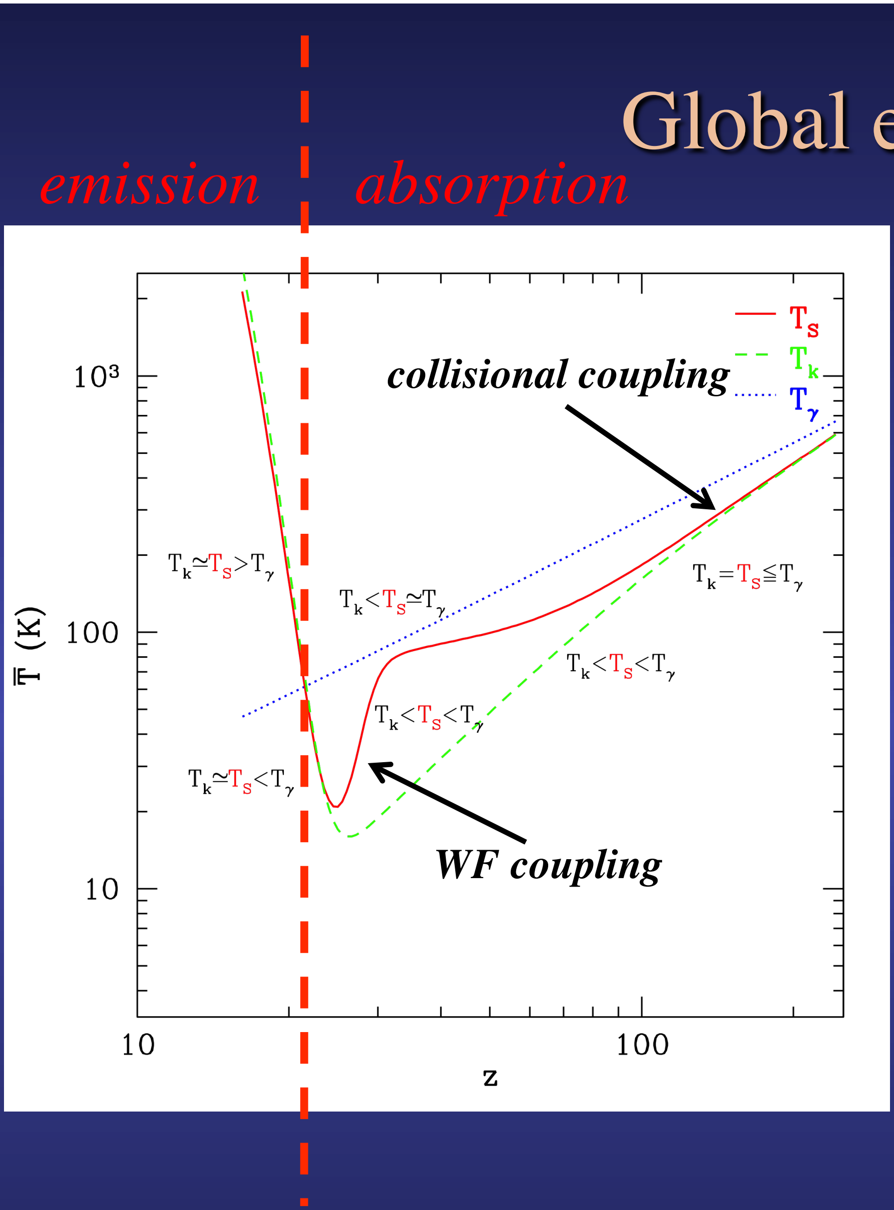
Other sources of heating (e.g. Furlanetto 2006):

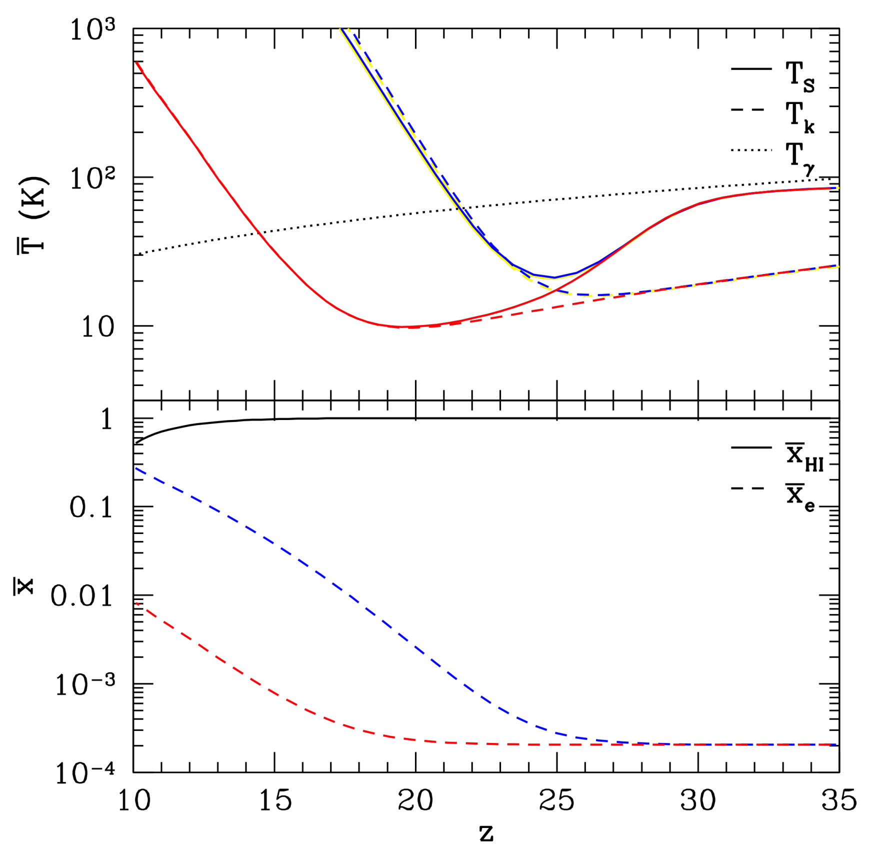
- *Compton* (high-z)
- *Lyα heating* (probably negligible: Chen & Miralda-Escude 2004, Rybicki 2006, Furlanetto & Pritchard 2006)
- *Shock heating* (not at strong at high-z in the IGM, e.g. Furlanetto & Loeb 2004; subdominant to X-ray heating for fiducial models)
- *DM annihilation* (likely minor, e.g. Mapelli et al. 2006, Furlanetto+ 2006, Ripamonti+2007, Valdes+ 2007, though depends on halo profiles and clumping., e.g. Chuzhoy 2008)

Including X-ray heating and Lyα pumping

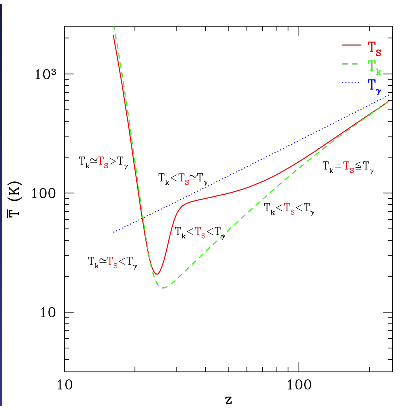
- Numerically integrate outward/back in time, summing the received photons
- Number density of sources is computed by conditional f_{coll}, again bypassing halo finder

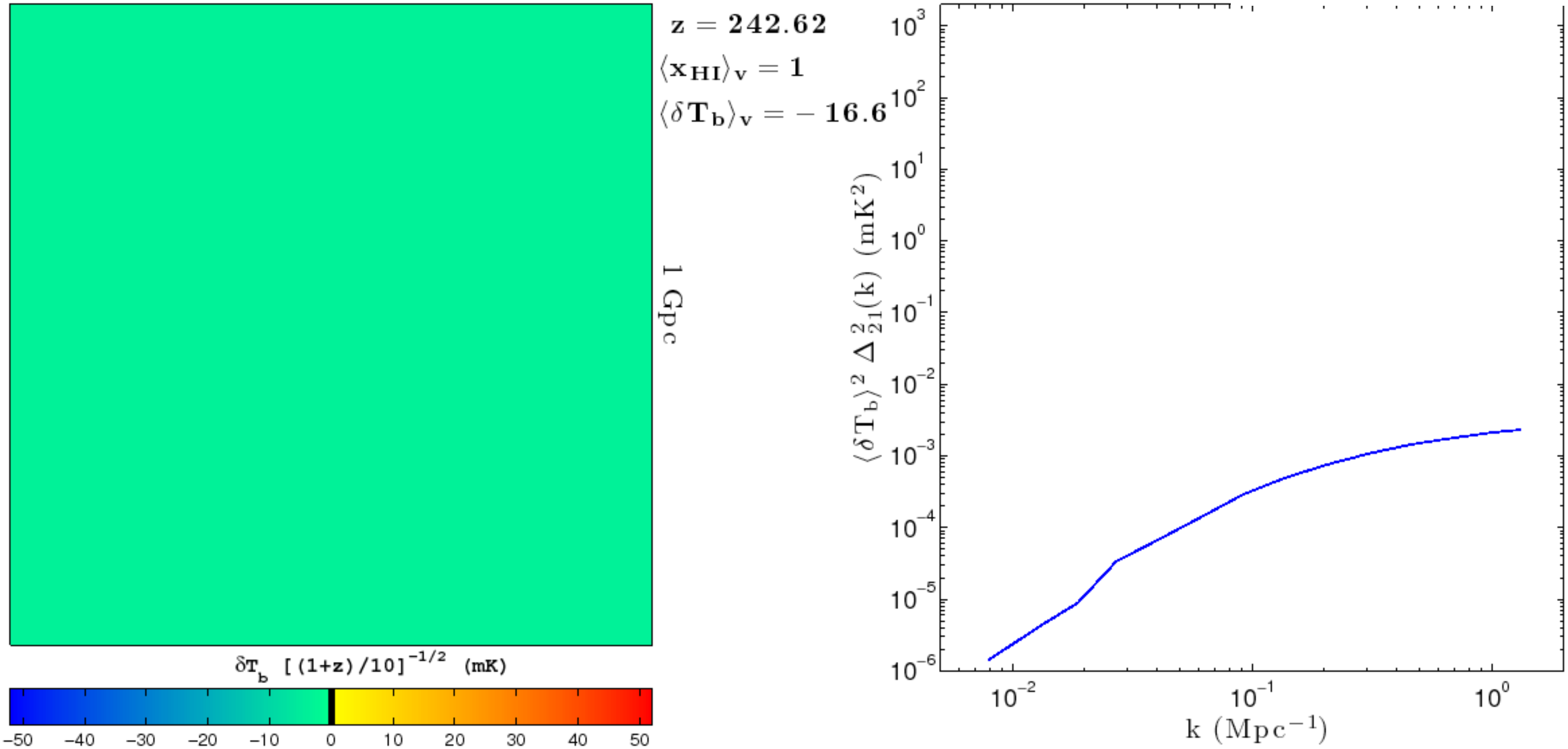
Global evolution





http://www.astro.princeton.edu/~mesinger/21cm_Movie.html





21cmFAST; publicly available (Mon):

download at http://www.astro.princeton.edu/~mesinger

- Portable and FAST! (if it's in the name, it must be true…)
  - A realization can be obtained in ~ minutes on a single CPU
  - Does not require lots of RAM (unlike DexM)
- Run on arbitrarily large scales
- No need to "run-down" a sim to a particular redshift
- Optimized for the 21cm signal
- Vary many independent free parameters; cover wide swaths of parameter space
- Calibrated to hydrodynamic cosmological simulations

in true marketing fashion, we also offer a “professional” version, with an even more pretentious title:

Deus ex Machina (DexM)

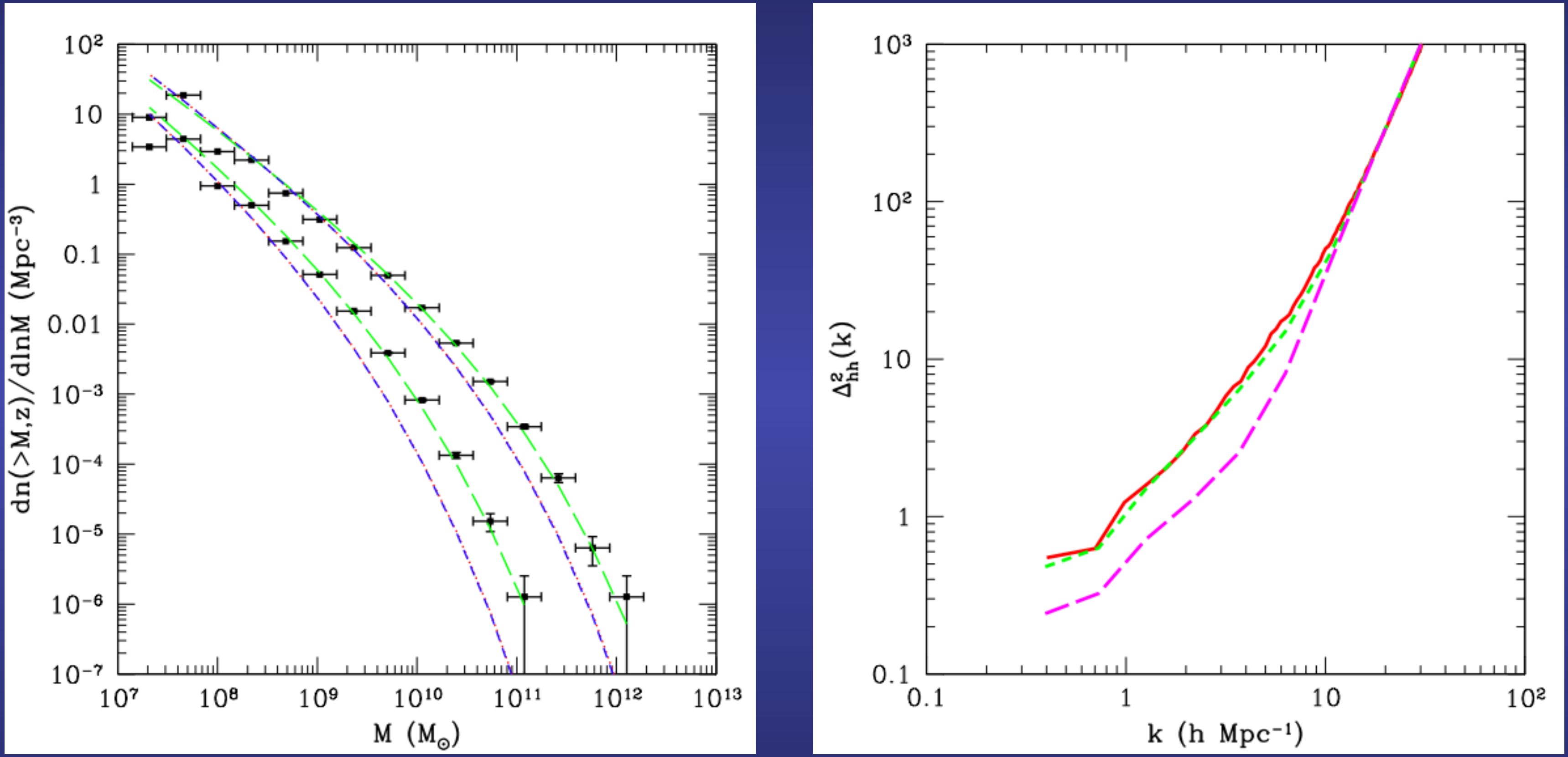
Etymology: New Latin
Literally: "God from a Machine", translation of Greek theos ek mechanes

- a person or thing that appears unexpectedly and provides a contrived solution to an apparently insoluble difficulty
(http://www.merriam-webster.com/dictionary/deus%20ex%20machina)

but you will need lots of RAM to take advantage of added benefits, such as…

Halo Finder

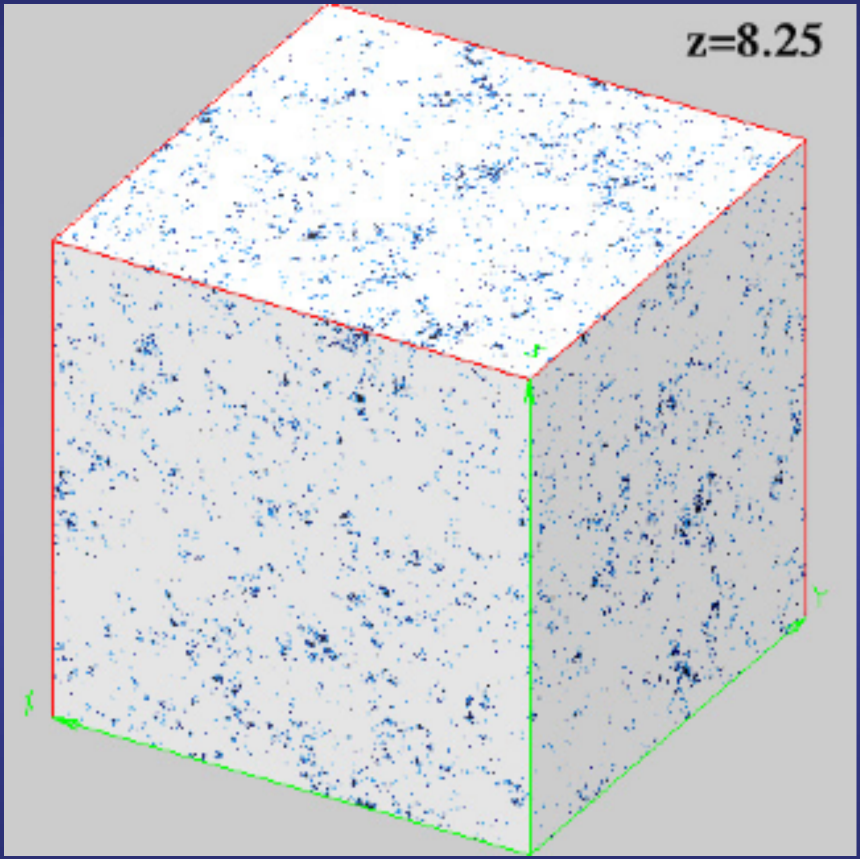
Mesinger & Furlanetto (2007); Mesinger+ (2009, in preparation)



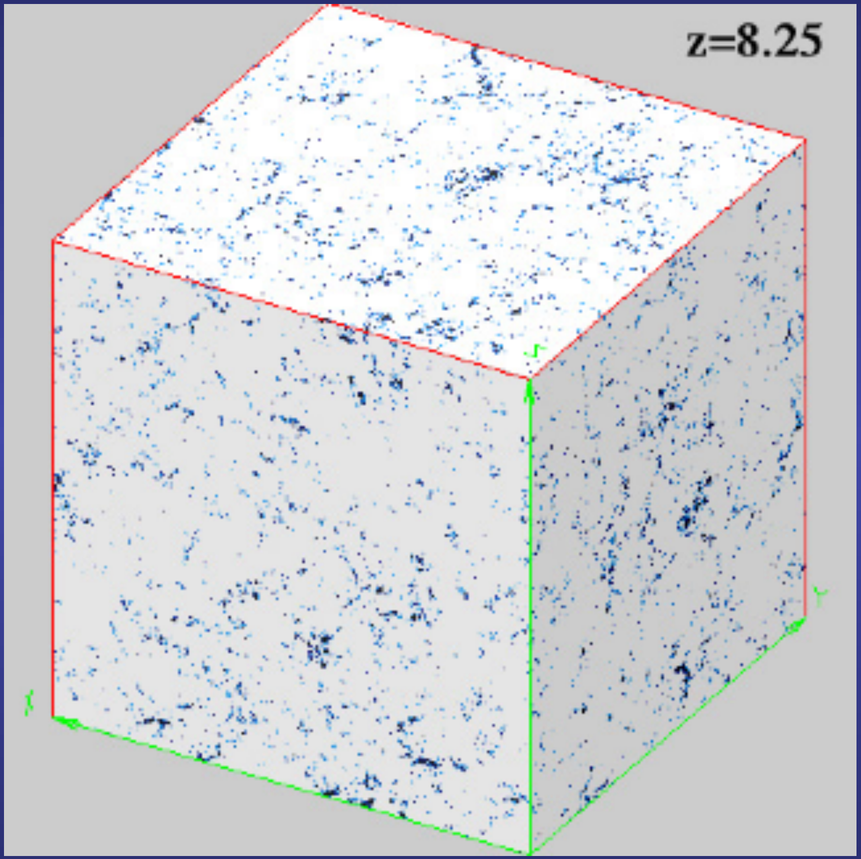
z=8.7 N-body halo field from McQuinn et al. (2007)

Halo Finder

Mesinger & Furlanetto (2007)



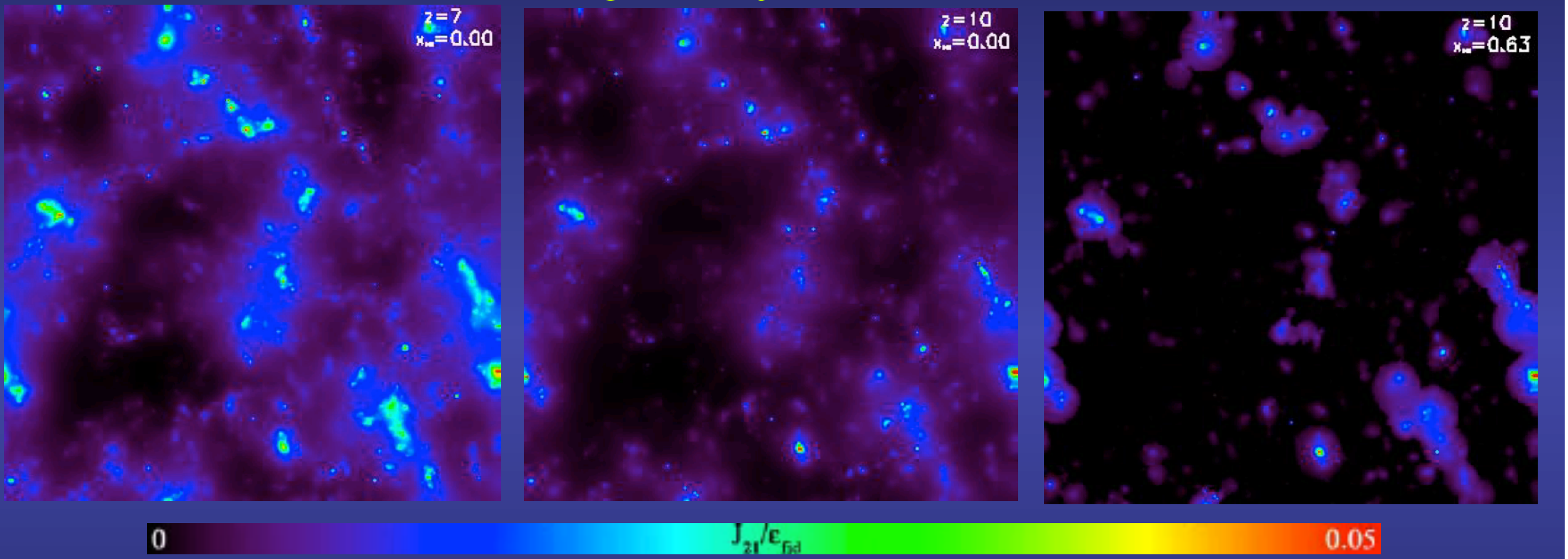
without adjusting halo locations



with adjusting halo locations

Ionizing UV Flux Fields

Mesinger & Dijkstra (2008)



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

and maybe soon, absorption systems

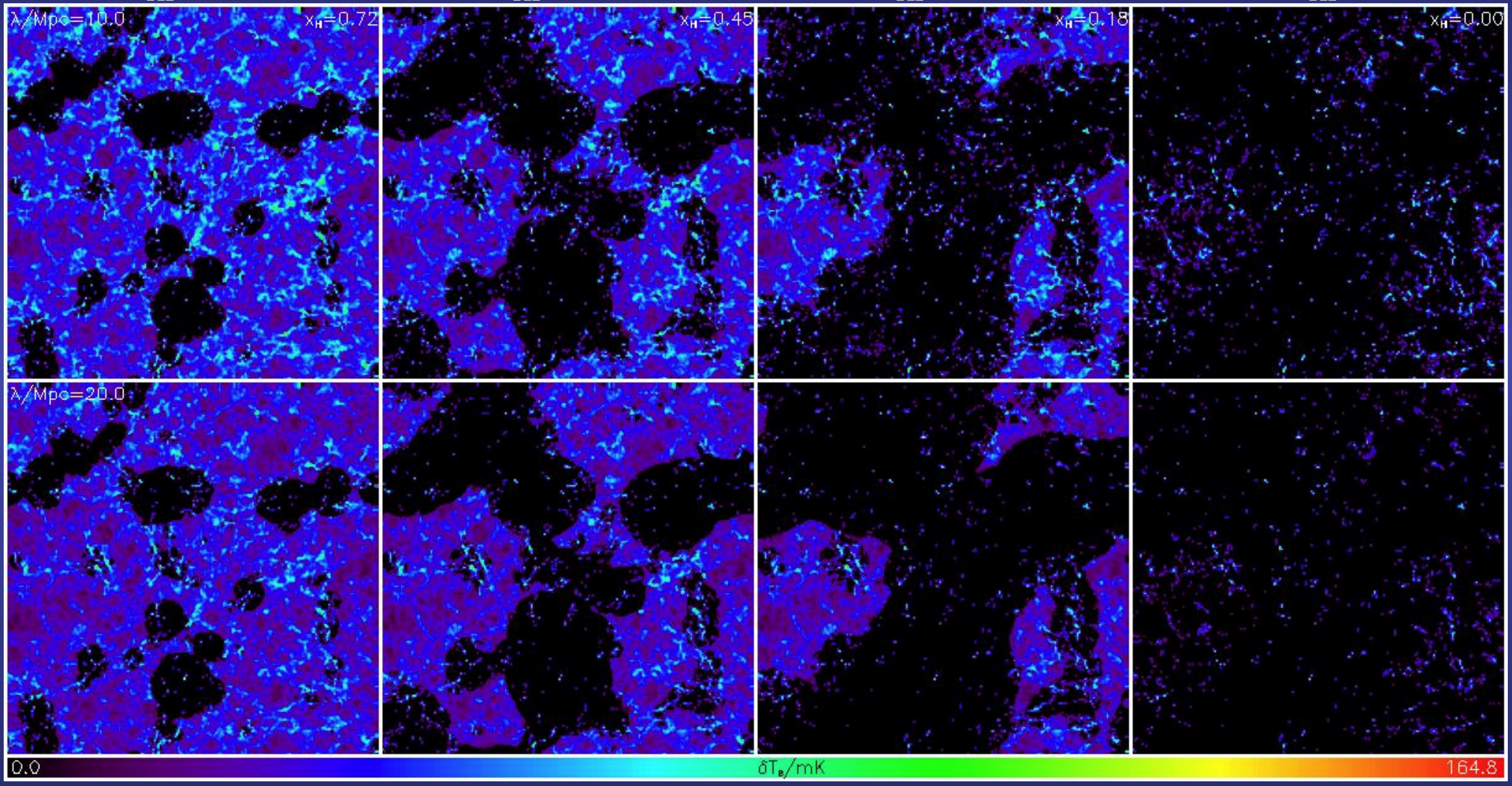
Crociani+ (2009, in preparation)

x_{HI}=0.72 x_{HI}=0.45 x_{HI}=0.18 x_{HI}=0

mfp=

10Mpc

20Mpc



PR Movie

http://www.astro.princeton.edu/~mesinger