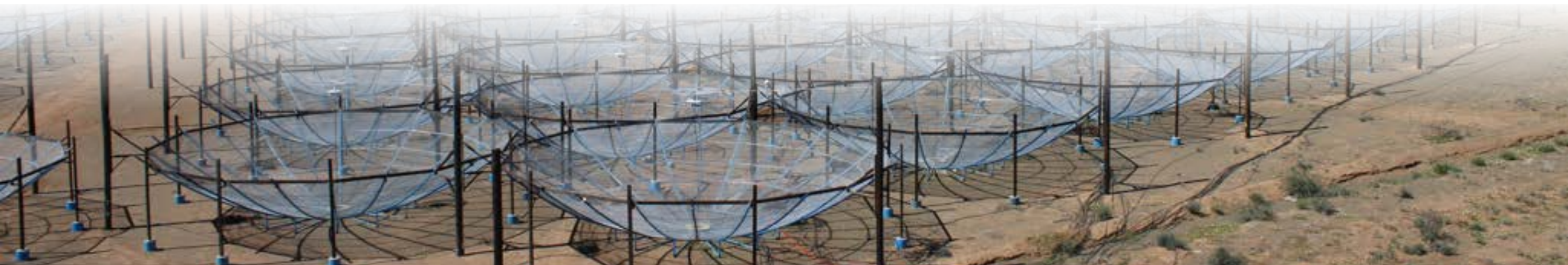


New Insights on Cosmic Dawn Astrophysics from 21 cm Telescopes

Nick Kern
Hubble Fellow

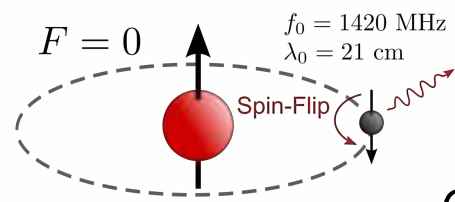
September 21, 2023
NHFP Symposium



The takeaway...

- 21 cm cosmology is a **burgeoning field**, aiming to access untapped cosmological information spanning a wide redshift range
- With new upper limits, 21 cm telescopes are constraining **X-ray heating models of the IGM** at $z > 8$
- For a detection, we need new analysis frameworks that can **more robustly** extract the 21 cm signal amidst foregrounds and systematics

Cosmic tomography with the 21 cm line



emitted at 1420 MHz, measured at ...

80 MHz

150 MHz

300 MHz

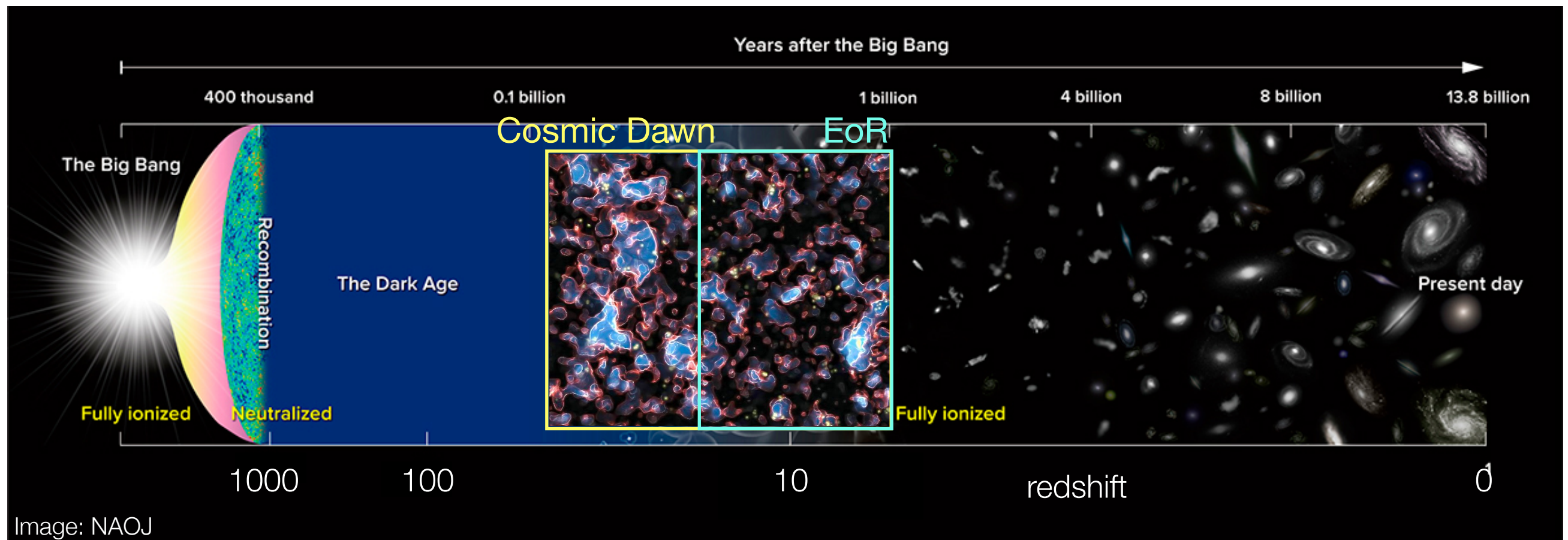


Image: NAOJ

CMB
primary anisotropies

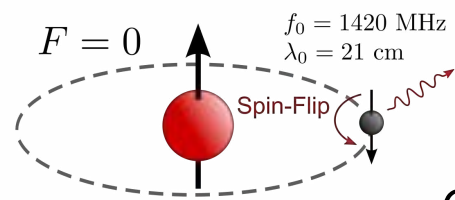
HERA, MWA, LOFAR, GMRT, ...

Ly-a forest

spectroscopic
galaxy surveys

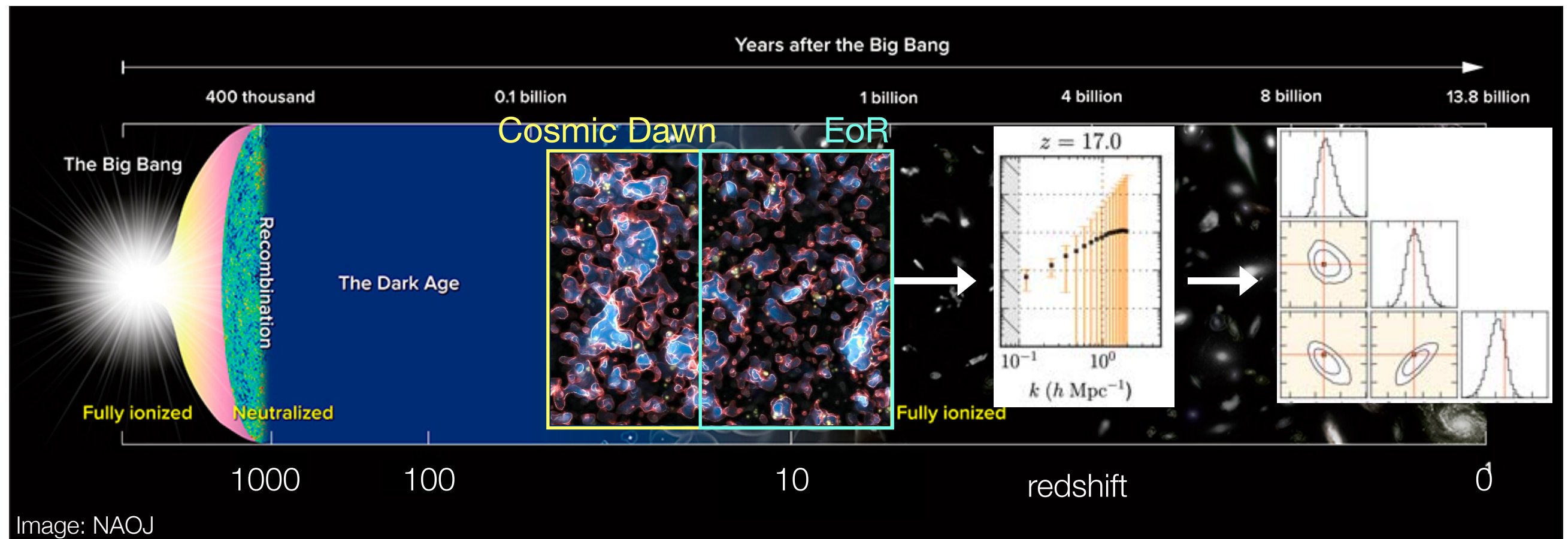
hydrogen surveys (and other LIM probes)

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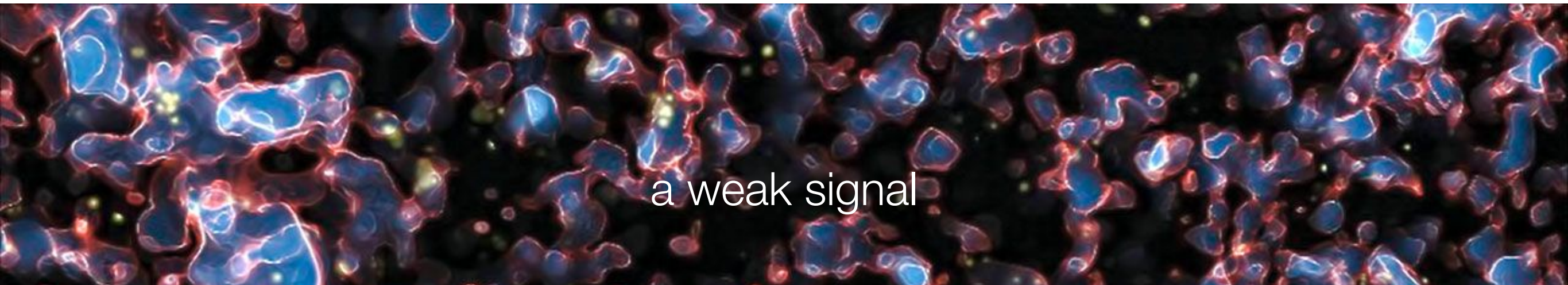
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Ly- α forest

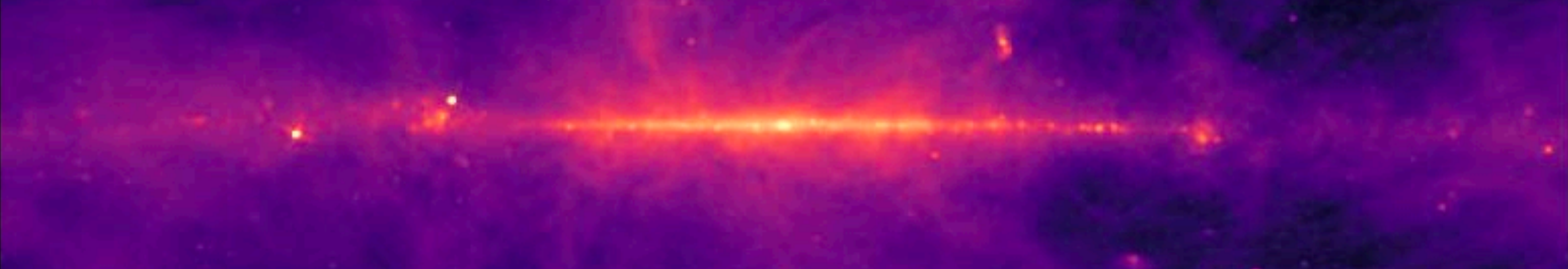
spectroscopic
 galaxy surveys

hydrogen surveys (and other LIM probes)

Measuring the signal is complicated by bright foregrounds and complex systematics...



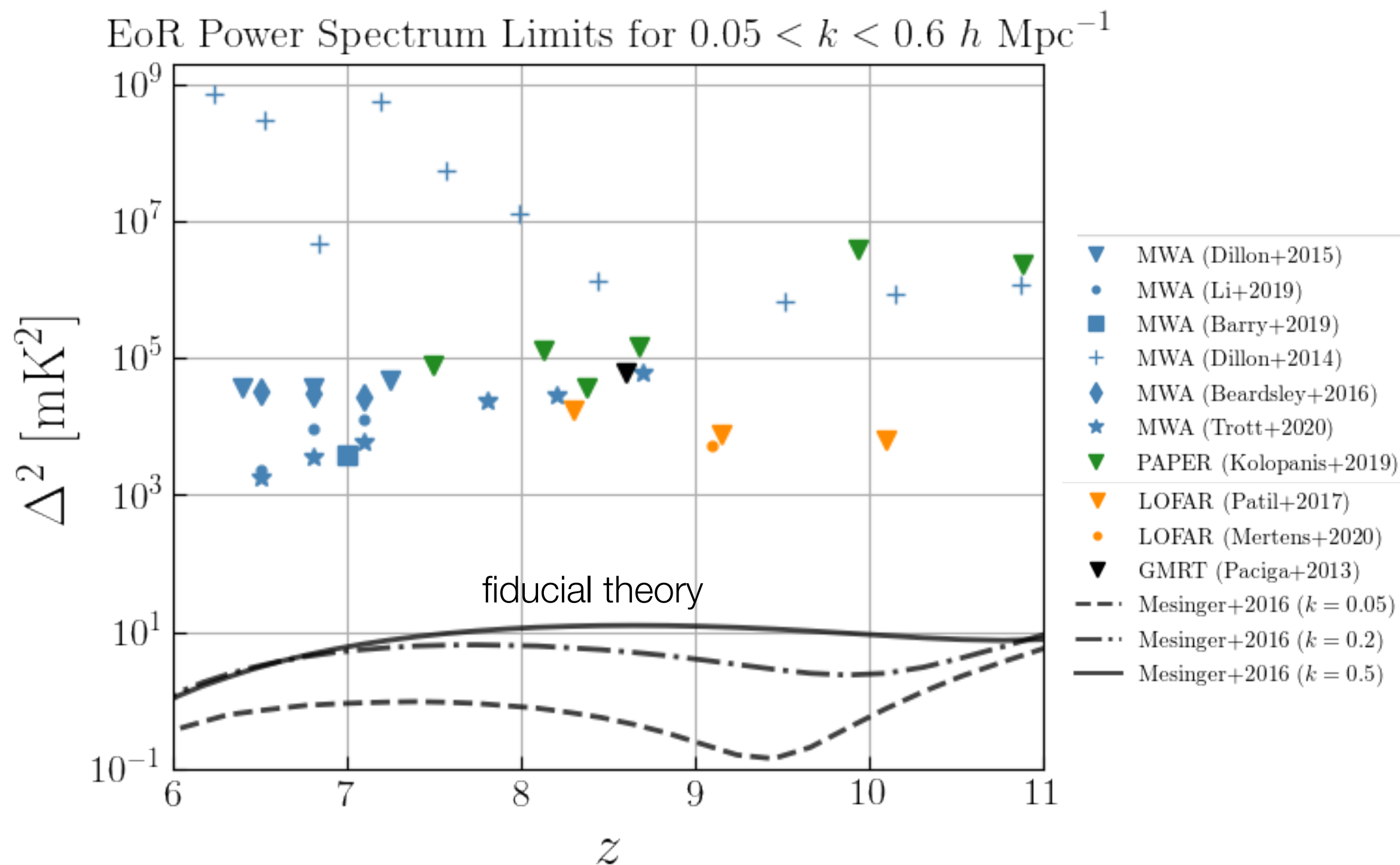
masked by incredibly bright ($\times 10^5$) foreground emission at low frequencies



modulated by a complex instrumental response



Best 21 cm upper limits at EoR (prior to 2022)

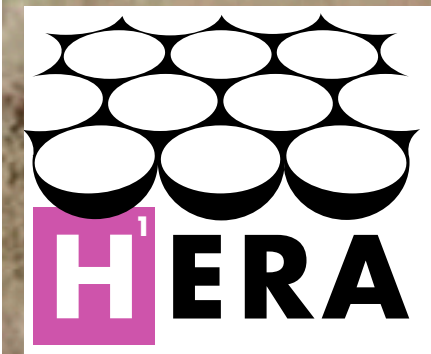


Hydrogen Epoch of Reionization Array

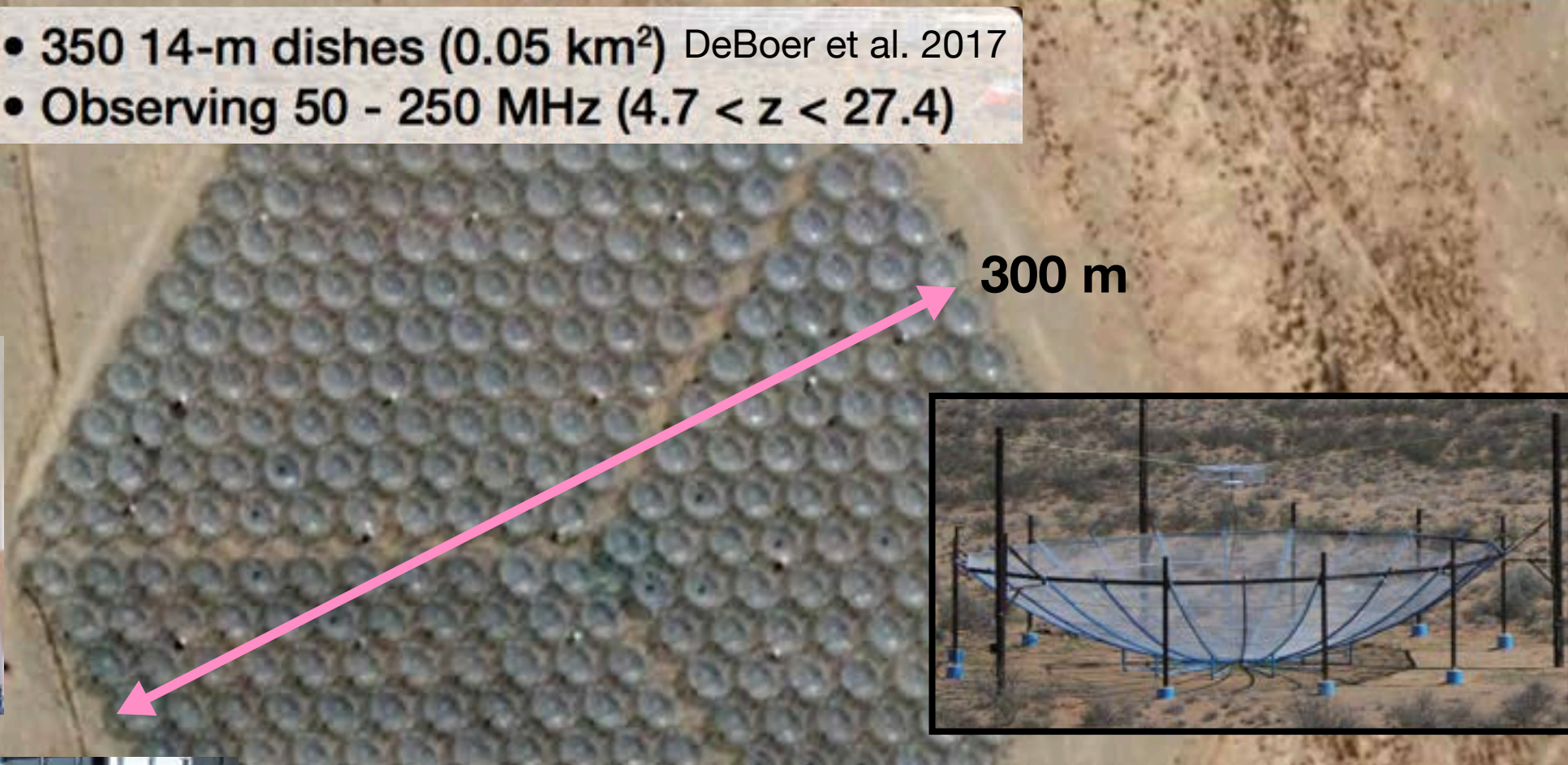


Google Earth
Data SIO, NOAA, U.S. Navy

Hydrogen Epoch of Reionization Array



- 350 14-m dishes (0.05 km²) DeBoer et al. 2017
- Observing 50 - 250 MHz ($4.7 < z < 27.4$)

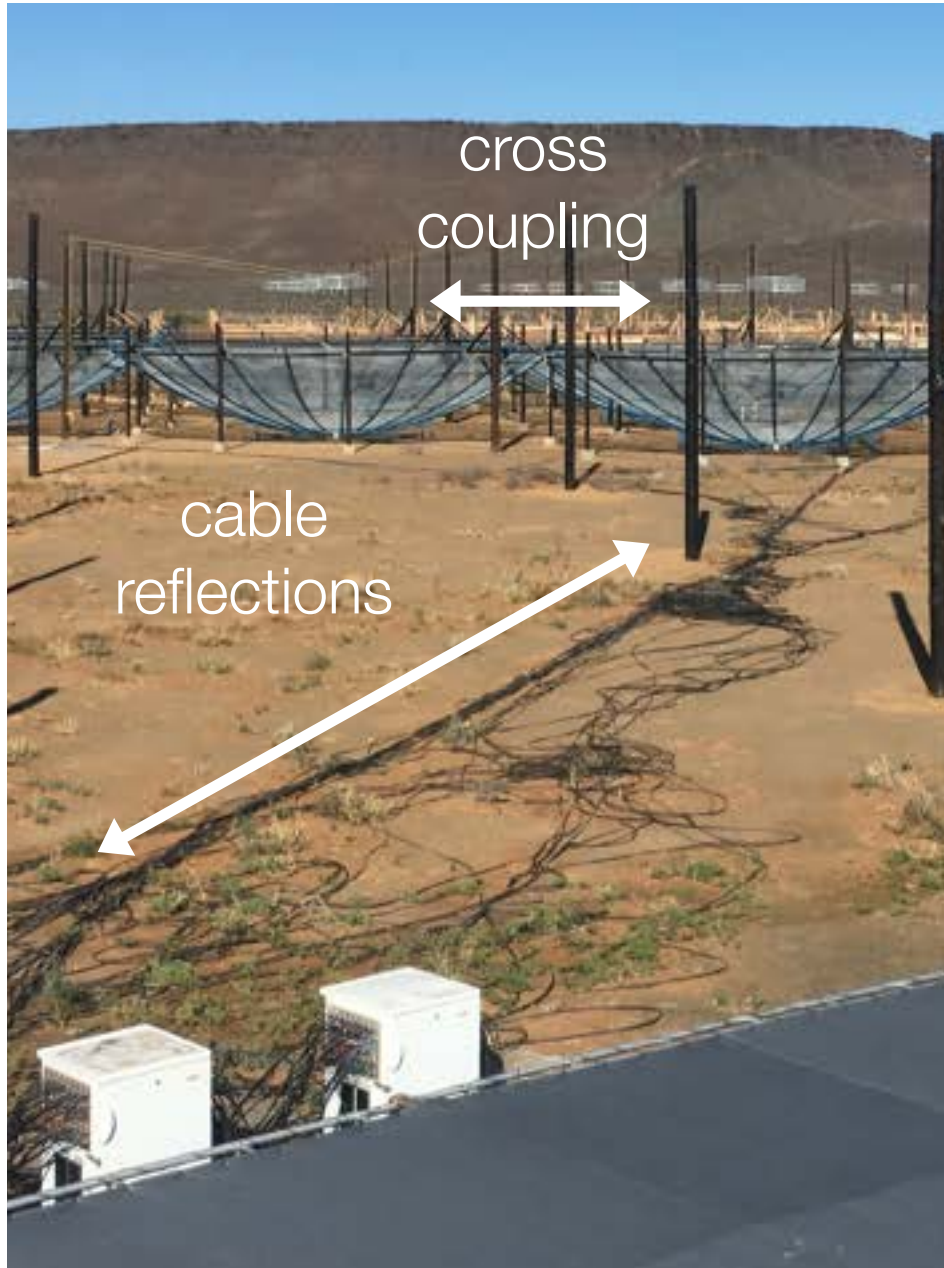


Phase I observing campaign

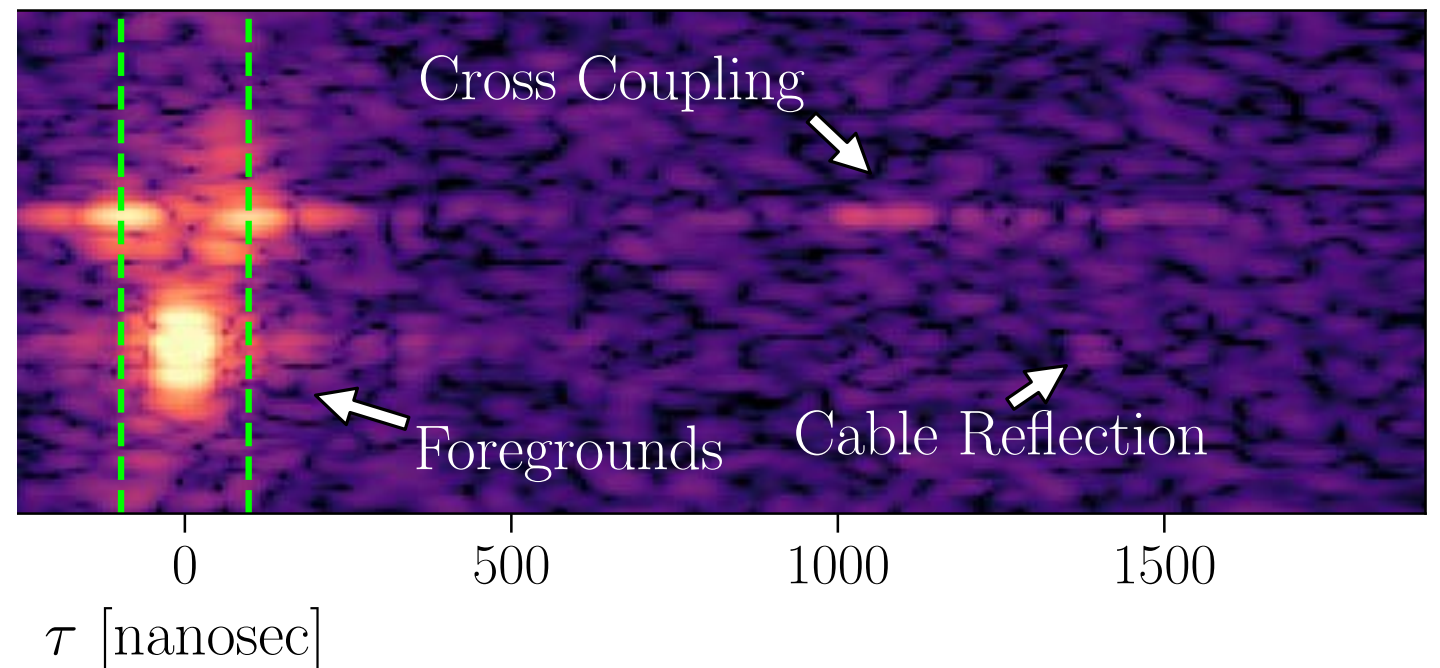
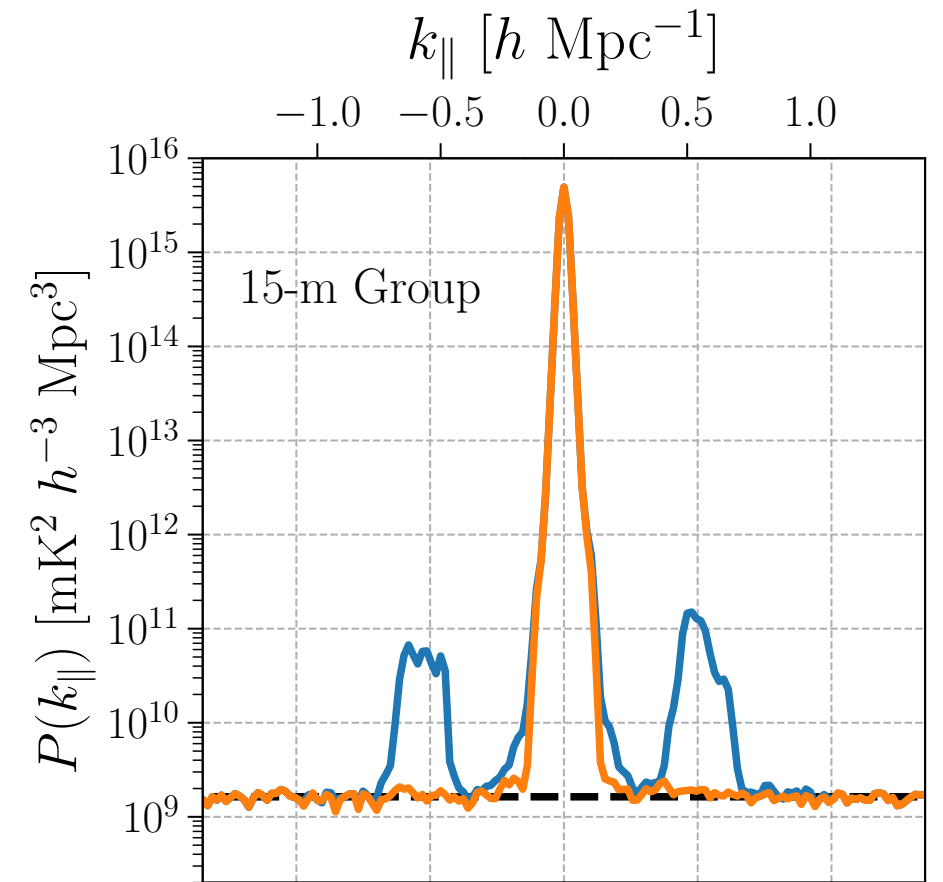


**HERA Phase I
2017 - 2018
50 antennas**

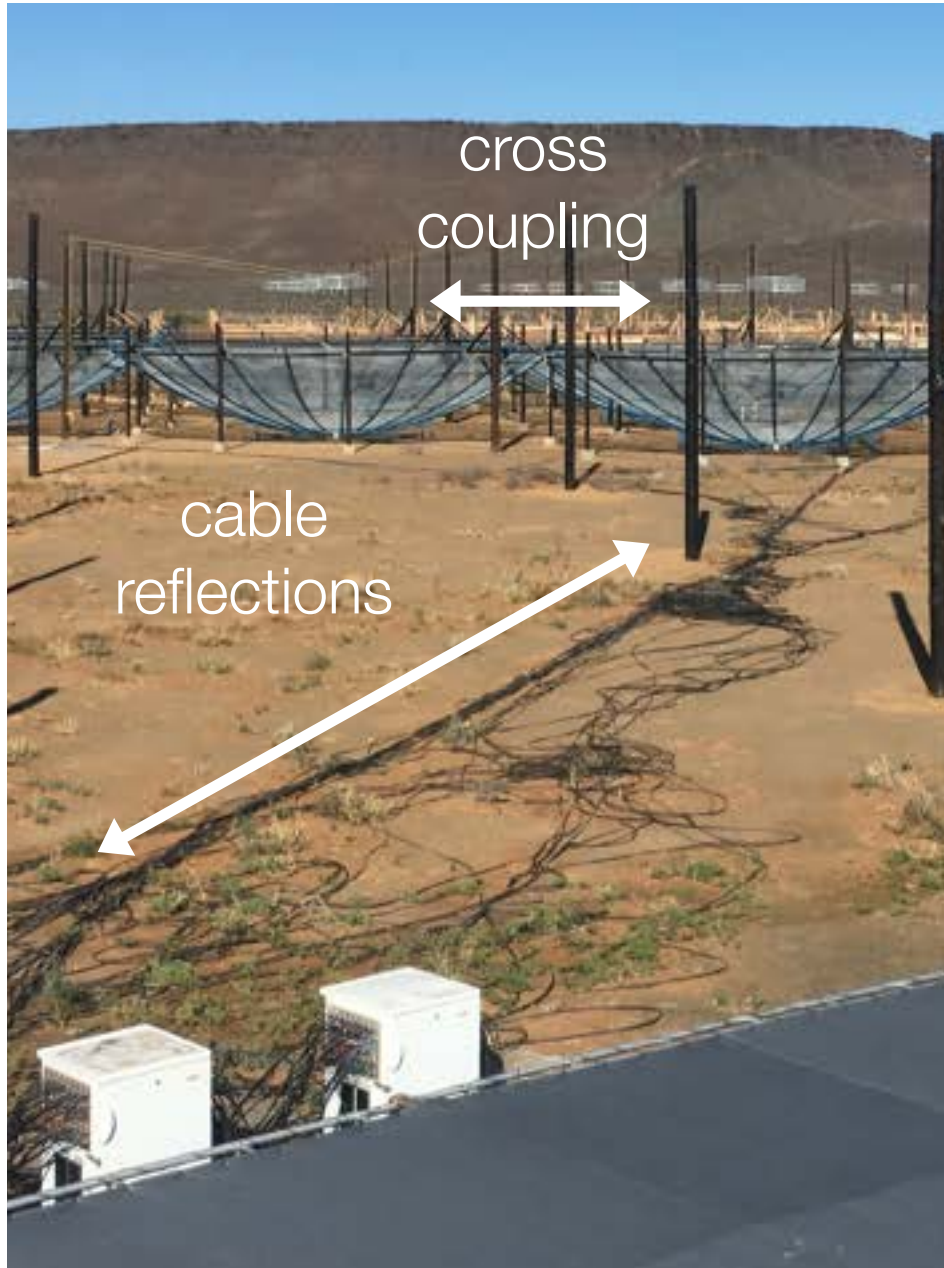
Addressing instrumental systematics



- No Systematic Removal
- With Systematic Removal
- - Noise Floor

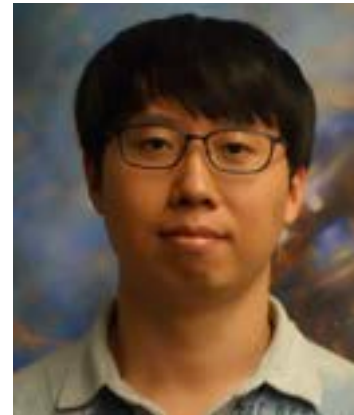


Addressing instrumental systematics



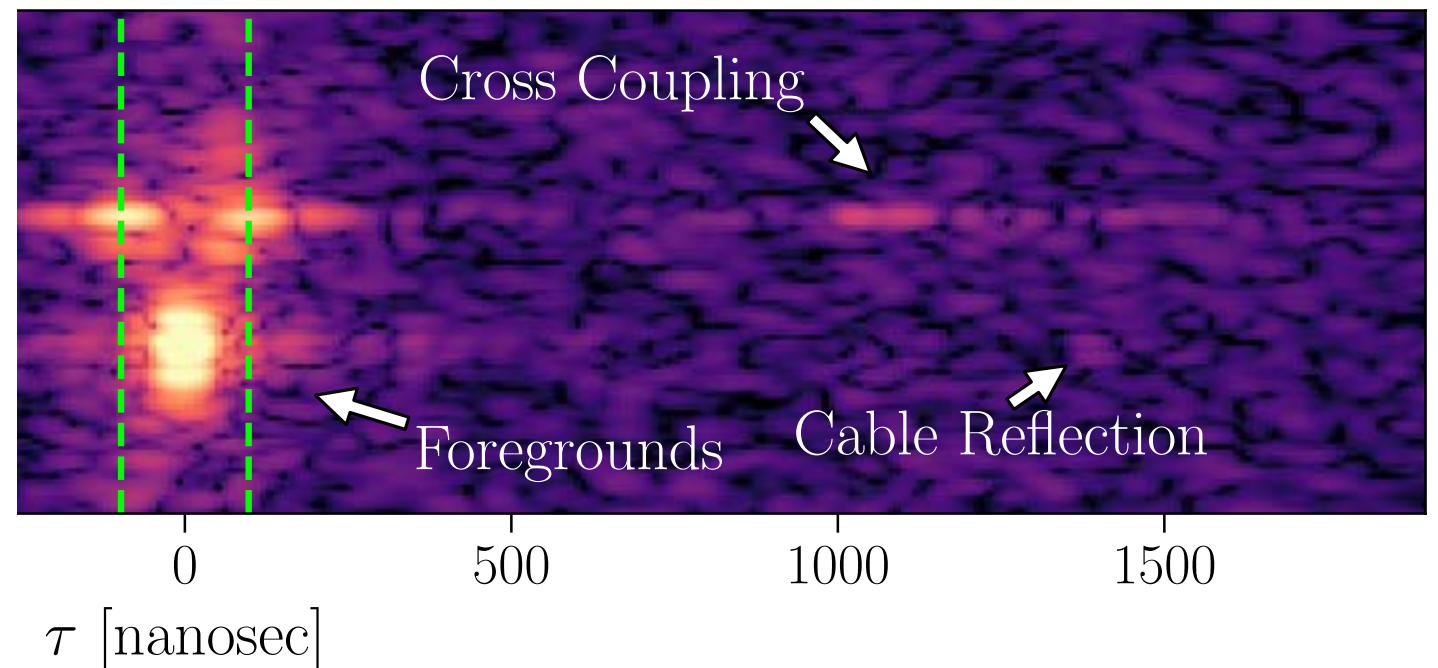
Nstikelelo Charles, U. Rhodes PhD grad
Charles, **NK**, et al. 2023, MNRAS

Custom filters for mitigating poorly understood diffuse emission on calibration

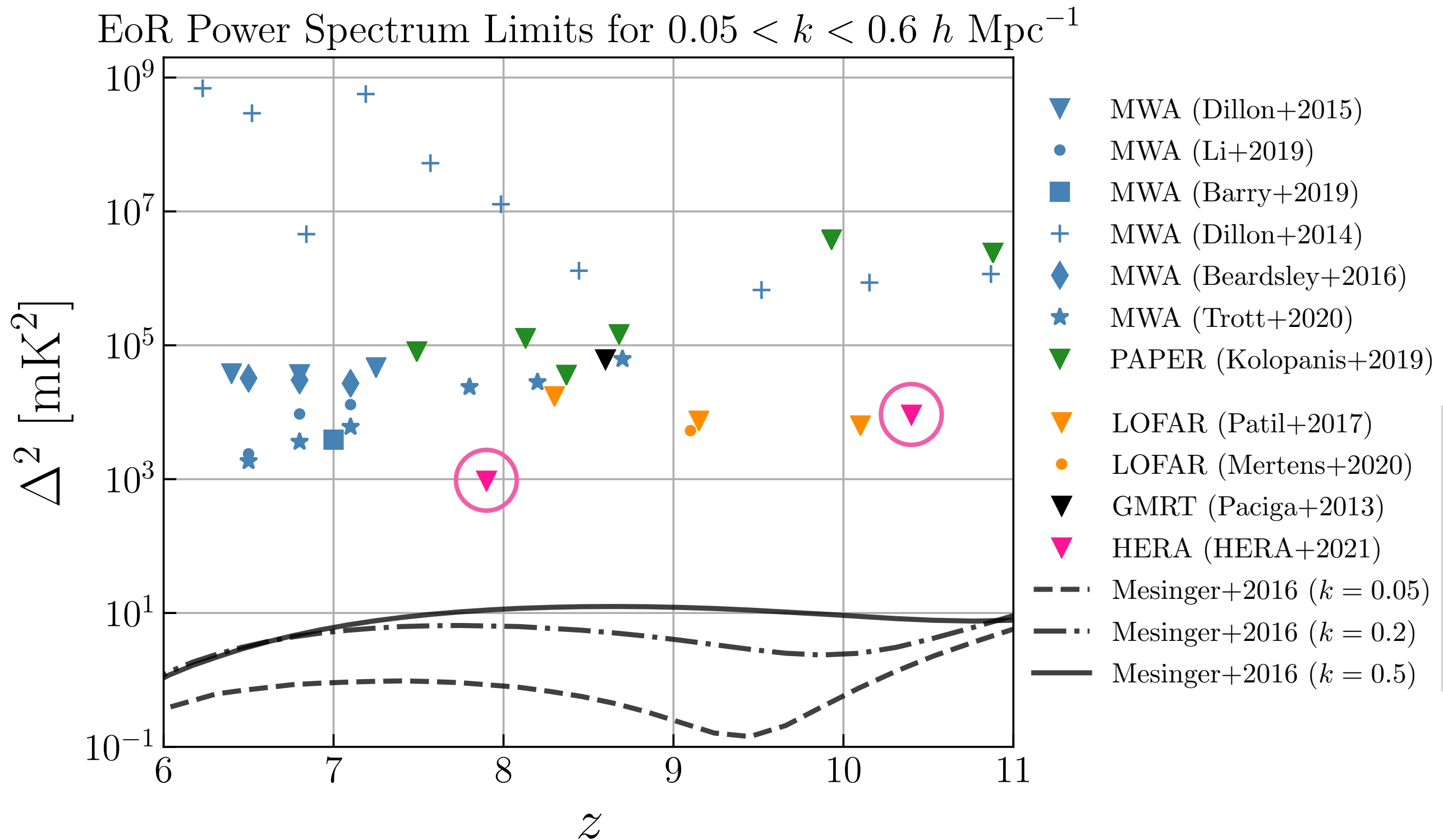


Honggeun Kim, MIT PhD grad
Kim, **NK**, et al. 2023, MNRAS

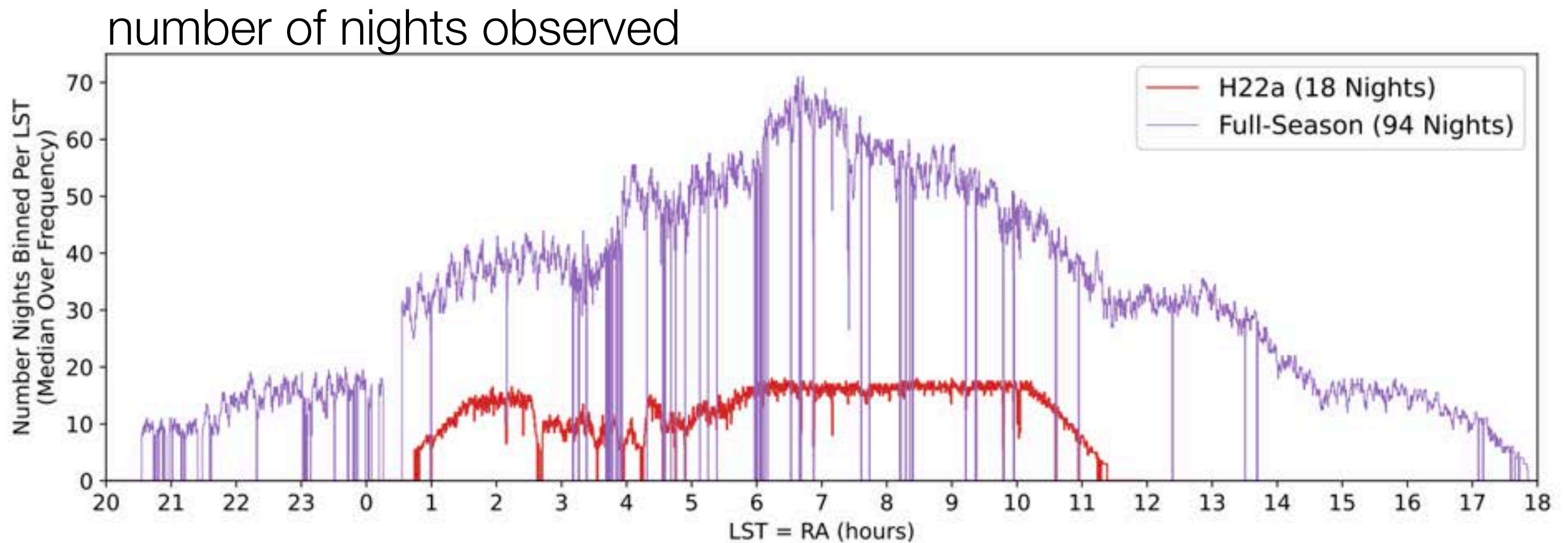
Custom filters for mitigating antenna feed displacement errors on calibration



Significant improvement at $z=7.9$



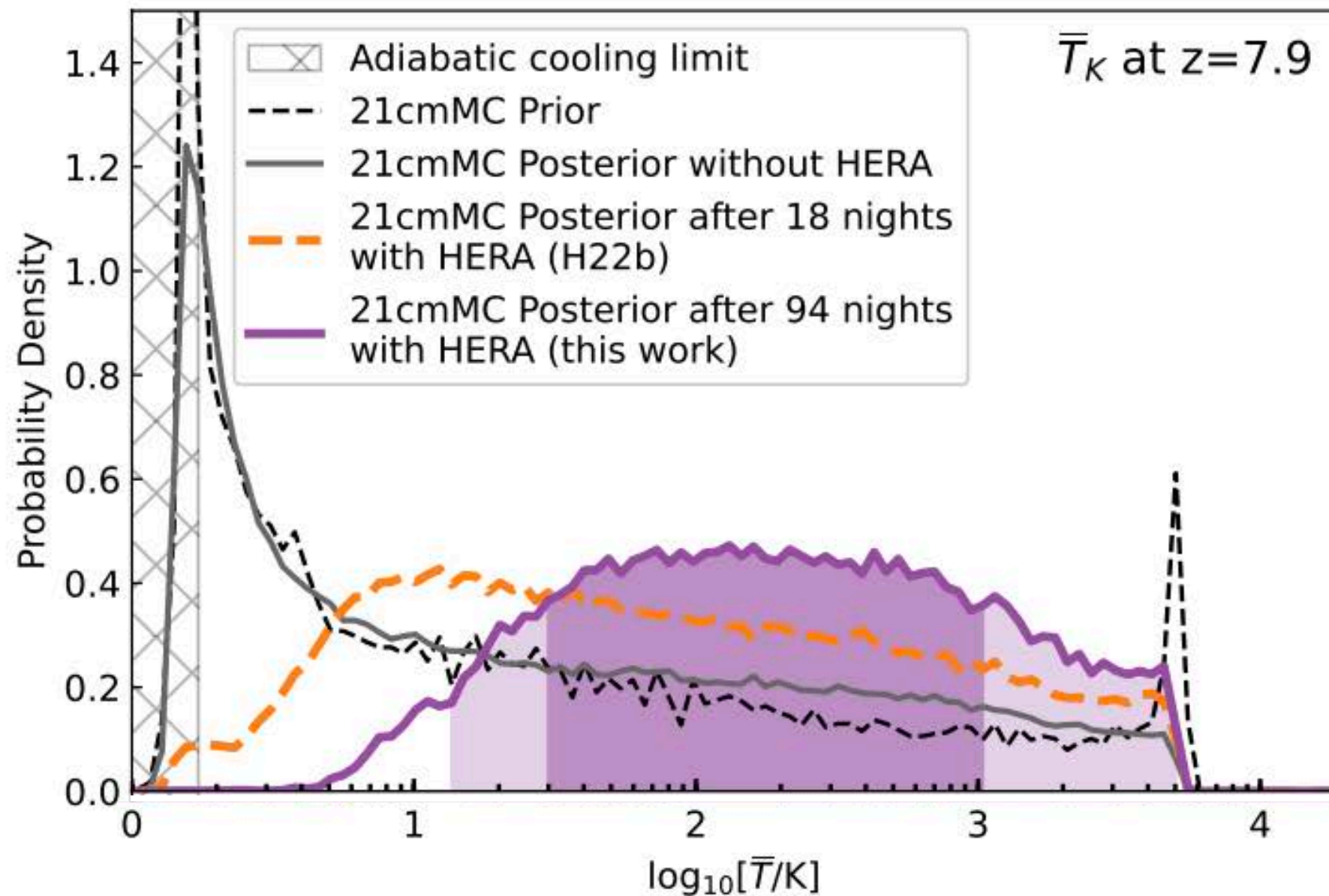
Analyzing full-season Phase I data



telescope RA pointing

~2x improvement in limits
at $z=7.9$ and $z=10.4$

Constraints on the IGM temperature



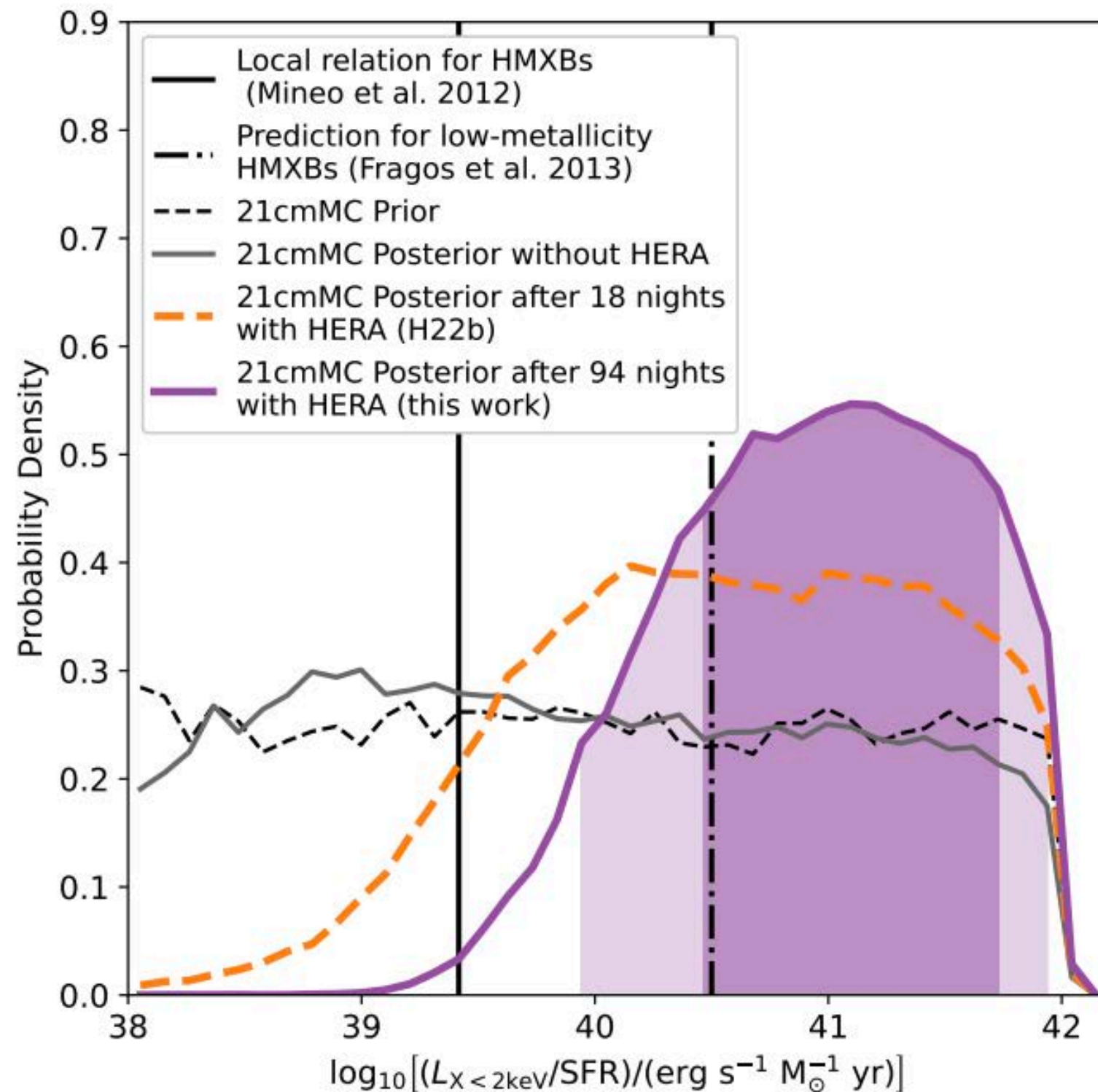
Without HERA:

- UV luminosity functions
- QSO dark fraction
- CMB optical depth

With HERA:

- HERA likelihood favors a heated IGM at $z=8$, $T_s > 13$ K at 95% conf.

First indication of a low-metal HMXB population*

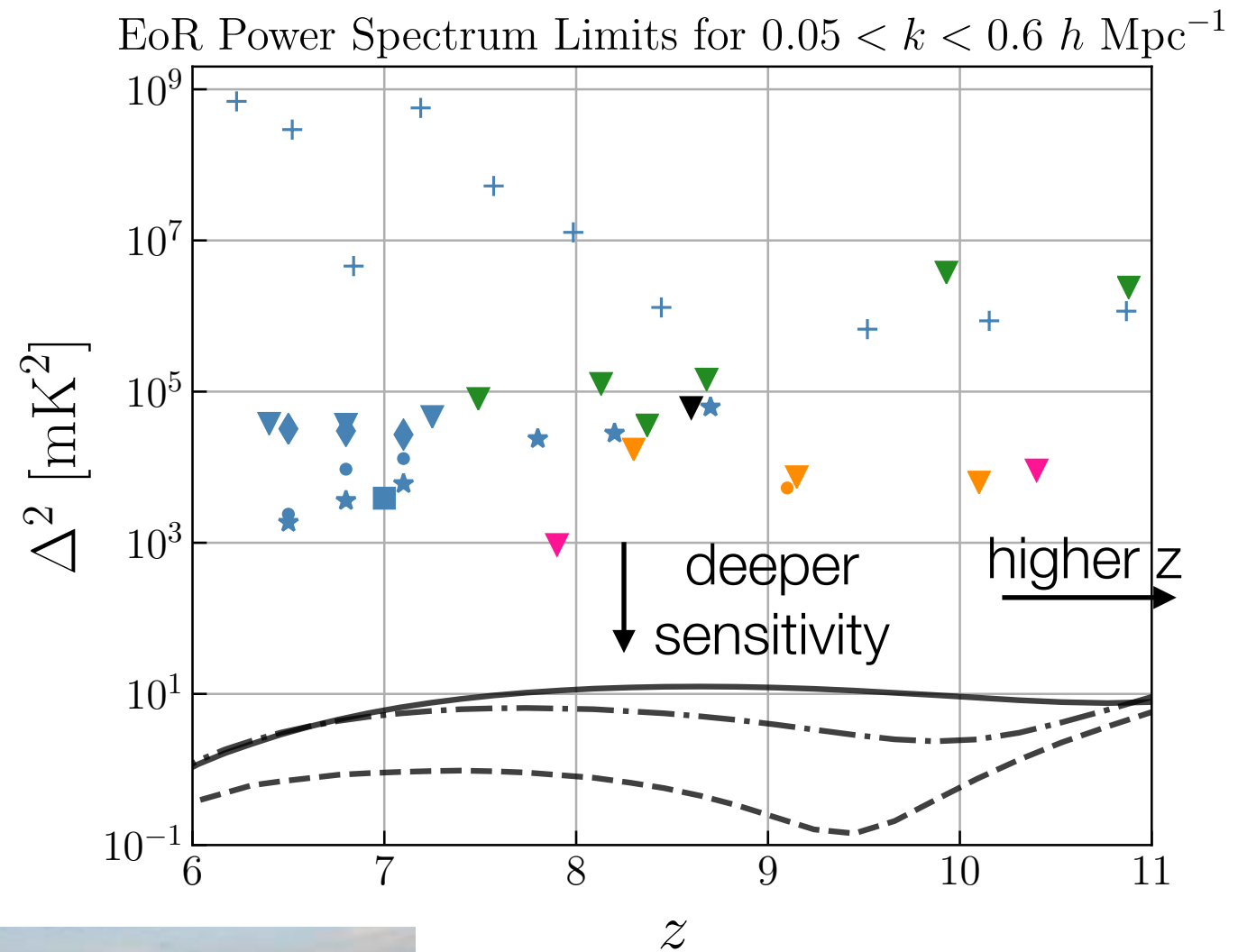
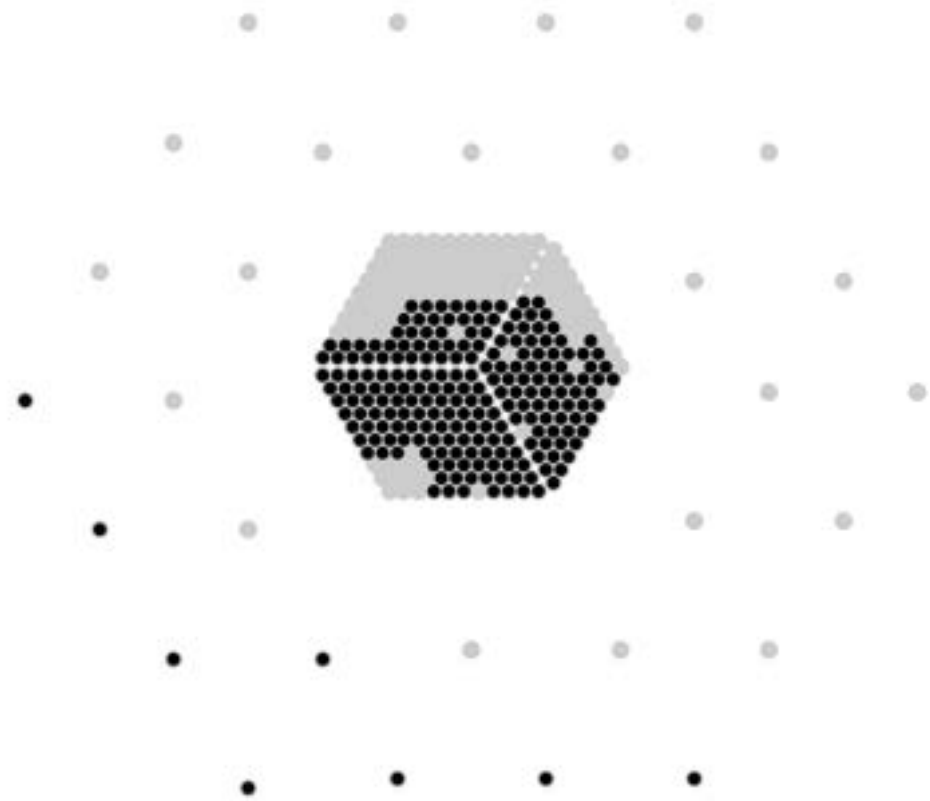


*Assumes the dominant X-ray contribution is from HMXB
see Lazare+2023

X-ray production efficiency →

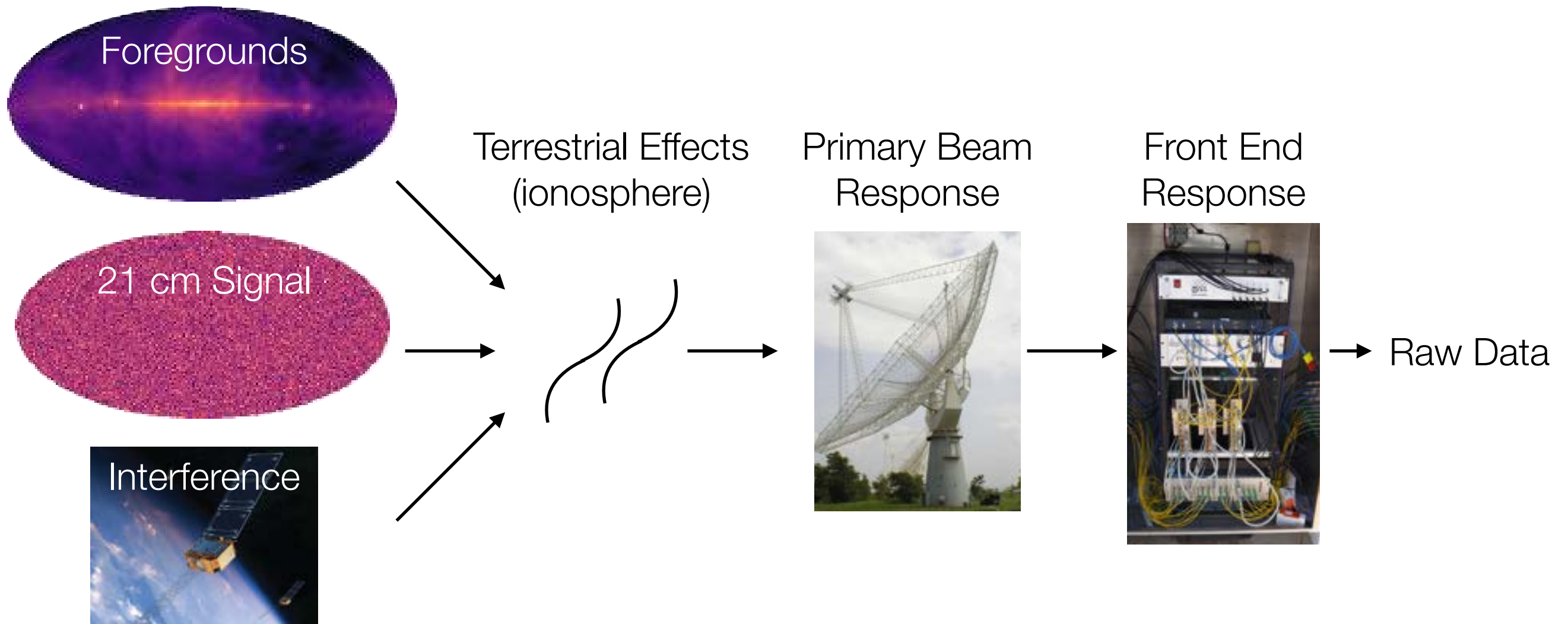
What's next for HERA?

Currently commissioning Phase II

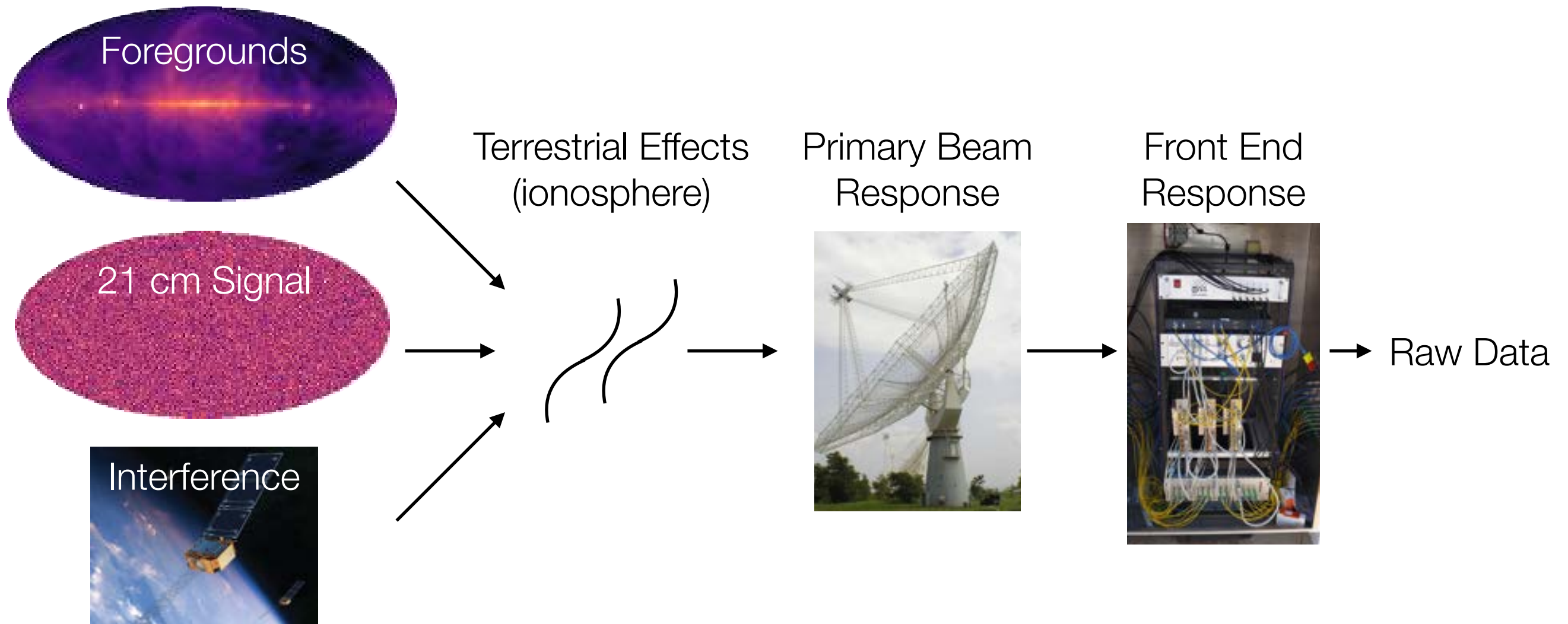


Next-generation analysis frameworks:
How do we get to a *robust* detection?

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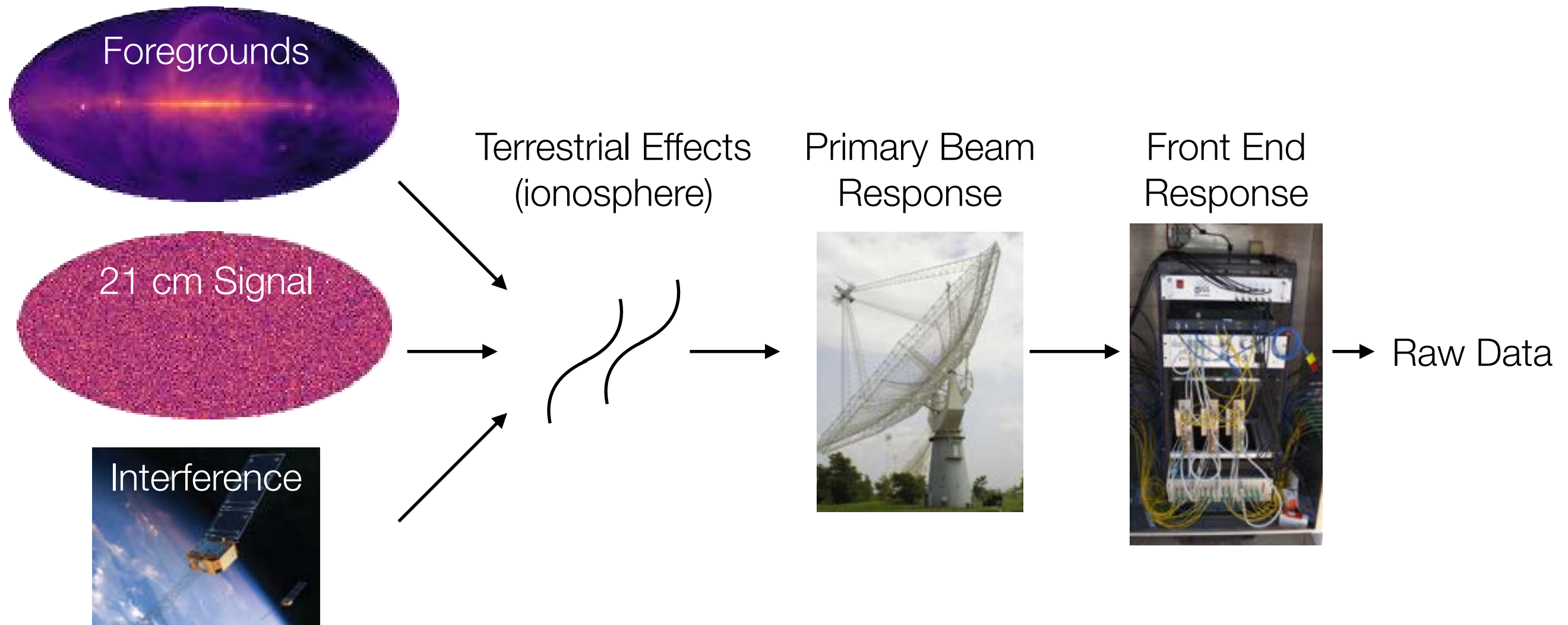


Next-generation analysis frameworks: How do we get to a *robust* detection?



$N_{\text{frequencies}}$, $N_{\text{integrations}}$, $N_{\text{baselines}}$ (N_{antenna}^2), $N_{\text{sky_pixels}}$

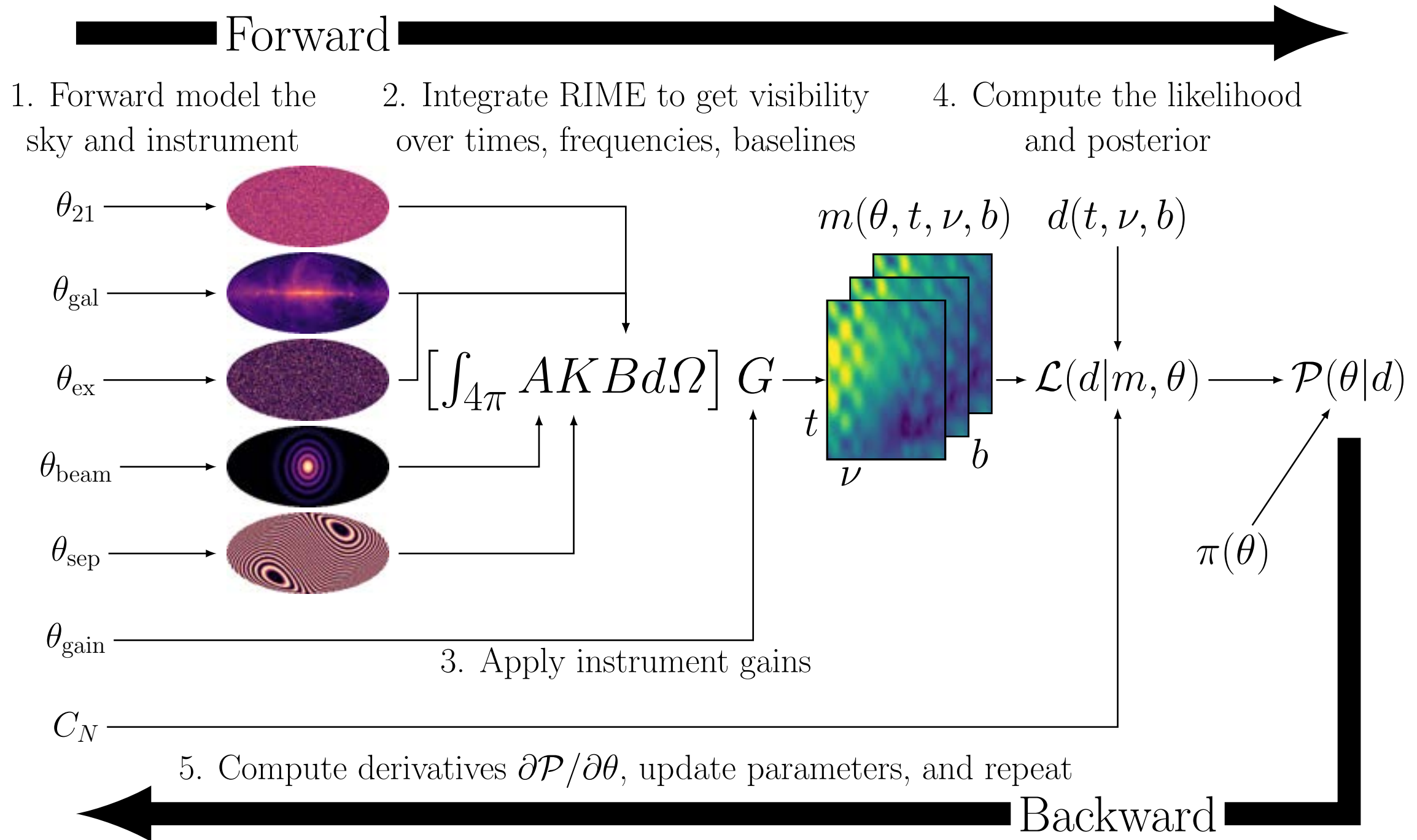
Next-generation analysis frameworks: How do we get to a *robust* detection?



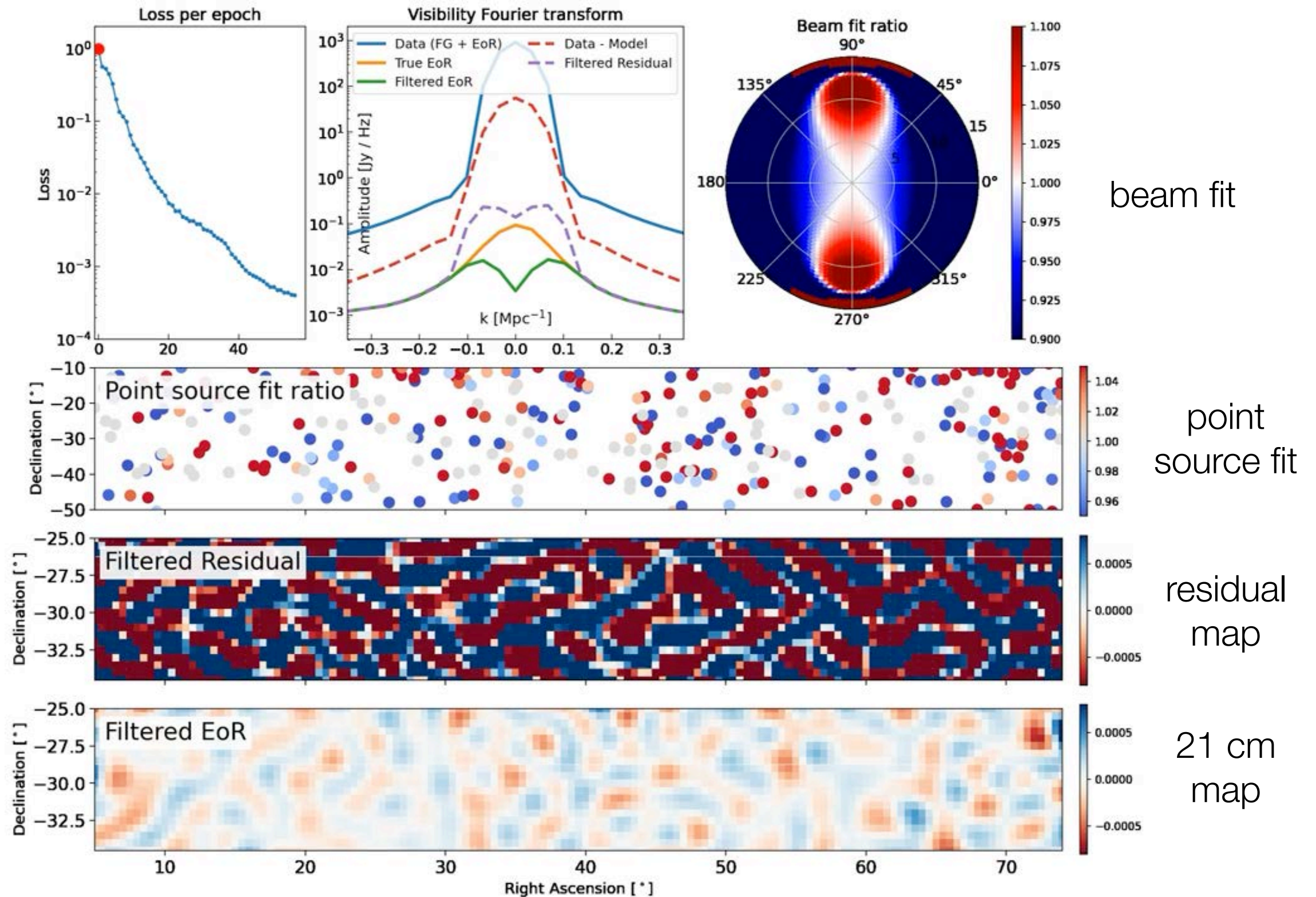
$N_{\text{frequencies}}$, $N_{\text{integrations}}$, $N_{\text{baselines}}$ (N_{antenna}^2), $N_{\text{sky_pixels}}$

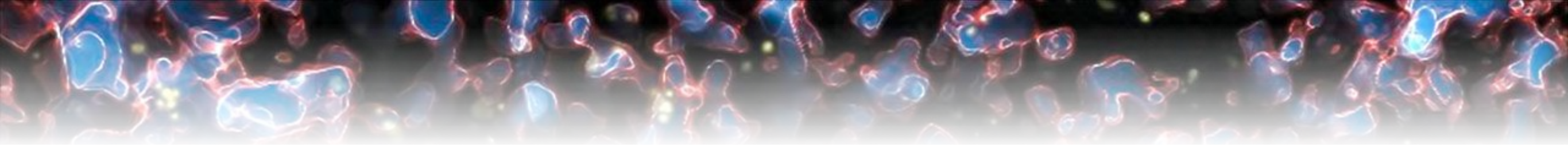
We usually assume we know one component, while fitting for the others...

BayesLIM: the first end-to-end Bayesian forward model for 21 cm telescopes



Toy model: joint beam + point source modeling





First science from 21 cm telescopes at the EoR

- HERA's first science results are beginning to narrow down the allowable parameter space of Cosmic Dawn astrophysics!
- Near-future results from HERA Phase II will push to higher redshifts to constrain more complex IGM heating models, aiming for a 21 cm detection
- Next-generation forward model frameworks will be a paradigm shift in how we interpret an eventual first detection from HERA, with wide applicability to other 21 cm and LIM experiments more broadly

