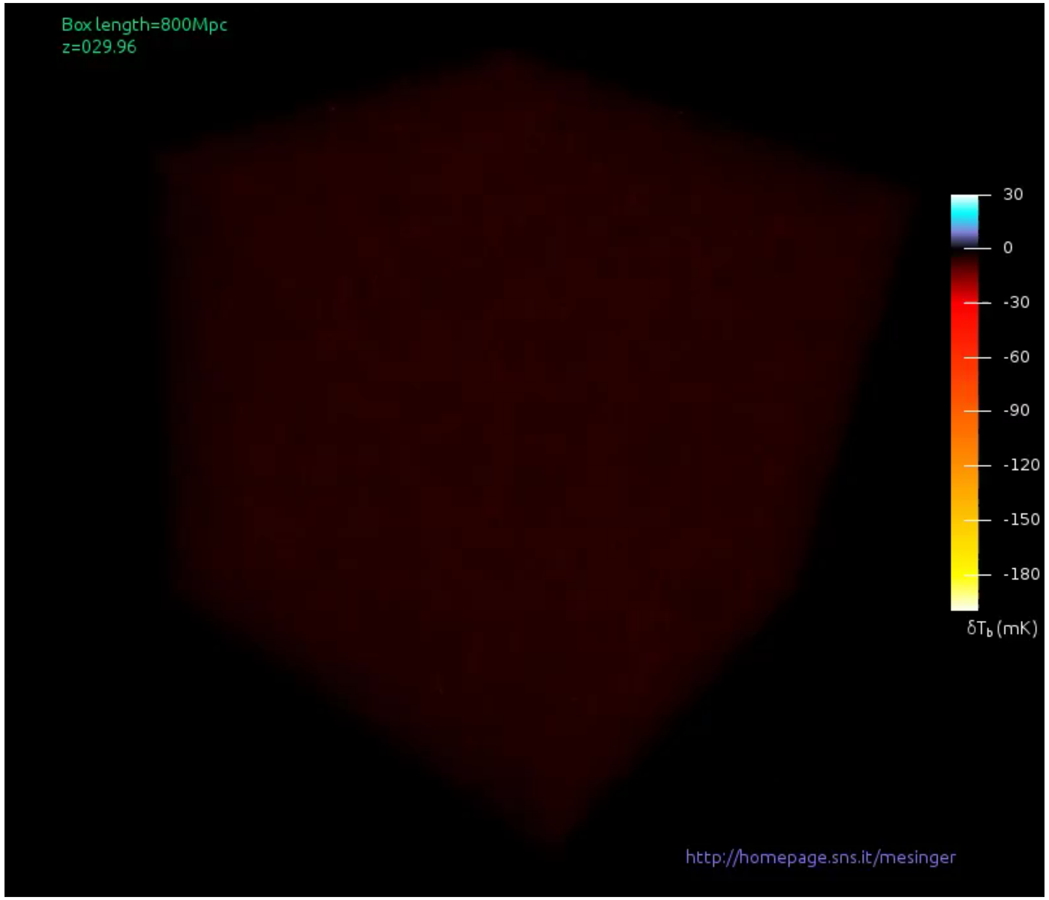
Reionization and Cosmic Dawn with Next Generation Radio Interfeormeters



http://*homepage.sns.it*/
mesinger/EOS.html

Andrei Mesinger
Scuola Normale Superiore, Pisa

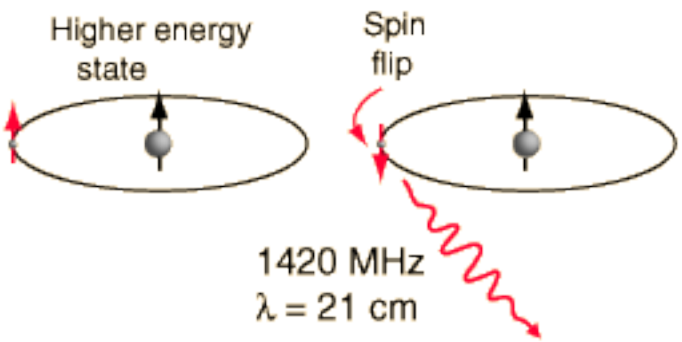
AiDA

SCUOLA NORMALE SUPERIORE

erc
European Research Council

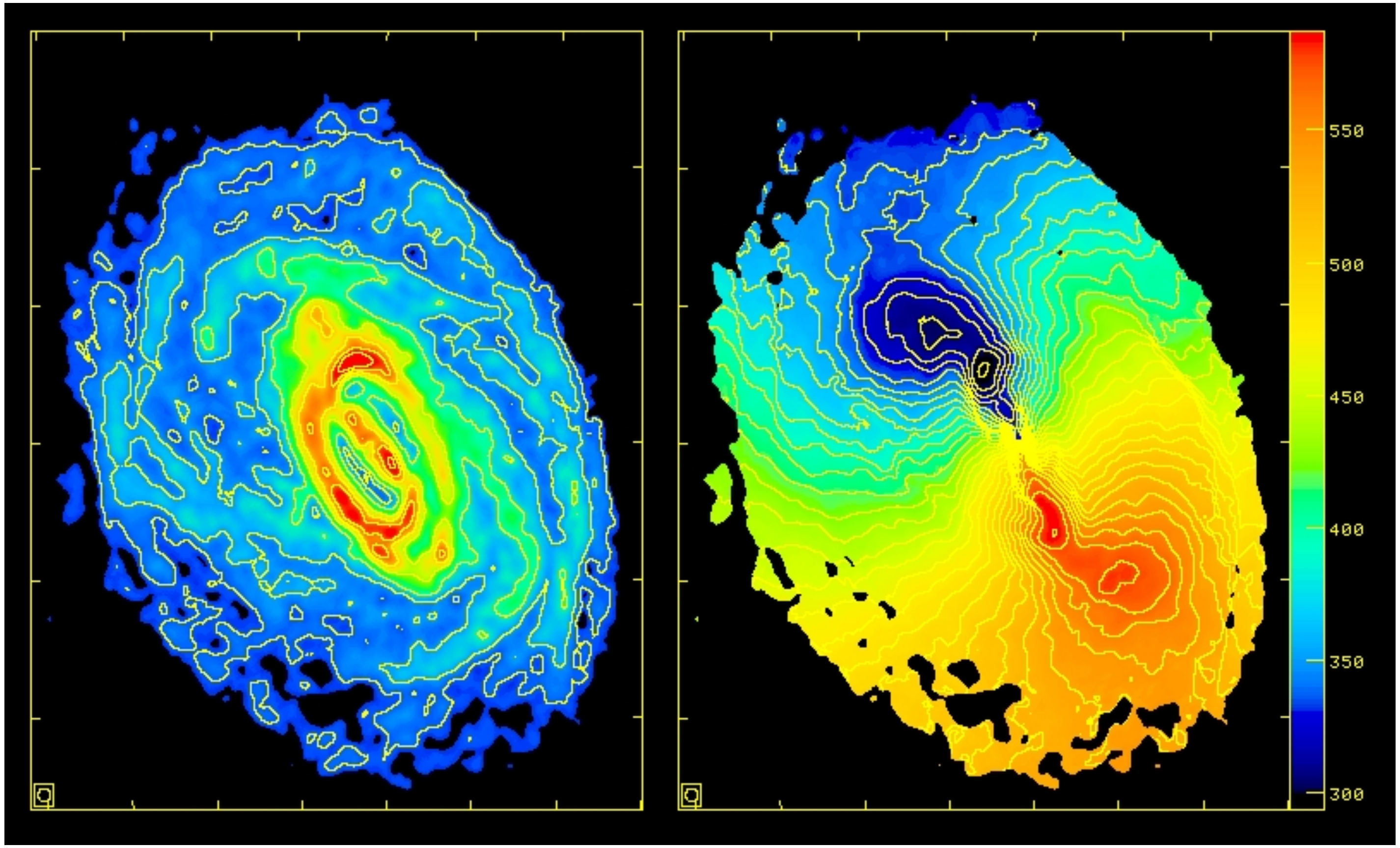
THE FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION
HORIZON 2020

21 cm line from neutral hydrogen



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

Widely used to map the HI content of our galaxy and nearby galaxies



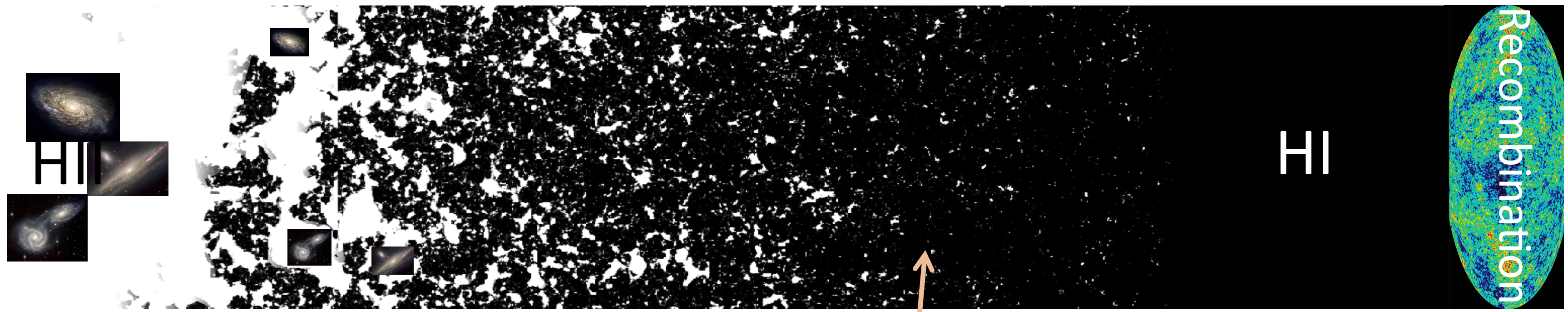
Circinus Galaxy

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} ~ 14 Gyr

z ~ 6

t_{age} ~ 1 Gyr

z ~ 20

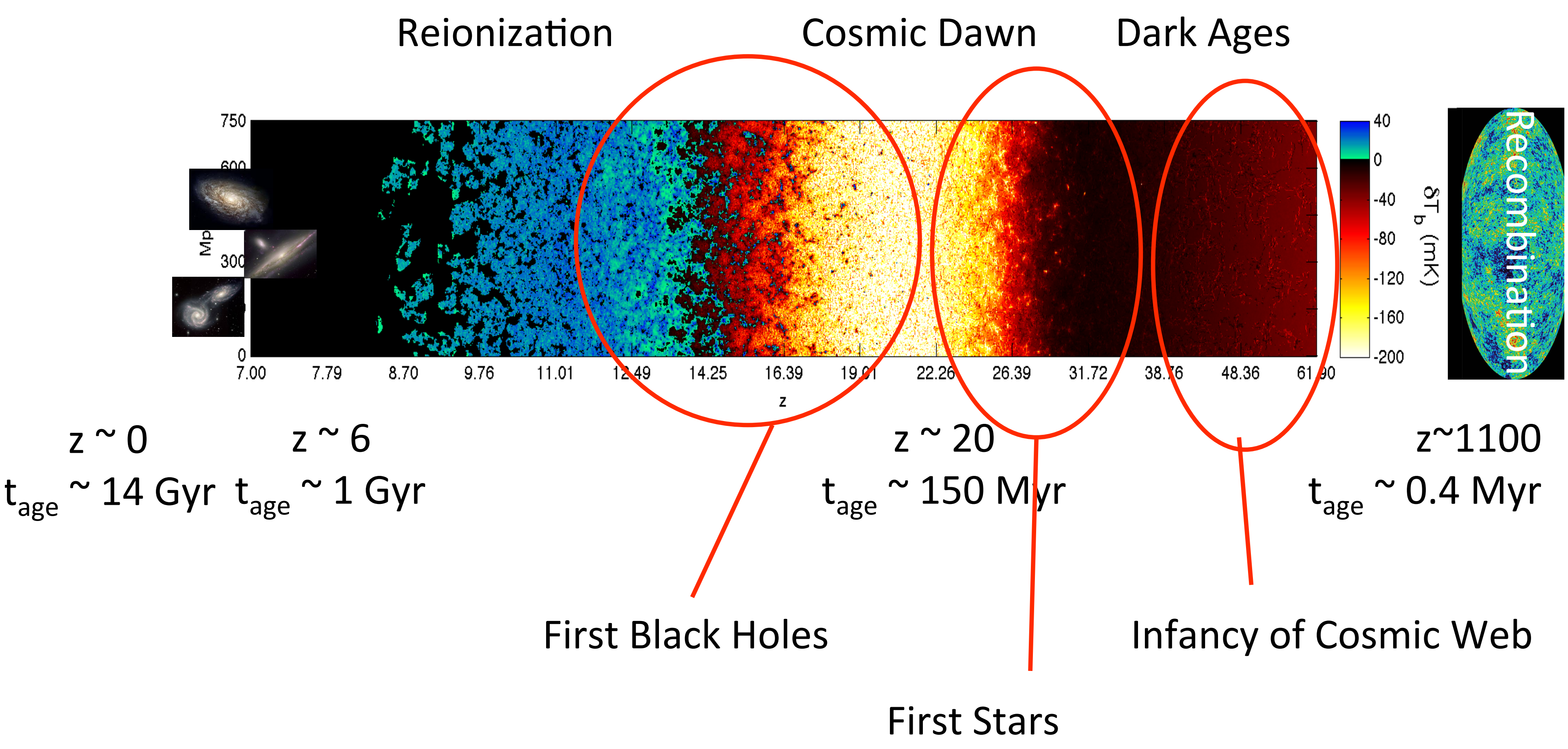
t_{age} ~ 150 Myr

z~1100

t_{age} ~ 0.4 Myr

Lots of neutral hydrogen!

Cosmic history in 21cm

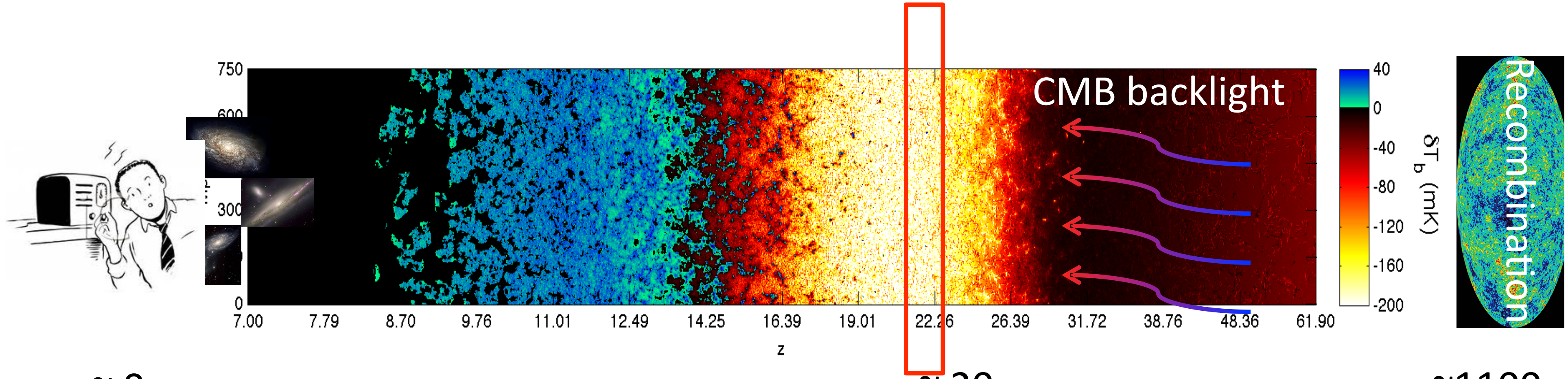


Cosmic history in 21cm

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

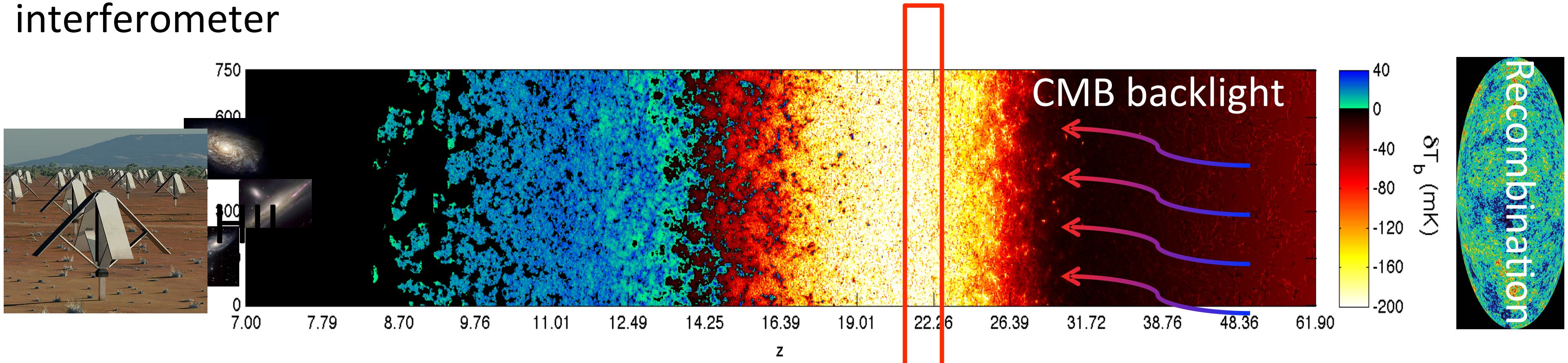
Cosmic history in 21cm

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
2^{nd} gen: HERA, SKA

Why so colorful? Physics-rich probe

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

neutral fraction

gas density

LOS velocity gradient

spin temperature

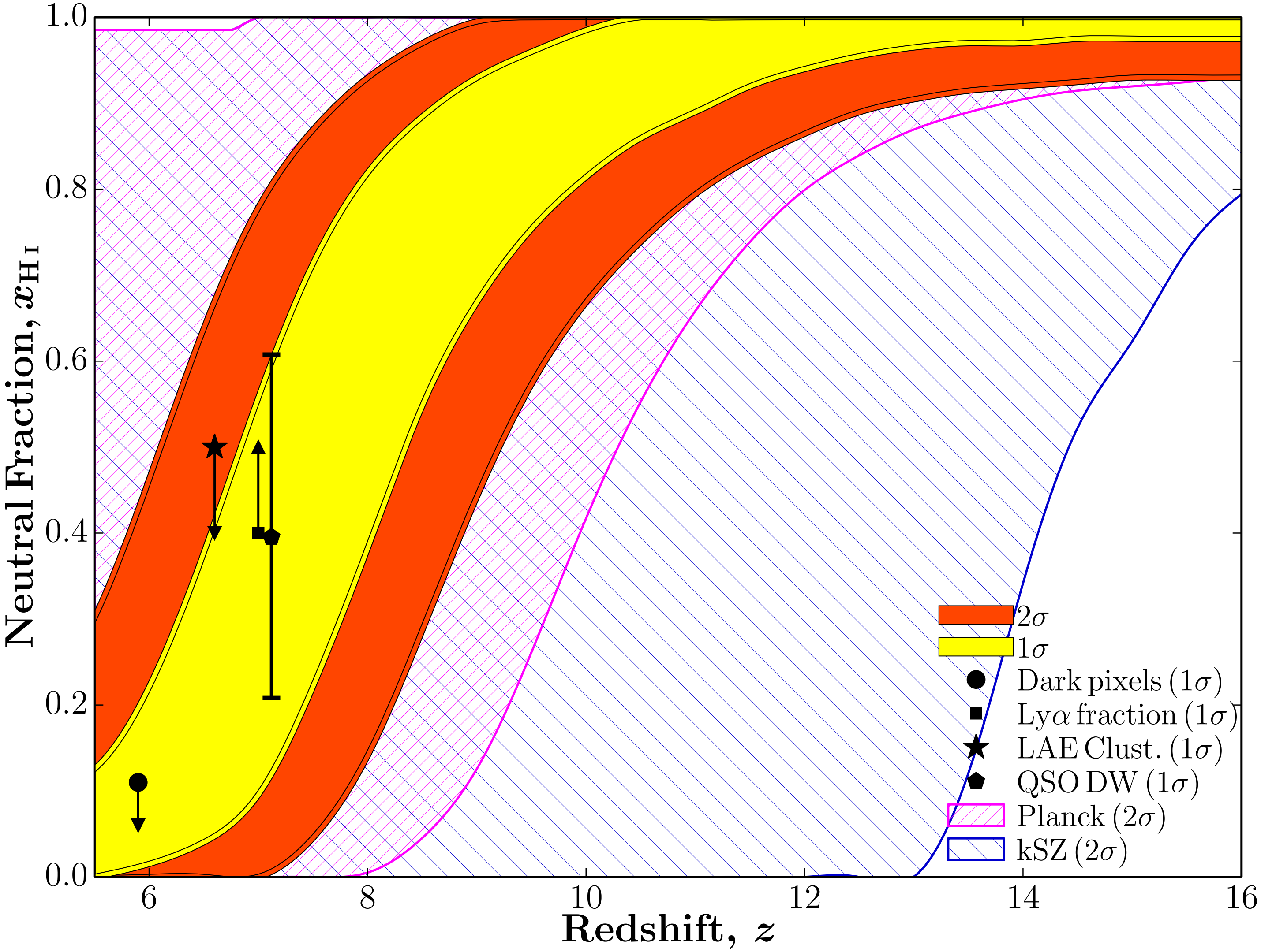
Signal contains both **ASTROPHYSICAL** and **COSMOLOGICAL** terms

Epoch of Reionization

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

What we want to know: When? What? How?...

When?

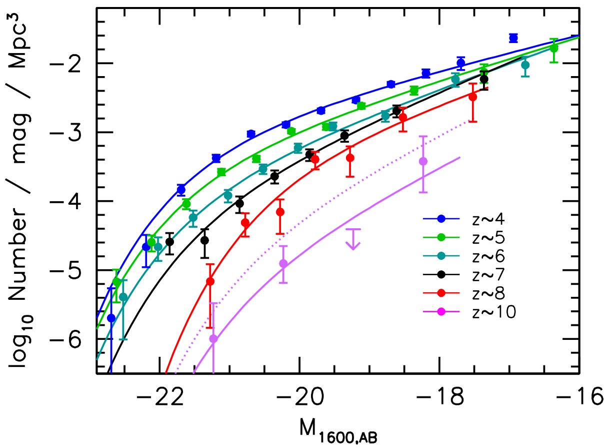


Greig & AM (2016)
see also Planck 2016;
Price+2016; Mitra+2016

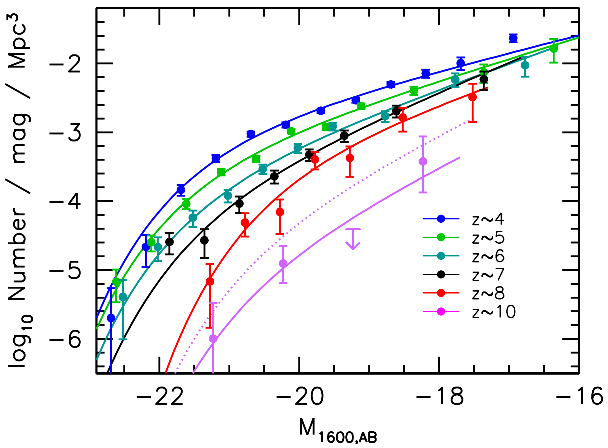
What? How?

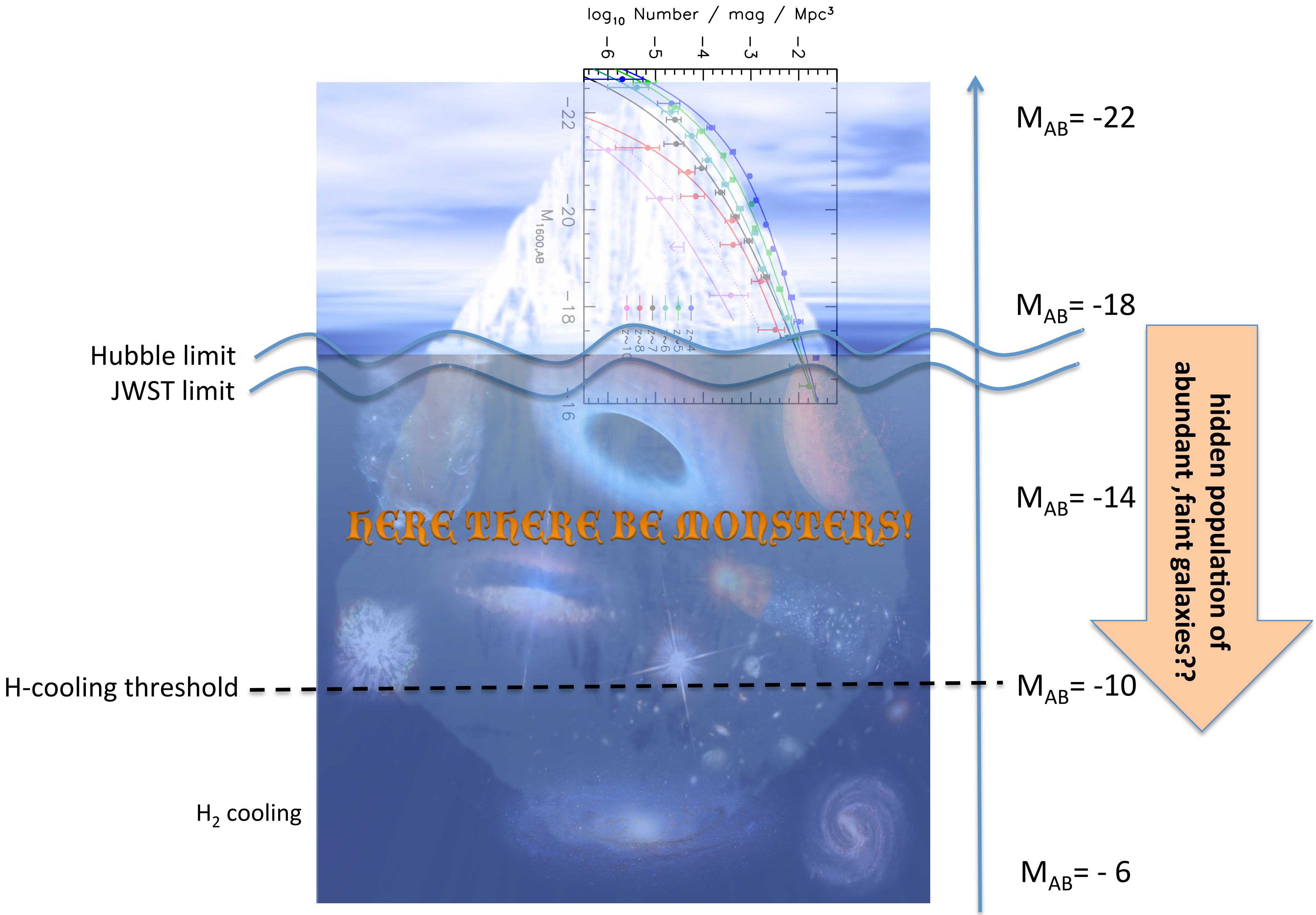
- Galaxy candidates have been found out to z~10. Are these the sources of reionization?? Estimates suggest they are too few…

Bouwens+(2014)



Tip of the iceberg

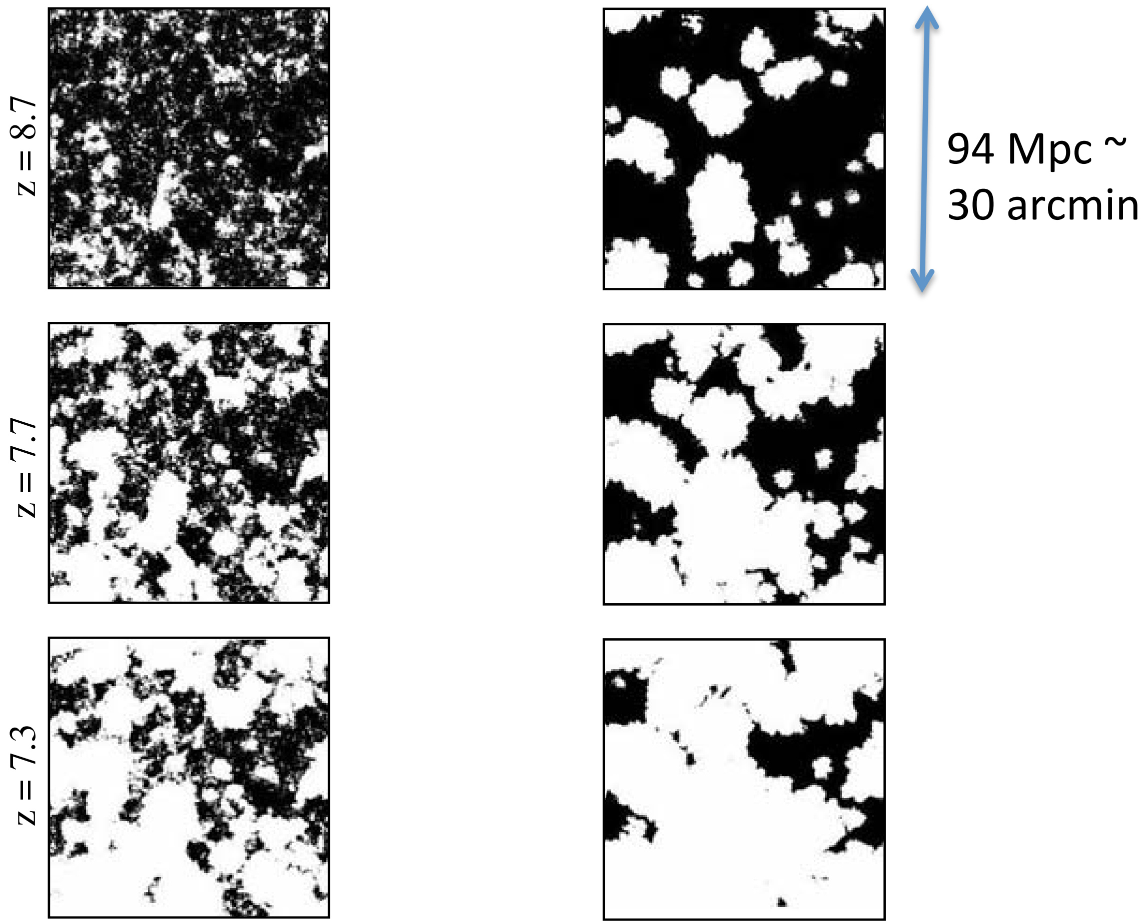




log10 Number / mag / Mpc3
M1600,AB
Hubble limit
JWST limit
HERE THERE BE MONSTERS!
H-cooling threshold
H2 cooling
MAB= -22
MAB= -18
MAB= -14
MAB= -10
MAB= - 6
hidden population of abundant ,faint galaxies??

How do we detect the first galaxies?

- Galaxy clustering + stellar properties → *evolution of large-scale EoR/CD structures*



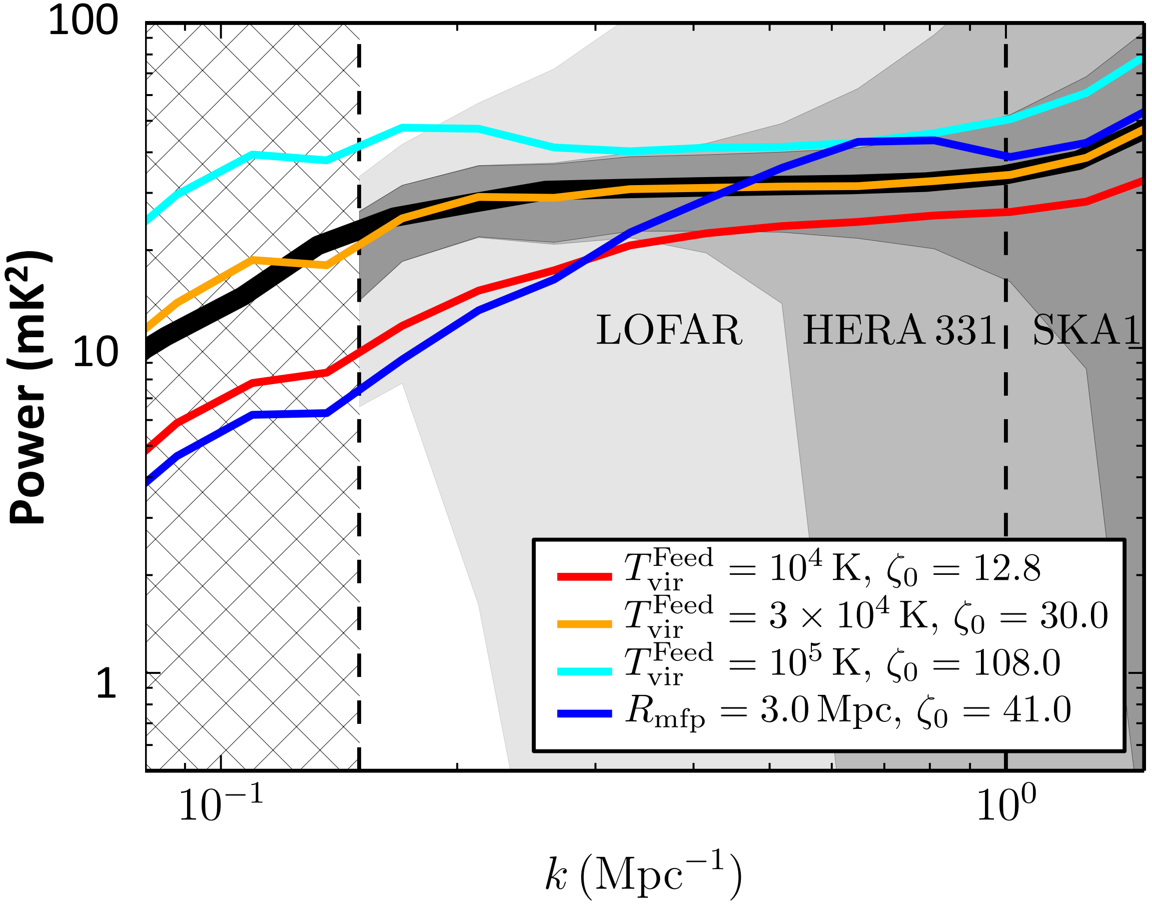
McQuinn+ 2007

Abundant, faint galaxies vs **Rare, bright galaxies**

21cm interferometry probes the 3D structure of the EoR!!!

- A powerful discriminant of EoR models: a factor of ~10 variation on large scales, at a fixed EoR epoch!

PS at the same mean neutral fraction



Rare, bright galaxies

Abundant, faint galaxies

Faint galaxies + clumpy IGM

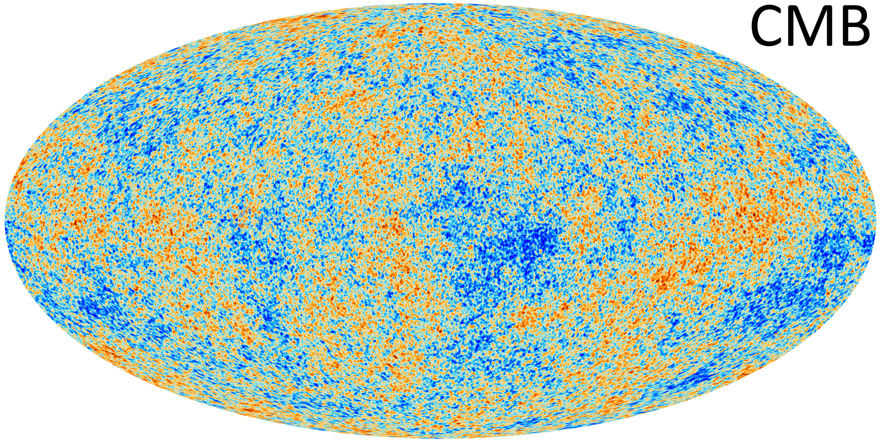
Greig & AM (2015)

How to quantify what we will learn??

21CMMC (Greig & AM 2015) – publicly-available, massively-parallelized MCMC driver for the 21-cm simulation code ***21cmFAST*** (AM+2007, 2011)

Physical cosmology

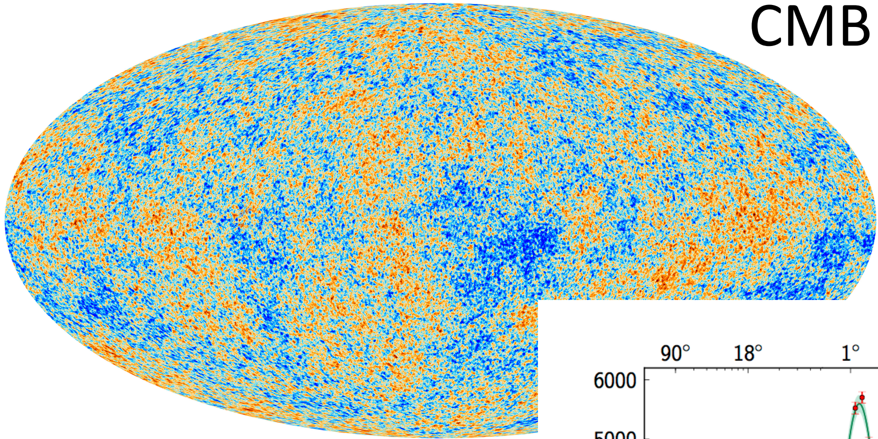
CMB map



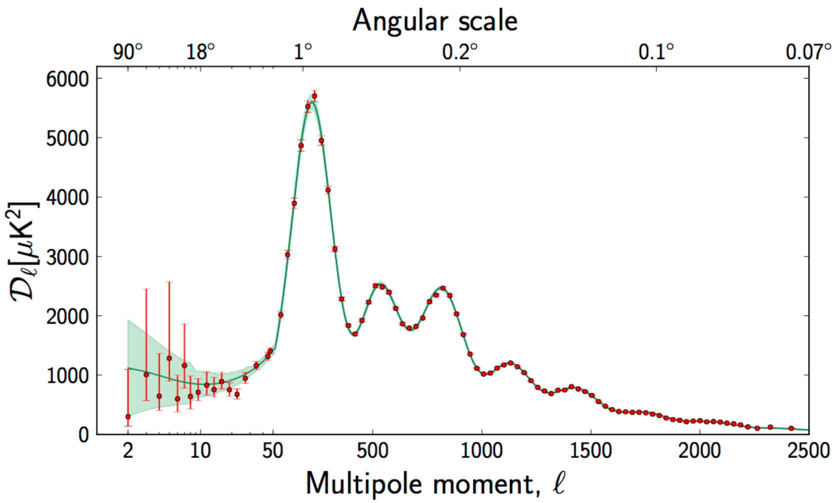
Planck 2013; 2015

Physical cosmology

CMB map



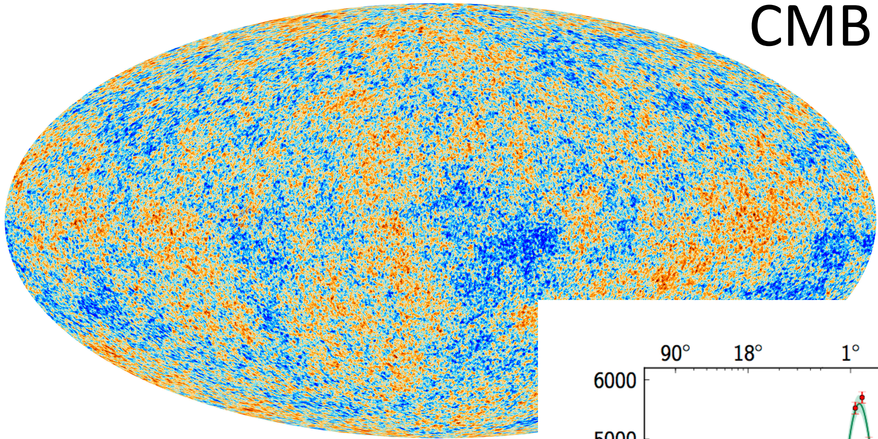
power spectrum



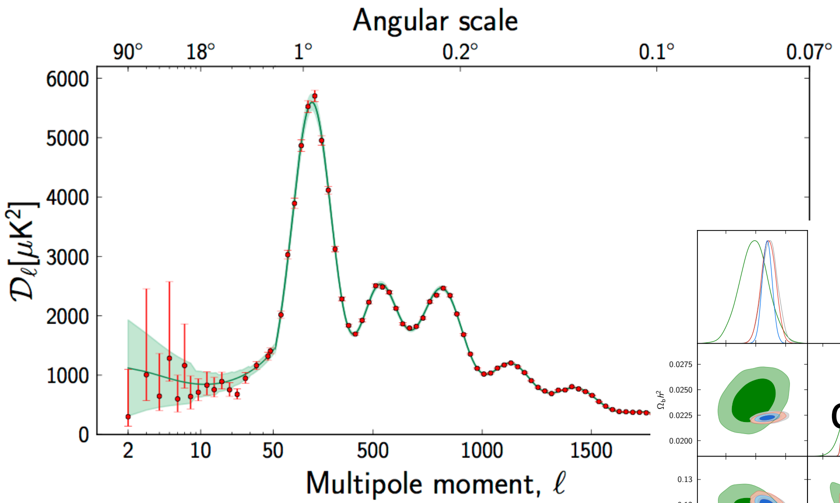
Planck 2013; 2015

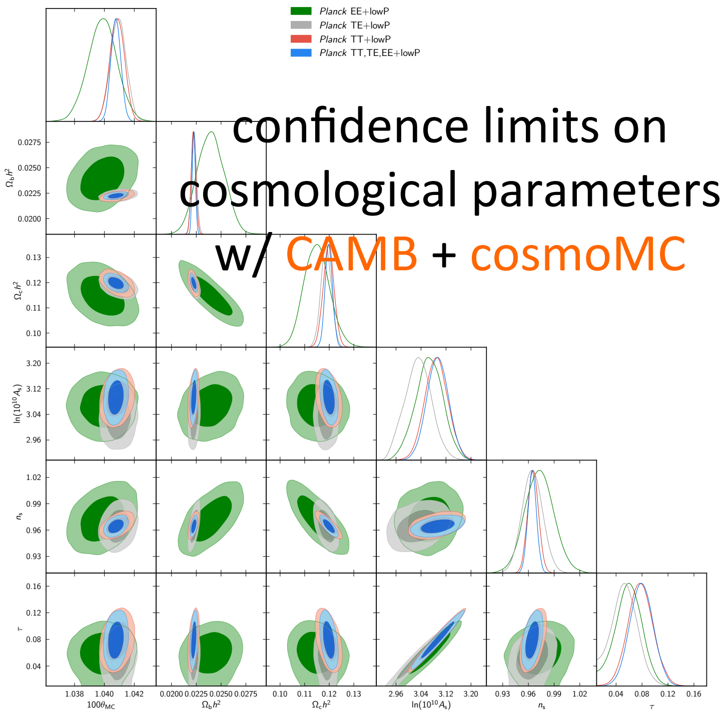
Physical cosmology

CMB map



power spectrum



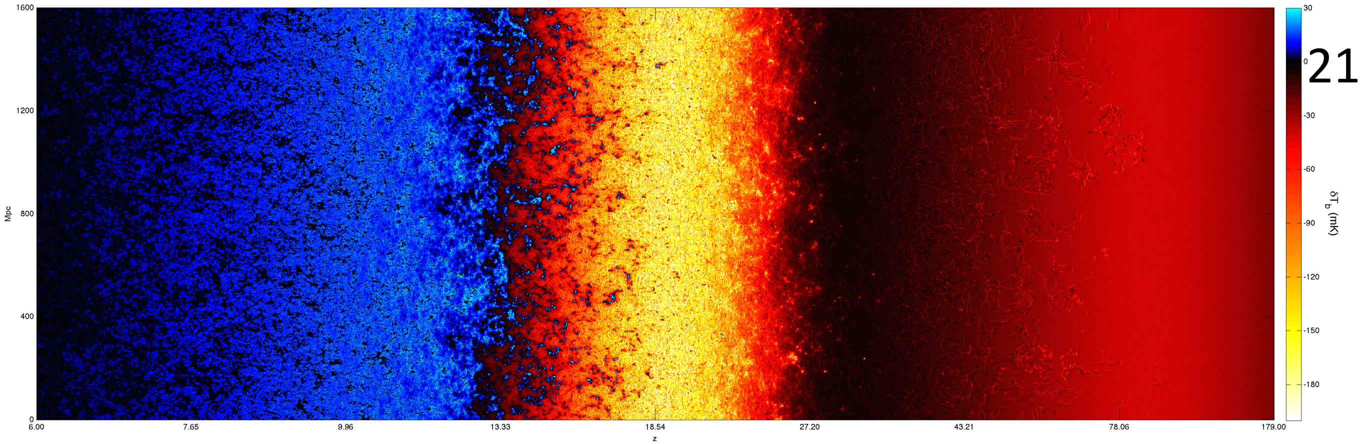


confidence limits on cosmological parameters w/ CAMB + cosmoMC

Planck 2013; 2015

*Astro*physical cosmology

← time

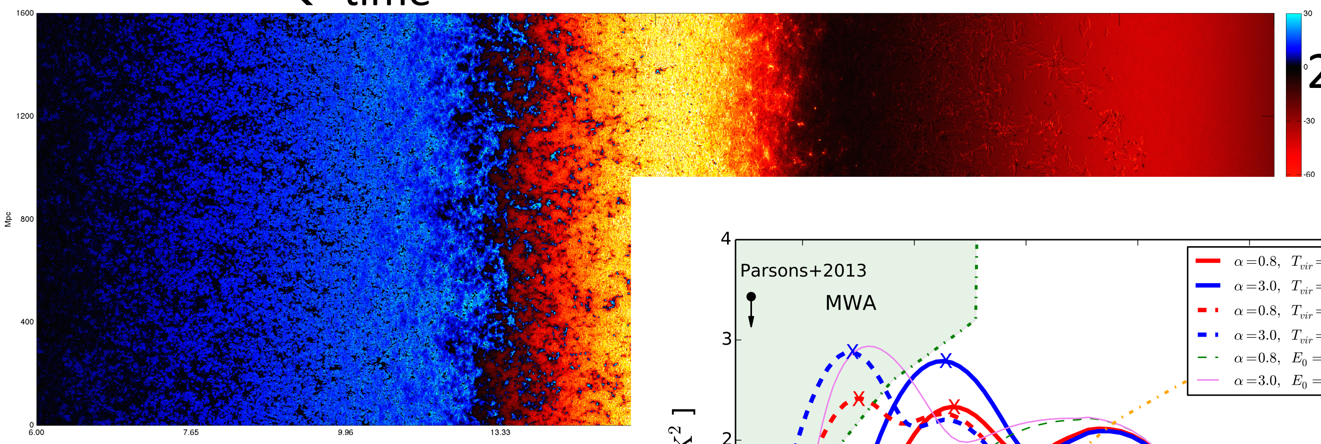


21cm ***3D*** map

Greig & AM (2015)

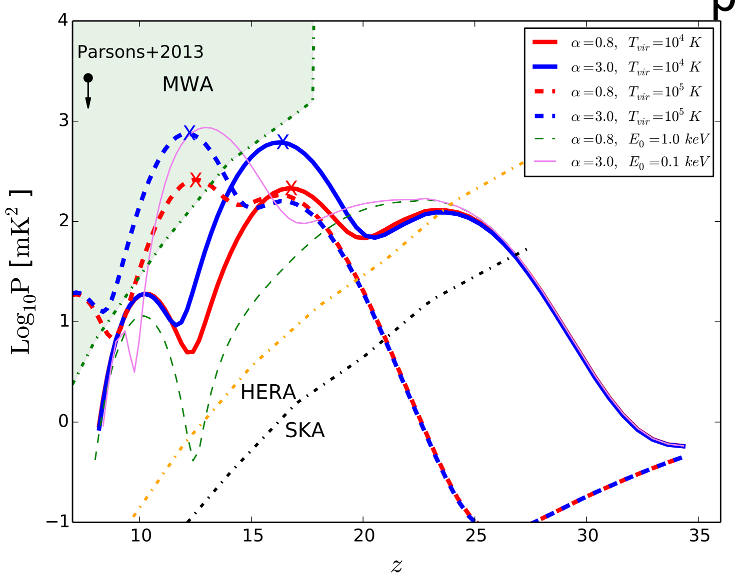
*Astro*physical cosmology

← time



21cm ***3D*** map

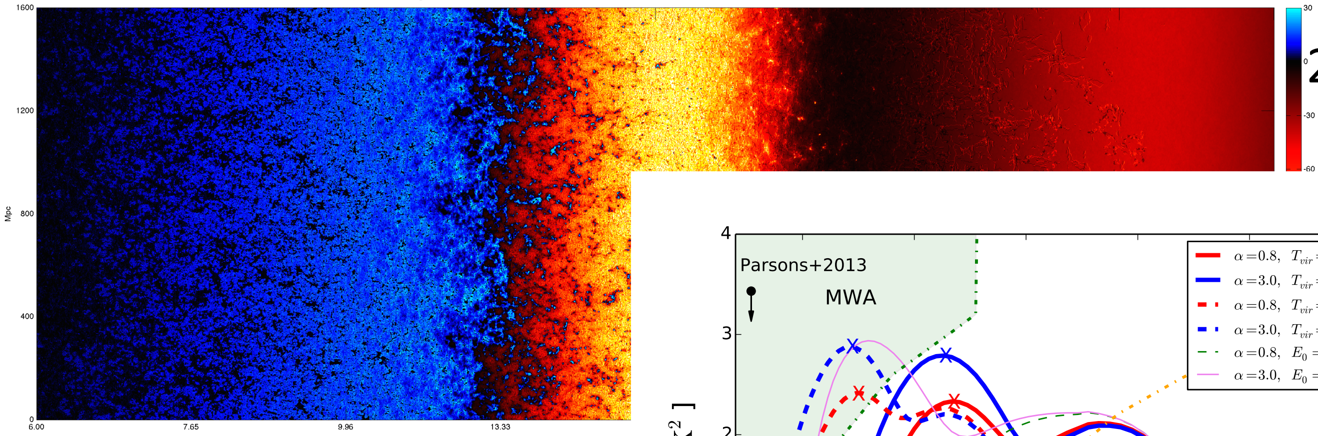
power spectrum



Greig & AM (2015)

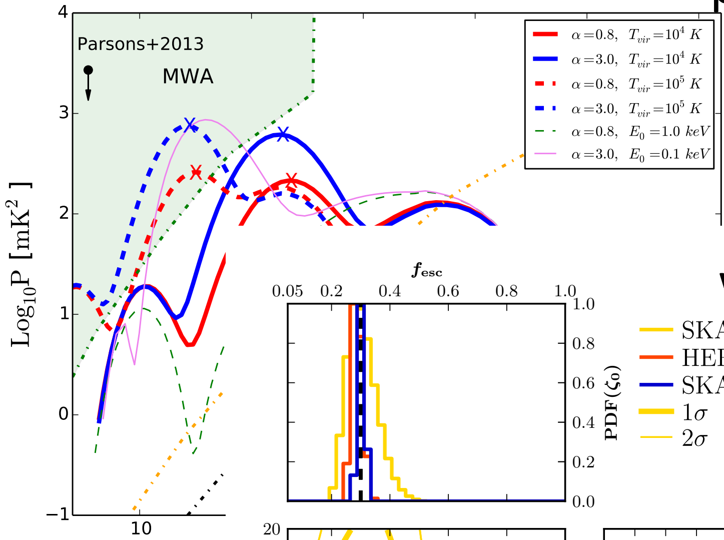
*Astro*physical cosmology

← time

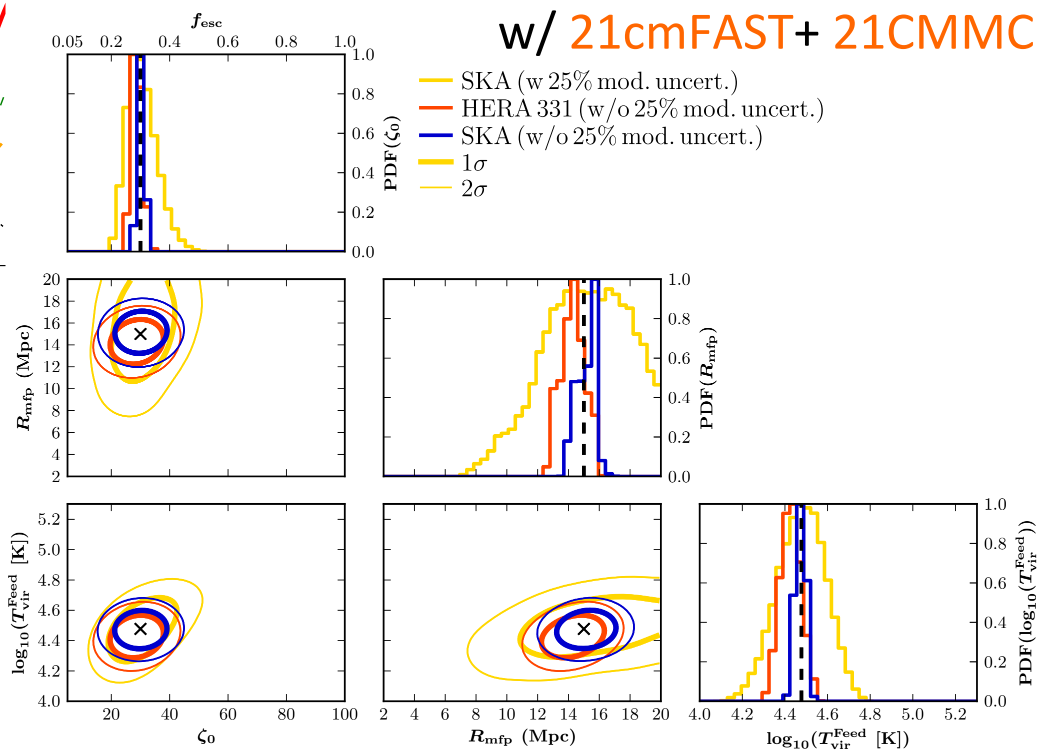


21cm ***3D*** map

power spectrum



confidence limits on ***astro*** parameters w/ 21cmFAST+ 21CMMC

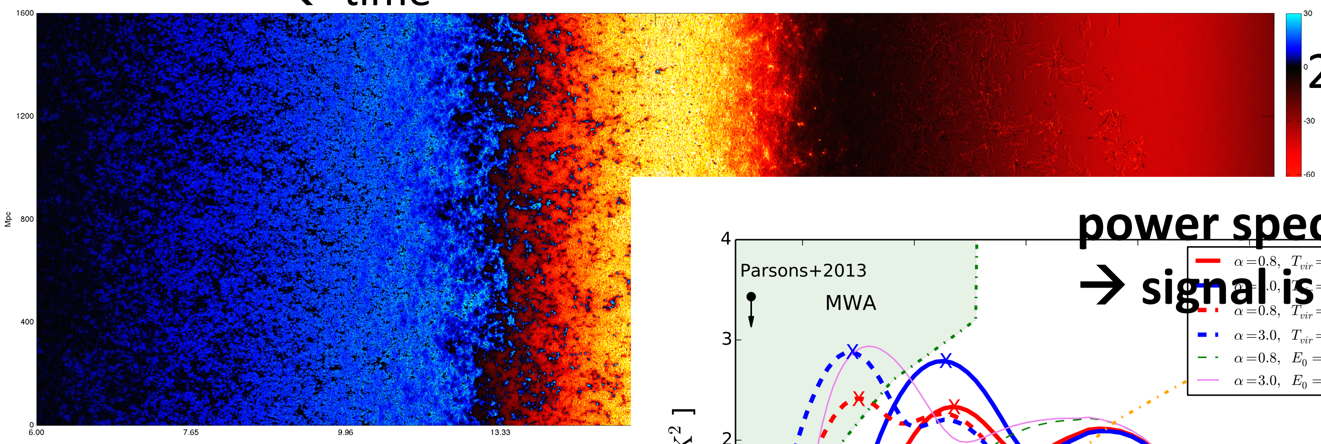


~ percent level constraints available with SKA1

Greig & AM (2015)

*Astro*physical cosmology

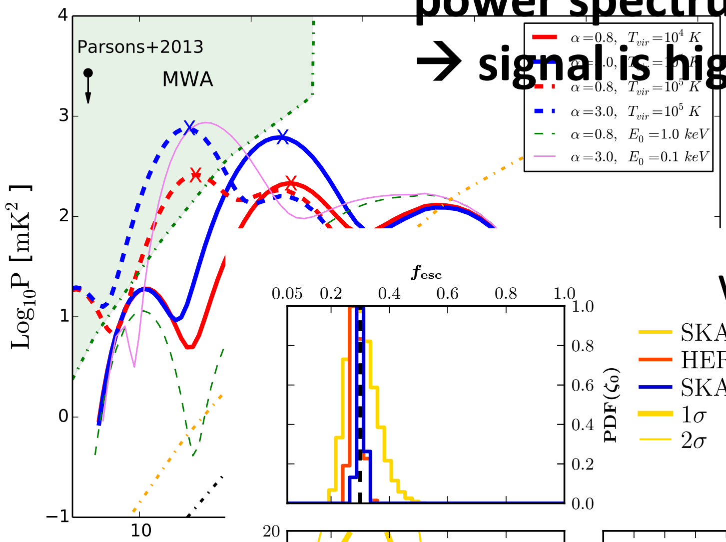
← time



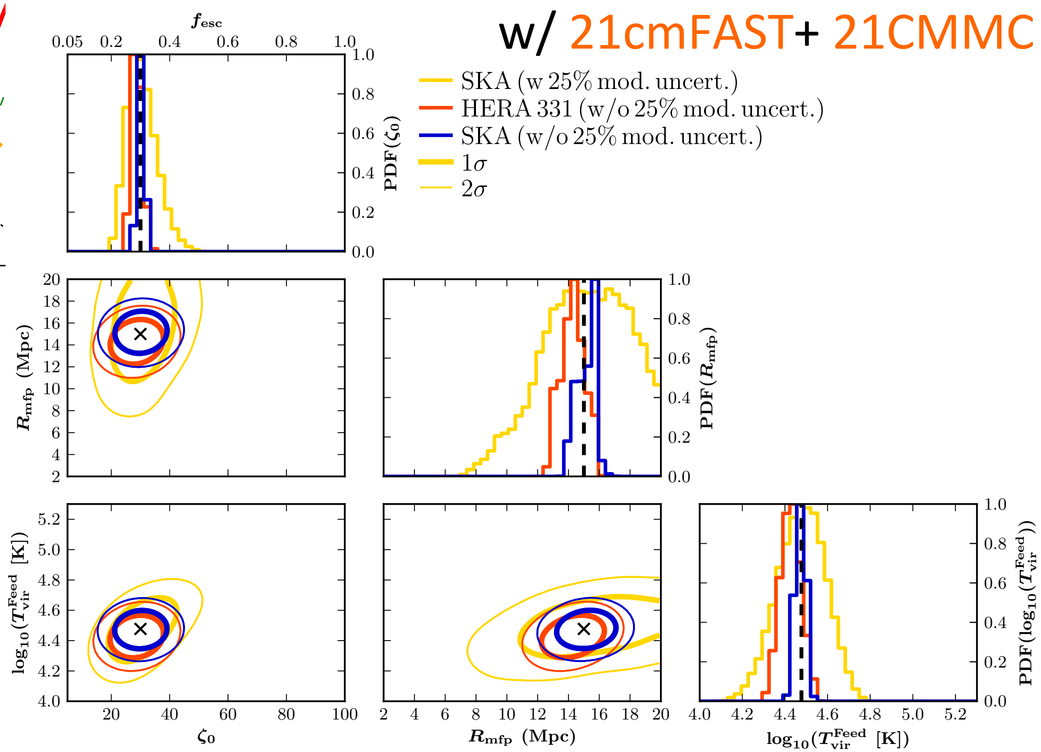
21cm ***3D*** map

power spectrum??

→ signal is highly non-Gaussian



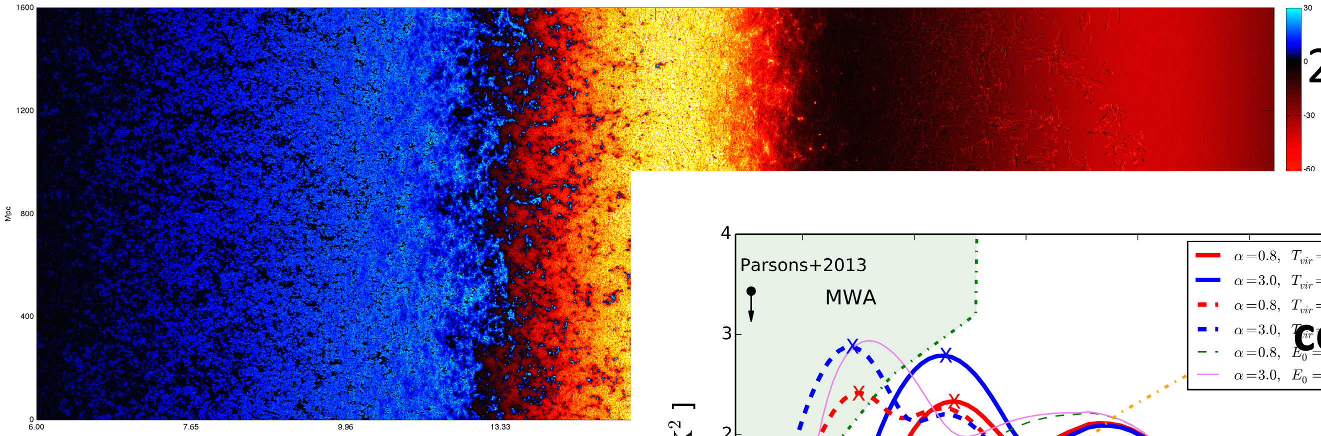
confidence limits on ***astro*** parameters w/ 21cmFAST+ 21CMMC



Greig & AM (2015)

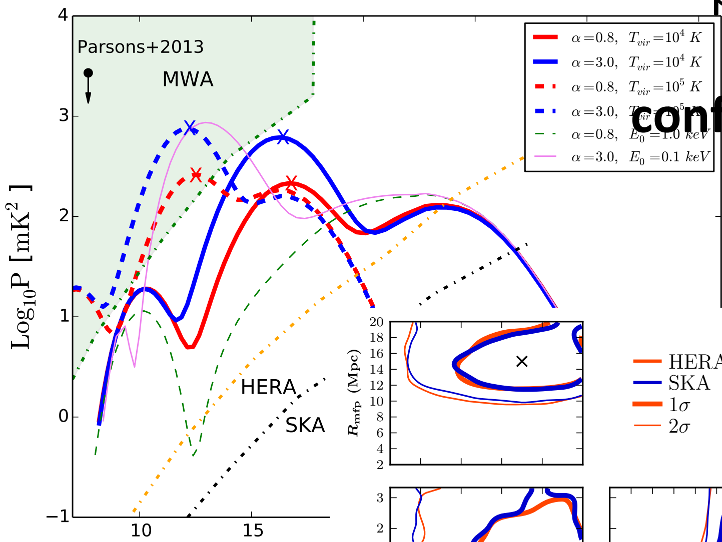
*Astro*physical cosmology

← time



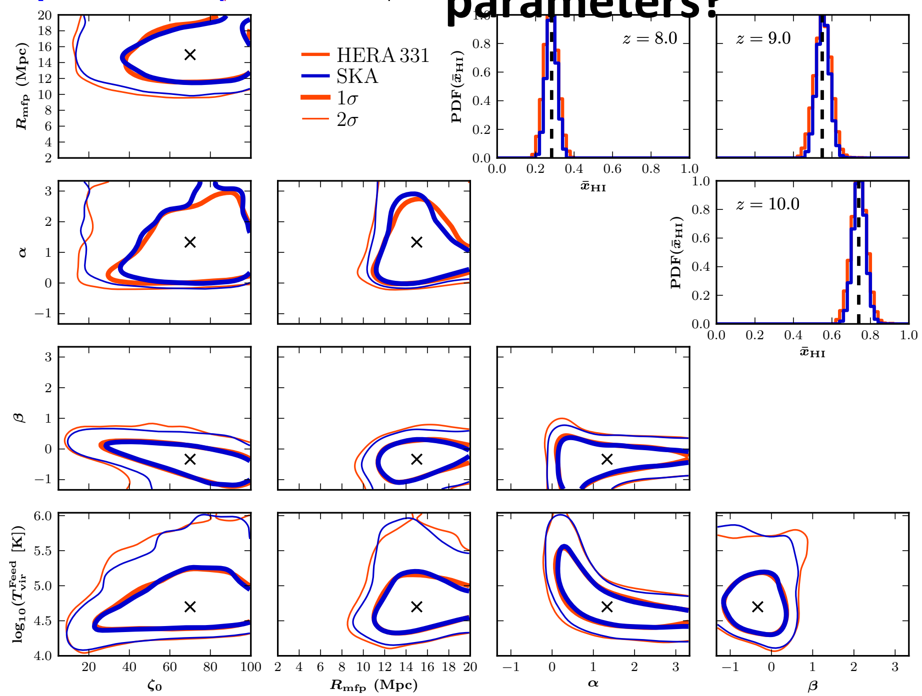
21cm ***3D*** map

power spectrum



confidence limits on *astro* parameters???

→ what are astro parameters?



Greig & AM (2015)

The full power of 21cm is to reach back into the infancy of galaxy formation beyond other probes....

Cosmic Dawn

IGM Temperature

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

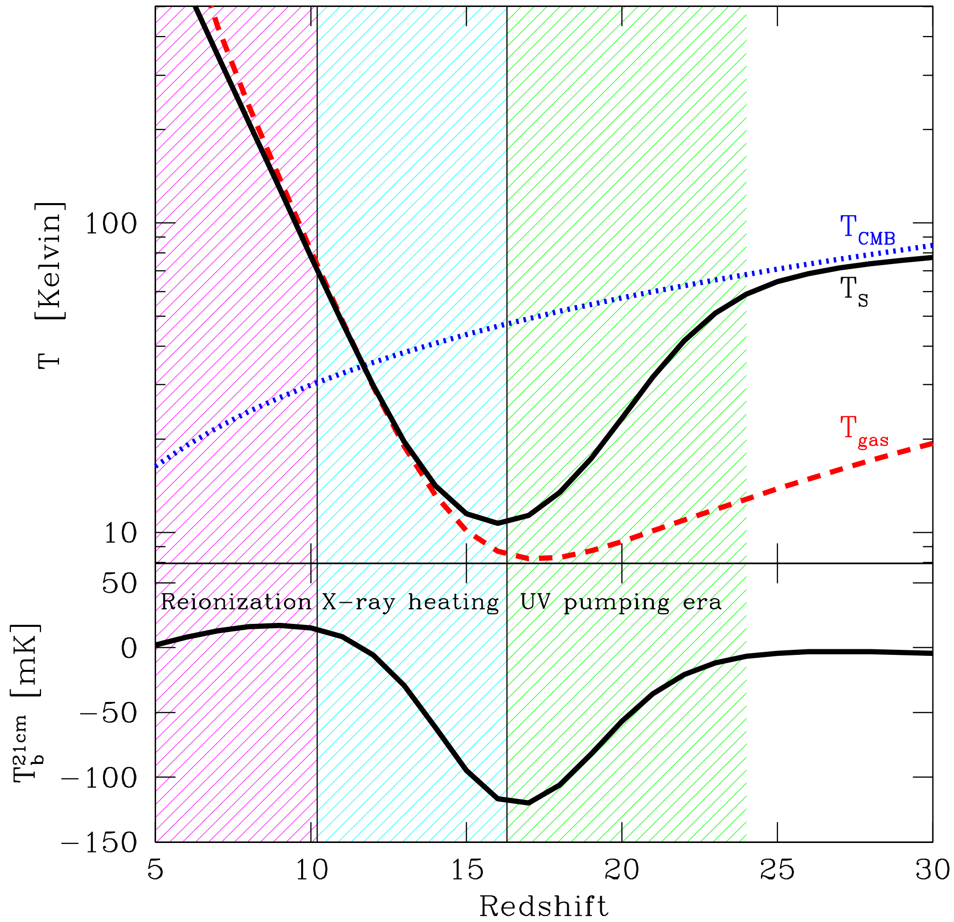
spin temperature

Shortly after the first stars turn on, the pervasive soft UV background they create couples the spin temperature to the kinetic temperature (so-called Lyα pumping), even in the diffuse IGM:

$$T_s \sim T_k$$

- **when Ts < Tcmb – signal is seen in absorption**
- **when Ts > Tcmb – signal is seen in emission**
- **when Ts >> Tcmb – signal does not care about the temperature**

"*Fiducial*" scenario: the IGM is heated by X-rays from HMXBs before reionization



SFR required to reionize the Universe:

$$[\dot{\rho}_{\rm SFR}]_{\rm ion} = 4.4 \times 10^{-1}\, \bar{x}_i\, Z_{20}^{3/2} \left(\frac{t_{\rm SFR}}{0.1\, t_H}\right)^{-1} \times \left(\frac{f_{\rm esc}}{0.1}\frac{N_{\rm ion}}{4000}\right)^{-1} \; {\rm M_\odot\ yr^{-1}\ Mpc^{-3}}, \quad (11)$$

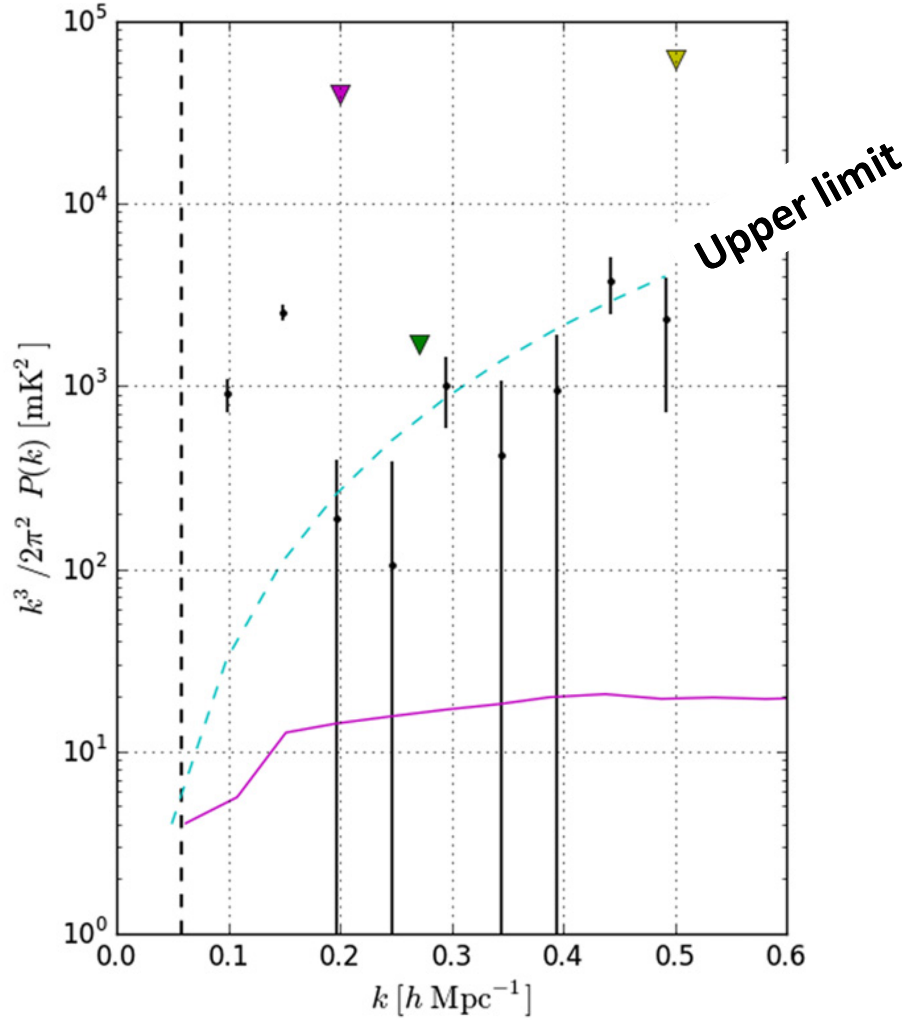
is much larger than the SFR needed to heat it with HMXBs:

$$[\dot{\rho}_{\rm SFR}]_{\rm X} = 4.0 \times 10^{-2}\, Z_{20}^{5/2} \left(\frac{t_{\rm SFR}}{0.1\, t_H}\right)^{-1} \left(\frac{f_X}{0.2}\right)^{-1} \times \left(\frac{L_X/{\rm SFR}}{10^{40}\ {\rm erg\ s^{-1}\ M_\odot{}^{-1}\ yr}}\right)^{-1} \; {\rm M_\odot\ yr^{-1}\ Mpc^{-3}}, \quad (10)$$

McQuinn & O'Leary (2012)
see also Furlanetto (2006), Mesinger+ (2013)

Observational evidence of IGM pre-heating

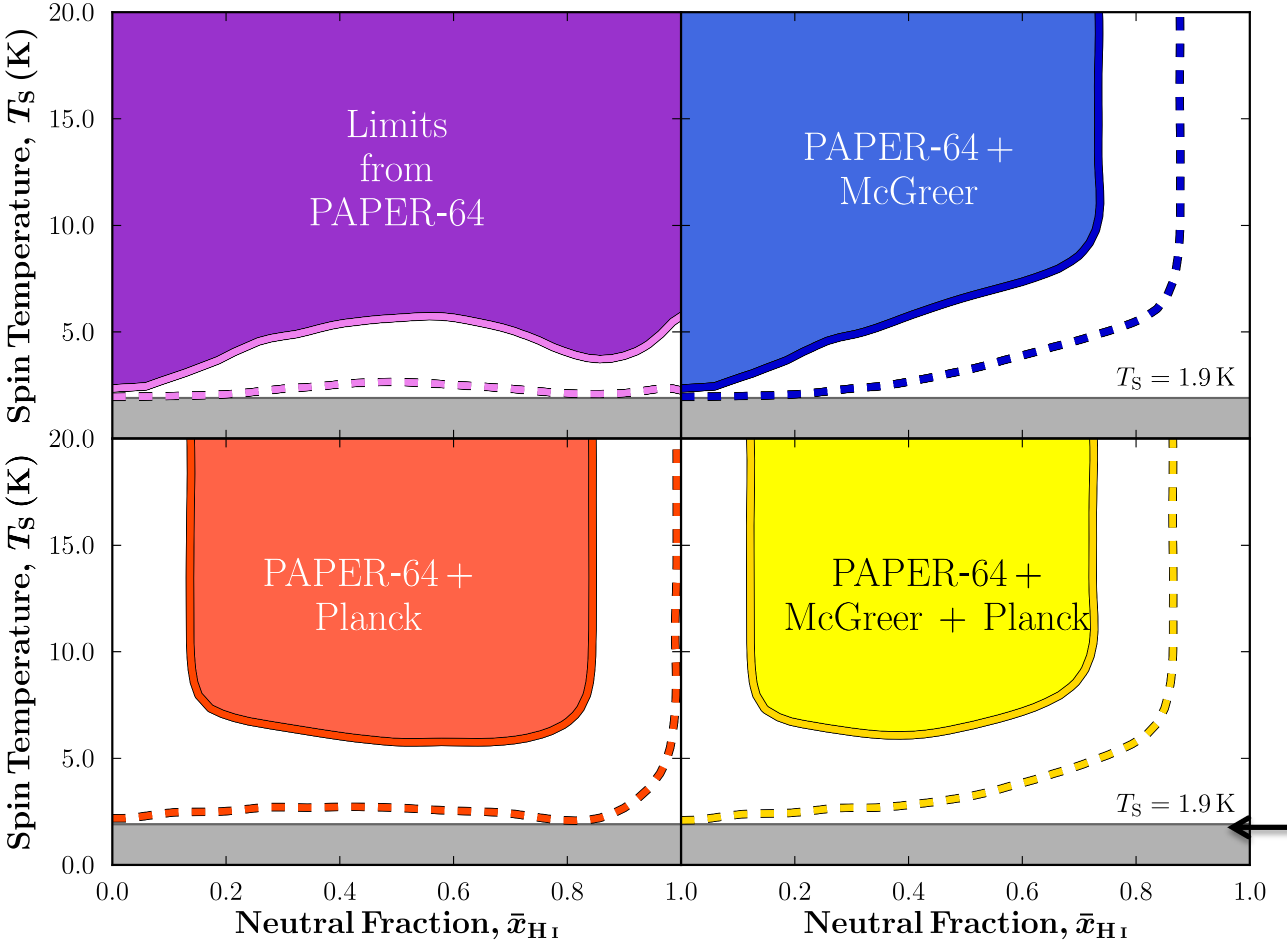
Preliminary data at z=8.4 from PAPER64:



Ali+ (2015)

Observational evidence of IGM pre-heating

Applying 21CMMC to preliminary data (marginalizing over EoR models):

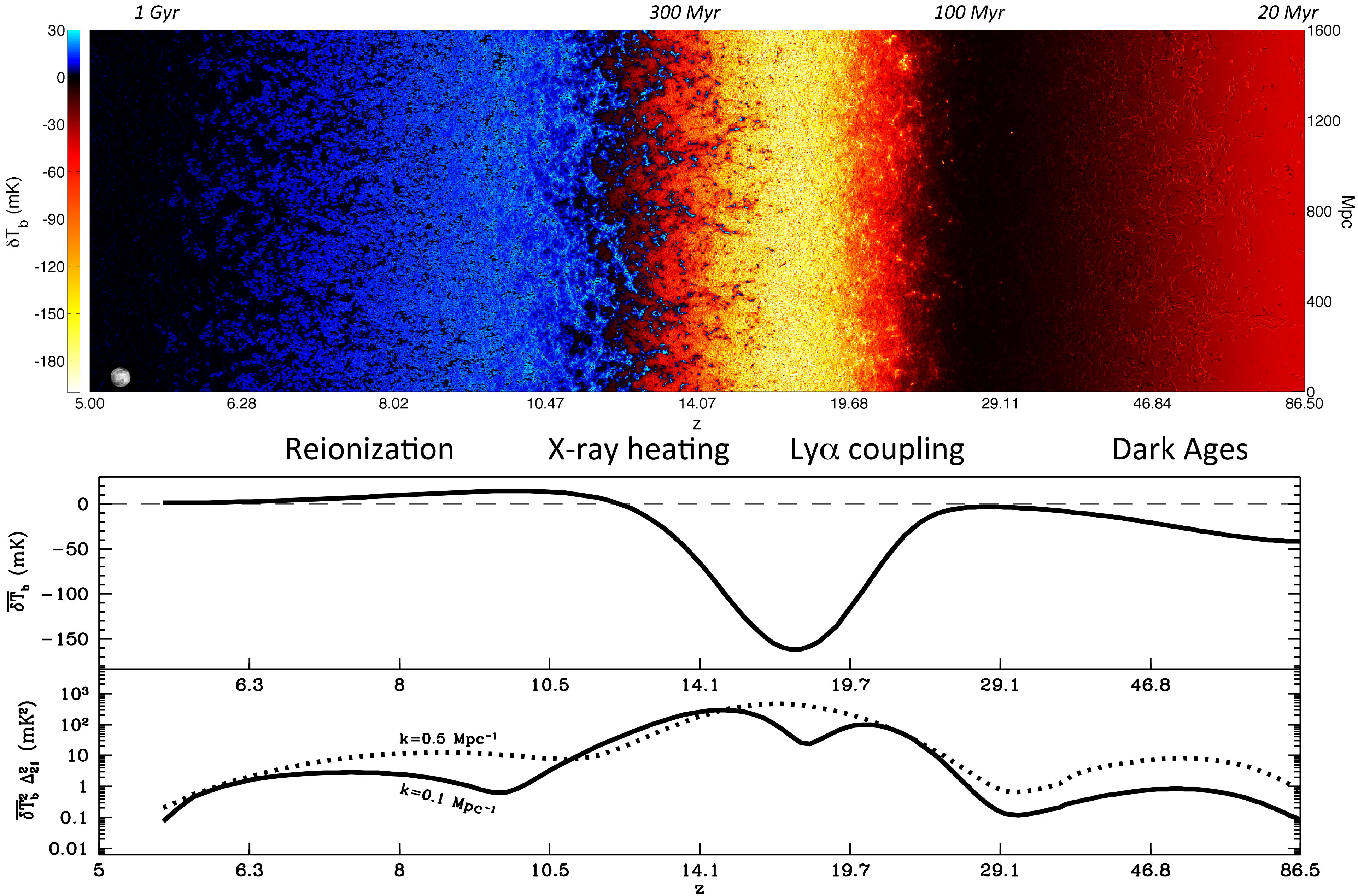


$\langle T_{HI} \rangle > 6$ K @ z=8.4

adiabatically-cooled IGM

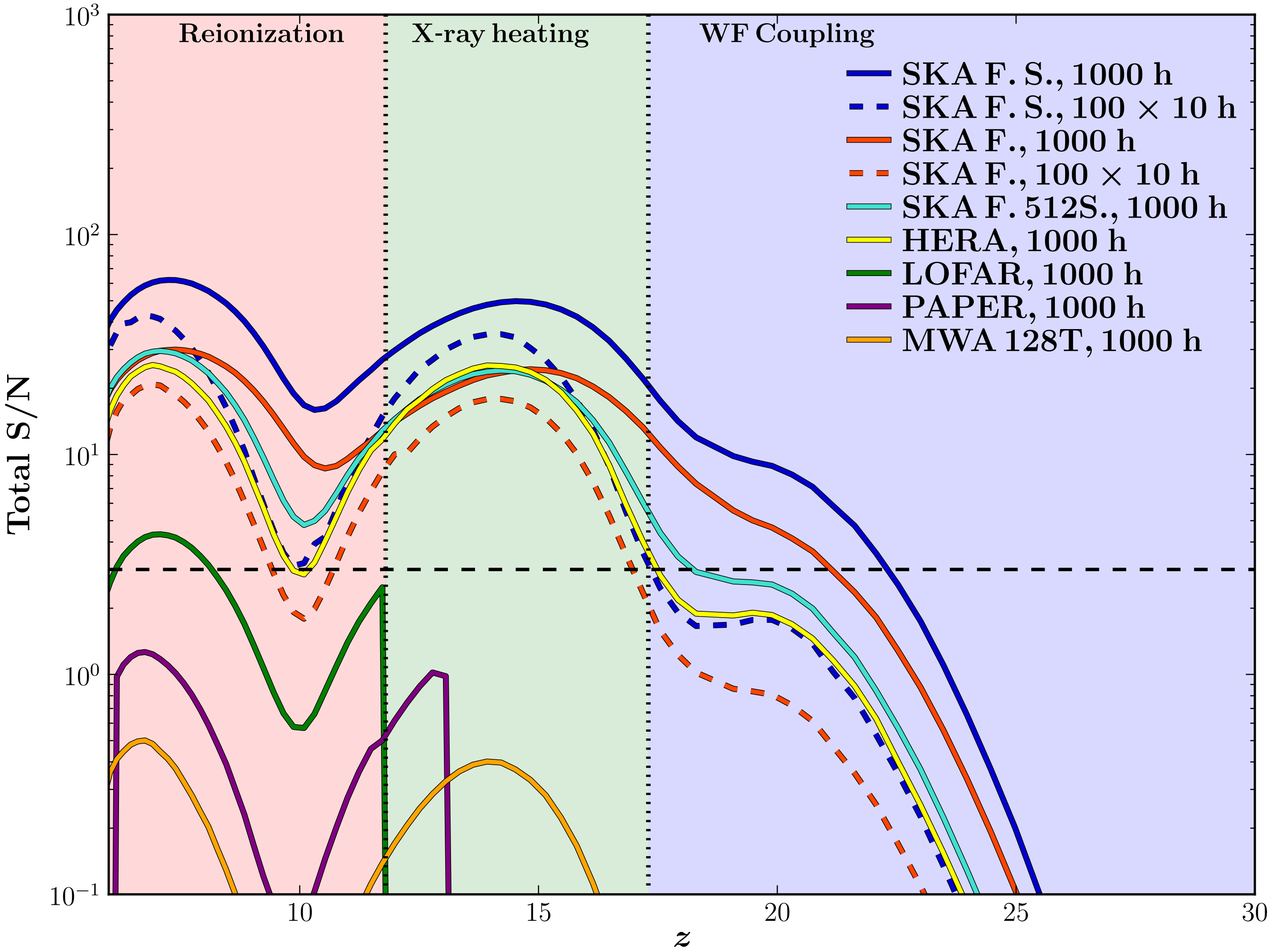
some source of heating is required…

Greig, AM, Pober (2016)
(see also Pober+2015)



Evolution of 21cm Structure (EOS) 2016 data release. Mesinger+ (2016)

and we should get a high S/N detection with HERA and SKA



Mesinger+ (2016)

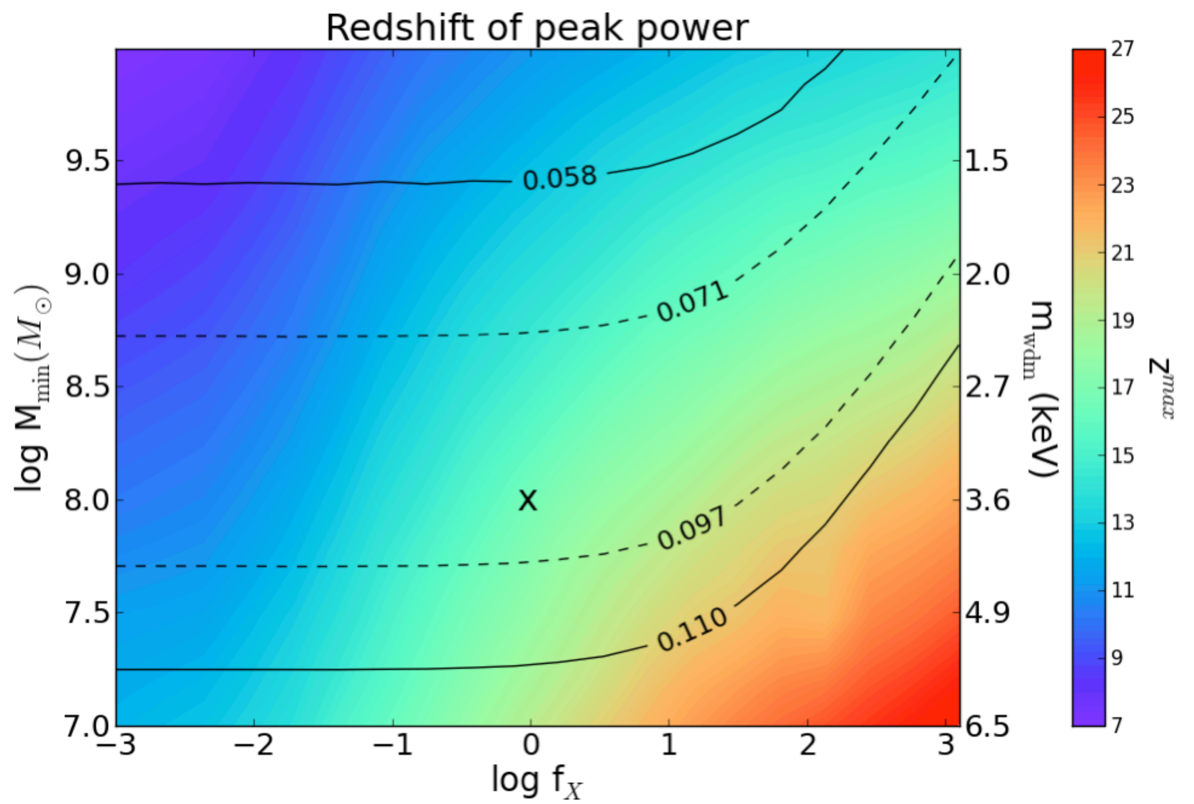
But what do we learn from detecting the Epoch of Heating (EoH)???

Redshift of X-ray peak

Just the redshift at which the large-scale 21-cm power peaks already tells us a combination of which halos hosted early galaxies and what were their X-ray luminosities

Mesinger+2014

Mass of halos hosting early galaxies



Lx/SFR

fx=1 corresponds to Lx/SFR from local star-forming galaxies (Mineo+2012)

is Lx/SFR different in the first galaxies?? e.g. lower metalicity -> more abundant and more luminous HMXBs? (Fragos+2012; Basu-Zych+2016)

But we can learn more!

The X-ray mean free path through the IGM is very sensitive to E_x:

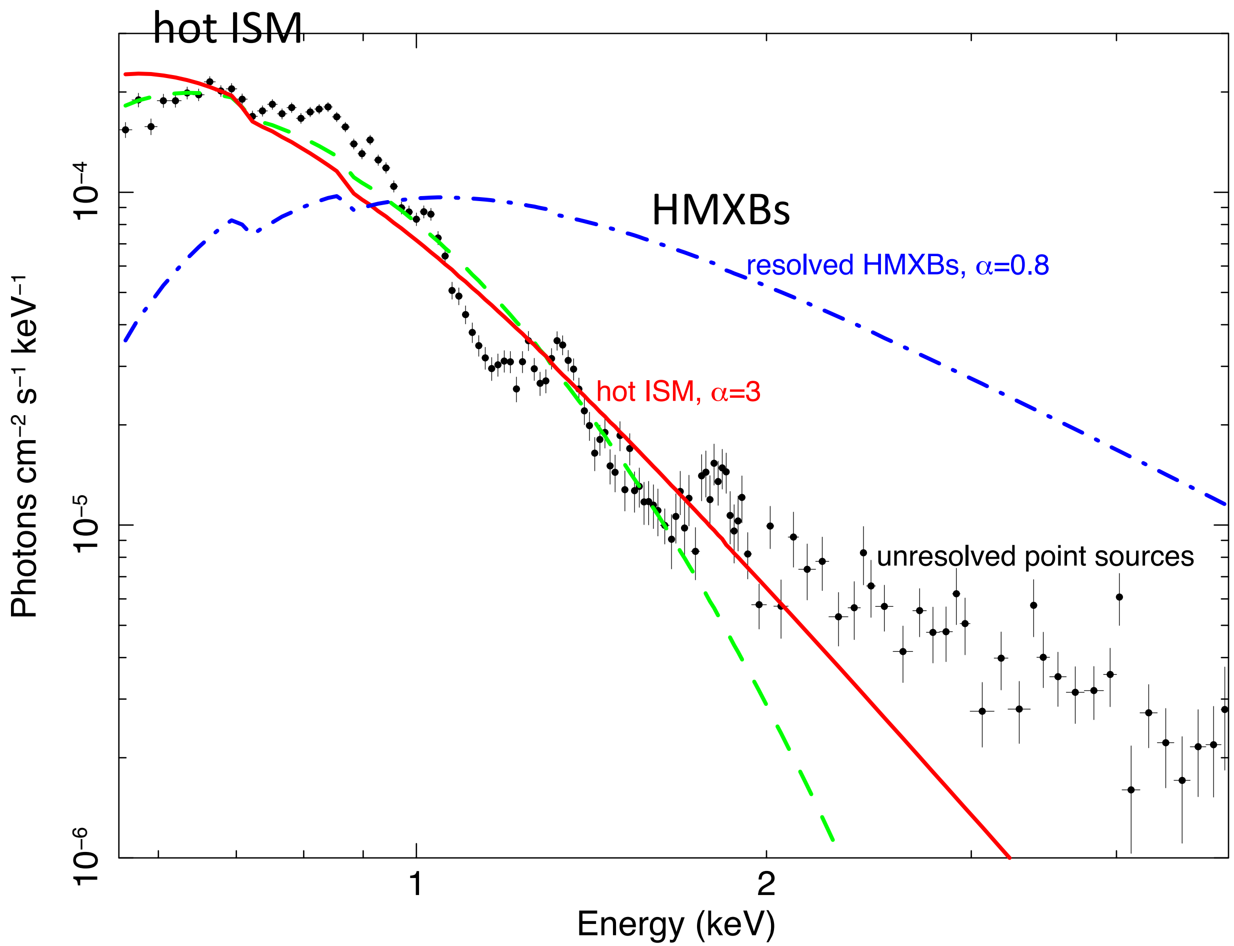
$$\lambda_X \approx 34\, \bar{x}_{HI}^{-1} \left(\frac{E_X}{0.5\ \mathrm{keV}} \right)^{2.6} \left(\frac{1+z}{15} \right)^{-2} \mathrm{comoving\ Mpc}\ ,$$

thus **the *patchiness* of the heating tells us about the X-ray SED**

Note that we only care about E_x <~ 2 keV. Higher energy photons a have mean free path longer than the Hubble length.

What could we expect?

Composite SEDs of local, star-forming galaxies

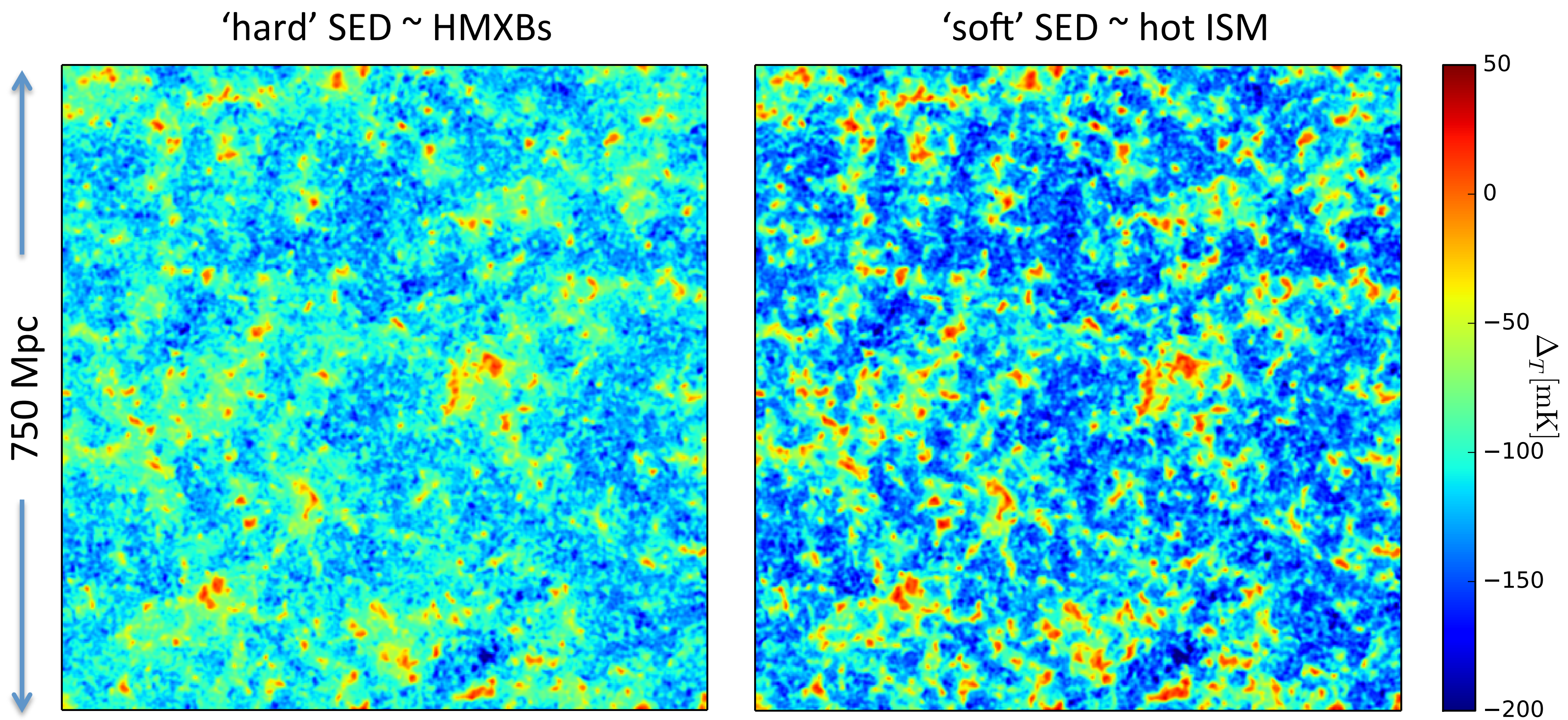


Pacucci, AM+ 2014

based on observations in Mineo+2012a,b

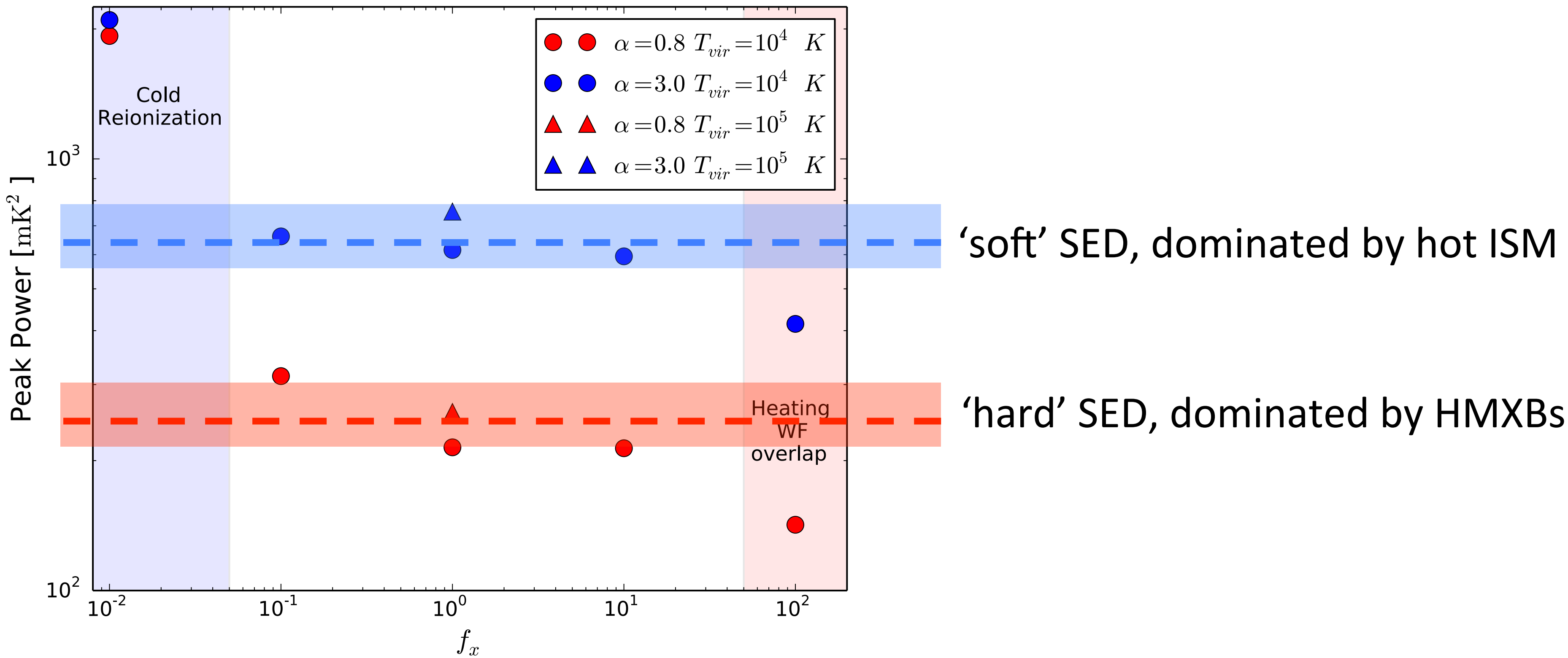
Luminosities of both hot ISM (soft) and HMXB (hard) scale with SFR

Softer SEDs result in more inhomogeous IGM heating



Pacucci, AM+ 2014

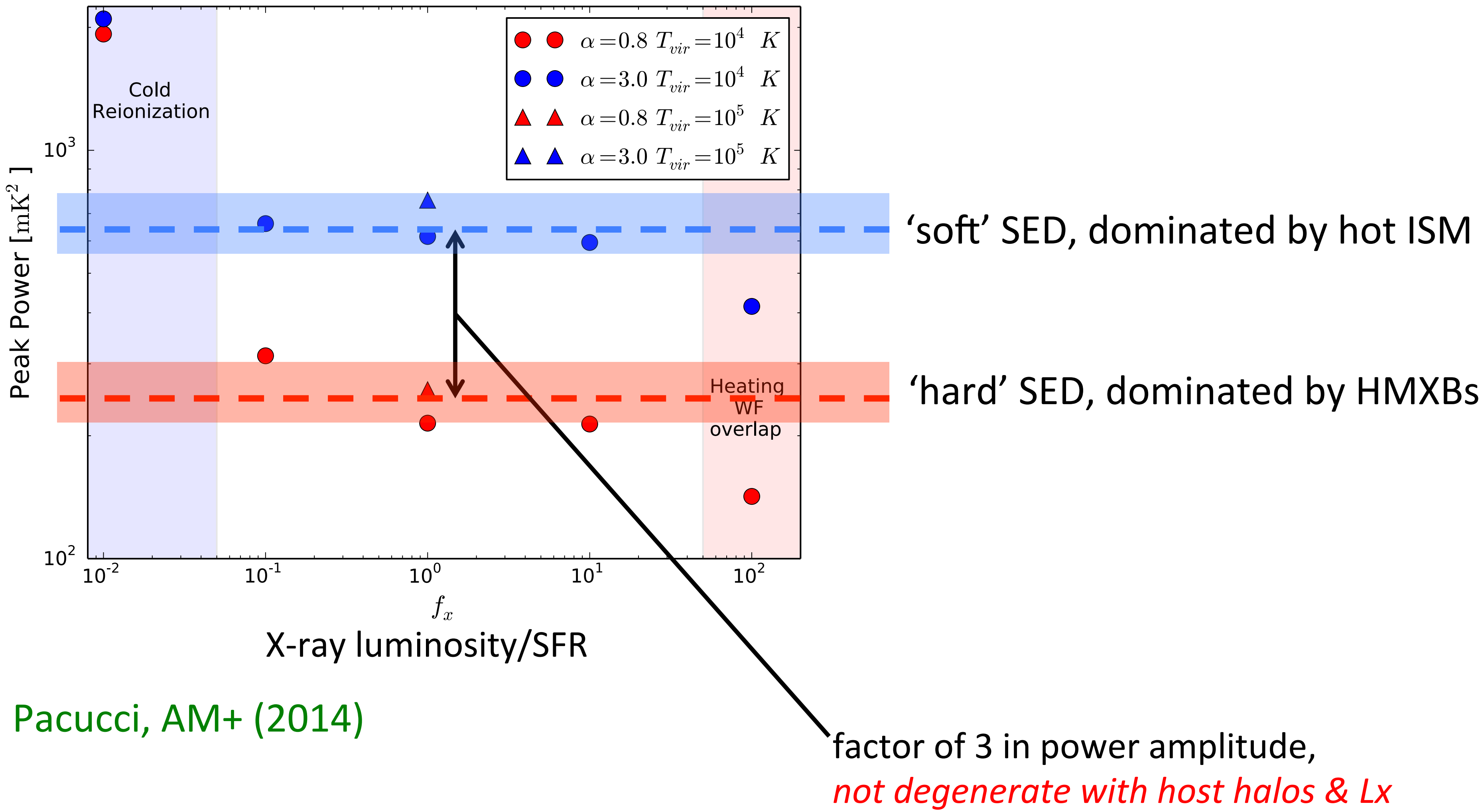
More inhomogeous heating means a higher 21cm power spectrum



X-ray luminosity/SFR

Pacucci, AM+ (2014)

Robustly extracting SED from 21cm fluctuations



Pacucci, AM+ (2014)

In addition to the first sources, the Cosmic Dawn also tells us about *physical cosmology*

Indirect probes of DM particles

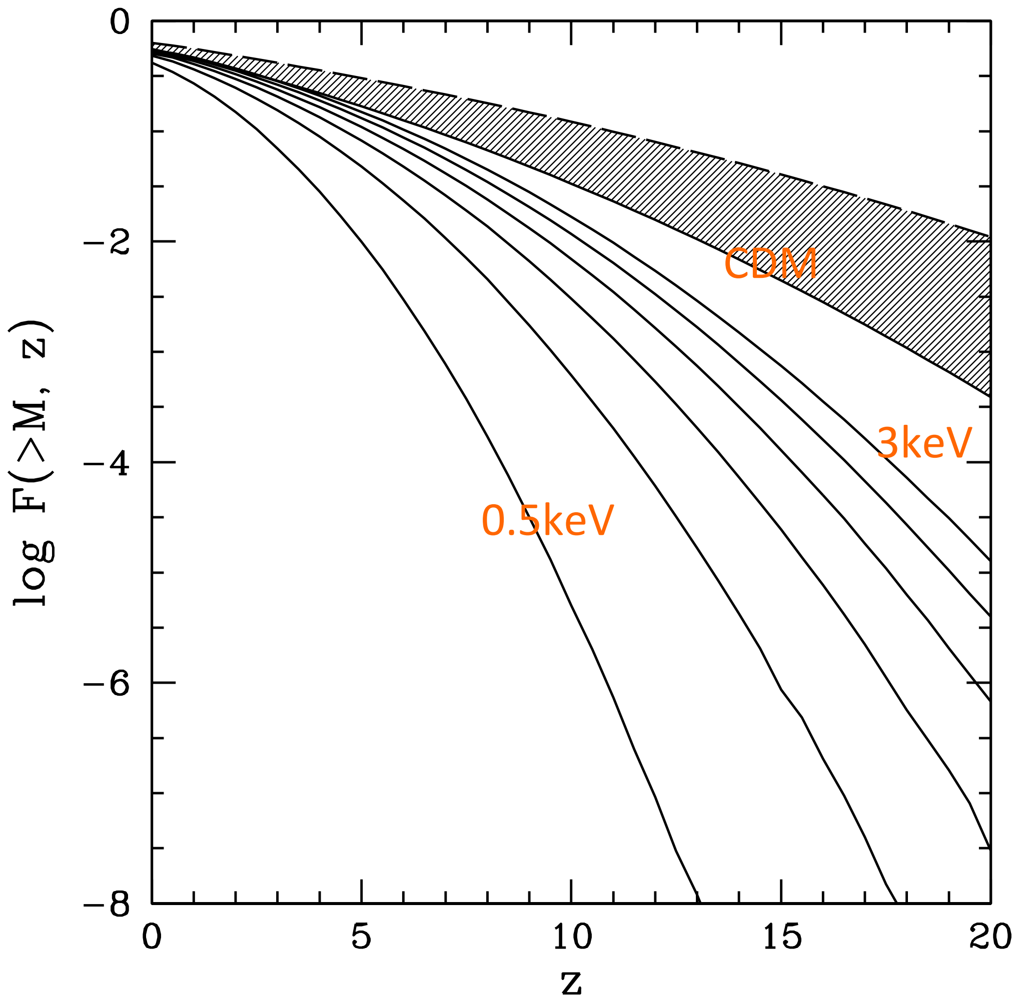
- CDM alternatives, like WDM, predict fewer small-mass halos

AND

- DM annihilations can drive an early, uniform heating

IGM thermal history is a powerful probe

High-z is the place to be

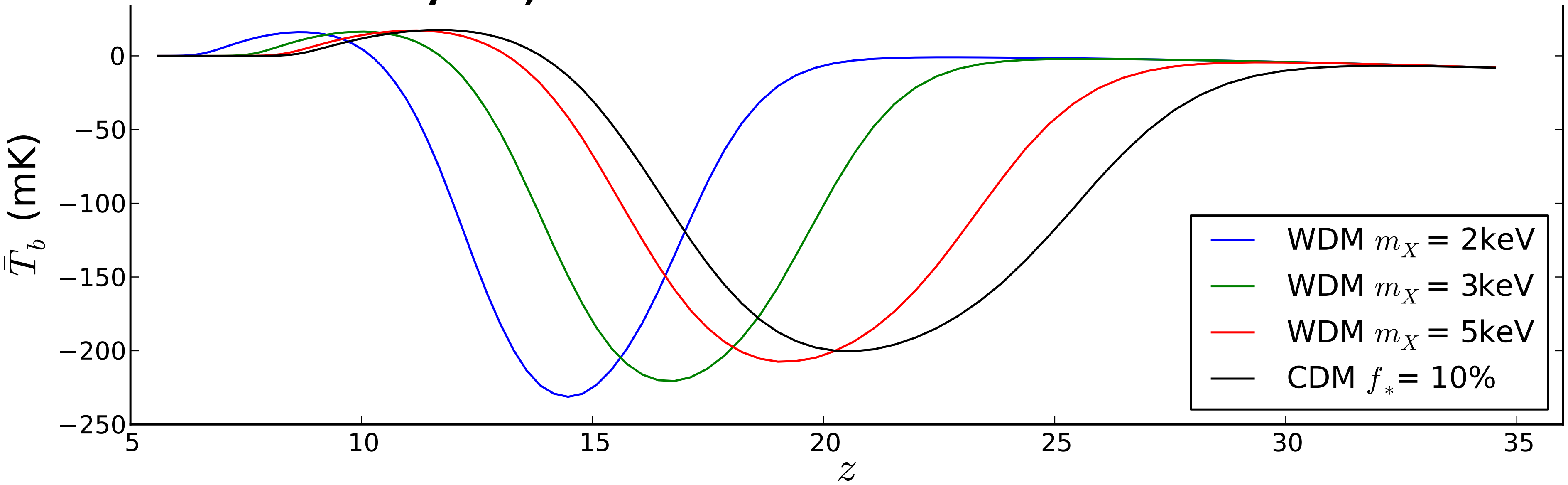


Mesinger+2005

Due to hierarchal structure formation, in WDM-like models, it is empty!

Global brightness temperature evolution

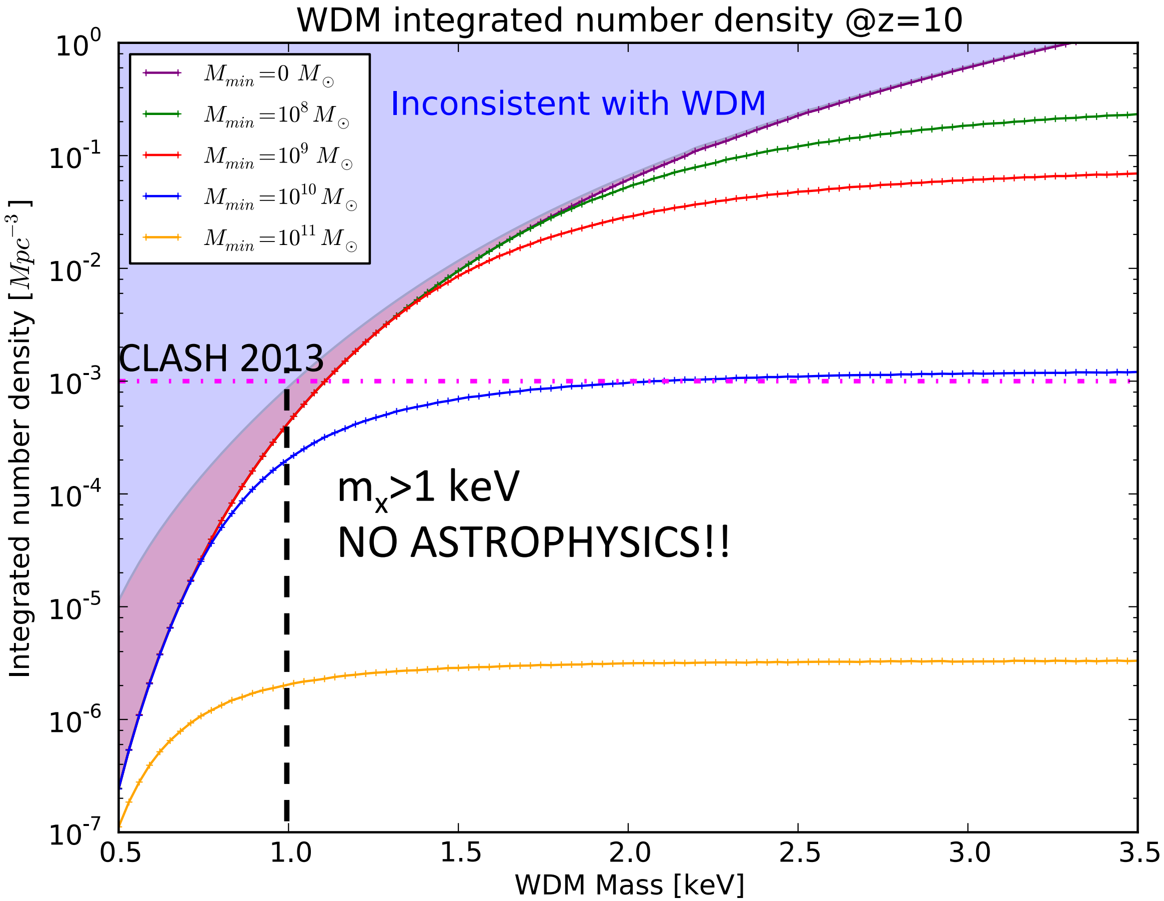
- From its suppression of halo abundances, the relevant epochs in WDM-like models are delayed, and then accelerated



Sitwell, AM+ (2014)

But this is degenerate with astrophysics…

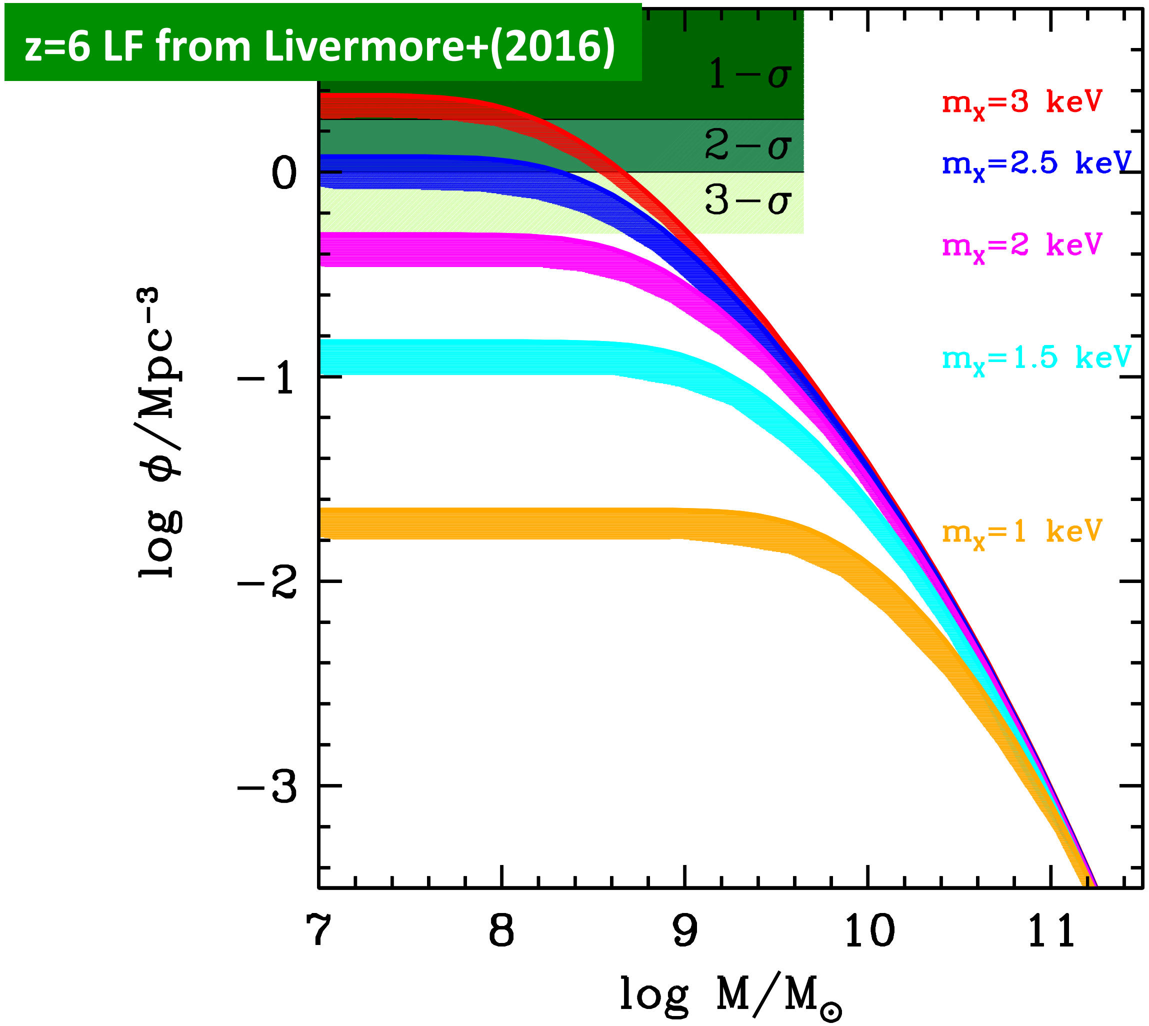
Direct galaxy observations are more robust…



No need to model M_h <-> L → zero degeneracy with astrophysics!! Pacucci, AM +(2013)

But this is degenerate with astrophysics…

Direct galaxy observations are more robust…

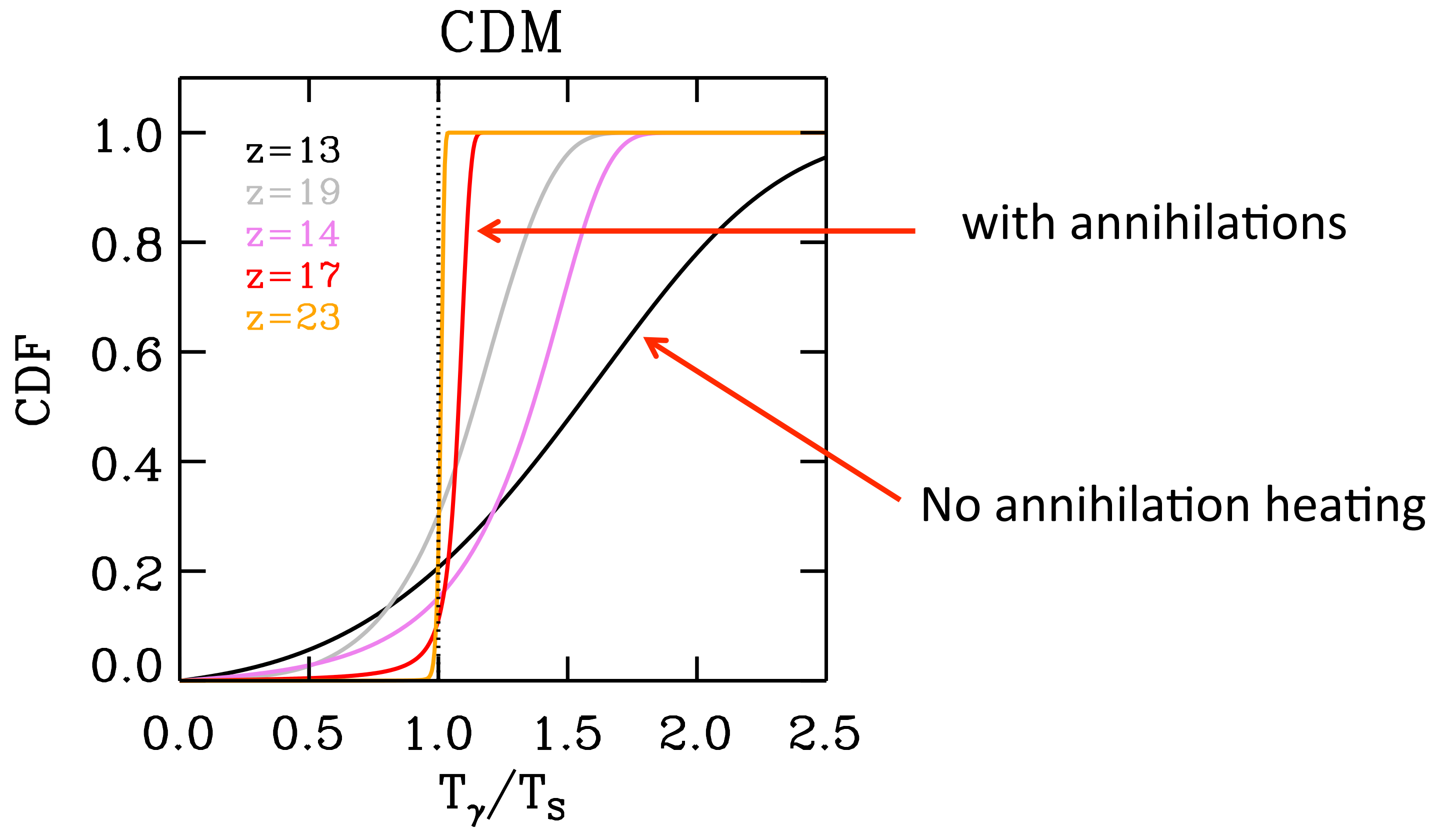


Menci+(2016)

More robust probe: direct heat injection from CDM annihilations

DM heating is more uniform than astrophysical

CDM, annihilating 10GeV Bino, thermal cross-sec

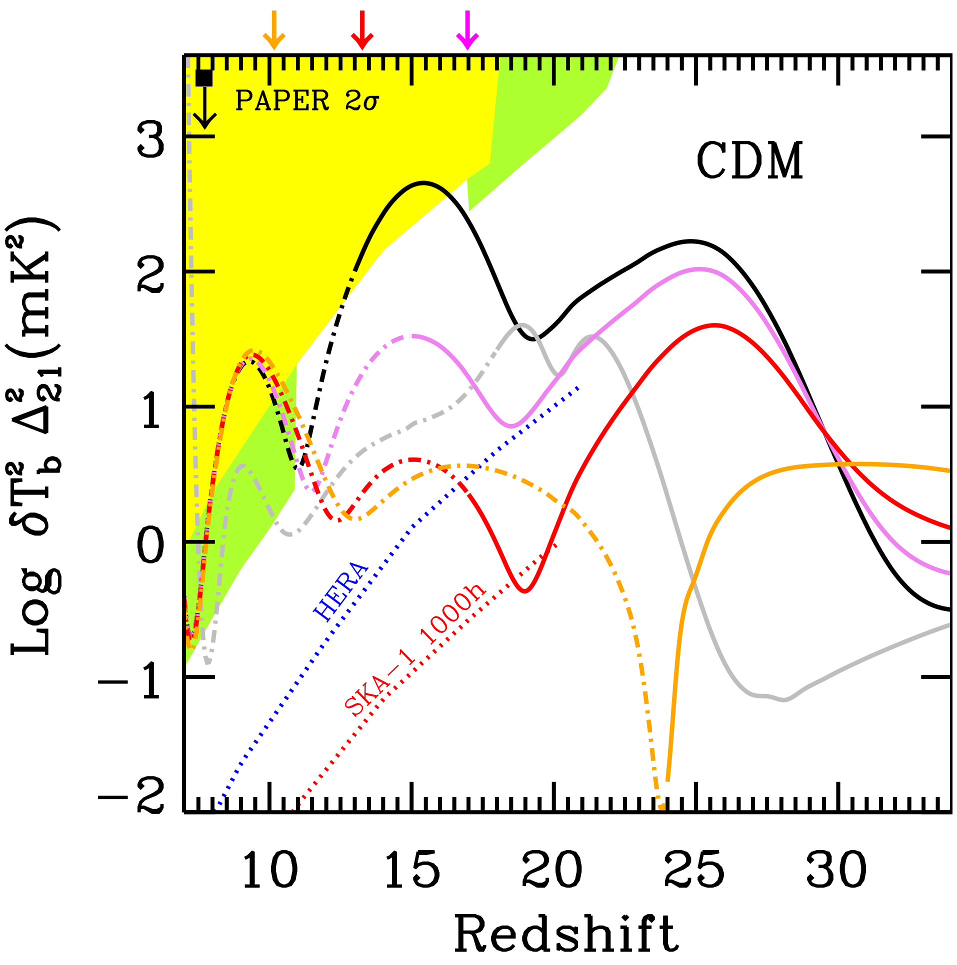


Evoli, AM+ (2014)

see also Lopez-Honorez+2016

This cannot be reproduced with reasonable astrophysics

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



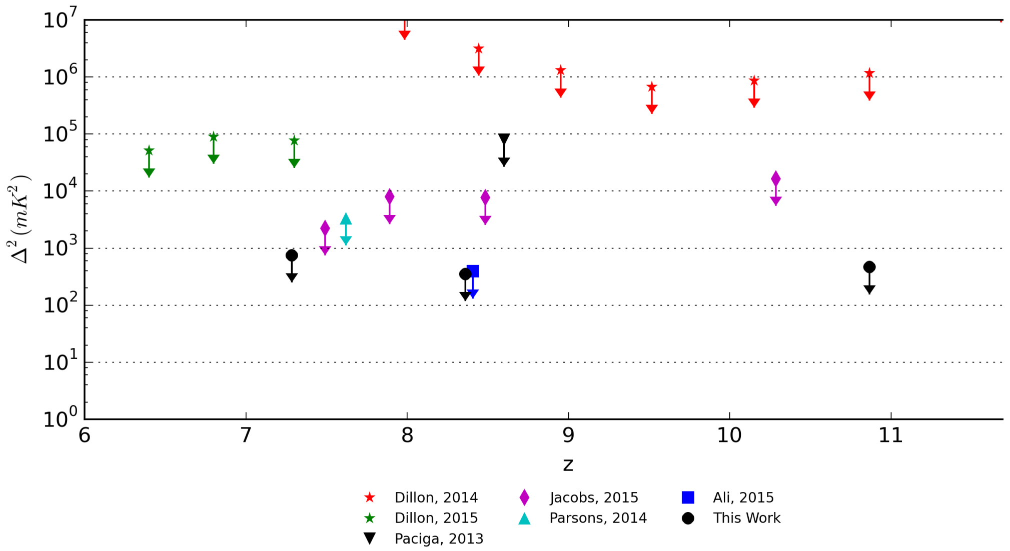
Peak is in **emission**!
Cannot be reproduced with astrophysics!!!

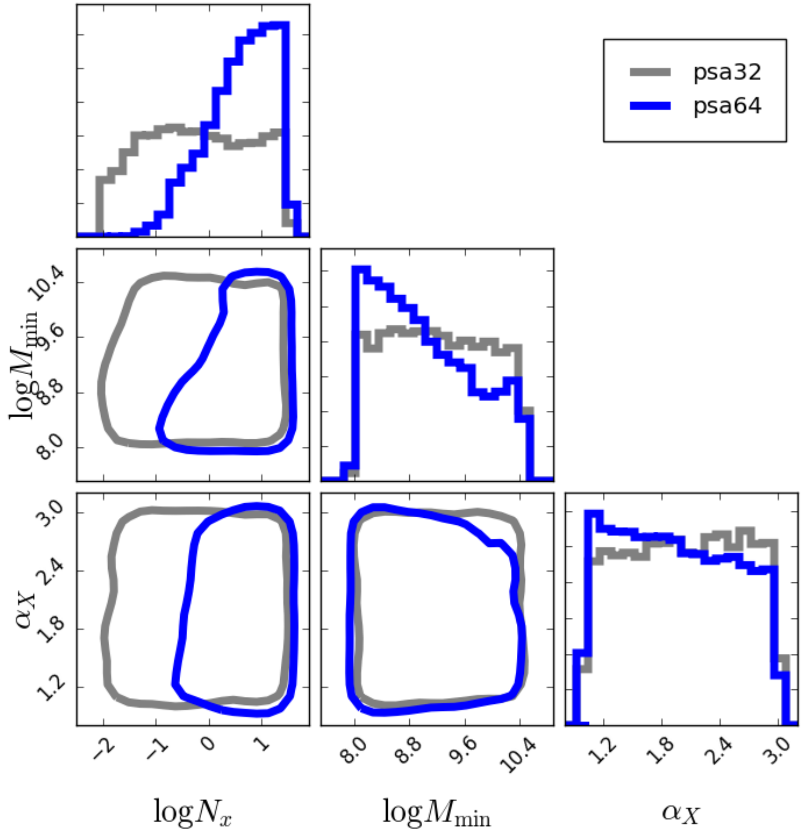
Evoli, AM+ (2014)
see also Lopez-Honorez+2016

The time is now!

- 1^{st} gen. interferometers are already taking data, ruling-out extreme models with no heating (Ali+2015, Pober+2015, Greig & AM 2015, Zaroubi+ in prep)

21-cm power upper limits on k~0.1 /Mpc scales

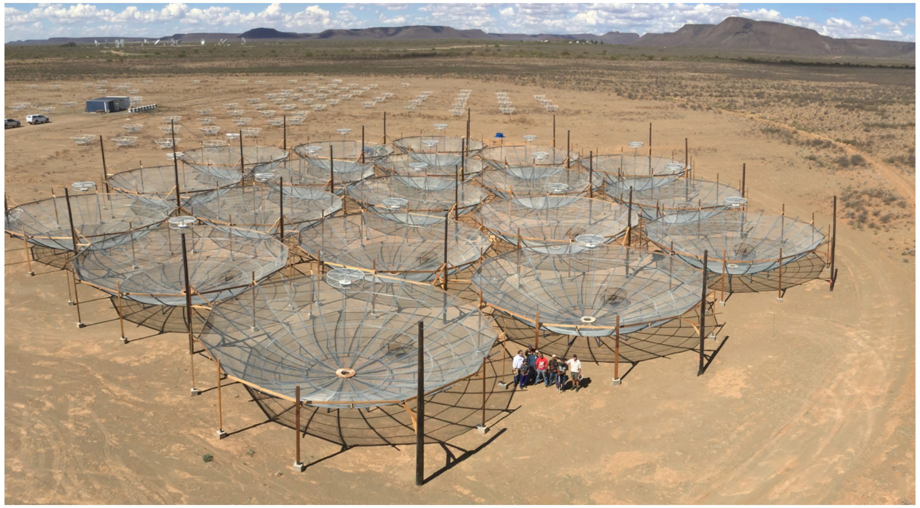




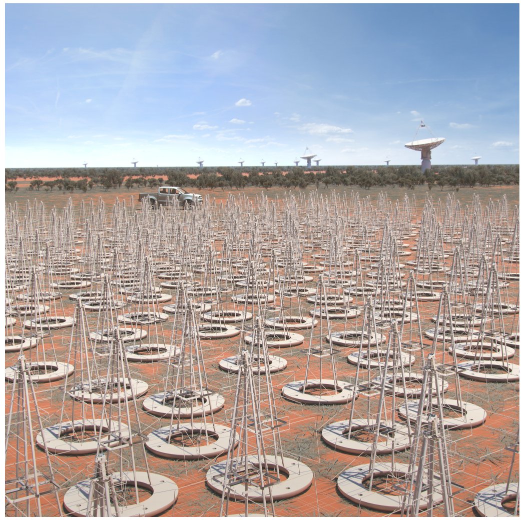
Kolopanis+ in prep
Jacobs, AM+ in prep

The time is now!

- 1st gen. interferometers are already taking data, ruling-out extreme models with no heating (Ali+2015, Pober+2015, Greig & AM 2015, Zaroubi+ in prep)
- 2nd gen. interferometers, HERA & SKA1, are coming in the next few years, bringing high S/N detections



first 19 of planned 350 HERA dishes



rendering of SKA1-Low

Conclusions

- We now know roughly when reionization occurred, but do not know anything about the astrophysical sources and sinks.
- The properties of sources and sinks are encoded in the 3D EoR structure → 21CMMC will allow us to quantify what we can learn from current and upcoming 21-cm interferometry observations
- The 21-cm signal is sensitive also to the thermal state of the gas → Epoch of Heating (new frontier!!!)
  - The redshift (i.e. frequency) at which the 21-cm power spectrum is at its peak tells us which halos hosted the first sources and what were their X-ray luminosities.
  - The amplitude of this peak tells us about the X-ray SED escaping the first galaxies: type of source (HMXBs, hot ISM) + absorption within the host galaxy.
  - More exotic heating scenarios like 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!).
- What more can we learn??