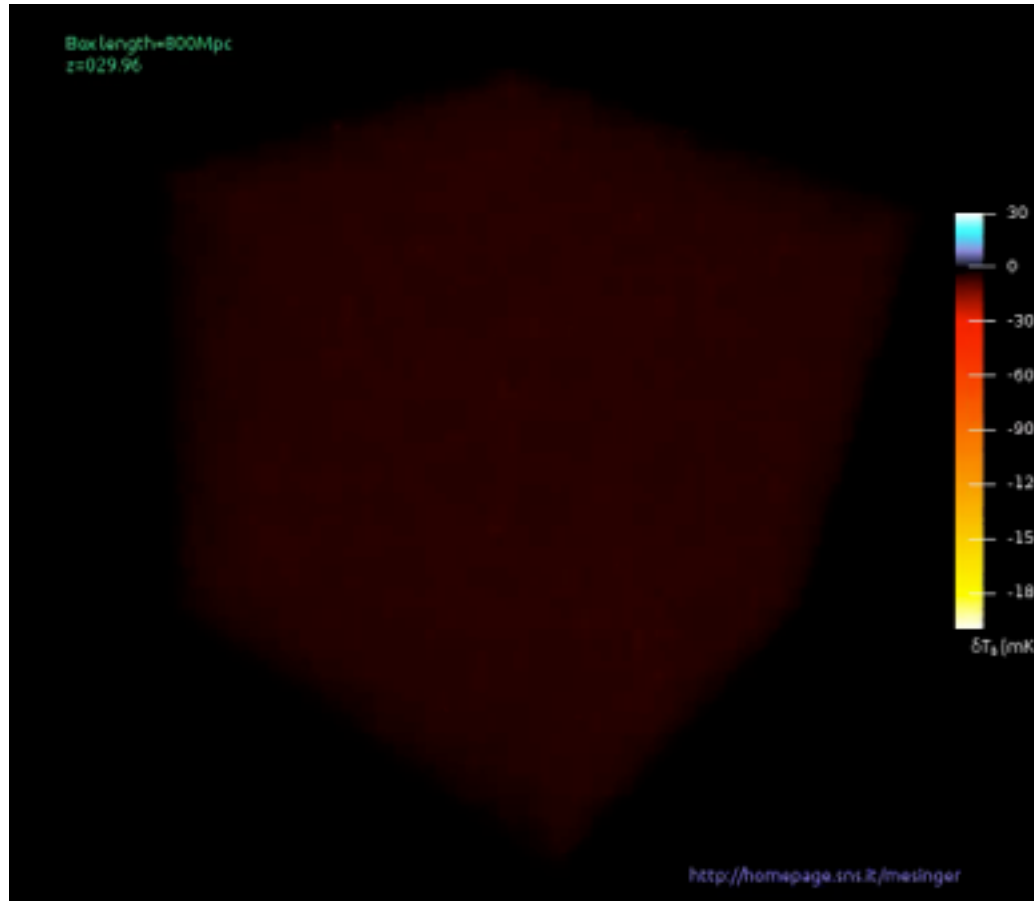


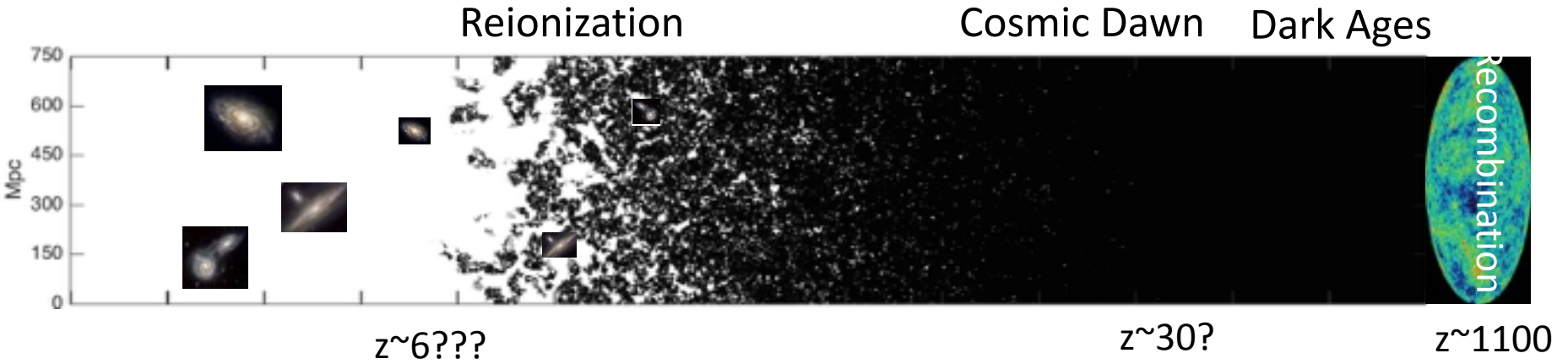
Learning about astrophysics with the cosmic 21-cm signal



<http://homepage.sns.it/mesinger/EOS.html>

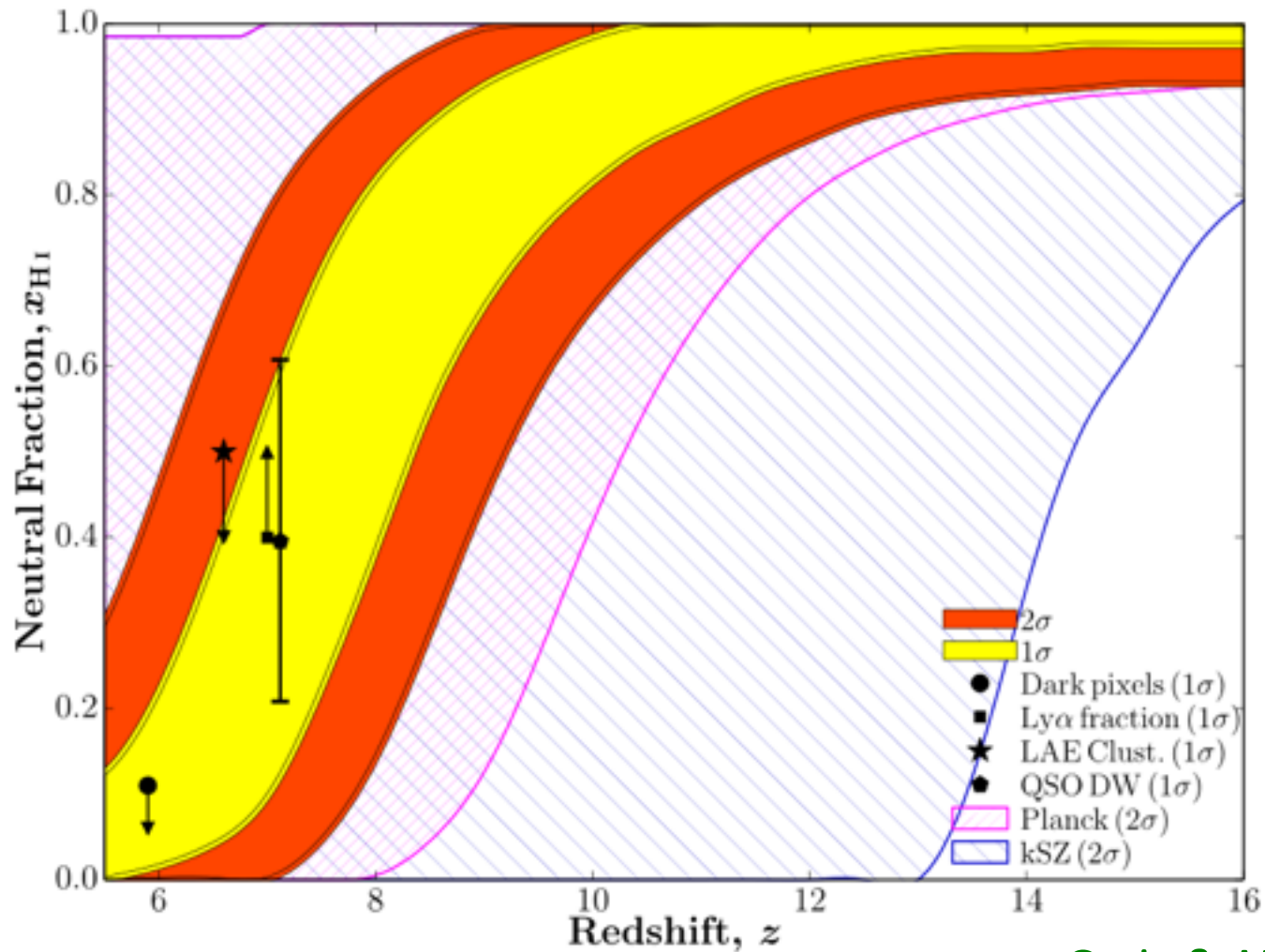
Andrei Mesinger

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?

When did the Universe reionize?



We now have a reasonable handle on when...

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

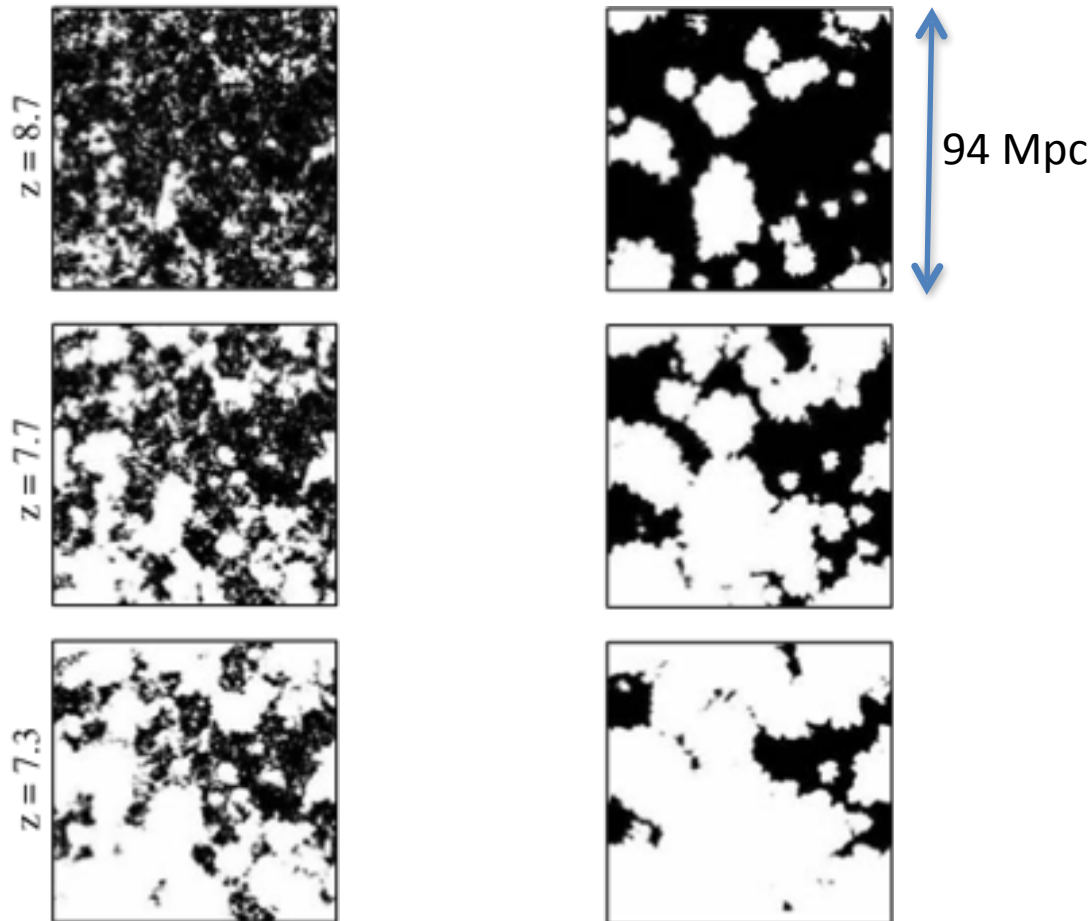
What and how??

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...

How do we learn about the hidden sources?

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



McQuinn+ 2007

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

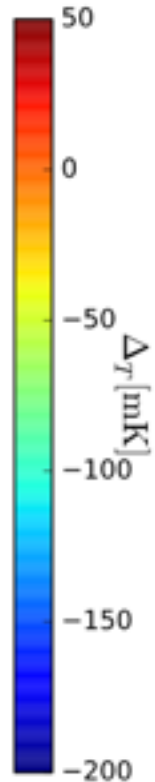
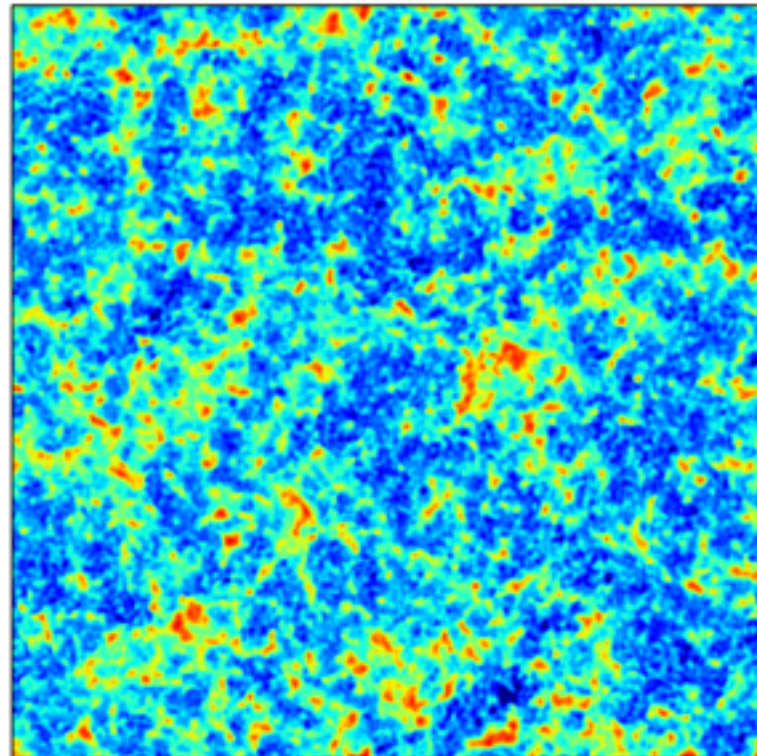
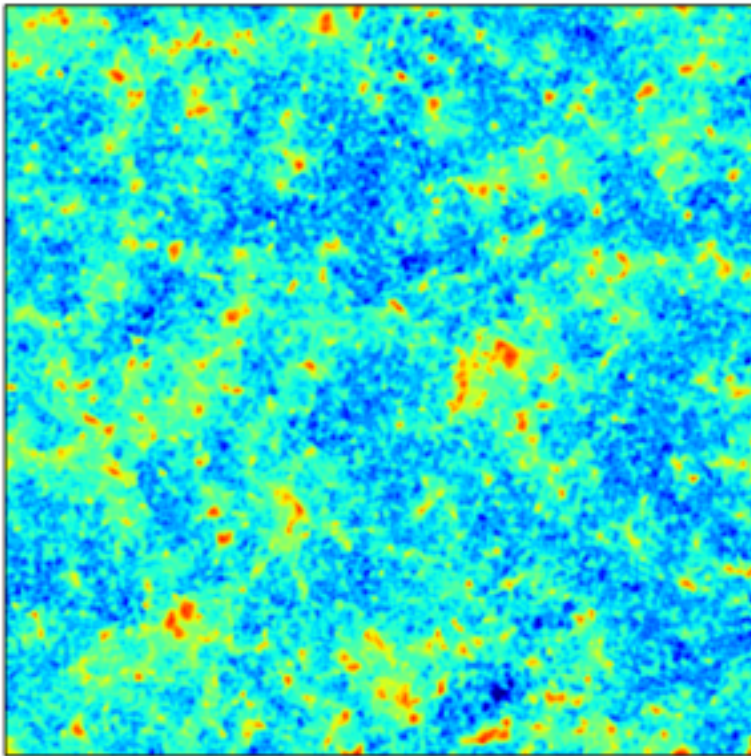
Patterns in the Epoch of Heating

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

'hard' SED ~ HMXBs

'soft' SED ~ hot ISM

750 Mpc



differences are easily detectable with HERA and the SKA

How to quantify what we will learn??

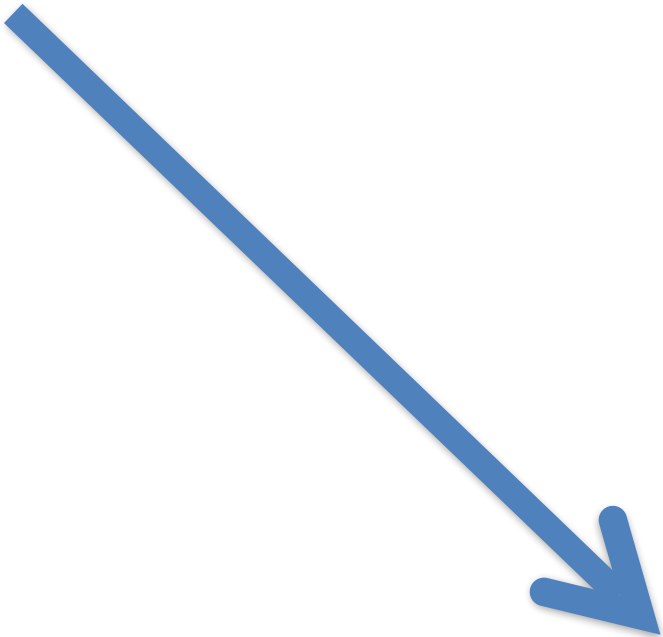
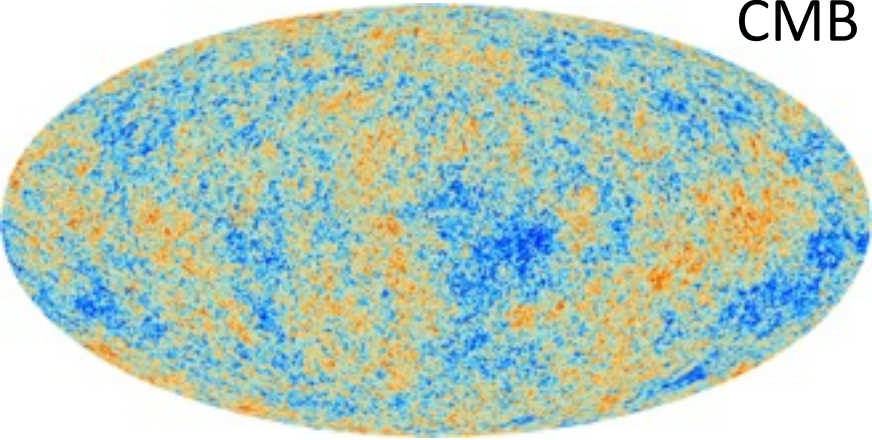
21cmFAST (AM+2007, 2011) — public, efficient semi-numerical 3D simulation code; extensively tested and currently used by *all* 21-cm efforts around the globe

+

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

Physical cosmology

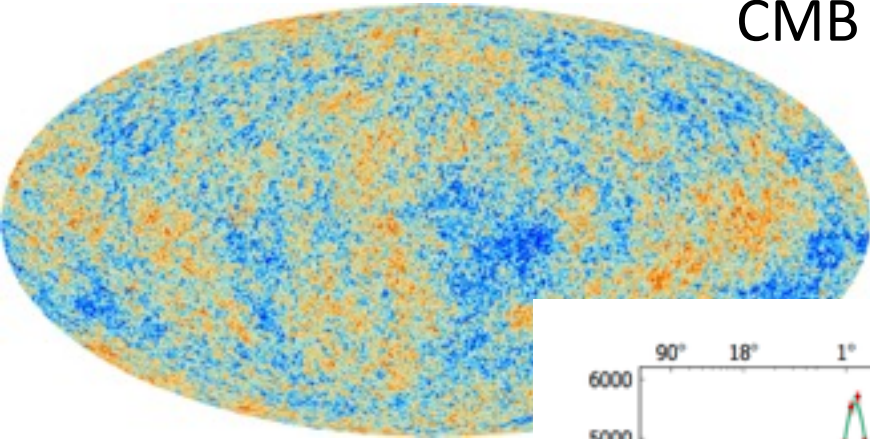
CMB map



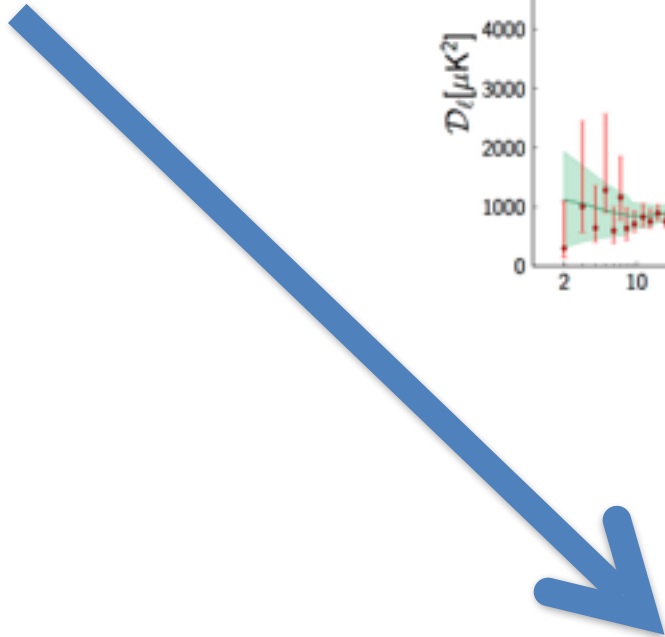
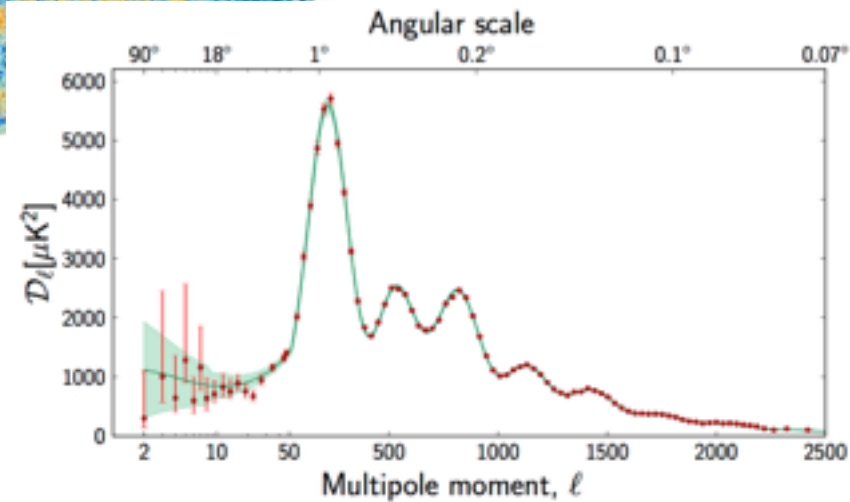
Planck 2013; 2015

Physical cosmology

CMB map

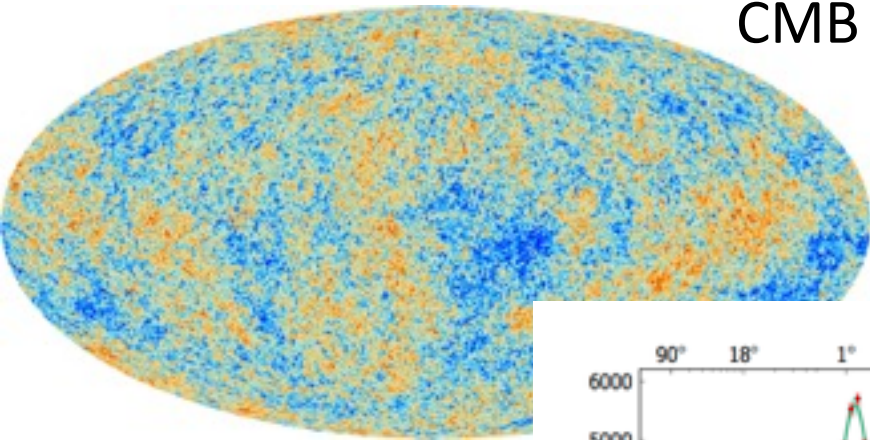


power spectrum

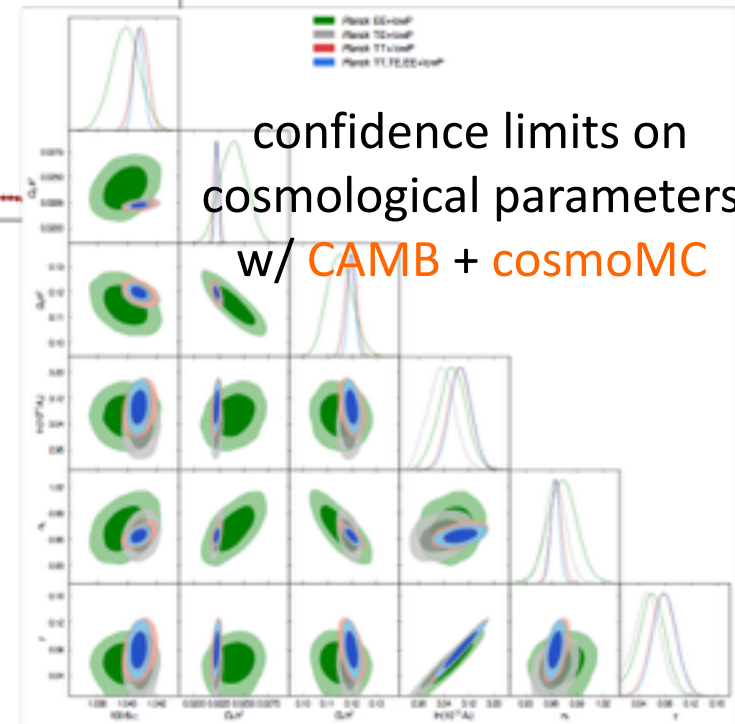
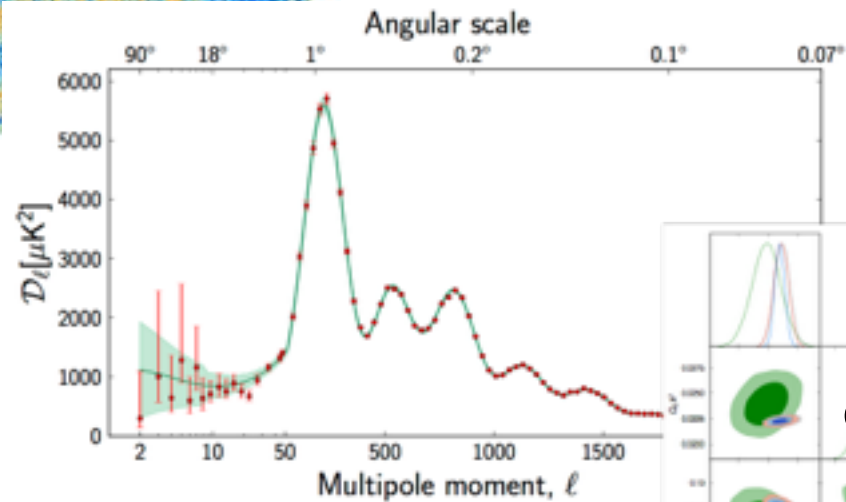


Physical cosmology

CMB map

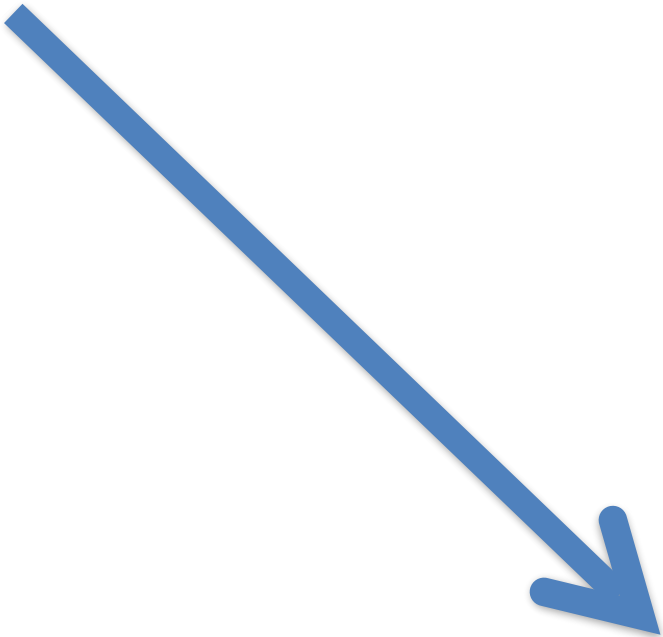
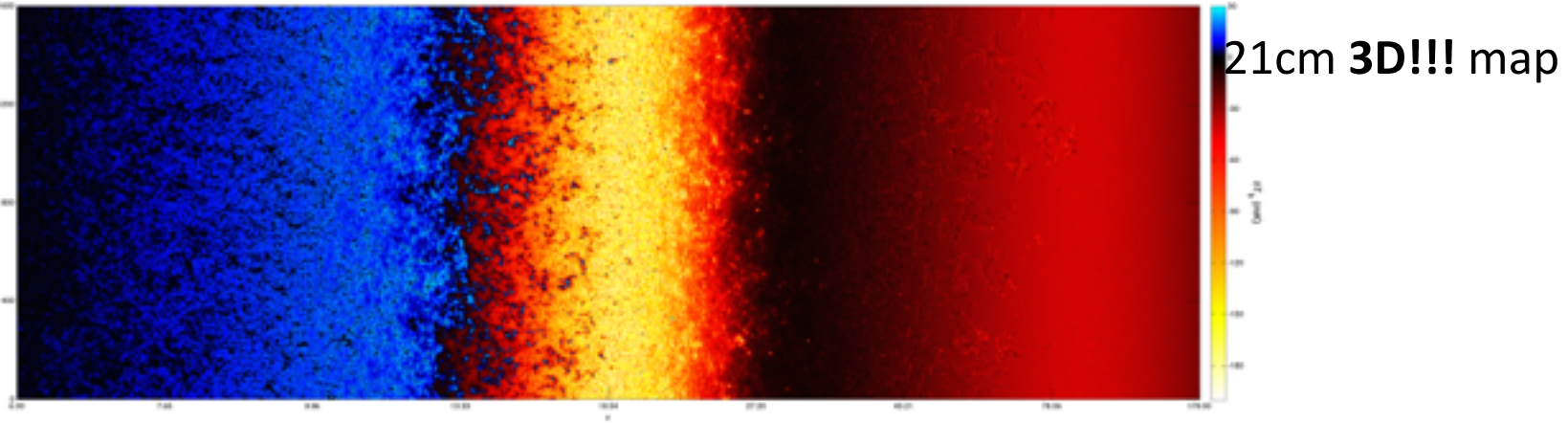


power spectrum



Astrophysical cosmology

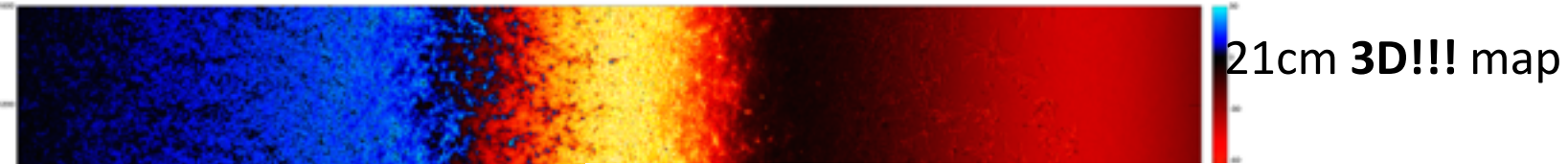
← time



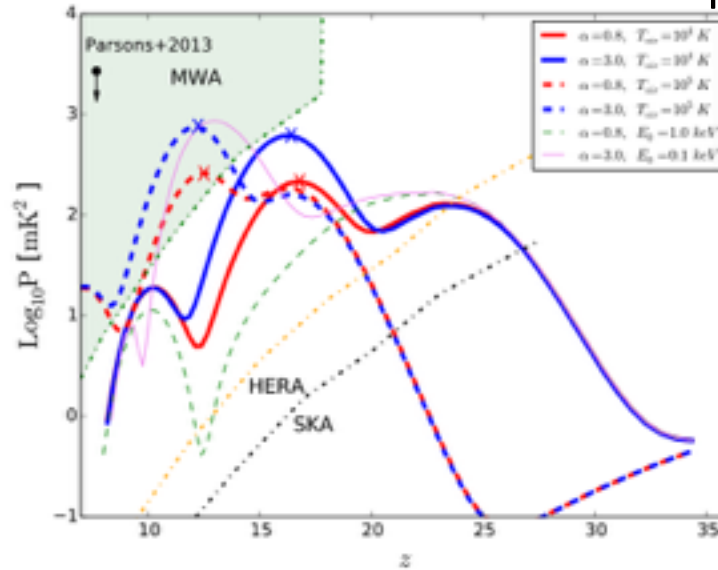
Greig & AM (2015)

Astrophysical cosmology

← time

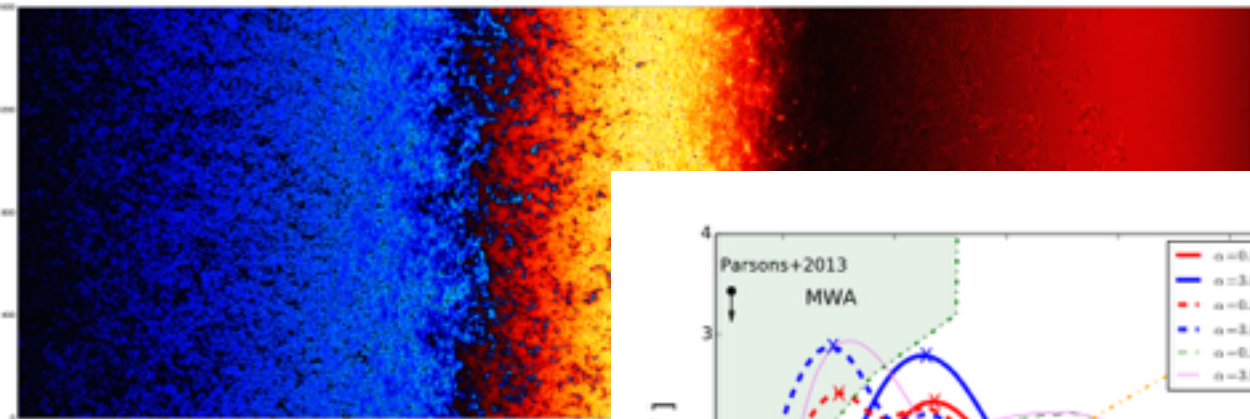


power spectrum??



Astrophysical cosmology

← time

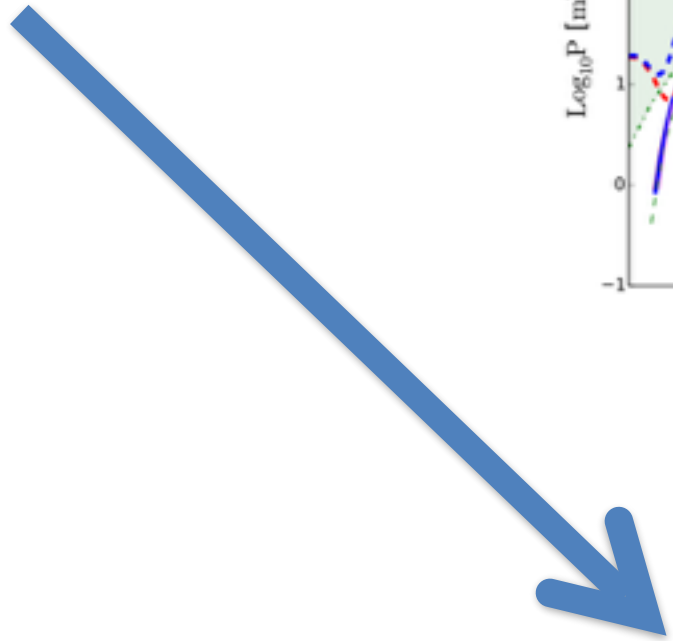
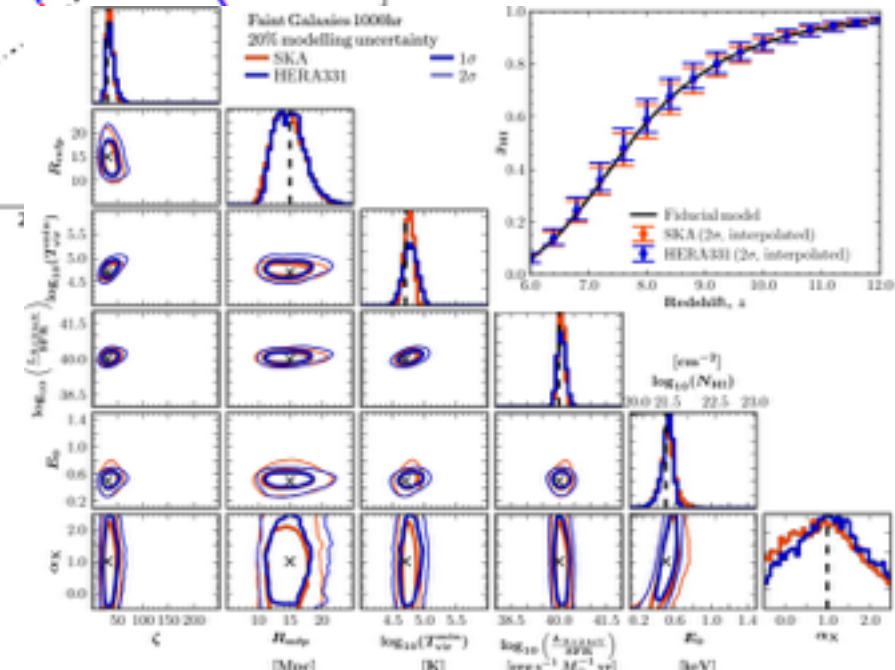
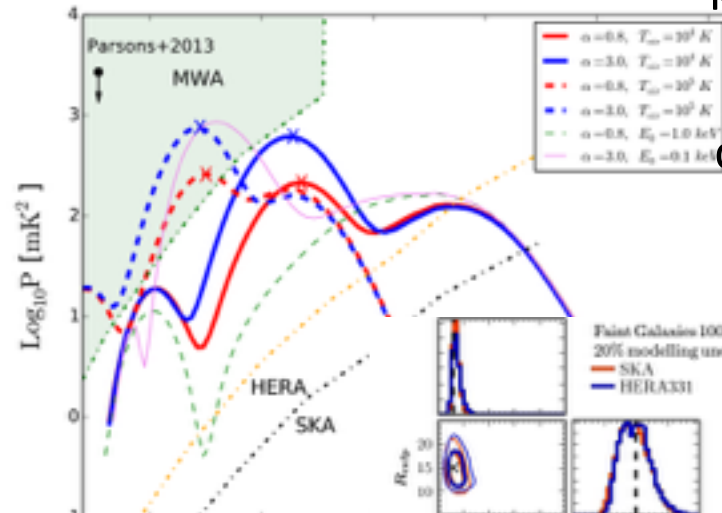


21cm 3D!!! map

power spectrum??

confidence limits on *astro* parameters

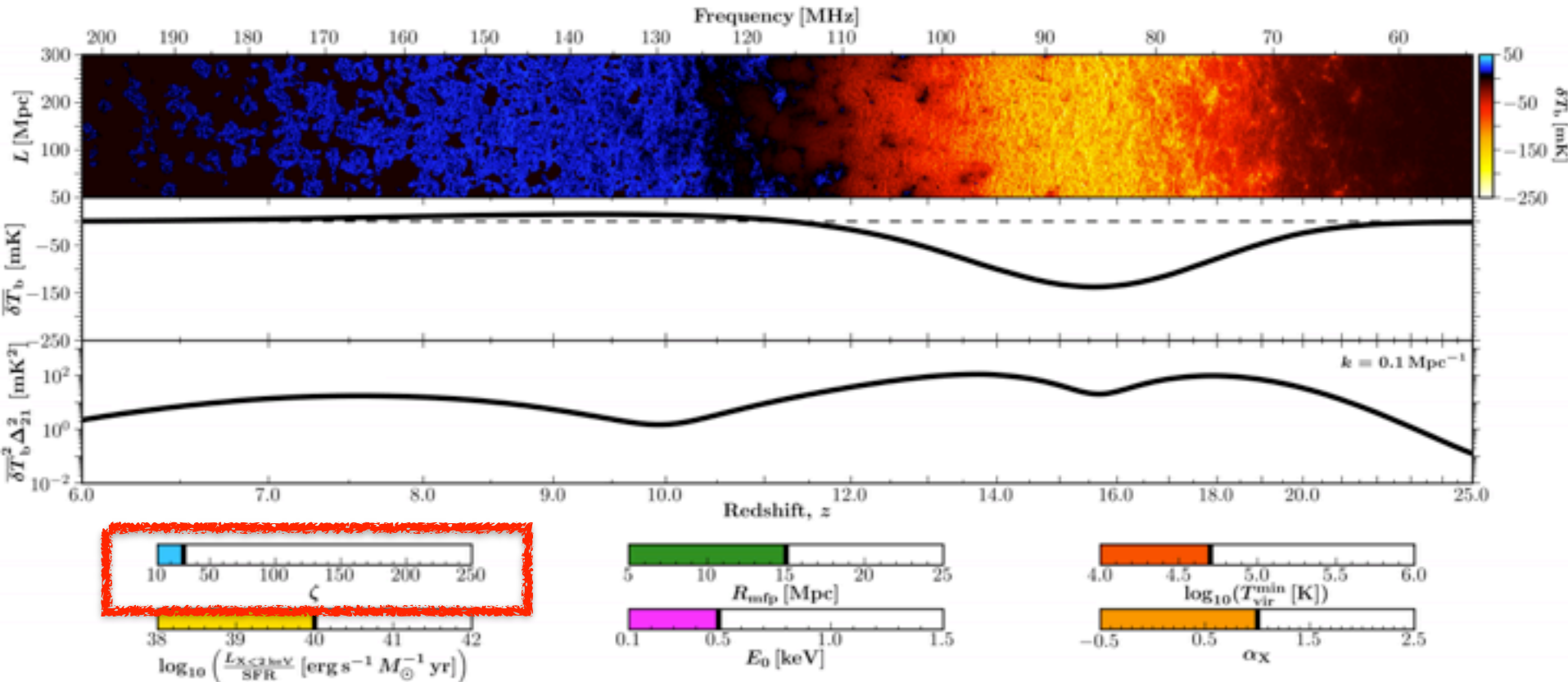
w/ 21cmFAST+ 21CMMC



What are *astrophysical* parameters?

<http://homepage.sns.it/mesinger/21CMMC.html>

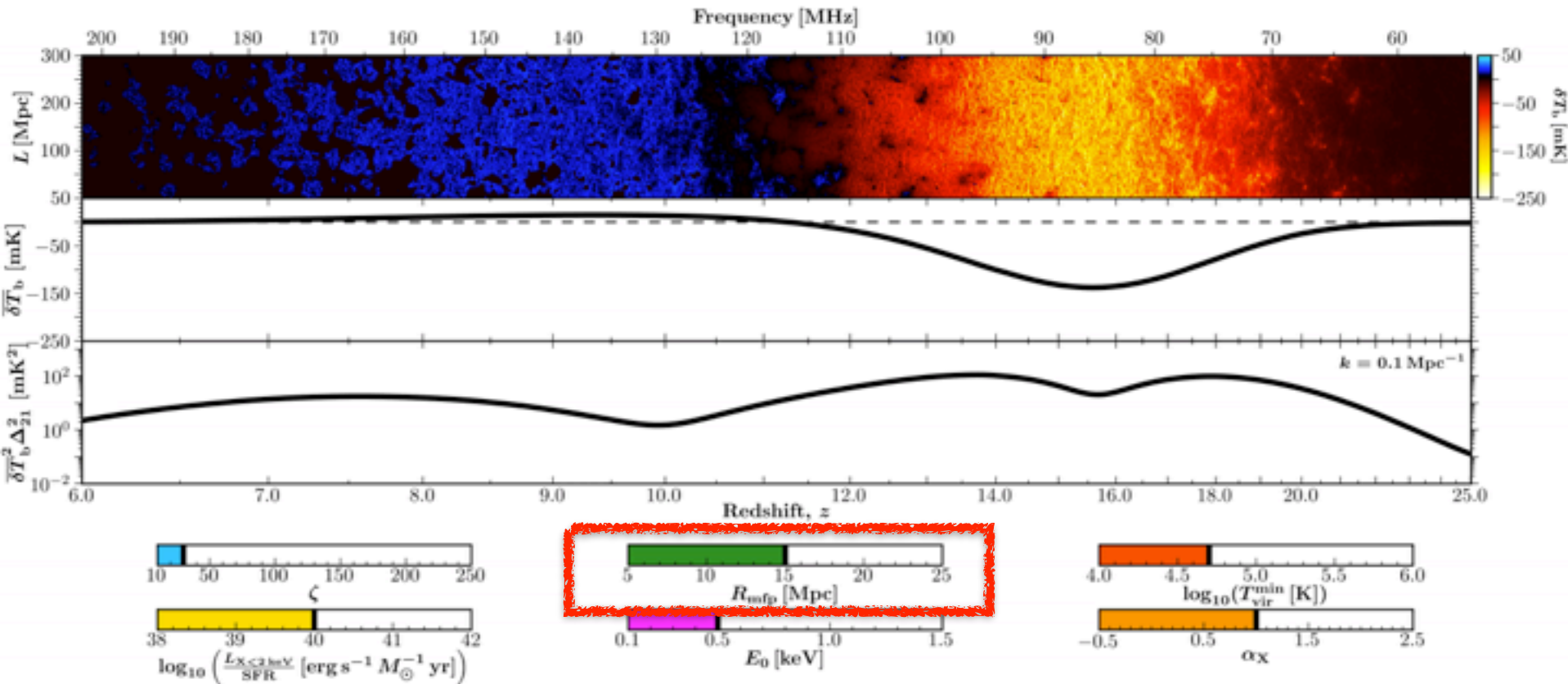
movie credit: B. Greig



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

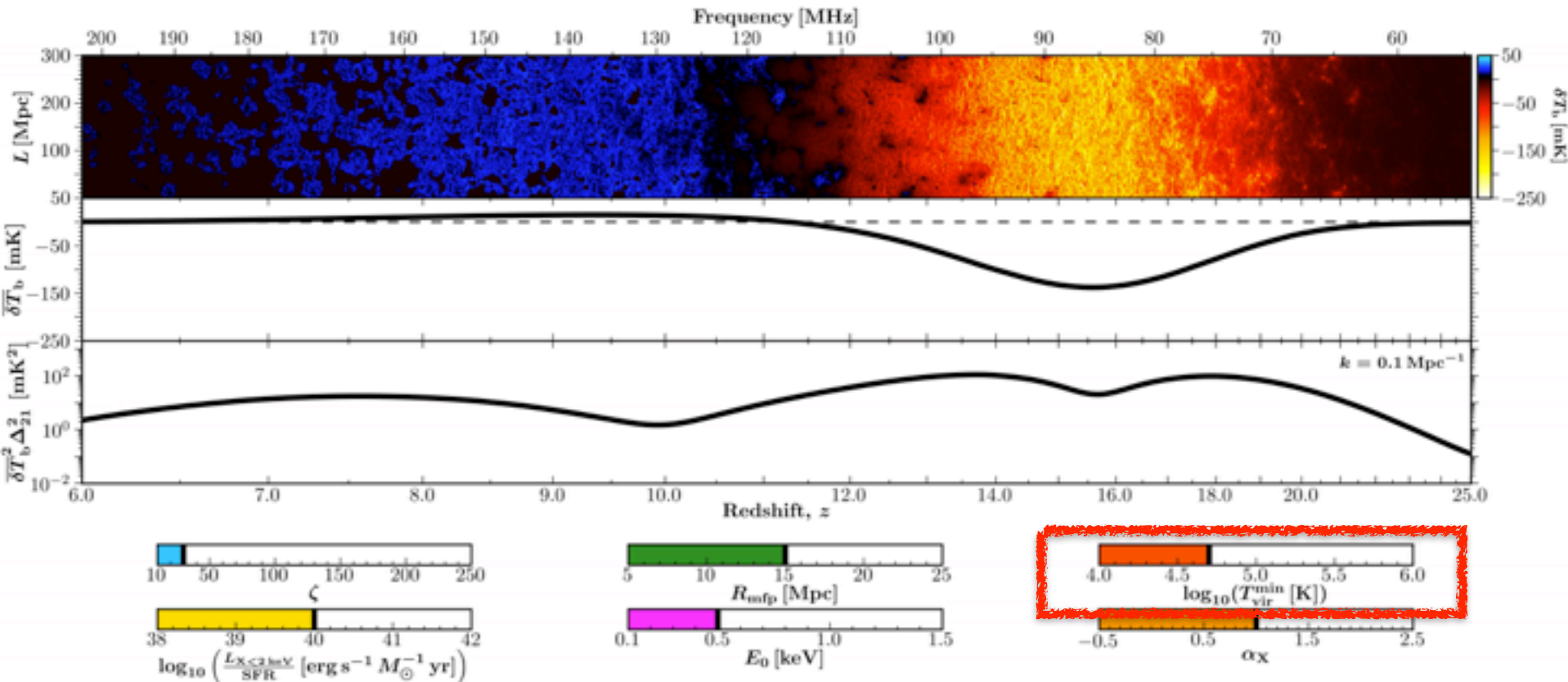
Greig & AM (2017)

What are *astrophysical* parameters?



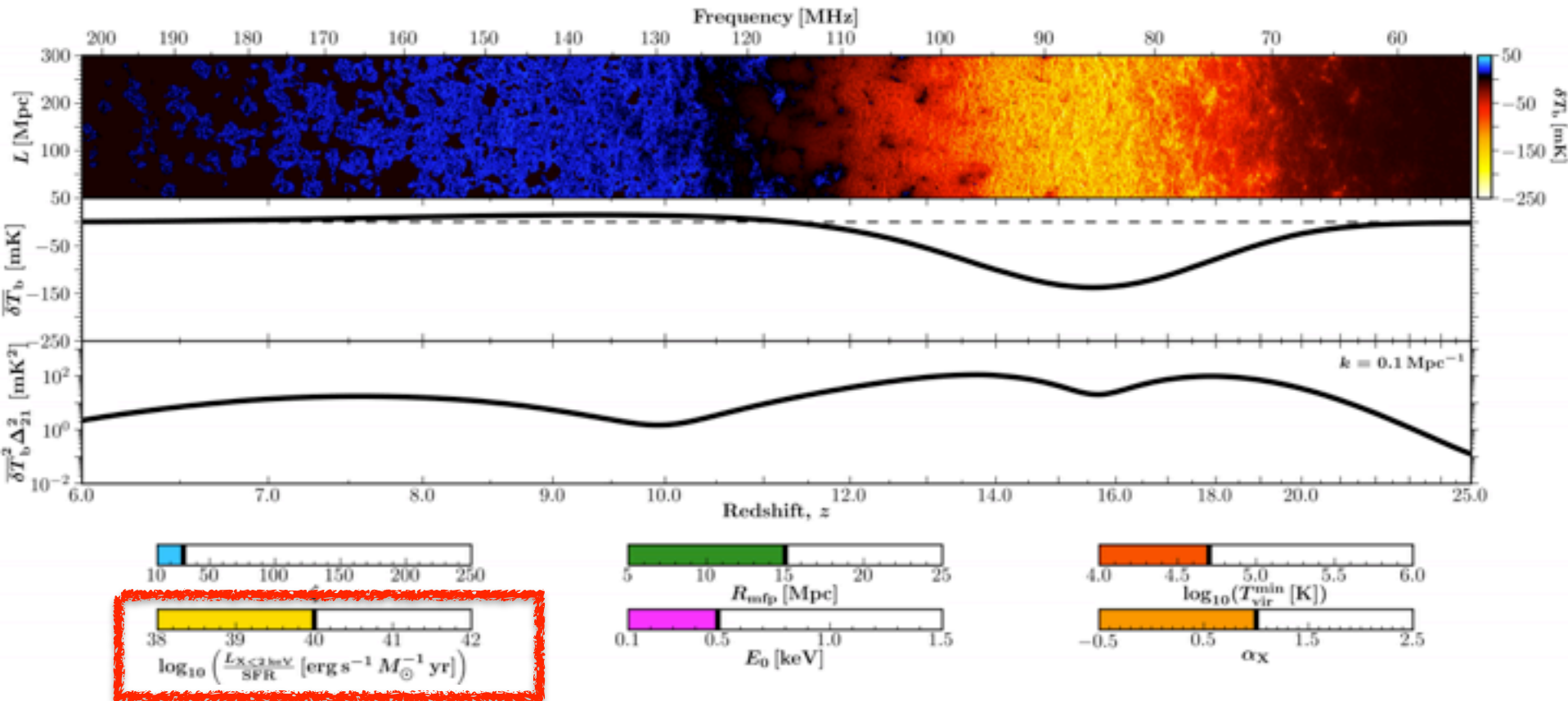
R_{mfp} – the typical horizon for ionizing photons (mean free path), set by IGM recombinations (Lyman limit systems)

What are *astrophysical* parameters?



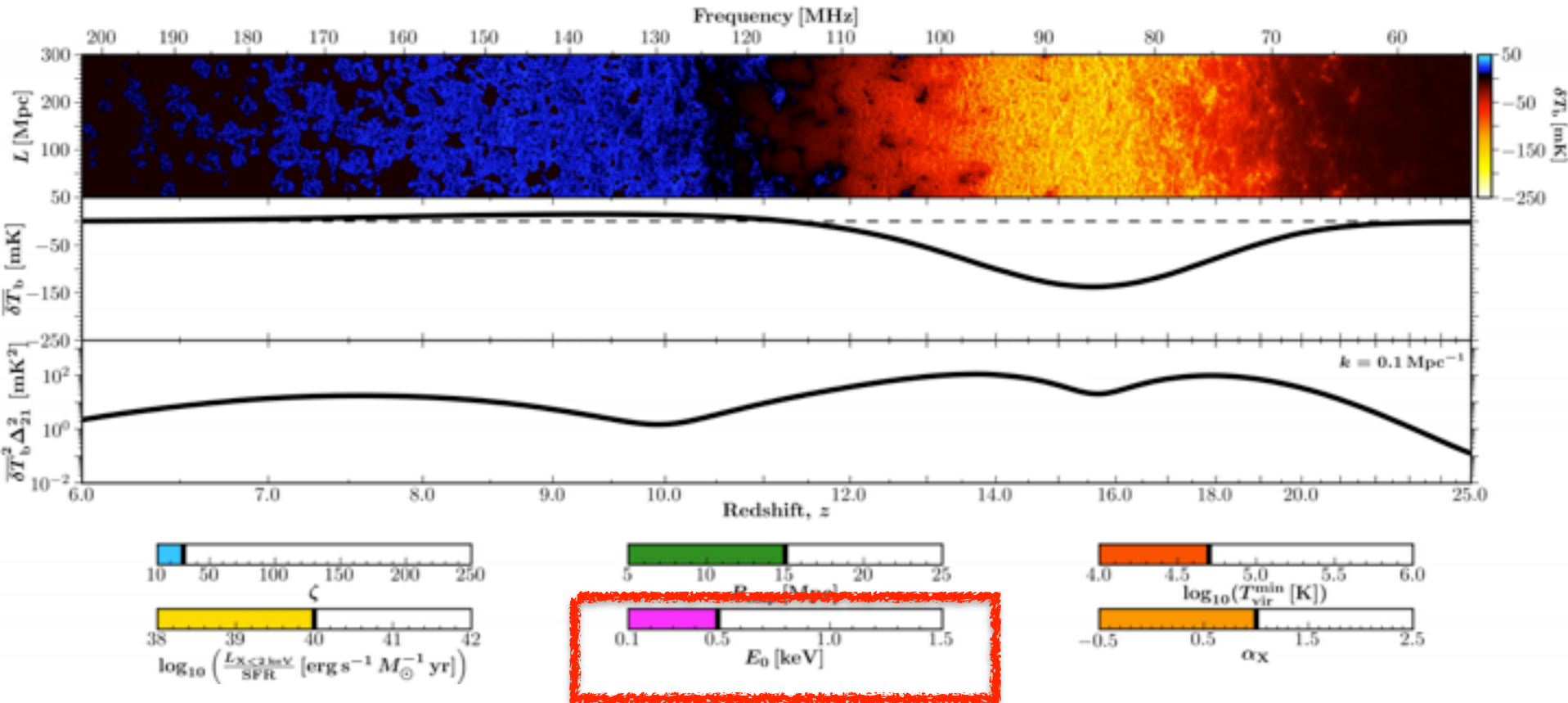
T_{vir} – the minimum virial temperature of halos hosting star-forming galaxies (set by cooling or feedback...)

What are *astrophysical* parameters?



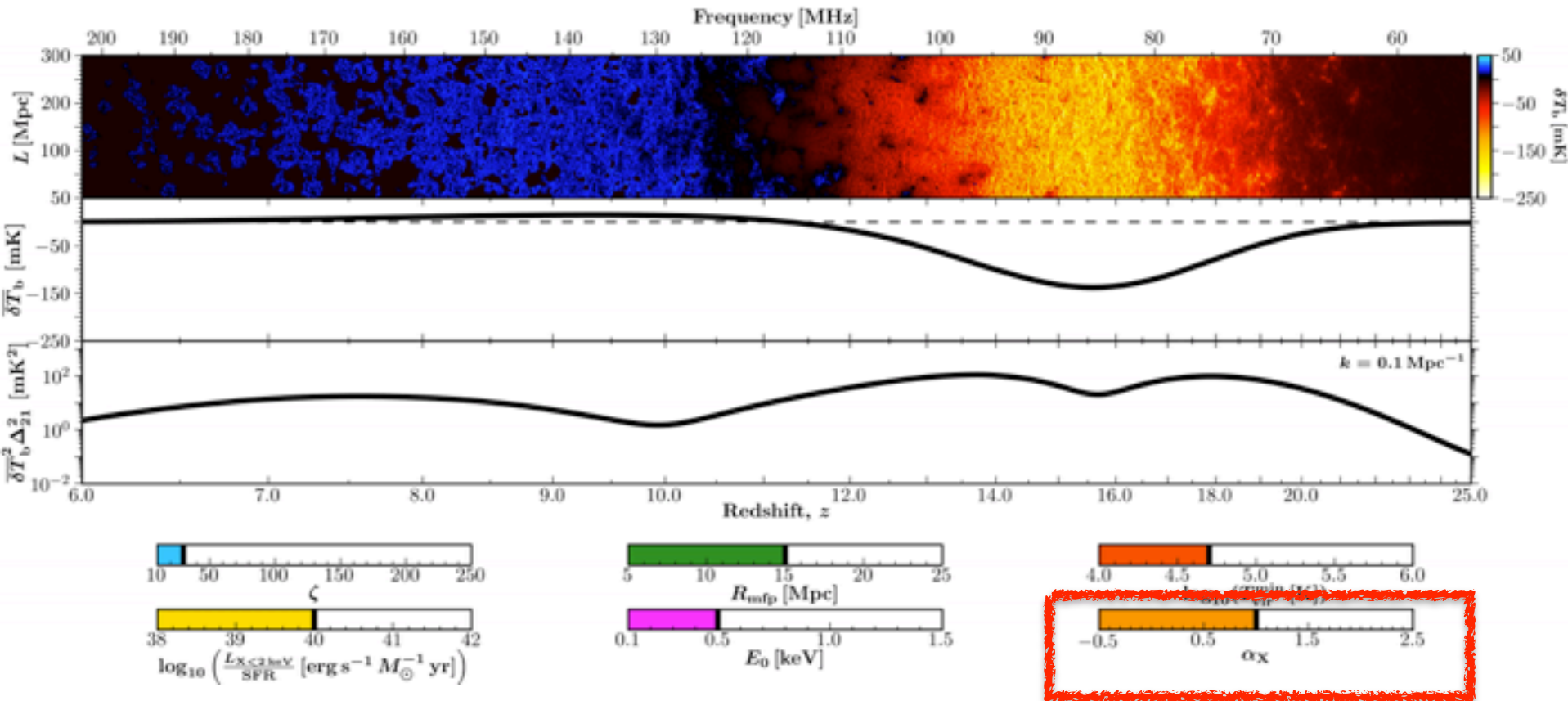
L_X / SFR – the soft-band X-ray luminosity per unit star formation of the first galaxies

What are *astrophysical* parameters?



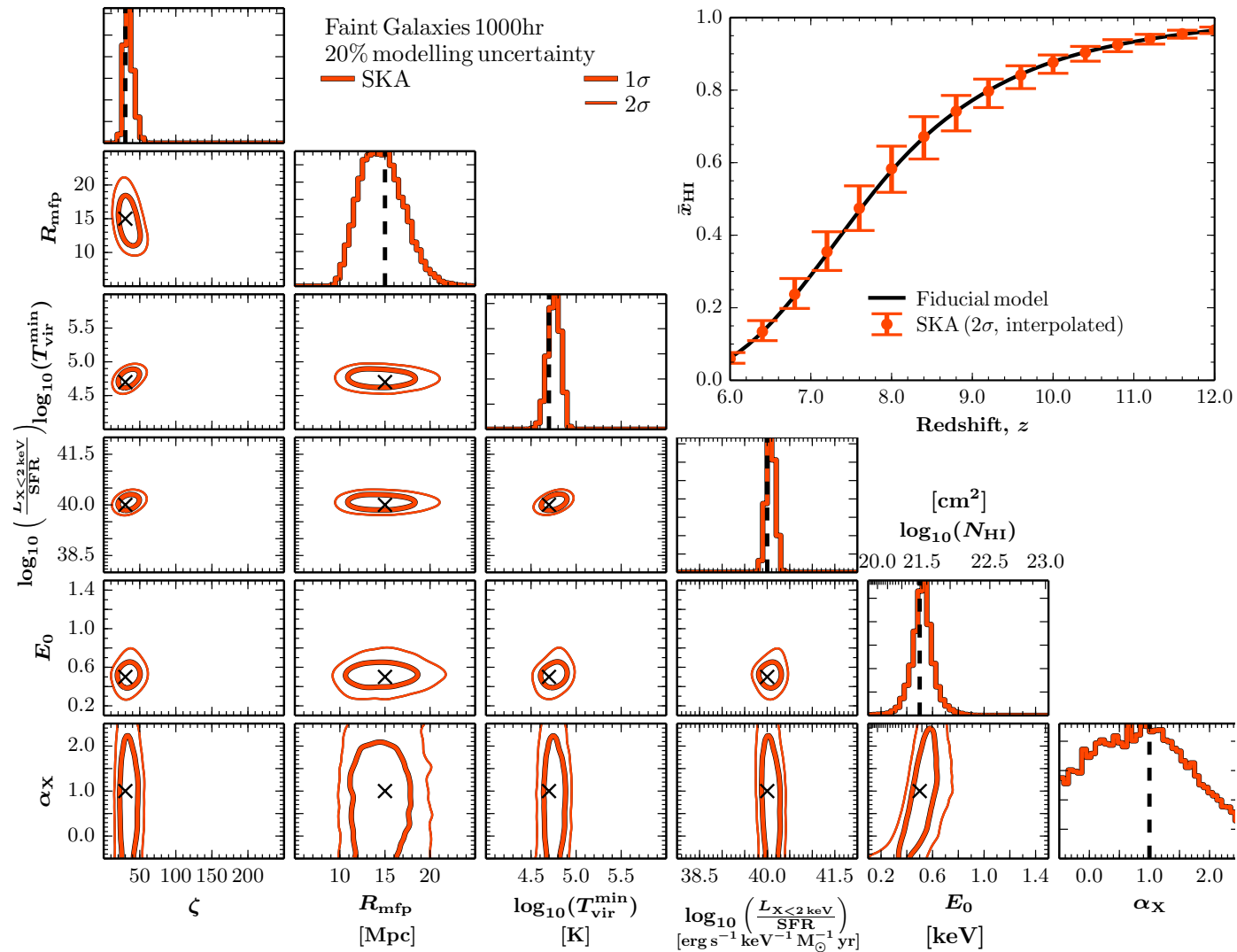
E_0 (or N_{HI}) – the minimum X-ray photon energy (corresponding to a typical N_{HI} of the first galaxies) capable of escaping the host galaxy into the IGM

What are *astrophysical* parameters?



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

Triangle plot from 21CMMC



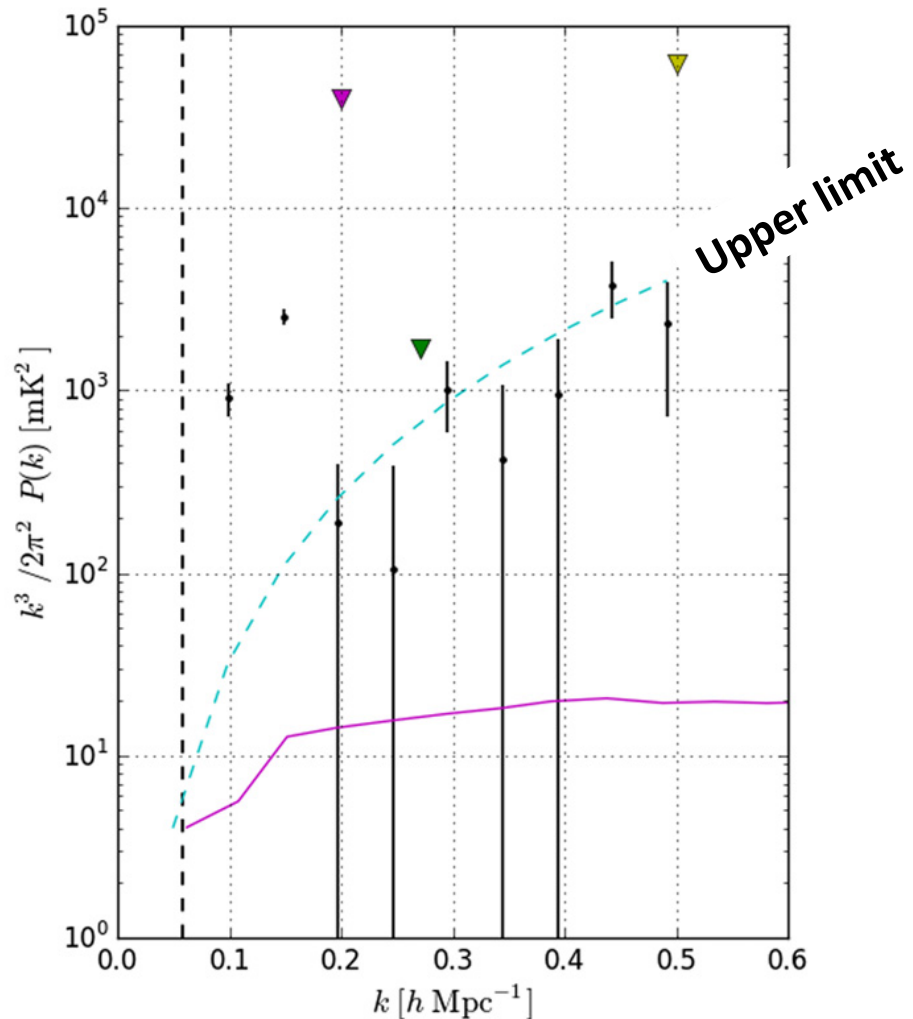
- percent level constraints on most astro params and EoR history w. SKA
- no strong degeneracies even with 6 parameter model

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?*

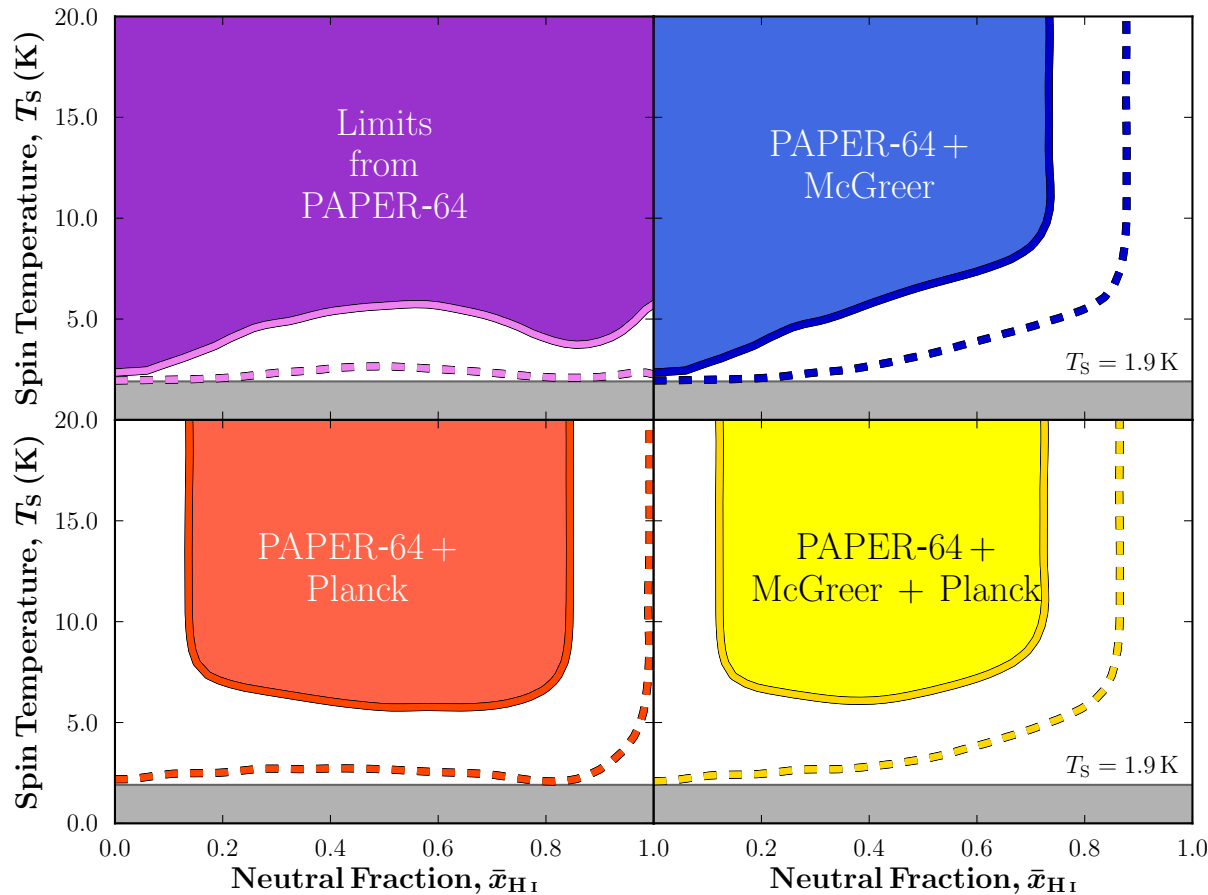
The time is now!

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



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



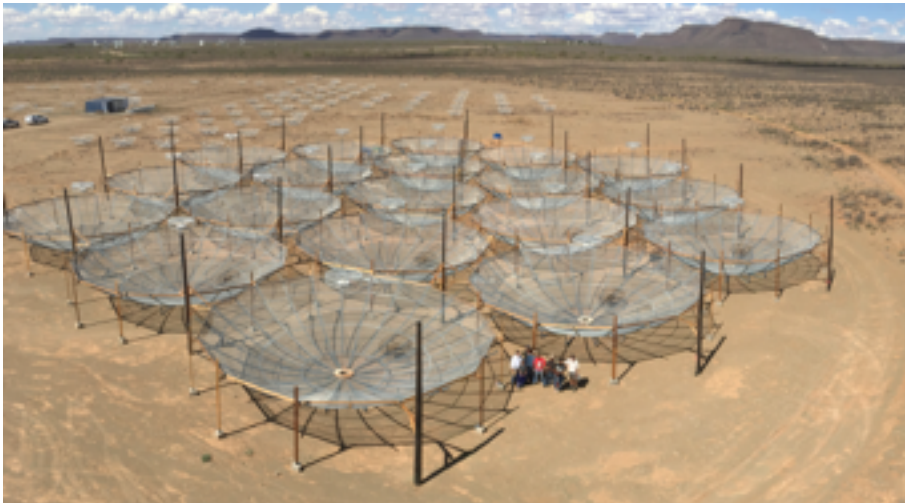
$\langle T_{\text{HI}} \rangle > 6$ K @ $z=8.4$

← adiabatically-cooled IGM

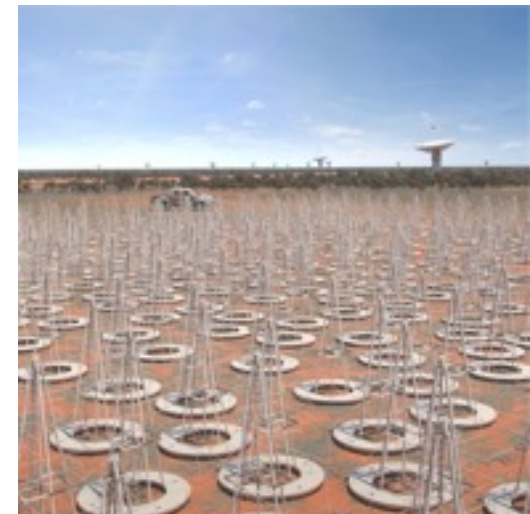
Greig, AM, Pober (2016)
(see also Pober+2015)

The time is now!

- 1st gen. interferometers are already taking data, ruling-out extreme models with no heating. *We should soon see a statistical detection of the EoR!*
- 2nd 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

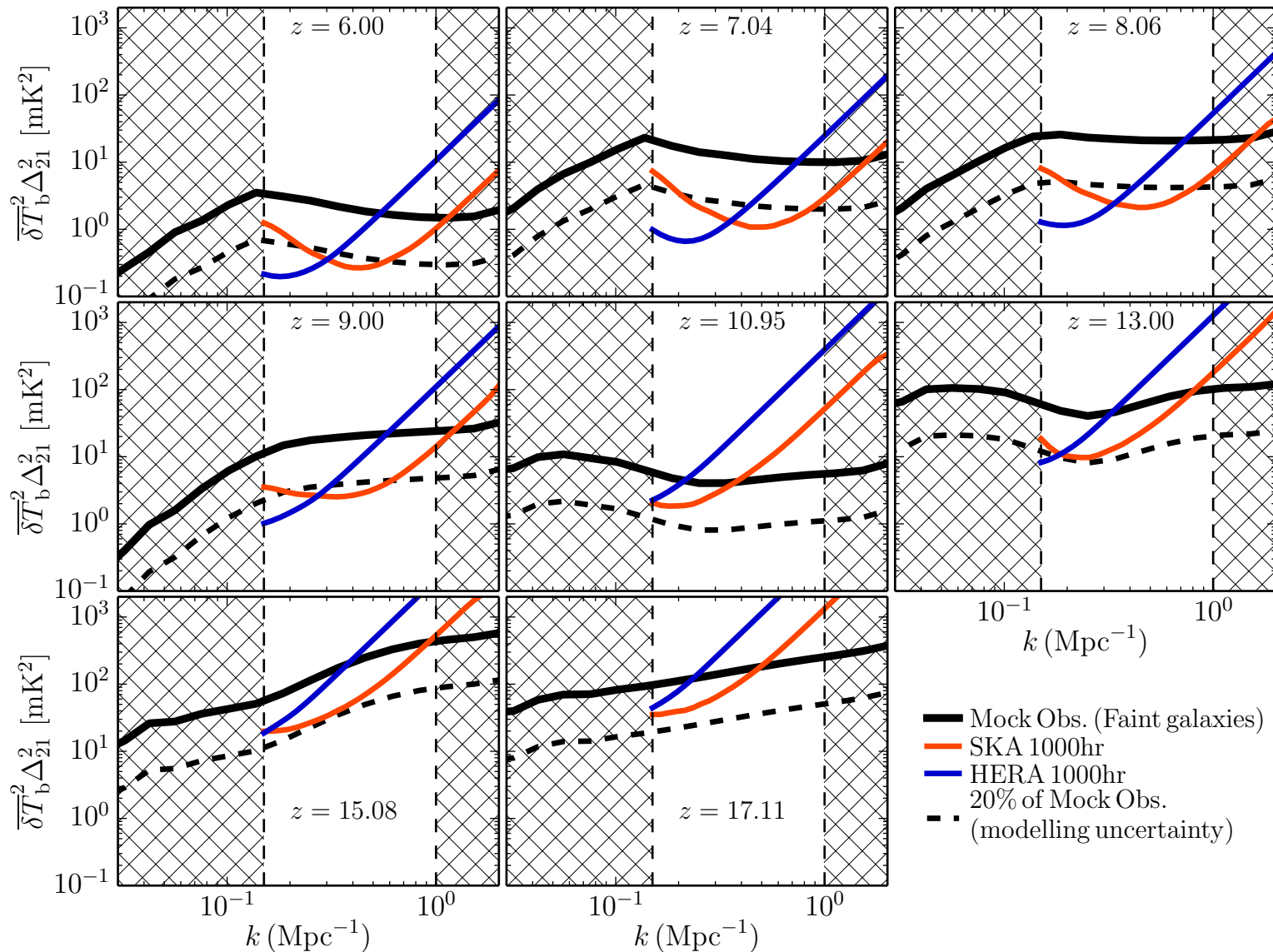


rendering of SKA1-Low

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: $\langle x_{\text{HI}} \rangle = 0.40_{-0.32}^{+0.41} (2 \sigma)$ **at $z \sim 7$** . 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 (21CMC) 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??**

Sensitivities



Simulation slice

