Precision Calibration for HERA and 21cm Cosmology

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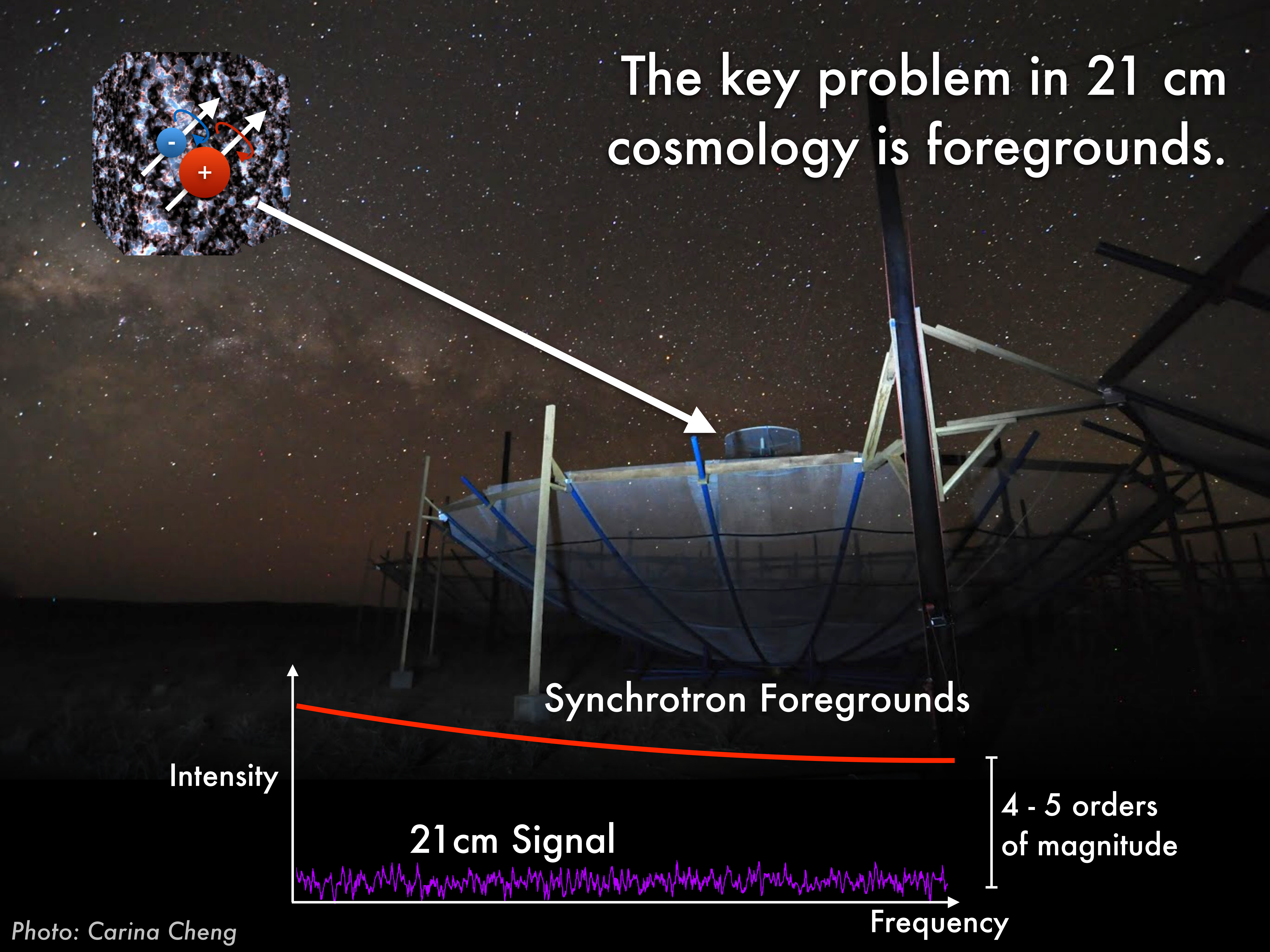
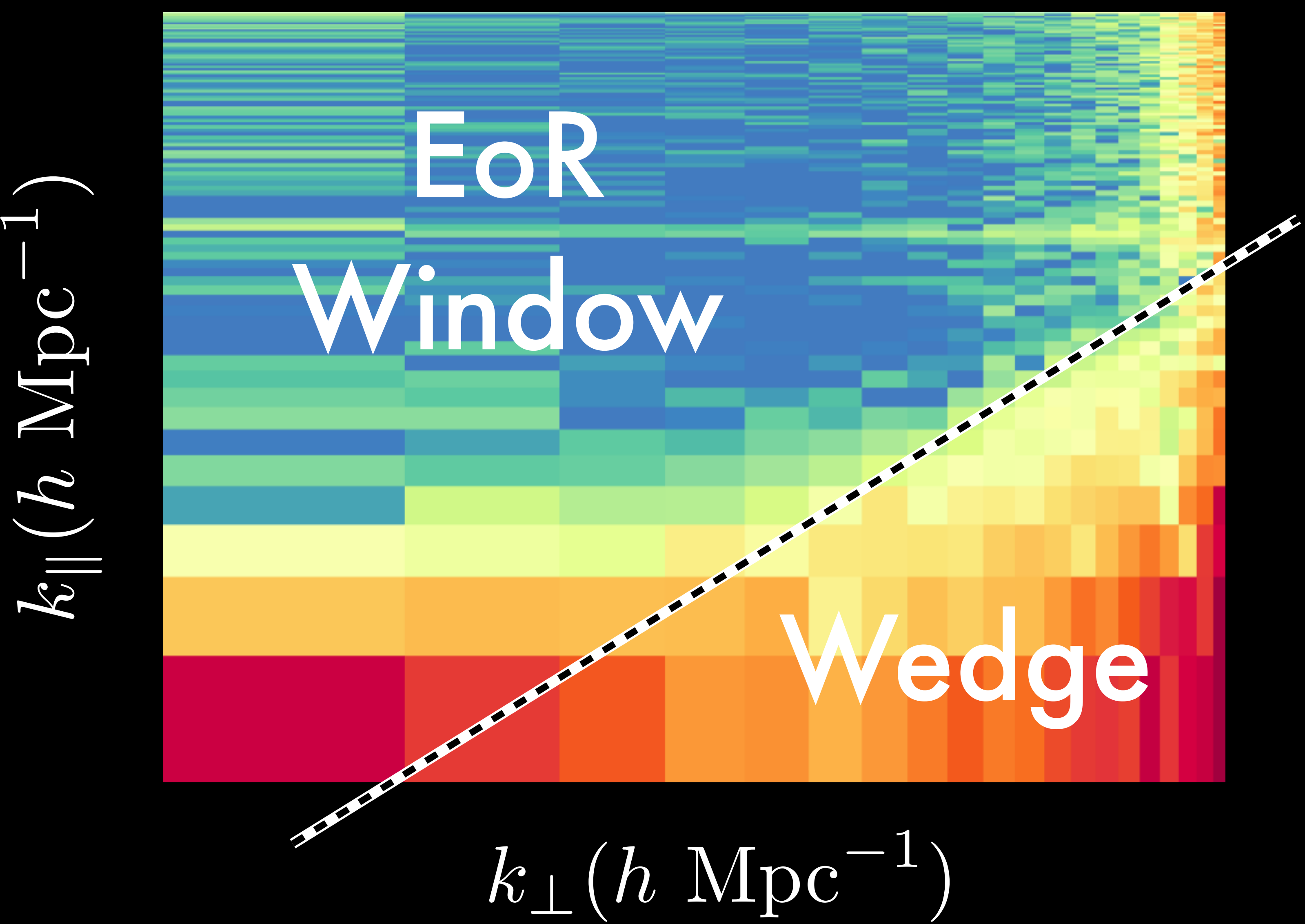

The key problem in 21 cm cosmology is foregrounds.
-
+
Synchrotron Foregrounds
Intensity
4 - 5 orders of magnitude
21cm Signal
Frequency
Photo: Carina Cheng

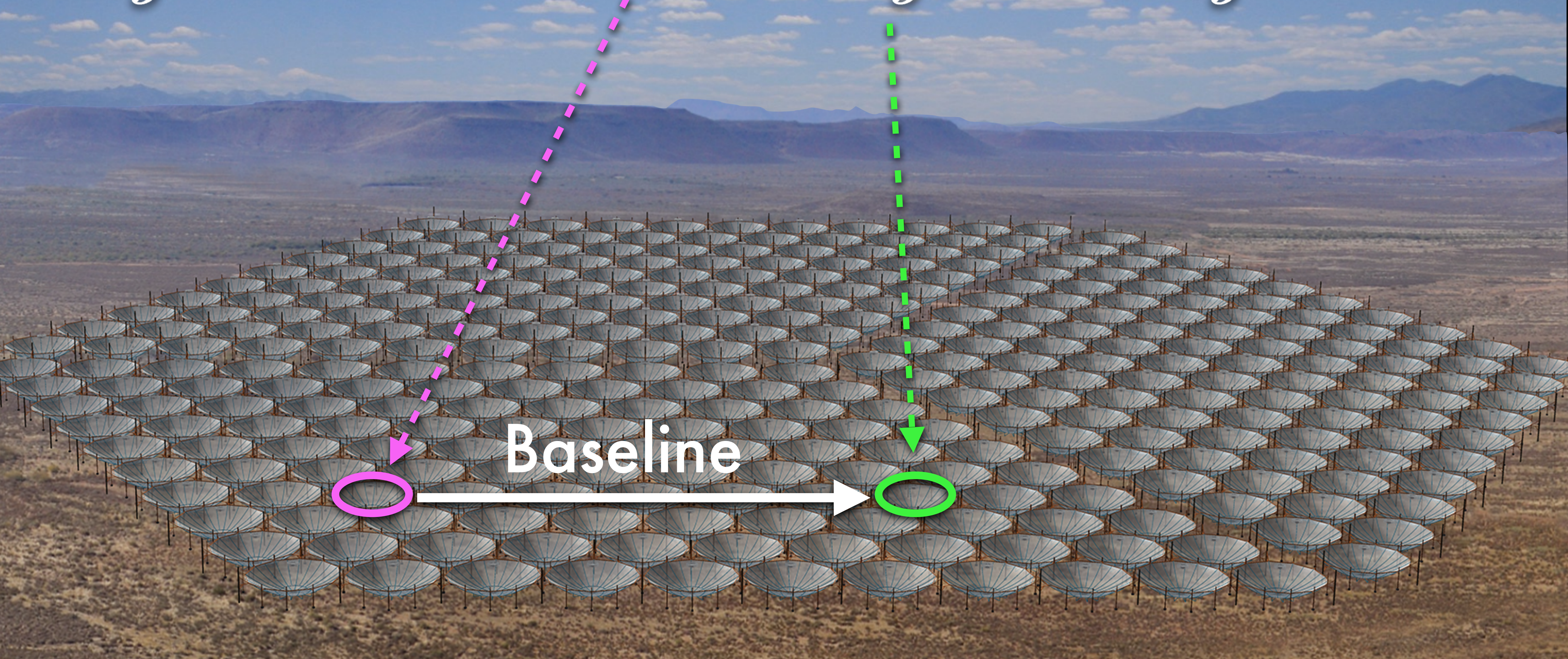
Instrumental chromaticity turns smooth foregrounds into the *wedge*, leaving the *EoR window* in the cylindrical power spectrum…



…but only if the instrument response is spectrally smooth.

Calibration is key to spectral smoothness.

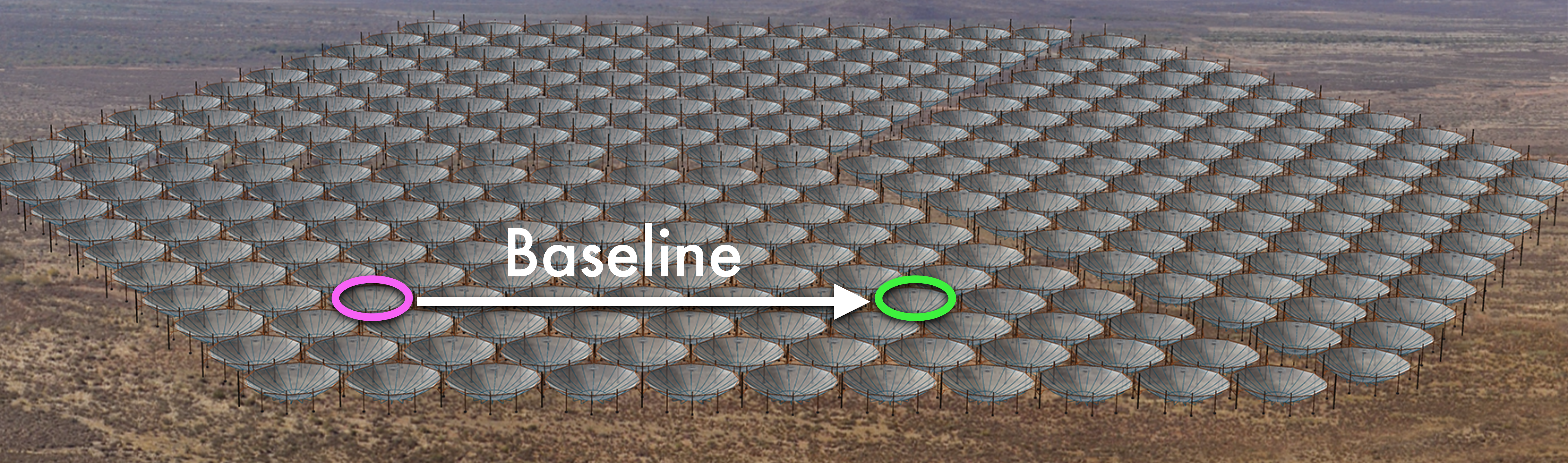
$$V_{ij}^{\mathrm{obs}}(\nu) = g_i(\nu) g_j^*(\nu) V_{ij}^{\mathrm{true}}(\nu)$$



Calibration is key to spectral smoothness.

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

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

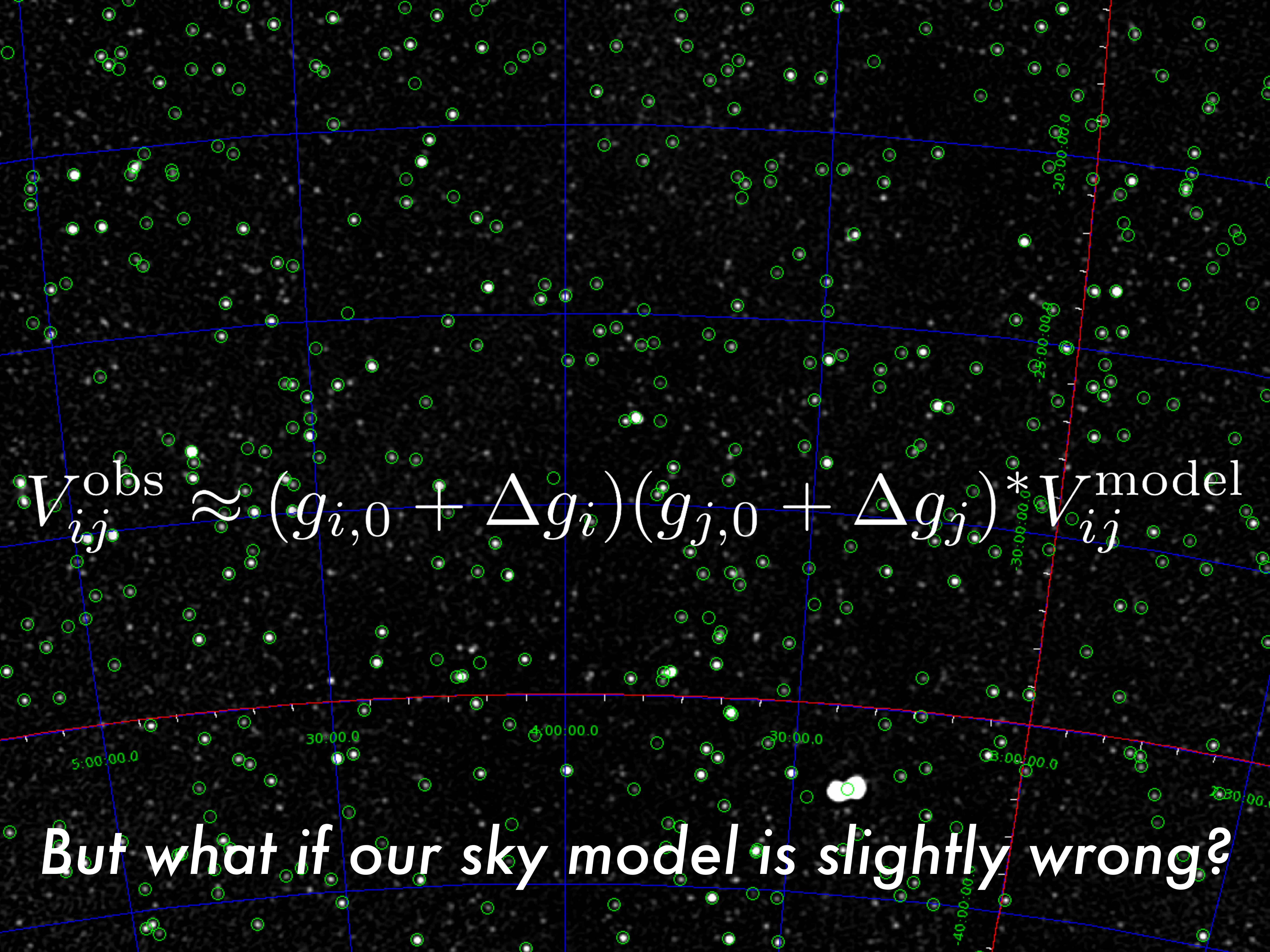


The Self-Cal Loop

Image, find sources,
build model.

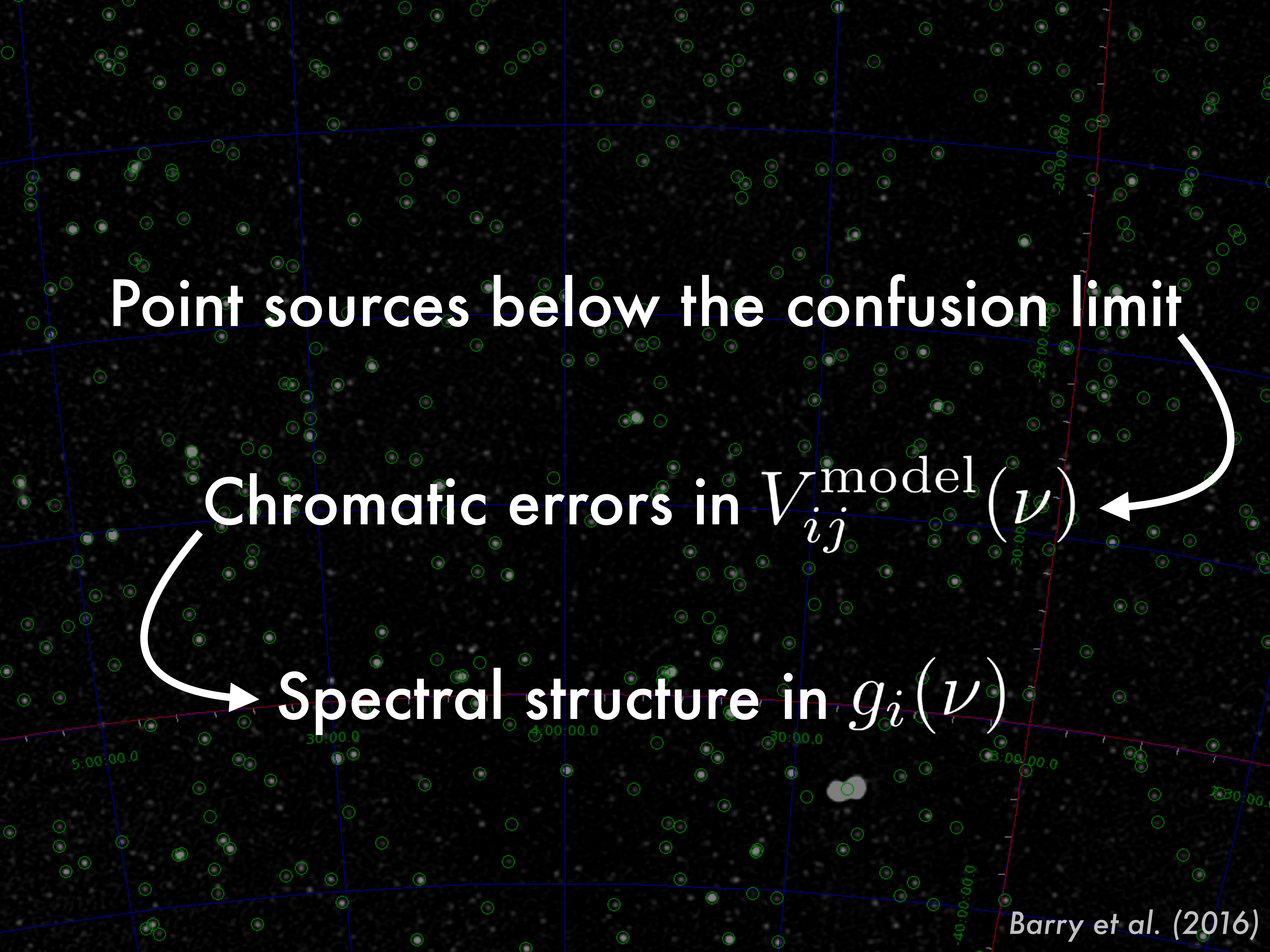
$$V_{ij}^{\mathrm{obs}} \approx (g_{i,0} + \Delta g_i)(g_{j,0} + \Delta g_j)^* V_{ij}^{\mathrm{model}}$$

Linearize and
solve for gains.



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

But what if our sky model is slightly wrong?



Point sources below the confusion limit

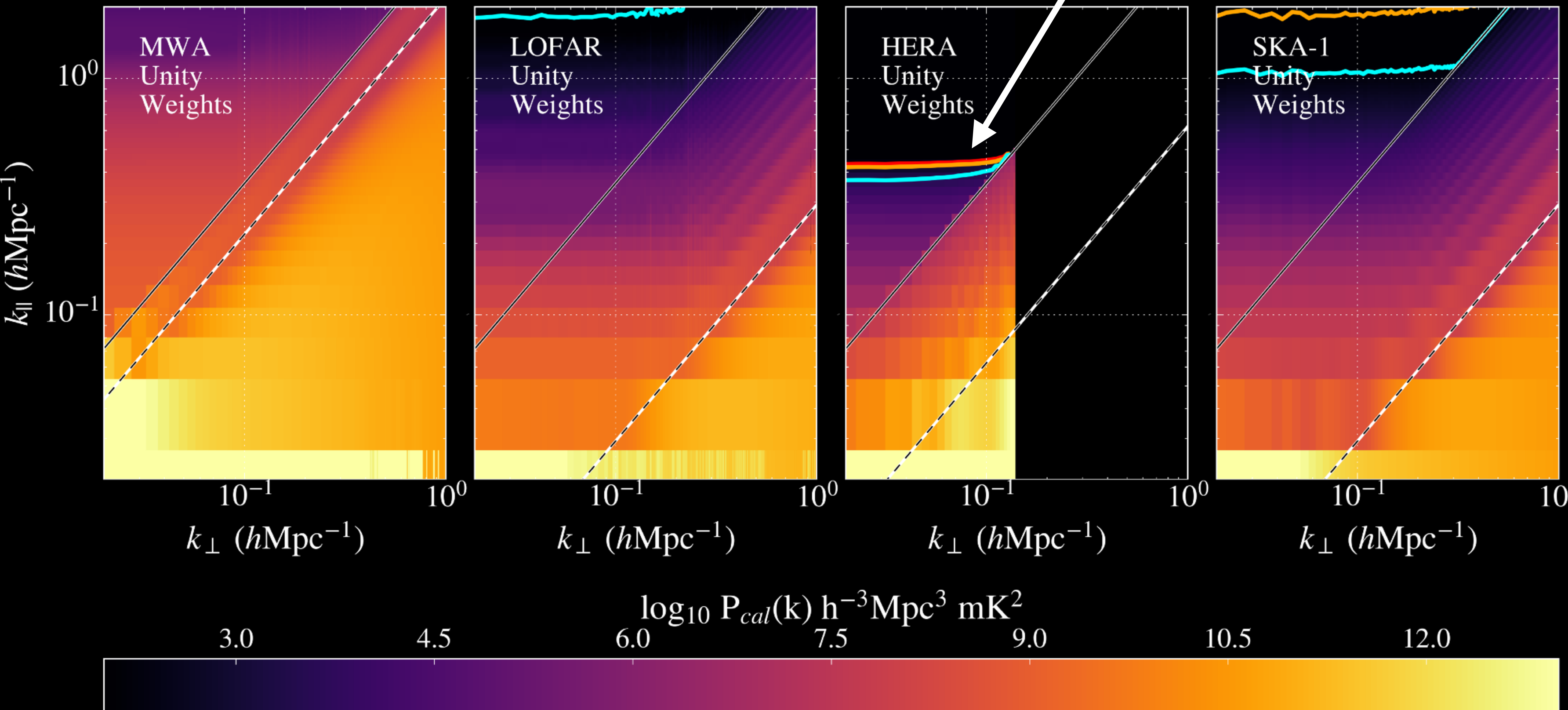
Chromatic errors in $V_{ij}^{\mathrm{model}}(\nu)$

Spectral structure in $g_i(\nu)$

Barry et al. (2016)

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

21 cm Signal = {1,5,10} x Modeling Bias



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

Our proposal: when linearizing and solving for gains, weight each equation in the system by

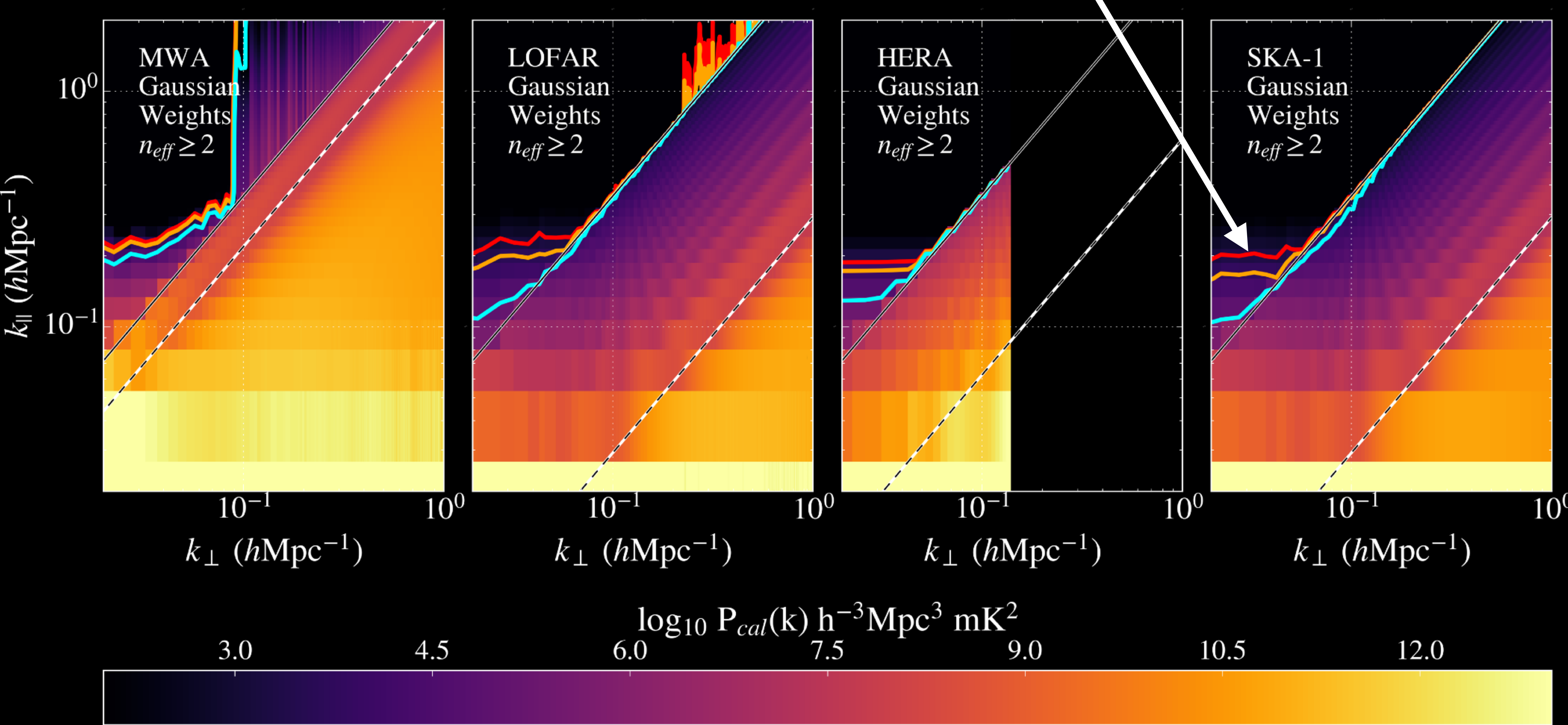
$$W_{ij} \propto e^{-b_{ij}^2/2\sigma_b^2}$$

to suppress gain chromatic leakage from long to short baselines.

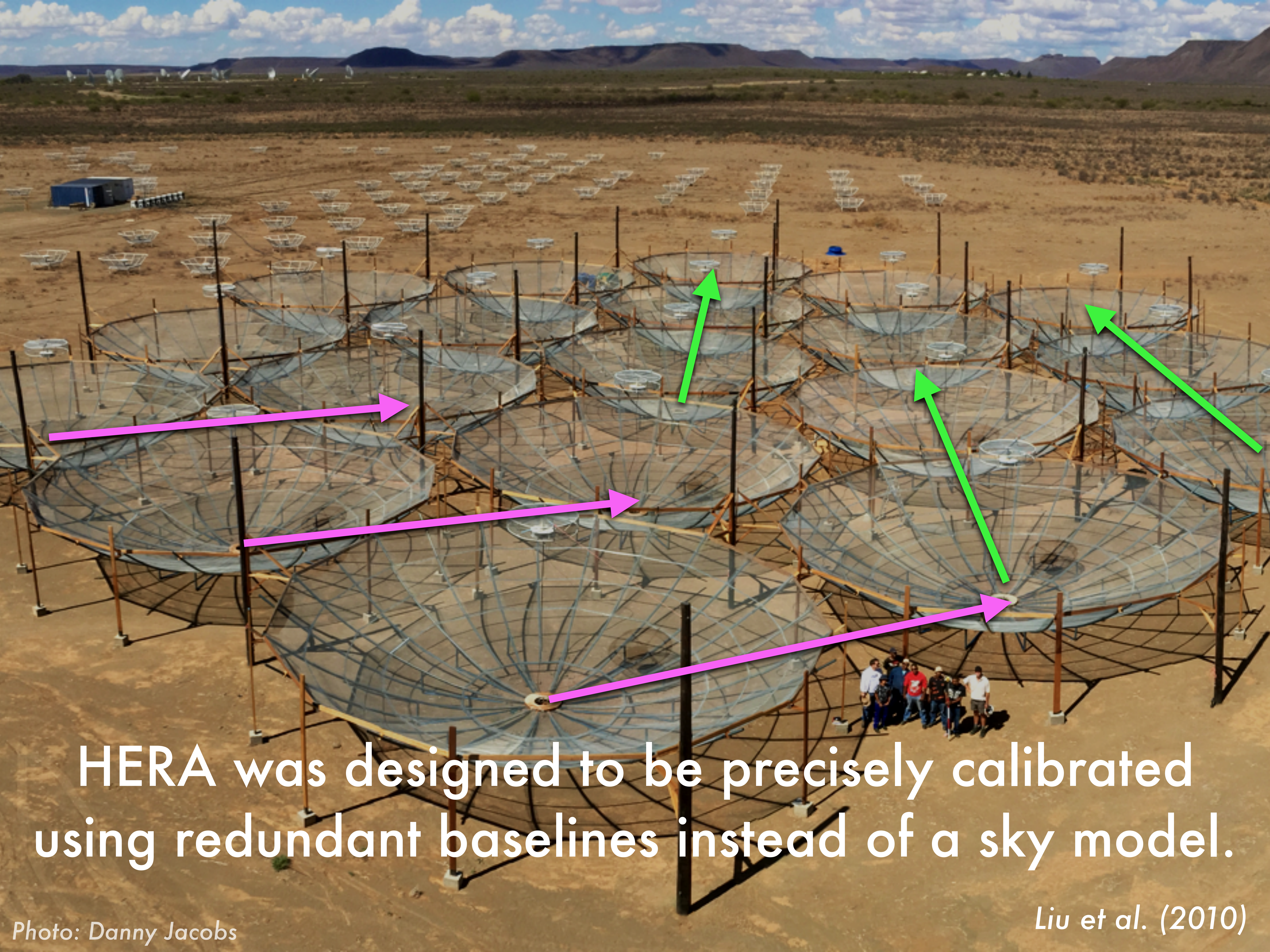
Ewall-Wice, Dillon, Liu, Hewitt (2016)

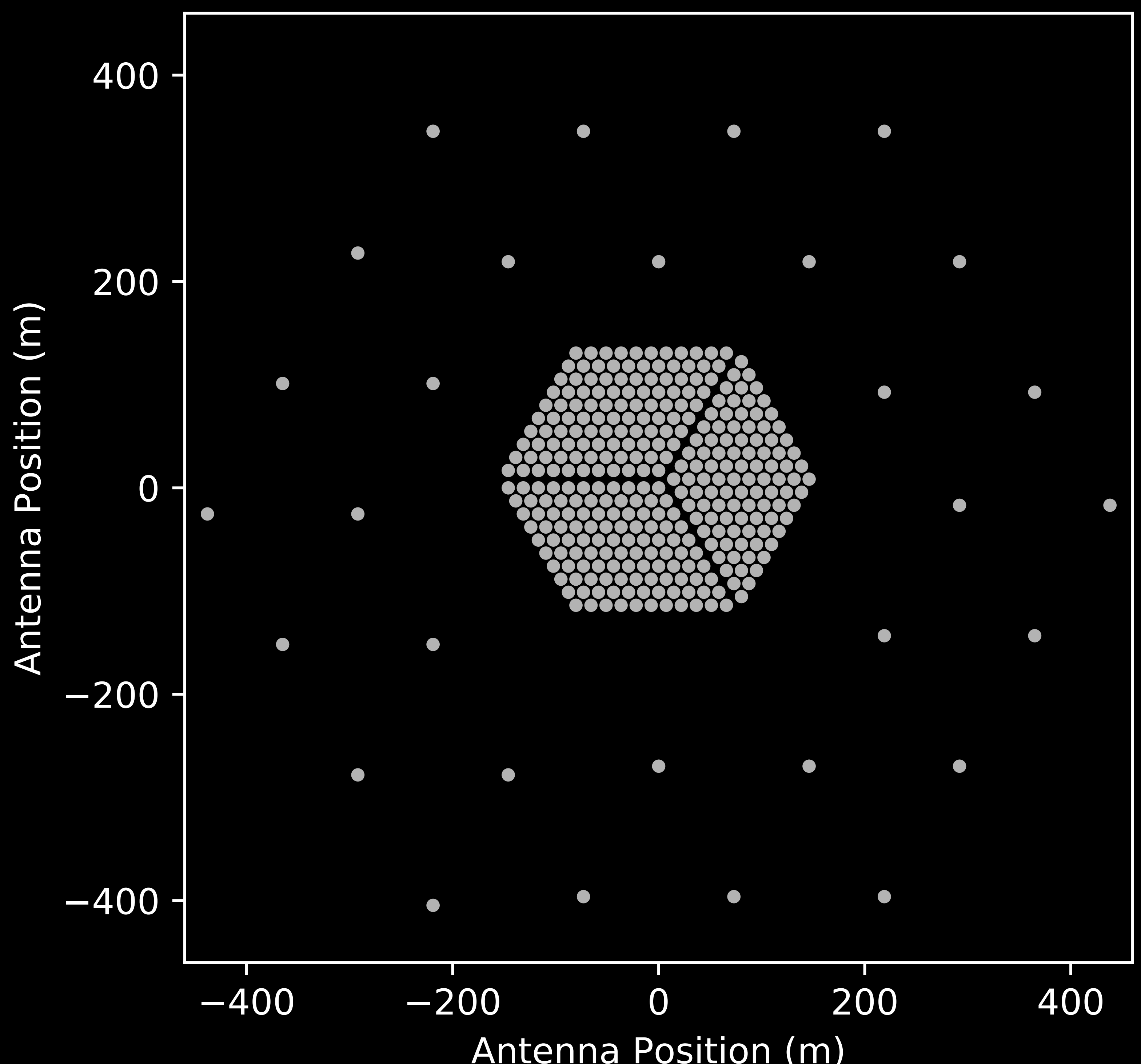
Down-weighting long baselines restores the EoR window.

21 cm Signal = {1,5,10} x Modeling Bias



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


HERA was designed to be precisely calibrated
using redundant baselines instead of a sky model.
Photo: Danny Jacobs
Liu et al. (2010)



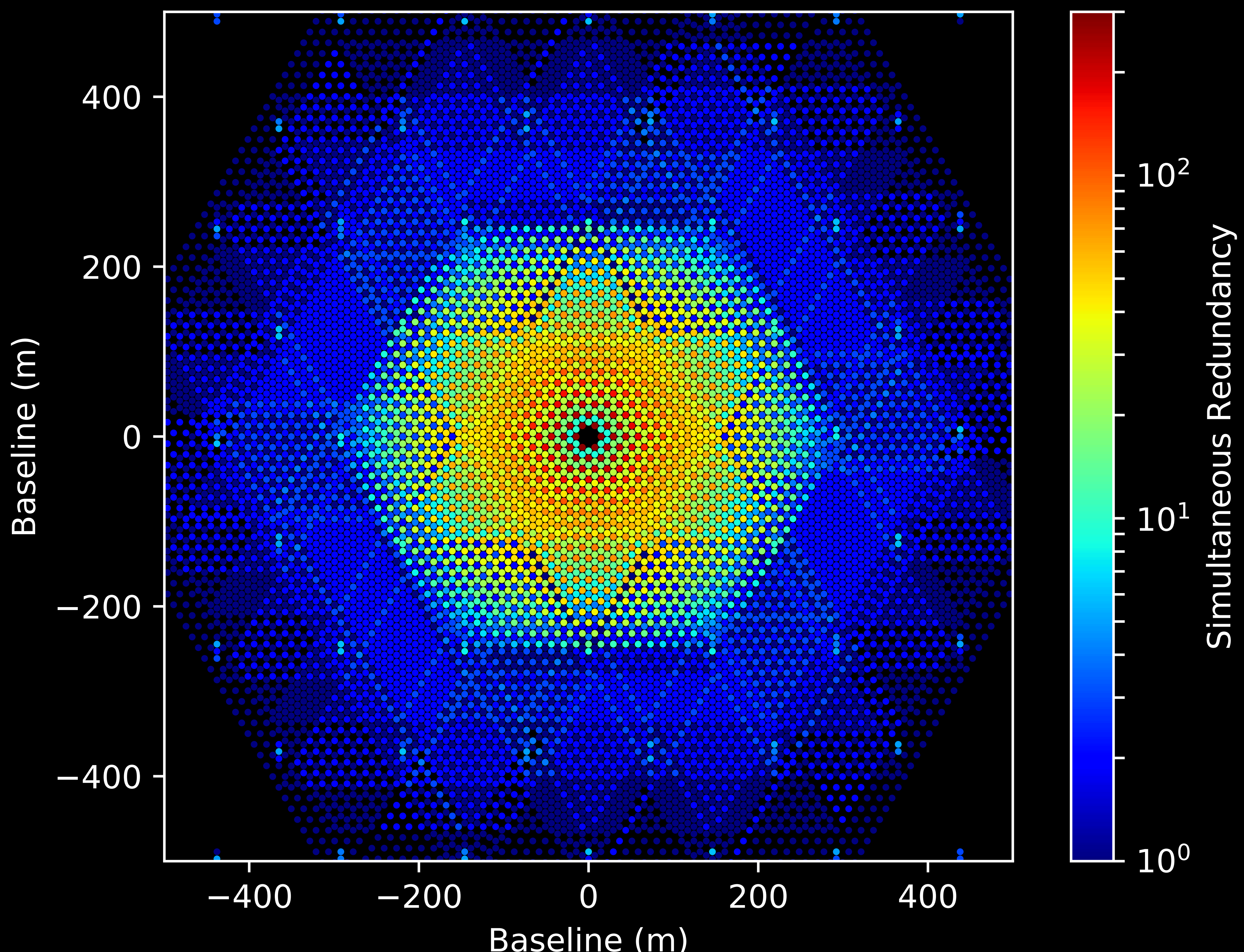
HERA's split configuration is designed for :

- Huge sensitivity on short baselines
- Dense sampling of the uv-plane
- Redundant calibratability
- FFT correlatability

Unique Baselines:

- *Solid Hexagon:* 630
- *Split-Core:* 1501
- + Outriggers: 6610

Dillon & Parsons (2016)

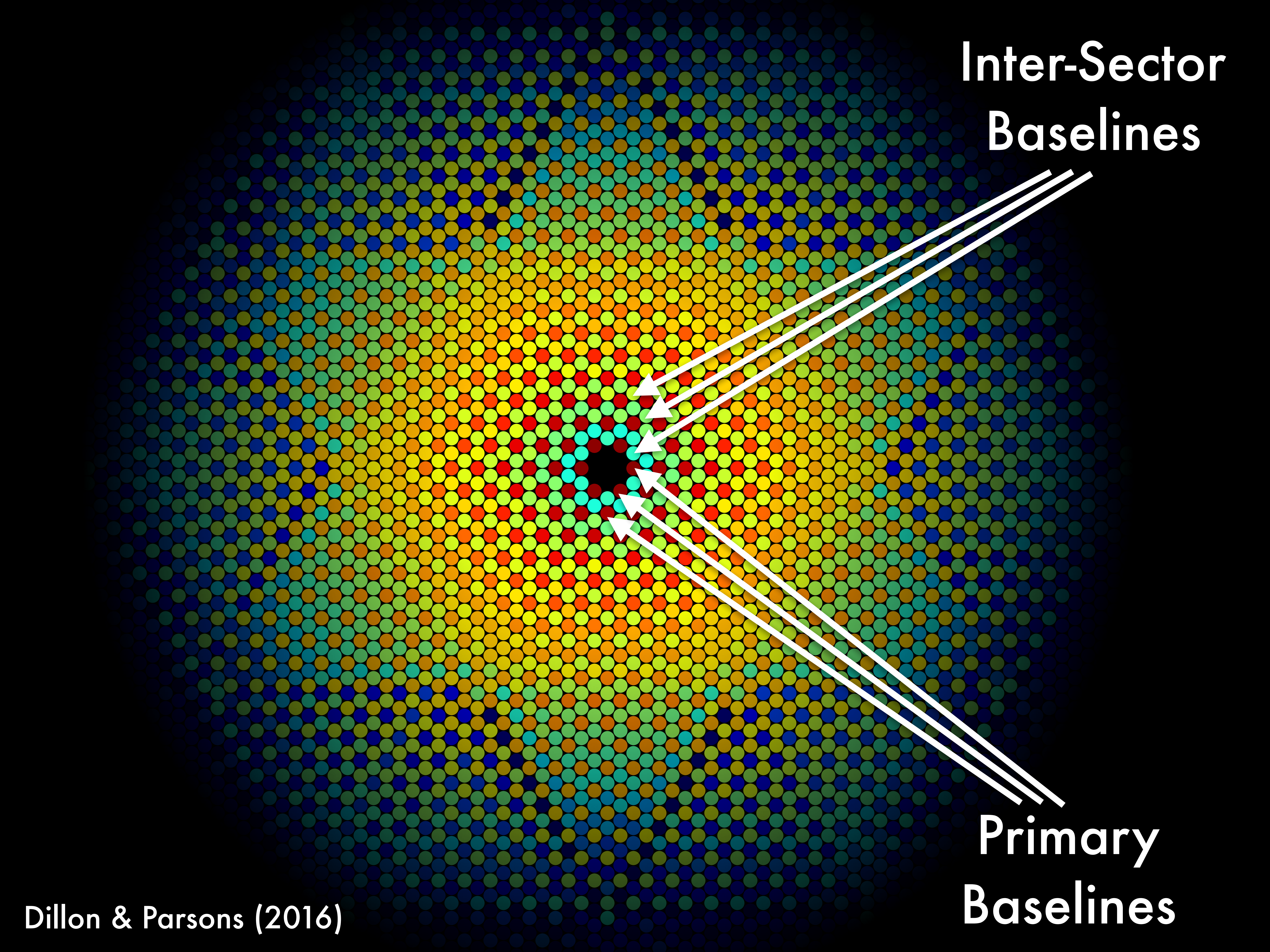


Solid Hexagon: 630

Split-Core: 1501

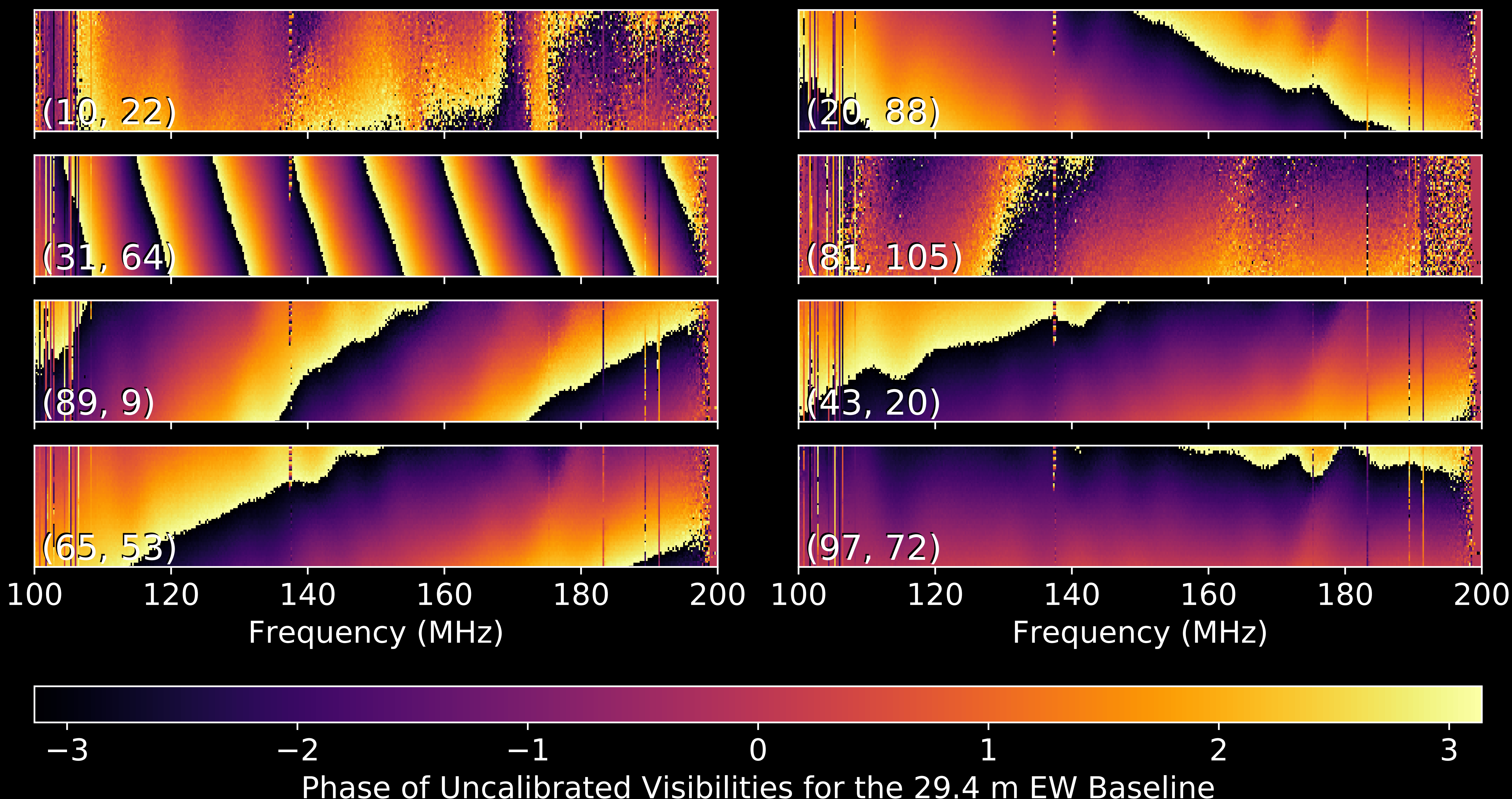
+ Outriggers: 6610

Dillon & Parsons (2016)

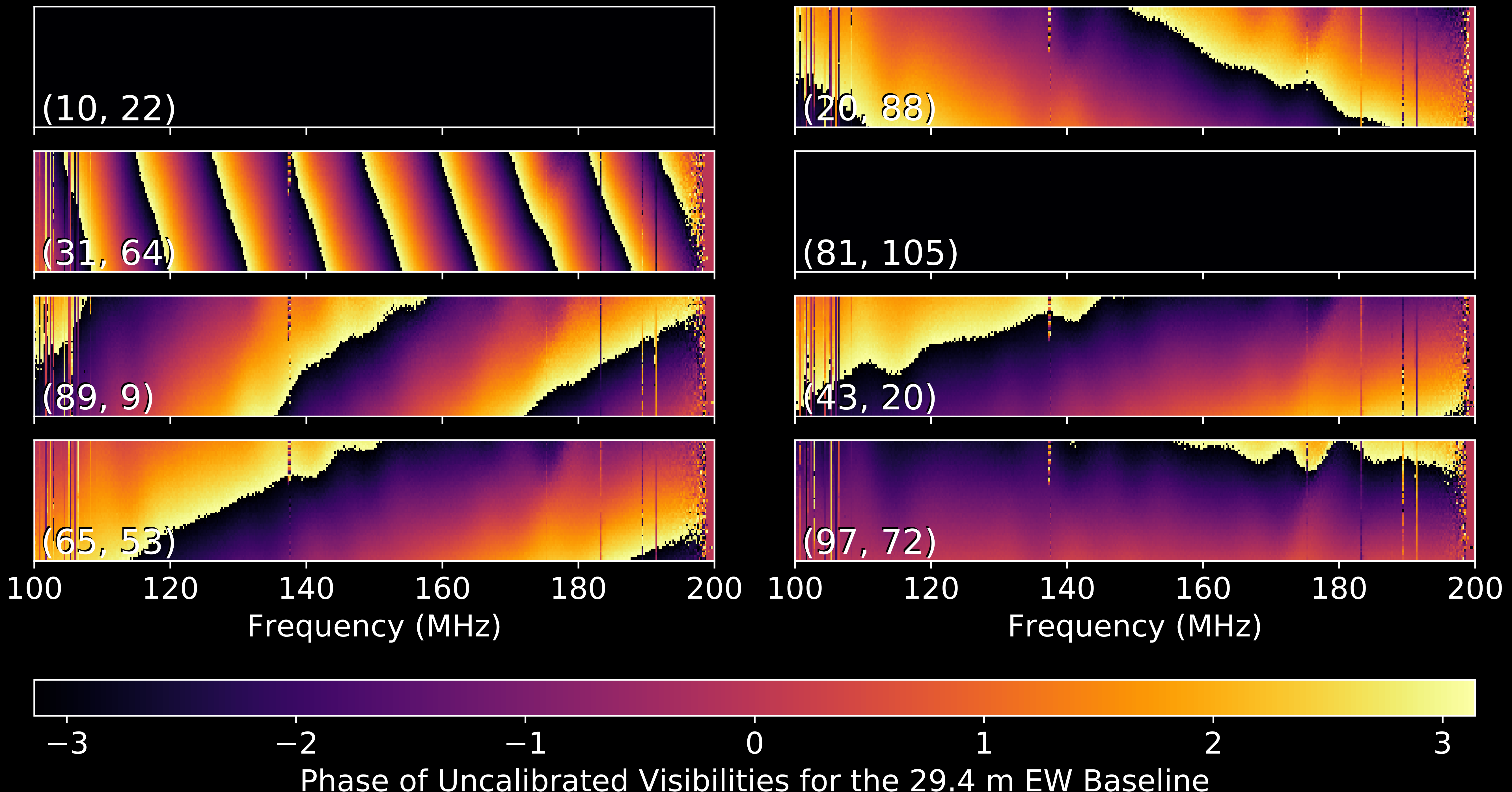

Inter-Sector
Baselines
Primary
Baselines
Dillon & Parsons (2016)

Redundant calibration of first seasons HERA data is going well.

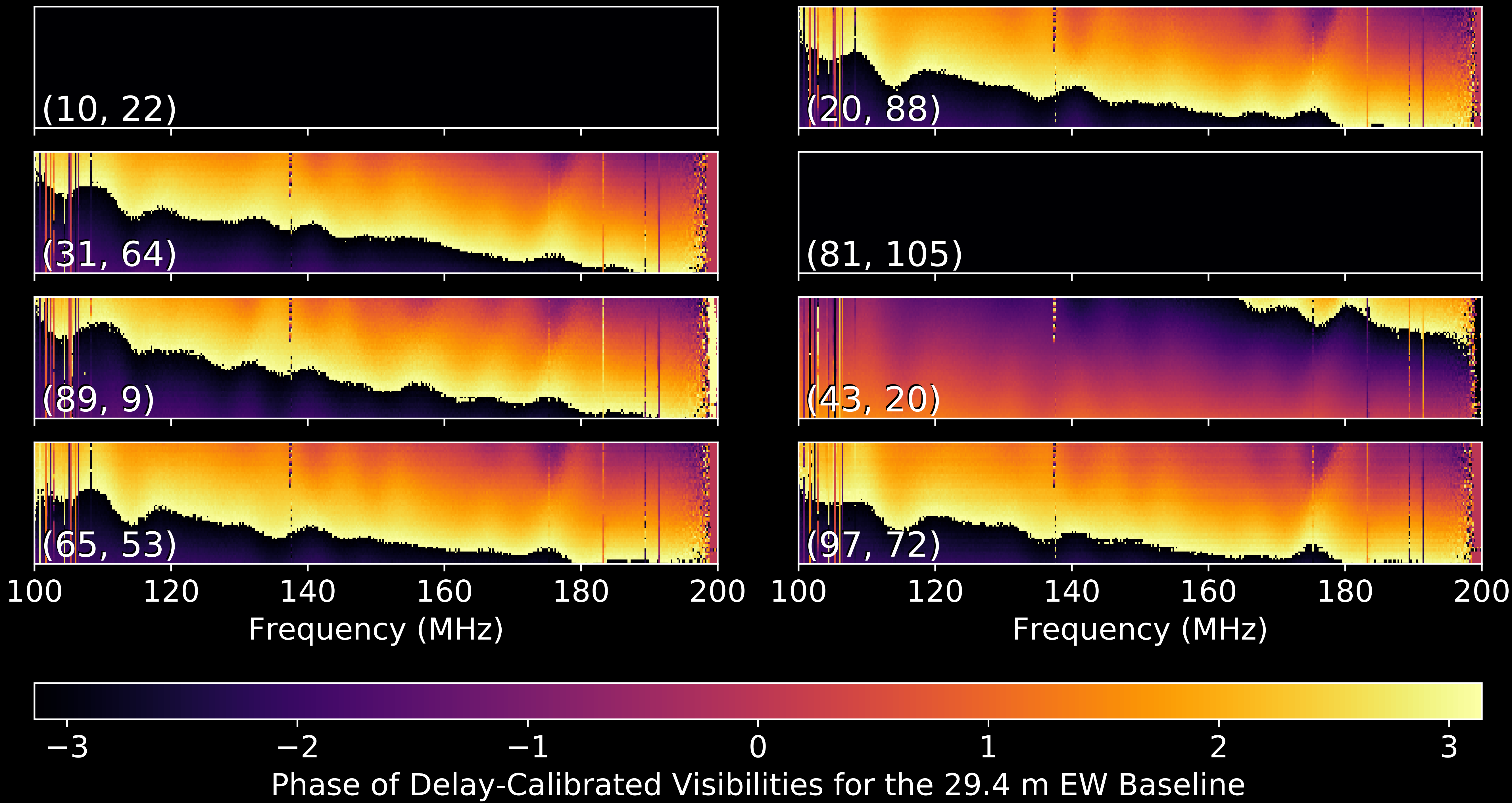
Raw HERA-19 data for a single “redundant” baseline.



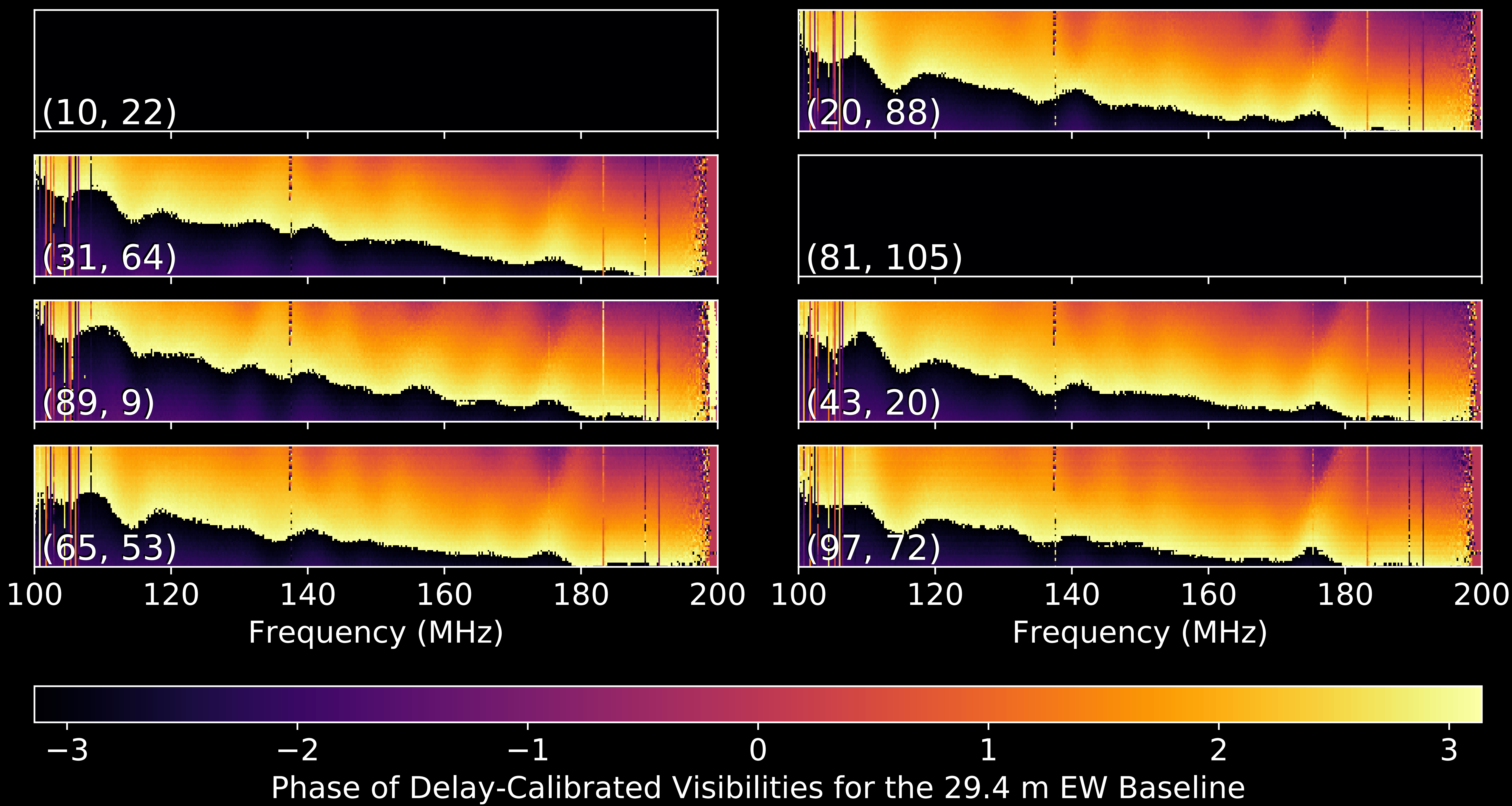
First we flag bad antennas.



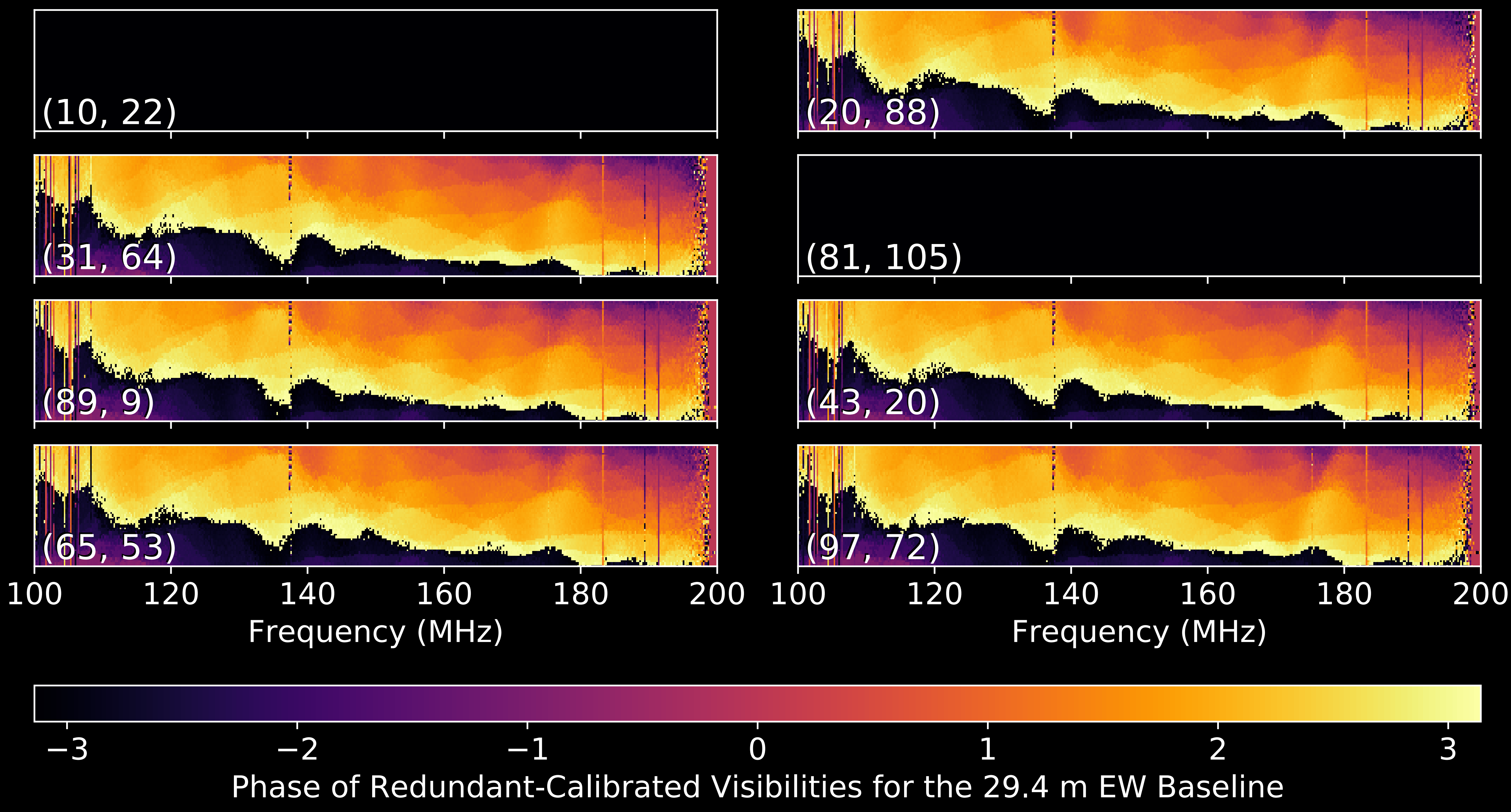
Then we calibrate out cable delays.



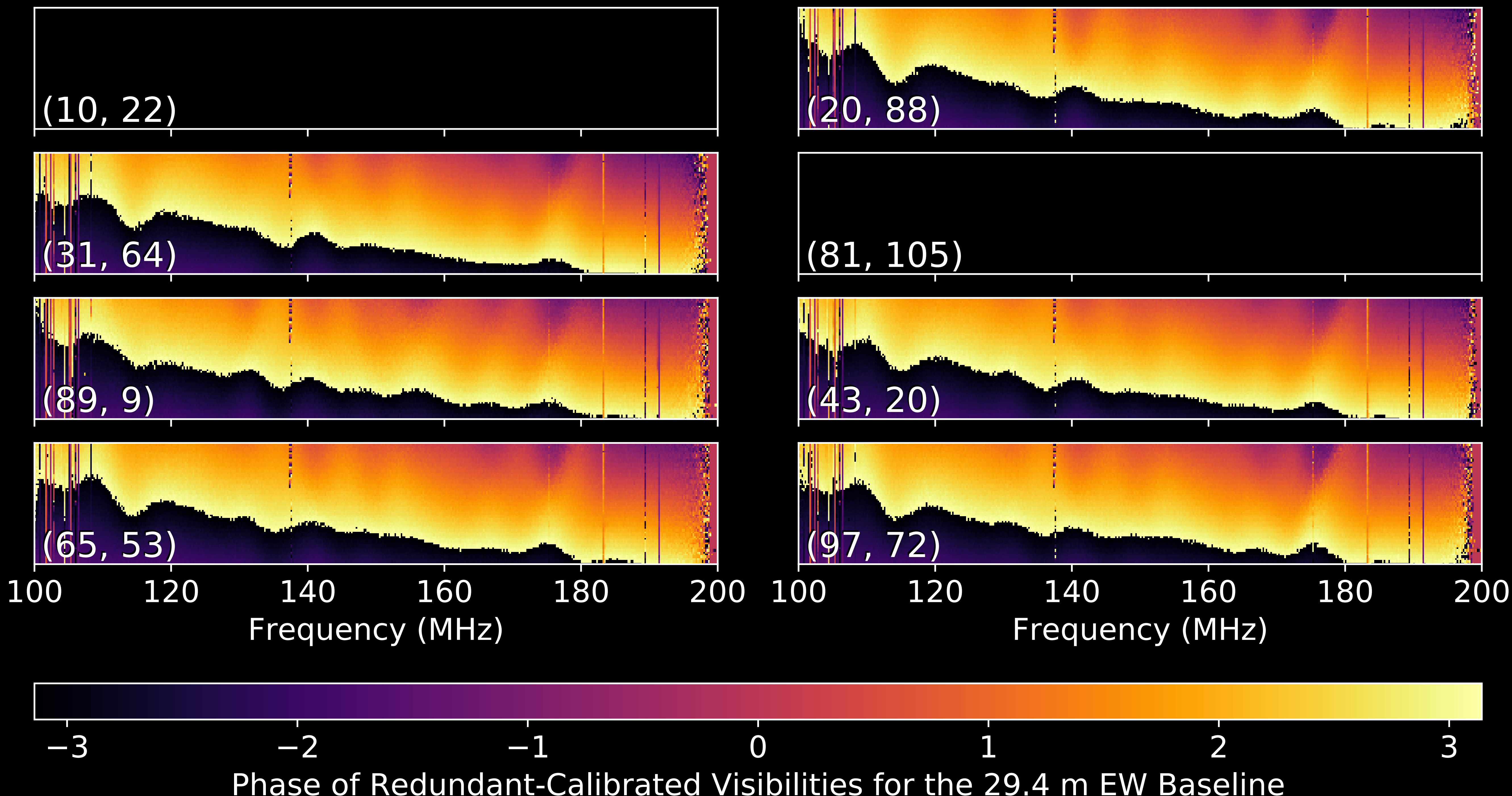
And fix the 180° rotated feed.



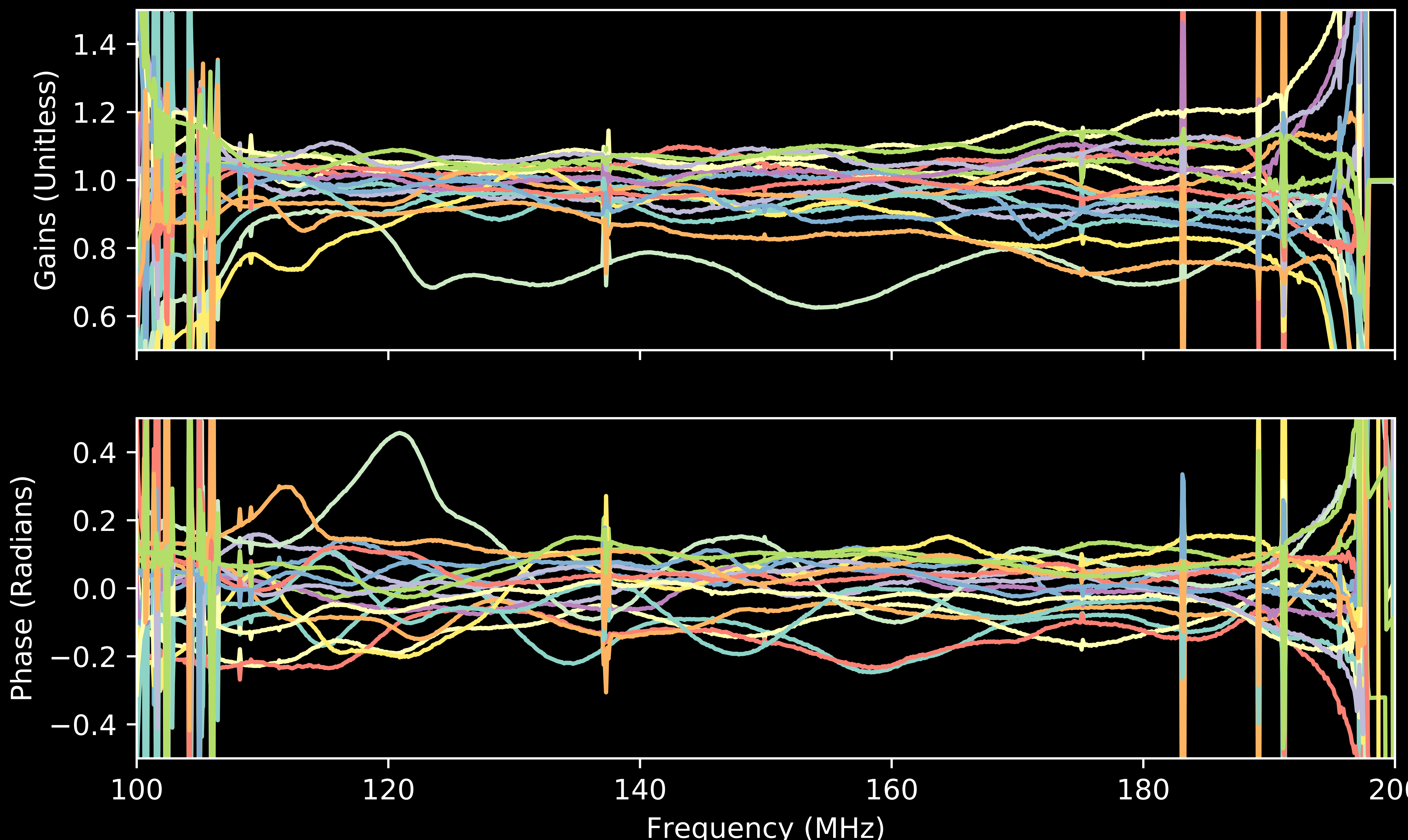
We solve for gains and unique visibilities simultaneously.



And then project out degeneracies to produce highly redundant visibilities.



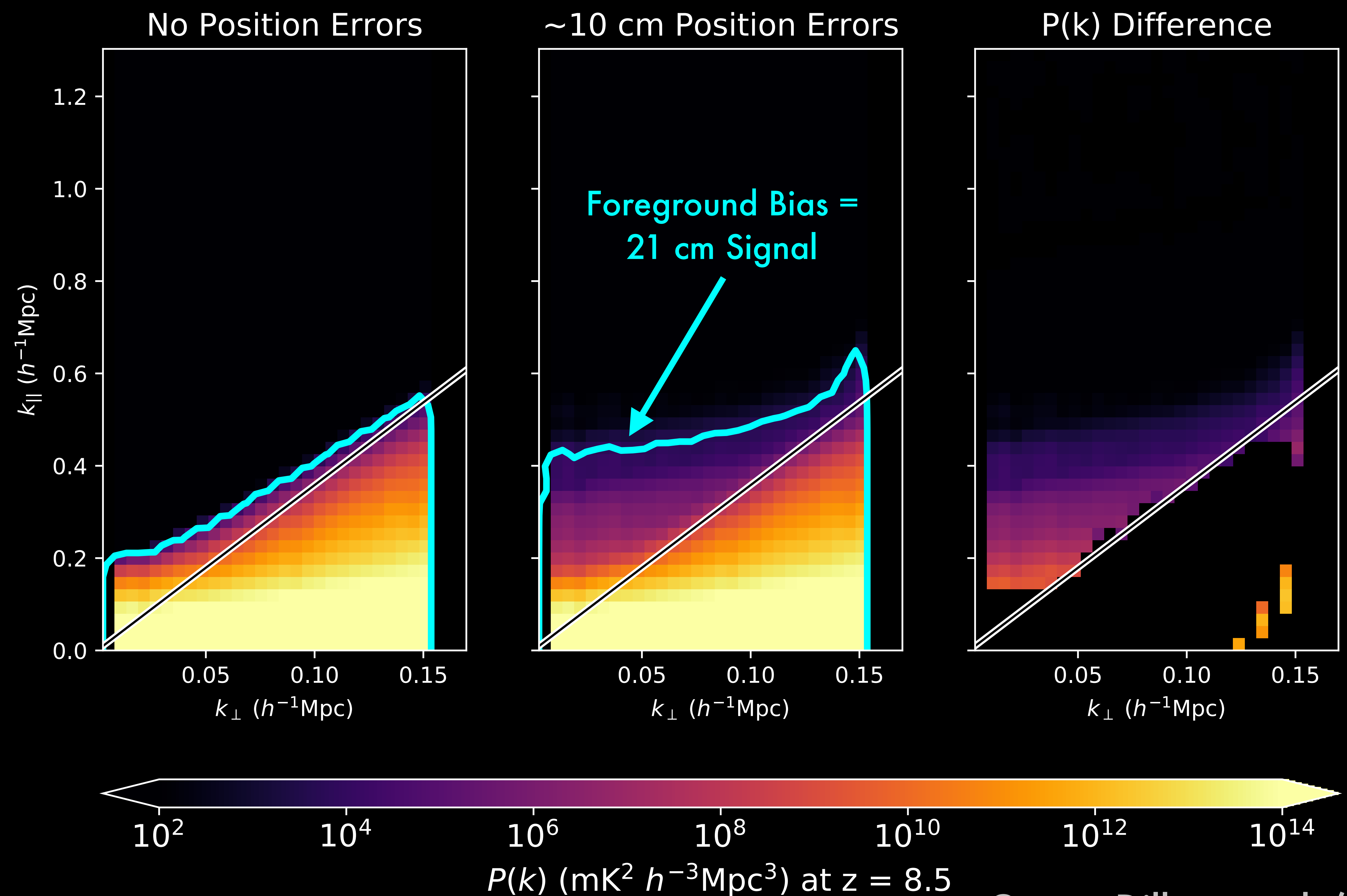
Redundant calibration is finding and fixing structure in the antenna gains.



But does redundant calibration work when the array is not quite redundant?

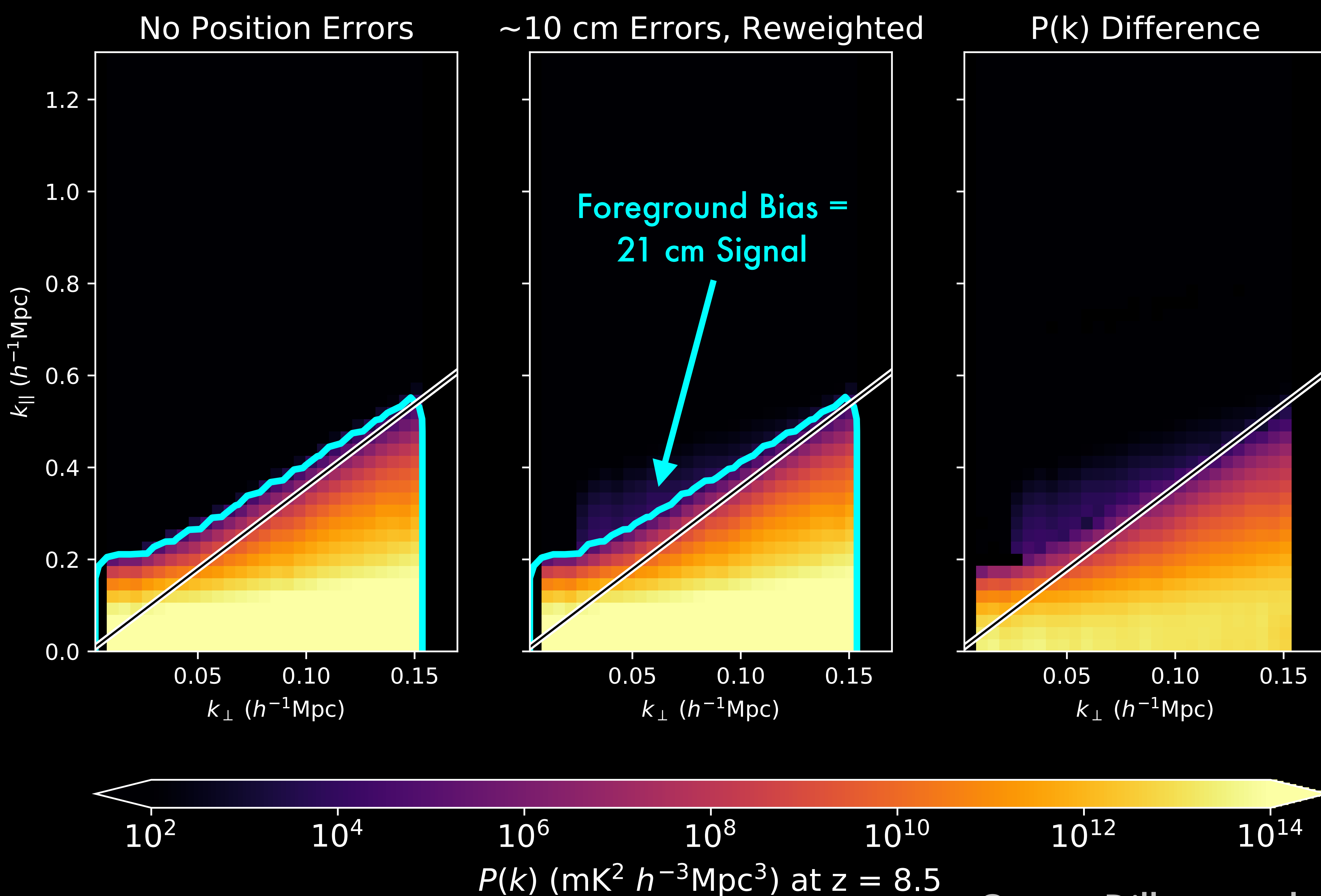

I can assure you that
we expect position errors.

Just like modeling errors in selfcal, position errors in redundant calibration mix long and short baselines.



Orosz, Dillon, et al. (in prep)

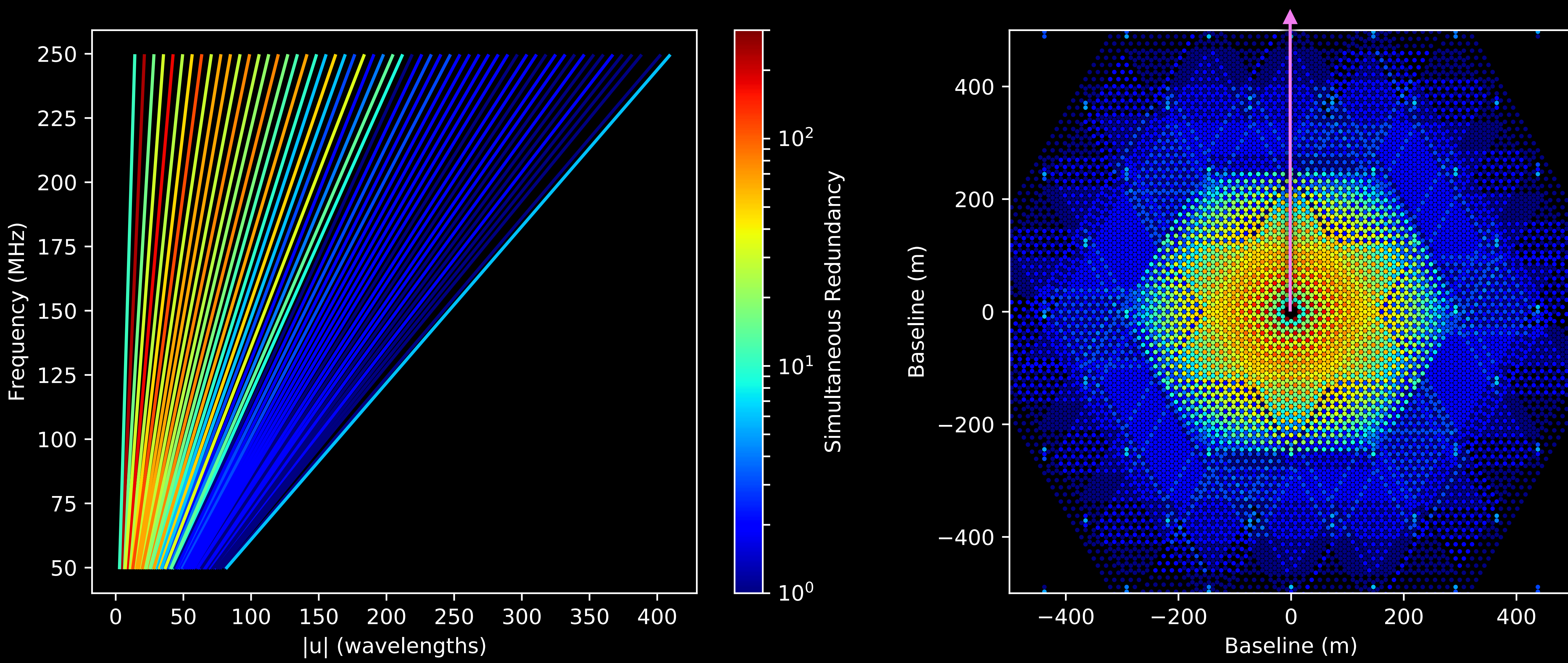
And again, up-weighting short baselines can restore the window-wedge separation.



Orosz, Dillon, et al. (in prep)

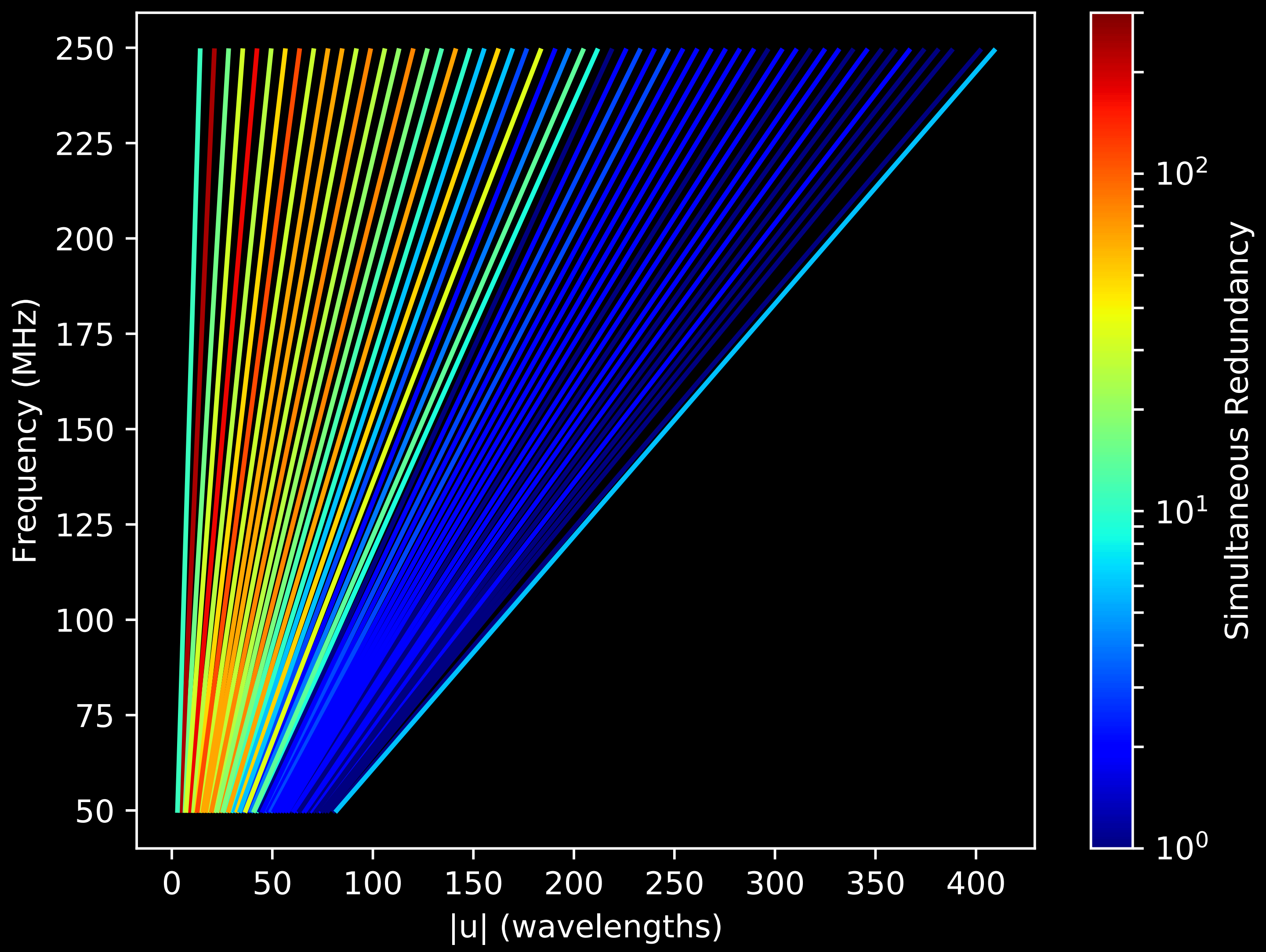
Redundant calibration isn’t the end of the story: it can’t solve for an overall bandpass.

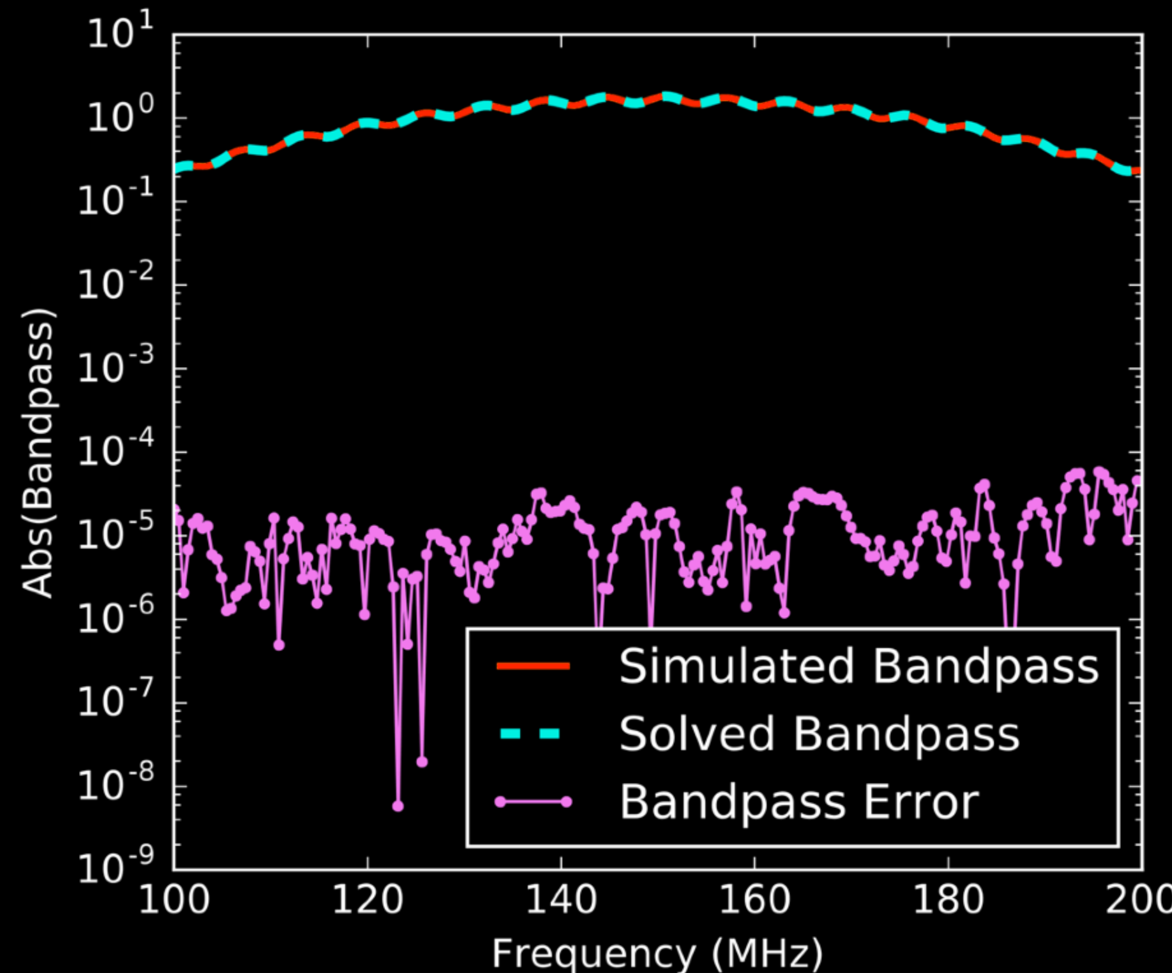
But HERA's design gives massive "redundancy" in u, which can tie frequencies together...



Dillon, et al. (in prep)

...and perhaps let us calibrate our bandpass without reference to a sky model.



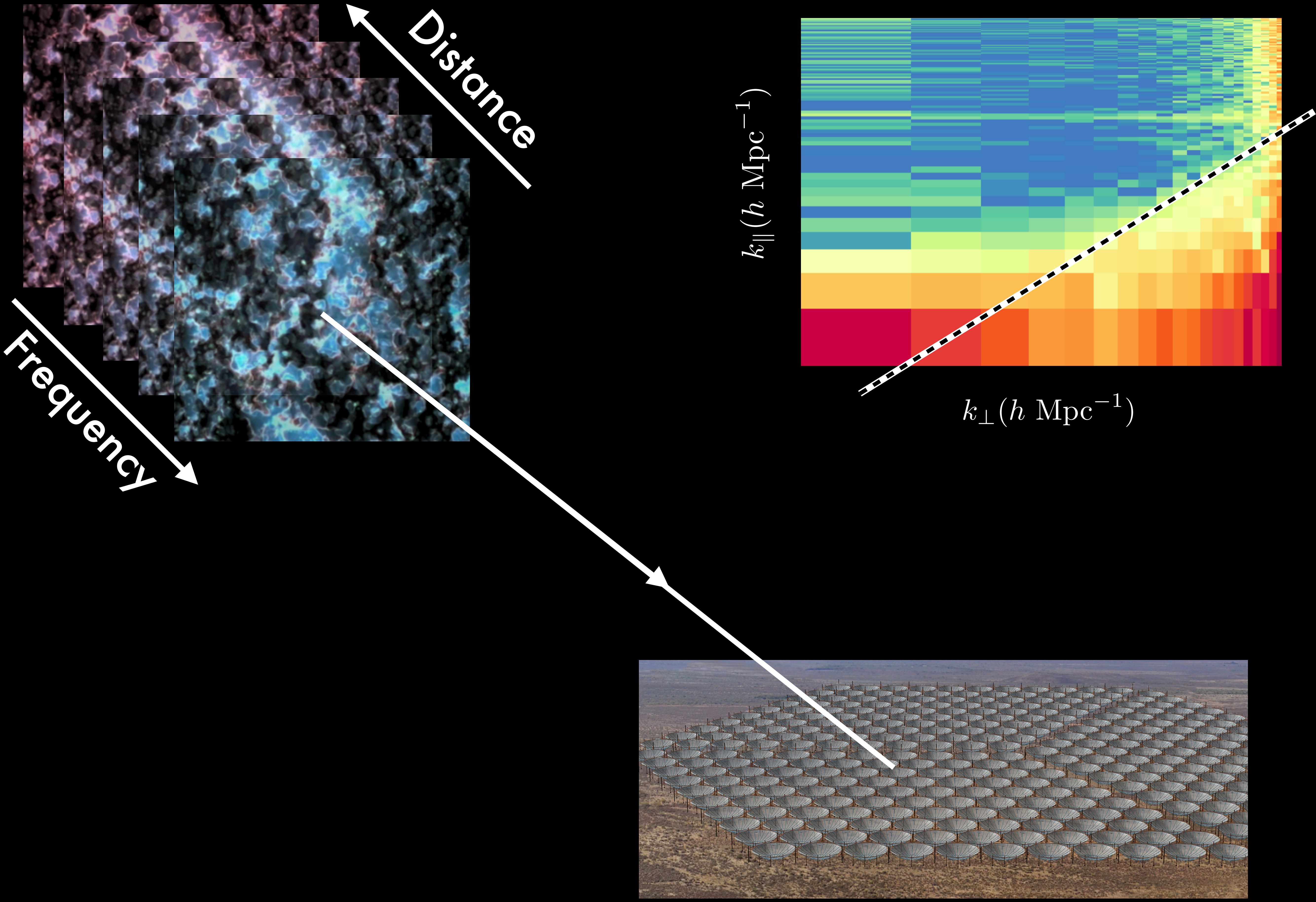


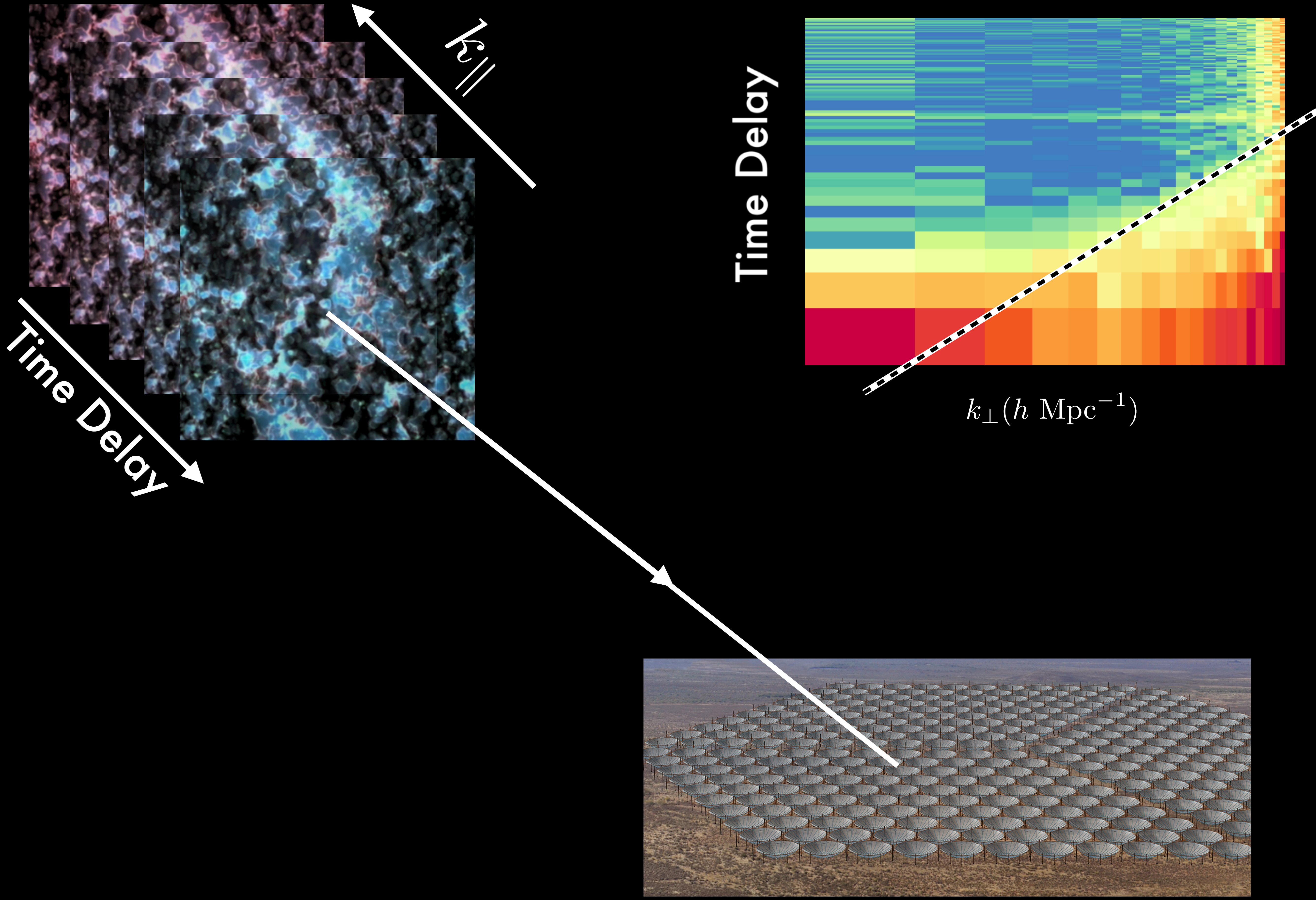
Dillon, et al. (in prep)

In Summary

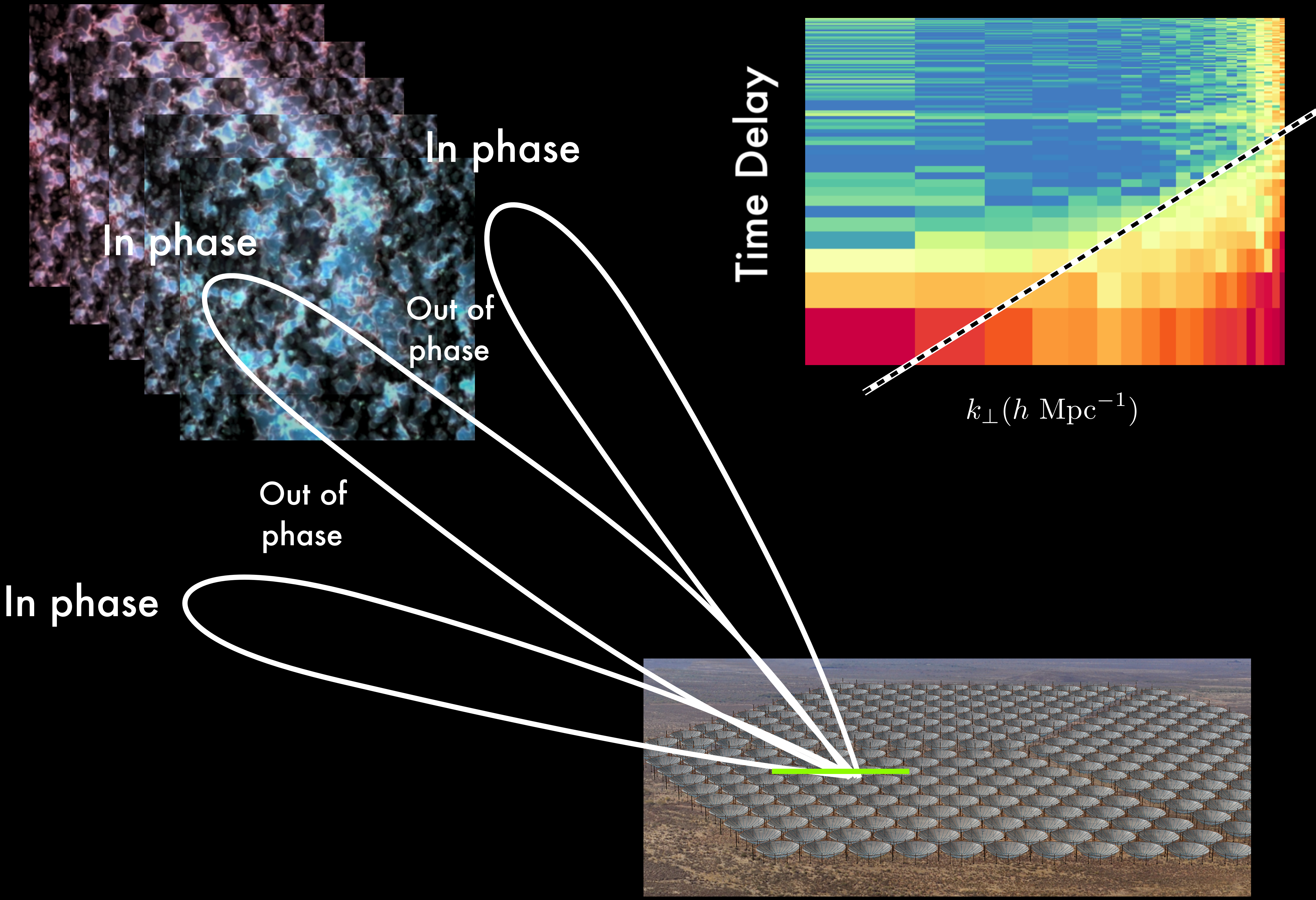
- Calibration is key to spectral smoothness and preserving the EoR window.
- Both self-cal and redundant calibration suffer from chromatic errors if we're not careful
- HERA is designed to use massive redundancy for relative gain (and maybe overall bandpass) calibration without sky model.
- HERA is observing now, analysis is preceding apace, and construction out to 350 antennas is scheduled to finish in 2019.

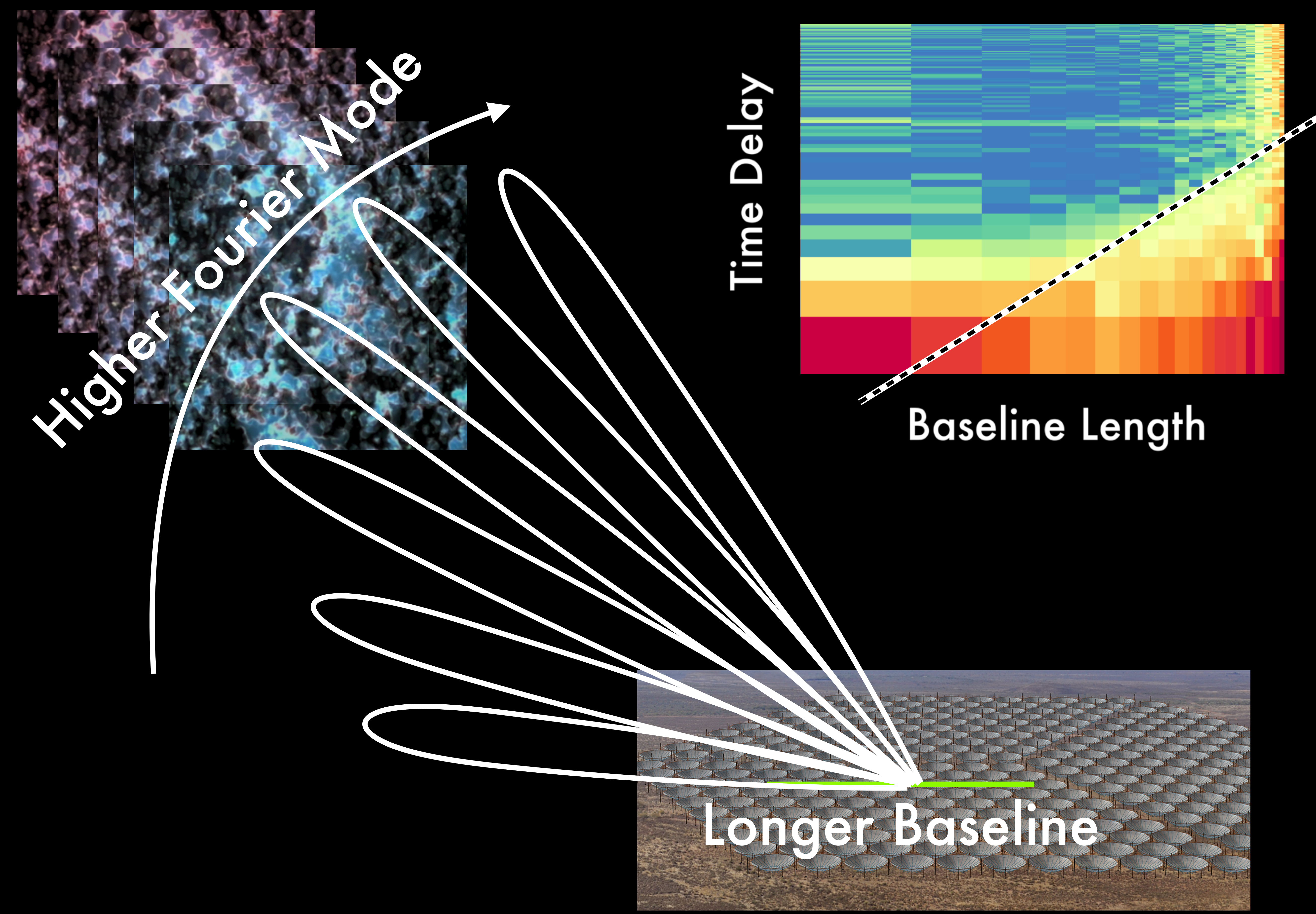
Extra Slides

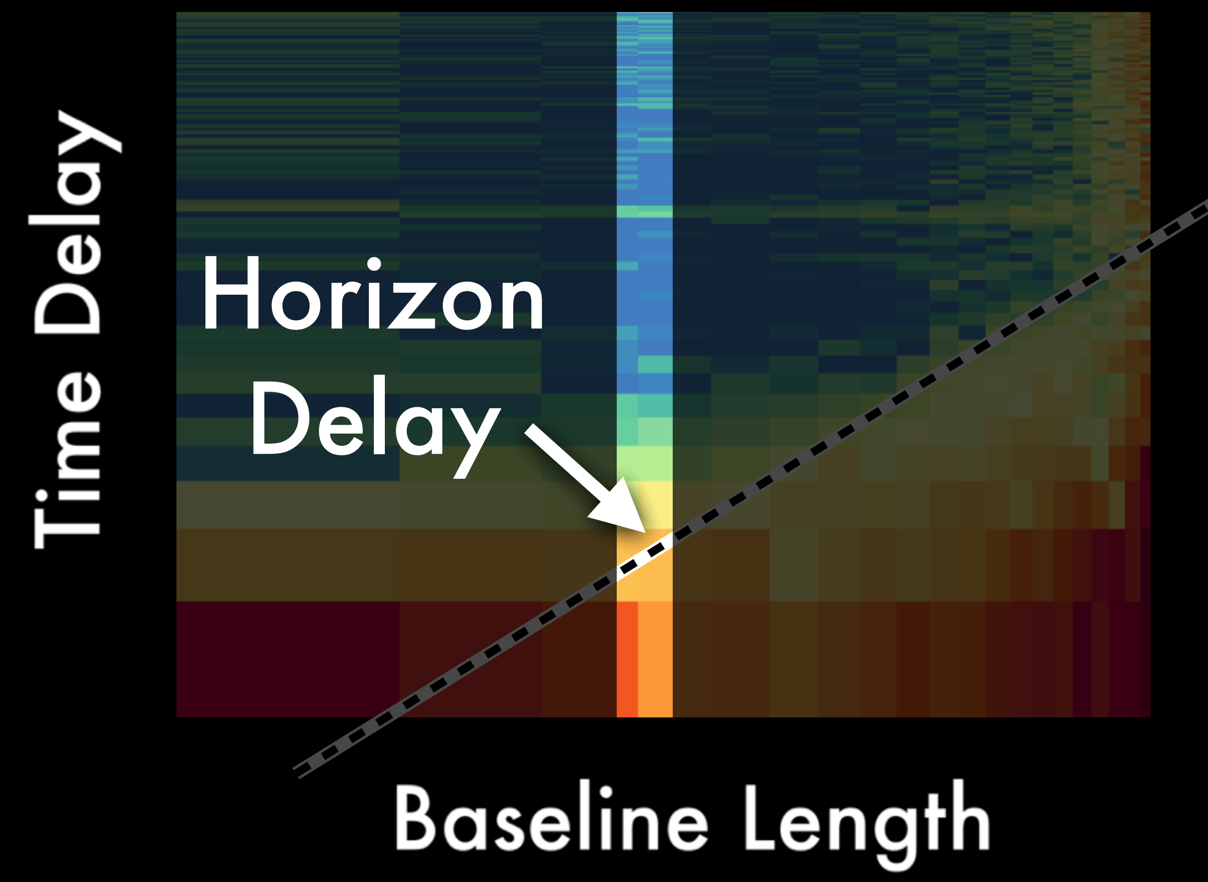

Distance
Frequency
$k_{\parallel}(h\ \mathrm{Mpc}^{-1})$
$k_{\perp}(h\ \mathrm{Mpc}^{-1})$

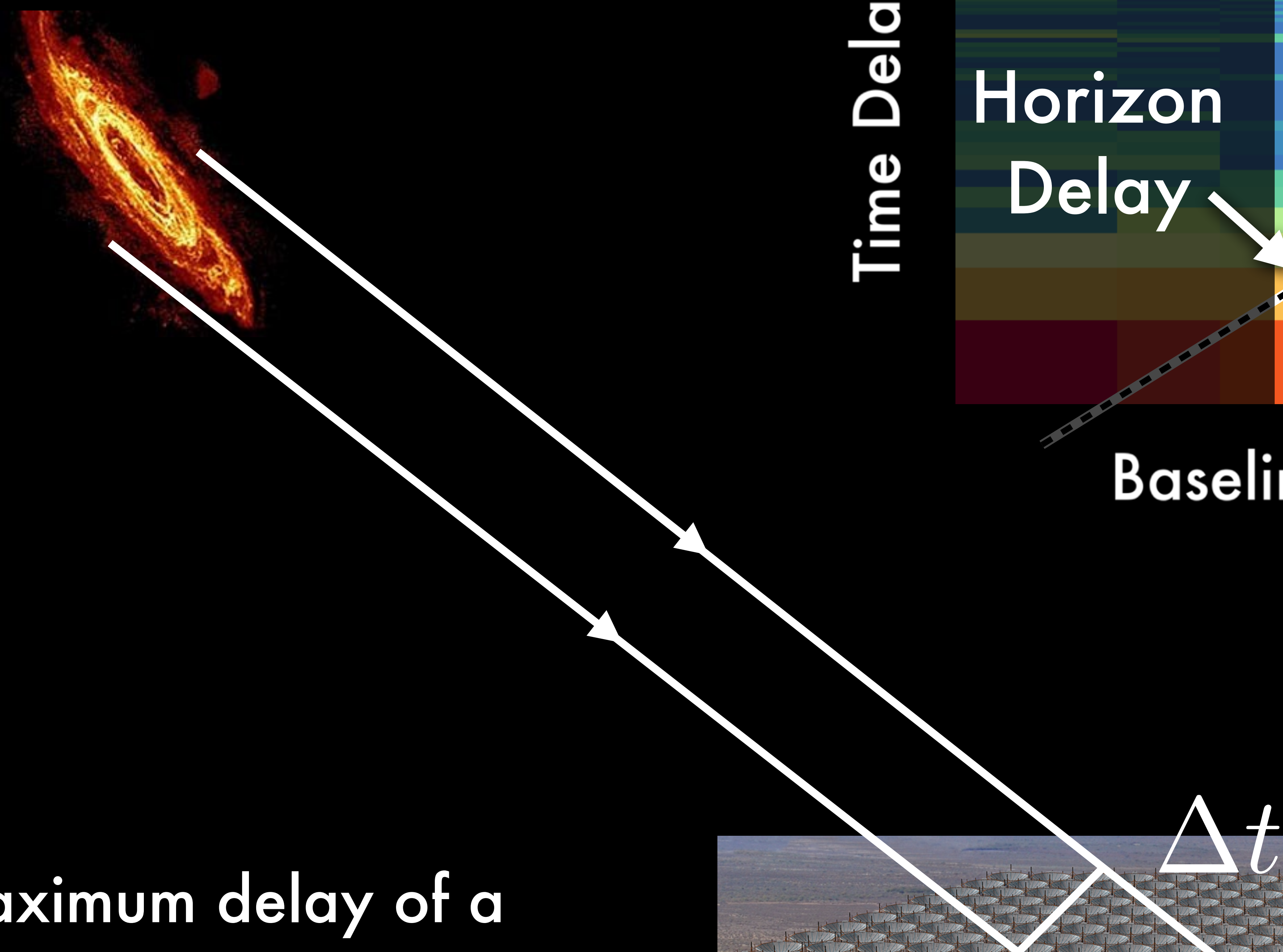


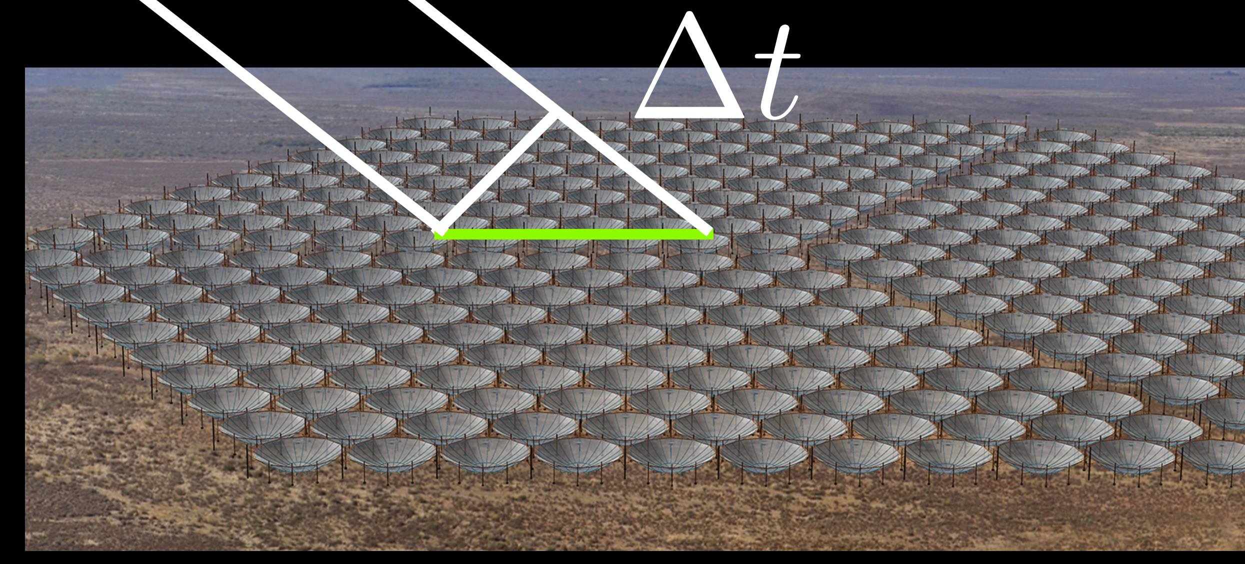
$k_{\|}$
Time Delay
Time Delay
$k_{\perp}(h\ \mathrm{Mpc}^{-1})$


In phase
In phase
Out of phase
Out of phase
In phase
Time Delay
$k_\perp (h \ \mathrm{Mpc}^{-1})$


Higher Fourier Mode
Time Delay
Baseline Length
Longer Baseline

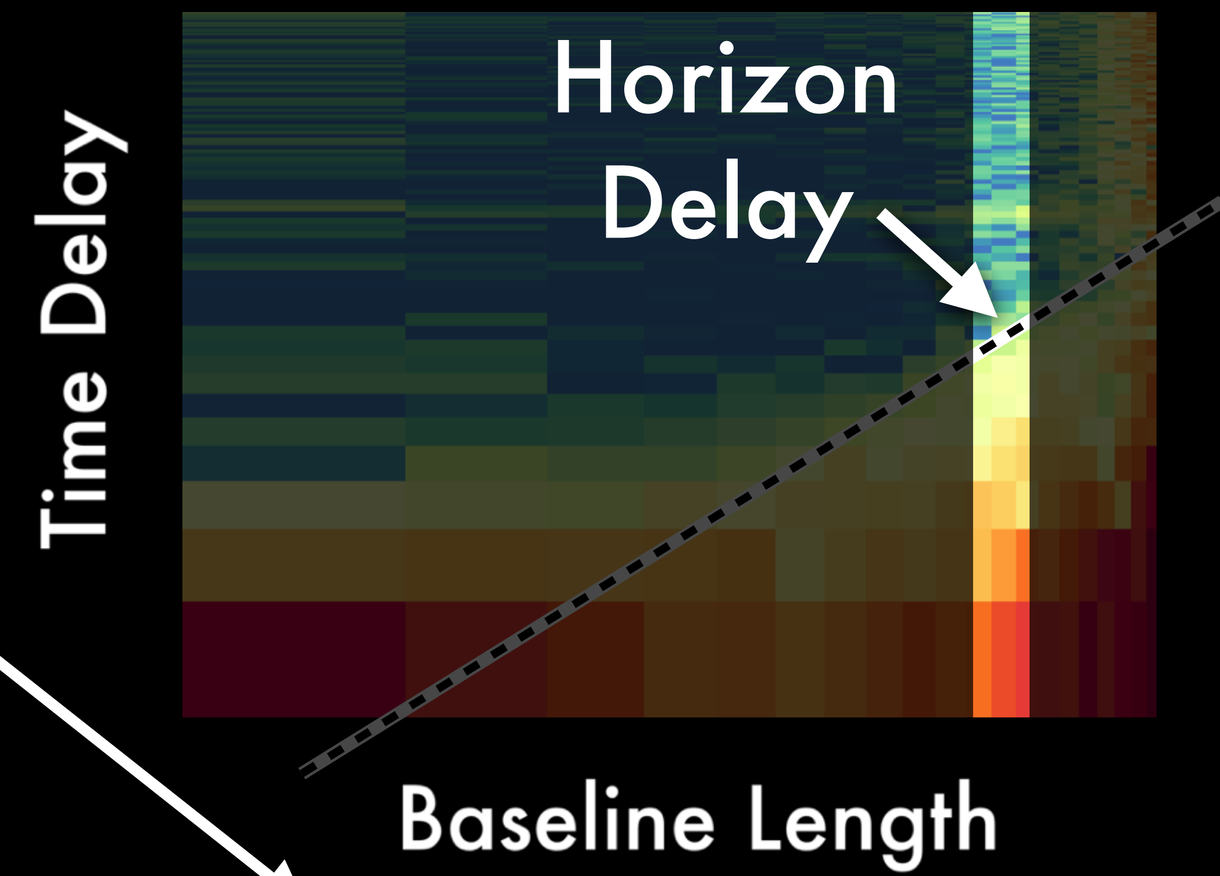


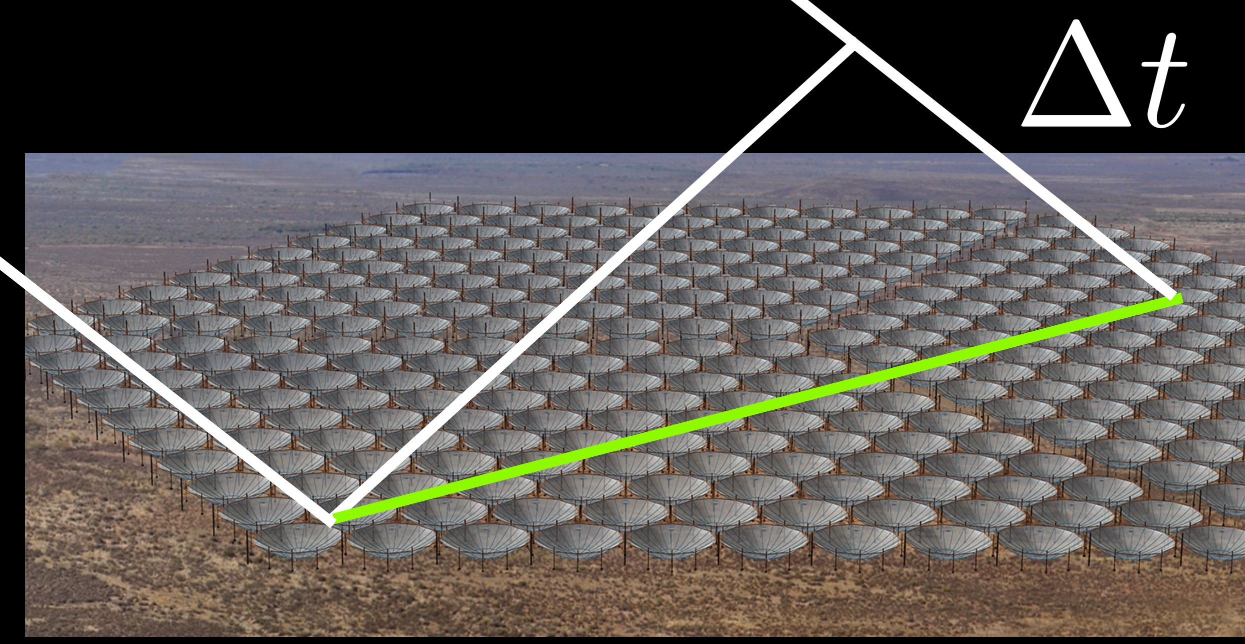




The maximum delay of a foreground object is set by the horizon and the length of the baseline.

Parsons et al. (2012)



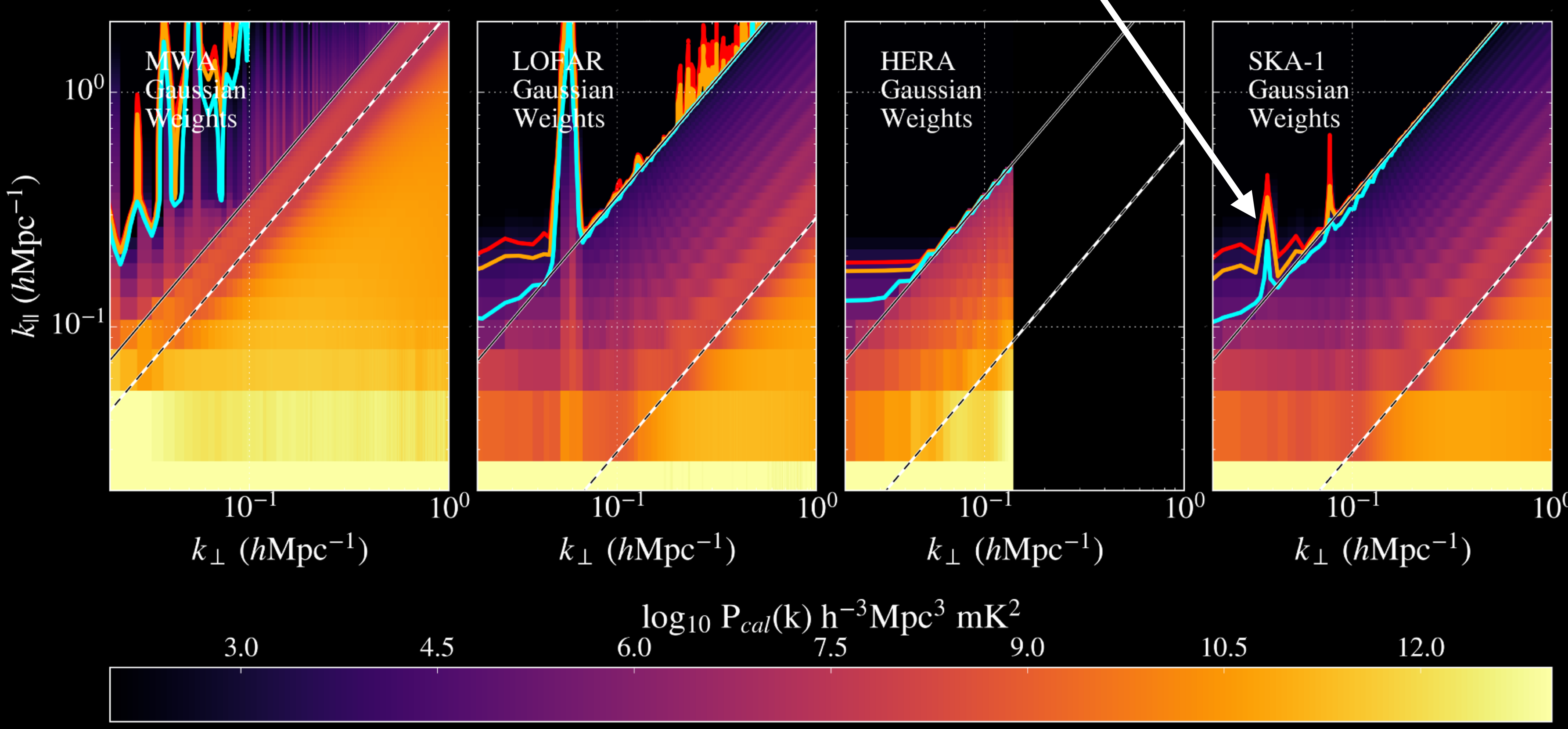


The maximum delay of a foreground object is set by the horizon and the length of the baseline.

Parsons et al. (2012)

This is better, but there's still some contaminated k modes.

21 cm Signal = {1,5,10} x Modeling Bias



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


LOFAR
Gaussian
Weights
Zuurdijk
Nieuwe Dijk
Beeksdijk
Exloërweg
Regenhamsdijk
Exloërweg
LOFAR