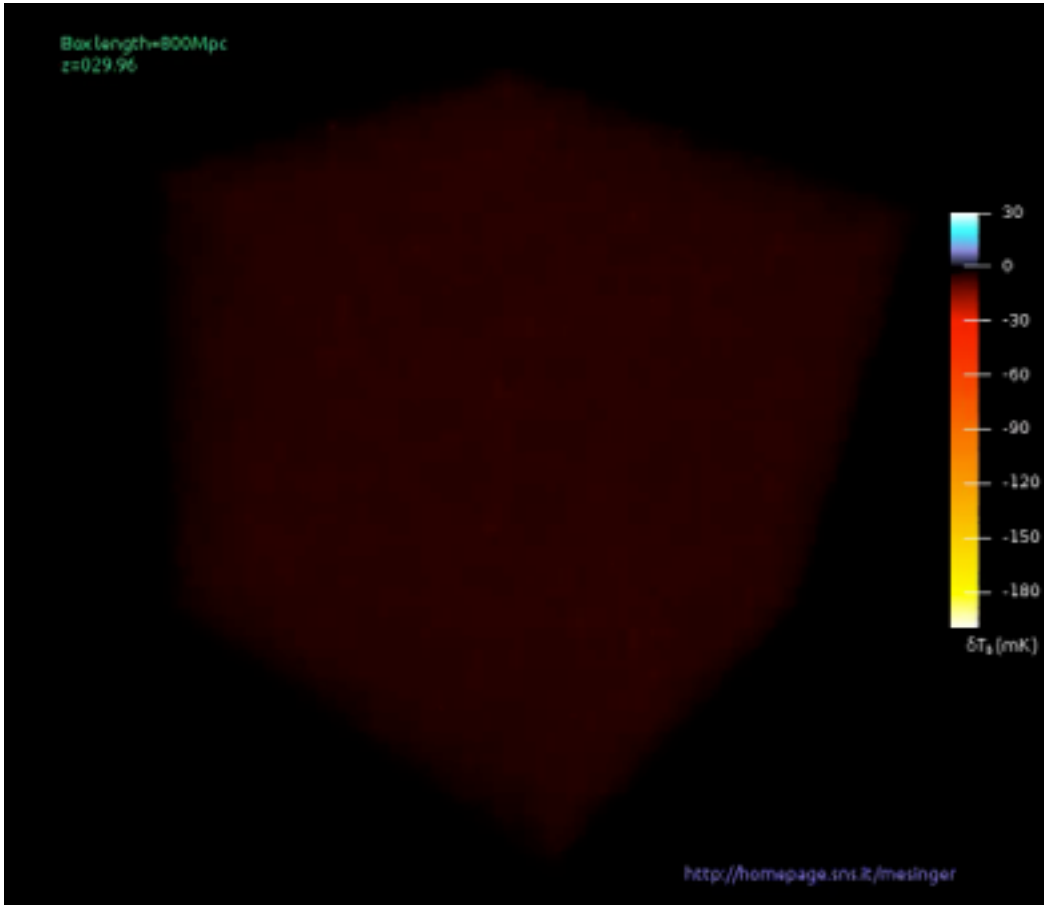
Illuminating the Cosmic Dawn



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

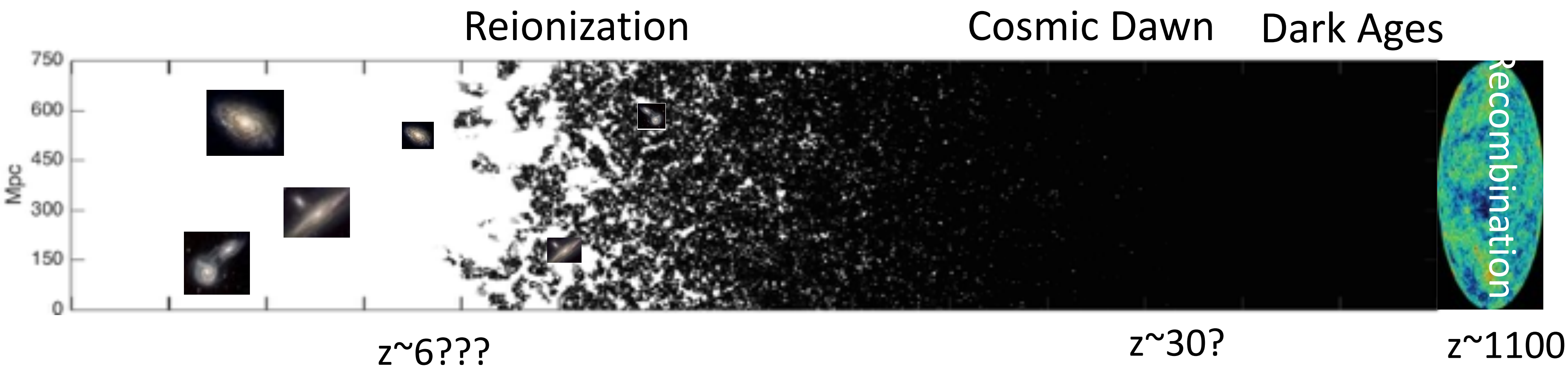
Andrei Mesinger

AiDA

SCUOLA
NORMALE
SUPERIORE

erc
European Research Council

Why Cosmic Dawn?



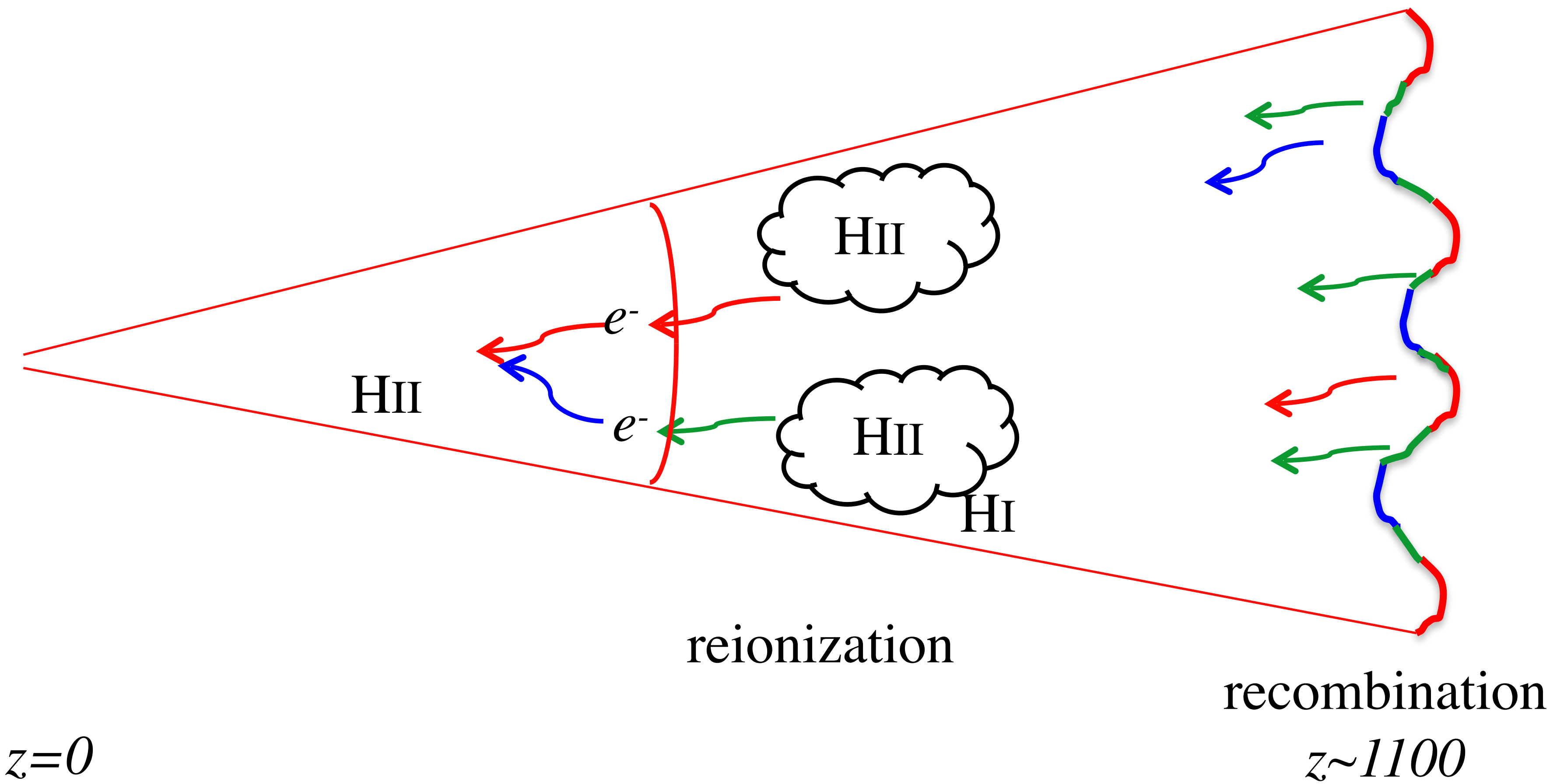
Potentially some fundamental questions: ***When*** *did the first generations of galaxies form?* ***What*** *were their properties?* ***How*** *did they interact with each other and the intergalactic medium? What is the structure of the intergalactic medium? What is the thermal and ionization history of the baryons?*

Outline

- What we know now…
  - Clues to the timing of reionization from galaxies, QSOs and the CMB
- What we will know soon…
  - The full picture from the cosmic 21 cm signal!

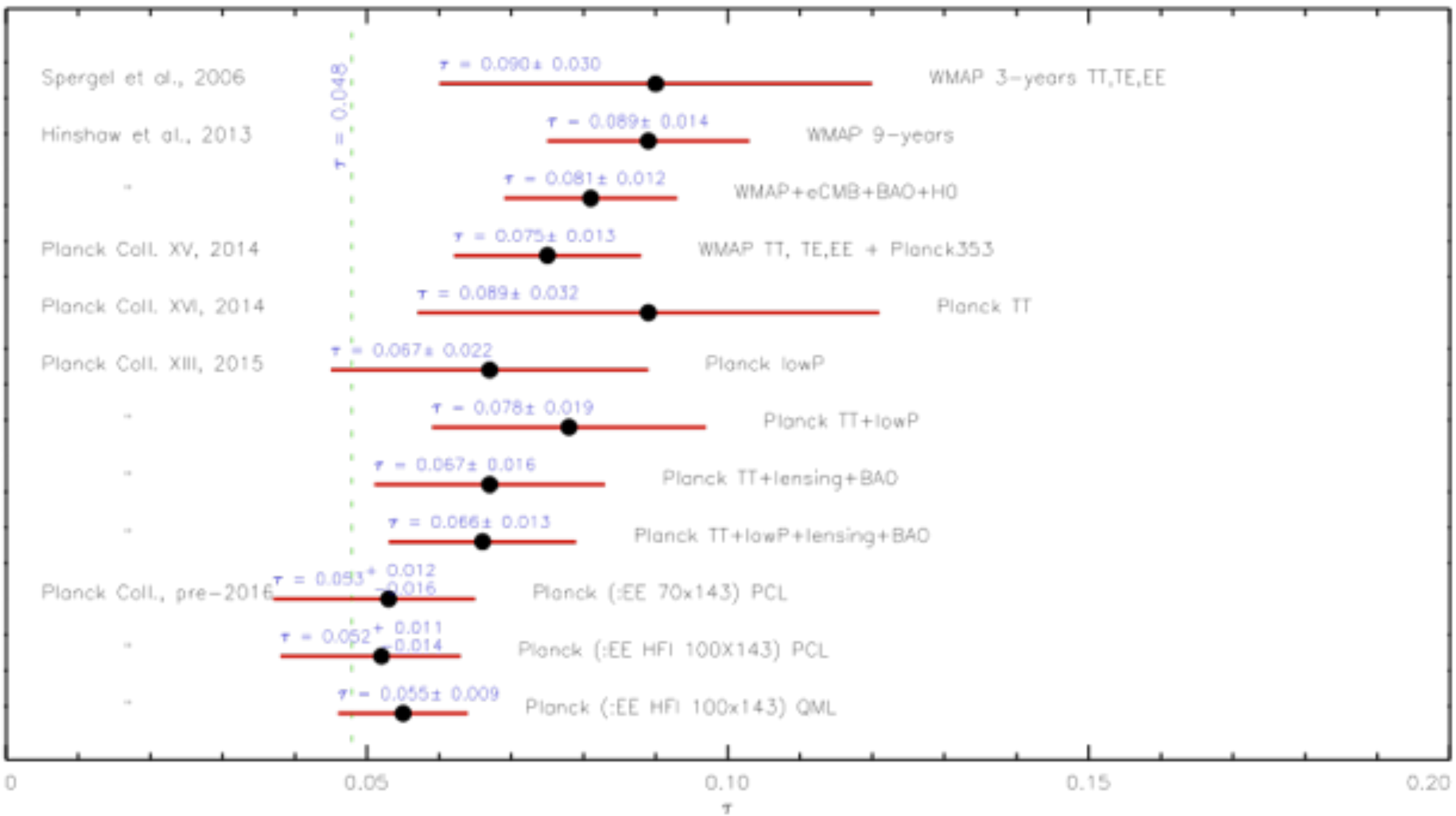
When?

- Two main classes of probes
  1. **Integral CMB constraints (e.g. τ_e, kinetic SZ)**



History of Thompson scattering optical depth measurements

WMAP1 2003

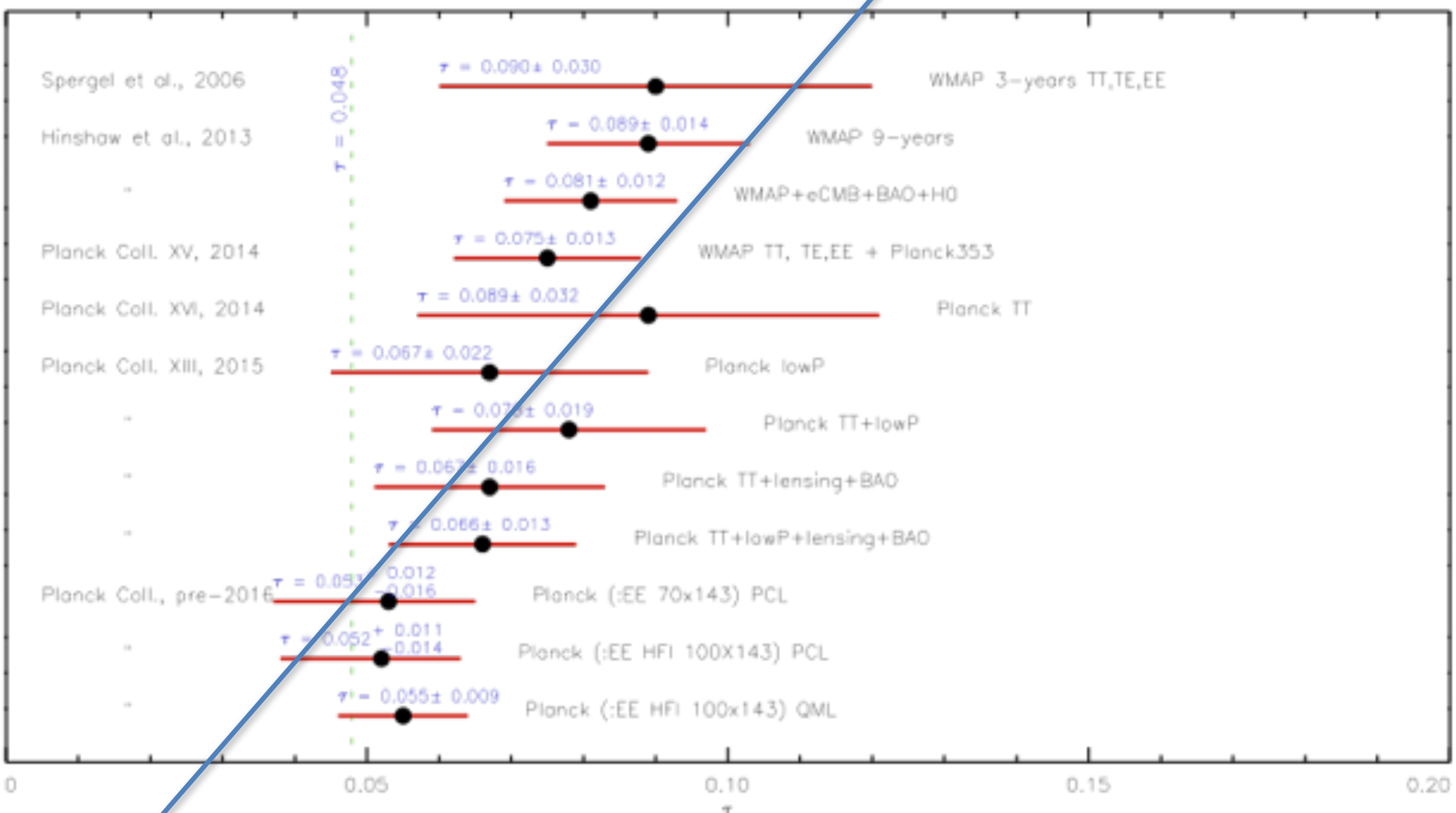


<— later reionization

Planck 2016

History of Thompson scattering optical depth measurements

WMAP1 2003



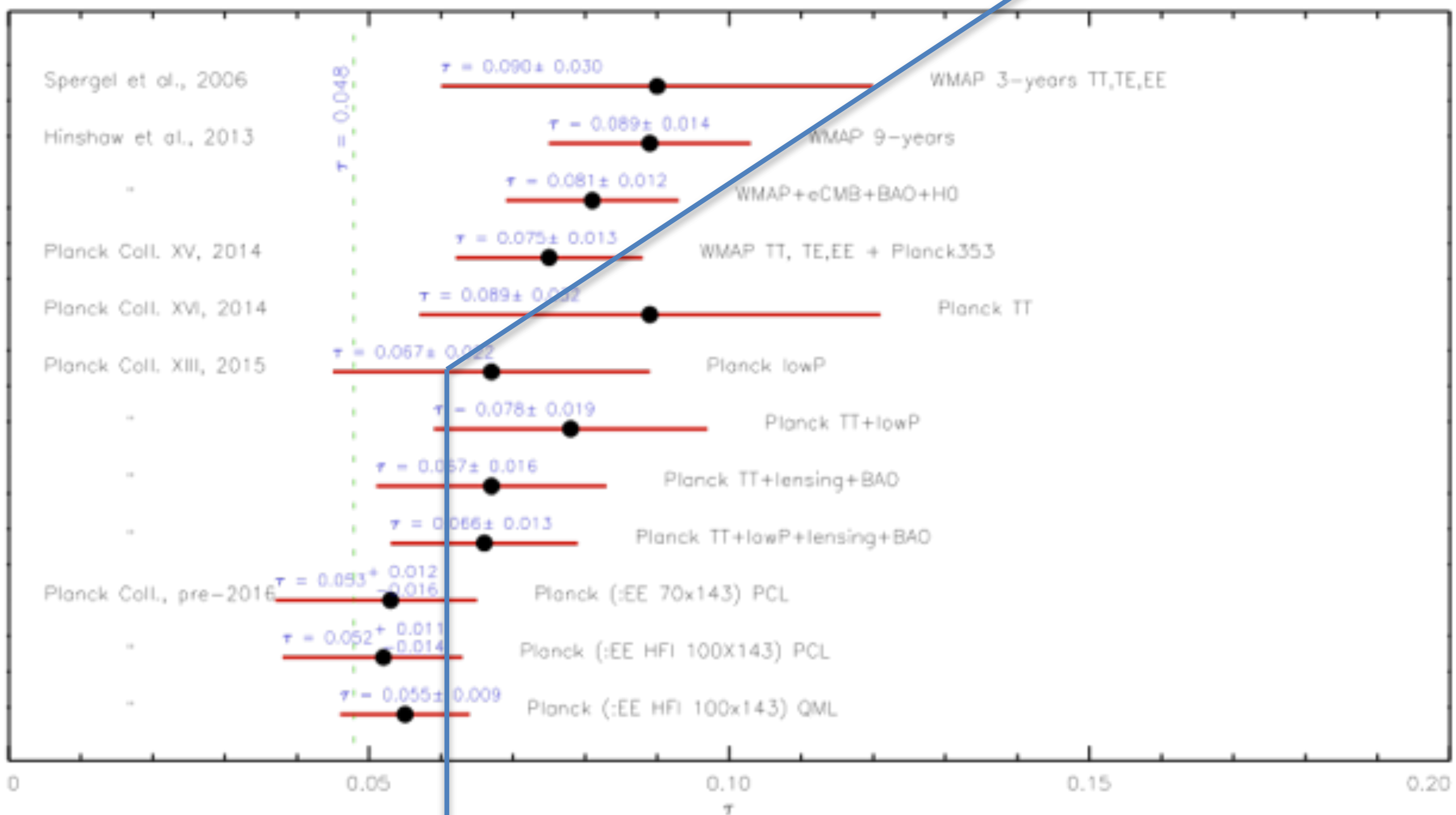
<— later reionization

~2020 – negative tau: Reionization never happened!

Planck 2016

History of Thompson scattering optical depth measurements

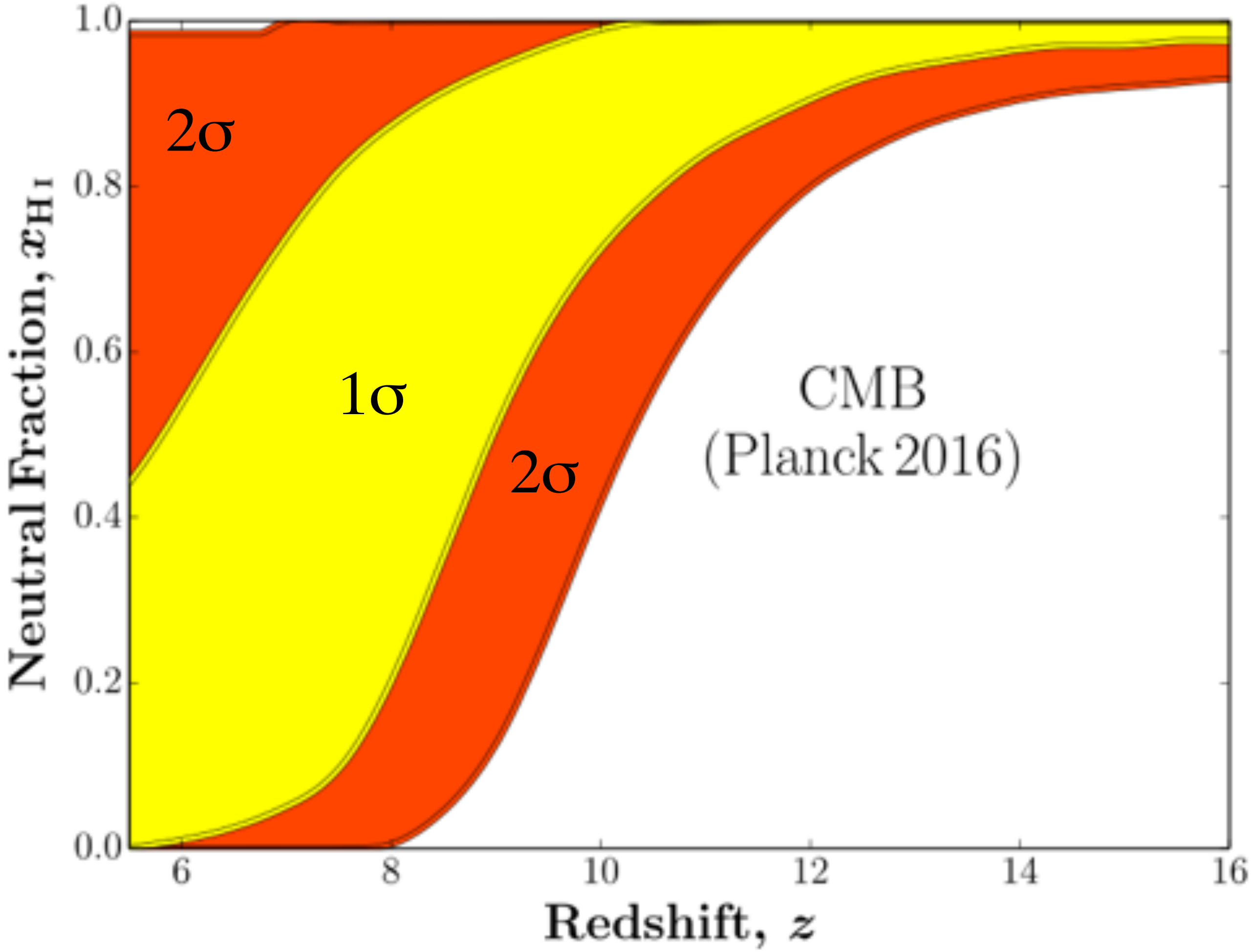
WMAP1 2003



<— later reionization

Planck 2016

What does this tell us about *when* reionization occurred?



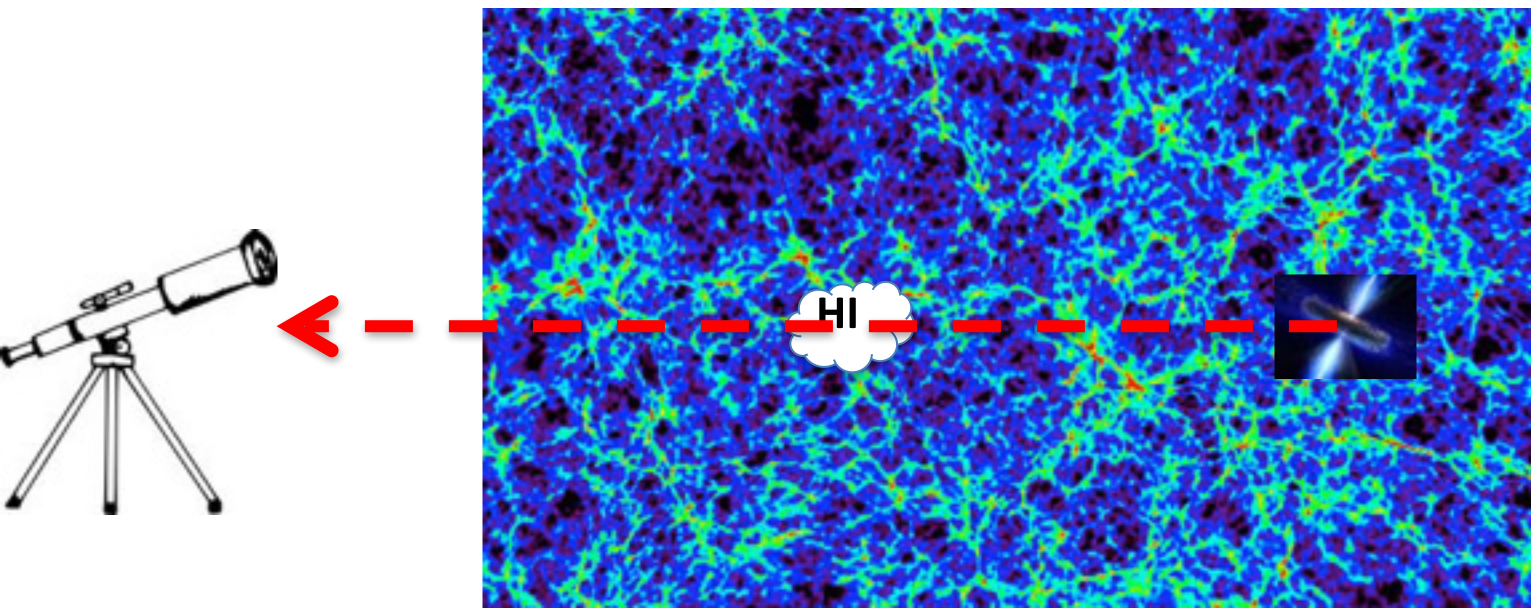
Greig & AM 2016

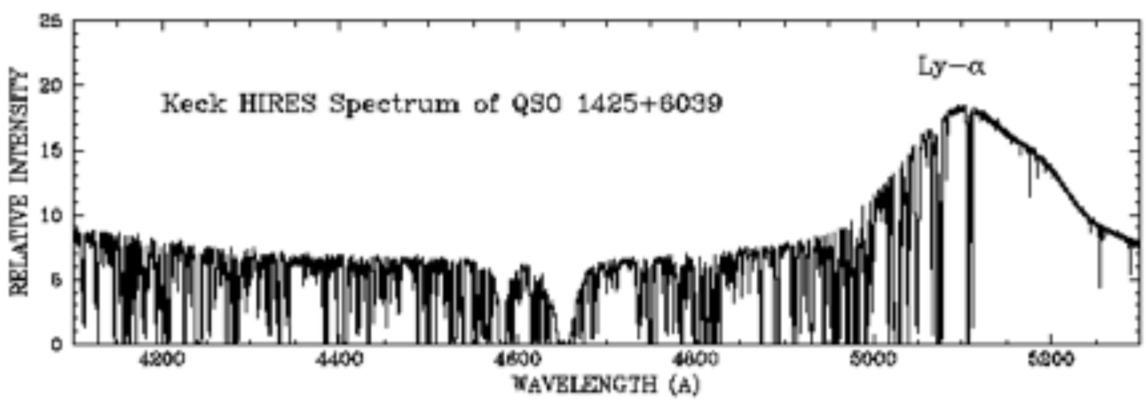
When?

- Two main classes of probes
  1. Integral CMB constraints (e.g. τ_e, kinetic SZ)
  2. **Astrophysical 'flashlights' (e.g. high-z galaxies, QSOs)**

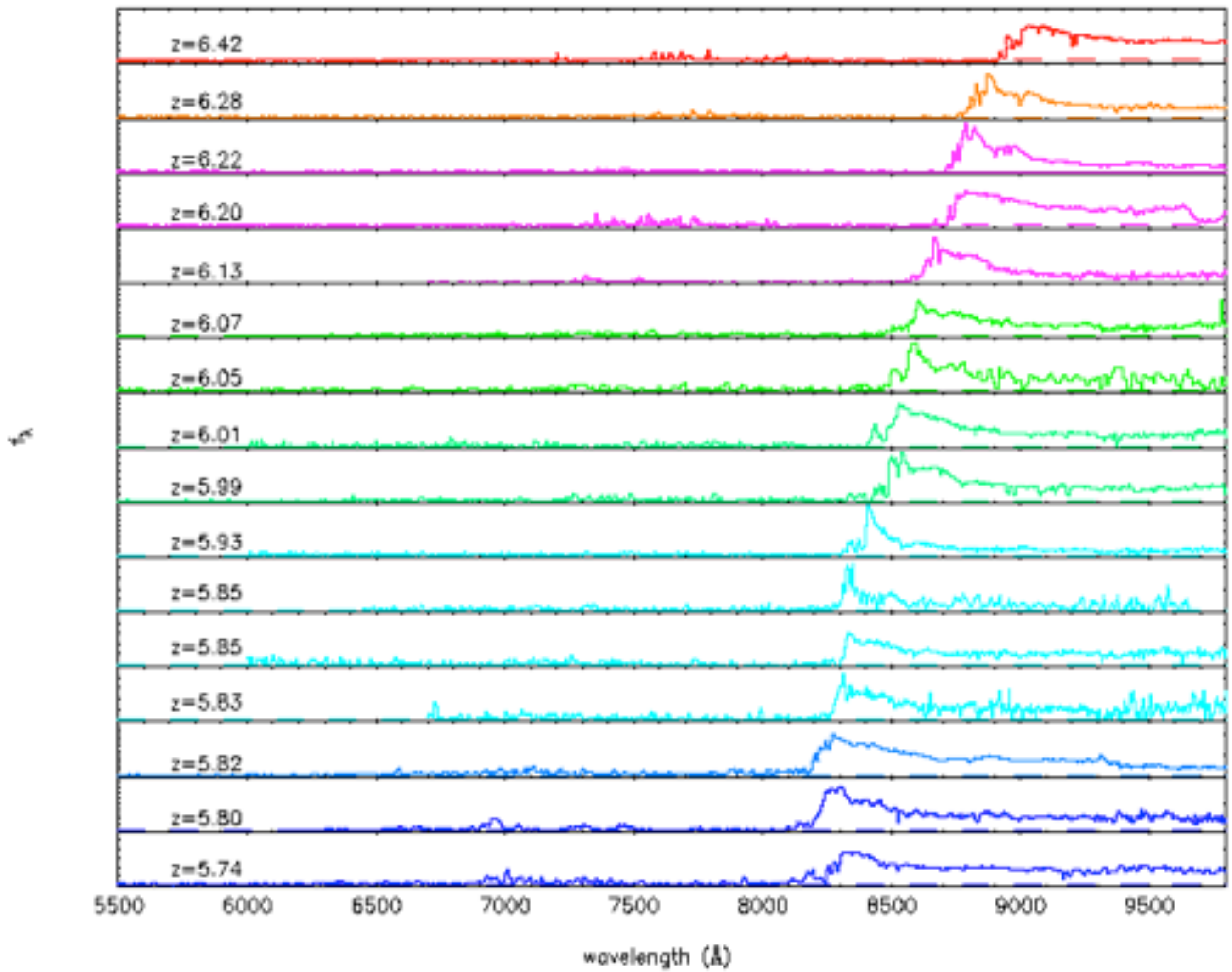
Astrophysical flashlights: Lyα

Post-reionization IGM





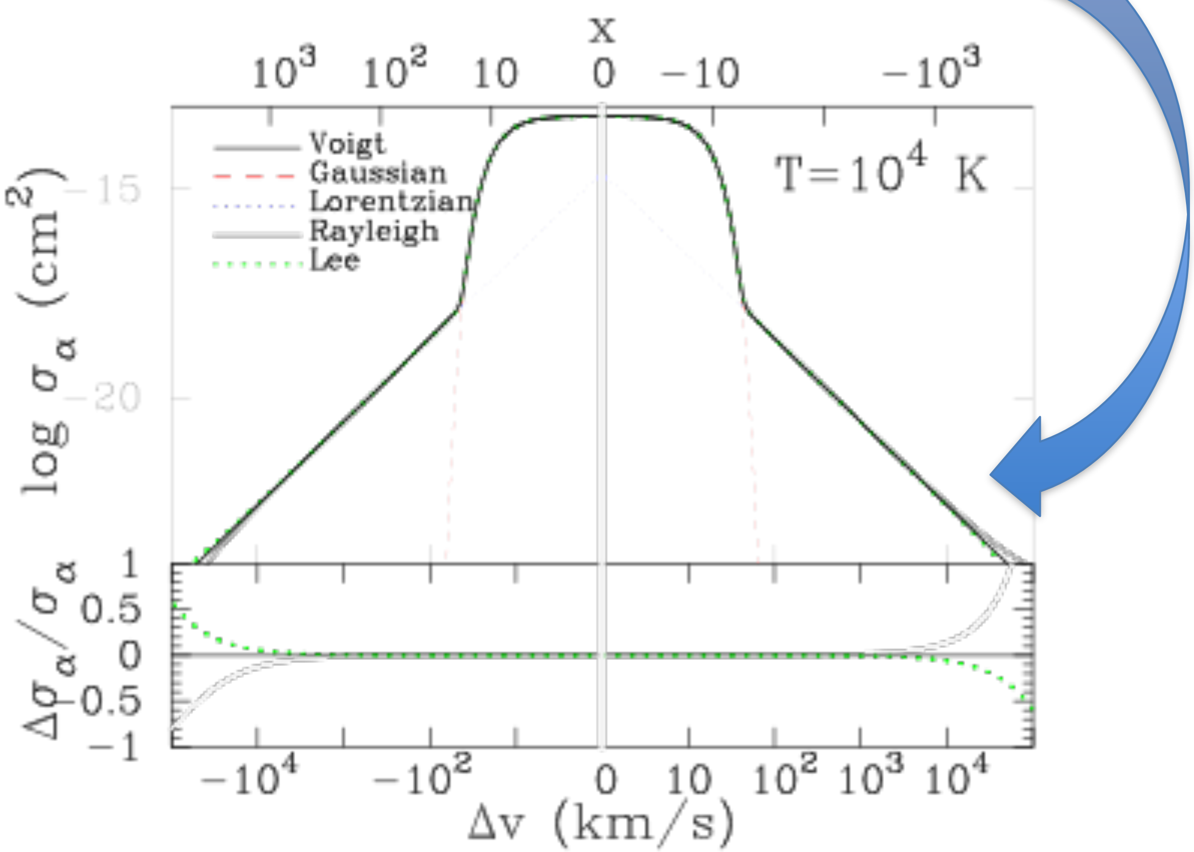
We can't directly observe the EoR in Lyα



Fan+ (2006)

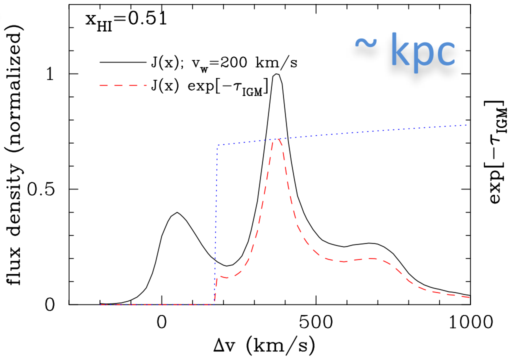
Lyα forest saturates at z>5, when the Universe becomes too dense.
Even trace amounts of HI, x_{HI} ~> 10^{-5} result in no flux being detected in the forest.

But... *damping wing*!



Dijkstra 2014

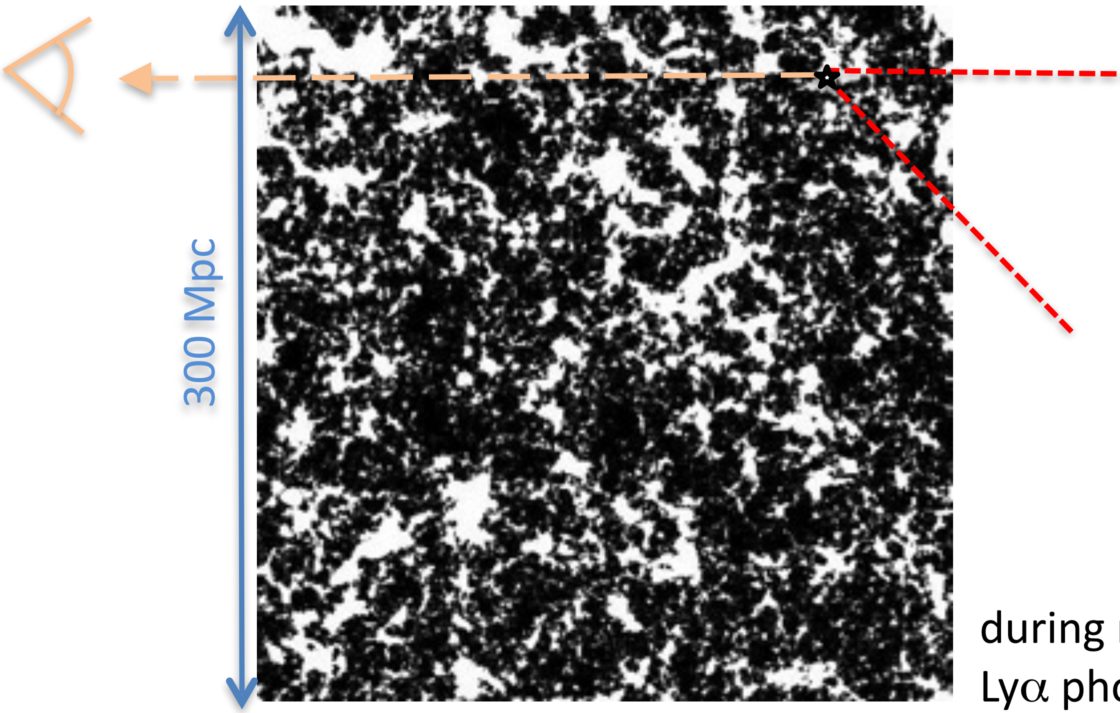
Lyα damping wing absorption as a probe of the EoR

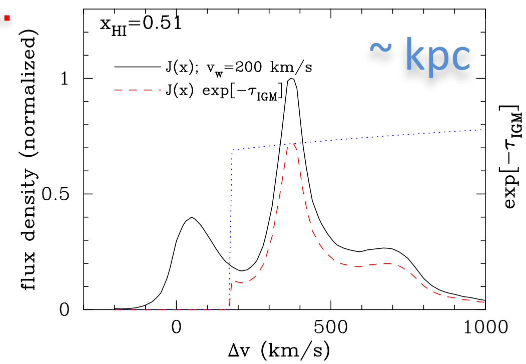


e.g. Dijkstra, AM+2011

Lyman alpha line emerging from galaxies is shaped by the ISM/CGM (winds, infall, dust, geometry..)

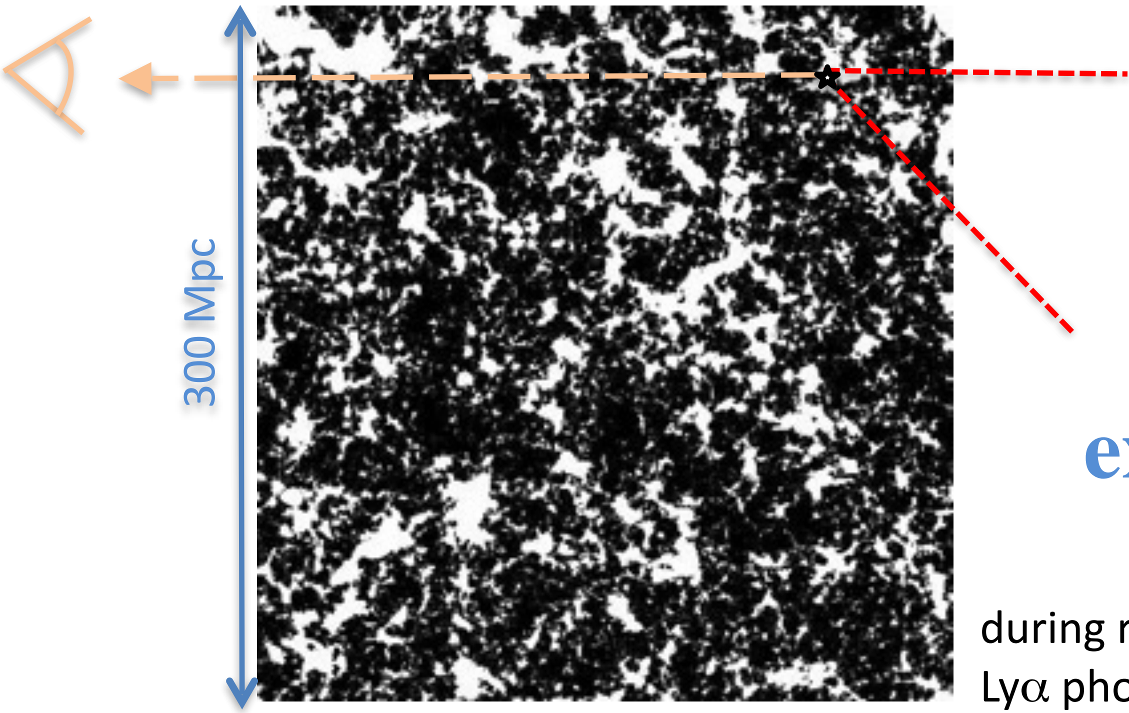
Lyα damping wing absorption as a probe of the EoR

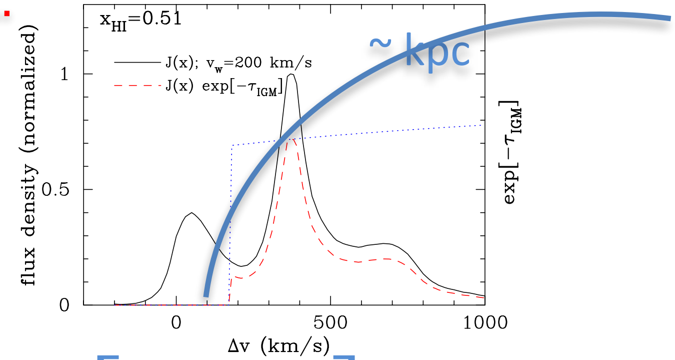




during reionization, cosmic HI patches absorb Lyα photons in the damping wing of the line

Lyα damping wing absorption as a probe of the EoR



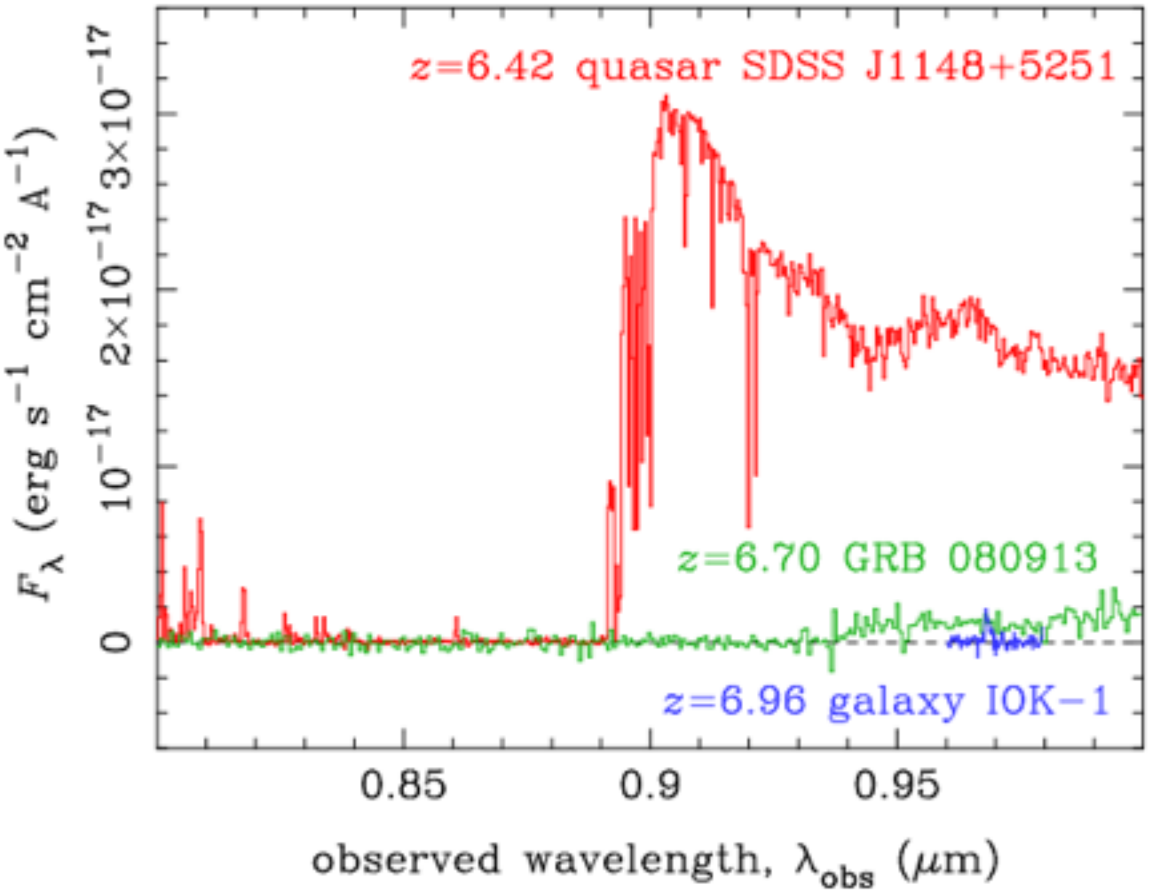


$$\exp[-\tau_{reion}]$$

during reionization, cosmic HI patches absorb Lyα photons in the damping wing of the line

QSOs: the brightest cosmic flashlights

$f = A e^{-\tau}$



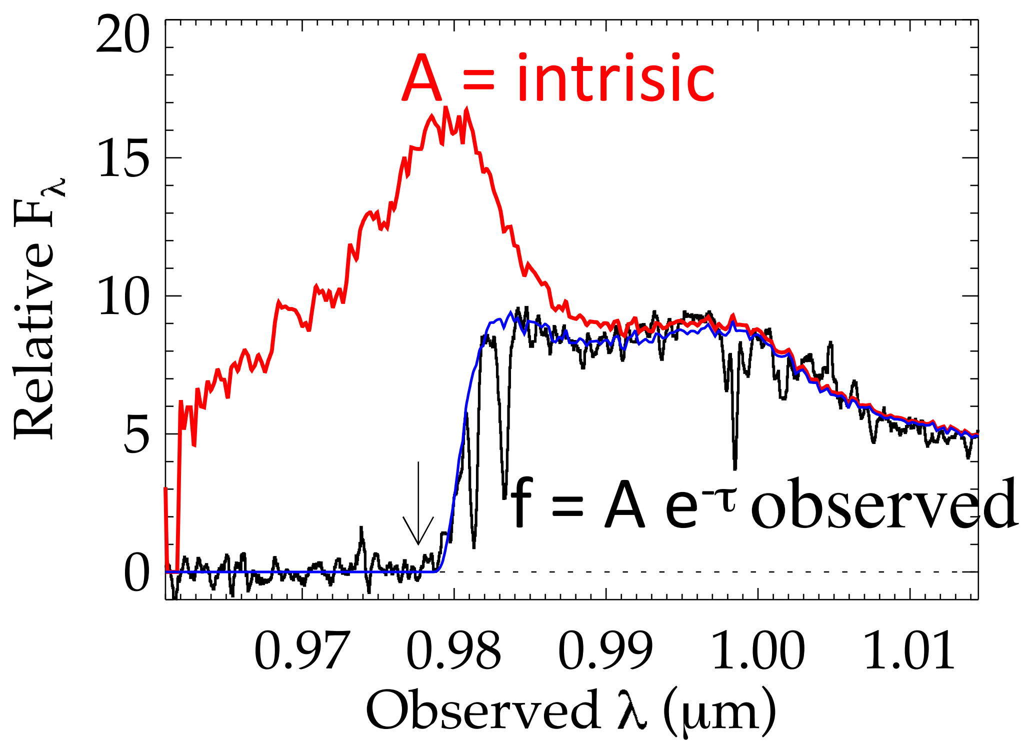
QSO spectra can be analyzed ***individually***, unlike galaxies which require a statistically significant sample

figure courtesy of D. Mortlock

Damping wing in QSO spectra

- *Caution:* We must *jointly* sample the uncertainties in the **intrinsic (pre IGM absorption) QSO emission** together with the **sightline to sightline scatter of the EoR**

z=7.1 spectra



Simcoe+2012

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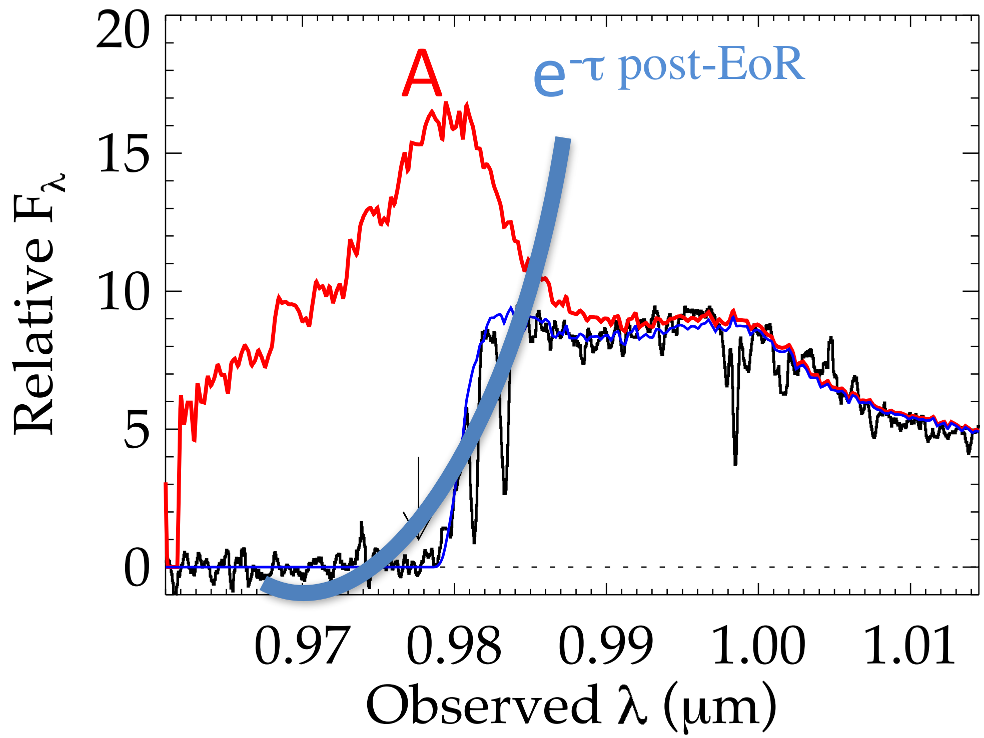

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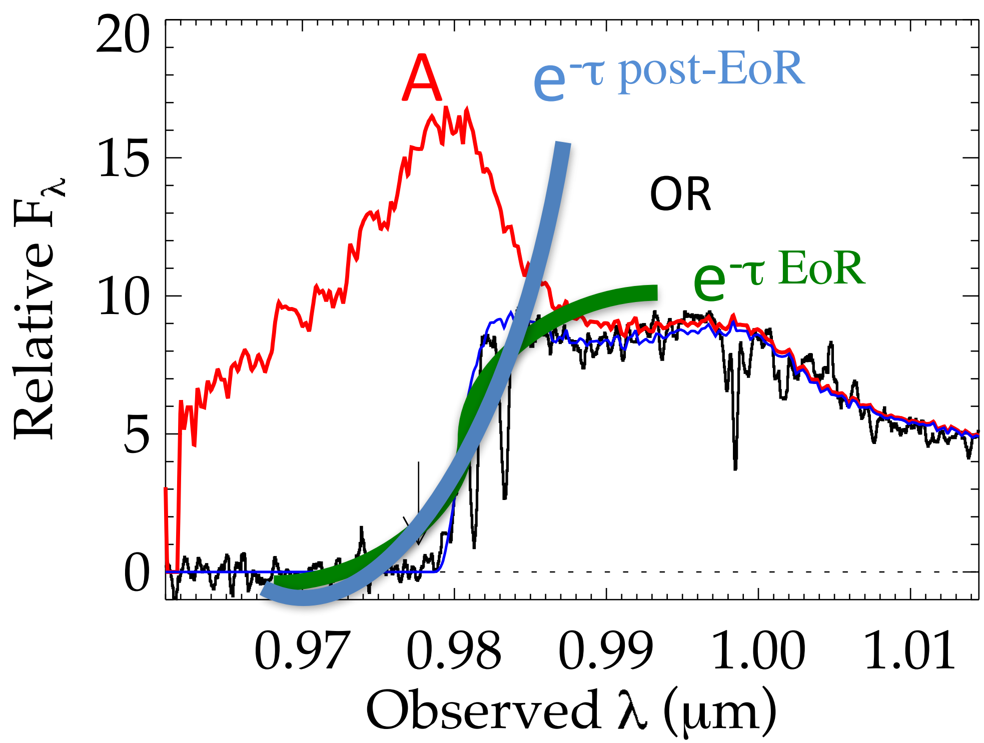

z=7.1 spectra

Simcoe+2012

Analysis of z=7.1 QSO ULASJ1120

- **Step 1:** reconstruct the intrinsic Lyα emission of ULASJ1120 by sampling a covariance matrix of emission line properties built from ~1700 high S/N BOSS spectra (Greig, AM+ 2016a)

Analysis of z=7.1 QSO ULASJ1120

- **Ste** :
  ULA
  em s/
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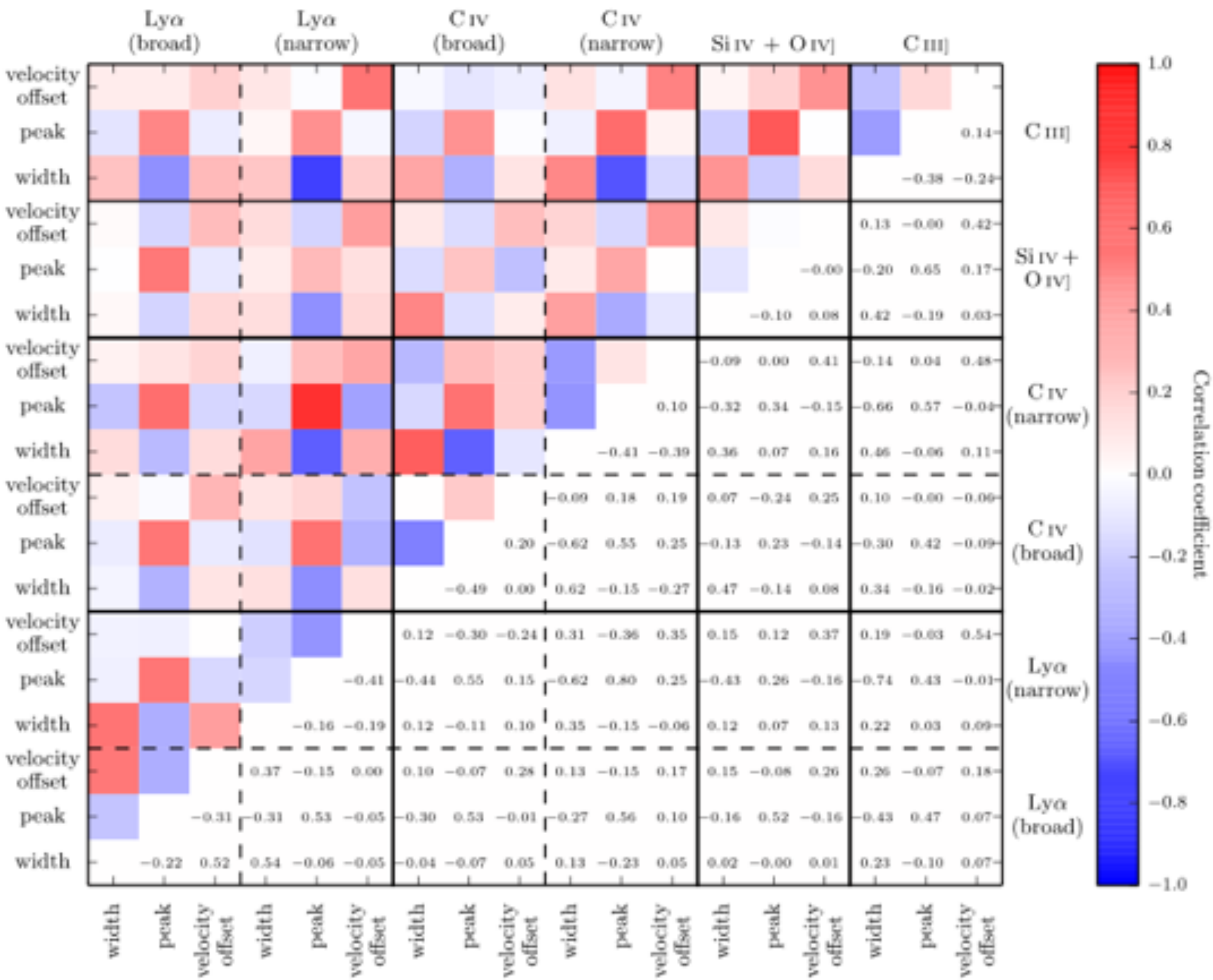


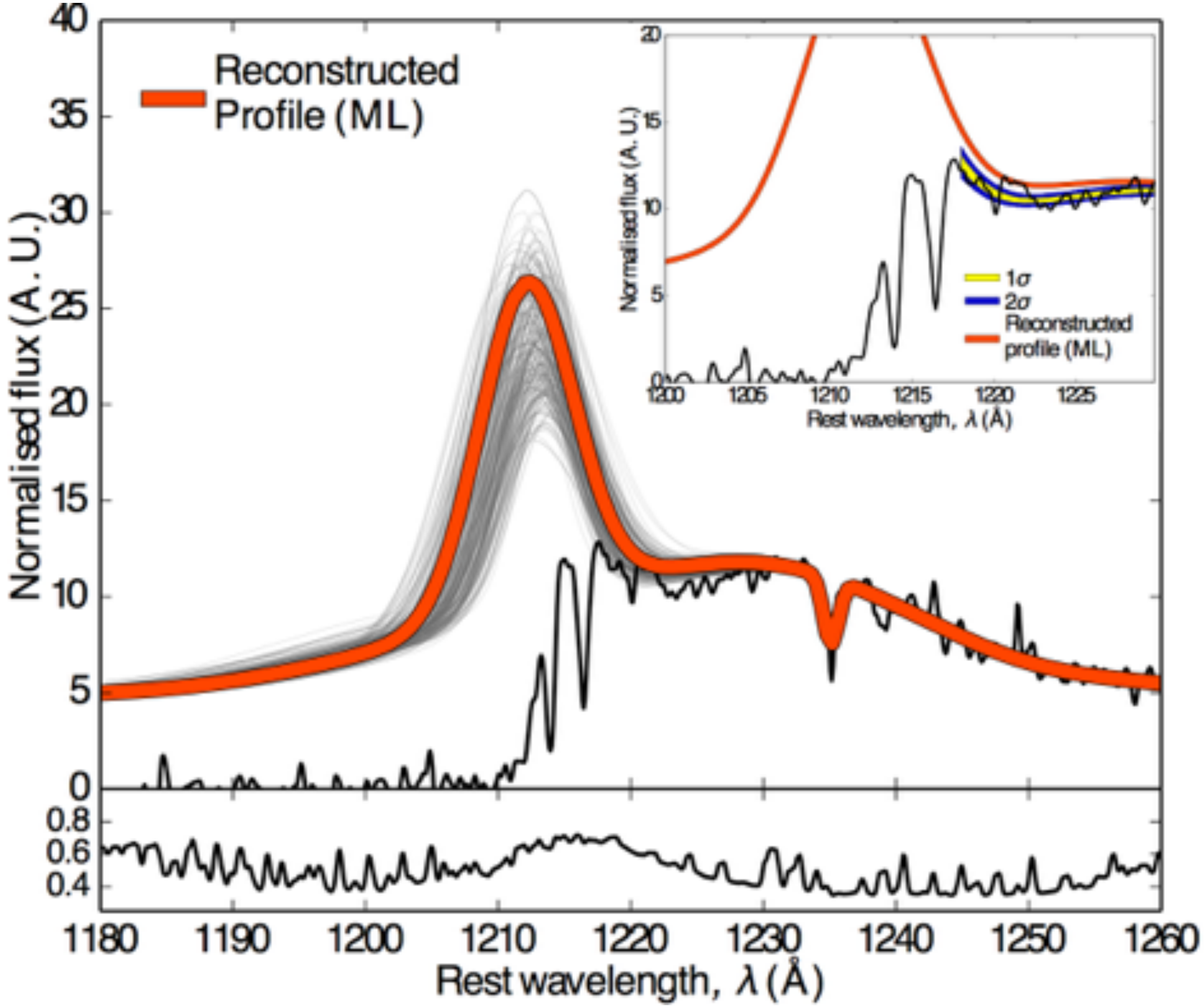
Analysis of z=7.1 QSO ULASJ1120

- **Step 1:** reconstruct the intrinsic Lyα emission of ULASJ1120 by sampling a covariance matrix of emission line properties built from ~1700 high S/N BOSS spectra (Greig, AM+ 2016a)
- **Step 2:** run large-scale, state-of-the-art simulations of reionization, spanning a range of uncertainties in the EoR topology (AM+ 2016)

Analysis of z=7.1 QSO ULASJ1120

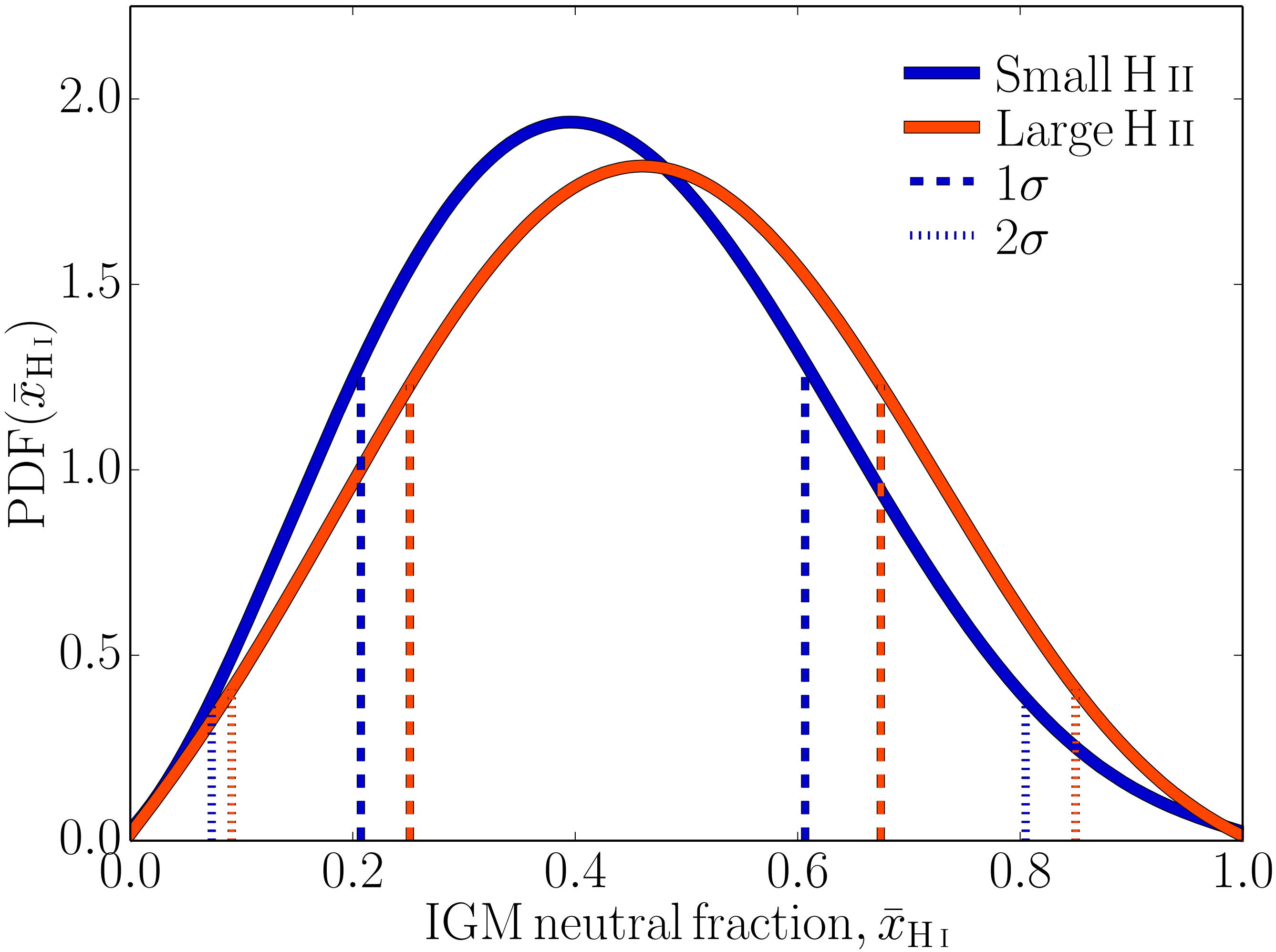
- **Step 1:** reconstruct the intrinsic Lyα emission of ULASJ1120 by sampling a covariance matrix of emission line properties built from ~1700 high S/N BOSS spectra (Greig, AM+ 2016a)
- **Step 2:** run large-scale, state-of-the-art simulations of reionization, spanning a range of uncertainties in the EoR topology (AM+ 2016)
- **Step 3:** Simultaneously sample intrinsic emission + IGM absorption, in a Bayesian framework (Greig, AM+ 2016b)

Analysis of z=7.1 QSO ULASJ1120



Greig, AM+ 2016b

Analysis of z=7.1 QSO ULASJ1120



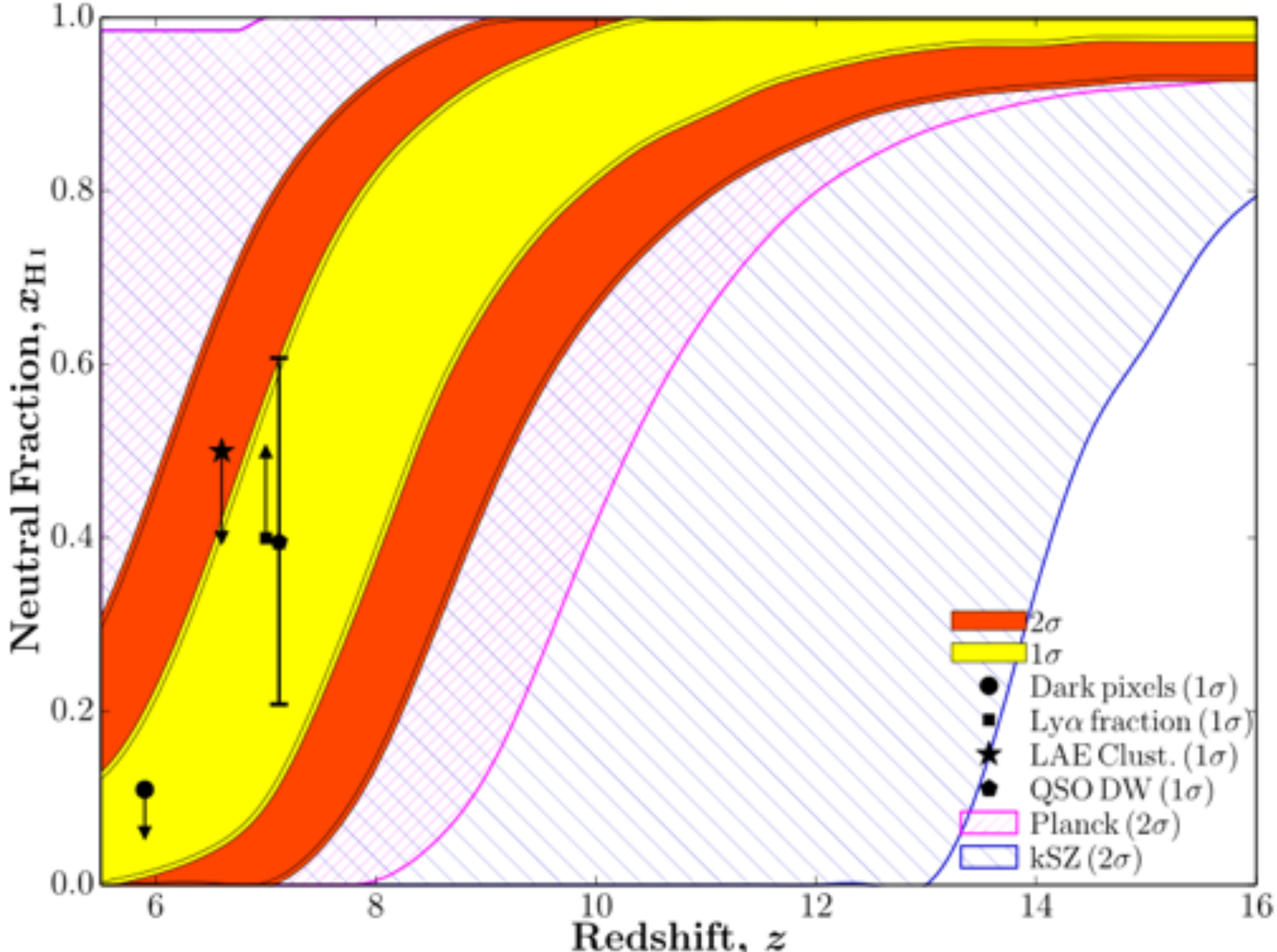
First detection of ongoing reionization!!!

$\langle x_{HI} \rangle = 0.40_{-0.32}^{+0.41}$ **(2 σ)**

Greig, AM+ 2016b

putting it all together…

When did the Universe reionize?



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

We now have a reasonable handle on when…

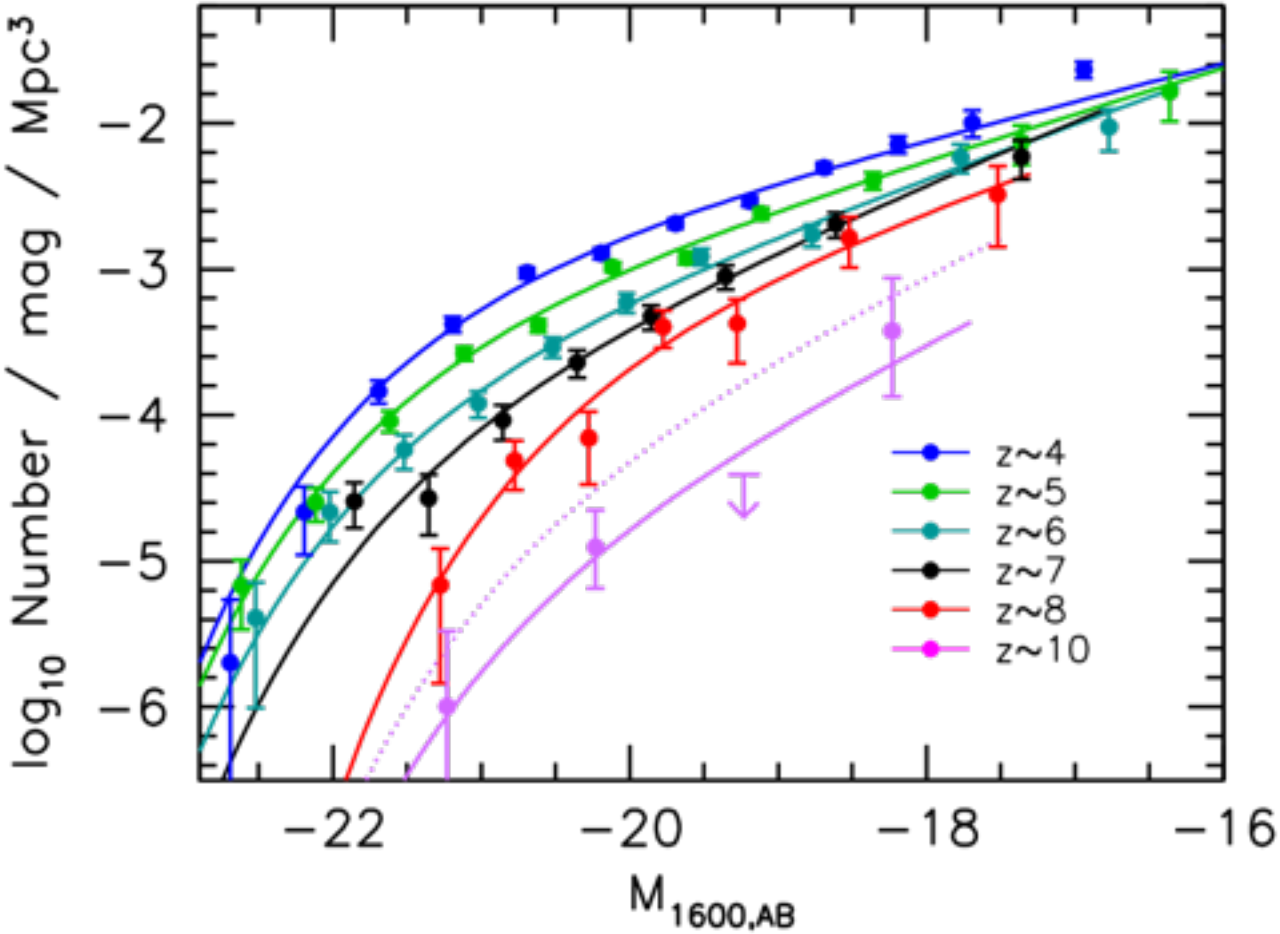
What and how??

stellar populations vs AGN, IMF in first galaxies, role of SNe and radiative feedback, metal pollution, efficiency of star formation, IGM structures, UVB evolution etc..

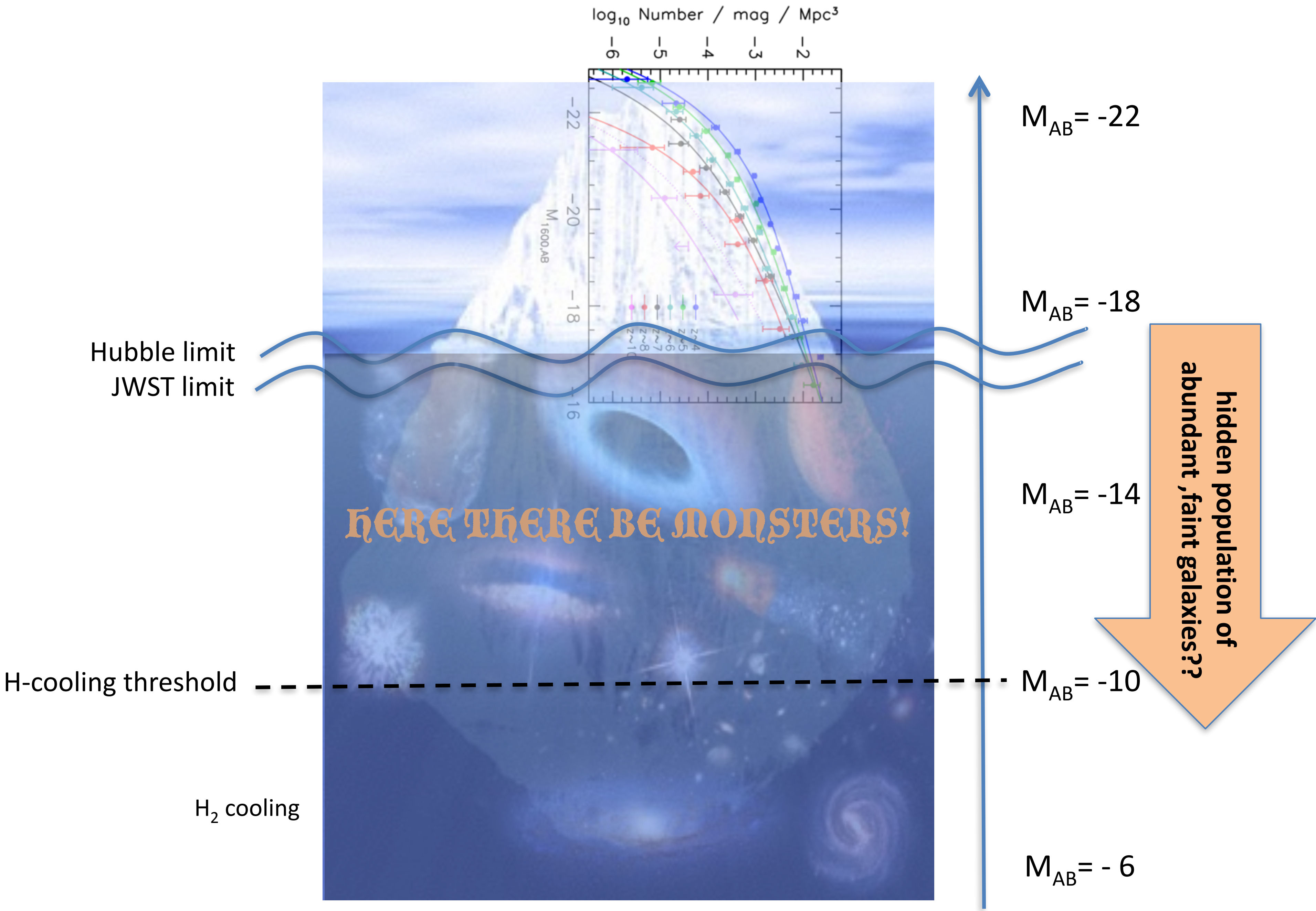
we don’t really know…

What and how?

- Galaxy candidates have been found out to z~10. Are these the stellar populations responsible for the Cosmic Dawn and reionization? Estimates suggest they are too few…

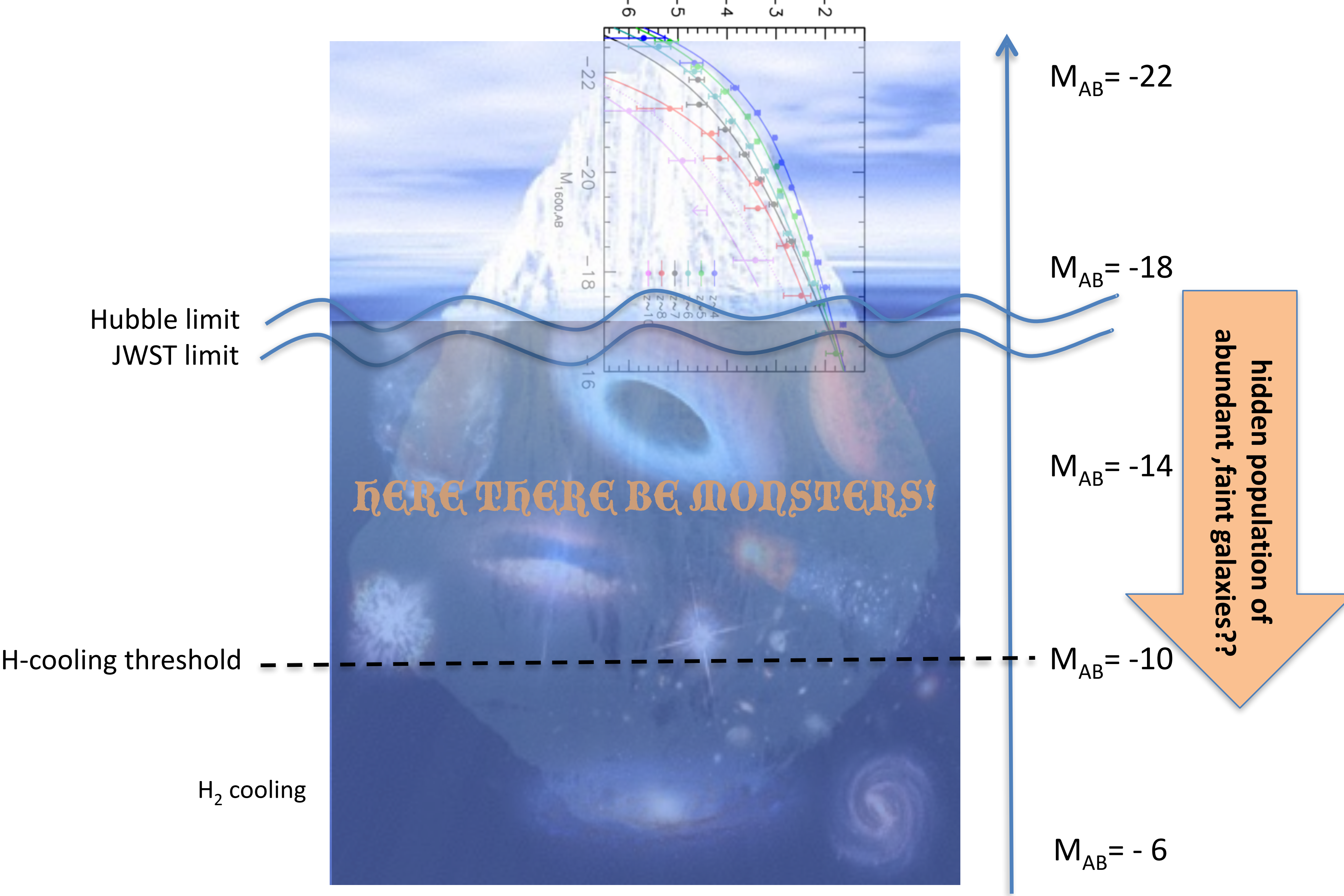


Bouwens+ (2015)



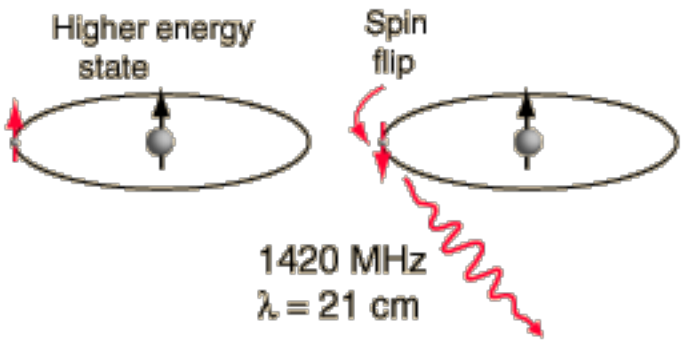
log10 Number / mag / Mpc3
M1600,AB
Hubble limit
JWST limit
HERE THERE BE MONSTERS!
H-cooling threshold
H2 cooling
MAB= -22
MAB= -18
MAB= -14
MAB= -10
MAB= - 6
hidden population of abundant ,faint galaxies??

Note: this is a log plot!



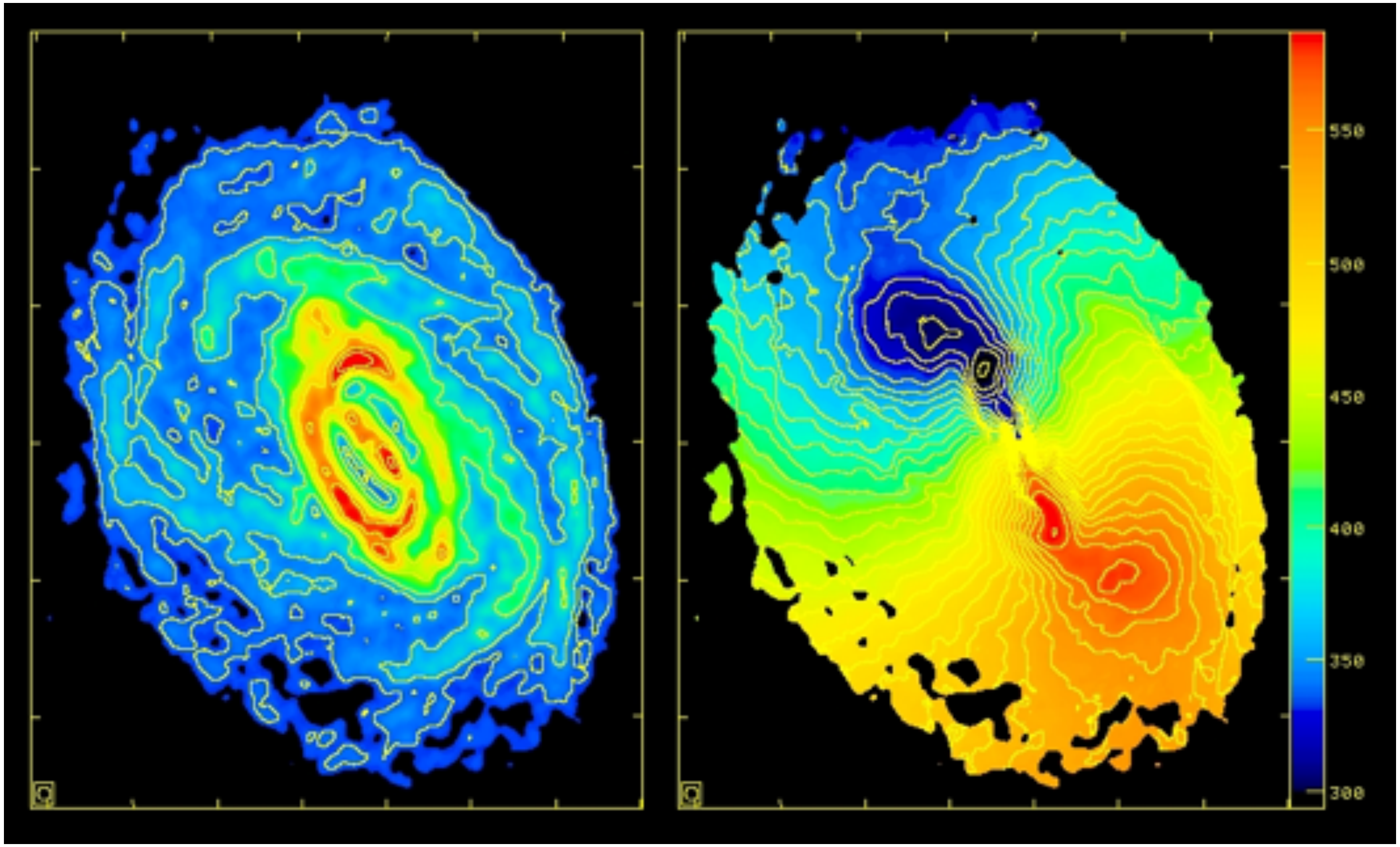
Get ready for the revolution:
the cosmic 21 cm signal

21 cm line from neutral hydrogen



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

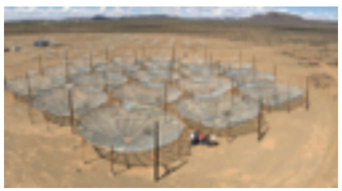
Widely used to map the HI content of our galaxy and nearby galaxies

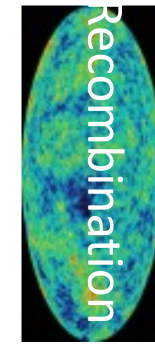


Circinus Galaxy

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

Cosmic 21-cm signal





z = 0

z~1100

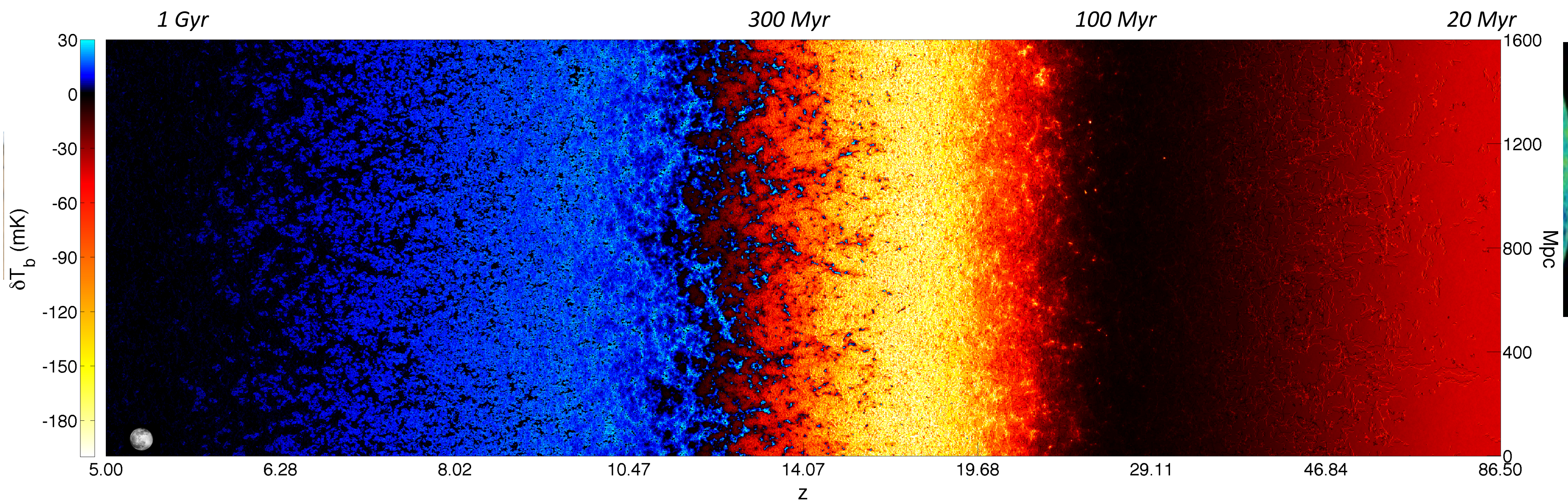
use the CMB as a background. measure the difference in intensities of the CMB and the cosmic HI, the so-called brightness temperature offset from the CMB:

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

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

Cosmic 21-cm signal

AM+ 2016



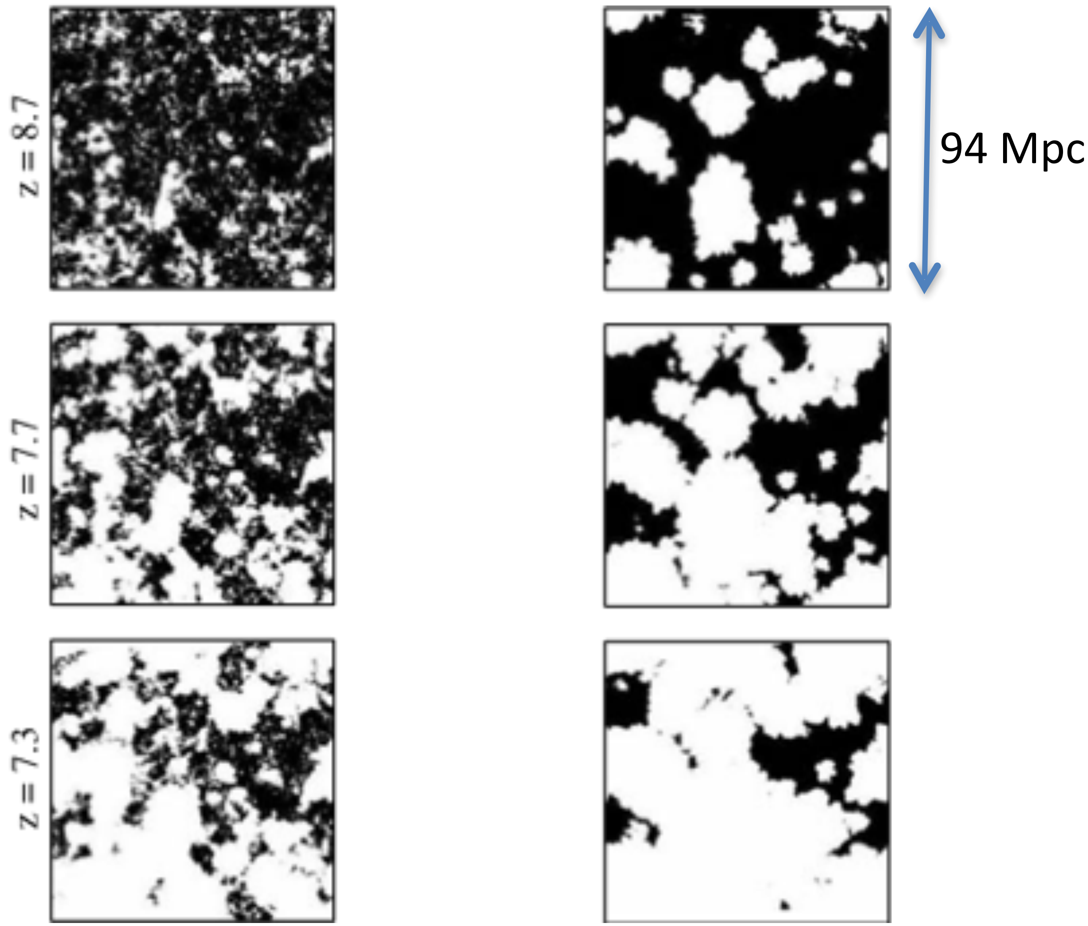
Reionization X-ray heating Lyα coupling Dark Ages

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

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

How do we learn about the hidden sources?

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



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

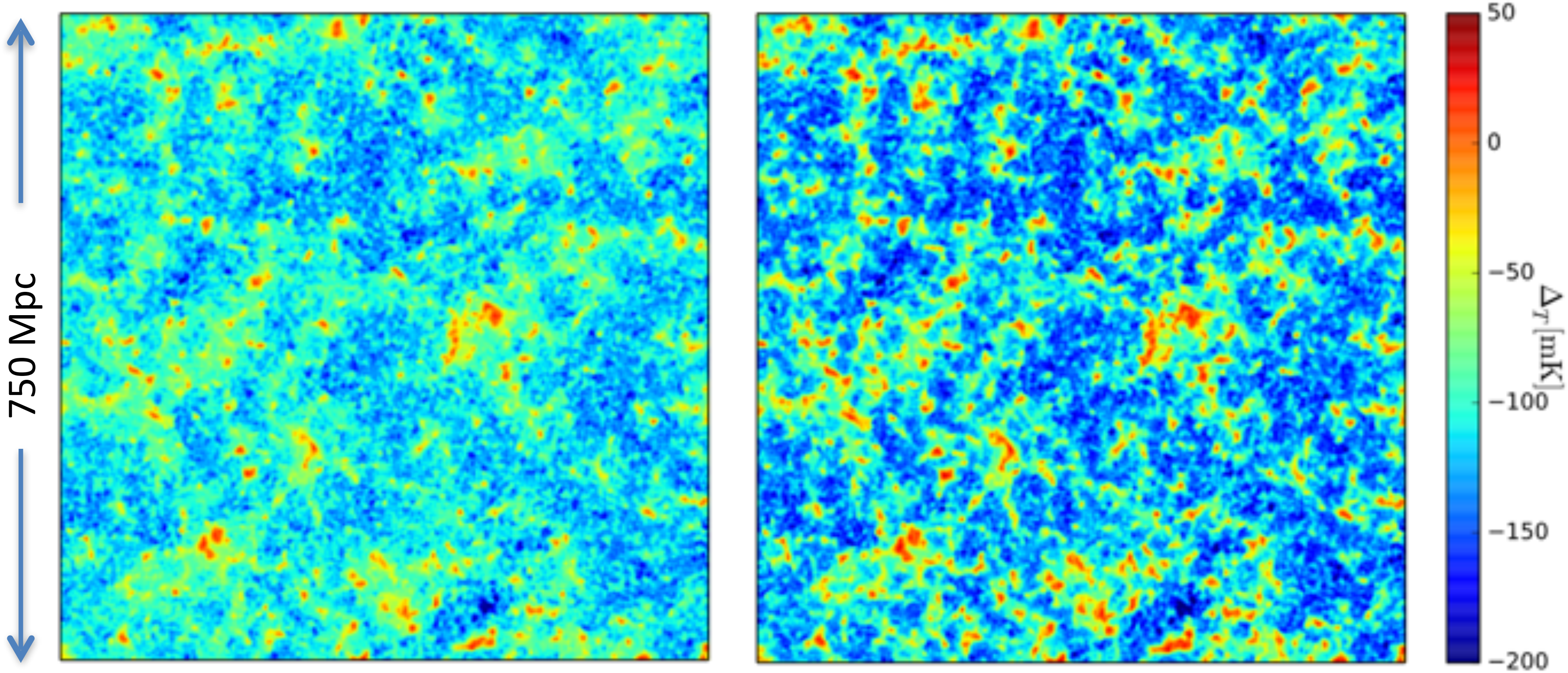
McQuinn+ 2007

Patterns in the Epoch of Heating

High-energy processes in the first galaxies are also encoded in the cosmic 21-cm signal

‘hard’ SED ~ HMXBs

‘soft’ SED ~ hot ISM



differences are easily detectable with HERA and the SKA

Pacucci, AM+ 2014

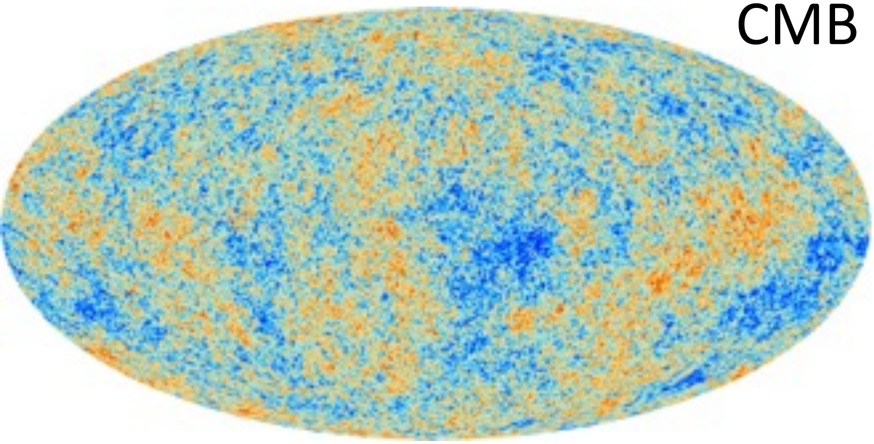
How to quantify what we will learn??

21cmFAST (AM+2007, 2011) — public, efficient semi-numerical 3D simulation code; extensively tested and currently used by *all* 21-cm efforts around the globe

+

21CMMC (Greig & AM 2015, 2017) – public, massively-parallelized MCMC driver for *21cmFAST*, based on EMCEE sampler (Forman-Mackey+ 2013)

Physical cosmology

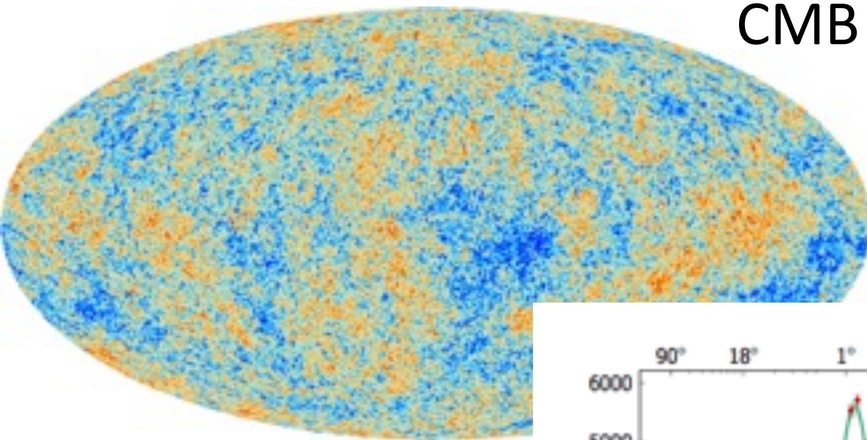


CMB map

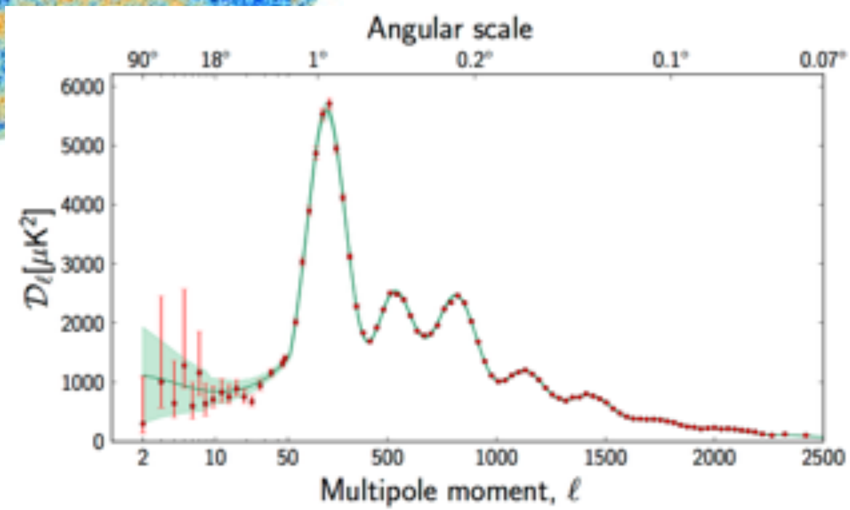
Planck 2013; 2015

Physical cosmology

CMB map



power spectrum



Planck 2013; 2015

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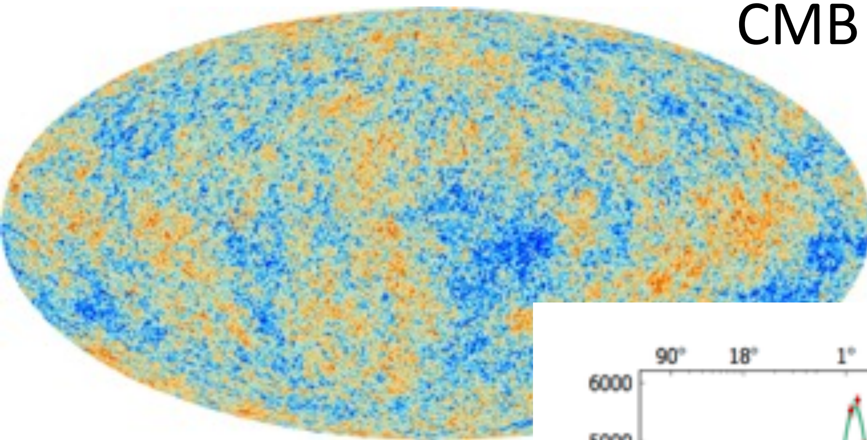
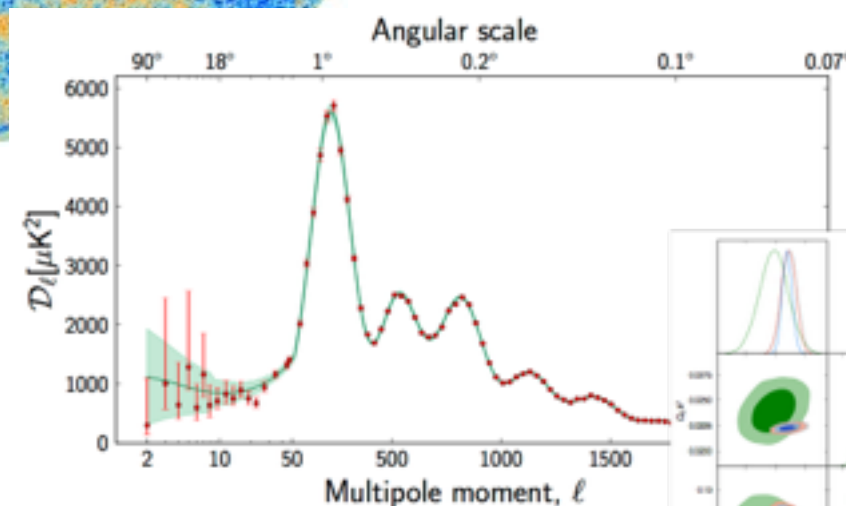
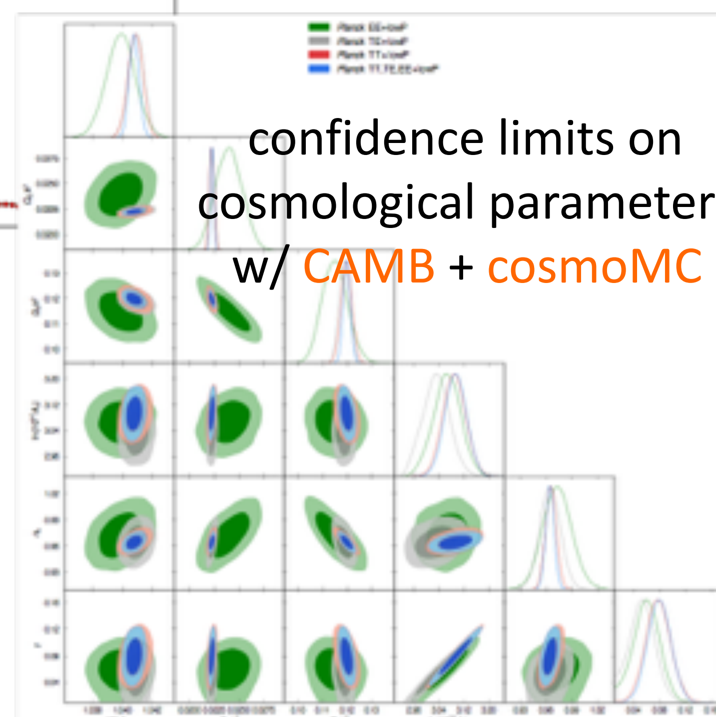


power spectrum



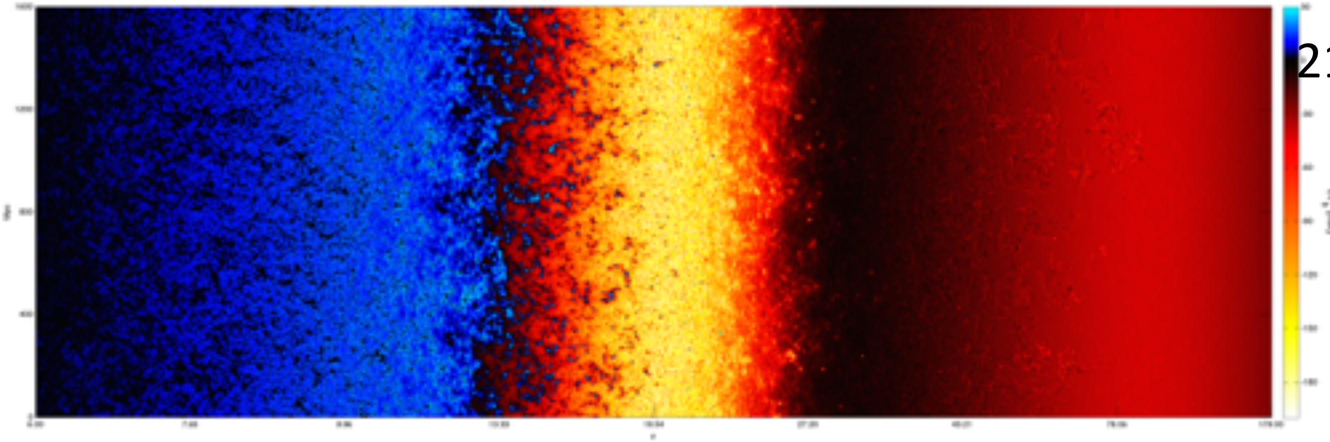
confidence limits on cosmological parameters w/ CAMB + cosmoMC



Planck 2013; 2015

*Astro*physical cosmology

← time

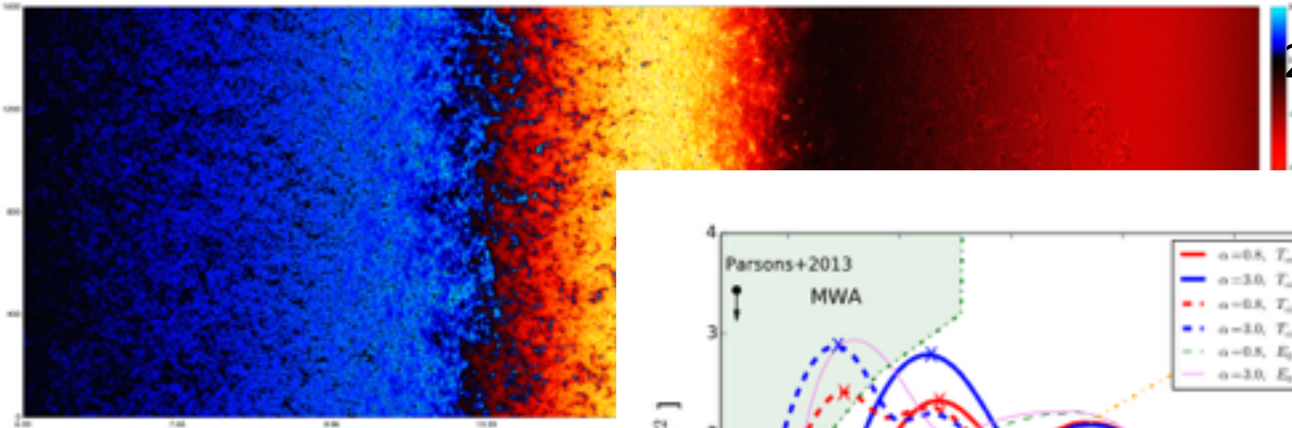


21cm **3D!!!** map

Greig & AM (2015)

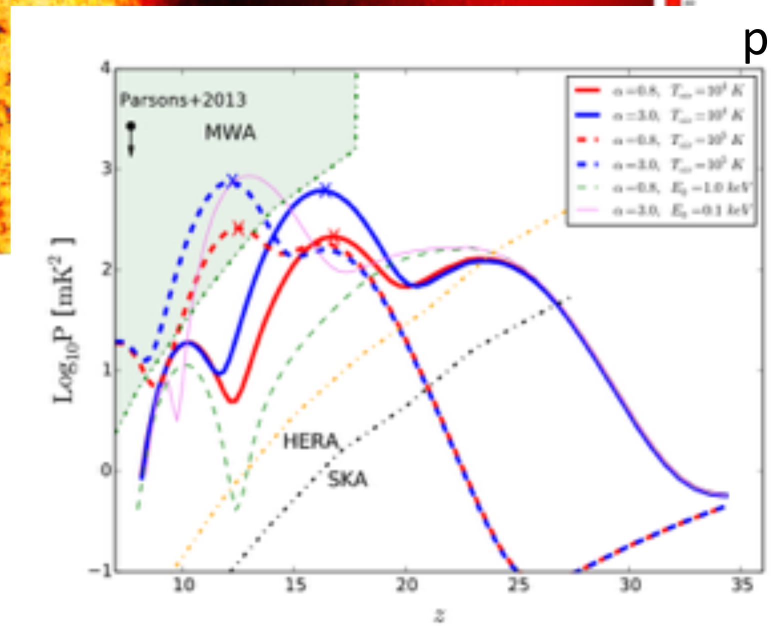
*Astro*physical cosmology

← time



21cm **3D!!!** map

power spectrum**??**



Greig & AM (2015)

*Astro*physical cosmology

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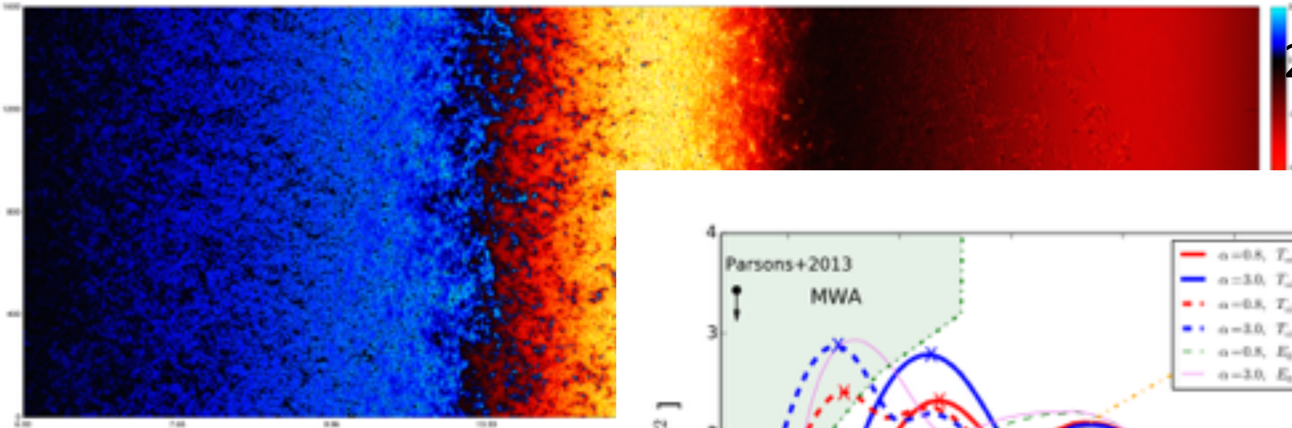

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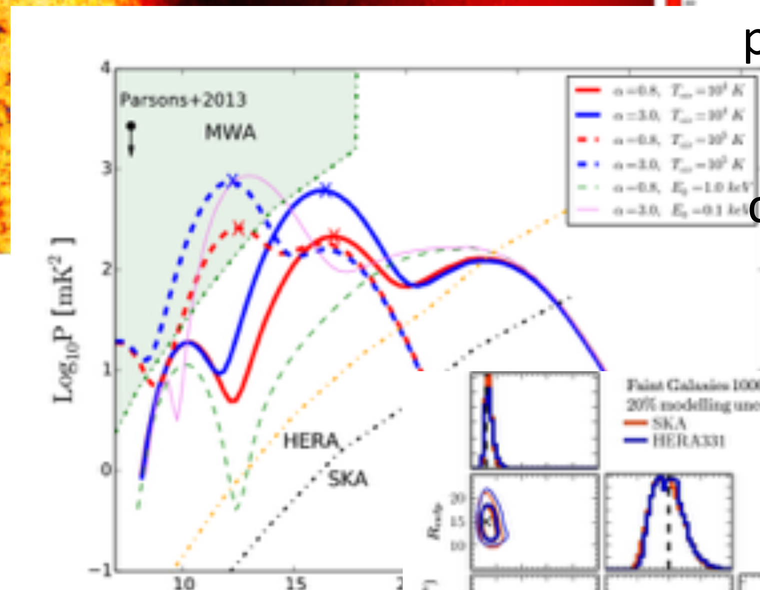
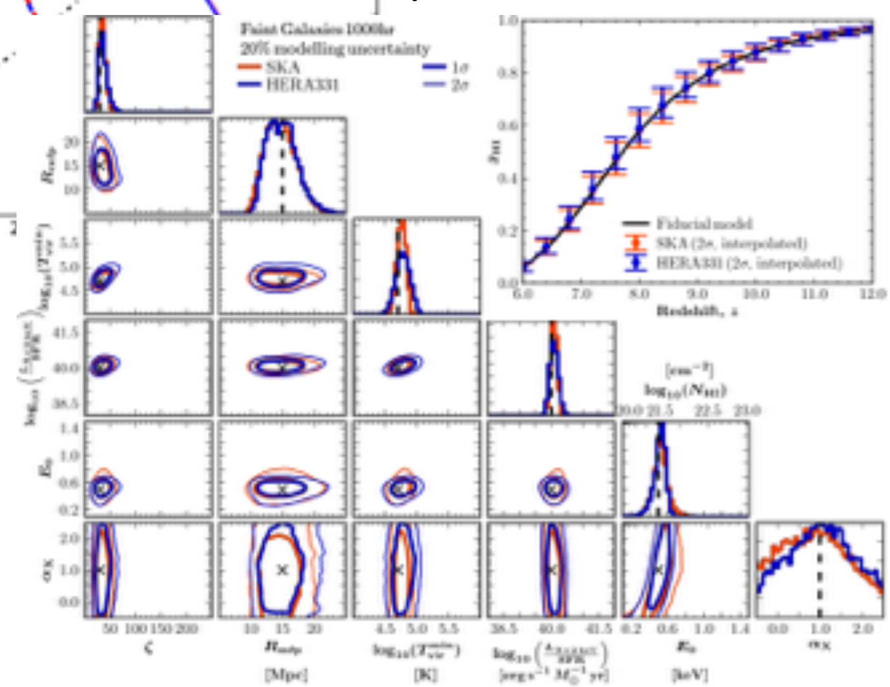
power spectrum**??**

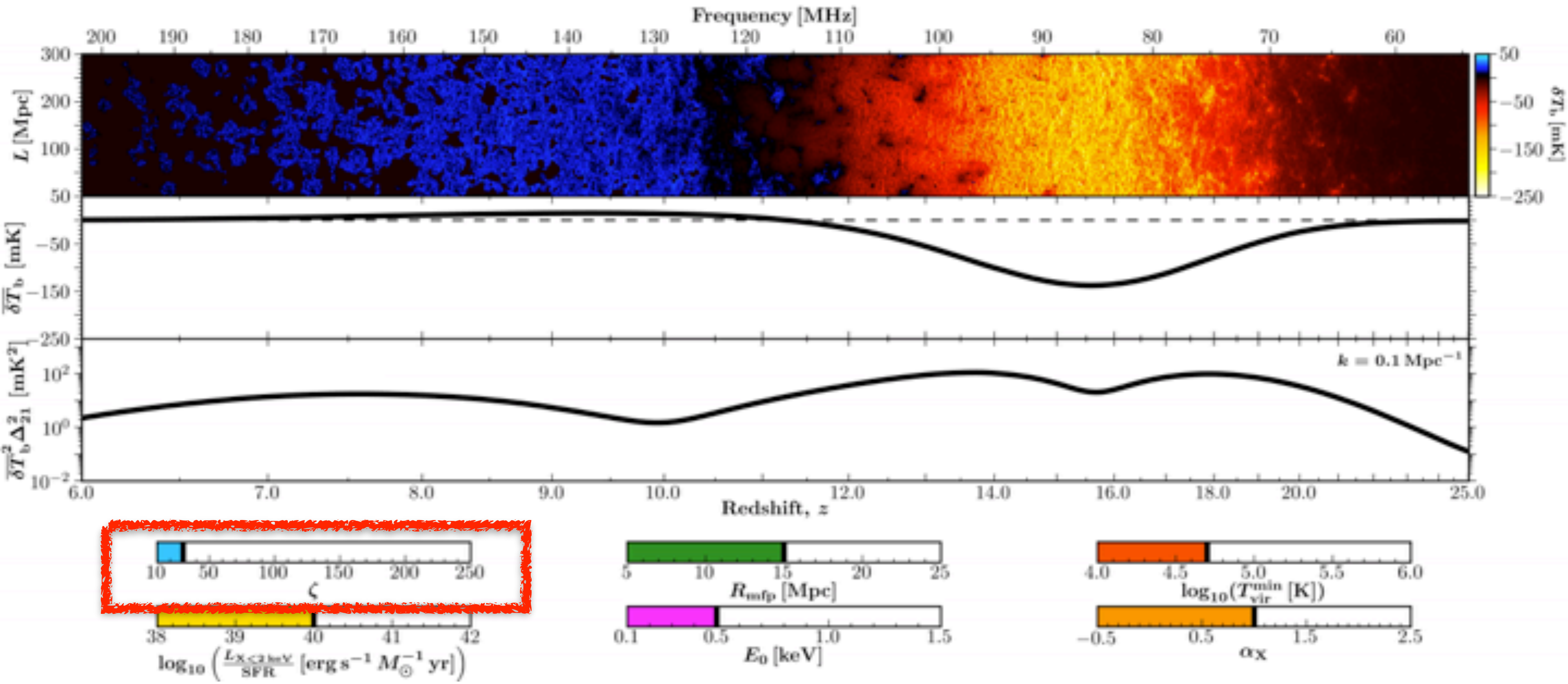


confidence limits on ***astro*** parameters
w/ 21cmFAST+ 21CMMC



Greig & AM (2015; 2017)

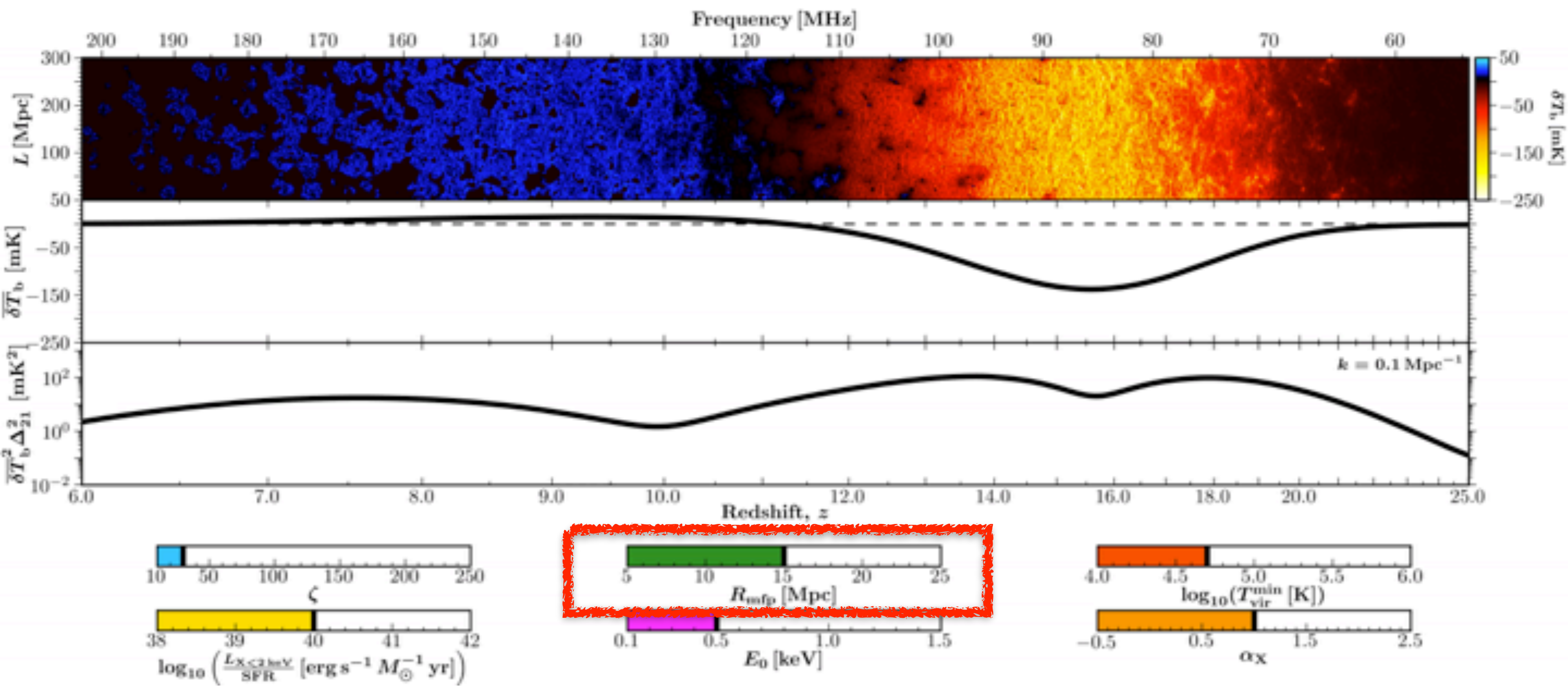
What are *astro*physical parameters?



ζ - the ionizing efficiency of galaxies. ζ is proportional to the product of the escape fraction, specific stellar mass and number of ionizing photons per baryon (set by the IMF)

Greig & AM (2017)

What are *astro*physical parameters?



R_{mfp} – the typical horizon for ionizing photons (mean free path), set by IGM recombinations (Lyman limit systems)

Greig & AM (2017)

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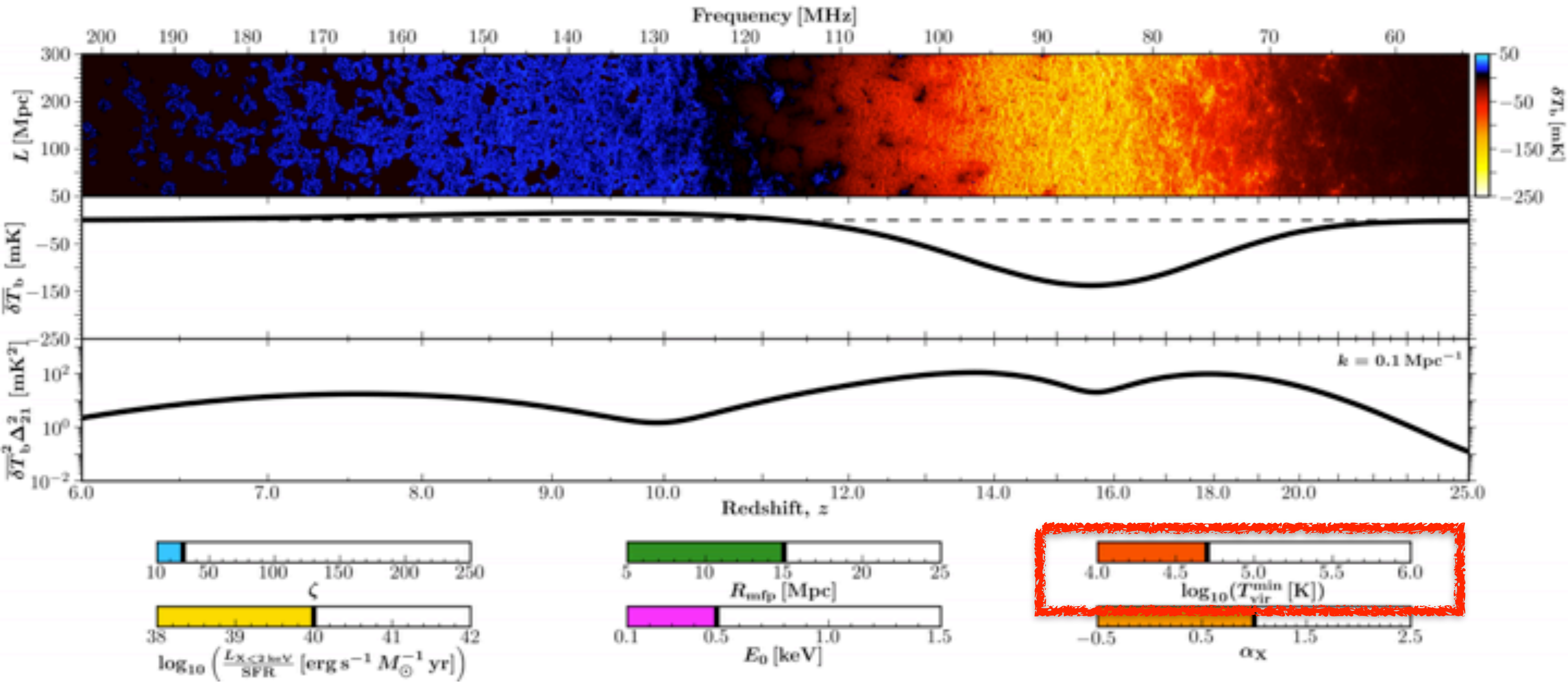
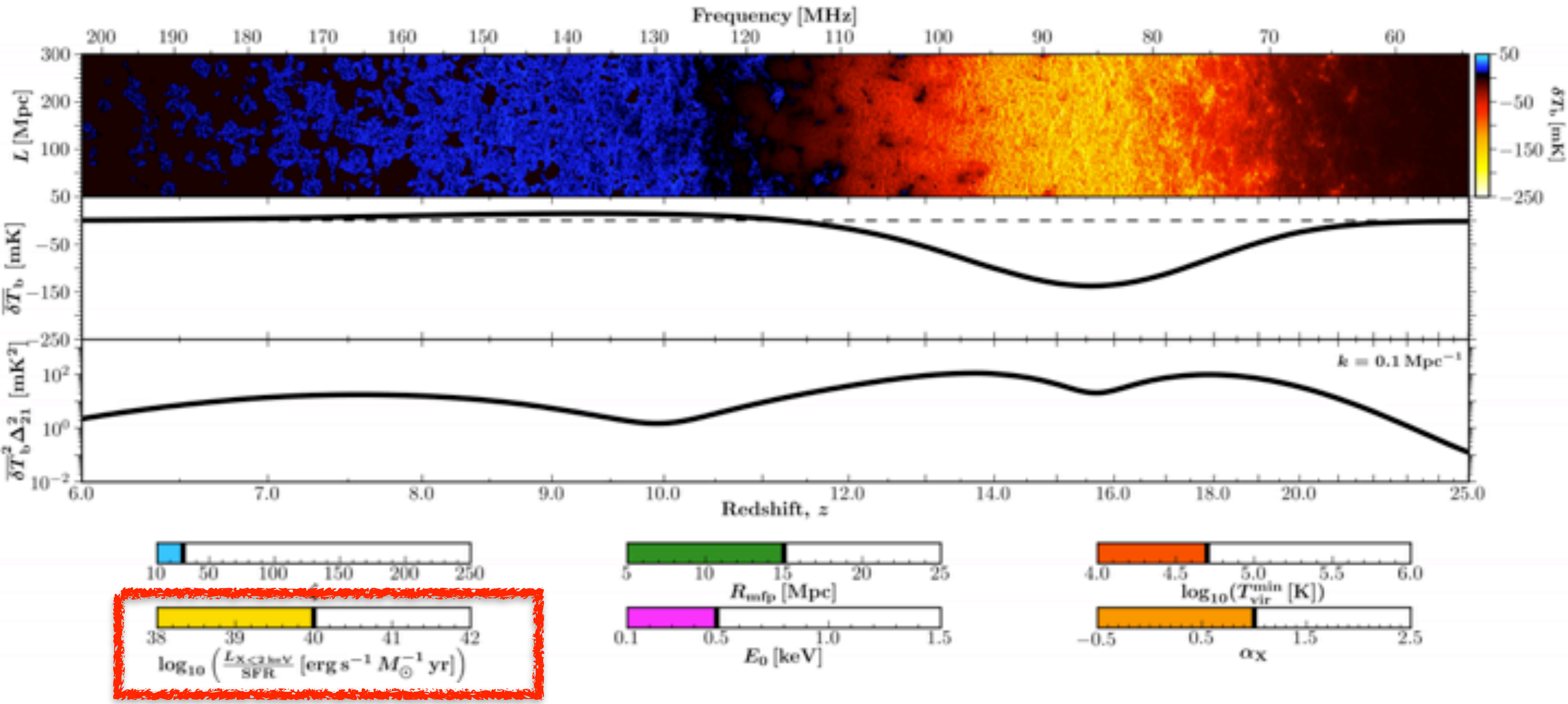


T_{vir} – the minimum virial temperature of halos hosting star-forming galaxies (set by cooling or feedback…)

Greig & AM (2017)

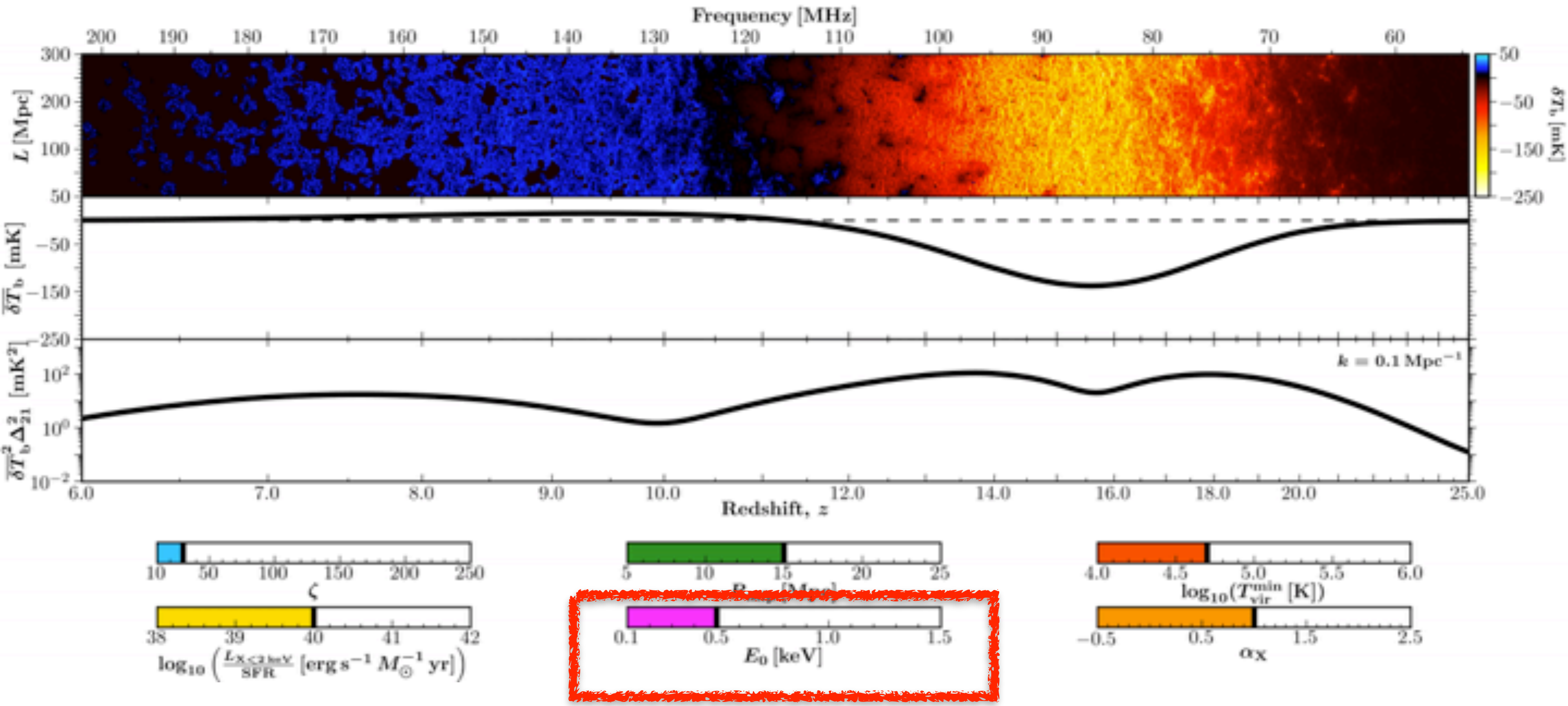
What are *astro*physical parameters?



L_X / SFR – the soft-band X-ray luminosity per unit star formation of the first galaxies

Greig & AM (2017)

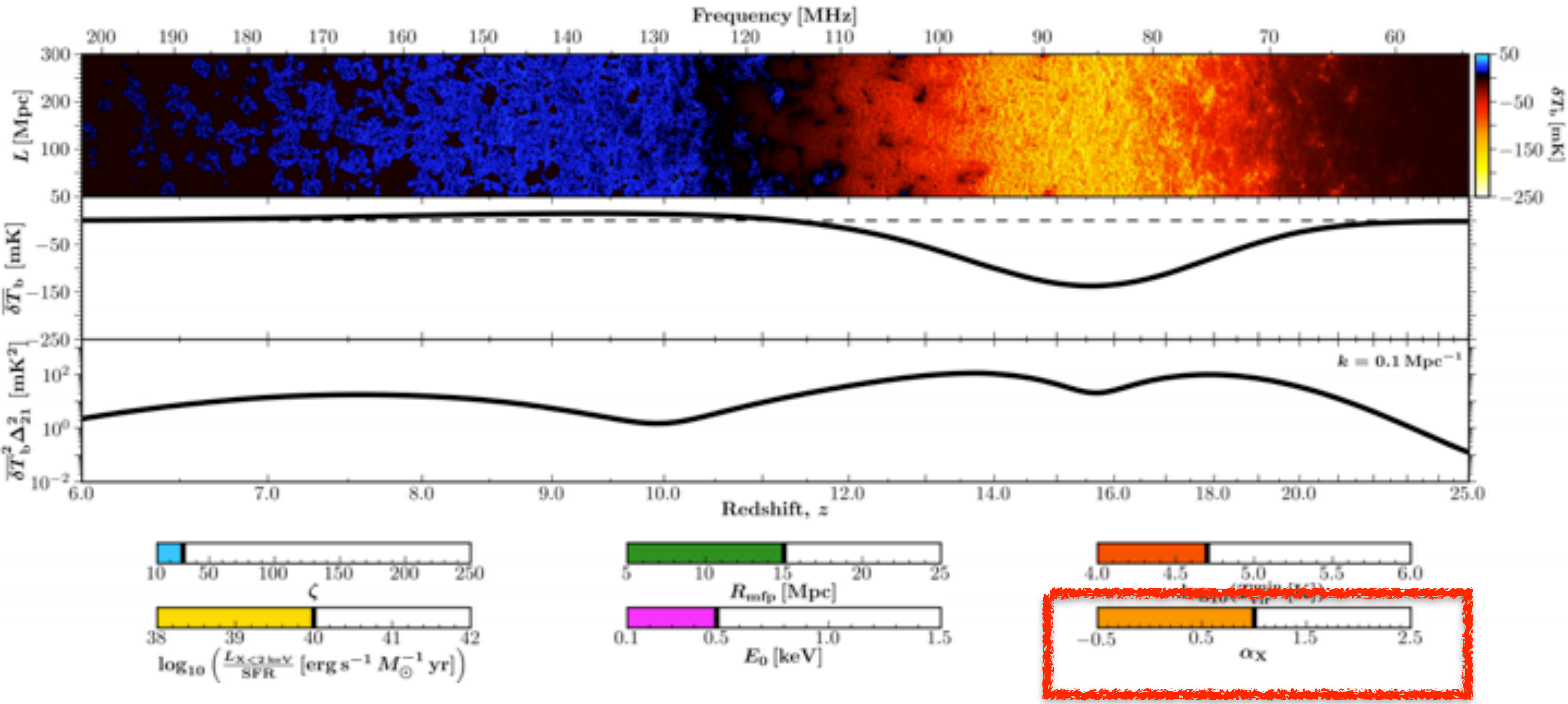
What are *astro*physical parameters?



E_0 (or N_{HI}) – the minimum X-ray photon energy (corresponding to a typical N_{HI} of the first galaxies) capable of escaping the host galaxy into the IGM

Greig & AM (2017)

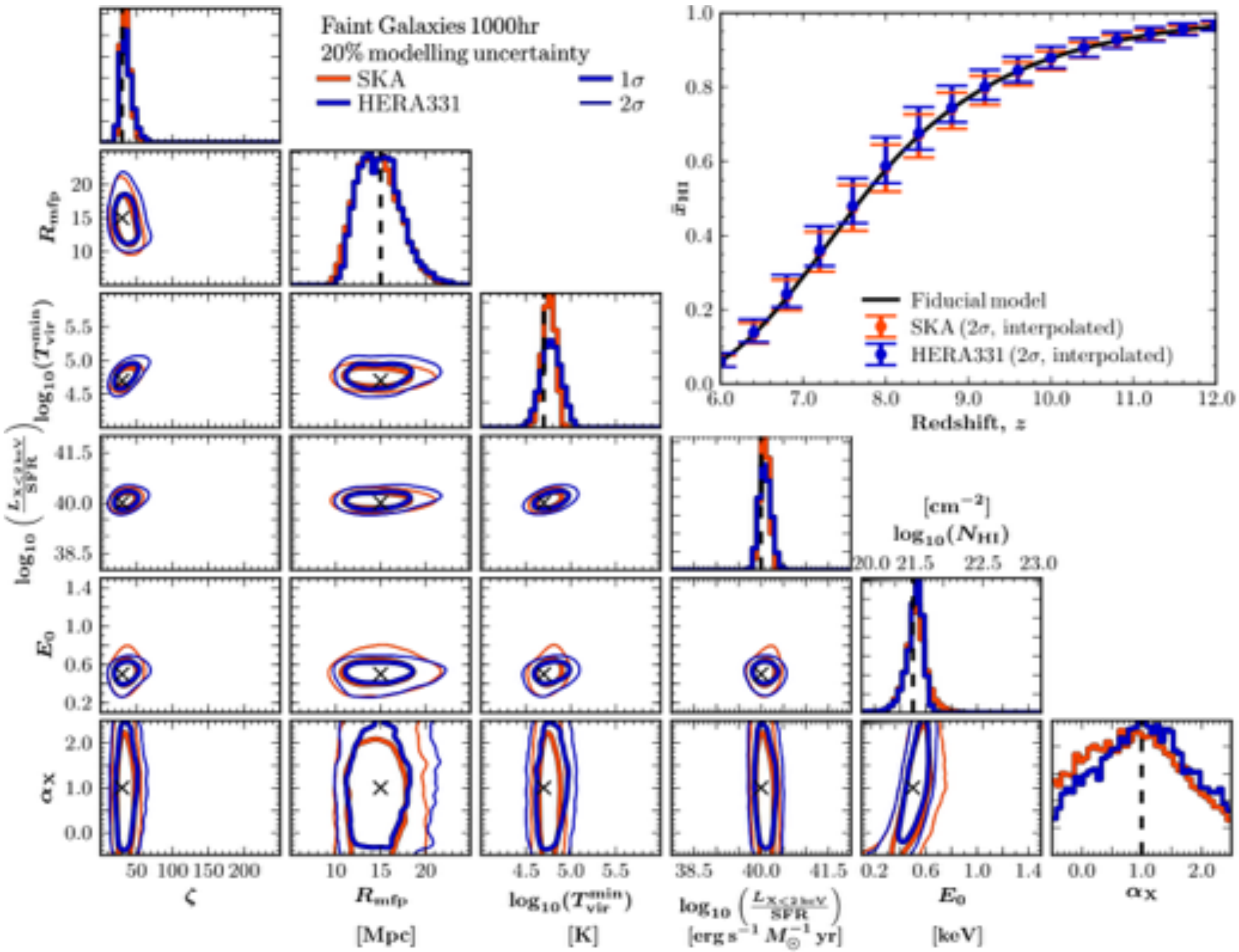
What are *astro*physical parameters?



α_X – the X-ray spectral energy index of typical SED

Greig & AM (2017)

Triangle plot from 21CMMC



- *percent level constraints on most astro params and EoR history w. SKA*
- *no strong degeneracies even with 6 parameter model*

Greig & AM (2017)

Upcoming….

- 21cmFAST + 21CMMC provides a powerful, Bayesian analysis framework for the 21-cm signal. *Parameter recovery can provide a figure-of-merit to test foreground-cleaning algorithms, instrument configurations, antenna design, observing strategies, etc.*

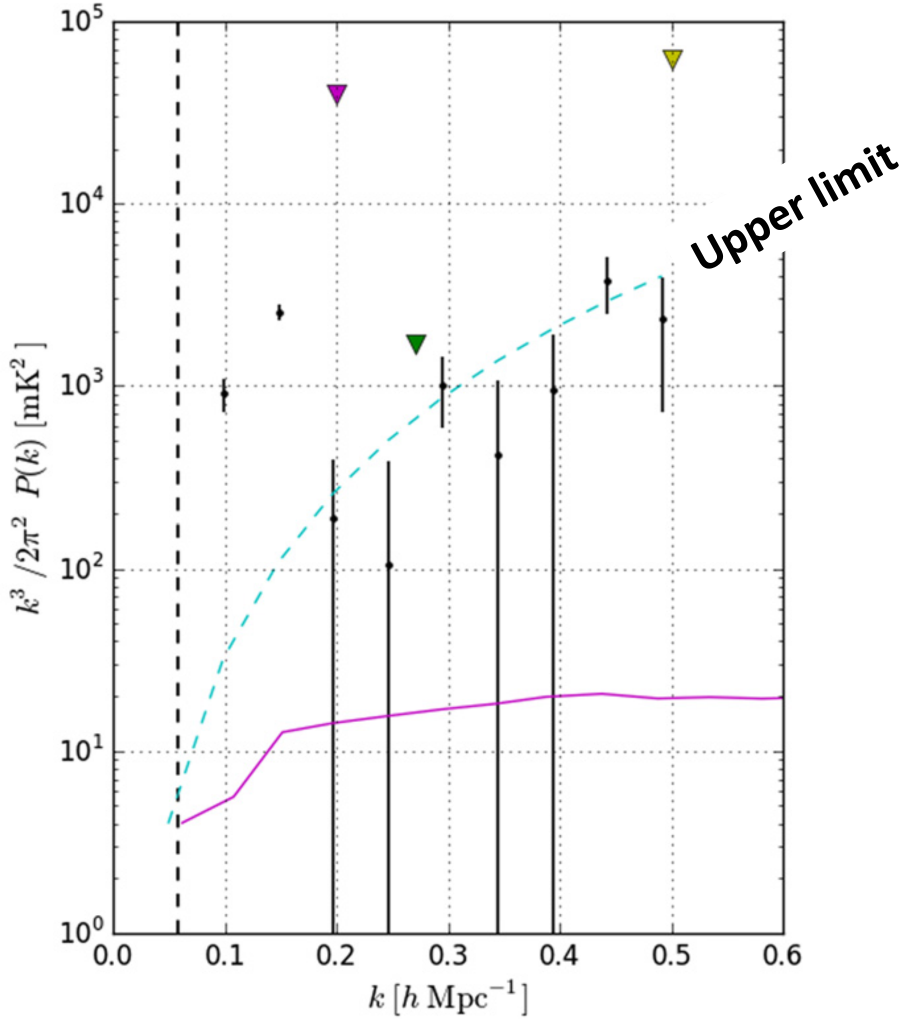
- Bayesian evidence can be used to discriminate between different astrophysical parameterizations. *Can we find a fundamental basis set for Cosmic Dawn astrophysics?*

- The signal is highly non-Gaussian. Since we generate on-the-fly 3D simulations, we can easily replace the PS when computing the likelihood. *Are non-Gaussian statistics a better discriminant for astrophysical parameters?*

- Our analysis framework now operates directly on the light-cone, bringing us closer to an end-to-end pipeline for 21-cm interferometers. *Can we eventually forward-model the signal?*

The time is now!

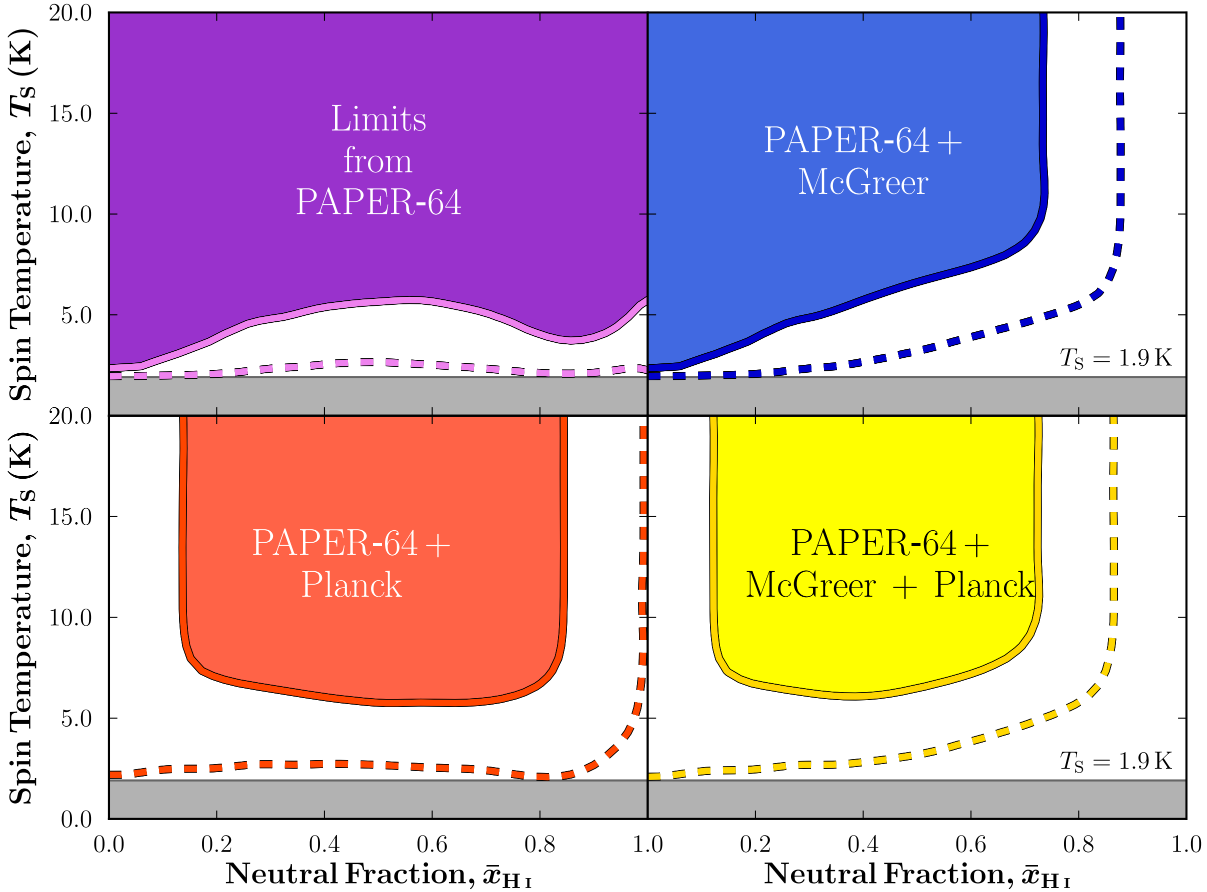
- 1st gen. interferometers are already taking data, ruling-out extreme models with no heating



Ali+ (2015)

The time is now!

- 1st gen. interferometers are already taking data, ruling-out extreme models with no heating



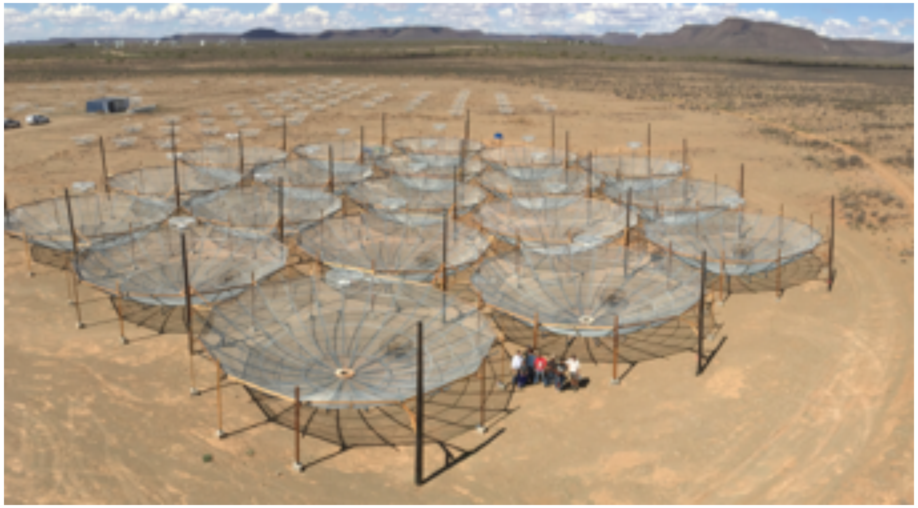
$\langle T_{HI} \rangle > 6$ K @ z=8.4

← adiabatically-cooled IGM

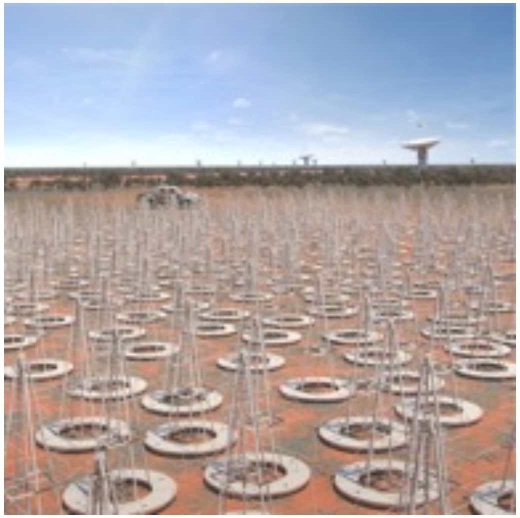
Greig, AM, Pober (2016)
(see also Pober+2015)

The time is now!

- 1^{st} gen. interferometers are already taking data, ruling-out extreme models with no heating. *We should soon see a statistical detection of the EoR!*
- 2^{nd} gen. interferometers, HERA & SKA1, are coming in the next few years, bringing high S/N detections throughout the Cosmic Dawn



first 19 of planned 350 HERA dishes



rendering of SKA1-Low

Conclusions

- Current probes tell us roughly when reionization occurred. The strongest constraints come from Planck 2016 (integral constraints), and the **first detection** from QSO ULASJ1120: **$\langle x_{HI} \rangle = 0.40_{-0.32}^{+0.41}$ (2 σ) at z~7**. But we do not know anything about the astrophysical sources and sinks.
- The properties of sources and sinks are encoded in the 3D EoR structure.
- To quantify what we can learn, we developed a Bayesian framework for astrophysical parameter estimation, capable of on-the-fly MCMC sampling (21CMMC) of 3D simulations (21cmFAST).
- Upcoming 21-cm interferometers will constrain astrophysical parameters to per cent level precision
- Our framework can be used to optimize *foreground-cleaning algorithms, instrument configurations, antenna design, observing strategies, Bayesian evidence model selection, optimal statistics, etc.*
- What more can we learn??