The 21cm signal from the Cosmic Dawn

Andrei Mesinger

SCUOLA NORMALE SUPERIORE

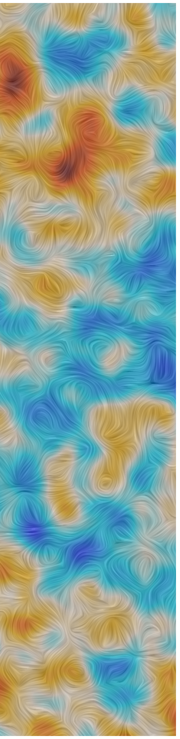
MUR
Ministero dell'Università e della Ricerca

erc
European Research Council

First billion years - birth of structure and Cosmic Dawn

Image: ESA

CMB



$z \approx 10^3$

cosmic time [yr]

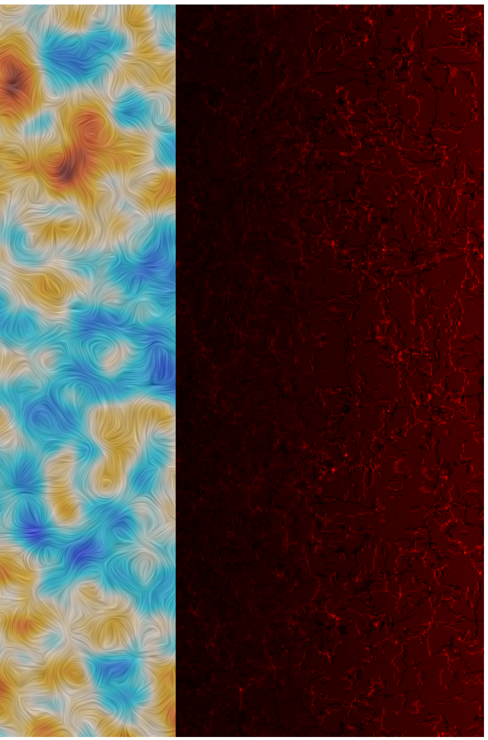
$4 \cdot 10^5$

First billion years - birth of structure and Cosmic Dawn

Image: ESA

AM+2016

CMB **Dark Ages**



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

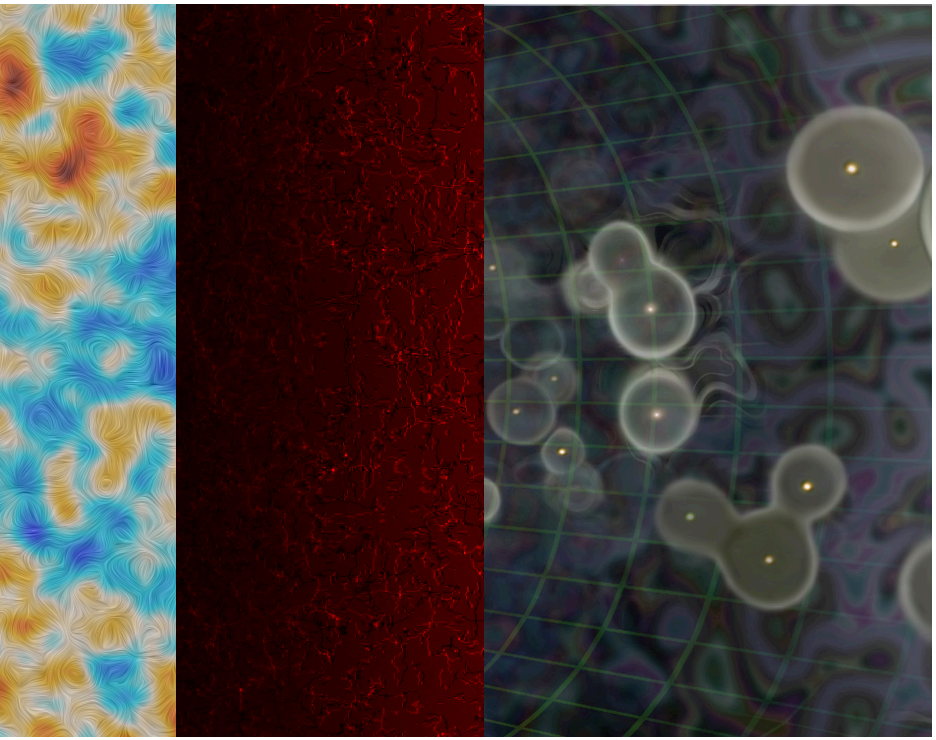
cosmic time [yr]

$4 \cdot 10^5$ 10^8

First billion years - birth of structure and Cosmic Dawn

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

CMB Dark Ages **Cosmic Dawn**



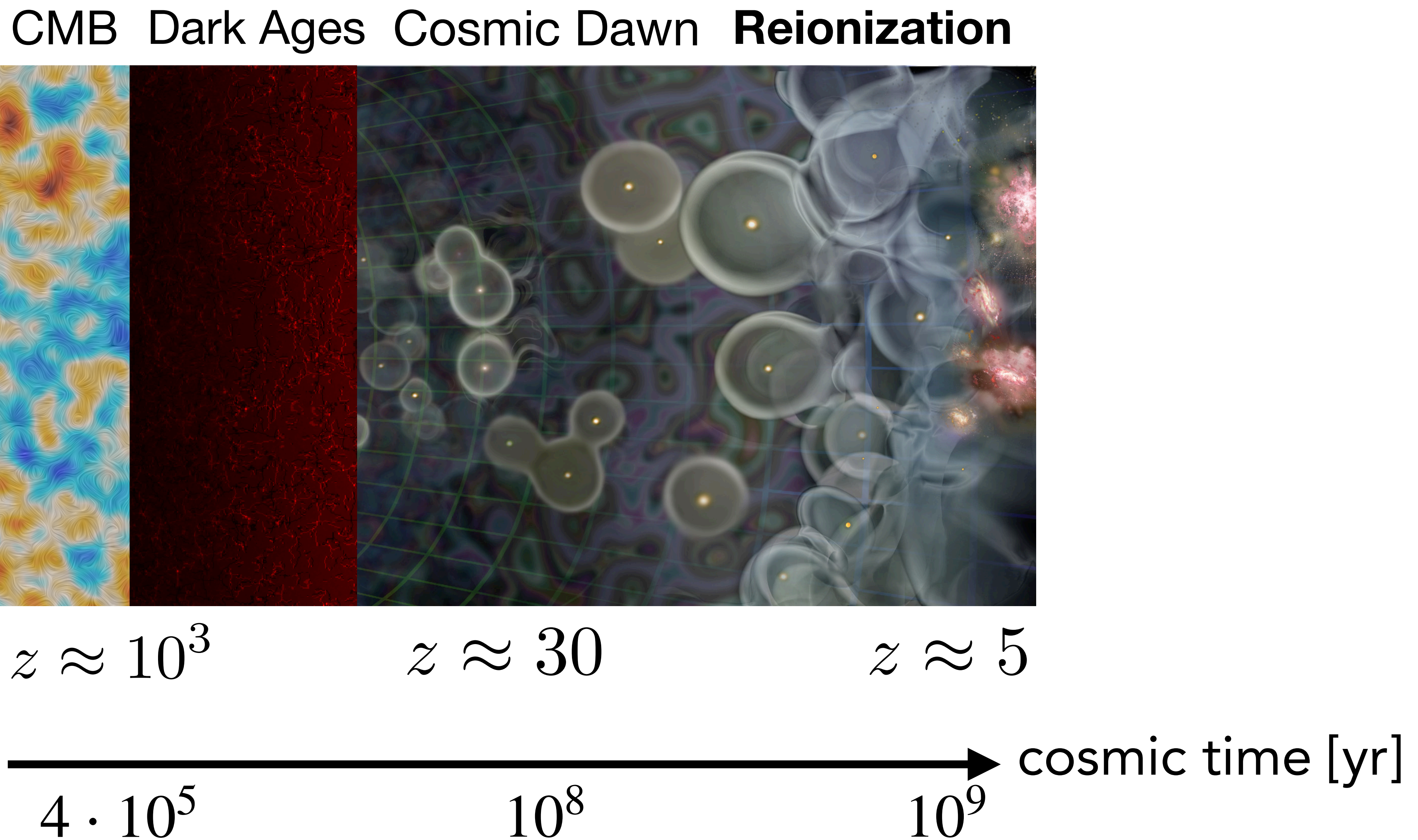
$z \approx 10^3$ $z \approx 30$

cosmic time [yr]

$4 \cdot 10^5$ 10^8

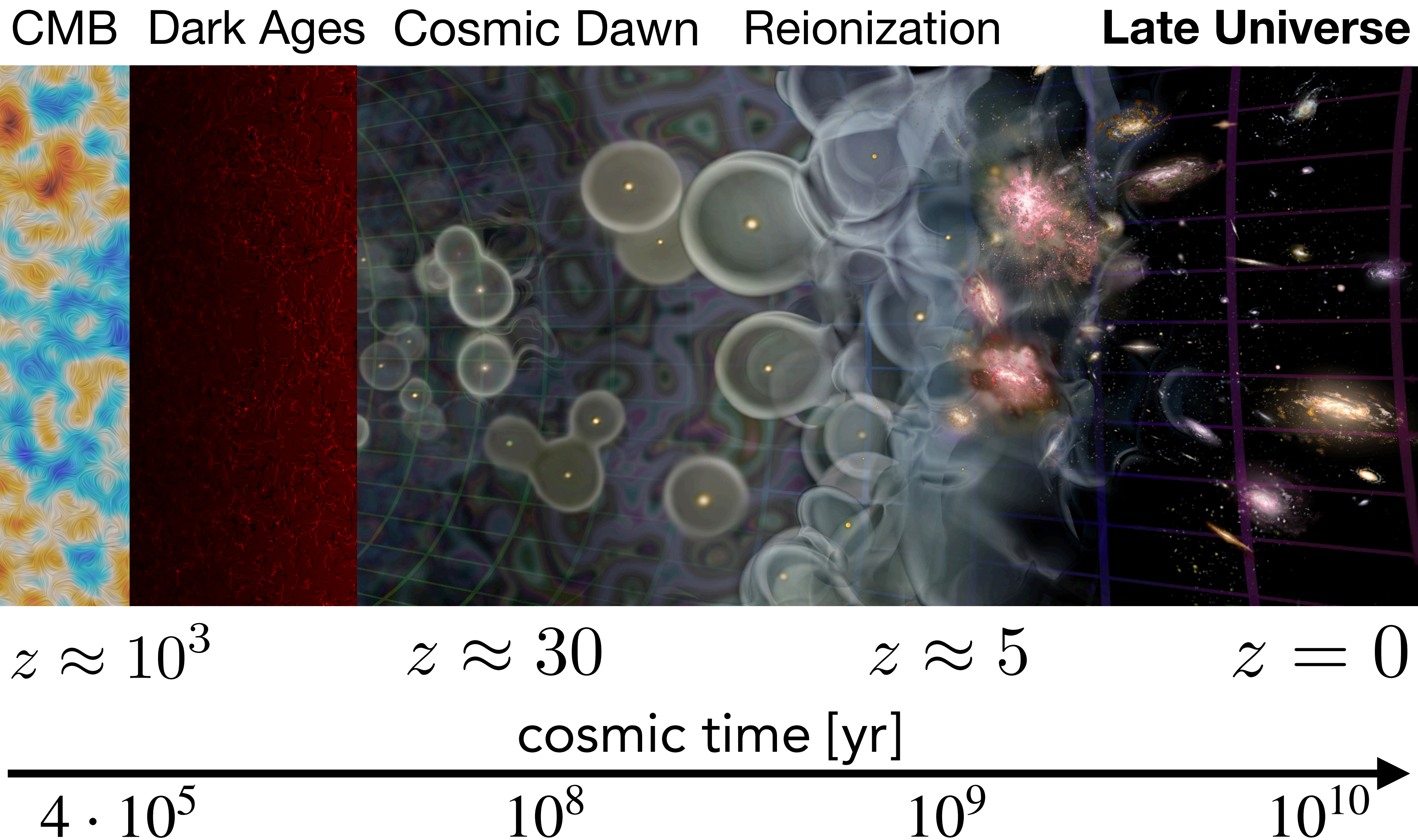
First billion years - birth of structure and Cosmic Dawn

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

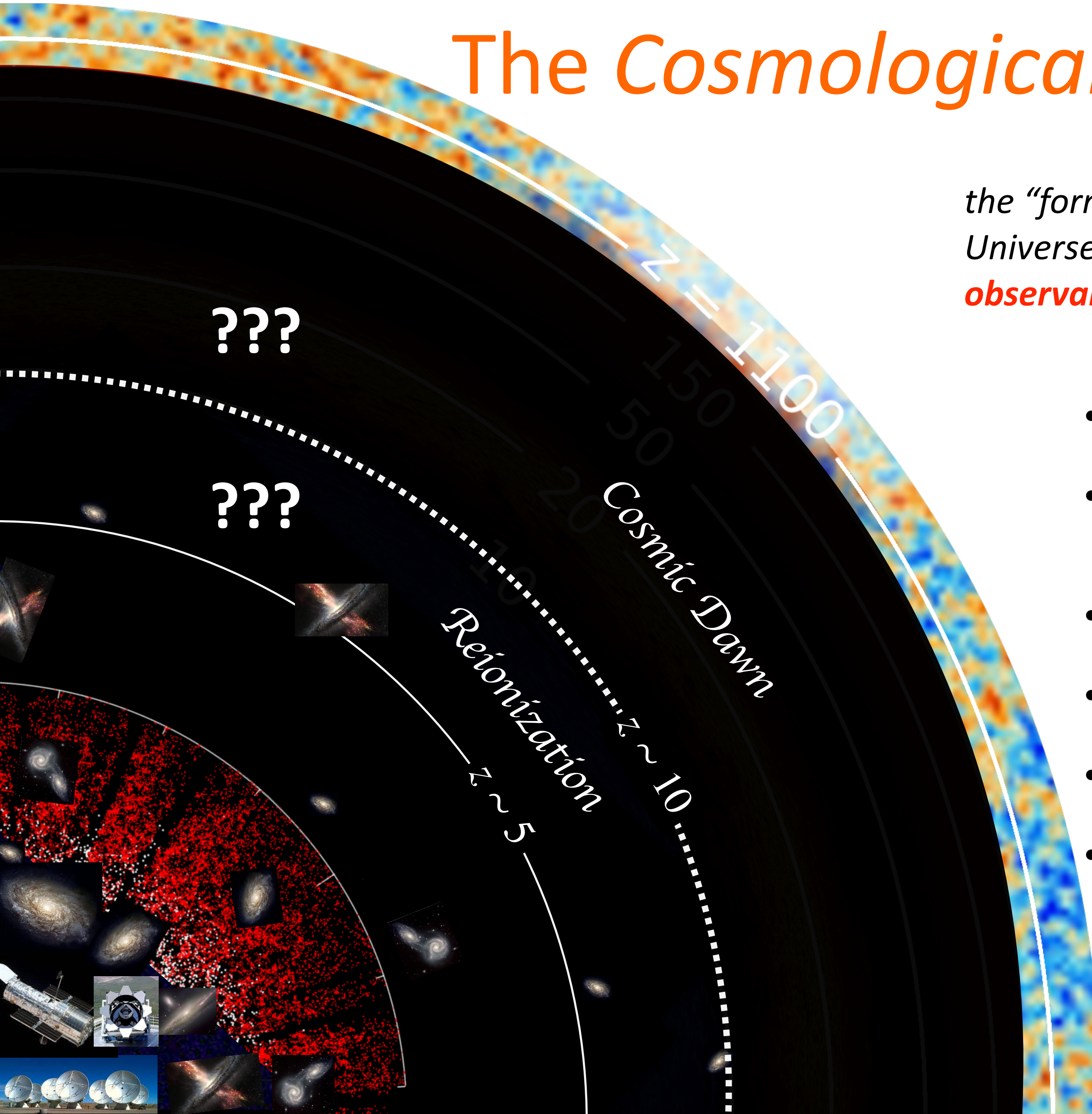


First billion years - birth of structure and Cosmic Dawn

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



The *Cosmological Frontier…*



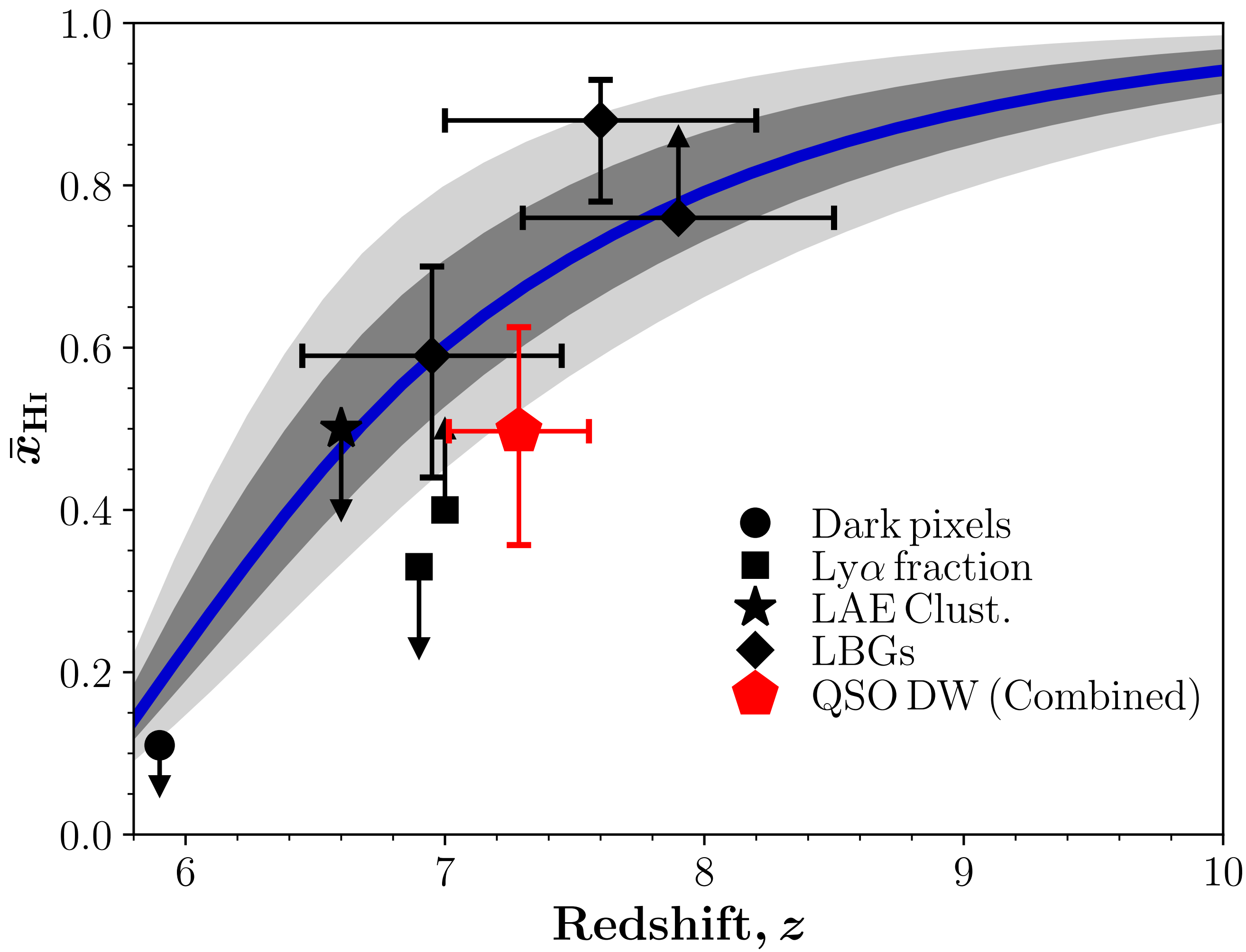
the "formative childhood" of the Universe, yet the ***majority of the observable volume***

- 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

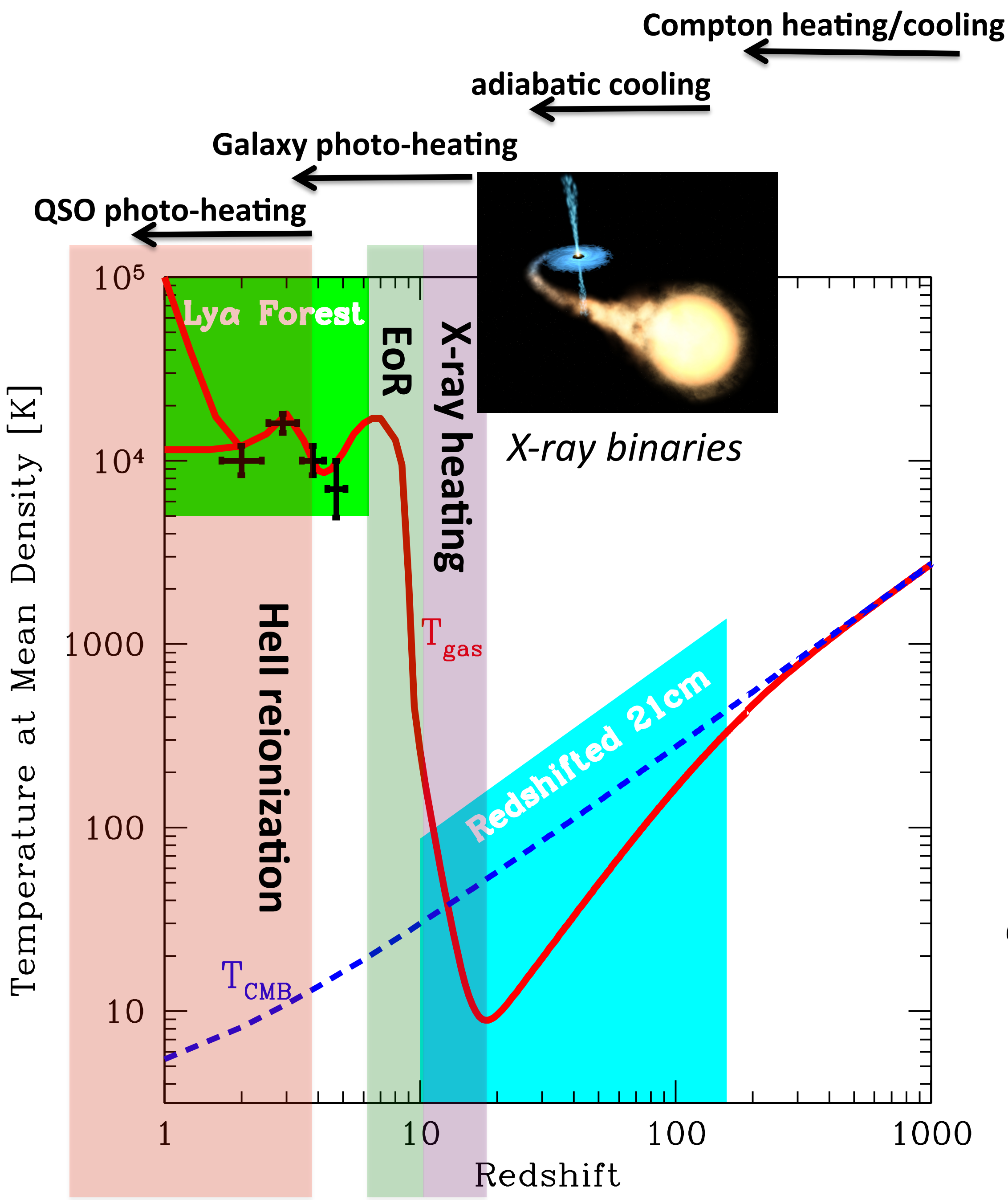
We know something about the *mean* IGM evolution during the Cosmic Dawn and Epoch of Reionization

Understanding the timing of reionization



Greig, AM+ 2021

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



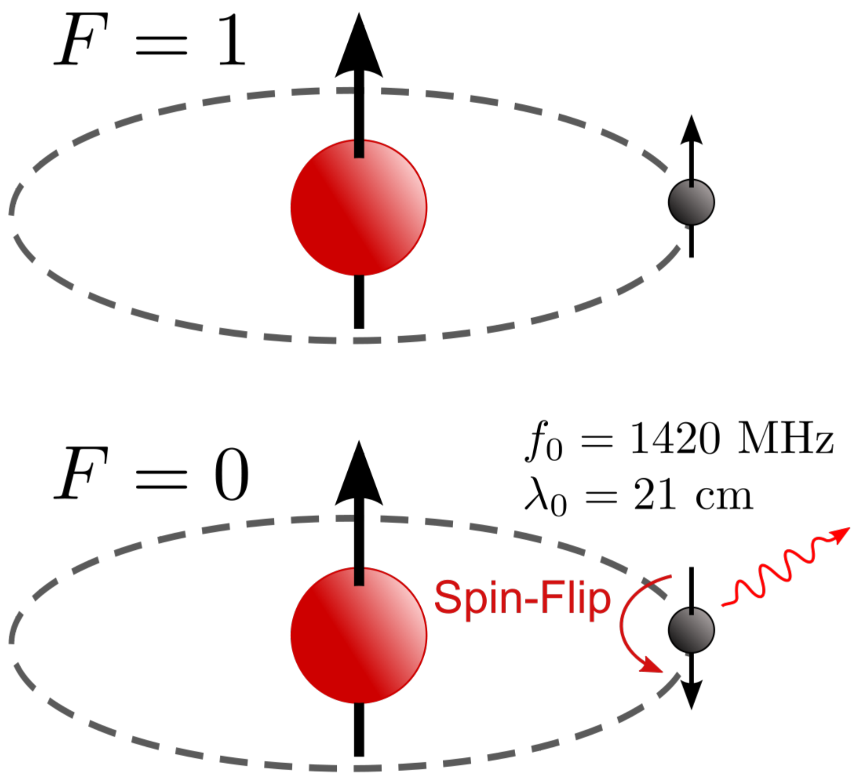
What about the heating history?

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.

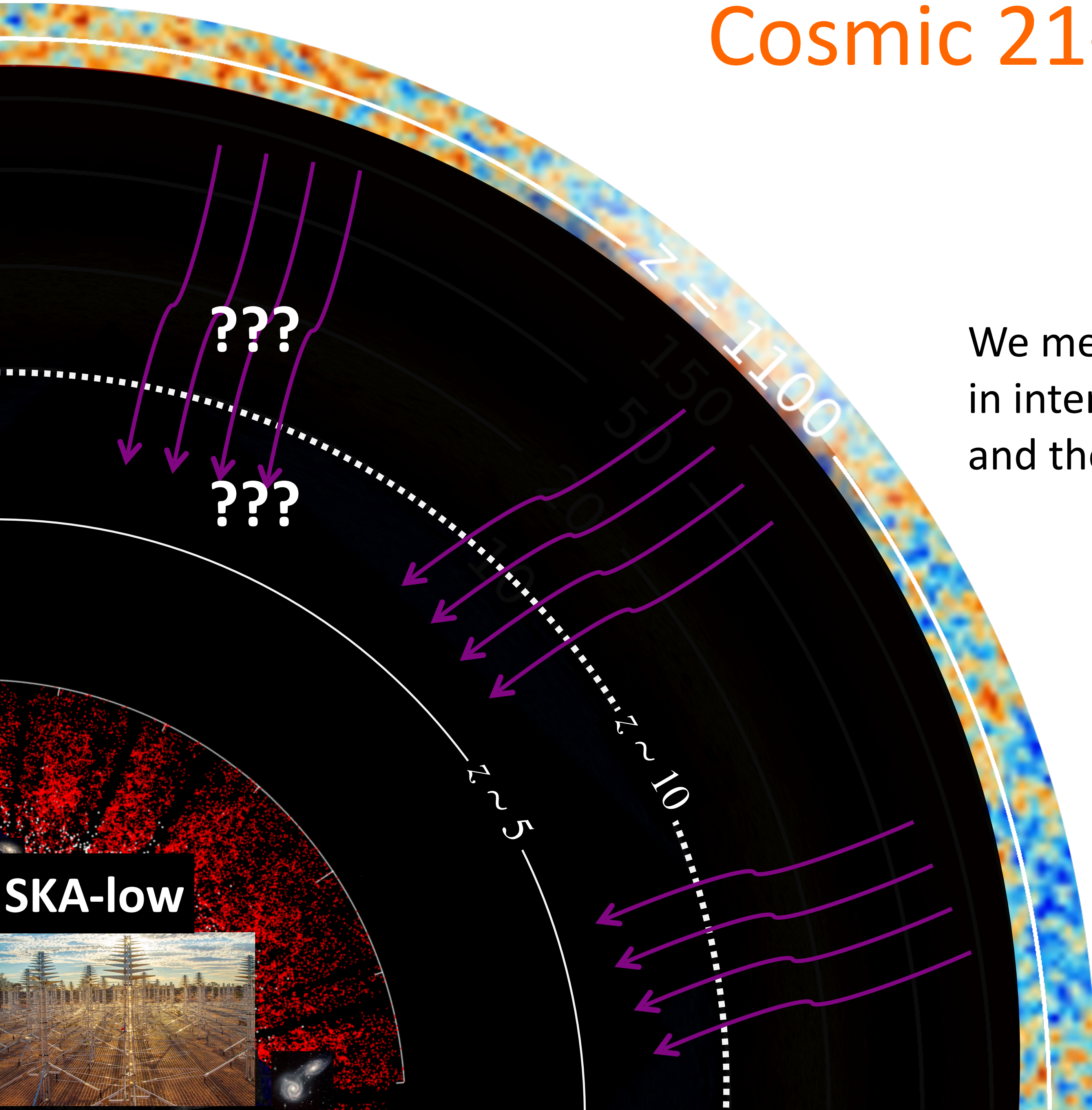
It has a "Goldilocks" optical depth for HI!

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

Cosmic 21-cm

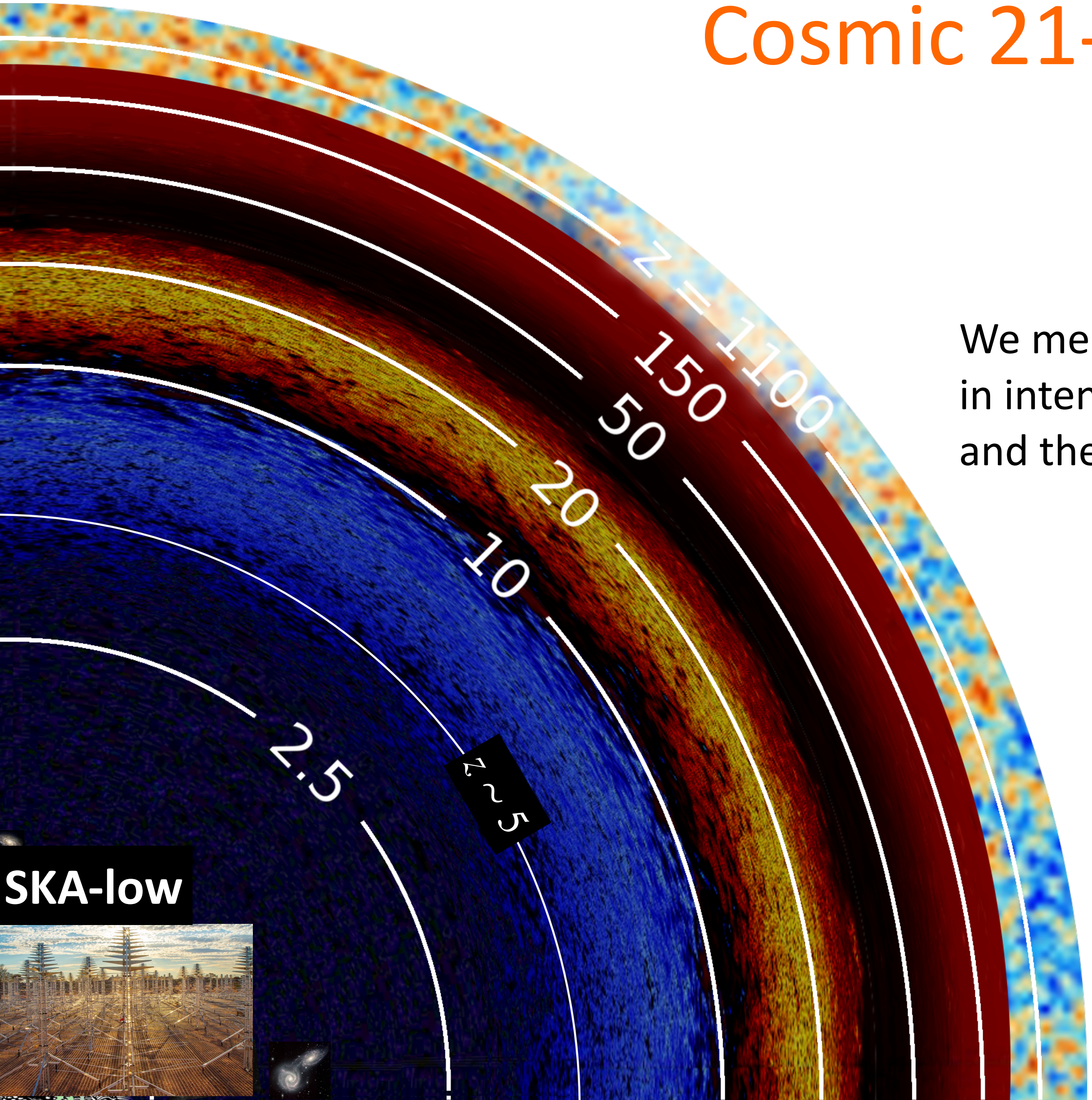
We measure the difference in intensities of the CMB and the cosmic HI.

Cosmic 21-cm



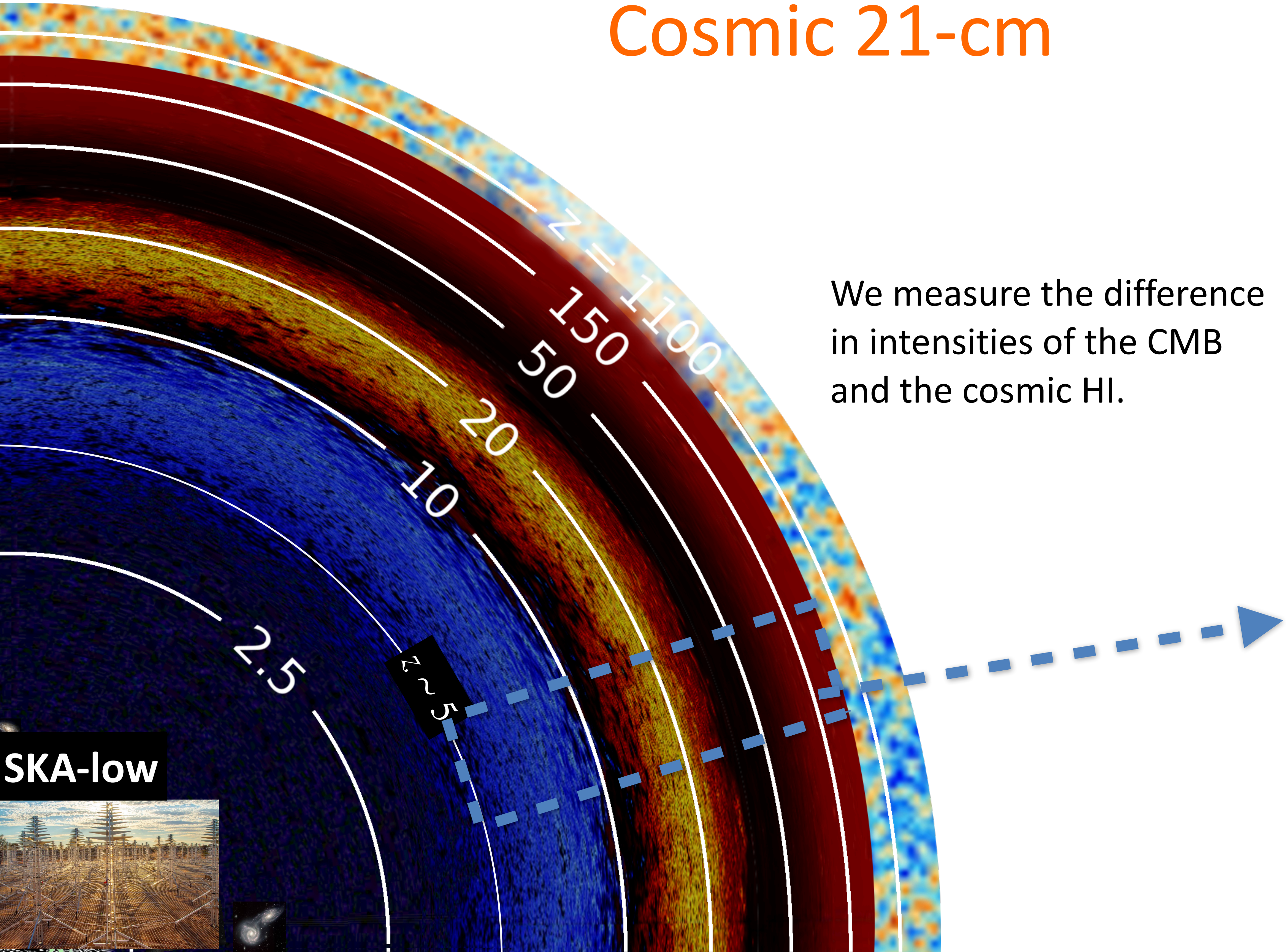
We measure the difference in intensities of the CMB and the cosmic HI.

Cosmic 21-cm



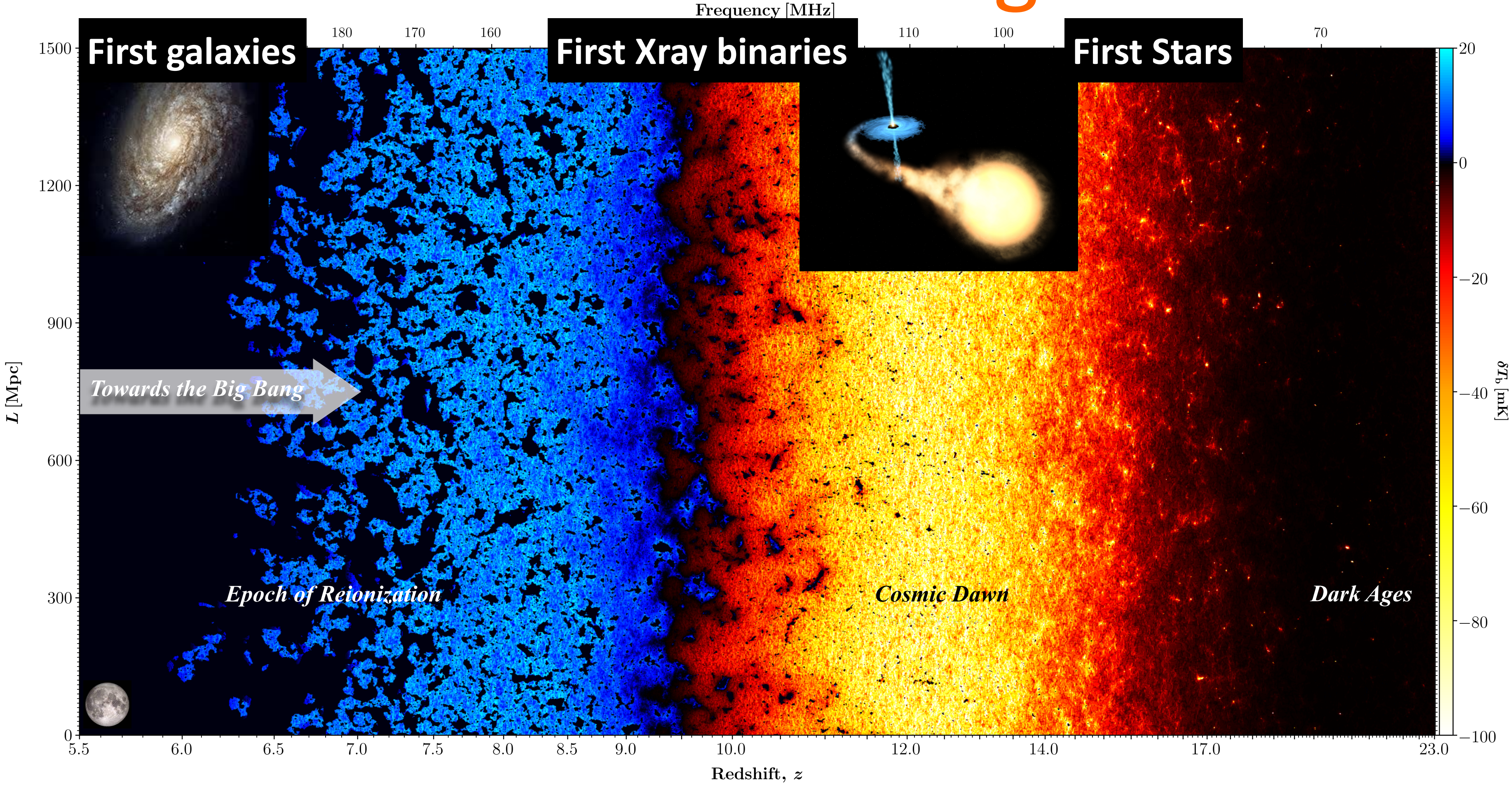
We measure the difference in intensities of the CMB and the cosmic HI.

Cosmic 21-cm



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

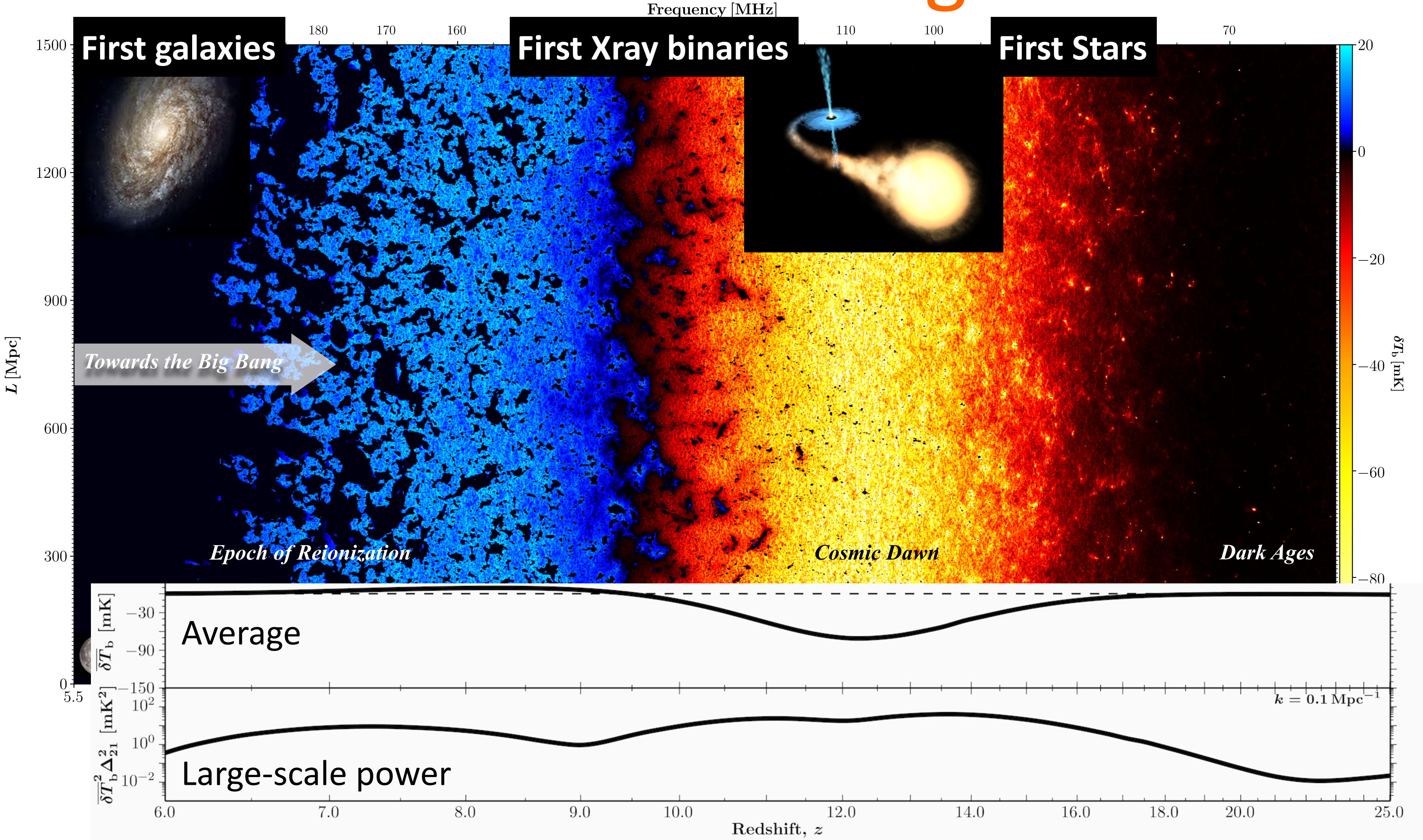
Cosmic 21-cm signal



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

Figure courtesy of J. Park

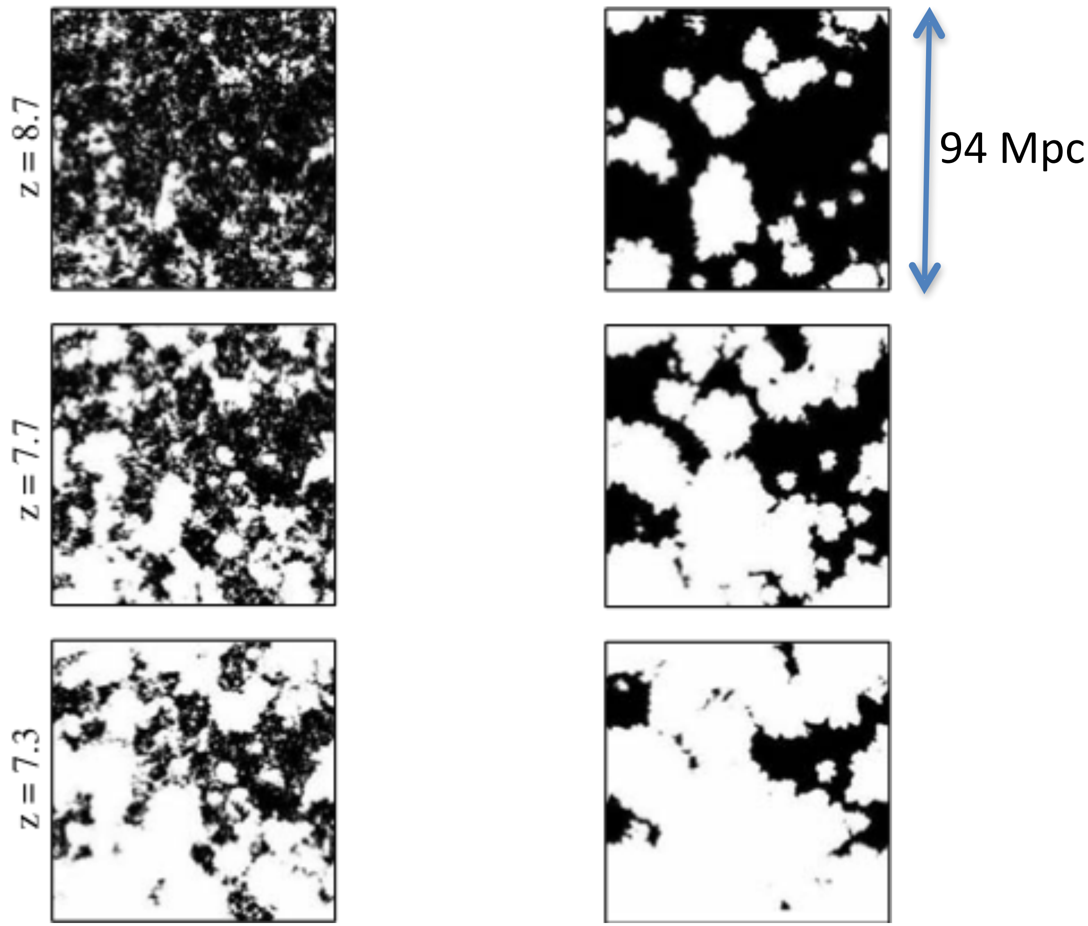
Cosmic 21-cm signal



So how do we learn about 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*

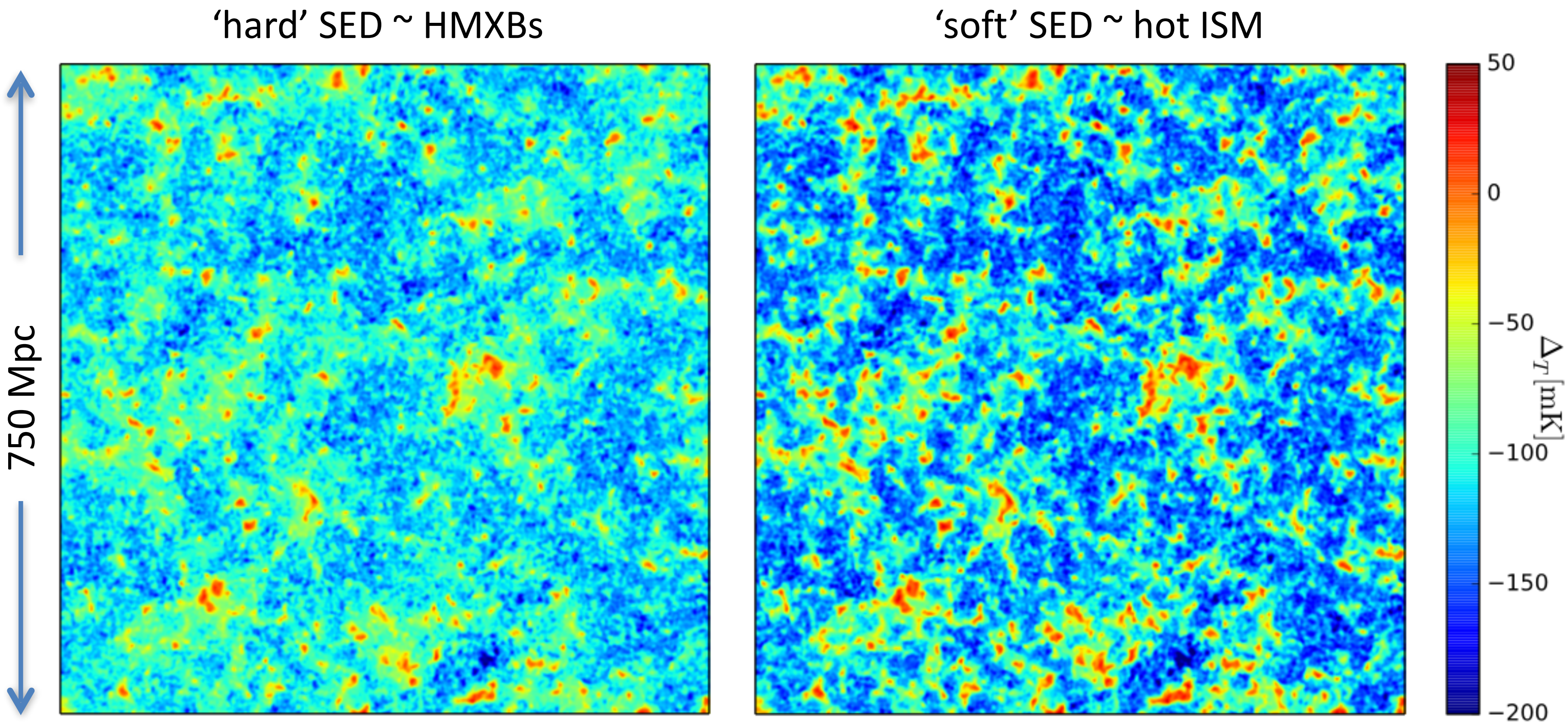


McQuinn+ 2007

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?

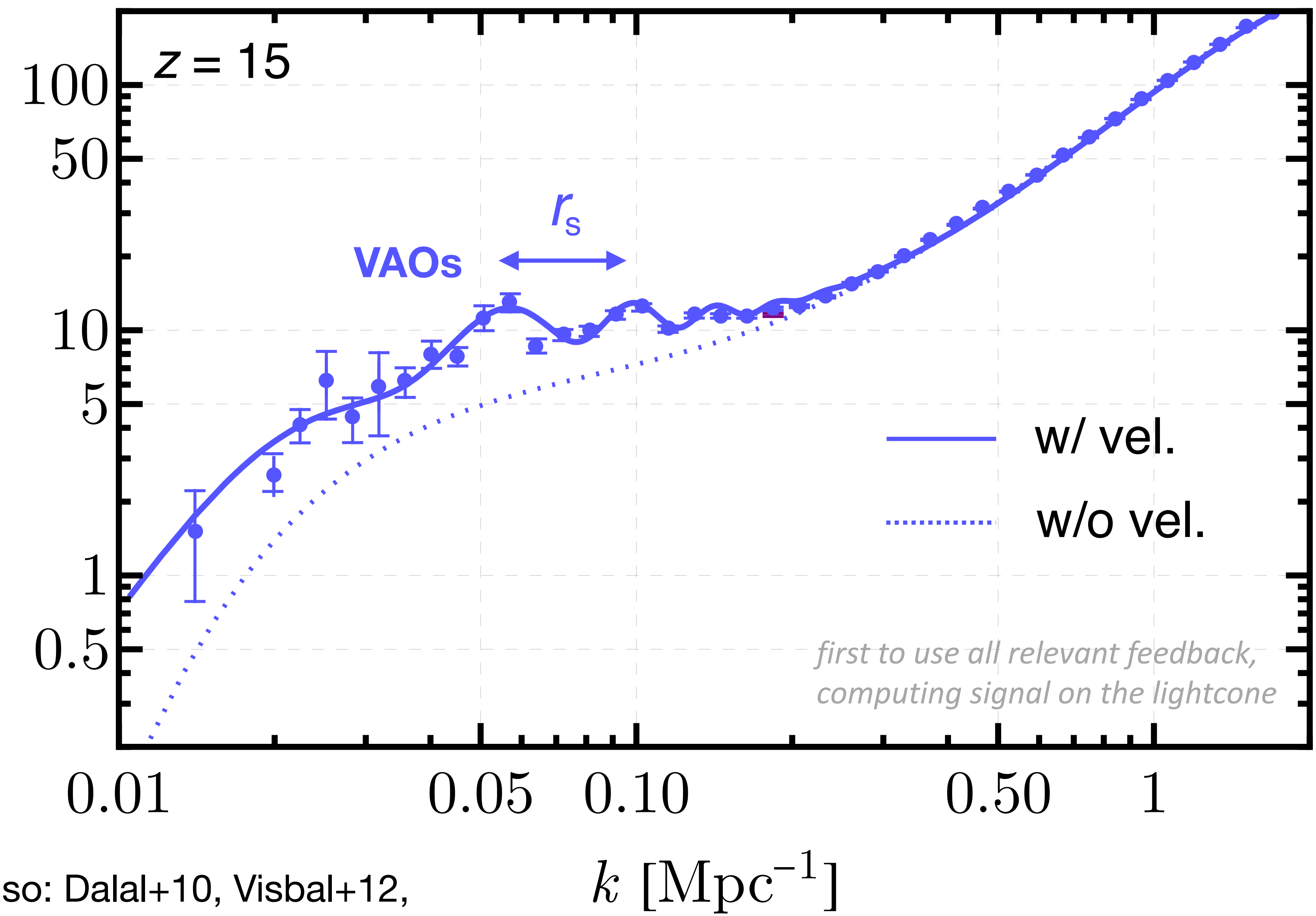
- Cosmic Rays? (e.g. Leite+2017; Jana and Nath 2018; Gessey-Jones+2023)

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

- Dark matter decay? (e.g. Facchinetti+ 2023; Sun+2025)

stay tuned…

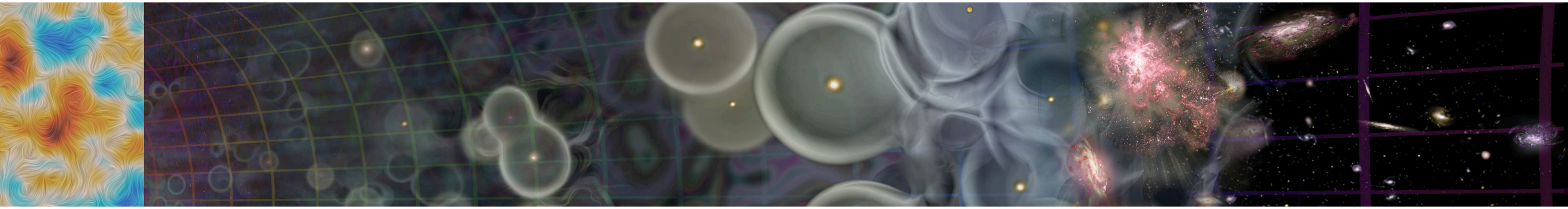
Standard ruler

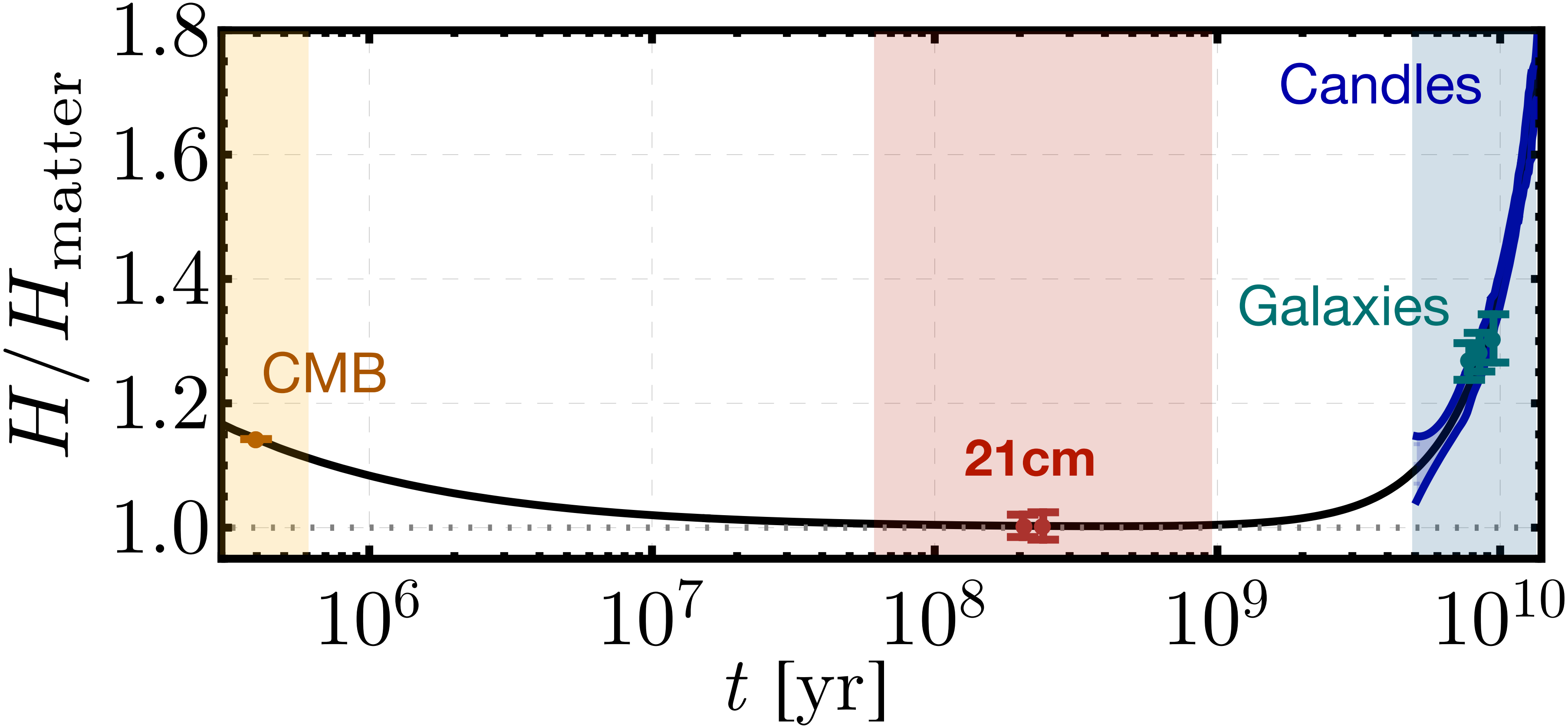


See also: Dalal+10, Visbal+12,
Fialkov+12, McQuinn+12
Munoz 19, Park+19, Cain+20, Sarkar+22

Munoz, Qin, AM+ 2022

Measuring the expansion history





Munoz+ 2019

That sounds great, but where are we now?

Current status
global experiments

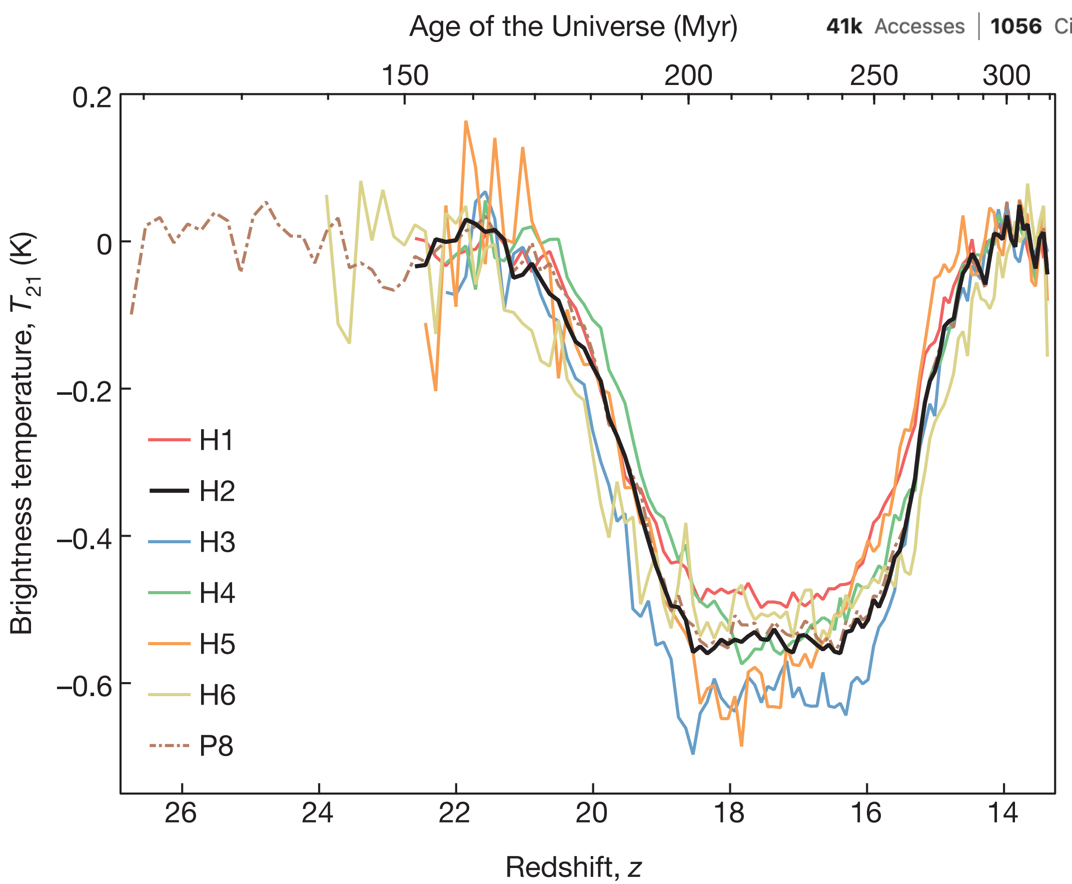
Letter | Published: 01 March 2018

An absorption profile centred at 78 megahertz in the sky-averaged spectrum

Judd D. Bowman, Alan E. E. Rogers, Raul A. Monsalve, Thomas J. Mozdzen & Nivedita Mahesh

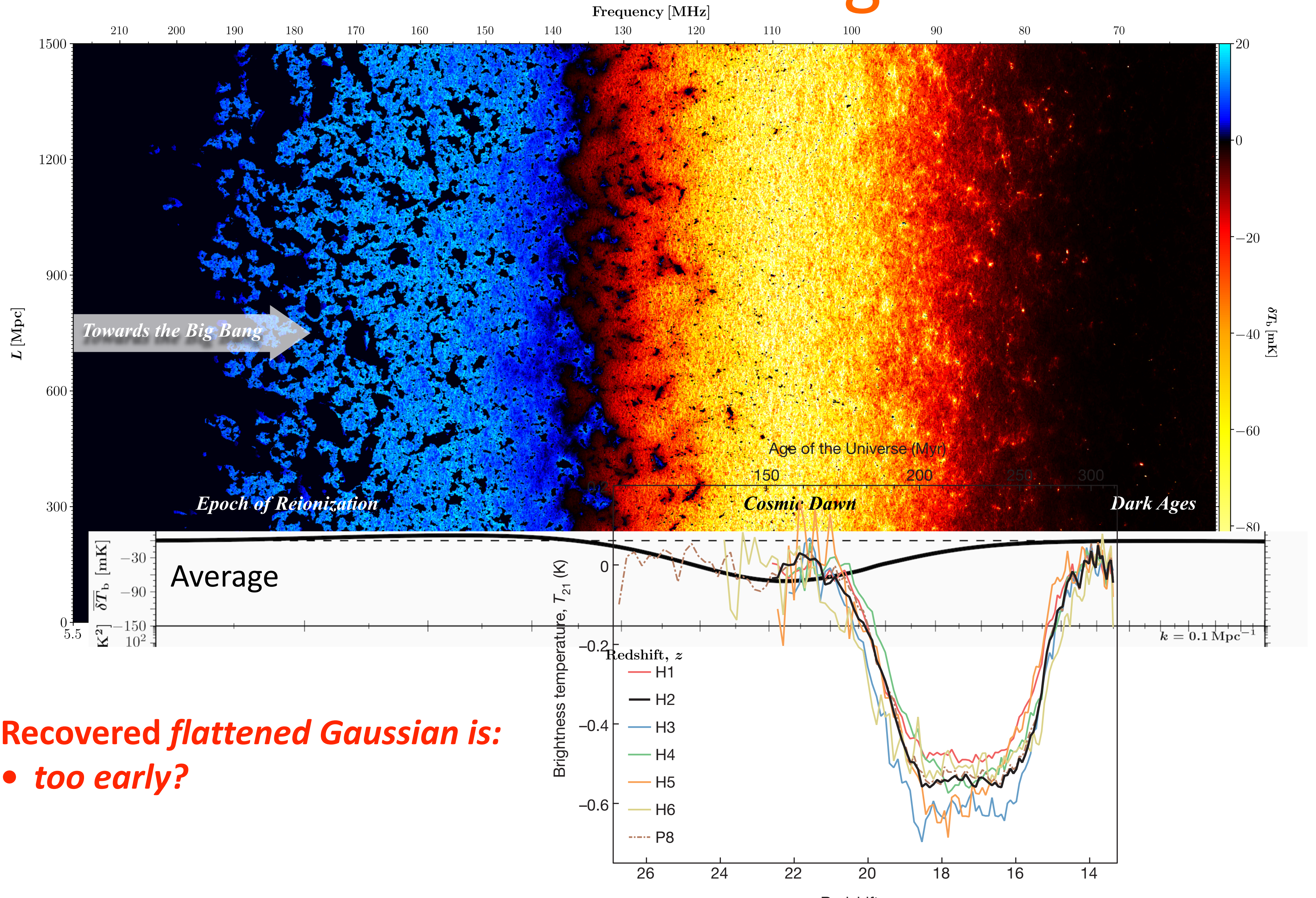
Nature **555**, 67–70 (2018) | Cite this article

Claim of a detection by EDGES



Bowman et al. 2018

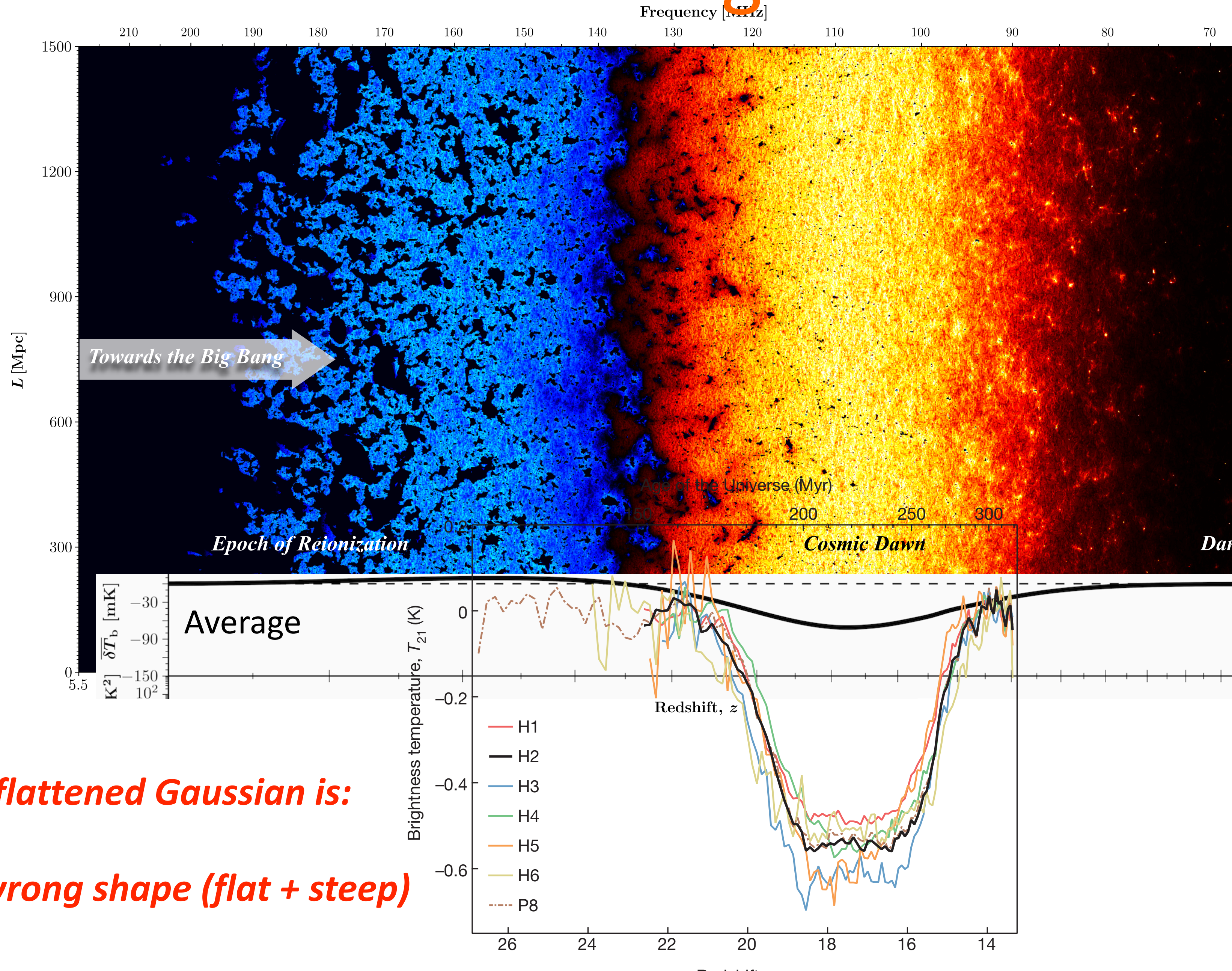
Cosmic 21-cm signal



Recovered *flattened Gaussian is:*

- ***too early?***

Cosmic 21-cm signal



Recovered *flattened Gaussian is:*

- ***too deep***
- ***has the wrong shape (flat + steep)***

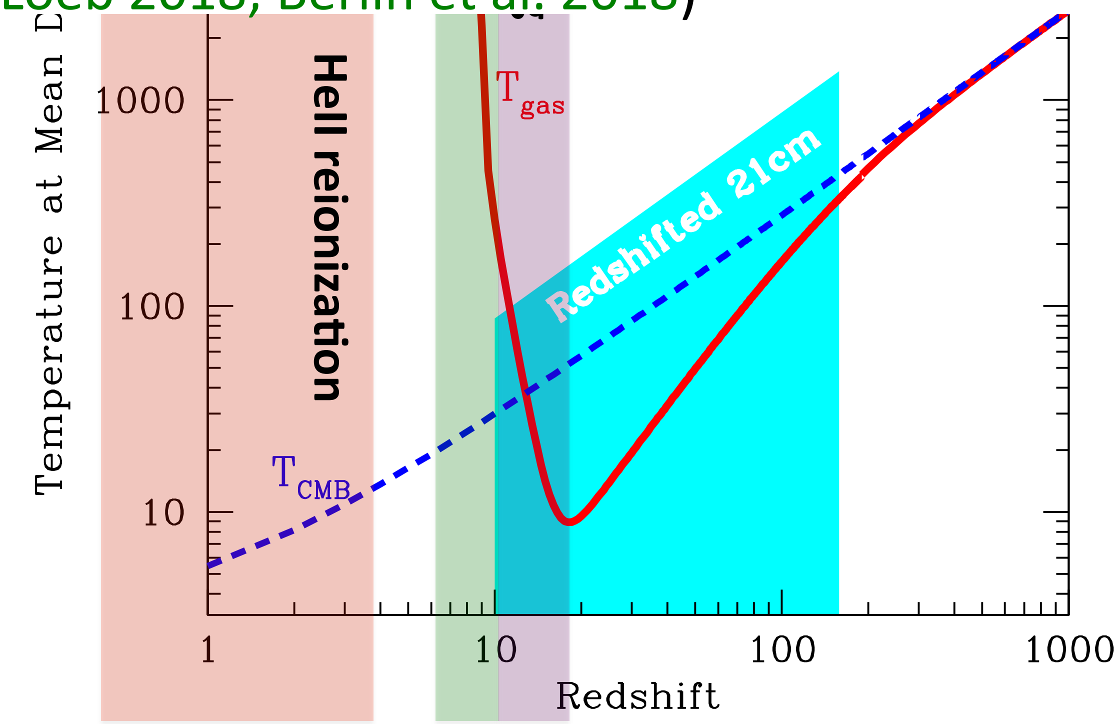
How to get a deep absorption trough?

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

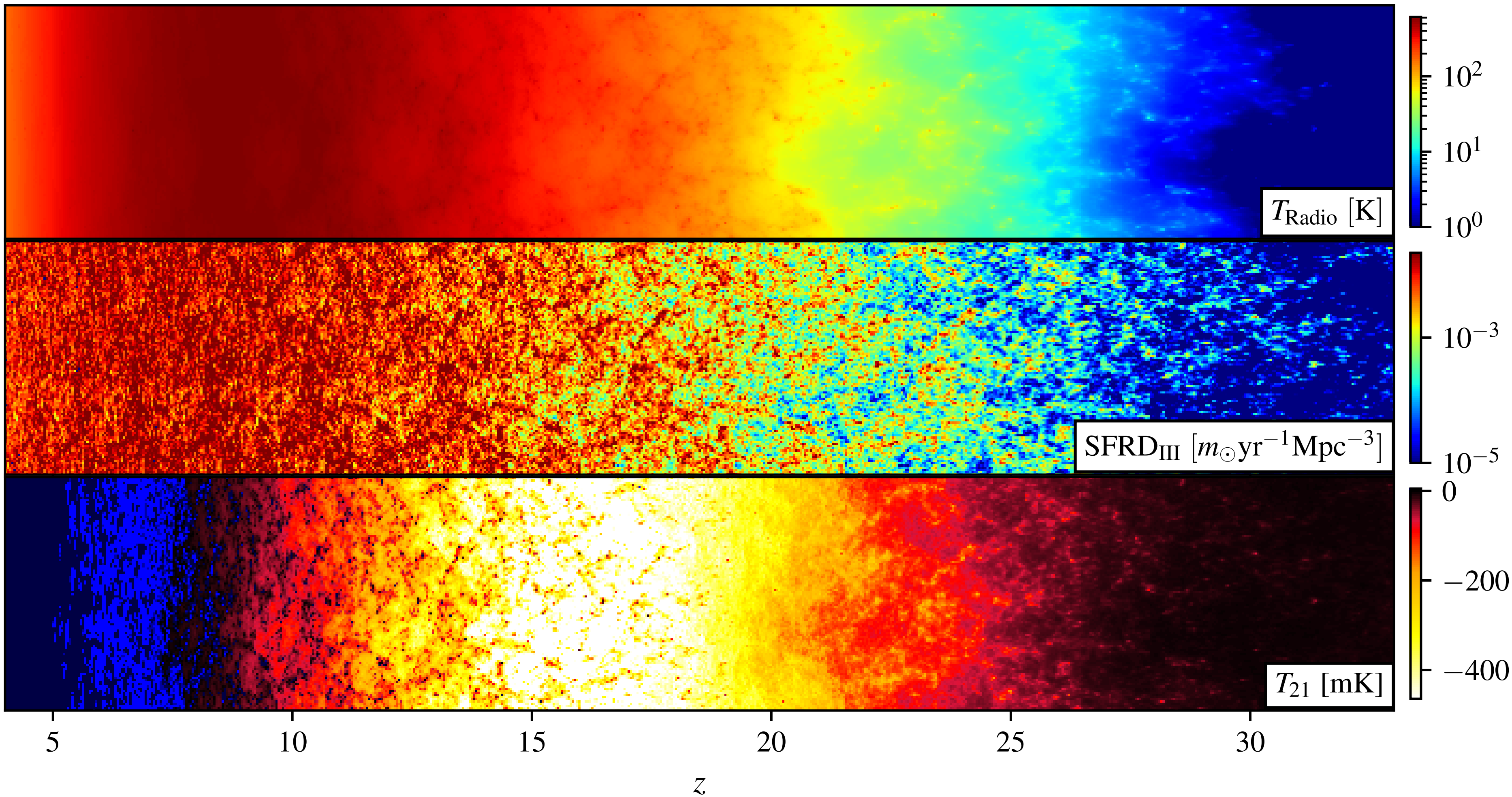
Either:

(i) increase **numerator** (extra radio background; e.g. Mirocha & Furlanetto 2019; Reis et al. 2020; Sikder et al. 2023) or

(ii) decrease **denominator** (baryon cooling through DM interaction; e.g. Barkana 2018; Muñoz & Loeb 2018; Berlin et al. 2018)



An example: excess radio background from PopIII hosting galaxies

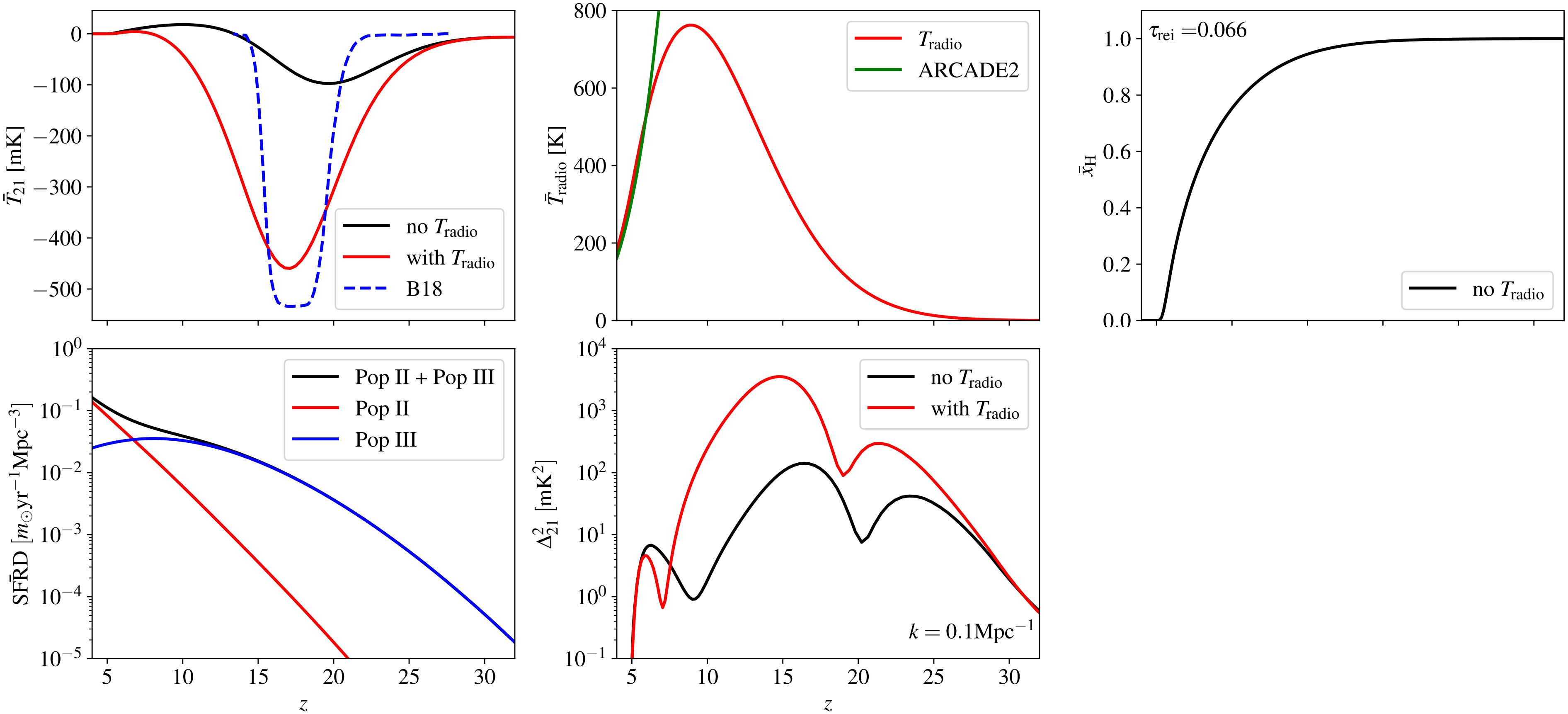


self-sterilize through the build up of a LW background —>

no need for ad-hod z_off parameter

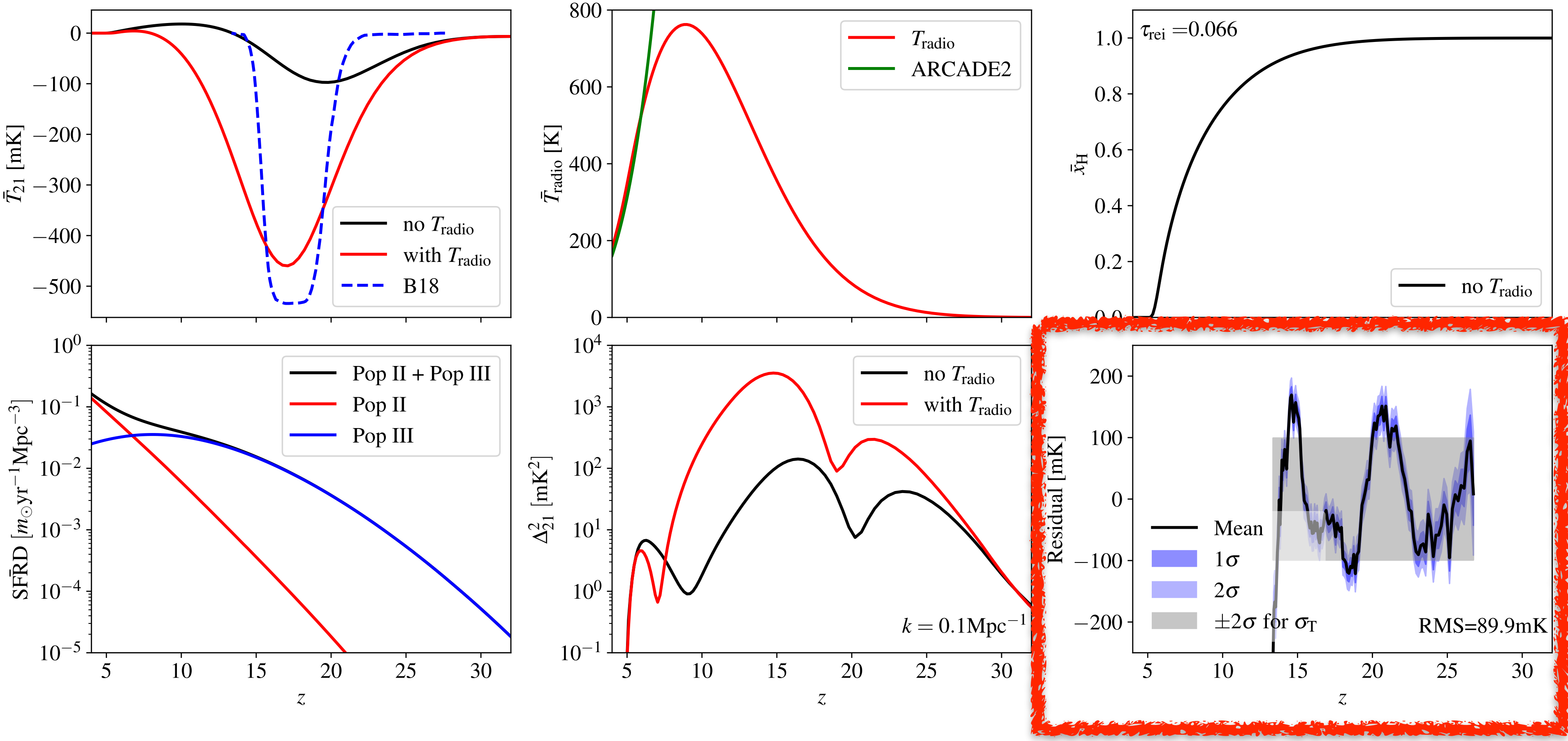
Cang, AM+ 2024

An example seemingly consistent with data



Cang, AM+ 2024

Doesn't actually explain the data!



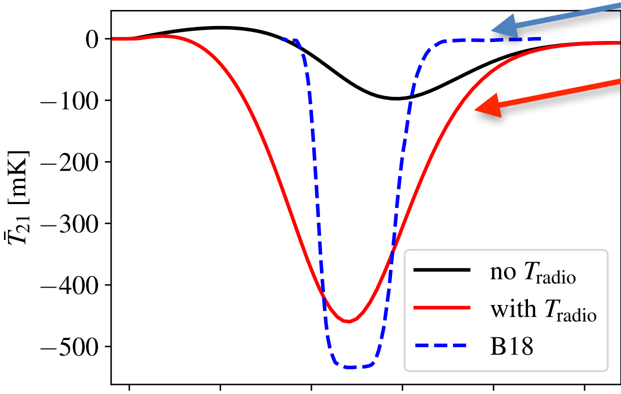
Residuals are not noise —> there is a "signal" that is missing from the forward model!

Cang, AM+ 2024

An example seemingly consistent with data

Backward-model using **Flattened Gaussian**

Forward-model with **Physical model**

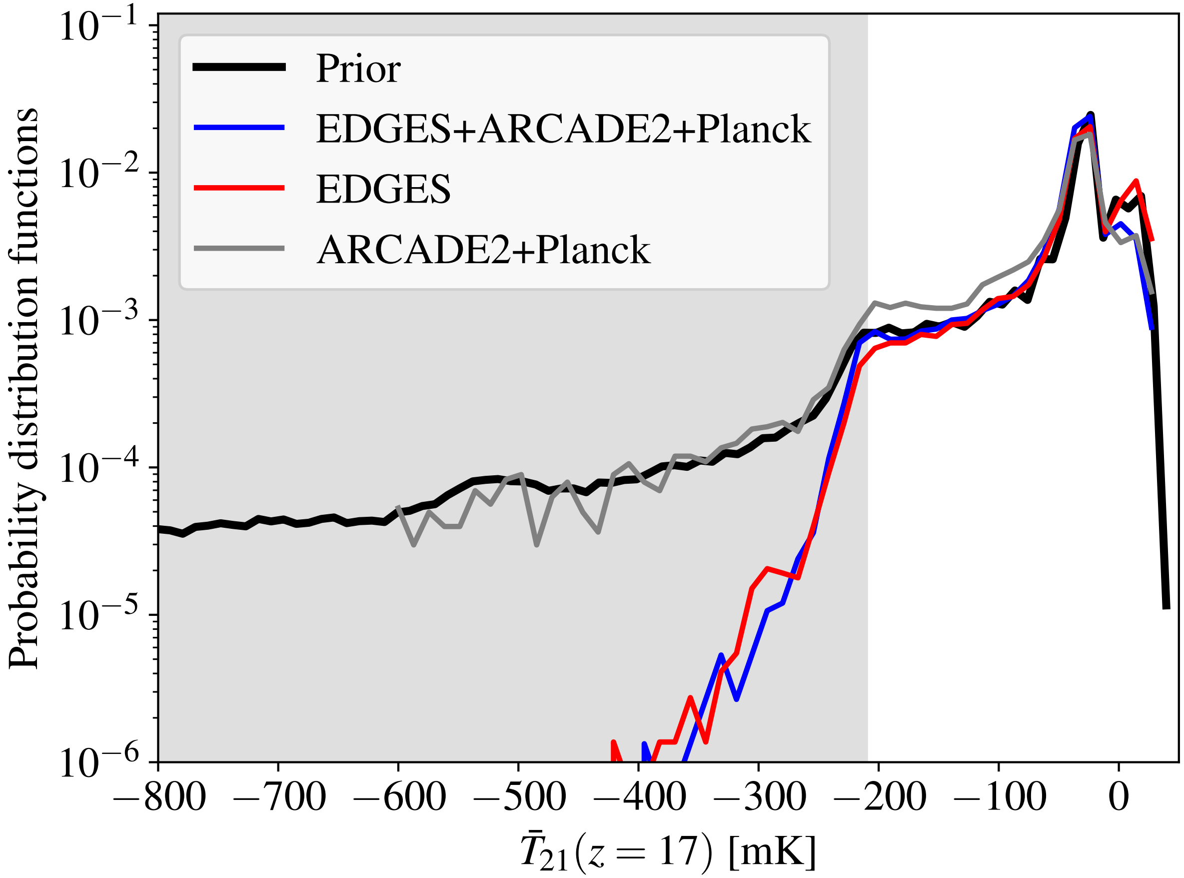


Almost all previous work just used this recovered profile to claim their cosmological model explains the data

One must use the **likelihood in data space**, NOT use some pseudo-likelihood based on flattened Gaussian recovery (see also Sims & Pober 2020)

Cang, AM+ 2024

EDGES actually **DISFAVORS** a strong cosmical signal



Cang, AM+ 2024

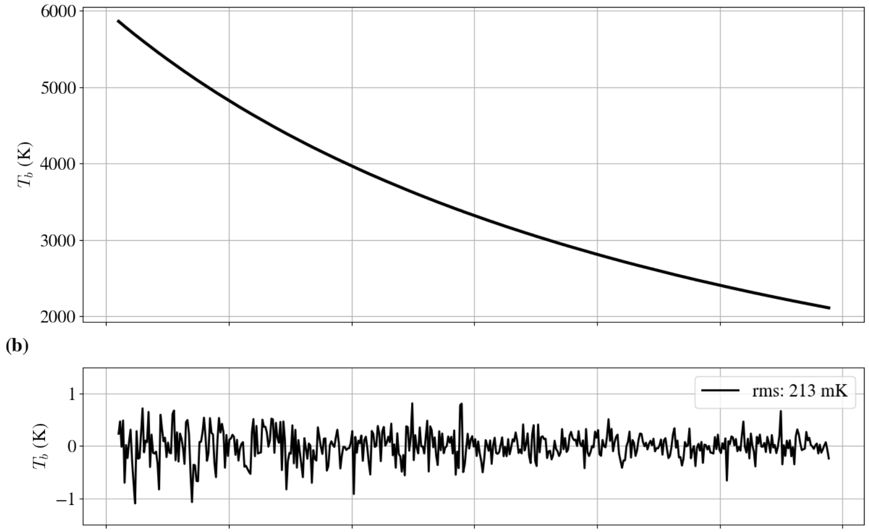
Physical models actually **get in the way** of foregrounds+systematics, which do a better job of explaining the signal.

Current status
global experiments

Claim of a detection by EDGES

BUT

No evidence of the signal in SARAS3 at 2σ



Singh+ 2021

6th order polynomial + NO cosmic signal

Current status
global experiments

Claim of a detection by EDGES

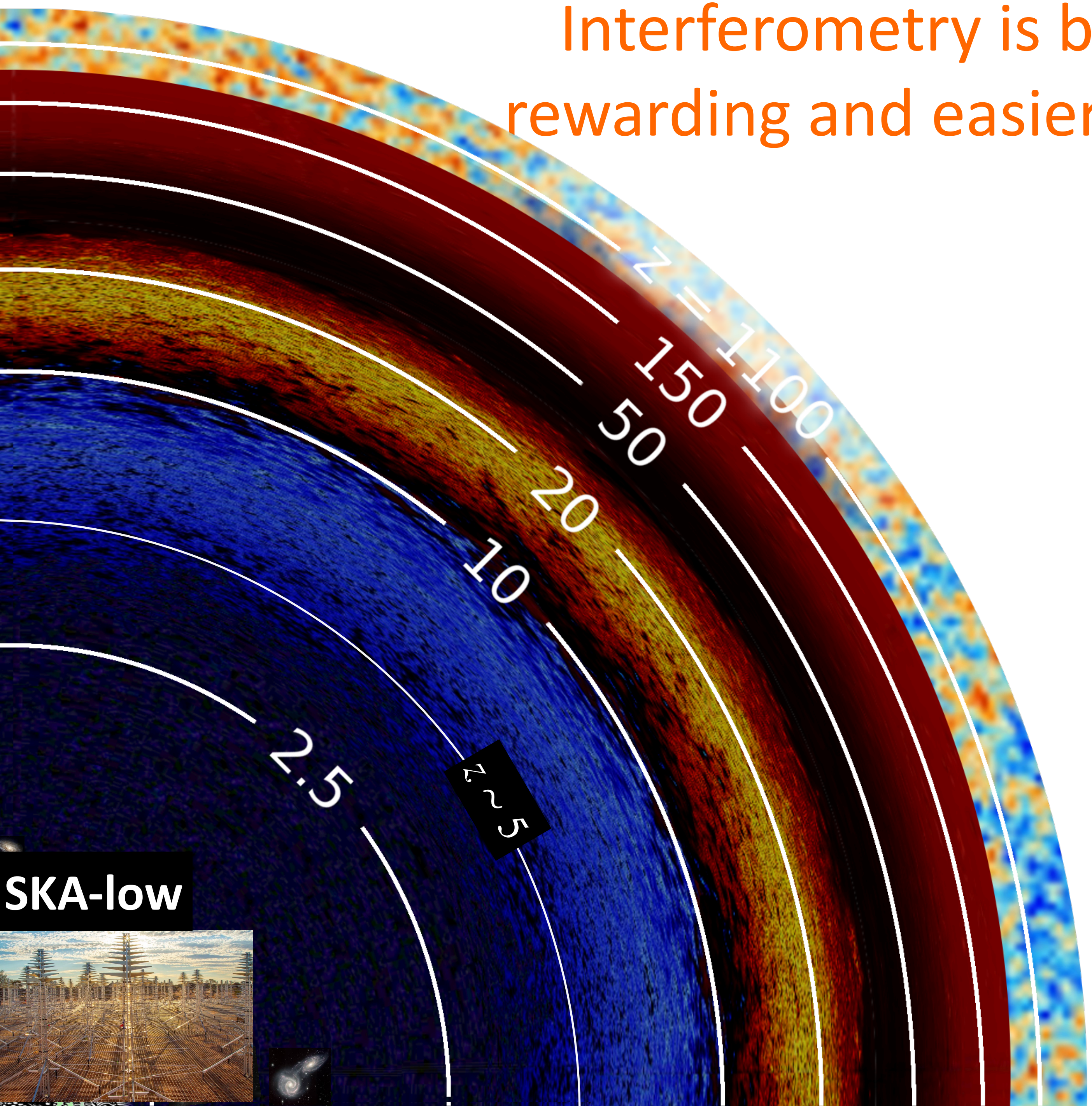
BUT

No evidence of the signal in SARAS3

Upcoming results from REACH, MIST, RHINO, etc.
updates from EDGES, SARAS

The interpretation is very challenging: with only an average measurement, you need to understand the systematics / sky / instrument to extremely high accuracy

Interferometry is both more rewarding and easier to confirm



First generation 21-cm interferometers

MWA

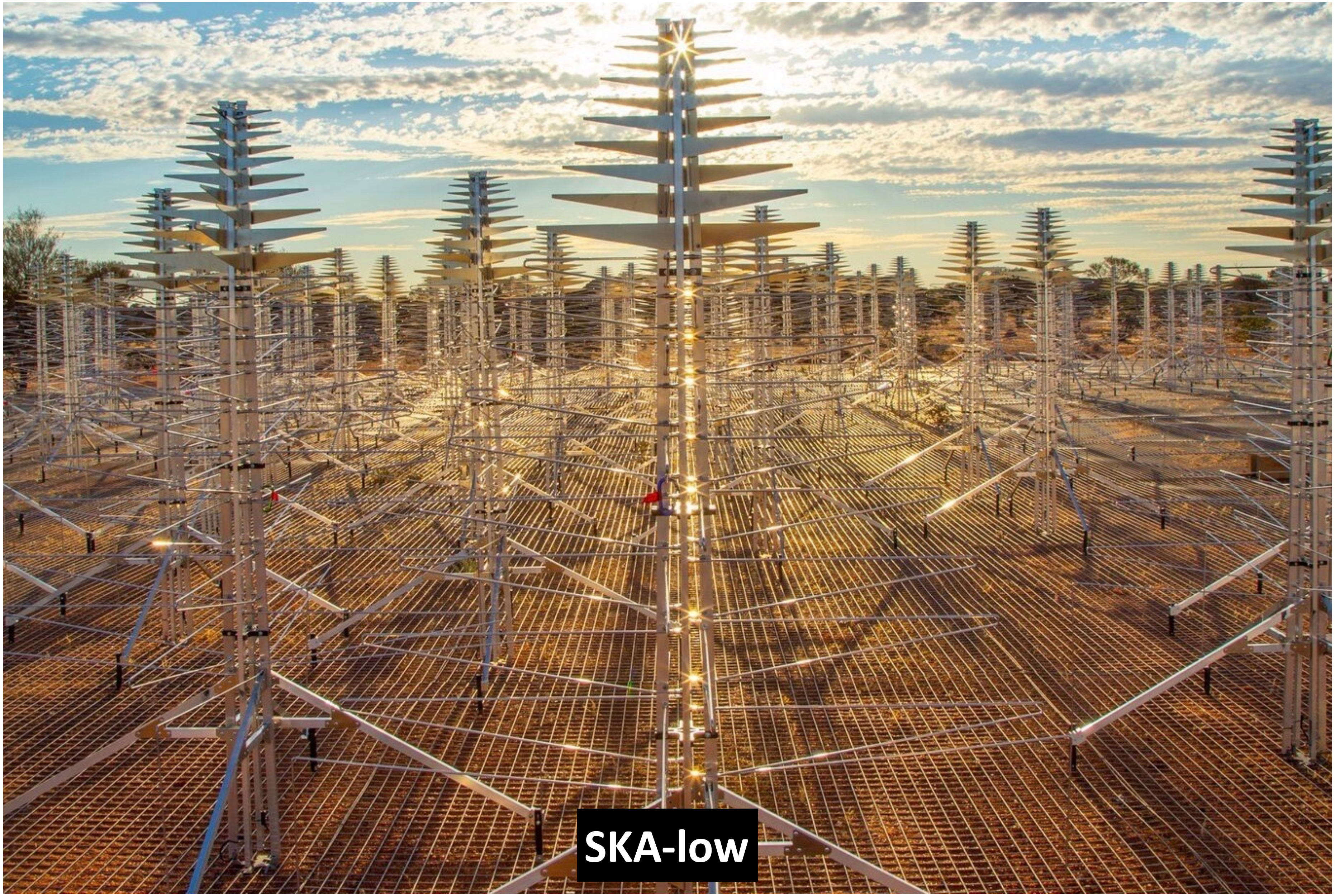
LOFAR

GMRT

PAPER

HERA

Next generation 21-cm interferometer



Observing is HARD!

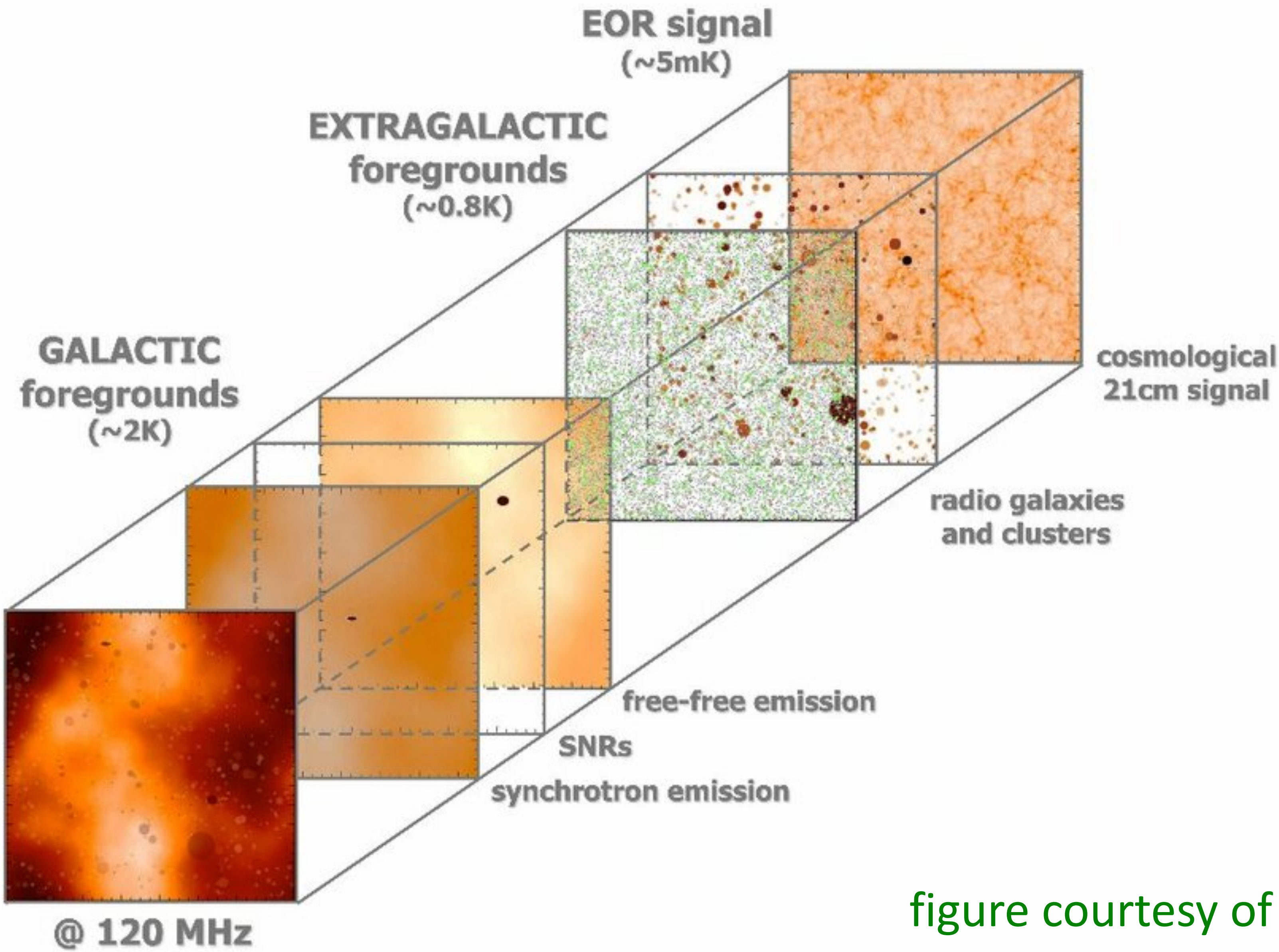
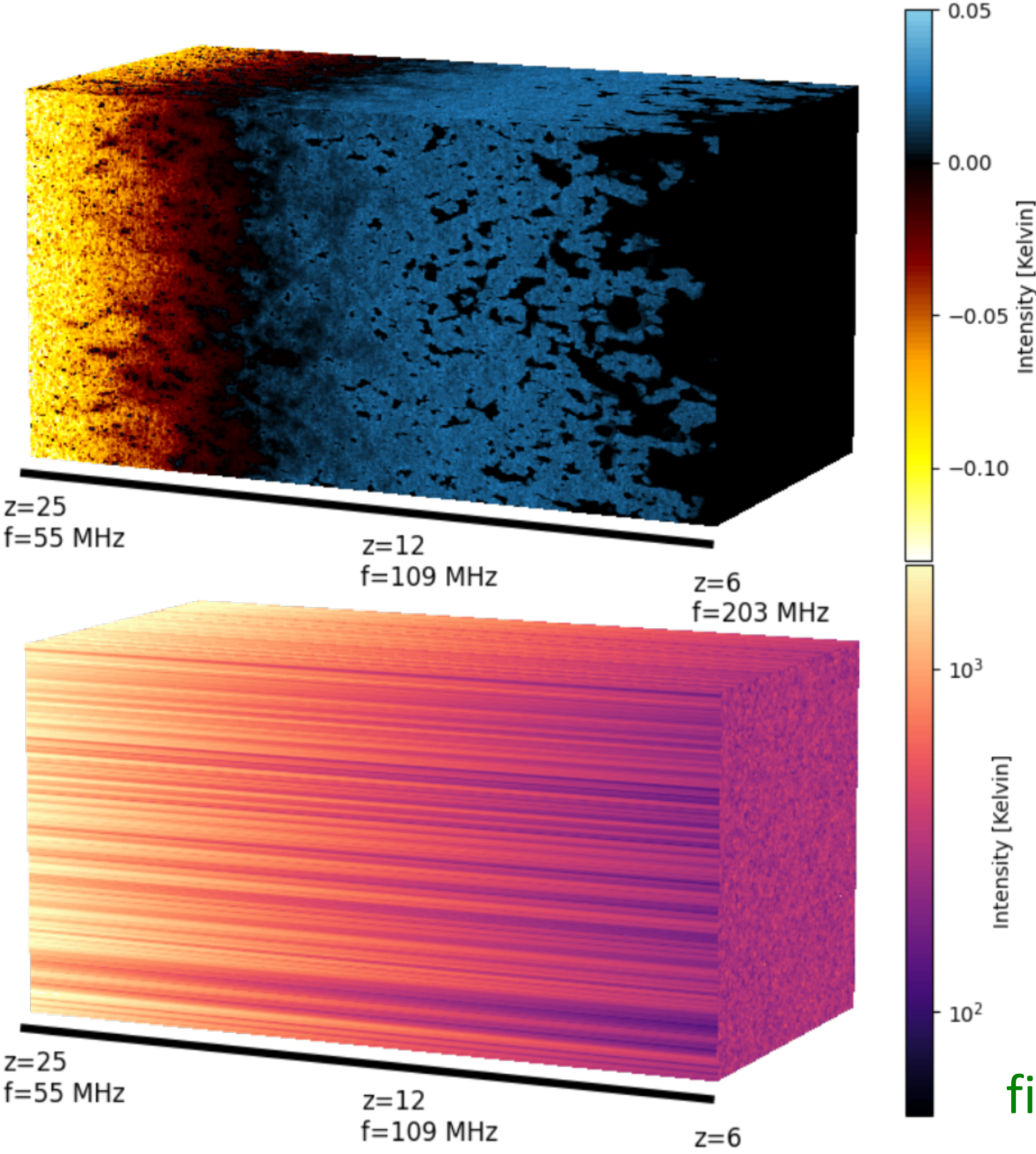


figure courtesy of V. Jelić

But foregrounds should be smooth in frequency!



Cosmic signal

Foregrounds

figure courtesy of F. Mertens

Hope is to measure PS in the "EoR window"

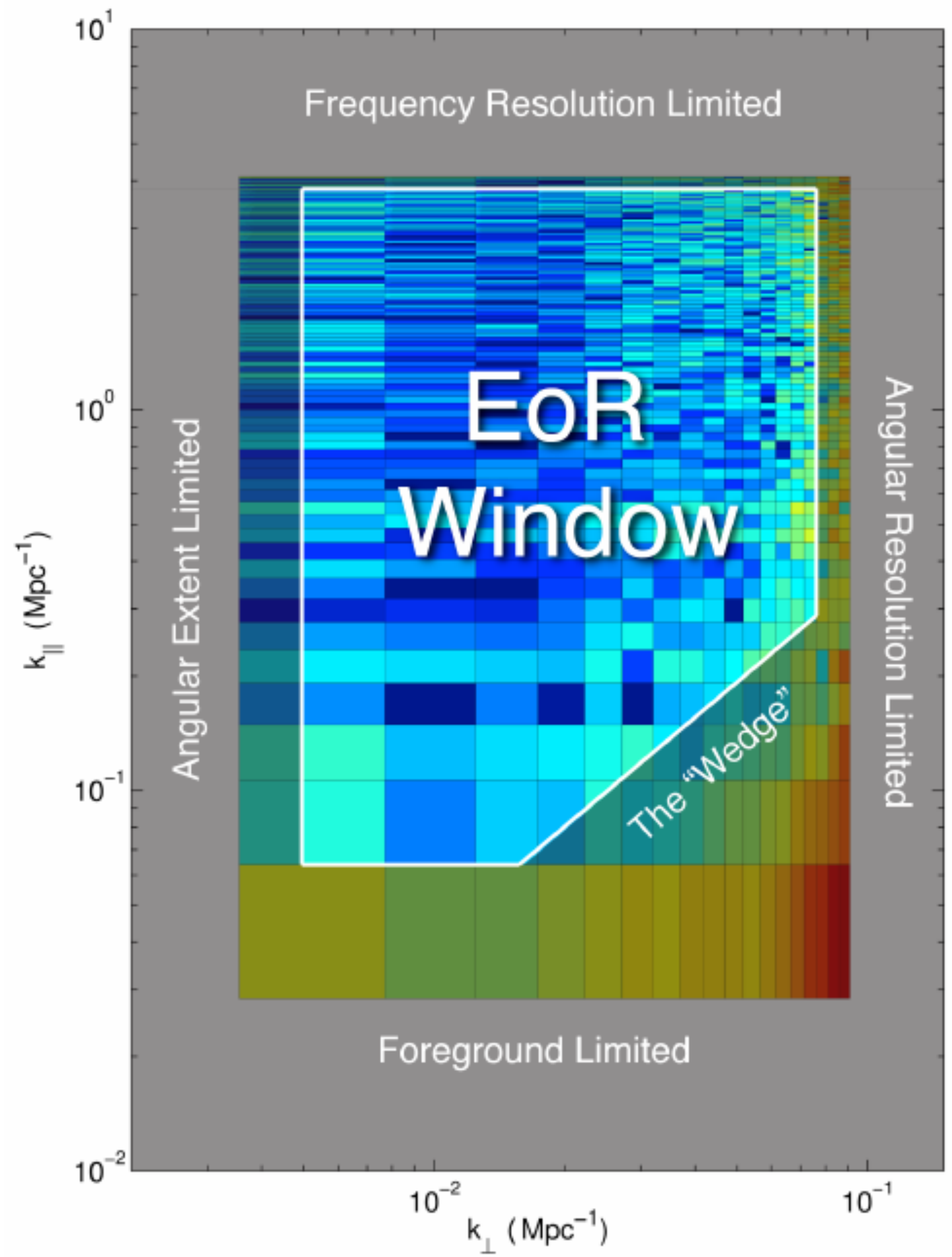


figure courtesy of J. Dillon

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

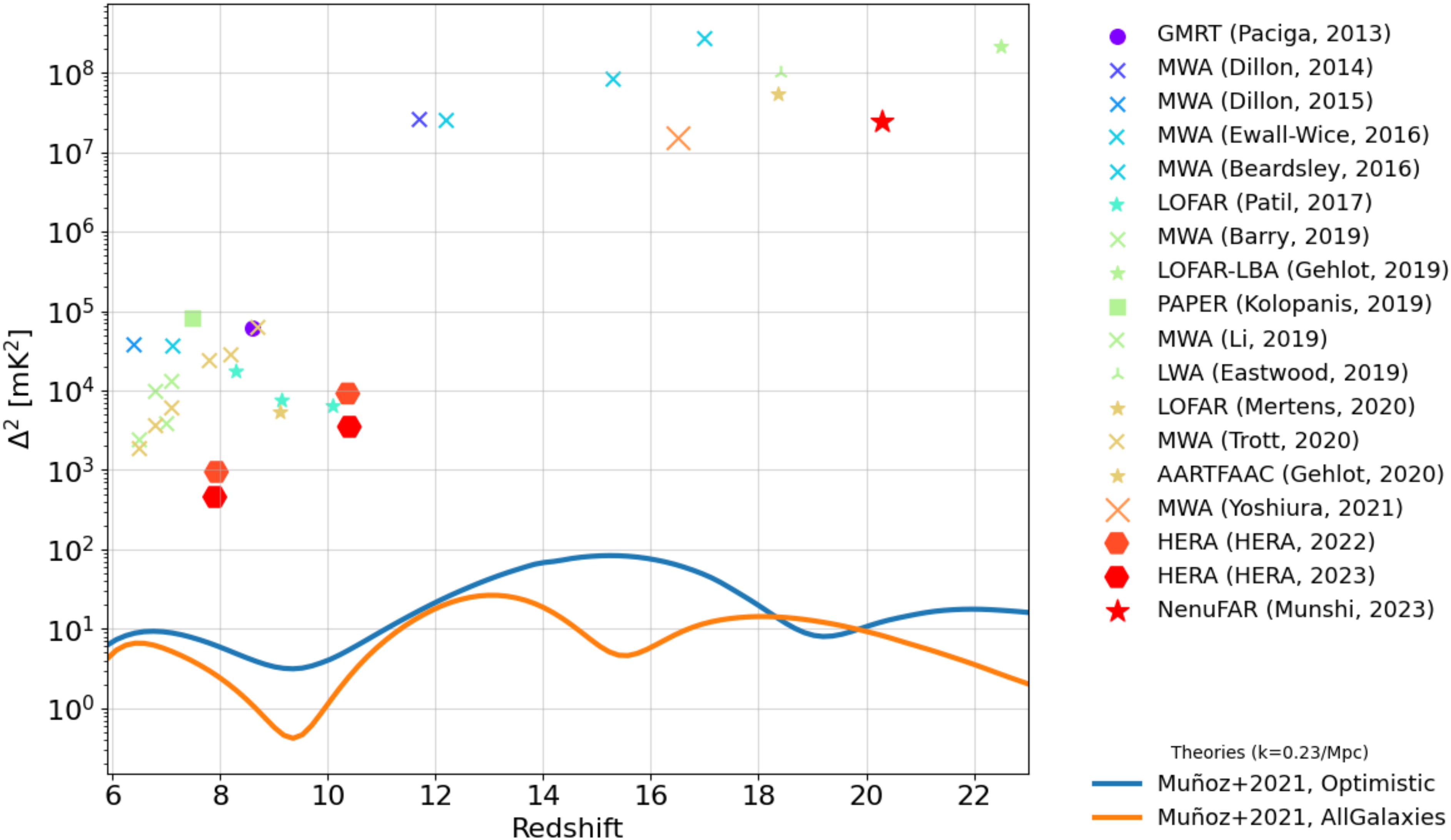


figure credit S. Murray

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

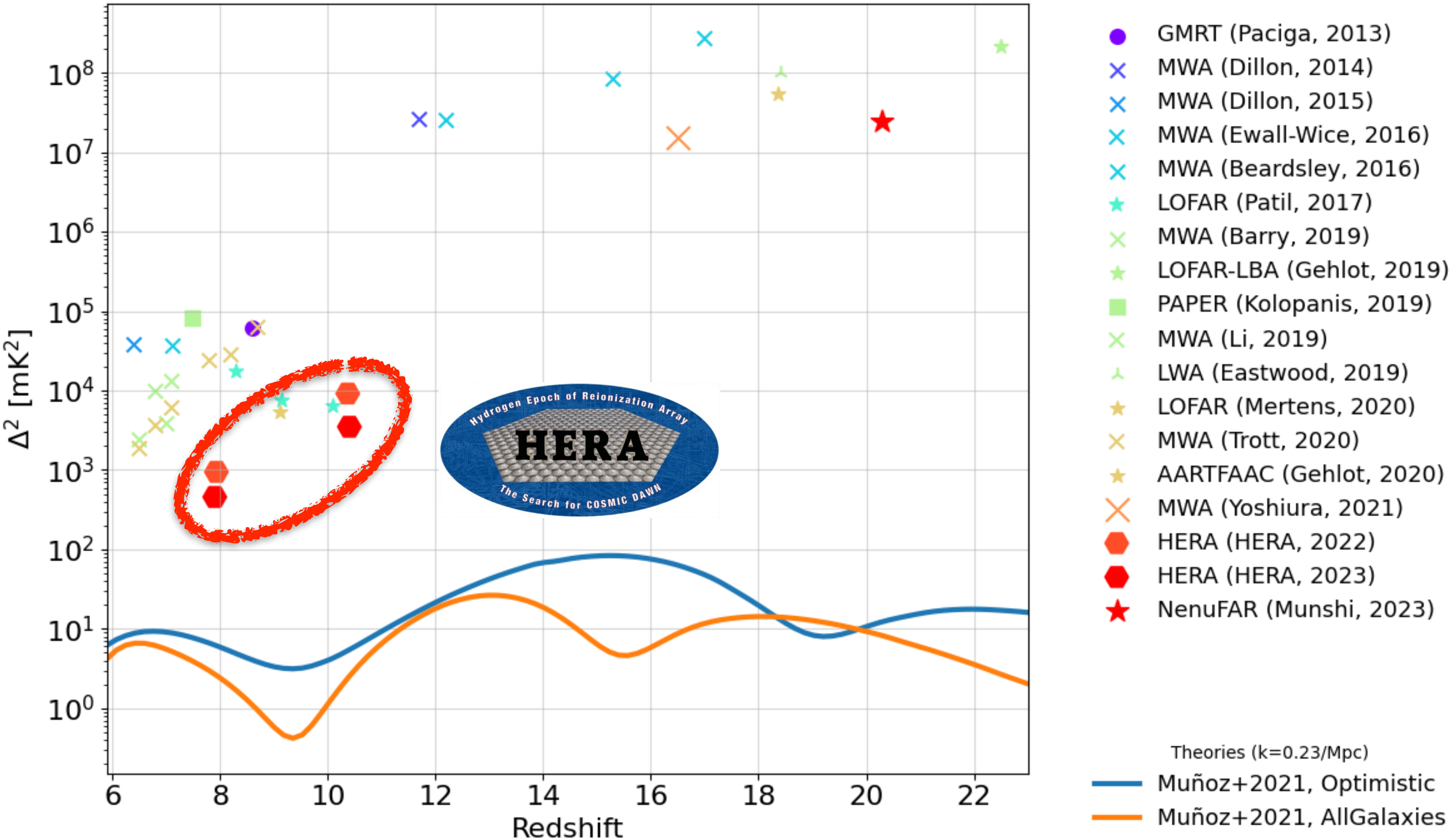


figure credit S. Murray

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)?

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

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

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

~ 0 — 1

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

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

~ 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)?

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

Models that are ruled out must have:

COLD IGM: $T_S \ll T_\gamma$

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

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

Models that are ruled out must have:

COLD IGM: $T_S \ll T_\gamma$

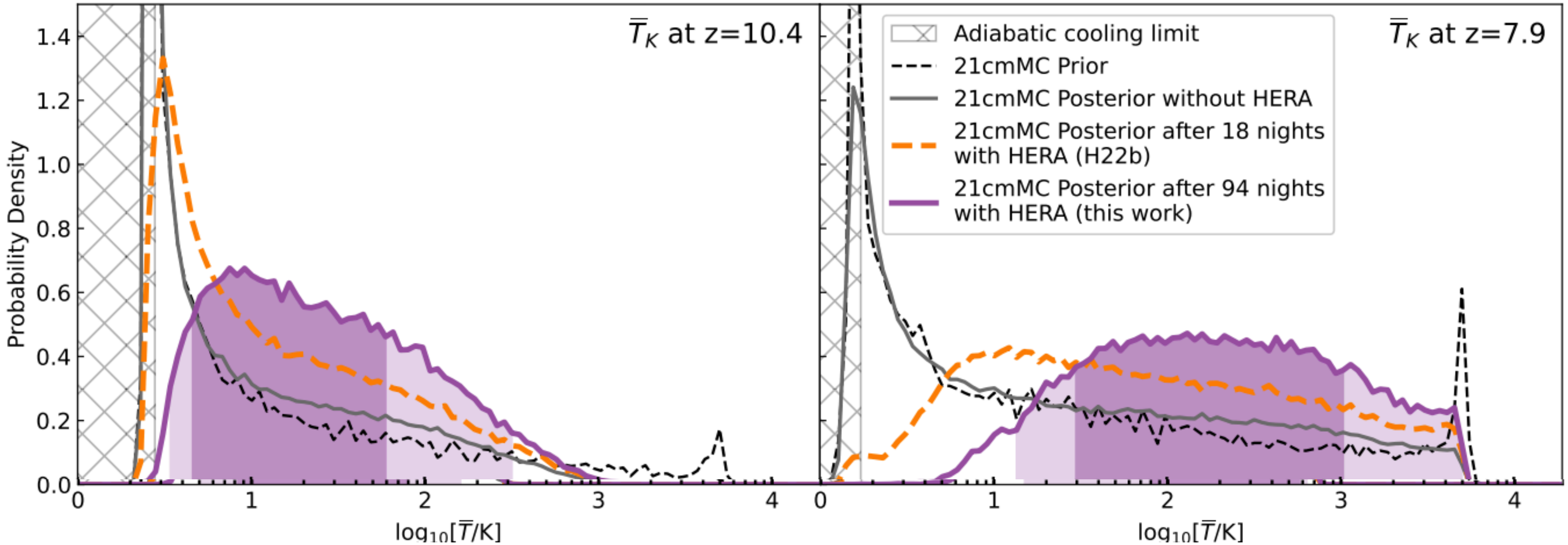
+

Spatial fluctuations *in either:*

- *ionization fraction (patchy EoR)*

Constraints on IGM properties

Adiabatically-cooling IGM *ruled out* by HERA



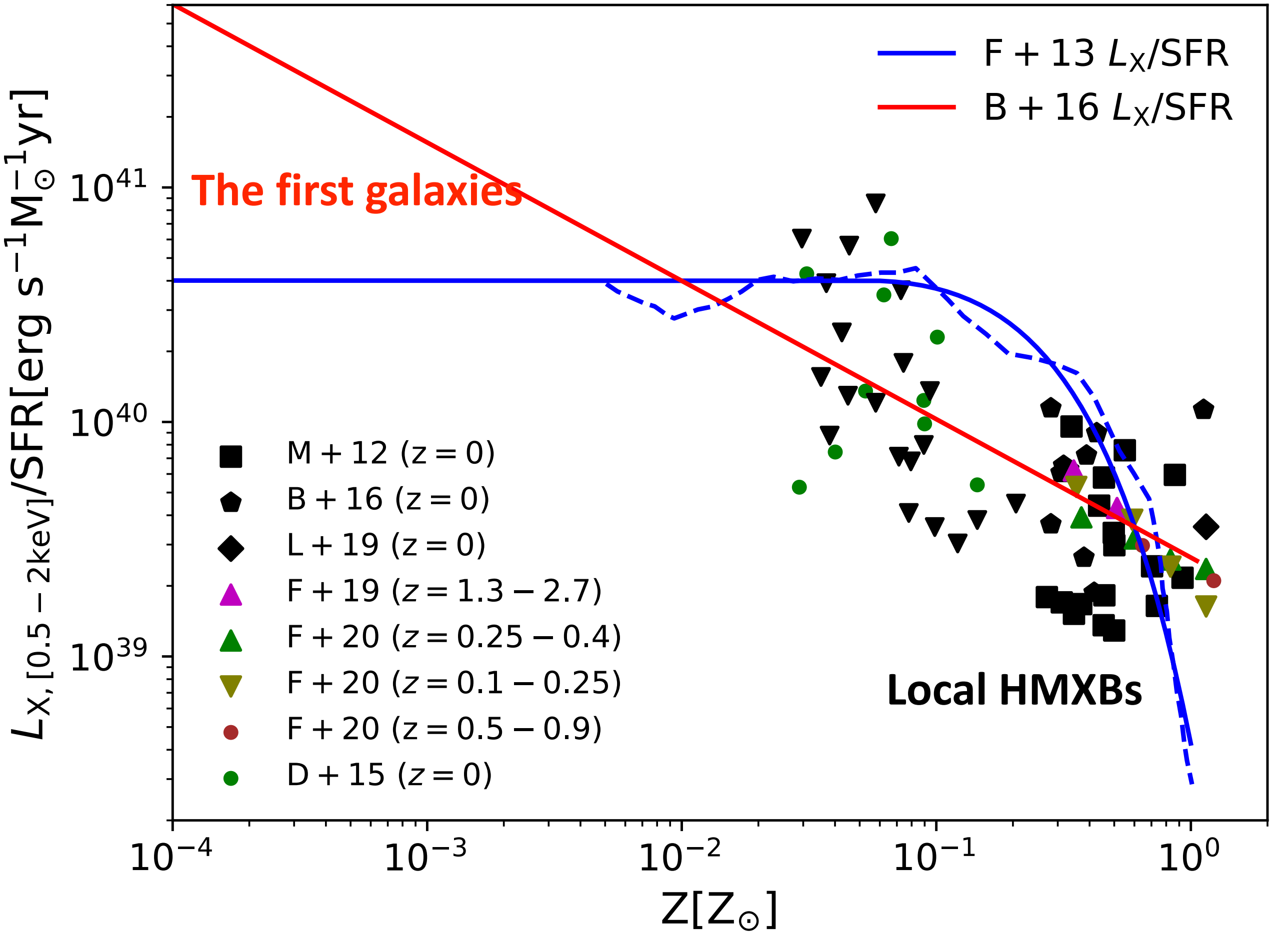
The HERA collaboration (2023)

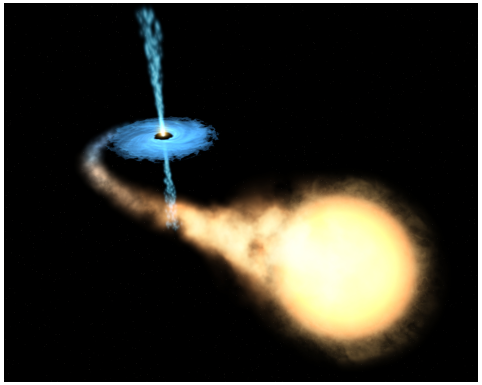
Forward-modeling with 21cmFAST and marginalizing over 10 galaxy parameters (*~1M large-scale reionization simulations*)

What is heating the IGM?

Fiducial scenario

HMXBs: *low mass galaxies + low metalicity*





Kaur, Qin, AM+ (2022)

But heating could also come from the dark sector

- Contribution from dark matter:
  - dark matter decay:

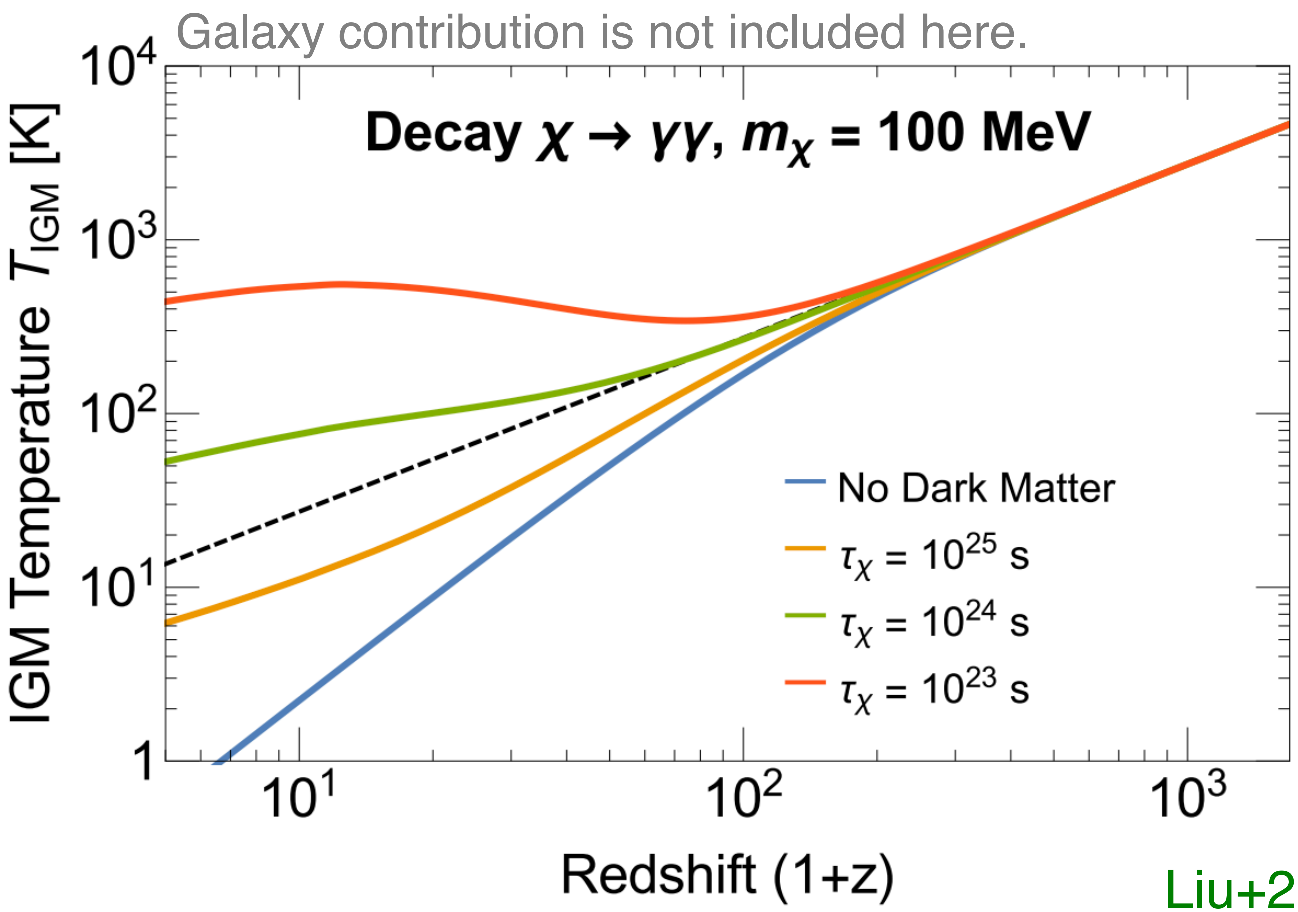
$$\left(\frac{dE}{dVdt}\right)_{\text{injected}} = \frac{\rho_\chi}{\boldsymbol{\tau}} \equiv \rho_{\chi,0}(1+z)^3 \boldsymbol{\Gamma}$$

  - dark matter annihilation:

$$\left(\frac{dE}{dVdt}\right)_{\text{injected}} = {\rho_\chi}^2 \frac{\langle \sigma_v \rangle}{m_\chi} \equiv {\rho_{\chi,0}}^2 (1+z)^6 \frac{\langle \boldsymbol{\sigma_v} \rangle}{\boldsymbol{m_\chi}}$$

sensitive to halo sub-structure (e.g. Evoli, AM+2014; Lopez-Honorez+2016)

But heating could also come from the dark sector



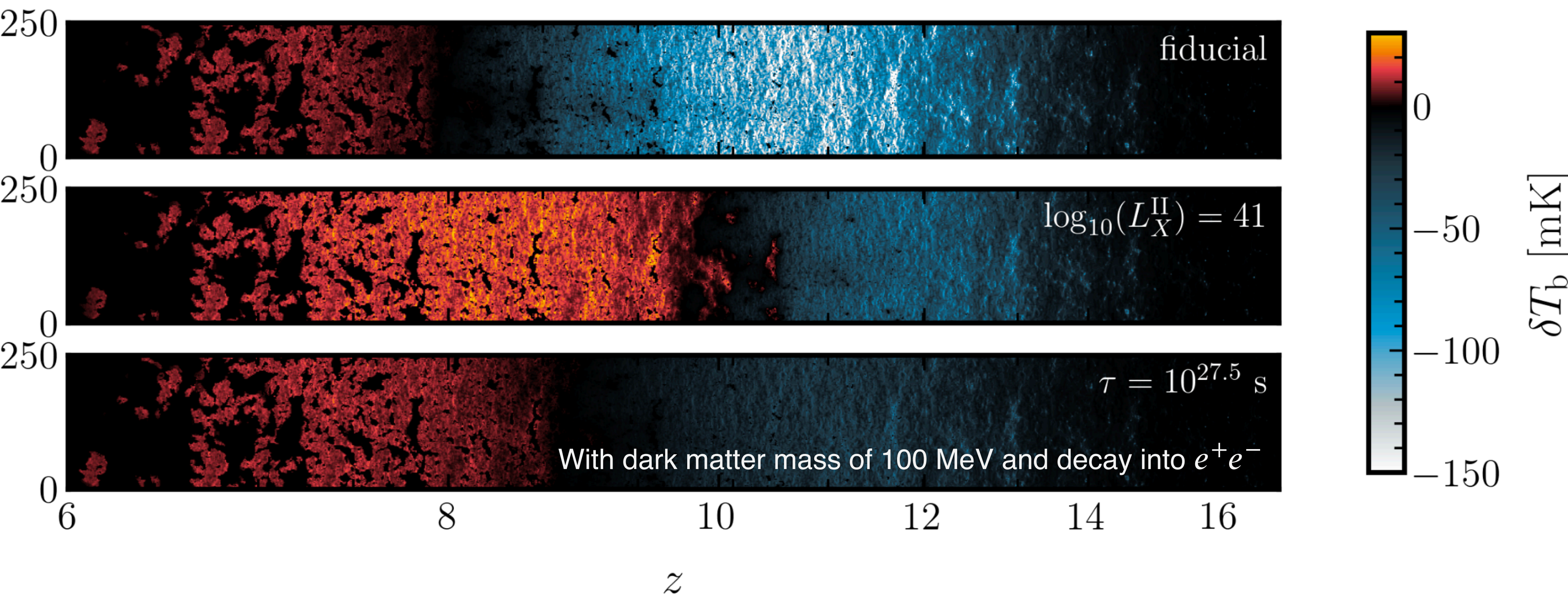
Liu+2016

Modeling 21cm with both galaxies and DM decay

- **exo21cmFAST** (Facchinetti+2024)
  - Uses **21cmFAST**(e.g. AM+2011) to compute 4D IGM lightcones, following inhomogeneous galactic radiation fields
  - including **DarkHistory** (Liu+2020) for energy deposition of dark matter decay and annihilation in e^+e^-or $\gamma\gamma$.

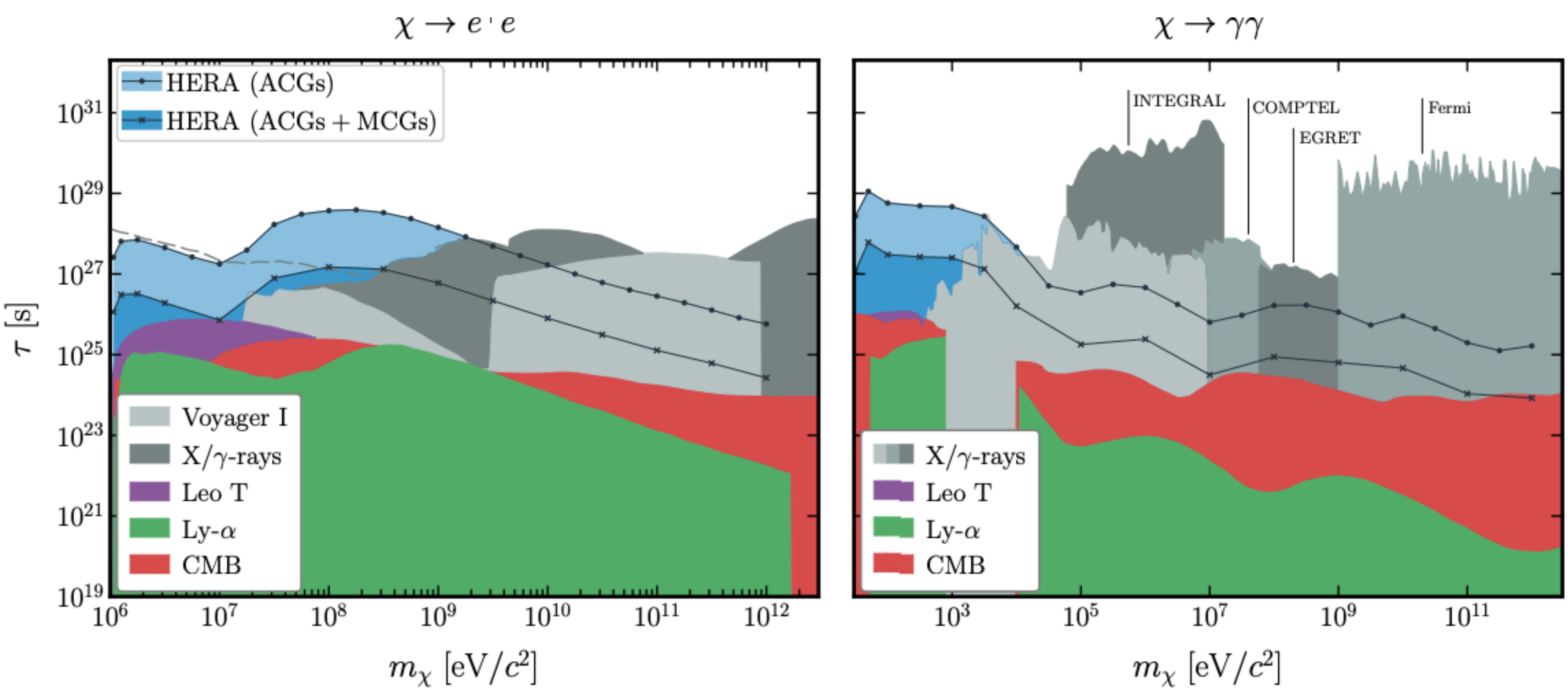
see also **DM21cm** by Sun et al. 2025…

Modeling 21cm with both galaxies and DM decay



Facchinetti+2024

Achievable constraints with 21cm PS



1000h observation with HERA, marginalizing over 8-11 galaxy parameters

Facchinetti+2024

Is there a *smoking gun*?

Smoking gun could be provided by DM heating/cooling/coupling Ts **BEFORE** galaxies form (e.g. Evoli, AM+2014; Agius & Slatyer 2025)

Might require going to very high redshifts —> space/moon based telescopes?

Otherwise, we need Bayesian model selection (Montes-Doria+, in prep)

Conclusions

- The cosmic 21cm signal will allow us to learn the **properties of the unseen first galaxies as well as physical cosmology.**

Conclusions

- The cosmic 21cm signal will allow us to learn the **properties of the unseen first galaxies as well as physical cosmology.**
- Contrary to initial claims, the EDGES “detection” of the global signal **disfavors a radio background excess** during the cosmic dawn; stay tuned for implications for **millicharged DM**…

Conclusions

- The cosmic 21cm signal will allow us to learn the **properties of the unseen first galaxies as well as physical cosmology.**
- Contrary to initial claims, the EDGES "detection" of the global signal **disfavors a radio background excess** during the cosmic dawn; stay tuned for implications for **millicharged DM**…
- **Upper limits** on the 21-cm power spectrum by SKA precursor, HERA, imply some **heating of the IGM by z>10**.

Conclusions

- The cosmic 21cm signal will allow us to learn the **properties of the unseen first galaxies as well as physical cosmology.**
- Contrary to initial claims, the EDGES “detection” of the global signal **disfavors a radio background excess** during the cosmic dawn; stay tuned for implications for **millicharged DM**…
- **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**.

Conclusions

- The cosmic 21cm signal will allow us to learn the **properties of the unseen first galaxies as well as physical cosmology.**
- Contrary to initial claims, the EDGES "detection" of the global signal **disfavors a radio background excess** during the cosmic dawn; stay tuned for implications for **millicharged DM**…
- **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**.
- Future 21cm power spectrum **detections** can place tighter constraints on dark matter decay lifetimes than existing probes in the low-mass regime