High-Redshift 21 cm Cosmology

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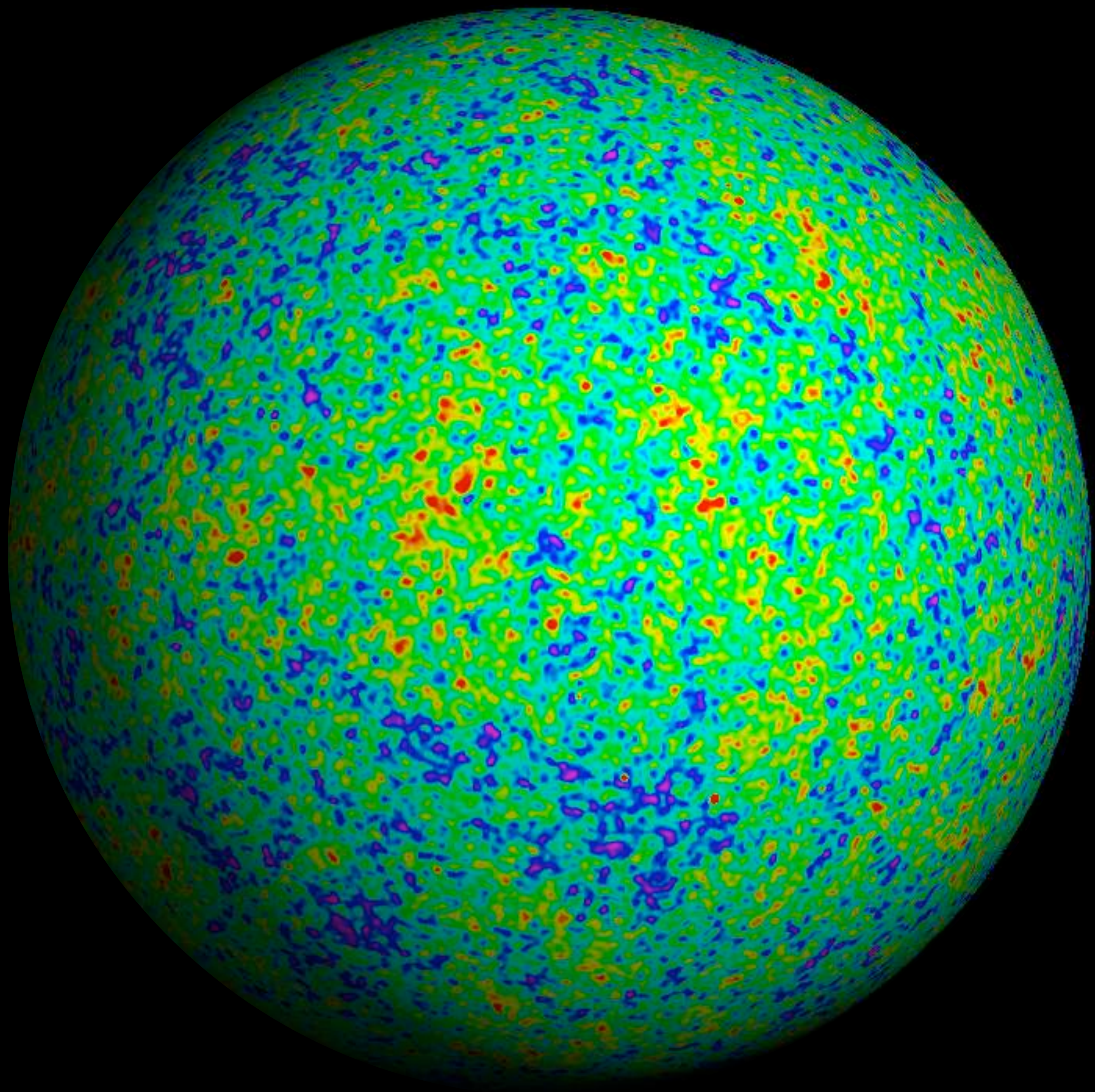
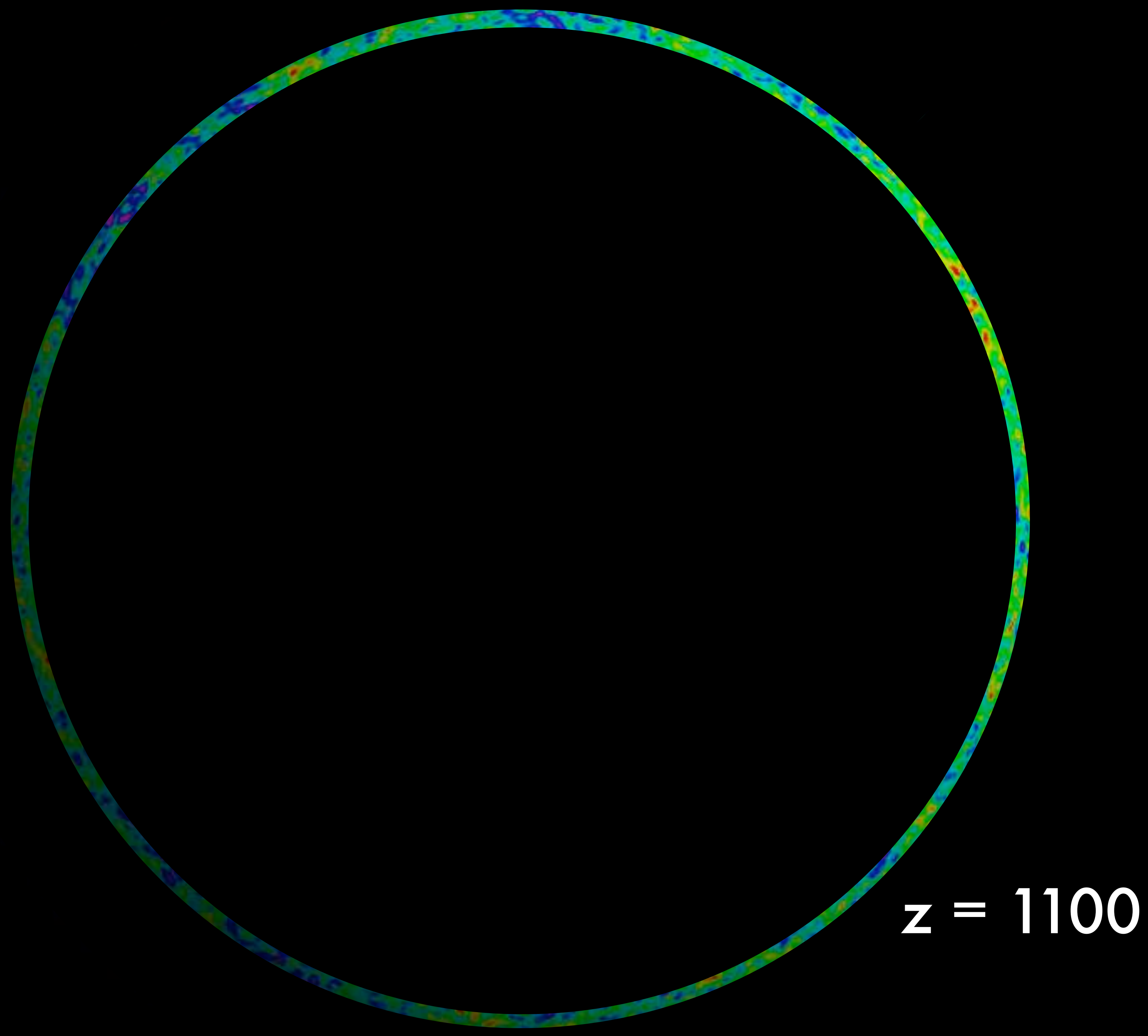
How can we map out our whole universe?

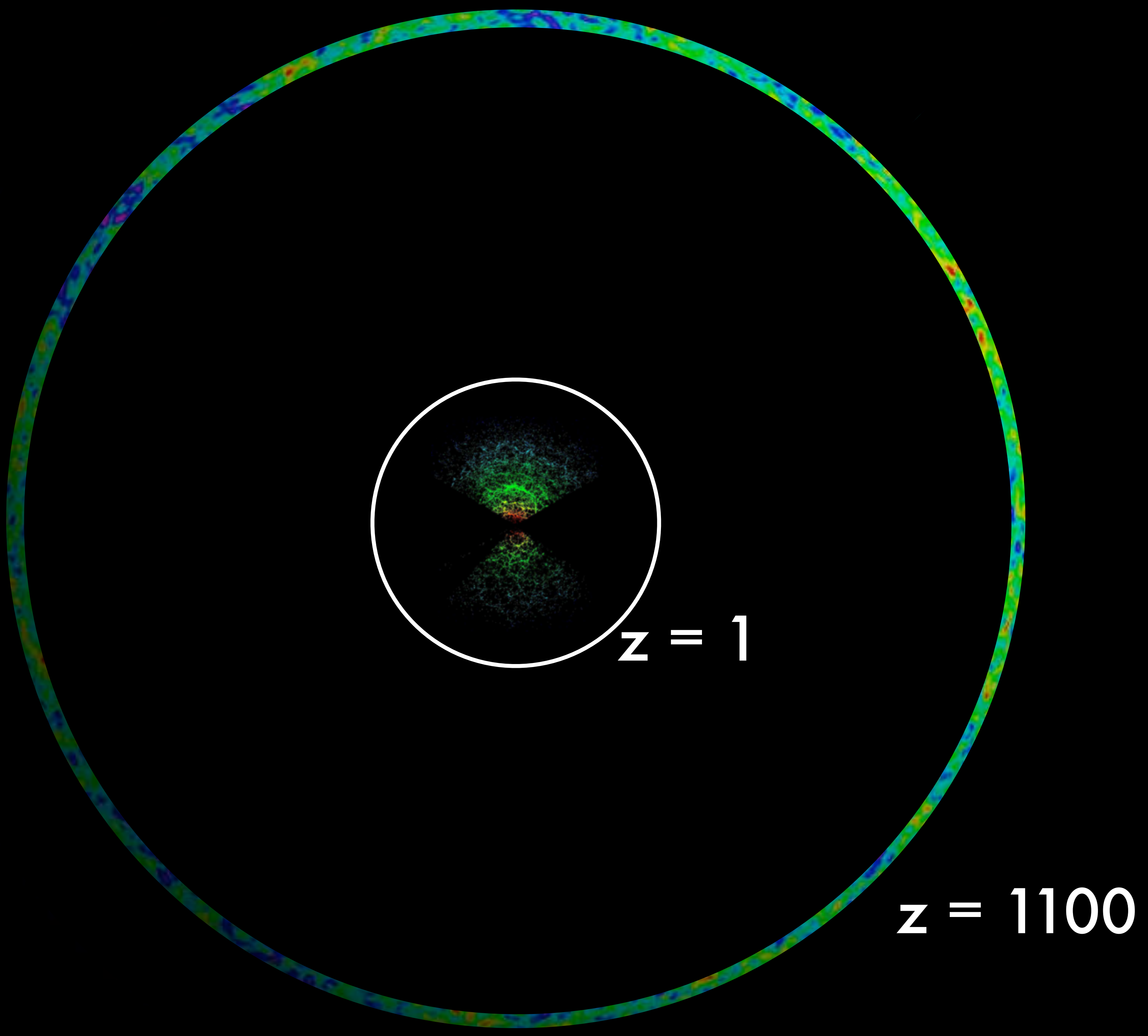
With the CMB...



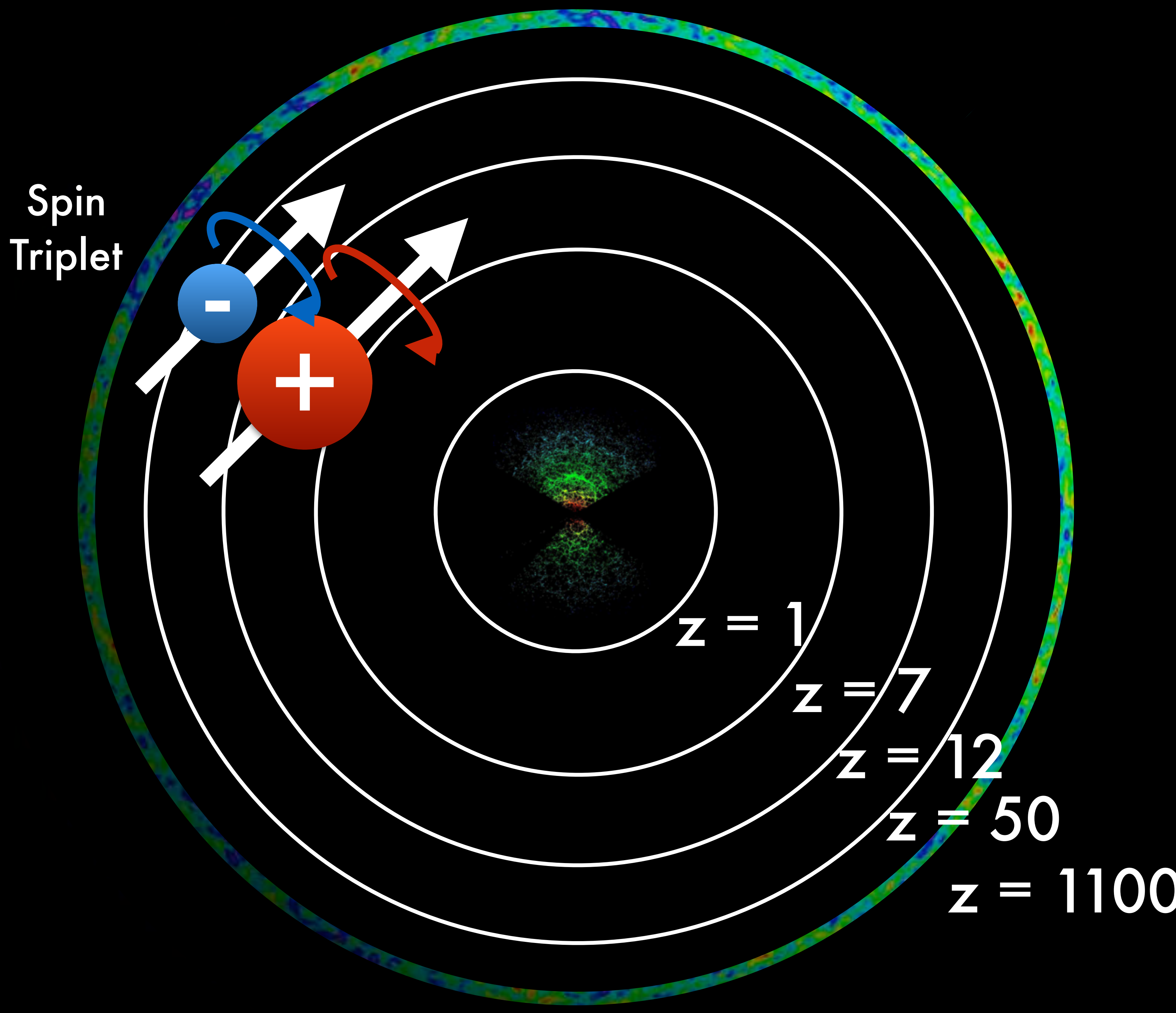
...we only get a thin shell at high redshift.



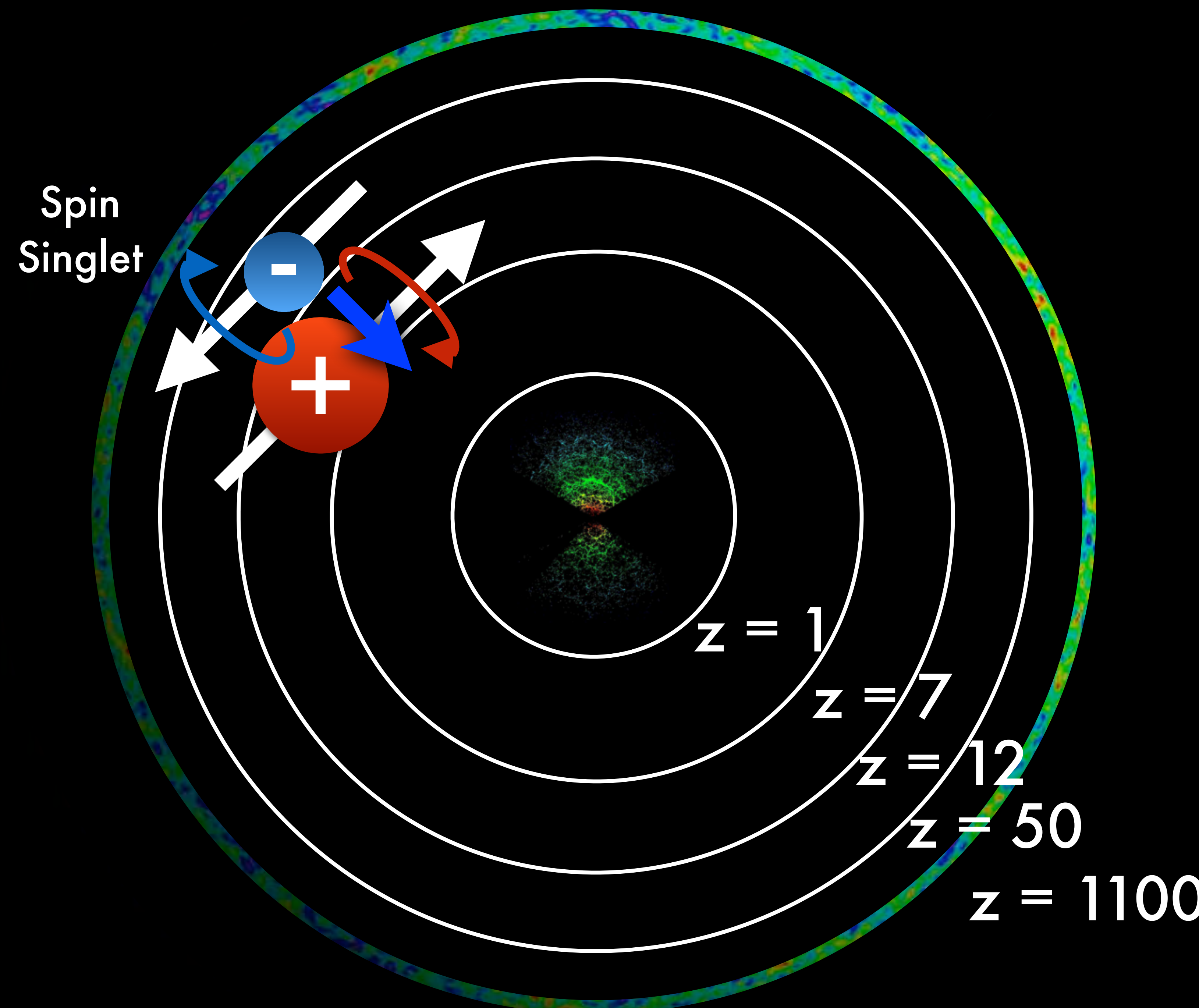
Galaxy surveys only tell us about the local universe.



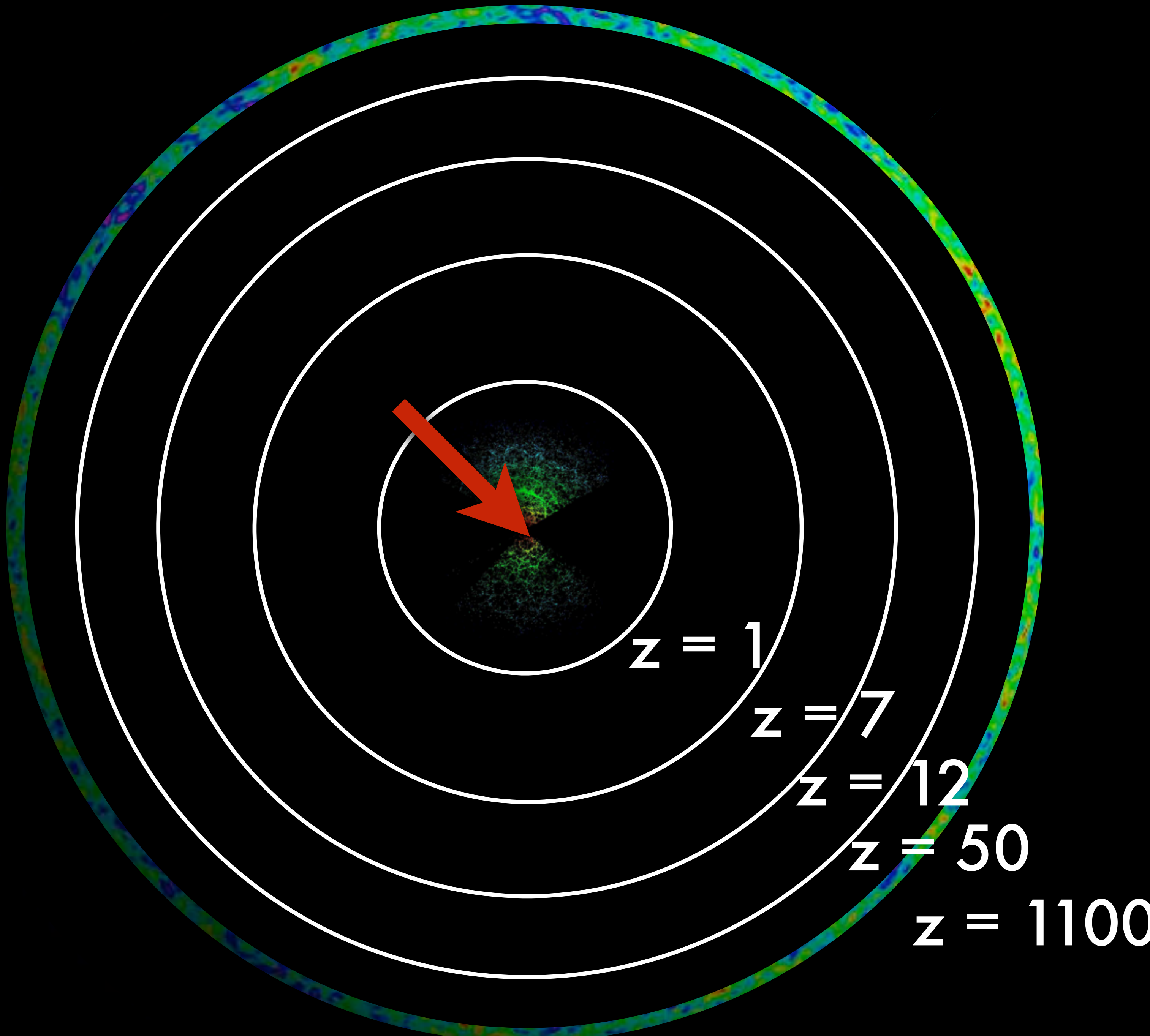
But using the 21 cm hydrogen line...



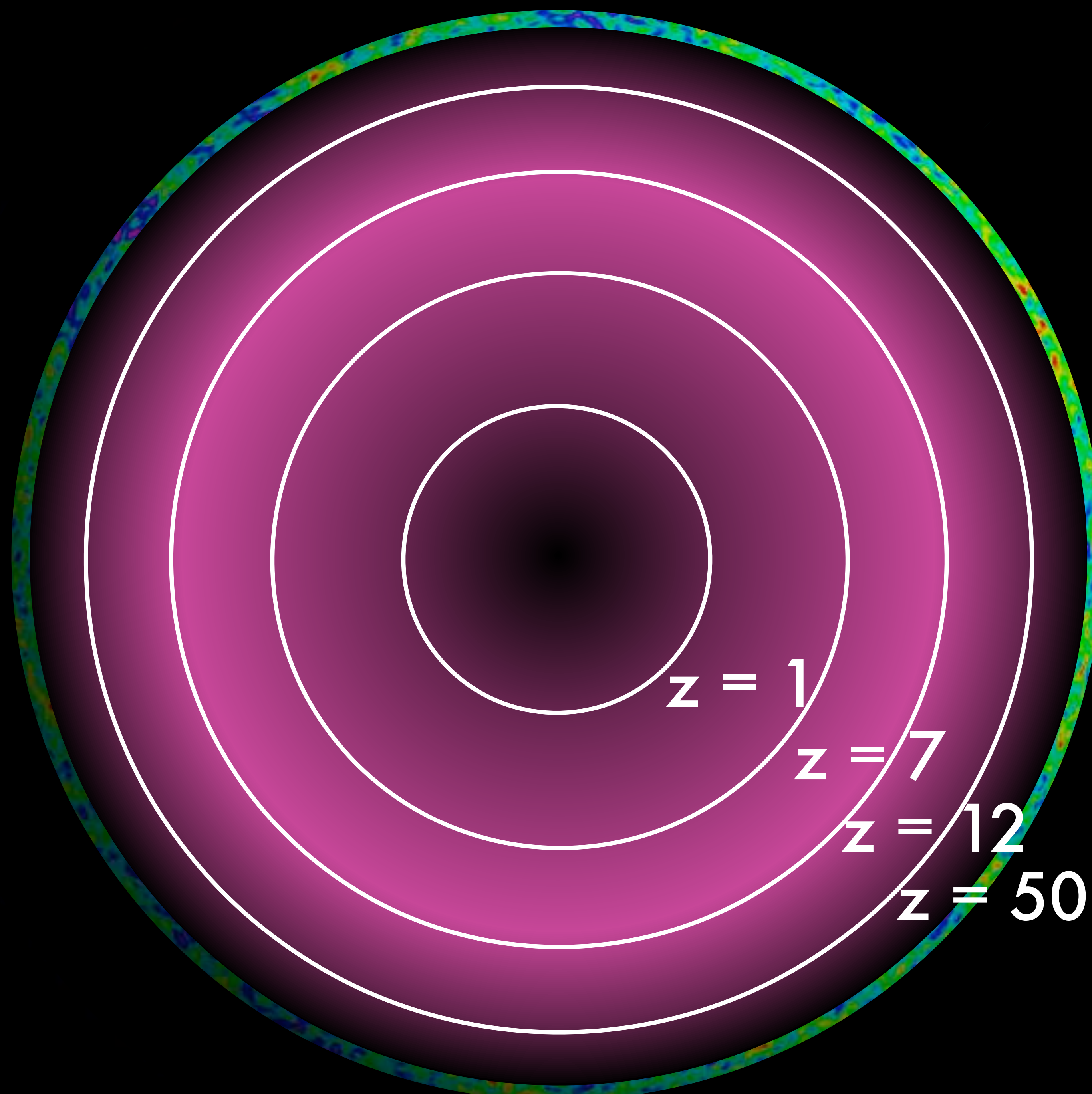
But using the 21 cm hydrogen line...



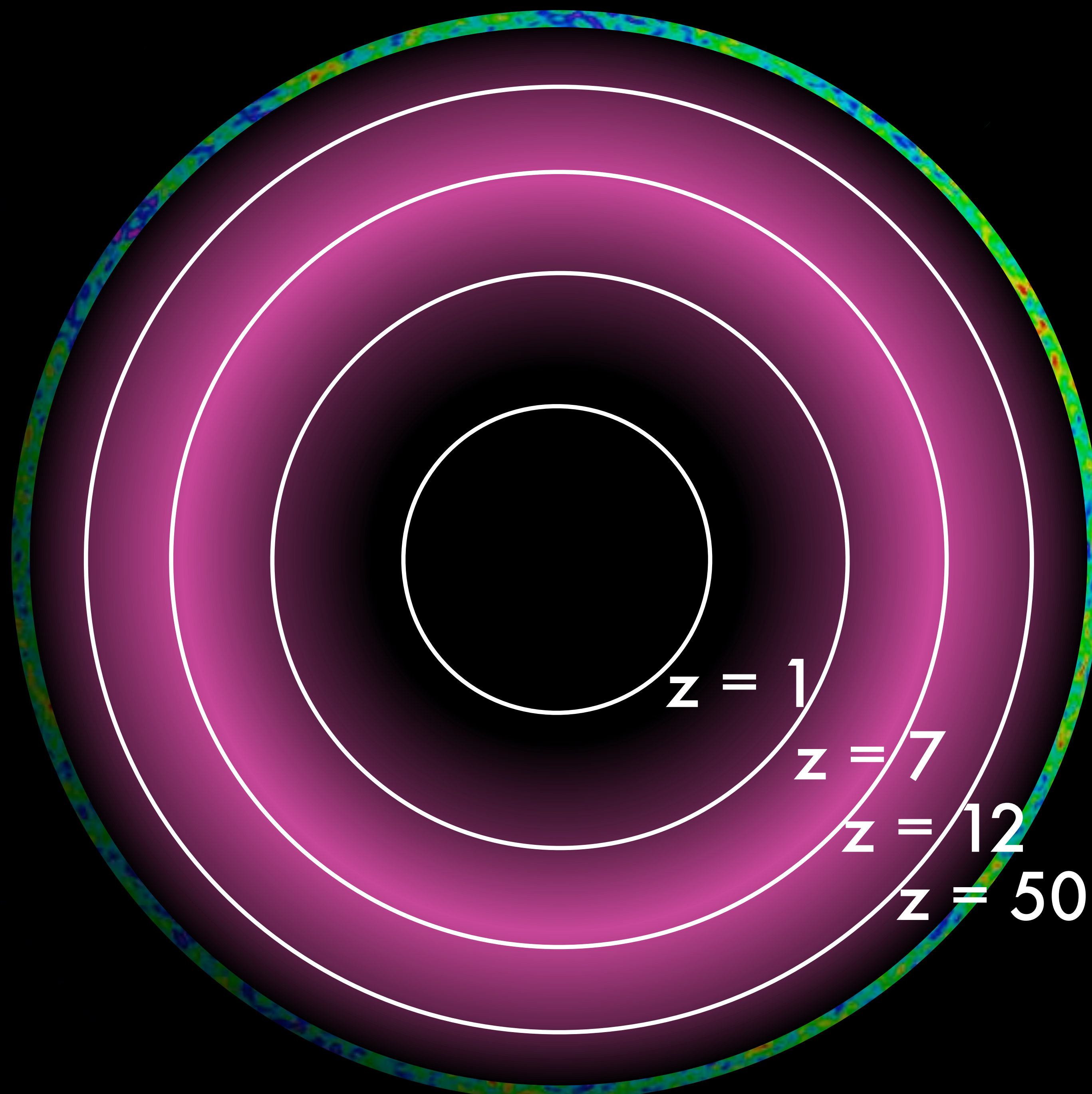
But using the 21 cm hydrogen line...



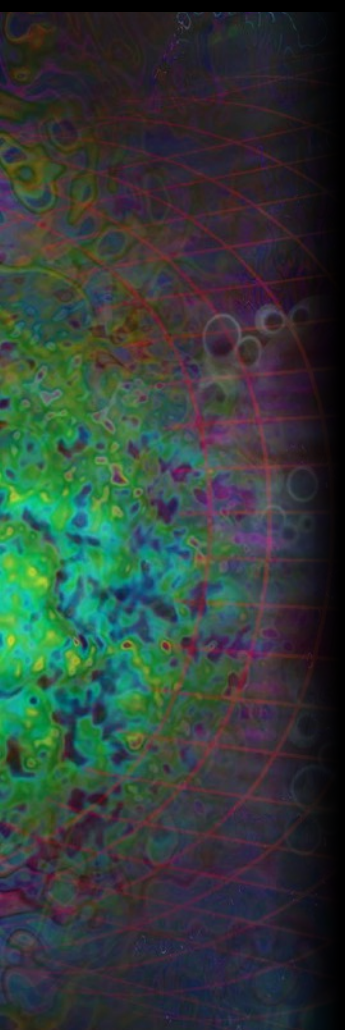
...a huge volume of the universe can be directly probed ($z \lesssim 200$).



At $z \gtrsim 6$, we can map the universe as it undergoes a dramatic transformation.

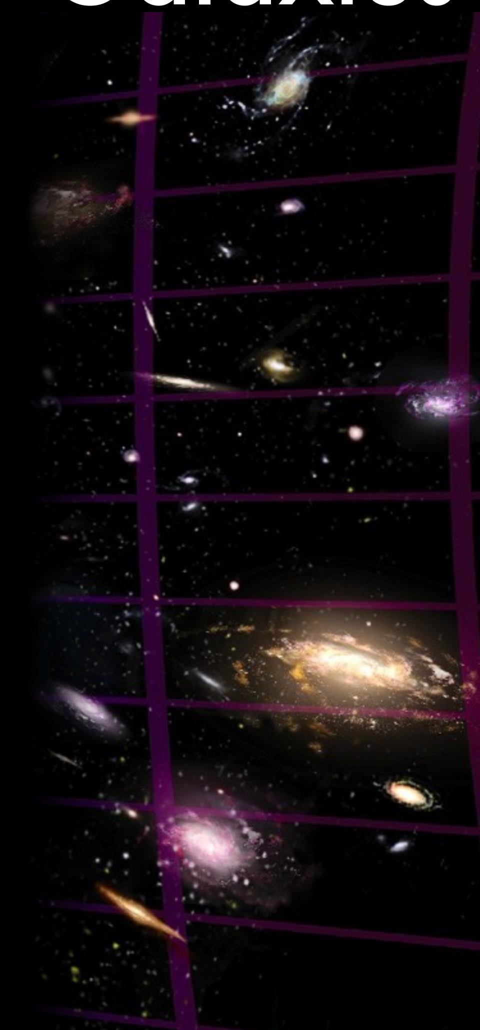


CMB



z =1100

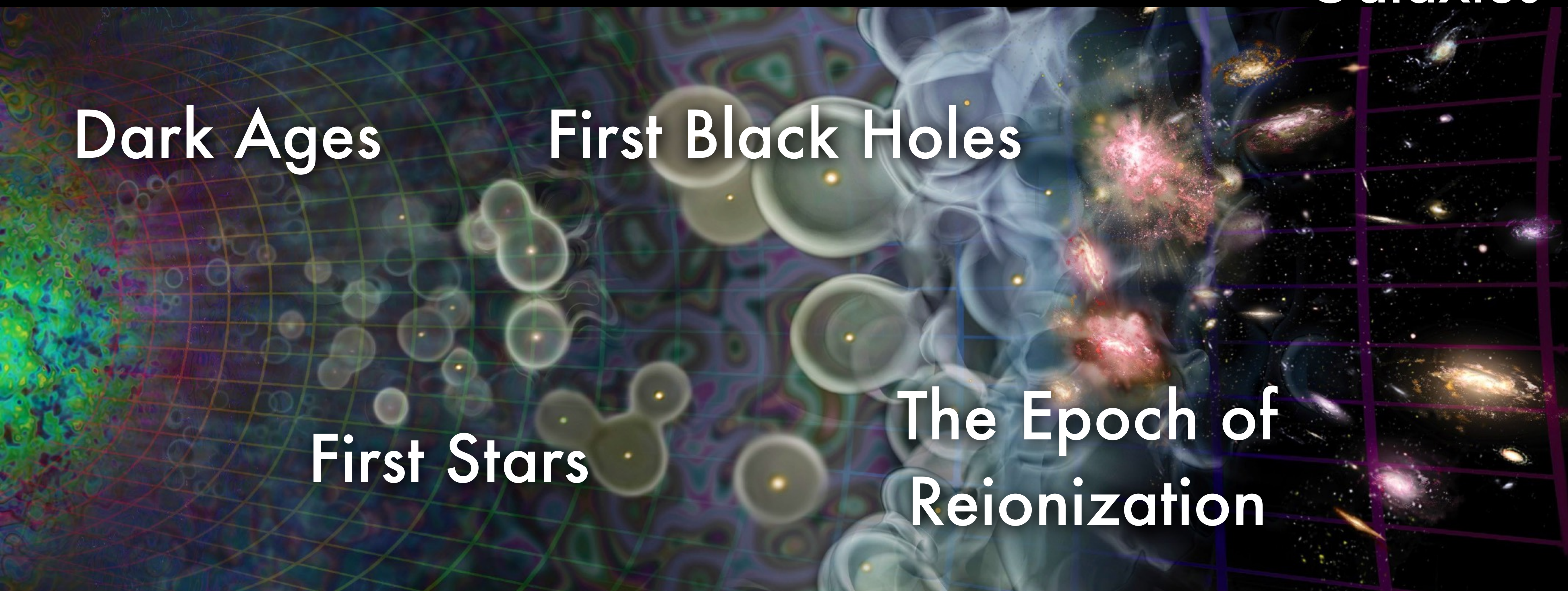
Modern
Galaxies



z < 6

CMB

Modern
Galaxies



$z = 1100$ $z \approx 50$ $z \approx 8$ $z < 6$

Image: Avi Loeb


First Black Holes
The Cosmic Dawn
First Stars
The Epoch of
Reionization

We already have some clues about reionization.

Quasar Lyman-α spectra tell us that reionization ended around redshift 6.

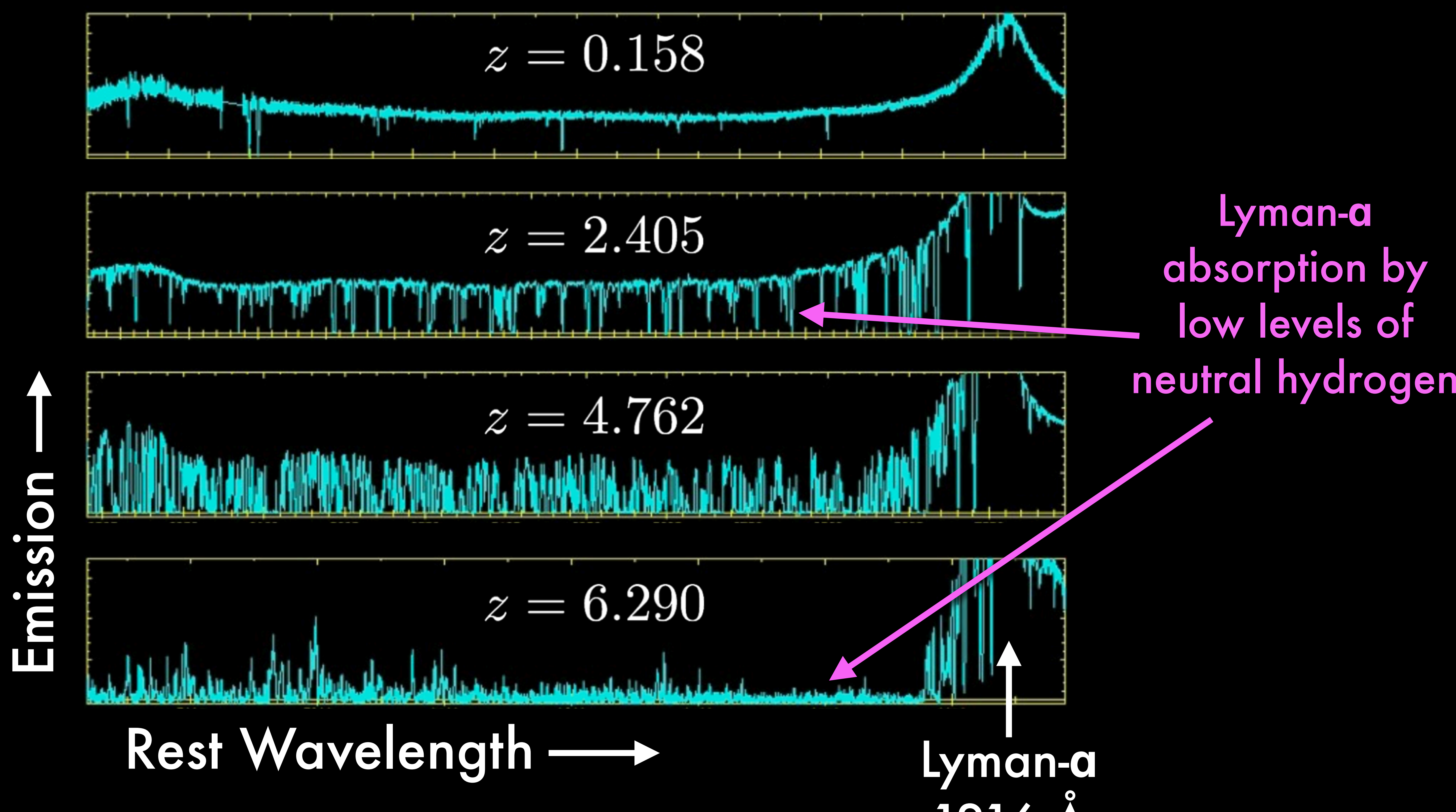


Image: Bob Carswell

We also get an integral constraint on reionization from the CMB polarization.

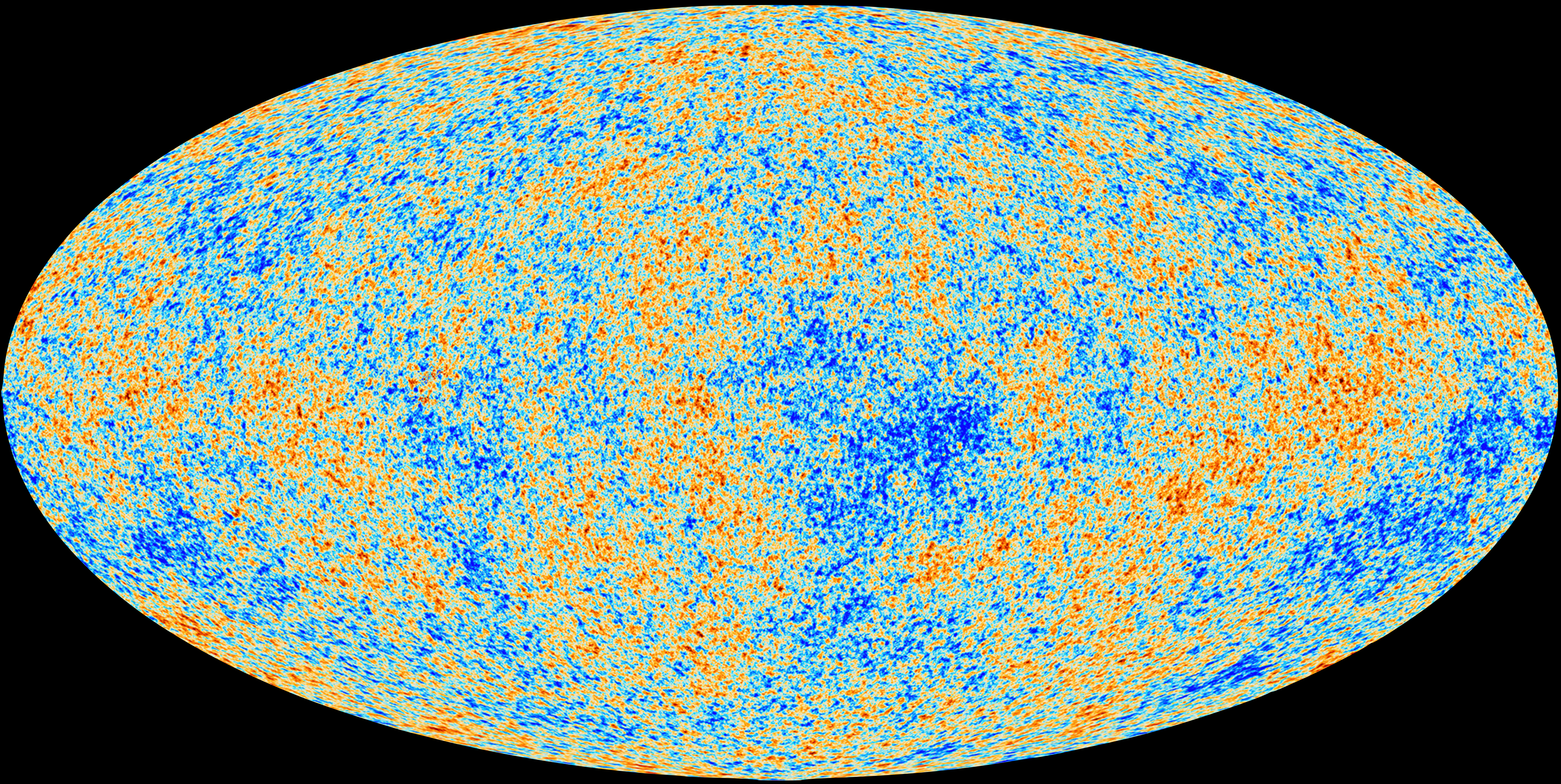


Image: Planck Collaboration

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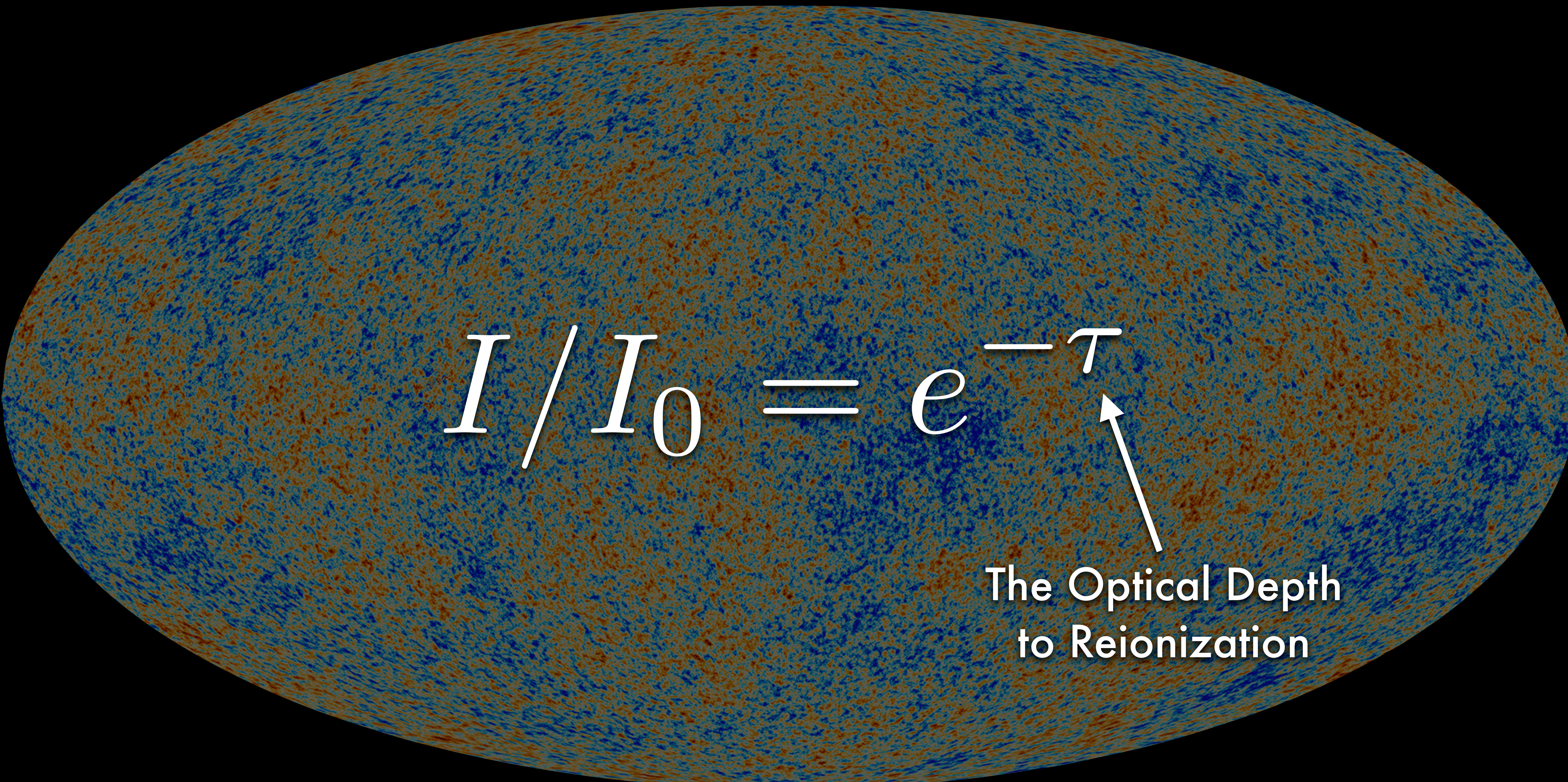


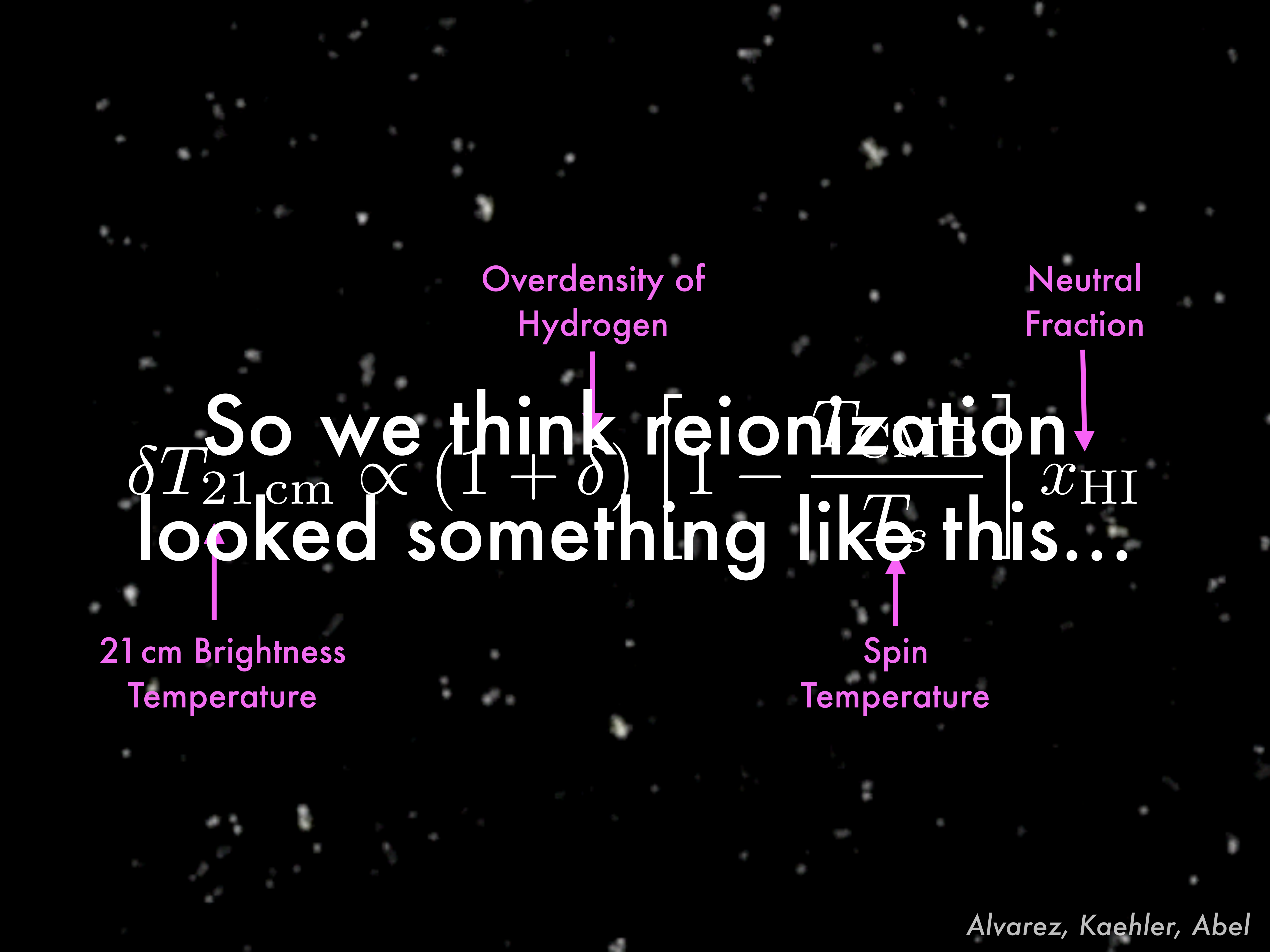
$$I/I_0 = e^{-\tau}$$

Image: Planck Collaboration

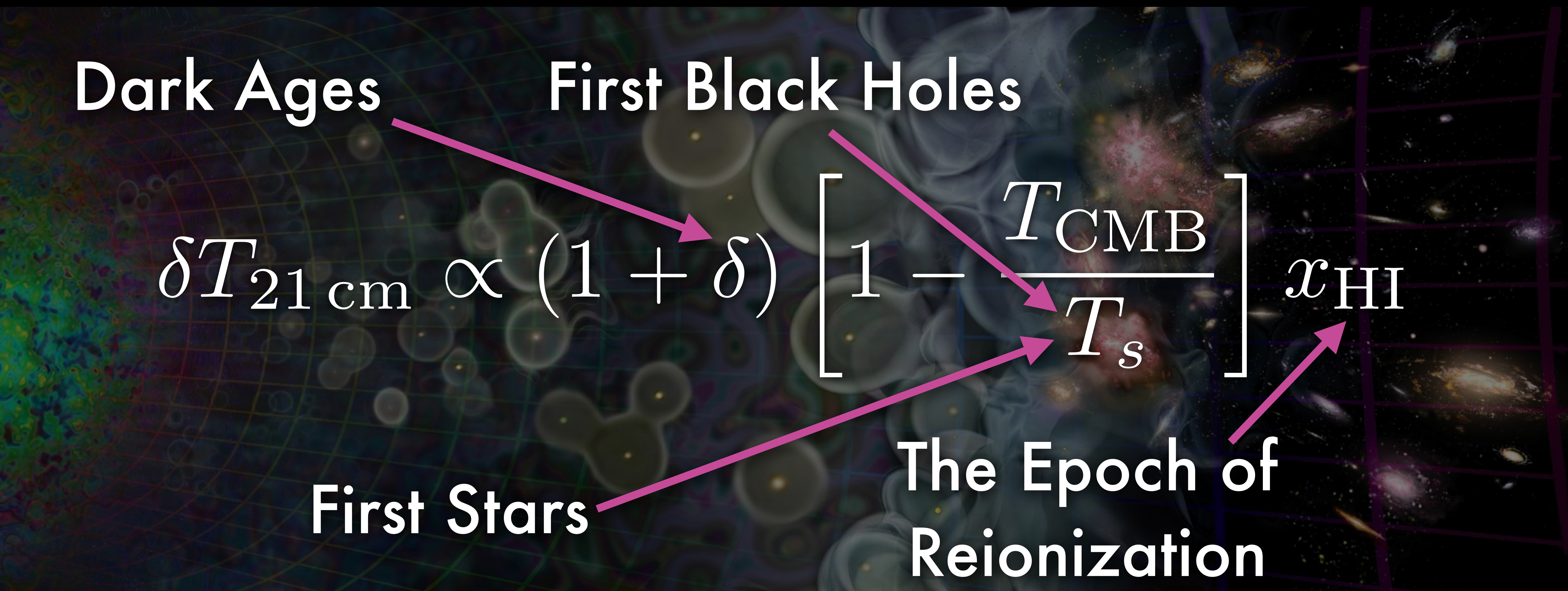
So we think reionization looked something like this…

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

- 21 cm Brightness Temperature
- Overdensity of Hydrogen
- Spin Temperature
- Neutral Fraction



The brightness temperature probes different physics at different times.

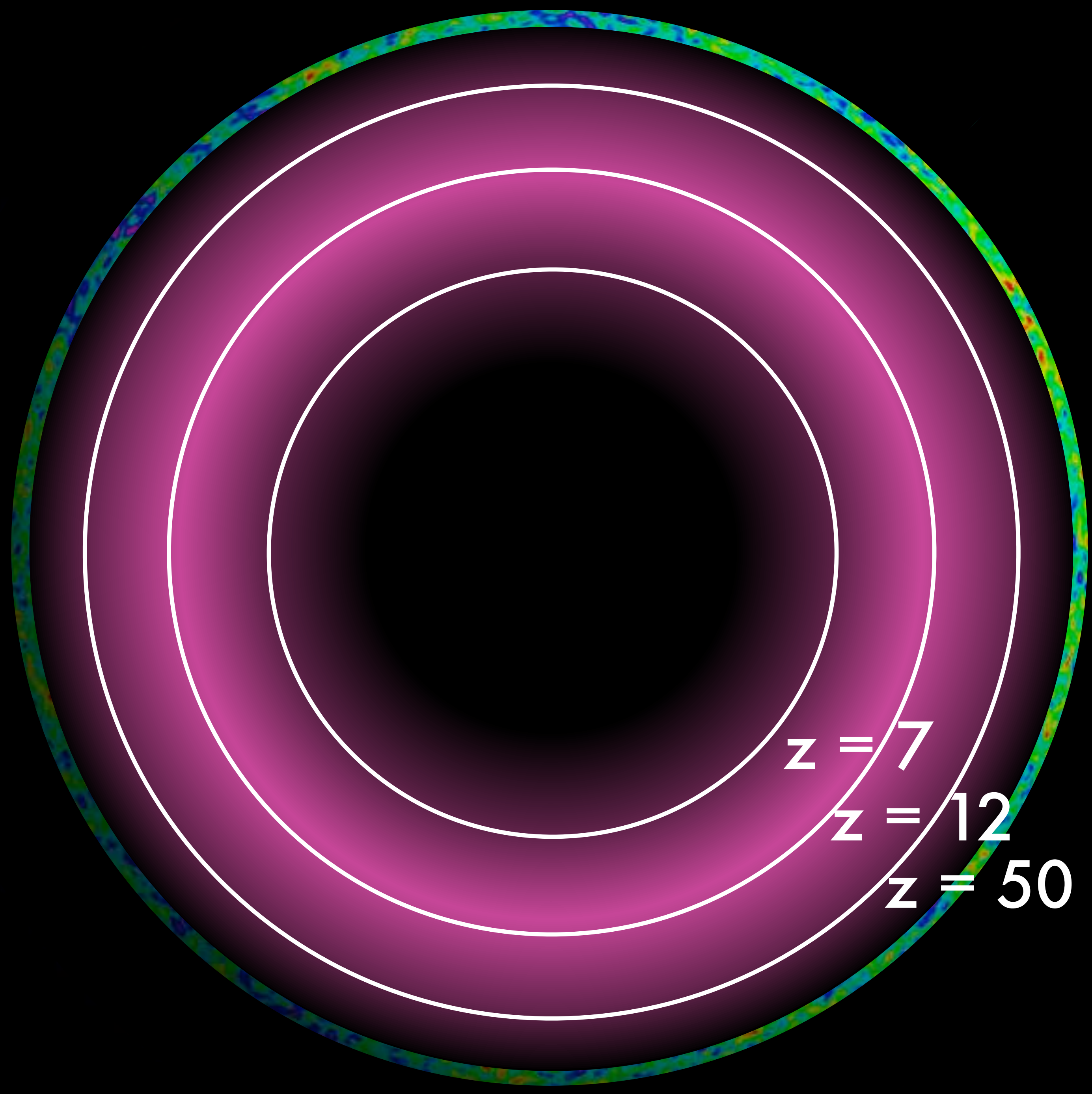


z =1100 z ≈ 50 z ≈ 8 z < 6

There's still a lot of open astrophysical questions.

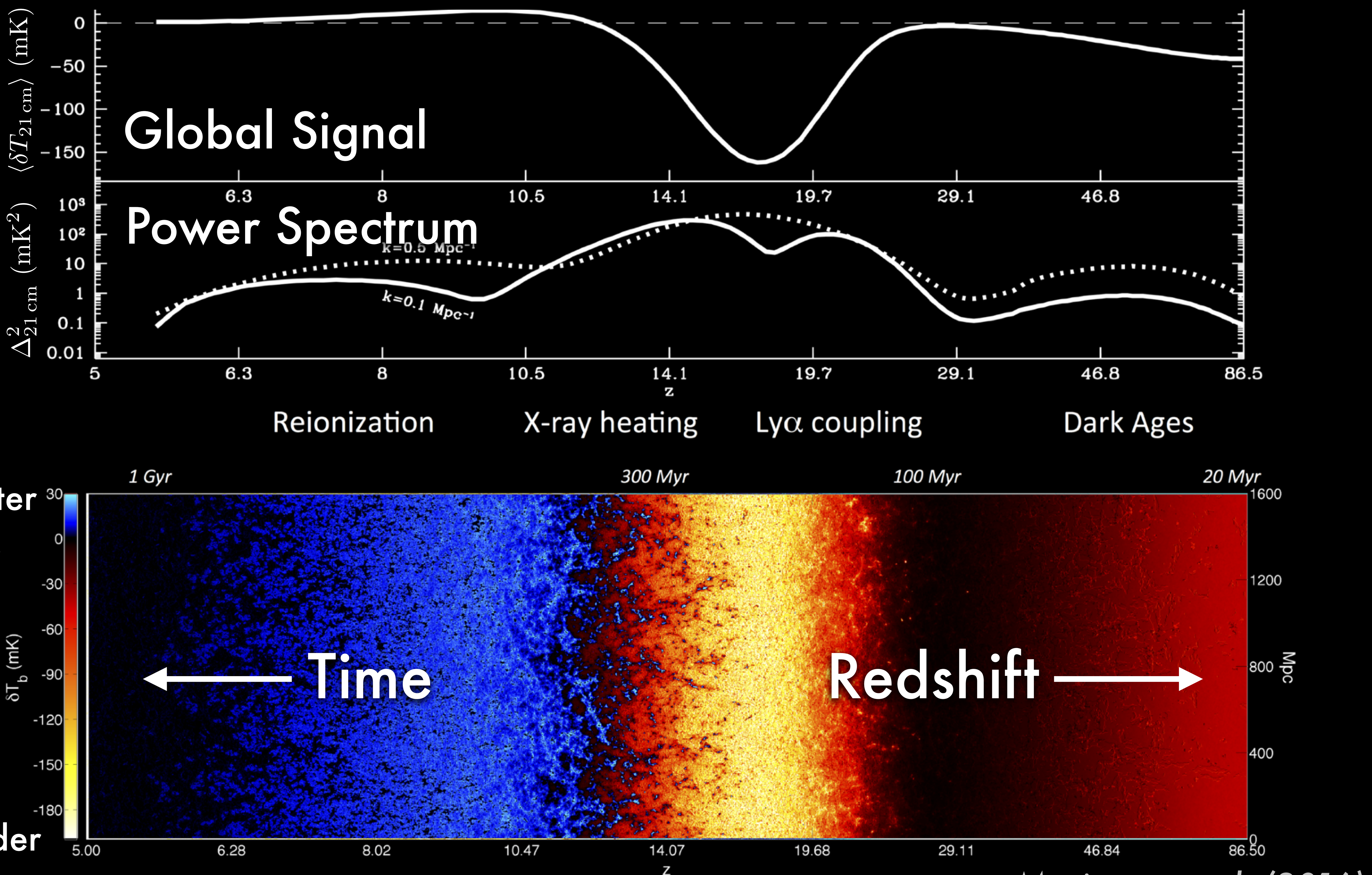
- What did the first stars look like? How and when how did they form?
- How did they die and were they the LIGO black hole progenitors? Or the seeds of supermassive black holes?
- What determined the thermal history of the intergalactic medium? Are there new physics at play?
- What reionized the universe and when?

The Cosmic Dawn is roughly half of the comoving volume of the observable universe.



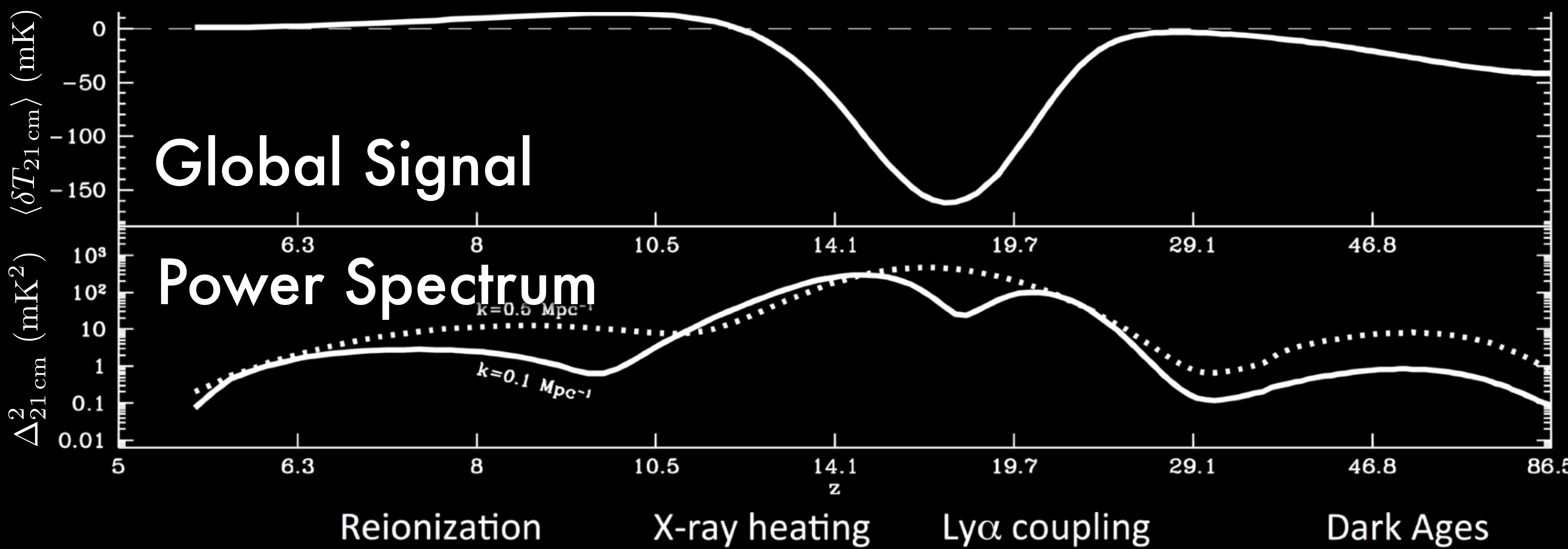
Enormous 3D maps would be amazing, but the first detection will be statistical.

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



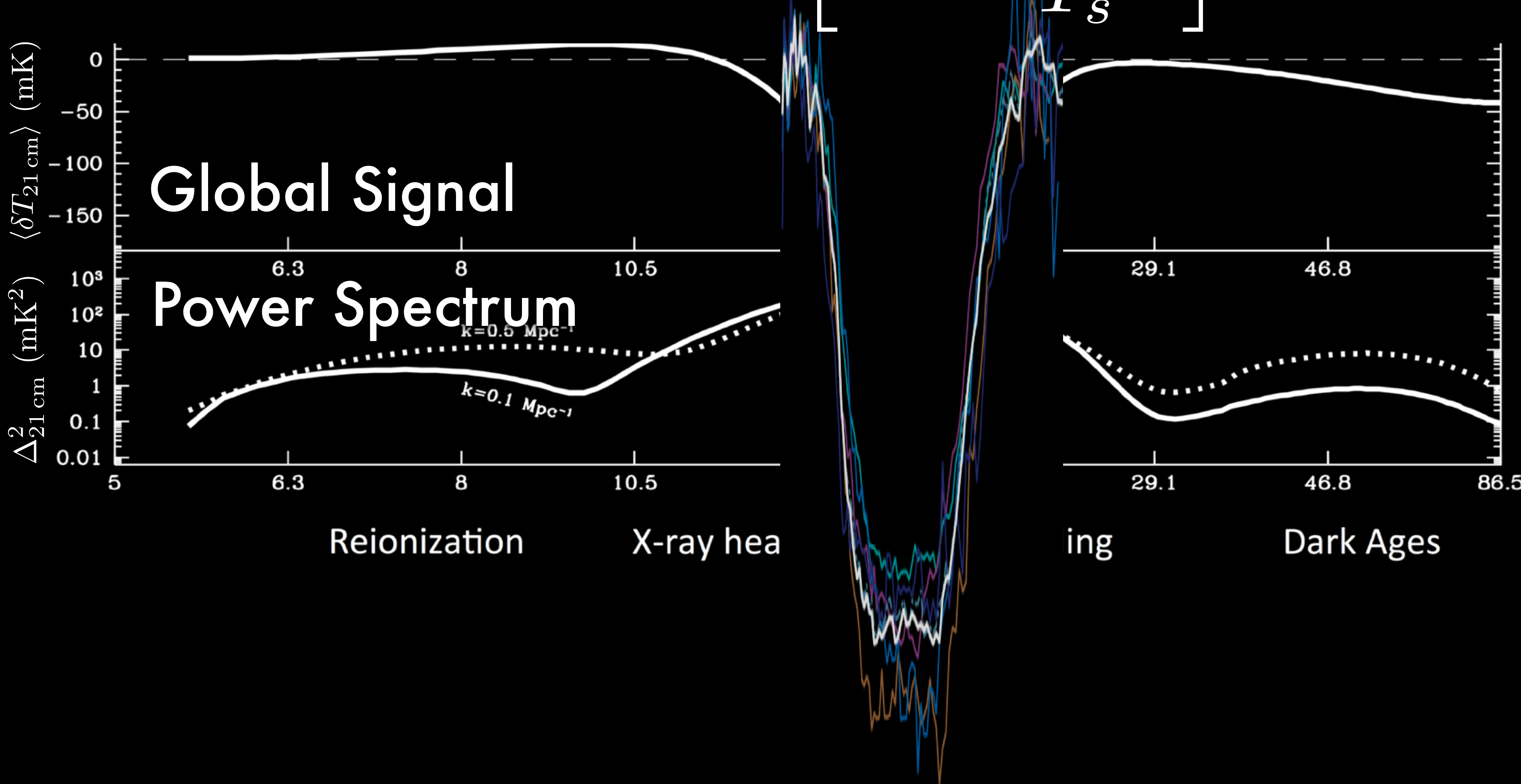
Mesinger et al. (2016)

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



And then came EDGES...

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



EDGES detected a much stronger absorption feature than anyone expected.

Bowman et al. (2018)

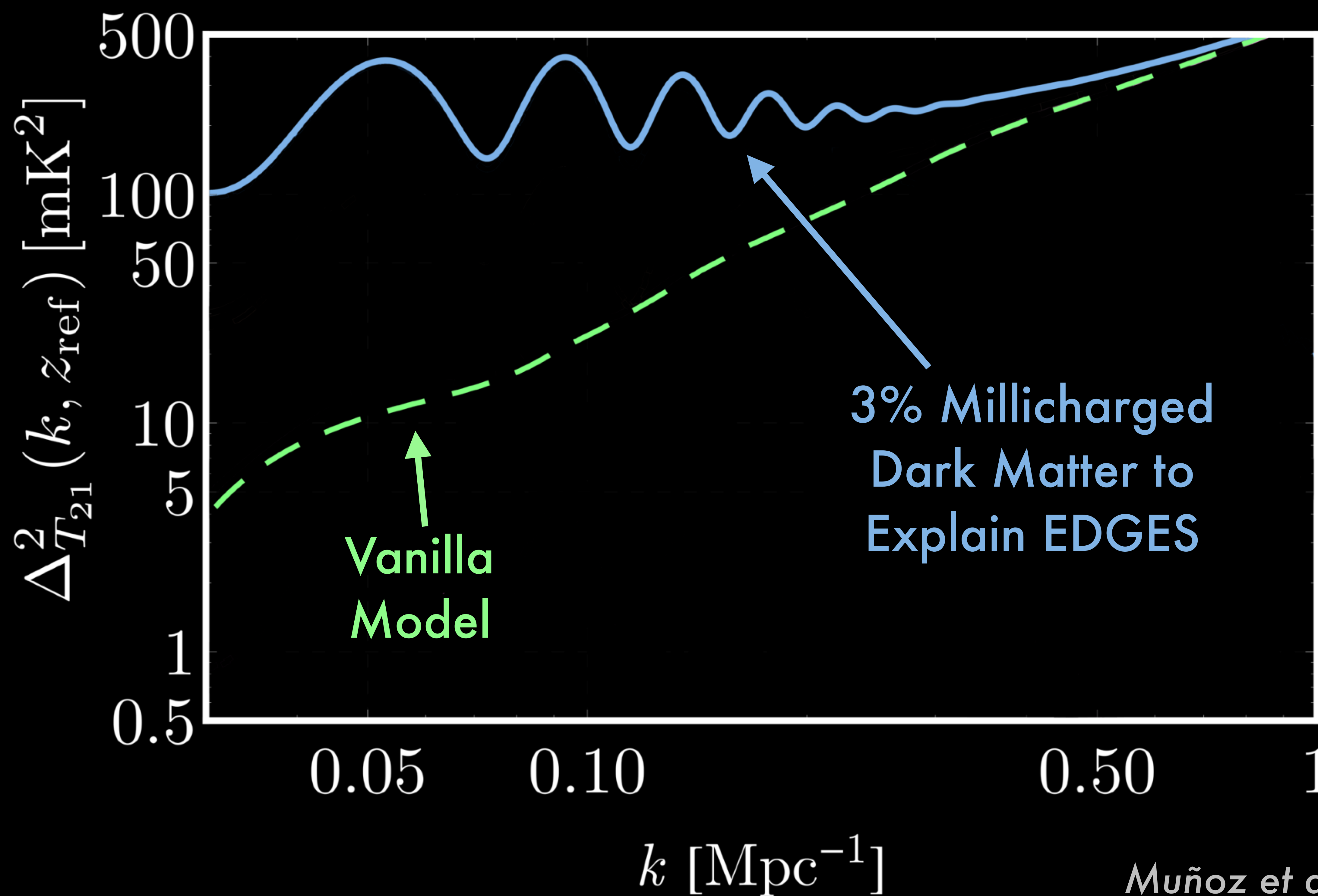
$$\delta T_{21\,\mathrm{cm}} \propto \left[1 - \frac{T_{\mathrm{CMB}}}{T_s}\right]$$

A. $T_s = T_{baryon}$ is cooled by the only thing colder than the baryons: dark matter.
   - *e.g. Barkana et al. (2018) and a ton of others*

B. T_{CMB} is actually T_{rad} and is dominated by something like very early radio-loud quasars.
   - *e.g. Feng & Holder (2018), Ewall-Wice et al. (2018)*

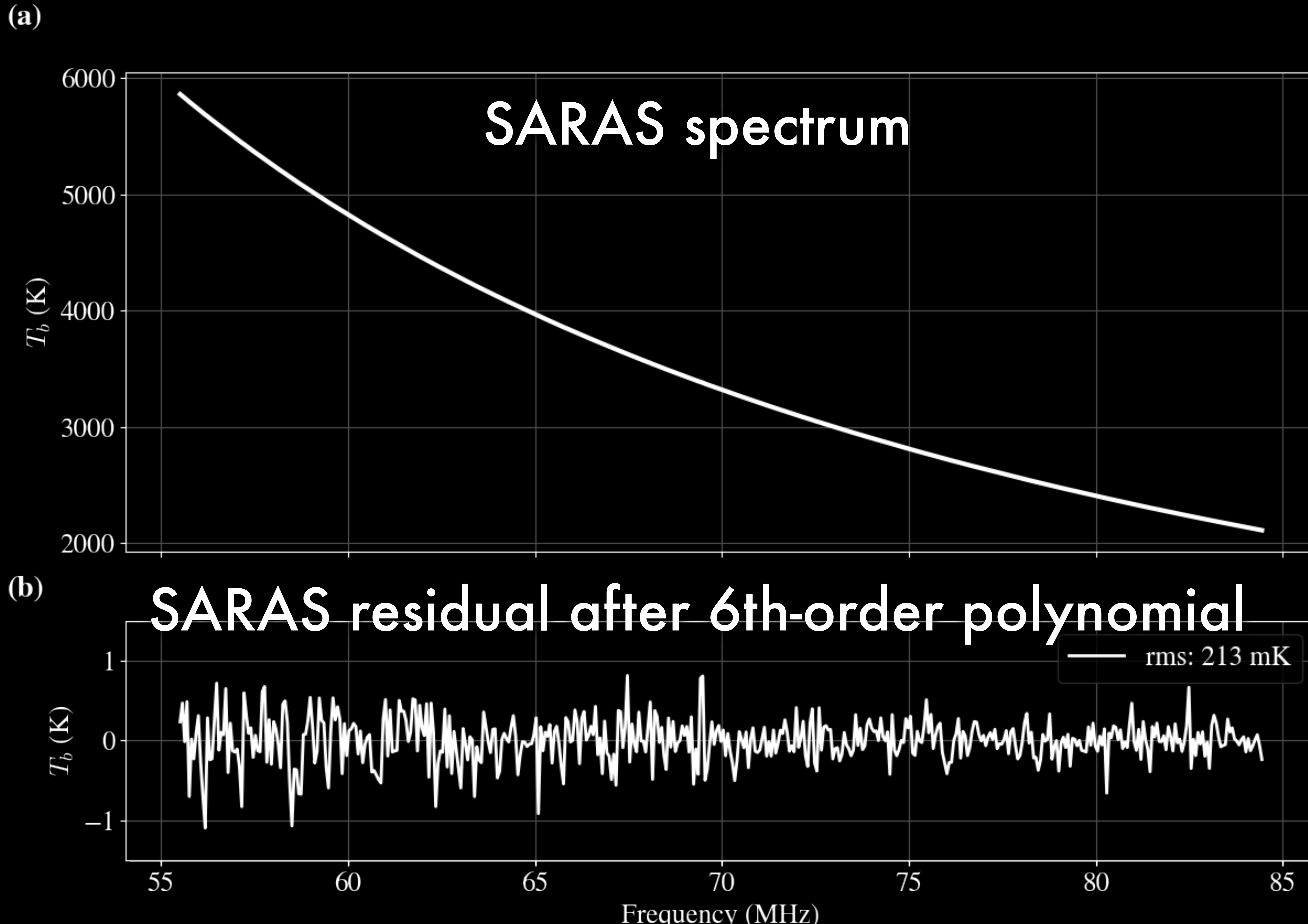
C. EDGES is seeing some systematic
   - *See e.g. the Hills et al. (2018) re-analysis of EDGES*

If EDGES is due to DM interactions, it should be obvious in the z = 17 power spectrum.



Muñoz et al. (2018)

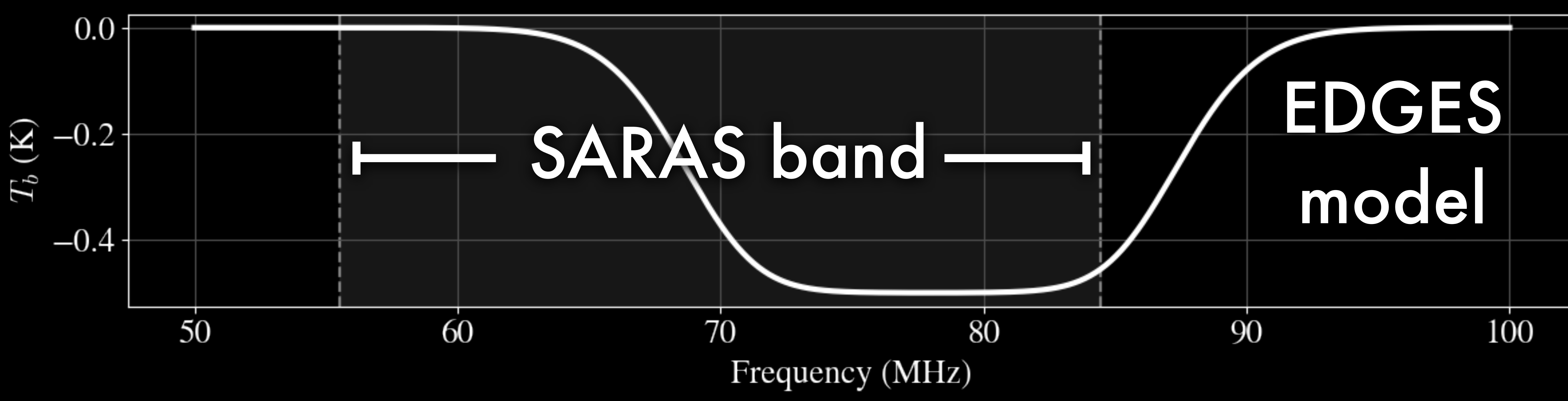

SARAS-3



Singh et al. (2022)

This rules out the EDGES best-fit model at ~95% confidence. Some caveats:

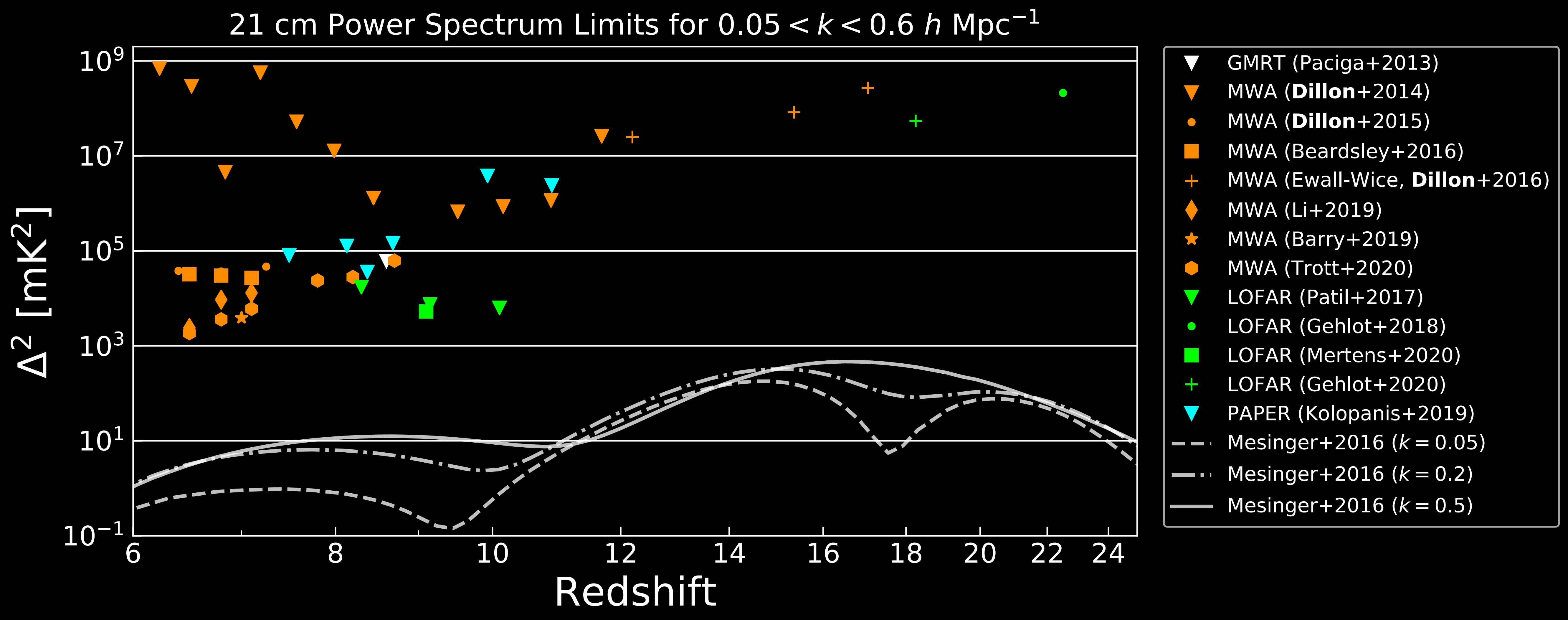
- EDGES's flattened Gaussian is by no-means the only model. It's not physically motivated, it just minimizes χ^2.
- SARAS has a smaller band, which makes it harder to constrain the signal and leaves less lever-arm for foreground mitigation.



Measuring the global signal is hard. What about the 21 cm power spectrum?

The first generation of interferometers for 21 cm cosmology got us started, deploying different strategies.

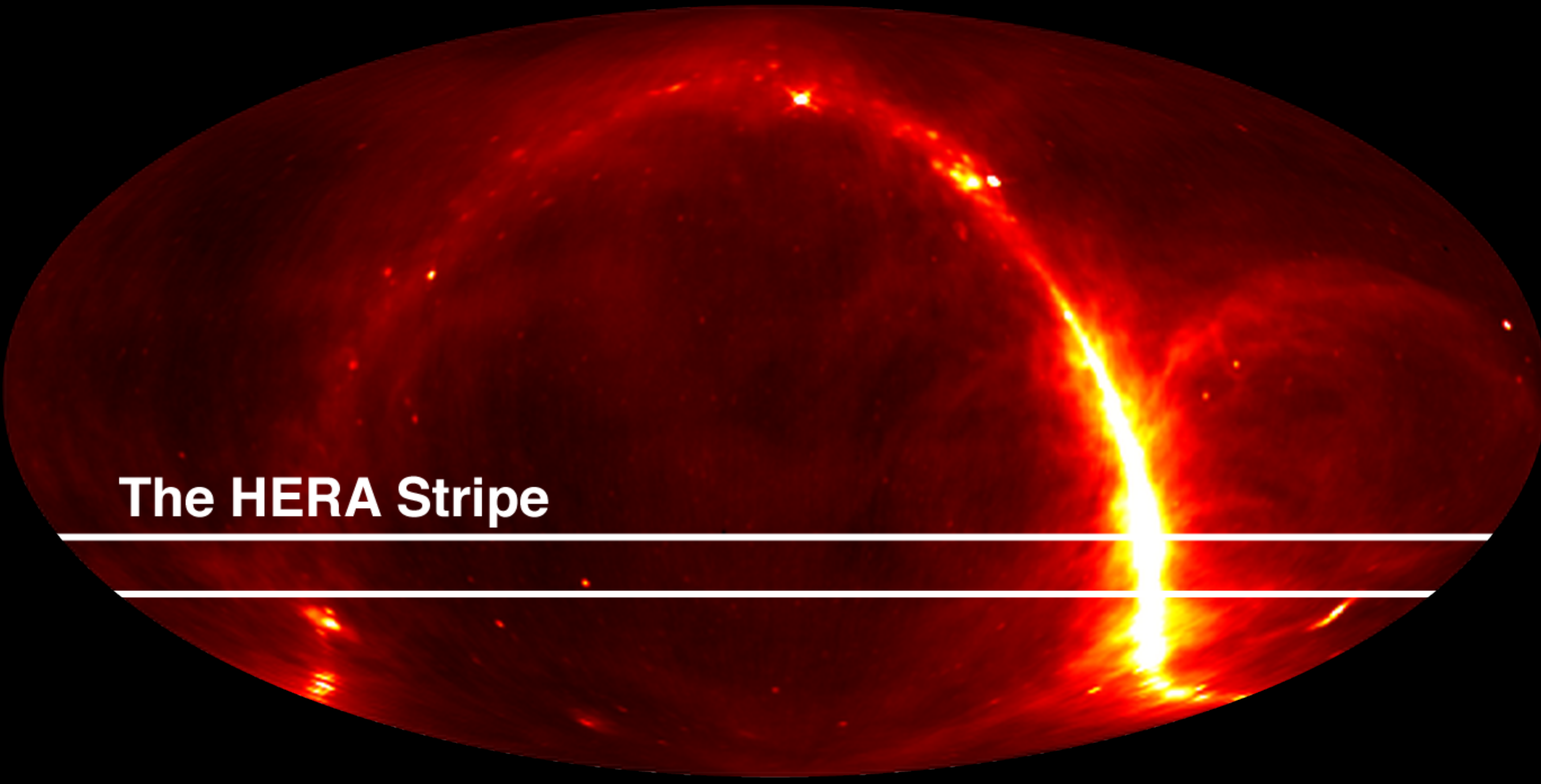
And over the last decade, power spectrum limits have been steadily coming down in the quest for the faint cosmological signal.



So we went bigger…

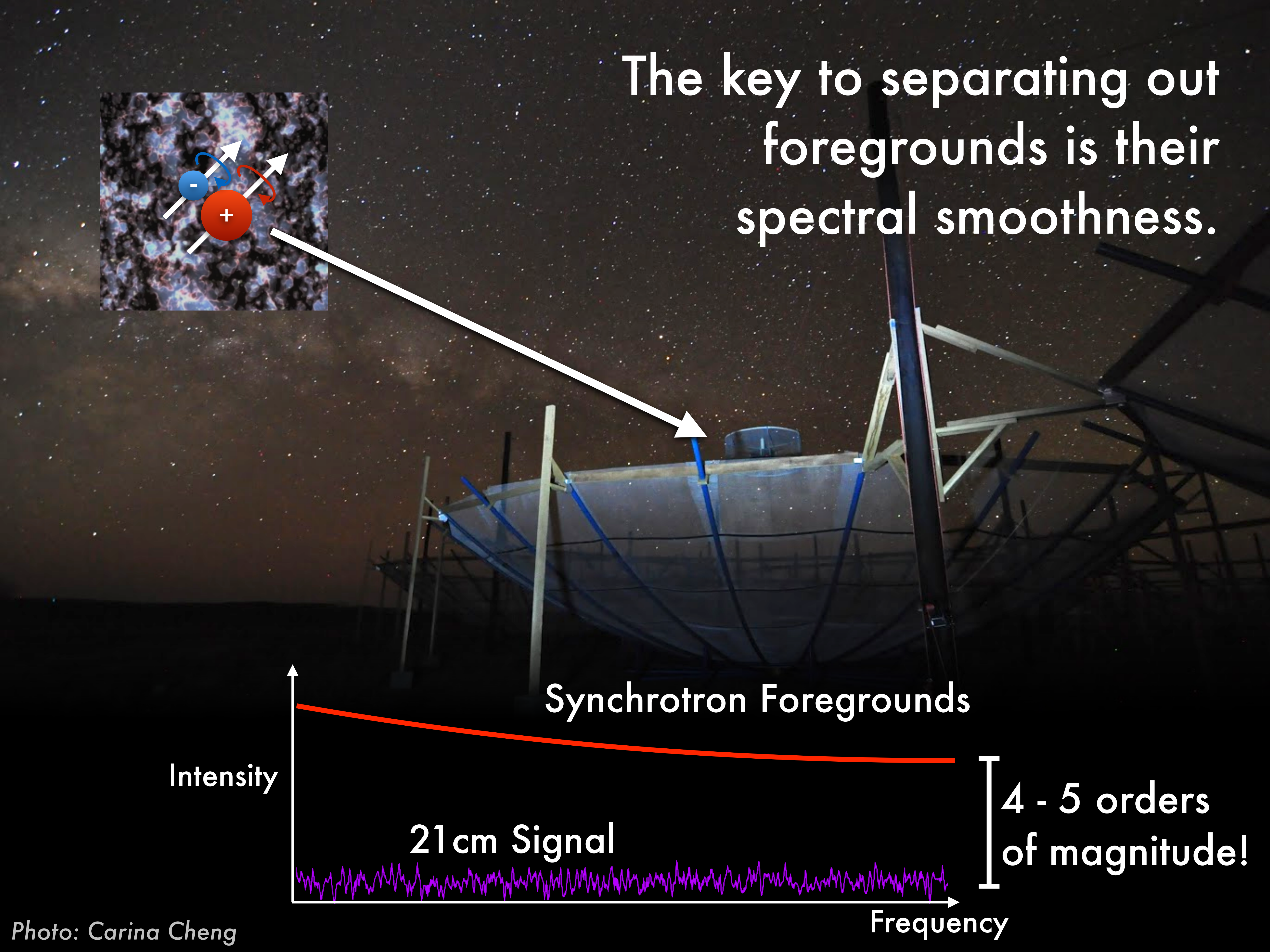

CAL POLY POMONA
THE UNIVERSITY OF CALIFORNIA UCLA LET THERE BE LIGHT
THE UNIVERSITY OF CALIFORNIA BERKELEY LET THERE BE LIGHT 1868
ARIZONA STATE UNIVERSITY 1885
MASSACHUSETTS INSTITUTE OF TECHNOLOGY 1861
UNIVERSITY OF WASHINGTON 1861 LVX SIT
SCUOLA NORMALE SUPERIORE
UNIVERSITY OF CAMBRIDGE
Penn University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


The 21 cm signal is faint,
so HERA is huge.
350 14-m diameter dishes



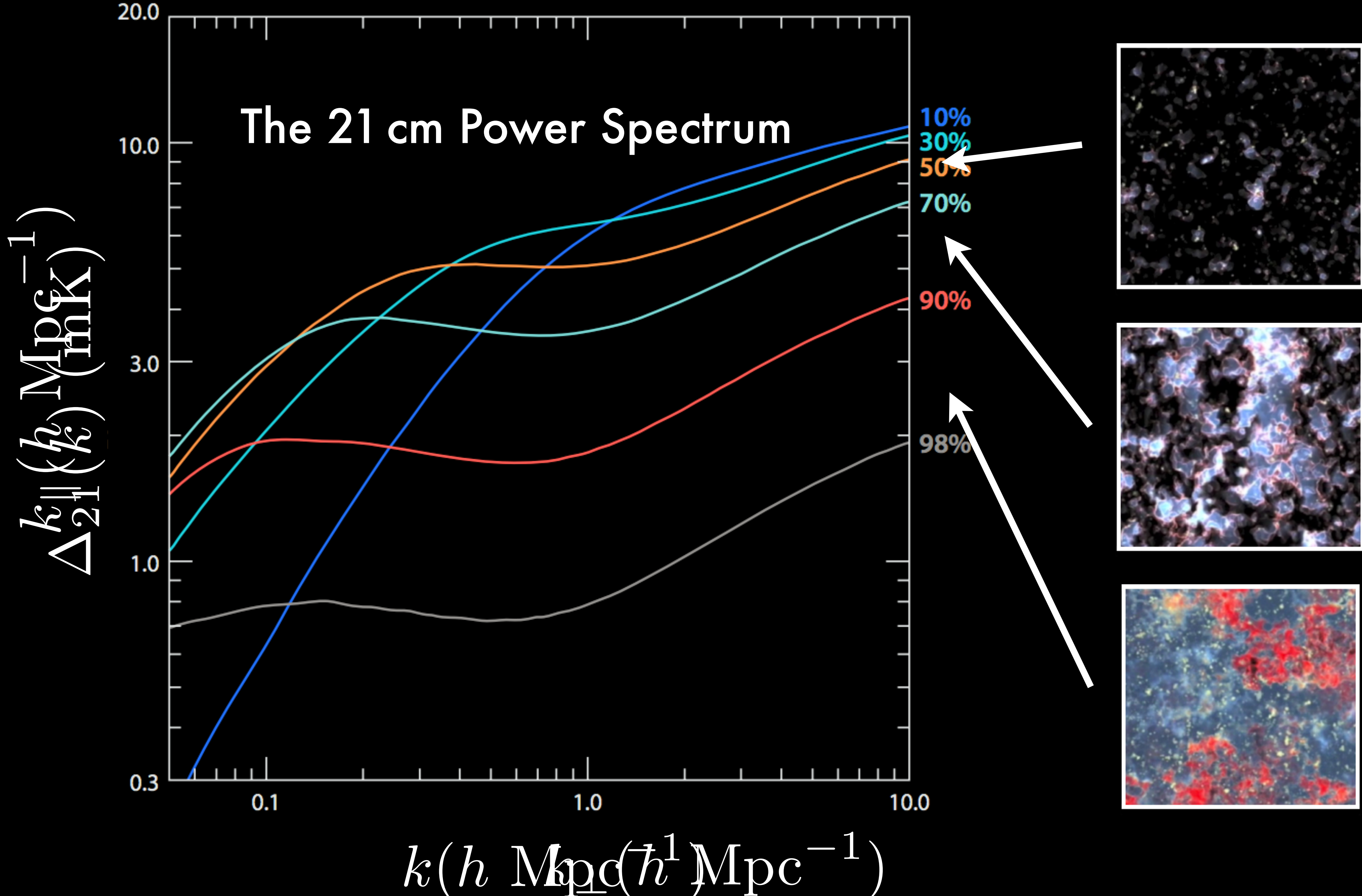
HERA is a drift scan instrument that maps out a stripe of constant declination.

Our biggest problem is foregrounds.


The key to separating out foregrounds is their spectral smoothness.
Synchrotron Foregrounds
Intensity
21cm Signal
4 - 5 orders of magnitude!
Frequency
Photo: Carina Cheng

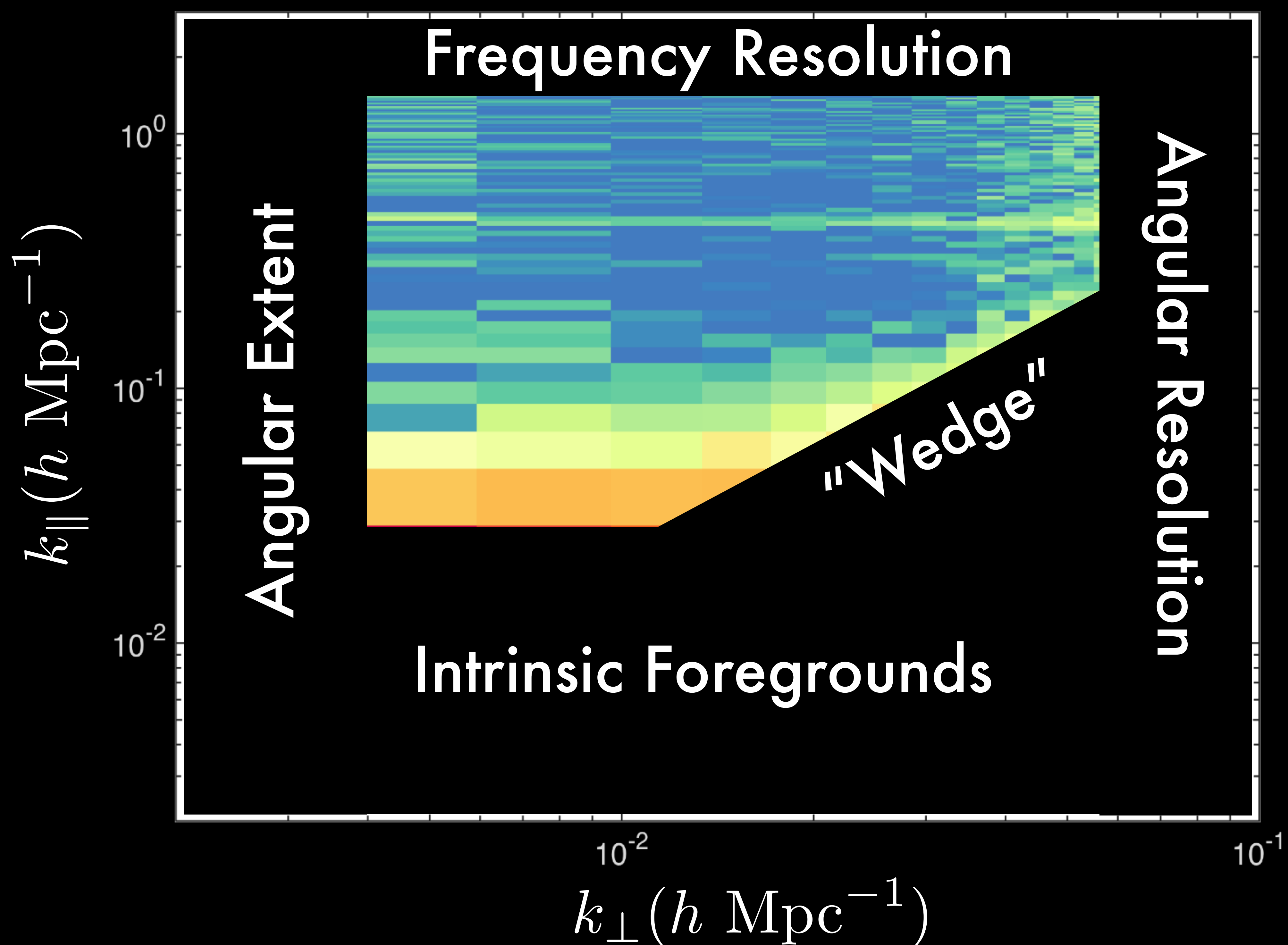
We separate out Fourier modes parallel and perpendicular to the line of sight.

So instead of spherically averaged Fourier space…

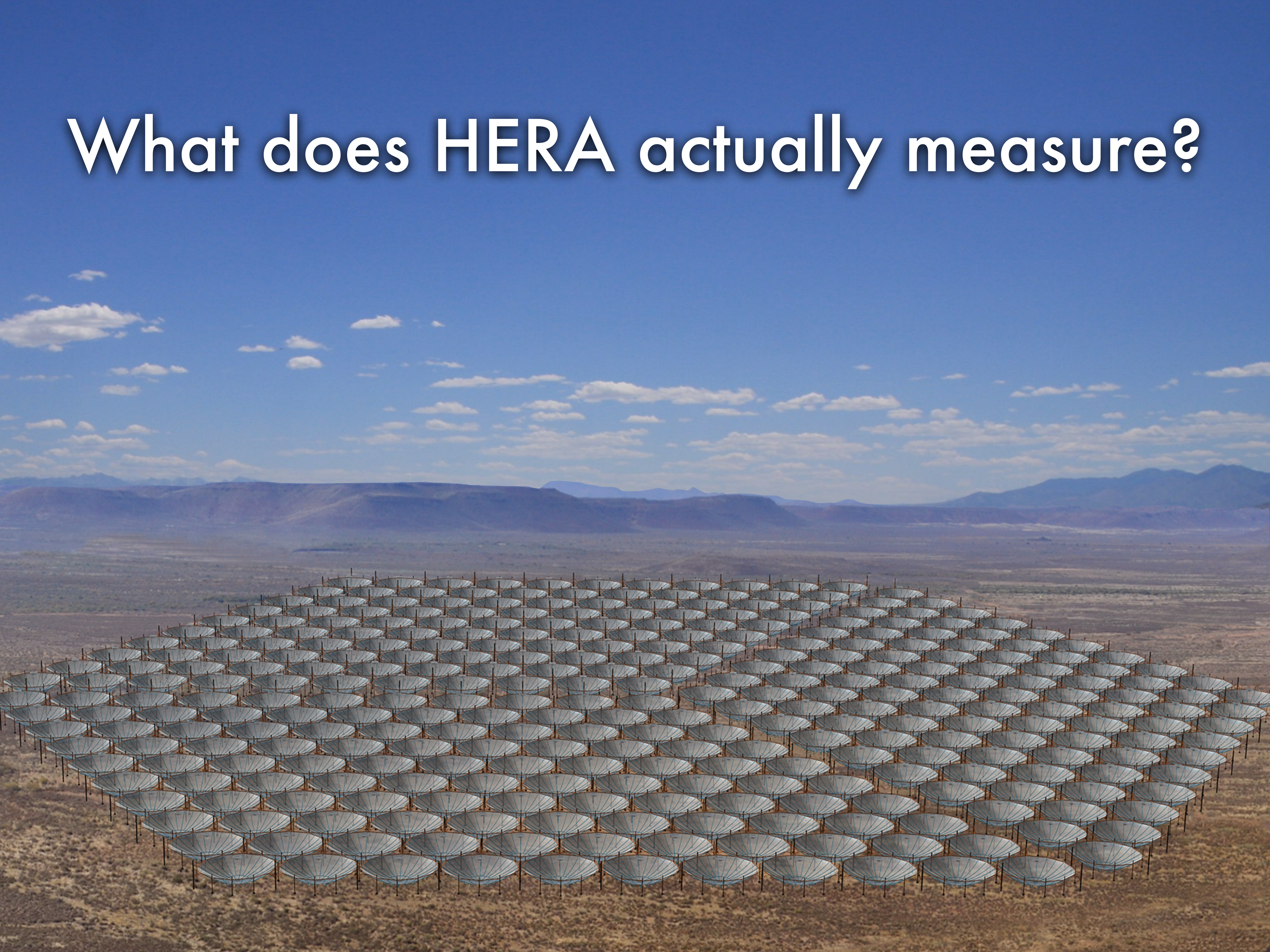


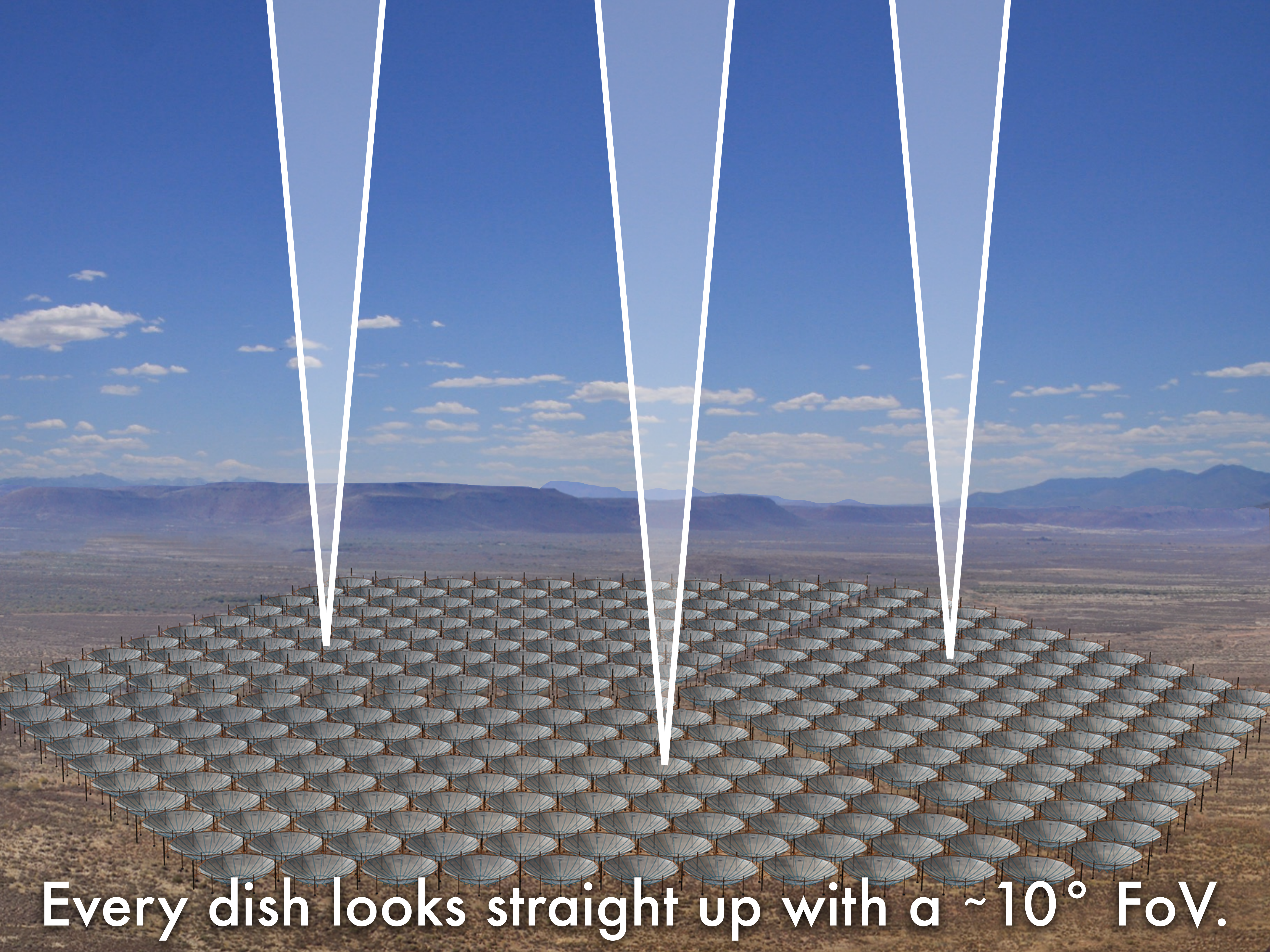
Barkana (2009), Morales & Wyithe (2010)

And we find a "window."

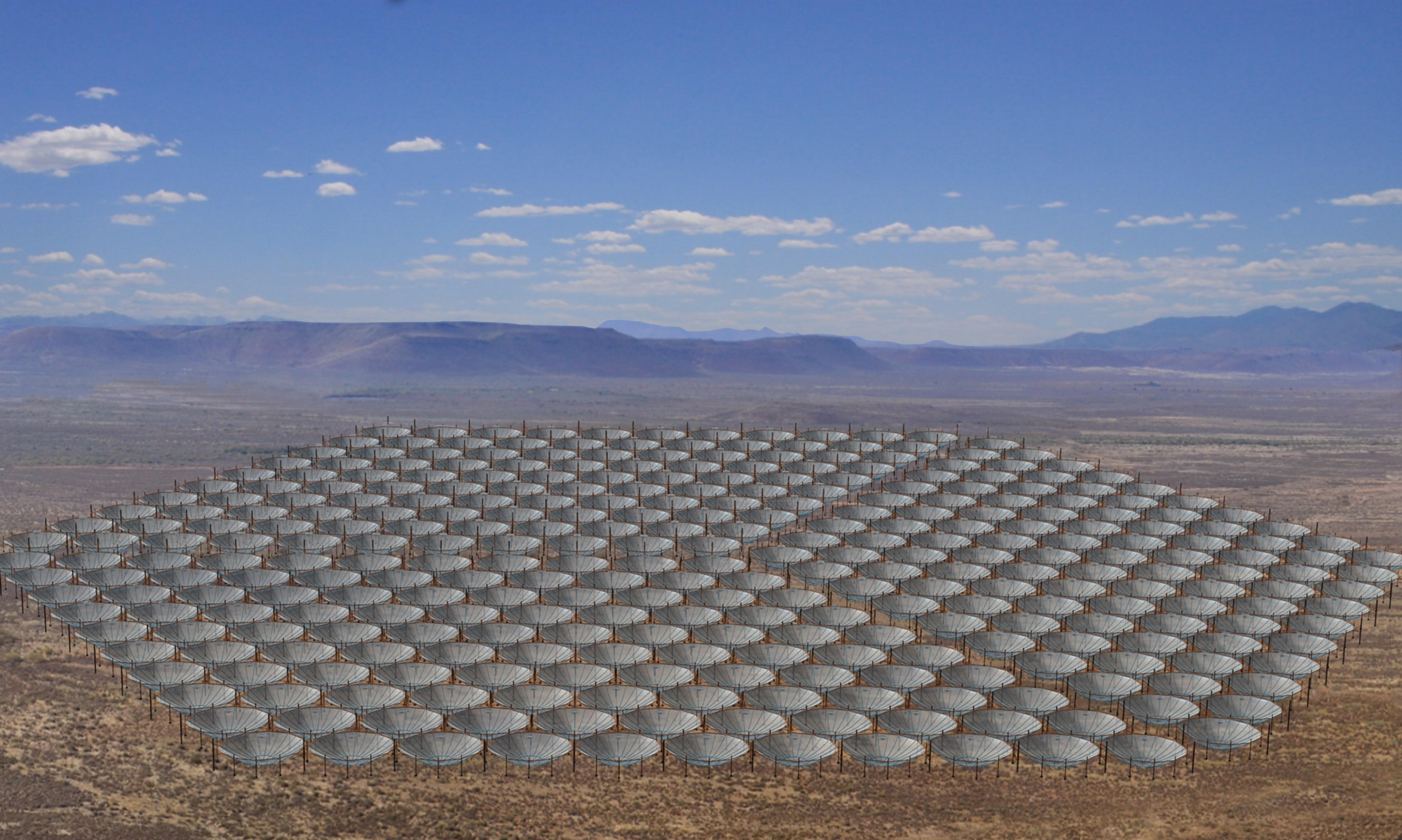


What does HERA actually measure?

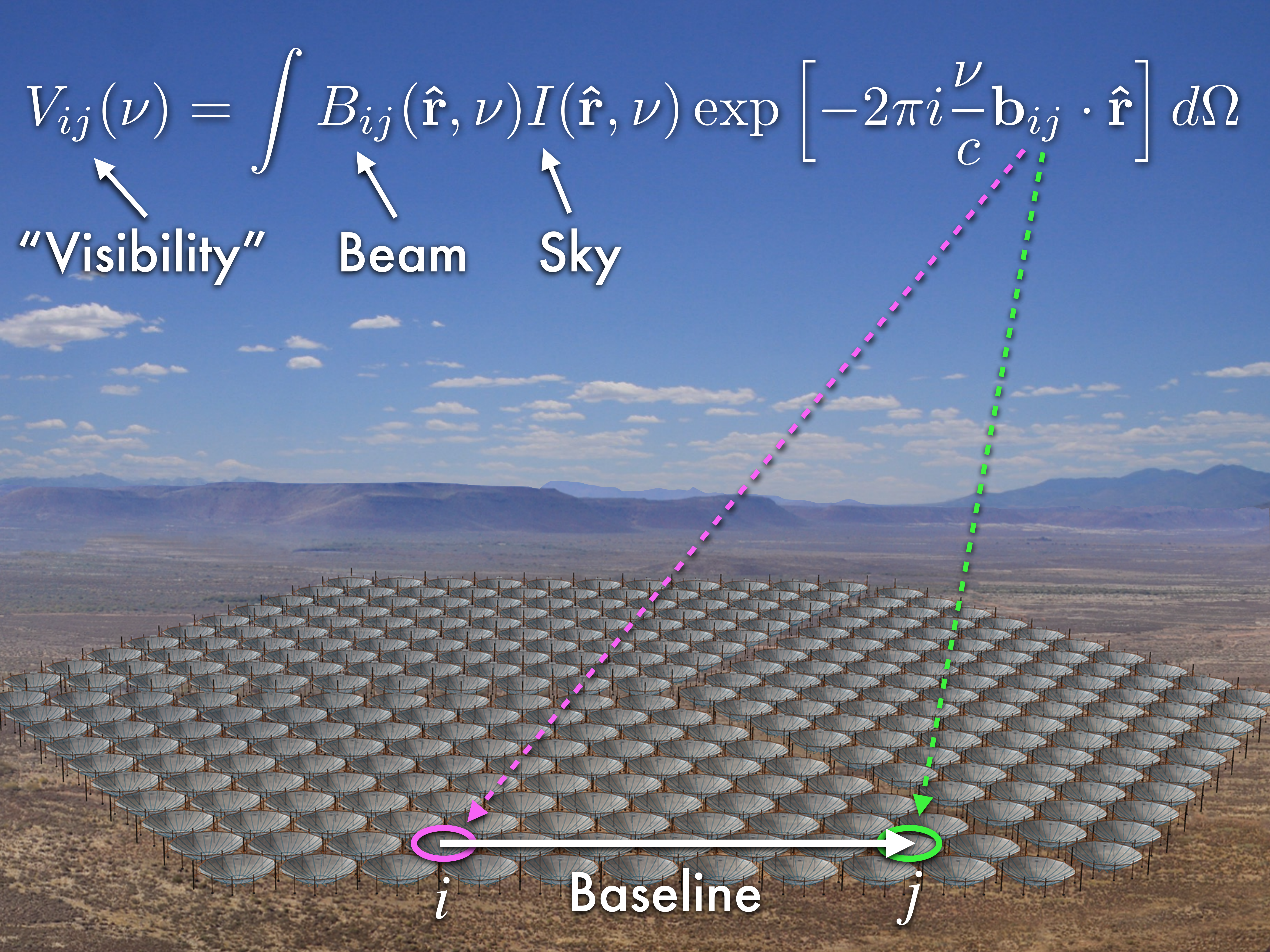


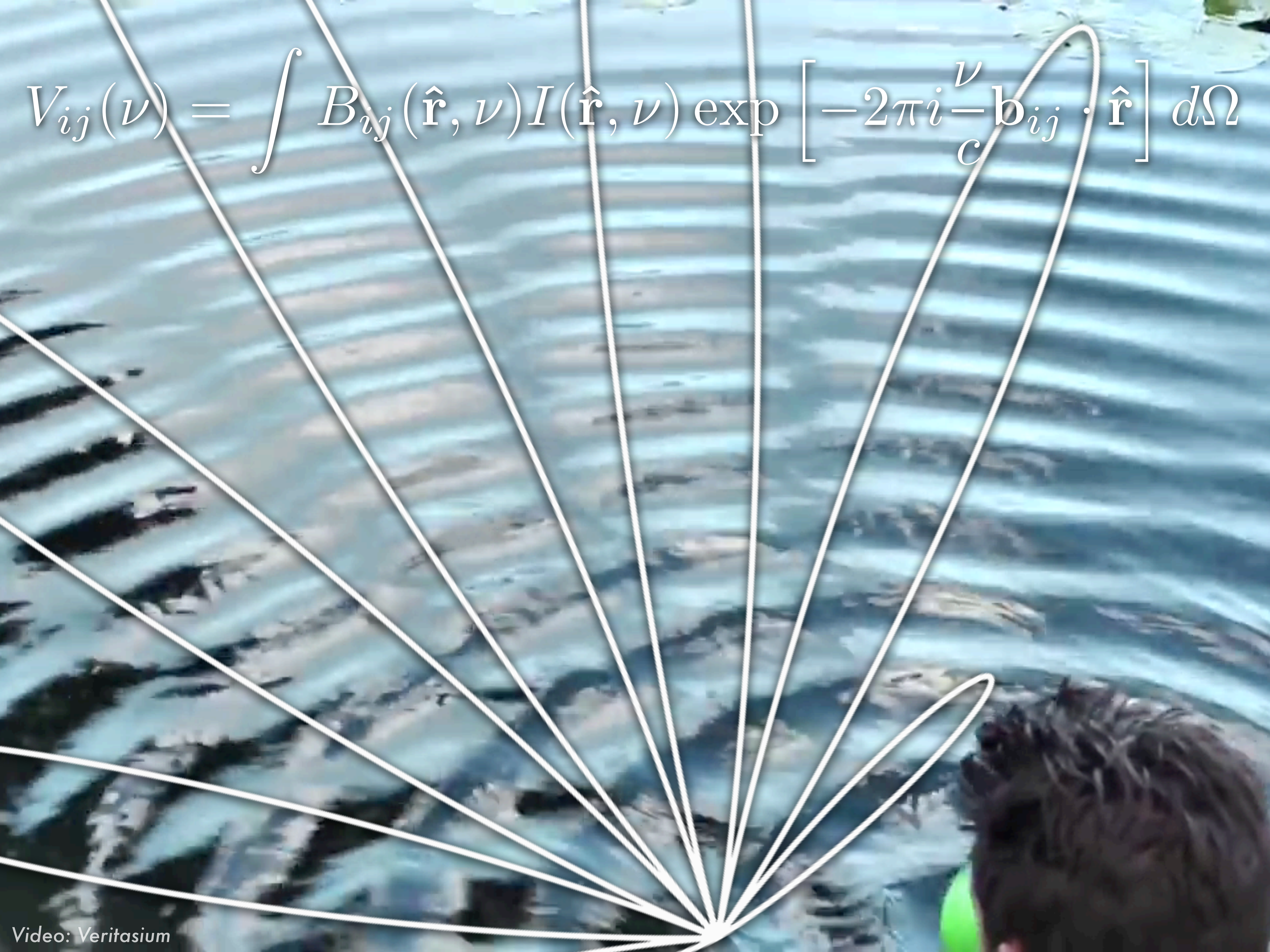

Every dish looks straight up with a ~10° FoV.

Interferometers measure Fourier modes on the sky, which we call "visibilities."



$$V_{ij}(\nu) = \int B_{ij}(\hat{\mathbf{r}}, \nu) I(\hat{\mathbf{r}}, \nu) \exp\left[-2\pi i \frac{\nu}{c} \mathbf{b}_{ij} \cdot \hat{\mathbf{r}}\right] d\Omega$$




$$V_{ij}(\nu) = \int B_{ij}(\hat{\mathbf{r}}, \nu) I(\hat{\mathbf{r}}, \nu) \exp\left[-2\pi i \frac{\nu}{c} \mathbf{b}_{ij} \cdot \hat{\mathbf{r}}\right] d\Omega$$
Video: Veritasium

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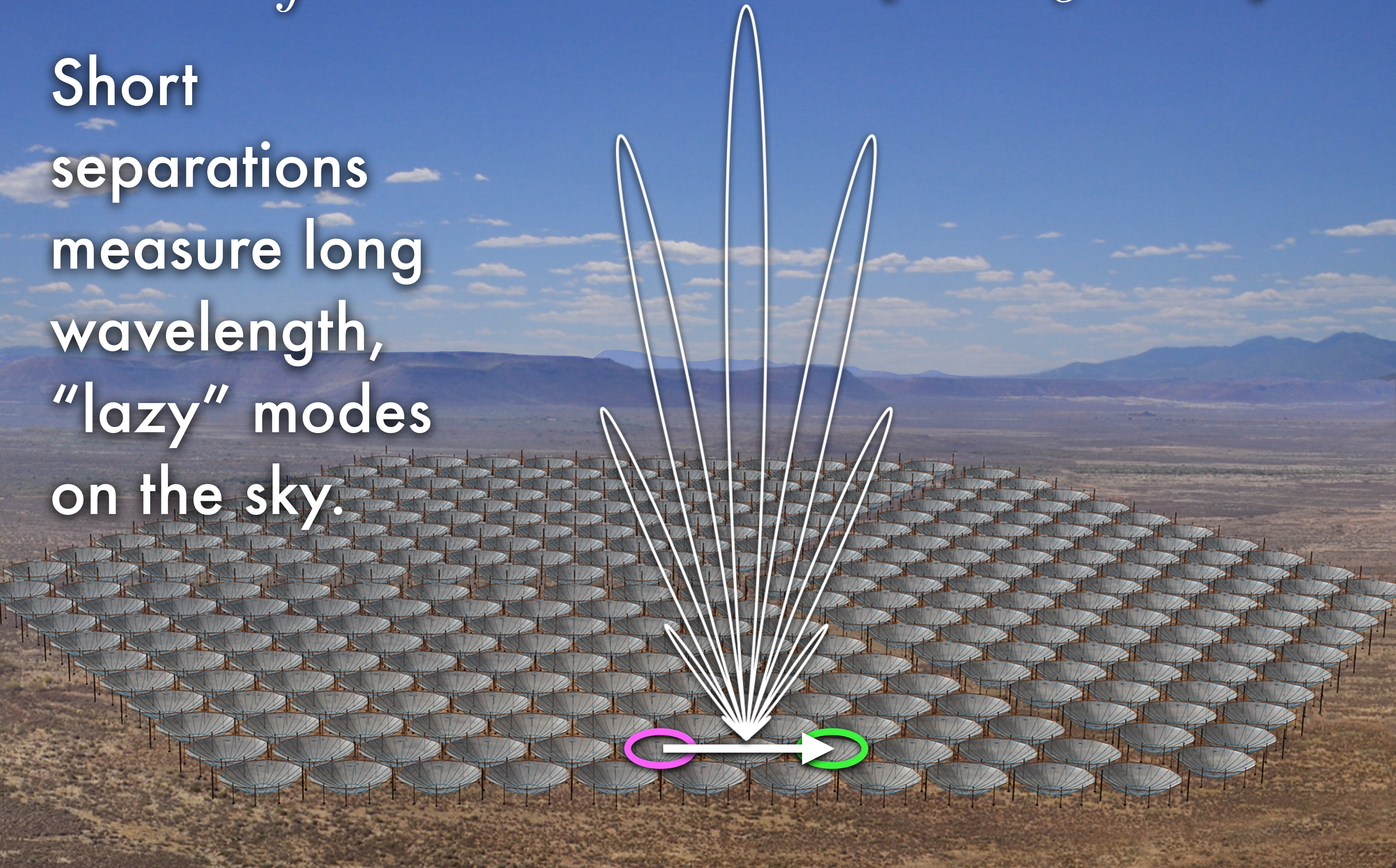
Short separations measure long wavelength, “lazy” modes on the sky.



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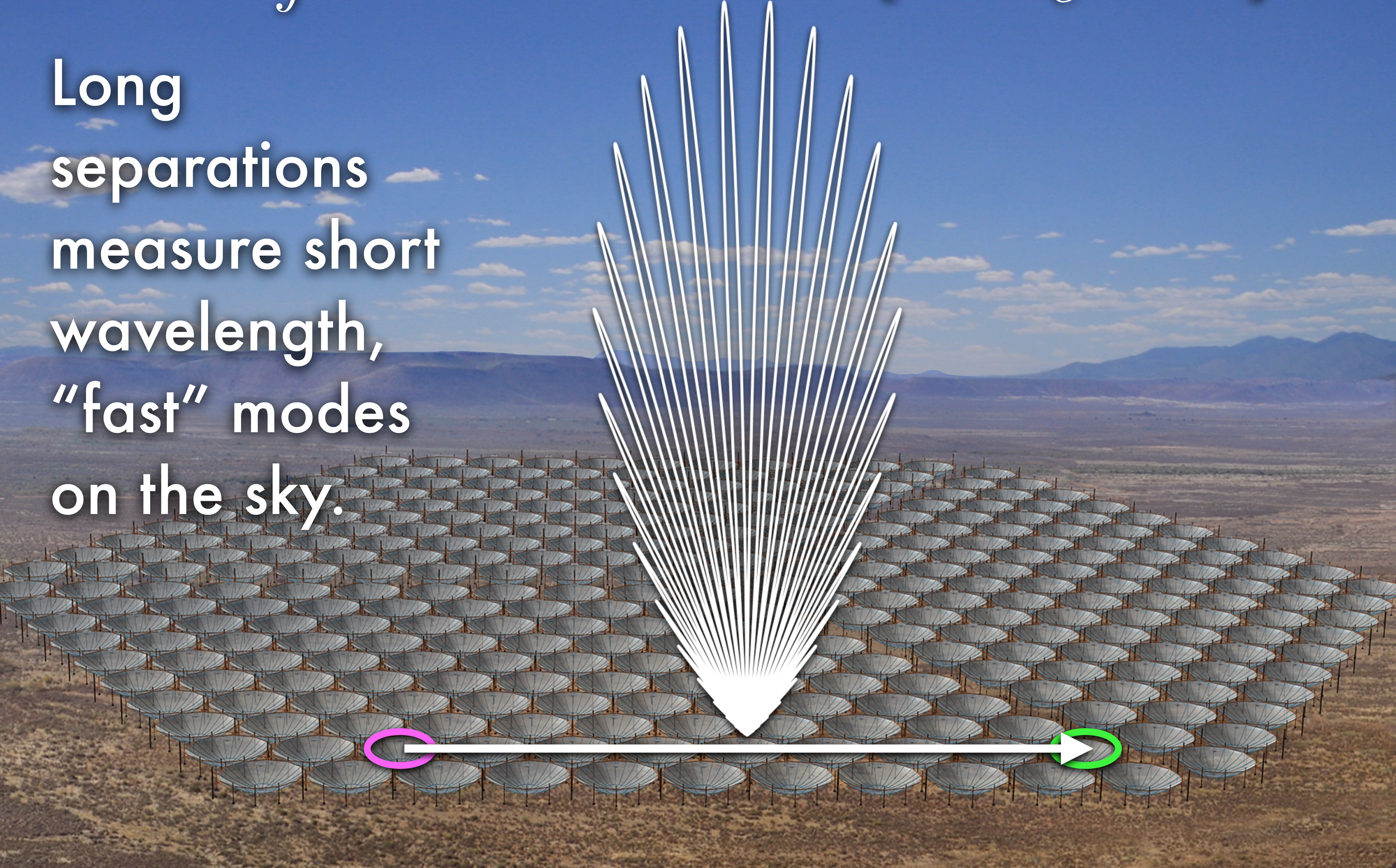
Long separations measure short wavelength, "fast" modes on the sky.



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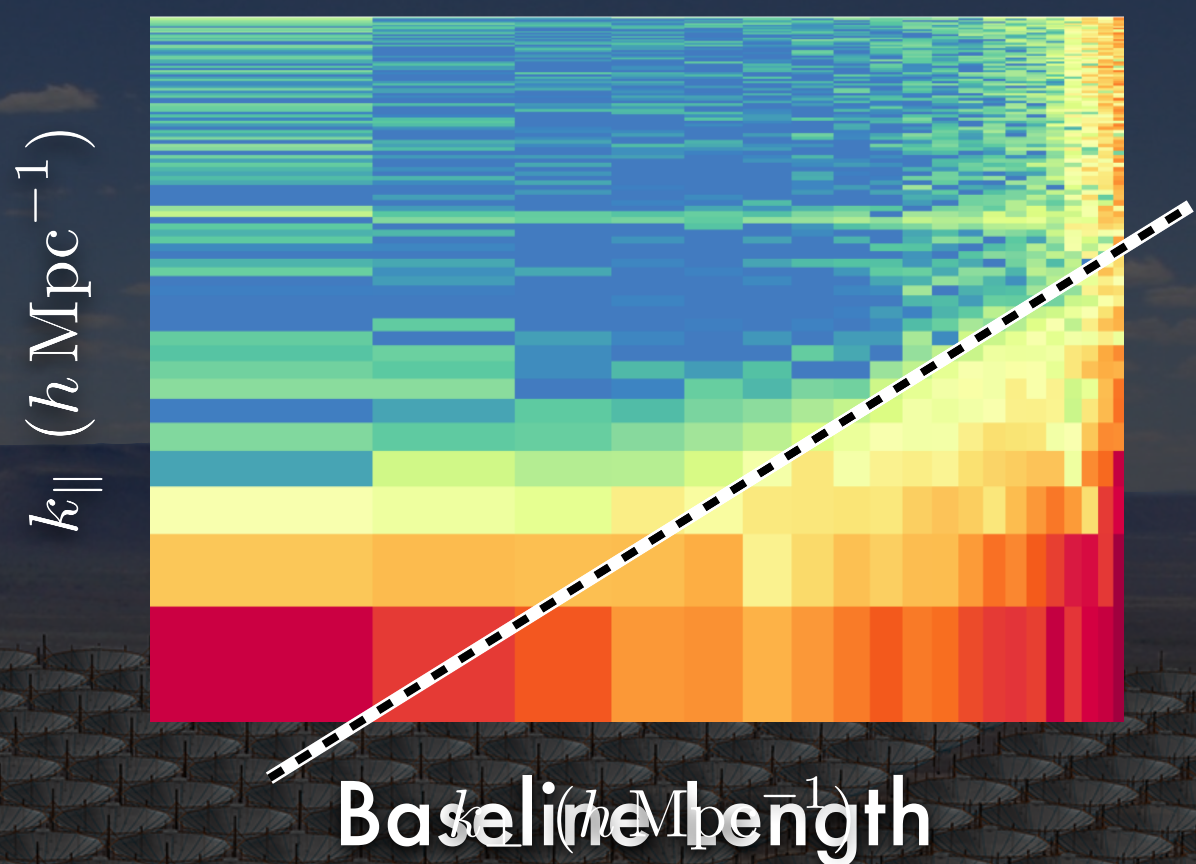
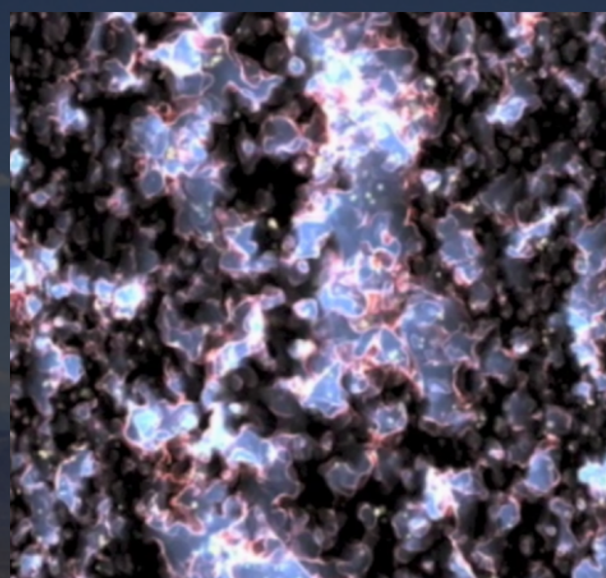
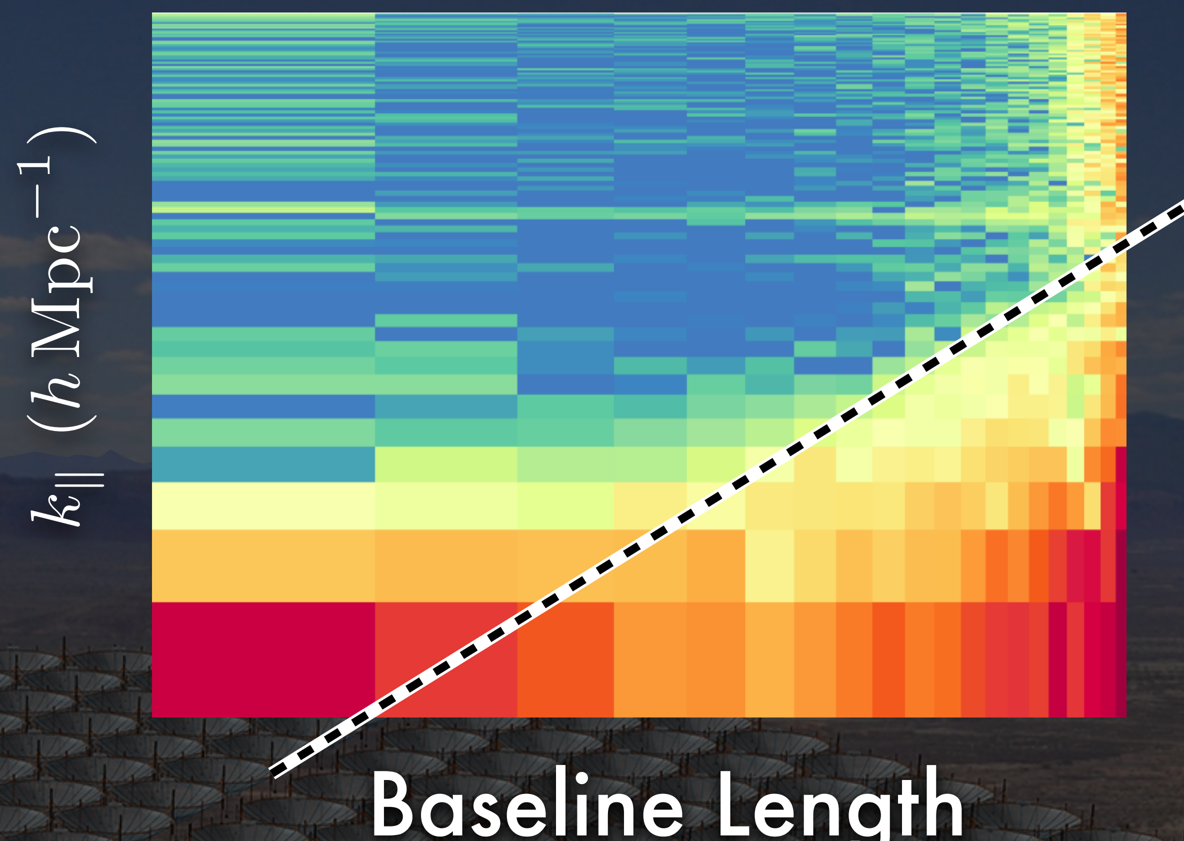


k⊥ is effectively baseline length.

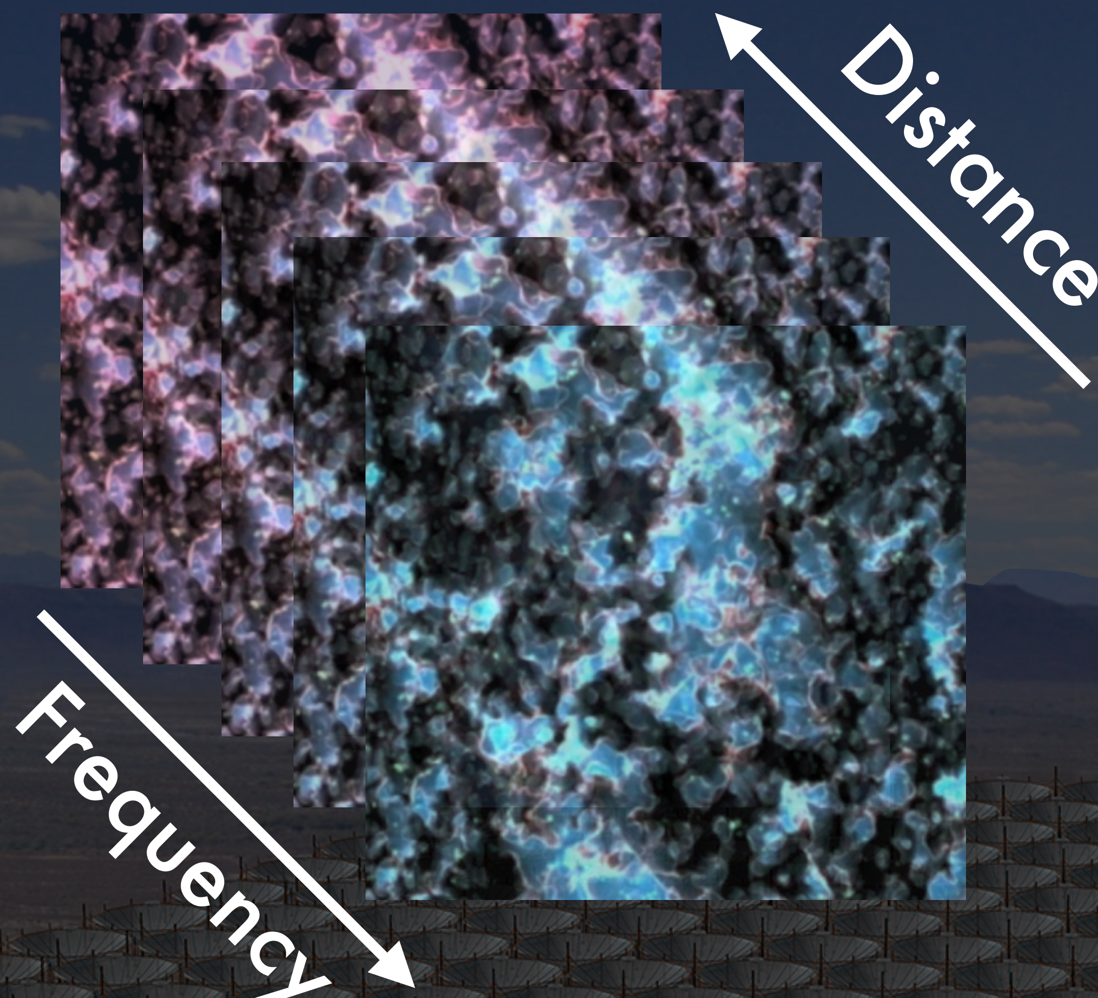
$$V_{ij}(\nu) = \int B_{ij}(\hat{\mathbf{r}}, \nu) I(\hat{\mathbf{r}}, \nu) \exp\left[-2\pi i \frac{\nu}{c} \mathbf{b}_{ij} \cdot \hat{\mathbf{r}}\right] d\Omega$$

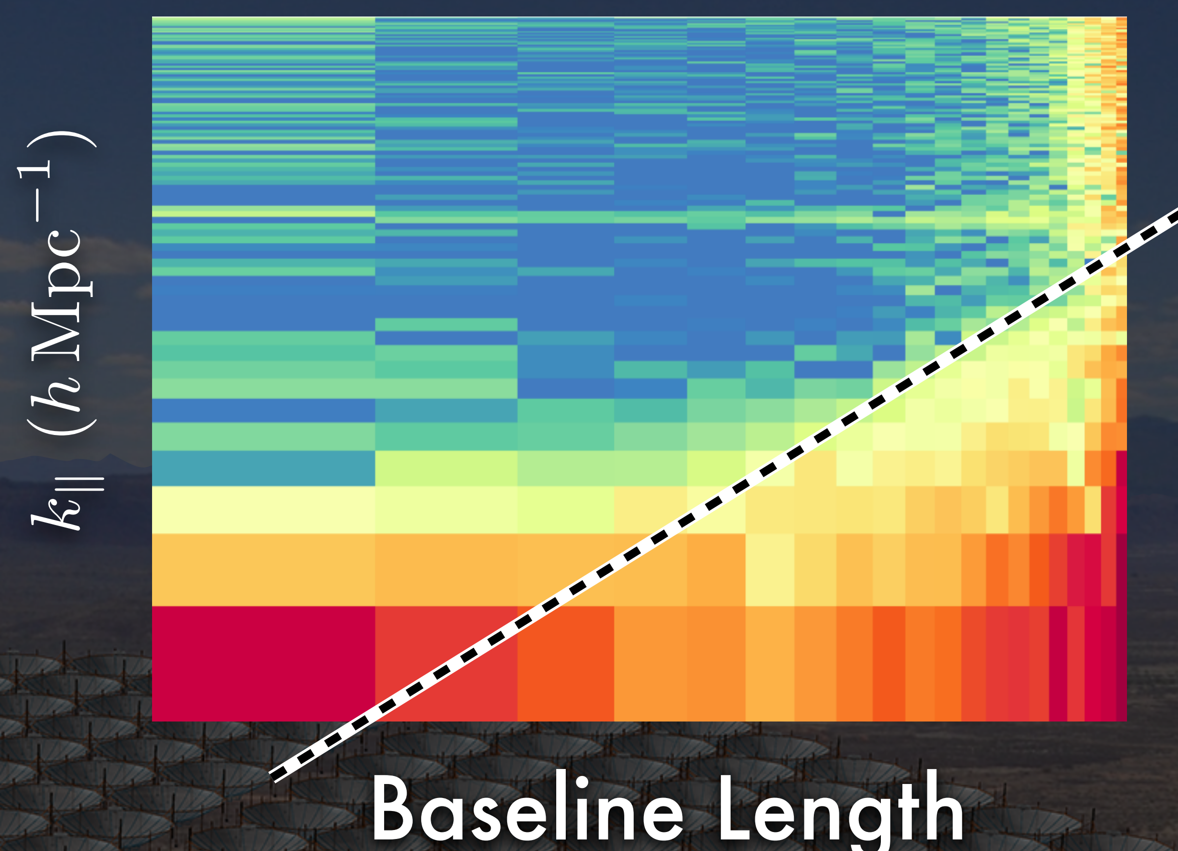




Since frequency maps to distance...

$$V_{ij}(\nu) = \int B_{ij}(\hat{\mathbf{r}}, \nu) I(\hat{\mathbf{r}}, \nu) \exp\left[-2\pi i \frac{\nu}{c} \mathbf{b}_{ij} \cdot \hat{\mathbf{r}}\right] d\Omega$$





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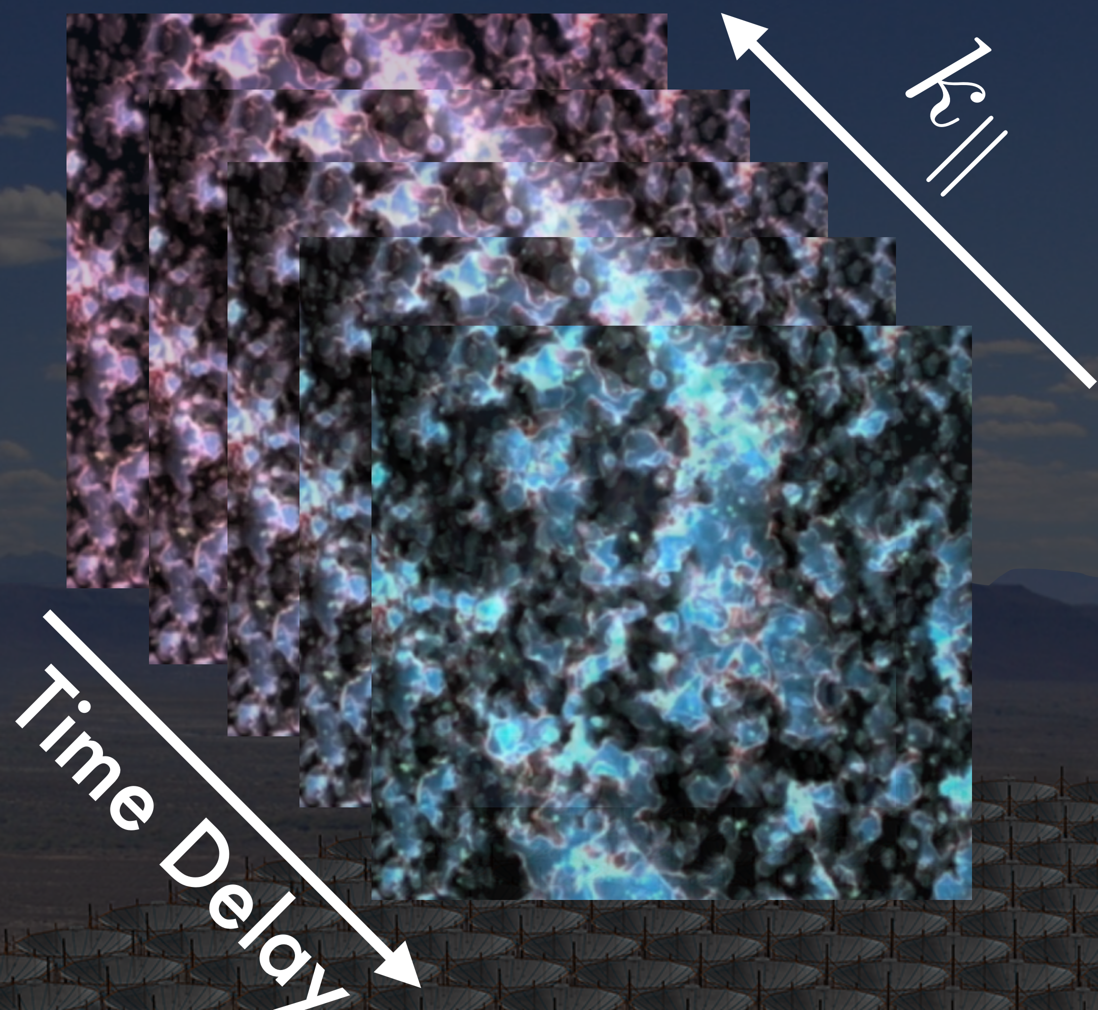
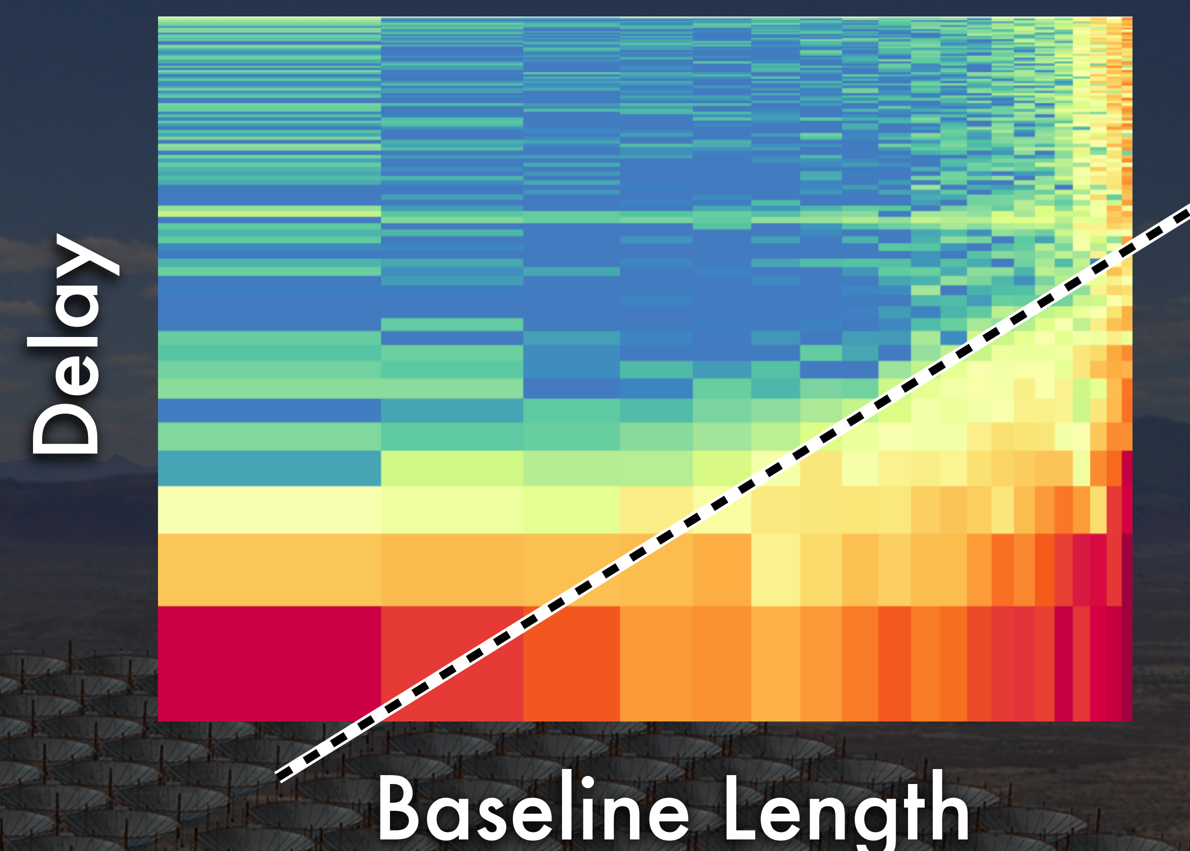
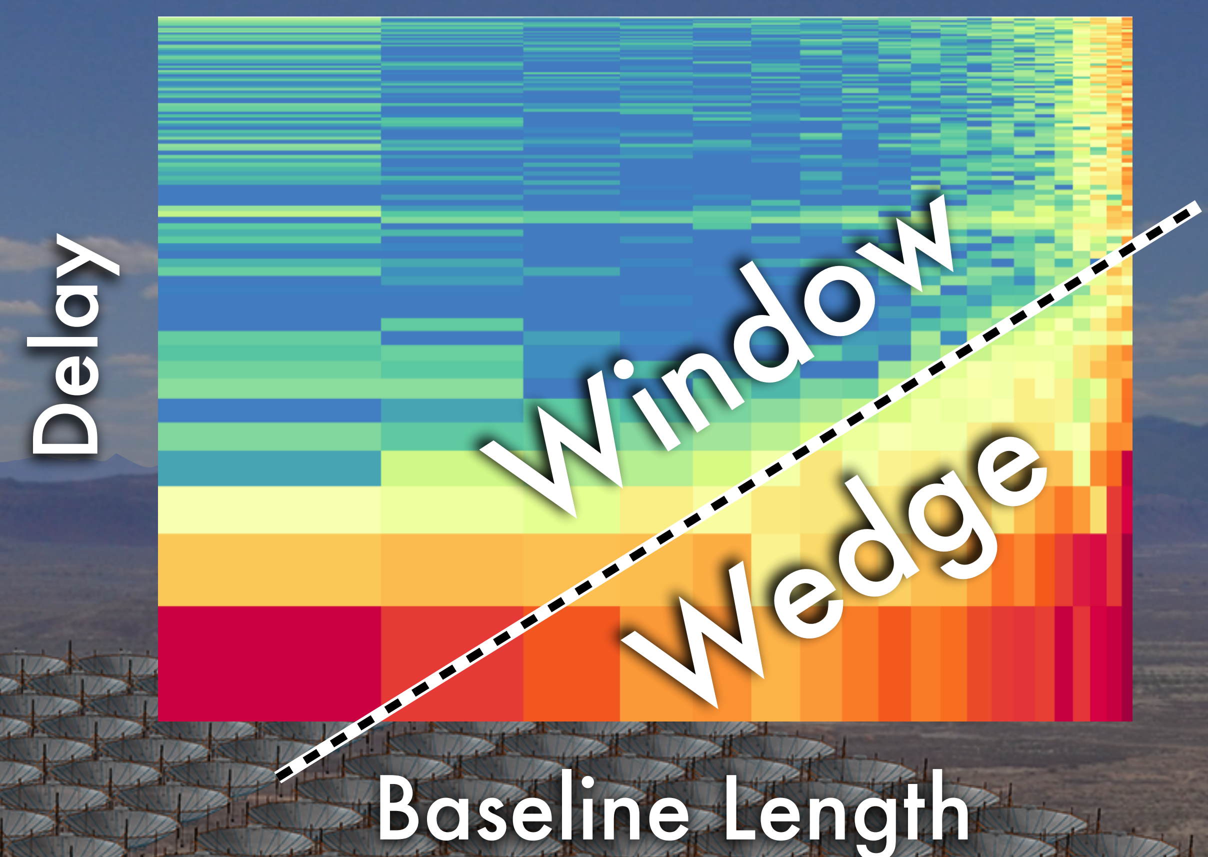




$k_\parallel$ is effectively time delay.

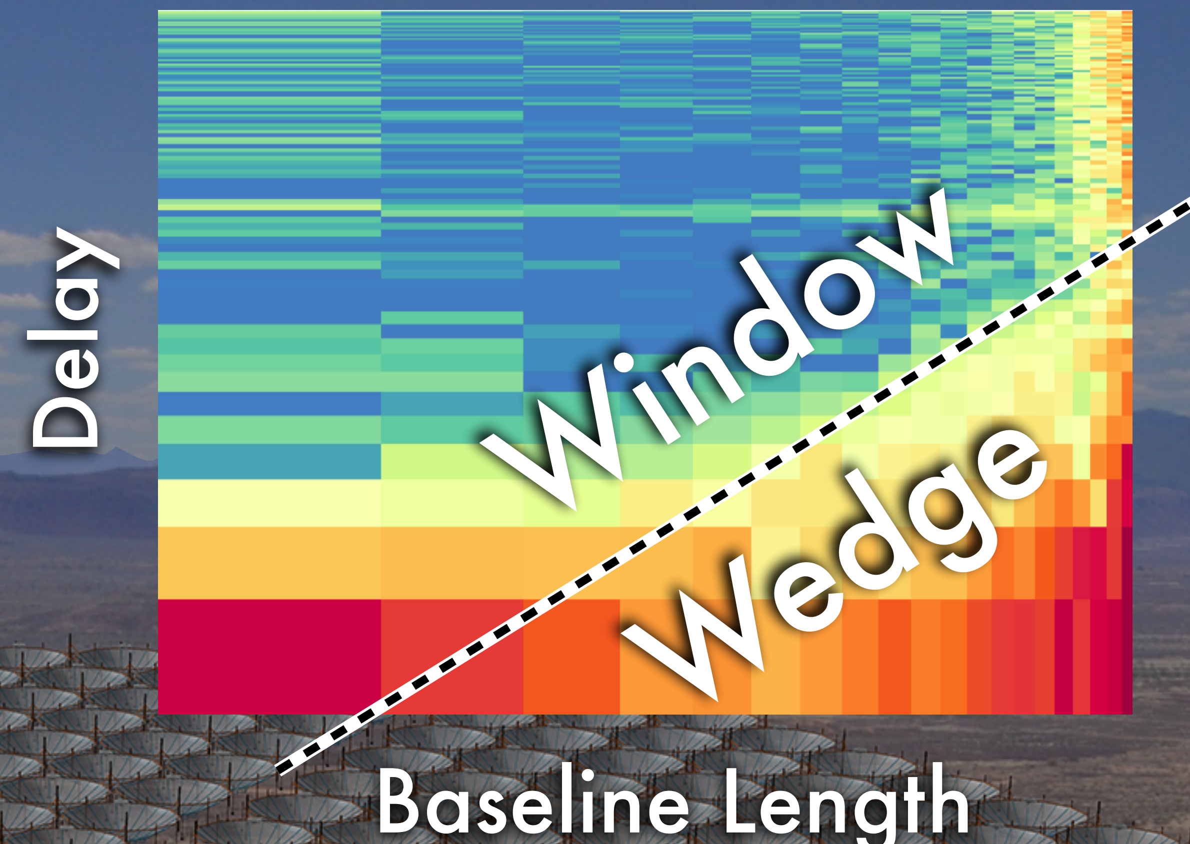
The maximum delay of foregrounds for a baseline is simply the light travel time.

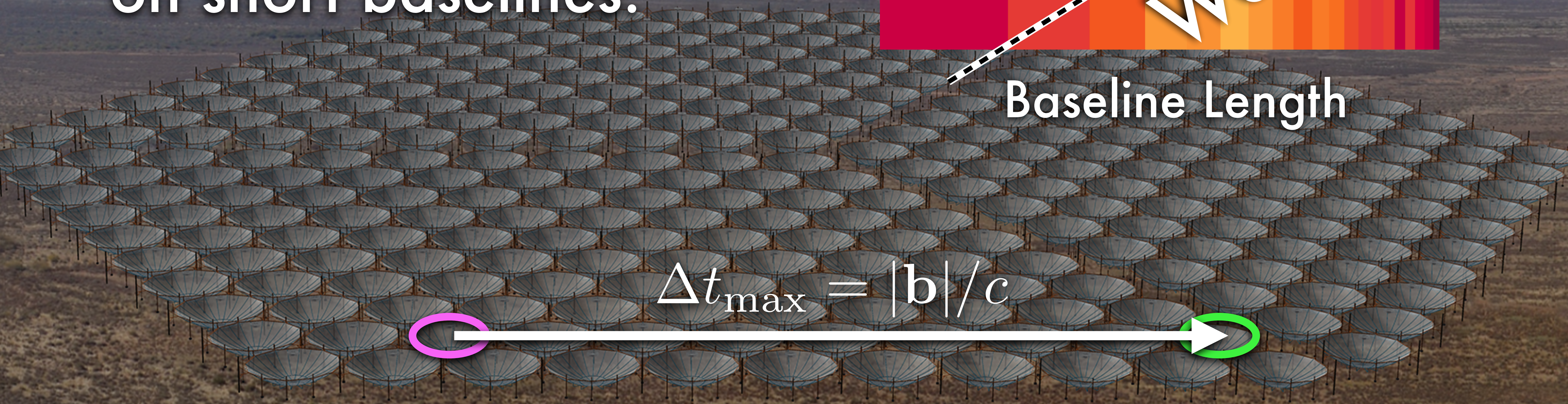


$$\Delta t_{\mathrm{max}} = |\mathbf{b}|/c$$

Parsons et al. (2012)

Our design for HERA's configuration maximizes sensitivity on short baselines.





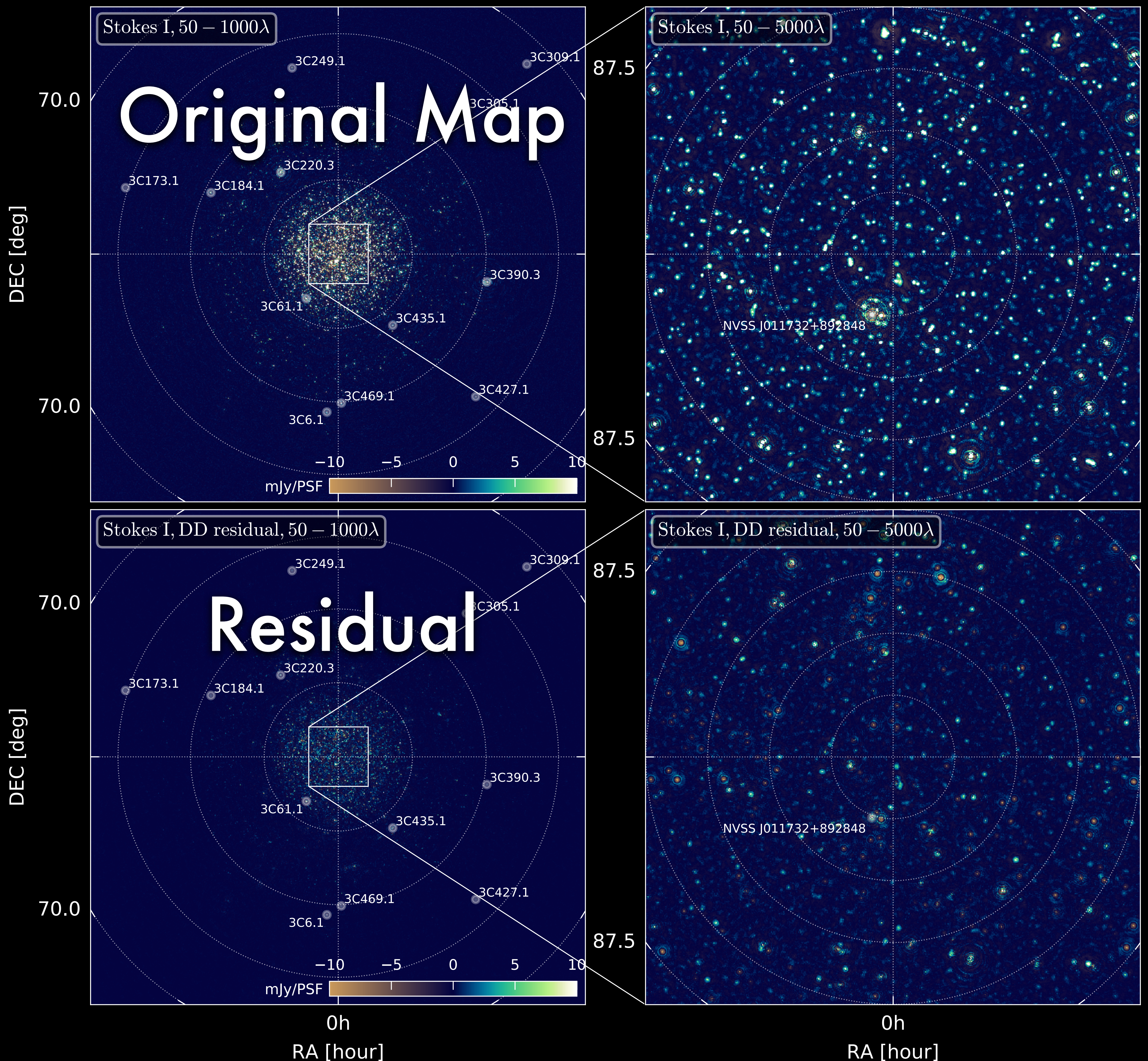
Dillon & *Parsons (2016)*

Working outside the wedge manages our ignorance — we trade sensitivity for robustness.


That's not the only approach...
MWA

LOFAR


SKA-Low is taking the
same basic approach.

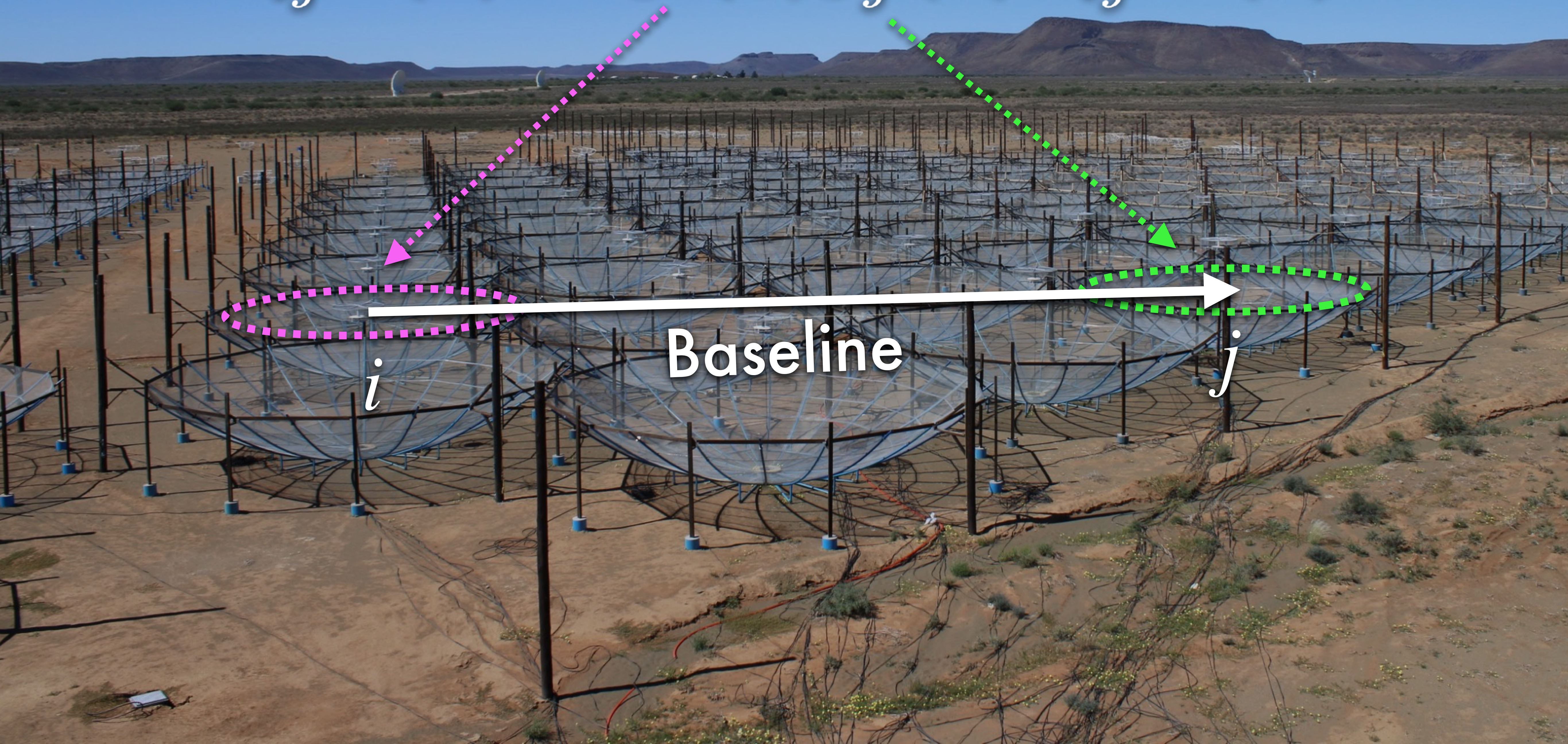


LOFAR relies on precise sky maps and beam models and even then needs some kind of high-pass filtering.

Mertens et al. (2020)

Neither foreground avoidance nor subtraction will work without precision calibration.

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



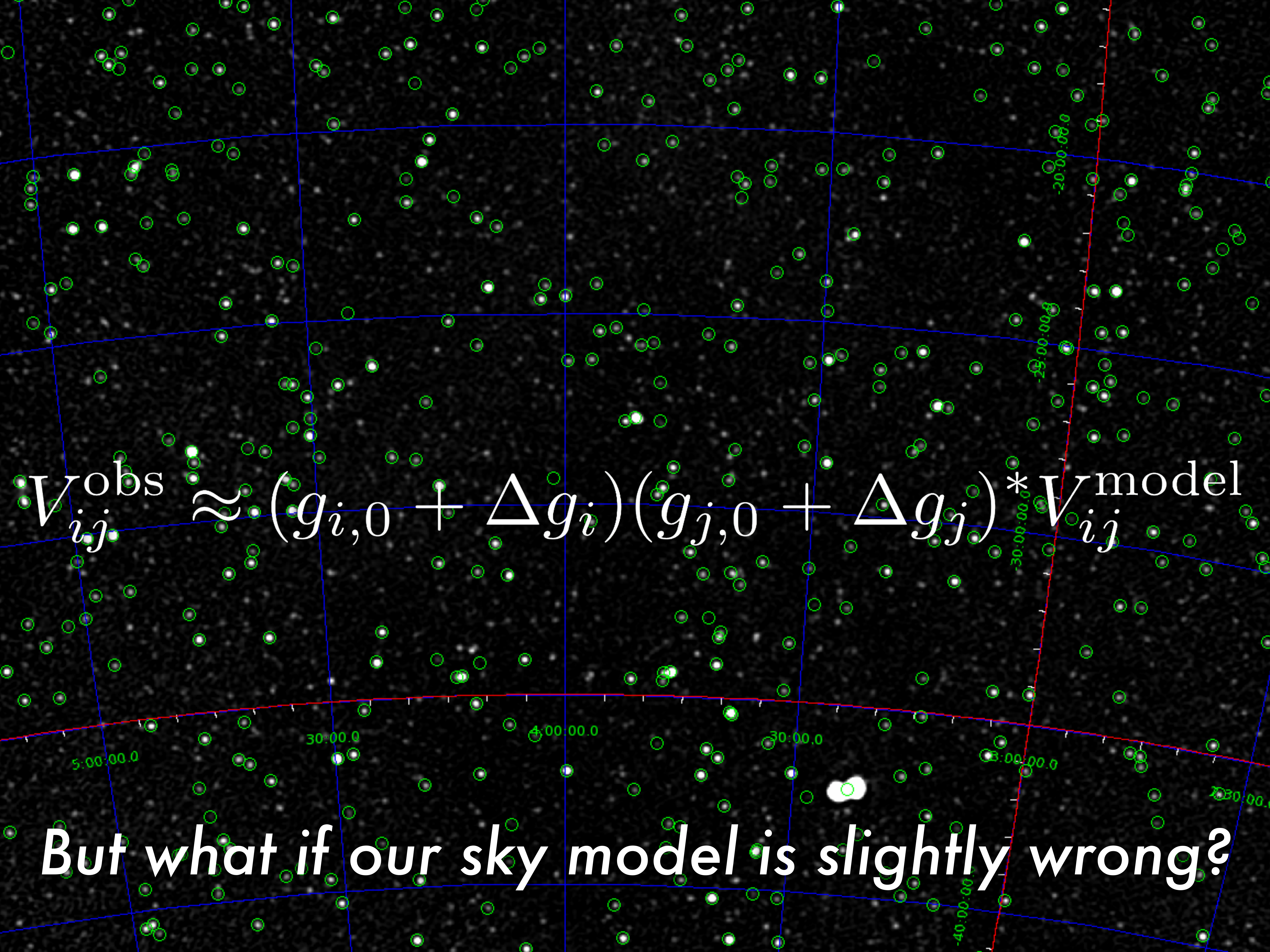
The Self-Cal Loop

Image, find sources, build model.

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

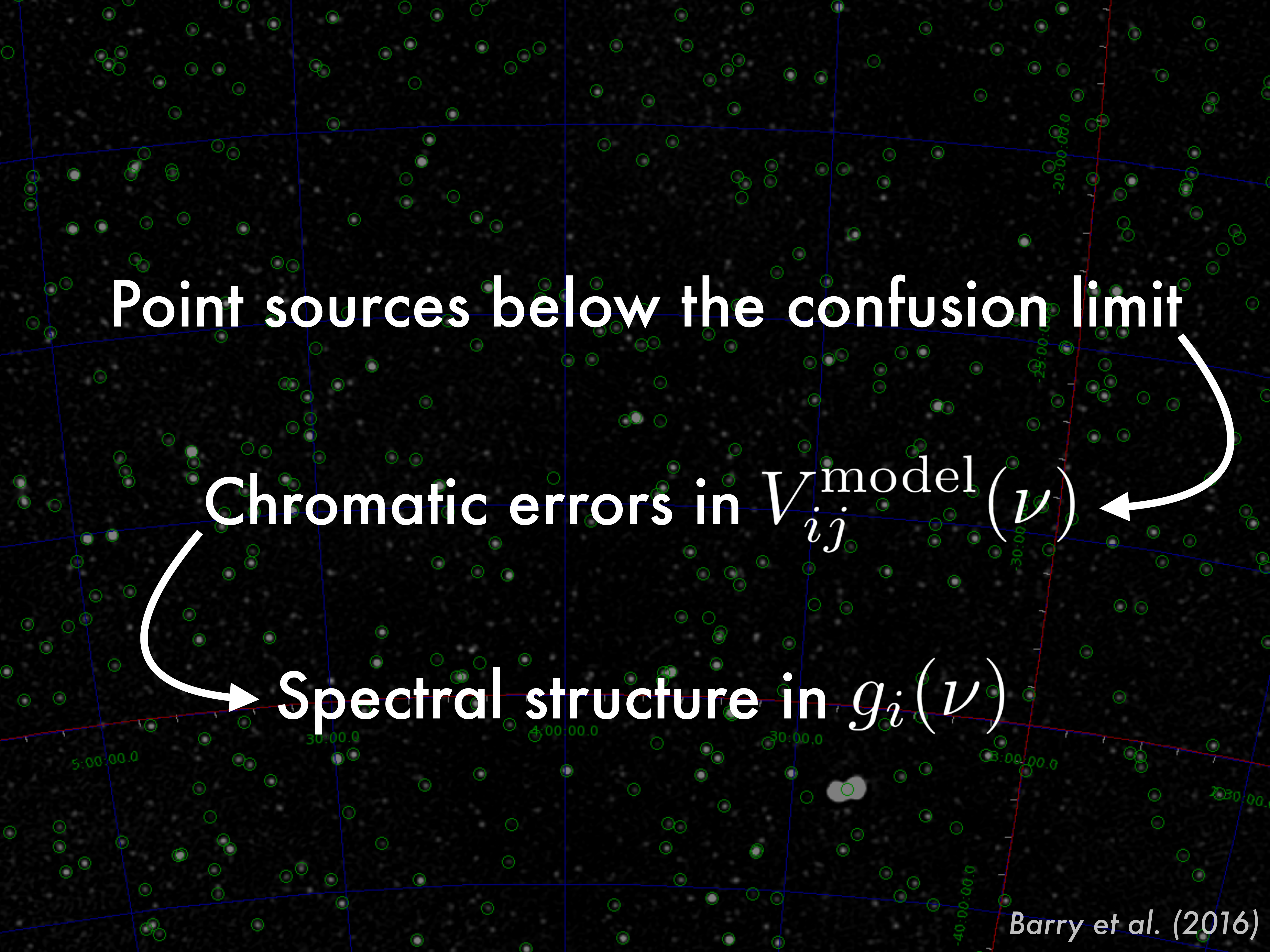
$$V_{ij}^{\mathrm{obs}} \approx (g_{i,0} + \Delta g_i)(g_{j,0} + \Delta g_j)^* V_{ij}^{\mathrm{model}}$$

Linearize and solve for gains.



$$V_{ij}^{\mathrm{obs}} \approx (g_{i,0} + \Delta g_i)(g_{j,0} + \Delta g_j)^* V_{ij}^{\mathrm{model}}$$

But what if our sky model is slightly wrong?



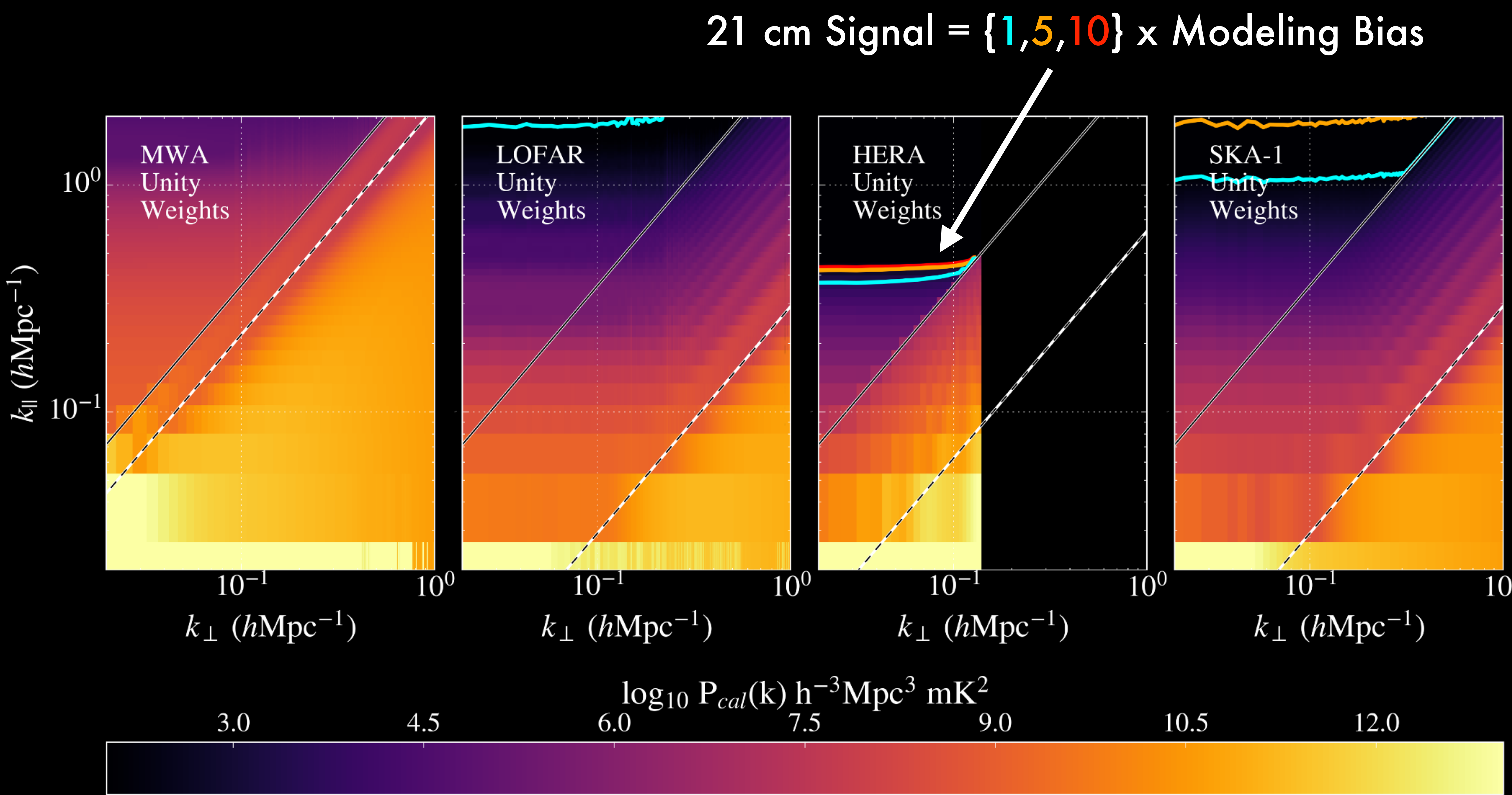
Point sources below the confusion limit

Chromatic errors in $V_{ij}^{\mathrm{model}}(\nu)$

Spectral structure in $g_i(\nu)$

Barry et al. (2016)

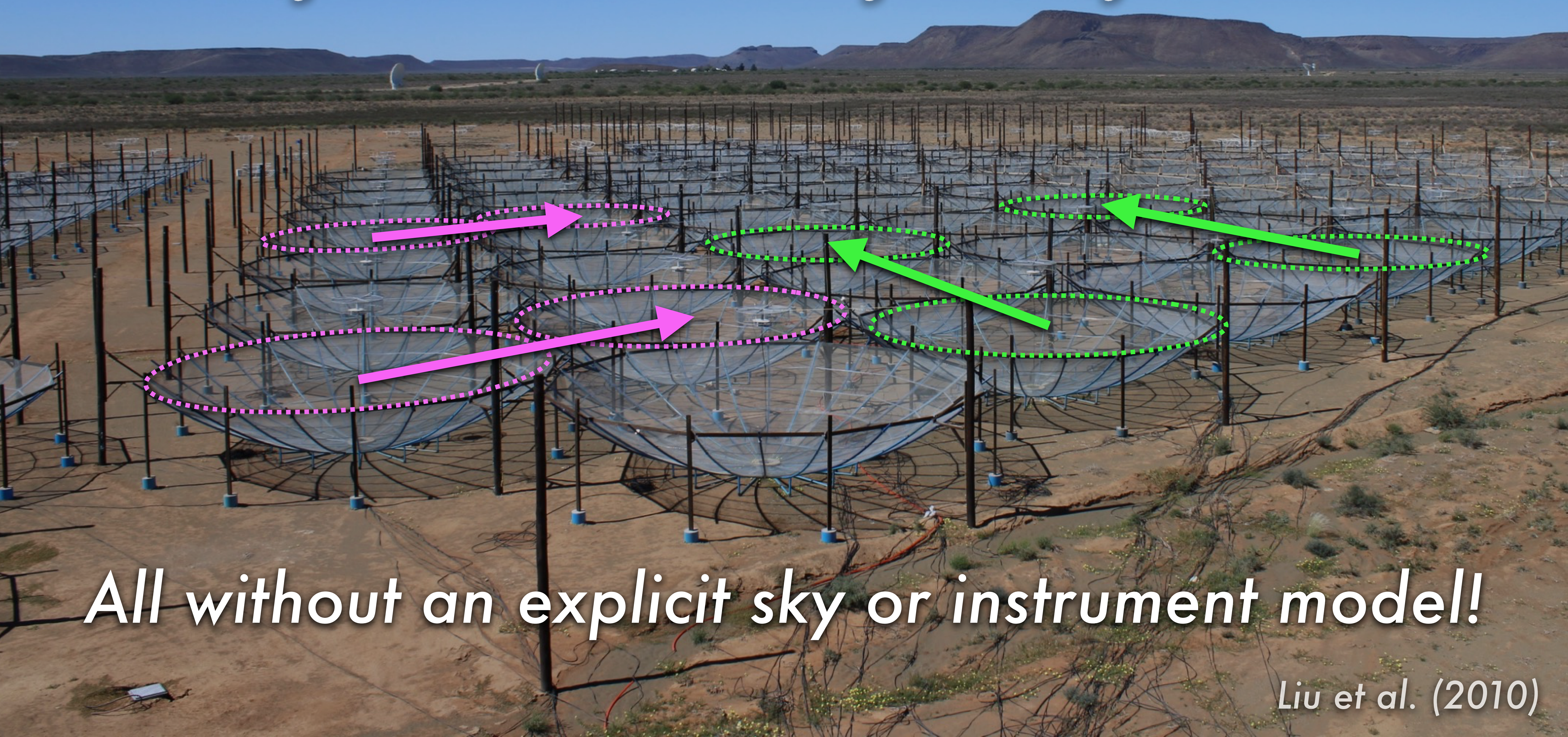
Structure in $g_i(\nu)$ is set by longest baseline b_{ij}. Modeling error turns the wedge into a brick.



Ewall-Wice, Dillon, Liu, Hewitt (2016)

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

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

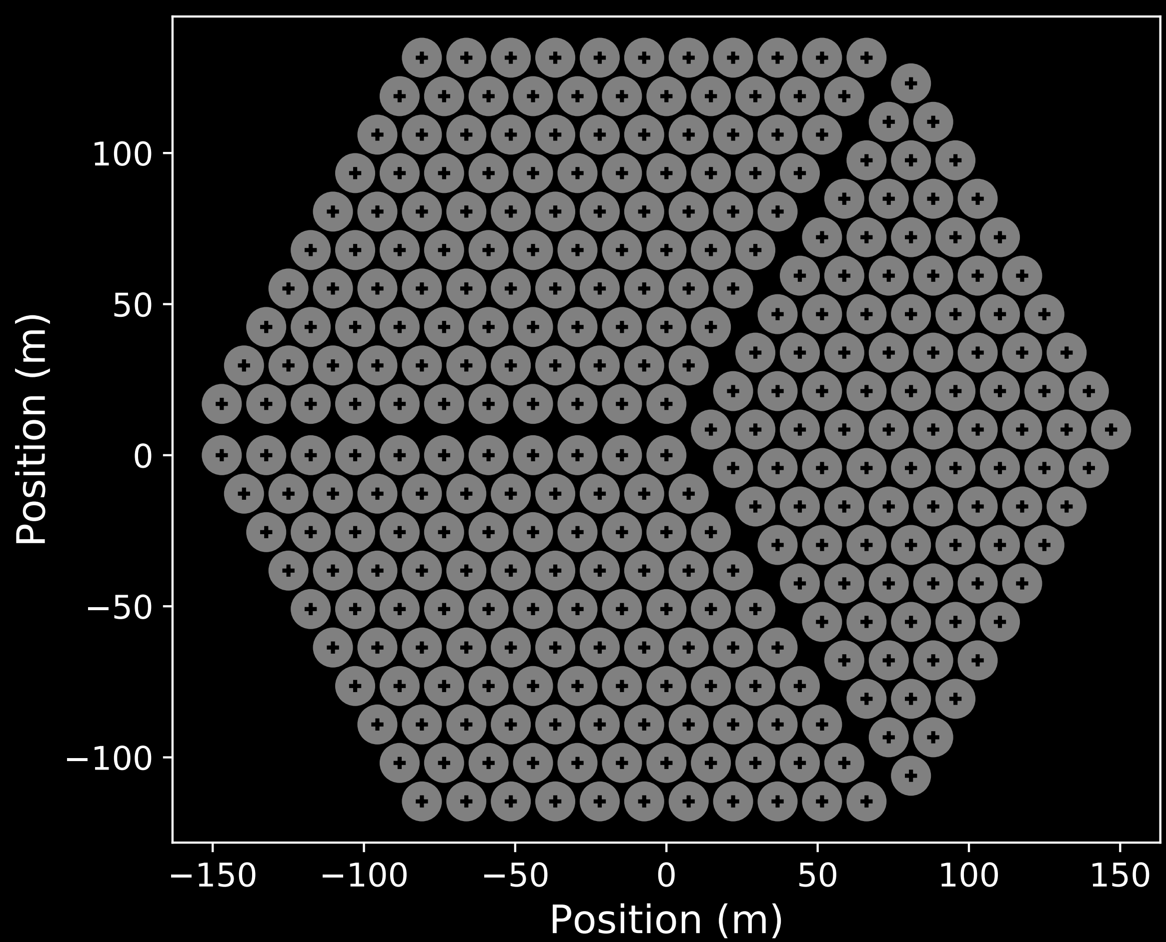


All without an explicit sky or instrument model!

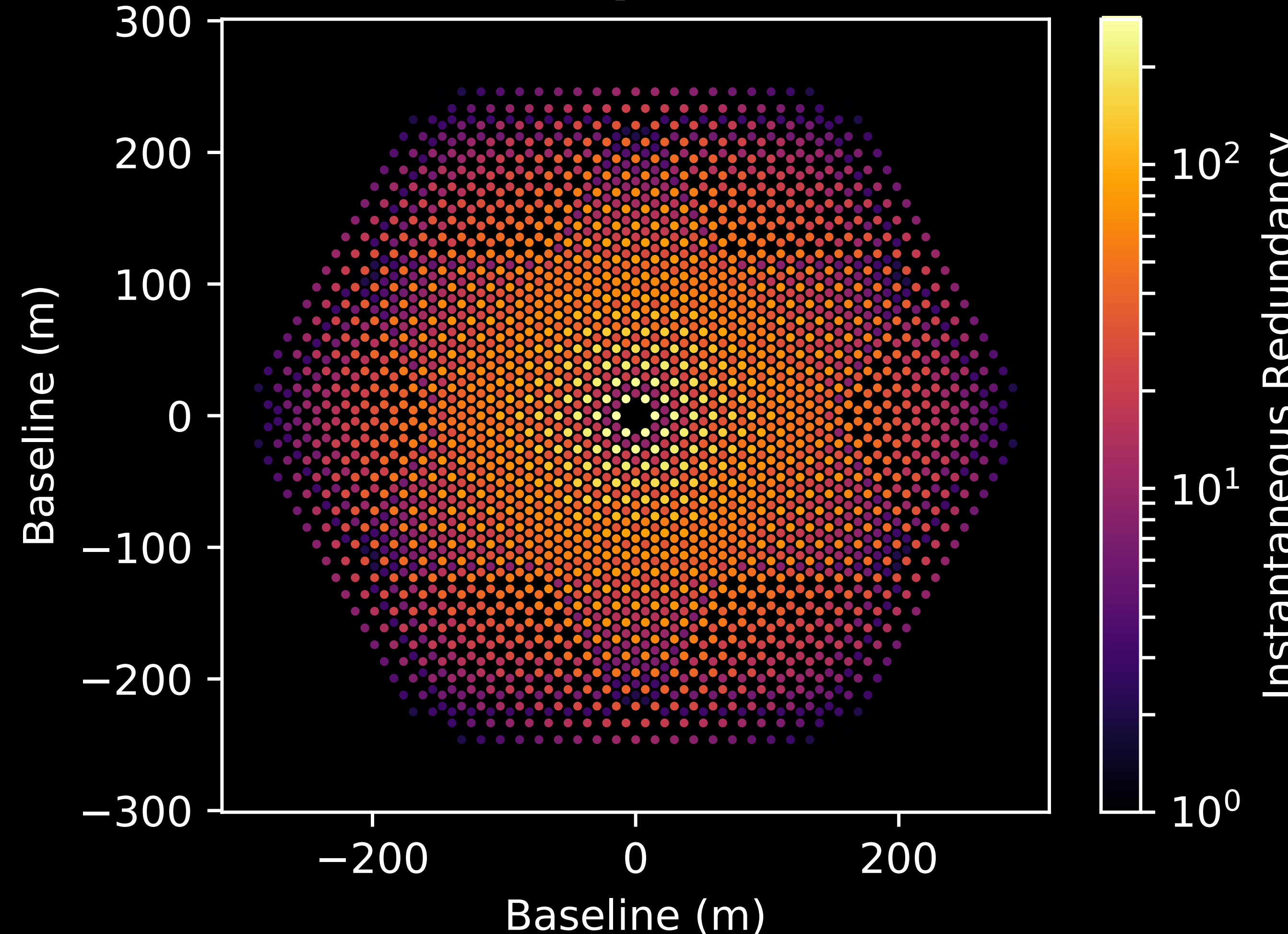
Liu et al. (2010)

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

320 Antenna Gains



1,501 Unique Visibilities



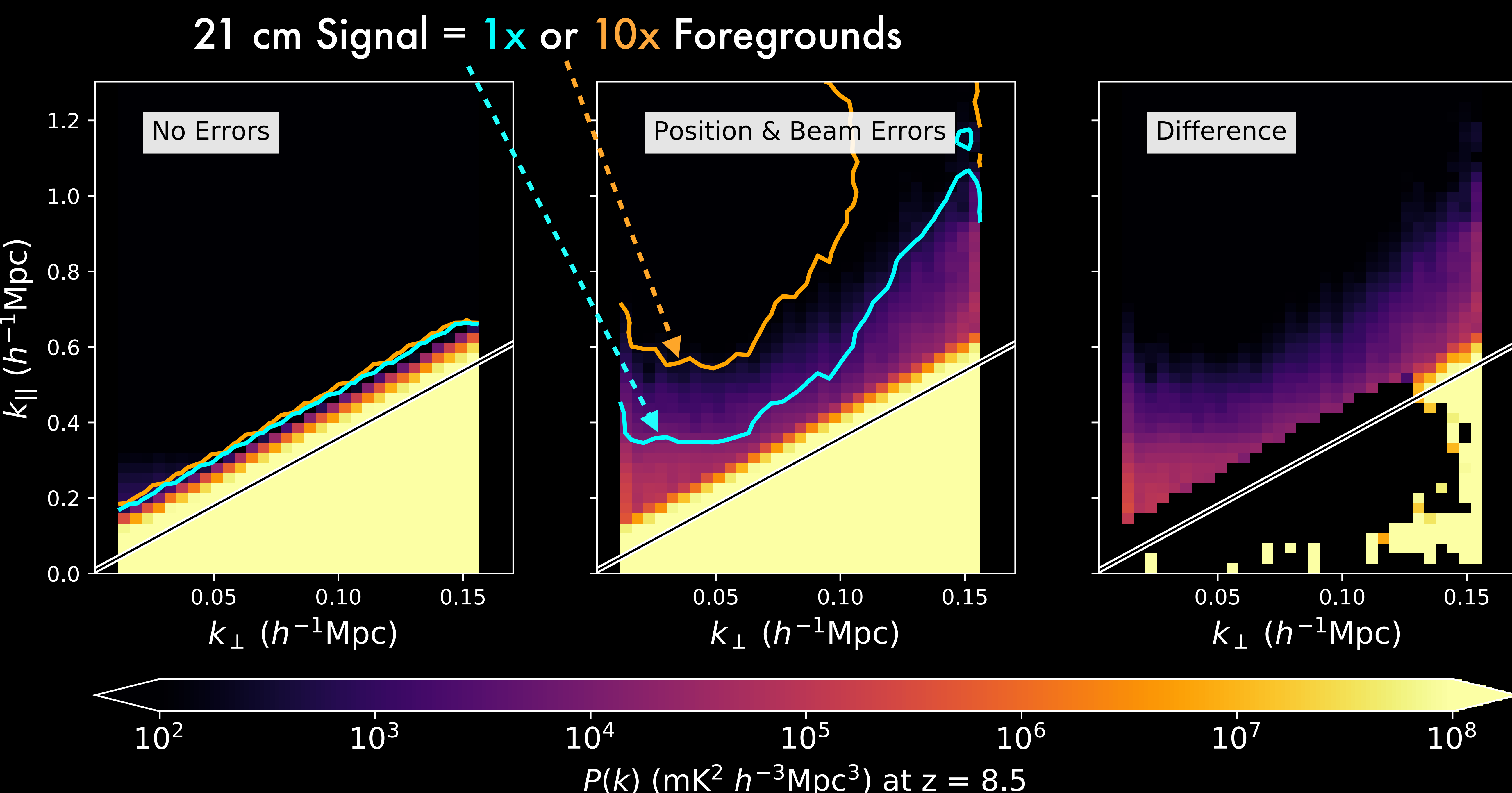
51,040 Total Measurements

Goal: Minimize $\chi^2 \equiv \sum \frac{\left| V_{ij}^{\mathrm{obs}} - g_i g_j^* V_{i-j}^{\mathrm{sol}} \right|^2}{\sigma_{ij}^2}$

Dillon & *Parsons (2016)*

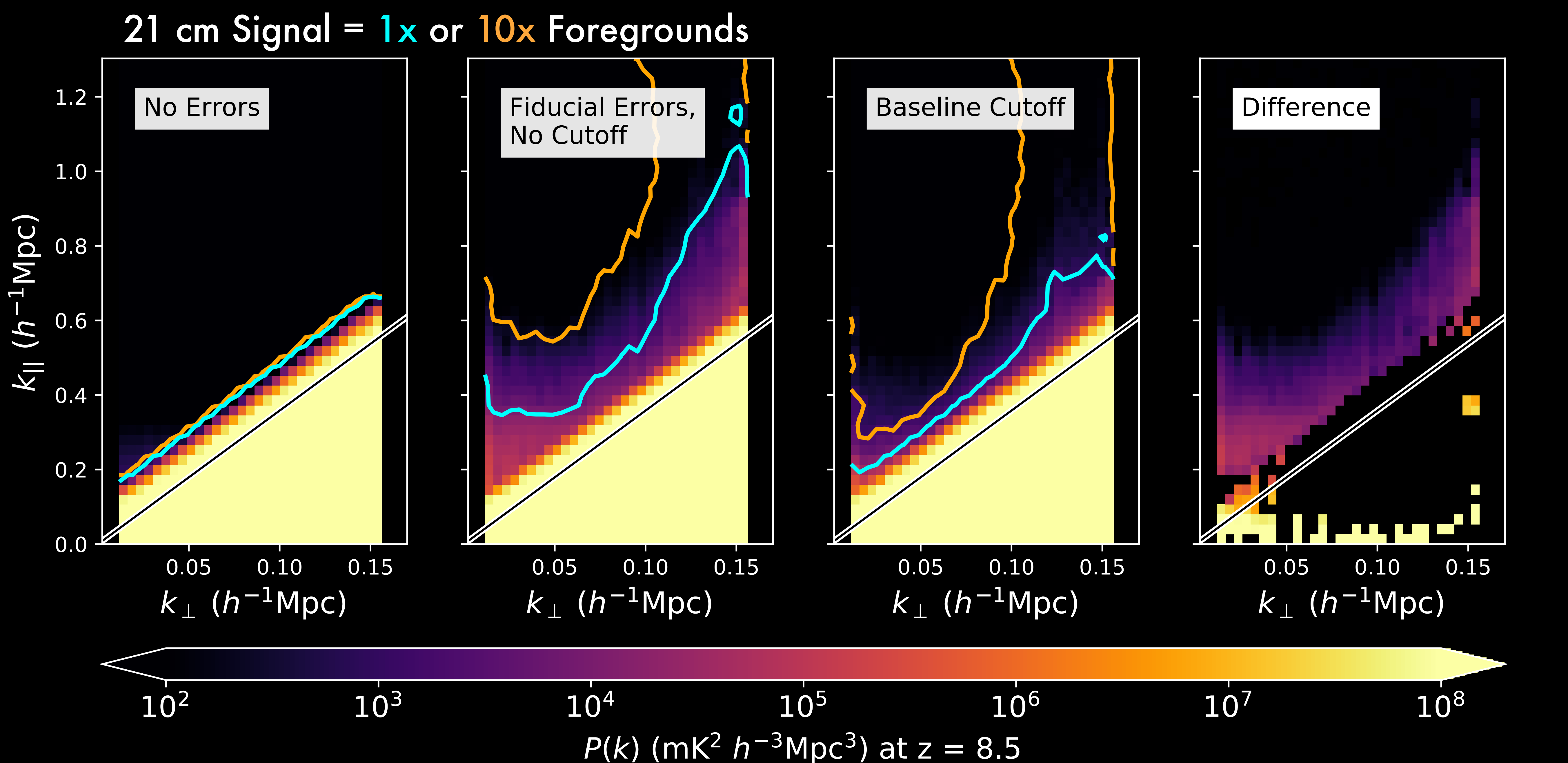

Redundant calibration is no panacea.
Naomi Orosz
Former UCB Undergraduate
CHAMBLISS POSTER
HERA
The Hydrogen Epoch of Reionization Array
Berkeley
The Effect of Antenna Position Errors on Redundant-Baseline Calibration of HERA
Naomi Orosz (UC Berkeley)
ABSTRACT
INTRODUCTION
Cosmic Dawn
METHODS
Measuring and Calibrating Visibilities
Redundant Baseline Calibration
SIMULATIONS
Science On a Sphere

Non-redundancy can contaminate the same region of Fourier space.



Orosz, **Dillon,** *et al. (2019)*

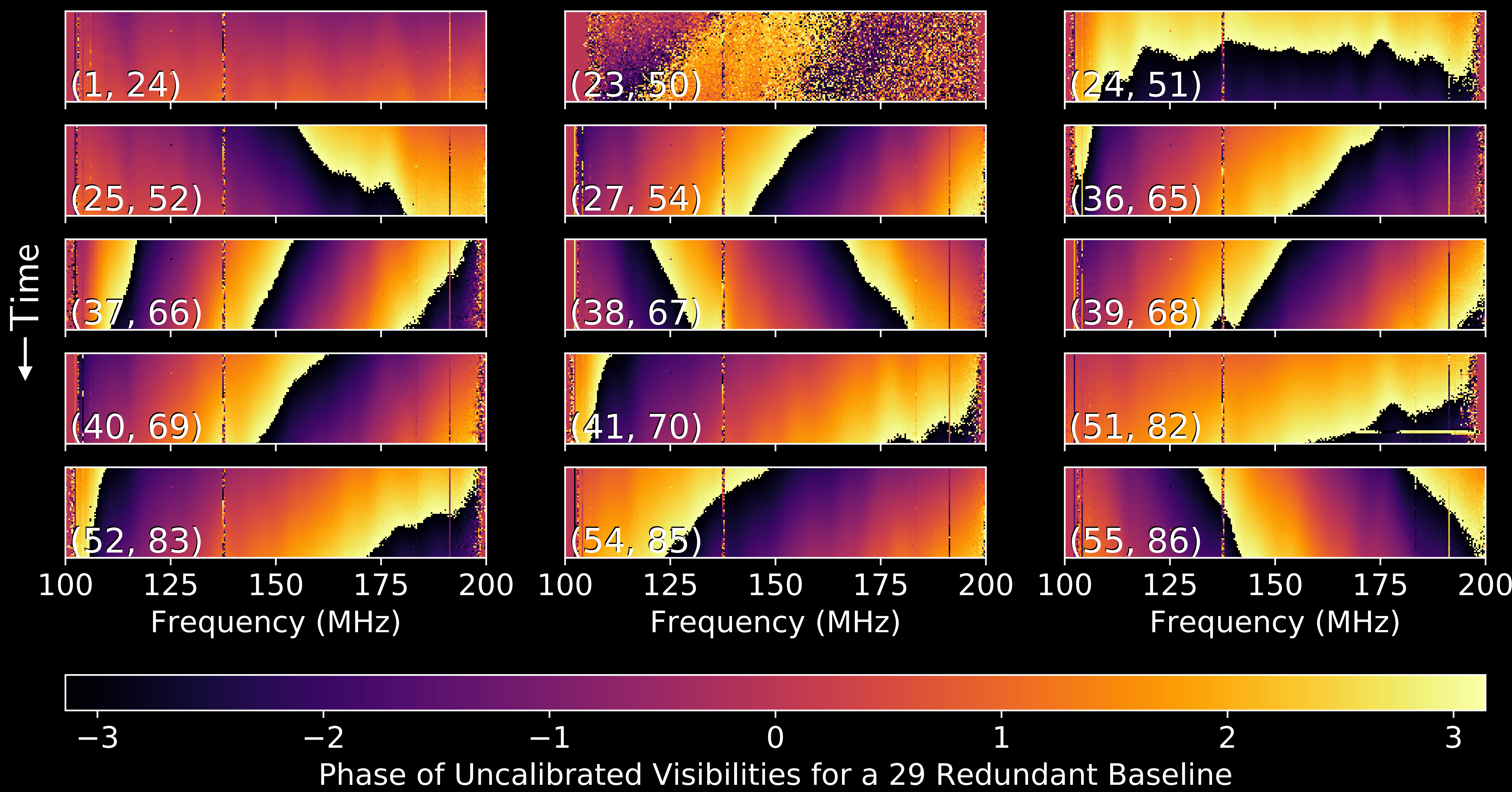
Being more careful—e.g. by calibrating without the longest baselines—gets us back most of our EoR window!



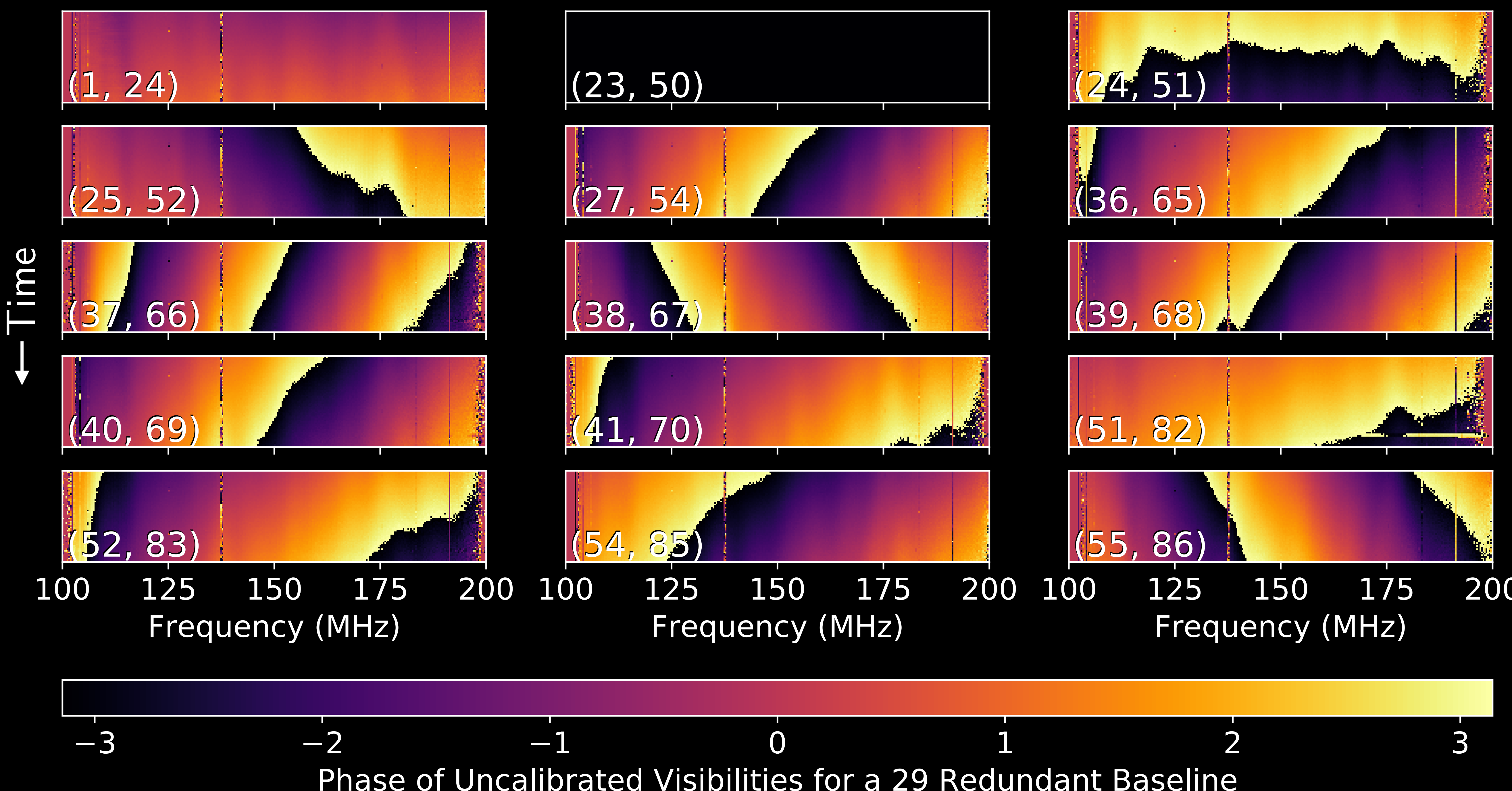
Orosz, **Dillon,** *et al. (2019)*

Redundant calibration is working well so far.

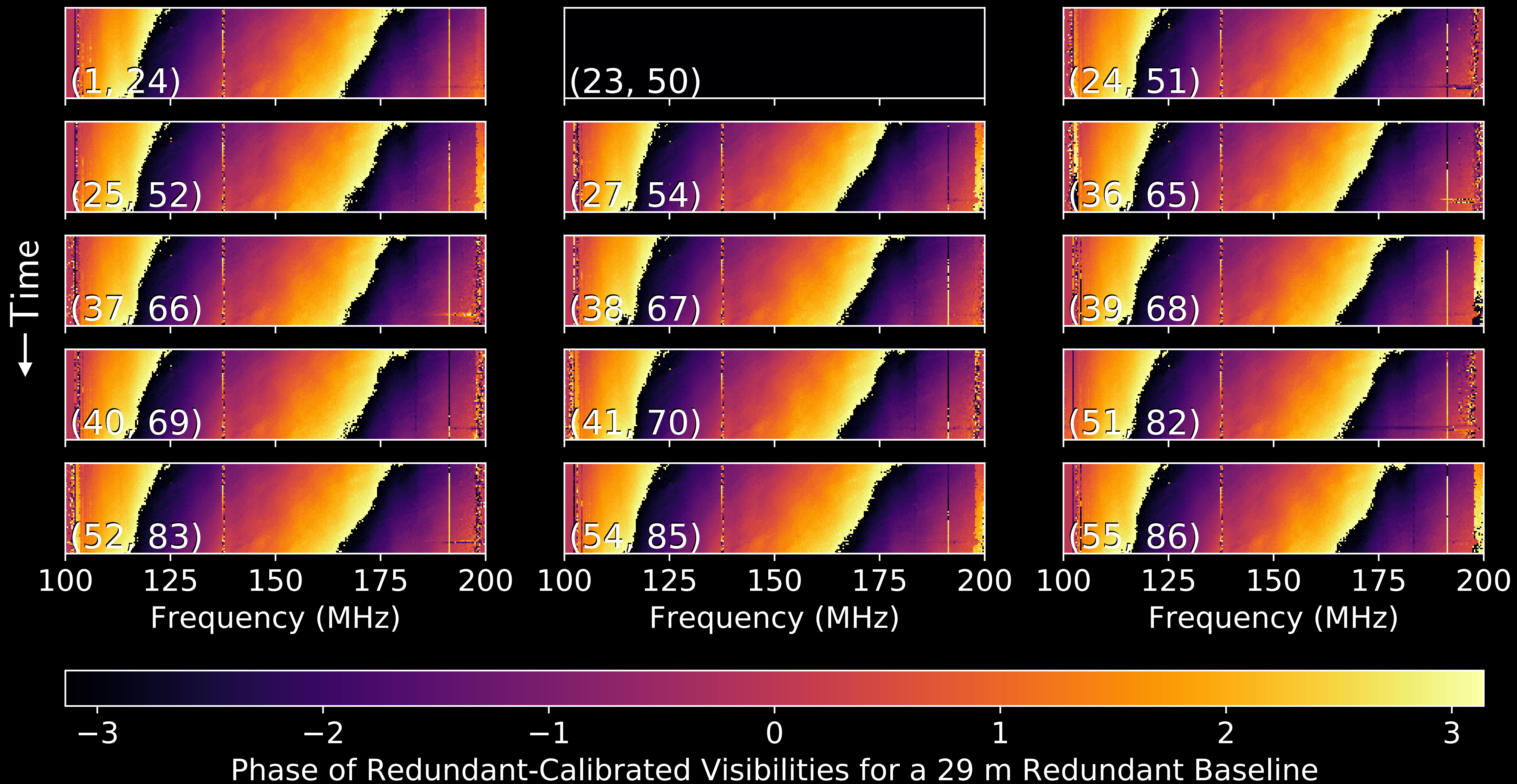
Example raw HERA data for a single redundant baseline group.



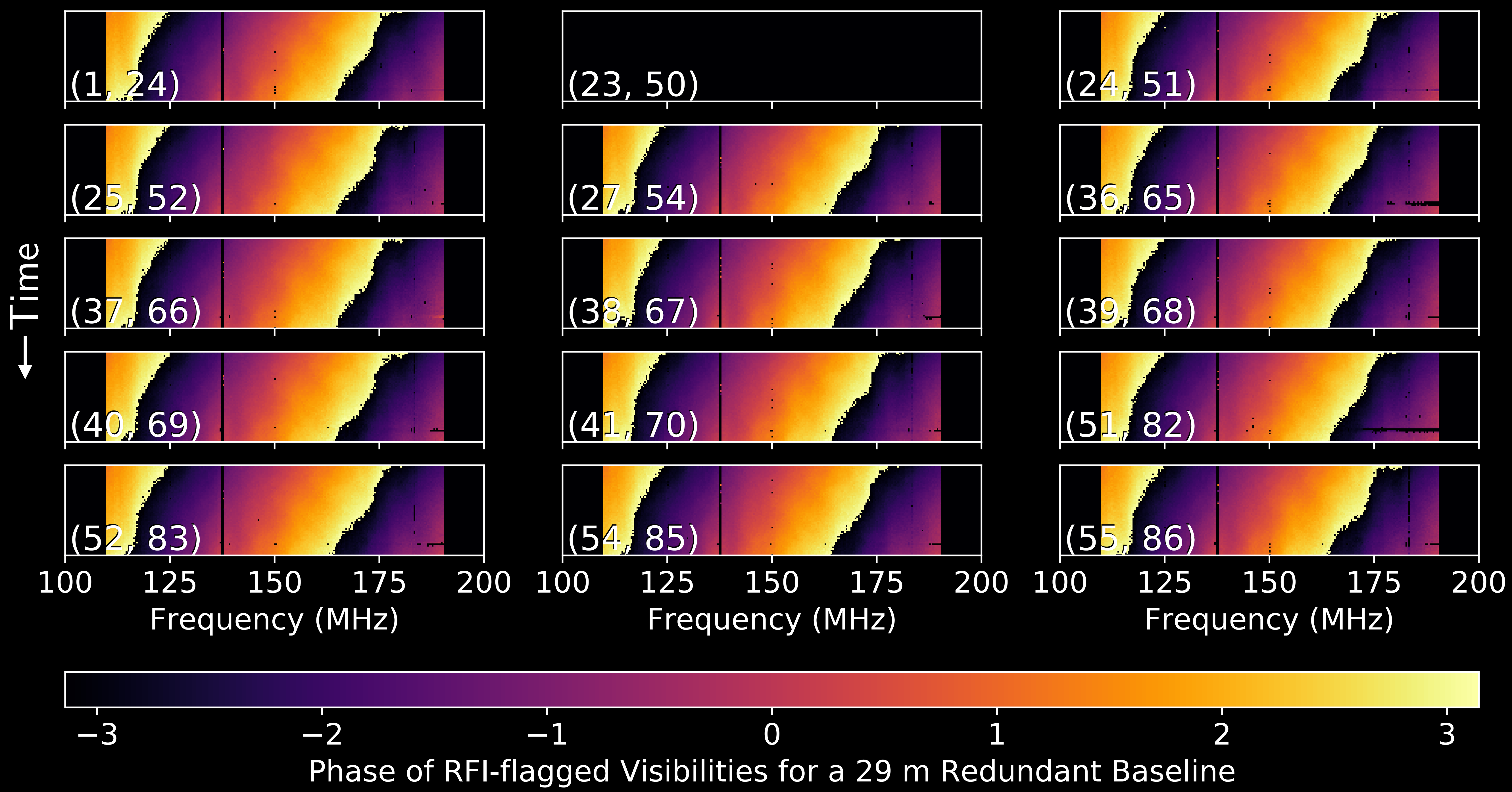
First we flag bad antennas.



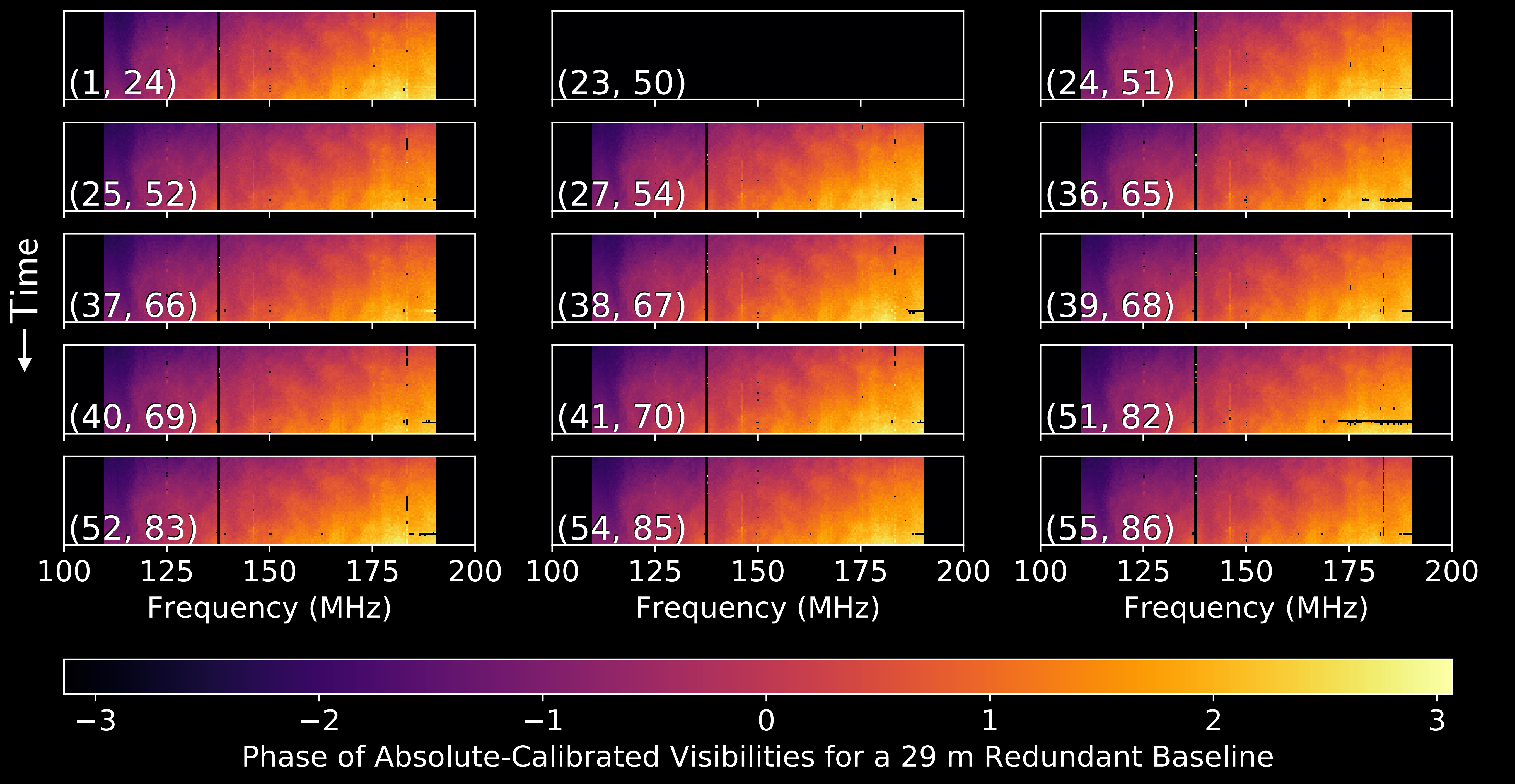
Next we impose the redundancy constraint to solve for all gains.



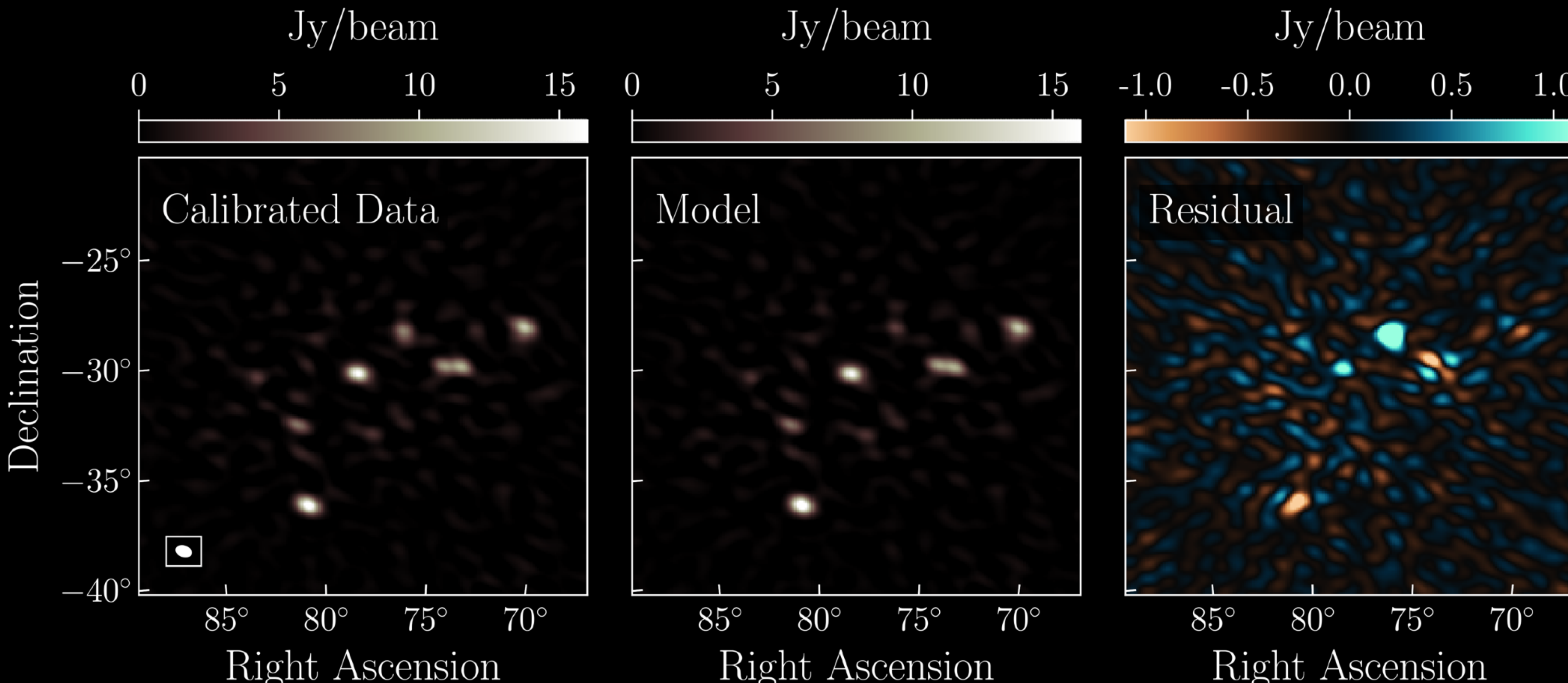
Then we mask-out band edges and radio-frequency interference.



Finally we fix to an absolute sky-reference.

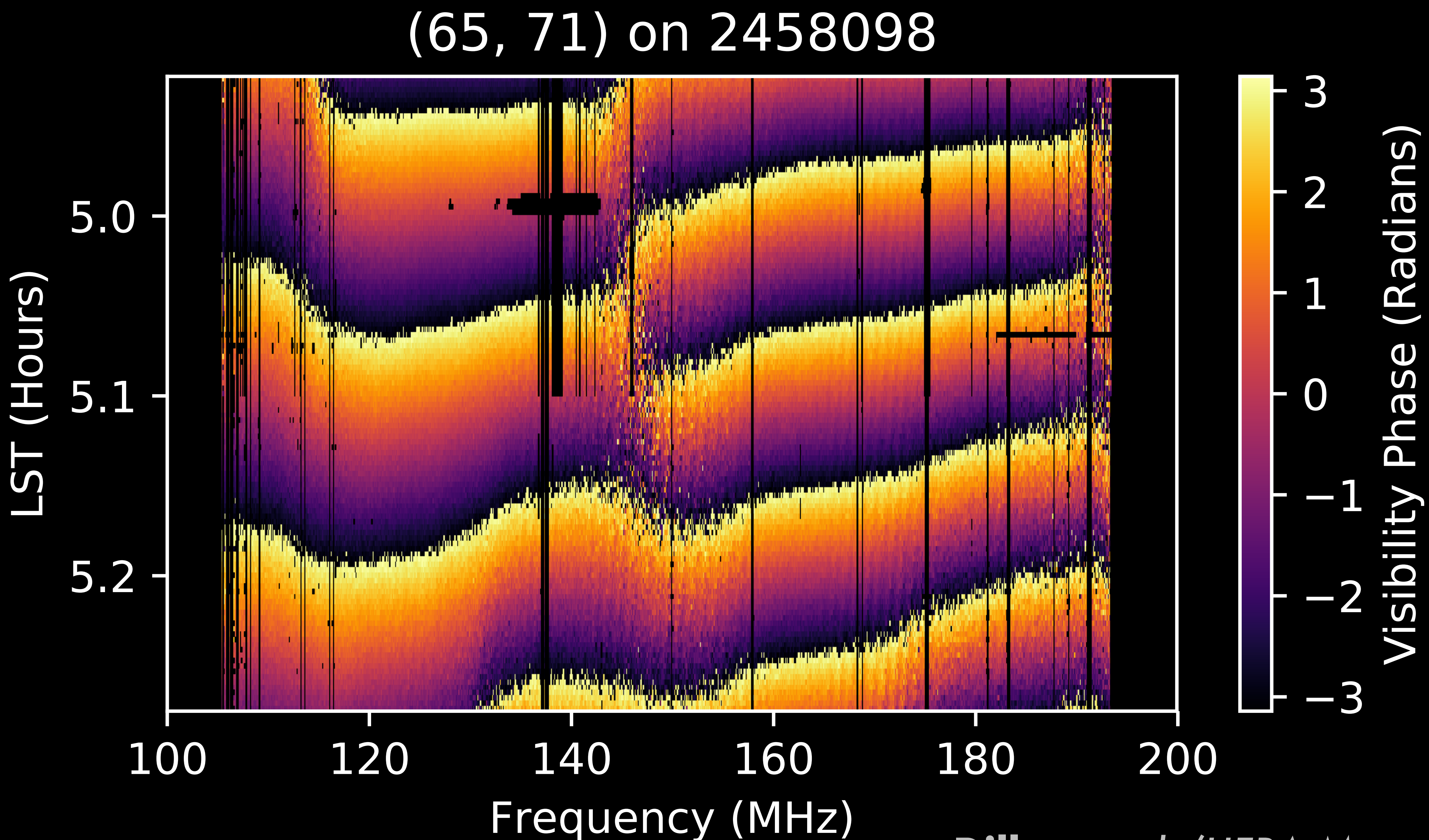


Finally we fix to an absolute sky-reference.



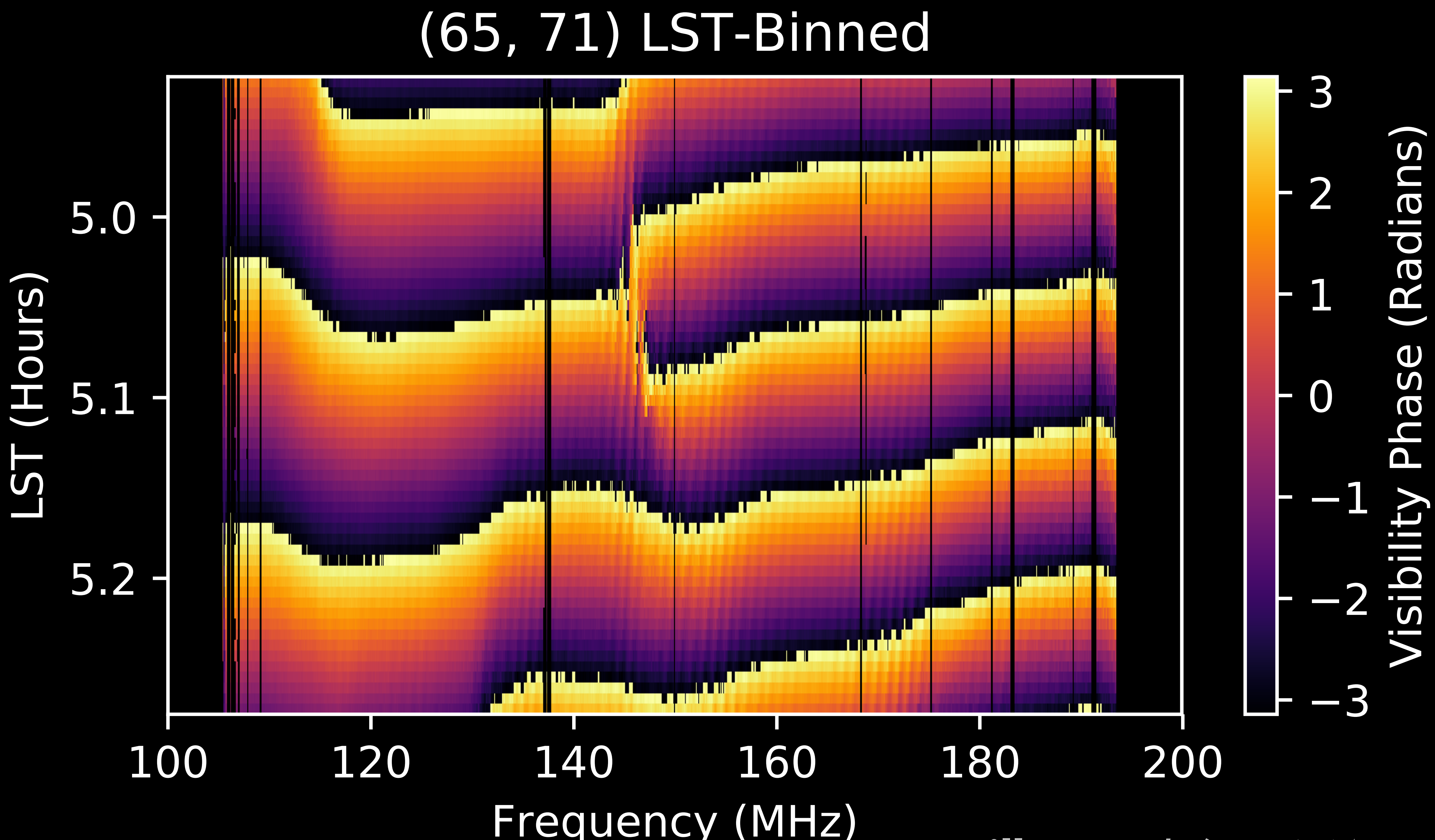
Kern, **Dillon**, *et al. (2019c)*

The instrument looks stable from day to day...



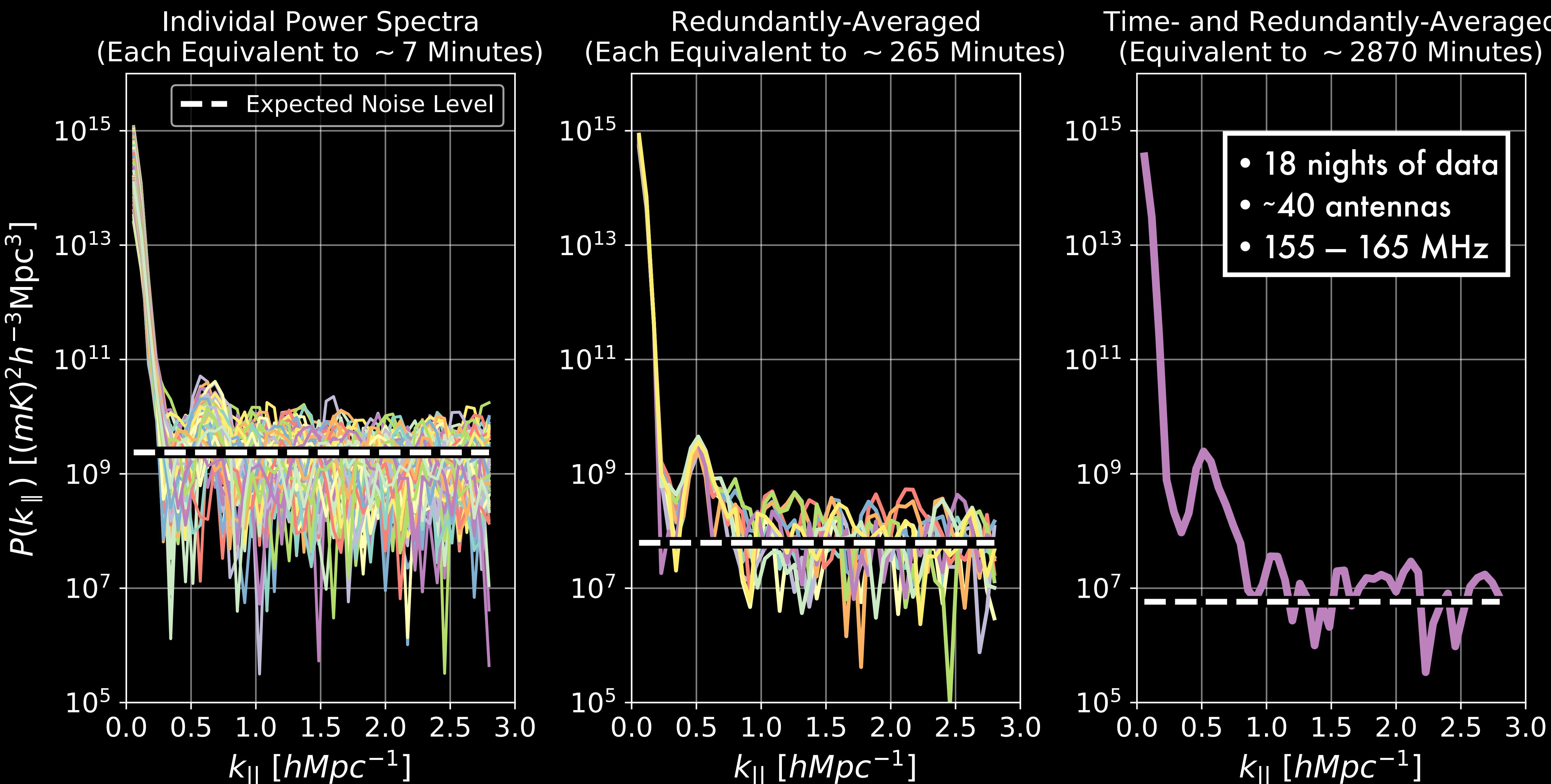
Dillon *et al. (HERA Memo #45)*

So we can keep integrating down to maximize sensitivity.

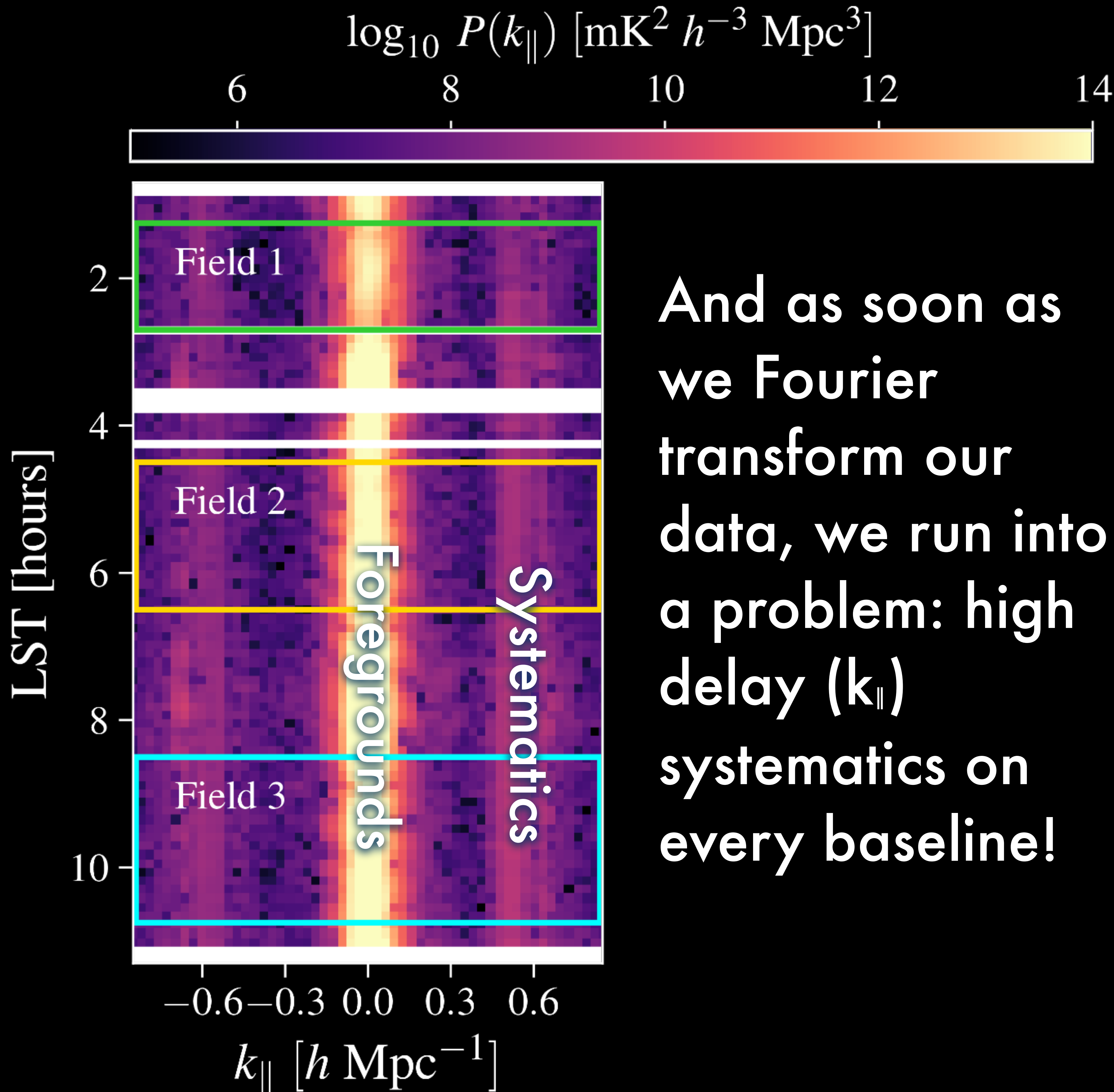


Dillon *et al.* *(HERA Memo #45)*

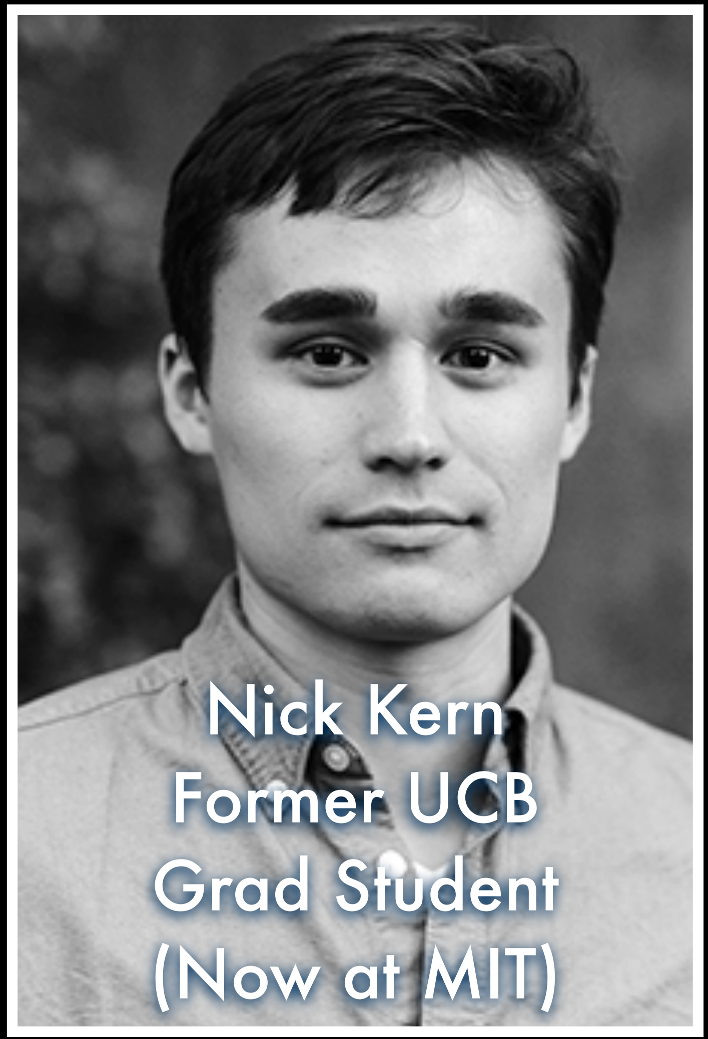
And start forming power spectra.



HERA Collaboration (2022)

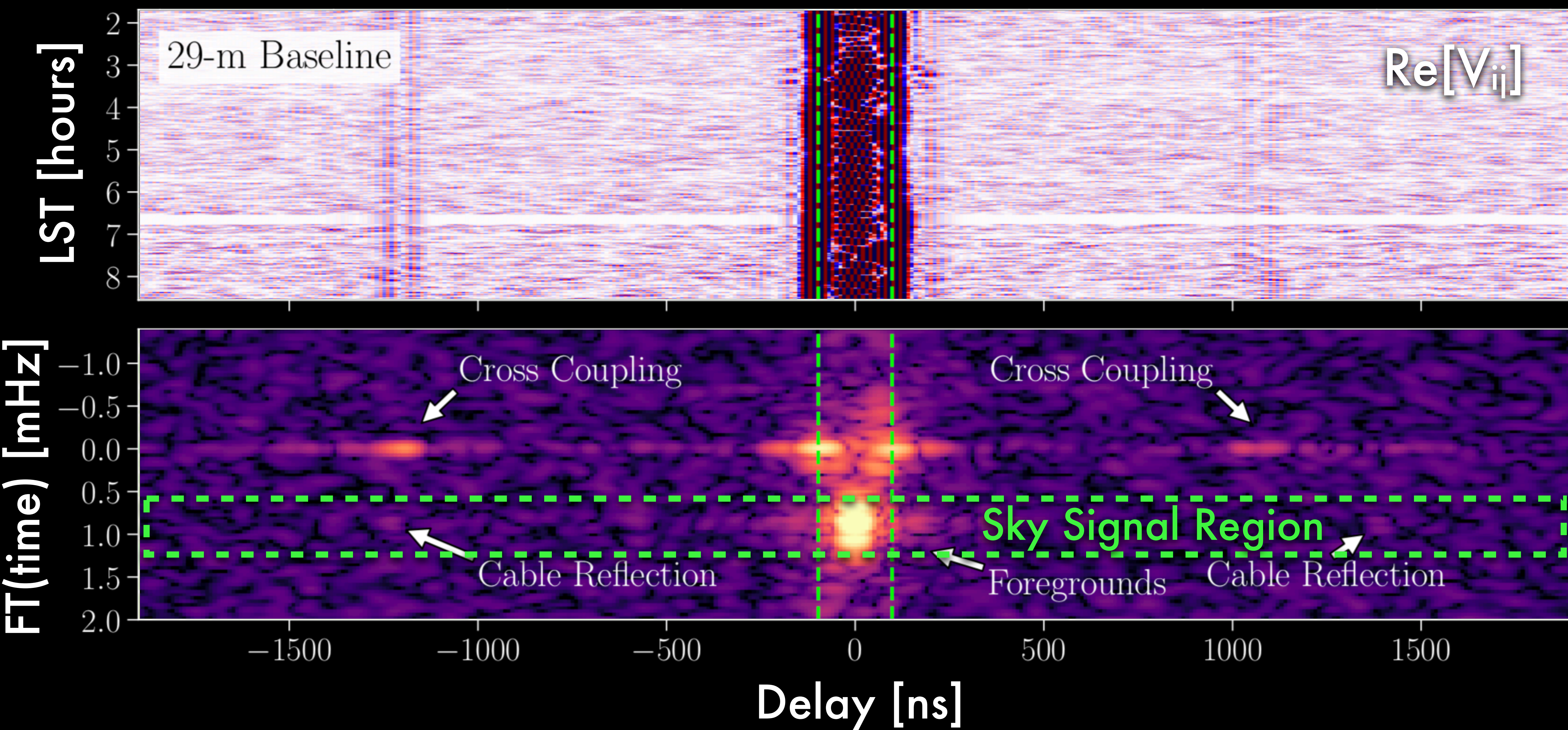


And as soon as we Fourier transform our data, we run into a problem: high delay ($k_\parallel$) systematics on every baseline!



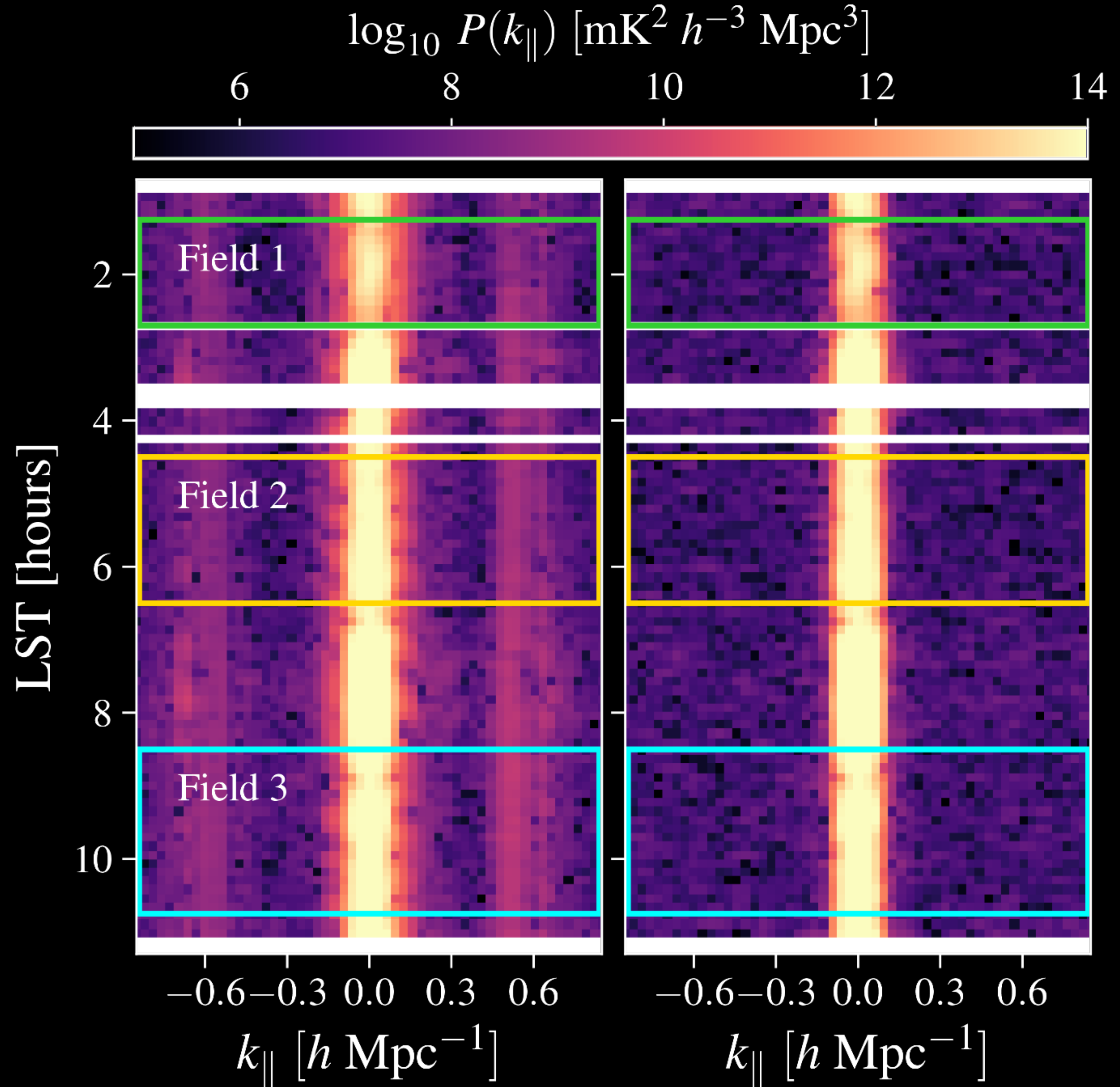
Kern, Parsons, ***Dillon****, et al. (2019ab)*

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



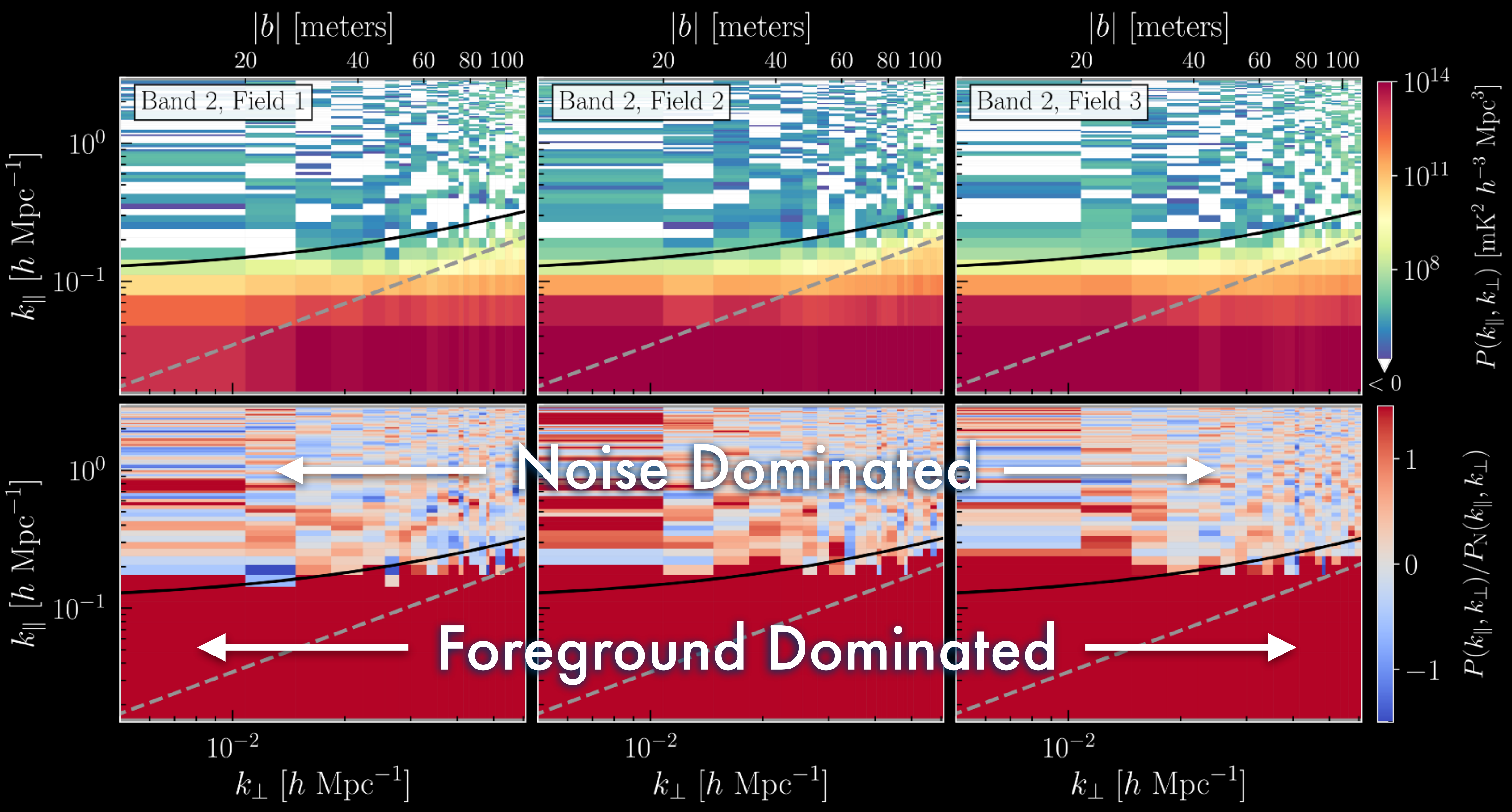
Kern, Parsons, ***Dillon****, et al. (2019ab)*

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



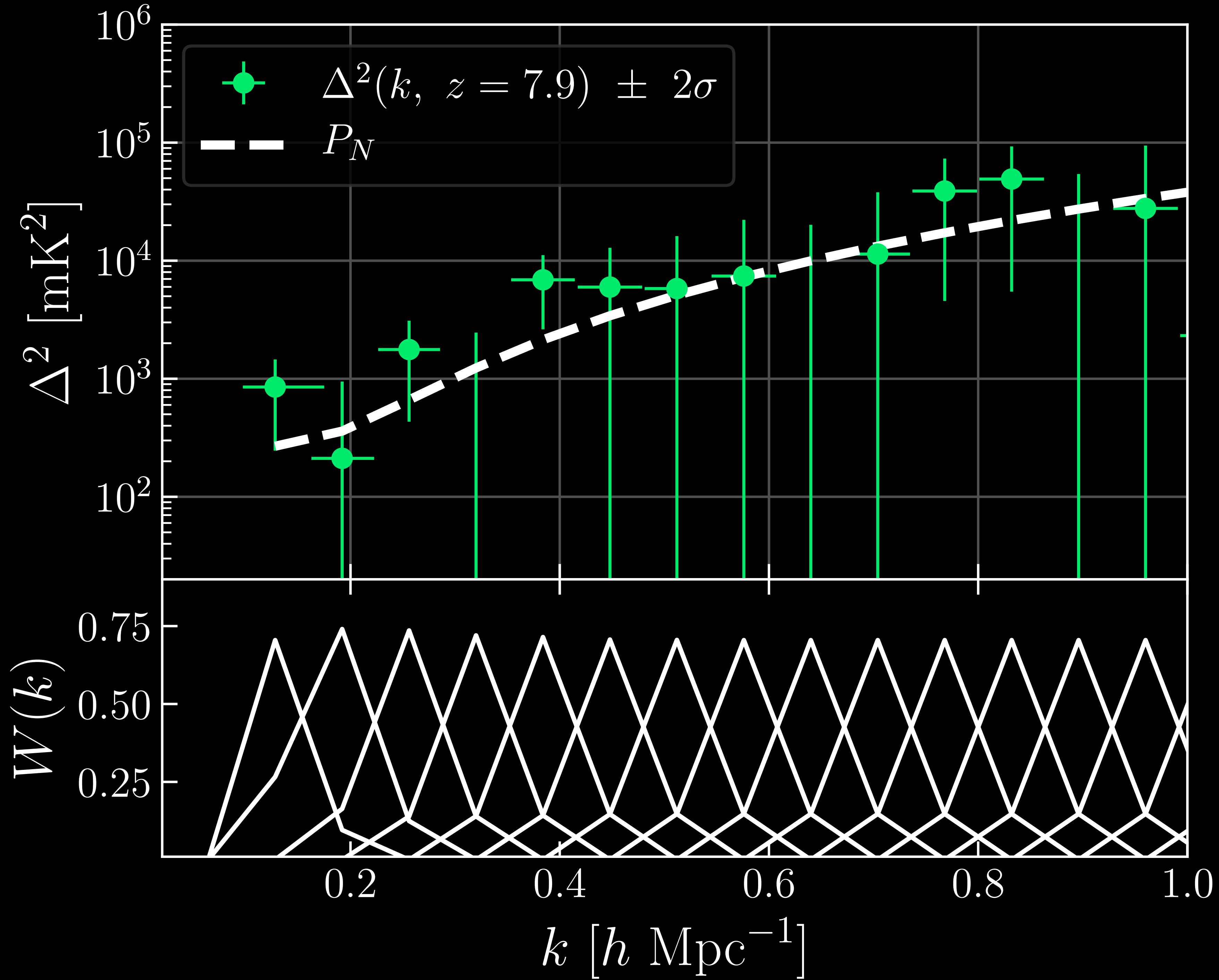
HERA Collaboration (2022)

With high-delay systematics mitigated, we can finally form our 2D power spectra.



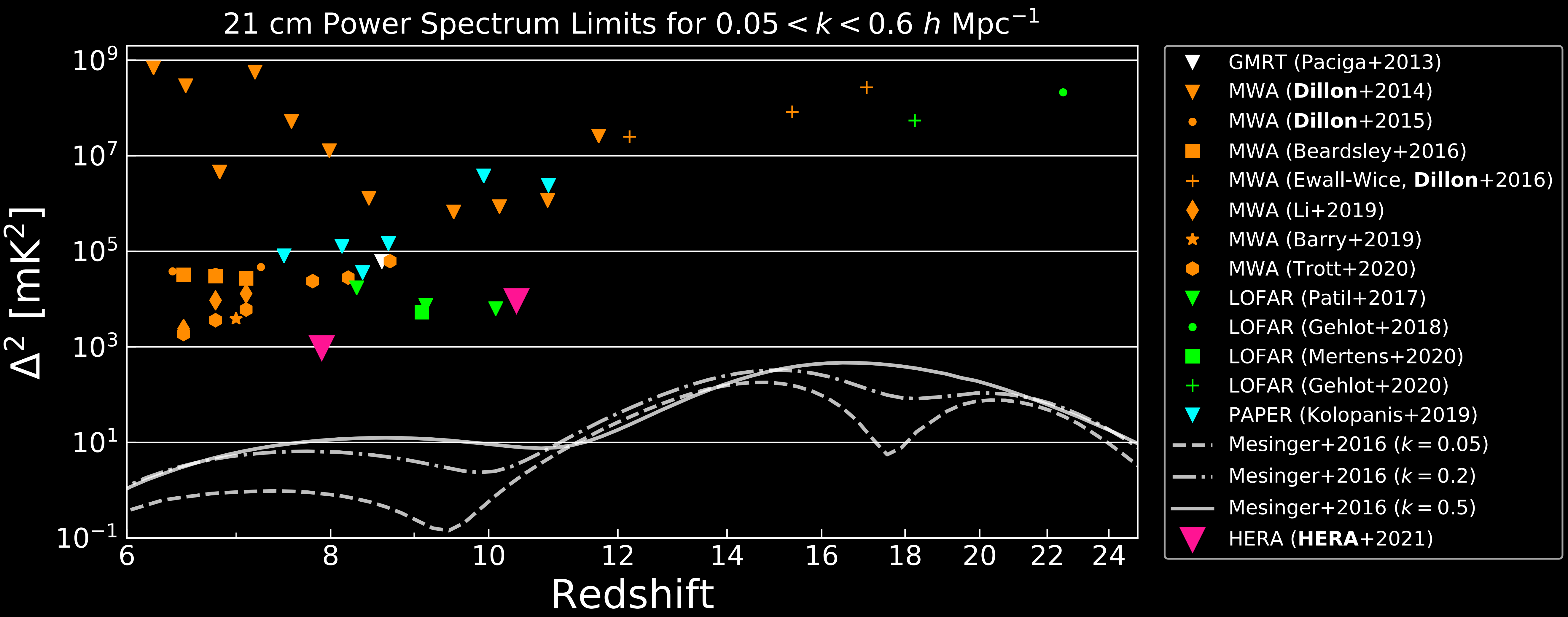
HERA Collaboration (2022)

Working outside the wedge, we get our power spectrum upper limit.



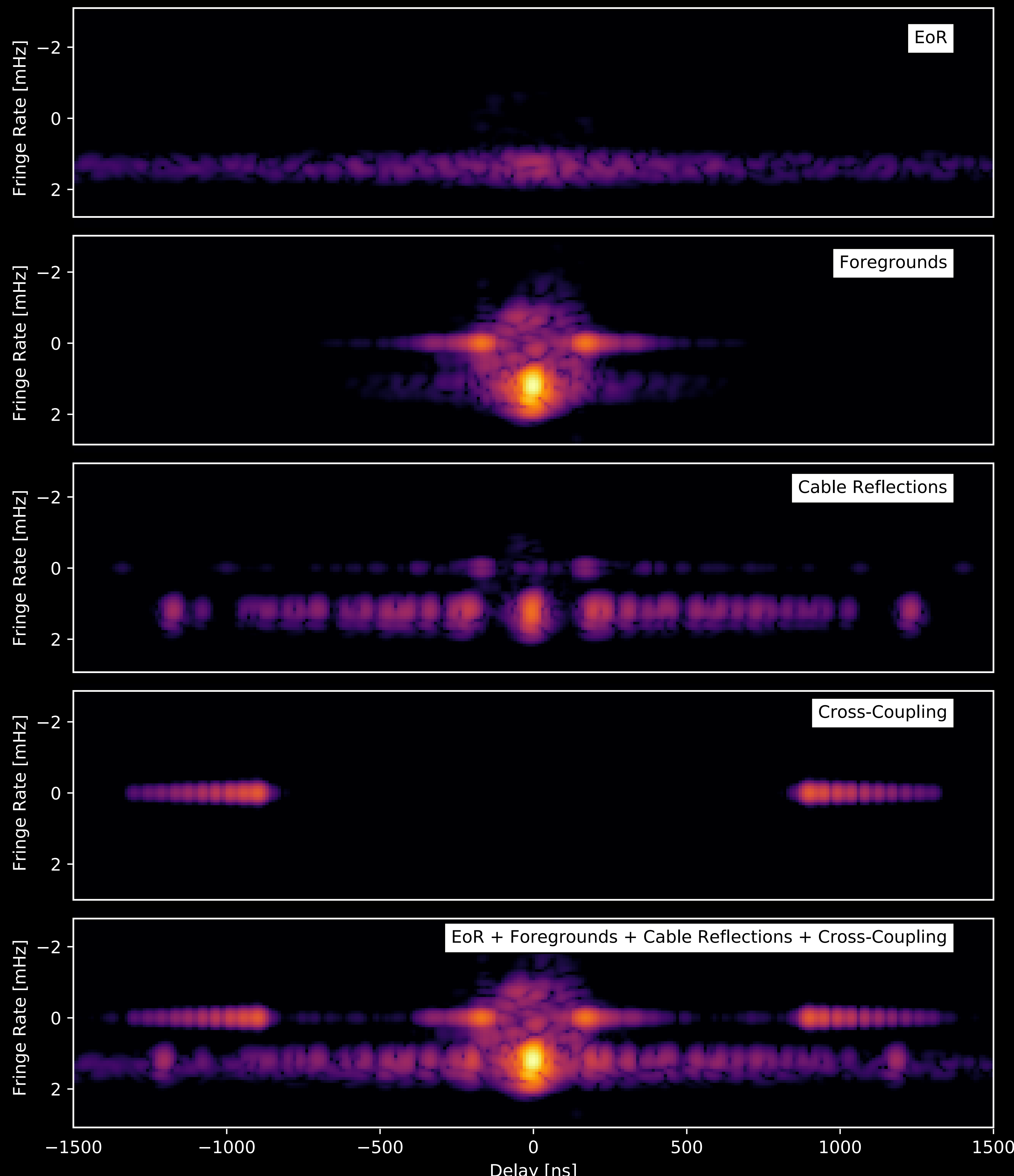
HERA Collaboration (2022)

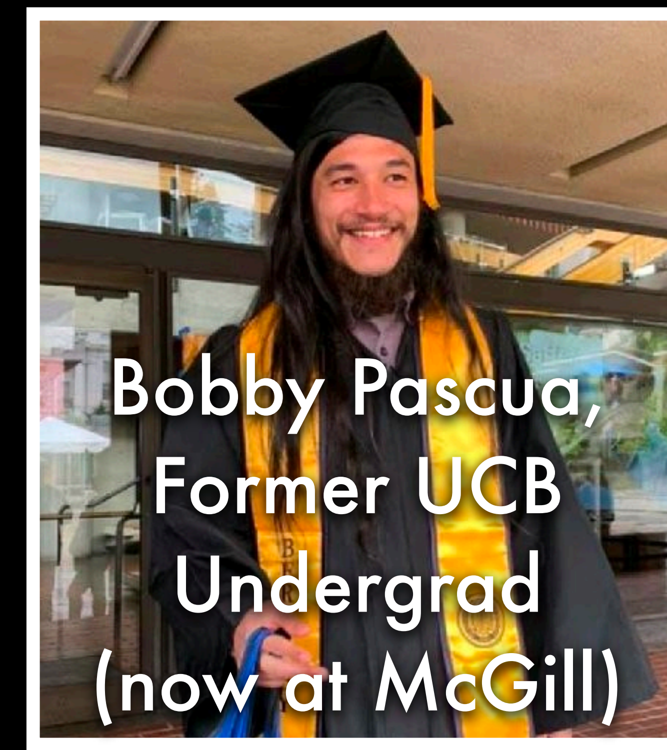
Our first (and world-leading!) limit with only 18 nights and just foreground-avoidance.



HERA Collaboration (2022)

How are we building confidence in our results?

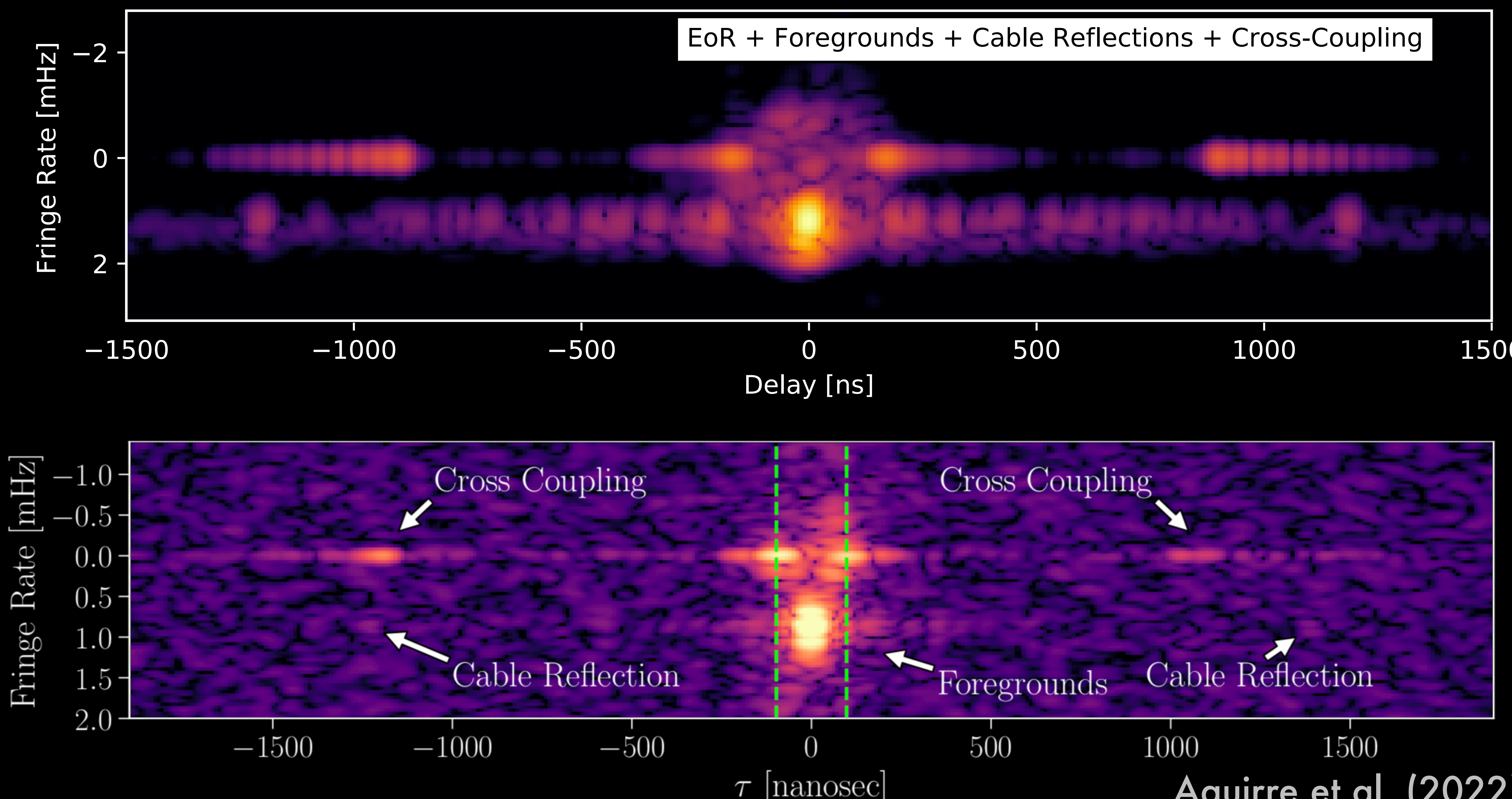




We built end-to-end tests of analysis pipeline with simulated EoR, foregrounds, and systematics.

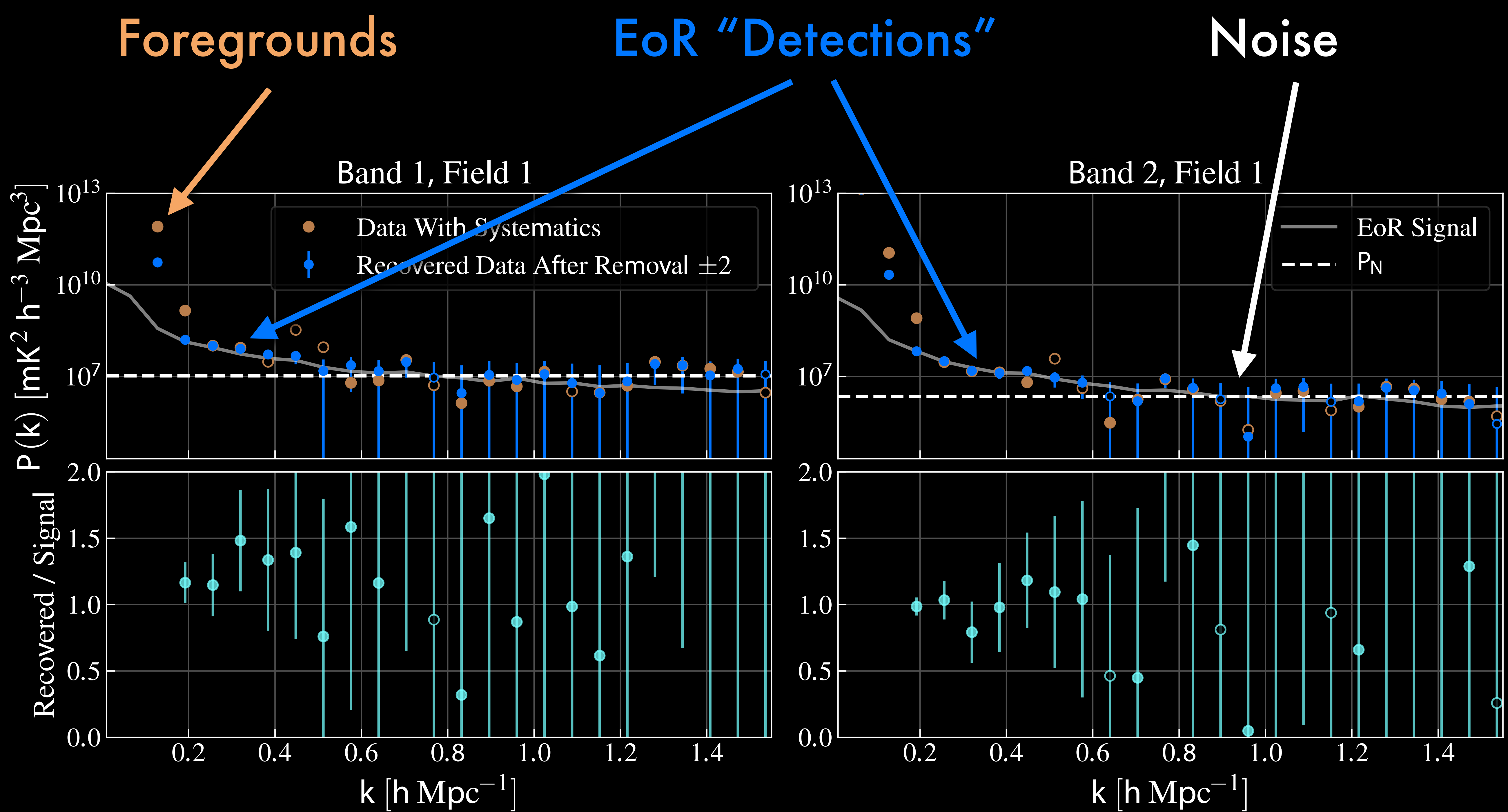
Aguirre et al. (2022)

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



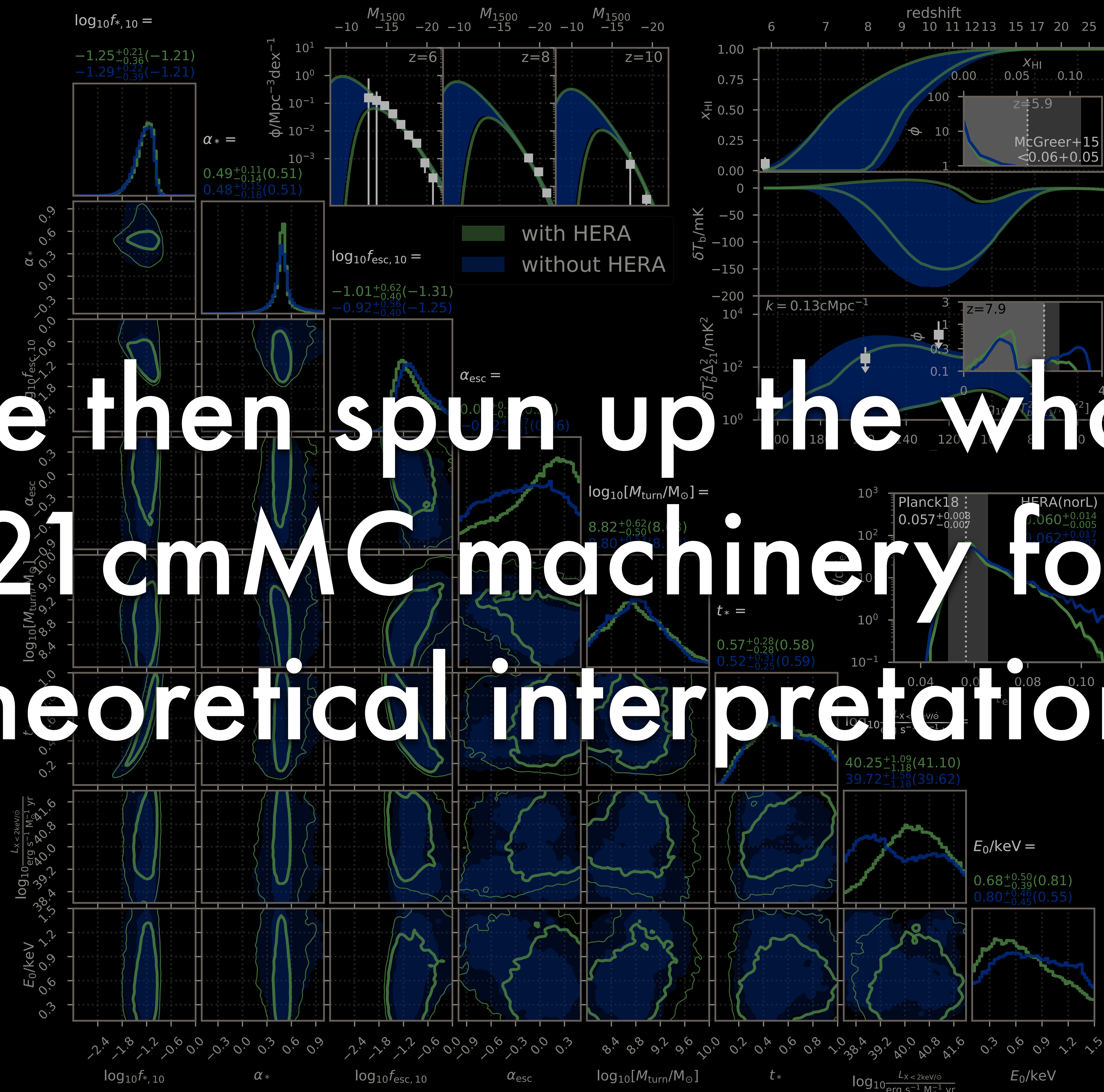
Aguirre et al. (2022)

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



Aguirre et al. (2022)

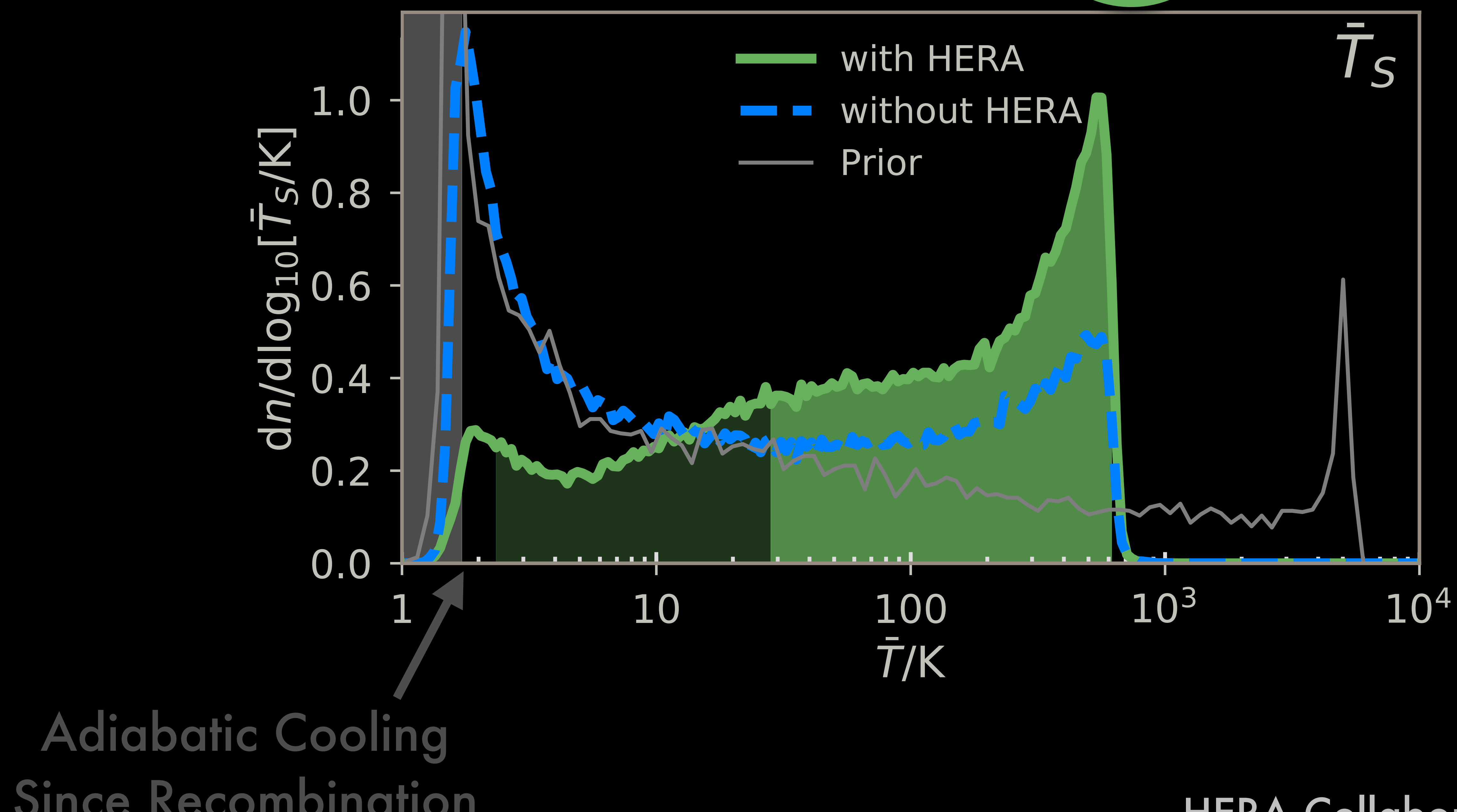
We then spun up the whole 21cmMC machinery for theoretical interpretation.



HERA Collaboration (2022)

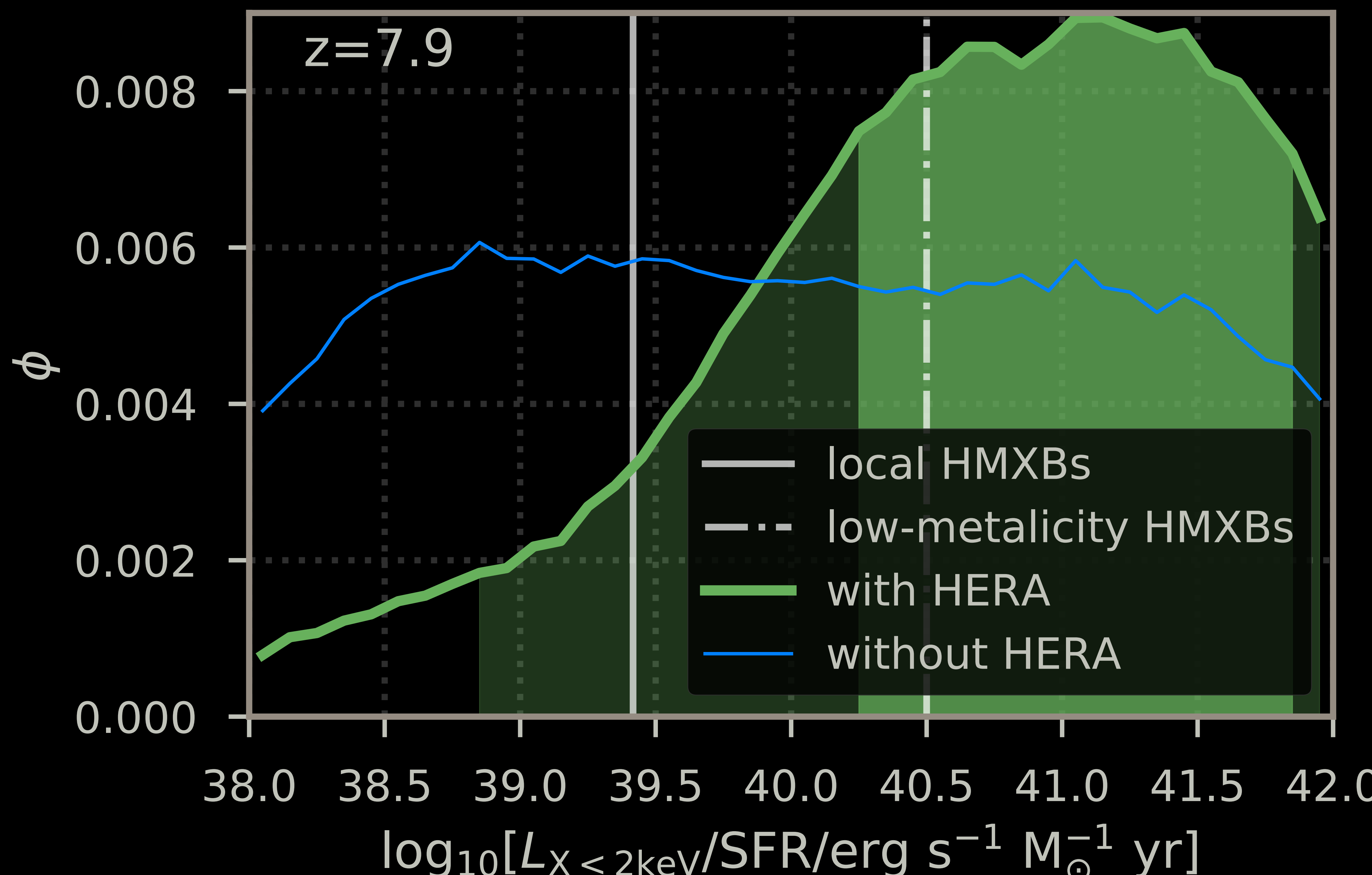
At >95% confidence, we can say the IGM was heated above the adiabatic limit at z = 7.9.

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



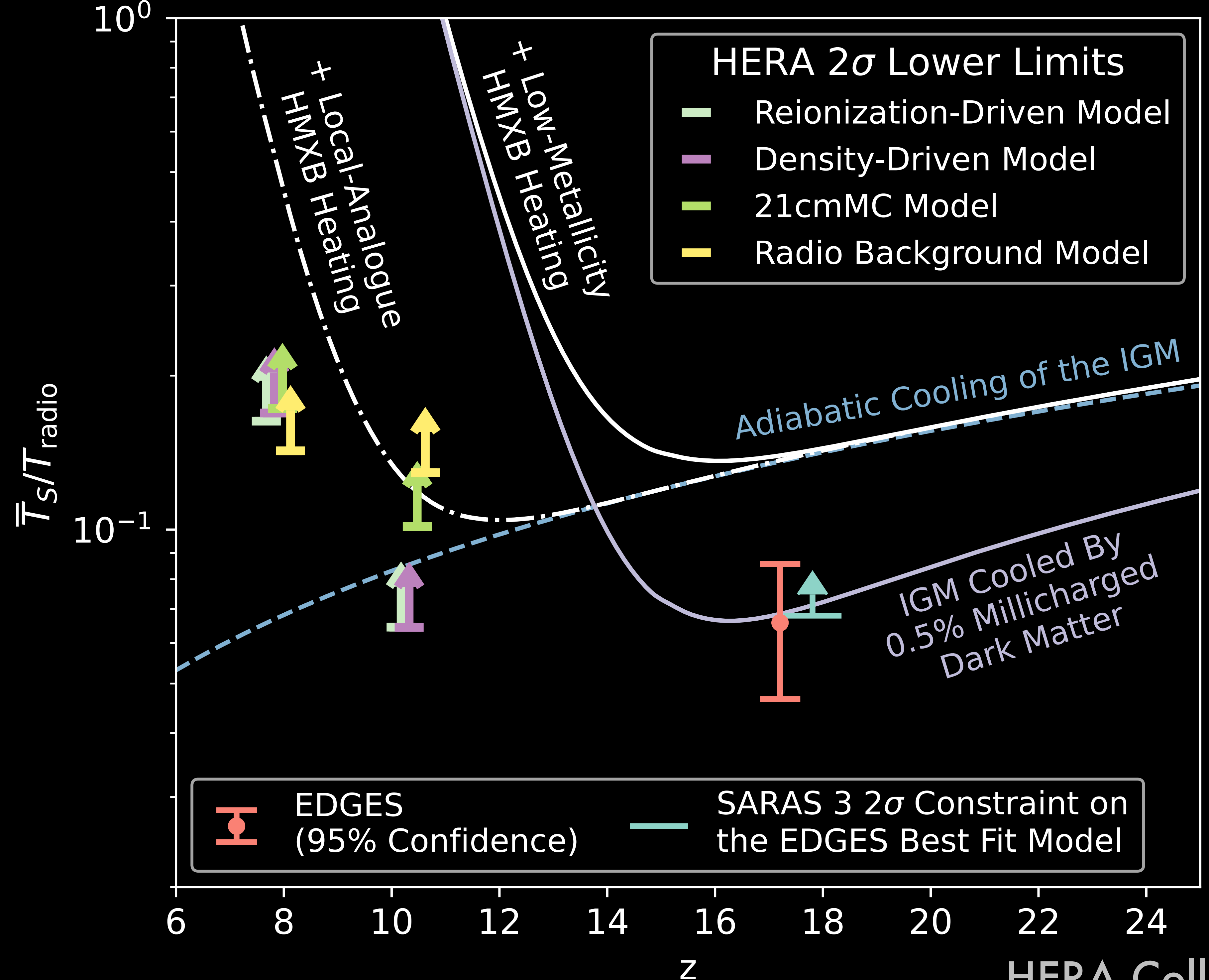
HERA Collaboration (2022)

If this heating is dominated by HMXBs, as is generally believed, this favors low-metallicity HMXBs over local analogues.



HERA Collaboration (2022)

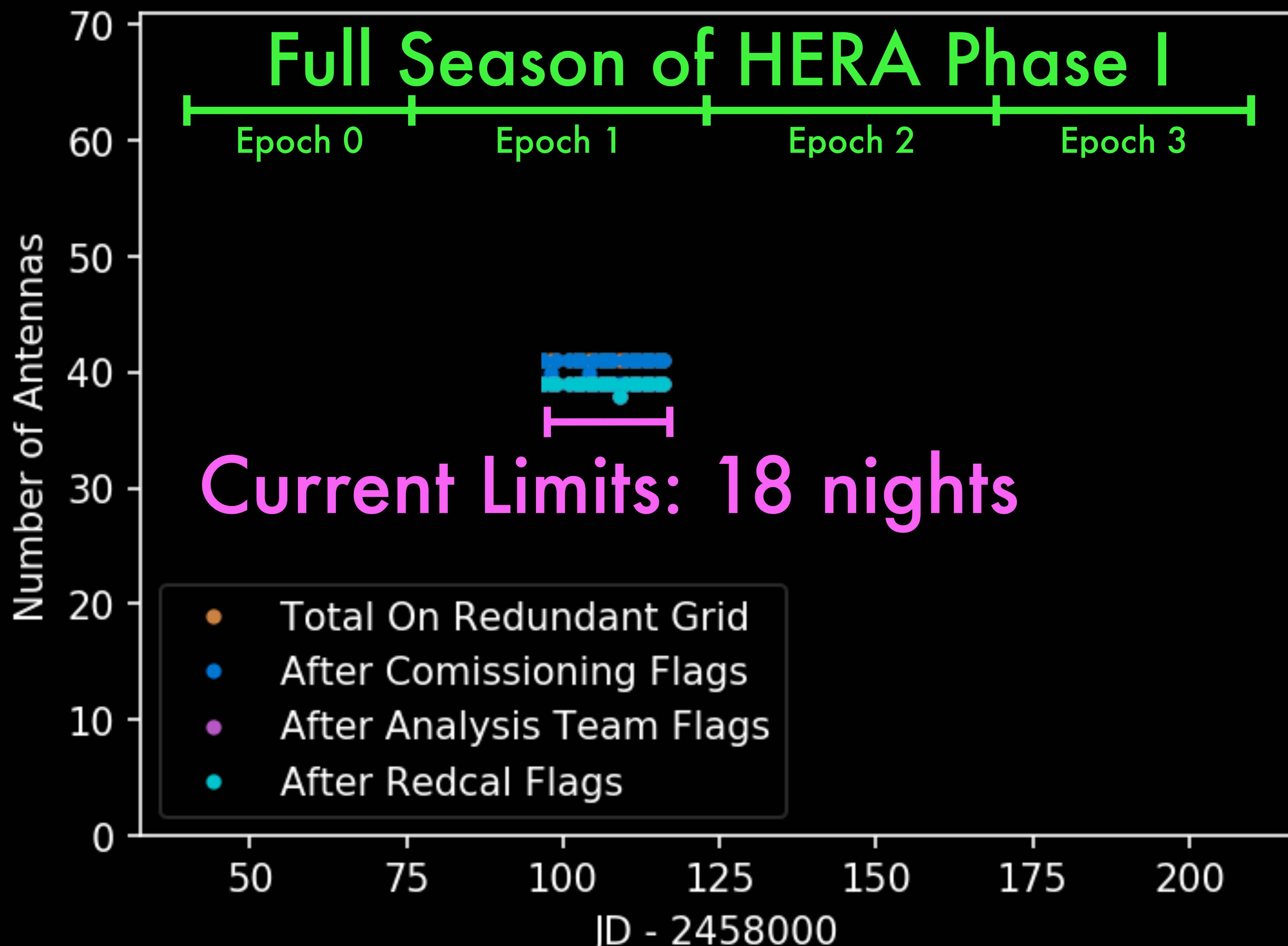
We studied heating with four independent models, which are generally consistent, but we can't say anything about EDGES quite yet.



HERA Collaboration (2022)

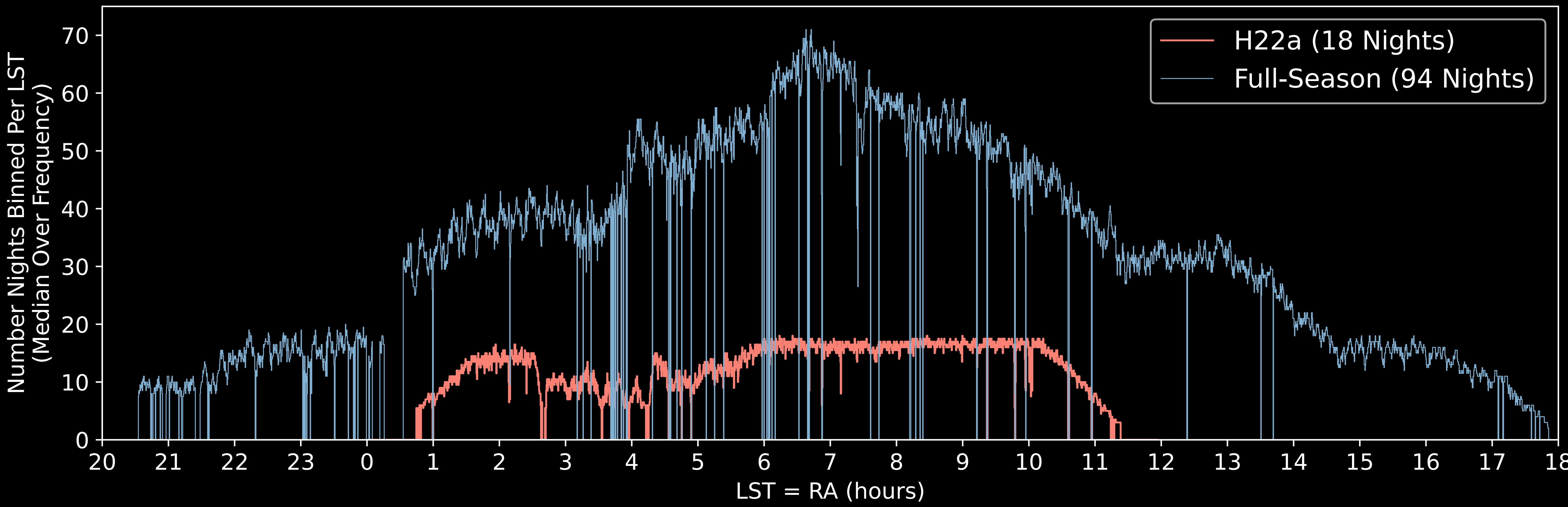
What’s next for HERA?

The simplest answer: use more data.



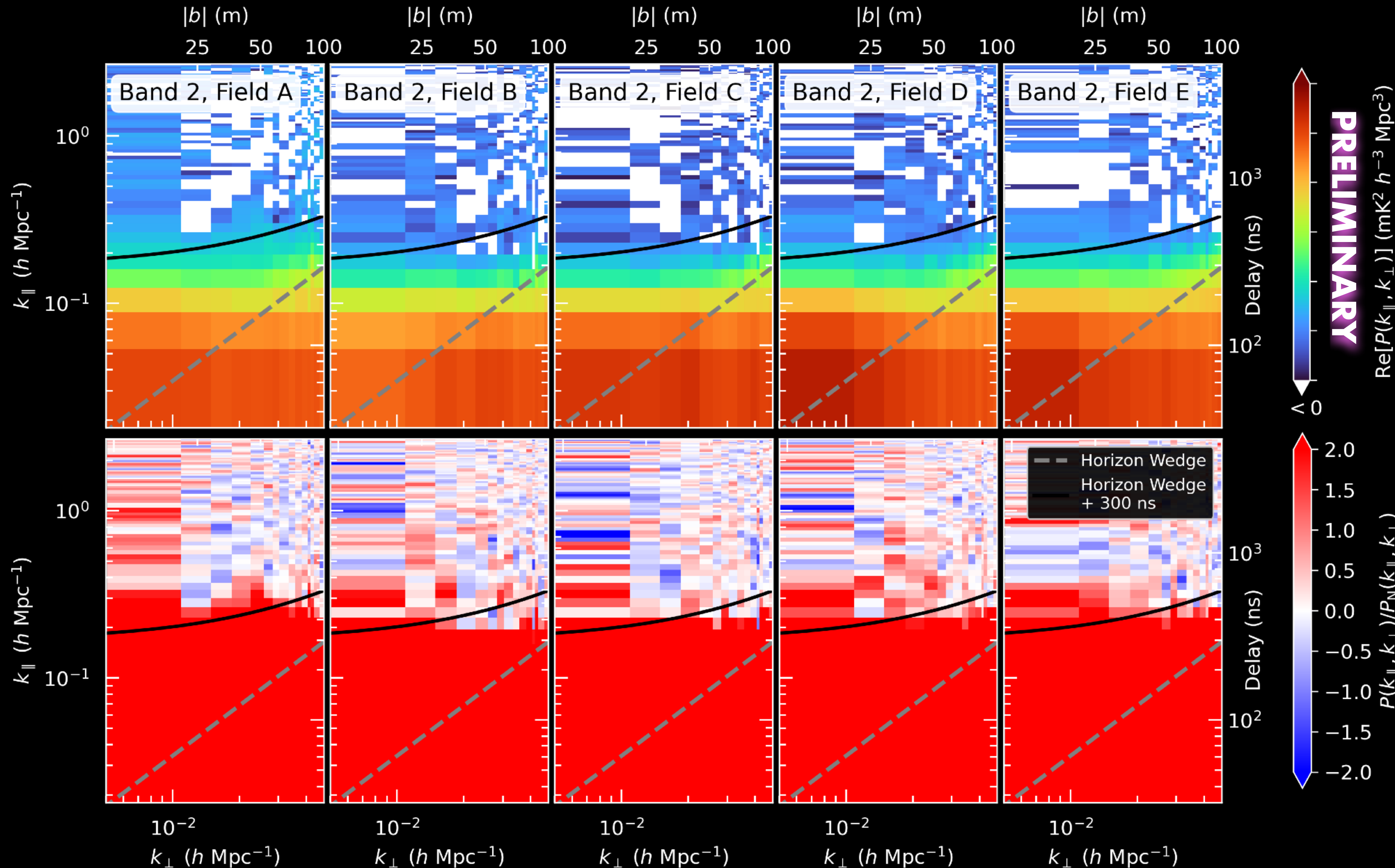
HERA Collaboration (in prep.)

After looking through hundreds of Jupyter notebooks, we've got 94 good nights of data with a similar number of antennas.



HERA Collaboration (in prep.)

With 94 nights, our power spectra and look pretty consistent with noise outside the wedge.



HERA Collaboration (in prep.)

Next steps for HERA Phase I:

- We've re-run our end-to-end simulations, our statistical tests and jack-knives, and our astrophysical inference and interpretation machinery.
- I'm writing everything up and we're in internal review now.
- From a pure sensitivity perspective, this P(k) limit could be as much as *~3 times deeper*.

HERA Collaboration (in prep.)

With a full season we'll likely be able to...

- Rule out most "cold-reionization" scenarios.
- Show that the IGM was X-ray heated at $z = 10.4$.
- Show that the HMXBs that probably heated the IGM were very low-metallicity.

HERA Collaboration (in prep.)


Meanwhile, we're continuing to build out to 350 antennas.
Photo: Dara Storer

Everything but the dishes is new, including our wide-band Vivaldi feeds that go from 50 – 250 MHz (4.7 > z > 29).

Photo: Ziyaad Halday

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

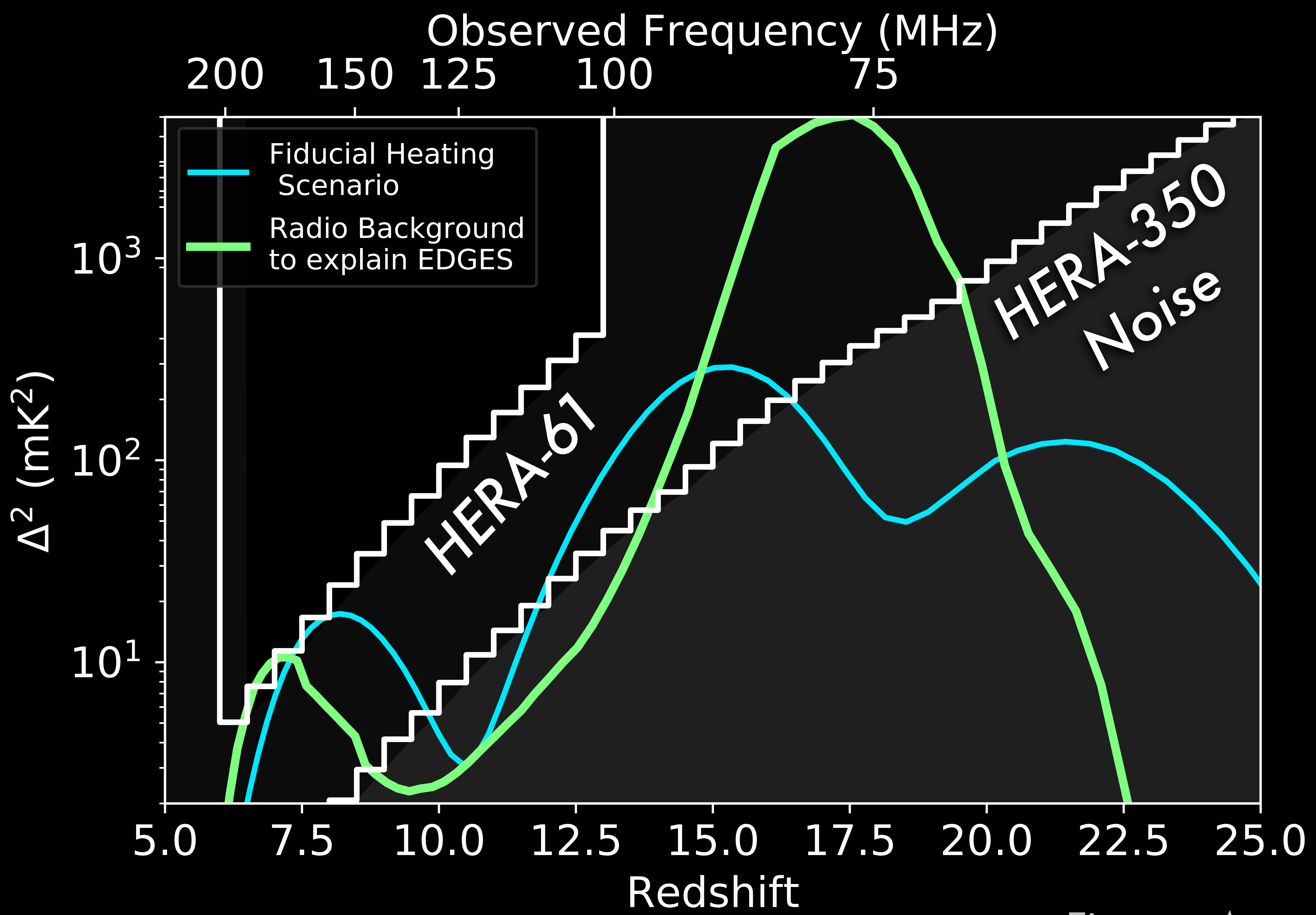
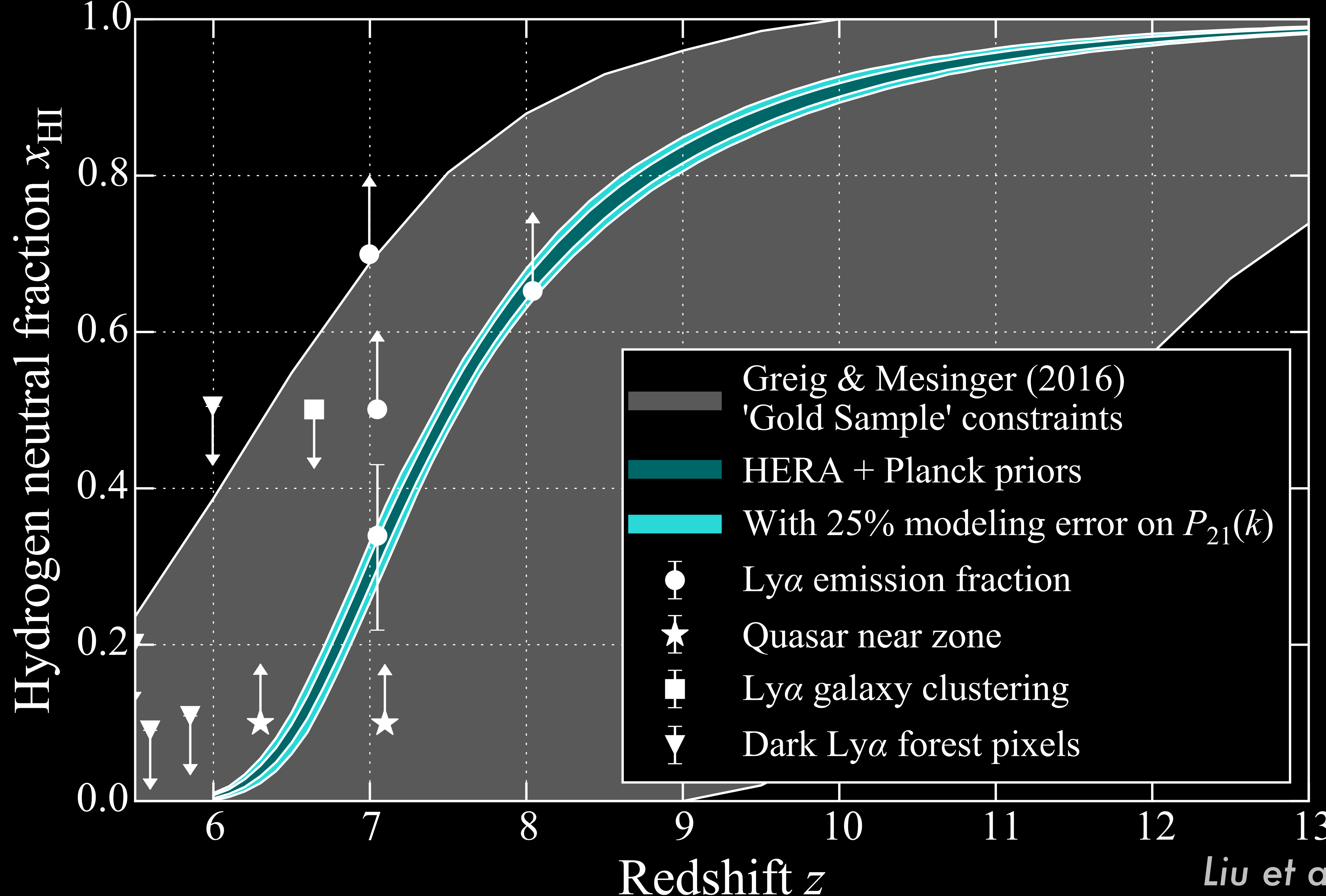


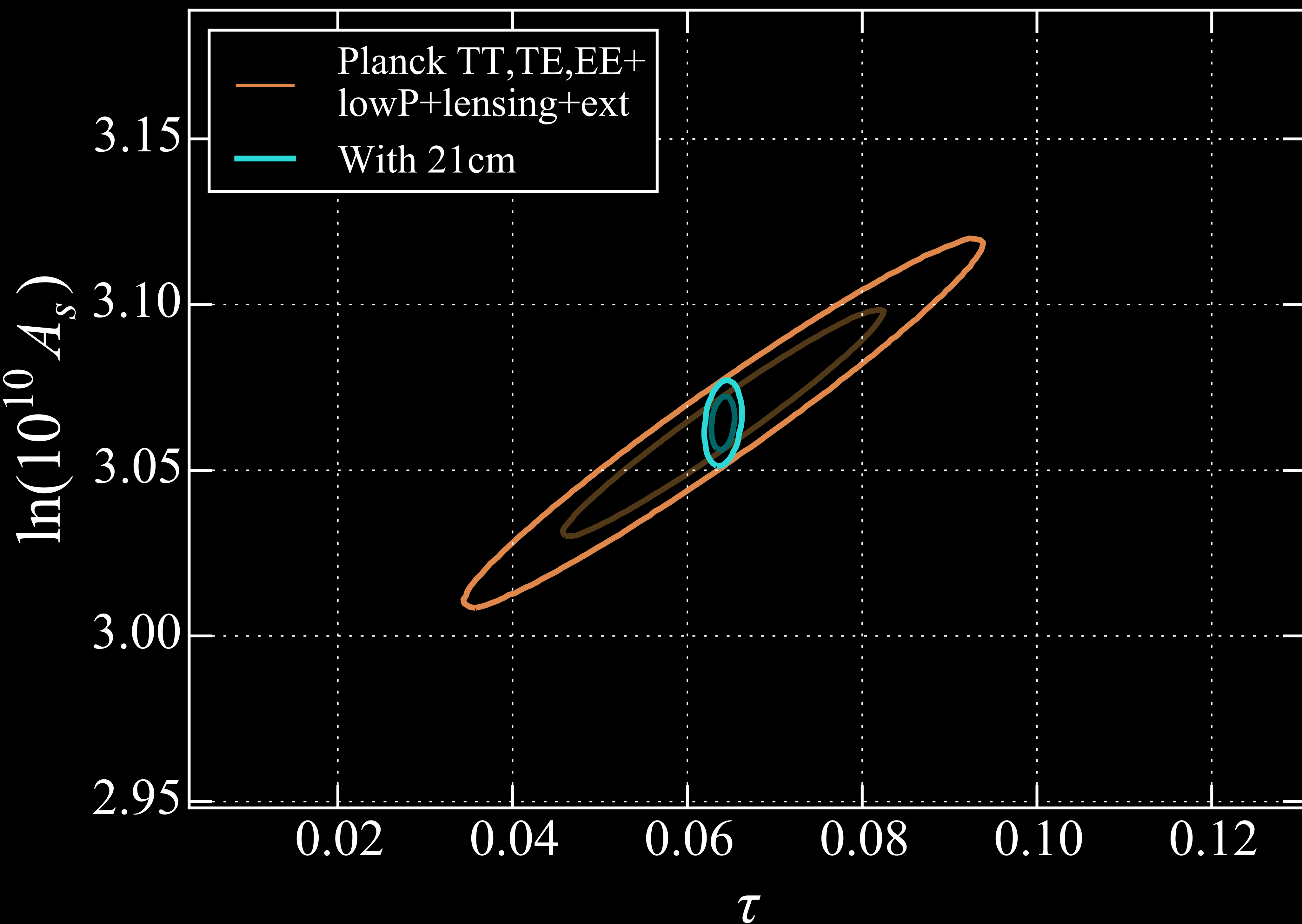
Figure: Aaron Ewall-Wice

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



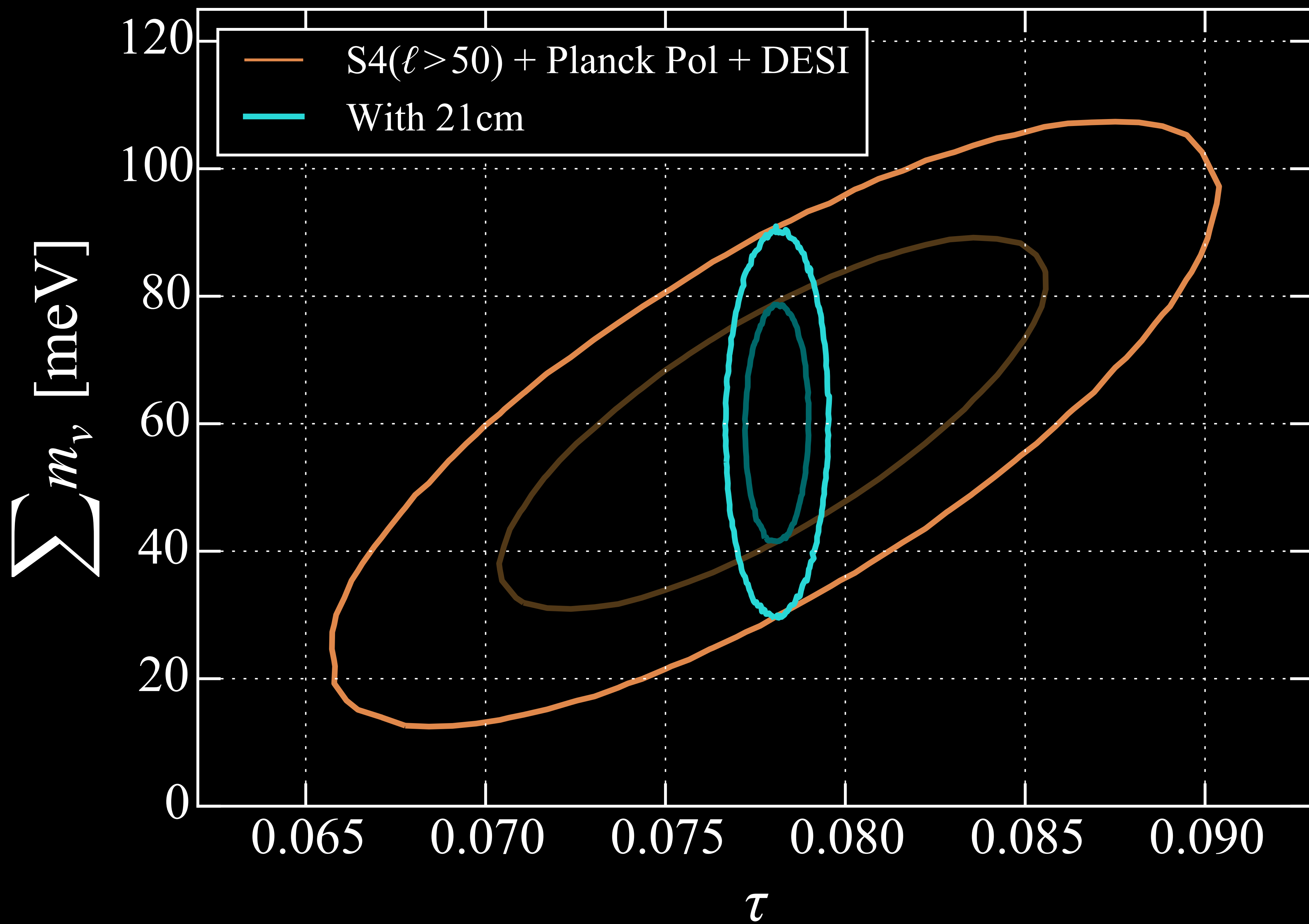
Liu et al. (2016)

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



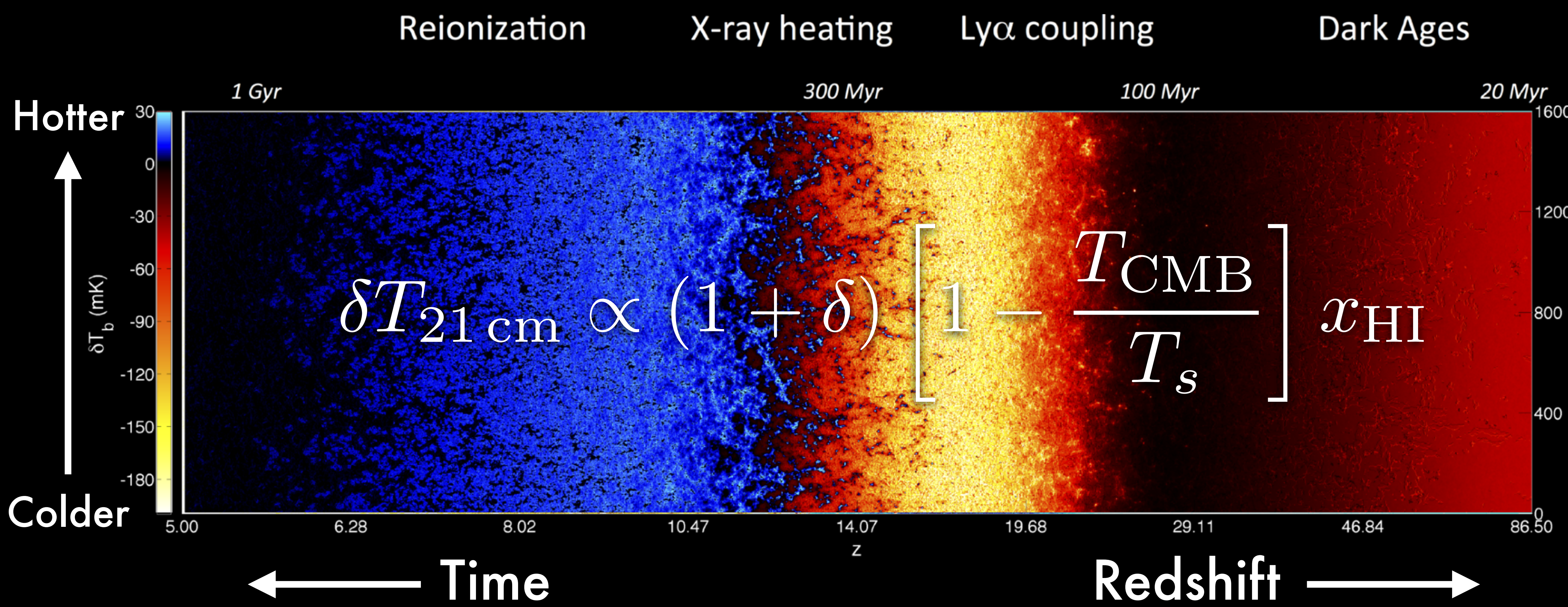
Liu et al. (2016)

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



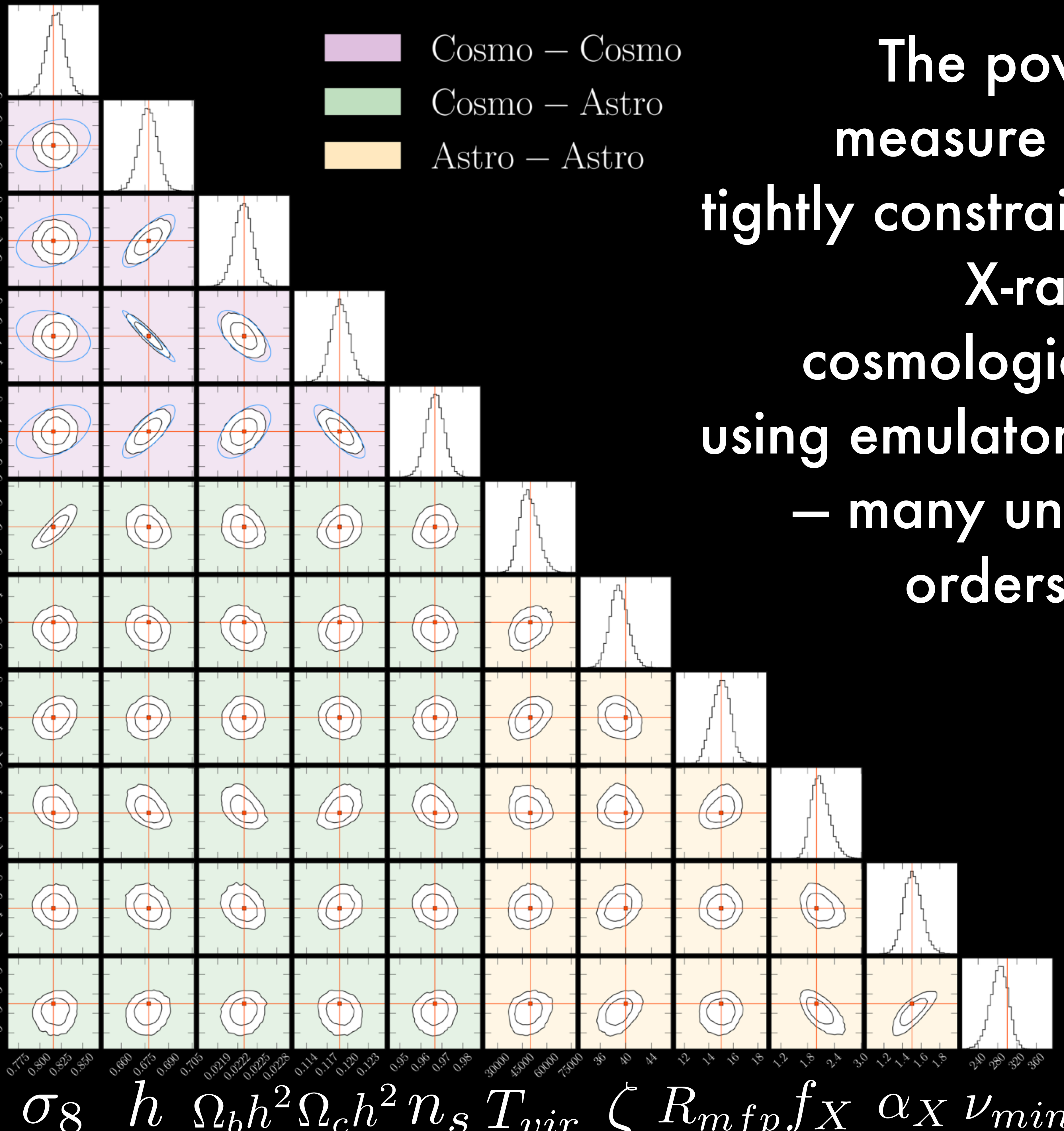
Liu et al. (2016)

There's also complex, interconnected astrophysics across a wide range of redshifts to explore, even if EDGES is wrong.



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

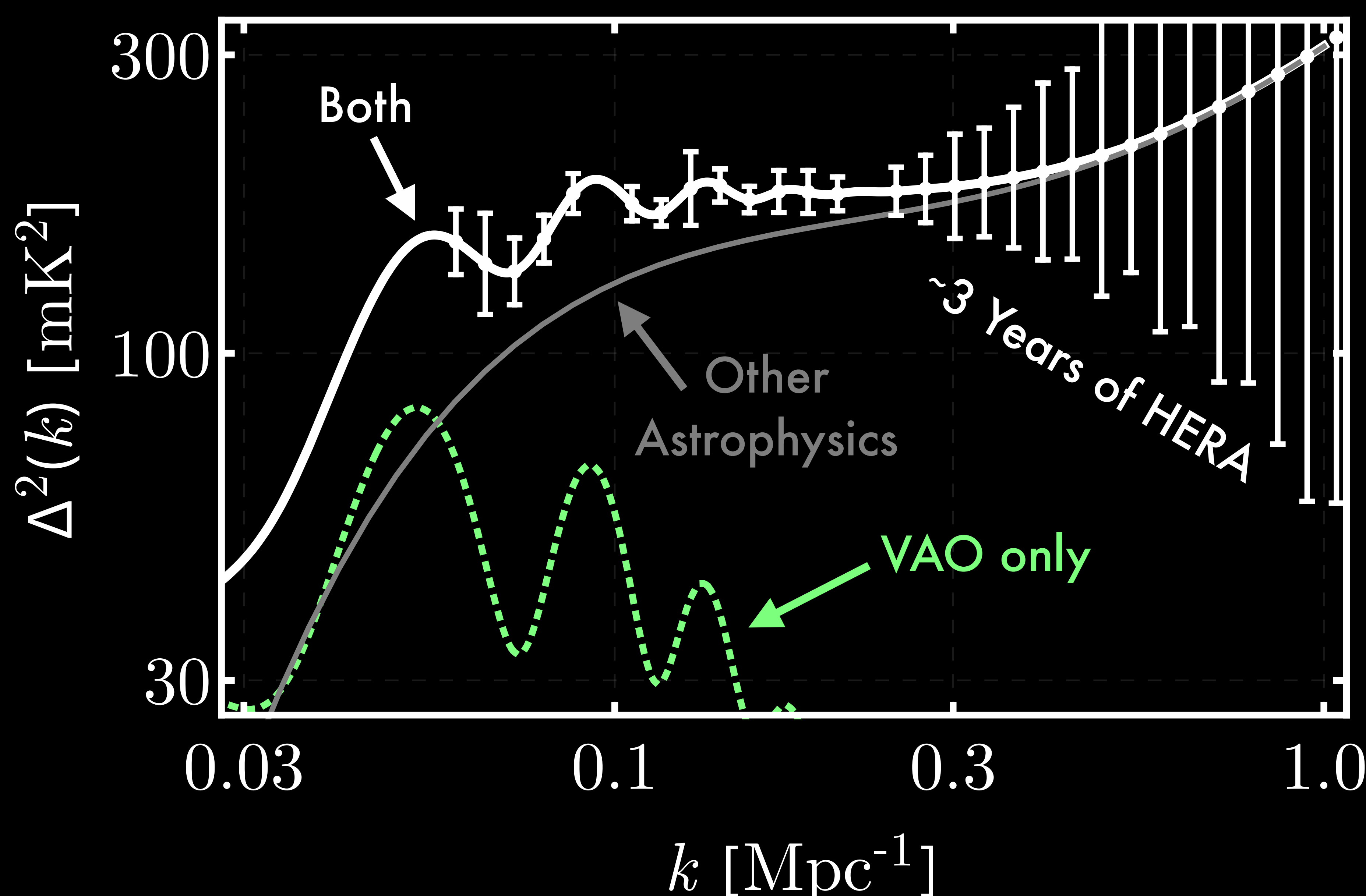
Mesinger et al. (2016)



The power spectra we measure with HERA will tightly constrain reionization, X-ray heating, and cosmological parameters using emulators and MCMCs — many unconstrained by orders of magnitude!

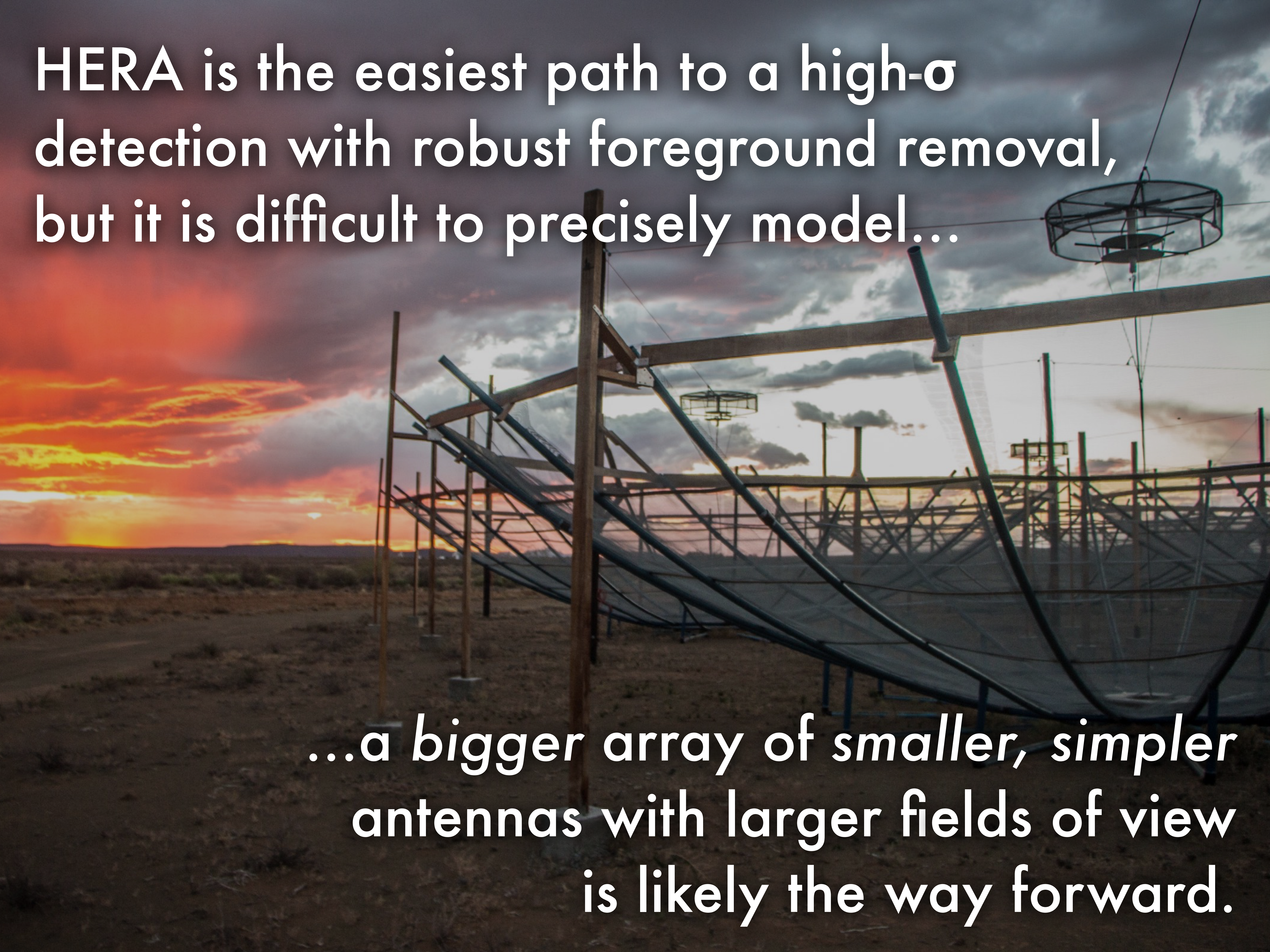
Kern et al. (2017)

With a few years of observing, we may detect velocity acoustic oscillations, providing a new standard ruler at z≈16.



Muñoz et al. (2019)

What comes next?


HERA is the easiest path to a high-σ
detection with robust foreground removal,
but it is difficult to precisely model...
...a *bigger* array of *smaller, simpler*
antennas with larger fields of view
is likely the way forward.

There's a problem with how we measure visibilities.

$$V_{ij}(\nu) = \int B_{ij}(\hat{\mathbf{r}}, \nu) I(\hat{\mathbf{r}}, \nu) \exp\left[-2\pi i \frac{\nu}{c} \mathbf{b}_{ij} \cdot \hat{\mathbf{r}}\right] d\Omega$$

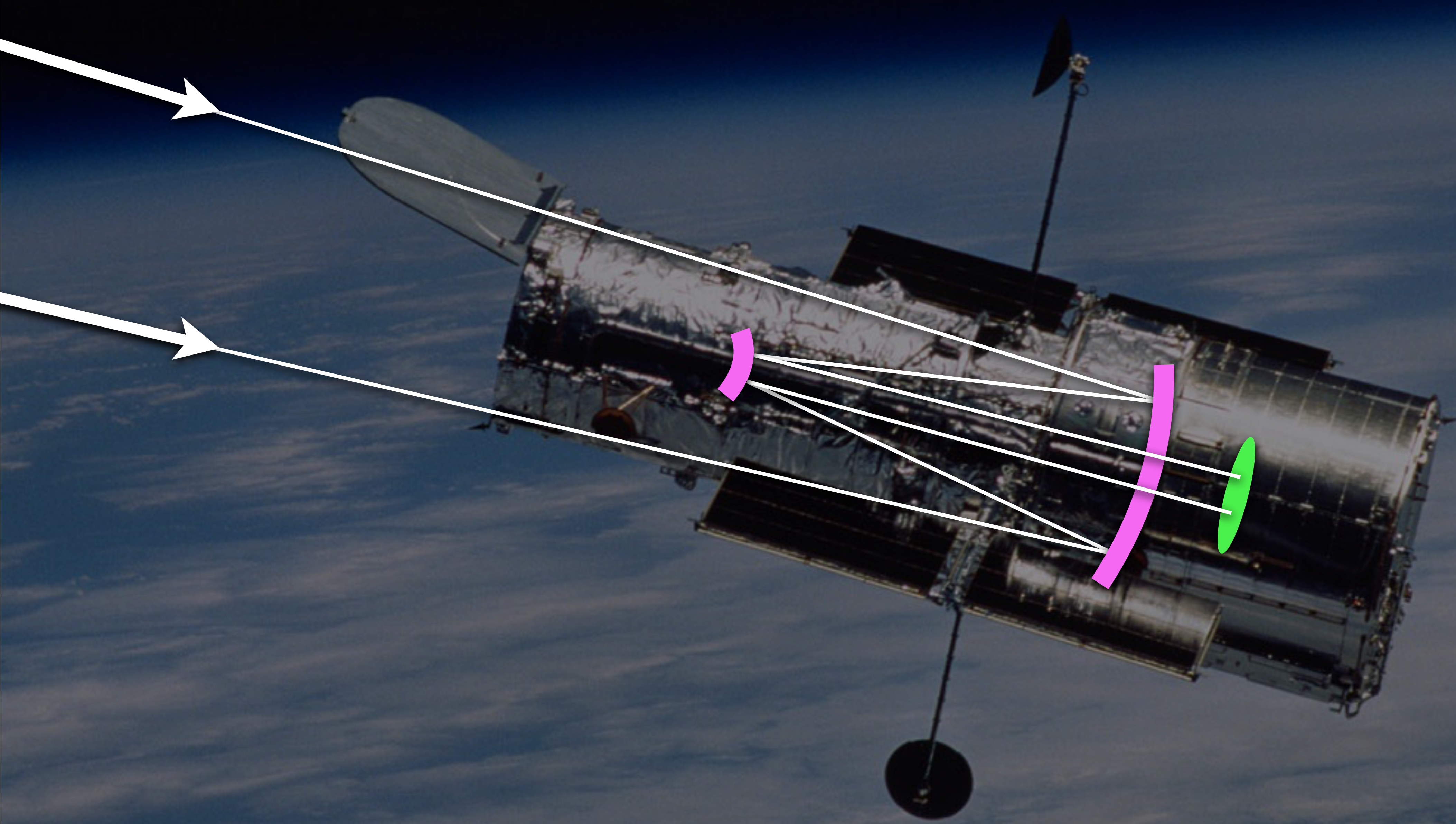
Measure antenna voltages $v_i(t)$. → Fourier transform to frequency: $\tilde{v}_i(\nu)$

→ Correlate antennas to form visibilities:

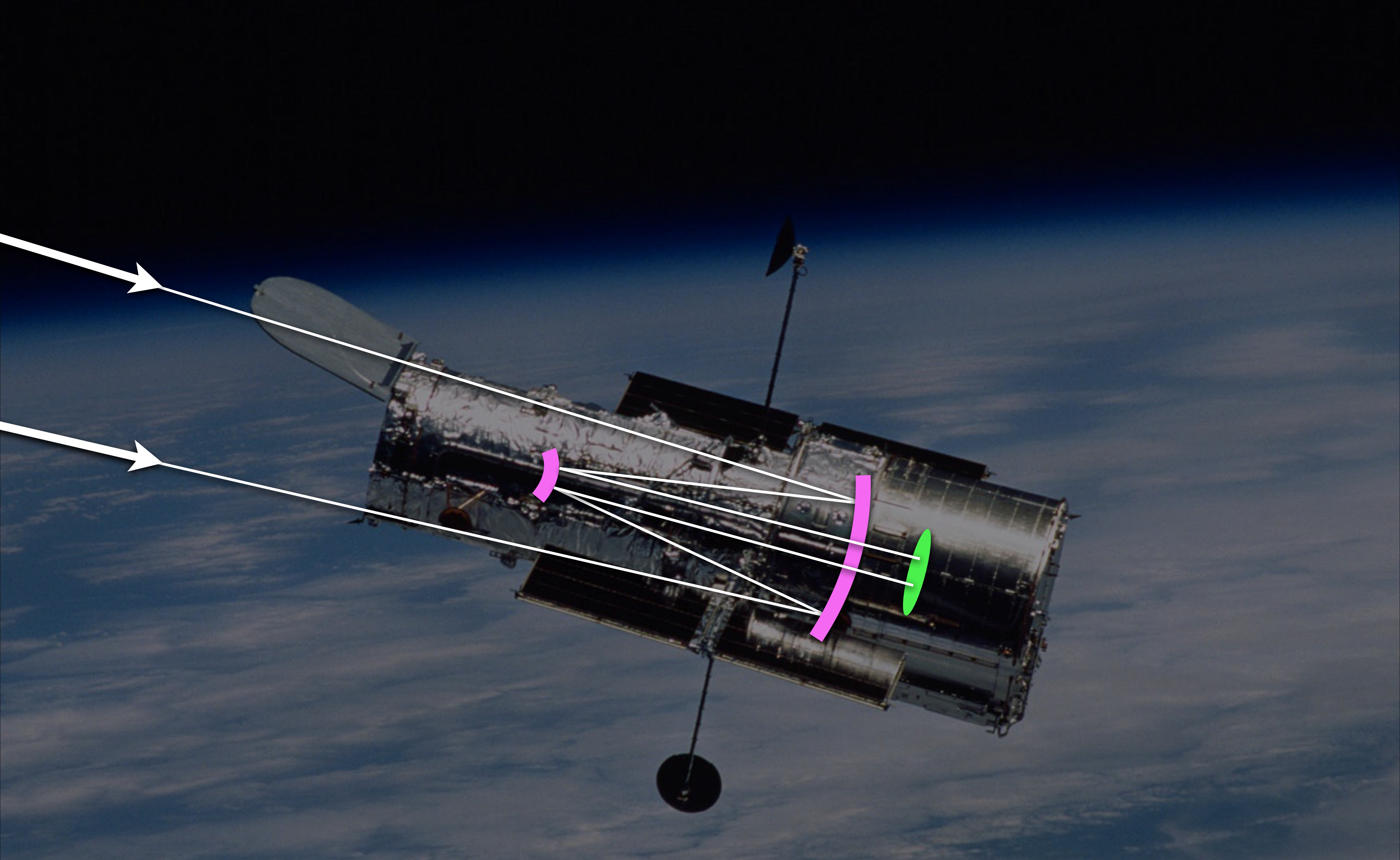
$$\langle \tilde{v}_i(\nu) \tilde{v}_j^*(\nu) \rangle = V_{ij}(\nu)$$

This scales like O(N²)!

All telescopes are Fourier transformers.



A telescope converts angles on the sky
to positions on the focal plane.



A telescope converts *photon momenta* to *positions* on the focal plane.

$$V_{ij}(\nu) = \int B_{ij}(\hat{\mathbf{r}}, \nu) I(\hat{\mathbf{r}}, \nu) \exp\left[-2\pi i \frac{\nu}{c} \mathbf{b}_{ij} \cdot \hat{\mathbf{r}}\right] d\Omega$$

can be rewritten suggestively as...

$$\langle \tilde{v}_i(k) \tilde{v}_j^* \rangle = \int B(\mathbf{k}) I(\mathbf{k}) \exp\left[i\mathbf{k} \cdot (\mathbf{x}_i - \mathbf{x}_j)\right] d\Omega$$

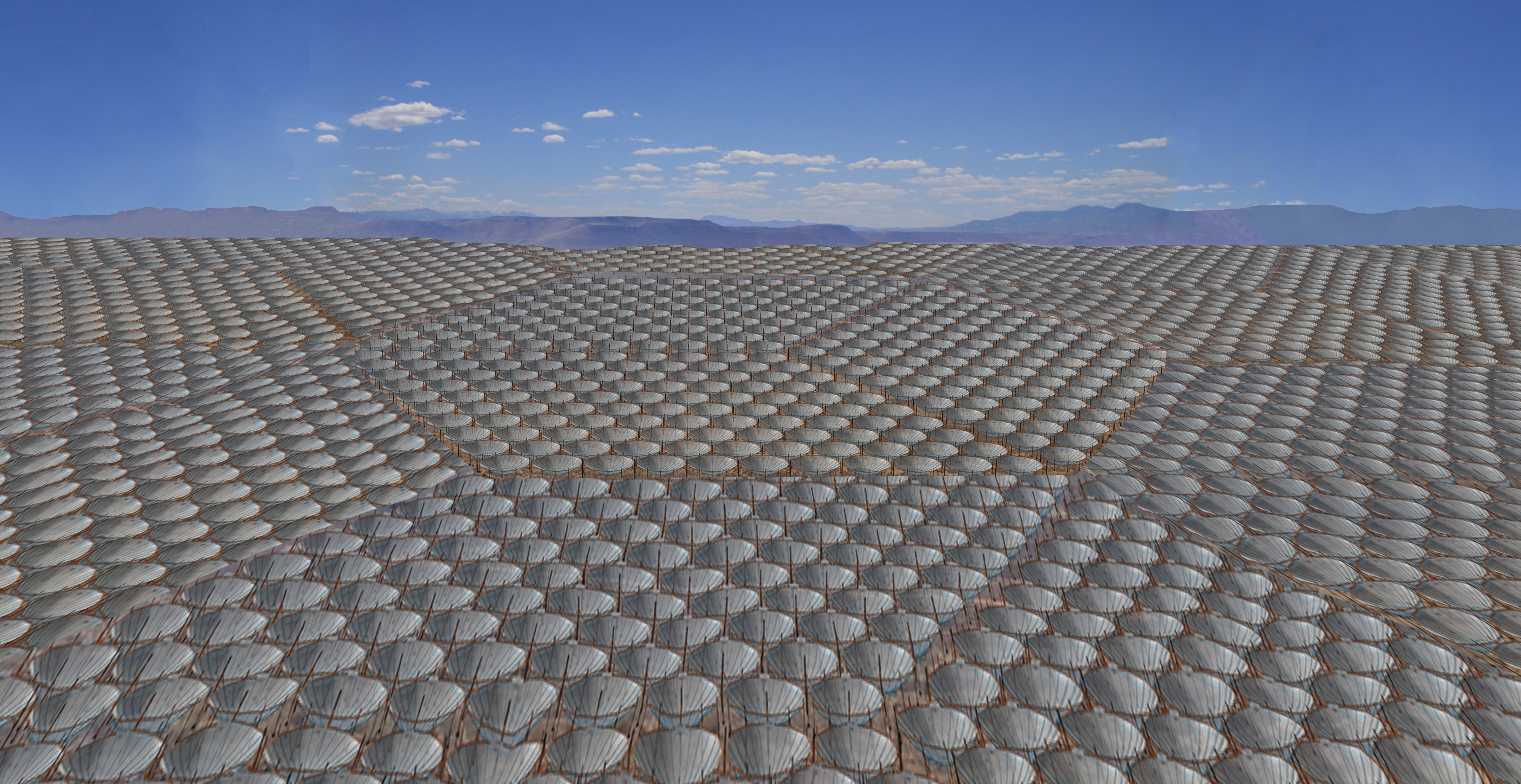
If antenna positions x_i are on a regular grid, we can directly sample the electric field, FFT, and square to get beam-weighted maps... effectively correlating in O(N log N)!

Tegmark & Zaldarriaga (2009)

An FFT Telescope can be bigger than HERA.

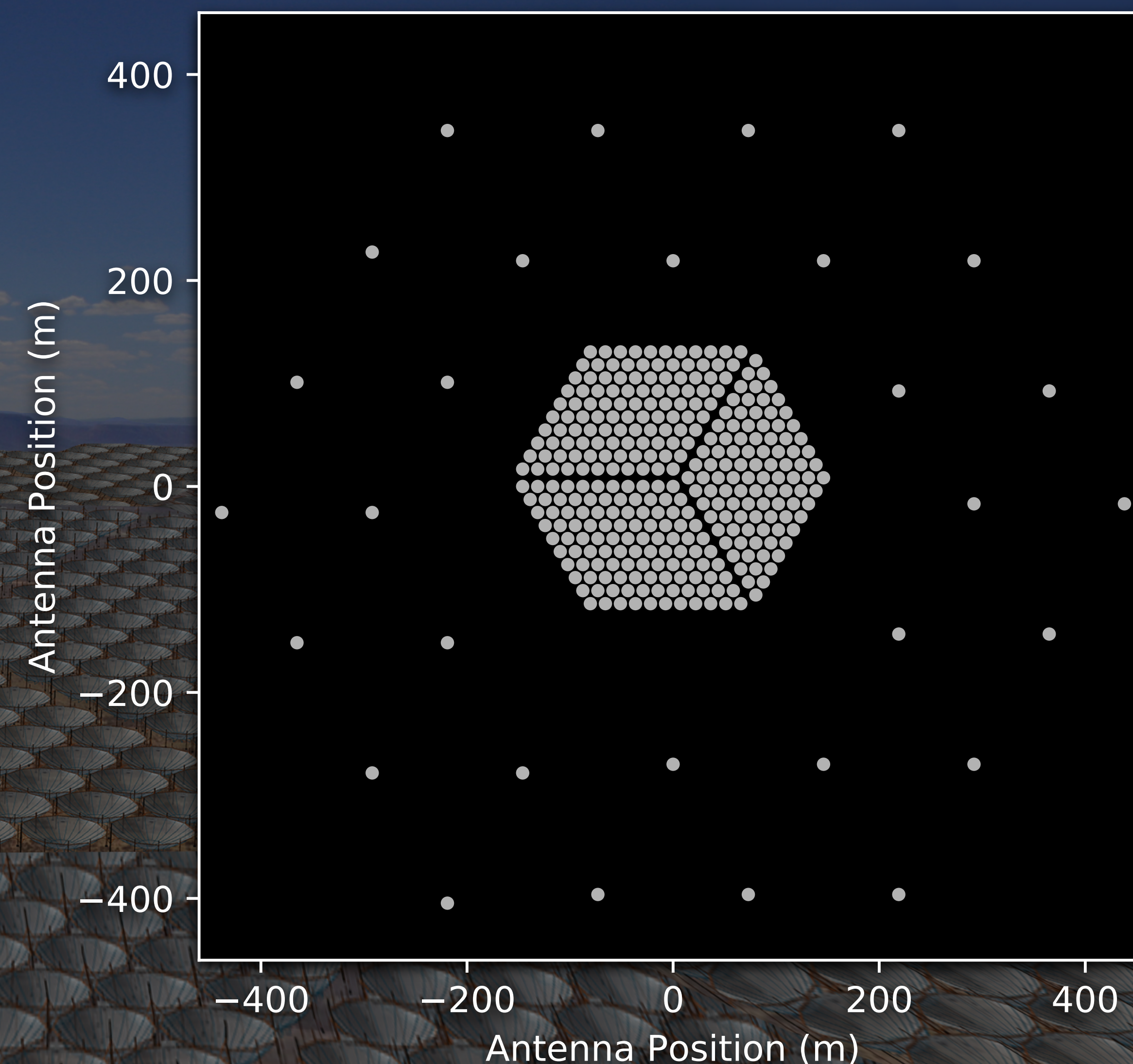
An FFT Telescope can be bigger than HERA.

Much, *much* bigger.



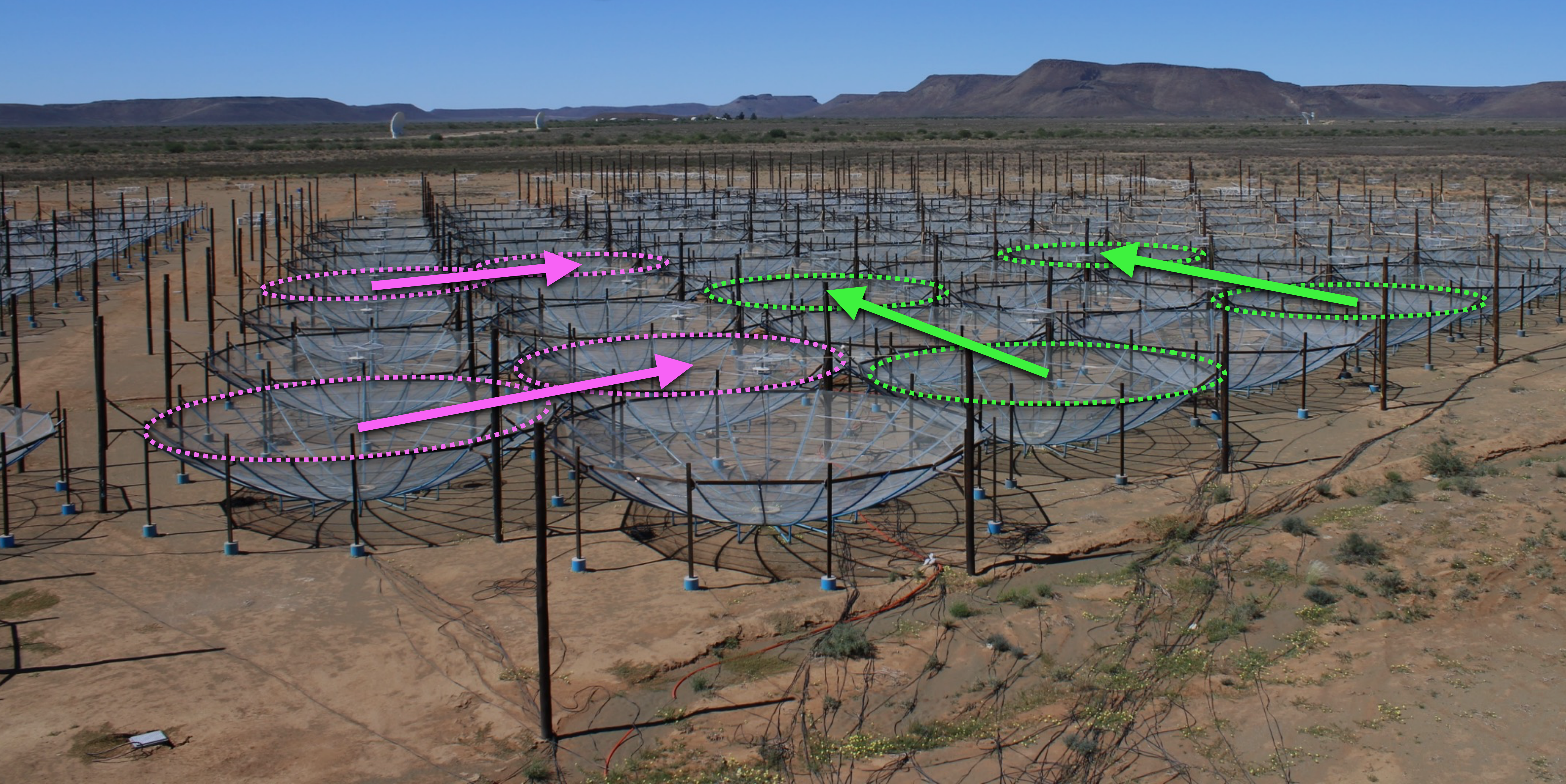
An FFT Telescope needs to be...

- Co-planar.
- Made up of identical antenna elements with identical beams.
  - *To avoid EoR window contamination (Orosz, **Dillon**, et al. 2018)*
- On a regular or hierarchically regular grid.
  - I designed HERA's layout for FFT correlation (**Dillon** & Parsons 2016)
- Calibrated in real time.

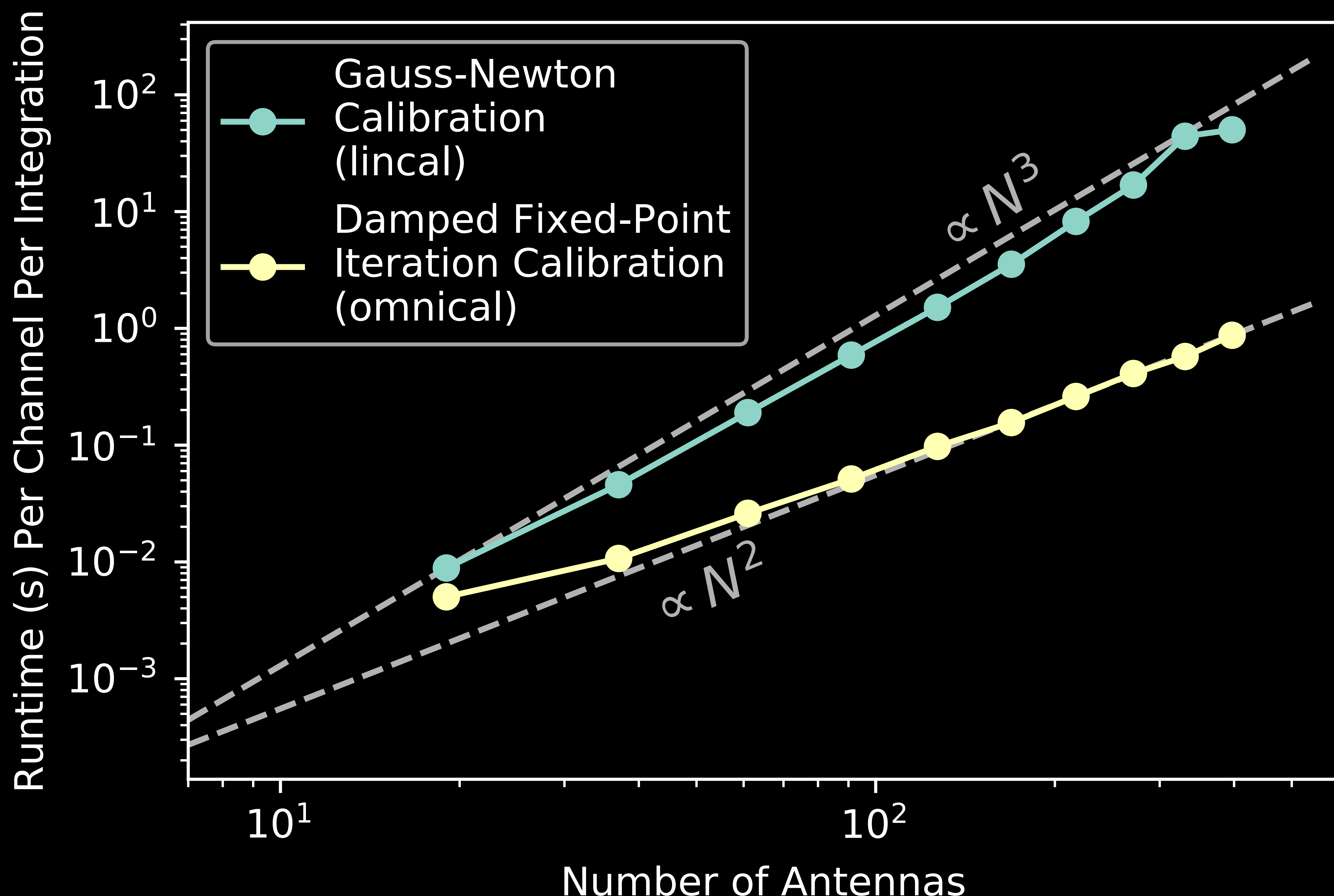


Tegmark & Zaldarriaga (2009, 2010)

Real-time redundant-baseline calibration of regular arrays is precisely what we're learning to do with HERA!



We showed how to speed up redundant calibration from O(N³) to O(N²).



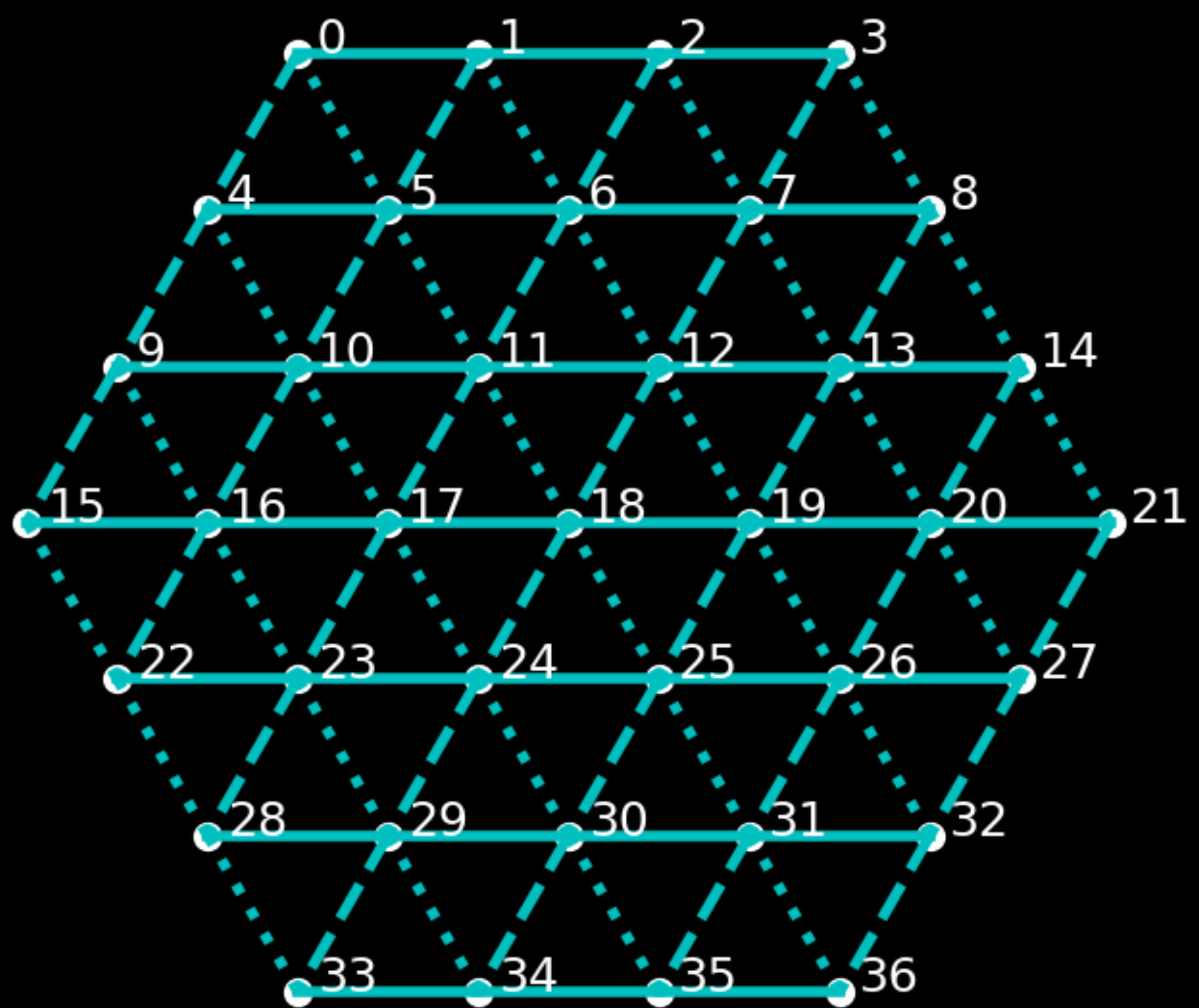
Dillon *et al.* (2020)

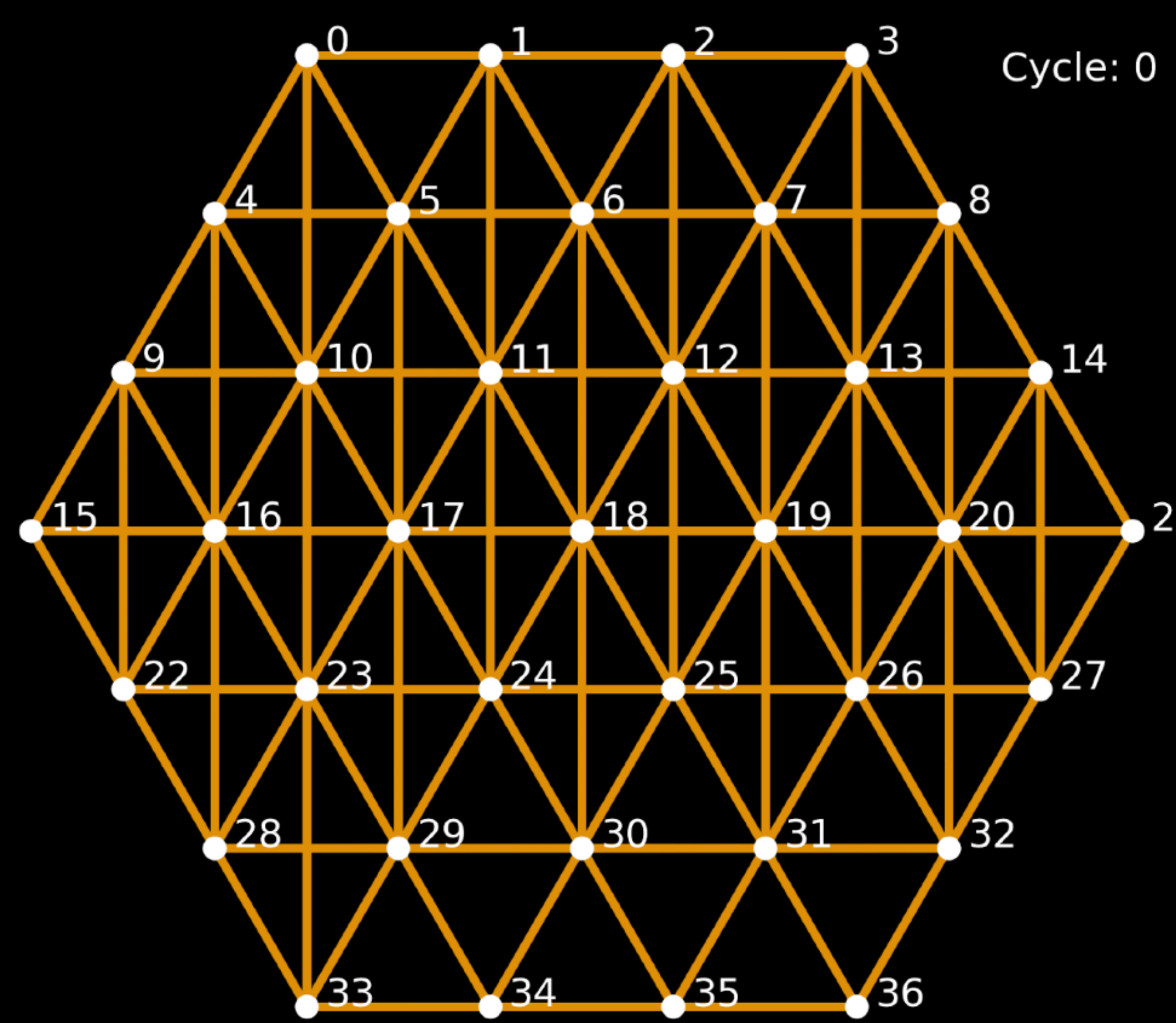
And how to use a subset of the data to reduce calibration from $O(N^2)$ to $O(N\log N)$.

Subset-Redundant Calibration

vs.

Low-Cadence Calibration





Gorthi, Parsons, ***Dillon*** *et al. (2021)*

FFTTs could map the majority of the volume of the observable universe, giving us…

Direct measurements of small-scale density fluctuations at early times:

- Warm dark matter (Sitwell et al. 2013)
- Tests of inflation via non-Gaussianity (Cooray et al. 2008) or spectral index running (Mao et al. 2008)

A precise thermal history of the universe, constraining:

- Dark matter annihilation and decay (Evoli et al. 2014)
- Primordial black hole evaporation (Mack & Wesley 2008)

Unprecedented constraints on the standard model of cosmology:

- Orders of magnitude better than Planck, e.g. $\Delta\Omega_k \approx .0002$ and $\Delta\Sigma\nu \approx 7$ meV (Mao et al. 2008)

In Summary:

- 21 cm cosmology promises to become the premier probe of the Cosmic Dawn and reionization.
- Foregrounds and systematics are major challenges. Different telescopes have taken very different approaches to overcome them.
- HERA has set the world-leading upper limits with just 18 nights of data and a very conservative analysis.
- A lot more data is coming down the pipe which will enable precise constraints of the astrophysics of reionization and, in time, tests of our cosmological models.