First Upper Limits from HERA on the 21 cm Power Spectrum

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Overdensity of Hydrogen

Neutral Fraction

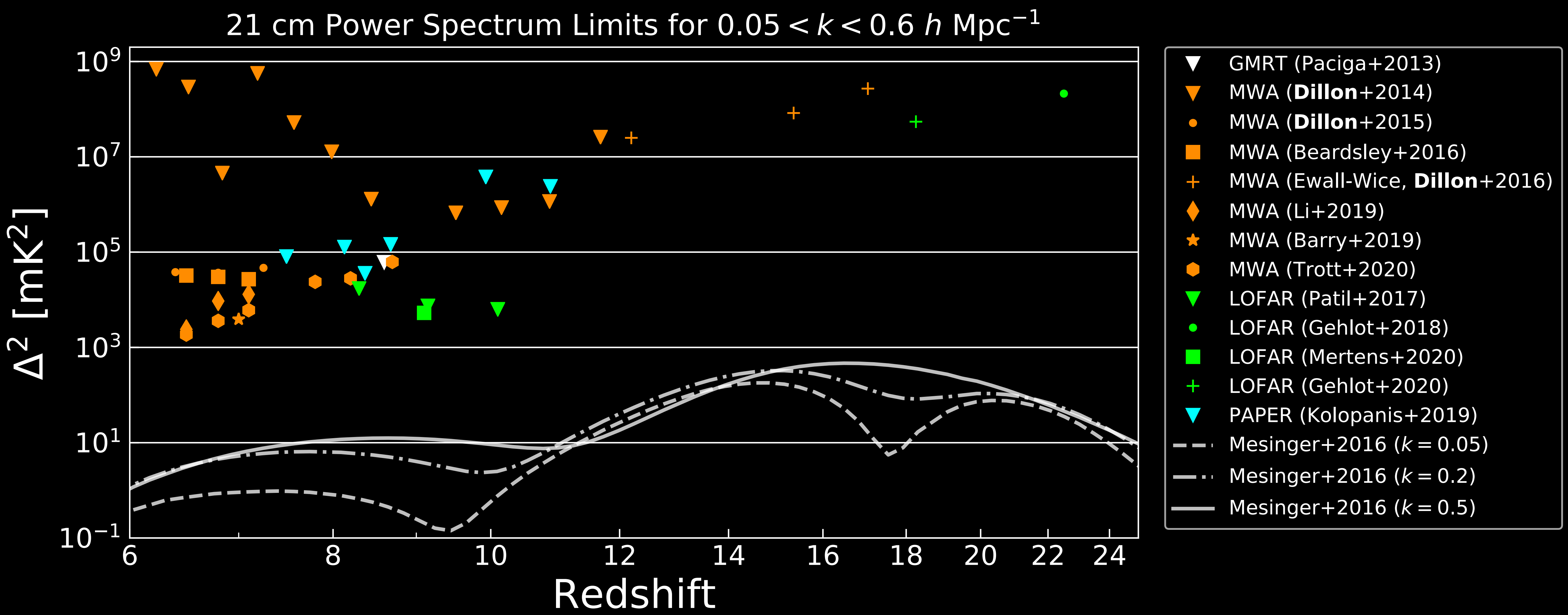
$$\delta T_{21\,\mathrm{cm}} \propto (1+\delta)\left[1-\frac{T_{\mathrm{CMB}}}{T_s}\right] x_{\mathrm{HI}}$$

21 cm Brightness Temperature

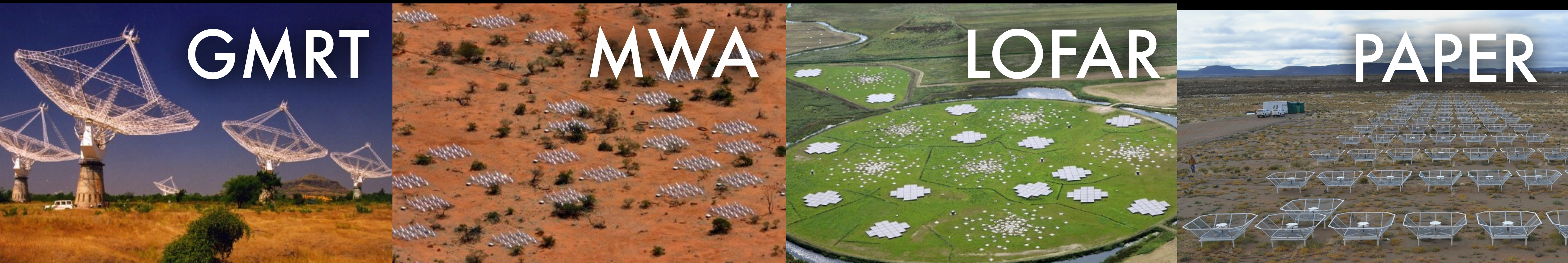
Spin Temperature

Alvarez, Kaehler, Abel

The first generation of telescopes got us started on measuring the 21 cm power spectrum.



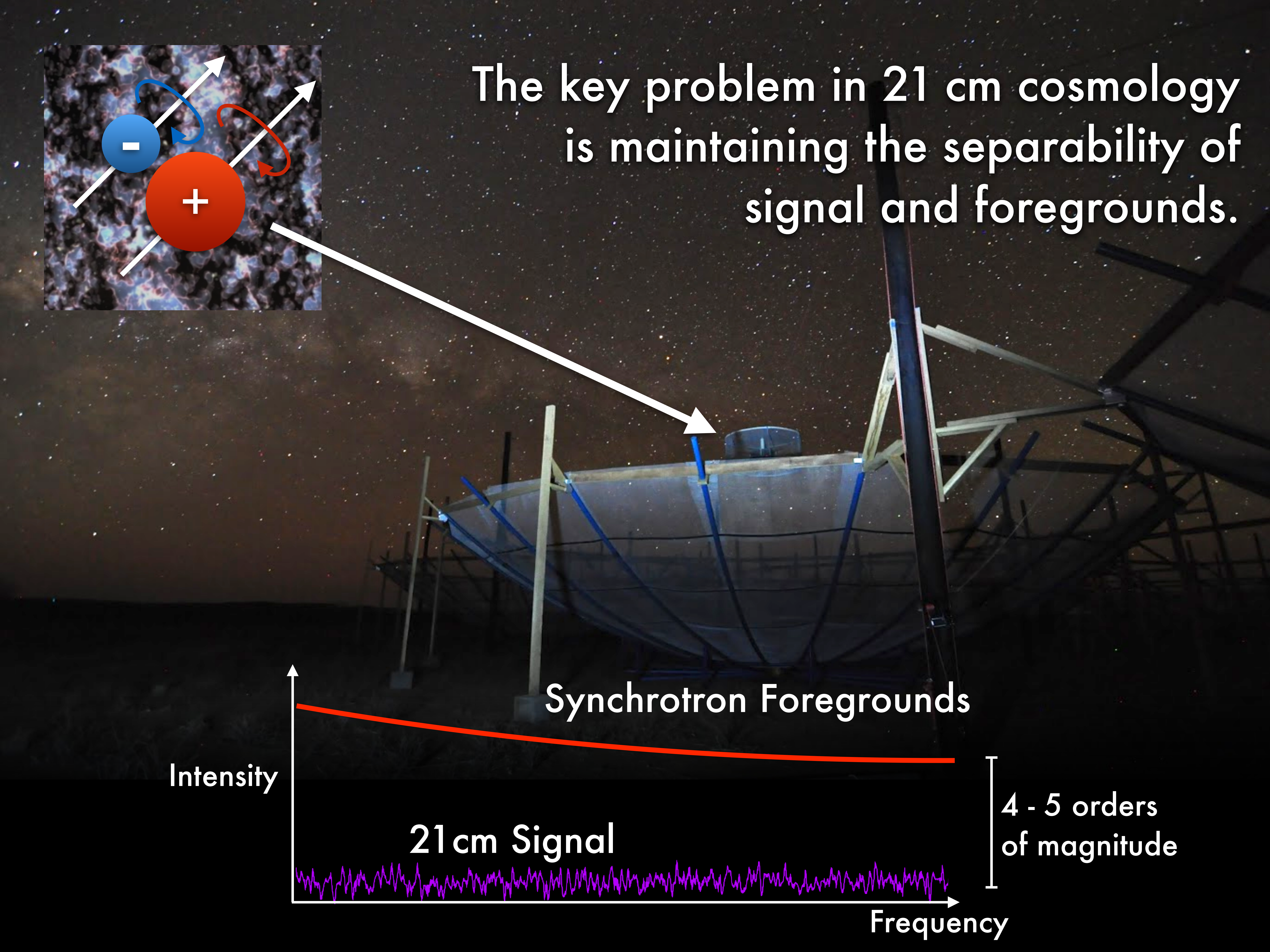
Ongoing




CAL POLY POMONA
THE UNIVERSITY OF CALIFORNIA
LET THERE BE LIGHT
UCLA
THE UNIVERSITY OF CALIFORNIA BERKELEY
LET THERE BE LIGHT
1868
ARIZONA STATE UNIVERSITY
GREAT SEAL OF THE STATE OF ARIZONA
DITAT DEUS
1912
1885
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
MENS ET MANUS
1861
UNIVERSITY OF WASHINGTON
LVX SIT
1861
SCUOLA NORMALE SUPERIORE
UNIVERSITY OF CAMBRIDGE
Penn
UNIVERSITY of PENNSYLVANIA
McGill UNIVERSITY
Queen Mary University of London
NRF National Research Foundation
SARAO South African Radio Astronomy Observatory
H 1 ERA
BROWN
VE RI TAS
HARVARD
UNIVERSITY OF KWAZULU-NATAL
SKA
SKA AFRICA
SQUARE KILOMETRE ARRAY
NRAO
The Hydrogen Epoch of Reionization Array
RHODES UNIVERSITY
Where leaders learn
RESPICE PROSPICE
UNIVERSITY of the WESTERN CAPE
GORDON AND BETTY MOORE FOUNDATION
NSF

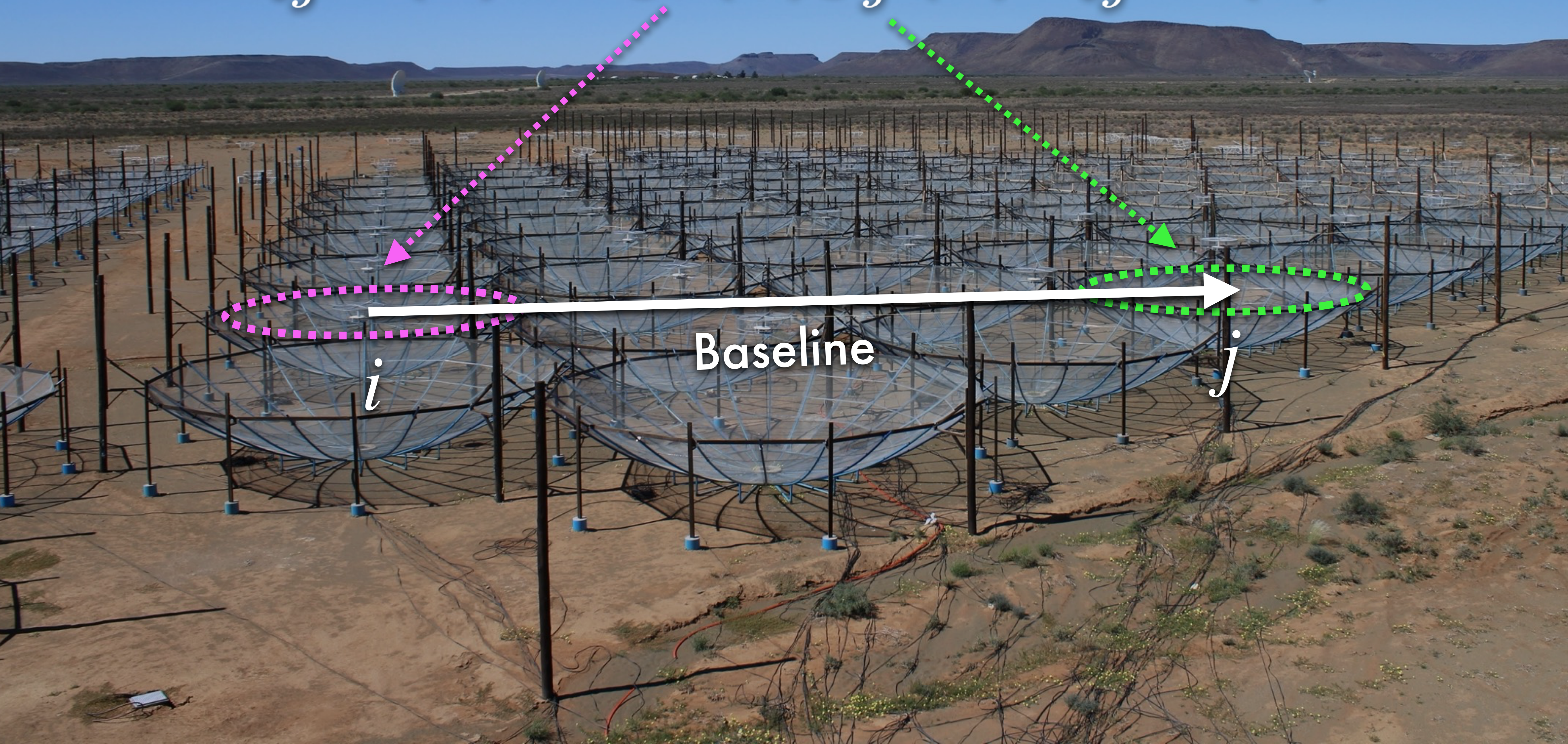
So how does HERA measure the 21 cm power spectrum?

Step 1: Calibration


The key problem in 21 cm cosmology
is maintaining the separability of
signal and foregrounds.
-
+
Synchrotron Foregrounds
Intensity
21cm Signal
4 - 5 orders
of magnitude
Frequency

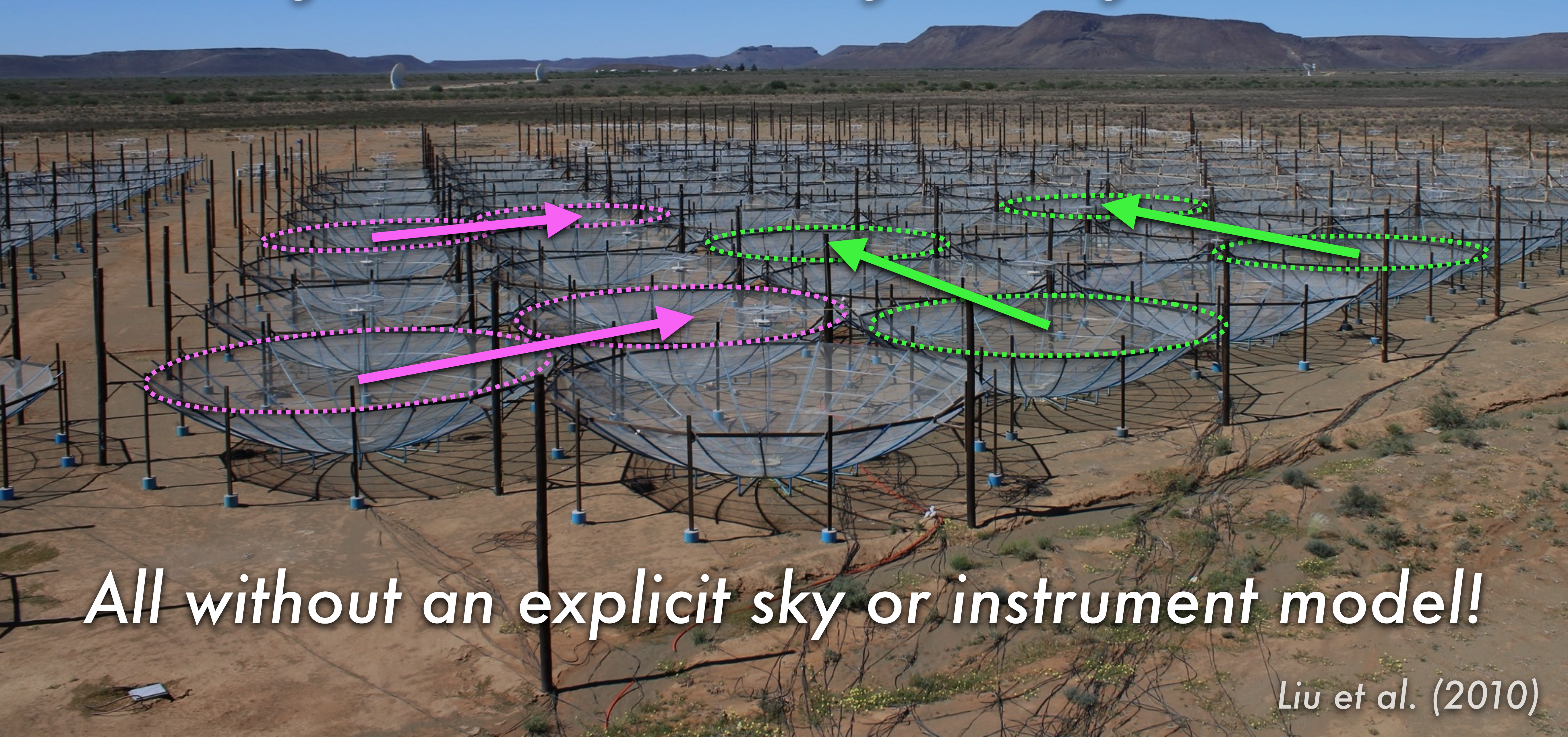
Individual antenna response must be precisely calibrated.

$$V_{ij}^{\mathrm{obs}}(\nu) = g_i(\nu) g_j^*(\nu) V_{ij}^{\mathrm{true}}(\nu)$$



HERA was designed to be calibrated using the internal consistency of redundant baselines.

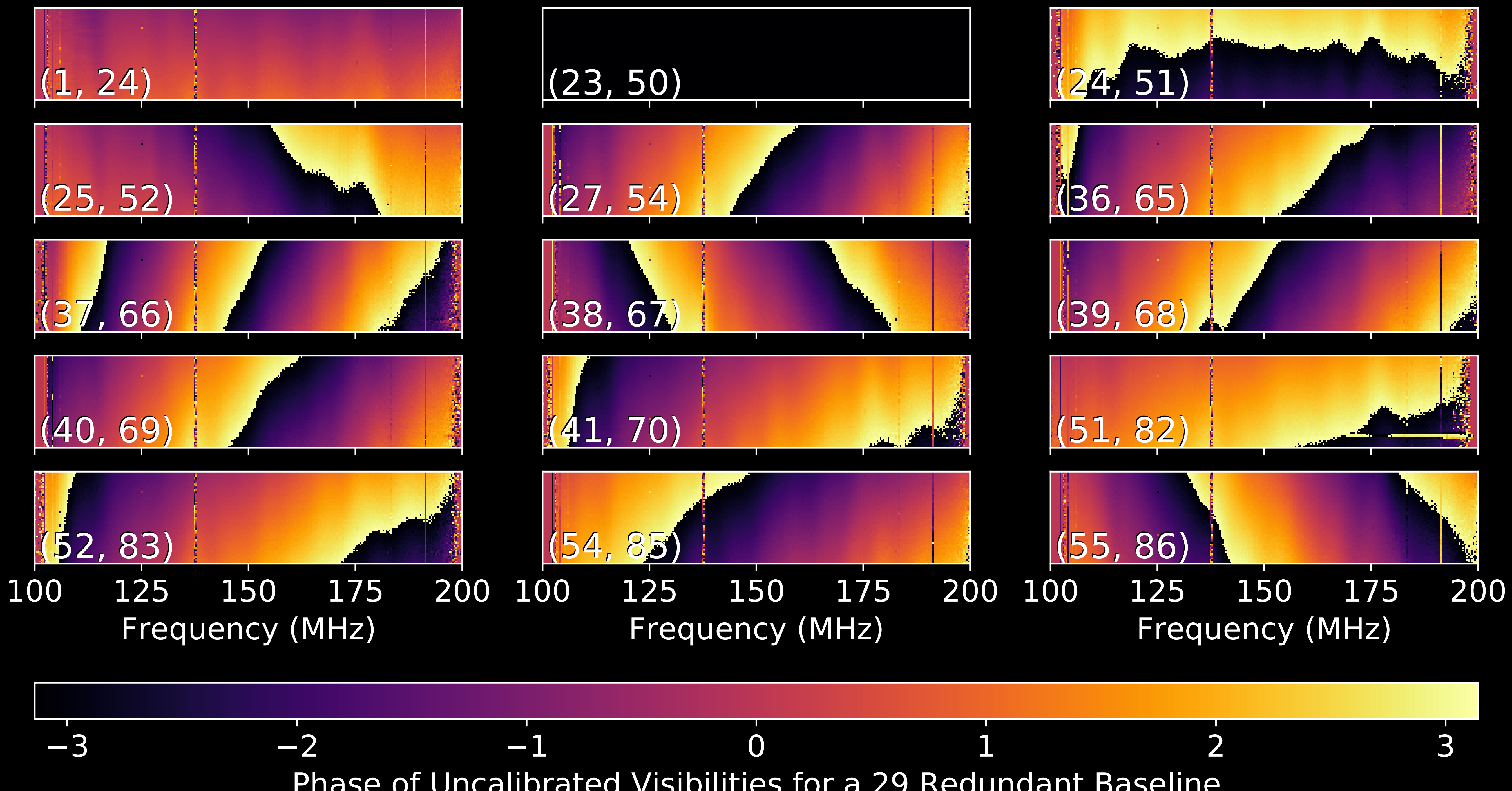
$$V_{ij}^{\mathrm{obs}}(\nu) = g_i(\nu) g_j^*(\nu) V_{ij}^{\mathrm{true}}(\nu)$$



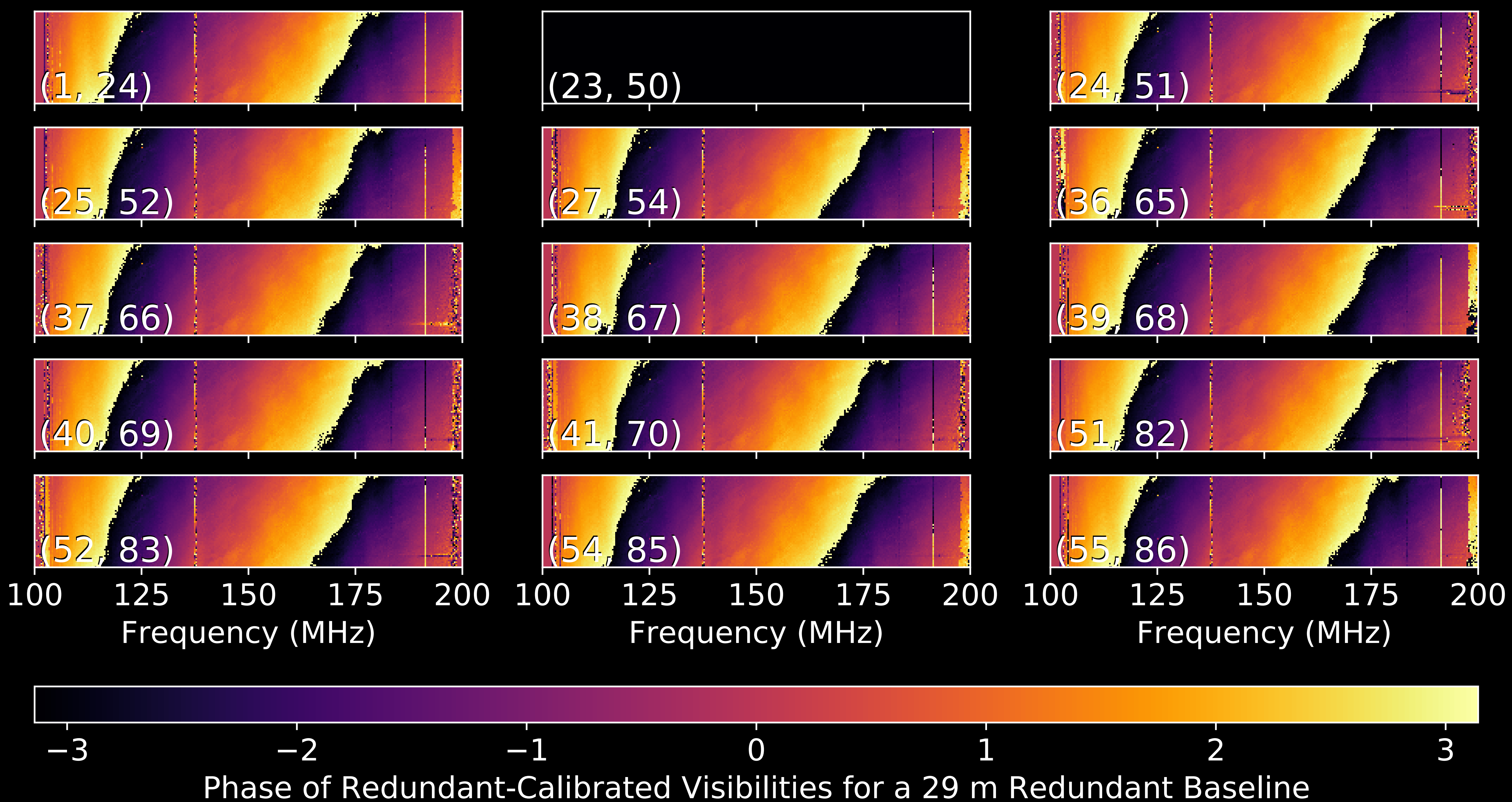
All without an explicit sky or instrument model!

Liu et al. (2010)

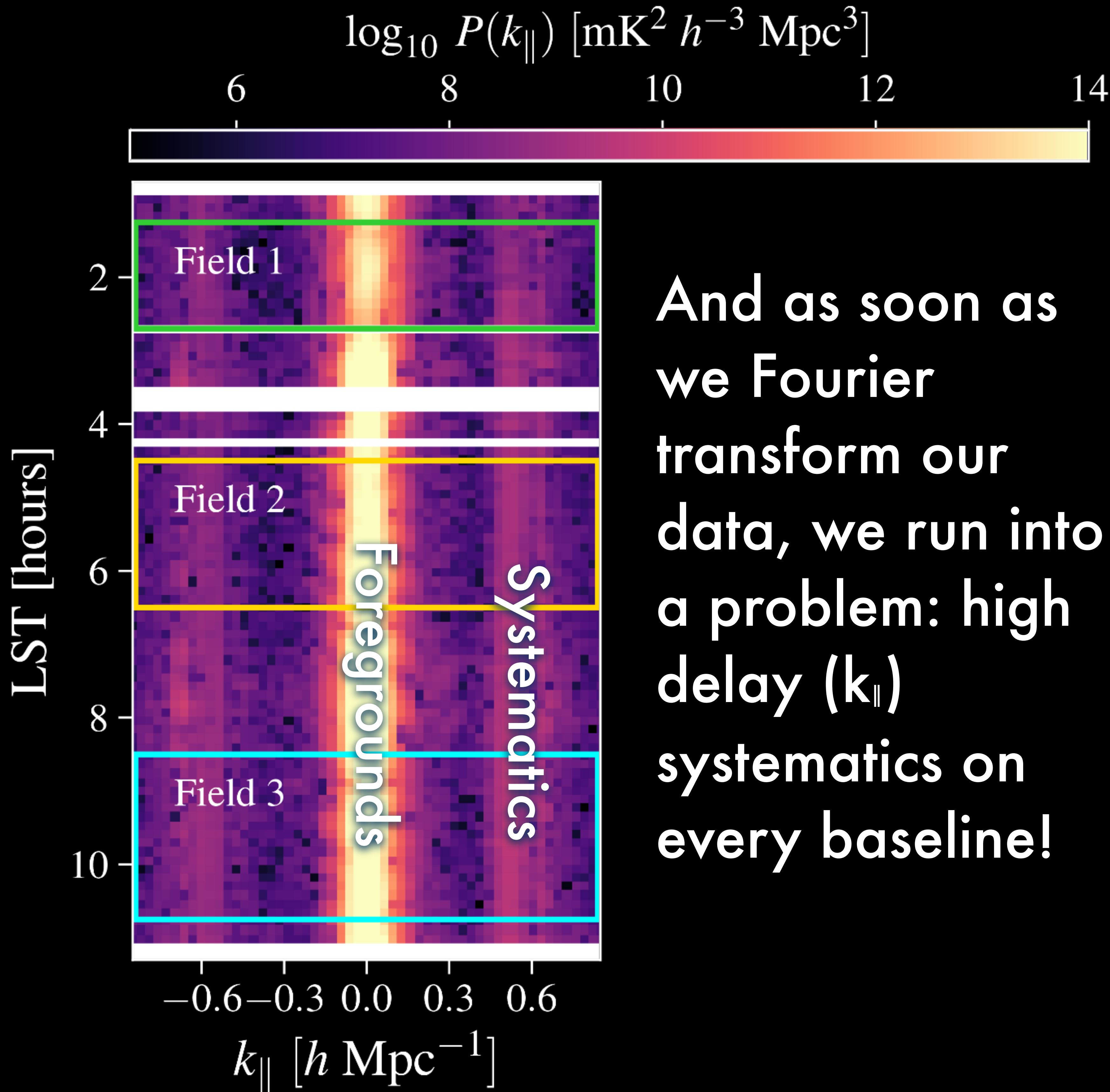
Example raw HERA data for a single redundant baseline:



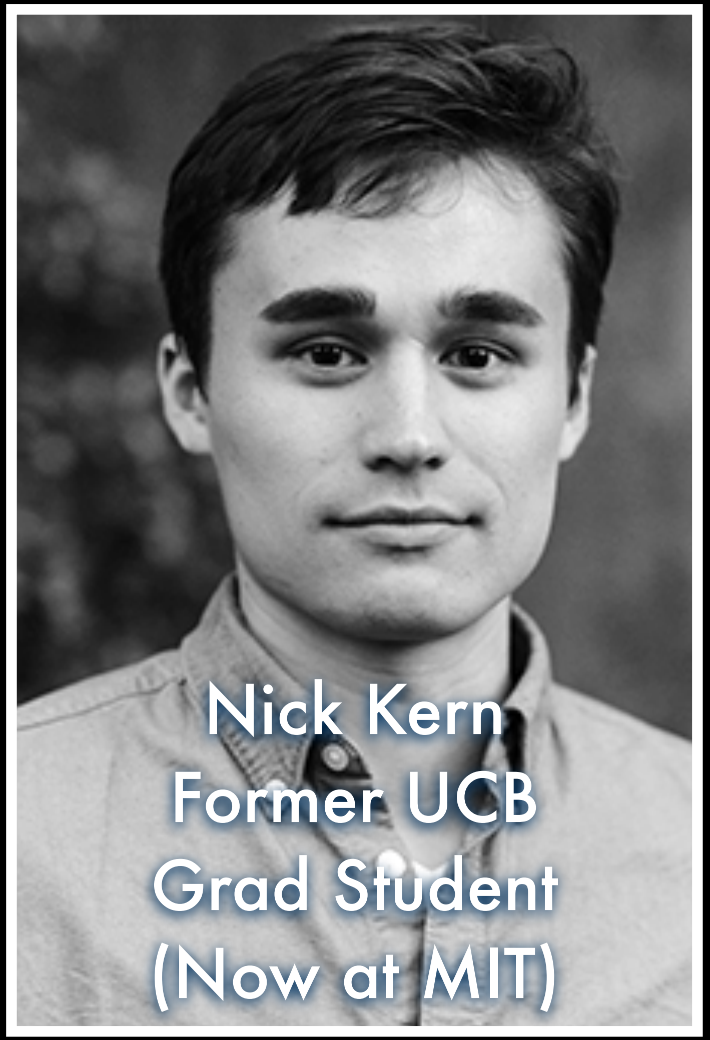
Imposing the redundancy constraint helps solve for all gains.



Step 2: Reflection and Cross-Talk Systematics

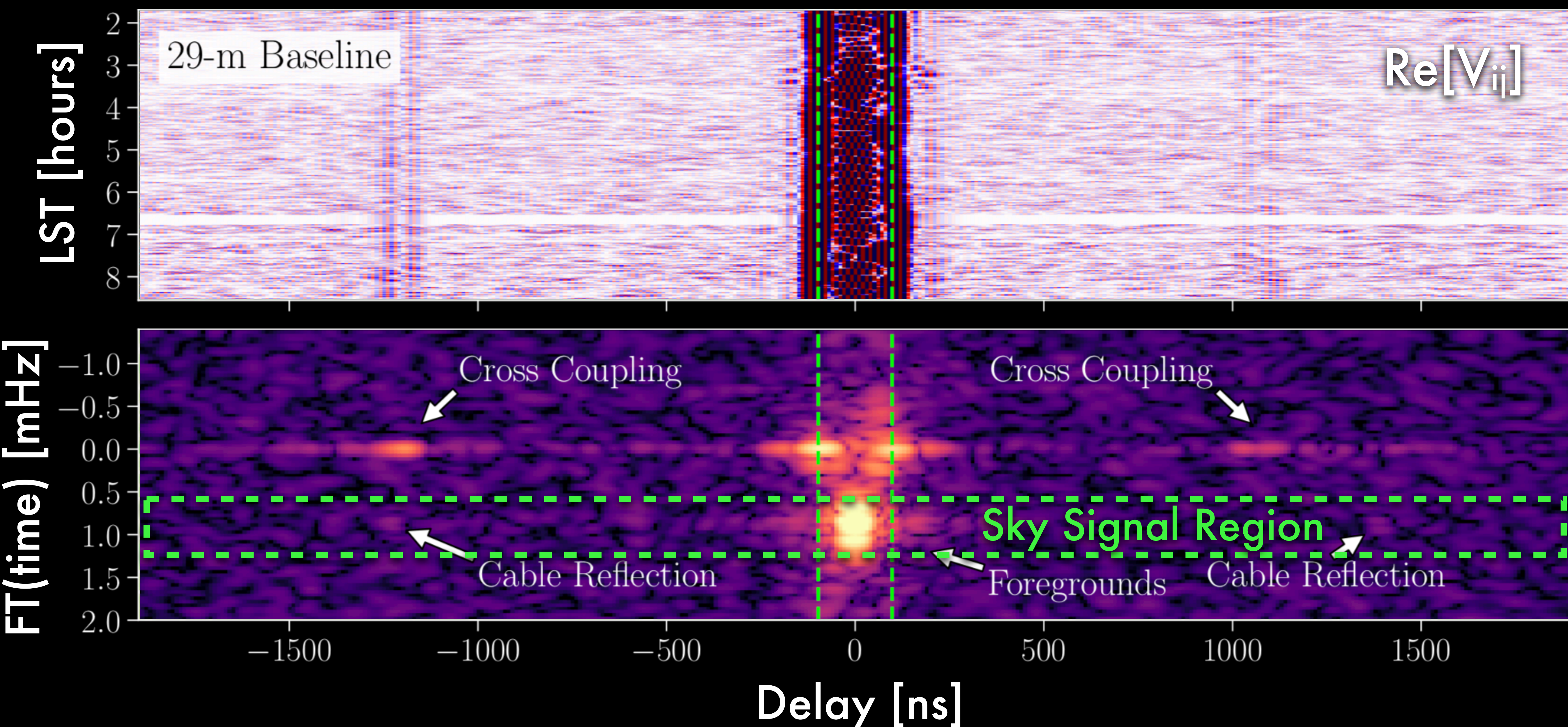


And as soon as we Fourier transform our data, we run into a problem: high delay ($k_\parallel$) systematics on every baseline!



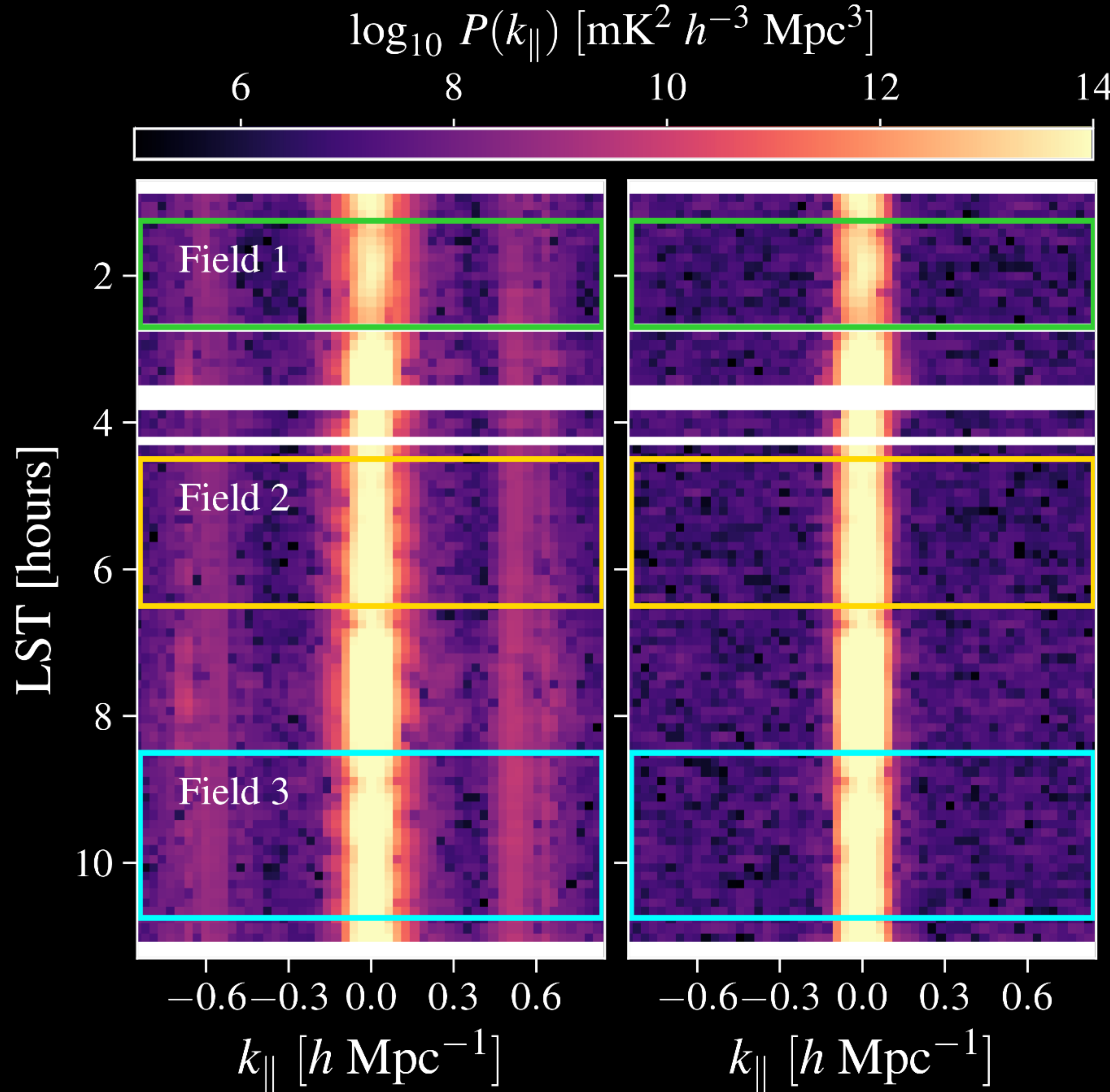
Kern, Parsons, **Dillon**, *et al. (2019ab)*

To understand this effect, we have to examine the temporal structure of the foregrounds and the systematics—how fast they "fringe."



Kern, Parsons, ***Dillon****, et al. (2019ab)*

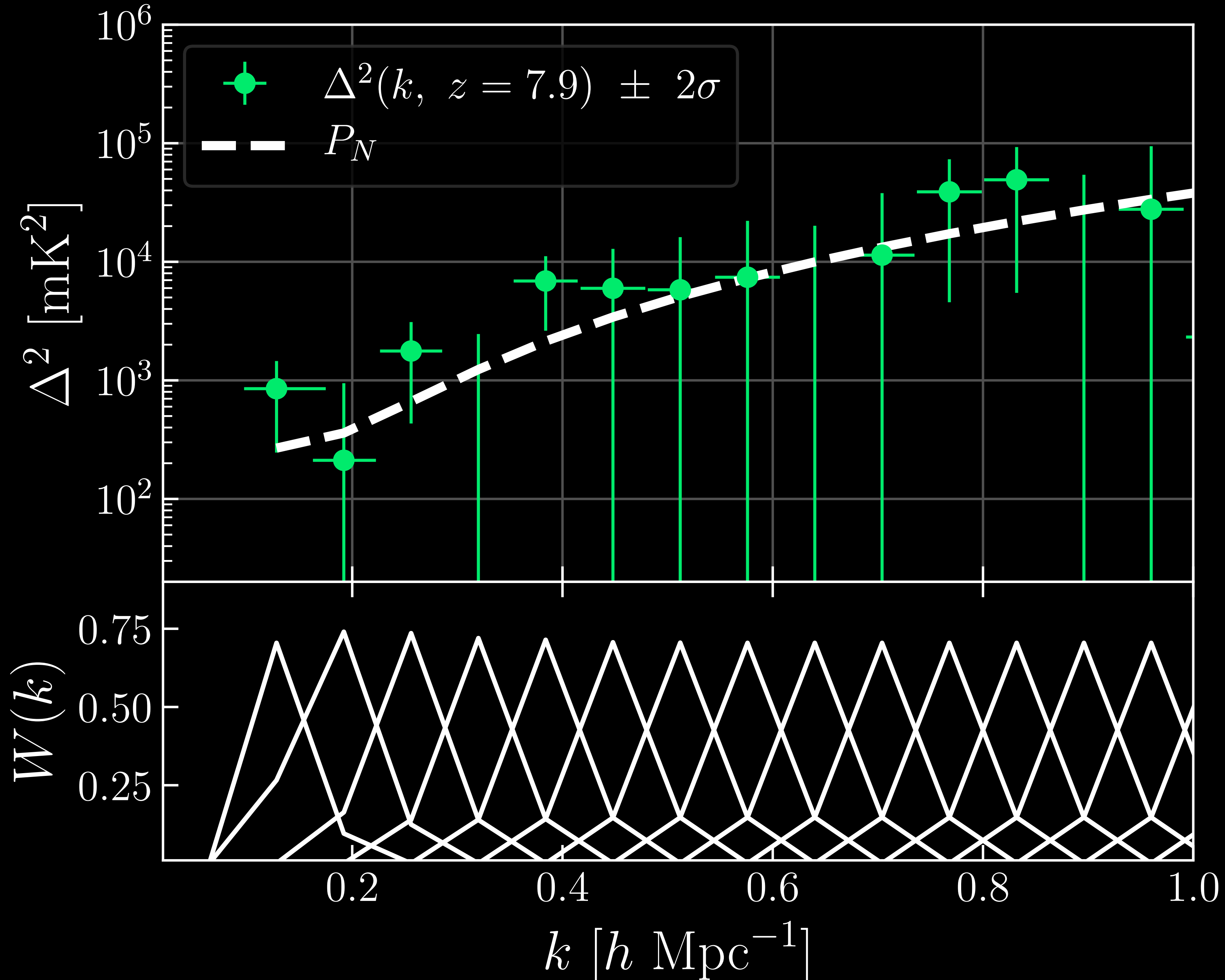
With our techniques for relatively lossless systematics removal, we're getting very close to the thermal noise limit.



HERA Collaboration (2021)

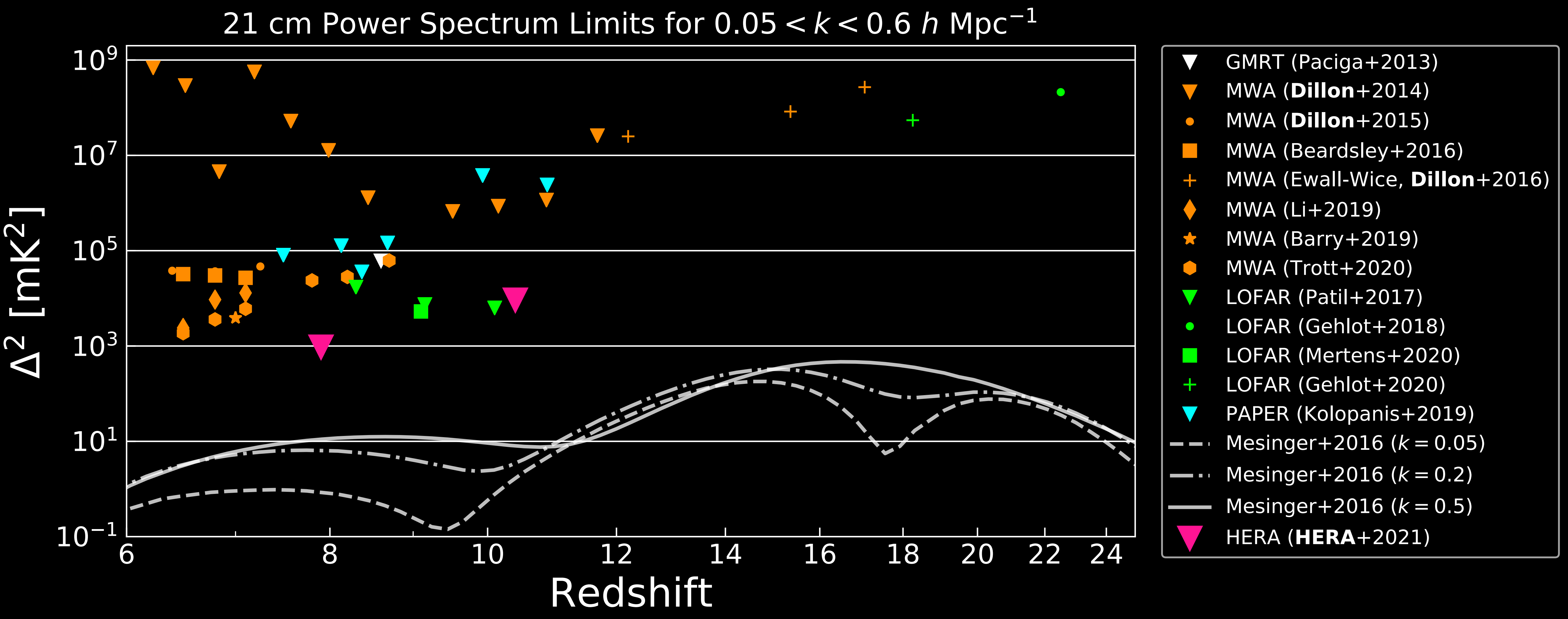
Step 3: Power Spectrum and Error Estimation

Working outside the foreground-dominated region, we get our power spectrum upper limit.



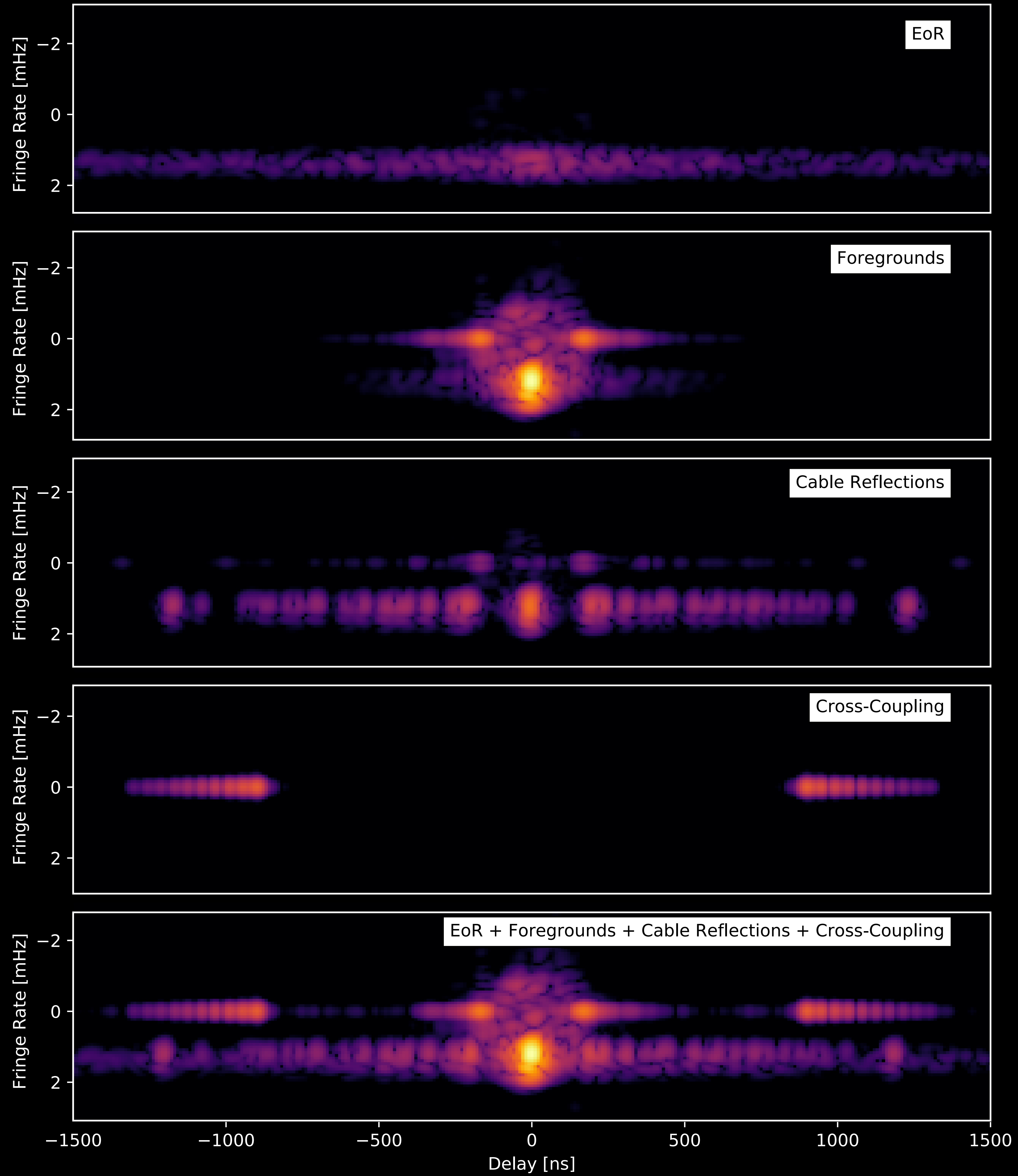
HERA Collaboration (2021)

Our first (and world-leading!) limit with just 18 nights and a very conservative analysis.



HERA Collaboration (2021)

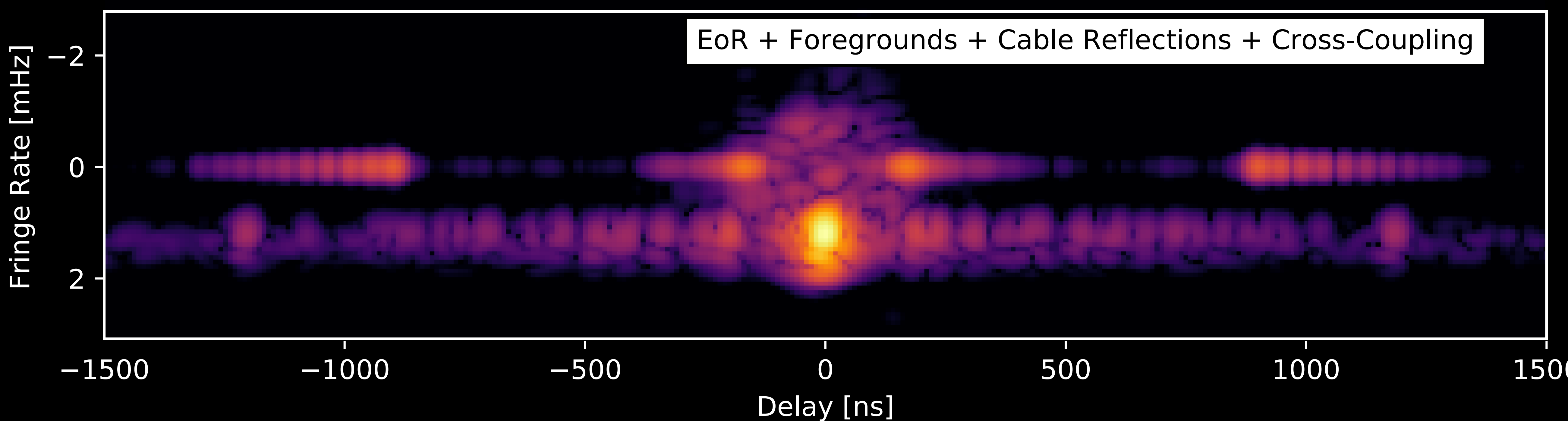
Step 4: Validation with End-to-End Simulations

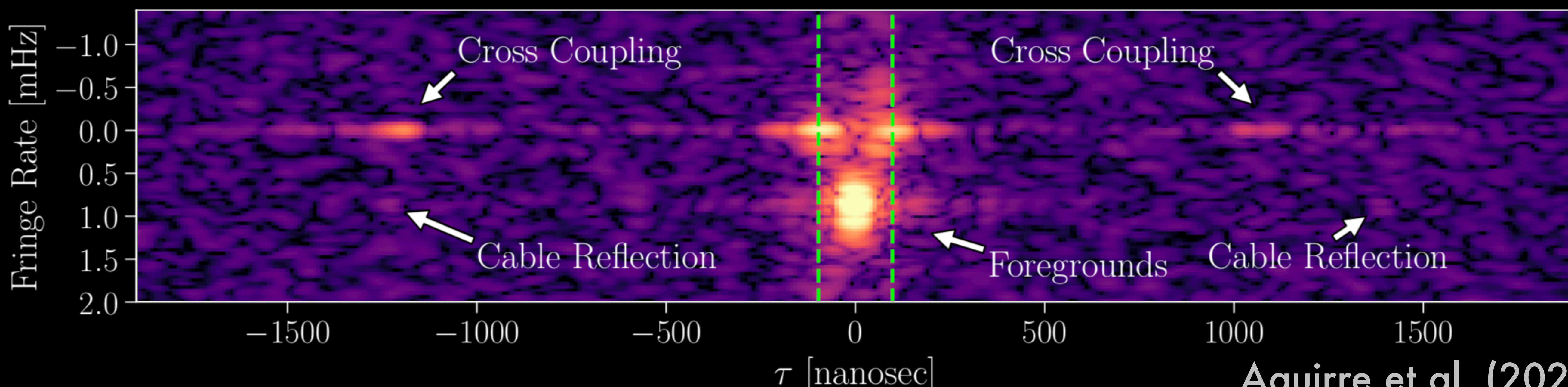


We simulated the most important real-world effects to test how well we could mitigate them.

Aguirre et al. (2021)

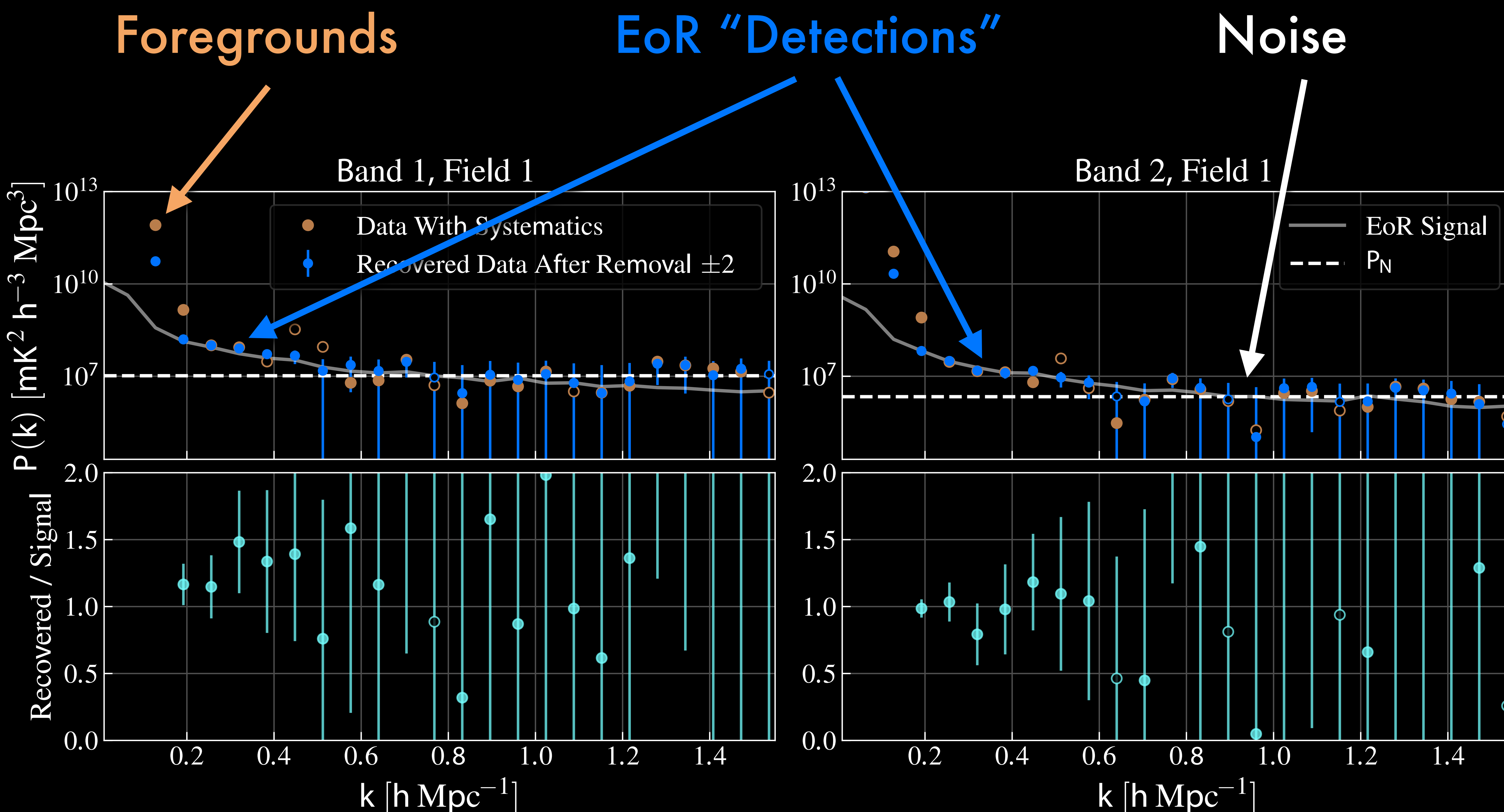
The simulation is really starting to reflect the complexity of real data.





Aguirre et al. (2021)

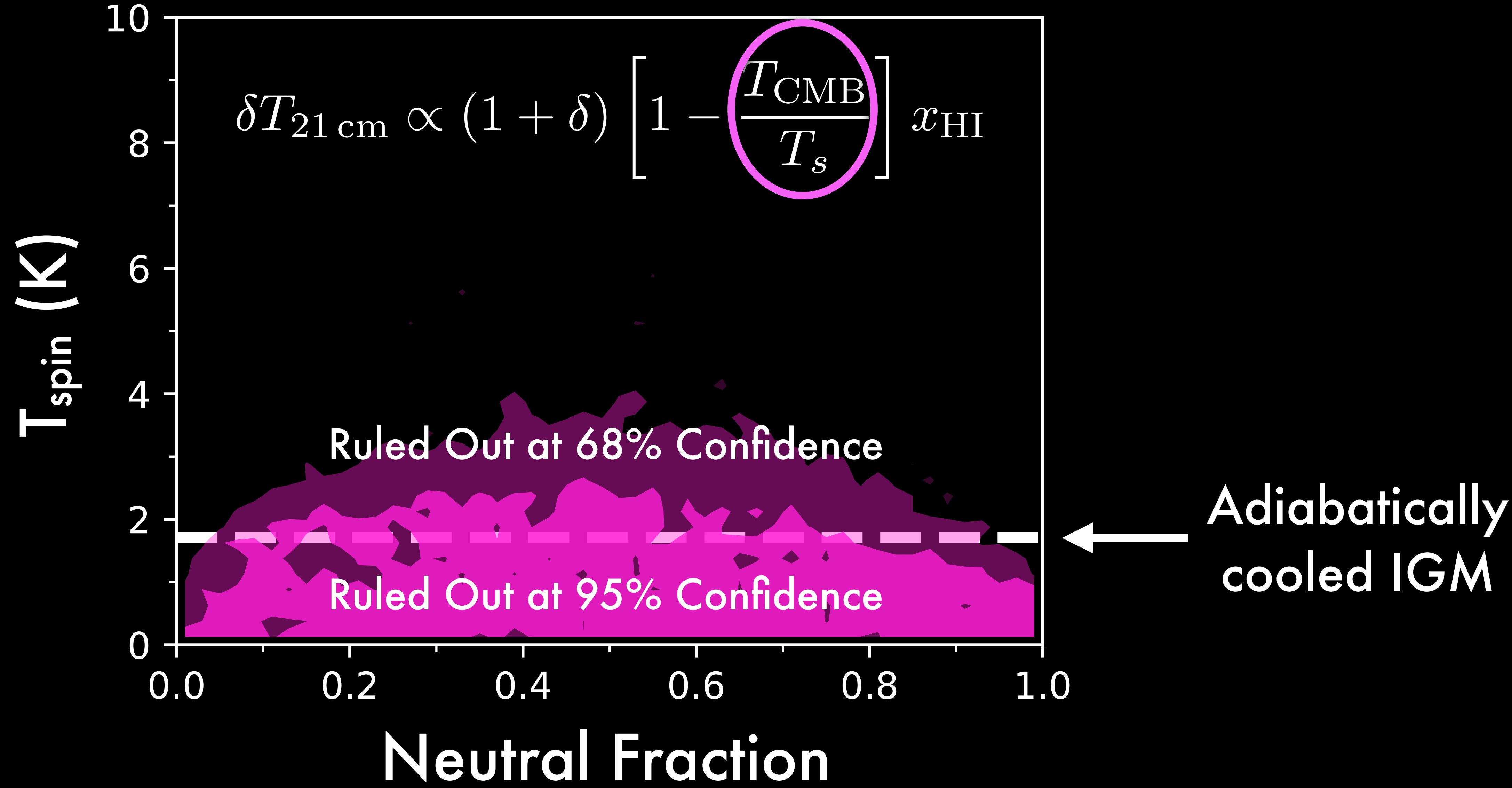
We're able to extract a simulated signal and quantify our biases, which raise our limits by ~10%.



Aguirre et al. (2021)

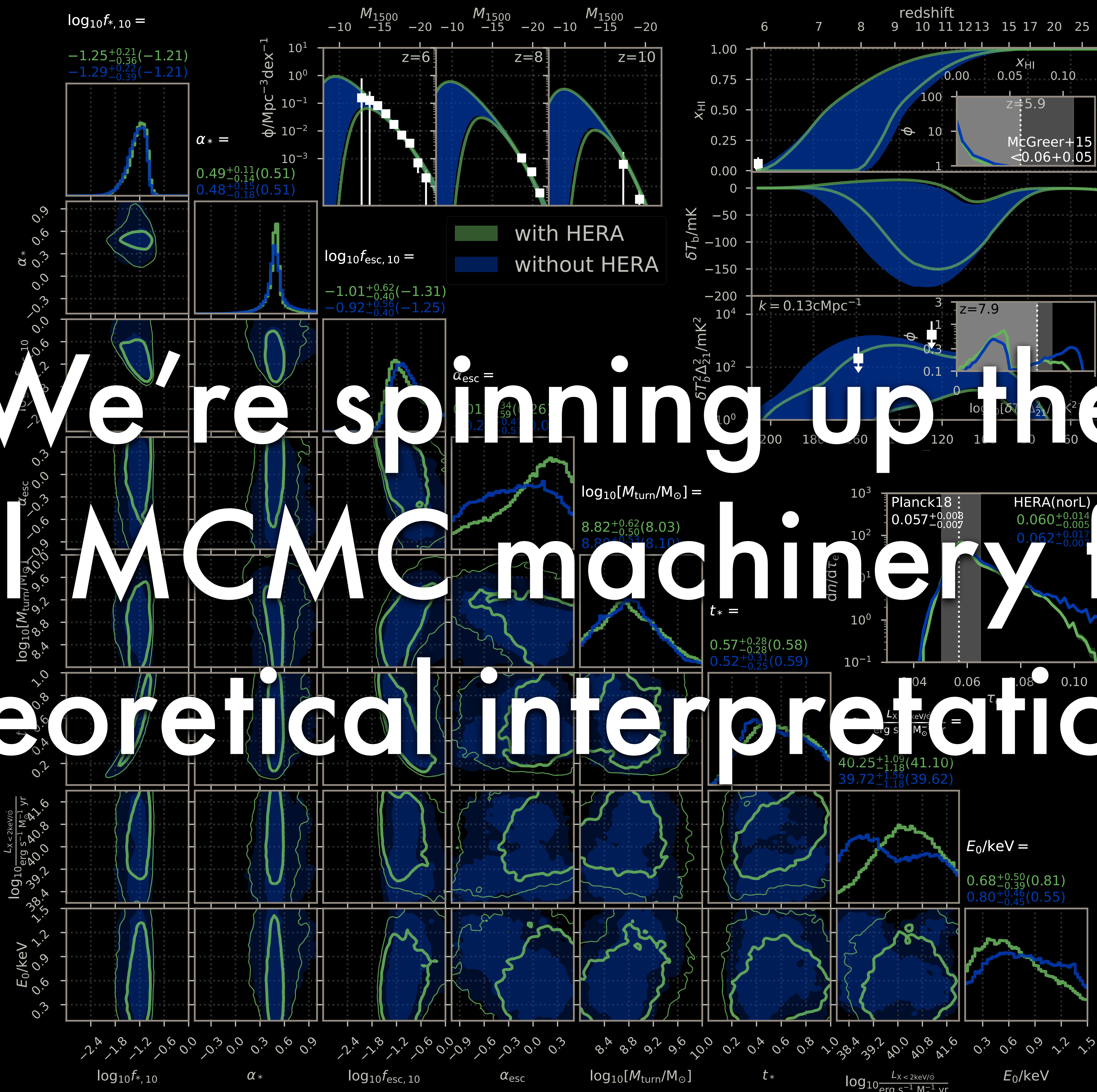
Step 5: Astrophysical and Cosmological Interpretation

We can already largely rule out an IGM unheated by X-rays at z = 7.9, though this is not at all surprising.



PRELIMINARY!

HERA Collaboration (in prep.)

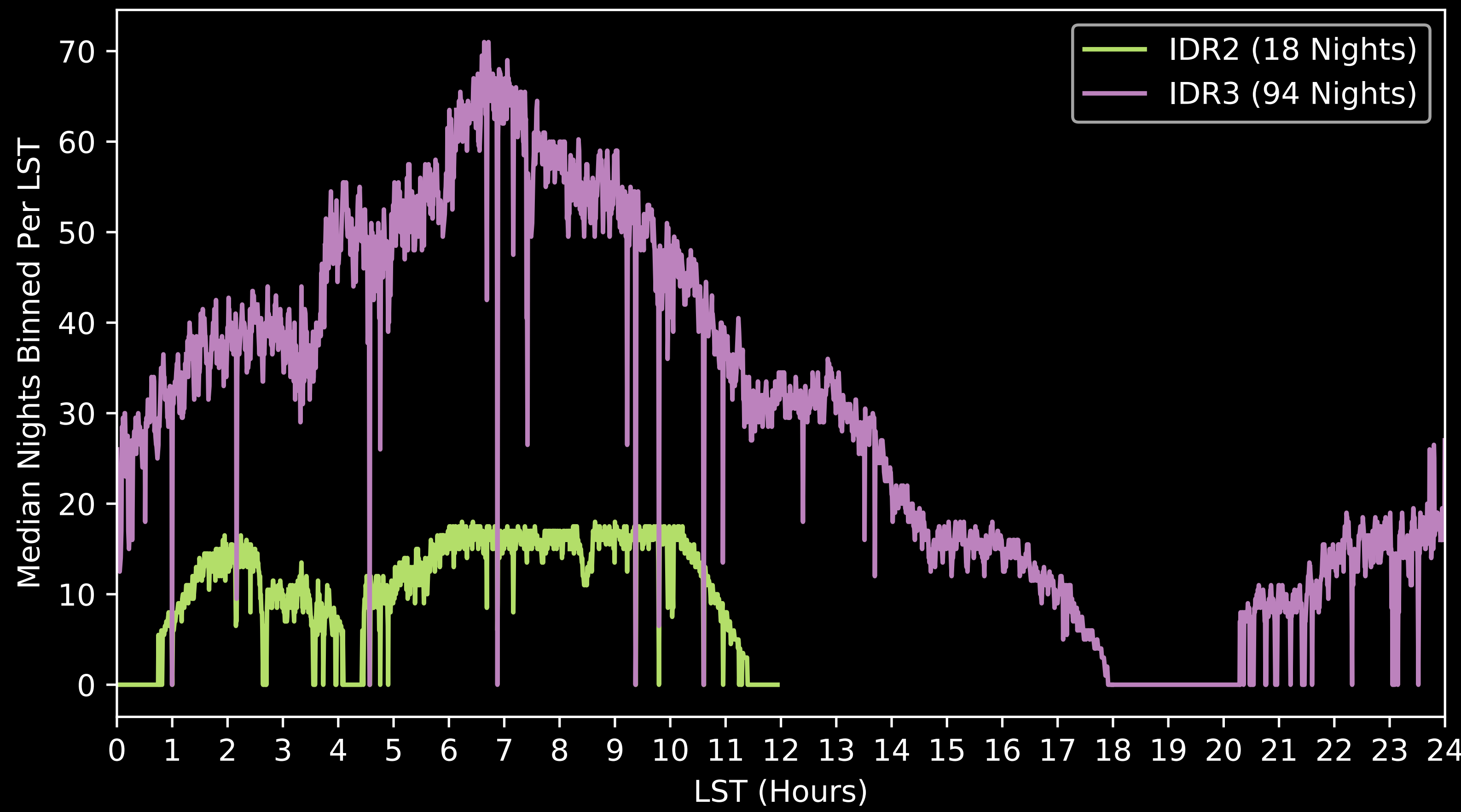


We're spinning up the full MCMC machinery for theoretical interpretation.

PRELIMINARY!

HERA Collaboration (in prep.)

What's next?



94 nights from HERA Phase 1 spanning nearly 24 hours in LST.

~12 good nights from our commissioning run of HERA Phase 2 with the new wideband feeds.

We'll have way more sensitivity with a full season (~100 nights) and the full array, and should easily rule EDGES in or out.

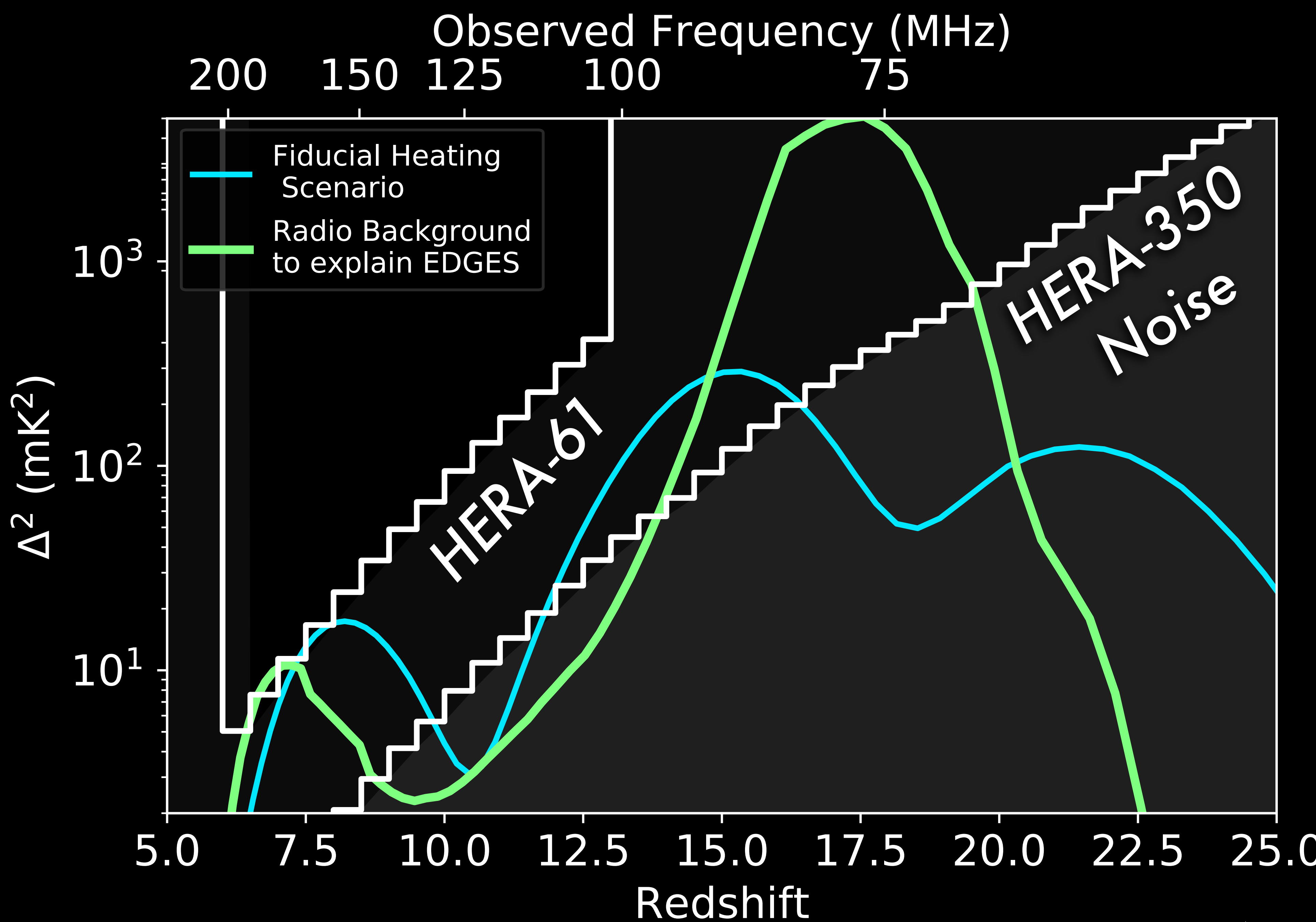
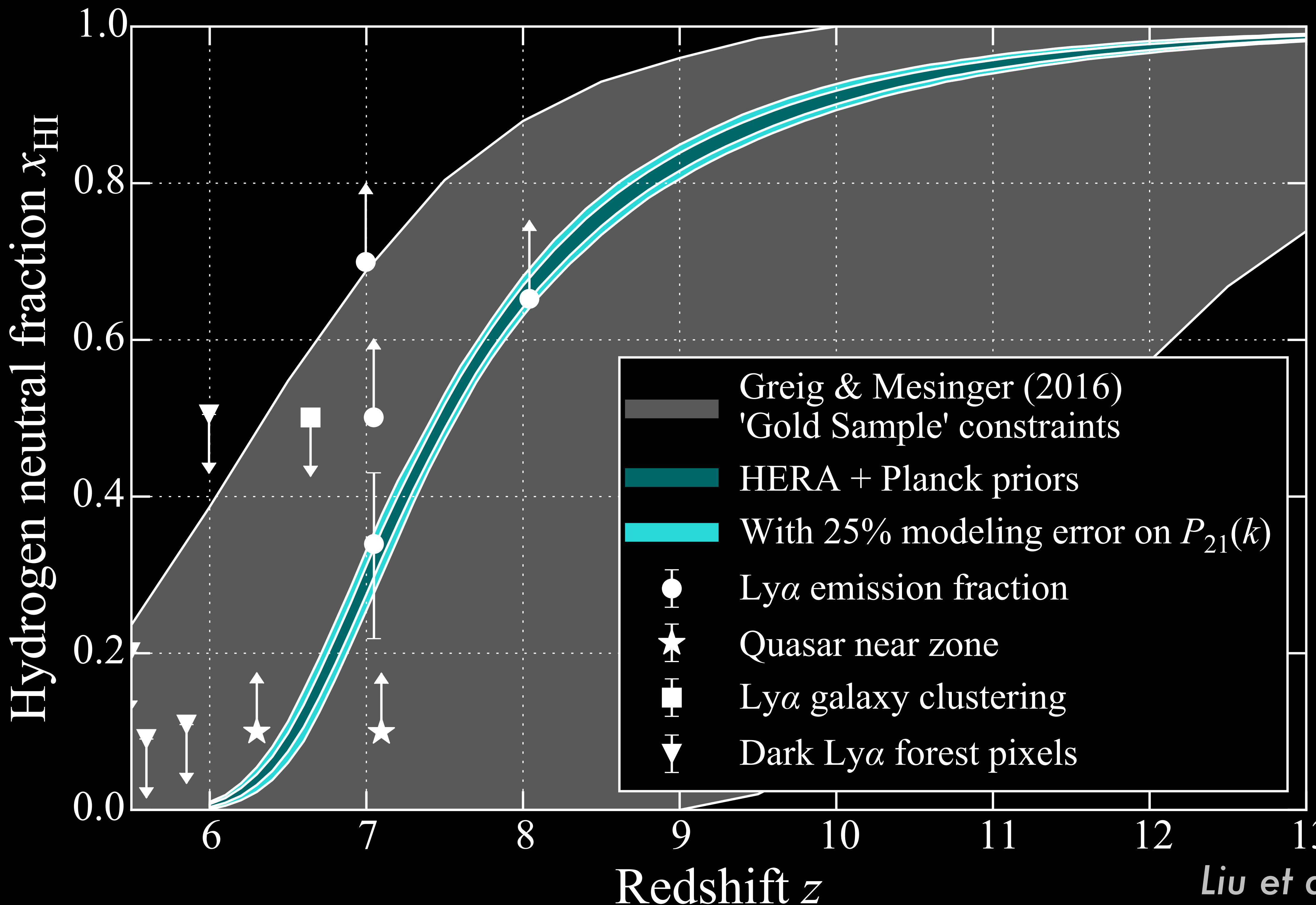


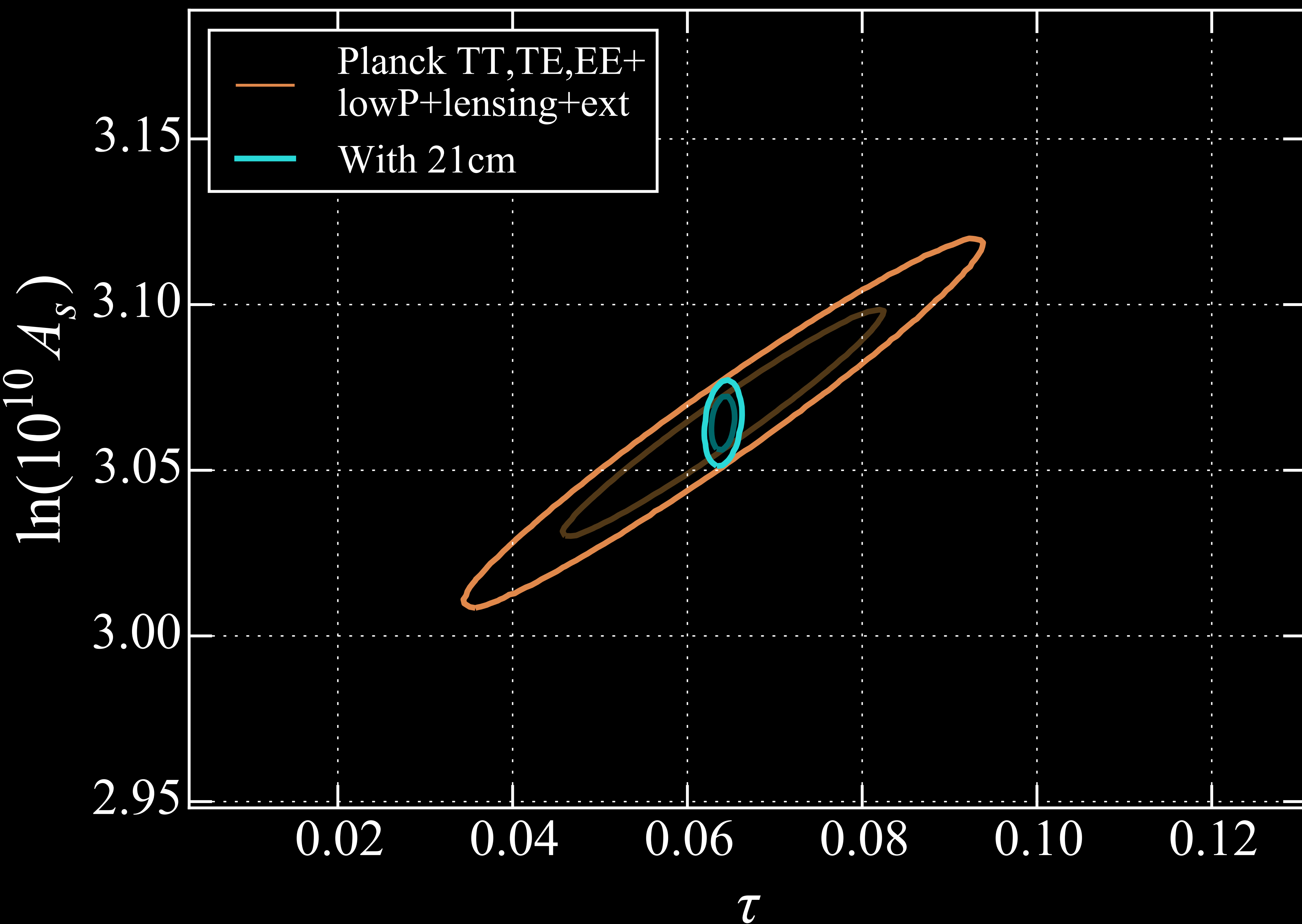
Figure: Aaron Ewall-Wice

Which means we can precisely measure the ionization history of the universe.



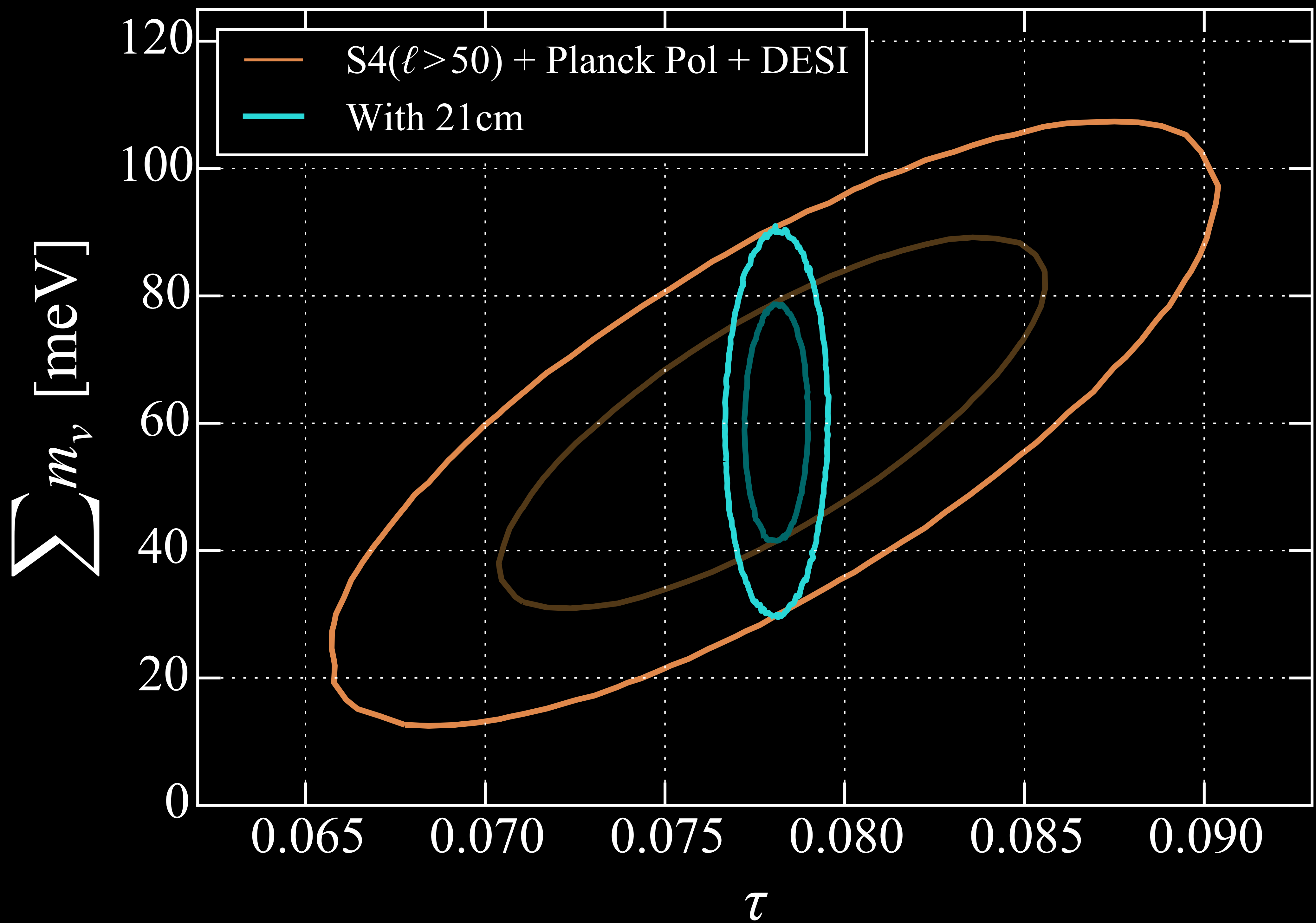
Liu et al. (2016)

We'll eliminate τ as a CMB nuisance parameter, improving A_s errors by a factor of 4.



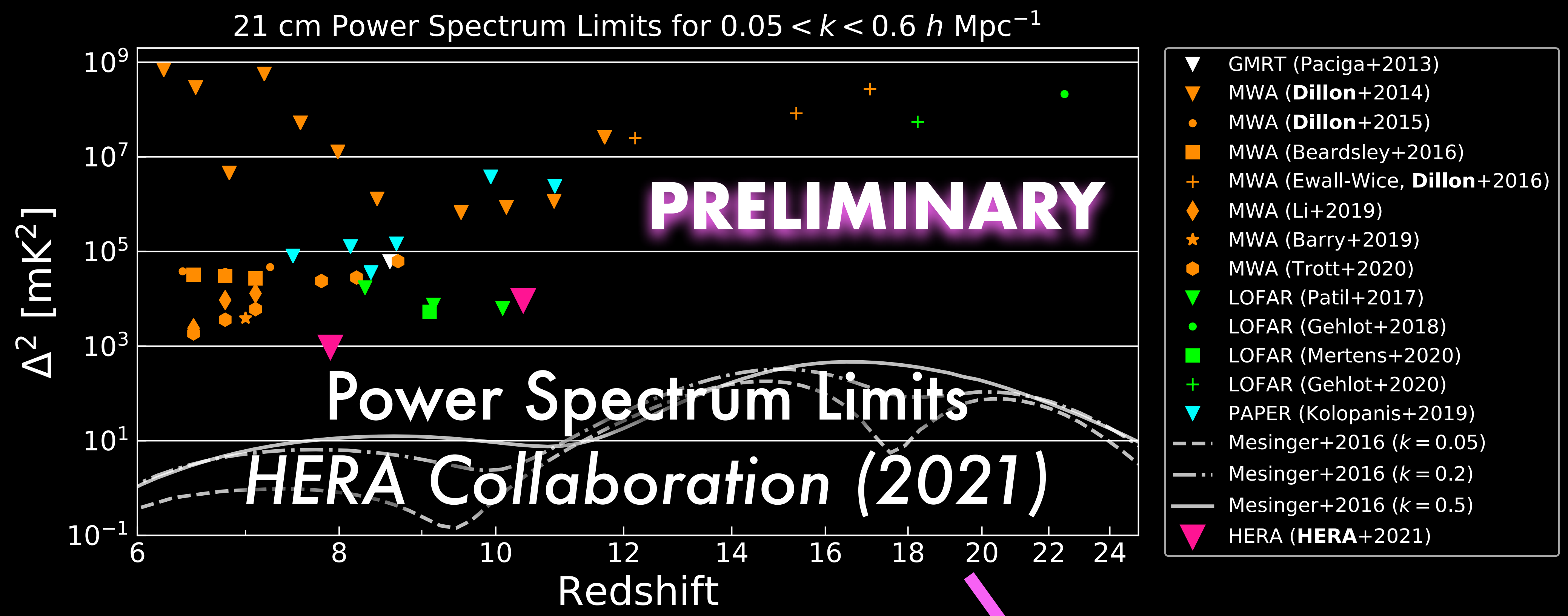
Liu et al. (2016)

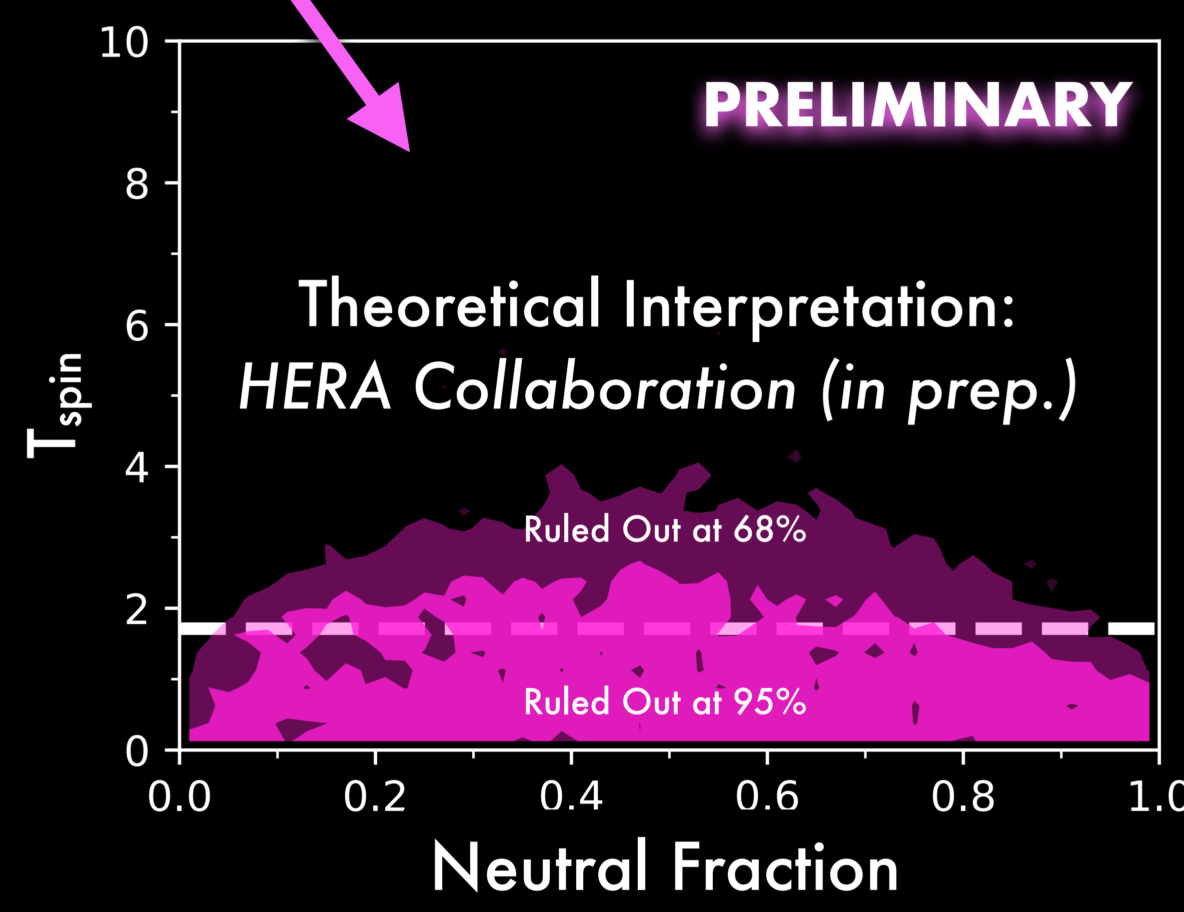
And, maybe increase the significance of a detection of non-zero Σm_ν with CMB-S4.



Liu et al. (2016)

In Summary...


21 cm Power Spectrum Limits for $0.05 < k < 0.6\ h\ \mathrm{Mpc}^{-1}$
Δ^2 [mK^2]
10^9
10^7
10^5
10^3
10^1
10^{-1}
6
8
10
12
14
16
18
20
22
24
Redshift
PRELIMINARY
Power Spectrum Limits
HERA Collaboration (2021)
GMRT (Paciga+2013)
MWA (**Dillon**+2014)
MWA (**Dillon**+2015)
MWA (Beardsley+2016)
MWA (Ewall-Wice, **Dillon**+2016)
MWA (Li+2019)
MWA (Barry+2019)
MWA (Trott+2020)
LOFAR (Patil+2017)
LOFAR (Gehlot+2018)
LOFAR (Mertens+2020)
LOFAR (Gehlot+2020)
PAPER (Kolopanis+2019)
Mesinger+2016 ($k = 0.05$)
Mesinger+2016 ($k = 0.2$)
Mesinger+2016 ($k = 0.5$)
HERA (**HERA**+2021)


PRELIMINARY
Theoretical Interpretation:
HERA Collaboration (in prep.)
Ruled Out at 68%
Ruled Out at 95%
T_{spin}
10
8
6
4
2
0
0.0
0.2
0.4
0.6
0.8
1.0
Neutral Fraction

Redundant Calibration
Dillon, Lee, et al. (2020)

Power Spectrum Error Estimation
Tan et al. (2020)

Absolute Calibration
Kern, **Dillon**, et al. (2020)

Systematics Mitigation
Kern, Parsons, **Dillon**, et al. (2019ab)

End-to-End Validation
Aguirre et al. (2021)