Introduction / report from the EoR SWG

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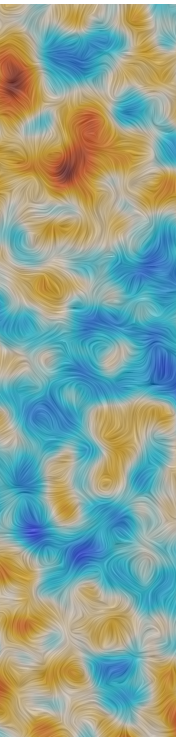
European Research Council

First billion years - birth of structure and Cosmic Dawn

Image: ESA

CMB



$z \approx 10^3$

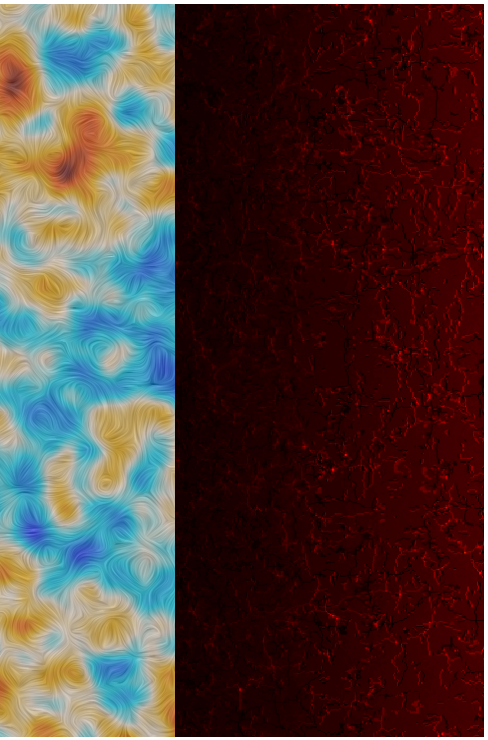
$4 \cdot 10^5$ ⟶ cosmic time [yr]

First billion years - birth of structure and Cosmic Dawn

Image: ESA

AM+2016

CMB **Dark Ages**



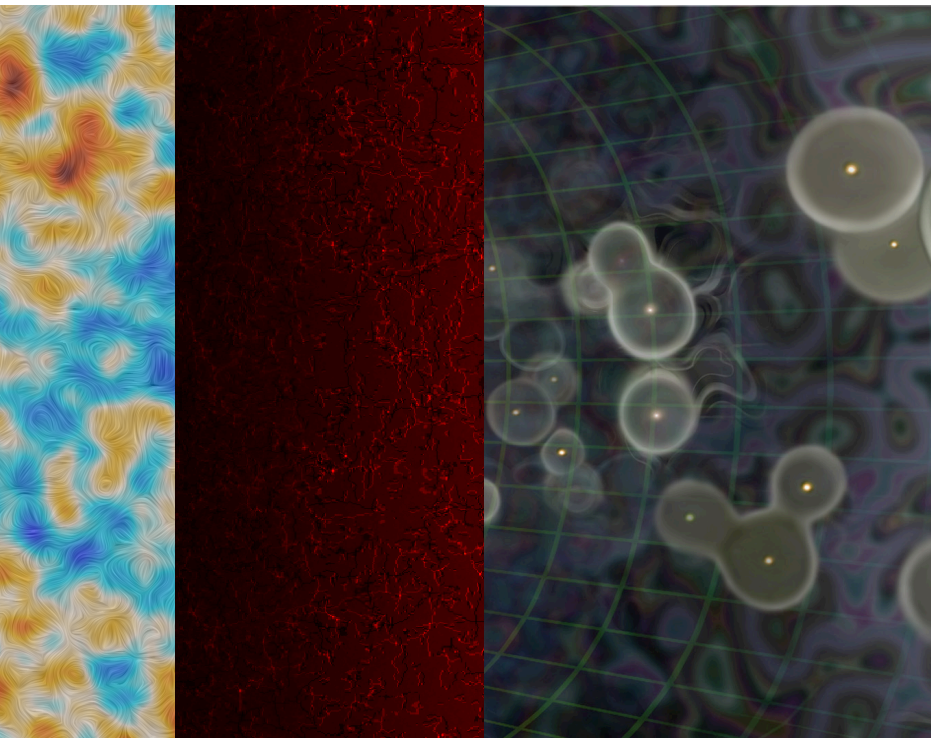
$z \approx 10^3$ $z \approx 30$

cosmic time [yr]

$4 \cdot 10^5$ 10^8

First billion years - birth of structure and Cosmic Dawn

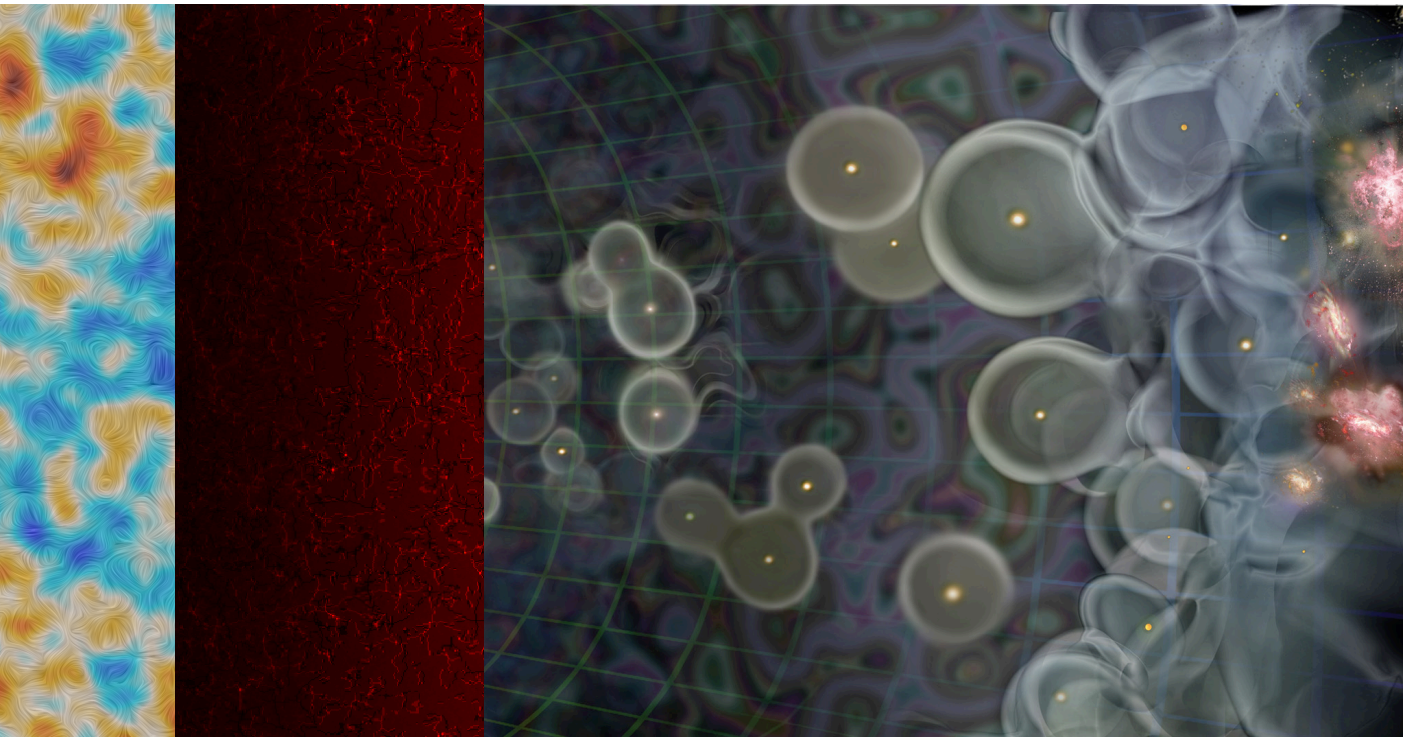
Image: NASA/
CXC/M.WEISS
AM+2016; J. Munoz



First billion years - birth of structure and Cosmic Dawn

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

CMB Dark Ages Cosmic Dawn **Reionization**



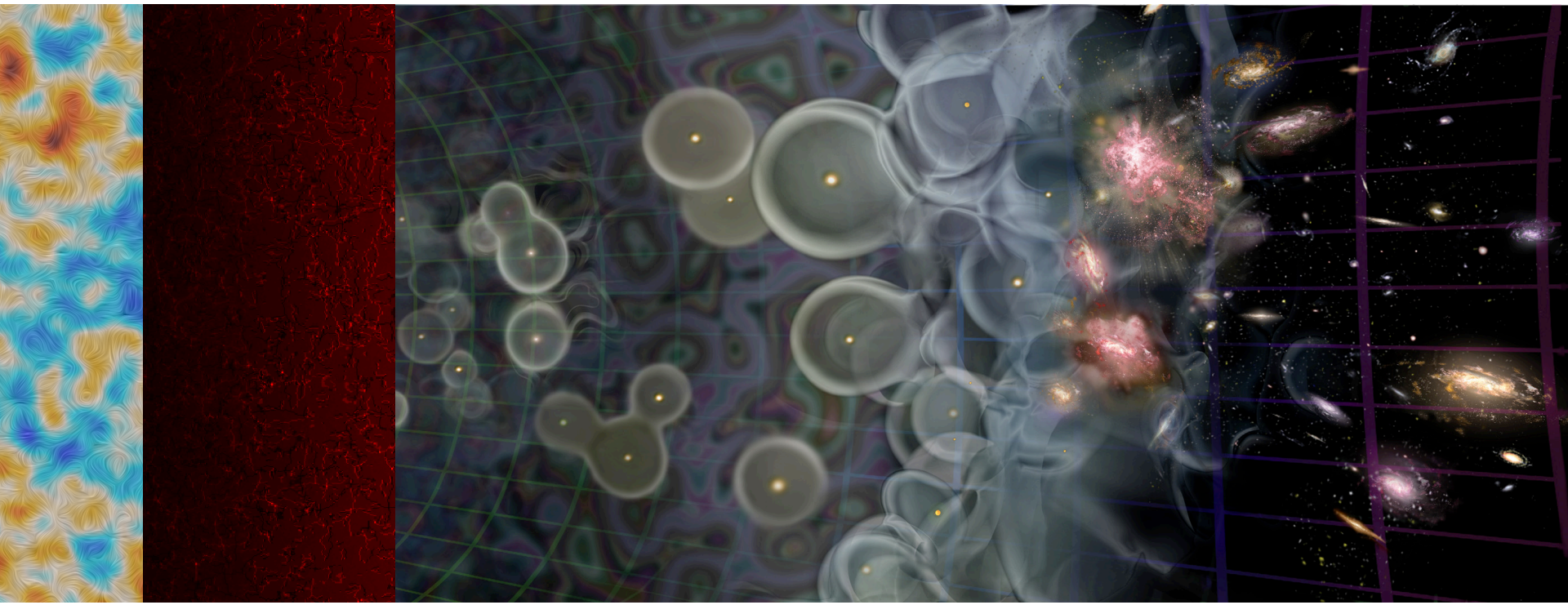
$z \approx 10^3$ $z \approx 30$ $z \approx 5$

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

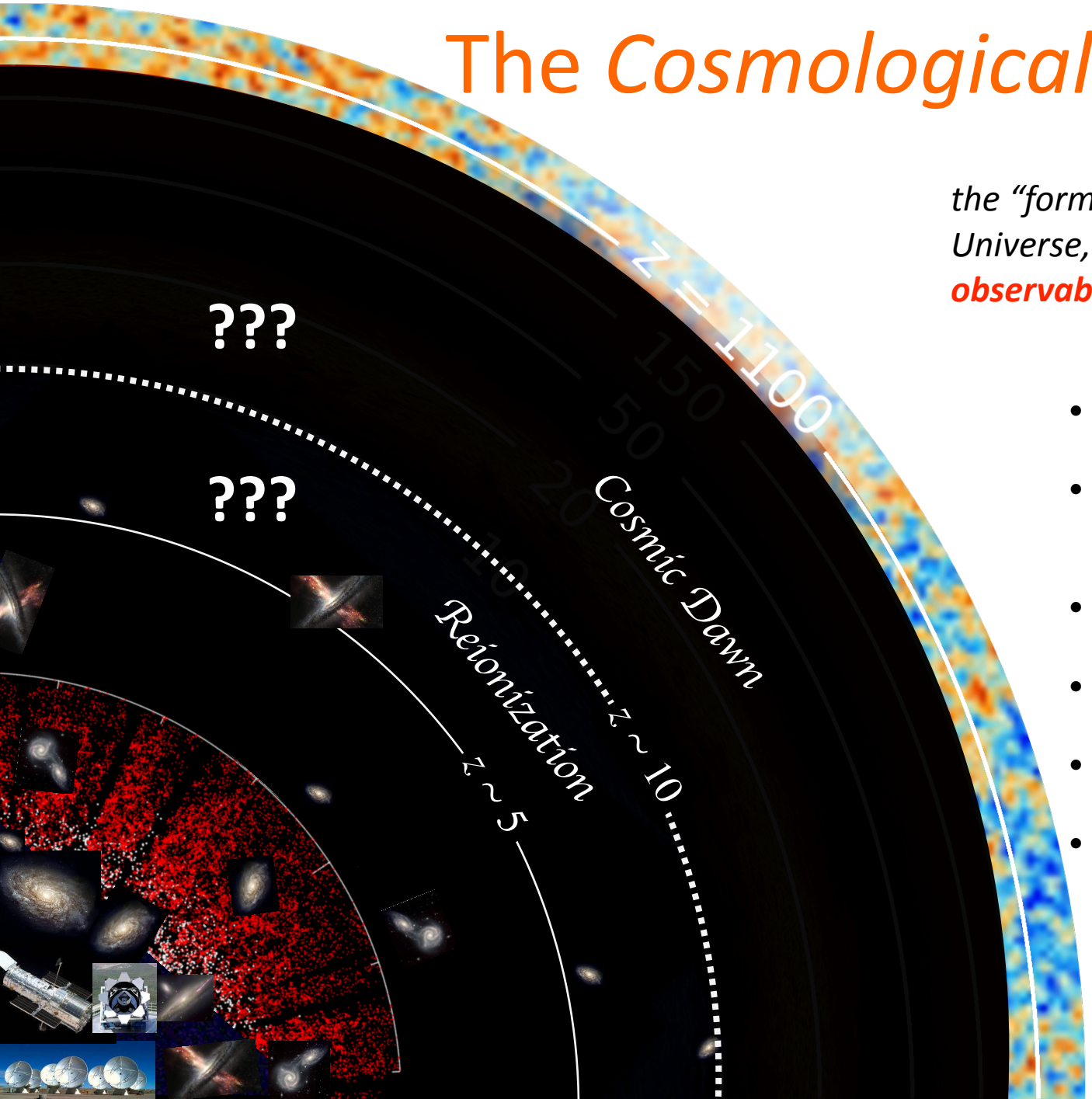


$z \approx 10^3$ $z \approx 30$ $z \approx 5$ $z = 0$

cosmic time [yr]

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

The *Cosmological Frontier…*

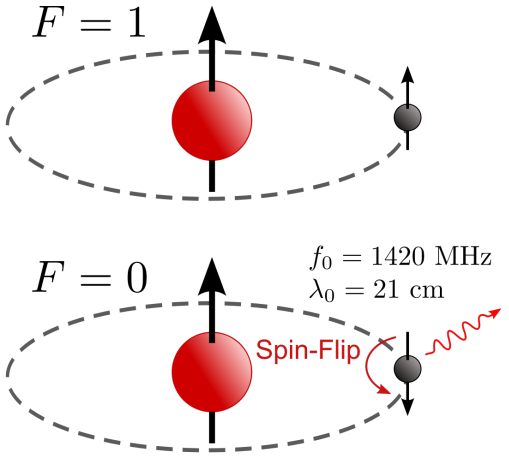


*the "formative childhood" of the Universe, yet the **majority of the observable volume***

- 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?

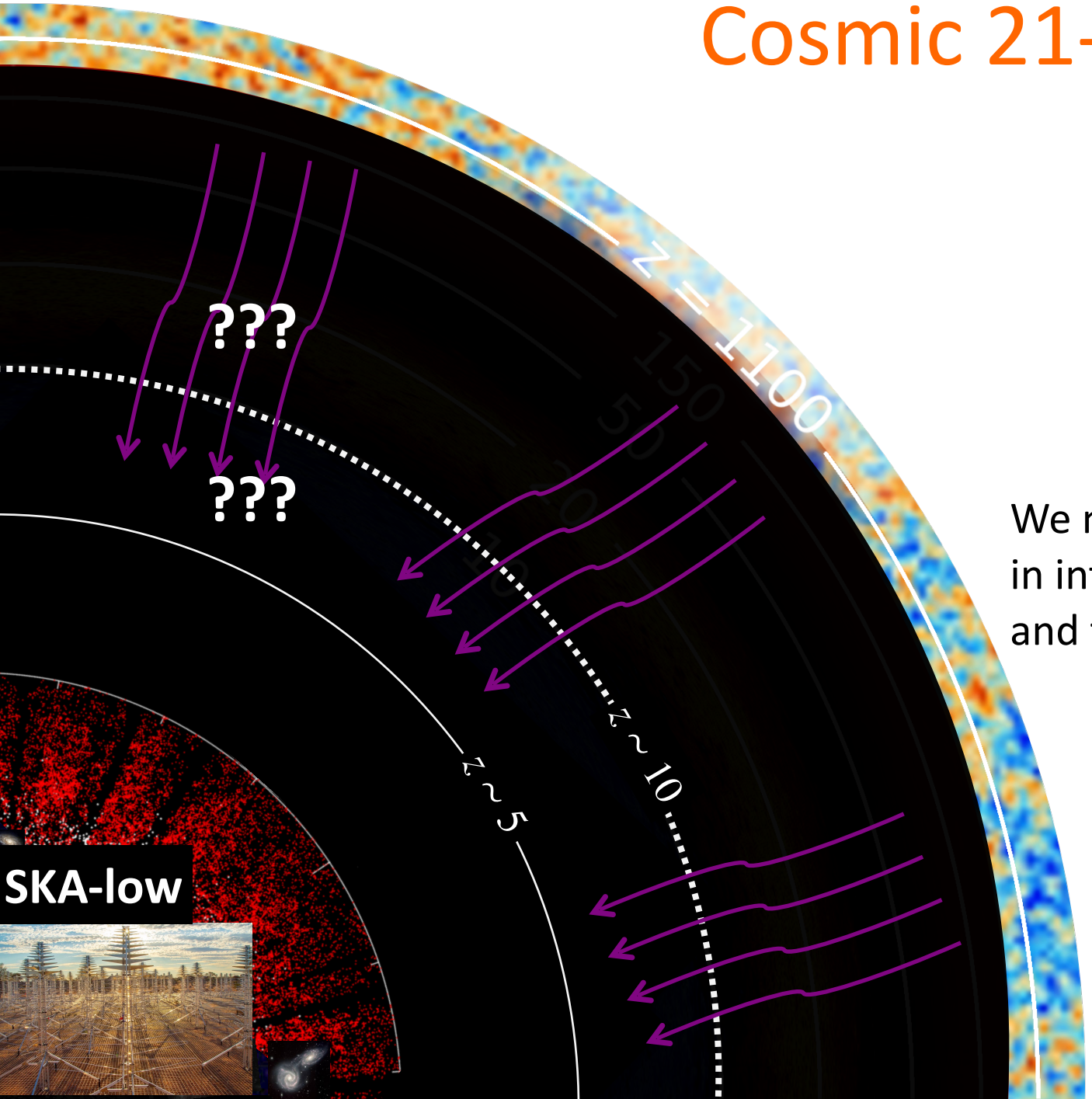
adapted from Cynthia Chiang

Cosmic 21-cm



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

Cosmic 21-cm



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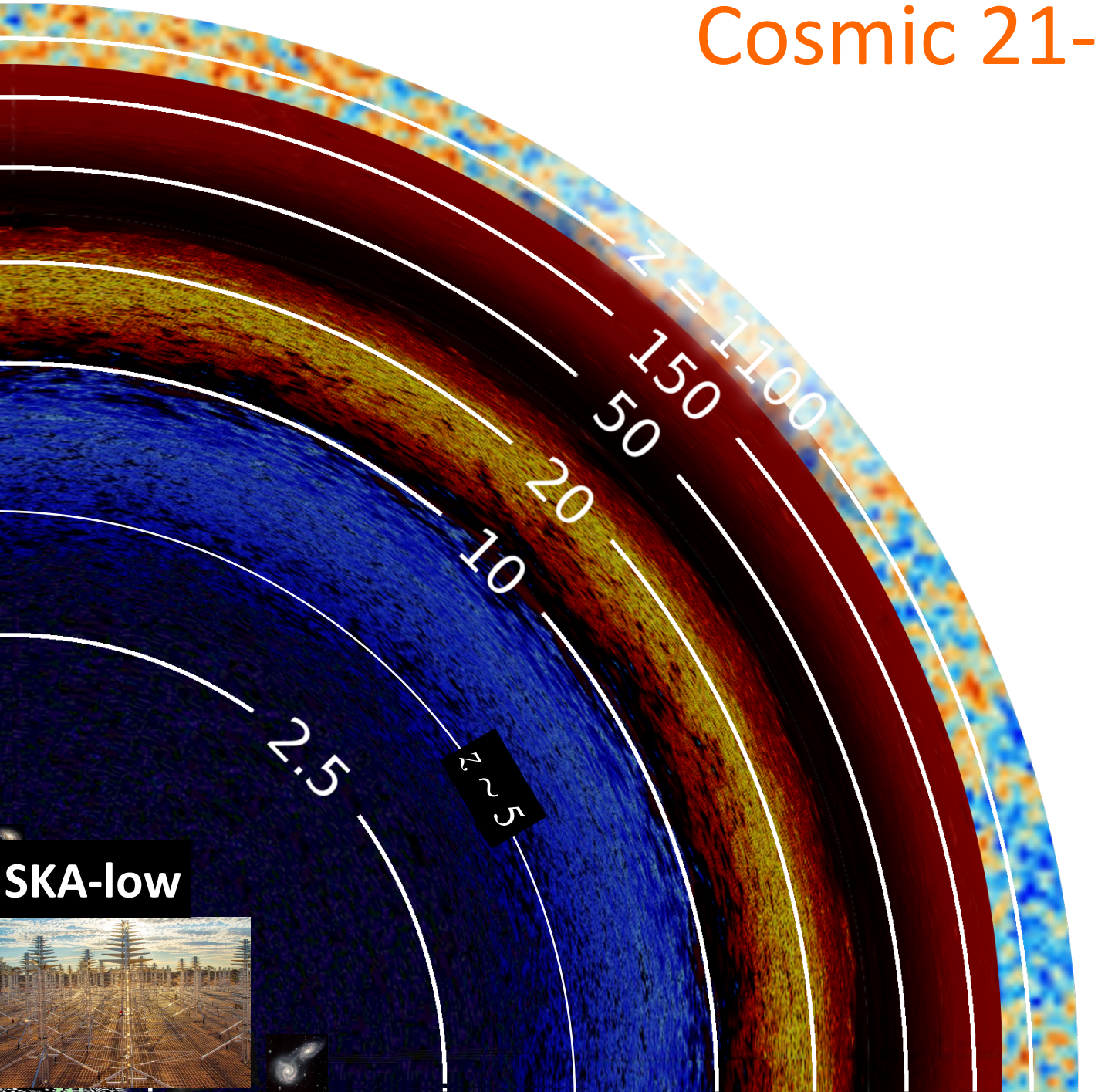
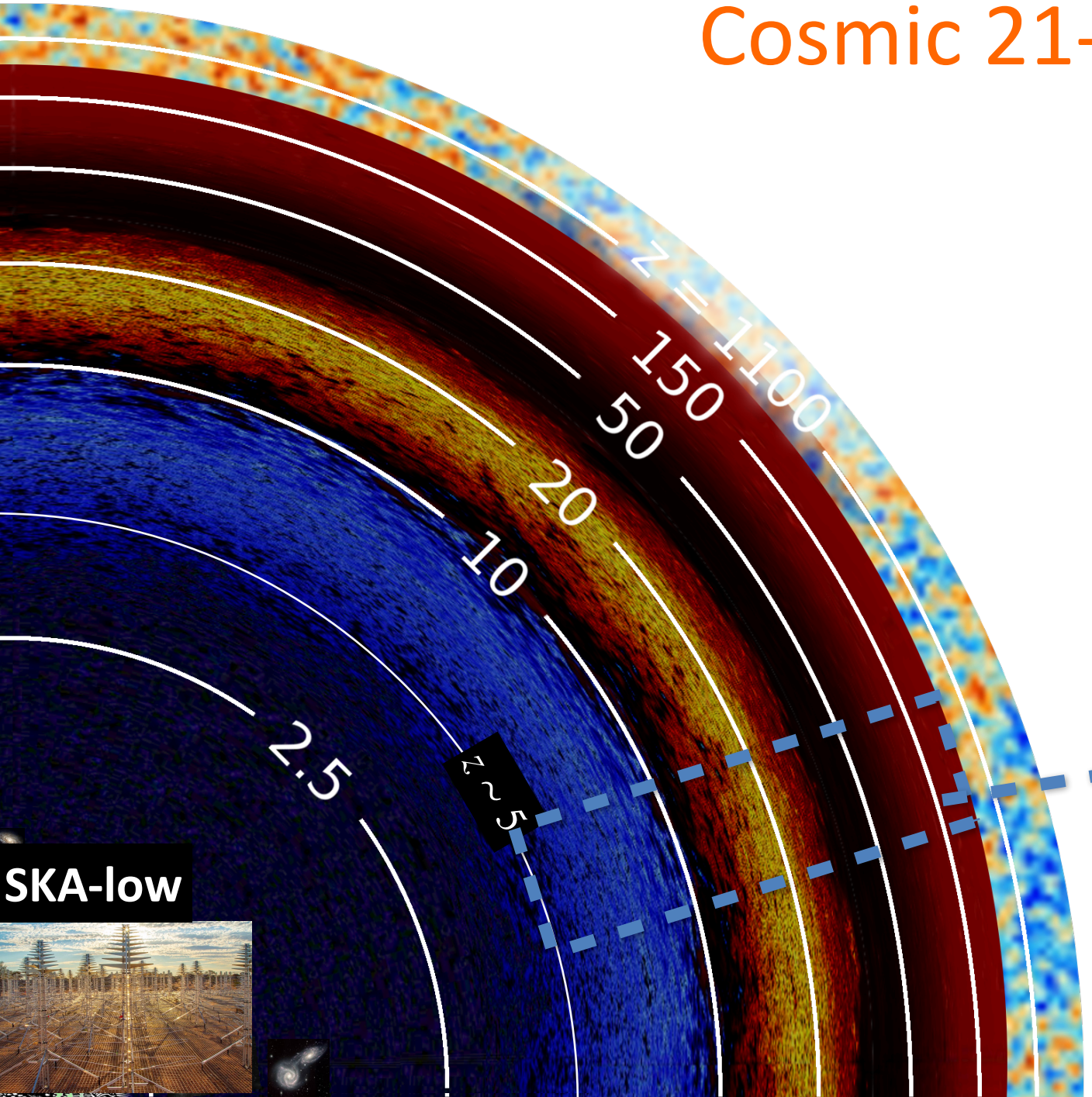
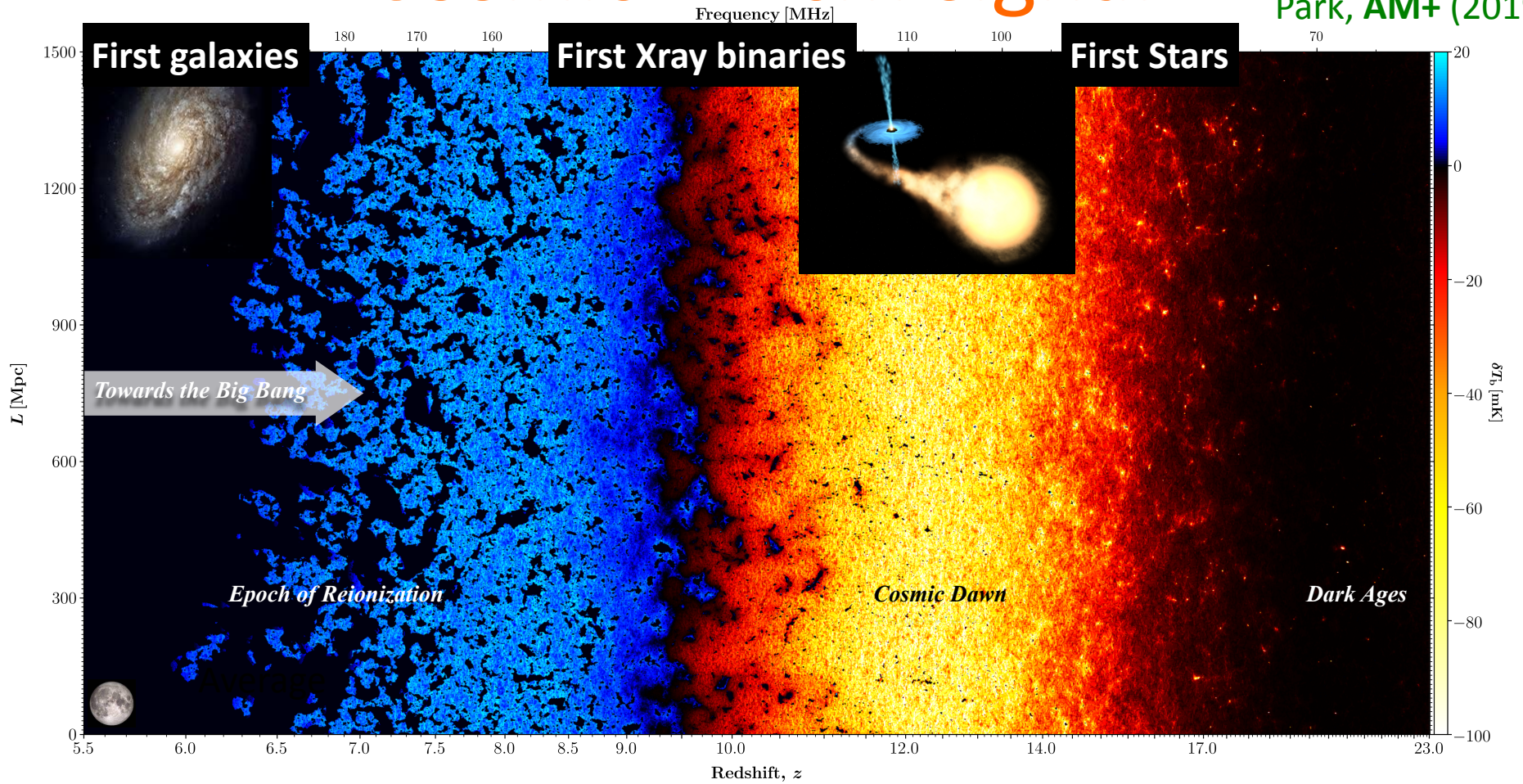


Cosmic 21-cm



Cosmic 21-cm signal

Park, **AM+** (2019)

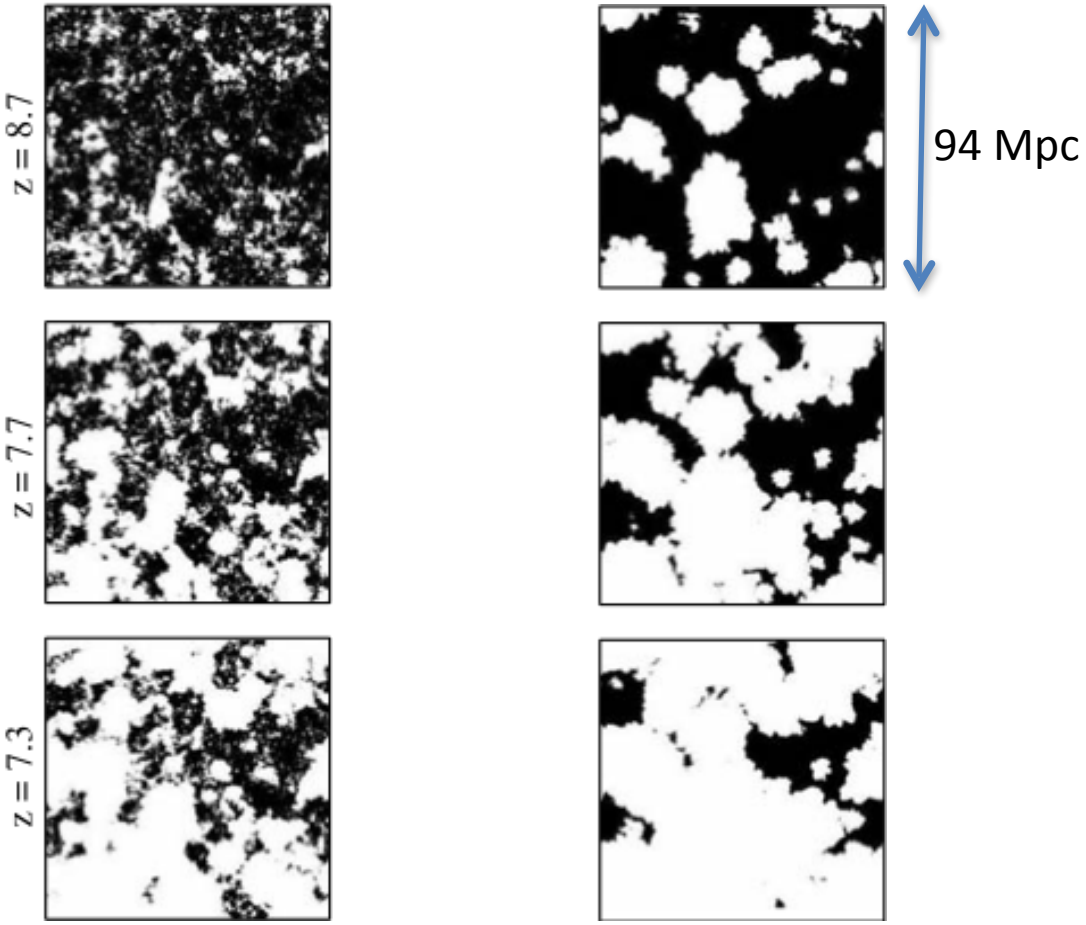


- **3D** signal with **> 10 orders of magnitude** more independent modes than in the CMB!
- data collection with upcoming Square Kilometre Array (SKA) will surpass **10x current global internet traffic**!
- even the narrowest fields will contain >billion of unseen galaxies
- **BIG DATA REVOLUTION**!

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*

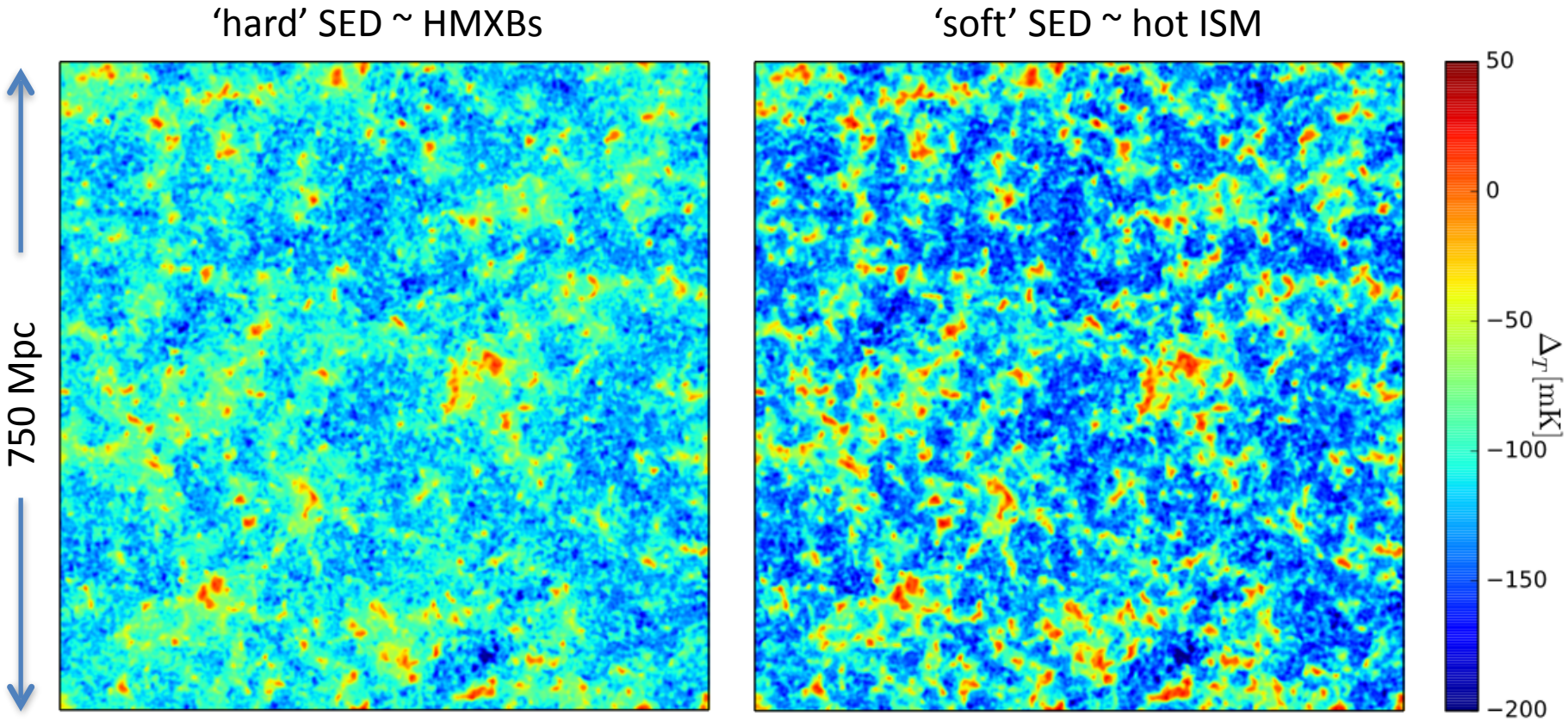


McQuinn+ 2007

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



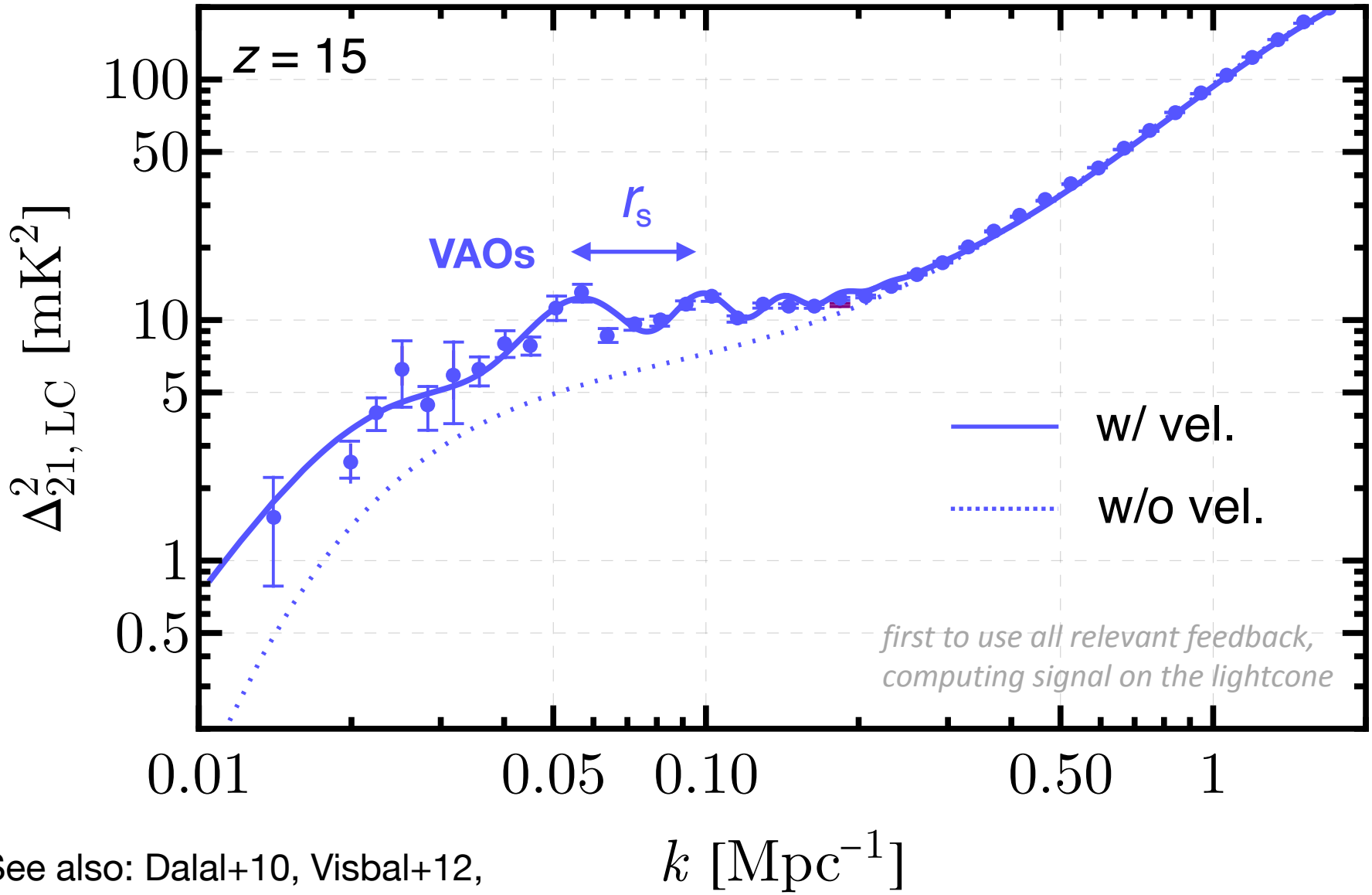
differences are easily detectable with HERA and the SKA

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)

Standard ruler



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

Munoz, Qin, AM+ 2022

But it ain’t easy!

Lessons learned from precursors…

First generation 21-cm interferometers

MWA

LOFAR

GMRT

HERA

PAPER

Observing is HARD!

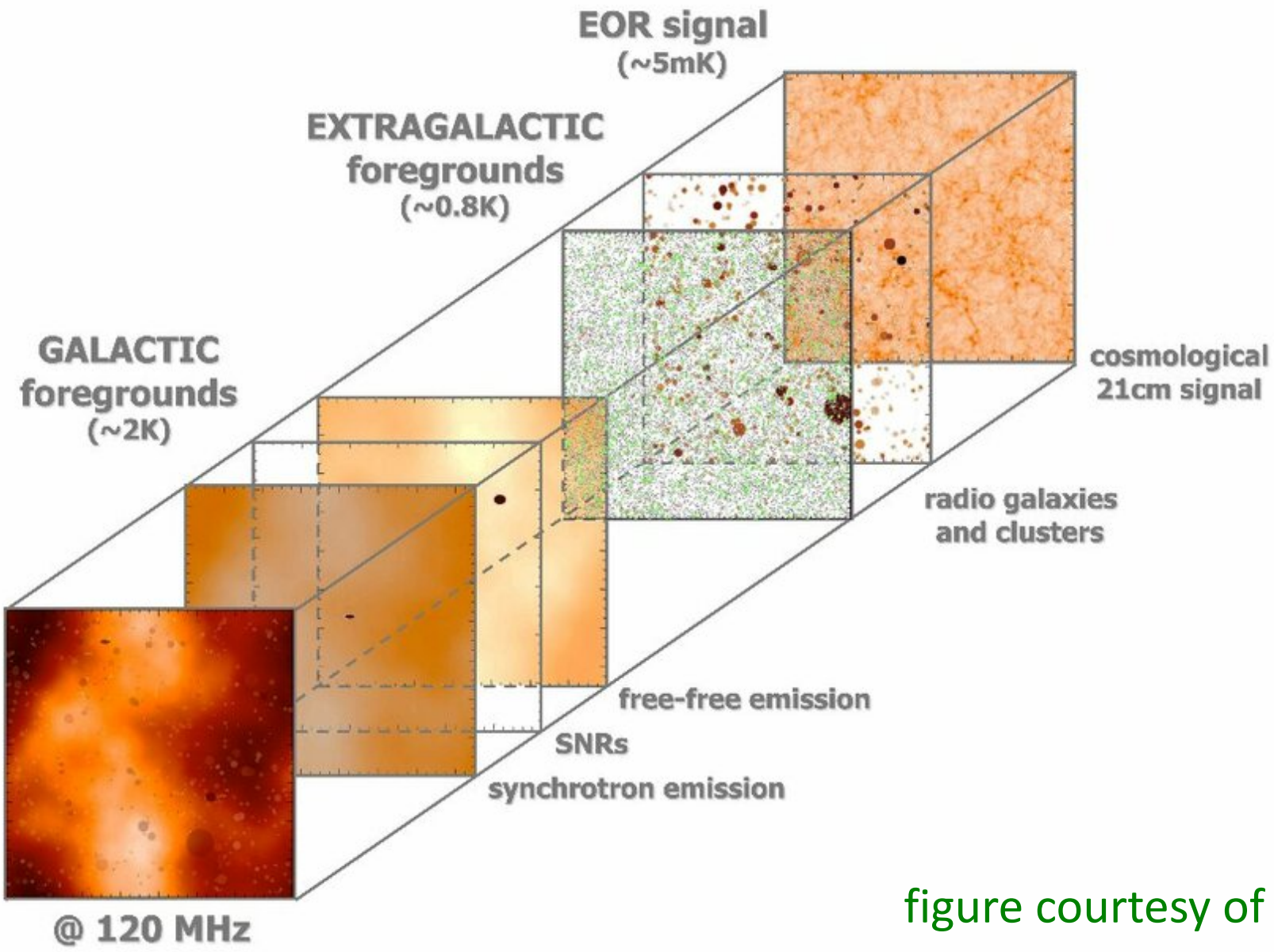
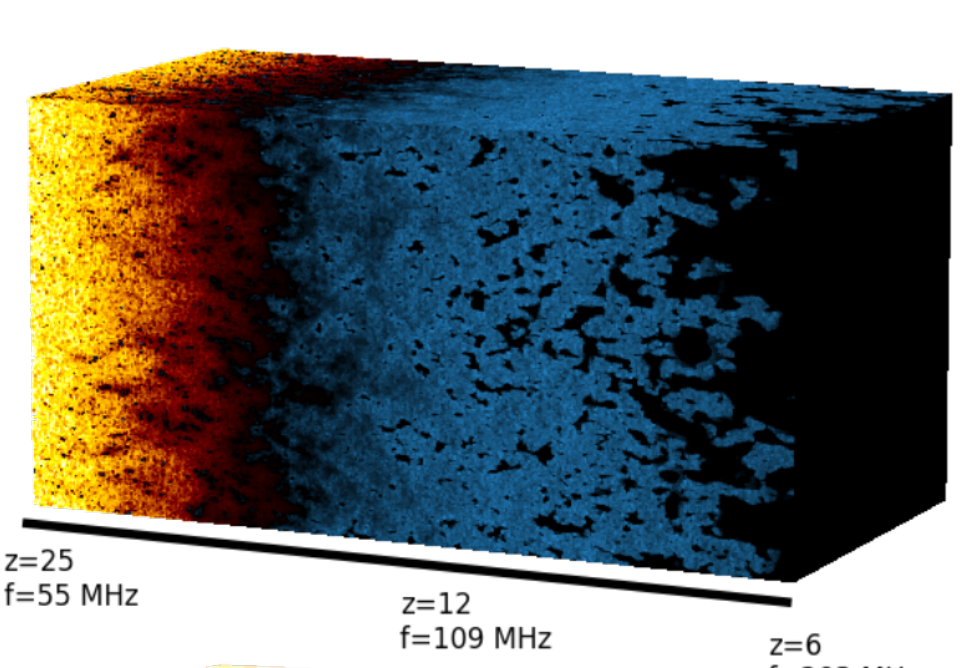
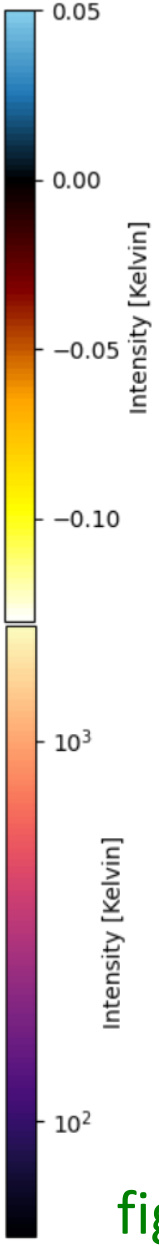


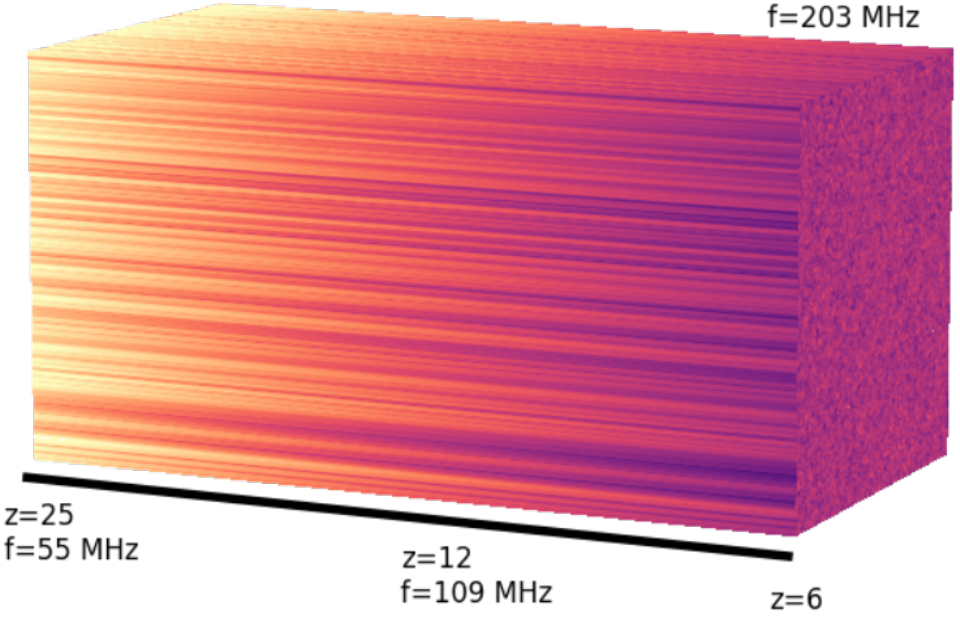
figure courtesy of V. Jelić

But foregrounds should be smooth in frequency!





Cosmic signal



Foregrounds

figure courtesy of F. Mertens

Hope is to measure PS in the “EoR window”

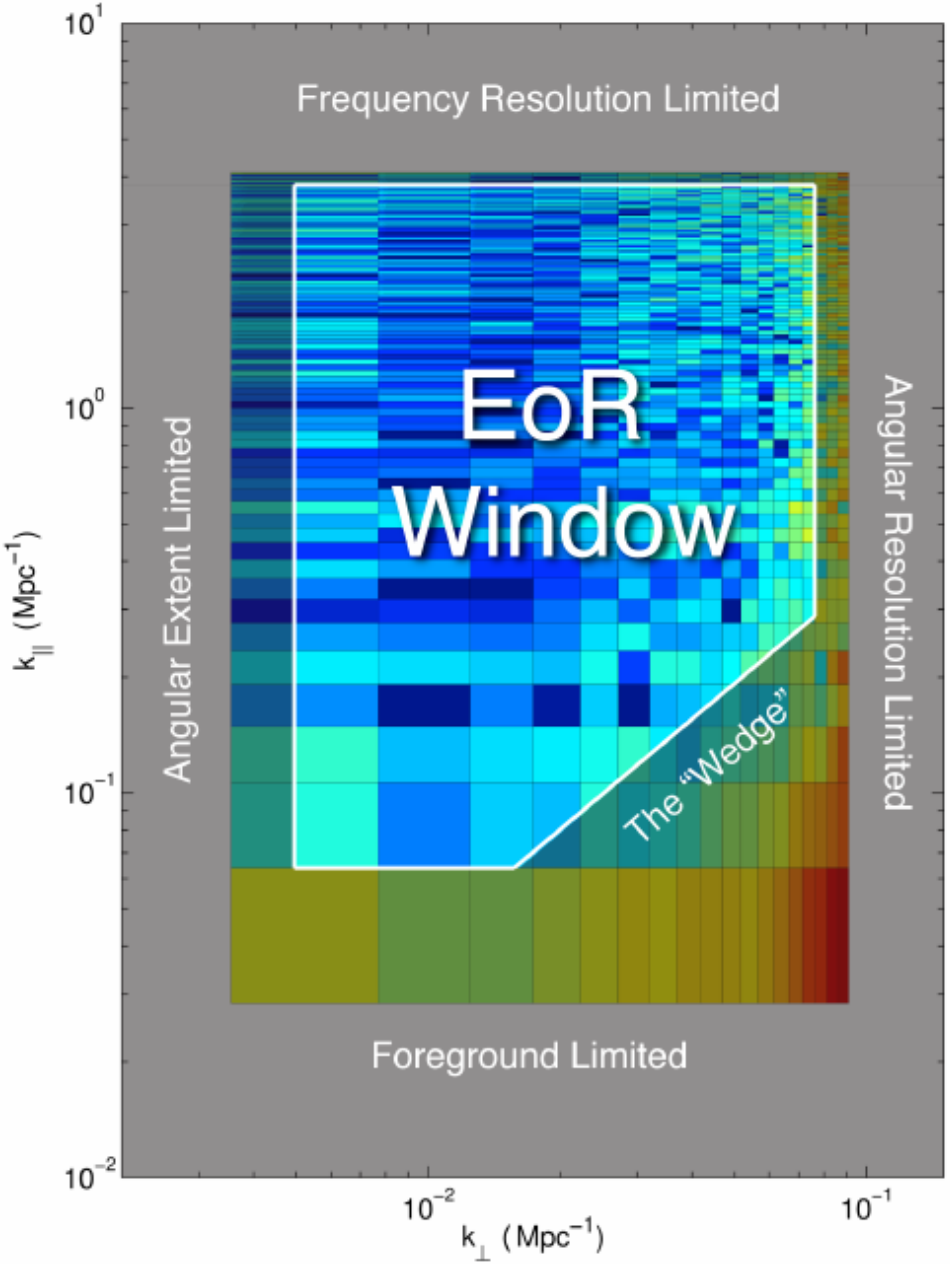
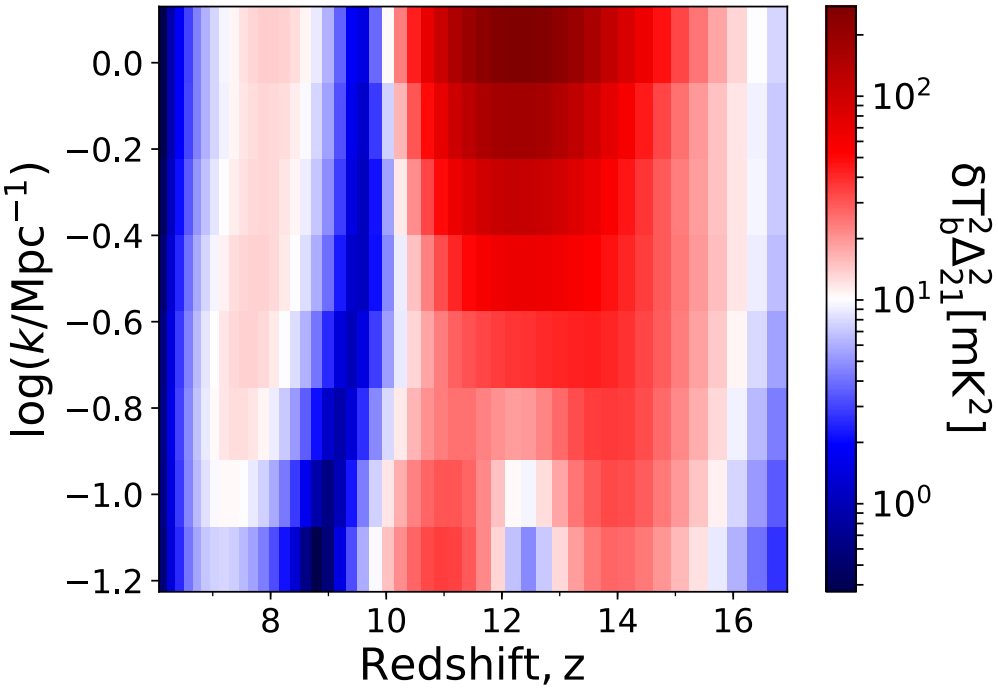


figure courtesy of J. Dillon

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

1D power spectrum from "fiducial model"

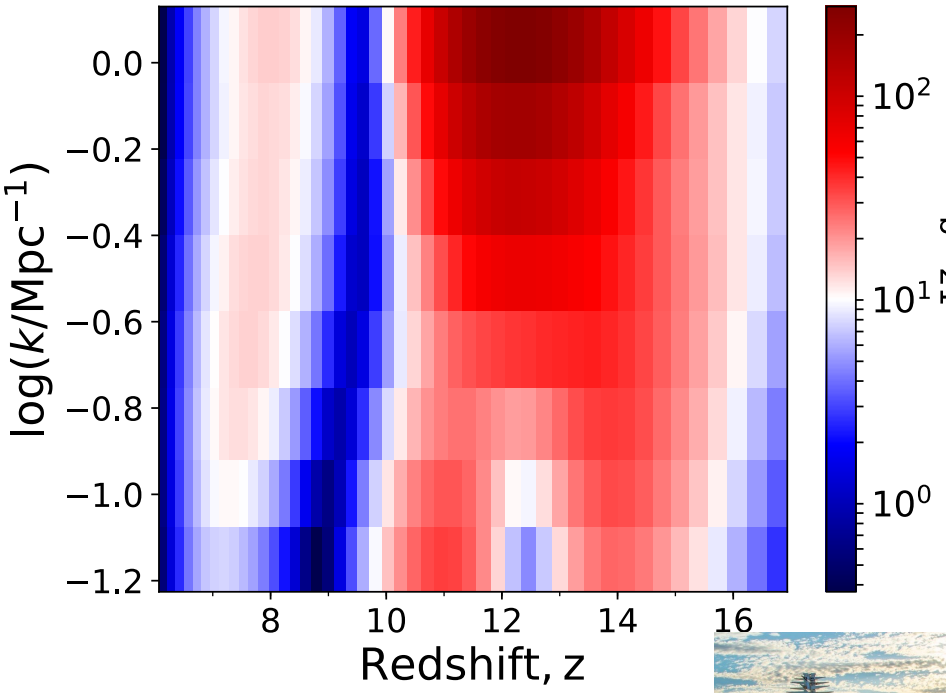


characteristic "three-peak" structure of the cosmic signal

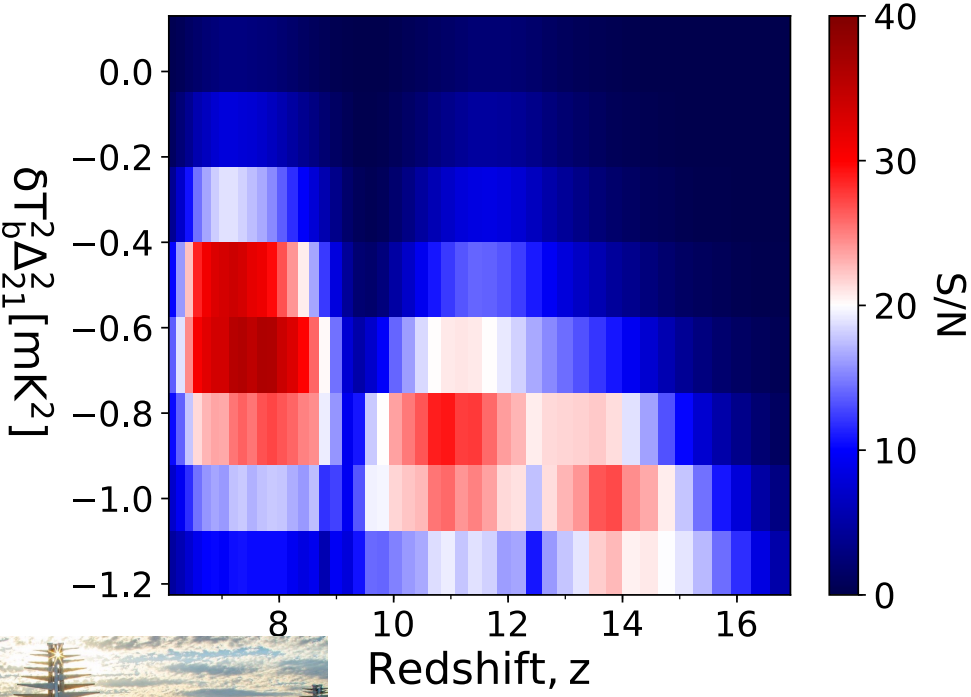
Kaur, Gillet, **AM** (2020)

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

1D power spectrum from "fiducial model"



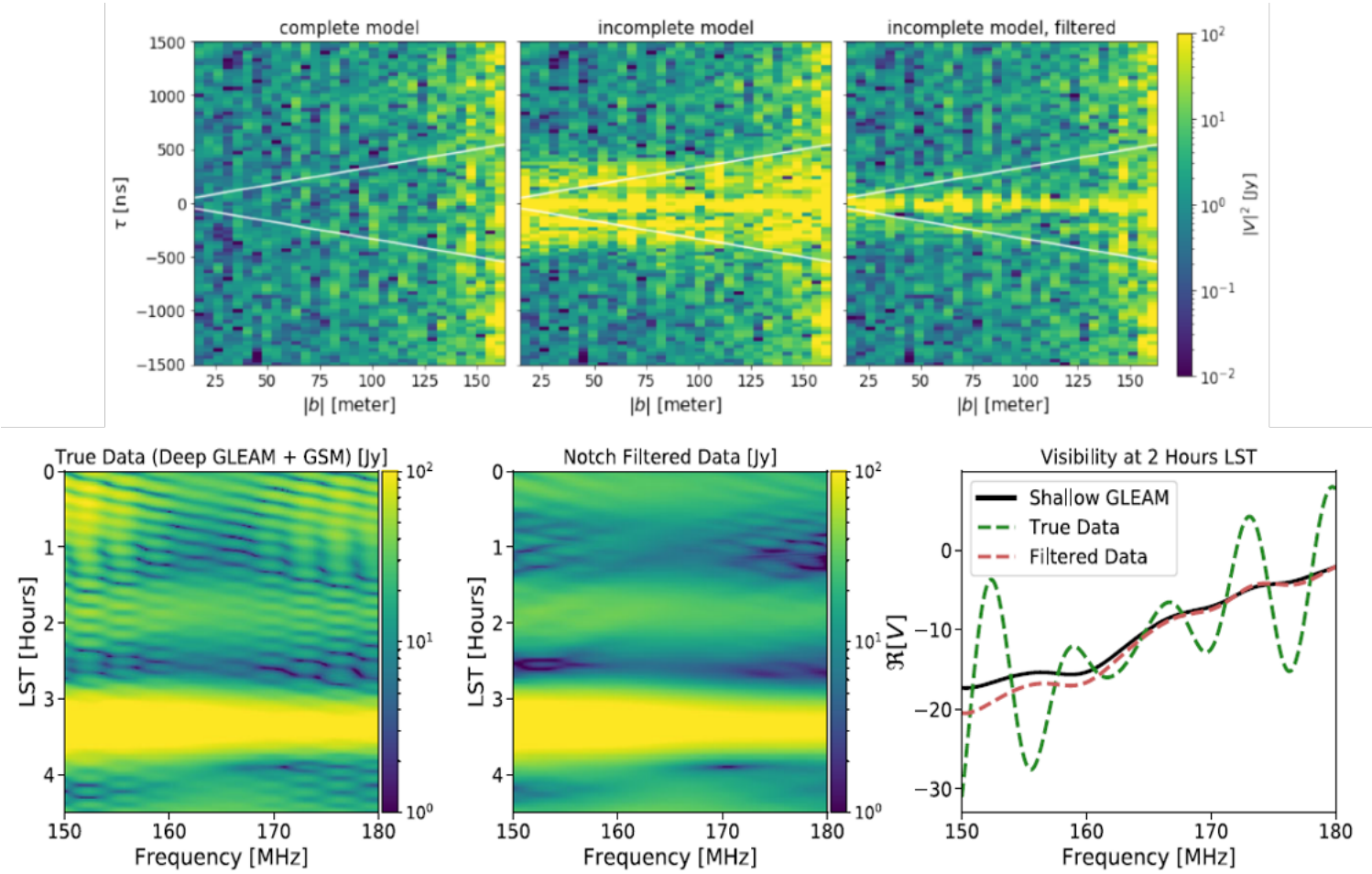
S/N from a 1000h SKA-low observation



MADE IN ITALY

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

Of course it is not that simple: **systematics**



Charles, **Bernardi** et al. (2022); Charles, Kern, **Bernardi** et al, (2024); Charles, Kern, Pascua, **Bernardi** et al. (2025)

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

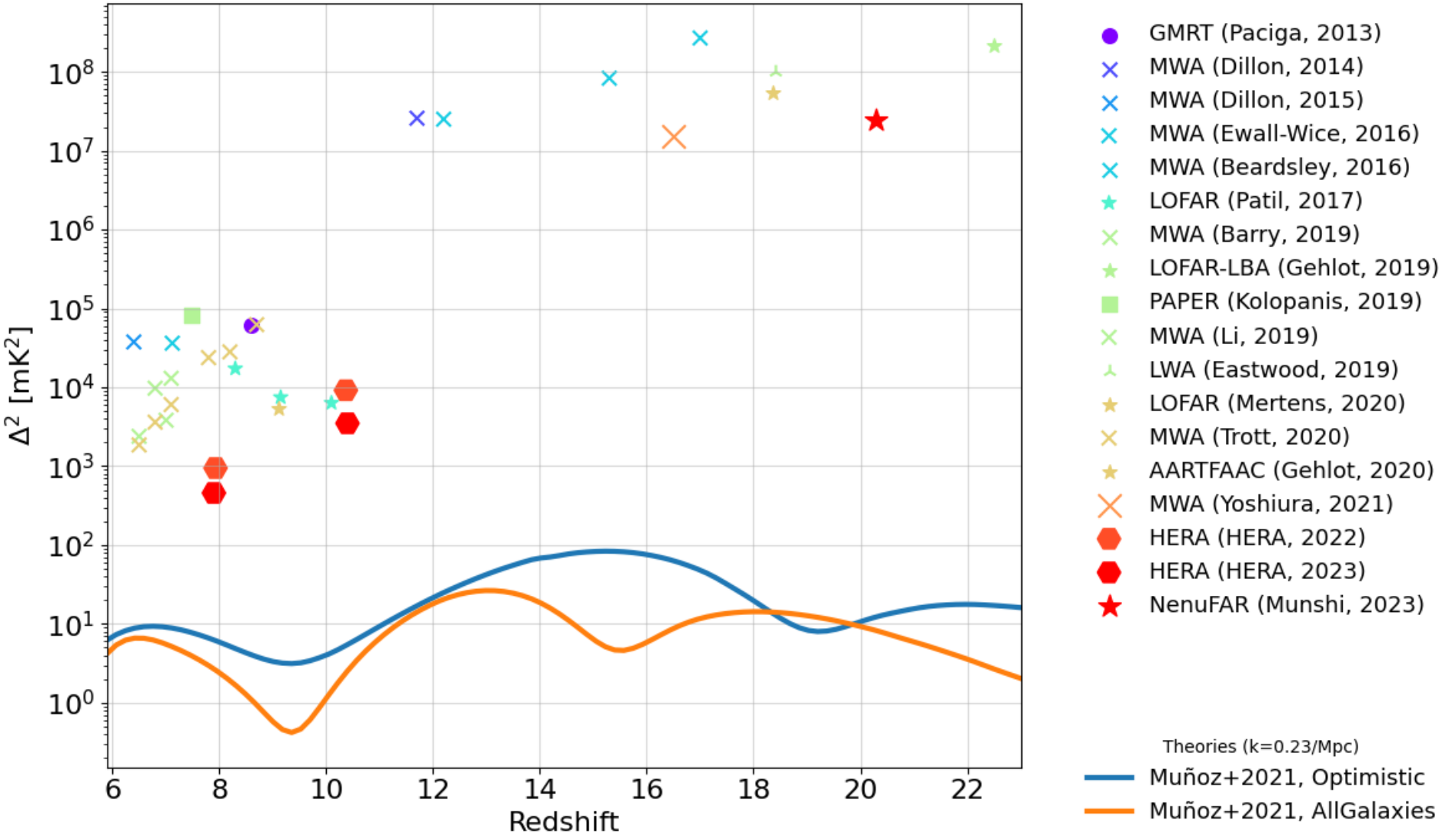


figure credit S. Murray

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

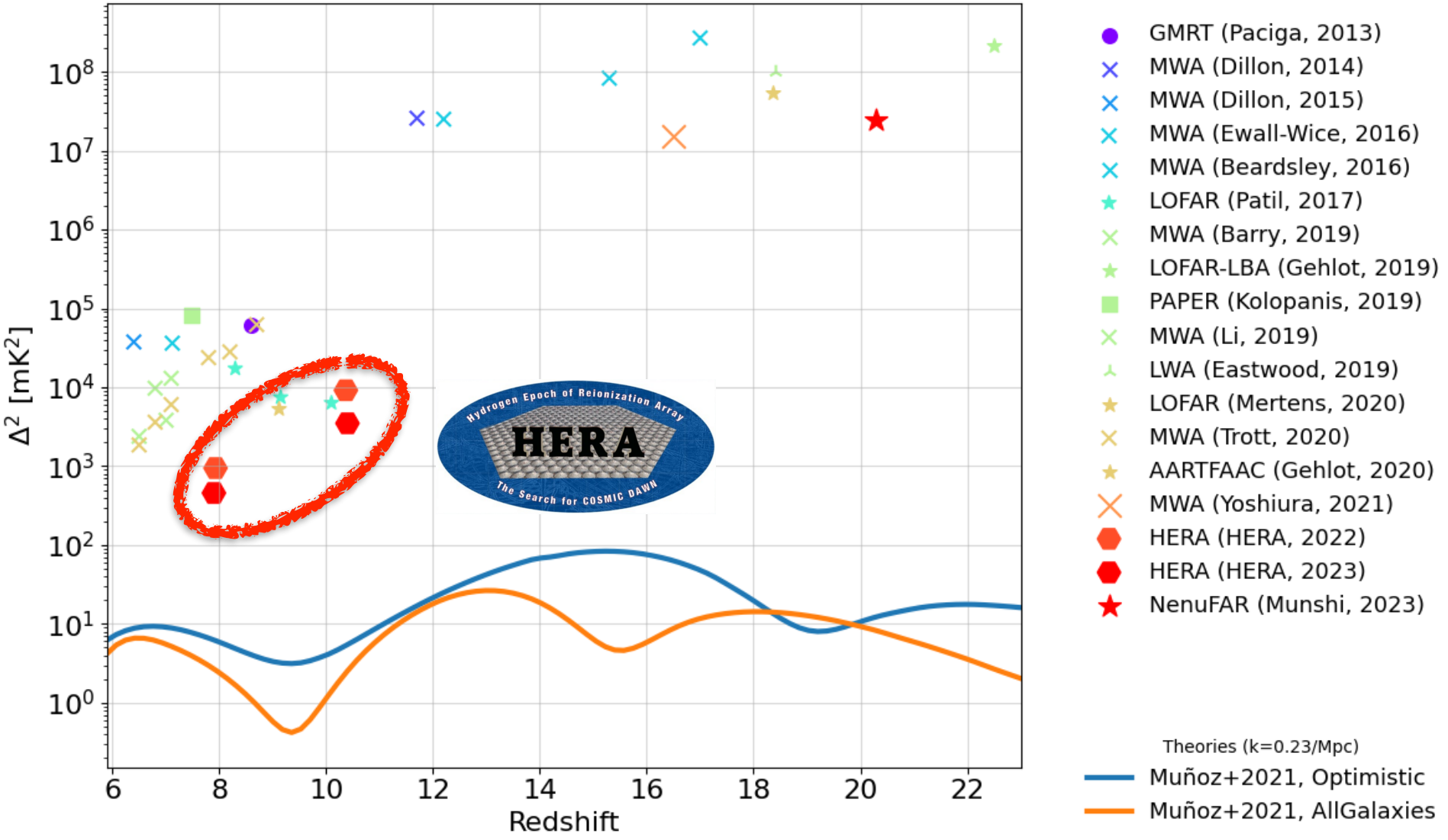
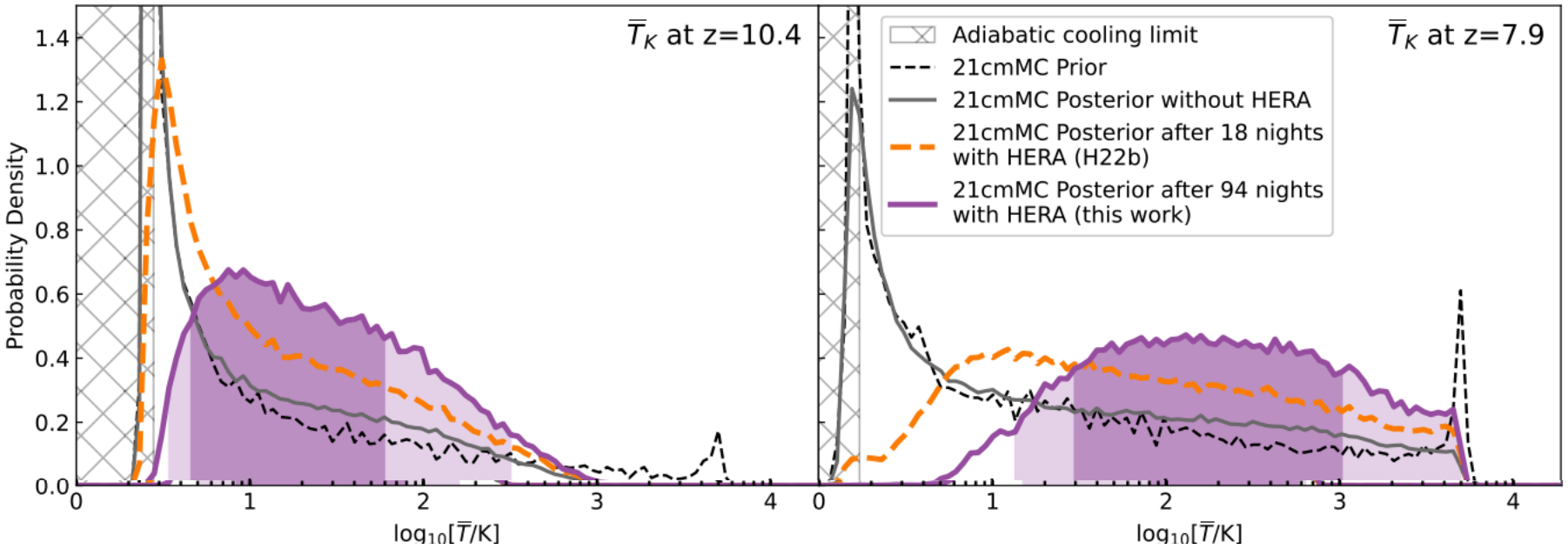


figure credit S. Murray

Upper limits already tell us there is some **NEW** source of heating at z>10!

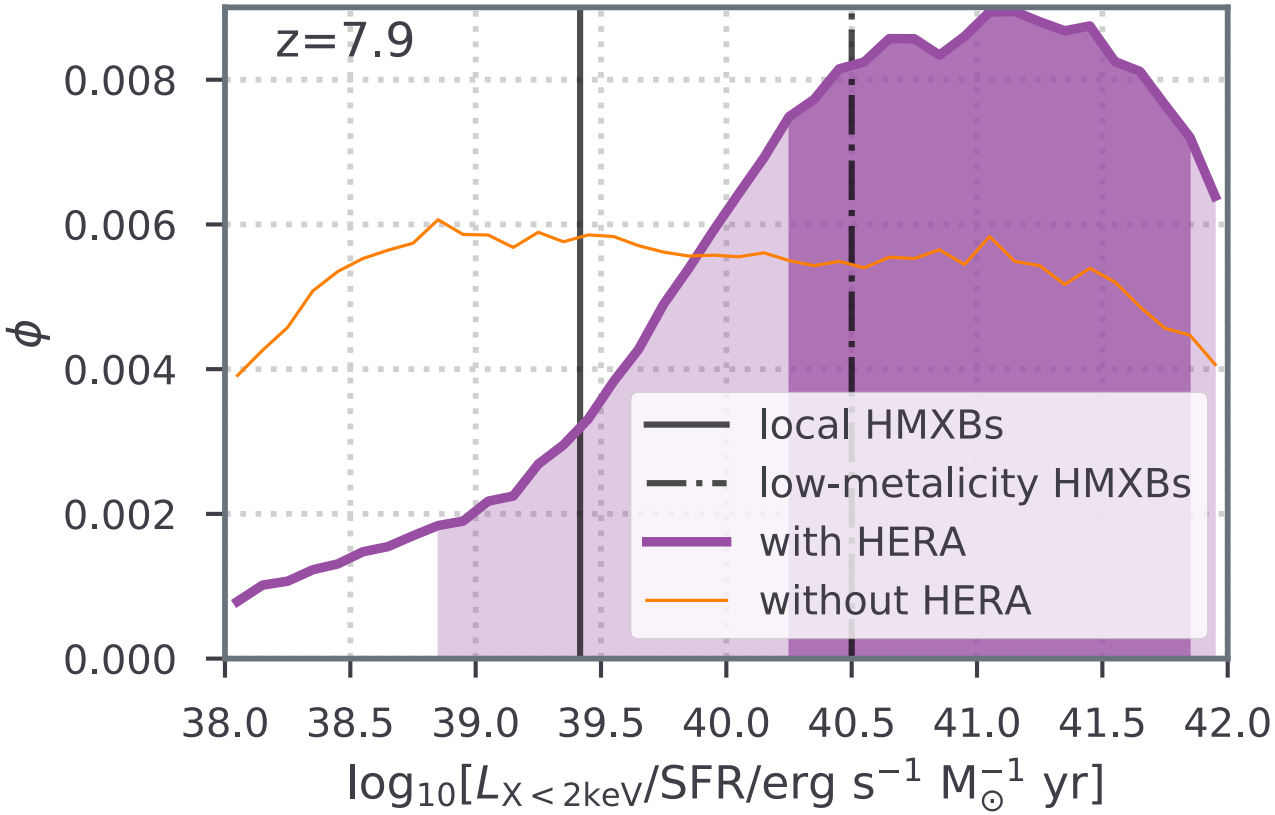
Adiabatically-cooling IGM *ruled out* by HERA



The HERA collaboration (2023)

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

If heating is done by X-ray binaries, they are very different from local ones!



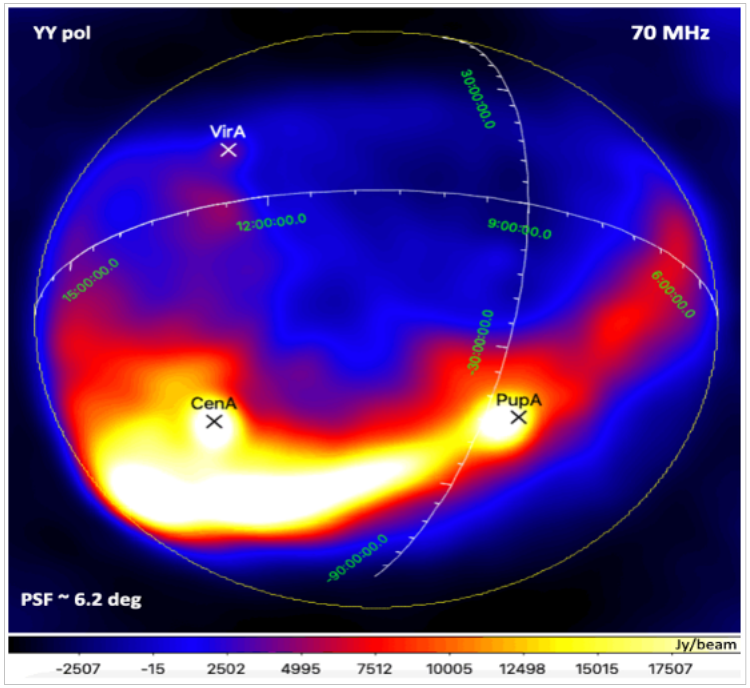
The HERA collaboration (2022)

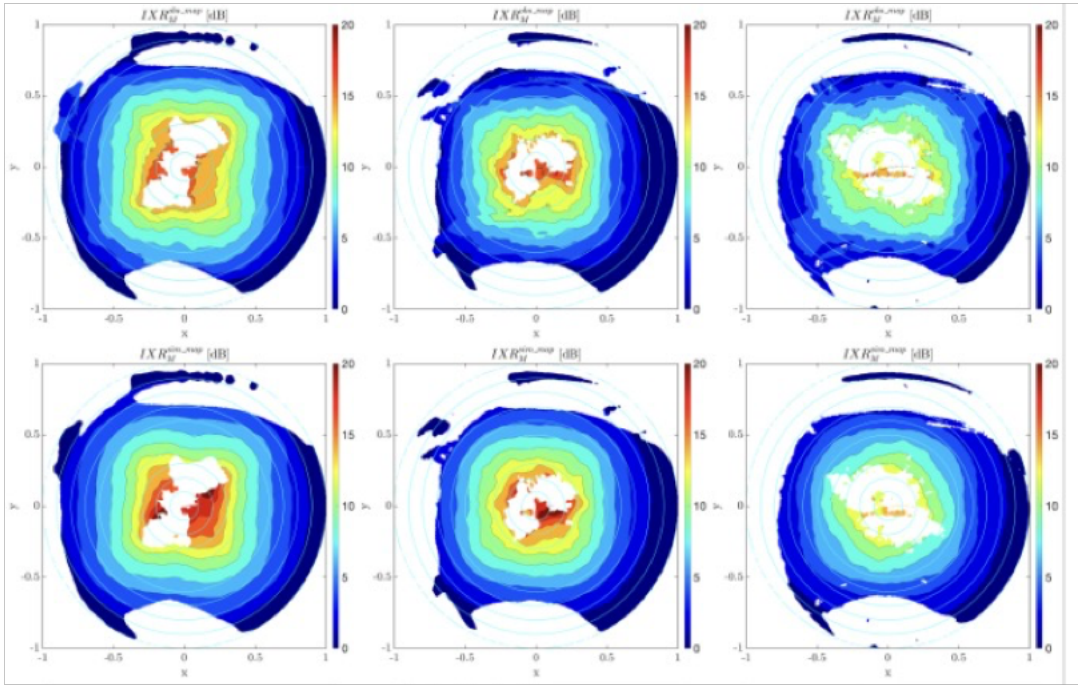
HERA is the first observation to constrain the X-ray luminosities of Cosmic Dawn galaxies, disfavoring the values seen in local, metal-enriched galaxies

Towards the first detection with SKA

Characterization of the AAVS2 prototype station (sensitivity estimates, calibration, polarization response)

AAVS2 all-sky images
(Macario, Pupillo, Bernardi et al, 2022)





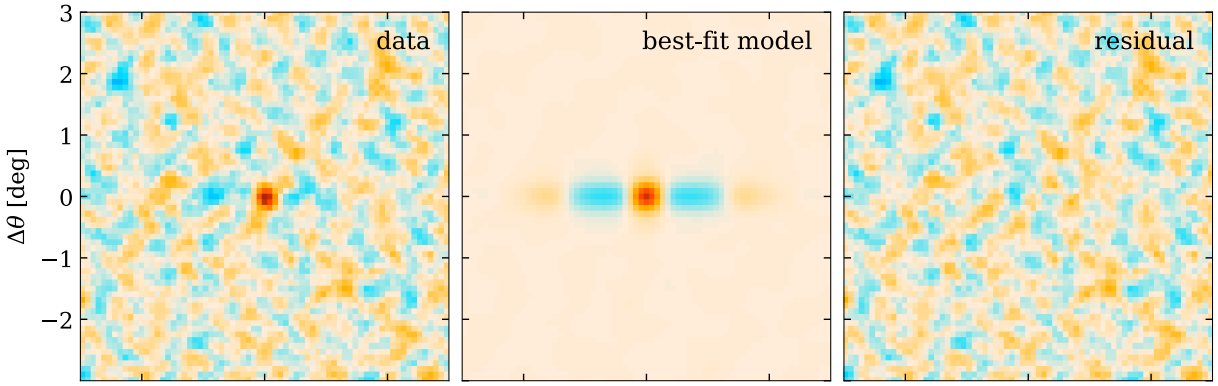
AAVS2 reconstructed instrumental polarization maps
(Macario, Pupillo, Bernardi et al, 2025)

A **MULTI-WAVELENGTH** approach will be essential to **make** and **confirm** the first detection

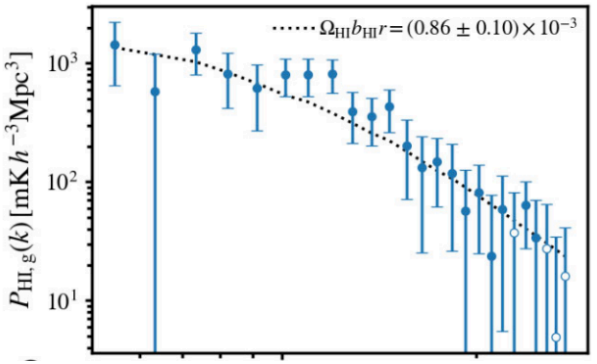
Cross-correlations

i) prove that initial claims of a 21cm detection are cosmological in origin

ii)make the signal easier to detect since systematics average out to zero

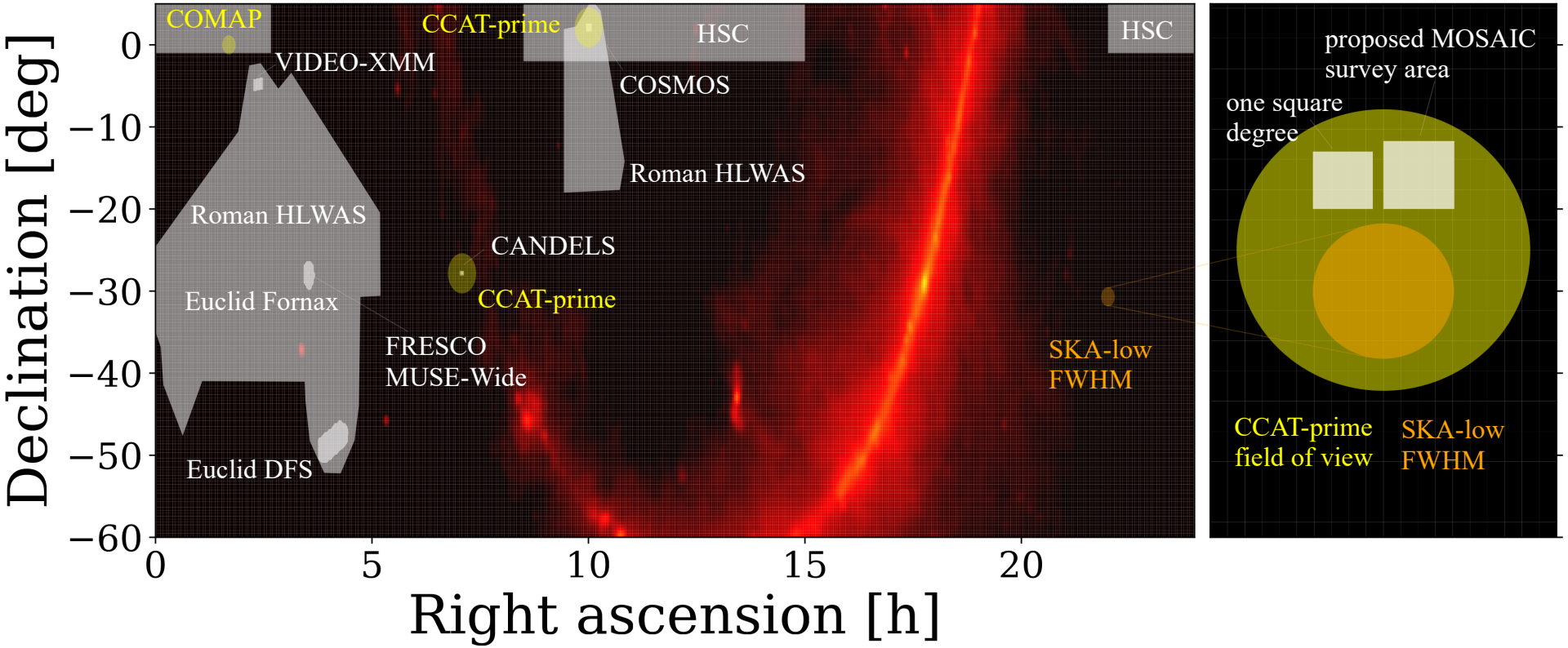


The CHIME collaboration 2022



MeerKAT collaboration 2023

Where should we point the SKA initially?

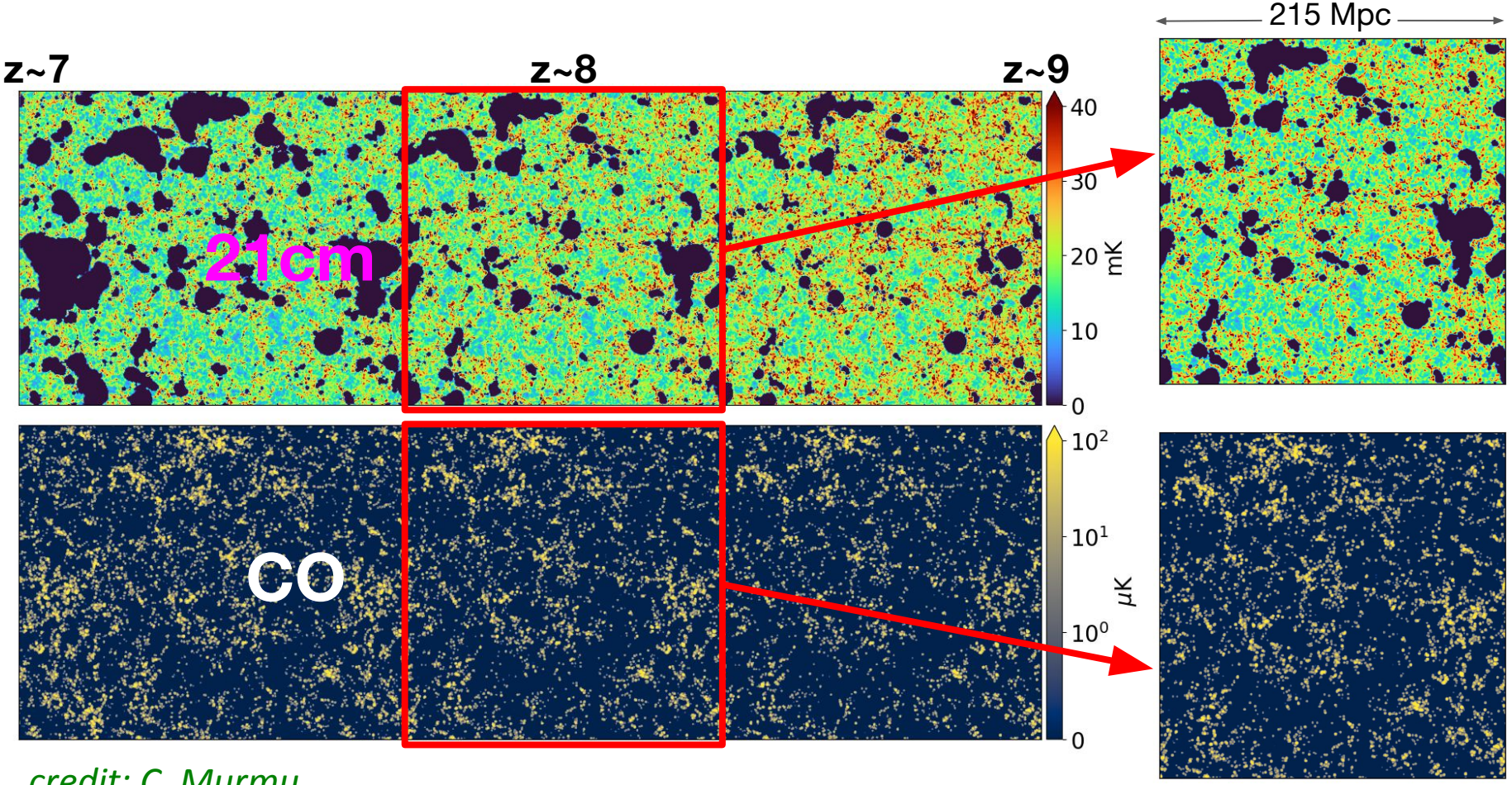


Synergy chapter in upcoming SKA whitebook

Stay tuned for talk by Sam Gagnon-Hartman!

An interesting synergy with MeerKAT Band5b

Lightcone CO and 21cm LIM signals



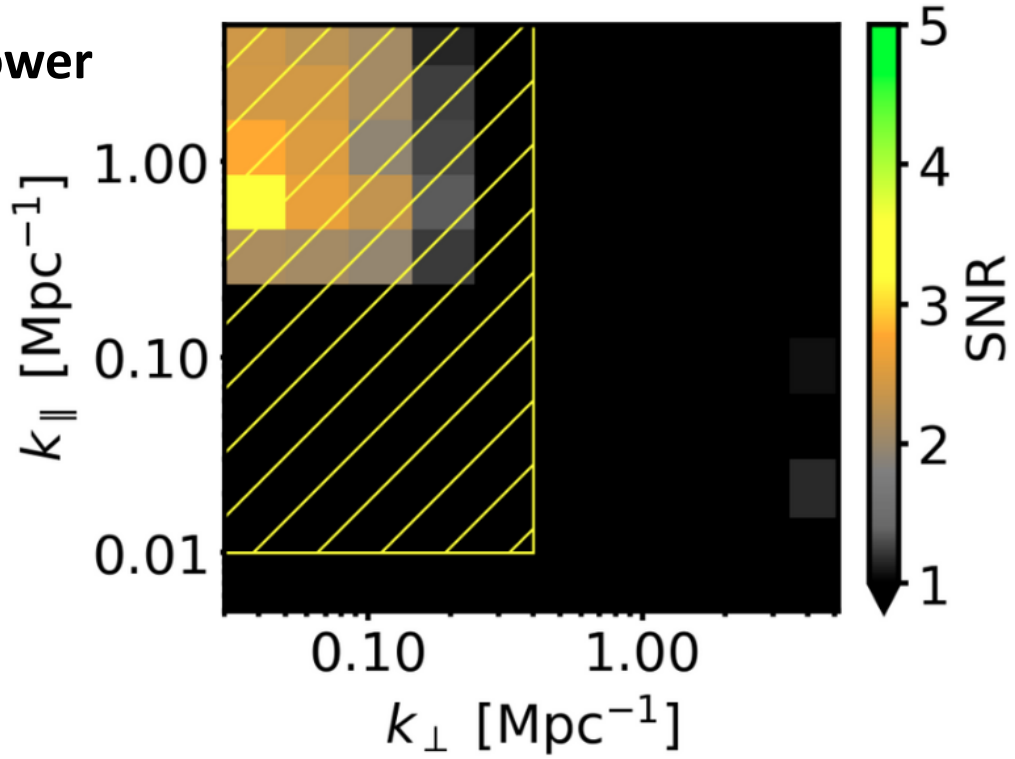
credit: C. Murmu

High redshift molecule chapter in Band5 whitebook

An interesting synergy with MeerKAT Band5b

credit: C. Murmu

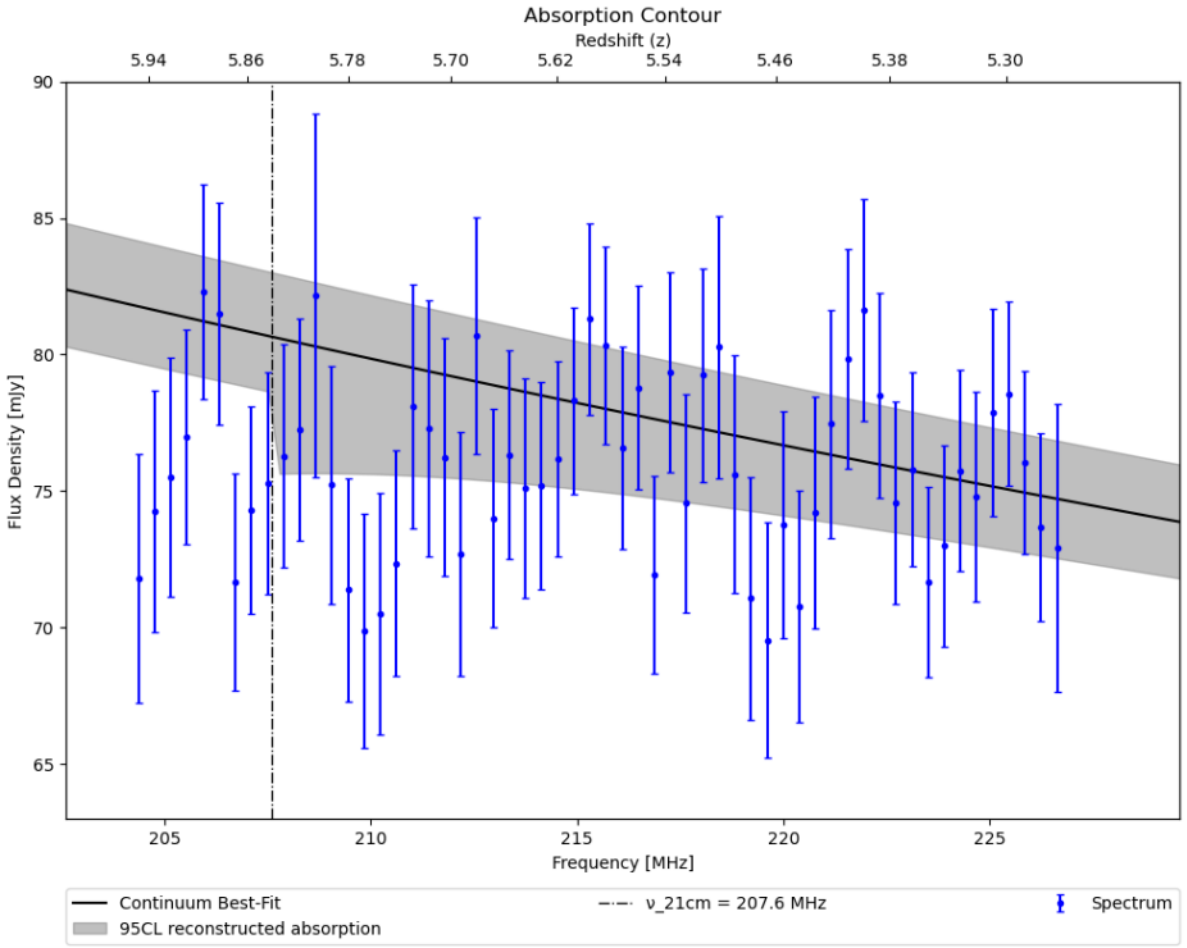
Forecasted high S/N detection of the CO-21cm cross-power



WORK IN PROGRESS

High redshift molecule chapter in Band5 whitebook

Another possibility with preliminary SKA data: detecting the 21cm forest?



GMRT

See Kongprachaya's talk

Conclusions

- The cosmic 21cm signal will allow us to learn the **properties of the unseen first galaxies as well as physical cosmology.**
- **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**.
- Precursor efforts are limited by **systematics**, though progress is being made and upper limits are continuously decreasing…
- We will need **cross correlations** to detect and confirm the 21cm signal. *Where should we point SKA-low??*