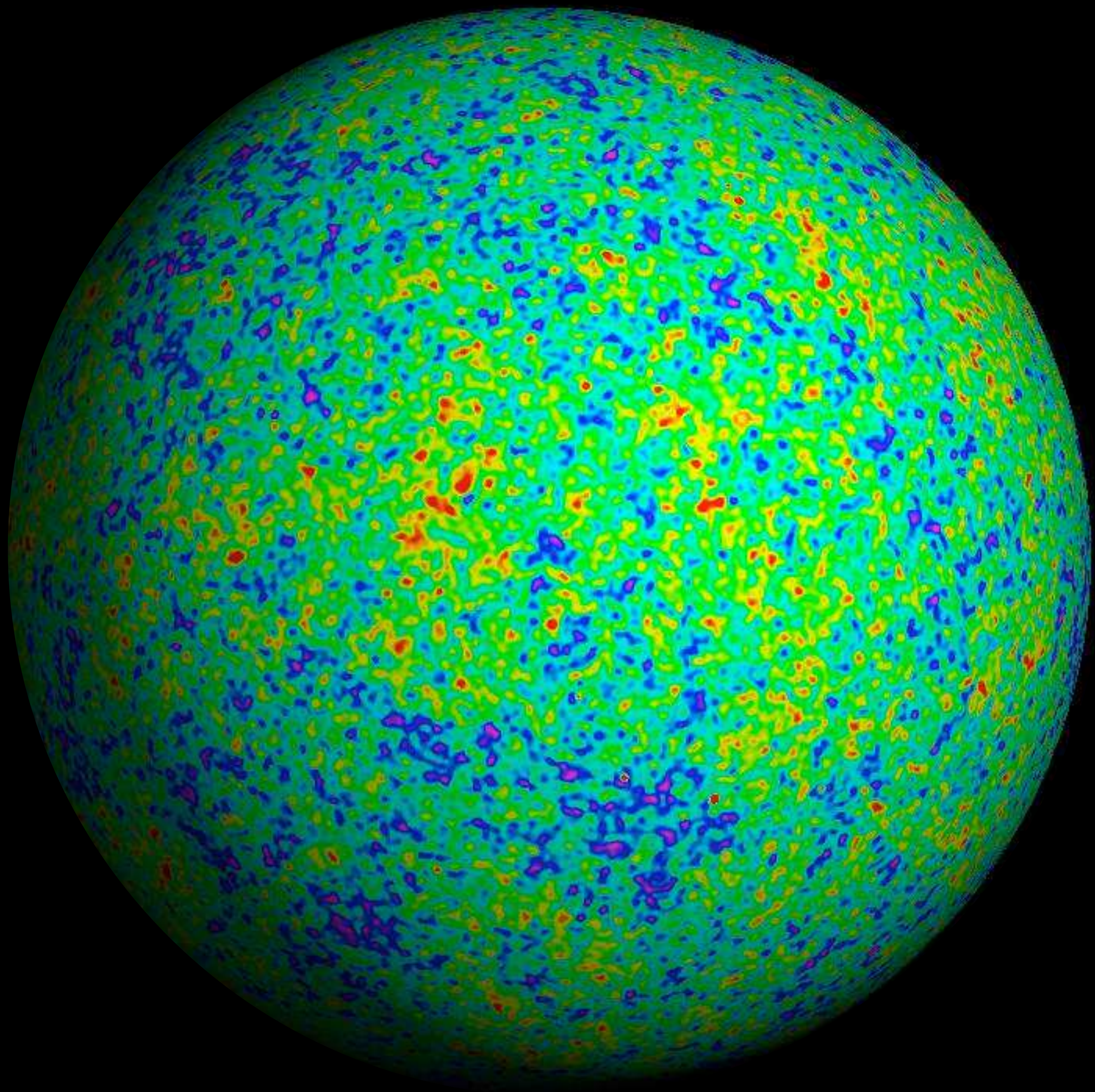
Precision Calibration for 21cm Cosmology with HERA

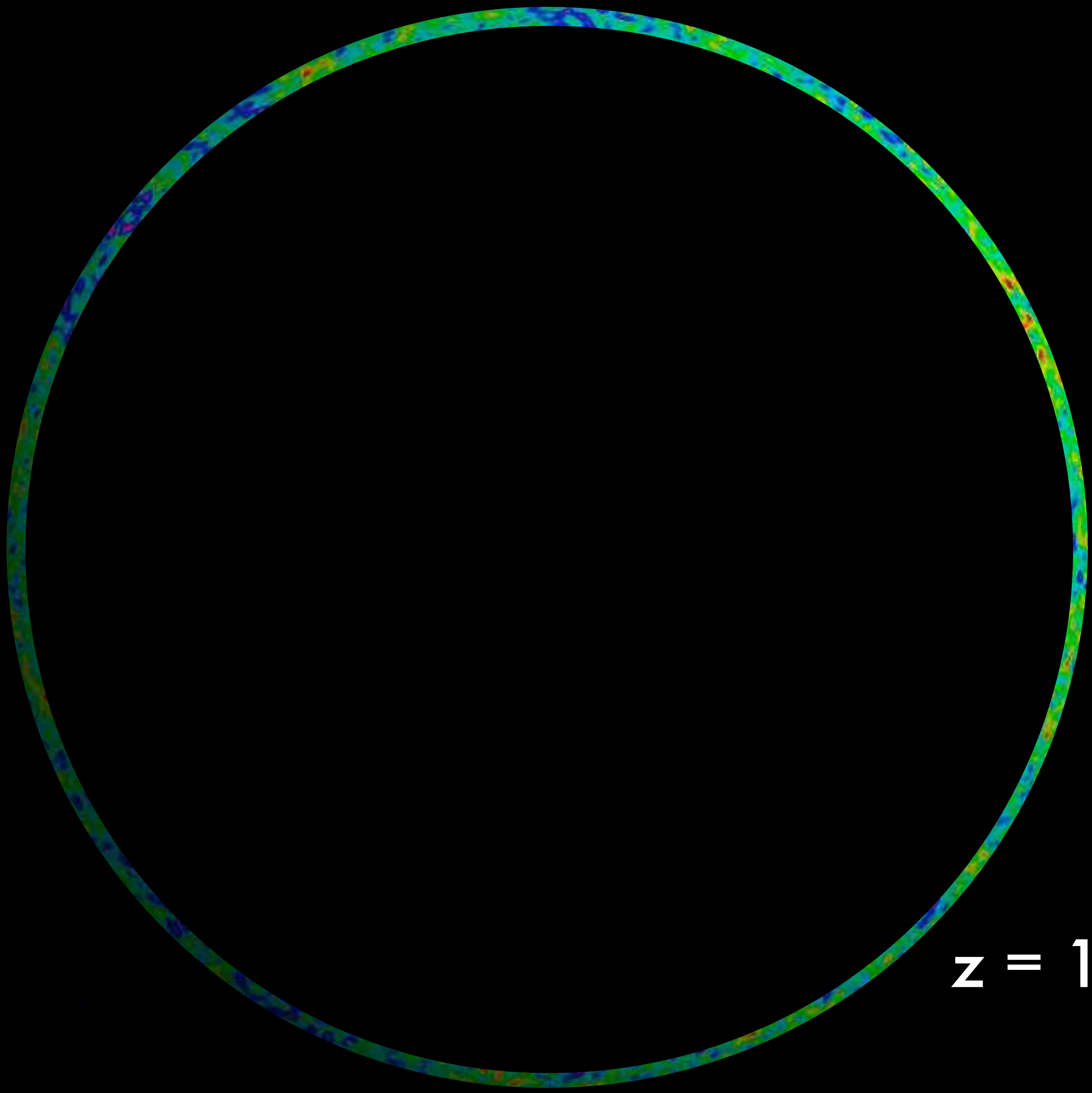
Josh Dillon
NSF Fellow, UC Berkeley

How can we map out our whole universe?

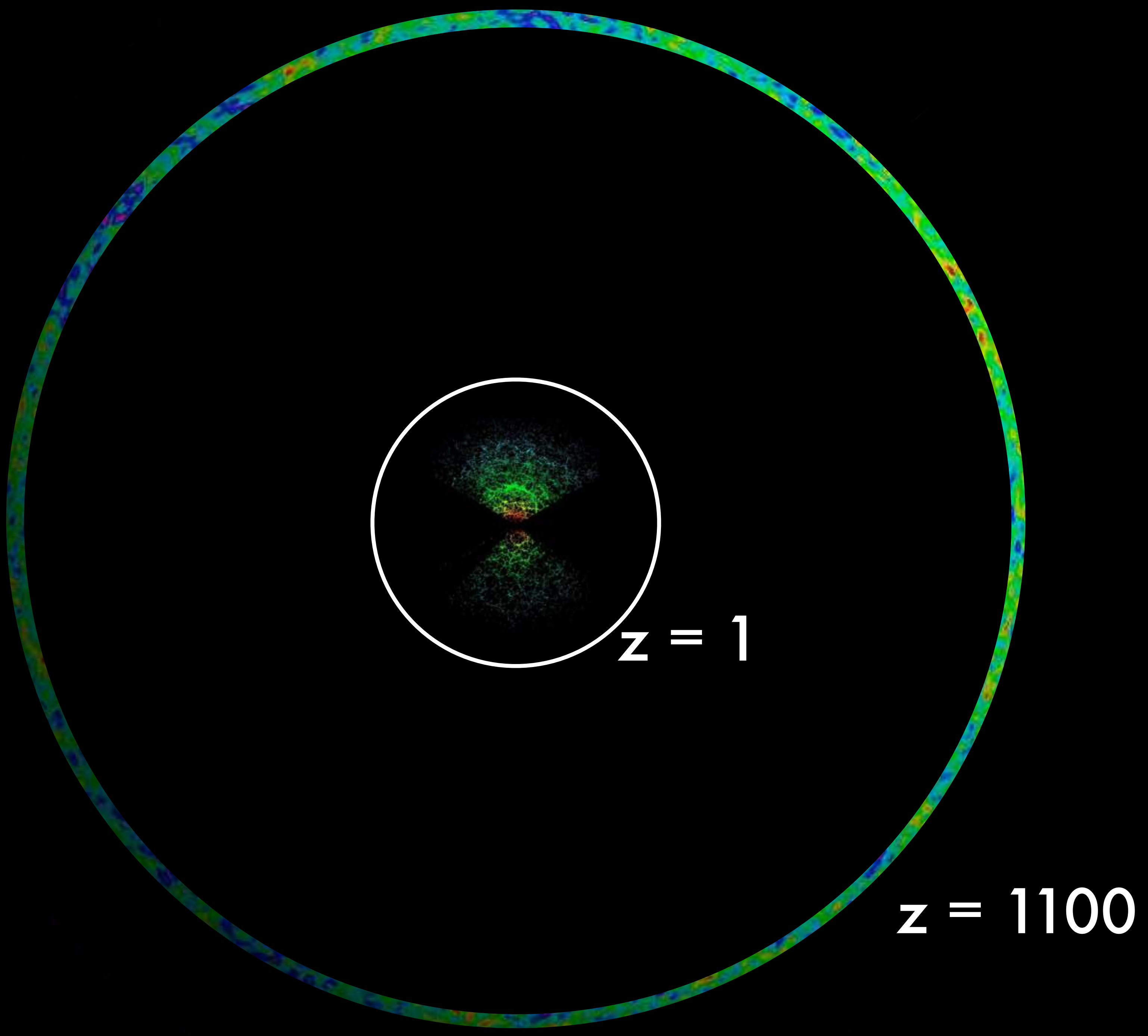
With the CMB...



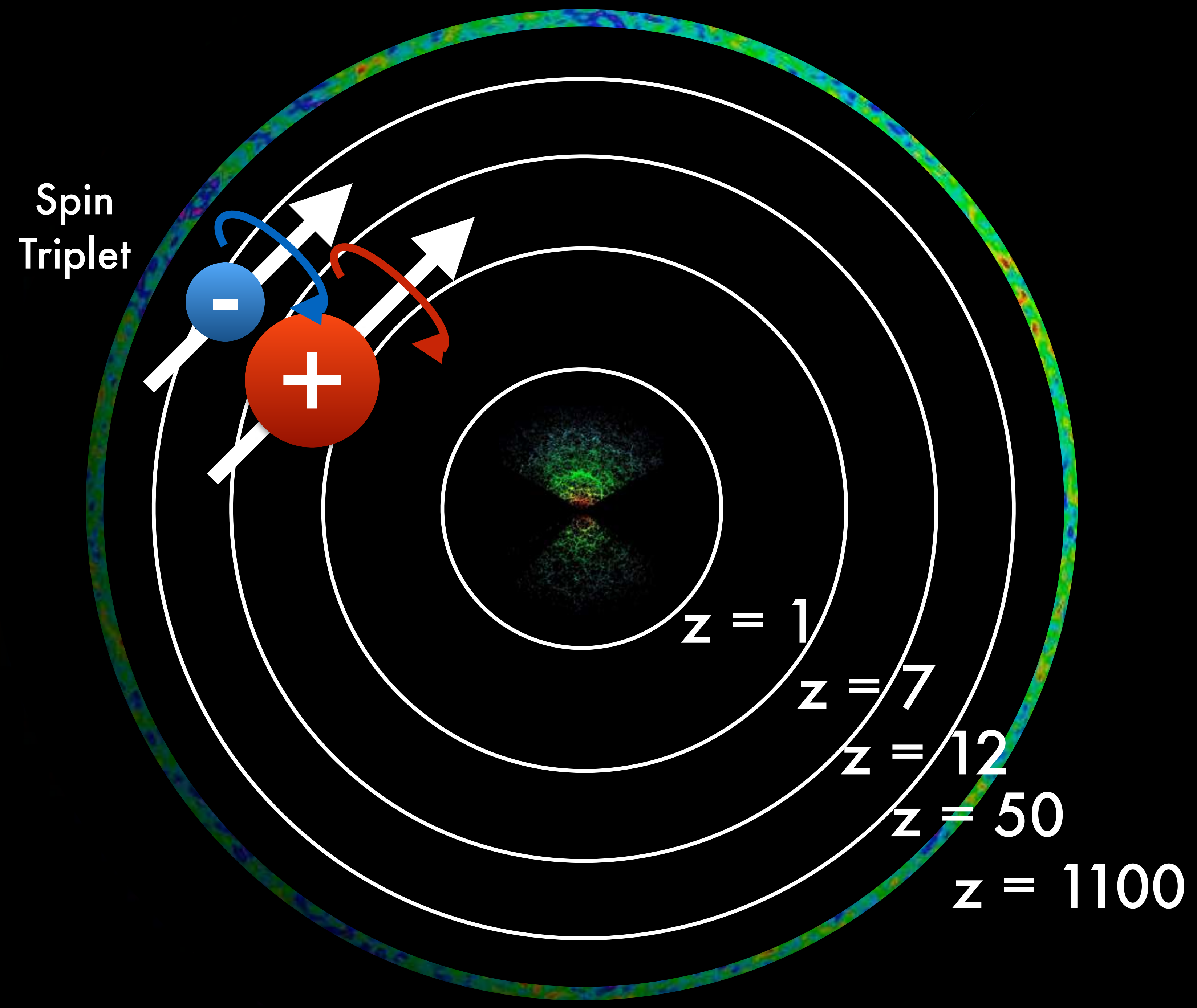
...we only get a thin shell at high redshift.



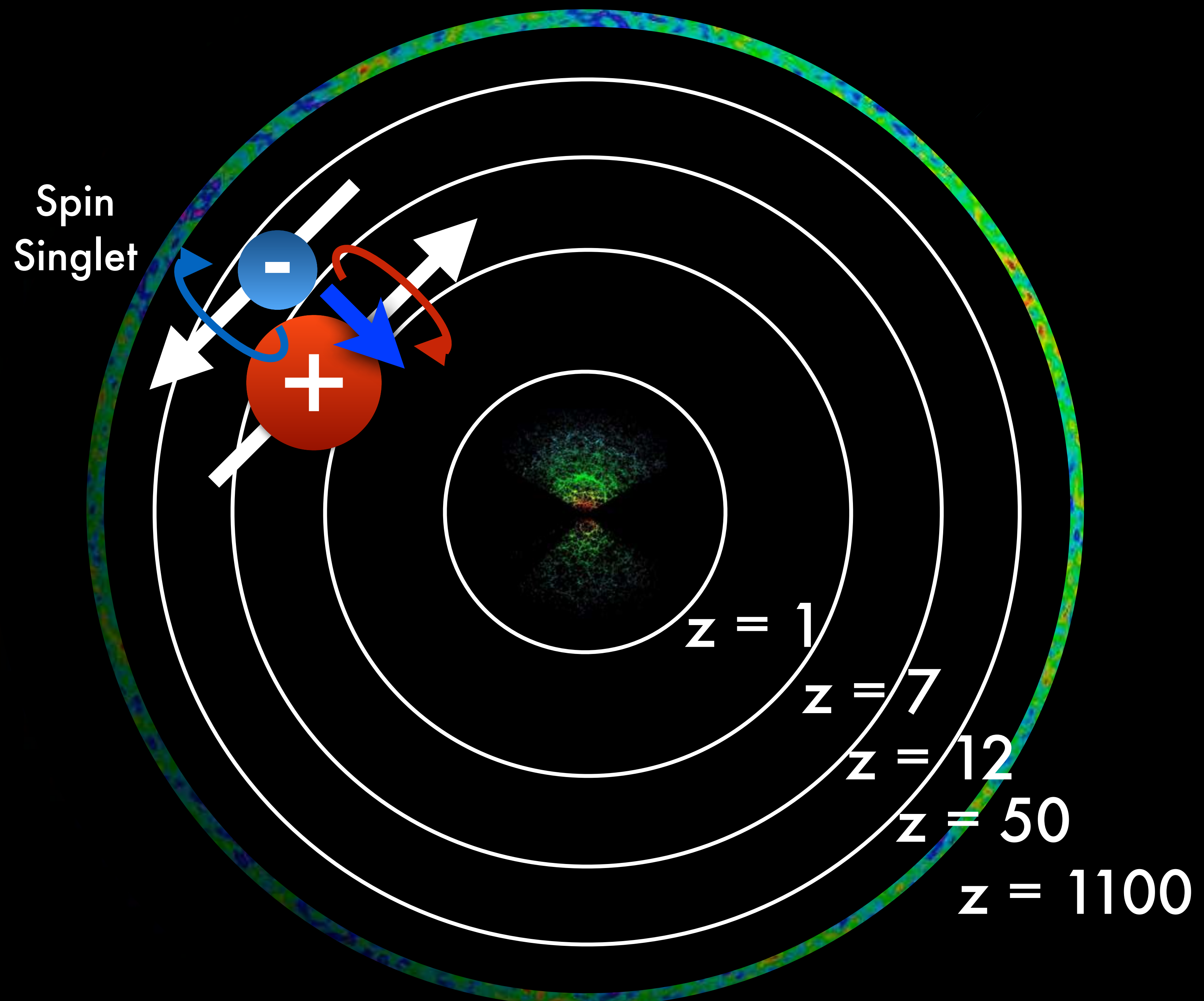
Galaxy surveys only tell us about the local universe.



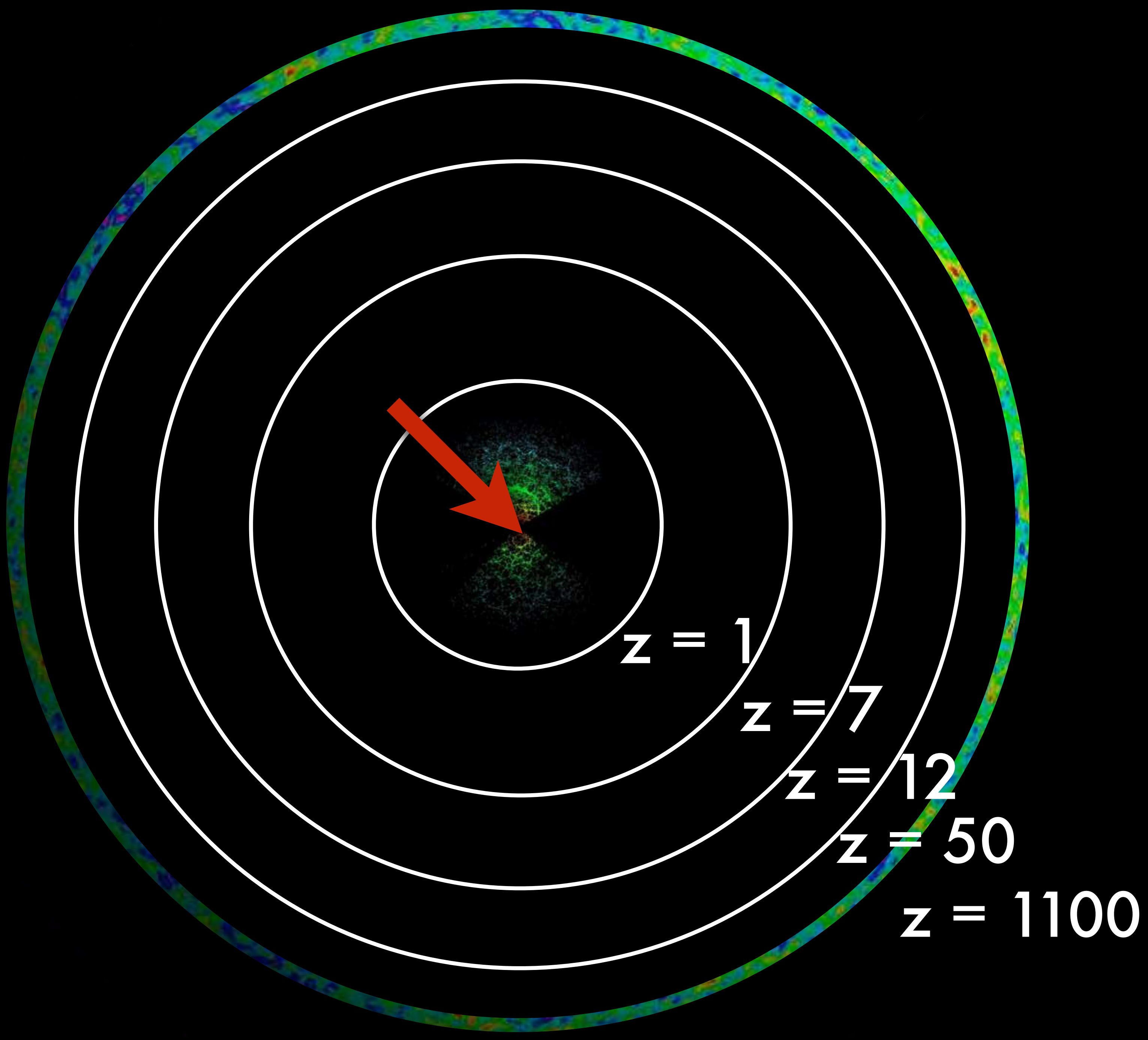
But using the 21 cm hydrogen line...



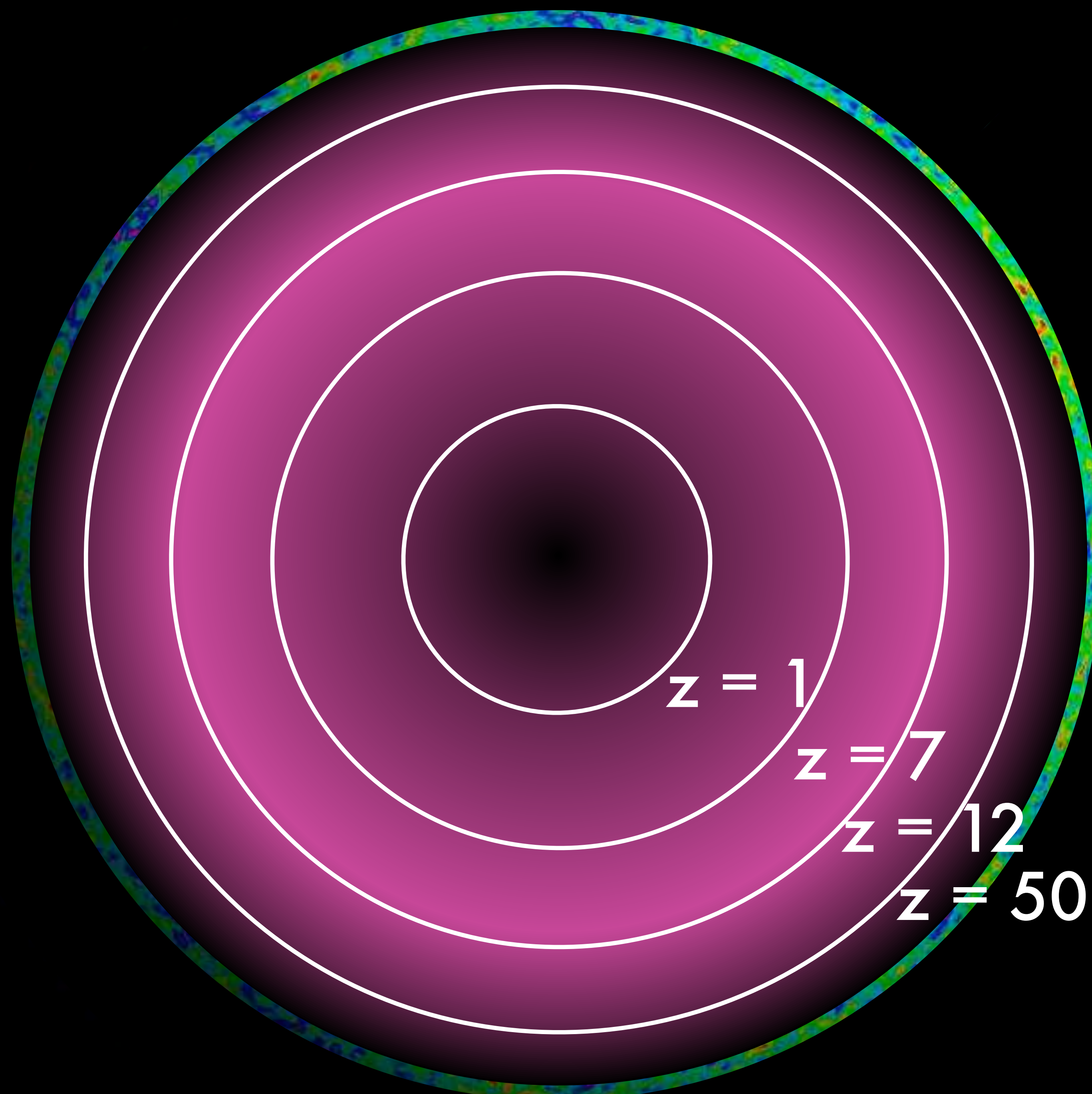
But using the 21 cm hydrogen line...



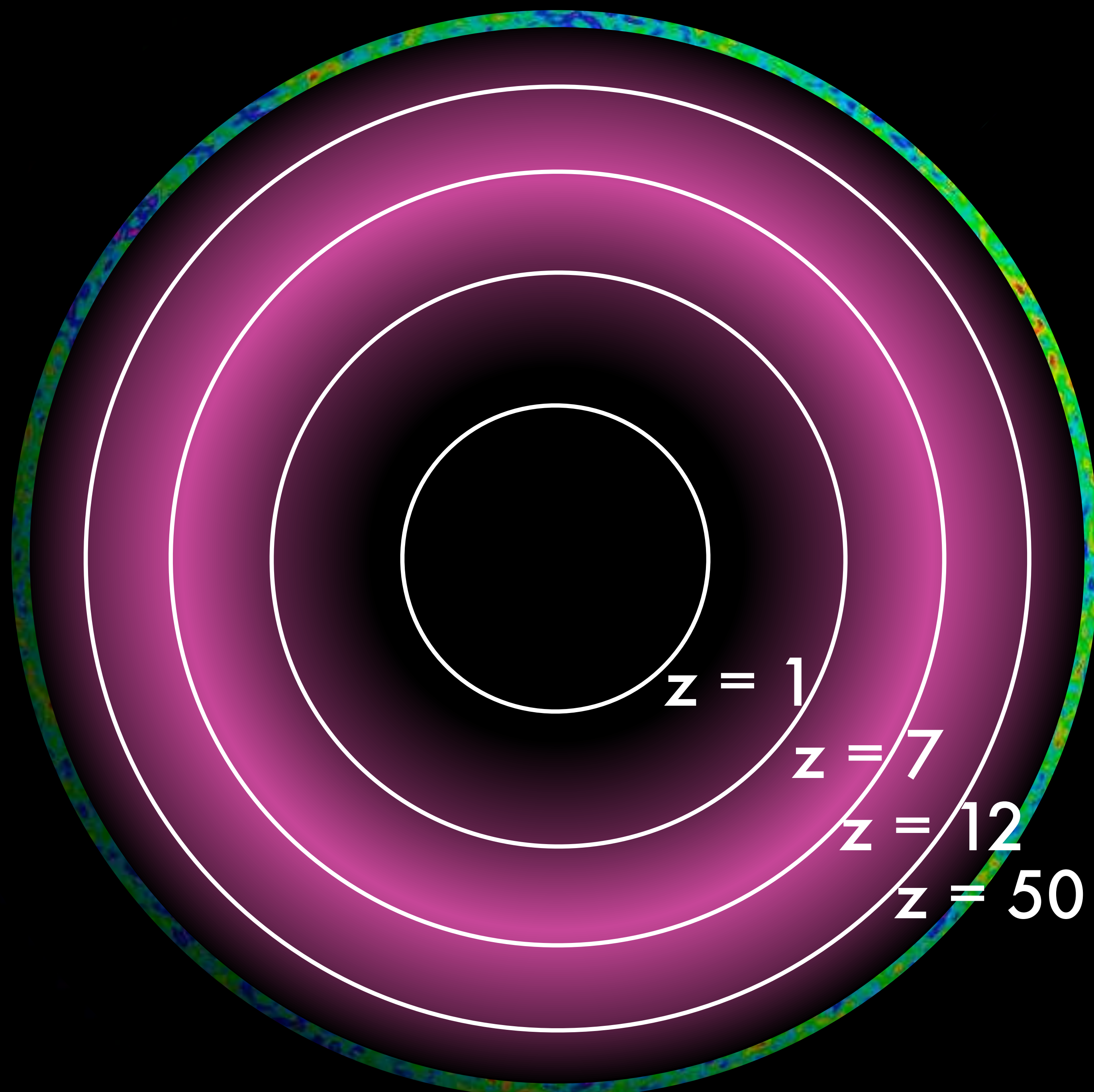
But using the 21 cm hydrogen line...



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

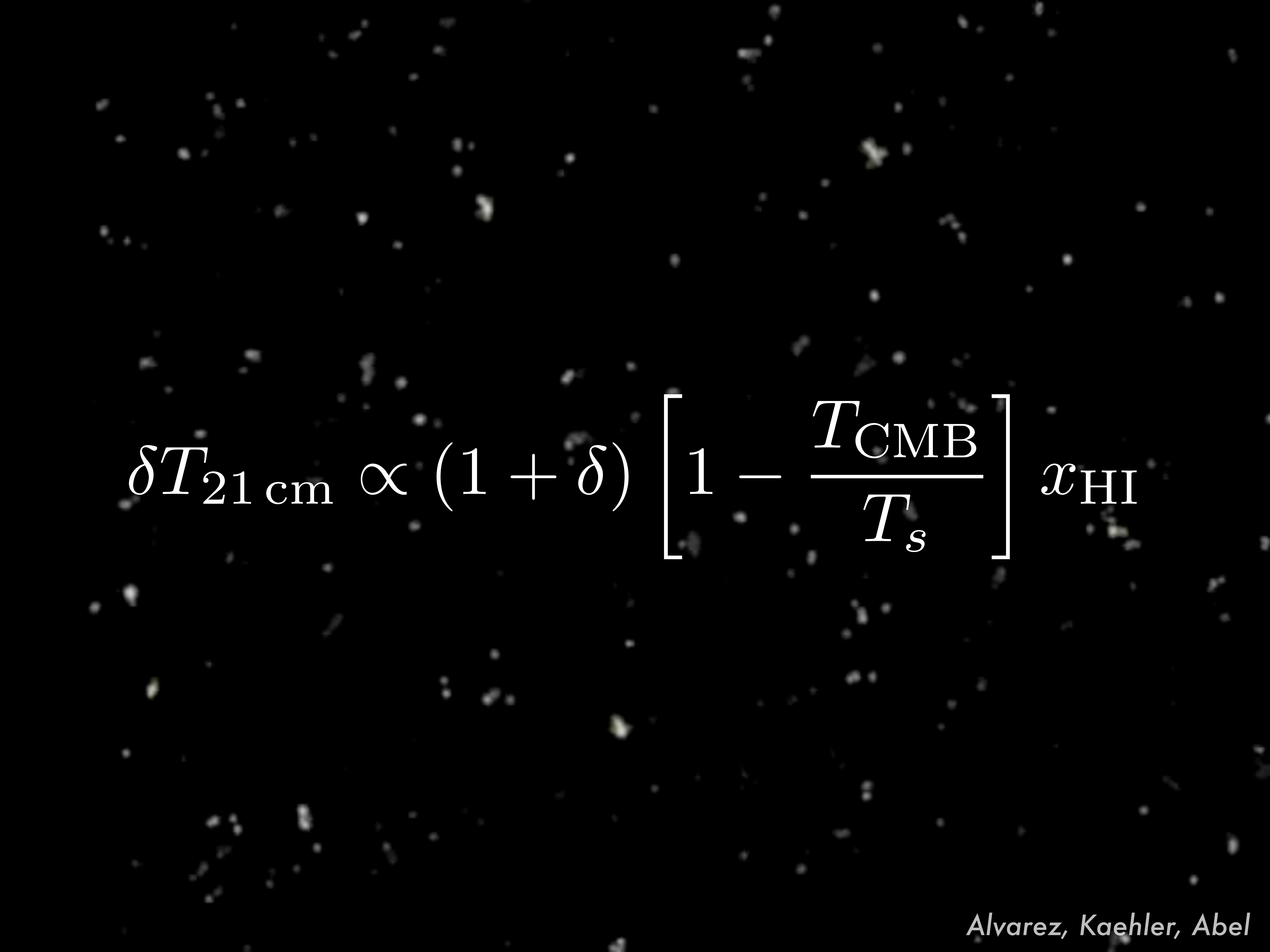


At $z \gtrsim 6$, 21 cm lets us map the universe as it undergoes a dramatic transformation.



Alvarez, Kaehler, Abel

Alvarez, Kaehler, Abel



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

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: Matter Power Spectrum

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

21 cm Brightness Temperature

Alvarez, Kaehler, Abel

Overdensity of Hydrogen: Matter Power Spectrum

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

21 cm Brightness Temperature

Spin Temperature: First Stars and Black Holes

Alvarez, Kaehler, Abel

Overdensity of Hydrogen: Matter Power Spectrum

Neutral Fraction: Reionization

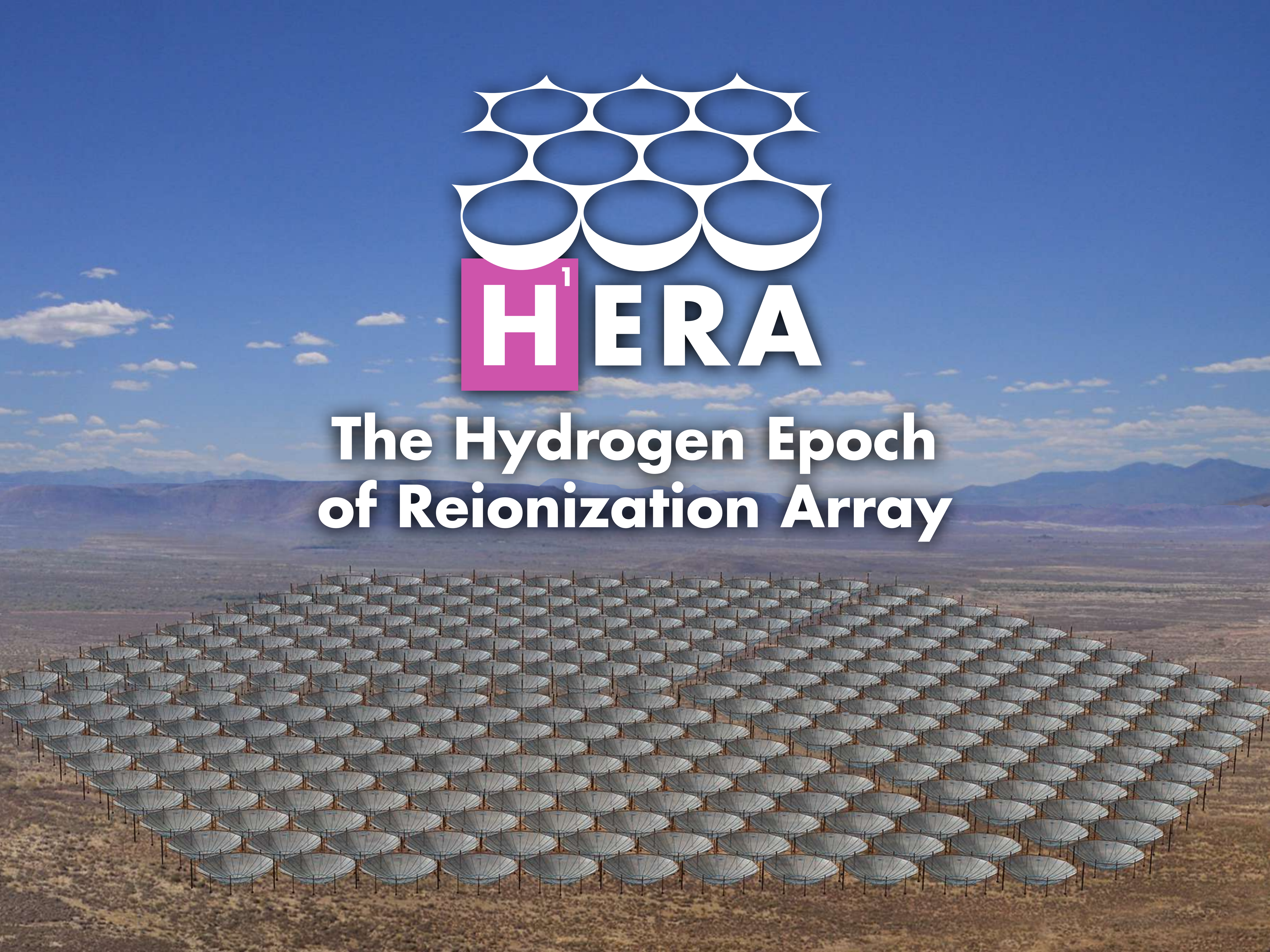
$$\delta T_{21\,\mathrm{cm}} \propto (1+\delta)\left[1-\frac{T_{\mathrm{CMB}}}{T_s}\right] x_{\mathrm{HI}}$$

21 cm Brightness Temperature

Spin Temperature: First Stars and Black Holes

Alvarez, Kaehler, Abel

How do we measure 21 cm brightness temperature fluctuations?


HERA
The Hydrogen Epoch
of Reionization Array

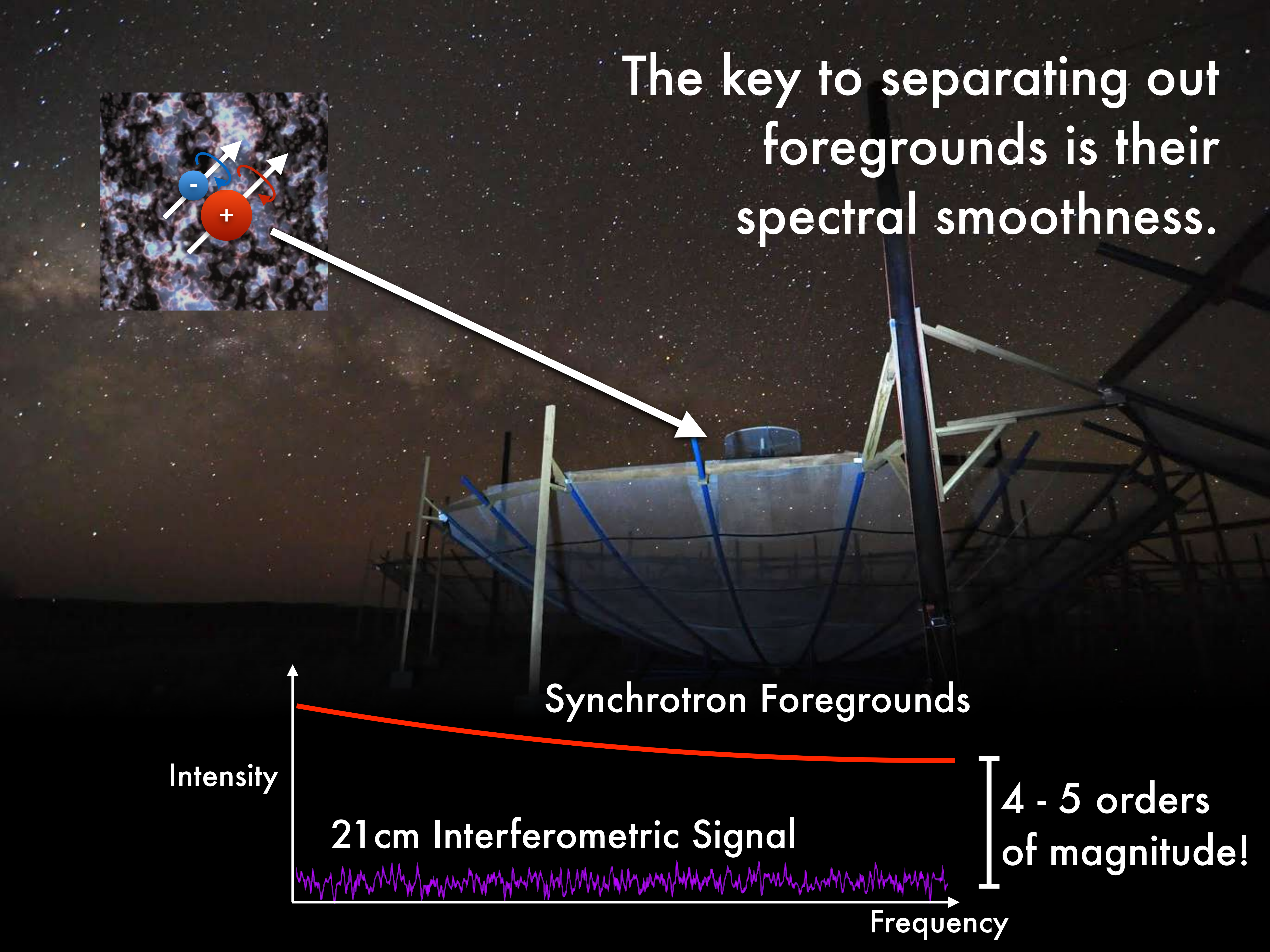

HERA
The Hydrogen Epoch of Reionization Array
CAL POLY POMONA
THE UNIVERSITY OF CALIFORNIA UCLA
THE UNIVERSITY OF CALIFORNIA BERKELEY 1868
ARIZONA STATE UNIVERSITY 1885
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
UNIVERSITY OF WASHINGTON 1861
SCUOLA NORMALE SUPERIORE
UNIVERSITY OF CAMBRIDGE
Penn University of Pennsylvania
McGill UNIVERSITY
Queen Mary University of London
NRF National Research Foundation
SARAO South African Radio Astronomy Observatory
BROWN
HARVARD
UNIVERSITY OF KWAZULU-NATAL
SKA AFRICA SQUARE KILOMETRE ARRAY
NRAO
RHODES UNIVERSITY Where leaders learn
UNIVERSITY of the WESTERN CAPE


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

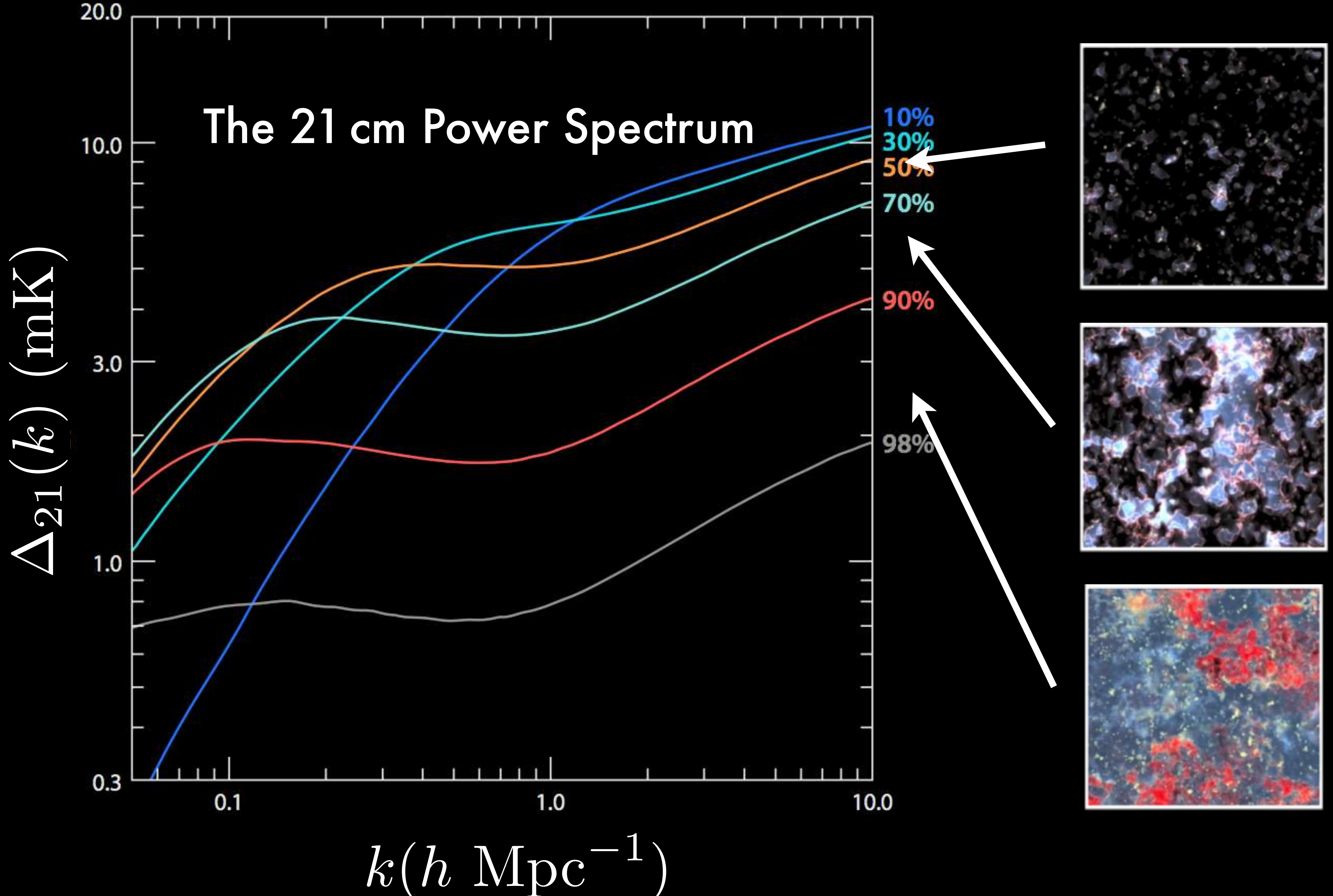

The 21 cm signal is faint,
so HERA is huge.
350 14-m diameter dishes

Our biggest problem is foregrounds.

Photo: Carina Cheng

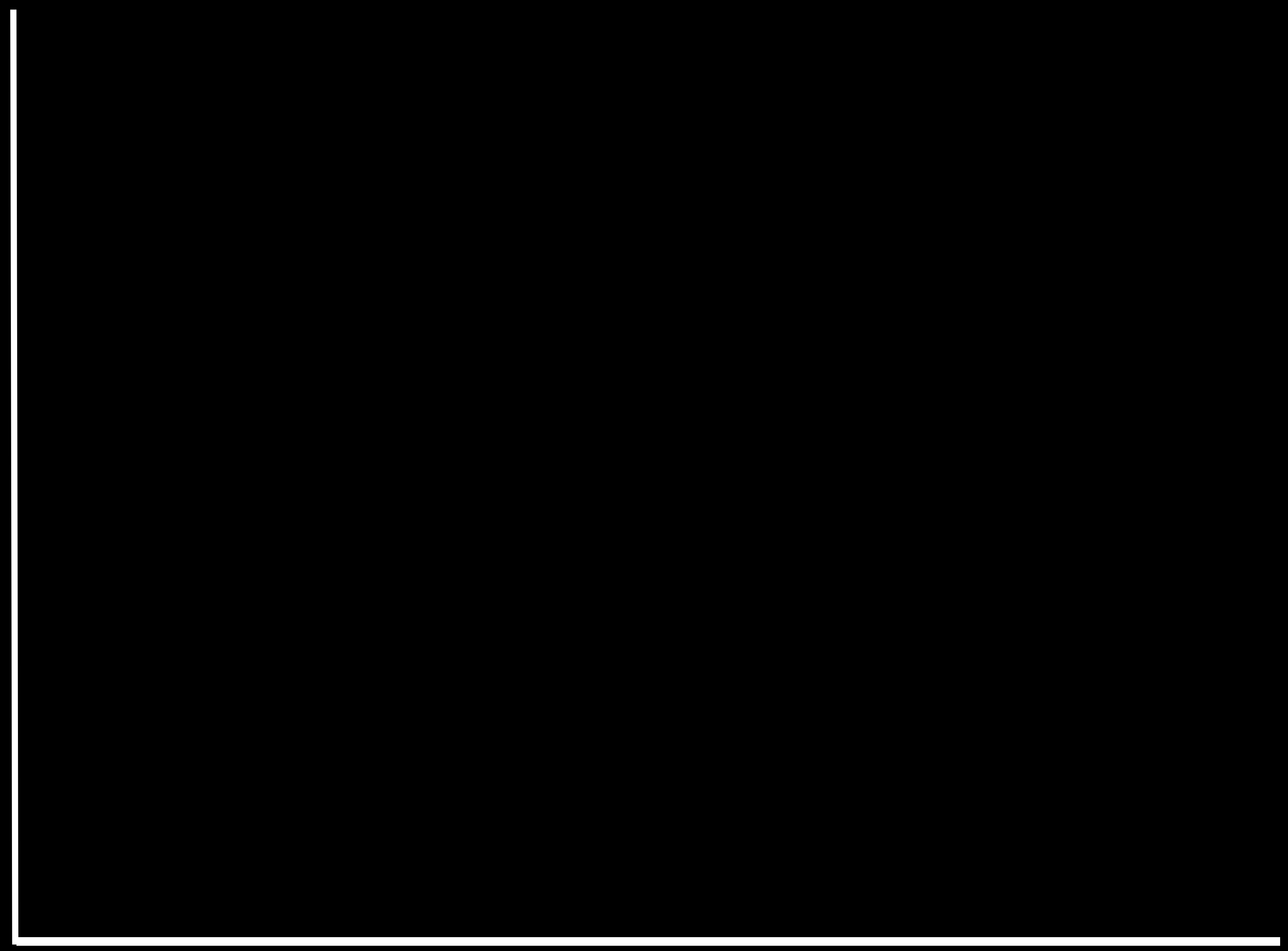

The key to separating out foregrounds is their spectral smoothness.
-
+
Synchrotron Foregrounds
Intensity
21cm Interferometric Signal
4 - 5 orders of magnitude!
Frequency

So instead of spherically averaged Fourier space…

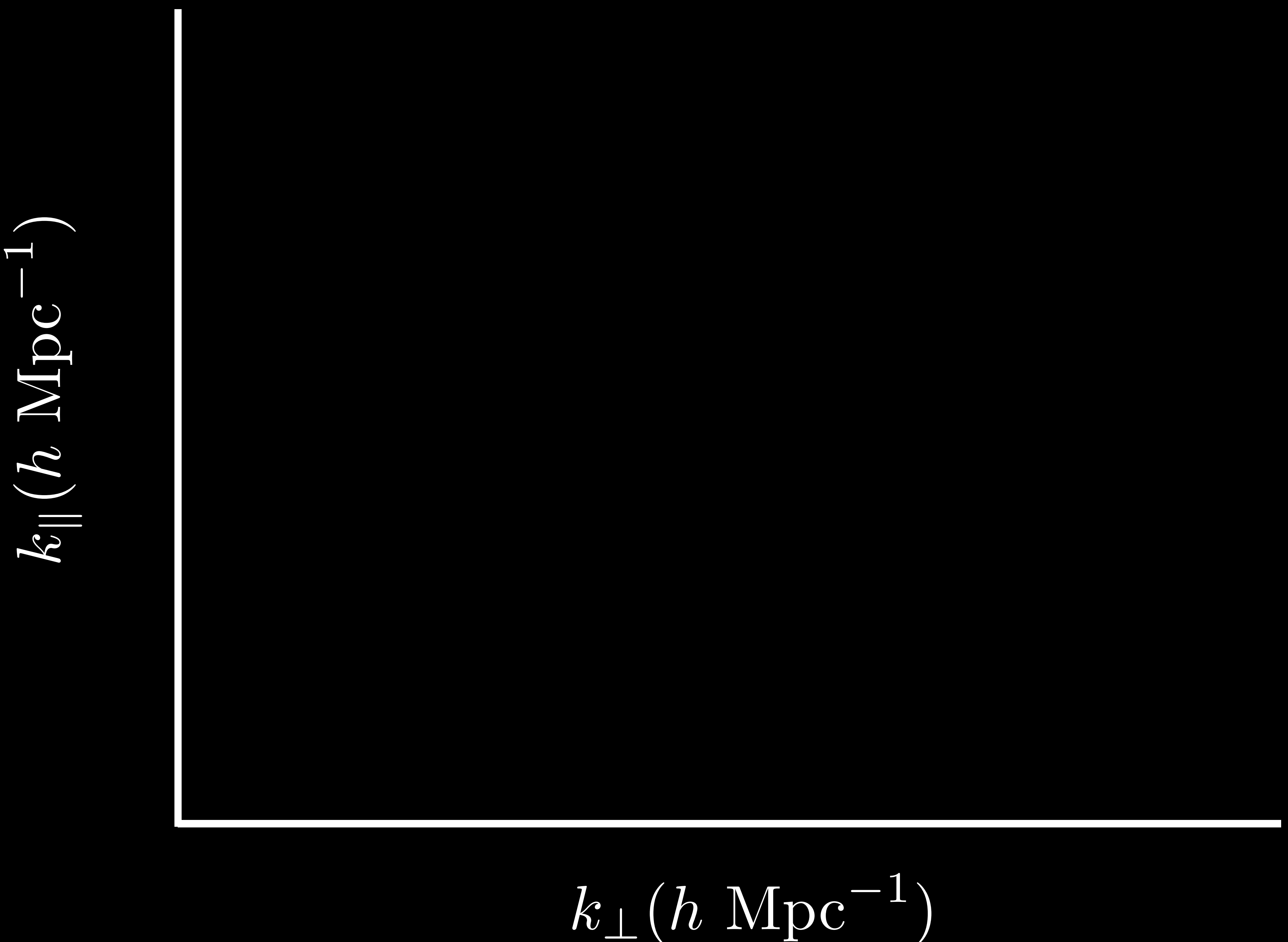


Barkana (2009), Morales & Wyithe (2010)

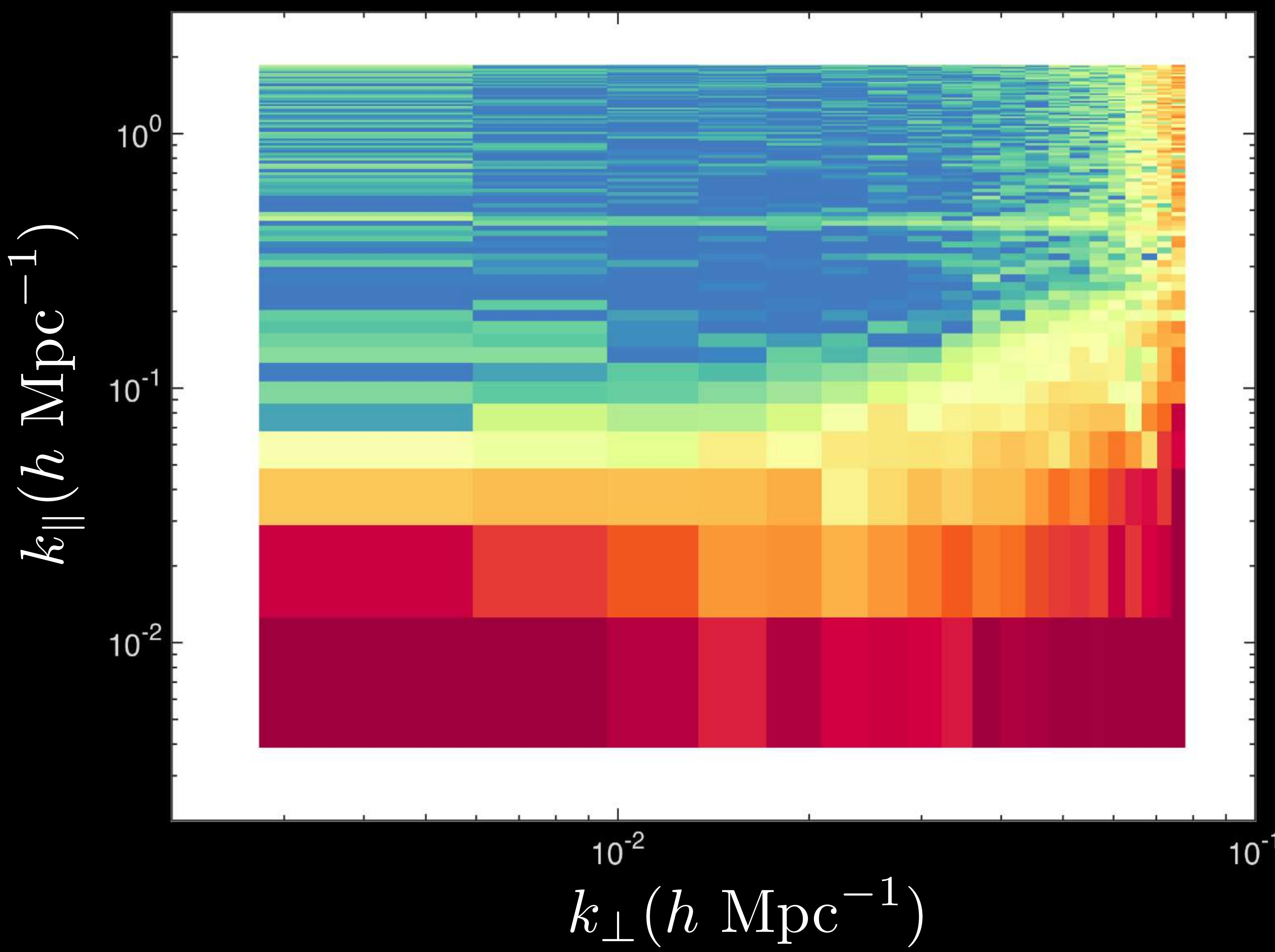
So instead of spherically averaged Fourier space…



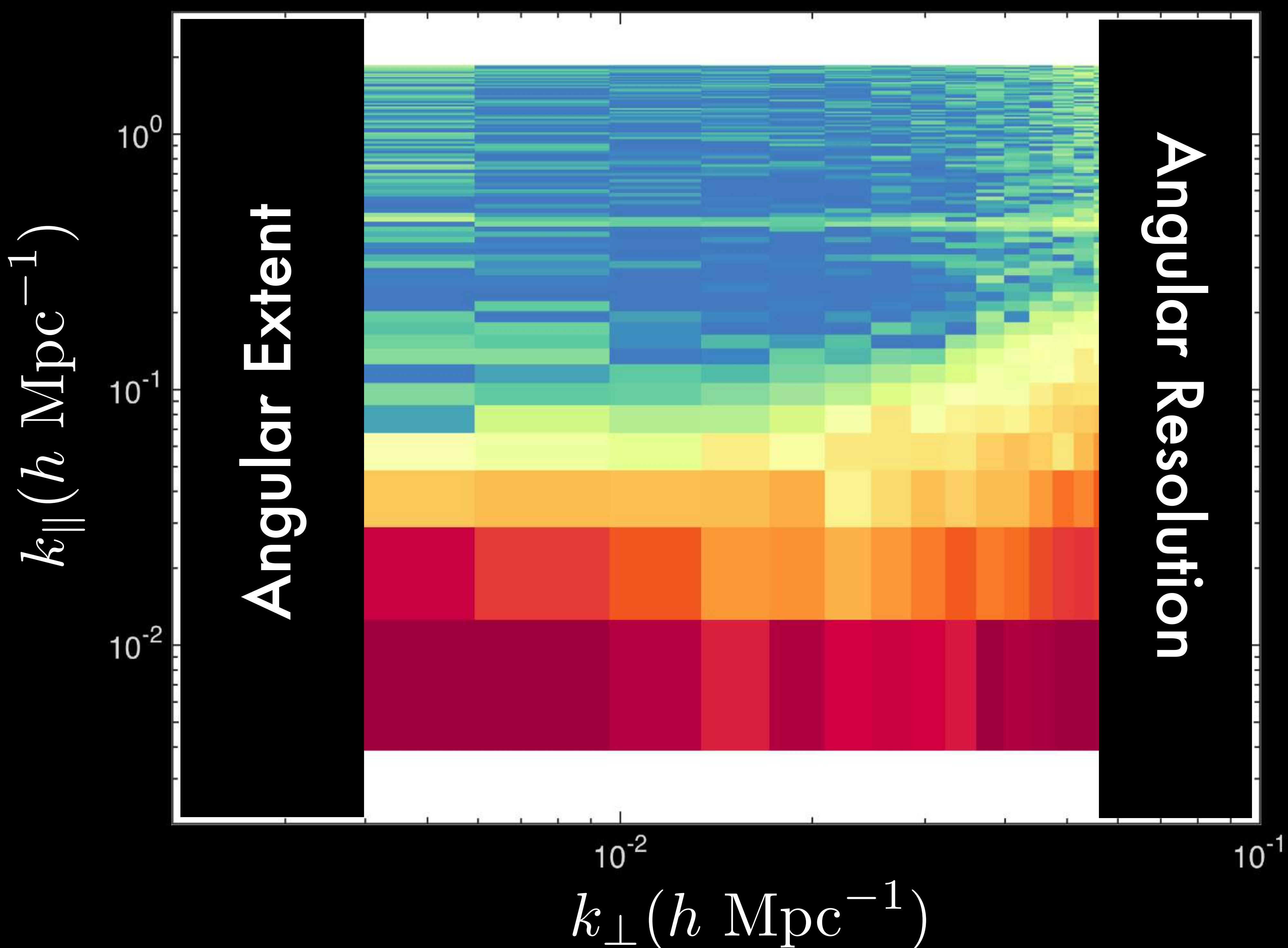
We separate out Fourier modes parallel and perpendicular to the line of sight.



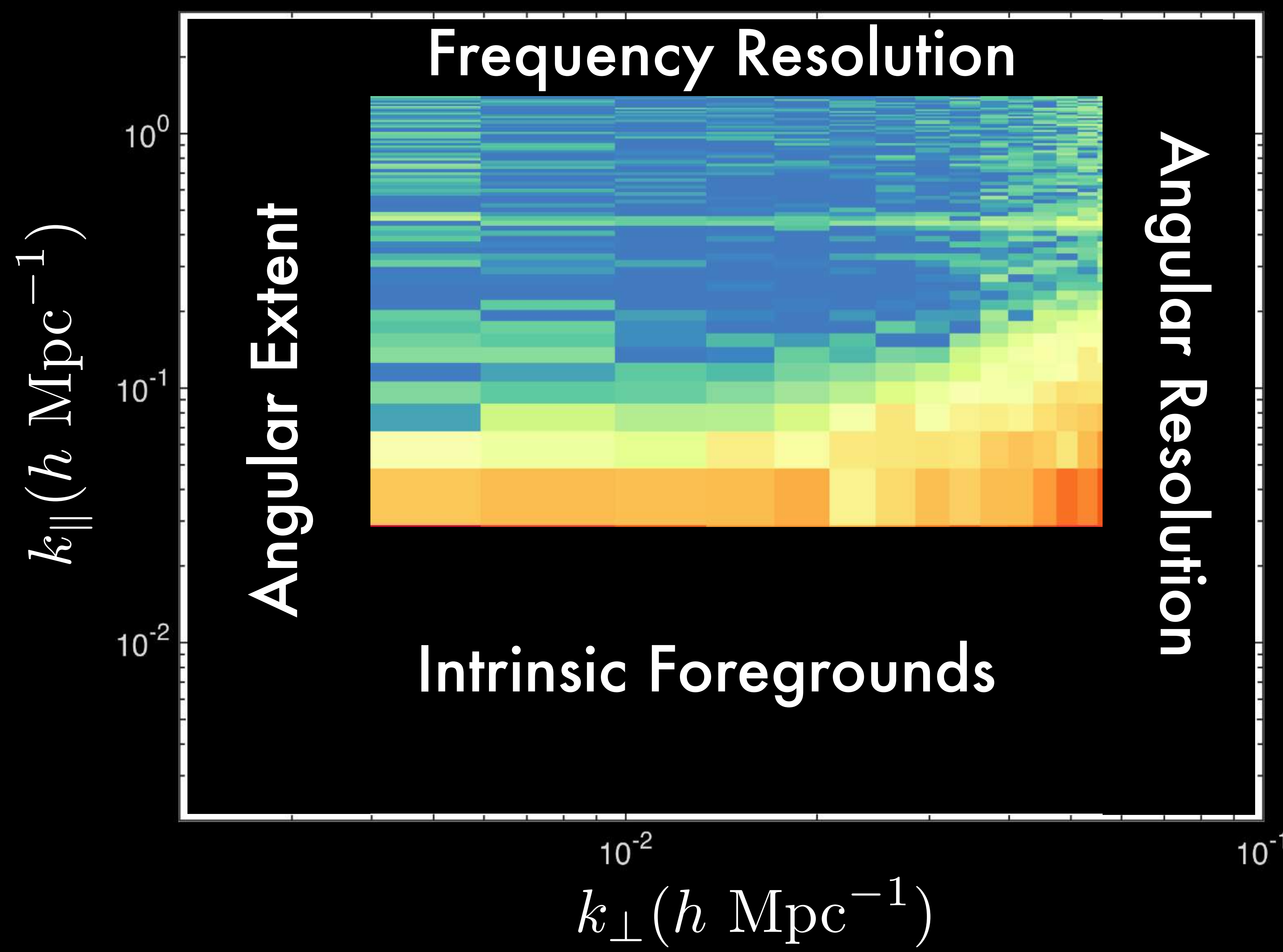
And we find a “window.”



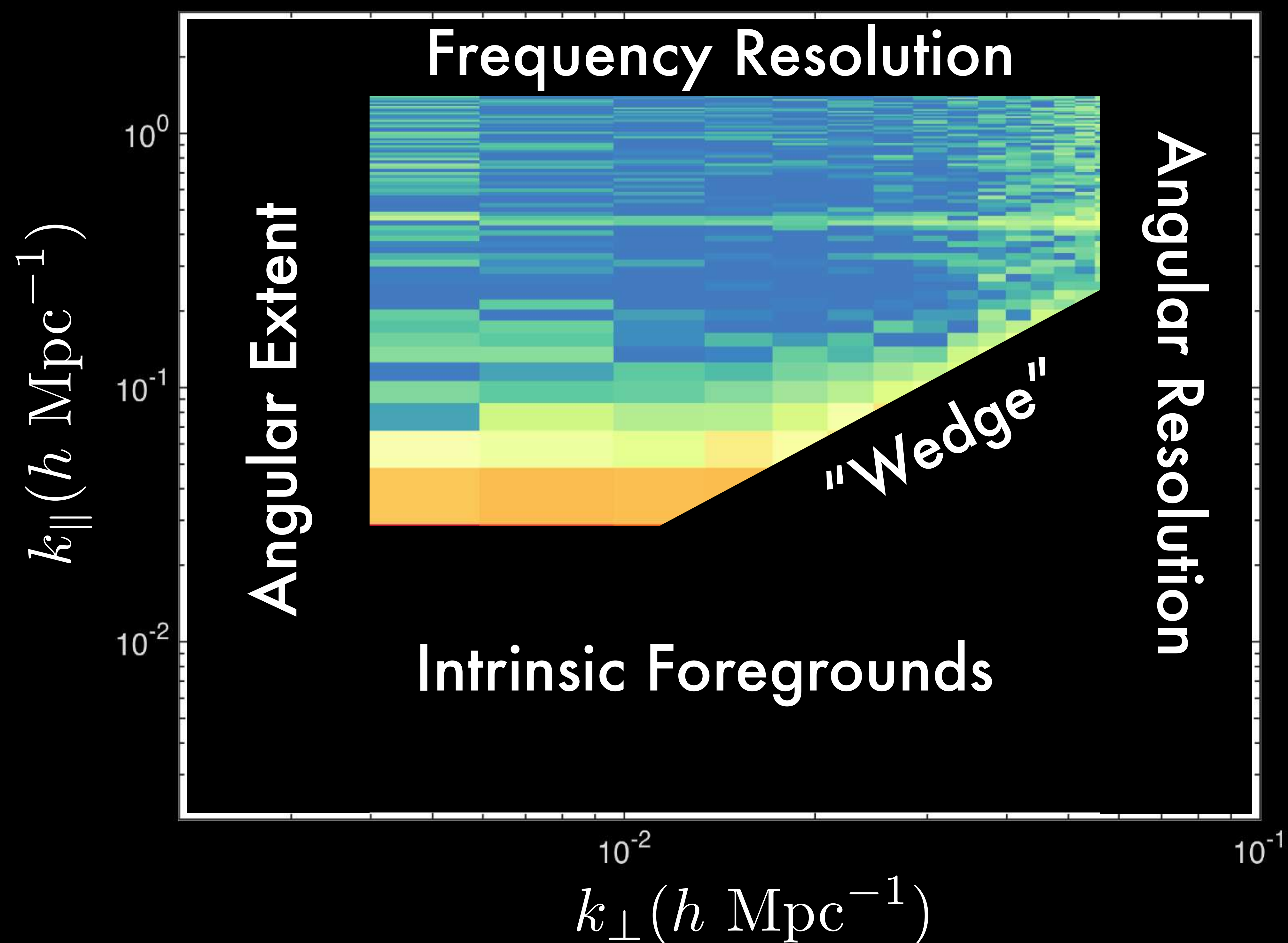
And we find a “window.”



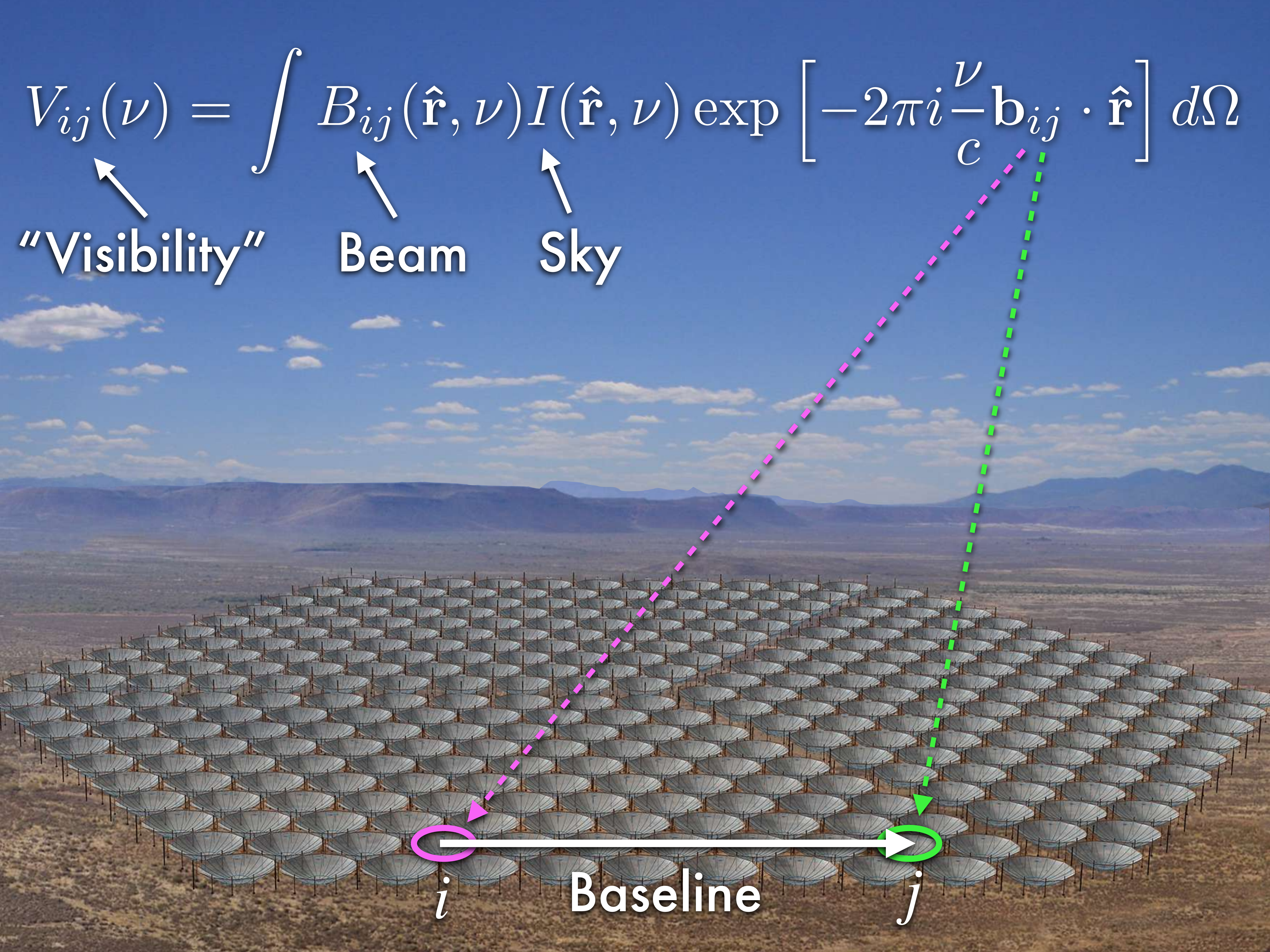
And we find a "window."



And we find a "window."

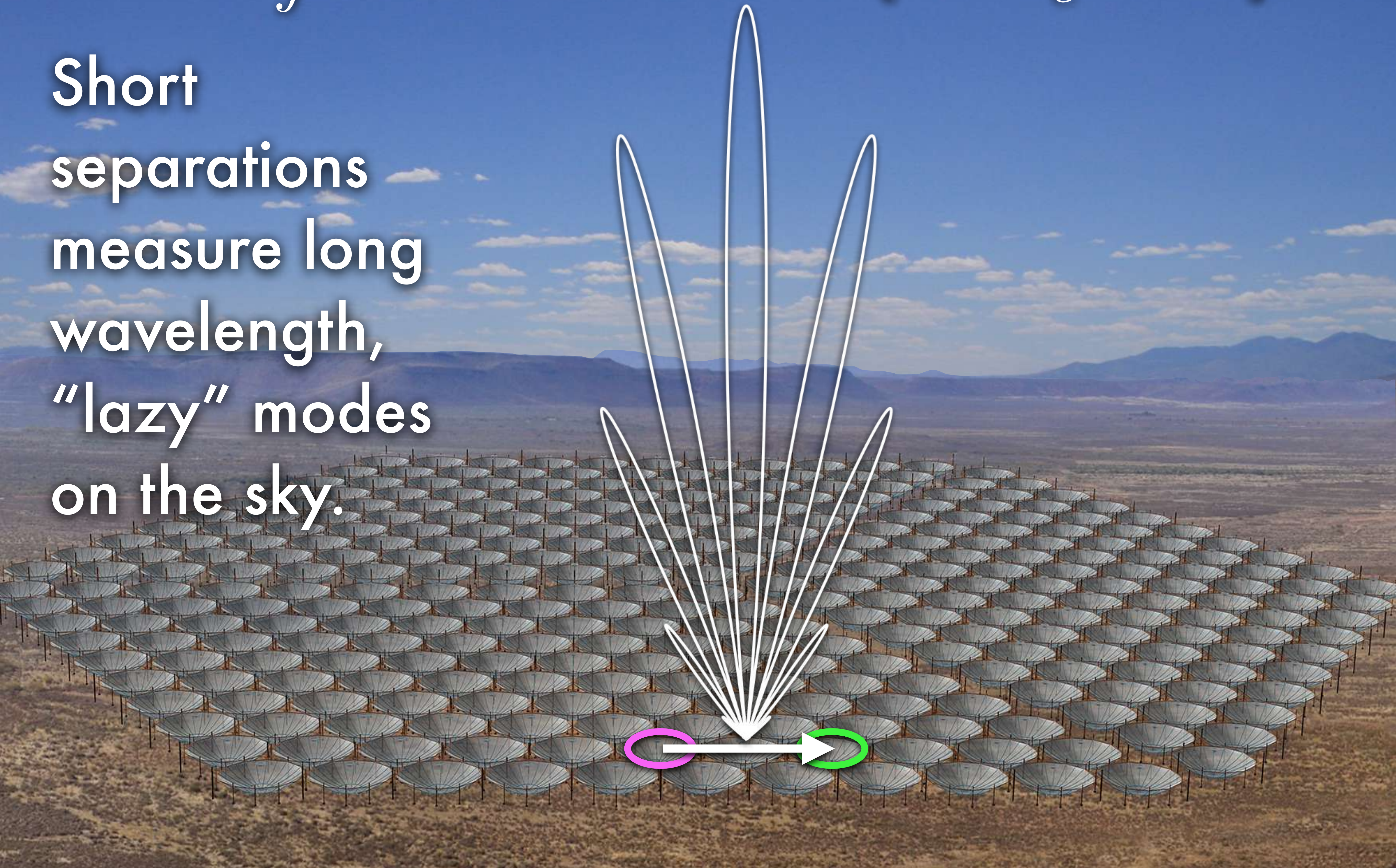


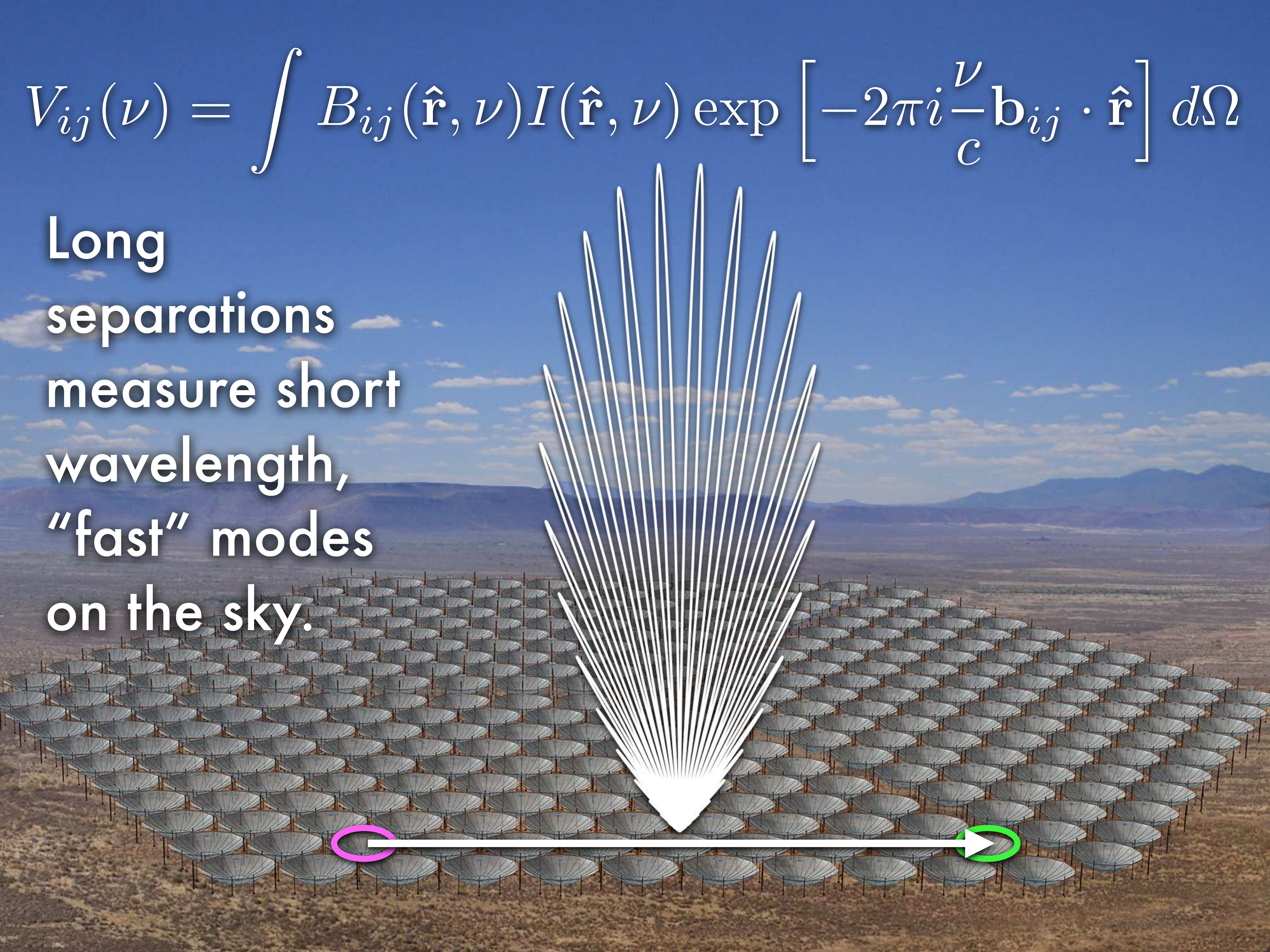
$$V_{ij}(\nu) = \int B_{ij}(\hat{\mathbf{r}}, \nu) I(\hat{\mathbf{r}}, \nu) \exp\left[-2\pi i \frac{\nu}{c} \mathbf{b}_{ij} \cdot \hat{\mathbf{r}}\right] d\Omega$$



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

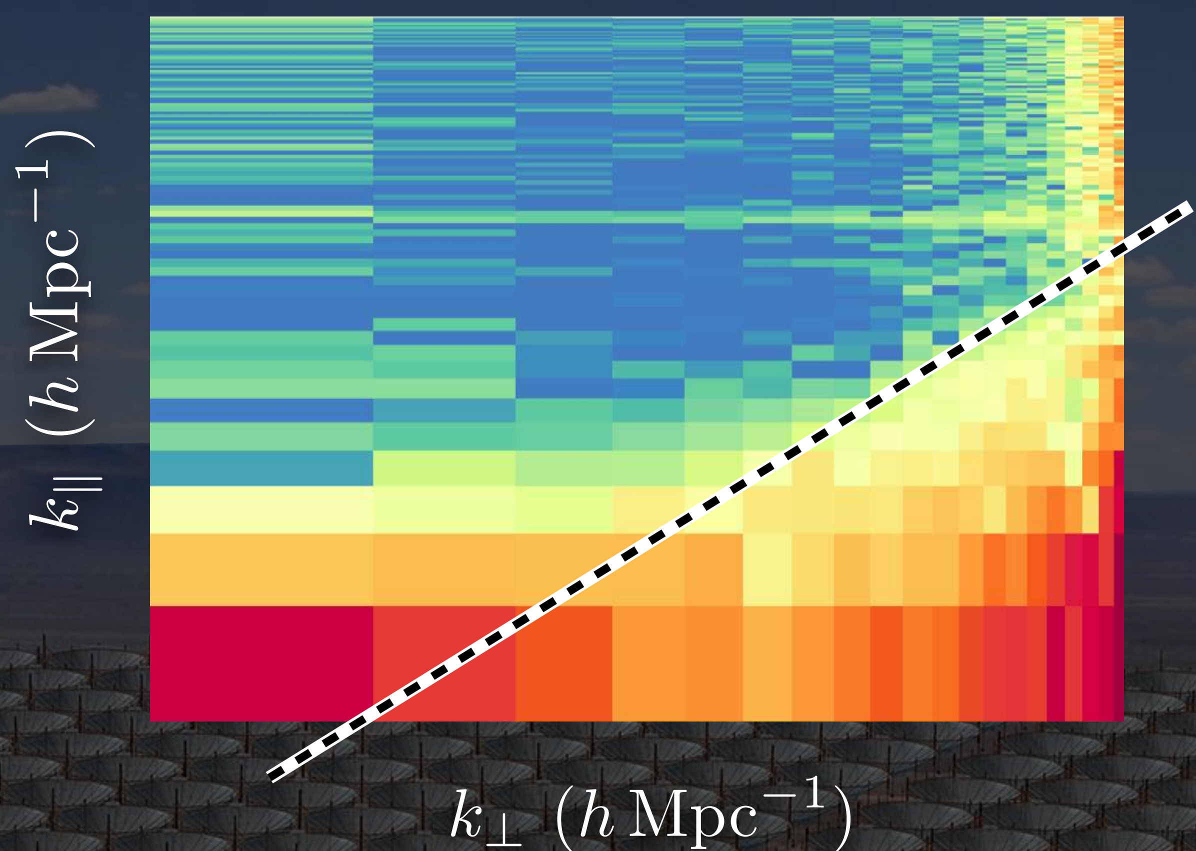
Short separations measure long wavelength, “lazy” modes on the sky.





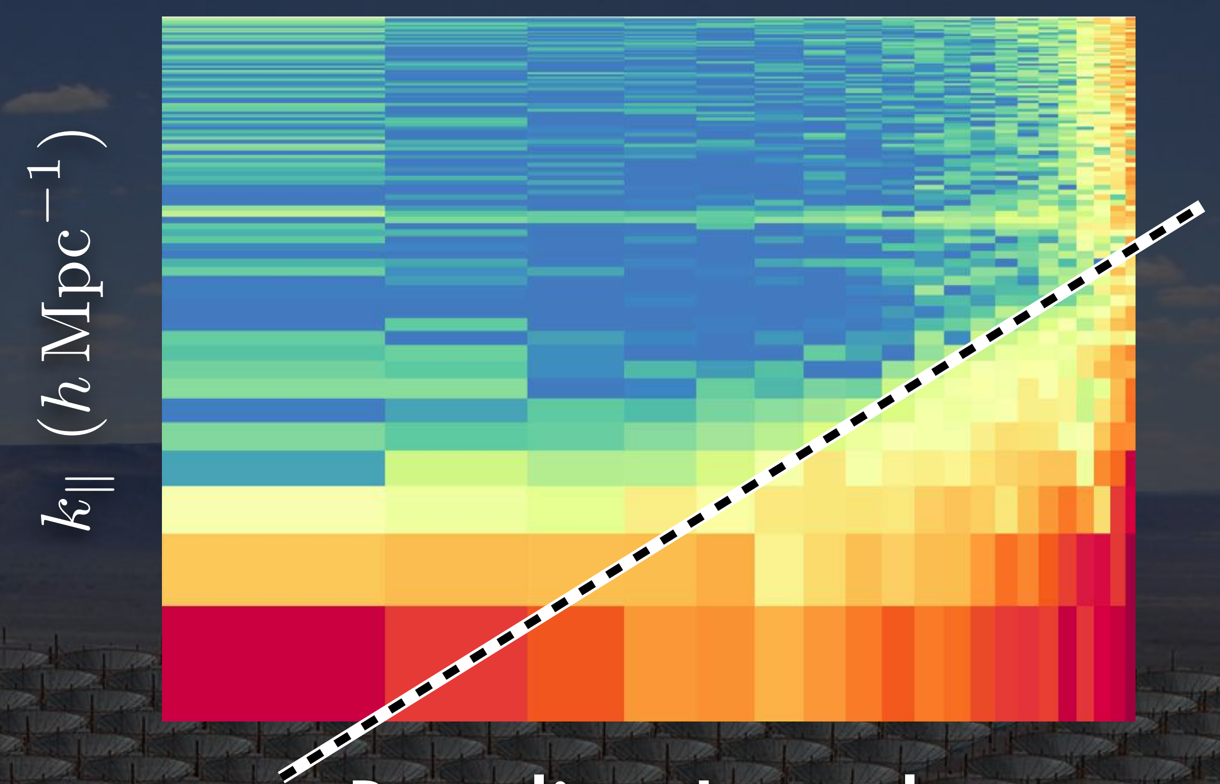
$$V_{ij}(\nu) = \int B_{ij}(\hat{\mathbf{r}}, \nu) I(\hat{\mathbf{r}}, \nu) \exp\left[-2\pi i \frac{\nu}{c} \mathbf{b}_{ij} \cdot \hat{\mathbf{r}}\right] d\Omega$$
Long separations measure short wavelength, “fast” modes on the sky.

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



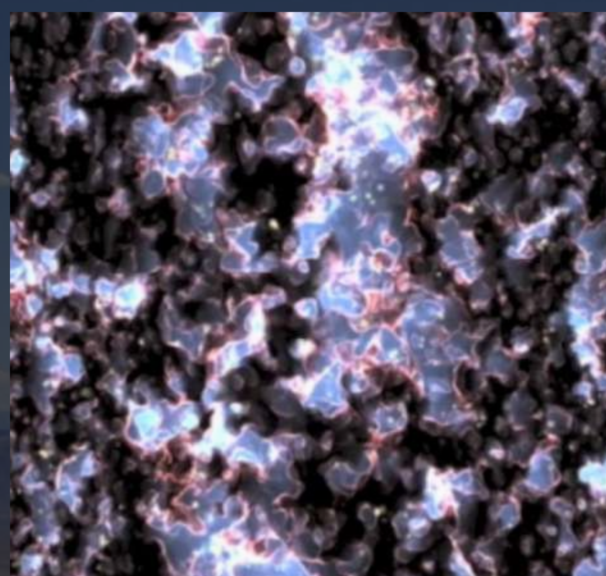
$k_{\perp}$ is effectively baseline length.

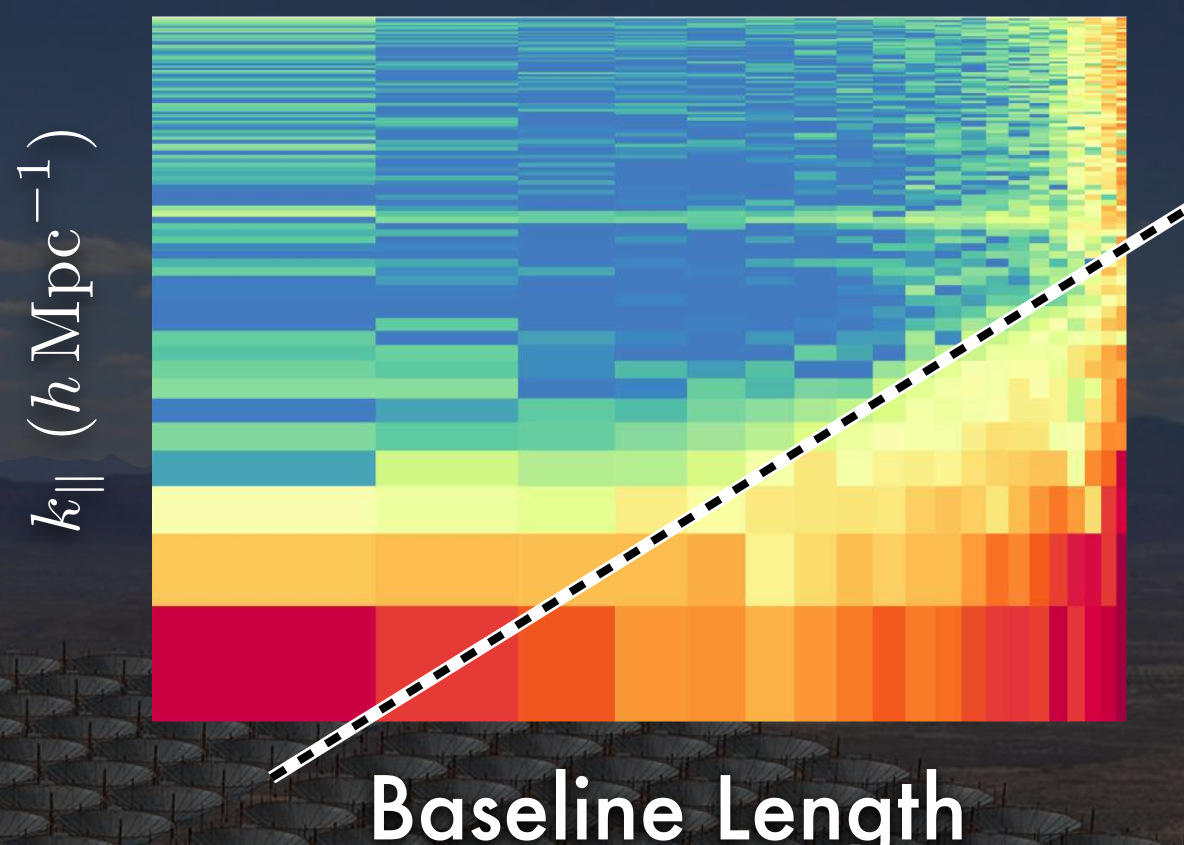
$$V_{ij}(\nu) = \int B_{ij}(\hat{\mathbf{r}}, \nu) I(\hat{\mathbf{r}}, \nu) \exp\left[-2\pi i \frac{\nu}{c} \mathbf{b}_{ij} \cdot \hat{\mathbf{r}}\right] d\Omega$$



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

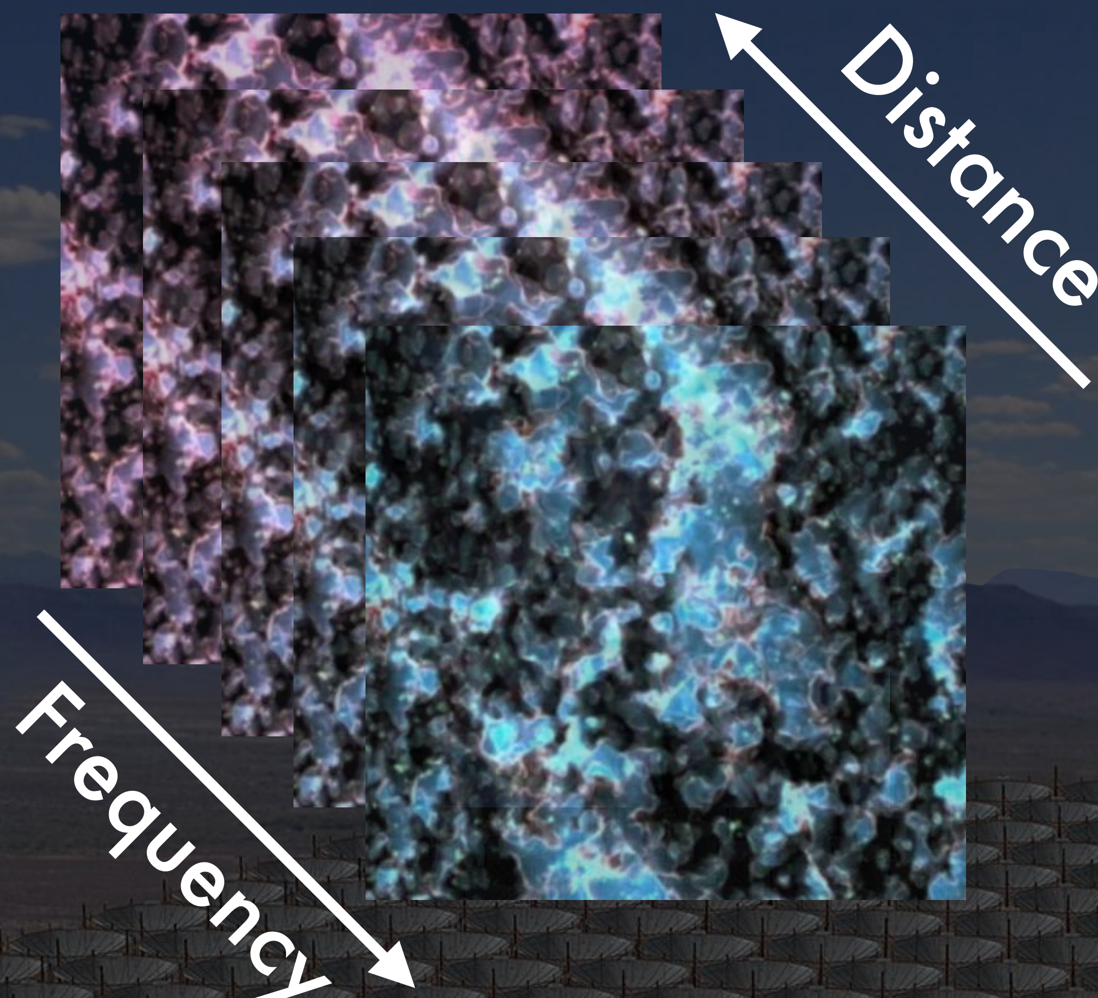
$$V_{ij}(\nu) = \int B_{ij}(\hat{\mathbf{r}}, \nu) I(\hat{\mathbf{r}}, \nu) \exp\left[-2\pi i \frac{\nu}{c} \mathbf{b}_{ij} \cdot \hat{\mathbf{r}}\right] d\Omega$$

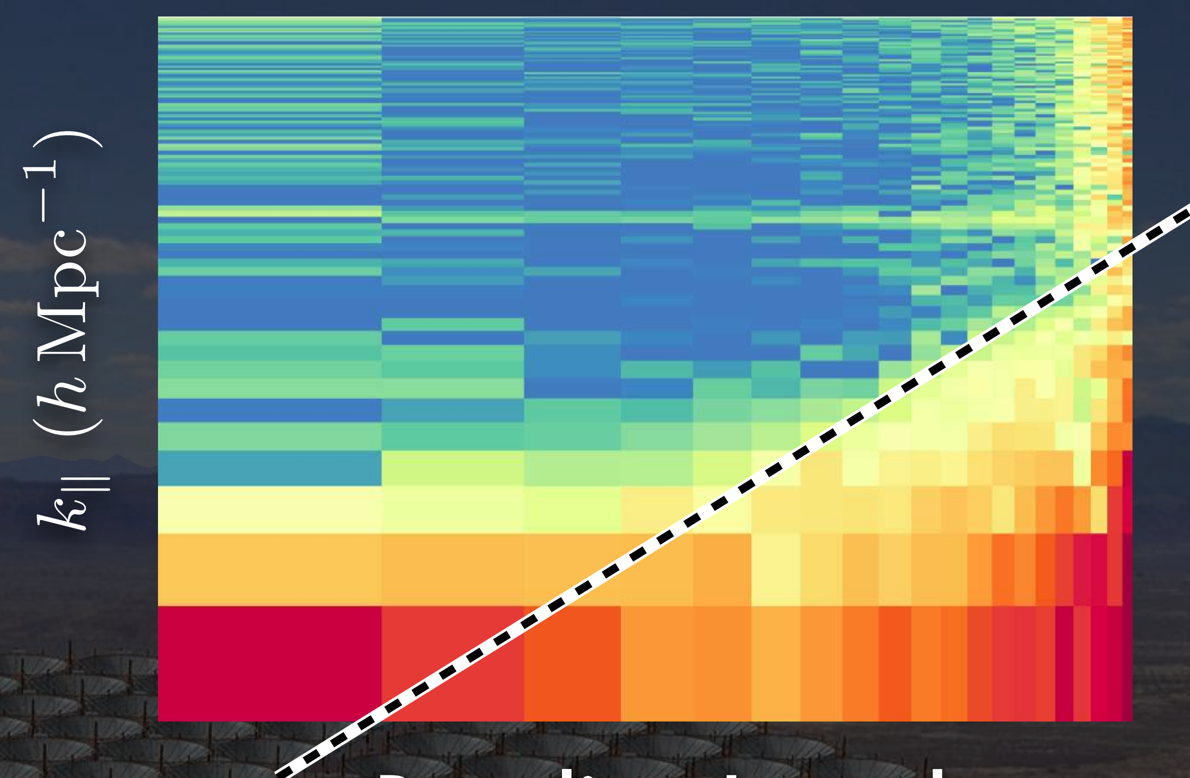




Since frequency maps to distance...

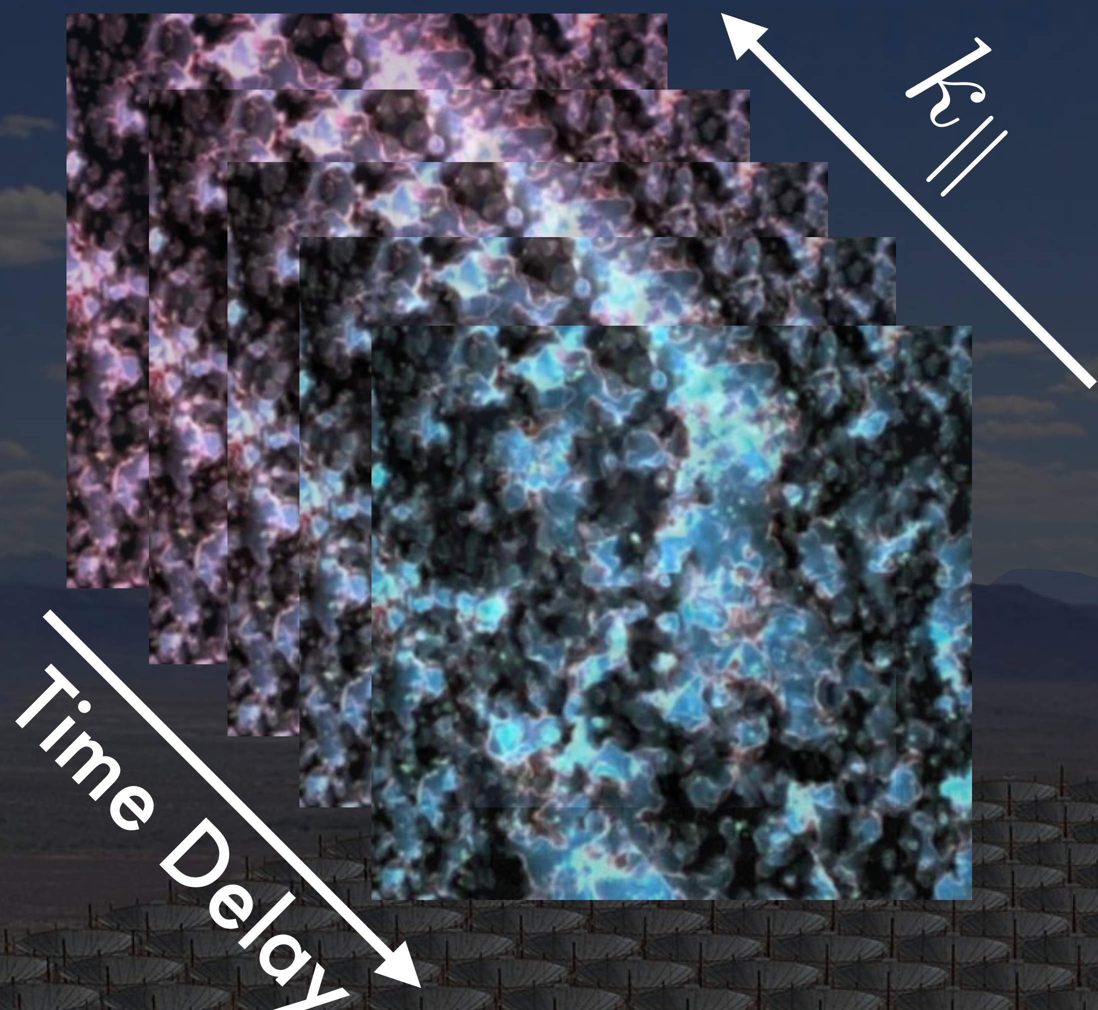
$$V_{ij}(\nu) = \int B_{ij}(\hat{\mathbf{r}}, \nu) I(\hat{\mathbf{r}}, \nu) \exp\left[-2\pi i \frac{\nu}{c} \mathbf{b}_{ij} \cdot \hat{\mathbf{r}}\right] d\Omega$$

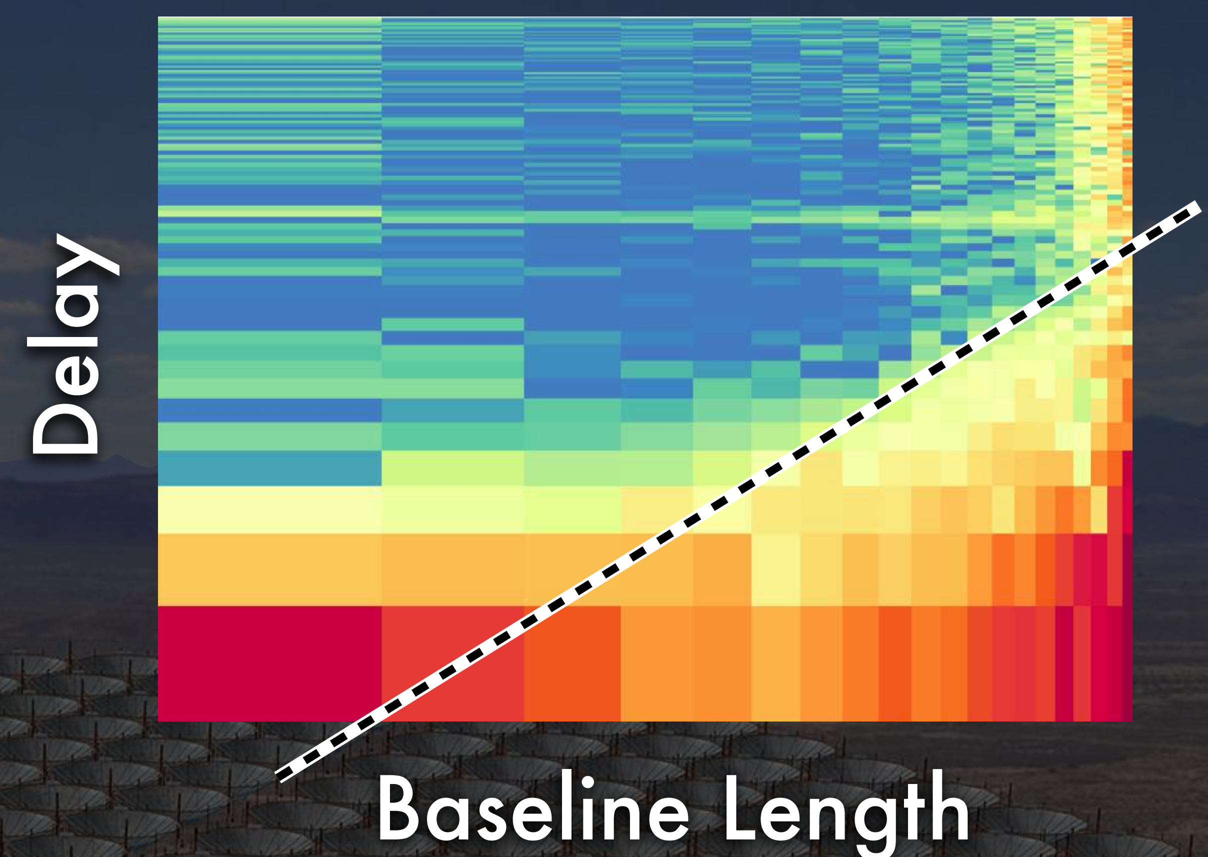




Since frequency maps to distance...

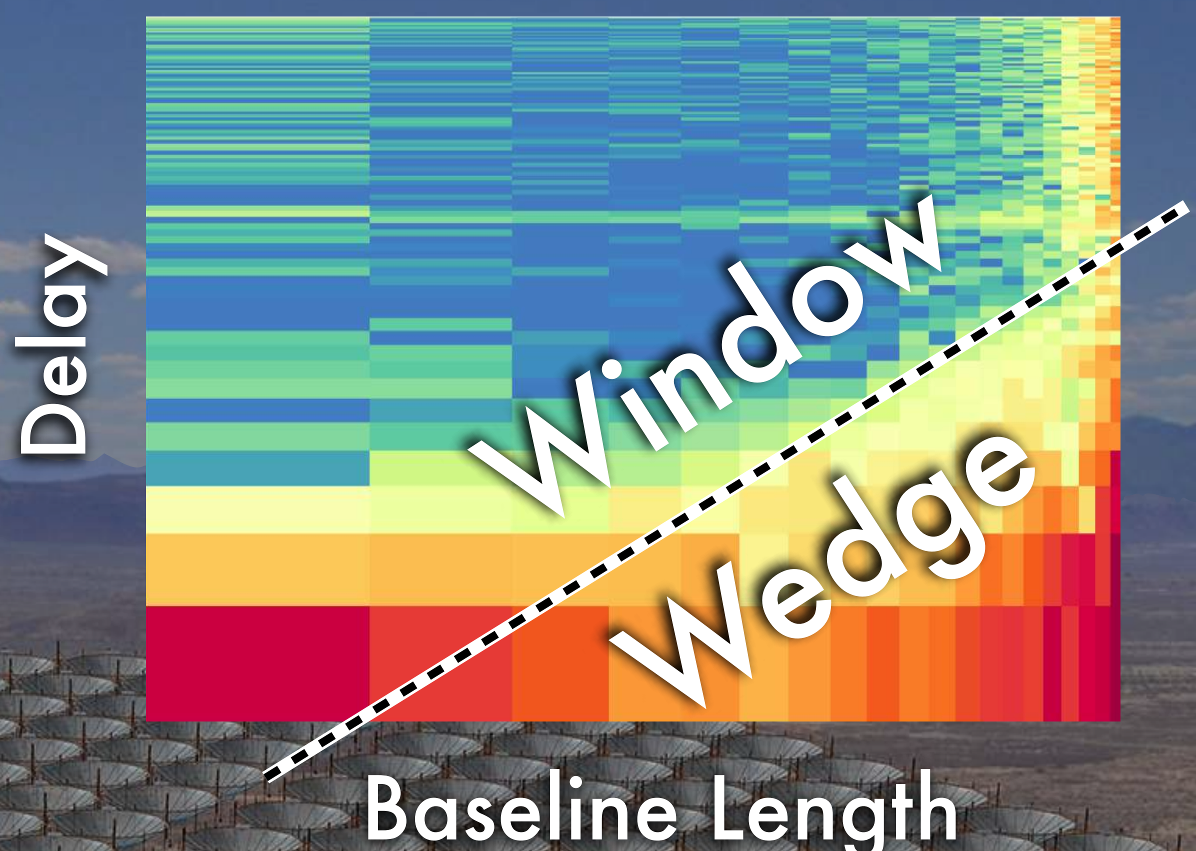
$$V_{ij}(\nu) = \int B_{ij}(\hat{\mathbf{r}}, \nu) I(\hat{\mathbf{r}}, \nu) \exp\left[-2\pi i \frac{\nu}{c} \mathbf{b}_{ij} \cdot \hat{\mathbf{r}}\right] d\Omega$$





$k_\parallel$ is effectively time delay.

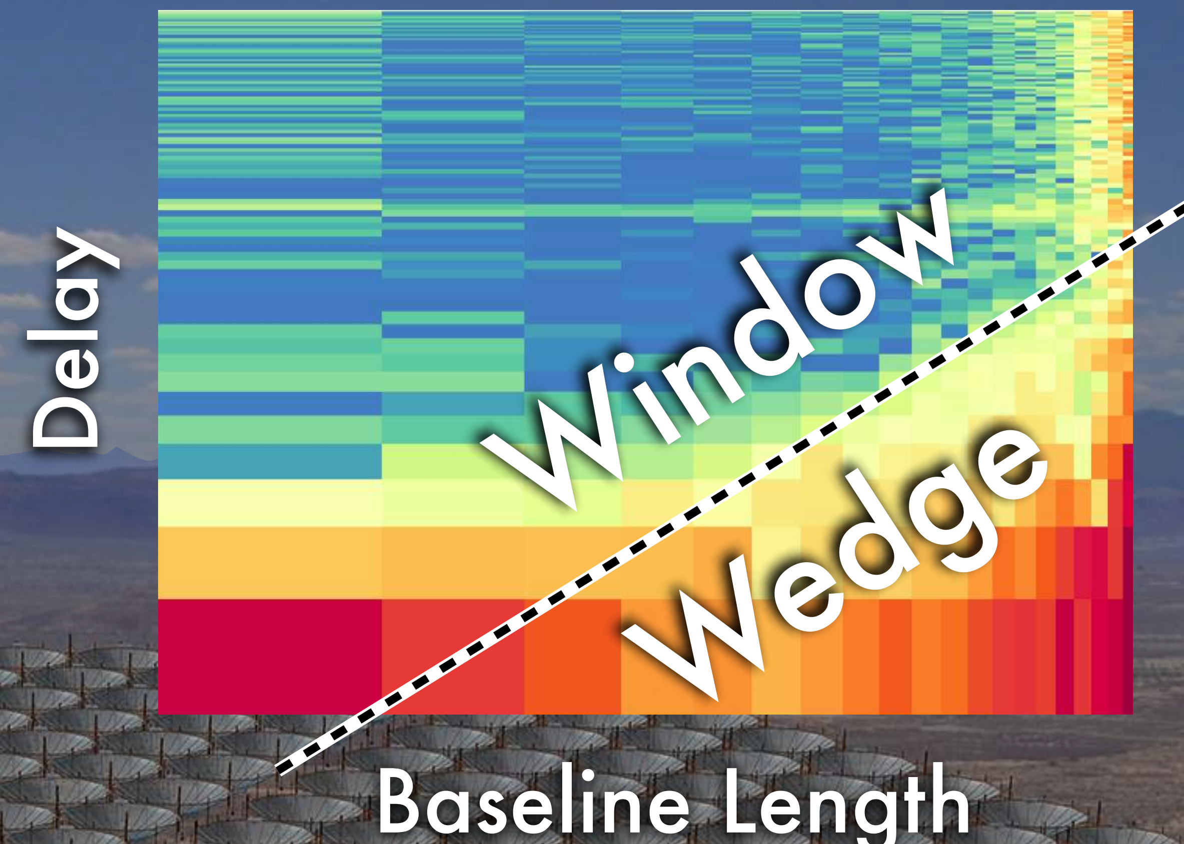
The maximum delay of foregrounds for a baseline is simply the light travel time.



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

Parsons et al. (2012)

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



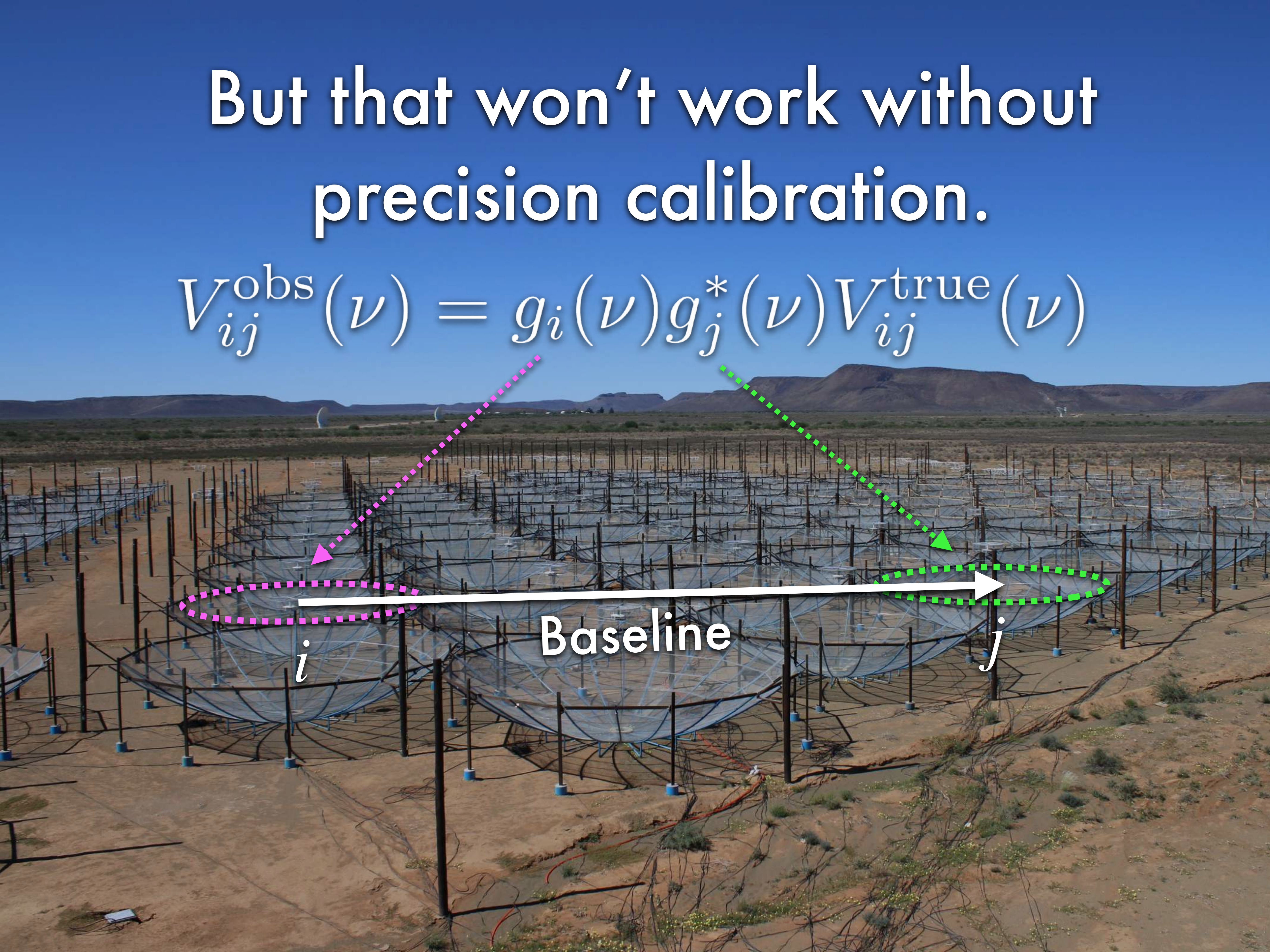
$$\Delta t_{\mathrm{max}} = |\mathbf{b}|/c$$

Dillon & *Parsons (2016)*

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

But that won't work without precision calibration.

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



HERA was designed to be precisely calibrated using redundant baselines.

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

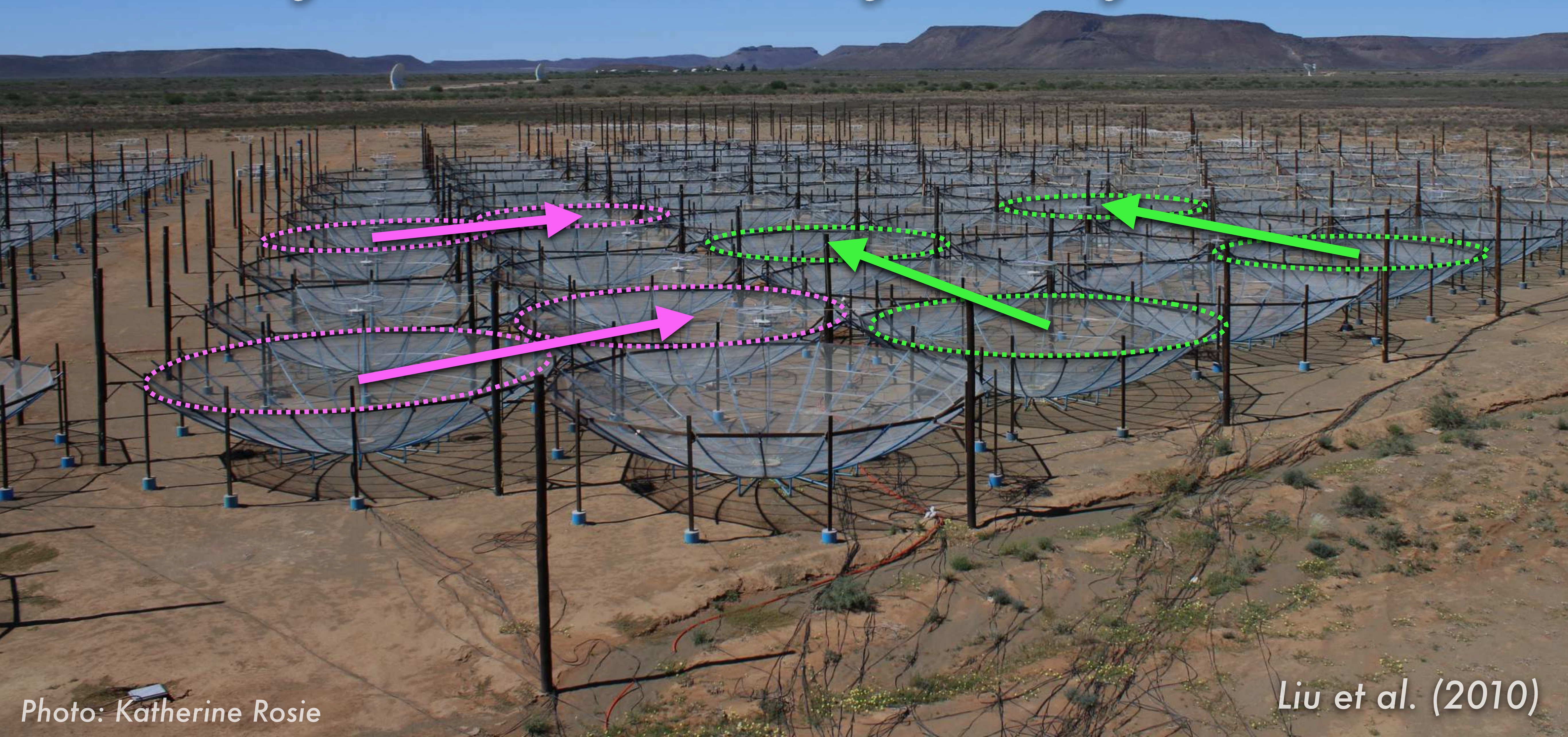
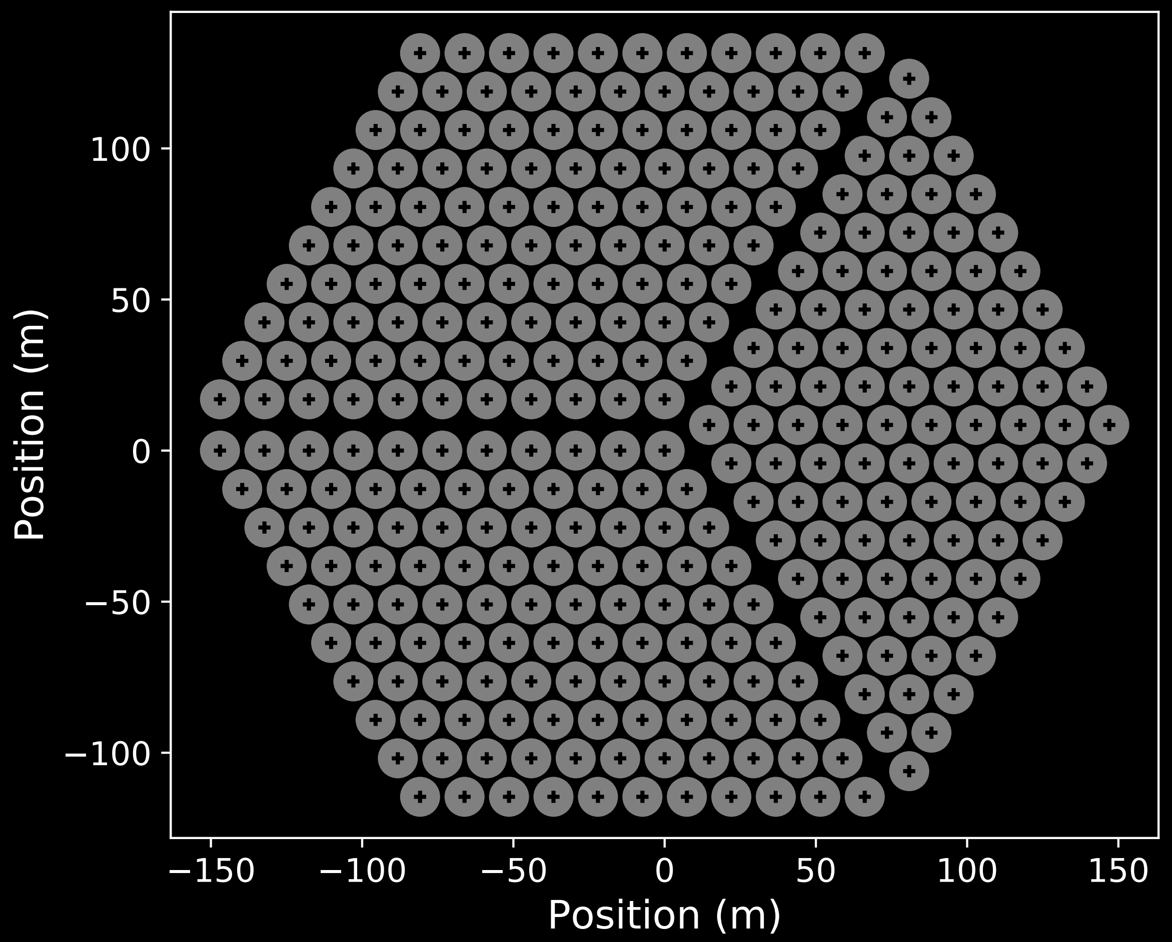


Photo: Katherine Rosie

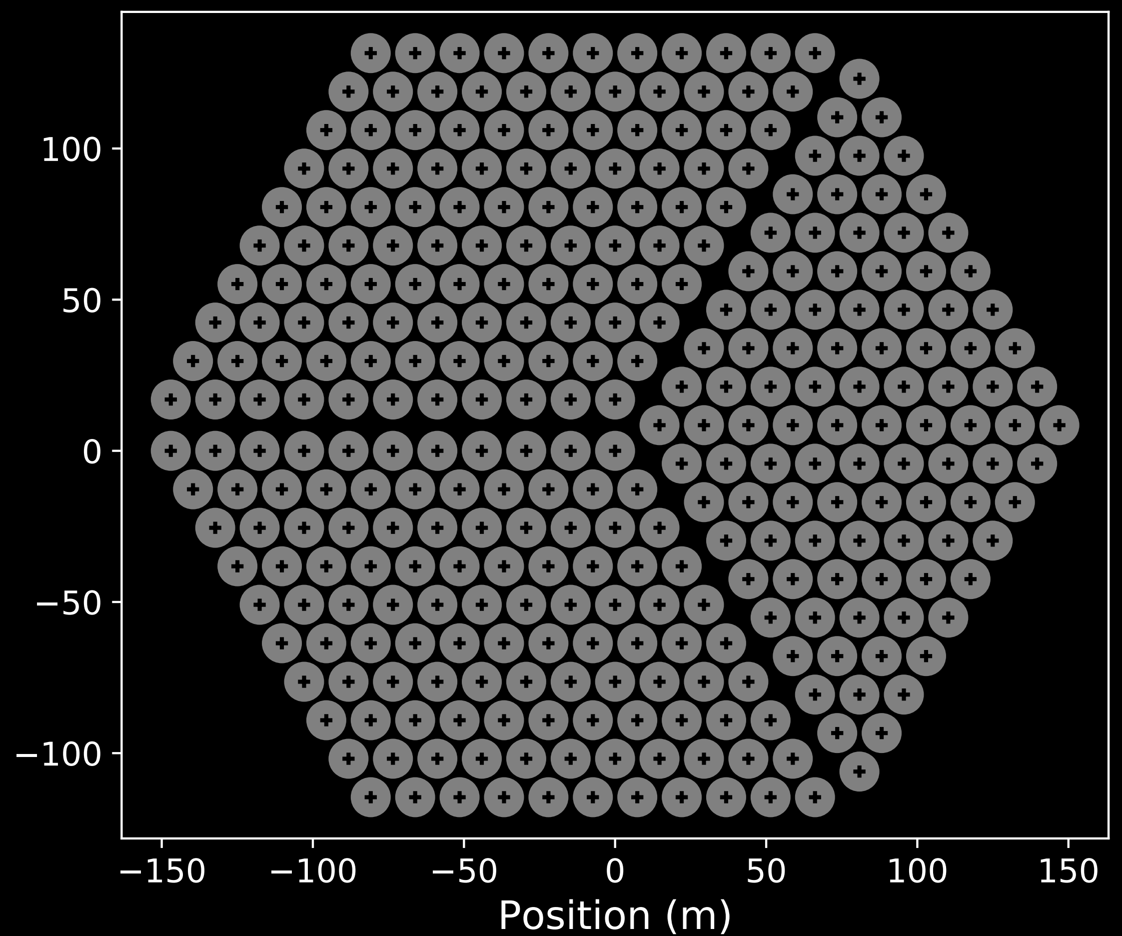
Liu et al. (2010)

320 Core Antenna Gains

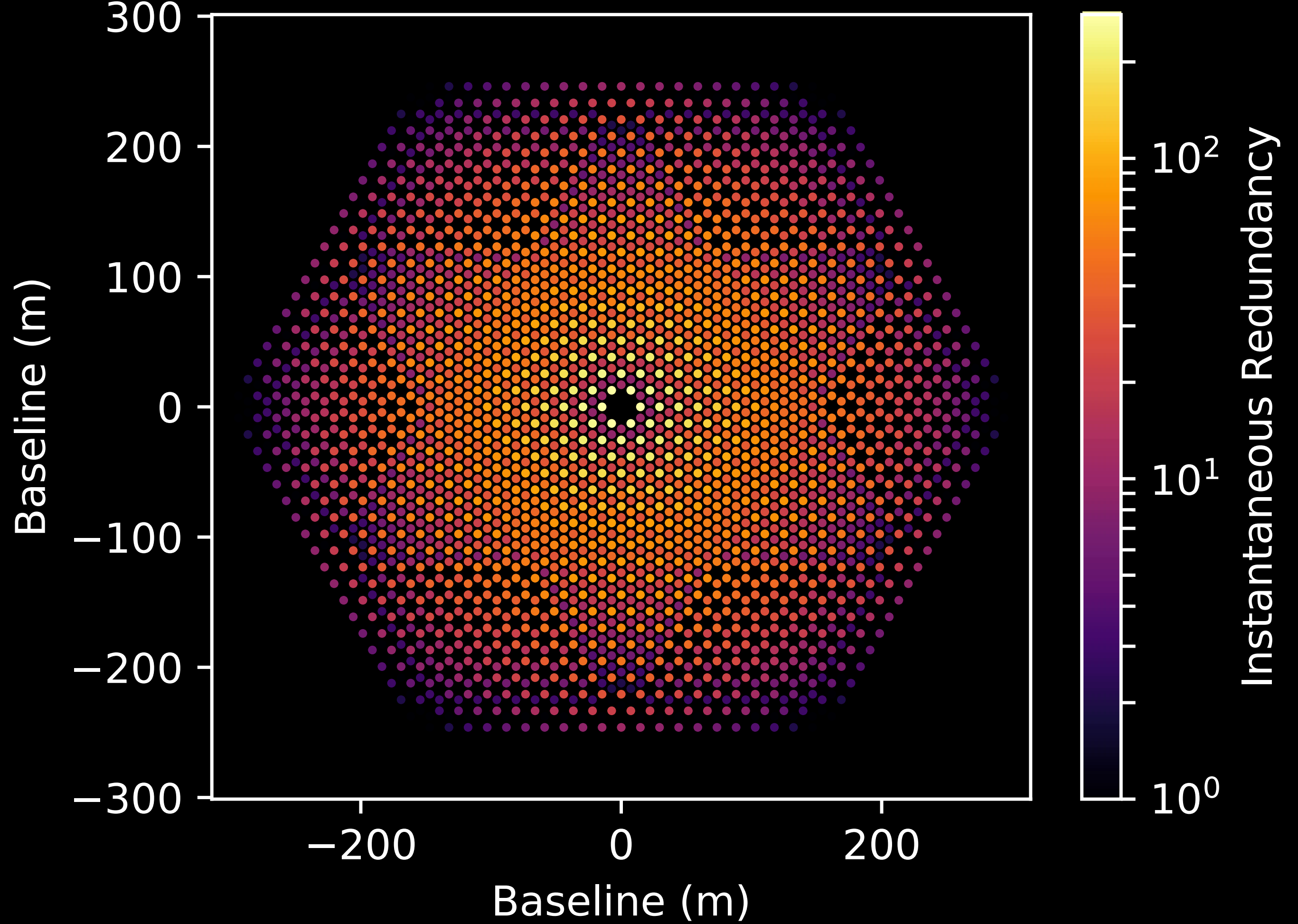


Dillon *& Parsons (2016)*

320 Core Antenna Gains

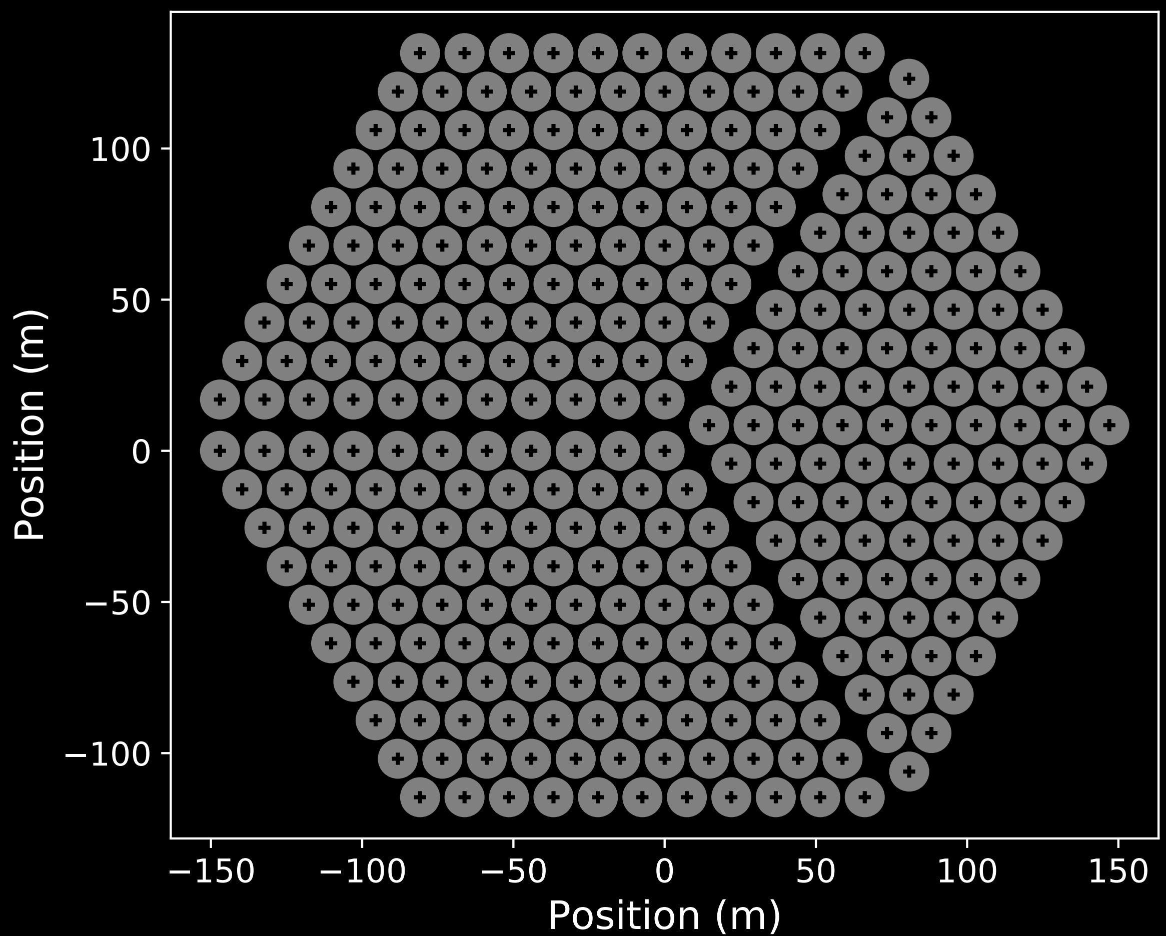


1,501 Unique Visibilities

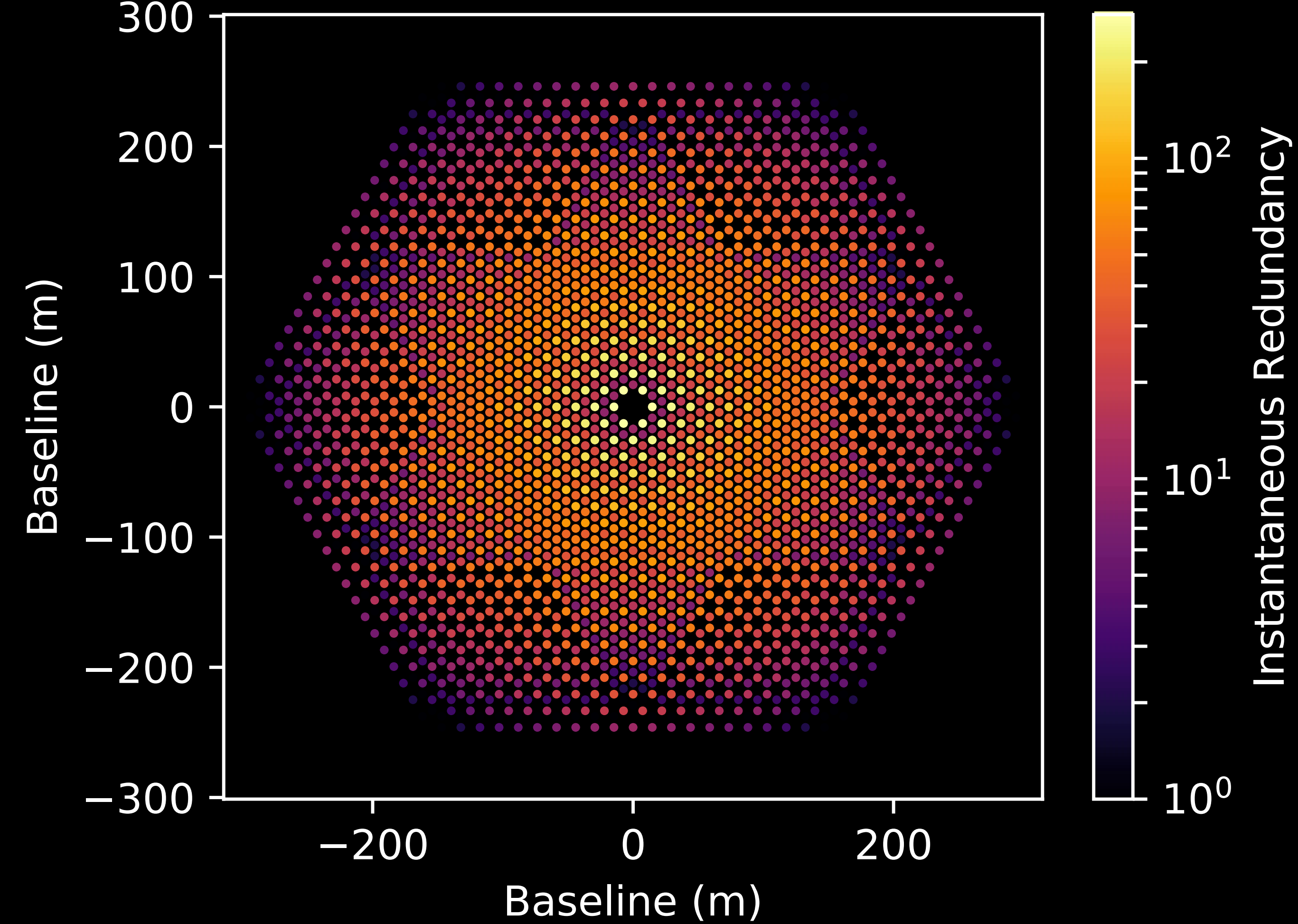


Dillon & *Parsons (2016)*

320 Core Antenna Gains



1,501 Unique Visibilities

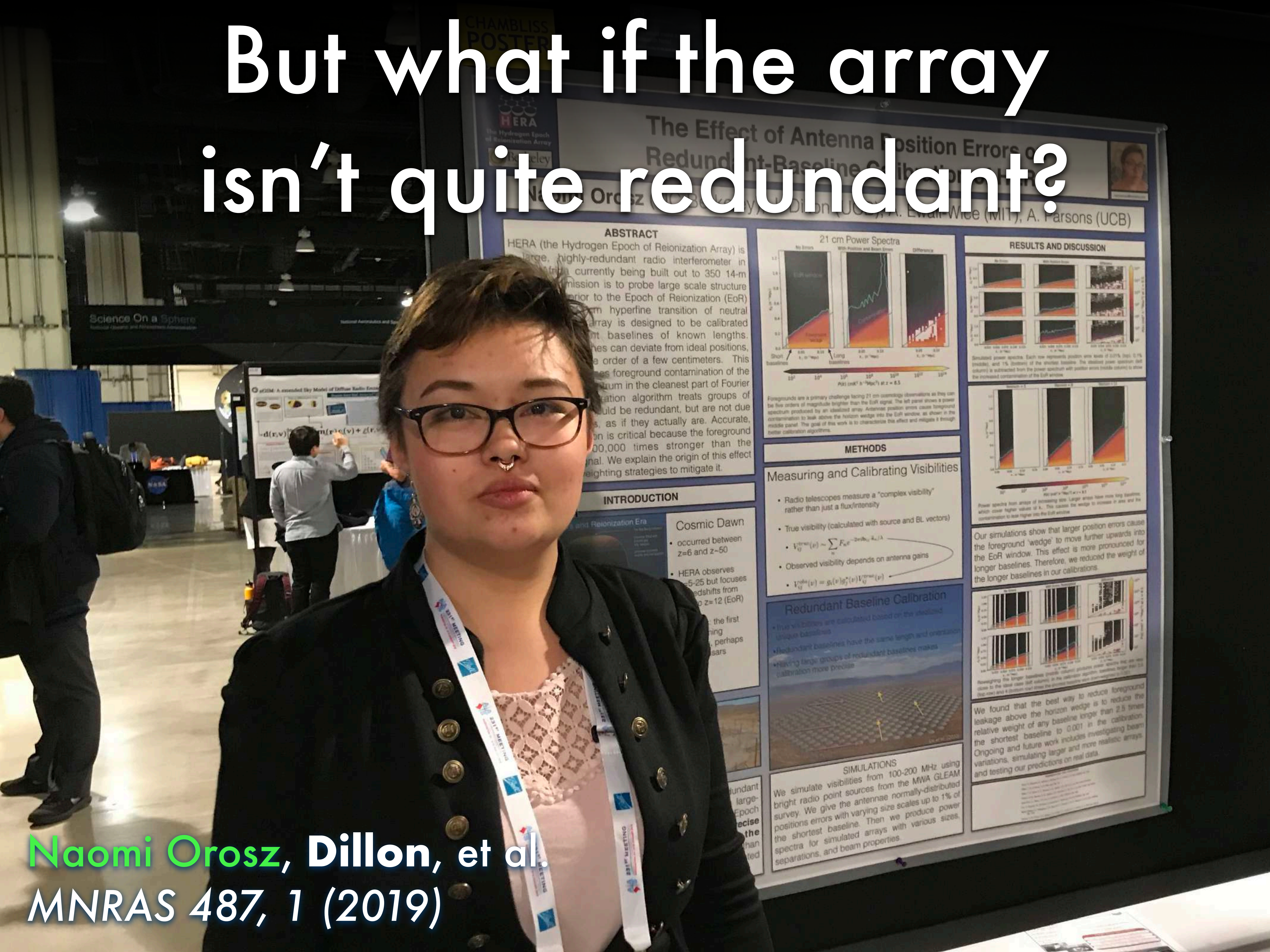


$$V_{ij}^{\mathrm{obs}}(\nu) = g_i(\nu) g_j^*(\nu) V_{ij}^{\mathrm{true}}(\nu)$$

51,040 Total Measurements

Dillon & *Parsons (2016)*

But what if the array isn't quite redundant?



Naomi Orosz, **Dillon**, et al.
MNRAS 487, 1 (2019)

We simulated HERA with…

Photo: Katherine Rosie

Orosz, **Dillon,** *et al.* (2018)

We simulated HERA with...

- Position Errors (0.4 to 10 cm)

Photo: Katherine Rosie

Orosz, **Dillon,** *et al. (2018)*

We simulated HERA with…

- Position Errors (0.4 to 10 cm)
- Pointing Errors (.04° to 1.0°)

Photo: Katherine Rosie

Orosz, **Dillon**, *et al. (2018)*

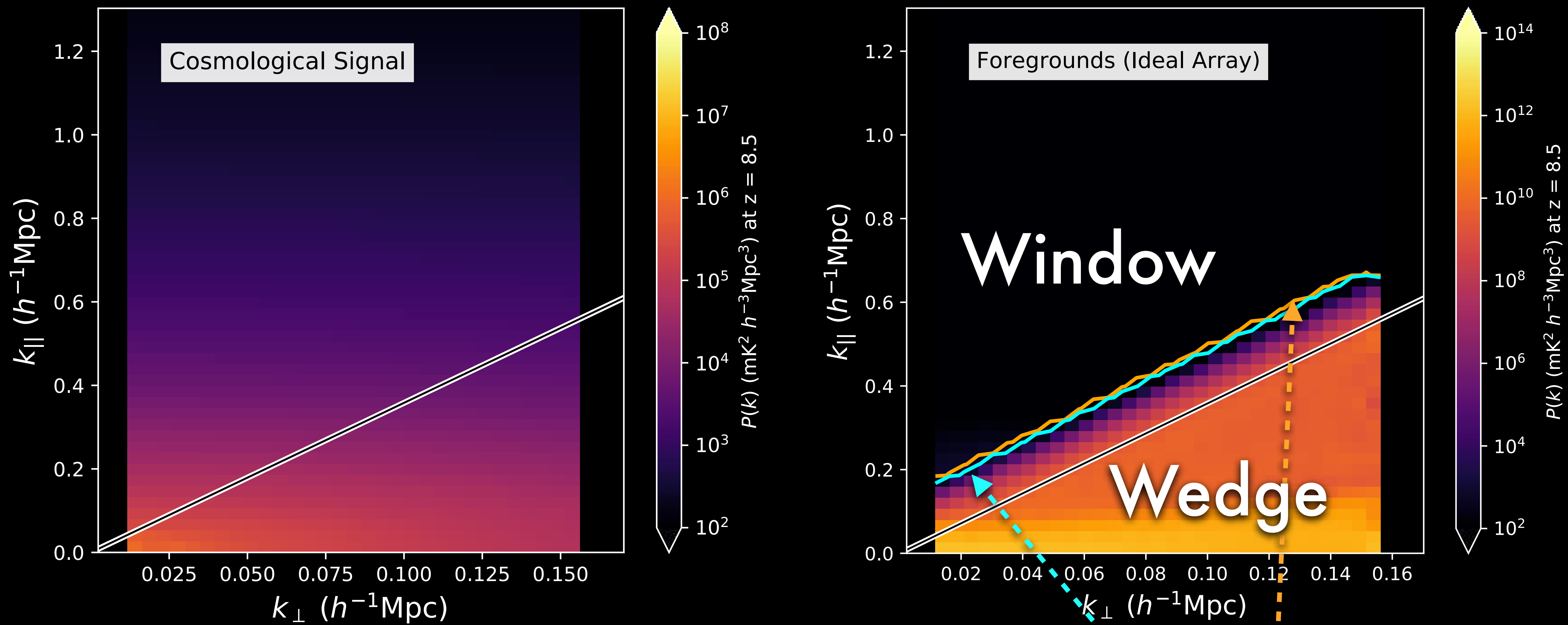
We simulated HERA with...

- Position Errors (0.4 to 10 cm)
- Pointing Errors (.04° to 1.0°)
- Beam Size Errors (.02° to 0.5°)

Photo: Katherine Rosie

Orosz, **Dillon,** *et al. (2018)*

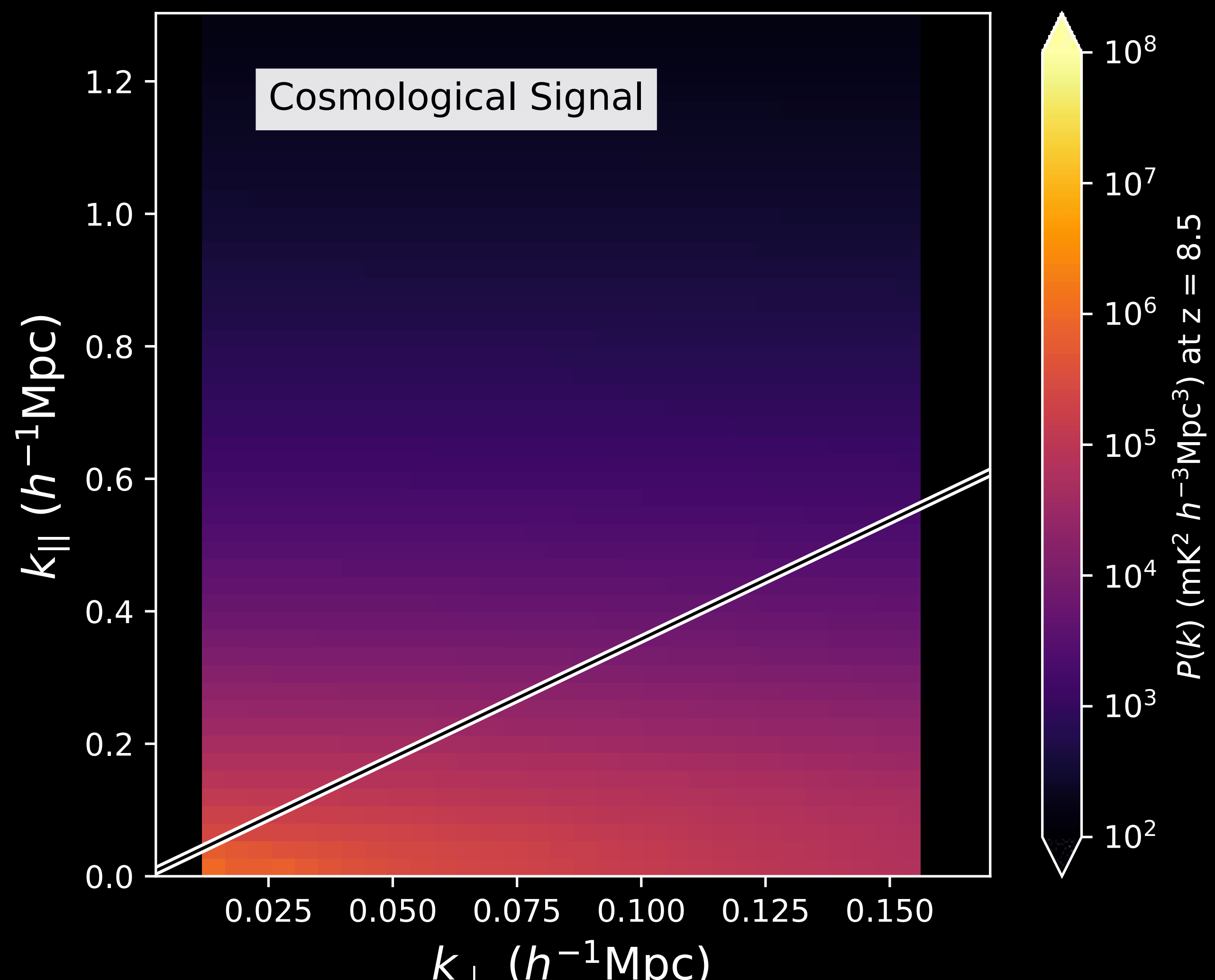
With no redundancy errors, the EoR window is clean.



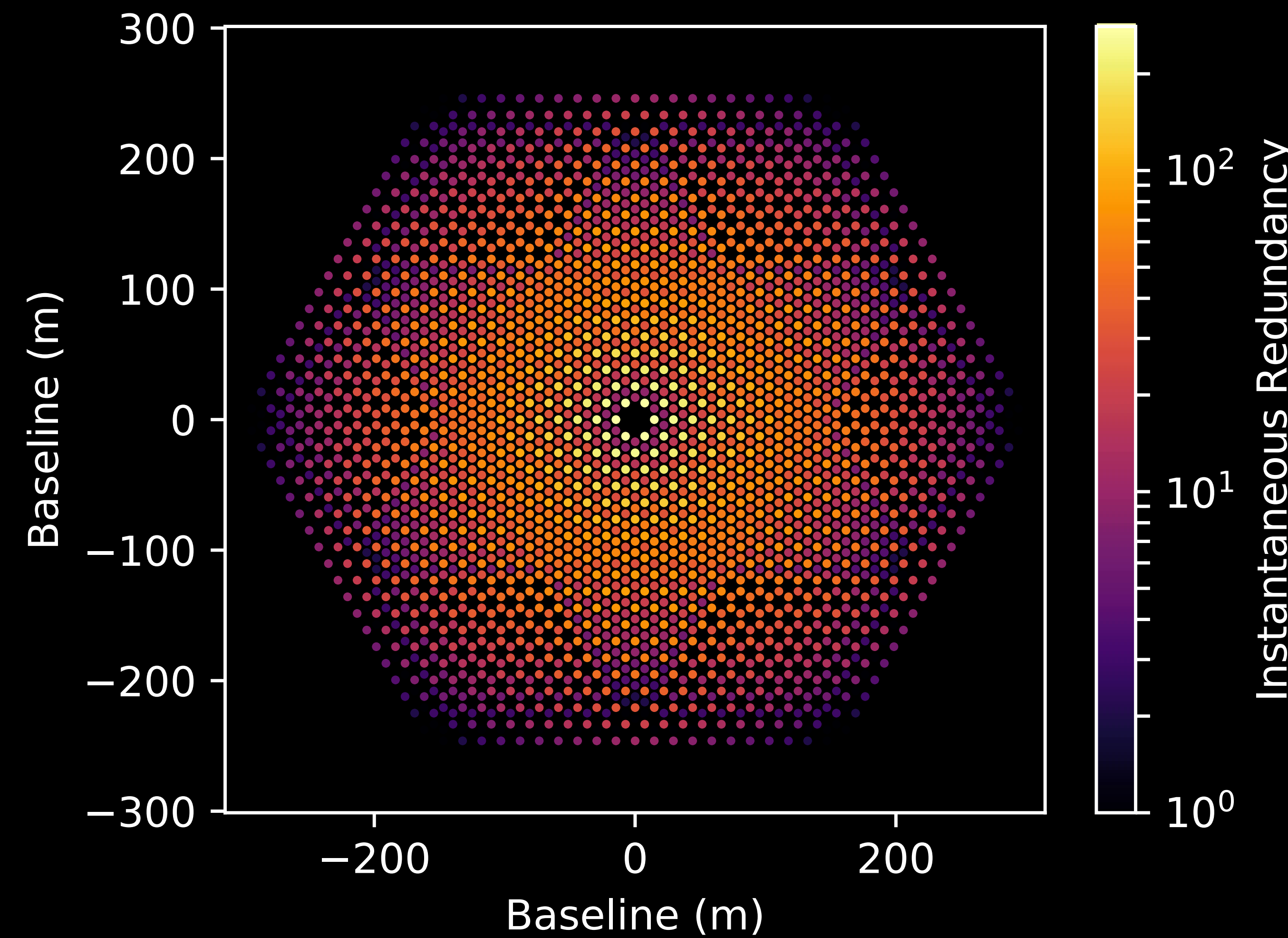
21 cm Signal = 1x or 10x Foregrounds

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

Low k has the largest signal.

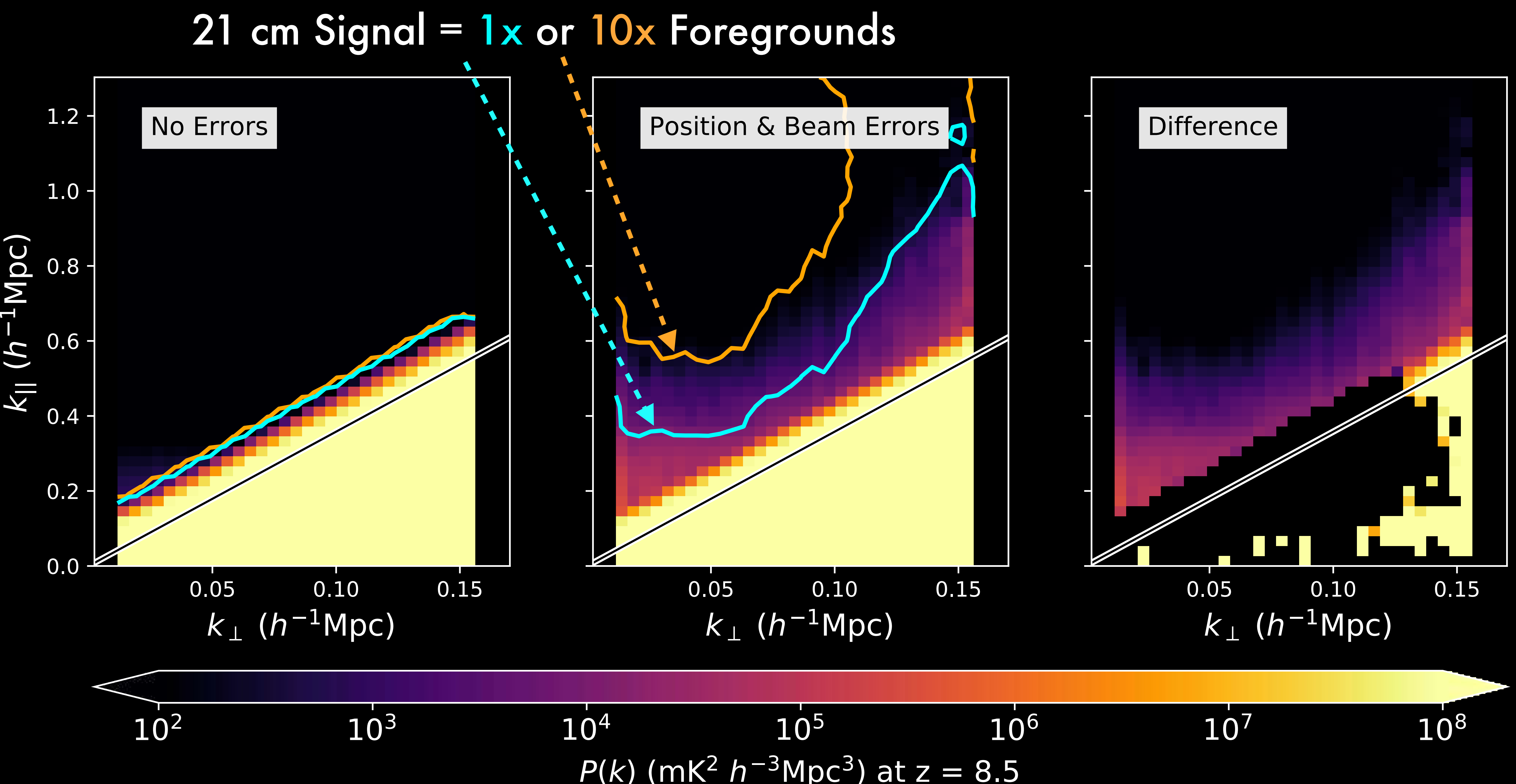


Low $k_\perp$ has the lowest noise.



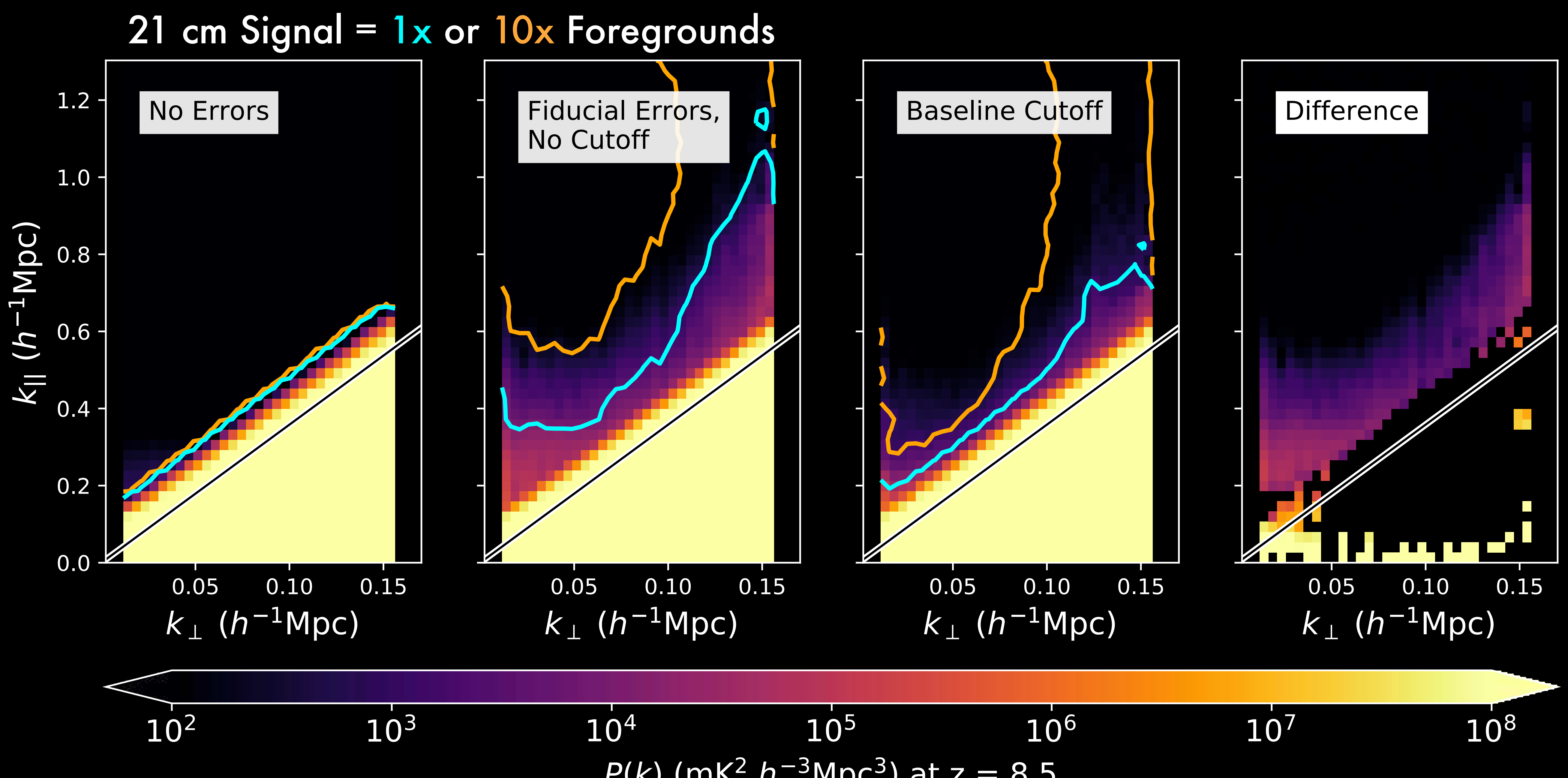
Dillon & *Parsons (2018)*

Non-redundancy contaminates the highest SNR region of Fourier space!



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

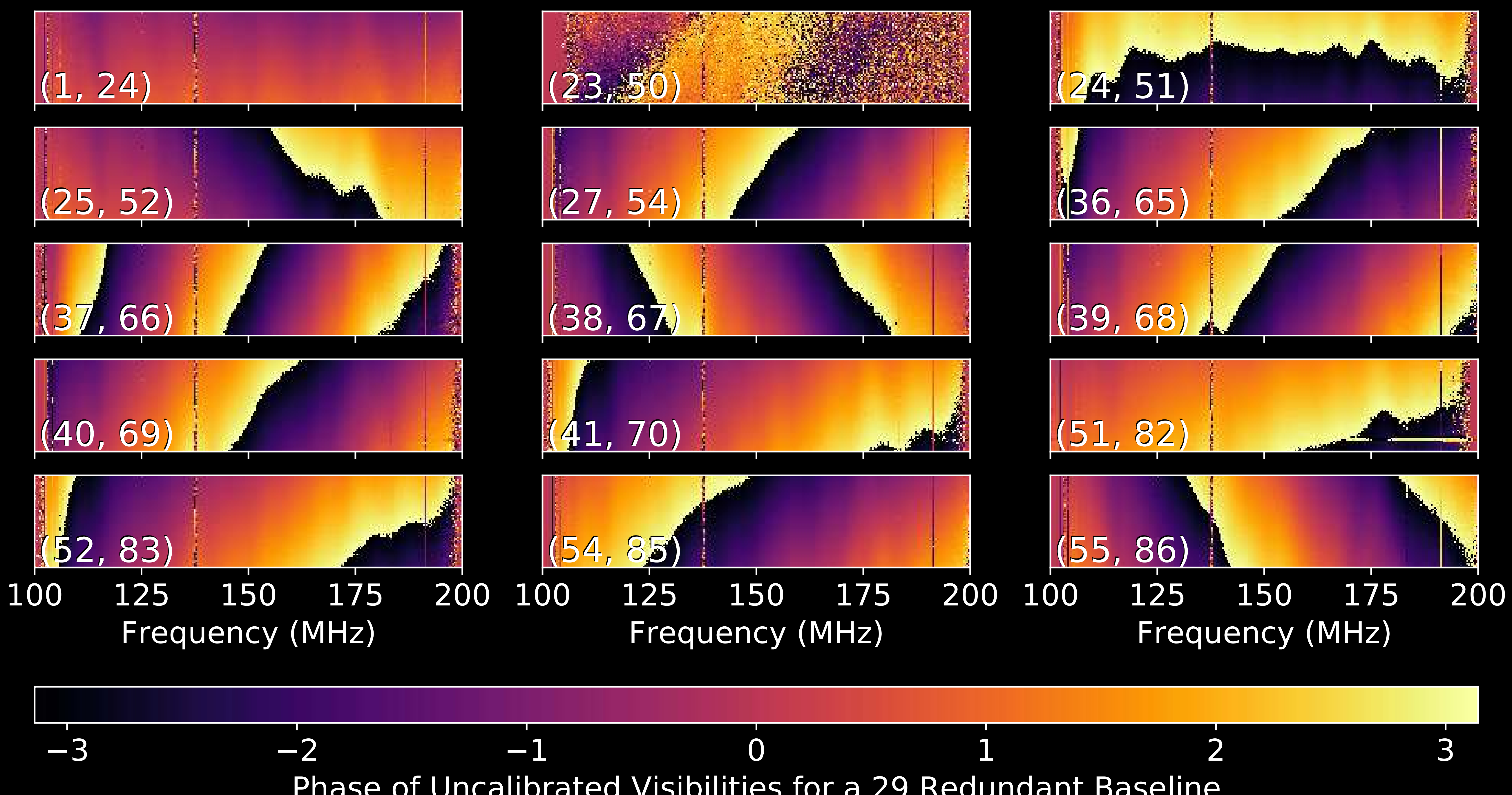
Calibrating with only the shortest baselines gets us back most of our EoR window!



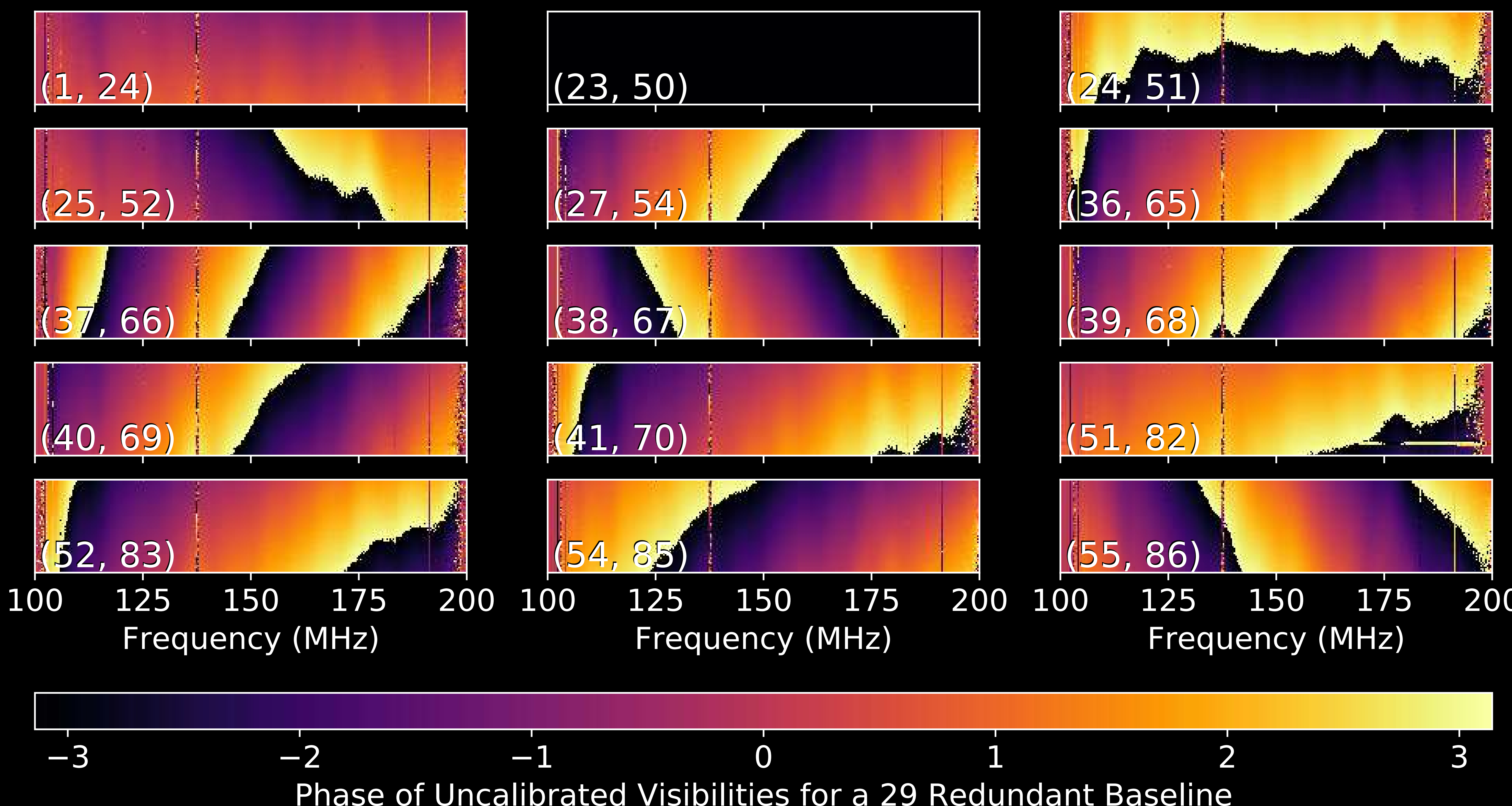
Orosz, **Dillon**, *et al. (2019)*

Redundant calibration and foreground avoidance are working quite well with real HERA data.

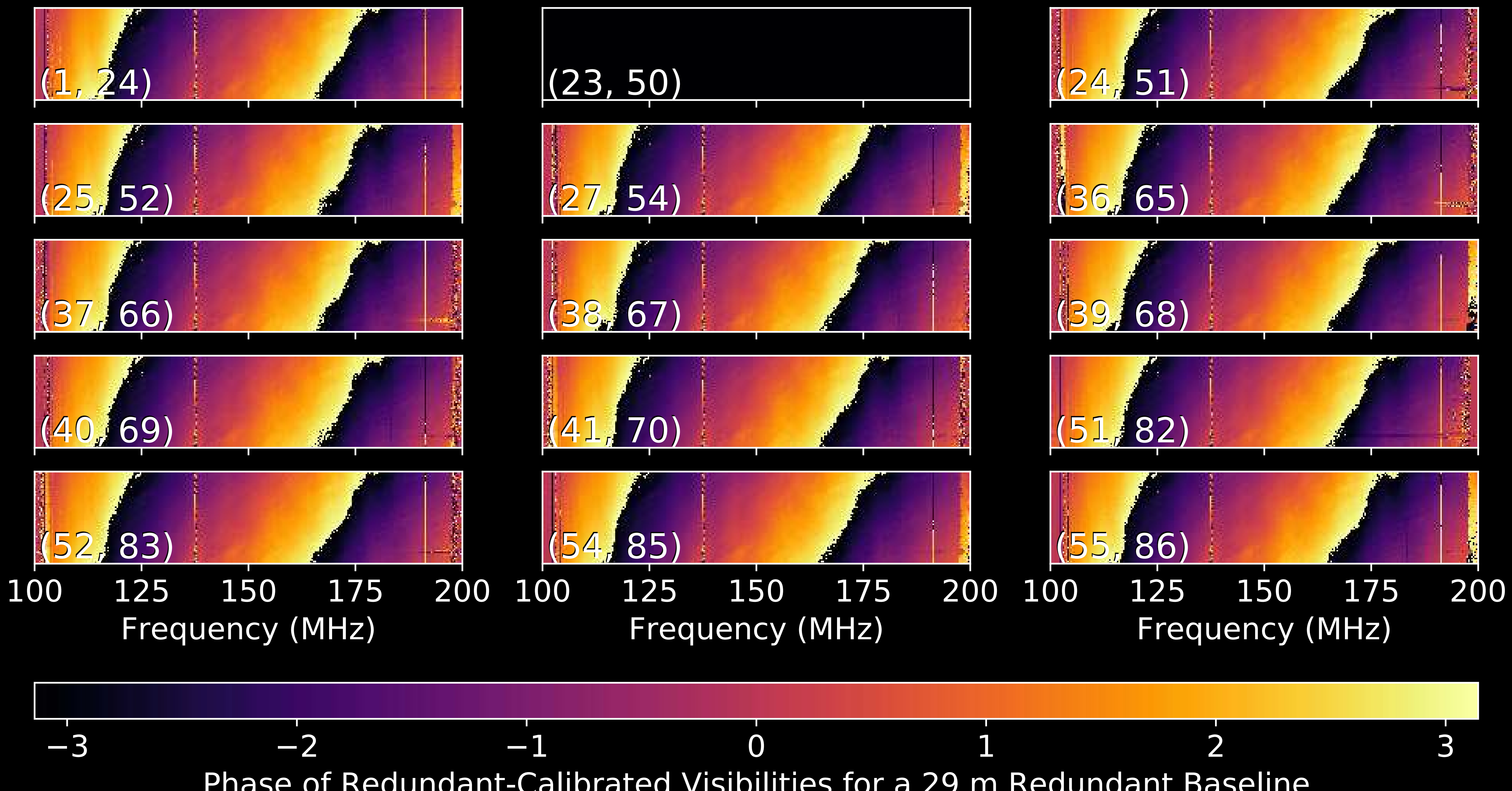
Example raw HERA data for a single redundant baseline.



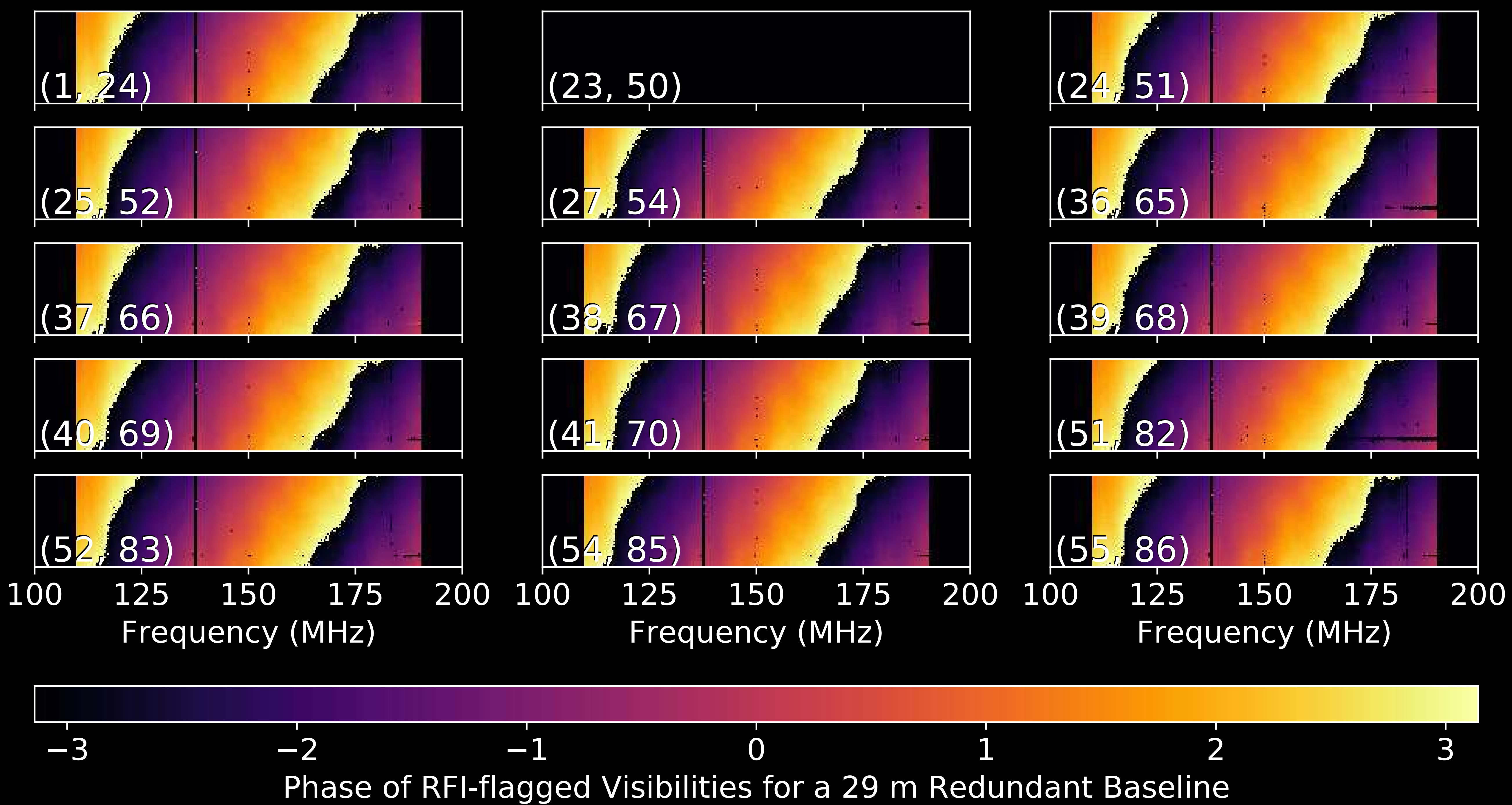
First we flag bad antennas.



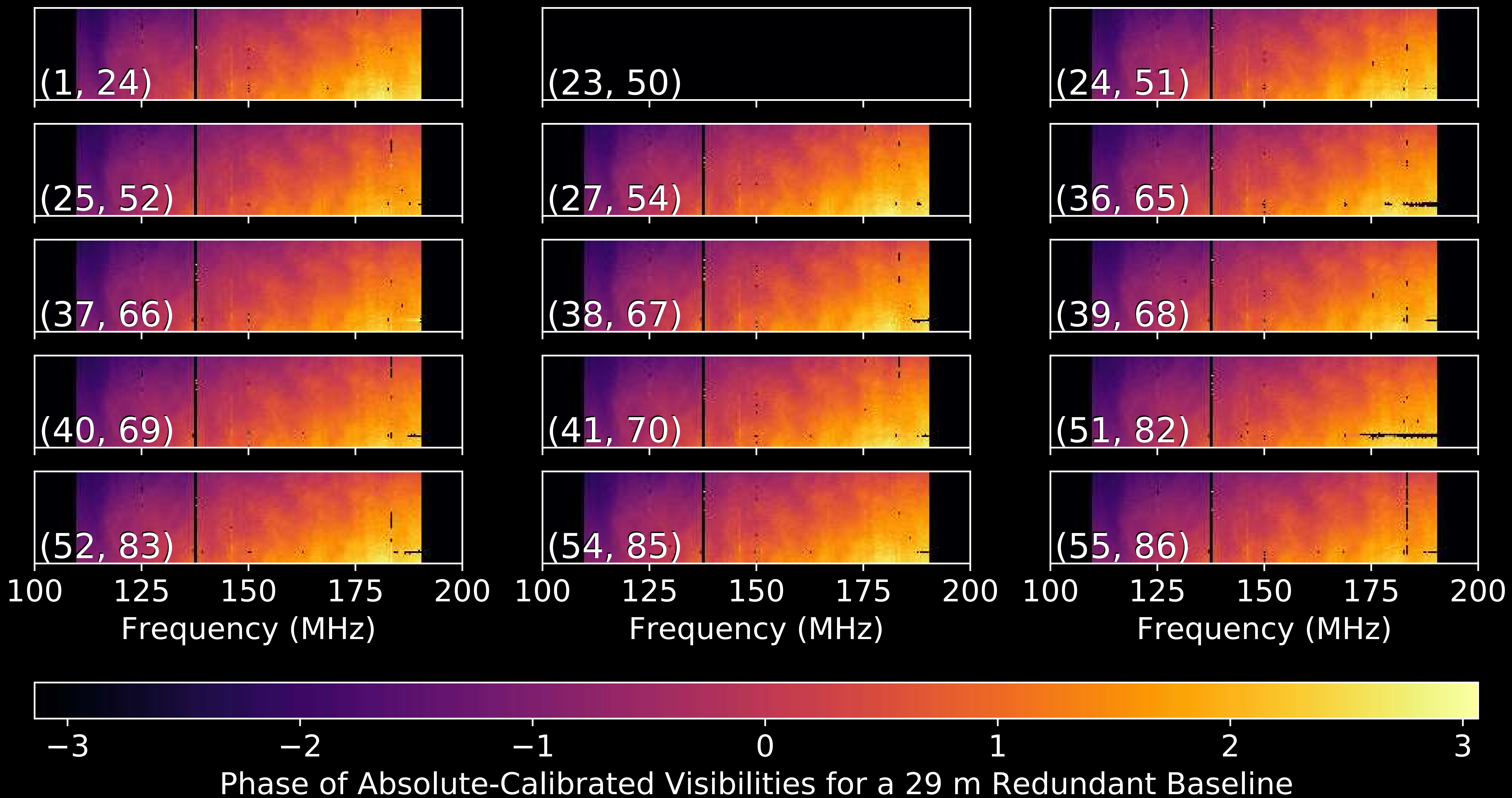
Next we impose the redundancy constraint to solve for all gains.



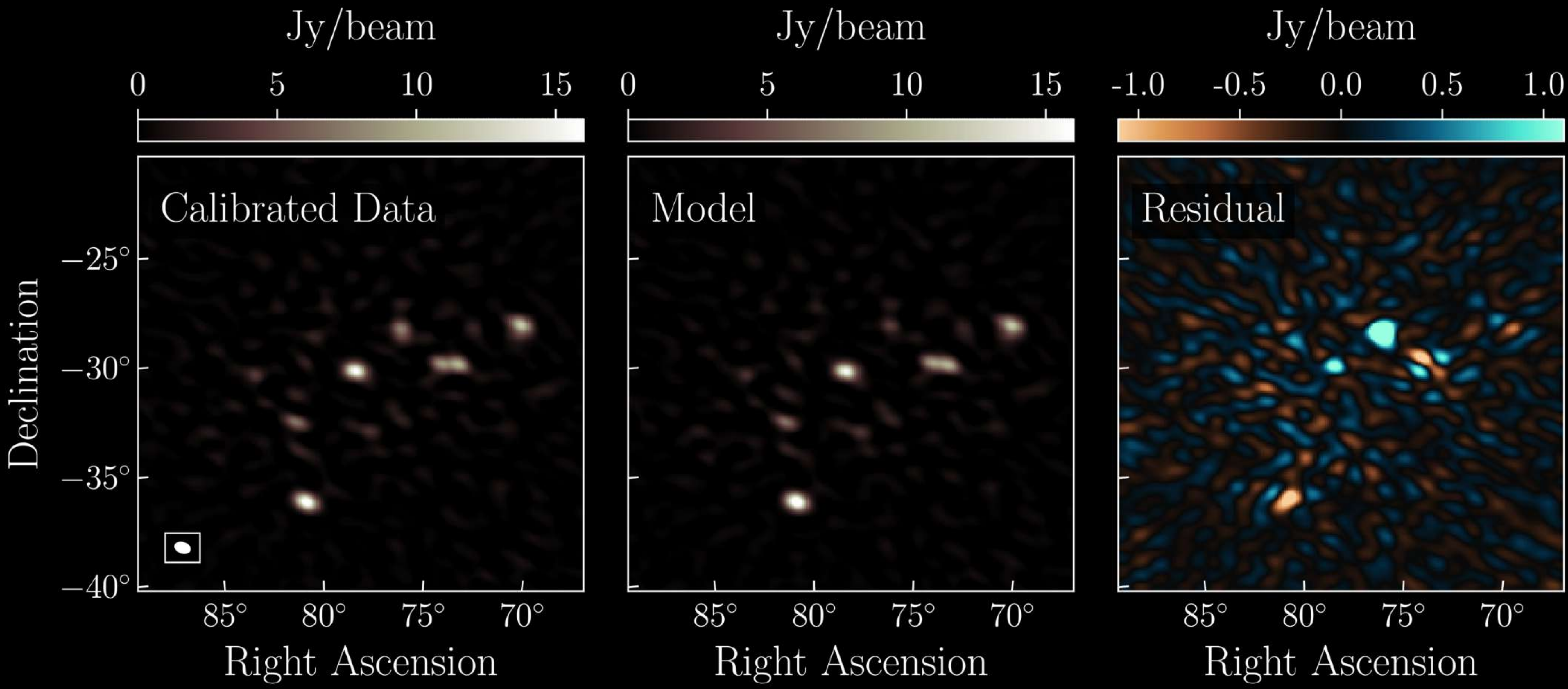
Then we mask-out band edges and radio-frequency interference.



Finally we fix to an absolute sky-reference.

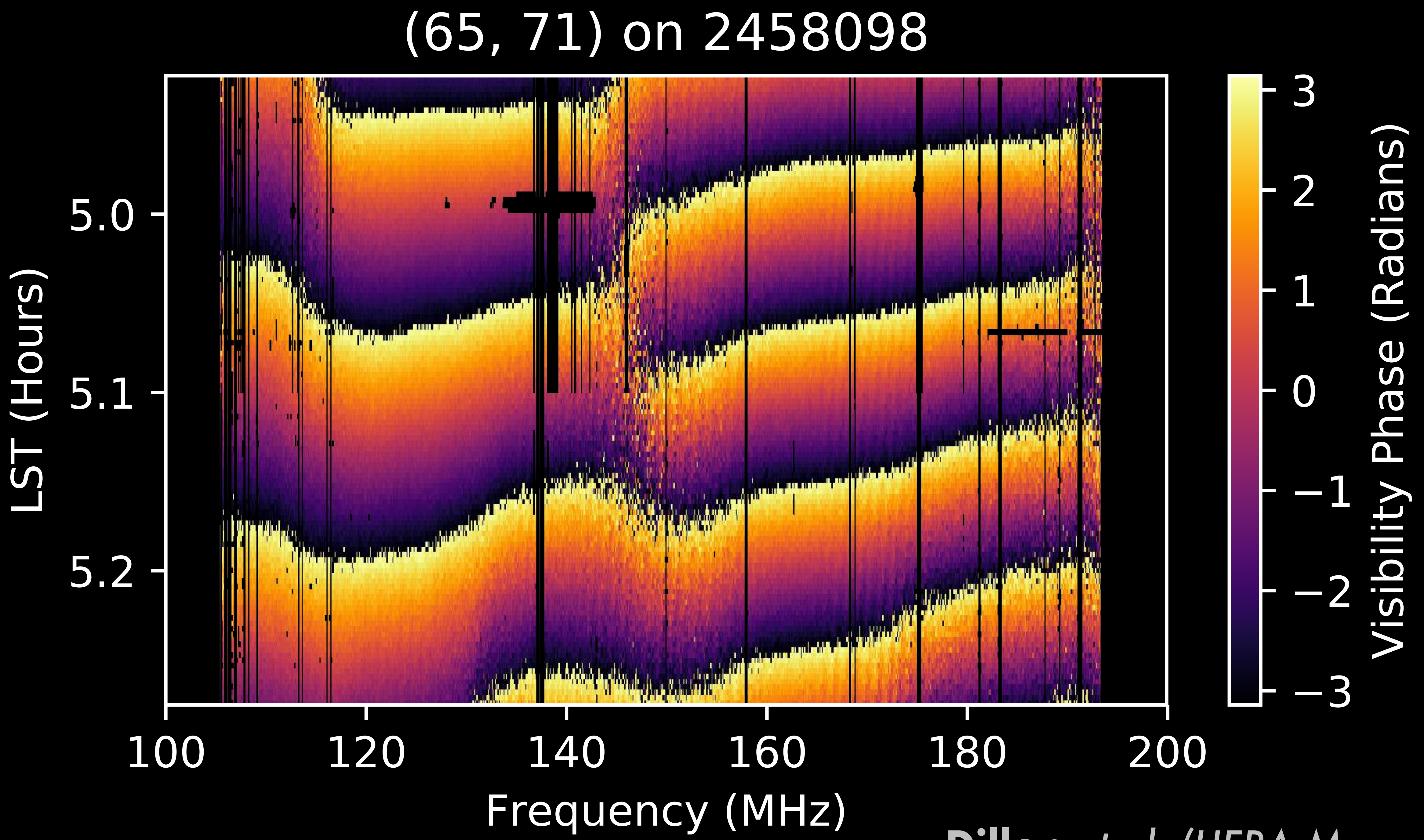


Finally we fix to an absolute sky-reference.



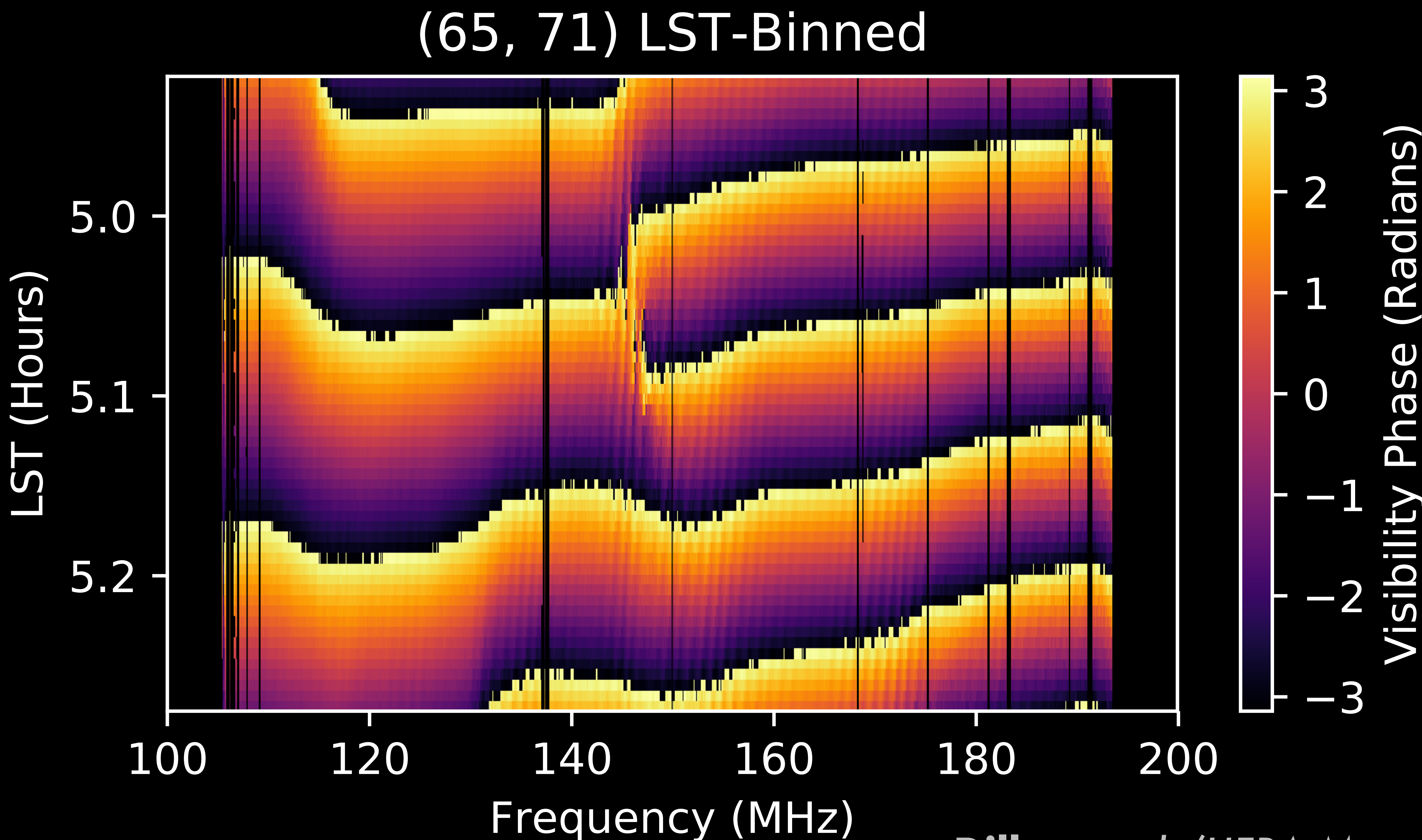
Kern, **Dillon**, *et al. (2019c)*

The instrument looks stable from day to day...



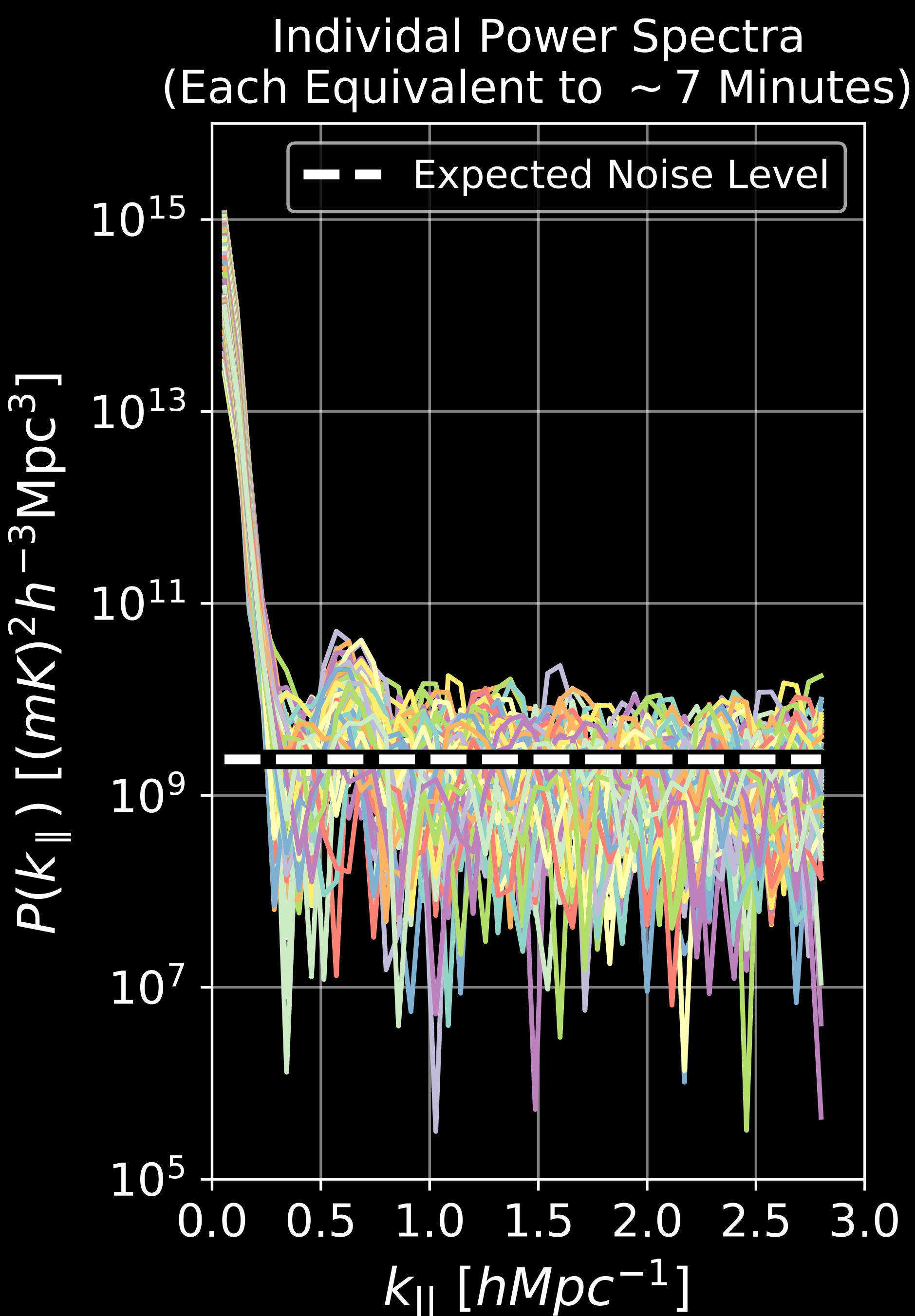
Dillon *et al. (HERA Memo #45)*

So we can keep integrating down to maximize sensitivity.



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

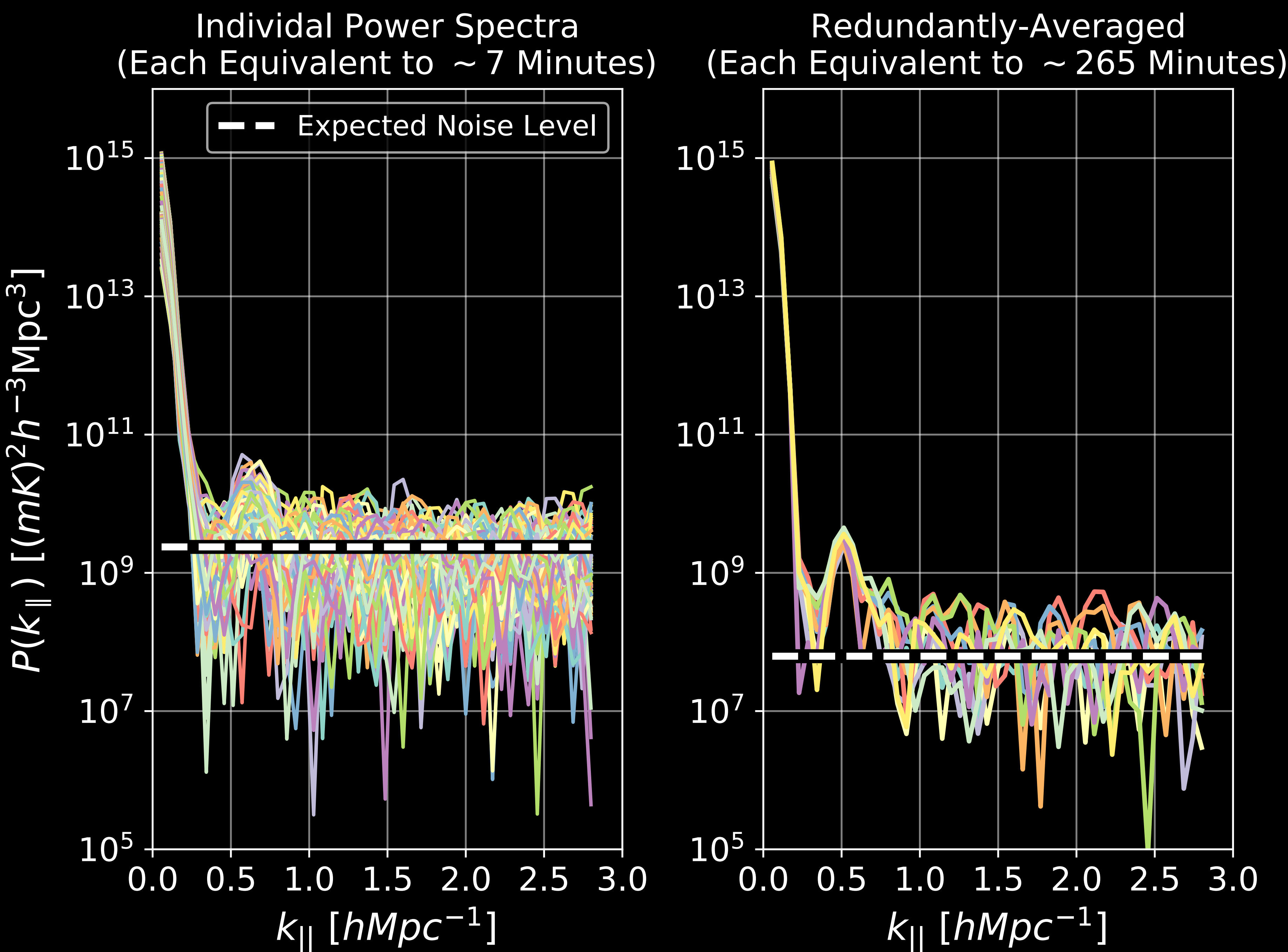
And start forming power spectra.



PRELIMINARY!

Figure: Nick Kern

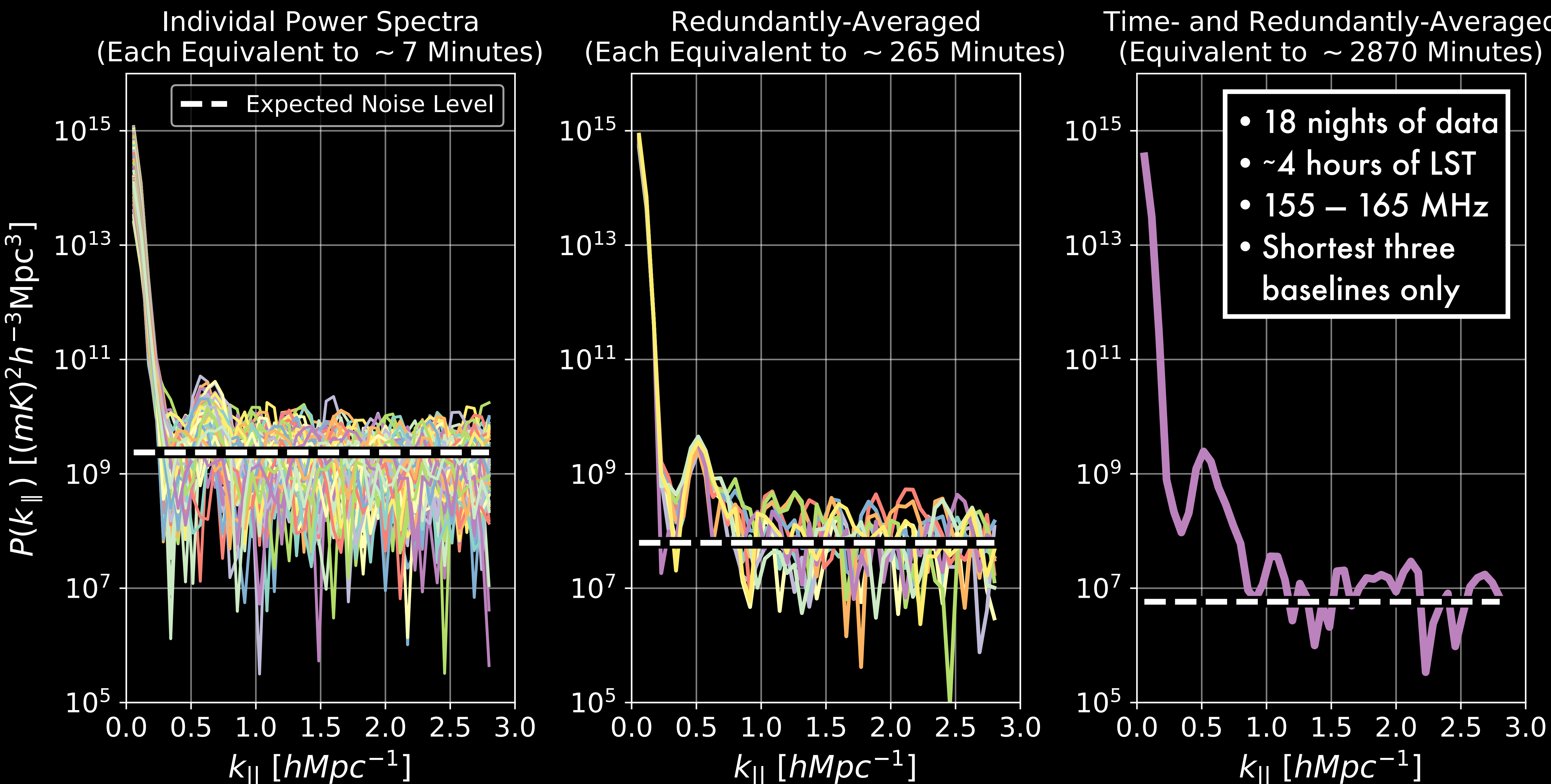
And start forming power spectra.



PRELIMINARY!

Figure: Nick Kern

And start forming power spectra.



PRELIMINARY!

Figure: Nick Kern

We’re upgrading right now with wide-band Vivaldi feeds that go from 50 – 250 MHz (4.7 > z > 29).

Photo: Ziyaad Halday

HERA will detect the 21 cm power spectrum and follow up on EDGES.

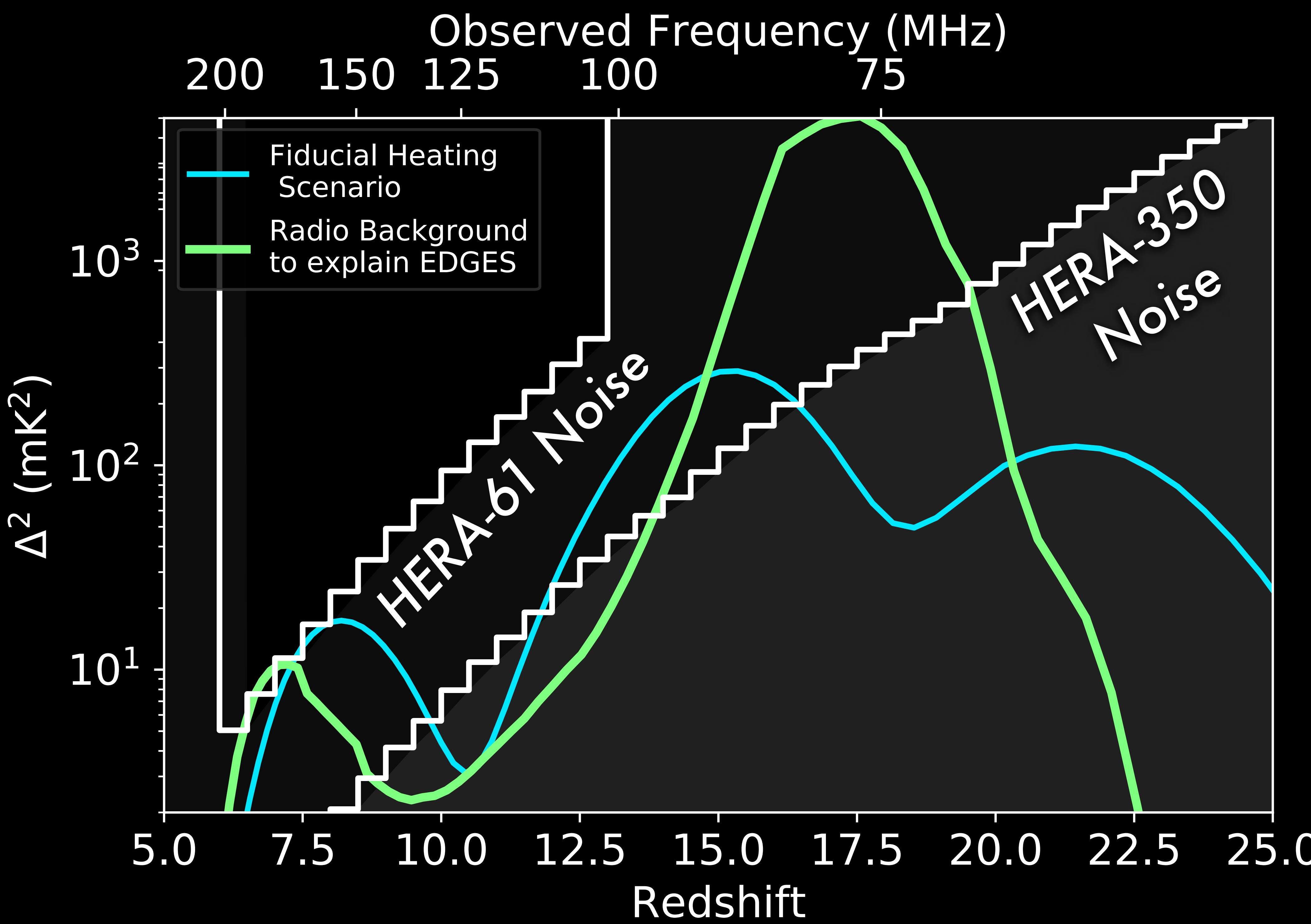
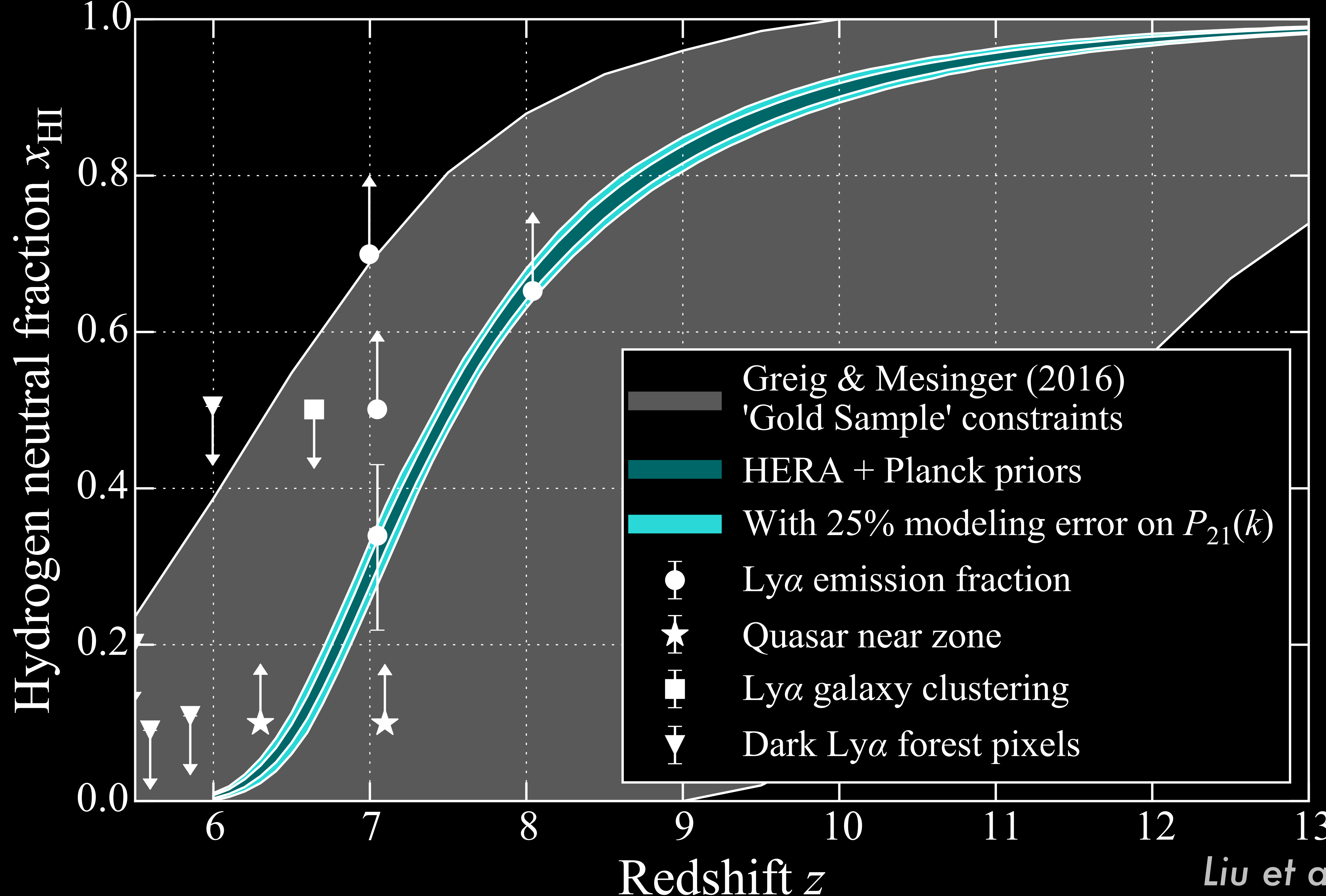


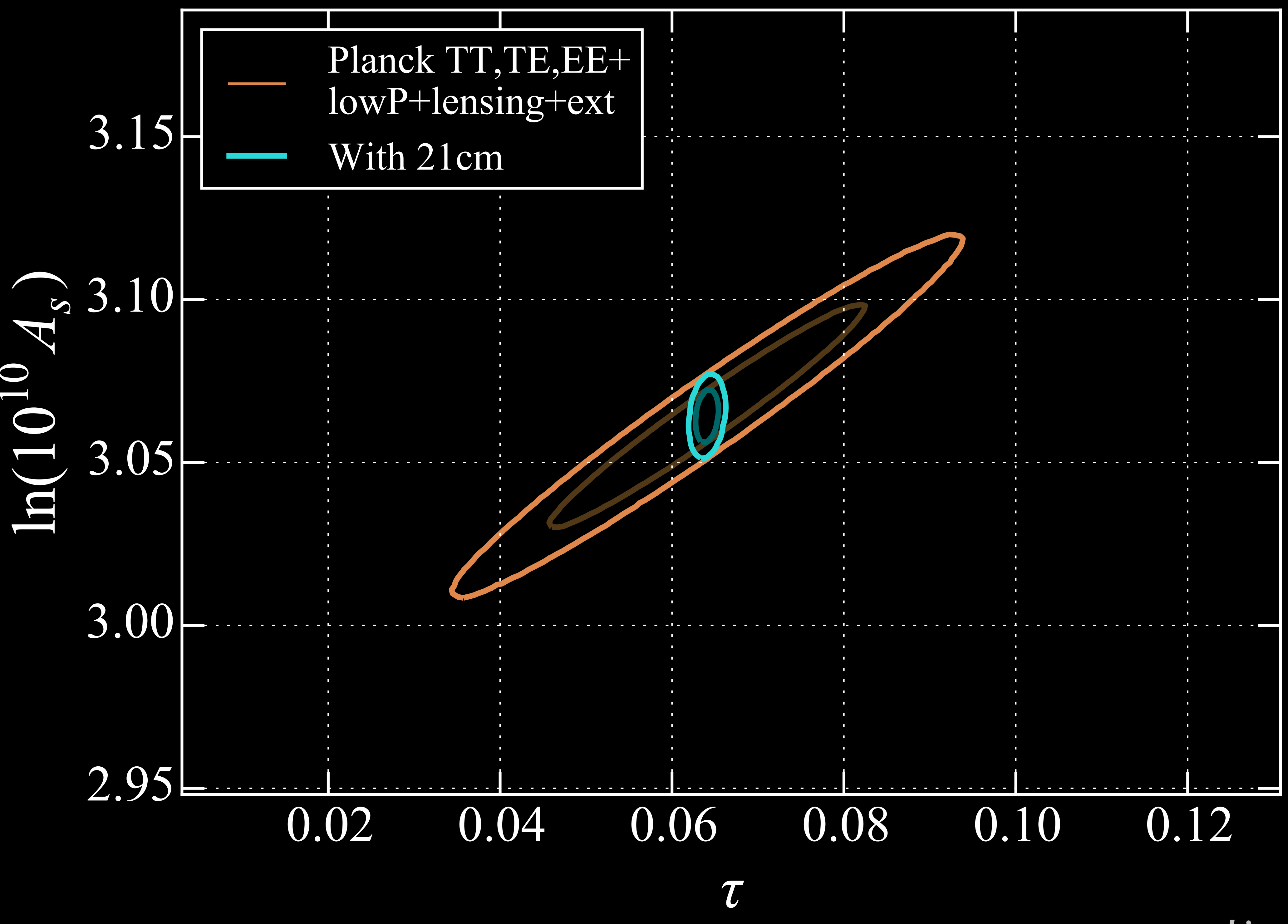
Figure: Aaron Ewall-Wice

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



Liu et al. (2016)

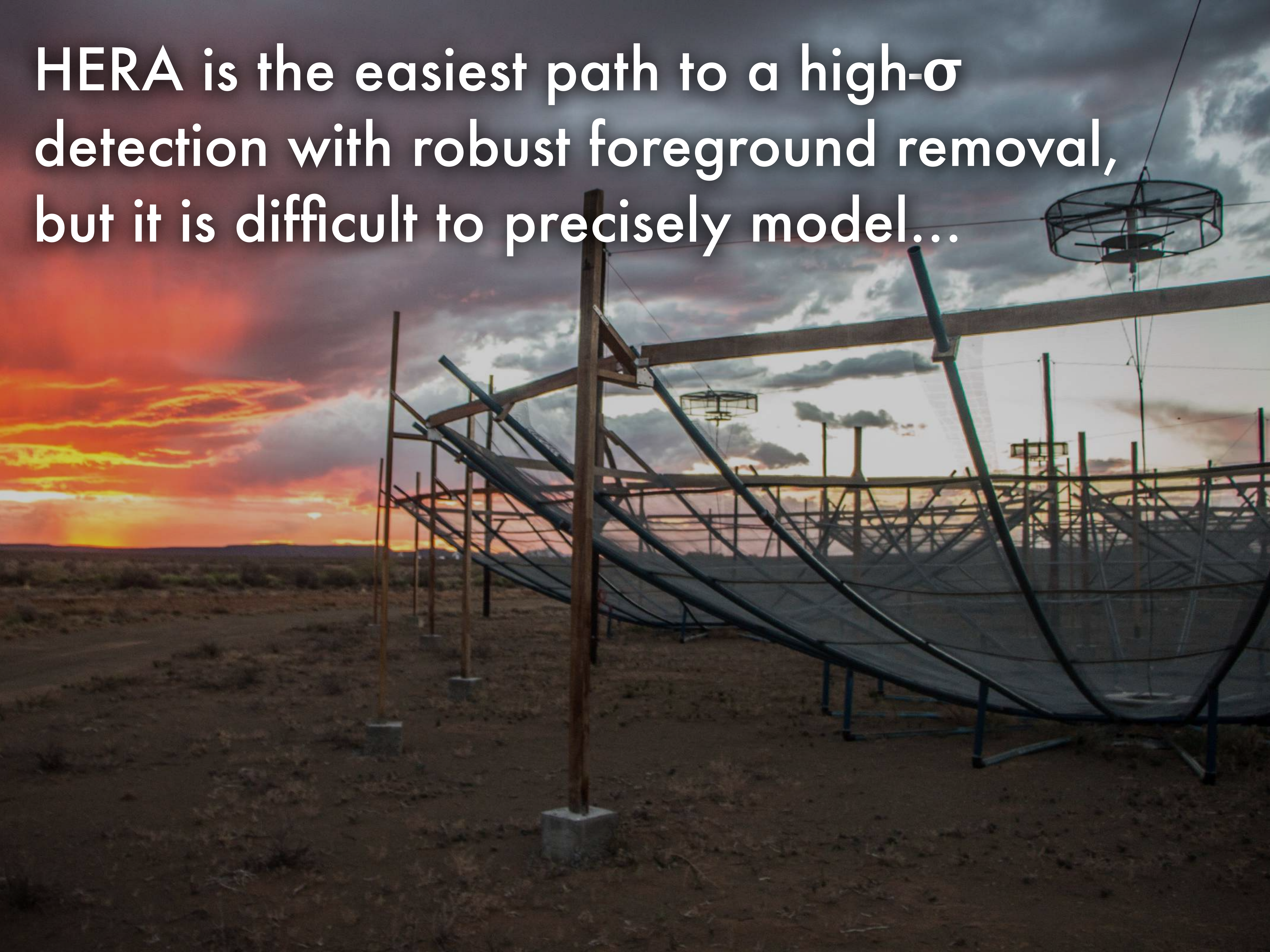
We'll eliminate τ as a CMB nuisance parameter, improving A_s errors by a factor of 4.

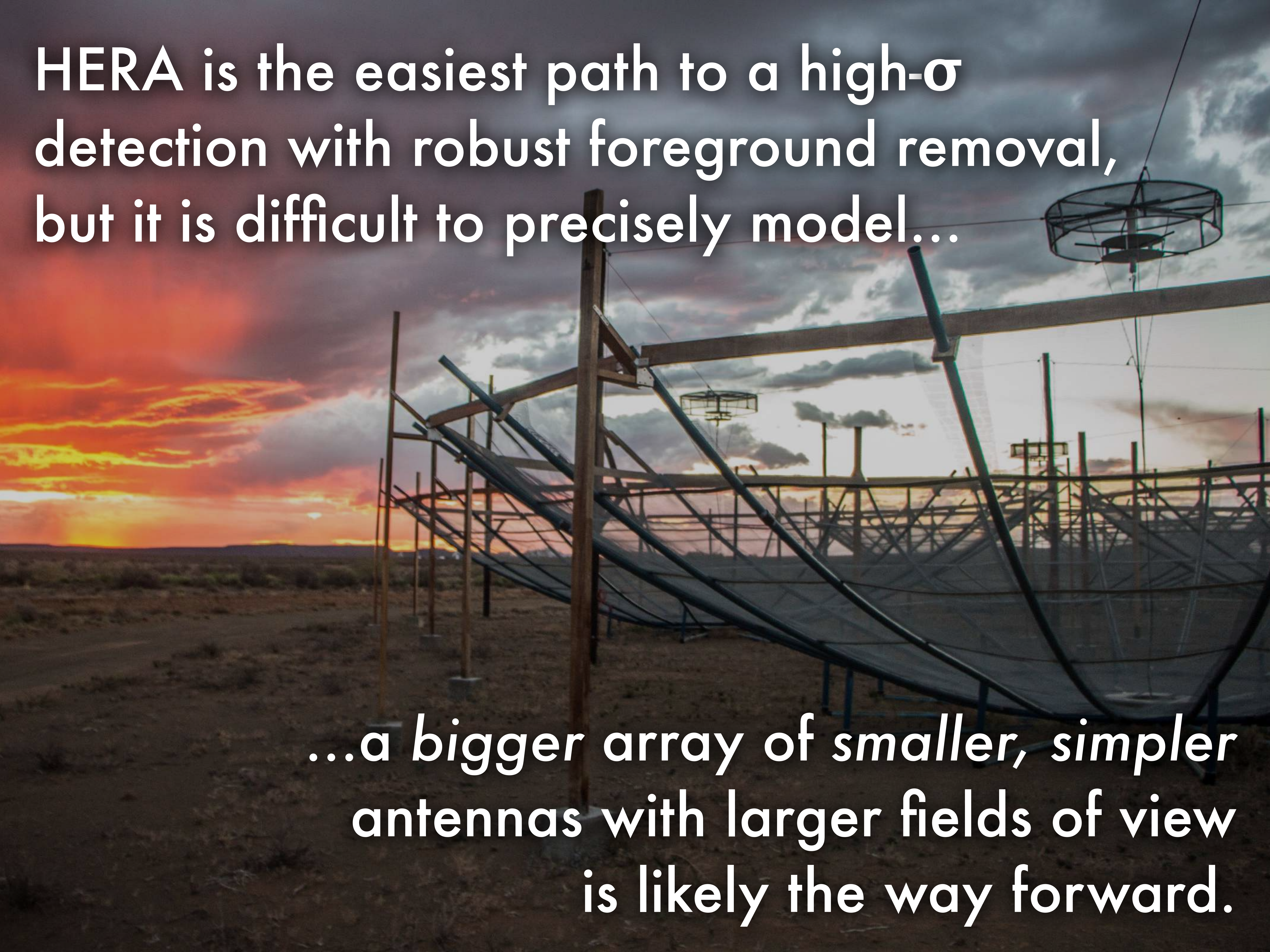


Liu et al. (2016)

What comes next?

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



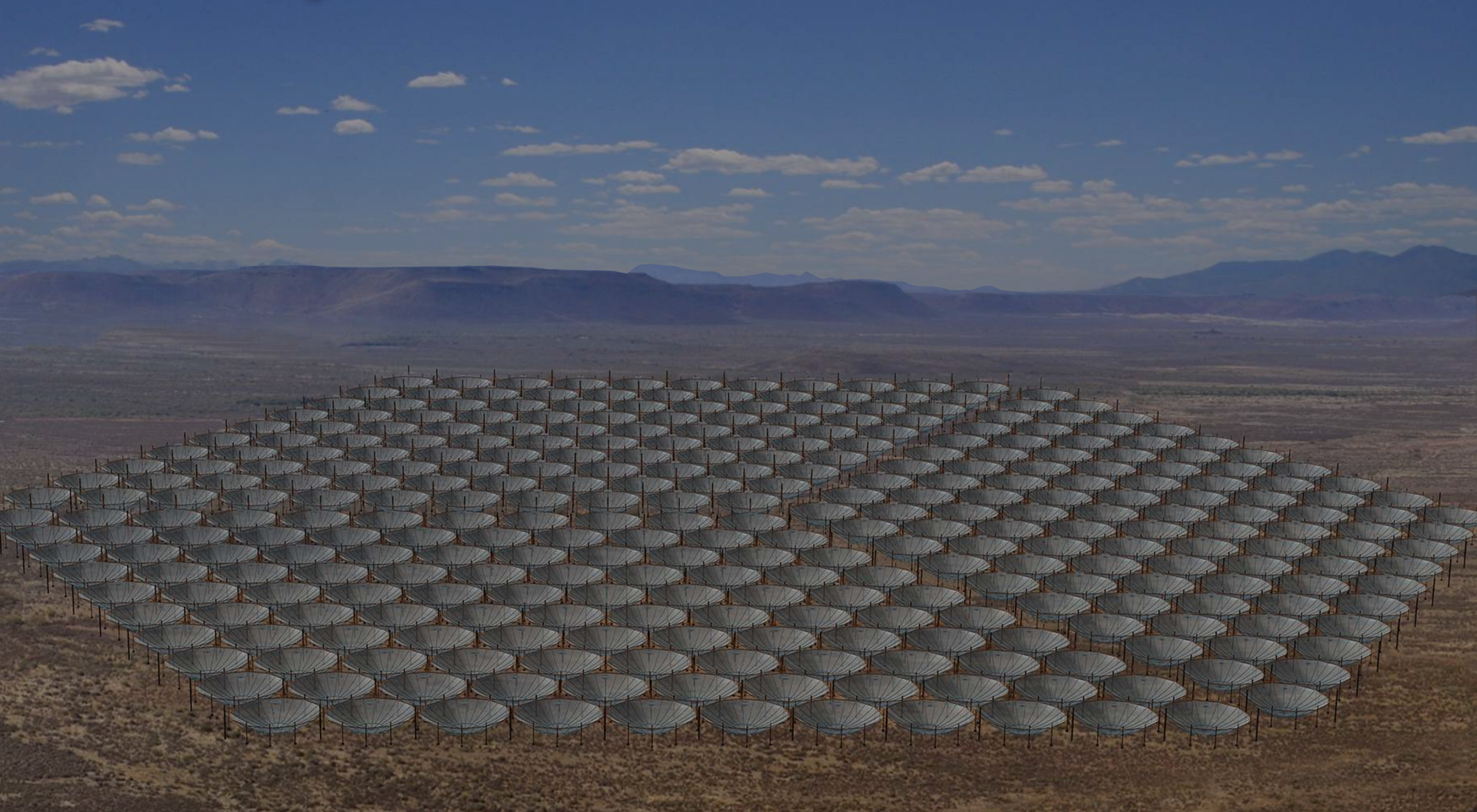


HERA is the easiest path to a high-σ detection with robust foreground removal, but it is difficult to precisely model...

...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.

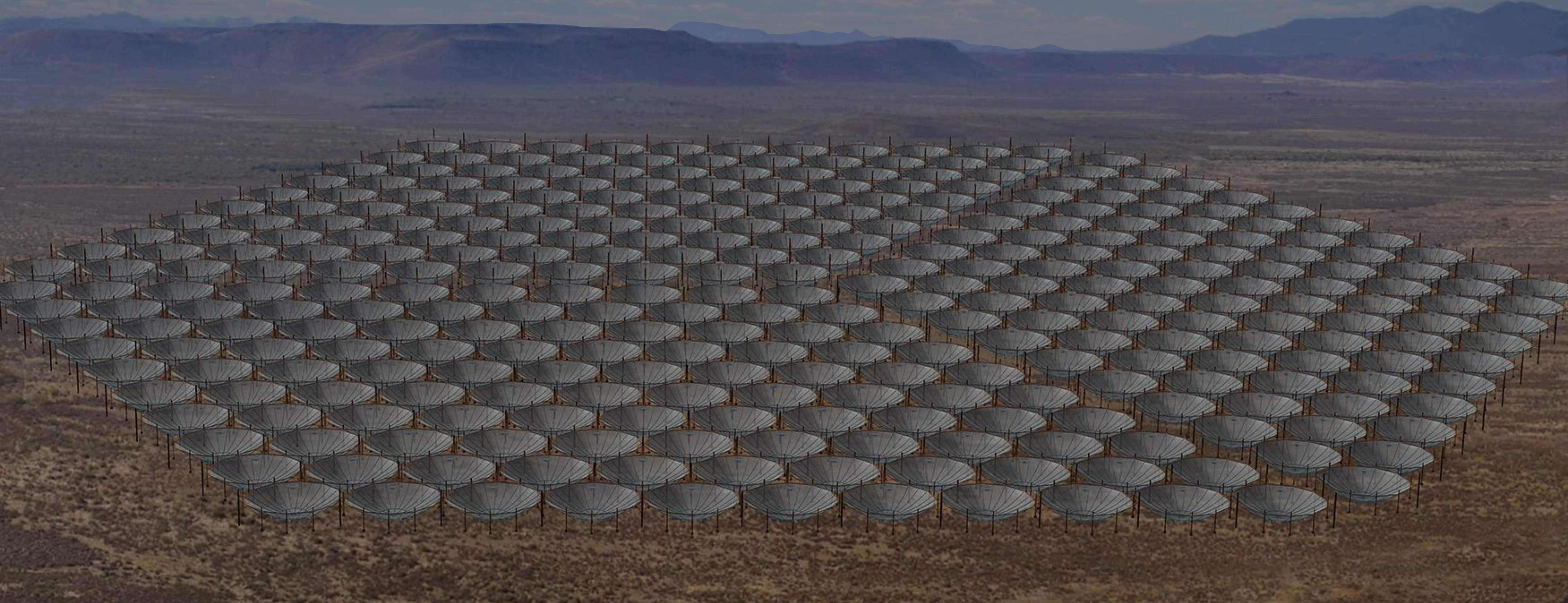
$$V_{ij}(\nu) = \int B_{ij}(\hat{\mathbf{r}}, \nu) I(\hat{\mathbf{r}}, \nu) \exp\left[-2\pi i \frac{\nu}{c} \mathbf{b}_{ij} \cdot \hat{\mathbf{r}}\right] d\Omega$$



There's a problem with how we measure visibilities.

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

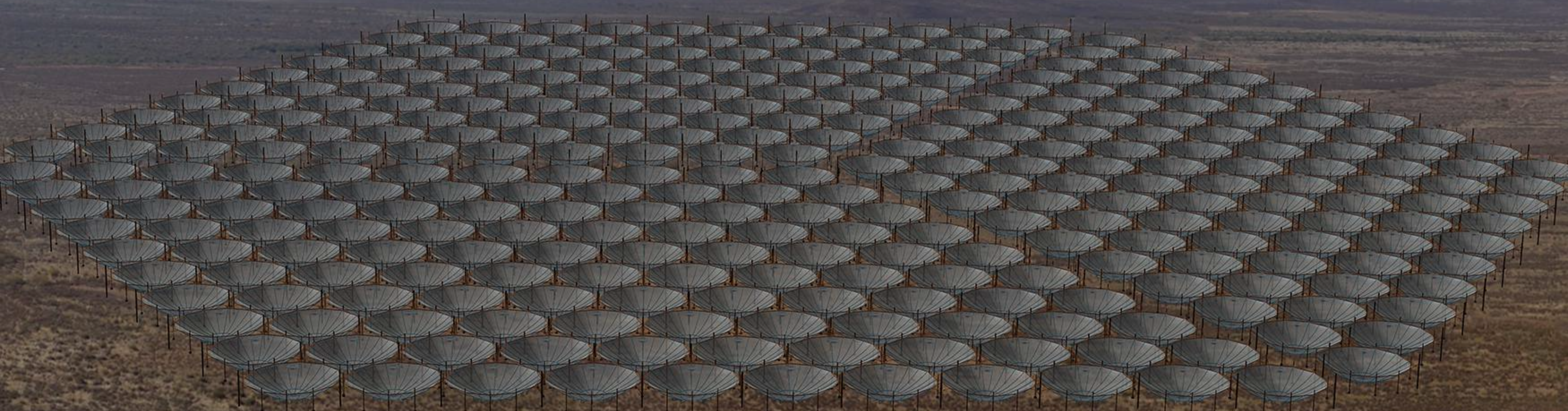
Measure antenna voltages $v_i(t)$.



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: $\tilde{v}_i(\nu)$



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:

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

There's a problem with how we measure visibilities.

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

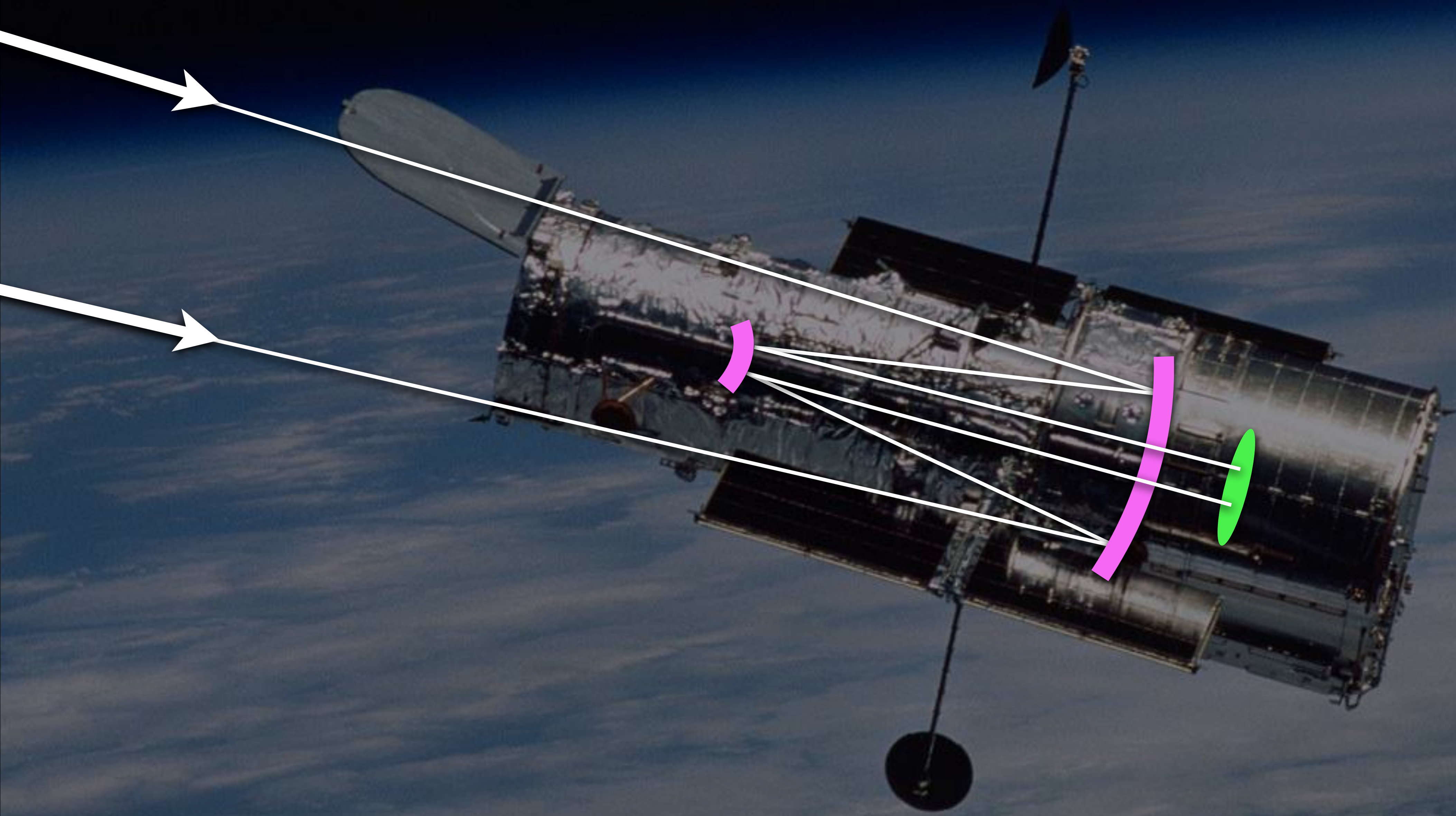
Measure antenna voltages $v_i(t)$. → Fourier transform to frequency: $\tilde{v}_i(\nu)$

→ Correlate antennas to form visibilities:

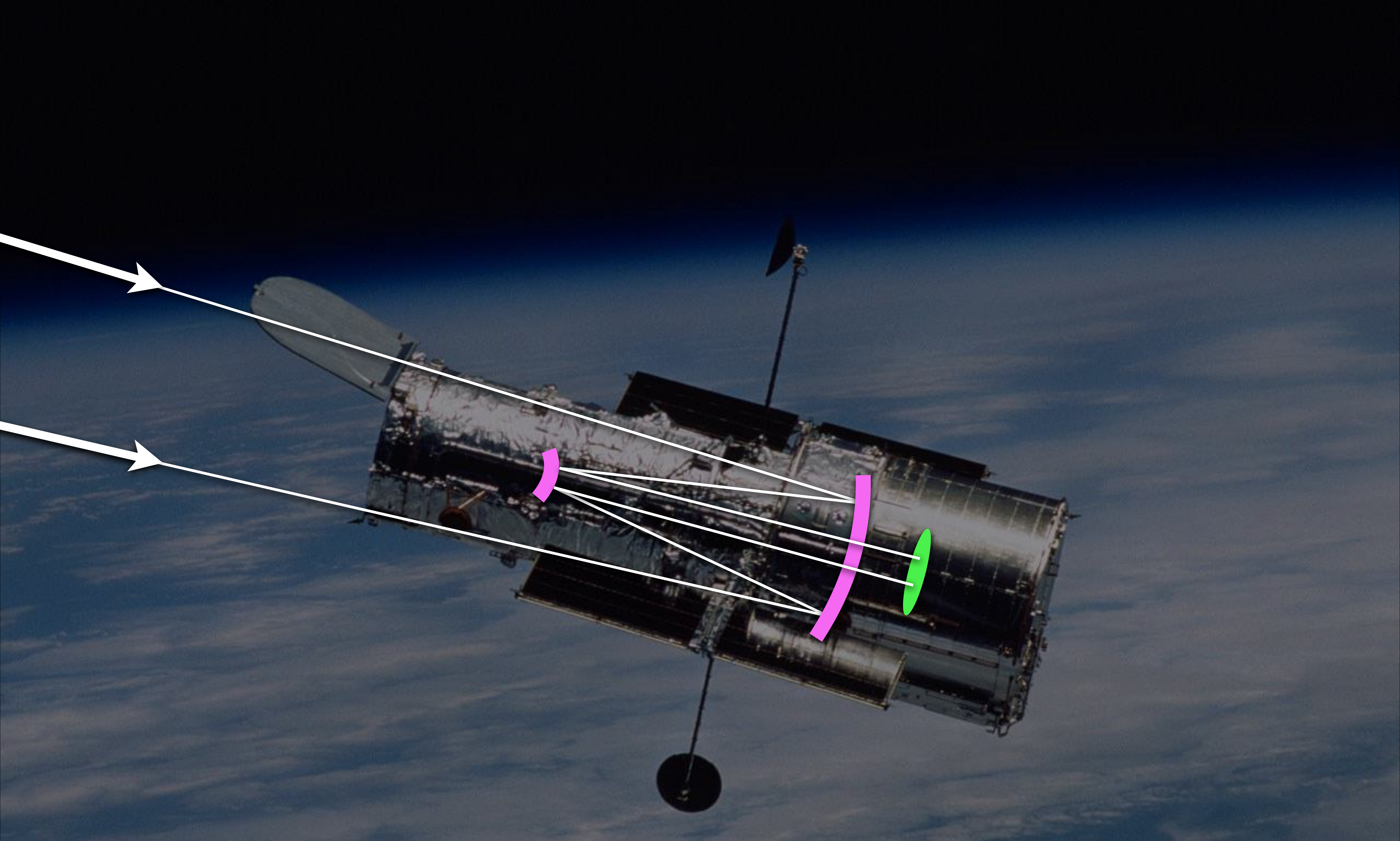
$$\langle \tilde{v}_i(\nu) \tilde{v}_j^*(\nu) \rangle = V_{ij}(\nu)$$

This scales like O(N²)!

All telescopes are Fourier transformers.



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

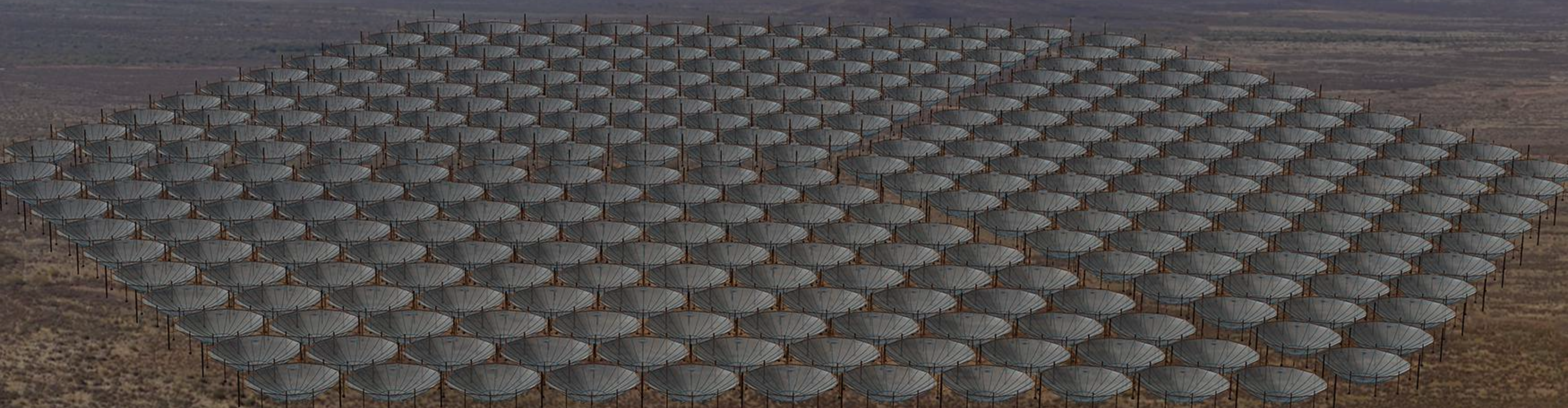


A telescope converts *photon momenta* to *positions* on the focal plane.

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

can be rewritten suggestively as...

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



Tegmark & Zaldarriaga (2009)

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

can be rewritten suggestively as...

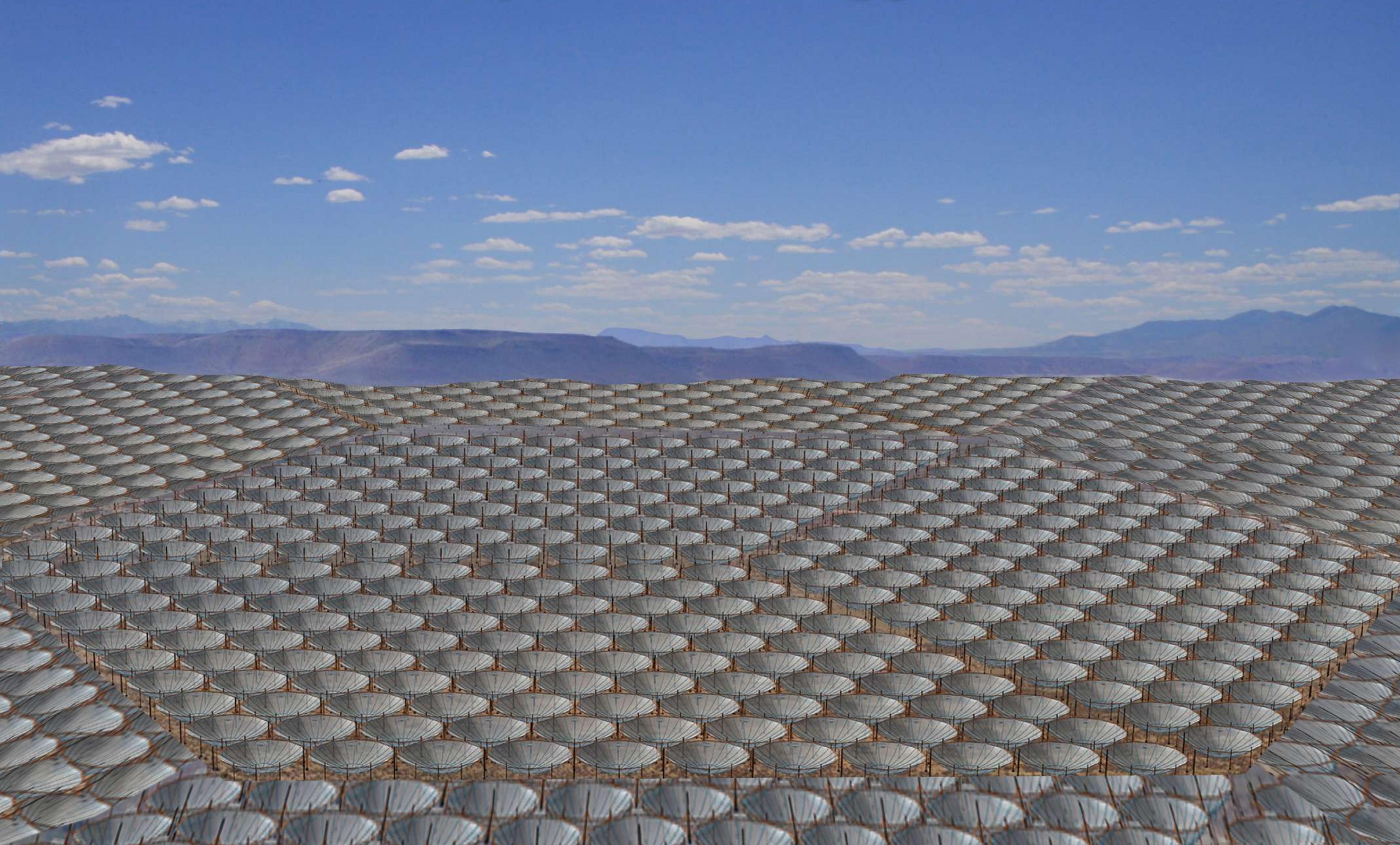
$$\langle \tilde{v}_i(k) \tilde{v}_j^* \rangle = \int B(\mathbf{k}) I(\mathbf{k}) \exp\left[i\mathbf{k} \cdot (\mathbf{x}_i - \mathbf{x}_j)\right] d\Omega$$

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)

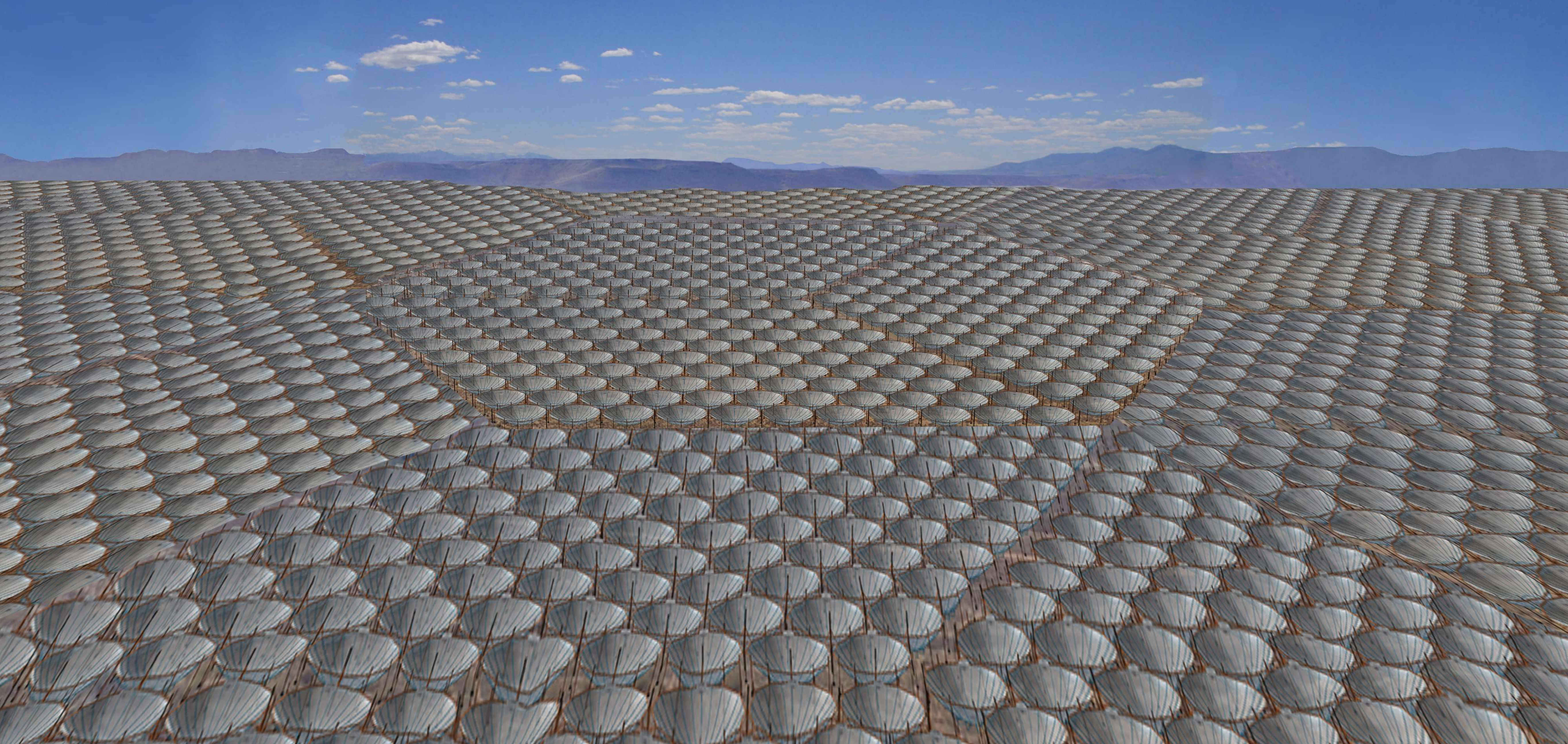
An FFT Telescope can be bigger than HERA.

An FFT Telescope can be bigger than HERA.

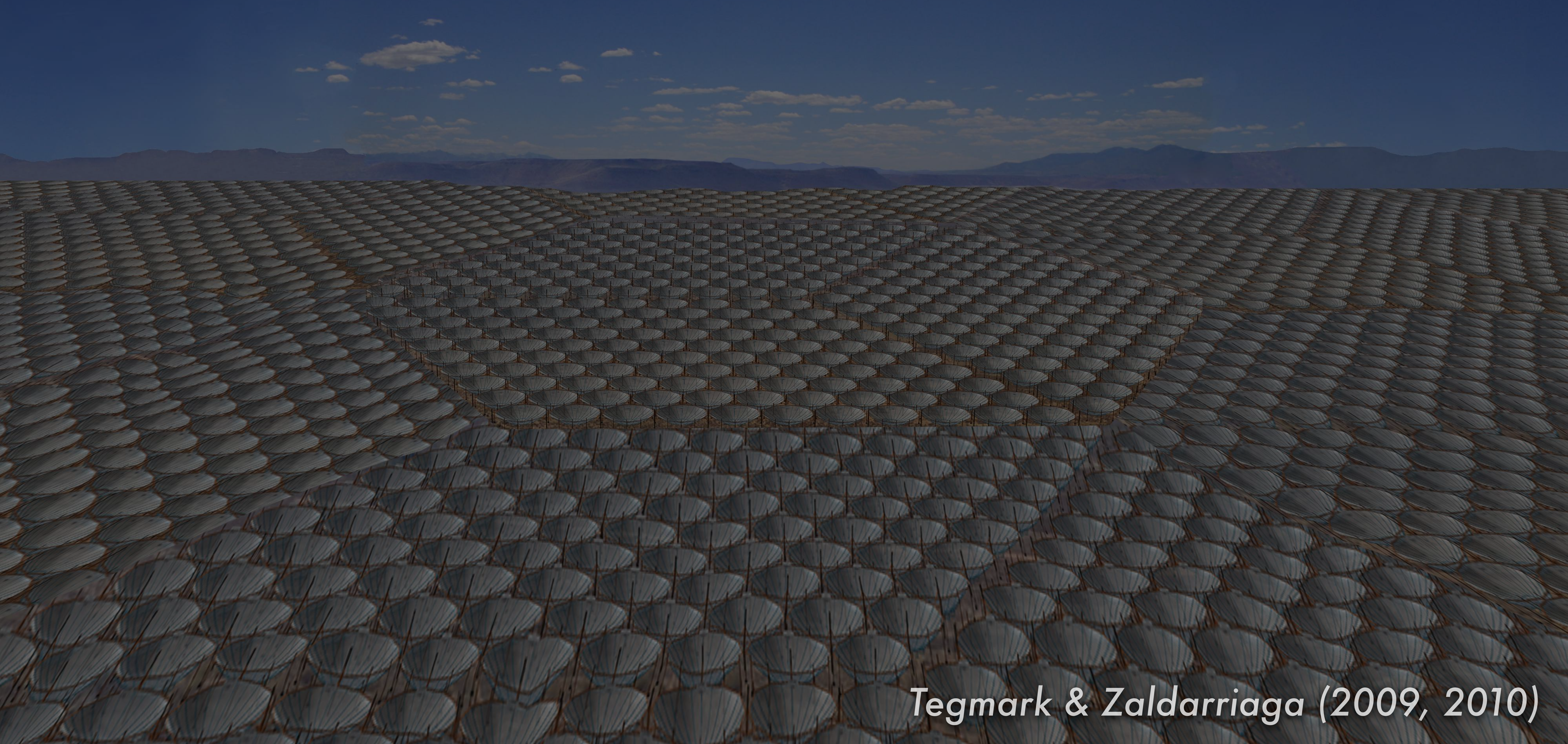


An FFT Telescope can be bigger than HERA.

Much, *much* bigger.



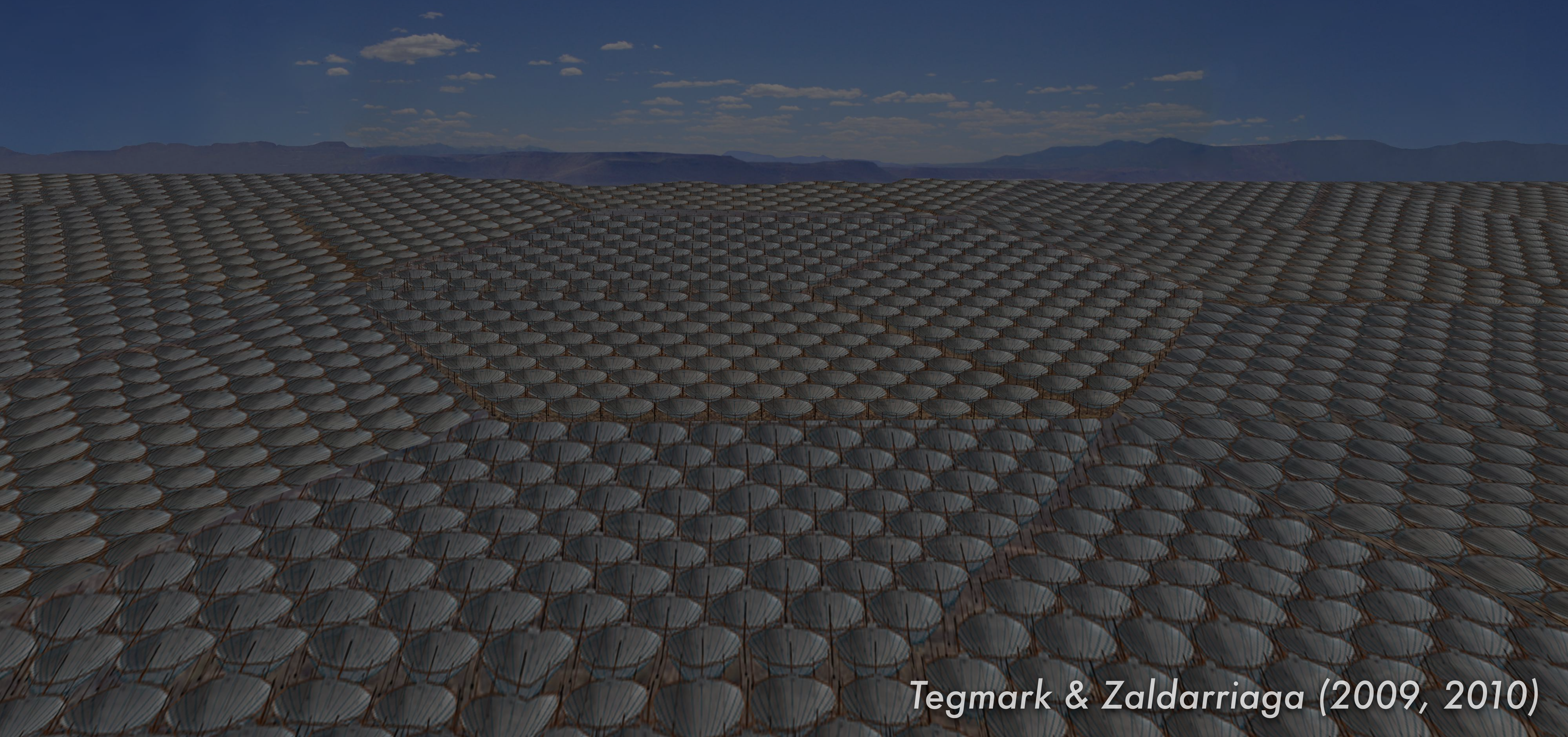
An FFT Telescope needs to be…



Tegmark & Zaldarriaga (2009, 2010)

An FFT Telescope needs to be...

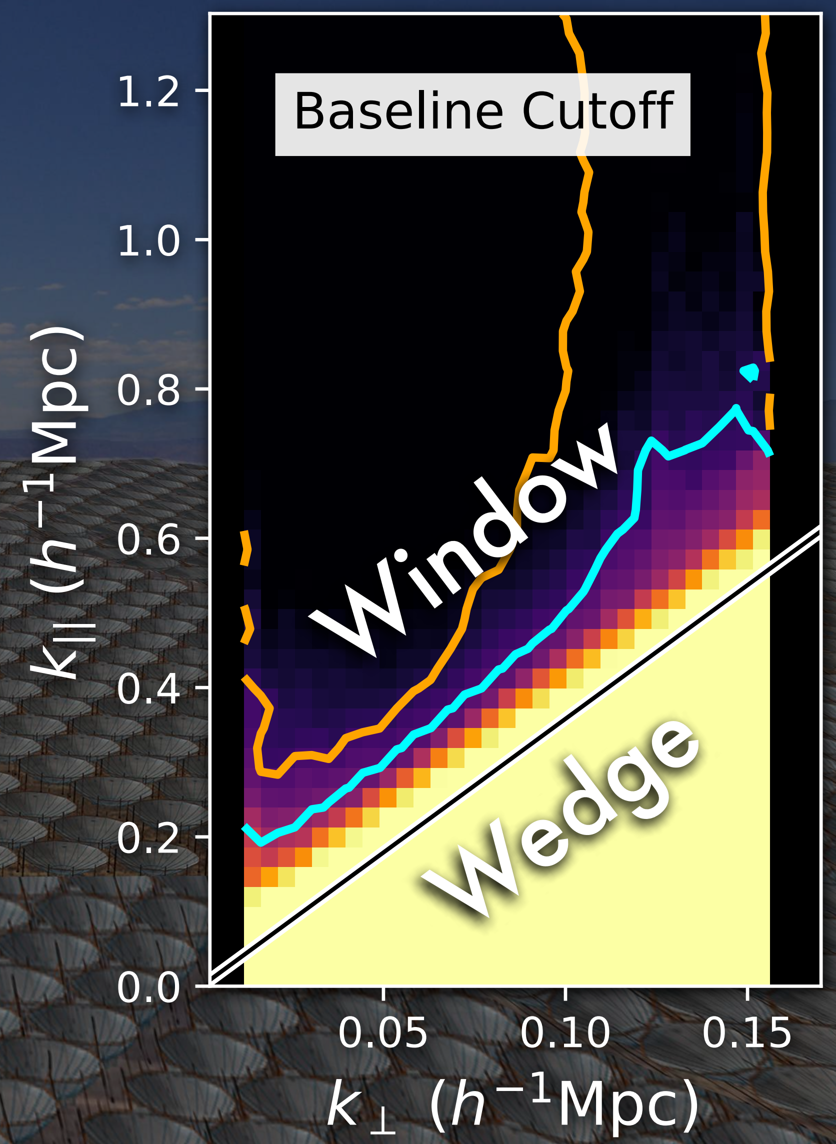
- Co-planar.



Tegmark & Zaldarriaga (2009, 2010)

An FFT Telescope needs to be...

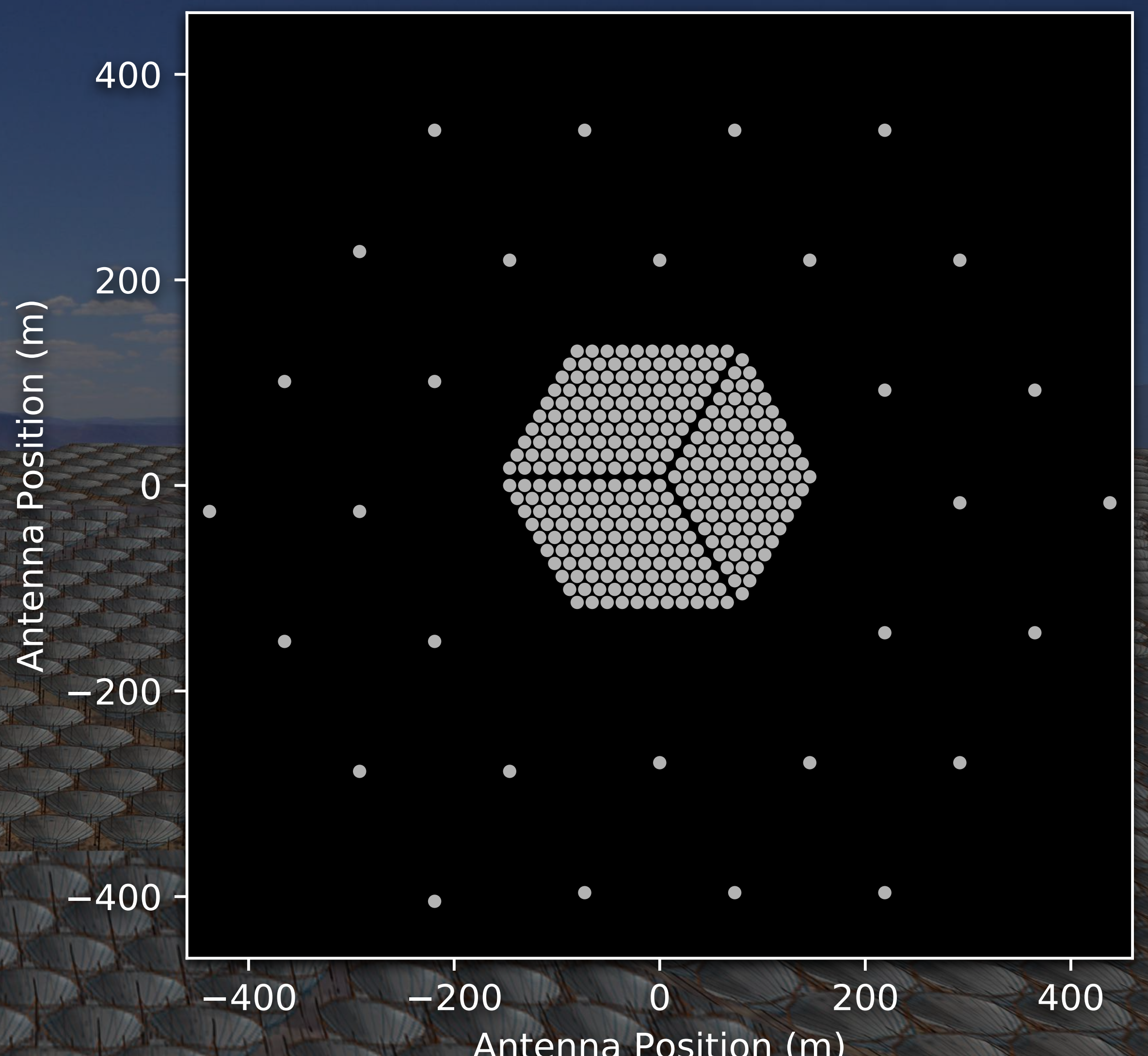
- Co-planar.
- Made up of identical antenna elements with identical beams.
  - *Otherwise the wedge will be contaminated (Orosz et al. 2018)*



Tegmark & Zaldarriaga (2009, 2010)

An FFT Telescope needs to be...

- Co-planar.
- Made up of identical antenna elements with identical beams.
  - *Otherwise the wedge will be contaminated (Orosz et al. 2018)*
- On a regular or hierarchically regular grid.
  - I designed HERA's layout for FFT correlation (Dillon & Parsons 2016)



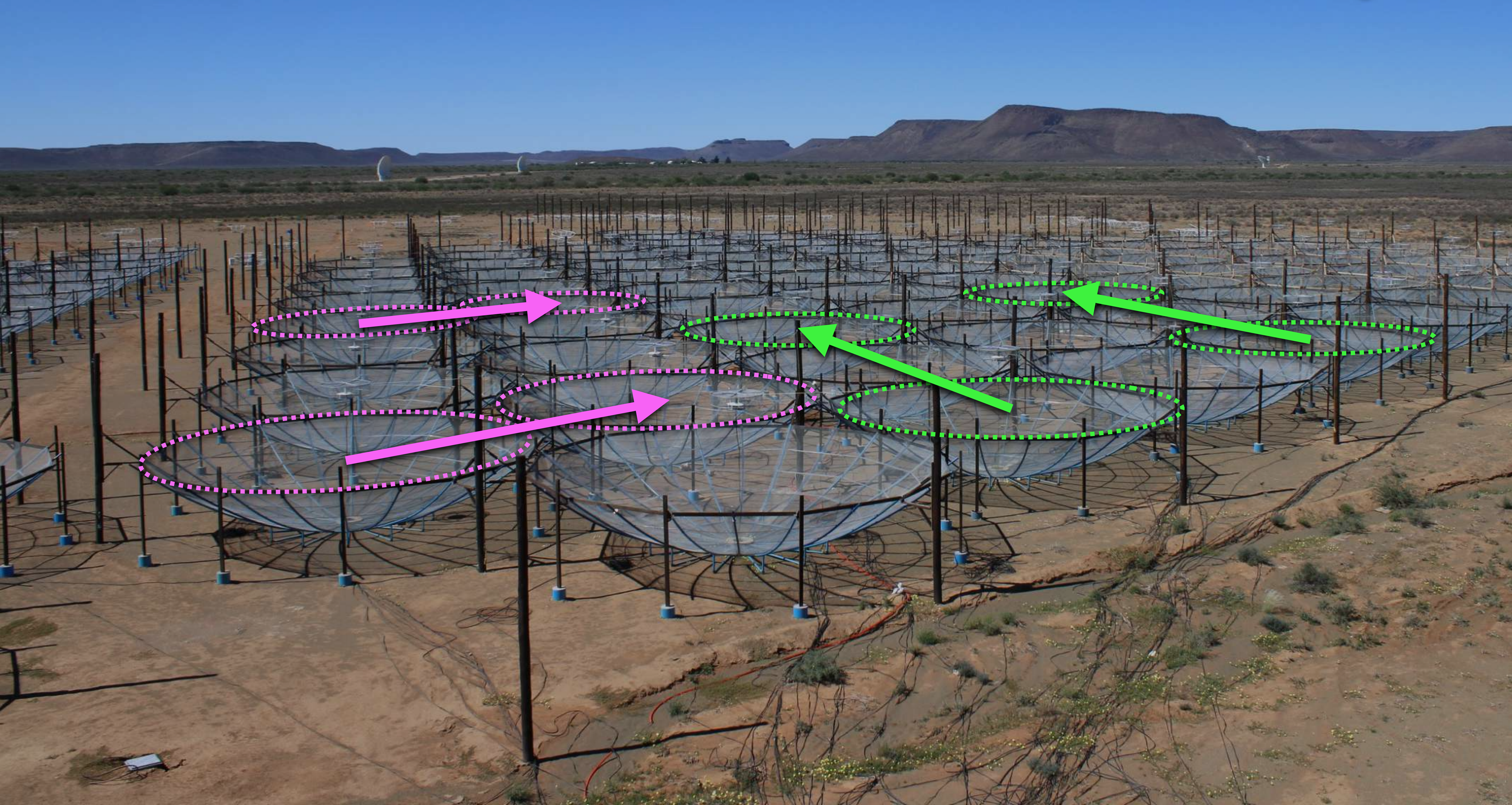
Tegmark & Zaldarriaga (2009, 2010)

An FFT Telescope needs to be…

- Co-planar.
- Made up of identical antenna elements with identical beams.
  - *Otherwise the wedge will be contaminated (Orosz 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.

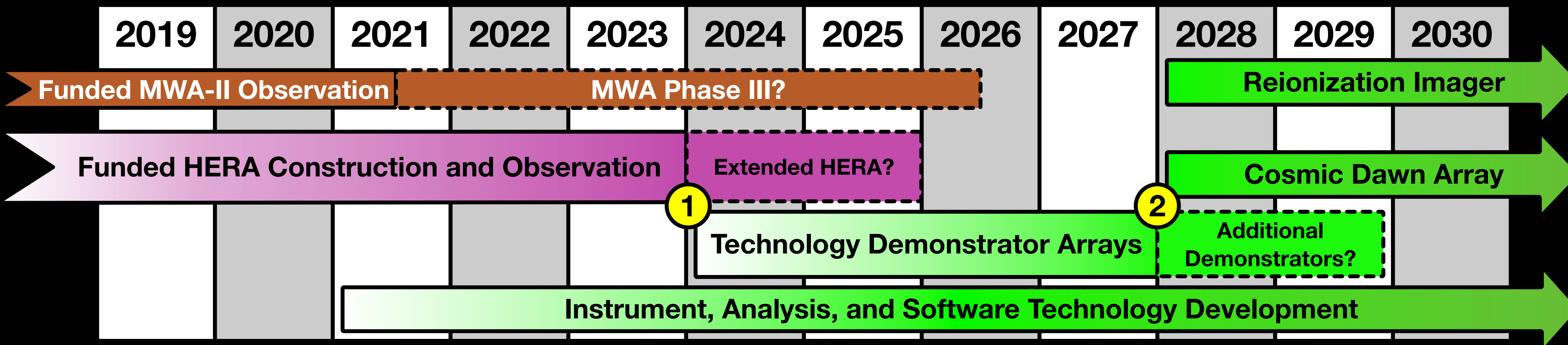
Tegmark & Zaldarriaga (2009, 2010)

But recall, regular arrays of identical elements can be calibrated redundantly!



A Roadmap for Astrophysics and Cosmology with High-Redshift 21 cm Intensity Mapping

The Hydrogen Epoch of Reionization Array (HERA) Collaboration:
James E. Aguirre,[1] Adam P. Beardsley,[2] Gianni Bernardi,[3] Judd D. Bowman,[2] Philip Bull,[4,5] Chris L. Carilli,[6] Wei-Ming Dai,[7] David R. DeBoer,[8] Joshua S. Dillon,[8,*] Aaron Ewall-Wice,[9] Steve R. Furlanetto,[10] Bharat K. Gehlot,[2] Deepthi Gorthi,[8] Bradley Greig,[11,12] Bryna J. Hazelton,[13,14] Jacqueline N. Hewitt,[15] Daniel C. Jacobs,[2] Nicholas S. Kern,[8] Matthew Kolopanis,[2] Paul La Plante,[1] Adrian Liu,[16] Yin-Zhe Ma,[7] Mthokozisi Mdlalose,[7] Steven G. Murray,[2] Aaron R. Parsons,[8,†] Jonathan C. Pober,[17] Peter H. Sims,[17] Nithyanandan Thyagarajan,[6] and Jordan Mirocha[16]



Submitted to Astro2020

In Summary

In Summary

- 21 cm cosmology promises to become the premier probe of our majority of the volume of our universe.

In Summary

- 21 cm cosmology promises to become the premier probe of our majority of the volume of our universe.
- HERA is a purpose-build 21 cm experiment designed for robust calibration and systematics control, now building out to 350 14-m dishes and funded to observe through 2023.

In Summary

- 21 cm cosmology promises to become the premier probe of our majority of the volume of our universe.
- HERA is a purpose-build 21 cm experiment designed for robust calibration and systematics control, now building out to 350 14-m dishes and funded to observe through 2023.
- Our HERA power spectra will follow-up on EDGES and precisely constrain the epoch of reionization.

In Summary

- 21 cm cosmology promises to become the premier probe of our majority of the volume of our universe.
- HERA is a purpose-build 21 cm experiment designed for robust calibration and systematics control, now building out to 350 14-m dishes and funded to observe through 2023.
- Our HERA power spectra will follow-up on EDGES and precisely constrain the epoch of reionization.
- One day, an FFTT will draw on the instrumental and analysis legacy of HERA to fulfill the promise of 21 cm cosmology.