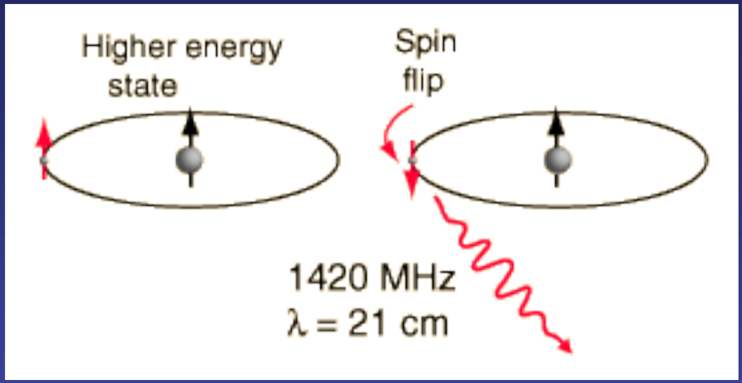
Probing dark mater with the cosmological 21cm signal

Andrei Mesinger

Scuola Normale Superiore, Pisa

21 cm line from neutral hydrogen

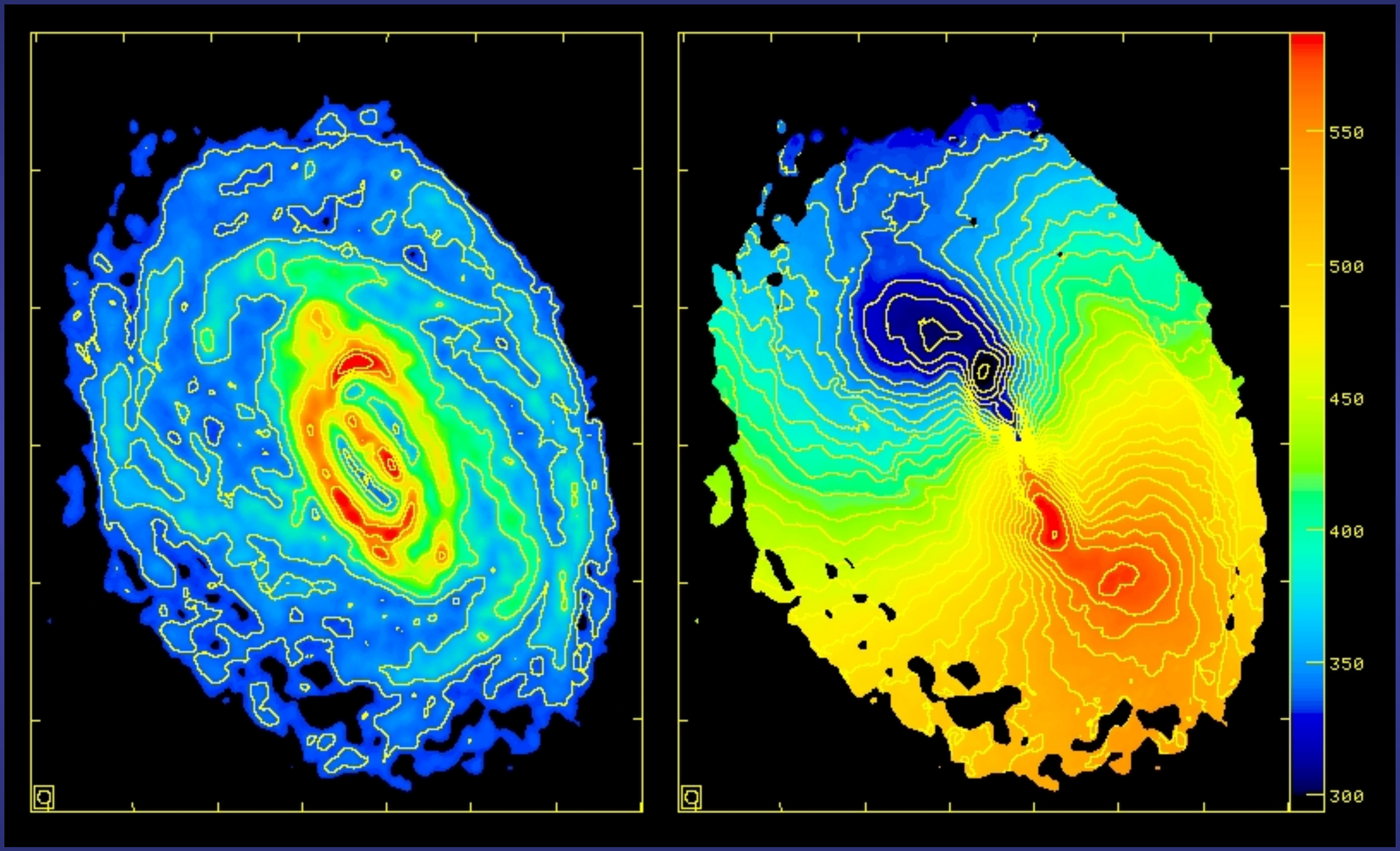


Hyperfine transition in the ground state of neutral hydrogen produces 21cm line.

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

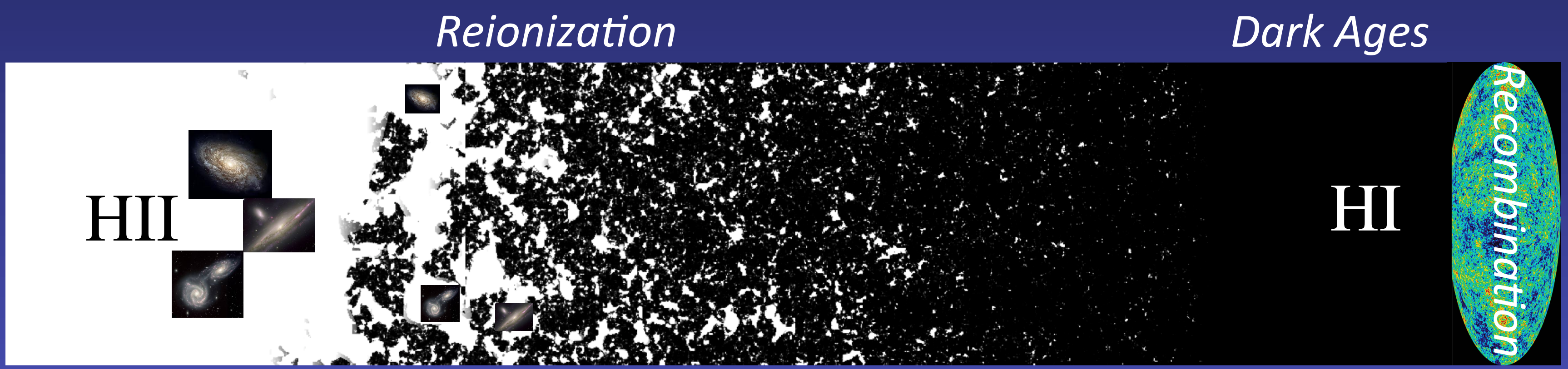
Now widely used to map the HI content of nearby galaxies



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: Reionization and Cosmic Dawn



z = 0 t_{age} ~ 14 Gyr

z ~ 6 t_{age} ~ 1 Gyr

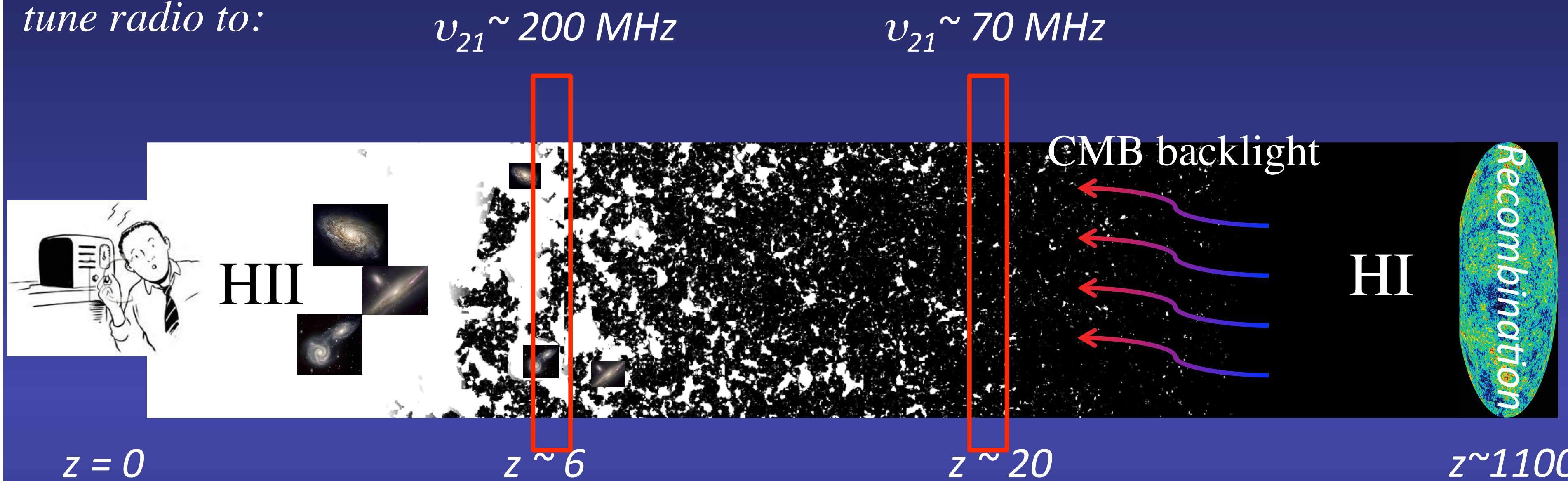
z ~ 20 t_{age} ~ 150 Myr

z~1100 t_{age} ~ 0.4 Myr

Once upon a time, HI was much more abundant

Redshifted 21cm signal.

tune radio to:



Once upon a time, HI was much more abundant

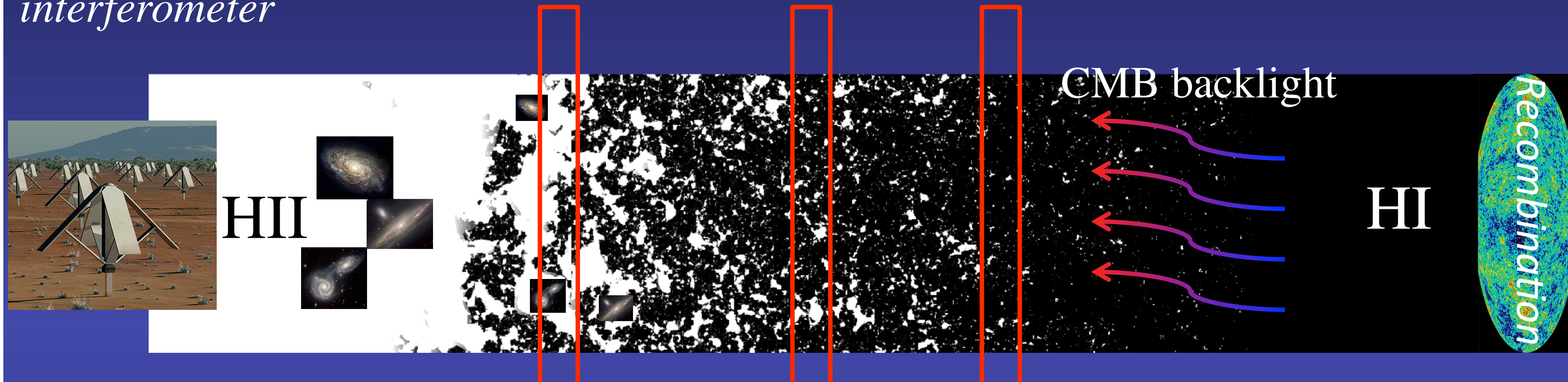
Redshifted 21cm signal.

tune ~~radio~~ to:

interferometer

υ_{21}~ 200 MHz

υ_{21}~ 70 MHz



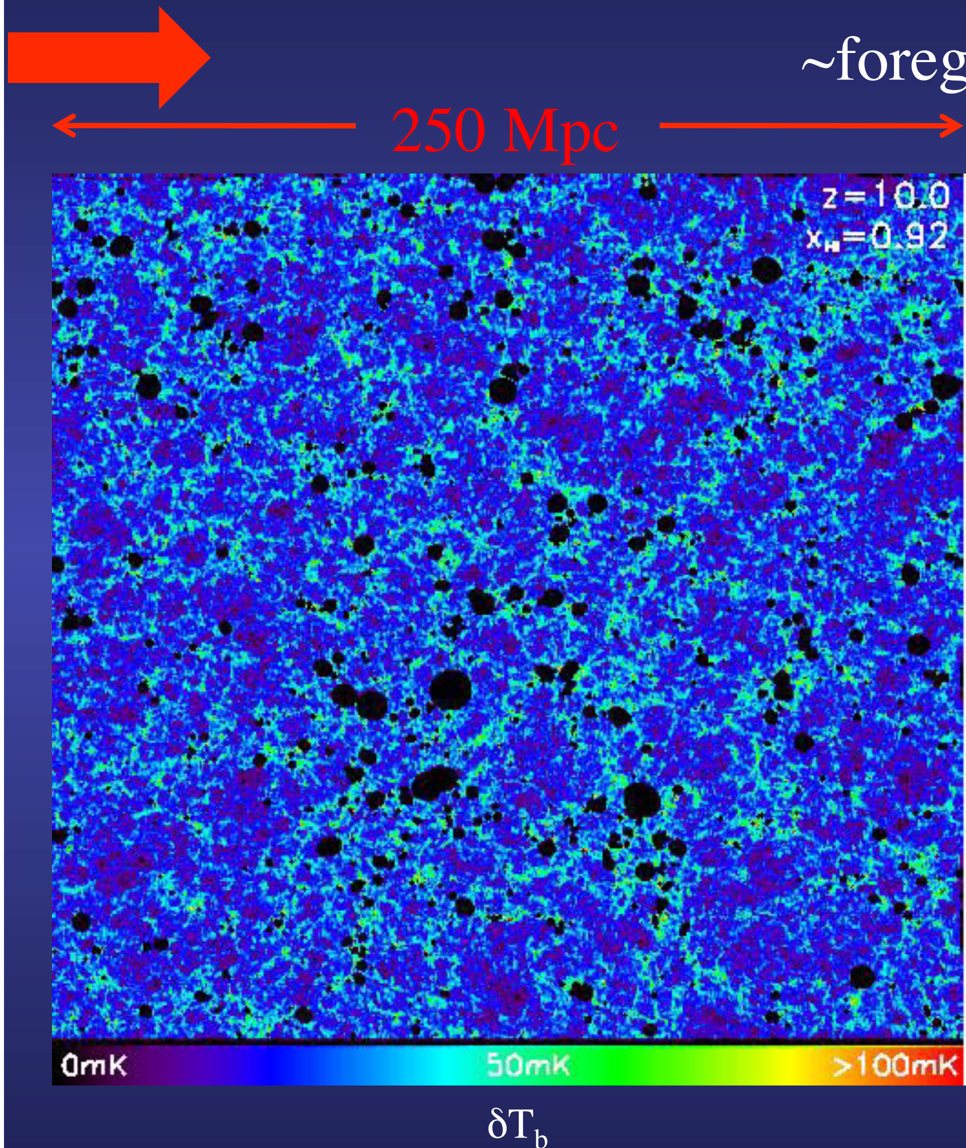
z ~ 6

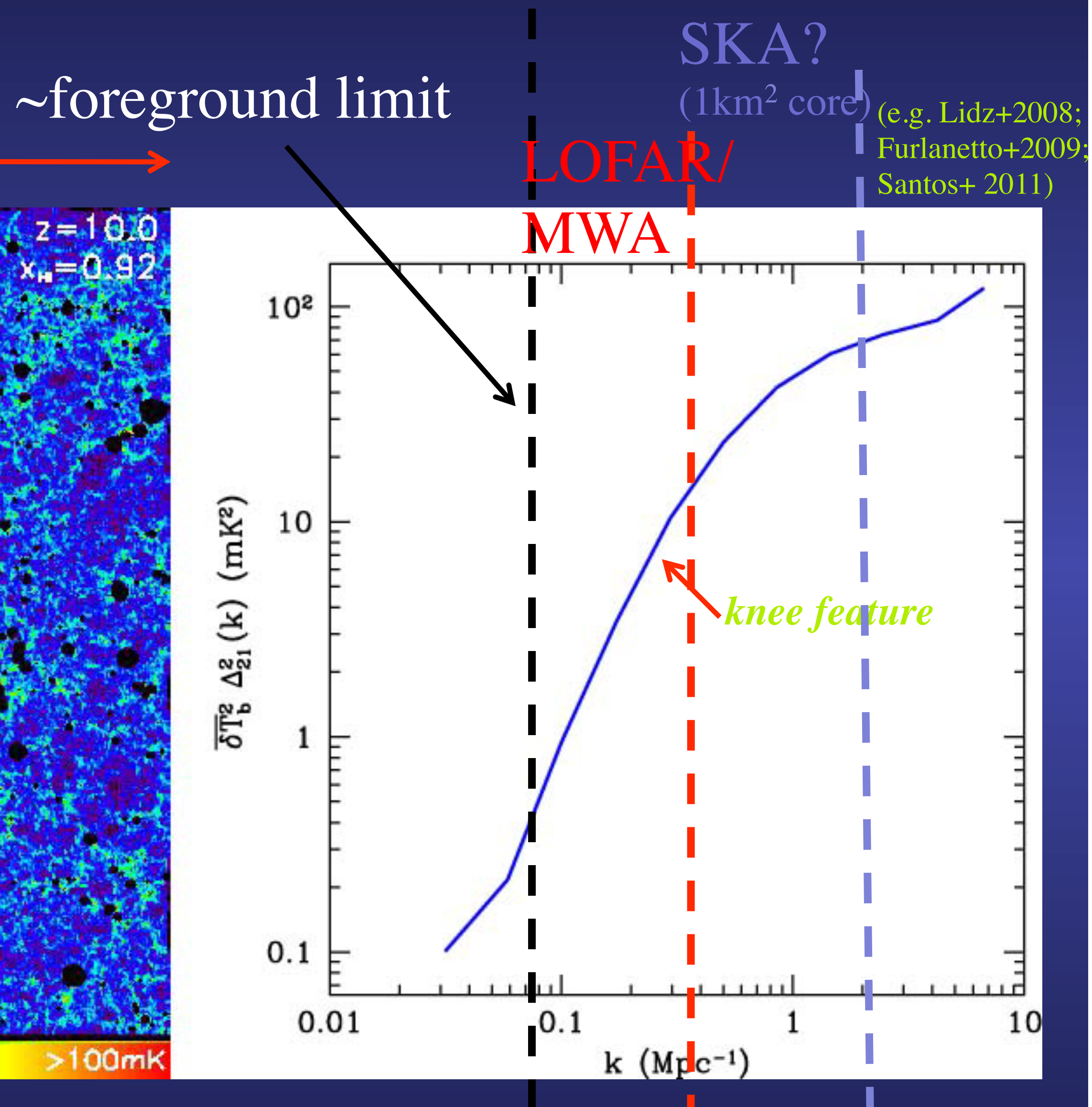
z ~ 20

z~1100

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

21cm power spectrum from reionization





Mesinger & Furlanetto 2007

If we see something, what do we learn??

If we understand it, a lot!!

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

spin temperature

LOS velocity gradient

neutral fraction

gas density

Cosmological 21cm Signal

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

Powerful probe:

Cosmology

&

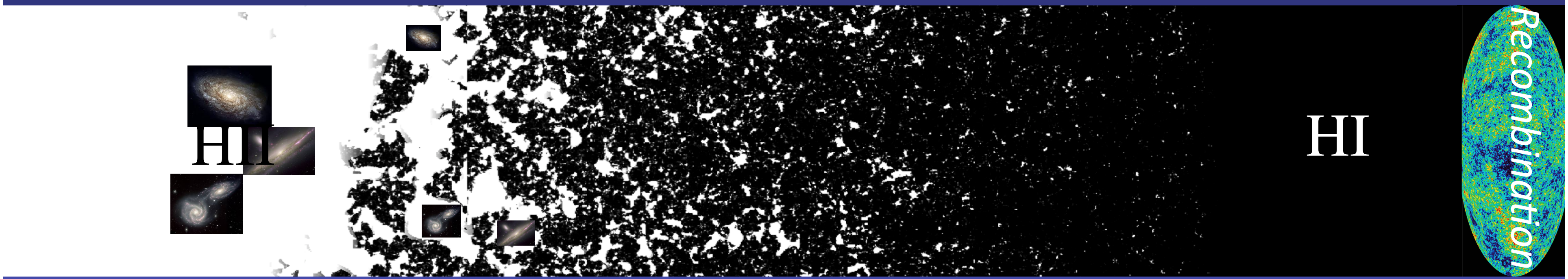
Astrophysics

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

- *separation of epochs and/or*
- *accurate, efficient modeling*

Let's look at Cosmic history in 21cm

Reionization *Dark Ages*

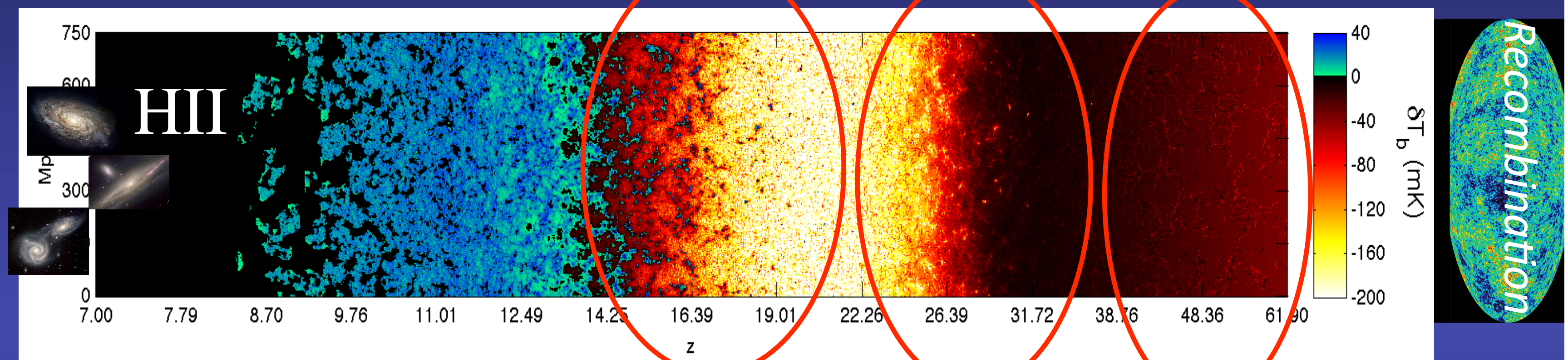


z = 0 *z ~ 6* *z ~ 20* *z~1100*

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

Let’s look at Cosmic history in 21cm

Reionization　　　　　　　　　　*Dark Ages*



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

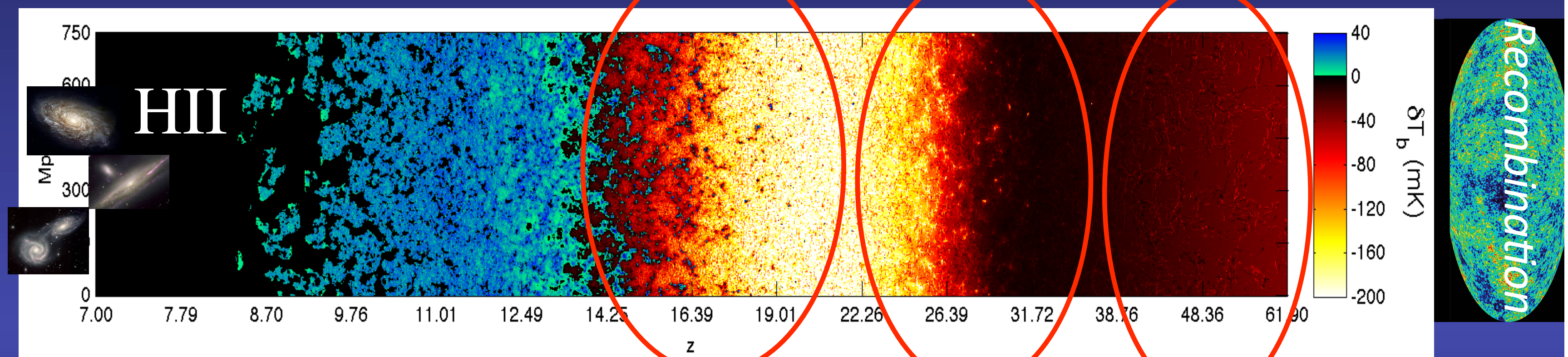
First Black Holes

Infancy of Cosmic Web

First Stars

Let's look at Cosmic history in 21cm

Reionization *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

21cm is the only upcoming probe with the potential to see the Cosmic Dawn

21cm is the only upcoming probe with the potential to see the Cosmic Dawn

Why do participants of the "**Dark Side of the Universe**" conference care about the **Cosmic Dawn**?

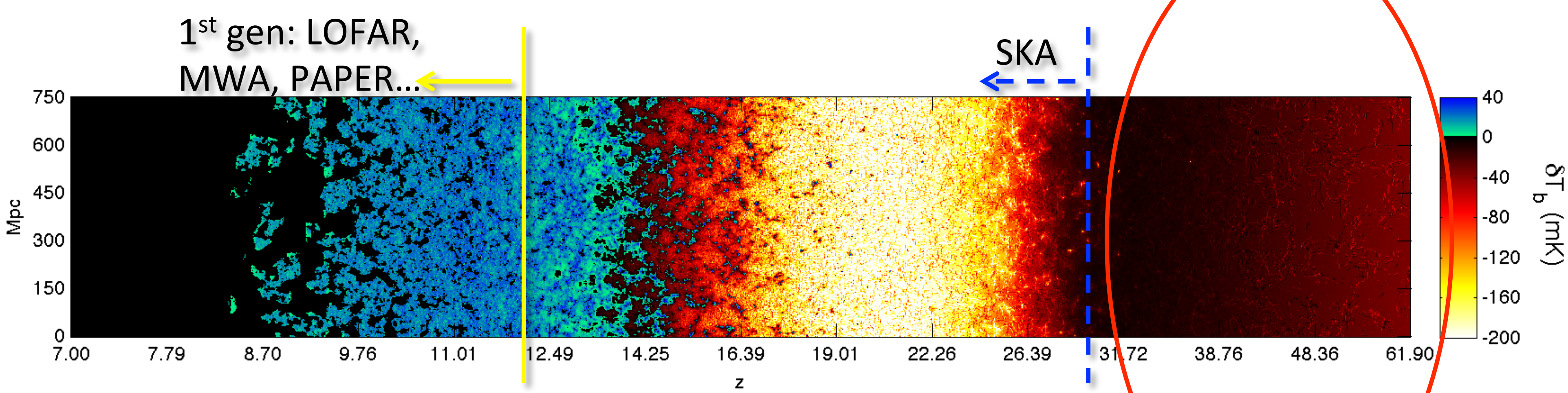
Digging out the cosmology…

1) Finding astrophysically “clean” epochs
2) Probing small-scale power through the abundance of high-z galaxies
3) Heating of the IGM through DM annihilations

21cm probes cosmology

1) "clean" epochs where cosmo signal dominates →

Dark Ages z > 40



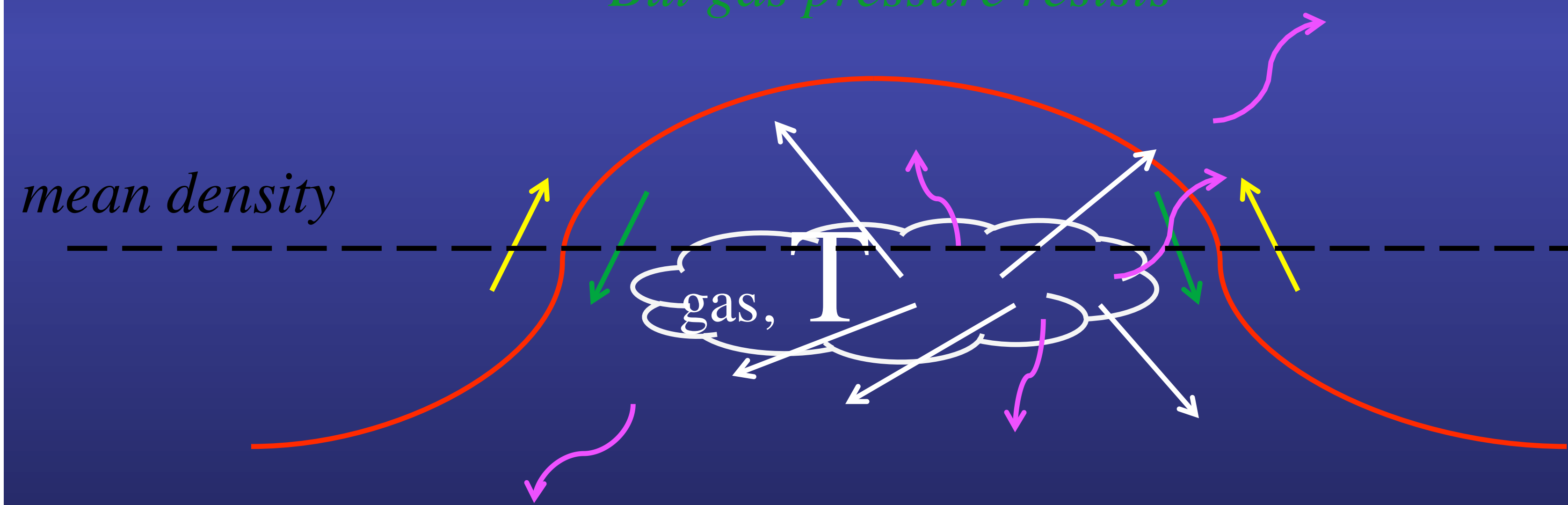
21cm probes cosmology

1) “clean” epochs where cosmo signal dominates →

Dark Ages z > 40 OR efficient thermal feedback z<20

material falls into overdensities through gravity

But gas pressure resists

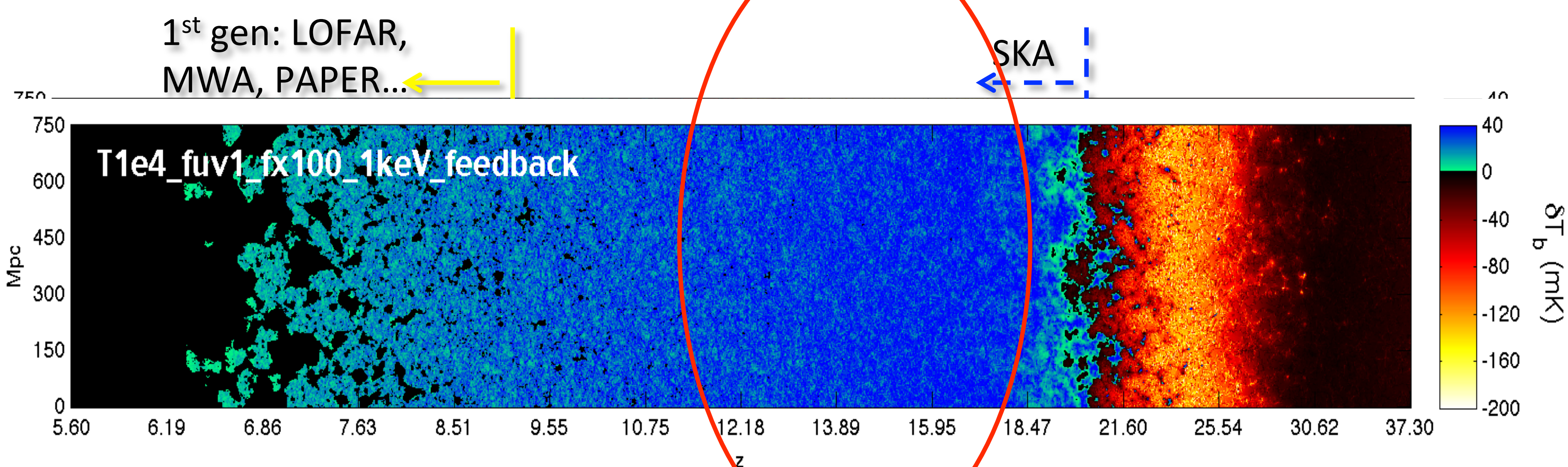


Heated gas is pressure supported →
wait for halo potential to grow for efficient star formation

21cm probes cosmology

1) "clean" epochs where cosmo signal dominates →

Dark Ages z > 40 OR efficient thermal feedback z<20



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

1 1

pre-reionization *completed heating*

AM+2013 (see also Ricotti & Ostriker 2004)

21cm probes cosmology

2) Models which suppress small-scale power, like Warm Dark Matter, result in a dearth of low mass galaxies, delaying astrophysical epochs in the 21cm signal

Although very successful on large (>~ Mpc scales), CDM seemingly doesn't do so well on small-scales

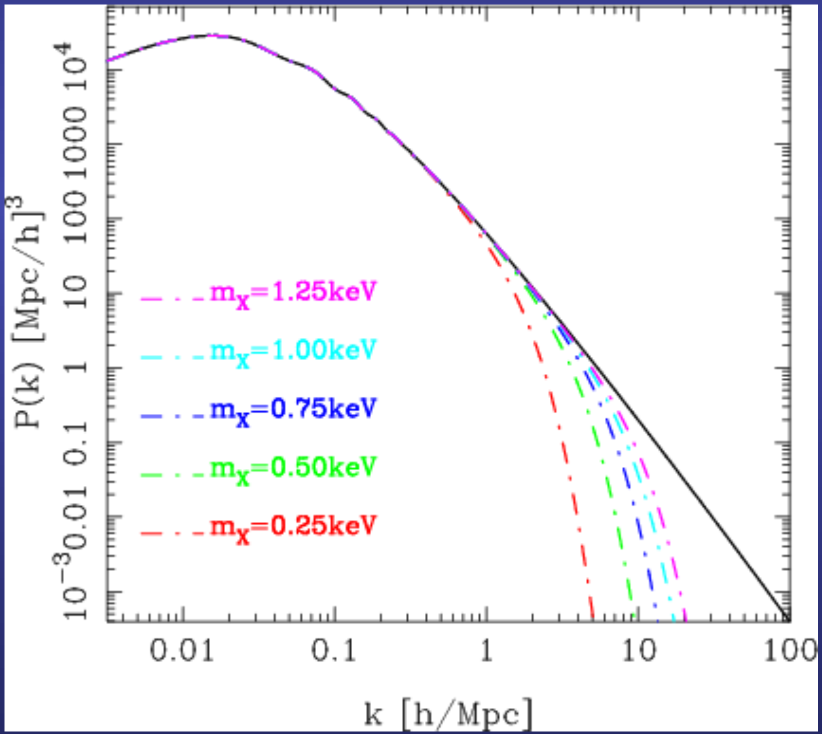
for example:

- Galactic halos are kinematically inconsistent with CDM: missing population of dense, massive satellites (Boylan-Kolchin+ 2012)
- Inner profiles of individual dwarf galaxies are too shallow (Moore+1994; de Blok+2001; Maccio+2012; Governato+2012)
- Number of satellite galaxies in Milky Way (Moore +1999; Klypin+1999) and in the field (ALFALFA survey; Papastergis+2011; Ferrero+2012) is too low
- … (see Sellwood & Kosowsky 2001; Menci+ 2012; Boylan-Kolchin+2012)

What about suppressing primordial power, e.g. Warm Dark Matter

e.g. free-streaming: particles stream out of primordial potential wells, truncating power on scales below the distance traveled up to ~ radiation-matter equality (Bode+ 2001):

$$R_s \approx 0.31\left(\frac{\Omega_X}{0.3}\right)^{0.15}\left(\frac{h}{0.65}\right)^{1.3}\left(\frac{\text{keV}}{m_X}\right)^{1.15} h^{-1}\ \text{Mpc}\ .$$



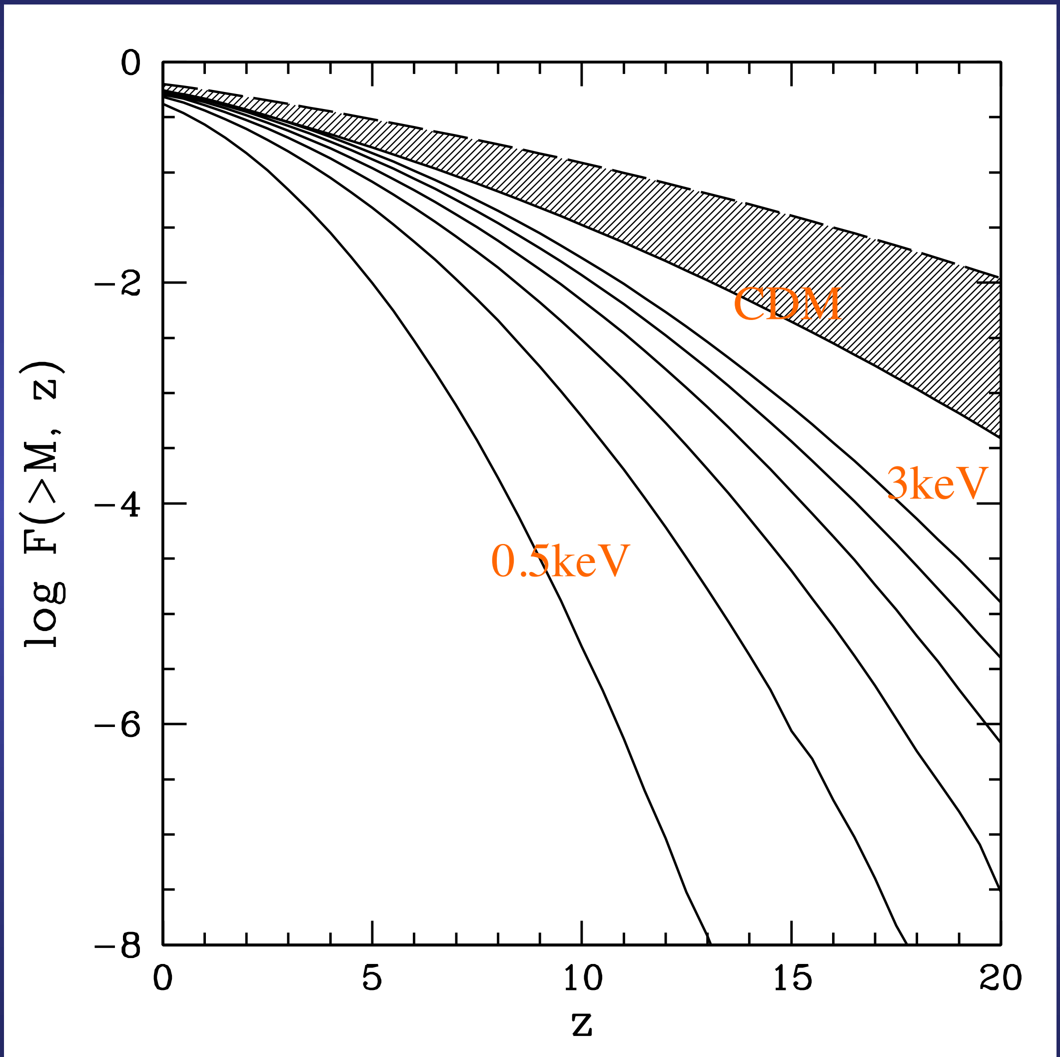
relativistic thermal relic

Smith+2011

Modification of the transfer function

$$T(k) \rightarrow T(k)\left[1 + (\epsilon k \lambda_s)^{2\nu}\right]^{-\eta/\nu}$$

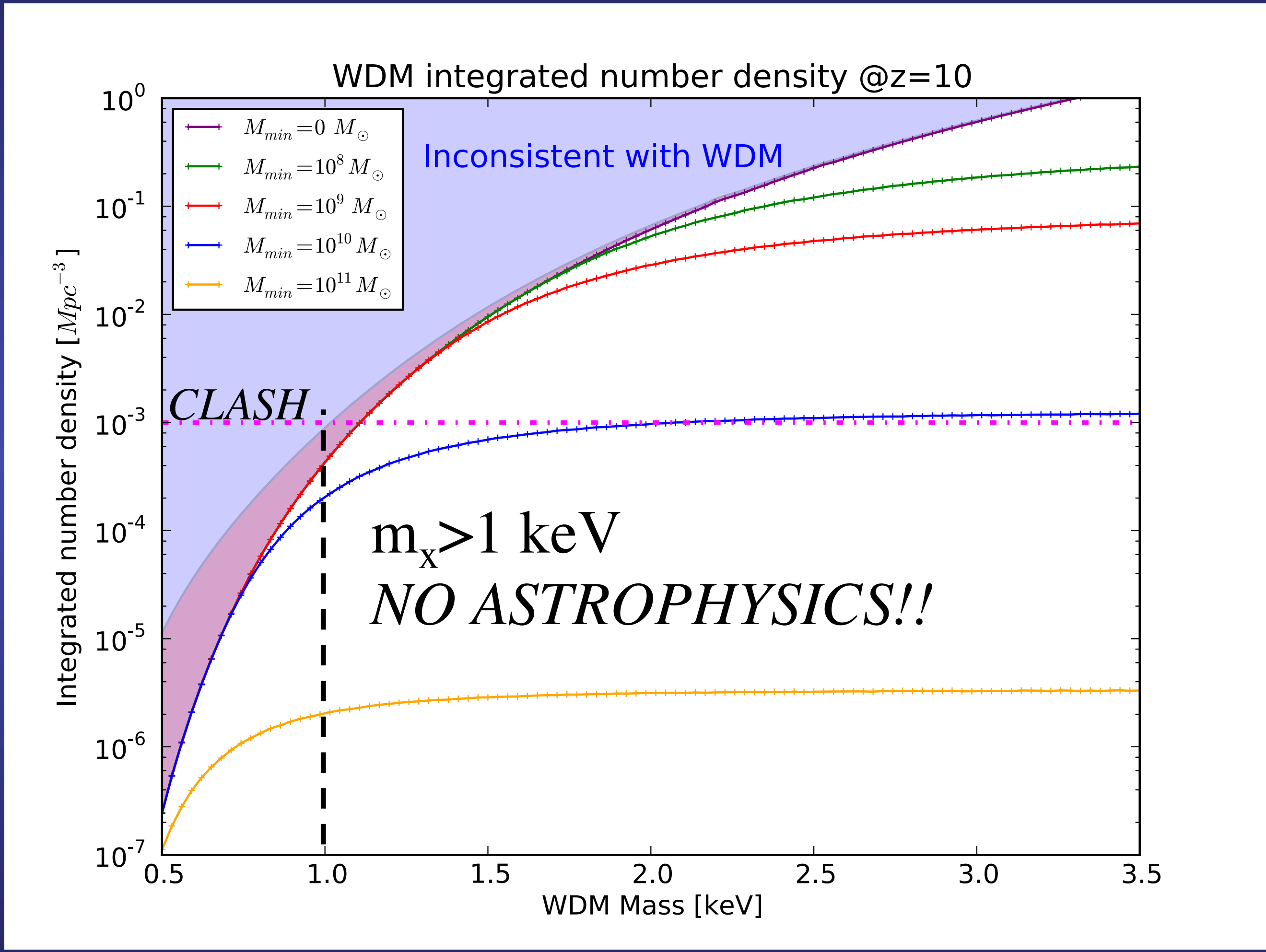
High-z is the place to be



Mesinger+2005

Due to heirarchal structure formation, in WDM it is empty!

Halo number density of lensed galaxies: *only constraint free of astrophysical degeneracies*

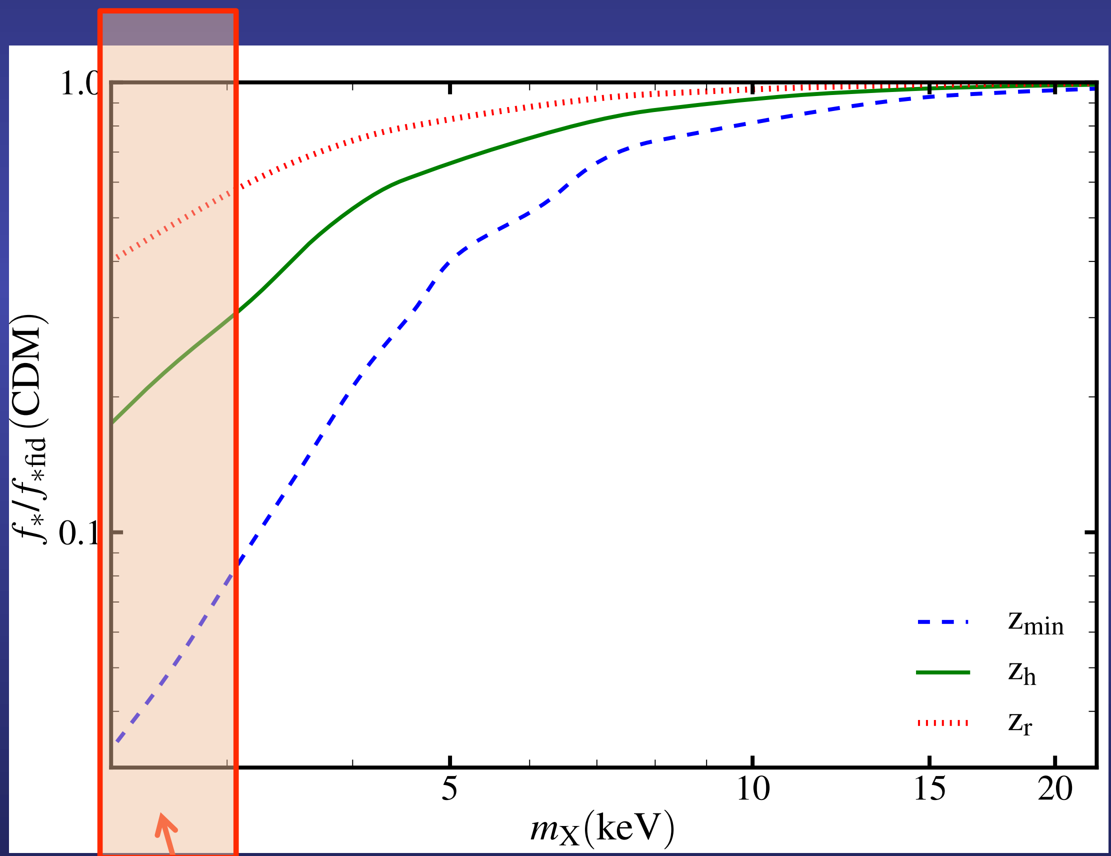


Limits can improve dramatically with future detections

Pacucci, AM, Haiman 2013

What does this mean for 21cm??

2) Models which suppress small-scale power, like WDM result in a dearth of low mass galaxies, delaying astrophysical epochs, and subsequently speeding them up



Gastrophysics only has to be known to within a factor of ~20 for the onset of heating to not be degenerate with WDM models

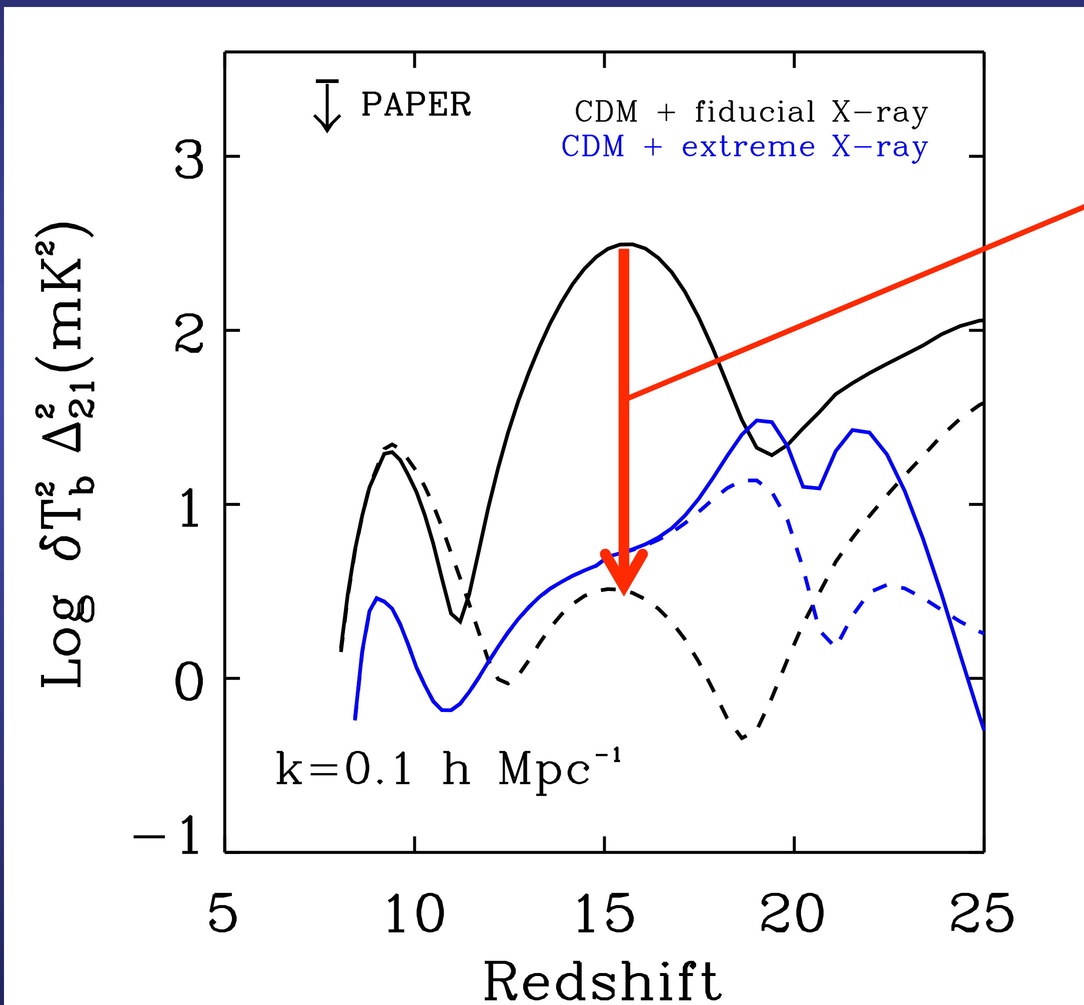
Sitwell, AM+ 2013

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

21cm probes cosmology

3) Heat input from DM annihilations

see Carmelo's talk



*Uniform heating is **unachiavable** with astrophysics*

(e.g. AM+2013)

Evoli, AM+ in prep

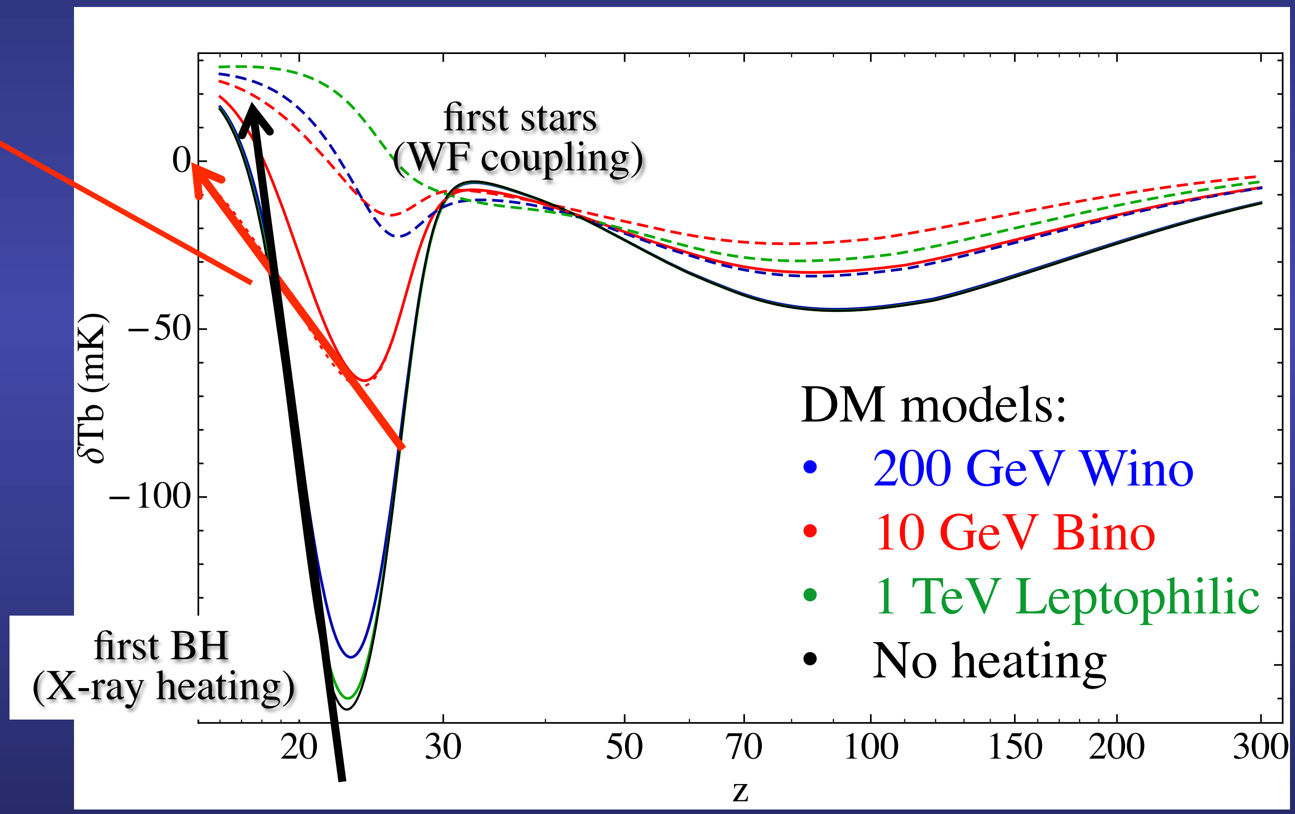
21cm probes cosmology

3) Heat input from DM annihilations

see Carmelo's talk

DM heating is slower than X-ray heating

Global signal

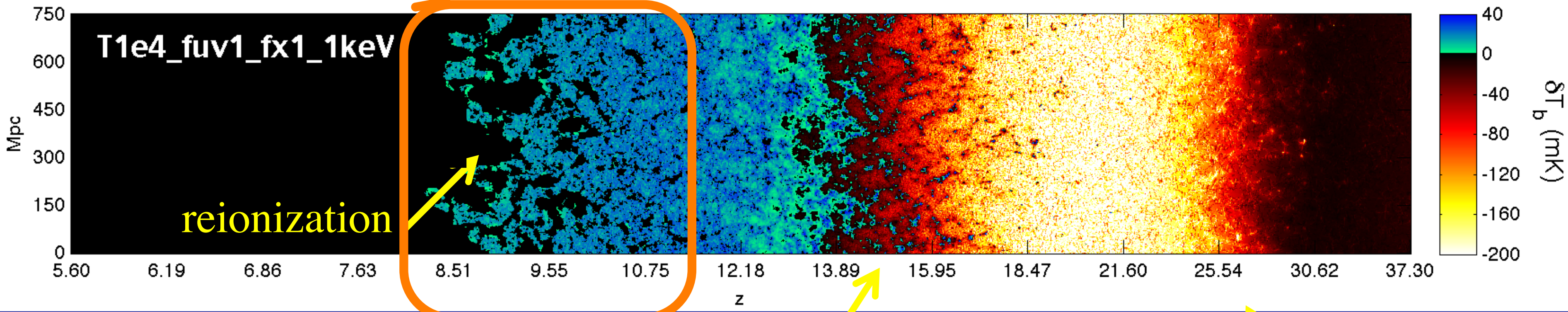


Valdes+2012

We are getting data as we speak!

1st gen..: LOFAR, PAPER

Cosmology:
DM heating, BAO, matter power spectrum



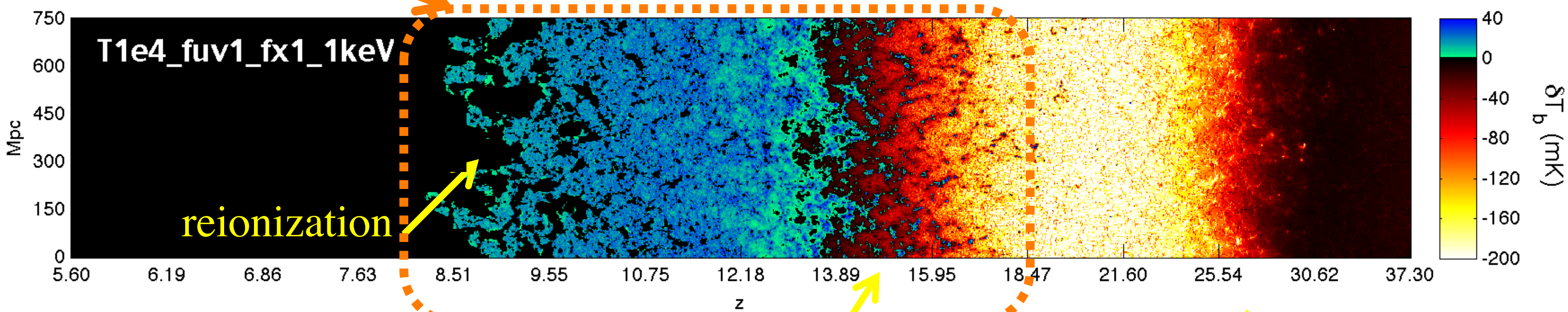
IGM heating
(first BH)

spin T coupling
(first stars)

Rich physics of the early Universe

1st gen.: MWA

Cosmology:
DM heating, BAO, matter power spectrum



IGM heating
(first BH)

spin T coupling
(first stars)

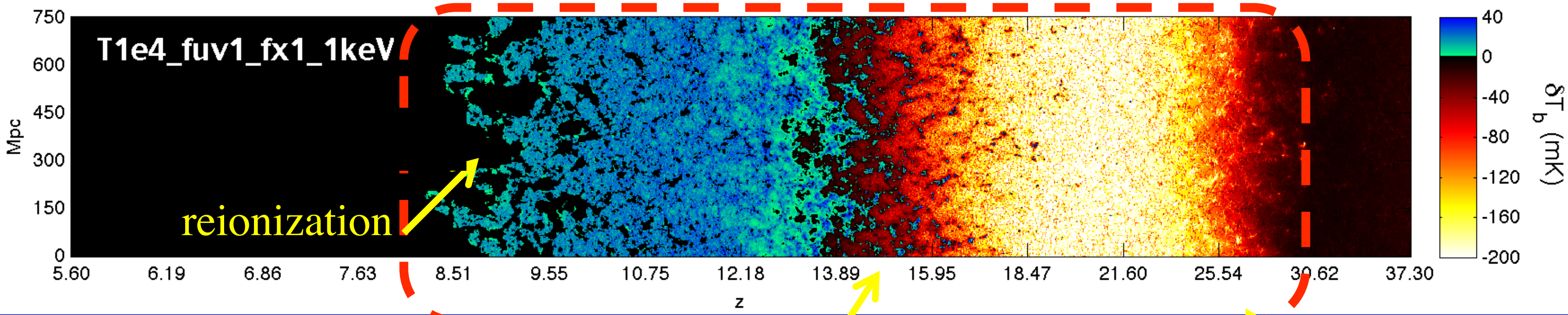
MWA 2013B*:*

Ewall-Wice+

"Constraining Xray and Dark Matter heating Before the Epoch of Reionization (EoR): Preliminary Observations at Low Frequency with the MWA"

Rich physics of the early Universe

Cosmology:
DM heating, BAO, matter power spectrum



reionization

IGM heating
(first BH)

spin T coupling
(first stars)

2^{nd} gen.: SKA, LUNAR

You have convinced me this is exciting, and relevant to my research. What do I do now?

21cmFAST

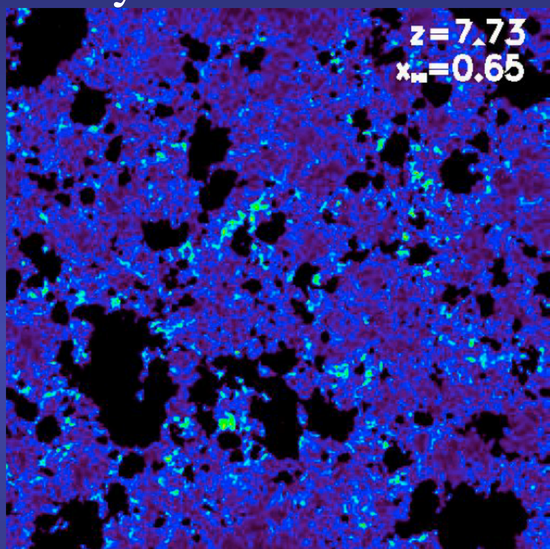
semi-numerical simulation (Mesinger, Furlanetto, Cen 2011)

- 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!

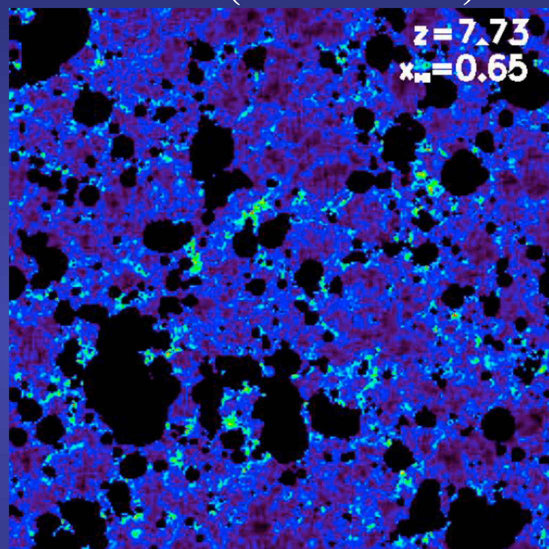
Previous halo-based version, DexM (Mesinger & Furlanetto 2007), has been used to interpret LAEs, QSO spectra, LLS distribution..

21cm comparison (without spin temperature)

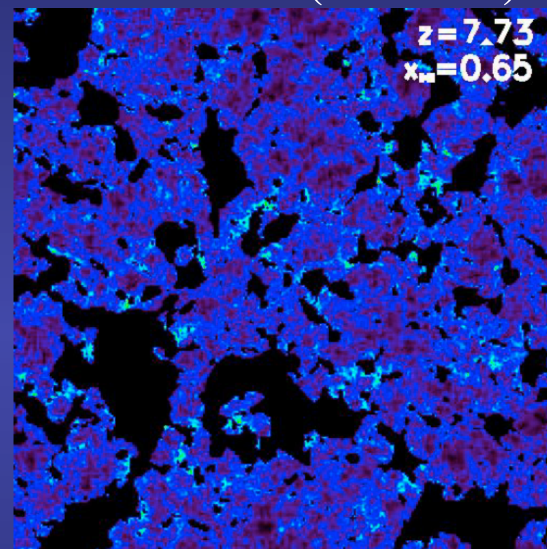
hydro+DM+RT



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

In just over 2 years, 21cmFAST is being used by researchers in 13 countries, and most of the 1st gen. 21cm experiments: LOFAR, MWA, 21CMA

Conclusions

- Cosmological 21cm signal is very rich in information, containing both cosmological and astrophysical components.
- The range of scales and unknown parameter space is enormous*: **21cmFAST!***
- The matter power spectrum (extending to very small-scales) can be measured directly either during (i) the Dark Ages at z>40 (difficult, Moon?); (ii) during a "respite" between heating and reionization (e.g. very high X-ray/SFR in early galaxies and/or efficient thermal feedback)
- The early Universe is a great test-bed for models involving a suppression of small-scale power, like WDM.
  - Driven by late-appearing galaxies, the 21cm signal would be delayed and subsequently more rapid
  - Current limits from CLASH lensed galaxies are only constraints with no astrophysics: m_x >~ 1 keV
- Dark matter annihilations can leave a robust footprint in the 21cm power spectrum by suppressing the heating peak.
- Exciting times are ahead!