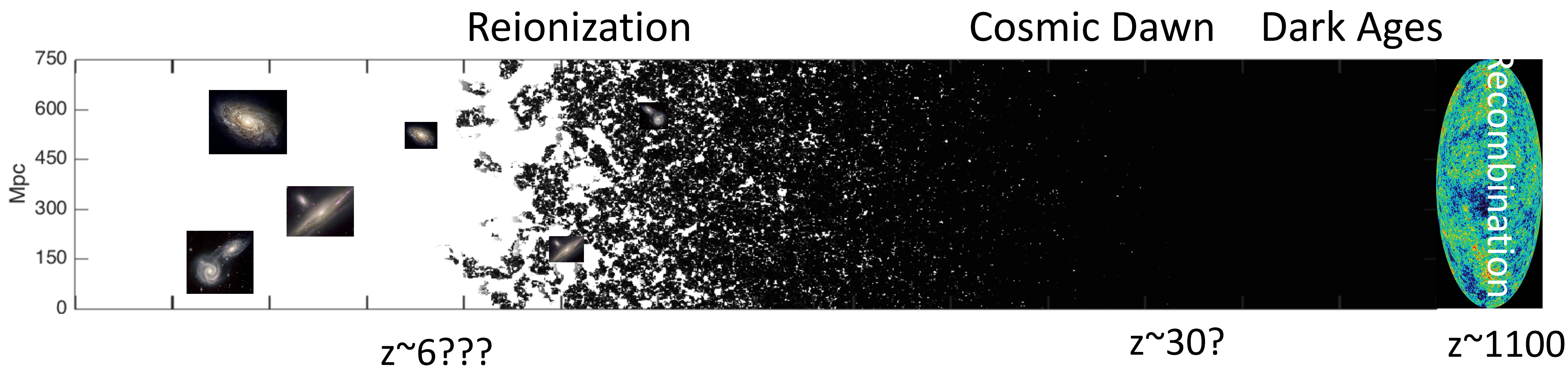
Reionization and Cosmic Dawn:
current status and future outlook

Andrei Mesinger

Why Cosmic Dawn?



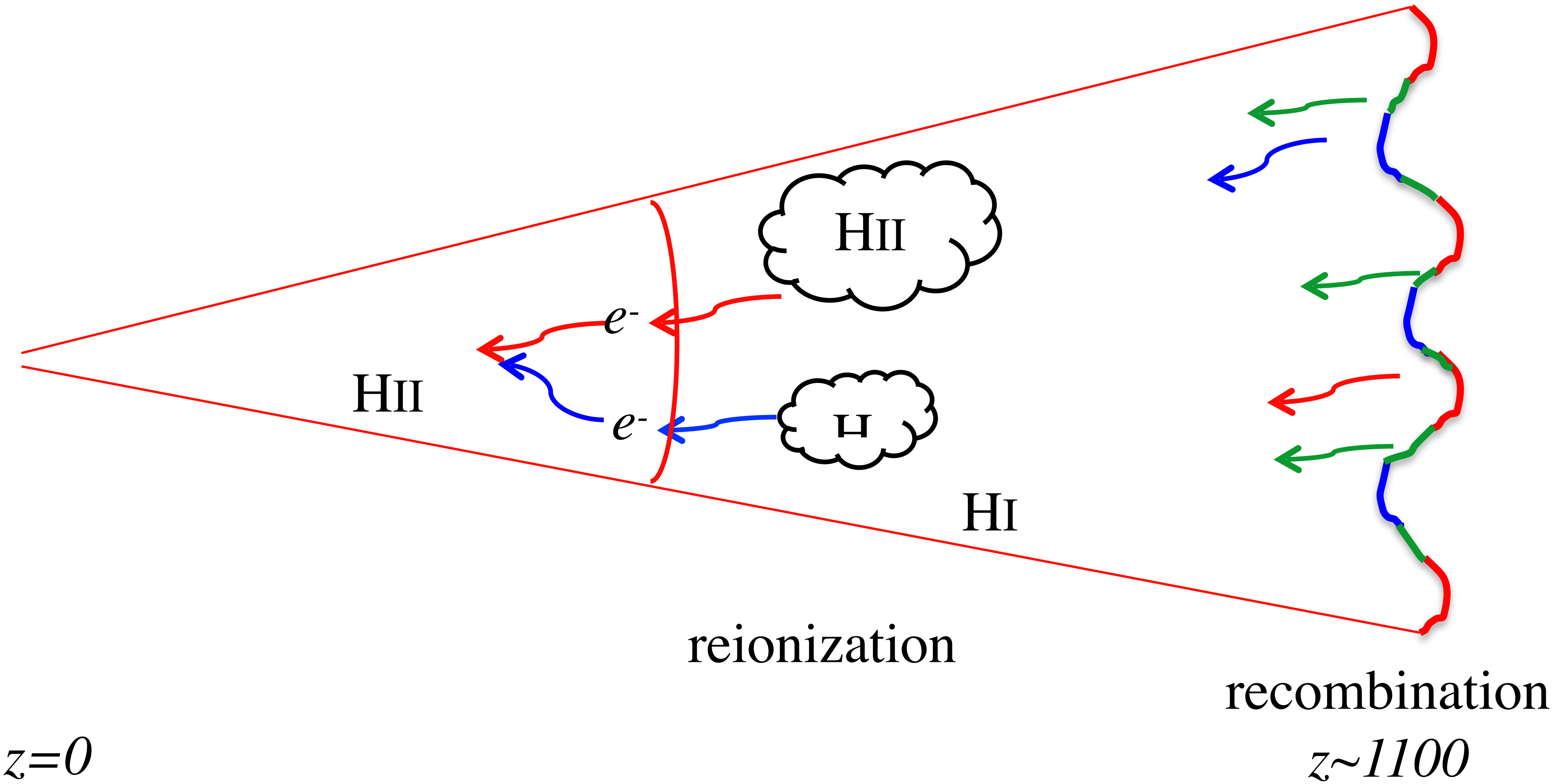
Potentially some fundamental questions: **When** did the first generations of galaxies form? **What** were their properties? **How** did they interact with each other and the intergalactic medium? What is the structure of the intergalactic medium? What is the thermal and ionization history of the baryons?

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!

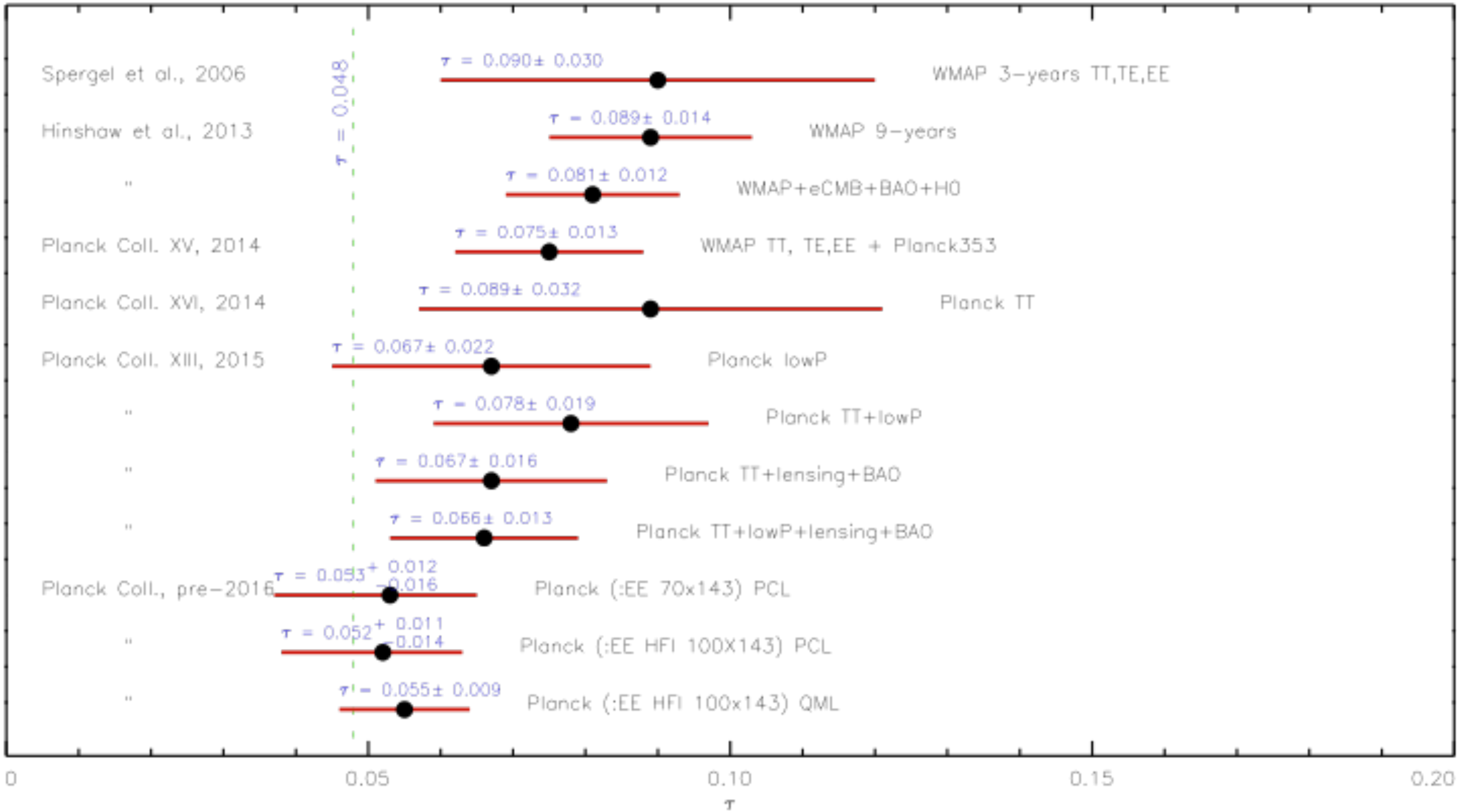
When?

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



History of Thompson scattering optical depth measurements

WMAP1 2003



Planck 2016

History of Thompson scattering optical depth measurements

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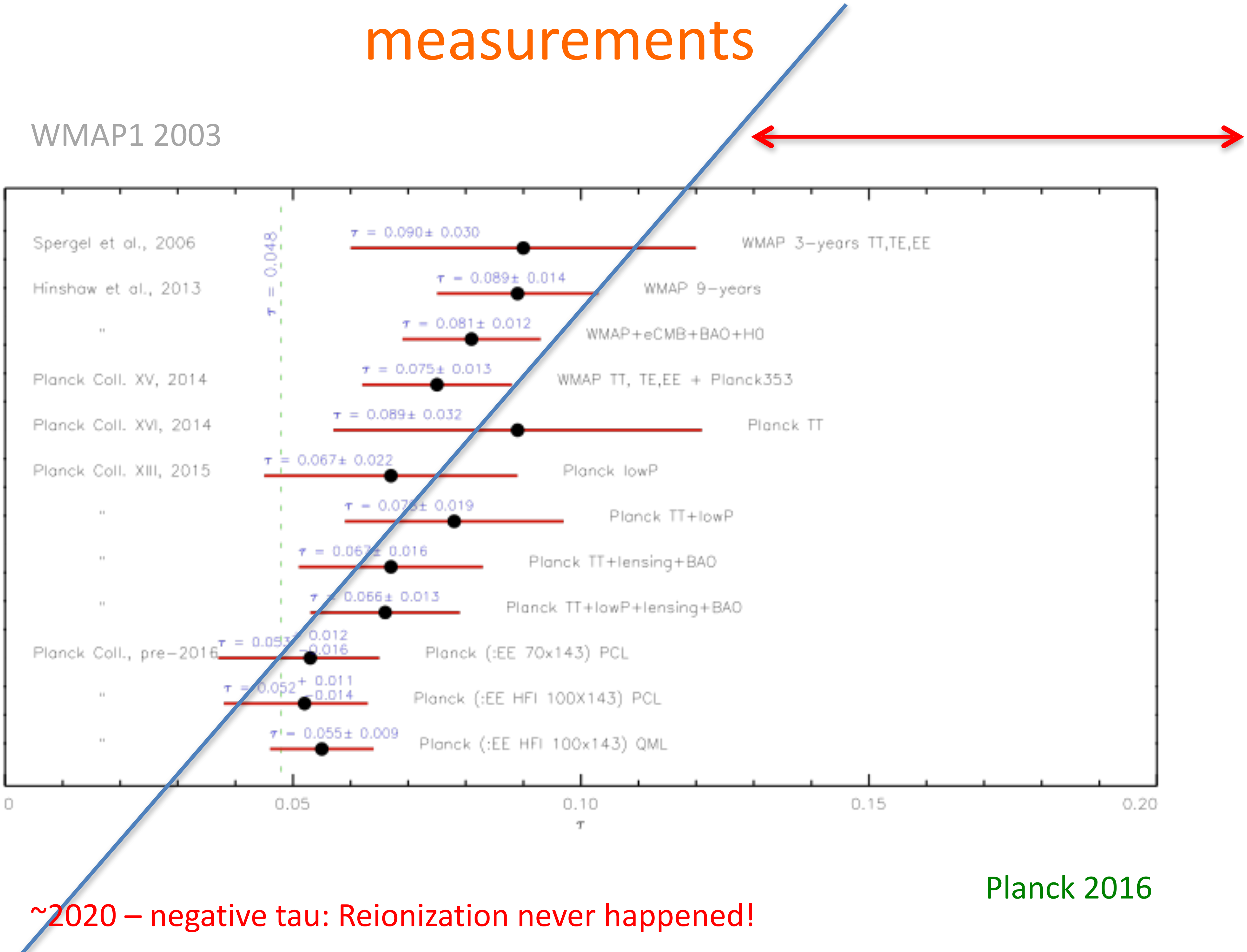

Planck 2016

~2020 – negative tau: Reionization never happened!

History of Thompson scattering optical depth measurements

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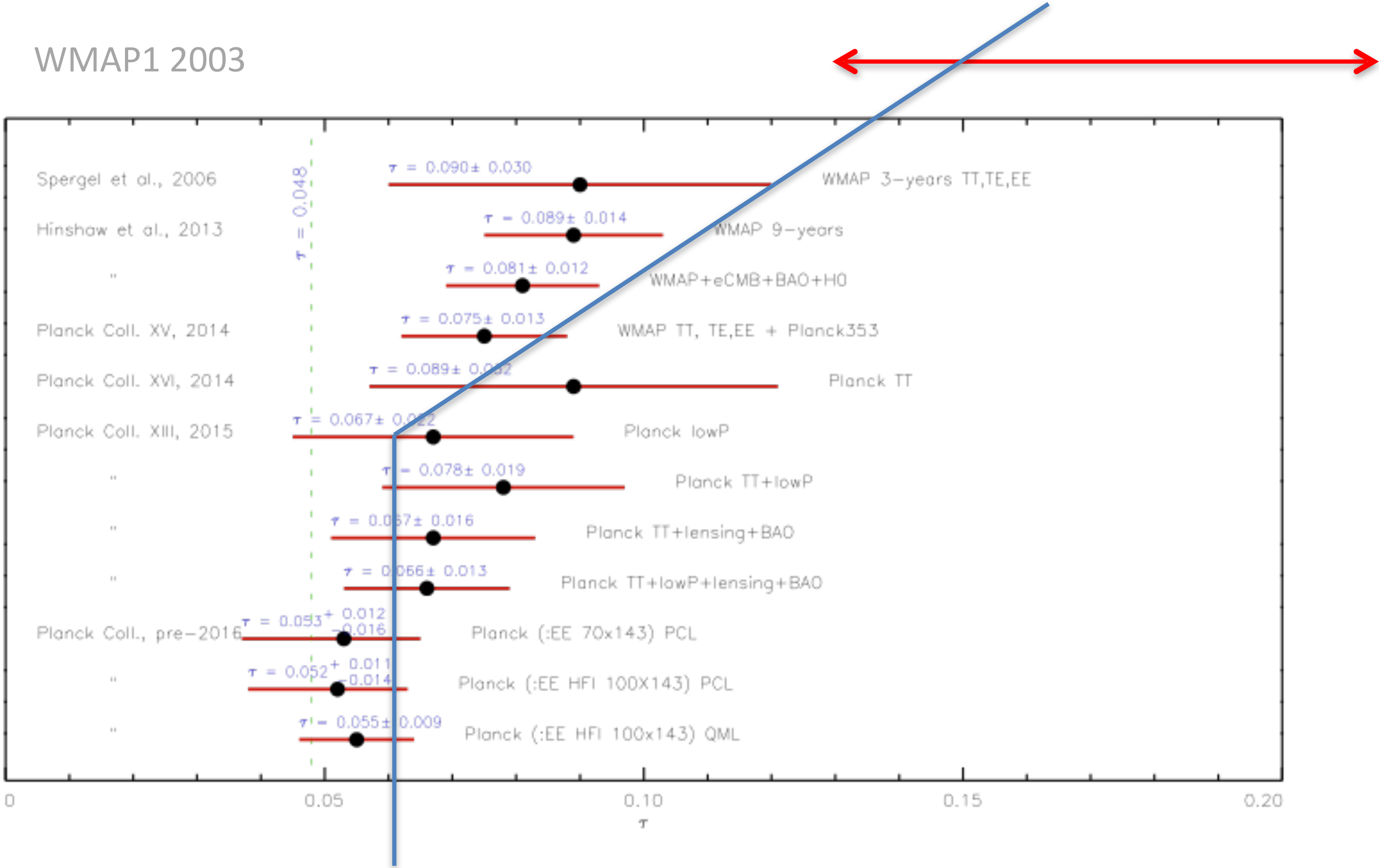
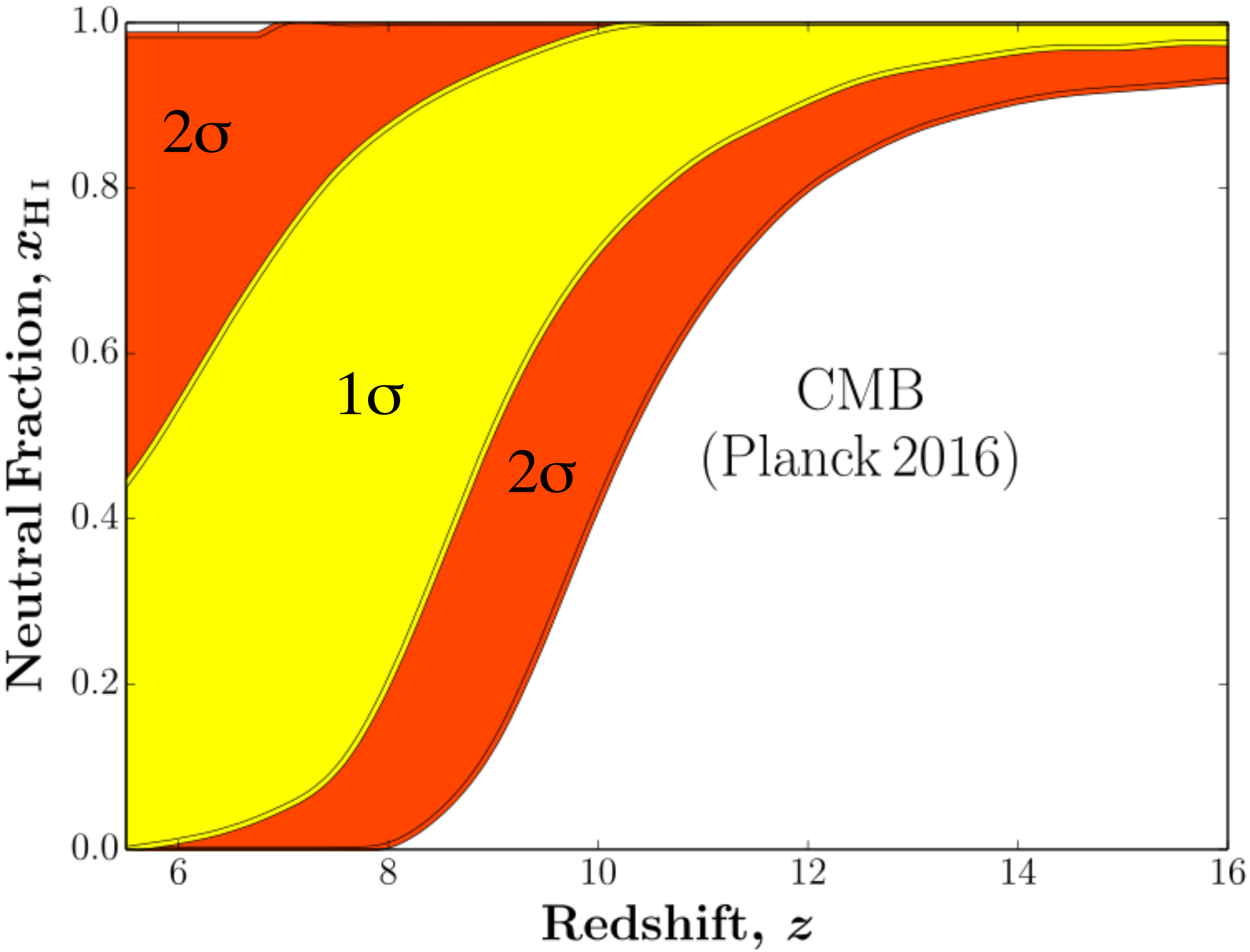


Planck 2016

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



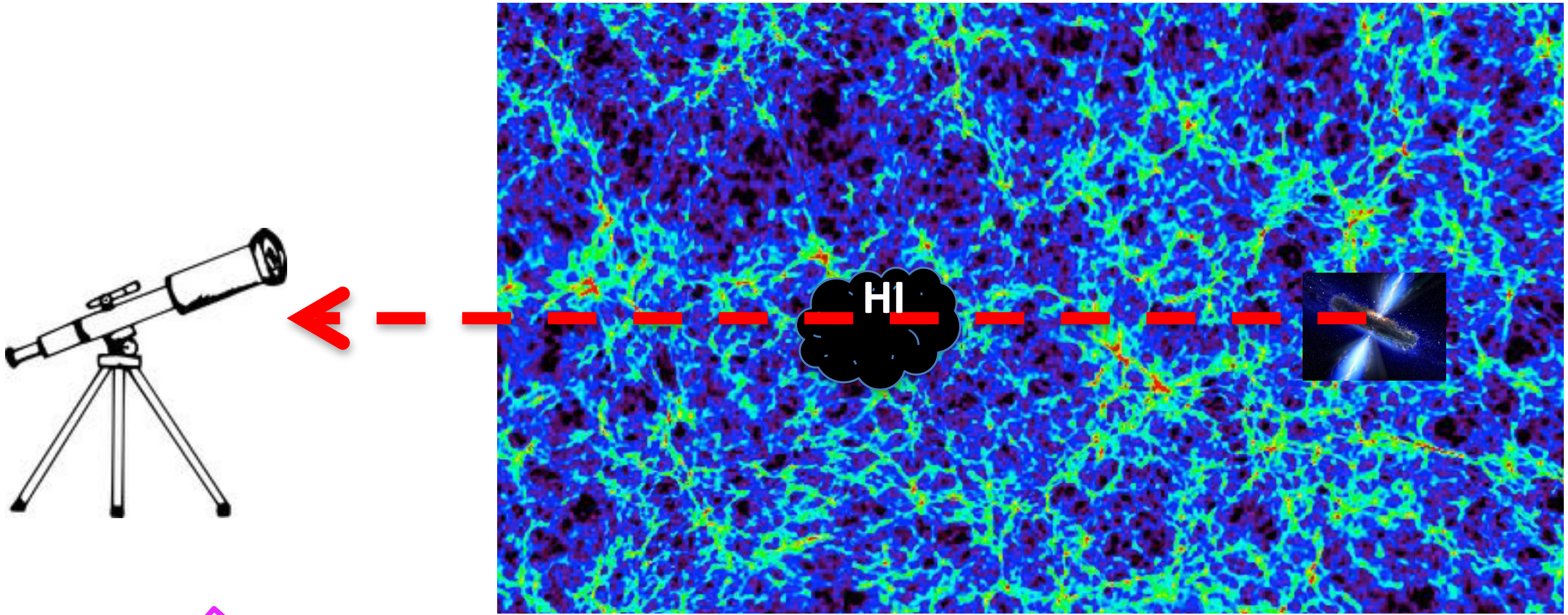
Greig & AM 2016

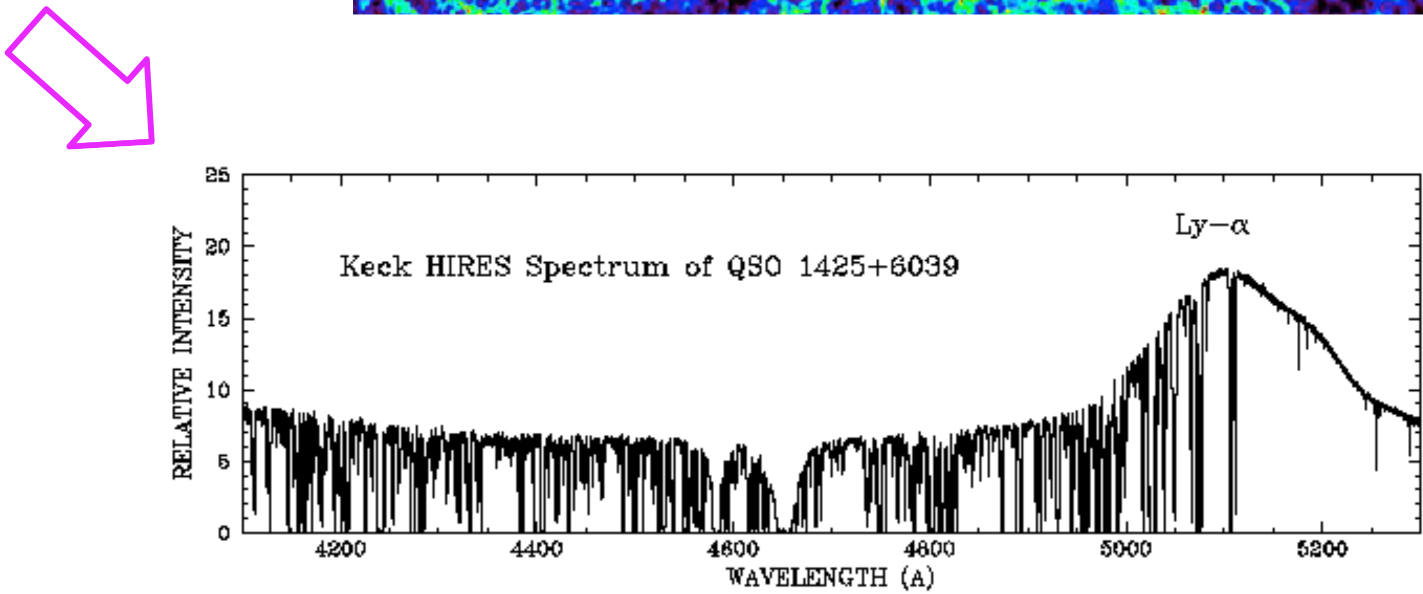
When?

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

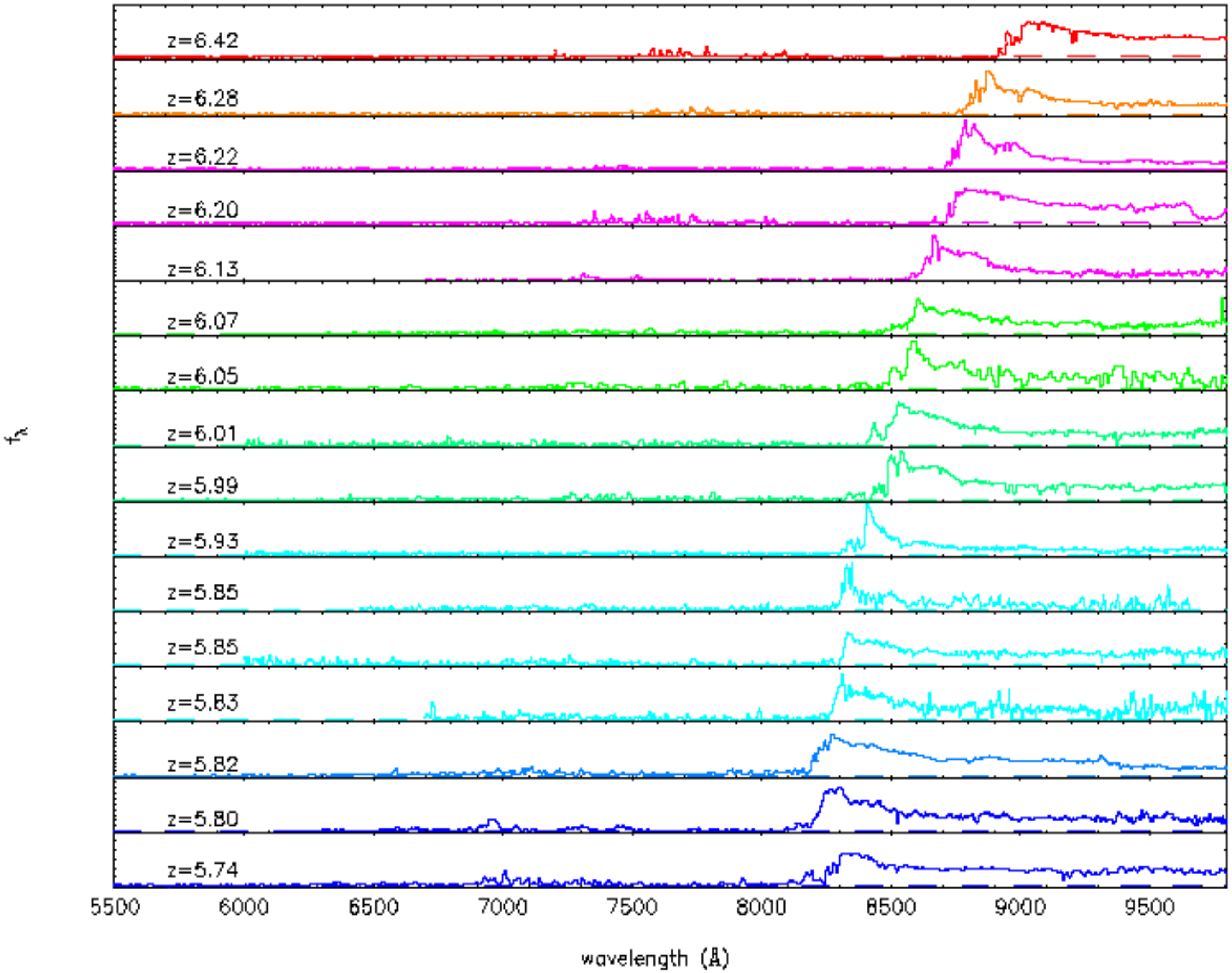
Astrophysical flashlights: Lyα

Post-reionization IGM





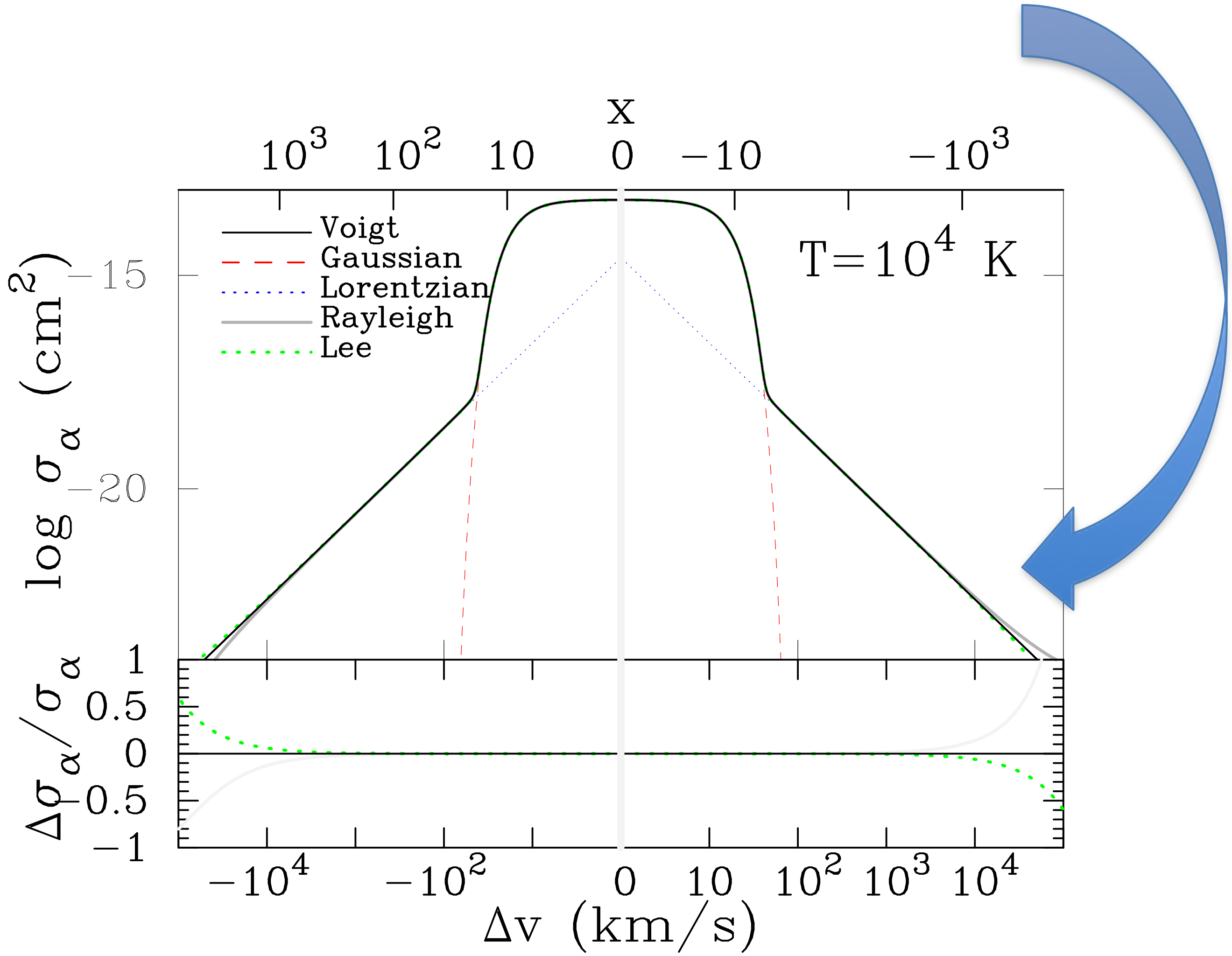
We can't directly observe the EoR in Lyα



Fan+ (2006)

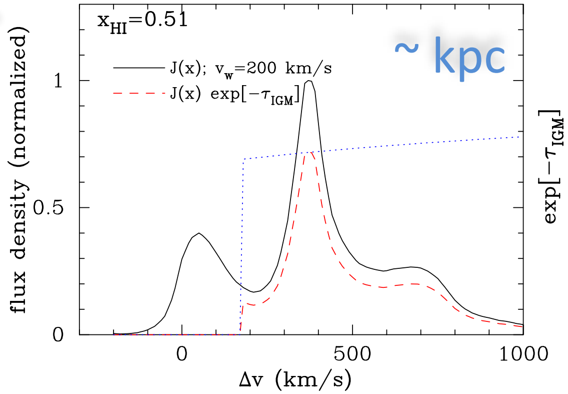
Lyα forest saturates at z>5, when the Universe becomes too dense.
Even trace amounts of HI, x_{HI} ~> 10^{-5} result in no flux being detected in the forest.

But... *damping wing*!



Dijkstra 2014

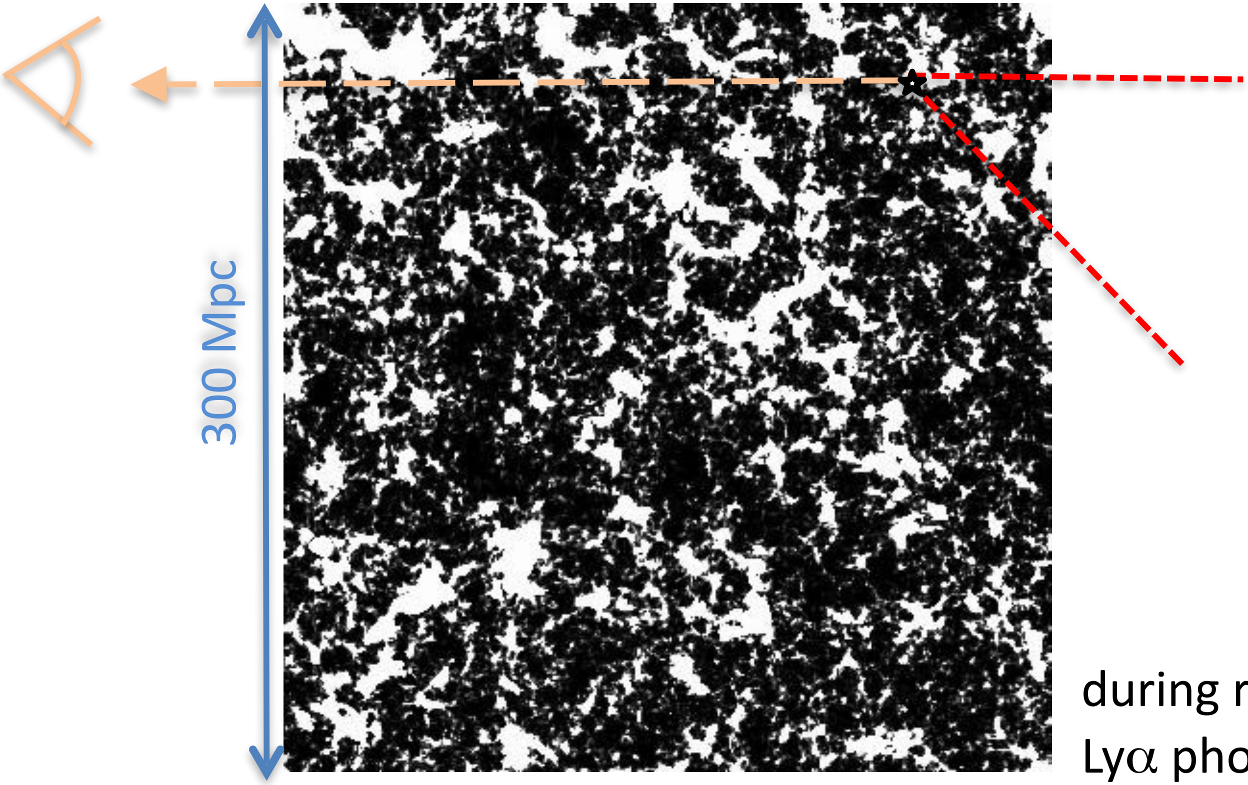
Lyα damping wing absorption as a probe of the EoR

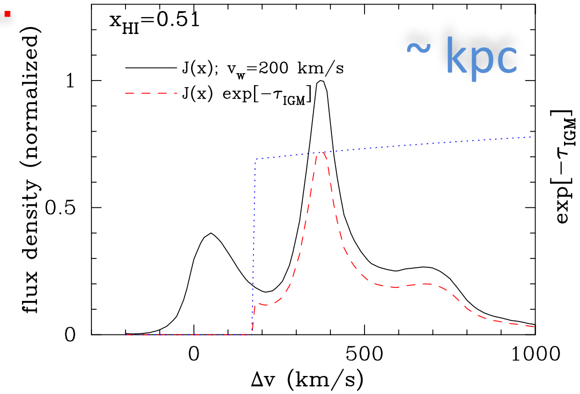


e.g. Dijkstra, AM+2011

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

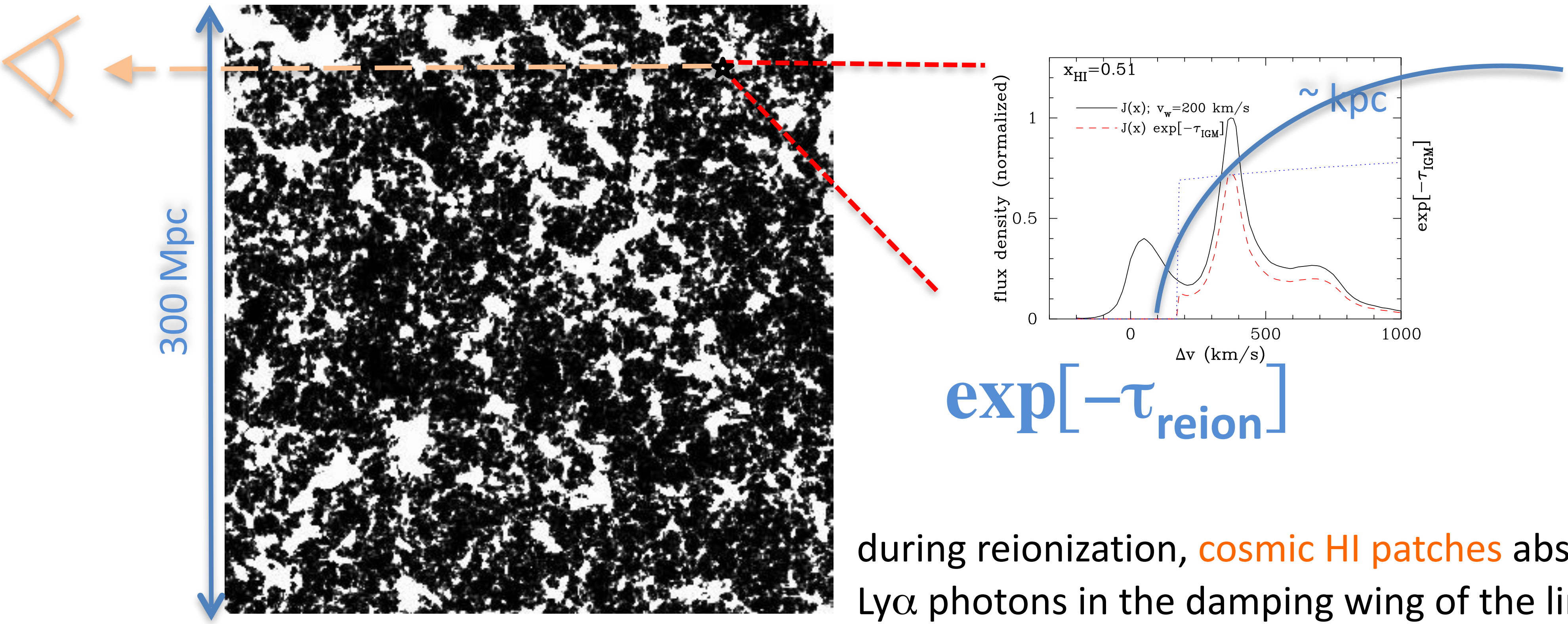
Lyα damping wing absorption as a probe of the EoR





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



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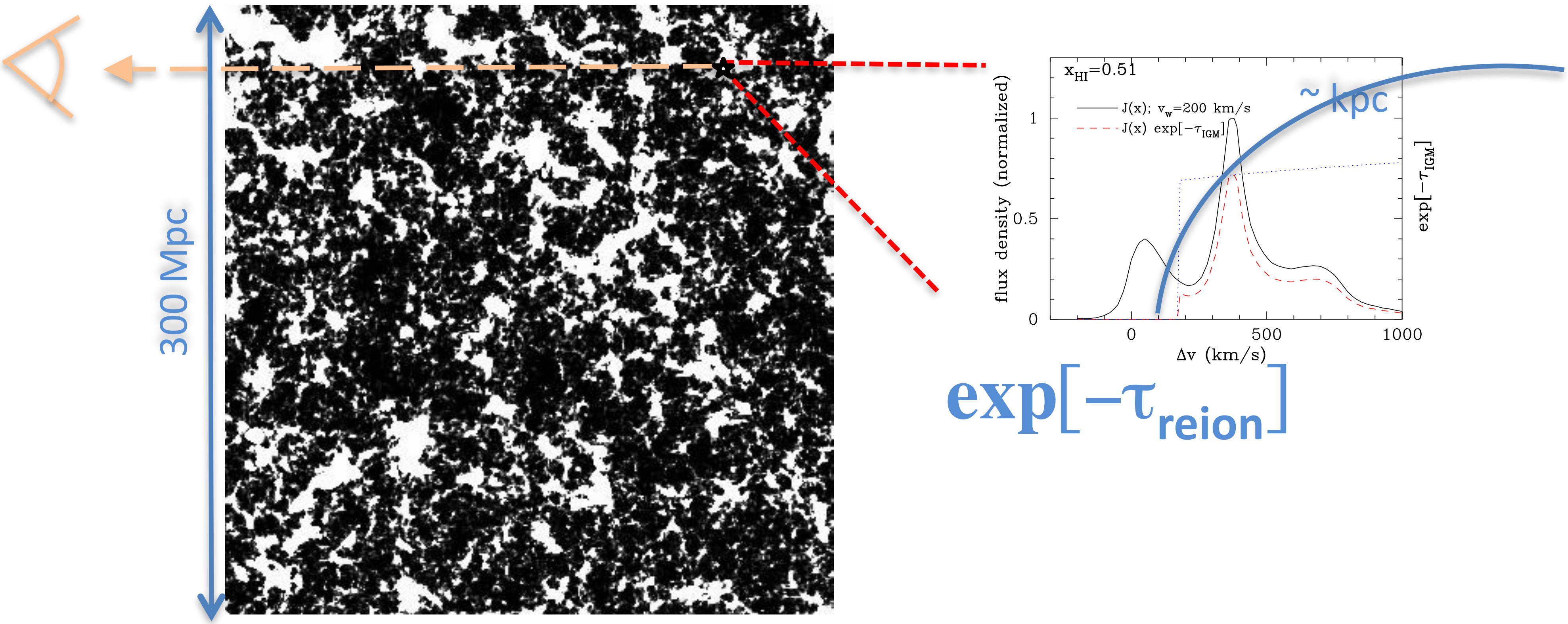


The EoR modulates:

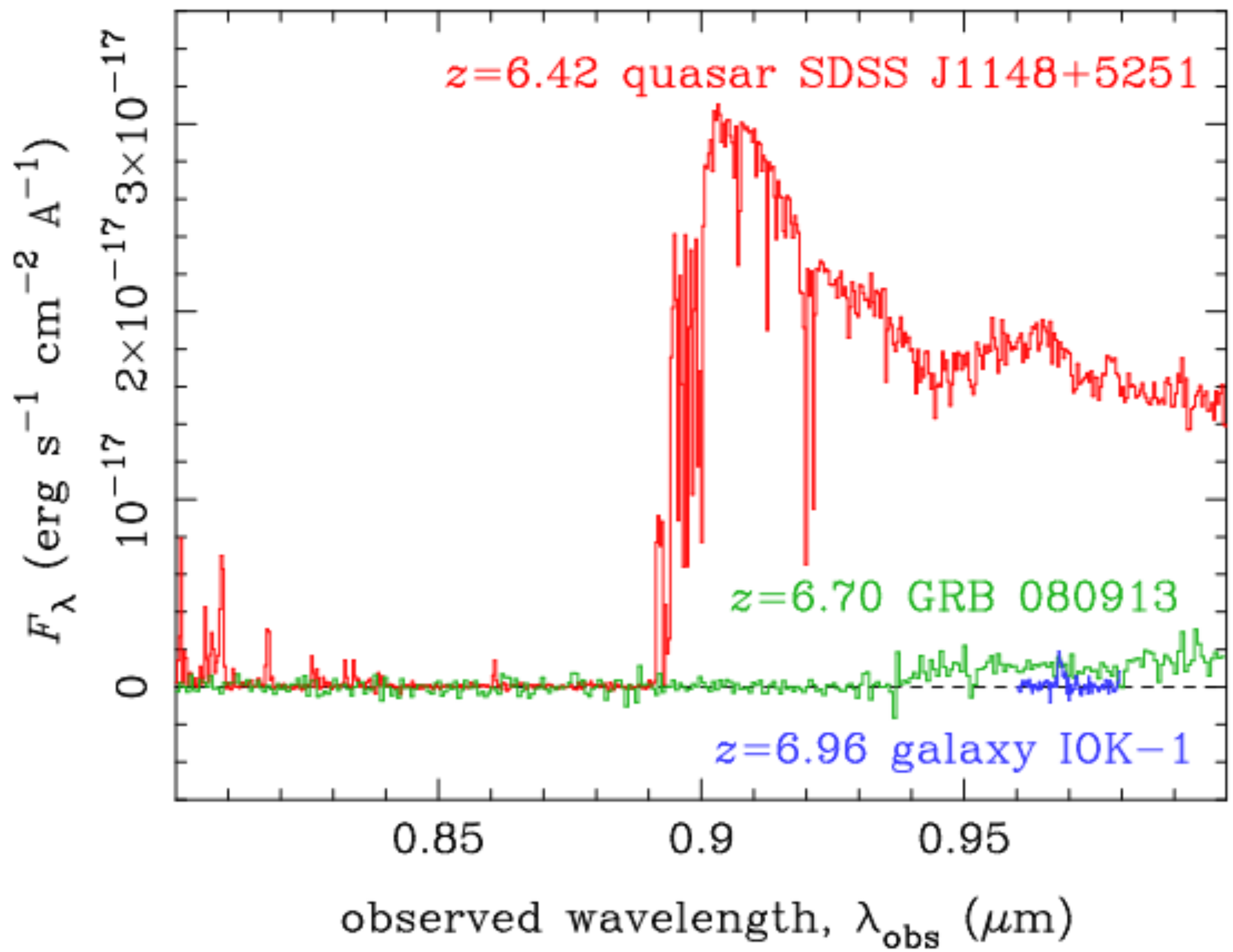
1. **the observability of Lyman alpha emission**
2. **the observed clustering of Lyα emitting galaxies**

an example:

the first detection of ongoing EoR from a z=7.1 QSO

QSOs: the brightest cosmic flashlights

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



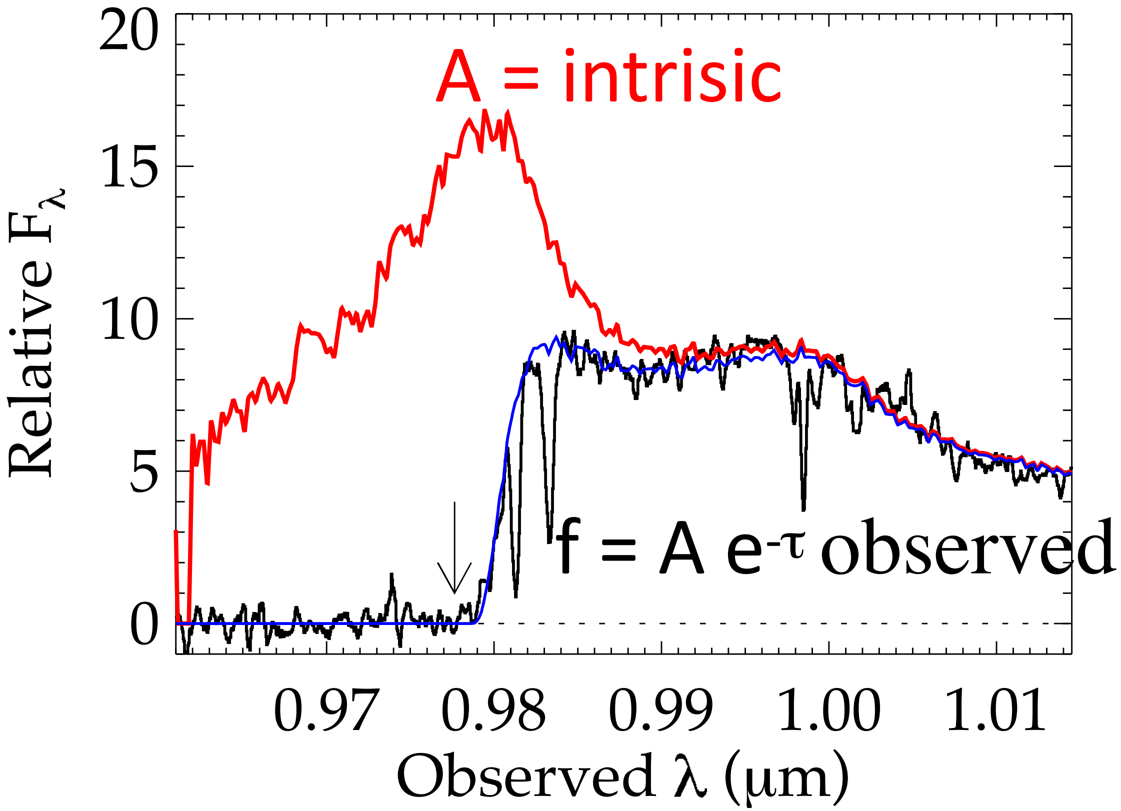
QSO spectra can be analyzed ***individually***, unlike galaxies which require a statistically significant sample

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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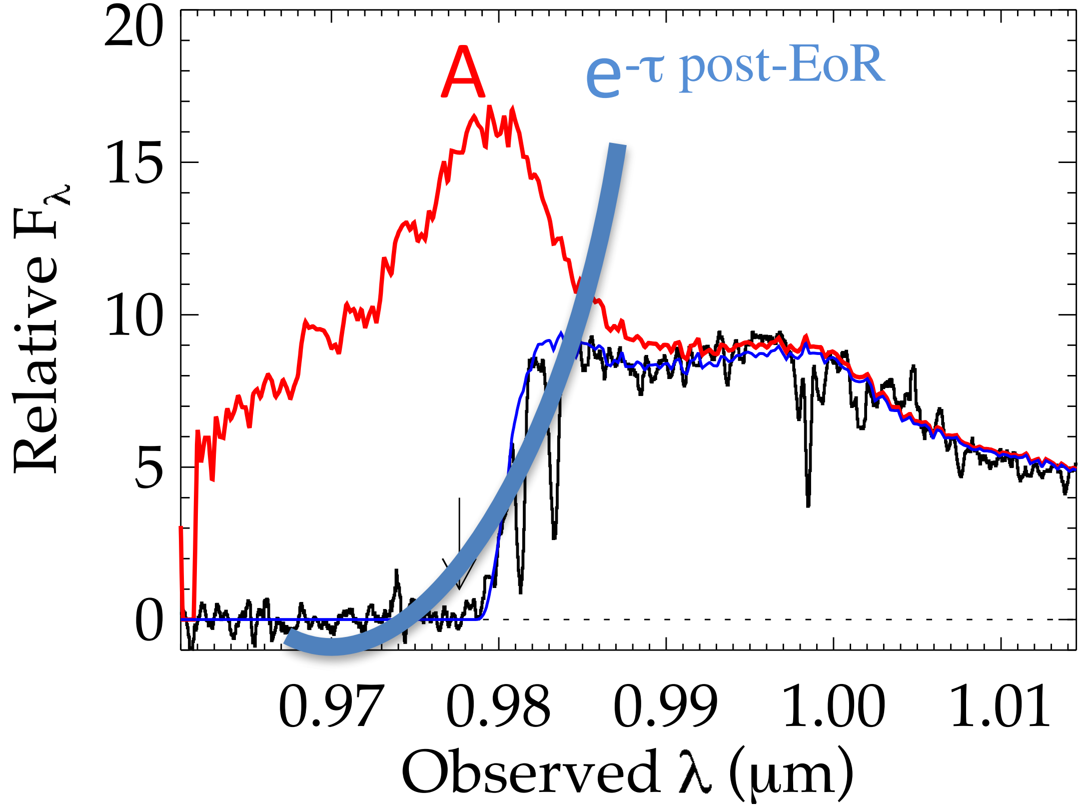

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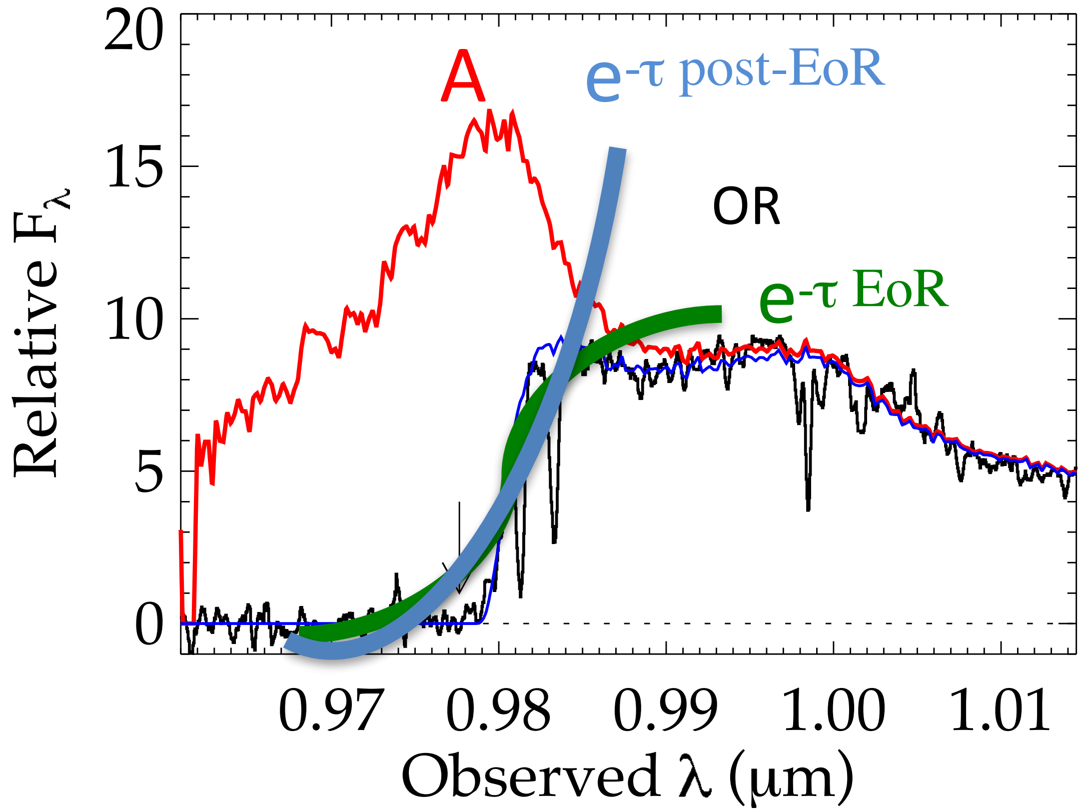

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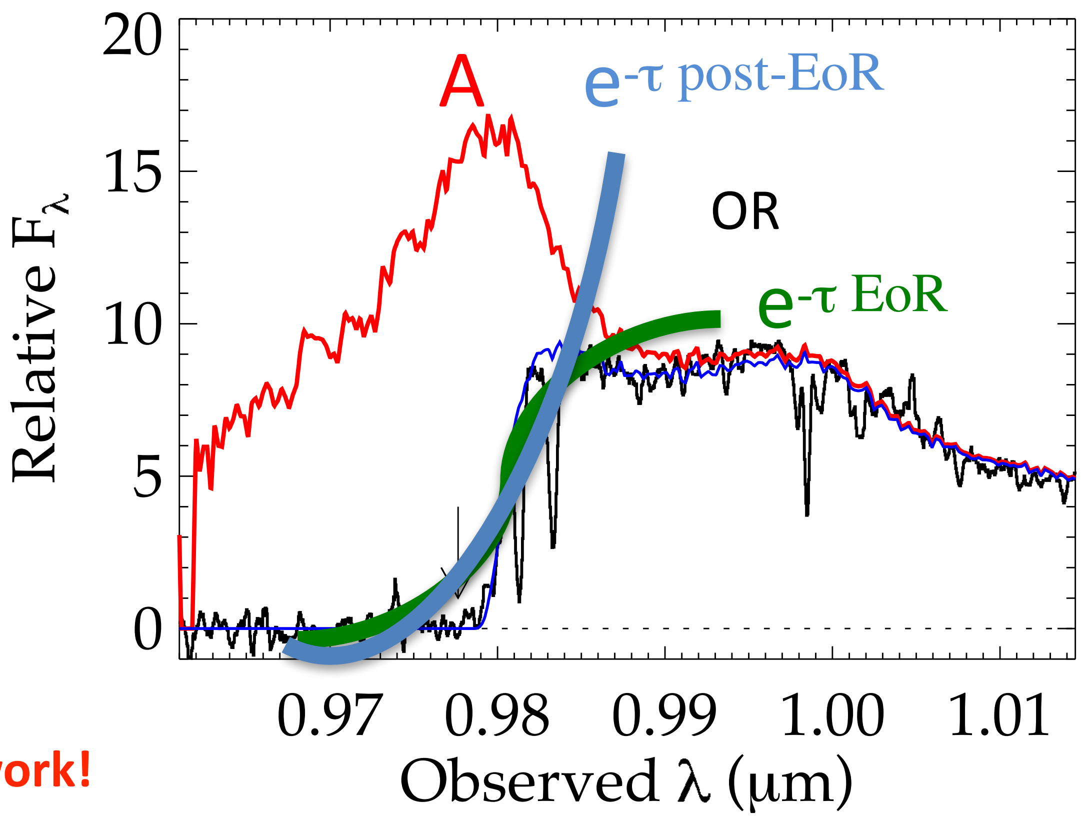

model both terms in Bayesian framework!

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

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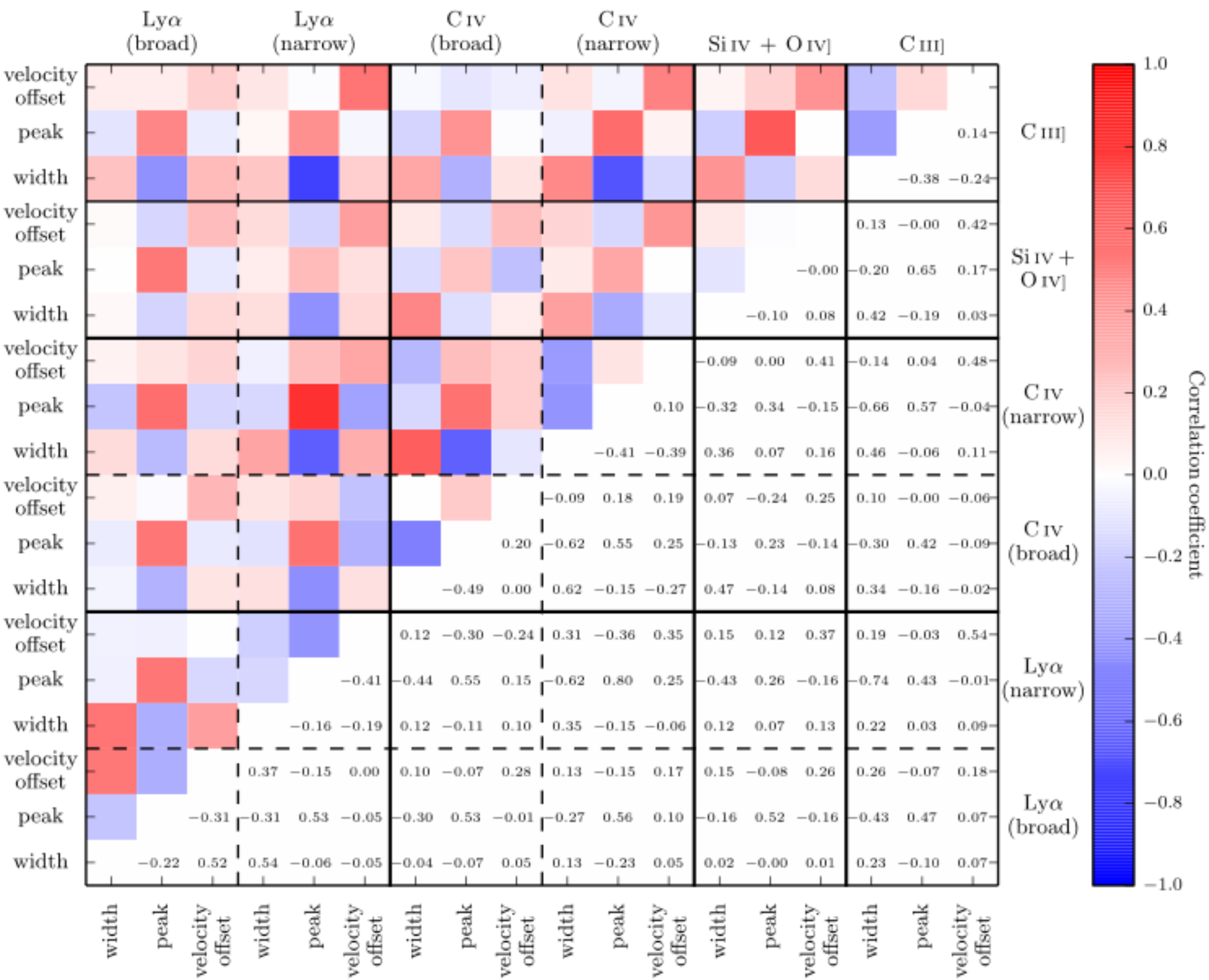

Analysis of z=7.1 QSO ULASJ1120

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- **Step 2:** run large-scale, state-of-the-art simulations of reionization, spanning a range of uncertainties in the EoR topology (AM+ 2016)

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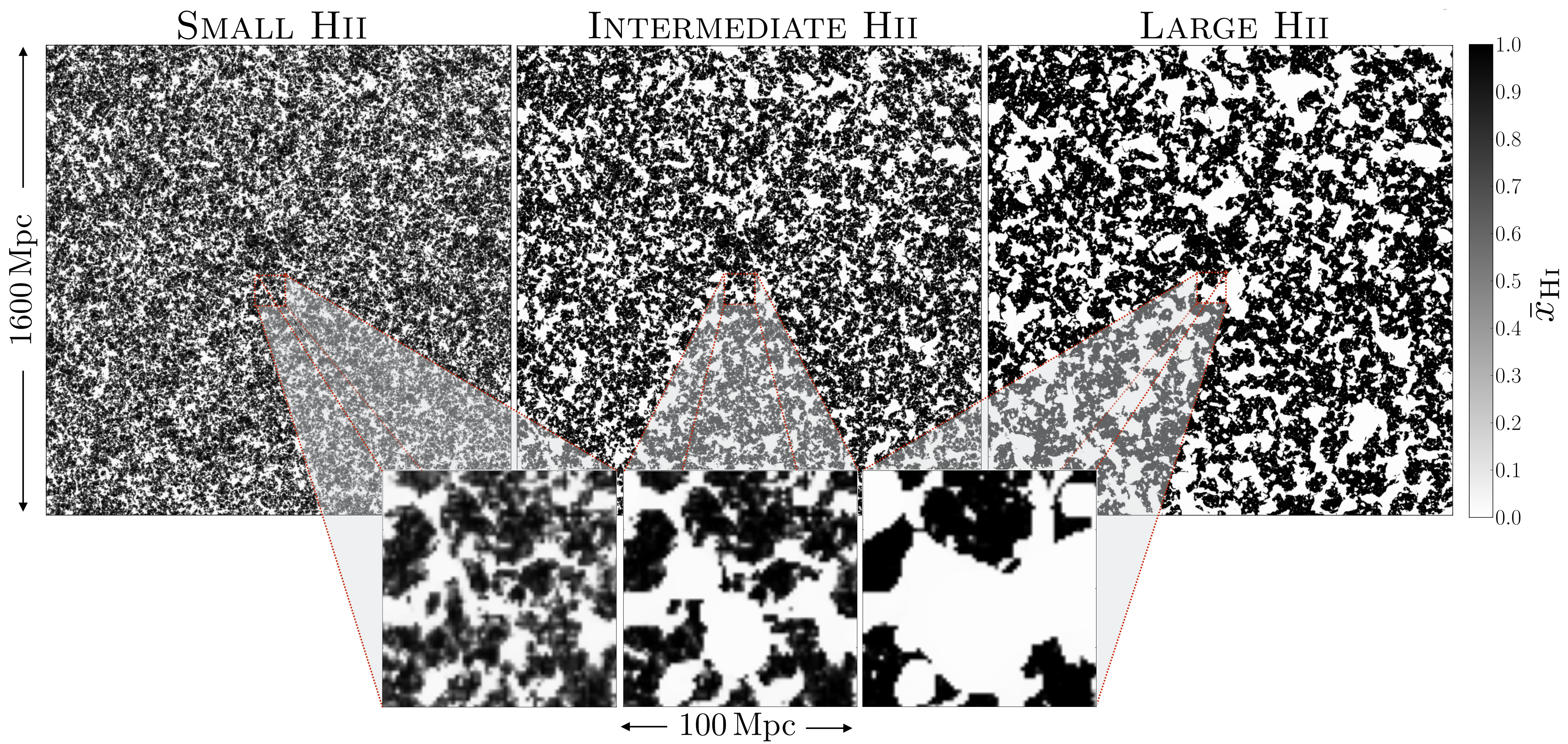

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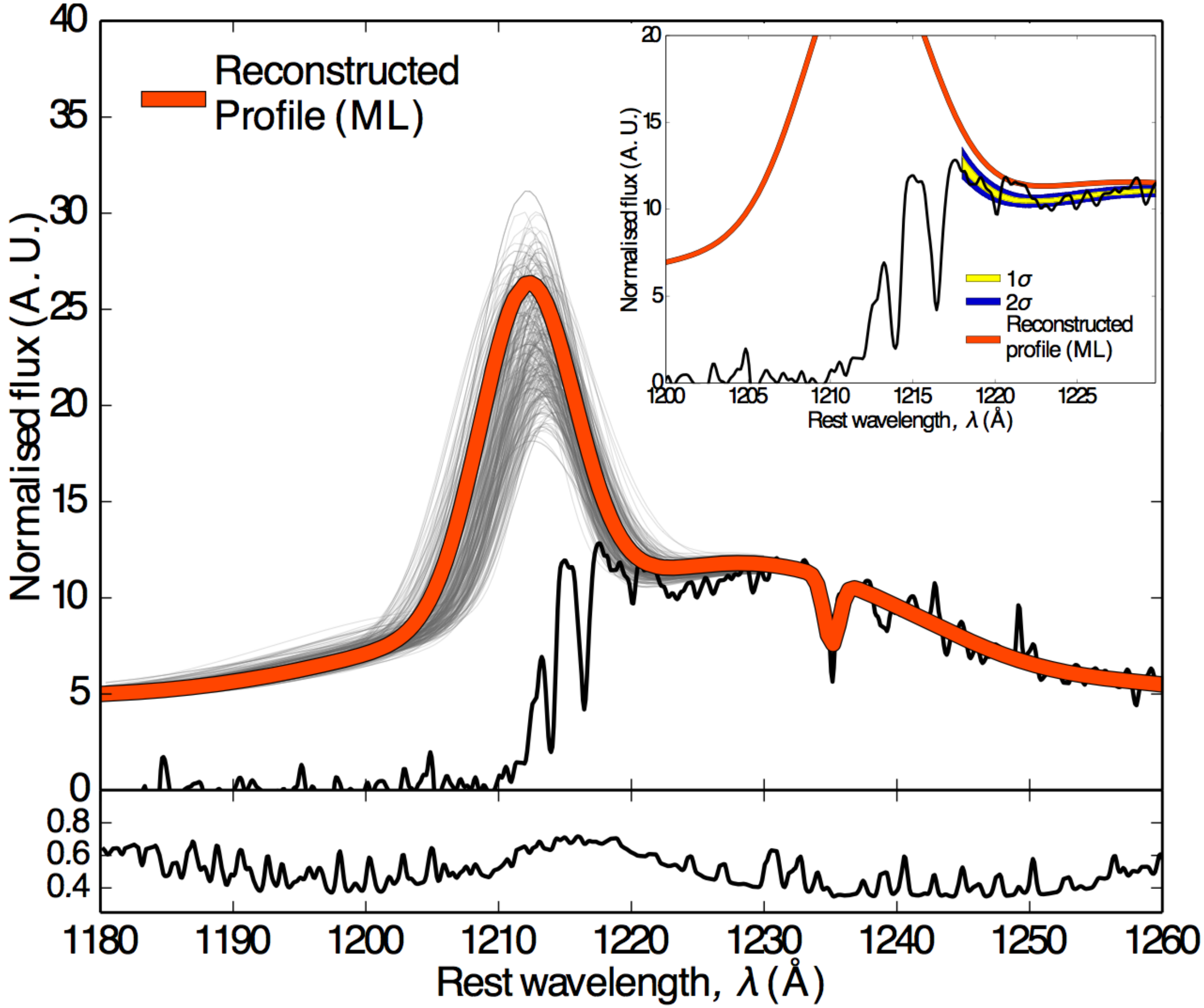
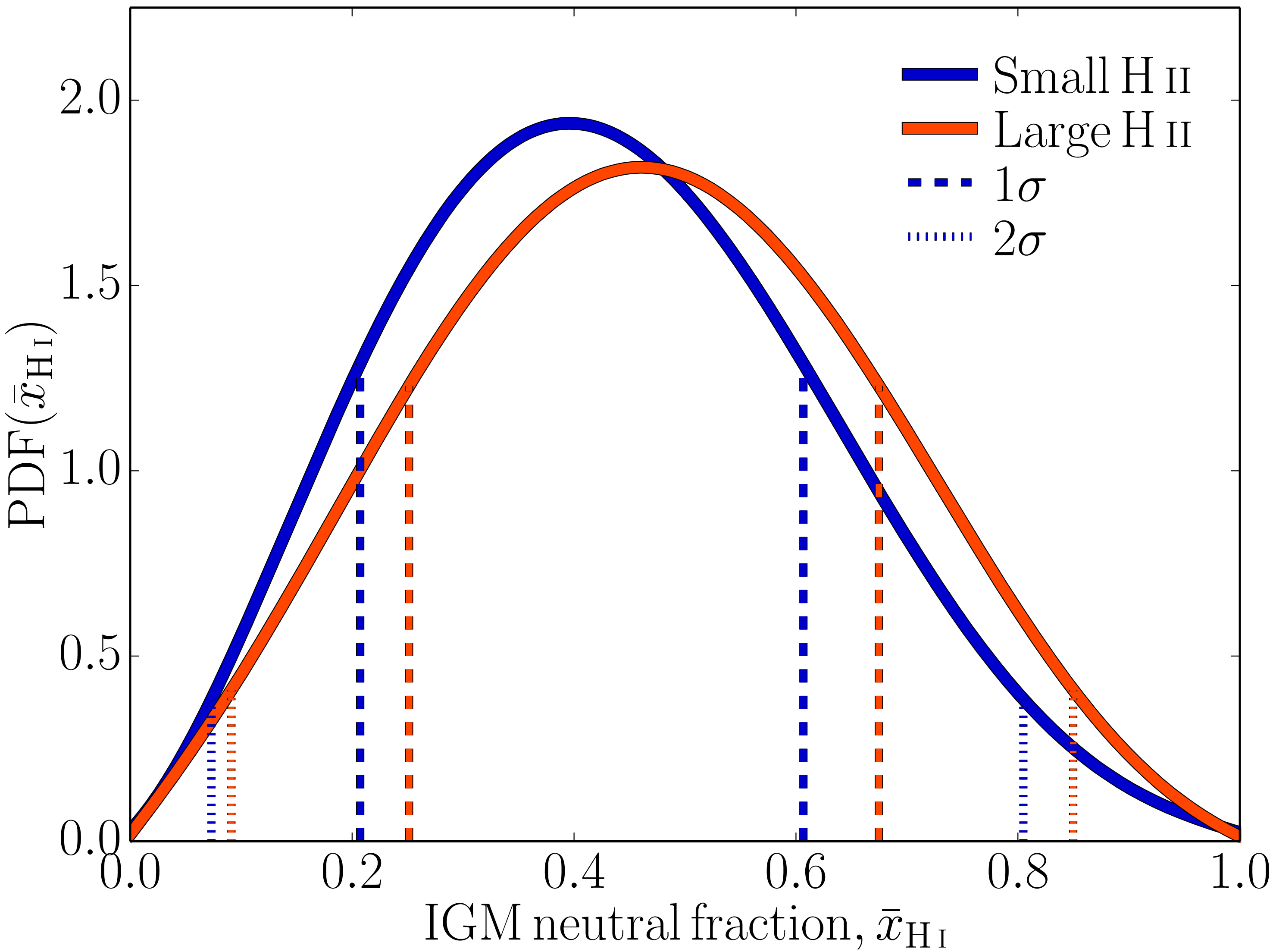
- **Step 2:** run large-scale, state-of-the-art simulations of reionization, spanning a range of uncertainties in the EoR topology (AM+ 2016)
- **Step 3:** Simultaneously sample intrinsic emission + IGM absorption, in a Bayesian framework (Greig, AM+ 2016b)

Analysis of z=7.1 QSO ULASJ1120



Greig, AM+ 2016b

Analysis of z=7.1 QSO ULASJ1120

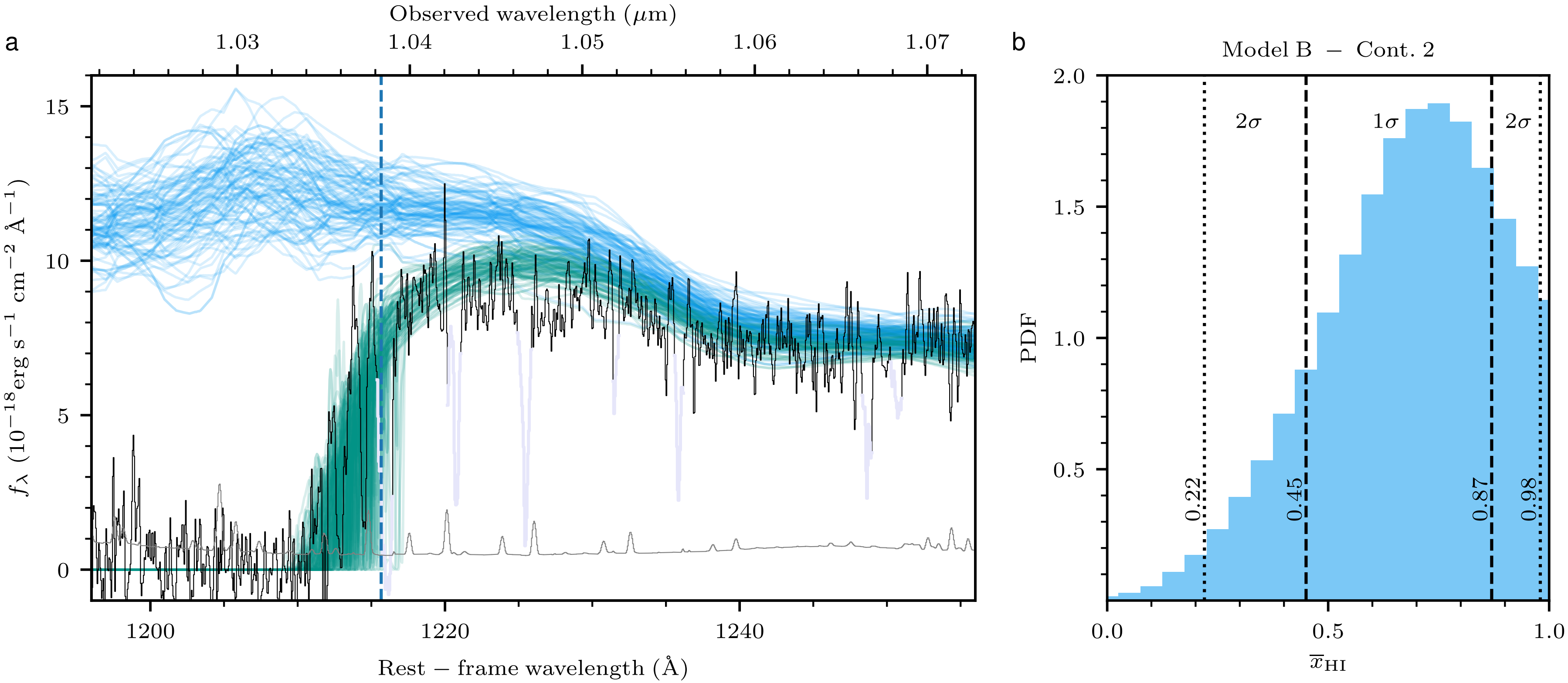


First detection of ongoing reionization!!!

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

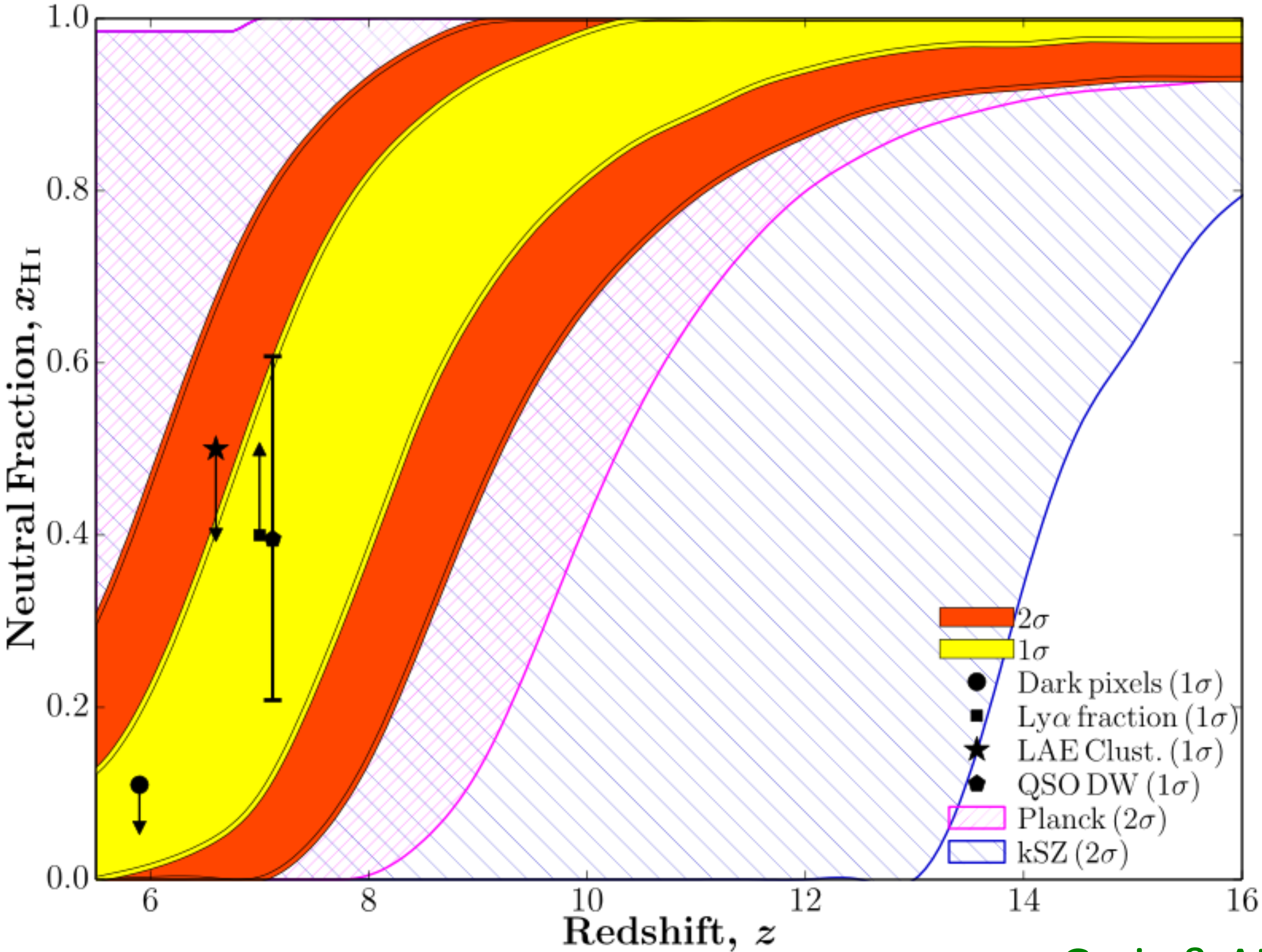
Greig, AM+ 2016b

Subsequent, similar analysis of z=7.1 and new z=7.5 QSO



Banados+2018

current state of knowledge:
When did the Universe reionize?



Greig & AM (2017)
see also Planck 2016;
Price+2016; Mitra+2016

We now have a reasonable handle on when…

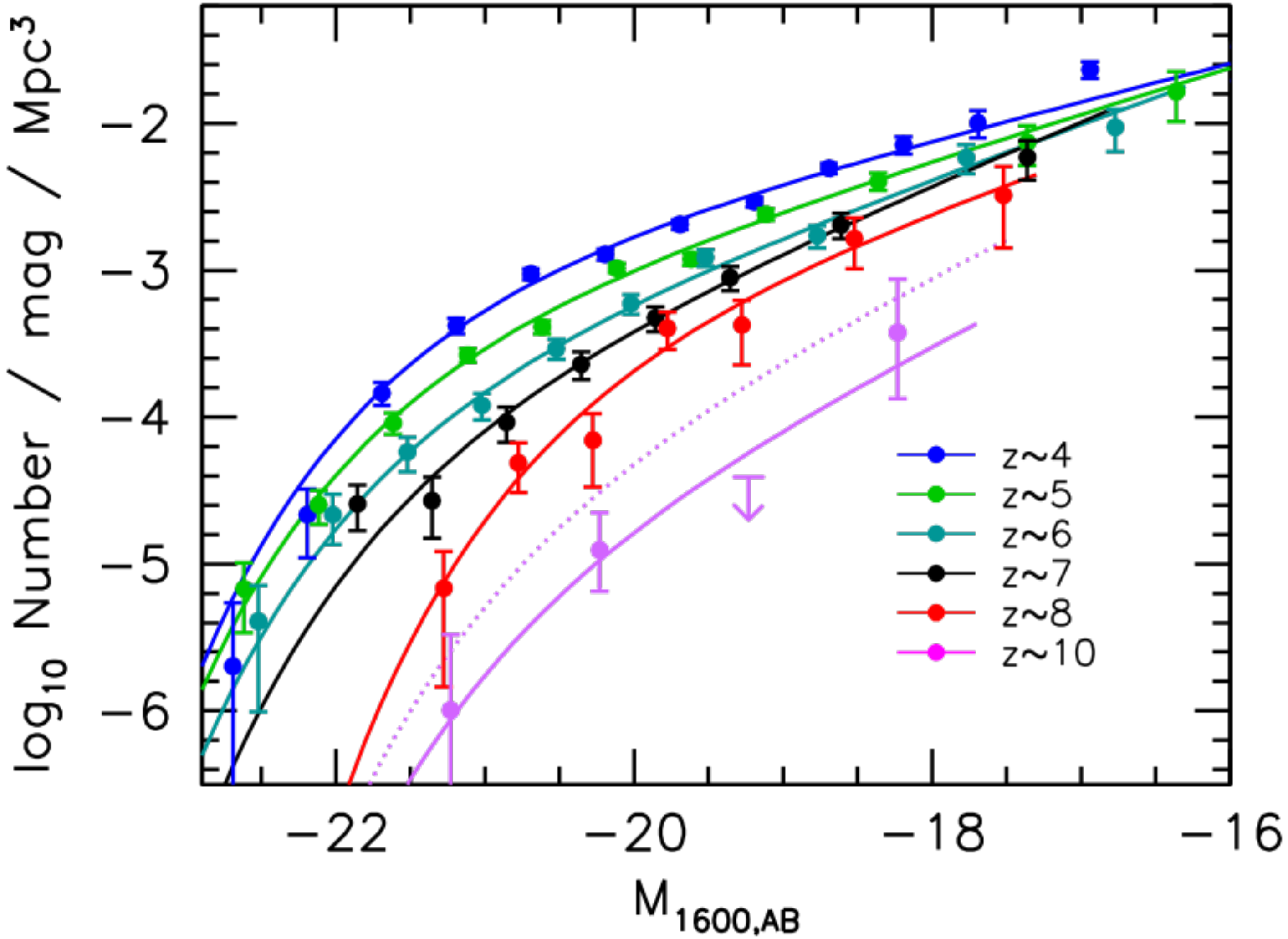
What and how??

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..

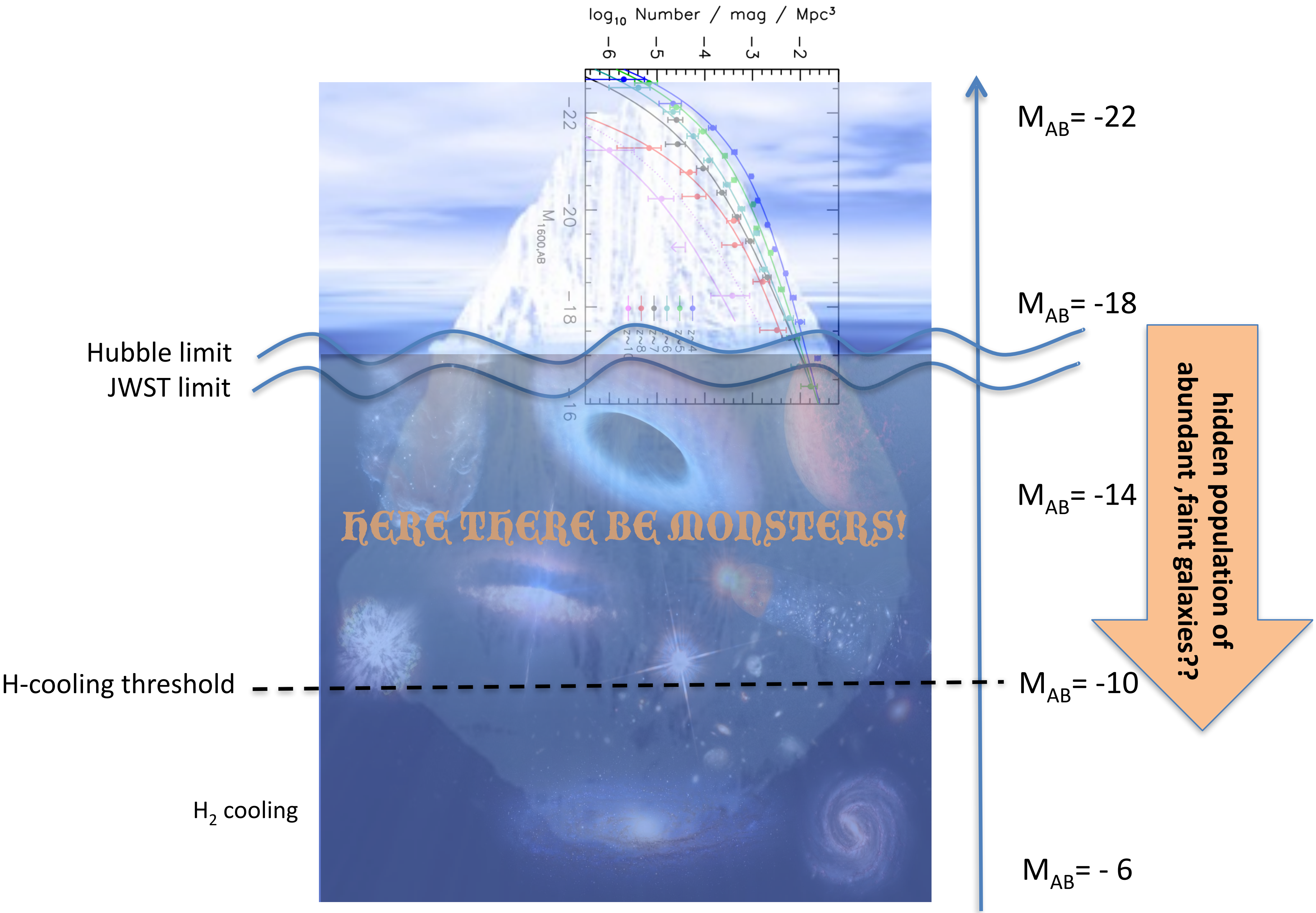
we don't really know…

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, with too few ionizing photos escaping

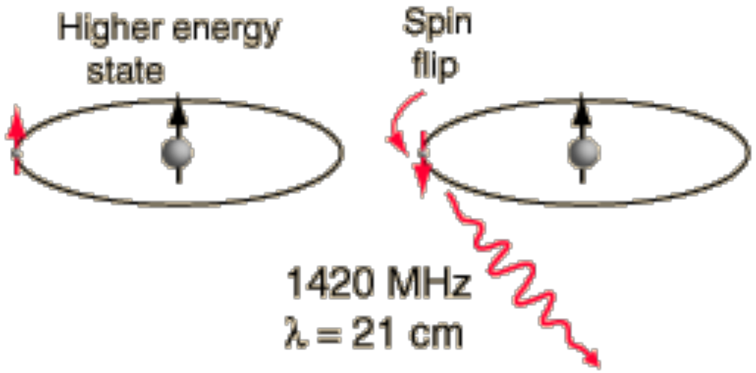


Bouwens+ (2015)


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??

Get ready for the revolution: the cosmic 21 cm signal

21 cm line from neutral hydrogen



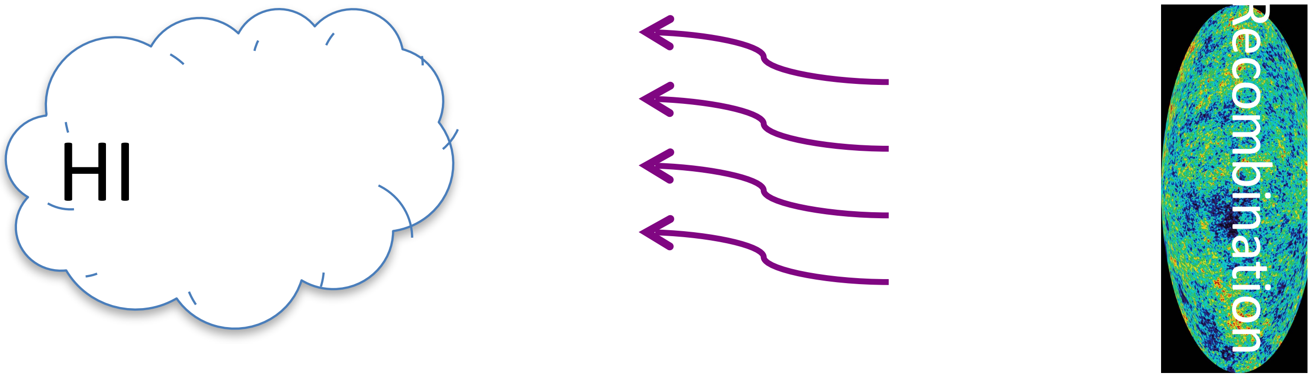
Hyperfine transition in the ground state of neutral hydrogen produces the 21cm line.

Cosmic 21-cm signal

HERA (2019—

SKA (202x —

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:

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

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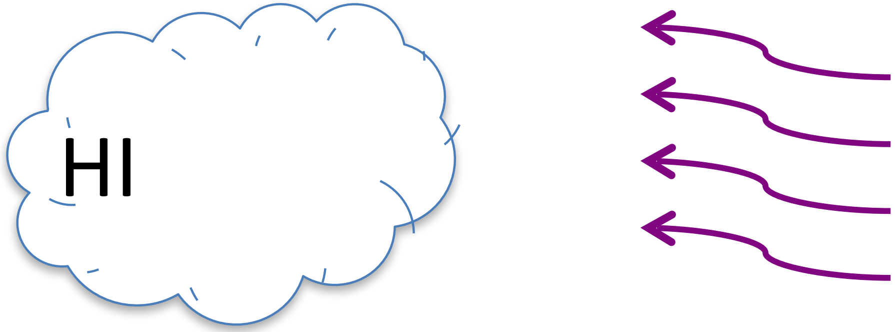

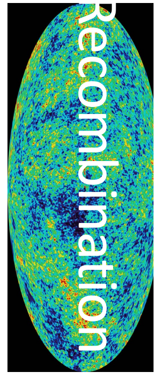

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Signal contains both **ASTROPHYSICAL**

Cosmic 21-cm signal

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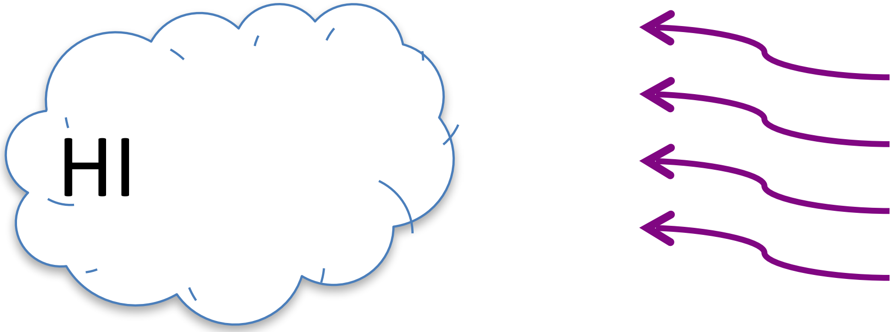

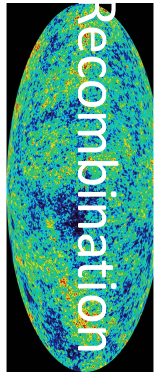

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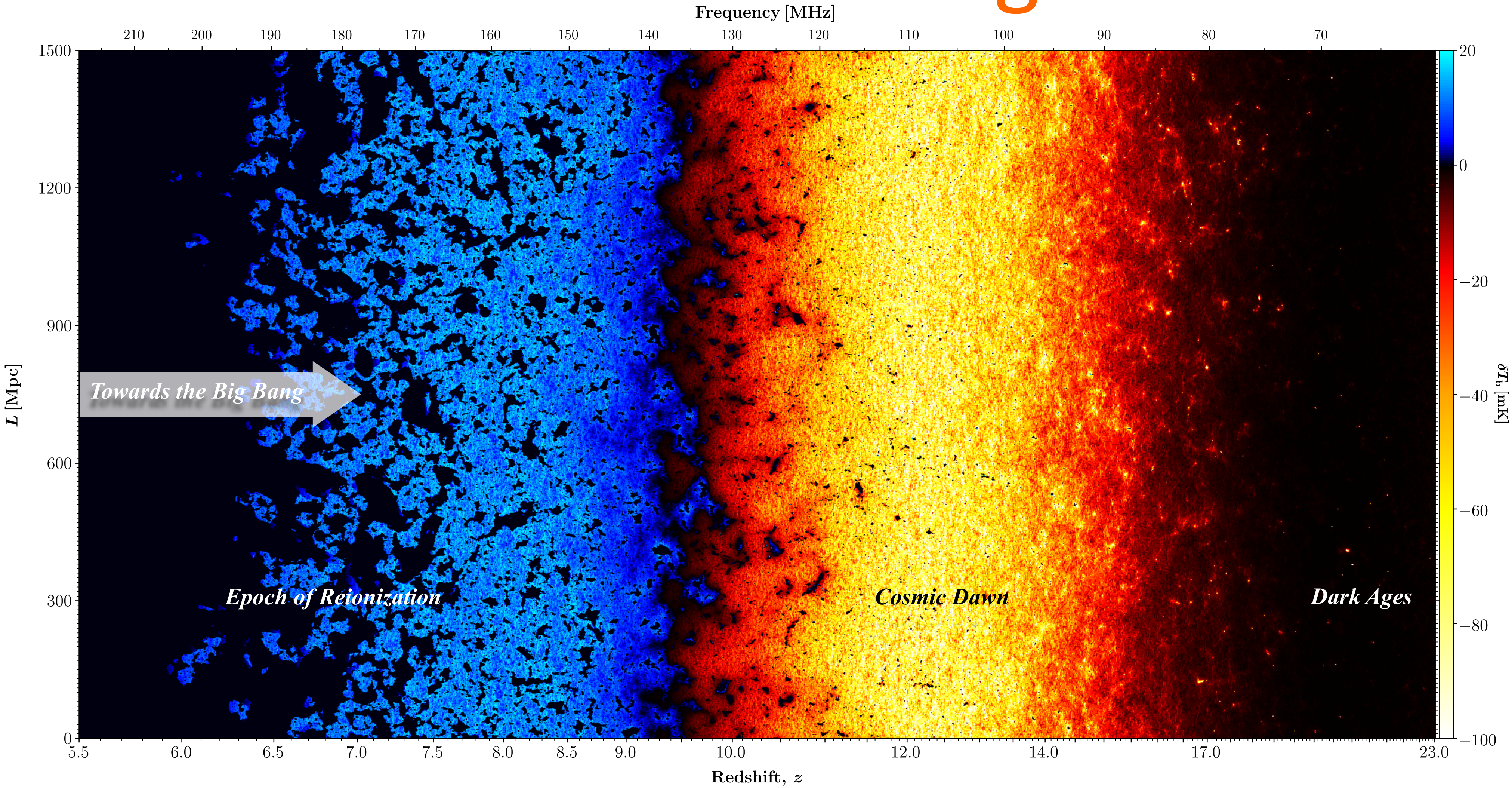
Signal contains both **ASTROPHYSICAL** and **COSMOLOGICAL** terms

Cosmic 21-cm signal



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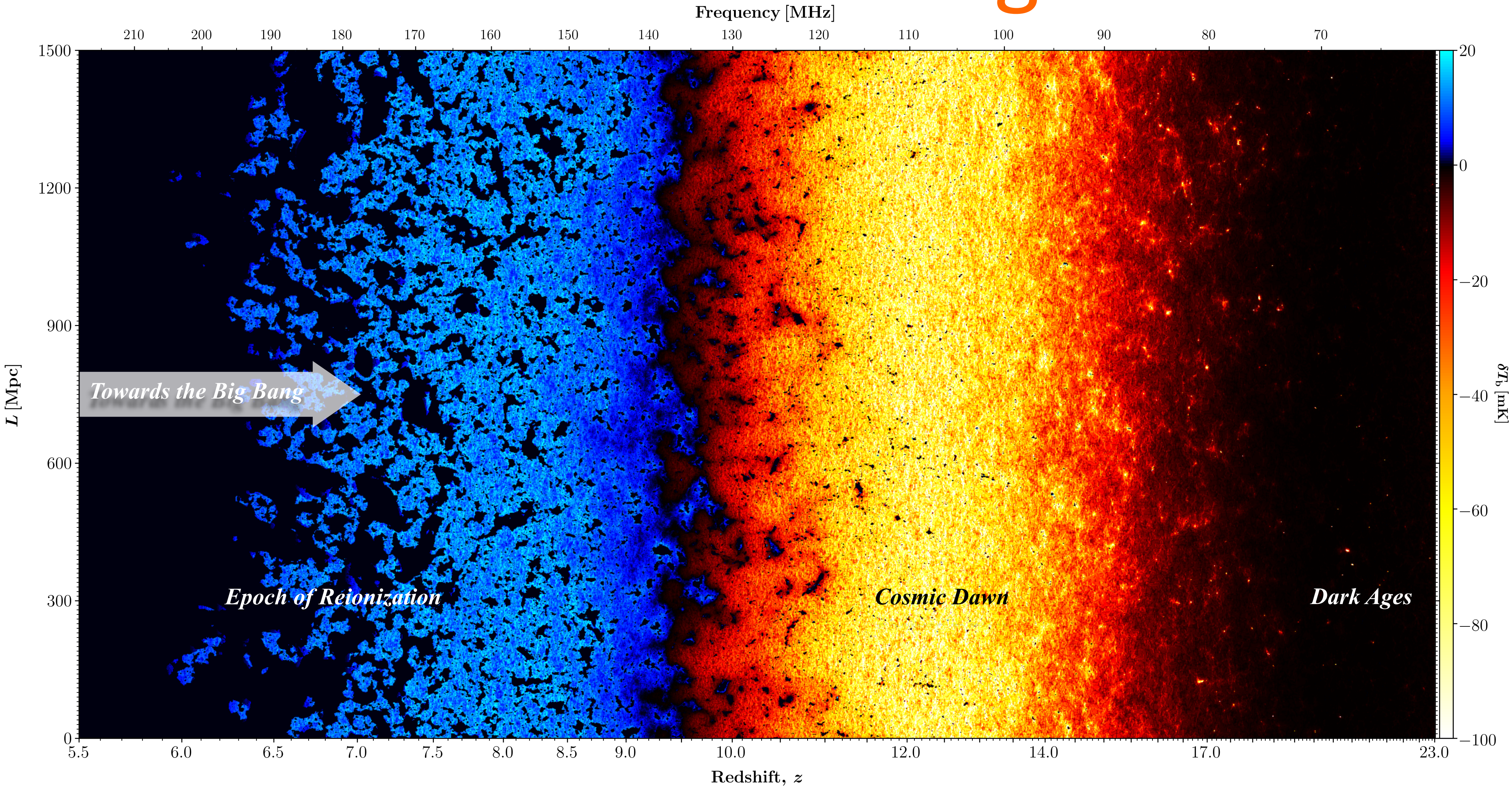


- **3D** signal with **> 10 orders of magnitude** more independent modes than in the CMB!
- data collection with upcoming Square Kilometre Array (SKA) will surpass **10x current global internet traffic**!
- even the narrowest fields will contain >billion of unseen galaxies
- **BIG DATA REVOLUTION**!

So how do we learn about the unseen first galaxies?

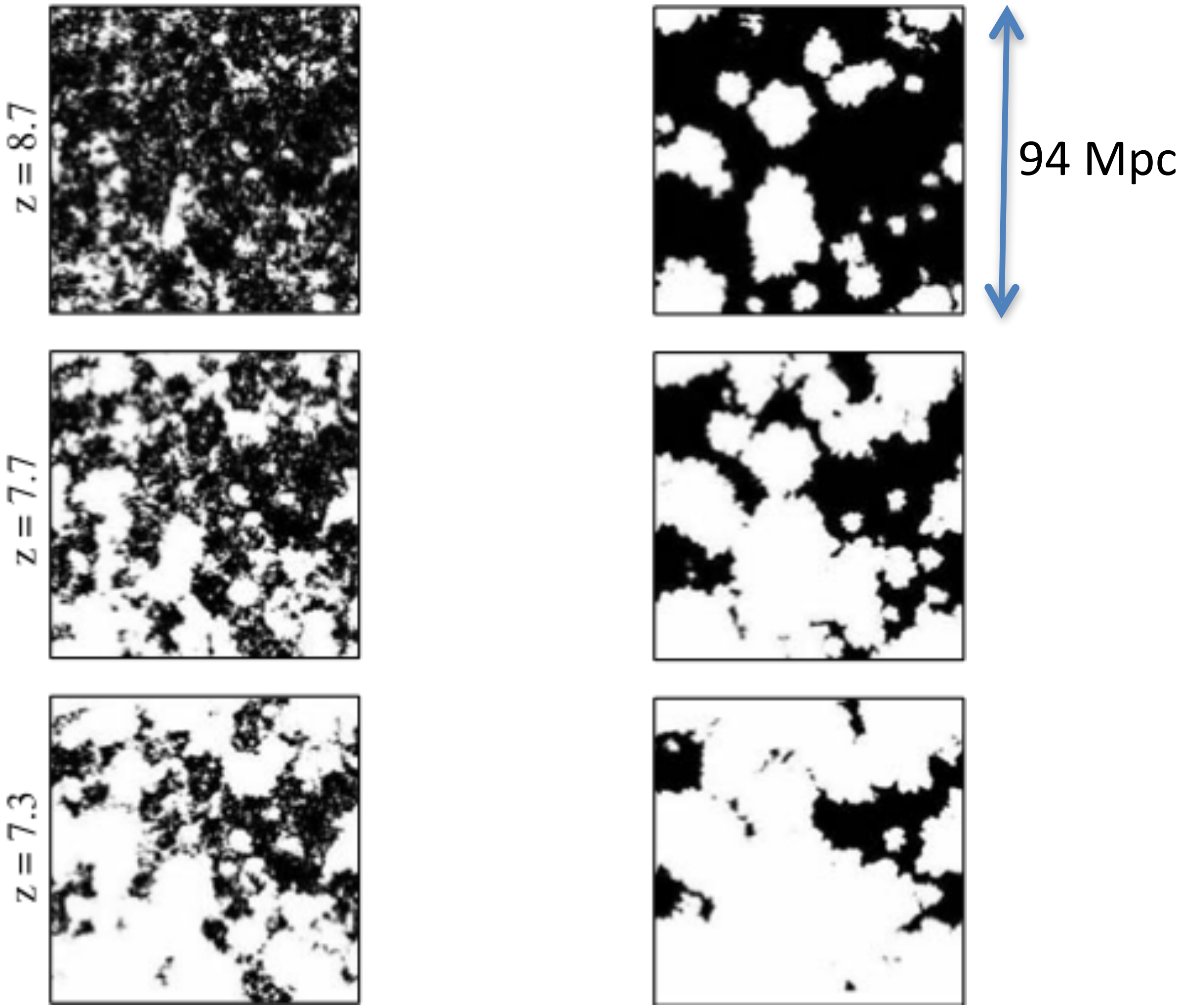
Reionization signal

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

- Short mean free path + long recombination times of mean IGM → *reionization is bimodal (~fully ionized and ~fully neutral patches)*

Its all about timing and the patterns!

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



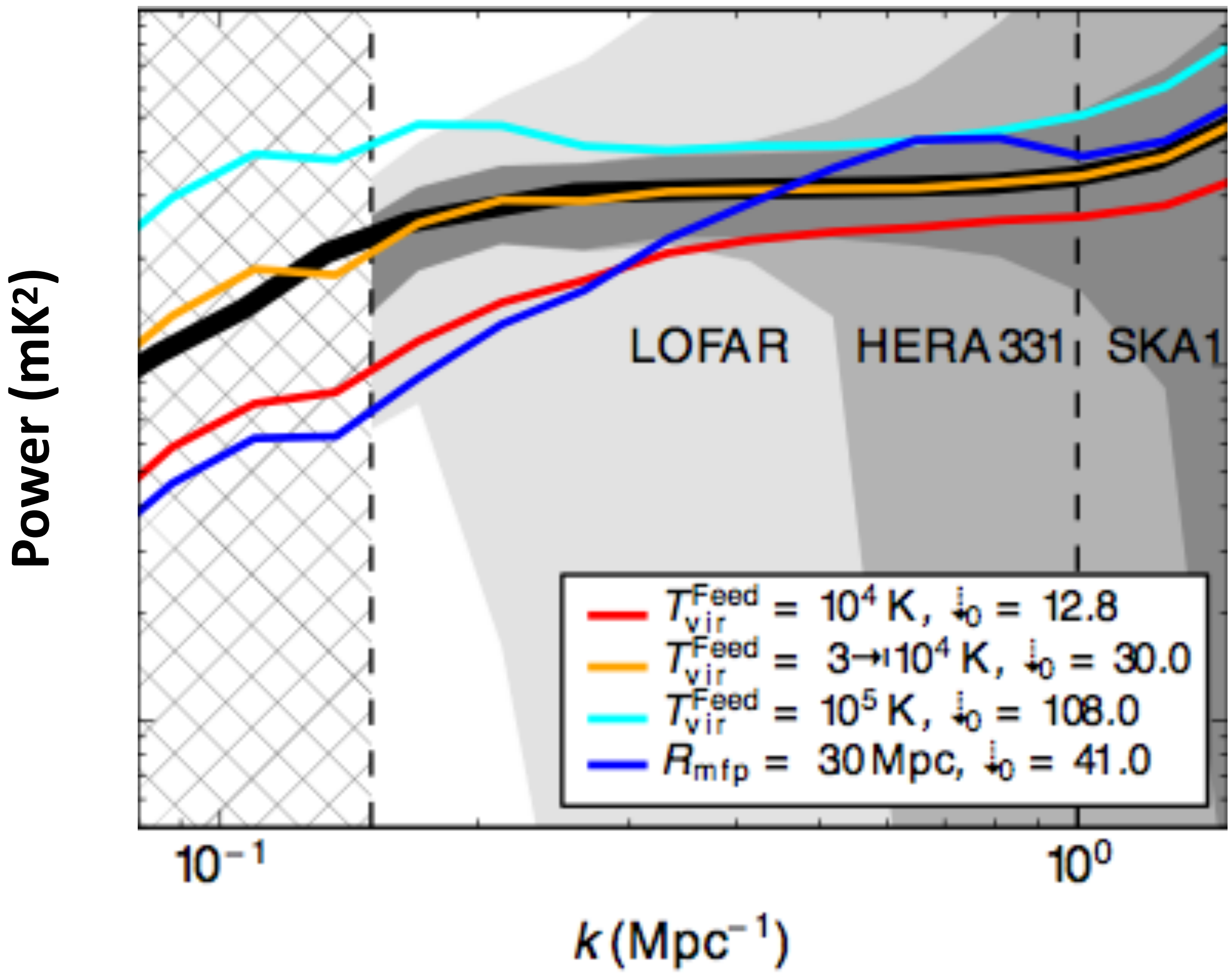
McQuinn+ 2007

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

Pictures are nice, but we need numbers

- Common/simple statistic: power spectrum during EoR

PS at the same mean neutral fraction



Greig & Mesinger (2015)

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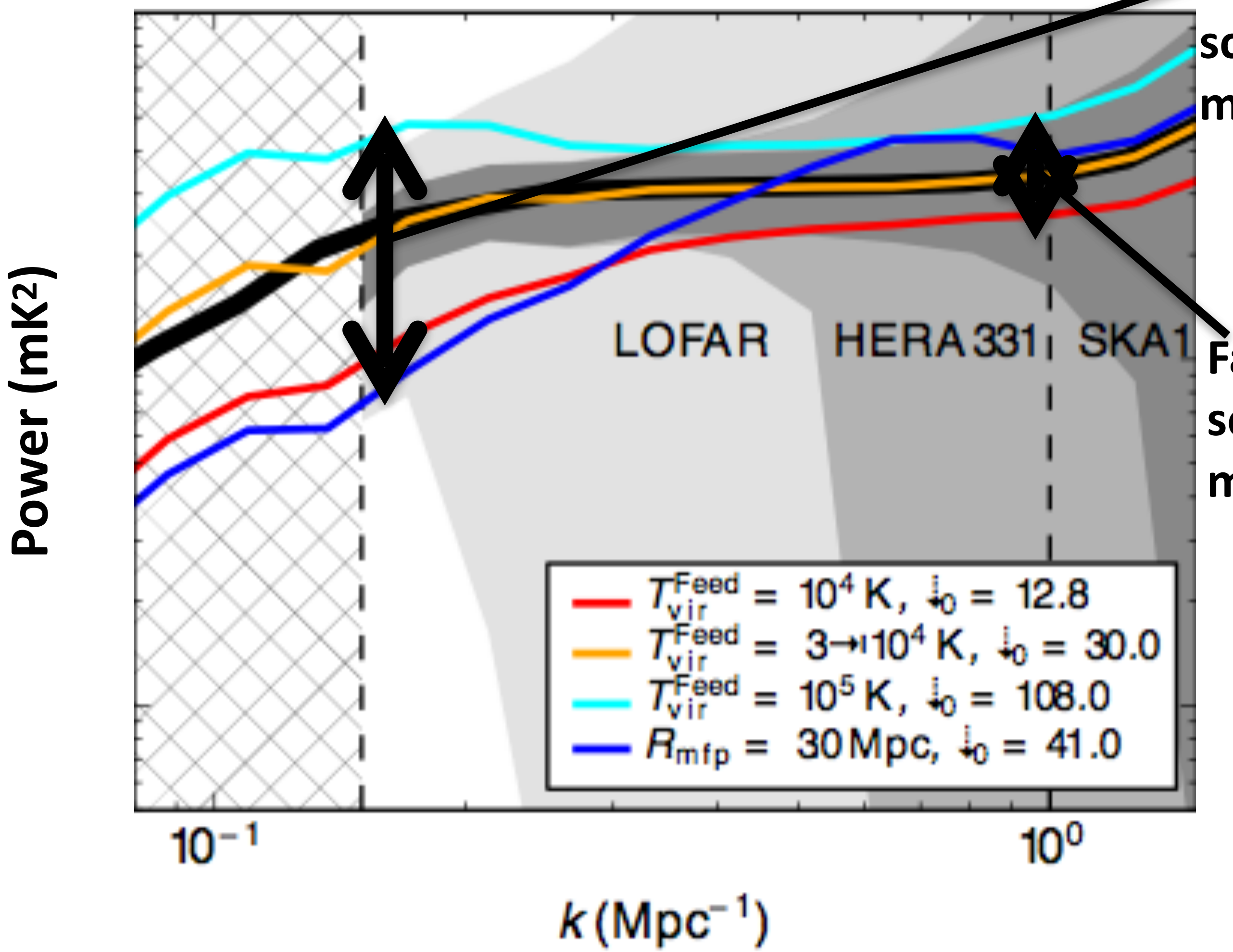

Factor of ~10 variation on large scales between astrophysical models, at a fixed EoR epoch.

Factor of ~2 variation on small scales between astrophysical models, at a fixed EoR epoch.

Greig & Mesinger (2015)

Cosmic Dawn

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

Pre-reionization signal

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

spin temperature

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

$$n_1/n_0 = 3 \exp[-0.068 \text{ K} / T_s]$$

Pre-reionization signal

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spin temperature

cosmologically:

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

T_γ – *temperature of the CMB*

T_K – *gas kinetic temperature*

T_α – *color temperature* $\sim T_K$

the spin temperature interpolates between T_γ *and* T_K

The spin temperature interpolates between T_γ and T_K

$$T_{\mathrm{S}}^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_{\mathrm{K}}^{-1}}{1 + x_\alpha + x_c}$$

two coupling coefficients:

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

collisional coupling

requires high densities

effective in the IGM at z>40

$$x_\alpha = 1.7 \times 10^{11} (1+z)^{-1} S_\alpha J_\alpha$$

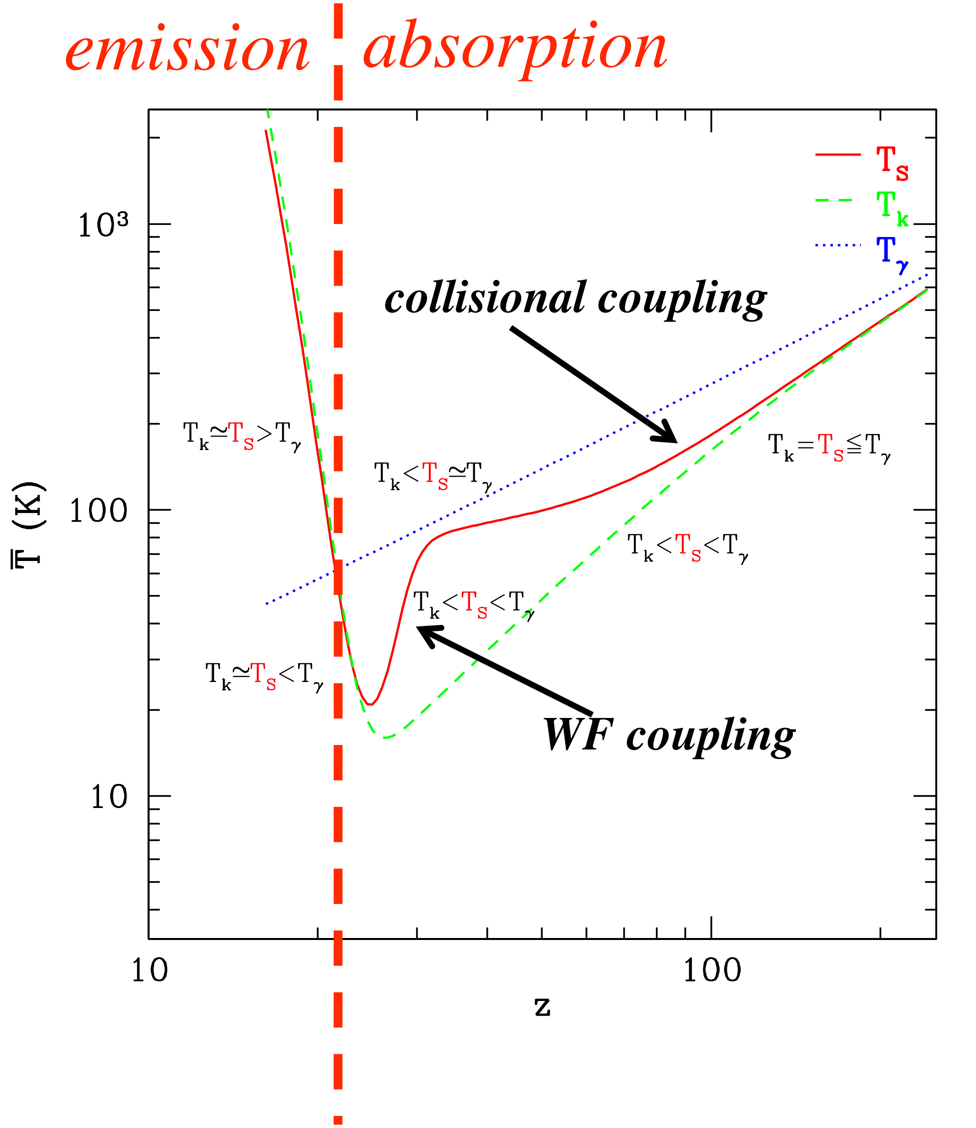
Wouthuysen-Field (WF)

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!

"*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:

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

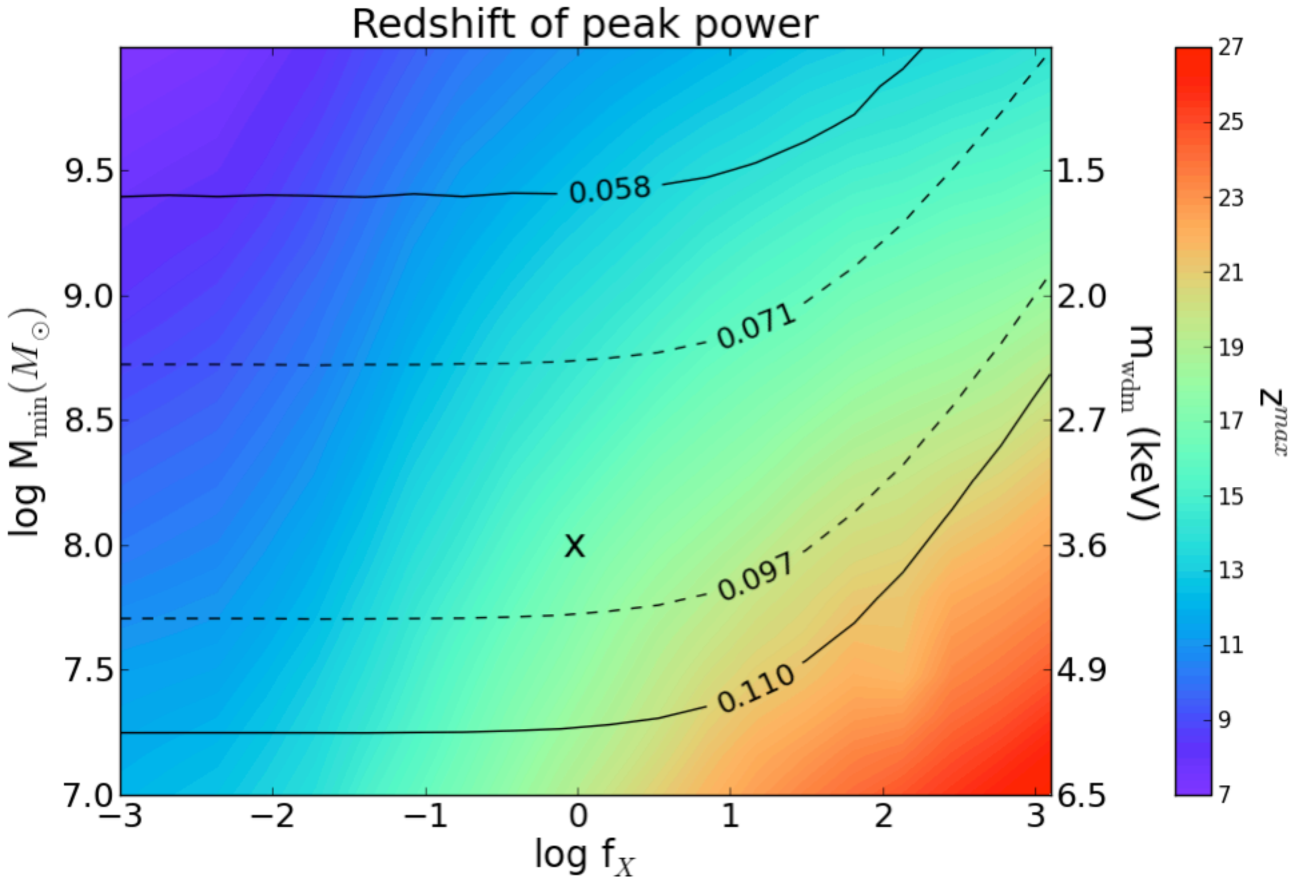
McQuinn & O'Leary (2012)
see also Furlanetto (2006), Mesinger+ (2013)

The timing of the Epoch of Heating (EoH)

Just the redshift at which the 21-cm power spectrum 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 metalicty -> more abundant and more luminous HMXBs? (Fragos+2012; Basu-Zych+2016)

But we can learn more!

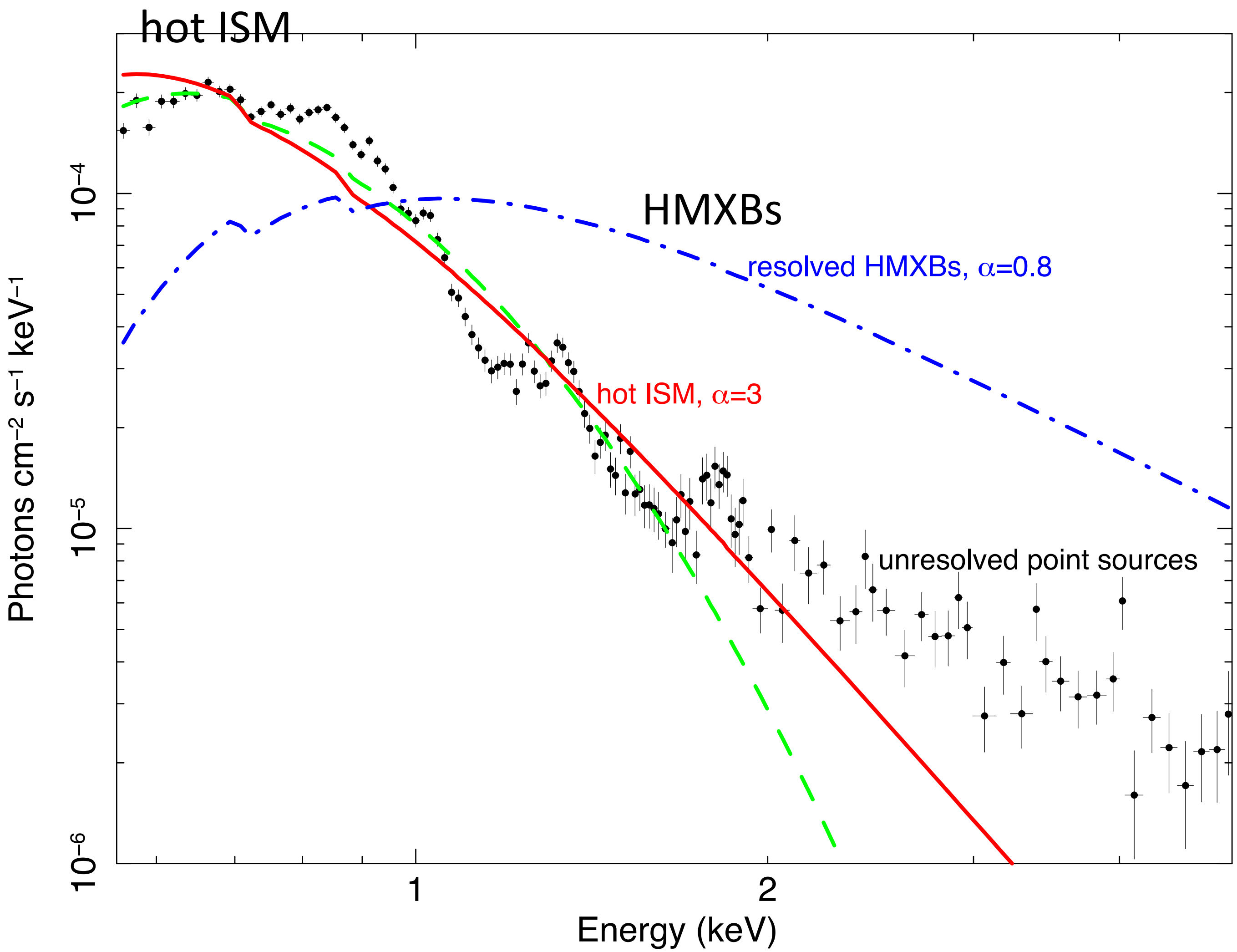
The X-ray mean free path through the IGM is very sensitive to E_x

$$\lambda_{\rm X} \approx 34\, \bar{x}_{\rm HI}^{-1} \left(\frac{E_{\rm X}}{0.5 \text{ keV}} \right)^{2.6} \left(\frac{1+z}{15} \right)^{-2} \text{ comoving Mpc },$$

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

Some candidate sources of X-rays

Composite SEDs of local, star-forming galaxies

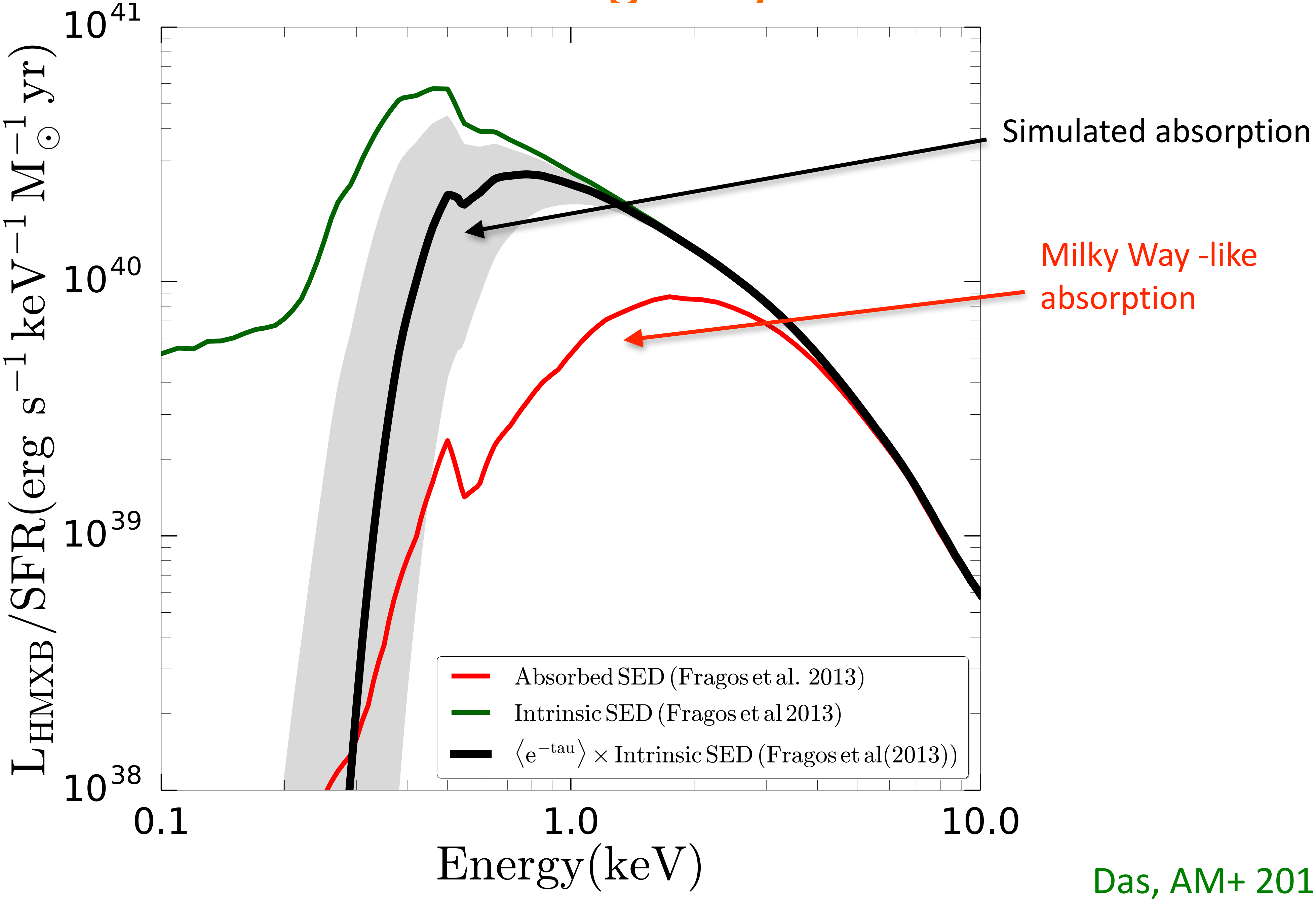


Pacucci, AM+ 2014

based on observations in Mineo+2012a,b

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

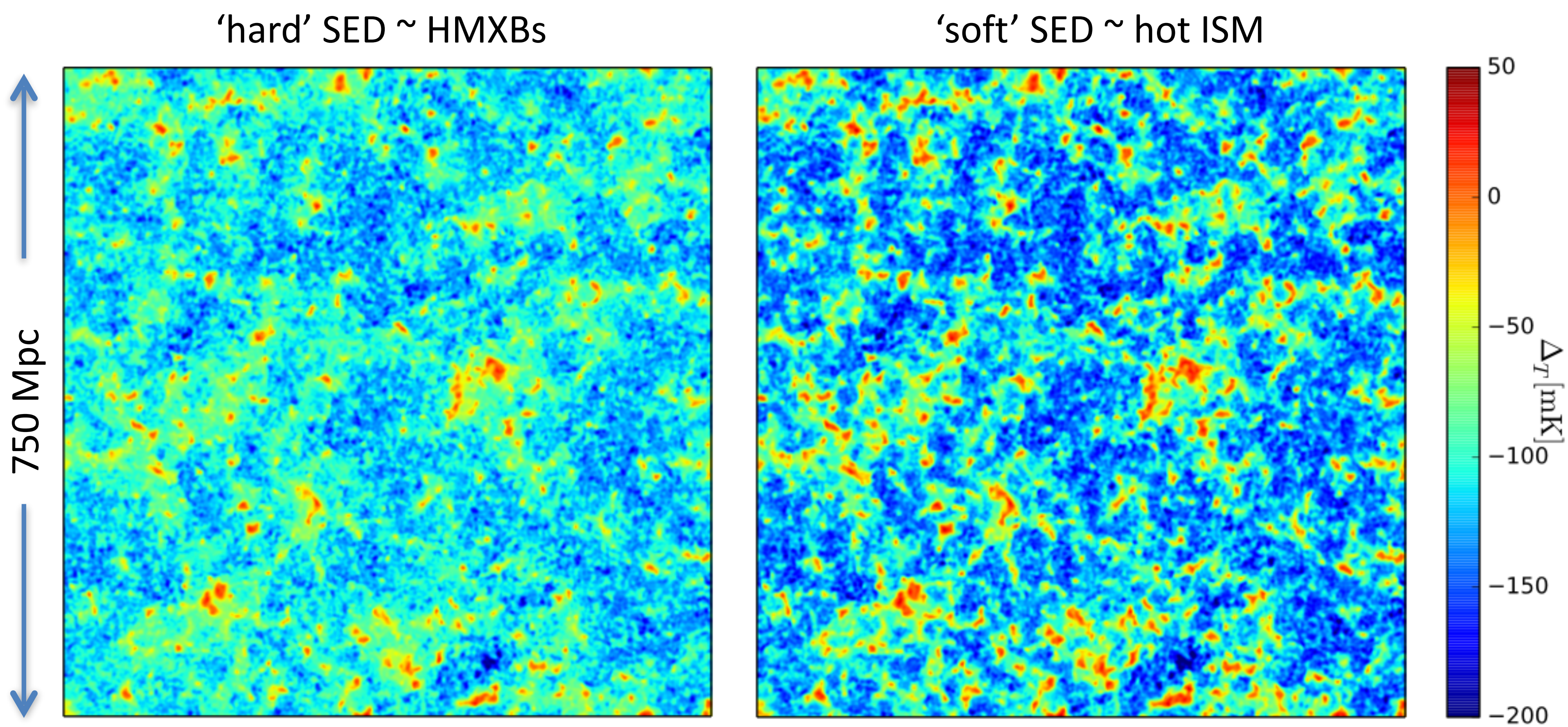
These X-rays must pass through the ISM of the host galaxy



Das, AM+ 2017

Softer SEDs result in more inhomogeous IGM heating

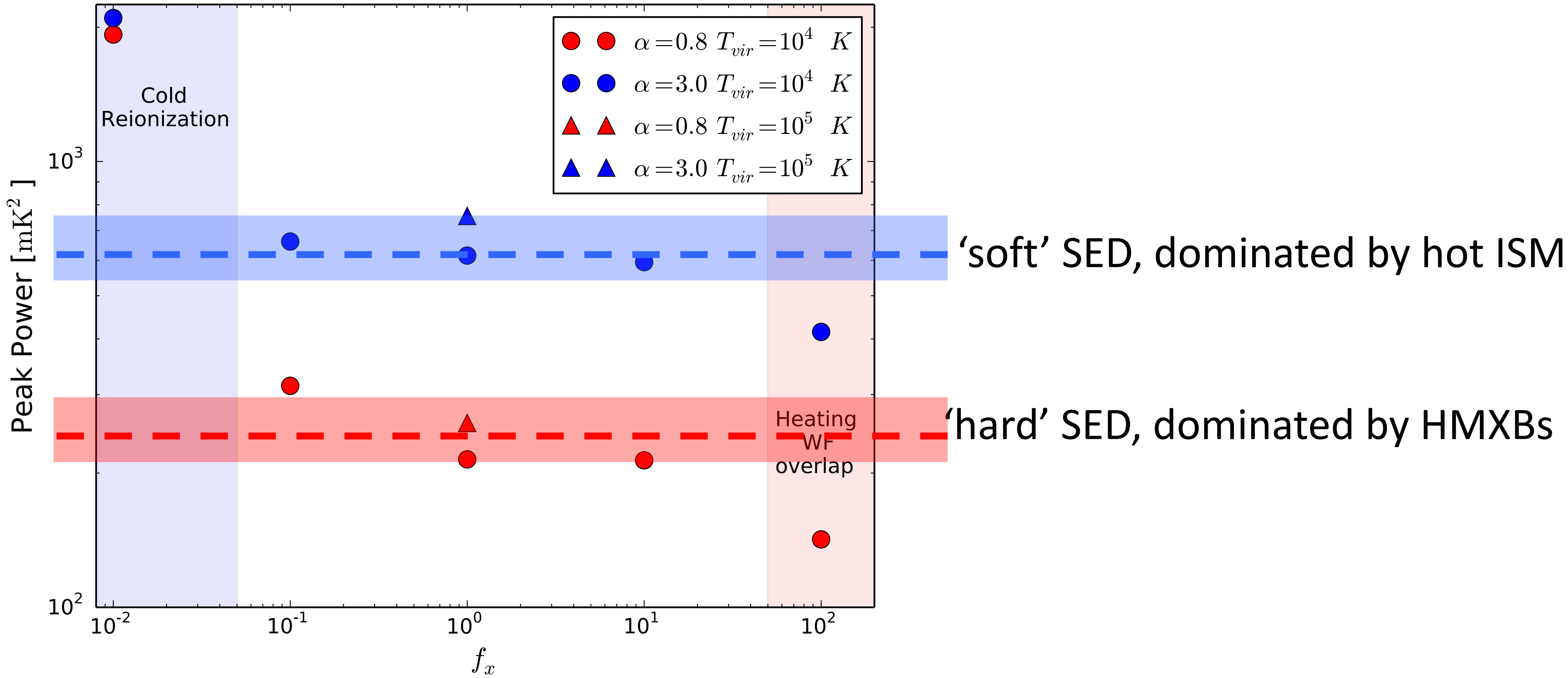
High-energy processes in the first galaxies are also encoded in the cosmic 21-cm signal



differences are easily detectable with HERA and the SKA

Pacucci+ 2014

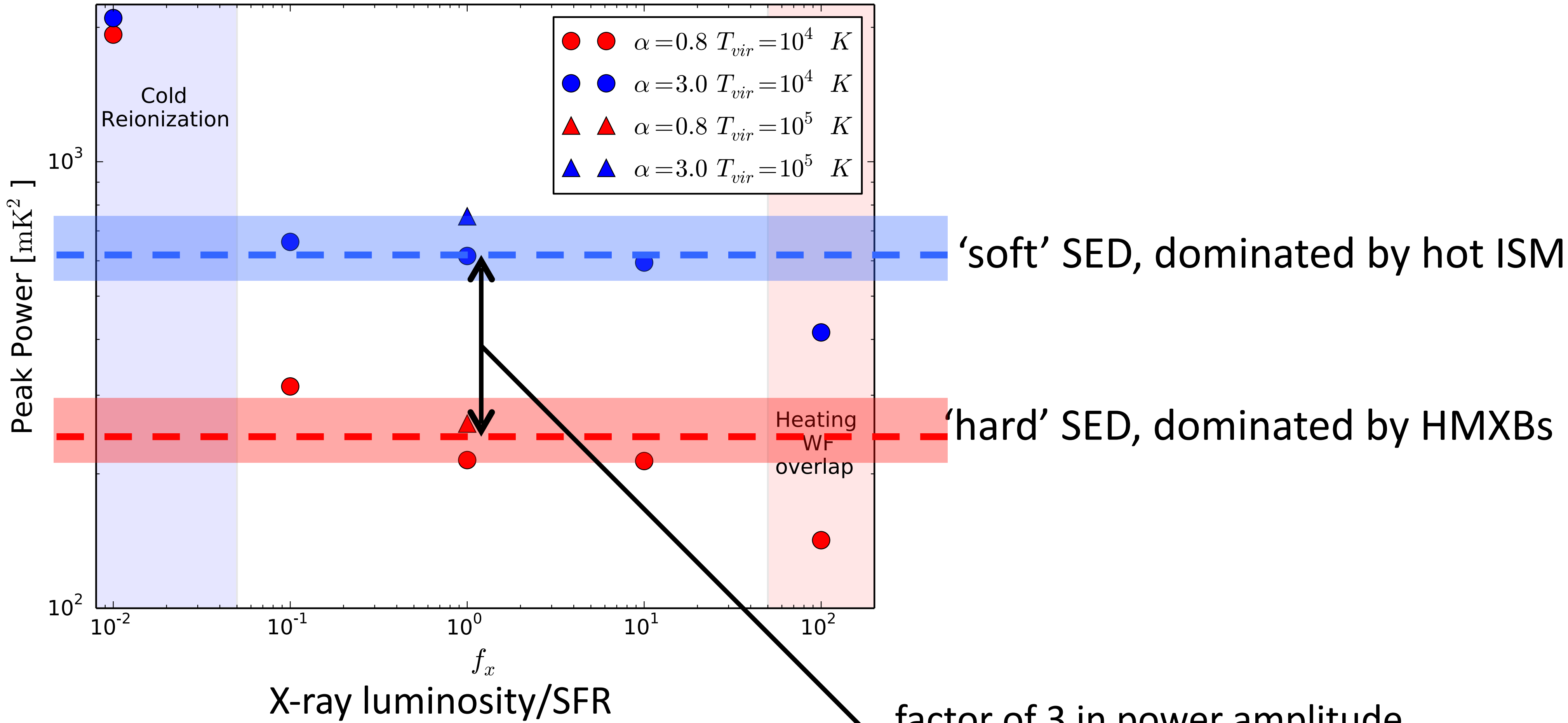
More inhomogeneous heating means a higher 21cm power spectrum



X-ray luminosity/SFR

Pacucci, AM+ (2014)

More inhomogeneous heating means a higher 21cm power spectrum

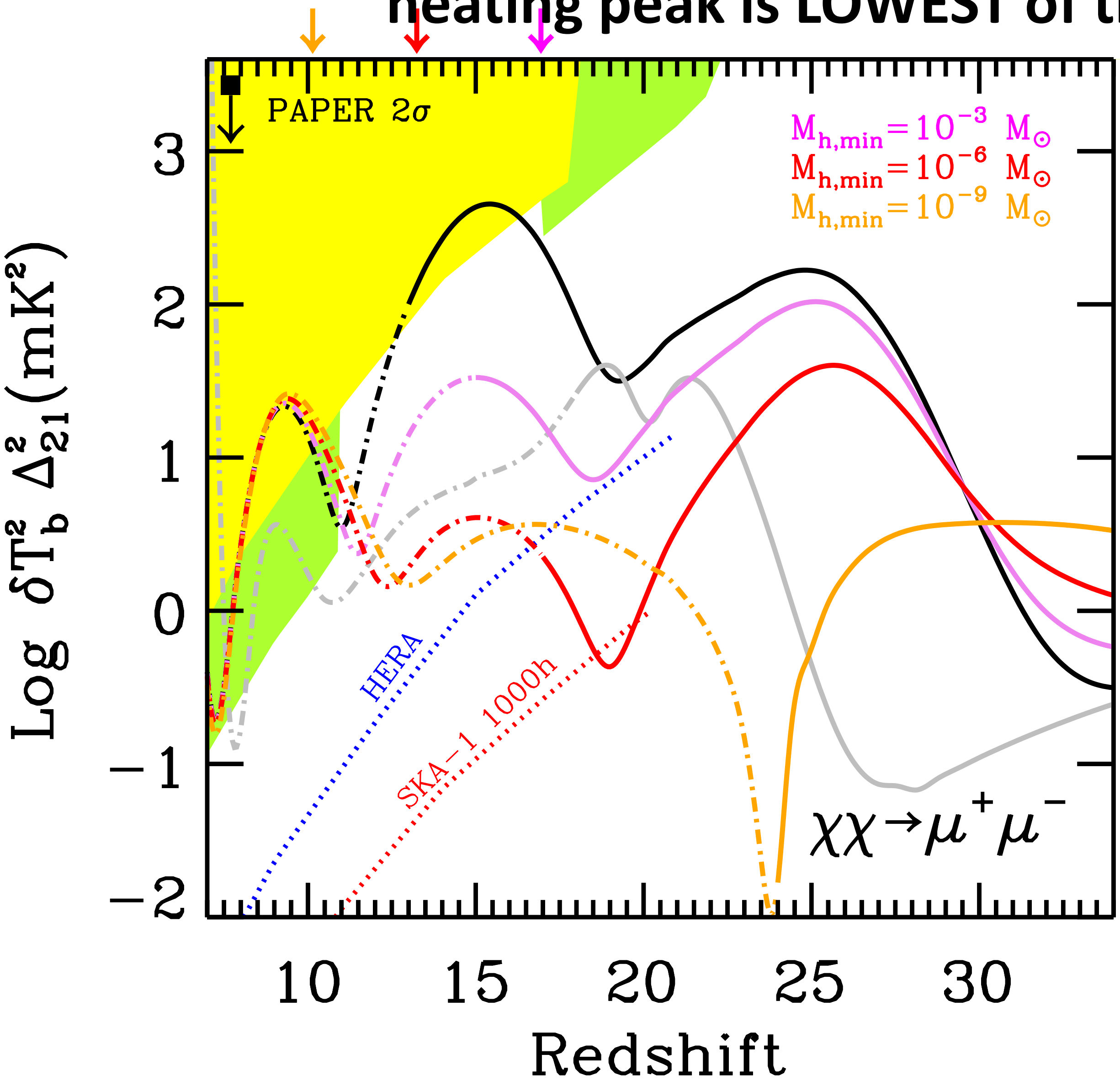


factor of 3 in power amplitude,
not degenerate with host halos & Lx

Pacucci, AM+ (2014)

Exotic sources of heat could also impact the signal

heating from DM annihilations is more uniform than astrophysical -> heating peak is LOWEST of the three



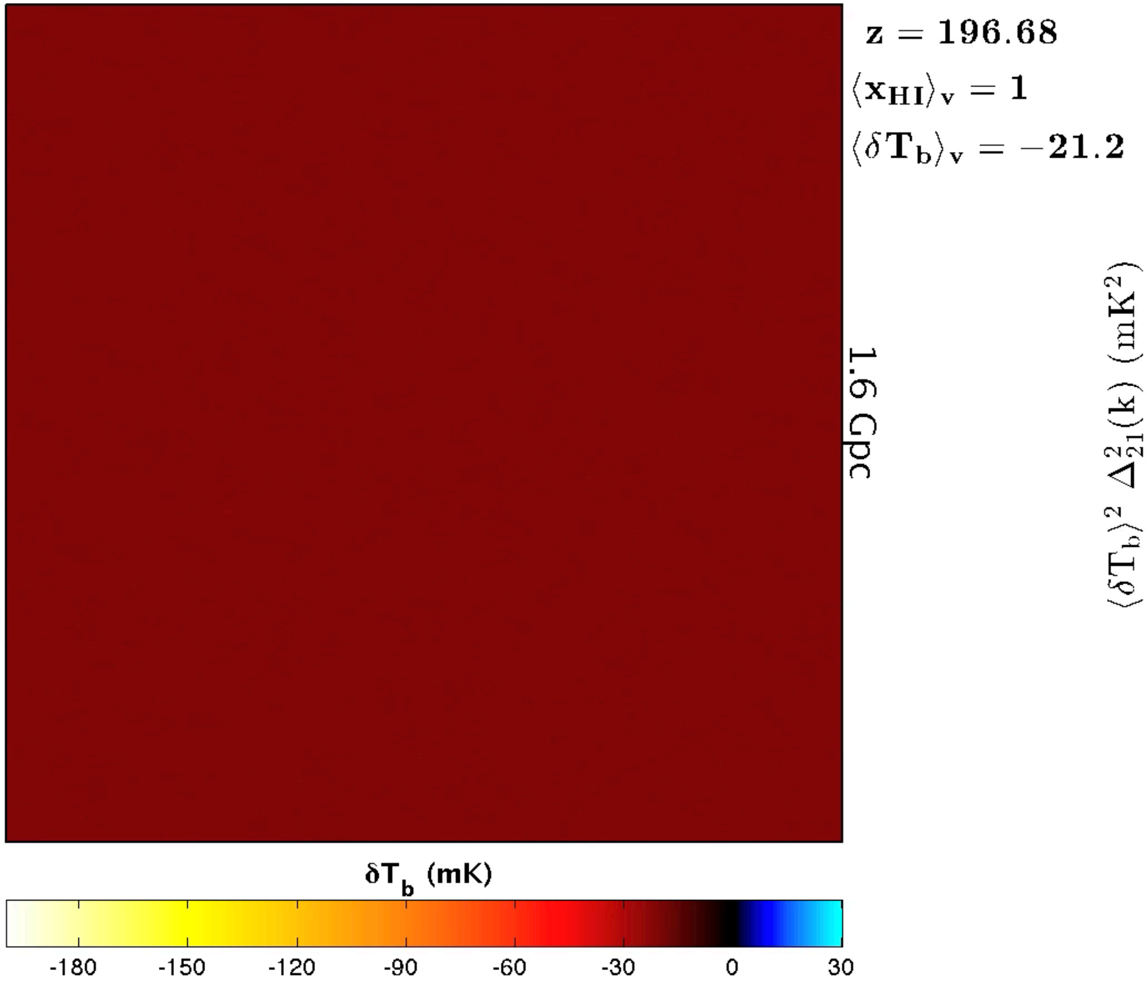
Peak is in **emission**! Cannot be reproduced with astrophysics!!!

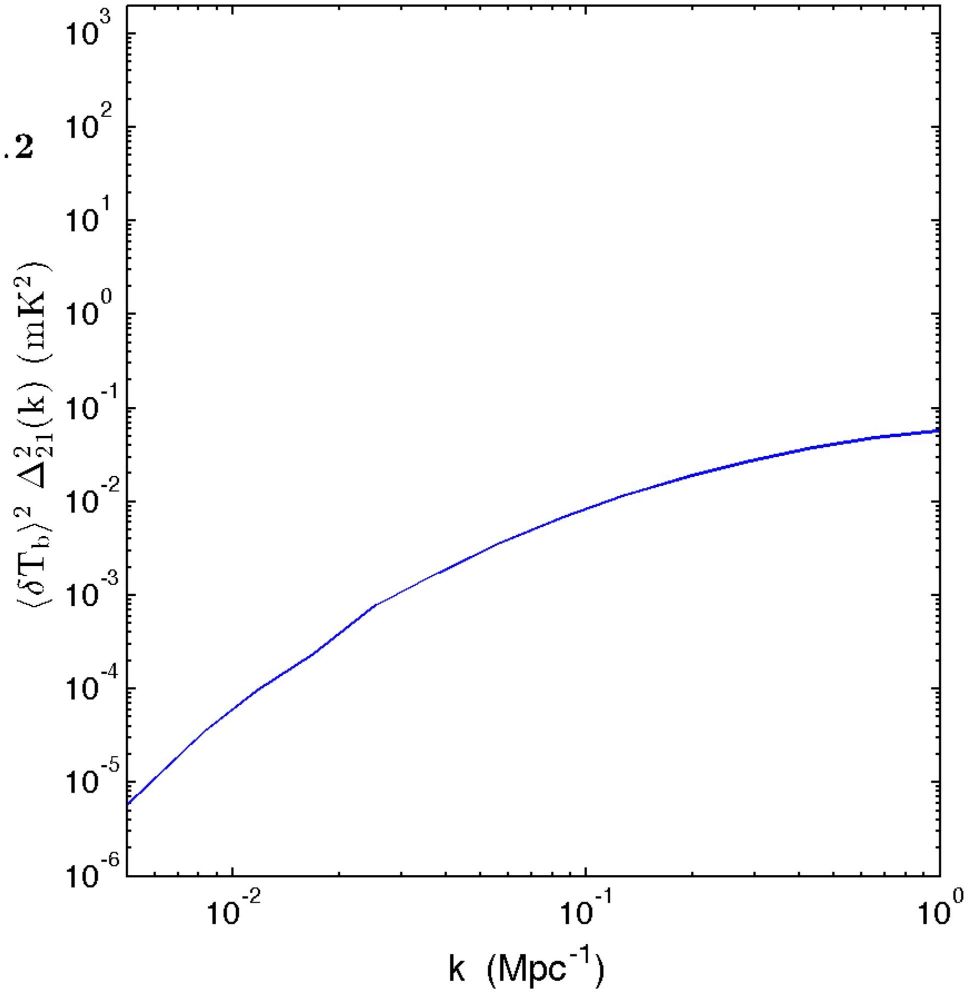
Evoli, AM, Ferrara (2014)

see also **Lopez-Honorez+2016**

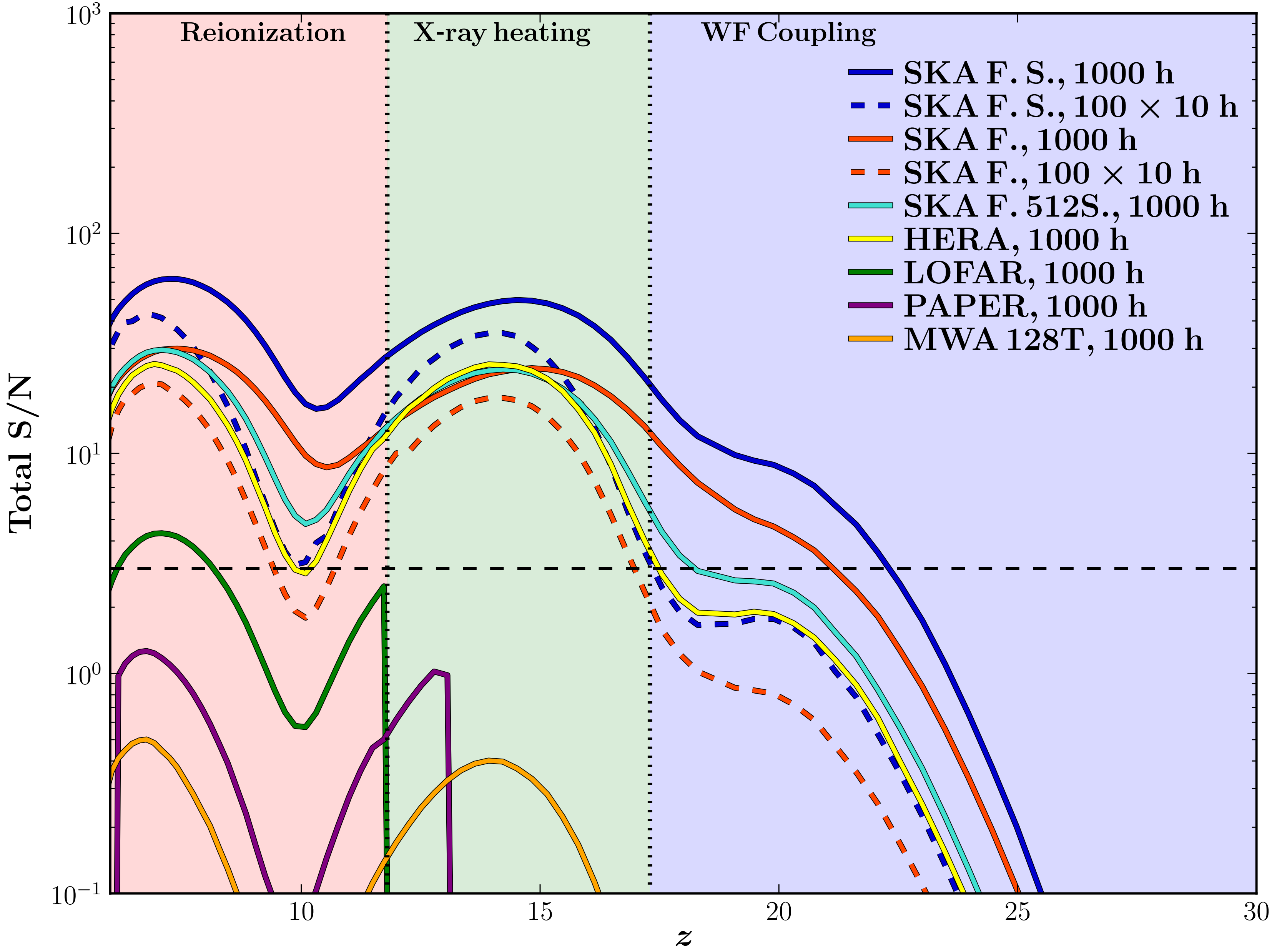
Cosmic Evolution:

putting it together





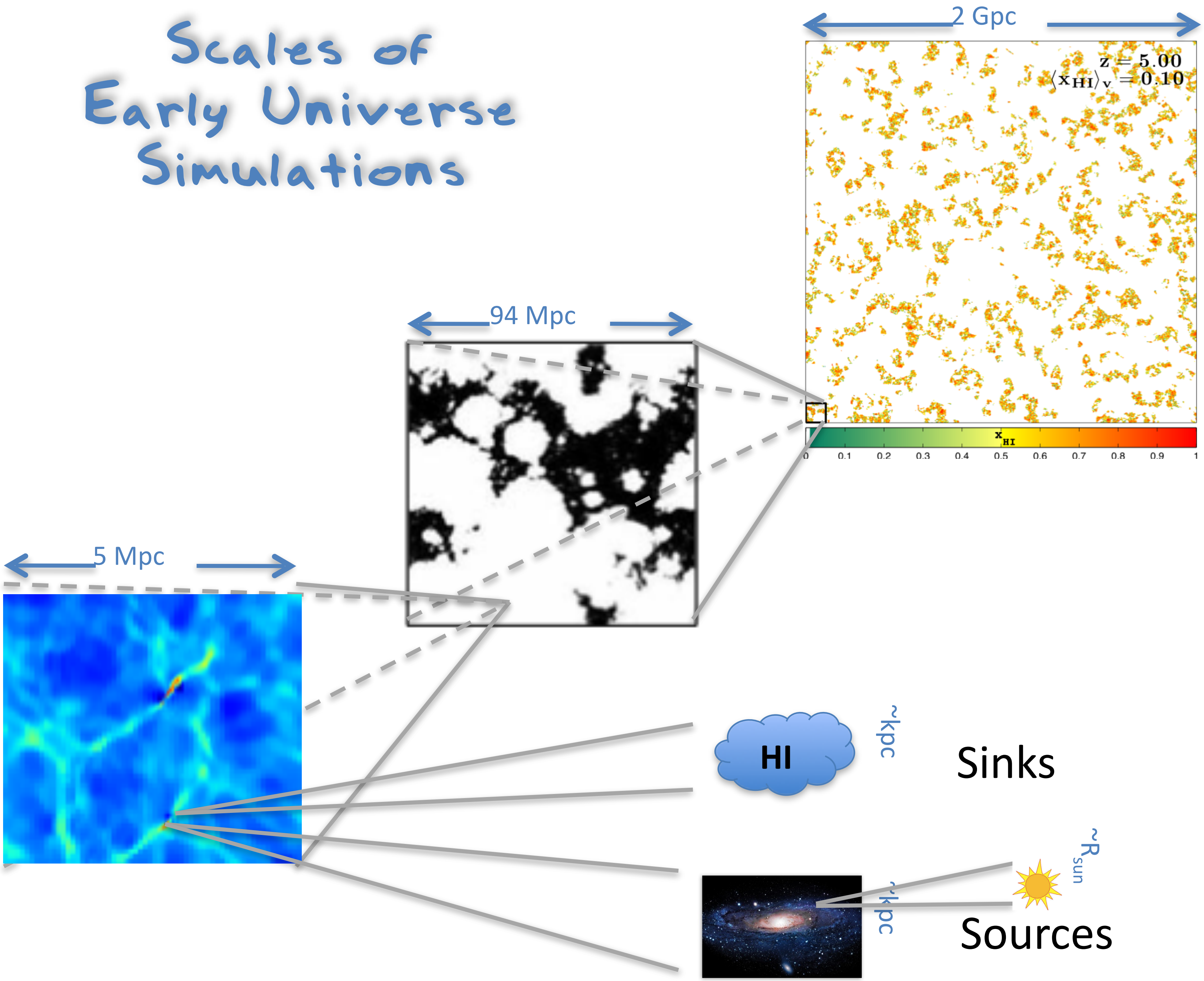
and we should get a high S/N detection with HERA and SKA



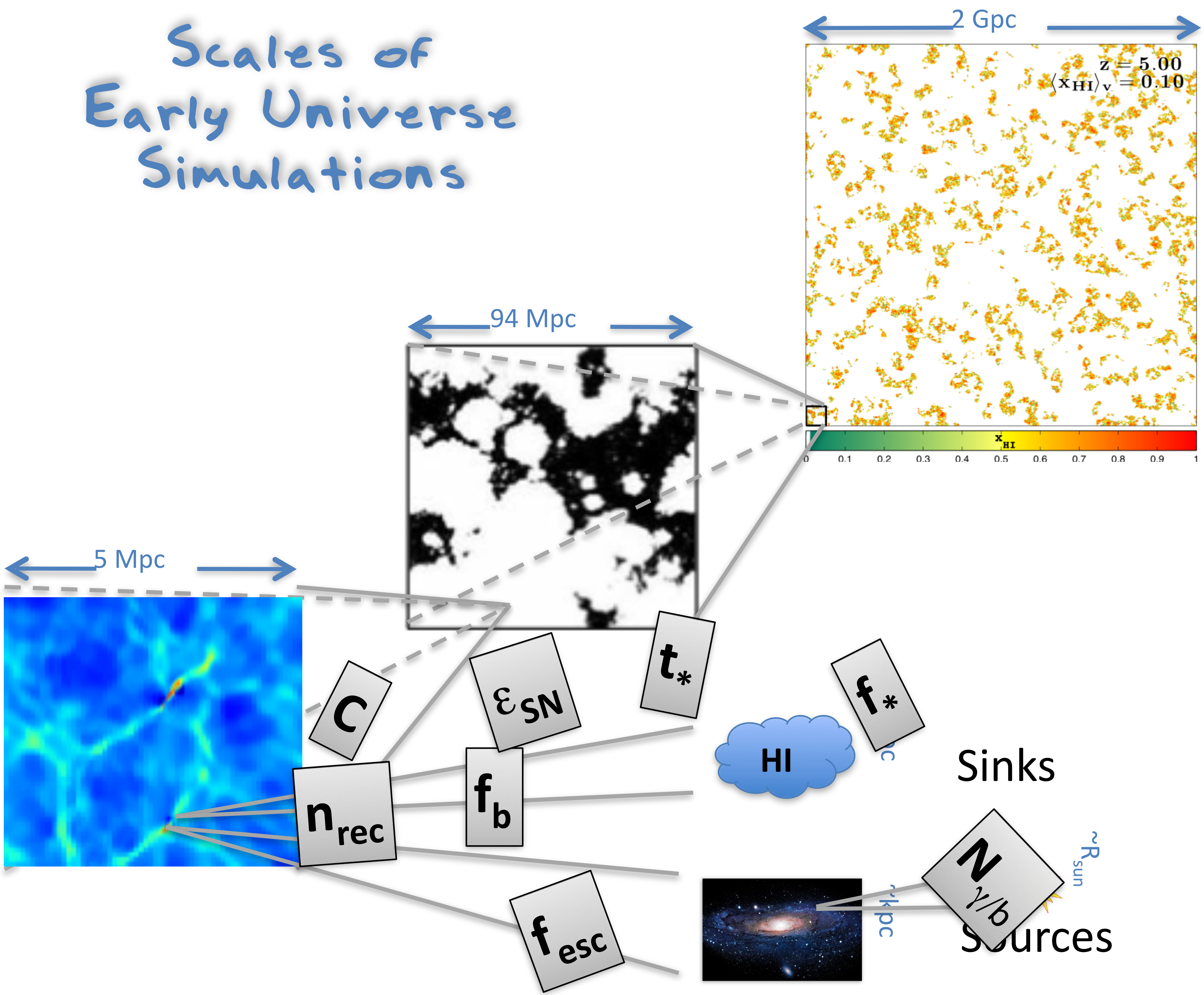
Mesinger+ (2016)

How to quantify what we will learn??

Scales of Early Universe Simulations

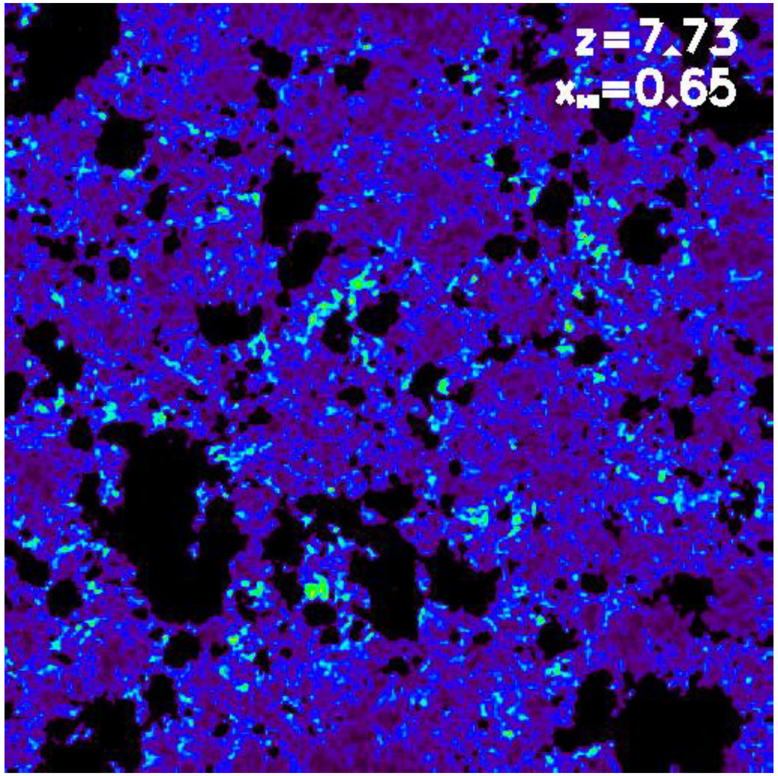


Astrophysical (known) unknowns

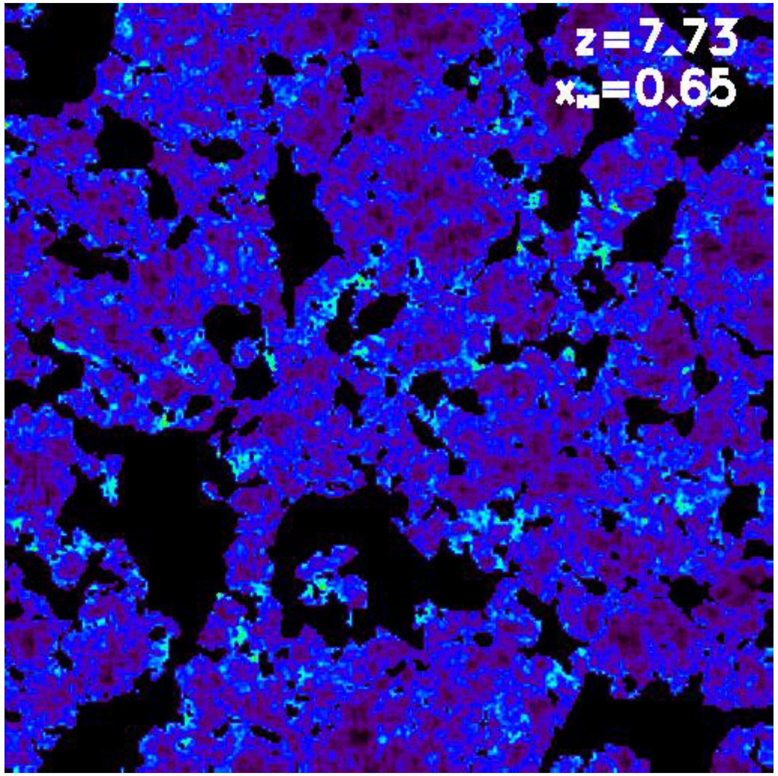


We need *fast, accurate* sims to *forward-model* the 21-cm signal

21cmFAST (AM+2007, 2011) — public, efficient semi-numerical 3D simulation code generating density fields (with 2LPT), and associated radiation fields (with a combination of excursion-set and lightcone integration).



hydro+RT (Trac+2009):
~10^7 CPU hours



21cmFAST:
~0.1 CPU hours

So, how does it work then?

Start with a galaxy model:
a flexible approach based on DM halos + galaxy LFs

Average properties of galaxies in halos of mass M_h:

$$\mathrm{M}_* = \mathbf{f}_{*,\mathbf{10}} \left(\frac{M_h}{10^{10} M_\odot} \right)^{\alpha_*} \frac{\Omega_b}{\Omega_M} M_h$$

$$L_{1500} \propto \frac{M_*}{\mathbf{t}_* H^{-1}}$$

$$L_{\rm ion} = \mathbf{f}_{\rm esc,10} \left(\frac{M_h}{10^{10} M_\odot} \right)^{\alpha_{\rm esc}} L_{1500}$$

$$f_{\rm duty} = \exp[-\mathbf{M}_{\rm turn}/M_h]$$

Park+ 2018
(see also Kuhlen+2012;
Dayal+ 2014; Mitra+ 2015;
Sun & Furlanetto 2016;
Mutch+ 2016; Yue+ 2016, …)

An flexible approach based on DM halos + galaxy LFs

Average properties of galaxies in halos of mass M_h:

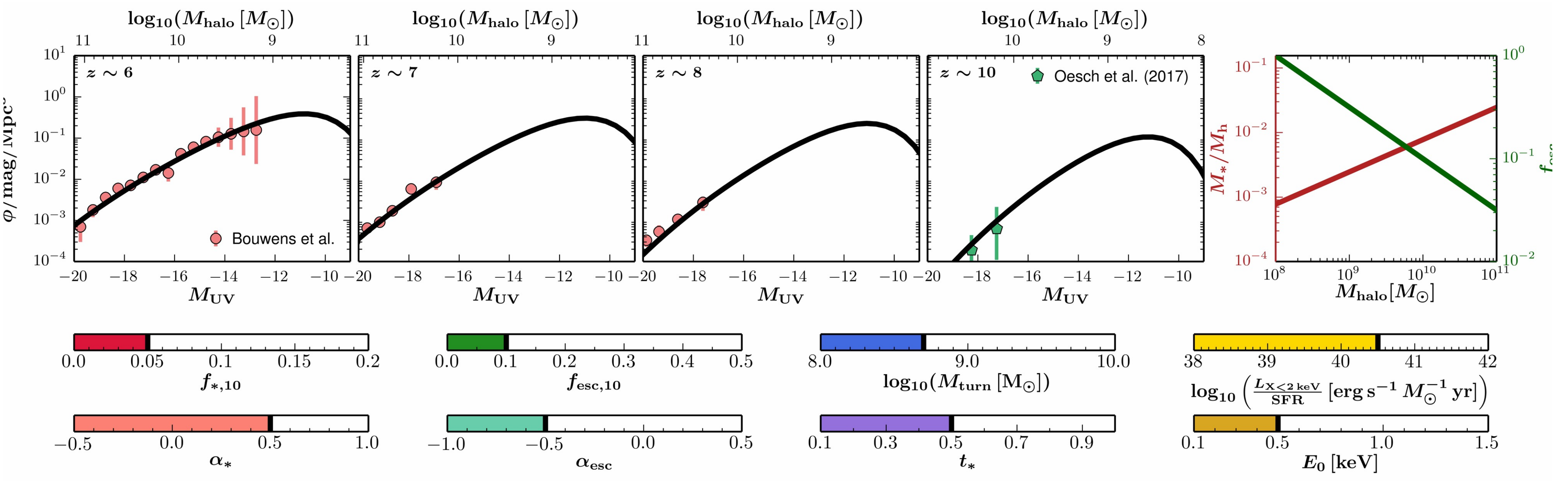
$$M_* = \mathbf{f_{*,10}} \left(\frac{M_h}{10^{10} M_\odot} \right)^{\alpha_*} \frac{\Omega_b}{\Omega_M} M_h$$

$$L_{1500} \propto \frac{M_*}{\mathbf{t_*} H^{-1}}$$

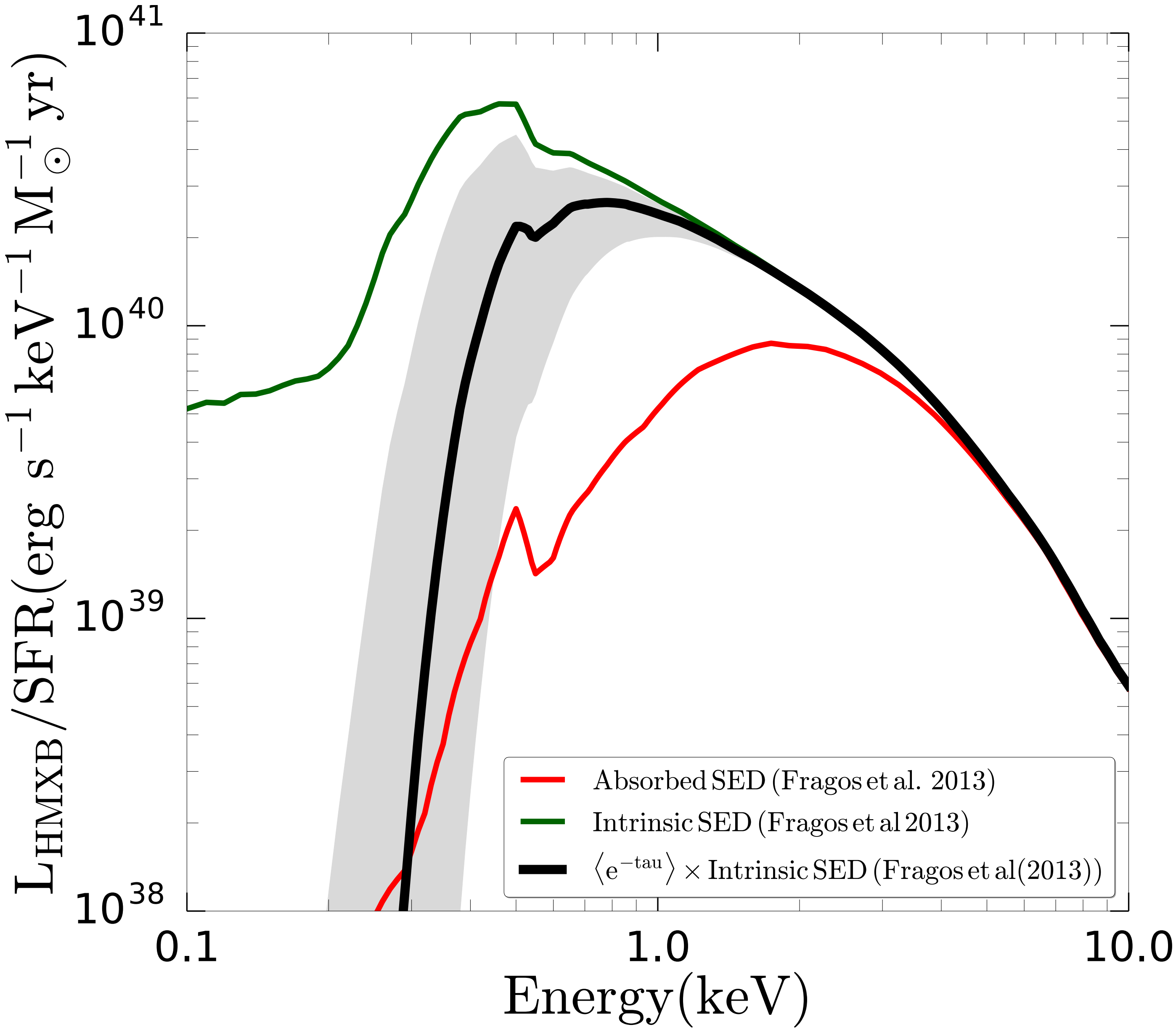
$$L_{\rm ion} = \mathbf{f_{\rm esc,10}} \left(\frac{M_h}{10^{10} M_\odot} \right)^{\alpha_{\rm esc}} L_{1500}$$

$$f_{\rm duty} = \exp[-\mathbf{M_{\rm turn}}/M_h]$$

six free parameters for star formation and UV photons



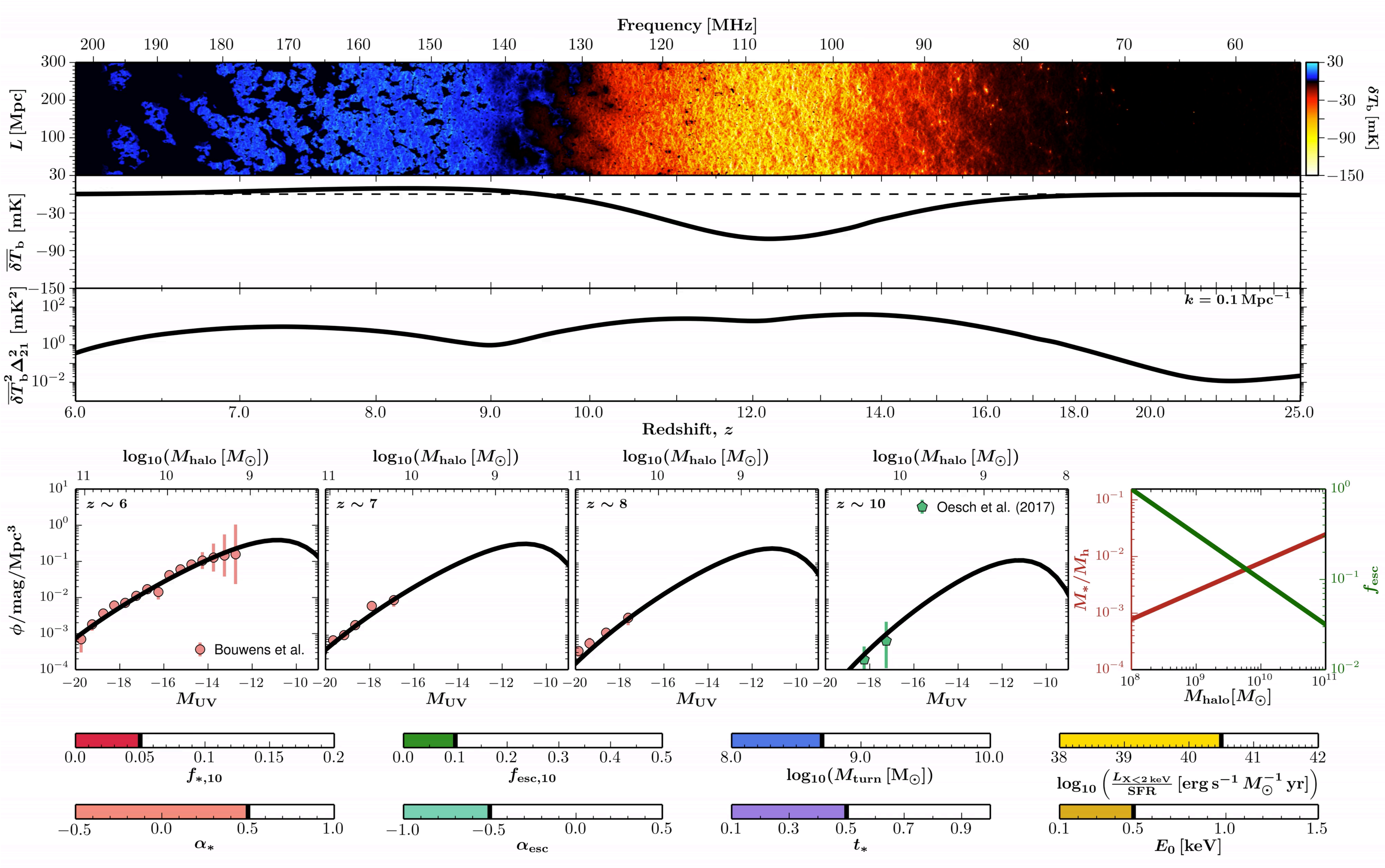
An flexible approach based on DM halos + galaxy LFs



X-ray free parameters characterizing emerging SED from galaxies

Das, AM+ 2016

Free parameters

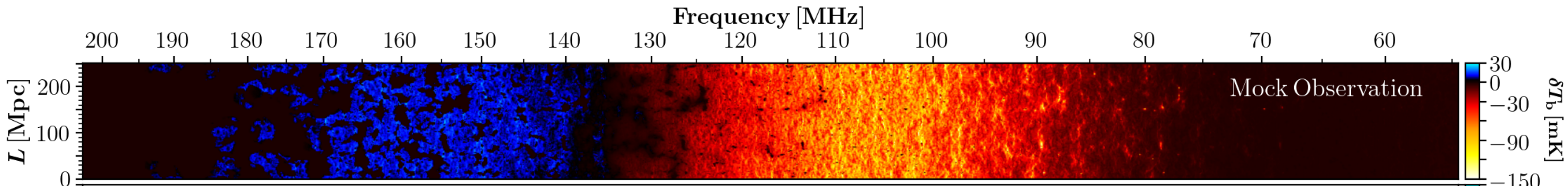


How to quantify what we will learn??

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

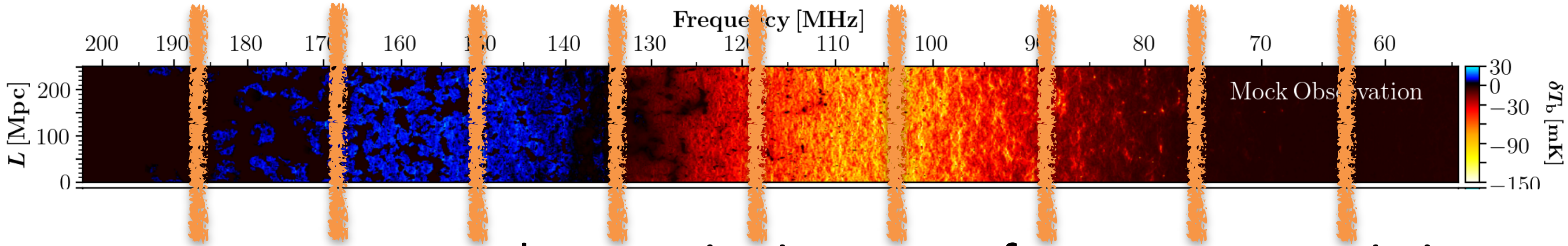
+

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



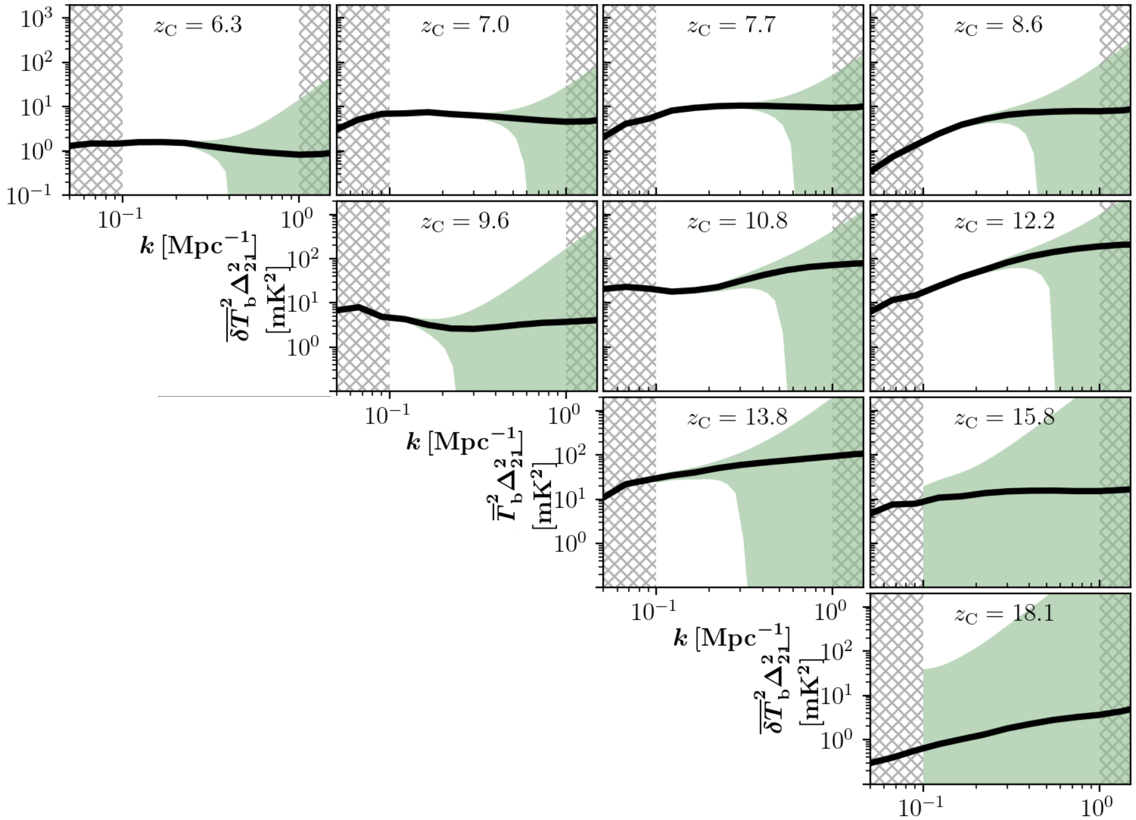
“observation”

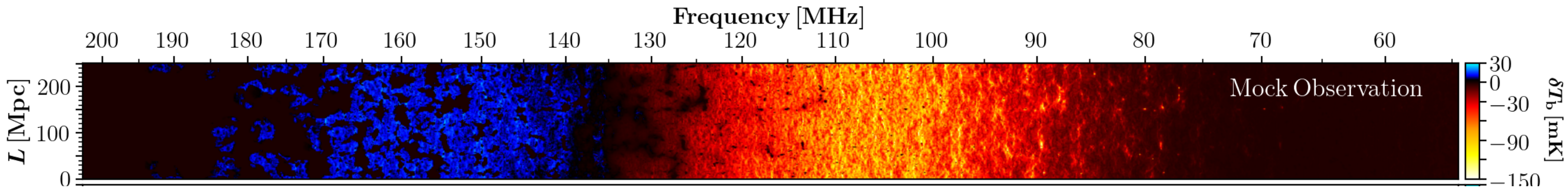
21cm **3D!!!** map



"observation"

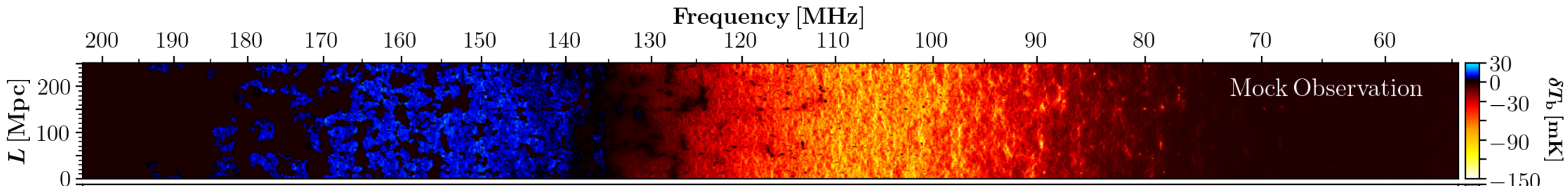
characterize in terms of a summary statistic:
power spectra with 1000h noise from HERA and moderate foreground contamination





(1) 21-cm

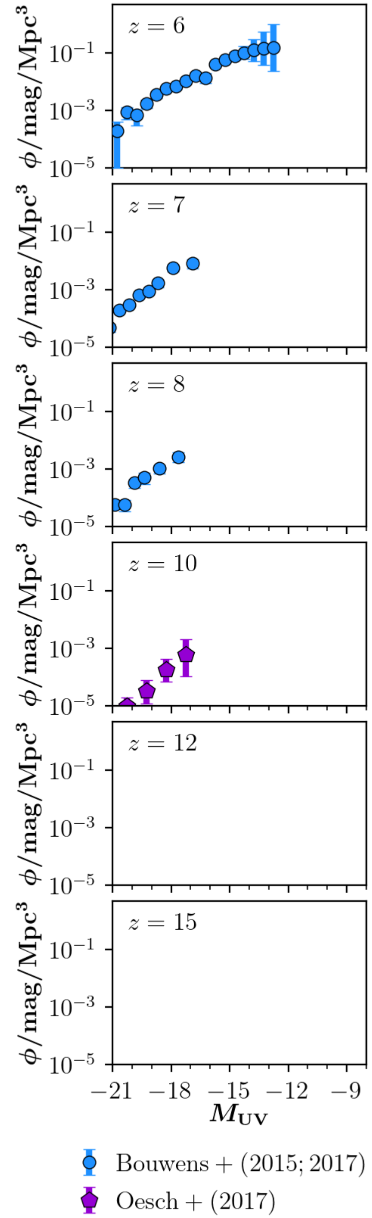
combine with other observations
in order to compute
likelihood



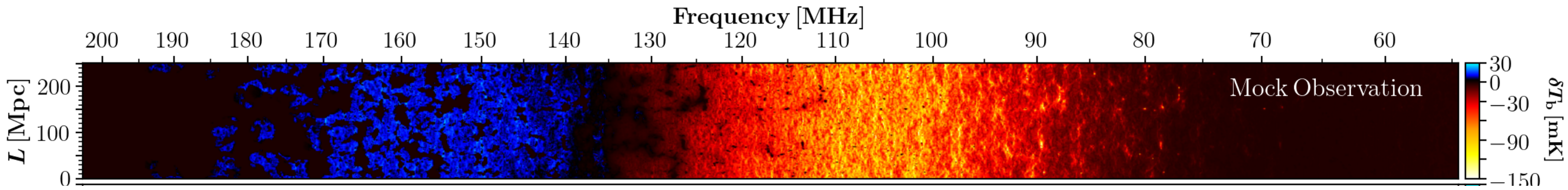
(1) 21-cm

+

(2) high-z galaxy LFs



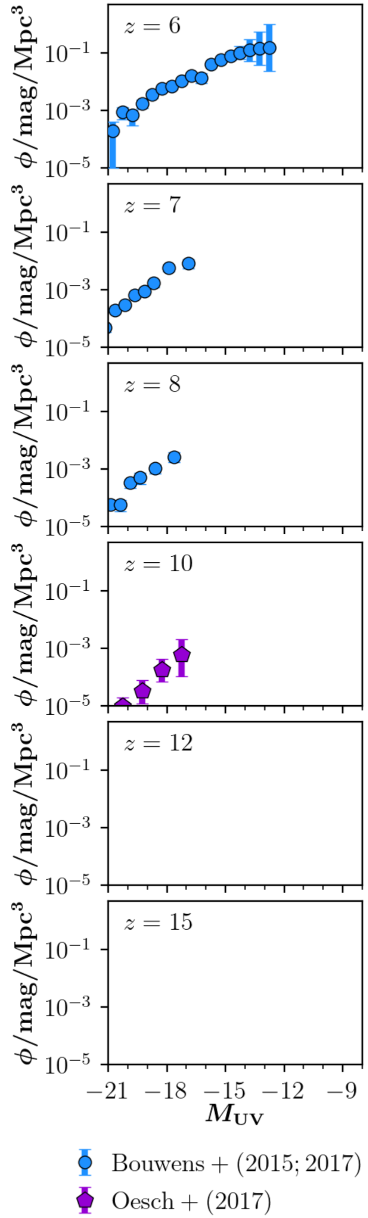
combine with other observations
in order to compute
likelihood



(1) 21-cm

+

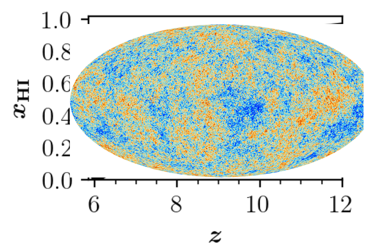
(2) high-z galaxy LFs

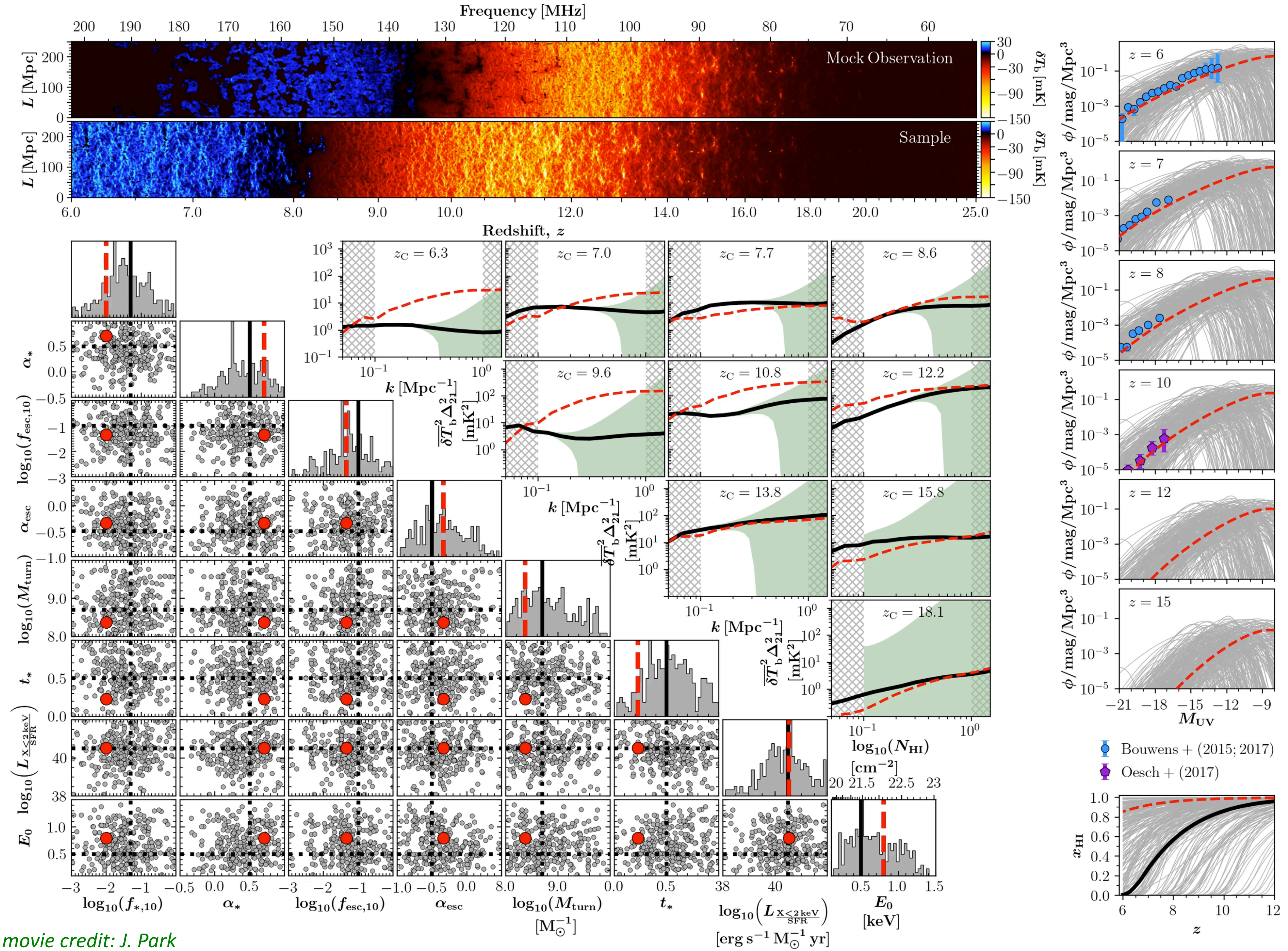


combine with other observations
in order to compute
likelihood

+

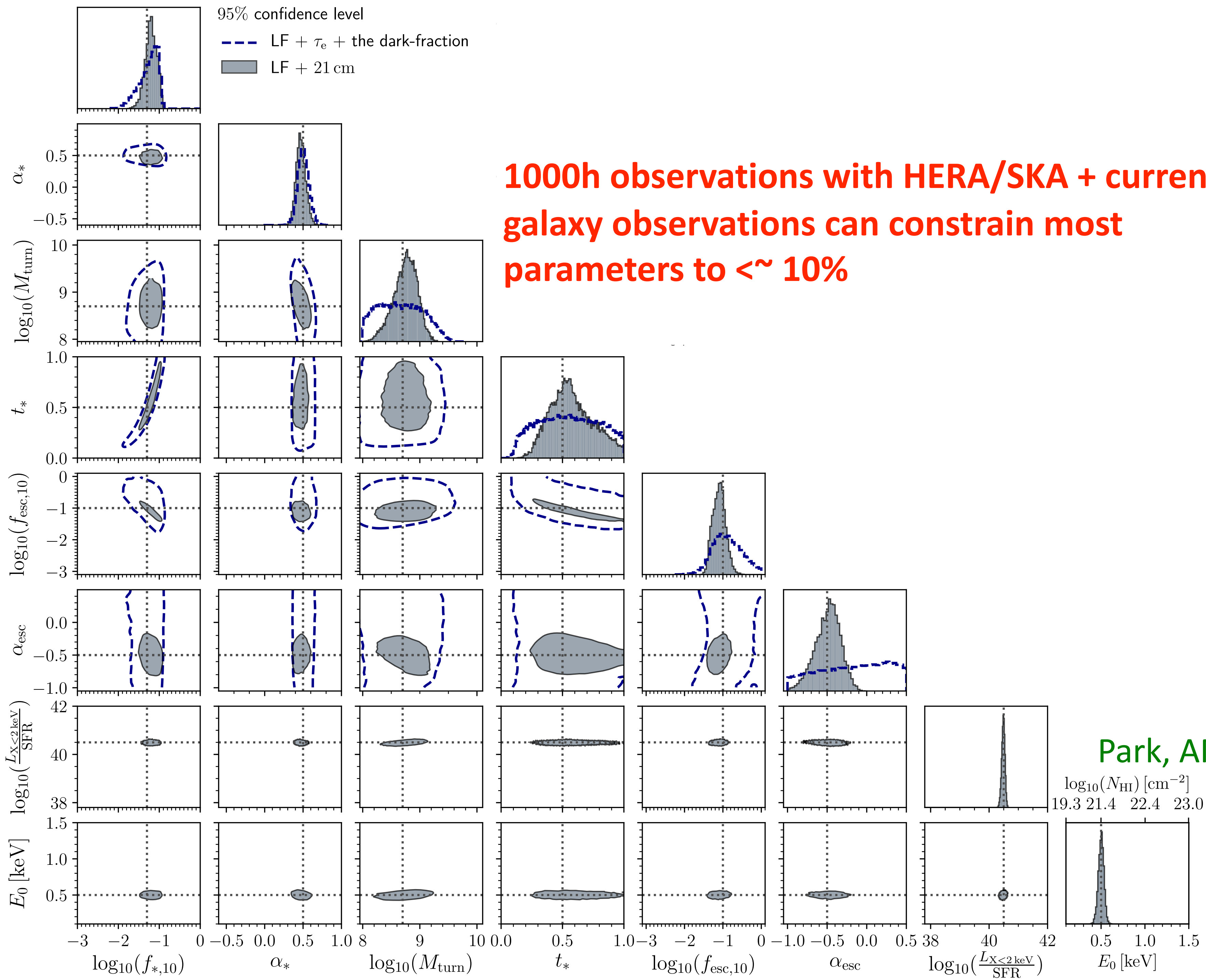
(3)
CMB τ_e





movie credit: J. Park

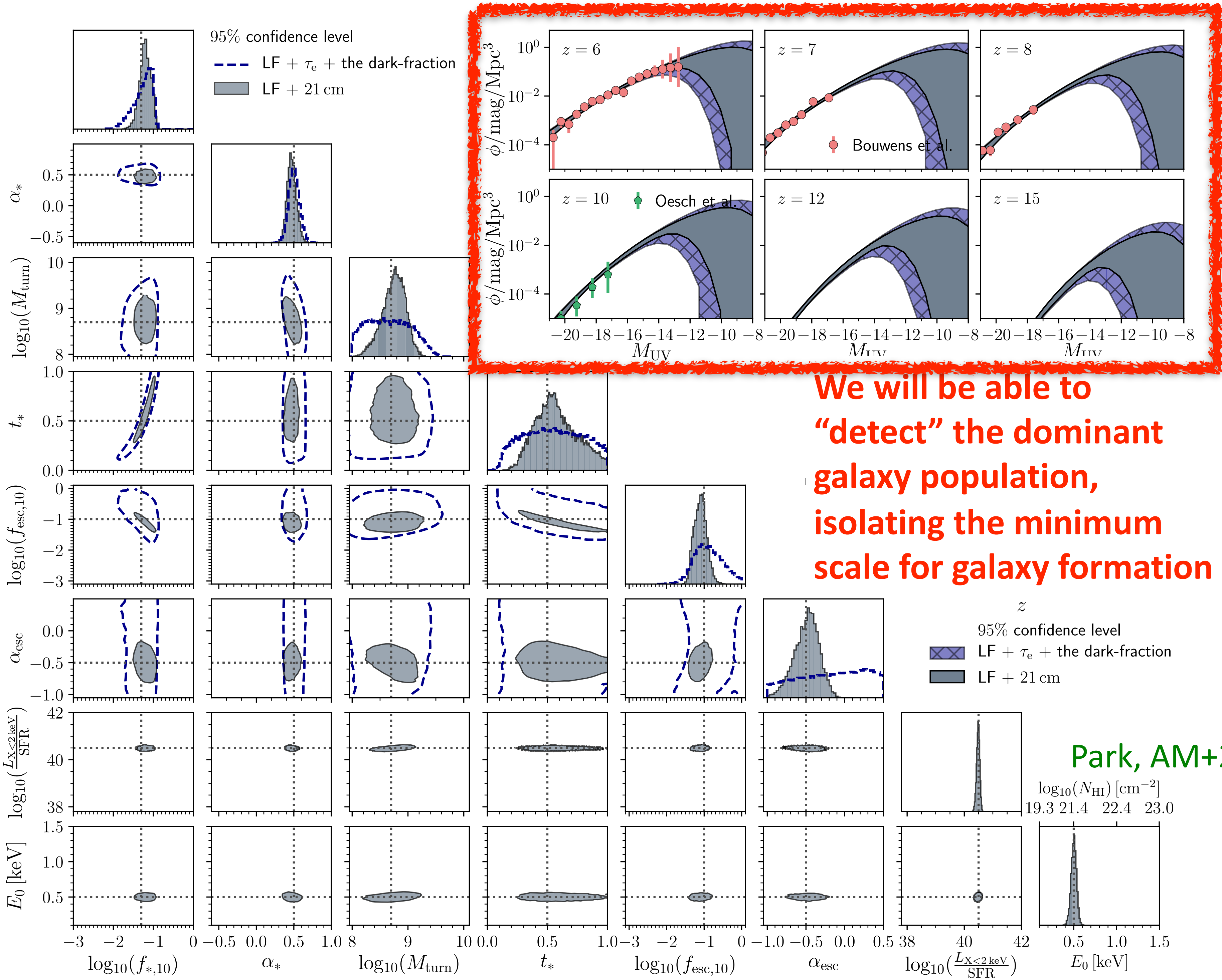
Parameter constraints: LF + 21cm



1000h observations with HERA/SKA + current galaxy observations can constrain most parameters to <~ 10%

Park, AM+2019

Parameter constraints: LF + 21cm

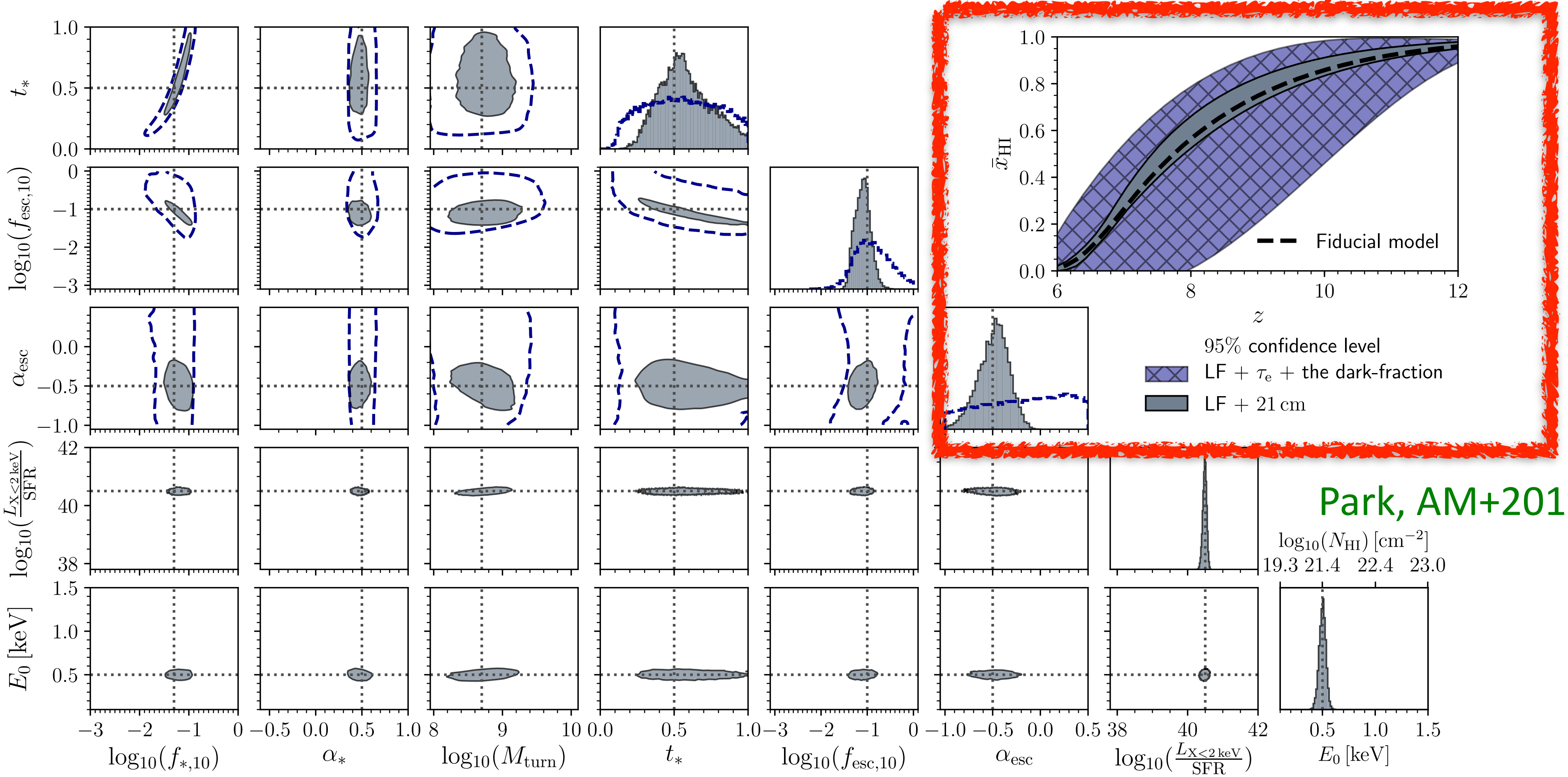


We will be able to "detect" the dominant galaxy population, isolating the minimum scale for galaxy formation

Park, AM+2019

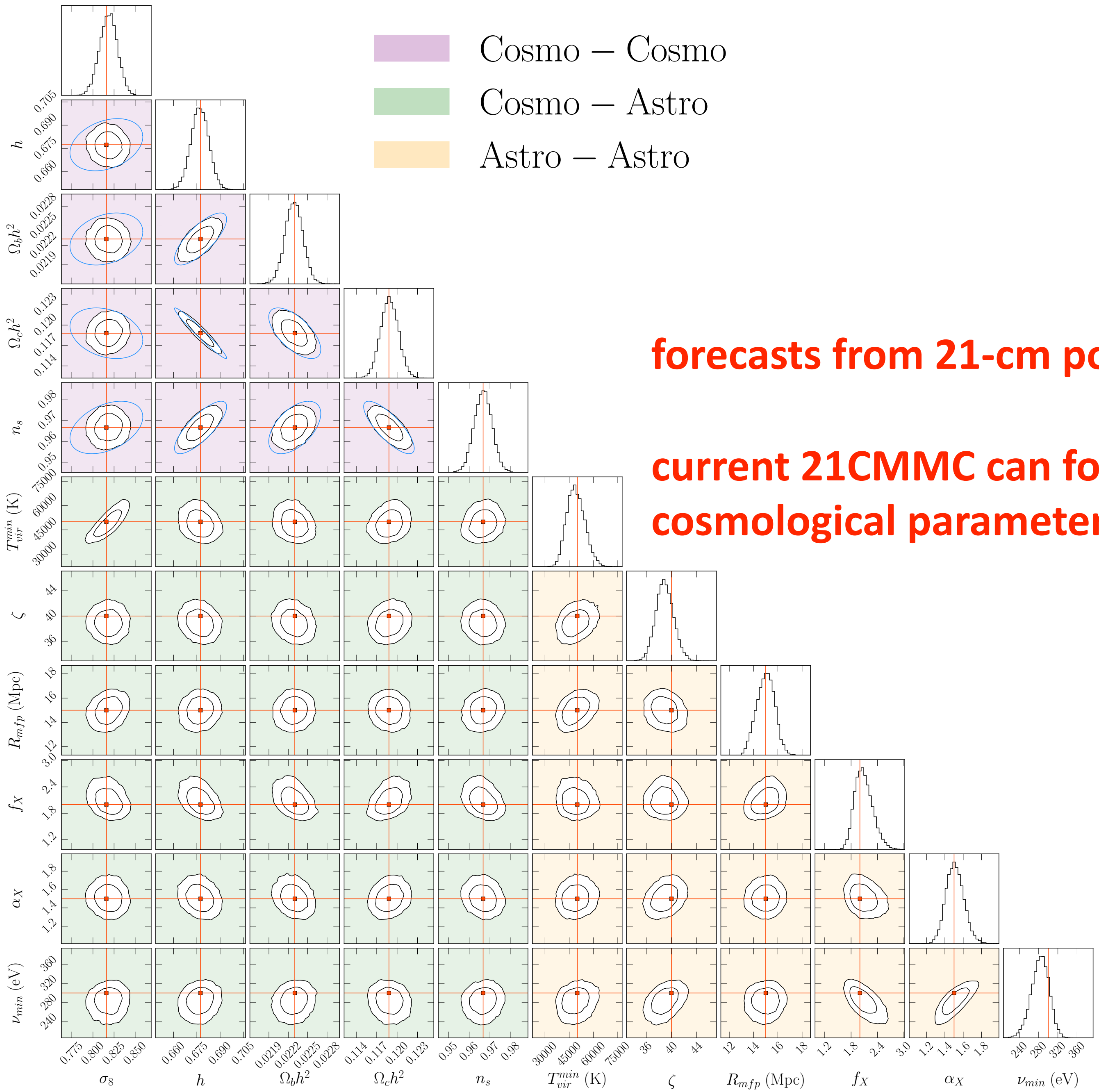
Parameter constraints: LF + 21cm

1000h observations with SKA can constrain EoR history to ~ 1%



Park, AM+2019

Including physical cosmology

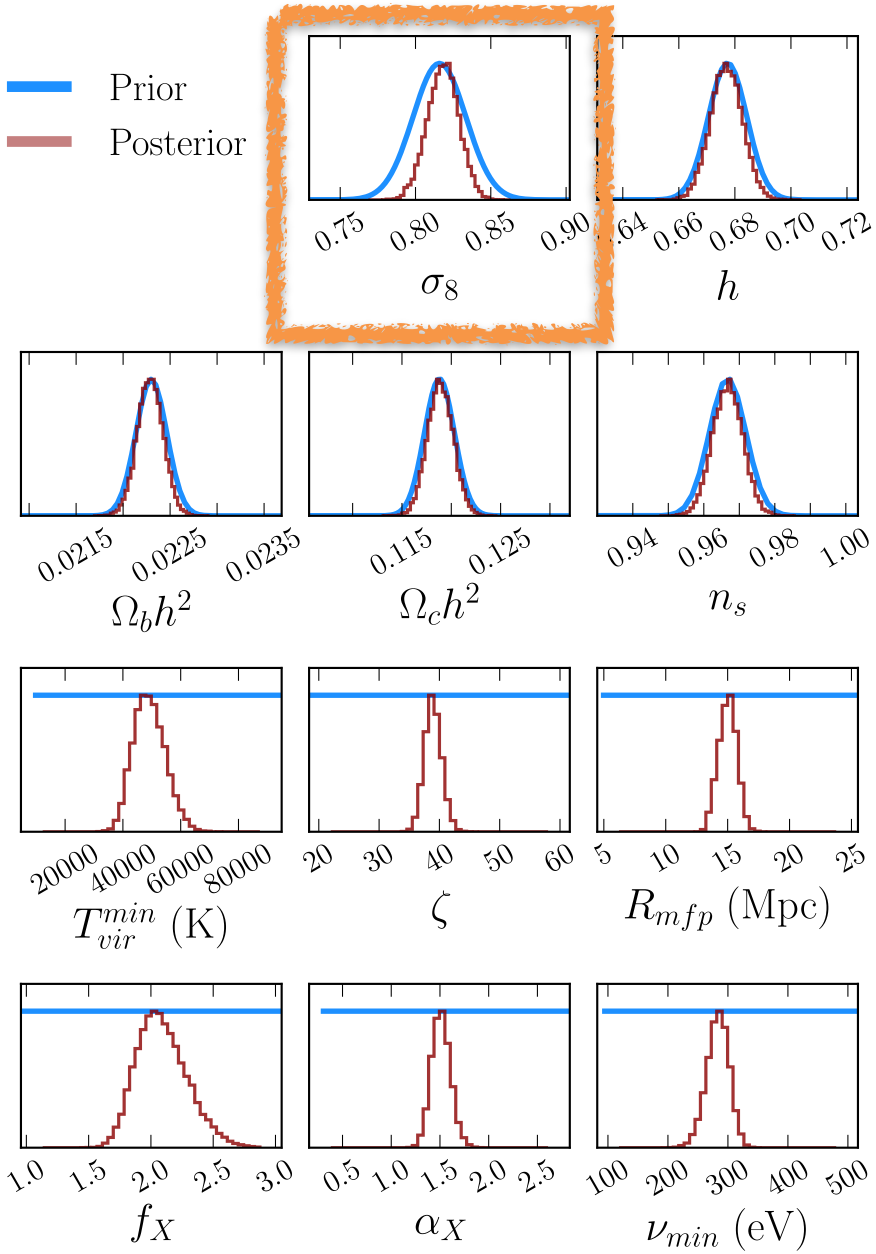


forecasts from 21-cm power spectra emulator

current 21CMMC can forward model cosmological parameters (on-the-fly)

Kern + (2017)

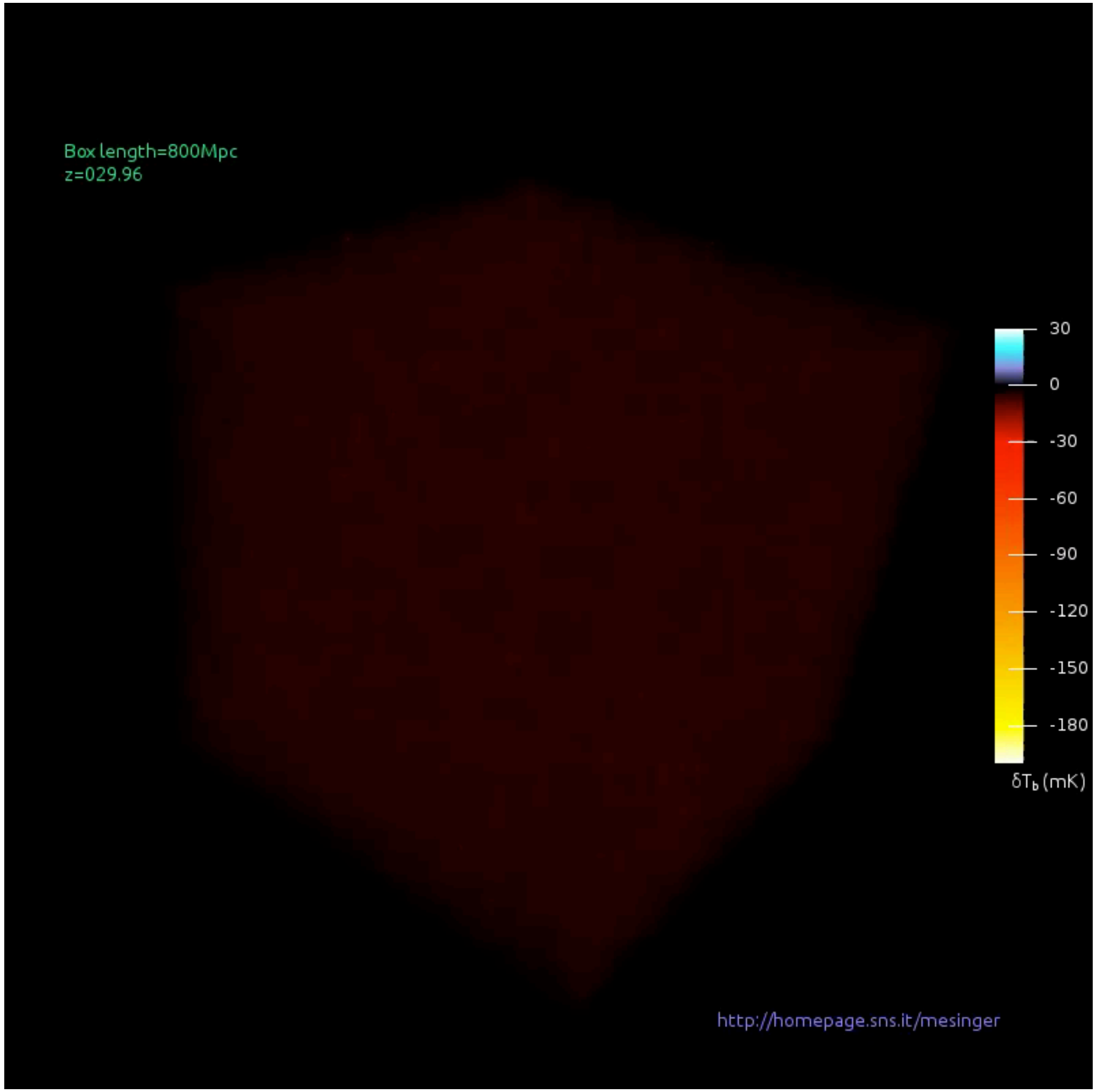
Including physical cosmology



21-cm observations of reionization can strengthen constraints on σ_8

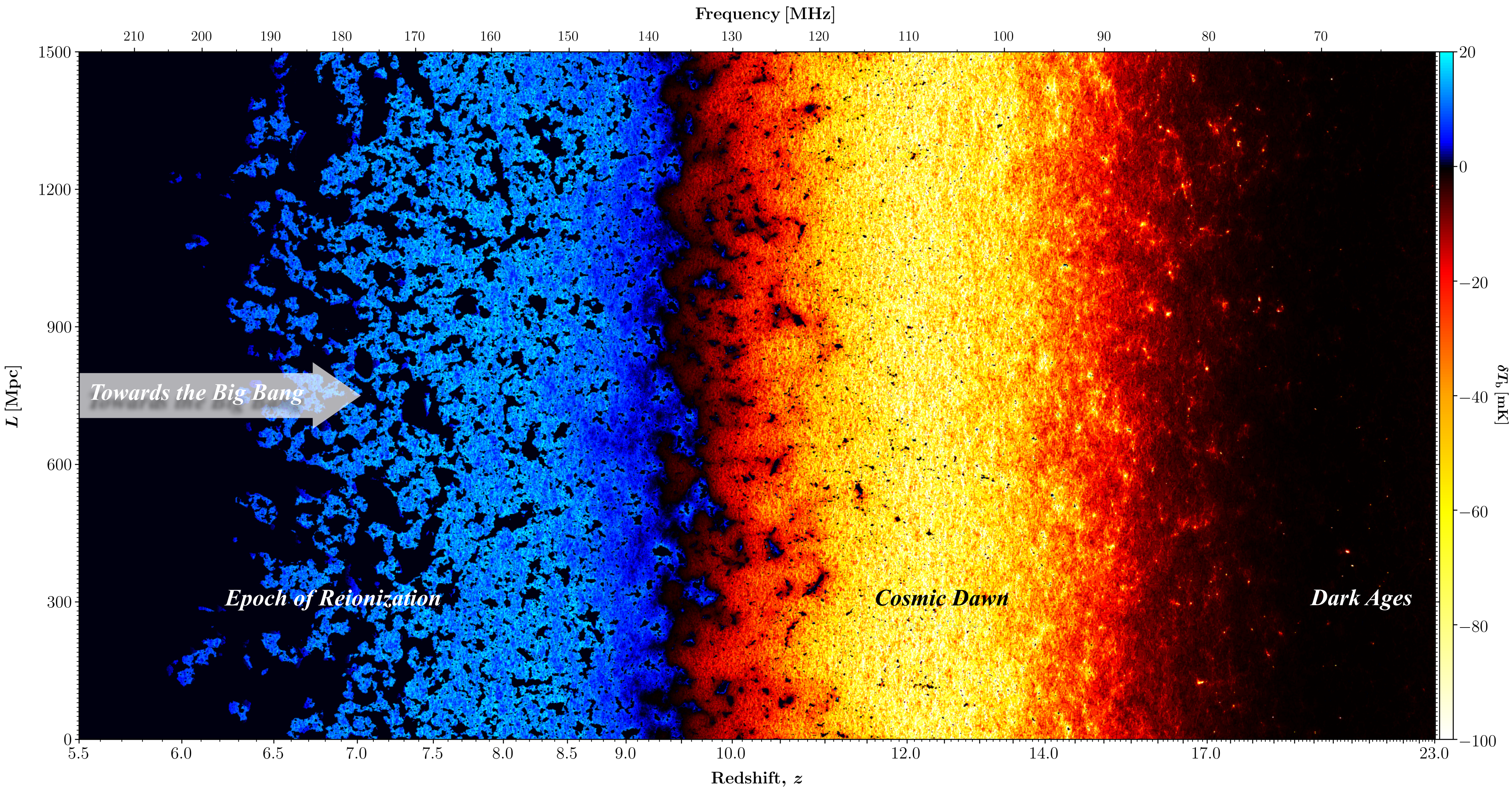
Kern + (2017)

SKA's revolutionary role will be in imaging the first billion years of our Universe



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

Astrophysical cosmology



The 21cm signal is **highly non-Gaussian.** Using only the power spectrum **wastes a lot of information!!!**

Greig & AM 2015; 2017

Exploring non-Gaussian statistics

1. **"Brute force" approach:** Simply replace the power spectrum in the likelihood calculation of 21CMMC with an alternate statistic, e.g. the bispectrum (Watkinson, AM+, in prep). *Does that statistic yield tighter constraints on the astrophysical parameters?* Repeat with other statistics, quantifying which one results in the strongest constraints.

Exploring non-Gaussian statistics

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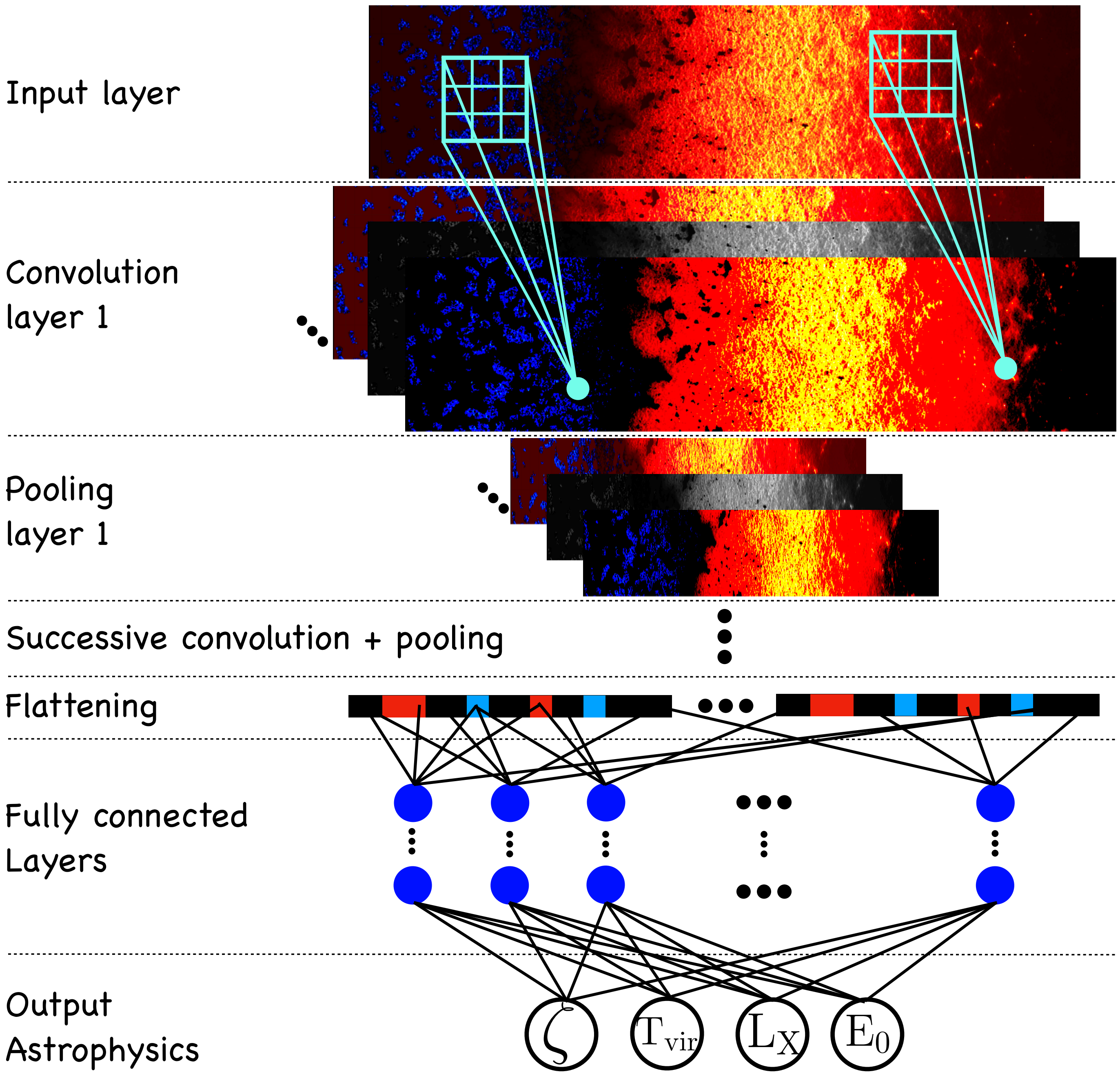
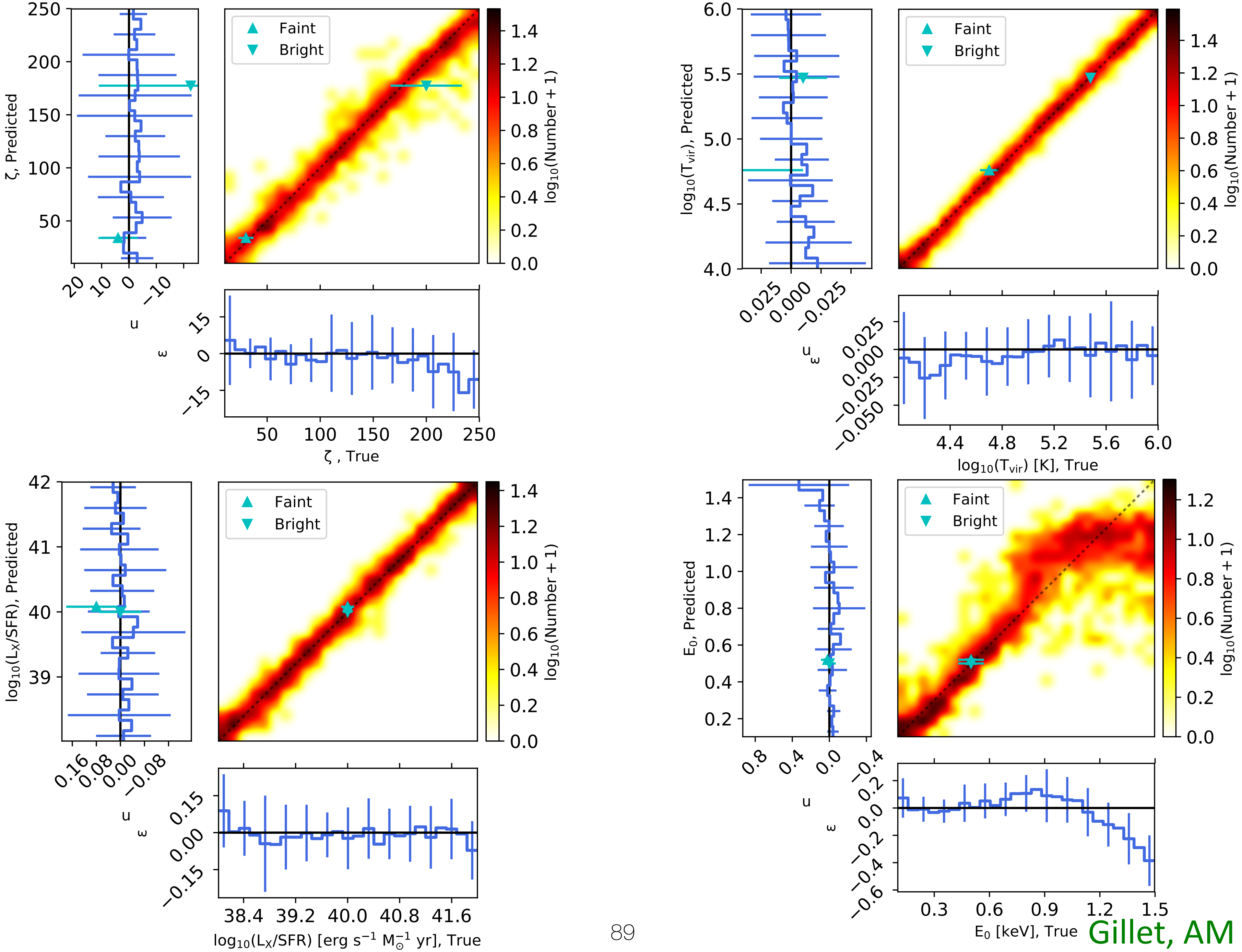
2. **Machine learning approach**: train Convolutional Neural Networks (CNN) to learn astrophysics and cosmology directly from 21-cm images (Gillet et al. 2018).

Deep learning with CNN: parameter recovery



Gillet, AM +, 2019

Deep learning with CNN: parameter recovery

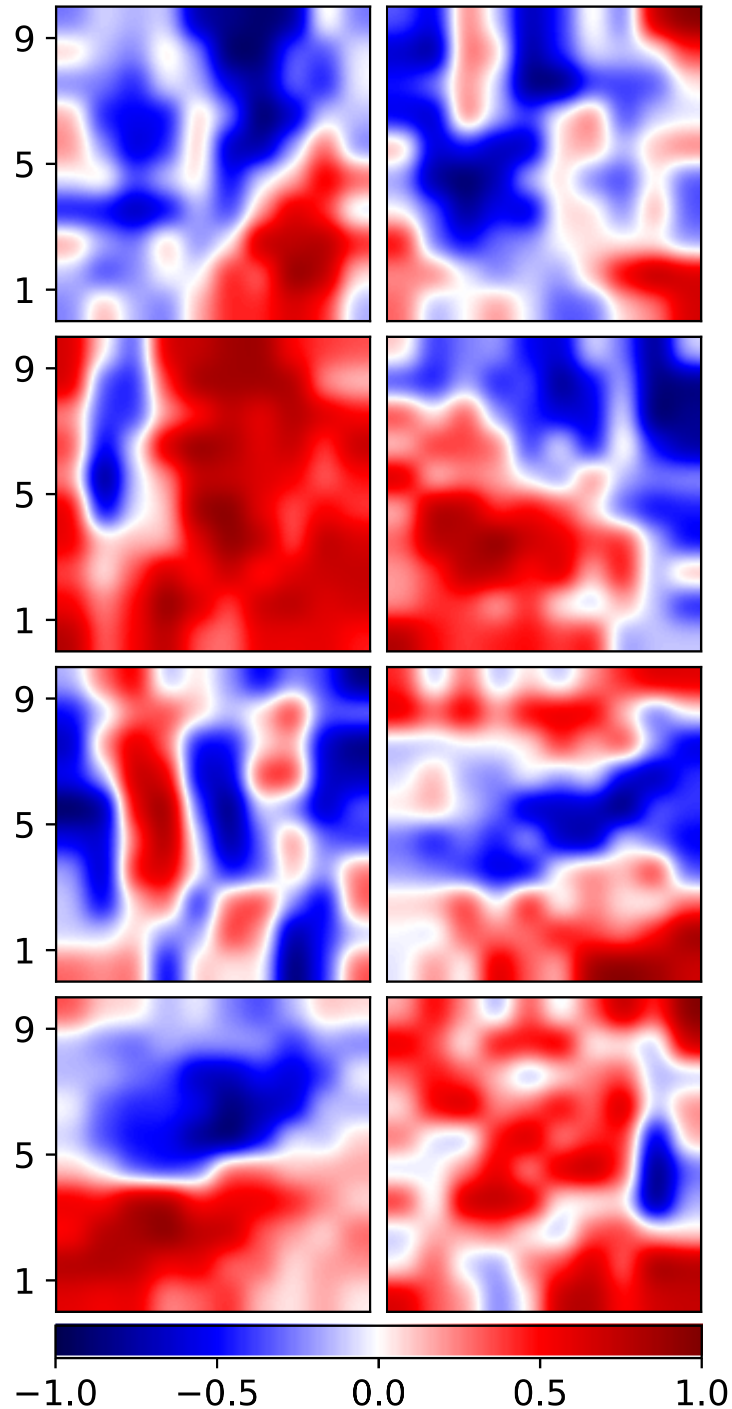


Gillet, AM +, 2019

CNN's eyes

- Filters of the 1st Convolution Layer

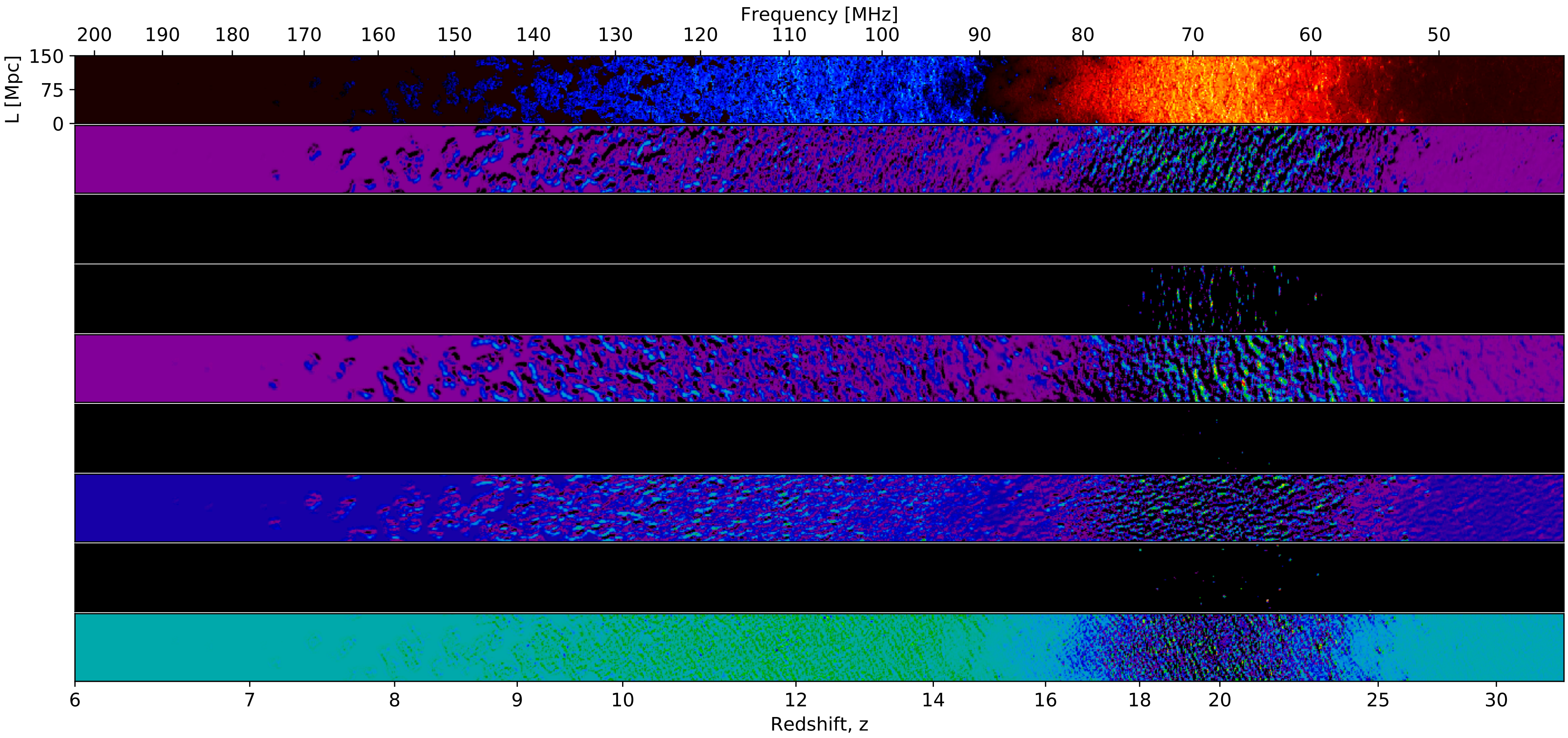
- 10x10 pixels (gaussian smooth)



Gillet, AM +, 2019

What the CNN sees

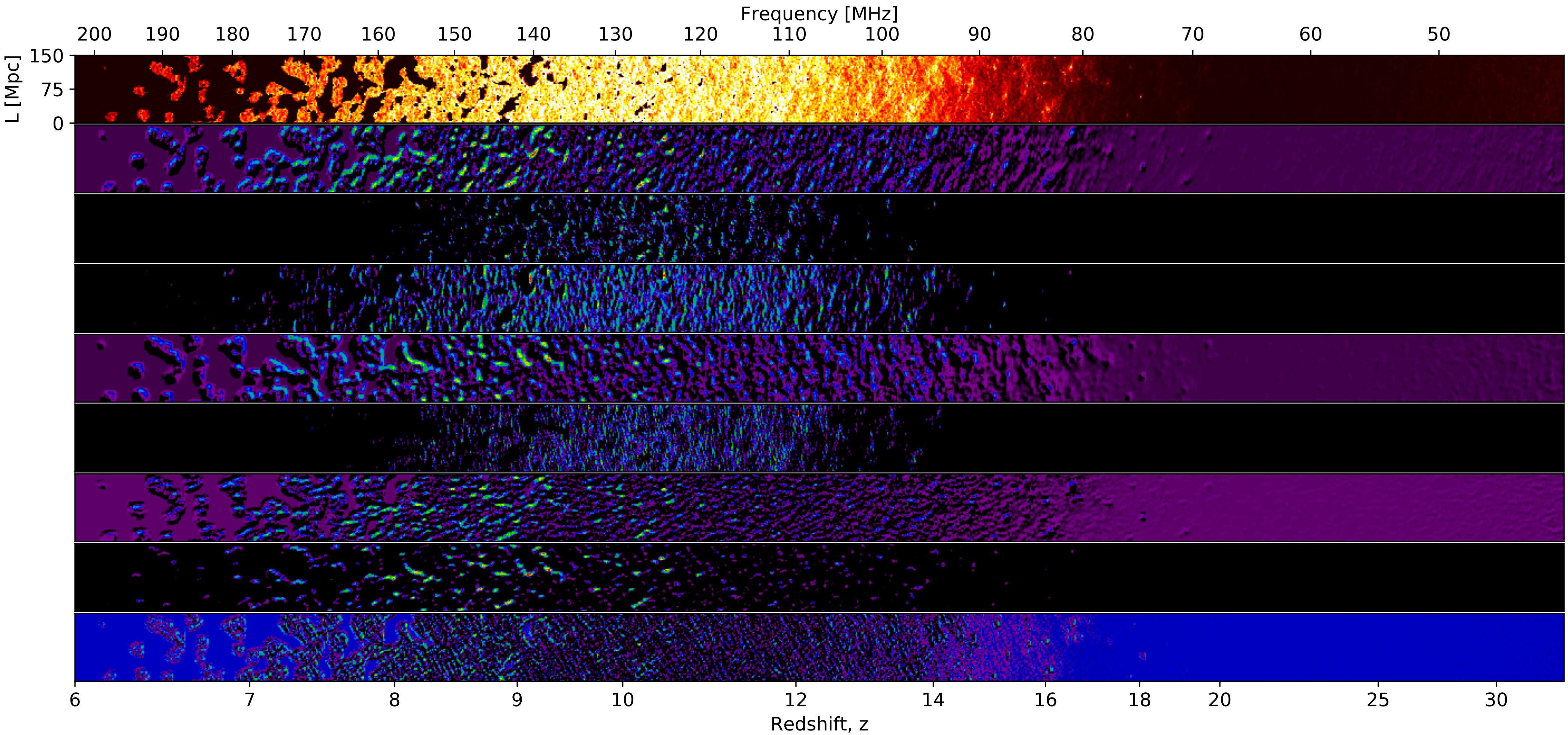
z~6 **z~30**



Gillet, AM +, 2019

What the CNN sees

z~6 **z~30**

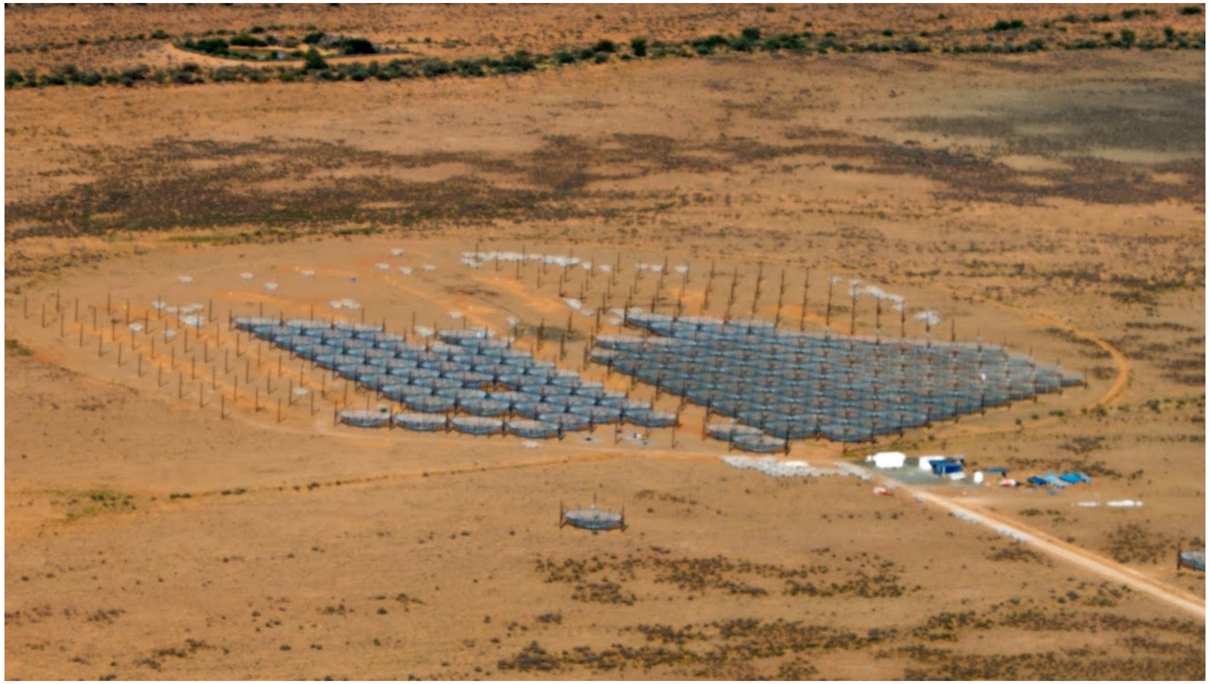


Gillet, AM +, 2019

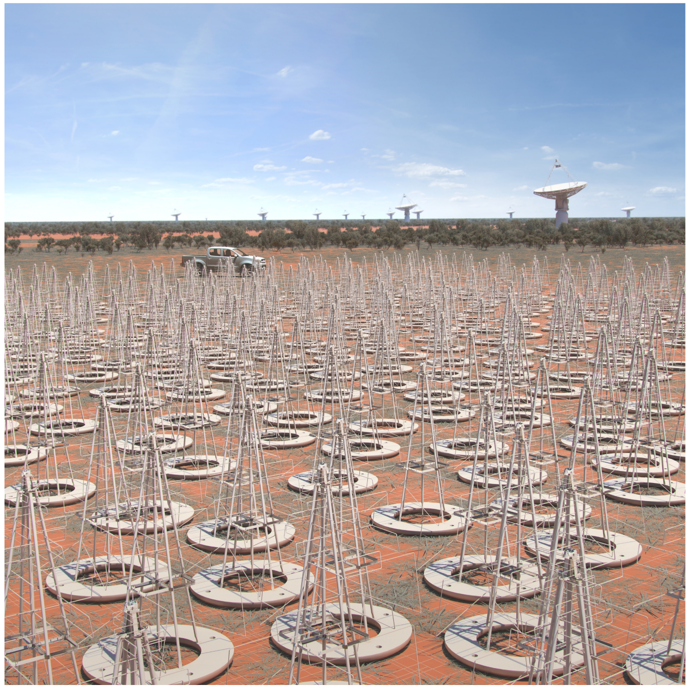
The time is now!

HERA (an SKA, second-generation precursor) will be fully operational in 2020

SKA will roll out early 2020s, with science runs mid-decade



HERA in 2019



rendering of SKA1-Low