Cosmology from the first billion years as seen with the 21cm line

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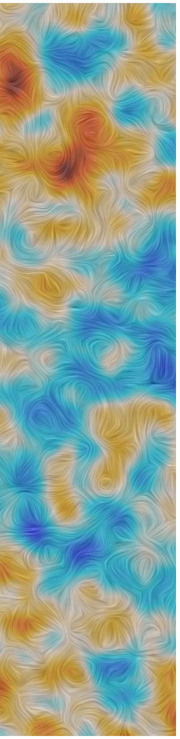
MUR
Ministero dell'Università e della Ricerca

erc
European Research Council

First billion years - birth of structure and Cosmic Dawn

Image: ESA

CMB



$z \approx 10^3$

cosmic time [yr]

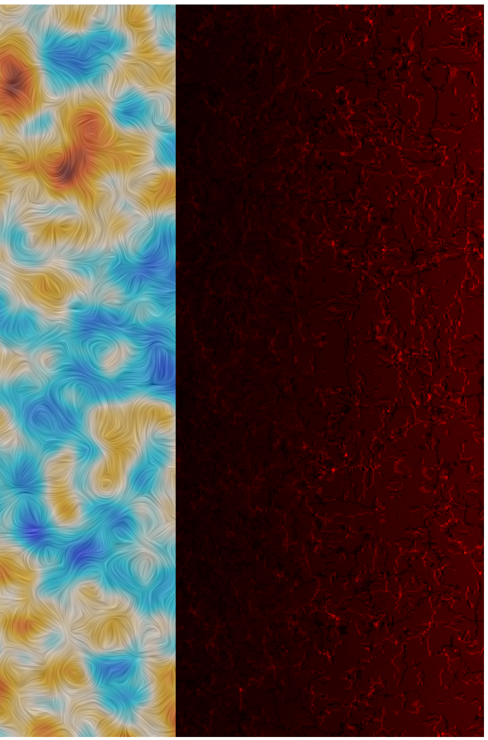
$4 \cdot 10^5$

First billion years - birth of structure and Cosmic Dawn

Image: ESA

AM+2016

CMB **Dark Ages**



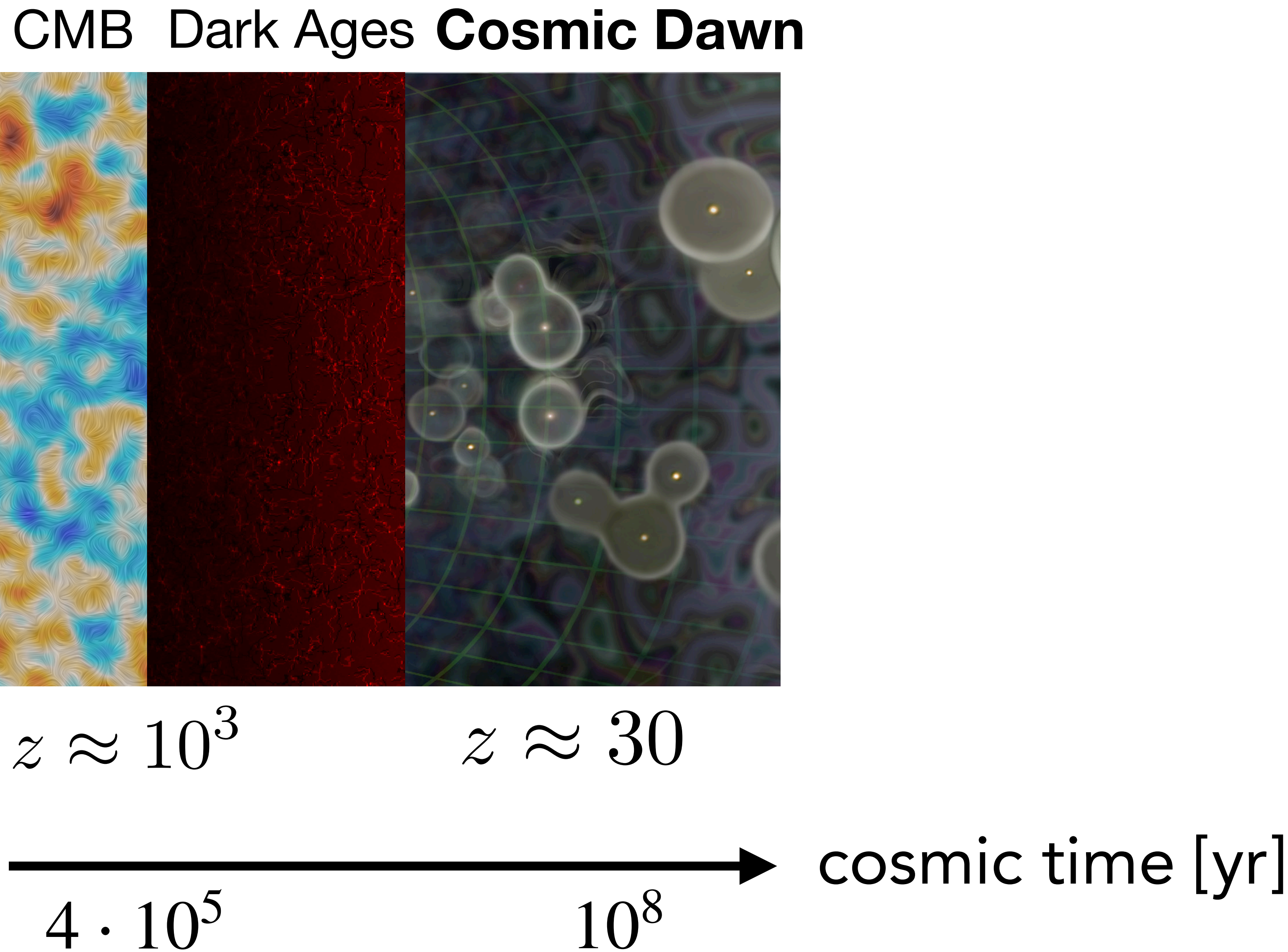
$z \approx 10^3$ $z \approx 30$

cosmic time [yr]

$4 \cdot 10^5$ 10^8

First billion years - birth of structure and Cosmic Dawn

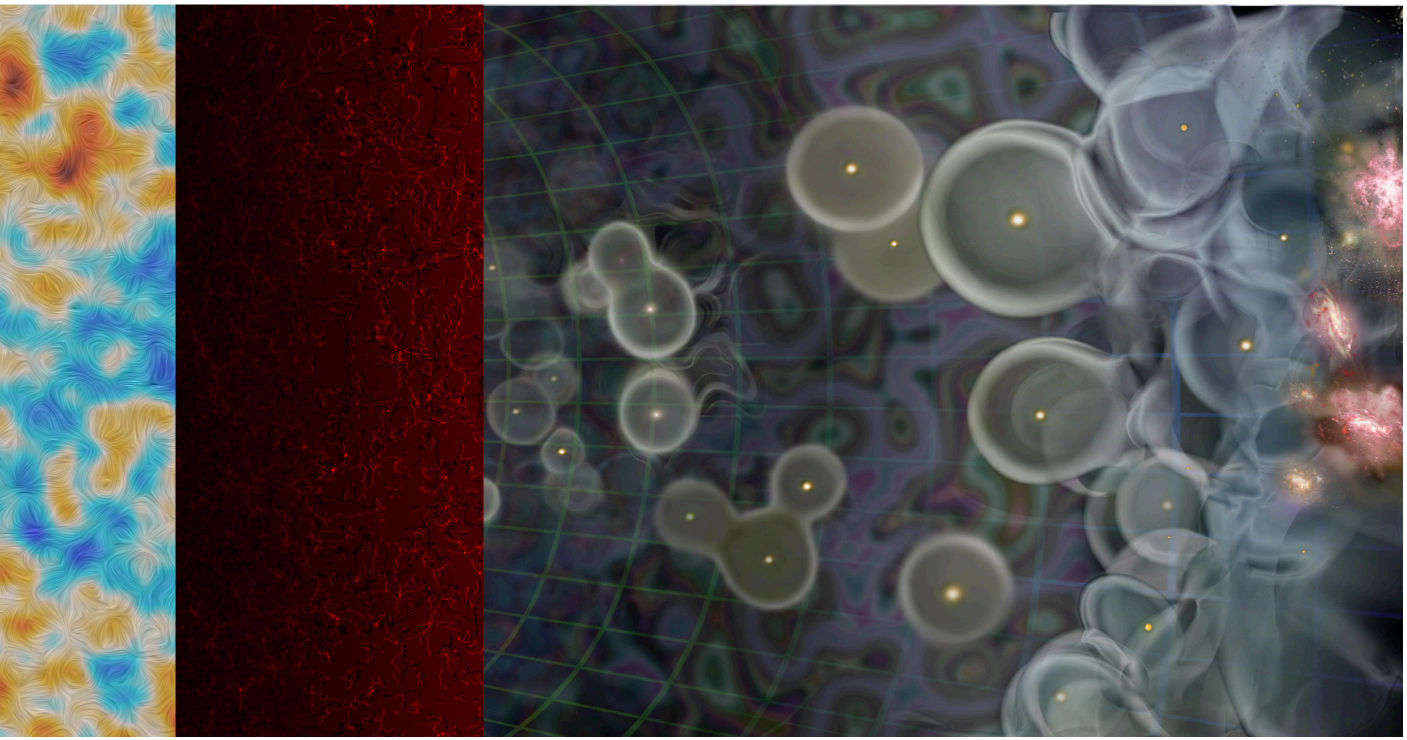
Image: NASA/
CXC/M.WEISS
AM+2016; J. Munoz



First billion years - birth of structure and Cosmic Dawn

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

CMB Dark Ages Cosmic Dawn **Reionization**



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

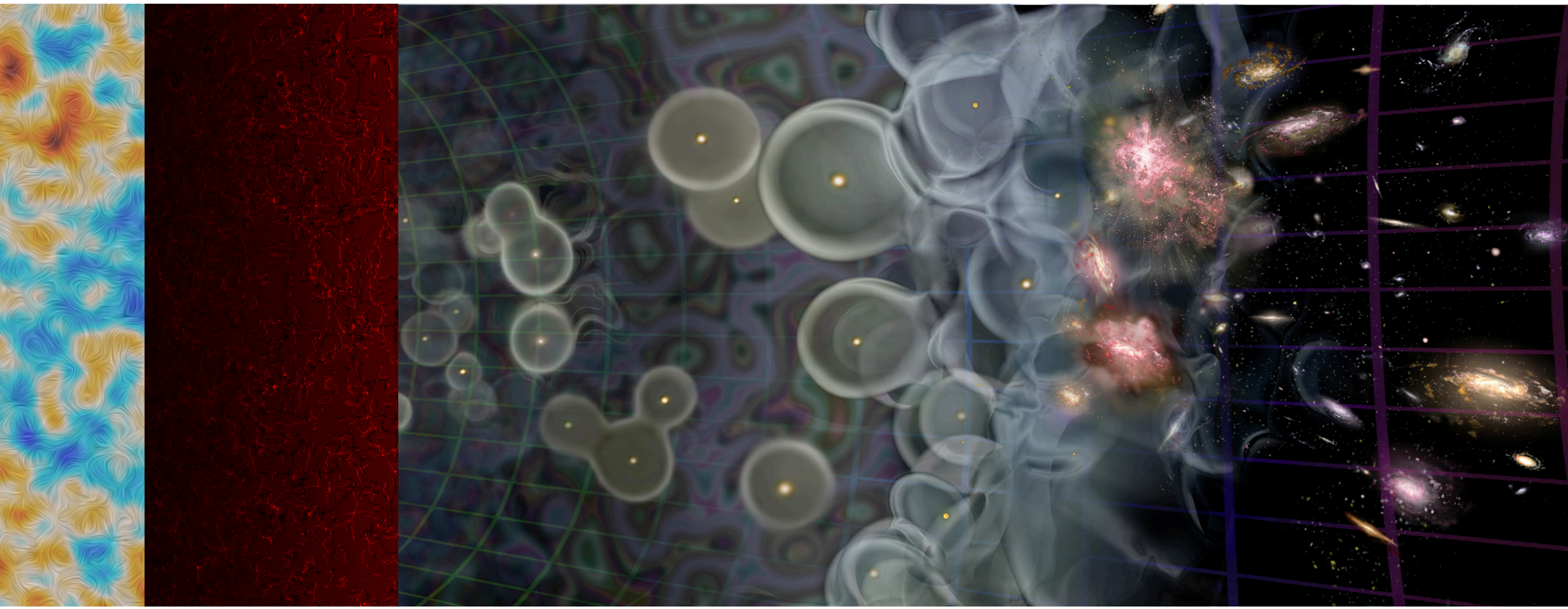
cosmic time [yr]

$4 \cdot 10^5$ 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**

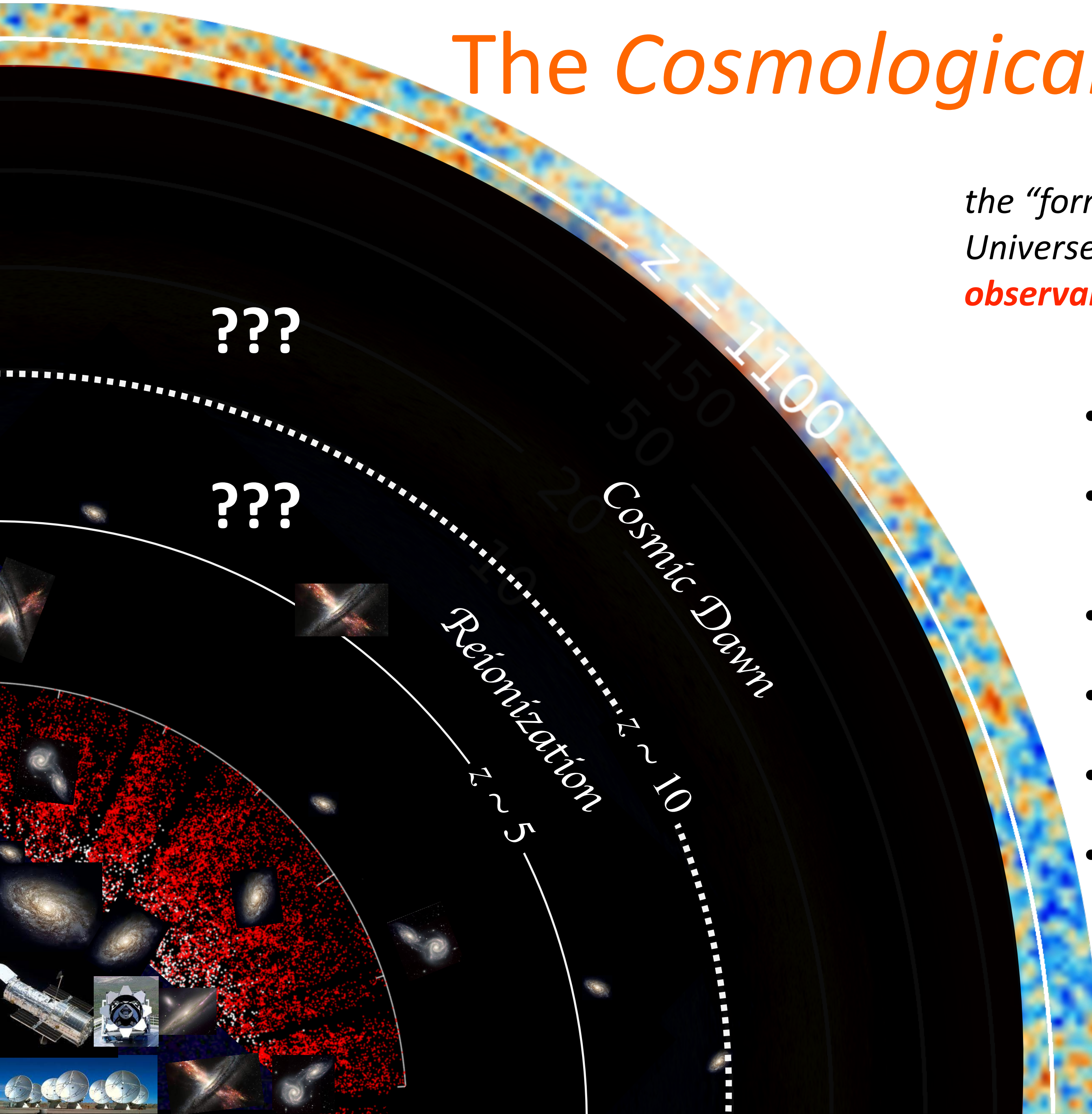


$z \approx 10^3$ $z \approx 30$ $z \approx 5$ $z = 0$

cosmic time [yr]

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

The *Cosmological Frontier…*



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

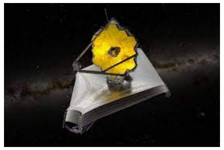
- When and how did the first galaxies form?
- How did they impact each other and their surroundings?
- What are the dominant feedback mechanisms?
- Can we learn about Dark Matter properties?
- How does the Hubble parameter evolve?
- What are the properties of the first stars and black holes?

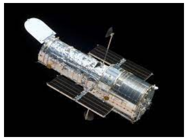
adapted from Cynthia Chiang

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

Doing a galaxy census….

Observe with Hubble / JWST and count galaxies

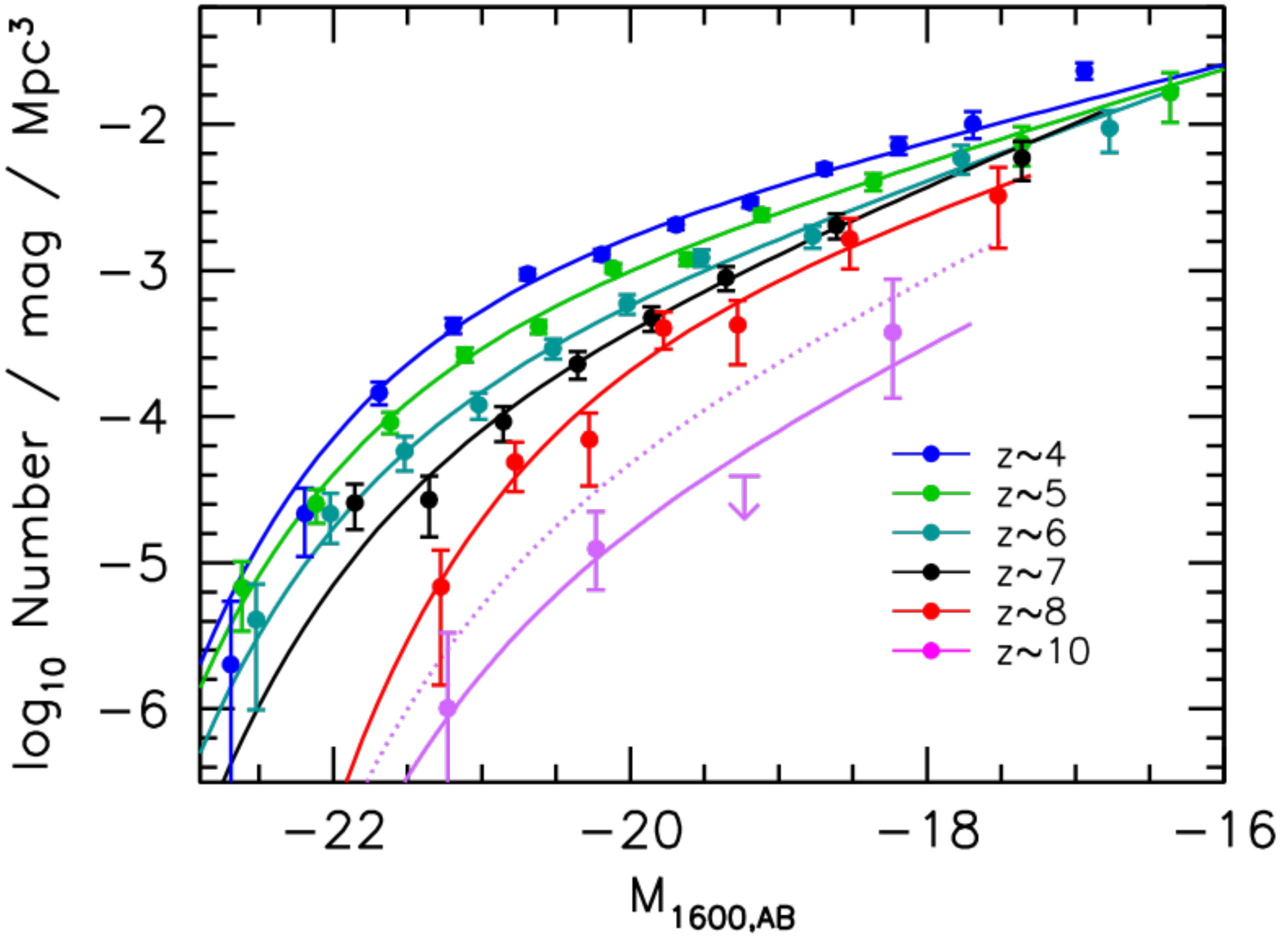




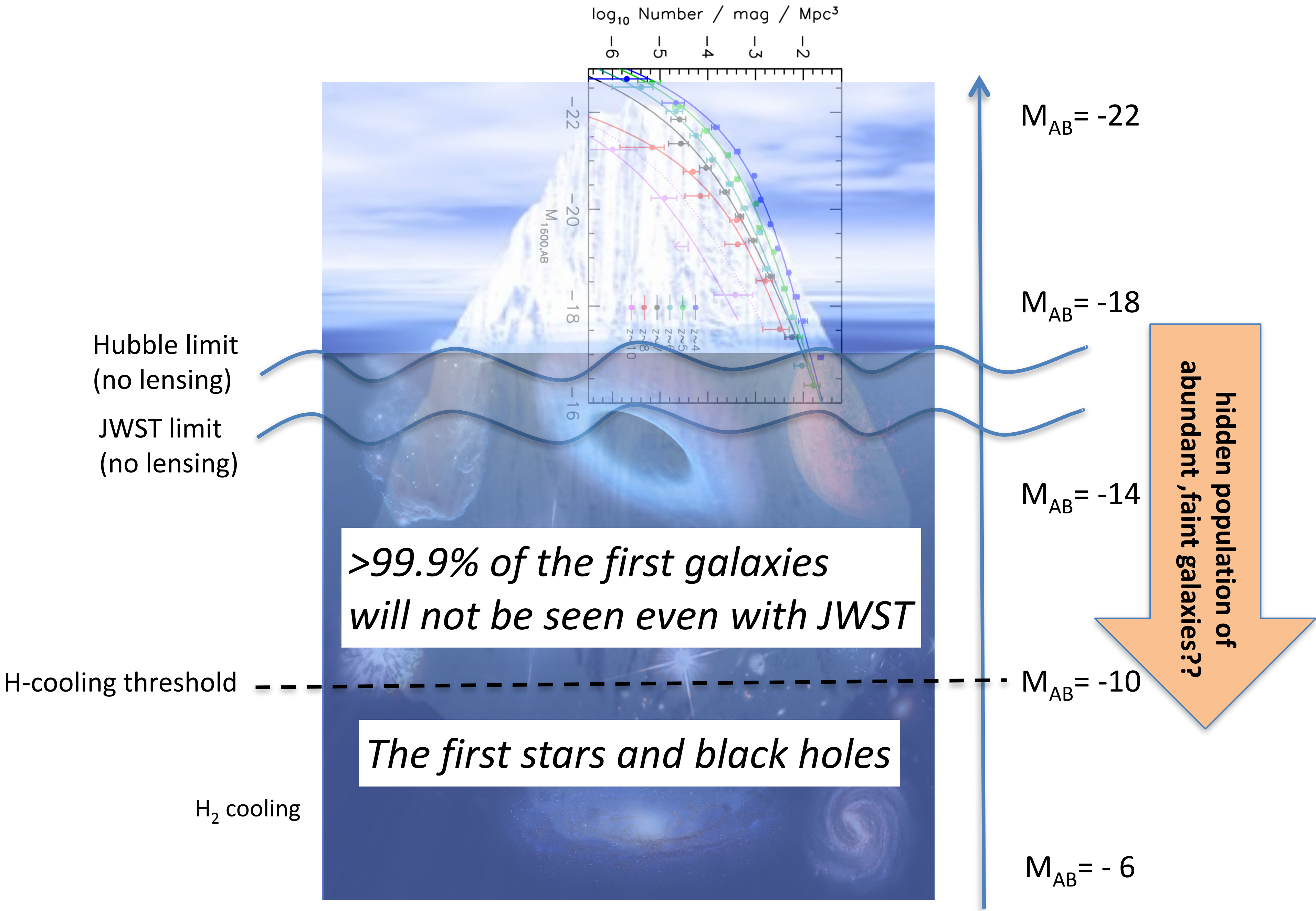
adapted from Cynthia Chiang

Galaxies during the first billion years

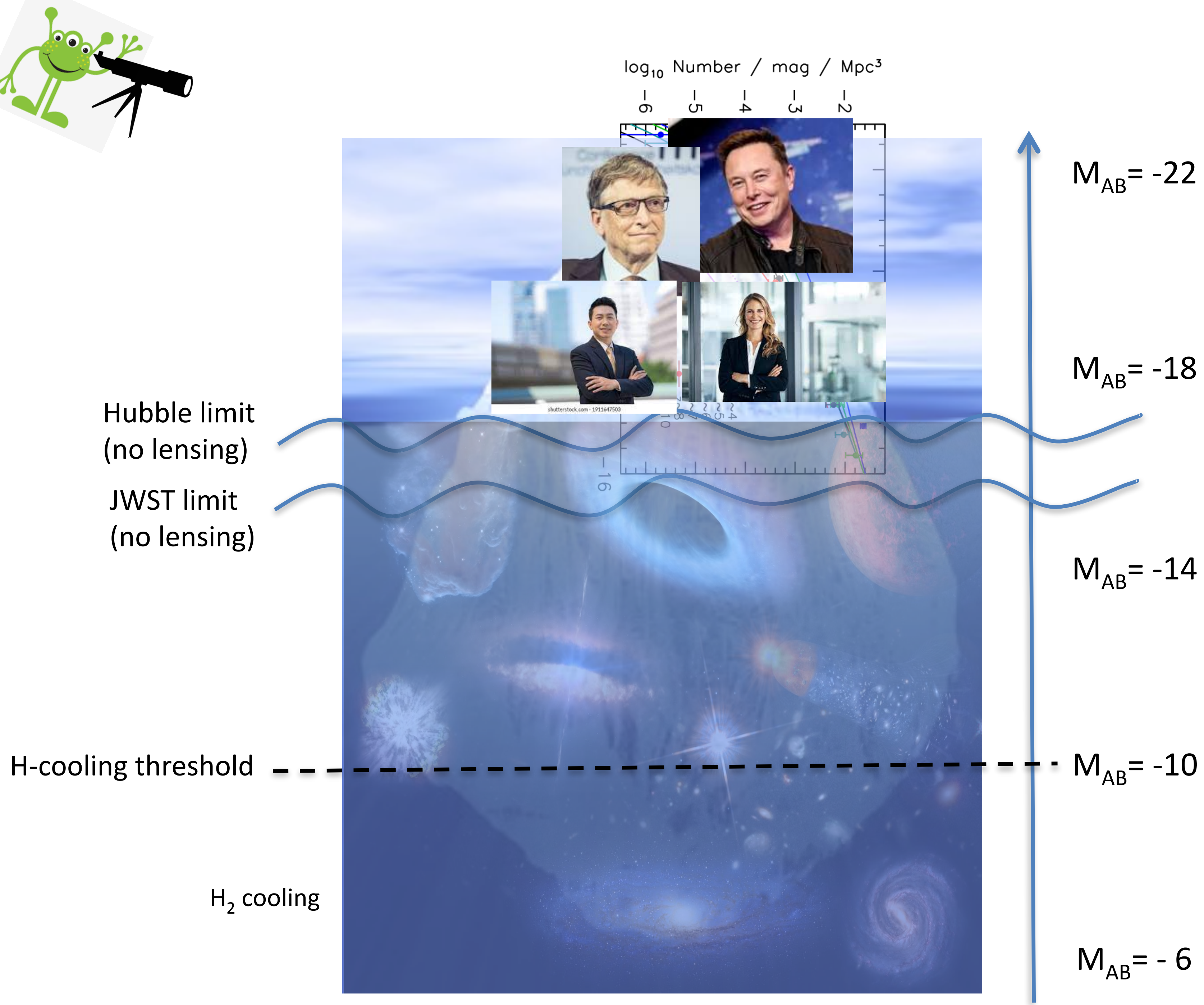
- Telescopes like Hubble and ALMA have enabled detailed studies of *the brightest galaxies*



Bouwens+ (2015)



log10 Number / mag / Mpc3
-6 -5 -4 -3 -2
-22 -20 -18 -16
M1600,AB
z~4 z~5 z~6 z~7 z~8 z~10
Hubble limit (no lensing)
JWST limit (no lensing)
>99.9% of the first galaxies will not be seen even with JWST
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??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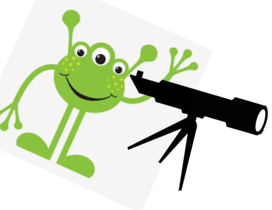

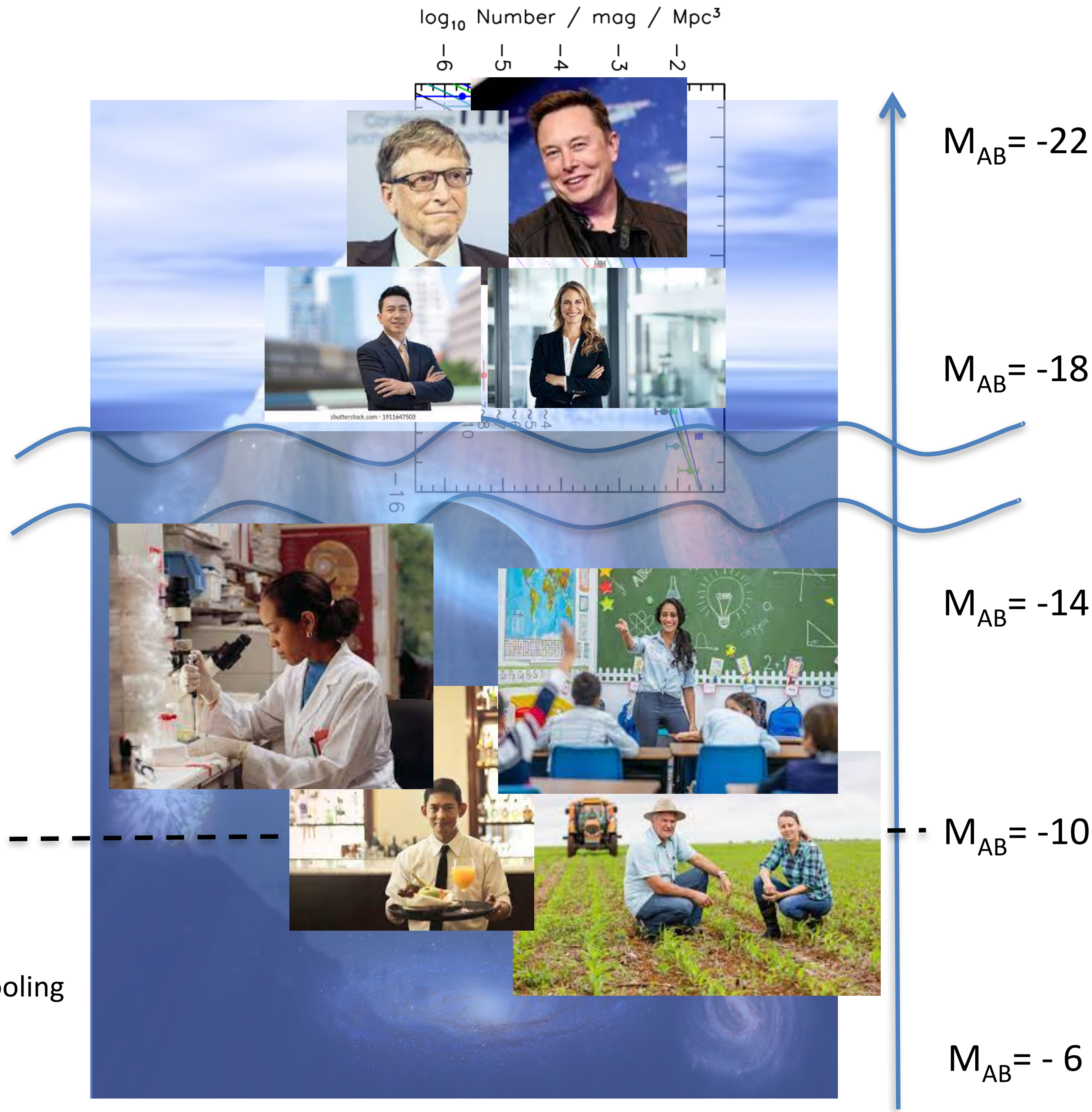

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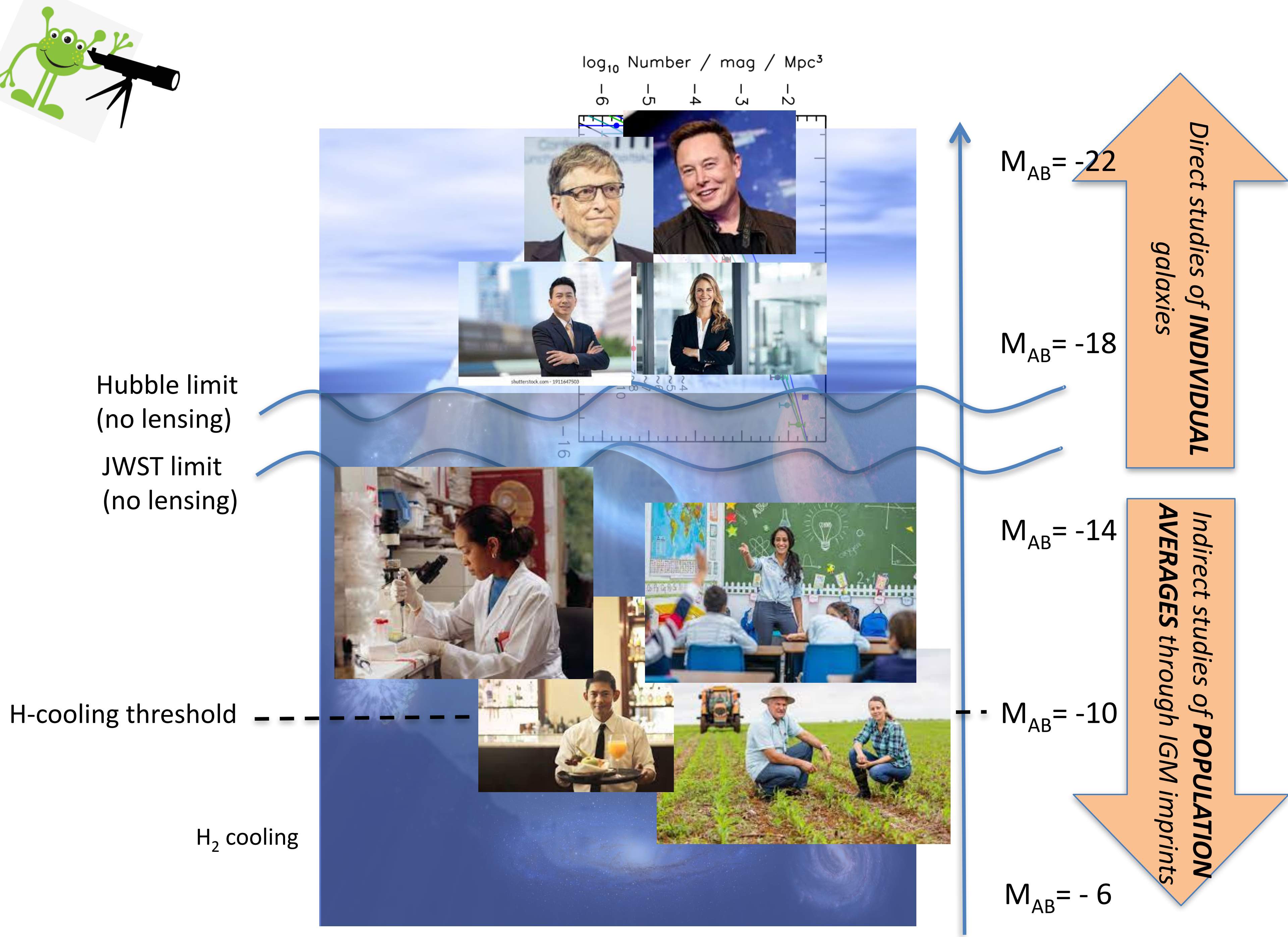

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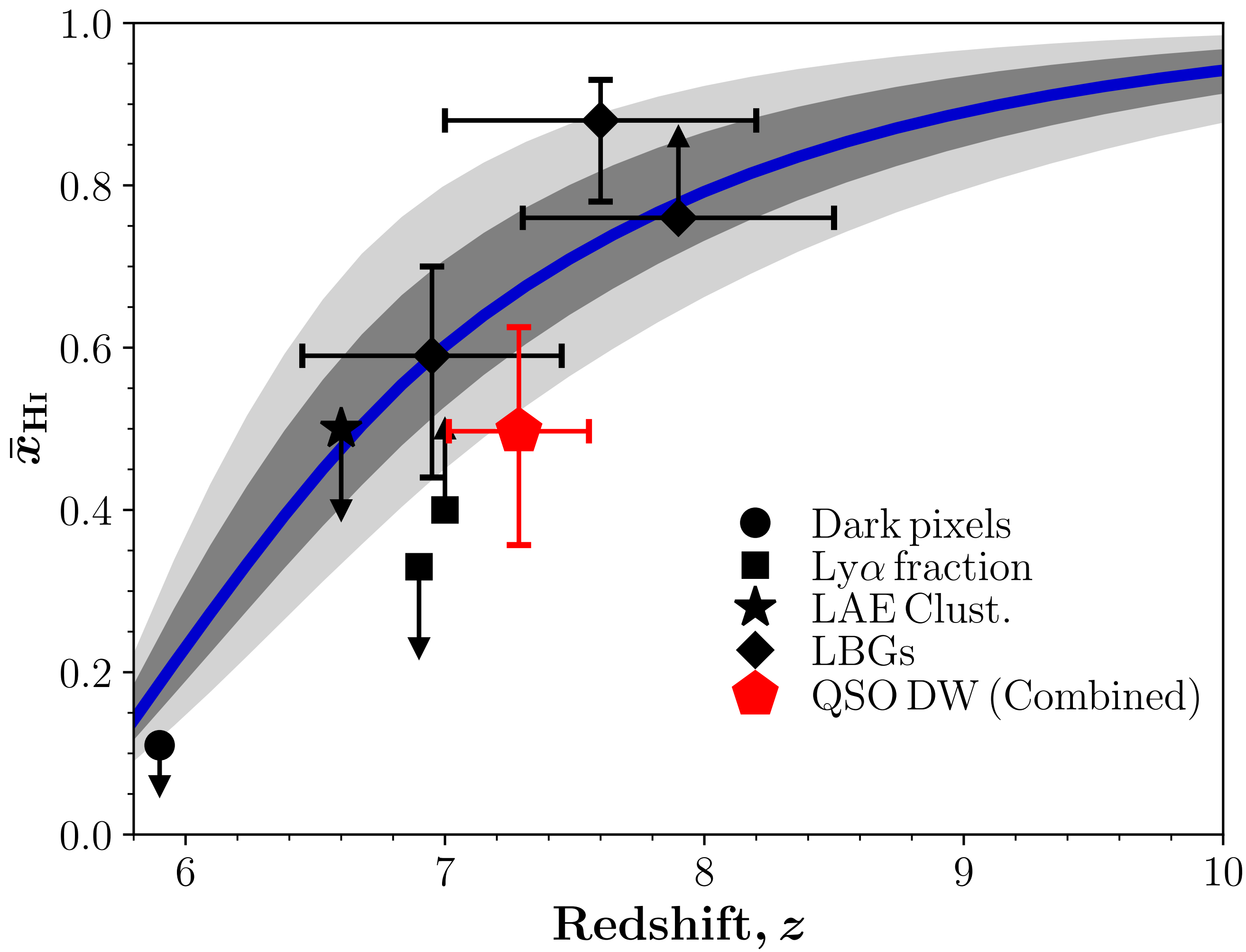
Direct studies of **INDIVIDUAL** galaxies
Indirect studies of **POPULATION AVERAGES** through IGM imprints

We already know something about the *mean* evolution during the Cosmic Dawn and Epoch of Reionization

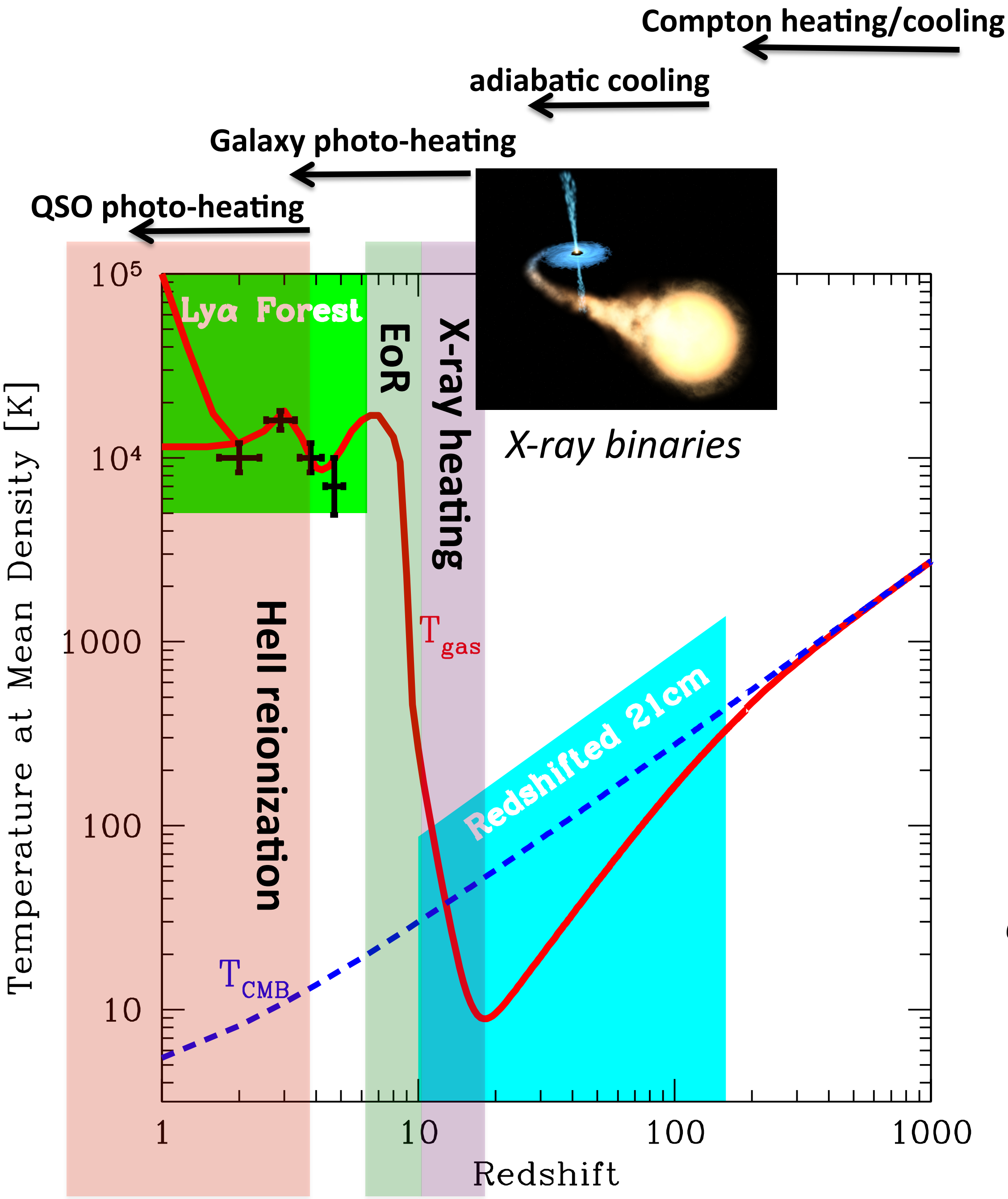
Understanding the timing of reionization



Greig, AM+ 2021

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

What about the heating history?

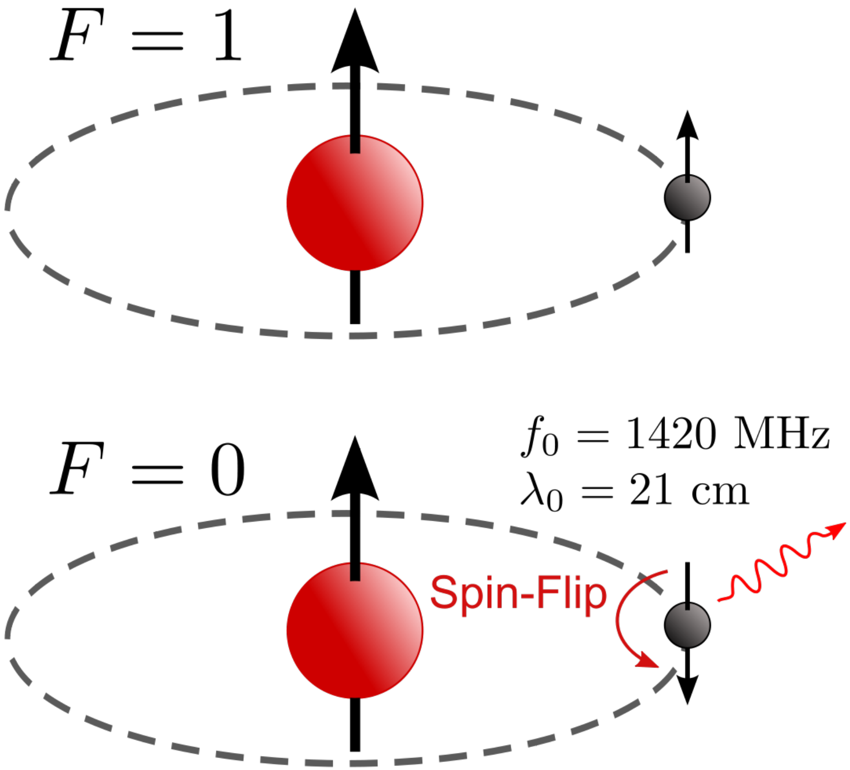


Until recently,
only constrained at z<~5….

adapted from McQuinn (2016)

How do we learn more?

The 21 cm line: the most powerful probe of the IGM during the first billion years



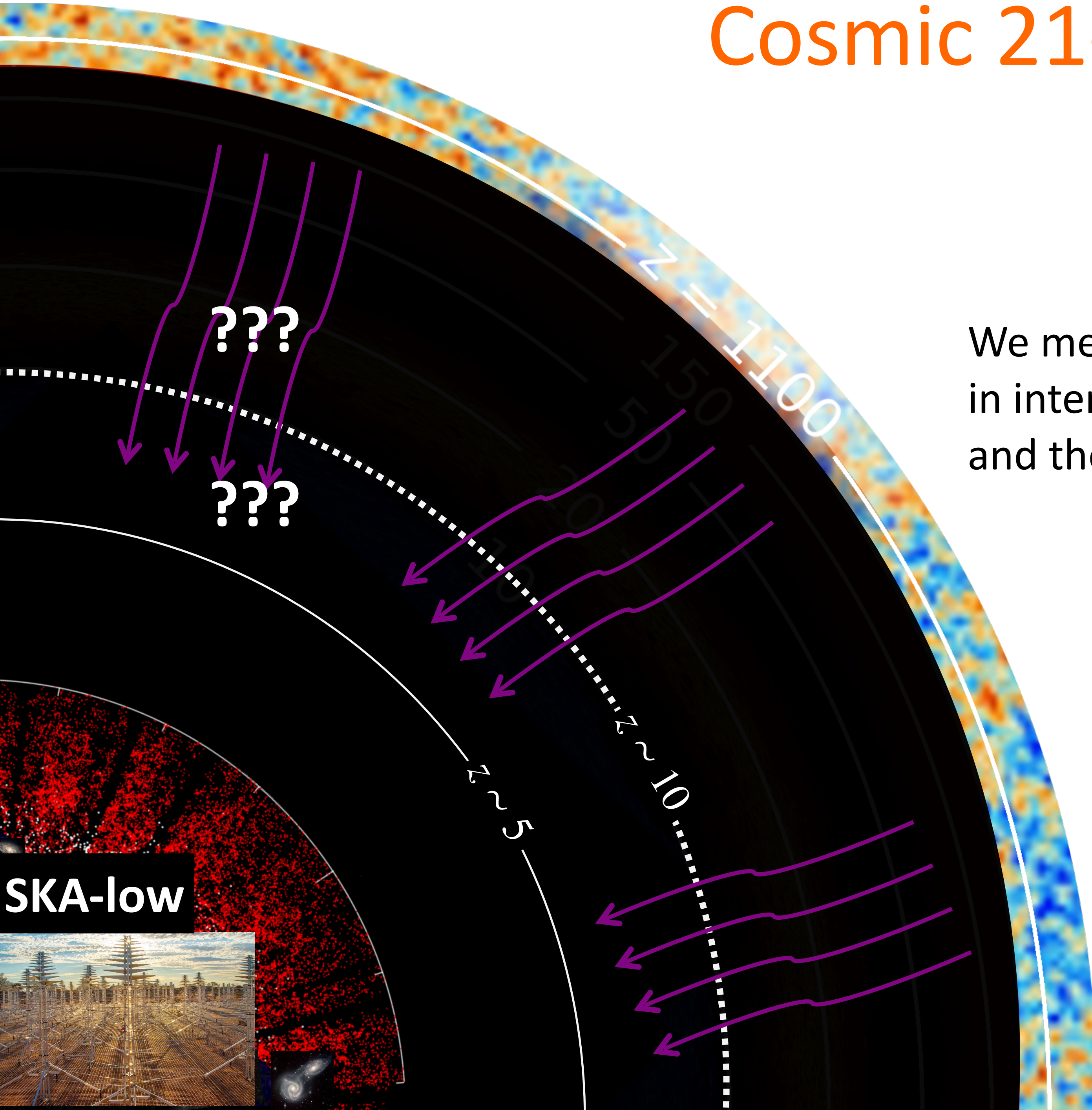
Hyperfine transition in the ground state of neutral hydrogen produces the 21cm line.

It has a “Goldilocks” optical depth for HI!

Cosmic 21-cm

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

Cosmic 21-cm



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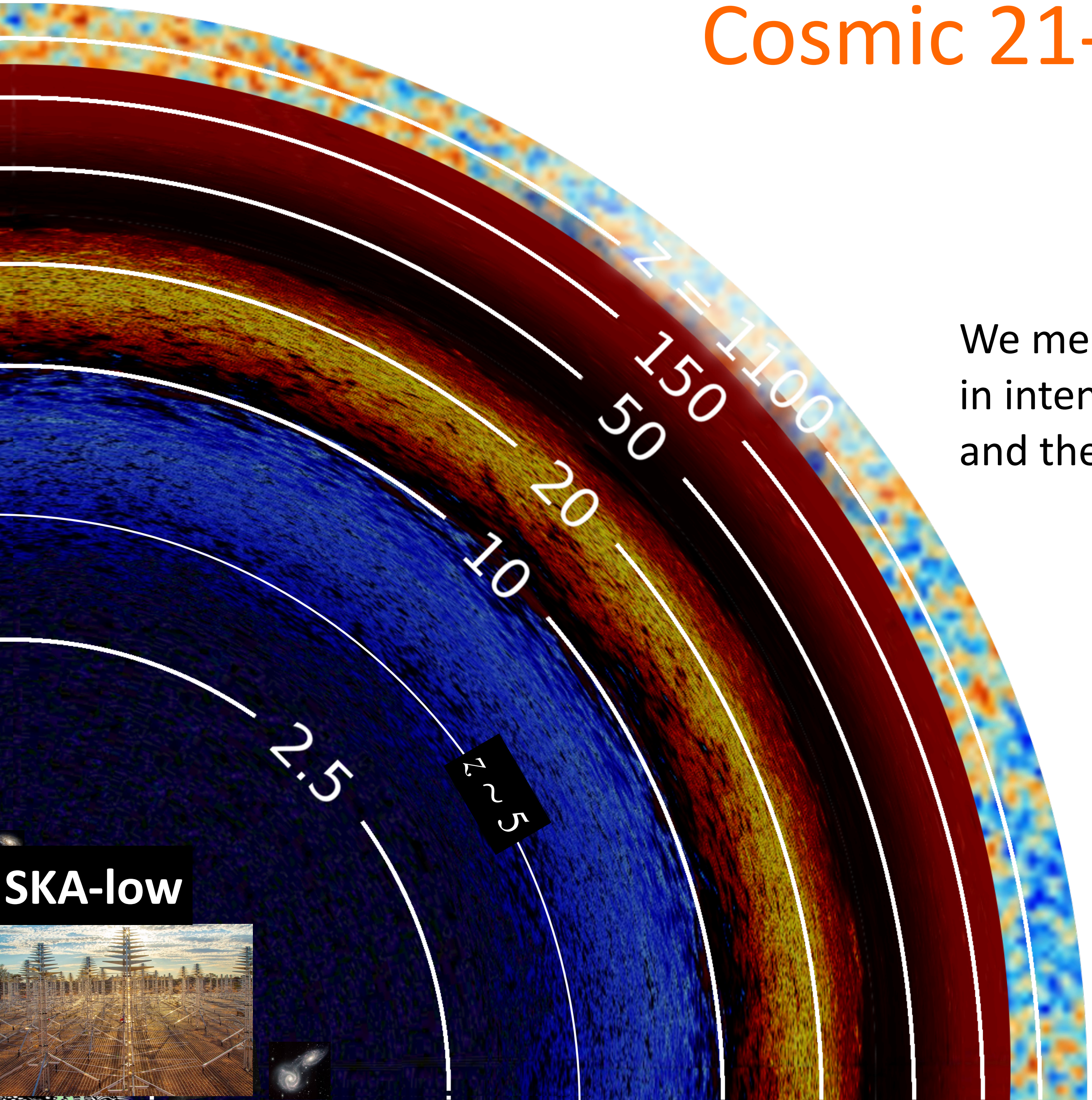
Cosmic 21-cm



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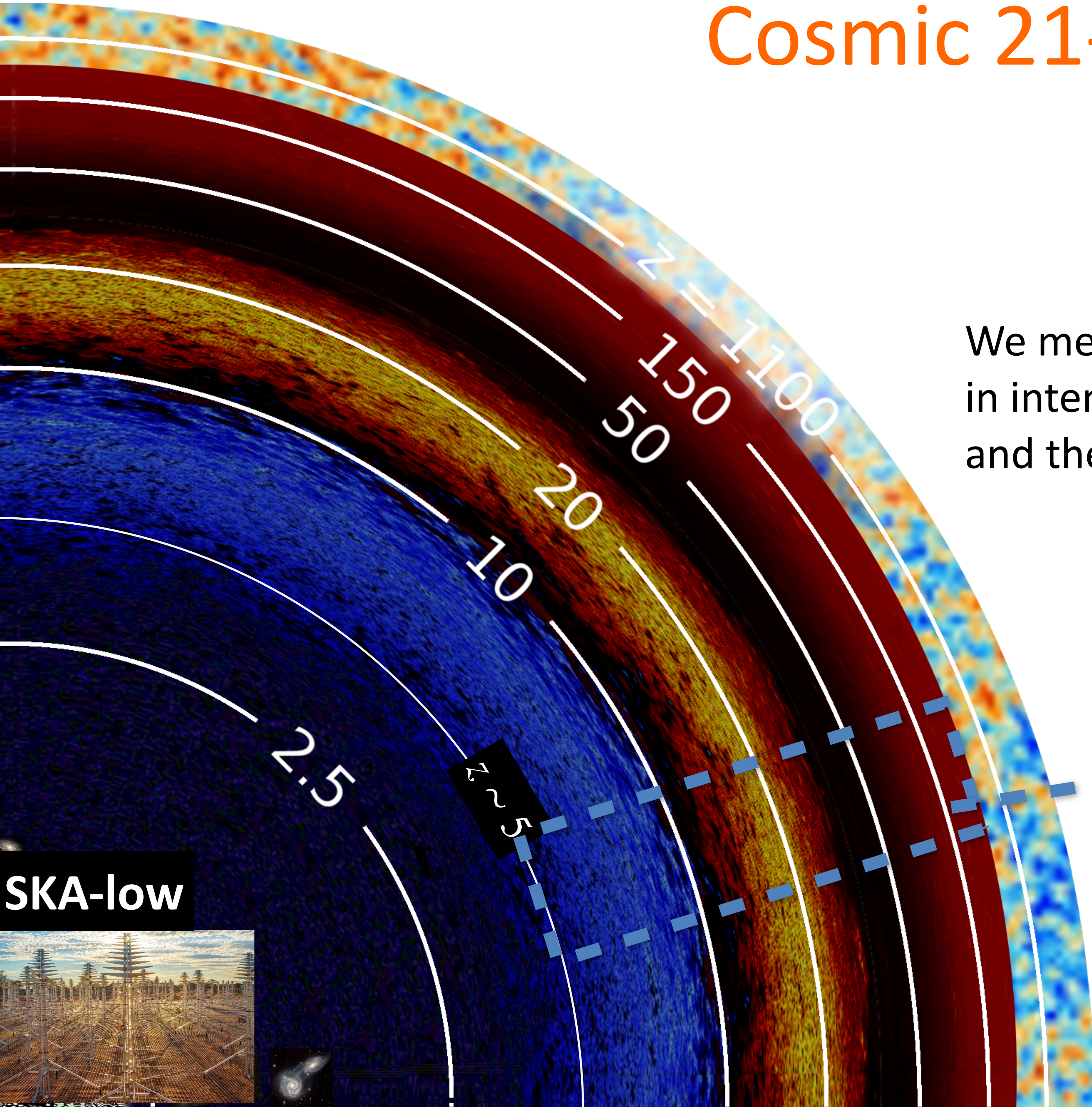
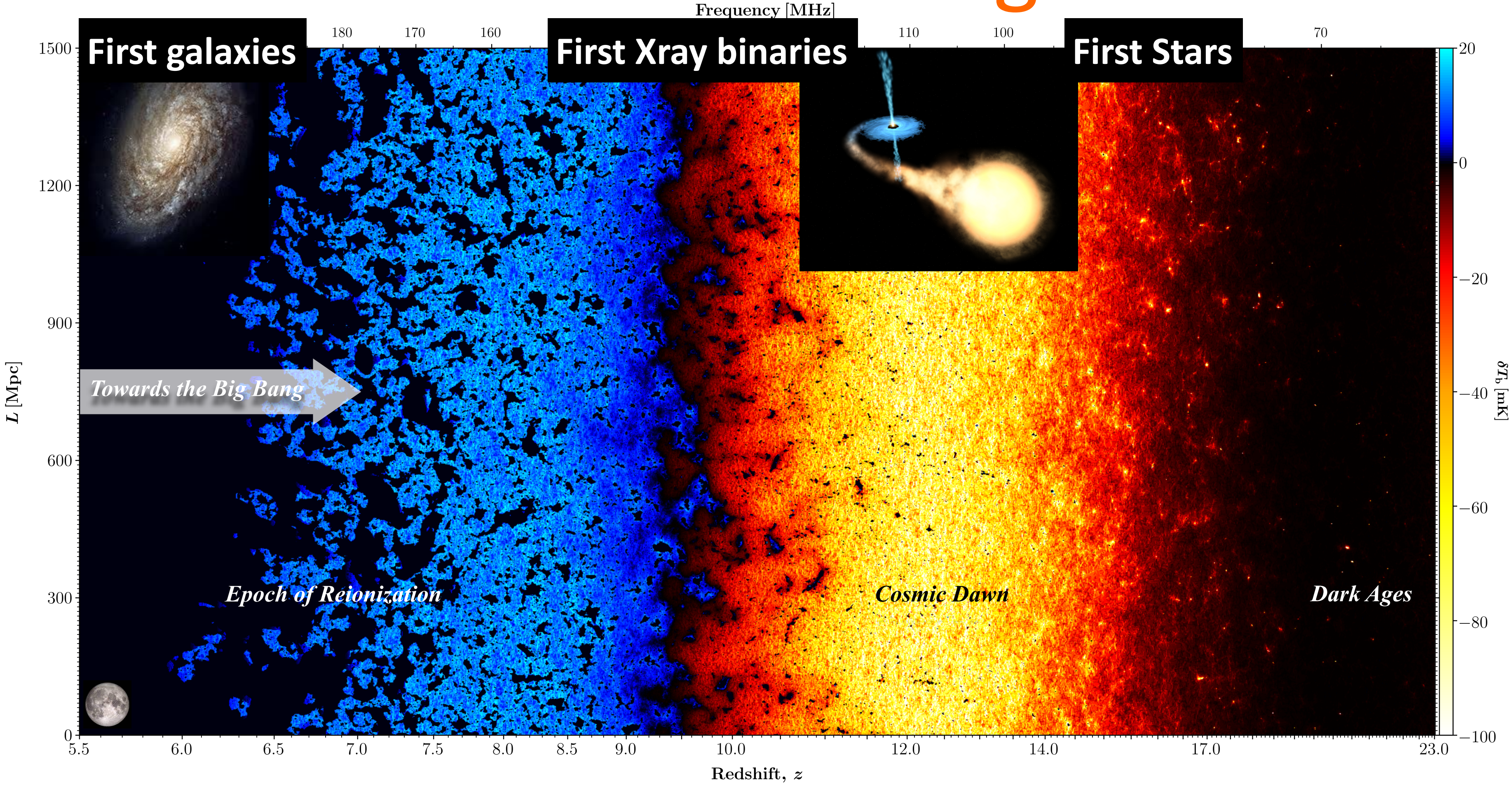
Cosmic 21-cm



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

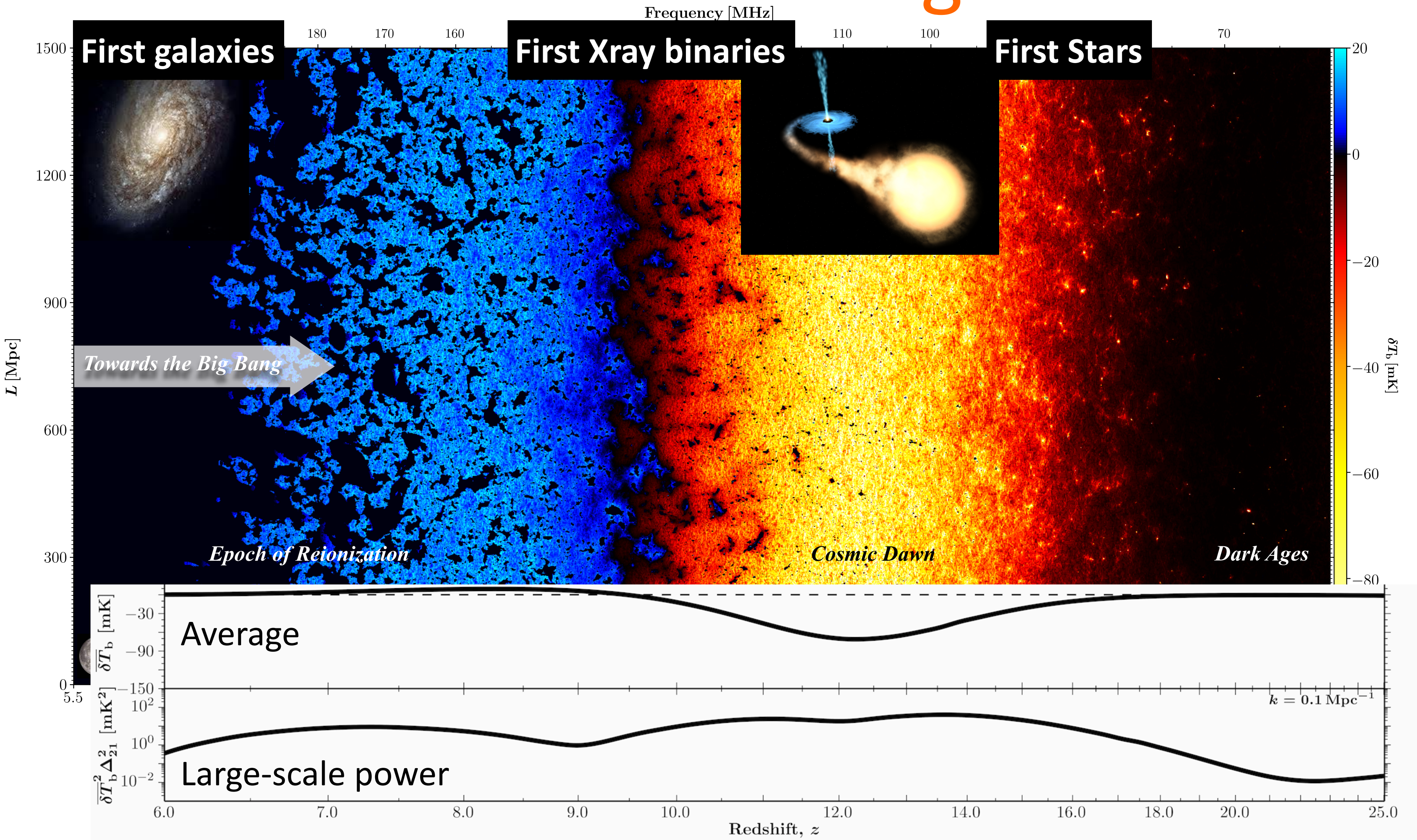
Cosmic 21-cm signal



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

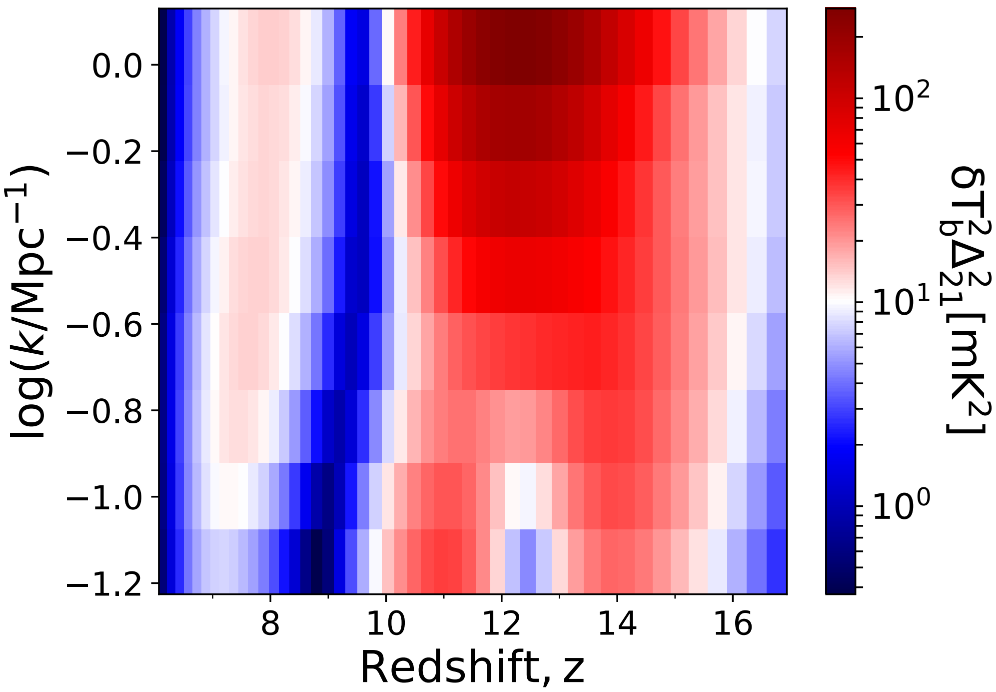
Figure courtesy of J. Park

Cosmic 21-cm signal



The SKA will detect the power spectrum of these fluctuations with very high signal to noise

1D power spectrum from "fiducial model"



characteristic "three-peak" structure of the cosmic signal

Kaur, Gillet, **AM** (2020)

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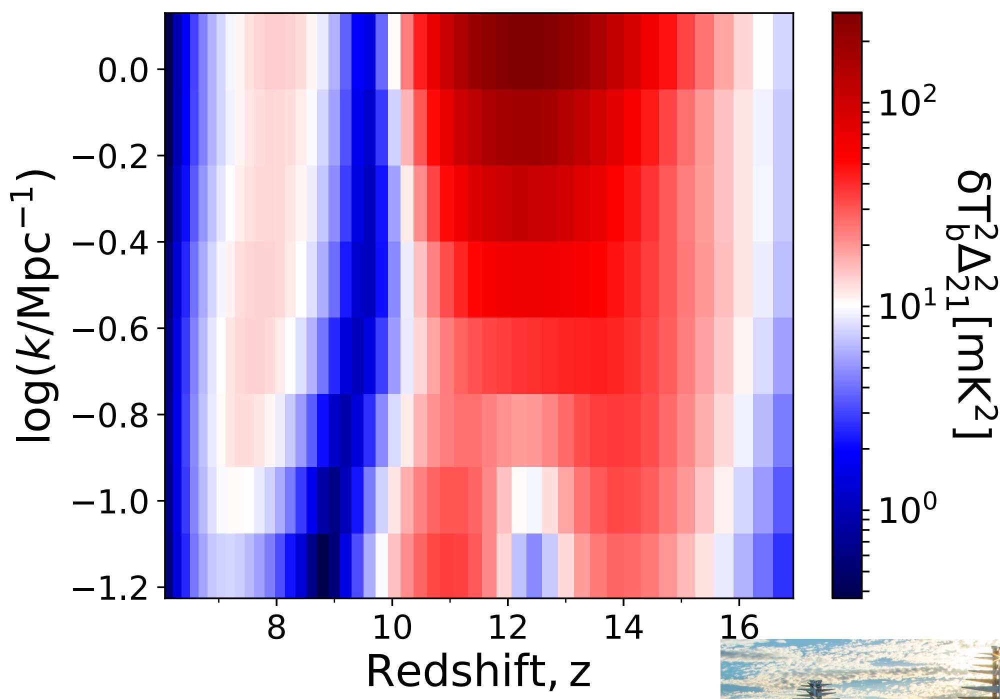
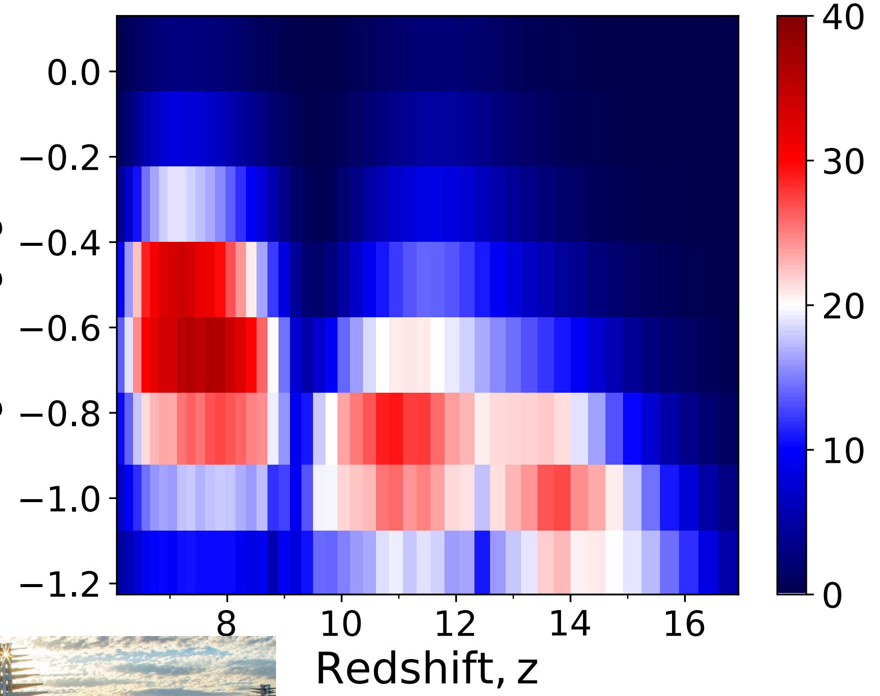
1D power spectrum from "fiducial model"



S/N from a 1000h SKA-low observation

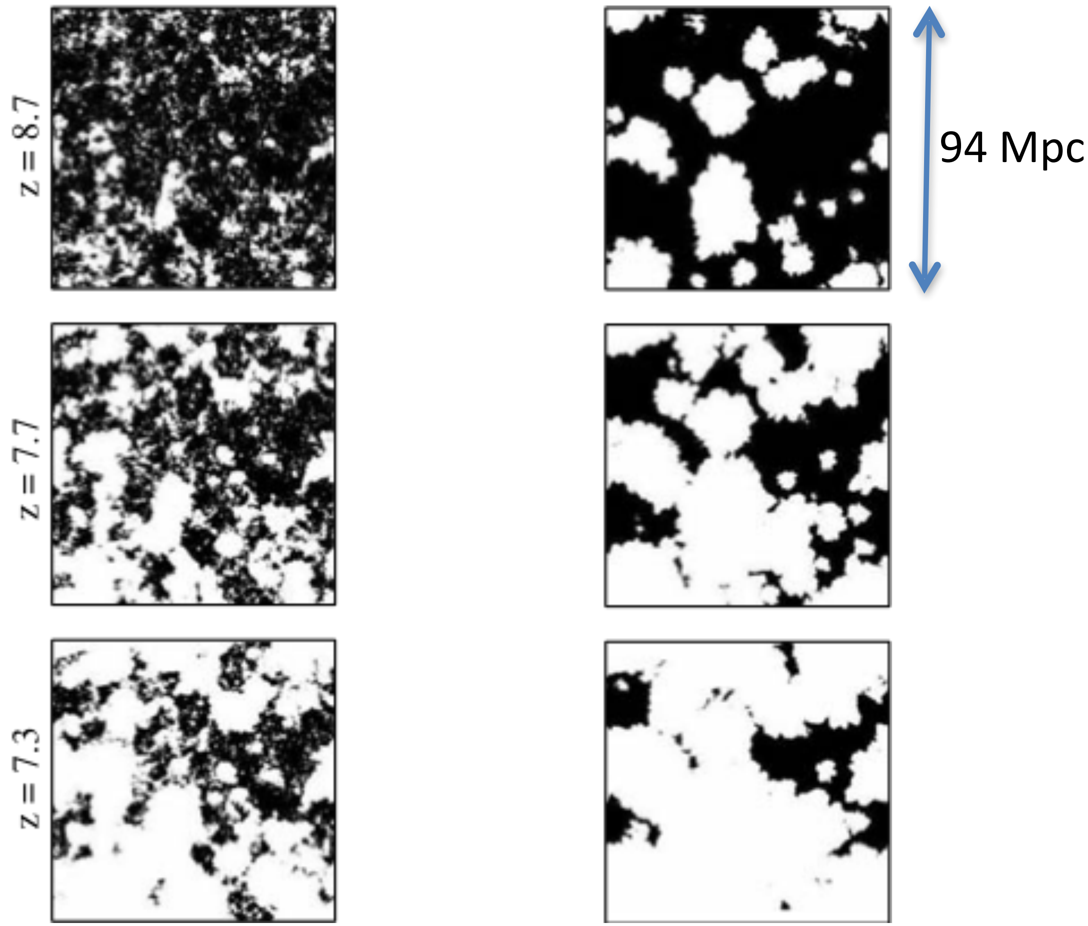


Kaur, Gillet, **AM** (2020)

So how do we learn about the unseen, "typical" galaxies and physical cosmology, from the cosmic 21-cm signal?

Timing of reionization and the properties of the (unseen) galaxies that drive it

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

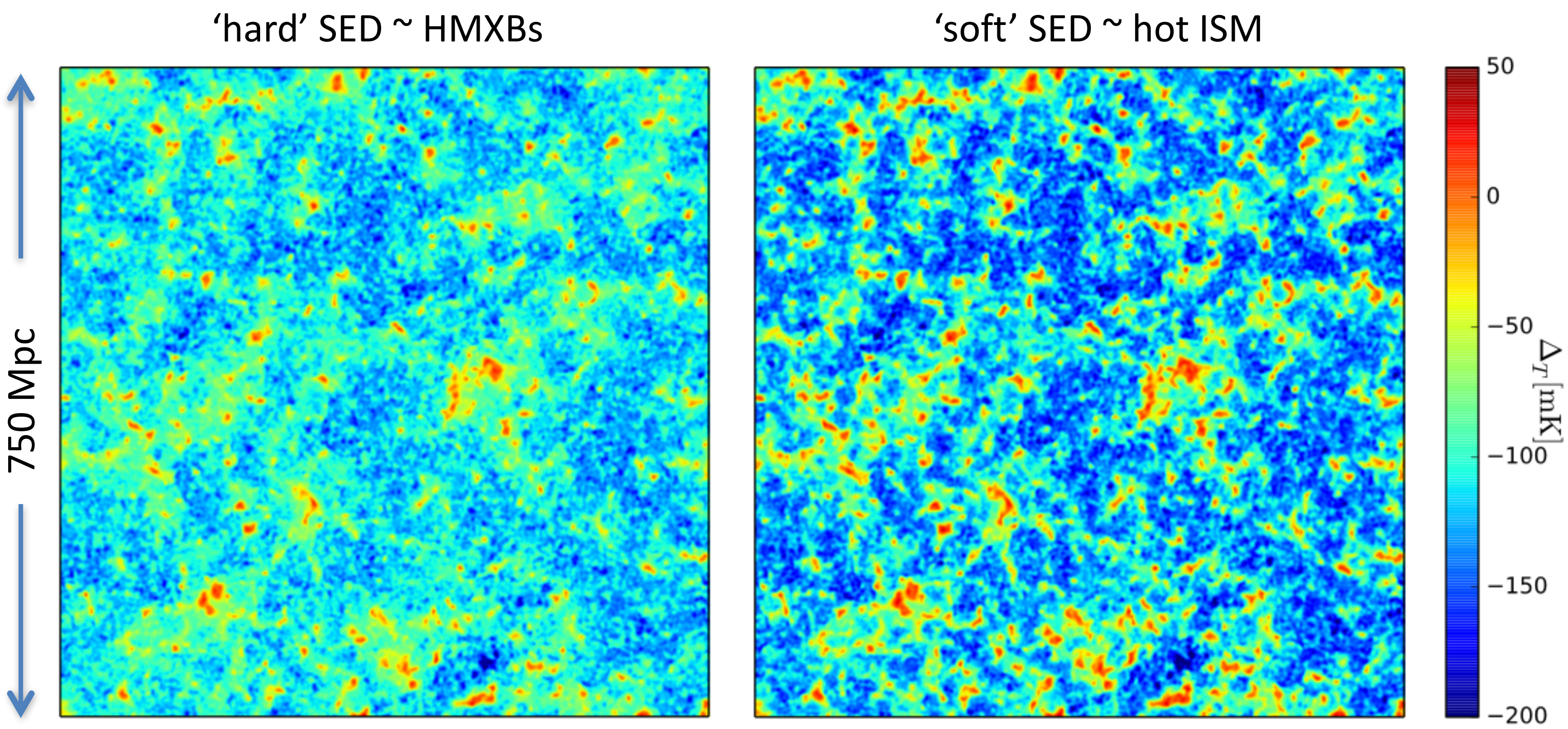


McQuinn+ 2007

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

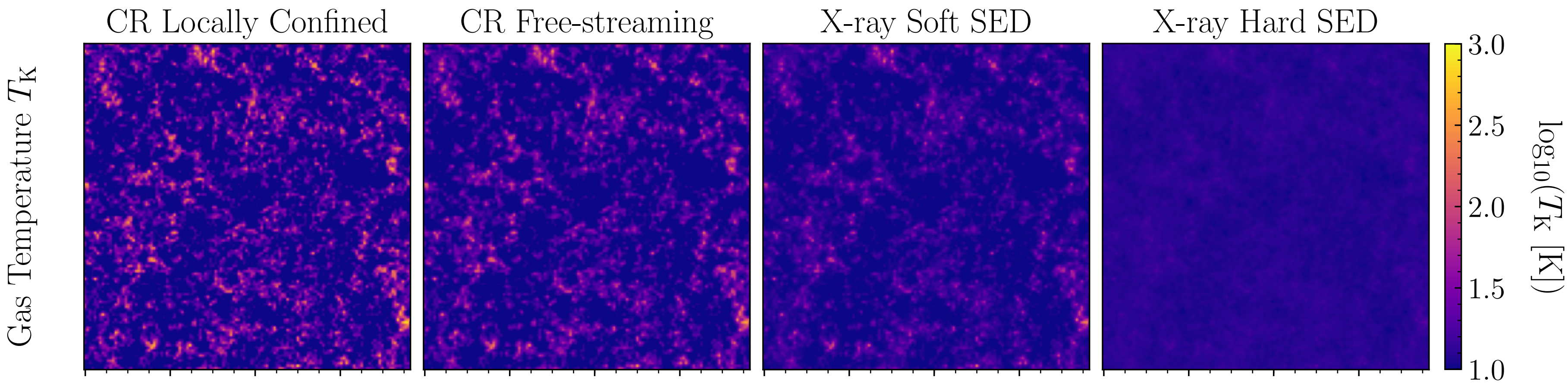


differences are easily detectable with HERA and the SKA

Pacucci, AM + 2014

More exotic sources of early IGM heating?

- Cosmic Rays? (e.g. Leite+2017; Jana and Nath 2018; Gessey-Jones+2023)



Gessey-Jones+2023

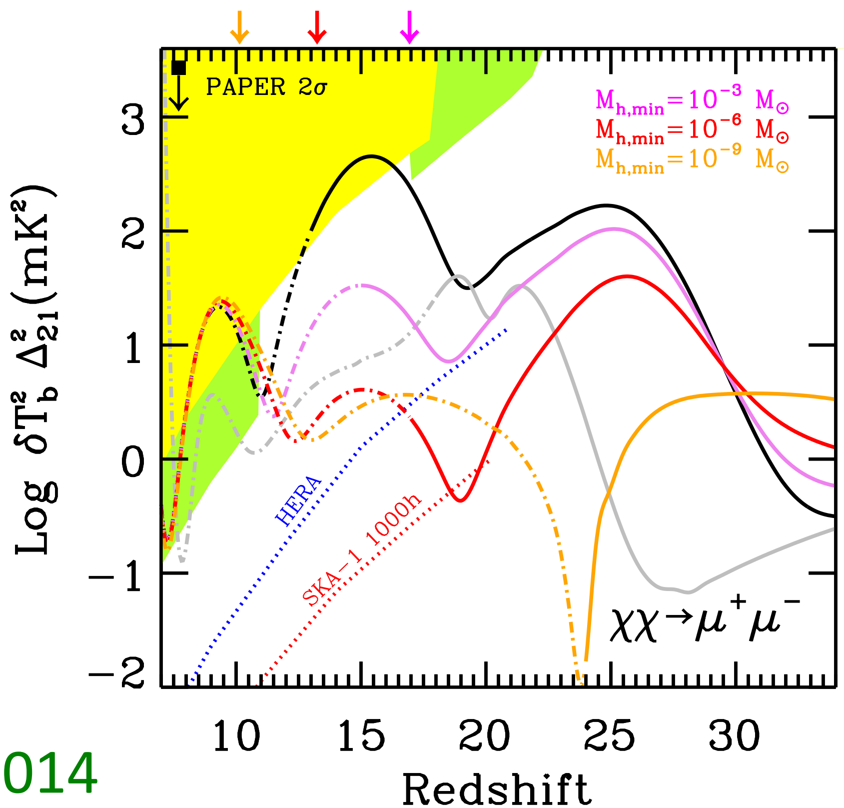
Different mean free paths —> patchiness of heating

More exotic sources of early IGM heating?

- Cosmic Rays? (e.g. Leite+2017; Jana and Nath 2018; Gessey-Jones+2023)

- Dark matter annihilations? (e.g. Evoli+2014; Lopez-Honorez+2016)

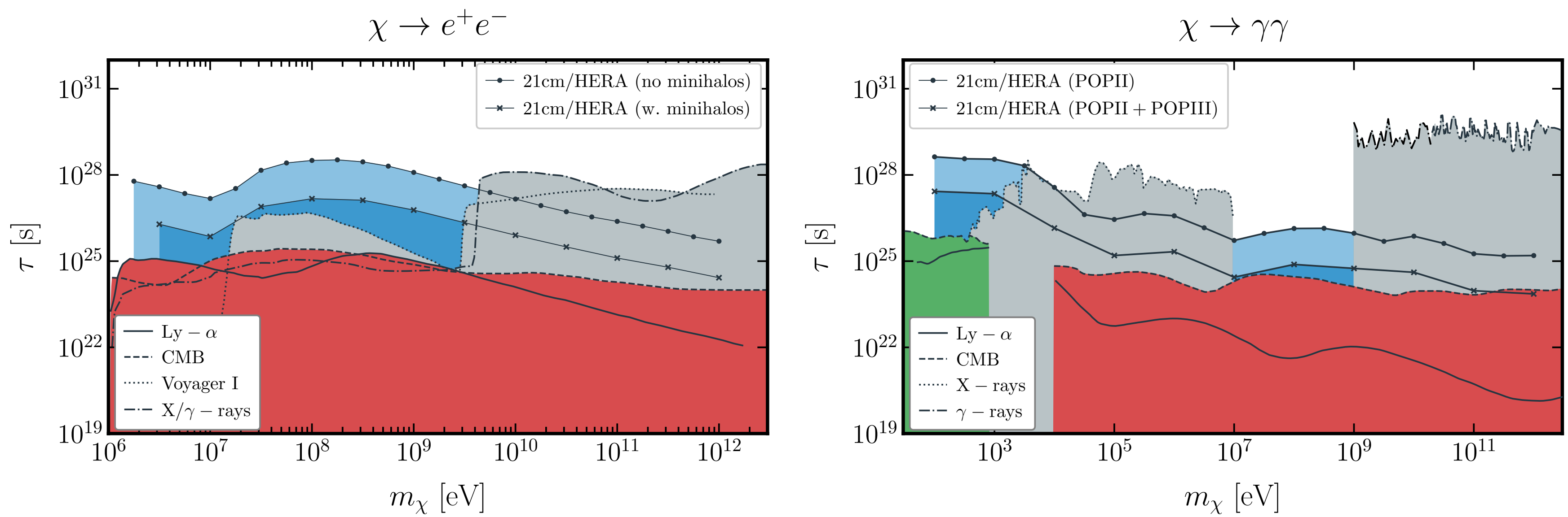
heating is more uniform —>
not degenerate with galaxy heating



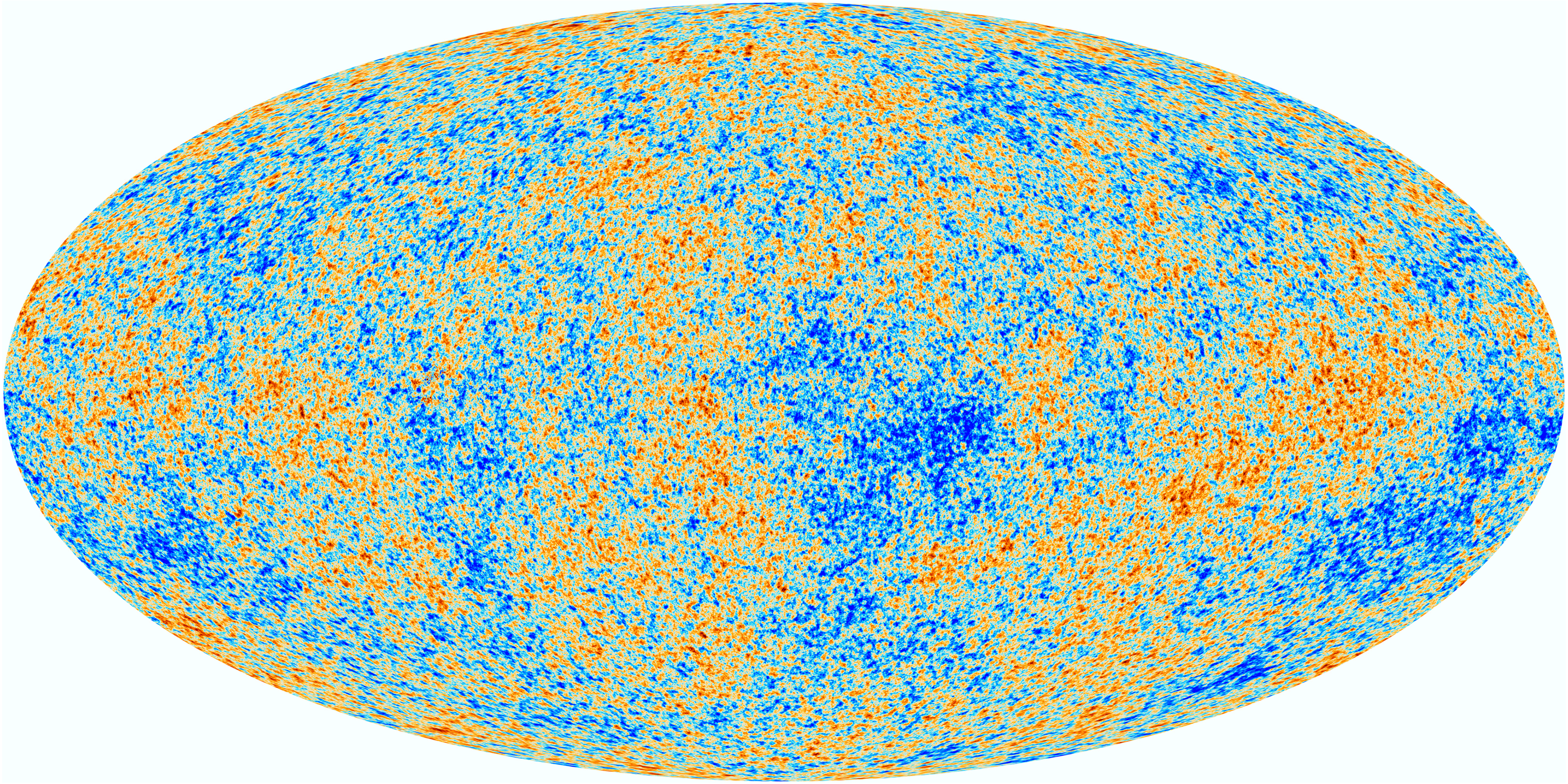
Evoli, AM+2014

More exotic sources of early IGM heating?

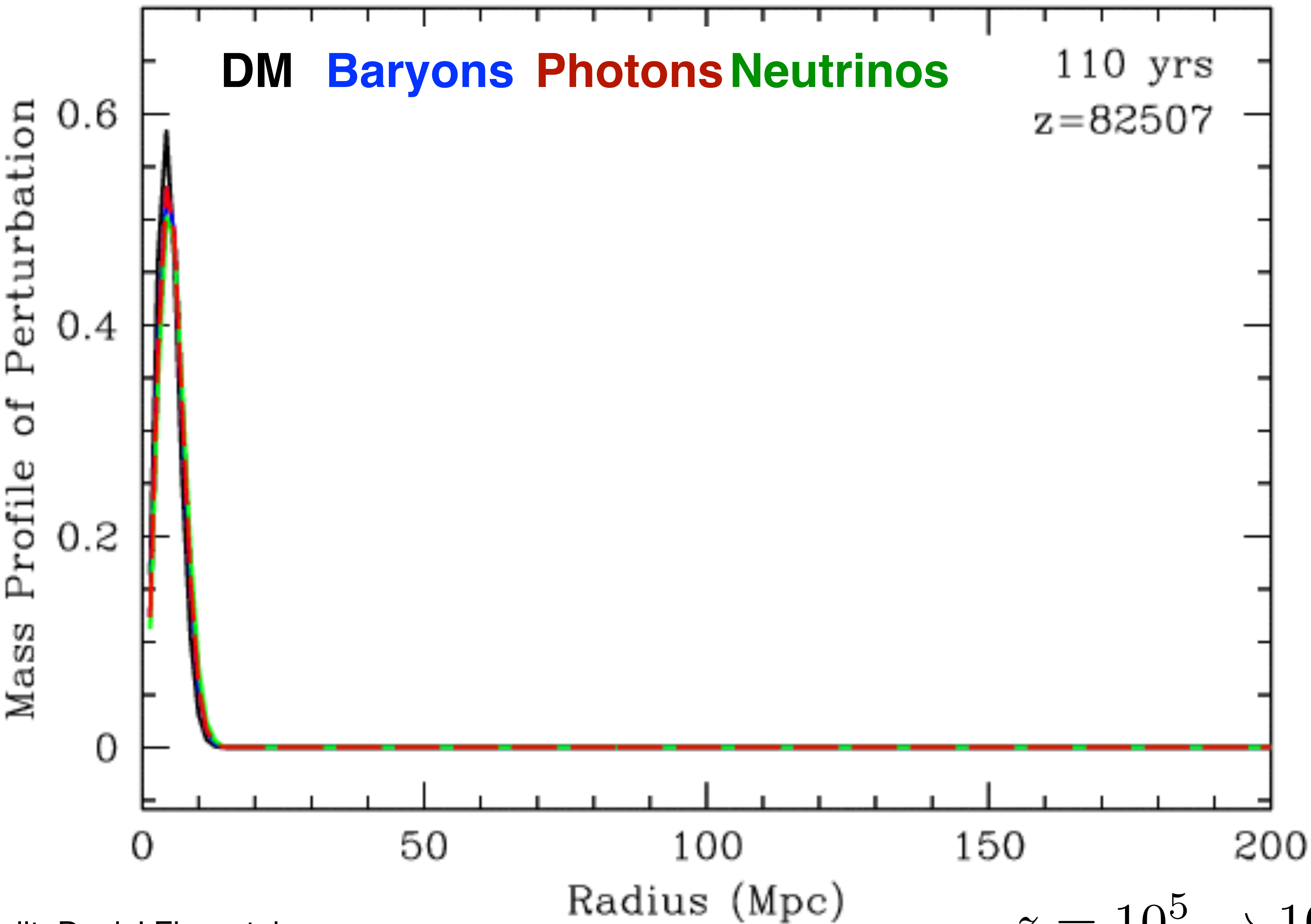
- Cosmic Rays? (e.g. Leite+2017; Jana and Nath 2018; Gessey-Jones+2023)
- Dark matter annihilations? (e.g. Evoli+2014; Lopez-Honorez+2016)
- Dark matter decay? (e.g. Facchinetti+ 2023)



A snapshot of the baryons at z=1100



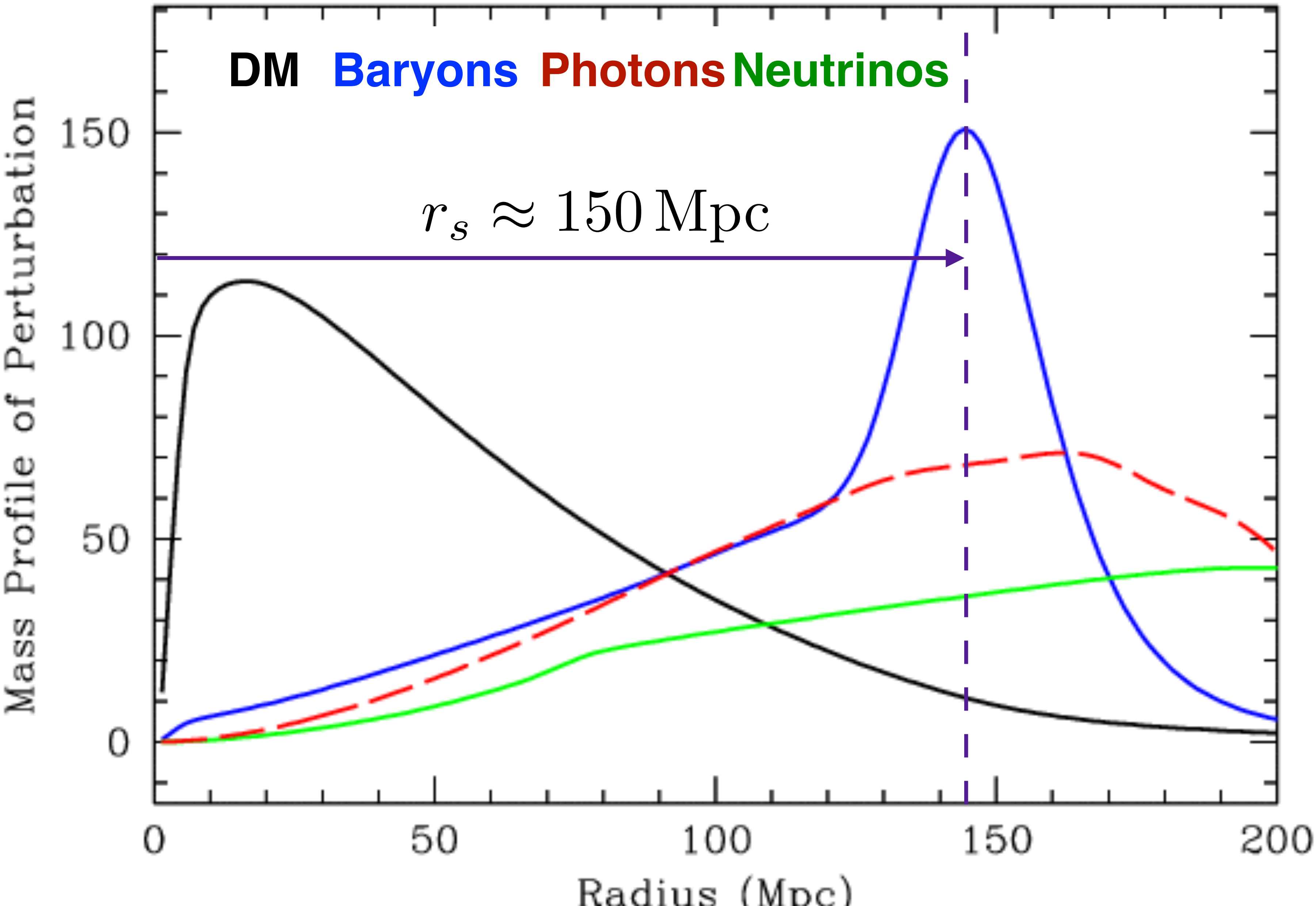
But DM decouples earlier



Credit: Daniel Eisenstein

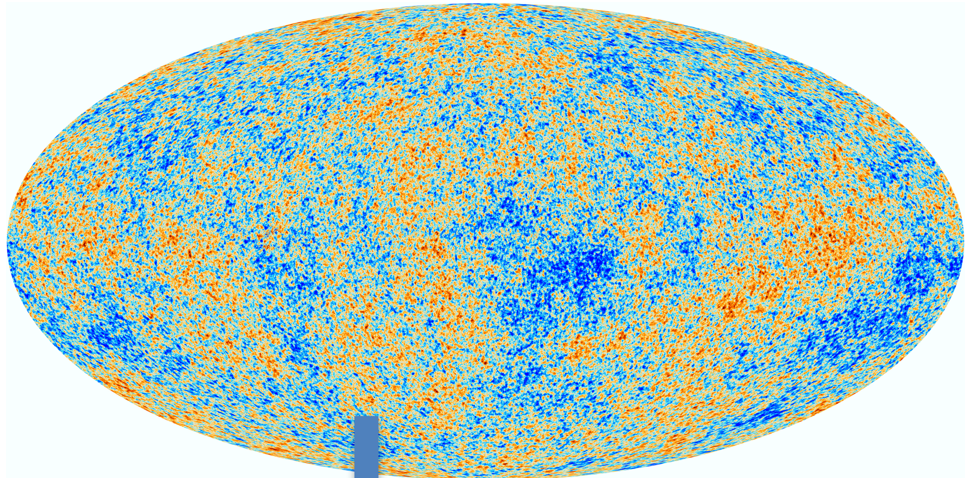
$z = 10^5 \rightarrow 10^3$

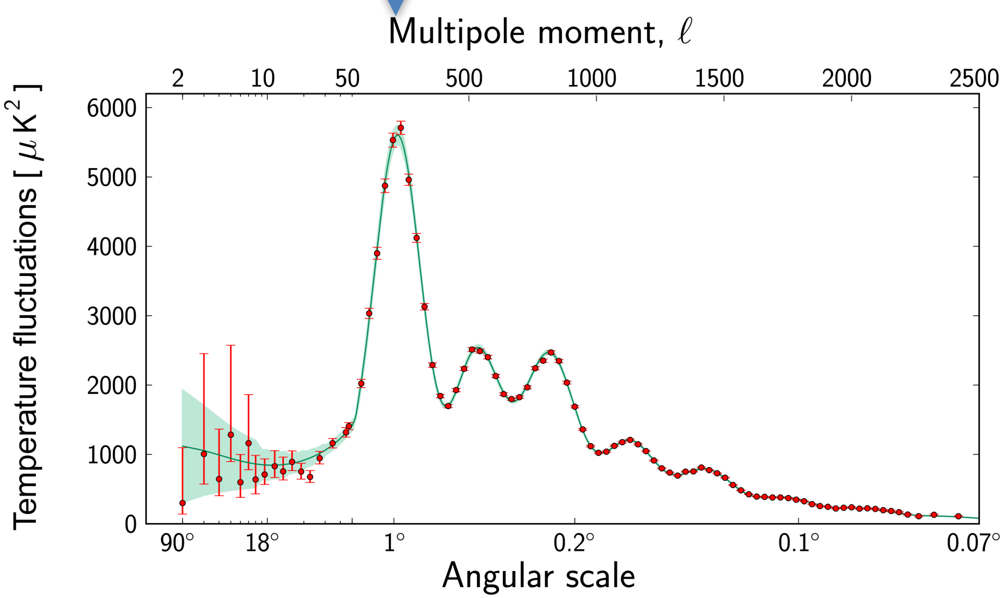
Baryon Acoustic Oscillations



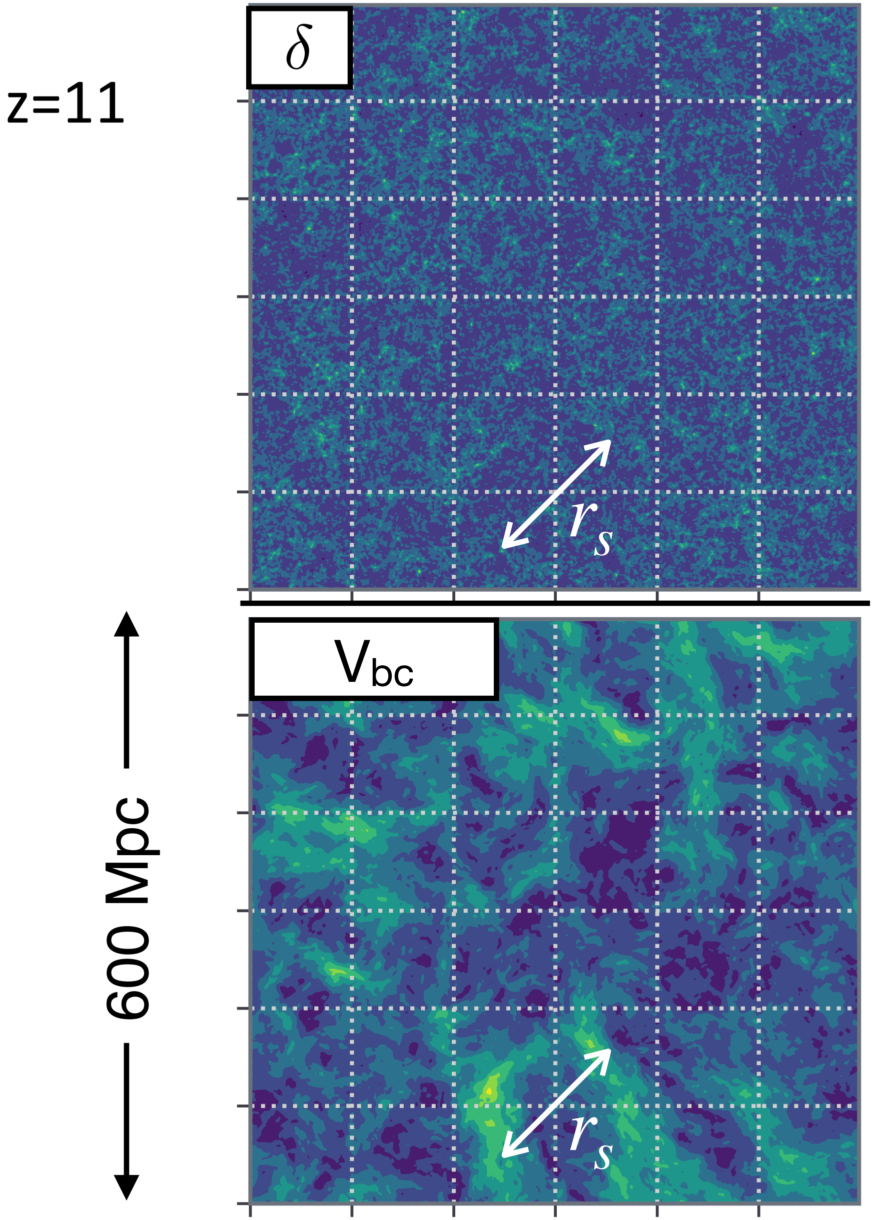
Credit: Daniel Eisenstein

A preferred distance scale





Acoustic oscillations -> standard ruller in v_{bc}



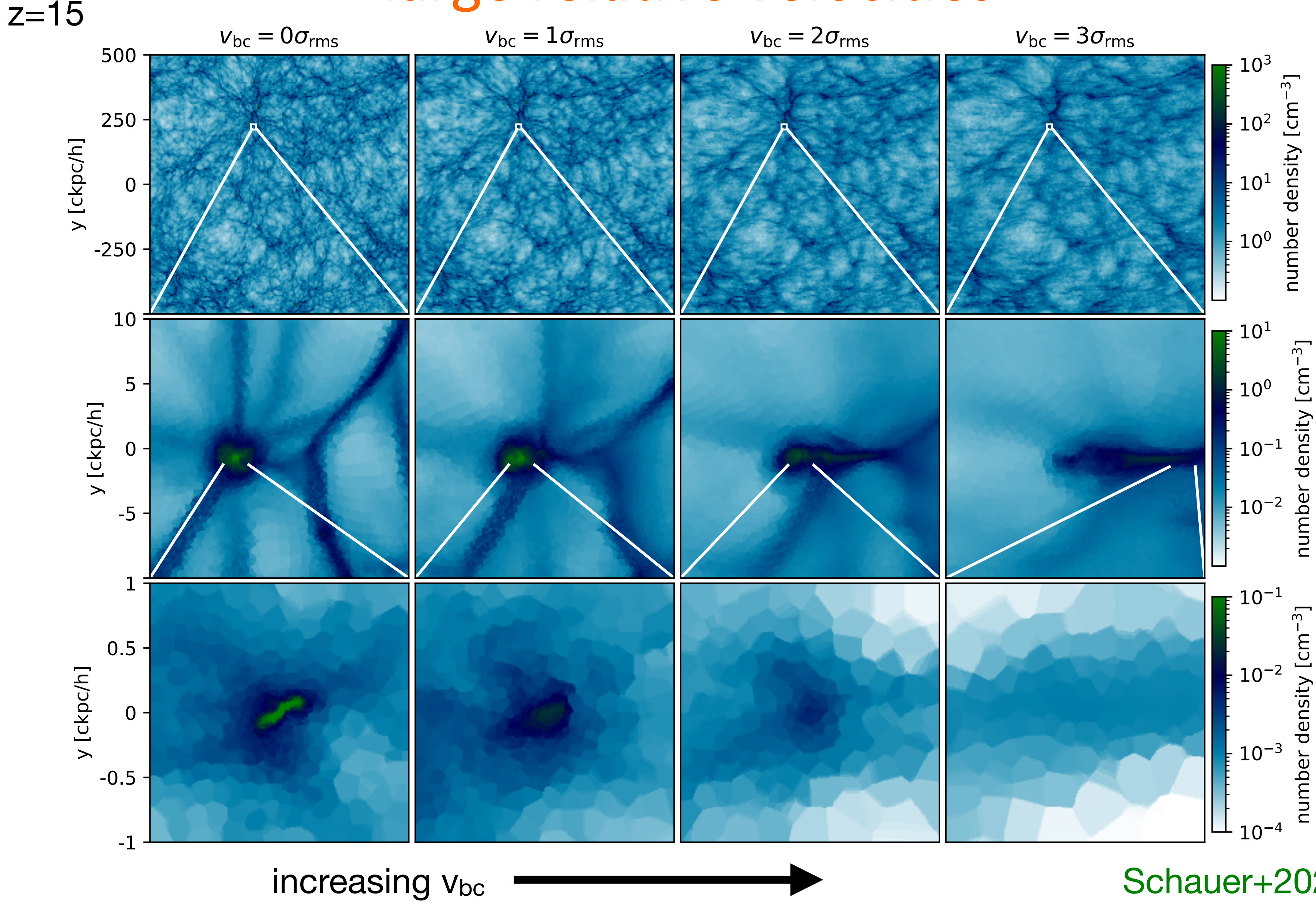
density contrast

relative velocities

Munoz, Qin, **AM**+2022

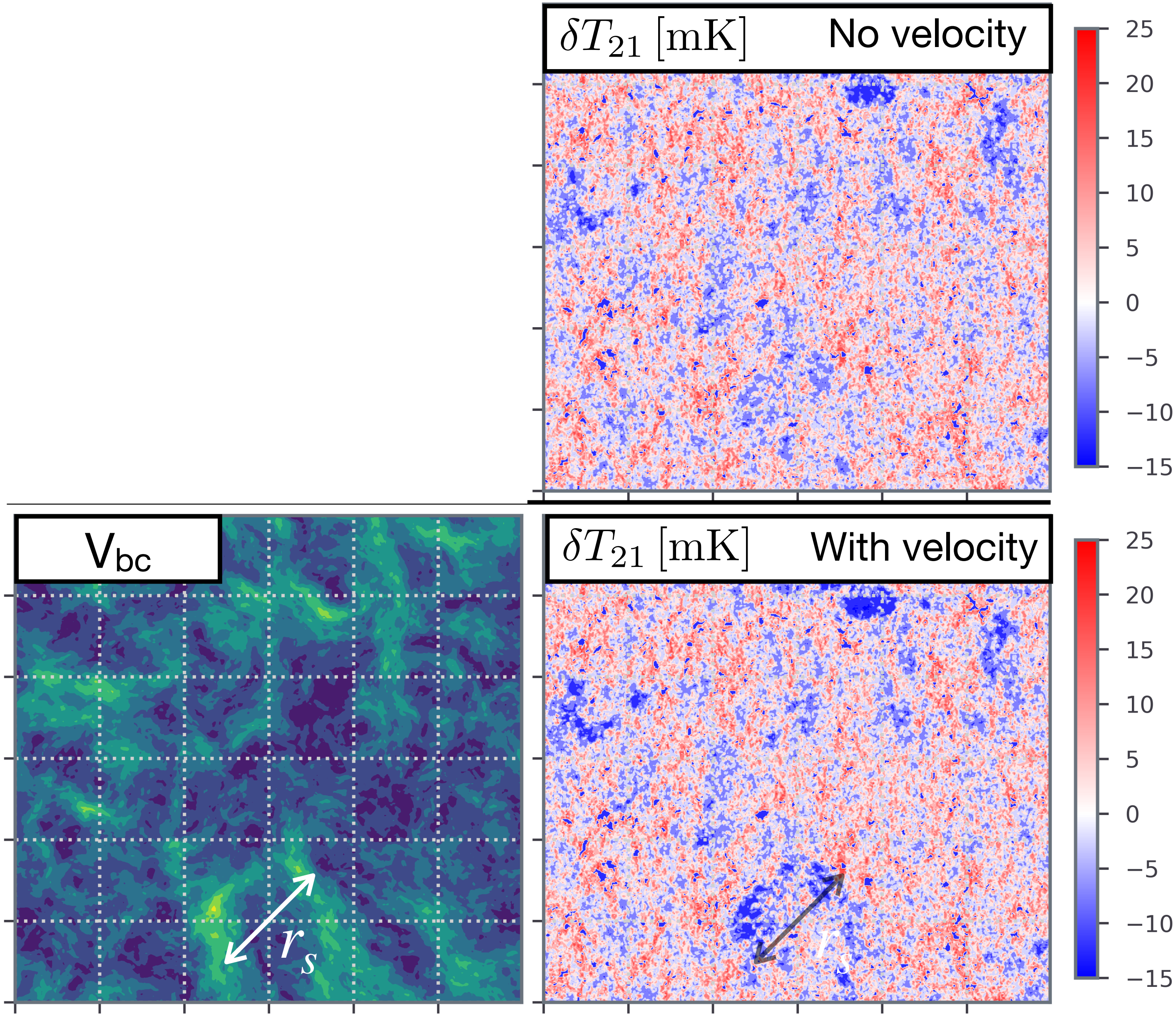
v_bc pointed out by Tseliakhovich & Hirata 2010

Star formation is suppressed in regions with large relative velocities



Schauer+2021

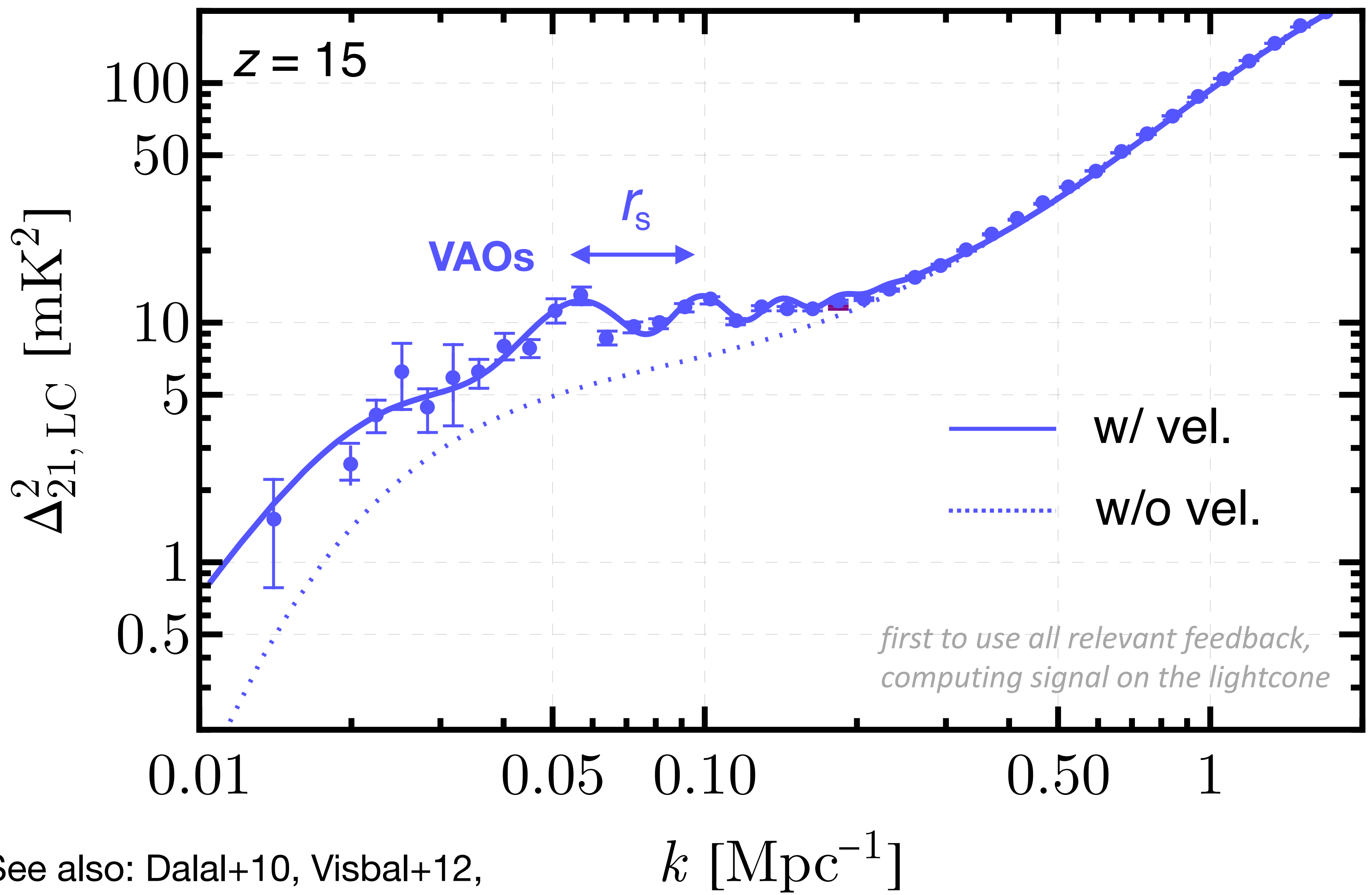
Acoustic oscillations -> standard ruller in v_{bc}



Munoz, Qin, **AM**+2022

v_bc pointed out by Tseliakhovich & Hirata 2010

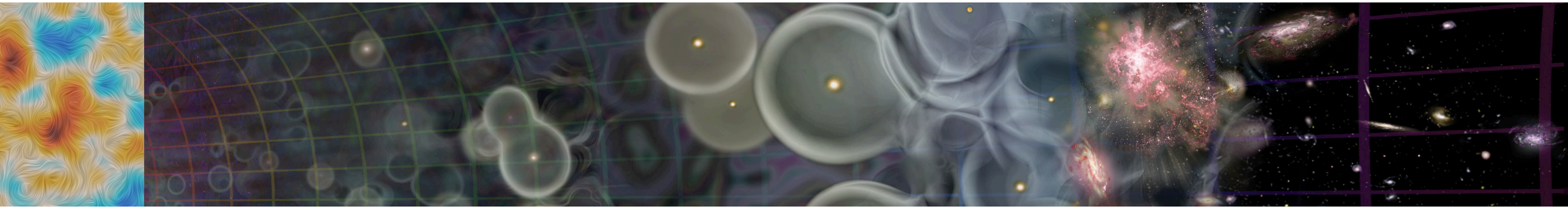
Standard ruler

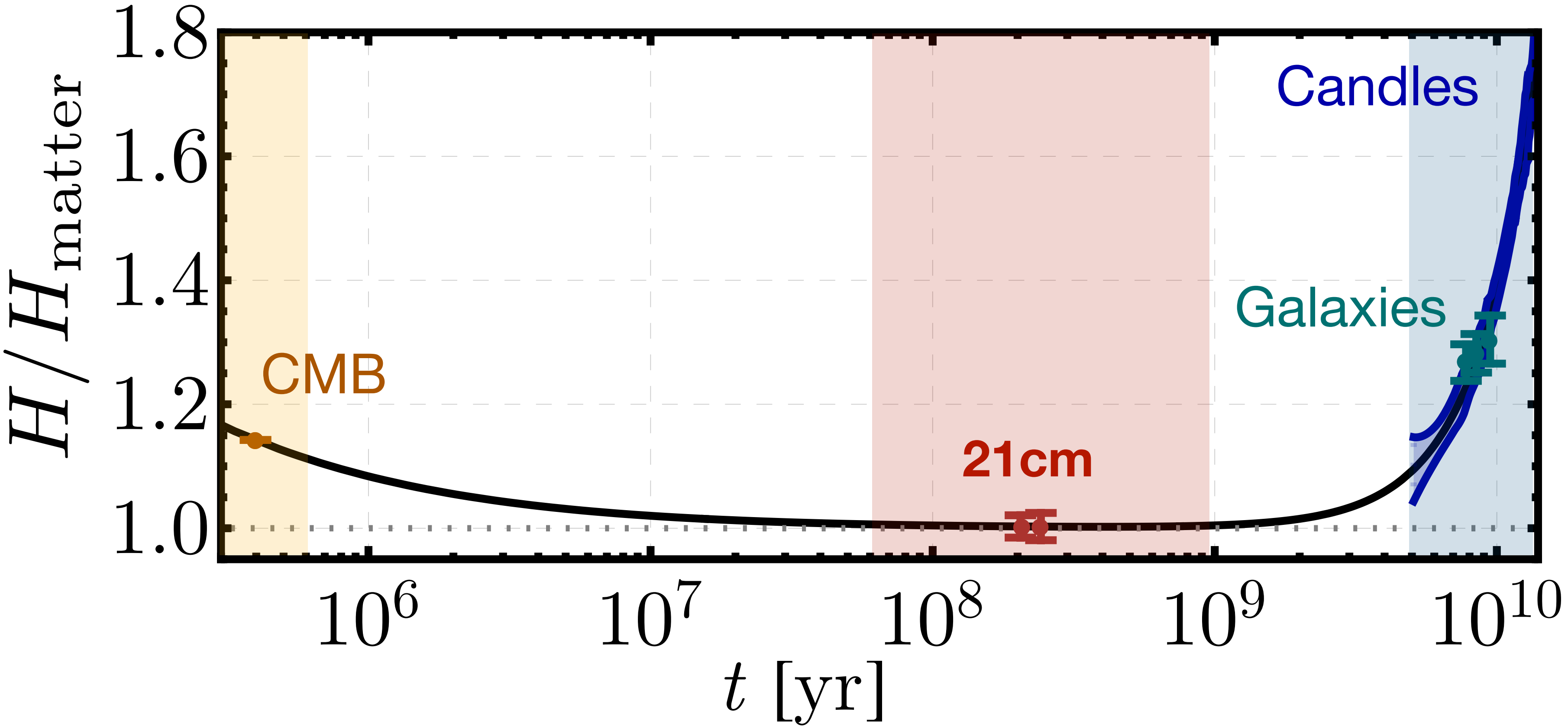


See also: Dalal+10, Visbal+12, Fialkov+12, McQuinn+12 Munoz 19, Park+19, Cain+20, Sarkar+22

Munoz, Qin, AM+ 2022

Measuring the expansion history





Munoz+ 2019

That sounds great, but where are we now?

First generation 21-cm interferometers

MWA

LOFAR

GMRT

PAPER

HERA

Observing is HARD!

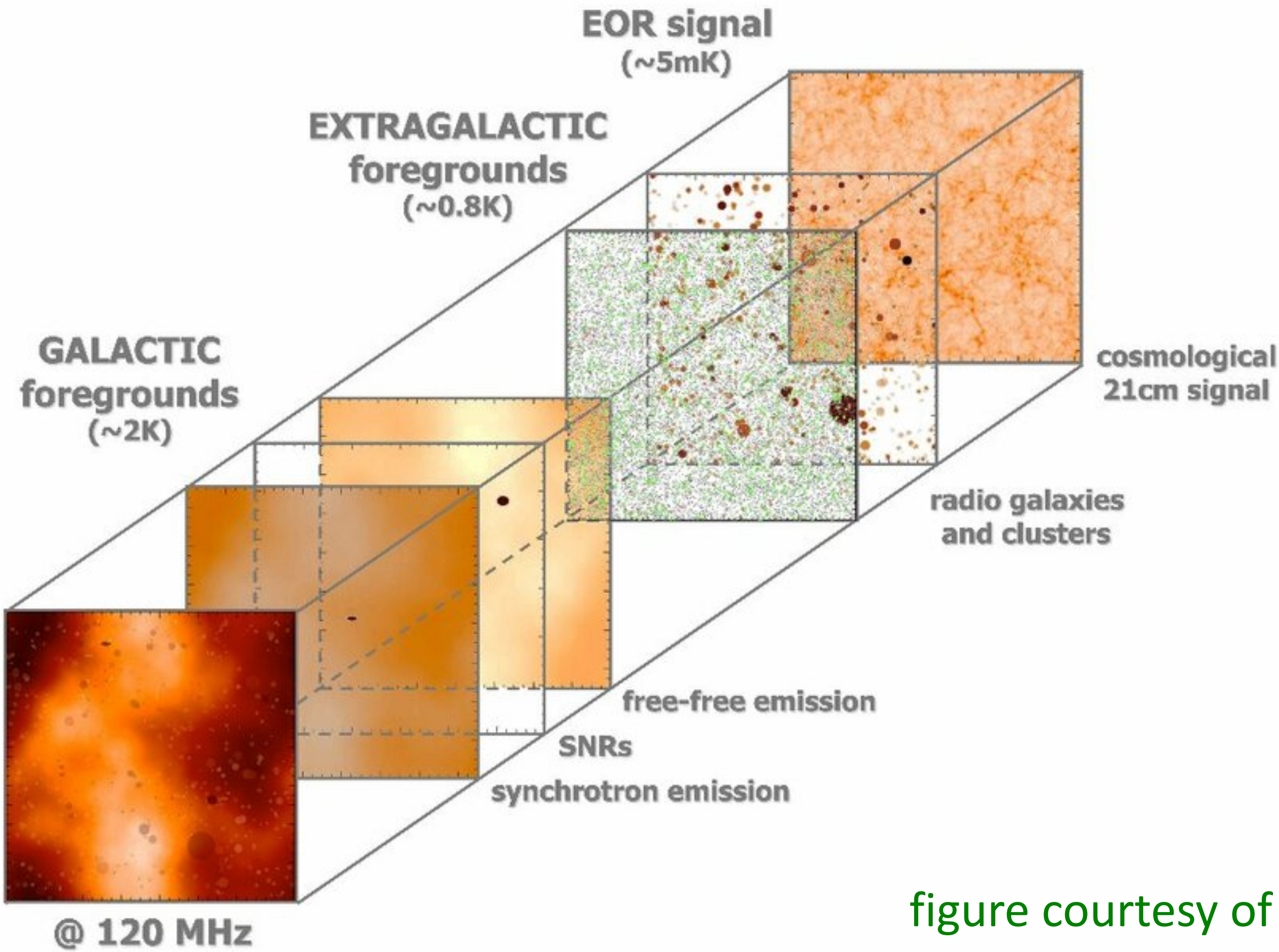
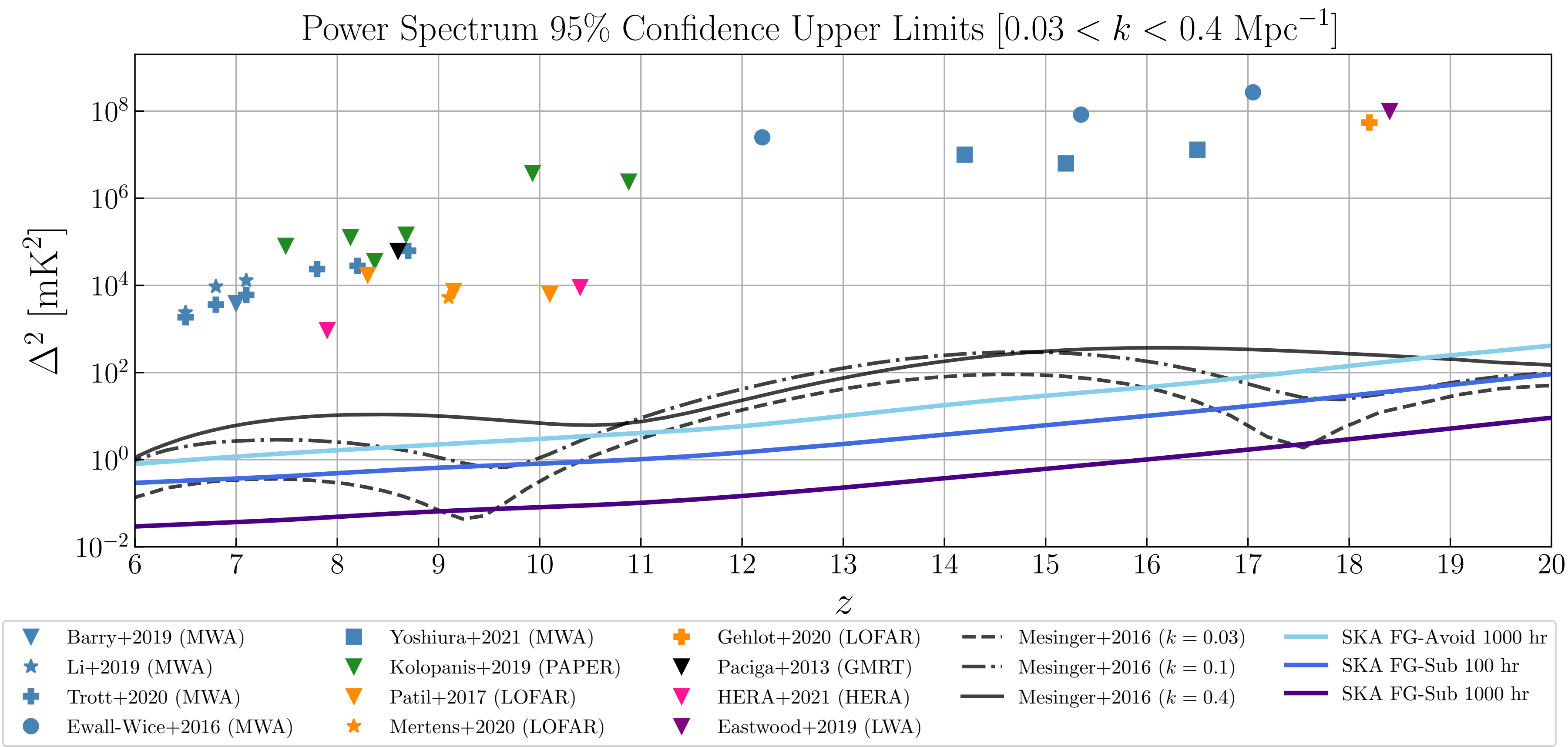


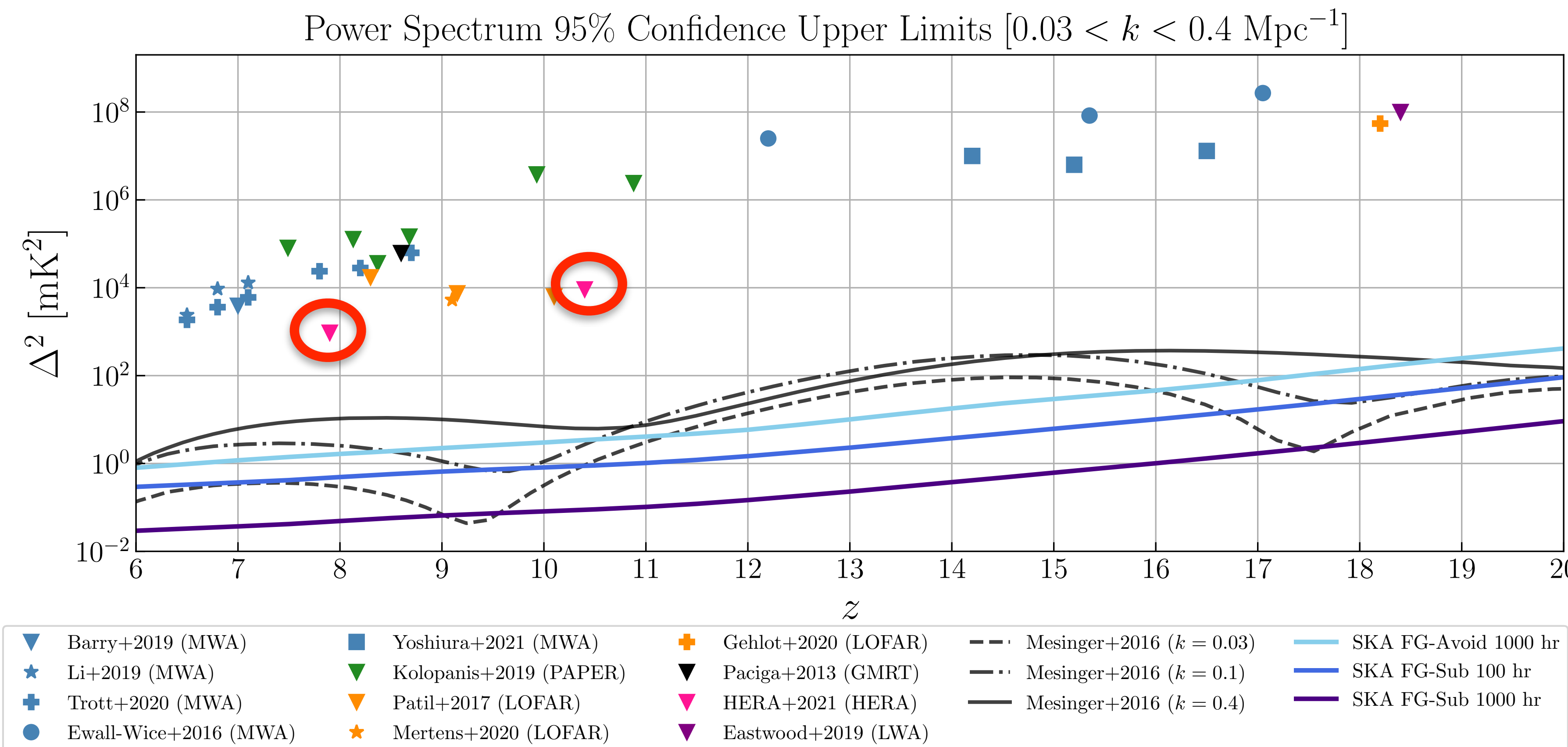
figure courtesy of V. Jelić

Measurements are improving, but currently only upper limits on the PS



Barry+ 2022

Currently only upper limits on the PS



Application to **HERA** (HERA collaboration 2022ab).

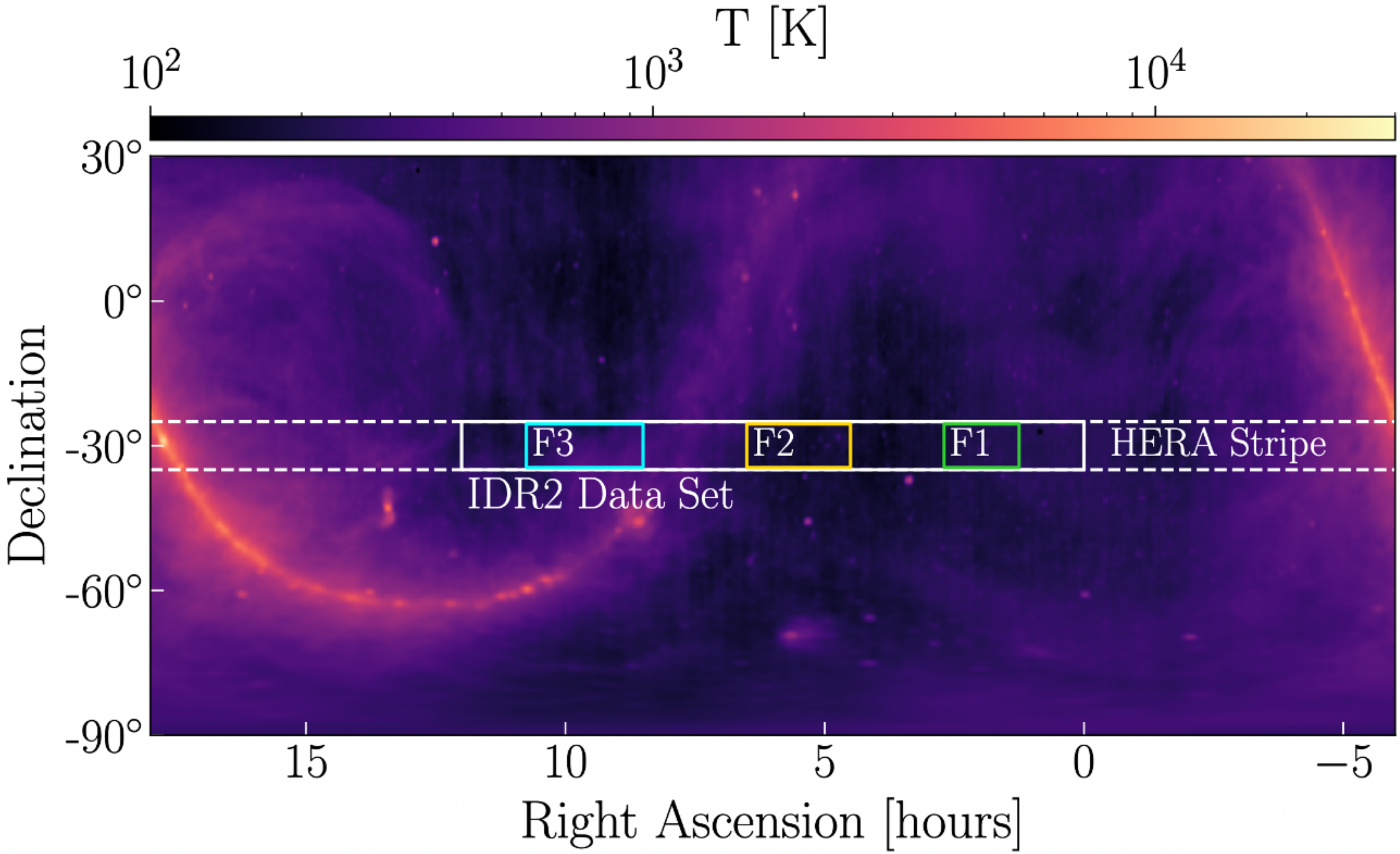
For similar studies on **LOFAR** and **MWA** data see (Ghara+2020; Mondal+2020; Greig+2020, Greig+2021)

HERA

courtesy: J. Dillon

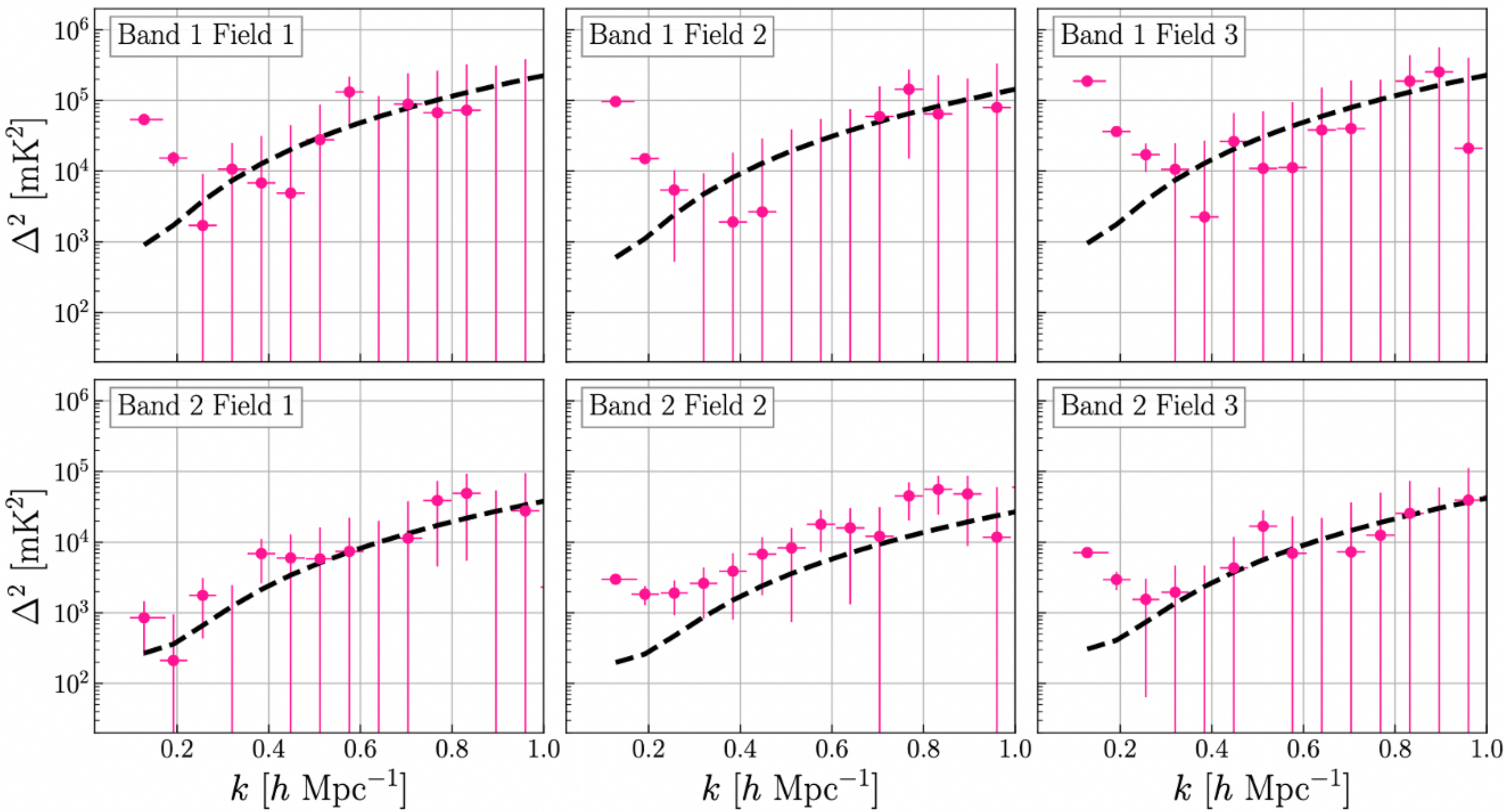
Recent results from HERA

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



HERA collaboration (2022a)

Interpreting recent results from HERA



These are consistent with thermal noise, and are still ~1-2 orders of magnitude above the expected signal

HERA collaboration (2022a; *led by Nick Kern)*

Can we learn something from upper limits that are still x10-100 above the expected signal?

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

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

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~ 0 — 1

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

~ 0.1 — 1

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

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

~ **-10(!)** — 1

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

$$\delta \mathrm{T}_b(\nu) \approx 27 \mathrm{x}_{\mathrm{HI}}(1+\delta_{\mathrm{nl}}) \left(\frac{\mathrm{H}}{\mathrm{dv}_r/\mathrm{dr}+\mathrm{H}}\right) \left(1-\frac{\mathrm{T}_\gamma}{\mathrm{T}_\mathrm{S}}\right) \left(\frac{1+\mathrm{z}}{10}\frac{0.15}{\Omega_\mathrm{M}\mathrm{h}^2}\right)^{1/2} \left(\frac{\Omega_b \mathrm{h}^2}{0.023}\right) \mathrm{mK}$$

Models that are ruled out must have:

COLD IGM: $T_\mathrm{S} \ll T_\gamma$

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

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

Models that are ruled out must have:

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+

Spatial fluctuations *in either:*

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Spatial fluctuations *in either:*

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

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

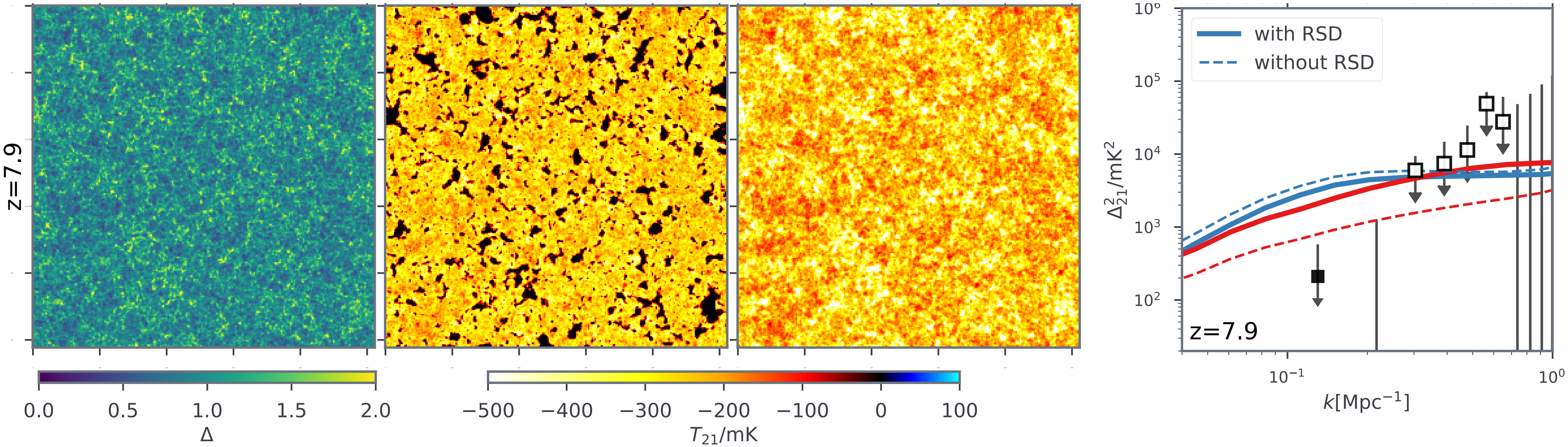
Examples

Density

21cm
COLD + EoR

21cm
COLD + density

21cm power



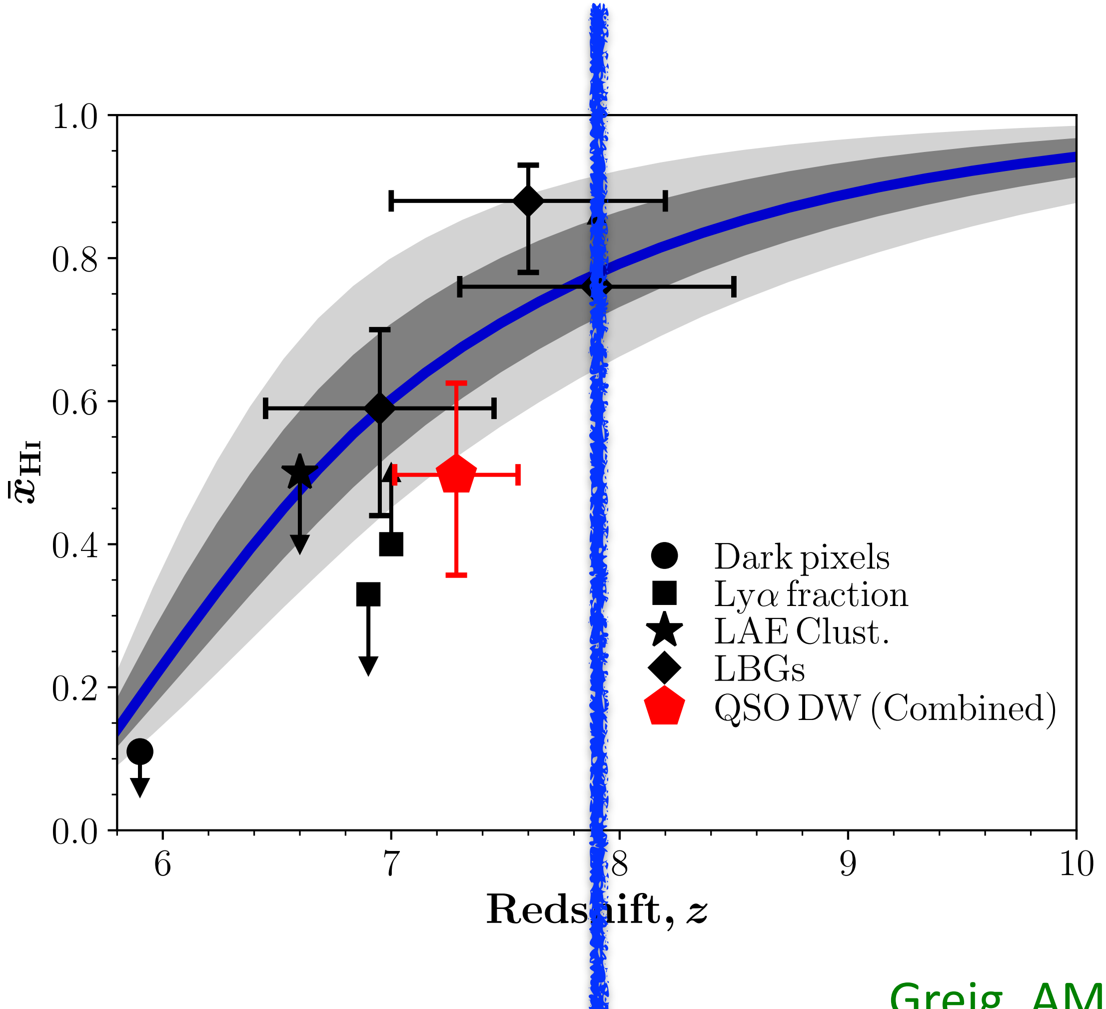
$\bar{x}_{\rm HI} \sim 0.5$ $\bar{x}_{\rm HI} \sim 1$

HERA collaboration (2021)

Current constraints on EoR history

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

HERA band 2



Greig, AM+2021

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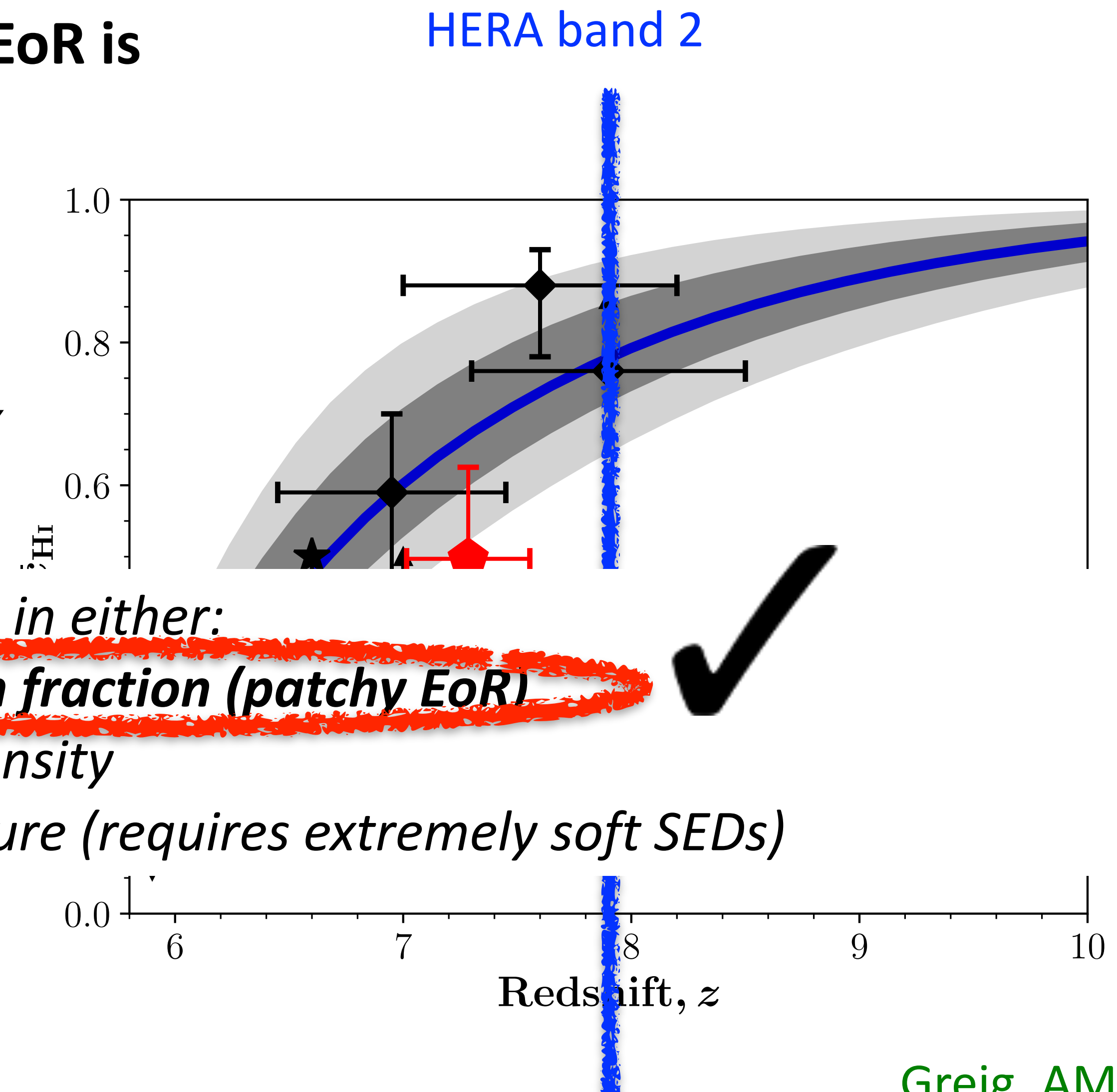
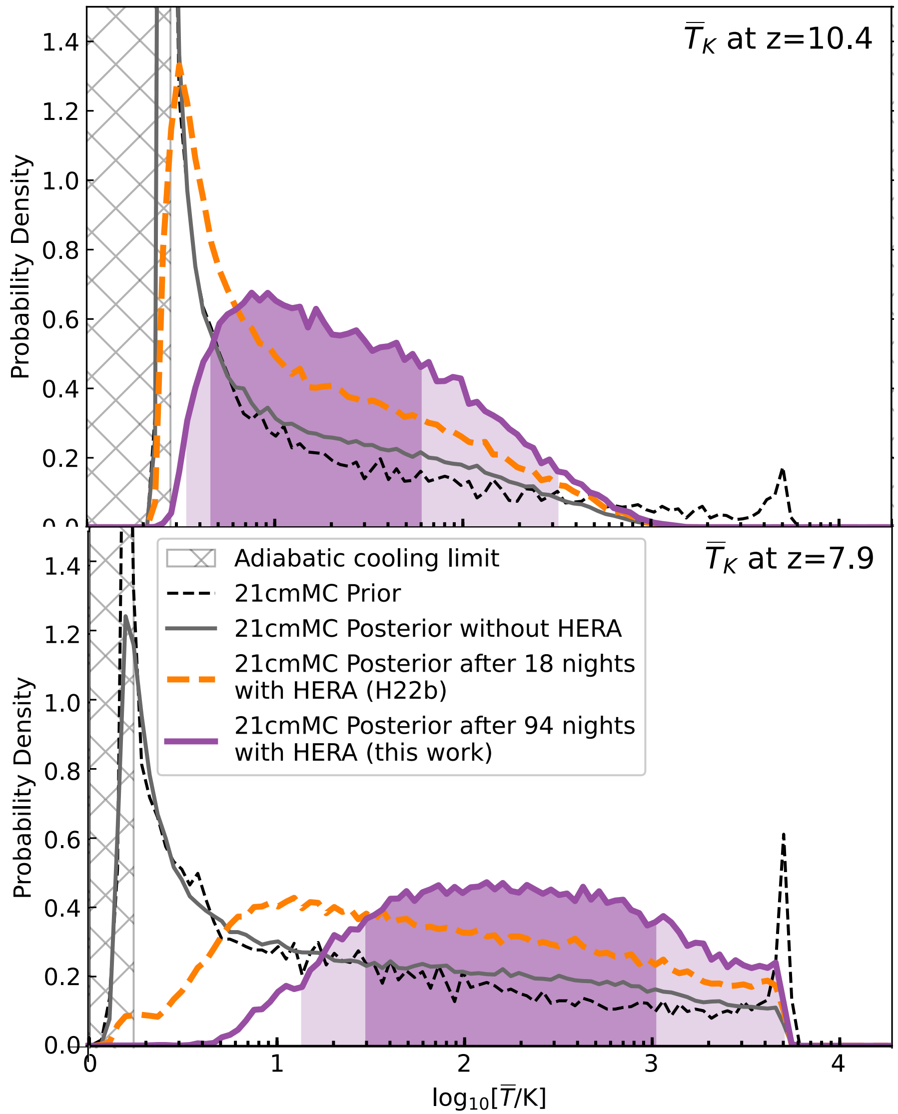


Greig, AM+2021

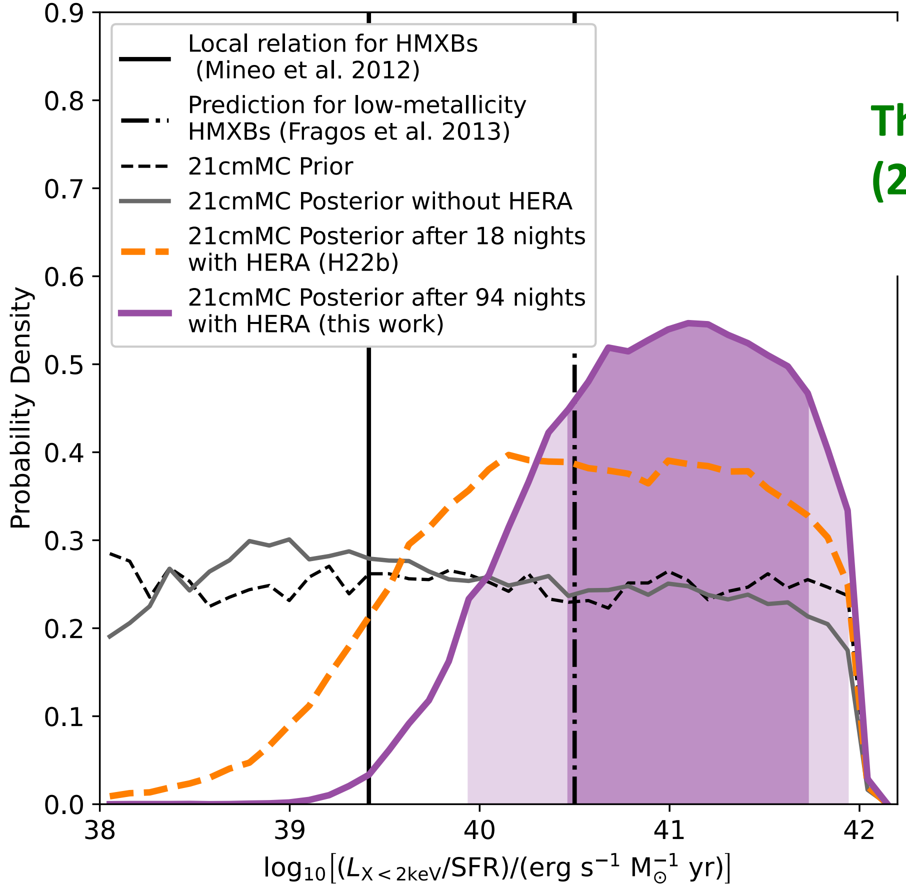
Constraints on IGM properties



Something must have heated the IGM at z>10!!

The HERA collaboration (2023)

If heating is provided by "normal" galaxies, they would need to be more luminous in X-rays than observed locally



The HERA collaboration (2023) - 94 nights of data

The HERA collaboration (2023; *led by J. Dillon*)

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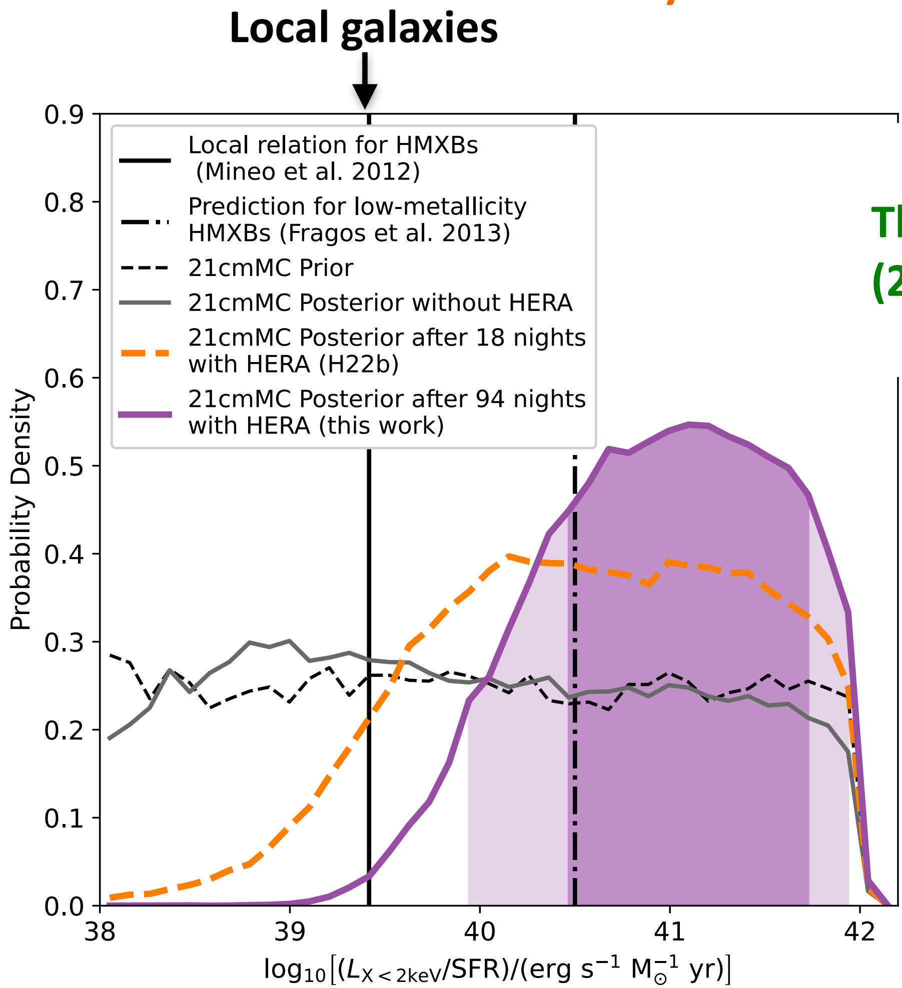


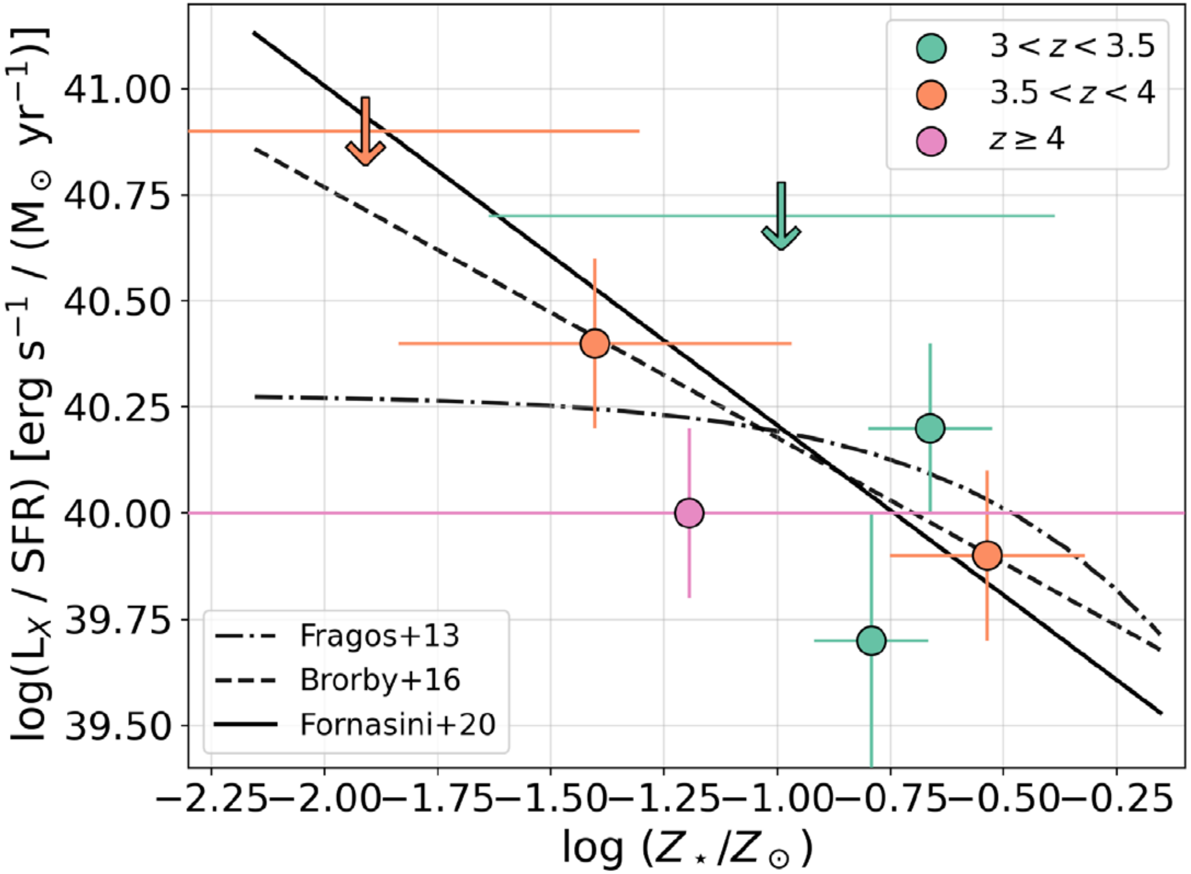
The HERA collaboration (2023) - 94 nights of data

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*

The HERA collaboration (2023; *led by J. Dillon*)

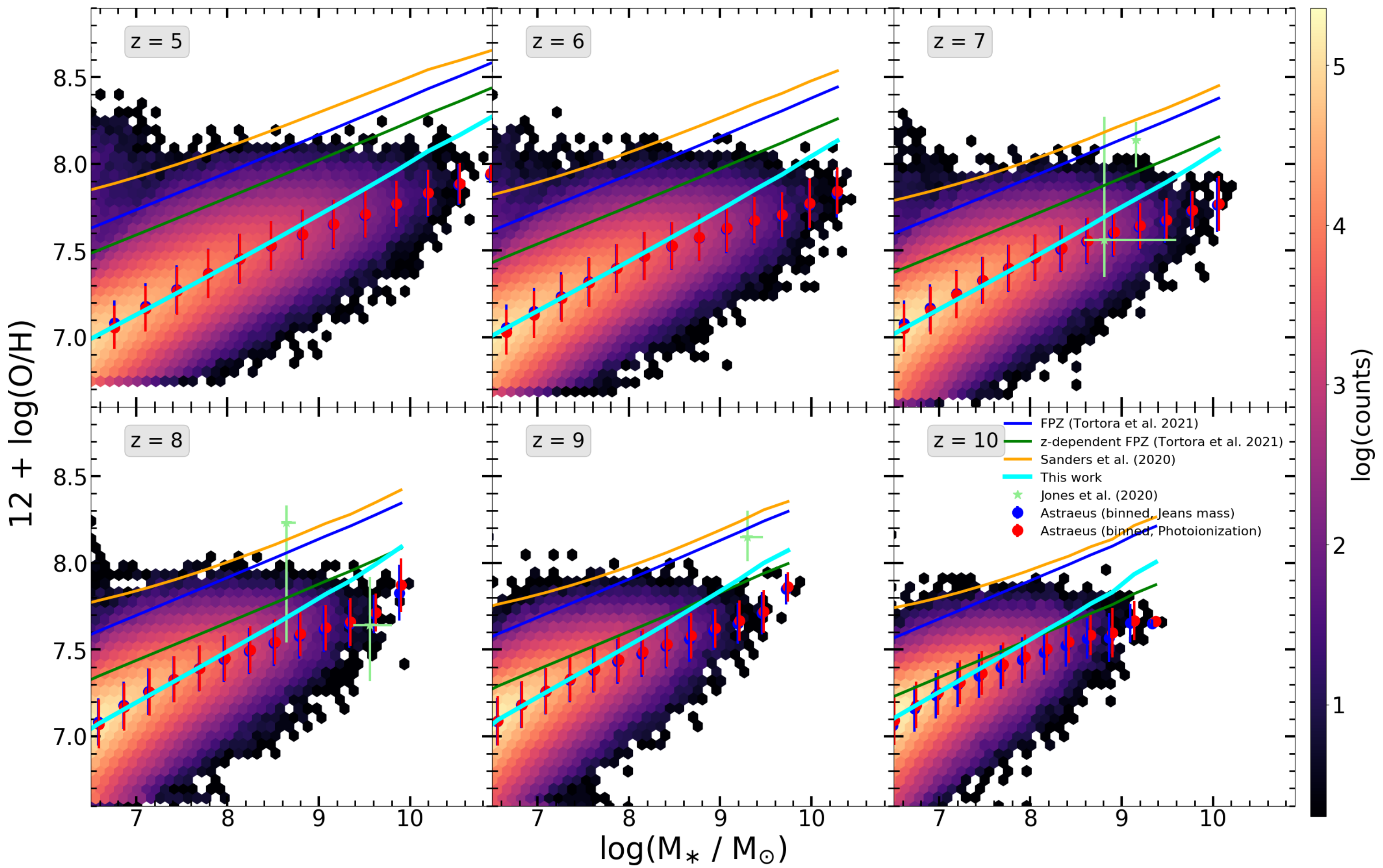
Is this surprising?

The Lx-SFR scaling of HMXBs depends on metalicity



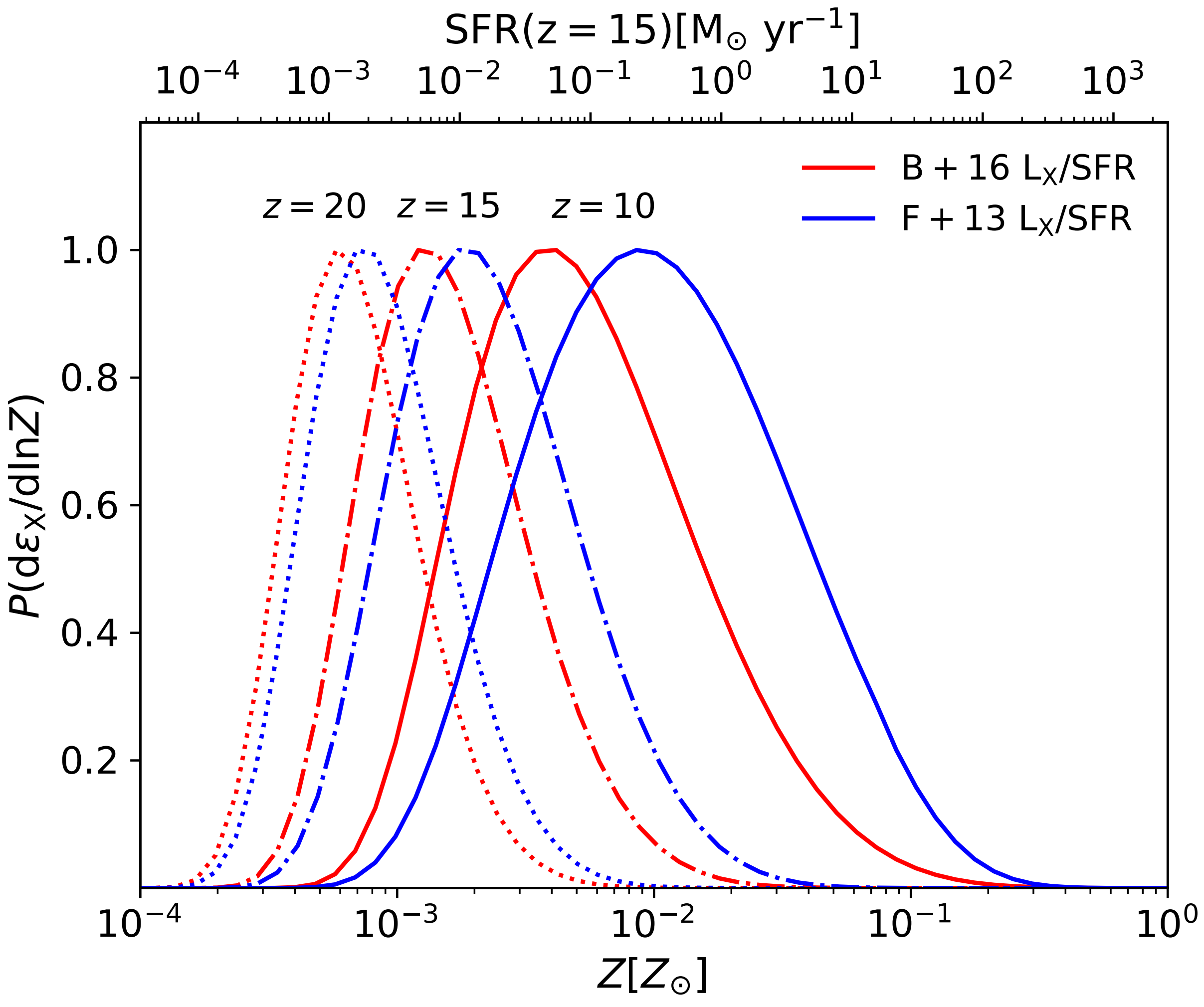
Saxoni+ (2022)

Metallicity evolves with galaxy mass



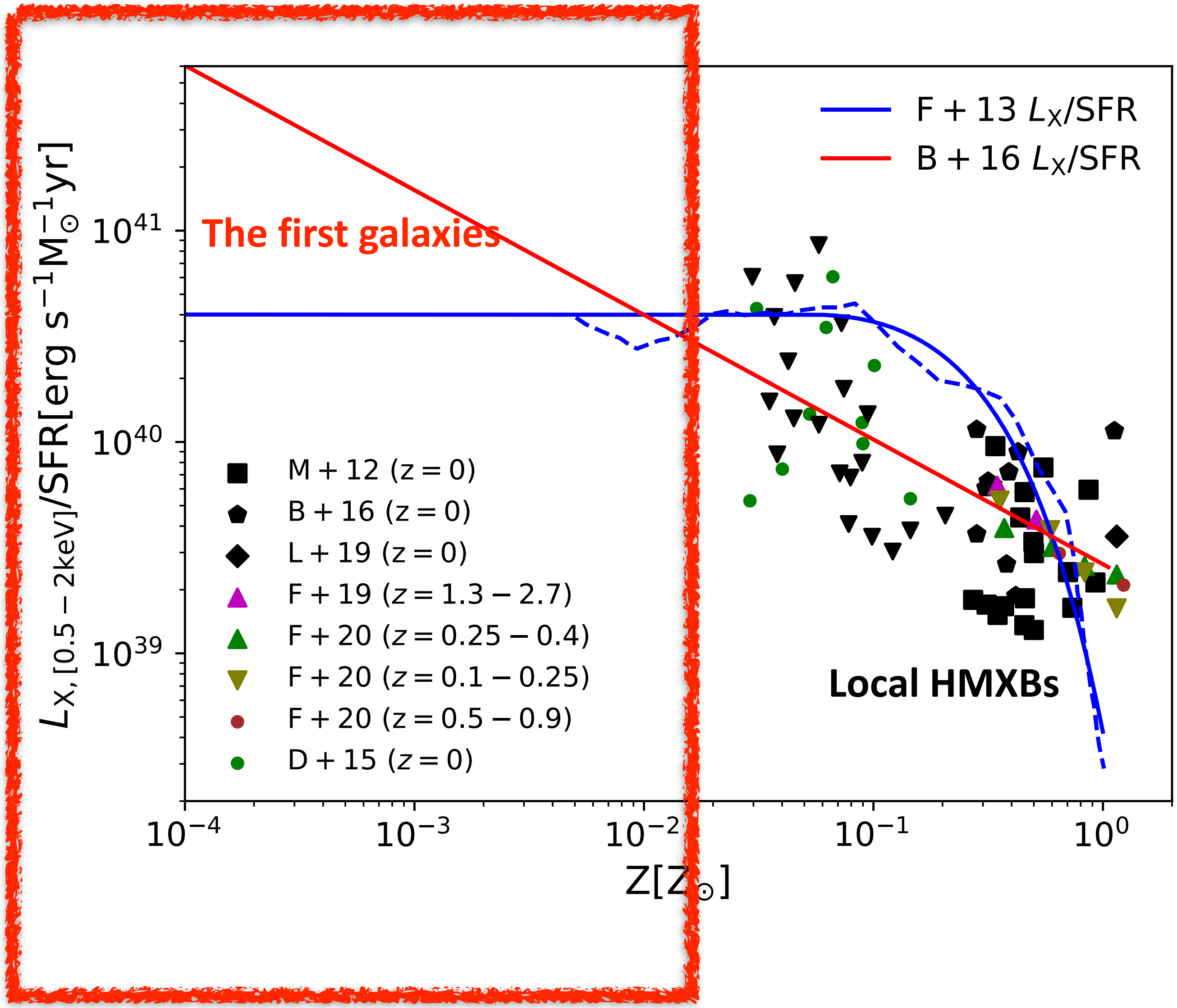
Ucci+ (2021)

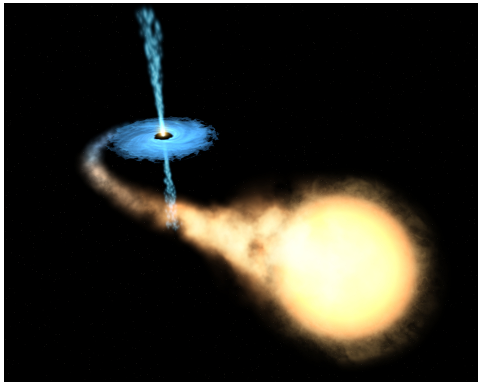
The 21-cm signal probes a new regime for HMXBs - ultra low mass, low metalicity



Kaur, Qin, AM+ (2022)

The 21-cm signal probes a new regime for HMXBs: *low mass galaxies + low metalicity*





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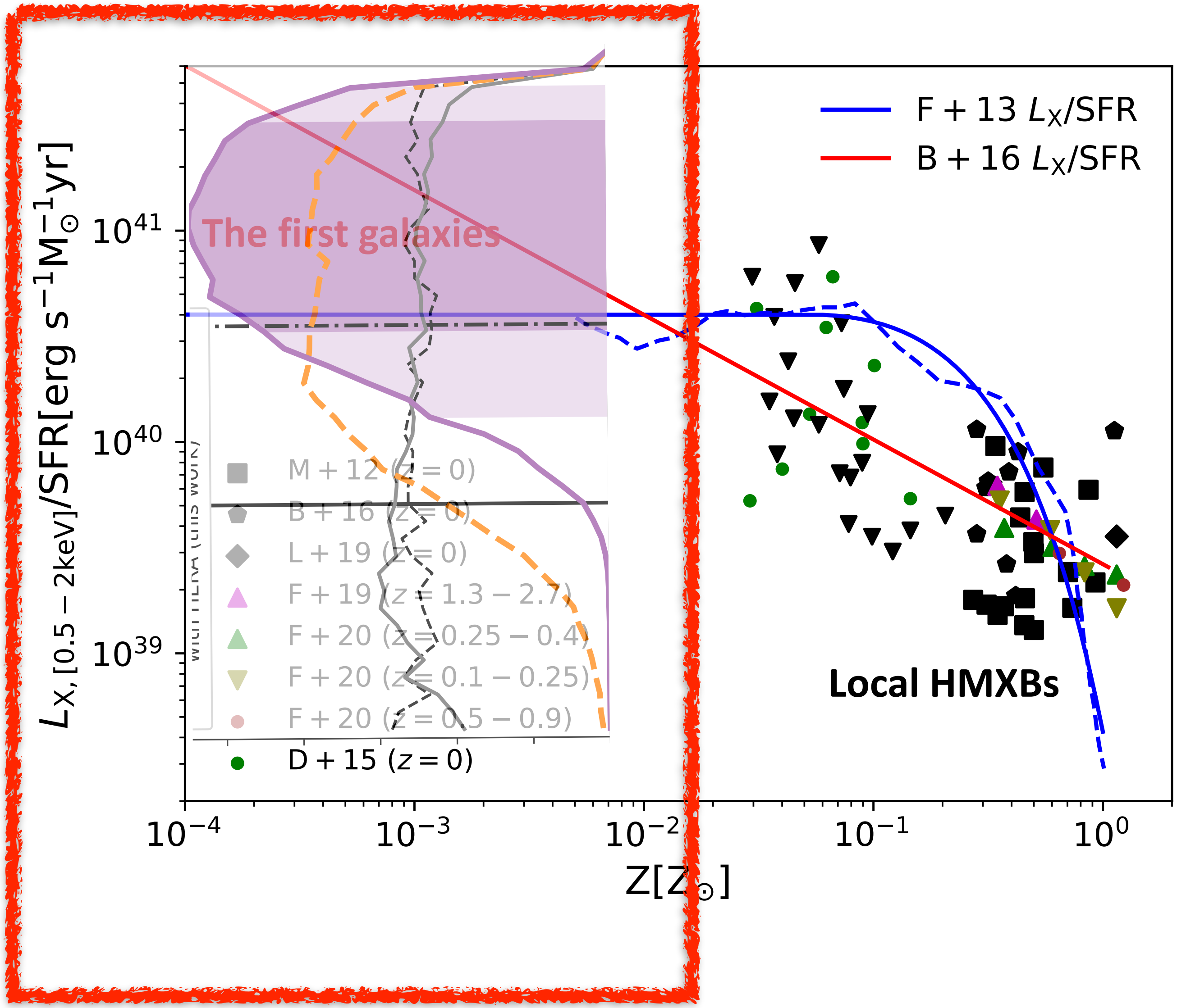
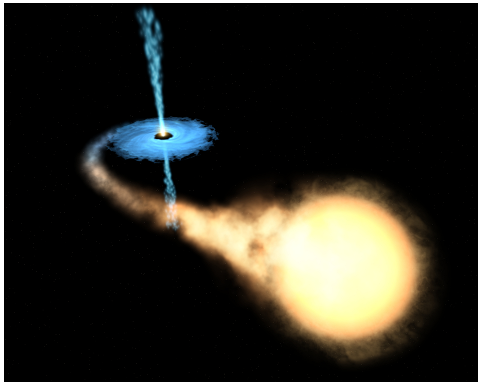
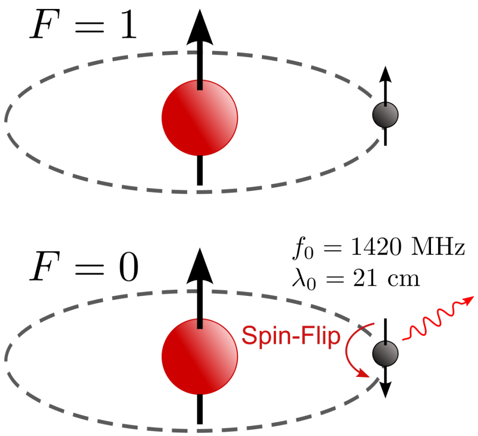




Kaur, Qin, AM+ (2022)

Milestones

aka "The path to the 21-cm revolution"



Where we are now

Upper limits on the 21-cm power spectrum

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- *understand **systematics**! can we parametrize / sample our uncertainties?*

Where we are now

Upper limits on the 21-cm power spectrum

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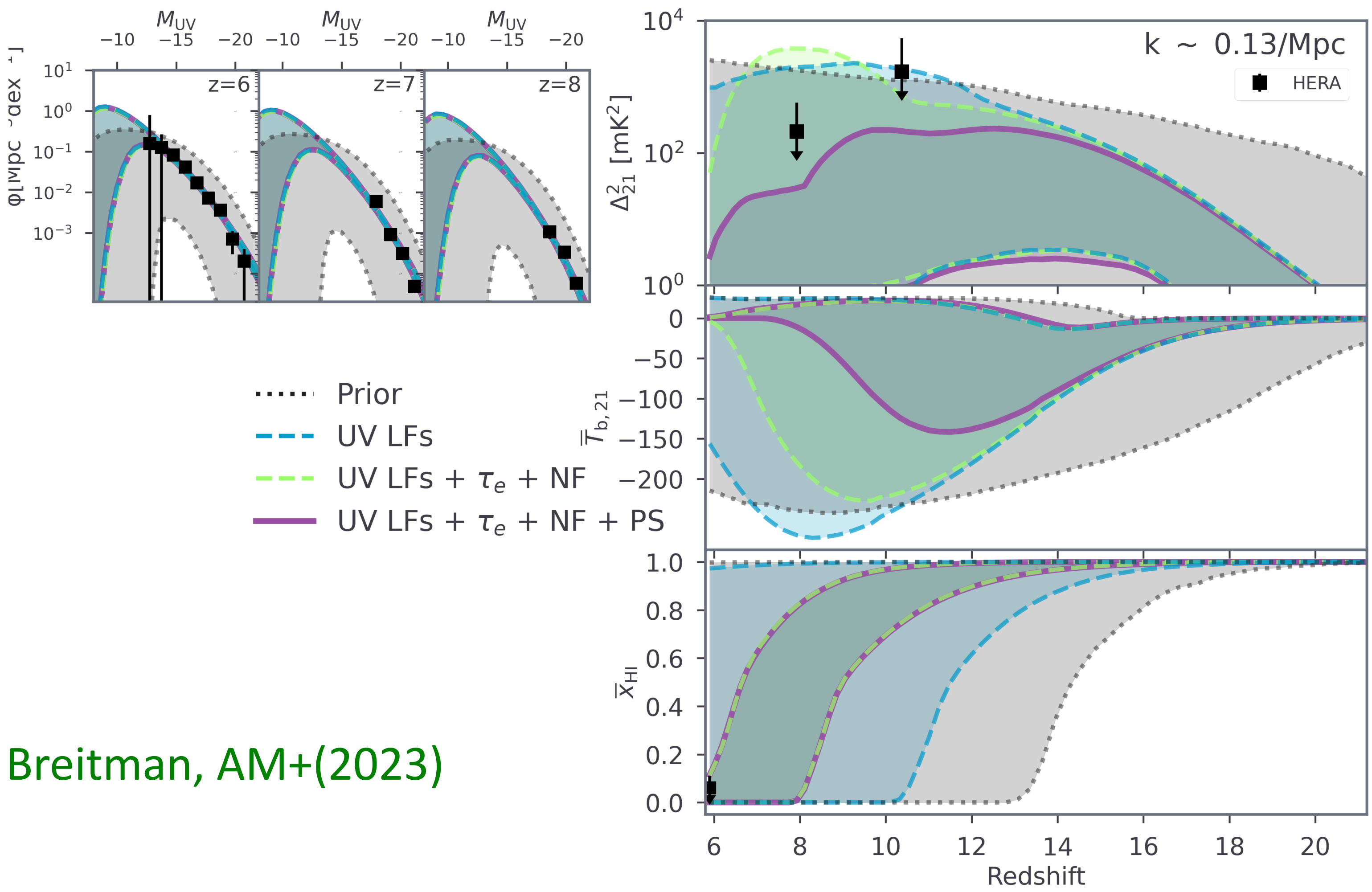
Contribution of different data



Breitman, AM+(2023)

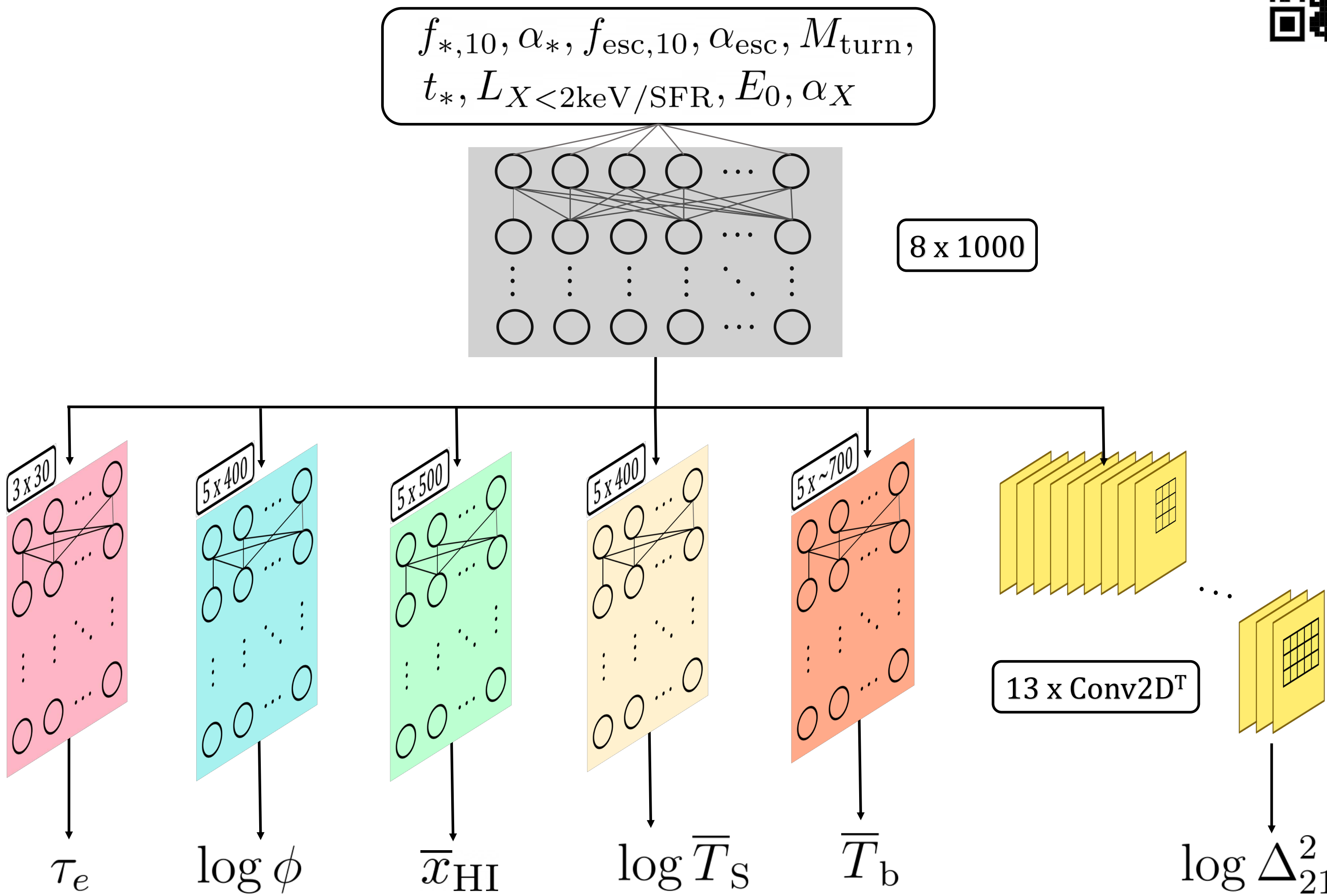
Where we are now

Upper limits on the 21-cm power spectrum

- *understand **systematics**! can we parametrize / sample our uncertainties?*
- *do we have all of the **physics** we need, especially regarding heating sources?*
- *posteriors will be **prior-dominated** UNLESS we have “realistic” galaxy models that can be constrained by other observations*
- ***emulators** are useful! error is currently sub-dominant*

  *(e.g. Kern+2017; Schmit & Pritchard 2017; Shimabukuro & Semelin 2017; Jennings+2019; Ghara+2020; Mondal+2022; Bye+2022a; Lazare+2023; Breitman, **AM**+2023)*

21cmEMU emulator



Breitman, AM+(2023)

Where we will be soon

Low S/N detection of the 21-cm PS

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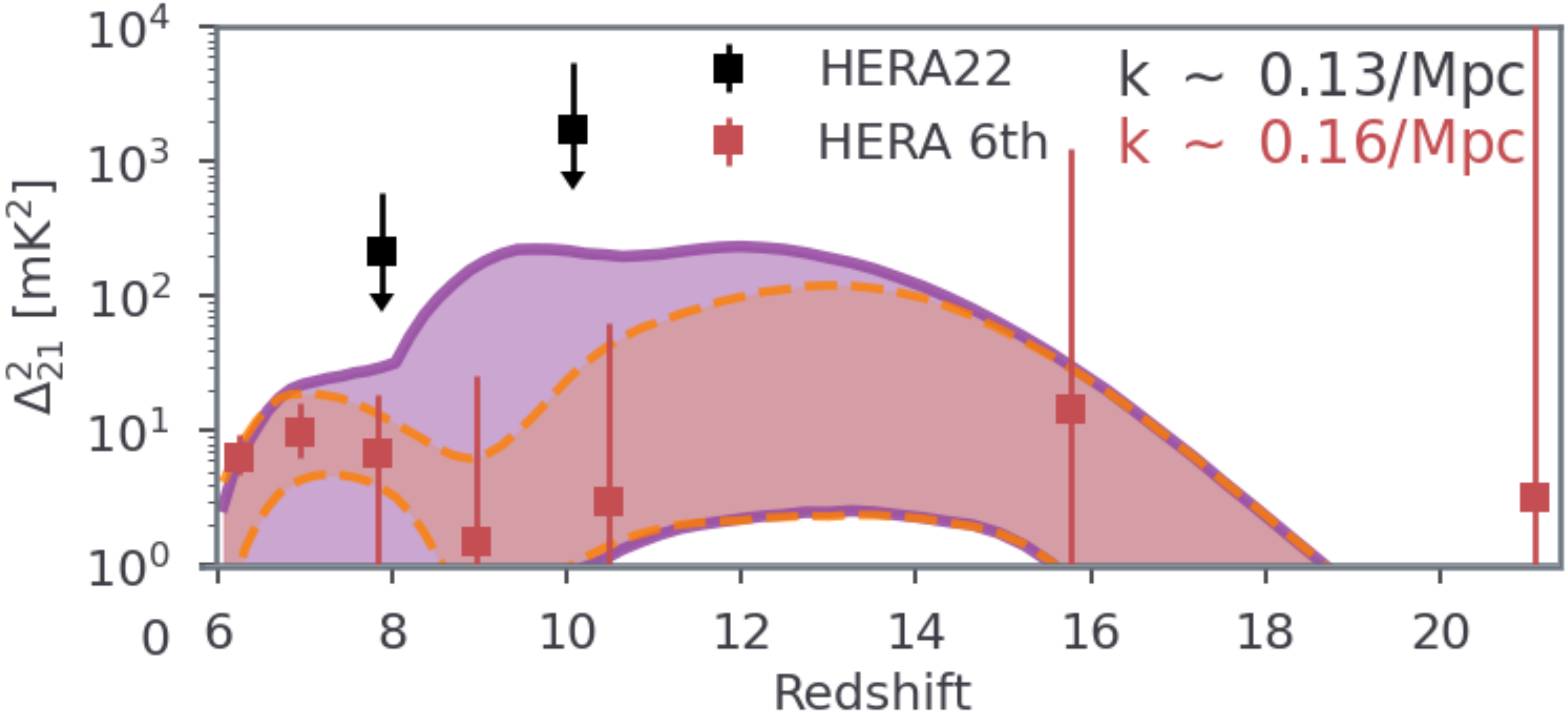
Low S/N detection of the 21-cm PS



Breitman, AM+(2023)

Where we will be soon

Low S/N detection of the 21-cm PS

- *understand* ***systematics****! can we parametrize / sample our uncertainties?*

Where we will be soon

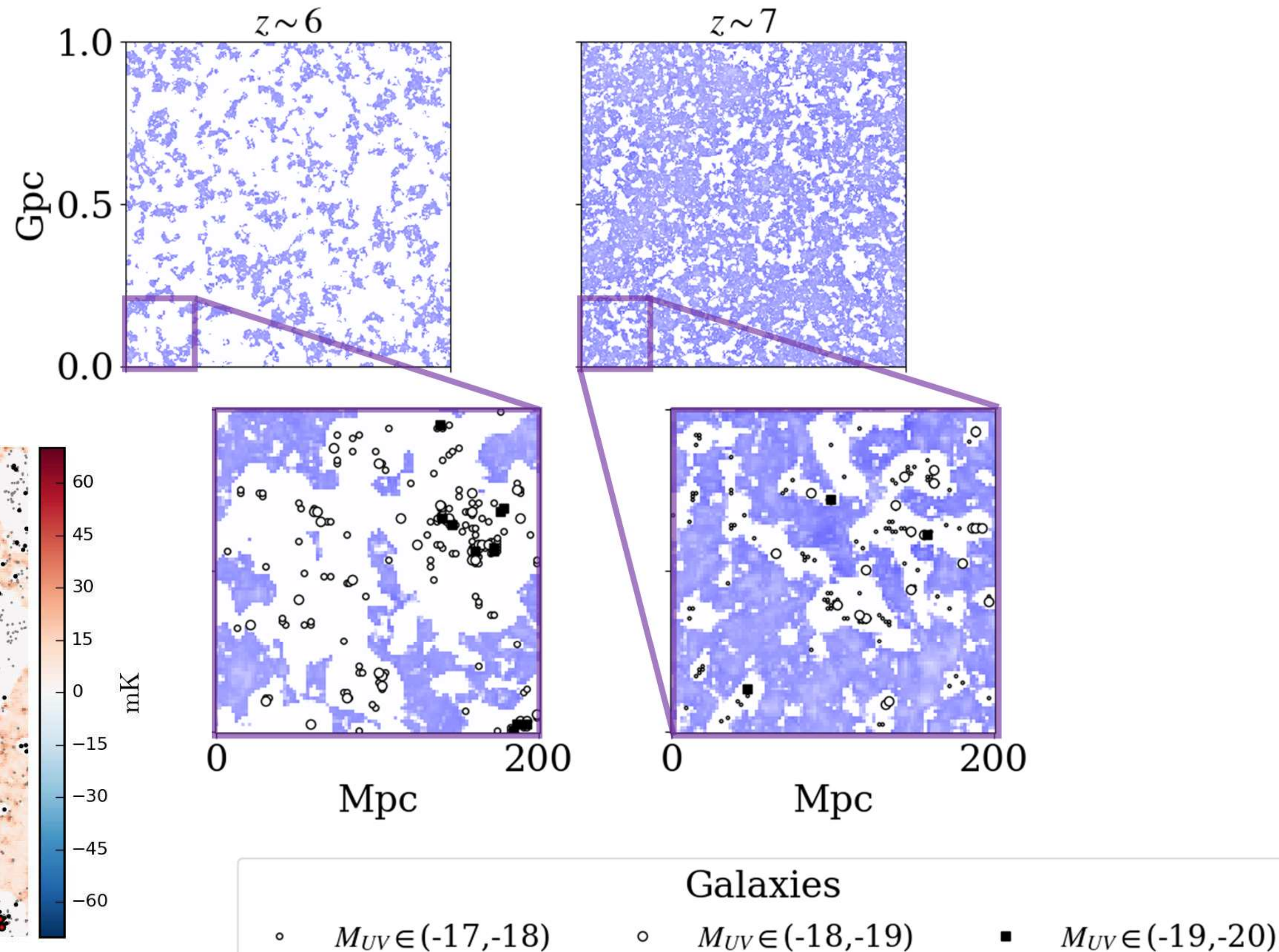
Low S/N detection of the 21-cm PS

- *understand* ***systematics****! can we parametrize / sample our uncertainties?*
- *how can we convince ourselves and everyone else that the detection is* ***REAL —> cross-correlation with signal of known cosmic origin***

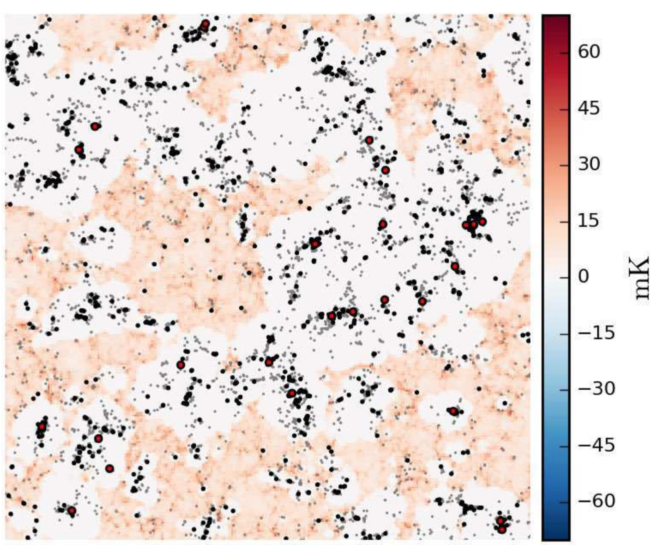
The importance of cross-correlations

- It is an important sanity check to verify claims of detection/analysis pipeline

Gagnon-Hartman, Davies, AM in prep

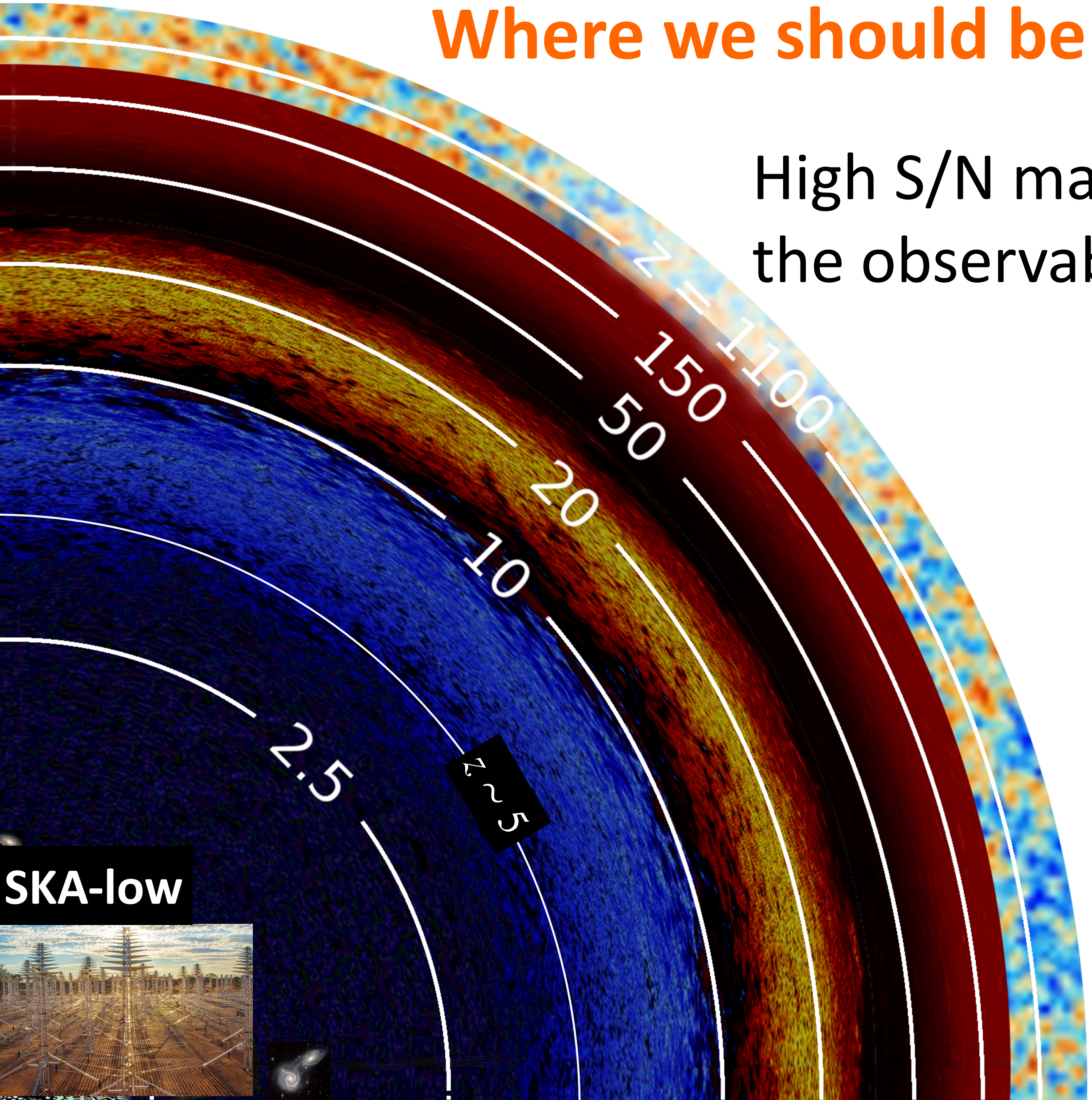


Moriwaki+2019



Where we should be >2030-2040

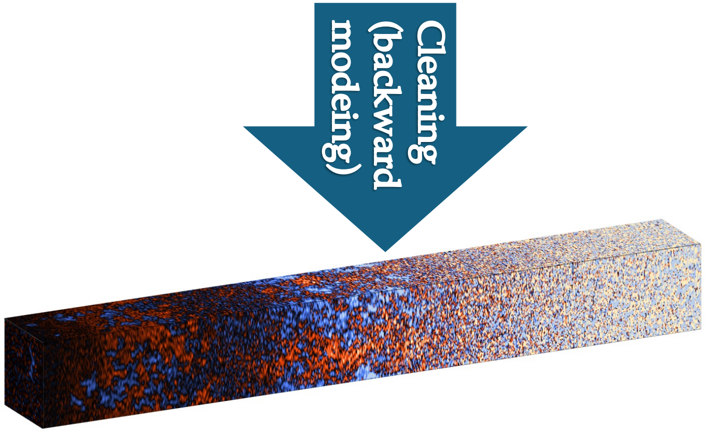
High S/N map of ~50% of the observable Universe



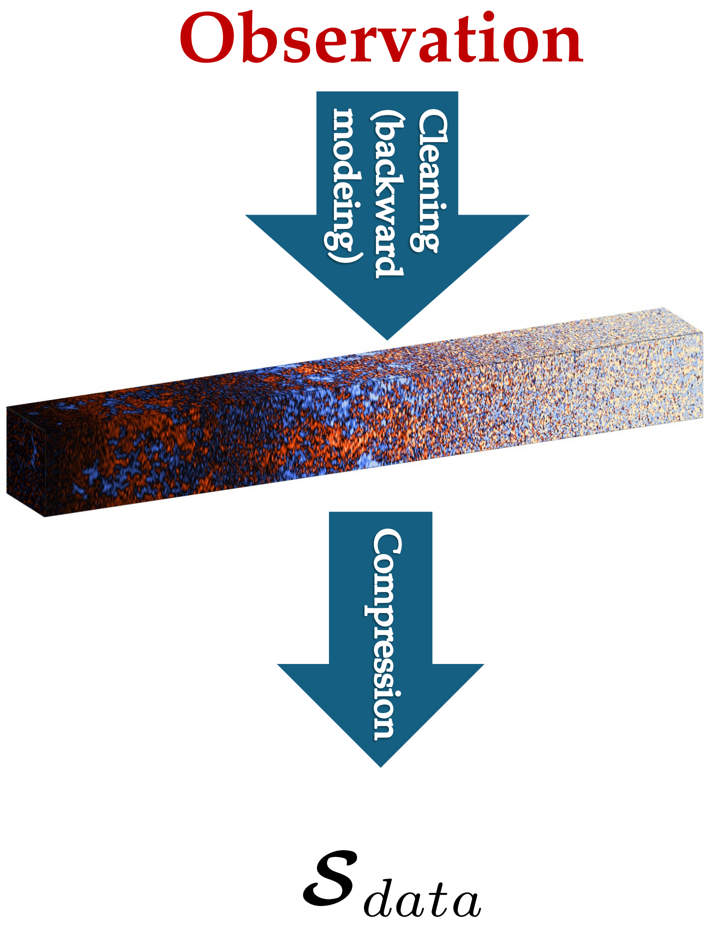
adapted from C. Chiang

Inference pipeline

Observation



Inference pipeline



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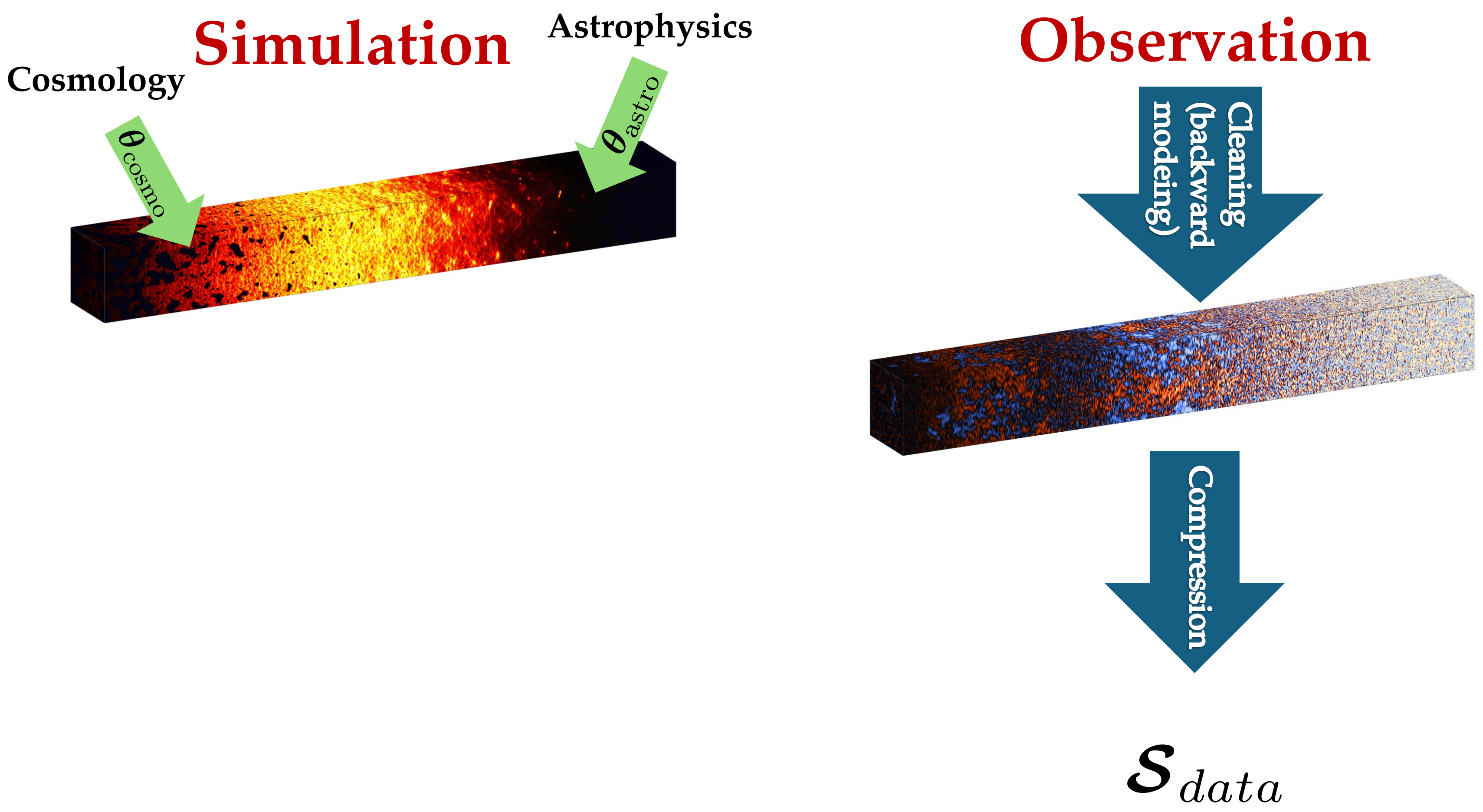
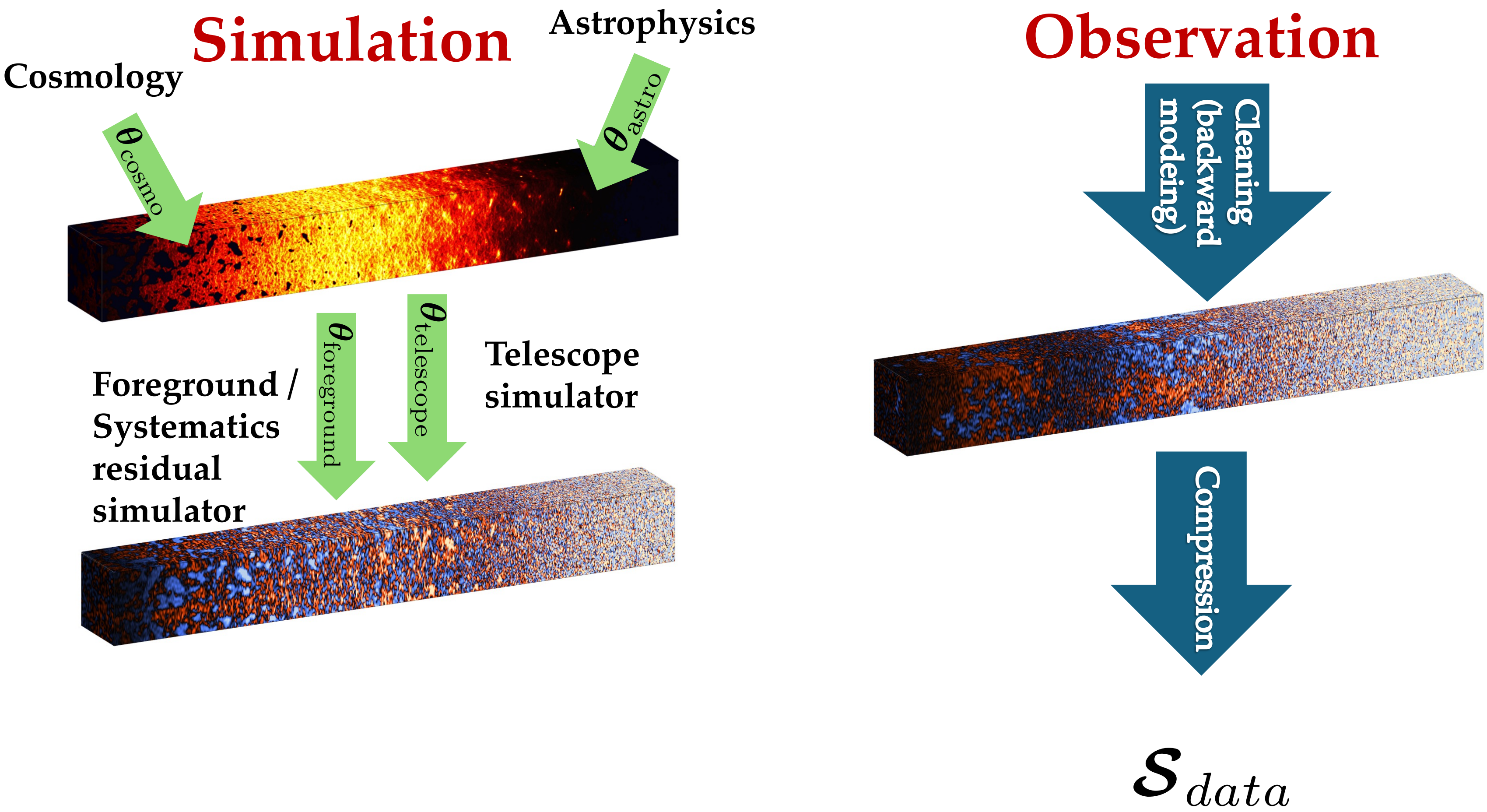


Inference pipeline



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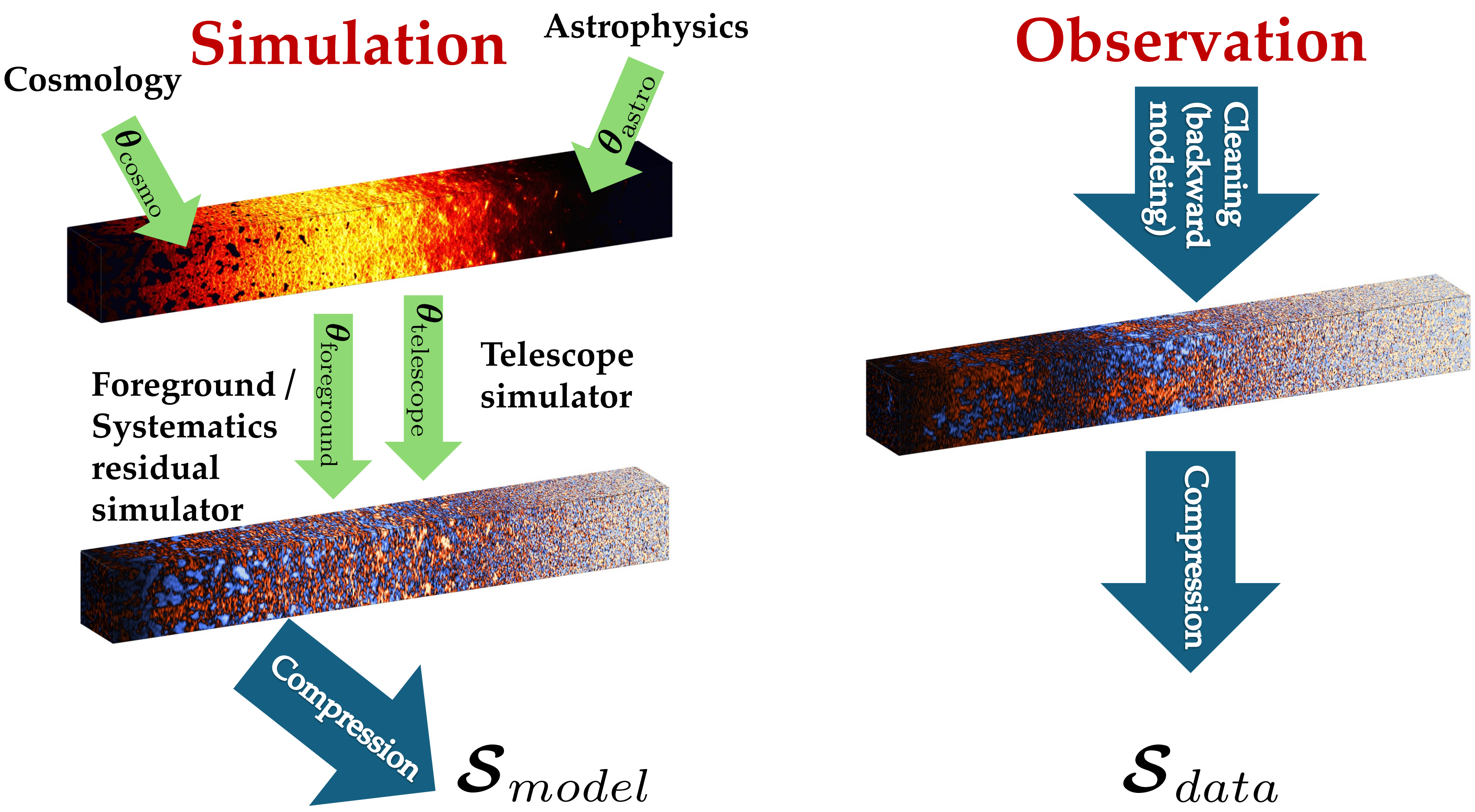

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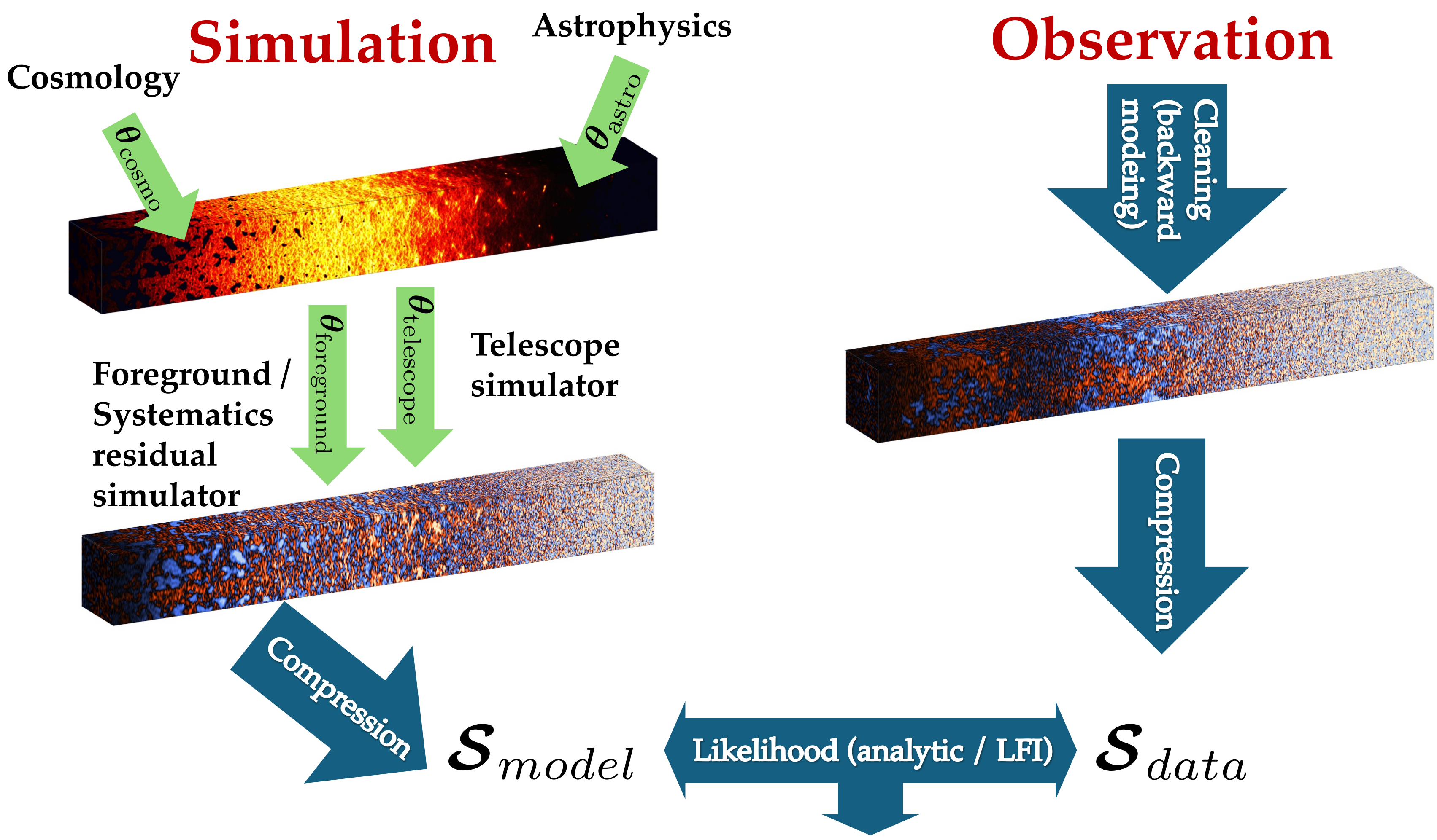

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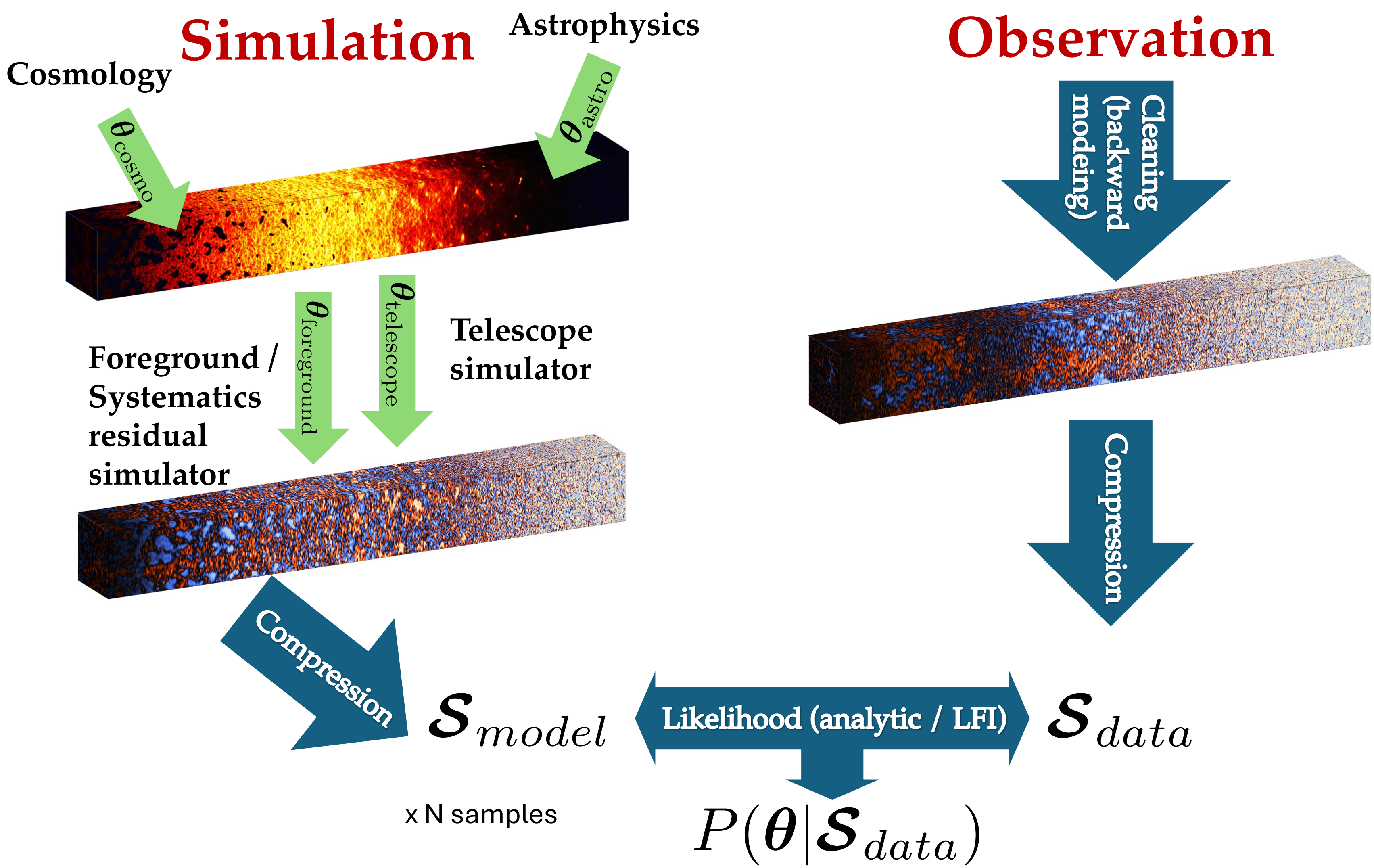
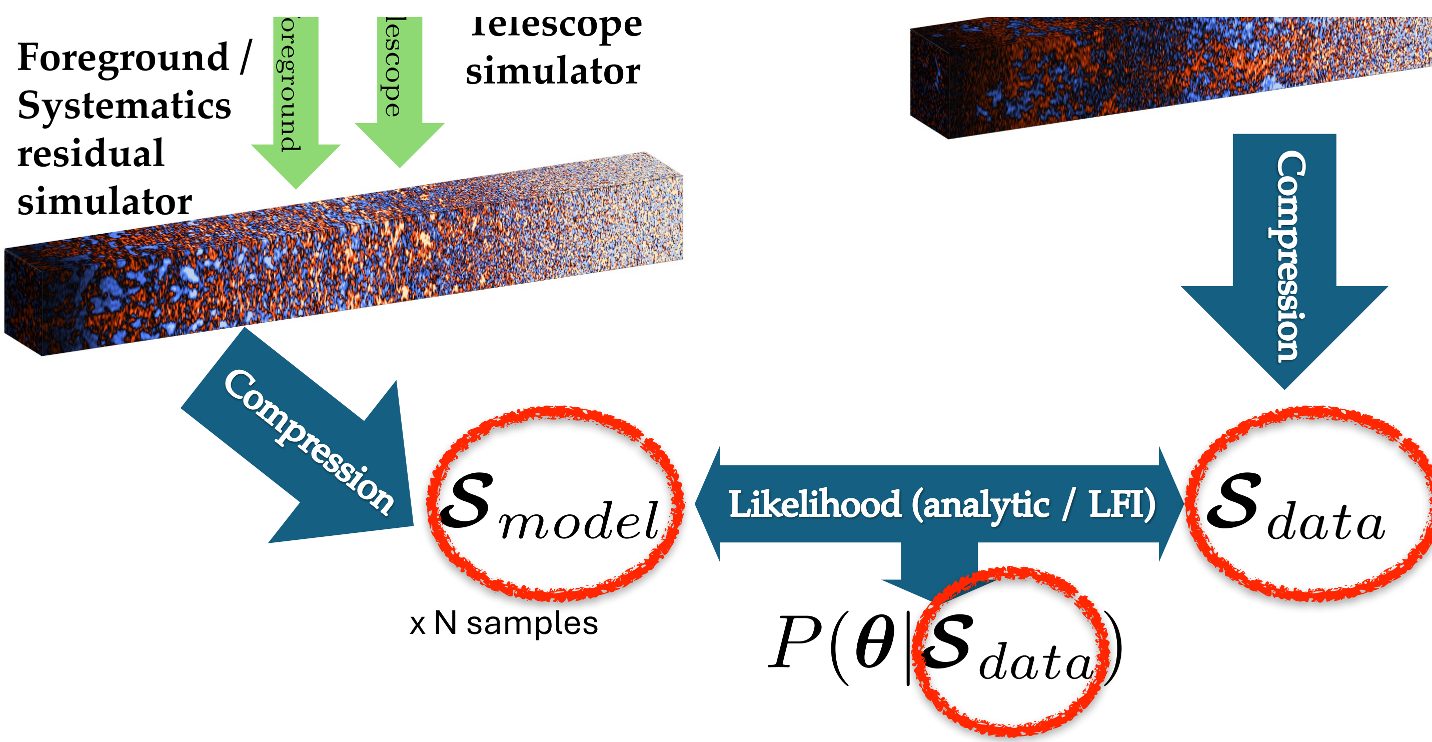
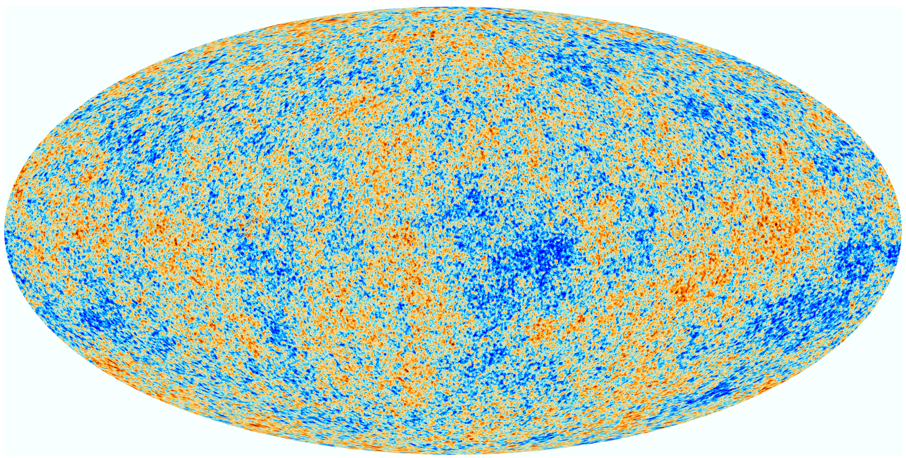


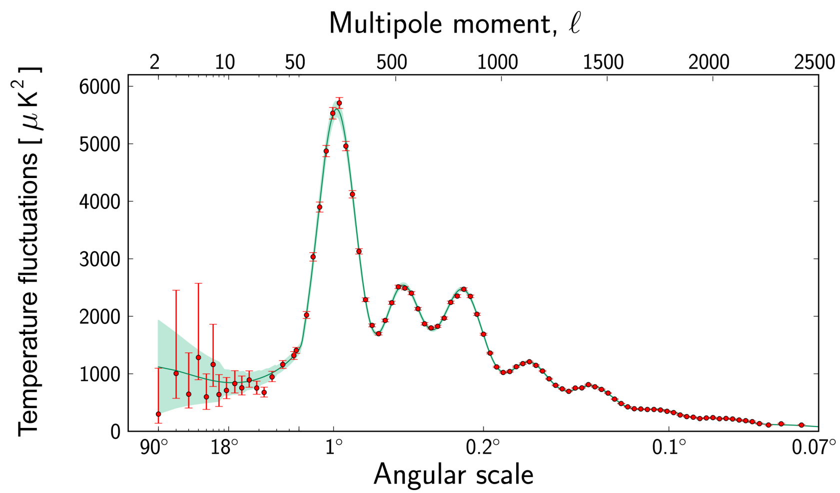
What is an “optimal” summary???



For Gaussian random fields, the power spectrum contains all information

Planck 2018





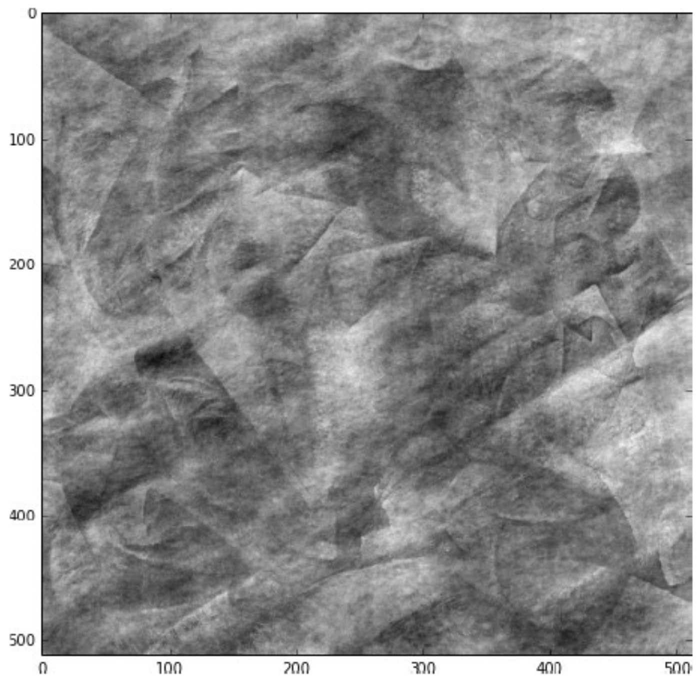
(T, x, y)

~10^6 data points

P(l)

~10^2 data points

Optimal summary for non-Gaussian fields??



*Figures have the **same power spectra***

figure curtesy of G. Bernardi

Where we should be >2030-2040

High S/N map with the SKA

- *optimal compression of **non-Gaussian** signal (e.g. bispectrum, Minkowski functionals, wavelets, data-driven compression…)*

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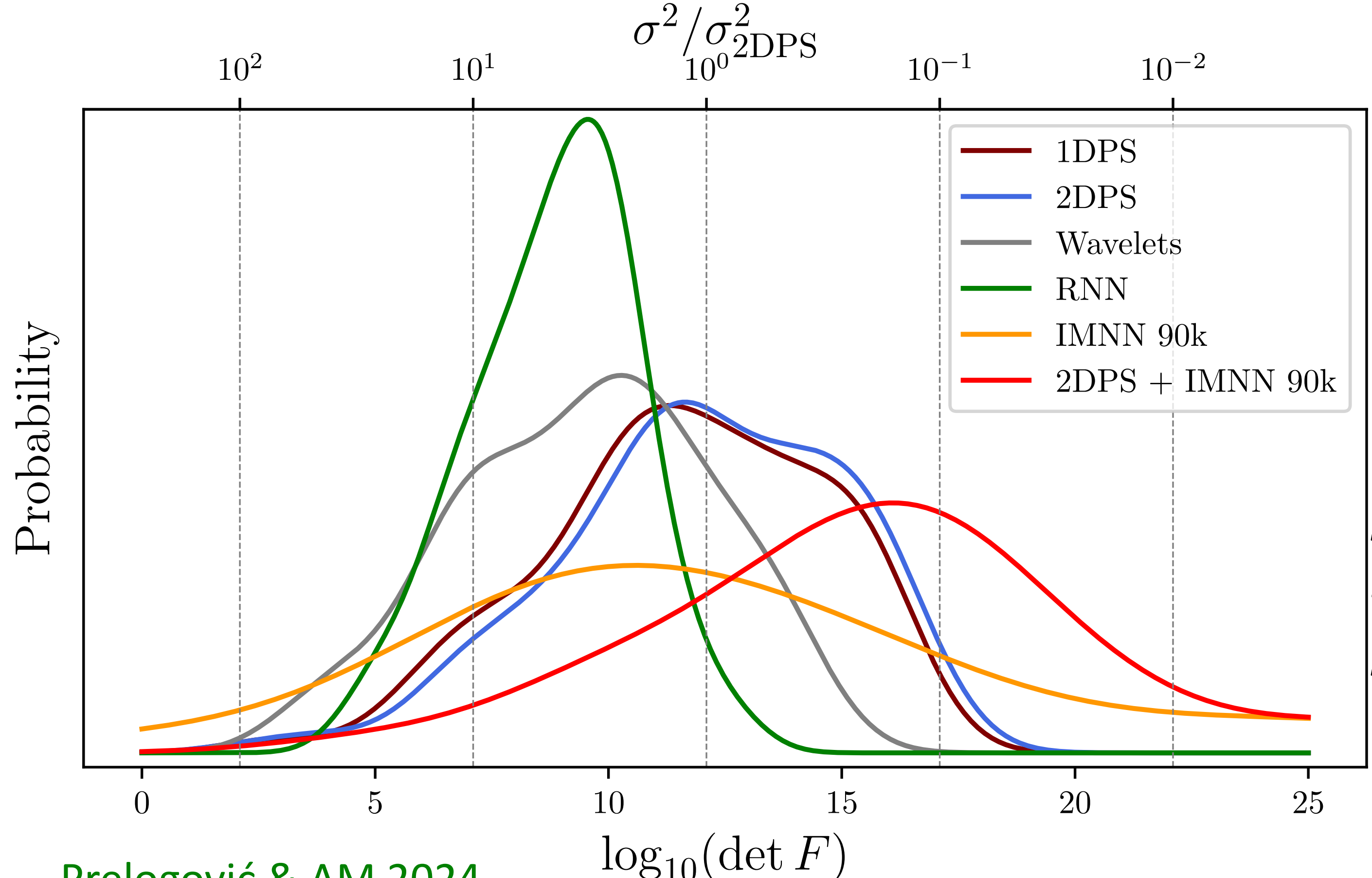
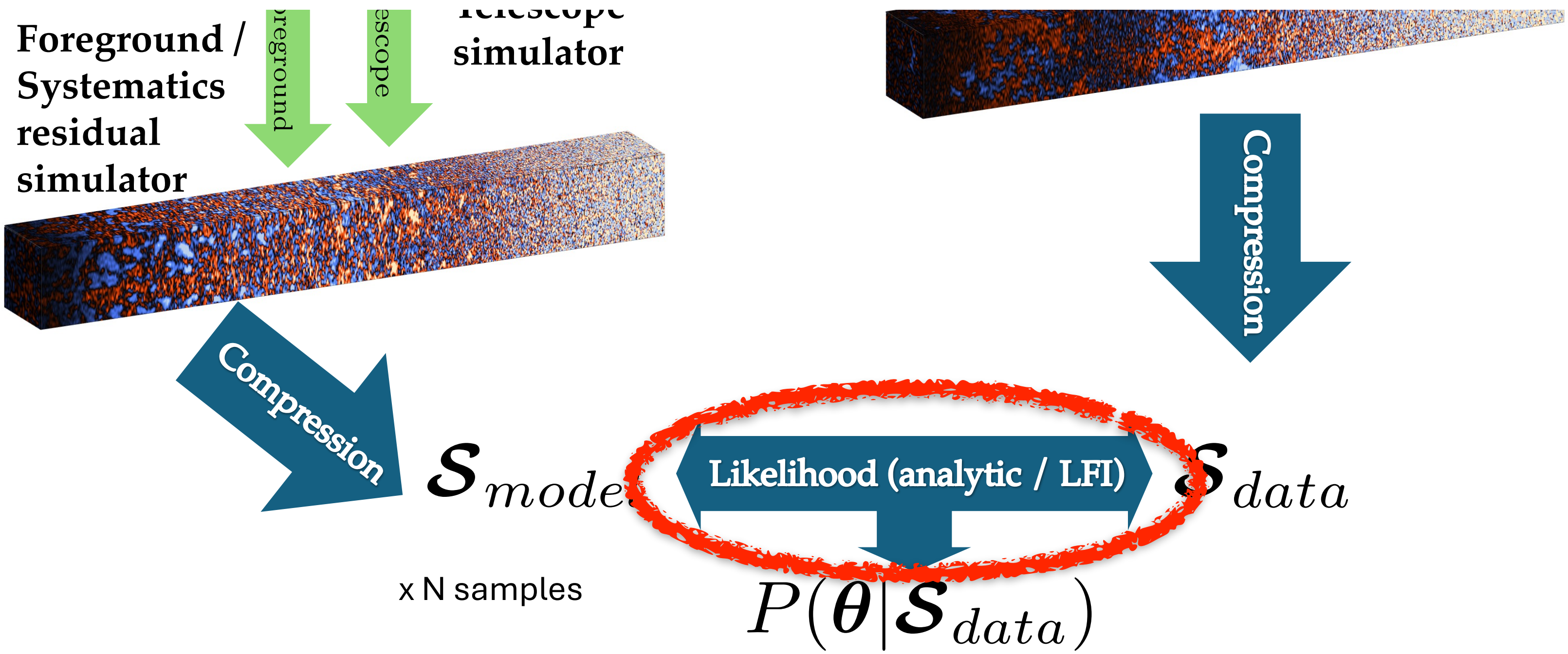


Compare constraining power of different summaries across prior volume

Prelogović & AM 2024

(see also, e.g. Watkinson+2017; Majumdan+2020; Chen+2019; Giri&Mellema2021; Kamran+2023…)

For any given summary, how do we write down a *likelihood*??



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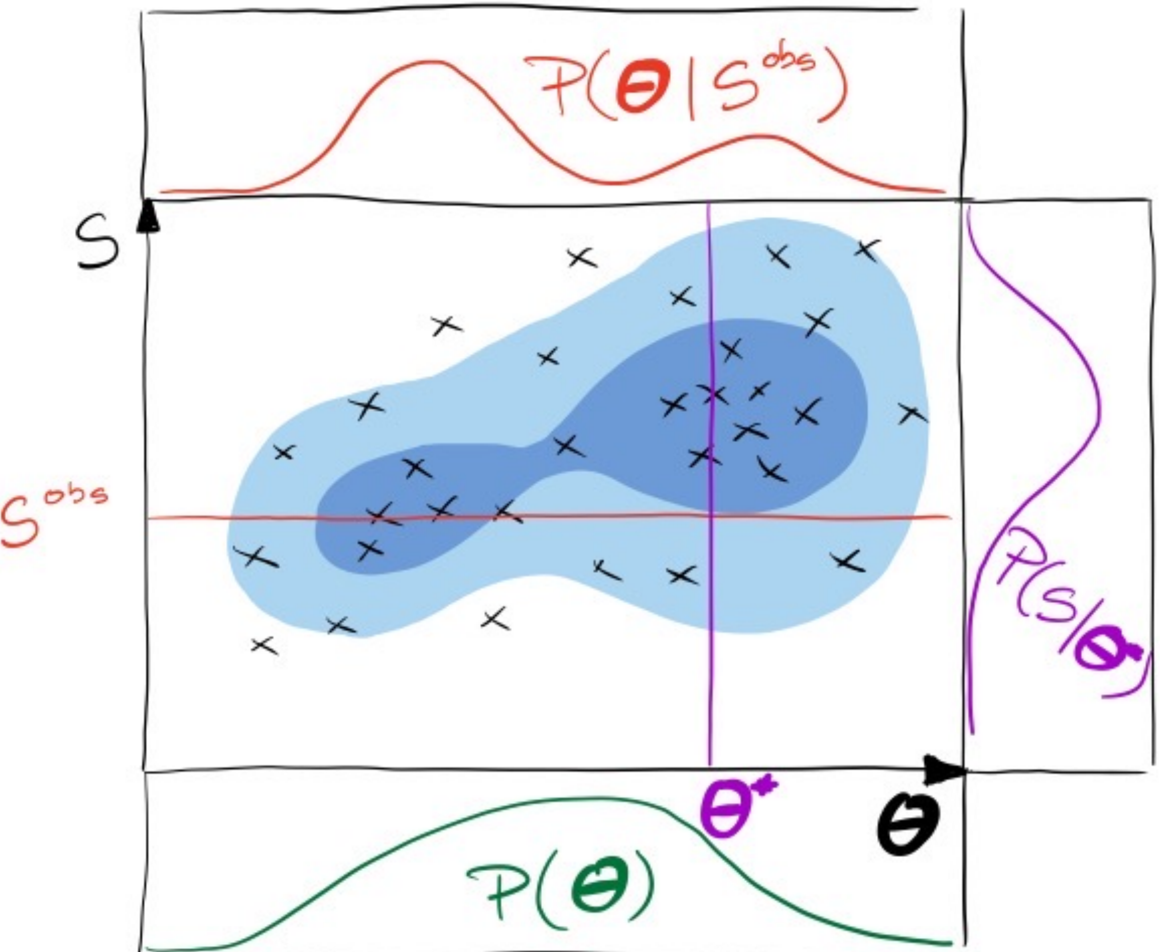
High S/N map with the SKA

- *optimal compression of* ***non-Gaussian*** *signal (e.g. bispectrum, Minkowski functionals, wavelets, data-driven compression…)*
- *do we actually know the likelihood analytically? —>* ***Simulation Based Inference (SBI)***

Simulation Based Inference (SBI)

Inference using SBI: *if including all main sources of stochasticity, each forward model is a sample from the joint distribution of model & data. The* ***likelihood*** *can just be fit with NDEs.*



Credit: Tom Charnock

No need for an analytic likelihood!!!

difficult to write down for non-Gaussian and correlated observations

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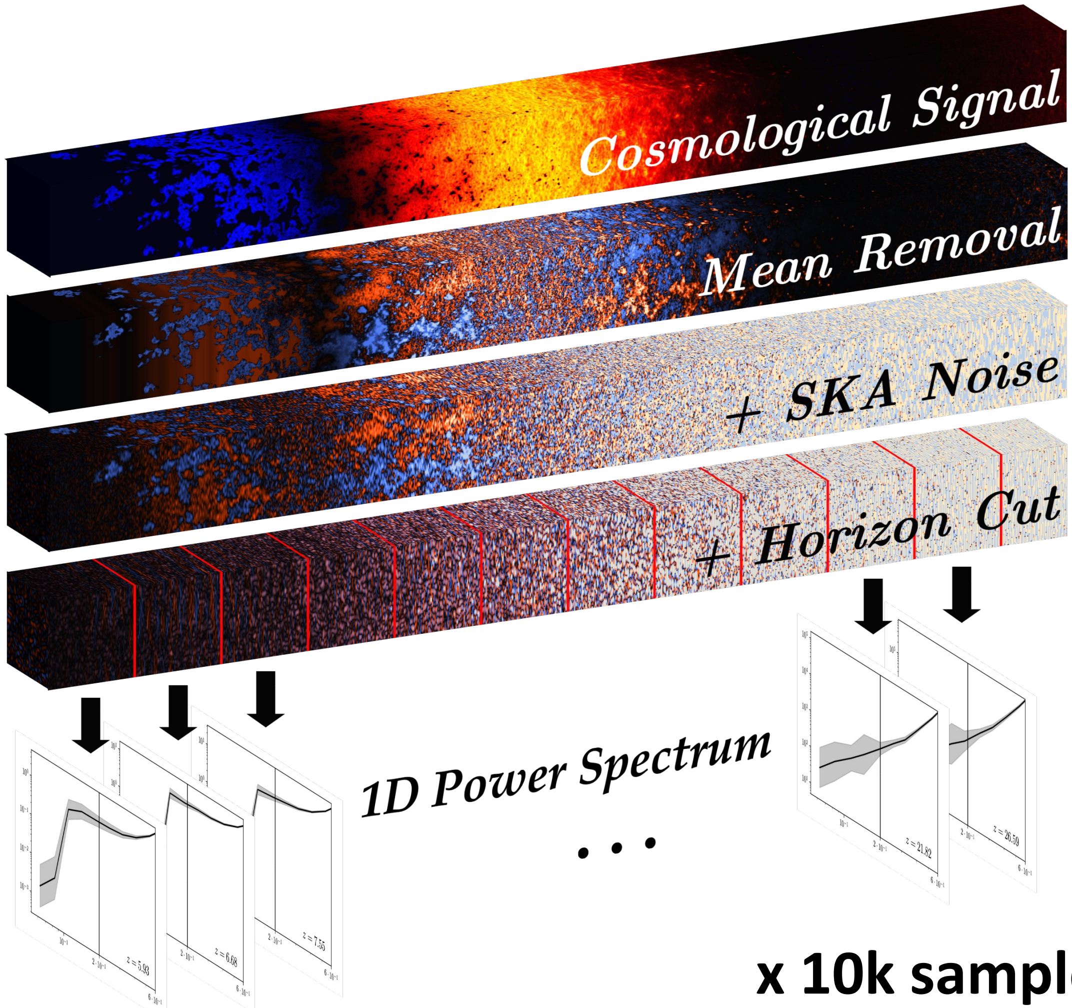

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x 10k samples

Prelogović & AM (2023)

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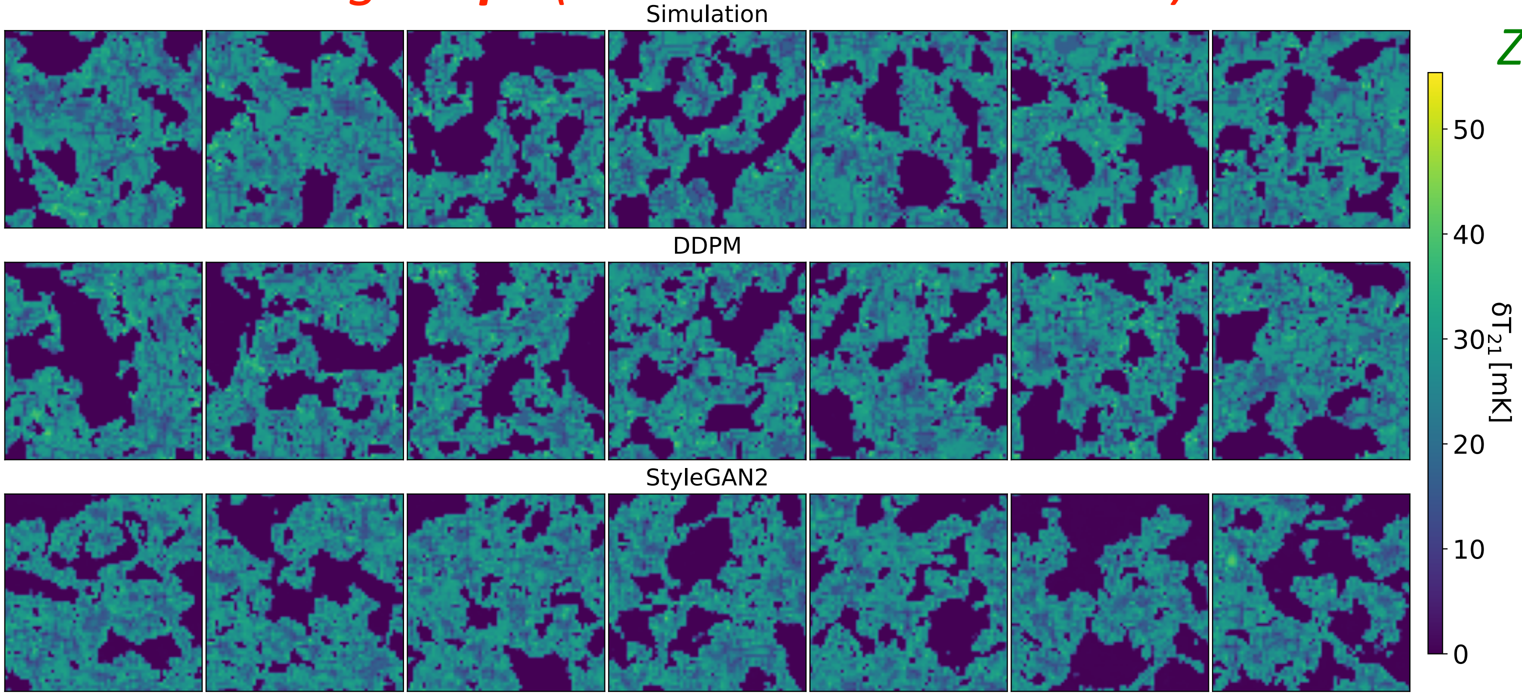

Zhao+ (2023)

Where we should be >2030-2040

High S/N map with the SKA

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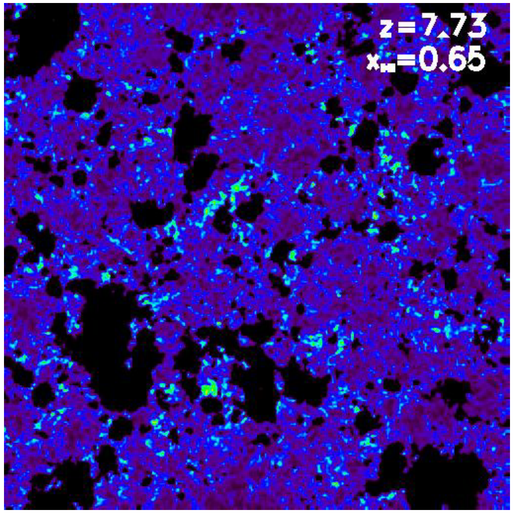
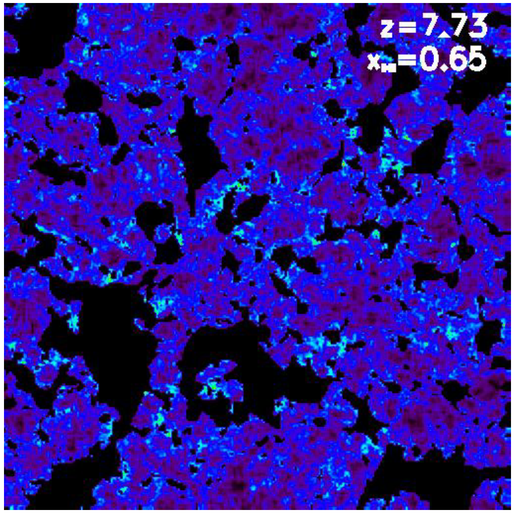
- *do we actually know the likelihood analytically? —>* ***Simulation Based Inference (SBI)***
- *emulating **maps** (do we trust emulators?)*
- *how well do we trust our **simulators** (analytic, semi-numeric, moment-based RT, ray tracing, hydro…)**??***

AM+ (2011)





Conclusions

- The cosmic 21cm signal will allow us to learn the **average UV and Xray properties of the unseen first galaxies.**
- SKA will also open a new window on **physical cosmology**, e.g.
  - exotic heating processes, e.g. DM annihilations and decay
  - standard ruler at z=10-15 from velocity-induced feedback on galaxies
- **Upper limits** on the 21-cm power spectrum by SKA precursor, HERA, imply some **heating of the IGM by z>10.** If heating is provided by high mass X-ray binary stars, they are likely **more luminous** then local ones, likely due to their **low-metallicities**.
- **ML** is currently used in **emulation** and **data cleaning.** With high S/N data, ML will be very useful in **optimal compression**, **implicit likelihood inference**, **map emulation**, **mitigating simulator errors**, etc…