21 cm Cosmology with HERA

Josh Dillon
UC Berkeley

Alvarez, Kaehler, Abel


So we think the cosmic dawn
looked something like this...
Alvarez, Kaehler, Abel

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

↑ 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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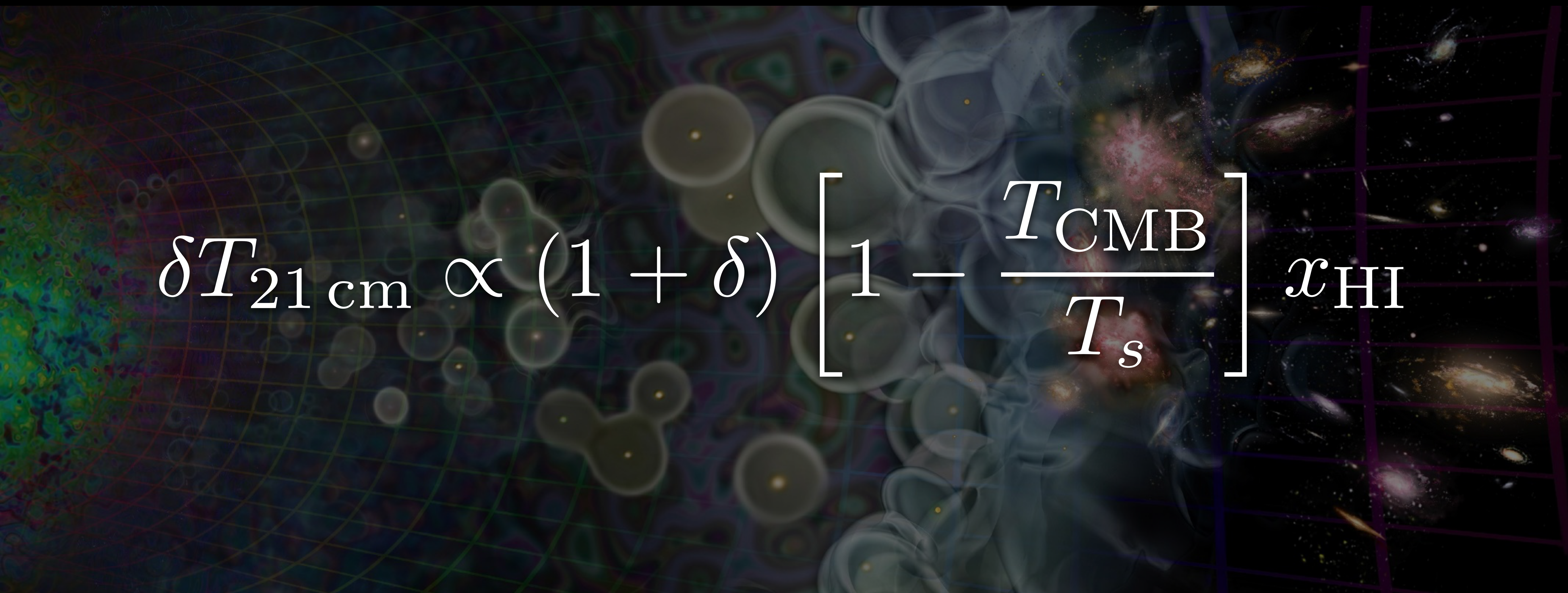
21 cm Brightness Temperature

Spin Temperature

Alvarez, Kaehler, Abel

The brightness temperature probes different physics at different times.



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

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

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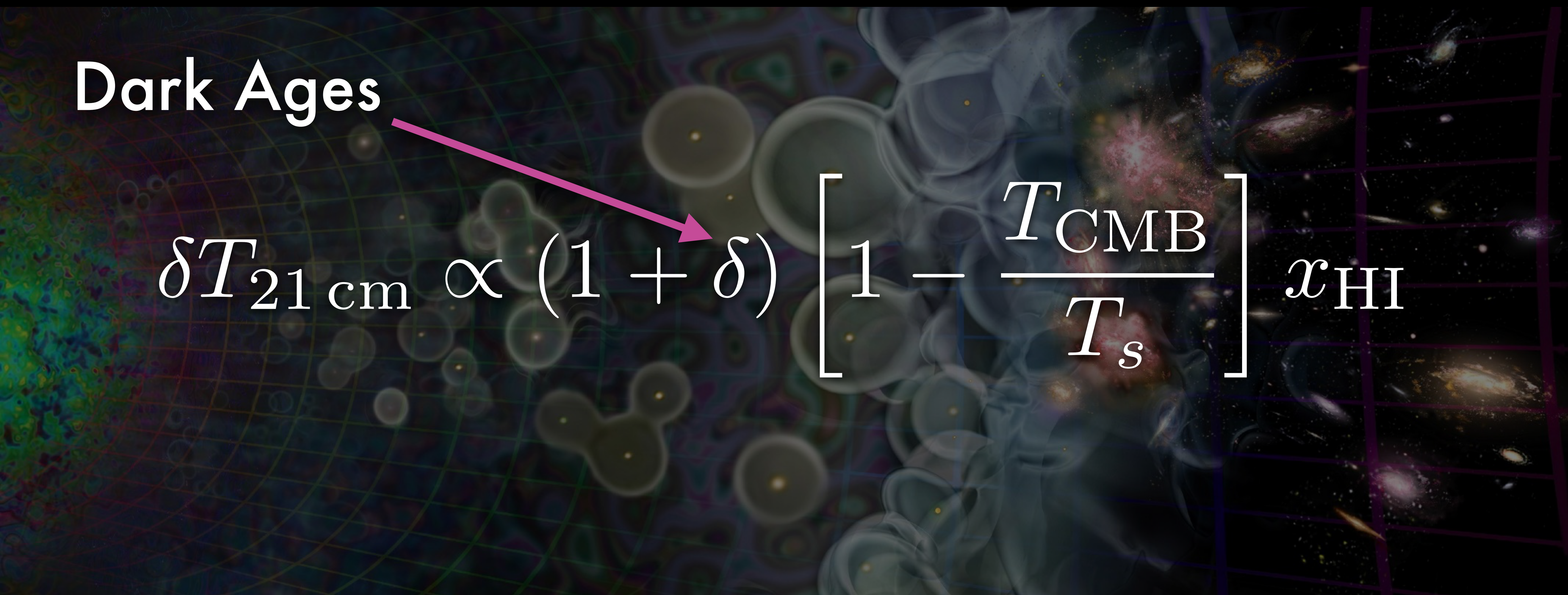

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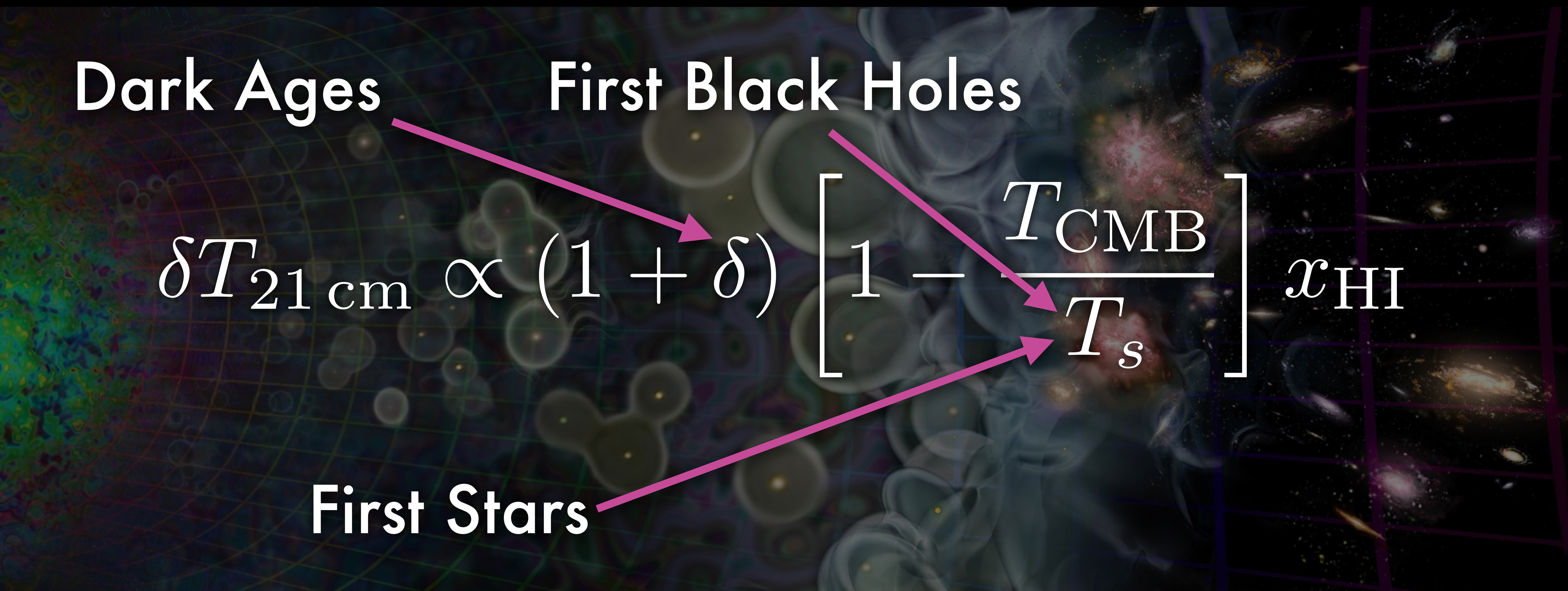

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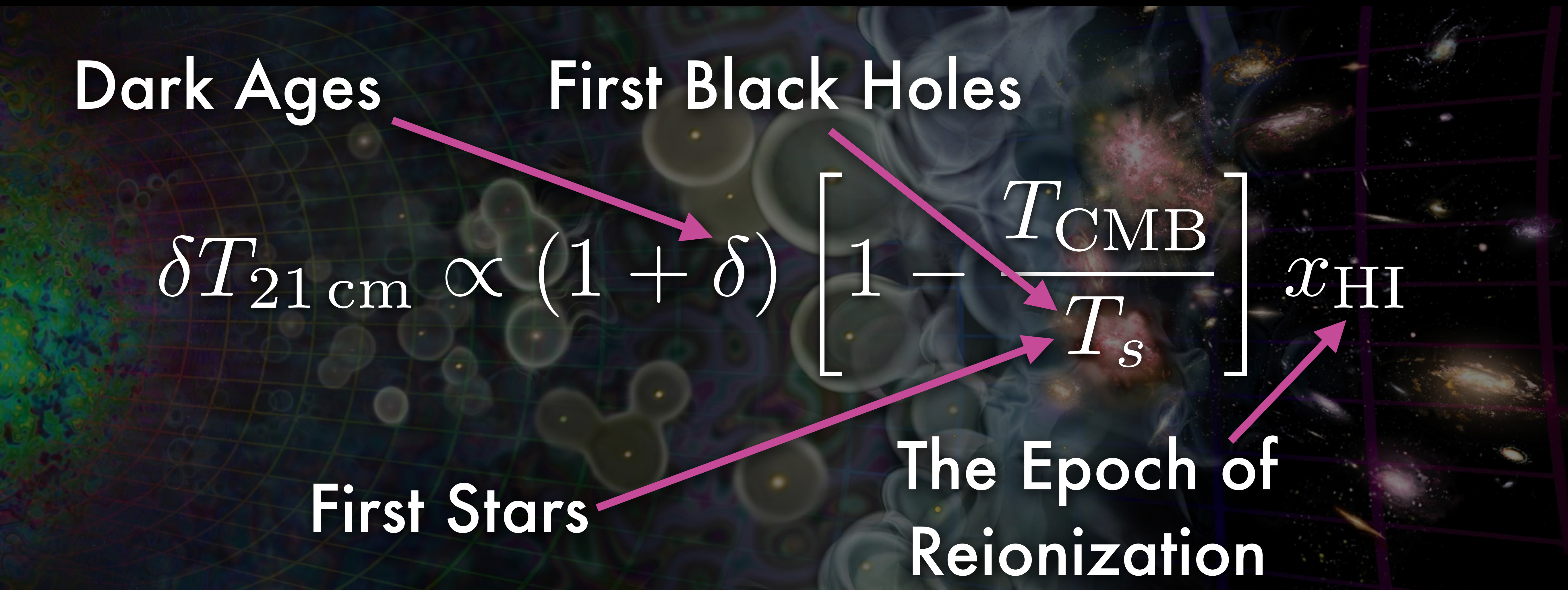

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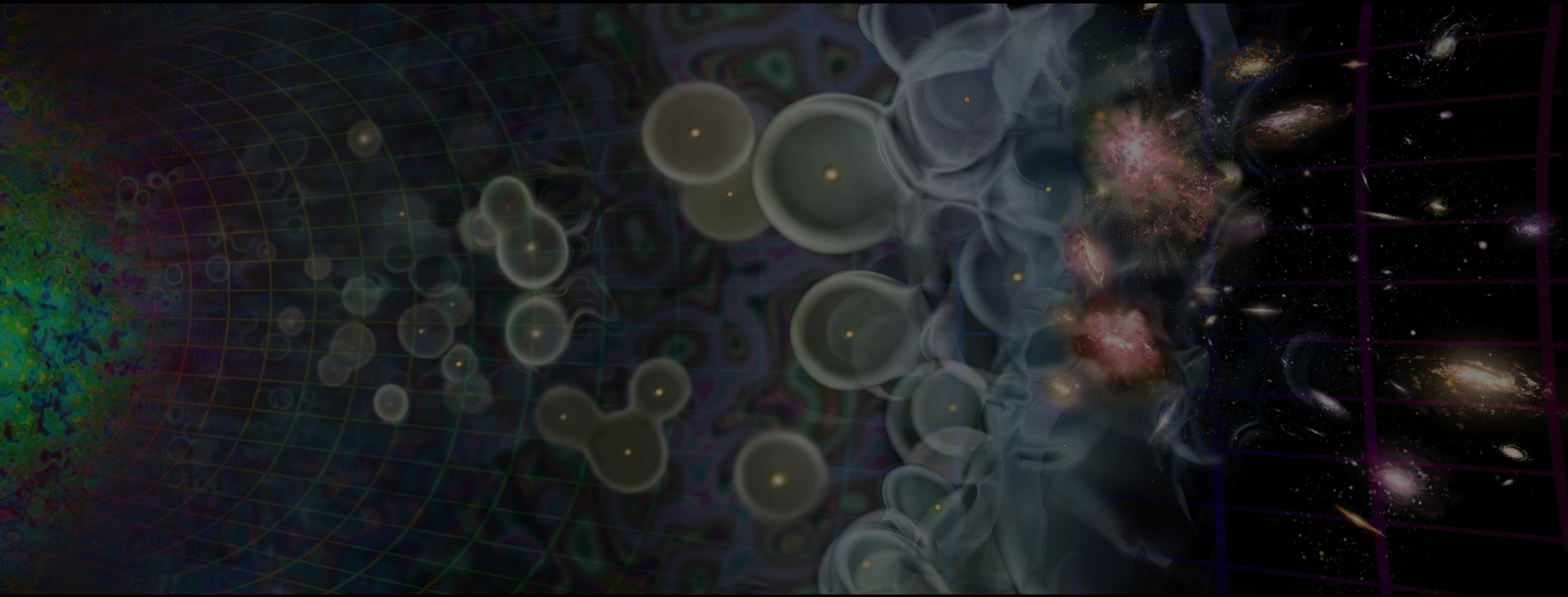
z =1100 | z ≈ 50 | z ≈ 8 | z < 6

There's still a lot of open astrophysical questions.



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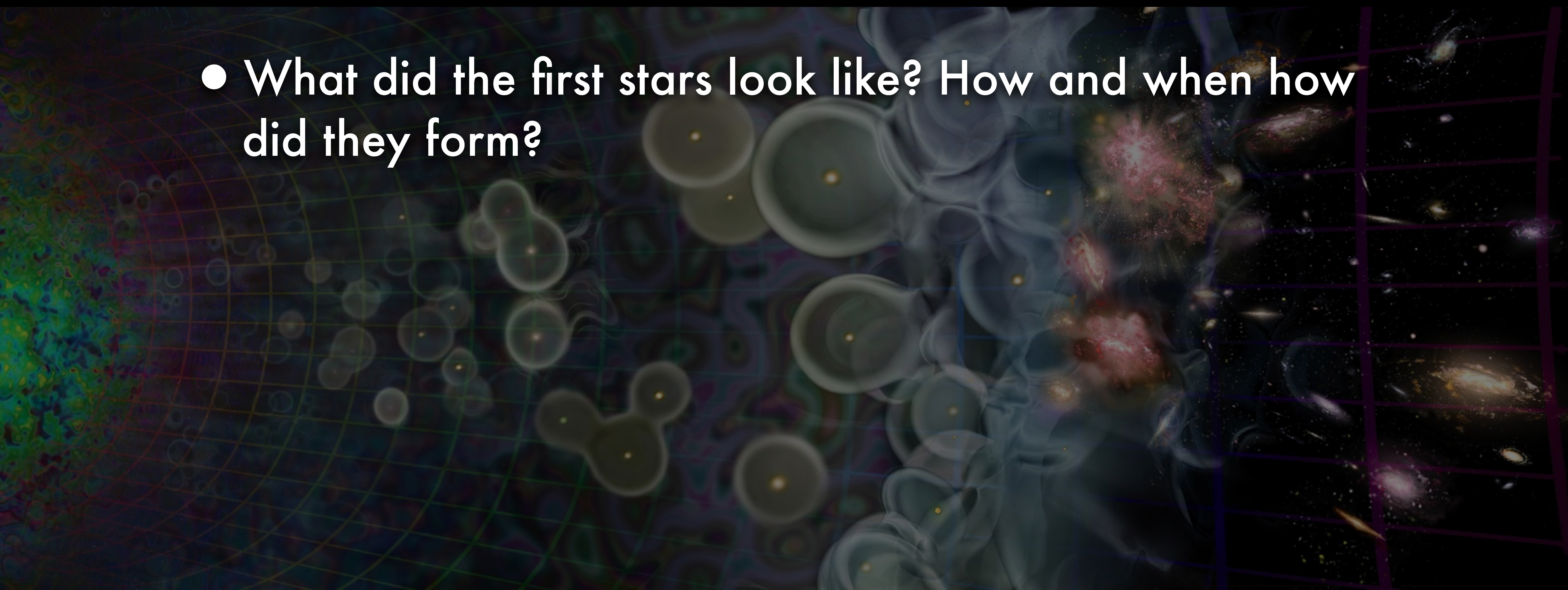
- What did the first stars look like? How and when how did they form?



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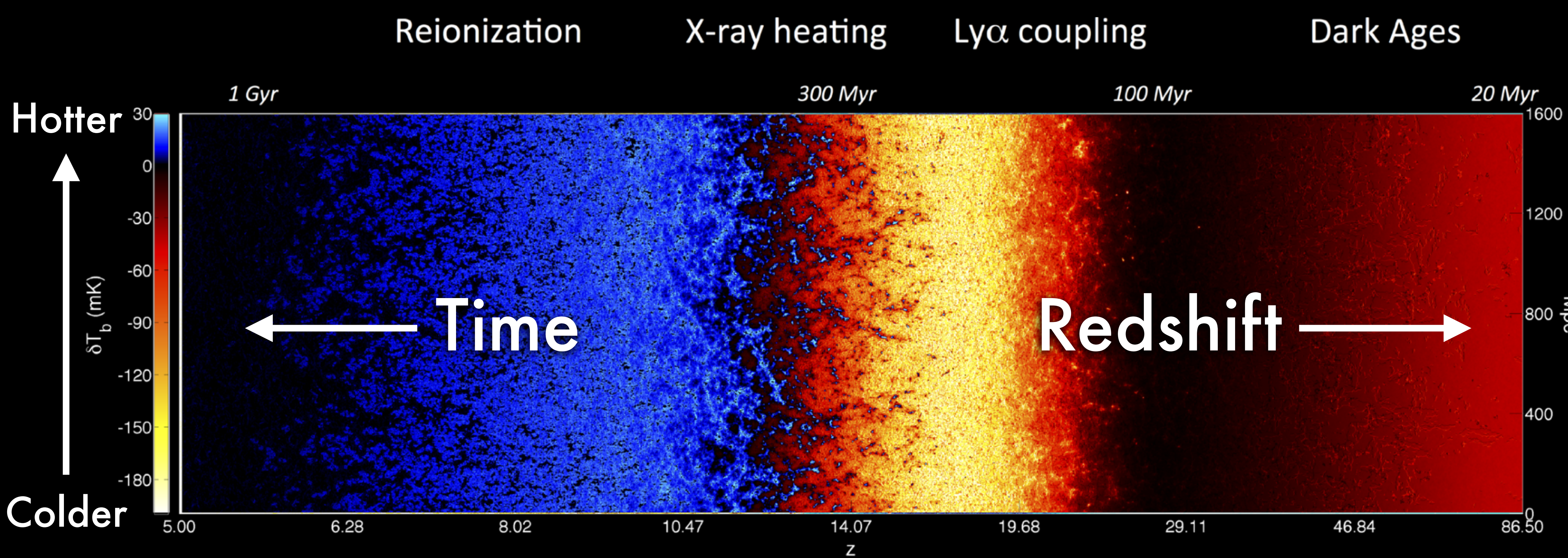
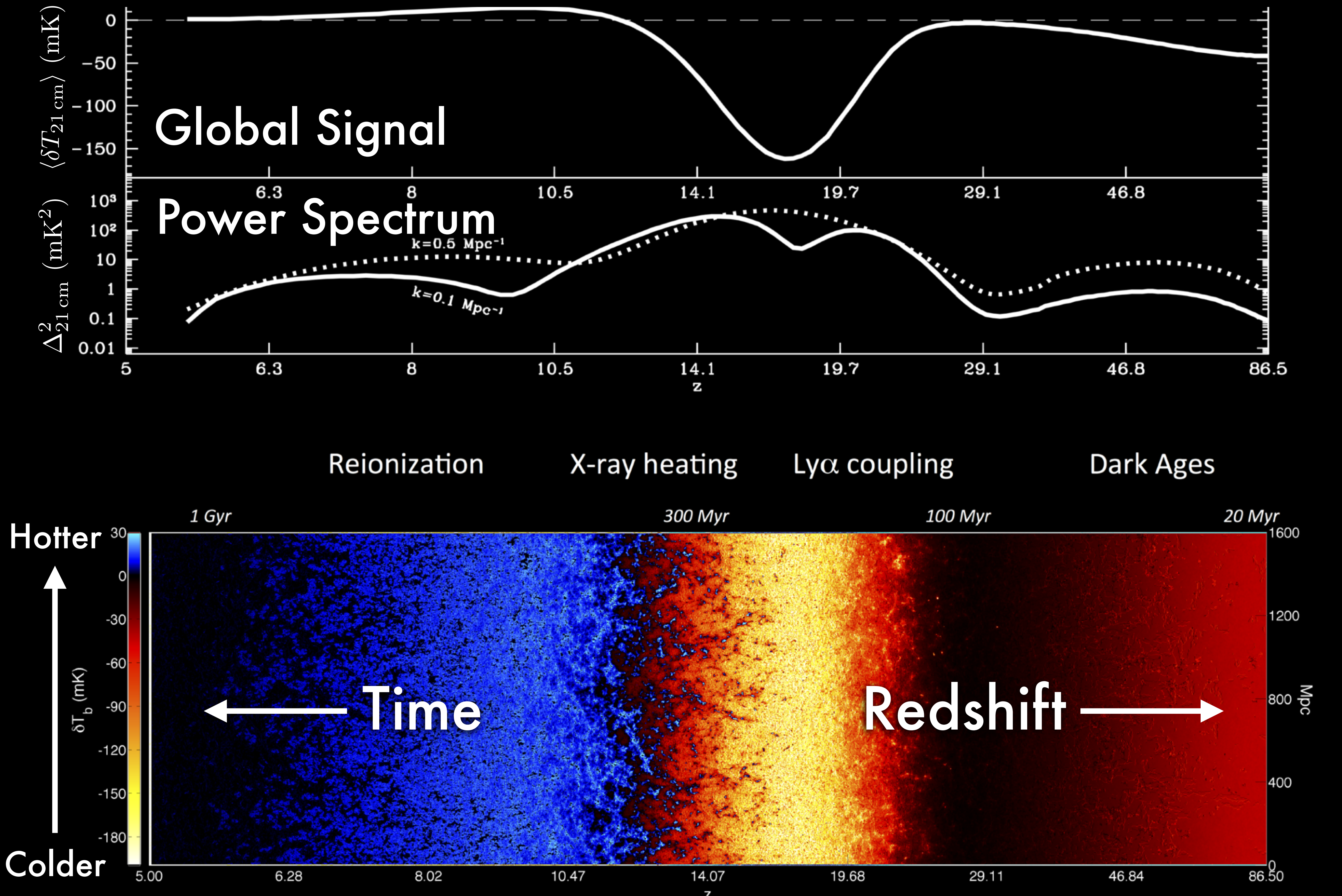
- What did the first stars look like? How and when how did they form?
- How did they die and were they the LIGO black hole progenitors? Or the seeds of supermassive black holes?
- What determined the thermal history of the intergalactic medium? Are there new physics at play?
- What reionized the universe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

If we want to understand the history of 21 cm signal, we have two primary statistical probes.



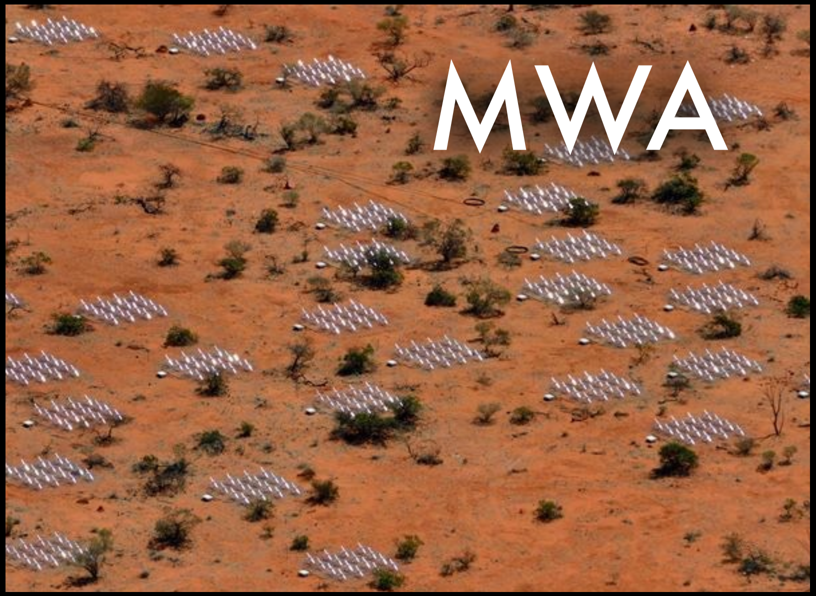
Mesinger et al. (2016)



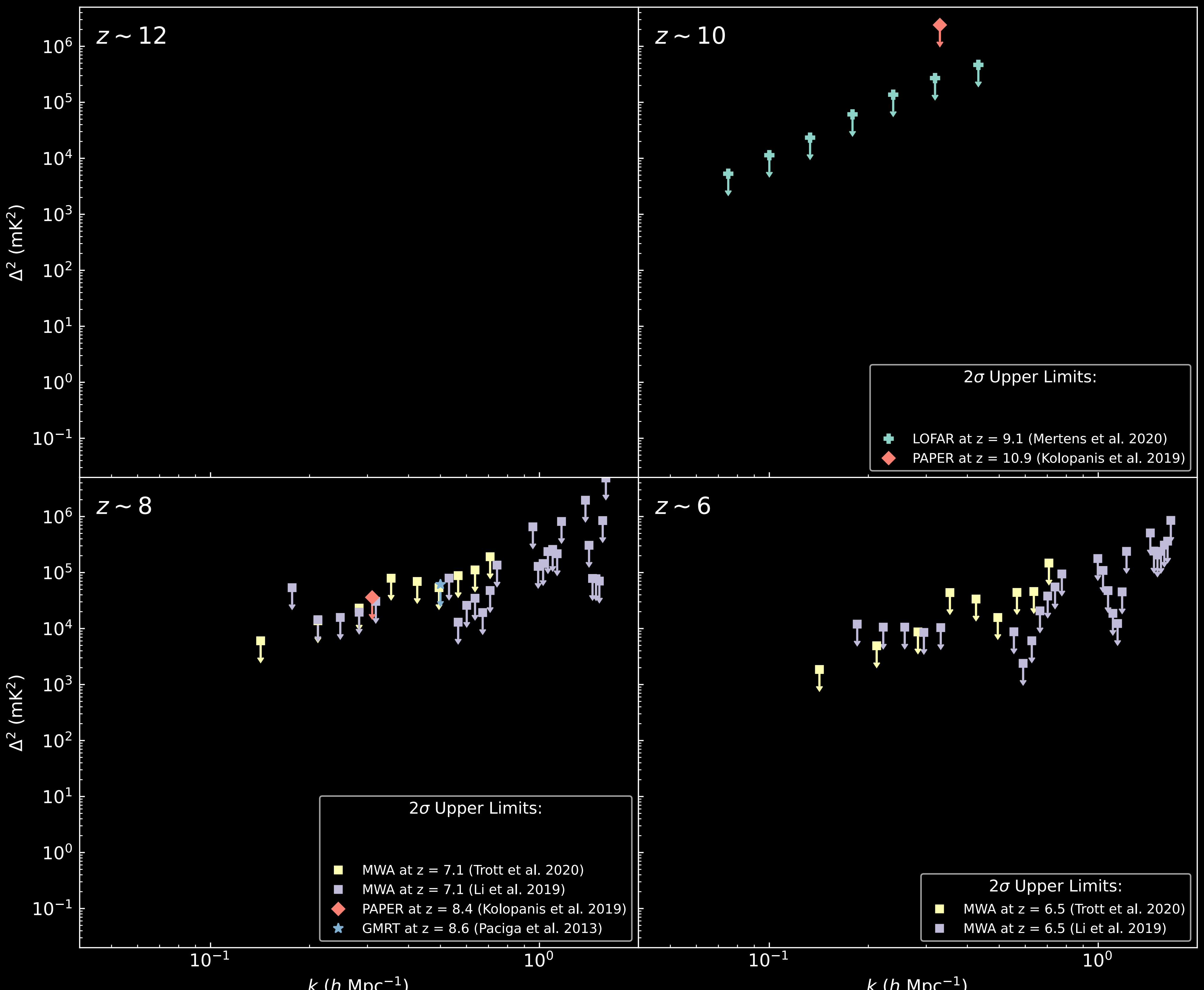
Mesinger et al. (2016)

On the global signal side, there's a tension between a reported EDGES detection at $z \approx 17$ and a SARAS non-detection.

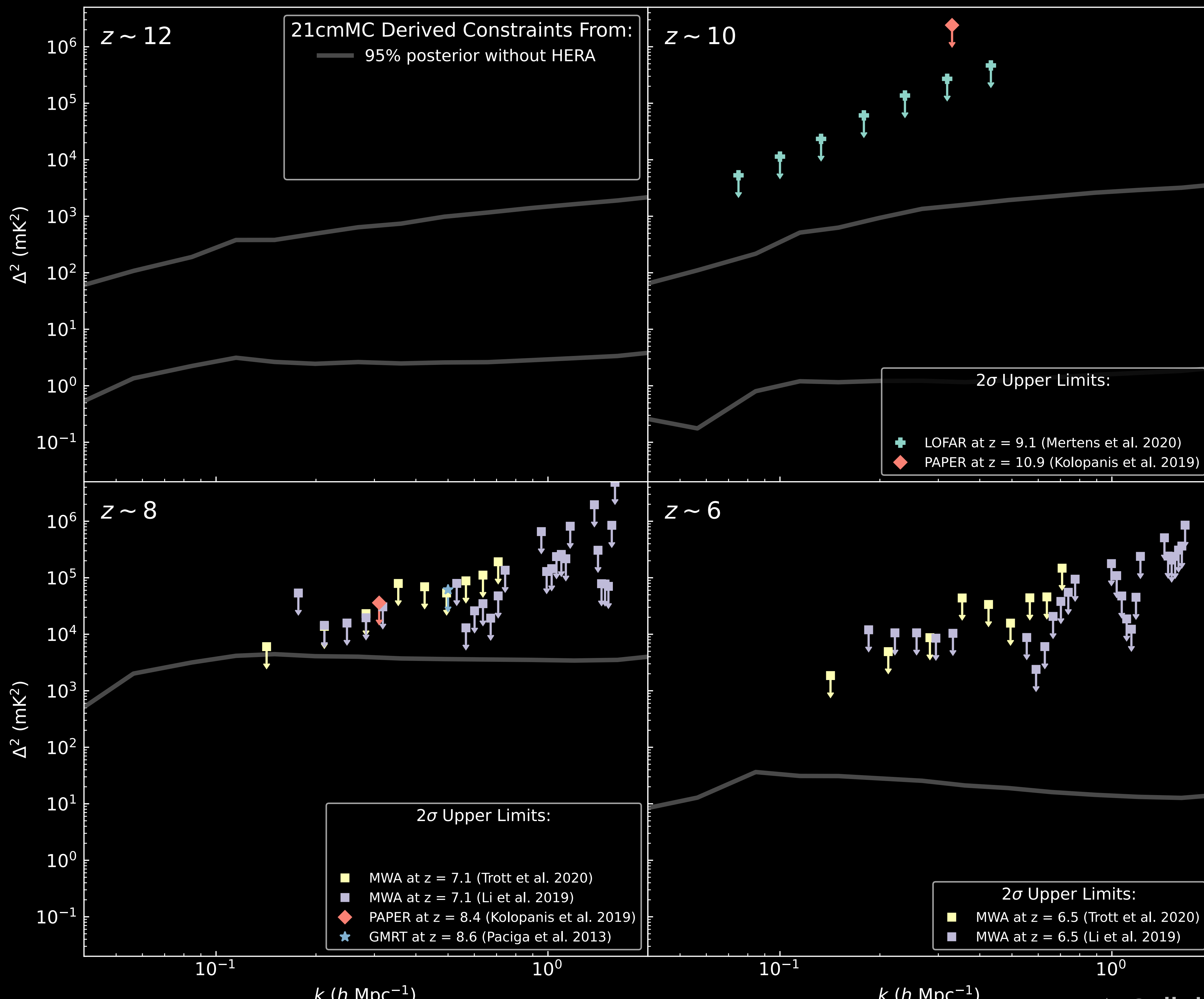
For the 21 cm power spectrum, a first generation of interferometers got us started, deploying different strategies.



Until last year, this was the state of the field:



Using 21cmMC, a wide range of power spectra were still possible, even with CMB and galaxy LF constraints.



HERA Collaboration (2022b)


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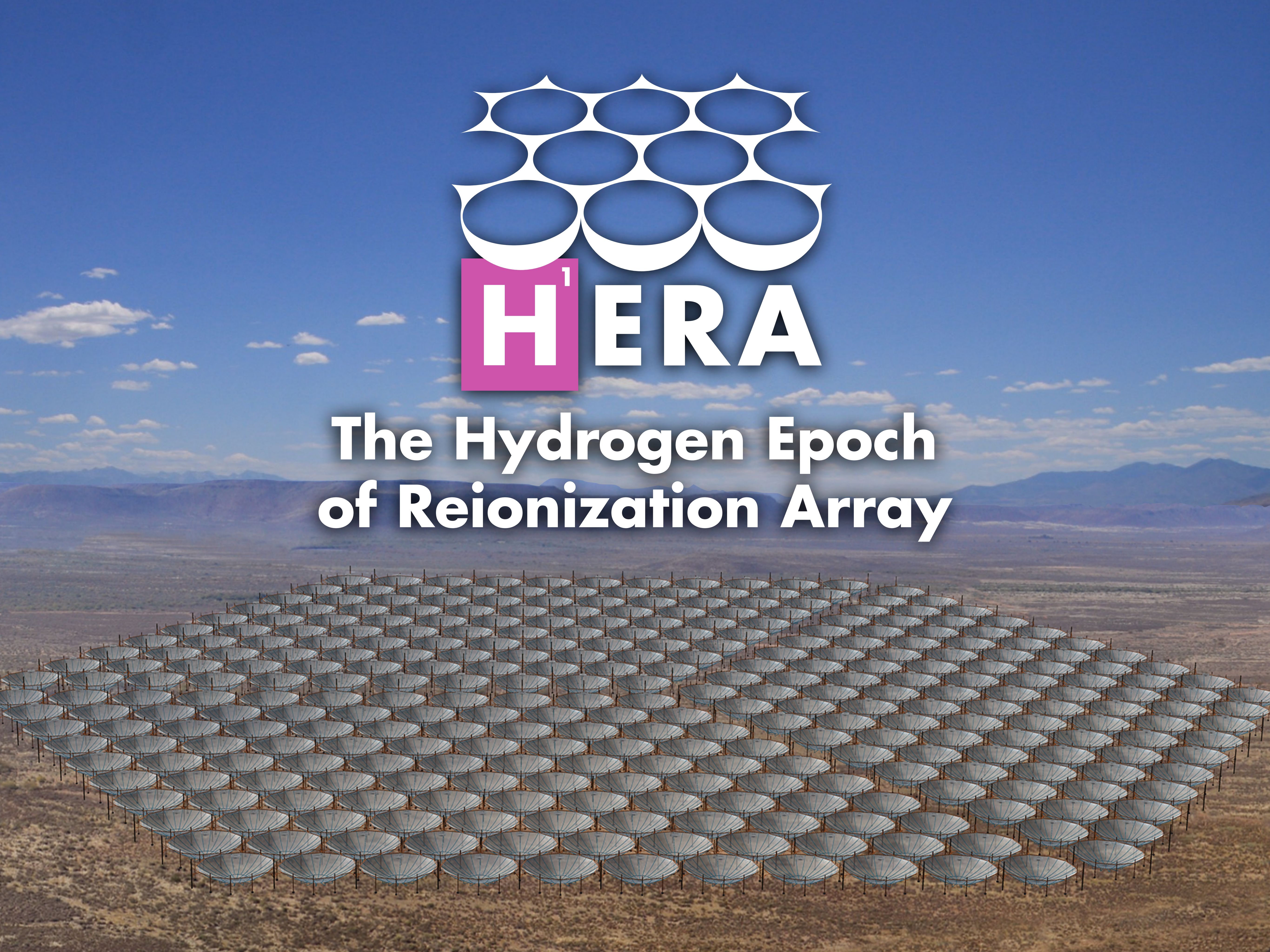
So we went bigger...


H[1] ERA
The Hydrogen Epoch
of Reionization Array

HERA
The Hydrogen Epoch of Reionization Array
CAL POLY POMONA
UCLA
SCUOLA NORMALE SUPERIORE
UNIVERSITY OF CAMBRIDGE
Queen Mary University of London
NRF National Research Foundation
SARAO South African Radio Astronomy Observatory
SKA AFRICA SQUARE KILOMETRE ARRAY
NRAO
Penn University of Pennsylvania
McGill UNIVERSITY
BROWN
HARVARD
UNIVERSITY OF KWAZULU-NATAL
RHODES UNIVERSITY Where leaders learn
UNIVERSITY of the WESTERN CAPE

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 · 1861

UNIVERSITY OF WASHINGTON · 1861

SCUOLA NORMALE SUPERIORE

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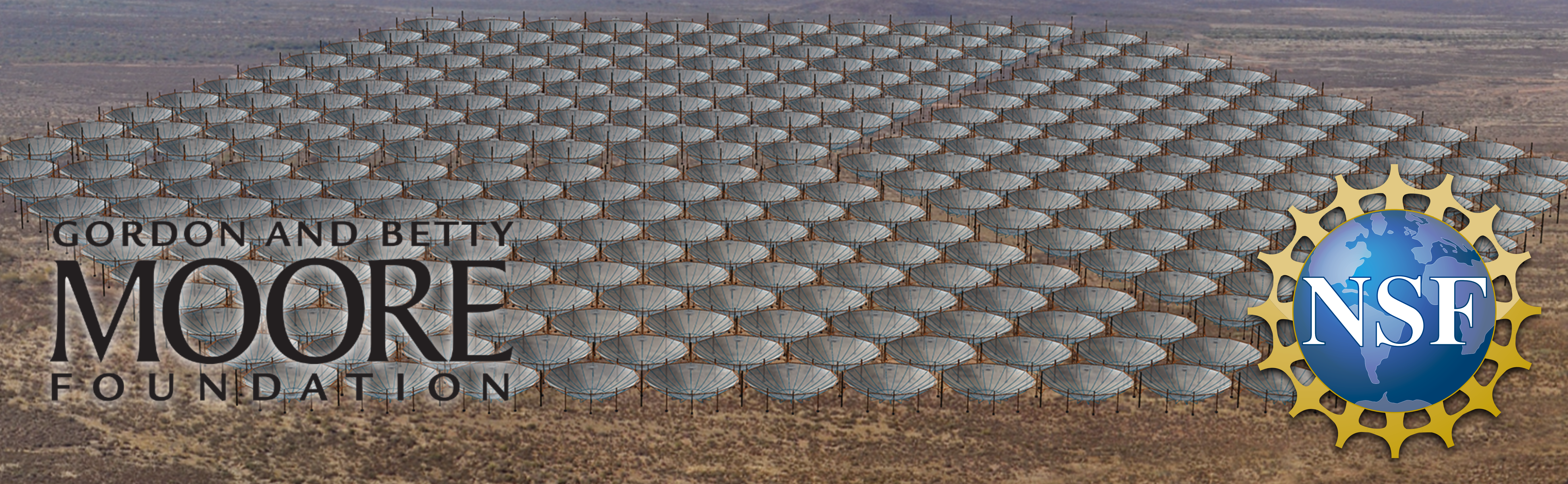
NRAO

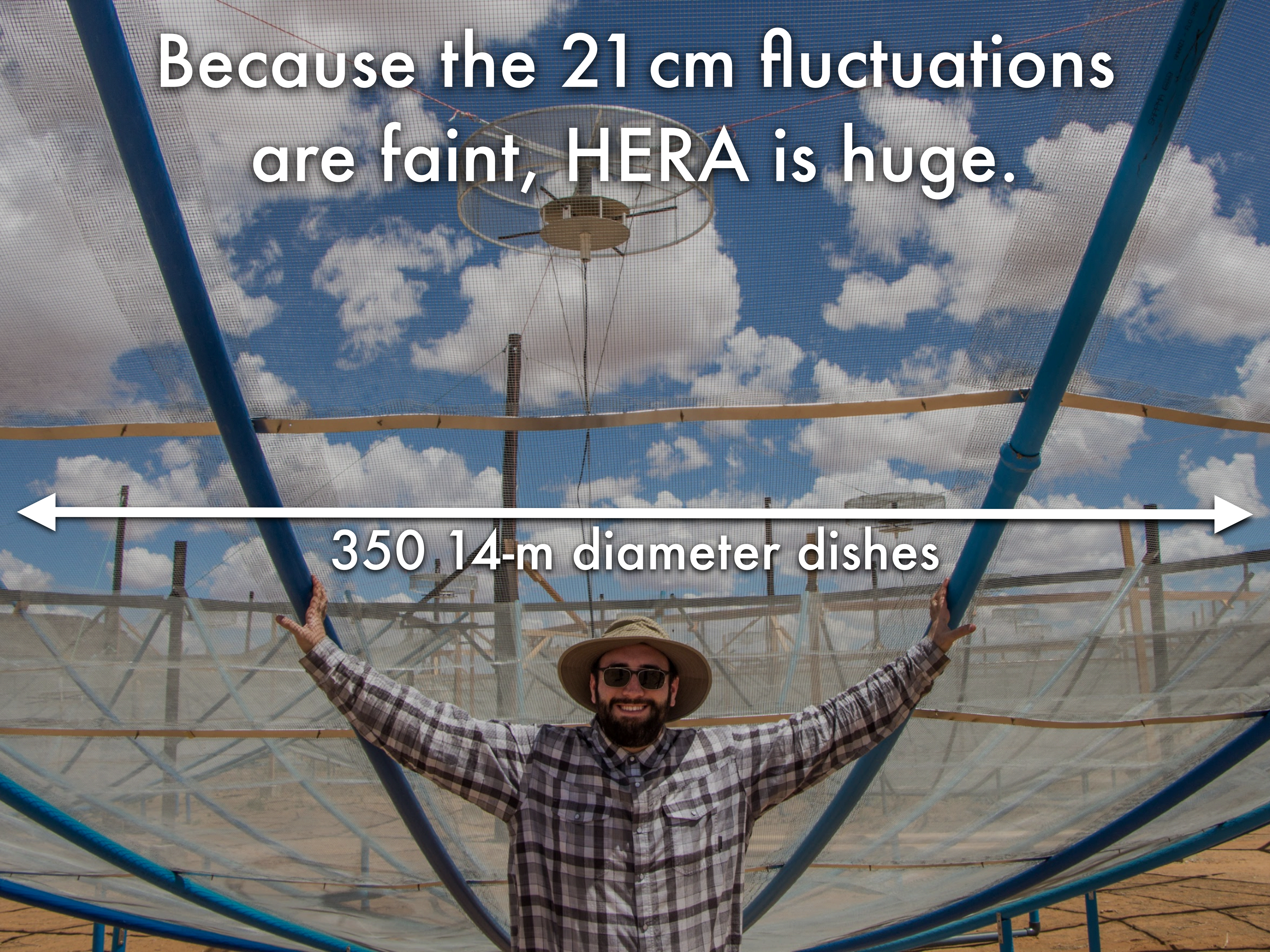
RHODES UNIVERSITY Where leaders learn

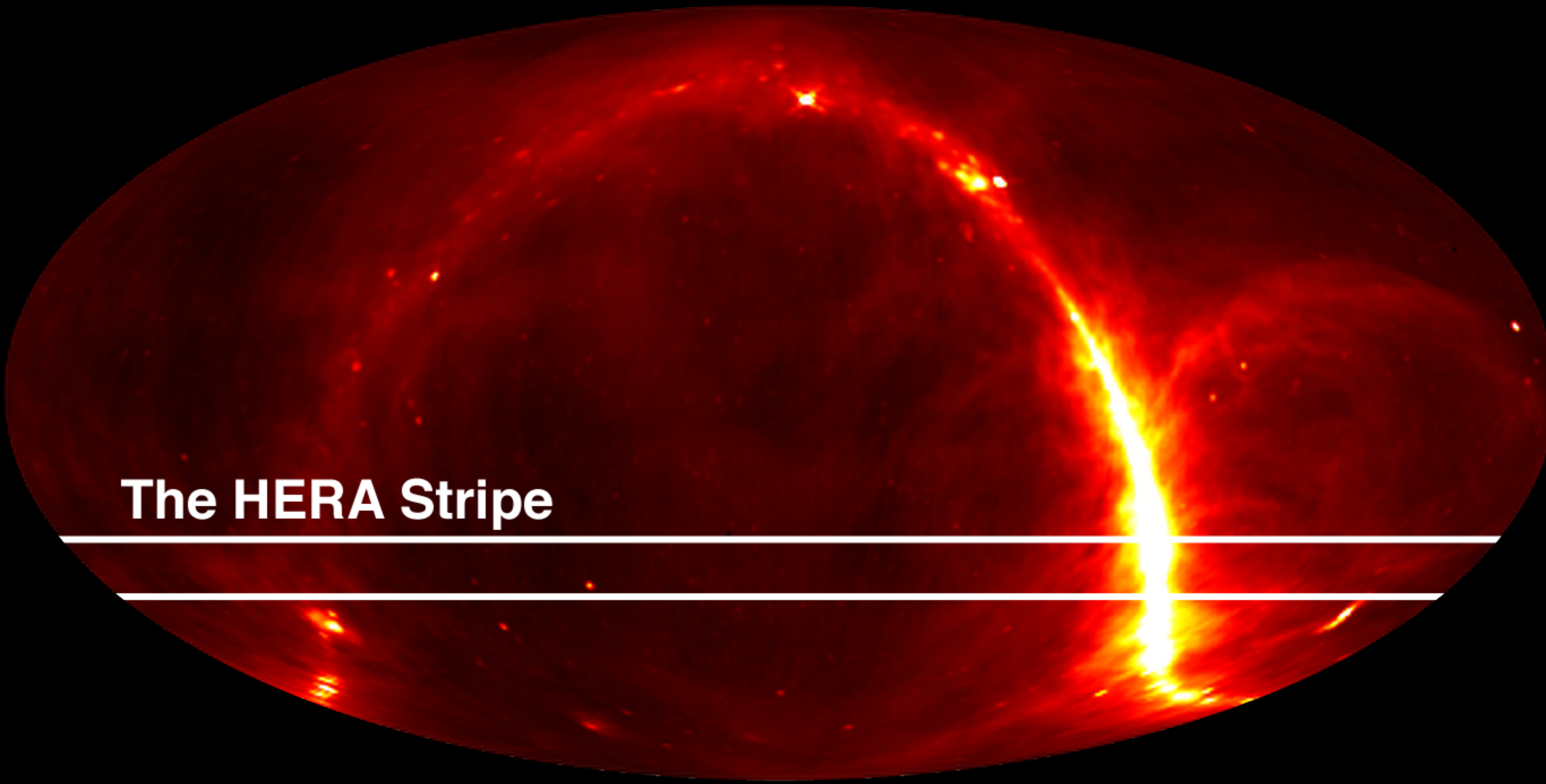
UNIVERSITY of the WESTERN CAPE · RESPICE PROSPICE



GORDON AND BETTY MOORE FOUNDATION

NSF


Because the 21 cm fluctuations are faint, 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.

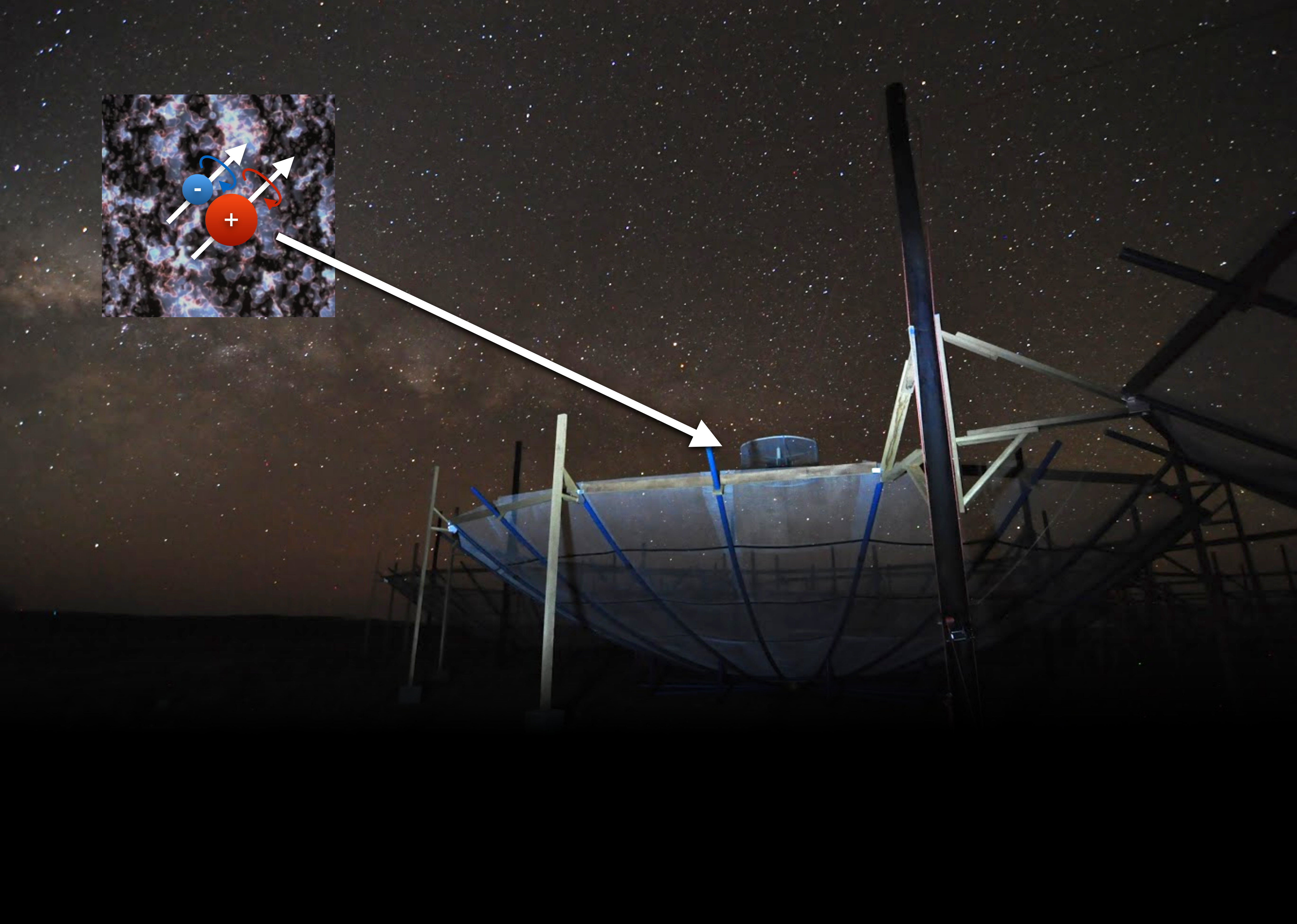
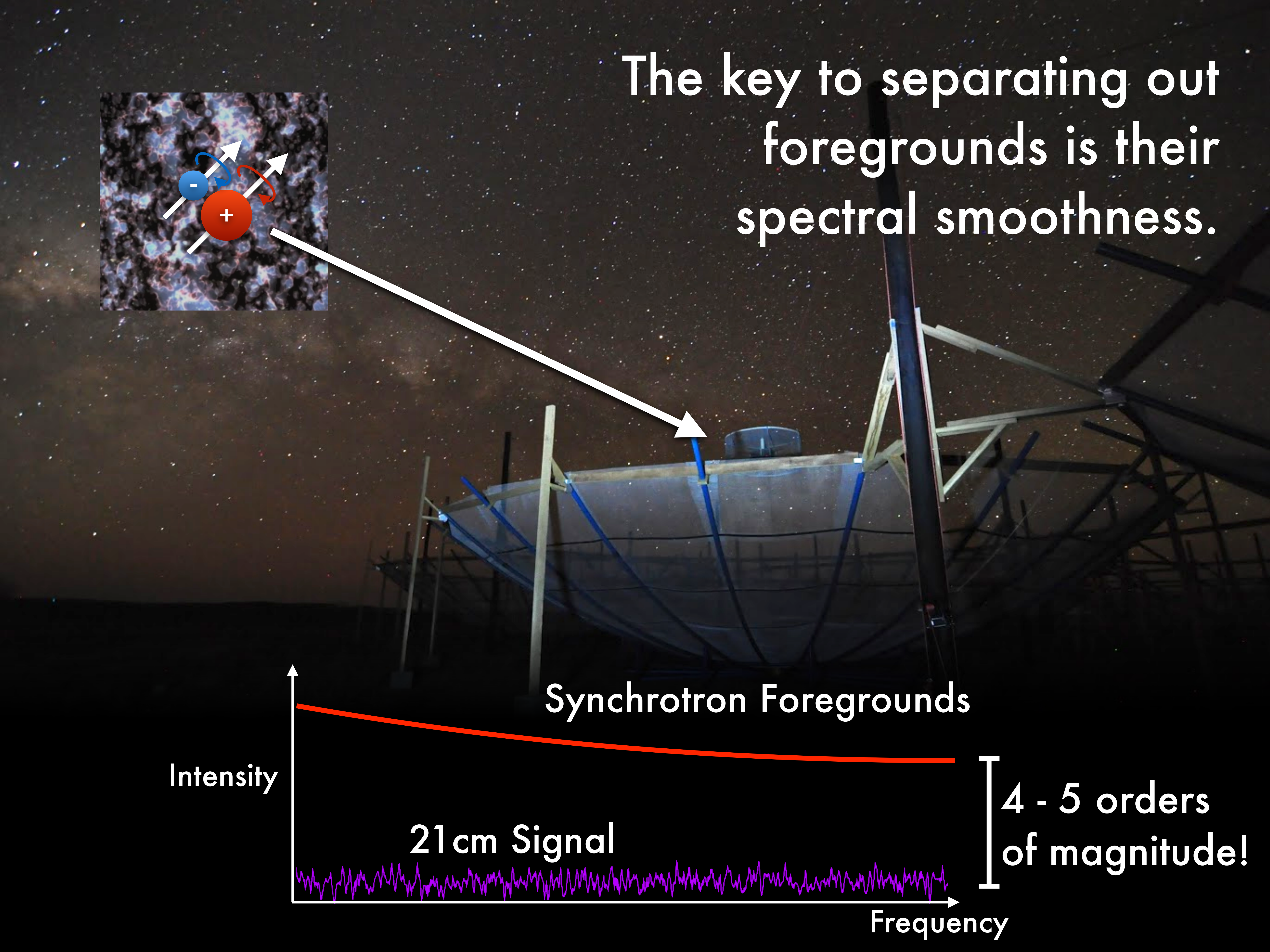
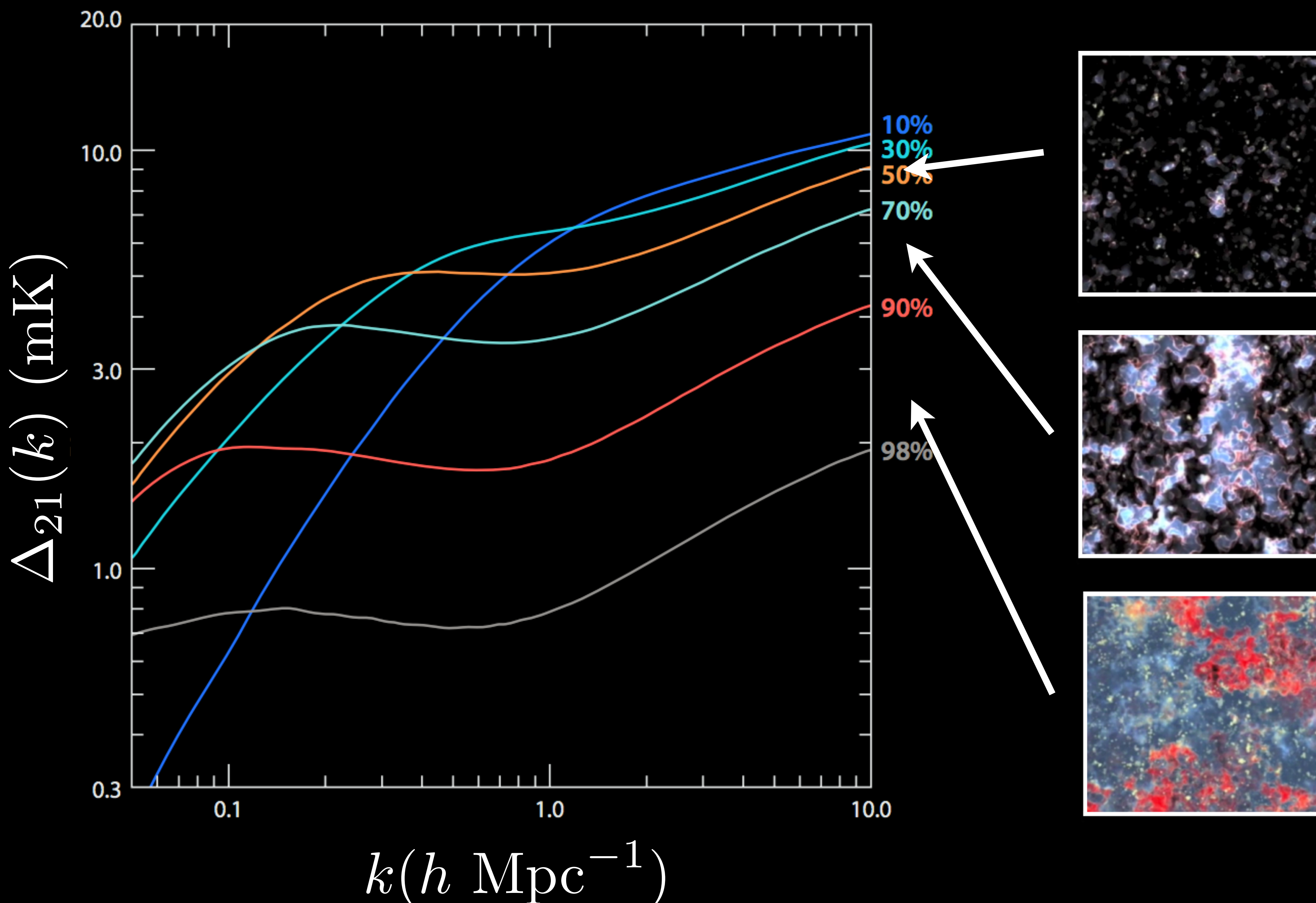


Photo: Carina Cheng


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...



Barkana (2009), Morales & Wyithe (2010)

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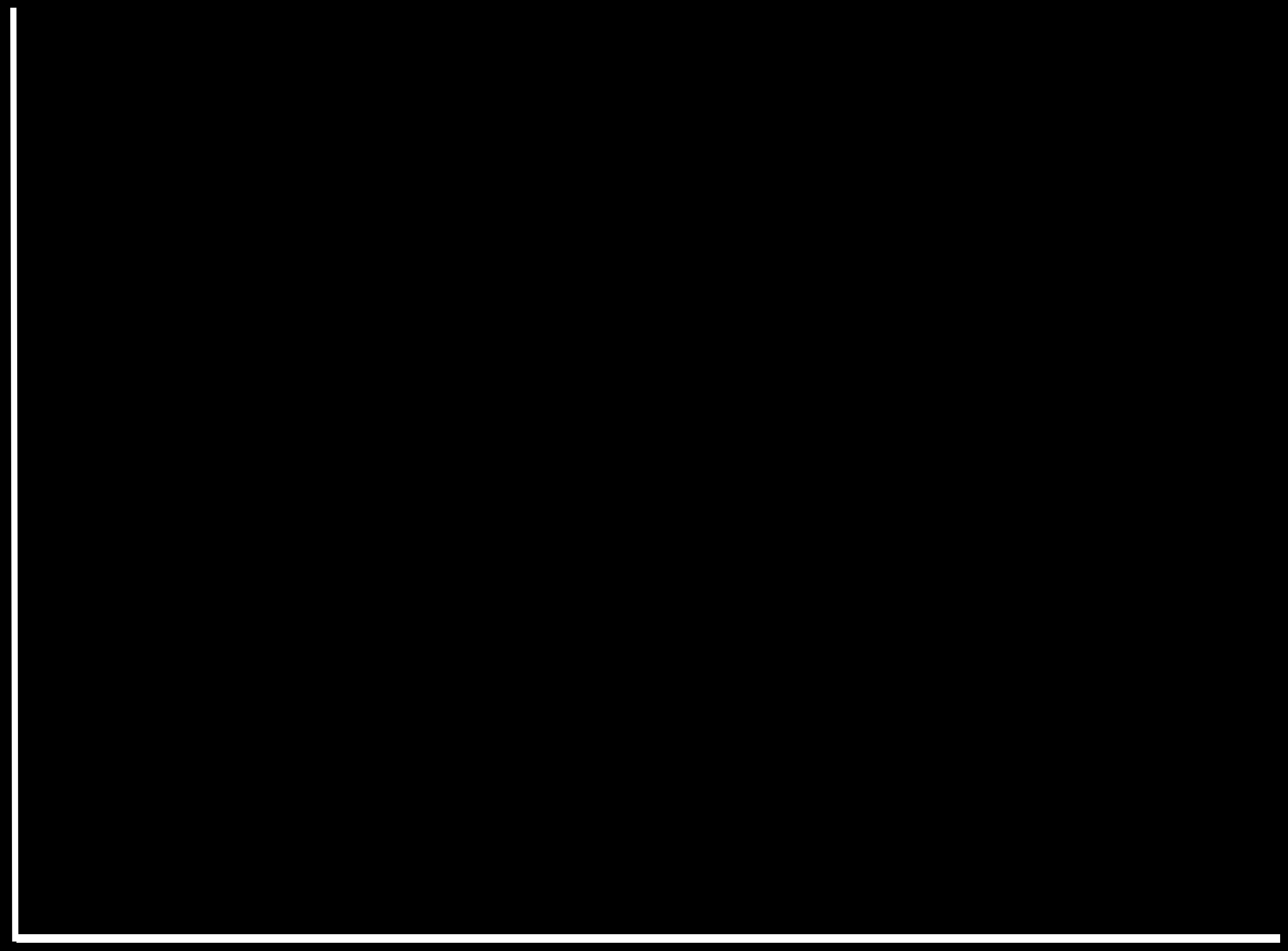
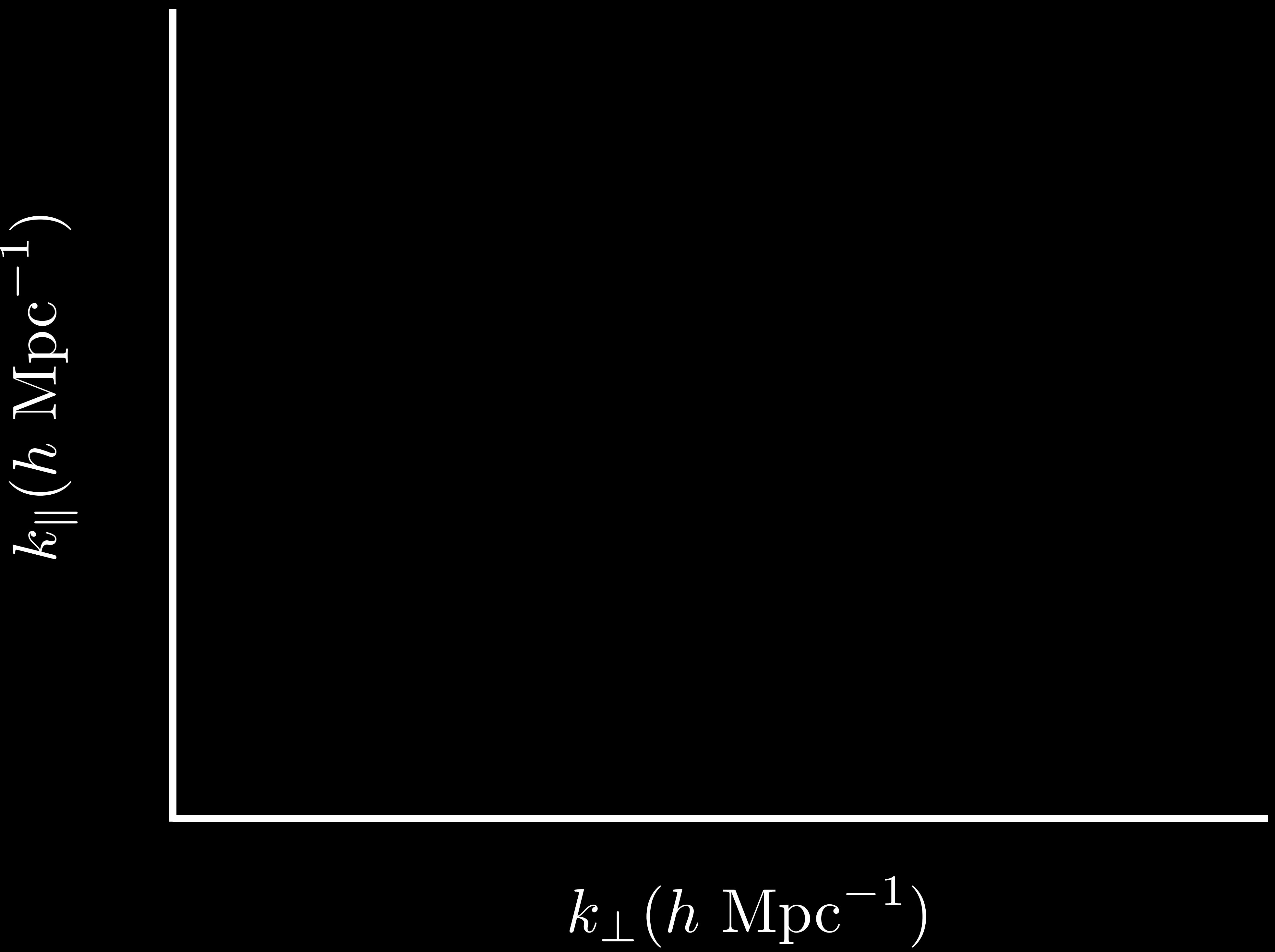
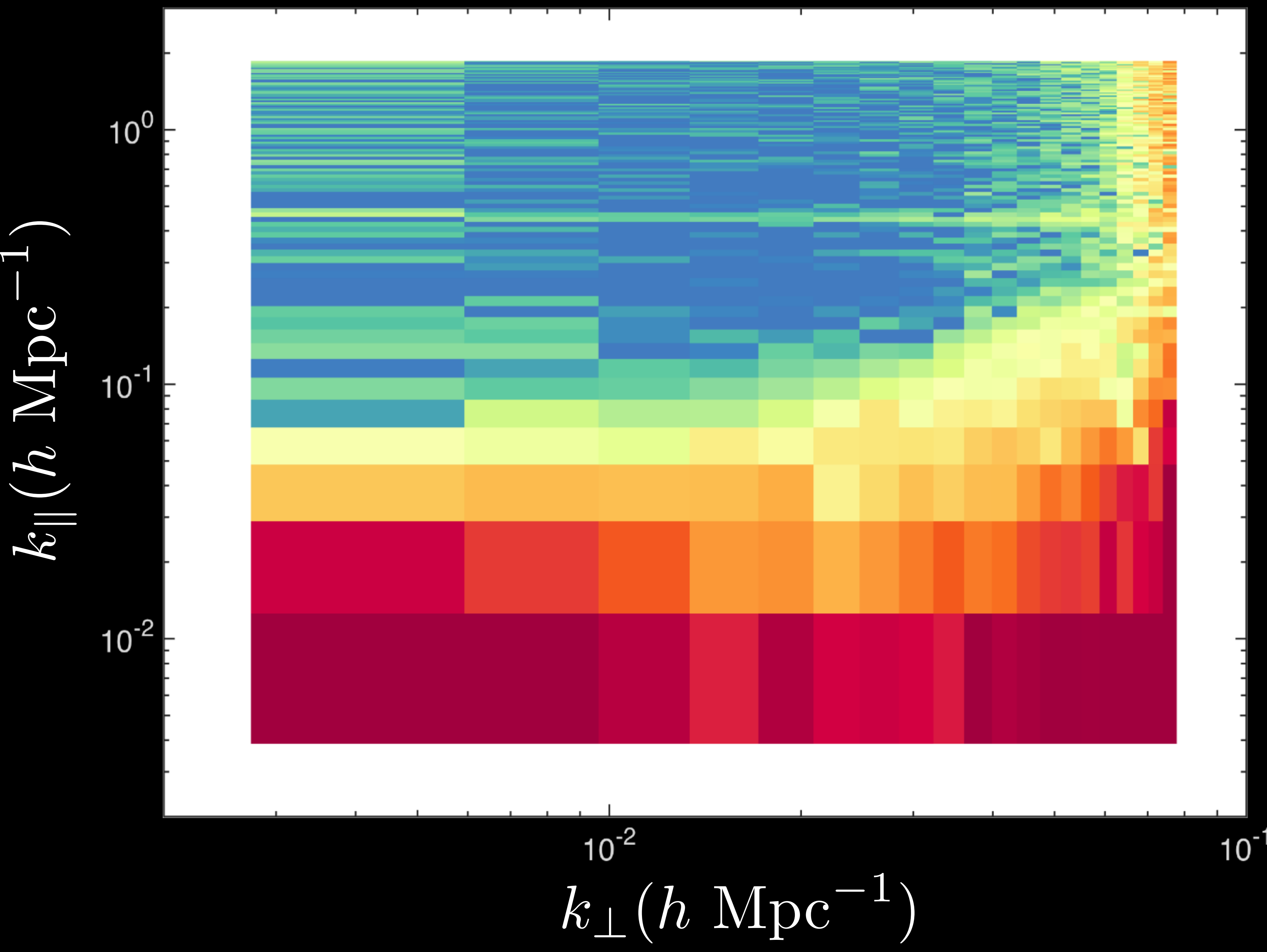


We separate out Fourier modes parallel and perpendicular to the line of sight.



And we find a "window."



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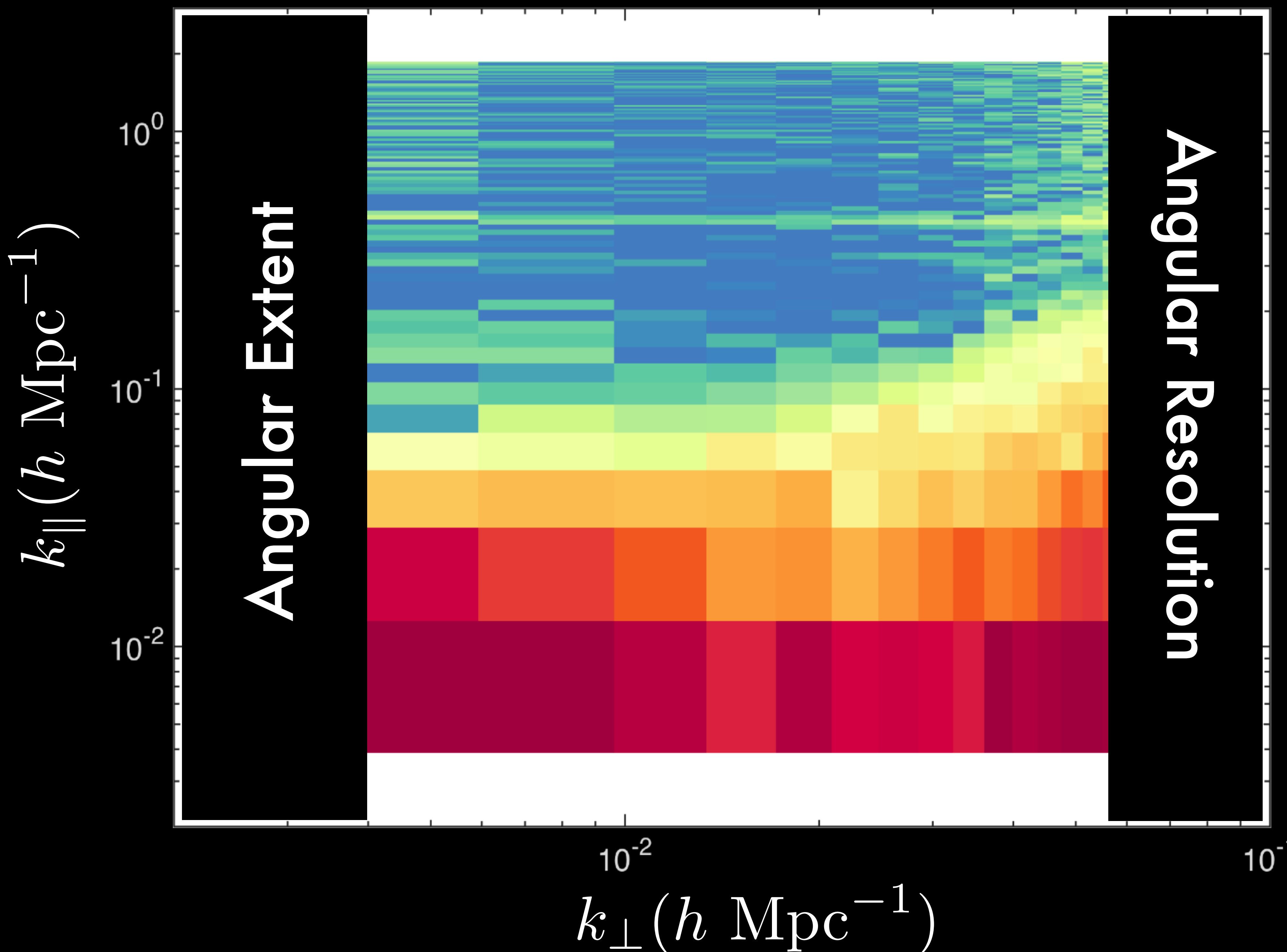

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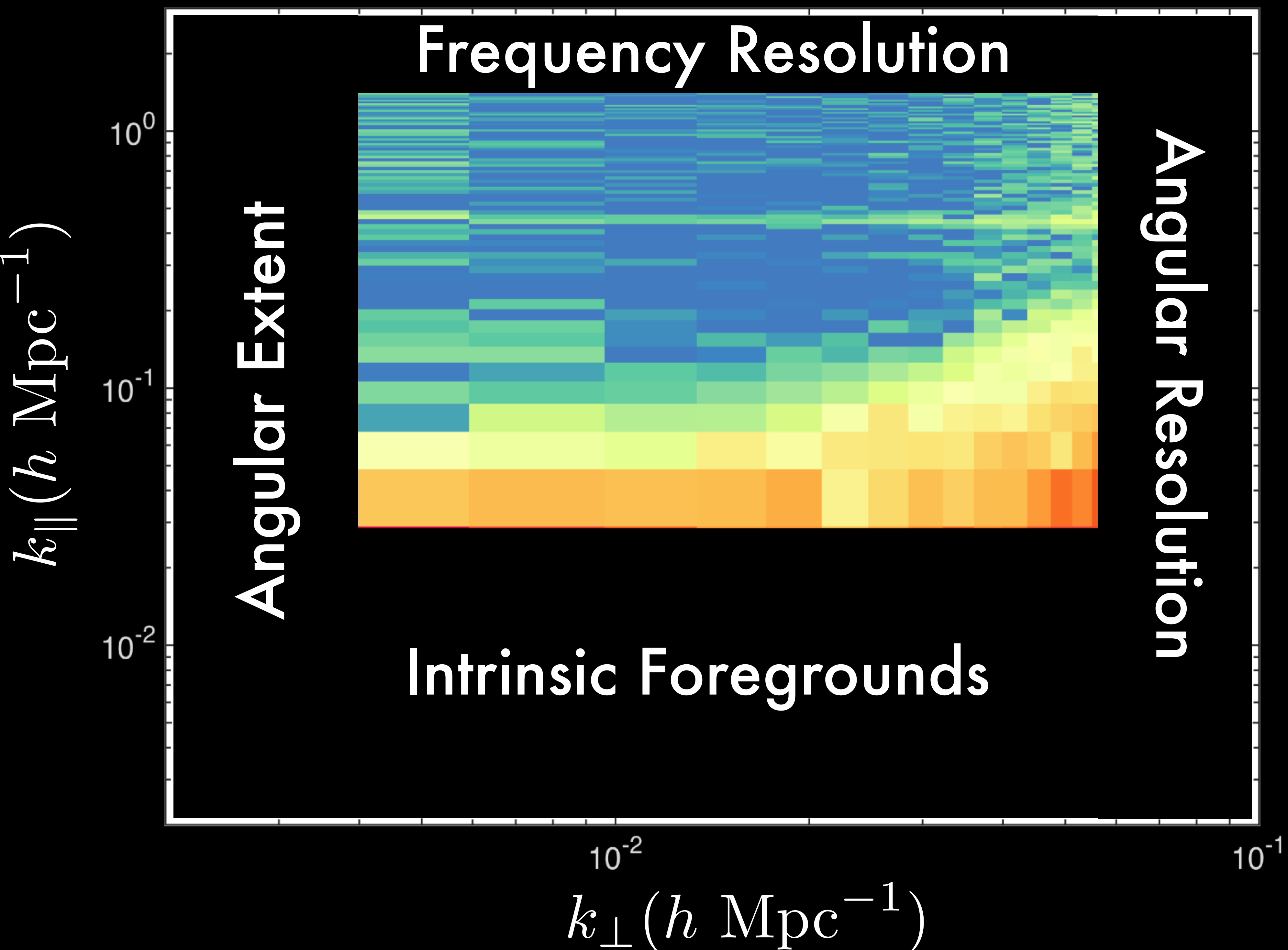

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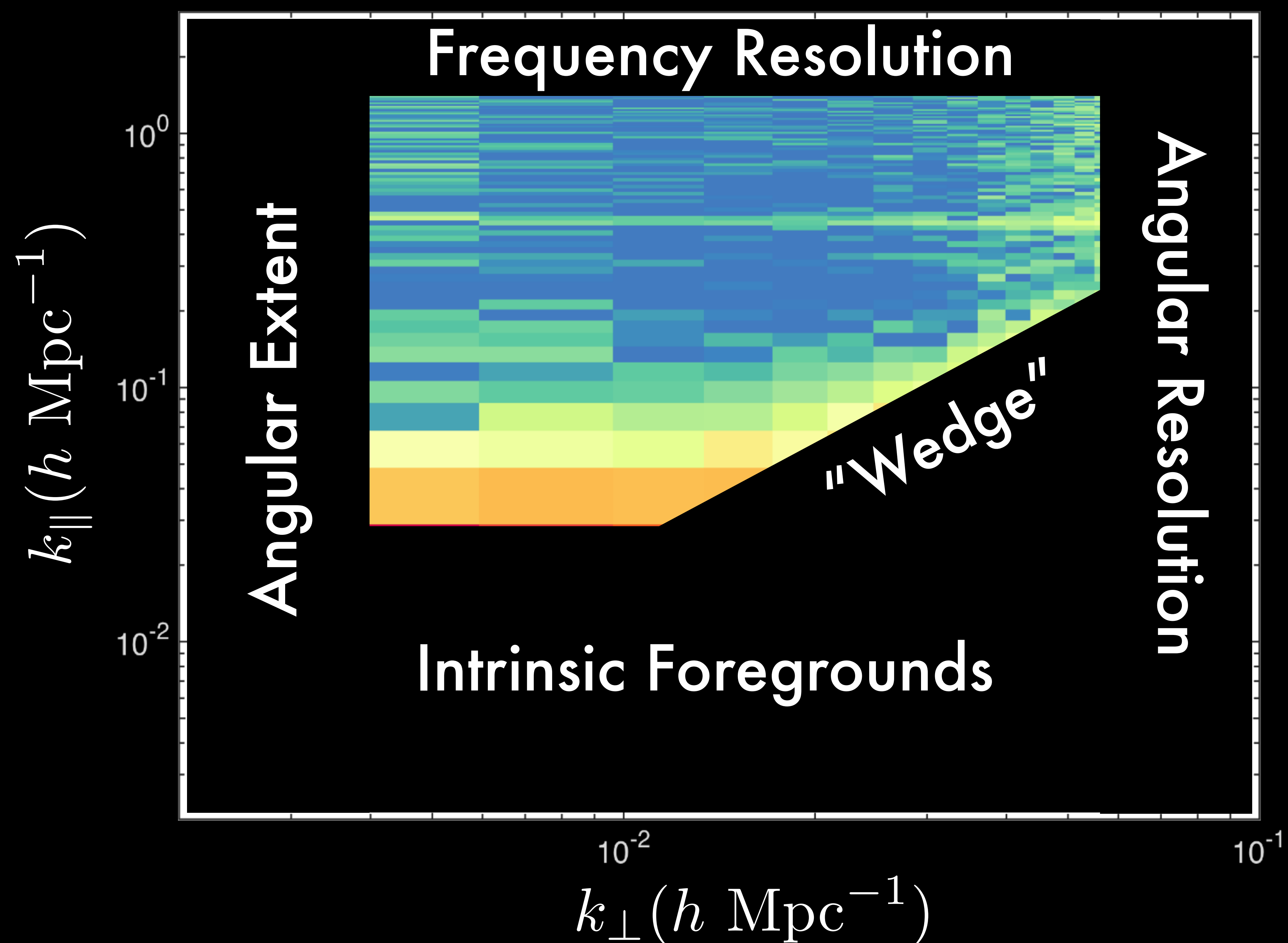
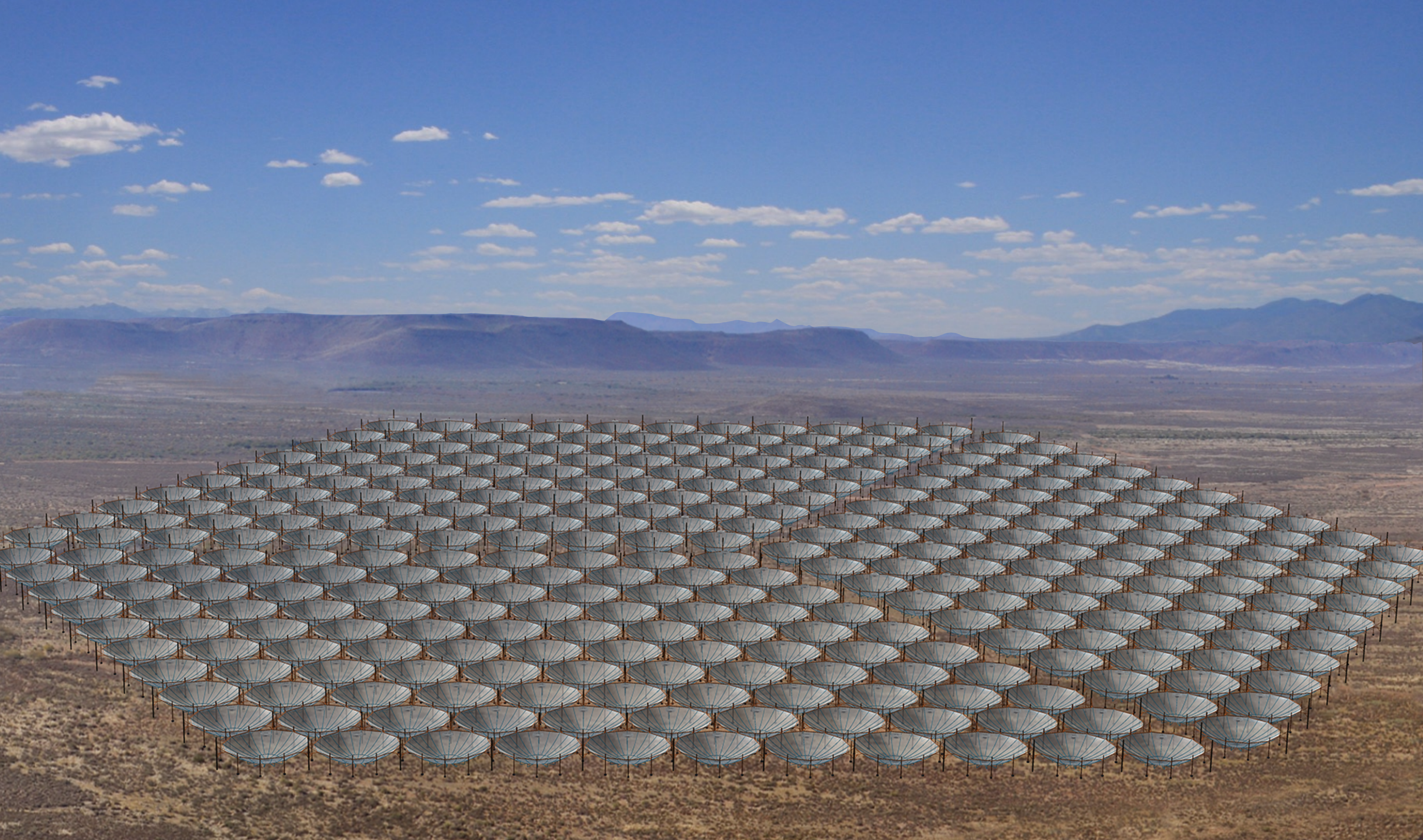
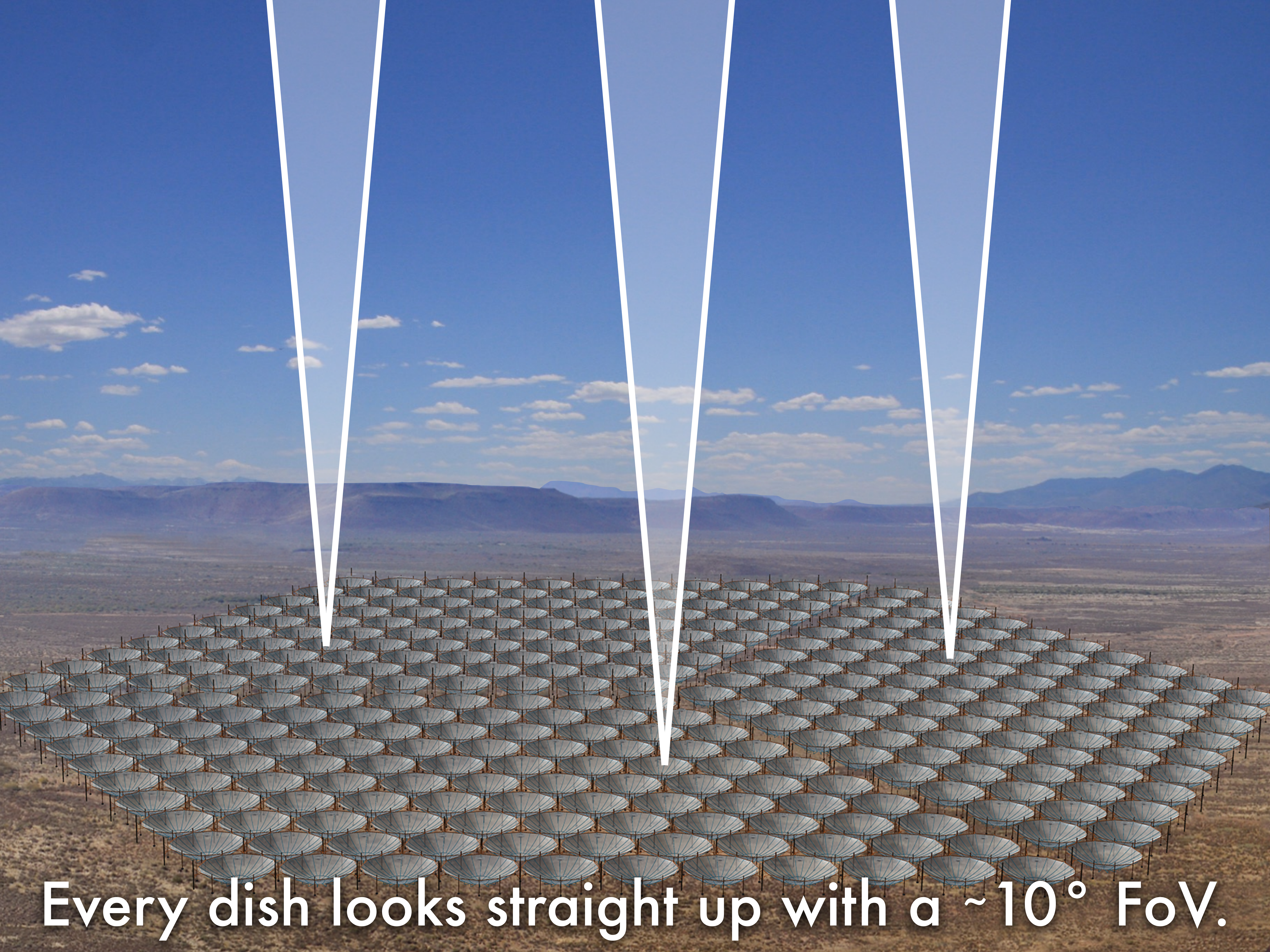
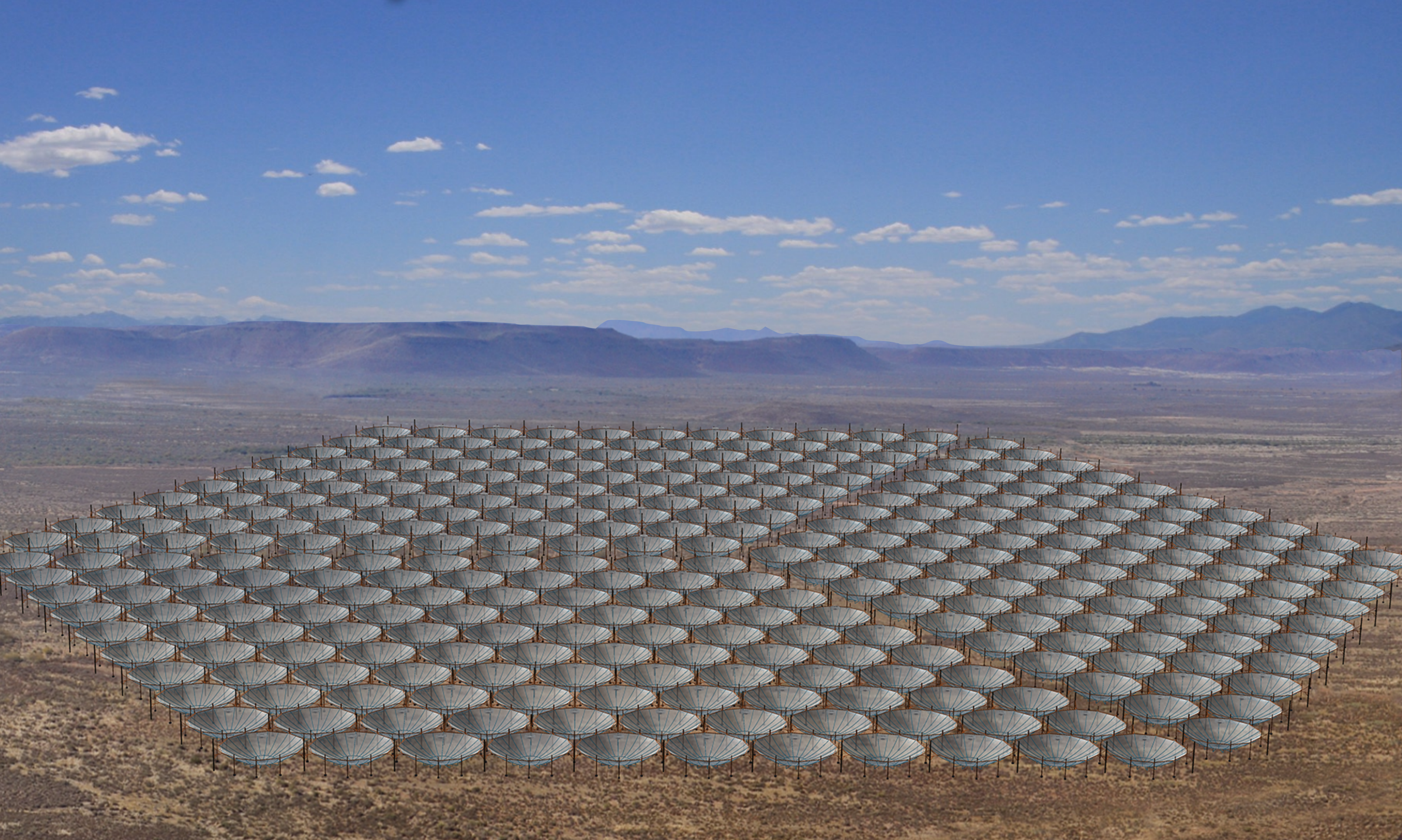


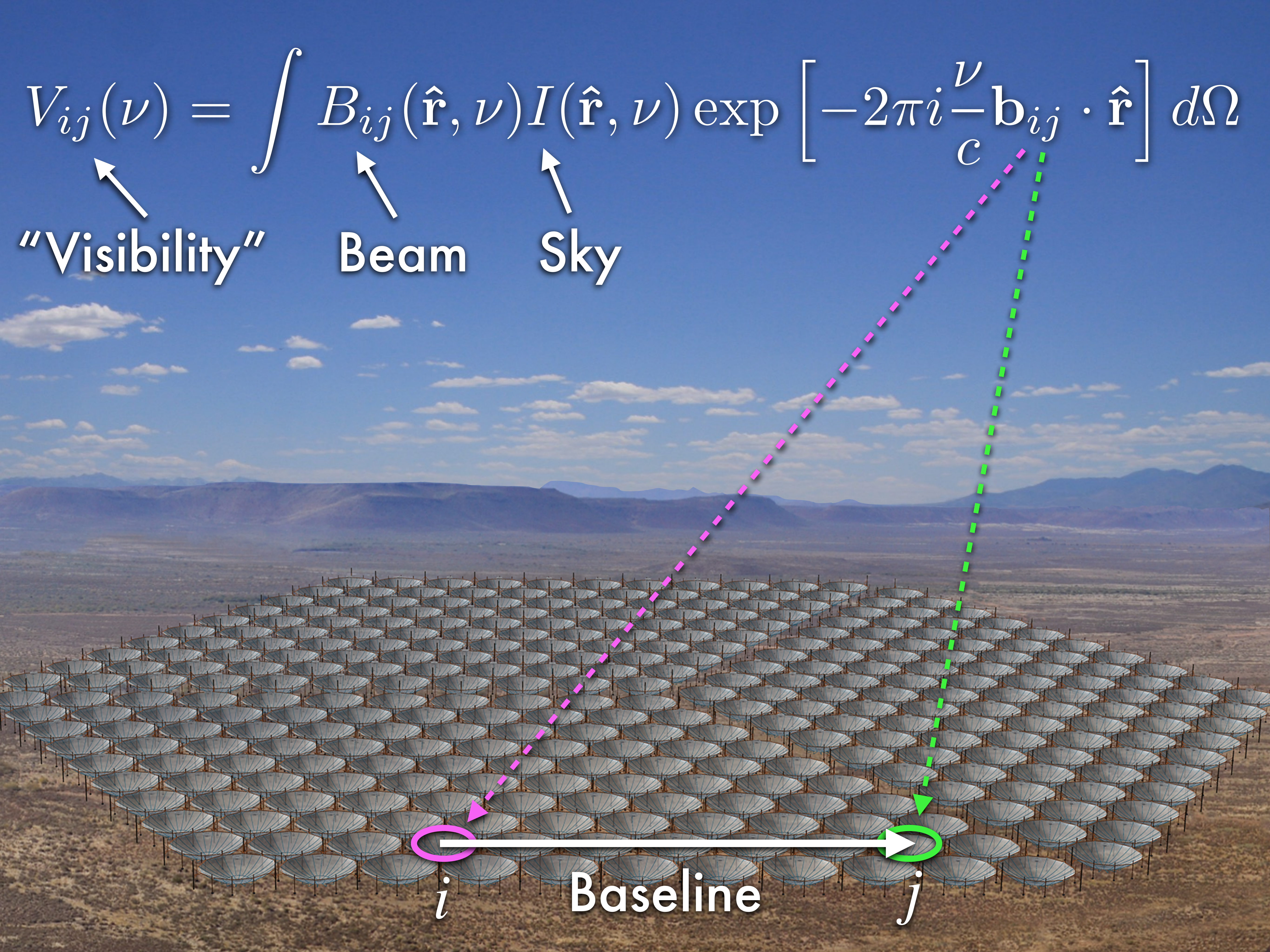
What does HERA actually measure?




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

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




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

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Video: Veritasium

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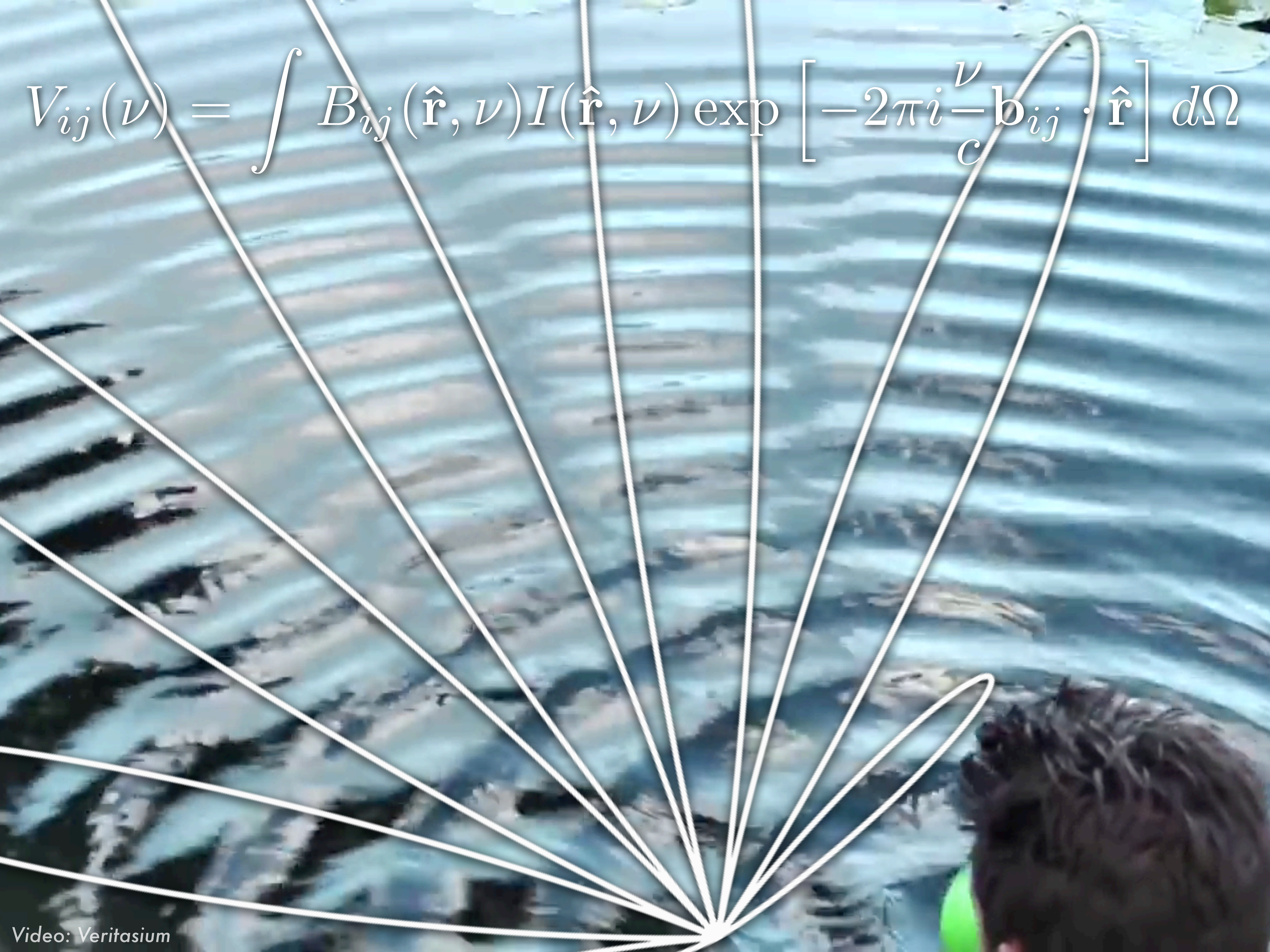

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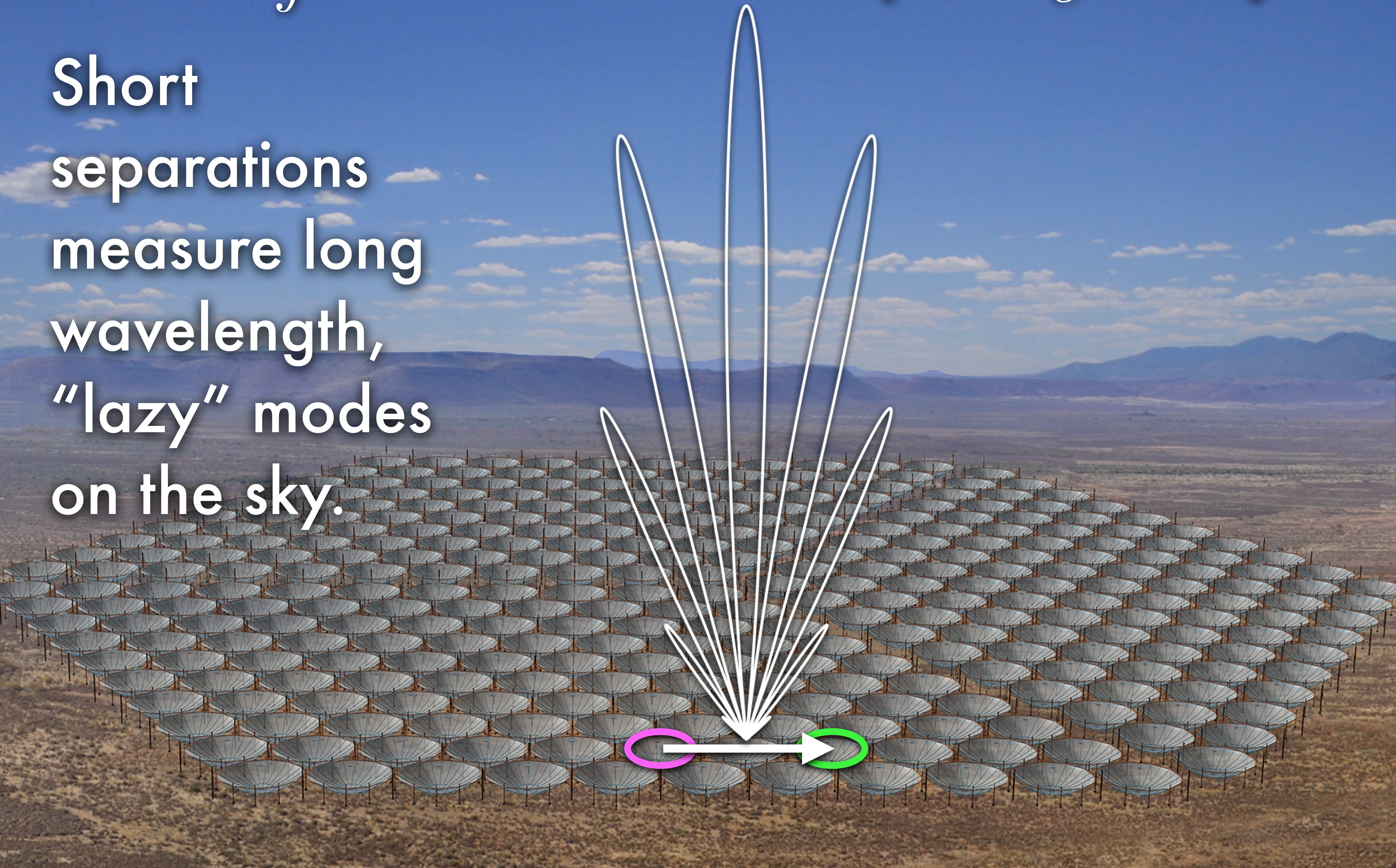
Short separations measure long wavelength, “lazy” modes on the sky.



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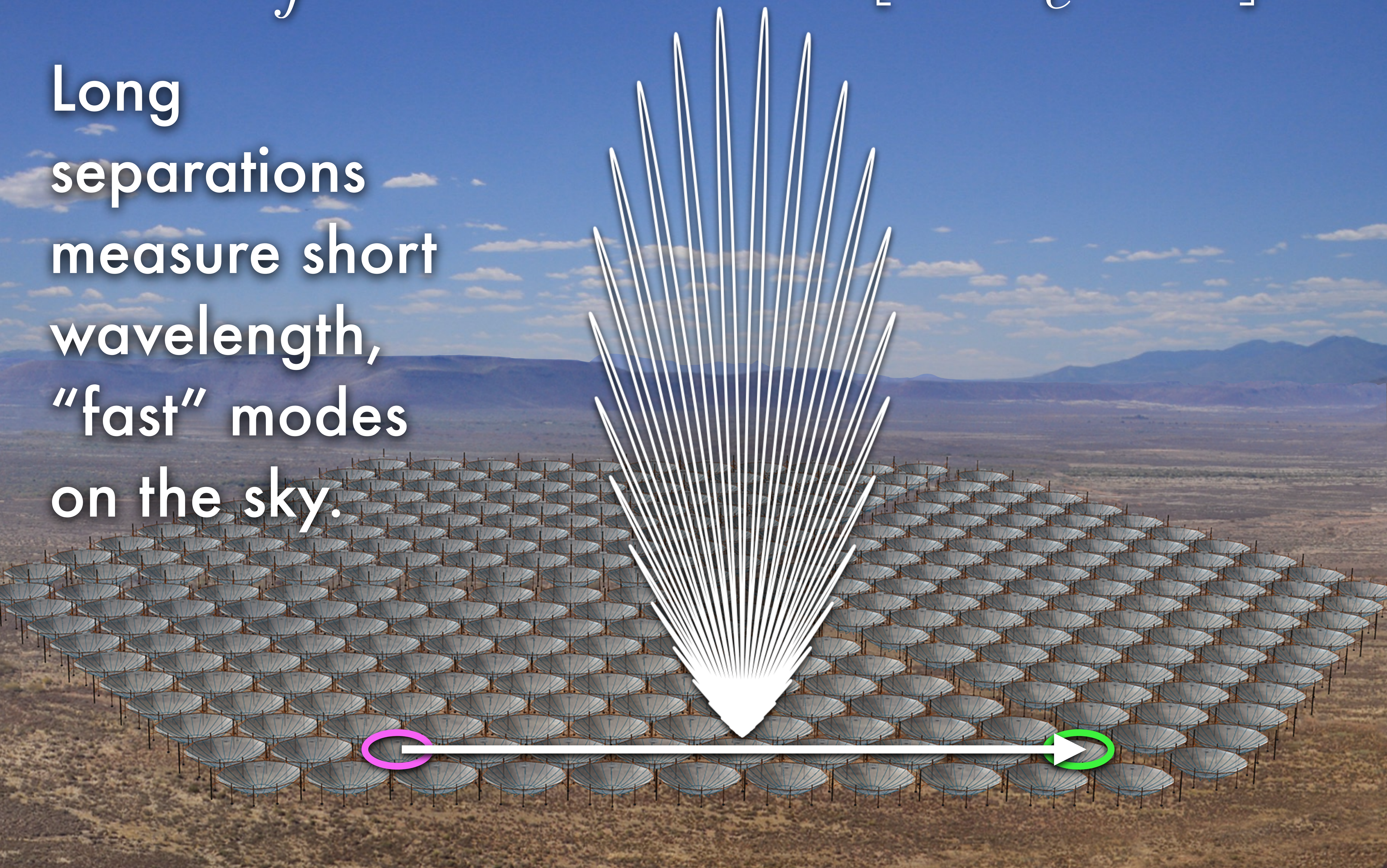
Long separations measure short wavelength, “fast” modes on the sky.



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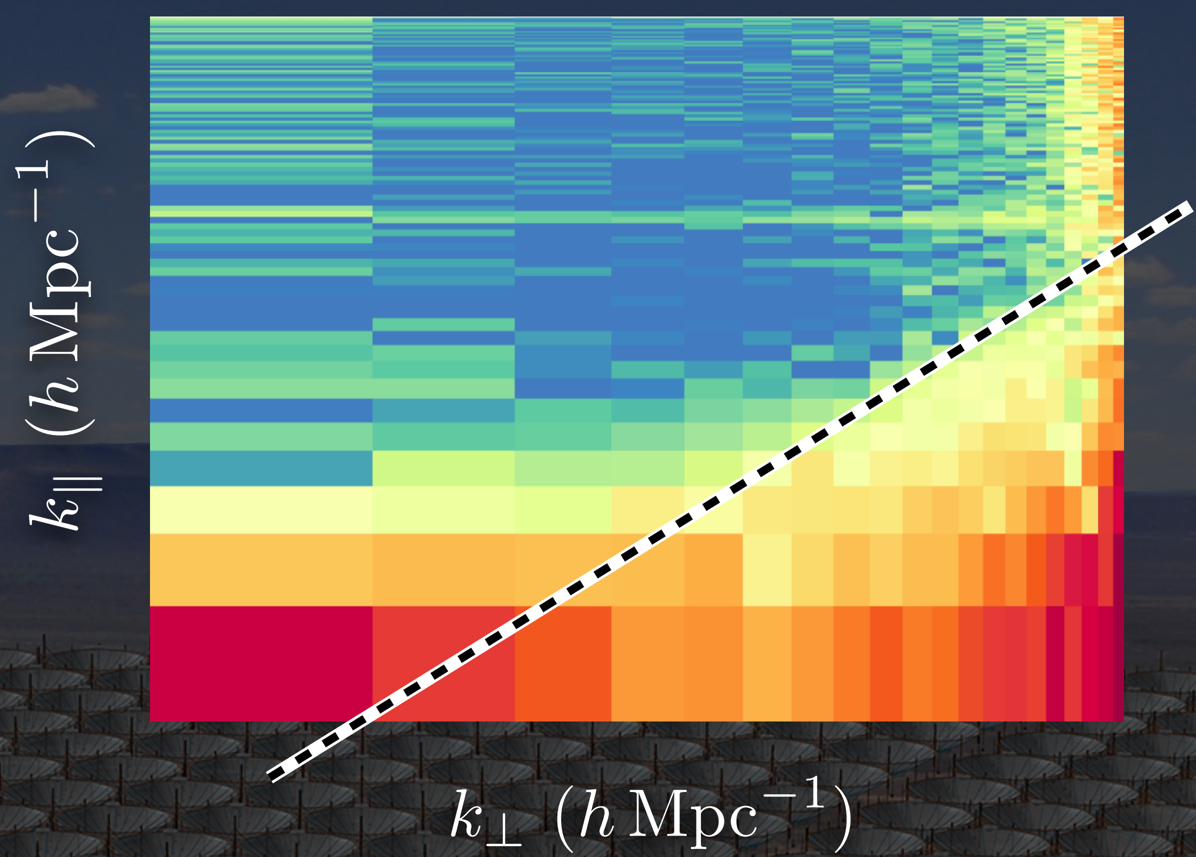

$k_\perp$ is effectively baseline length.

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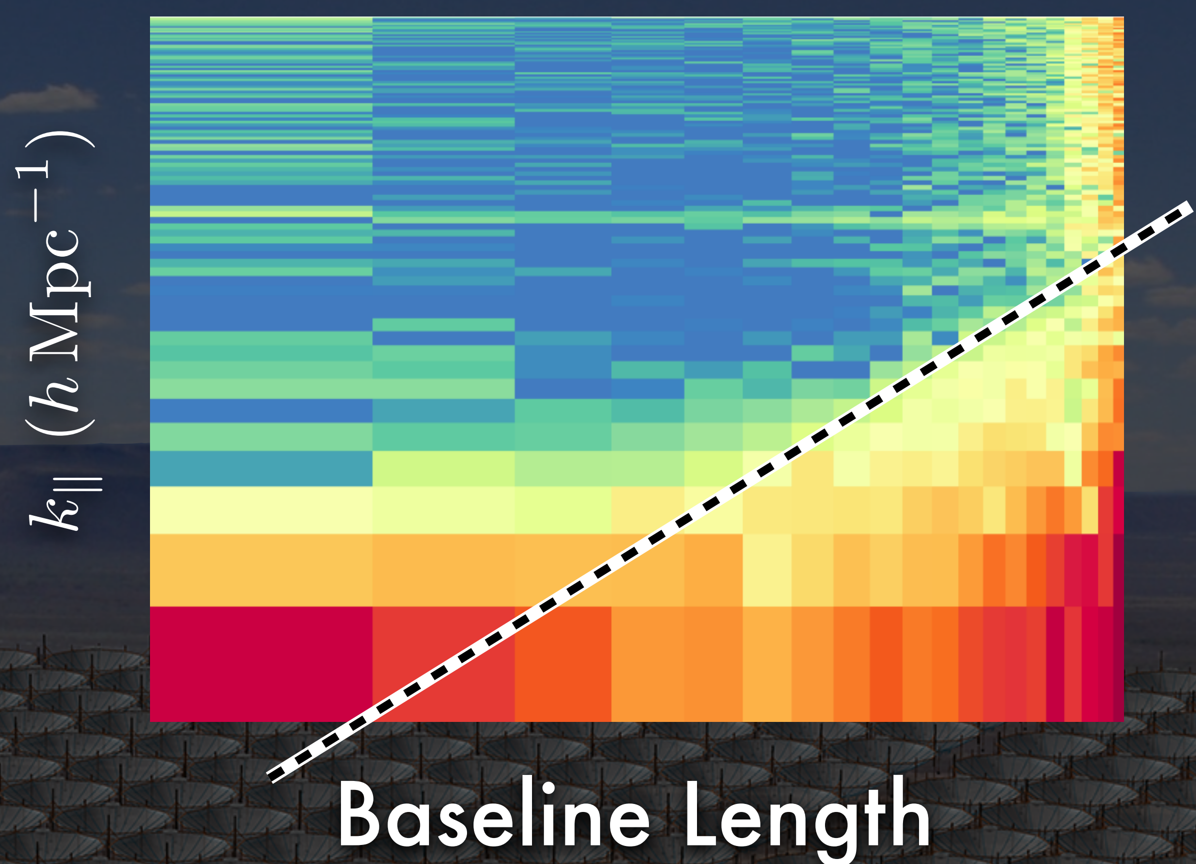

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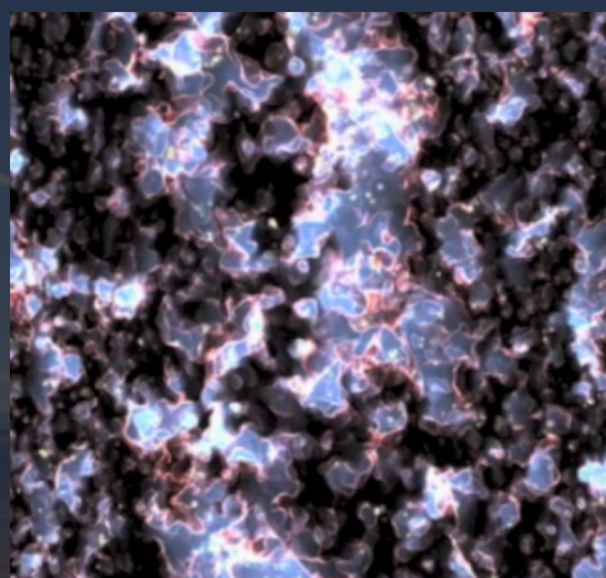

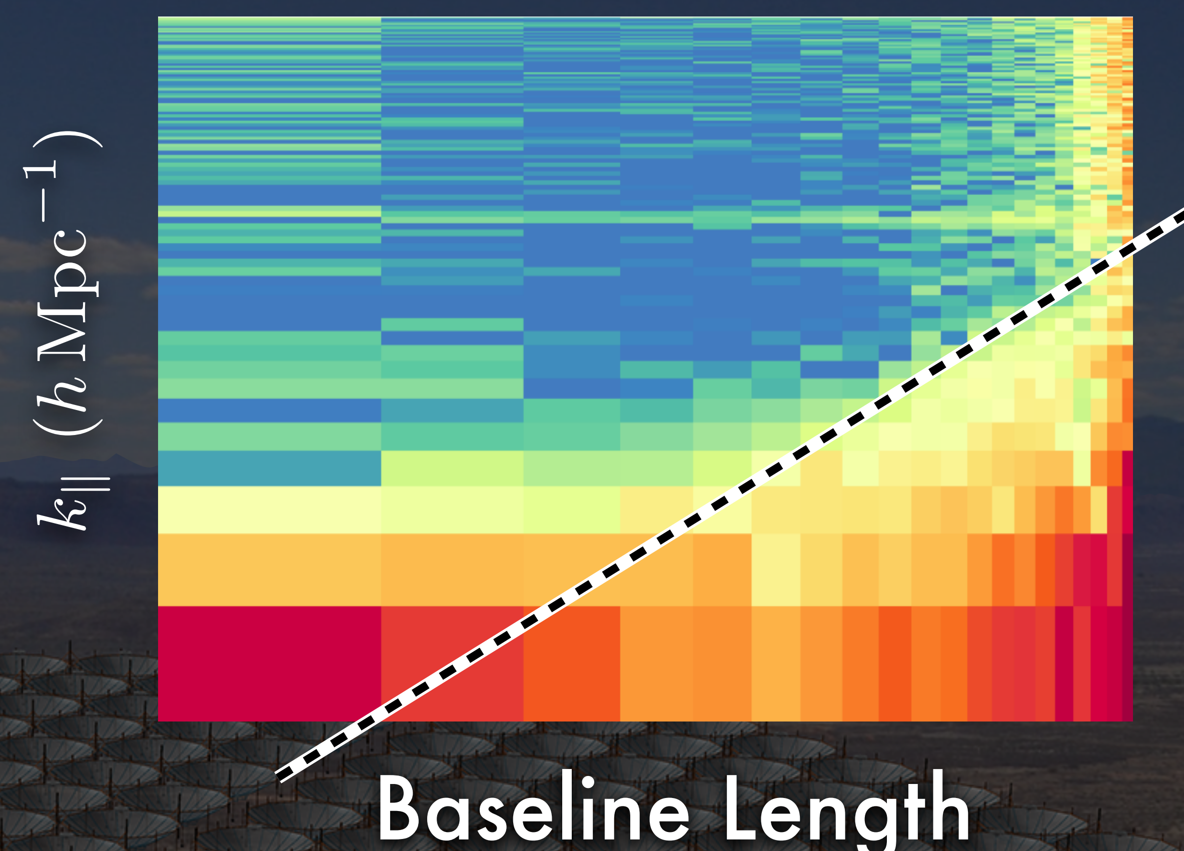

Since frequency maps to distance...

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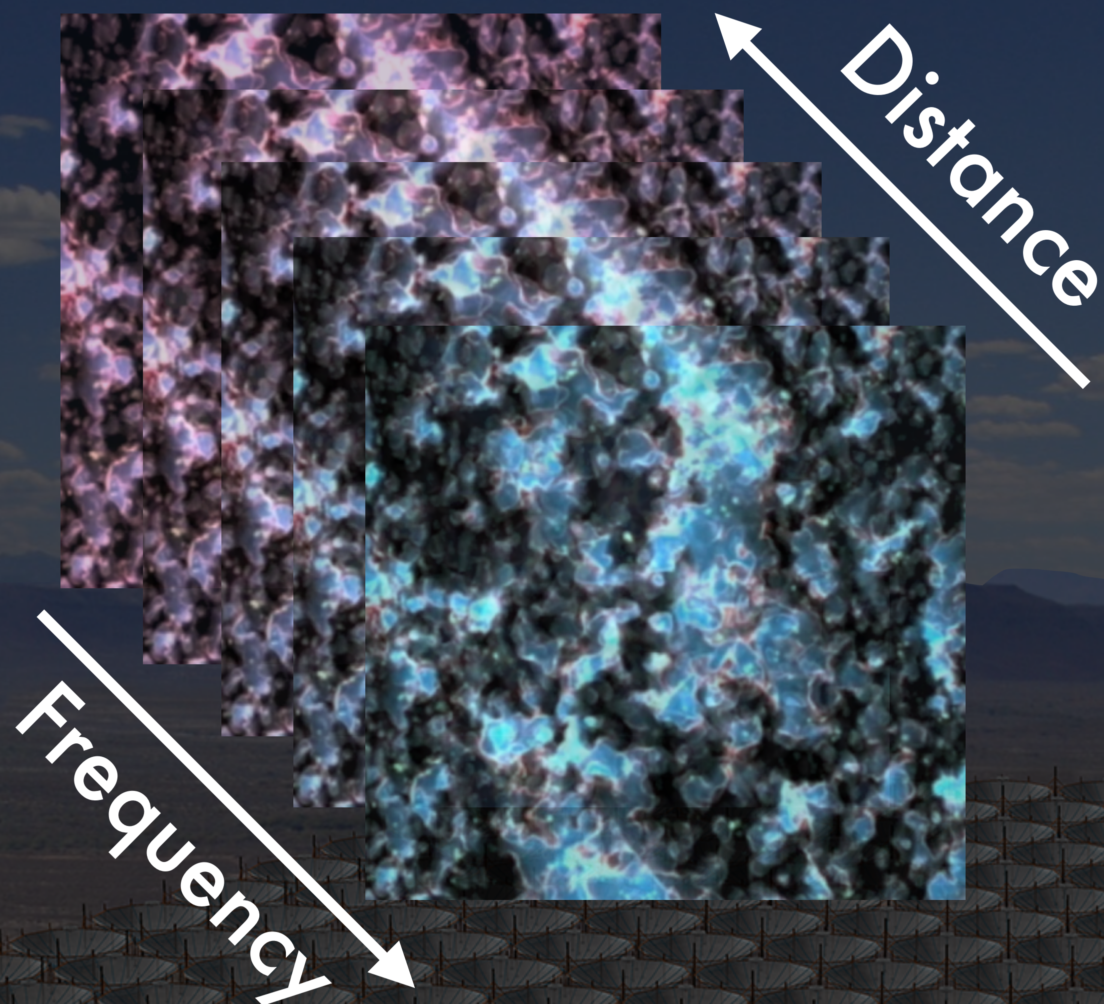

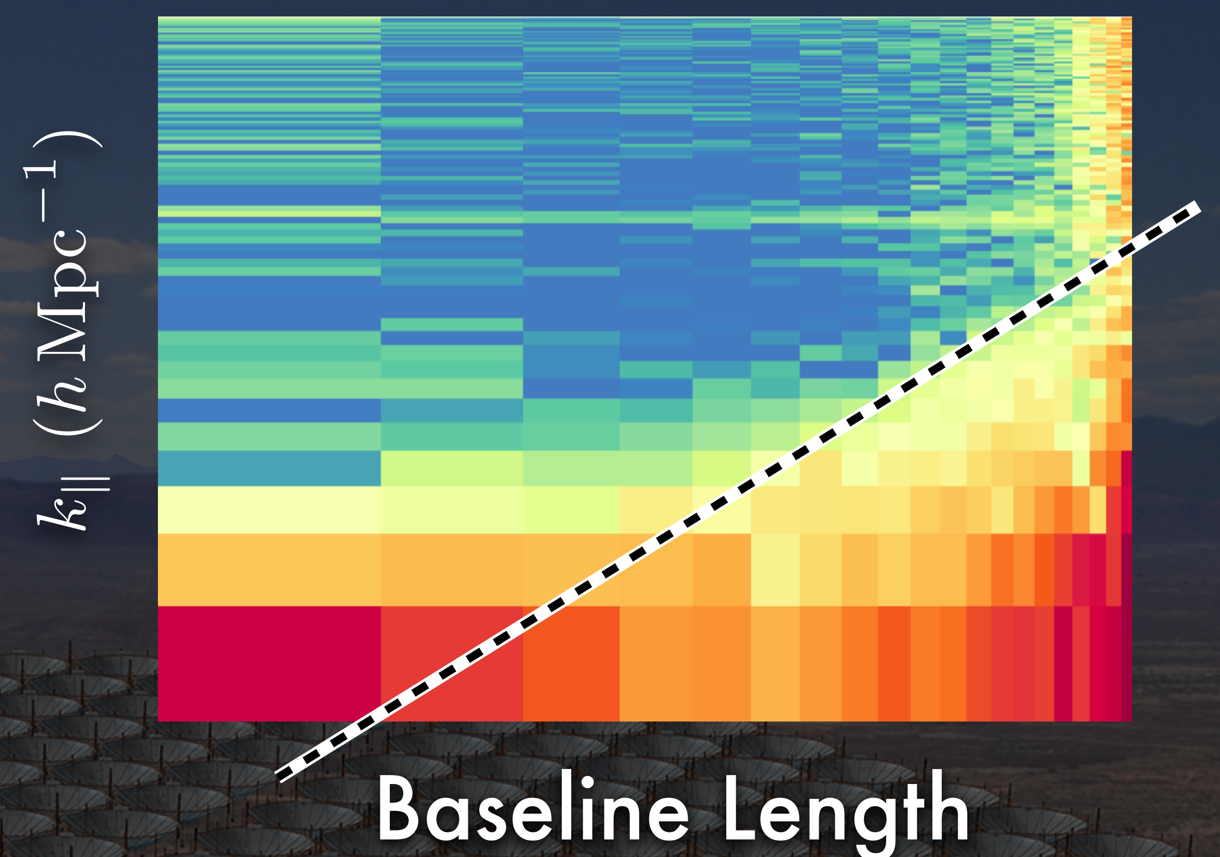

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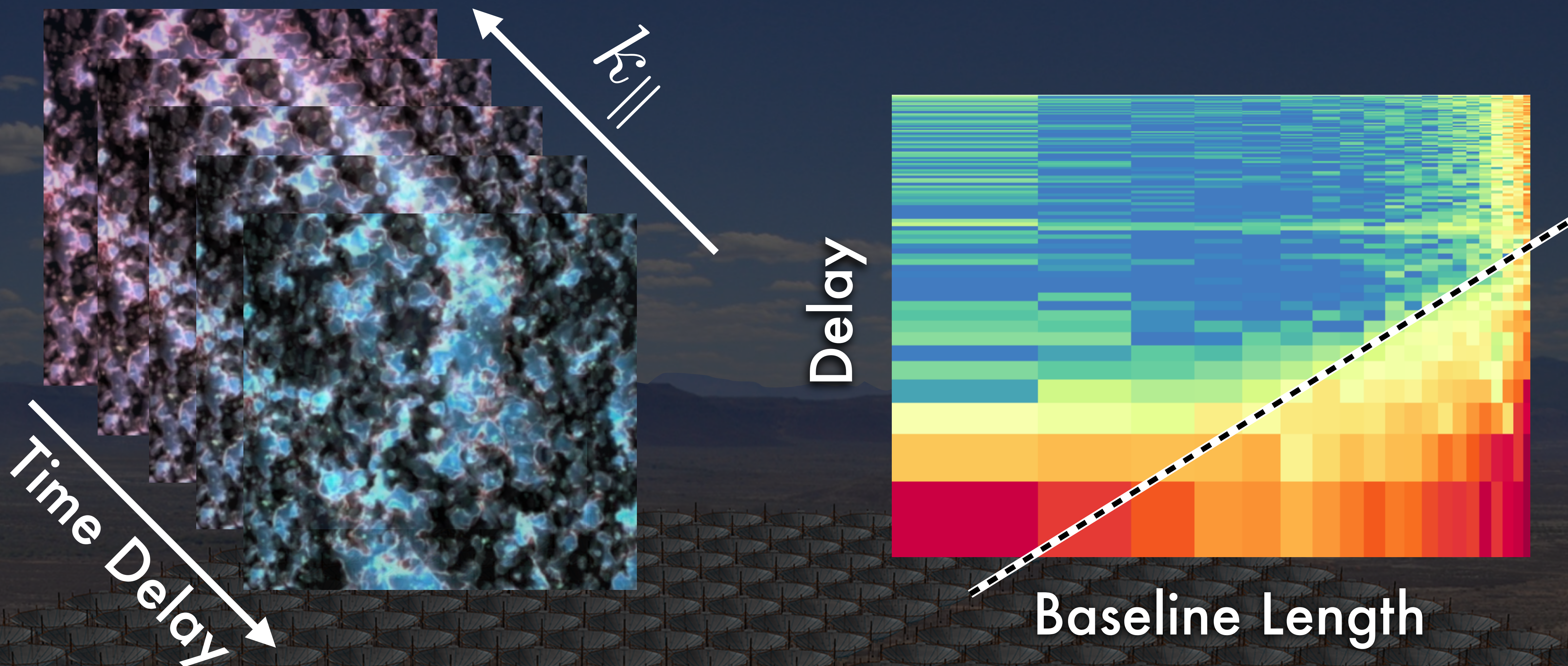
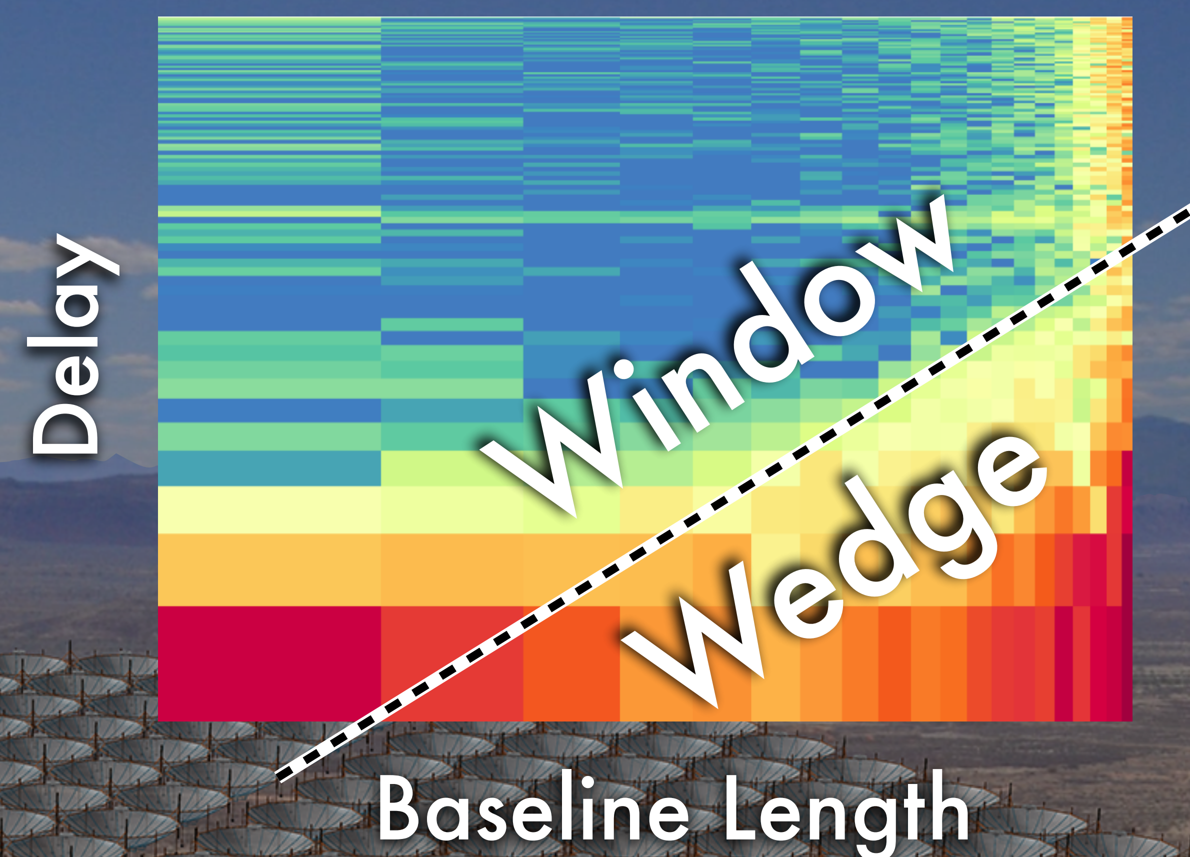


$k_{\|}$ is effectively time delay.

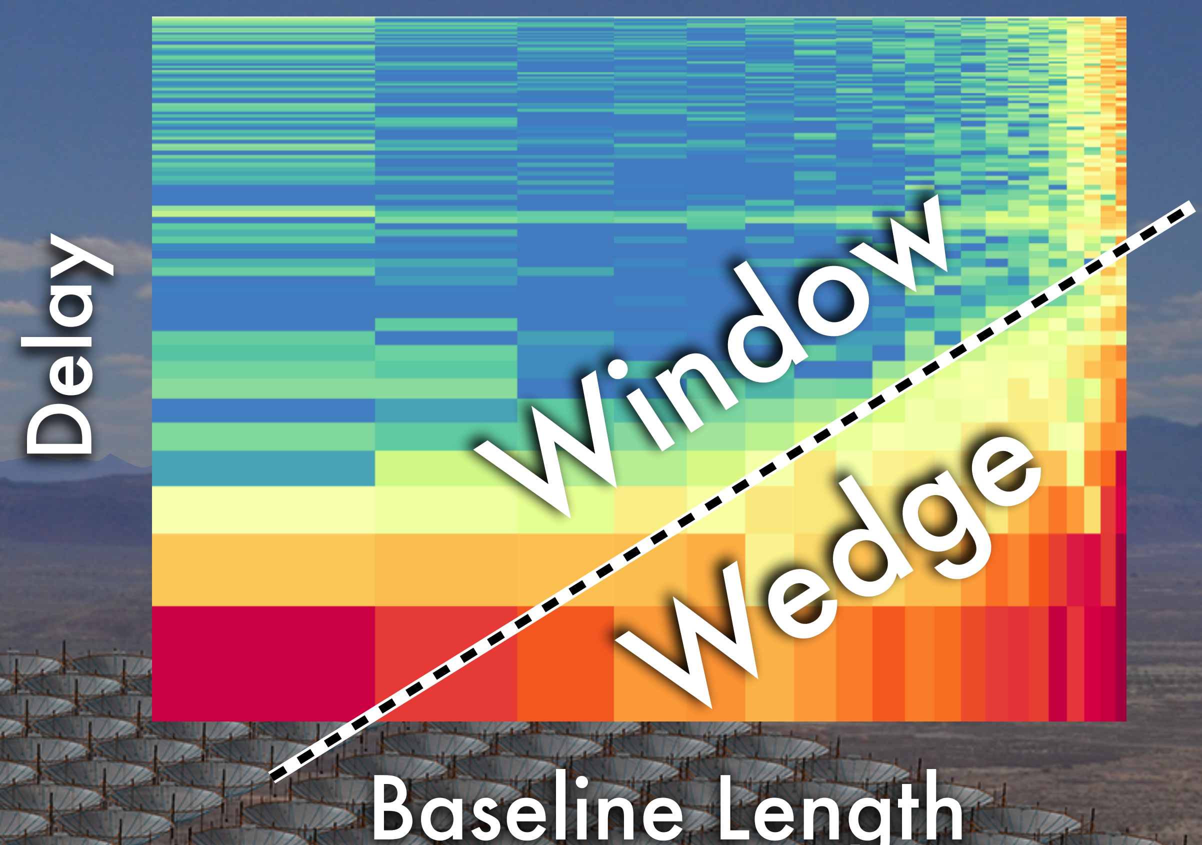
The maximum delay of foregrounds for a baseline is simply the light travel time.



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

Parsons et al. (2012)

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



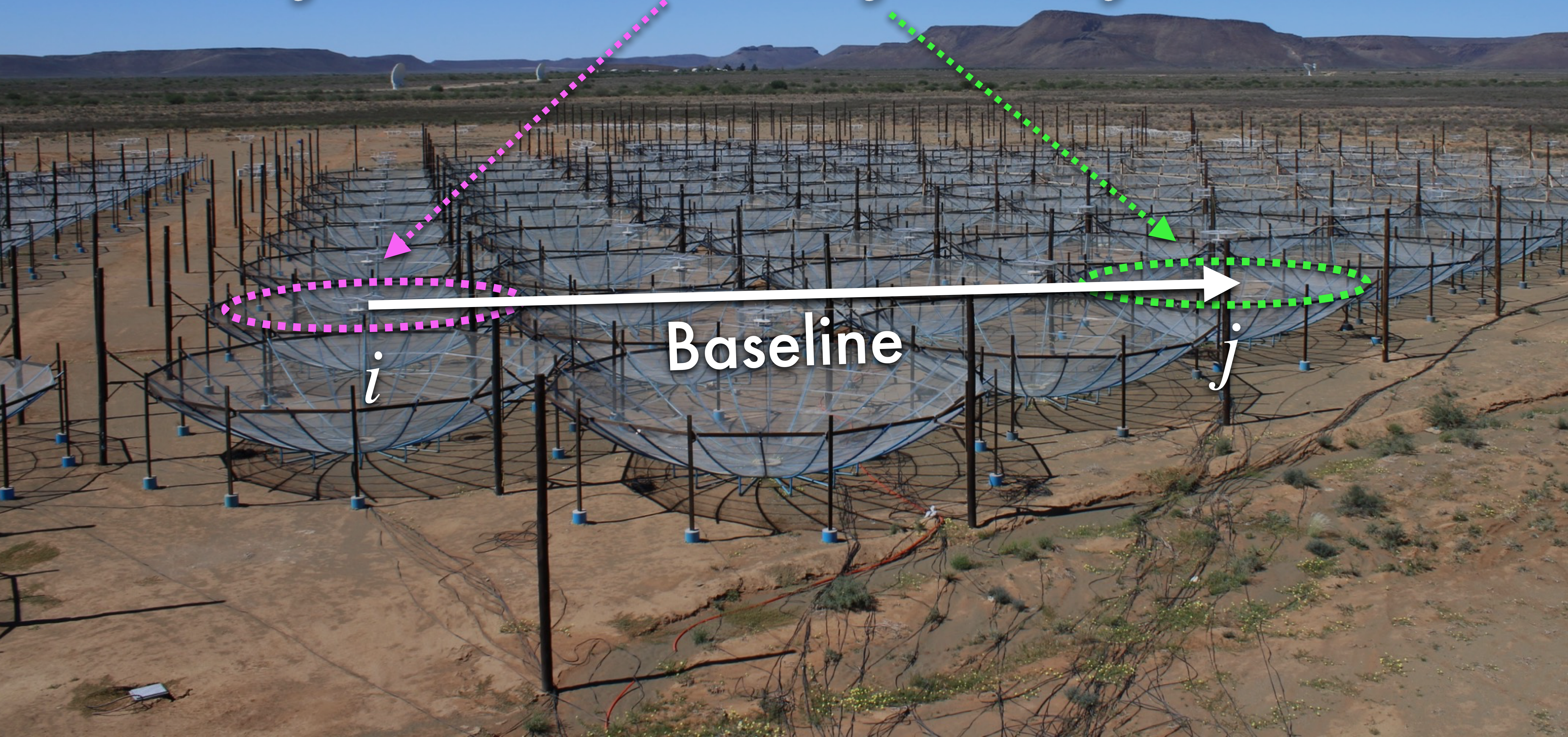
$$\Delta t_{\mathrm{max}} = |\mathbf{b}|/c$$

Dillon & *Parsons (2016)*

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

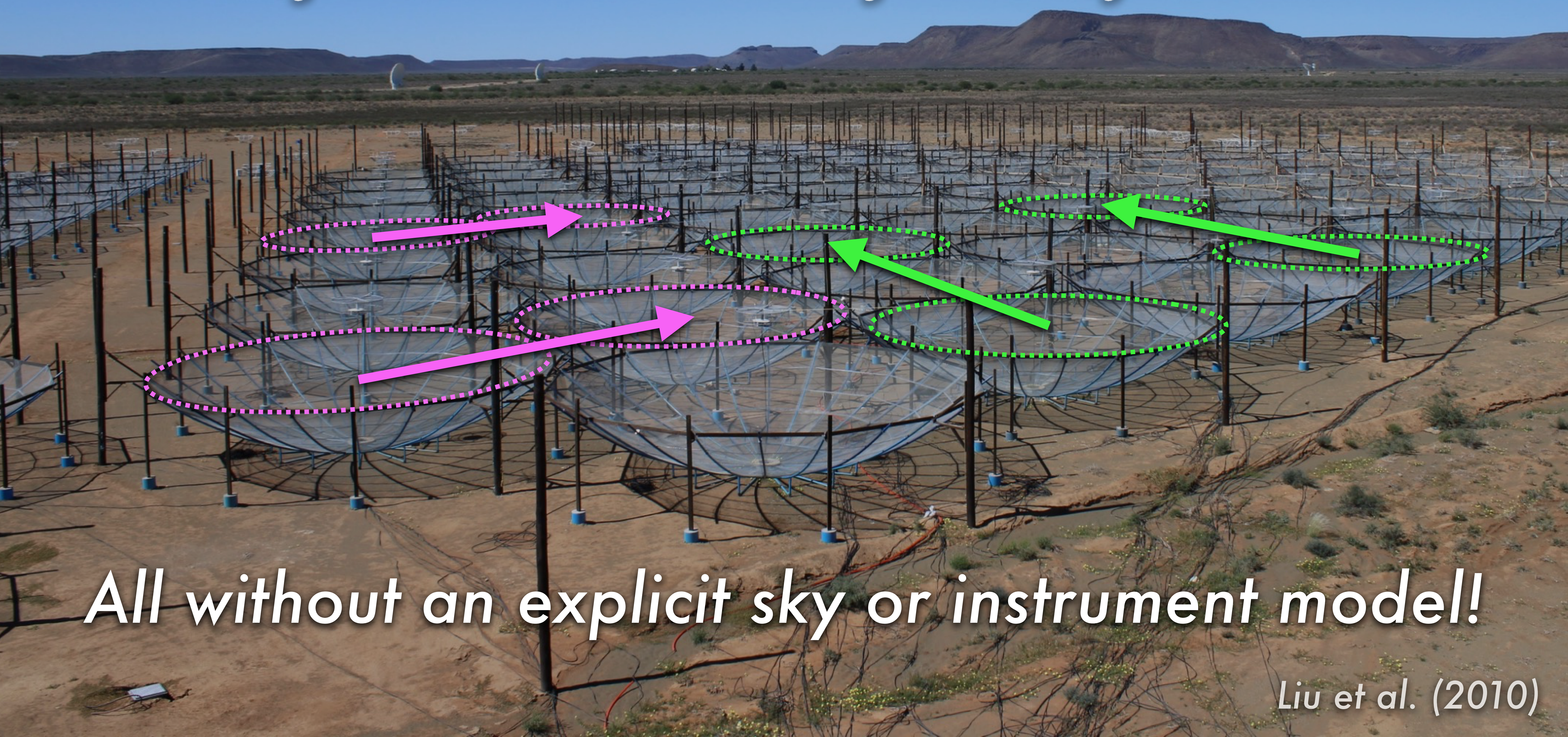
Foreground avoidance won't work without precision calibration.

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



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

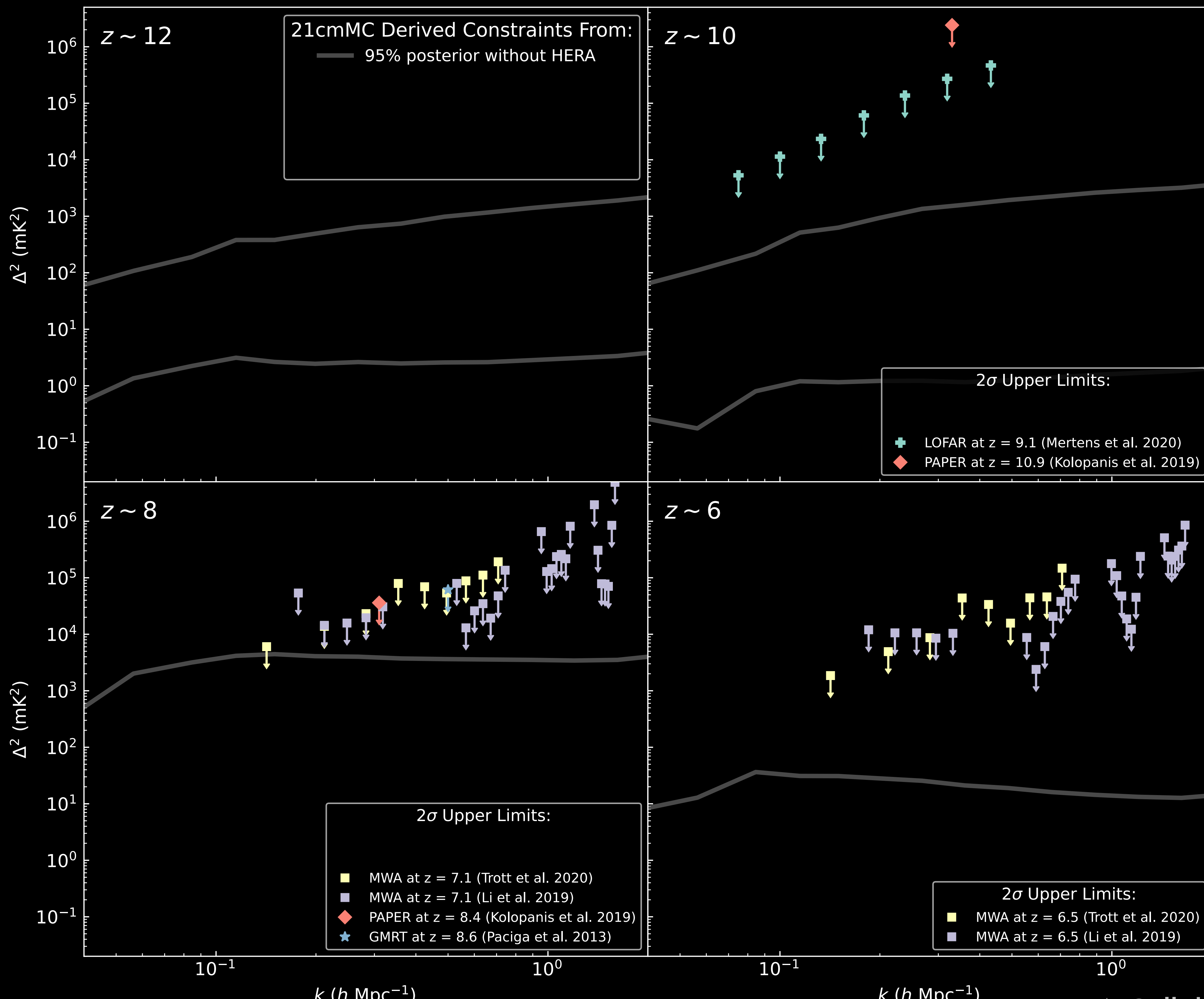
$$V_{ij}^{\mathrm{obs}}(\nu) = g_i(\nu) g_j^*(\nu) V_{ij}^{\mathrm{true}}(\nu)$$



All without an explicit sky or instrument model!

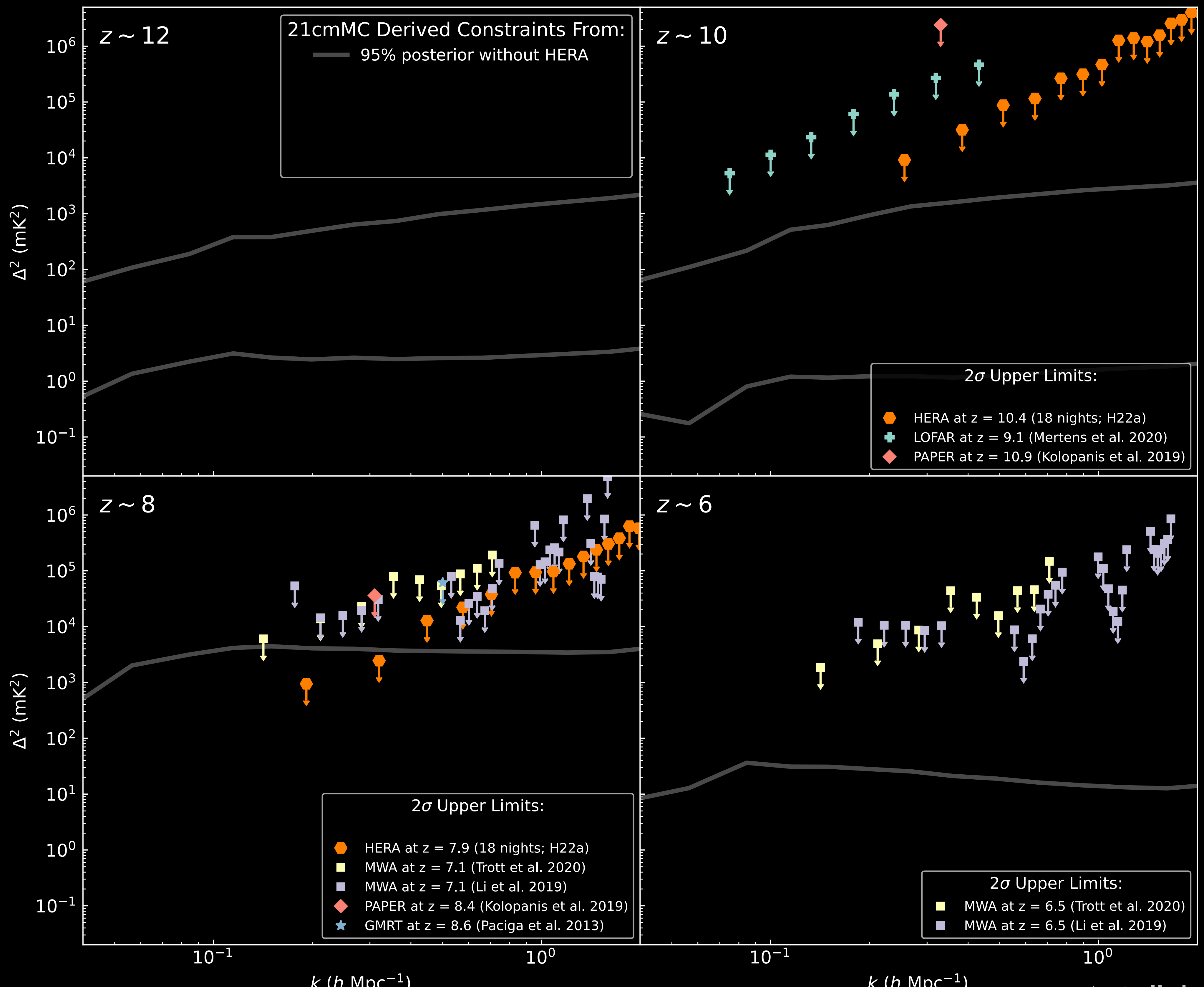
Liu et al. (2010)

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



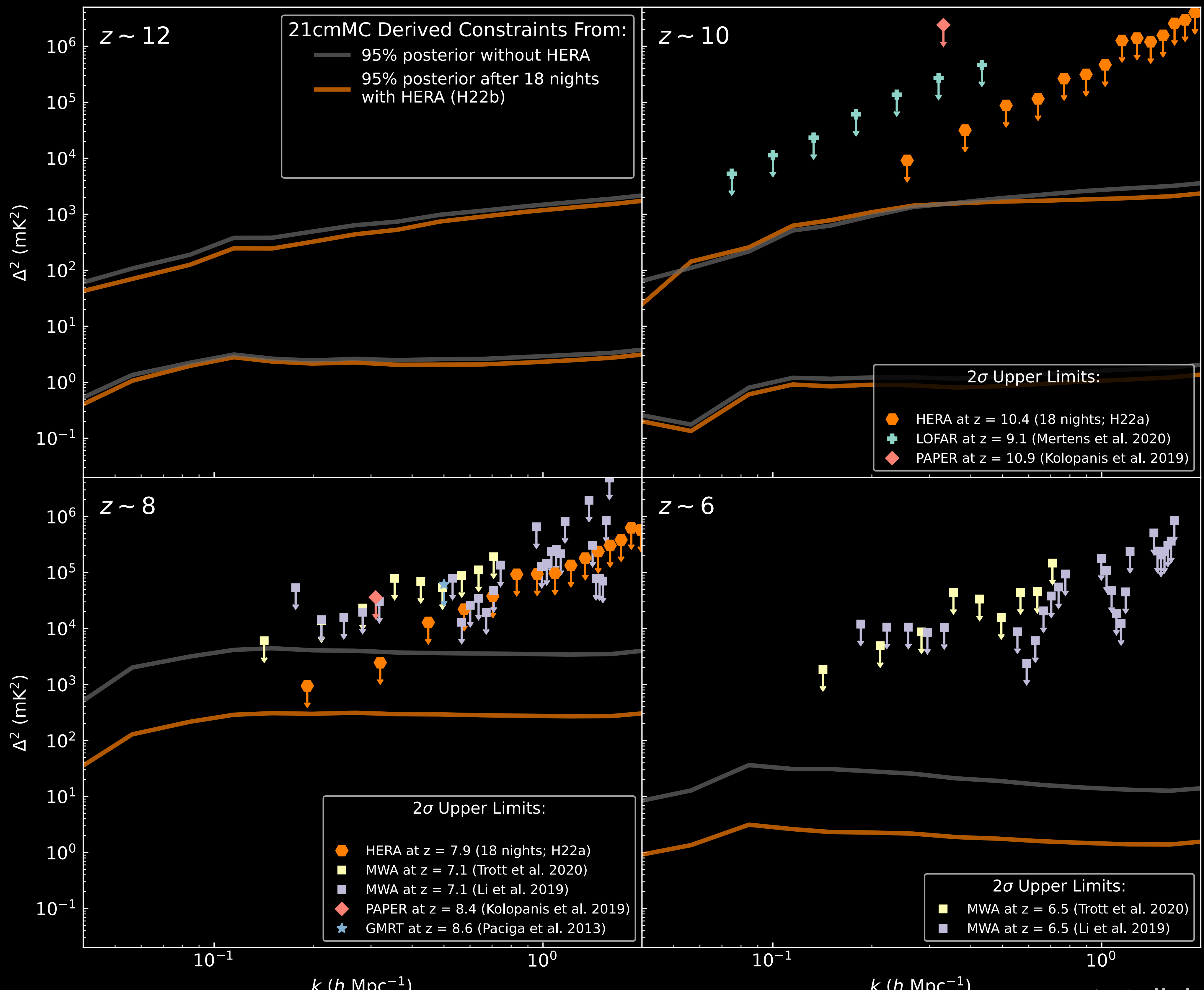
HERA Collaboration (2022b)

With just 18 nights and 40 antennas, HERA set world-leading upper limits on the 21cm power spectrum.

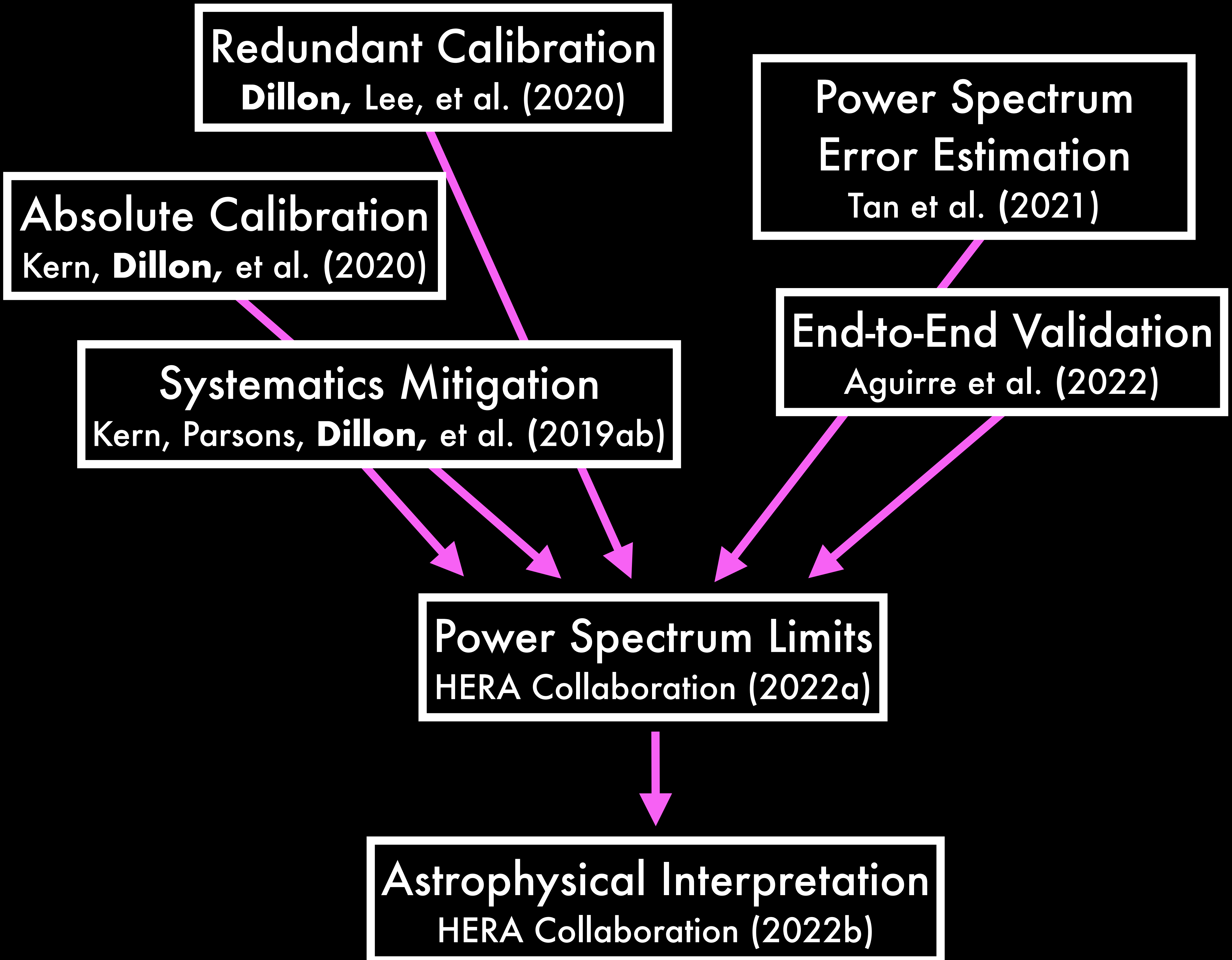


HERA Collaboration (2022a)

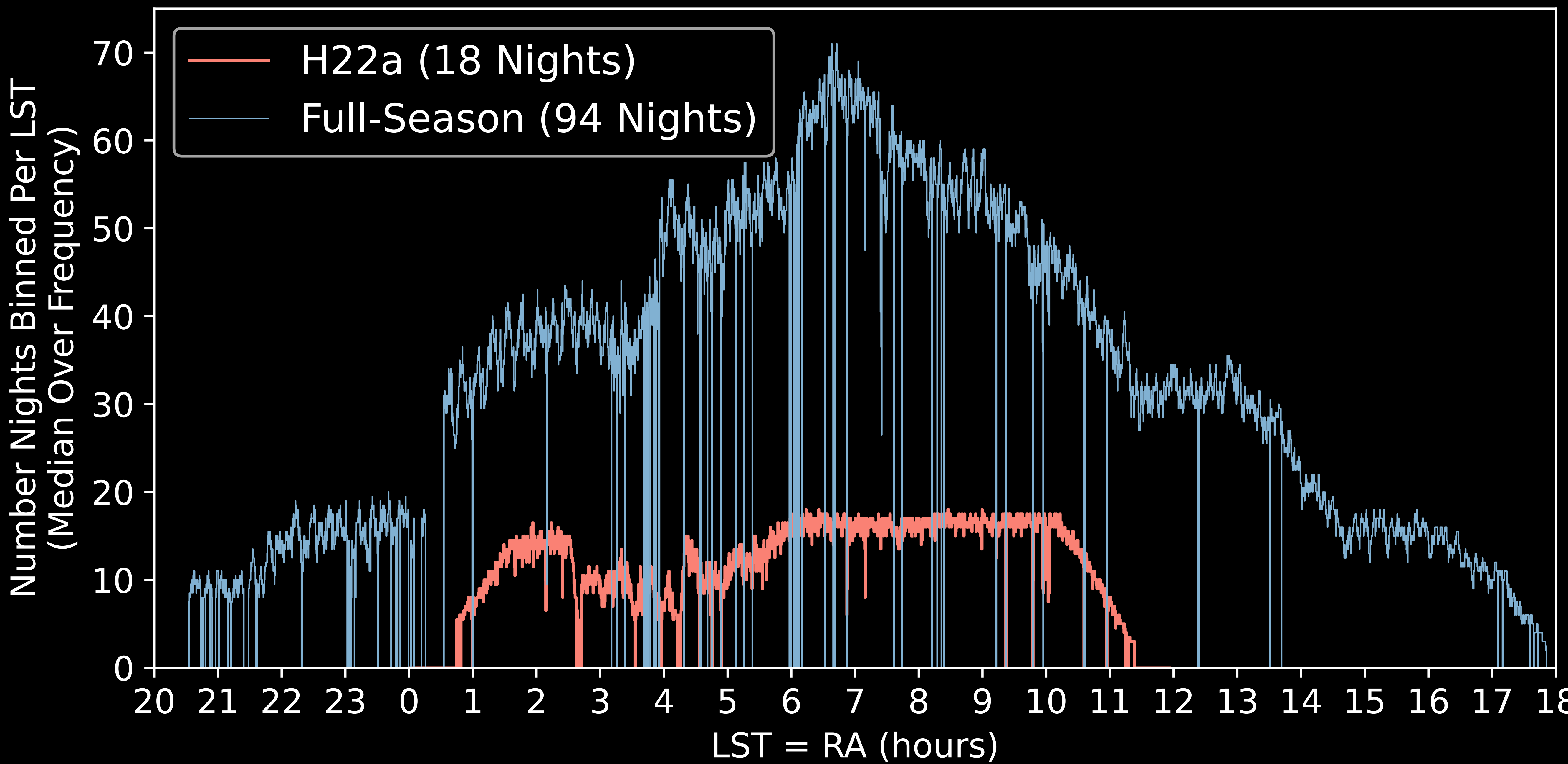
Which constrained the space of models, largely by ruling out an IGM unheated by X-rays at z = 8.



HERA Collaboration (2022b)

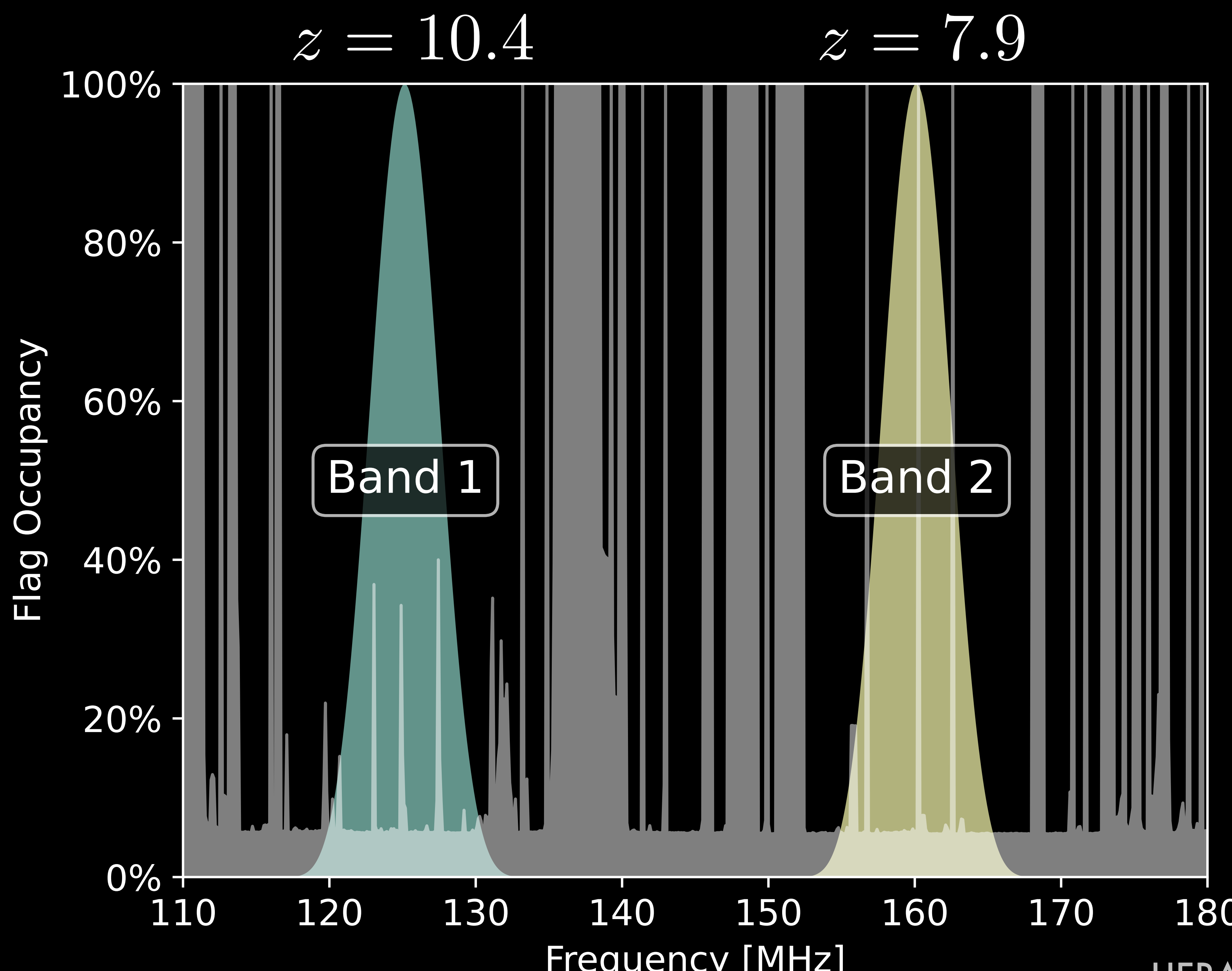

Redundant Calibration
Dillon, Lee, et al. (2020)
Power Spectrum
Error Estimation
Tan et al. (2021)
Absolute Calibration
Kern, **Dillon**, et al. (2020)
Systematics Mitigation
Kern, Parsons, **Dillon**, et al. (2019ab)
End-to-End Validation
Aguirre et al. (2022)
Power Spectrum Limits
HERA Collaboration (2022a)
Astrophysical Interpretation
HERA Collaboration (2022b)

But all that was with only 18 nights of data... and we had 94 good nights from that season.



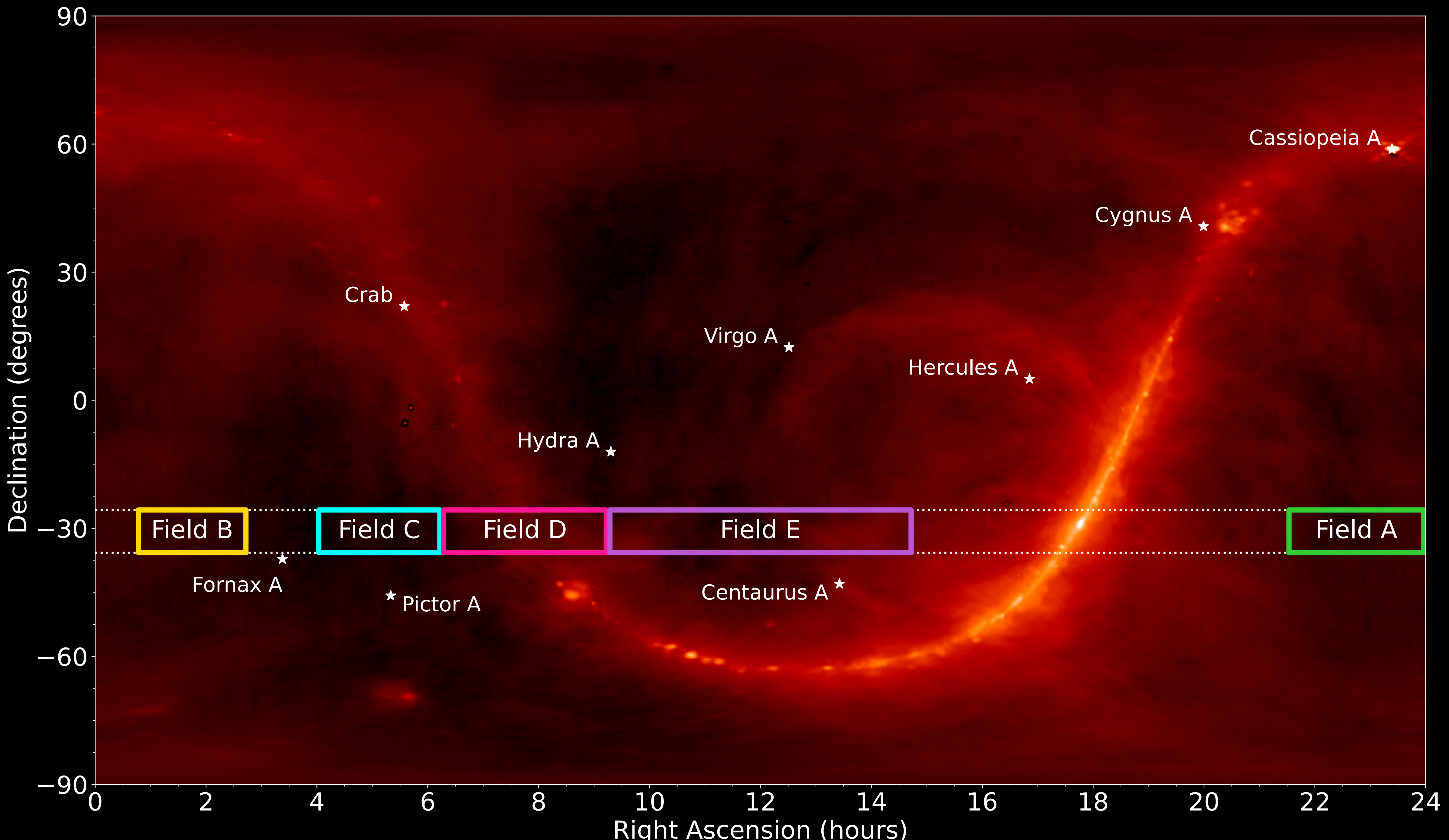
HERA Collaboration (2023)

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



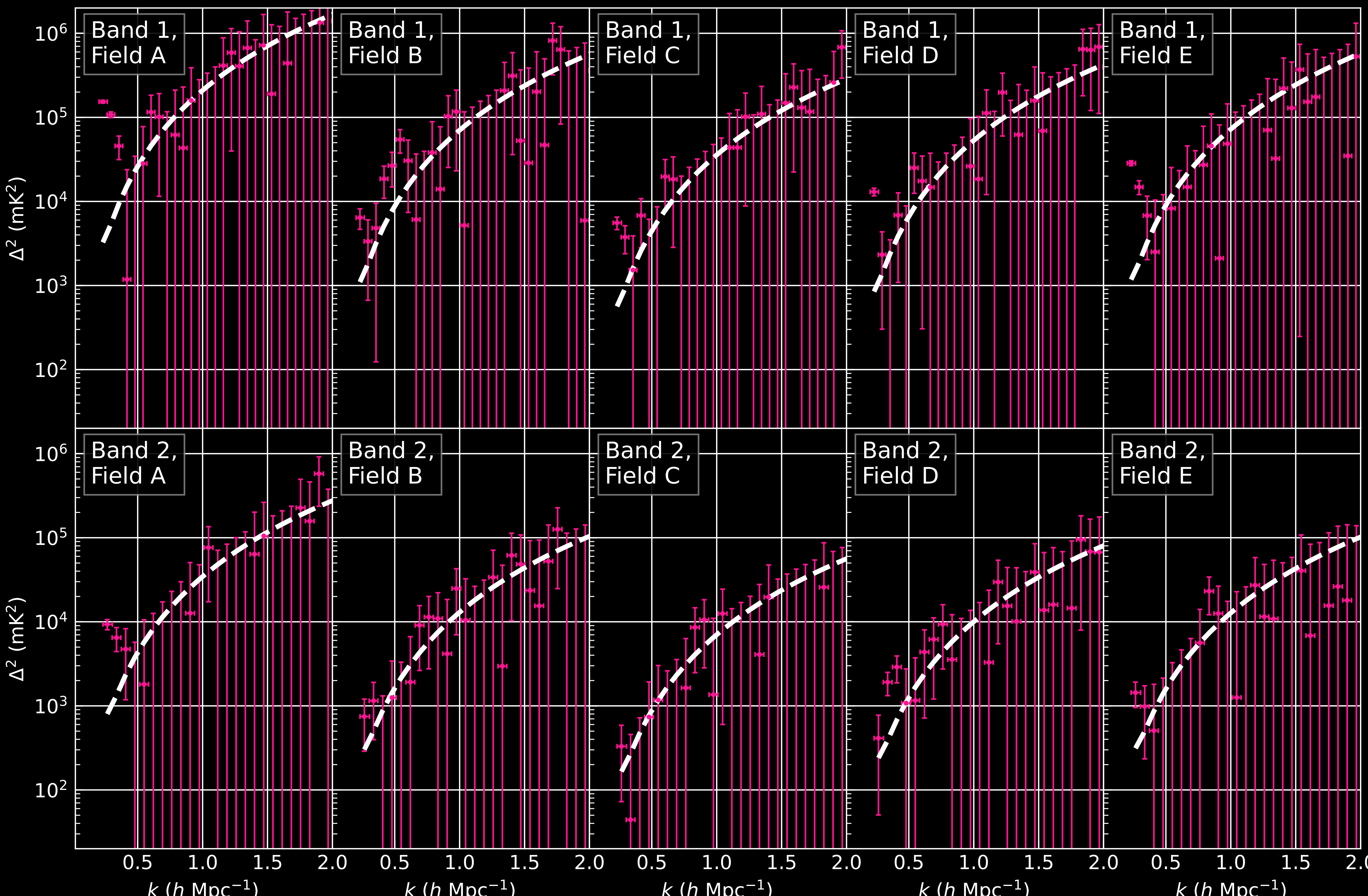
HERA Collaboration (2023)

We divided our observed LSTs into five fields.



HERA Collaboration (2023)

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



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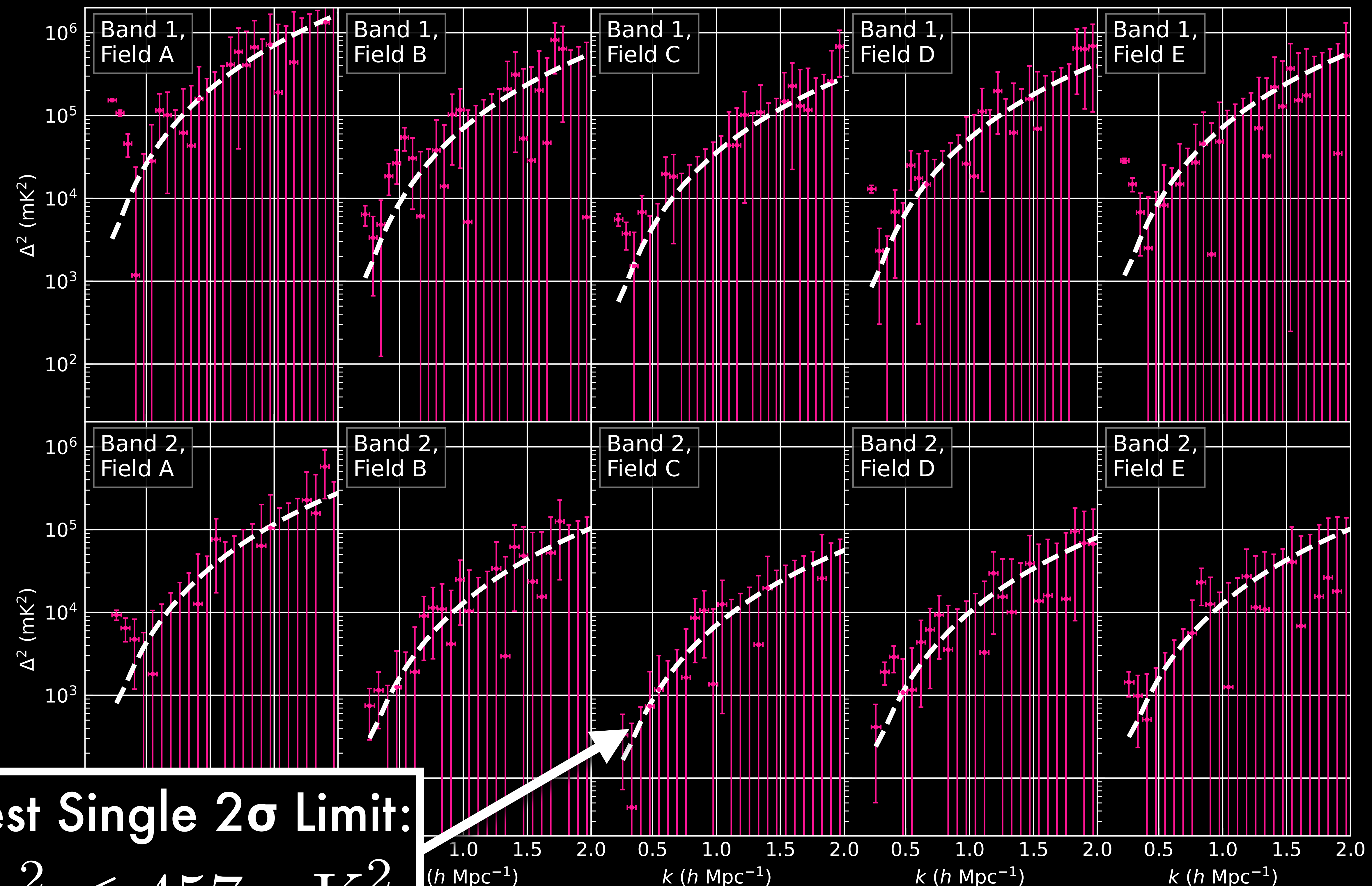
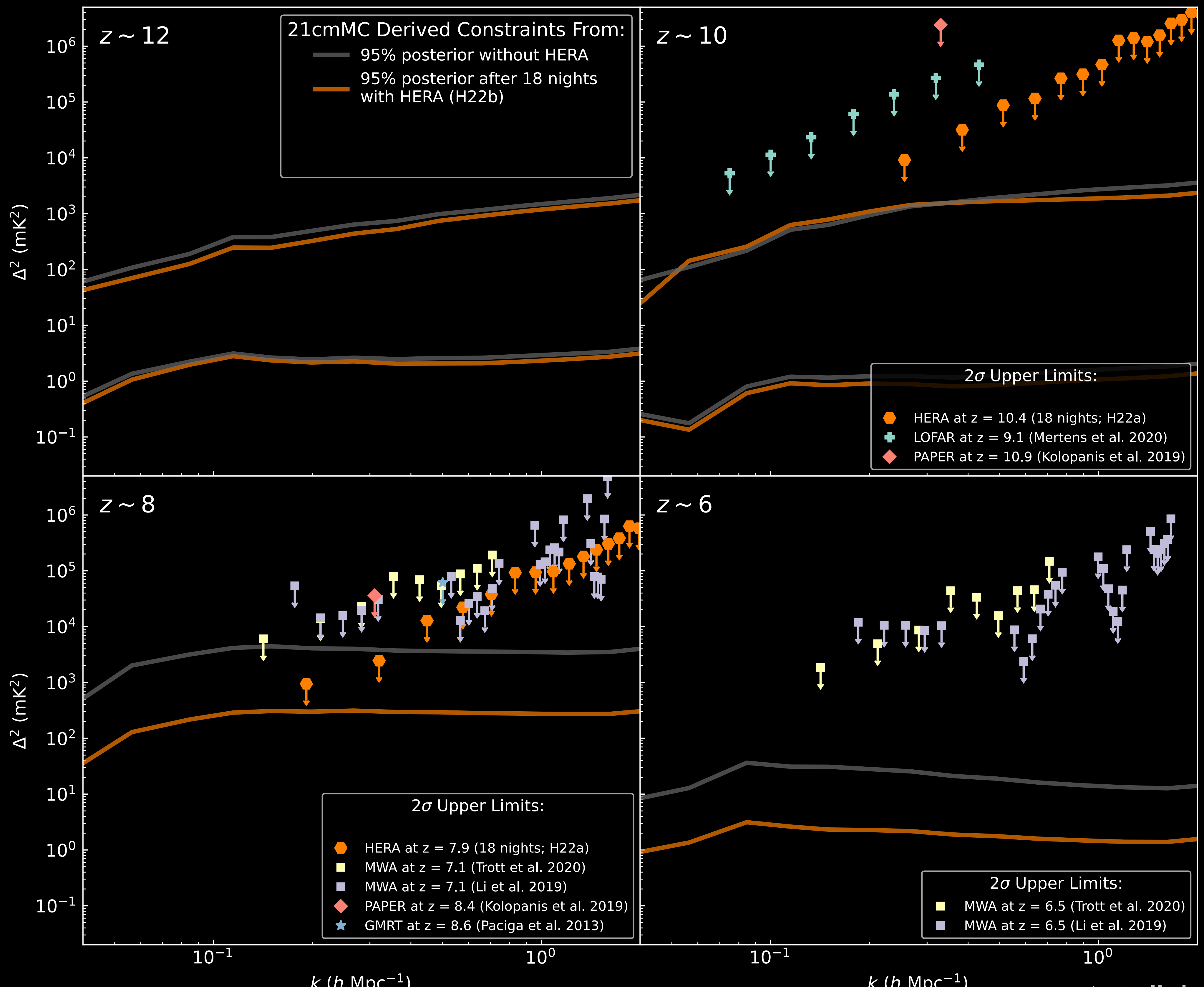


Best Single 2σ Limit:

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

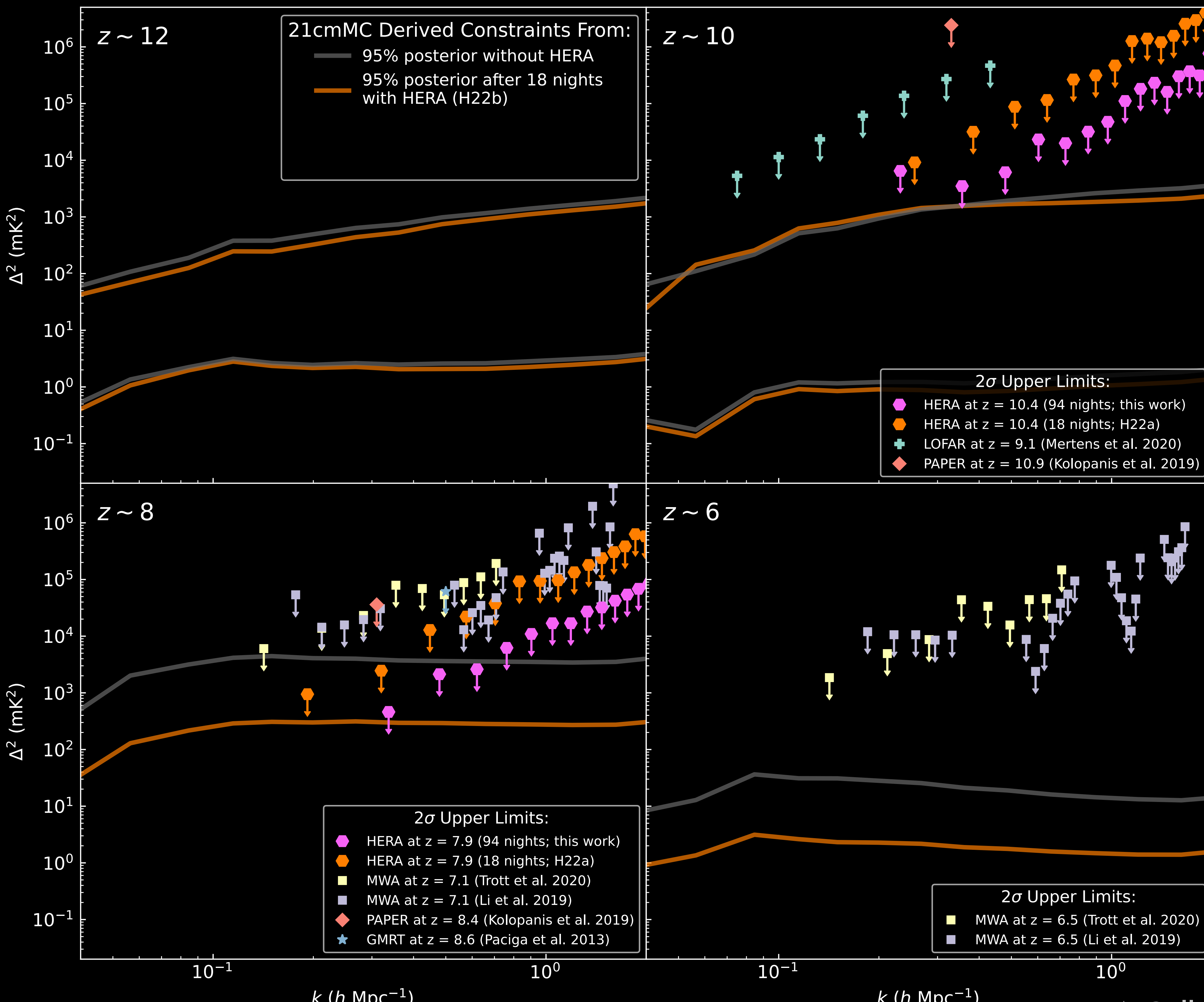
HERA Collaboration (2023)

So here's where we were again...



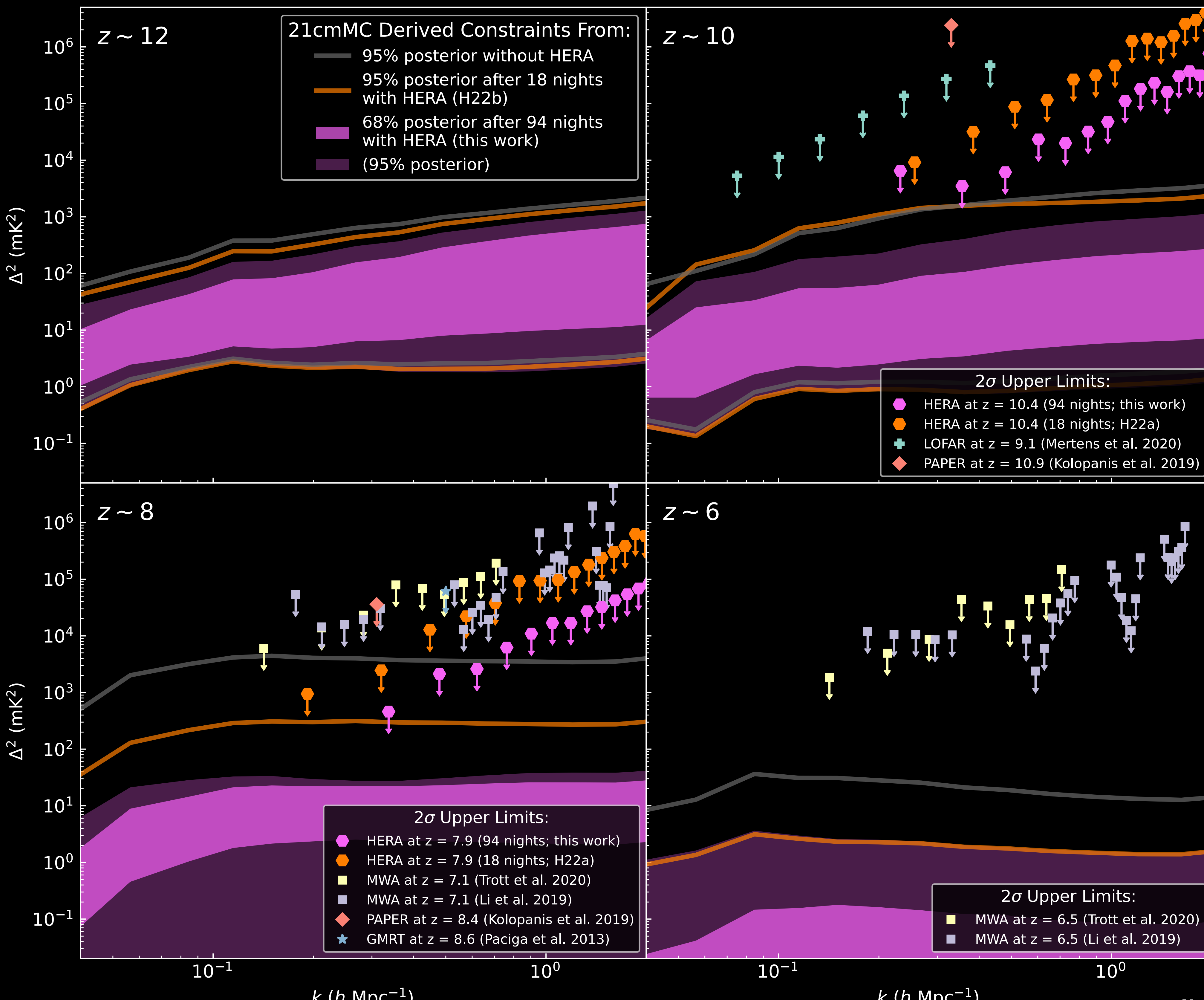
HERA Collaboration (2022b)

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



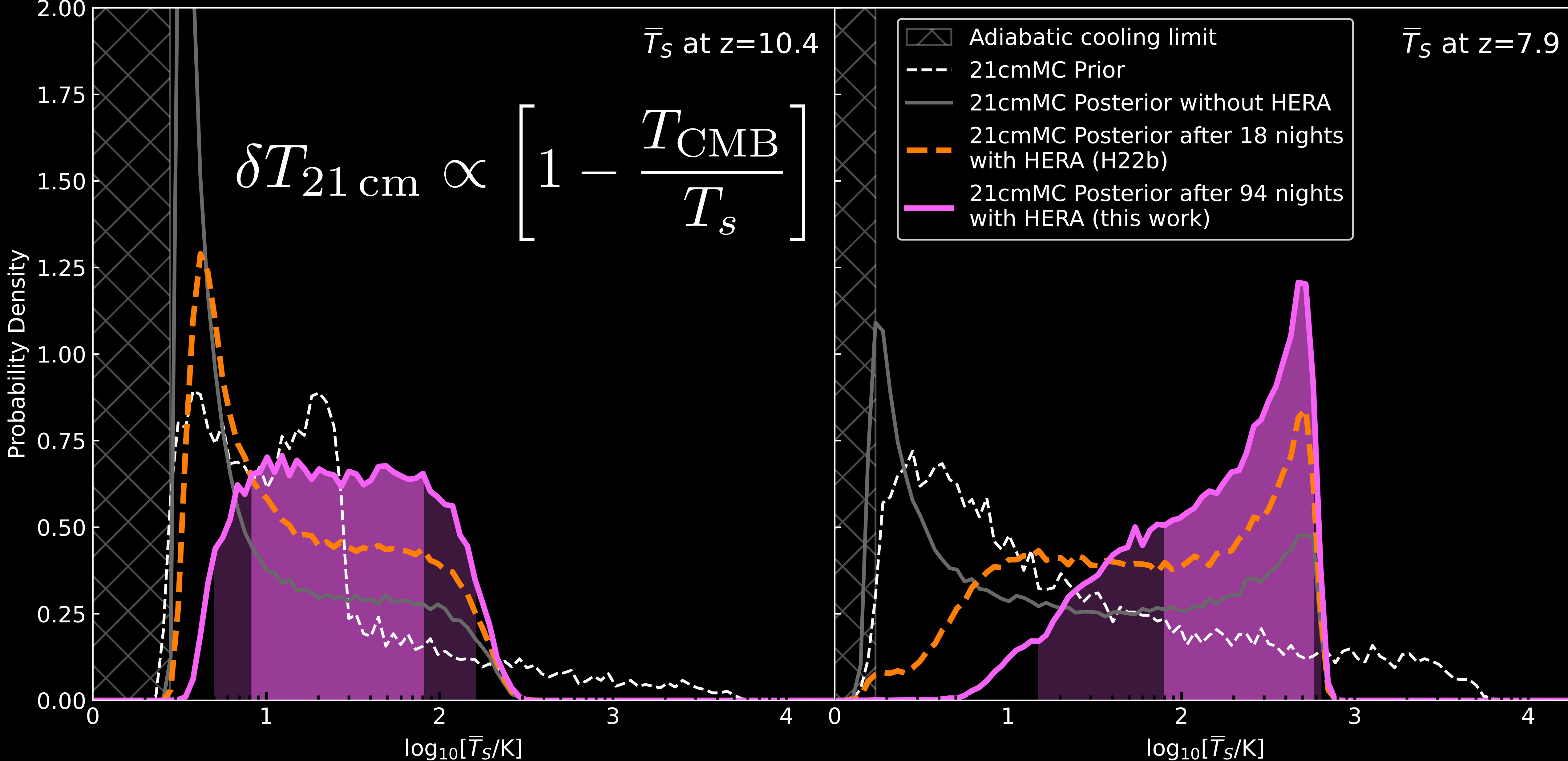
HERA Collaboration (2023)

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



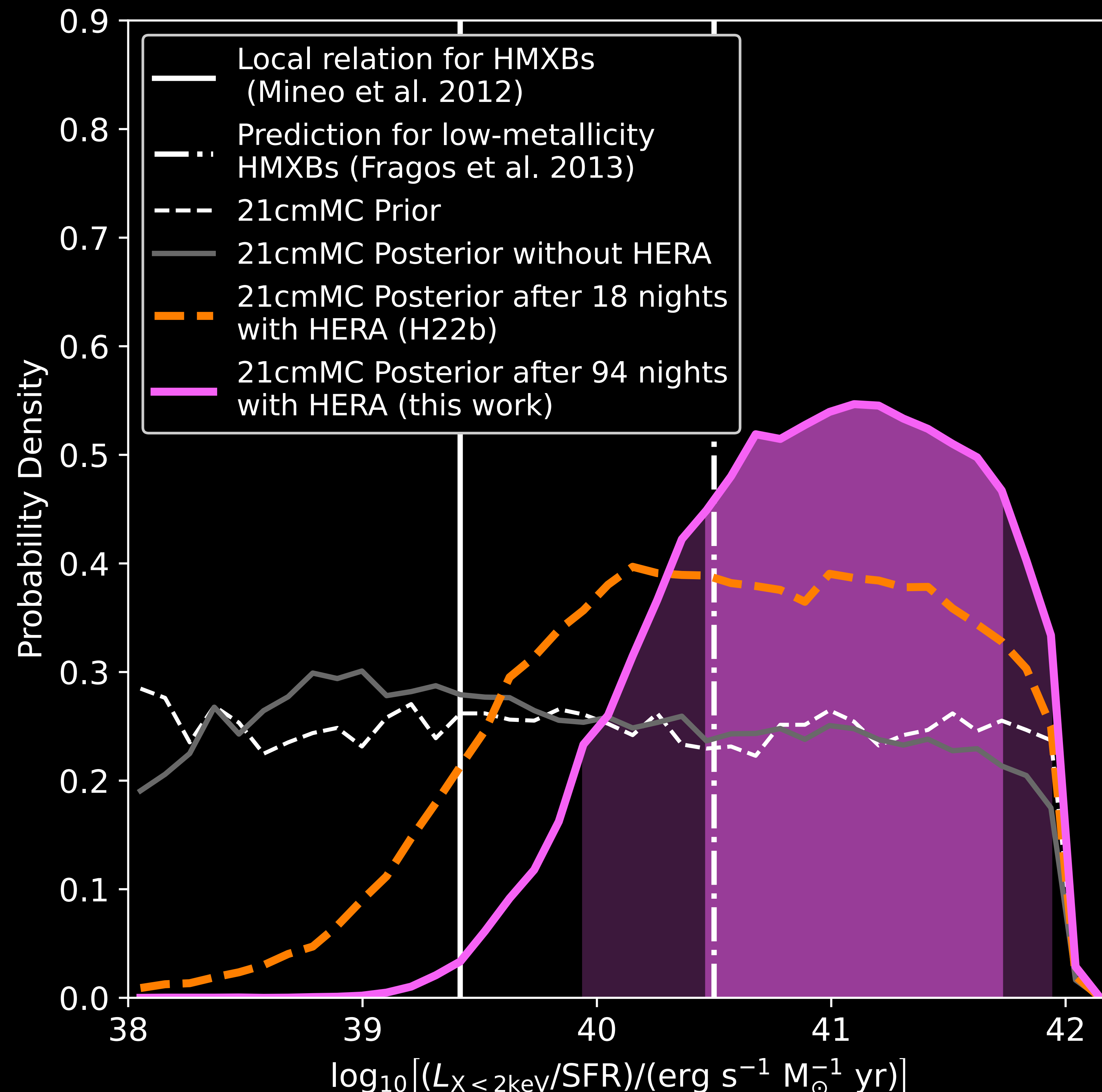
HERA Collaboration (2023)

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



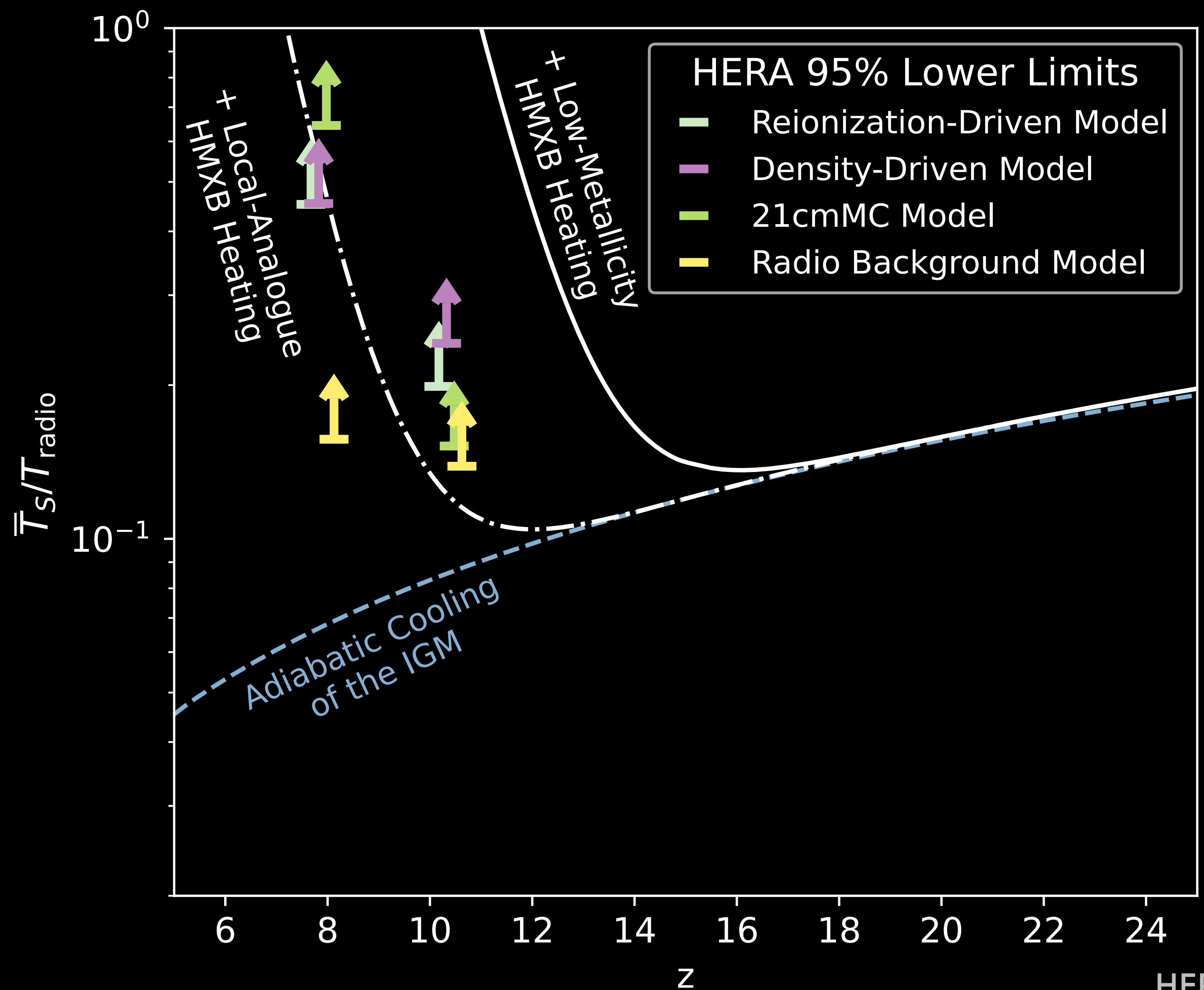
HERA Collaboration (2023)

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.



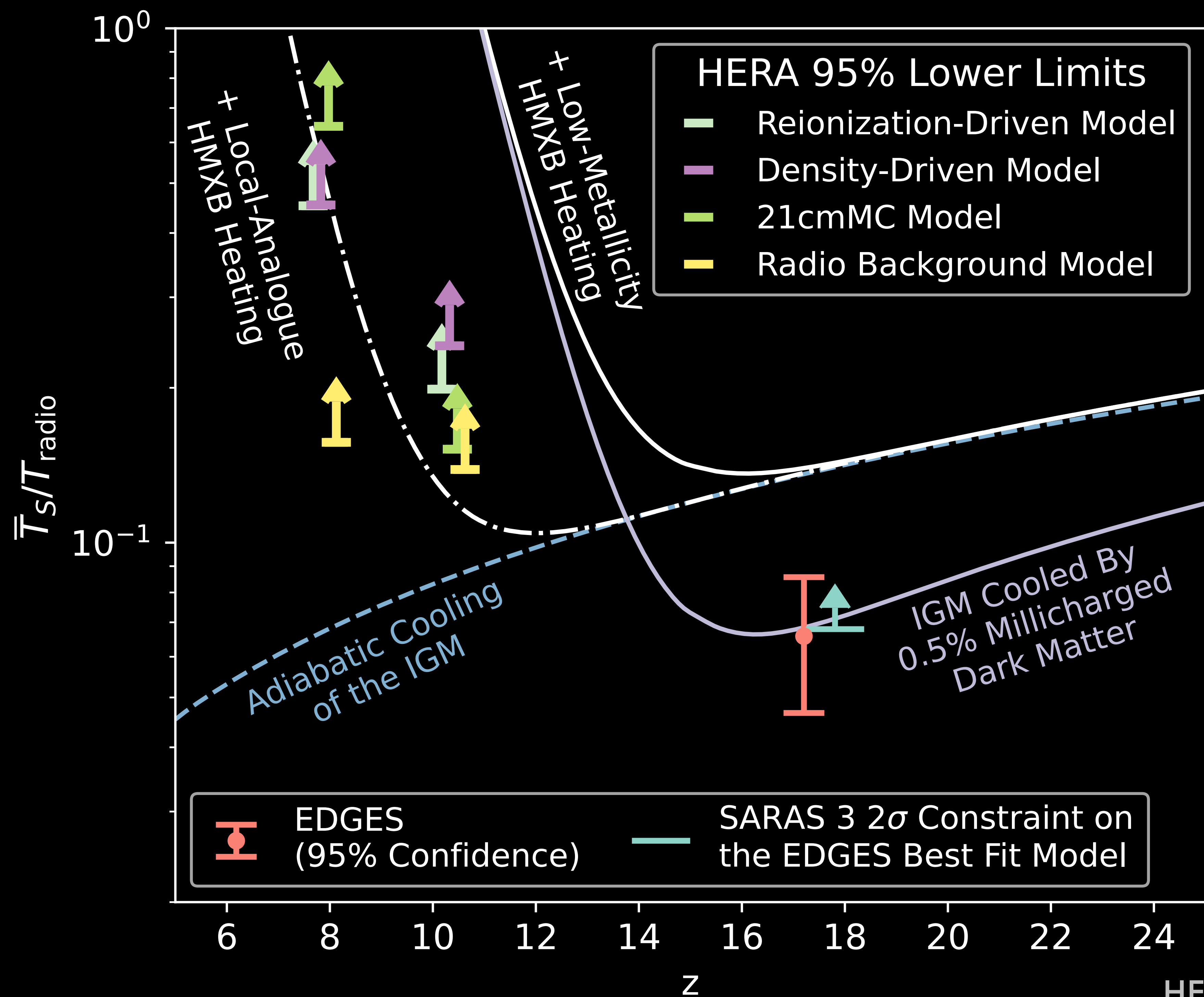
HERA Collaboration (2023)

Four independent theoretical models agree the IGM was heated before z = 10.4, likely by low-metallicity HMXB.



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?

We just finished an observing season (~150 good nights) observing with over 200 antennas as we build out to 350.

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

With a full season and the full array, we'll have the sensitivity to detect the 21 cm signal and distinguish between models.

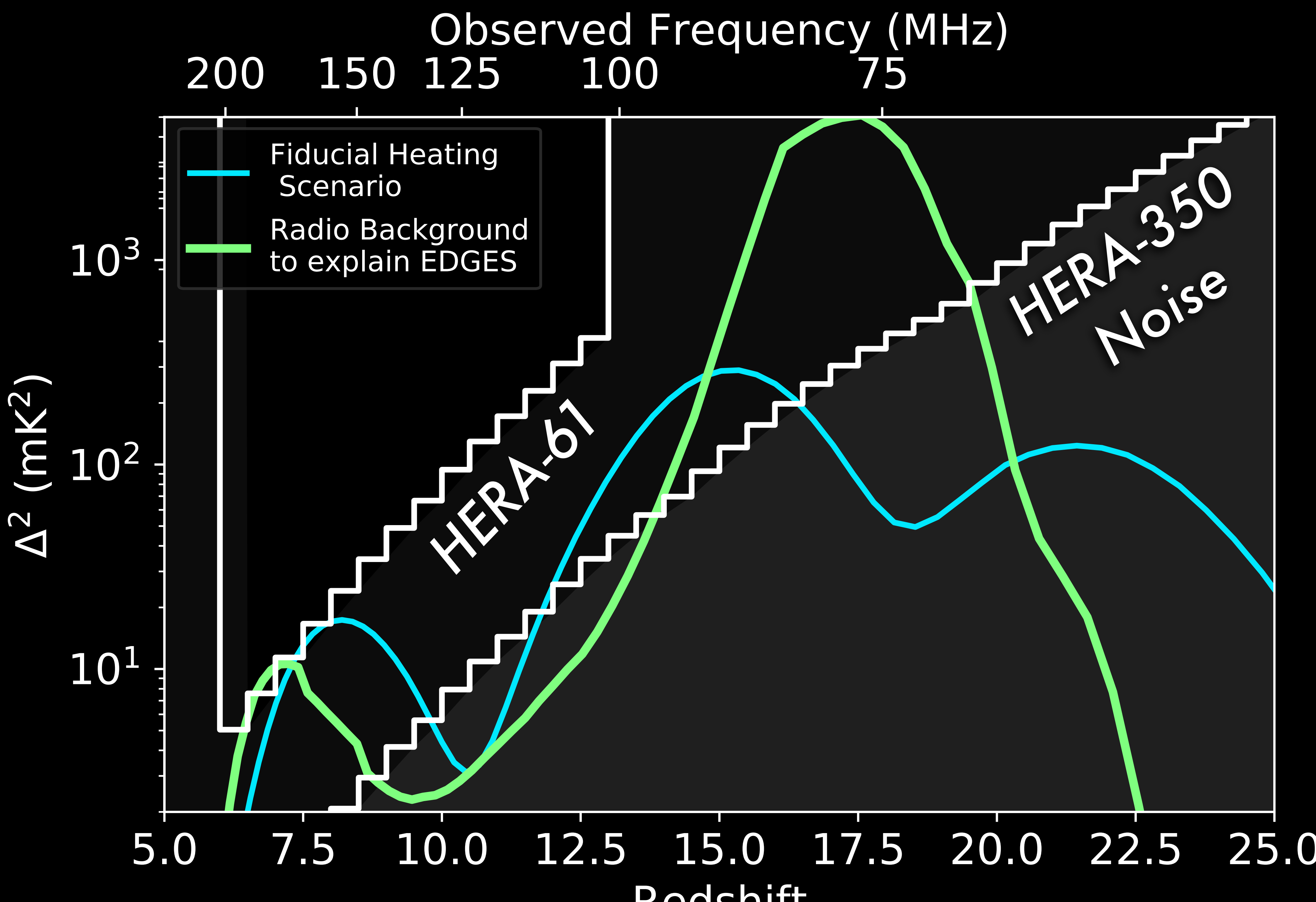
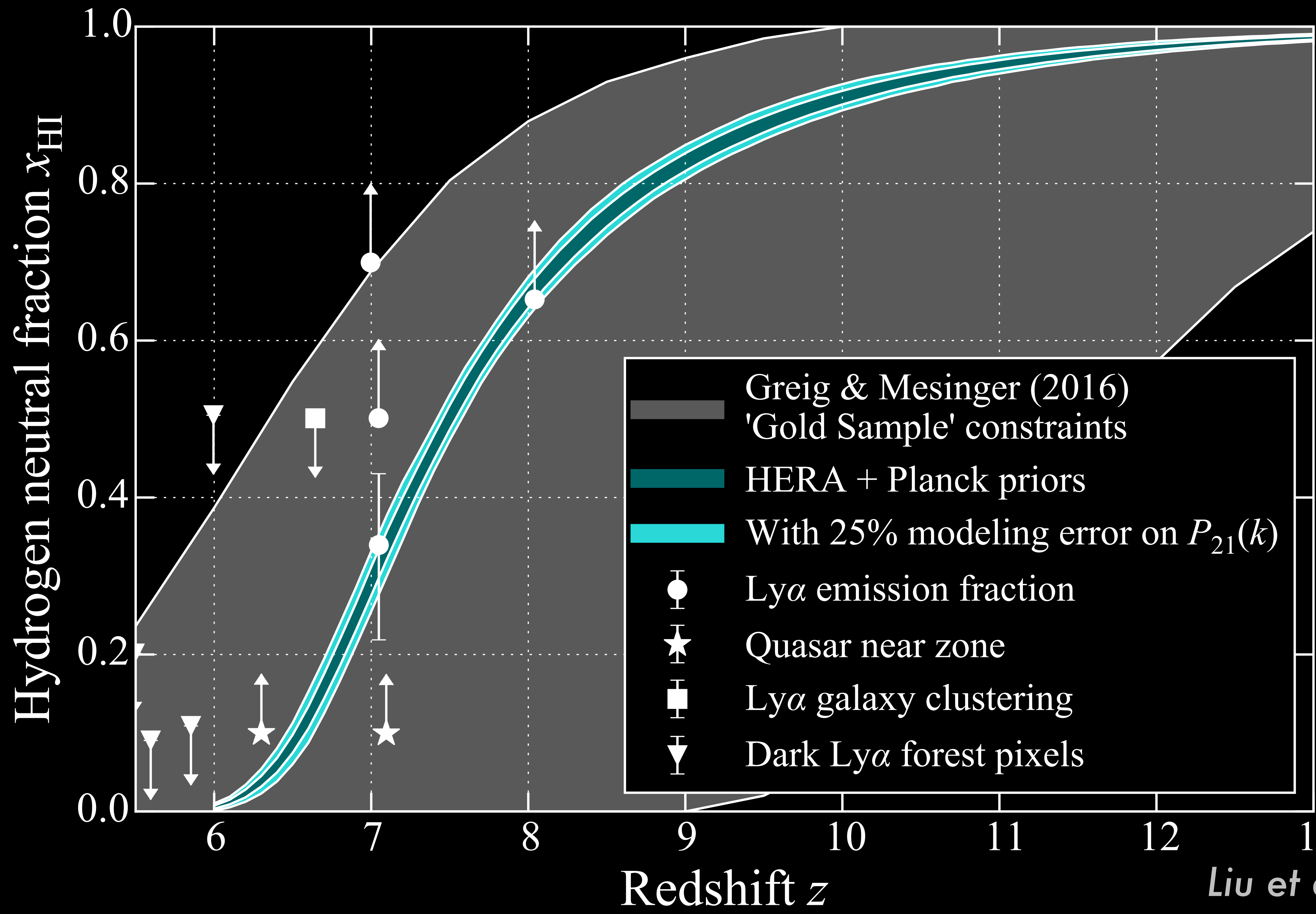


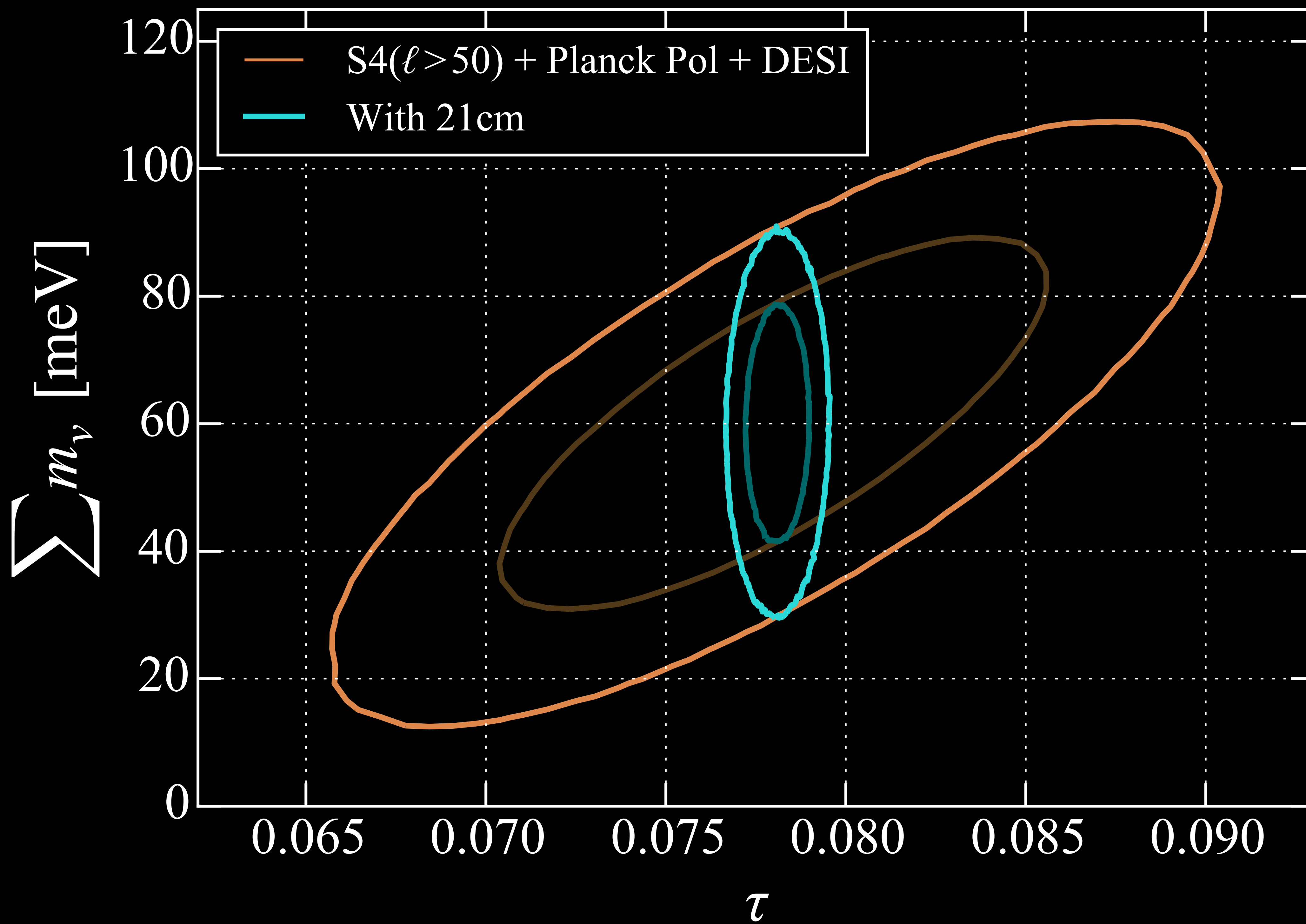
Figure: Aaron Ewall-Wice

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



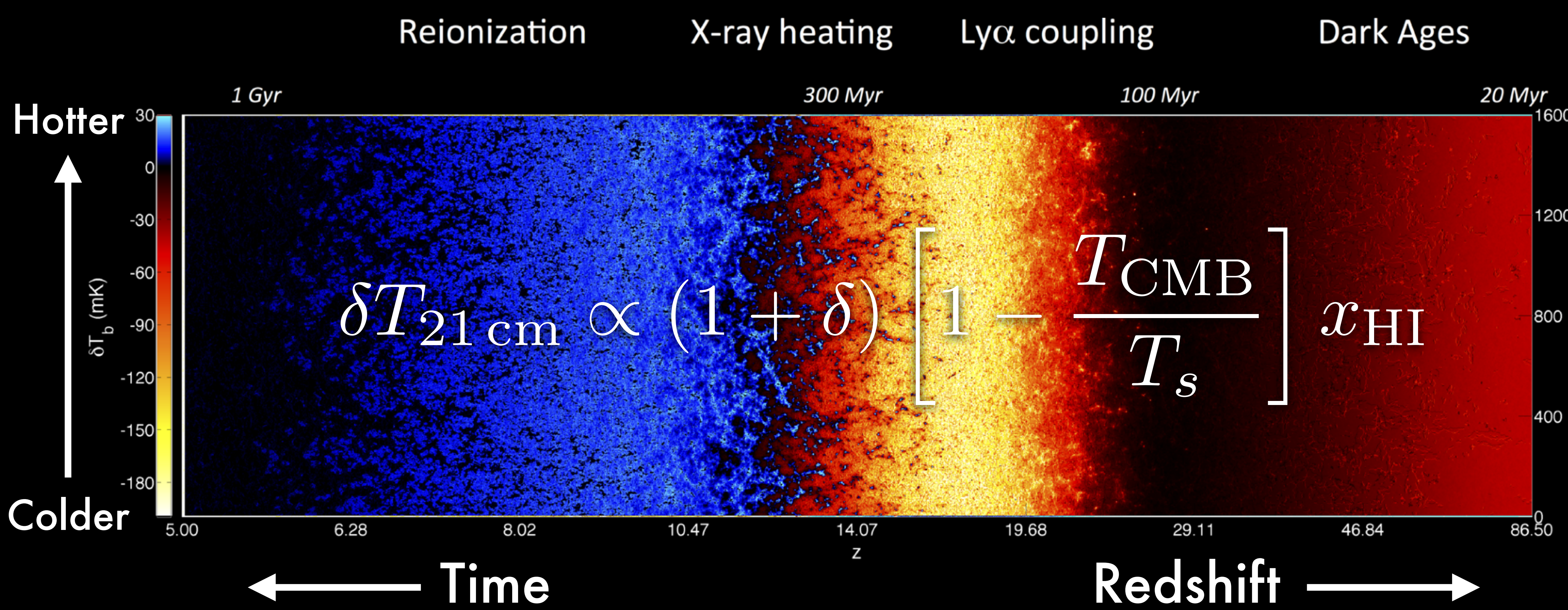
Liu et al. (2016)

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

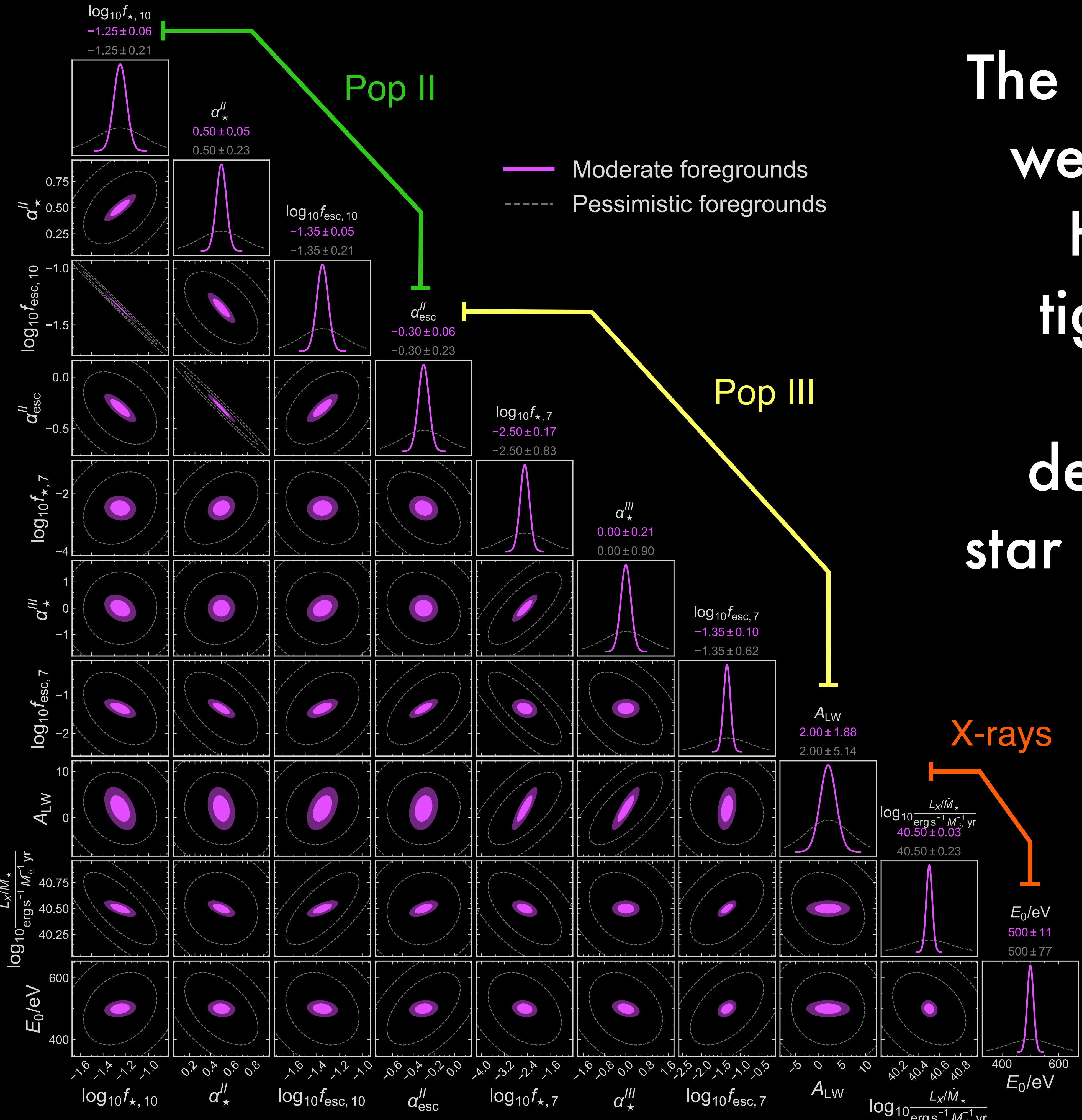


Liu et al. (2016)

There's also complex, interconnected astrophysics to explore before the EoR, even if EDGES is wrong.



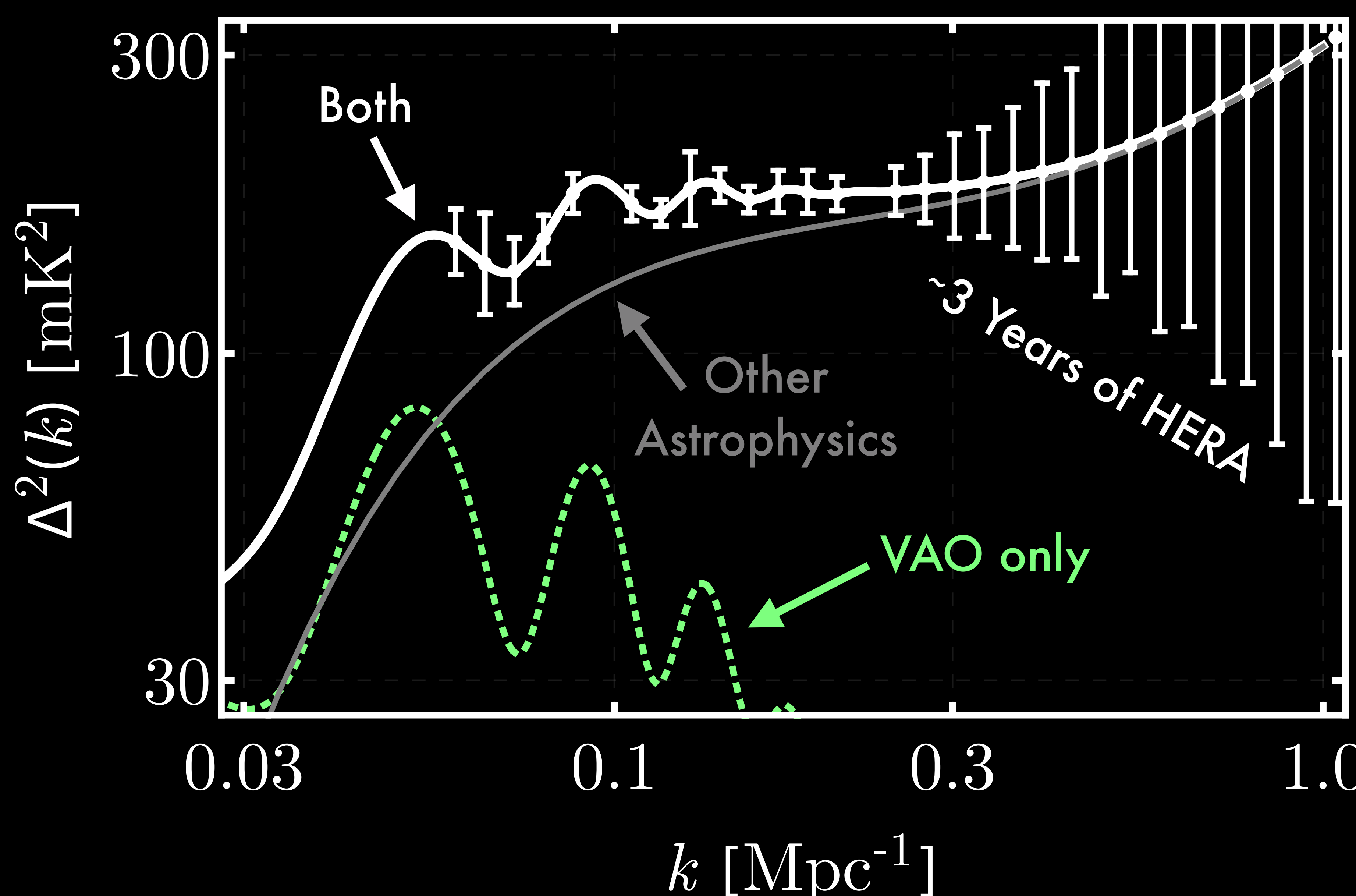
Mesinger et al. (2016)



The power spectra we measure with HERA will also tightly constrain parameters describing early star formation and X-ray heating.

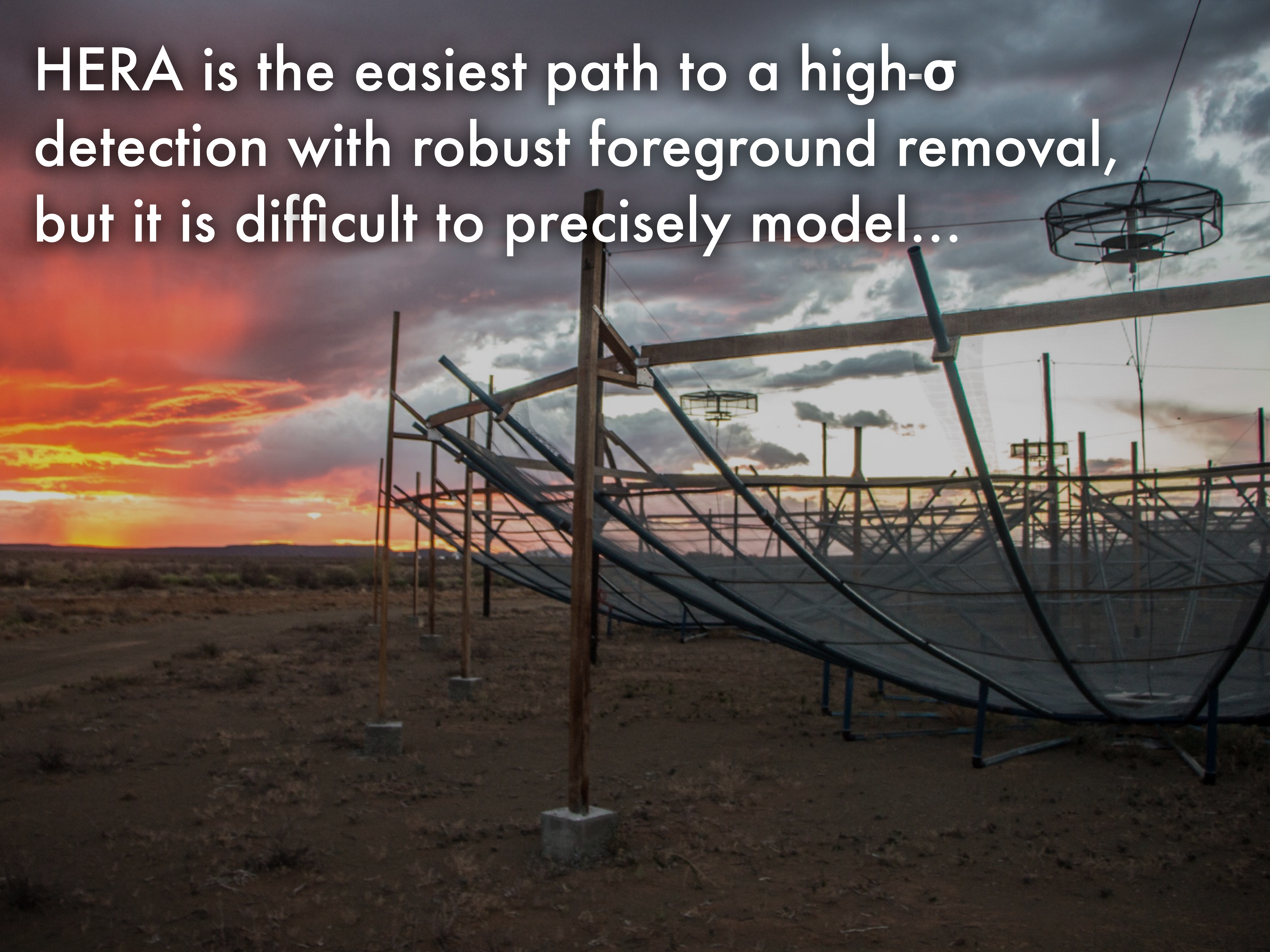
Mason et al. (2022)

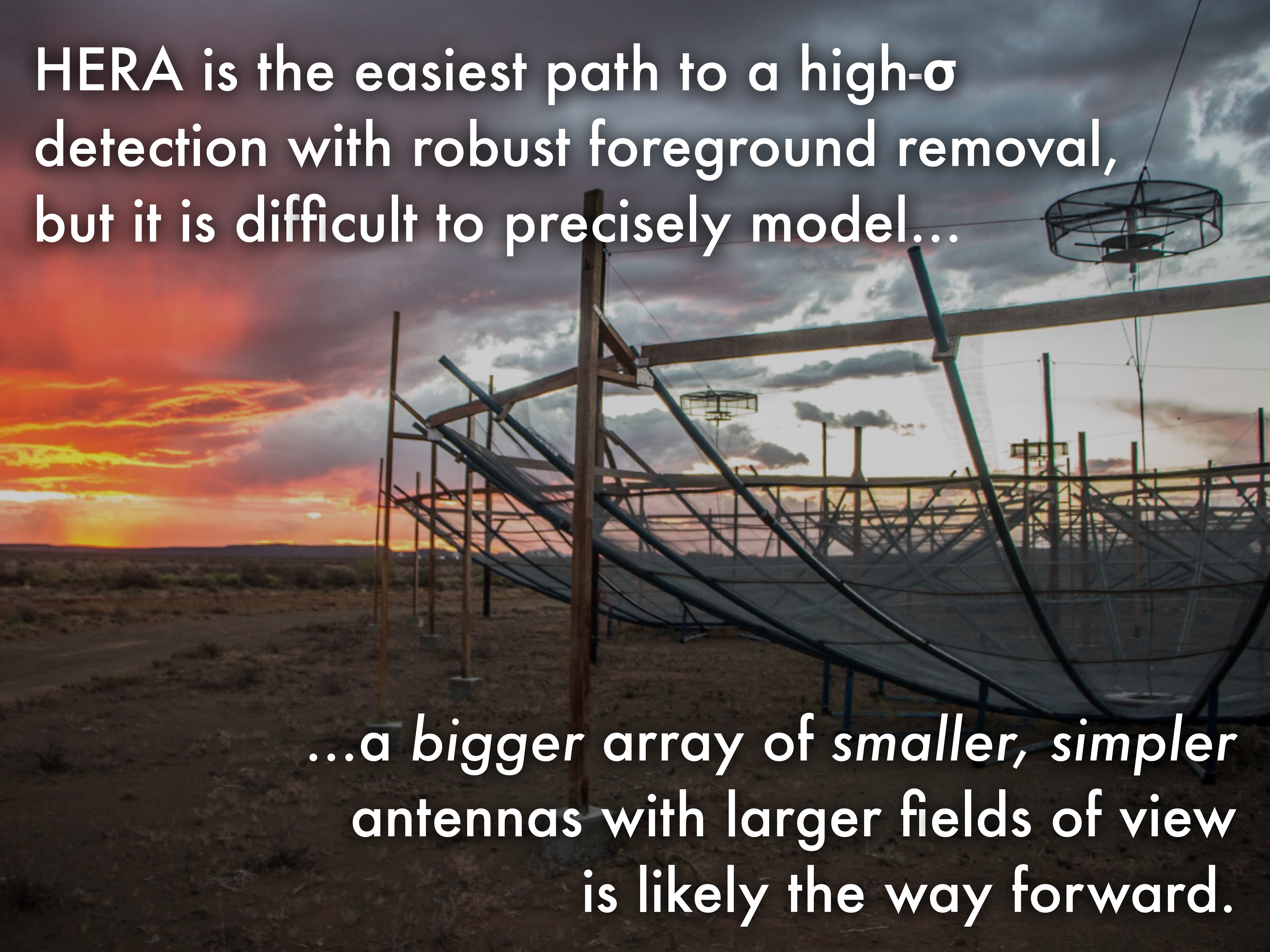
With a few years of observing, we may detect velocity acoustic oscillations, providing a new standard ruler at z≈16.



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...

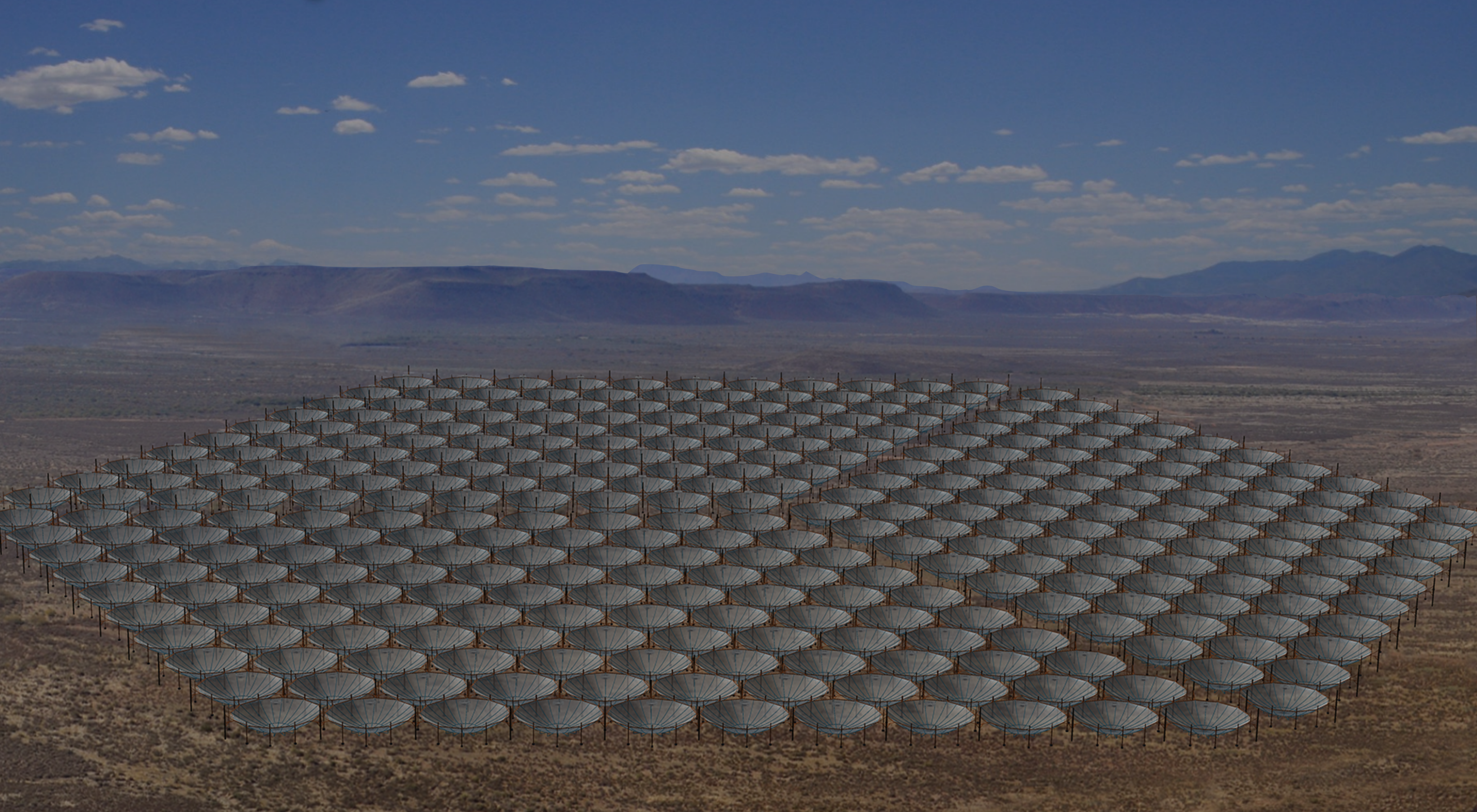


HERA is the easiest path to a high-σ detection with robust foreground removal, but it is difficult to precisely model…

…a *bigger* array of *smaller, simpler* antennas with 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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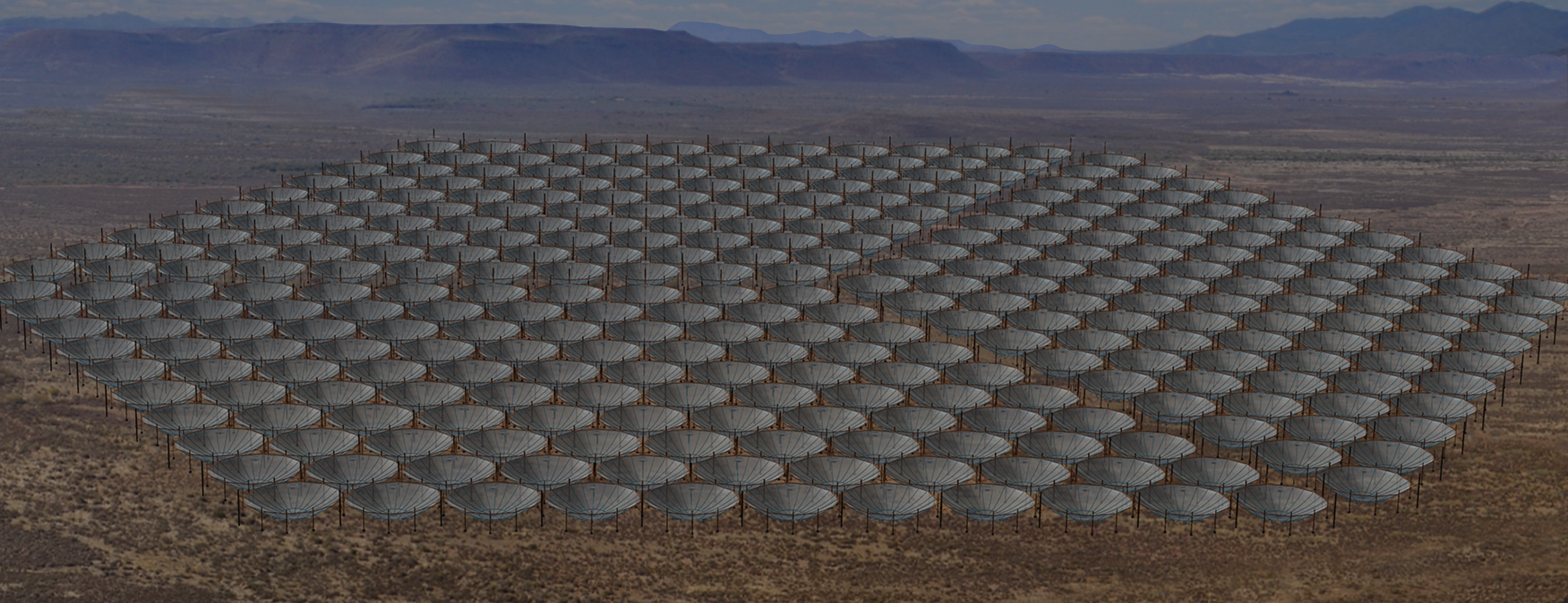
Measure antenna voltages $v_i(t)$.



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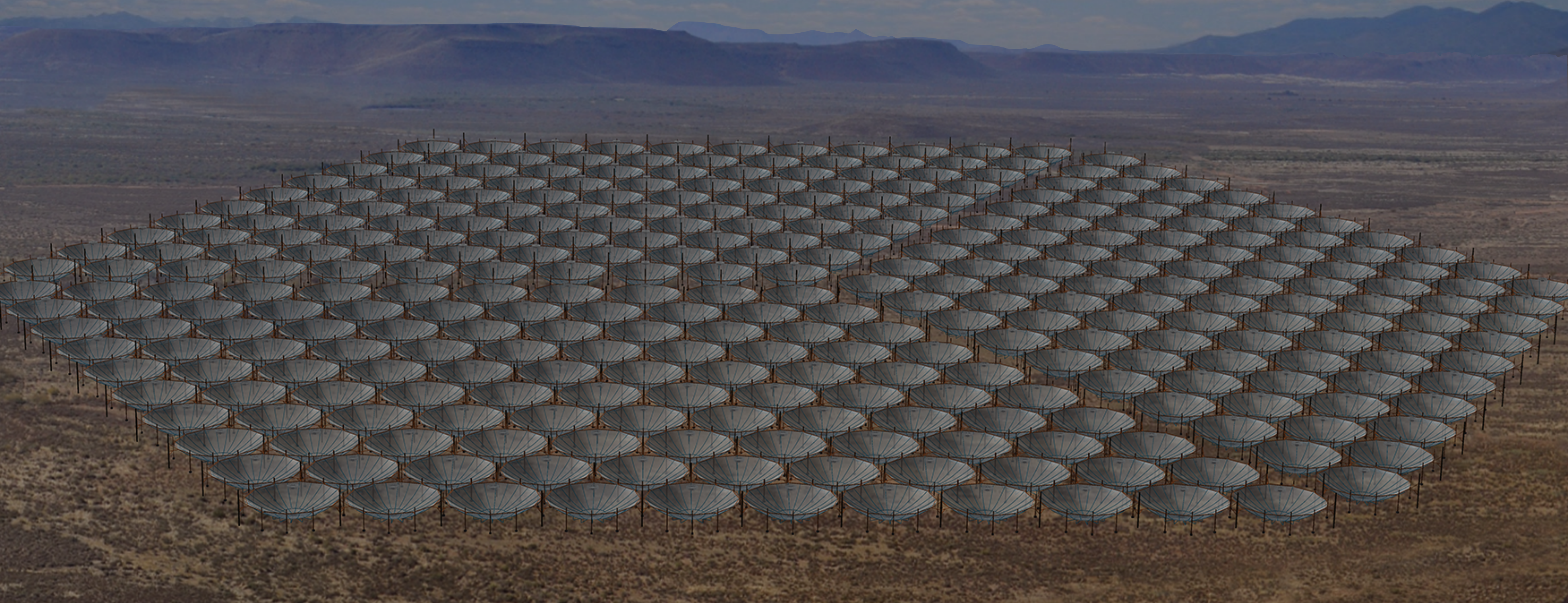

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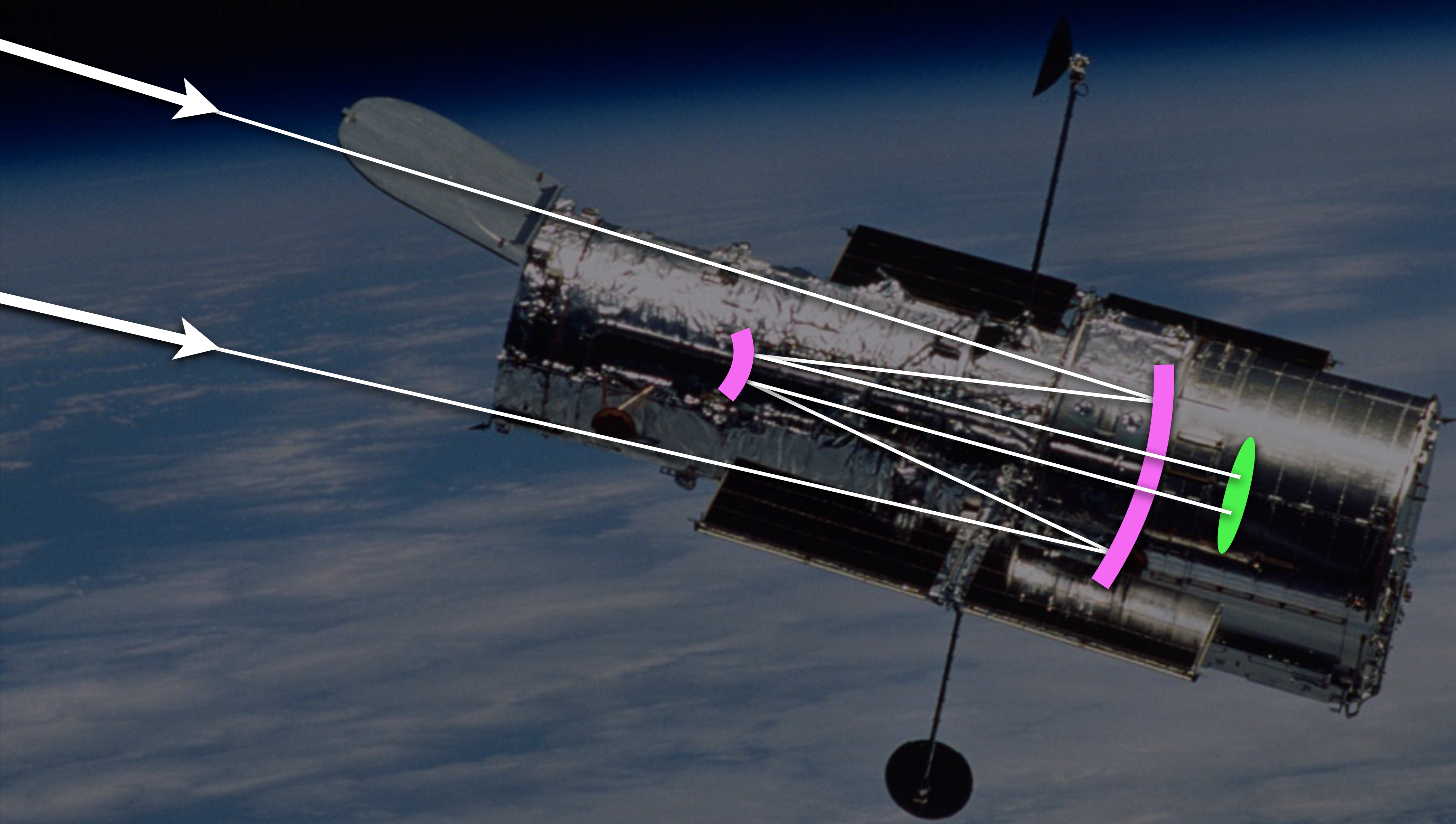
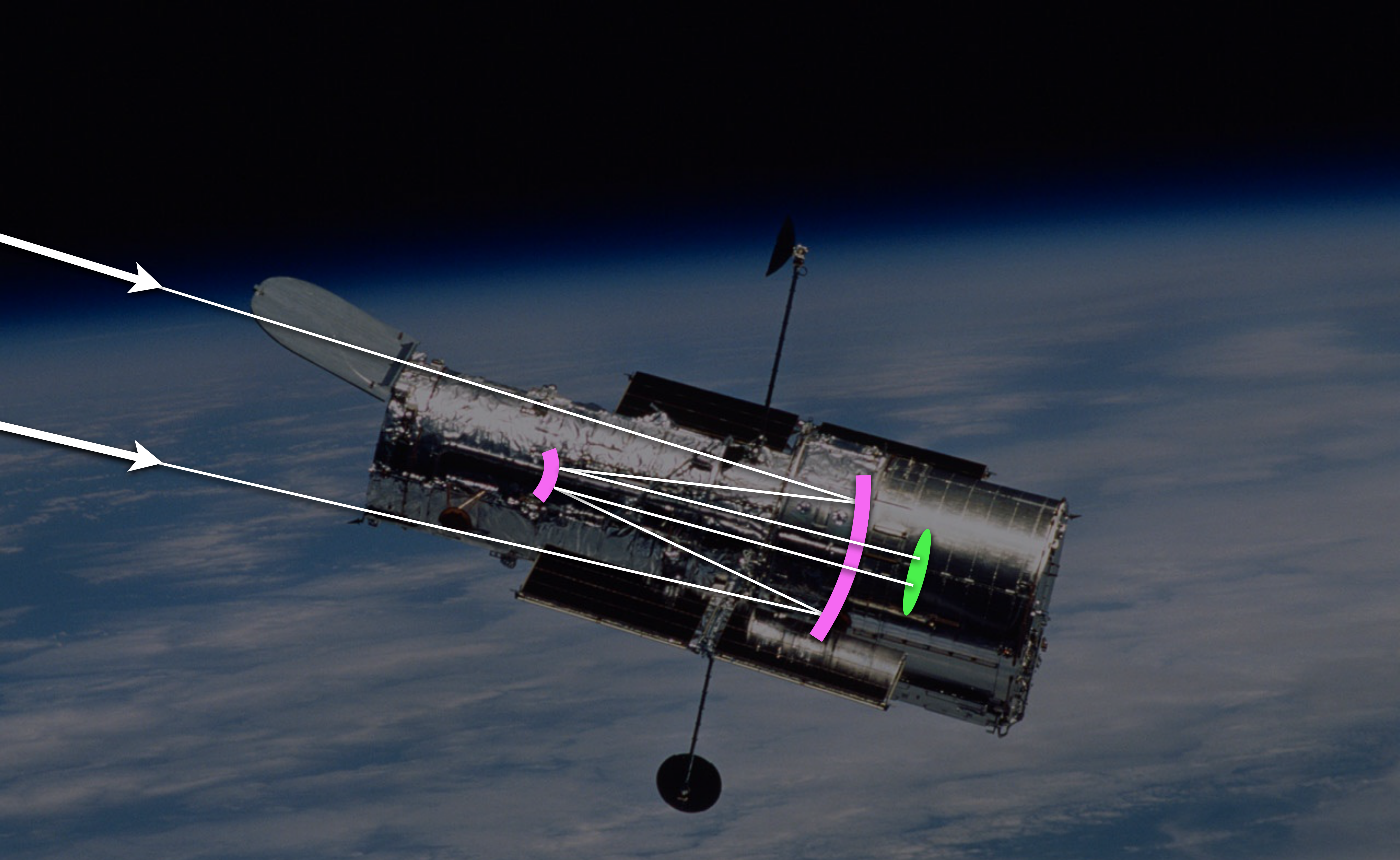
This scales like $O(N^2)$!

All telescopes are Fourier transformers.



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

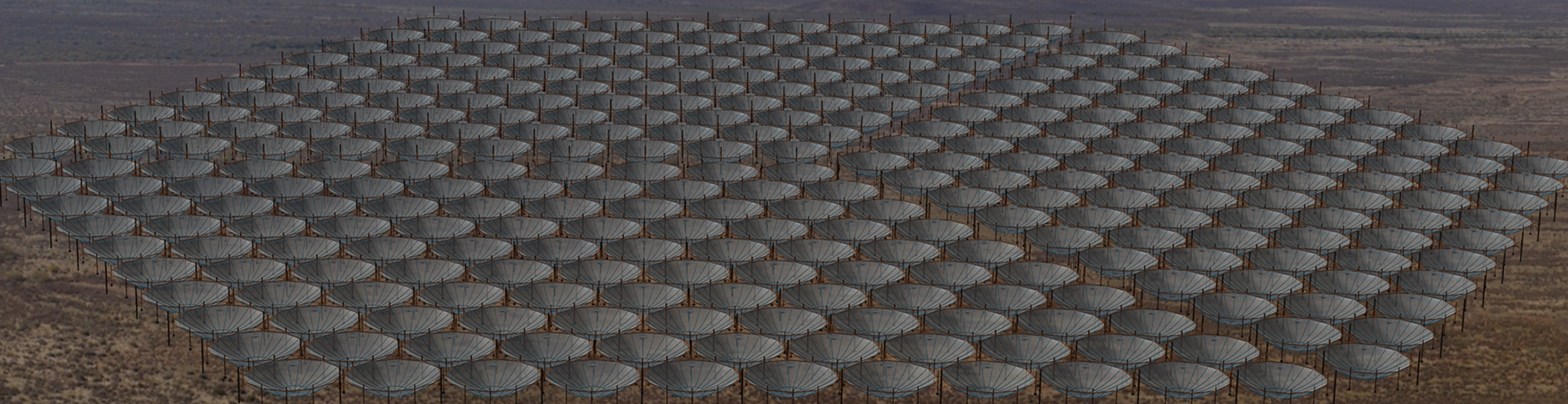


A telescope converts *photon momenta* to *positions* on the focal plane.

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

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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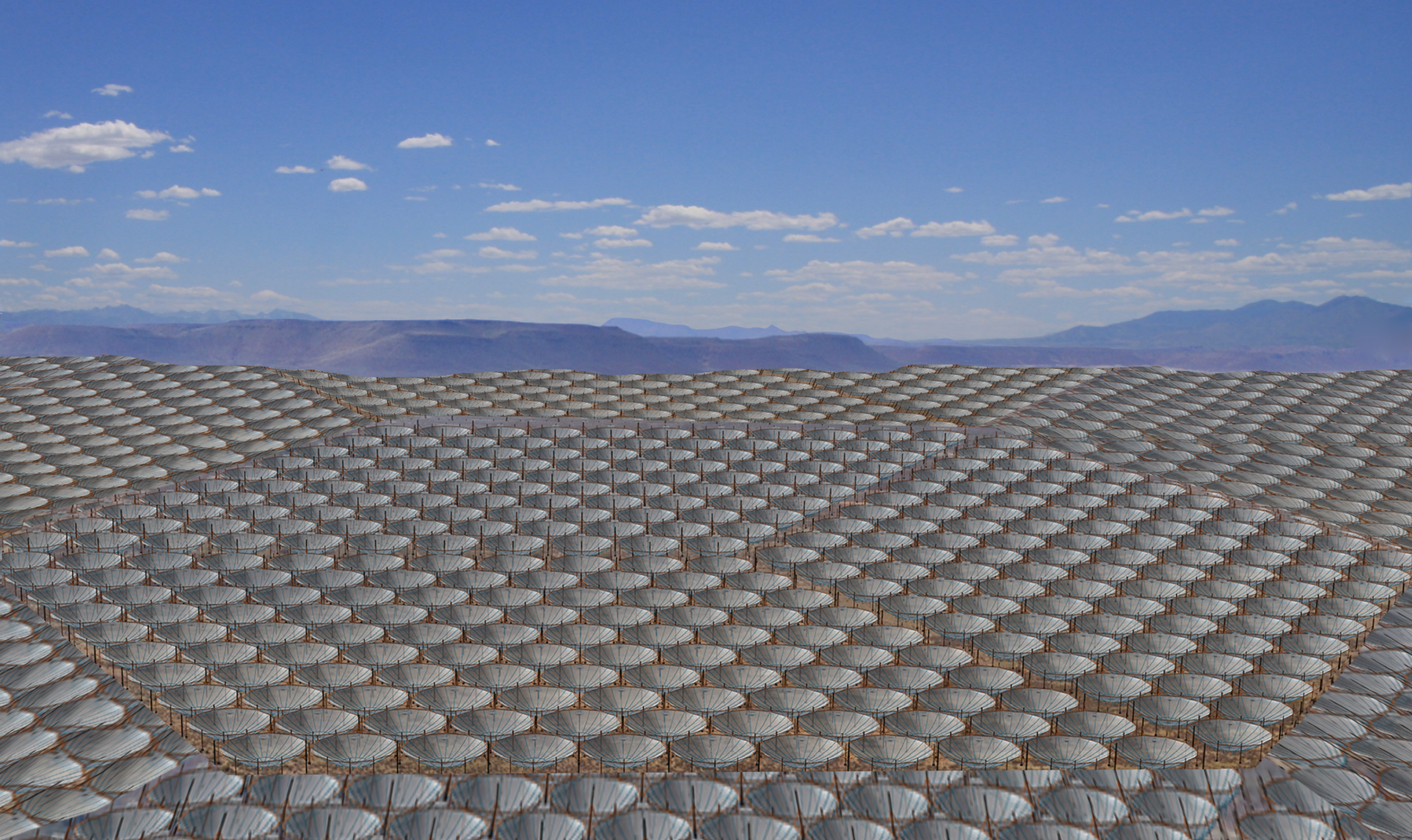
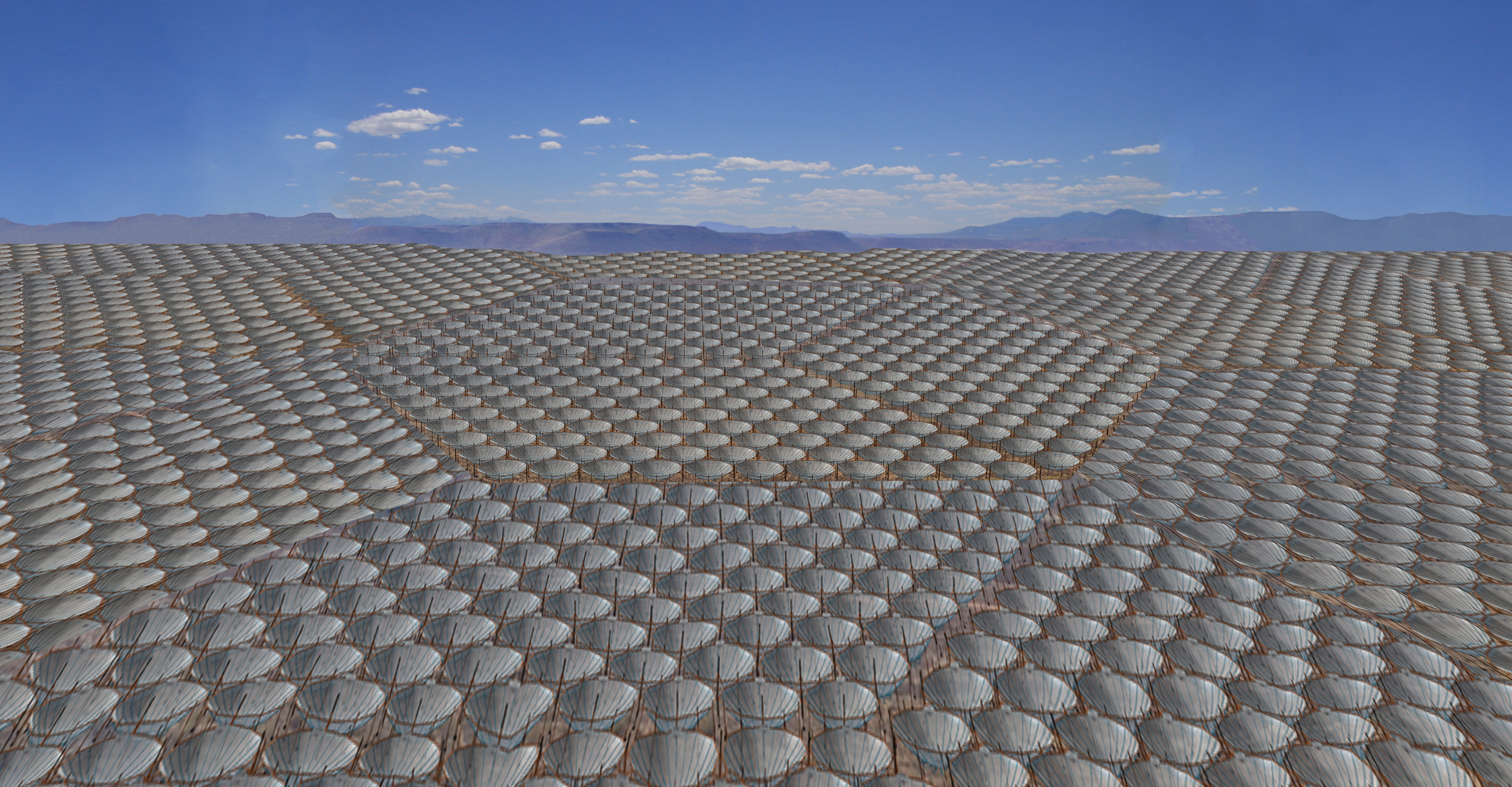
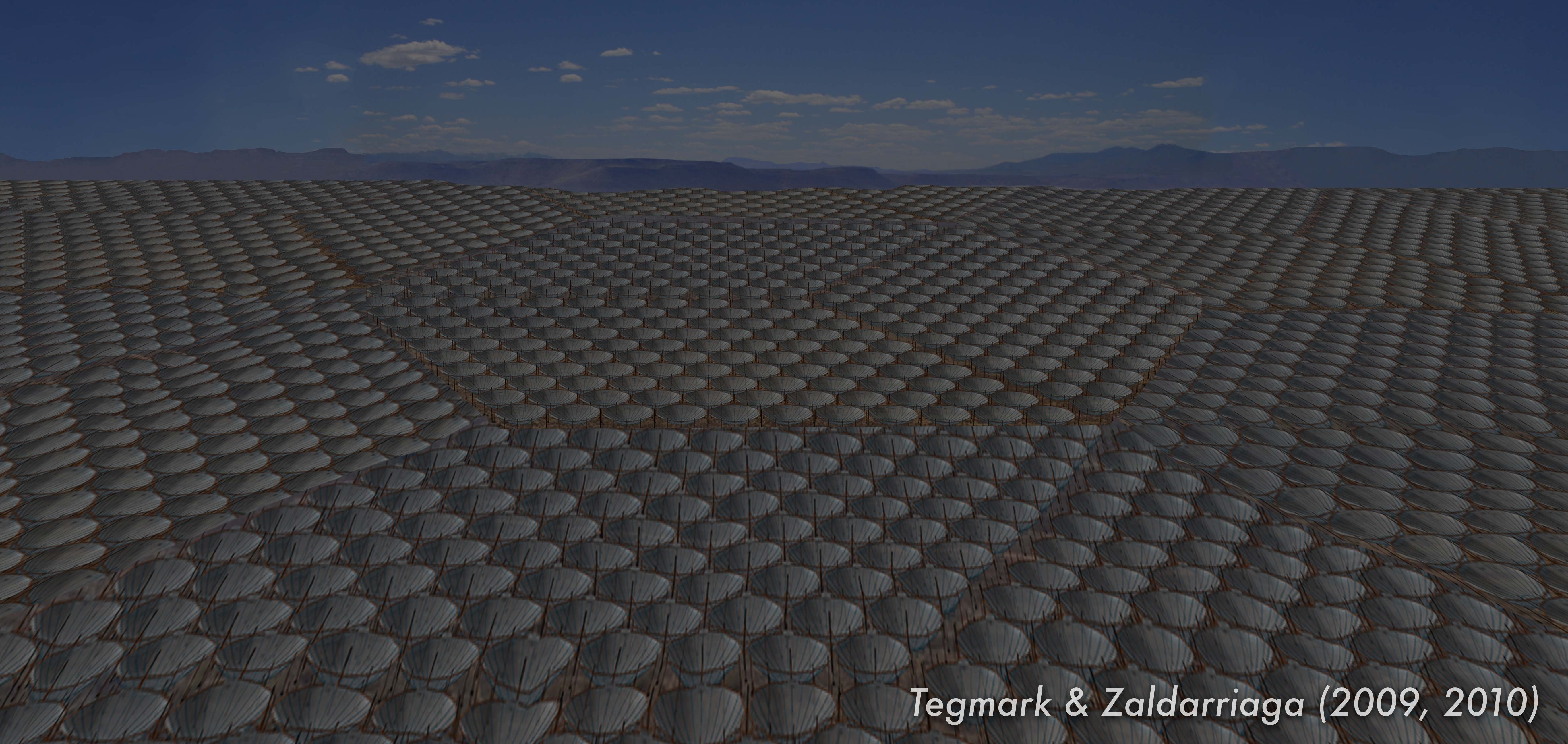


An FFT Telescope can be bigger than HERA.

Much, *much* bigger.



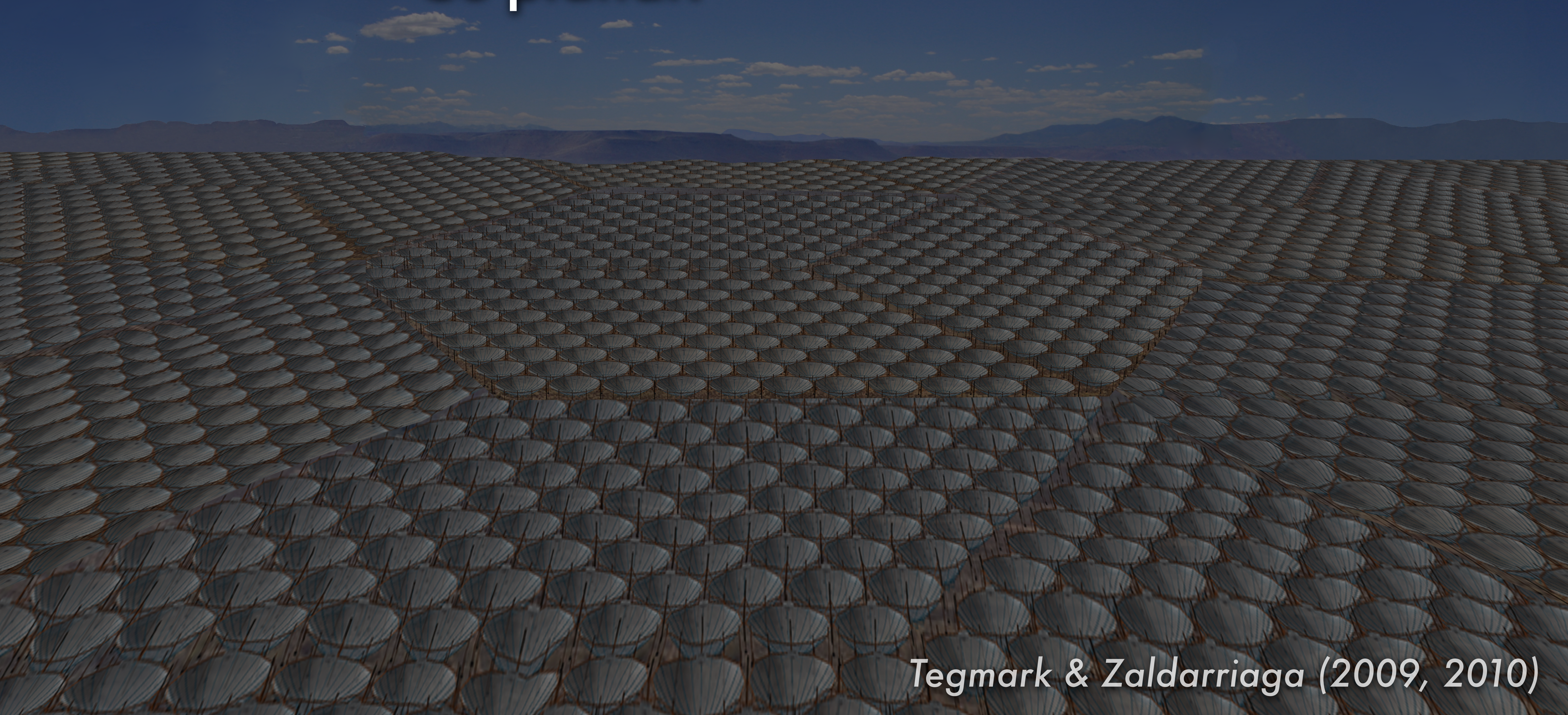
An FFT Telescope needs to be...



Tegmark & Zaldarriaga (2009, 2010)

An FFT Telescope needs to be...

- Co-planar.



Tegmark & Zaldarriaga (2009, 2010)

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Tegmark & Zaldarriaga (2009, 2010)

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Tegmark & Zaldarriaga (2009, 2010)

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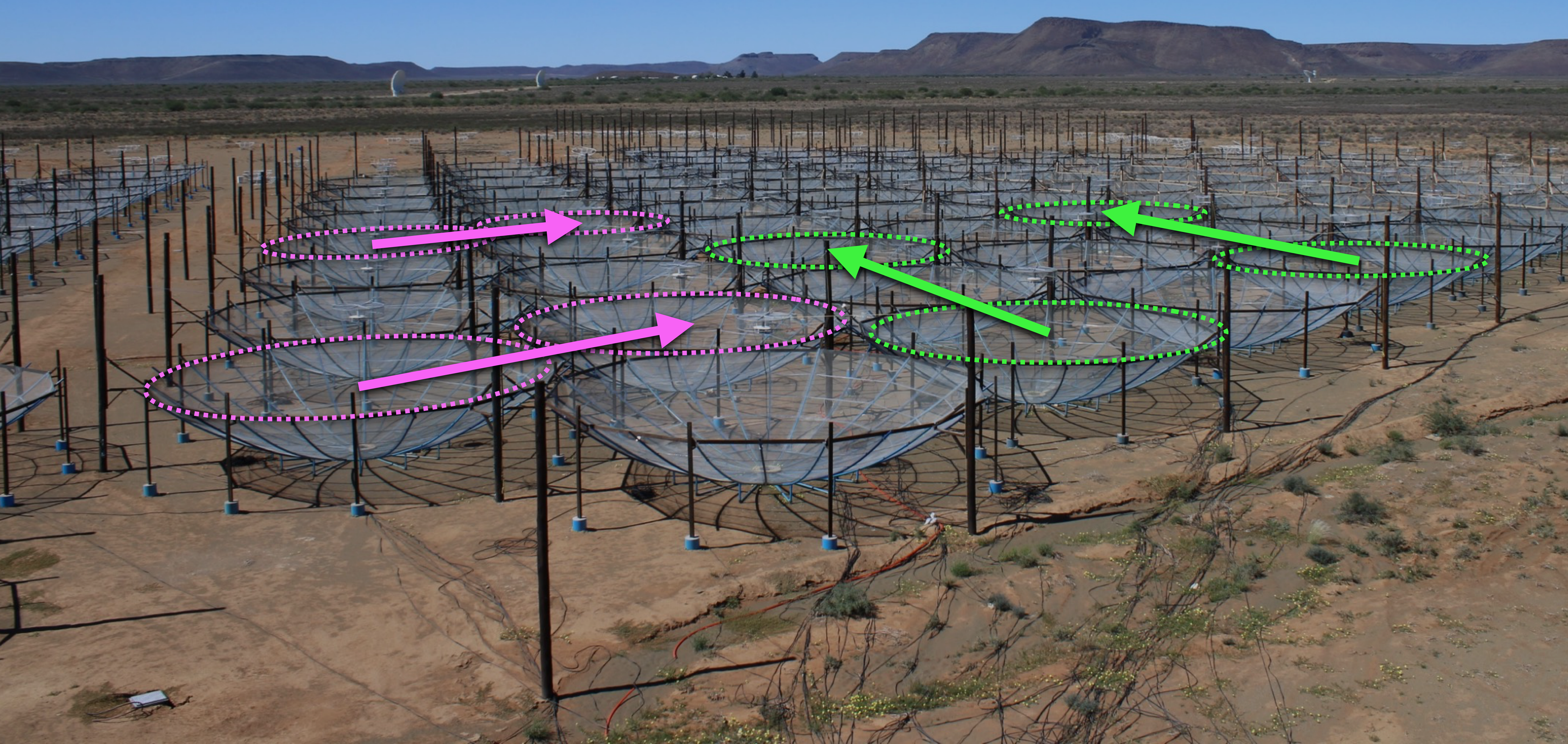
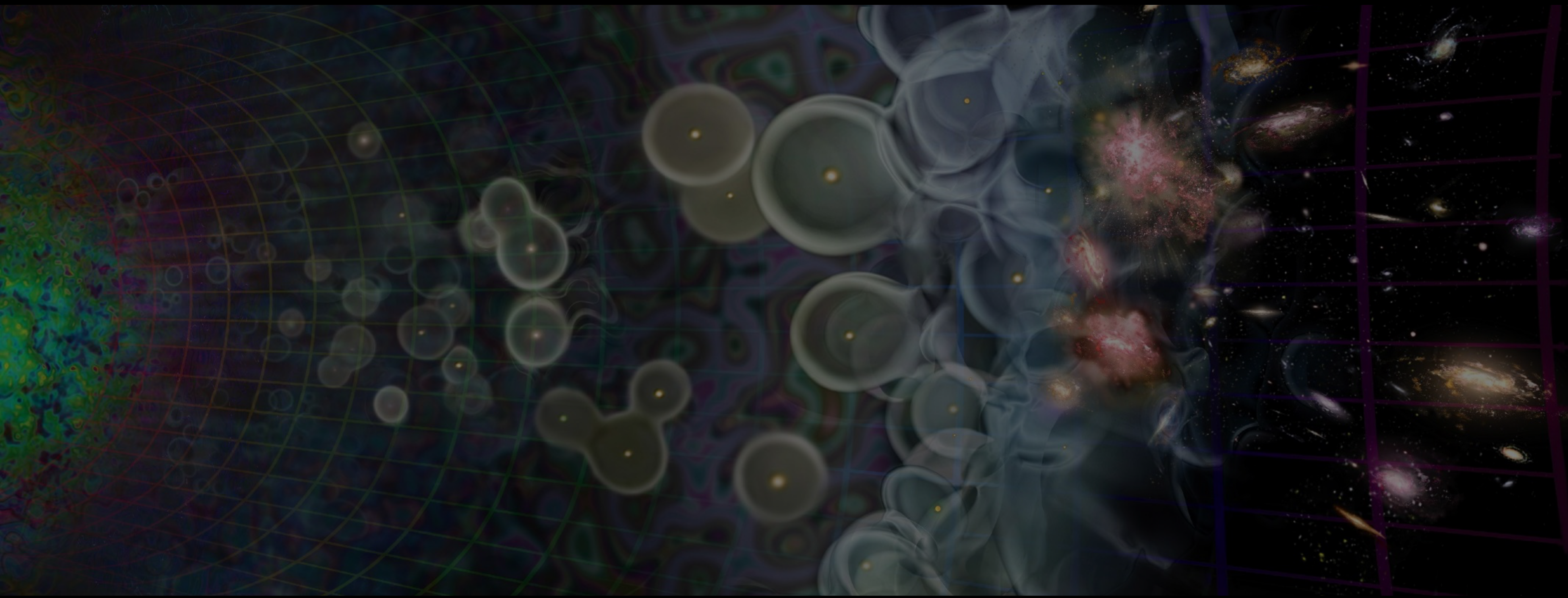
- On a regular or hierarchically regular grid.
- Calibrated in real time.

Tegmark & Zaldarriaga (2009, 2010)

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



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



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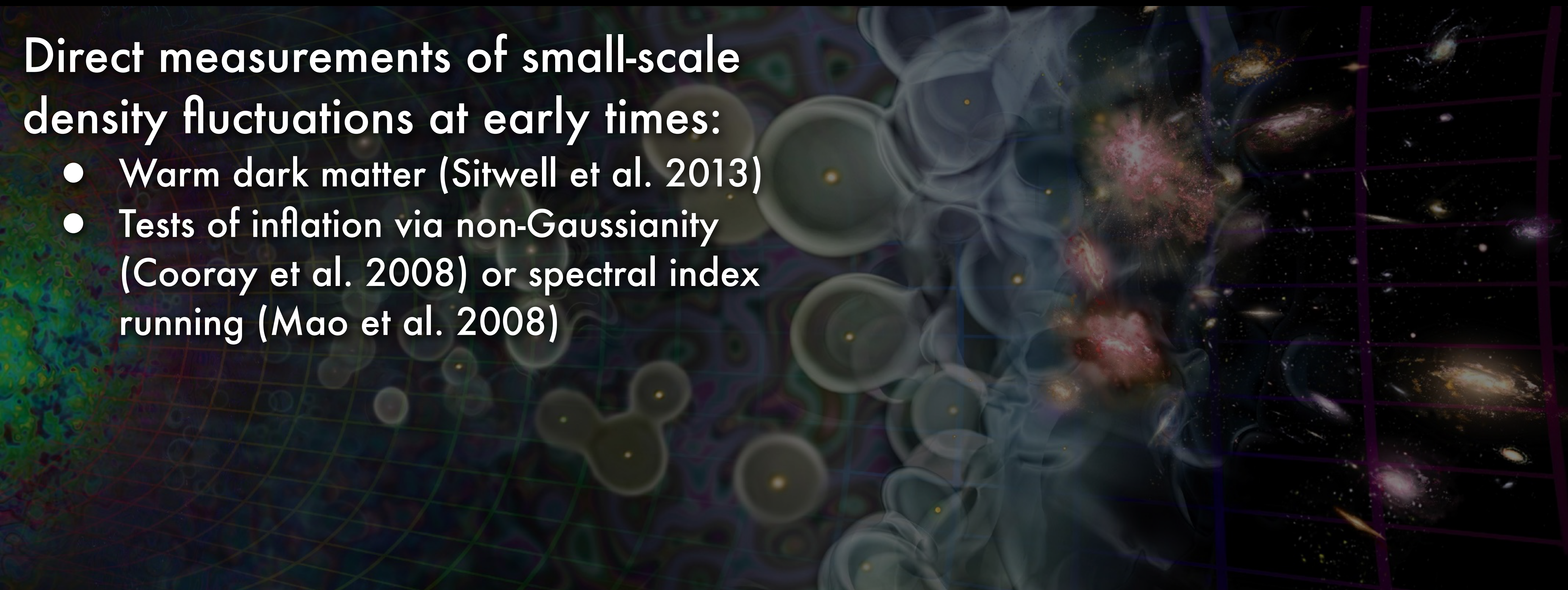

Direct measurements of small-scale density fluctuations at early times:

- 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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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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- With our full array and wider bandwidth, we should have the sensitivity necessary to detect and characterize the 21 cm signal from the EoR and the Cosmic Dawn.
- One day, an FFTT will draw on the instrumental and analysis legacy of HERA to fulfill the promise of 21 cm cosmology.

Photo: Dara Storer