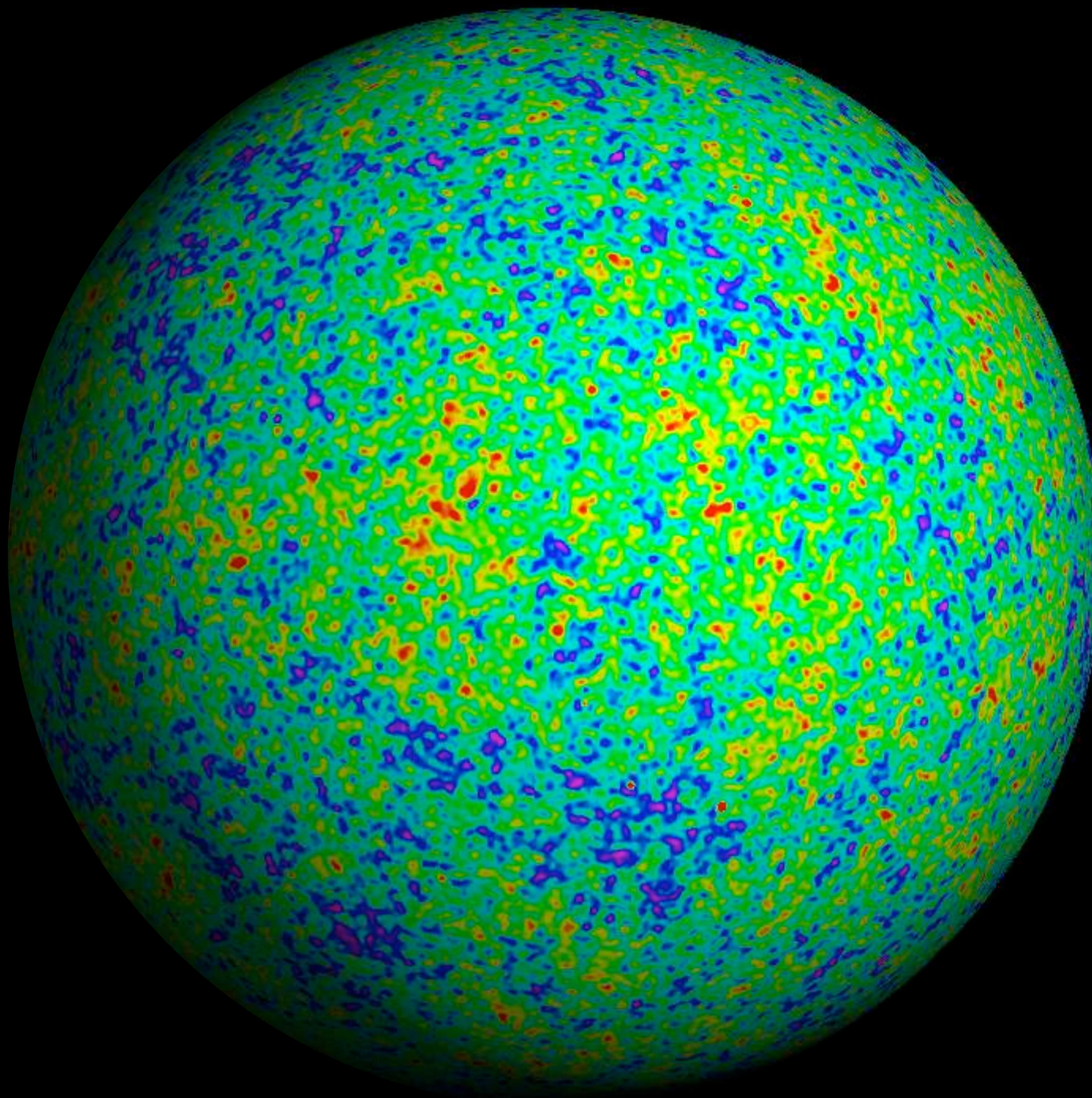
Recent Progress in 21 cm Cosmology with HERA

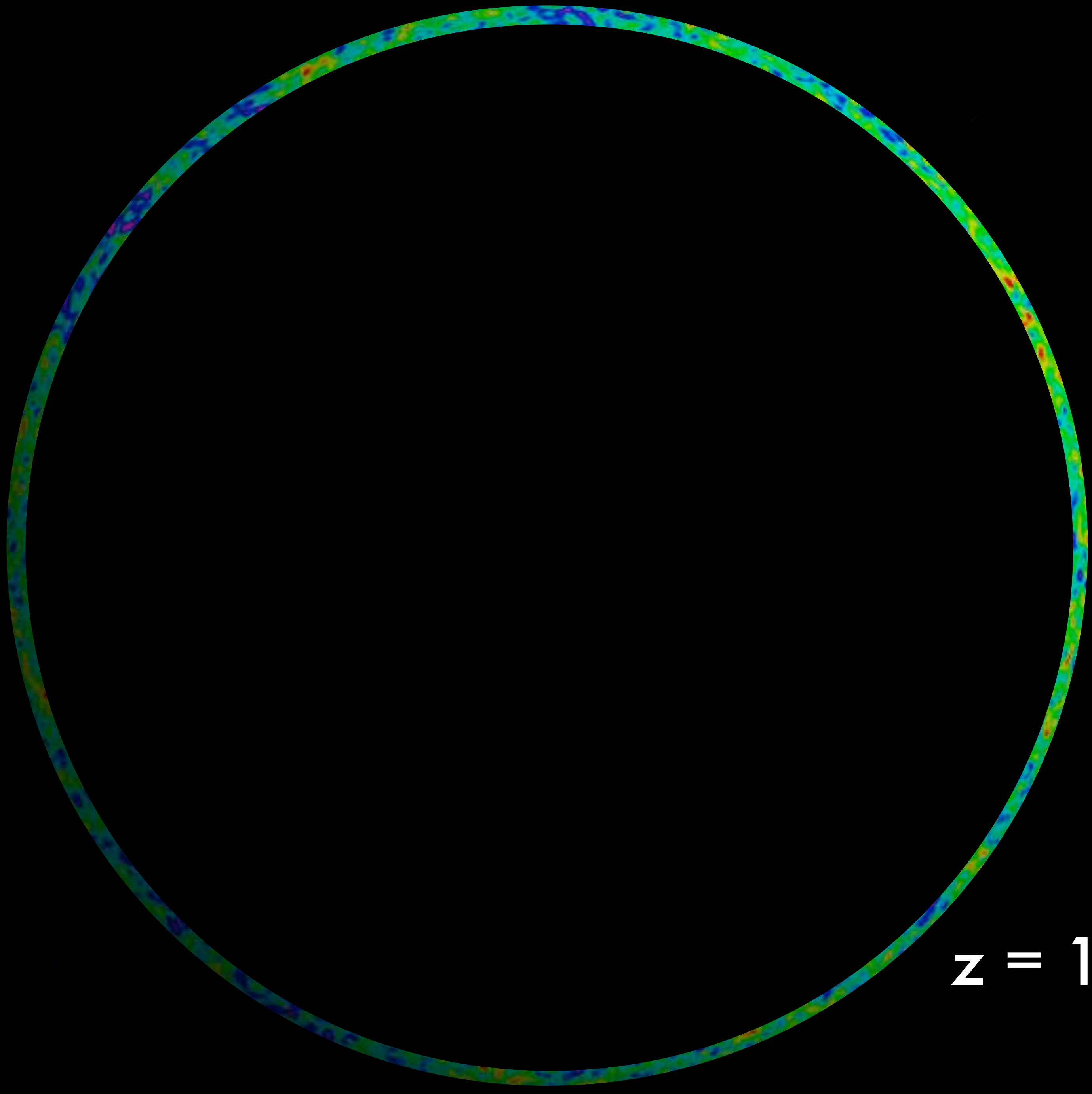
Josh Dillon
UC Berkeley

How can we map out our whole universe?

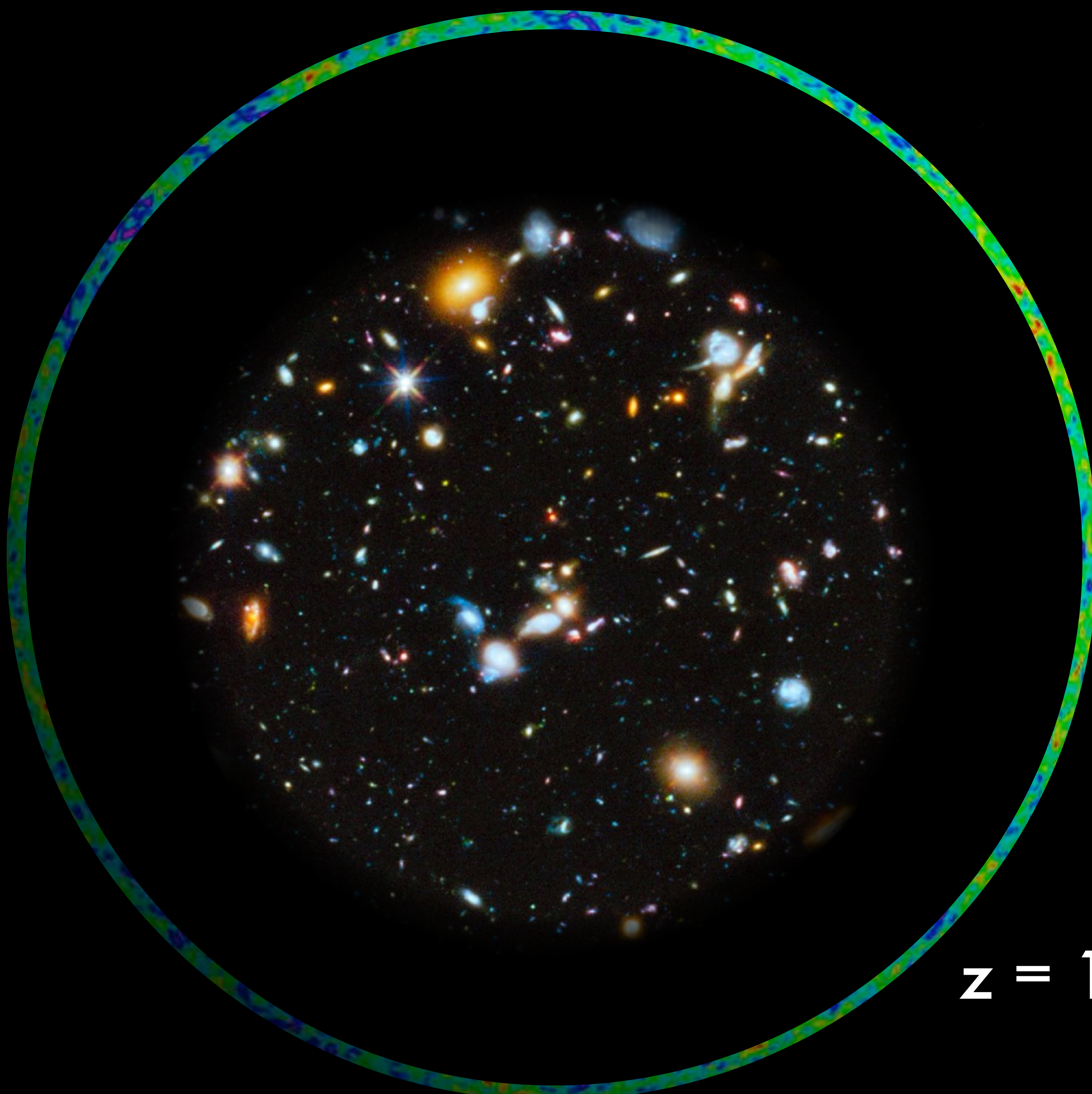
With the Cosmic Microwave Background...



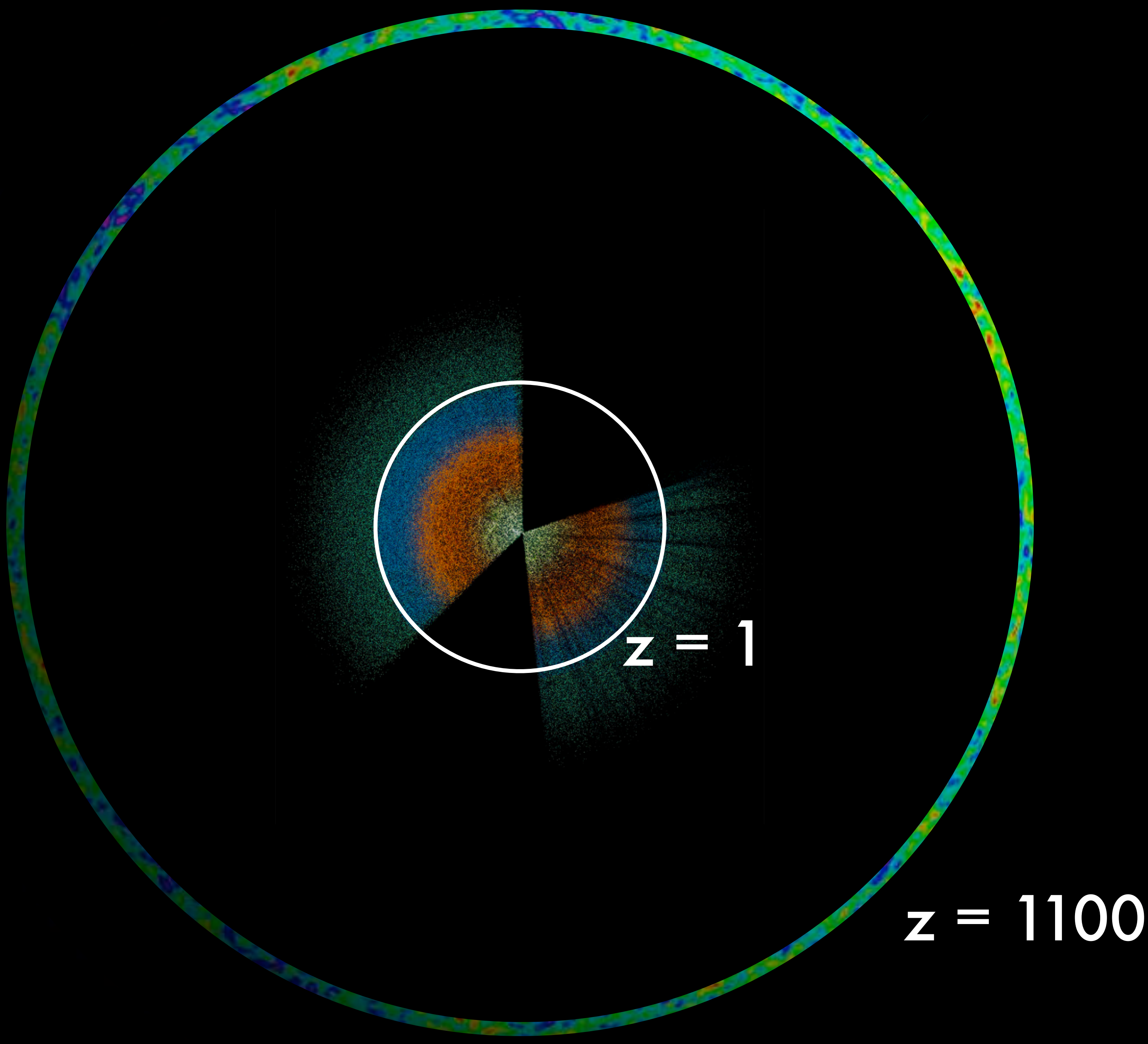
...we only get a thin shell at high redshift.



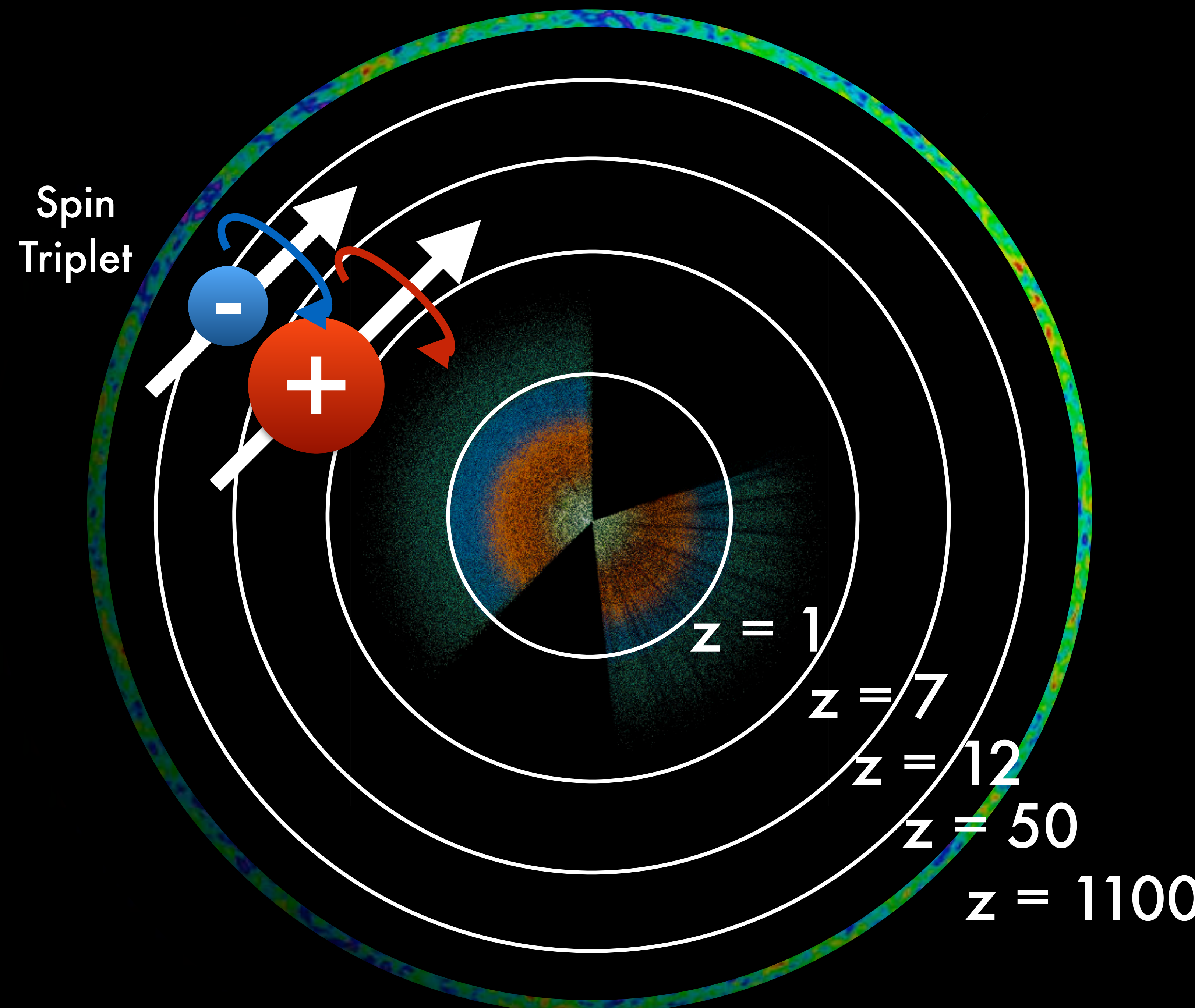
Even with huge surveys of galaxies...



...we only map out the local universe.



But using the 21 cm hydrogen line...



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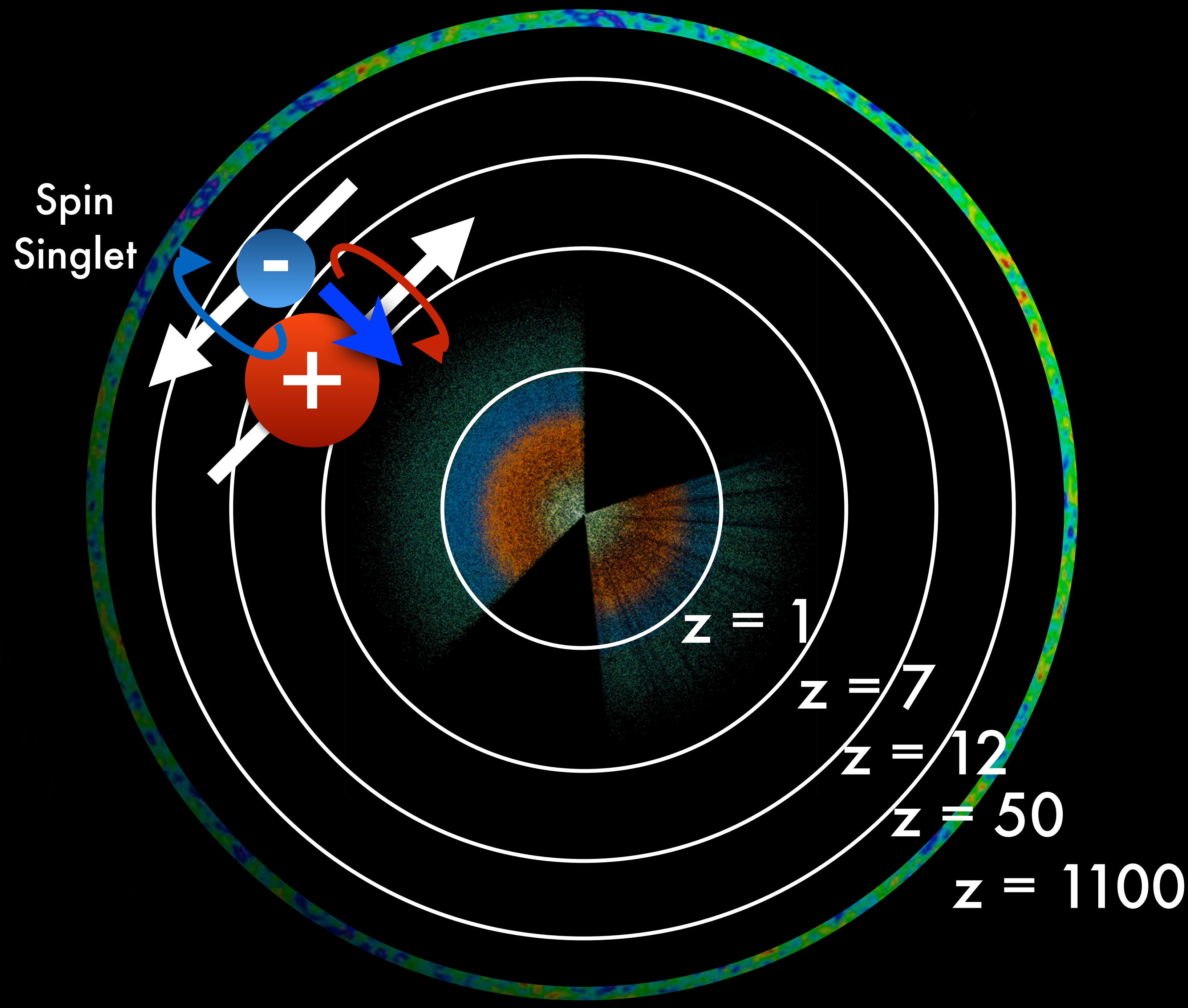

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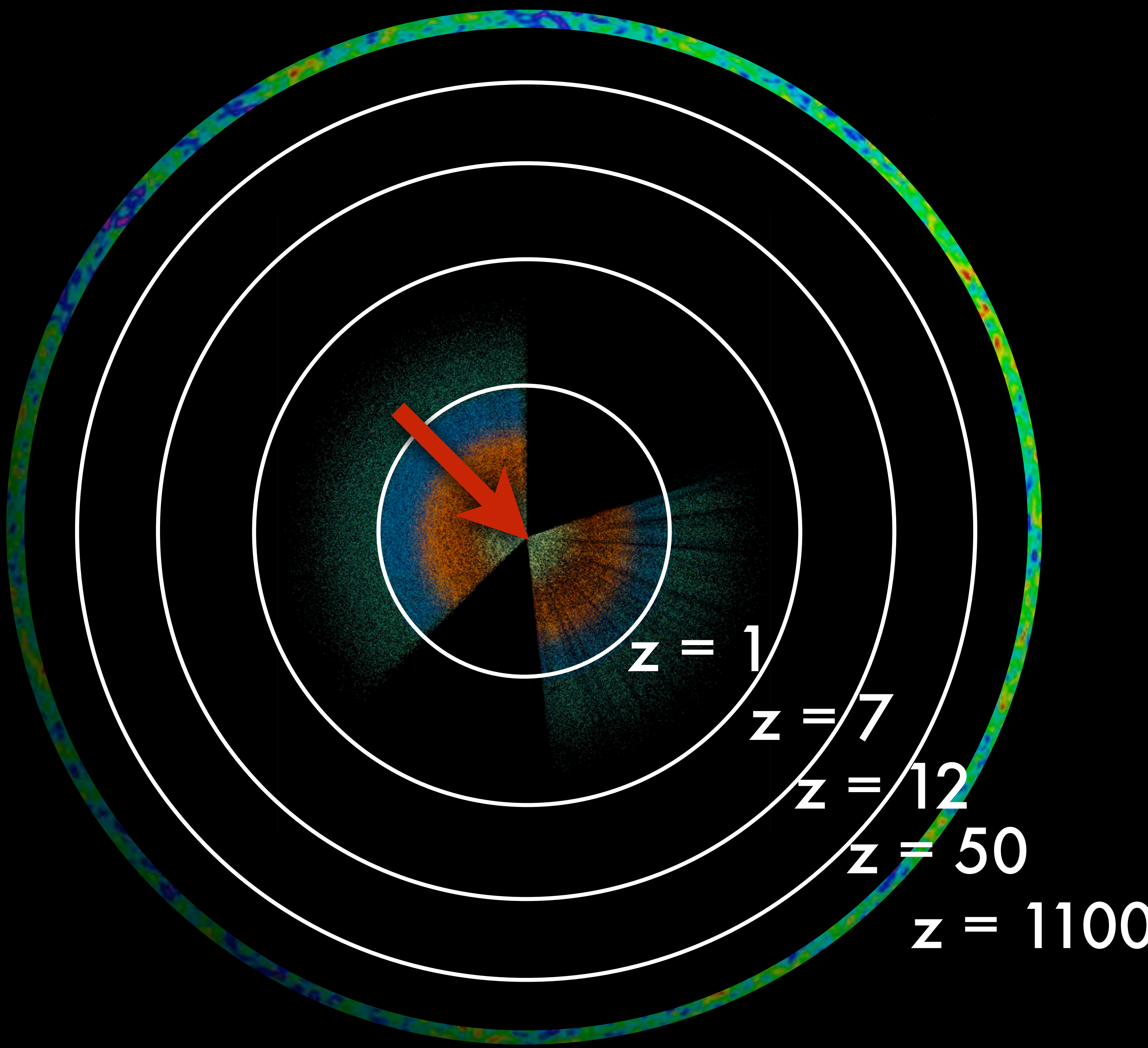
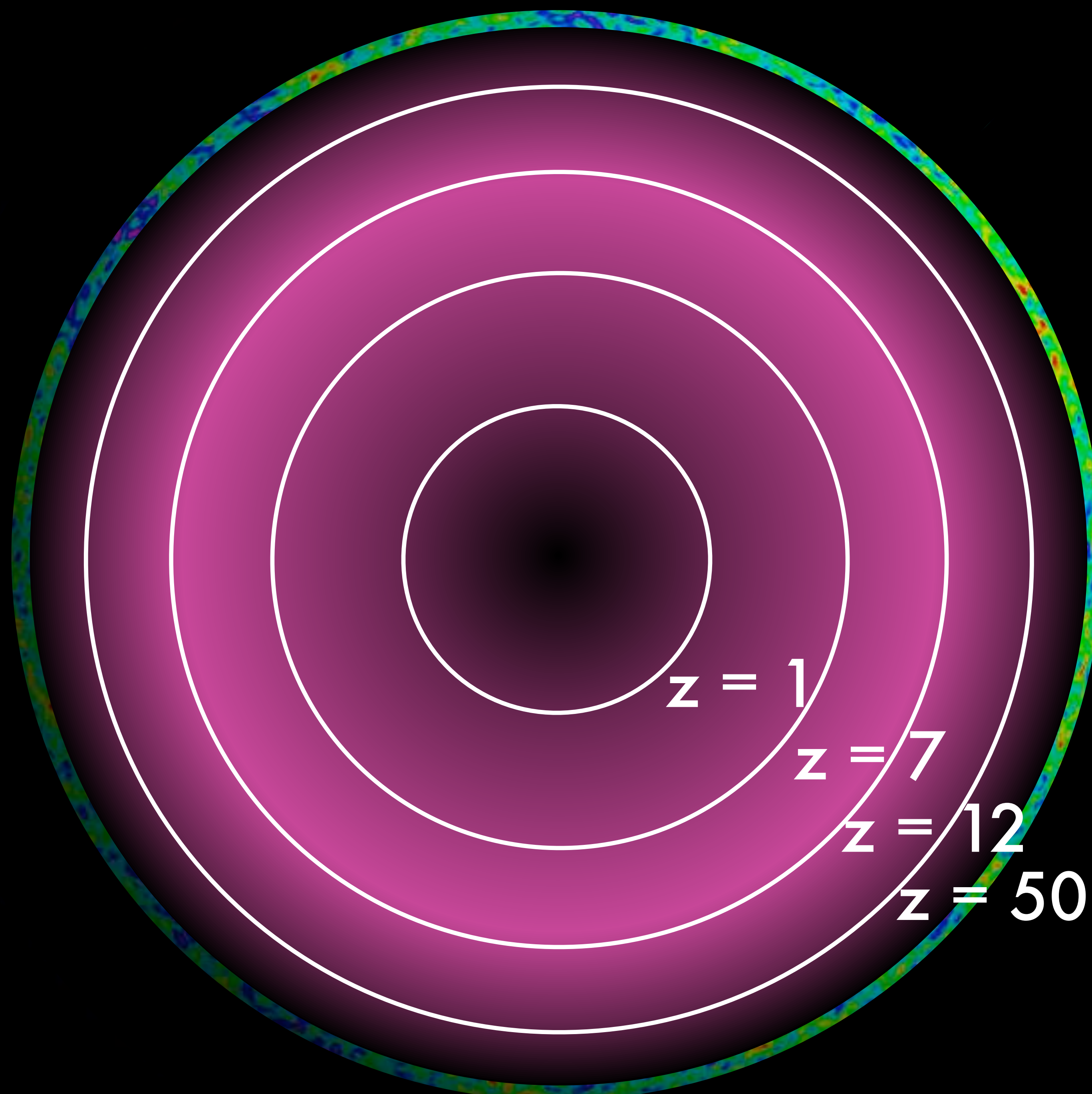
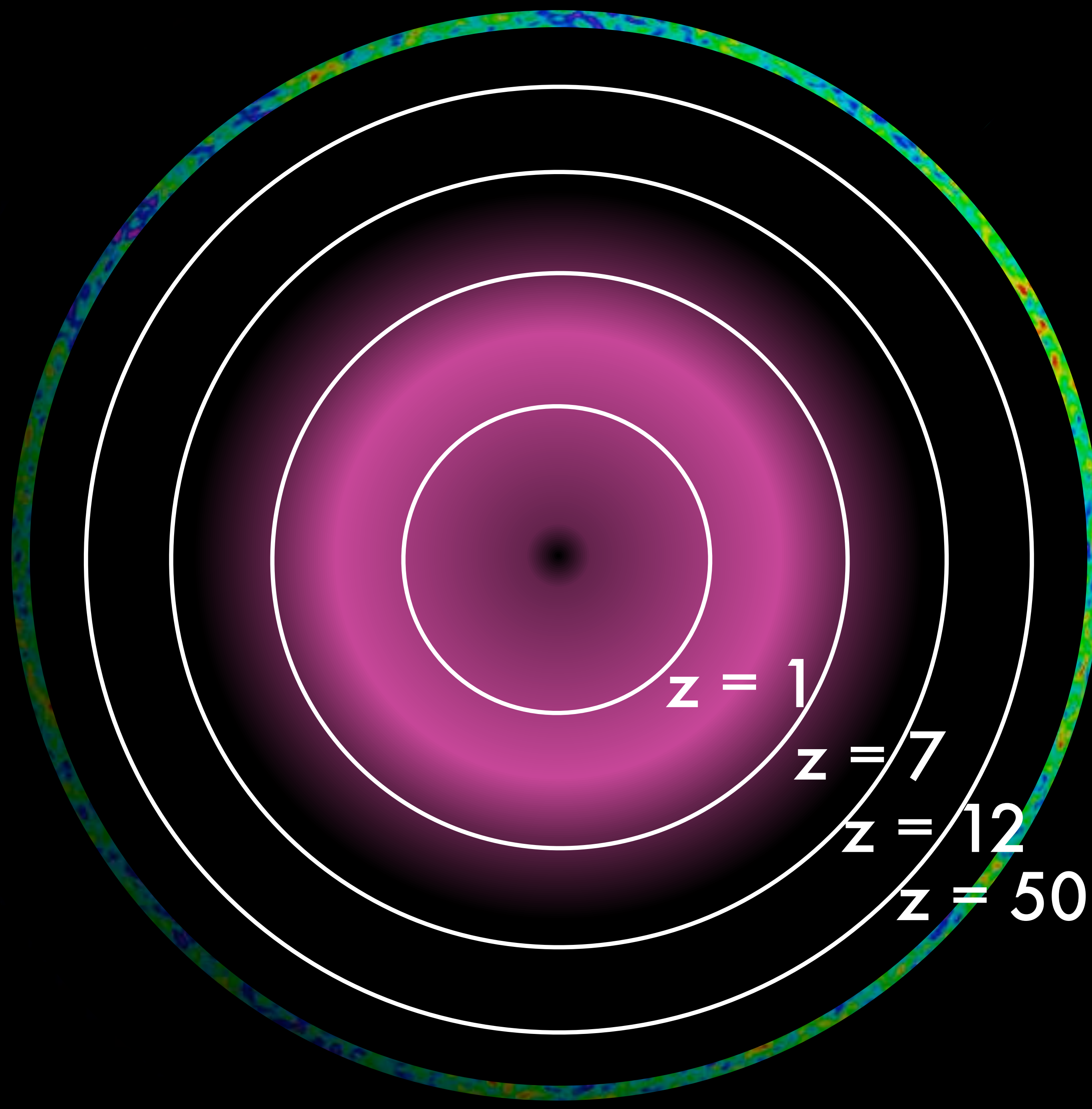


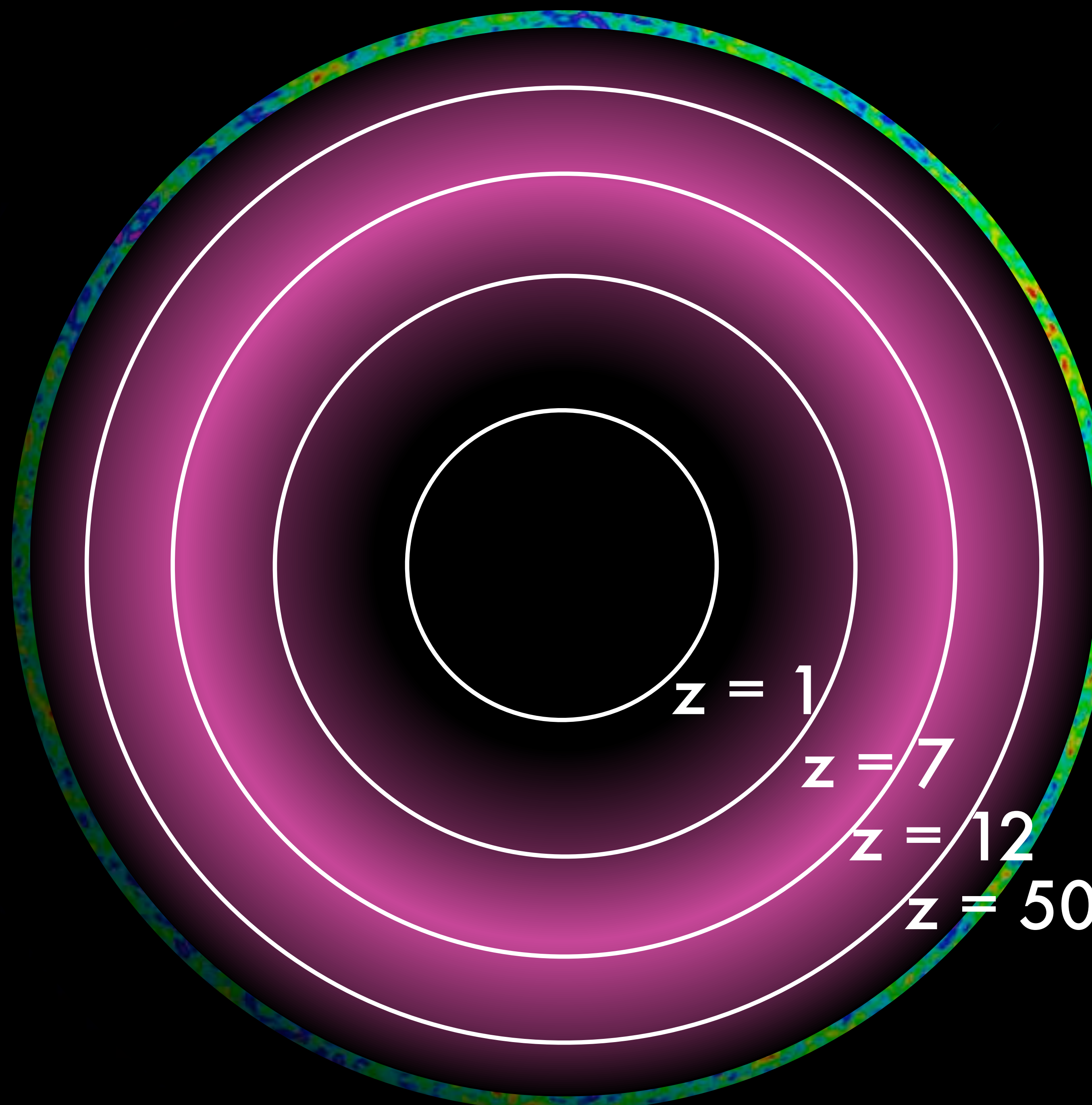
...a huge volume of the universe can be directly probed ($z \lesssim 200$).



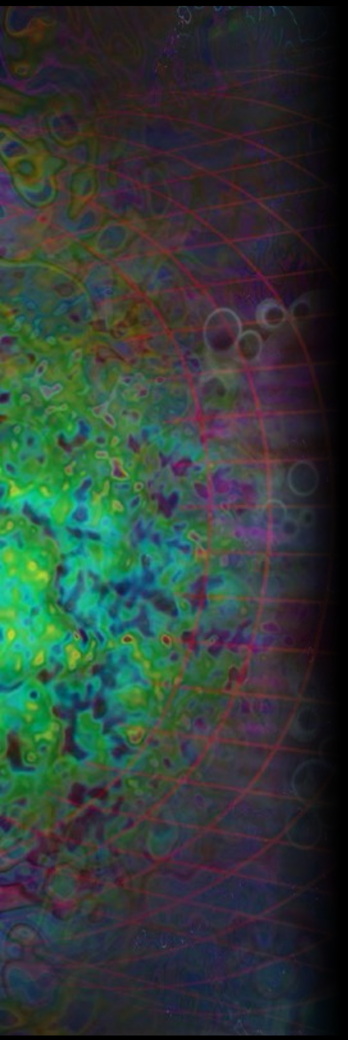
At “low” redshift, 21 cm can probe large-scale structure by tracing atomic gas in galaxies.



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

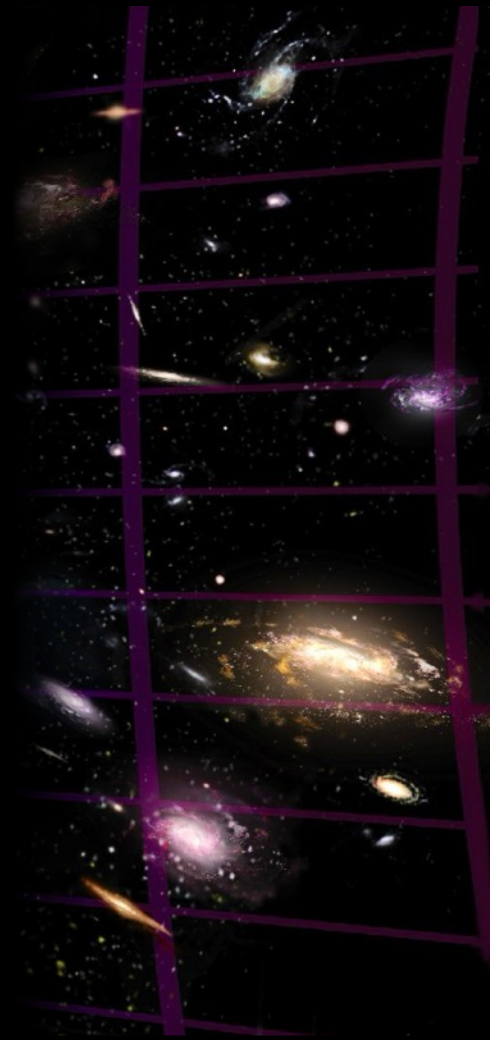


CMB



$z = 1100$

Modern Galaxies



$z < 6$

Image: Avi Loeb

CMB

Modern Galaxies

z =1100

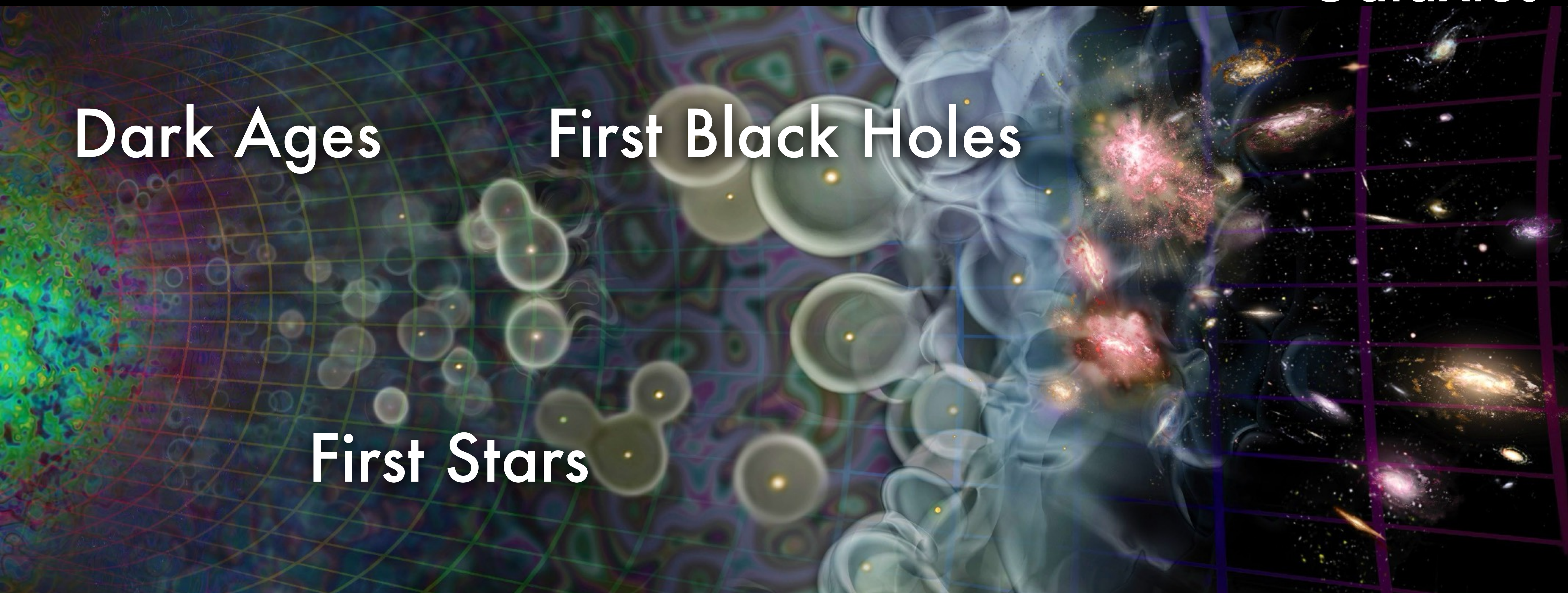
z < 6

Image: Avi Loeb


CMB
Modern
Galaxies
Dark Ages
First Stars
z =1100
z ≈ 50
z < 6
Image: Avi Loeb

CMB

Modern Galaxies



z =1100 | z ≈ 50 | z < 6

Image: Avi Loeb

CMB

Modern
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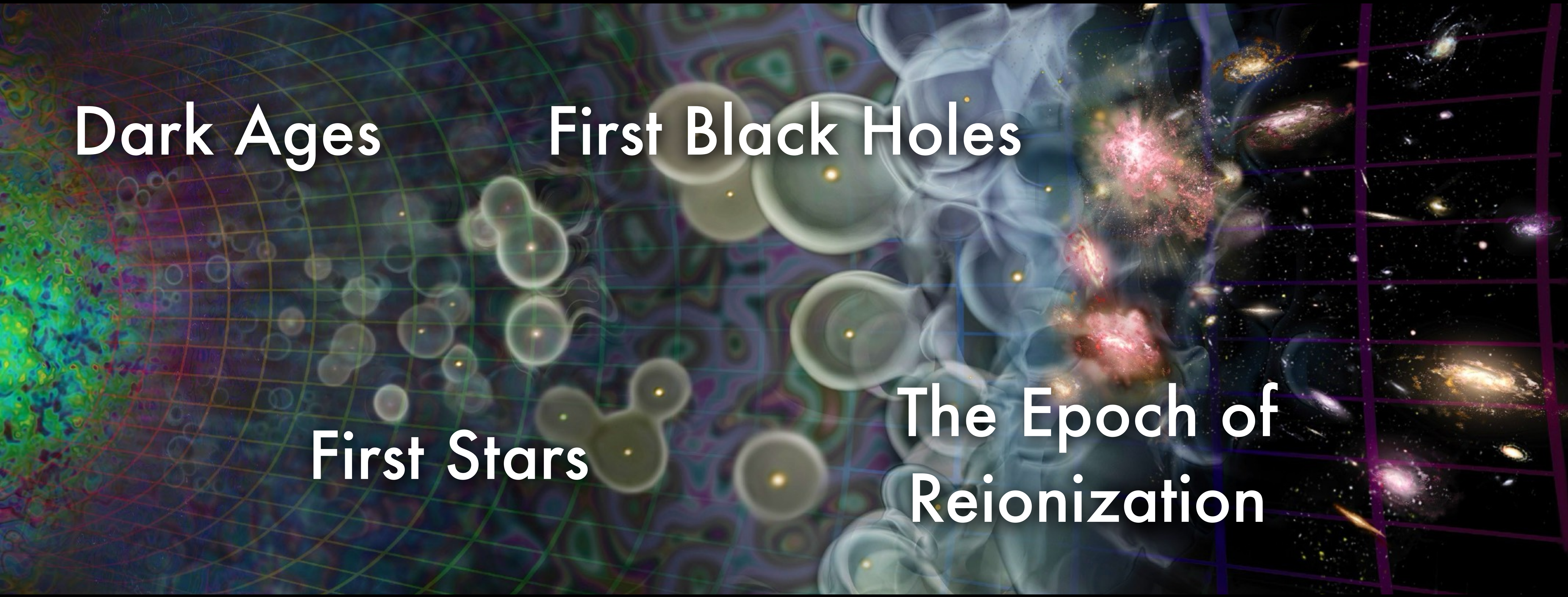

z =1100 z ≈ 50 z ≈ 8 z < 6

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.

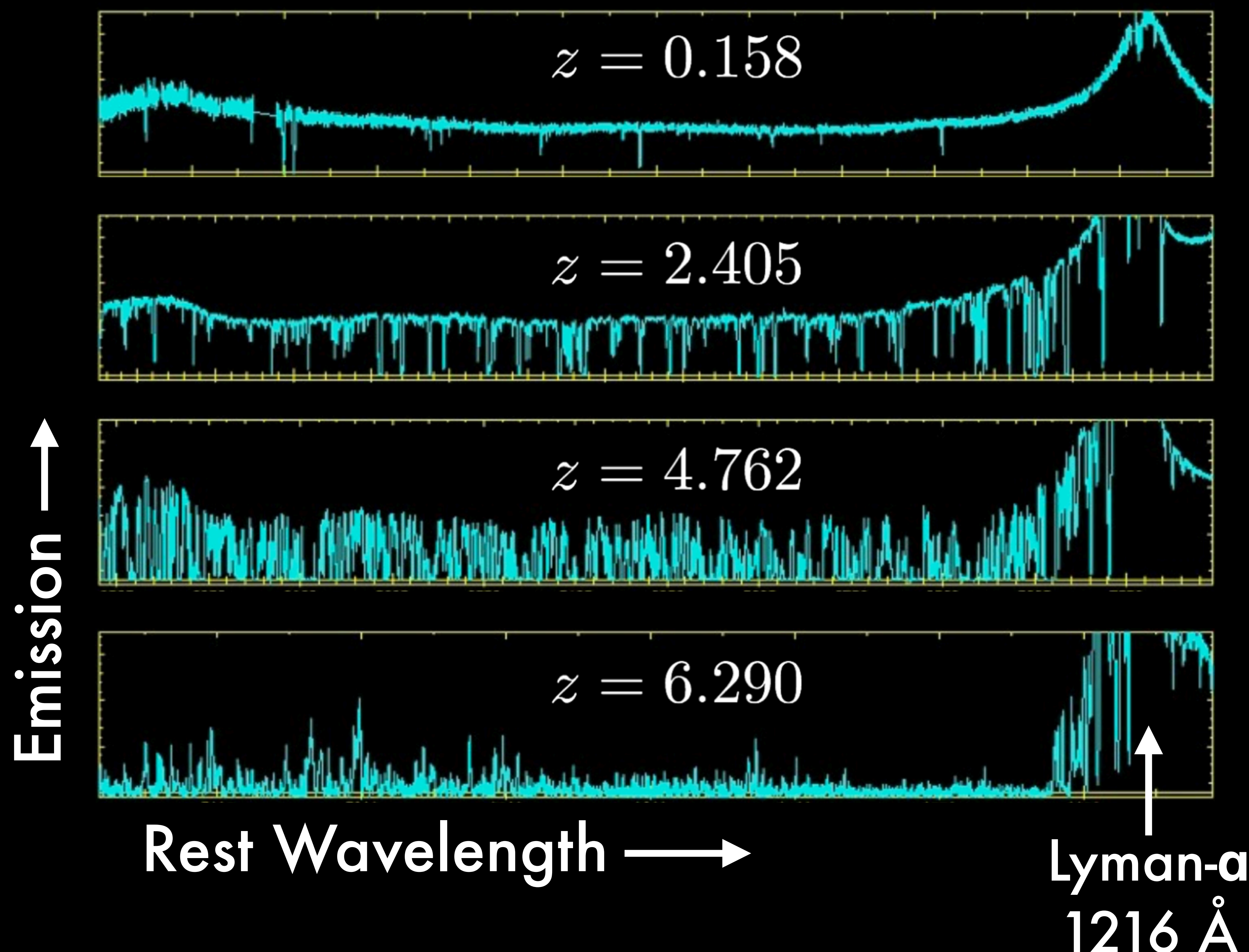

Image: Bob Carswell

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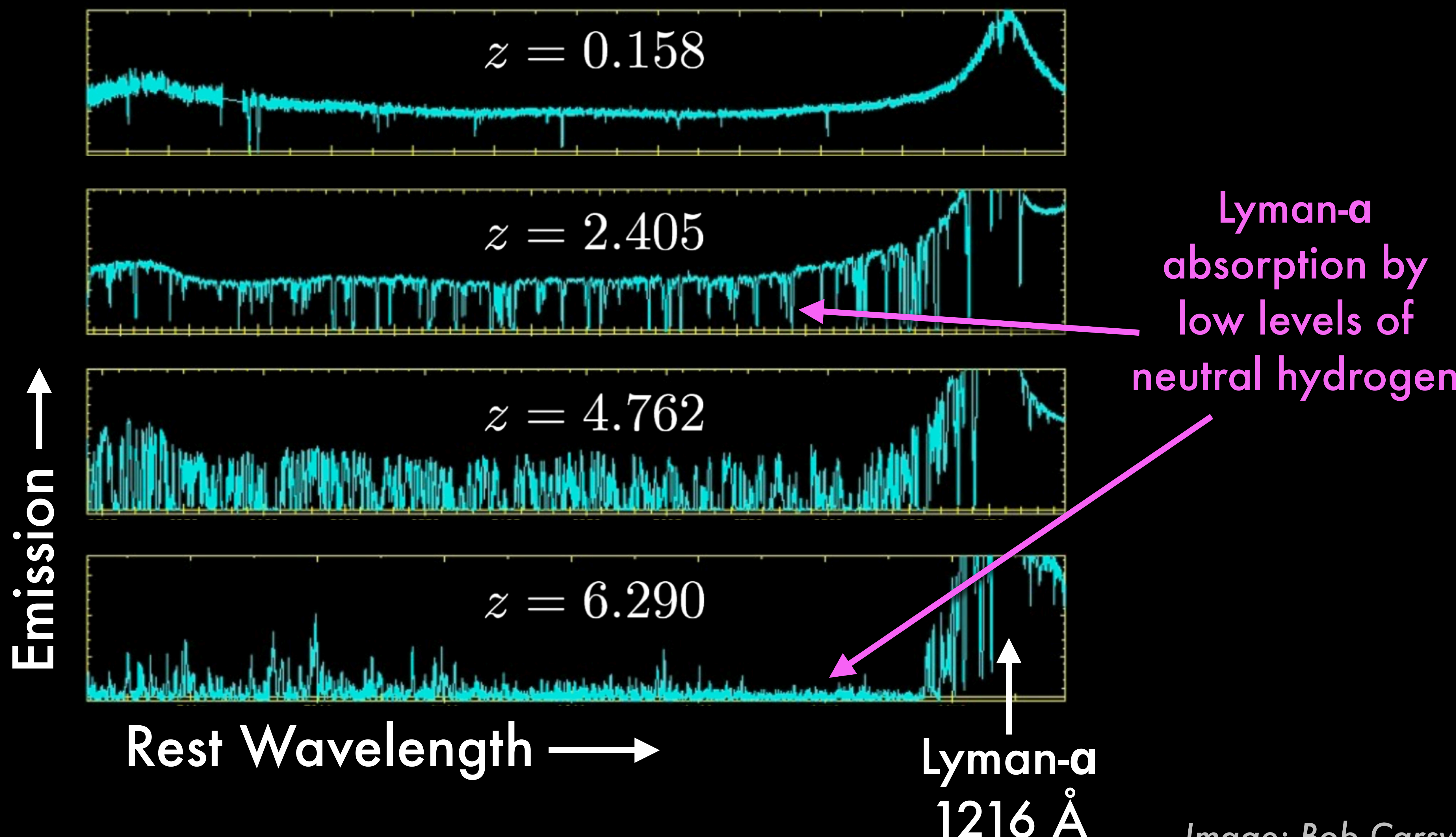

Image: Bob Carswell

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

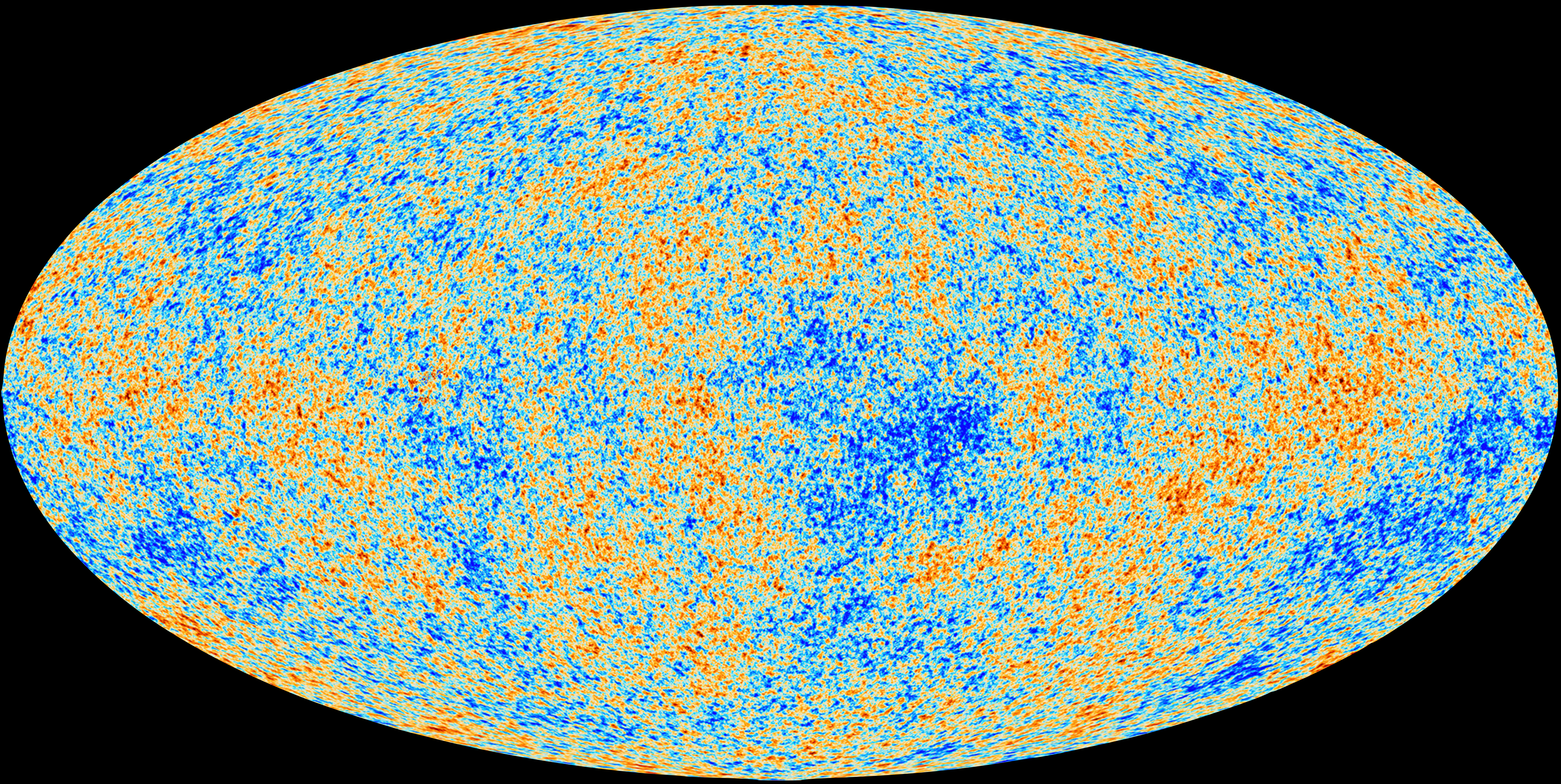

Image: Planck Collaboration

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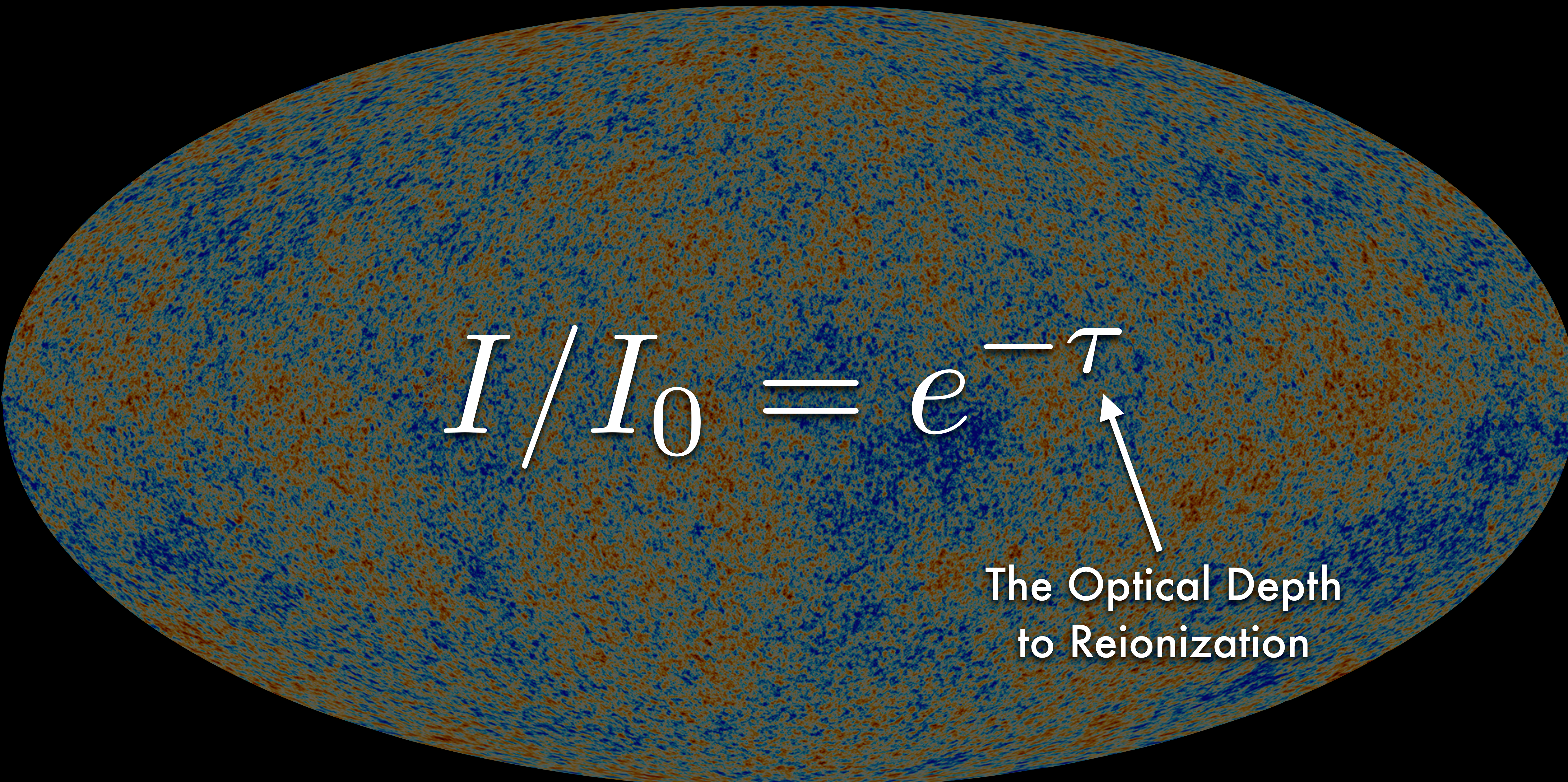

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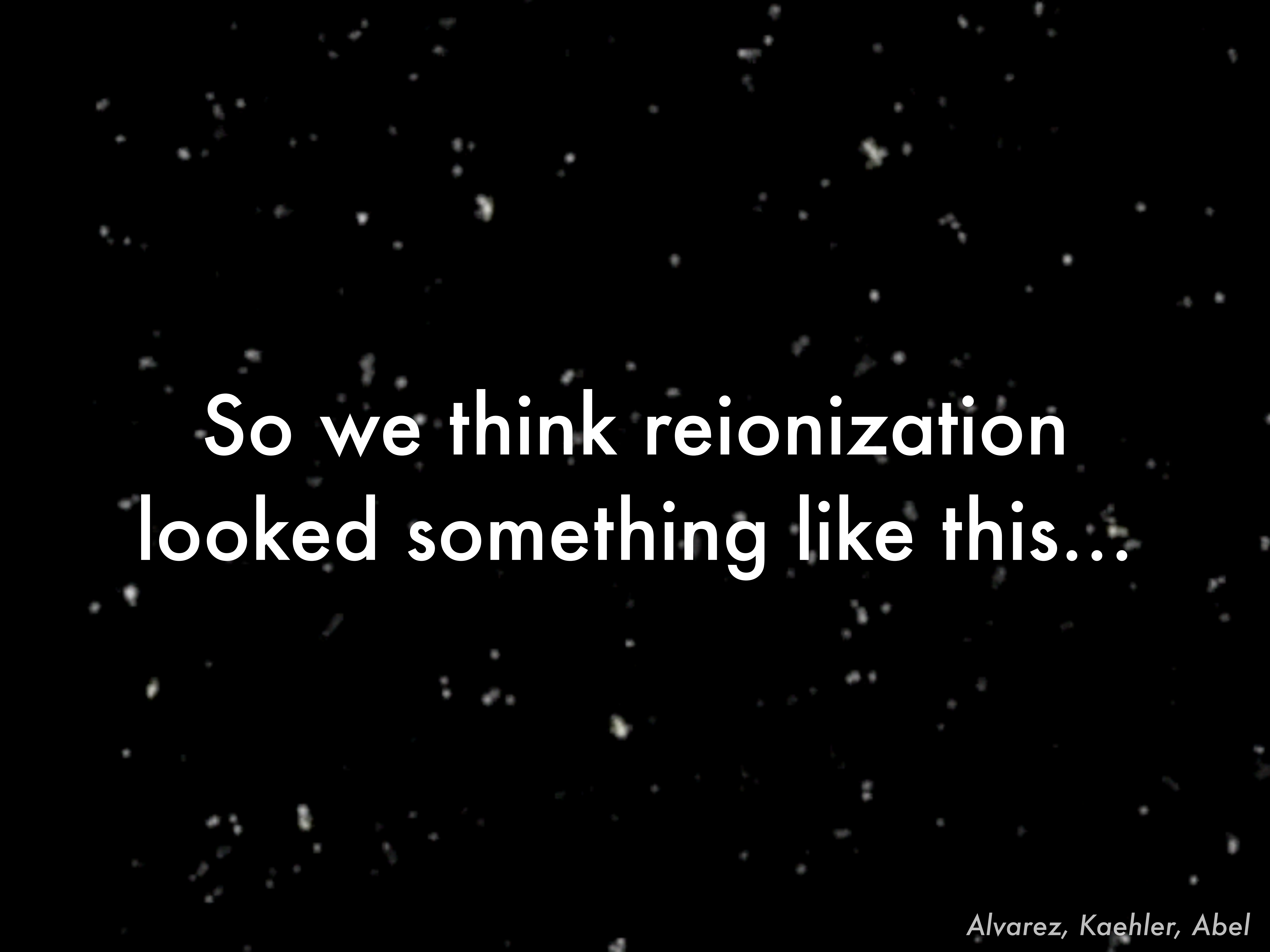
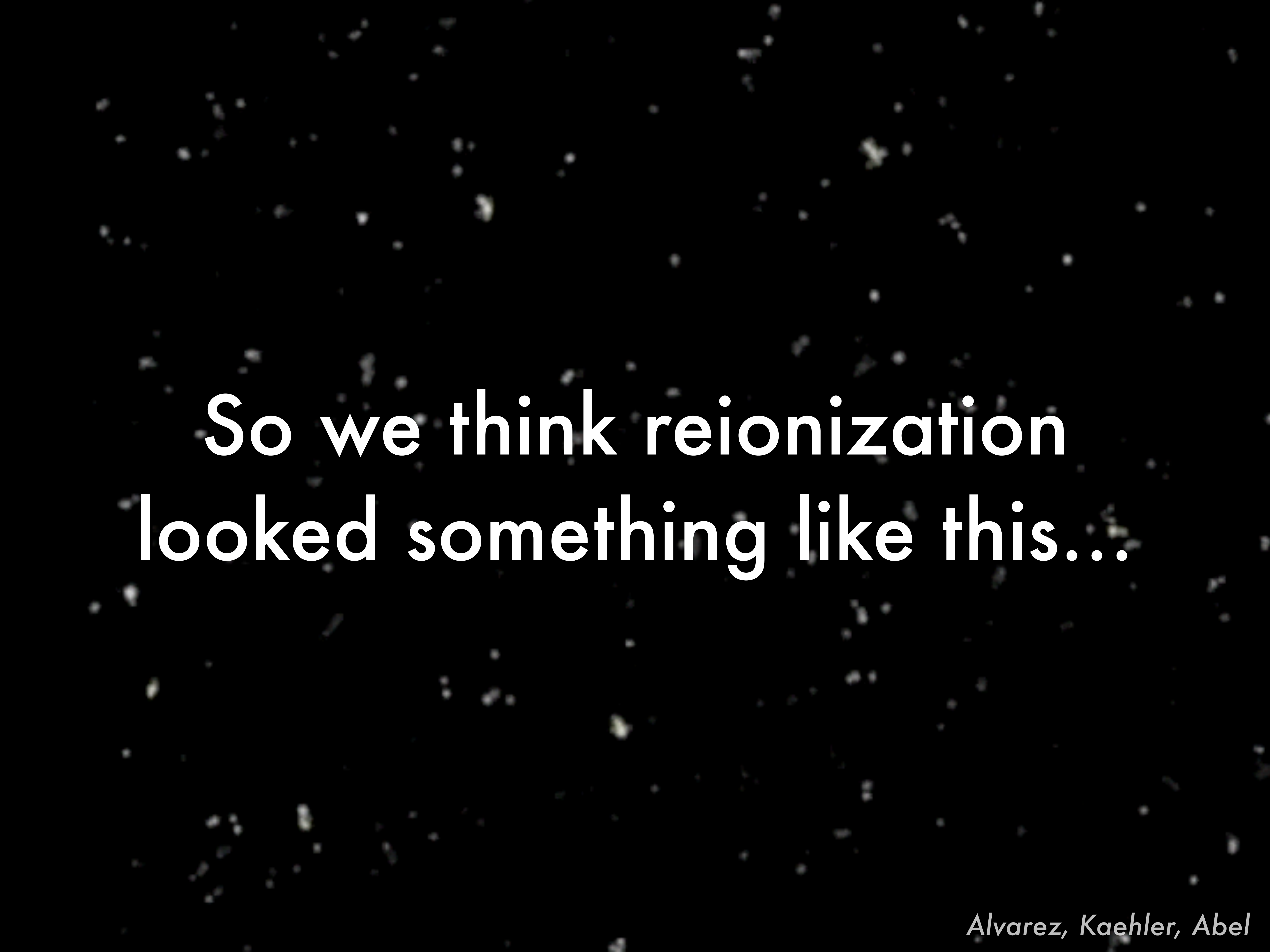

So we think reionization
looked something like this...
Alvarez, Kaehler, Abel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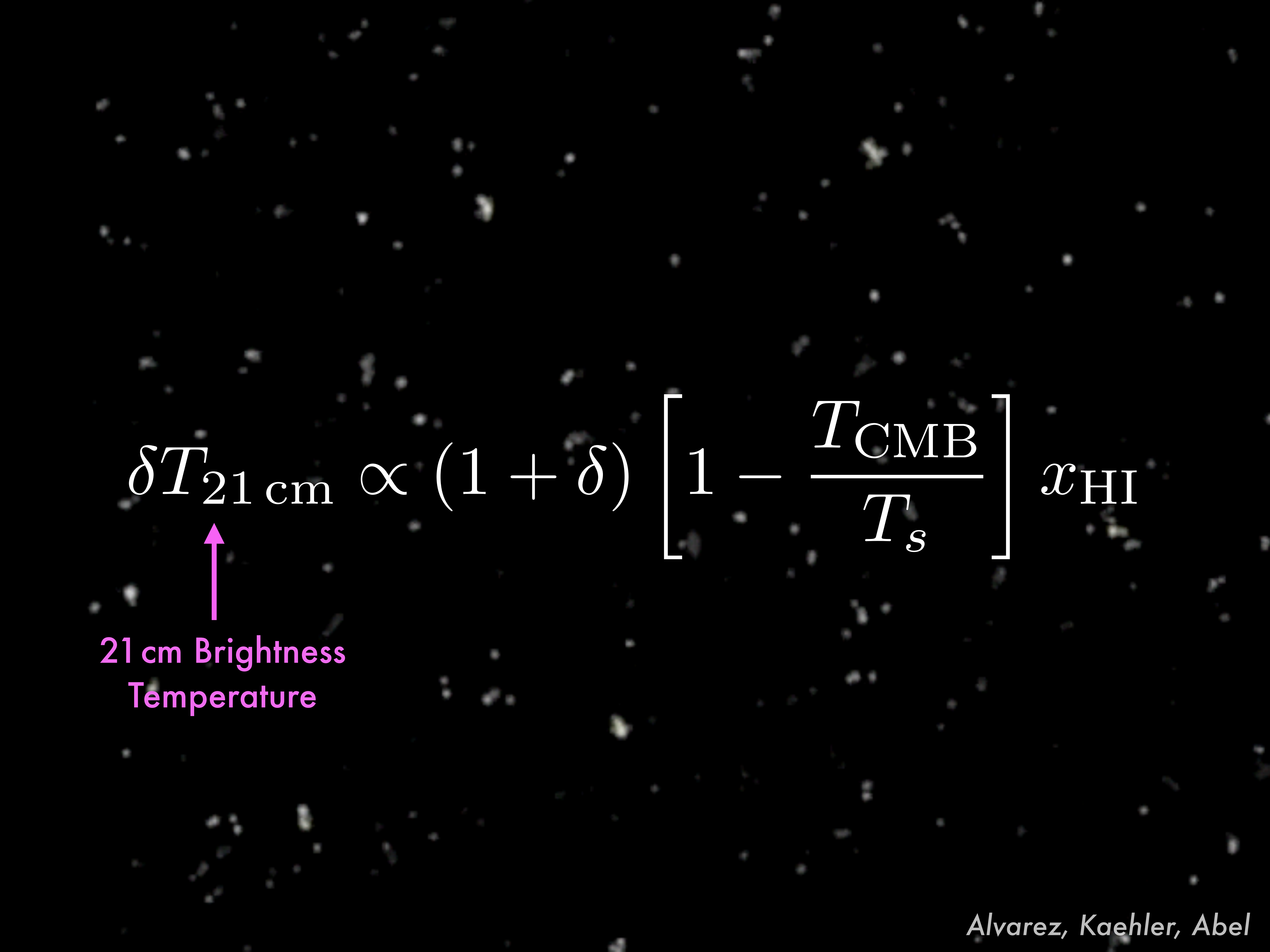

$$\delta T_{21\,\mathrm{cm}} \propto (1+\delta)\left[1 - \frac{T_{\mathrm{CMB}}}{T_s}\right] x_{\mathrm{HI}}$$

21 cm Brightness Temperature

Alvarez, Kaehler, Abel

Overdensity of Hydrogen

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21 cm Brightness Temperature

Spin Temperature

Alvarez, Kaehler, Abel

Overdensity of Hydrogen

Neutral Fraction

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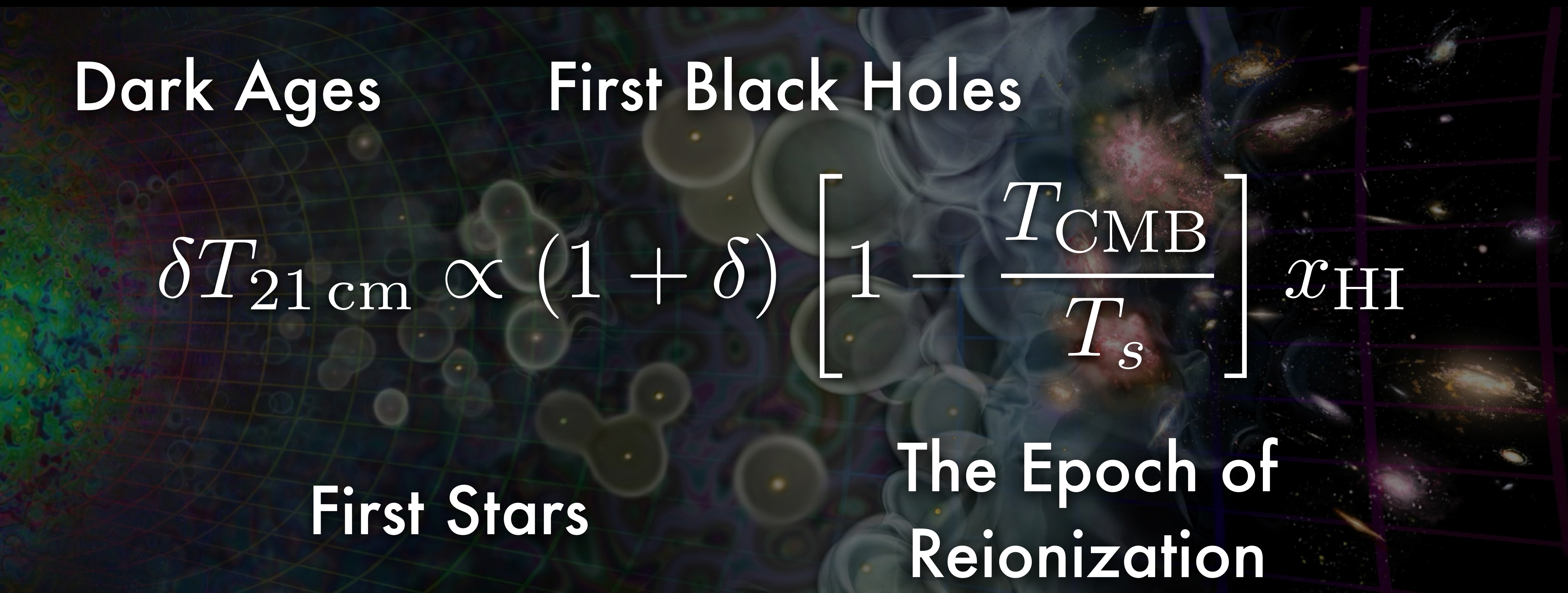
21 cm Brightness Temperature

Spin Temperature

Alvarez, Kaehler, Abel

The brightness temperature probes different physics at different times.



z =1100 z ≈ 50 z ≈ 8 z < 6

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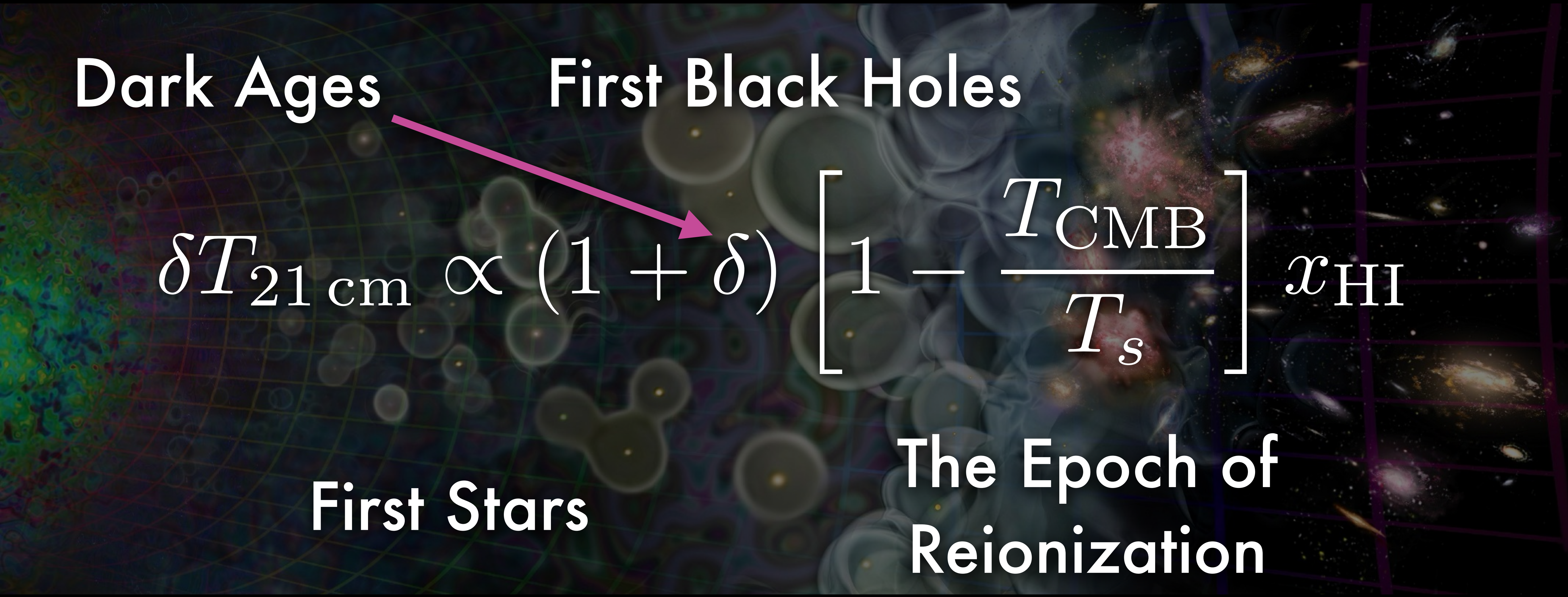

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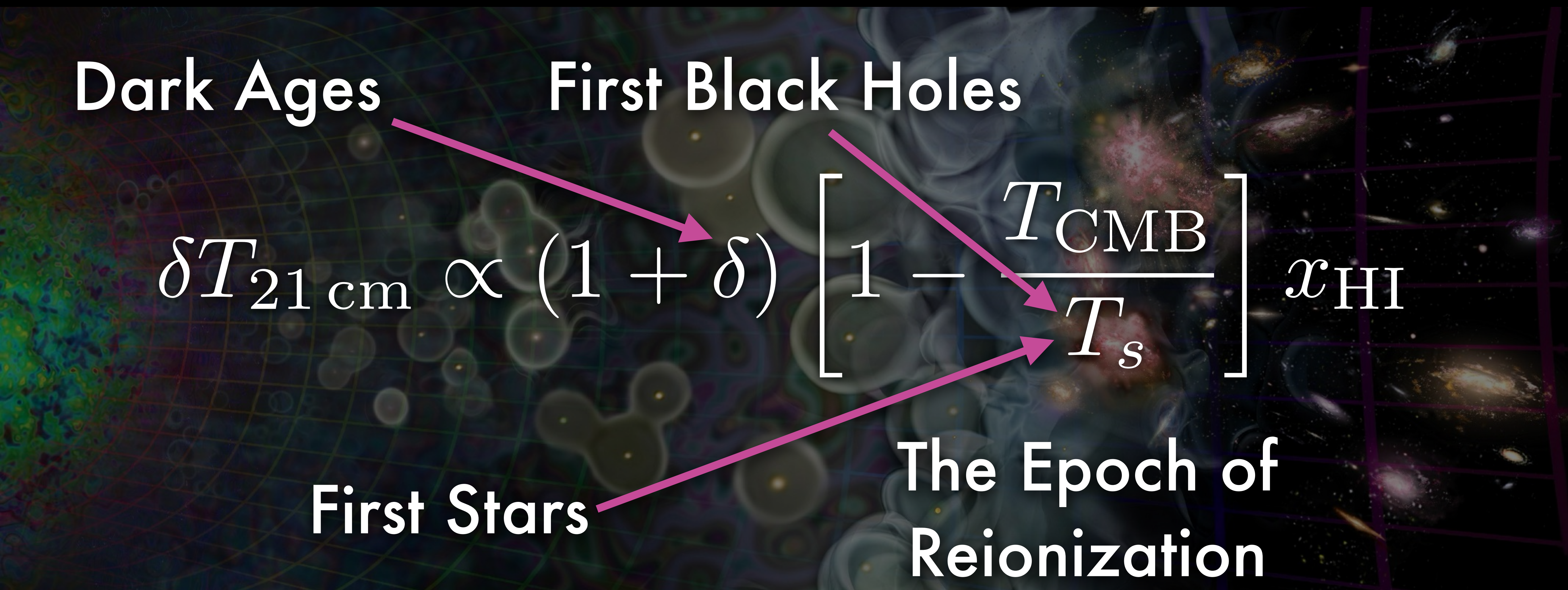

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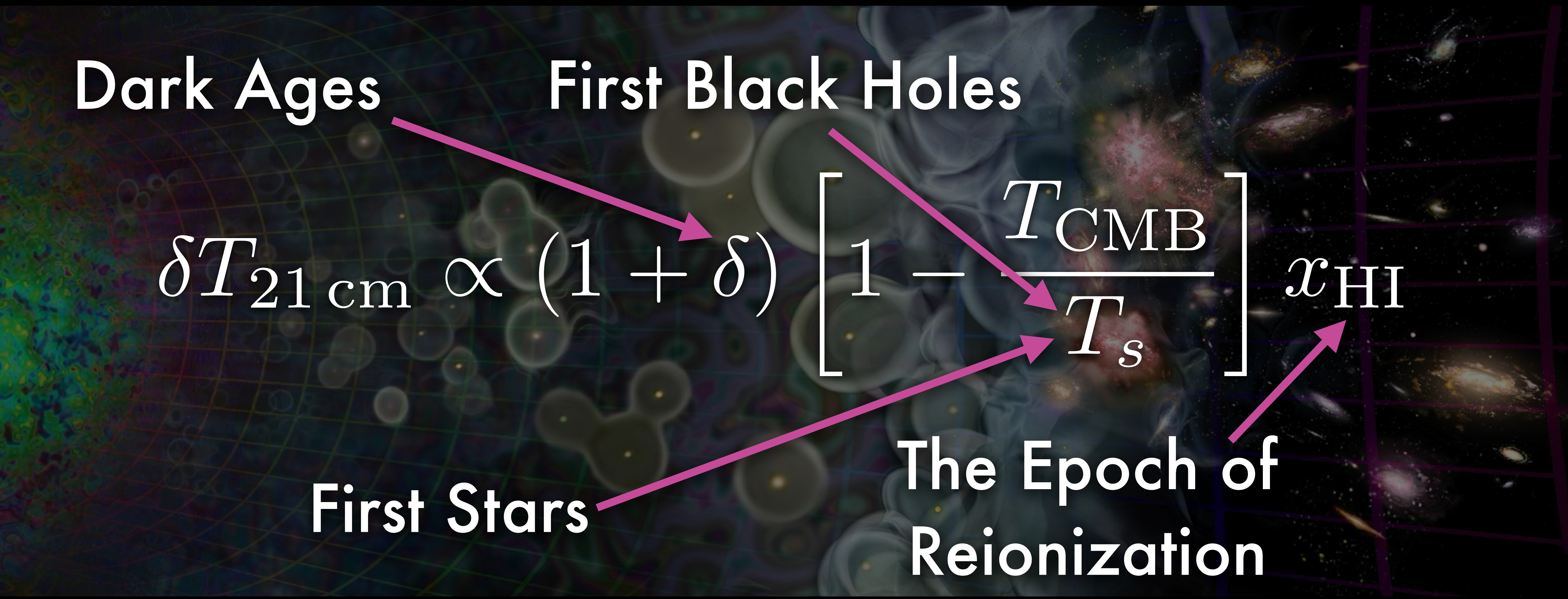
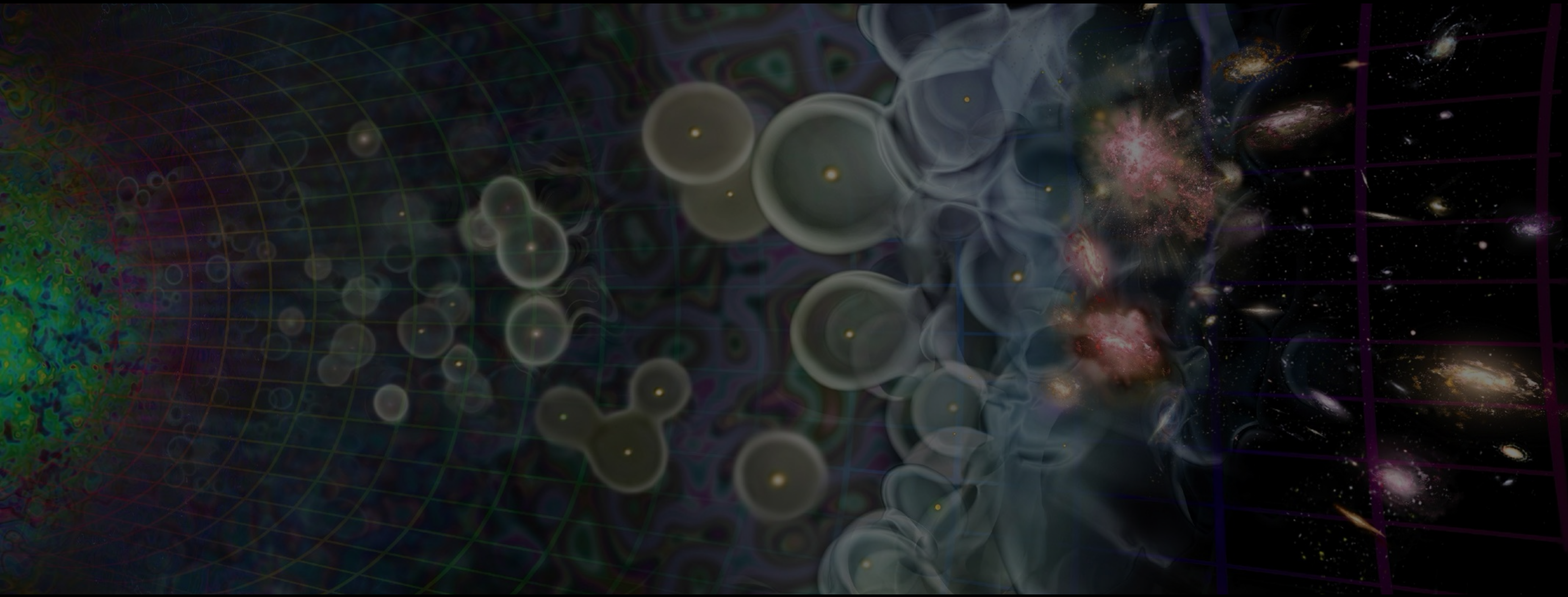


z =1100 z ≈ 50 z ≈ 8 z < 6

There's still a lot of open astrophysical questions.



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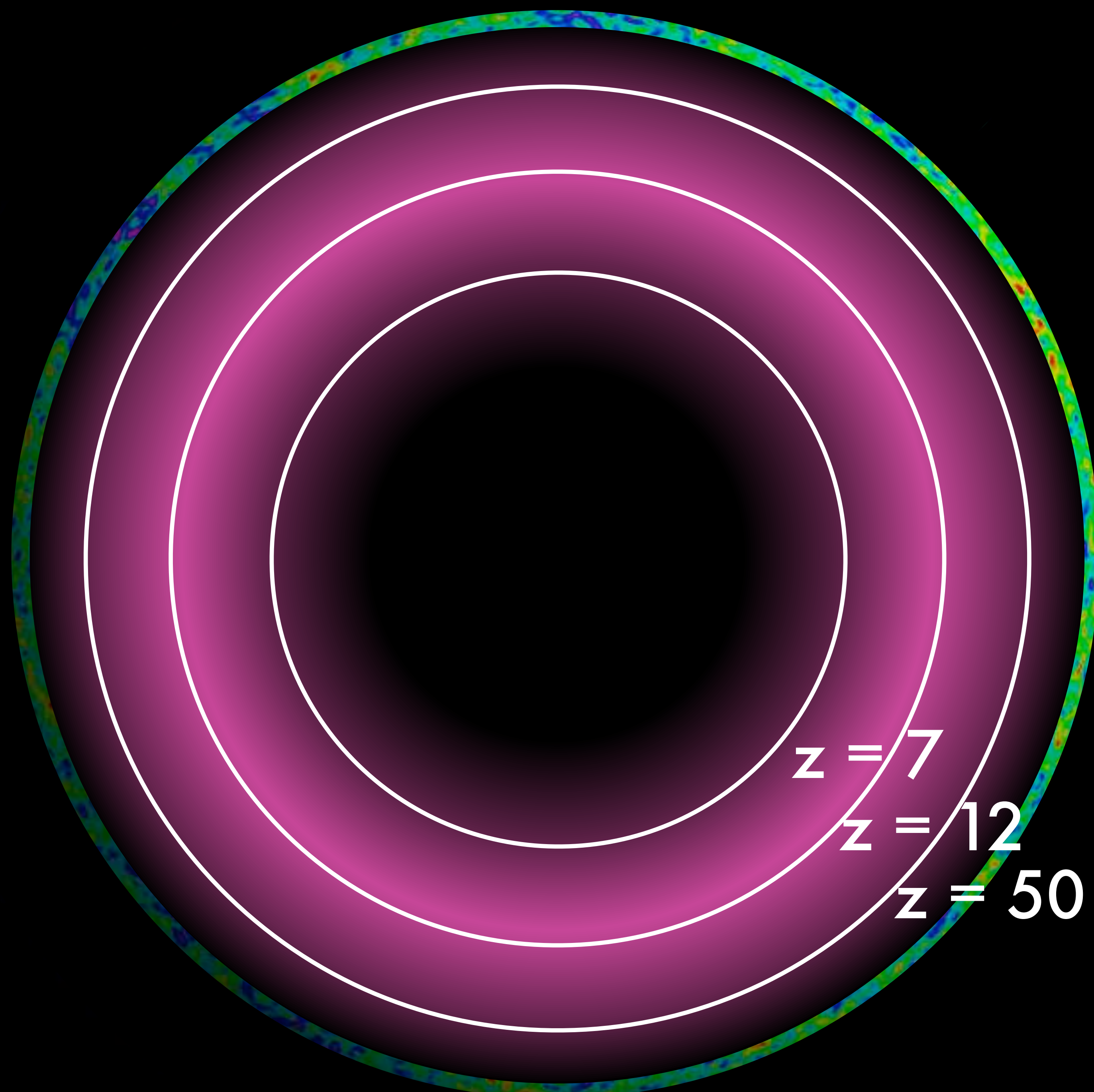
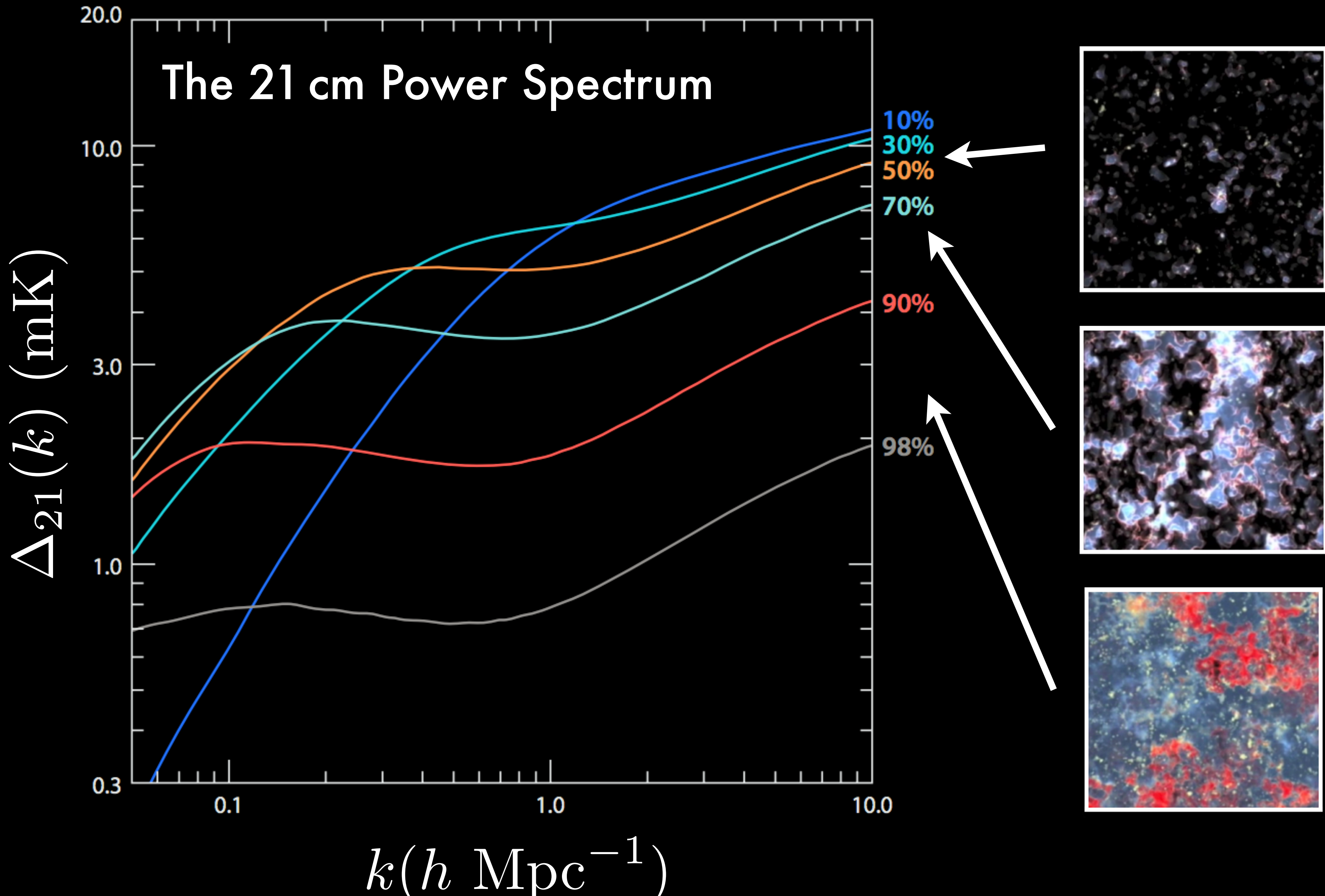
- How and when how did the first stars form?
- How did they die and were they the LIGO black hole progenitors? Or the seeds of supermassive black holes?
- What determined the thermal history of the intergalactic medium? Are there new physics at play?
- What reionized the universe and when? What role did very high redshift galaxies found by JWST play?

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



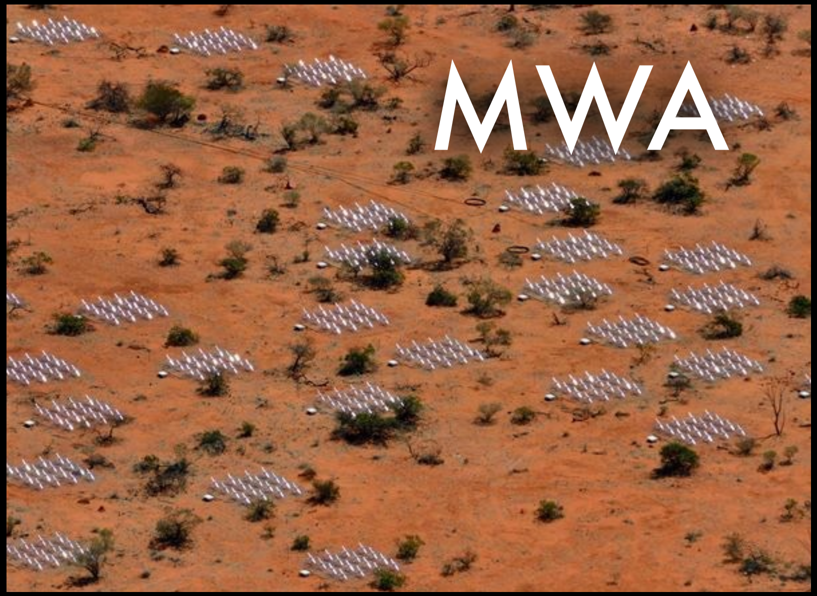
The first detection
will be statistical.

Our best probe is the power spectrum — the evolution of brightness temperature fluctuations as a function of time and spatial scale.

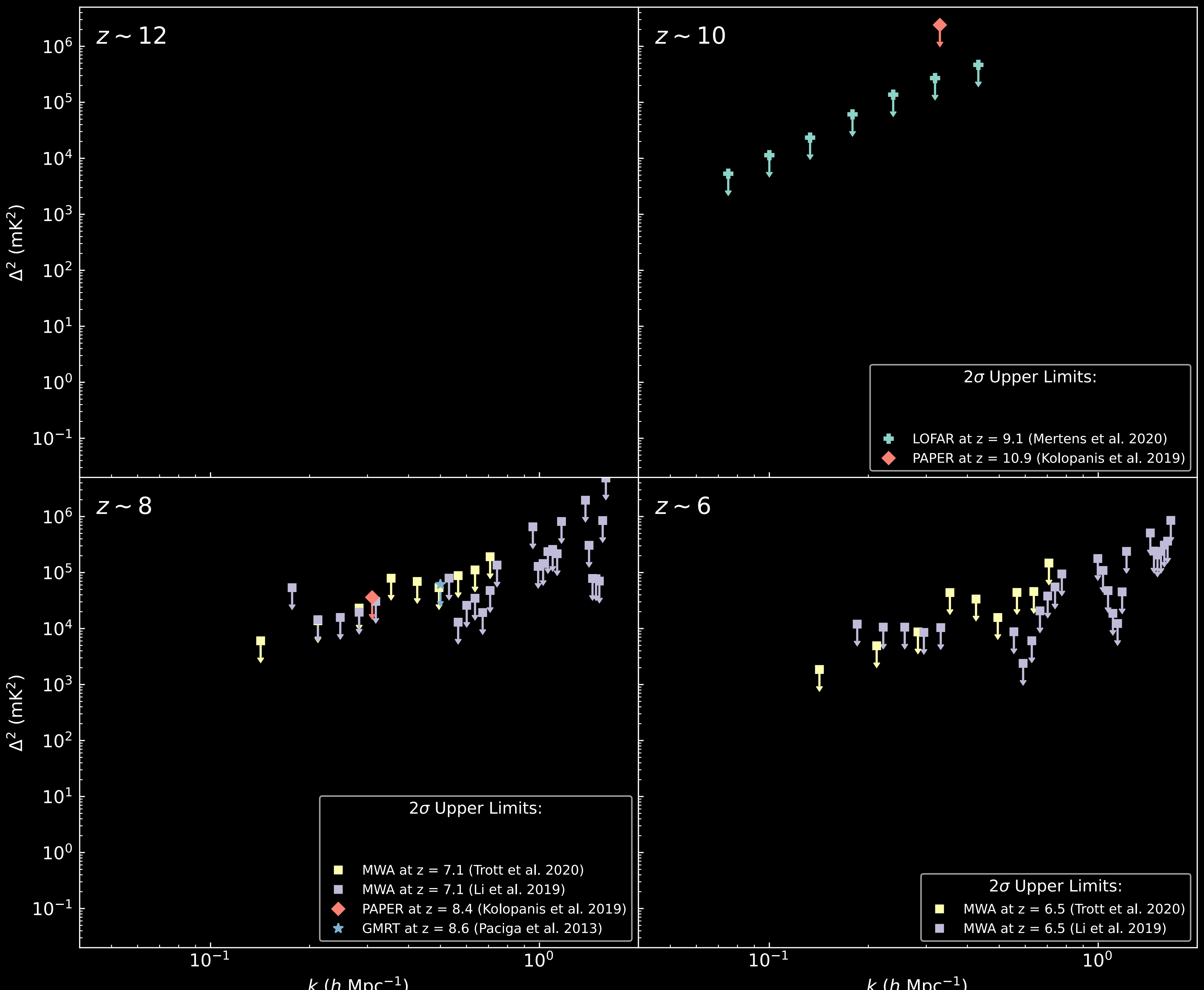


Barkana (2009), Morales & Wyithe (2010)

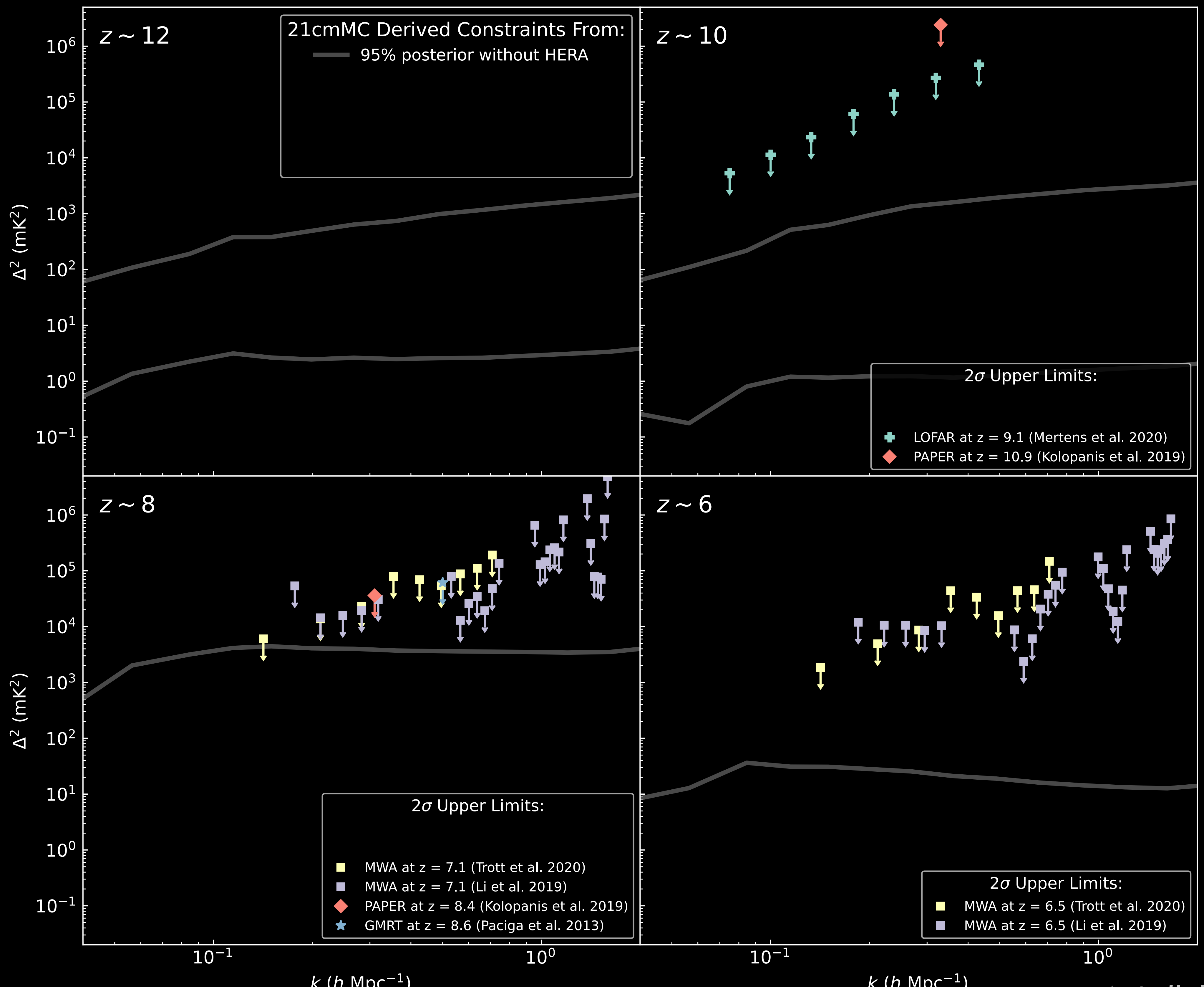
The first generation of interferometers for 21 cm cosmology got us started, deploying different strategies.



Before HERA, the state of the field was upper limits still quite far from the expected EoR signal.



A wide range of power spectra were still possible, even with CMB and galaxy luminosity function constraints.



HERA Collaboration (2023)


Google Earth
Data SIO, NOAA, U.S. Navy
So we went bigger...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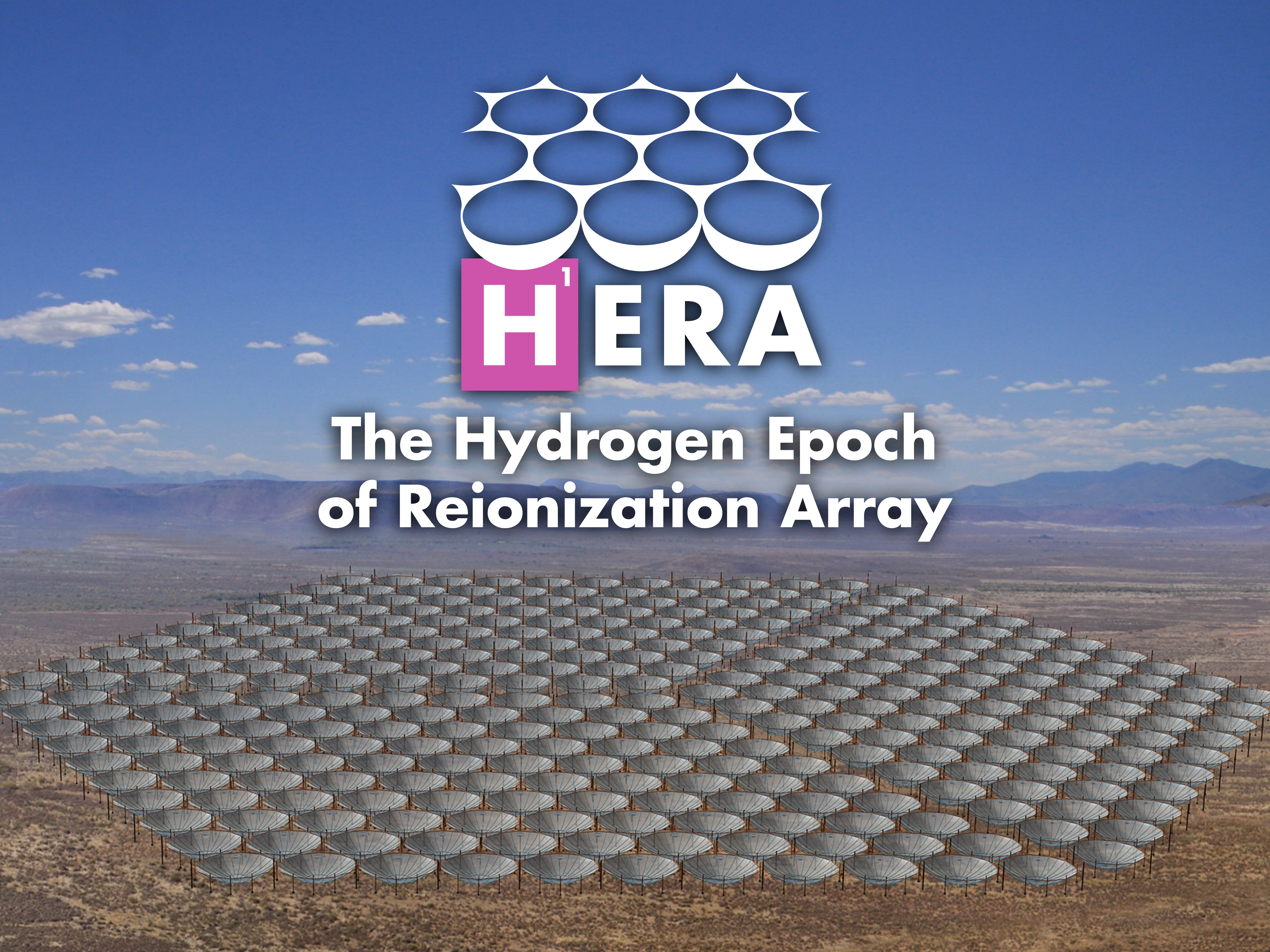
So we went bigger...


HERA
The Hydrogen Epoch
of Reionization Array


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 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
HERA
BROWN
VE RI TAS
HARVARD
UNIVERSITY OF KWAZULU-NATAL
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The Hydrogen Epoch of Reionization Array
RHODES UNIVERSITY
Where leaders learn
RESPICE PROSPICE
UNIVERSITY of the WESTERN CAPE


CAL POLY POMONA
THE UNIVERSITY OF CALIFORNIA
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UCLA
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ARIZONA STATE UNIVERSITY
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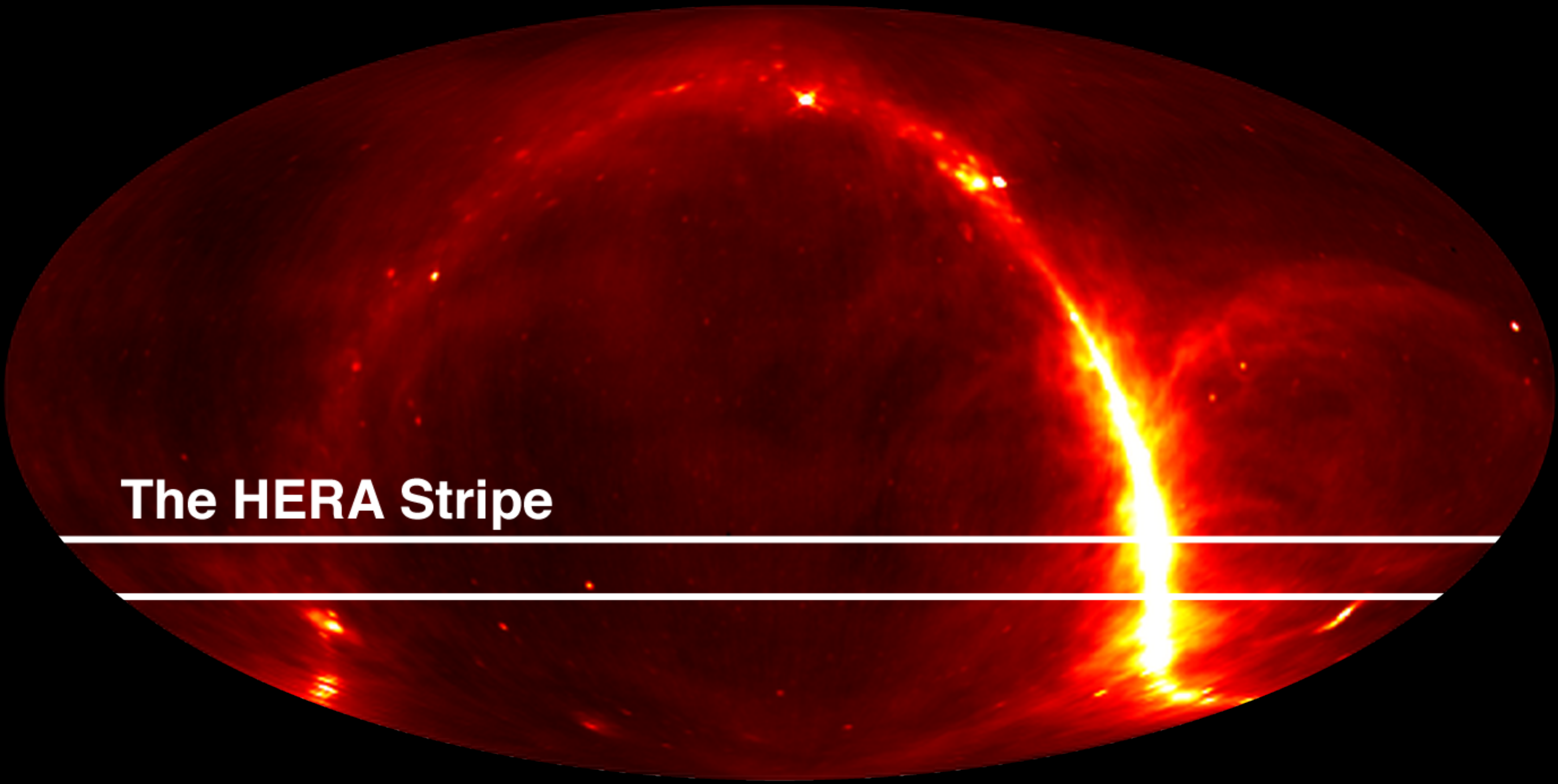
GORDON AND BETTY
MOORE
FOUNDATION
NSF

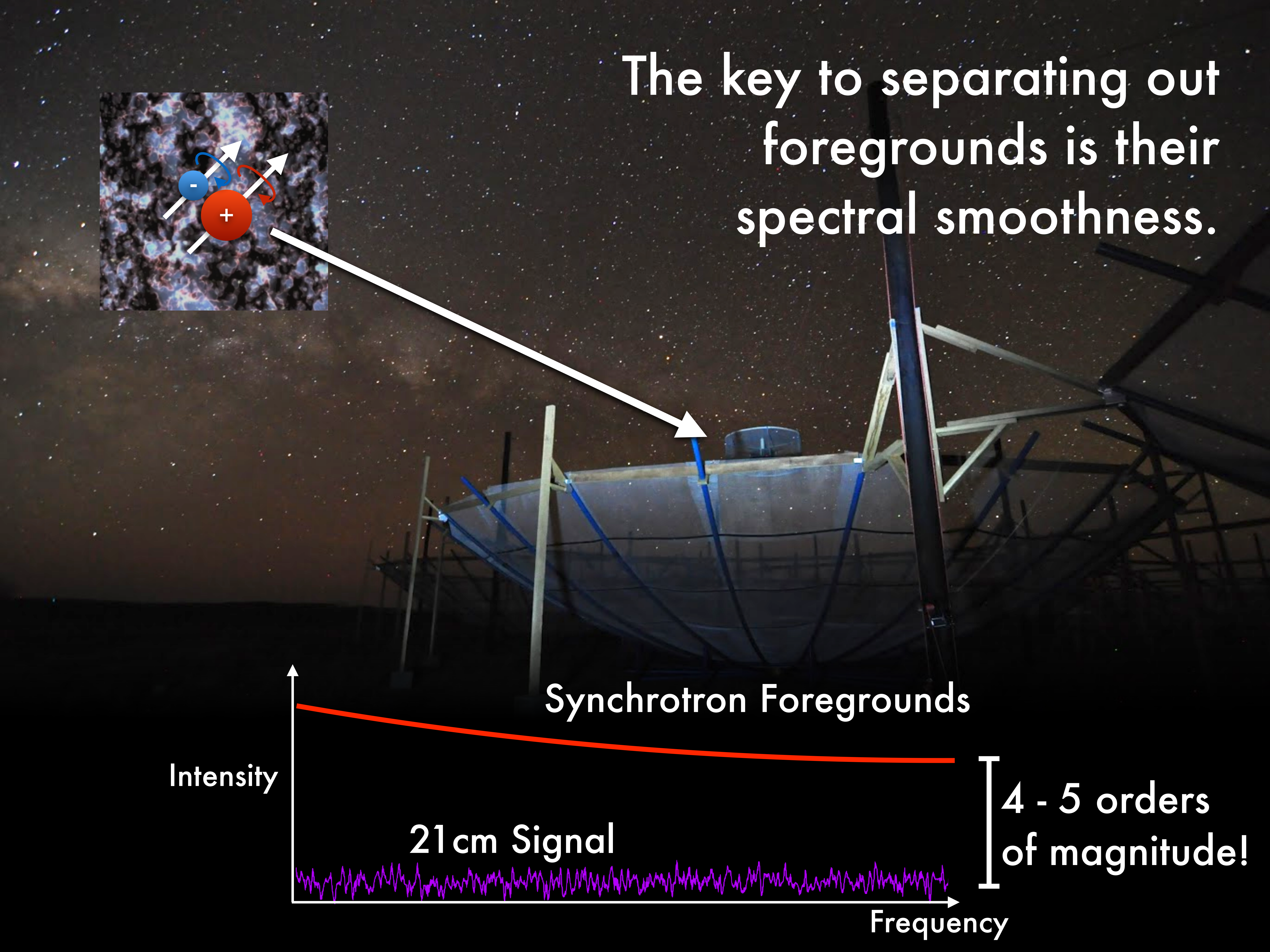

The 21 cm signal is faint,
so HERA is huge.
350 14-m diameter dishes



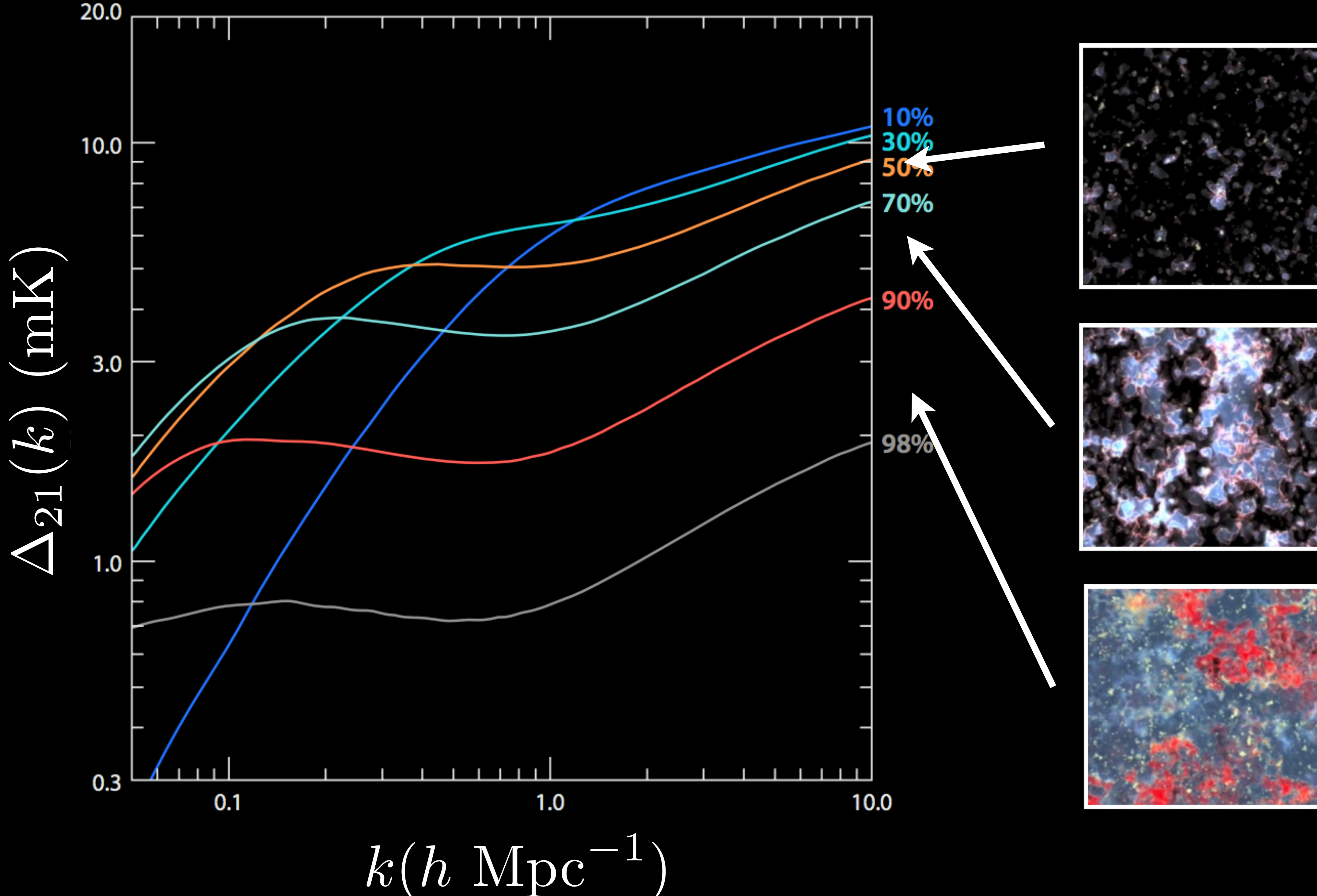
HERA is a drift scan instrument that maps out a stripe of constant declination.

Our biggest problem is foregrounds.

Photo: Carina Cheng


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

So instead of spherically averaged Fourier space...



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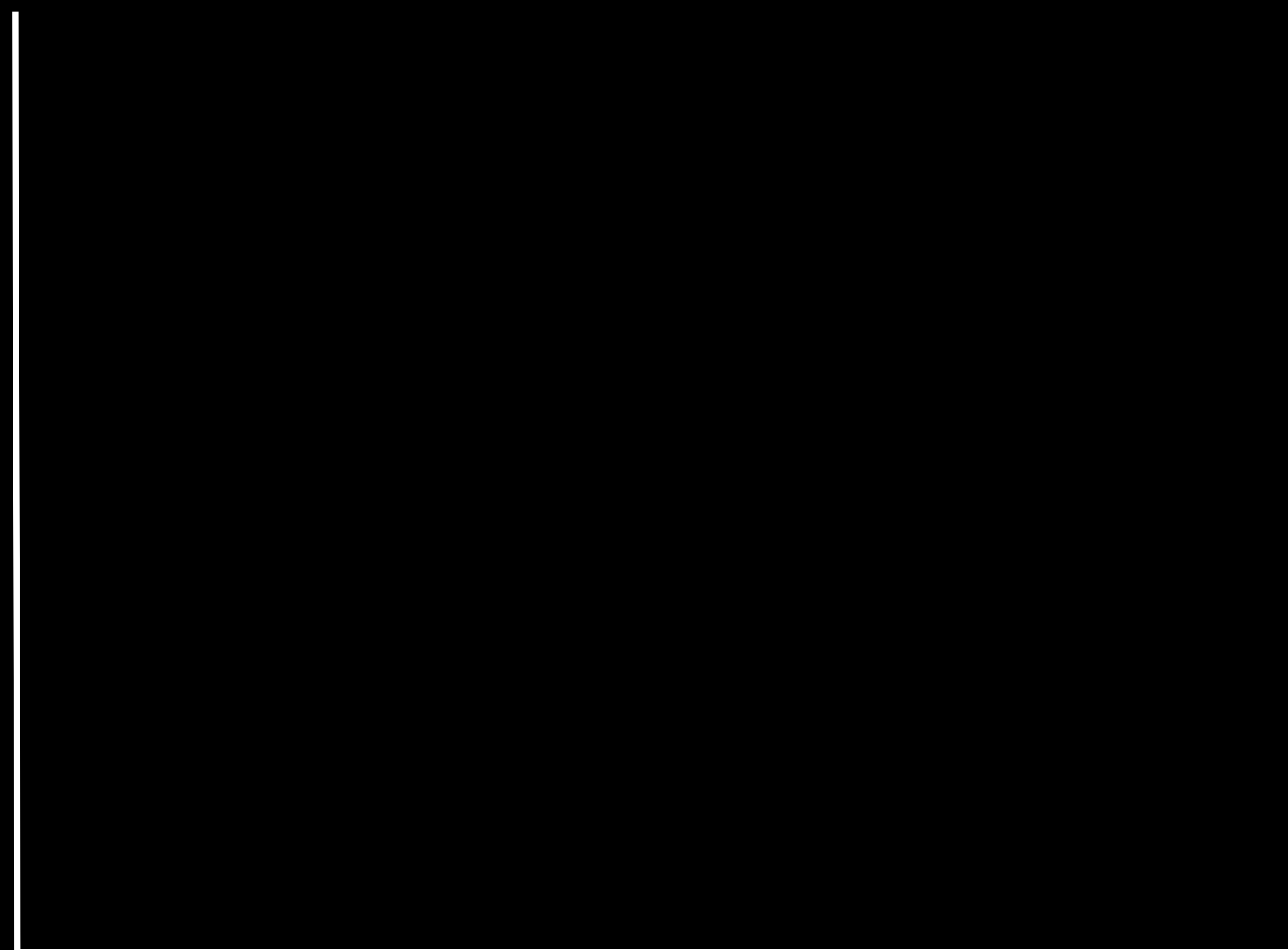
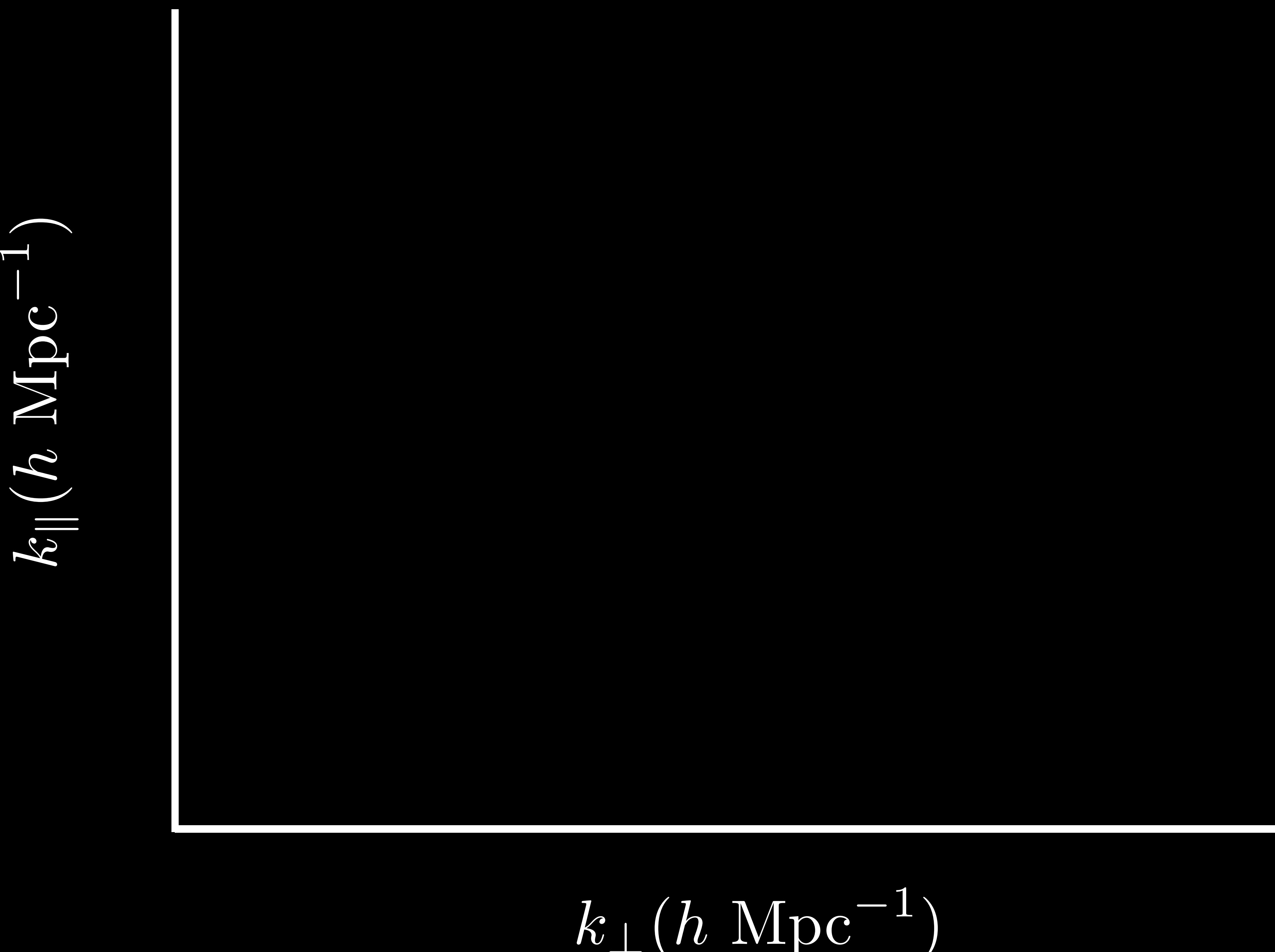
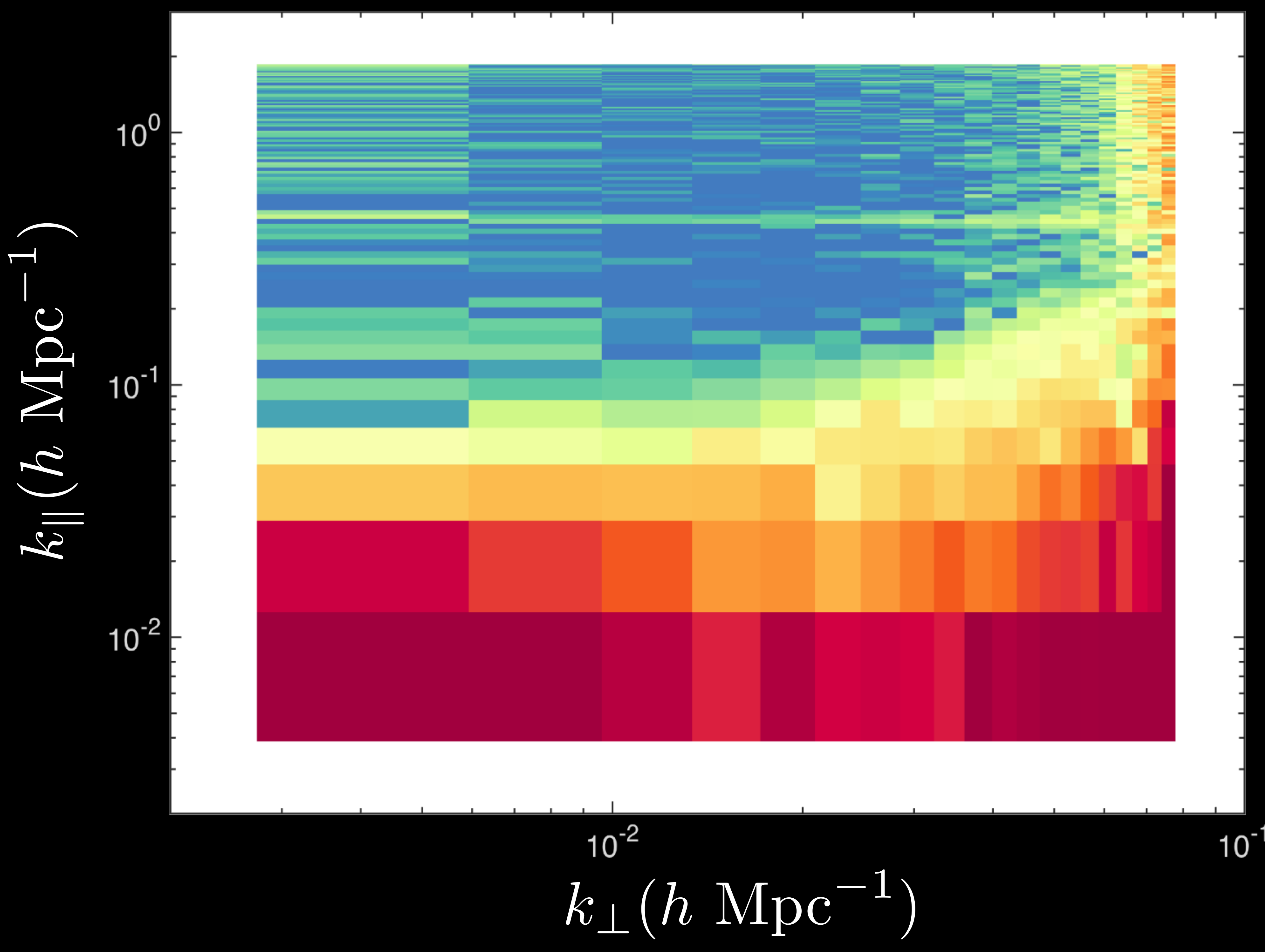


We separate out Fourier modes parallel and perpendicular to the line of sight.



And we find a “window.”



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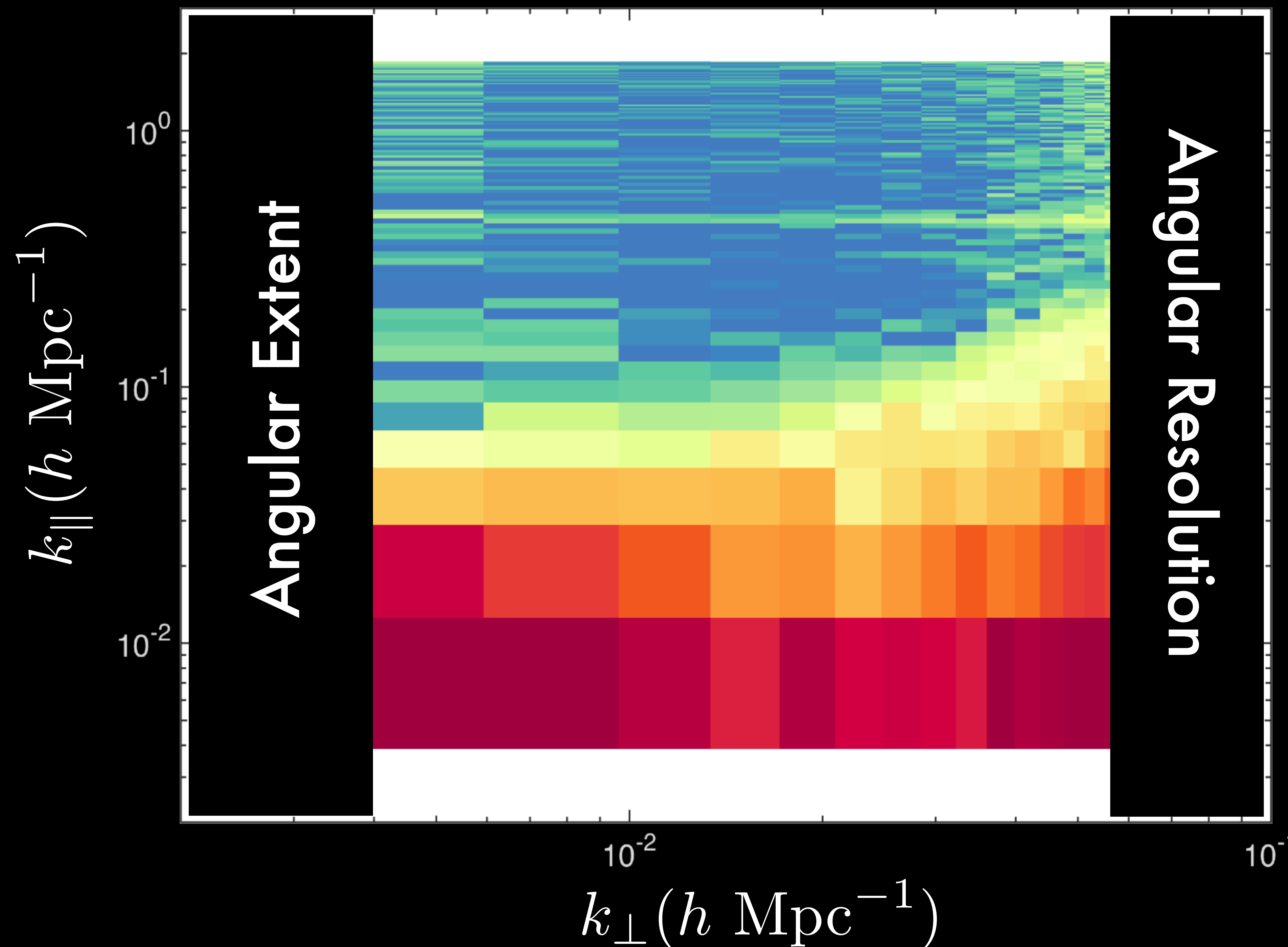

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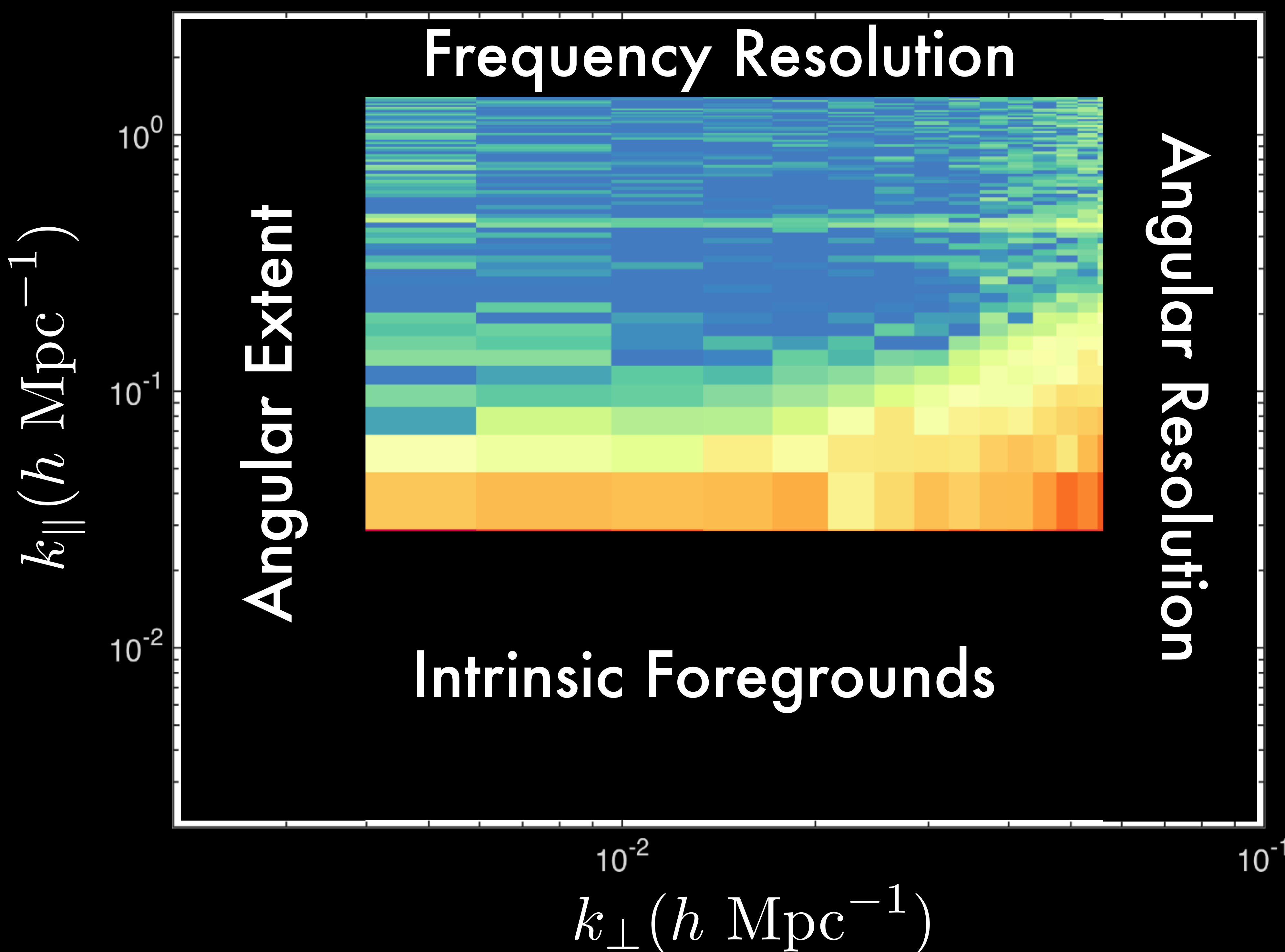

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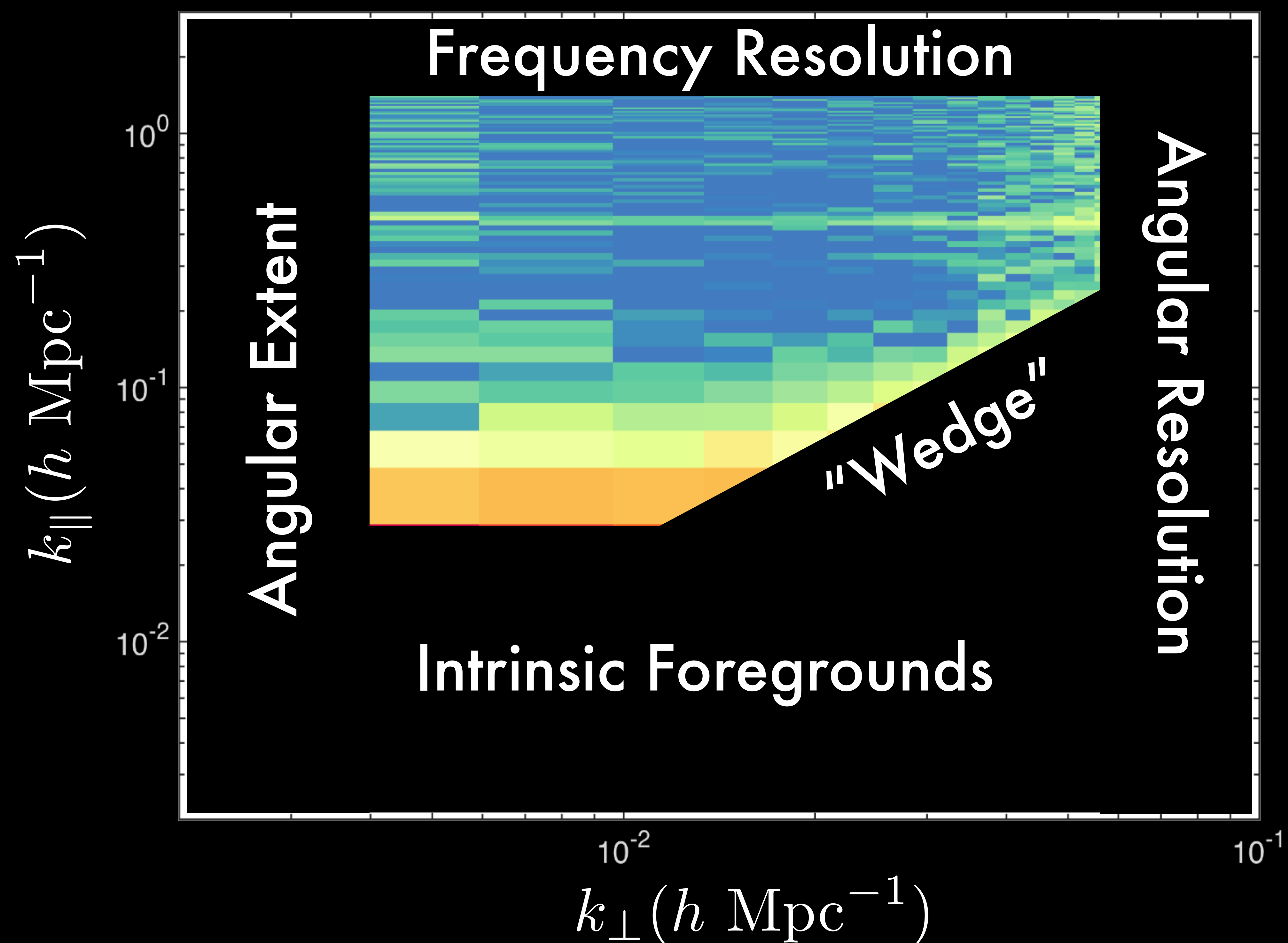
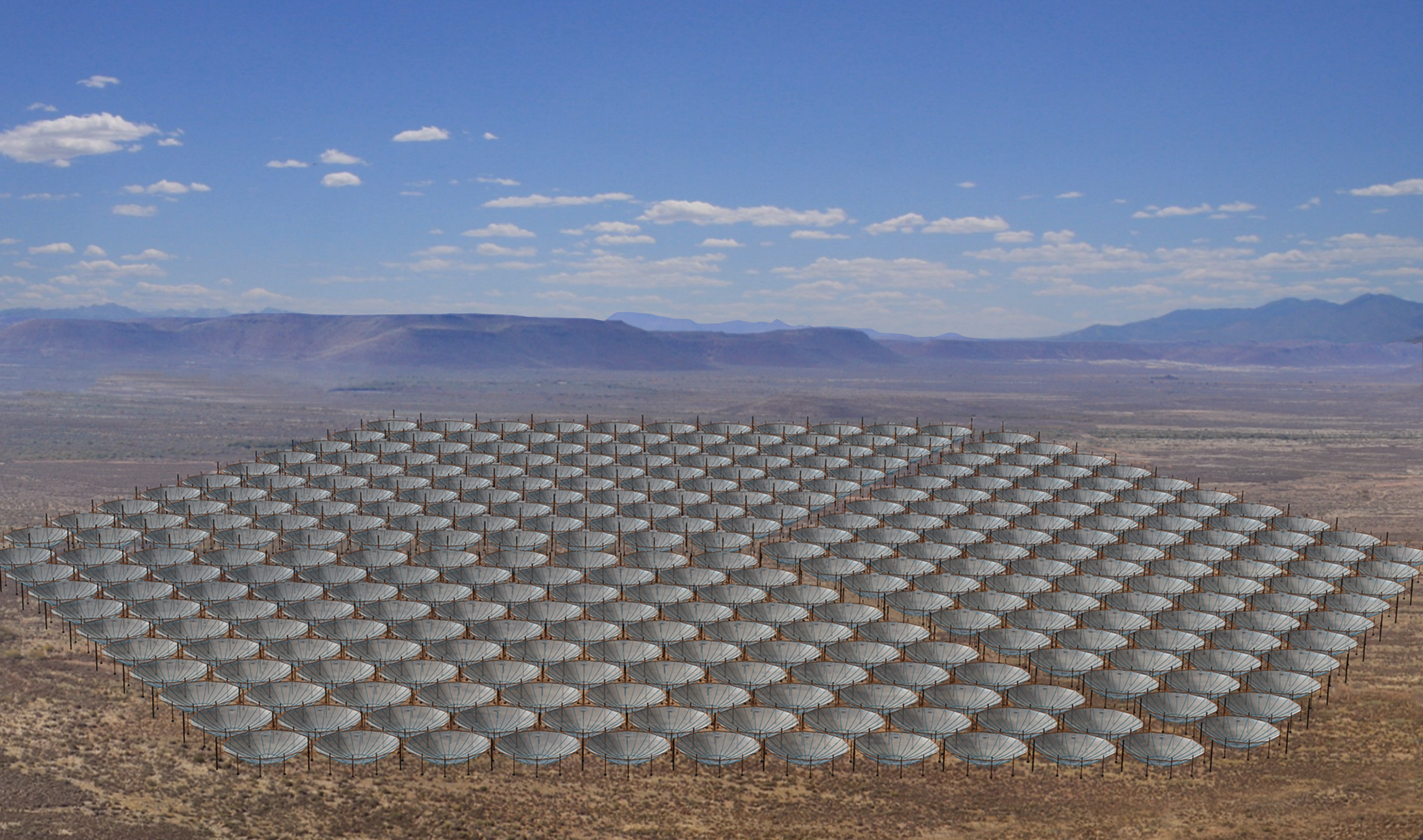
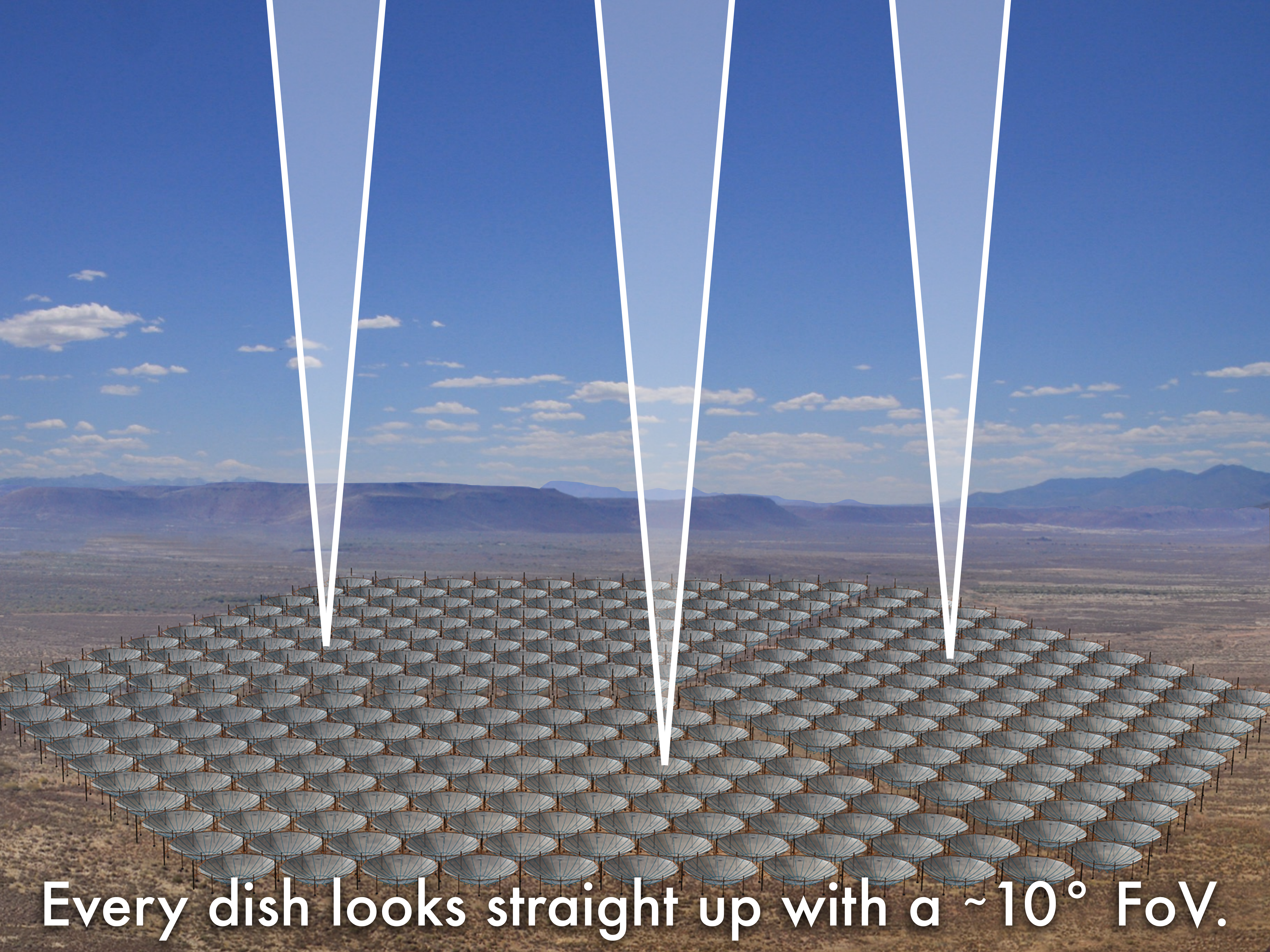


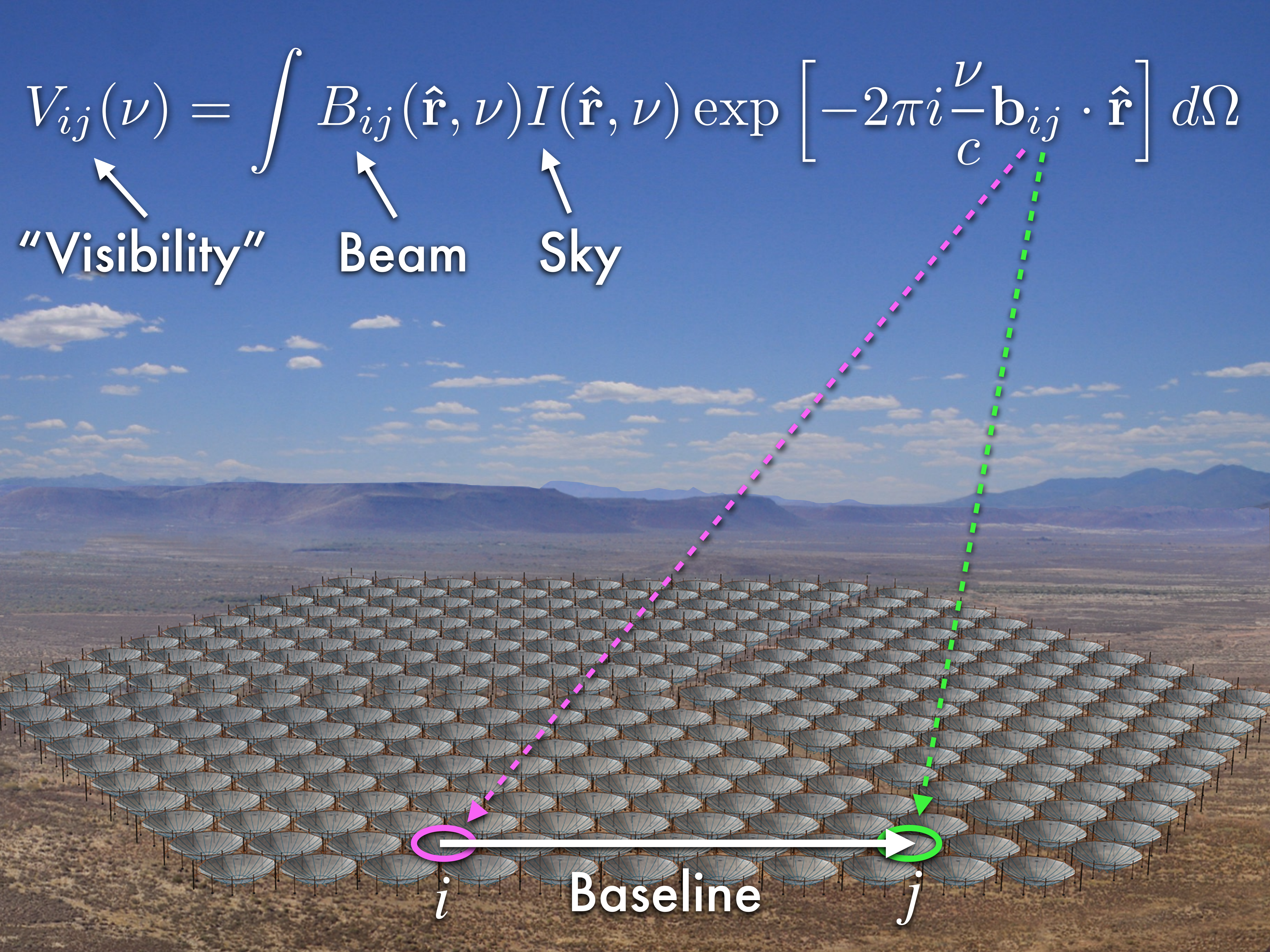
What does HERA actually measure?




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

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

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



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Video: Veritasium

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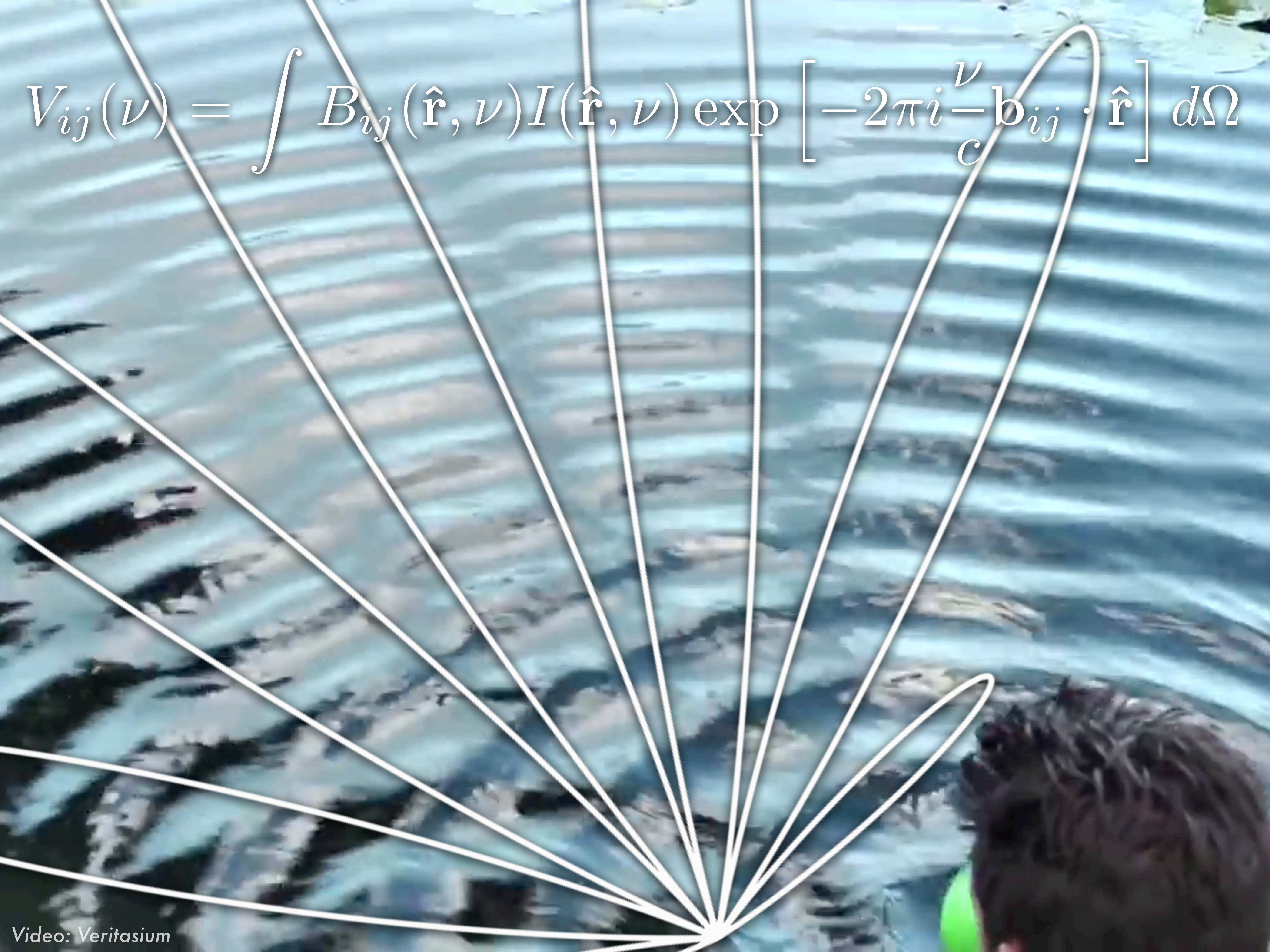

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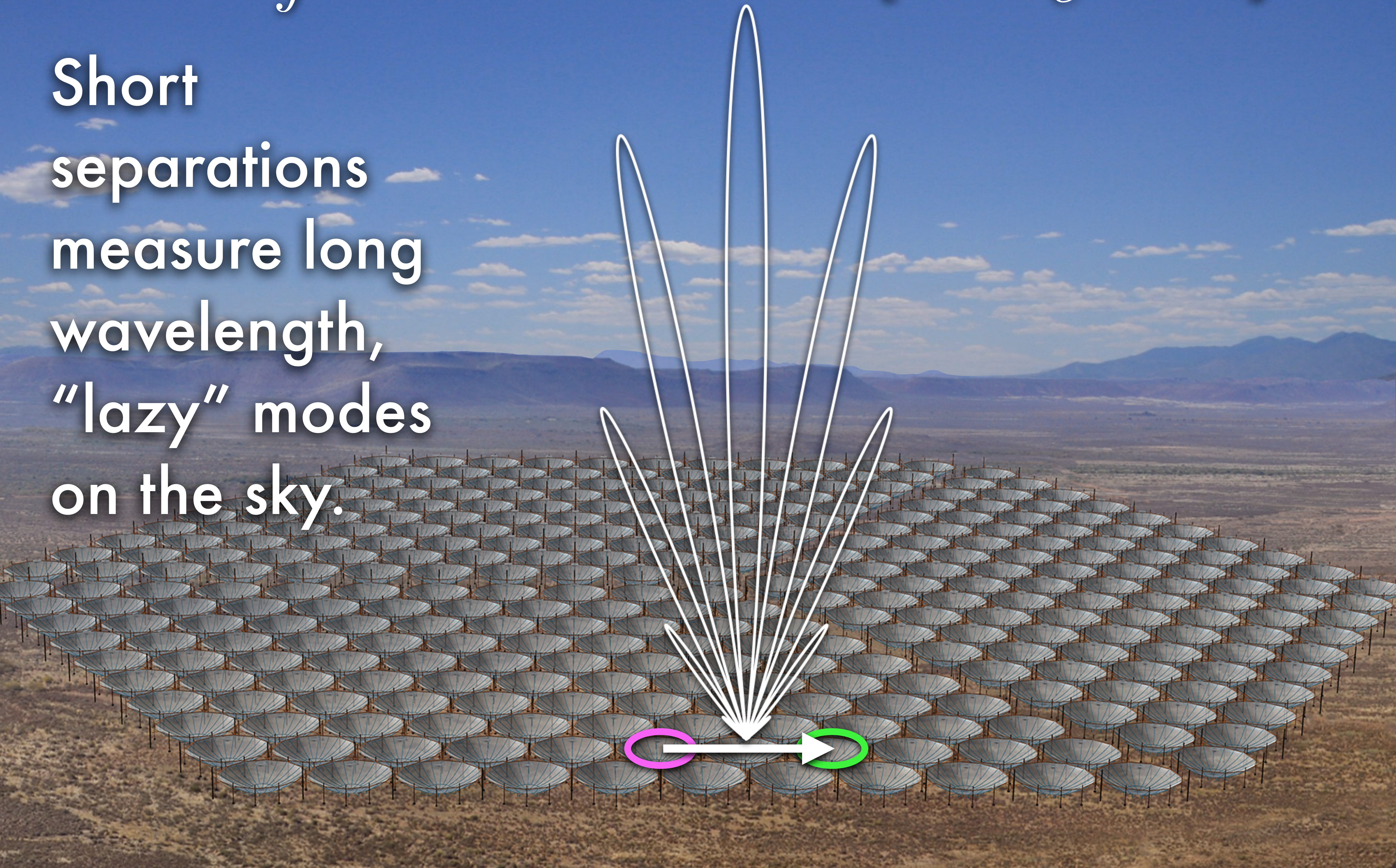
Short separations measure long wavelength, “lazy” modes on the sky.



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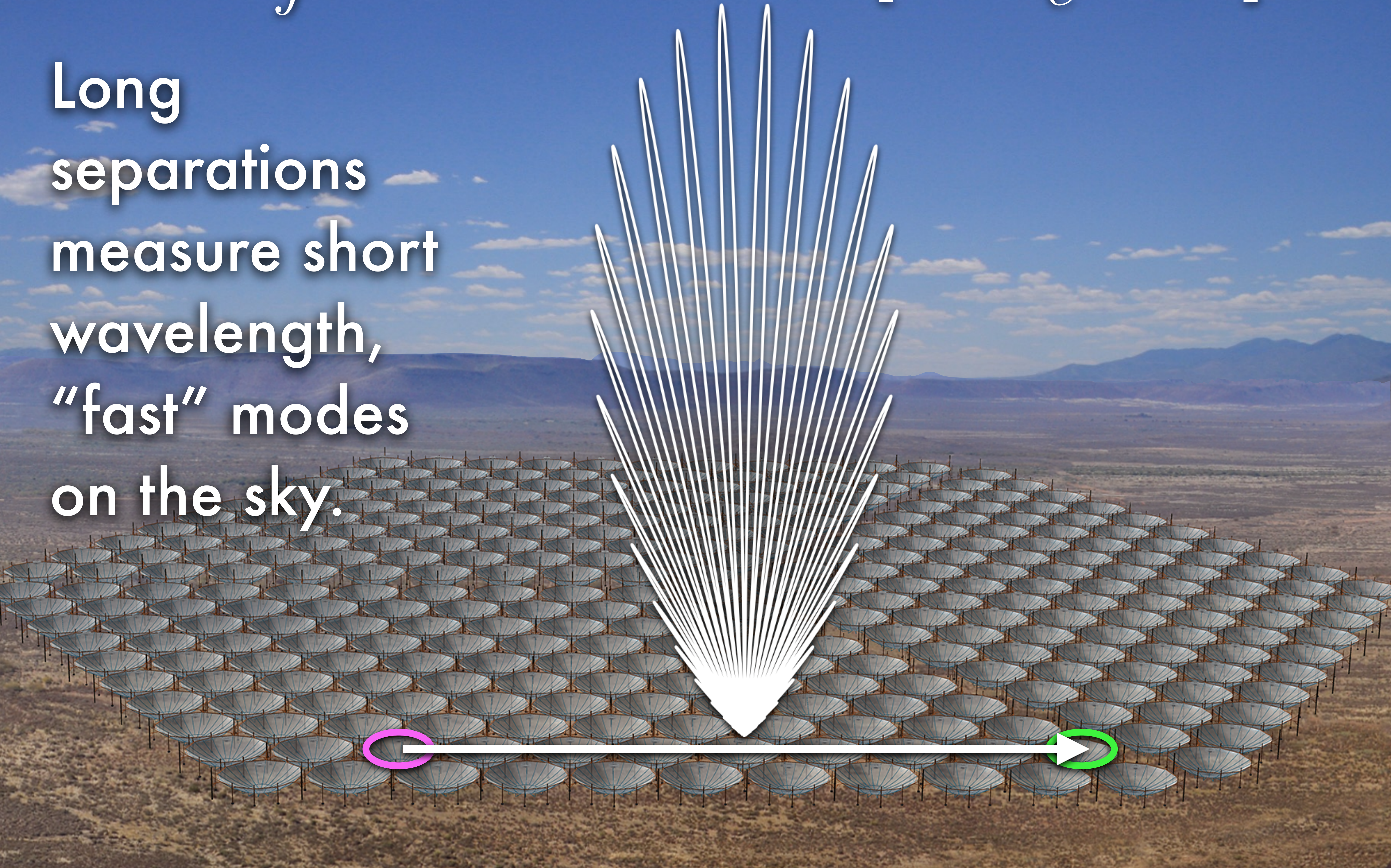
Long separations measure short wavelength, “fast” modes on the sky.



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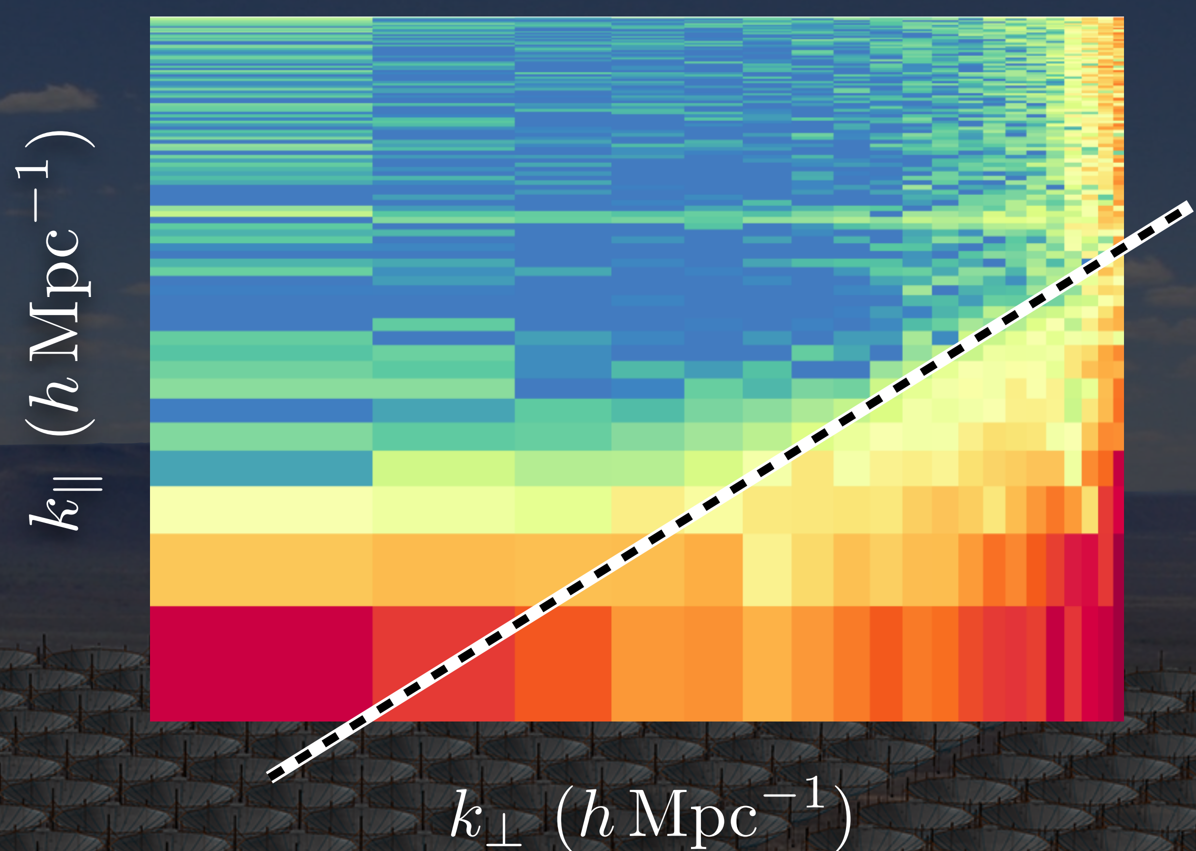

$k_{\perp}$ is effectively baseline length.

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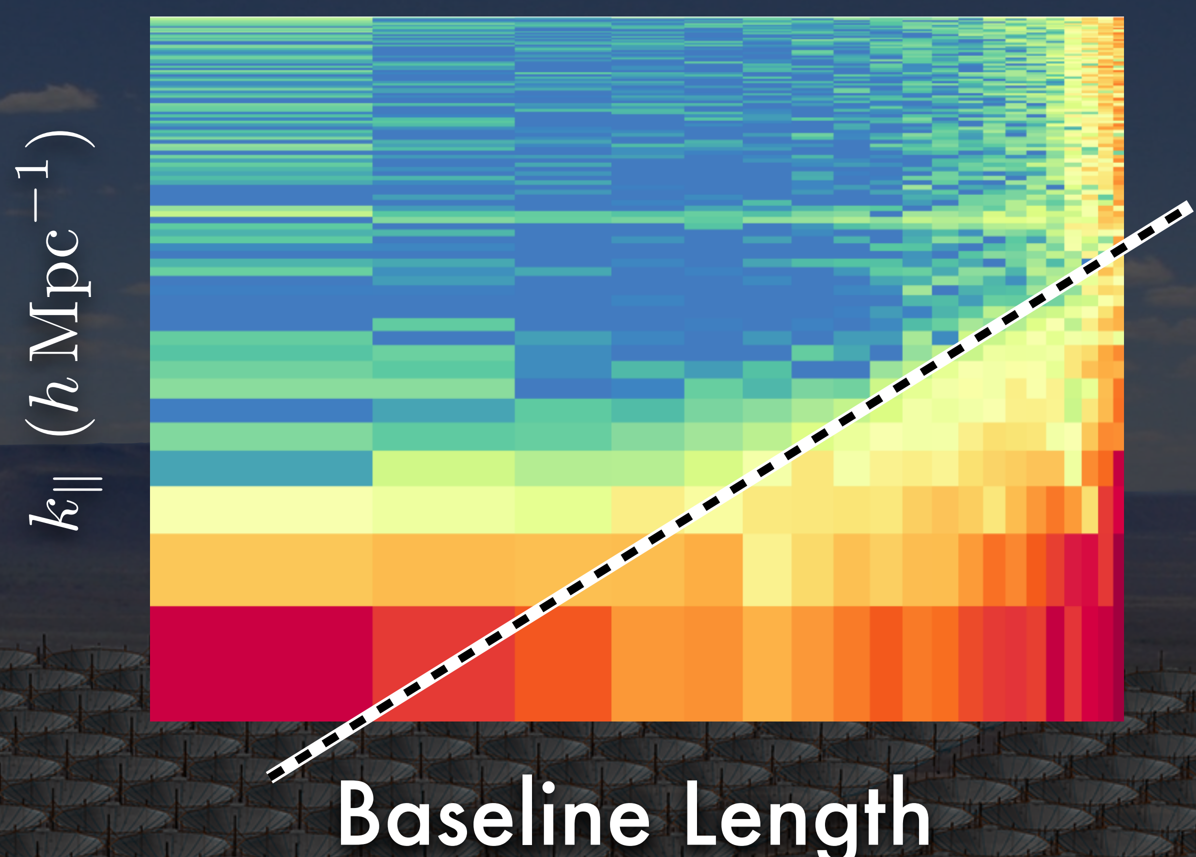
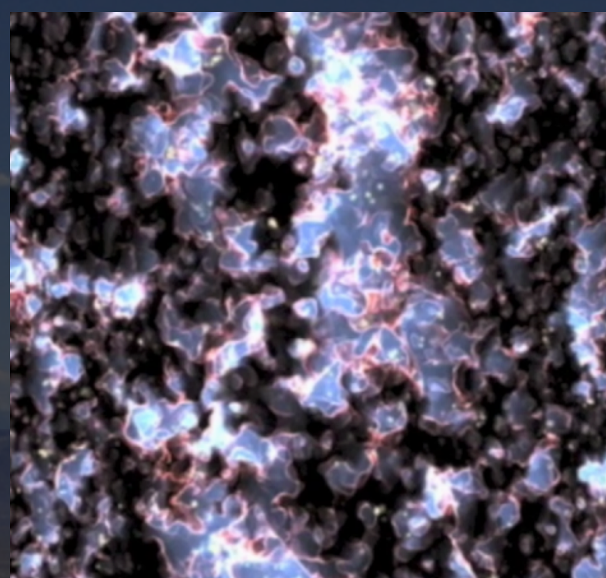
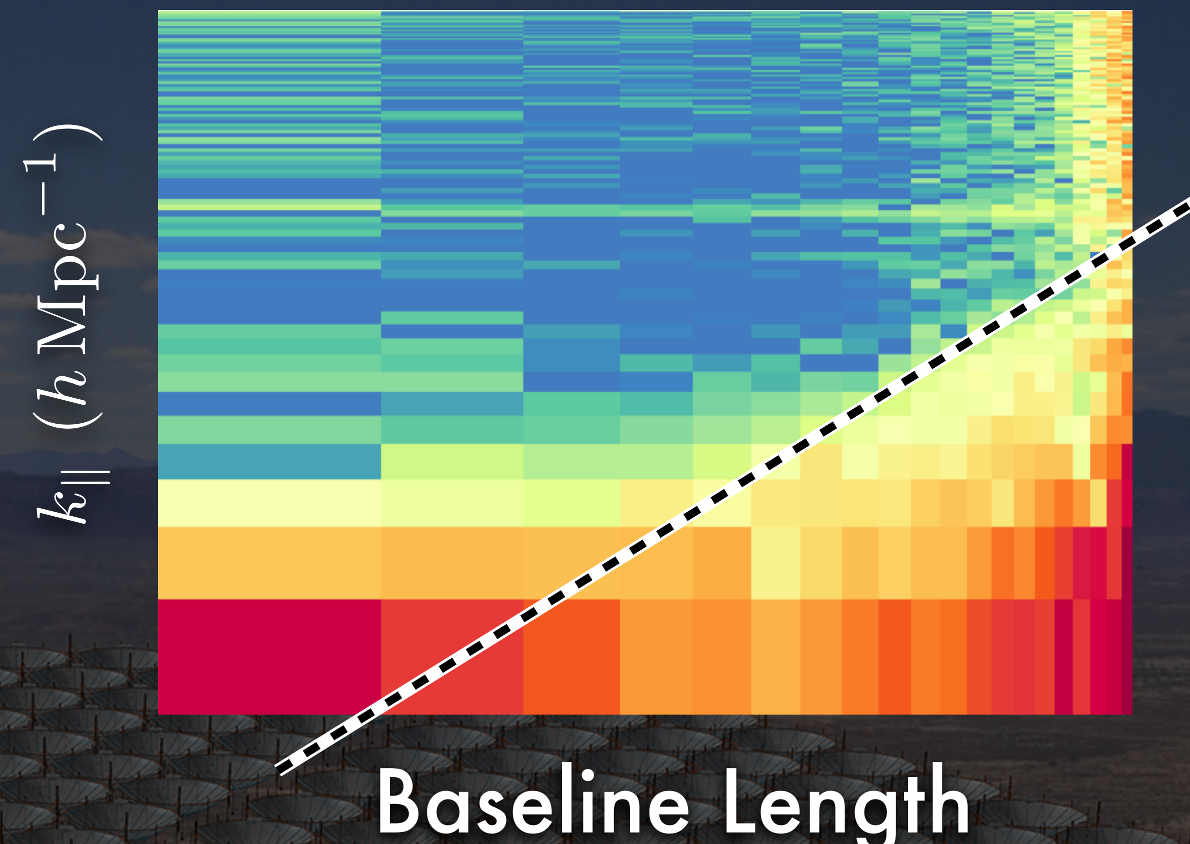


$k_{\perp}$ is effectively baseline length.

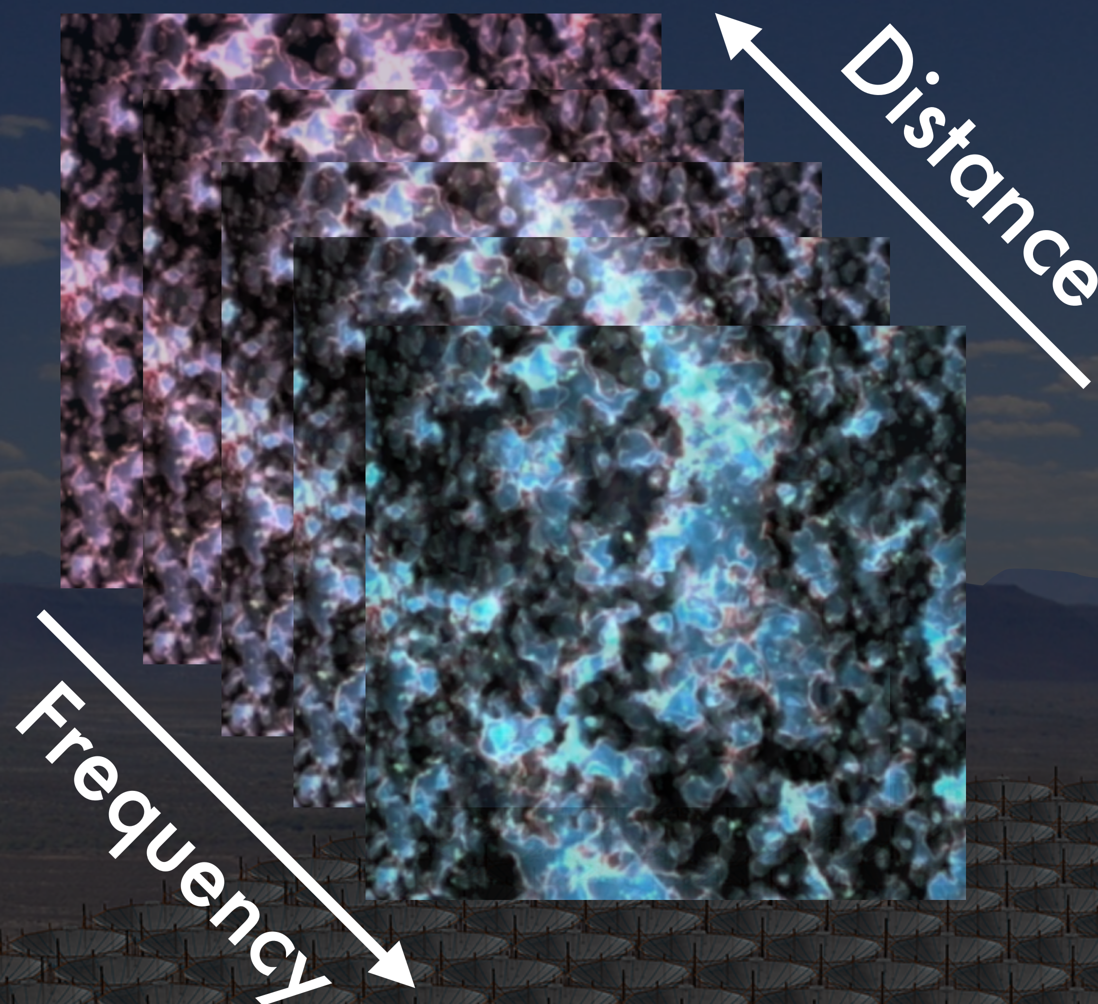
$$V_{ij}(\nu) = \int B_{ij}(\hat{\mathbf{r}}, \nu) I(\hat{\mathbf{r}}, \nu) \exp\left[-2\pi i \frac{\nu}{c} \mathbf{b}_{ij} \cdot \hat{\mathbf{r}}\right] d\Omega$$

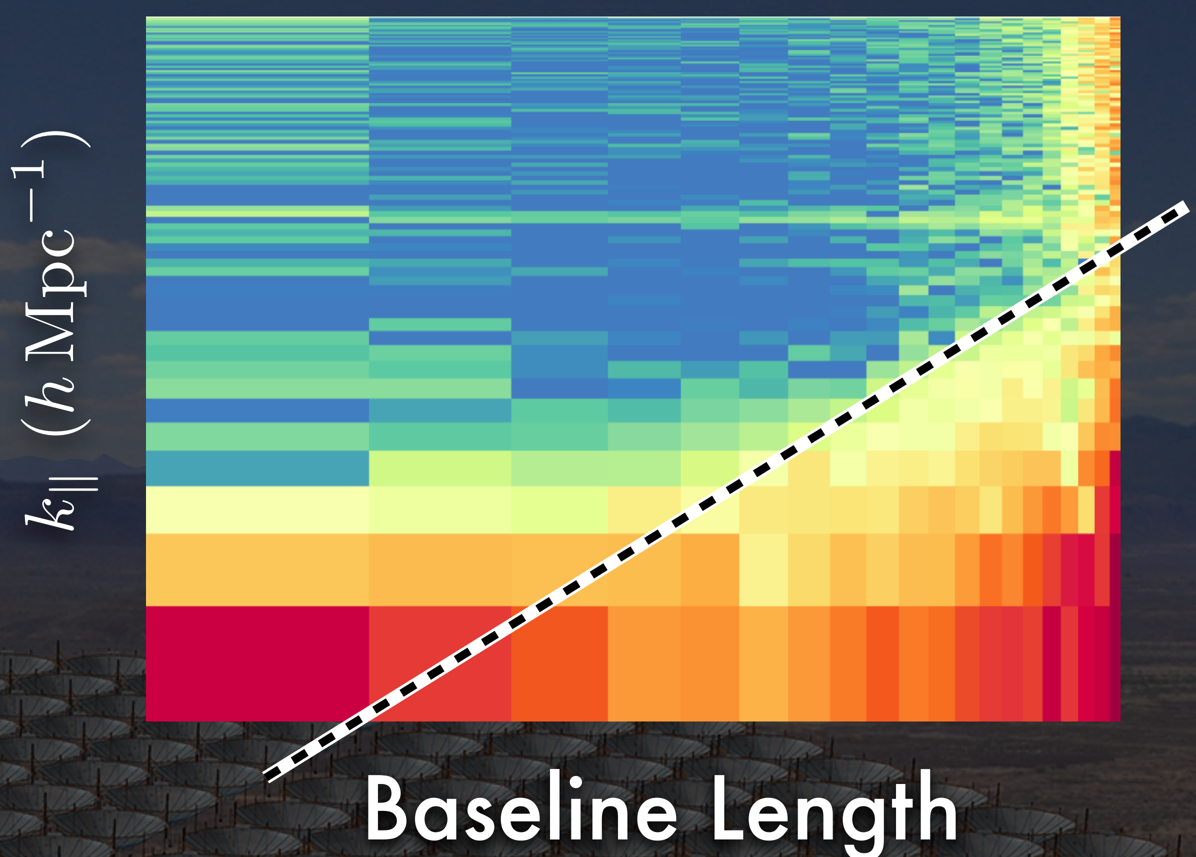




Since frequency maps to distance...

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





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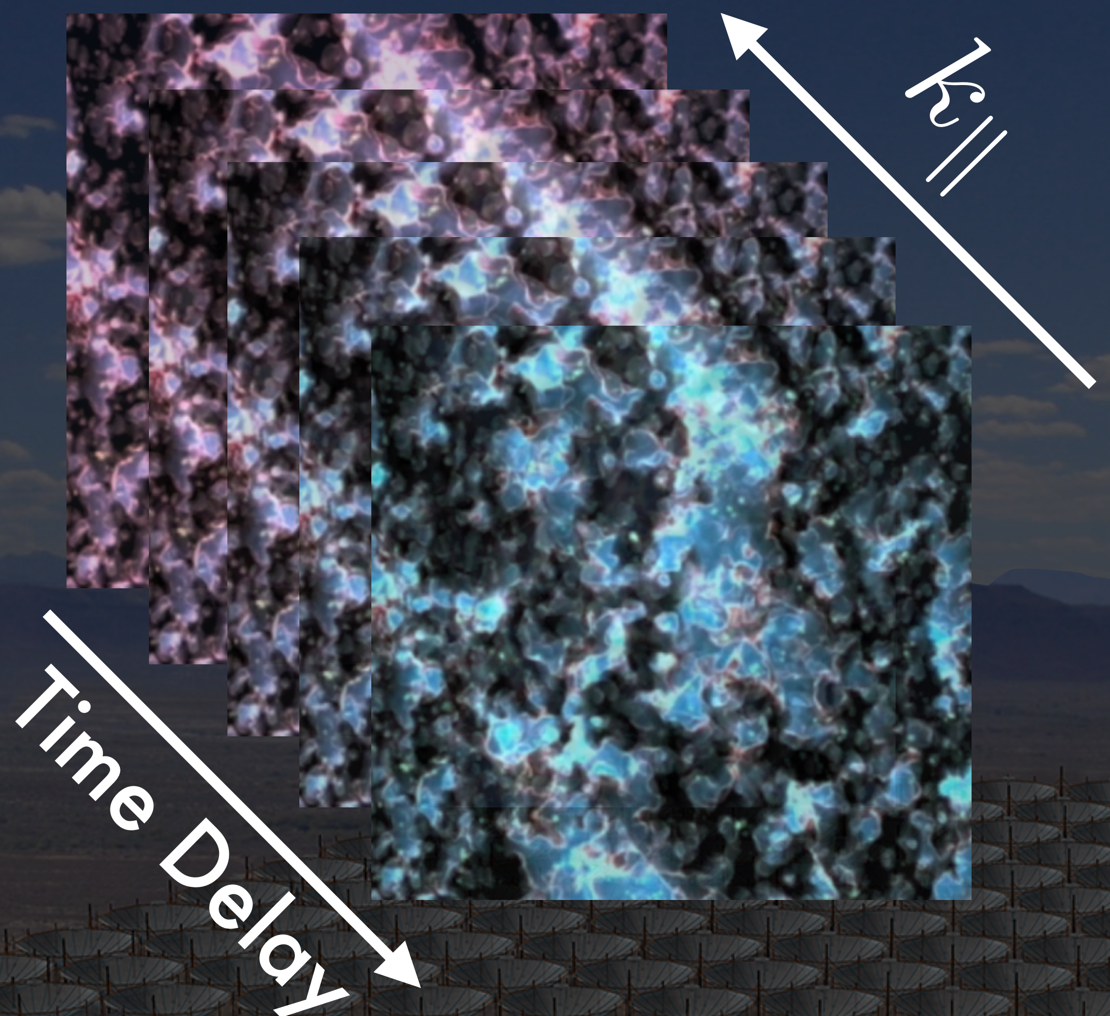
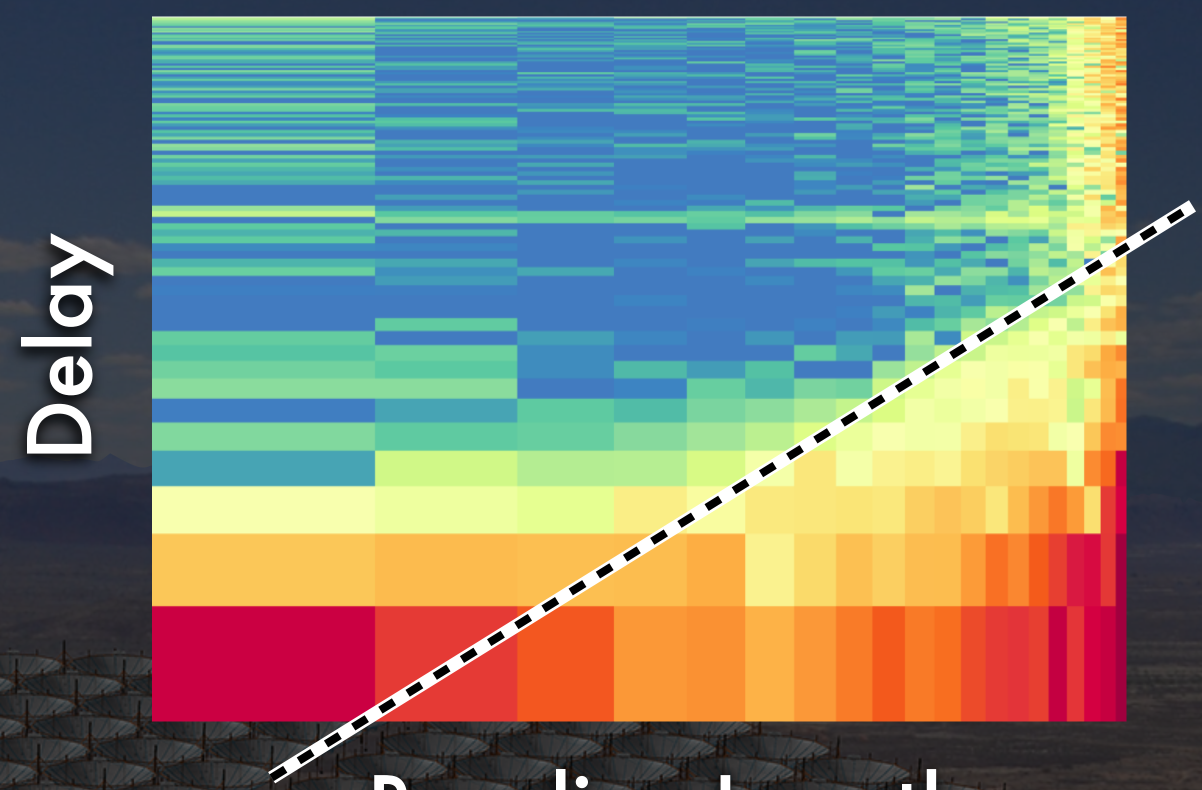
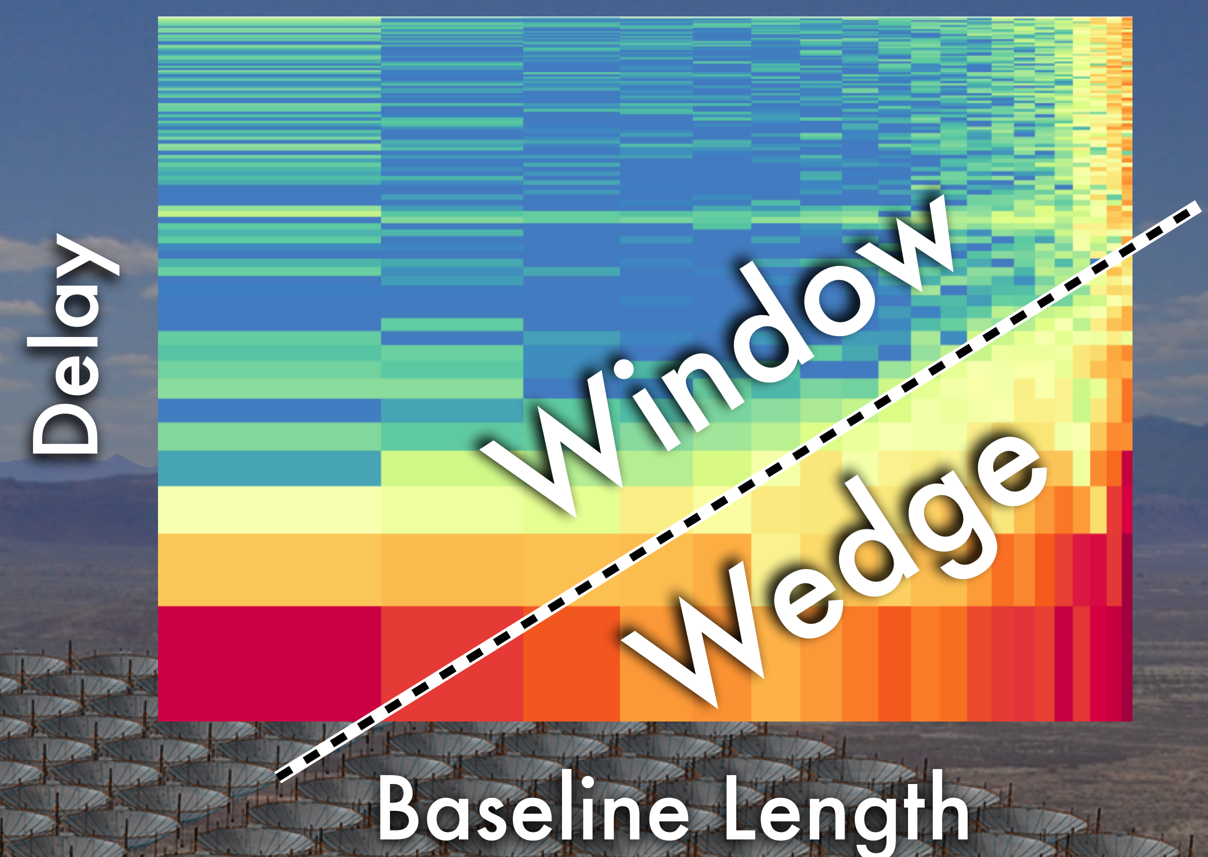




$k_{\parallel}$ is effectively time delay.

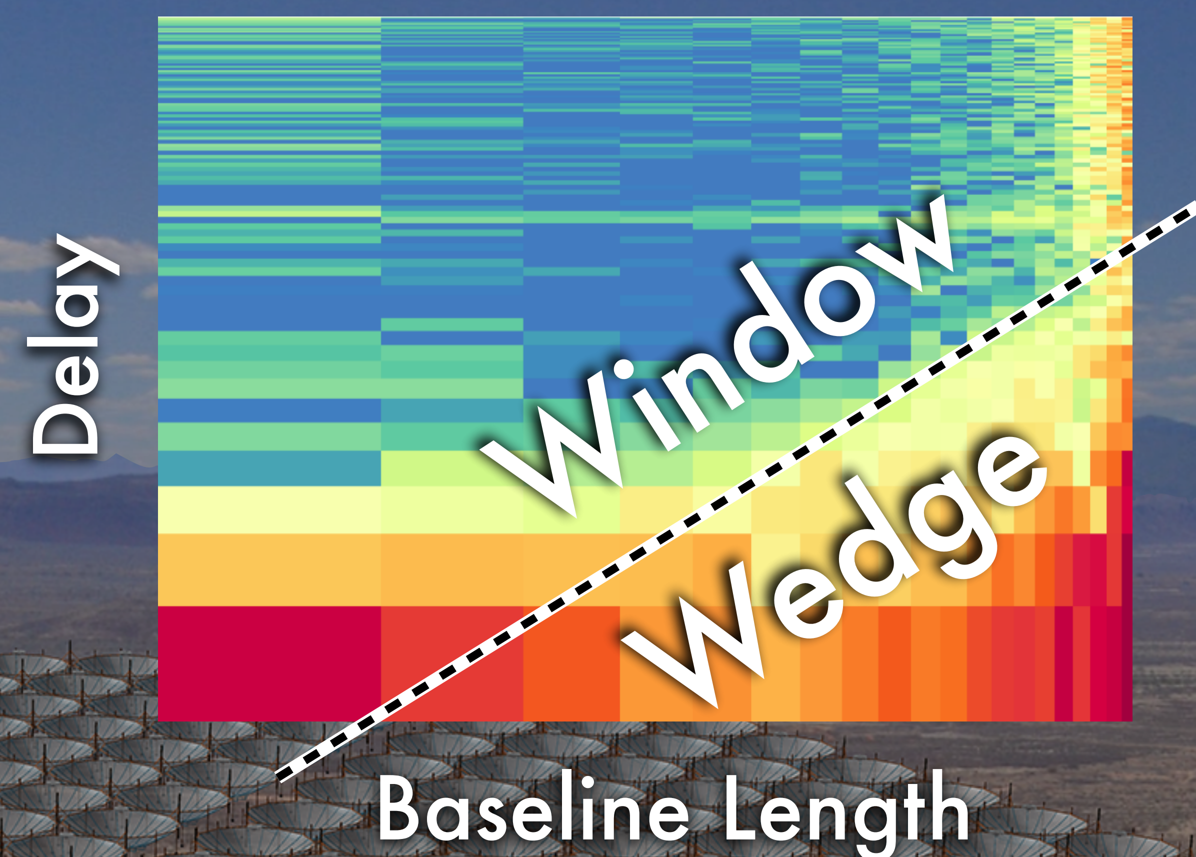
The maximum delay of foregrounds for a baseline is simply the light travel time.



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

Parsons et al. (2012)

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

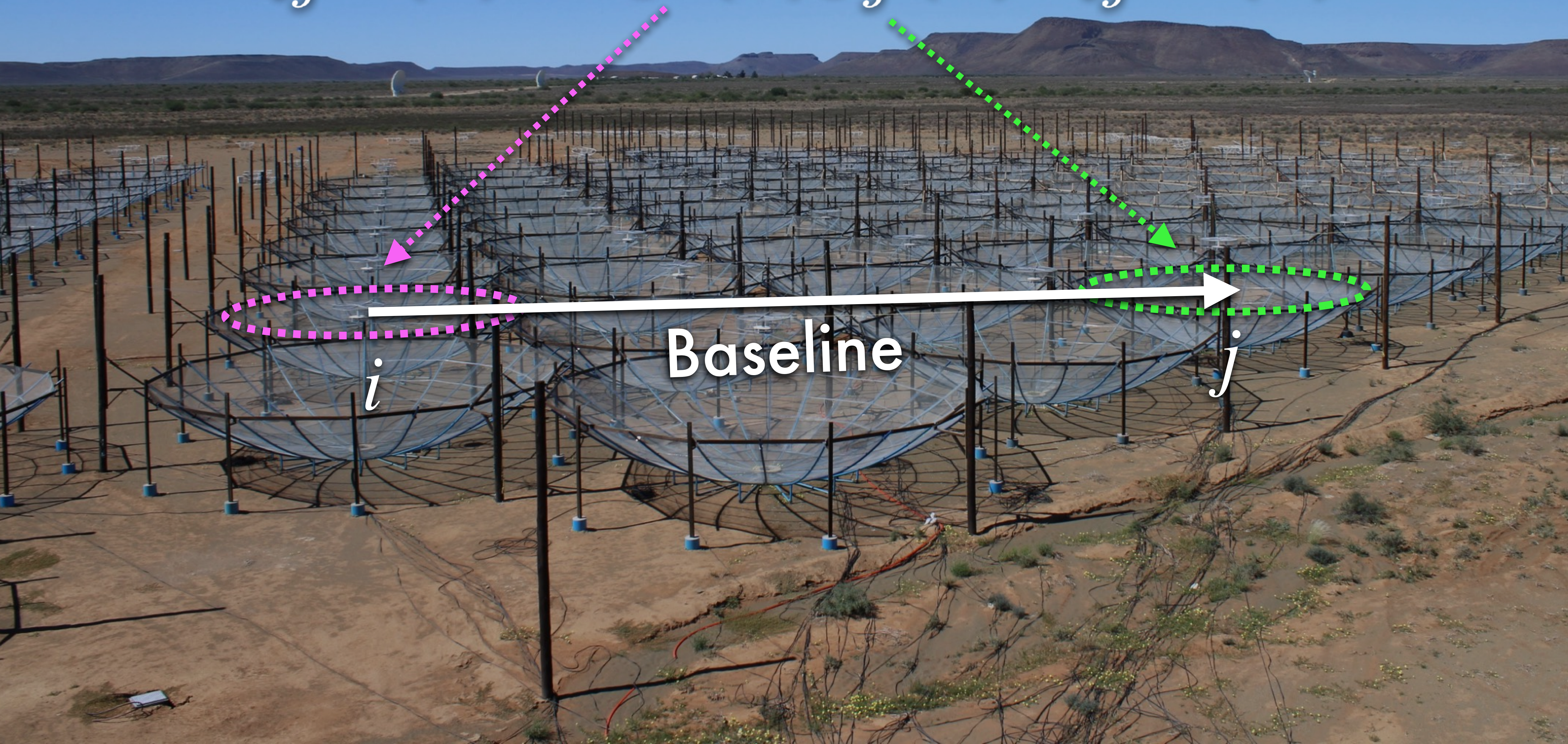


$$\Delta t_{\max} = |\mathbf{b}|/c$$

Dillon & Parsons (2016)

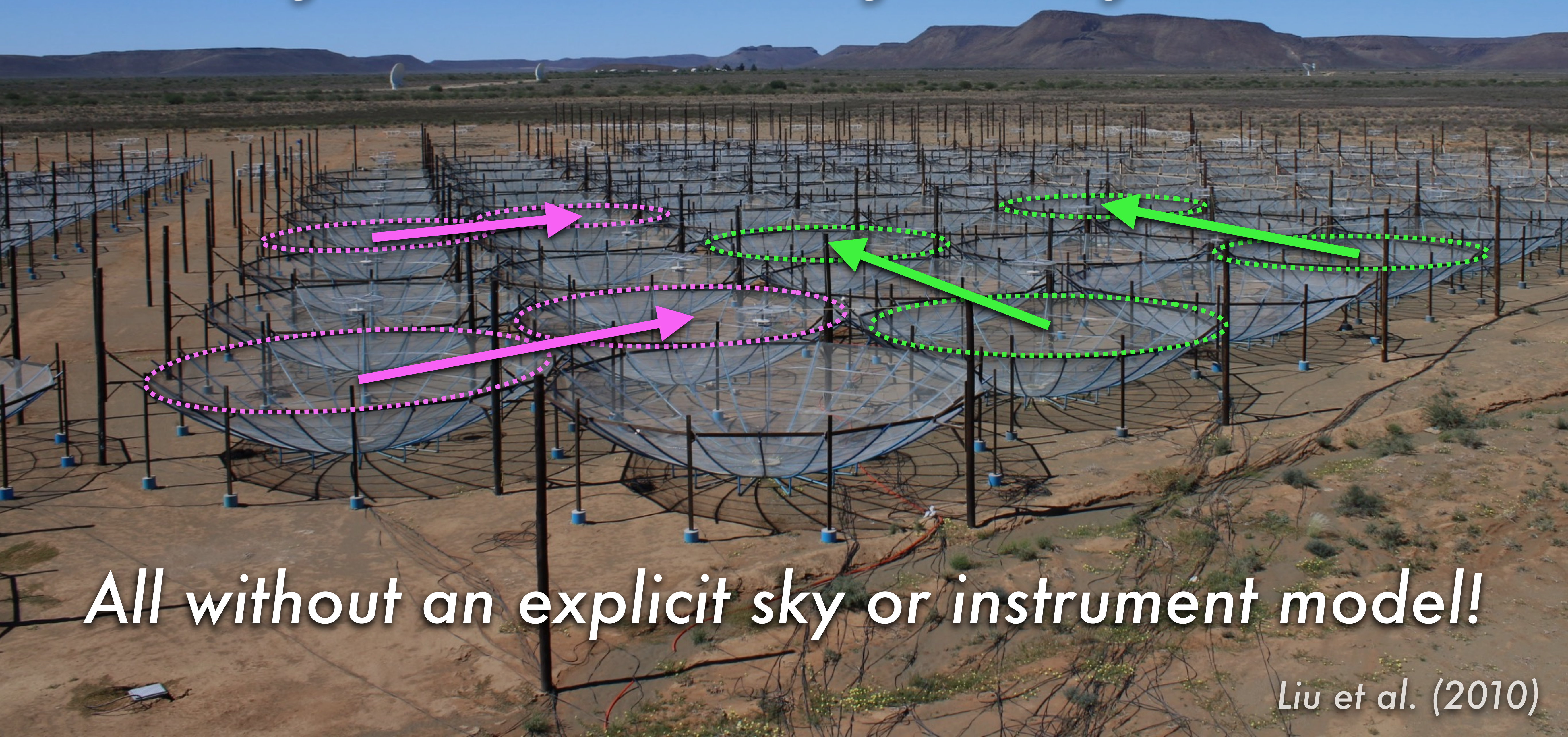
Foreground avoidance won't work without precision calibration.

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



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

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



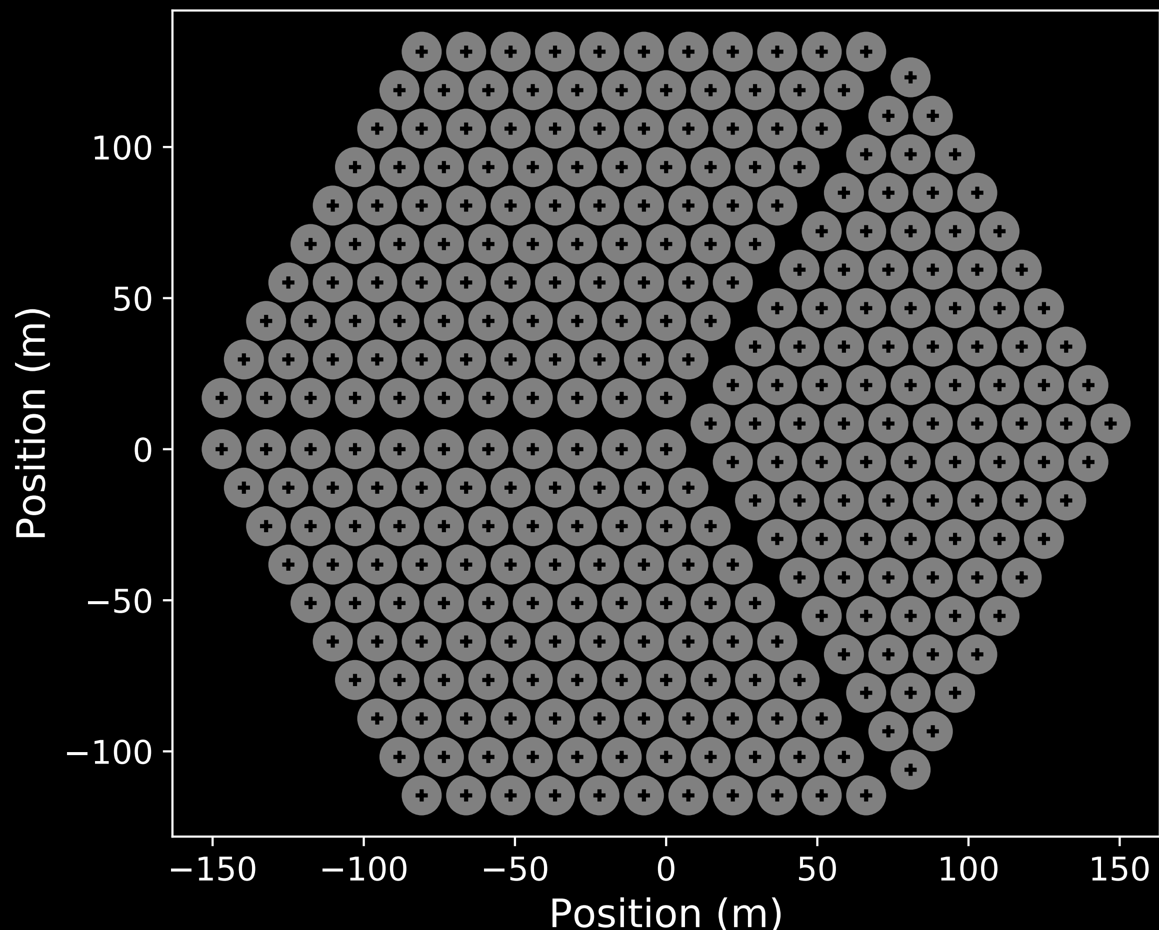
All without an explicit sky or instrument model!

Liu et al. (2010)

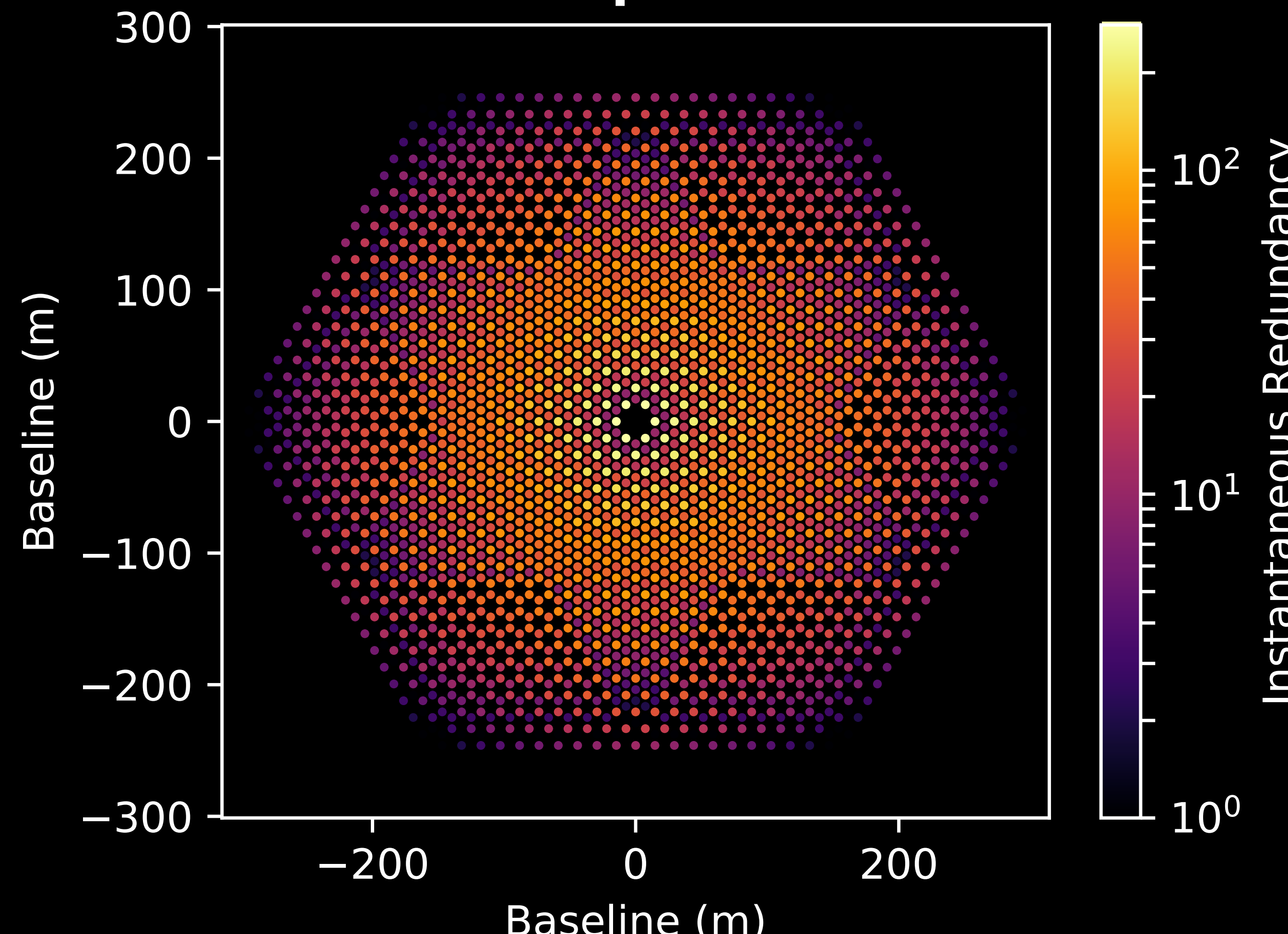
$$V_{ij}^{\mathrm{obs}}(\nu) = g_i(\nu)g_j^*(\nu)V_{ij}^{\mathrm{true}}(\nu)$$

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

320 Antenna Gains



1,501 Unique Visibilities

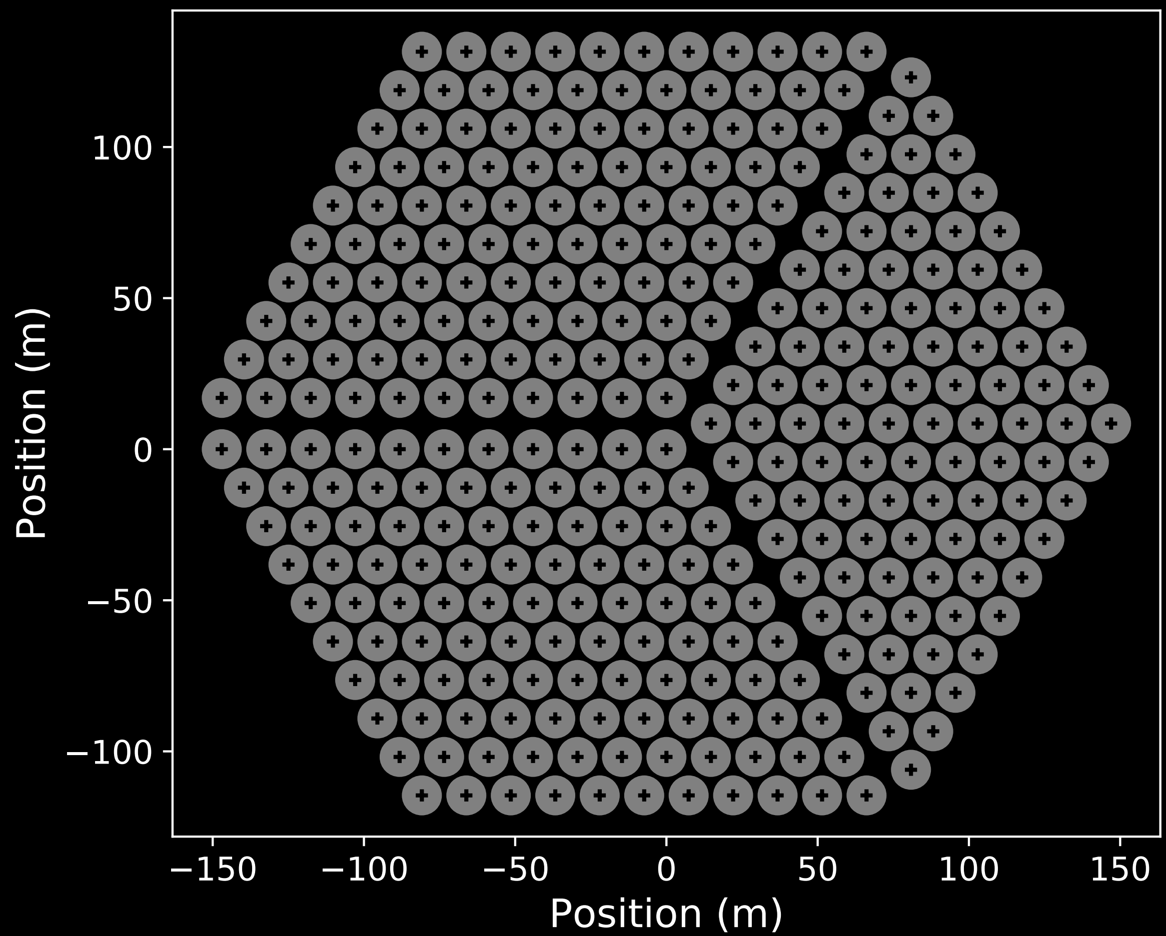


51,040 Total Measurements

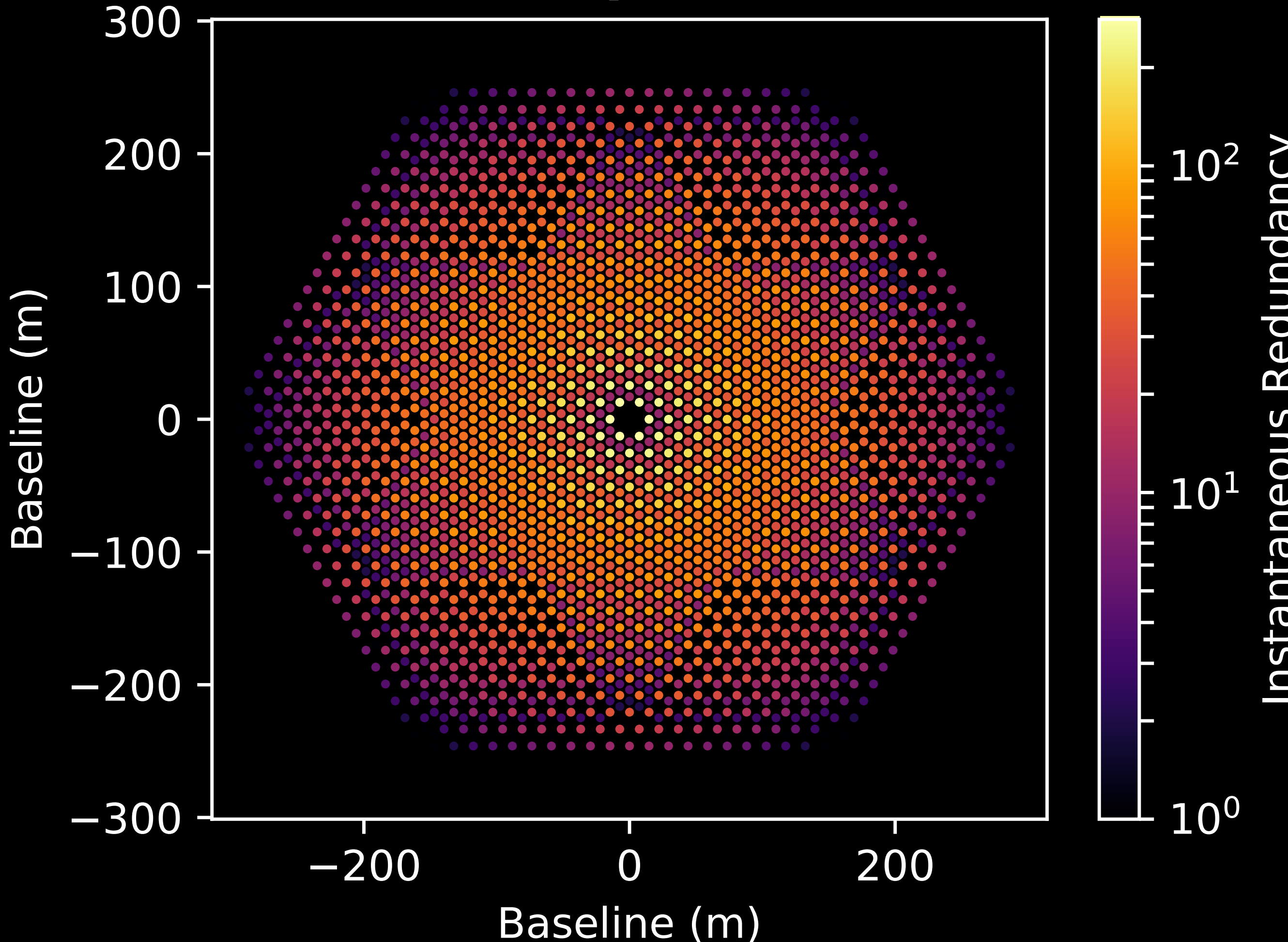
Dillon & *Parsons (2016)*

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

320 Antenna Gains



1,501 Unique Visibilities



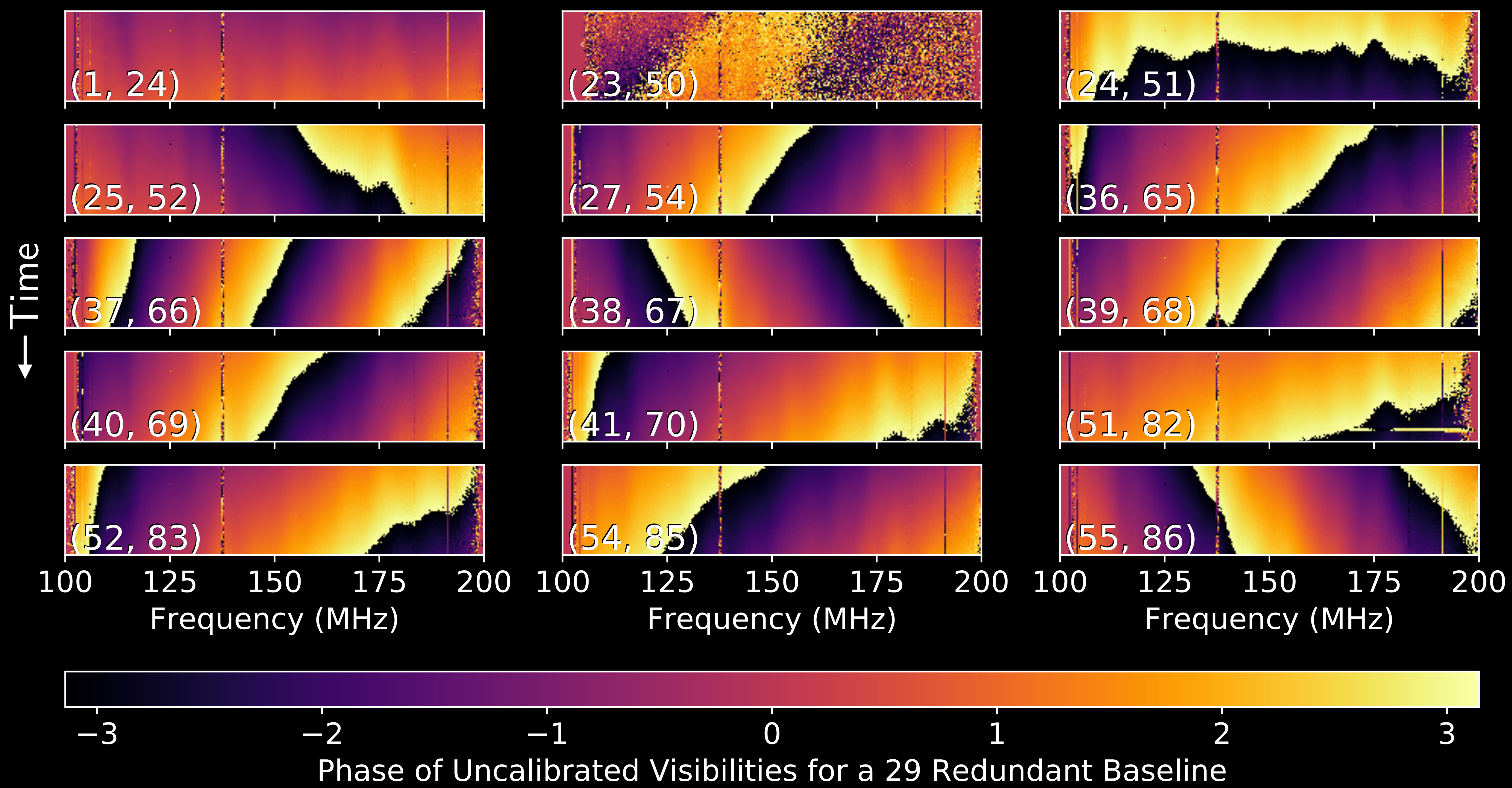
51,040 Total Measurements

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

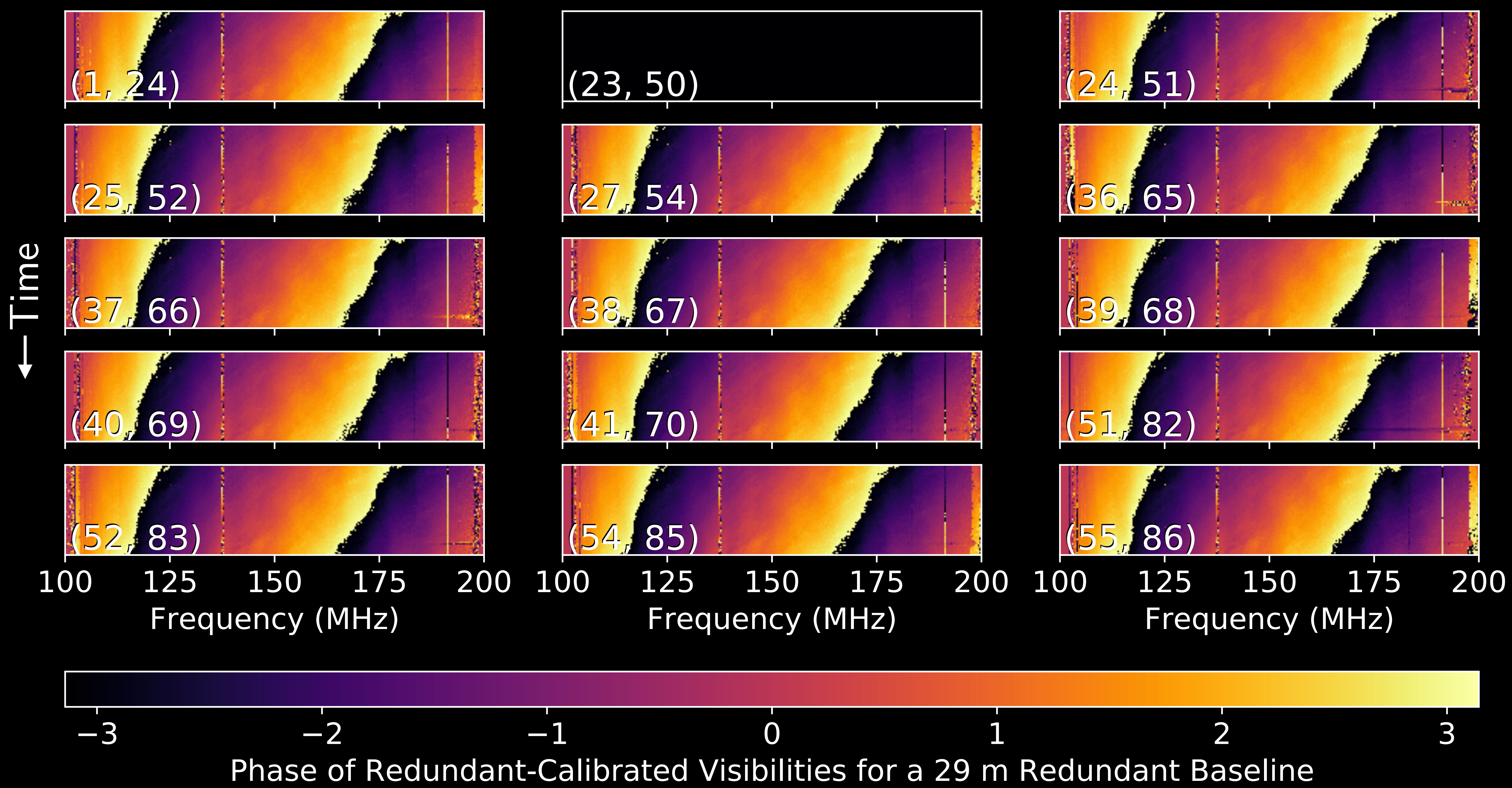
Dillon & *Parsons (2016)*

Redundant calibration is working quite well.

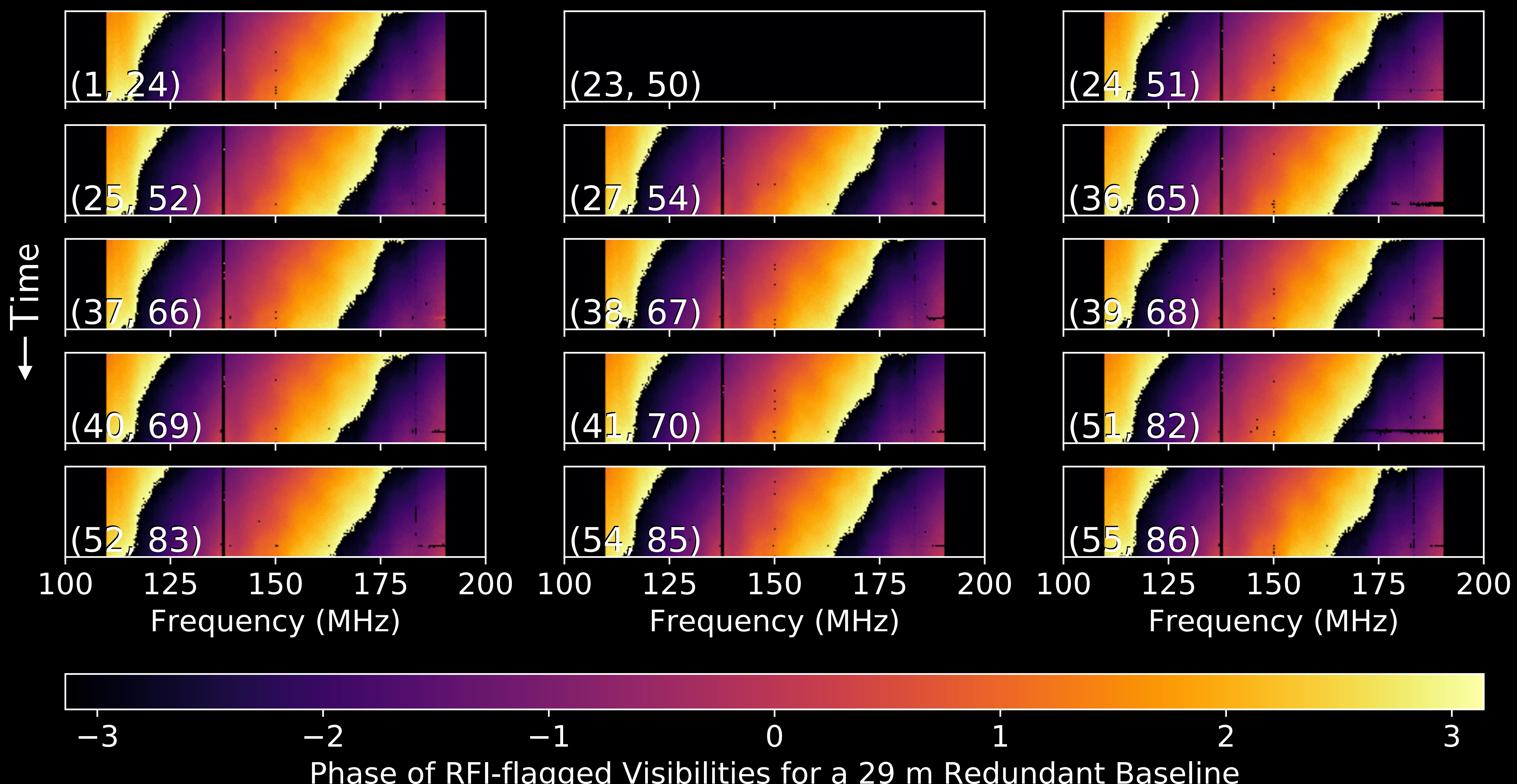
Example raw HERA data for a single redundant baseline group.



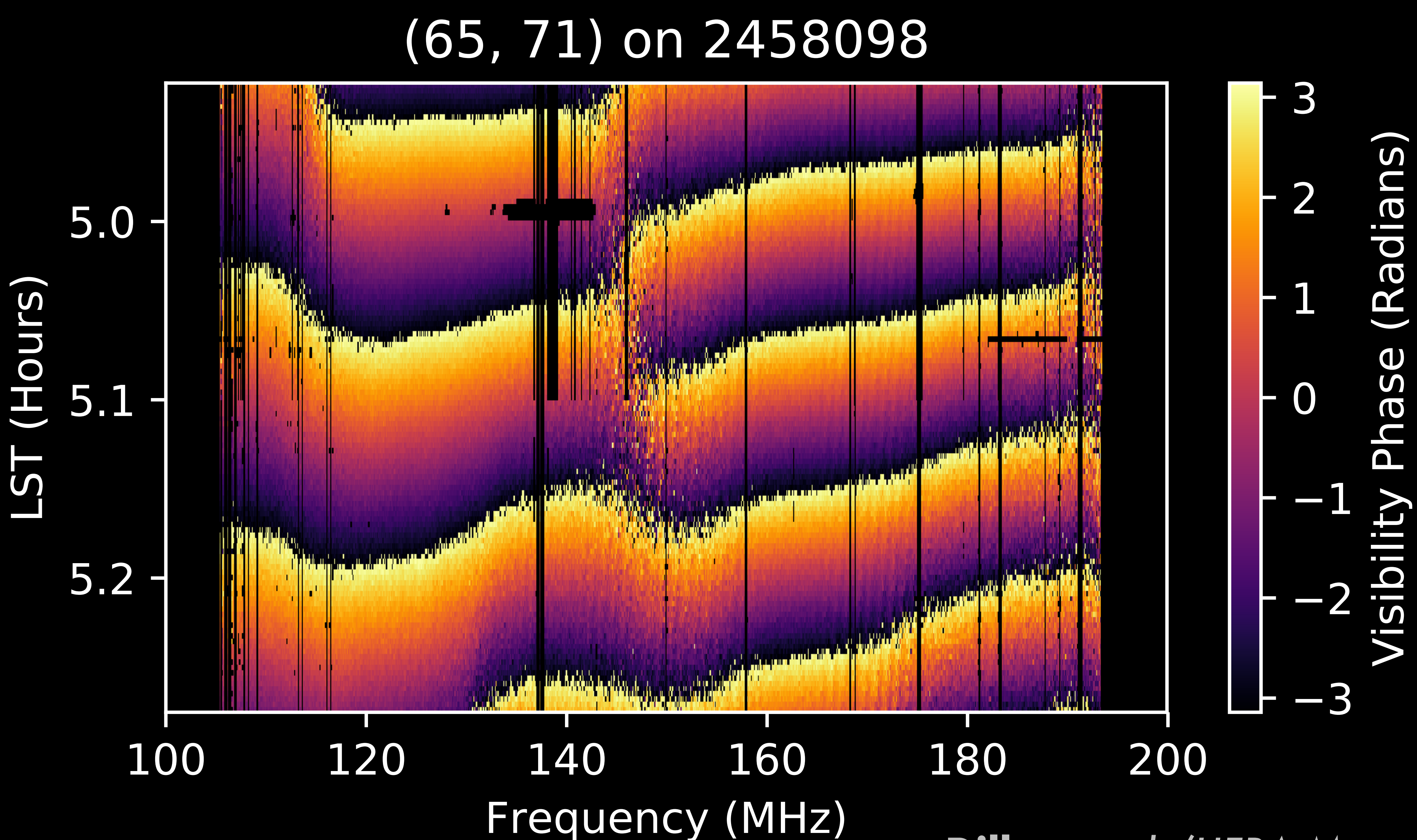
Next we flag bad antennas and impose the redundancy constraint to solve for all gains.



Then we mask-out radio-frequency interference (RFI).

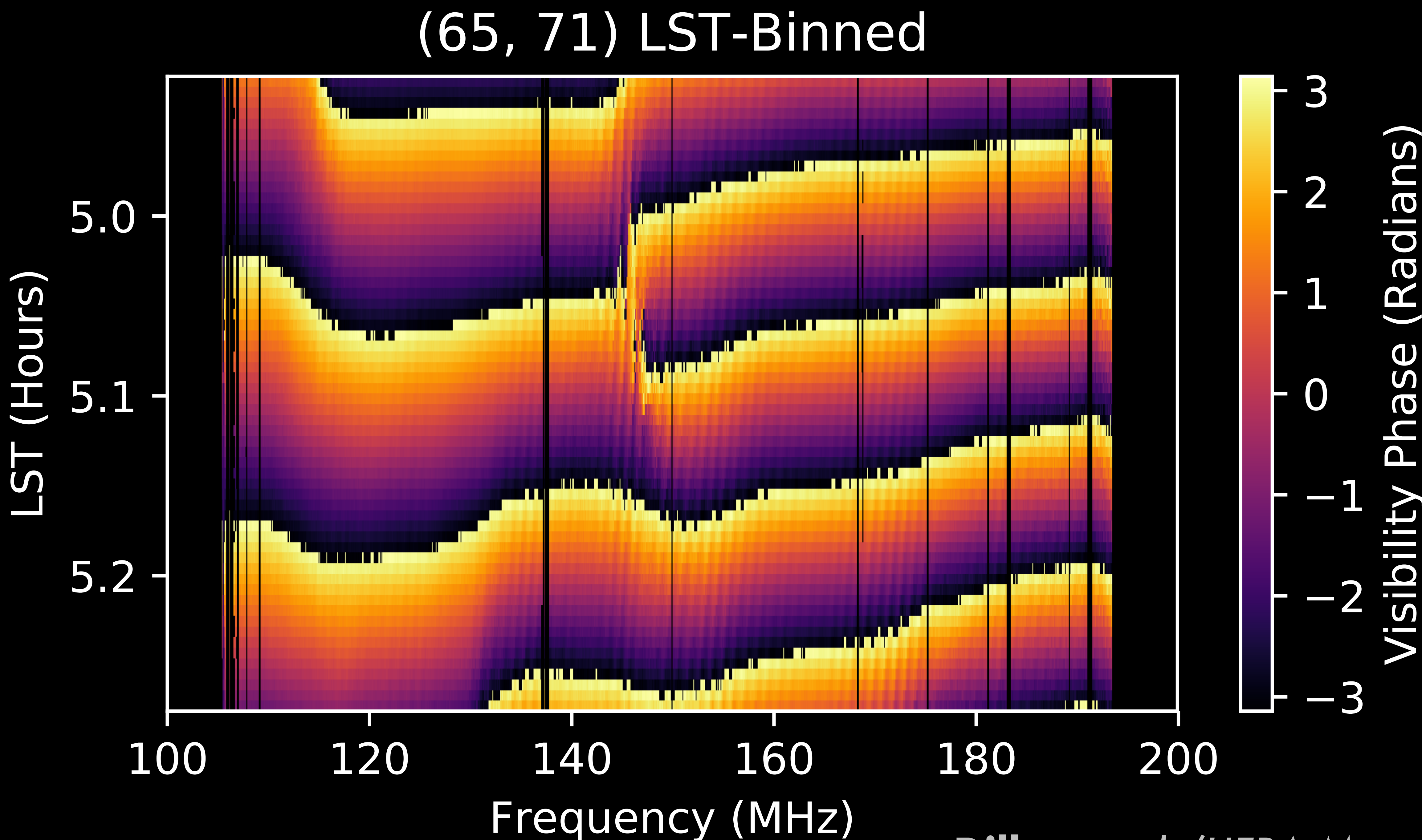


The instrument looks stable from day to day...

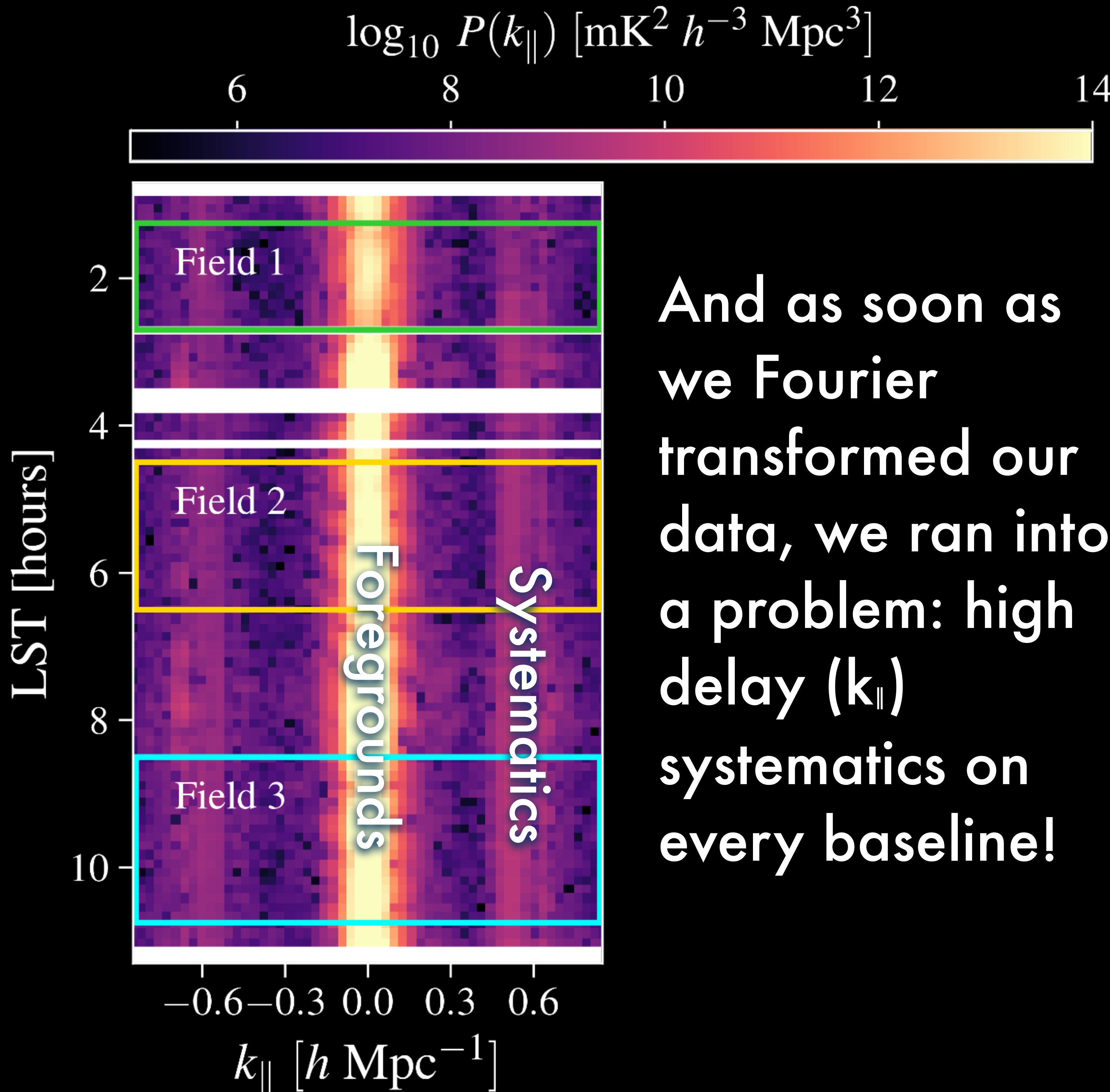


Dillon *et al. (HERA Memo #45)*

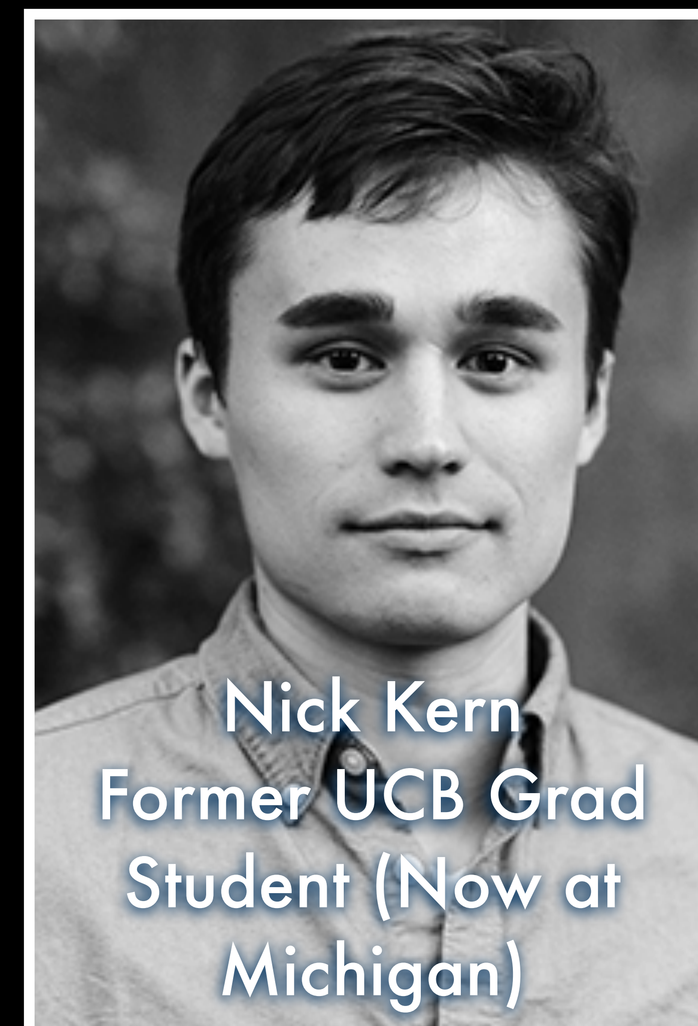
So we can keep integrating down to maximize sensitivity.



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

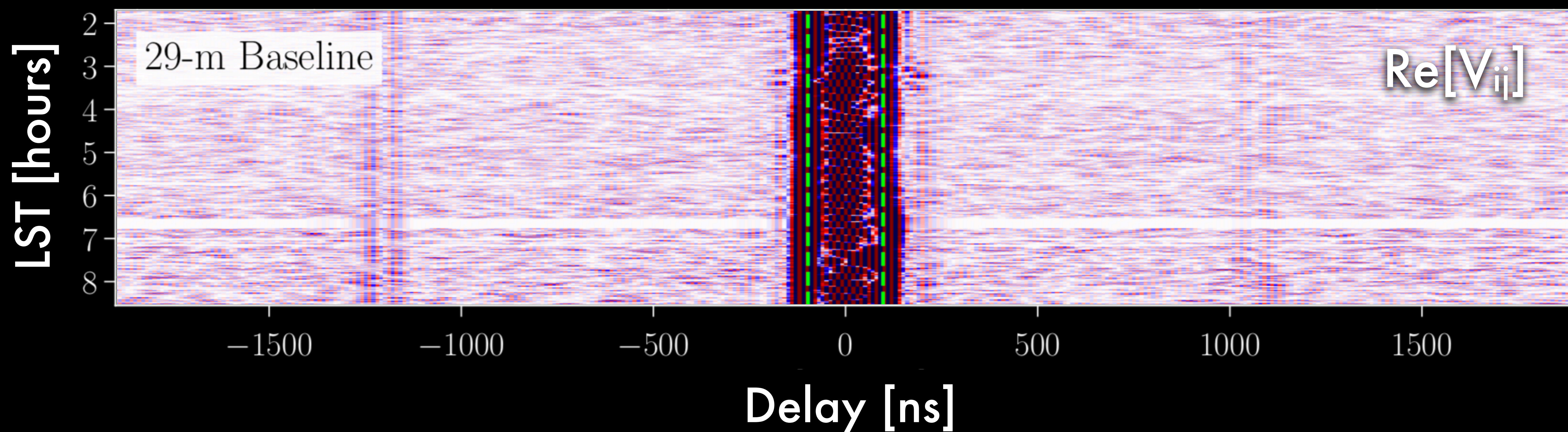


And as soon as we Fourier transformed our data, we ran into a problem: high delay ($k_\parallel$) systematics on every baseline!



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)*

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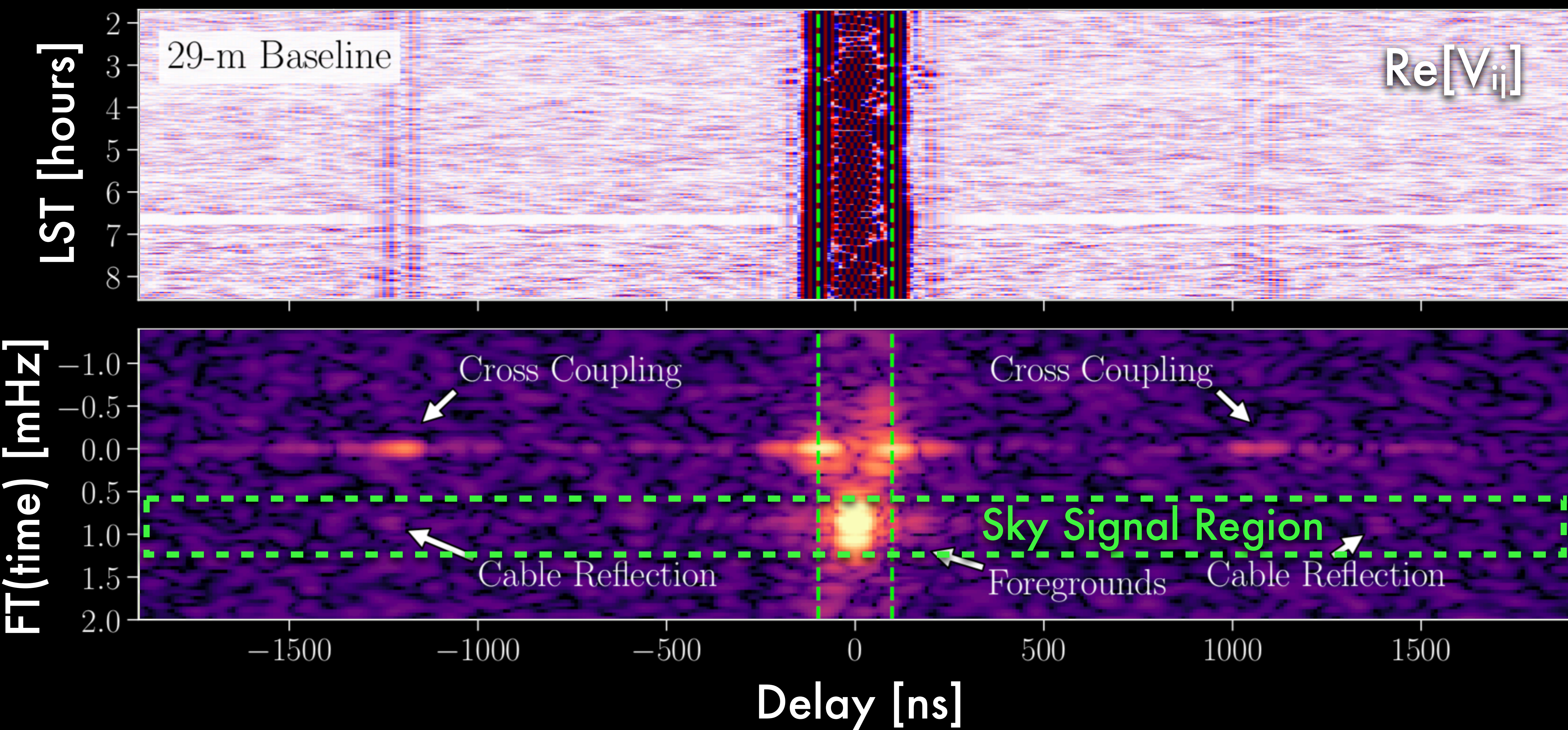
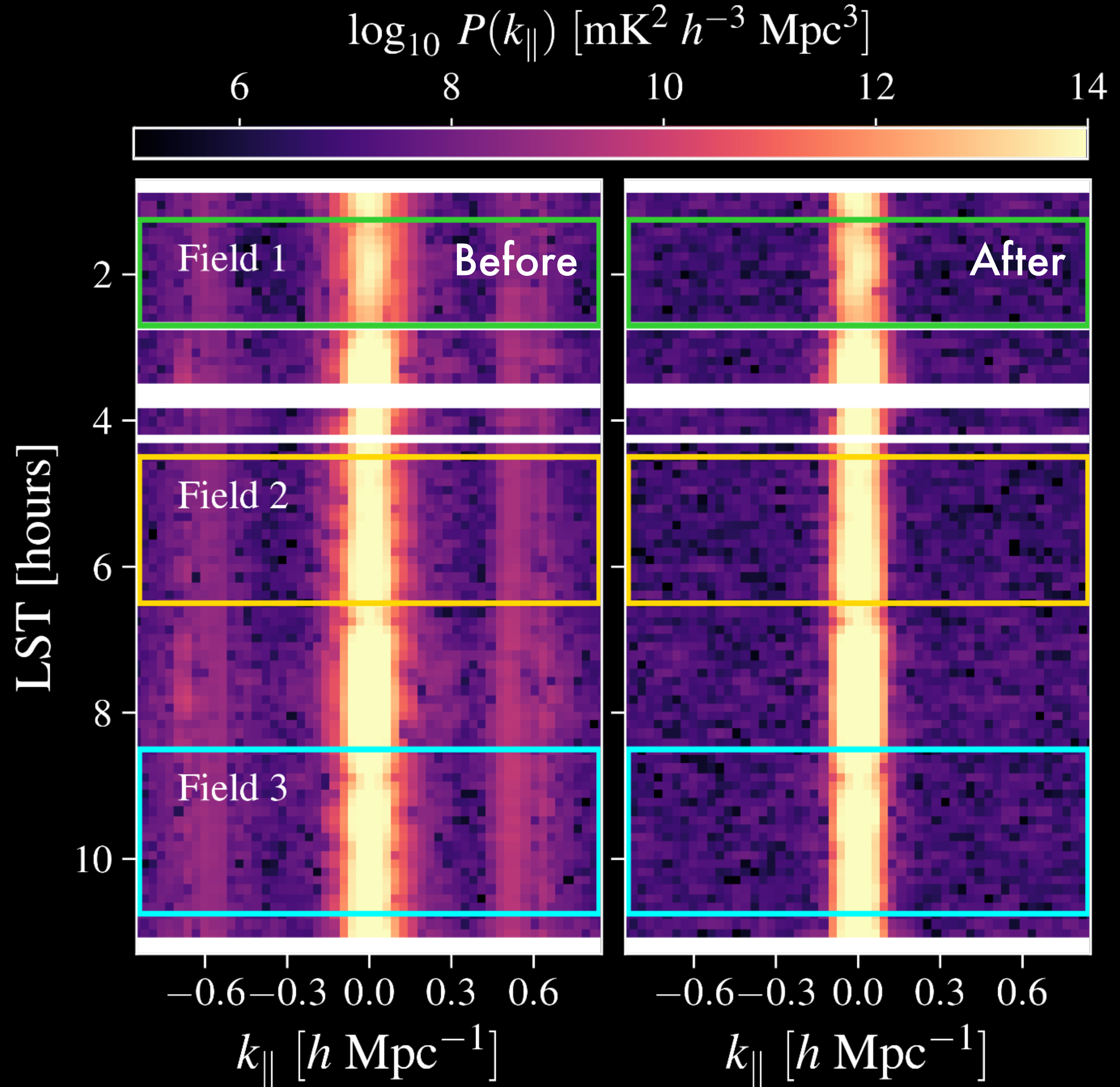


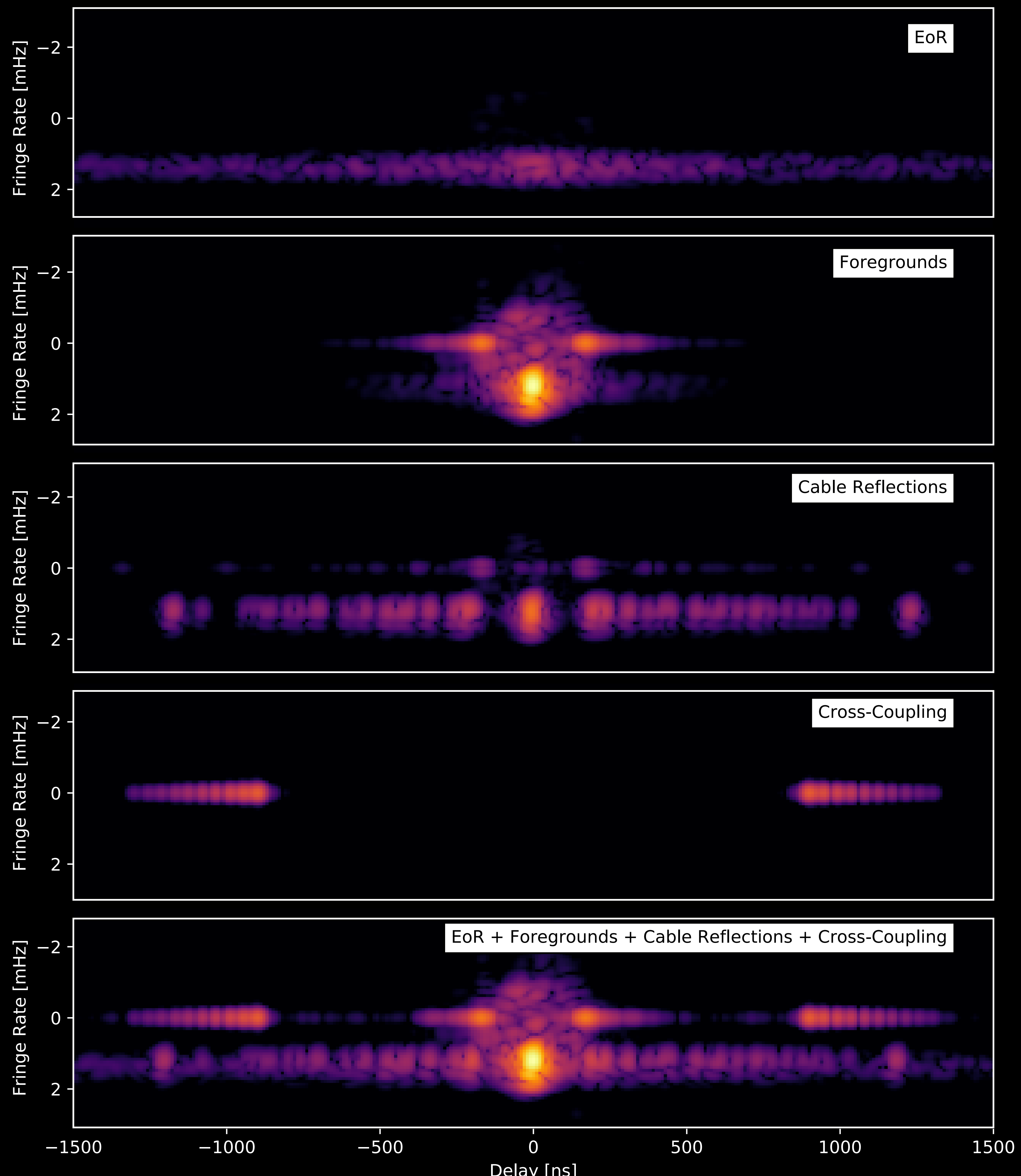
*Kern, Parsons, **Dillon**, et al. (2019ab)*

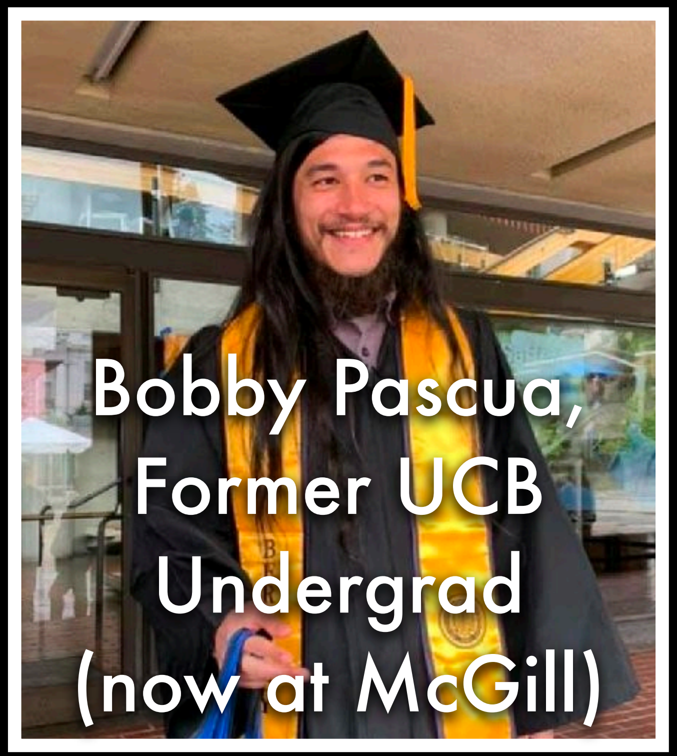
With our techniques for relatively lossless systematics removal, we're getting very close to the thermal noise limit.



HERA Collaboration (2022)

How are we building confidence in our techniques and quantifying signal loss?

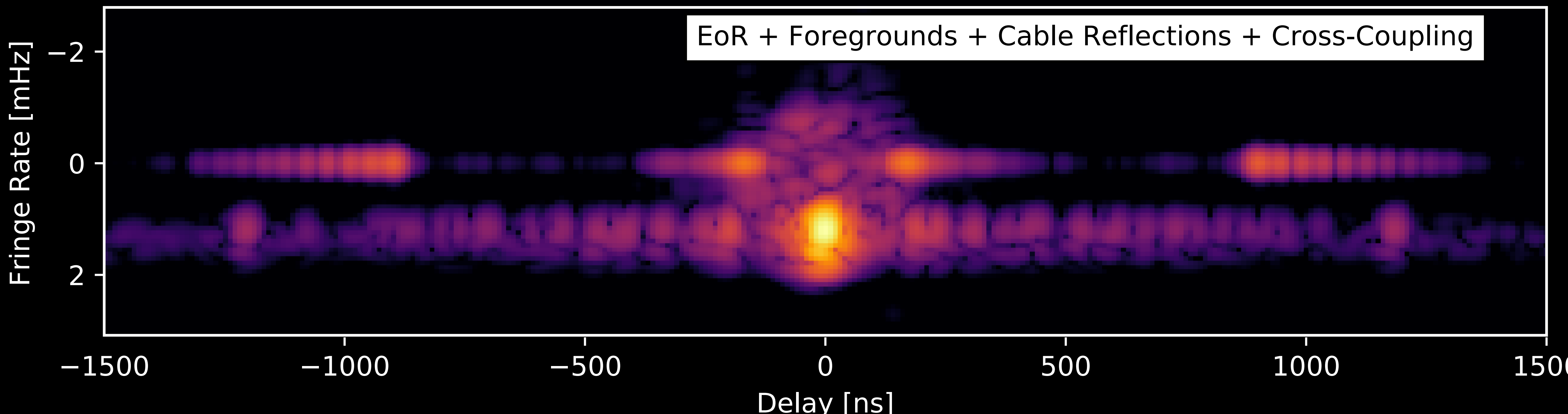


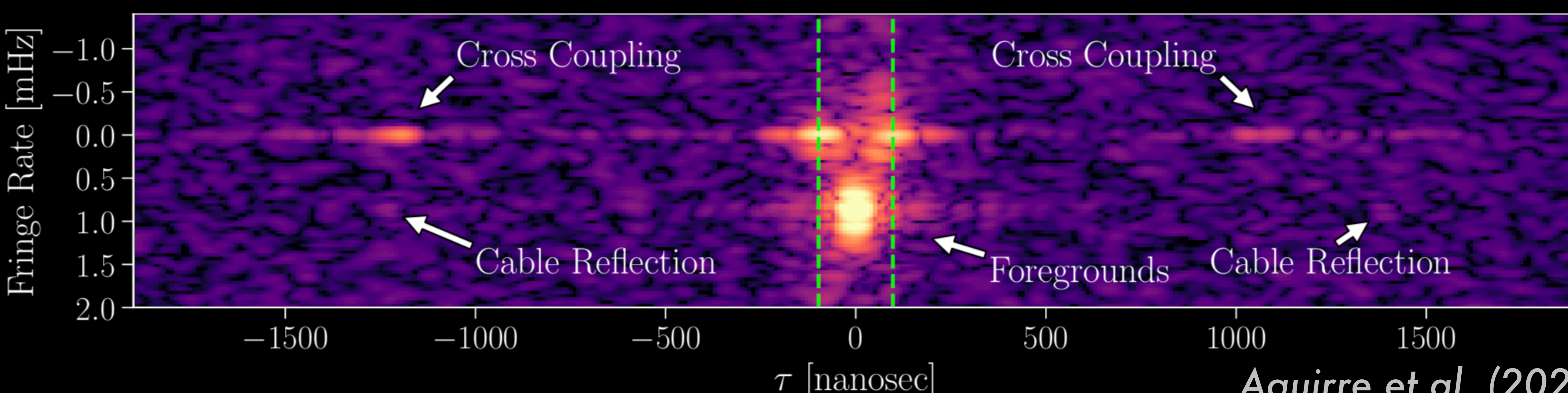


We built end-to-end tests of analysis pipeline with simulated EoR, foregrounds, and systematics.

Aguirre et al. (2022)

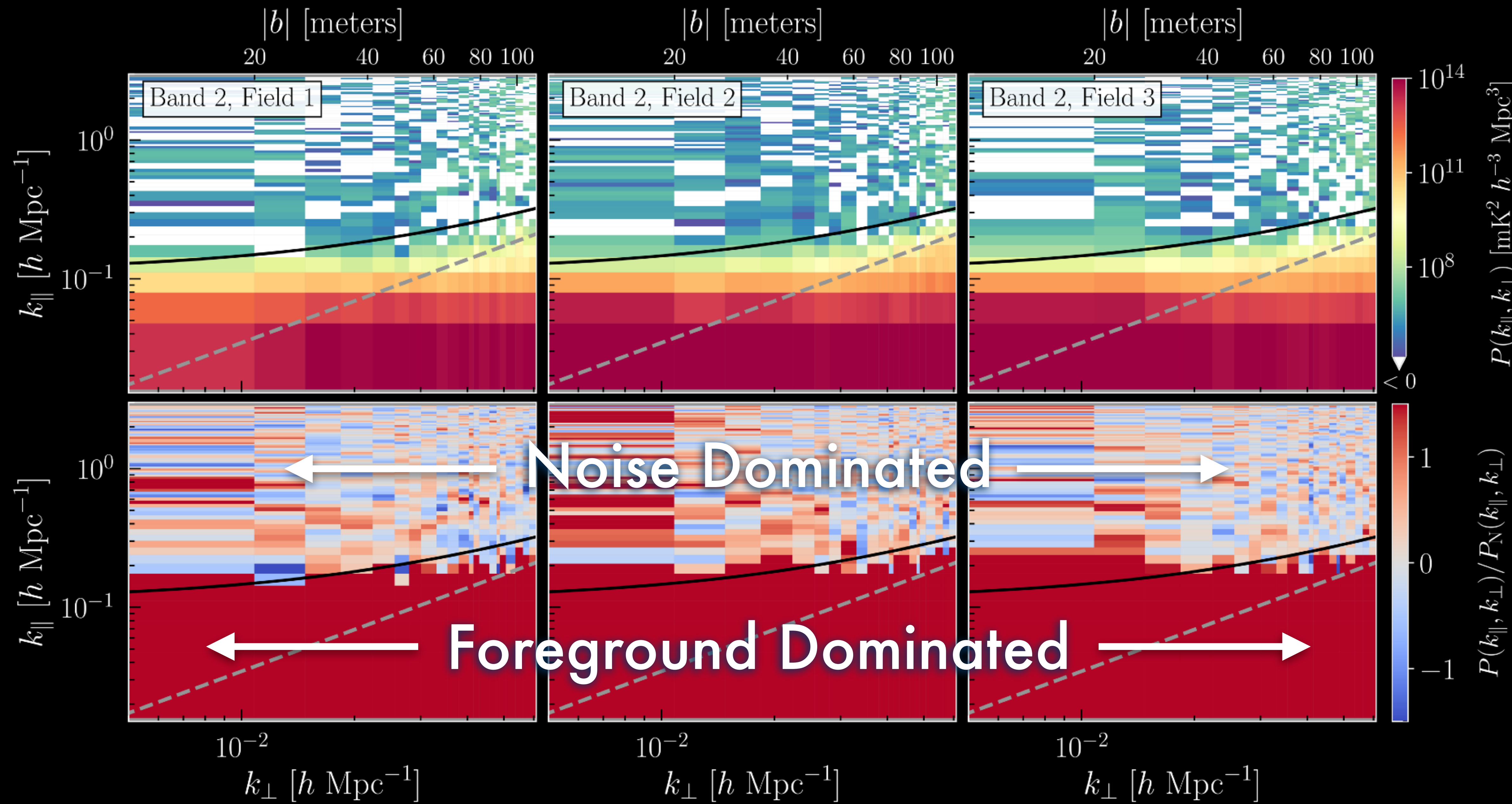
The simulation is really starting to reflect the complexity of real data.





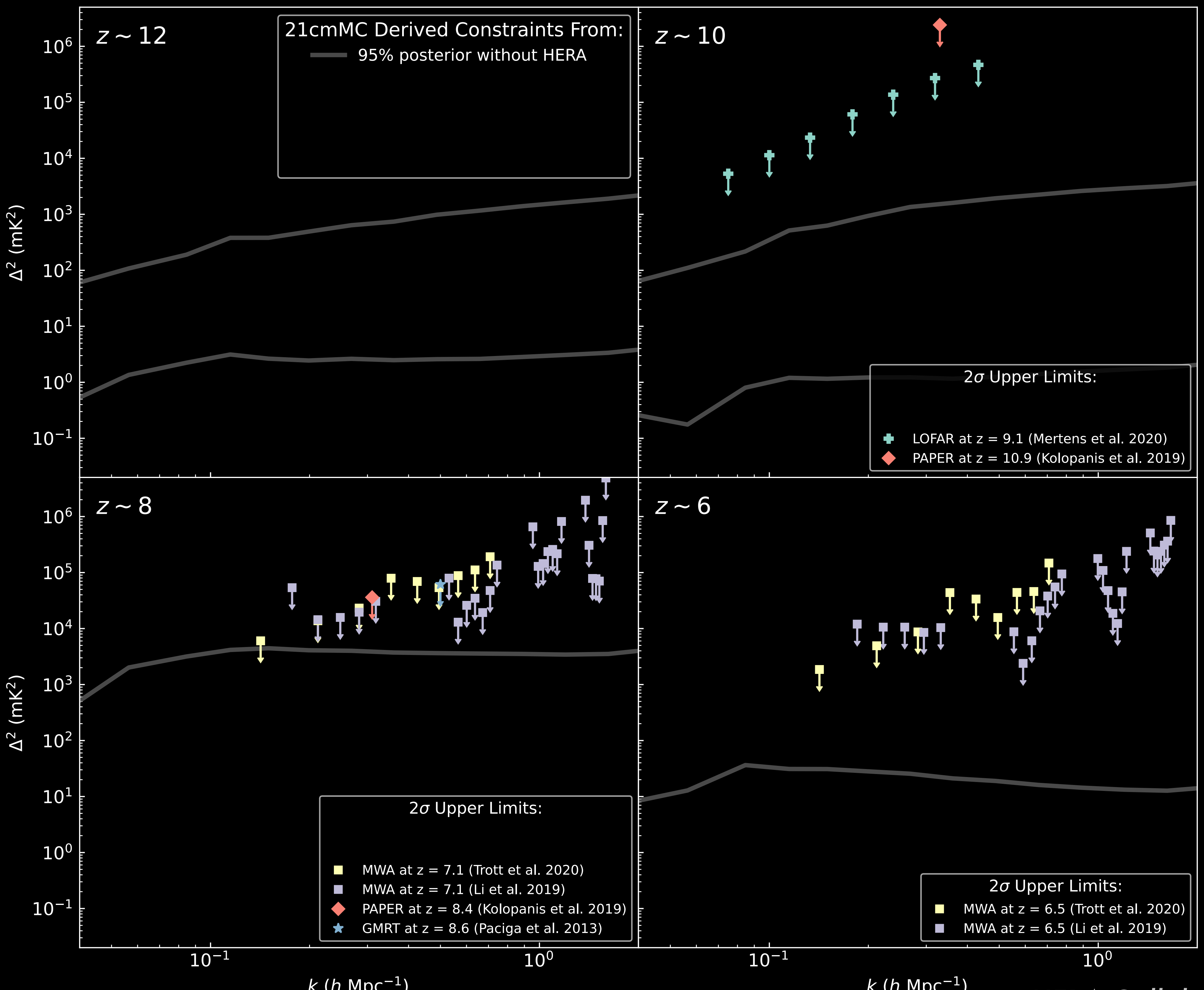
Aguirre et al. (2022)

With high-delay systematics mitigated, we can finally form power spectra with those 18 nights.



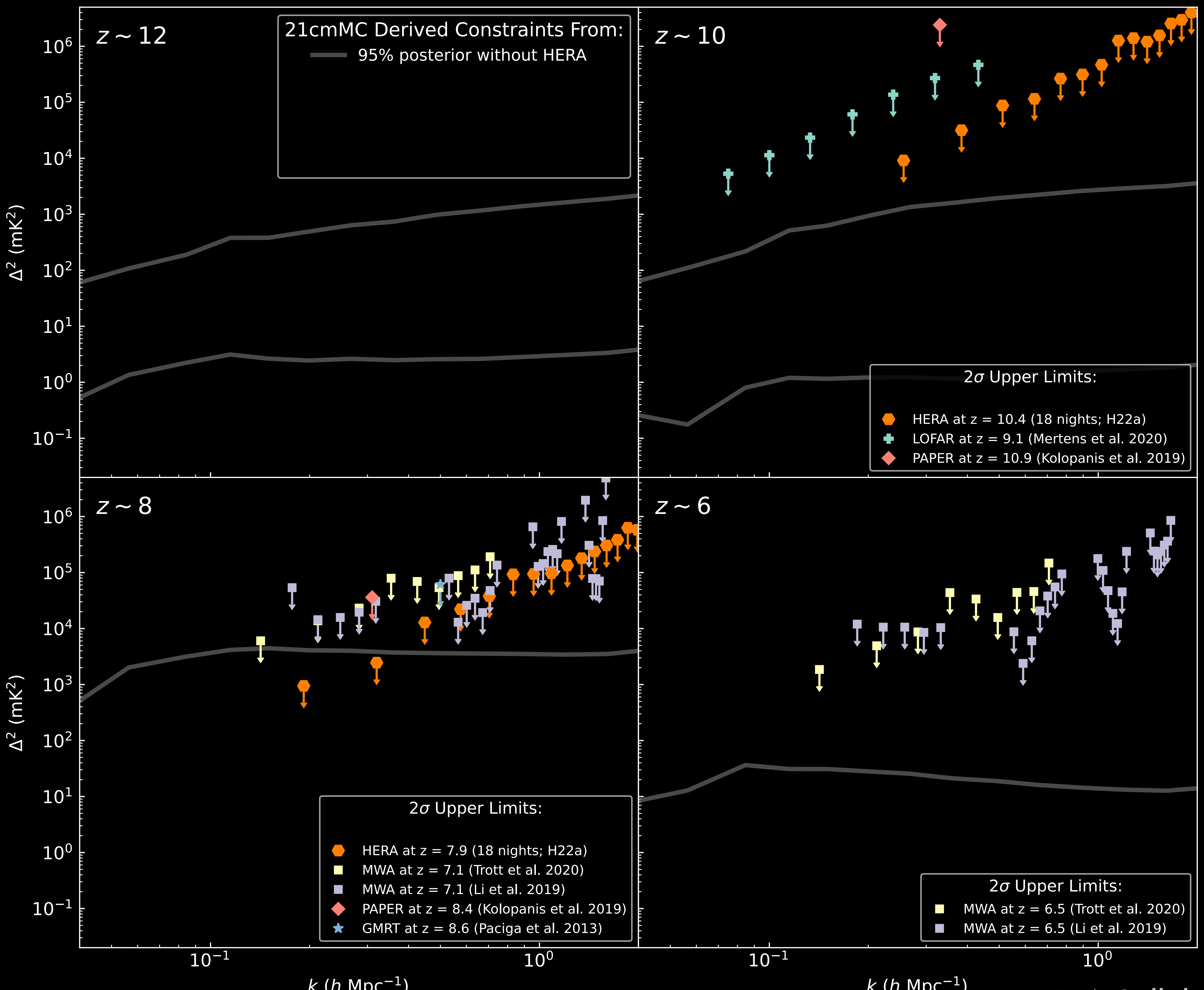
HERA Collaboration (2022a)

So again, here's where we were before HERA.



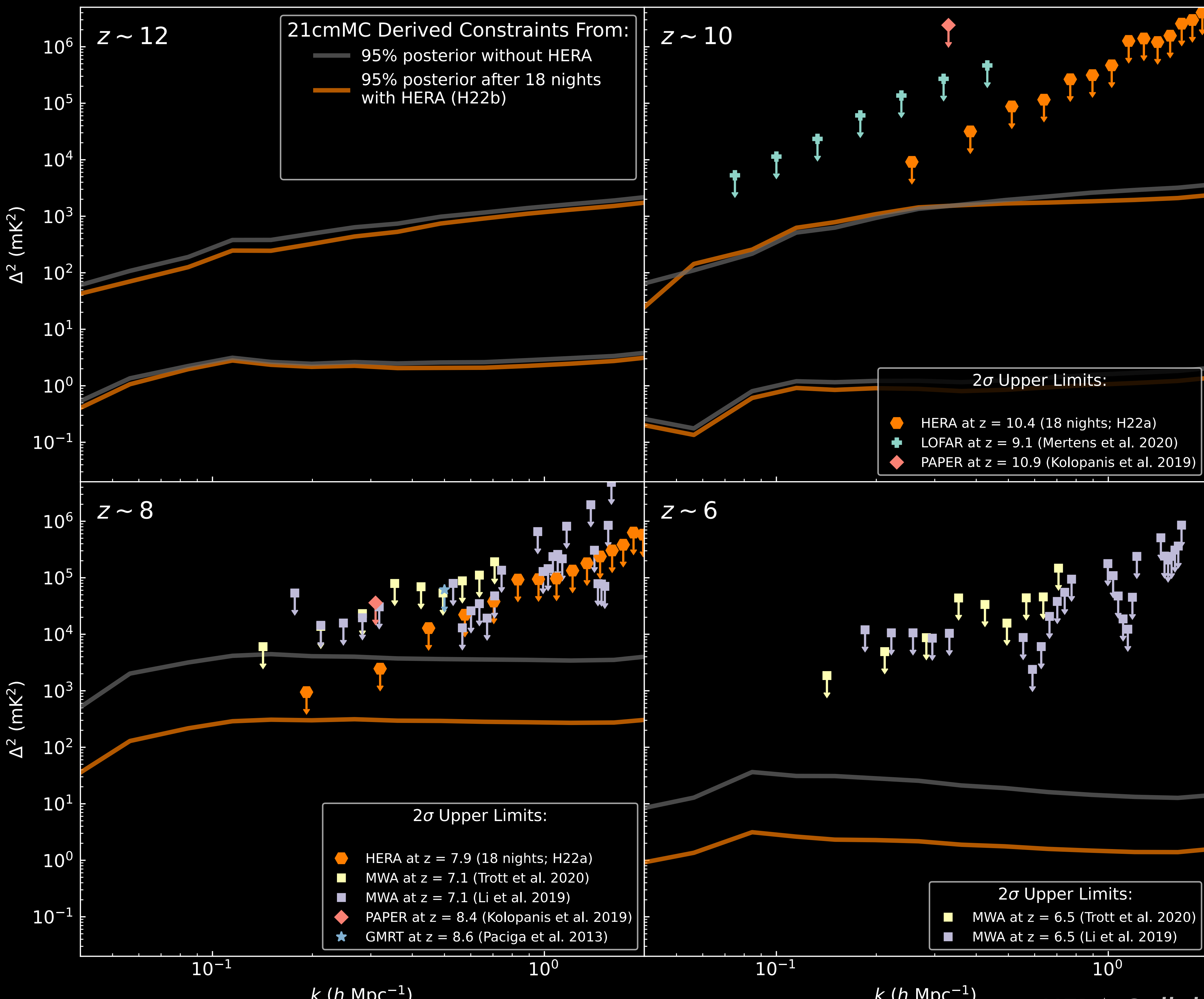
HERA Collaboration (2022b)

And here are HERA's first, world-leading upper limits on the 21cm power spectrum.



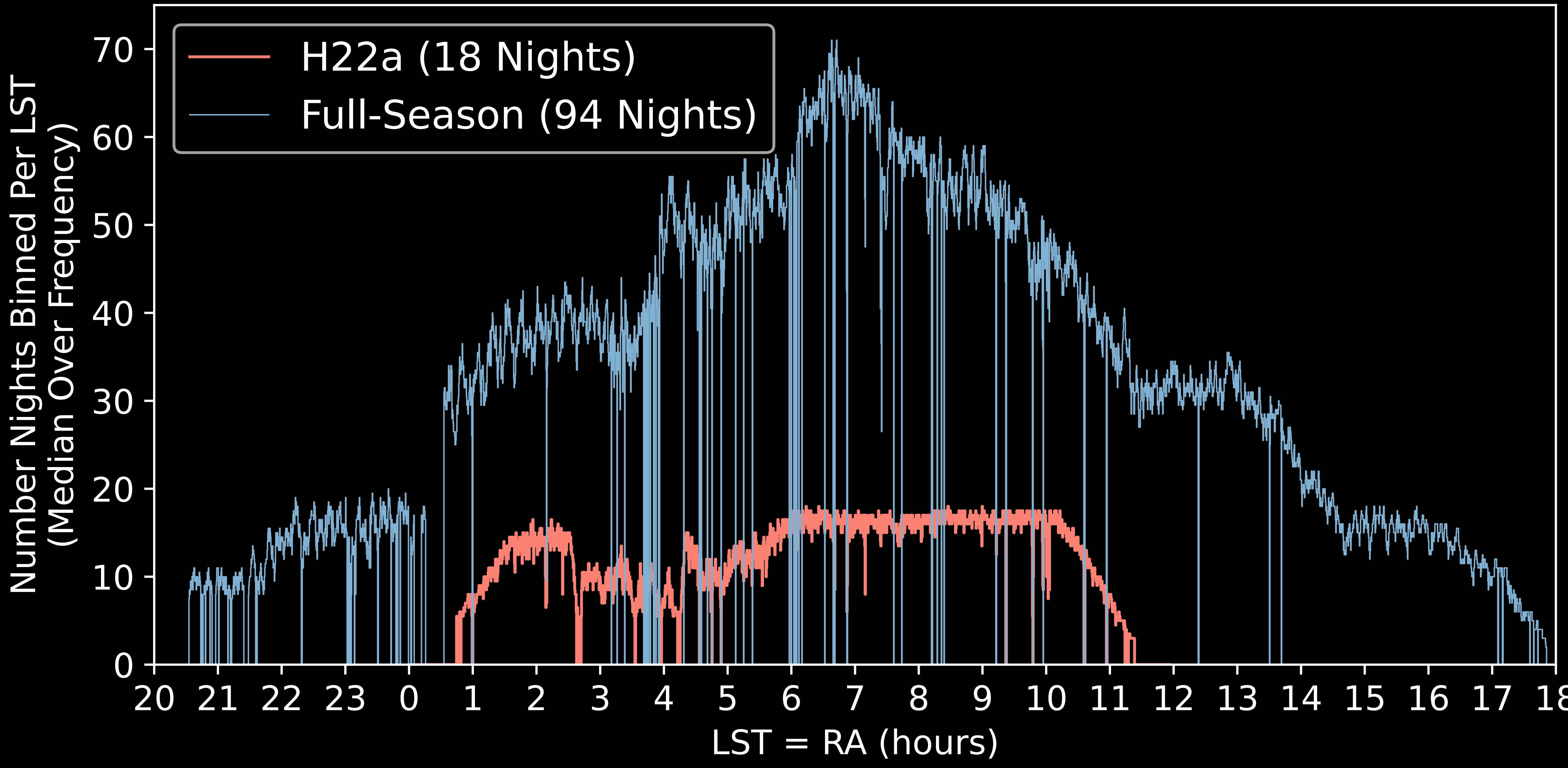
HERA Collaboration (2022a)

Which constrained the space of models, largely by ruling out an IGM unheated by X-rays at z = 8.



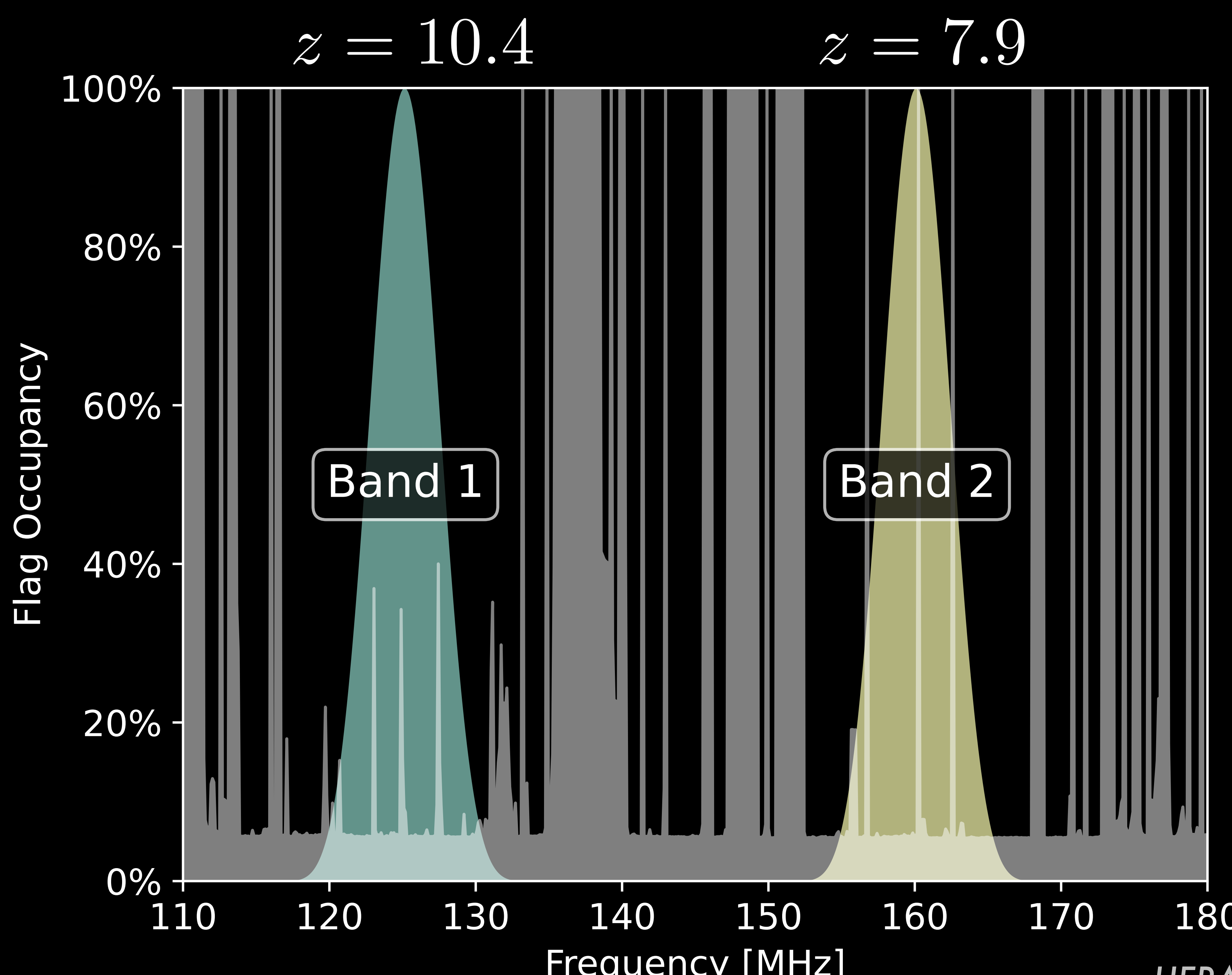
HERA Collaboration (2022b)

But all that was with only 18 nights of data. We had 94 good nights from HERA's first season.



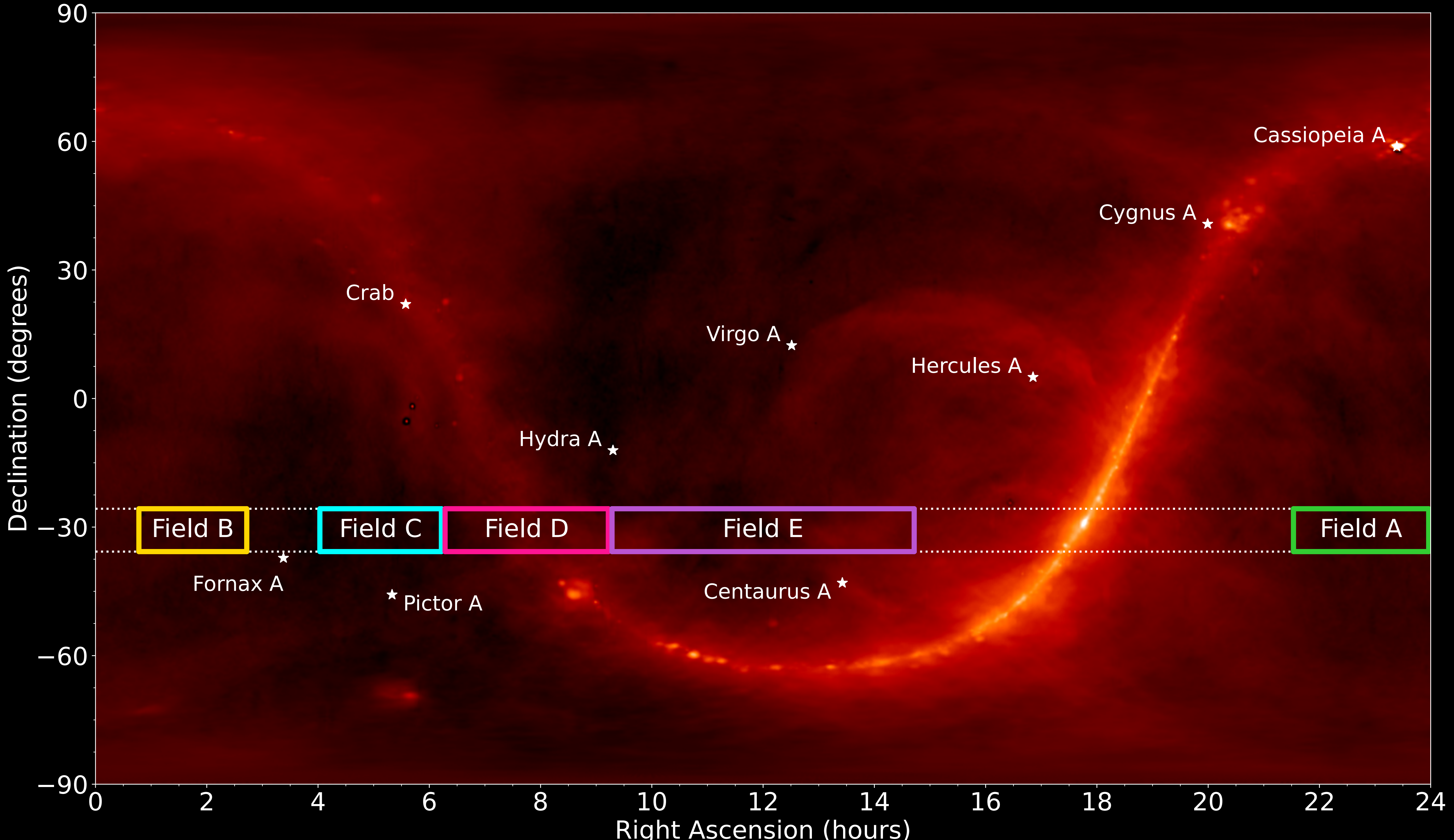
HERA Collaboration (2023)

Adapting the same analysis techniques to the larger data set, we picked two redshift bands with minimal RFI contamination.



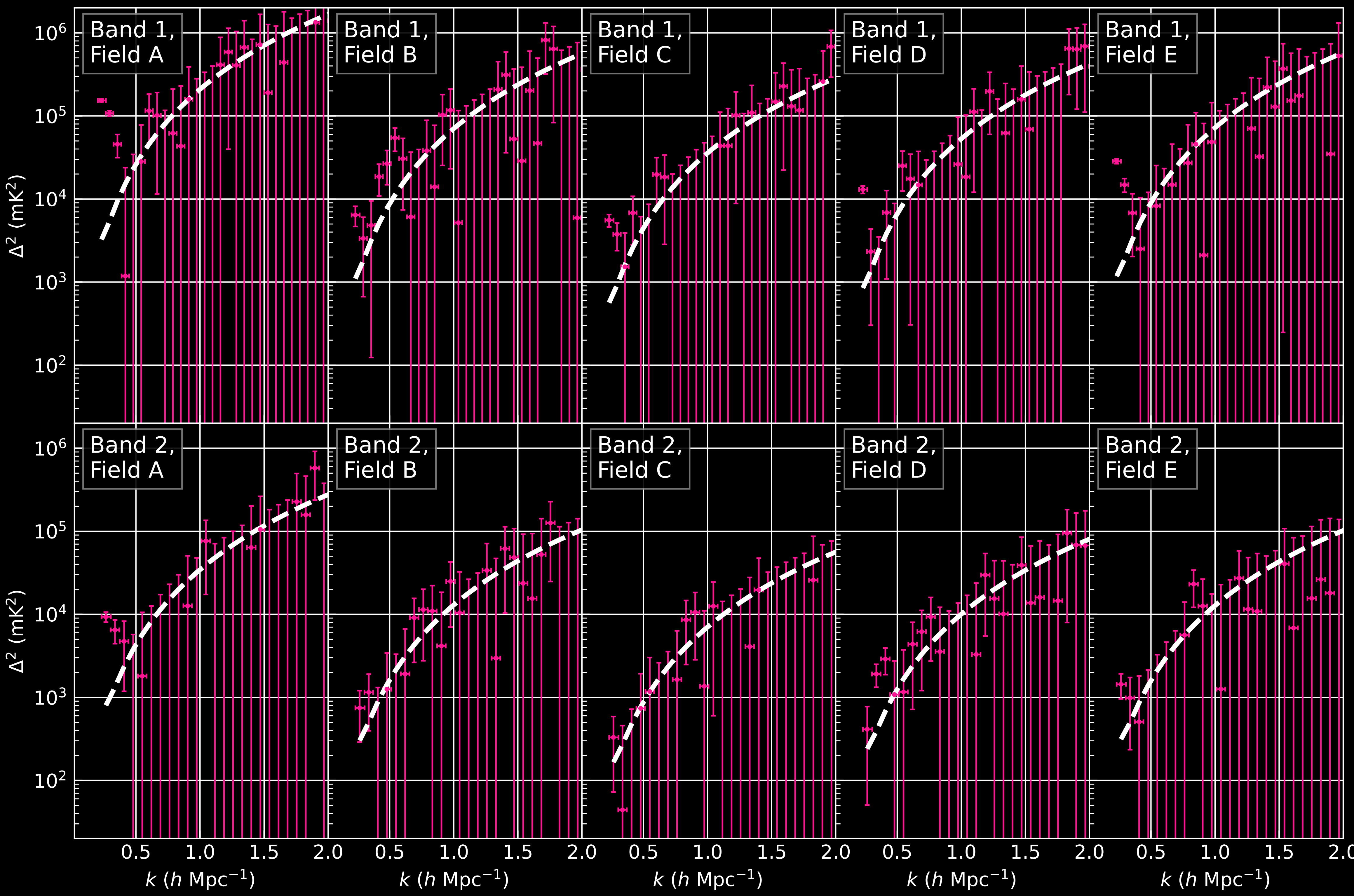
HERA Collaboration (2023)

We divided our LSTs observed into five fields.



HERA Collaboration (2023)

And thus set power spectrum upper limits across bands and fields.



HERA Collaboration (2023)

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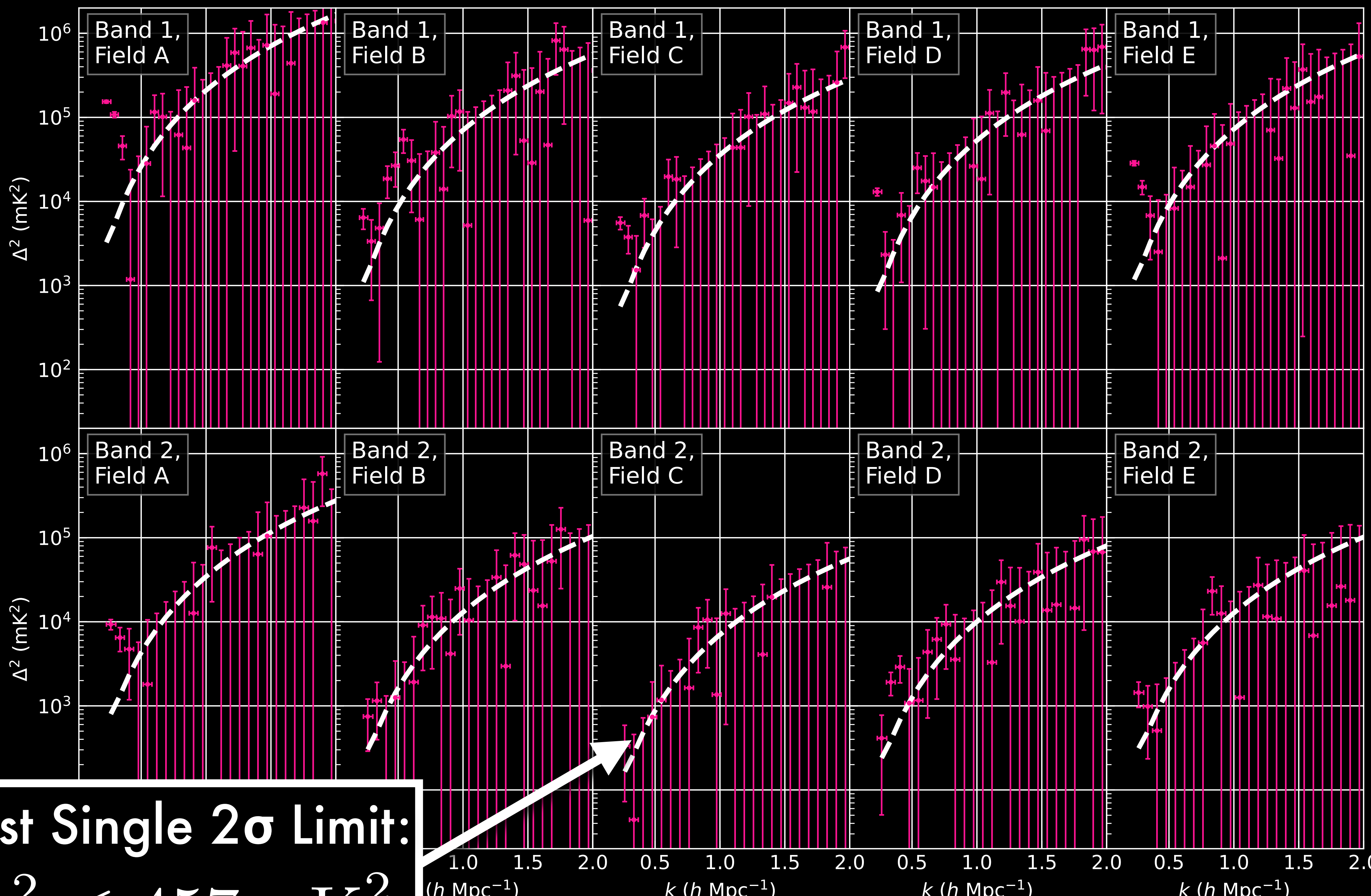
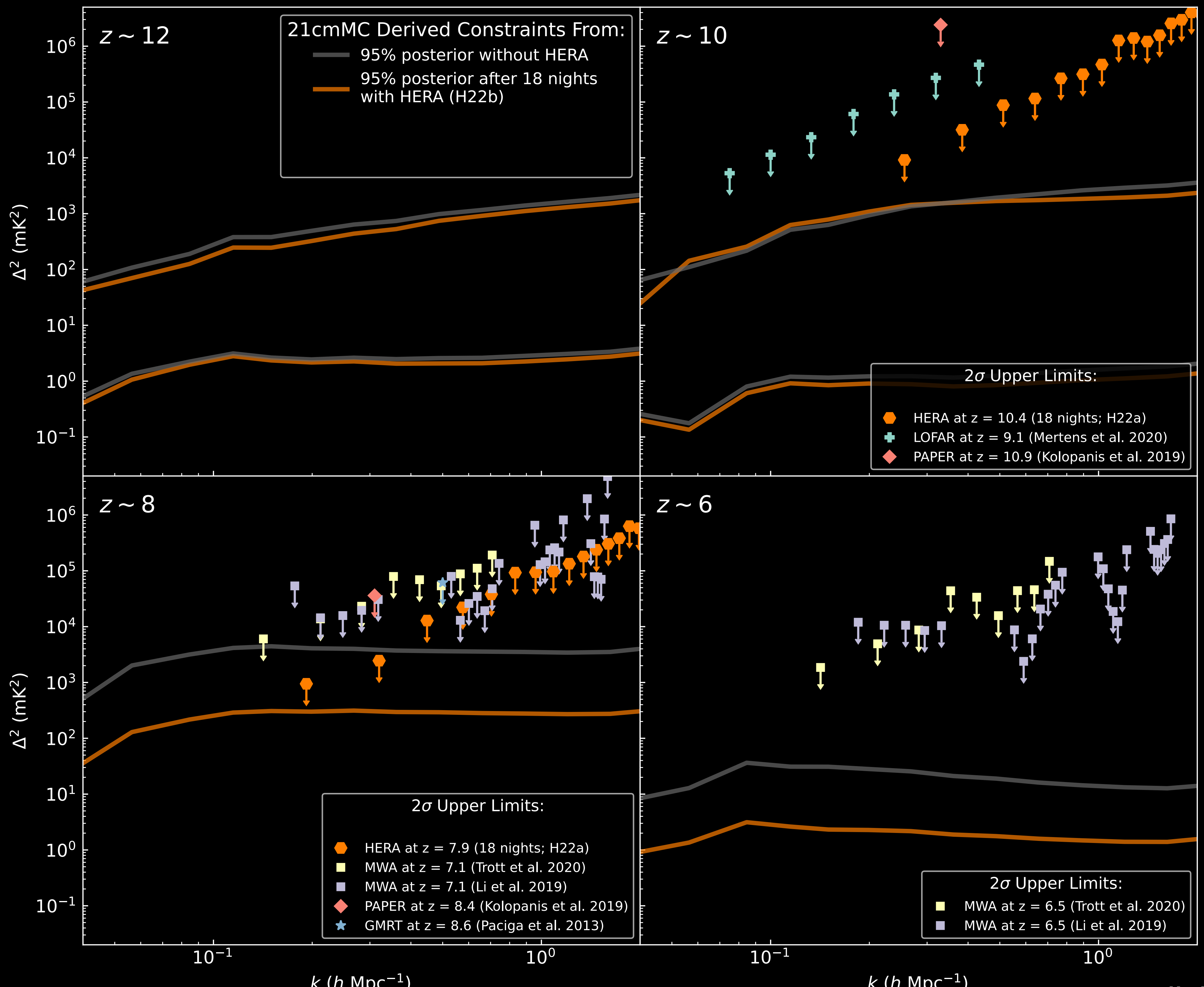


Best Single 2σ Limit:

$$\Delta^2 \leq 457\,\mathrm{mK}^2$$

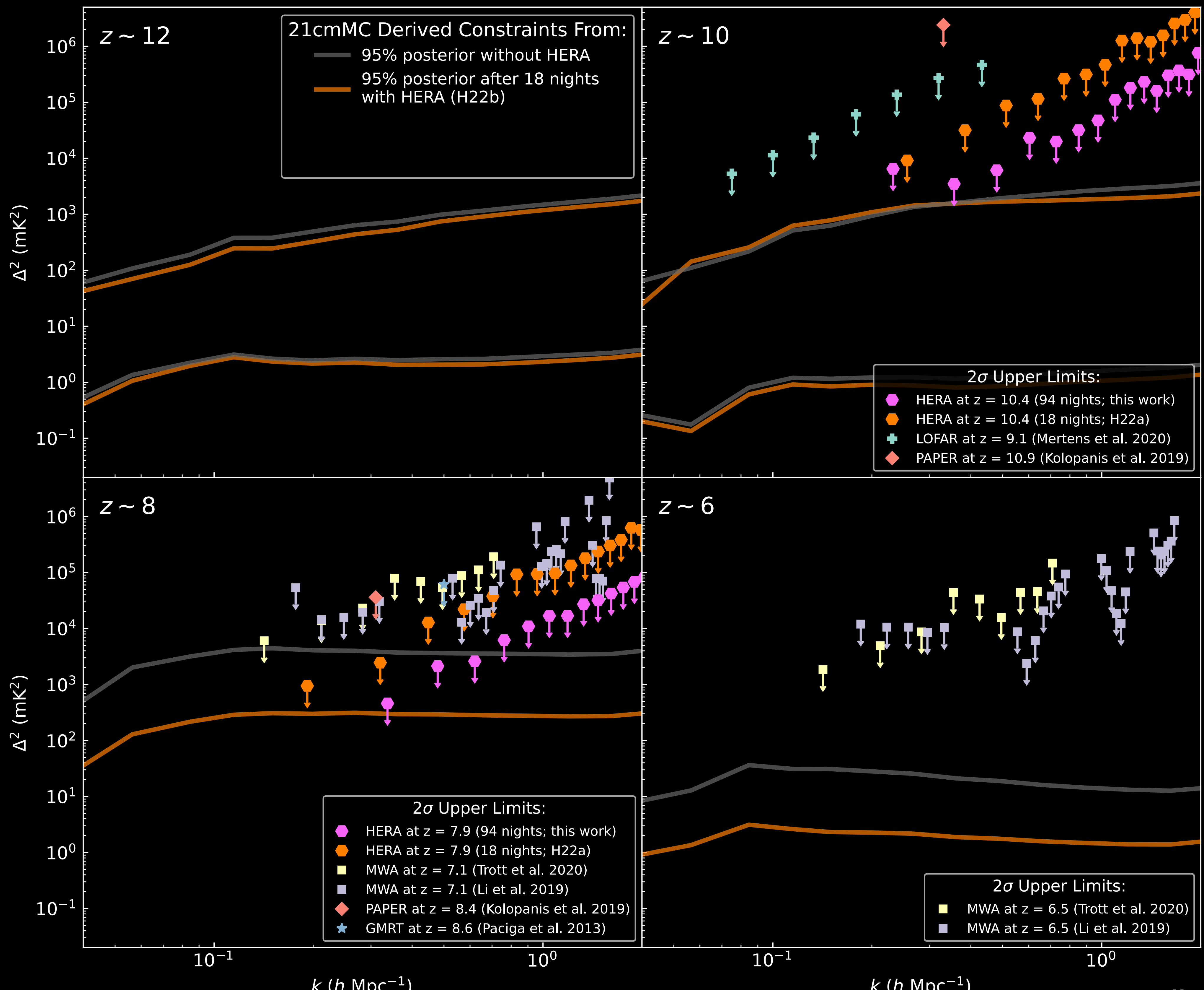
HERA Collaboration (2023)

So here's where we were again...



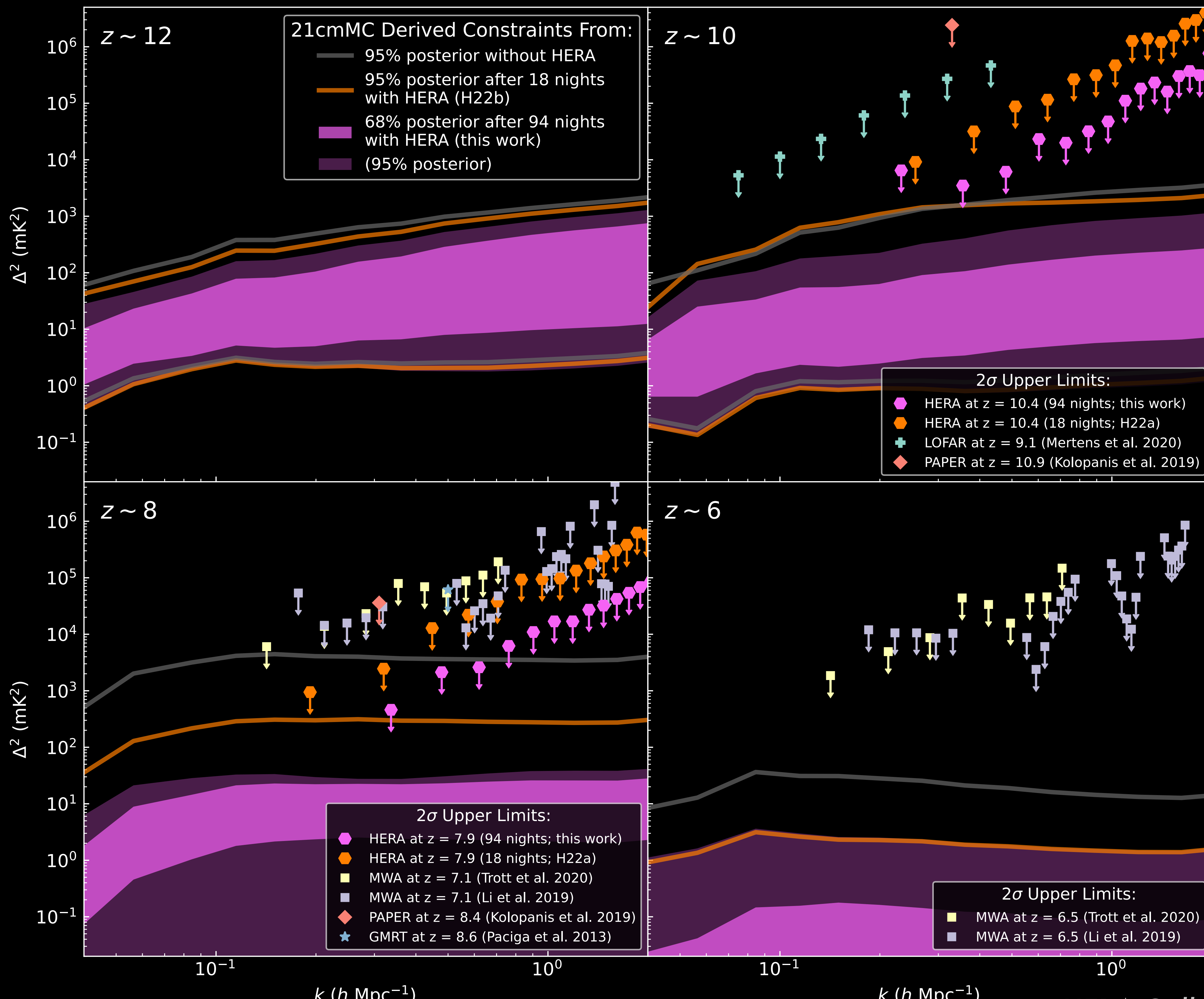
HERA Collaboration (2023)

With a full season, our limits come down by more than a factor of 2 at both redshifts.



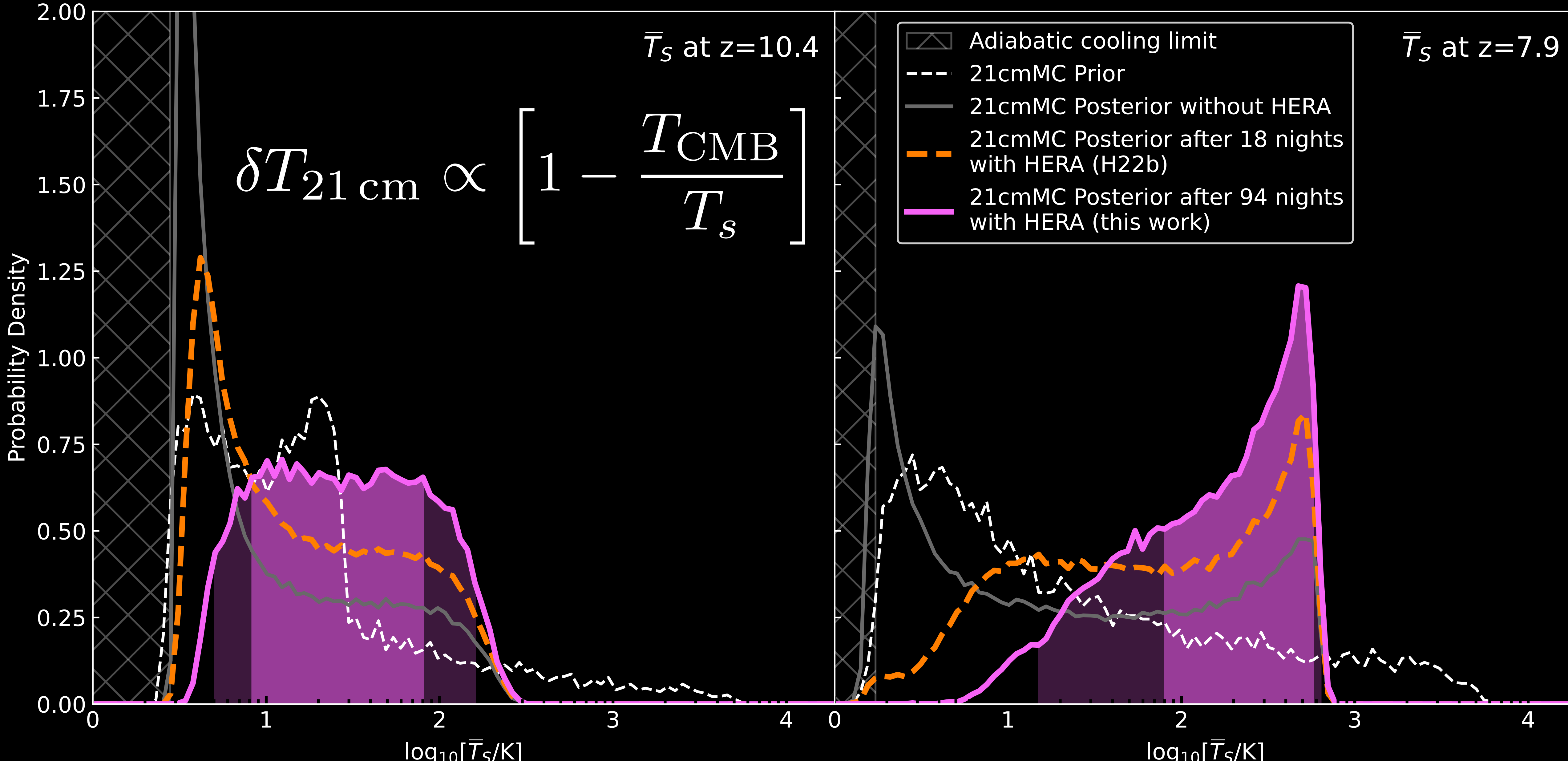
HERA Collaboration (2023)

Our posterior for the power spectrum with 21cmMC tightens substantially.



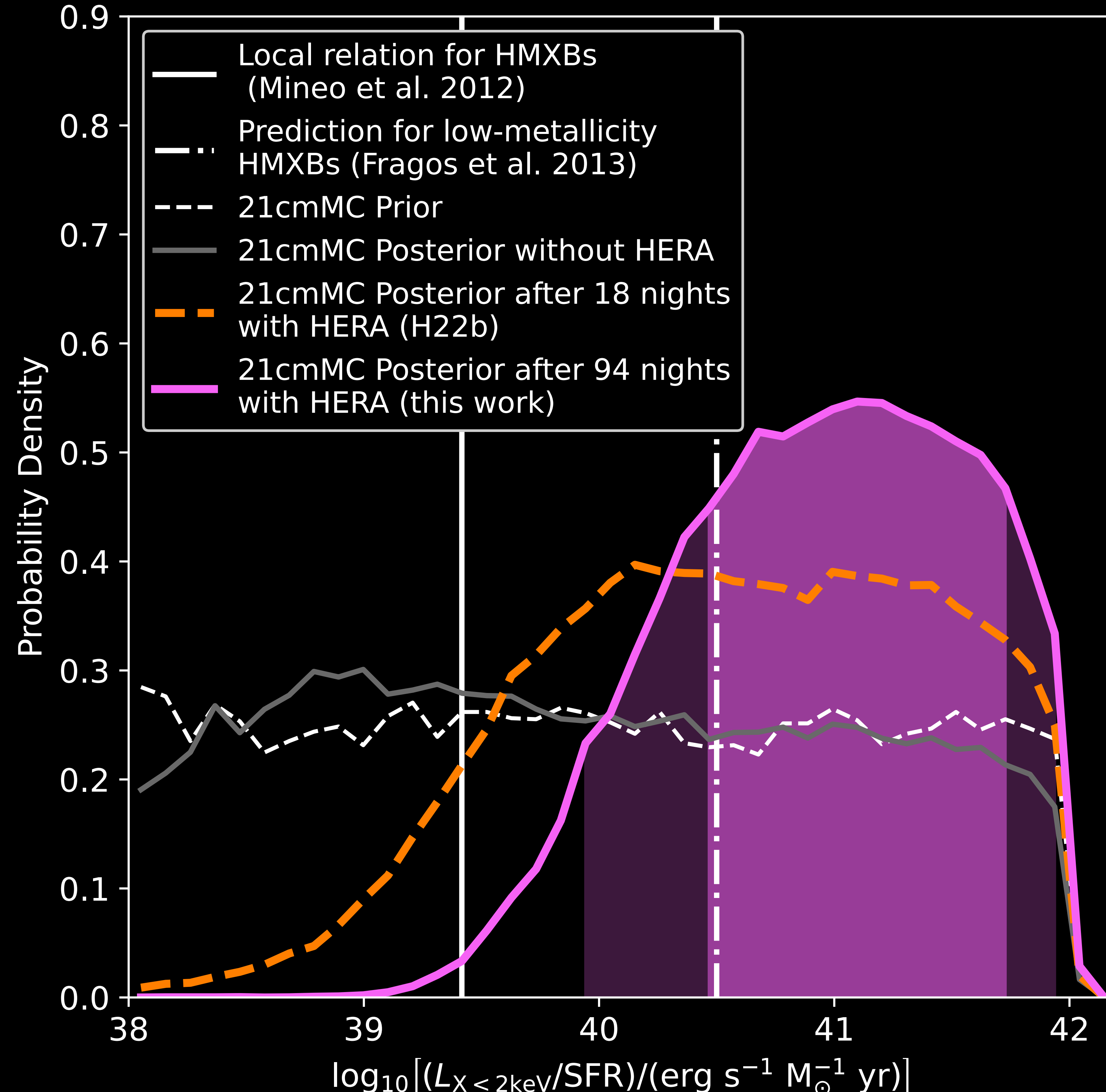
HERA Collaboration (2023)

The big shift comes from showing the IGM was heated by z = 10.4, since a cold IGM produces a bright 21 cm signal.



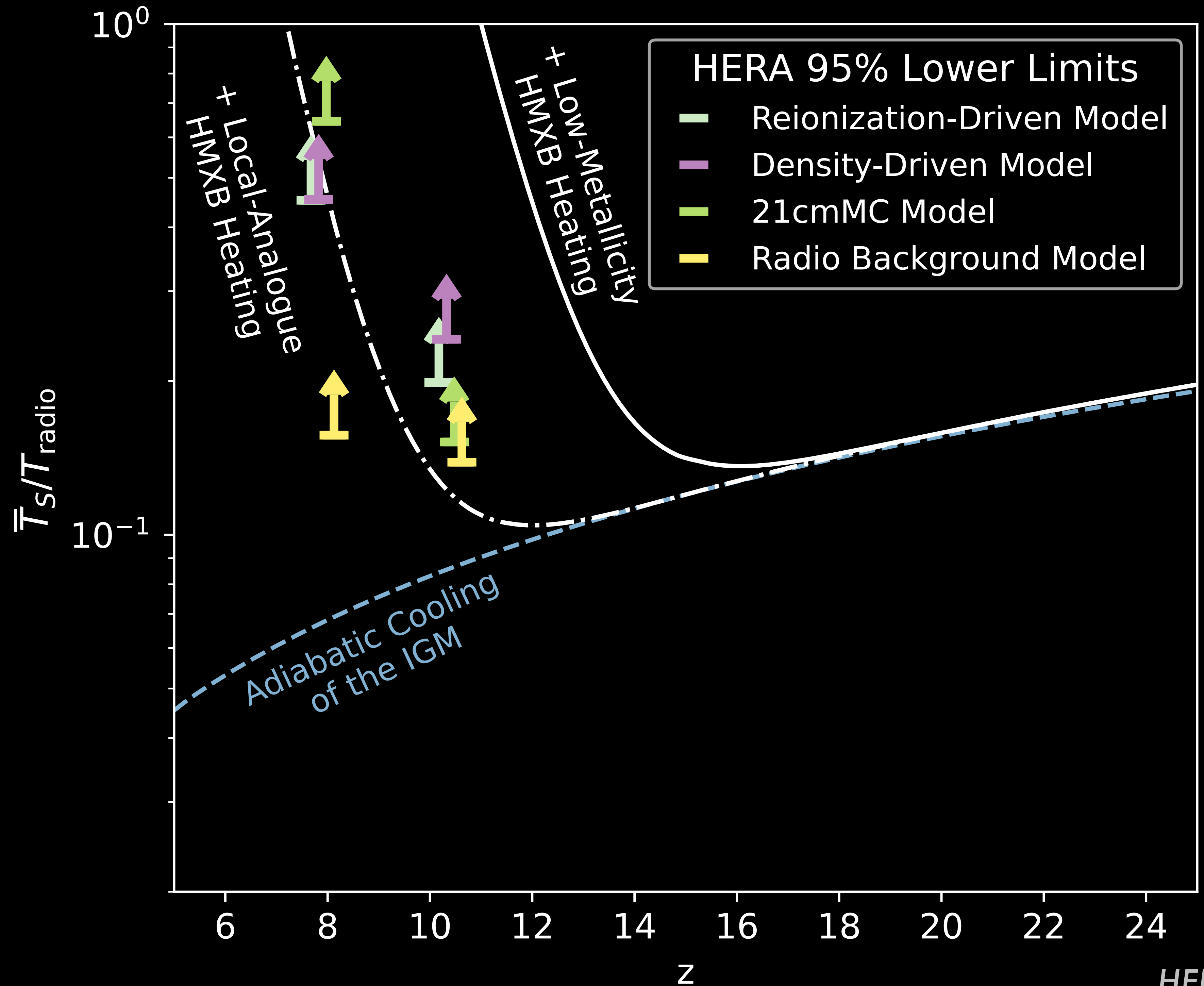
HERA Collaboration (2023)

If the IGM was heated by high-mass X-ray binaries — as is generally believed — this result rules out high-metallicity HMXBs (which are less X-ray-efficient per unit SFR) and thus requires heating driven by evolved low-metallicity stars.



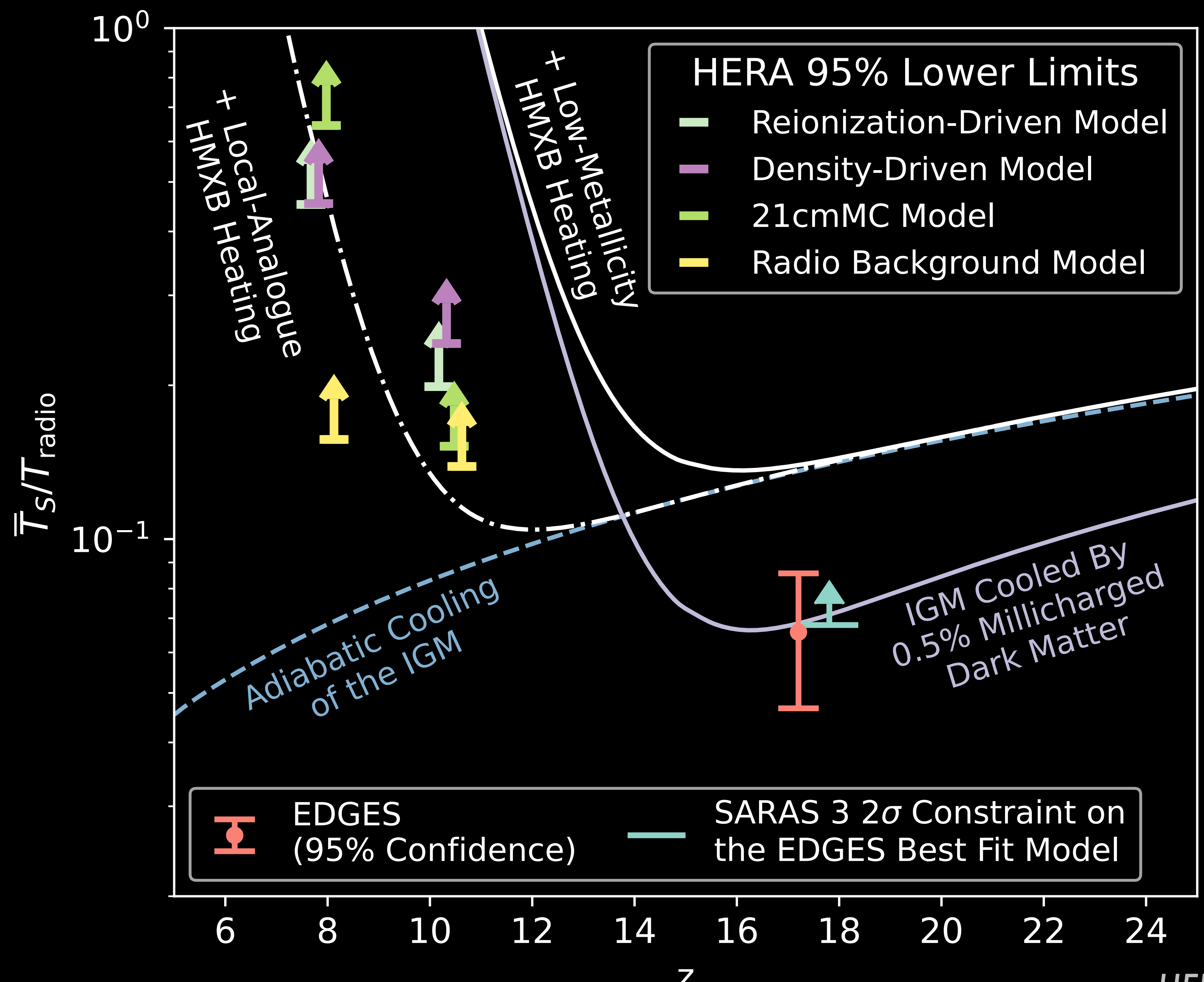
HERA Collaboration (2023)

Four independent theoretical models agree: the IGM was heated before z = 10.4.



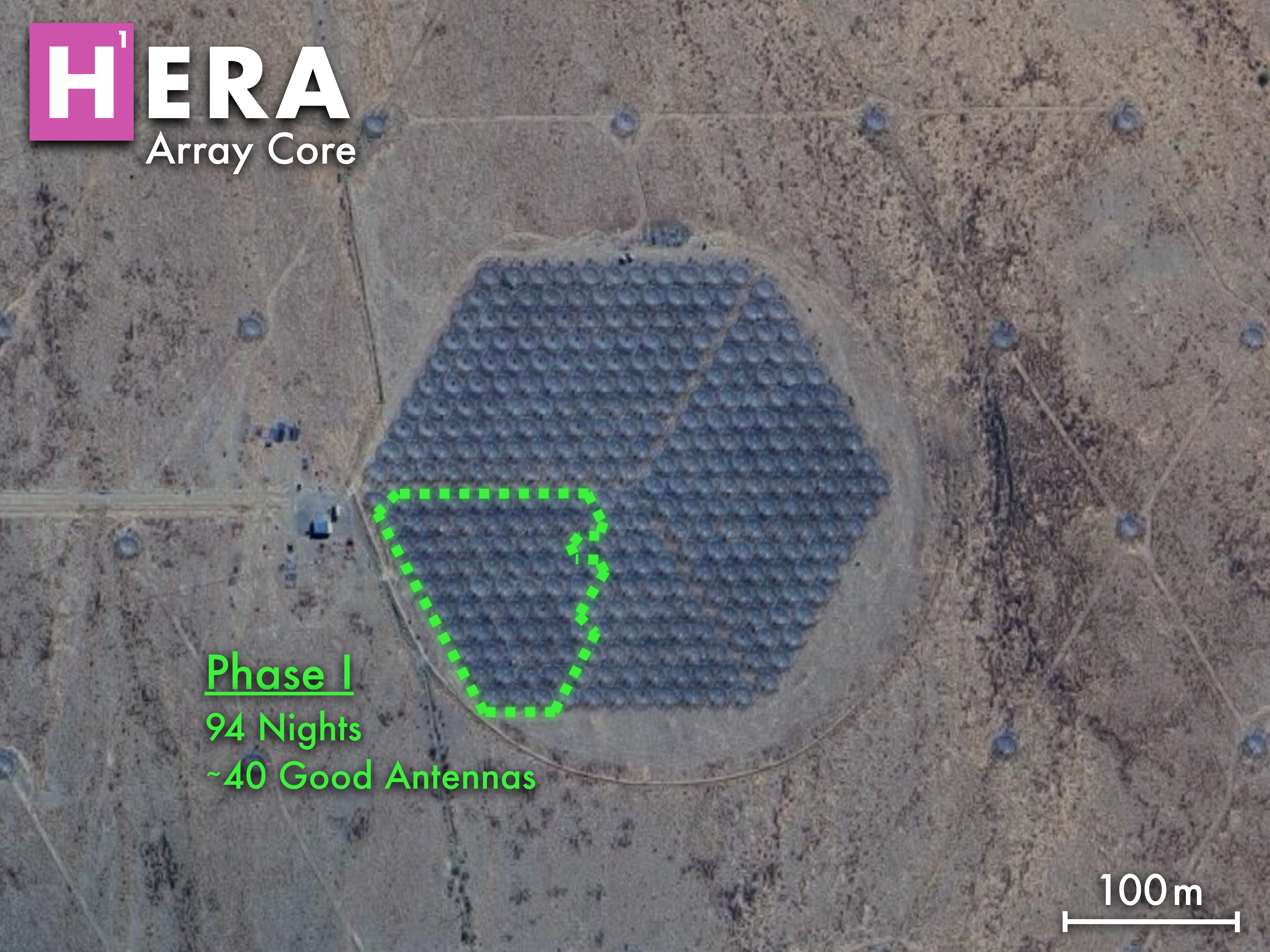
HERA Collaboration (2023)

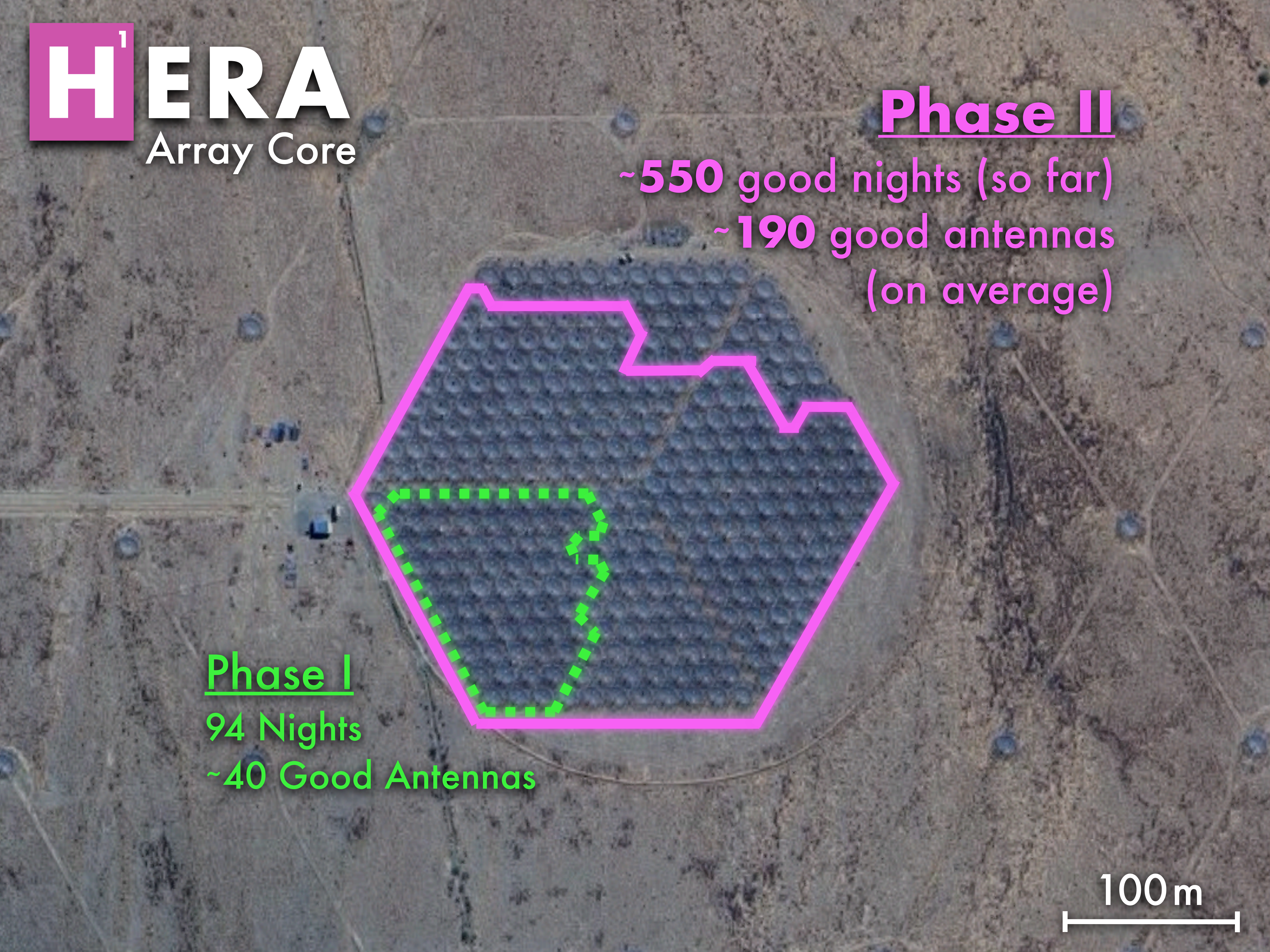
However, we are not yet able to say much about the tension between EDGES and SARAS or the exotic models invoked to explain EDGES.

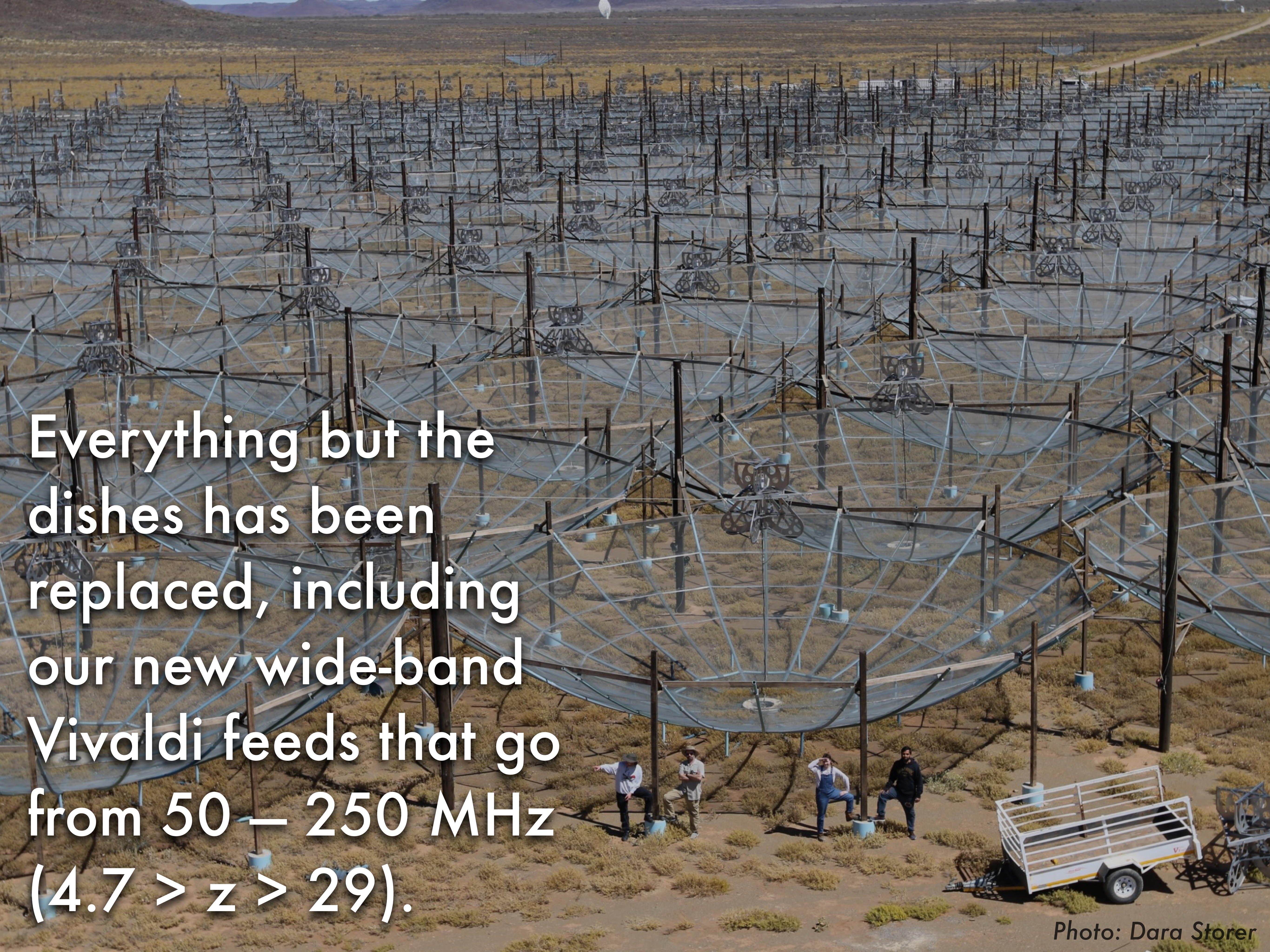


HERA Collaboration (2023)

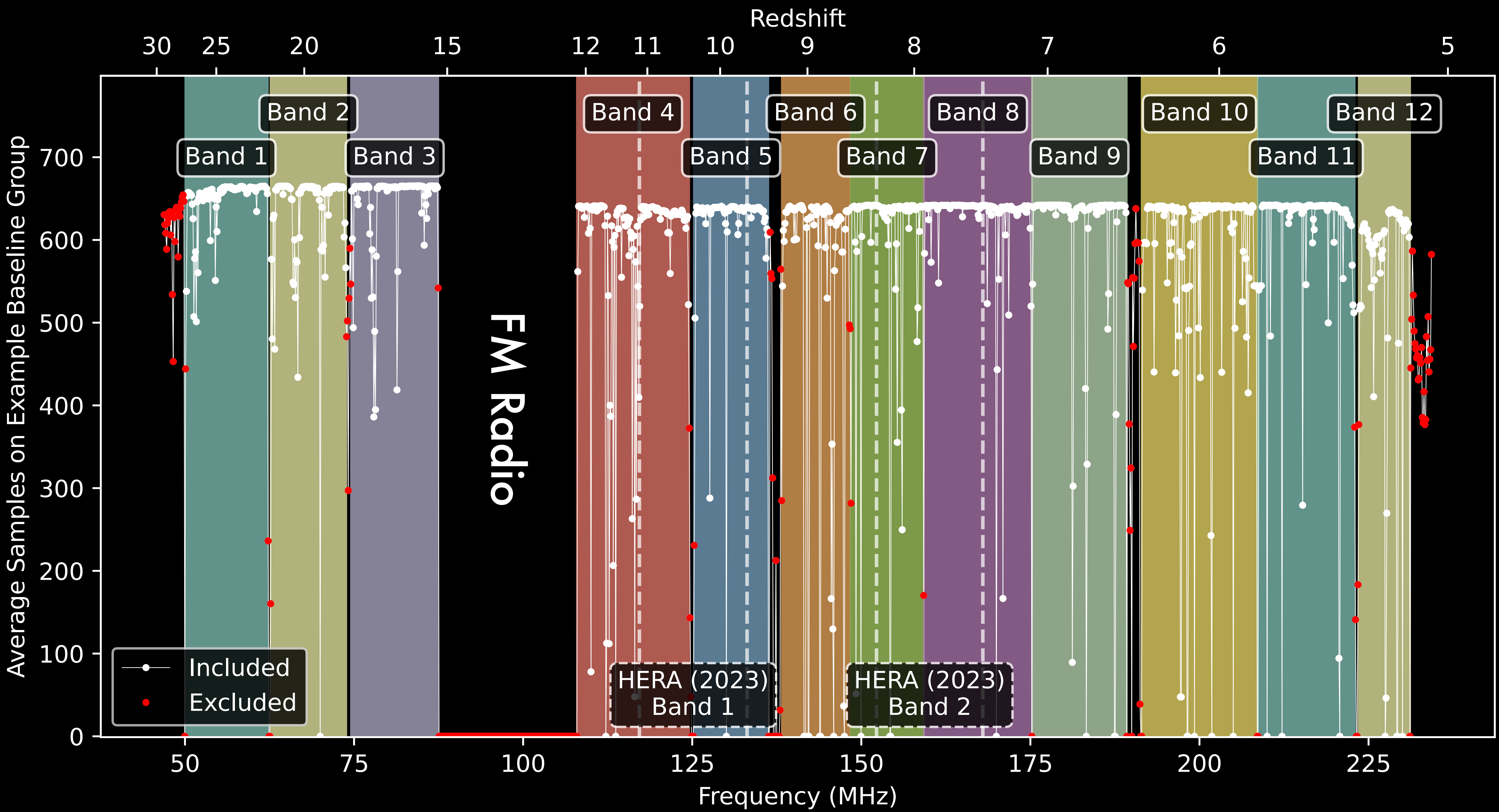
What’s next for HERA?


HERA
1
Array Core
Phase I
94 Nights
~40 Good Antennas
100 m


HERA
Array Core
Phase II
~550 good nights (so far)
~190 good antennas
(on average)
Phase I
94 Nights
~40 Good Antennas
100 m

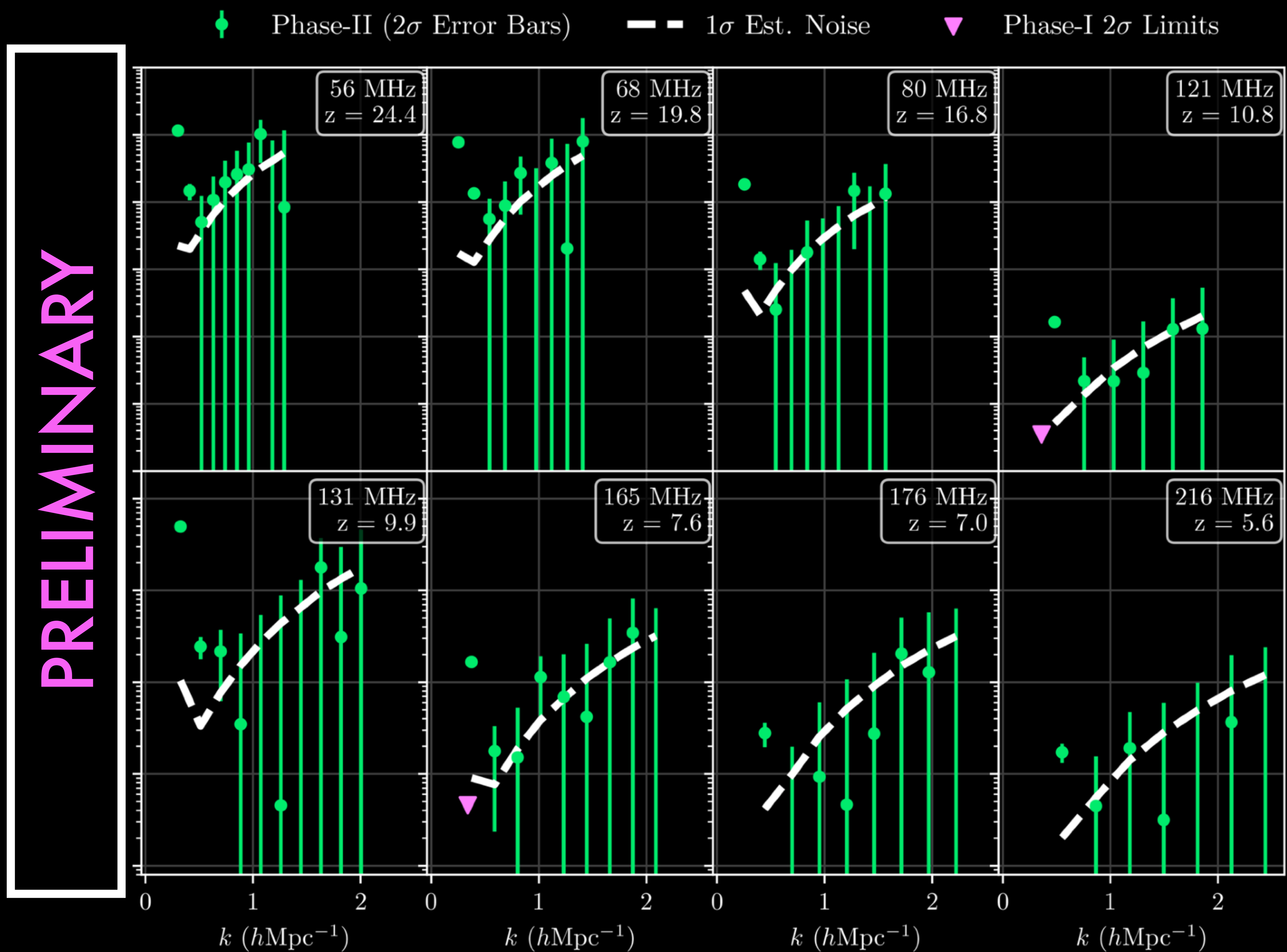

Everything but the dishes has been replaced, including our new wide-band Vivaldi feeds that go from 50 – 250 MHz (4.7 > z > 29).
Photo: Dara Storer

With this data set, we're looking at a much wider range of redshifts, including in the pre-reionization epoch.



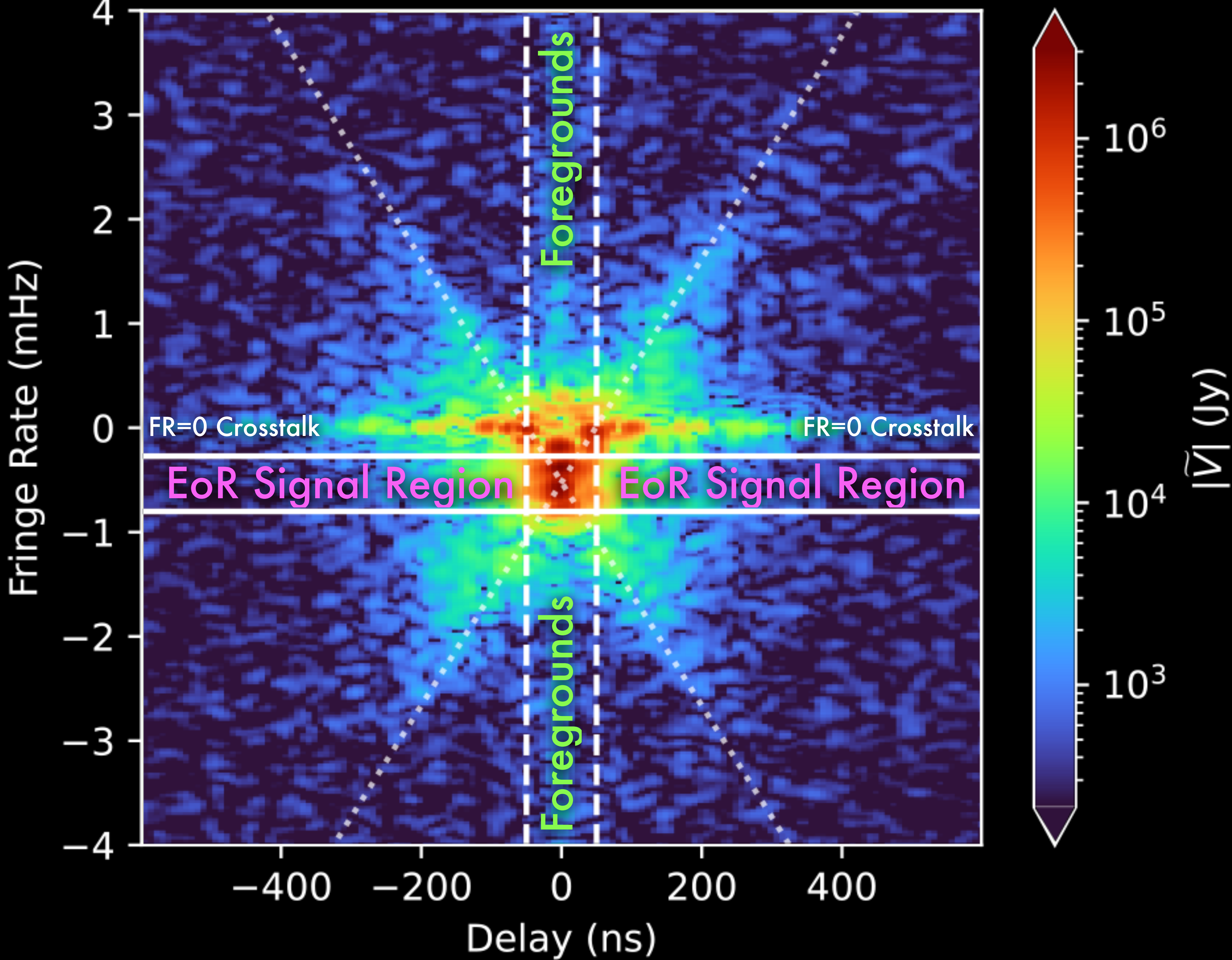
HERA Collaboration (in prep.)

We're now writing up limits from the first 14 nights of Phase II data, testing our brand new pipeline.

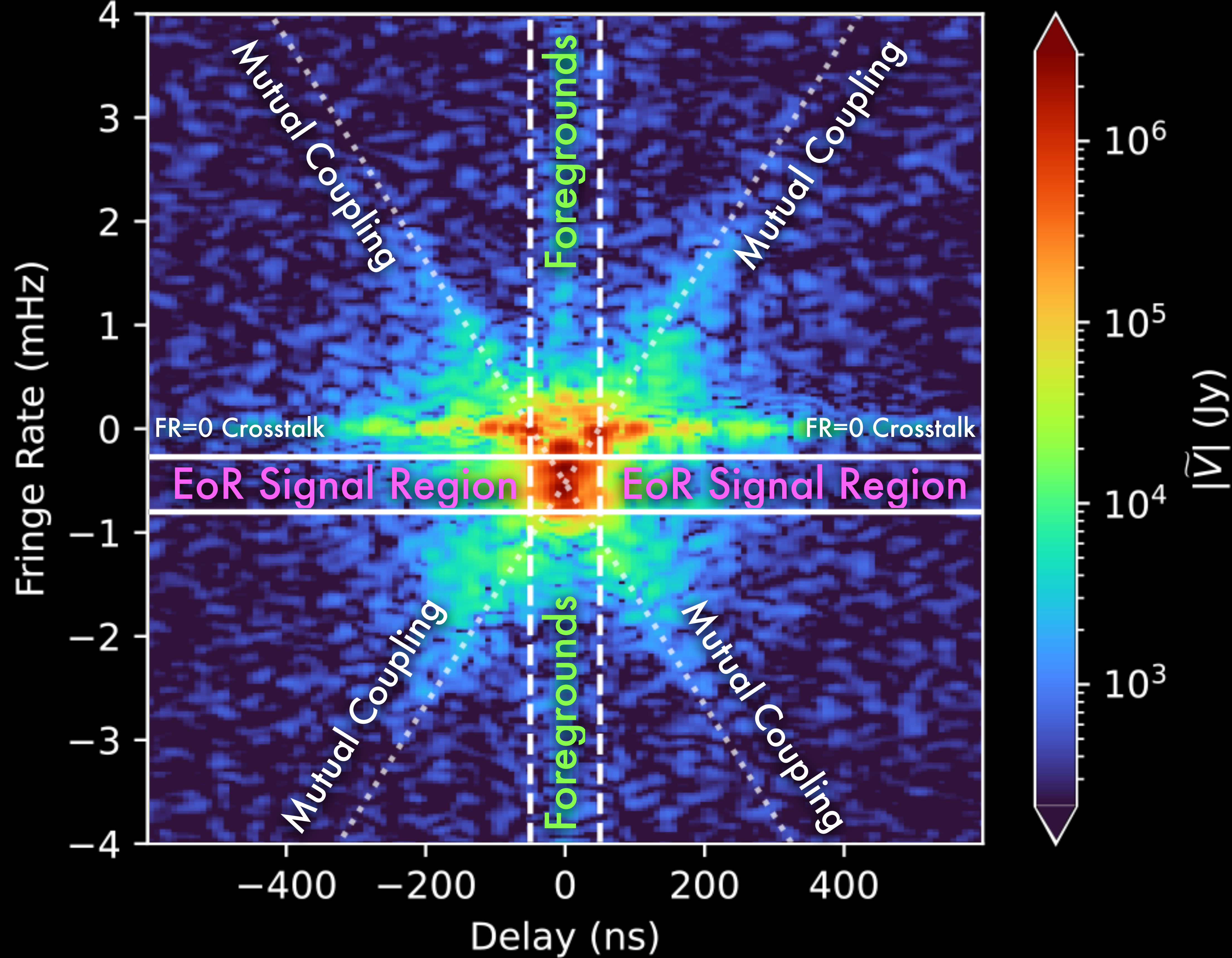


HERA Collaboration (in prep.)

But the new array presents new systematics...

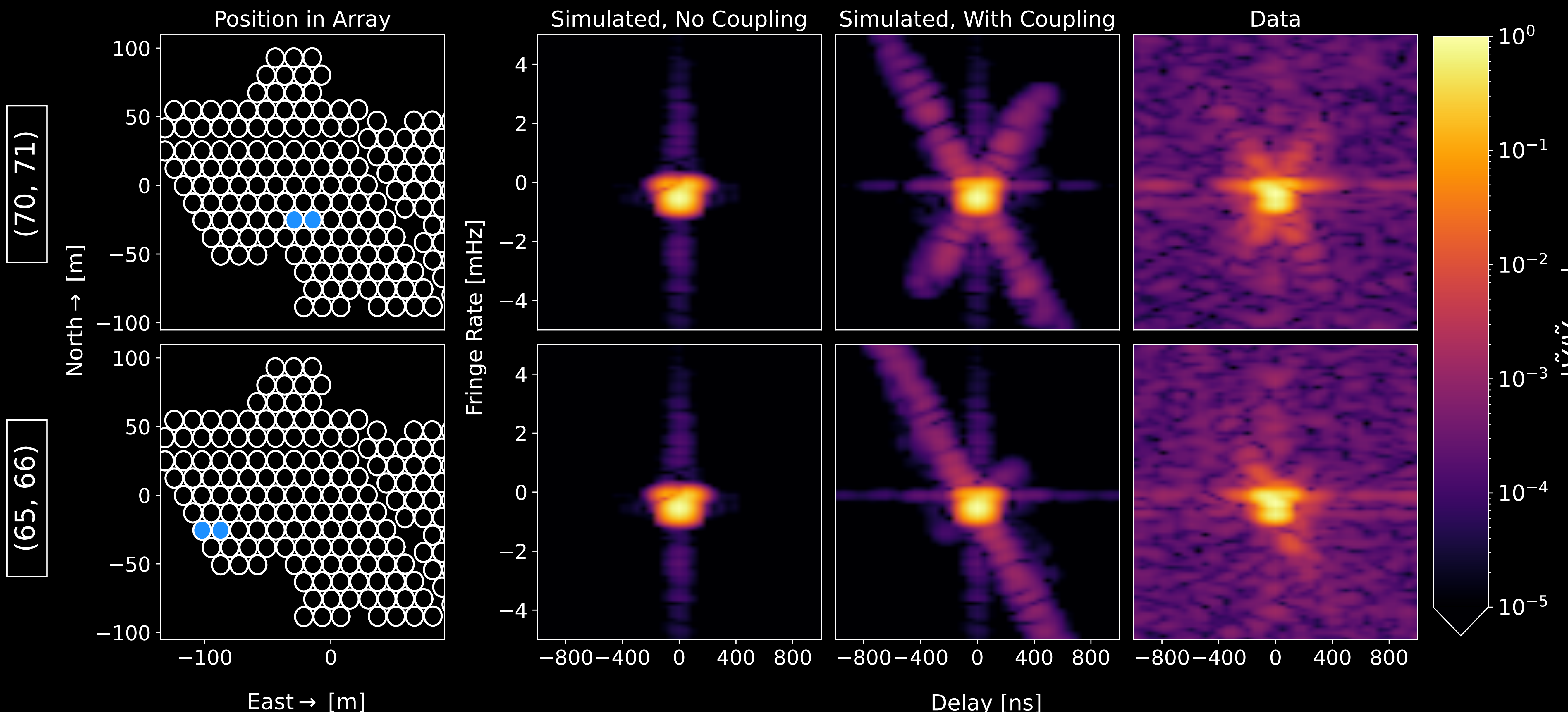


But the new array presents new systematics...



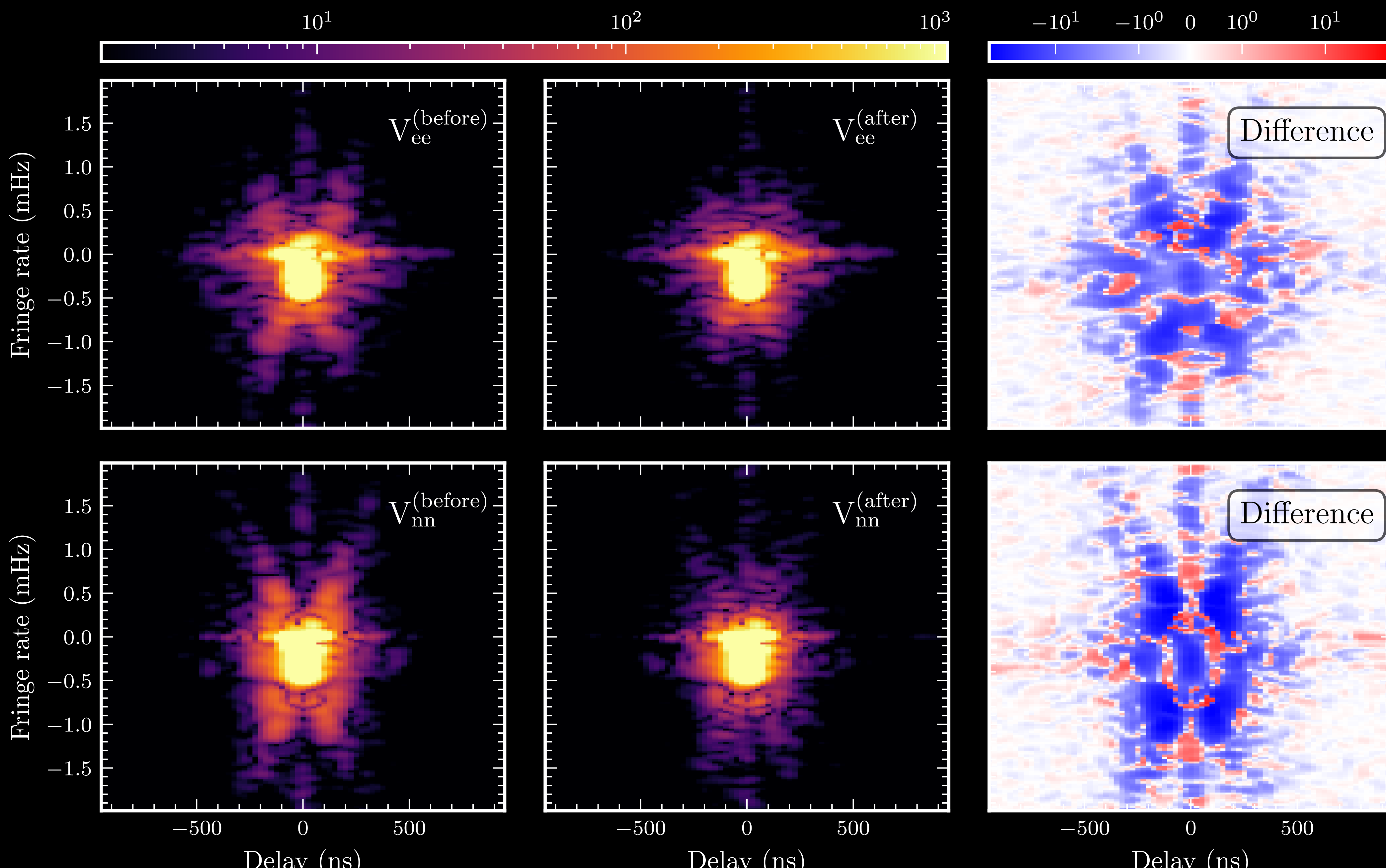

HERA's dishes aren't the most electromagnetically isolated elements....
Photo: Dara Storer

We now have a good qualitative picture for how leakage of visibilities into one another via mutual coupling causes this "X."



Rath, Pascua et al. (2025)

We're making good progress modeling and suppressing the contribution from mutual coupling on our first 14 nights of data.

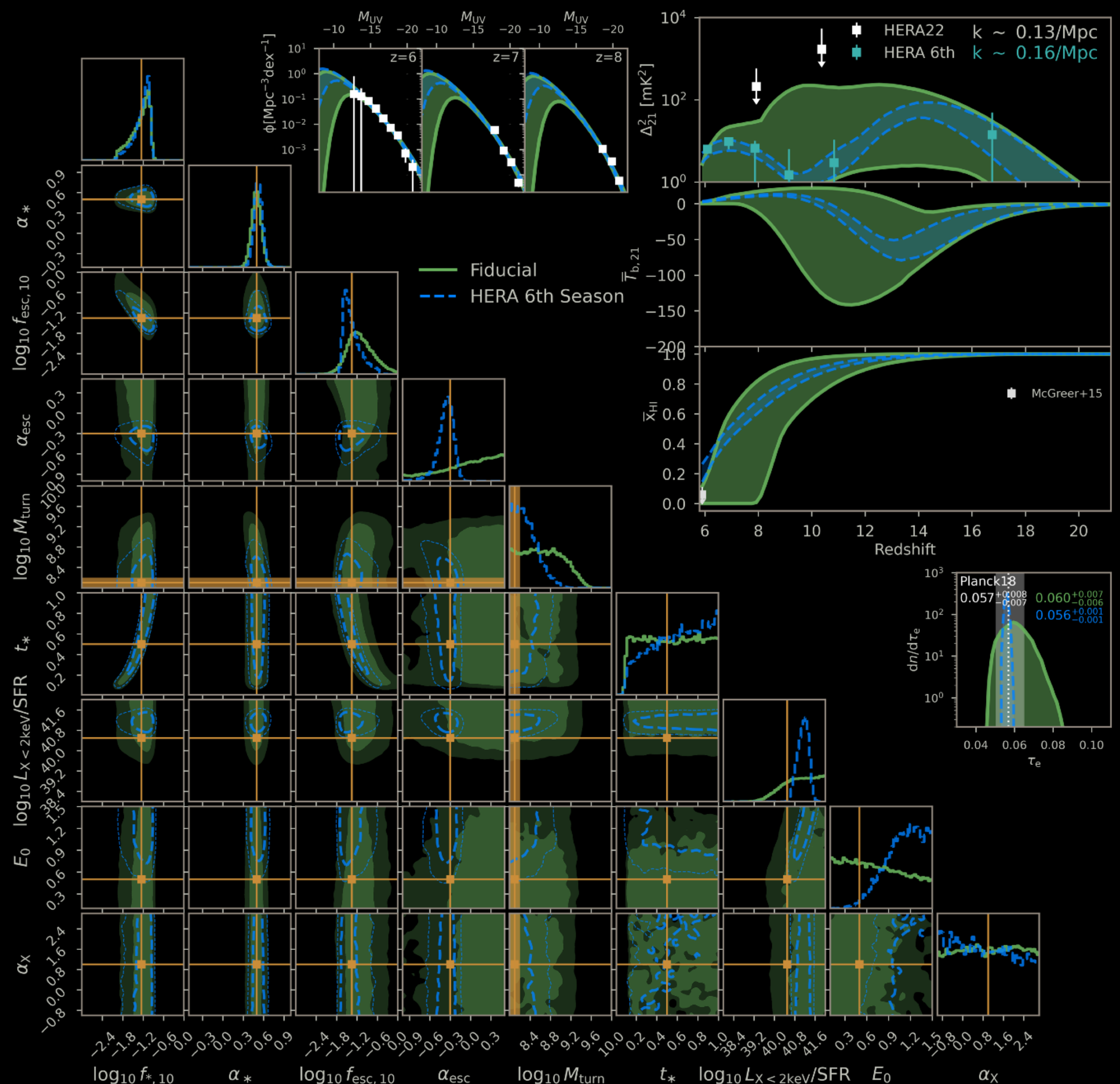


PRELIMINARY

Cox et al. (in prep.)

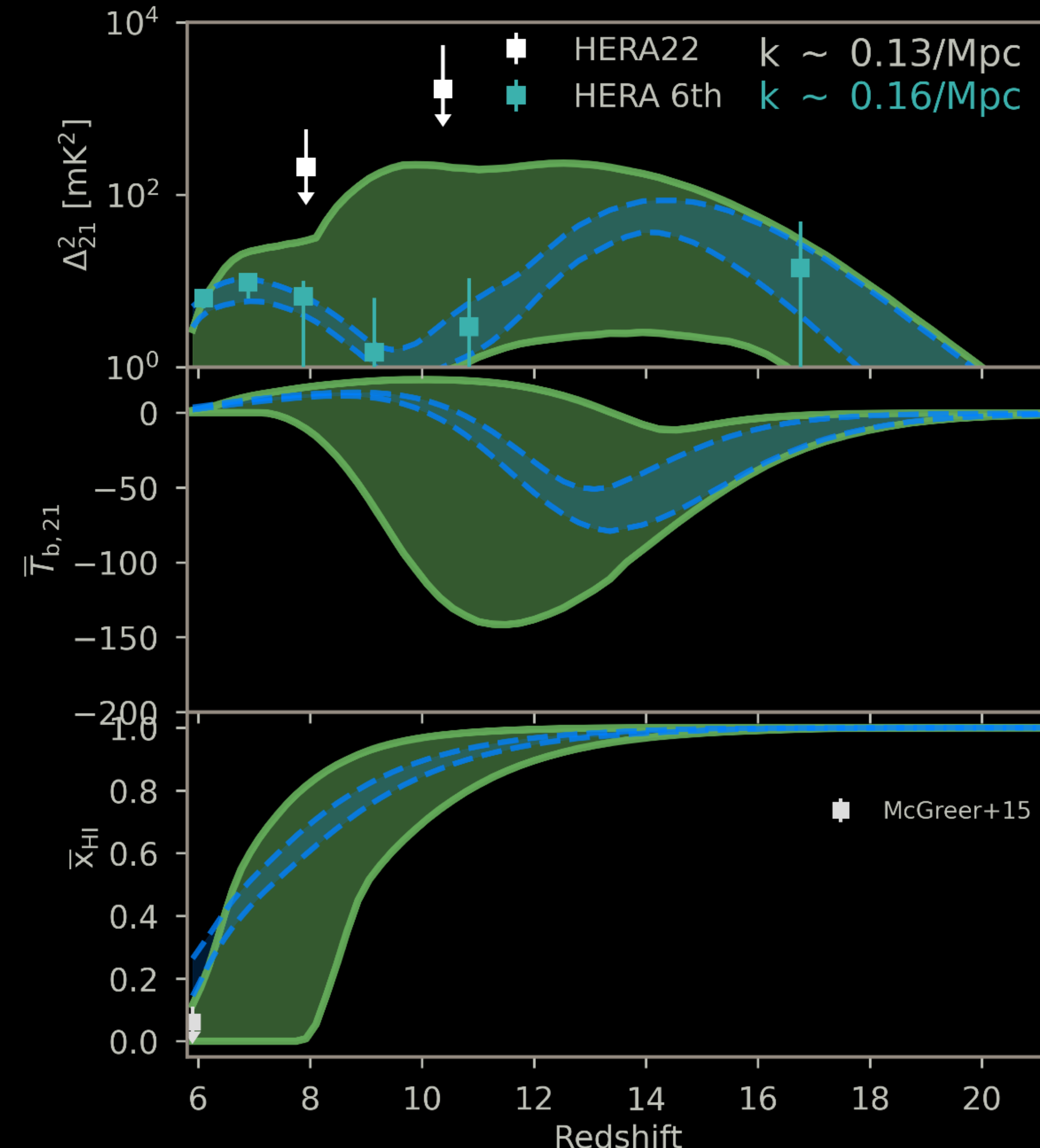
What do we expect to learn from Phase II?

The HERA theory team has already spun up on their new 21CMFAST emulator to forecast HERA's sensitivity to a fiducial model for IGM heating and reionization.



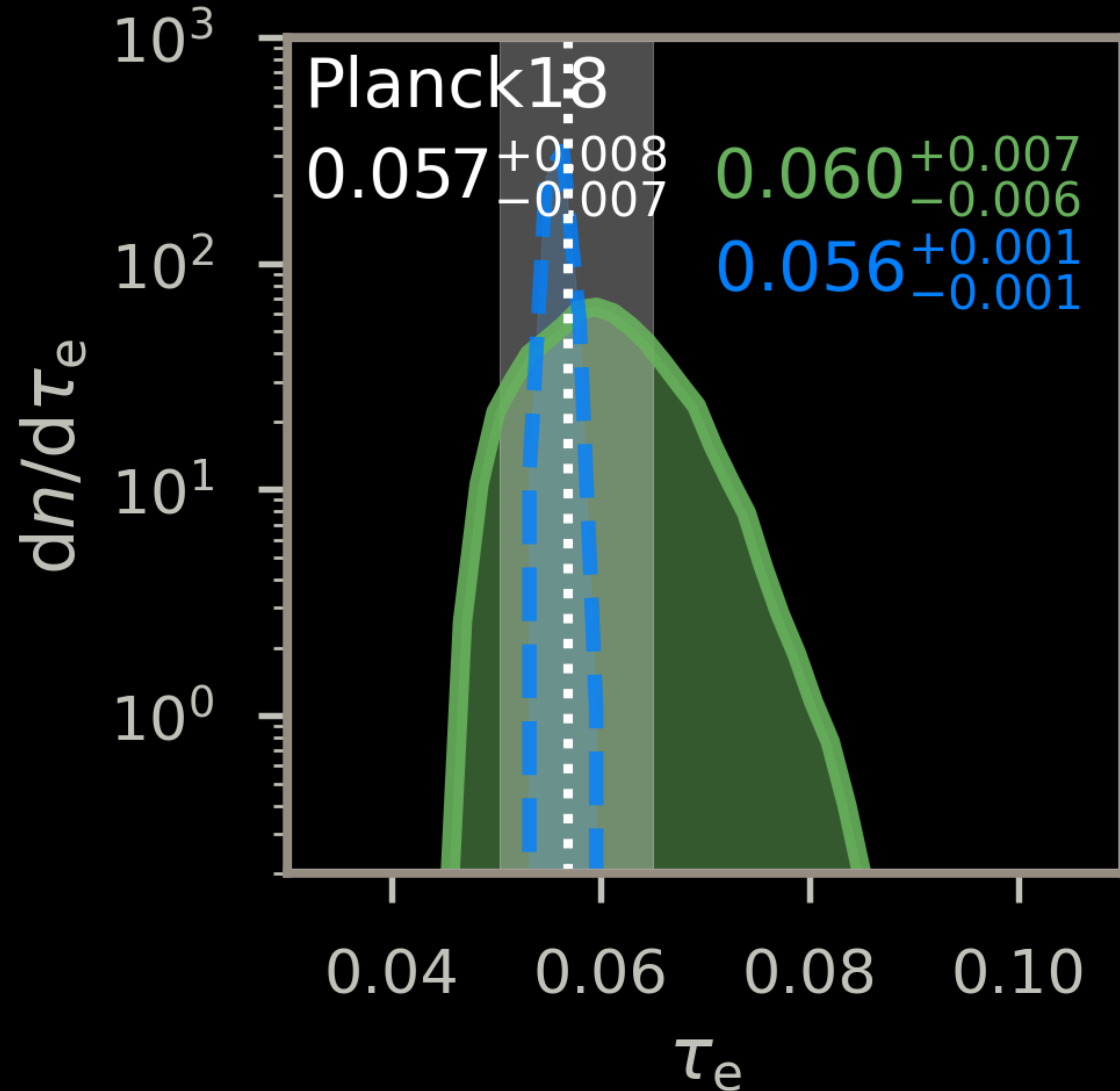
Breitman et al. (2023)

If we can get as close to the wedge as we did in the published limits, the data in hand is sensitive enough to make a ~5σ detection of a fiducial EoR power spectrum.



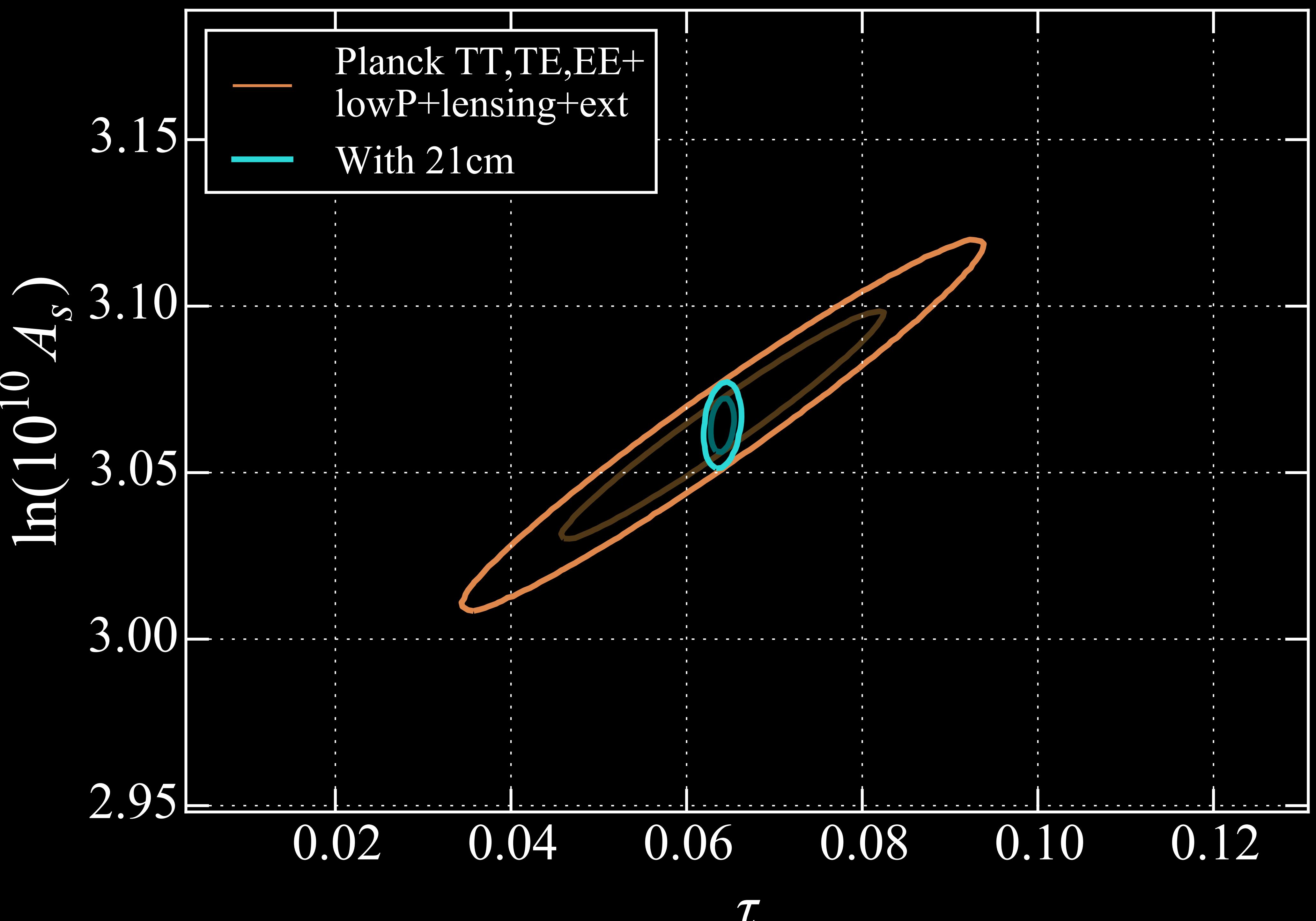
Breitman et al. (2023)

And we'll make our first major contribution to cosmology: a ~6 times tighter constraint on τ, improving CMB constraints of more "fundamental" cosmological parameters.



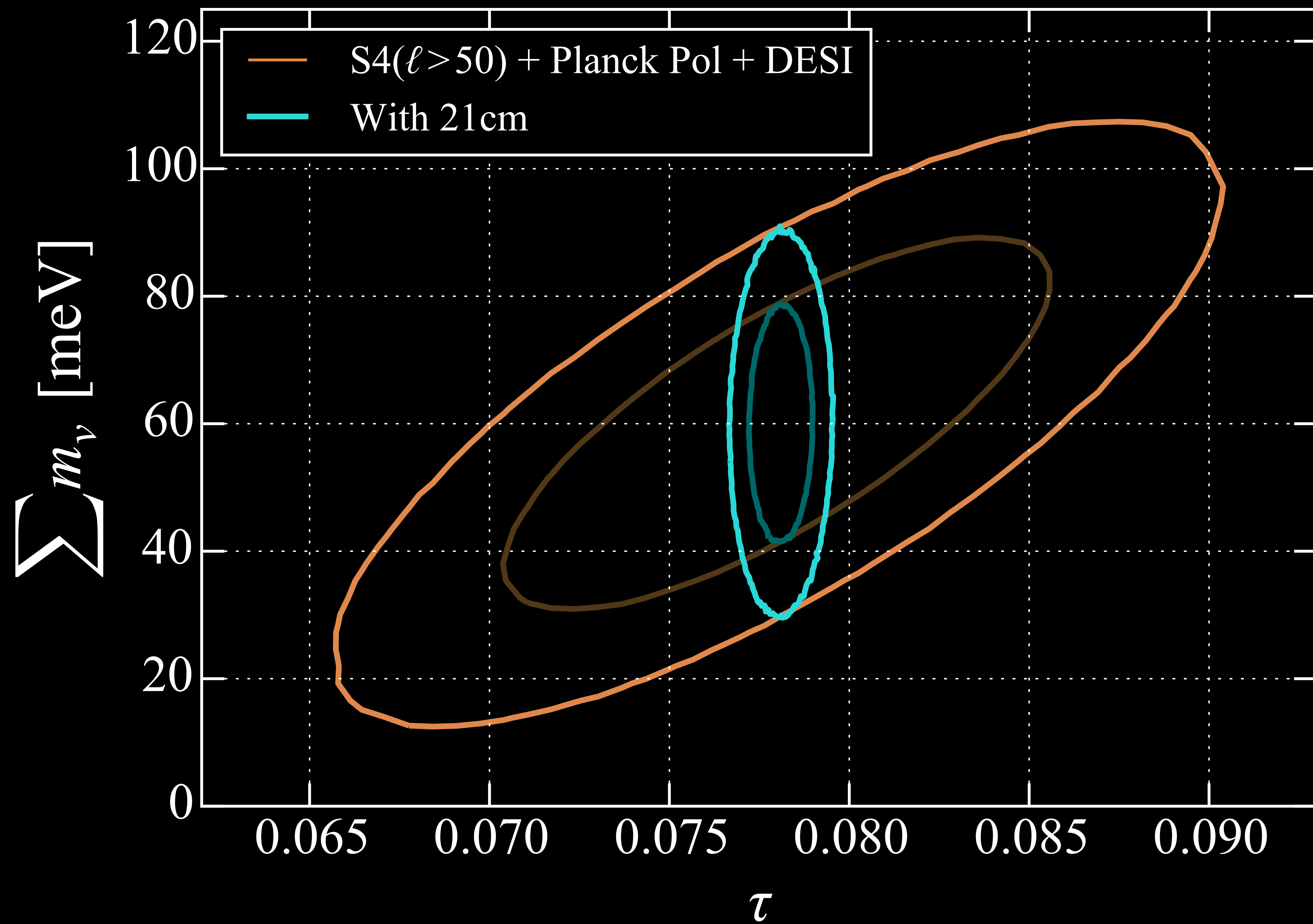
Breitman et al. (2023)

With our full data set, we'll eliminate τ as a CMB nuisance parameter, improving A_s errors by a factor of 4.



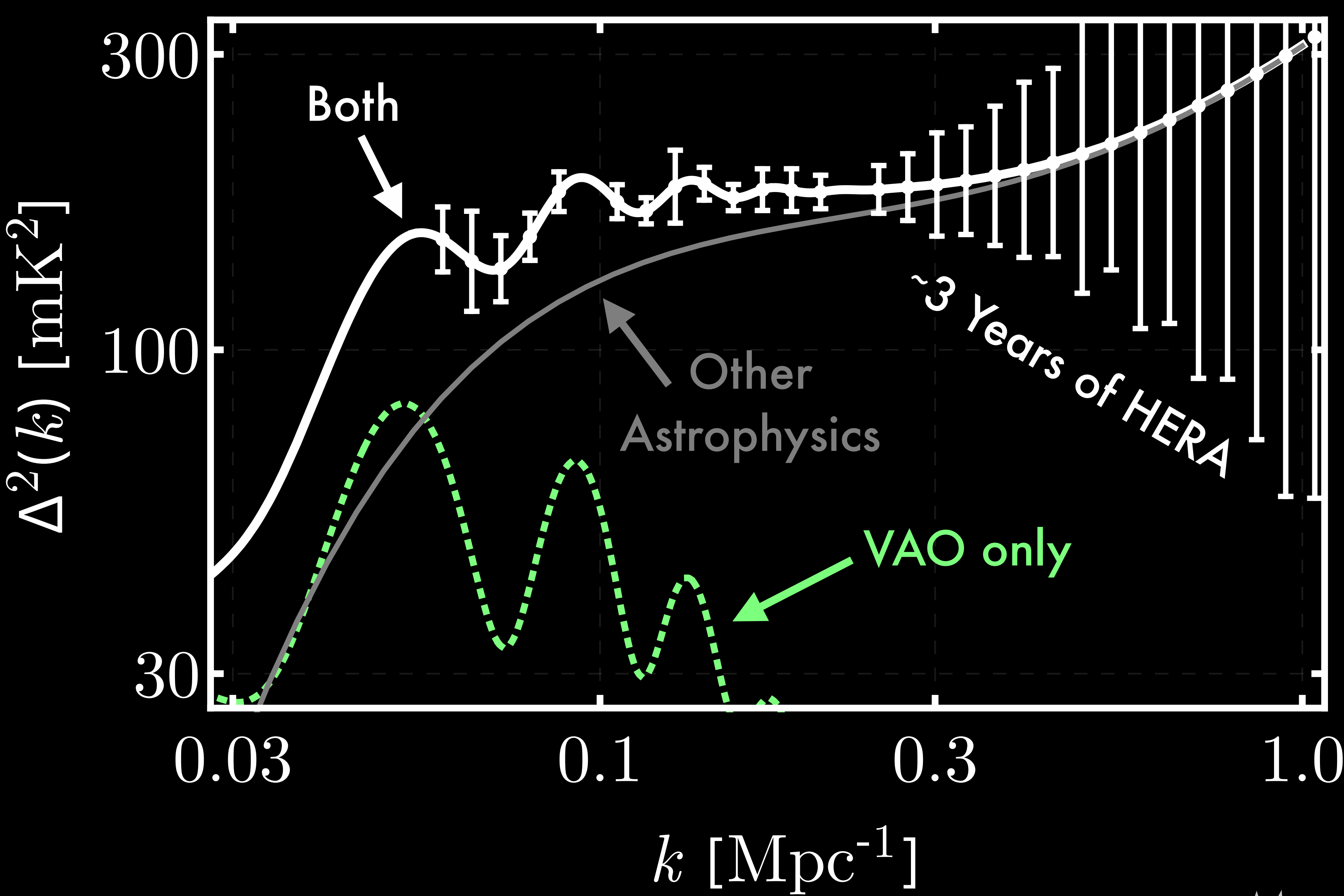
Liu et al. (2016)

Combined with CMB-S4, we can likely detect a non-zero Σmν, distinguishing between neutrino hierarchies.



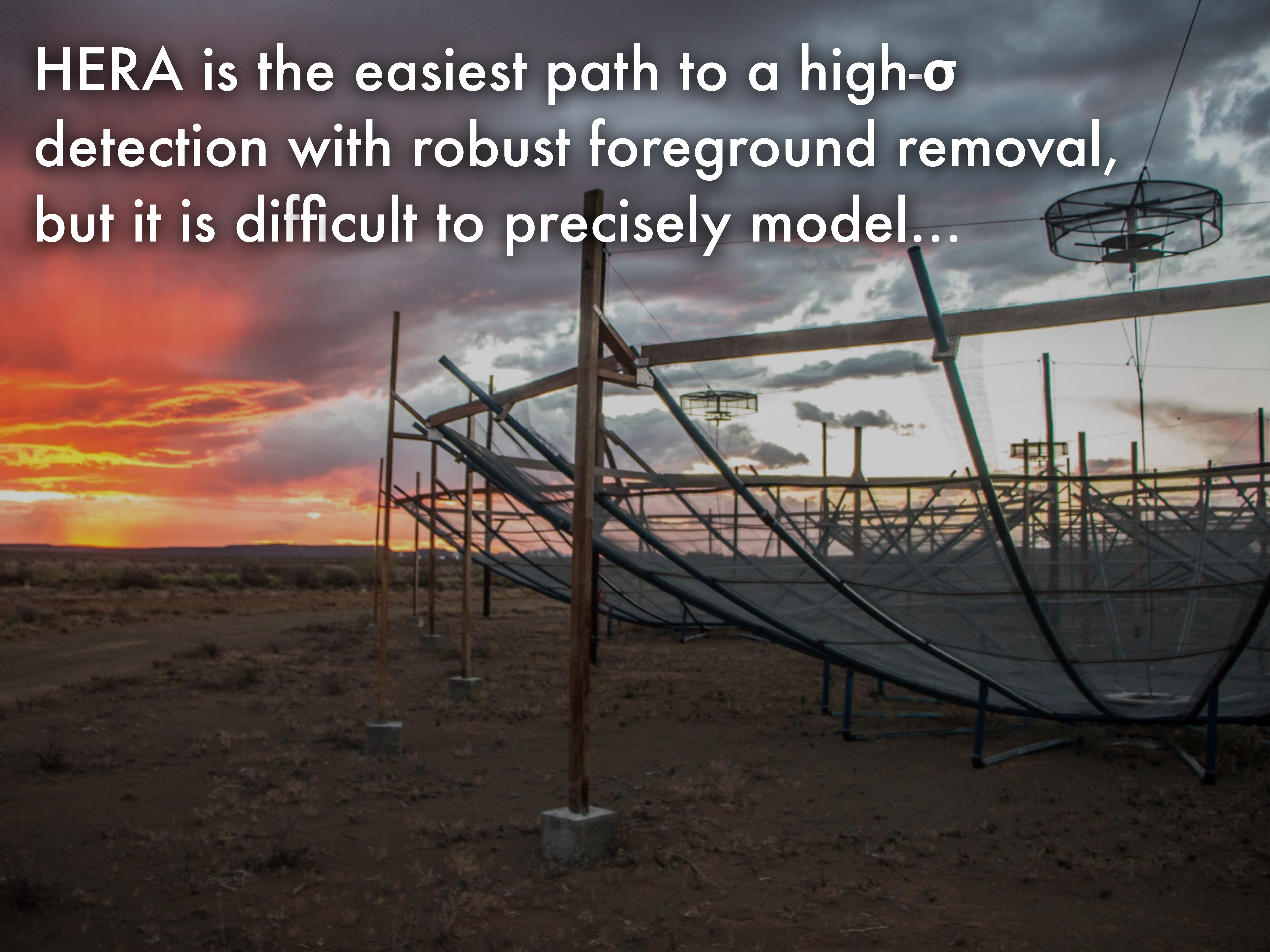
Liu et al. (2016)

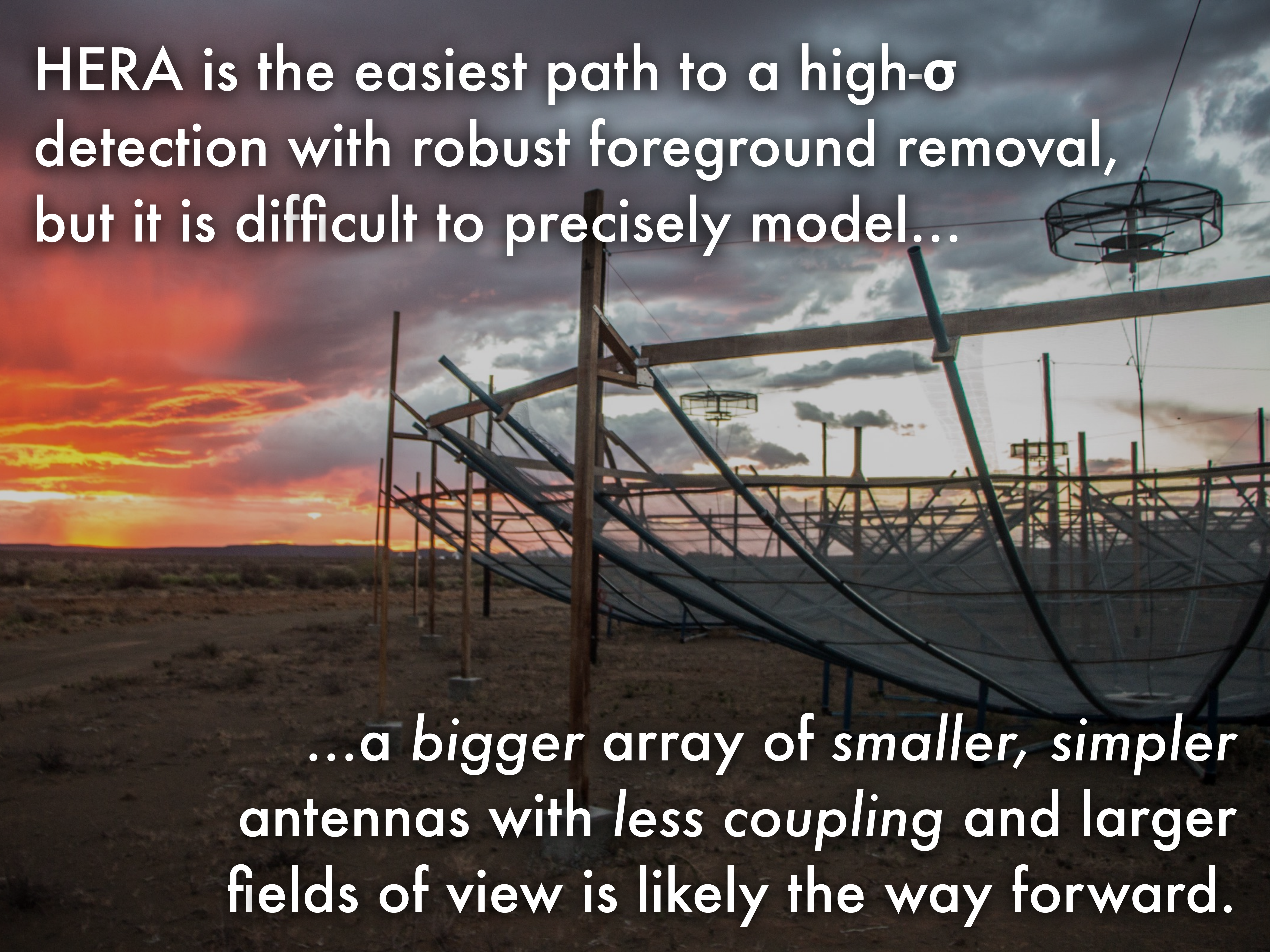
With a few years of observing, we may detect velocity acoustic oscillations, providing a new standard ruler at z ≈ 16.



Muñoz et al. (2019)

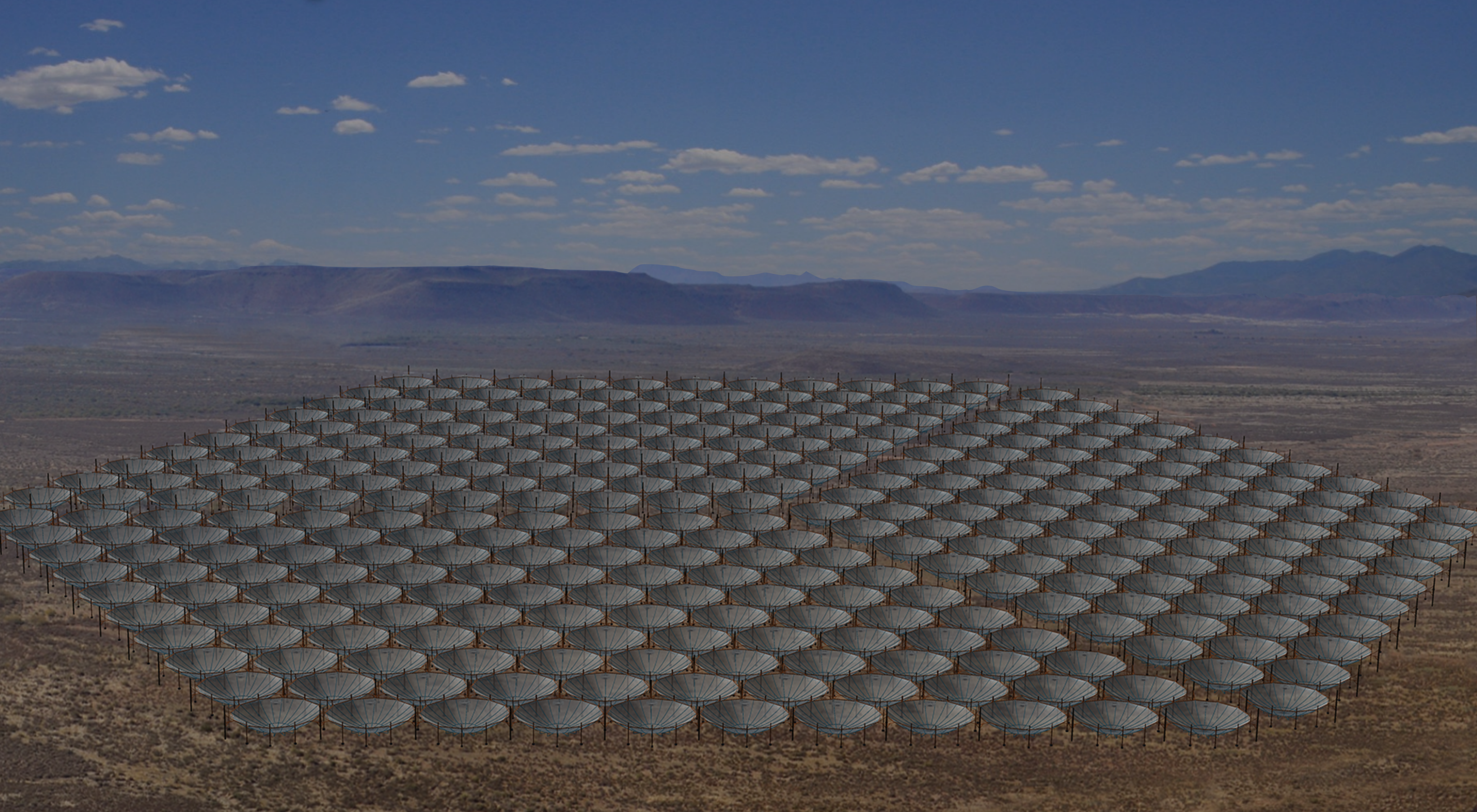
What comes after HERA?


HERA is the easiest path to a high-σ detection with robust foreground removal, but it is difficult to precisely model...


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 *less coupling* and larger fields of view is likely the way forward.

There's a problem with how we measure visibilities.

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



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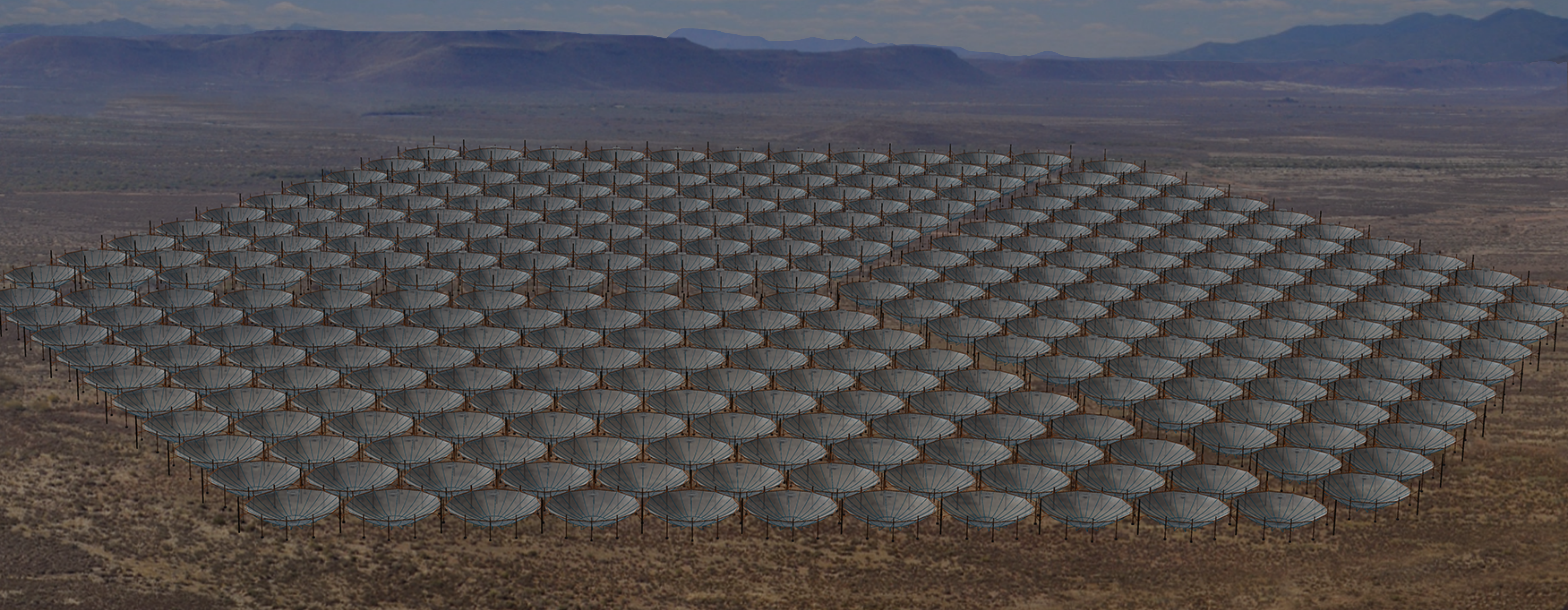
Measure antenna voltages $v_i(t)$.



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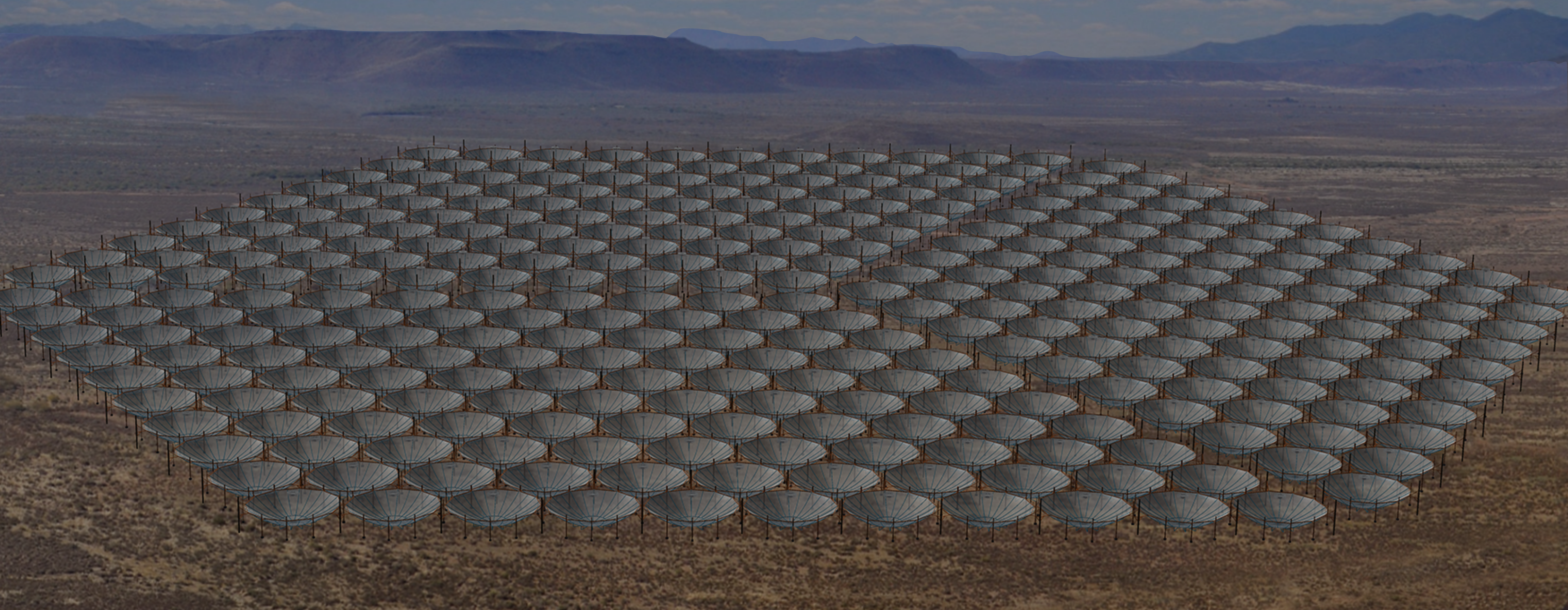
Measure antenna voltages $v_i(t)$. → Fourier transform to frequency: $\tilde{v}_i(\nu)$



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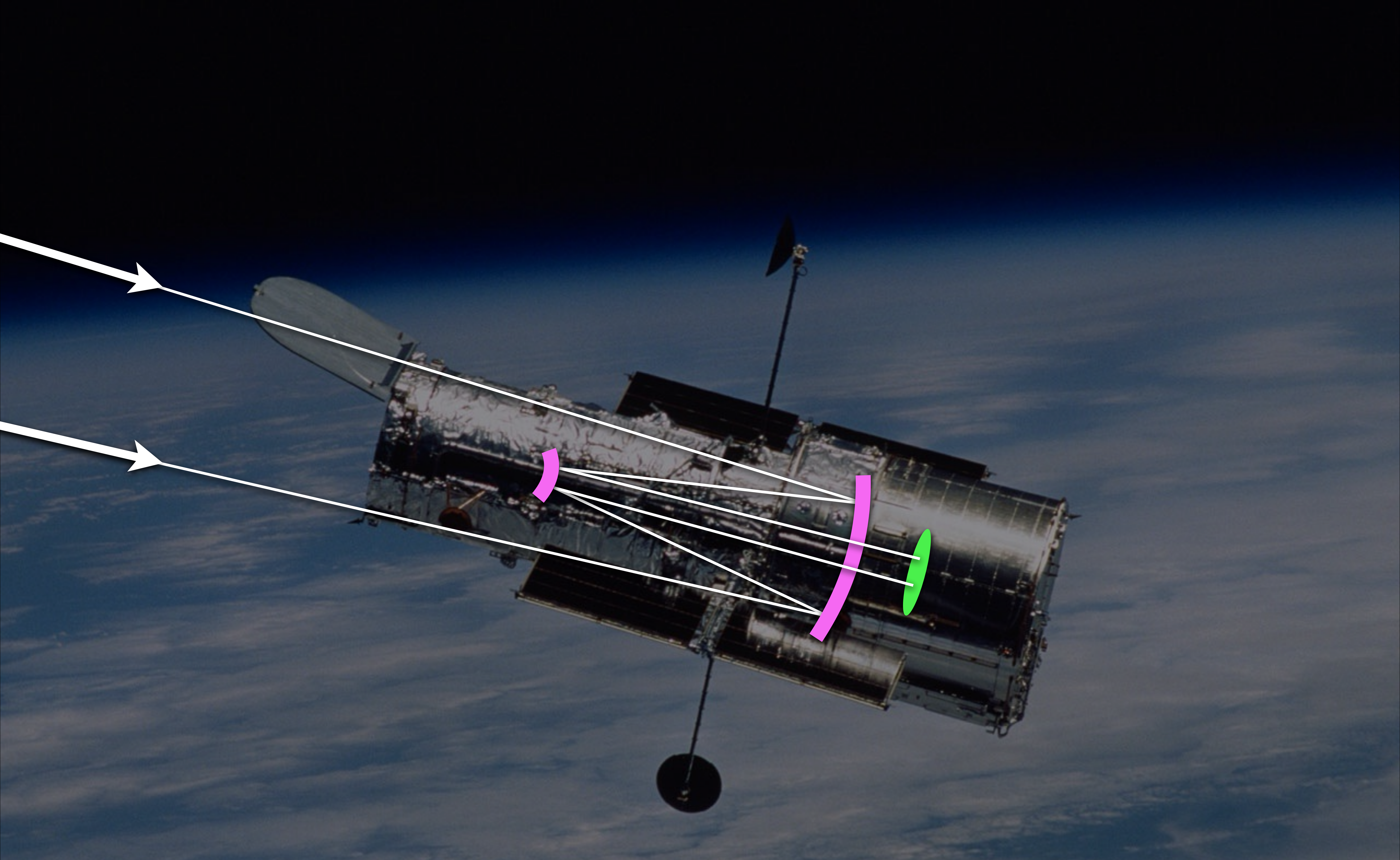
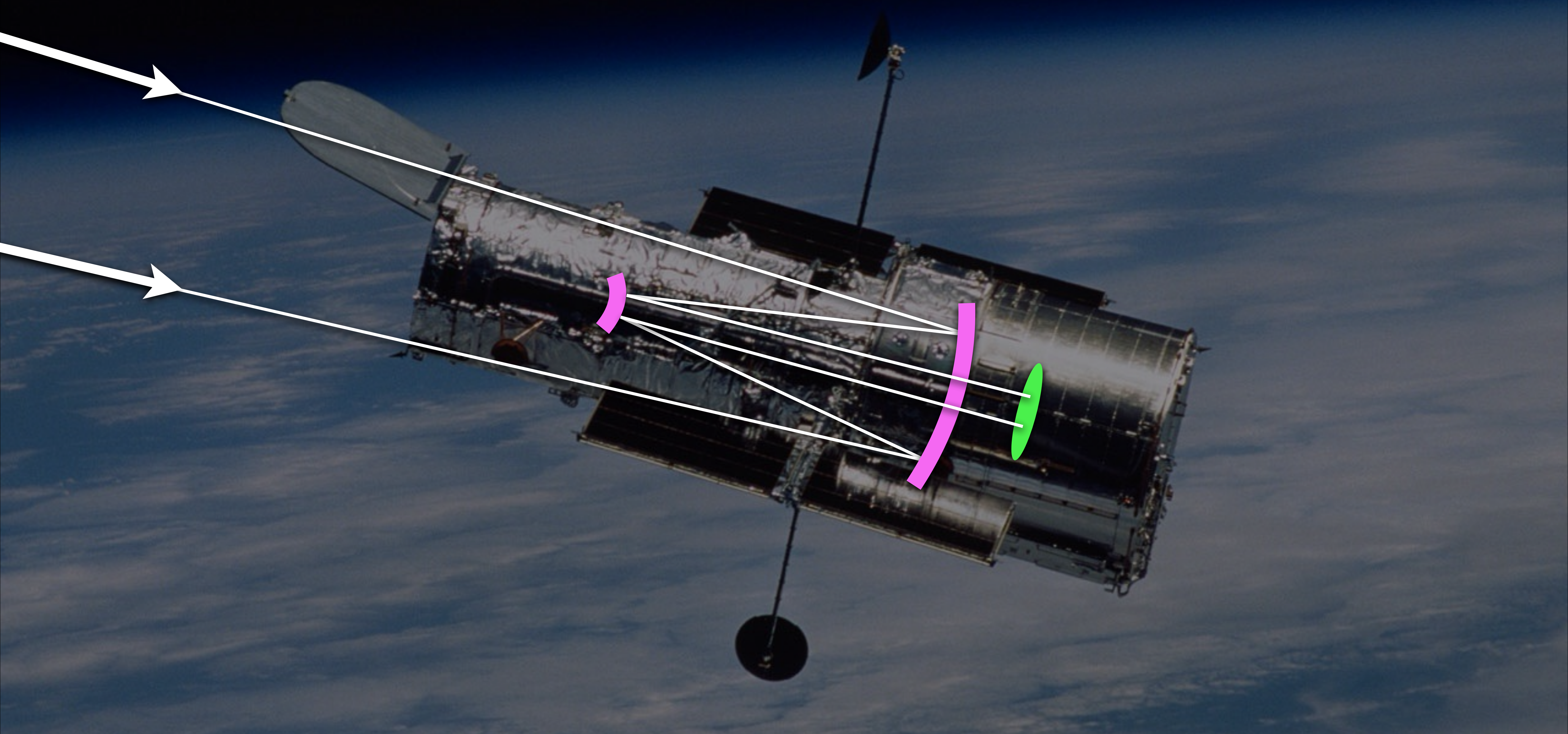
This scales like O(N²)!

All telescopes are Fourier transformers.



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

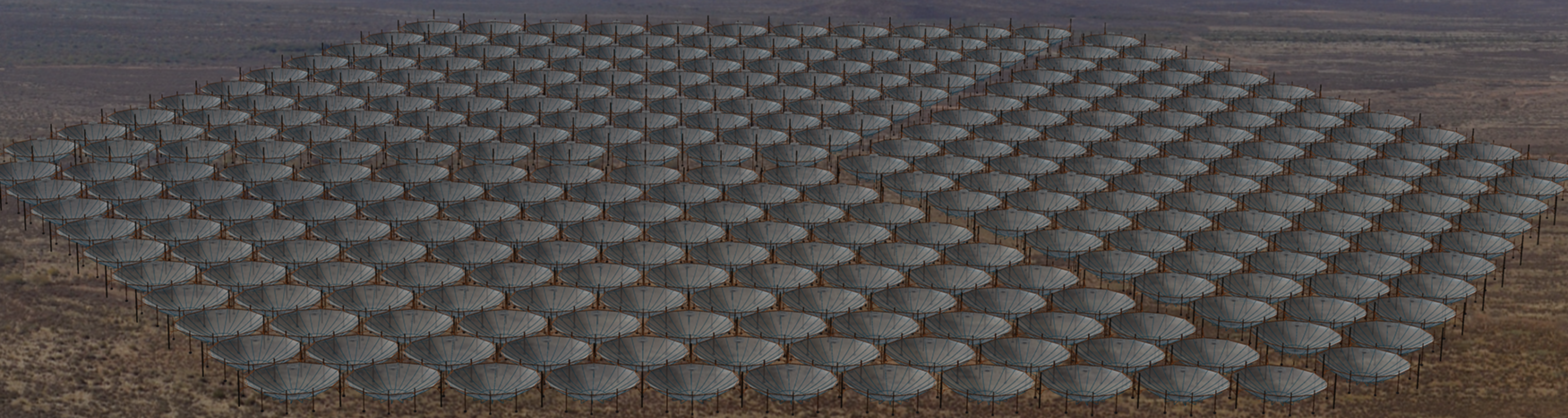


A telescope converts *photon momenta* to *positions* on the focal plane.

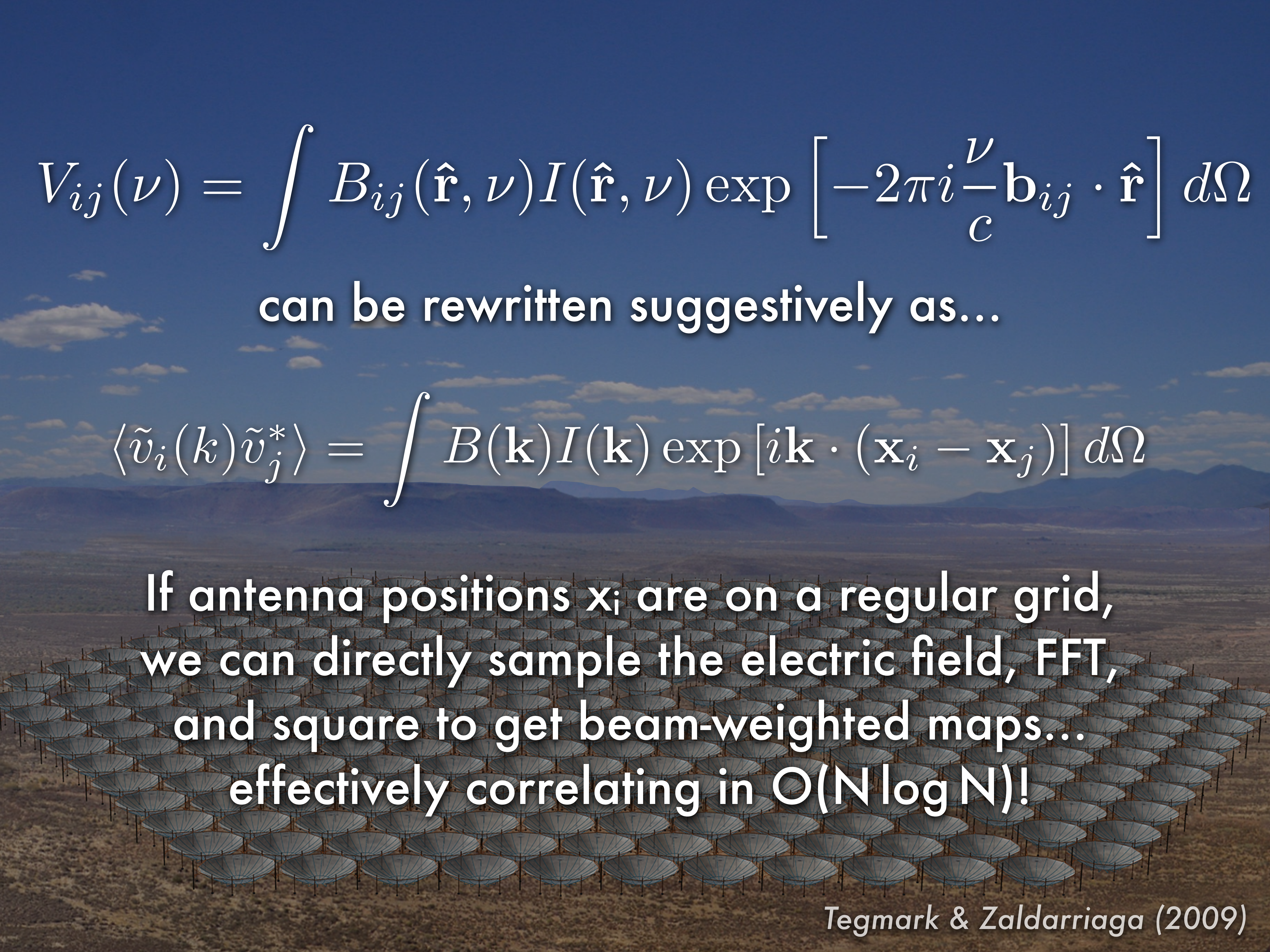
$$V_{ij}(\nu) = \int B_{ij}(\hat{\mathbf{r}}, \nu) I(\hat{\mathbf{r}}, \nu) \exp\left[-2\pi i \frac{\nu}{c} \mathbf{b}_{ij} \cdot \hat{\mathbf{r}}\right] d\Omega$$

can be rewritten suggestively as...

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



Tegmark & Zaldarriaga (2009)



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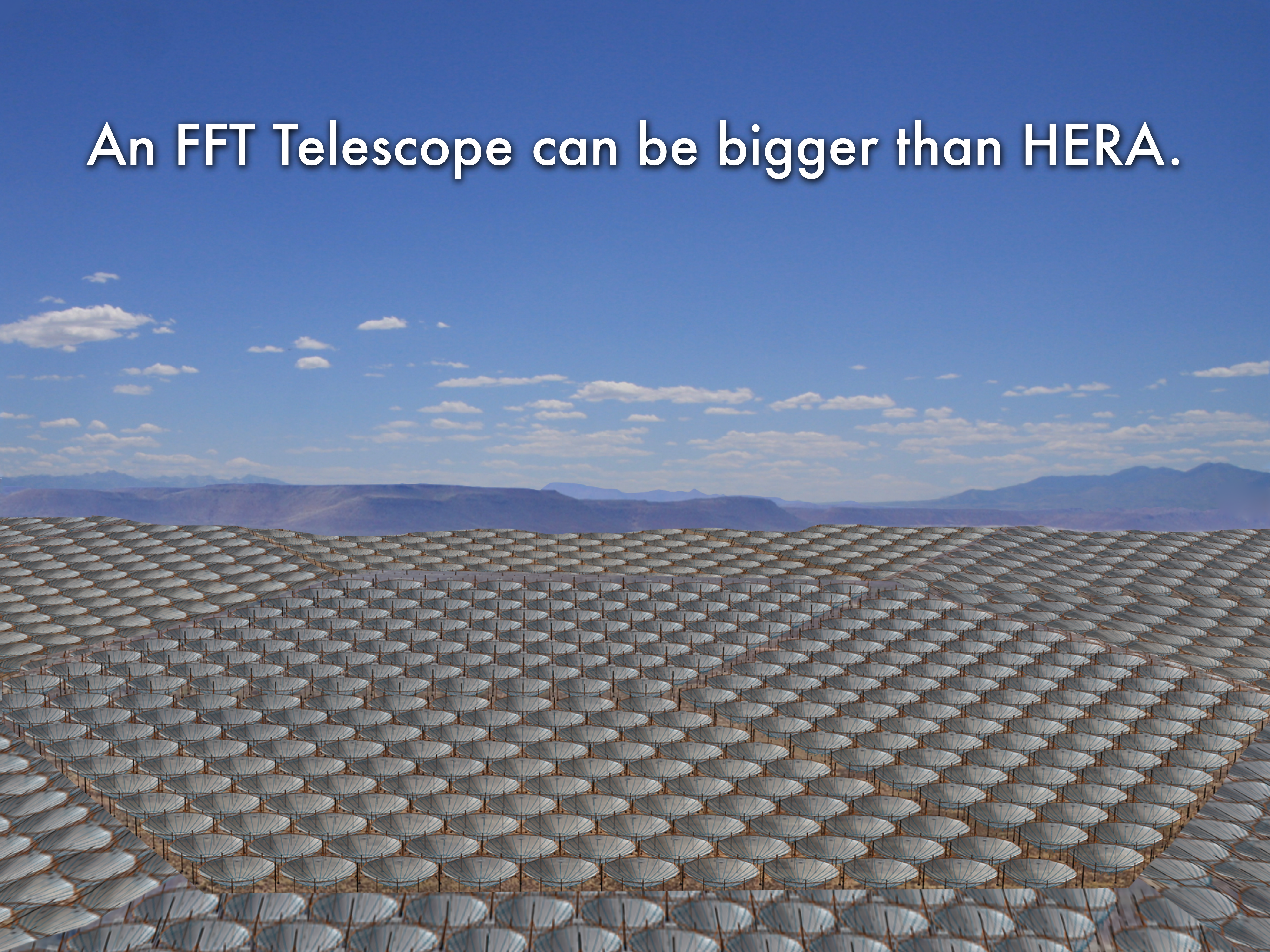
If antenna positions x_i are on a regular grid, we can directly sample the electric field, FFT, and square to get beam-weighted maps... effectively correlating in O(N log N)!

Tegmark & Zaldarriaga (2009)

An FFT Telescope can be bigger than HERA.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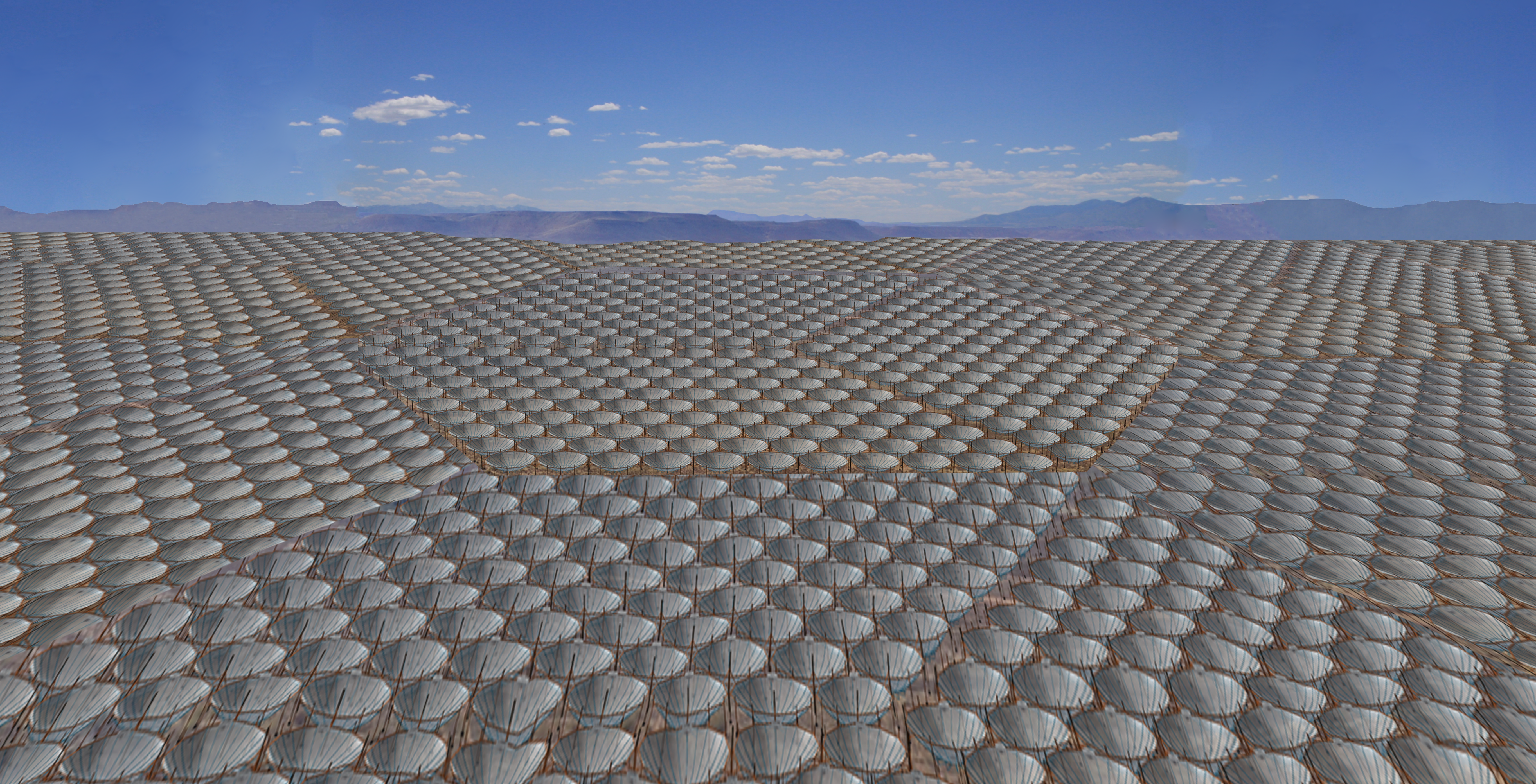
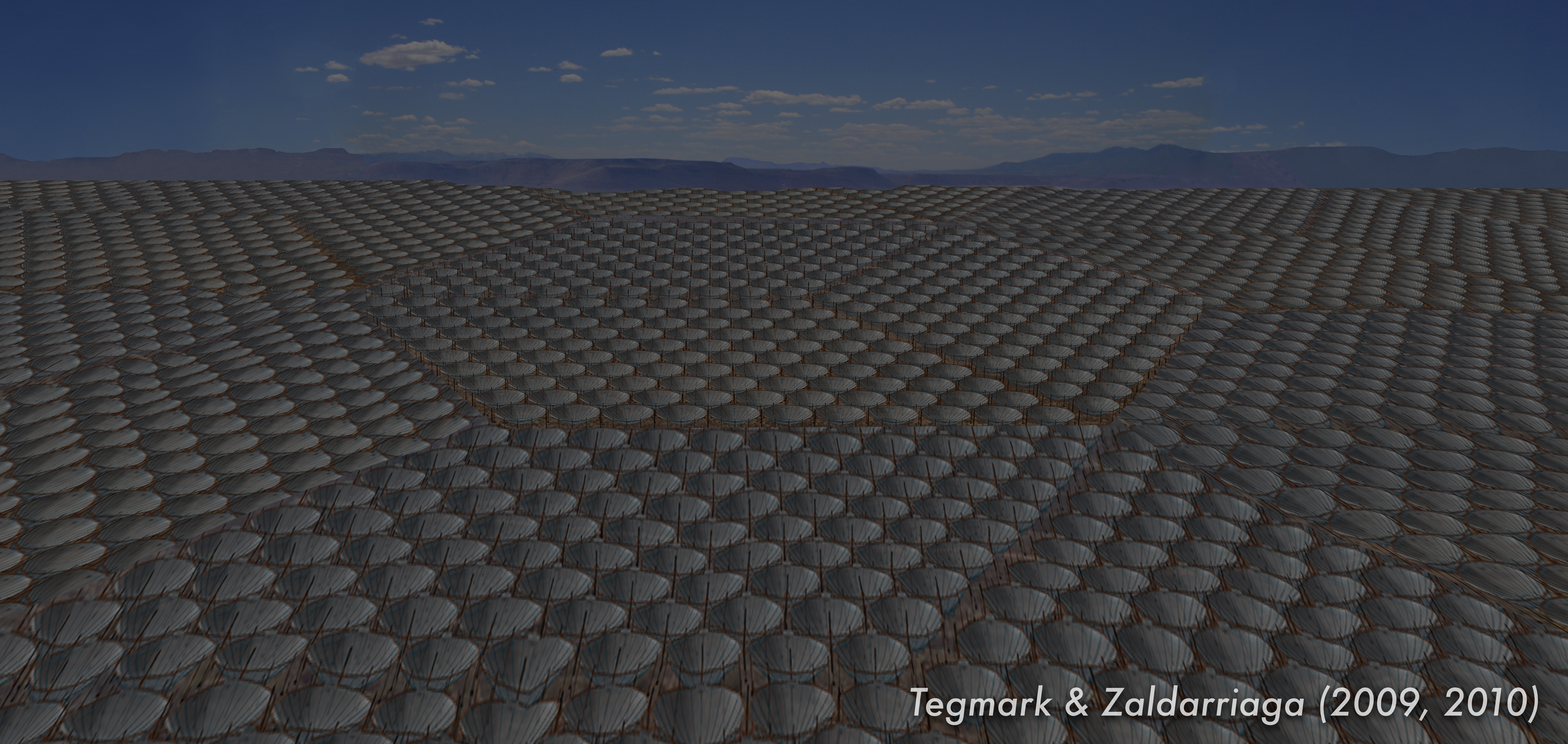
An FFT Telescope can be bigger than HERA.

Much, *much* bigger.



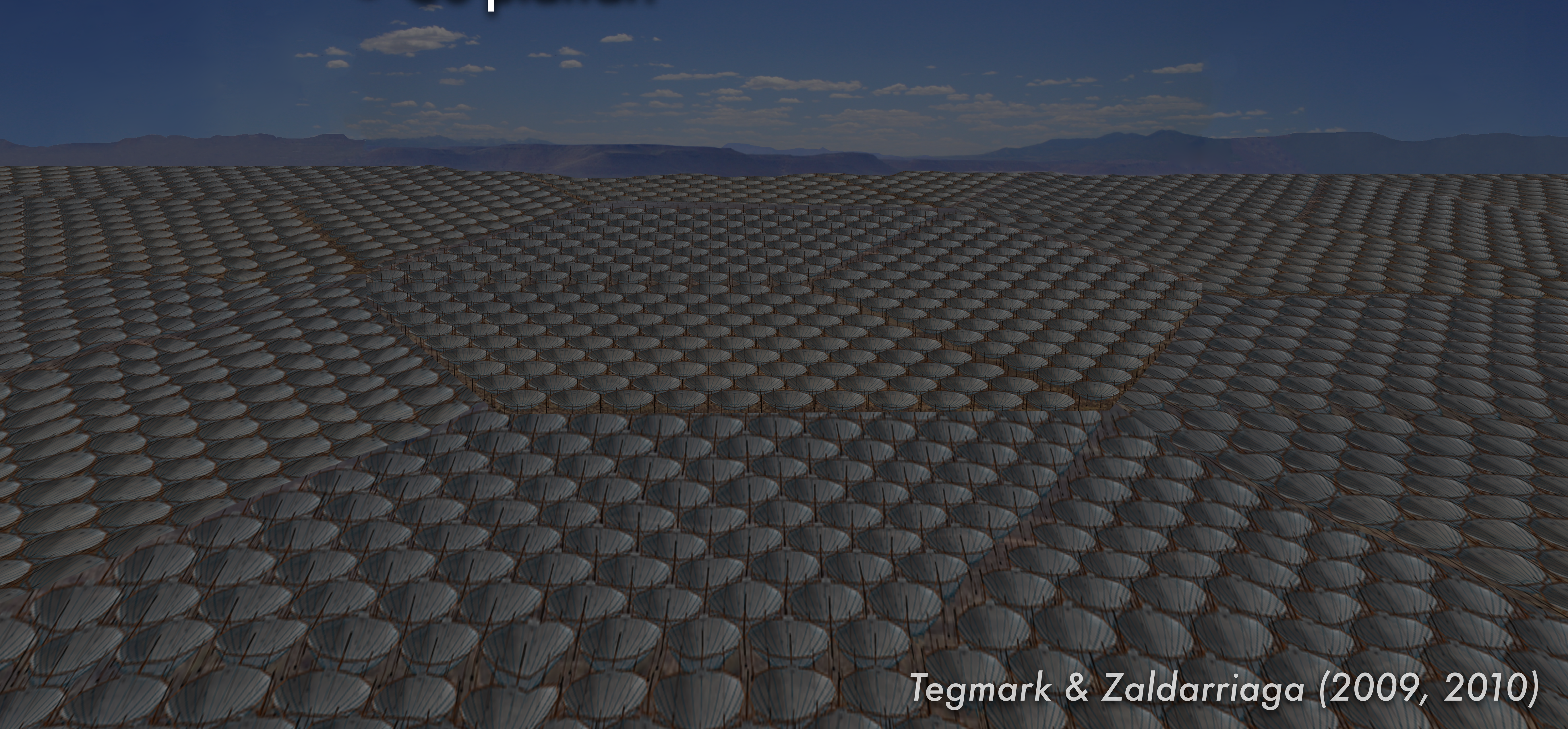
An FFT Telescope needs to be...



Tegmark & Zaldarriaga (2009, 2010)

An FFT Telescope needs to be...

- Co-planar.



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An FFT Telescope needs to be...

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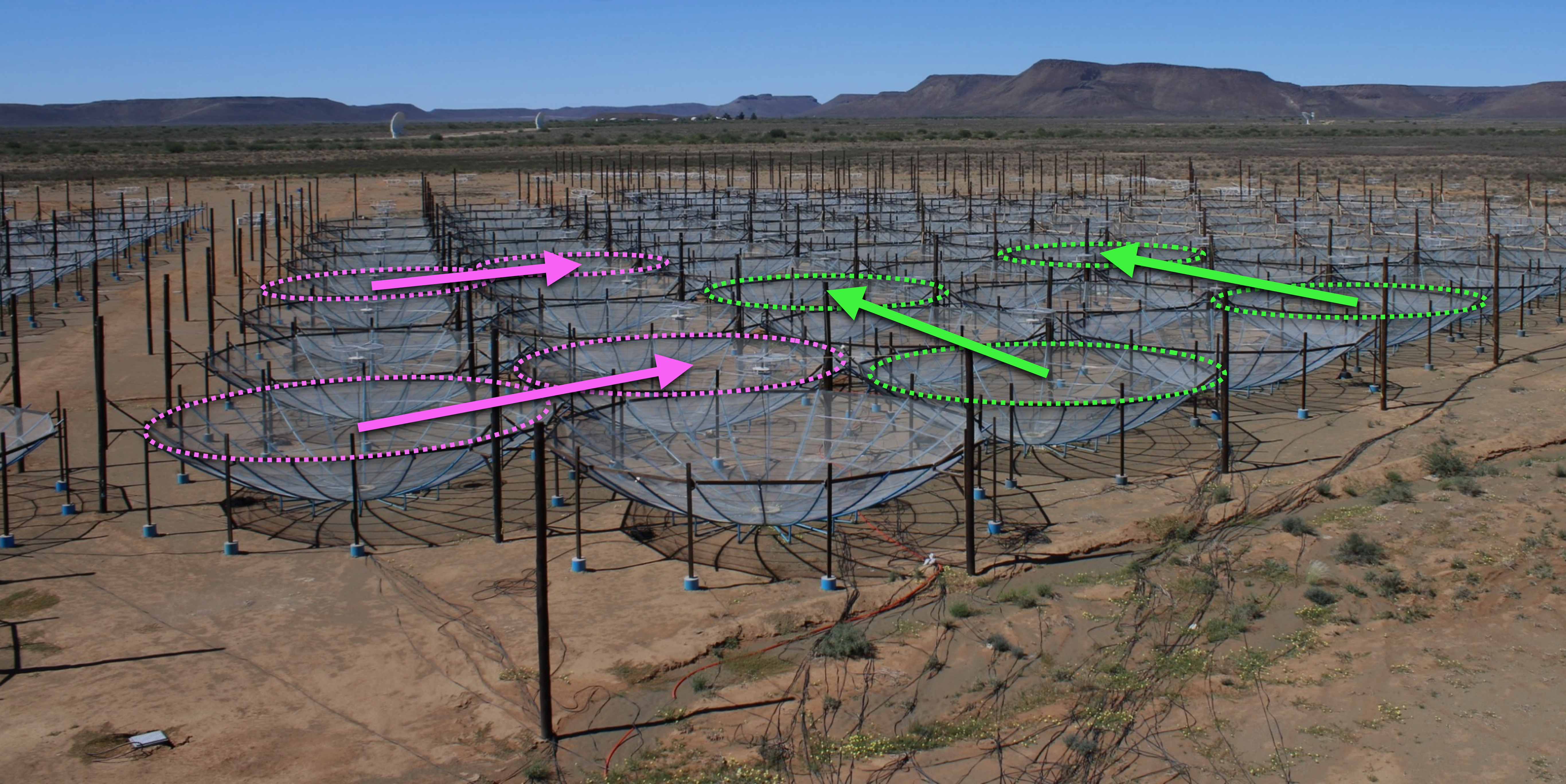
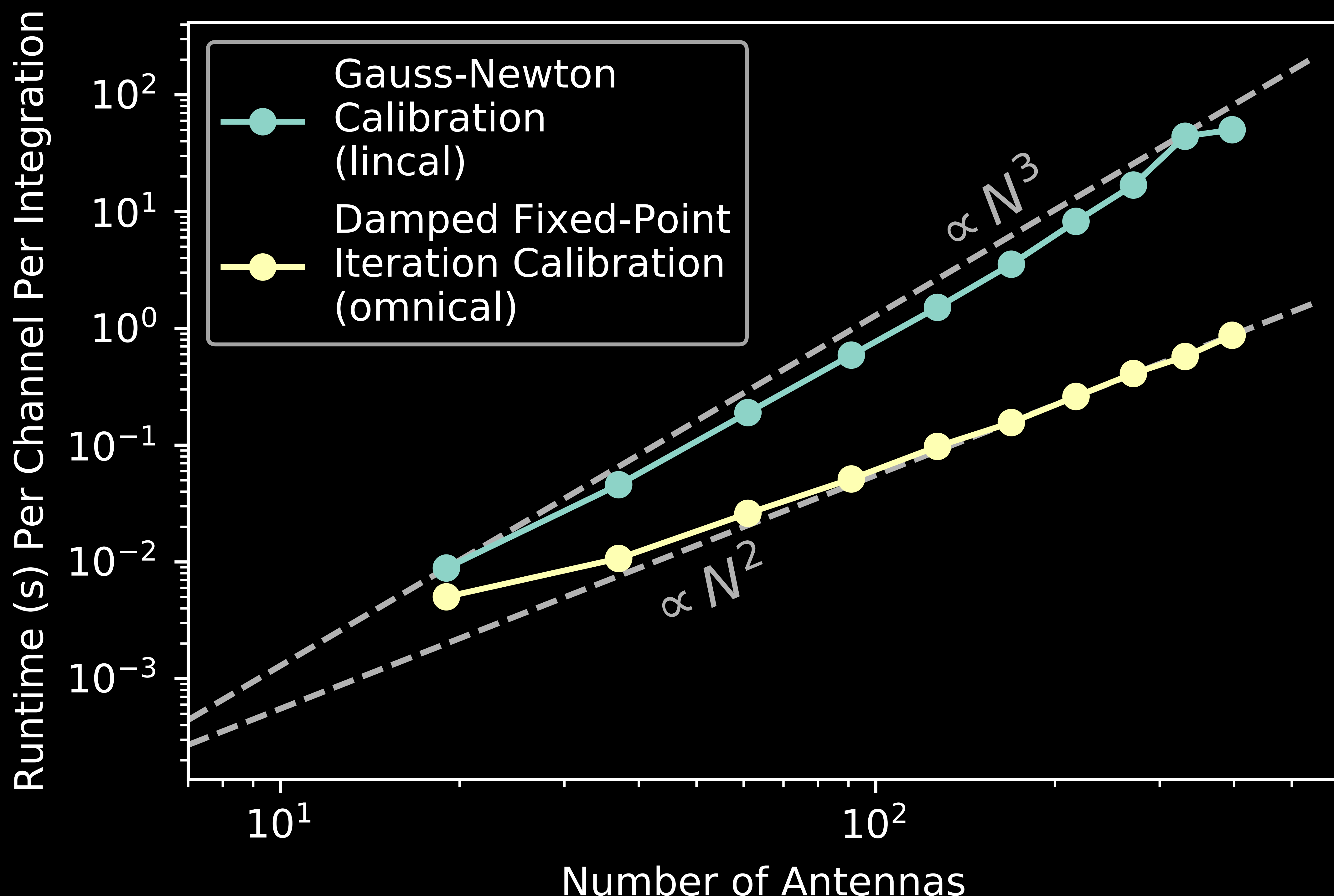
- Calibrated in real time.

Tegmark & Zaldarriaga (2009, 2010)

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

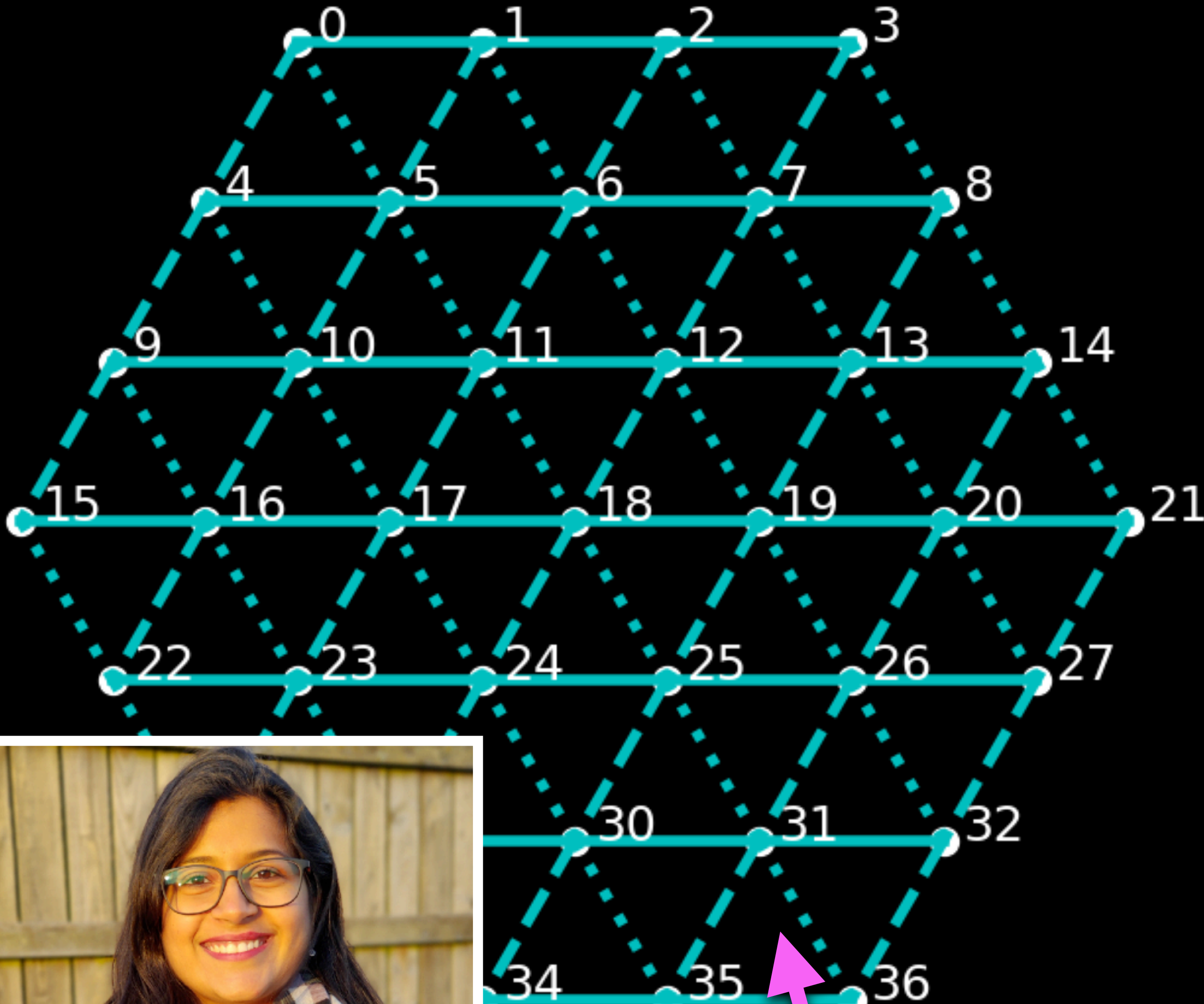


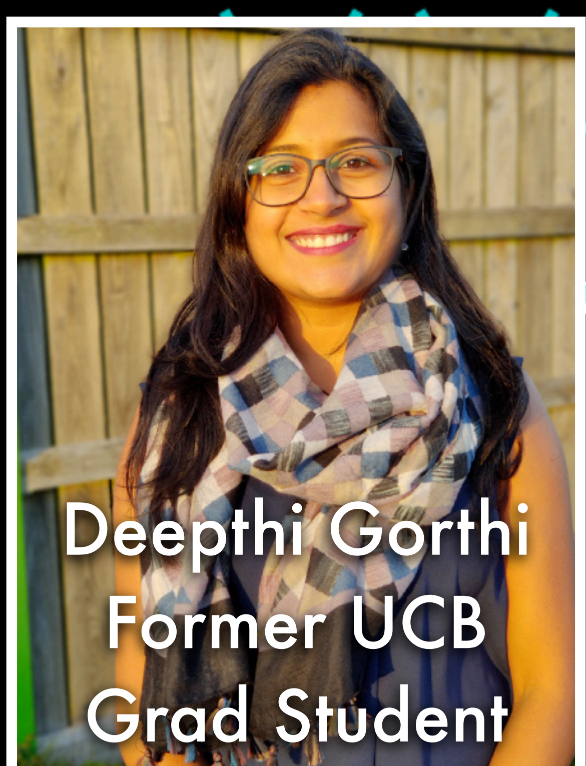
We showed how to speed up redundant calibration from $O(N^3)$ to $O(N^2)$.

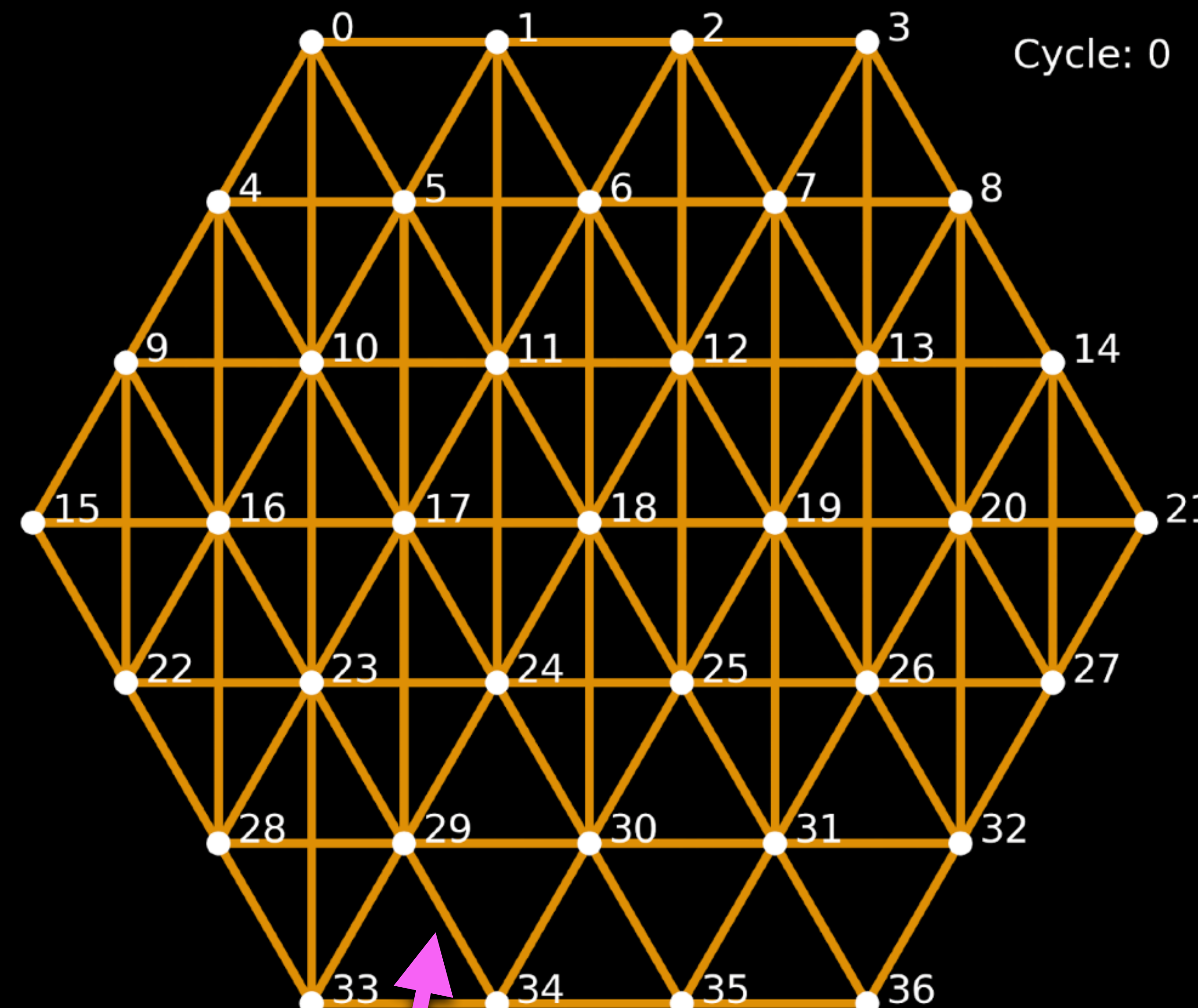


Dillon *et al.* (2020)

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)*

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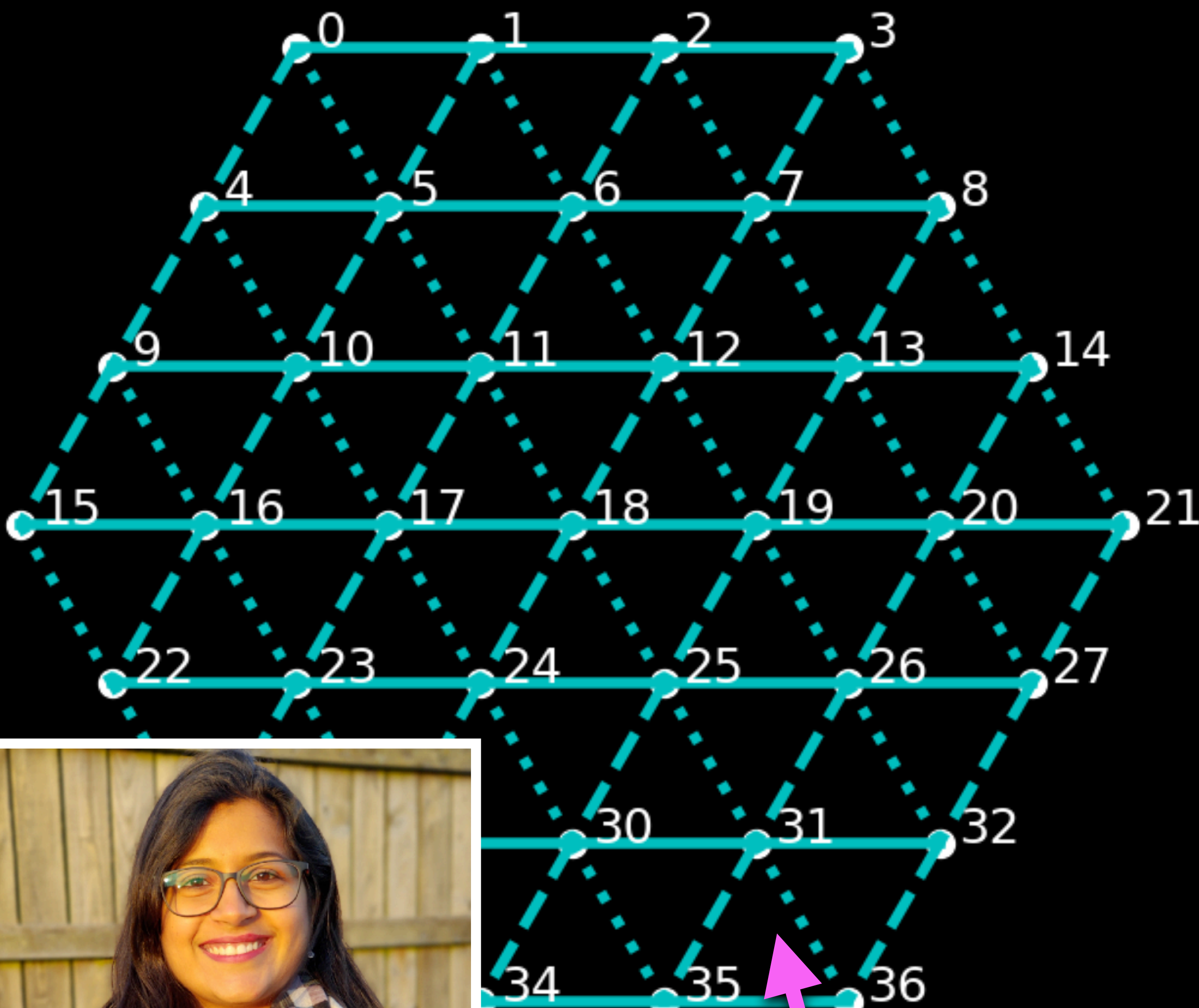

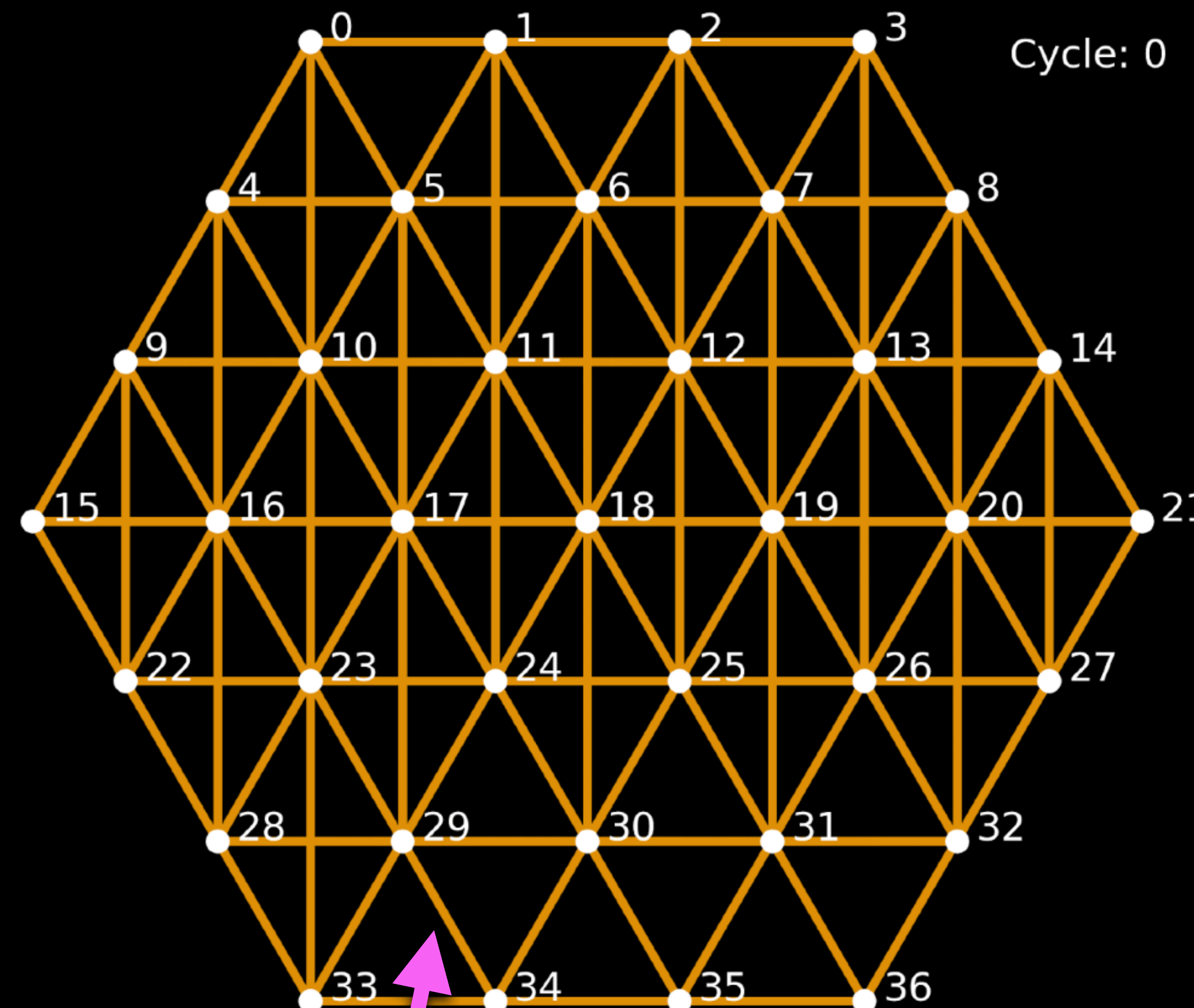

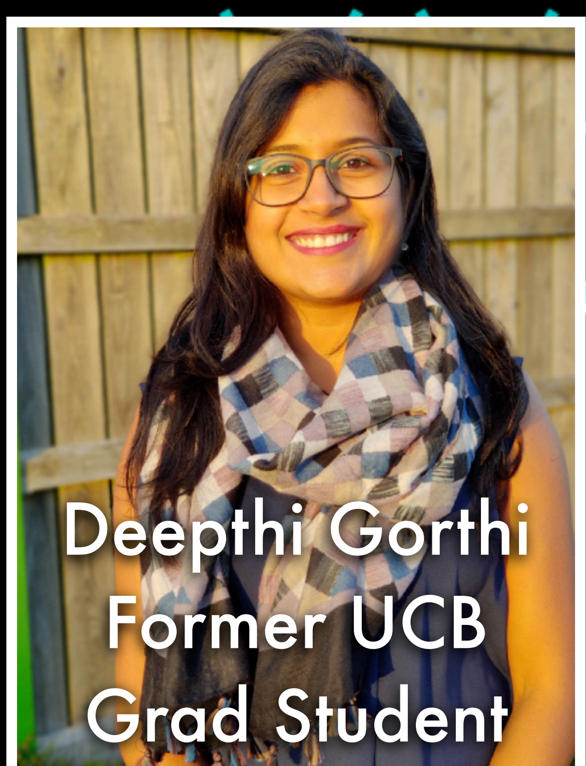

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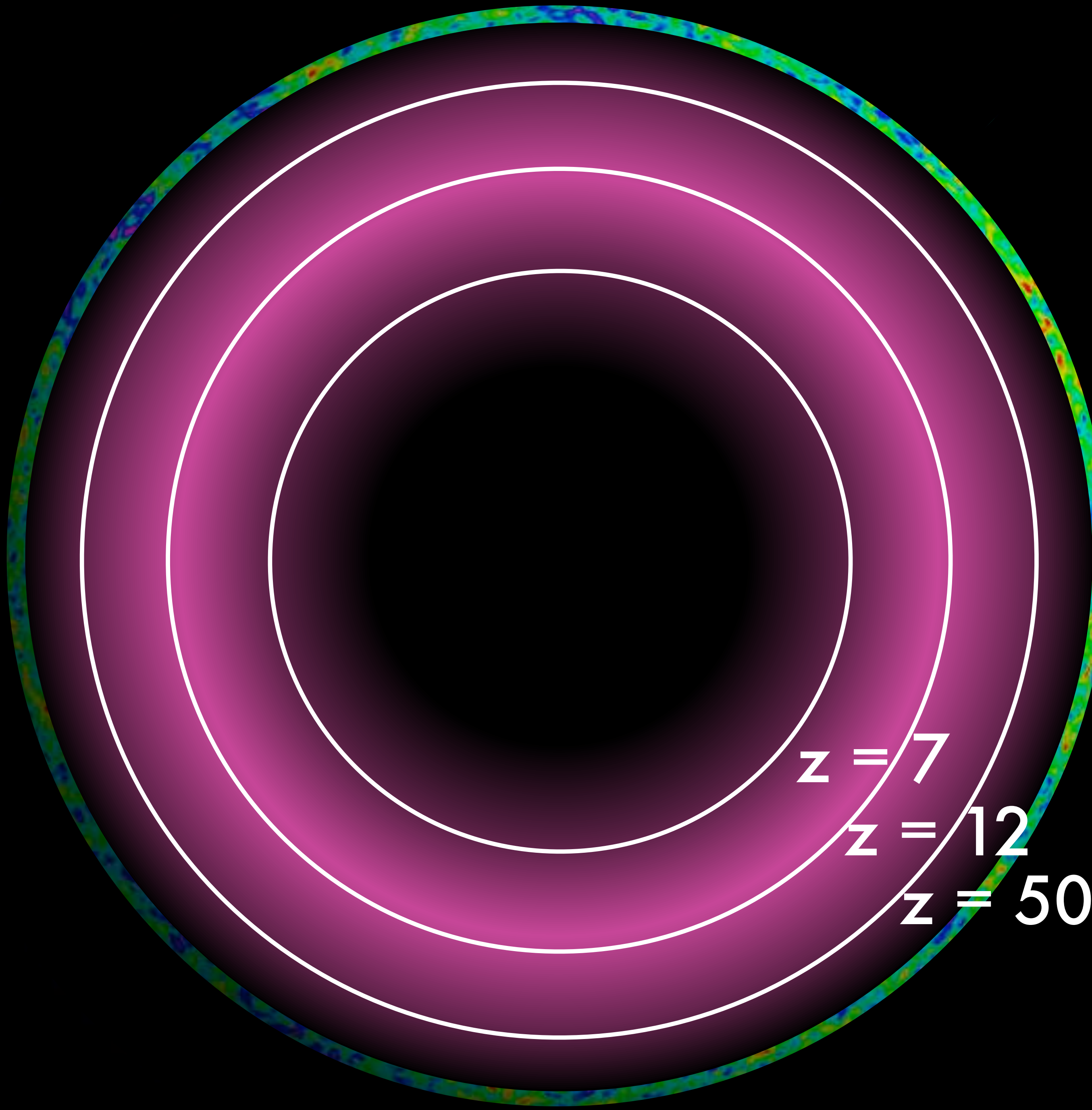
FFTTs could map the majority of the volume of the observable universe, giving us...



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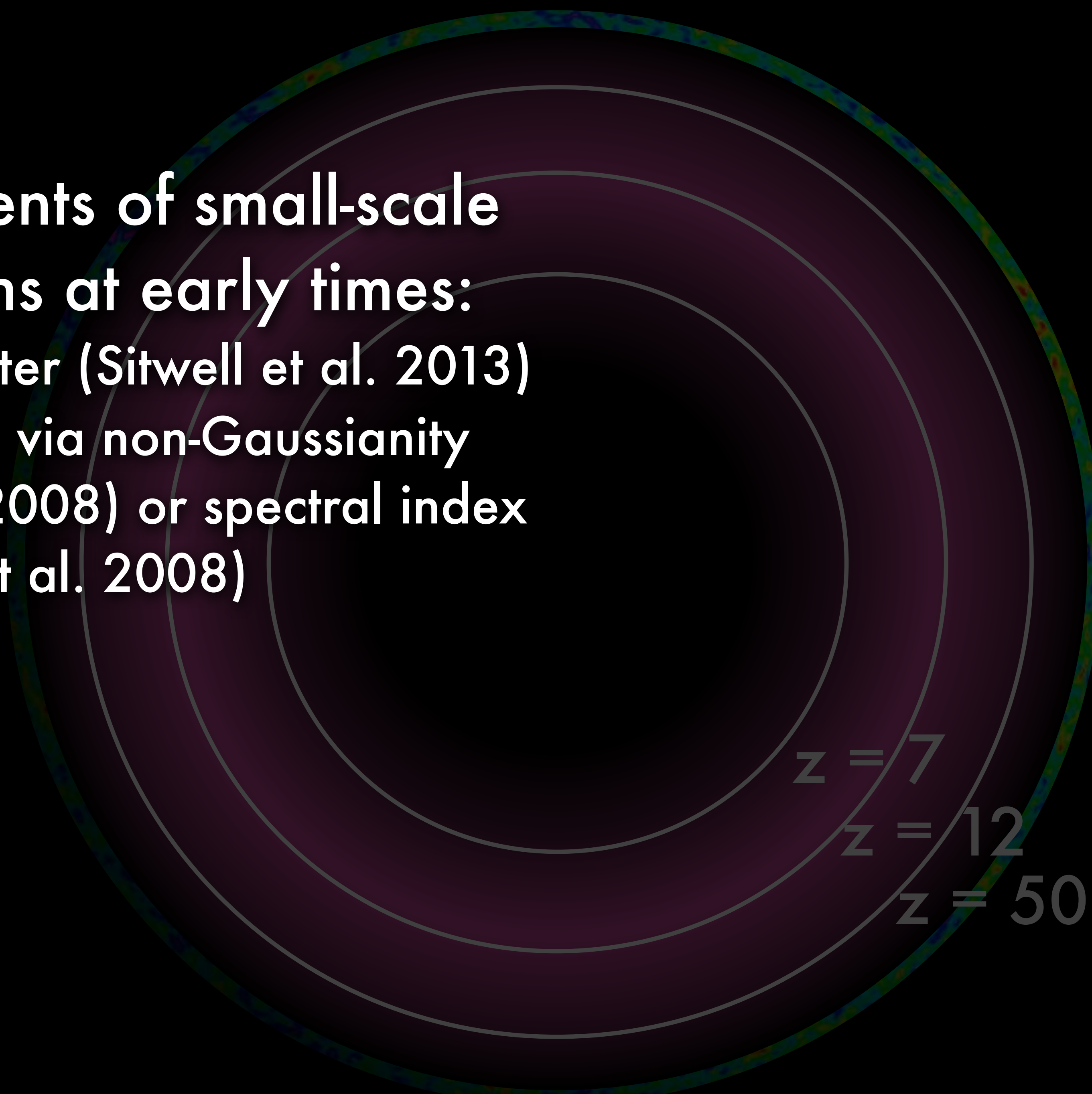
Direct measurements of small-scale density fluctuations at early times:

- 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)



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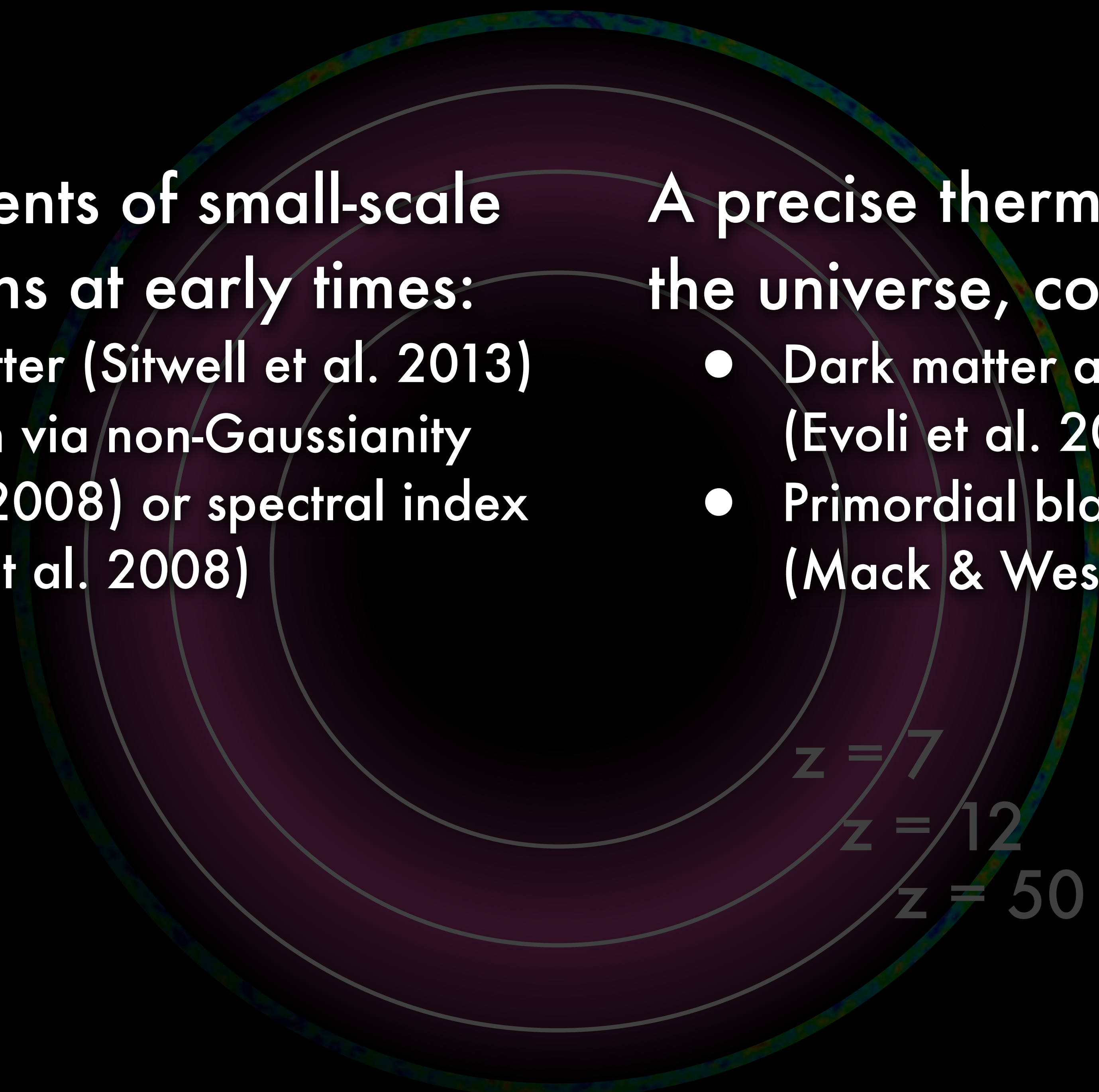

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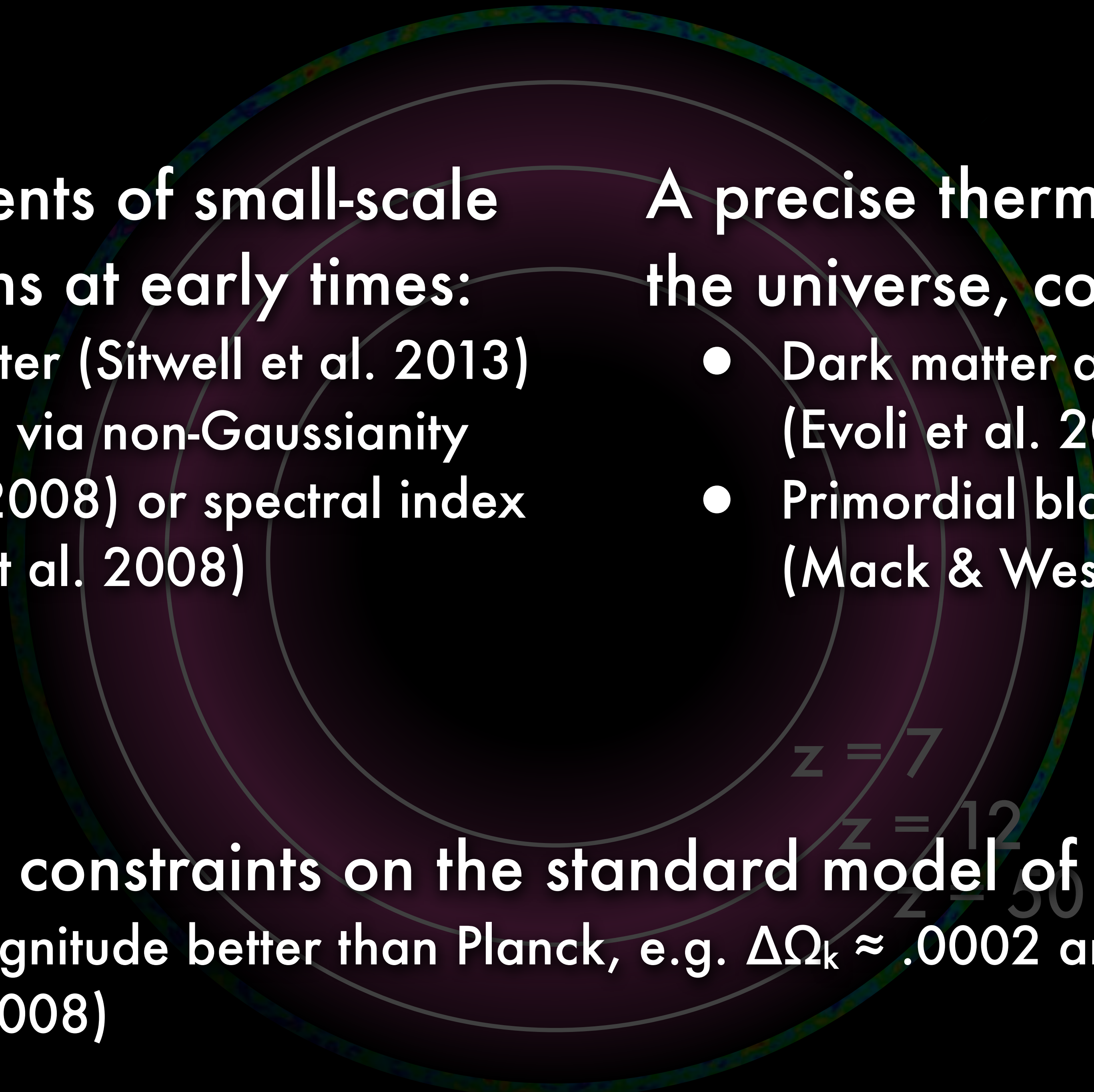

Unprecedented constraints on the standard model of cosmology:

- 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:
Photo: Dara Storer

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- 21 cm cosmology promises to become the premier probe of our Cosmic Dawn, and thus half the volume of the observable of the universe.

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- HERA is elucidating key systematics as we scale to instruments that can realize the potential of 21 cm cosmology

Photo: Dara Storer