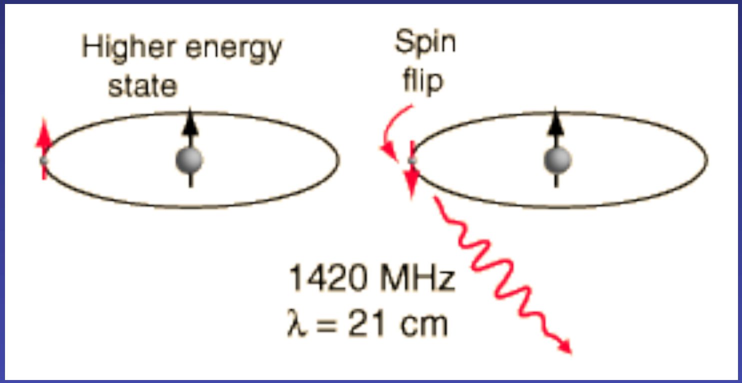
The imprint of dark matter on the cosmological 21cm signal

Andrei Mesinger
Scuola Normale Superiore, Pisa

Outline

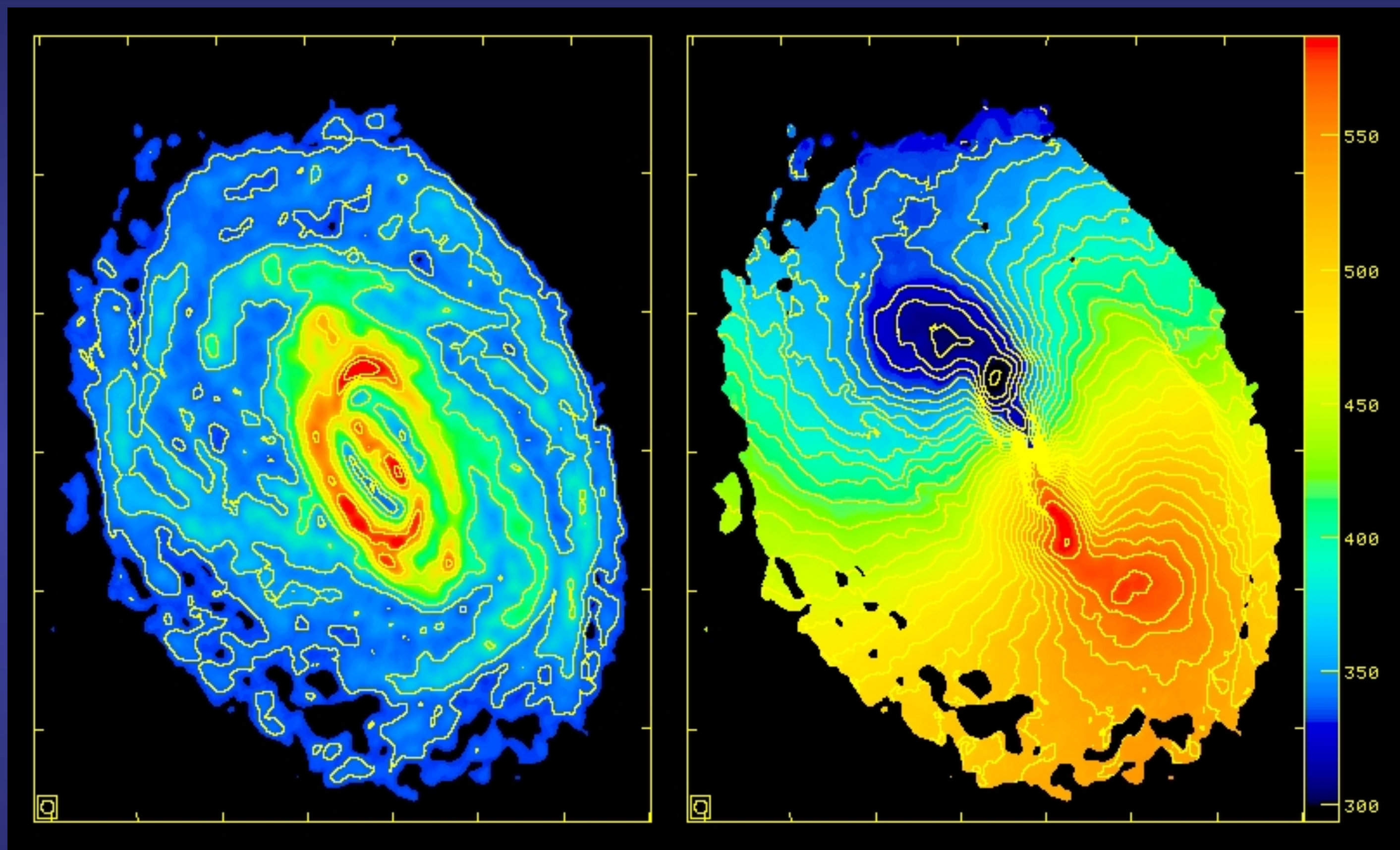
- The cosmological 21cm signal
  - Relevant physics
  - Modeling challenges
- Imprint of DM:
  - Direct probe of the matter power spectrum
  - Suppression in the abundance of early galaxies (WDM)
  - Heating the IGM through decay (WDM) and annihilations (CDM)

21 cm line from neutral hydrogen



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

Now widely used to map the HI content of nearby galaxies

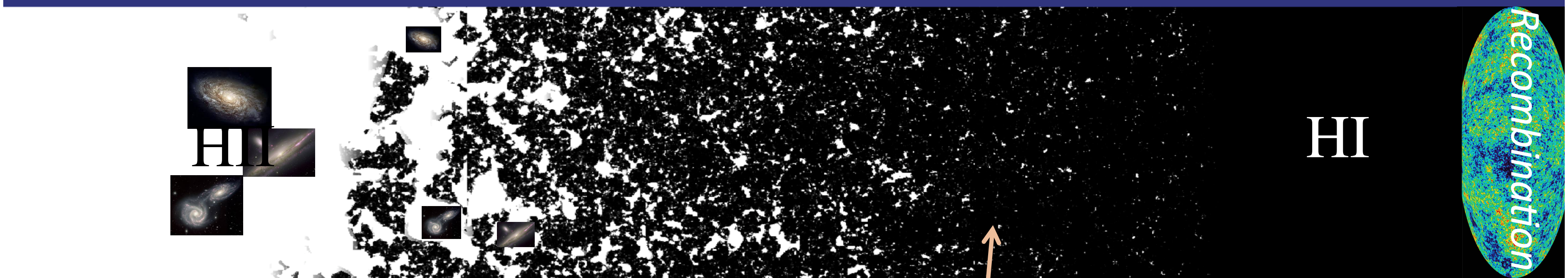


Circinus Galaxy

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

Cosmic history

Reionization *Dark Ages*



$z = 0$ — $t_{age} \sim 14$ Gyr

$z \sim 6$ — $t_{age} \sim 1$ Gyr

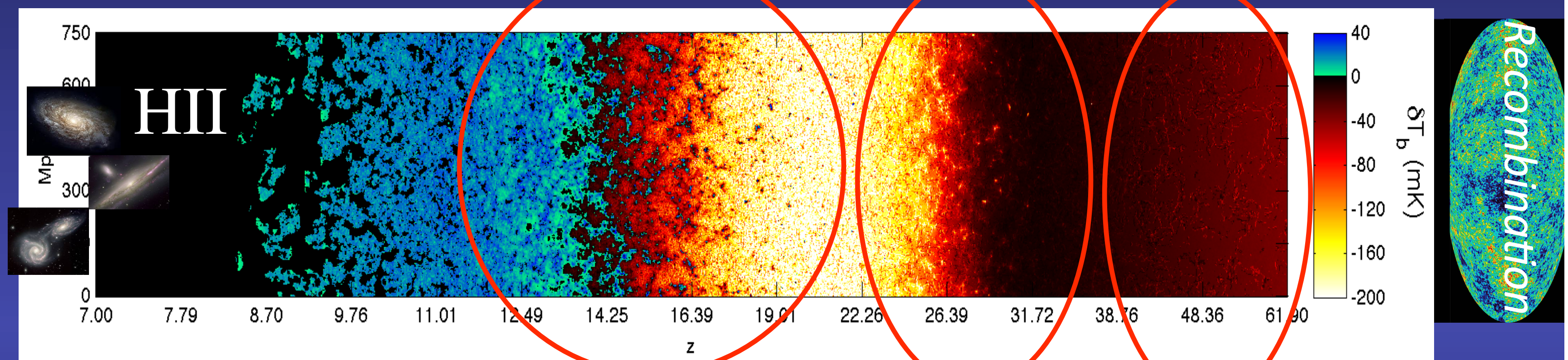
$z \sim 20$ — $t_{age} \sim 150$ Myr

$z \sim 1100$ — $t_{age} \sim 0.4$ Myr

Lots of neutral hydrogen!

Cosmic history in 21cm

Reionization *Cosmic Dawn* *Dark Ages*



z ~ 0 *z ~ 6* *z ~ 20* *z~1100*

t_{age} ~ 14 Gyr *t_{age} ~ 1 Gyr* *t_{age} ~ 150 Myr* *t_{age} ~ 0.4 Myr*

First Black Holes

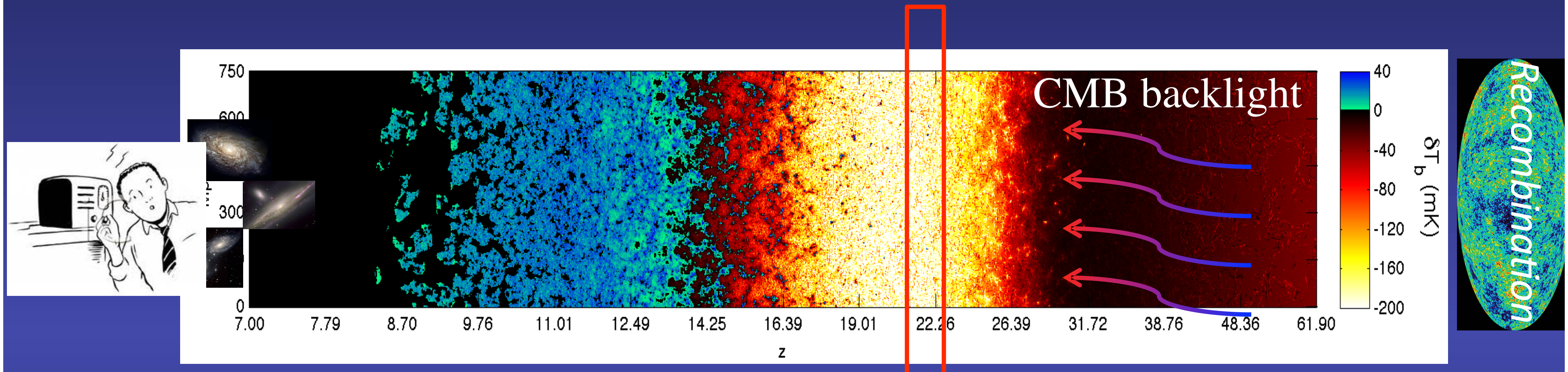
Infancy of Cosmic Web

First Stars

Cosmic history in 21cm

Redshifted 21cm signal.
tune radio to:

υ_{21} ~ 70 MHz



z ~ 0
t_{age} ~ 14 Gyr

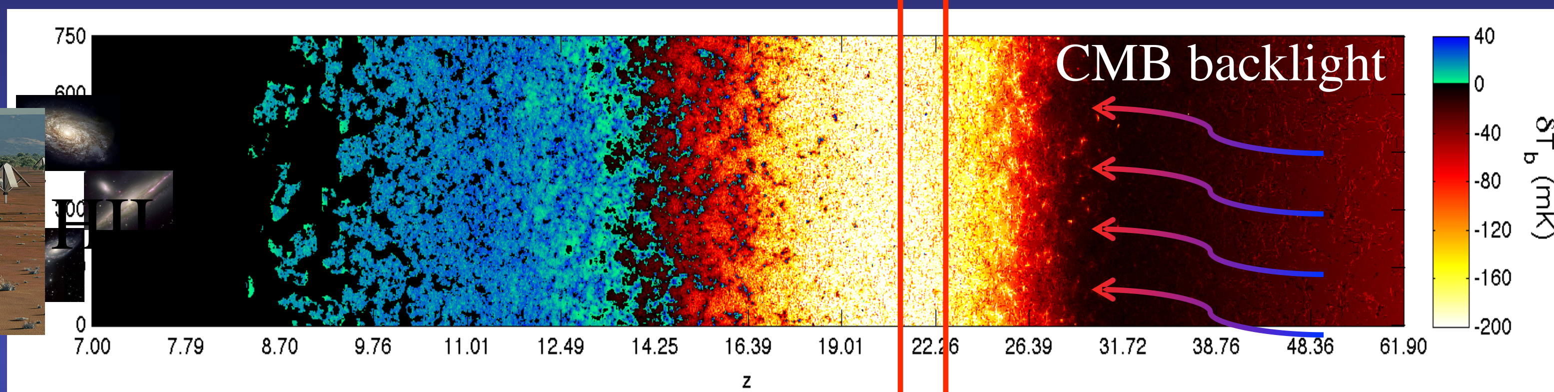
z ~ 20
t_{age} ~ 150 Myr

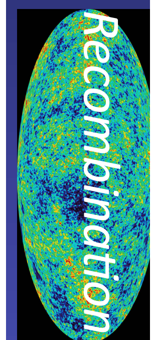
z~1100
t_{age} ~ 0.4 Myr

Cosmic history in 21cm

Redshifted 21cm signal.
tune radio to:
interferometer

υ_{21}~ 70 MHz





z ~ 20
t_{age} ~ 150 Myr

z~1100
t_{age} ~ 0.4 Myr

LOFAR,
MWA,
PAPER,
21CMA,
GMRT
2nd gen: HERA, SKA

Why so colorful? Physics-rich probe

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

spin temperature

LOS velocity gradient

neutral fraction

gas density

Cosmological 21cm Signal

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

Powerful probe:

Cosmology

&

Astrophysics

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

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

The full power of 21cm to reach back into the infancy of galaxy formation….

Pre-reionization signal

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

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

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

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:

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

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!

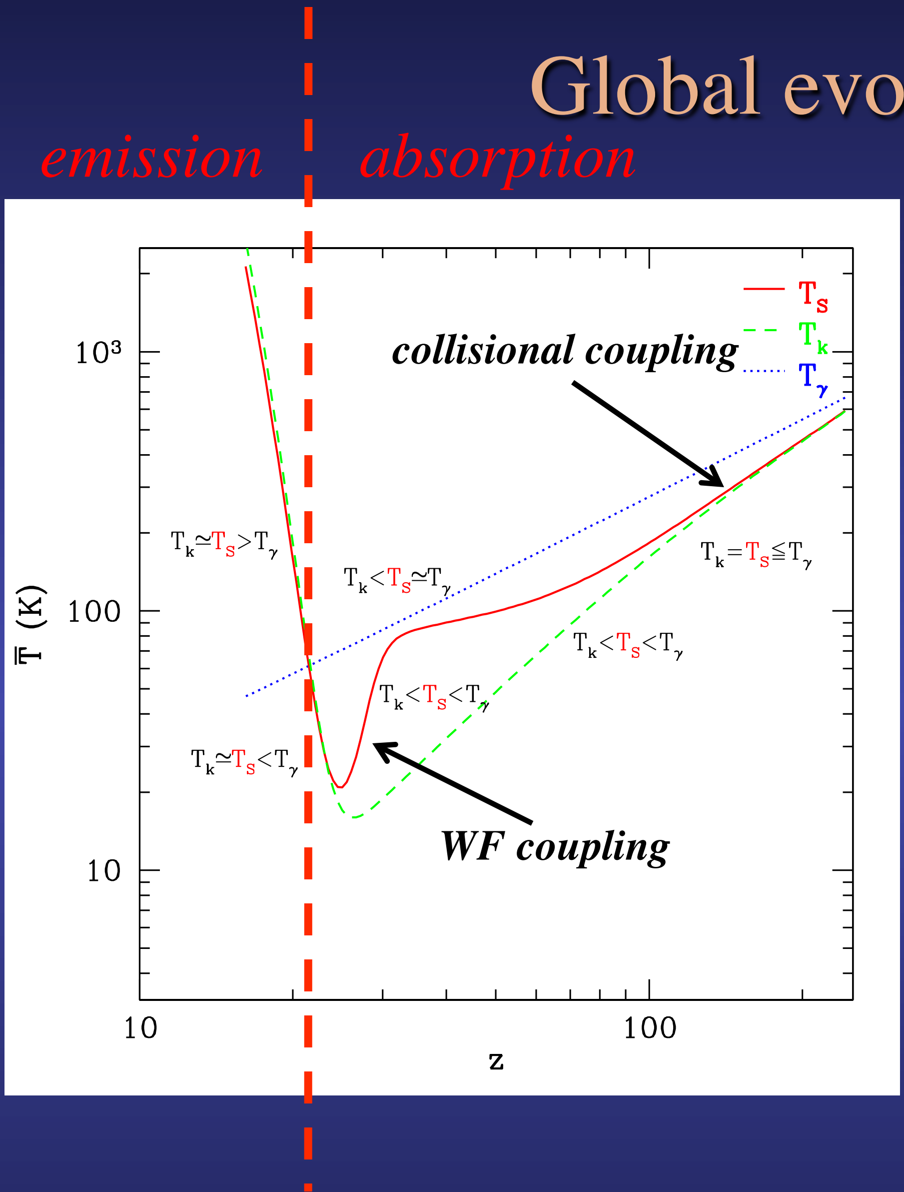
What do the temperatures do?

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 (or dark matter annihilations; stay tuned…).

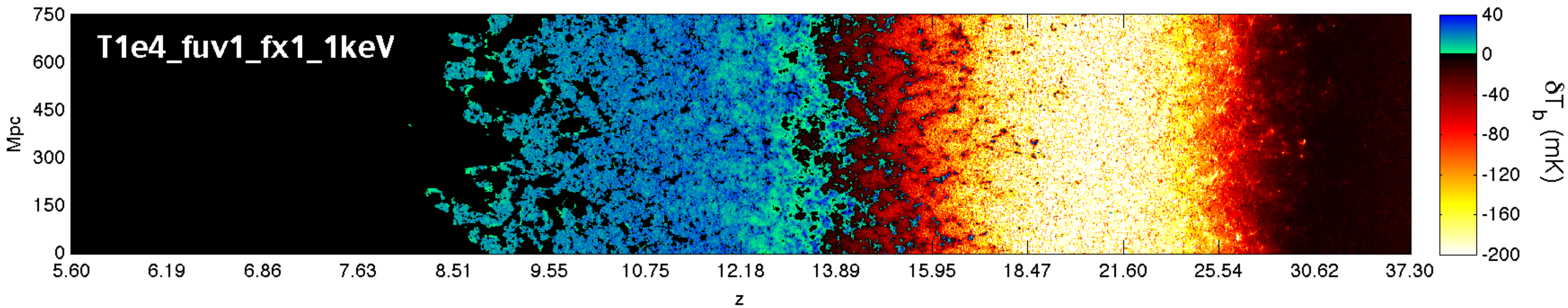
Global evolution: T_S, T_K, T_{CMB}

emission *absorption*



Global evolution: dT_b

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

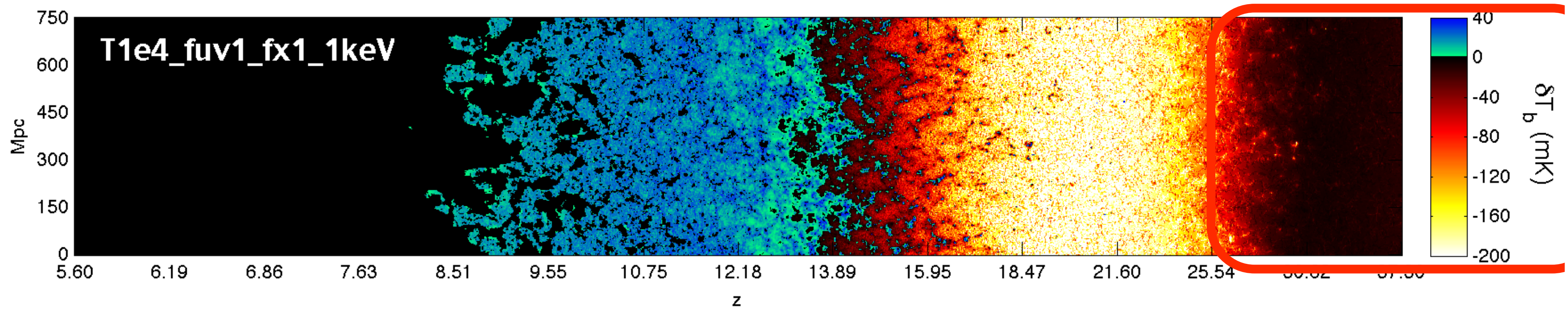


Main stages:

- Collisional coupling (z>~100)

Global evolution: dT_b

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

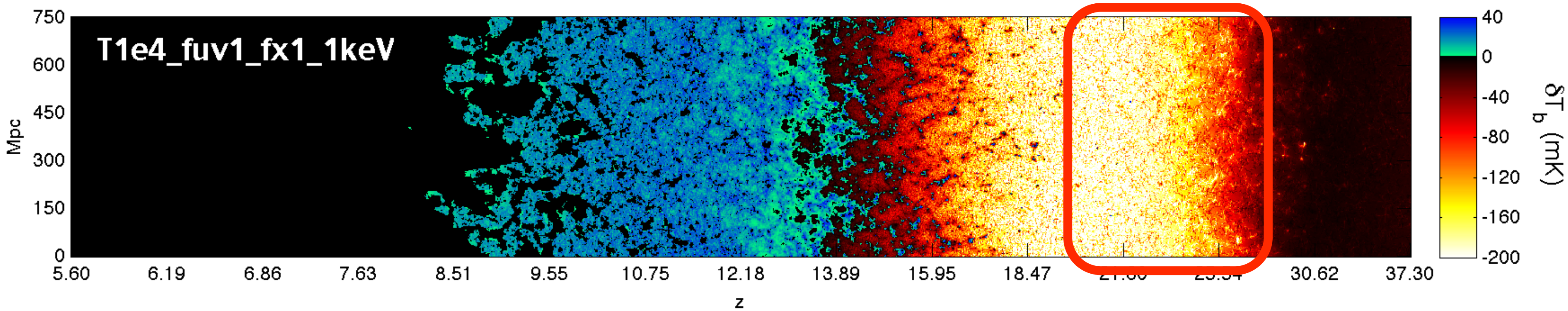


Main stages:

- Collisional coupling (z>~100)
- Collisional decoupling (25<z<100)

Global evolution: dT_b

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

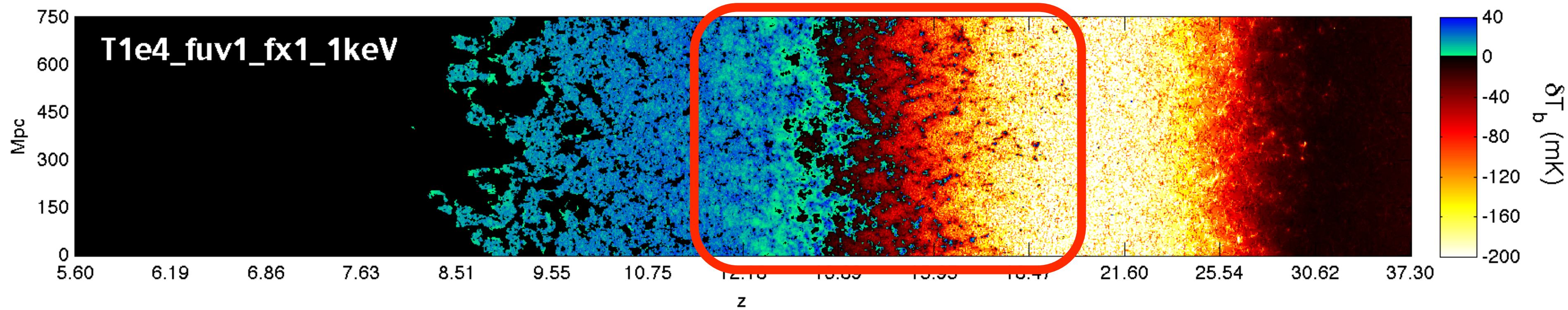


Main stages:

- Collisional coupling (z>~100)
- Collisional decoupling (25<z<100)
- WF coupling (Lyα pumping)

Global evolution: dT_b

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

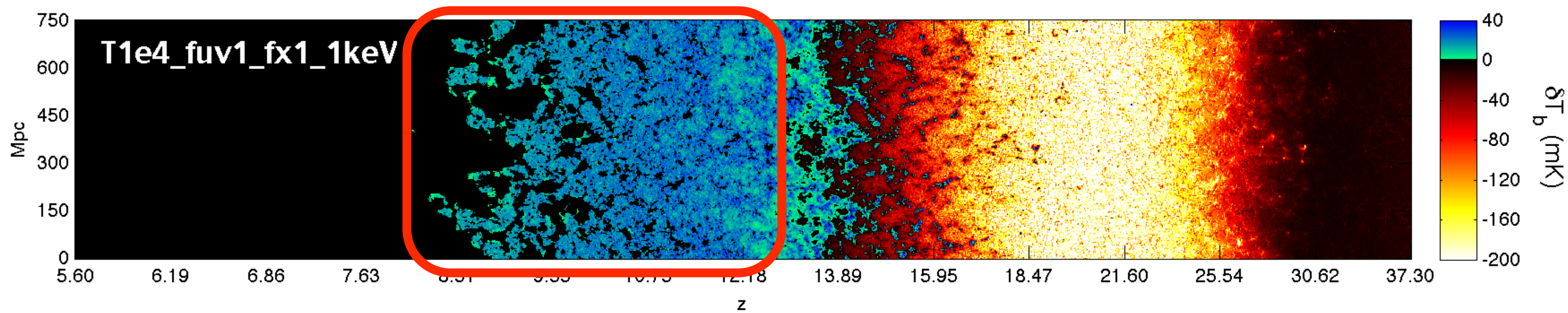


Main stages:

- Collisional coupling (z>~100)
- Collisional decoupling (25<z<100)
- WF coupling (Lyα pumping)
- IGM heating (X-rays)

Global evolution: dT_b

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

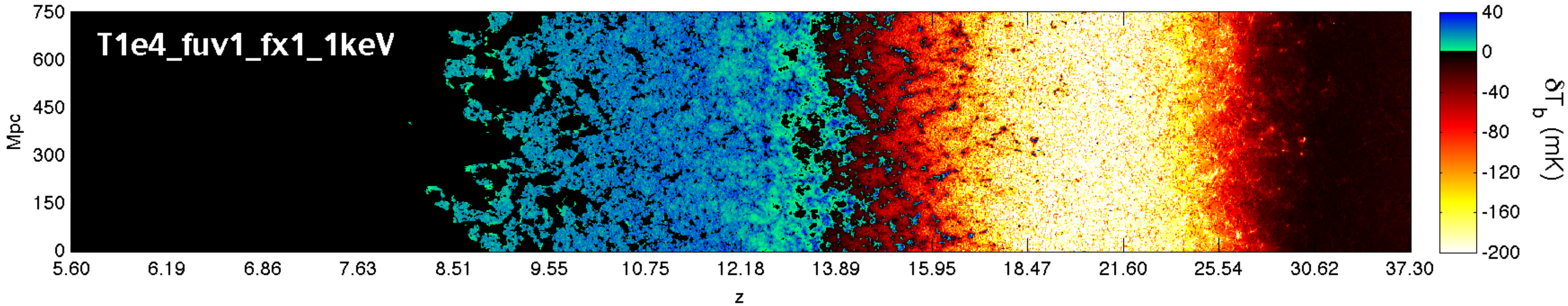


Main stages:

- Collisional coupling (z>~100)
- Collisional decoupling (25<z<100)
- WF coupling (Lyα pumping)
- IGM heating (X-rays)
- Reionization

Global evolution: dT_b

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



Likely overlap!

DARK AGES

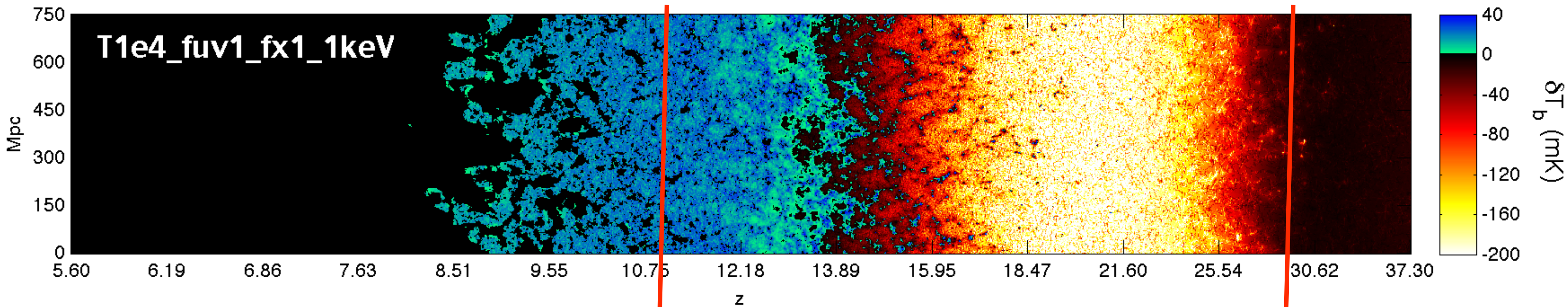
COSMIC DAWN

Main stages:

- Collisional coupling ($z>\sim100$)
- Collisional decoupling ($25<z<100$)
- WF coupling (Lyα pumping)
- IGM heating (X-rays)
- Reionization

Global evolution: dT_b

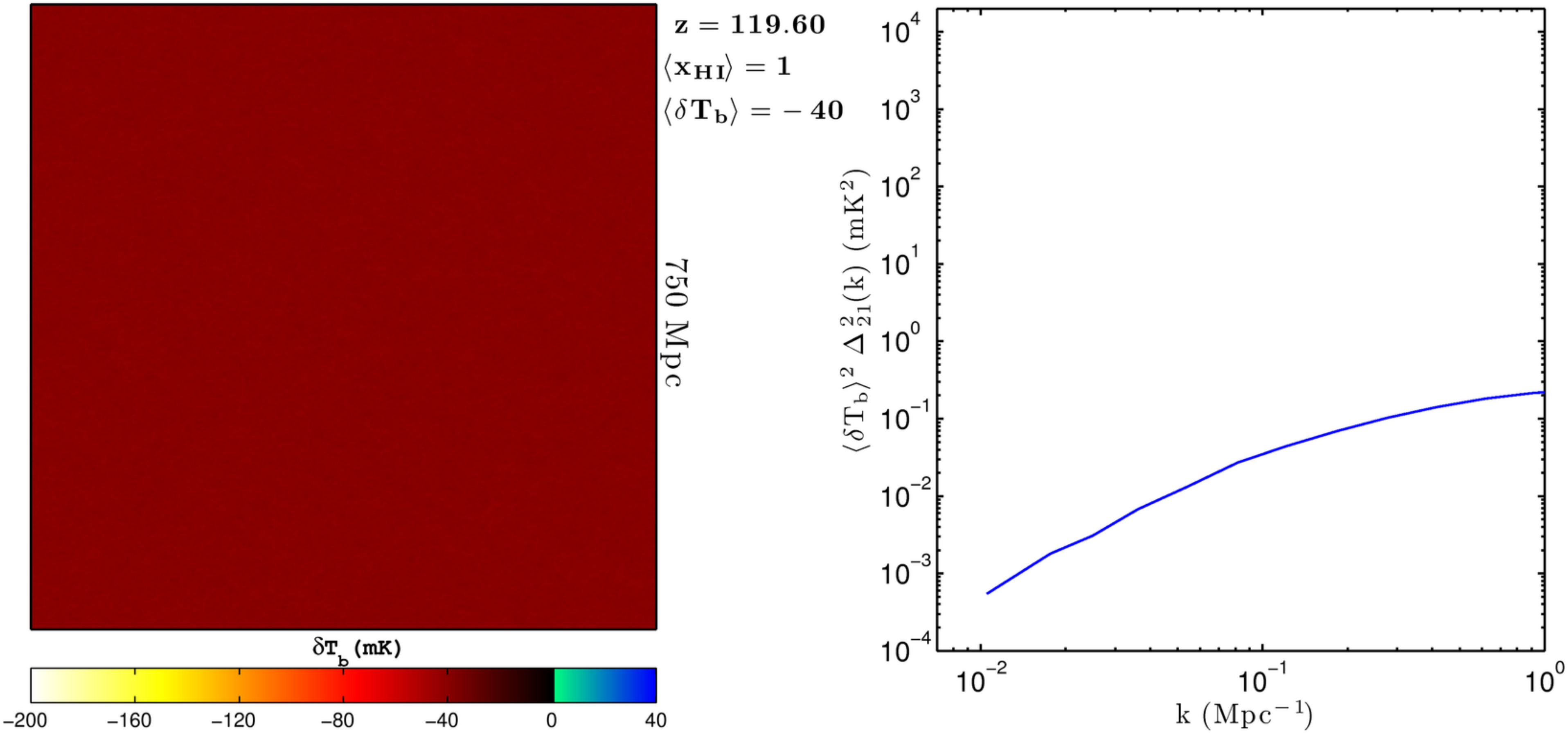
$$\delta T_b(\nu) \approx 27 x_{\rm HI}(1+\delta_{\rm nl})\left(\frac{H}{dv_r/dr + H}\right)\left(1-\frac{T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\frac{0.15}{\Omega_M h^2}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right) \mathrm{mK}$$



1^{st} gen.
LOFAR, MWA, PAPER, 21CMA

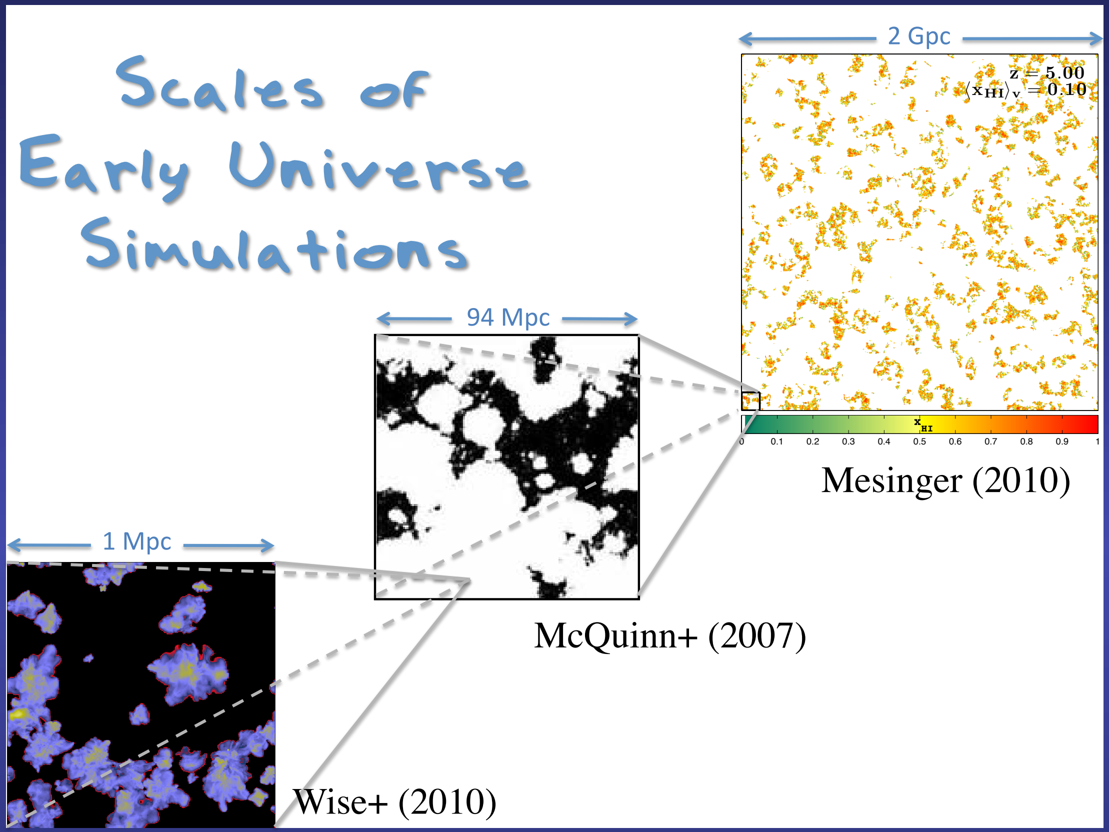
2^{nd} gen.
SKA, HERA

http://homepage.sns.it/mesinger/21cm_fiducial.mov



How do we interpret upcoming observations?

How to understand and model 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!

How to approach the problem

Seminumerical Simulations
or Analytic Estimates

↑

Seminumerical Simulations or
lower resolution large-scale numerical simulations

↑

Hydrodynamical Numerical Simulations (+RT)

↑ *scale*

21cmFAST

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

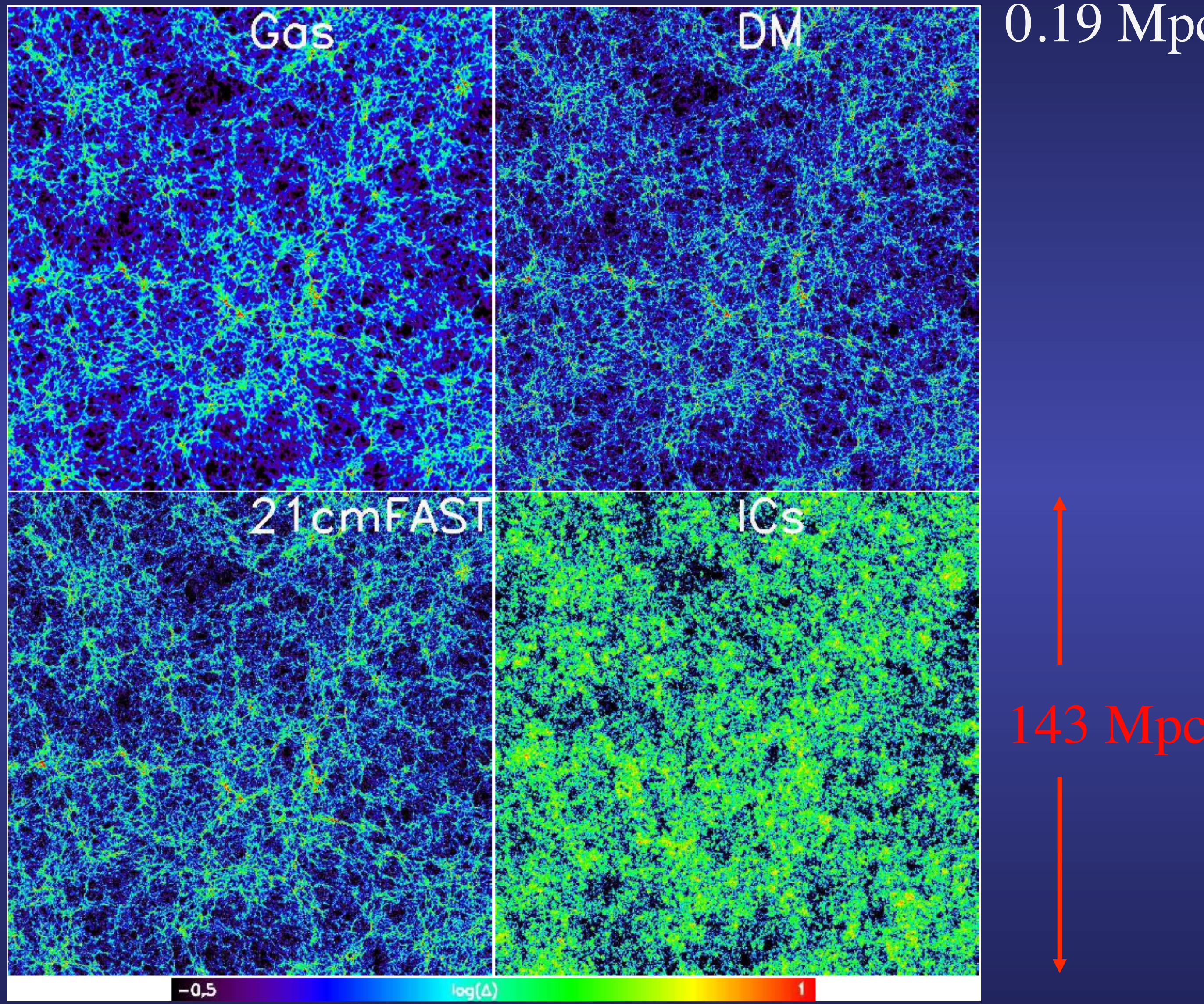
- Combines excursion-set approach with perturbation theory for efficient generation of large-scale density, velocity, halo, ionization, 21cm brightness fields
- Portable and FAST! (if it's in the name, it must be true…)
  - A realization can be obtained in ~ minutes on a single CPU
  - *New* parallelized 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!

Previous halo-based version, DexM (Mesinger & Furlanetto 2007), has been used to interpret LAEs, QSO spectra, LLS distribution..

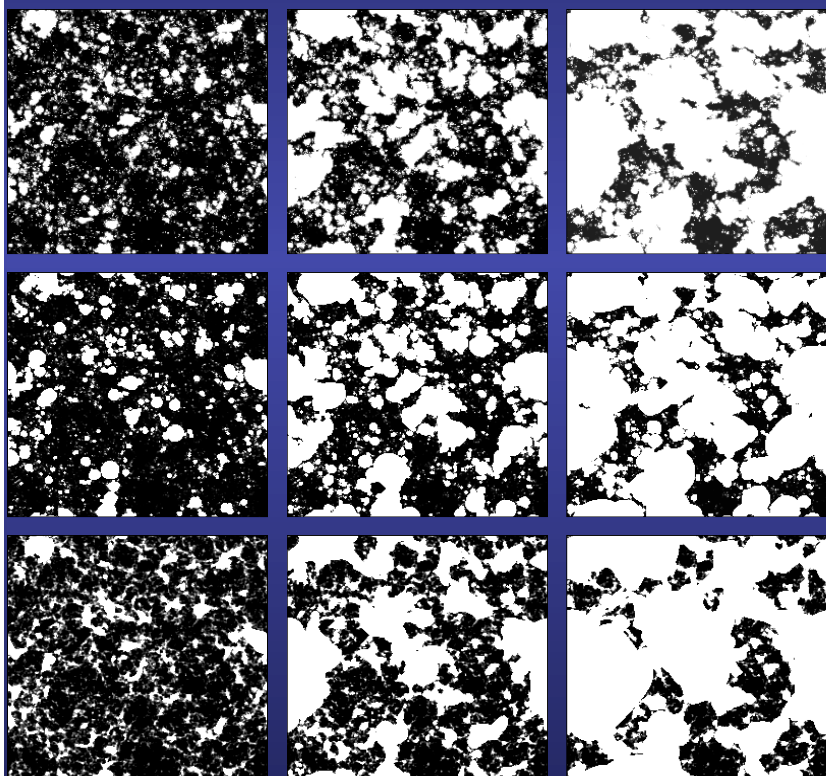
Density Fields

z=7

0.19 Mpc cells



Ionization fields



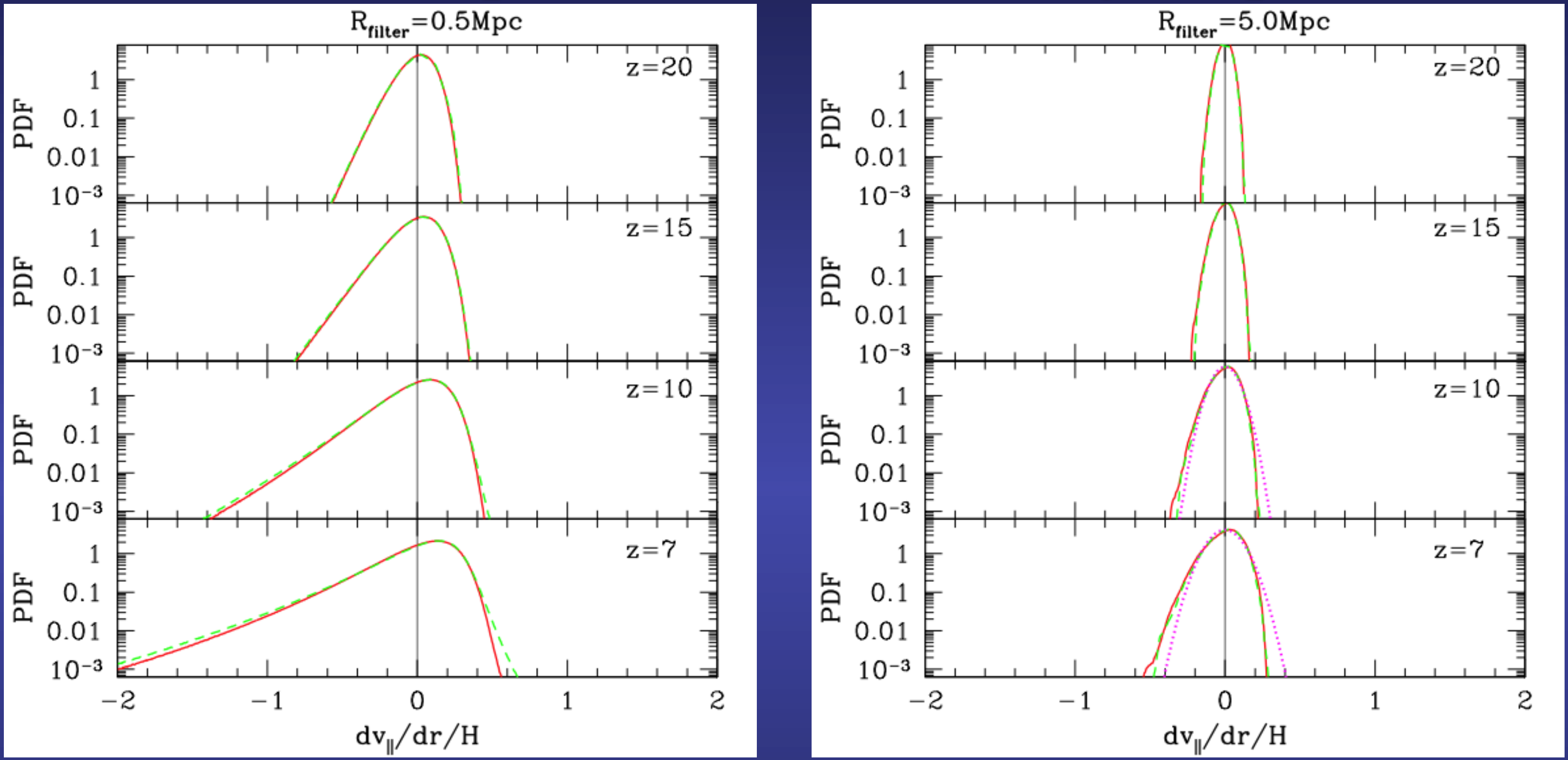
Trac & Cen (2007)

DexM (with halos;
Mesinger & Furlanetto; 2007)

21cmFAST (Mesinger+ 2011)

Zahn+ (2010)

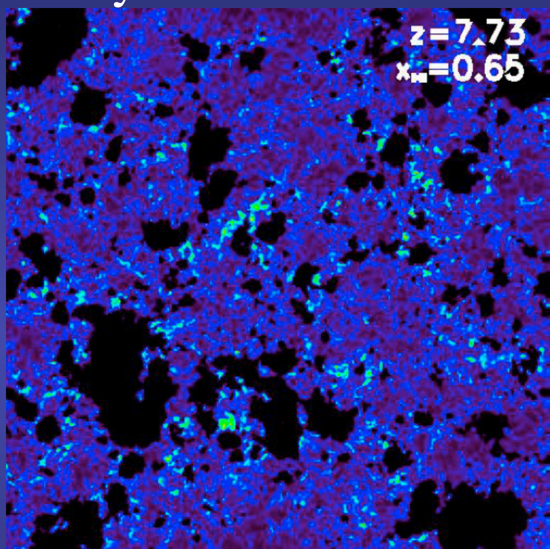
Redshift space distortions (sorry no pics)



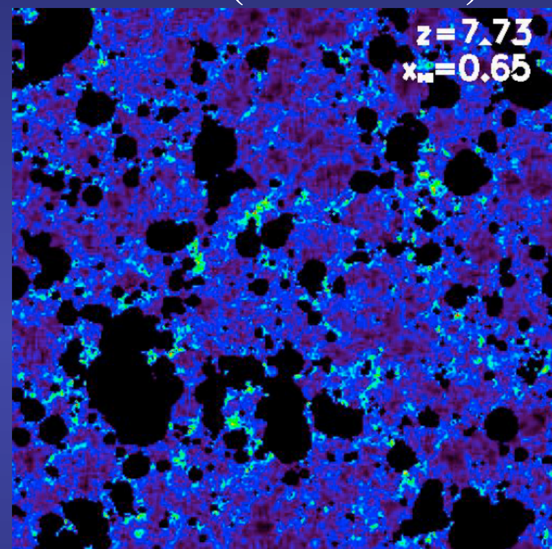
nonlinear structure formation creates an asymmetric velocity gradient distribution

Full 21cm comparison (without spin temperature)

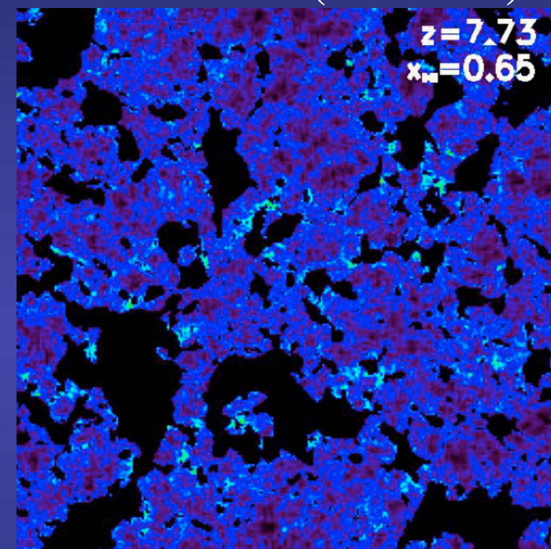
hydro+DM+RT



DexM (with halos)



21cmFAST (no halos)



~ 1 week on 1536 cores ⟵ 100 Mpc/*h* ⟶ *~ few min on 1 core*

Get on board!

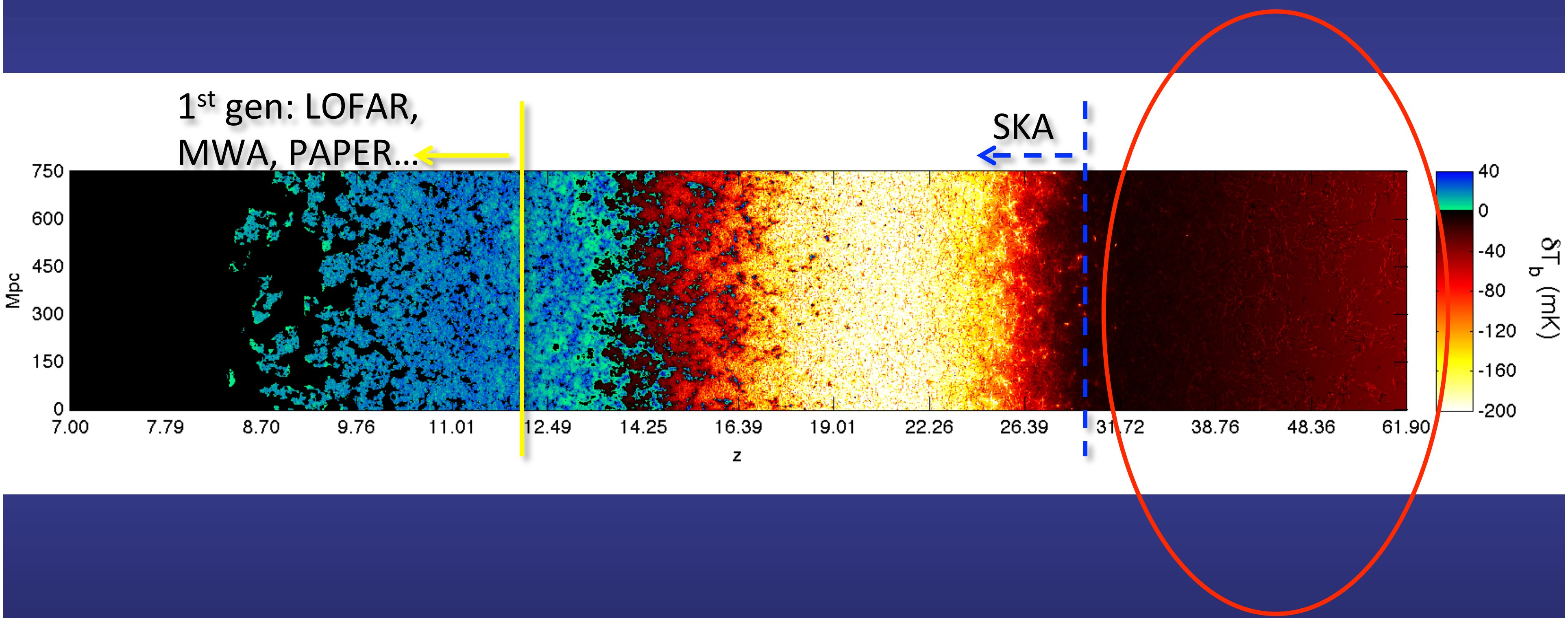
http://homepage.sns.it/mesinger/Sim

Three years following its release, 21cmFAST is being used by researchers in 15 countries and most of the 1st gen. 21cm experiments: LOFAR, MWA, 21CMA, GMRT

Fine. Please start talking about (warm) dark matter…

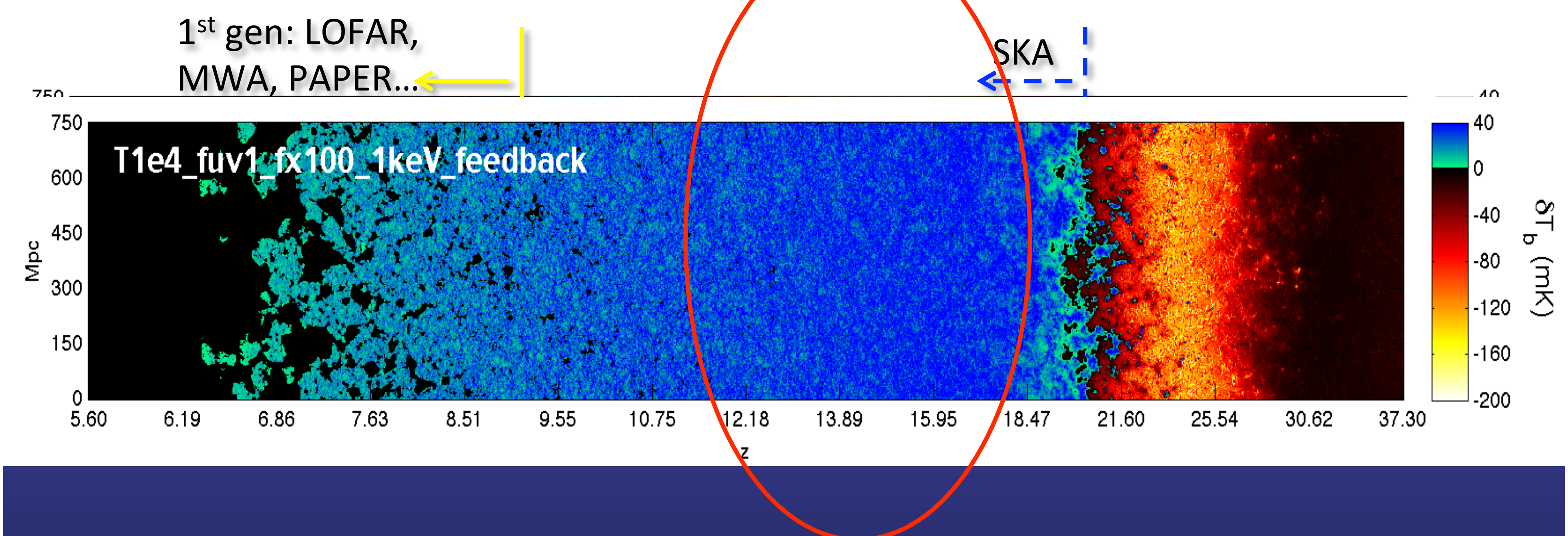
It would be great to see into the Dark Ages

Astrophysically "clean" epoch where cosmo signal dominates.. → would require Lunar interferometer



Direct probe of matter power spectrum

Astrophysically “clean” epoch where cosmo signal dominates.. → OR efficient thermal feedback z<20



astrophysical ‘half-time’

AM+2013

(see also Ricotti & Ostriker 2004)

Indirect probes

- From its suppression of halo abundances, the relevant epochs in WDM models are delayed, and then accelerated

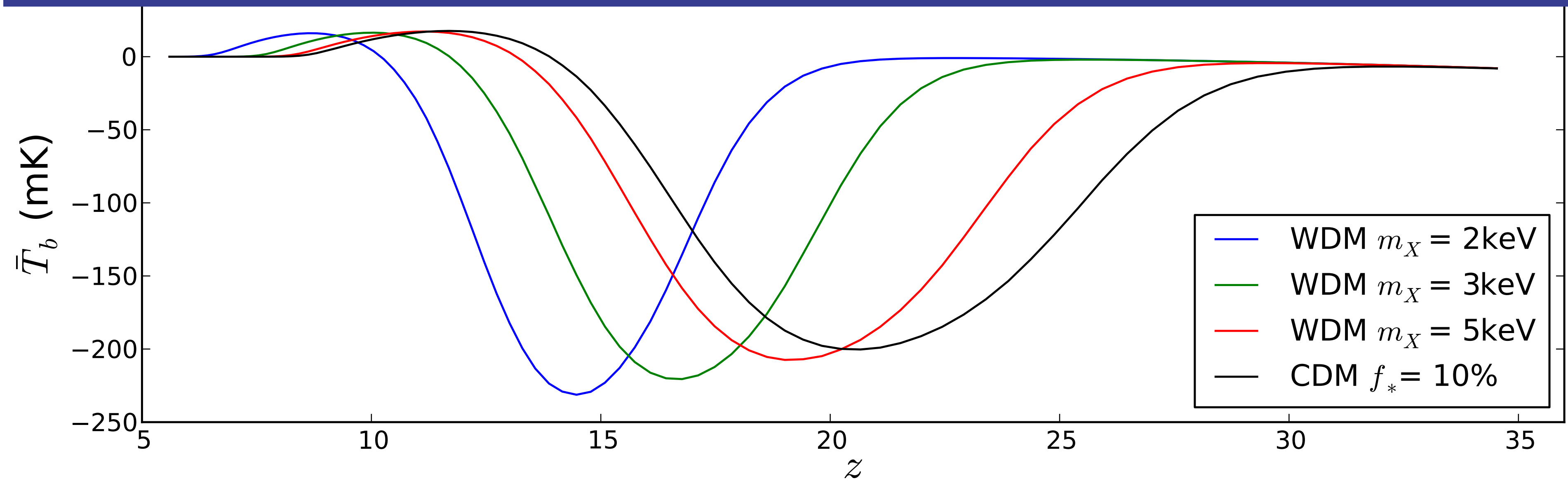
AND

- Can contribute to the epoch of IGM heating through WDM particle decay (or through annihilations for CDM)

Thermal history pre-reionization is a powerful probe

Global brightness temperature evolution

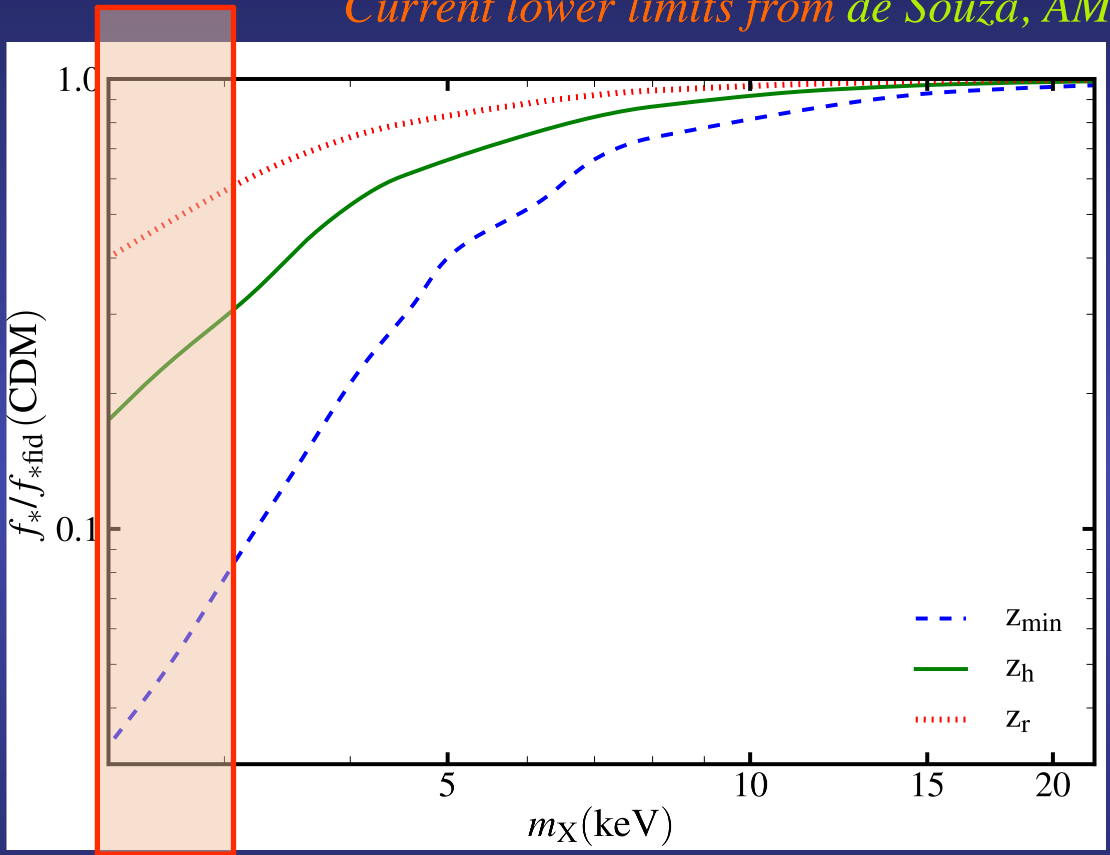
- From its suppression of halo abundances, the relevant epochs in WDM models are delayed, and then accelerated



Sitwell+, AM (2014)

But this is degenerate with star formation

Current lower limits from de Souza, AM+ 2013, Viel+2013…



Sitwell, AM+ (2014)

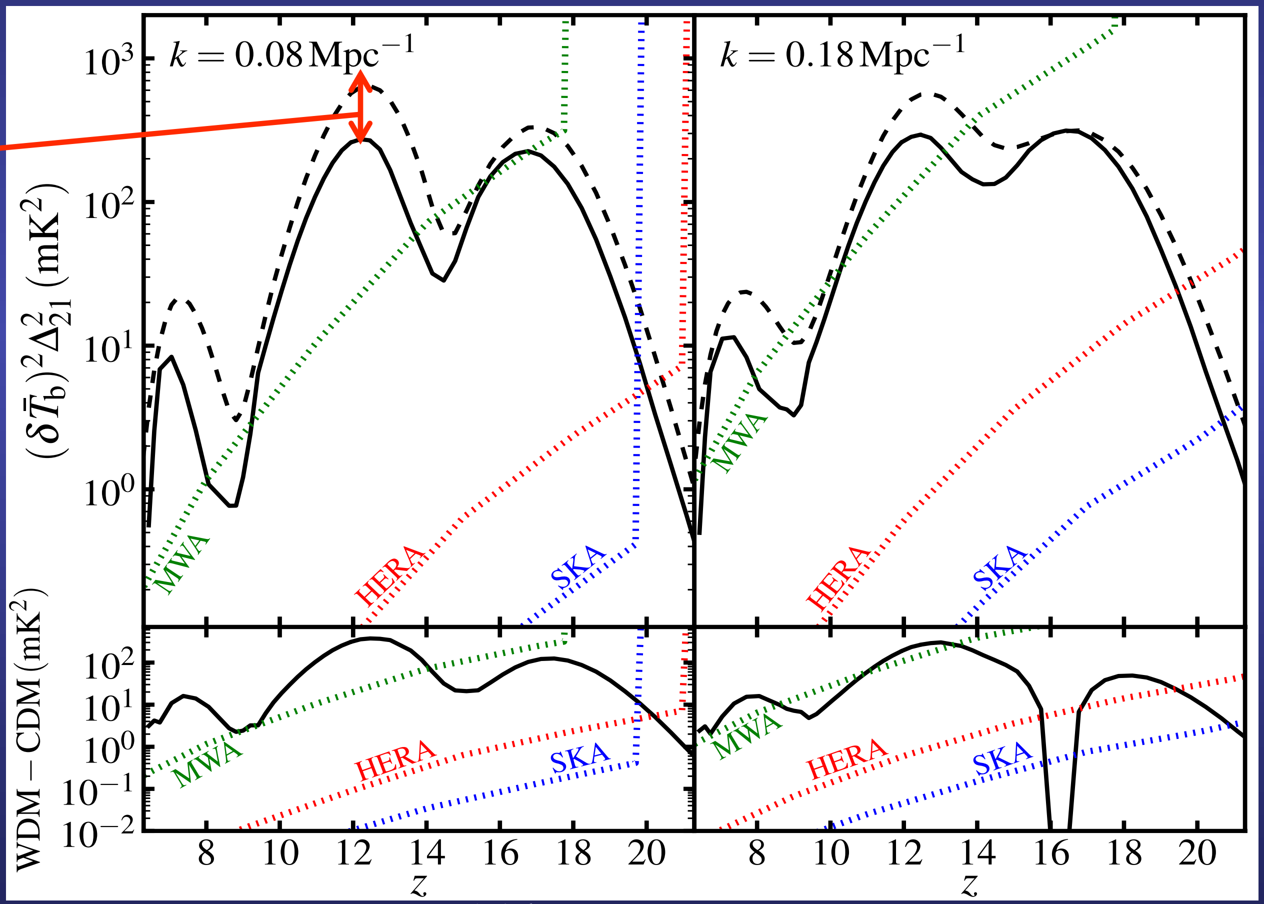
- *Best bet is high-z regime (heating epoch)*
- *For m_x > 5keV, we must know astrophysics to better than a factor of 2*
- *For m_x > 3keV, order of magnitude is sufficient!*

It is not *completely* degenerate with star-formation

Evolution of the 21cm power spectrum, amplitude, leaving star-formation as free parameter

Difference due to more biased halos hosting galaxies in WDM

detectable

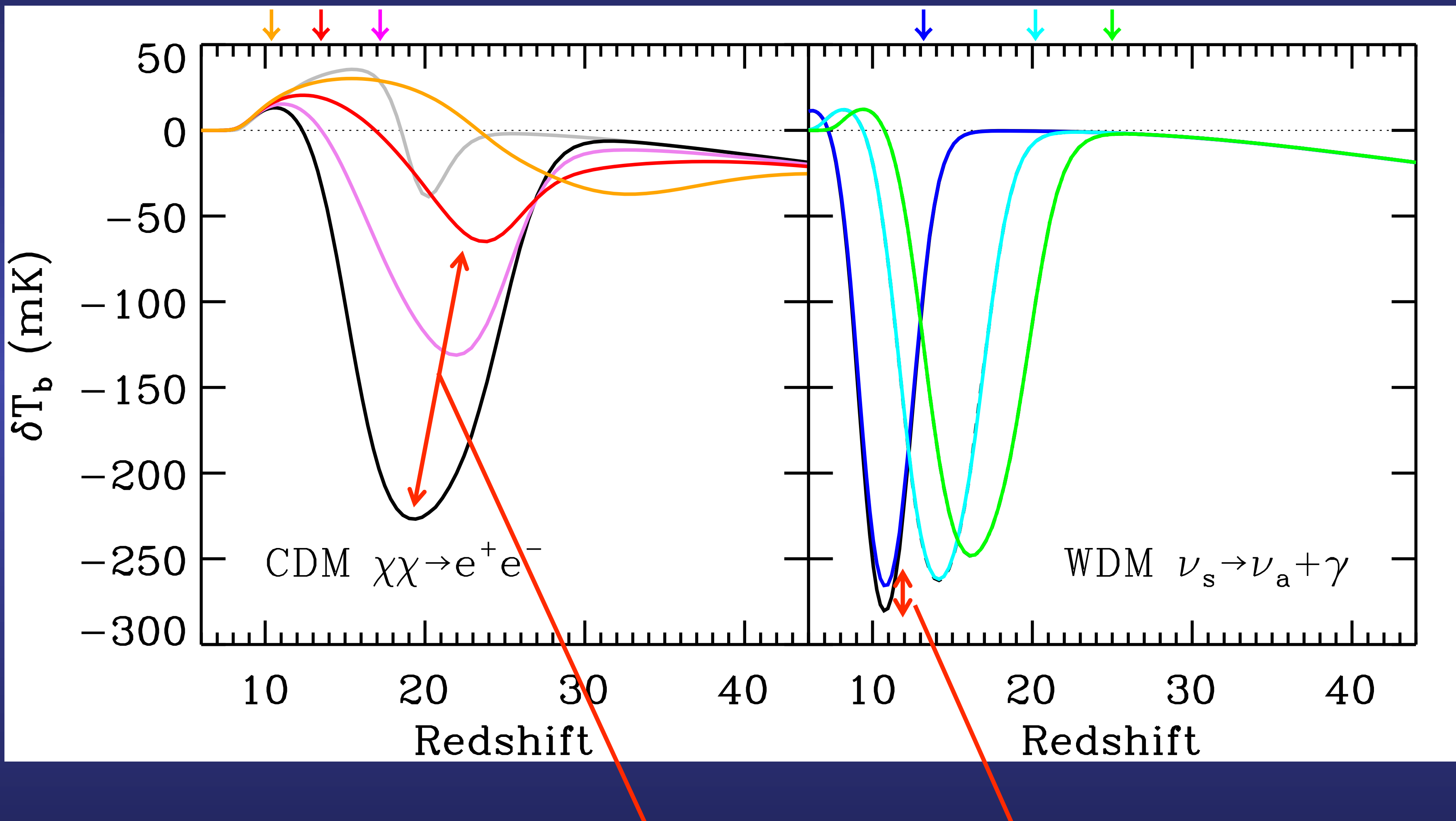


caveat: we still need to know star-formation would be possible in the 'missing halos'

Sitwell, AM+ (2014)

Dark Matter heating:
WDM decay and CDM annihilations

Heating impact on global signal



Heating by DM annihilations

Heating by 1keV sterile neutrino

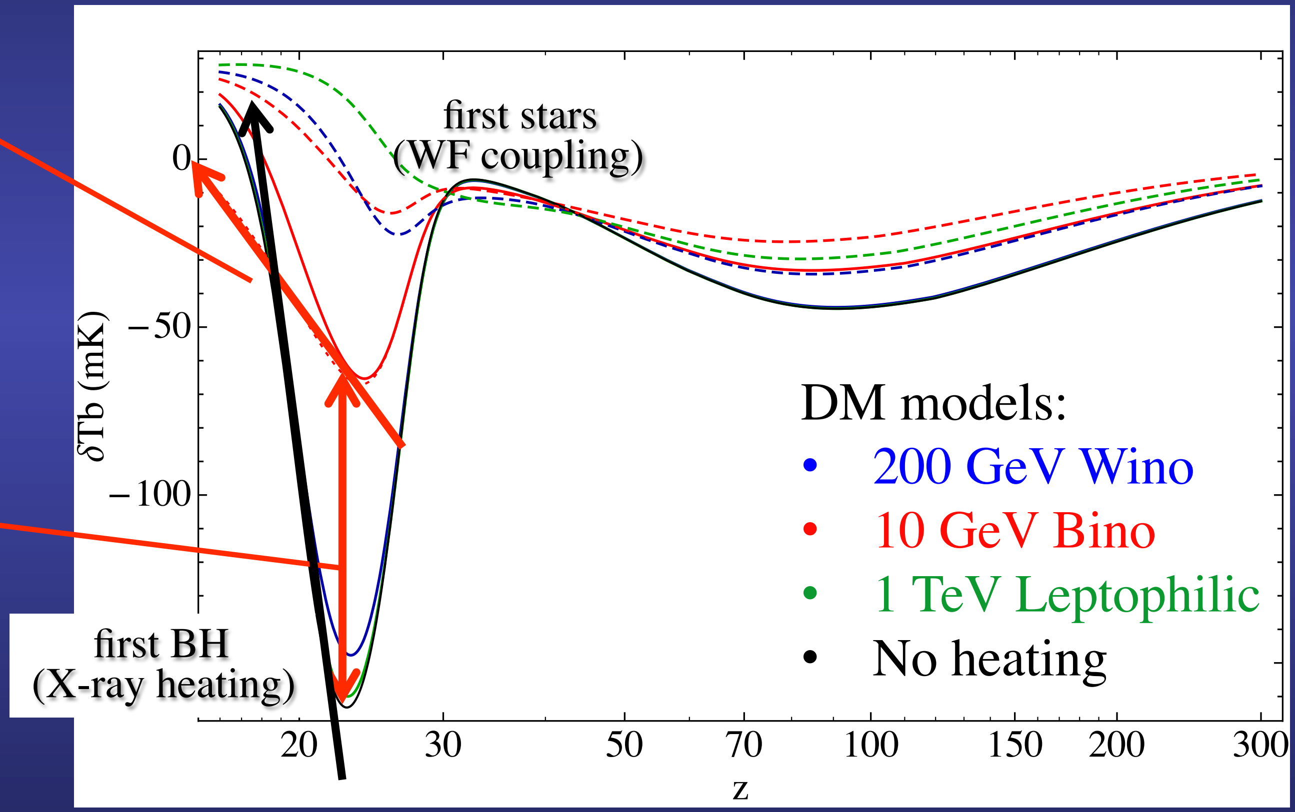
DM heating can affect the global signal

DM heating is slower than X-ray heating (extremely weakly degenerate with astro!)

AND

DM heating suppresses absorption trough (degenerate with more abundant X-rays)

DM annihilation heating +"fiducial" astrophysics

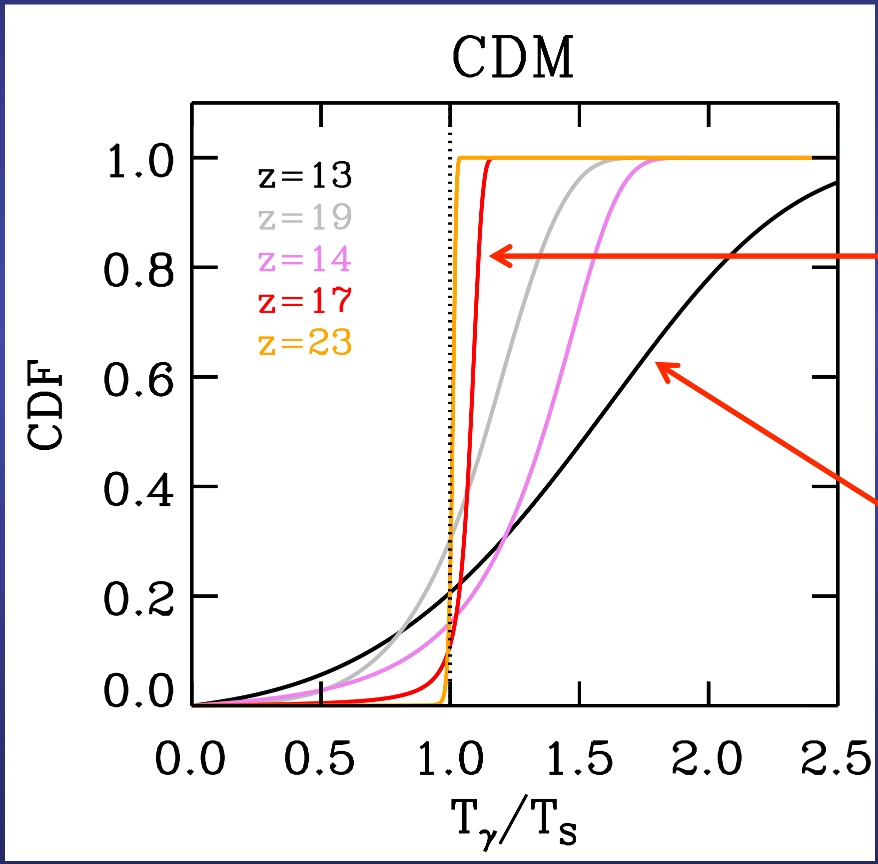


Valdes, Evoli, AM+2013

annihilation heating computed with MEDEA2 (Evoli+)

DM heating is more uniform than astrophysical

CDM, annihilating 10GeV Bino, thermal cross-sec

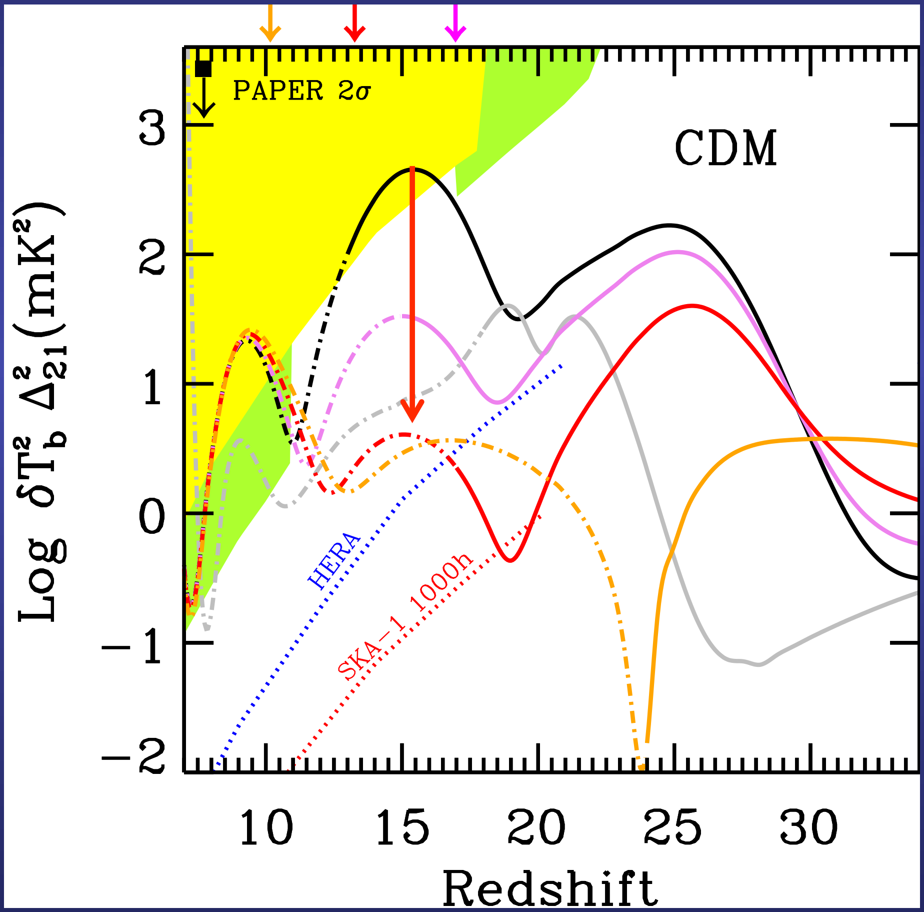


with annihilations

No annihilation heating

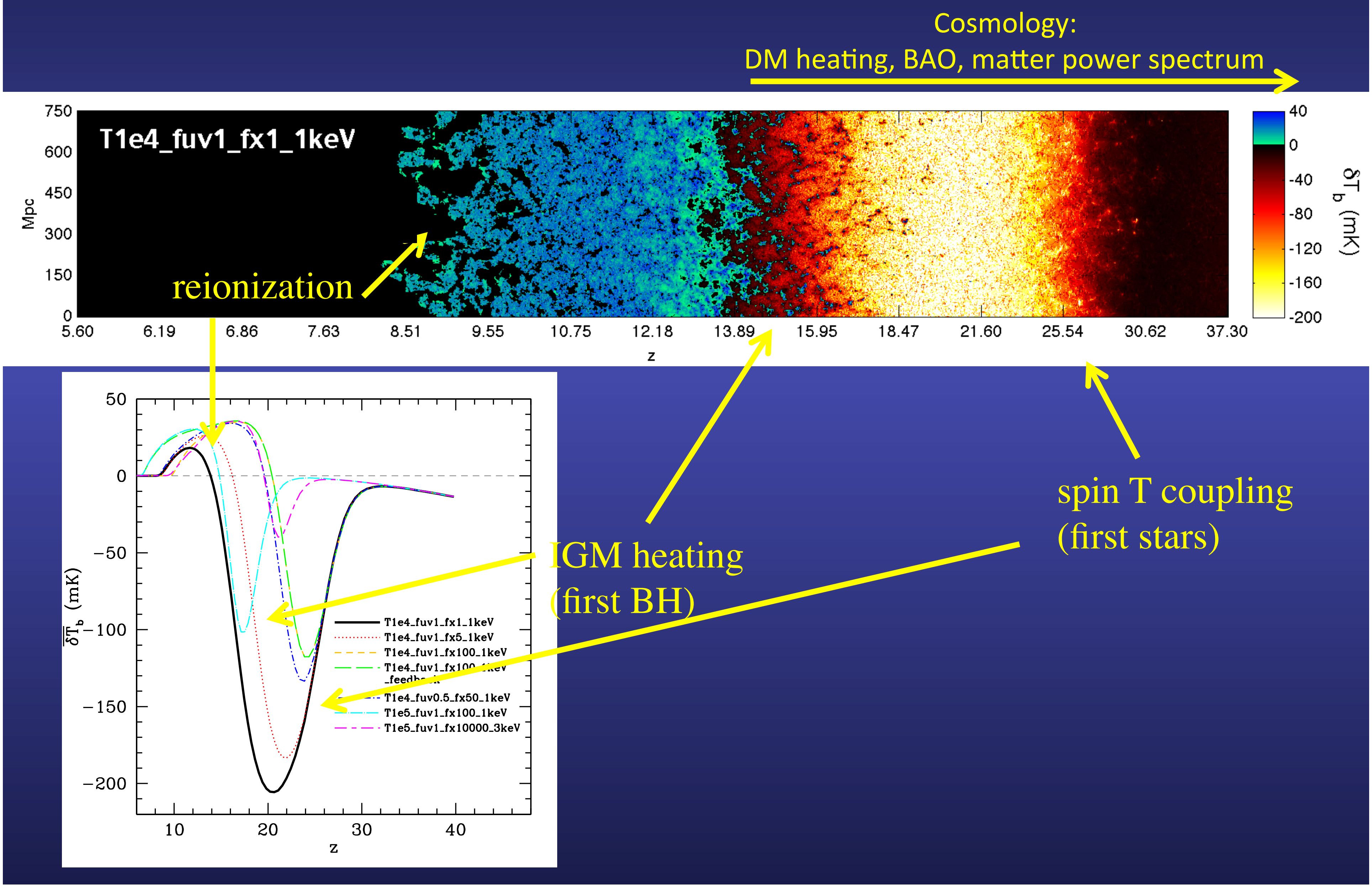
This cannot be reproduced with reasonable astrophysics

DM heating is more uniform than astrophysical→ heating peak is LOWEST of the three

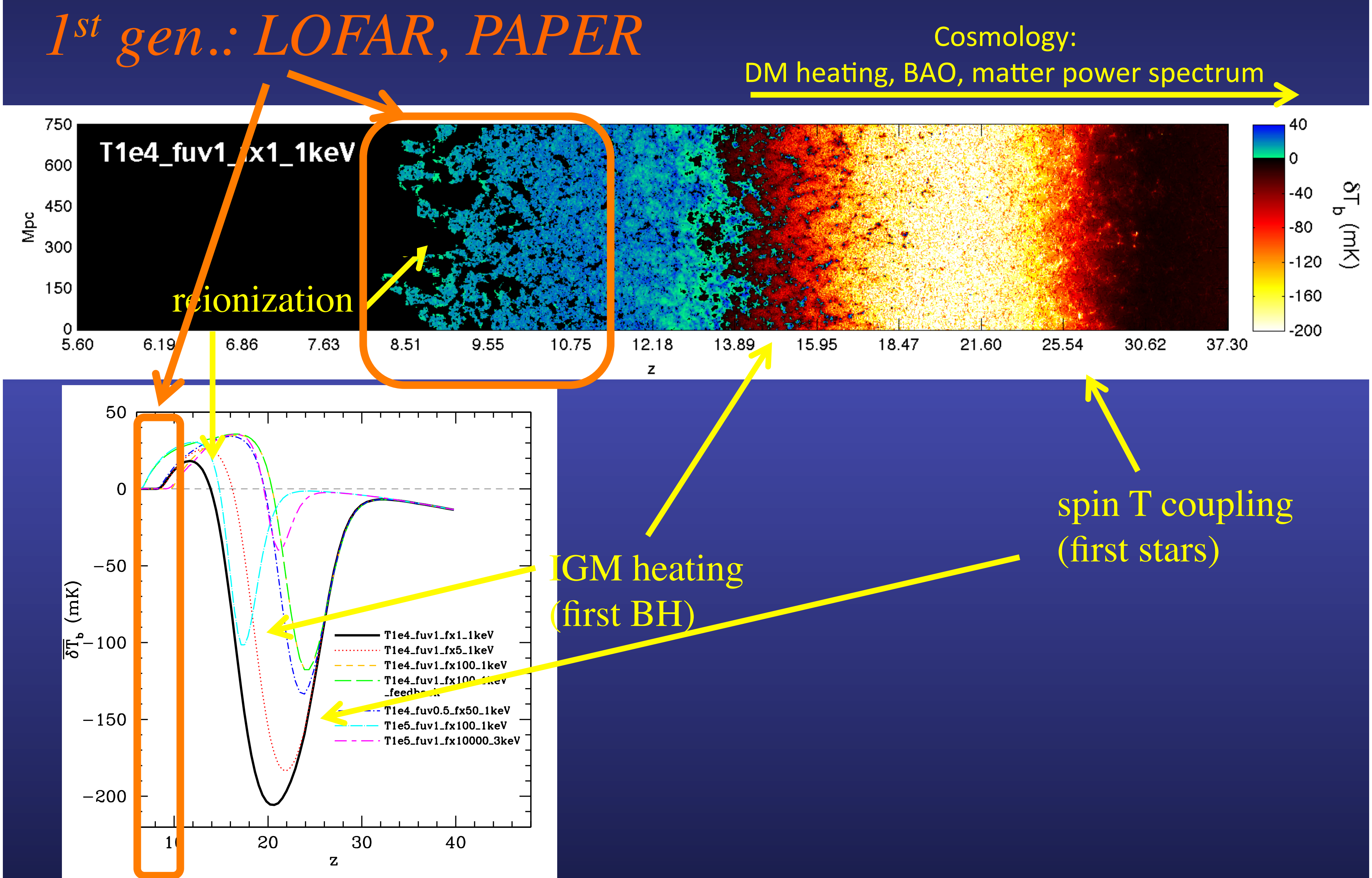


*Peak is supressed and is in **emission**!*
(cannot be reproduced with astro!)

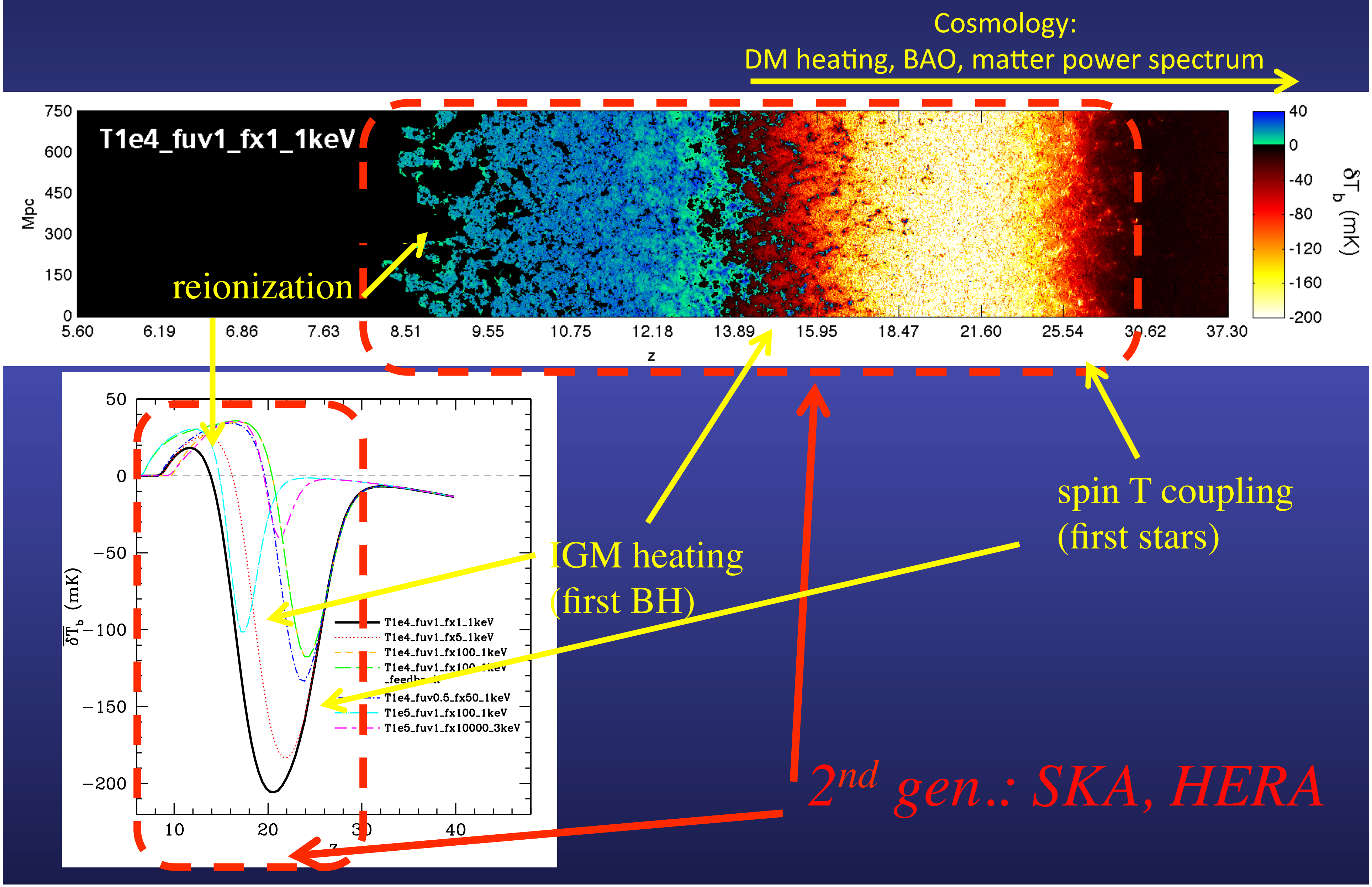
Rich physics of the early Universe



Rich physics of the early Universe



Rich physics of the early Universe



Conclusions

- Cosmological 21cm signal is very rich in information about the first structures, provided we can interpret it robustly. High-z is the place to be for cosmology!
- Direct measurements of the matter power spectrum are possible either (i) during the dark ages (LUNAR mission?); or (ii) between X-ray heating and reionization, provided thermal feedback is efficient (observable with SKA and HERA)
- WDM models (or other cosmologies with a dearth of small-scale power) result in a delayed and more rapid evolution of the 21cm signal.
- Fixing the evolution of the mean signal, WDM can be distinguished by an increase in the 21cm power, driven by the higher bias of the more massive halos. This could be detectable even with 1st generation instruments.
- WDM decay heating is negligible, HOWEVER dark matter annihilations can leave a robust footprint in the 21cm power spectrum by suppressing the heating peak, which can occur when the gas is in *emission* (you cannot reproduce this with astro).
- 1st gen. interferometers are already taking data, 2nd gen. soon to follow. Exciting times are ahead!