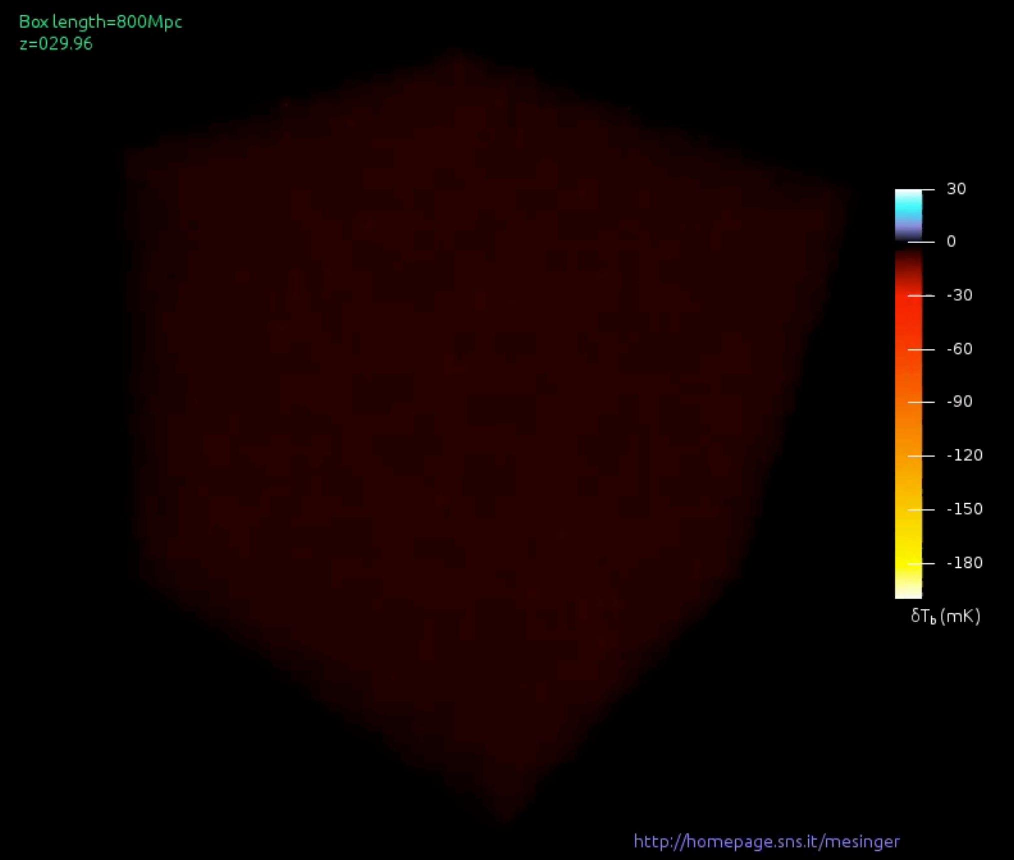
Status and future prospects for studying Reionization and Cosmic Dawn



Andrei Mesinger

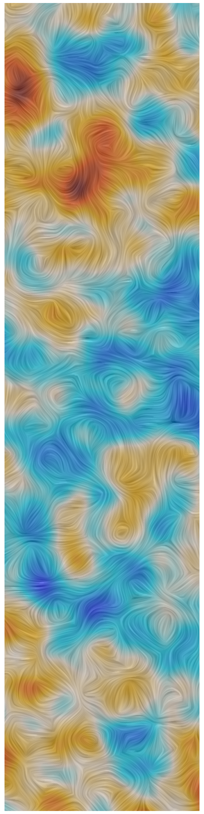
SCUOLA NORMALE SUPERIORE

European Research Council
Established by the European Commission

First billion years - birth of structure and Cosmic Dawn

Image: ESA

CMB



$z \approx 10^3$

$4 \cdot 10^5$

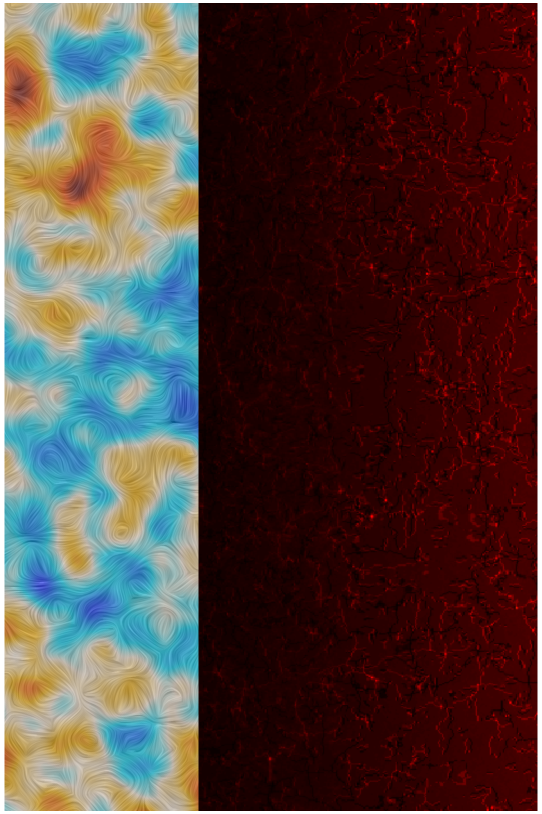
cosmic time [yr]

First billion years - birth of structure and Cosmic Dawn

Image: ESA

AM+2016

CMB **Dark Ages**



$z \approx 10^3$ $z \approx 30$

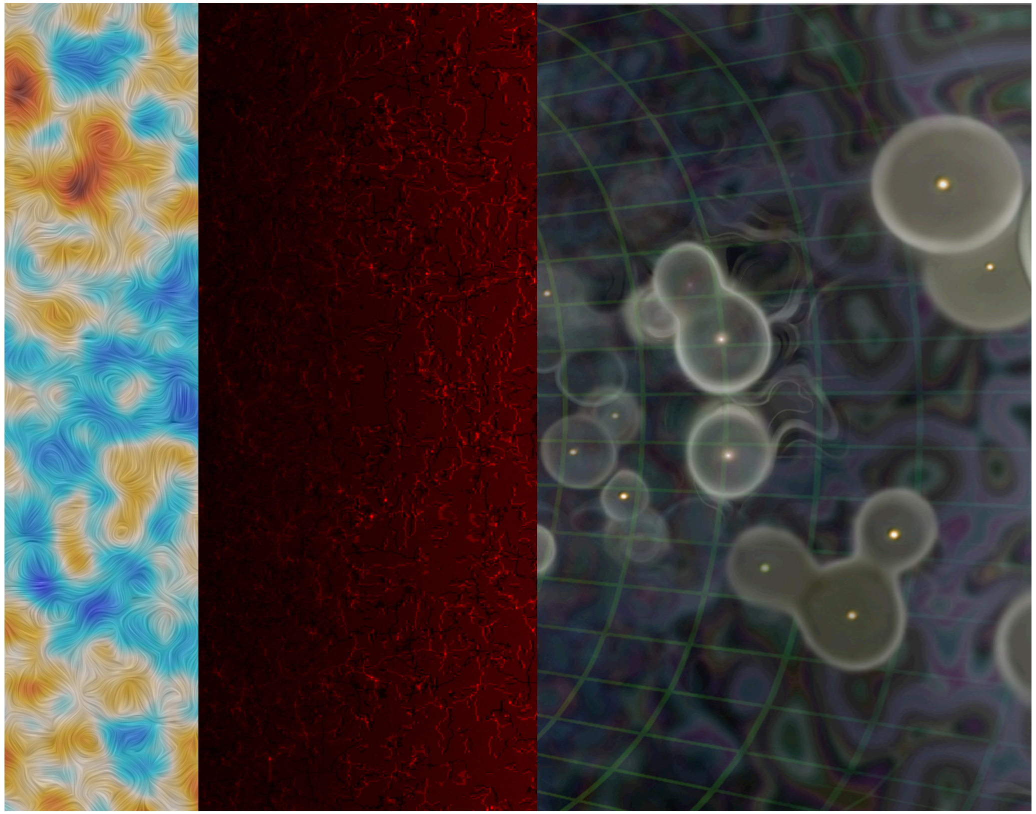
cosmic time [yr]

$4 \cdot 10^5$ 10^8

First billion years - birth of structure and Cosmic Dawn

Image: NASA/
CXC/M.WEISS
AM+2016; J. Munoz

CMB Dark Ages **Cosmic Dawn**



$z \approx 10^3$ $z \approx 30$

cosmic time [yr]

$4 \cdot 10^5$ 10^8

First billion years - birth of structure and Cosmic Dawn

Image: NASA/
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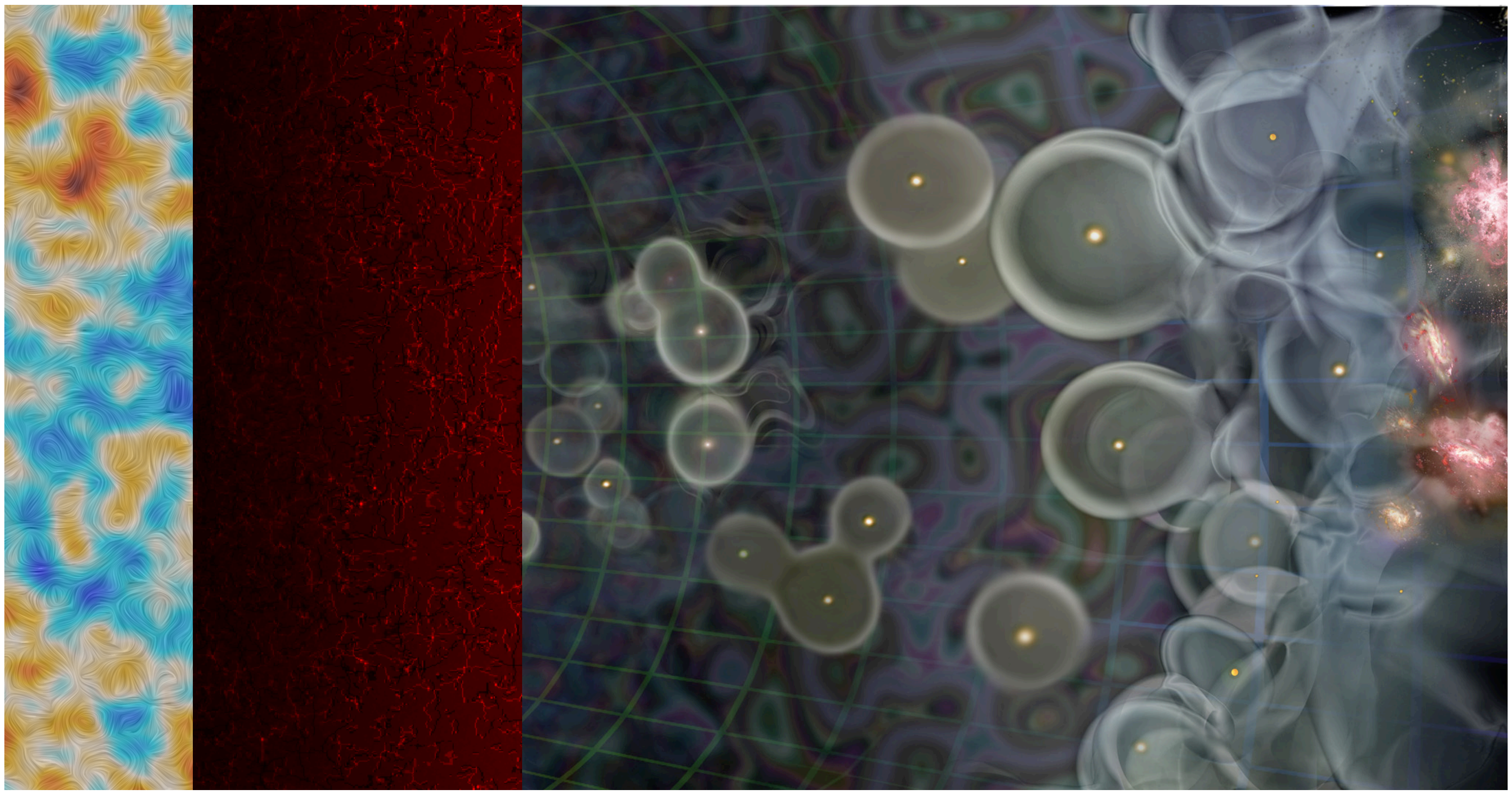


$z \approx 10^3$ $z \approx 30$ $z \approx 5$

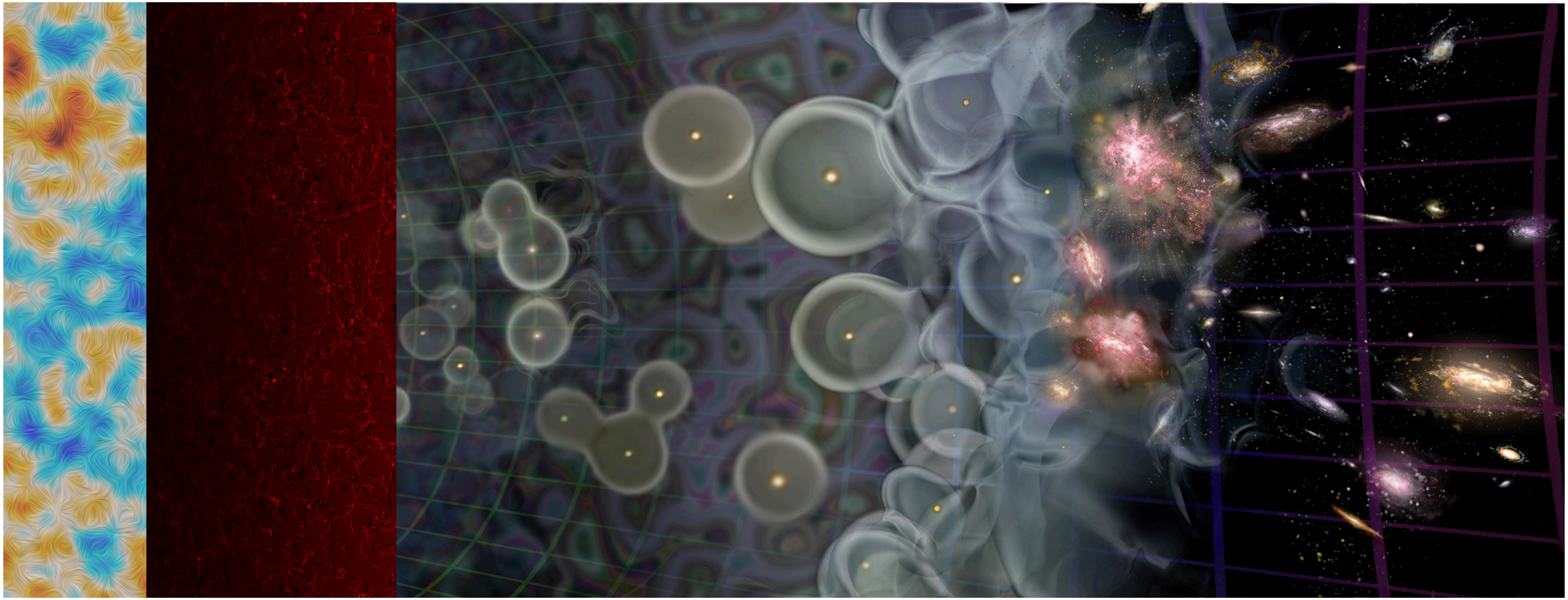
cosmic time [yr]

$4 \cdot 10^5$ 10^8 10^9

First billion years - birth of structure and Cosmic Dawn

Image: NASA/
CXC/M.WEISS
AM+2016; J. Munoz

CMB Dark Ages Cosmic Dawn Reionization **Late Universe**



$z \approx 10^3$ $z \approx 30$ $z \approx 5$ $z = 0$

cosmic time [yr]

$4 \cdot 10^5$ 10^8 10^9 10^{10}

What do we know **now** about the IGM and galaxies during the first billion years?

Observations of the Epoch of Reionization

- We have constraints from:
  1. Lyα + Lyβ forest dark fraction
  2. Lyα forest opacity distributions
  3. QSO damping wings
  4. Redshift evolution of Lyα EW
  5. Redshift evolution of LAE
  6. Clustering of LAEs
  7. CMB primary anisotropies (τ_e)
  8. CMB secondary anisotropies (kinetic SZ)

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Probes IGM through Lyman alpha scattering

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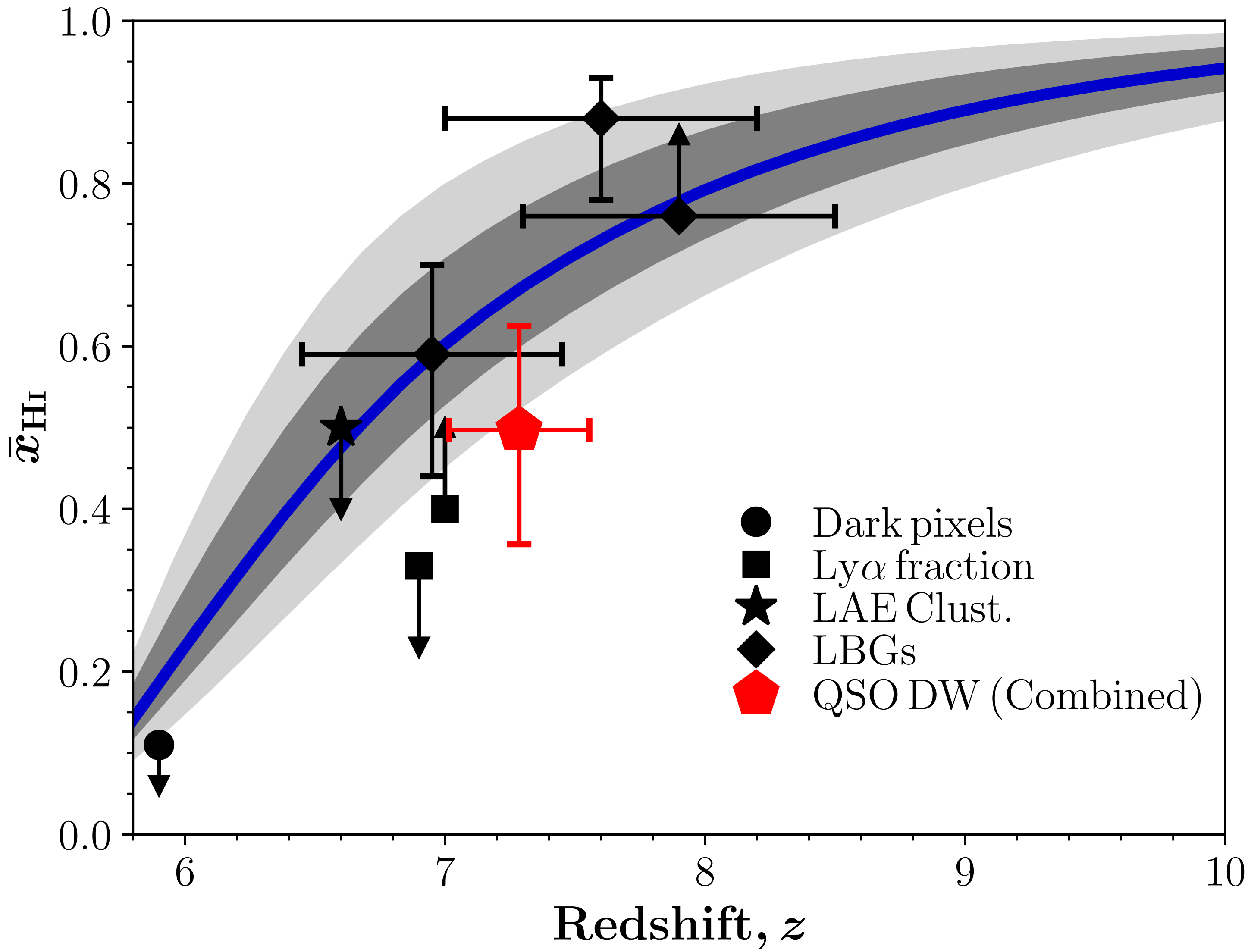
  7. ***CMB primary anisotropies (τ_e)***
  8. ***CMB secondary anisotropies (kinetic SZ)***

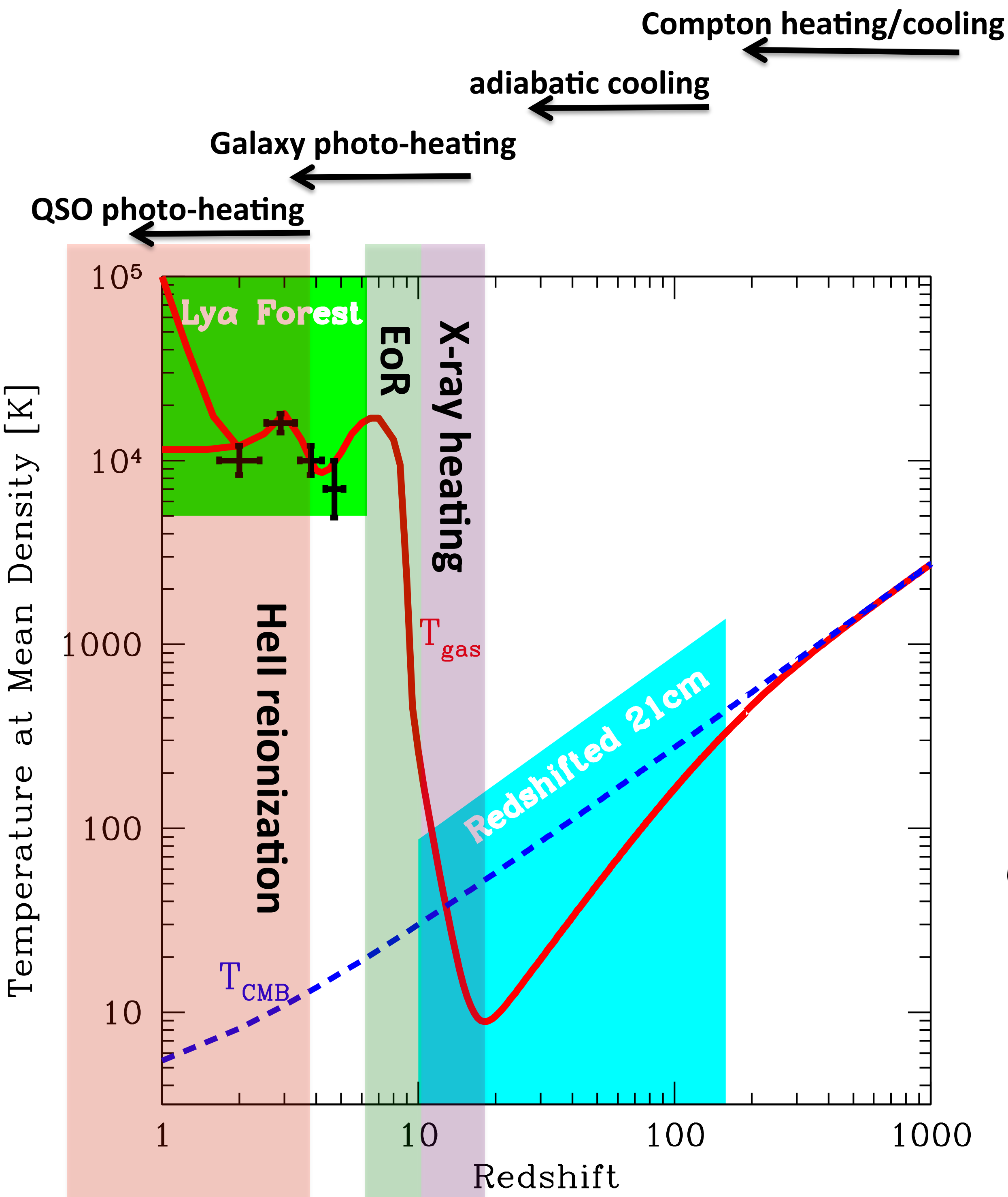
Probes IGM through Compton scattering

Understanding the timing of reionization



Greig, AM+ 2021

*We now have a reasonable handle on when the **bulk** of reionization happened…*

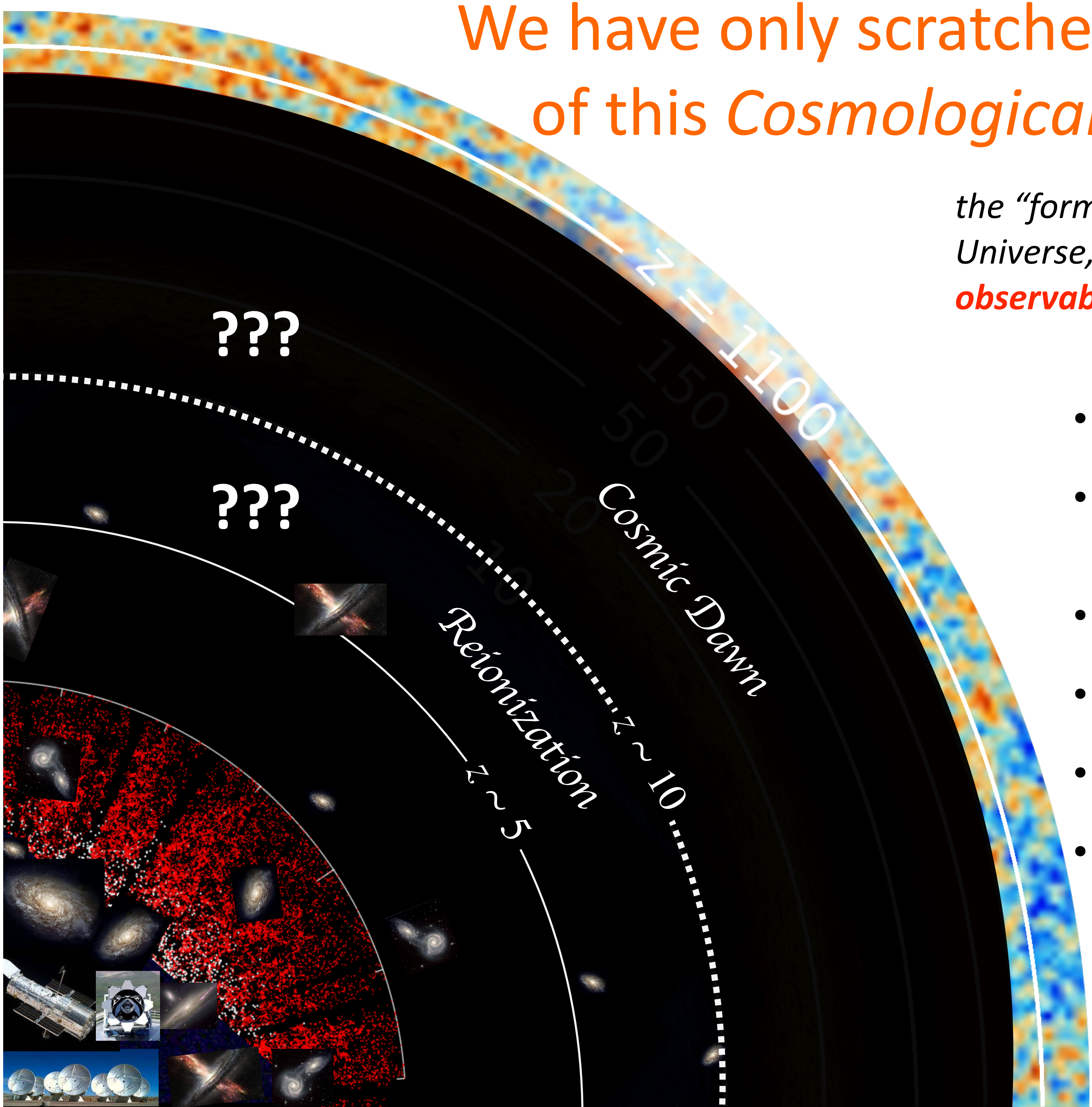


What about the heating history?

Only constrained at z<5….

adapted from McQuinn (2016)

We have only scratched the surface of this *Cosmological Frontier*…

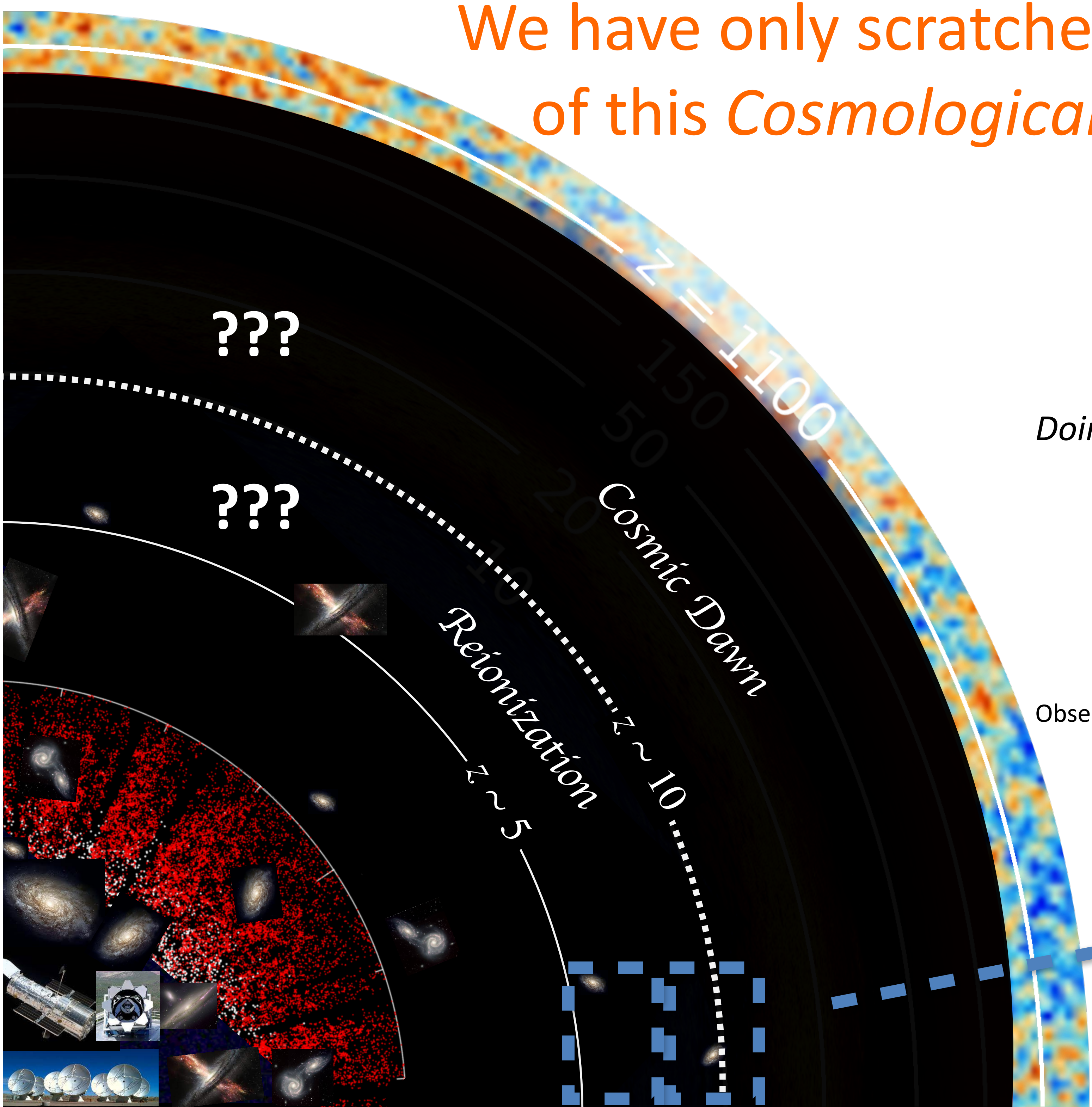


the "formative childhood" of the Universe, yet the ***majority of the observable volume***

- When and how did the first galaxies form?
- How did they impact each other and their surroundings?
- What are the dominant feedback mechanisms?
- Can we learn about Dark Matter properties?
- How does the Hubble parameter evolve?
- What are the properties of the first stars and black holes?

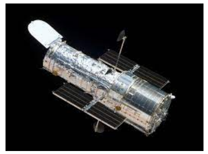
adapted from C. Chiang

We have only scratched the surface of this *Cosmological Frontier*...



Doing a galaxy census....

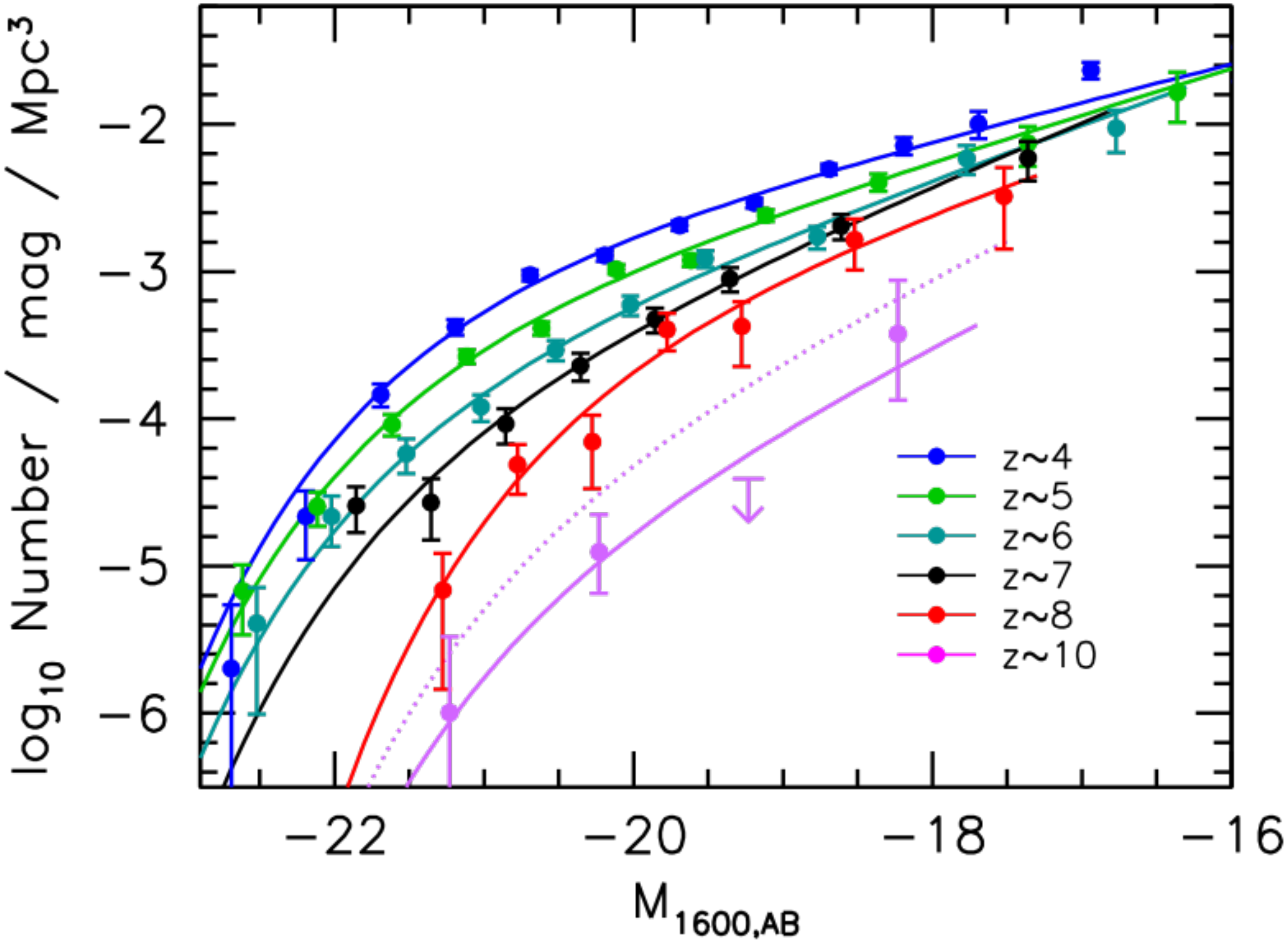
Observe with Hubble and count galaxies



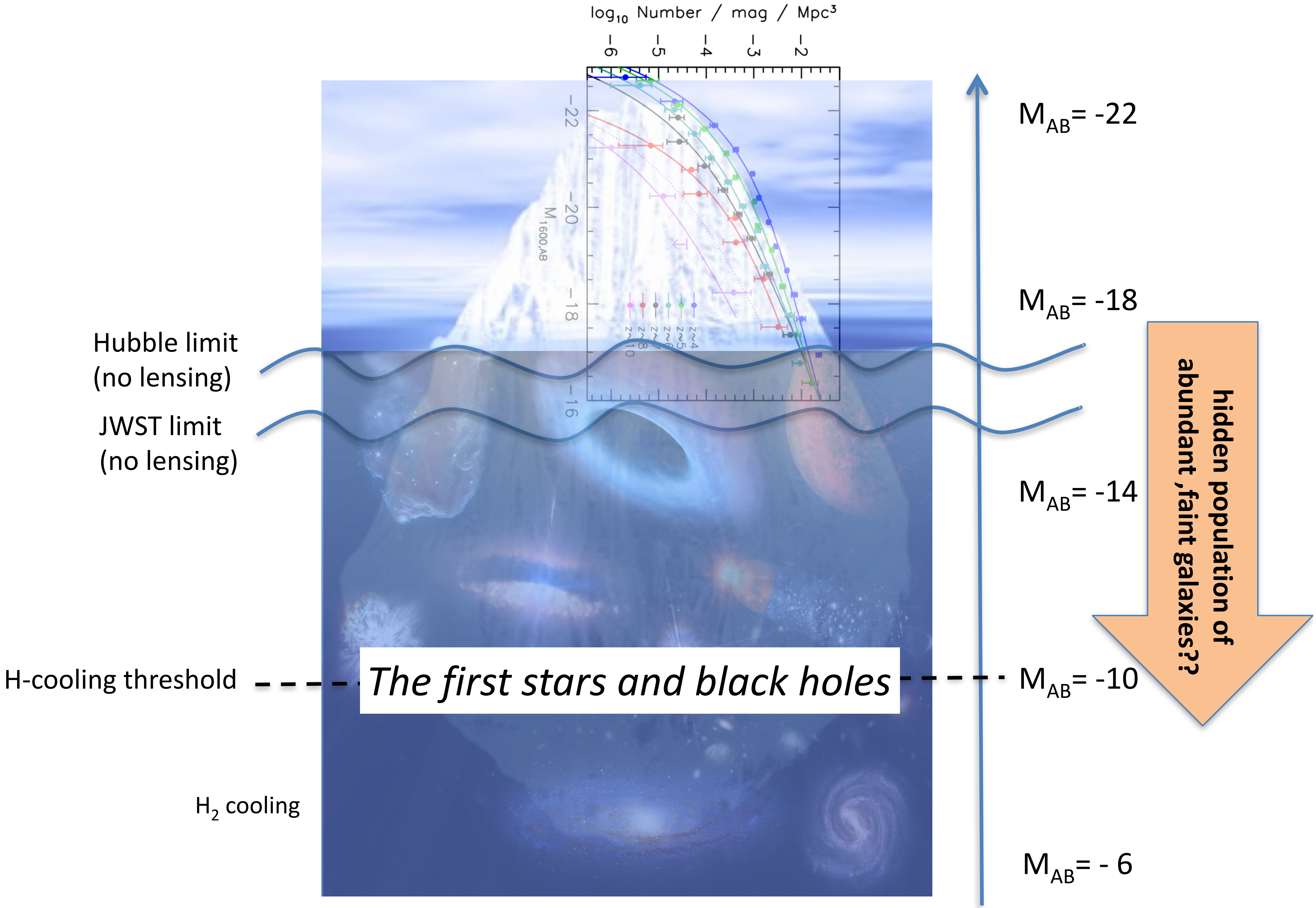
adapted from C. Chiang

Galaxies during the first billion years

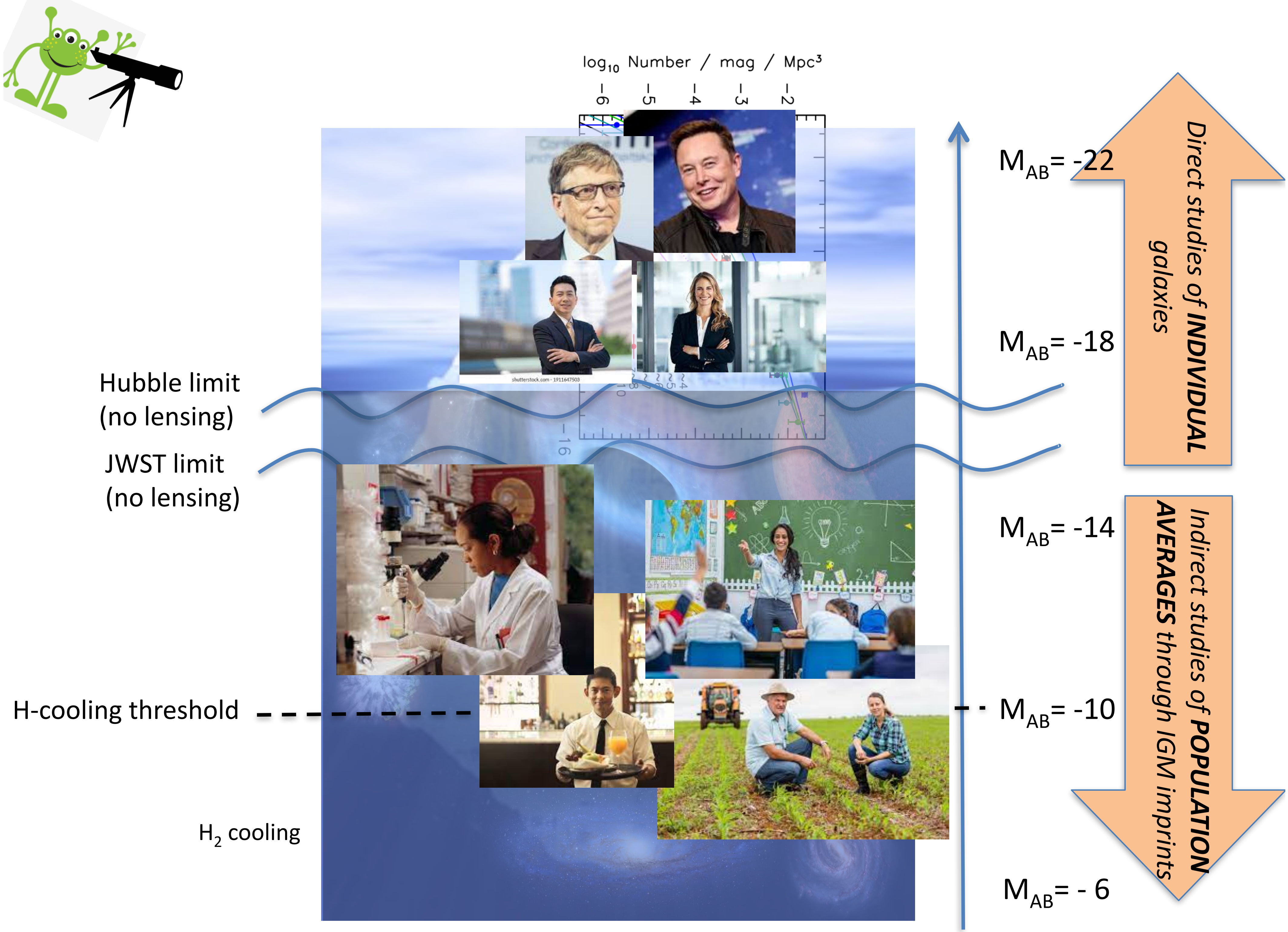
- Telescopes like Hubble and ALMA have enabled detailed studies of *the brightest galaxies*



Bouwens+ (2015)



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


log10 Number / mag / Mpc3
-6
-5
-4
-3
-2
-16
Hubble limit (no lensing)
JWST limit (no lensing)
H-cooling threshold
H2 cooling
MAB= -22
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Direct studies of INDIVIDUAL galaxies
Indirect studies of POPULATION AVERAGES through IGM imprints

Routes towards progress

- JWST + ALMA will improve our understanding of ISM physics in the brightest galaxies at z<~15
- Probes of the IGM during the Epoch of Reionization (EoR) will continue nailing down the mean ionization history of the IGM at z<10
- The cosmic 21-cm signal will constrain the IGM ionization and temperature evolution throughout the Cosmic Dawn (**5<z<30**) as well as the *average* UV and X-ray properties of the the first galaxies

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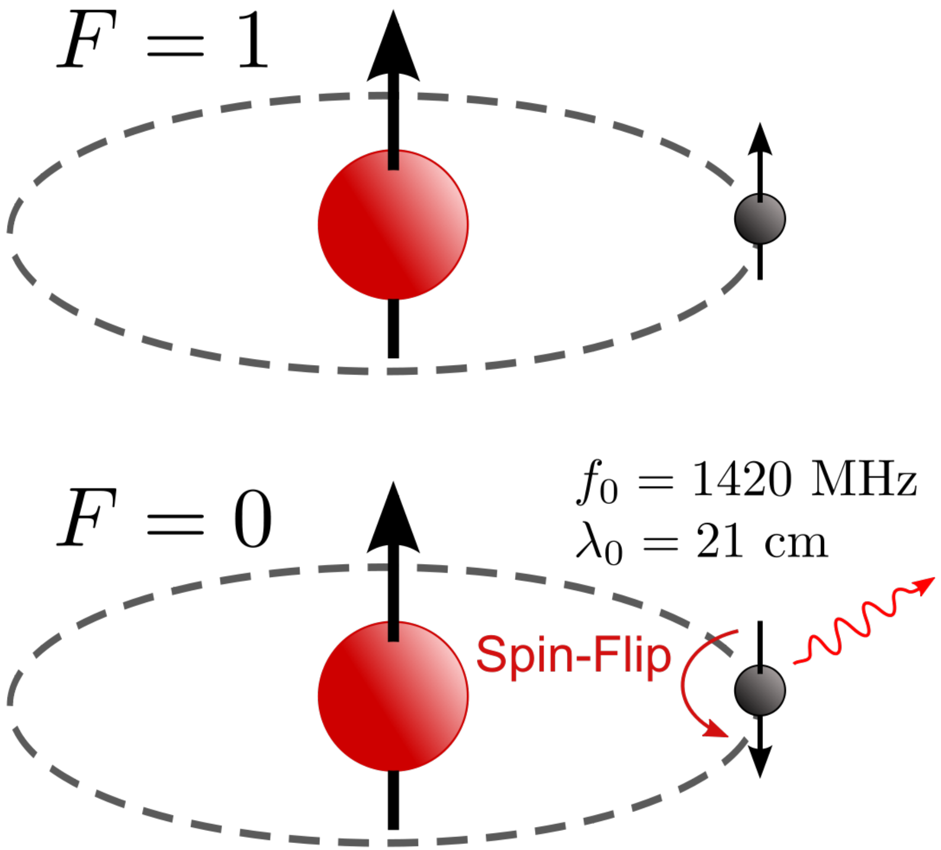
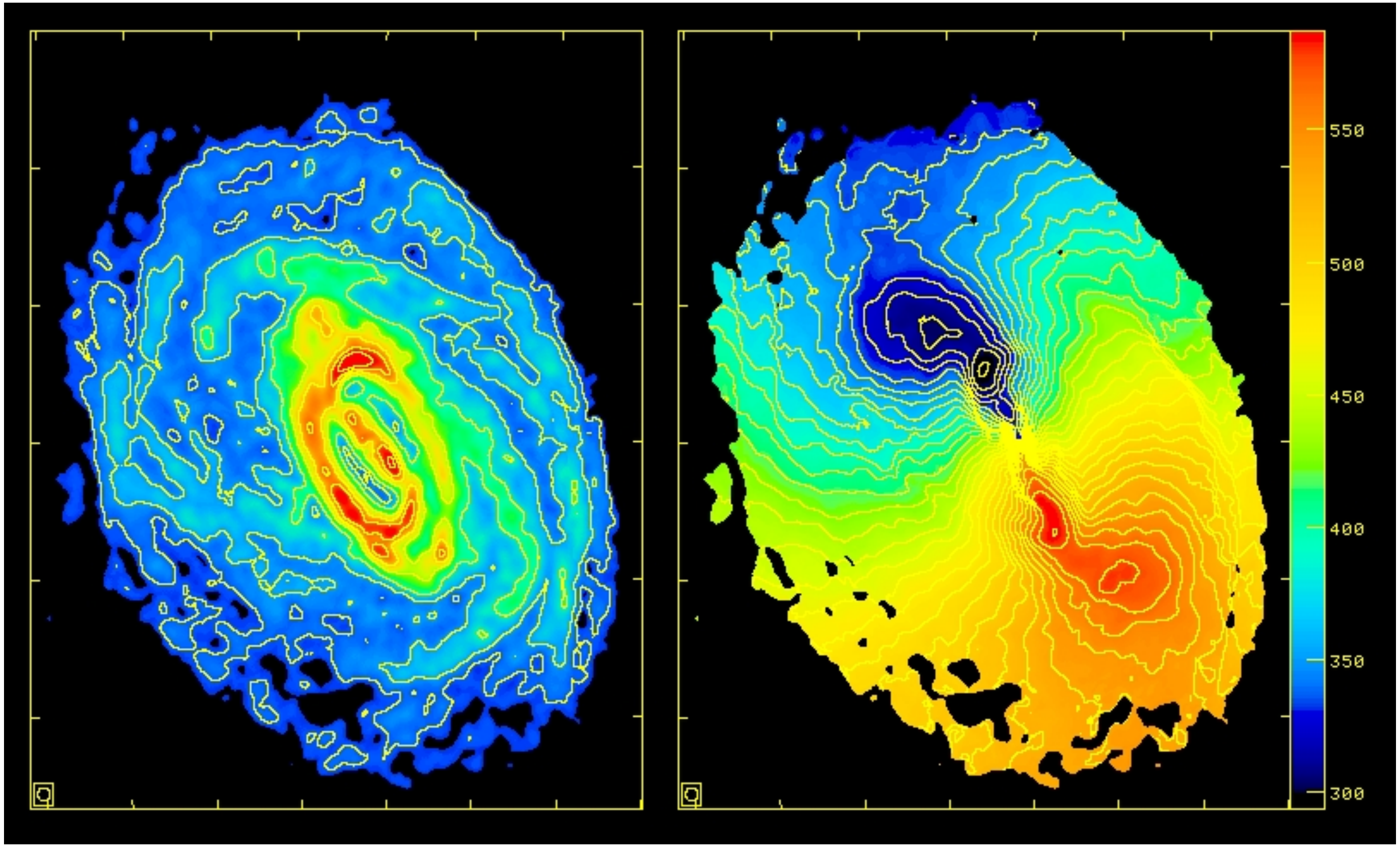
21 cm line from neutral hydrogen



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

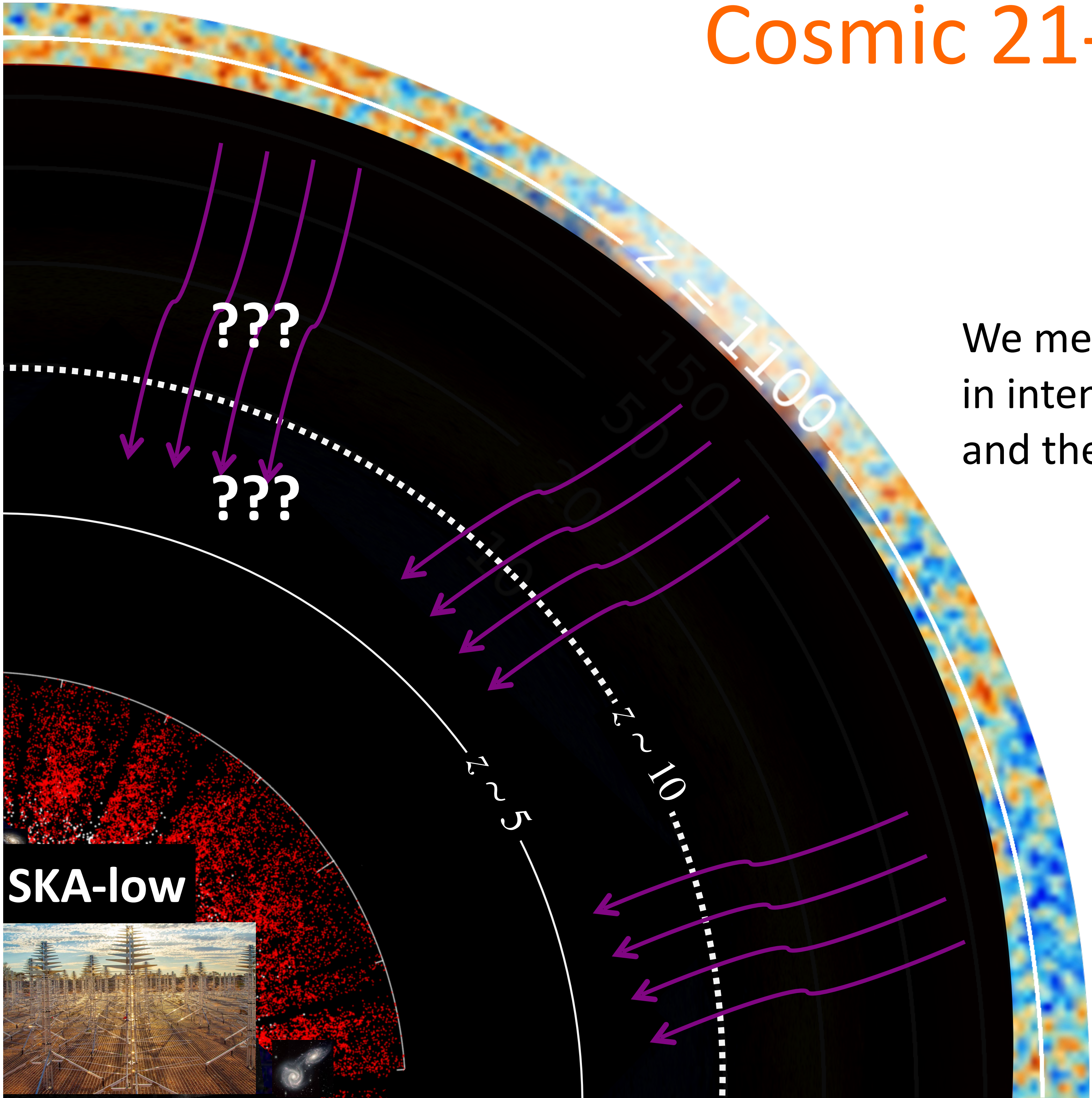
ATCA HI image by B. Koribalski (ATNF, CSIRO), K. Jones, M. Elmouttie (University of Queensland) and R. Haynes (ATNF, CSIRO).

Cosmic 21-cm

We measure the difference in intensities of the CMB and the cosmic HI.

adapted from C. Chiang

Cosmic 21-cm



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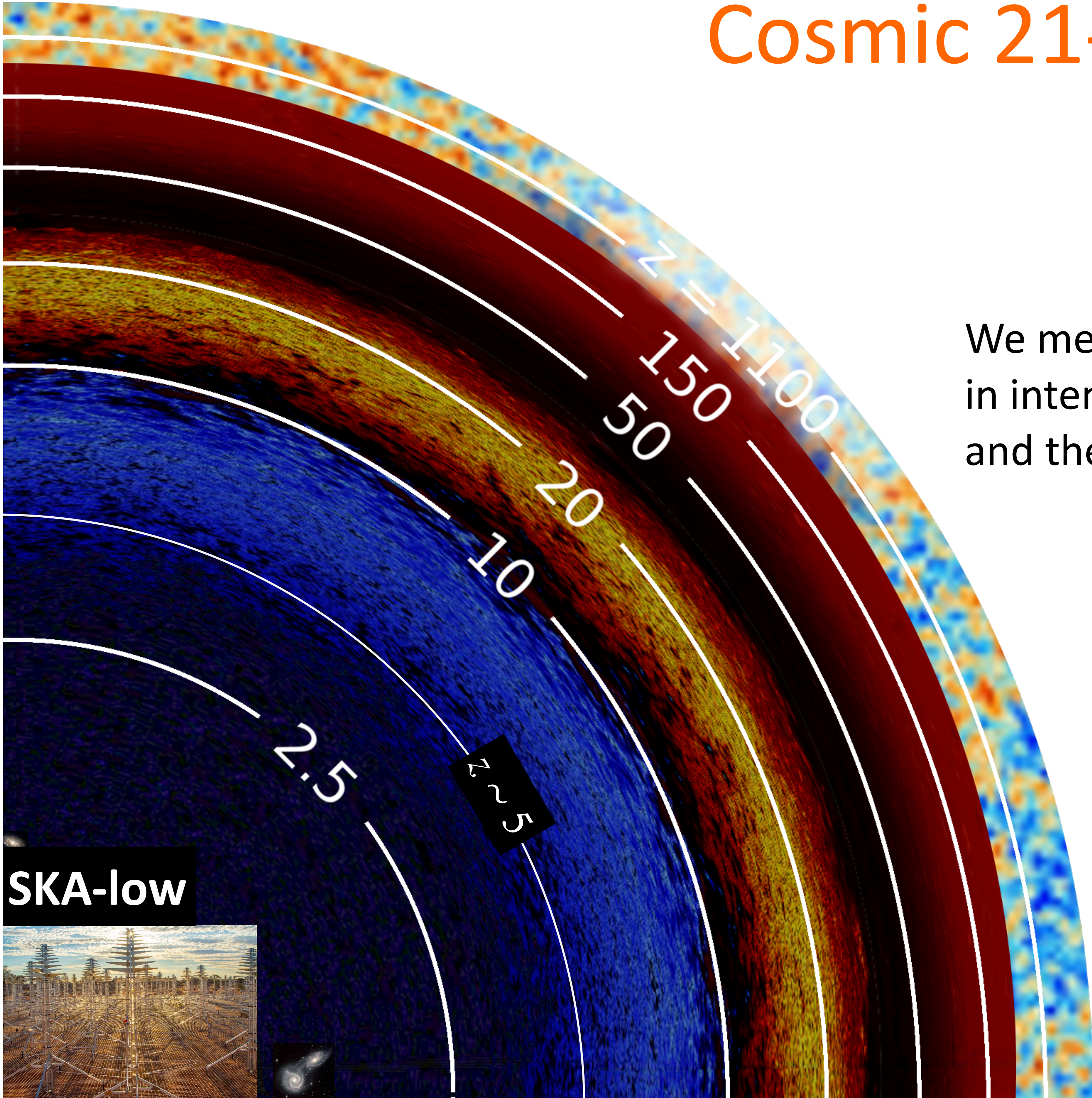

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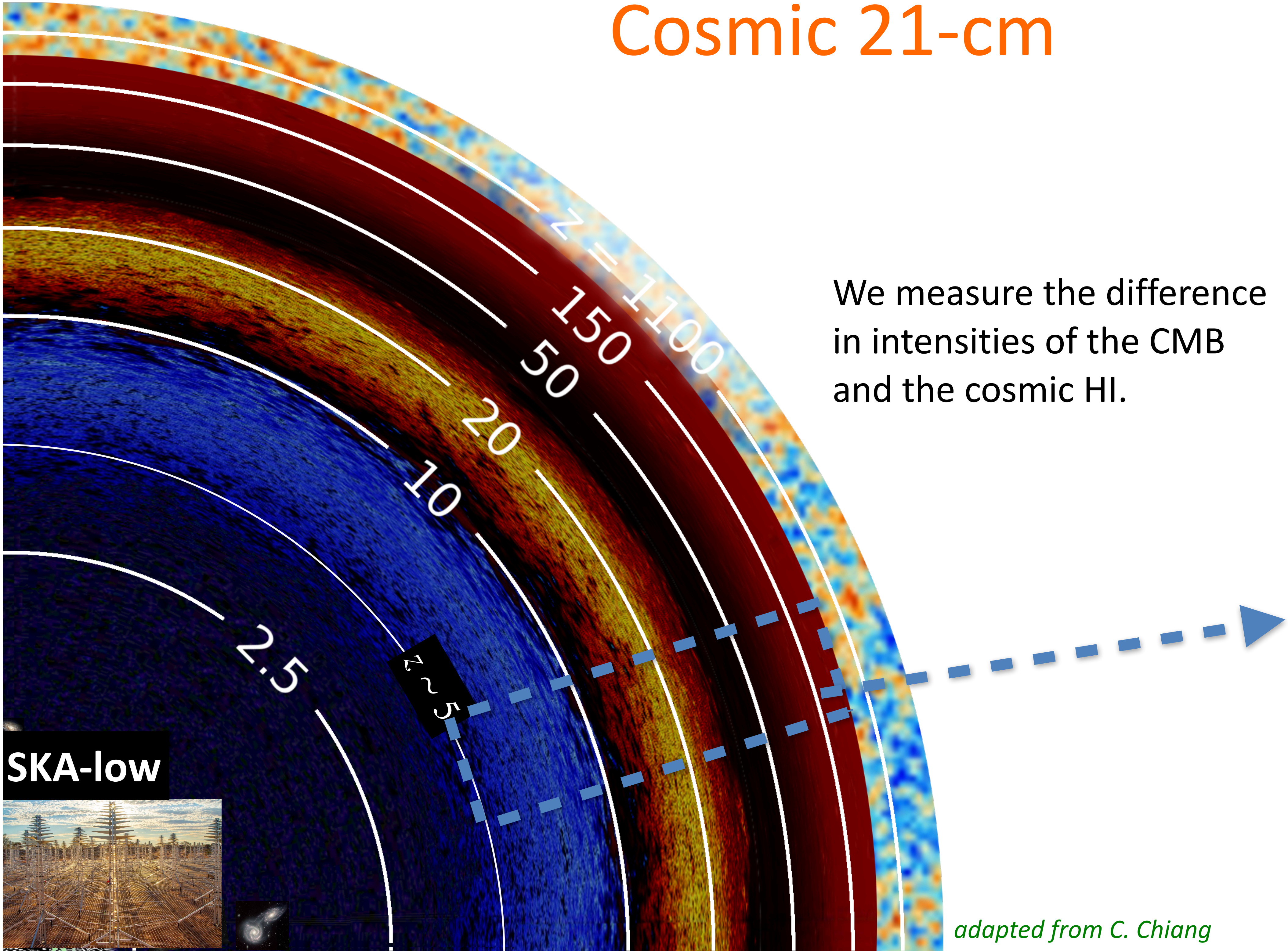
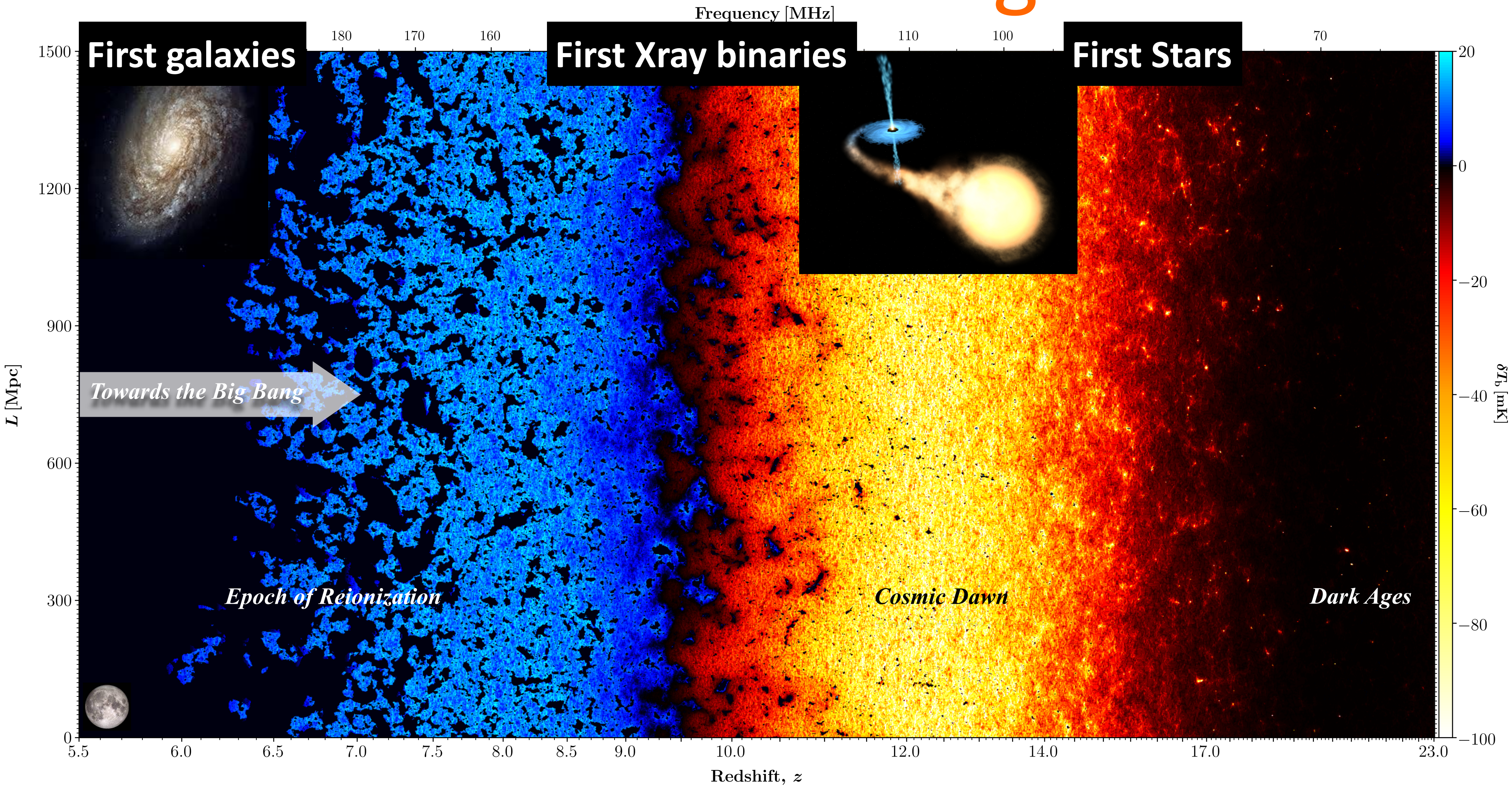


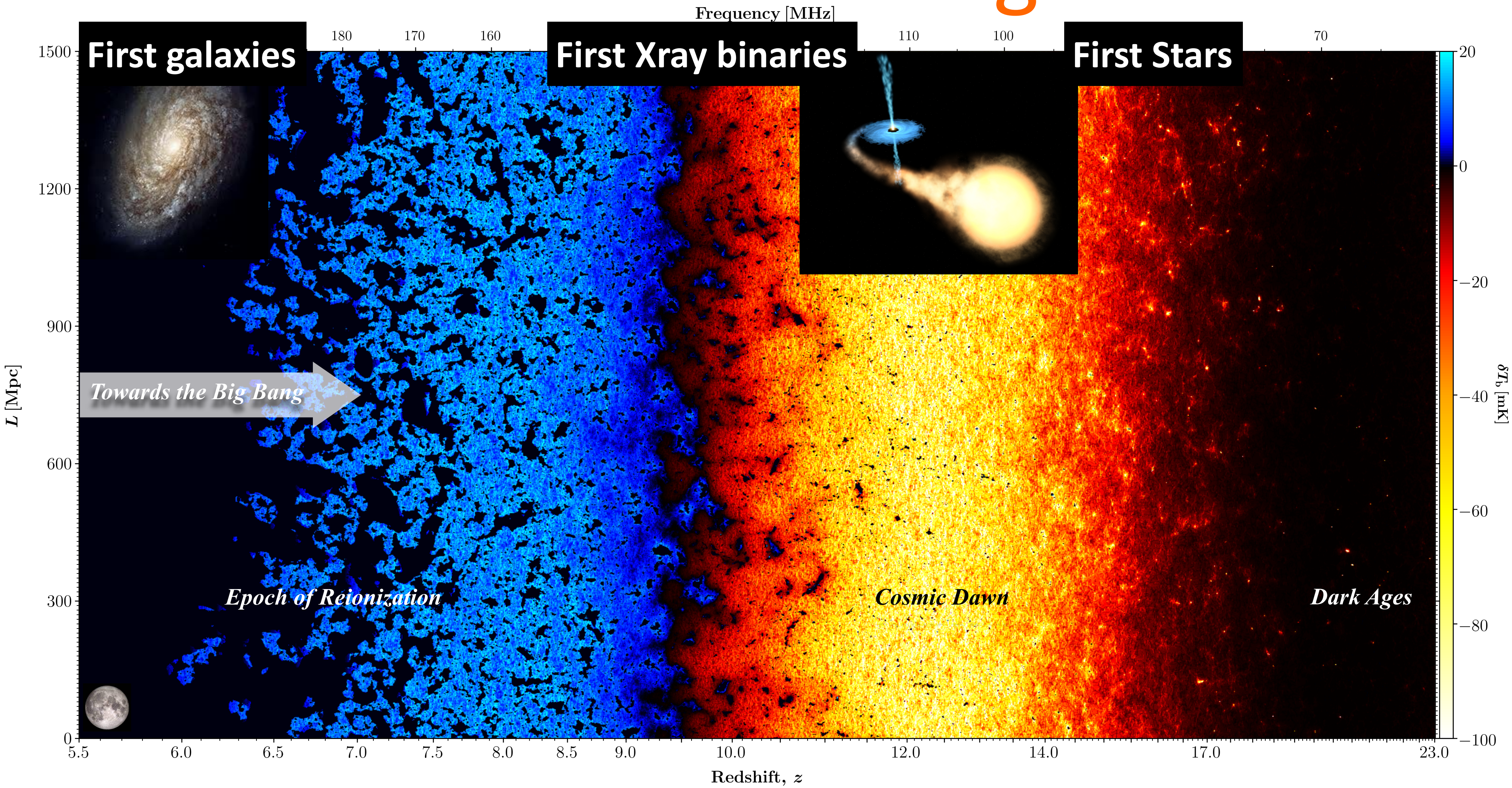
adapted from C. Chiang

Cosmic 21-cm signal



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

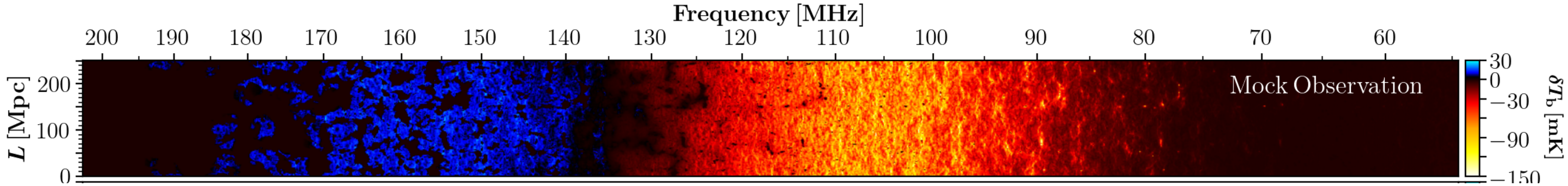
Cosmic 21-cm signal



- **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**! —> **BIG DATA REVOLUTION**!
- even the narrowest fields will contain >billion of unseen galaxies
- the timing and the patterns of the signal tell us about both **Astrophysics** and **Cosmology**

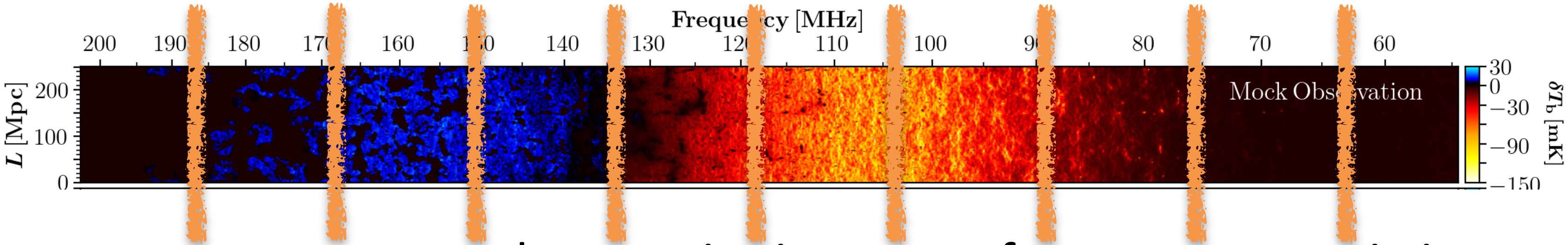
How do we take advantage of this Big Data revolution?

We forward model the first billion years



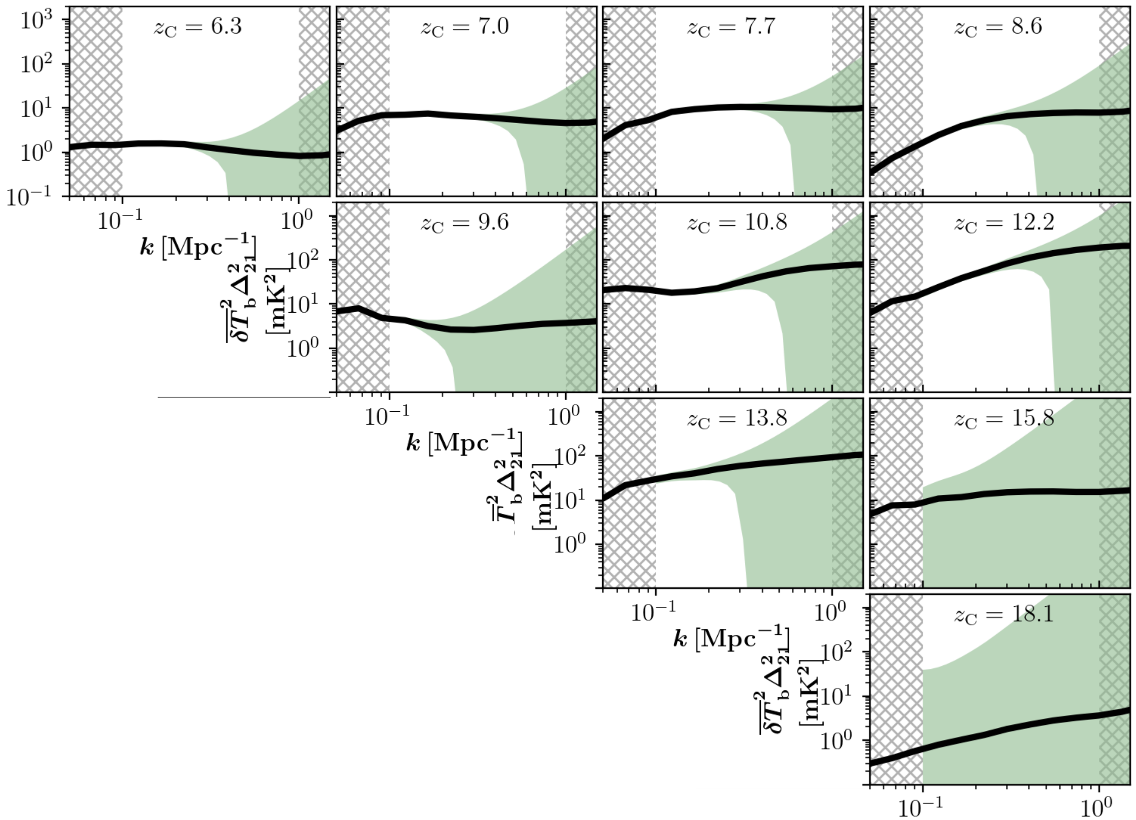
“observation”

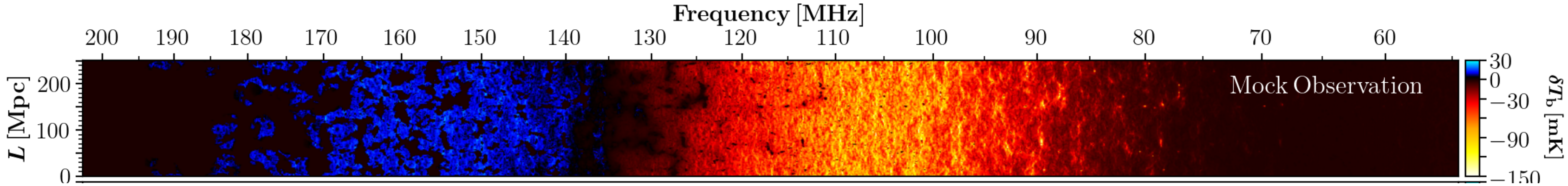
21cm **3D!!!** map



“observation”

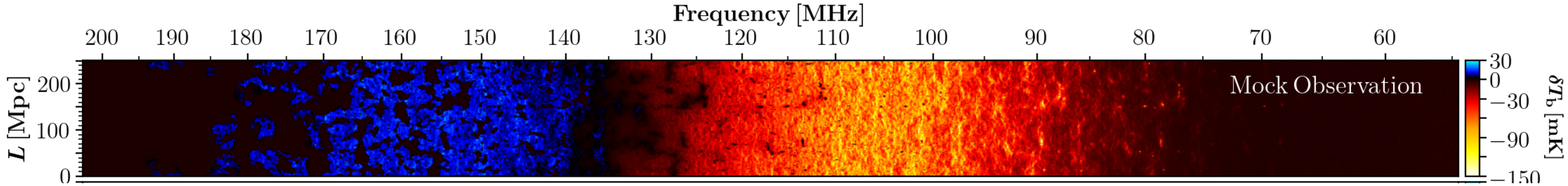
characterize in terms of a summary statistic:
power spectra with 1000h noise from HERA and moderate foreground contamination





(1) 21-cm

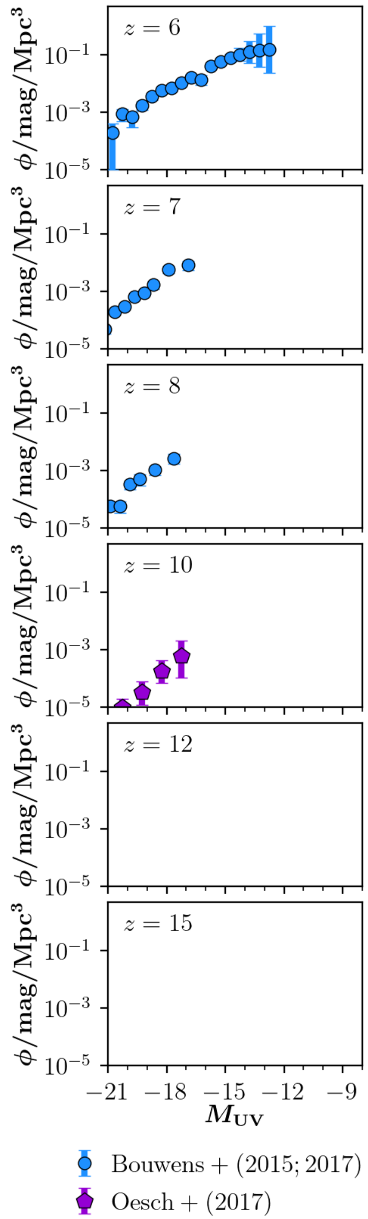
combine with other observations
in order to compute
likelihood



(1) 21-cm

+

(2) high-z galaxy LFs



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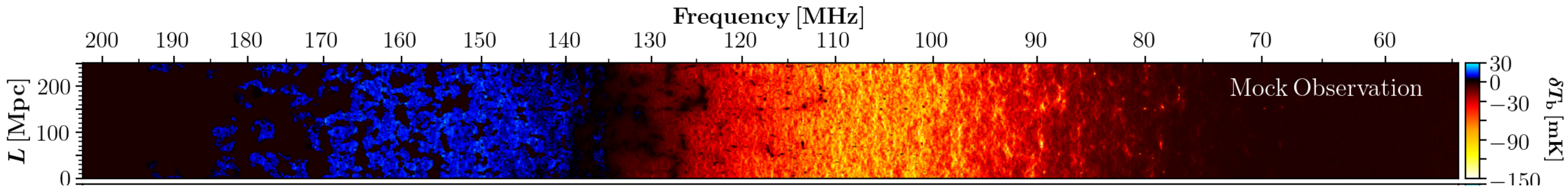

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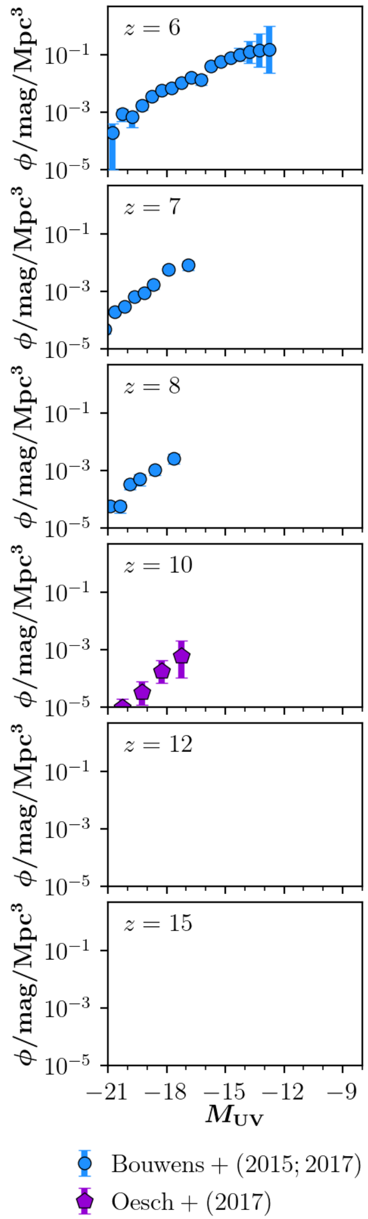
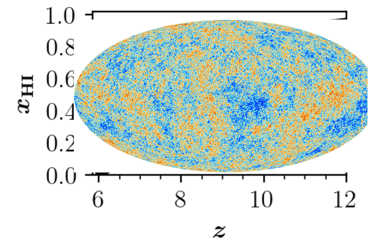


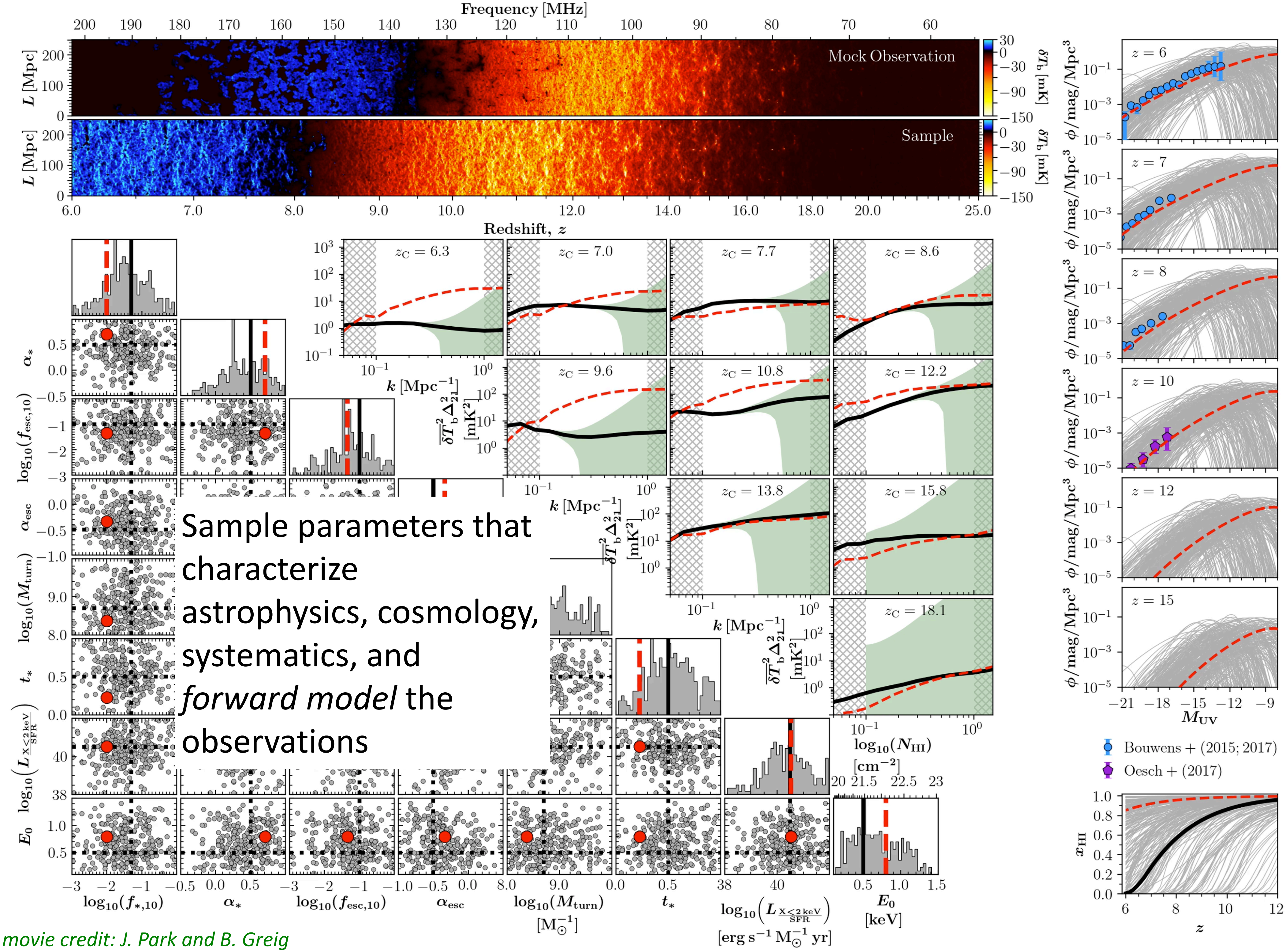
+

combine with other observations
in order to compute
likelihood

+

(3)
CMB τ_e



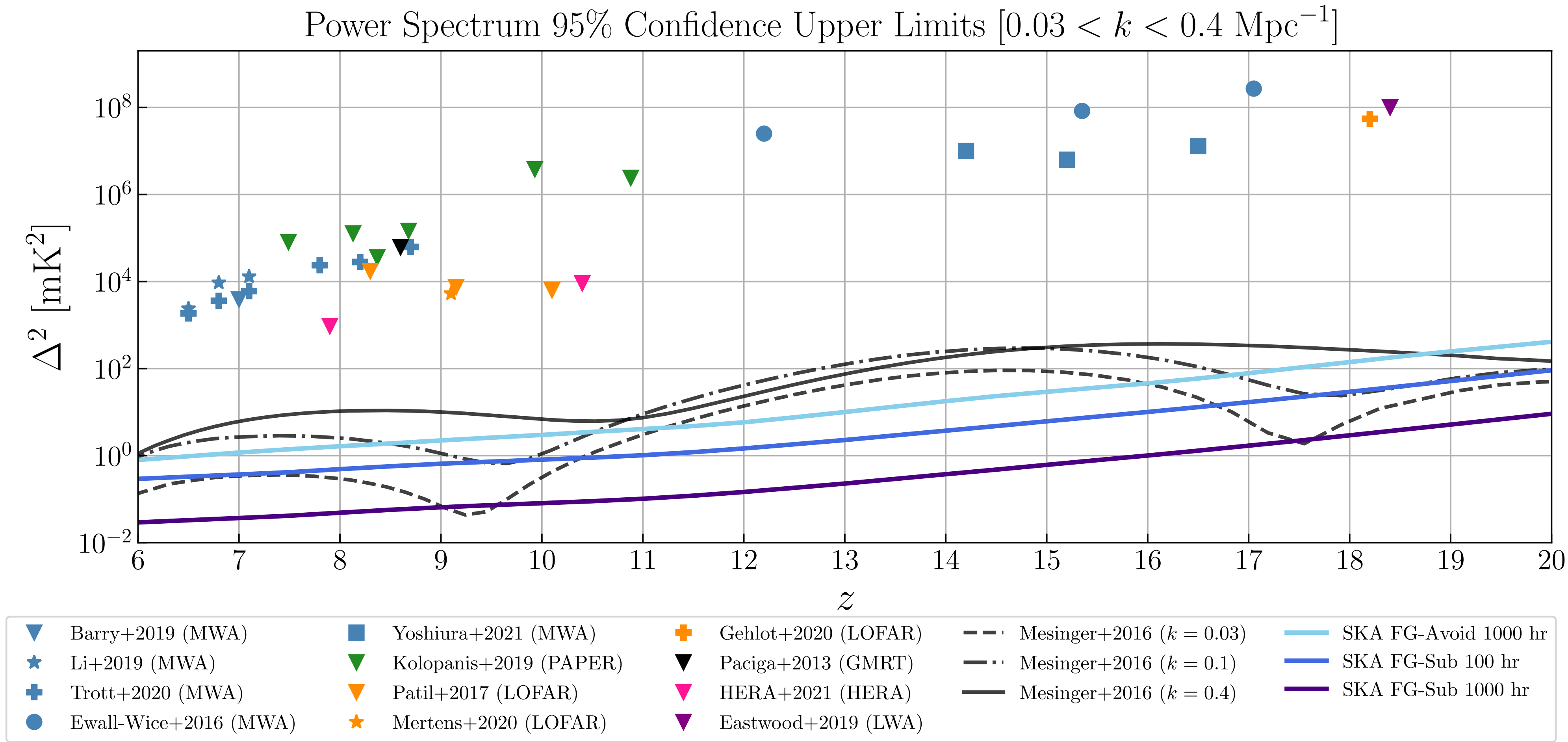


Sample parameters that characterize astrophysics, cosmology, systematics, and *forward model* the observations

movie credit: J. Park and B. Greig

SKA will be revolutionary, but we actually have data (upper limits) NOW

Currently only upper limits on the PS



Barry+ 2022

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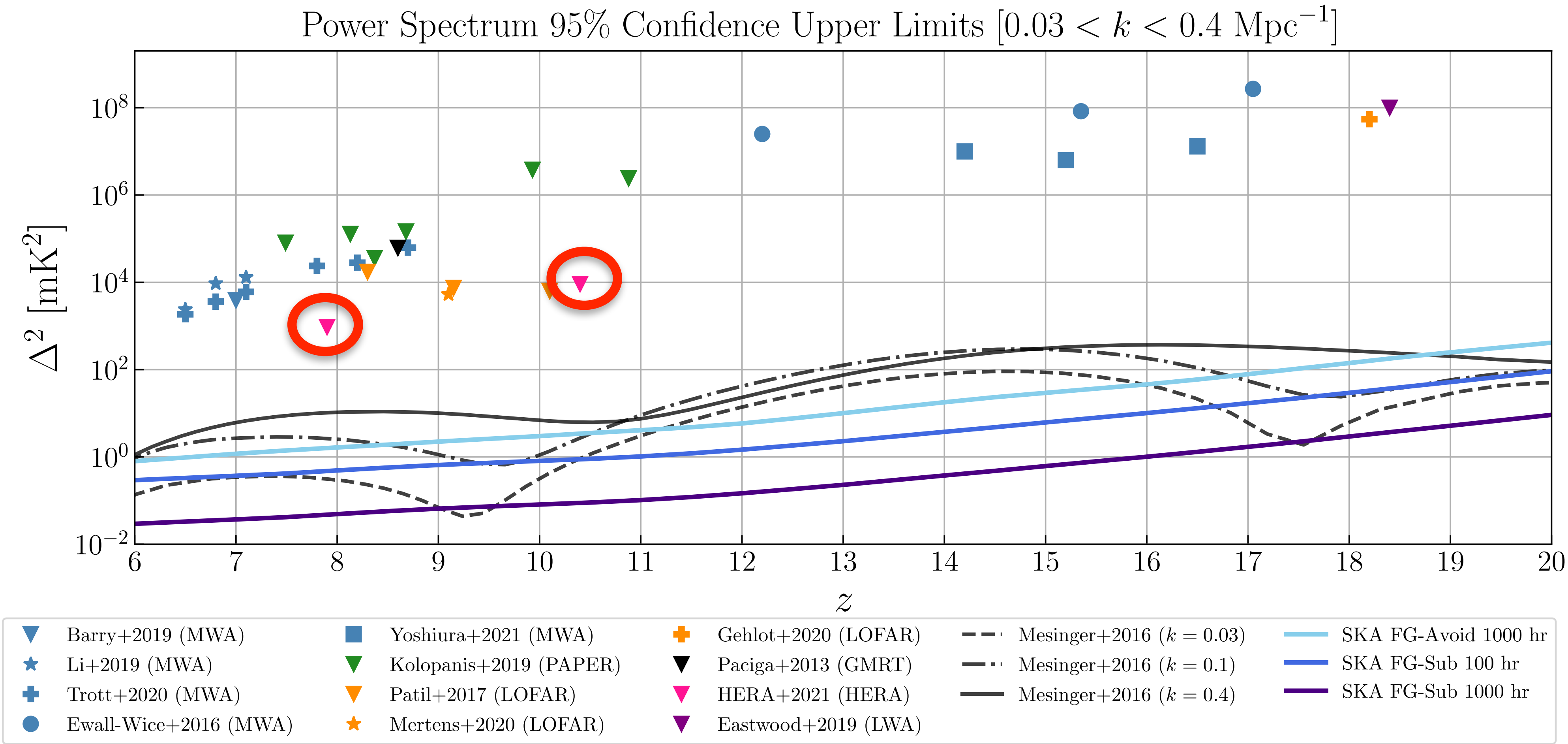
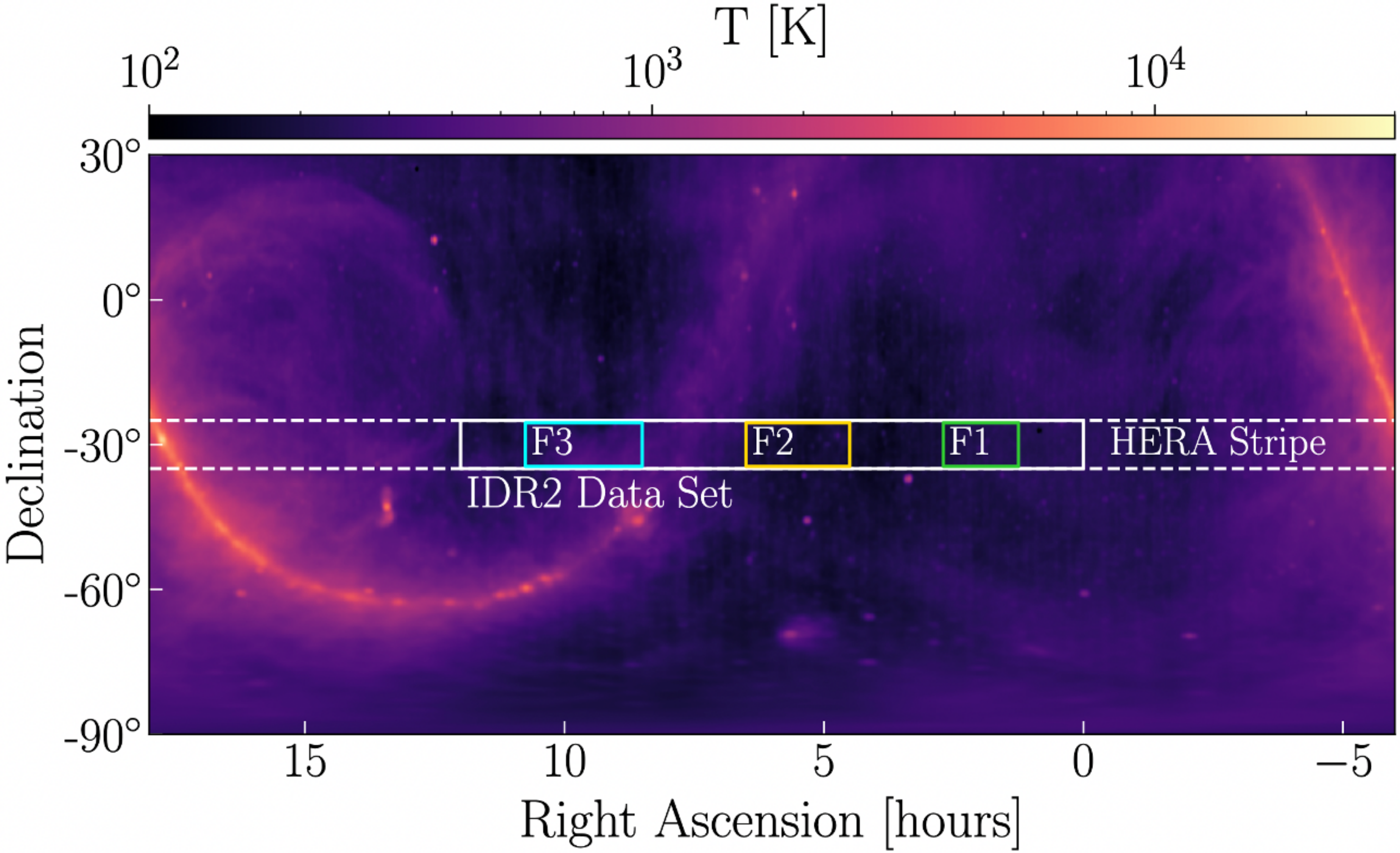


Barry+ 2022

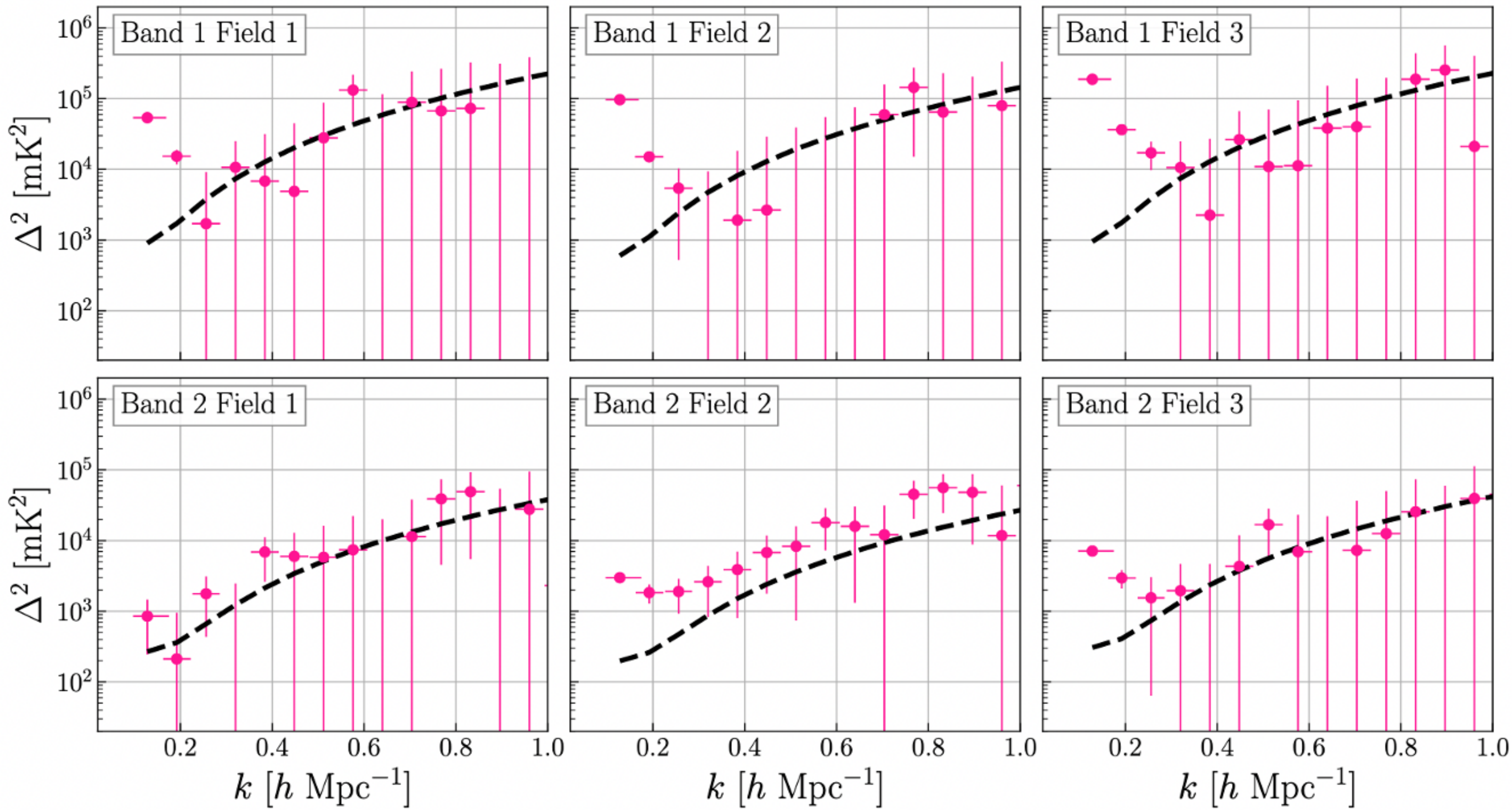
Recent results from HERA

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



HERA collaboration (2021)

Interpreting recent results from HERA



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

HERA collaboration (2021)

What kind of models are the easiest to rule out (i.e. have the largest power)?

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

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~ 0 — 1

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~ 0.1 — 1

What kind of models are the easiest to rule out (i.e. have the largest power)?

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~ **-10(!)** — 1

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Models that are ruled out must have:

COLD IGM: $T_S \ll T_\gamma$

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+

Spatial fluctuations *in either:*

- *ionization fraction (patchy EoR)*

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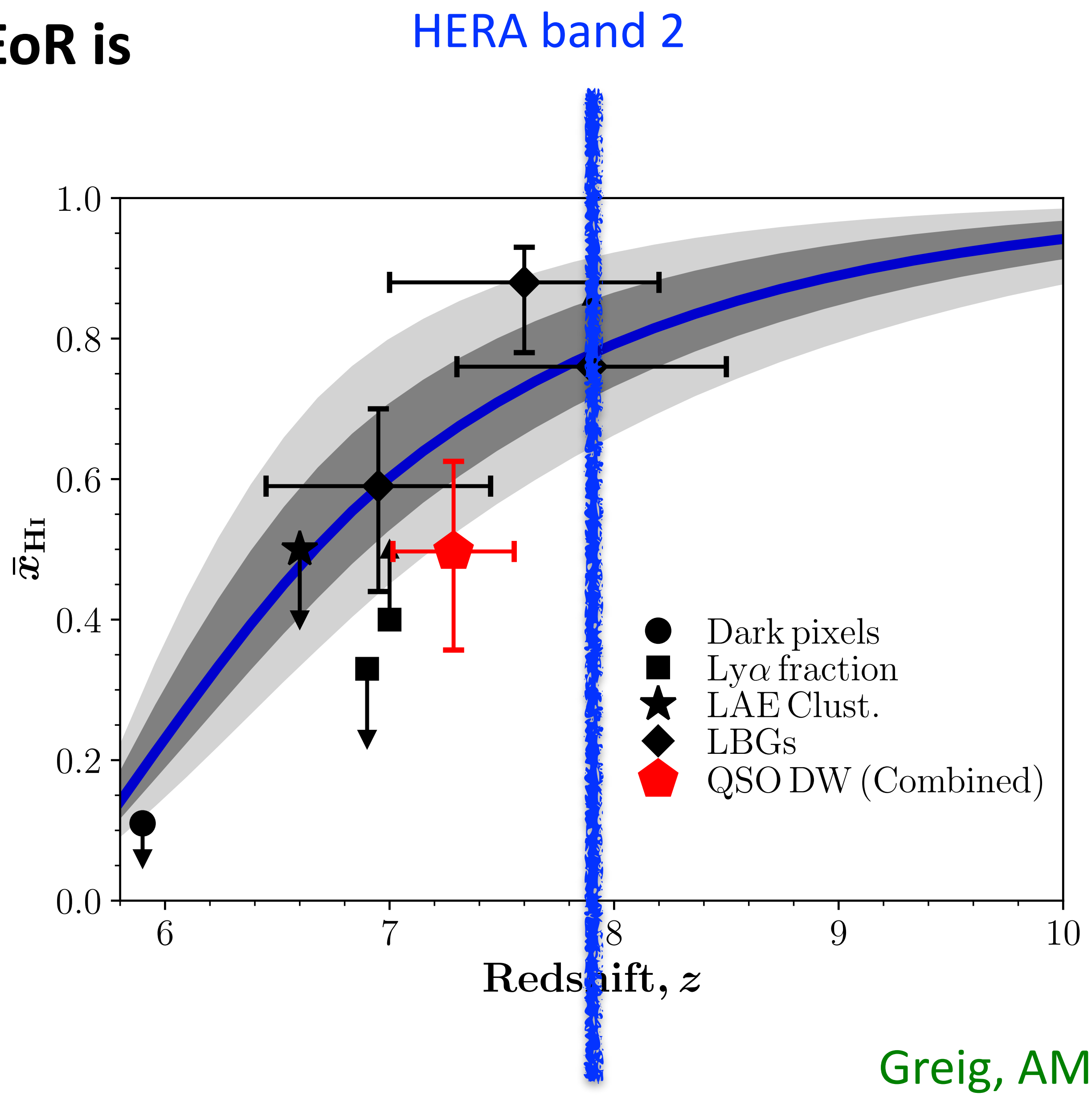
Spatial fluctuations *in either:*

- ***ionization fraction (patchy EoR)***
- ***matter density***
- *temperature (requires "unrealistically" soft SEDs)*

see also e.g. Ewall-Wice+2013; Ghara+2020; Greig+2020; Mondal+2020; Reis+2020; Greig+2021

Current constraints on EoR history

BUT we know the EoR is underway at z~8!



Greig, AM+2021

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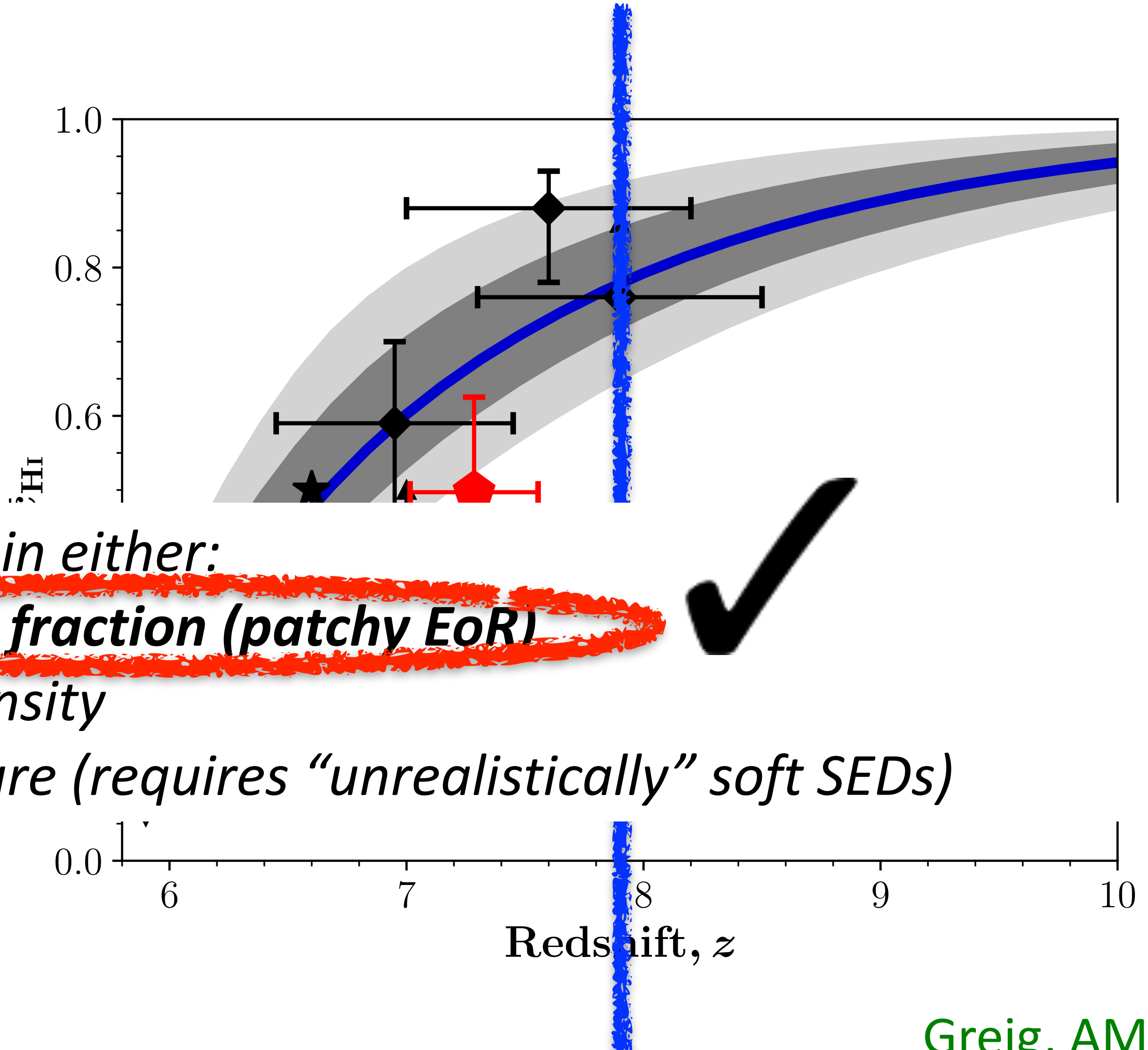
HERA band 2



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+

Spatial fluctuations *in either:*

- ***ionization fraction (patchy EoR)*** ✓
- *matter density*
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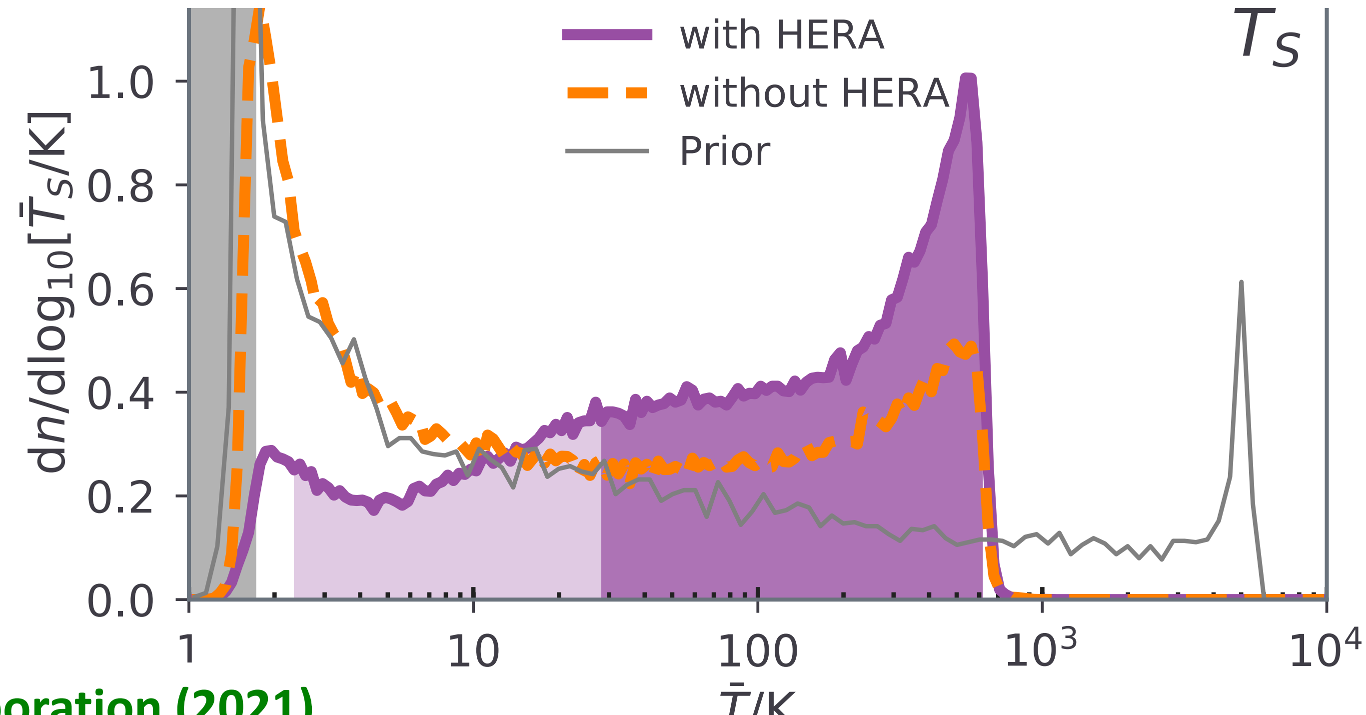
Greig, AM+2021

Constraints on IGM properties

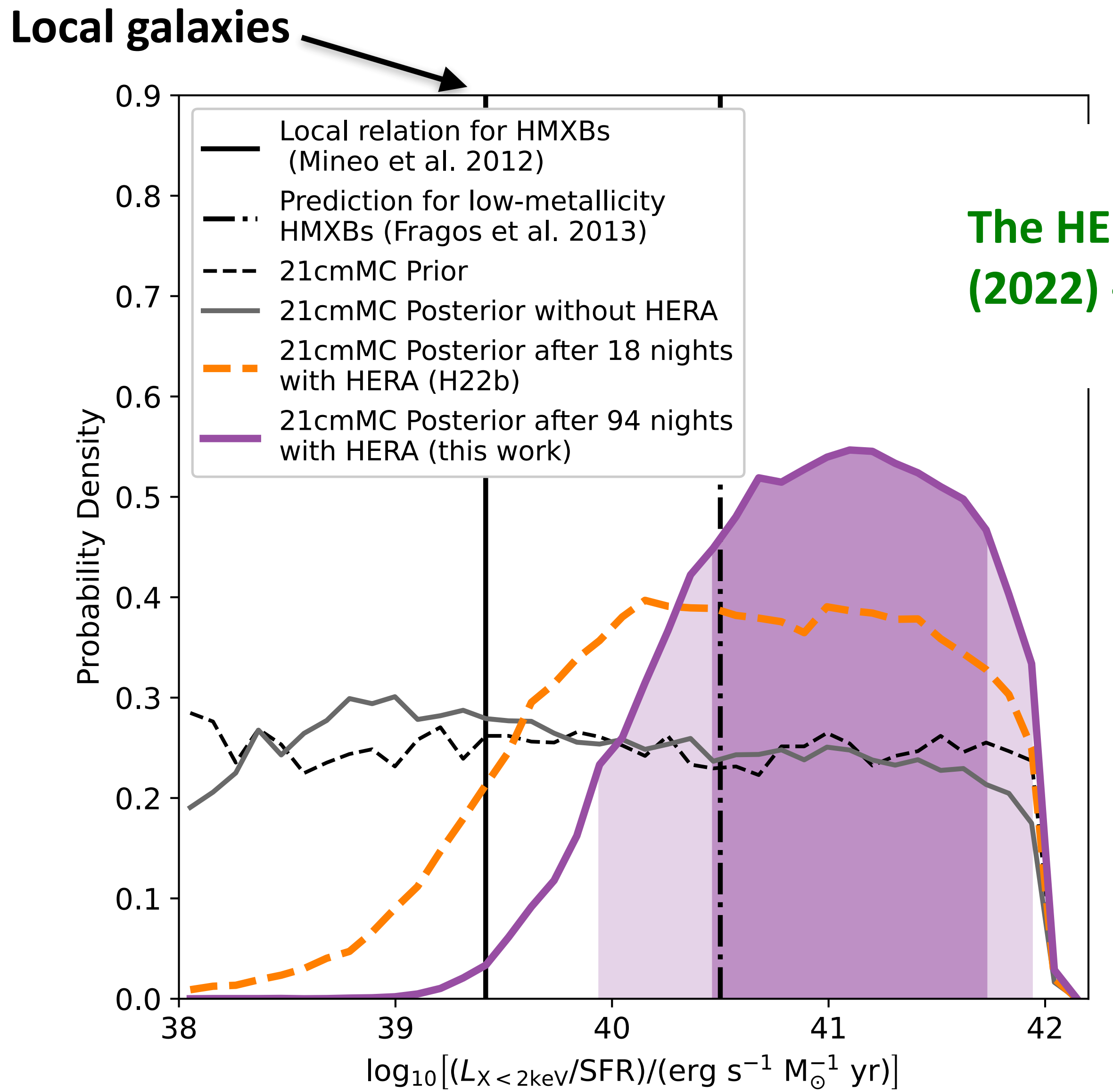
Cold IGM disfavored by HERA



The HERA collaboration (2021)

led by Y. Qin

Assuming heating is dominated by galaxies, we can constraint the X-ray luminosity per unit SFR



The HERA collaboration (2022) - 94 nights of data

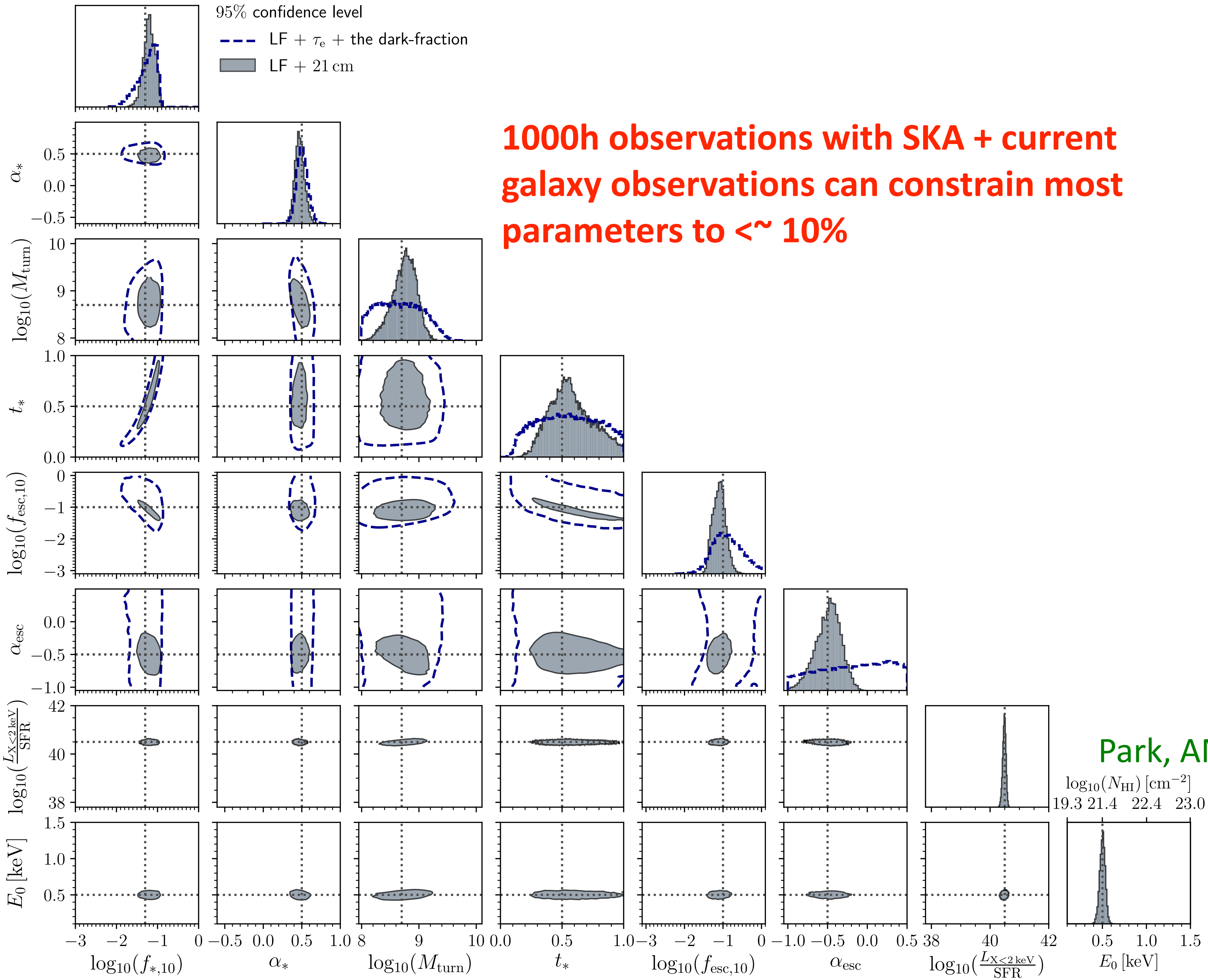
We inferred the X-ray properties of the first galaxies, ruling-out the values seen in local, metal-enriched galaxies.

led by Y. Qin

What can we learn using **full** upcoming data?

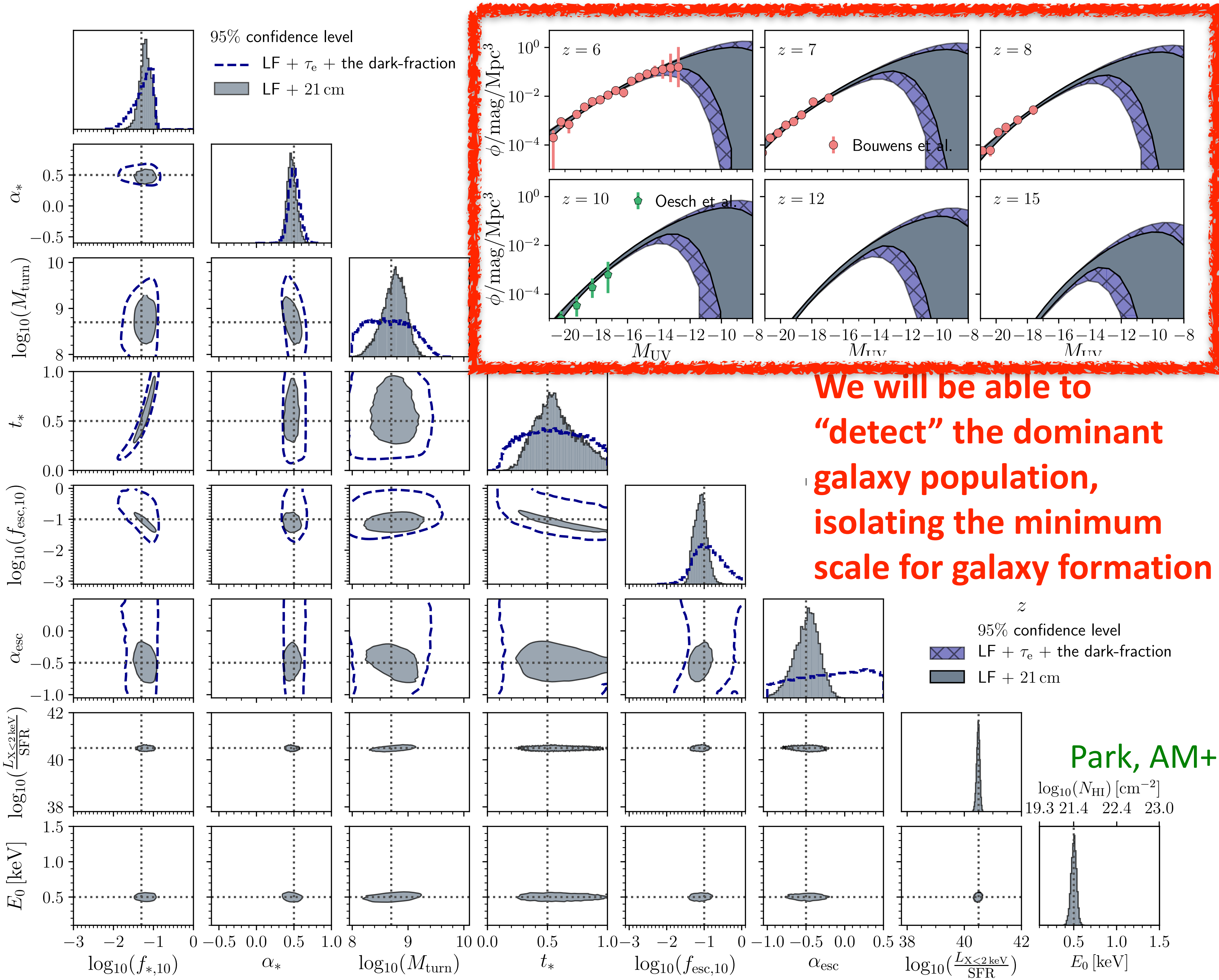
Parameter constraints

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



Park, AM+2019

Parameter constraints

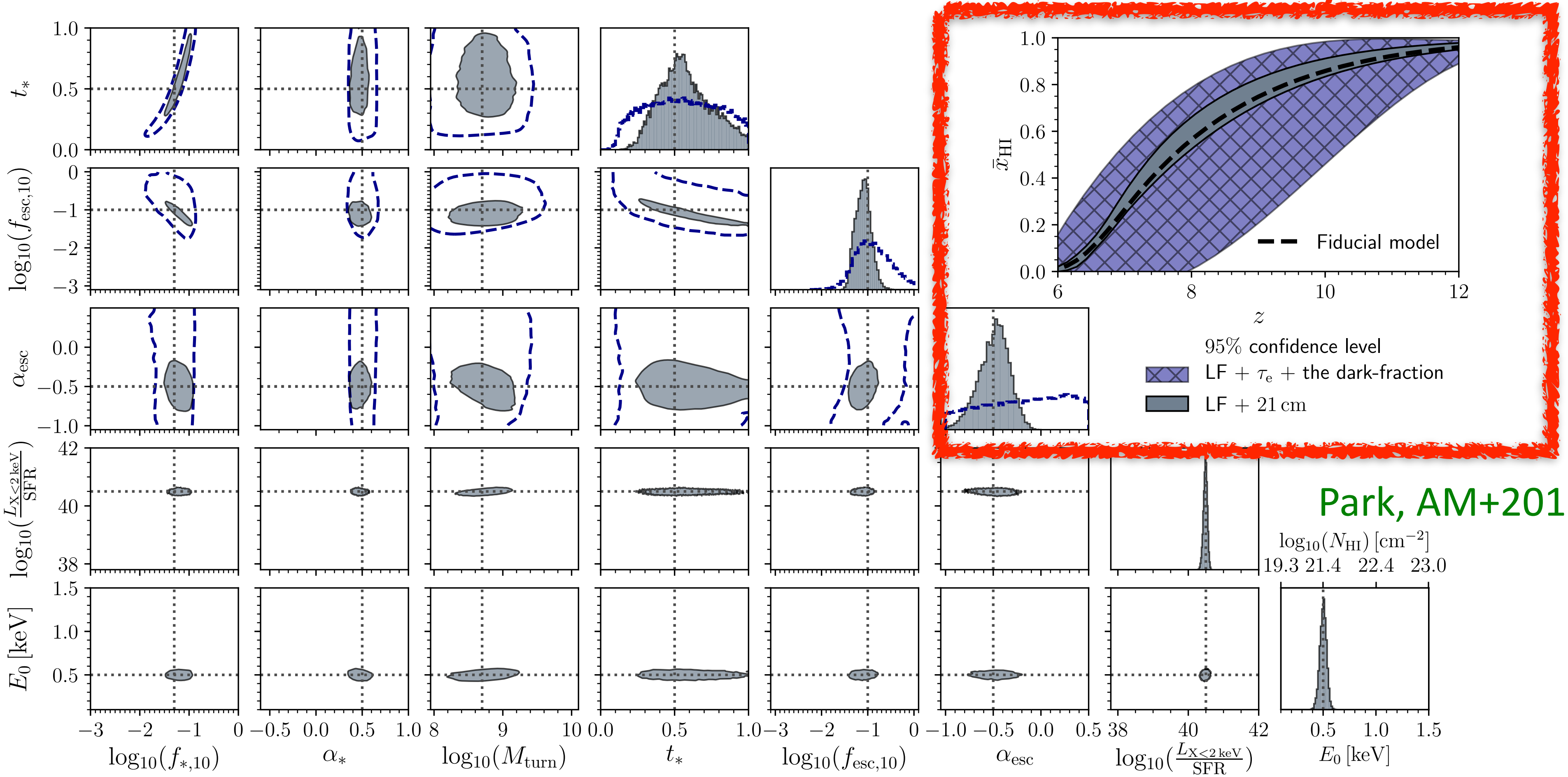


We will be able to "detect" the dominant galaxy population, isolating the minimum scale for galaxy formation

Park, AM+2019

Parameter constraints

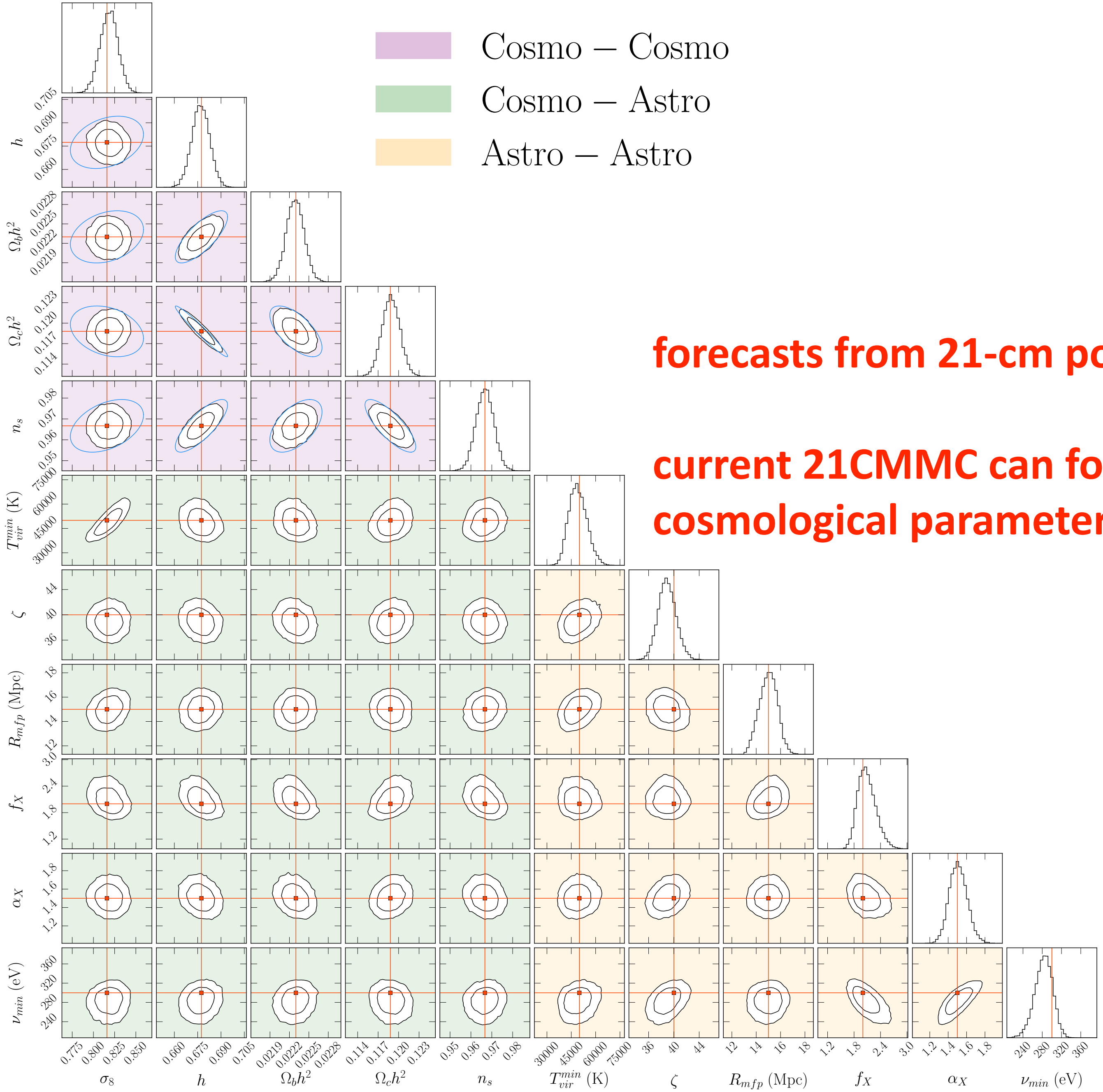
1000h observations with HERA will be able constrain EoR history to ~ 1%



Park, AM+2019

In addition to the unknown astrophysics of the ***first galaxies***, 21-cm will be a physics rich probe of ***physical cosmology***

Co-vary cosmological parameters



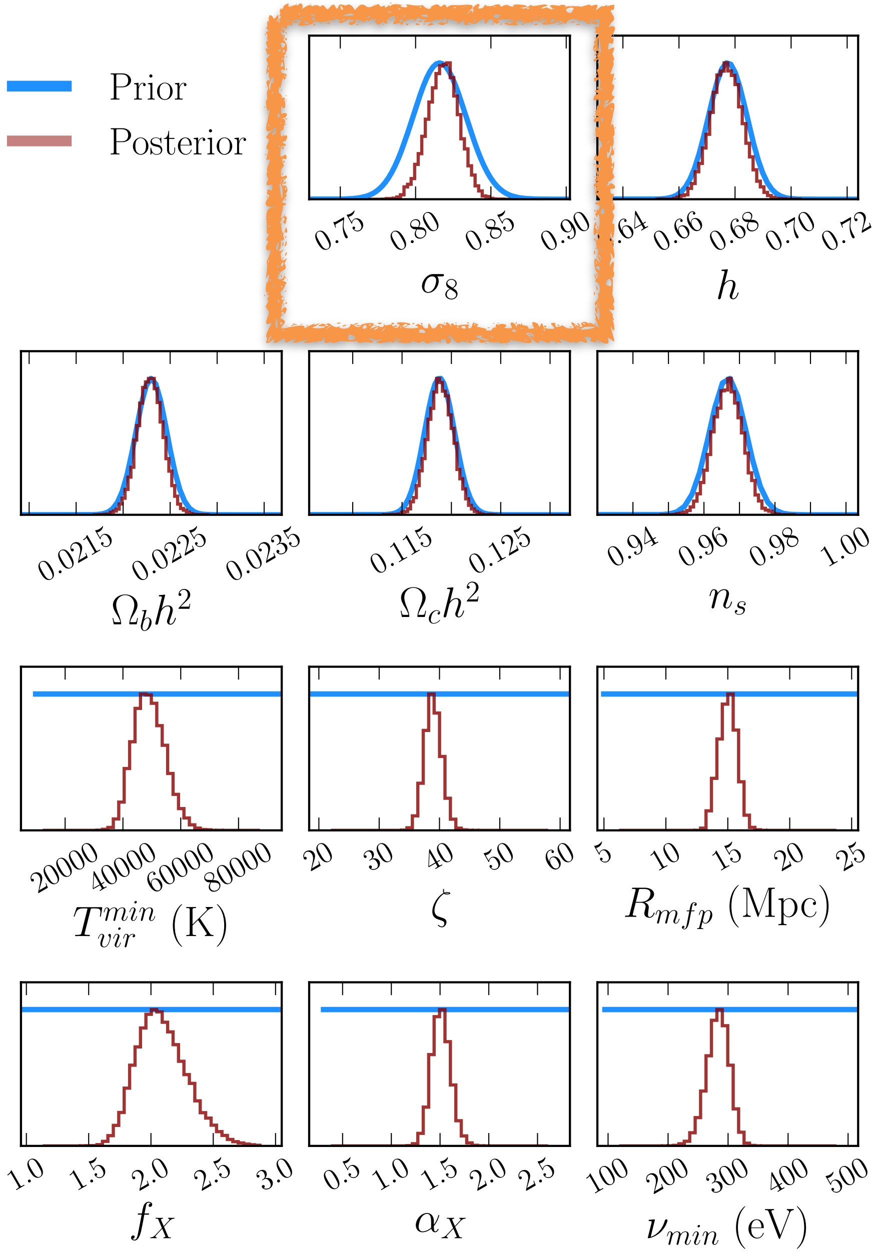
forecasts from 21-cm power spectra emulator

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

Kern + (2017)

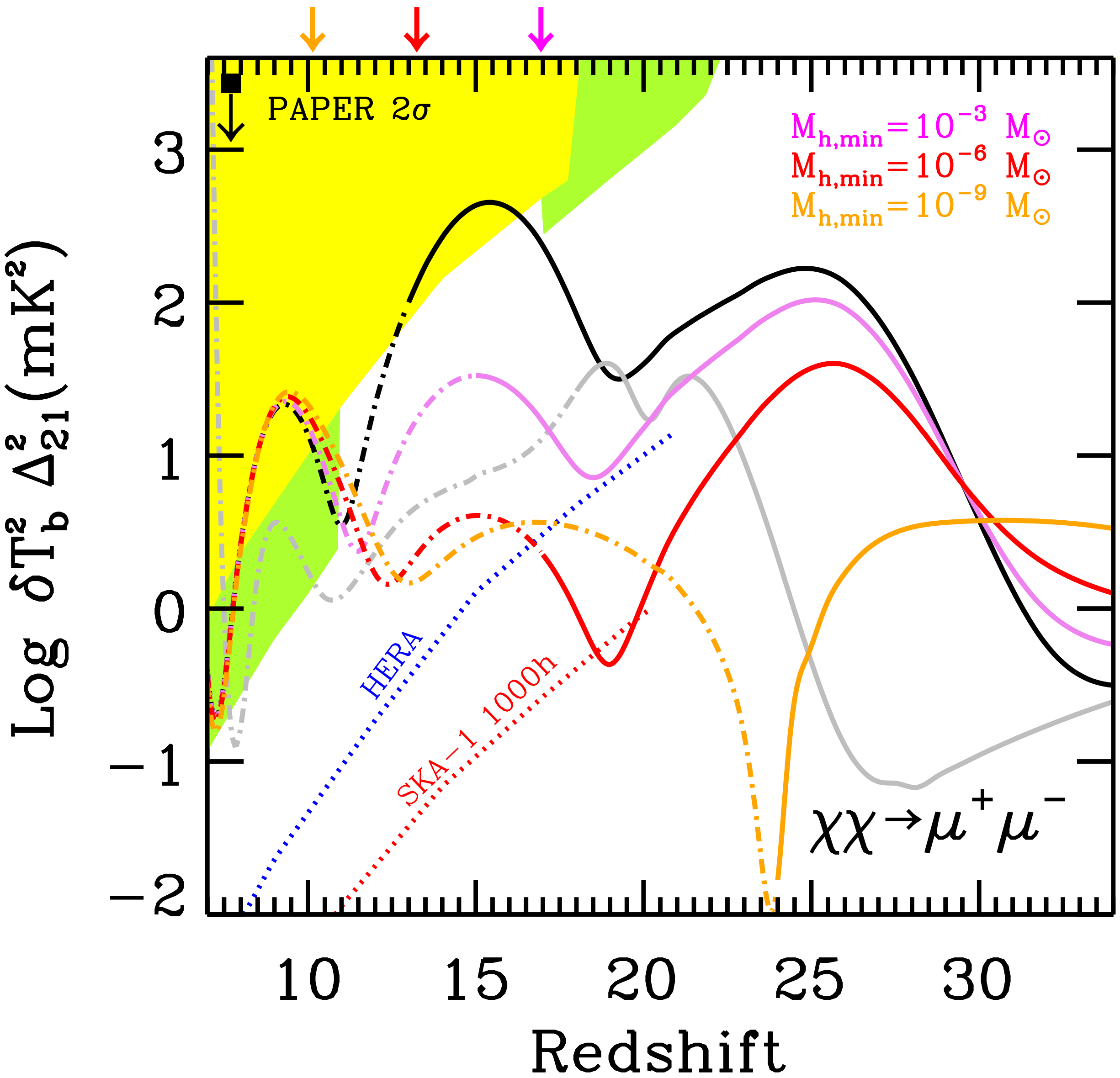
Co-vary cosmological parameters

21-cm observations of reionization can strengthen constraints on σ_8



Kern + (2017)

Heating from Dark Matter annihilations and/or decay?



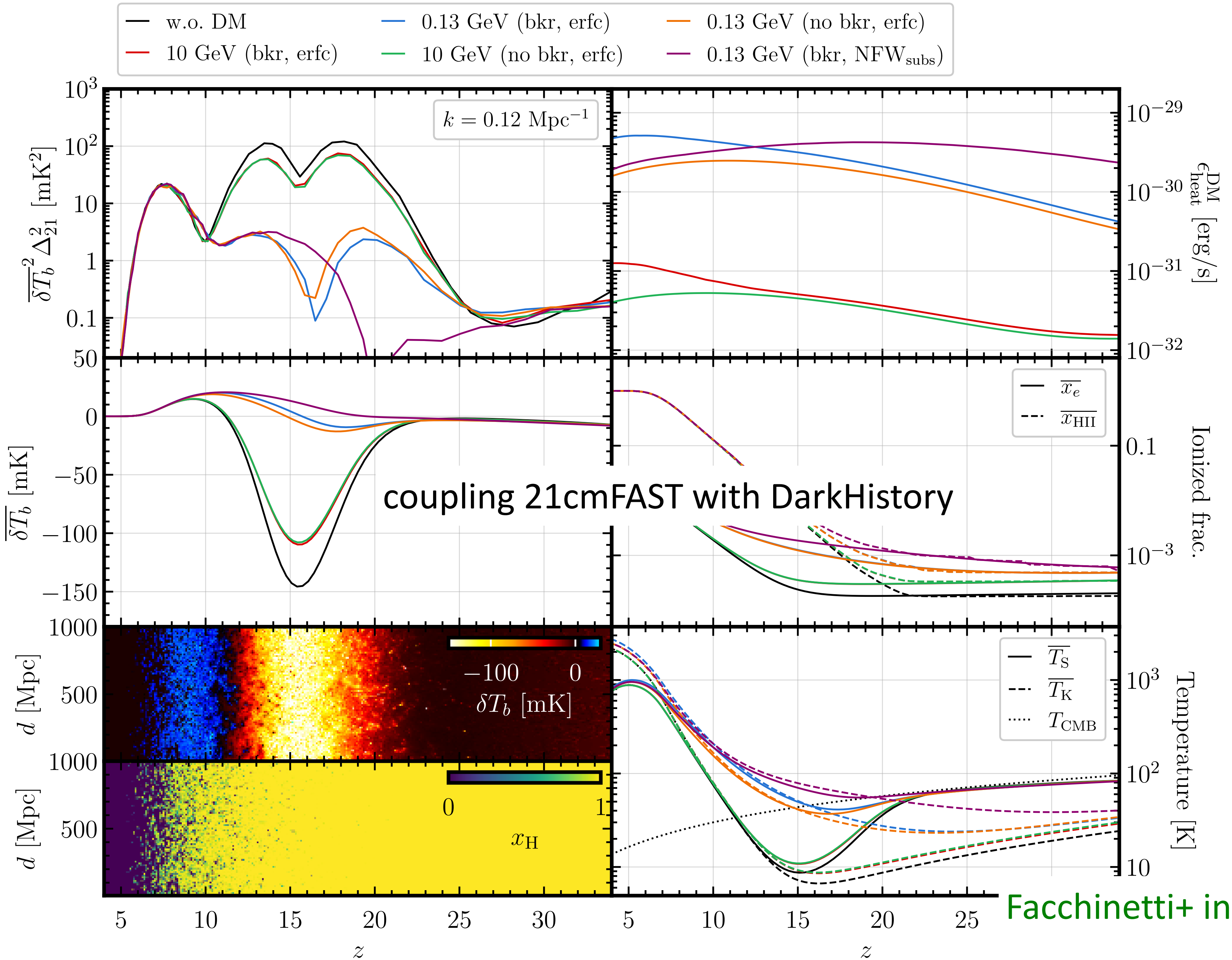
Dark matter annihilations heat the IGM more uniformly than galaxies!

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

Evoli, AM, Ferrara (2014)

see also Lopez-Honorez+2016

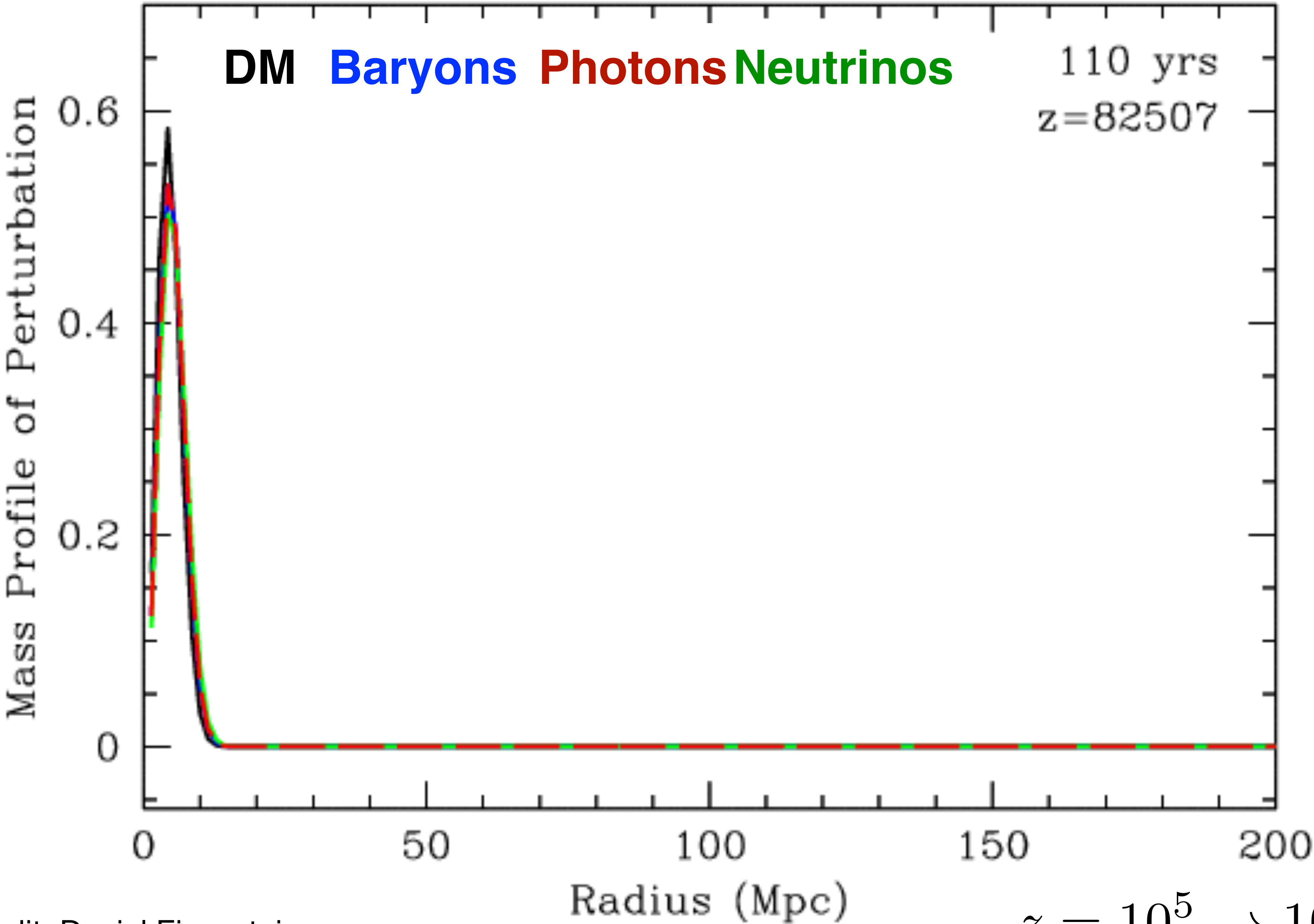
$\chi\chi \to e^+e^-$



coupling 21cmFAST with DarkHistory

Facchinetti+ in prep

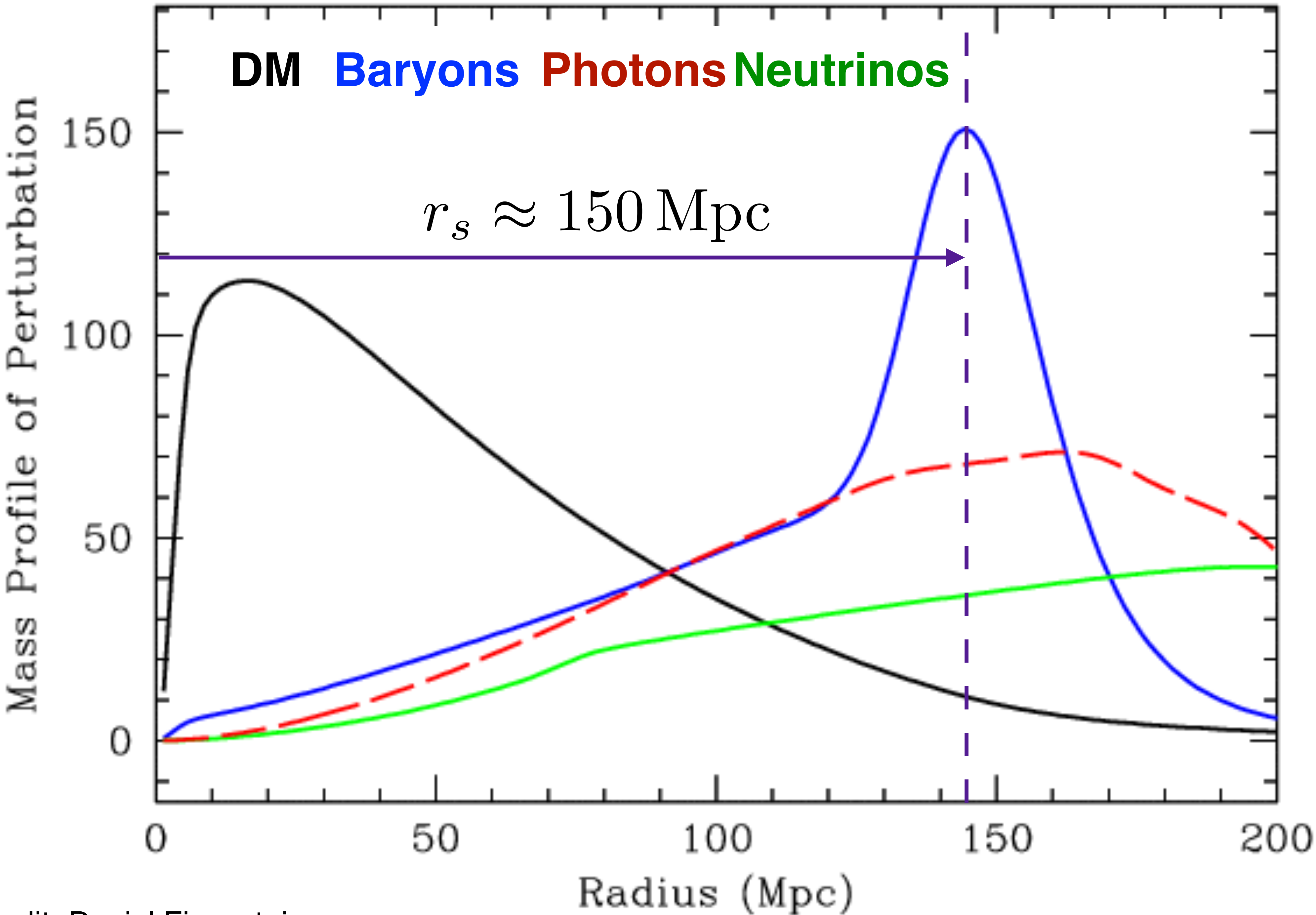
21cm can also measure acoustic oscillations!



Credit: Daniel Eisenstein

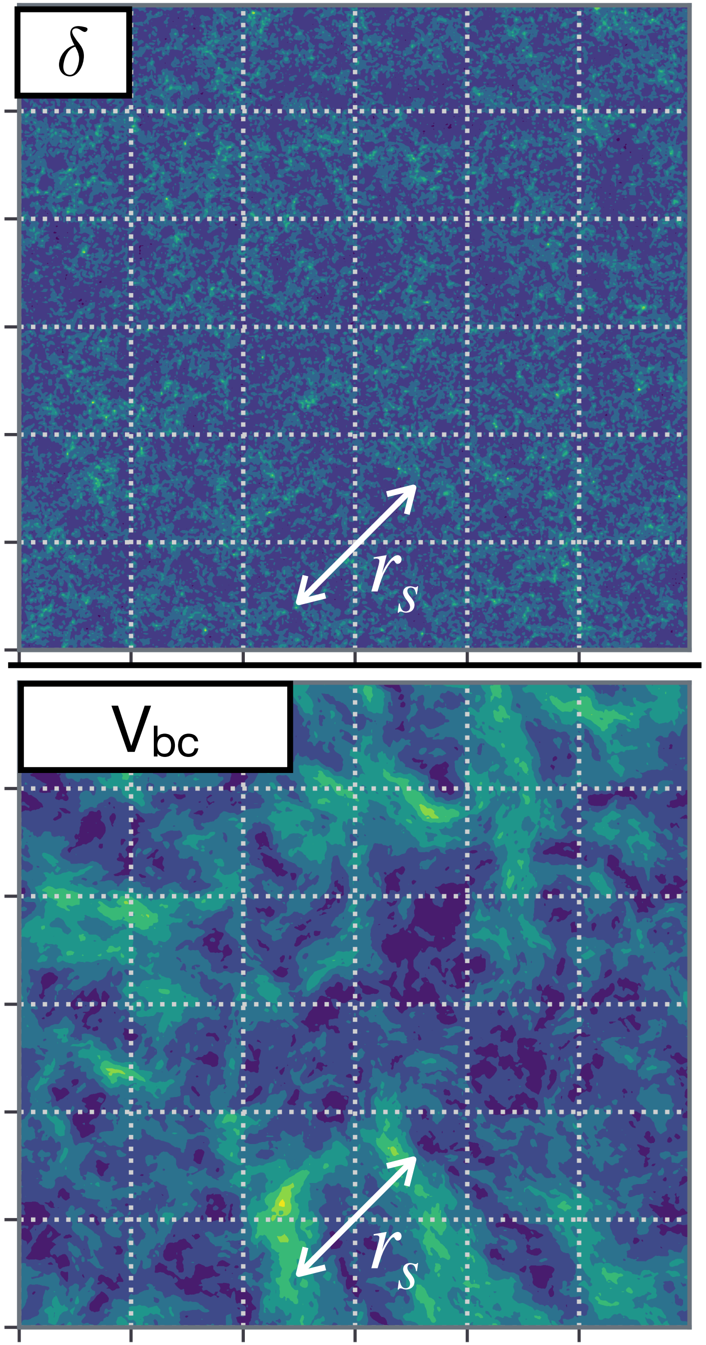
$$z = 10^5 \rightarrow 10^3$$

21cm can also measure acoustic oscillations!



Credit: Daniel Eisenstein

Acoustic oscillations -> standard ruller in v_{bc}



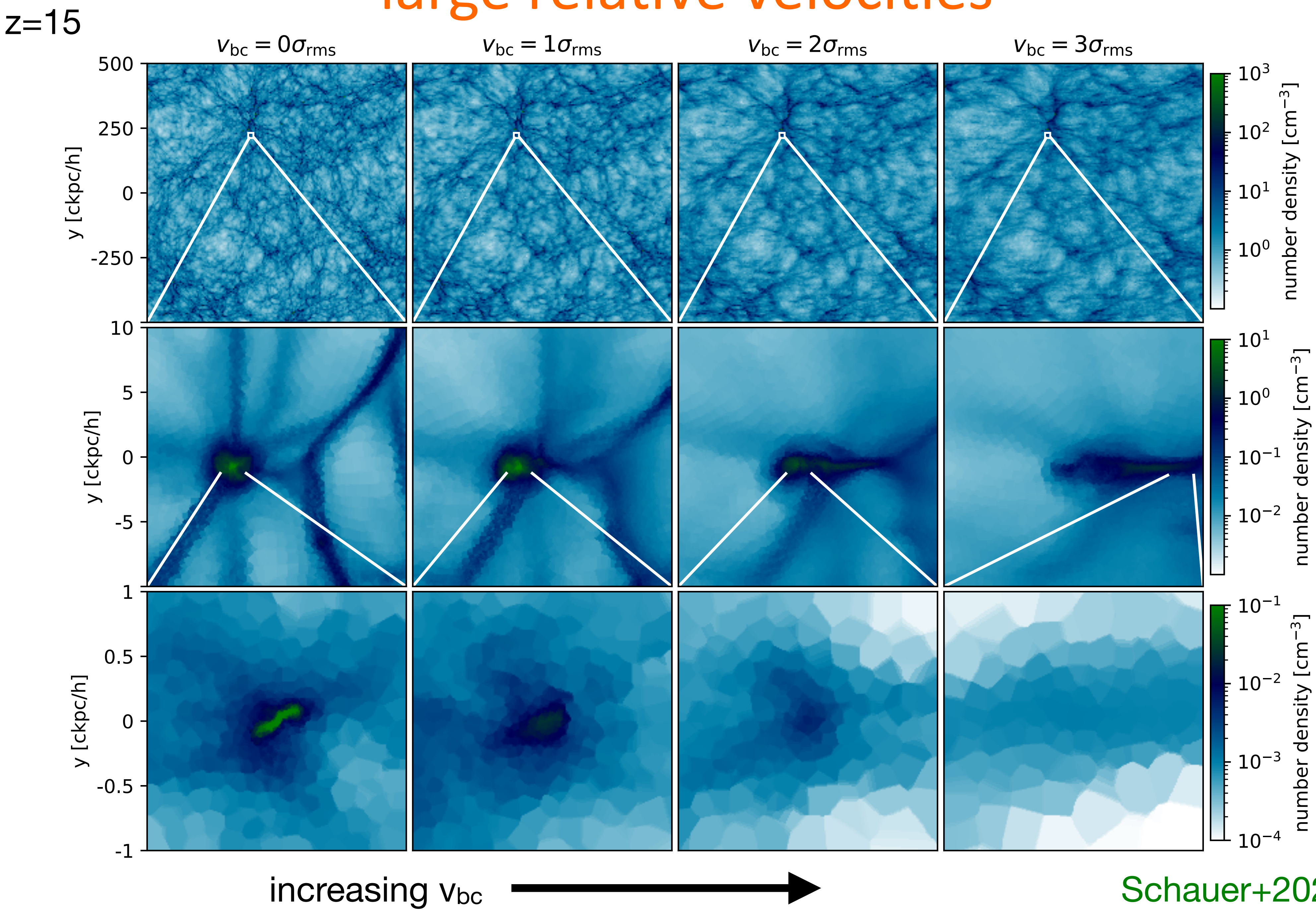
density contrast

relative velocities

Munoz, Qin, **AM**+2022

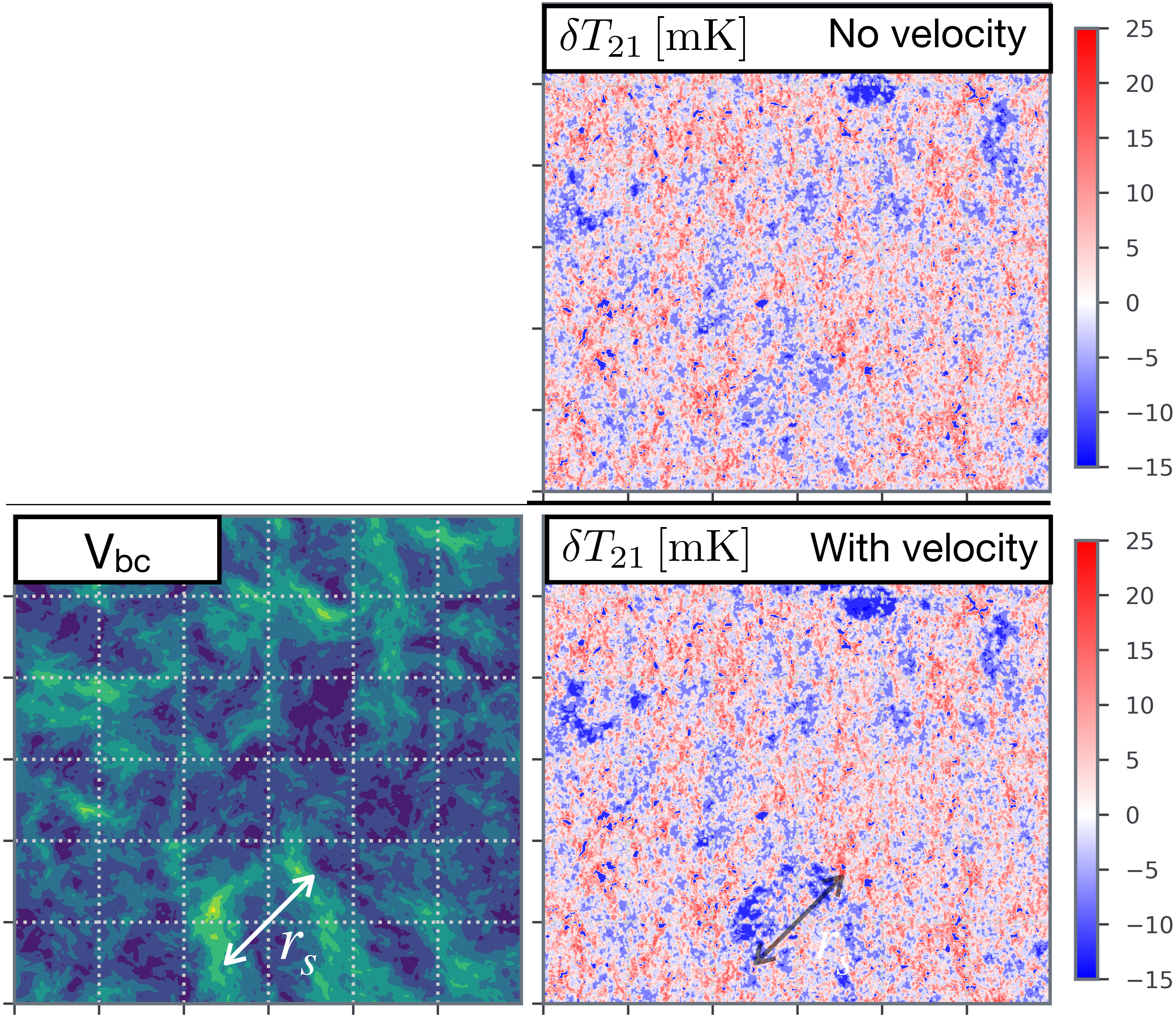
v_bc pointed out by Tseliakhovich & Hirata 2010

Star formation is suppressed in regions with large relative velocities



Schauer+2021

Acoustic oscillations -> standard ruller in v_{bc}



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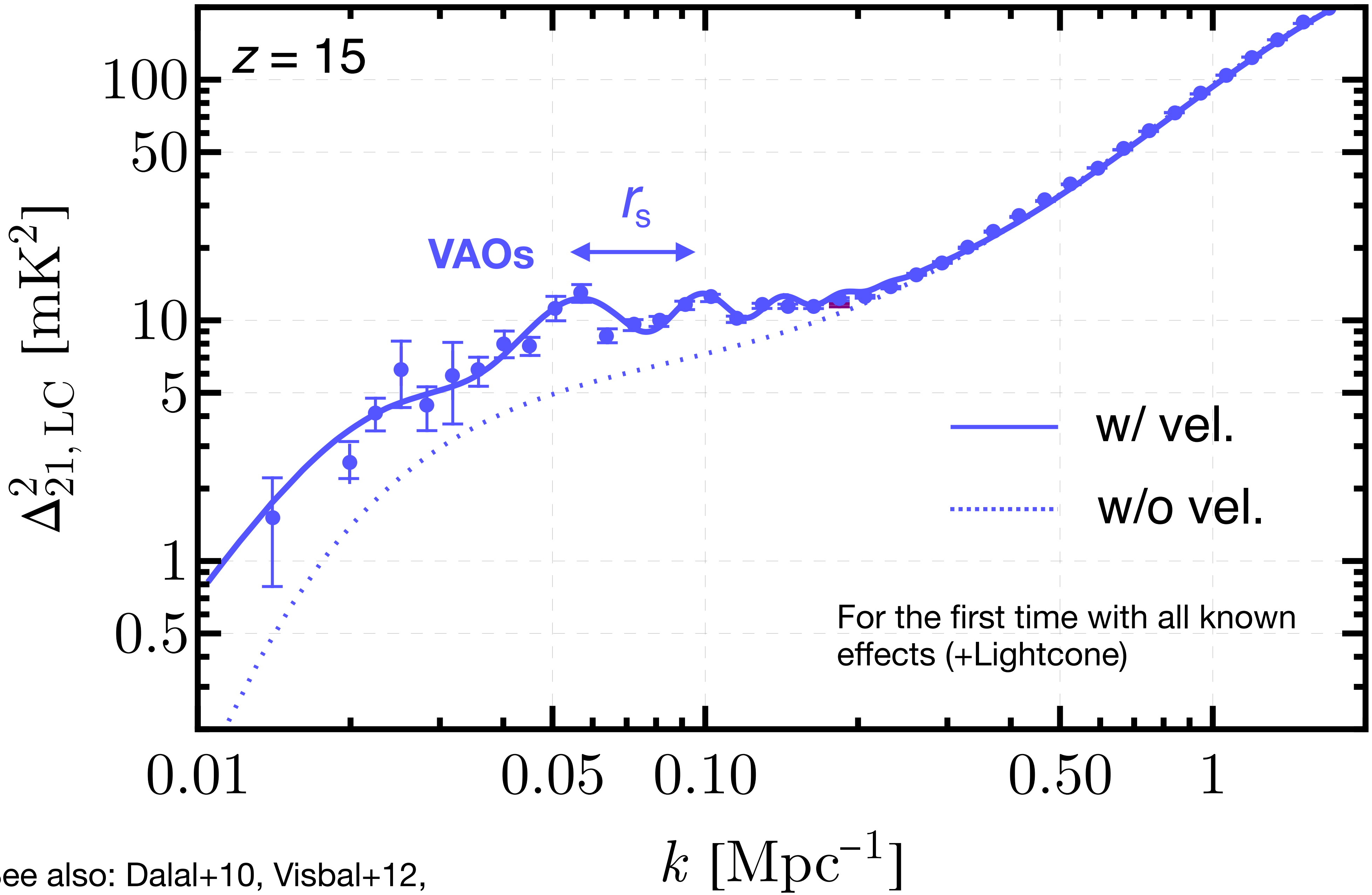
v_bc pointed out by Tseliakhovich & Hirata 2010

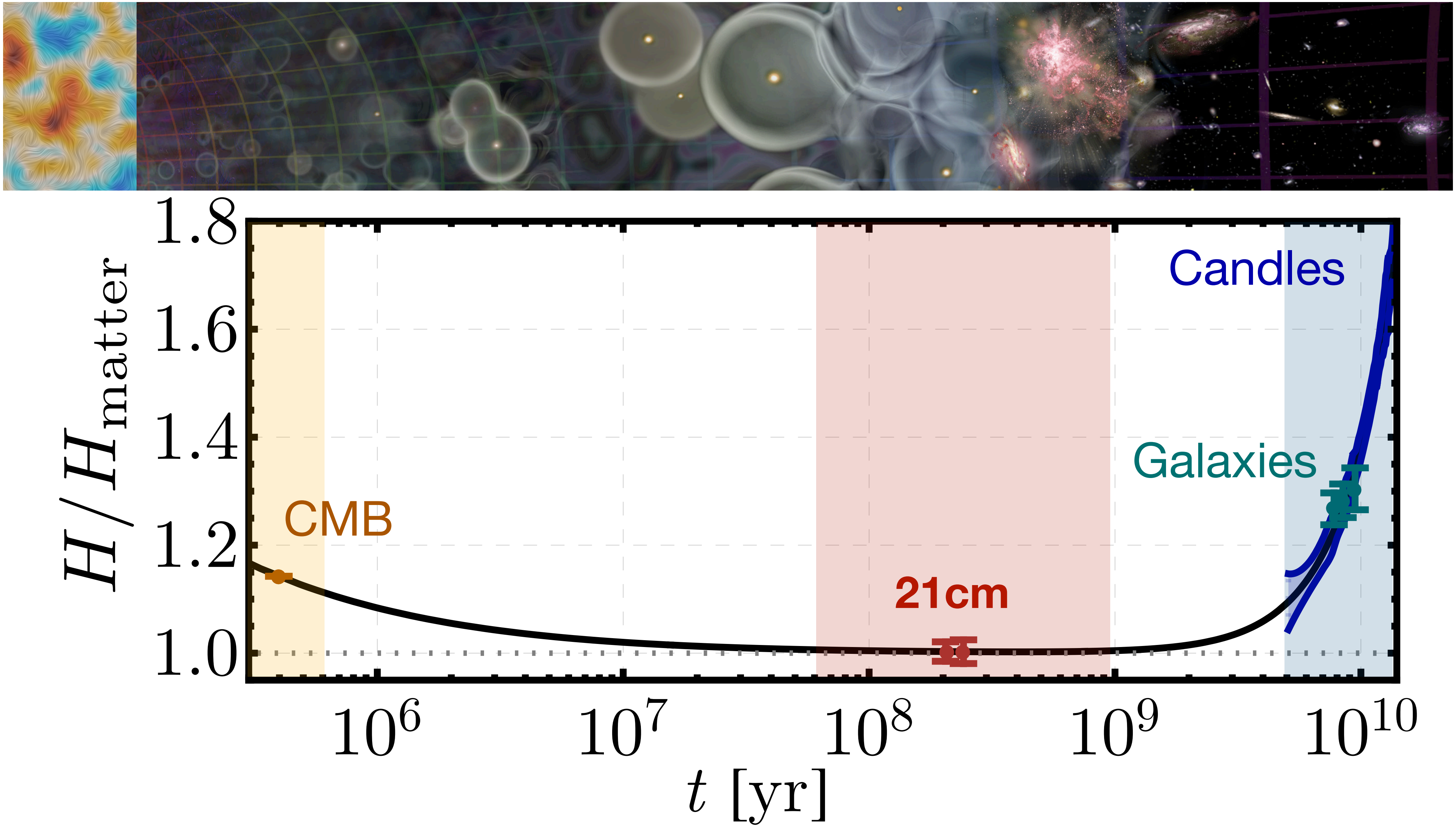
Standard ruler



See also: Dalal+10, Visbal+12, Fialkov+12, McQuinn+12 Munoz 19, Park+19, Cain+20

Munoz, Qin, AM+ 2022

Measuring the expansion history



Munoz+ 2019

Conclusions

- Direct observations of individual galaxies with *JWST* and ground based telescopes is allowing us to **study the brightest EoR galaxies**
- Recent observations of the IGM during the first billion years using Lya absorption and integral scattering to the CMB allowed us to narrow down the **timing of reionization** to $\Delta z \sim 1$
- The cosmic 21cm signal will allow us to map the IGM during the first billion years, constraining the **average UV and Xray properties of the first galaxies**
- Even preliminary data from HERA constrains the **heating history** of the Universe, implying that the first X-ray binaries were **more X-ray luminous** than local ones —> lower metalicity environments
- The cosmic 21-cm signal also allows us to study **physical cosmology**, e.g.
  - co-vary cosmological and astrophysical parameters
  - exotic heating processes, e.g. DM annihilations and decay
  - standard ruler at z=10-15 from velocity-induced feedback on galaxies
- Analysis framework is fully Bayesian -> you can change the underlying model and let the **Evidence** tell you which model the data prefers