Enabling parameter space exploration of the cosmic 21cm signal:

next generation tools for early Universe astrophysics

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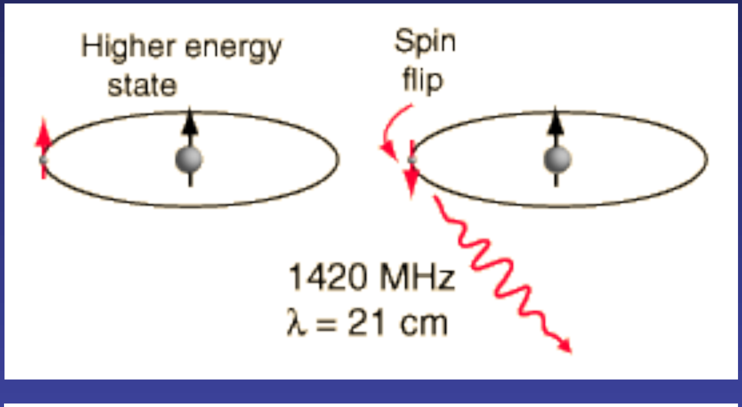
Outline

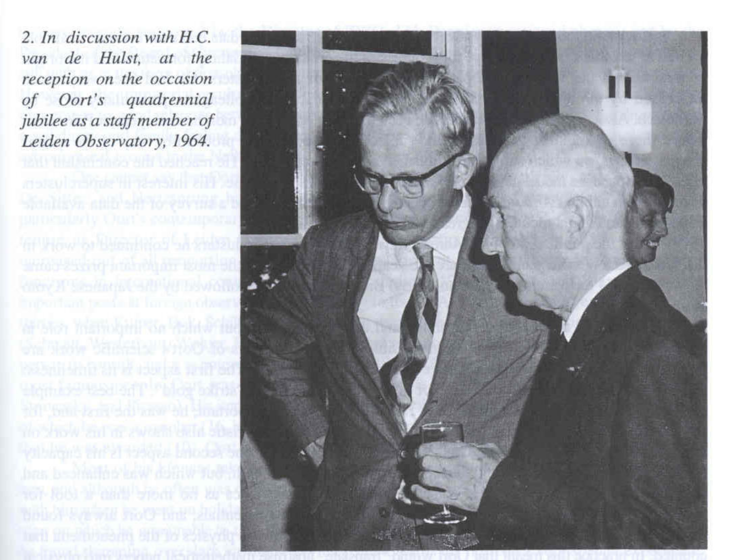
- Basics of the redshifted 21cm signal
- Modeling challenges and 21cmFAST commercial
- Three recent studies with 21cmFAST
  - Reionization and kinetic Sunyaev-Zel'dovich effect
  - Pre-reionization and X-rays 

  - DM annihilation heating 

21 cm line from neutral hydrogen



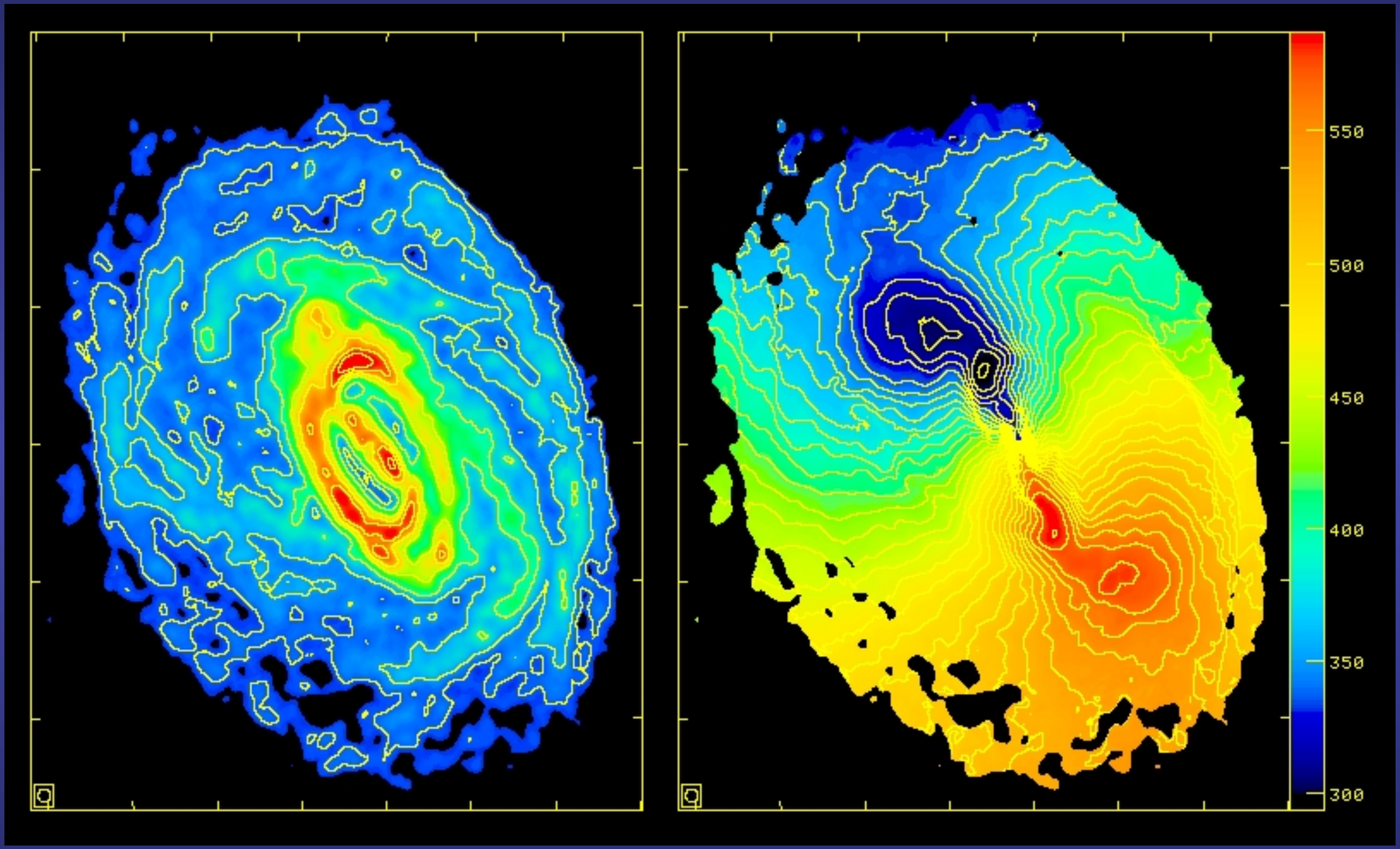
Hyperfine transition in the ground state of neutral hydrogen produces 21cm line.



2. In discussion with H.C. van de Hulst, at the reception on the occasion of Oort's quadrennial jubilee as a staff member of Leiden Observatory, 1964.

Predicted by van den Hulst when Oort told him to find unknown radio lines to study our galaxy

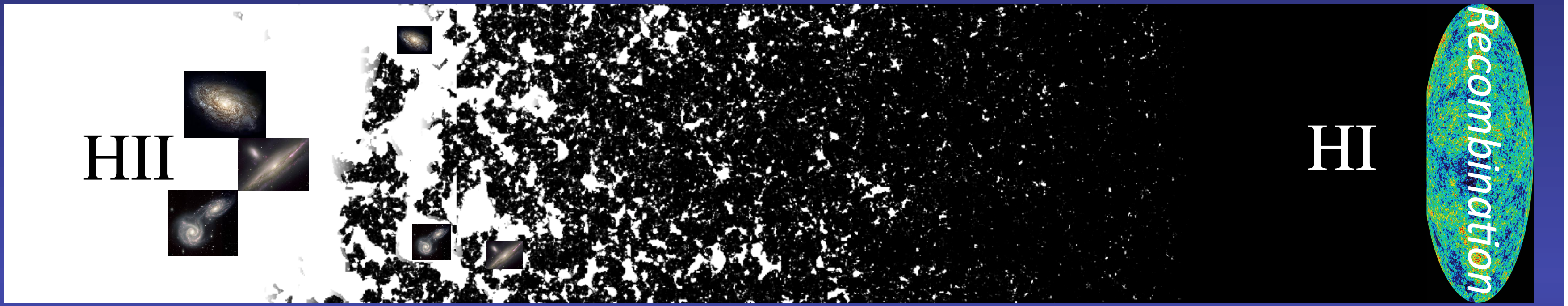
Now widely used to map the HI content of nearby galaxies



Circinus Galaxy

ATCA HI image by B. Koribalski (ATNF, CSIRO), K. Jones, M. Elmouttie (University of Queensland) and R. Haynes (ATNF, CSIRO).

Once upon a time, HI was much more abundant



$z = 0$

$t_{age} \sim 14$ Gyr

$z \sim 6$

$t_{age} \sim 1$ Gyr

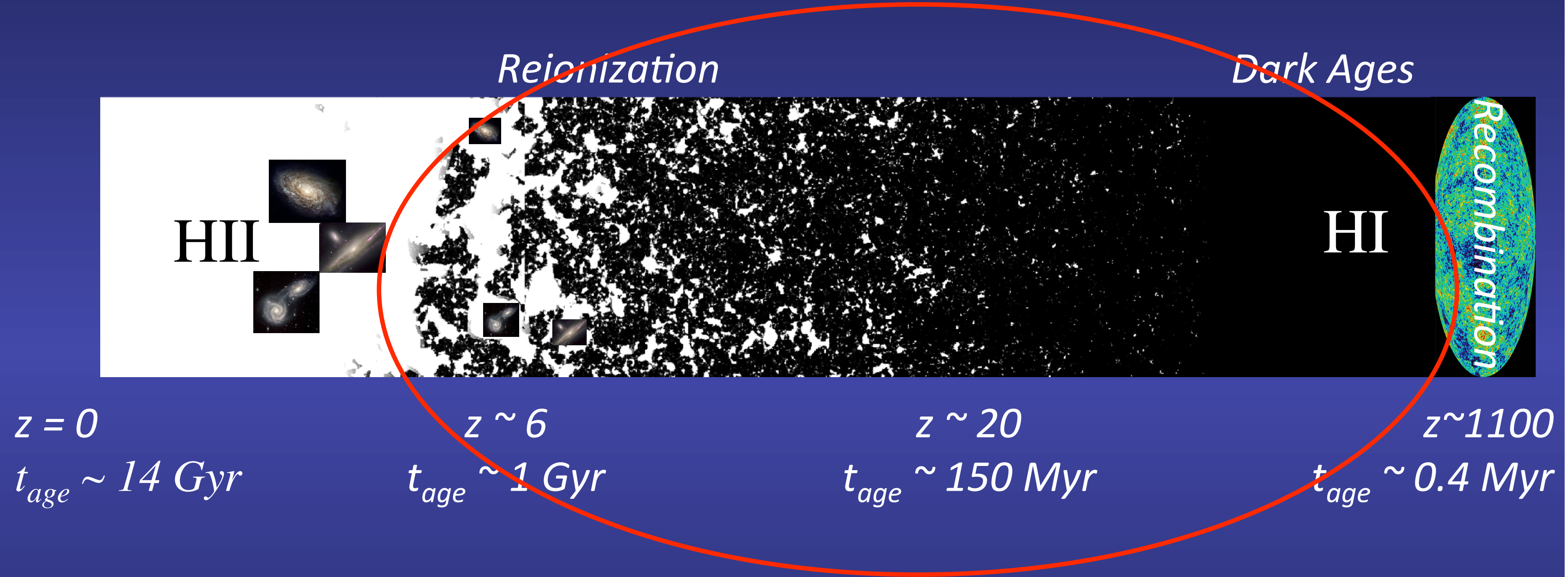
$z \sim 20$

$t_{age} \sim 150$ Myr

$z \sim 1100$

$t_{age} \sim 0.4$ Myr

Once upon a time, HI was much more abundant



z = 0
t_{age} ~ 14 Gyr

z ~ 6
t_{age} ~ 1 Gyr

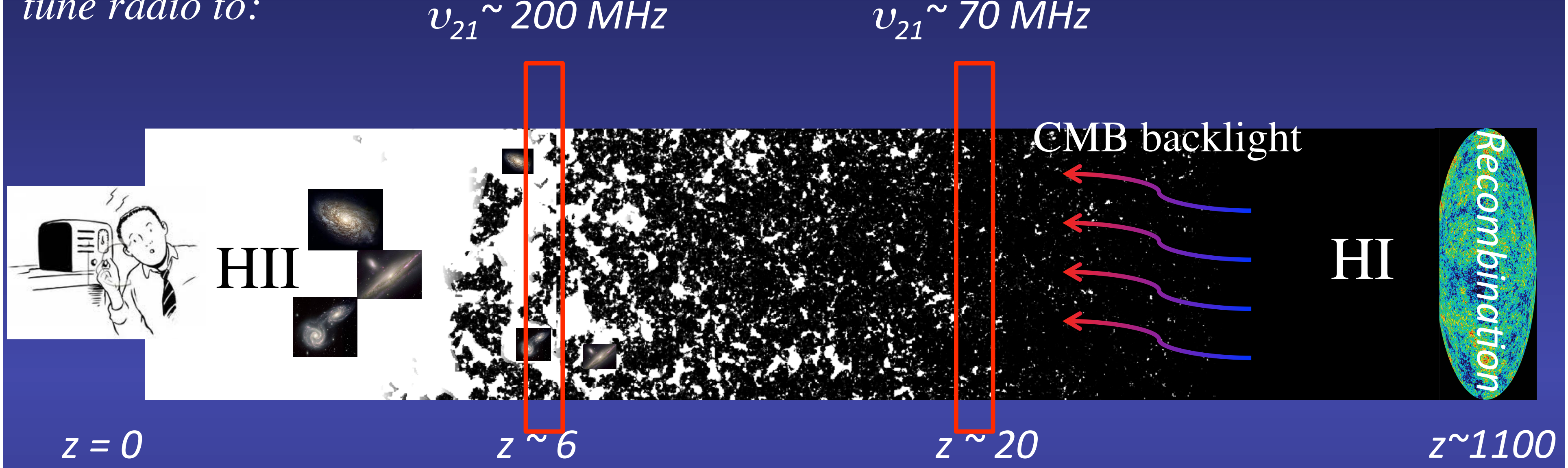
z ~ 20
t_{age} ~ 150 Myr

z~1100
t_{age} ~ 0.4 Myr

Bulk of our light cone: *observational future!*
Best probe: *21cm!*

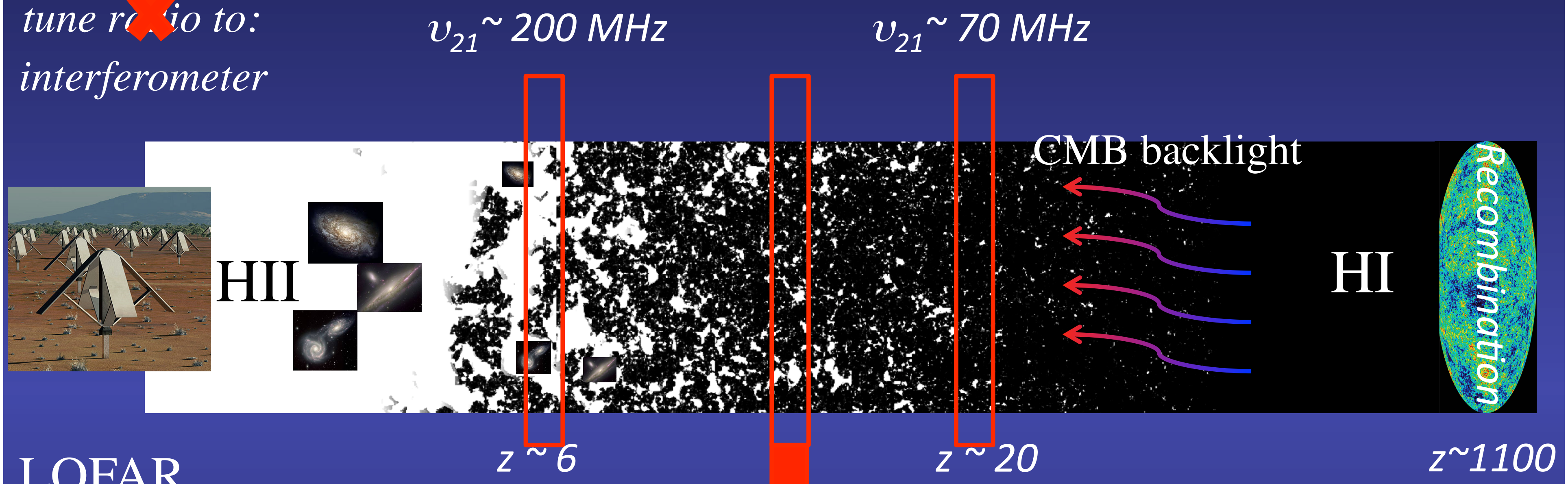
Once upon a time, HI was much more abundant

Redshifted 21cm signal.
tune radio to:



Once upon a time, HI was much more abundant

Redshifted 21cm signal.
tune radio to:
interferometer



LOFAR,
MWA,
PAPER,
21CMA,
GMRT

2nd gen: SKA

Cosmic 21cm signal

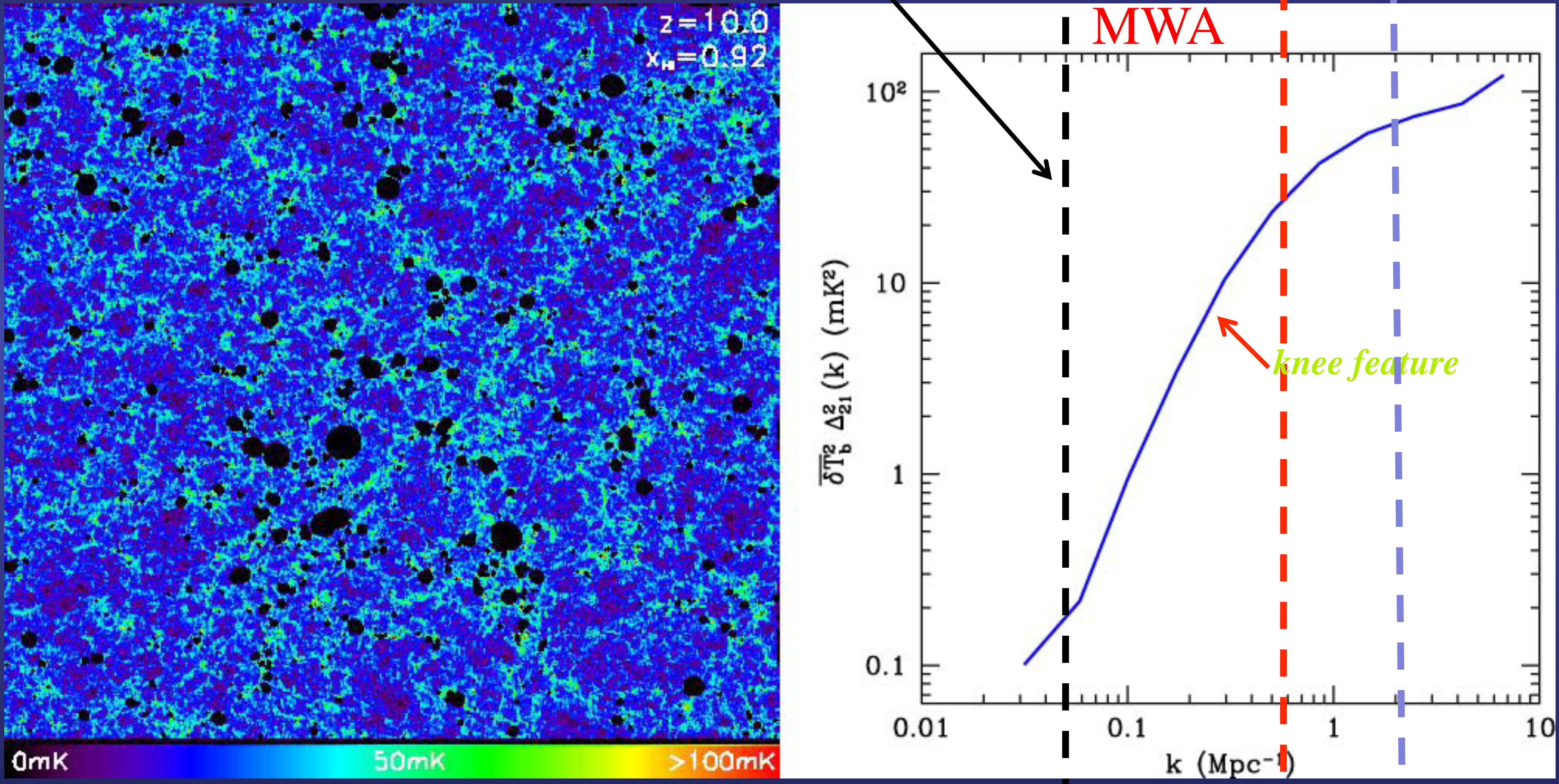
~foreground limit

SKA?
(1km^2 core)

(e.g. Lidz+2008; Furlanetto+2009; Santos+ 2011)

LOFAR/
MWA

250 Mpc



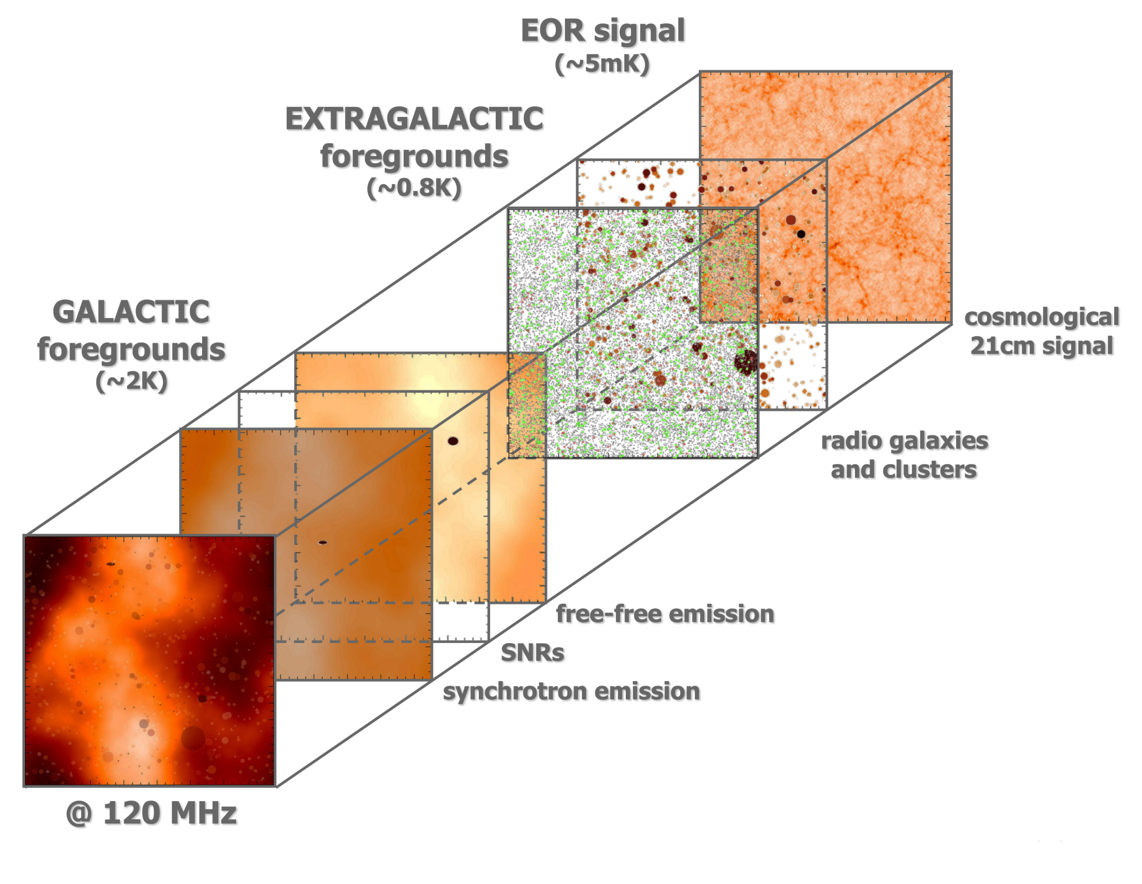
knee feature

δT_b

Mesinger & Furlanetto 2007

Astrophysical Foregrounds

Zaroubi+ (2009)



can be fitted-out using their spectral smoothness

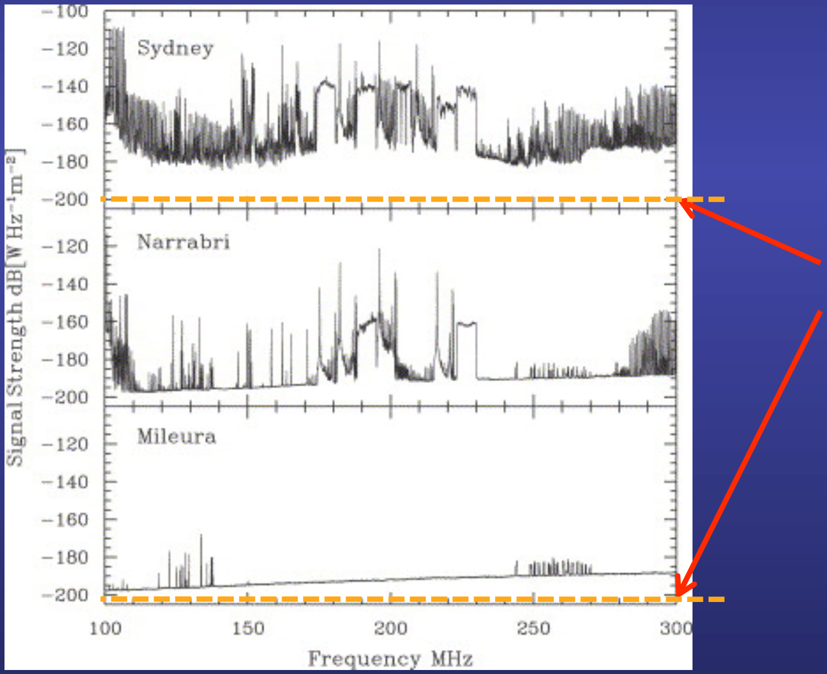
Observational Foregrounds

Instrumental effects

Ionosphere – smears out sources; radio "adaptive optics"

very messy at low frequencies/high redshifts!

RFI – radio frequency interference



~12 orders of magnitude larger than cosmological signal!

solution: find "clean" bands, understand RFI well, remove transients.

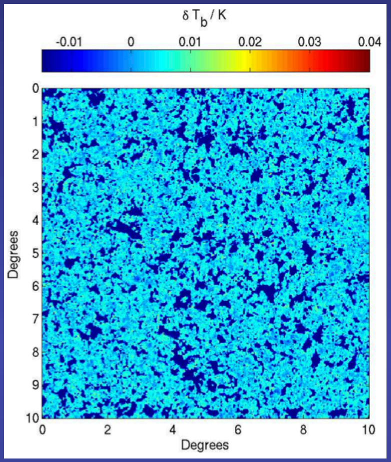
Tough, but doable: LOFAR down to system temperature

courtesy of A. Chippendale and R. Beresford (taken as part of the ATNF SKA Site Monitoring Program)

Digging out the cosmic signal (case of LOFAR):

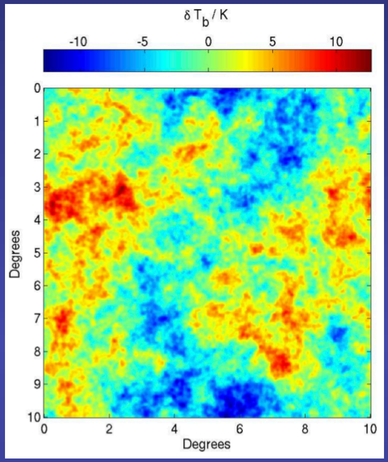
DATA=

cosmic signal
(z=9.5, 150MHz)
21cmFAST



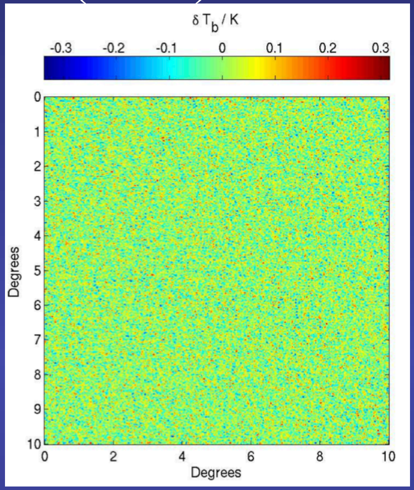
+

foregrounds
(Jelic+2010)

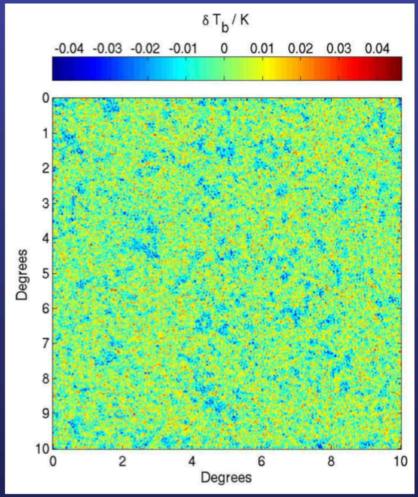


+

LOFAR noise
(600h)

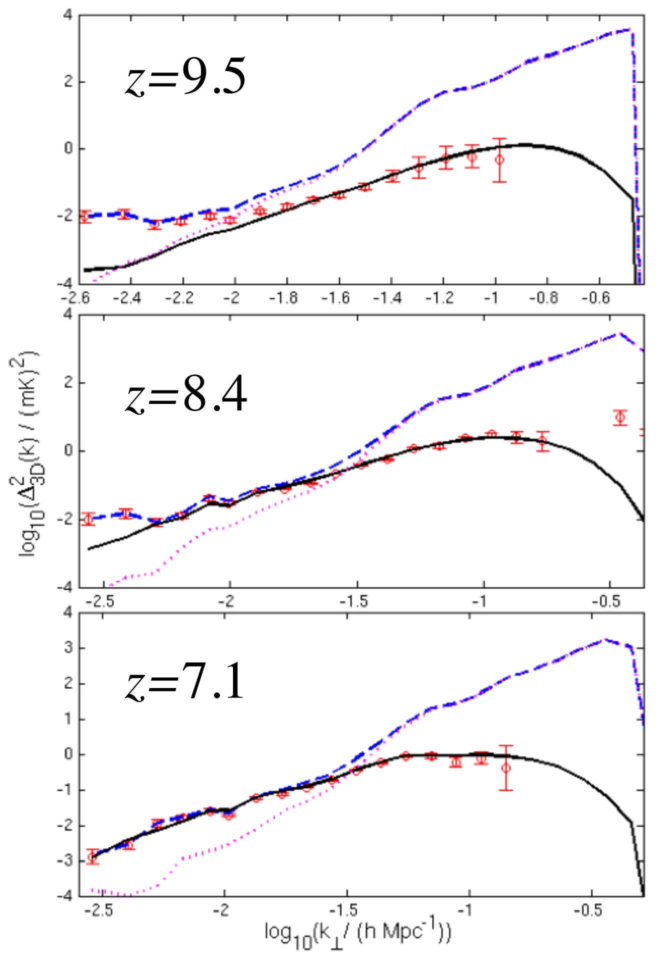


reconstructed signal = DATA − FASTICA fg
fg removal
(Chapman+ 2012) − noise
(600h) =



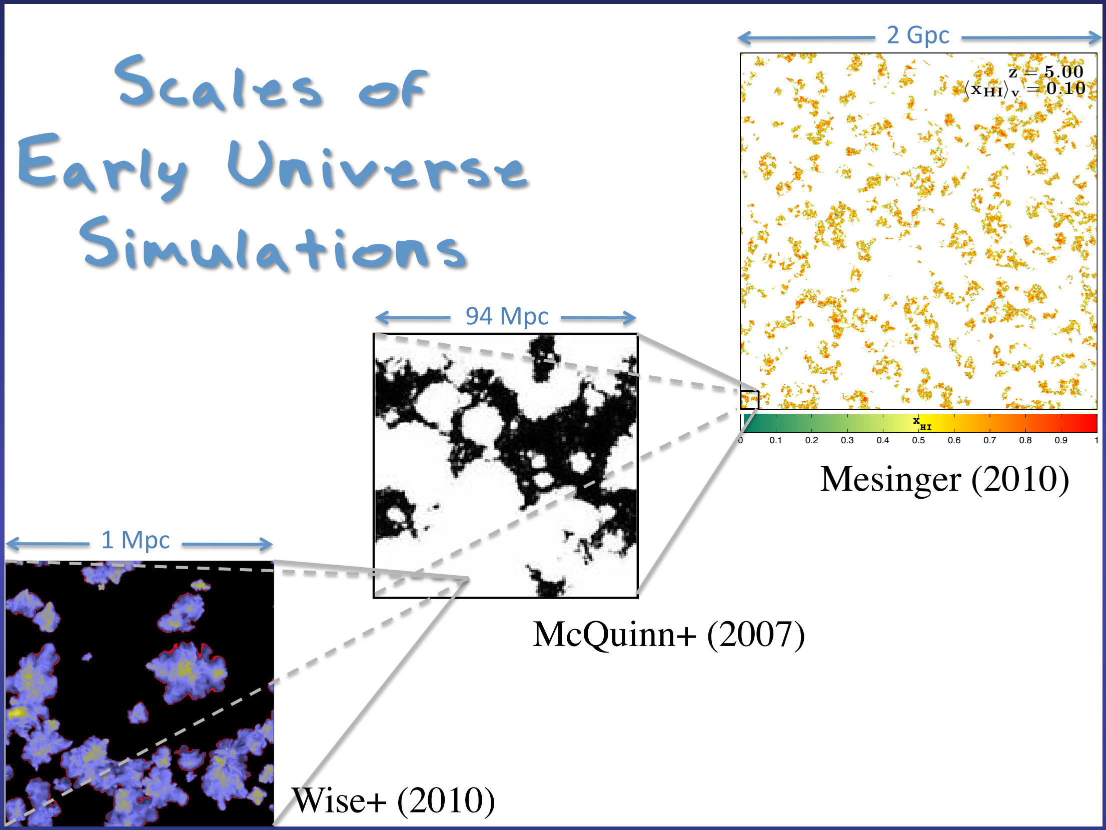
Chapman+ 2012

Digging out the cosmic signal (case of LOFAR):



Chapman+ 2012

Simulating and interpreting the signal



~ FoV of 21cm interferometers

- *Dynamic range required is enormous: single star --> Universe*
- *We know next to nothing about high-z --> ENORMOUS parameter space to explore*
- *Numerical simulations are computationally expensive: not good for parameter studies*
- *Most relevant scales are in the linear to quasi-linear regime*

--> use the right tool for each task!

21cmFAST

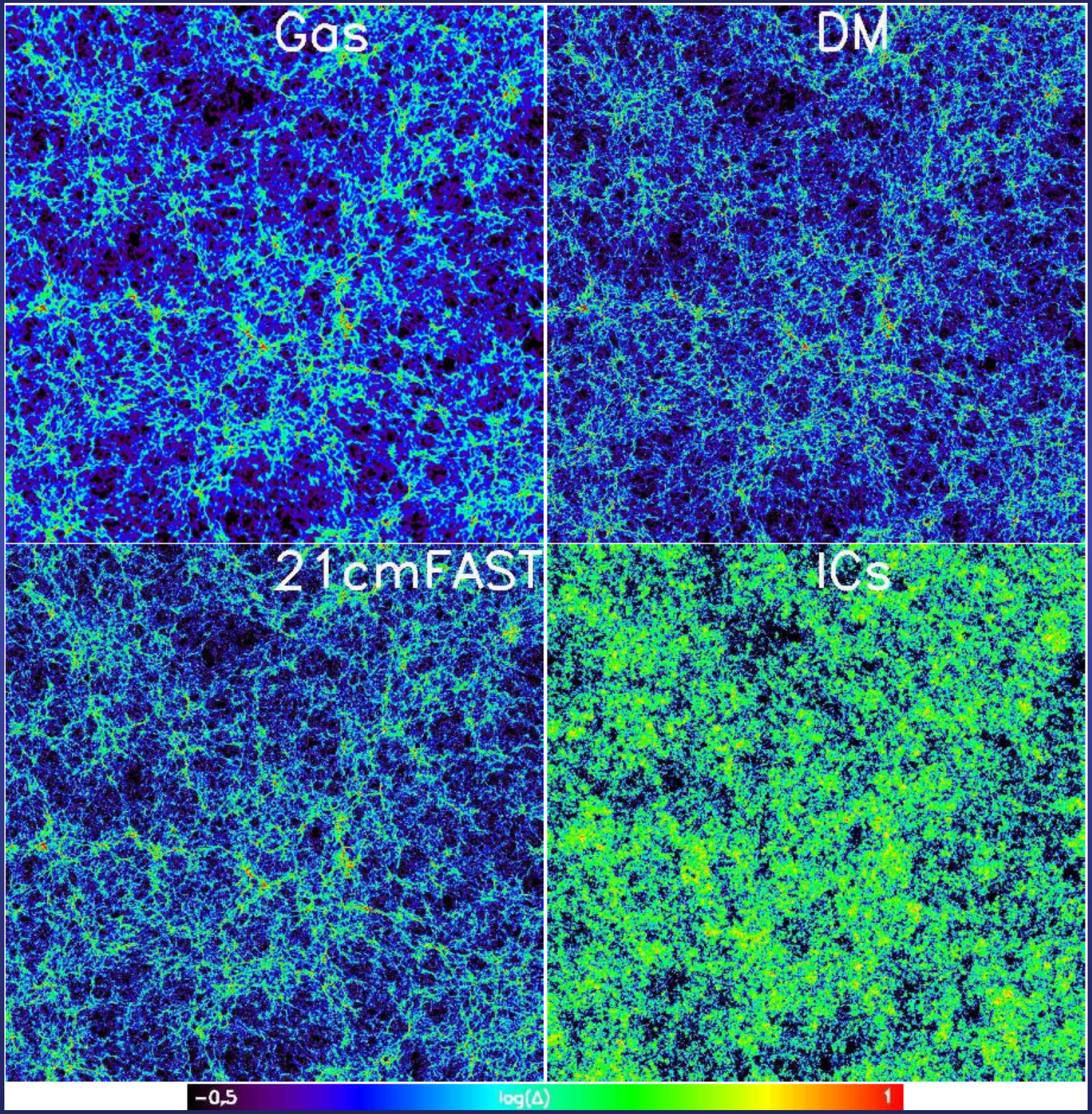
semi-numerical simulation (Mesinger, Furlanetto, Cen 2011)

- Combines excursion-set approach with perturbation theory for efficient generation of large-scale density, velocity, halo, ionization, 21cm brightness fields
- Portable and FAST! (if it's in the name, it must be true…)
  - A realization can be obtained in ~ minutes on a single CPU
  - *New* parallelized version, optimized for parameter studies
- Run on arbitrarily large scales
- Optimized for the 21cm signal
- Vary many independent free parameters; cover wide swaths of parameter space
- Tested against state-of-the-art hydrodynamic cosmological simulations (Trac & Cen 2007; Trac+ 2008)
- Publically available!

Density Fields

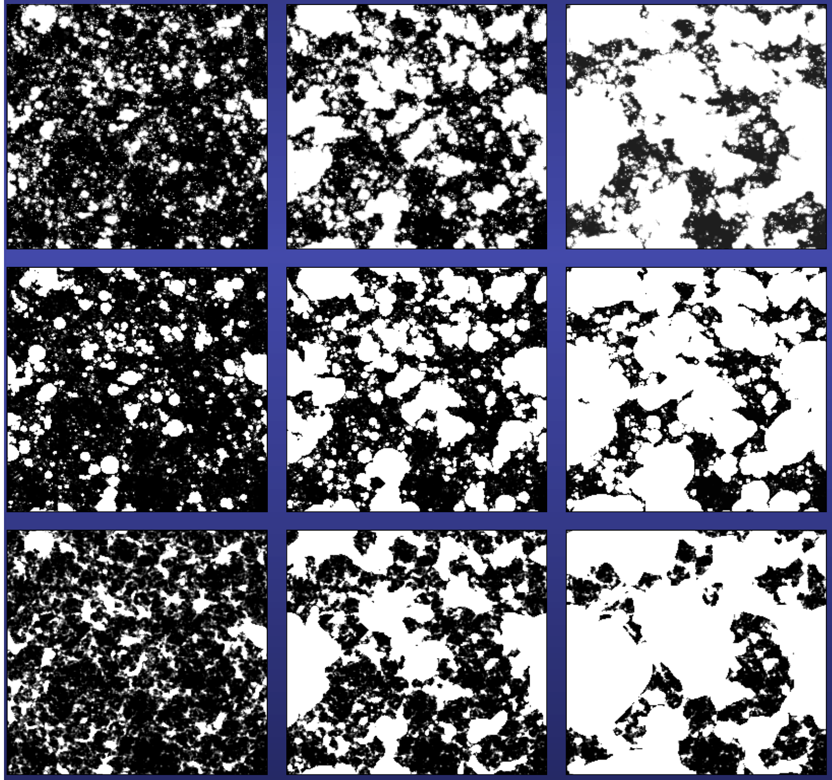
z=7

0.19 Mpc cells



143 Mpc

Ionization fields



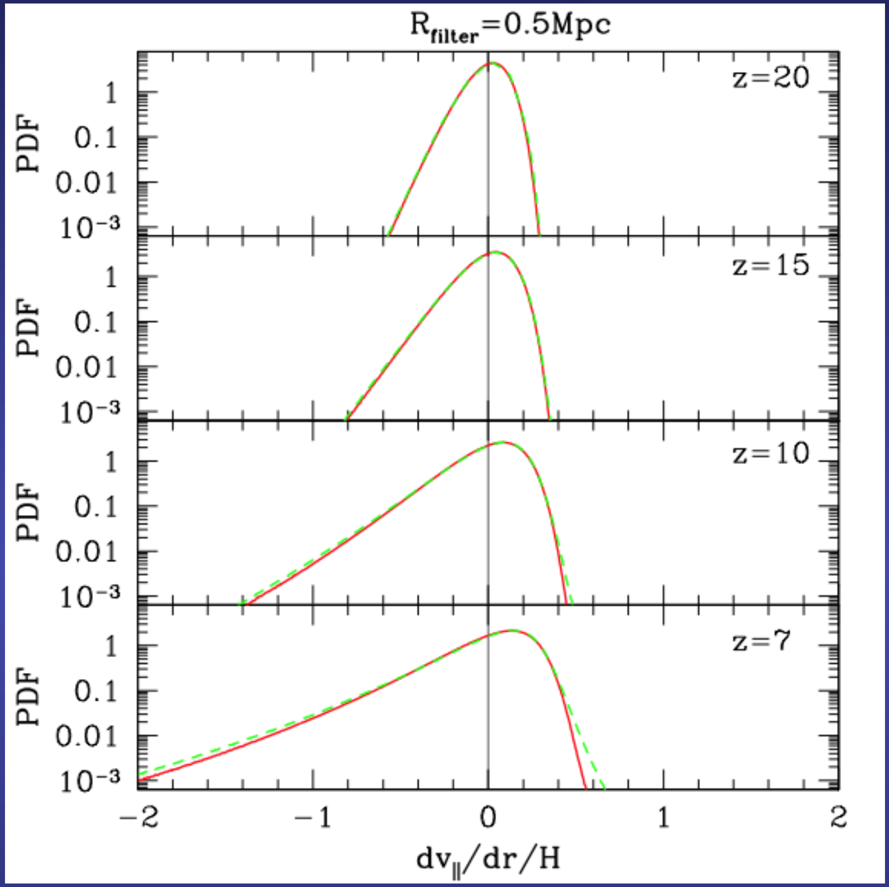
Trac & Cen (2007)

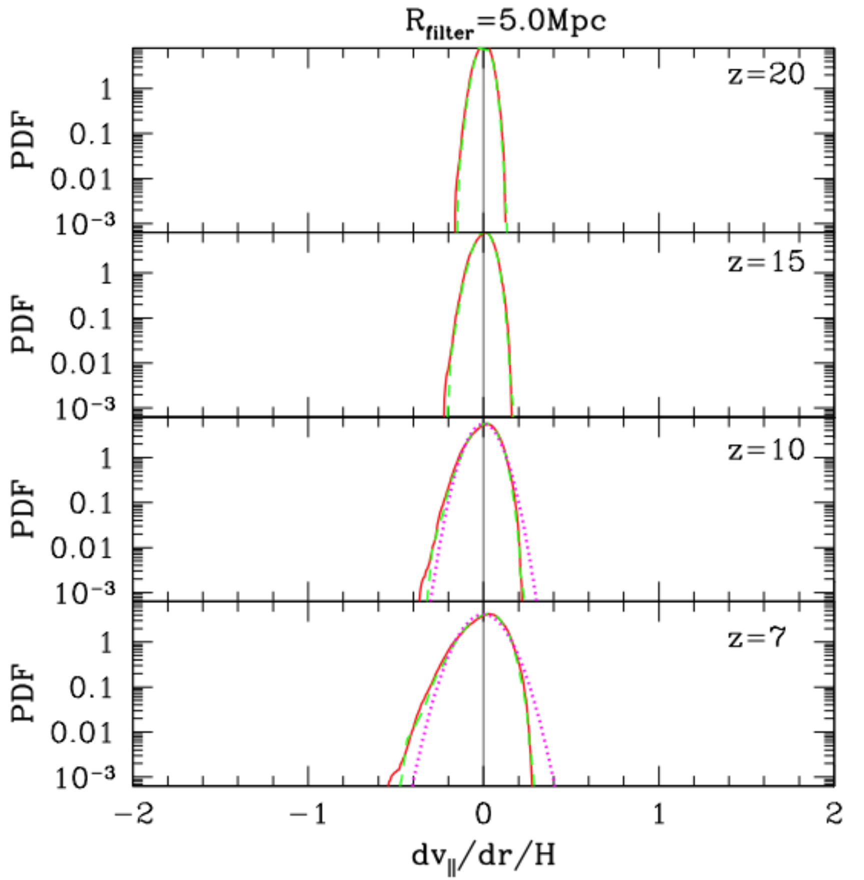
DexM (with halos;
Mesinger & Furlanetto; 2007)

21cmFAST (Mesinger+ 2011)

Zahn+ (2010)

Redshift space distortions (sorry no pics)

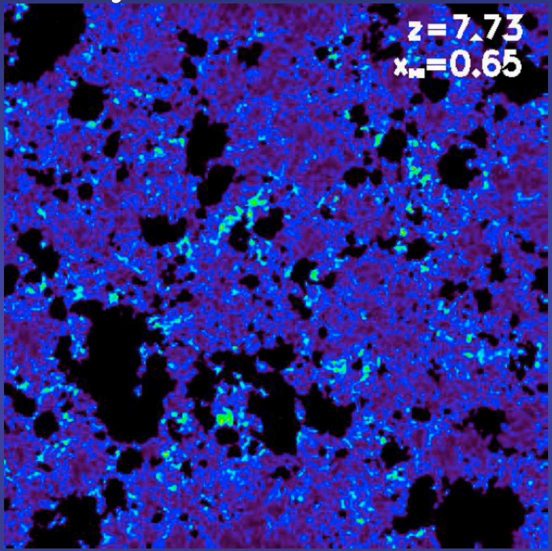




nonlinear structure formation creates an asymmetric velocity gradient distribution

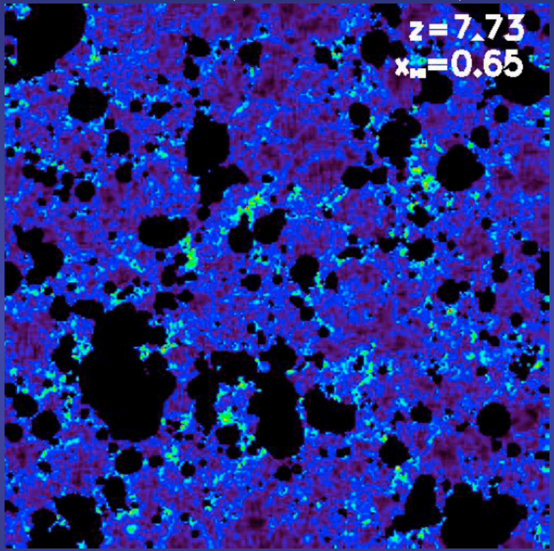
Full 21cm comparison (without spin temperature)

hydro+DM+RT



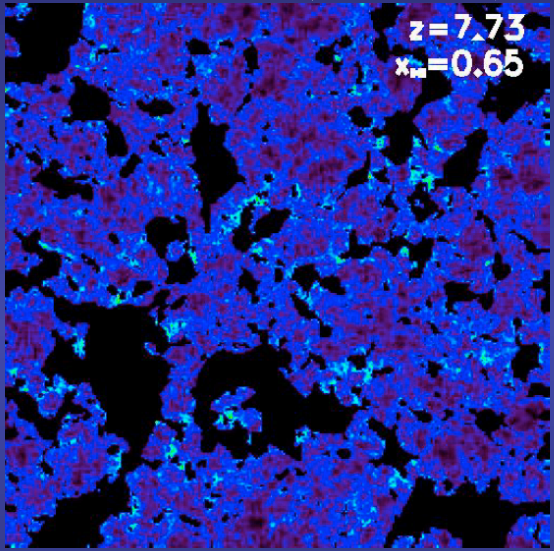
~ 1 week on 1536 cores

DexM (with halos)



⟵ 100 Mpc/*h* ⟶

21cmFAST (no halos)



~ few min on 1 core

Get on board!

http://homepage.sns.it/mesinger/Sim

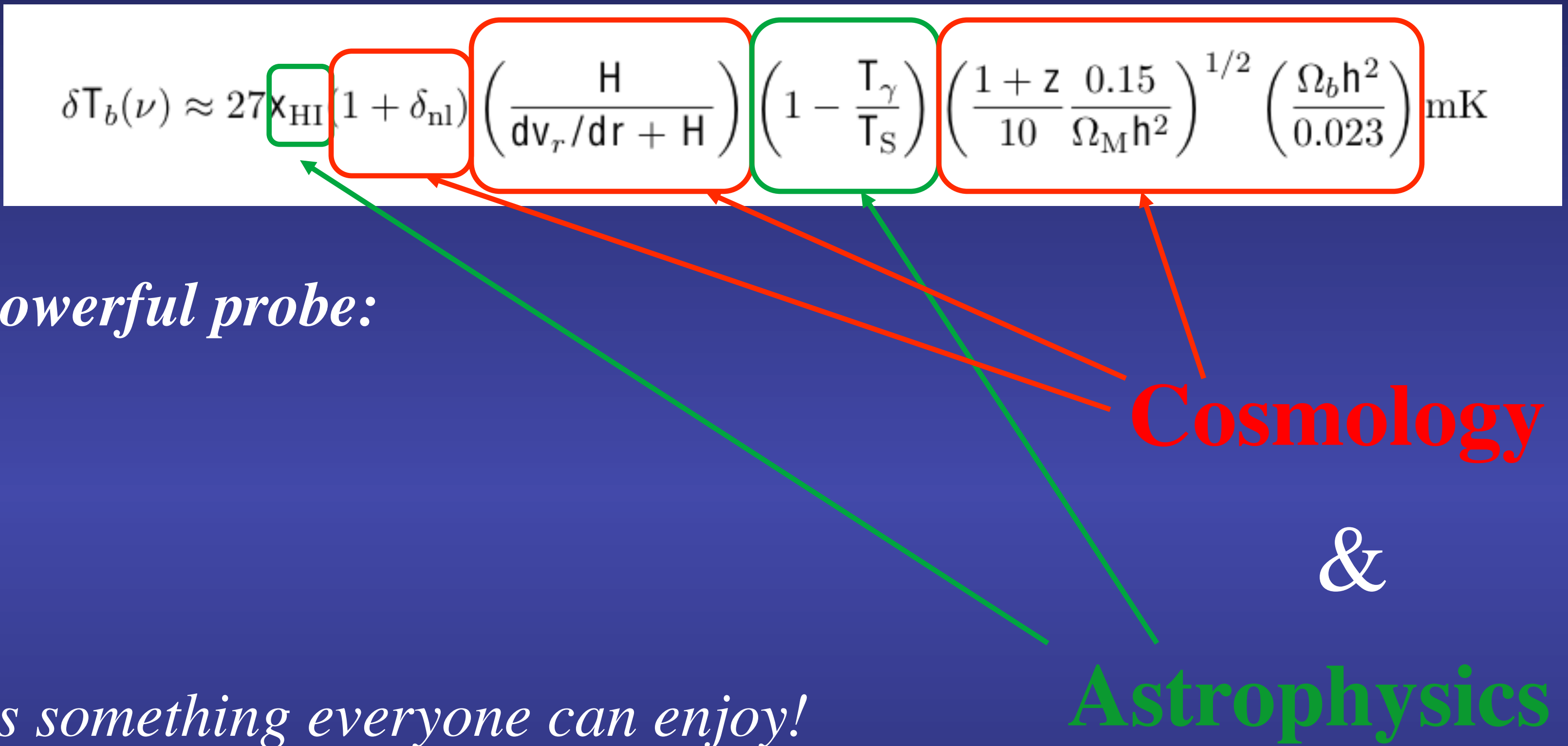
recent converts: LOFAR, MWA

In just over 2 years, 21cmFAST is being used by researchers in 11 countries, and most of the 1st gen. 21cm experiments: LOFAR, MWA, 21CMA

What can we learn: cosmological 21cm signal

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

Cosmological 21cm Signal



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

Powerful probe:

Cosmology

&

Astrophysics

Has something everyone can enjoy!
The trick is to disentangle the components:

- *accurate, efficient modeling (21cmFAST) and/or*
- *separation of epochs*

Now focus on astrophysics

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

Powerful probe:

Reionization

Heating

Power of semi-numerical approach: *parameter studies of reionization*

Example 1:
interpreting the recent SPT constraint on the kinetic Sunyaev-Zel'dovich signal

New constraints on reionization kSZ power at l~3000 from SPT (Reichardt+ 2011)*:*

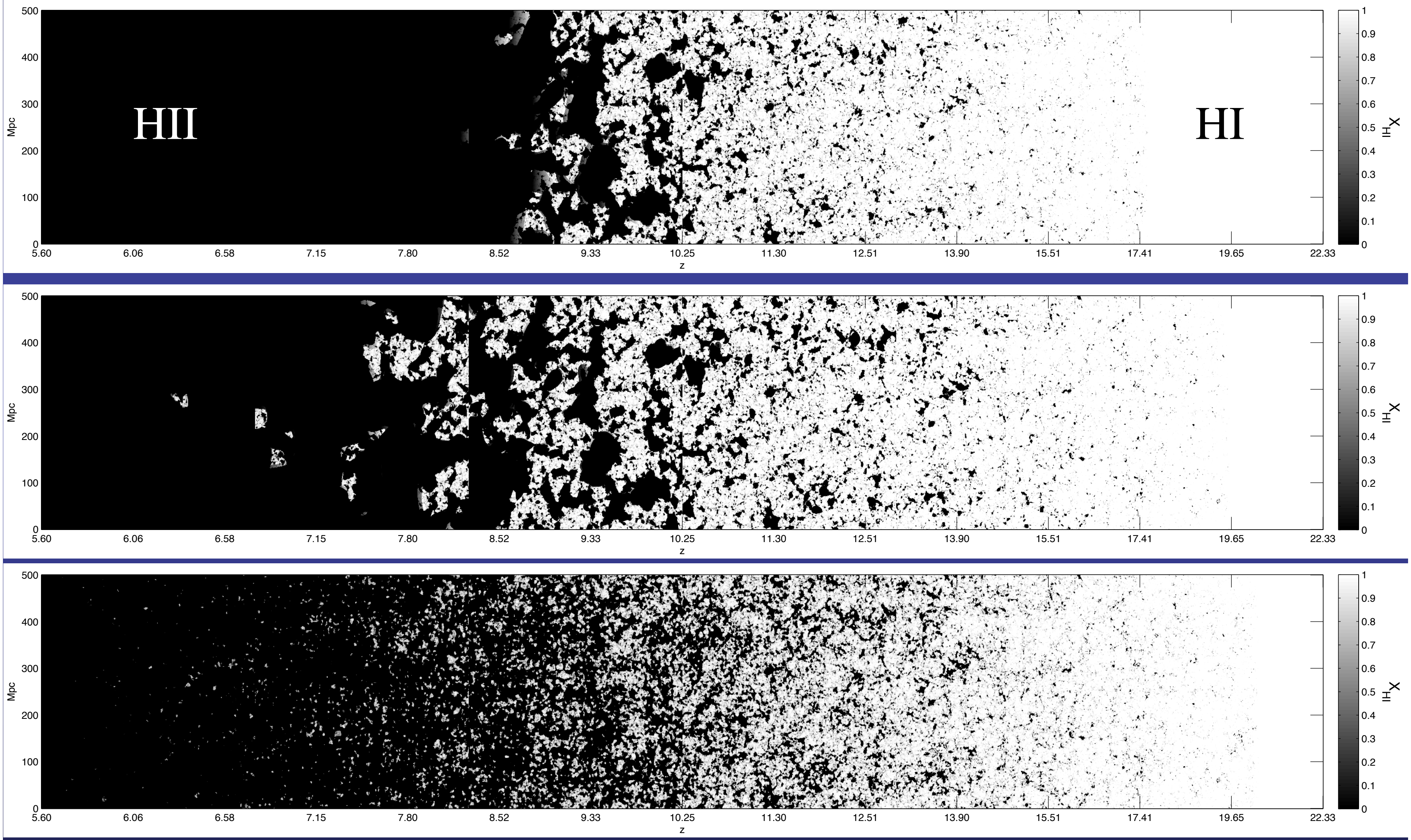
- P_{kSZ}^{patchy} <~ 1 μK^2 (95% CL) assuming no tSZ-CIB correlation
- P_{kSZ}^{patchy} <~ 4 μK^2 (95% CL) allowing tSZ-CIB correlation

Use 21cmFAST to generate density, velocity and ionization fields.

3 free parameters:

- **ζ - ionizing efficiency** of high-redshift galaxies. for example: $\zeta = f_{esc}\, f_* \,N_\gamma/(1+n_{rec})$
- **T_{vir} – minimum virial temperature** of halos which can host stars
- **R_{mfp} – mean free path of ionizing photons** inside ionized IGM (set, e.g. by LLSs). R_{mfp}~50Mpc at z~6

Generate > 100 realizations of reionization!!

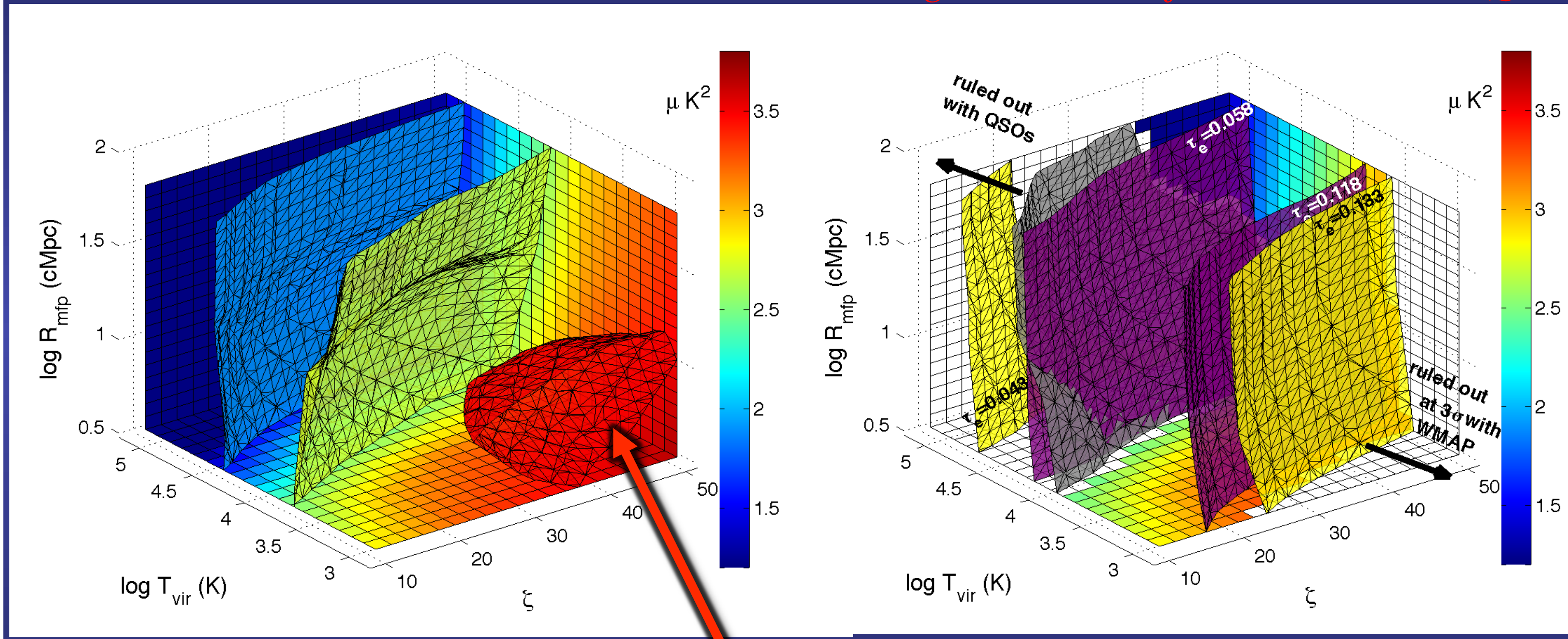


z →

Explore parameter space for the signal

Mesinger+ (2012)

Including constraints from WMAP and QSOS



Easiest to detect or rule out (i.e. largest signal):

models driven by small galaxies which form early, evolve slowly, and where ionization is retarded by abundant absorption systems

kSZ conclusions

- In physically-motivated reionization scenarios:

  $$1.5\ \mu K^2 \lesssim P_{kSZ}^{patchy} \lesssim 3.5\ \mu K^2$$

- This means that NO models fit the aggressive SPT lower bound! Reasons:
  1. There is a sizable tSZ-CIB cross-correlation (indeed all models fit the conservative bound)

     AND/OR

  2. High-energy photons from X-ray sources or exotic particles contribute significantly
- We should soon have a detection, but why wait…

Example 2:
21cmFAST allows us to study the thermal history of the universe before reionization, including the first sources of X-rays

Strongest imprint of early X-rays is through heating the IGM prior to reionization

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

spin temperature

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

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

Pre-reionization signal

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

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_γ and T_K

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

two coupling coefficients:

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

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)

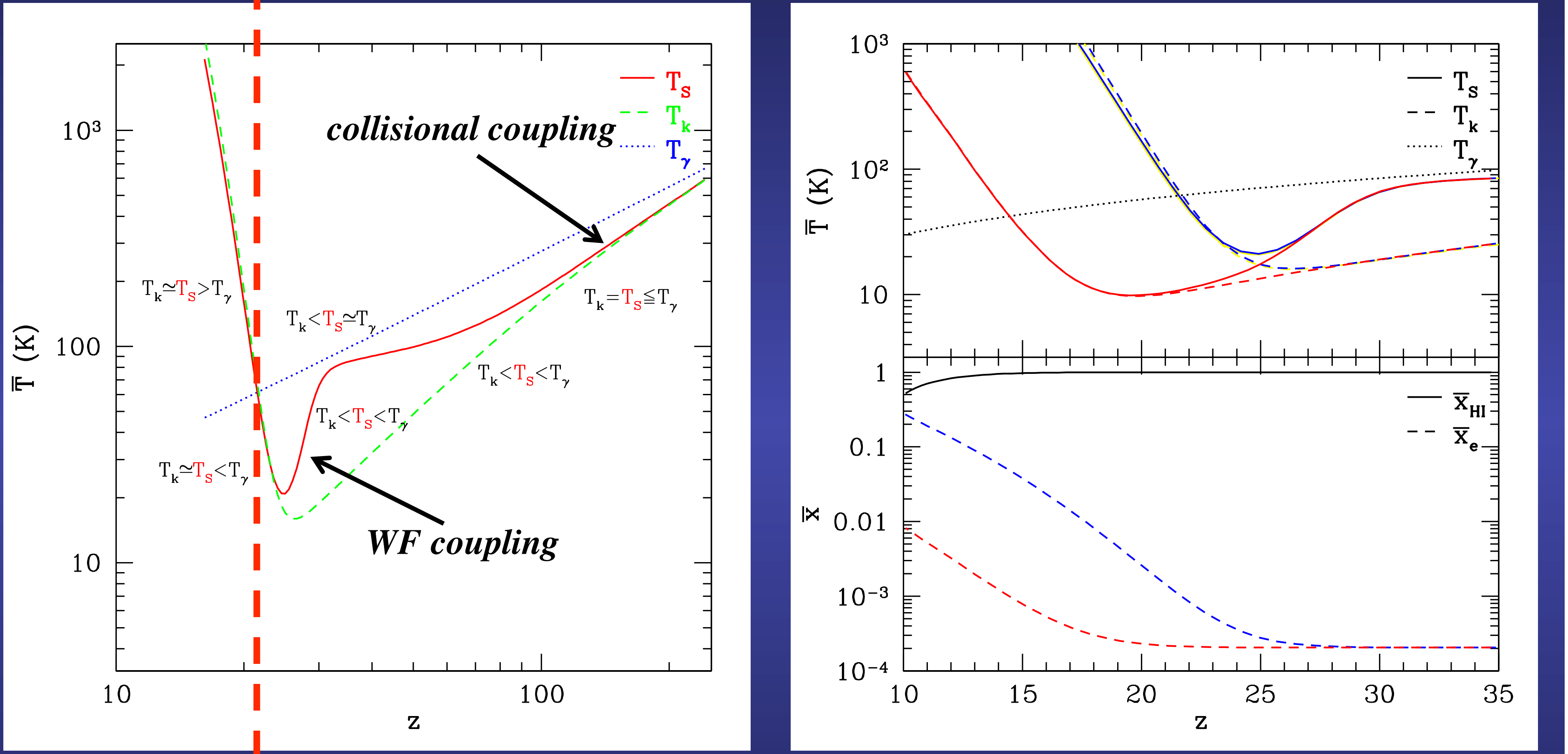
T_K – coupled to the CMB at high z ~>250. Then after decoupling adiabatically cools as ~$(1+z)^2$. When first astrophysical sources ignite, they heat the IGM through their X-rays.

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

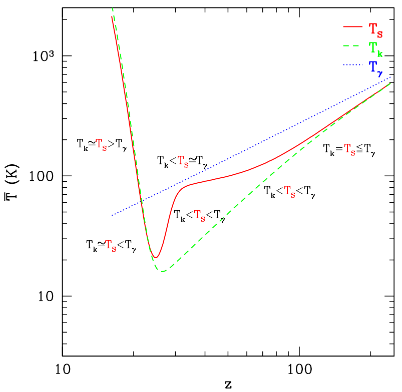
- *Compton* (high-z)
- *Lyα heating* (probably negligible: Chen & Miralda-Escude 2004, Rybicki 2006, Furlanetto & Pritchard 2006)
- *Shock heating* (not at strong at high-z in the IGM, e.g. Furlanetto & Loeb 2004; subdominant to X-ray heating for fiducial models)
- *DM annihilation* (stay tuned!)

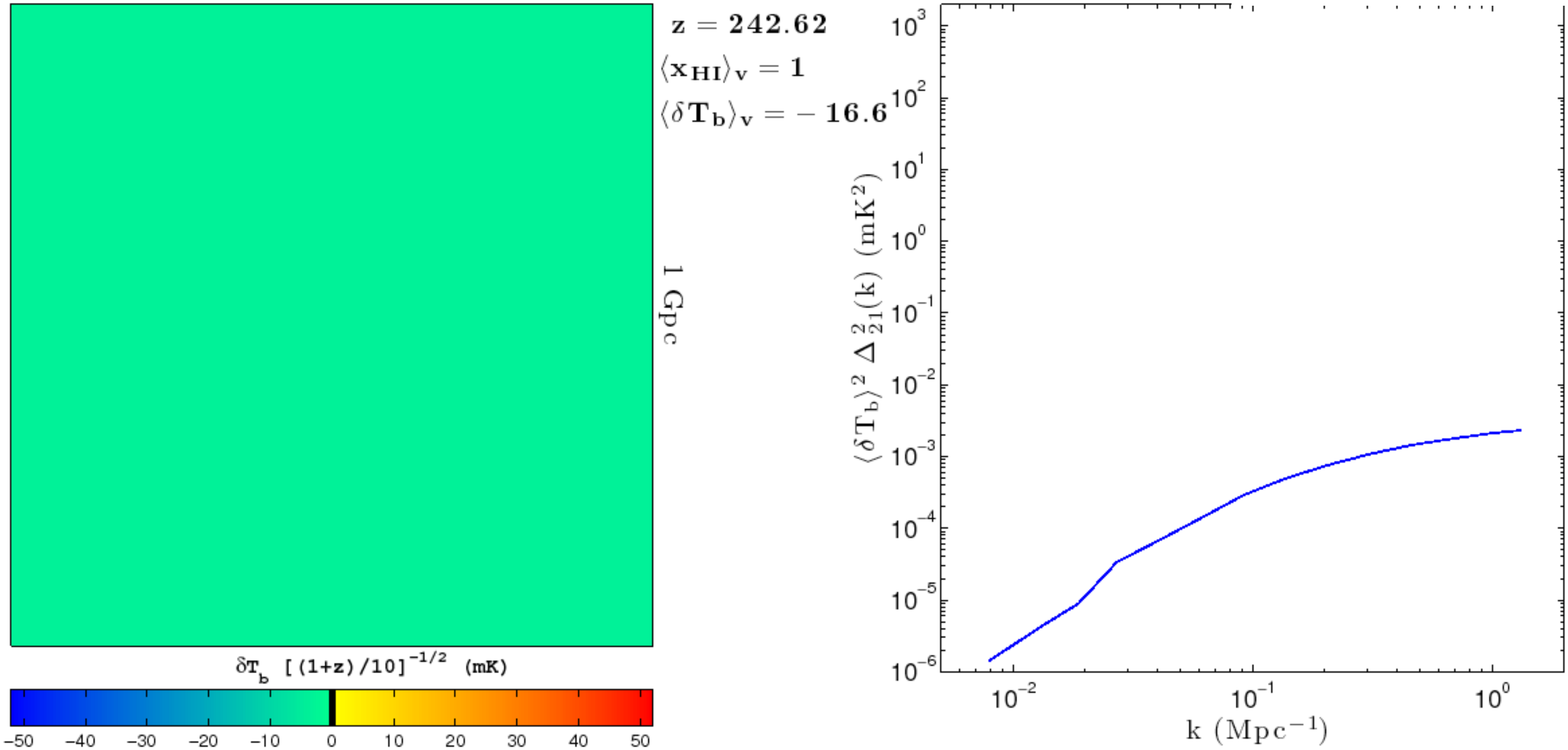
Global evolution

emission *absorption*



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





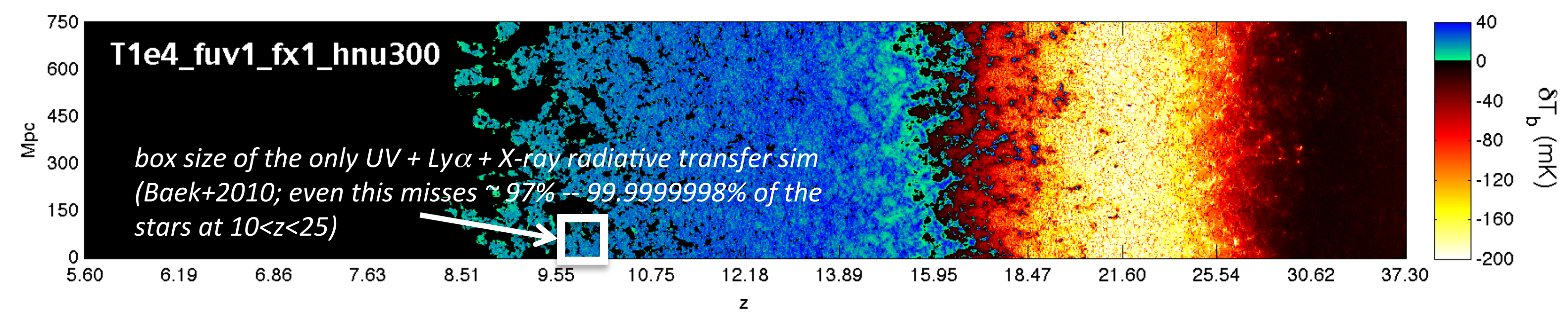
Let’s look at more scenarios

“fiducial” model:

reionization
(stellar-driven)

first BHs
(X-rays)

first stars
(UV)



box size of the only UV + Lyα + X-ray radiative transfer sim (Baek+2010; even this misses ~ 97% -- 99.9999998% of the stars at 10<z<25)

Mesinger+, in-prep

WORK IN PROGRESS

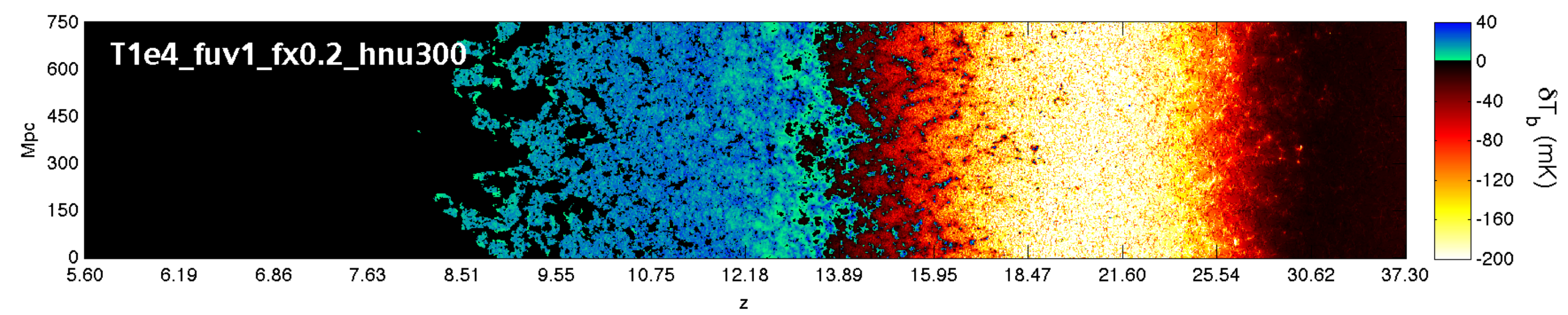
Let’s look at more scenarios

~0.2 times as efficient X-rays:

reionization
(stellar-driven)

first BHs
(X-rays)

first stars
(UV)



Mesinger+, in-prep

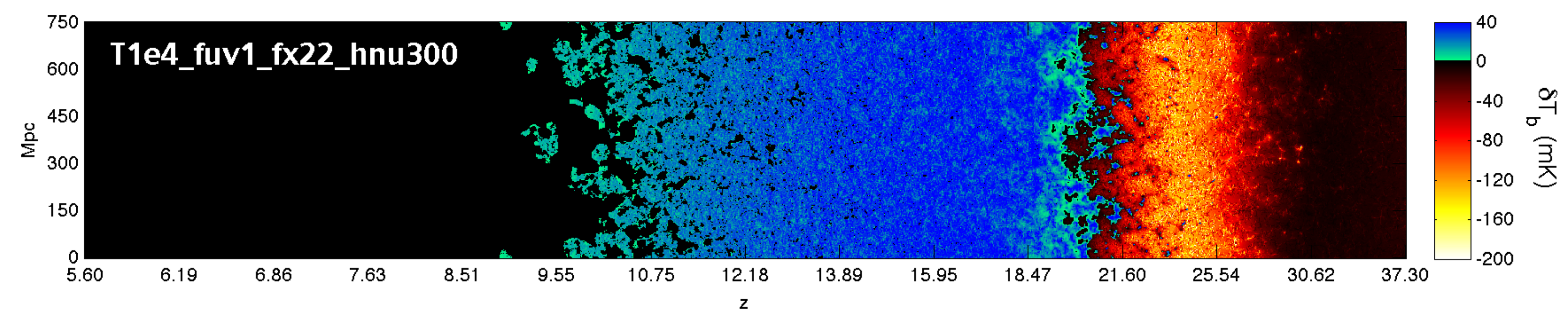
Let’s look at more scenarios

~20 times as efficient X-rays:

reionization
(UV + X-rays)

first BHs
(X-rays)

first stars
(UV)



Mesinger+, in-prep

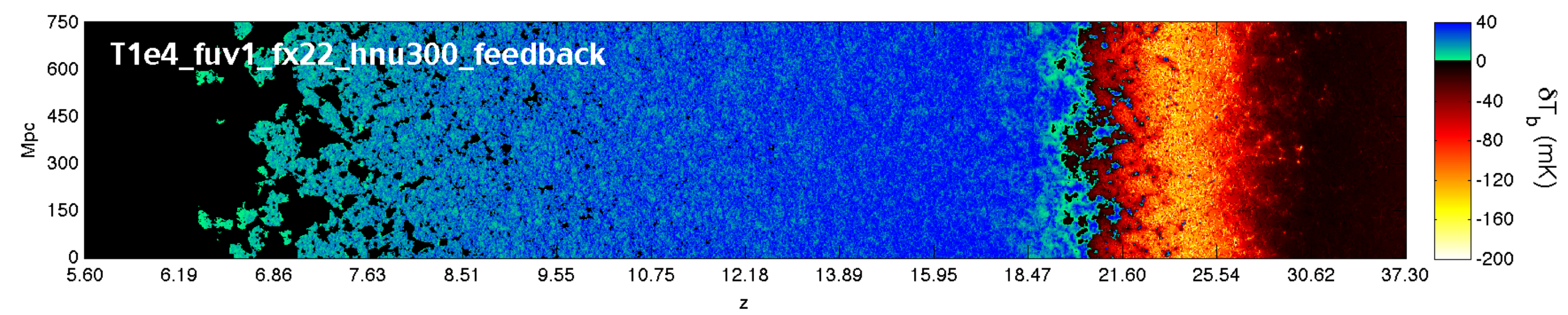
Let’s look at more scenarios

~20 times as efficient X-rays, including extreme thermal feedback:

reionization
(UV + X-rays)

first BHs
(X-rays)

first stars
(UV)



Mesinger+, in-prep

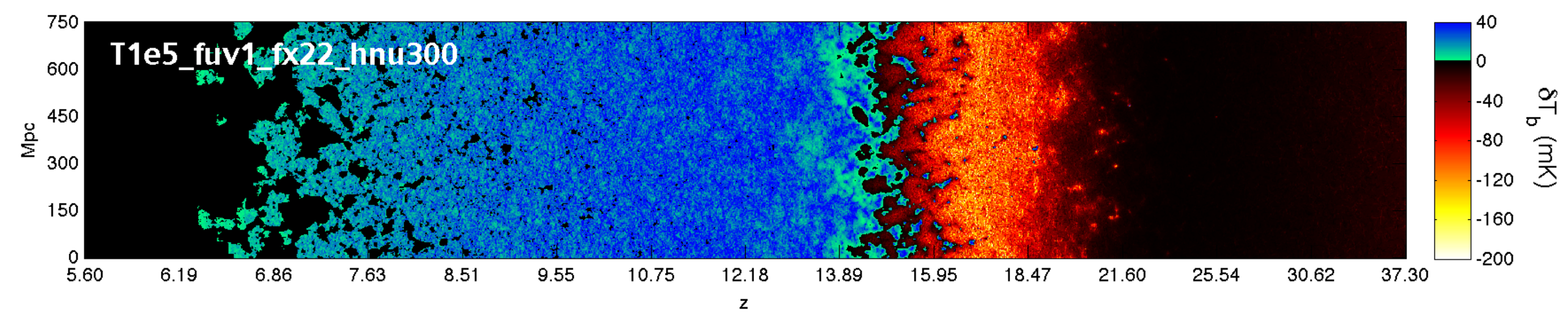
Let’s look at more scenarios

~20 times as efficient X-rays, but inside more massive halos:

reionization
(UV + X-rays)

first BHs
(X-rays)

first stars
(UV)



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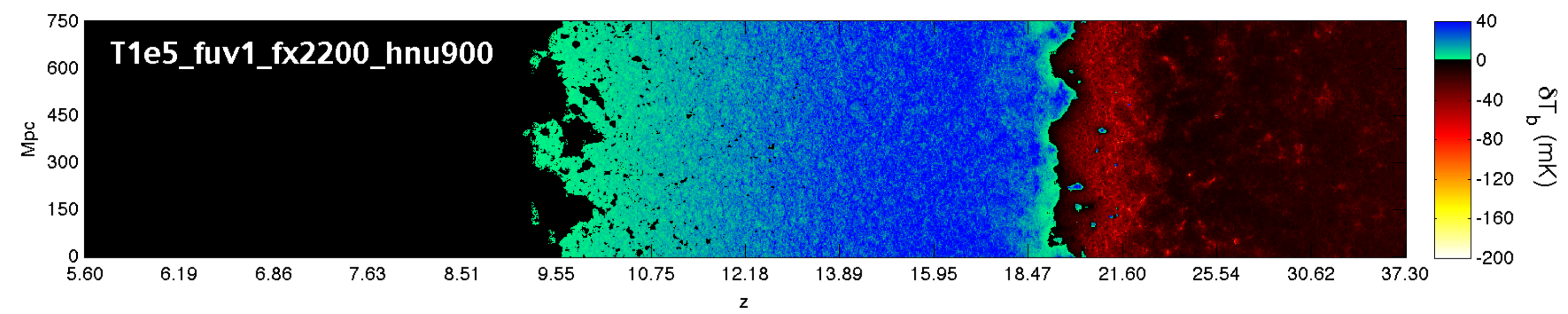
Let’s look at more scenarios

“extreme” X-rays:

~2000 times as efficient, harder, X-rays, inside massive halos:

reionization
(X-rays)

first BHs
(X-rays)



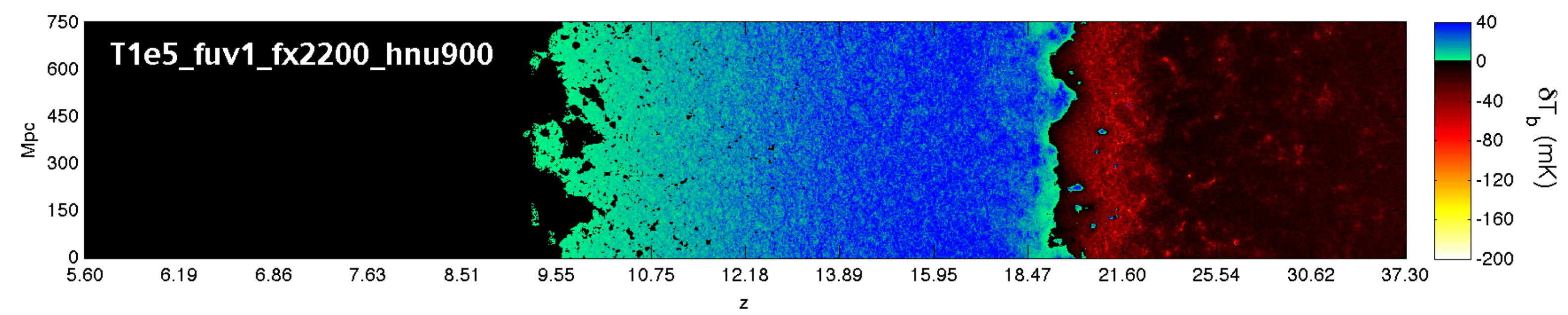
Mesinger+, in-prep

Let’s look at more scenarios

“extreme” X-rays:
~2000 times as efficient, harder, X-rays, inside massive halos:

reionization
(X-rays)

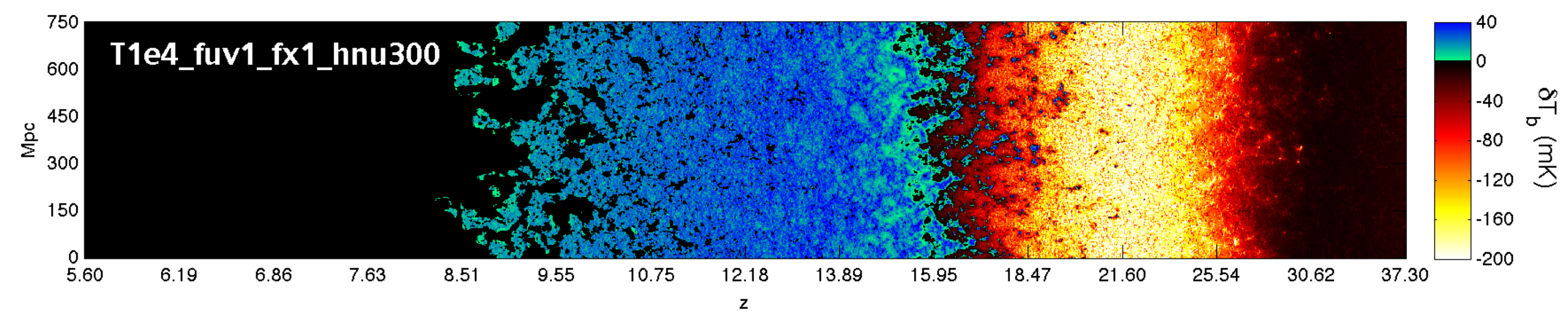
first BHs
(X-rays)



“fiducial”

vs

Mesinger+, in-prep



Example 3:

including heating from DM annihilations

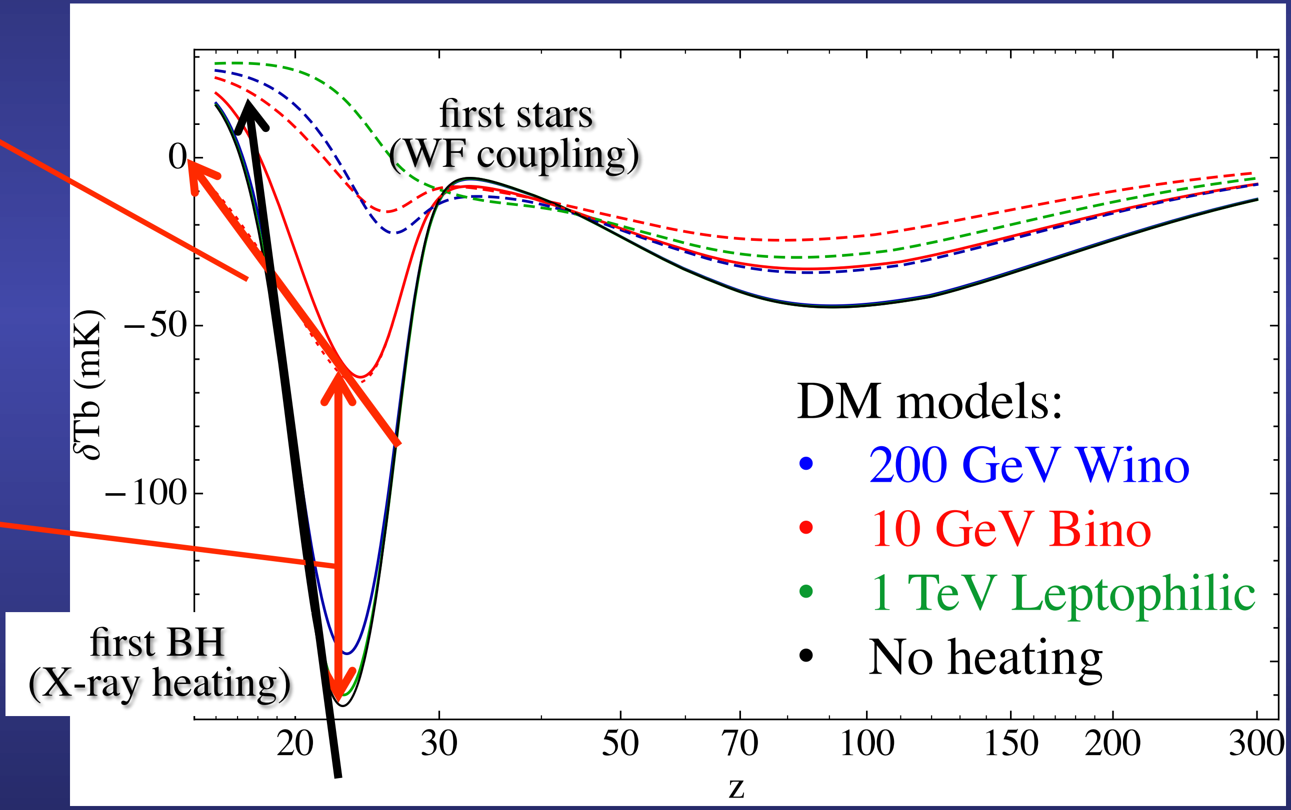
Include energy depositions from MEDEA2 (Valdes+ in prep)

DM heating is slower than X-ray heating

AND

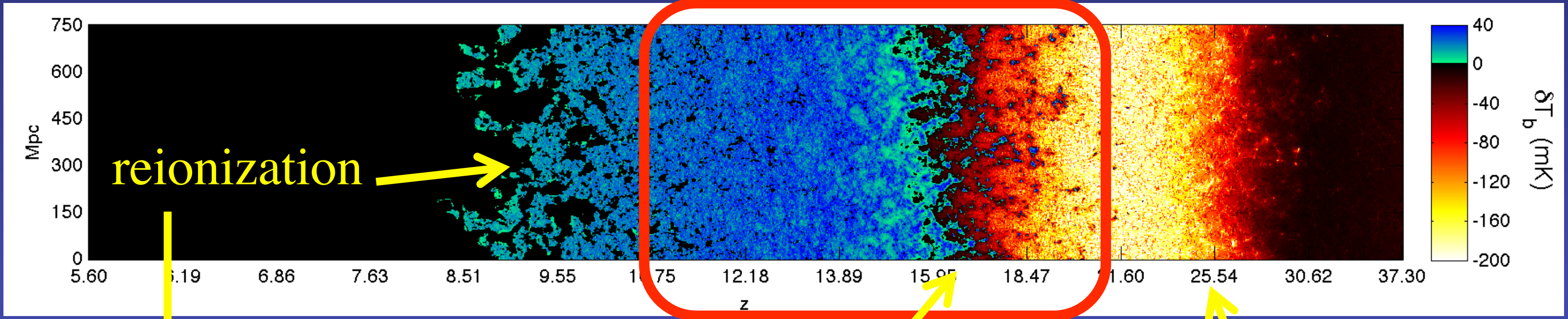
DM heating suppresses absorption trough

DM annihilation heating +“fiducial” astrophysics

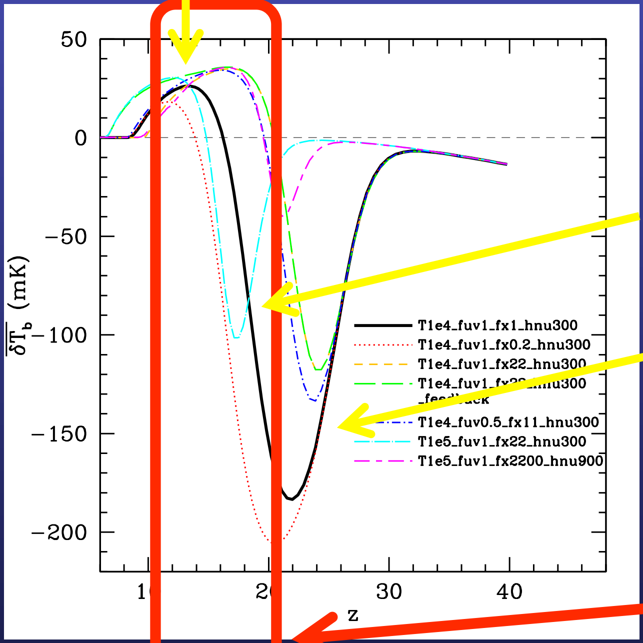


We need 2nd generation, SKA: rich physics of the early Universe

Cosmology:
DM heating, BAO, matter power spectrum



reionization



IGM heating
(first BH)

spin T coupling
(first stars)

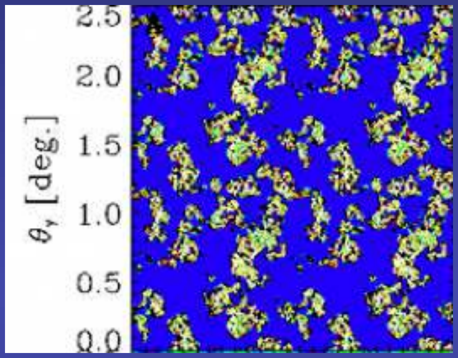
only accessible with
SKA

Conclusions

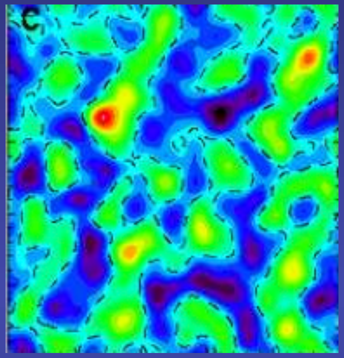
- Cosmological 21cm signal is very rich in information, containing both cosmological and astrophysical components.
- Astrophysical milestones such as reionization are likely the only practical way of observing the primordial zoo of astrophysical objects in the near future
- The range of scales and unknown parameter space is enormous! We need parameter explorations and efficient modeling tools to make sense of the upcoming observations: 21cmFAST
- Pre-reionization epoch allows us to study processes which heat the IGM, as well as the matter power spectrum
- We need the SKA: (i) make certain we can detect even early reionization; (ii) image reionization; (iii) probe pre-reionization epoch of the first stars and black holes
- We are living in exciting times!

We need 2nd generation, SKA: imaging reionization

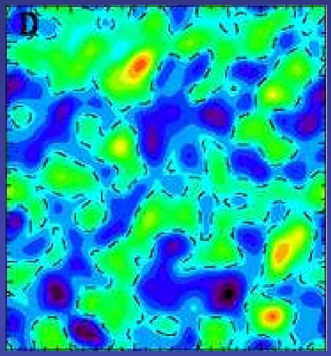
cosmic signal
(21cmFAST)



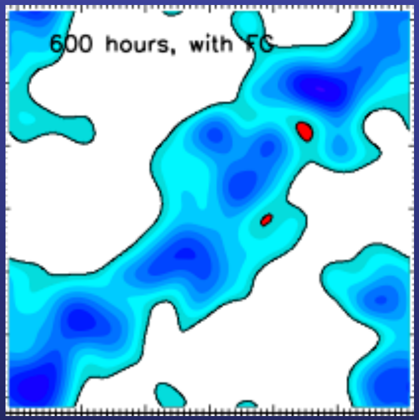
+ 20’ smoothing
+ 600h LOFAR noise



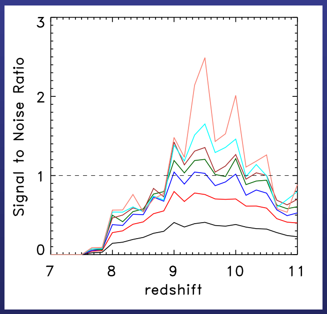
+ foregrounds (Jelic+)
- foregrounds (Wp)



reconstructed phase



original phase



Zaroubi+(2012)

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

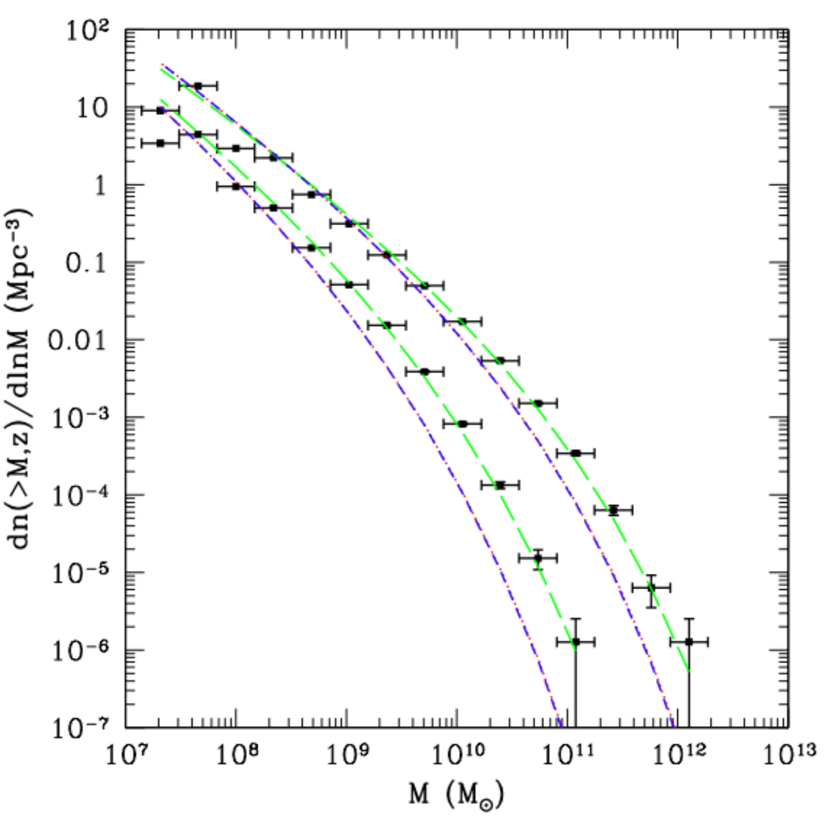
- a person or thing that appears unexpectedly and provides a contrived solution to an apparently insoluble difficulty

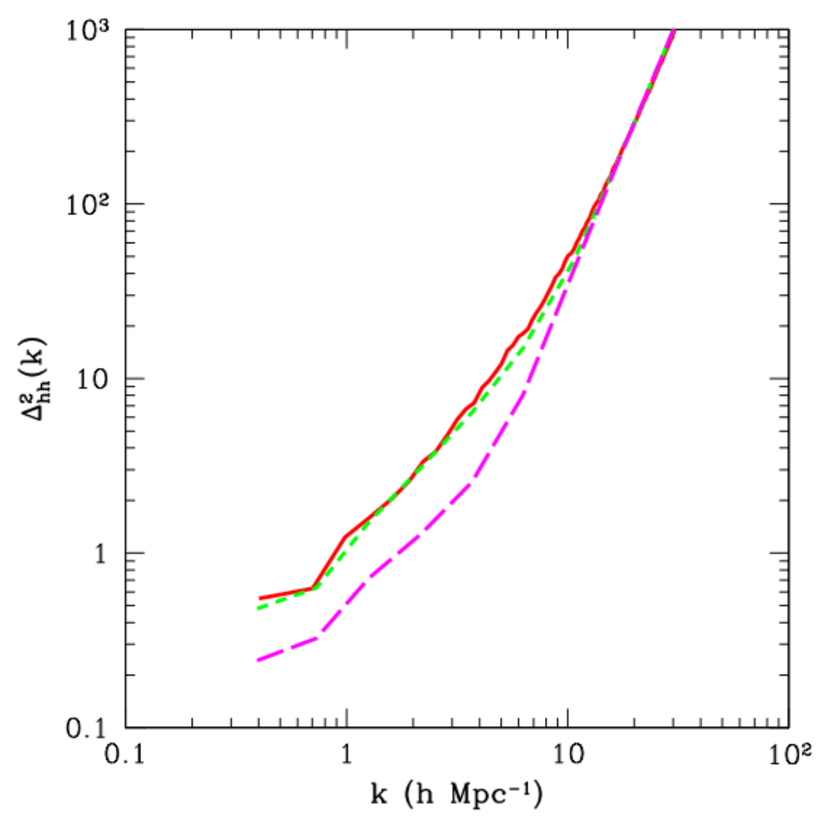
(http://www.merriam-webster.com/dictionary/deus%20ex%20machina)

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

Halo Finder

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

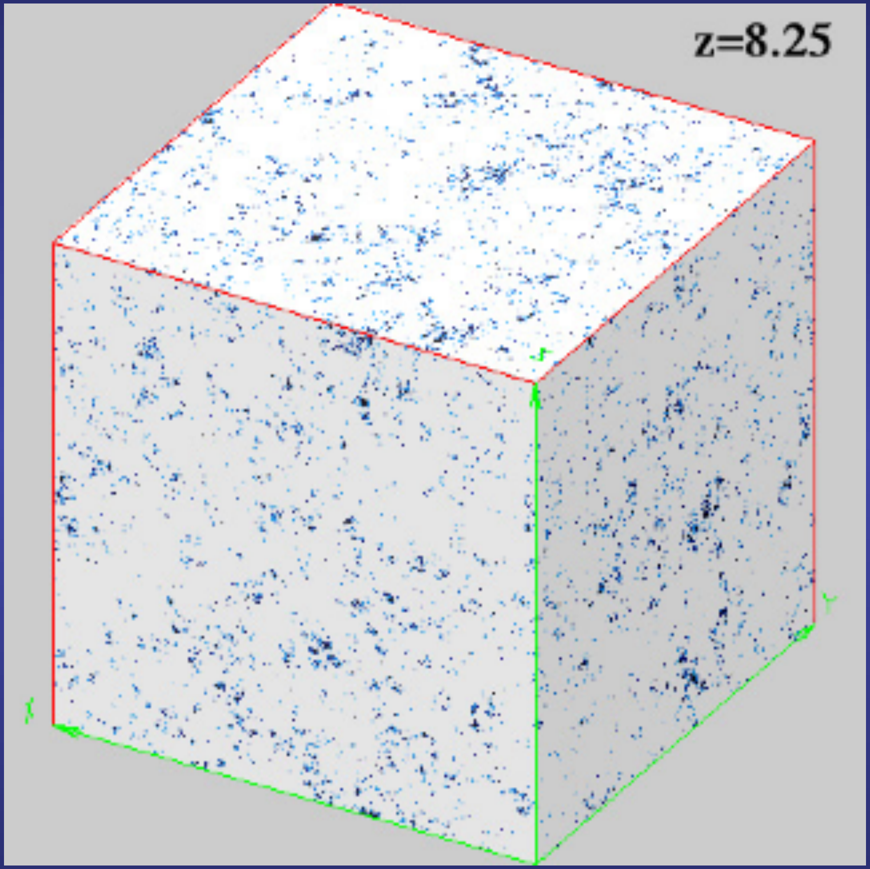




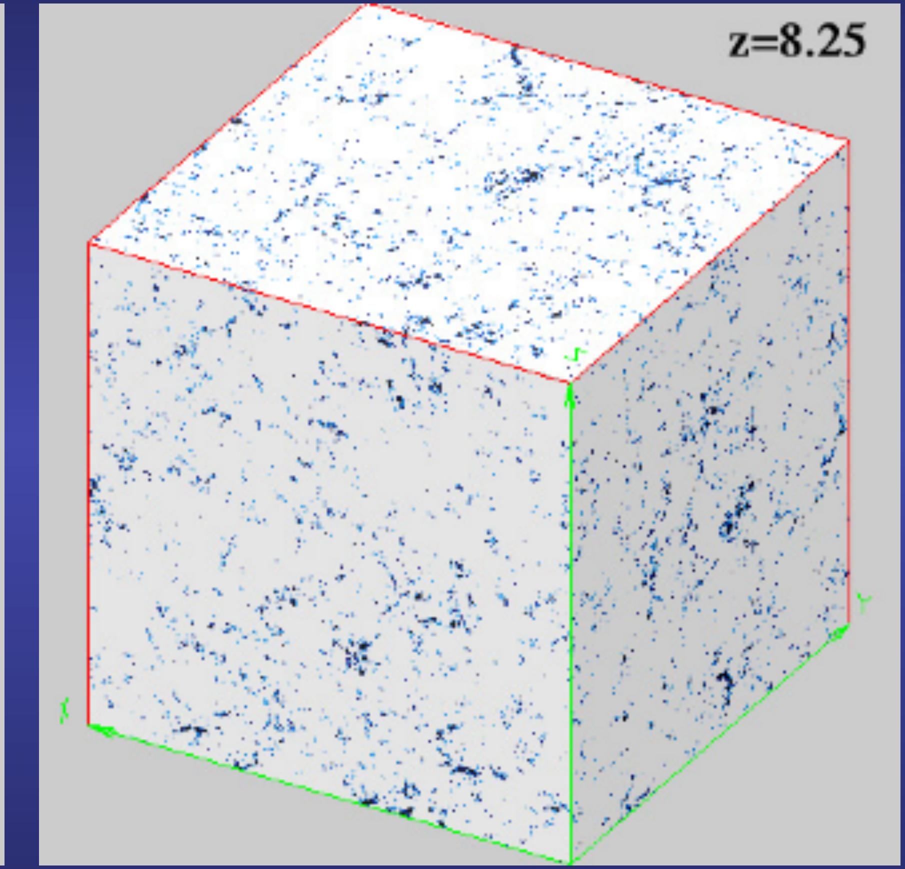
z=8.7 N-body halo field from McQuinn et al. (2007)

Halo Finder

Mesinger & Furlanetto (2007)



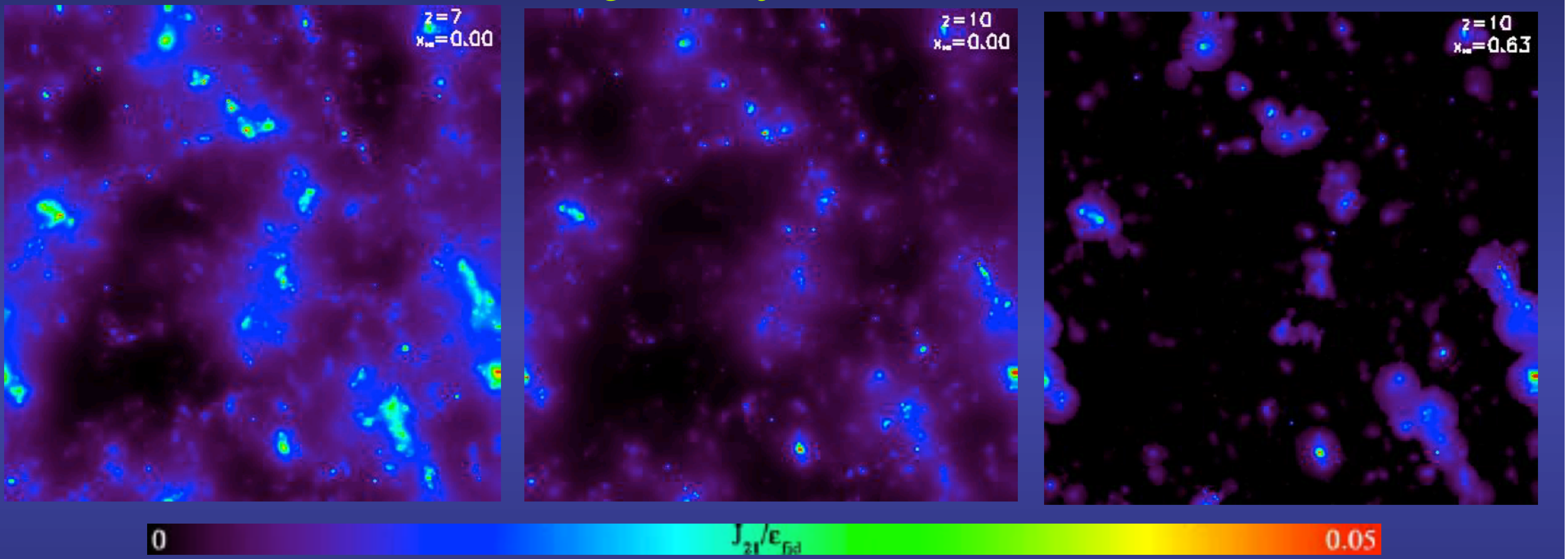
without adjusting halo locations



with adjusting halo locations

Ionizing UV Flux Fields

Mesinger & Dijkstra (2008)



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