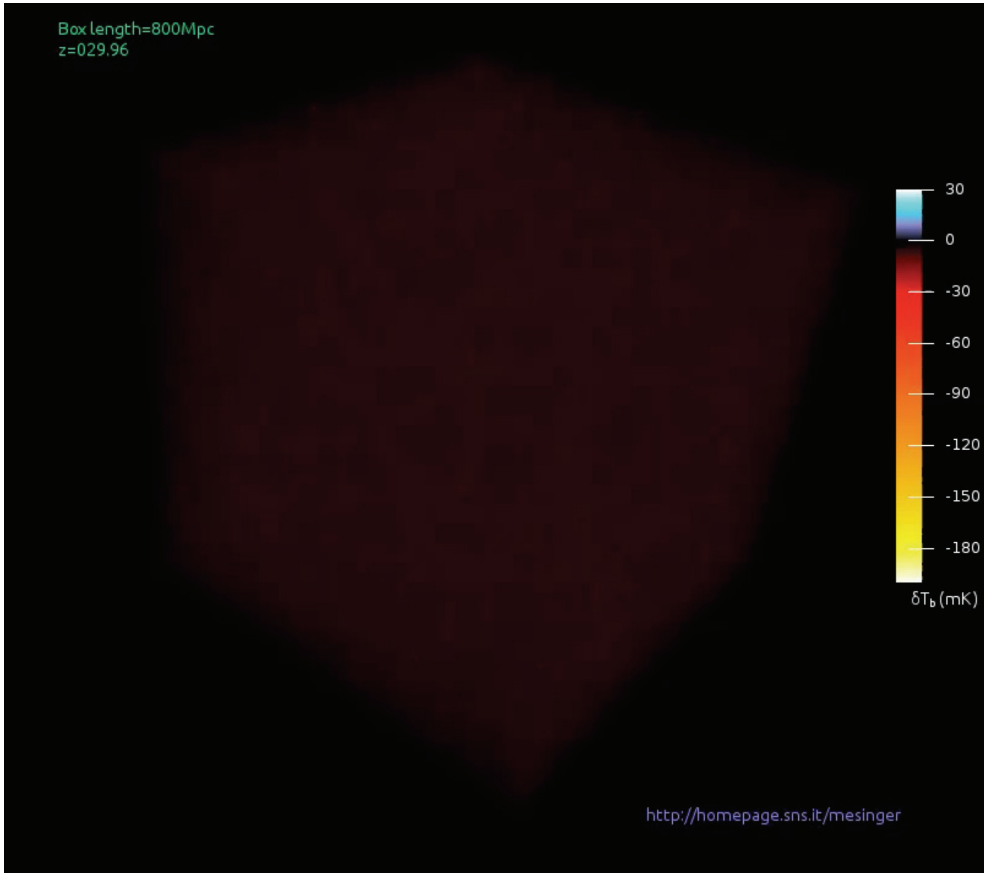
Forward-modeling
the first billion years of our Universe



Andrei Mesinger

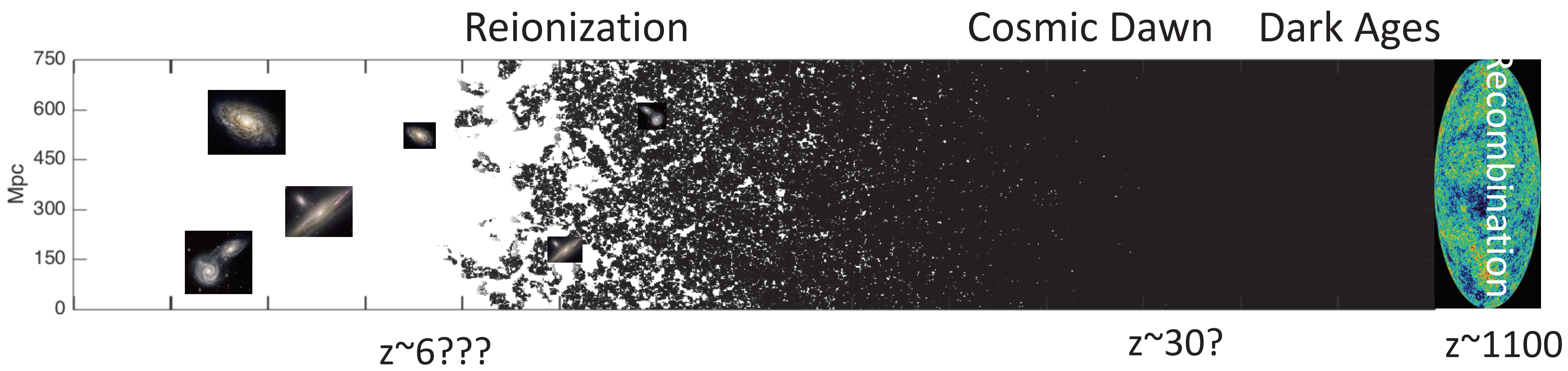
SCUOLA NORMALE SUPERIORE

European Research Council

Outline

- Intro and challenges of understanding the Cosmic Dawn and the first billion years
- Intro to Bayesian inference
- What we know now about reionization
- What we will know soon!

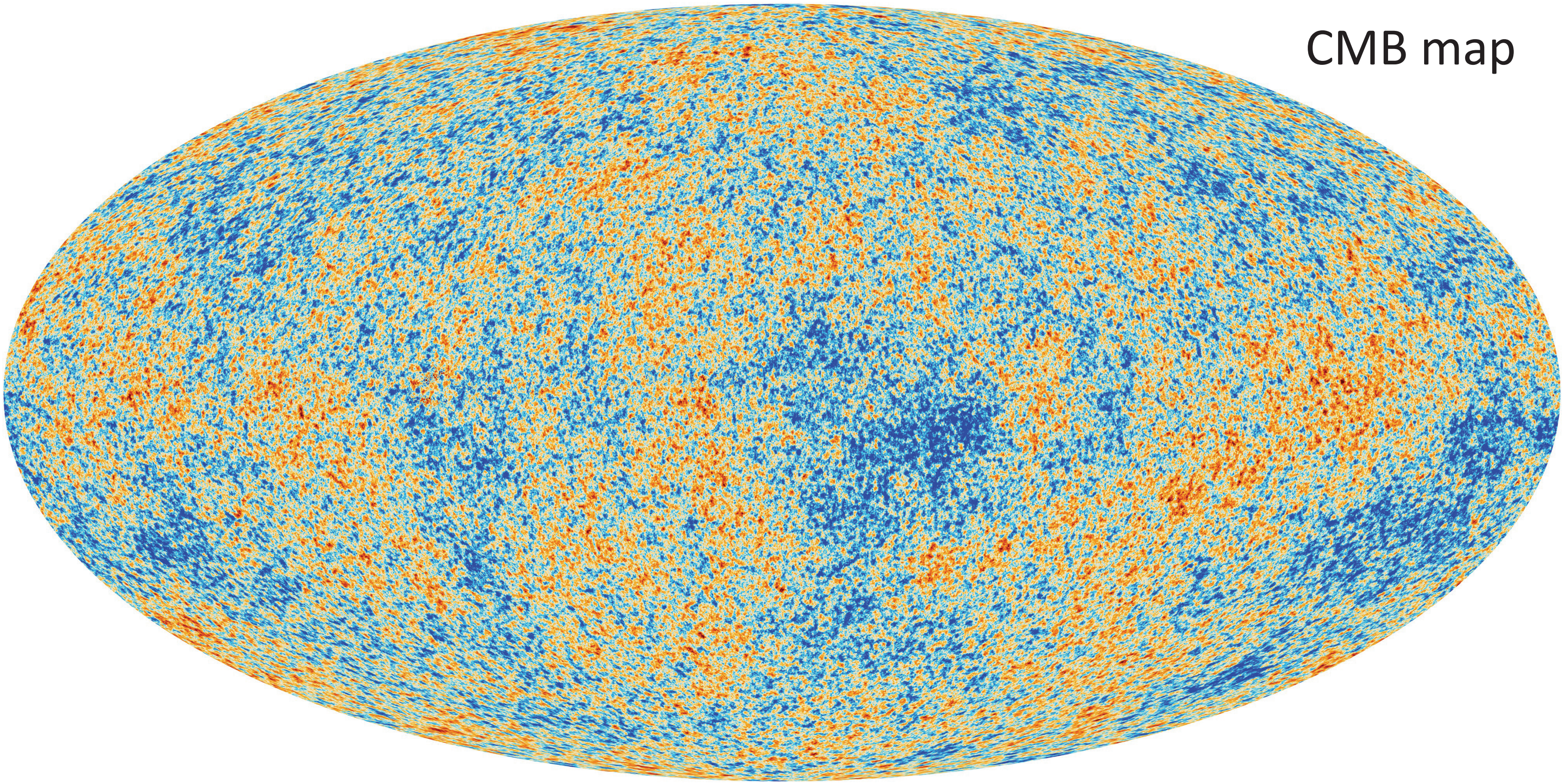
Why Cosmic Dawn?



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?

the "formative childhood" of the Universe, yet the ***majority of the observable volume***

We know (statistically) the initial conditions of the Universe

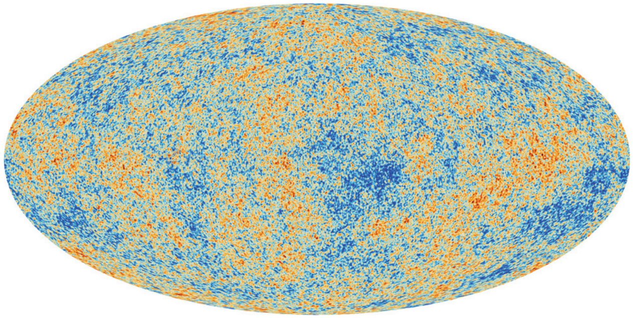


CMB map

snapshot of the Universe at t=0.4 Myr (~1 day old)

Planck collaboration (2018)

And gravity is (relatively) easy



Sample power spectrum of initial conditions

evolve (locally) as a pressure-less fluid

$$\frac{\partial \rho}{\partial t} + \nabla_{\mathbf{p}} \cdot (\rho \mathbf{v}_{\mathbf{p}}) = 0$$

$$\frac{\partial \mathbf{v}_{\mathbf{p}}}{\partial t} + (\mathbf{v}_{\mathbf{p}} \cdot \nabla_{\mathbf{p}}) \mathbf{v}_{\mathbf{p}} = -\nabla_{\mathbf{p}} \Phi$$

$$\nabla_p^2 \Phi = 4\pi \mathrm{G} \rho$$

in a given background cosmology

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

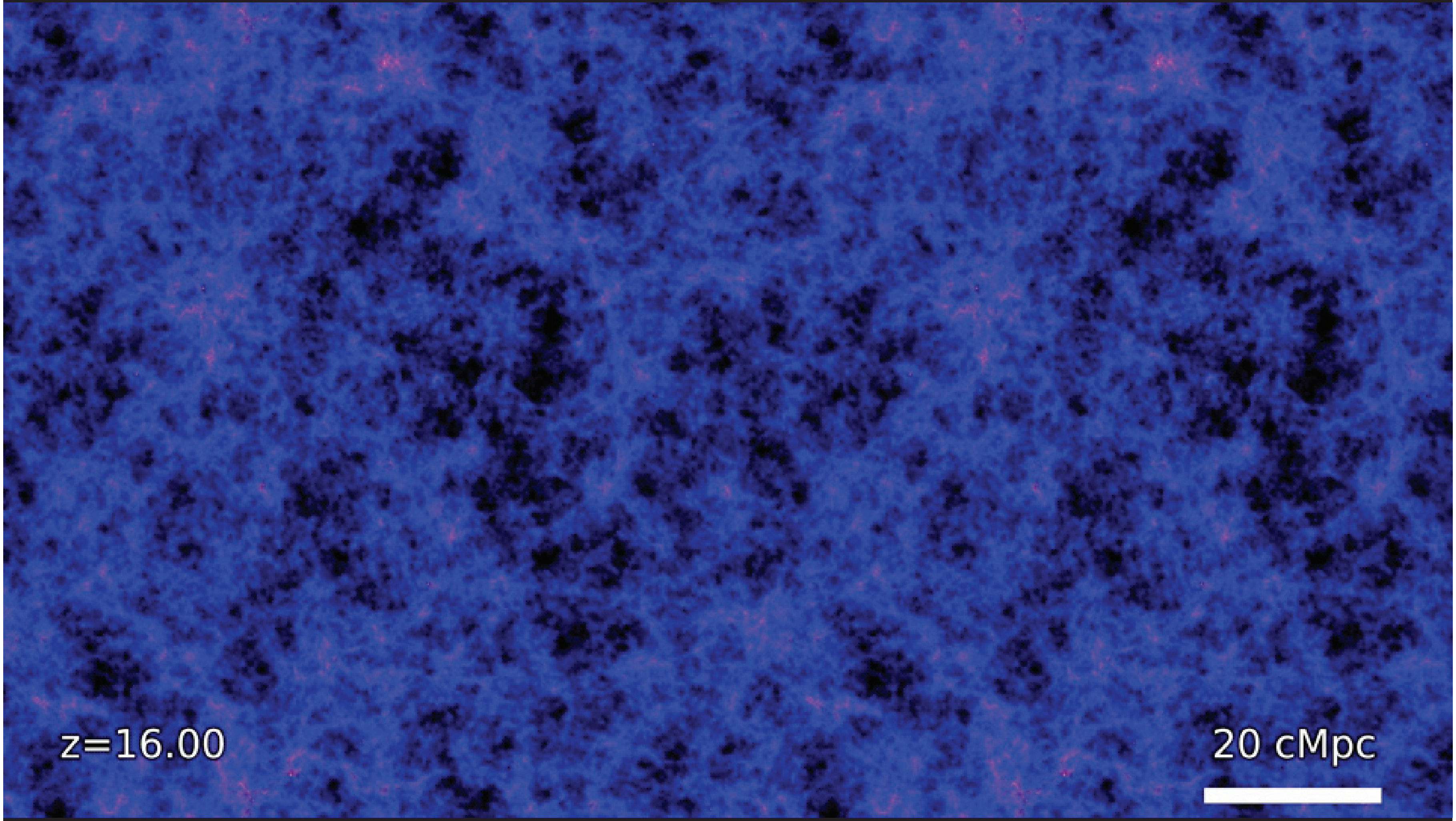
$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - ka^{-2}$$

Simulate the Universe???

Millenium simulation

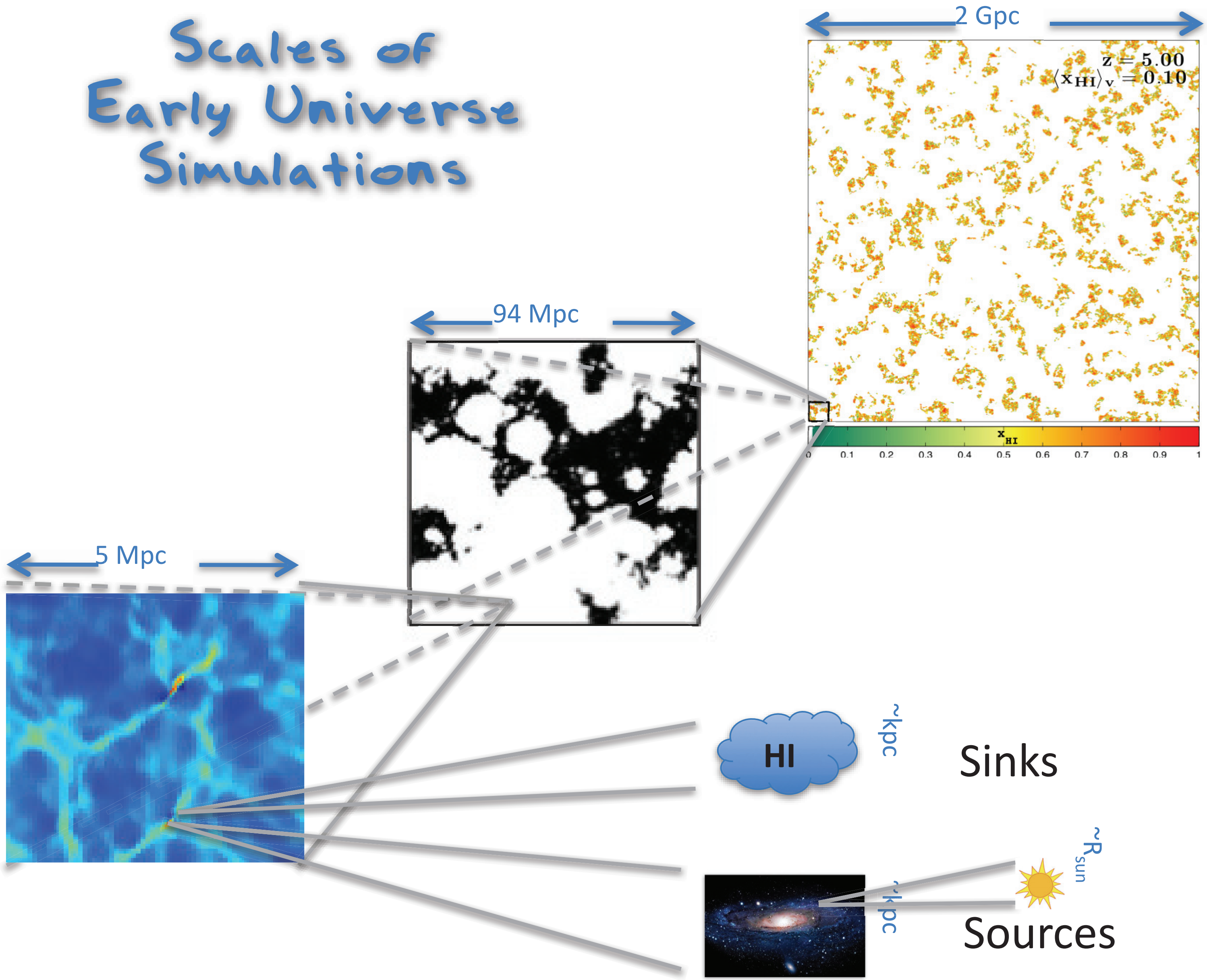
Baryons are HARD!!!

Temperature



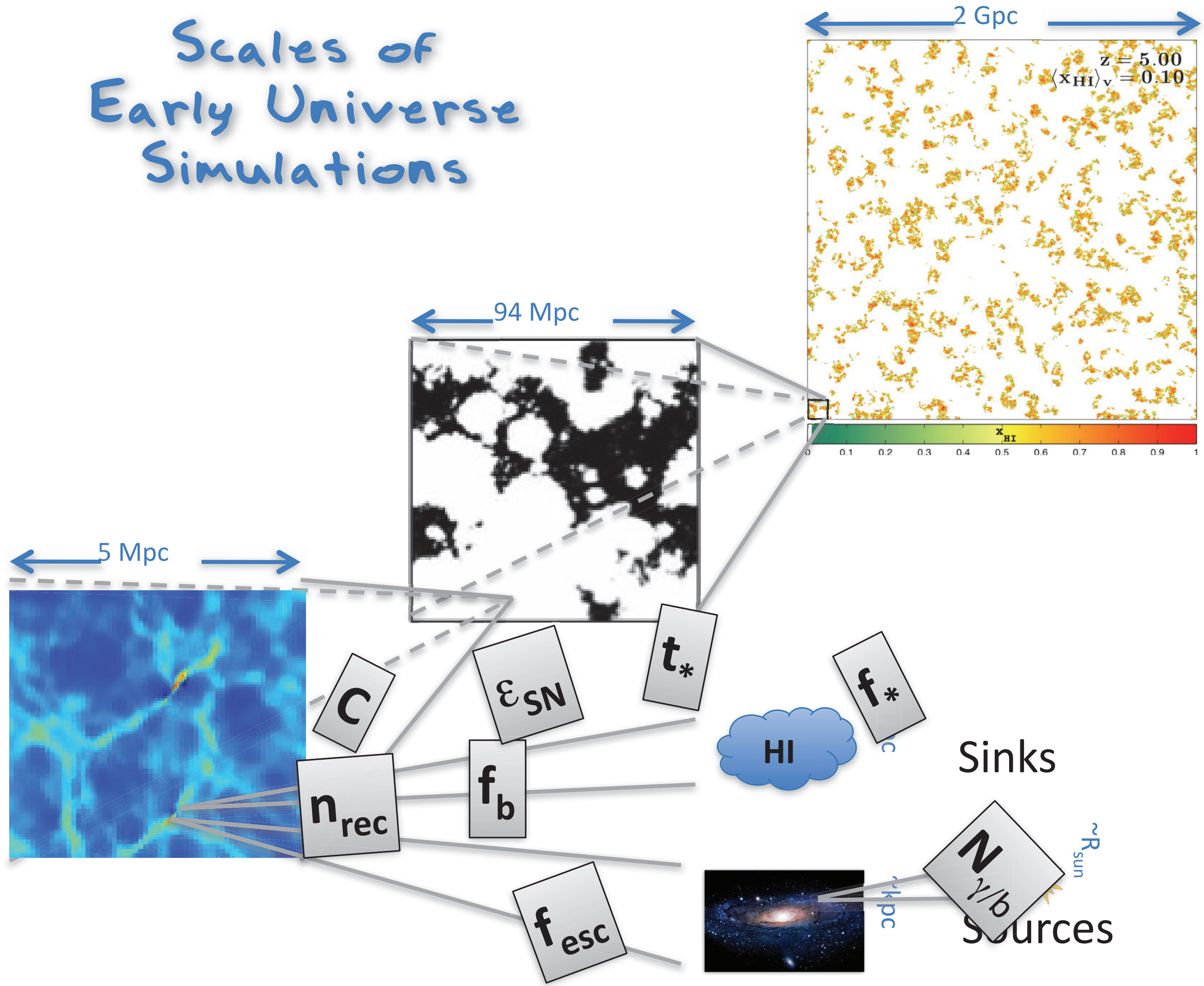
Thesan project

We have to include physics sub-grid



Astrophysical (known) unknowns

Scales of Early Universe Simulations



A single *realization* of Cosmic Reionization

simulation volume contains *billions* of galaxies. approximations *must* be made.

Alvarez & Abel

So how to we make progress??

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We need **observations**!

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We need a **model**, characterized by some uncertain parameters

So how to we make progress??

We need **observations**!

We need a **model**, characterized by some uncertain parameters

We need a quantitative way of **comparing** the model to the observations

So how to we make progress??

Bayes' formula: $$P(\theta|X) = \frac{P(X|\theta)P(\theta)}{P(X)}$$

Mathematically trivial statement of conditional probabilities

So how to we make progress??

Bayes' formula: $$P(\theta|X) = \frac{P(X|\theta)P(\theta)}{P(X)}$$

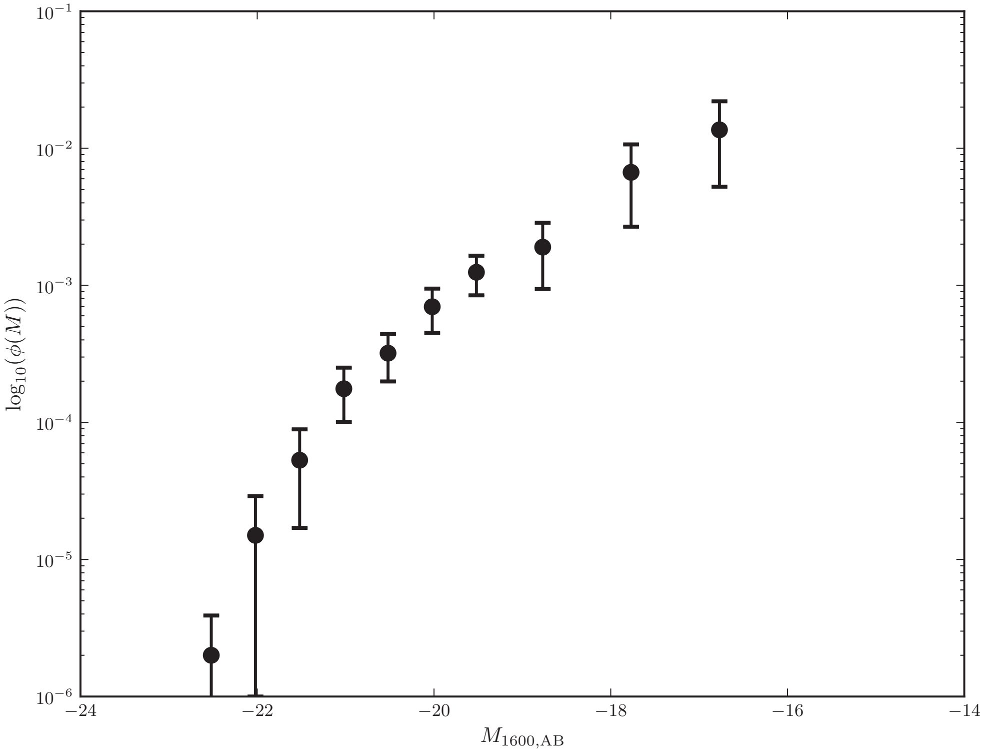
θ	Model parameter set
X	Data (Observation/Simulation)
$P(\theta\|X)$	Posterior. Probability of our model parameters given the data
$P(X\|\theta)$	Likelihood. How well our parameters match the data.
$P(\theta)$	Prior. How well we know the model parameters. Observational/physical constraints etc.
$P(X)$	Evidence. Confidence that the data was generated by the model distribution

So how to we make progress??

Bayes' formula: $$P(\theta|X) = \frac{P(X|\theta)P(\theta)}{P(X)}$$

1. Simulate the physics we know. Parametrize what we do not know, θ.
2. Sample from our *prior* knowledge of the uncertain parameters P(θ)
3. For a sampled parameter set, θ, *forward-model* an observation
4. Compare the (mock) observation to the actual observation, *X:* $P(X|\theta)$
5. repeat steps (2) - (4) throughout your parameter space.
6. Normalize the product of the likelihood * prior to integrate to unity, obtaining the **posterior distribution:** $P(\theta|X)$

Simple example: UV luminosity function



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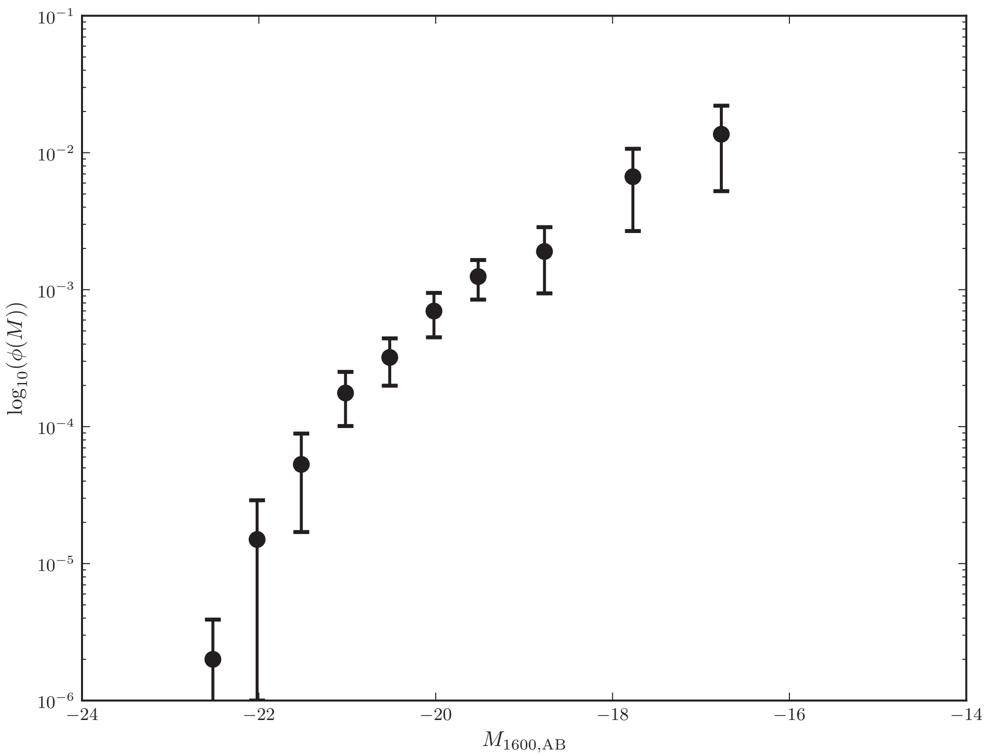
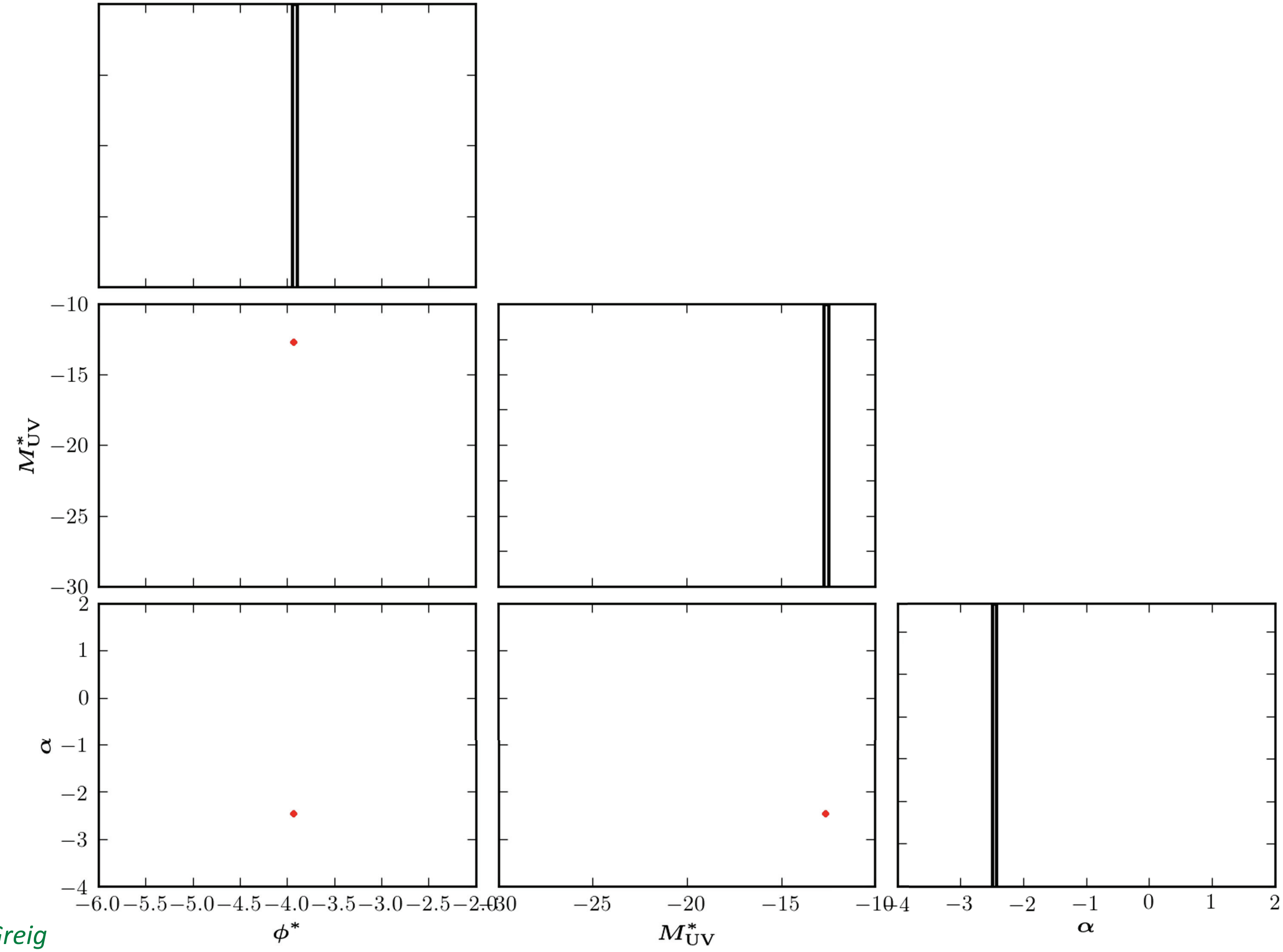


- Fit with Schechter function,

$$\phi(M) = \phi^* \left(\frac{\ln(10)}{2.5}\right) 10^{-0.4(M-M^*)(\alpha+1)} \exp\left(-10^{-0.4(M-M^*)}\right)$$

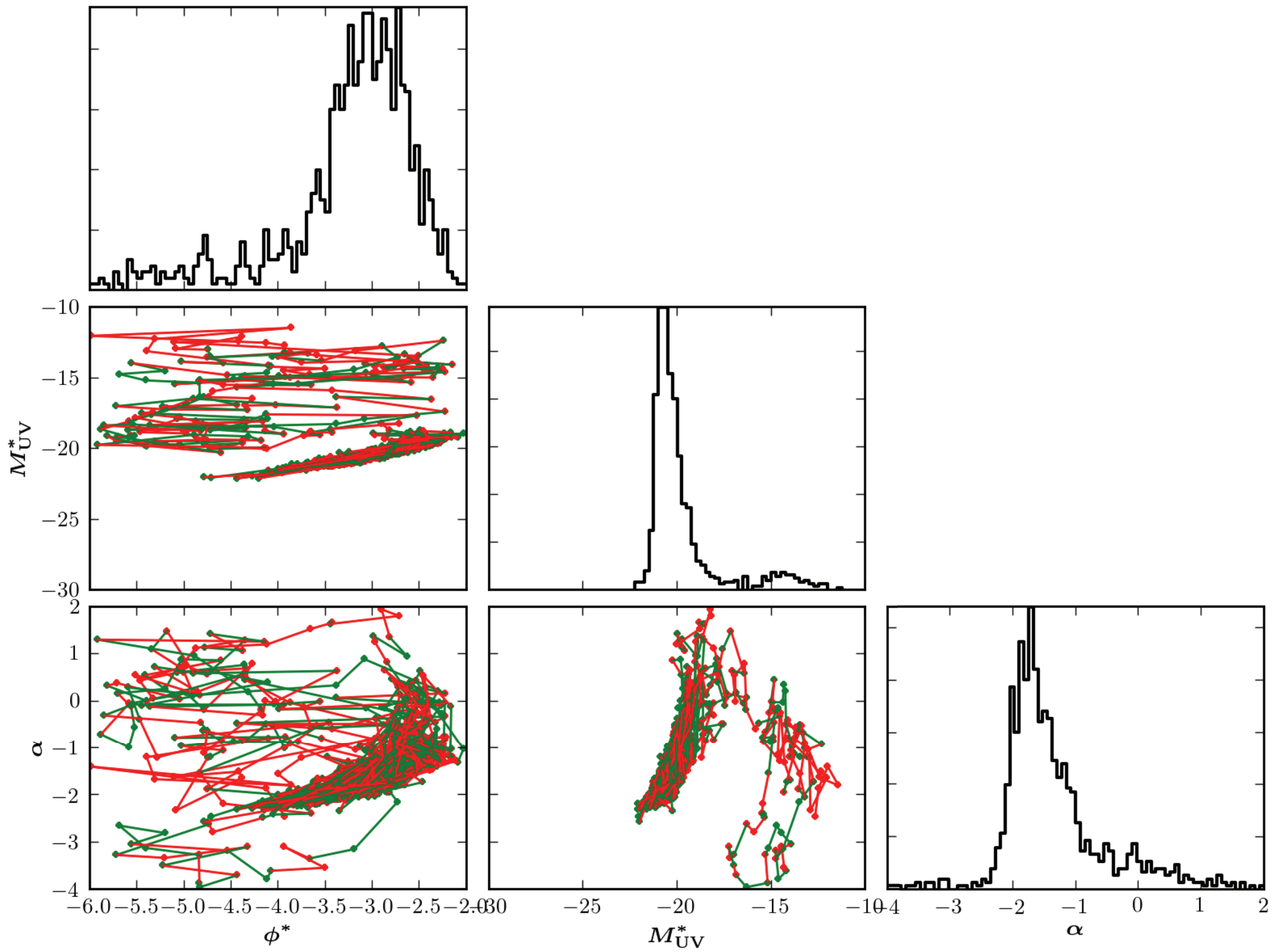
Three free parameters, $\phi^*,\ M^*,\ \alpha$

Simple example: UV luminosity function

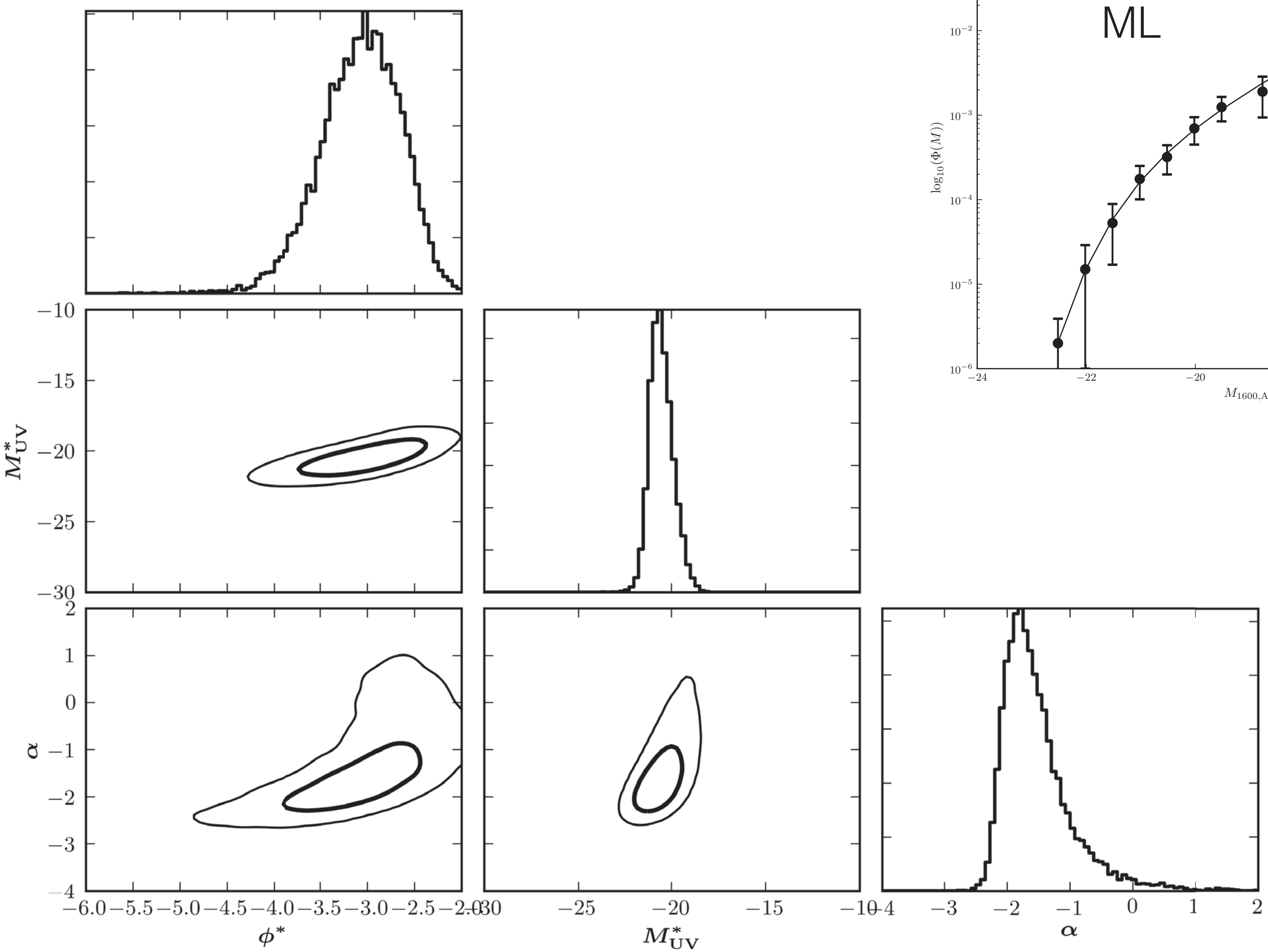


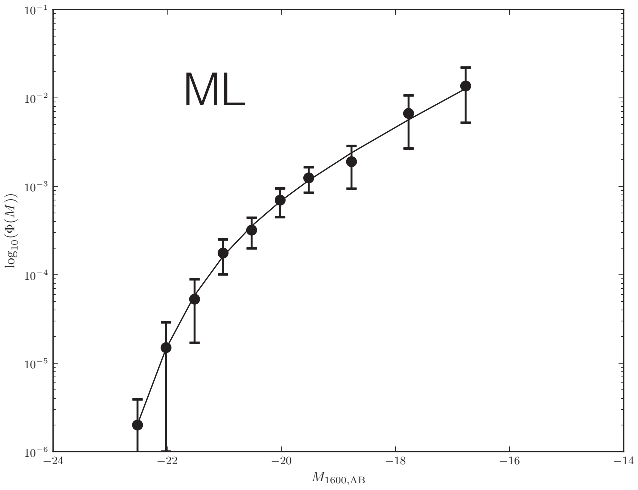
movie credit: B. Greig

Simple example: UV luminosity function



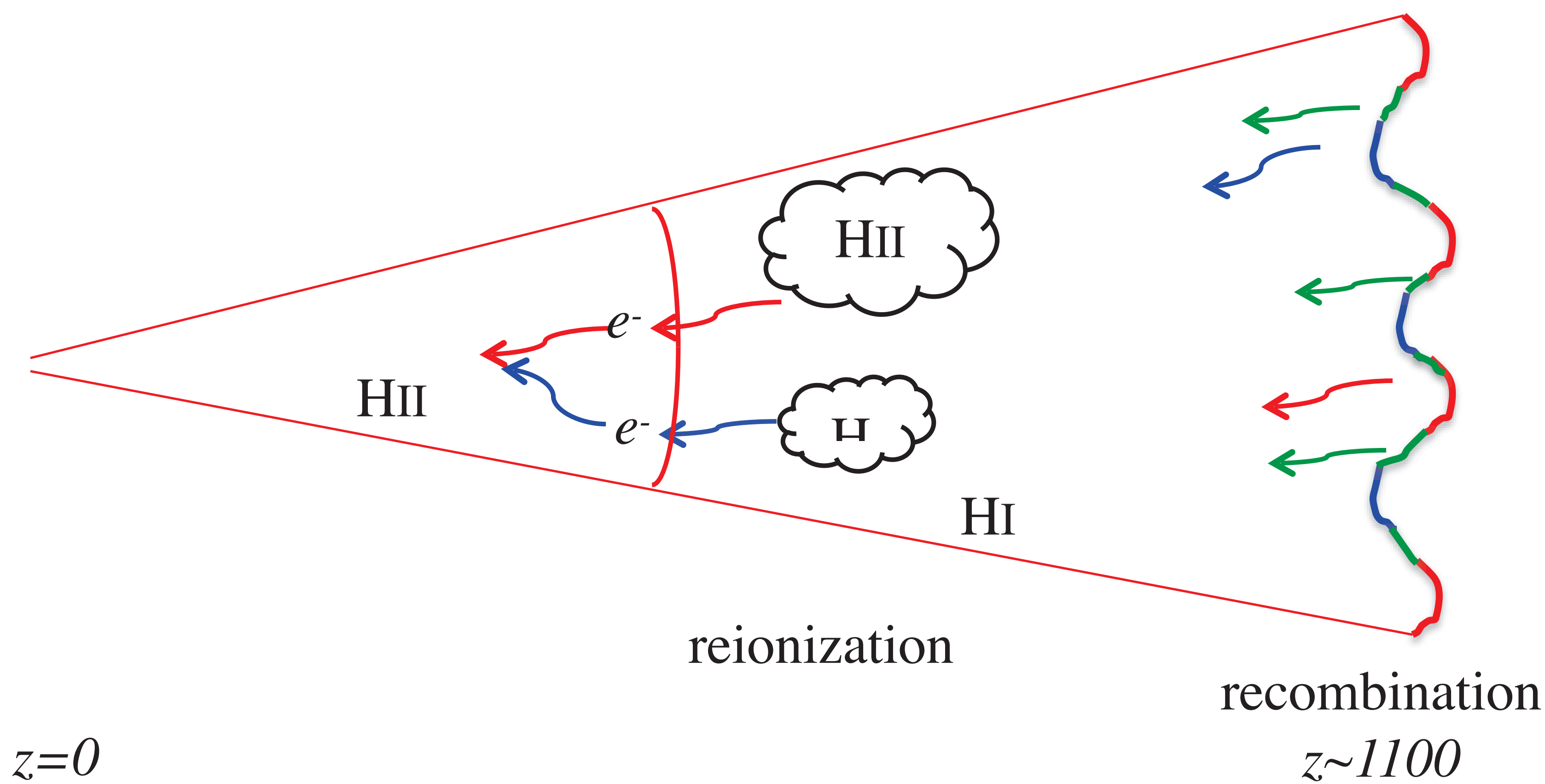
Simple example: Report Results





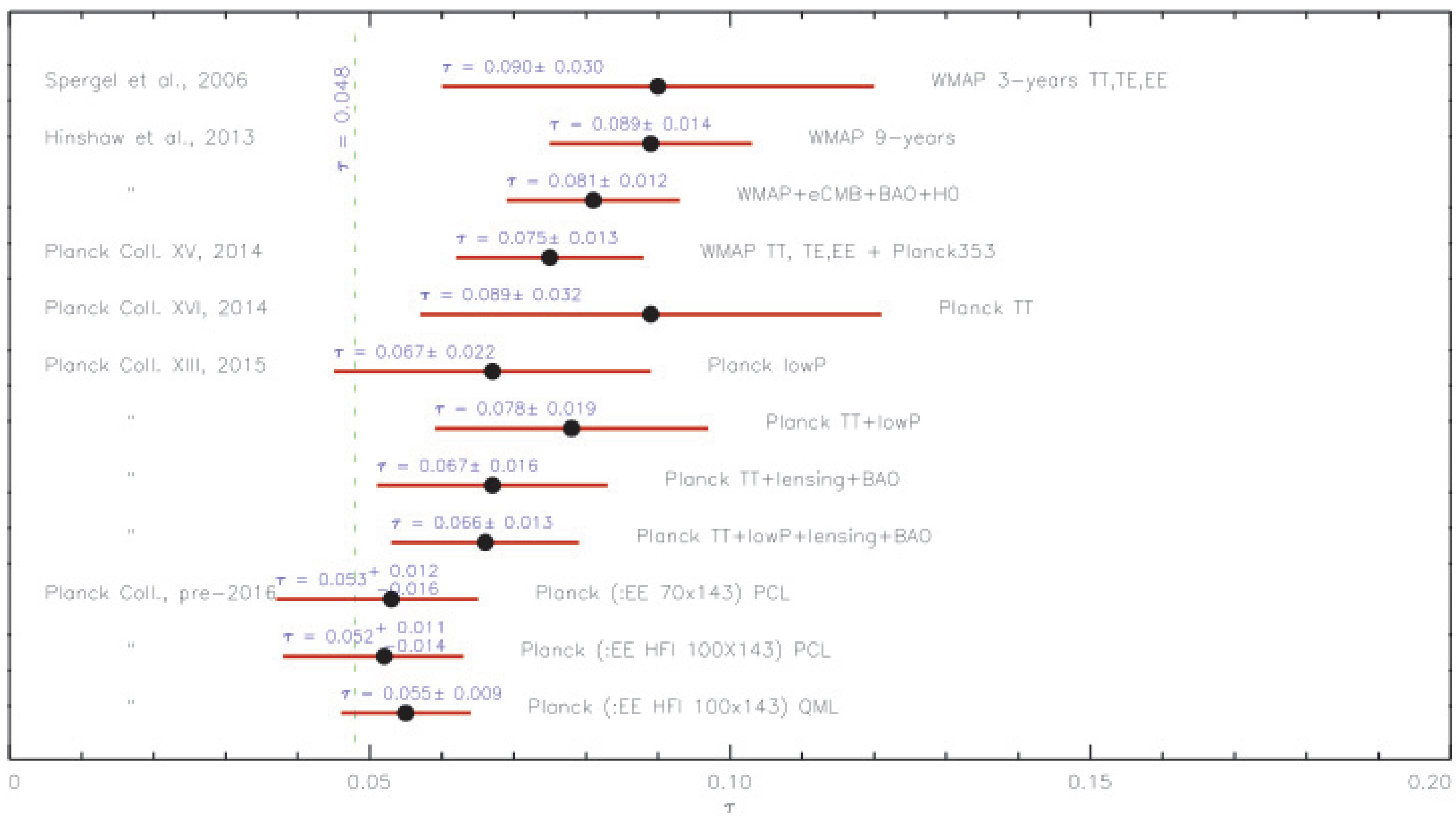
What other observations do we have of the Epoch of Reionization?

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



History of Thompson scattering optical depth measurements

WMAP1 2003

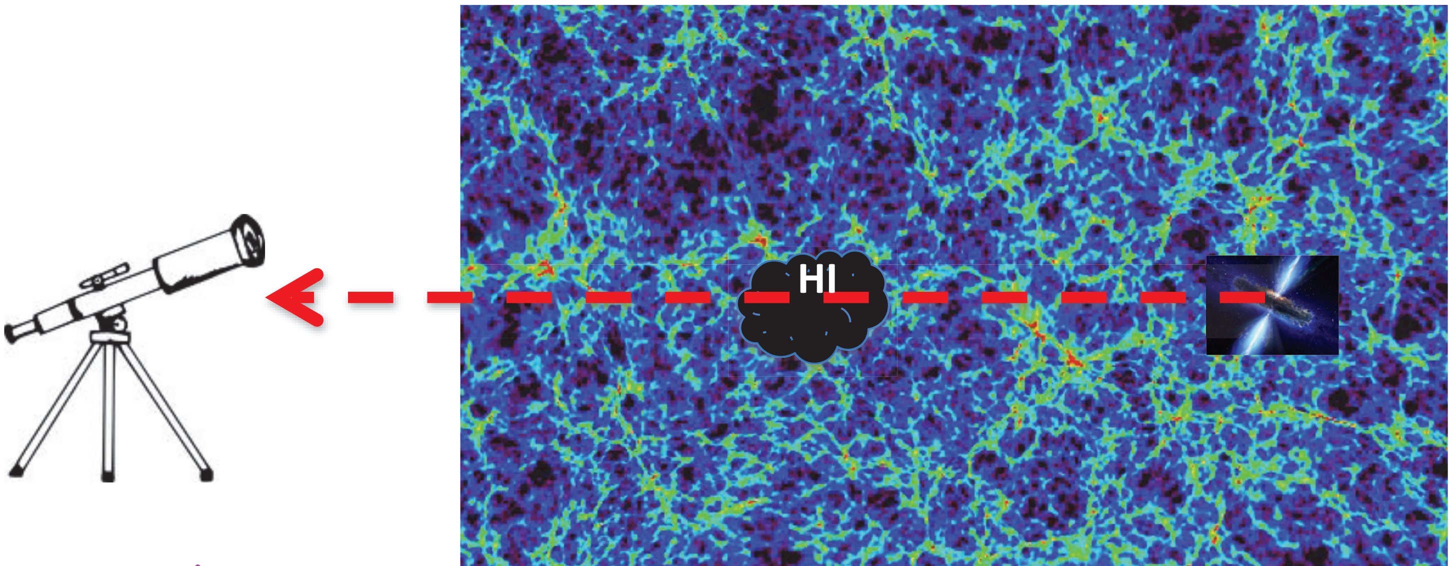


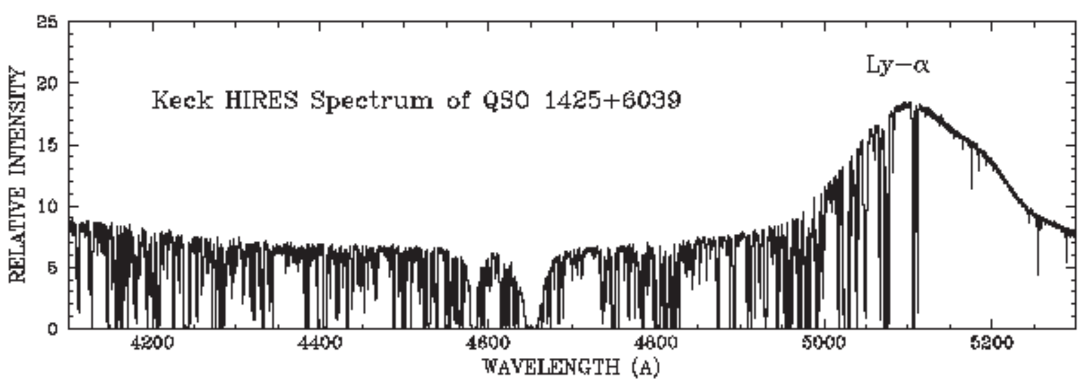
Planck 2016

Observations of the Epoch of Reionization

- 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

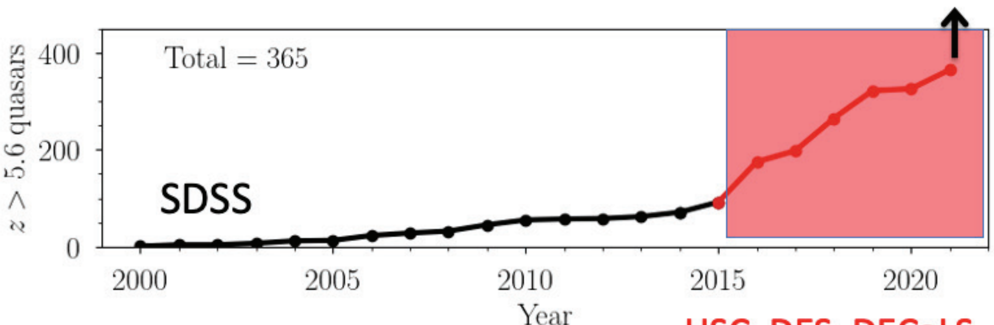




An example:
forward-modeling the Lyman alpha forest

Recent years have seen a ***huge increase*** in the number of high-S/N, high-z QSO spectra

~5x more quasars
in the last 5 years



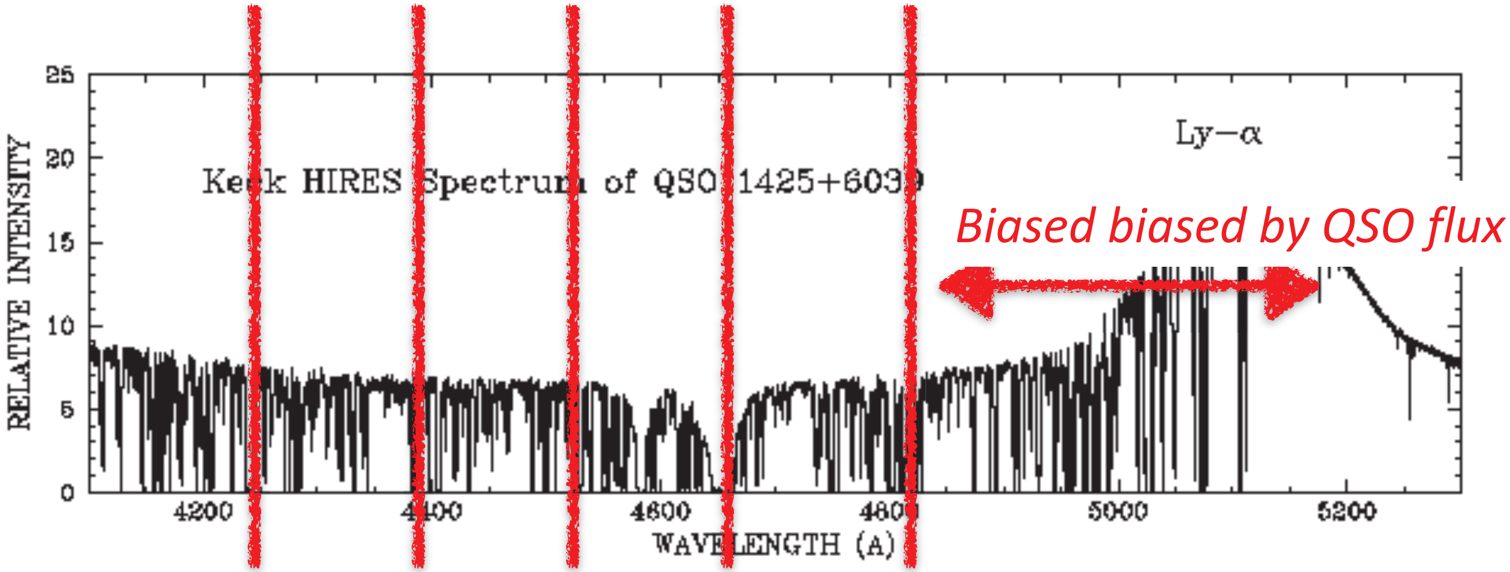
HSC, DES, DECaLS
Pan-STARRS1, VHS, UHS

Andika+2020
Bañados+2015-2021
Belladitta+2020
Carnall+2015
Fan+2019
Jiang+2015-2016
Matsuoka+2016-2019
Mazzucchelli+2017

Pons+2019
Reed+2015-2019
Tang+2019
Venemans+ 2015ab
Wang+2016-2021
Yang+2017-2020
Wu+2015
...

slide courtesy of E. Banados

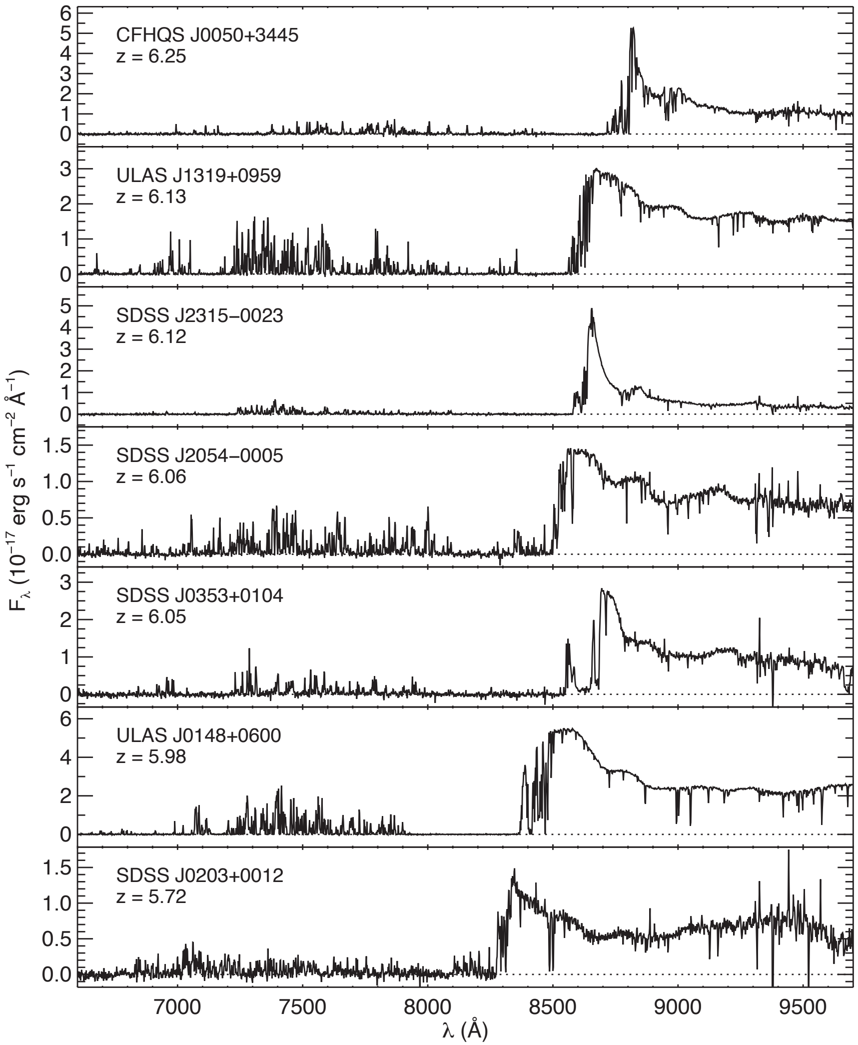
Let's get more quantitative…



Define "effective optical depth" over each segment:

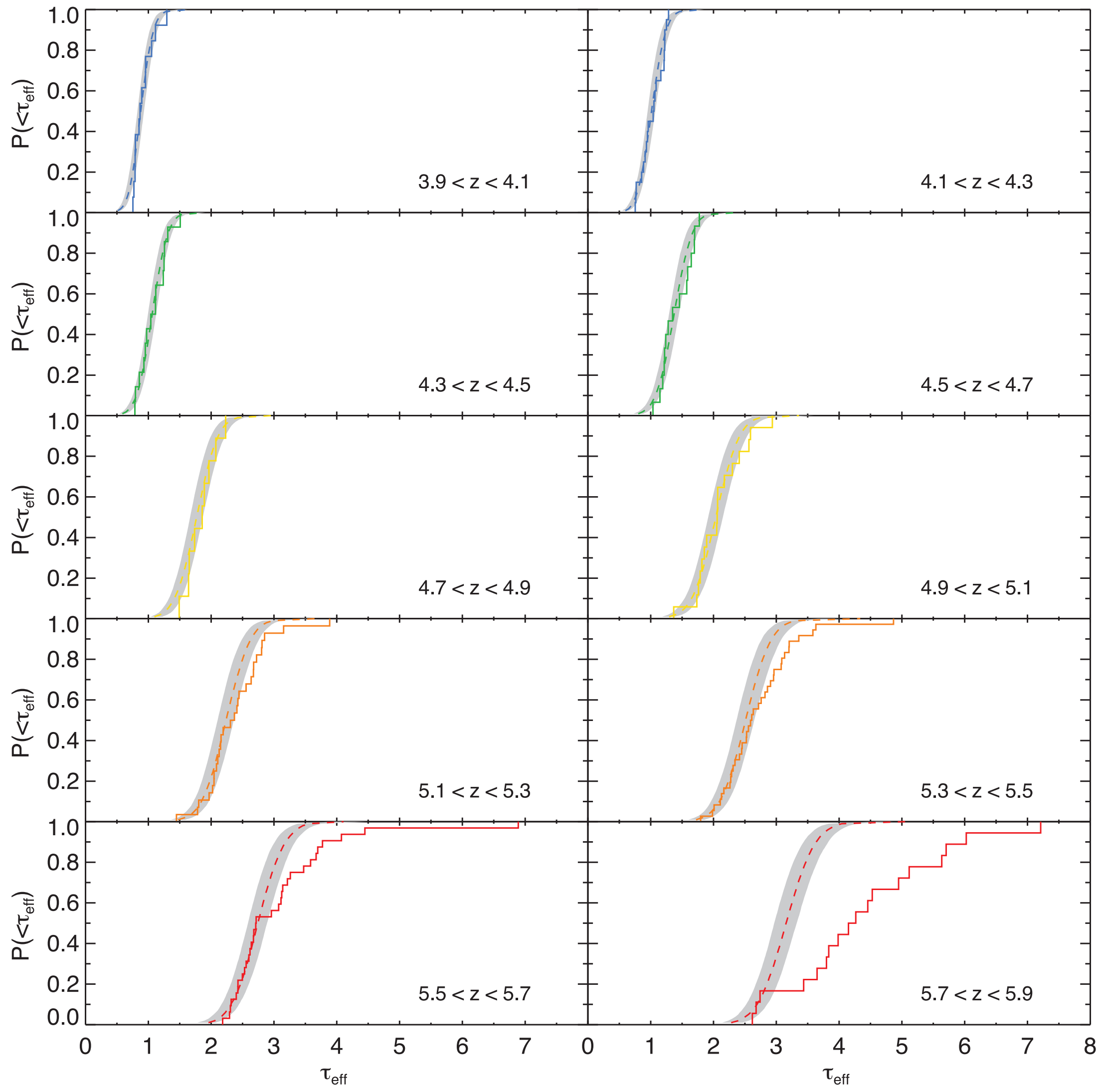
$$\tau_{\rm eff} \equiv -\ln\langle f \rangle_{50{\rm Mpc}}$$

But there is significant sightline to sightline scatter!



Becker+ (2012)

CDFs of effective optical depth



Distributions of τ_{eff} are ***TOO BROAD*** to be consistent with a uniform, pervasive UVB

Becker+ 2015

What can increase these fluctuations in τ_{eff}?

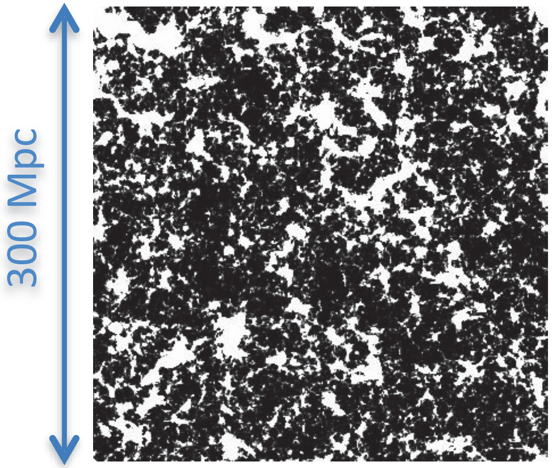
Remember, the EoR is *patchy:*

Ionized component

$$\tau_{HII} \propto \frac{\Delta^2 \alpha_B(T)}{\Gamma_{\rm ion}} \propto \frac{\Delta^2 \alpha_B(T)}{\epsilon_{\rm ion} \lambda_{\rm mfp}}$$

Neutral component

$$\tau_{HI} \sim 10^5 - 10^6$$



Remember, the EoR is *patchy:*

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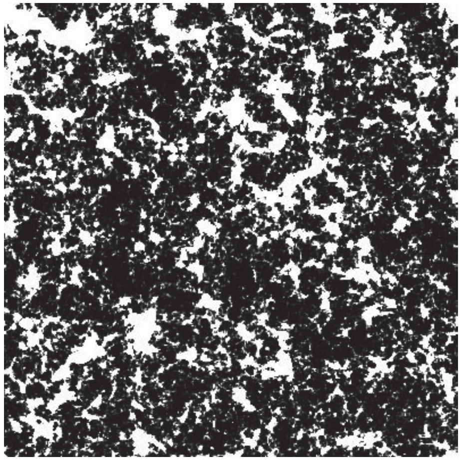
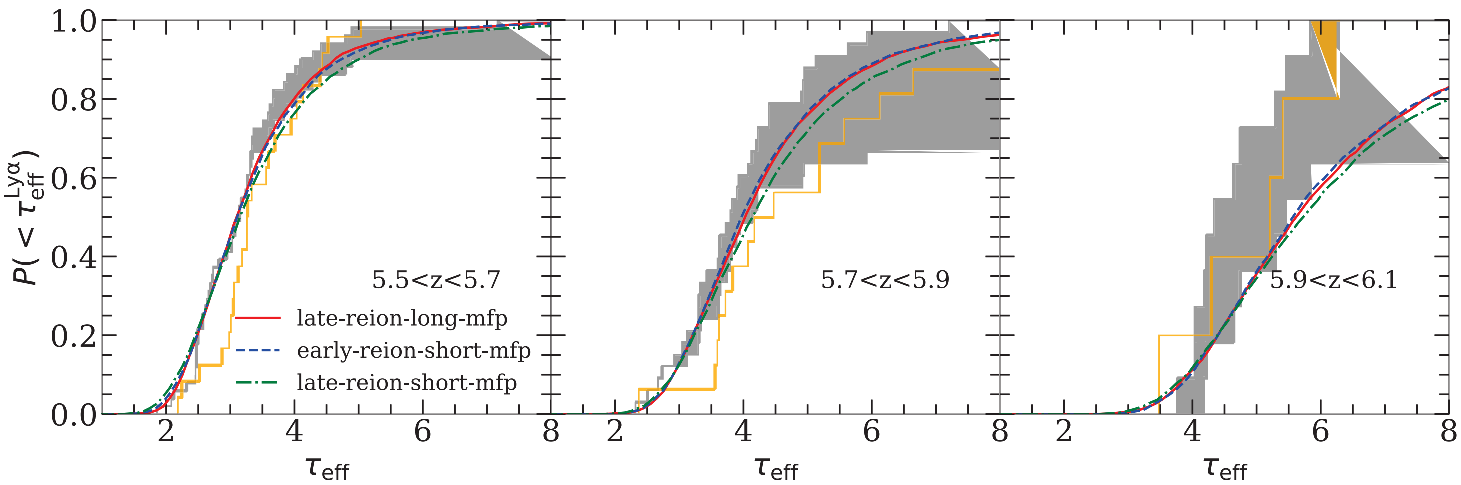


Large-scale fluctuations could be explained by (*tuning*):

- Temperature (e.g. D'Aloisio+15)
- Rare sources (Chardin+15,17; Meiksin+20)
- Mean free path (Davies+16)
- patchy EoR (Kulkarni+19; Keating+20; Choudhury+21)

There are degeneracies of course

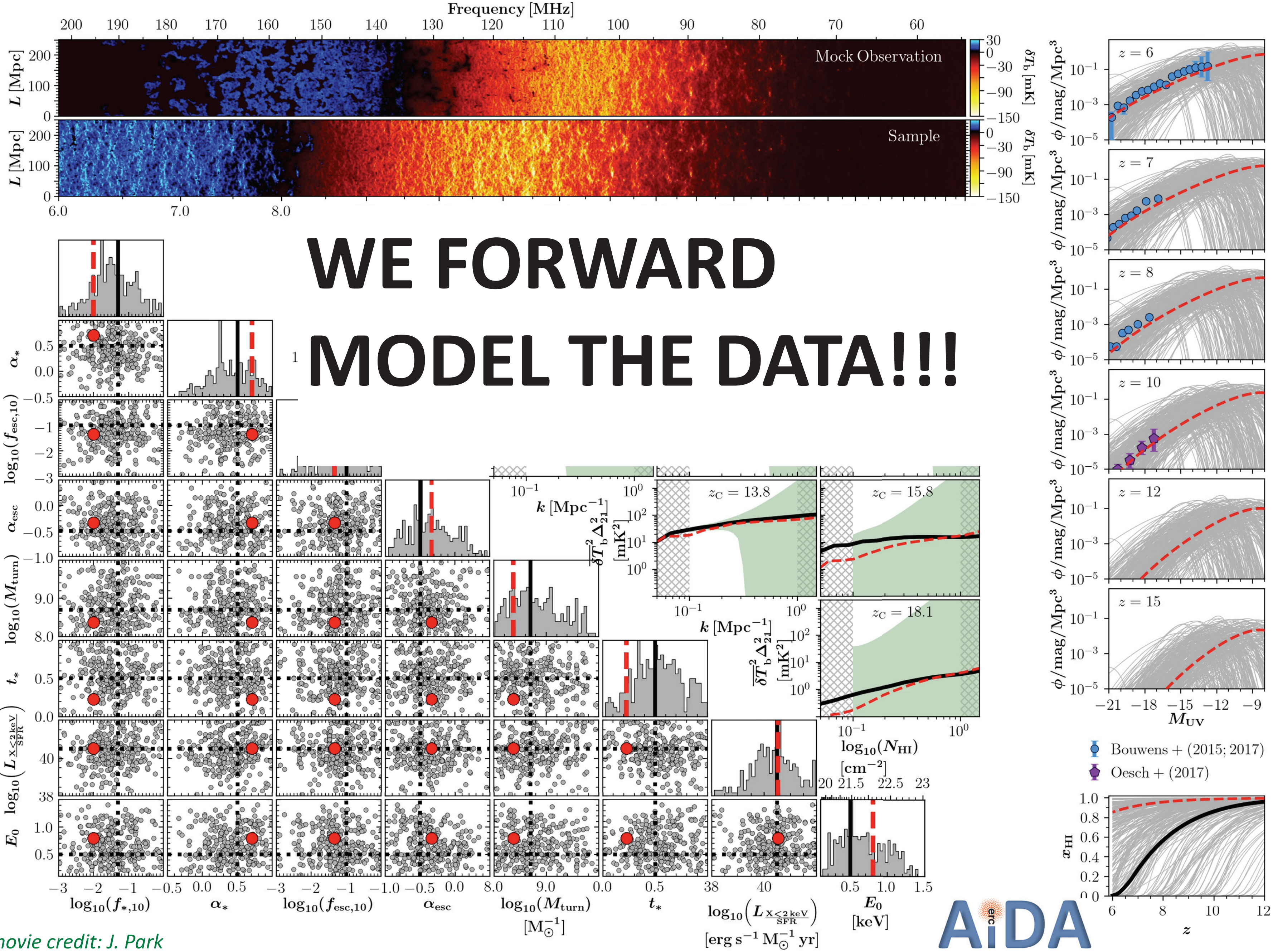


Nasir & D'Aloisio (2019)

And showing one or two models that "kinda look like the data" doesn't prove anything…

So how do we ***learn*** something quantitative?

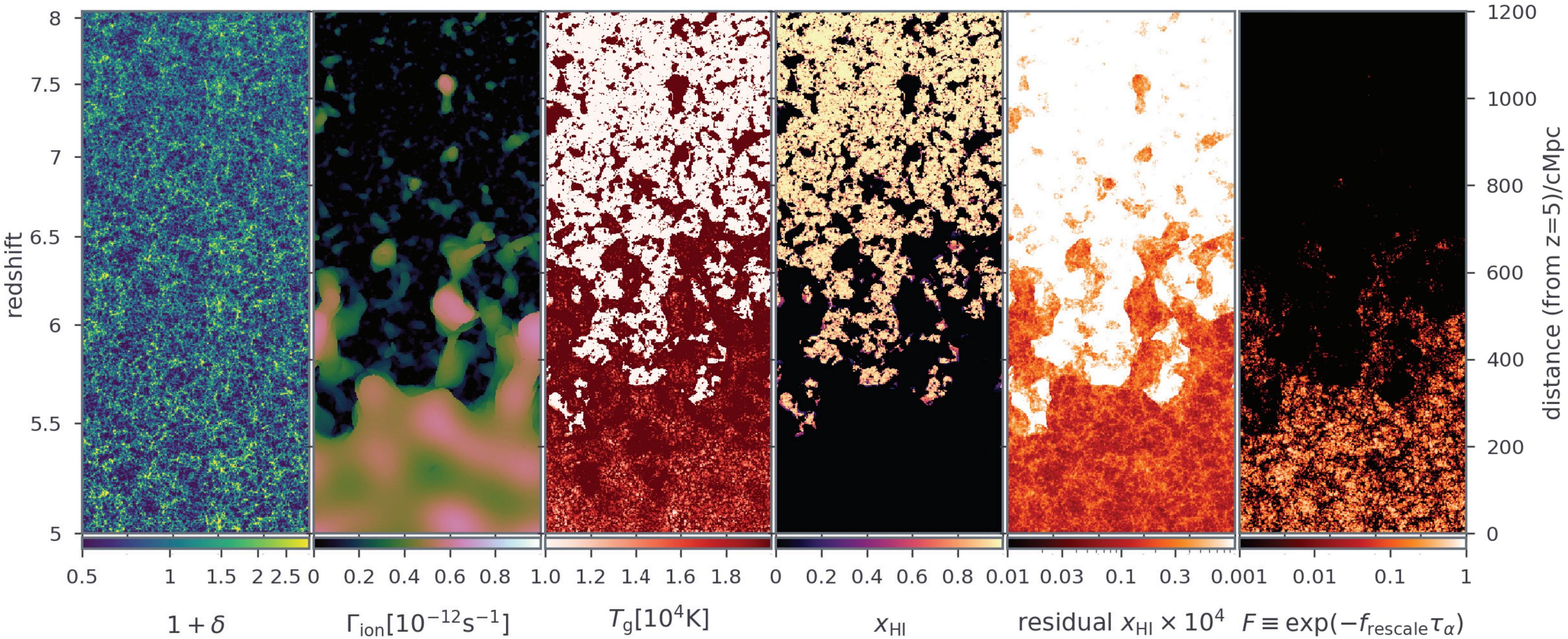
WE FORWARD MODEL THE DATA!!!



AiDA

movie credit: J. Park

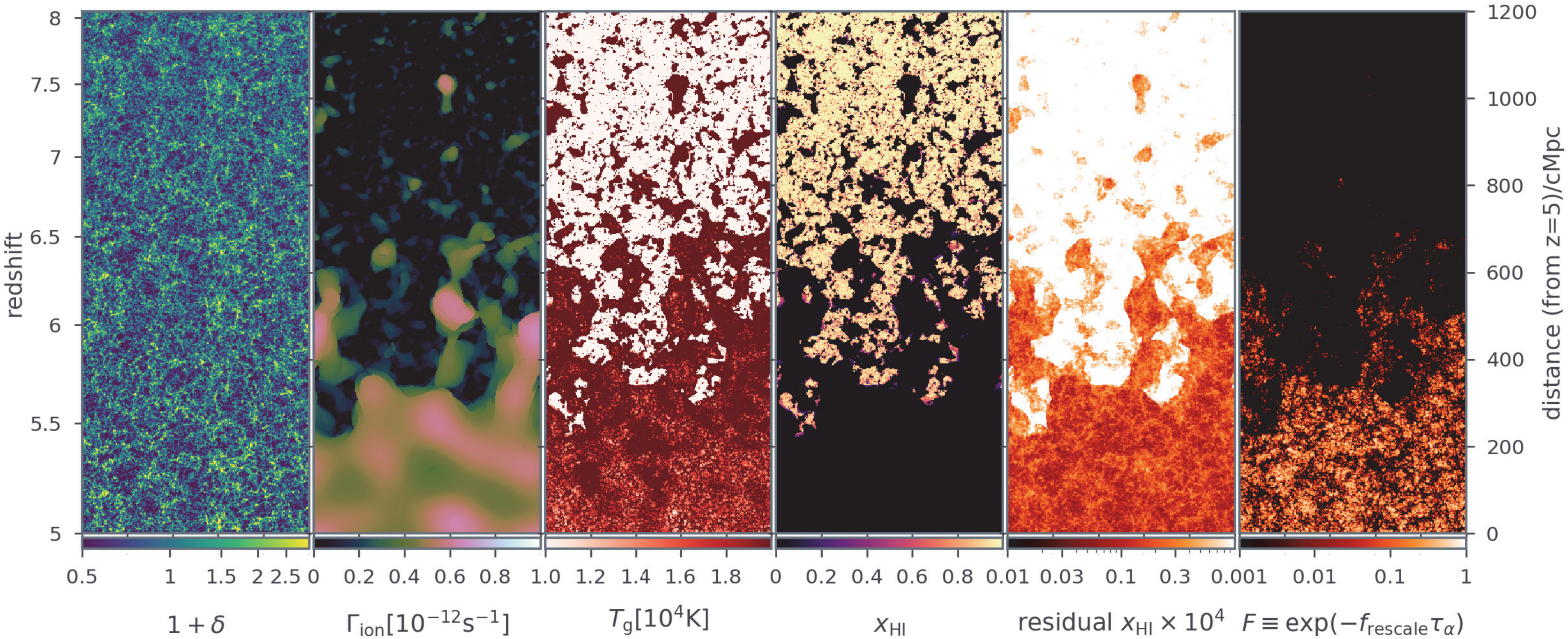
Sample parameters characterizing galaxy properties + systematics



Qin+ 2021

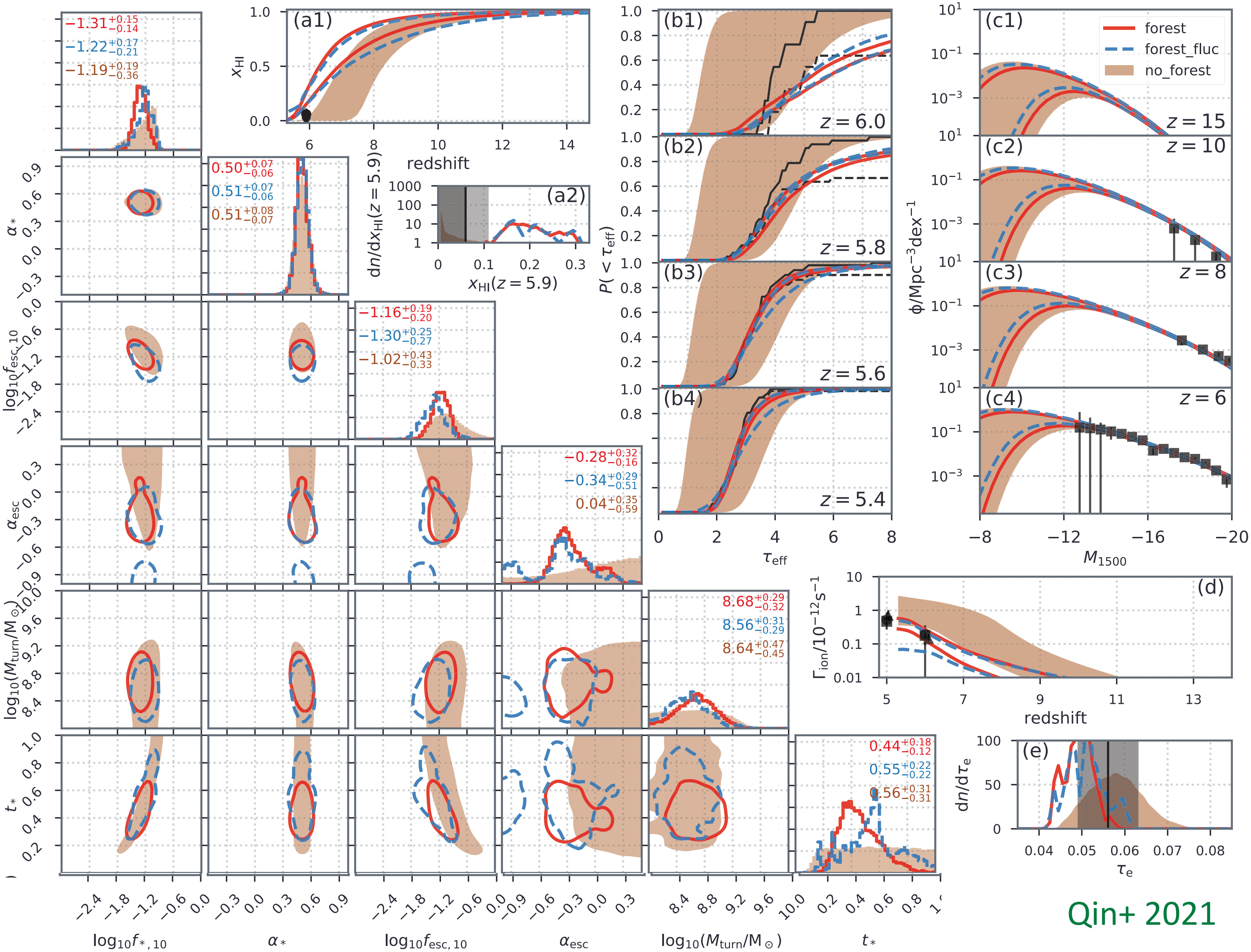
Sample parameters characterizing galaxy properties + systematics

Our MCMC makes **~100k** such lightcones, comparing them to **data***



***data** = UV LFs, dark fraction, CMB τ_e, Lyα τ_{eff} PDFs

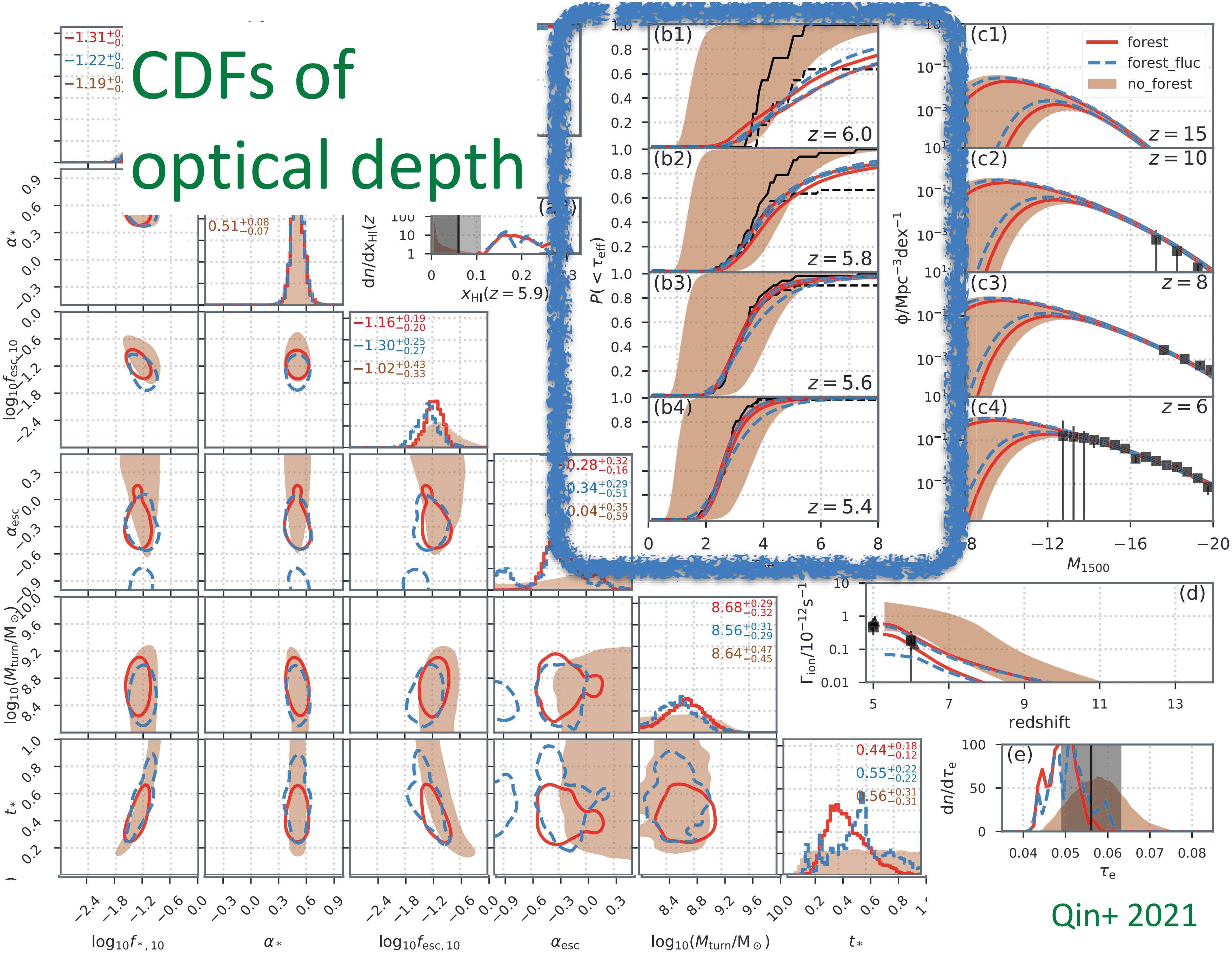
Qin+ 2021



(a1)
(a2)
(b1)
(b2)
(b3)
(b4)
(c1)
(c2)
(c3)
(c4)
(d)
(e)
forest
forest_fluc
no_forest
redshift
$x_{\rm HI}$
$dn/dx_{\rm HI}(z=5.9)$
$x_{\rm HI}(z=5.9)$
$P(<\tau_{\rm eff})$
$\tau_{\rm eff}$
$z=6.0$
$z=5.8$
$z=5.6$
$z=5.4$
$z=15$
$z=10$
$z=8$
$z=6$
$\phi/{\rm Mpc^{-3}dex^{-1}}$
M_{1500}
$\Gamma_{\rm ion}/10^{-12}{\rm s}^{-1}$
$dn/d\tau_{\rm e}$
$\tau_{\rm e}$
$-1.31^{+0.15}_{-0.14}$
$-1.22^{+0.17}_{-0.21}$
$-1.19^{+0.19}_{-0.36}$
$0.50^{+0.07}_{-0.06}$
$0.51^{+0.07}_{-0.06}$
$0.51^{+0.08}_{-0.07}$
$-1.16^{+0.19}_{-0.20}$
$-1.30^{+0.25}_{-0.27}$
$-1.02^{+0.43}_{-0.33}$
$-0.28^{+0.32}_{-0.16}$
$-0.34^{+0.29}_{-0.51}$
$0.04^{+0.35}_{-0.59}$
$8.68^{+0.29}_{-0.32}$
$8.56^{+0.31}_{-0.29}$
$8.64^{+0.47}_{-0.45}$
$0.44^{+0.18}_{-0.12}$
$0.55^{+0.22}_{-0.22}$
$0.56^{+0.31}_{-0.31}$
α_*
$\log_{10}f_{\rm esc,10}$
$\alpha_{\rm esc}$
$\log_{10}(M_{\rm turn}/{\rm M_\odot})$
t_*
$\log_{10}f_{*,10}$

Qin+ 2021

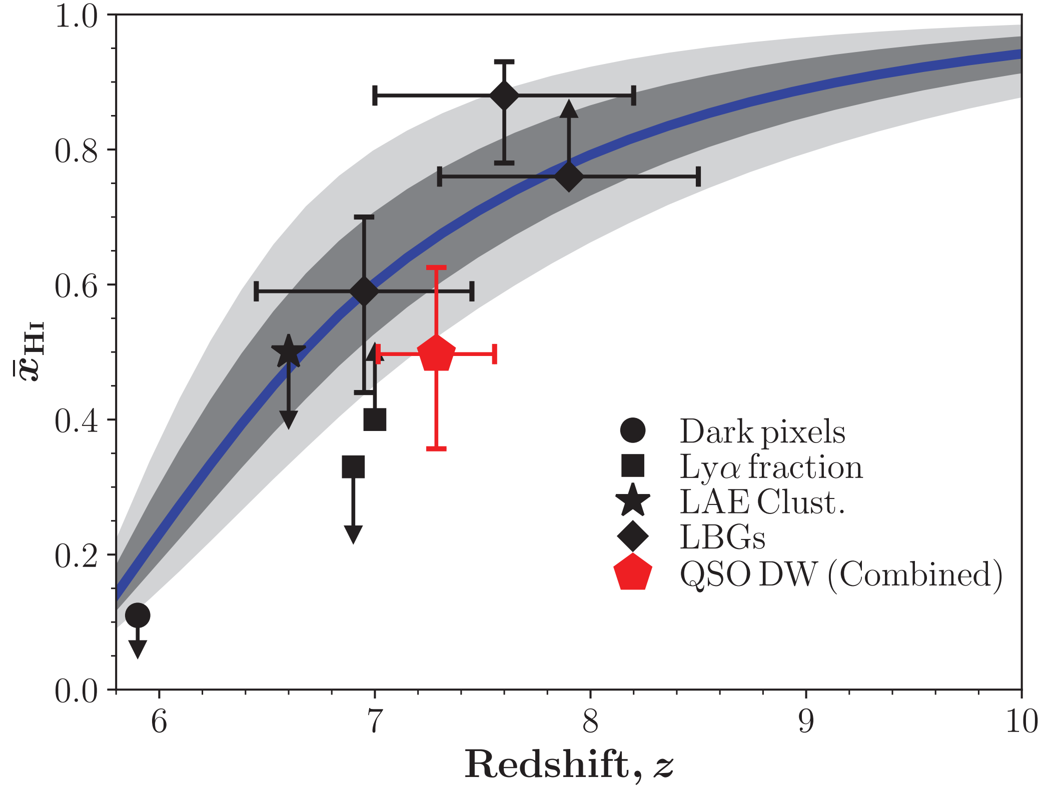
CDFs of optical depth



Qin+ 2021

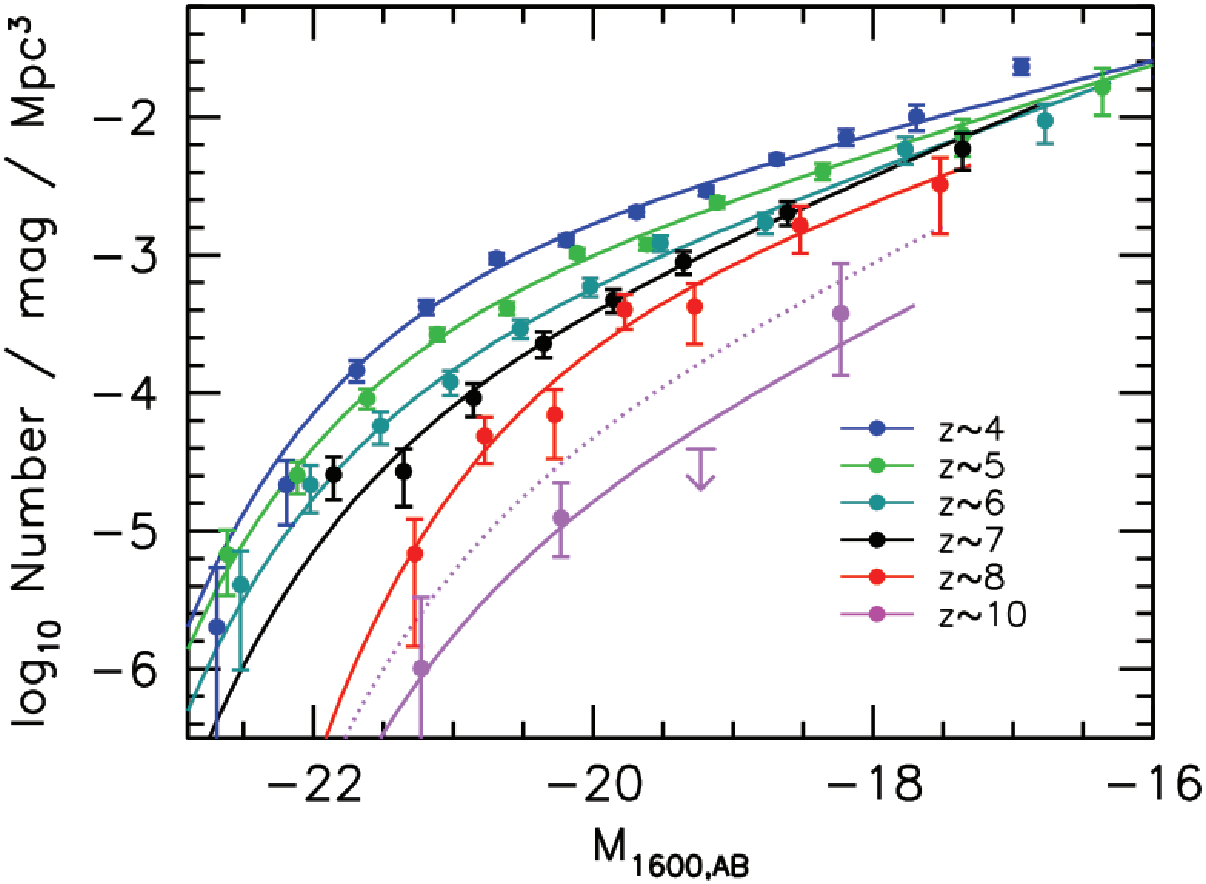
Summary of current knowledge:

- Reionization history is “reasonably” well known
- Galaxy properties are largely unknown

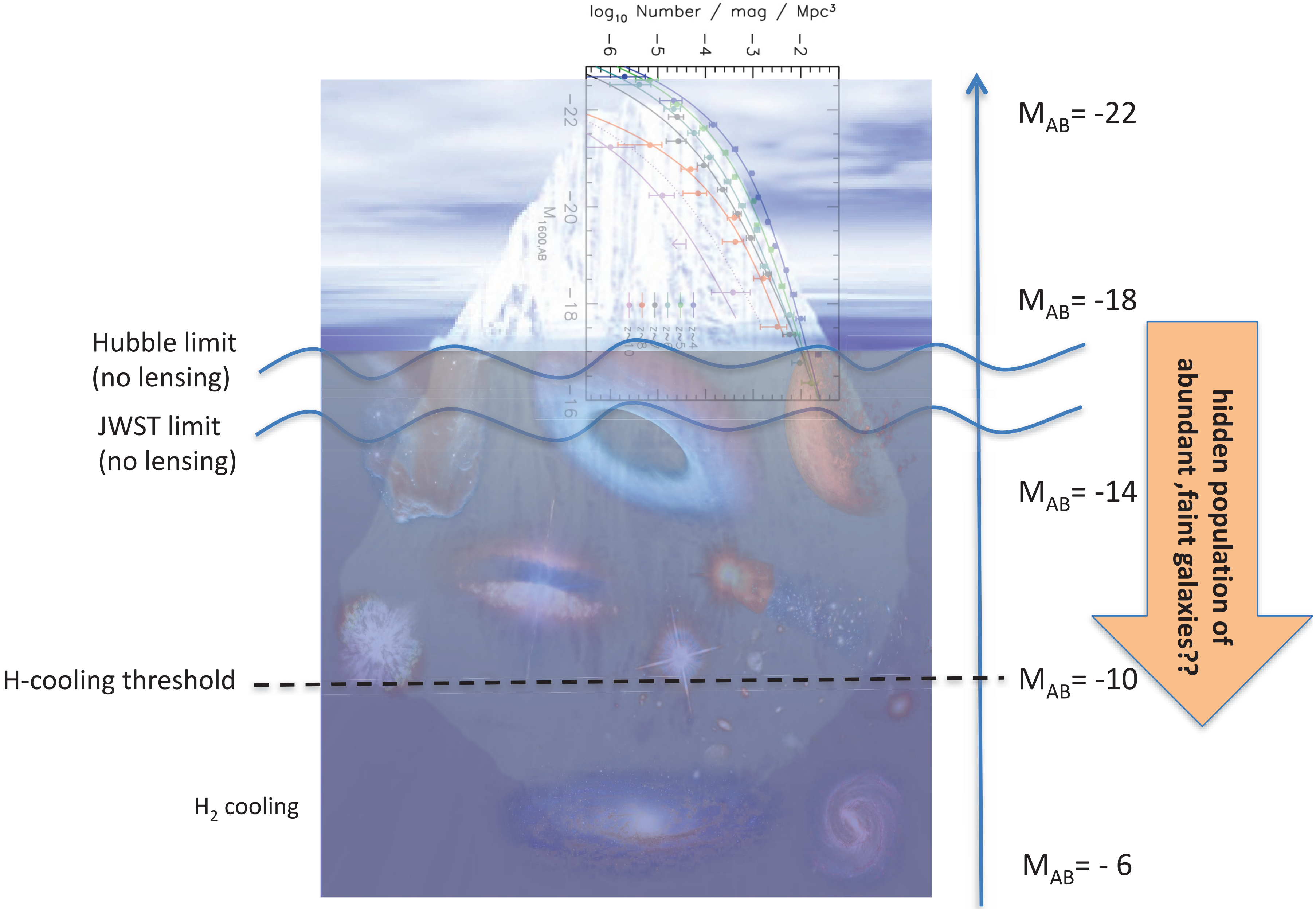


Qin, AM+ 2021;
Greig, AM+ in prep

Well how do we learn about the galaxies?



Bouwens+ (2015)

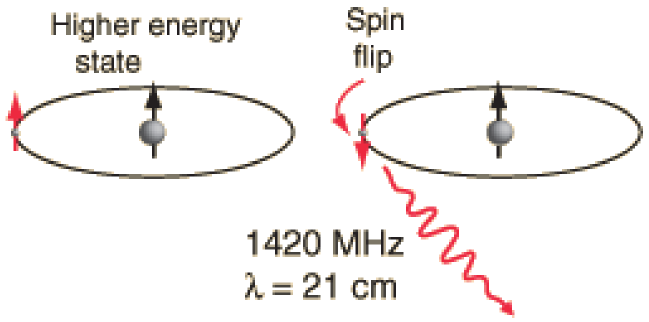


log10 Number / mag / Mpc3
M1600,AB
Hubble limit
(no lensing)
JWST limit
(no lensing)
H-cooling threshold
H2 cooling
MAB= -22
MAB= -18
MAB= -14
MAB= -10
MAB= - 6
hidden population of
abundant ,faint galaxies??

Welcome to the 21-cm revolution!

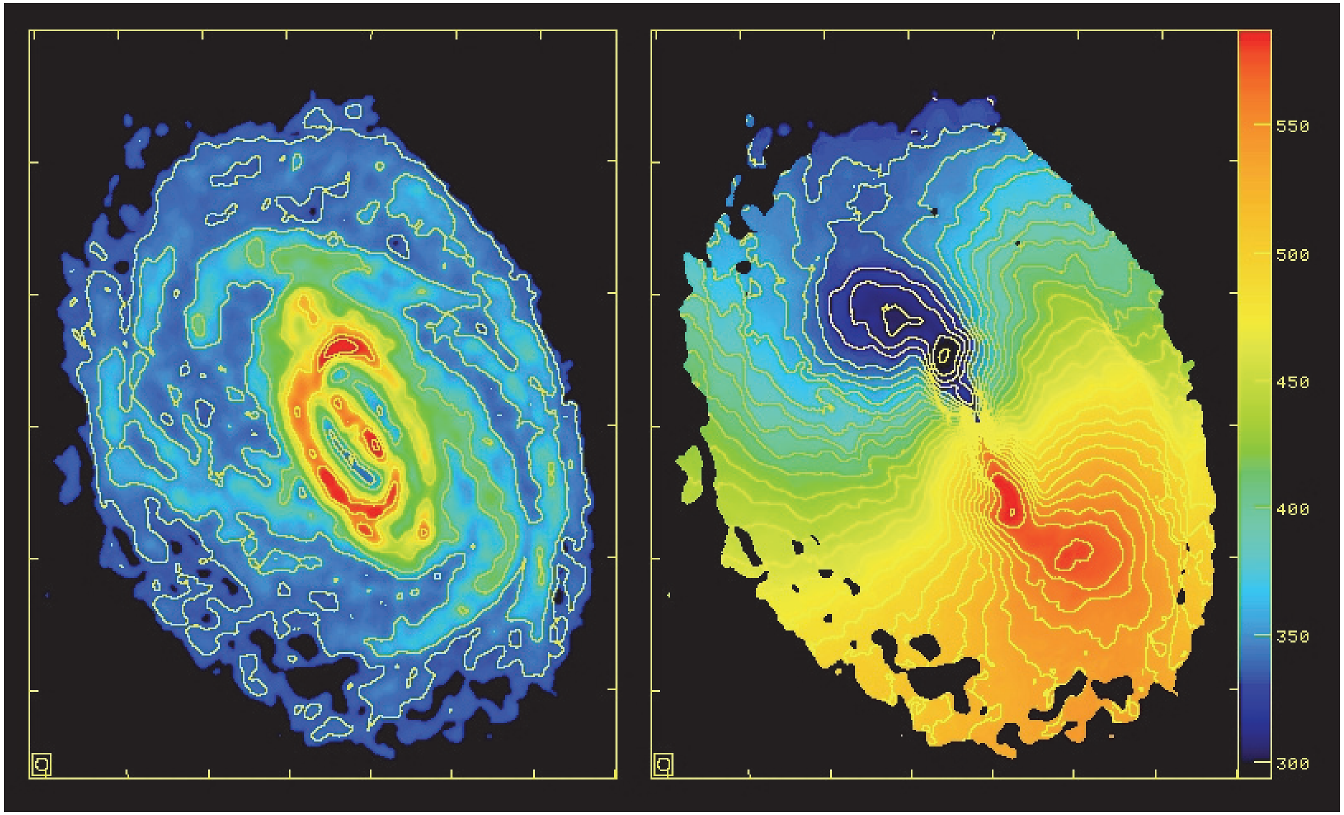
see review in
Mesinger (2019)

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

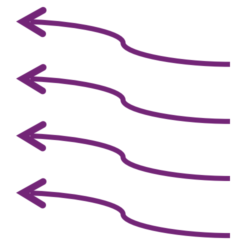
use the CMB as a background. measure the difference in intensities of the CMB and the cosmic HI, the so-called brightness temperature offset from the CMB:

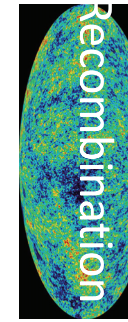
$$\delta T_b(\nu) \approx 27 x_{\rm HI}(1+\delta_{\rm nl})\left(\frac{H}{dv_r/dr + H}\right)\left(1-\frac{T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\,\frac{0.15}{\Omega_M h^2}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right)\,\mathrm{mK}$$

Cosmic 21-cm signal

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:

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Signal contains both **ASTROPHYSICAL**

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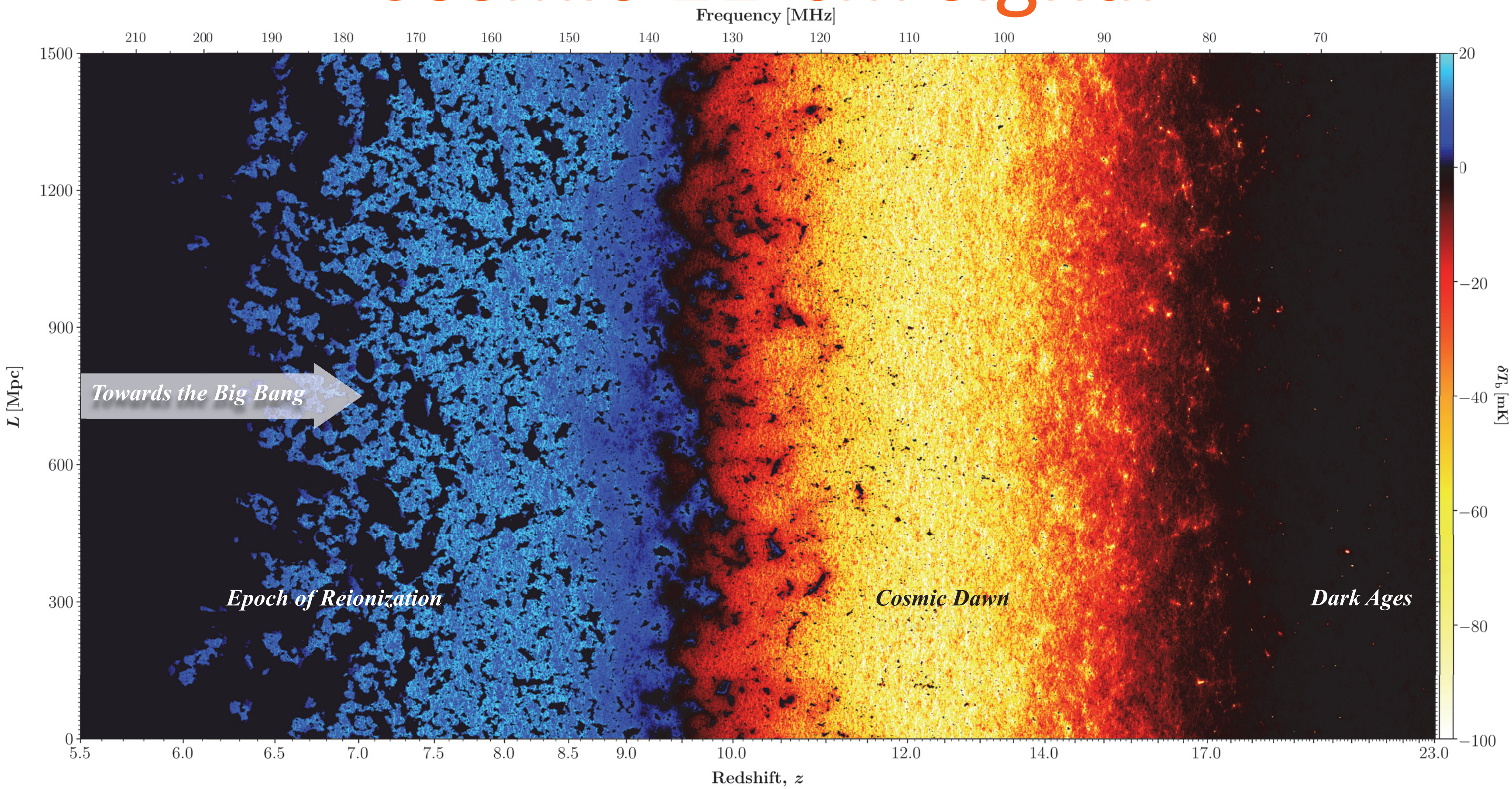
Signal contains both **ASTROPHYSICAL** and **COSMOLOGICAL** terms

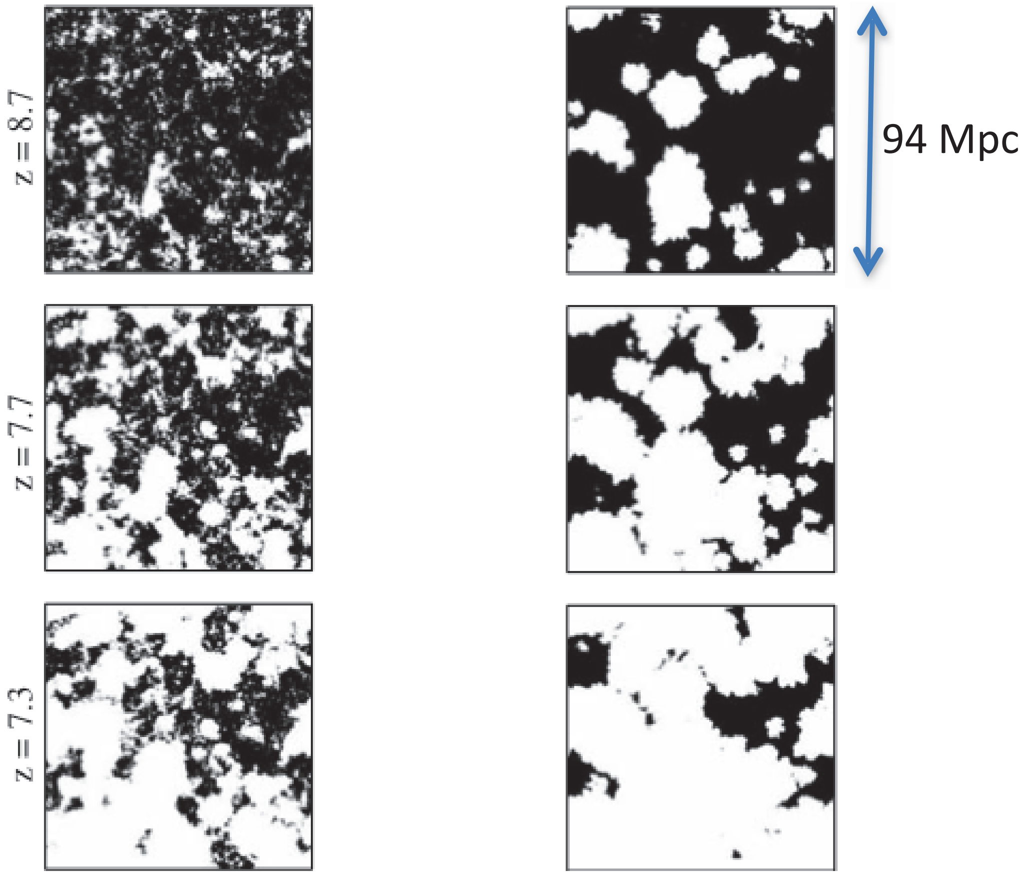
Cosmic 21-cm signal



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

How do we learn about the unseen sources?

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



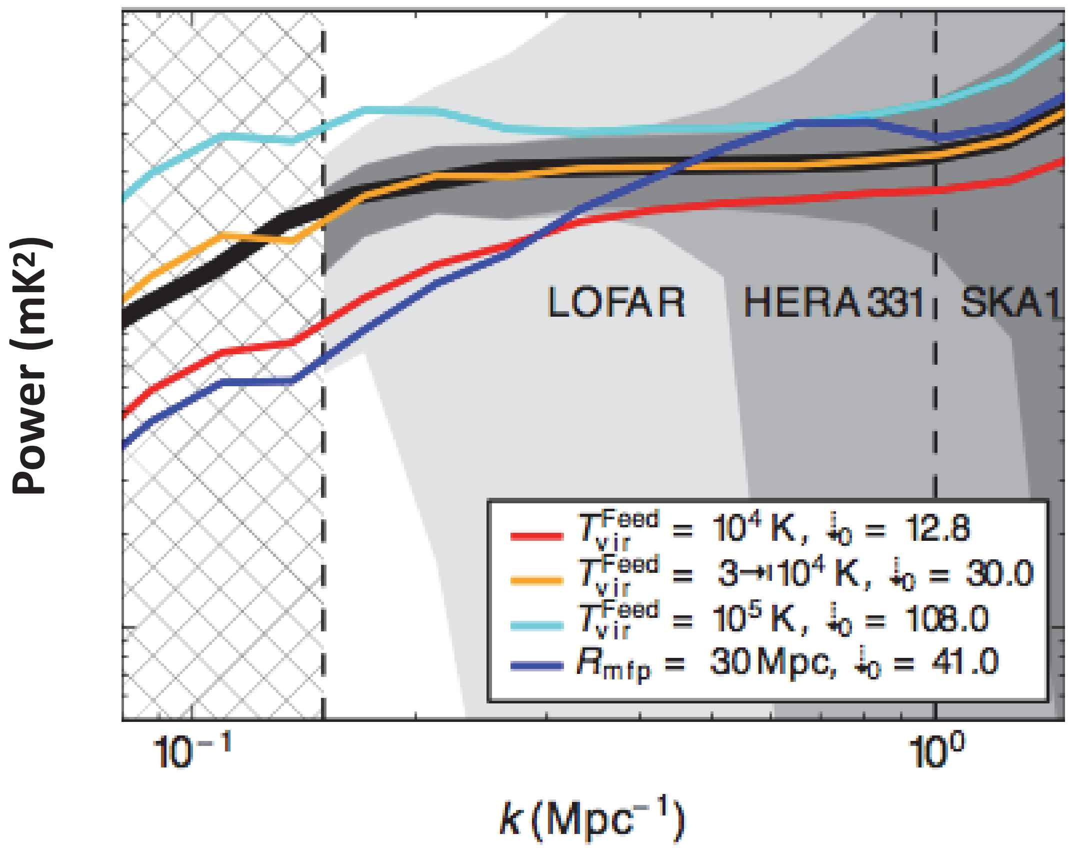
McQuinn+ 2007

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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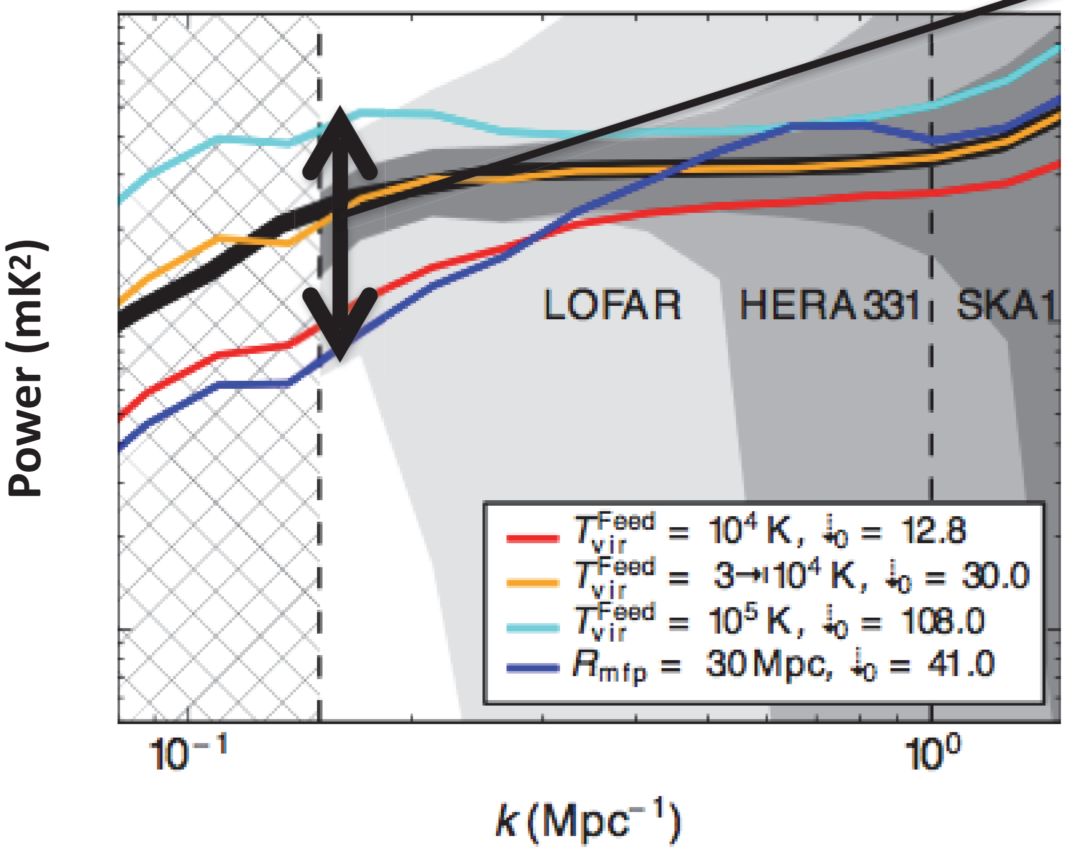


Factor of ~10 variation on large scales between astrophysical models, at a fixed EoR epoch.

Greig & Mesinger (2015)

Also a probe of temperature

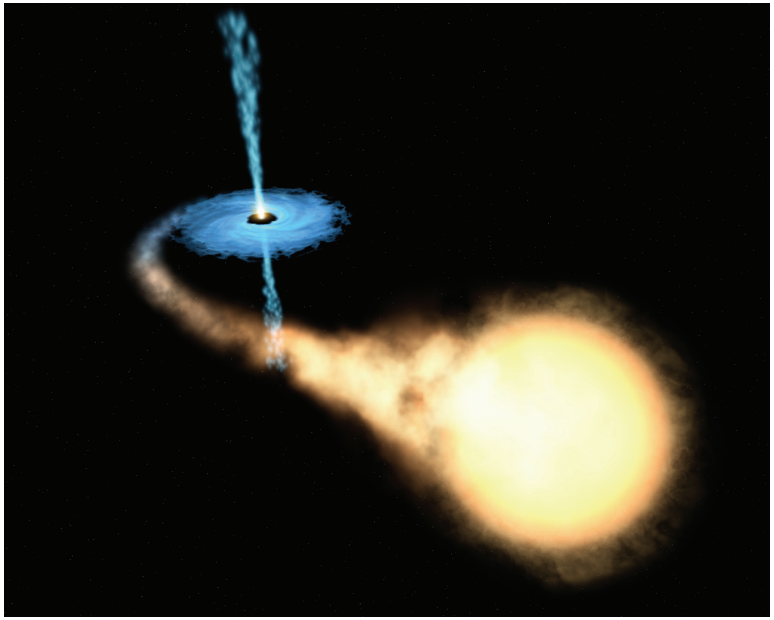
$$\delta T_b(\nu) \approx 27 x_{HI}(1+\delta_{nl}) \left(\frac{H}{dv_r/dr + H}\right) \left(1 - \frac{T_\gamma}{T_S}\right) \left(\frac{1+z}{10} \frac{0.15}{\Omega_M h^2}\right)^{1/2} \left(\frac{\Omega_b h^2}{0.023}\right) \mathrm{mK}$$

spin temperature

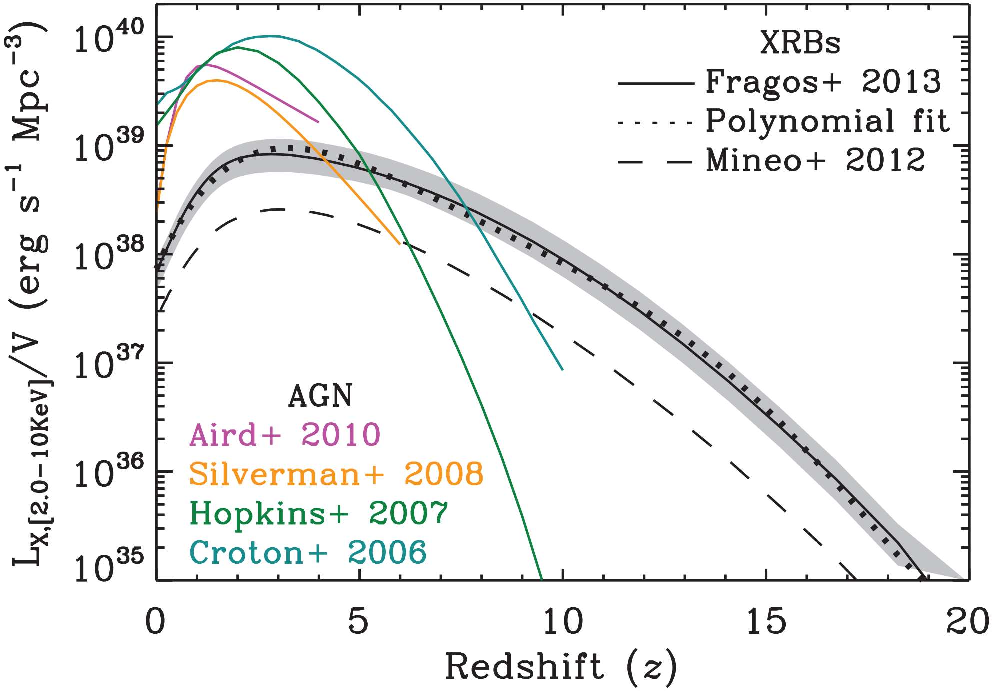
defined in terms of the ratio of the number densities of electrons occupying the two hyperfine levels:

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

X-ray binaries dominate IGM heating at high-z



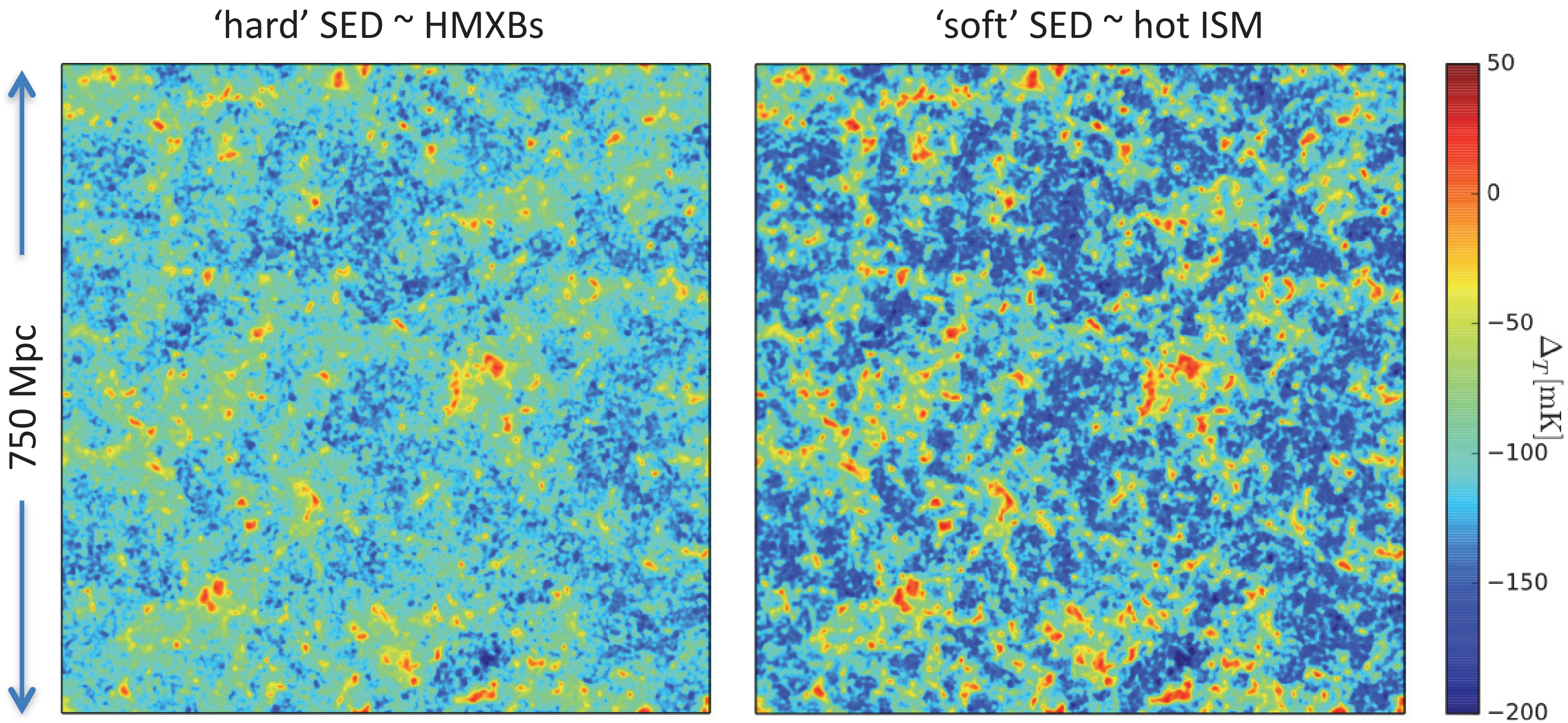
High Mass X-ray Binaries are expected to dominate the X-ray background beyond z >~ 5



Fragos+ 2013

Patterns in the Epoch of Heating

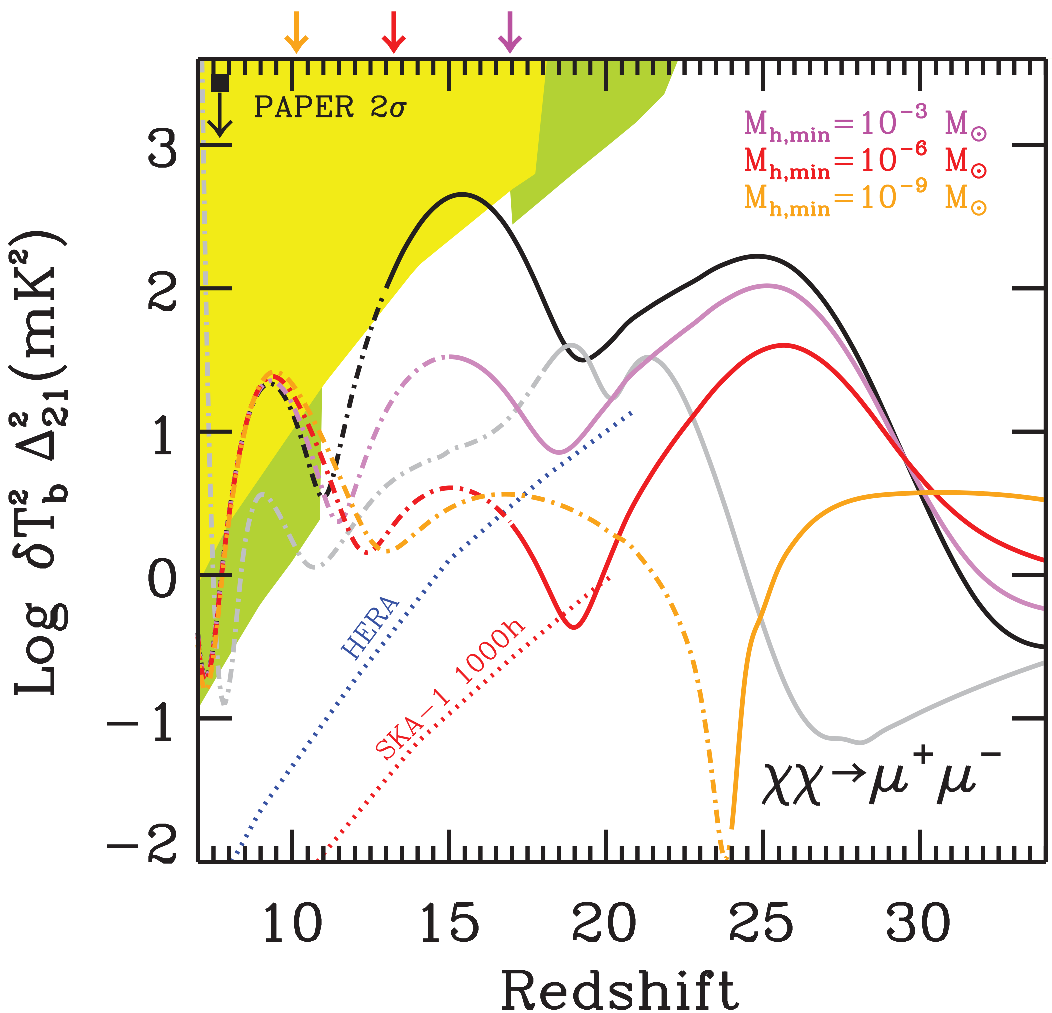
High-energy processes in the first galaxies are also encoded in the cosmic 21-cm signal



differences are easily detectable with HERA and the SKA

Pacucci, AM+ 2014

More exotic processes can leave imprints in the 21cm signal: *DM annihilations*



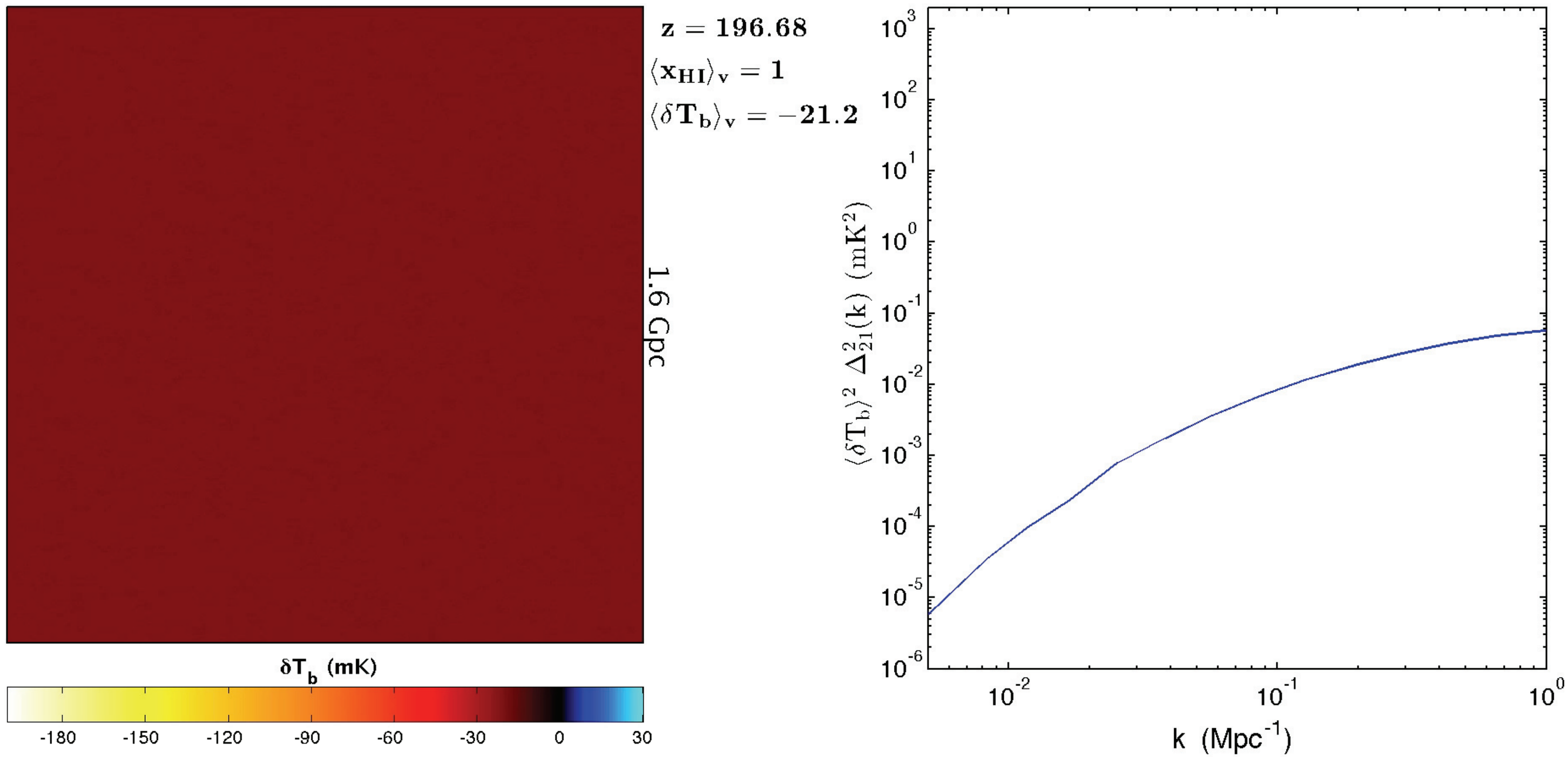
Dark matter annihilations heat the IGM more uniformly than galaxies!

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

Evoli, AM, Ferrara (2014)

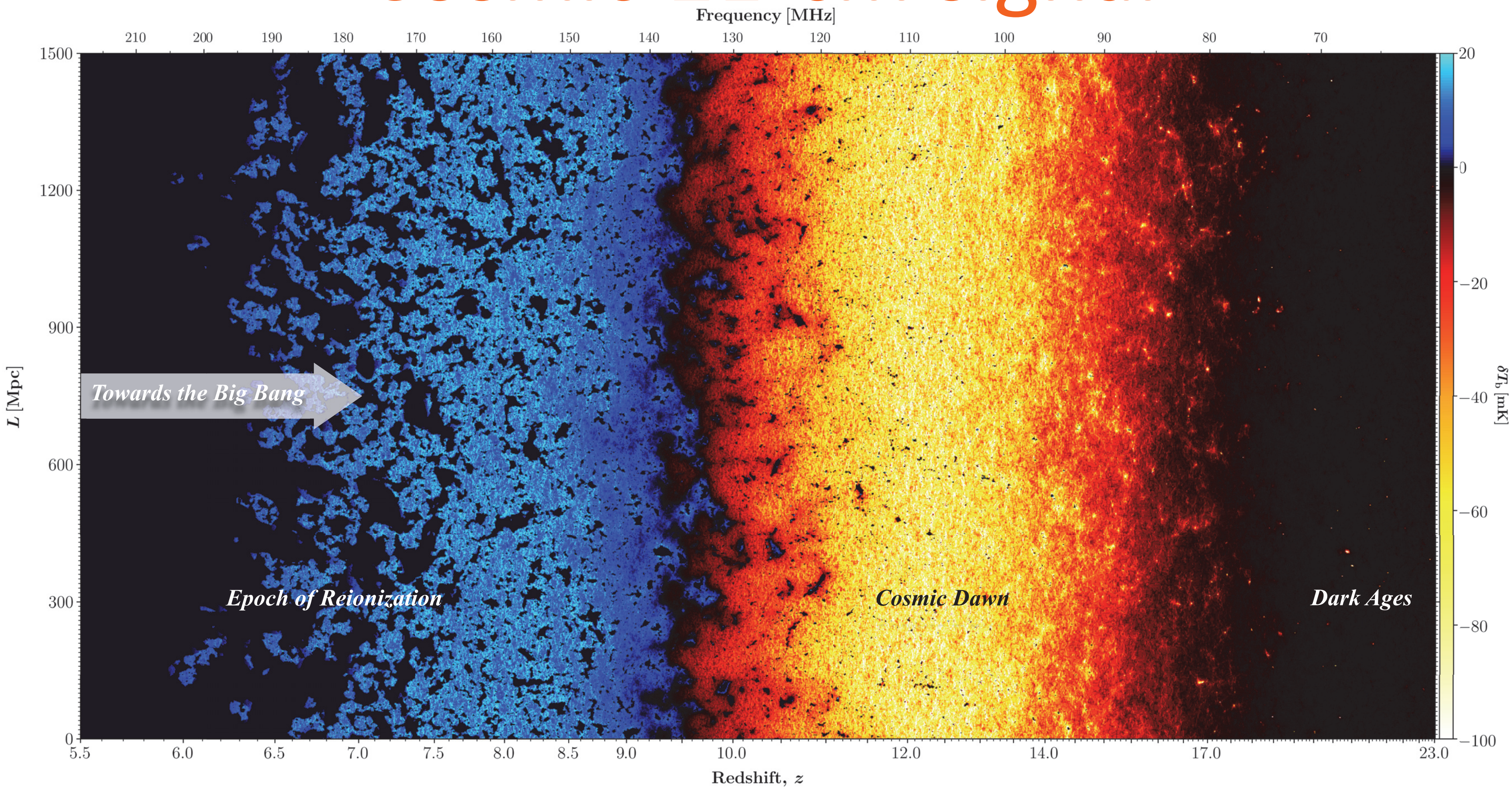
see also Lopez-Honorez+2016

Simulation slice



AM+ 2016

Cosmic 21-cm signal

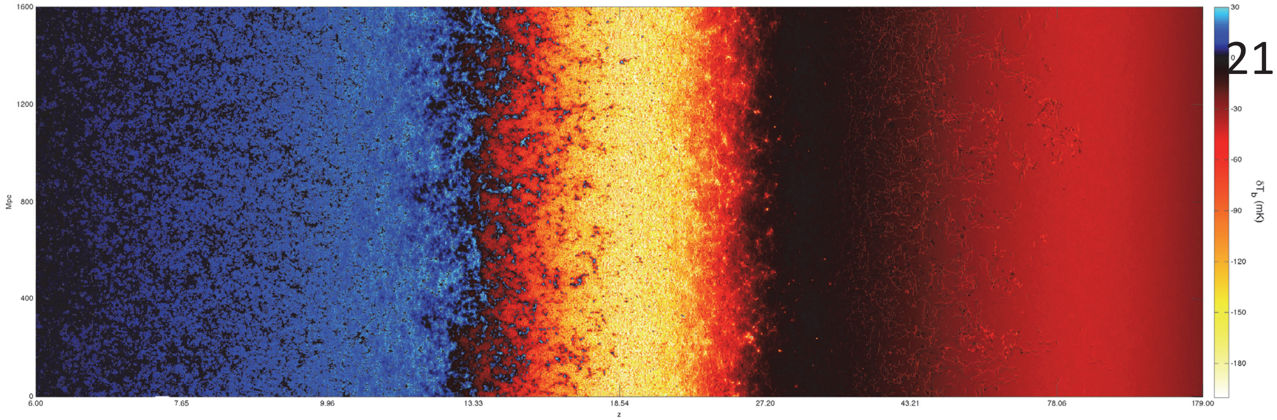


- **3D** signal with **> 10 orders of magnitude** more independent modes than in the CMB!
- data collection with upcoming Square Kilometre Array (SKA) will surpass **10x current global internet traffic**!
- even the narrowest fields will contain >billion of unseen galaxies
- **BIG DATA REVOLUTION**!

How to quantify what we will learn??

*Astro*physical cosmology

← time

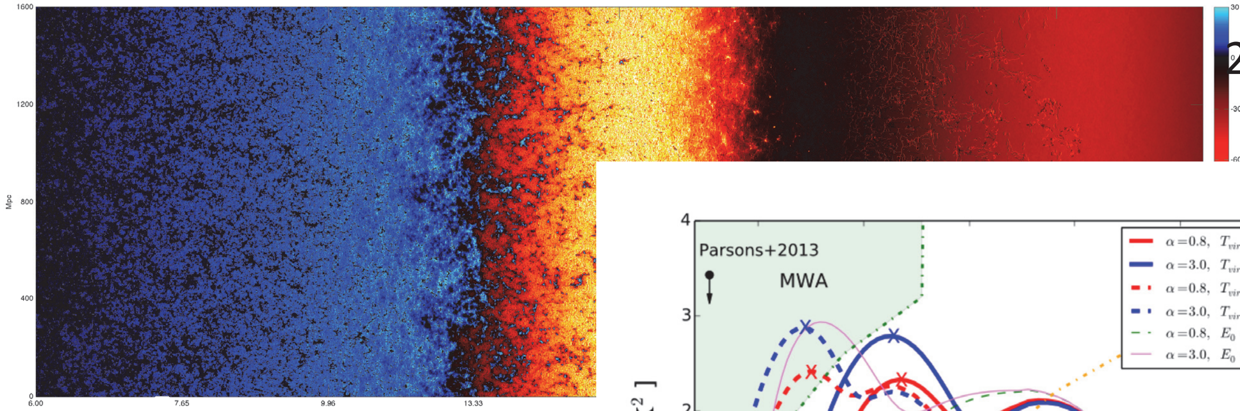


21cm **3D!!!** map

Greig & AM (2015)

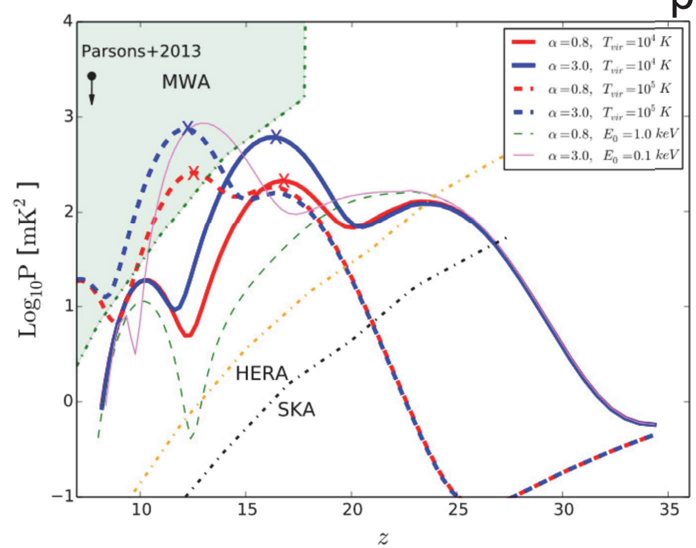
*Astro*physical cosmology

← time



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

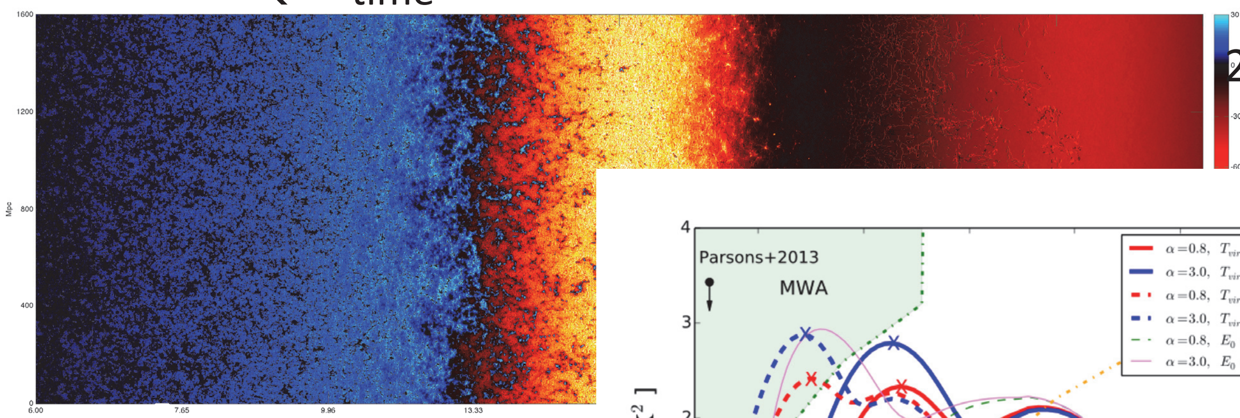
power spectrum**??**



Greig & AM (2015)

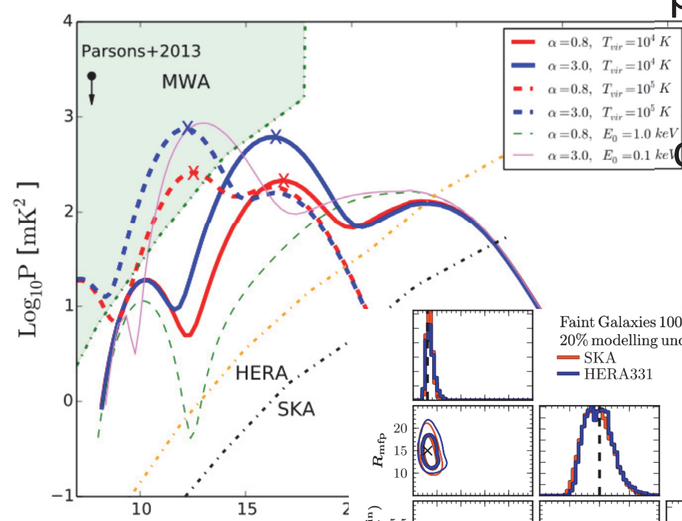
*Astro*physical cosmology

← time

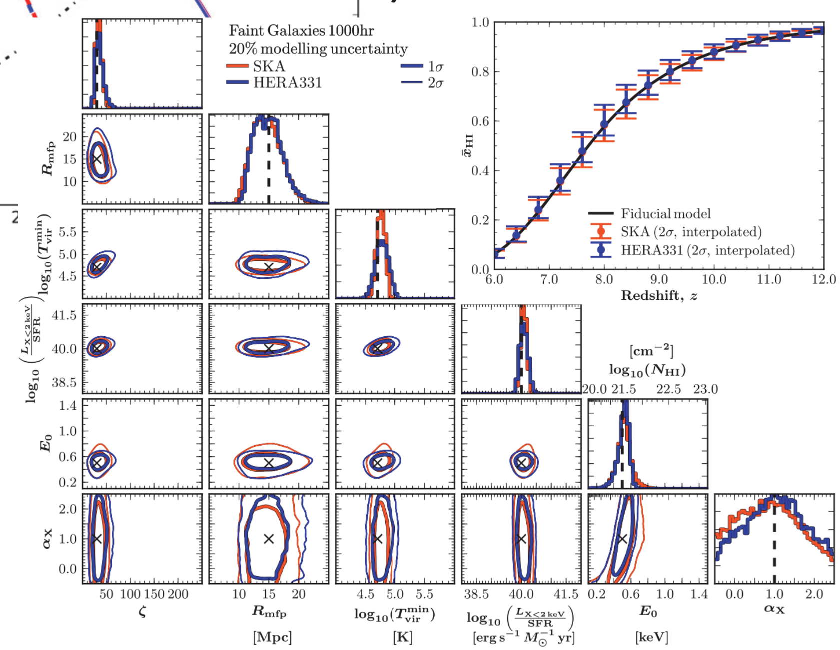


21cm **3D!!!** map

power spectrum**??**



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



Greig & AM (2015; 2017)

What are astrophysical parameters?????

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

Observable scales of 21-cm are sourced by > **hundreds of galaxies**… Population averaging -> power laws! **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+ 2019
(see also Kuhlen+2012; Dayal+ 2014; Mitra+ 2015; Sun & Furlanetto 2016; Mutch+ 2016; Yue+ 2016, …)

A flexible approach based on DM halos + galaxy LFs

Average properties of galaxies in halos of mass M_h:

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

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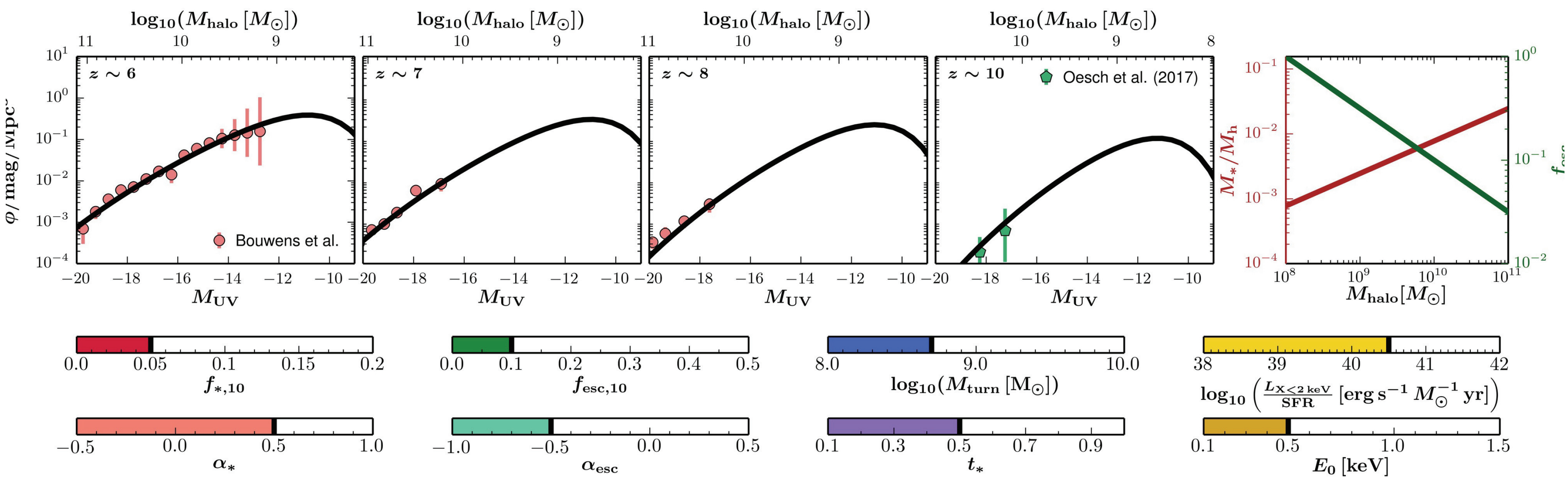
$$L_{\rm ion} = \mathbf{f_{esc,10}} \left(\frac{M_h}{10^{10} M_\odot} \right)^{\alpha_{\rm esc}} L_{1500}$$

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

six free parameters for star formation and UV photons



A flexible approach based on DM halos + galaxy LFs

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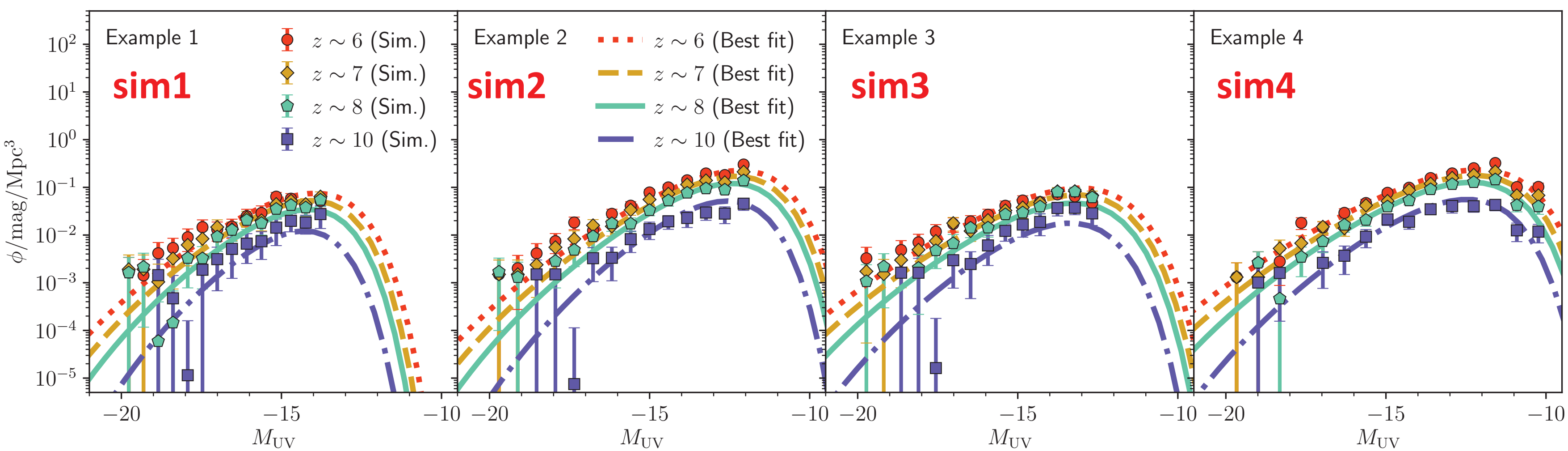
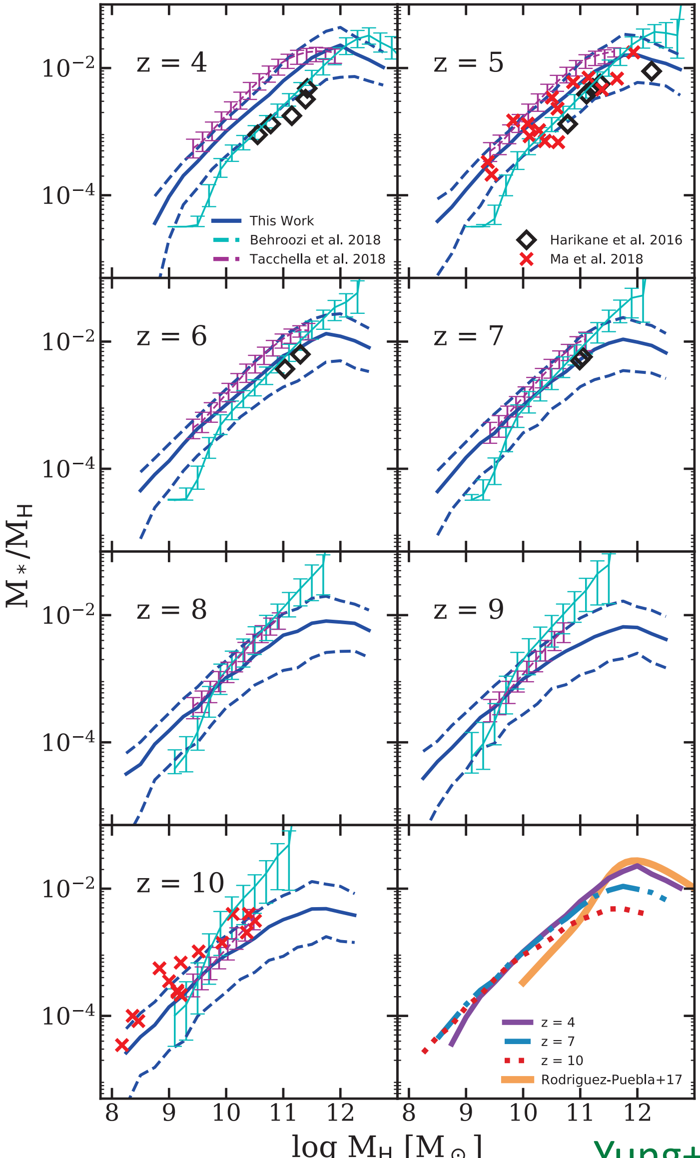
$$f_{\mathrm{duty}} = \exp[-\mathbf{M_{turn}}/M_h]$$

Can also fit diverse LFs from hydro simulations (Gillet+, in prep)



A flexible approach based on DM halos + galaxy LFs



Yung+ 2019

…os of mass M_h:

$$\ldots 10 \left(\frac{M_h}{10^{10} M_\odot}\right)^{\alpha_*} \frac{\Omega_b}{\Omega_M} M_h$$

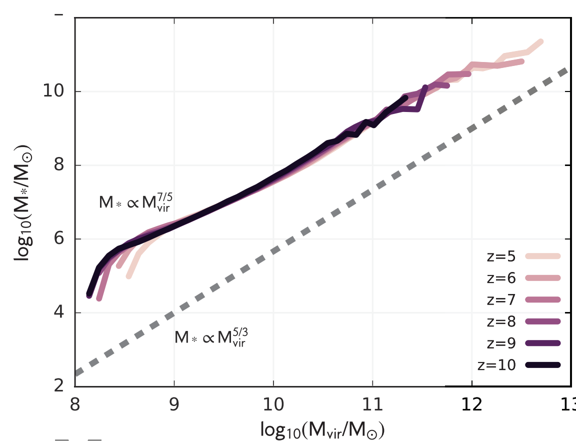
$$\frac{M_*}{t_* H^{-1}}$$

$$\ldots\text{esc},10 \left(\frac{M_h}{10^{10} M_\odot}\right)^{\alpha_{\rm esc}} L_{1500}$$

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

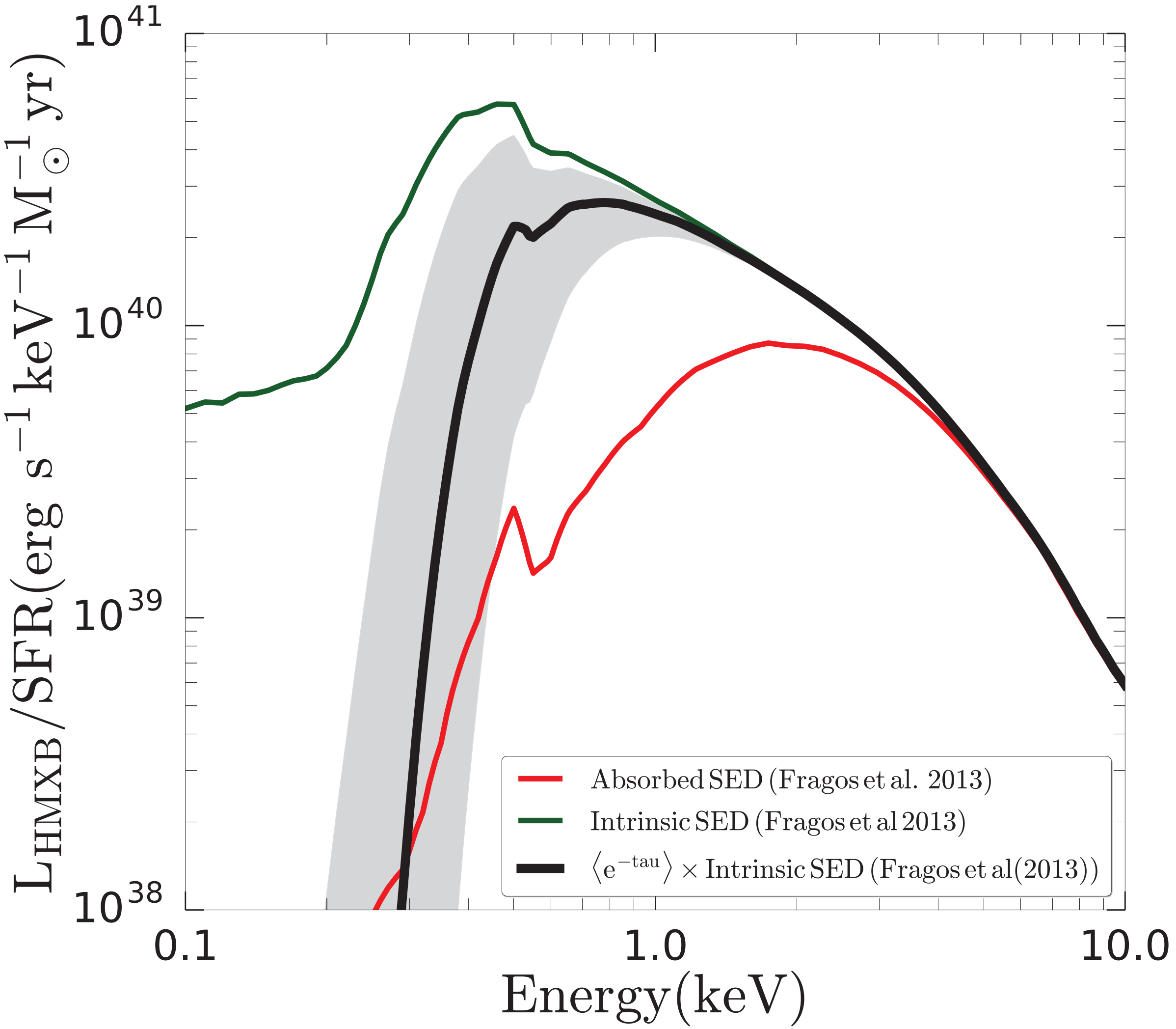
Can also fit diverse LFs from hydro simulations

AND SAMs



Mutch+ 2015

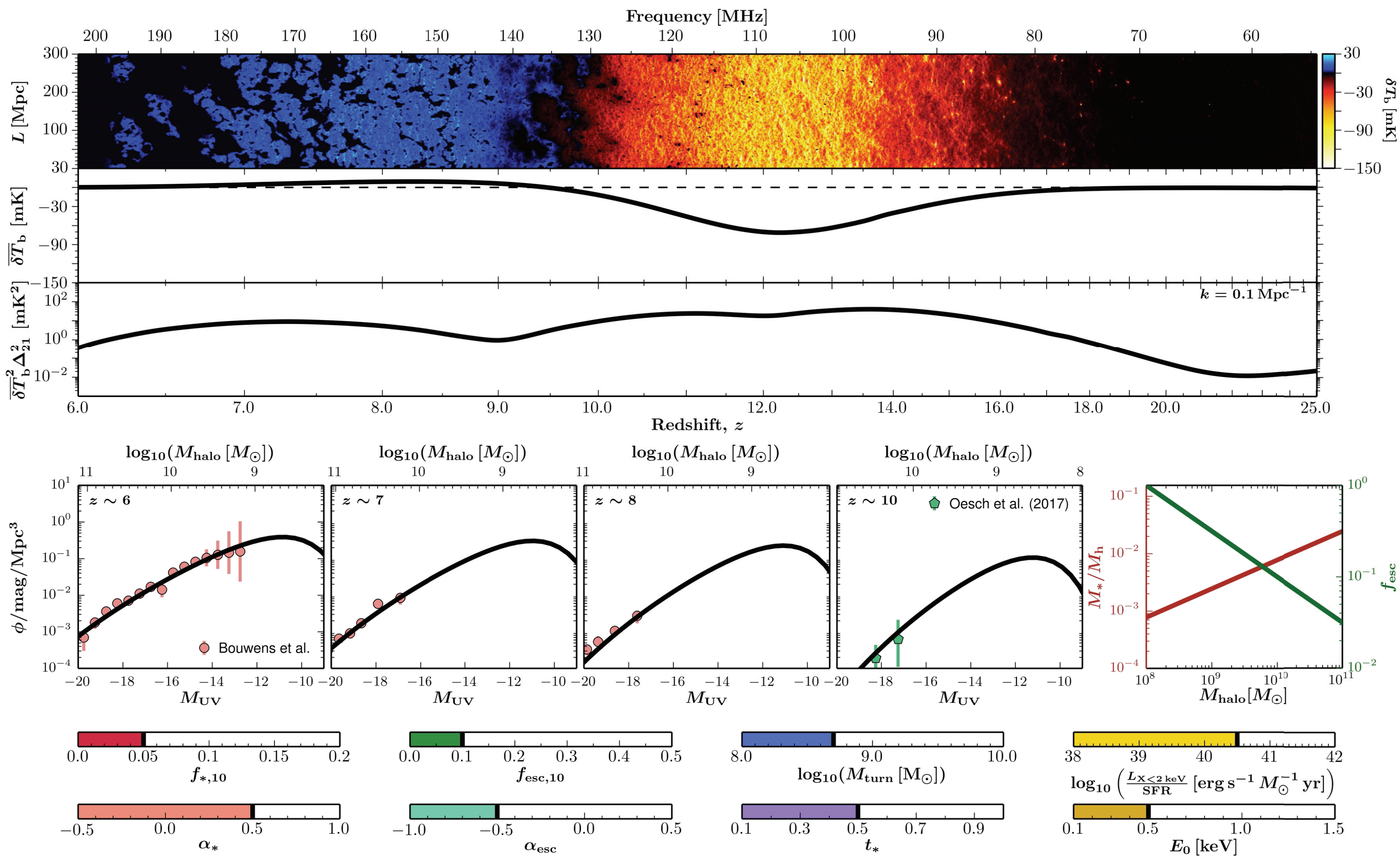
Additional 2 parameters for X-ray/SFR



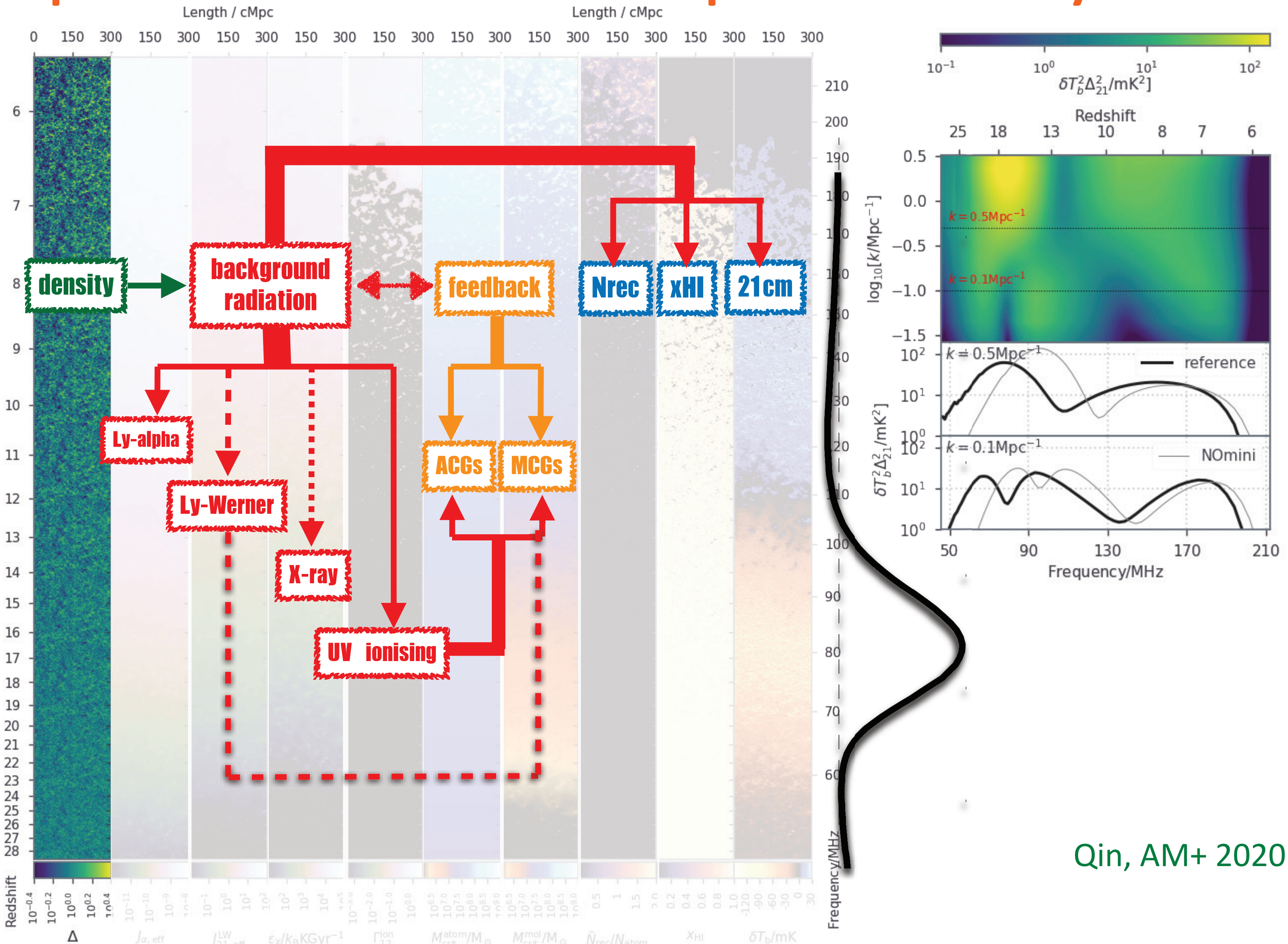
X-ray free parameters characterizing emerging SED from galaxies

Das, AM+ 2016

Free parameters



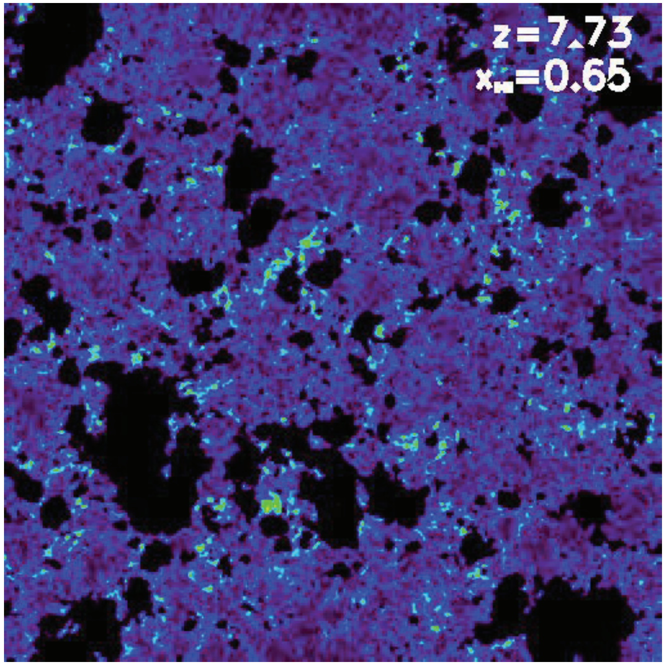
Spatial evolution requires many fields



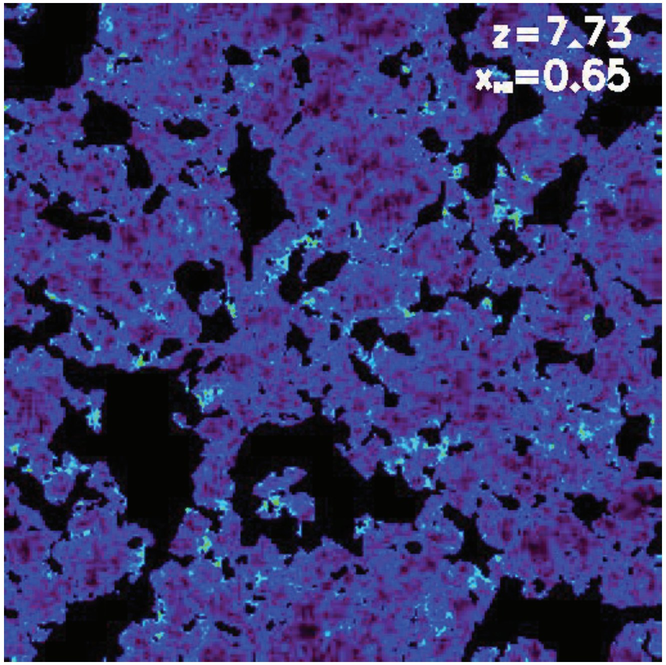
Qin, AM+ 2020

We need efficient simulations

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).

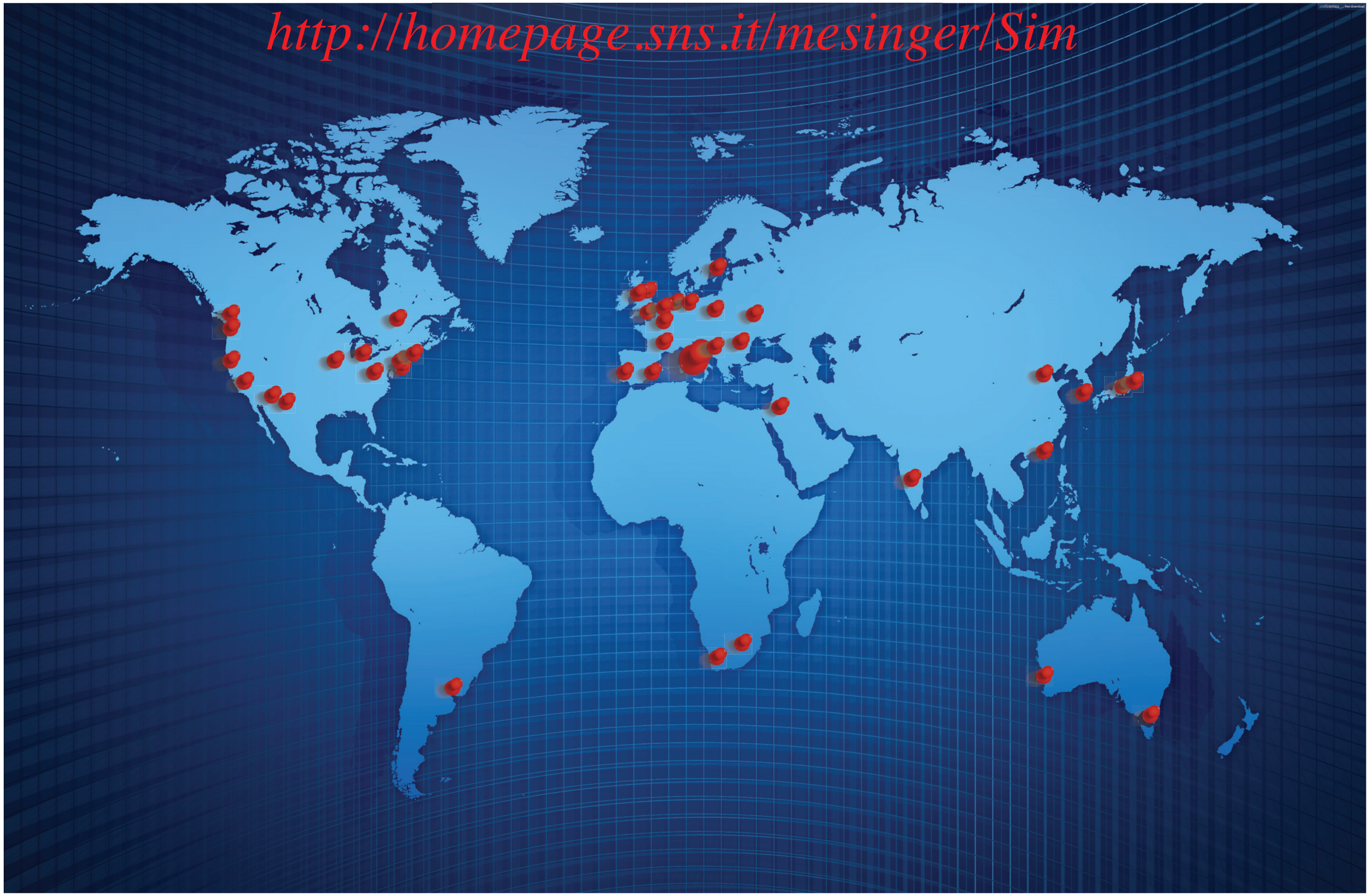


hydro+RT (Trac+2009):
~10^7 CPU hours



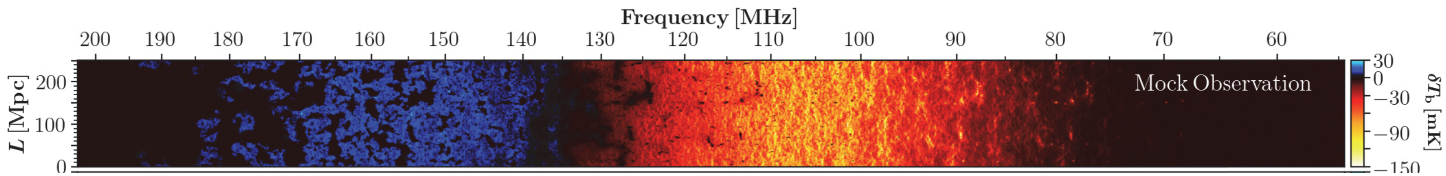
21cmFAST:
~0.1 CPU hours

Get on board!



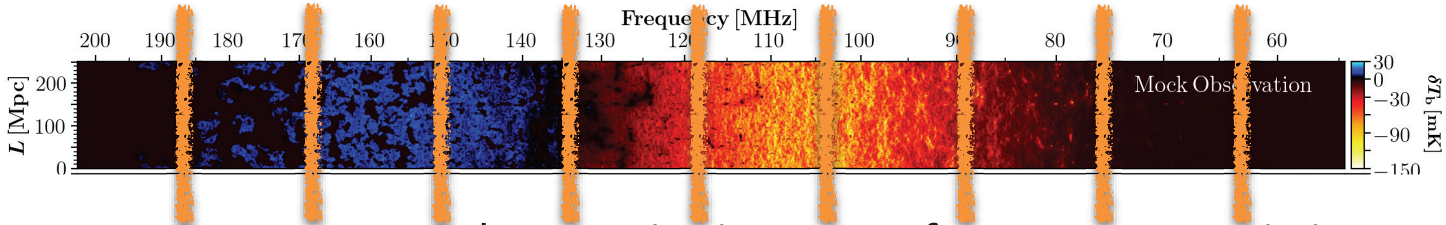
21cmFAST is being used by ***all*** *of the 21cm interferometers: LOFAR, MWA,PAPER, 21CMA, GMRT, HERA, SKA, with researchers in* ***25 countries*** *studying a broad range of early Universe topics*

Forward-modeling in an MCMC framework



“observation”

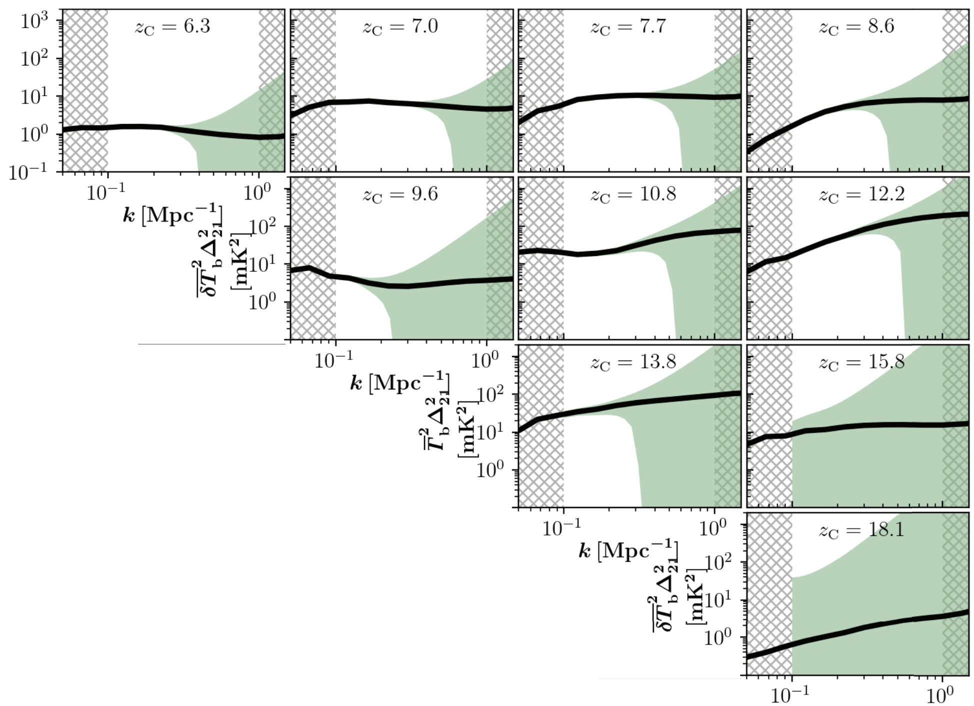
21cm **3D!!!** map

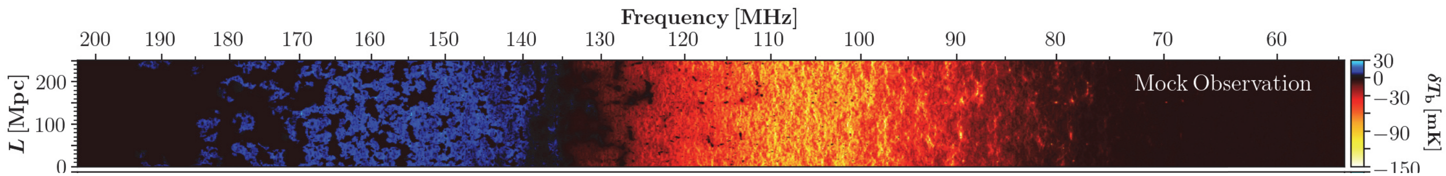


“observation”

characterize in terms of a summary statistic:

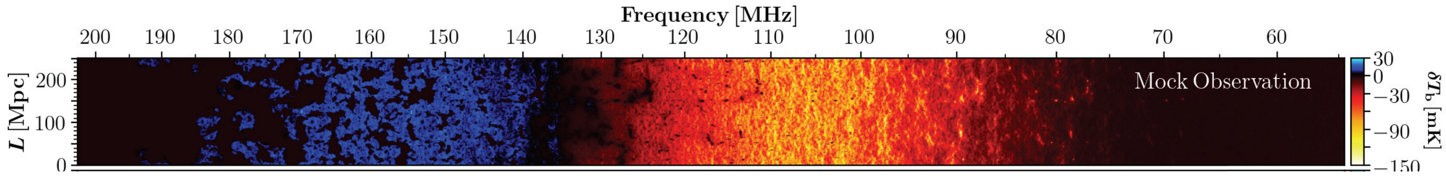
power spectra with 1000h noise from HERA and moderate foreground contamination





(1) 21-cm

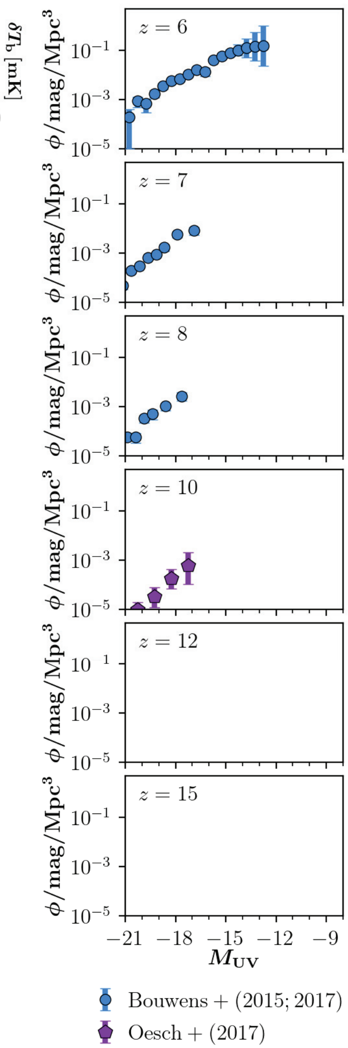
combine with other observations
in order to compute
likelihood



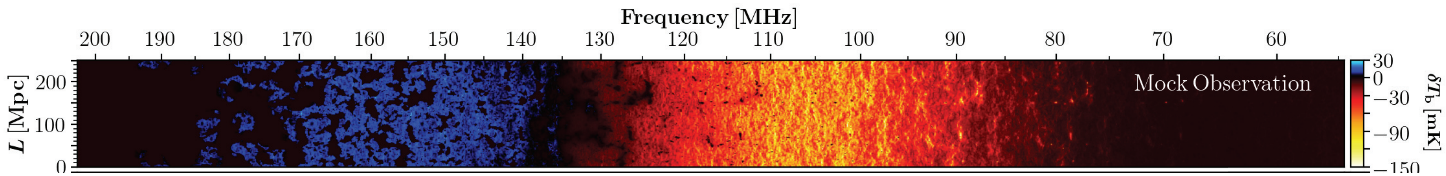
(1) 21-cm

+

(2) high-z galaxy LFs



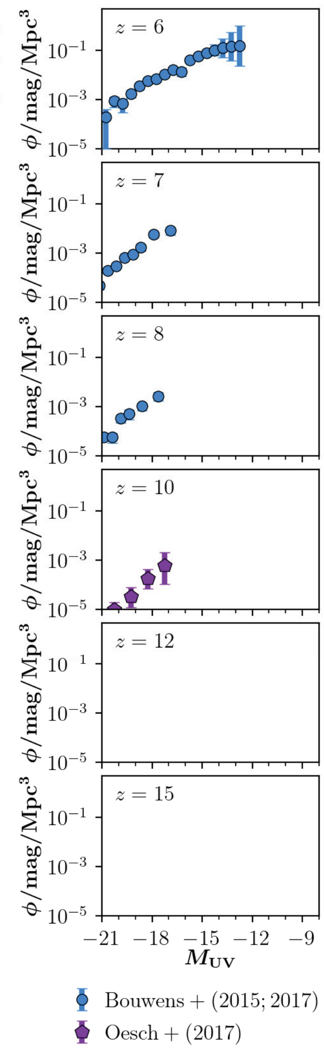
combine with other observations
in order to compute
likelihood



(1) 21-cm

+

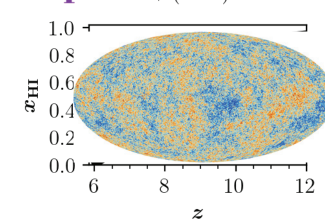
(2) high-z galaxy LFs

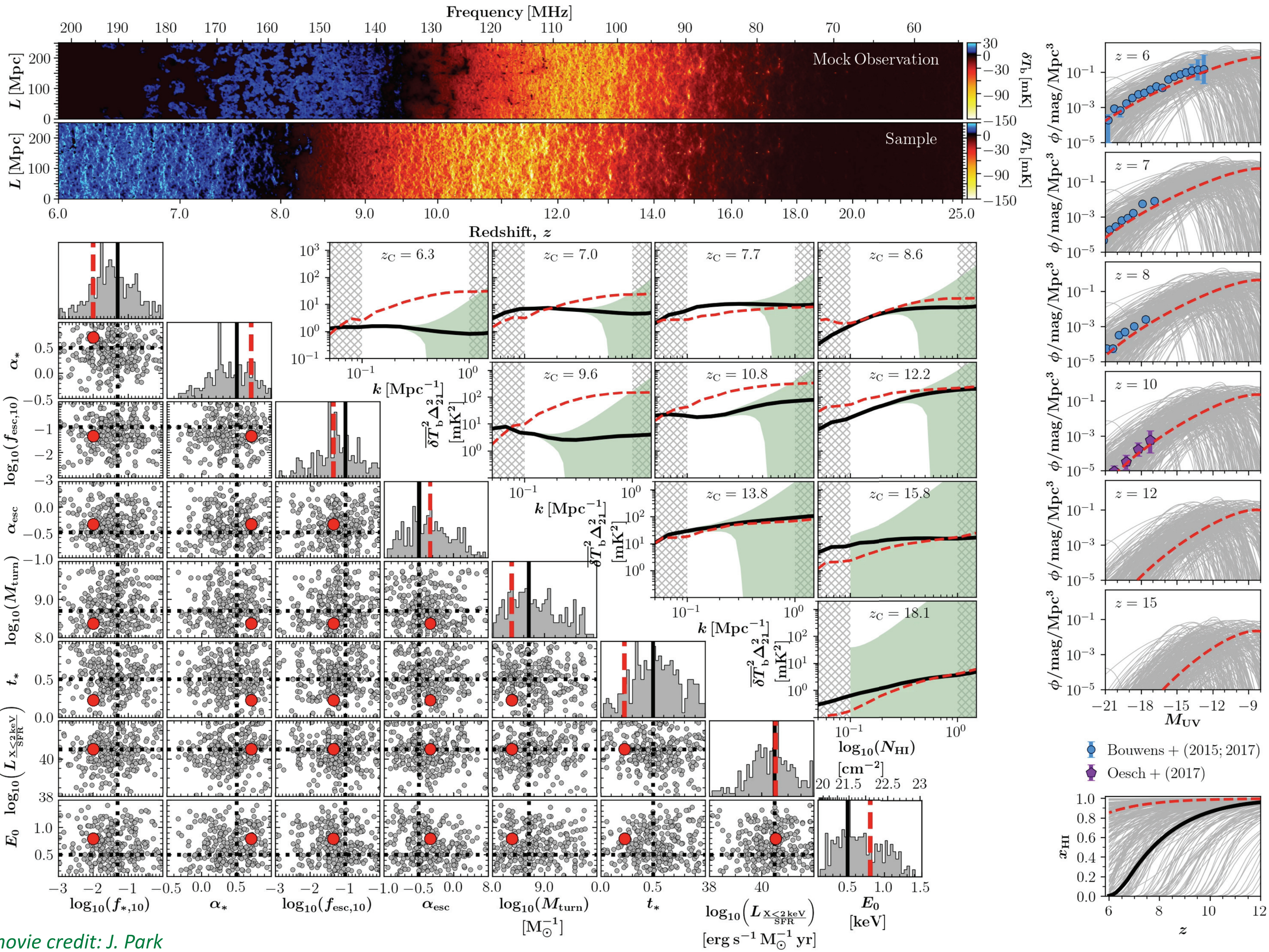


combine with other observations
in order to compute
likelihood

+

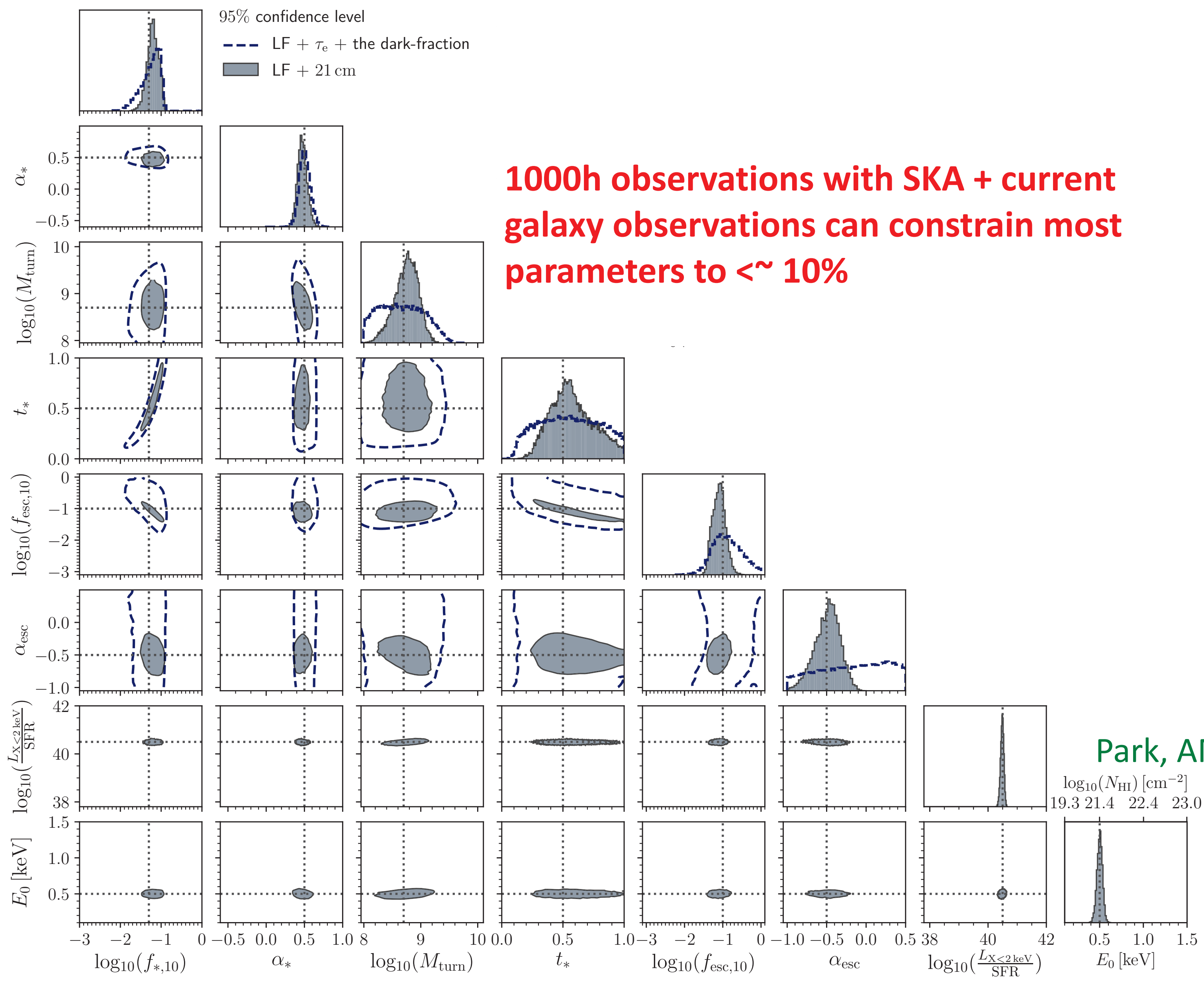
(3)
CMB τ_e





movie credit: J. Park

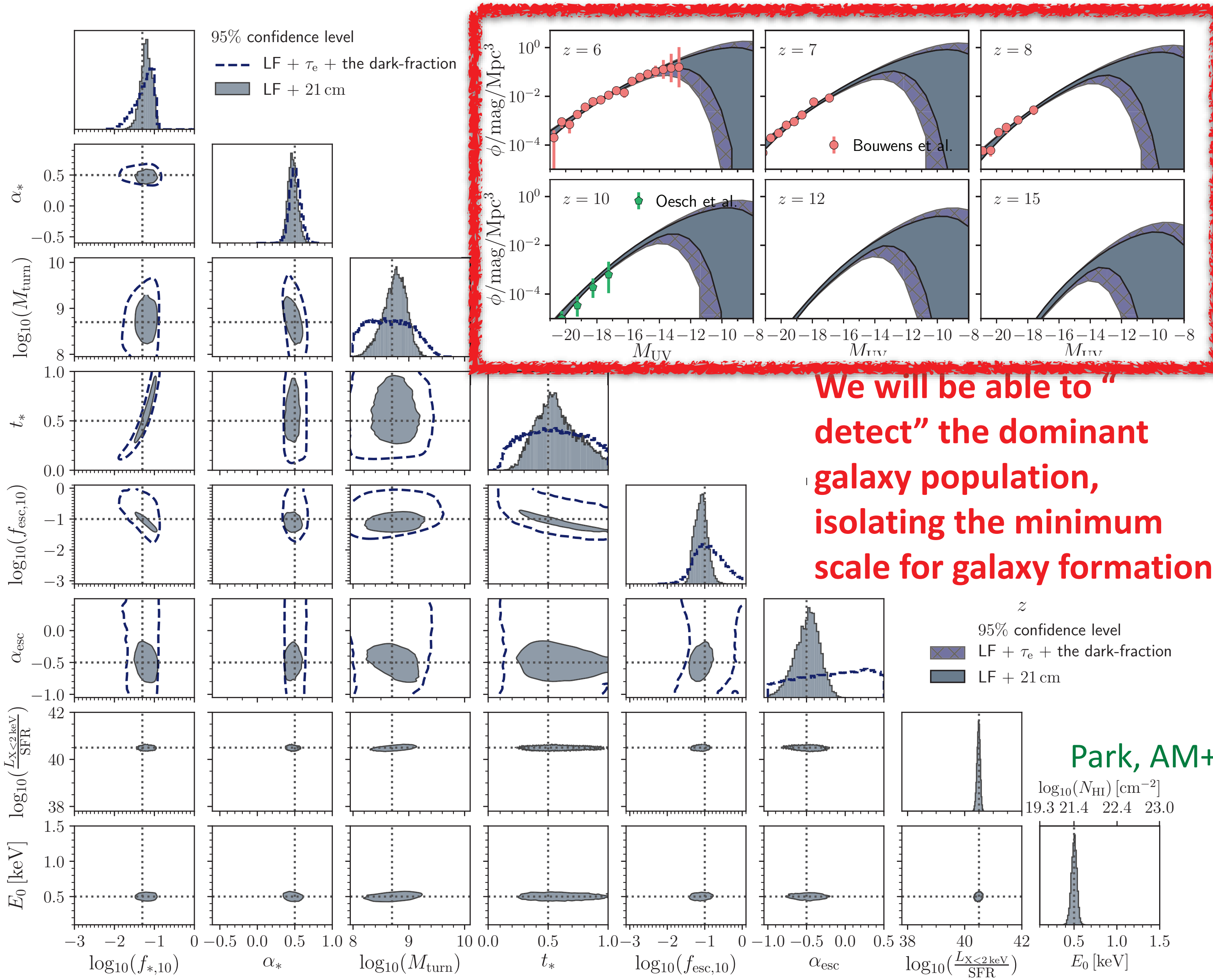
Parameter constraints



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

Park, AM+2019

Parameter constraints

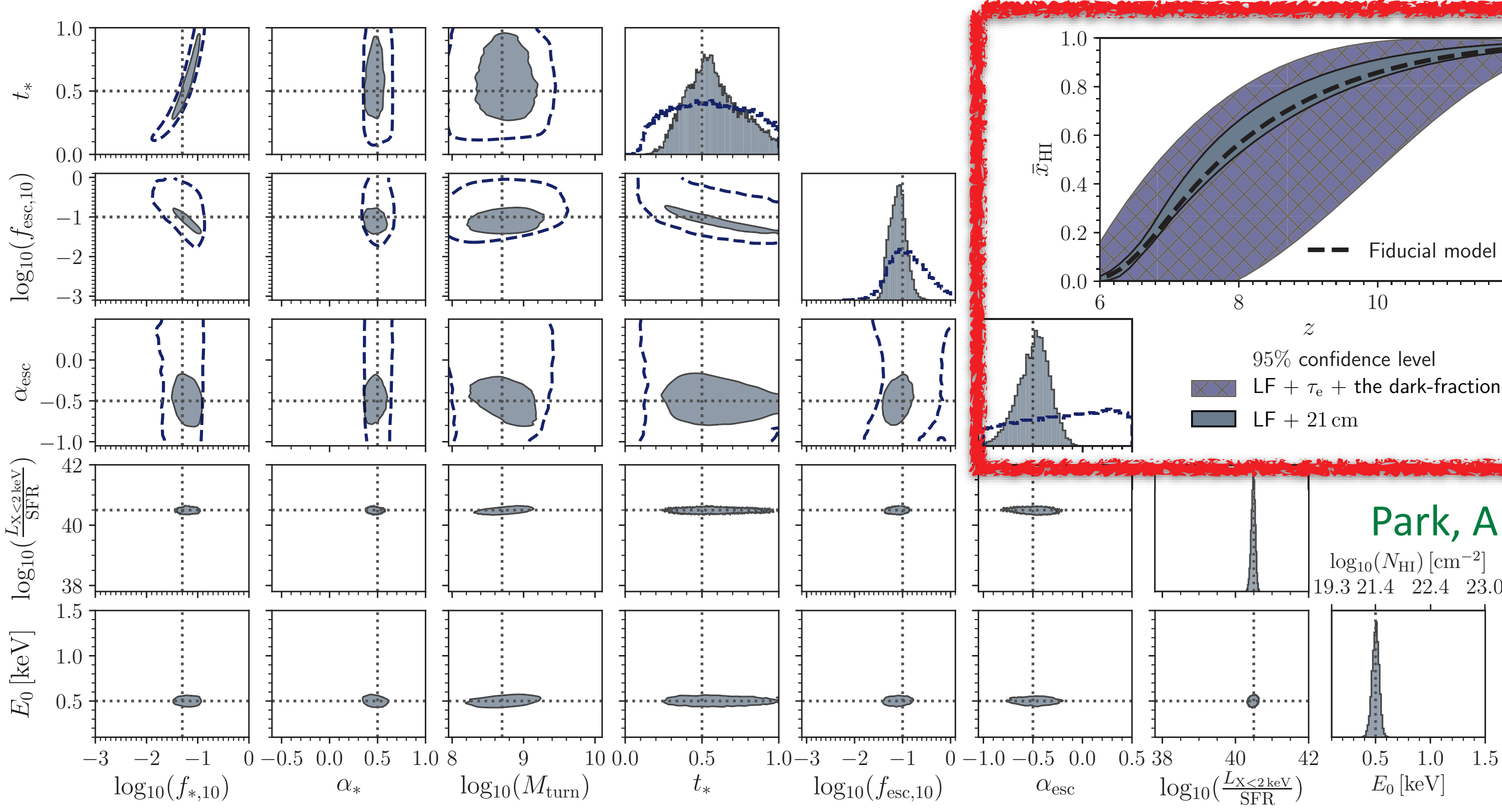


We will be able to " detect" the dominant galaxy population, isolating the minimum scale for galaxy formation

Park, AM+2019

Parameter constraints

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



Park, AM+2019

The time is now!

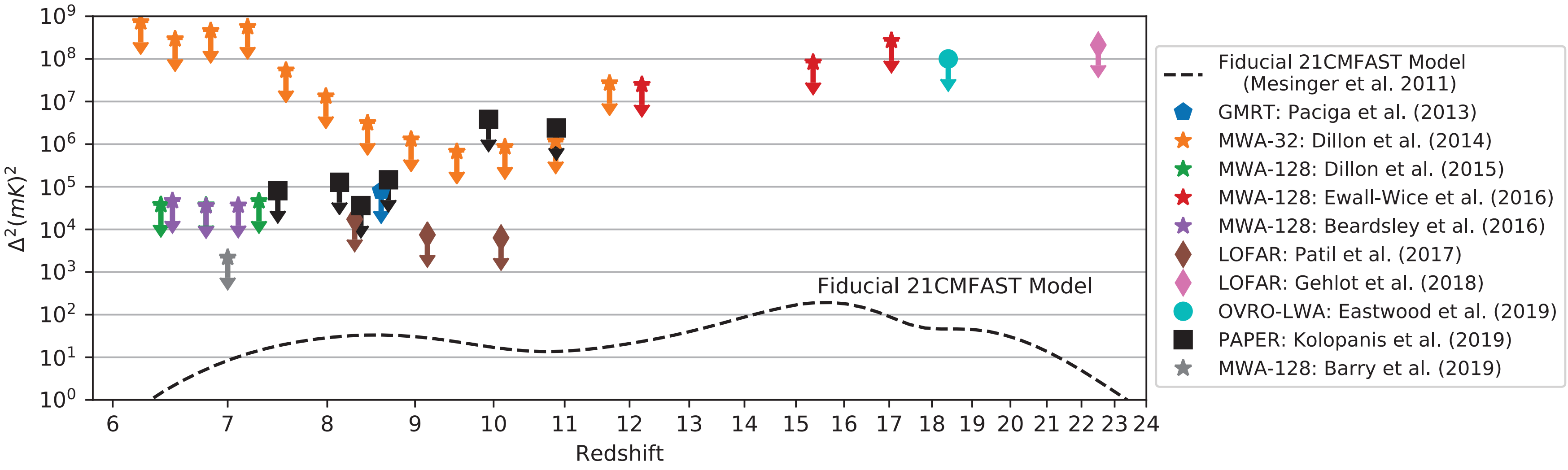
LOFAR (Netherlands+Europe)

MWA (Australia)

HERA (South Africa)

The time is now!

- Current interferometers (LOFAR, MWA, HERA) are making steady progress



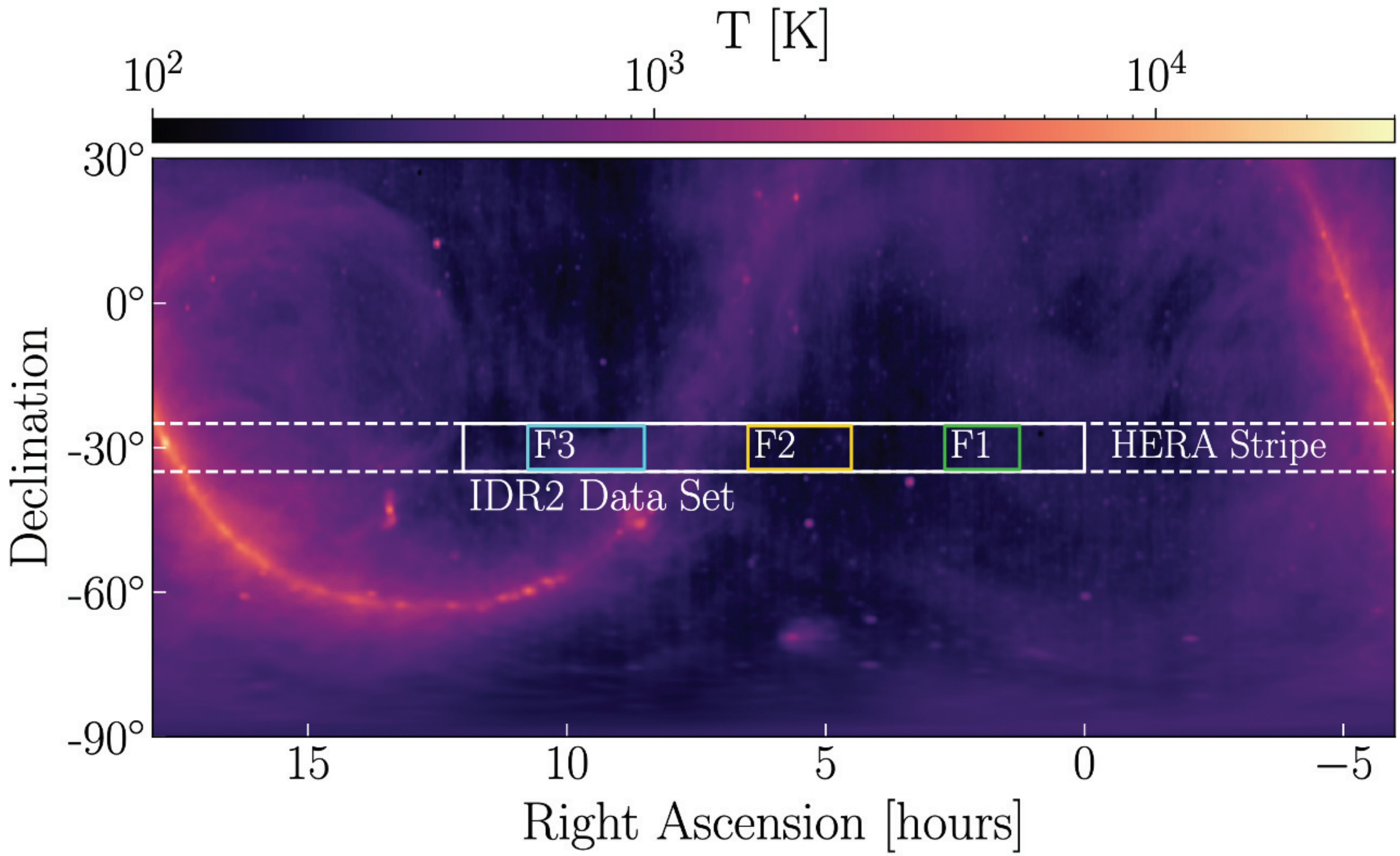
Liu & Shaw (2019)

An example: recent results from HERA

courtesy: J. Dillon

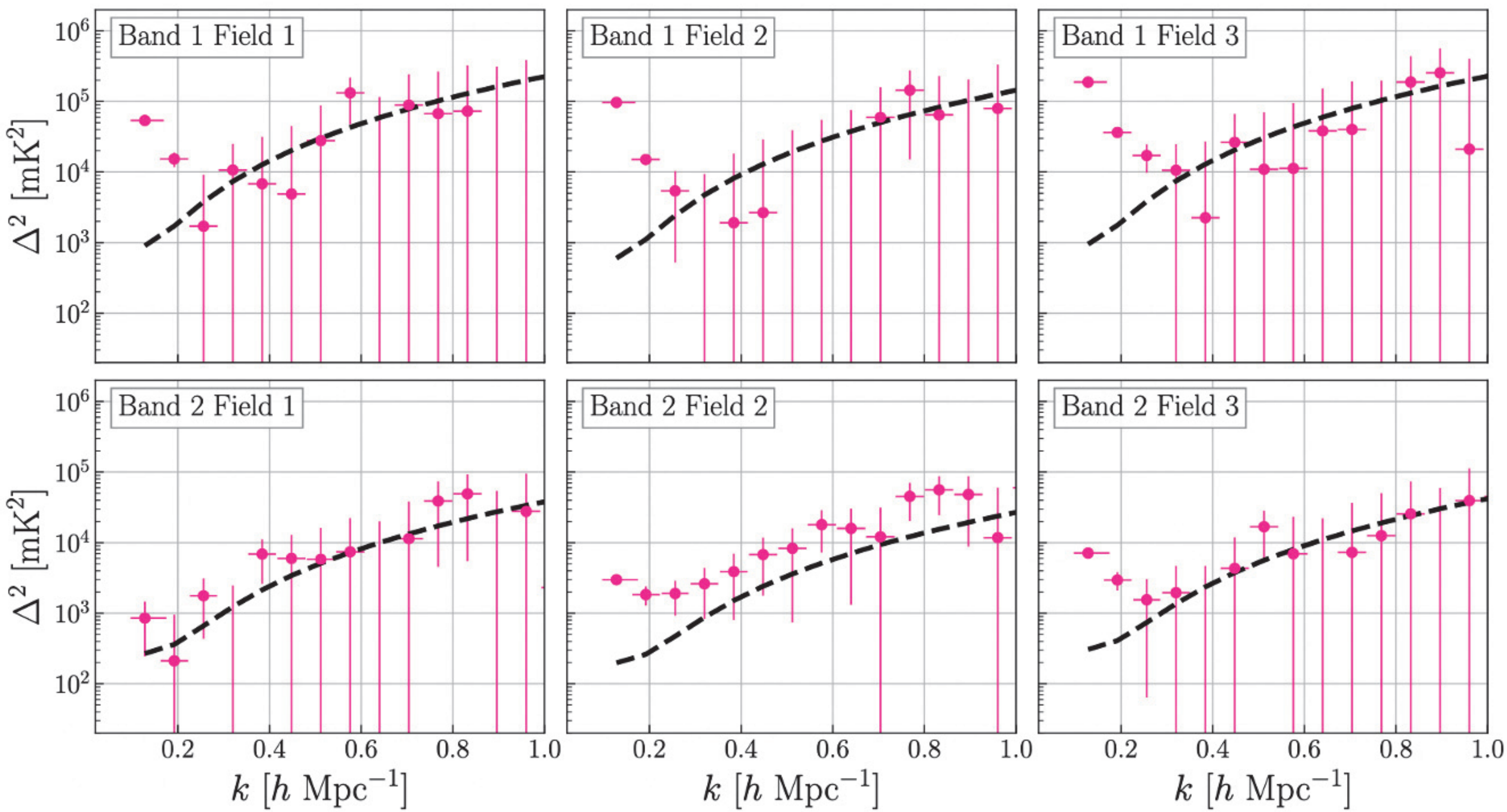
An example: recent results from HERA

An initial observing campaign in 2017-18, with just 39/~350 antennas and 18 nights(2108.02263).



HERA collaboration (2021)

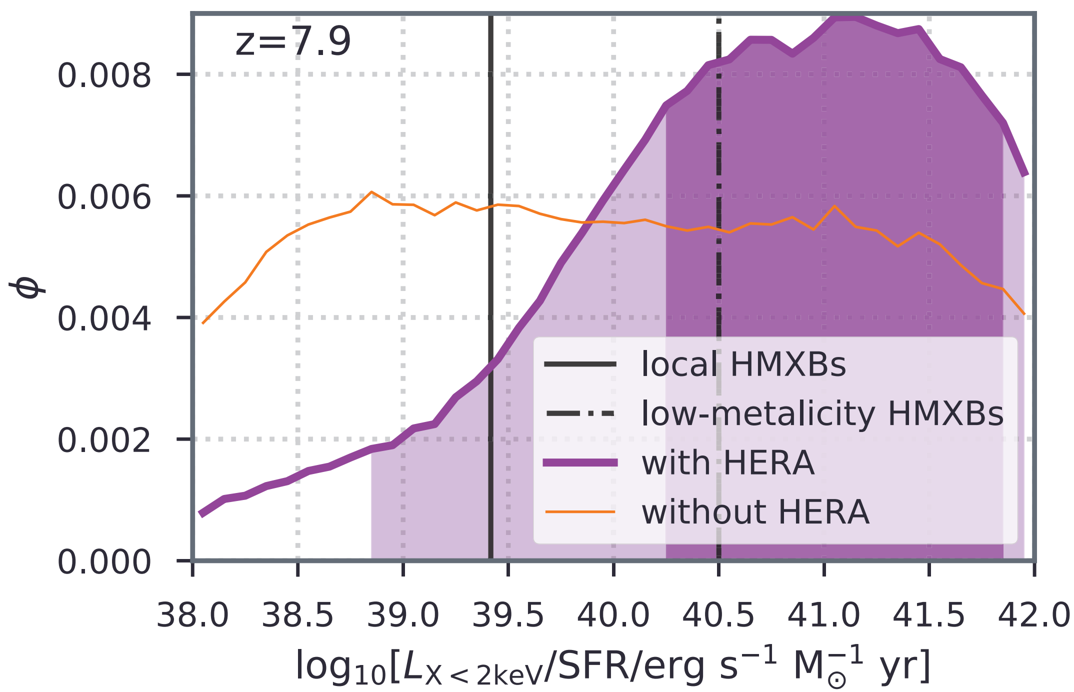
An example: recent results from HERA



These are consistent with thermal noise, and are still ~2 orders of magnitude above the expected signal

HERA collaboration (2021)

BUT they can still be useful for inference

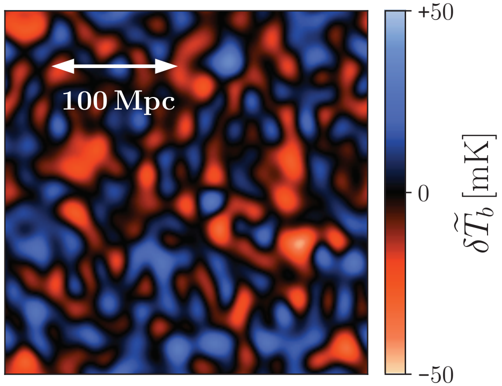


HERA is the first observation to constrain the X-ray luminosities of Cosmic Dawn galaxies (e.g., Fragos+13), disfavoring the values seen in local, metal-enriched galaxies (e.g., Mineo+12) at > 1σ.

HERA collaboration (2021)

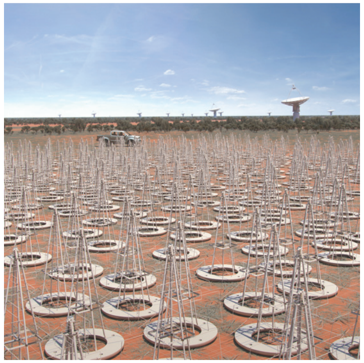
True revolution will come with the Square Kilometer Array (SKA)

- SKA-low, (completion ~2030) will provide a 3D map of the first billion years of our Universe!



single frequency map assuming pessimistic noise and foreground contamination

Prelogovic, AM+ 2021



rendering of SKA1-Low (Australia)

Conclusions

- The first billion years bore witness to the birth of the first structures (stars, black holes, galaxies) and the **last phase change of our Universe**: the epoch of reionization.
- Our observational data from this epoch has been increasing dramatically in recent years. To make **robust** conclusions from this data, we developed a Bayesian inference framework that can **forward-model 3D realizations of our Universe.**
- Current observations from the CMB and the Lyman alpha forest constrain roughly the timing of reionization. The properties of the galaxies responsible remain poorly known.
- With the cosmic 21-cm signal, we will **chart the first billion years of our Universe**, revolutionizing the field. The **properties of unseen sources and sinks** are encoded in the 3D topology and timing of the signal.
- Even preliminary observations using the HERA telescope can constrain viable models, implying that the first galaxies were **more X-ray luminous** than local ones.