It's always darkest before the Cosmic Dawn

First generation 21 cm results and lessons for next-generation arrays

Josh Dillon
UC Berkeley

And, of course...

- Aaron Parsons
- Max Tegmark
- Jacqueline Hewitt
- Adrian Liu
- Aaron Ewall-Wice
- Jeff Zheng
- Jonathan Pober
- Andrei Mesinger
- Abraham Neben
- Miguel Morales

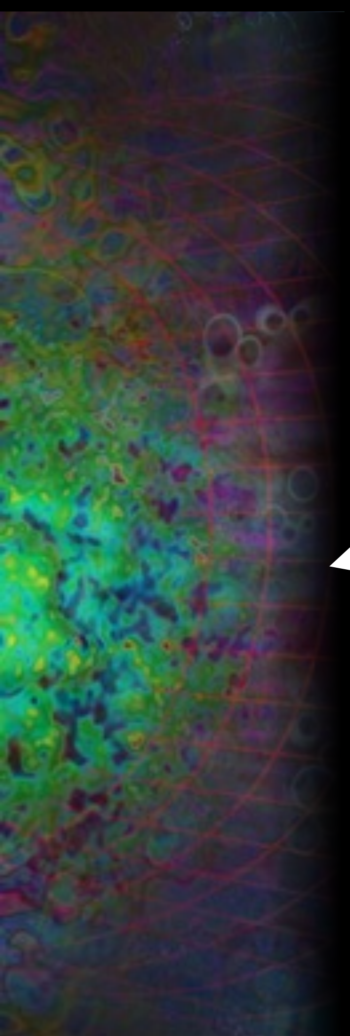
...and the MWA, PAPER, MITEoR, and HERA teams.

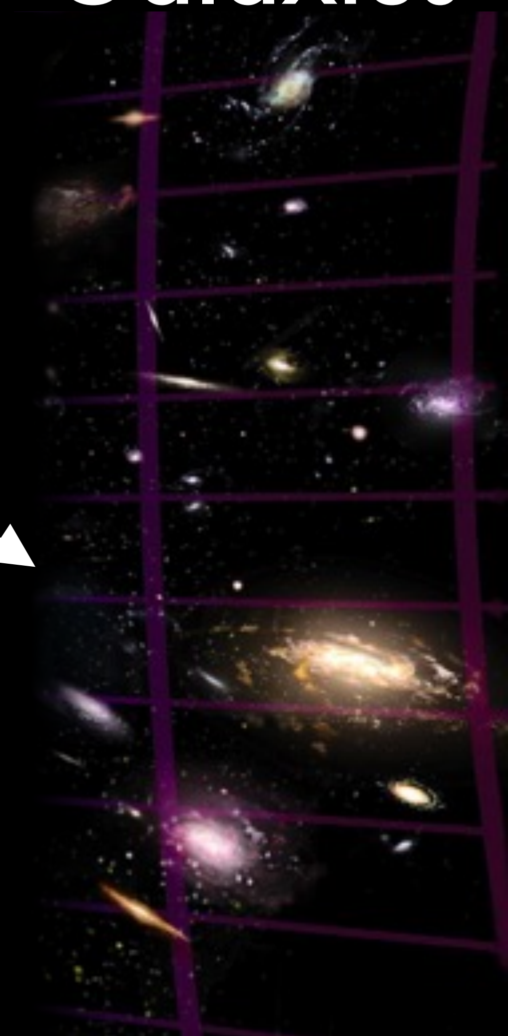
What is the "Cosmic Dawn"?

CMB

Observationally, we have few constraints on how we got from here to here.

Modern Galaxies

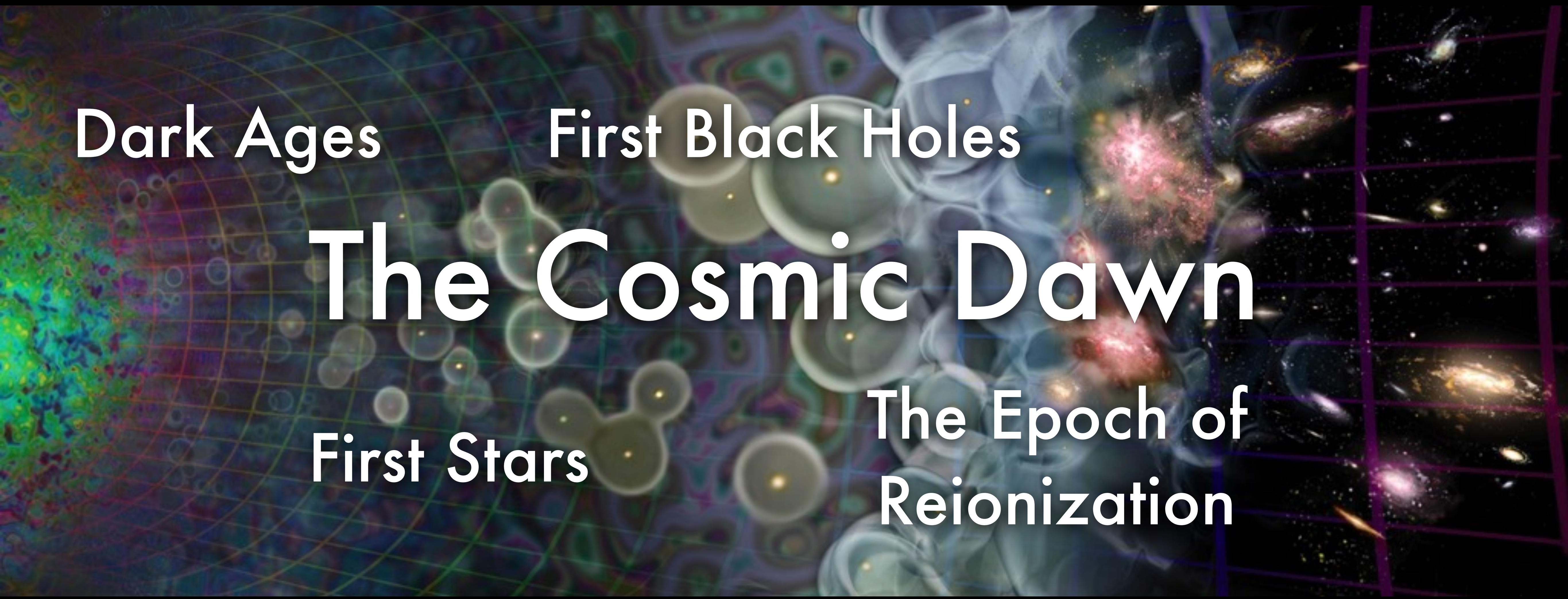




$z = 1100$

$z < 6$

Here's what we think...



$z = 1100$ $z < 6$

Image: Avi Loeb & Scientific American

And there's still a lot of open questions.

- What did the first stars, galaxies, and black holes look like and how did they form?
- What was the thermal and ionization history of the IGM and what determined it?
- Can we measure the matter power spectrum during this epoch and test ΛCDM?

Image: Avi Loeb & Scientific American

The Epoch of Reionization is our first target.

Marcelo Alvarez, Ralf Kaehler, Tom Abel

What do we know already?

Reionization ended around redshift 6.

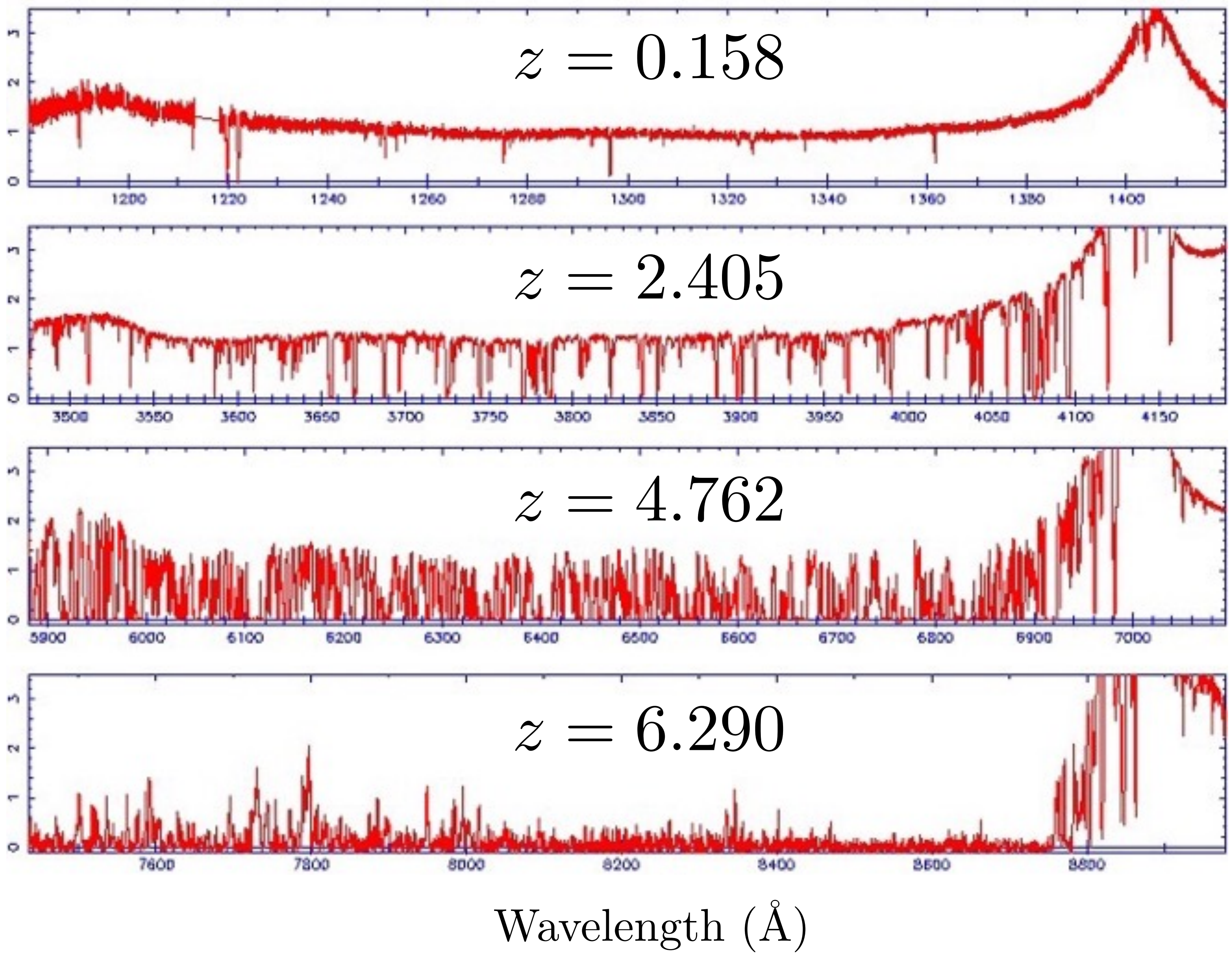
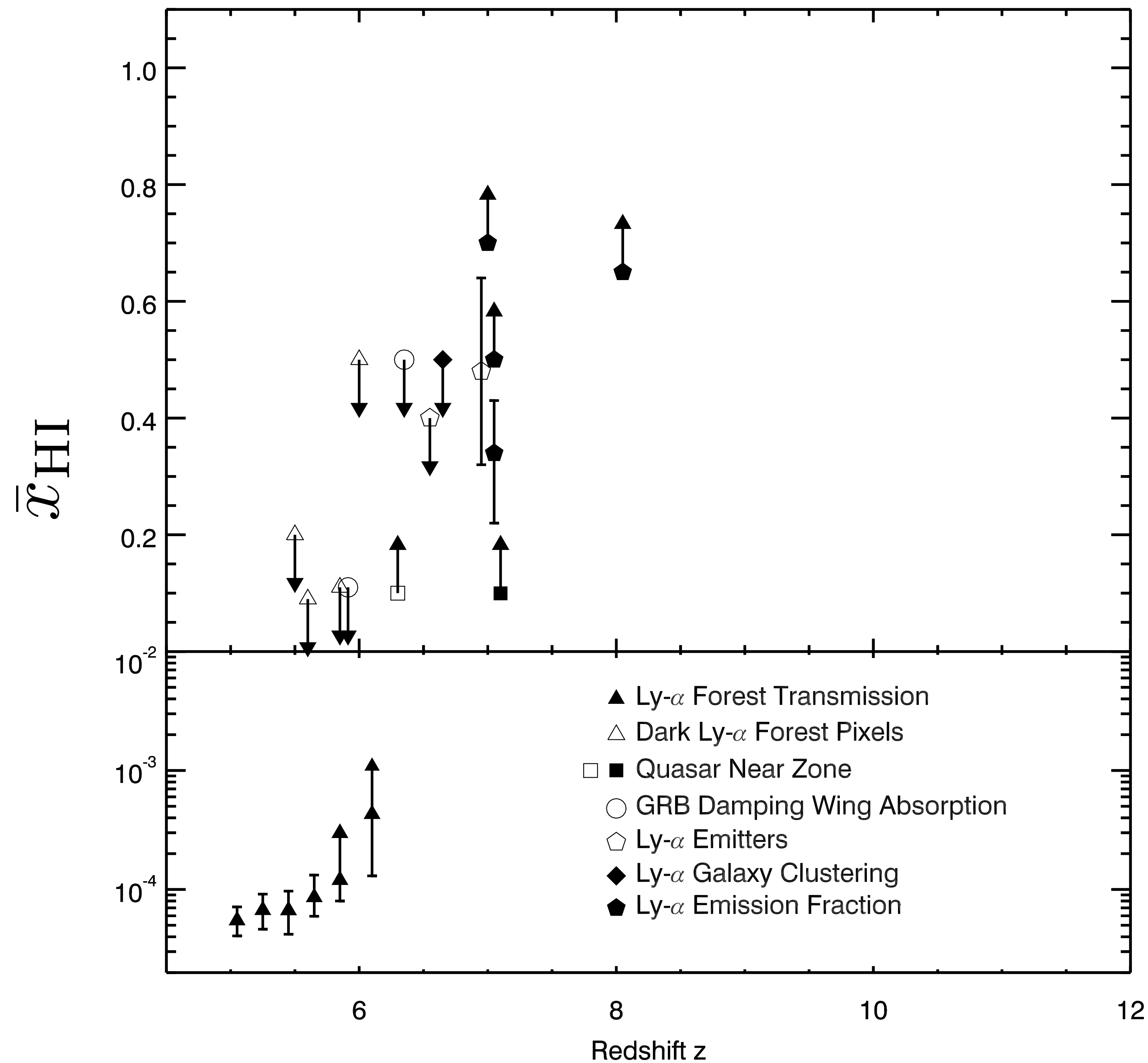


Image: Bob Carswell

But it's hard to figure out exactly when it started or how it proceeded.



Compiled by Robertson et al. (2015)

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

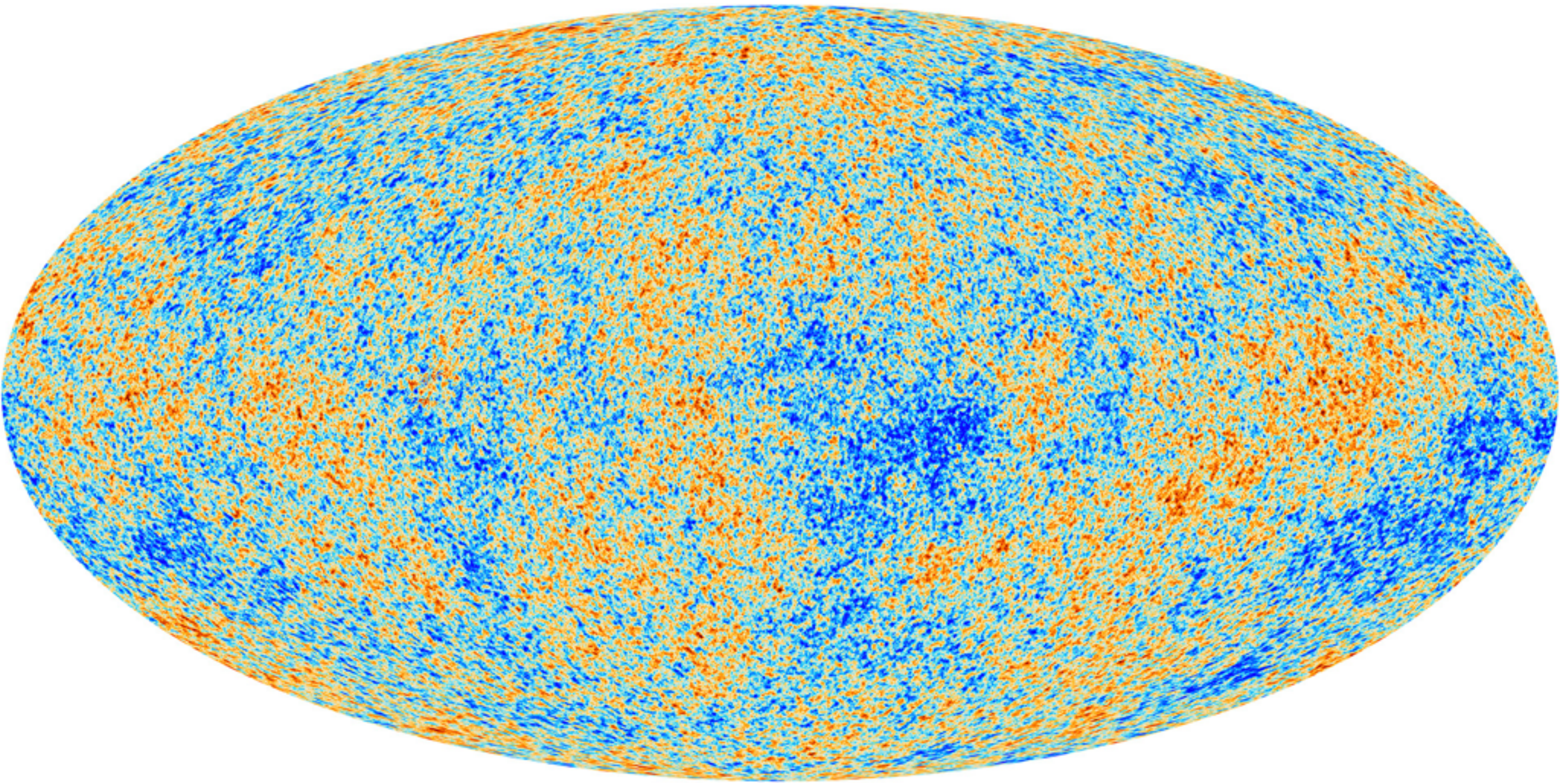


Image: Planck Collaboration

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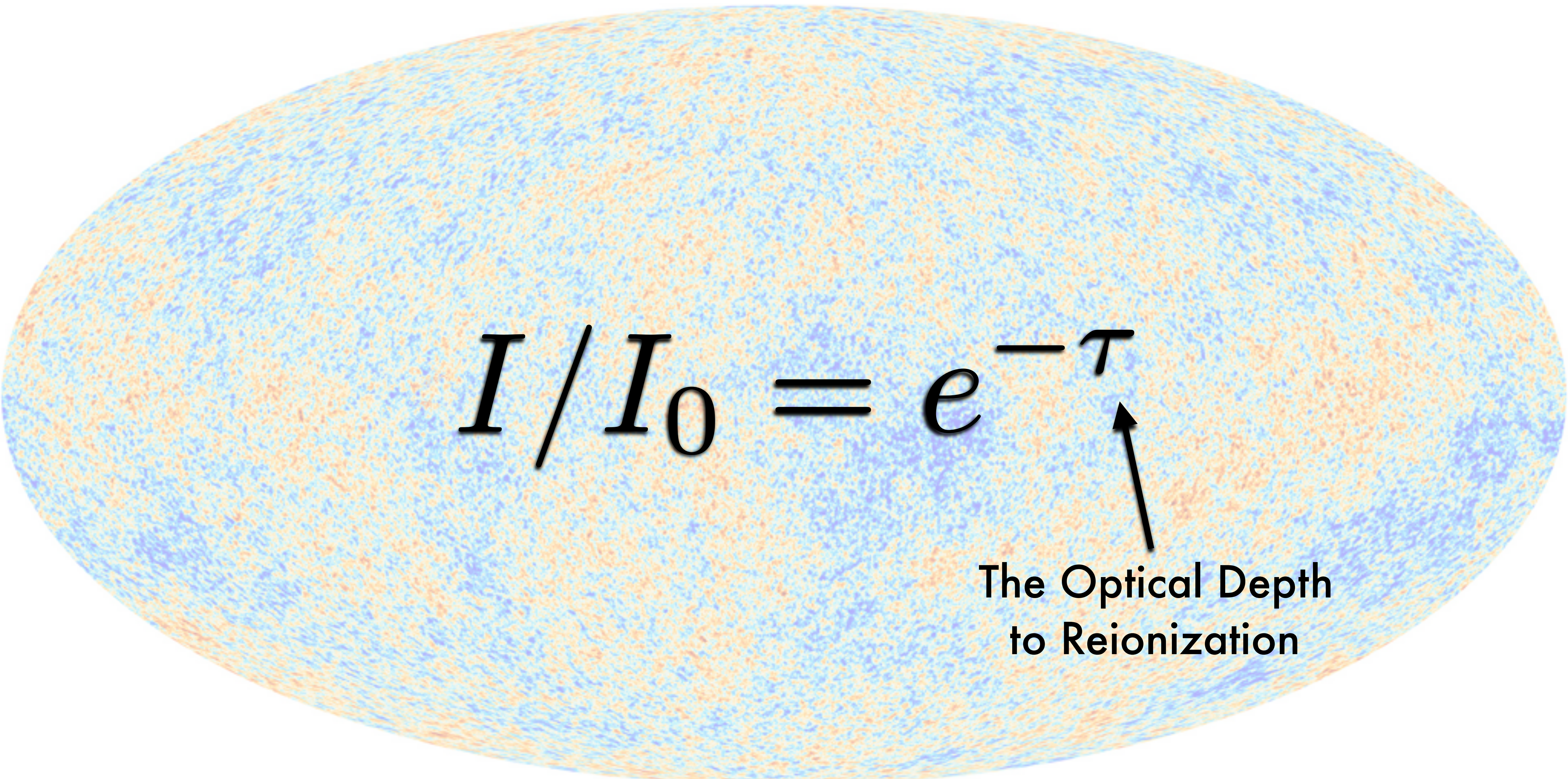
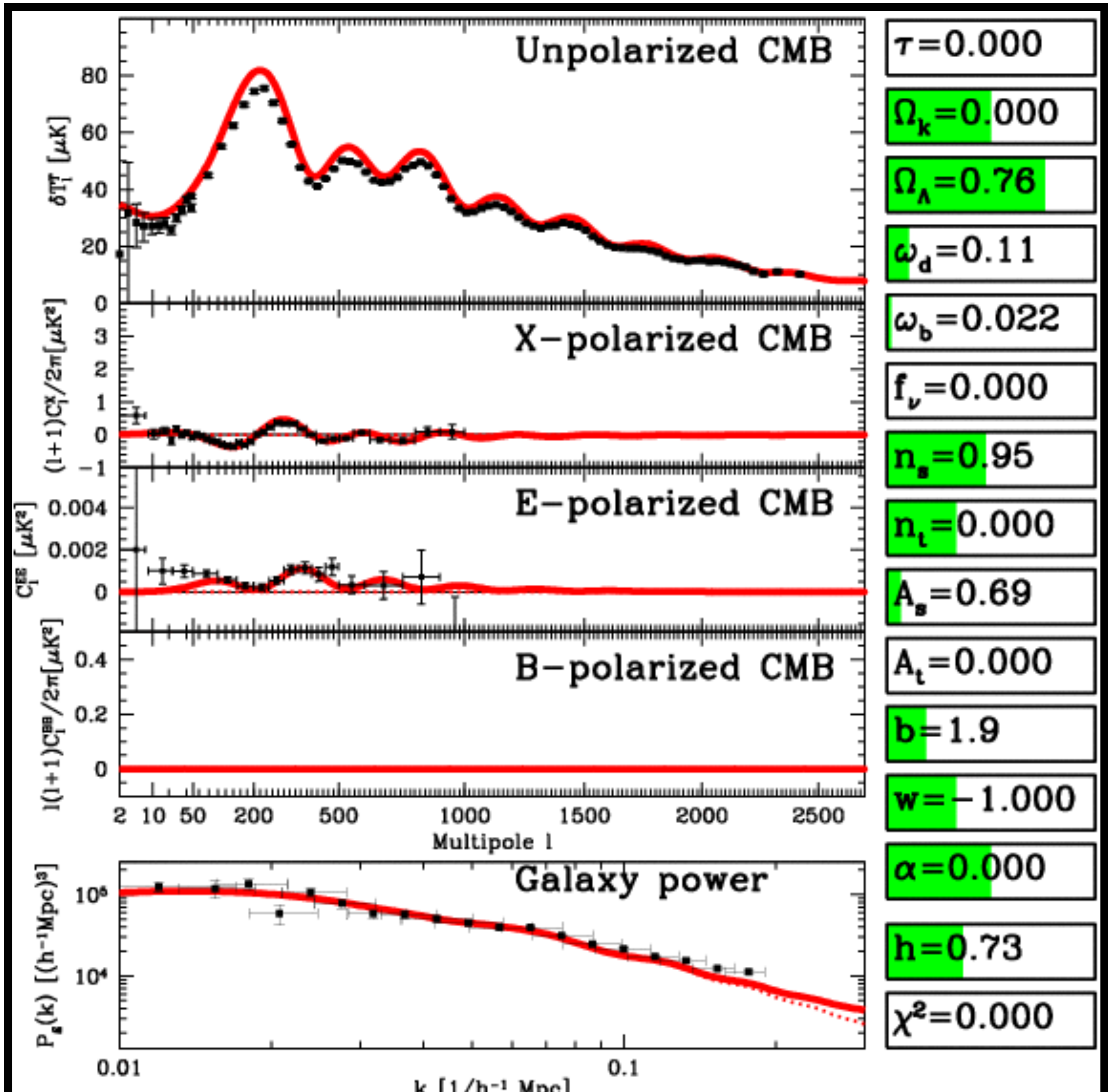


$$I/I_0 = e^{-\tau}$$

Image: Planck Collaboration

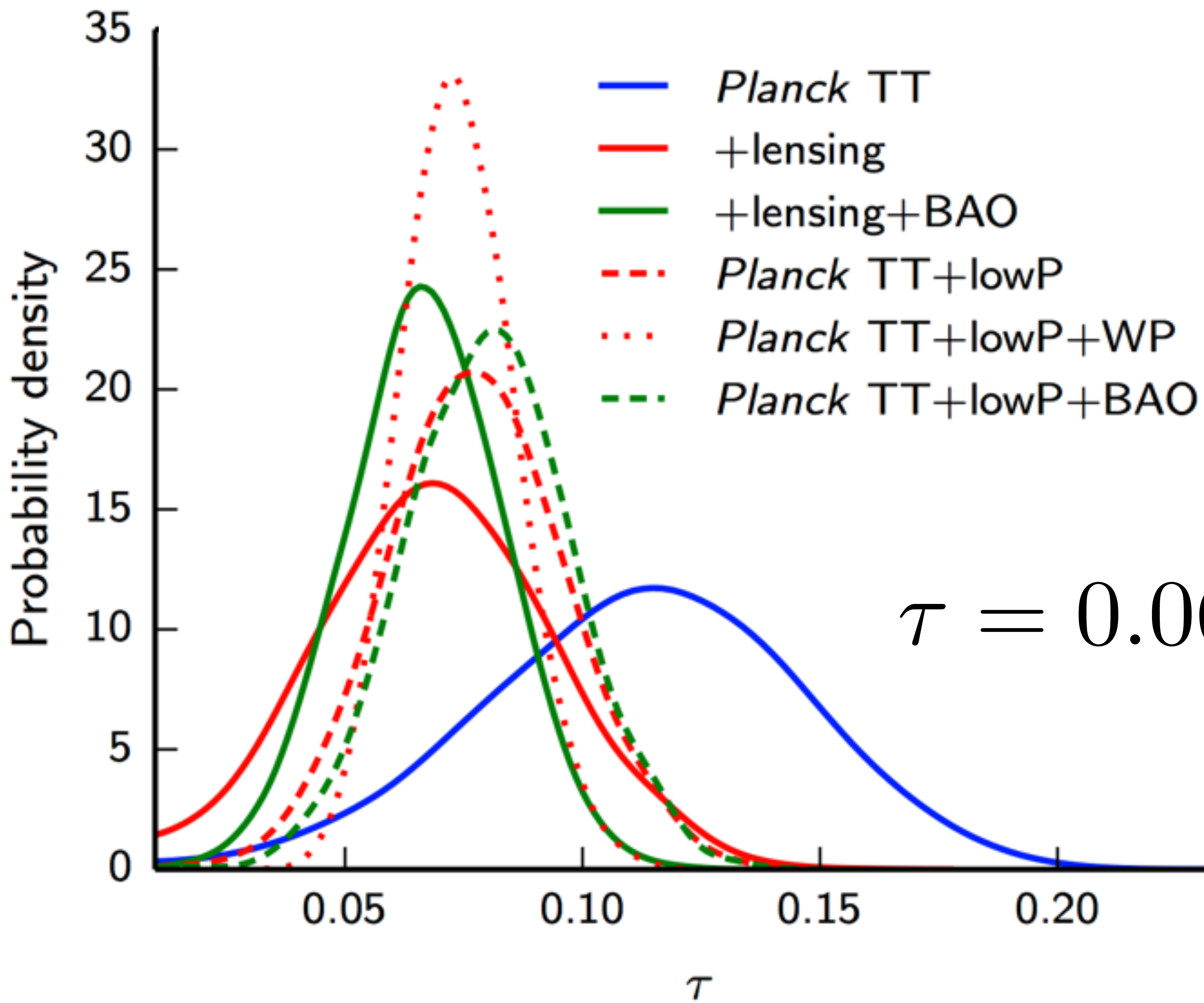
Constrainting Tau



Using the low-ℓ modes of the EE power spectrum, the optical depth can be constrained from the CMB alone.

http://space.mit.edu/home/tegmark/movies.html

In Planck 2015, τ came down by about 20% due to improved removal of diffuse polarized foregrounds.



$$\tau = 0.066^{+0.013}_{-0.013}$$

Planck Collaboration (2015)

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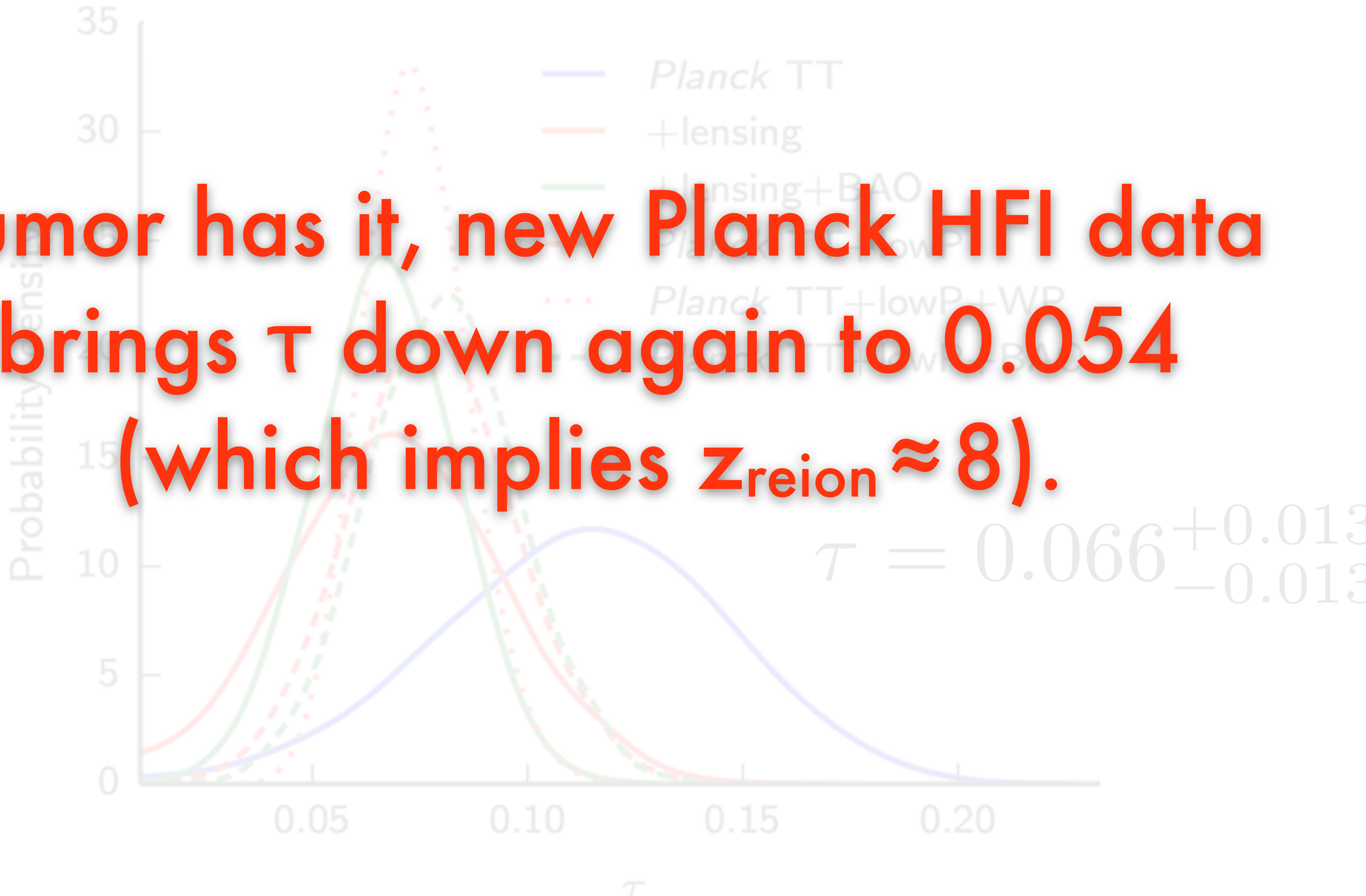
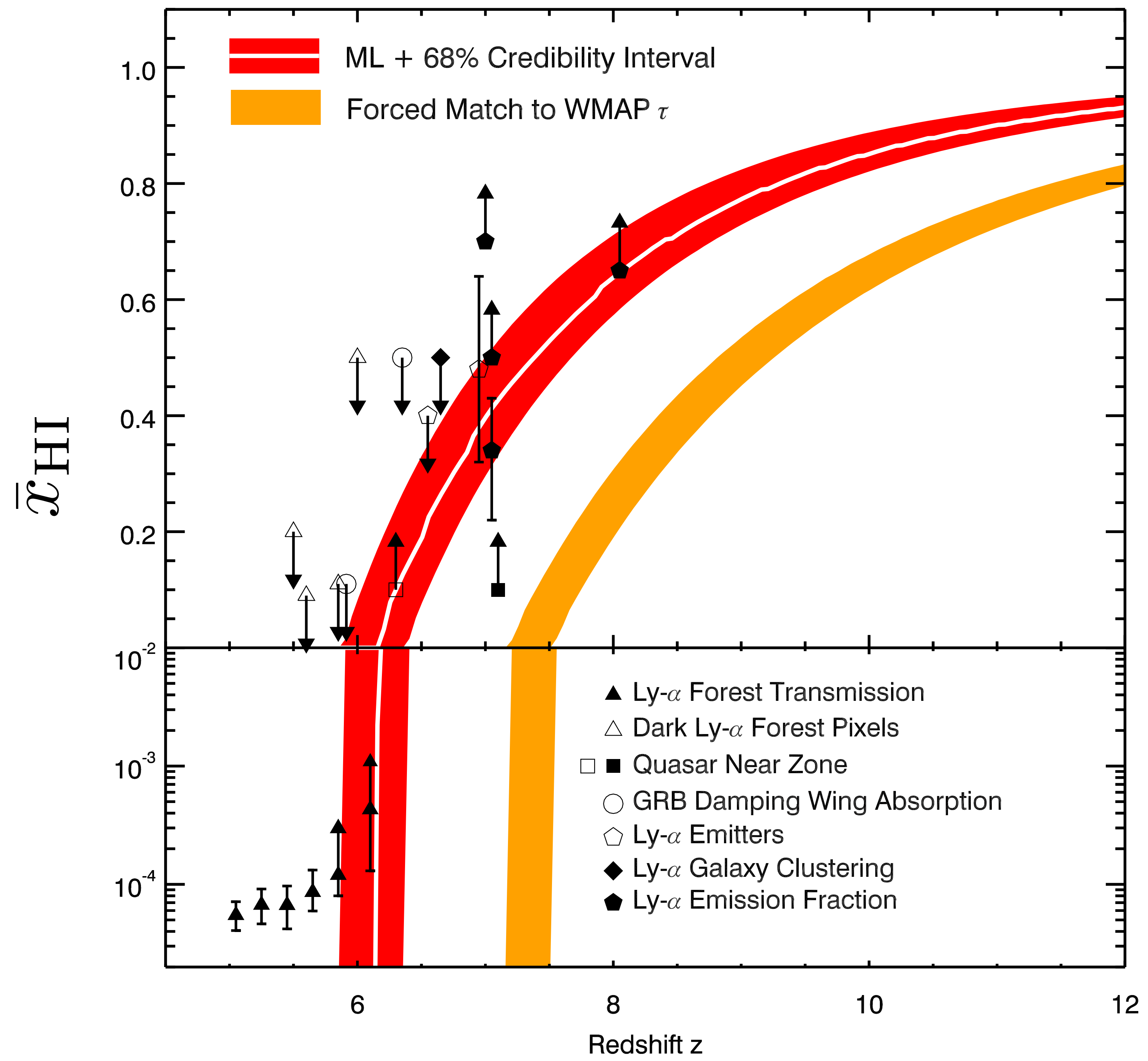


Rumor has it, new Planck HFI data brings τ down again to 0.054 (which implies z_{reion}≈8).

Planck Collaboration (2015)

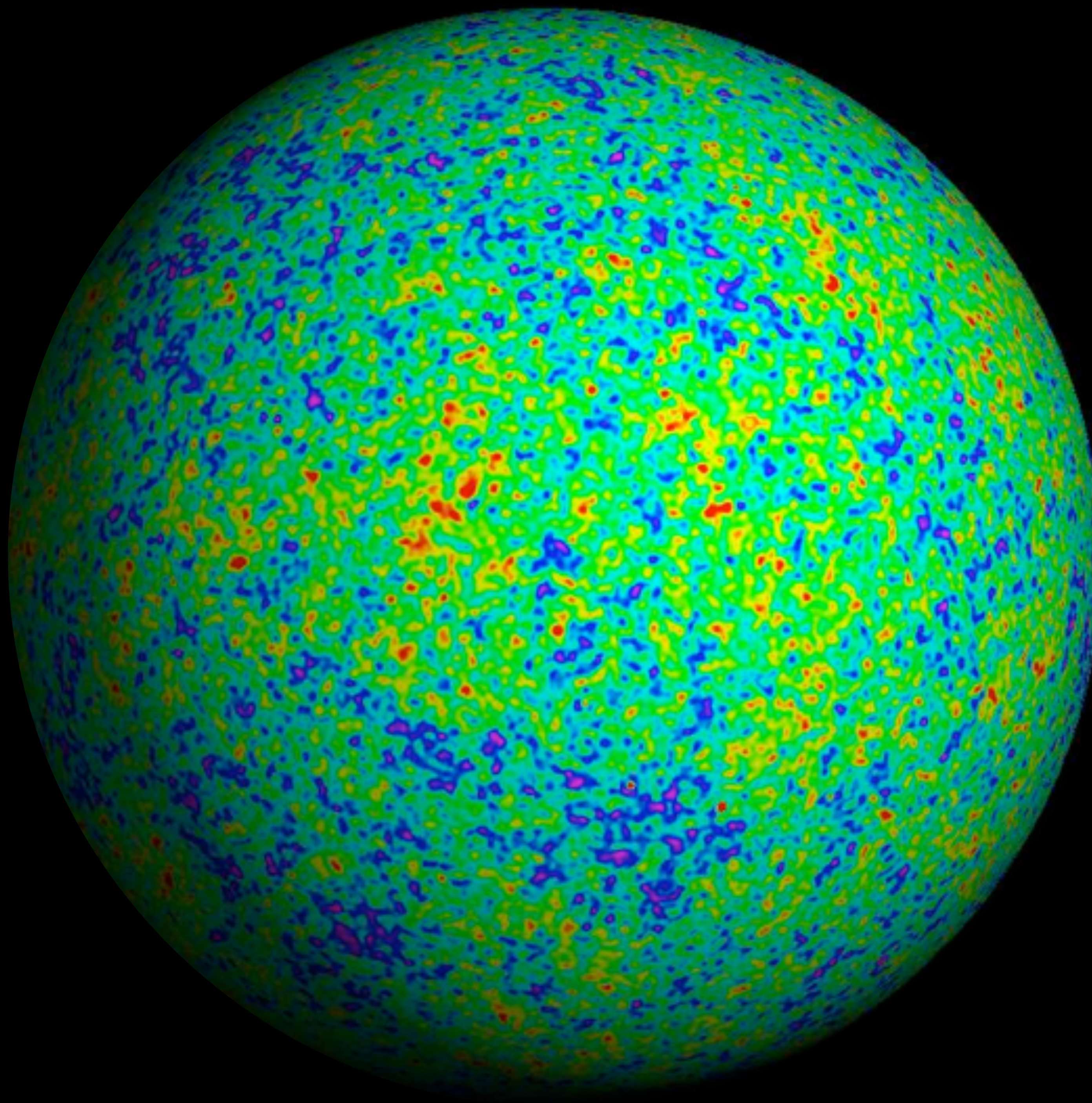
With some assumptions about reionization physics, it's possible to get a reionization history that's consistent with extrapolated SFR histories.



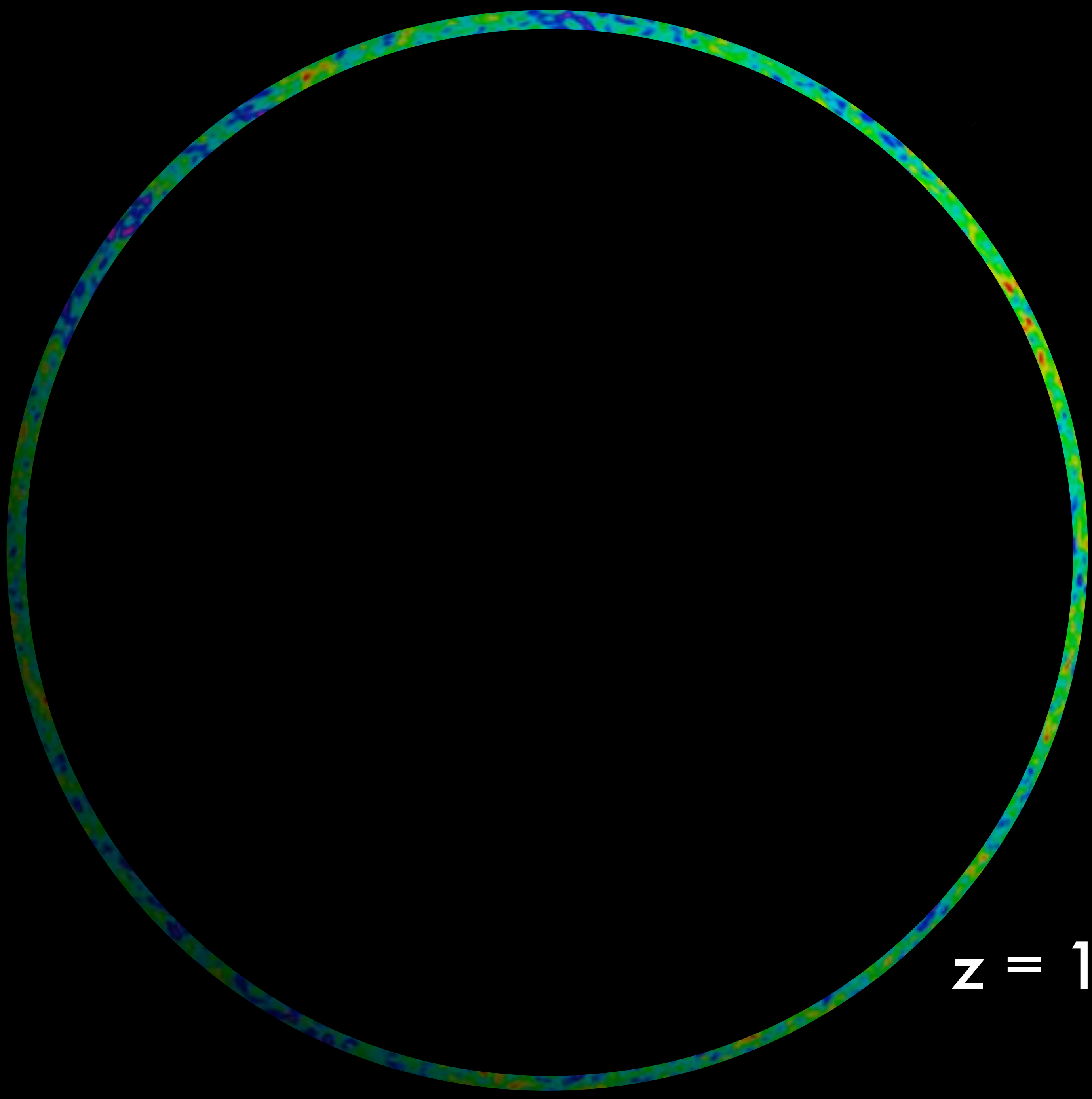
Robertson et al. (2015)

How can we observe the Cosmic Dawn directly?

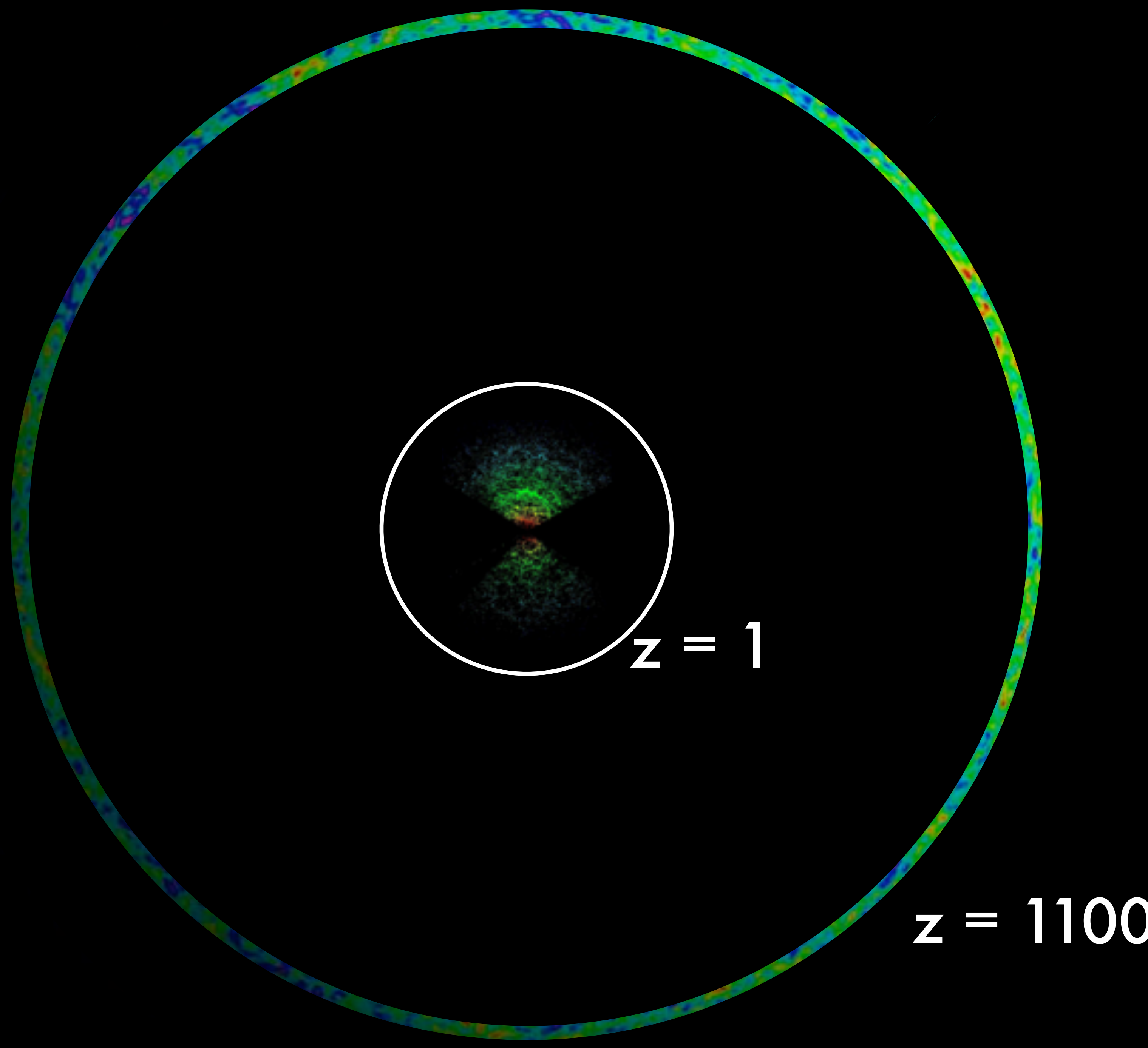
With the CMB…



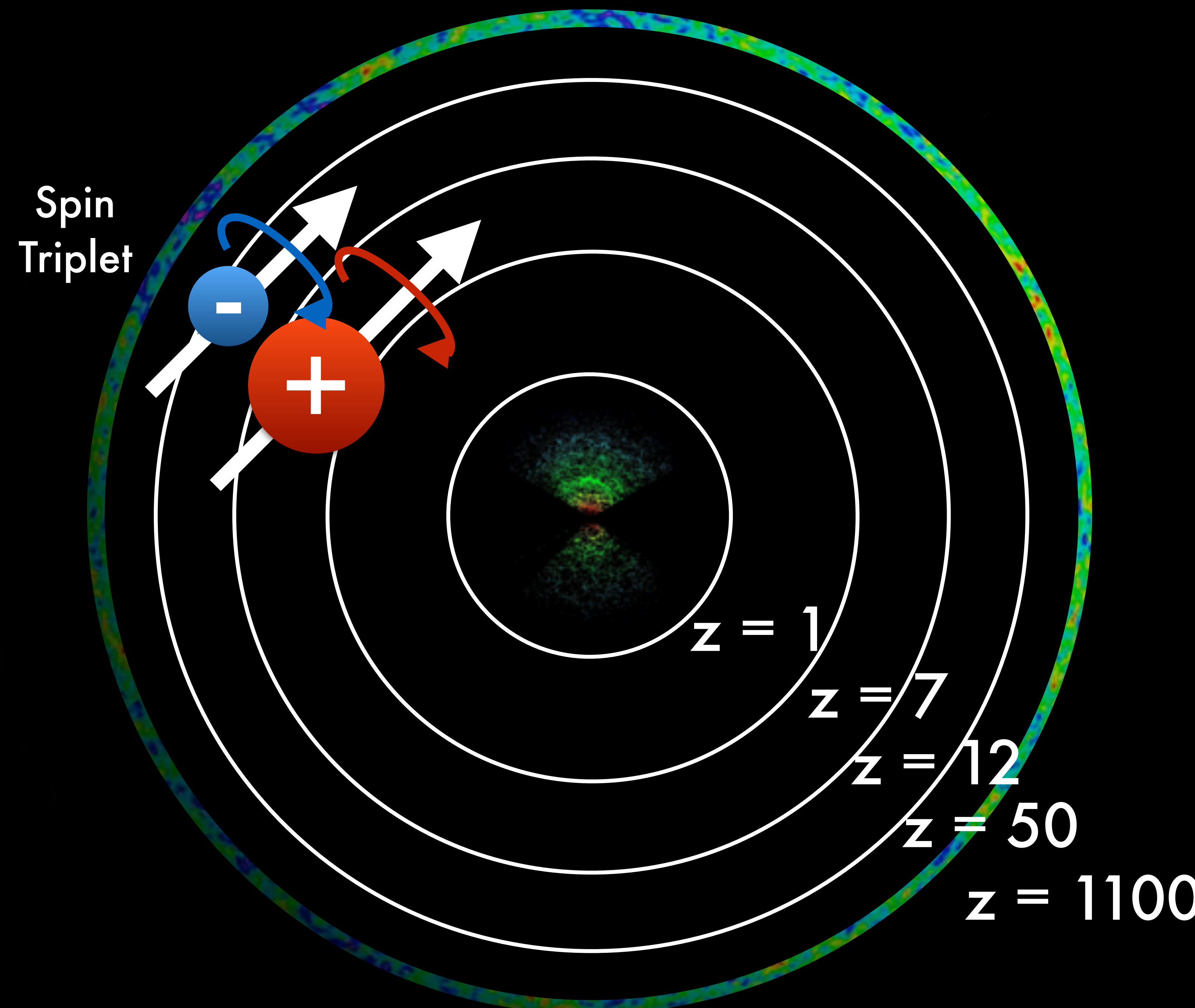
...we only get a thin shell at high redshift.



Galaxy surveys only tell us about the local universe.



So we turn to 21 cm Tomography.



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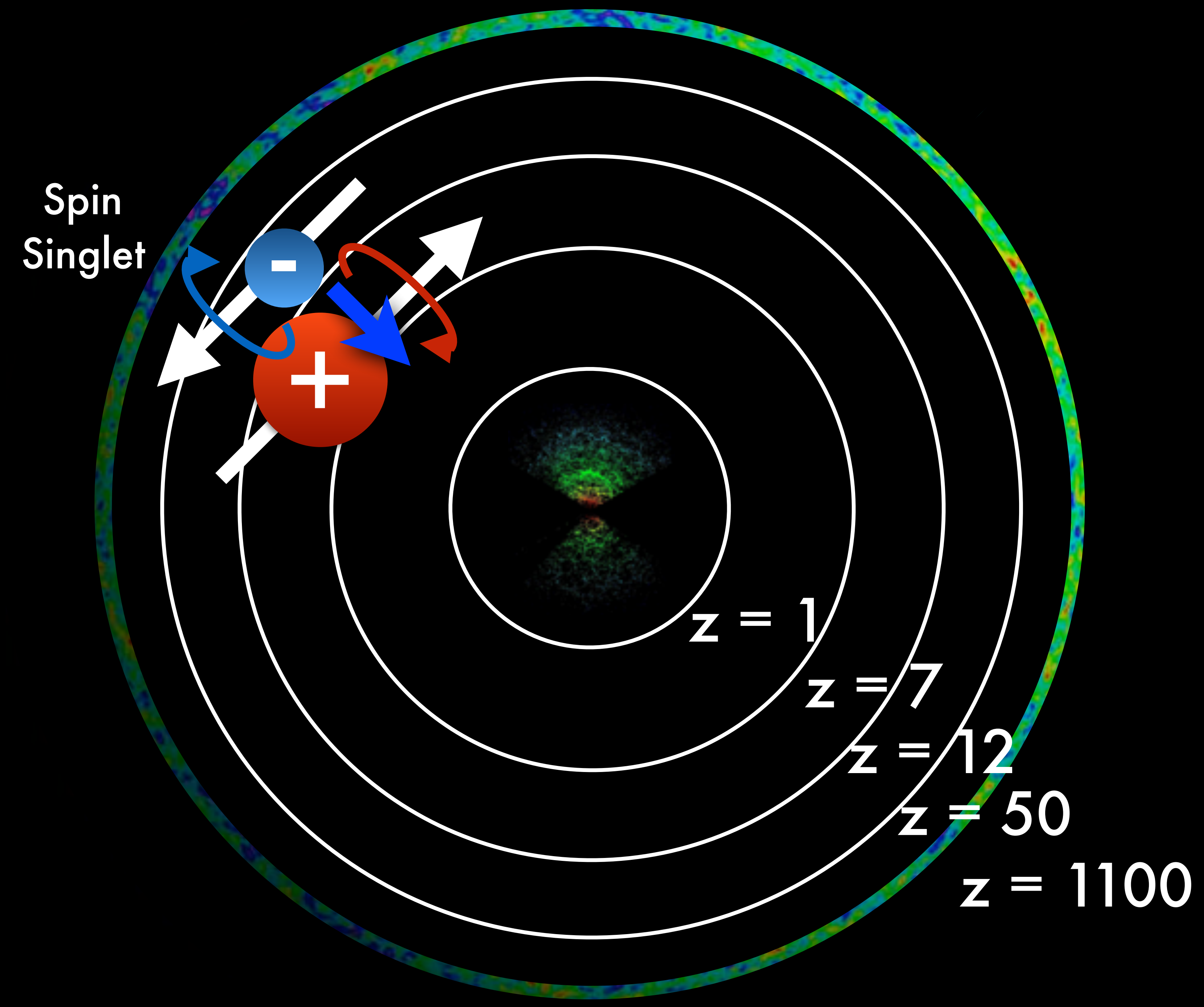

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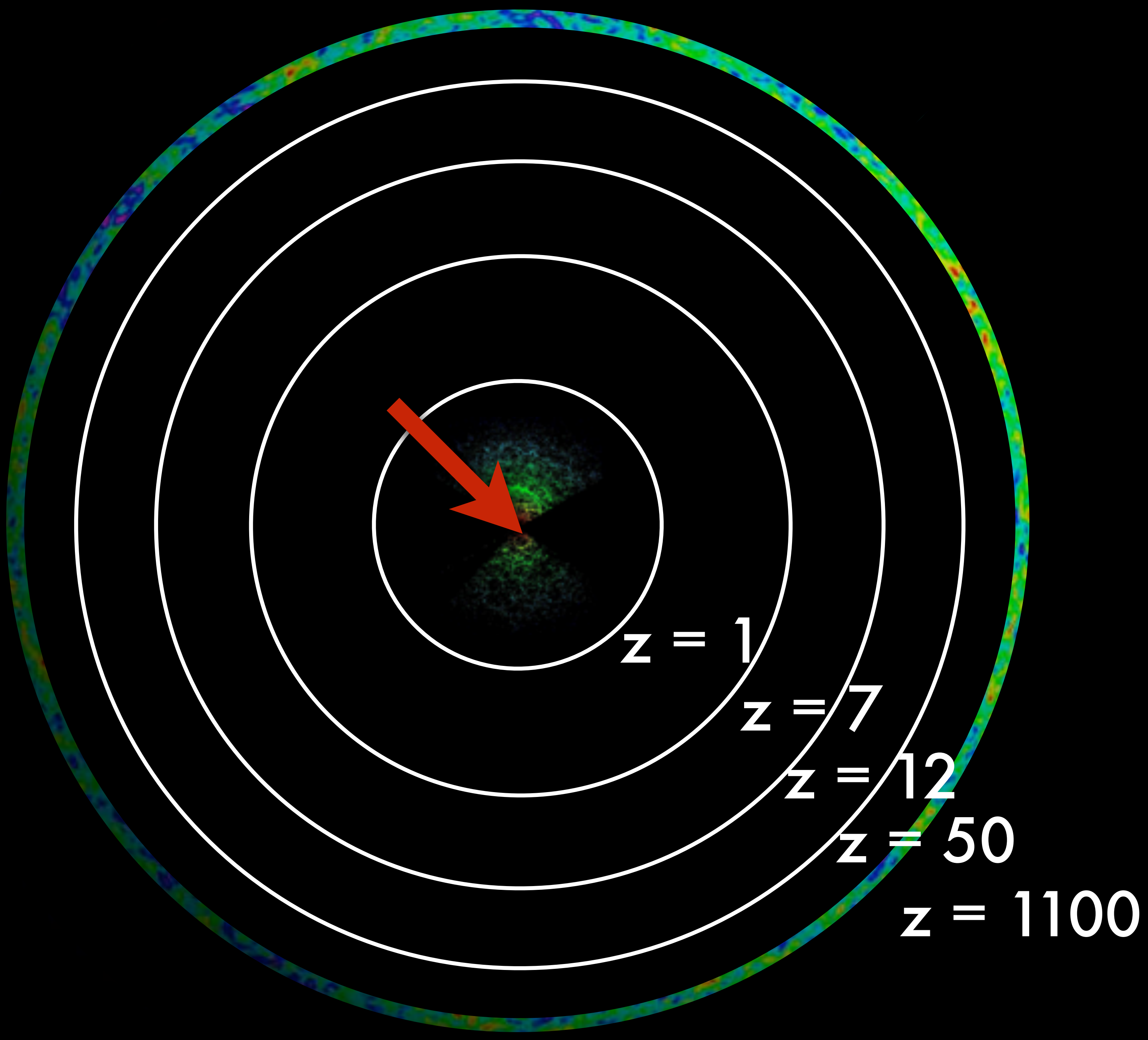
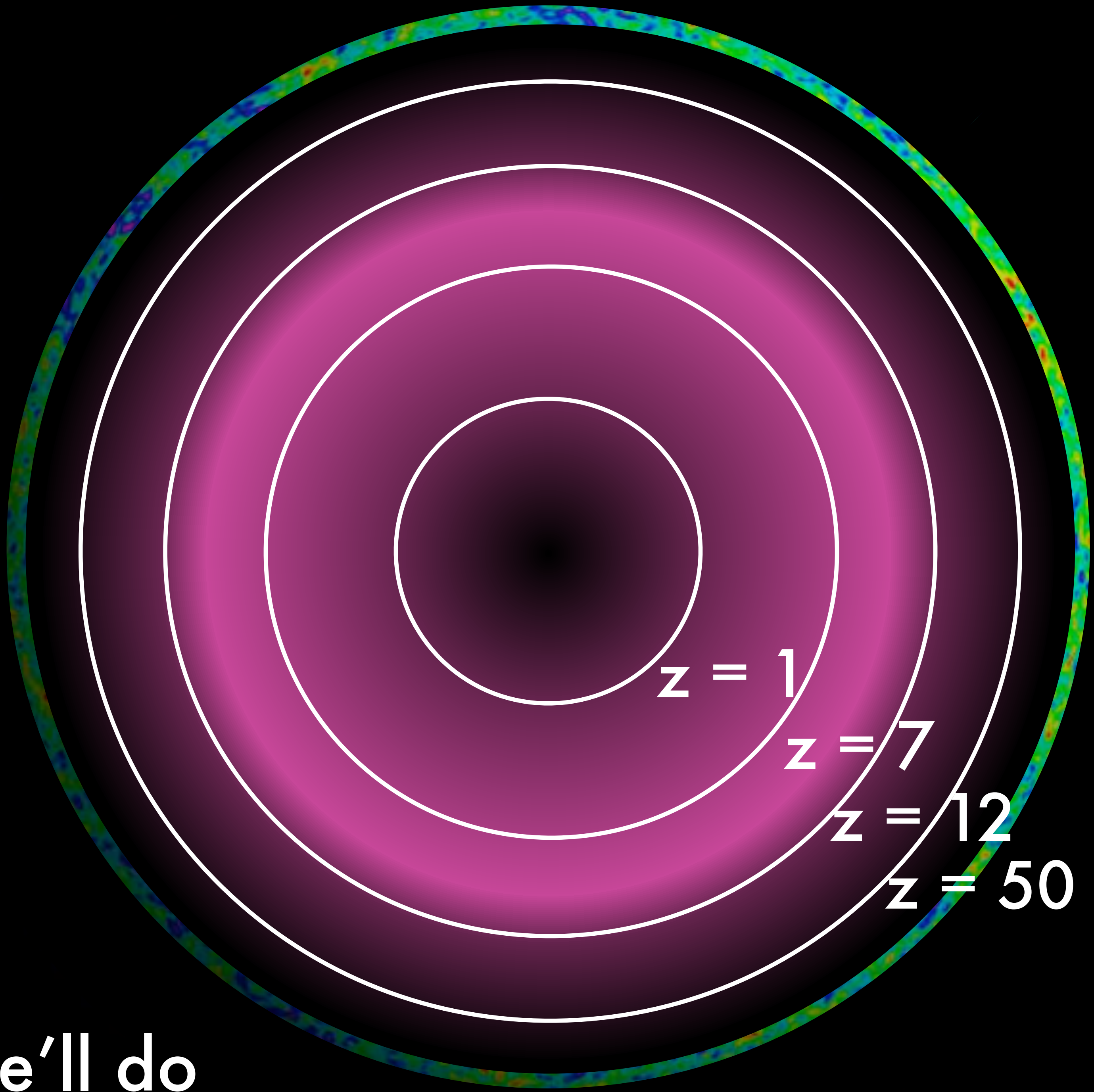
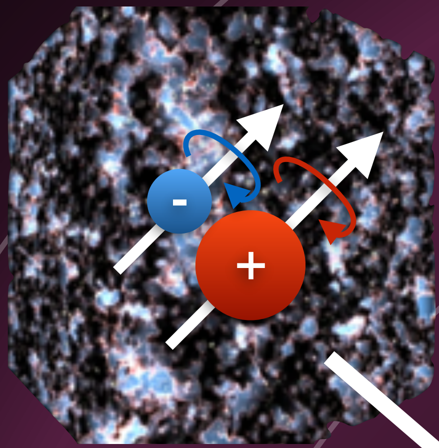


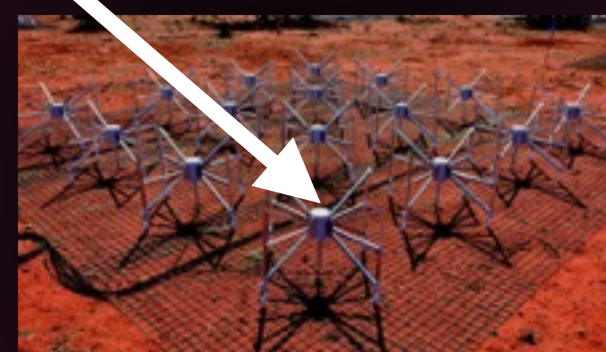
A huge volume of the universe can be explored with 21 cm tomography.



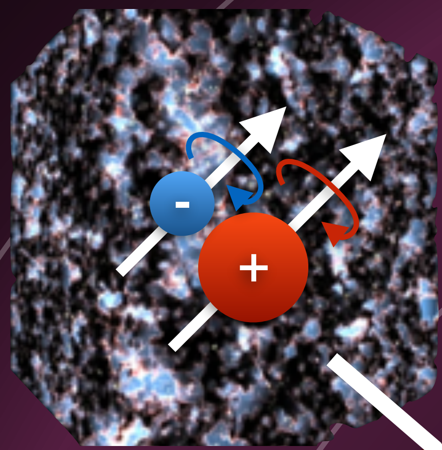
Eventually, we'll do cosmology very precisely.

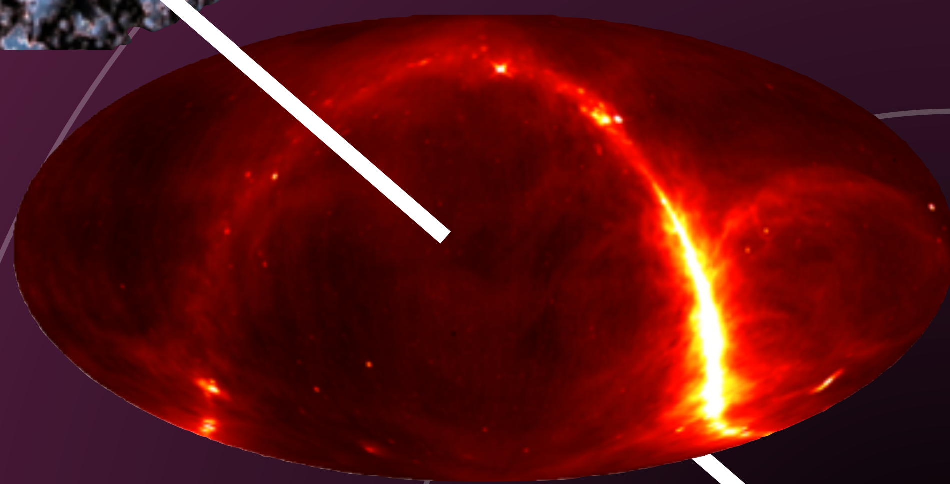


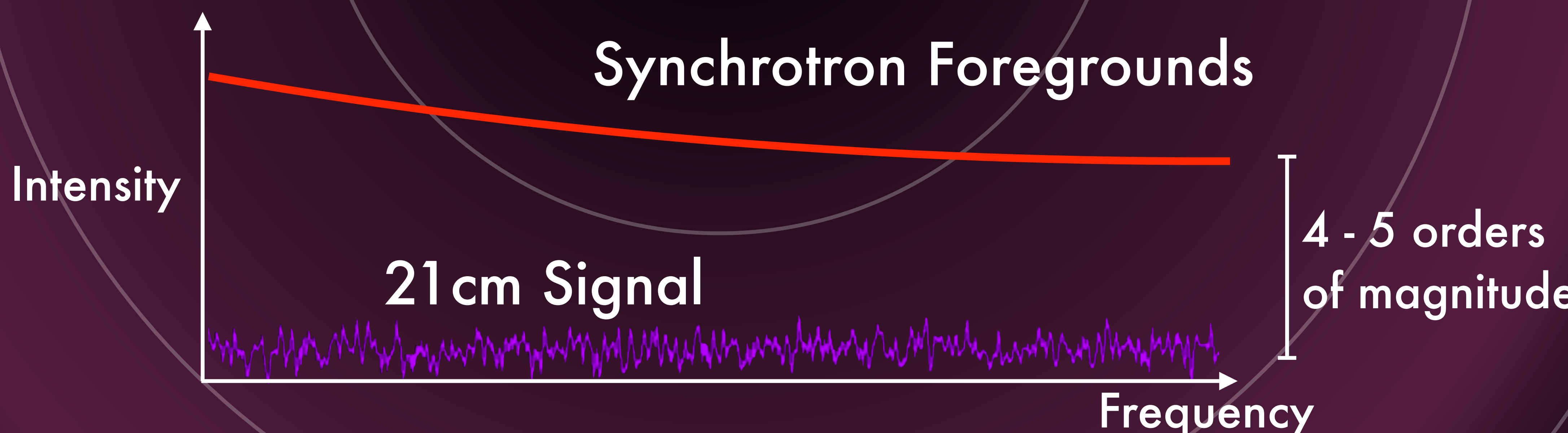
$$\delta T_{21\,\mathrm{cm}} \propto x_{\mathrm{HI}}(1+\delta)\left[1-\frac{T_{\mathrm{CMB}}}{T_s}\right]$$



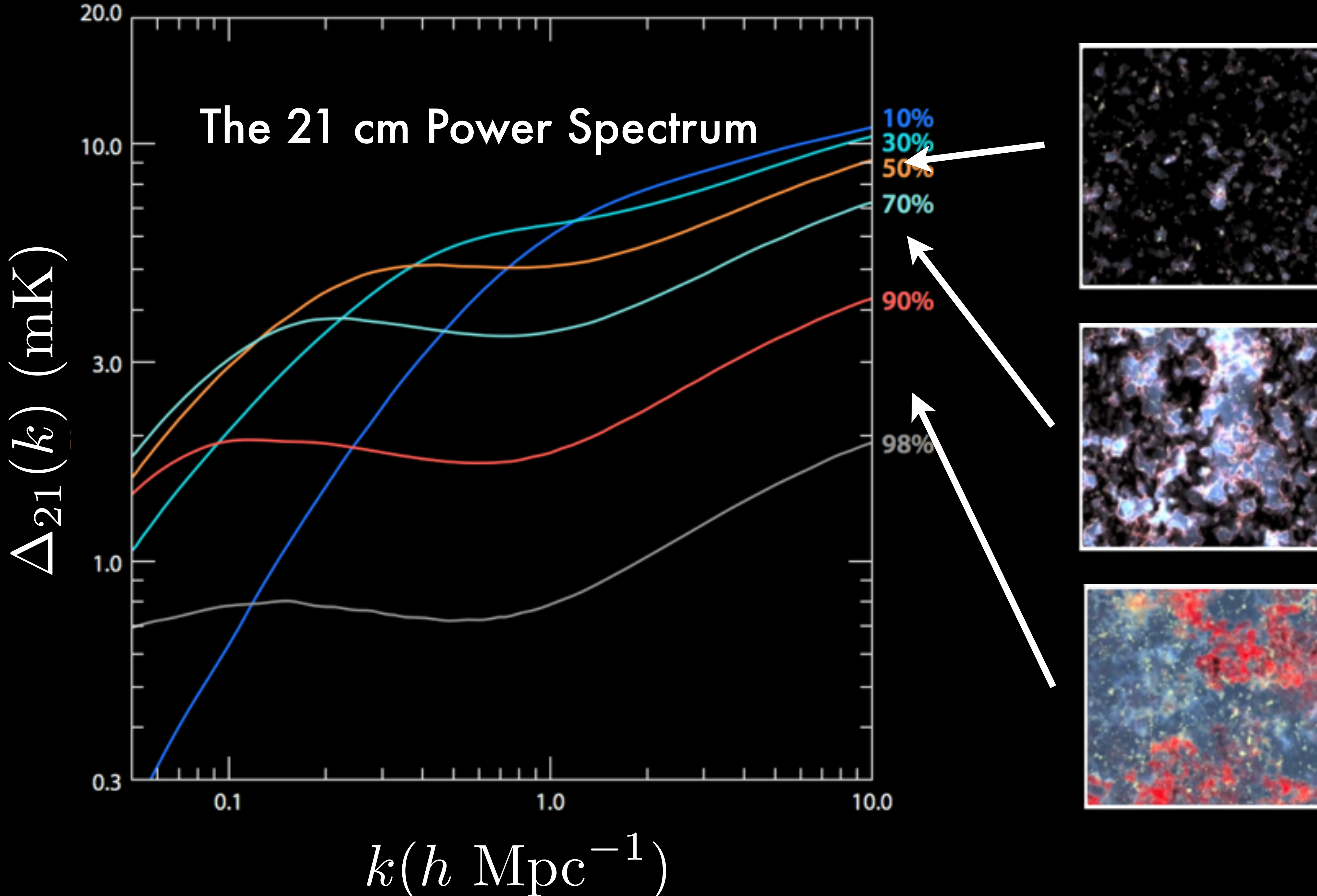
The problem is the foregrounds (our galaxy and other galaxies) that are in the way.







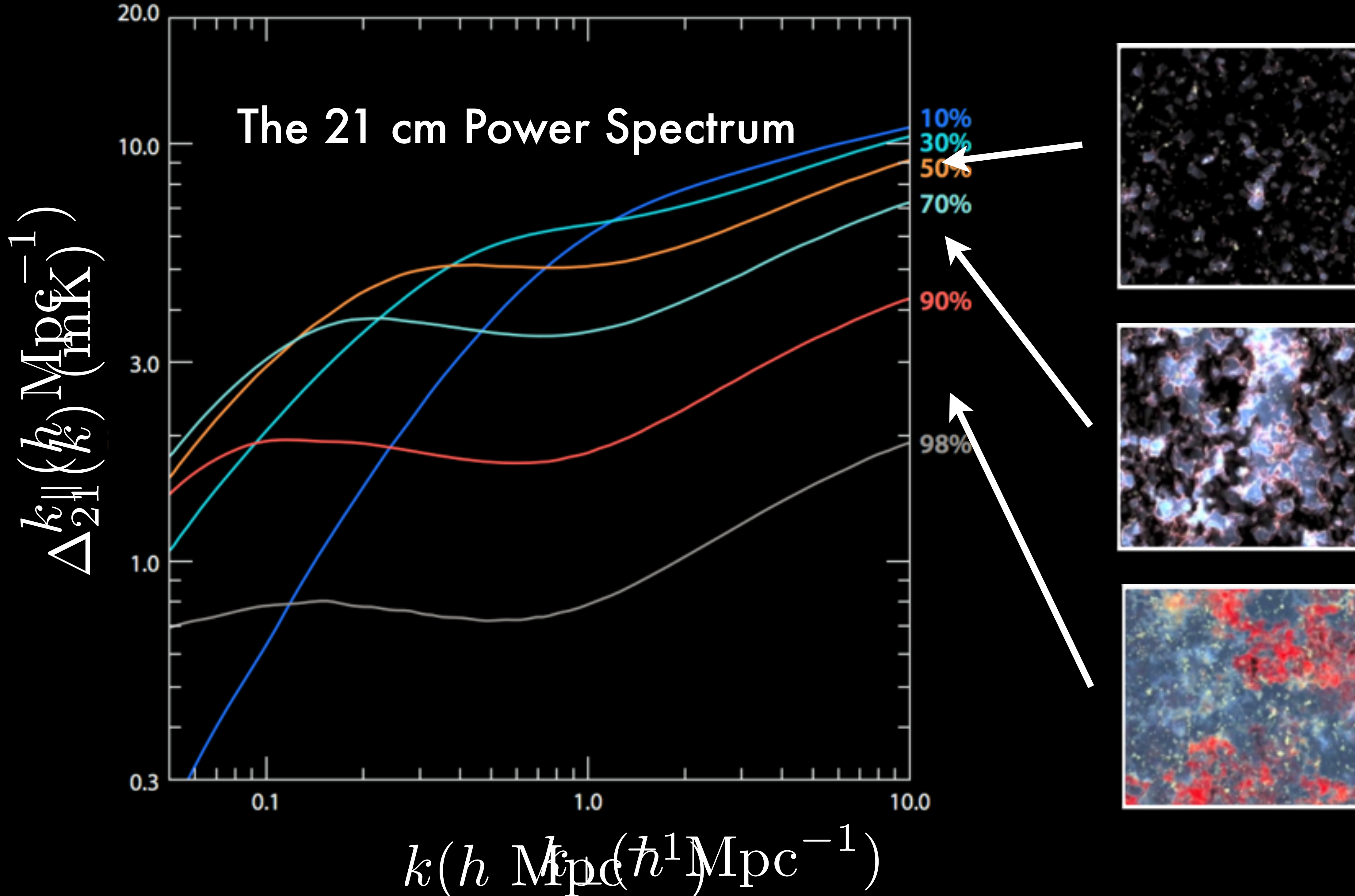
The first detection will be statistical.



Barkana (2009), Morales & Wyithe (2010)

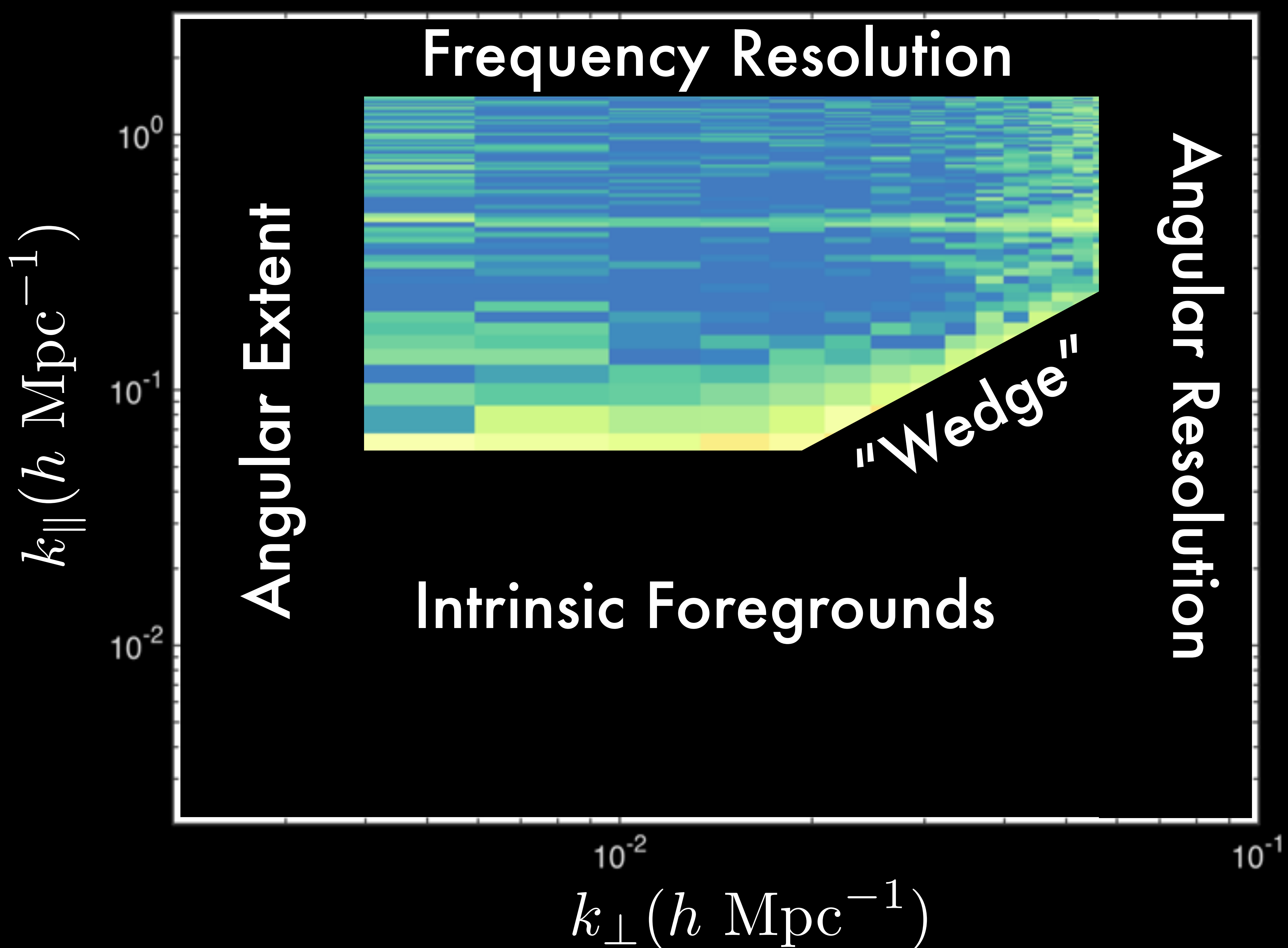
We separate out Fourier modes parallel and perpendicular to the line of sight.

But instead of spherically averaged Fourier space…

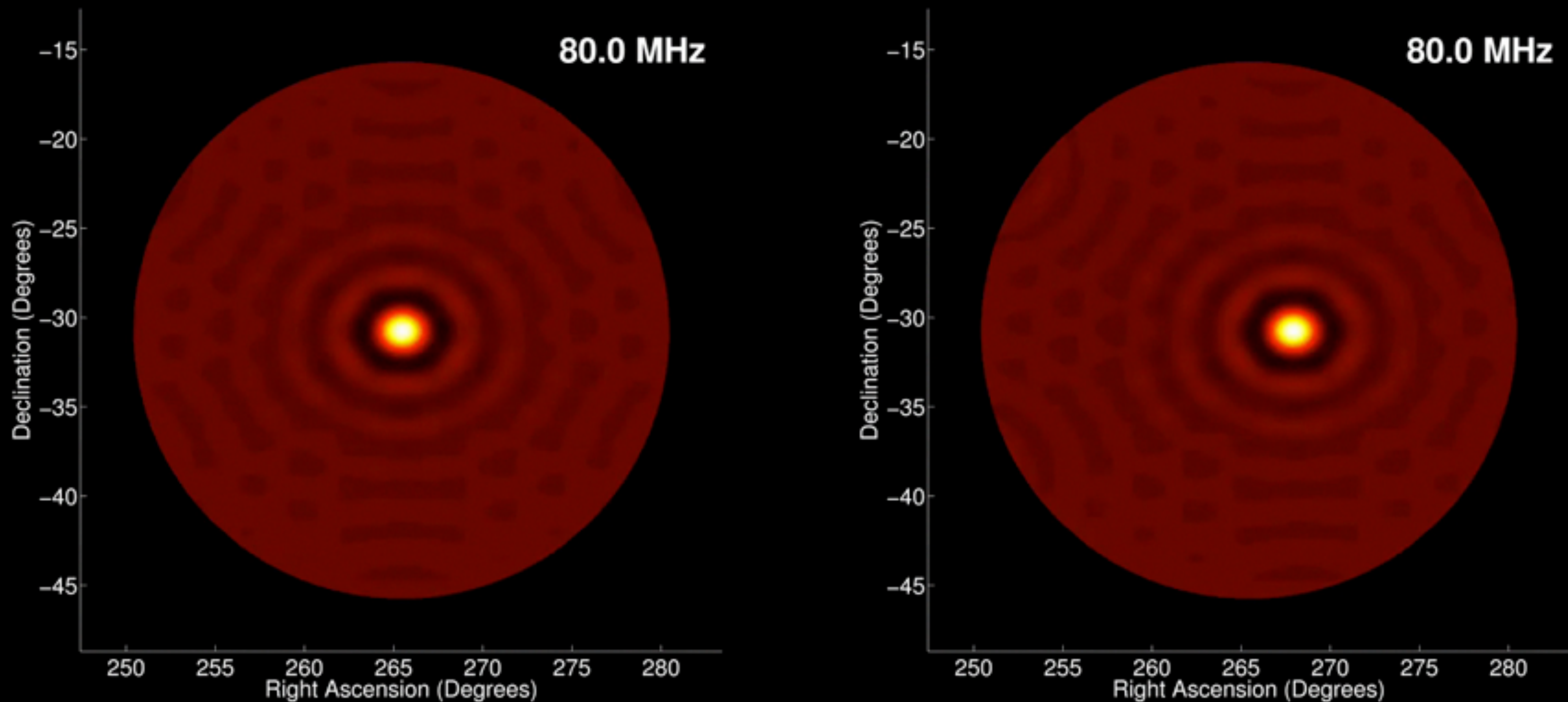


Barkana (2009), Morales & Wyithe (2010)

And we find an "EoR Window."

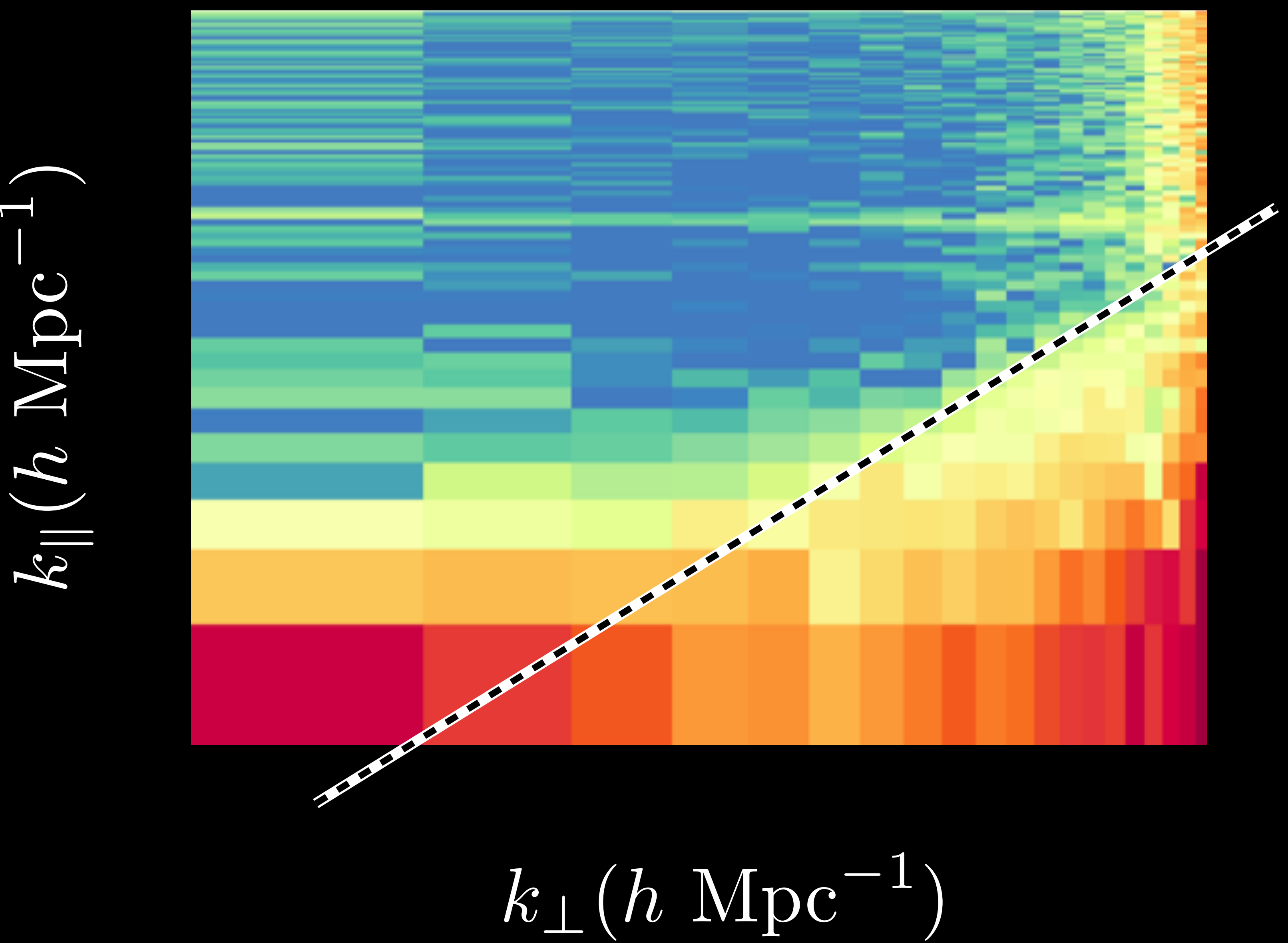


The "wedge" arises from the frequency-dependent point spread function creating spectral structure in spectrally smooth foregrounds.



Dillon et al. (2015)

The wedge is limited by geometry.



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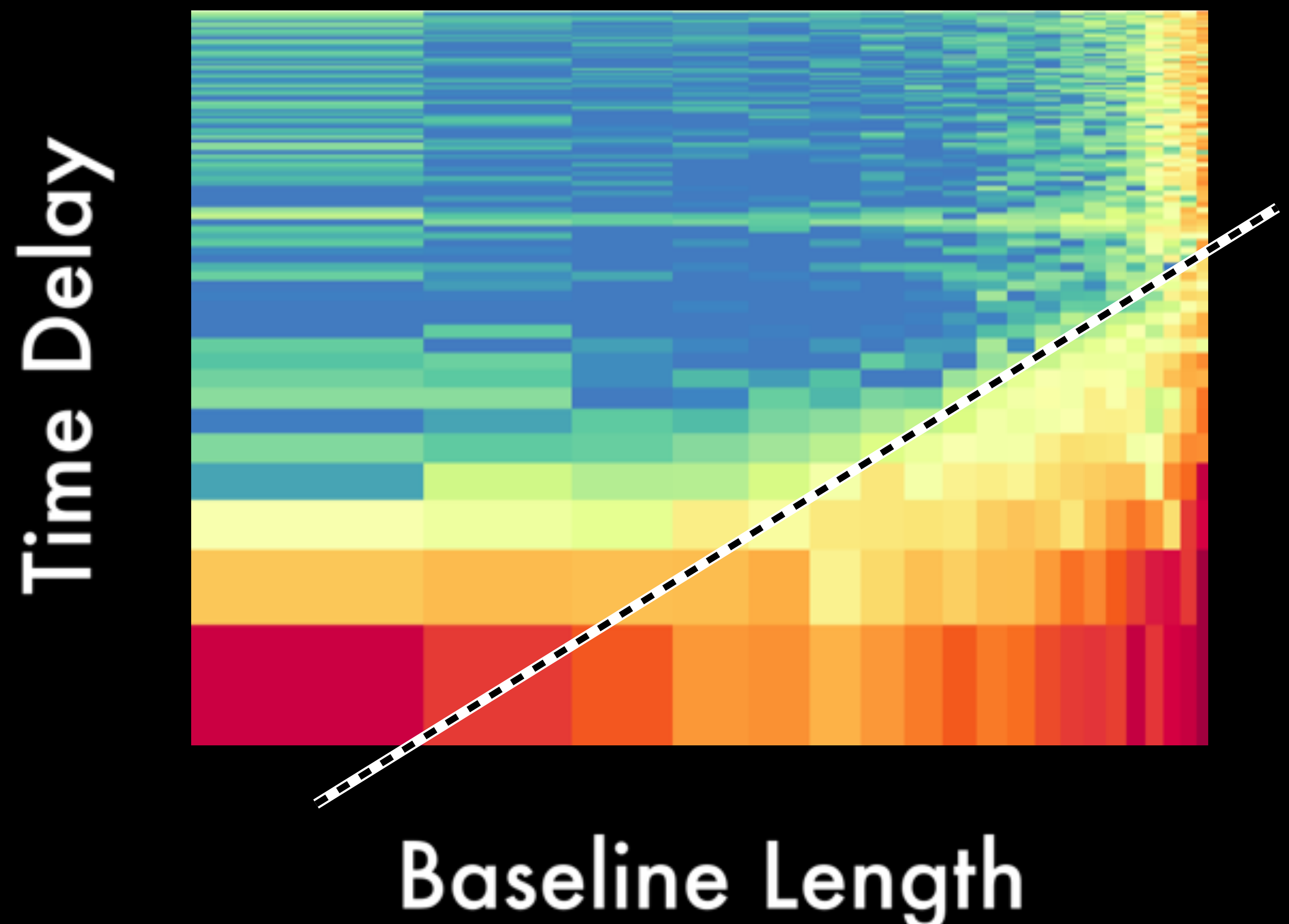
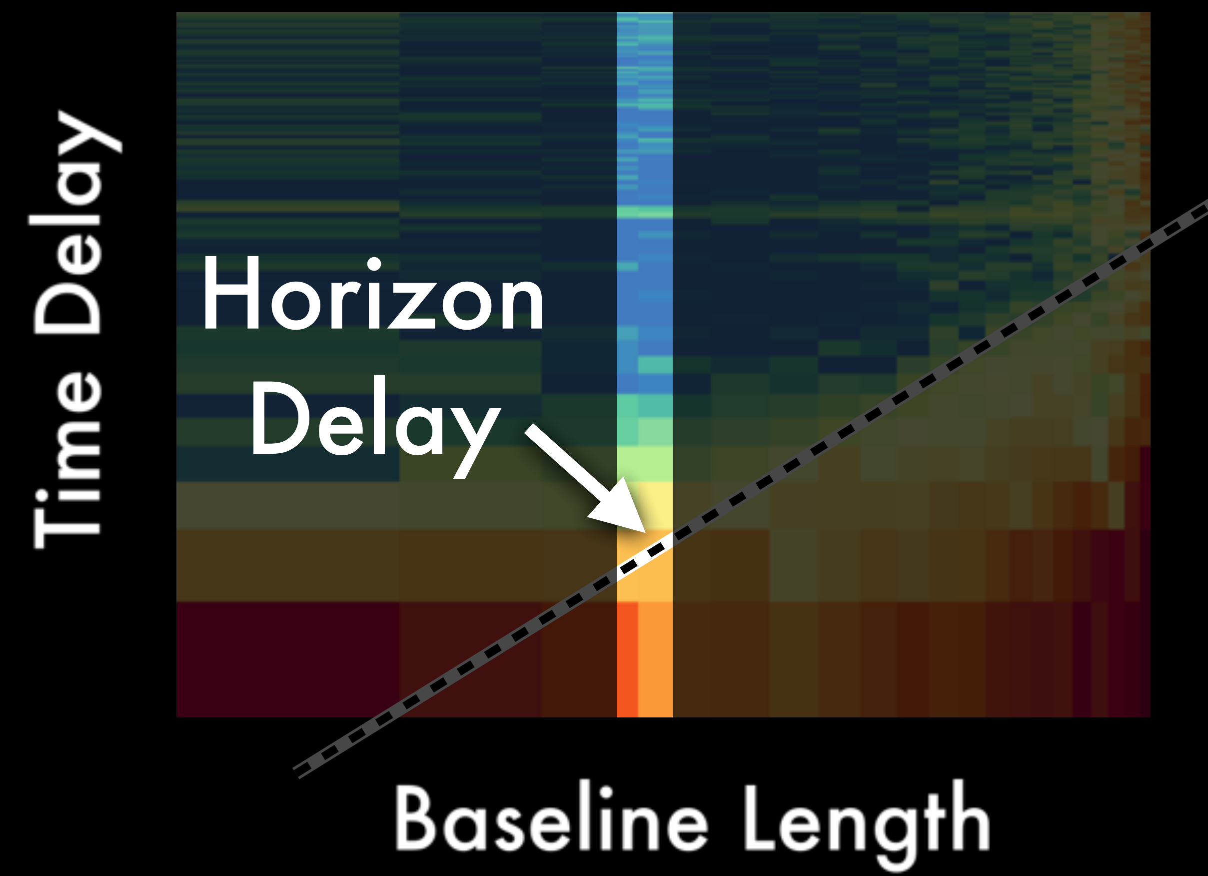
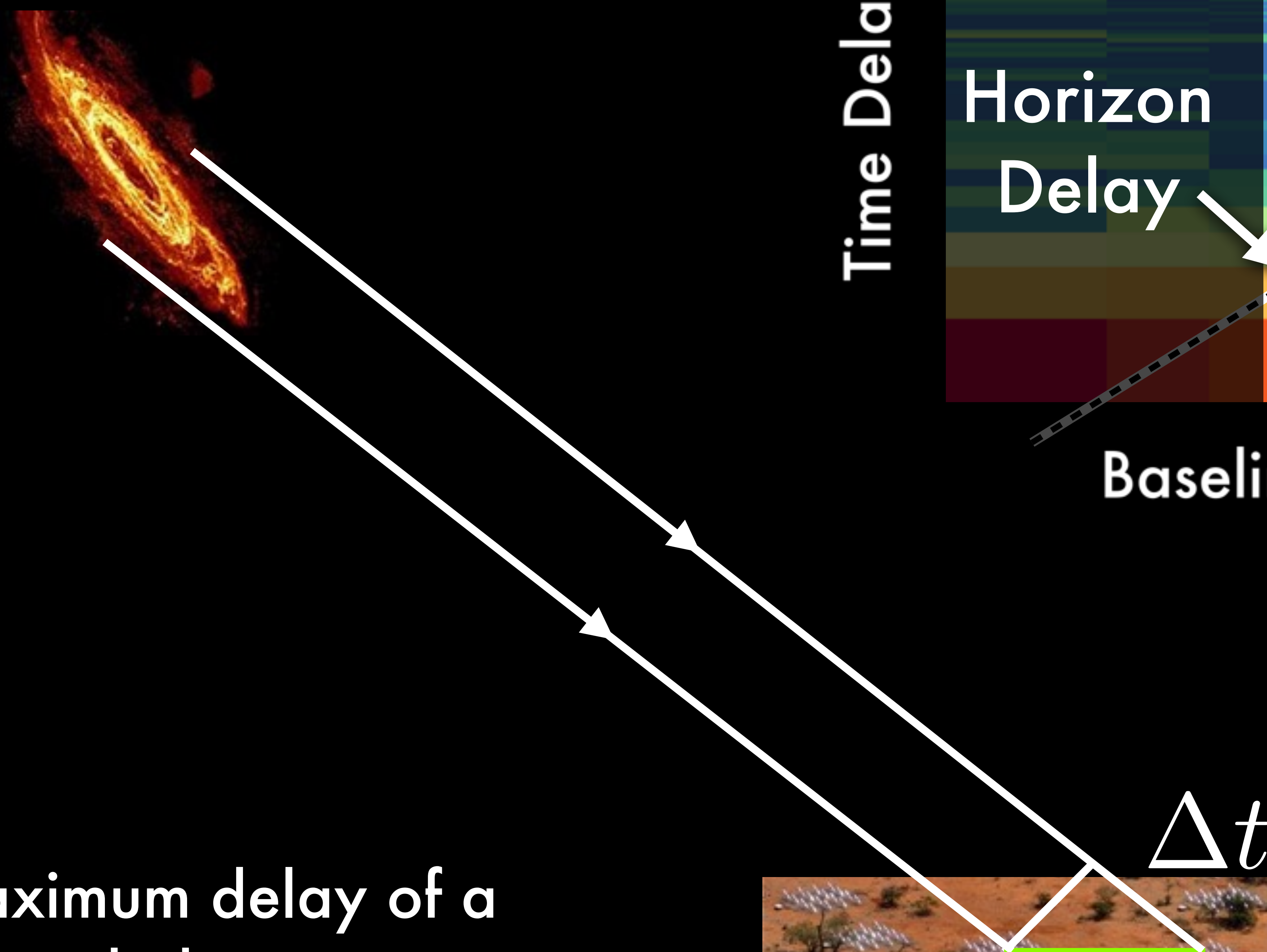
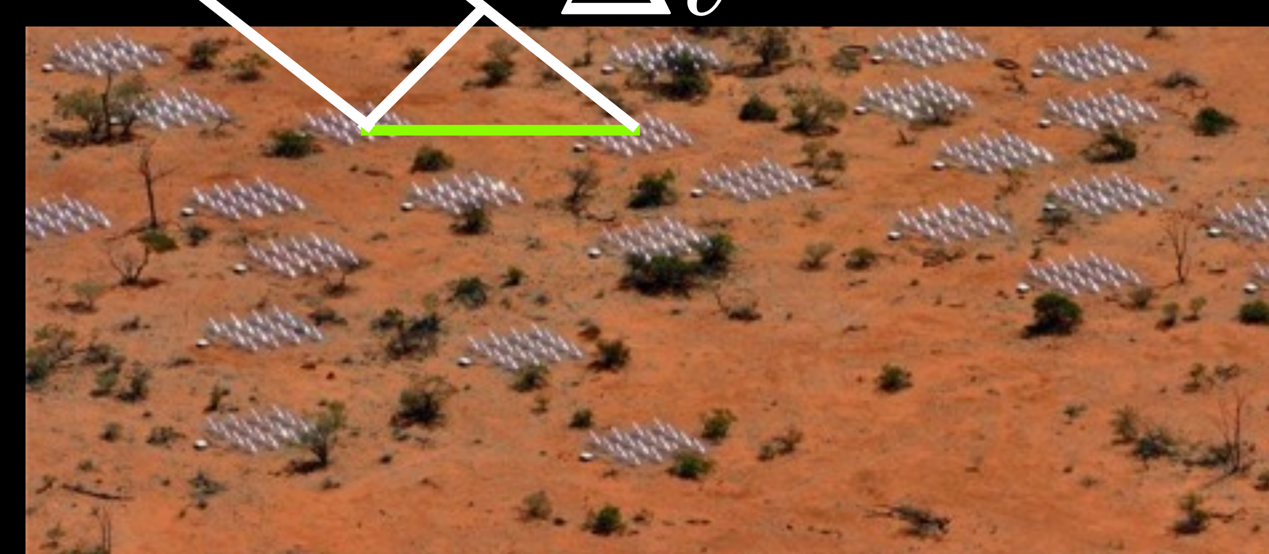


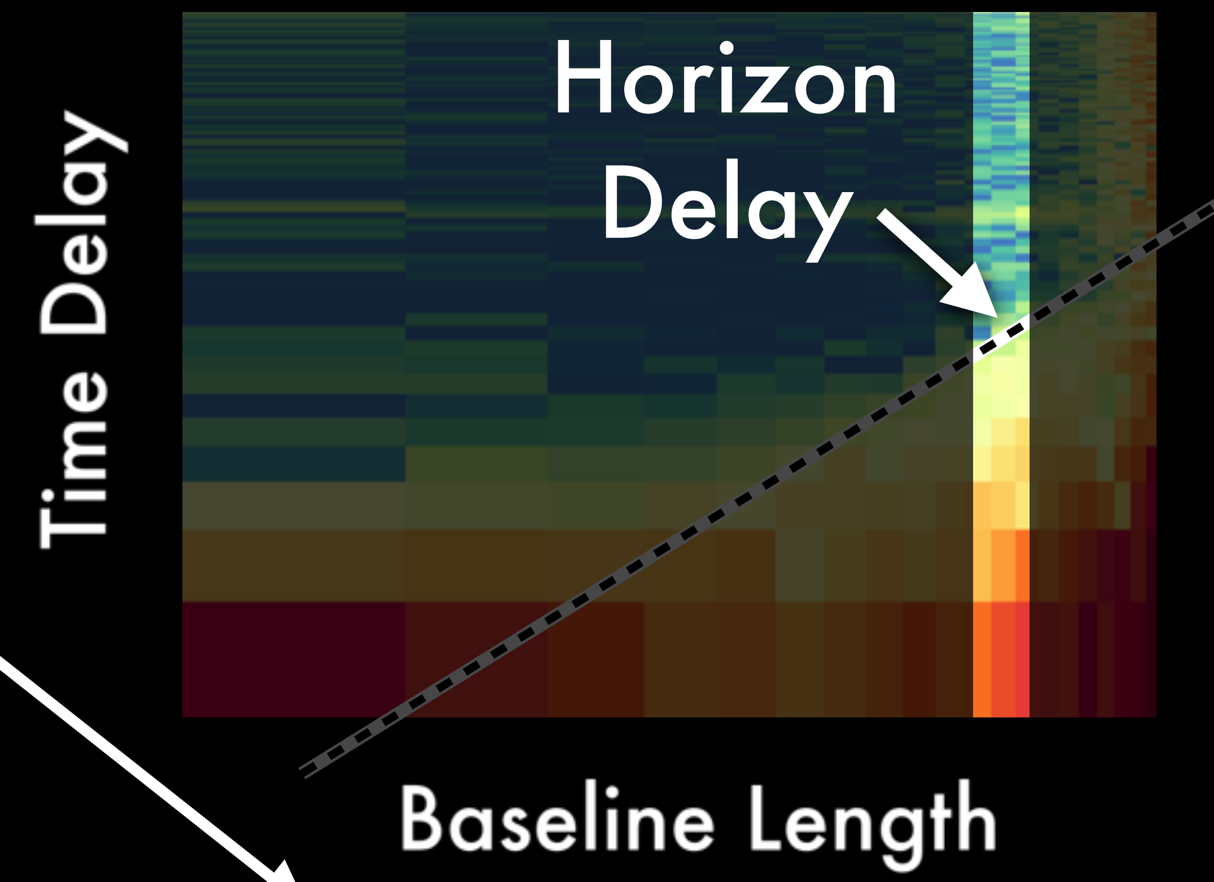


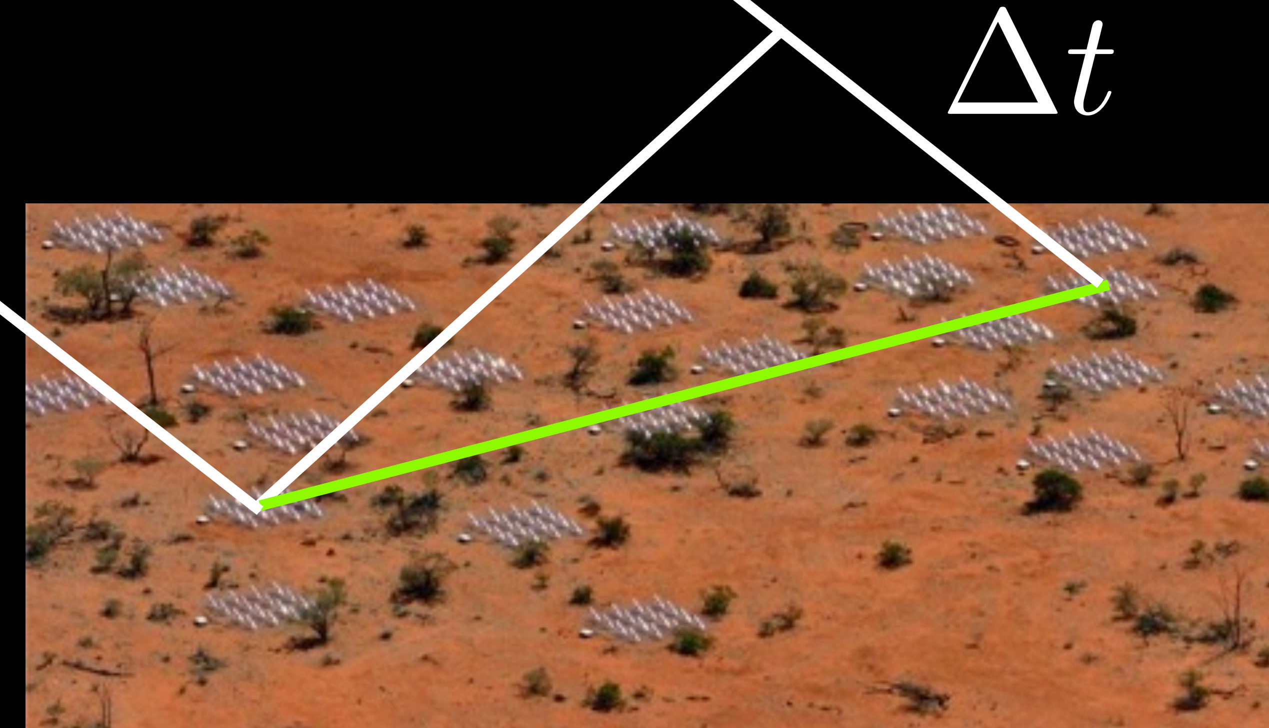




The maximum delay of a foreground object is set by the horizon and the length of the baseline.

Parsons et al. (2012)





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First generation interferometers are pursuing all sorts of different strategies for detecting the EoR.

And lots of related experiments in 21 cm Cosmology:
ASKAP, BAOBAB, BINGO, CHIME, CRT, DARE, EDGES, HIRAX
EMBRACE, GBT, KAT-7, LEDA, LWA, MeerKAT, SKA...and more.

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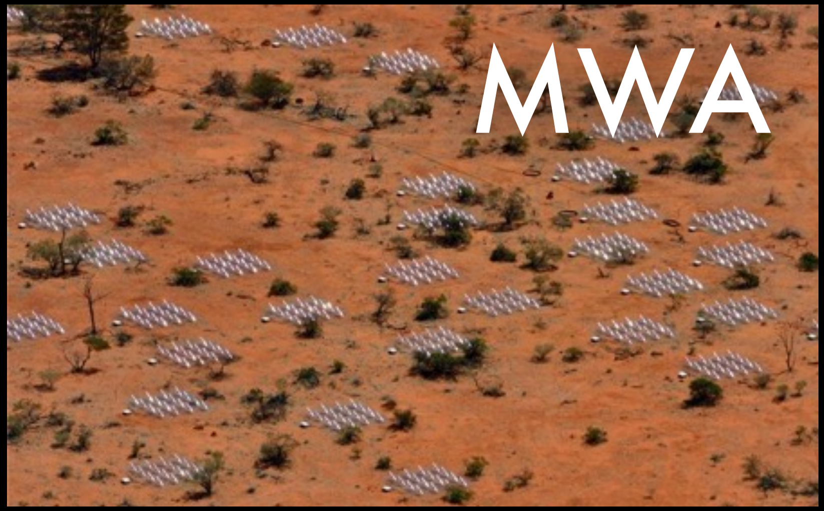

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ASKAP, BAOBAB, BINGO, CHIME, CRT, DARE, EDGES, HIRAX
EMBRACE, GBT, KAT-7, LEDA, LWA, MeerKAT, SKA...and more.

So, how do we keep the EoR window clean and understand our our measurements errors?

In an ideal world, there's an optimal estimator...

Invertible Normalization Matrix

Inverse Covariance Weighting

$$\mathbf{x}$$

Data

Fourier Transform and Bin

Quadratic Power Spectrum Estimator preserves all cosmological information (adapted from CMB and galaxy survey work)

Liu & Tegmark (2011)

...which we apply as best we can.

MWA: Noise and Foreground Weighting
PAPER: Delay-Filter and Weighting

$$\widehat{p}^{\beta} \equiv M^{\alpha\beta}\mathbf{x}^{\intercal}\mathbf{C}^{-1}\mathbf{Q}^{\alpha}\mathbf{C}^{-1}\mathbf{x}$$

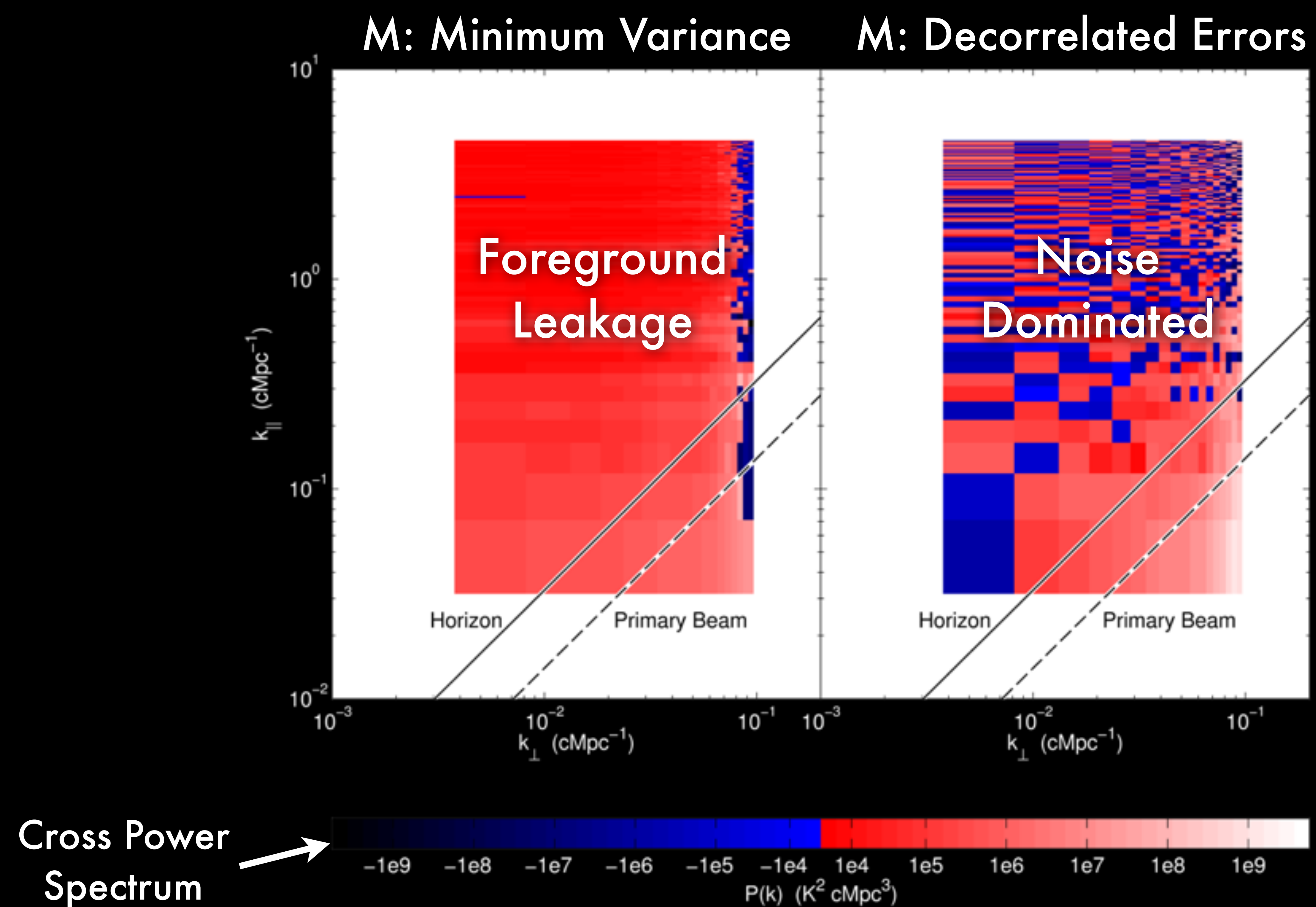
MWA: Image Cubes
PAPER: Visibilities

MWA: Fourier Transform and Bin
PAPER: Combine Redundant Visibilities

Liu & Tegmark (2011)

A good estimator helps preserve the EoR Window.

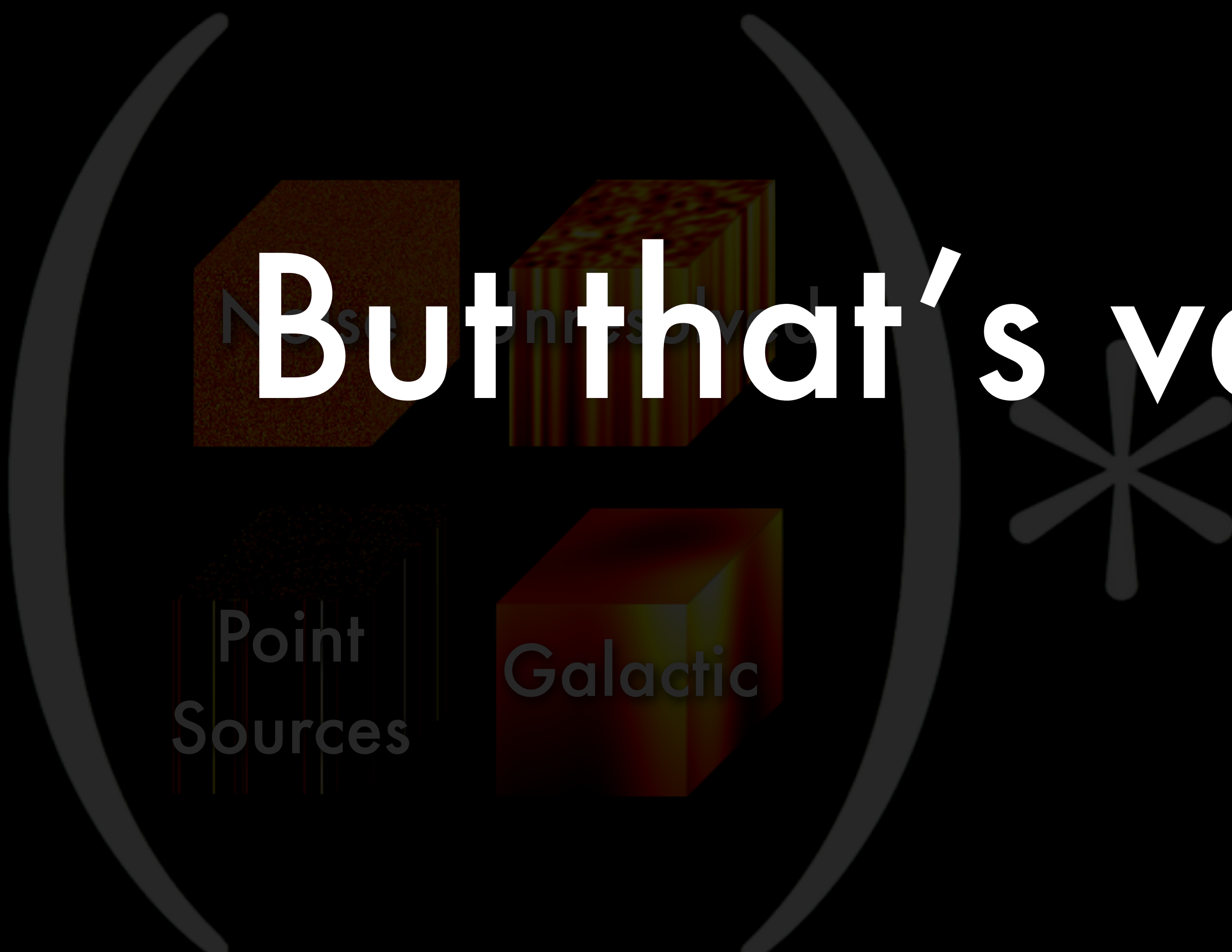
$$\mathrm{Cov}(\widehat{\mathbf{p}}) = \mathbf{M}\mathbf{F}\mathbf{M}^{\mathsf{T}}$$



Dillon et al. (2014)

We also learned that we needed to better understand the noise and foregrounds covariances better.

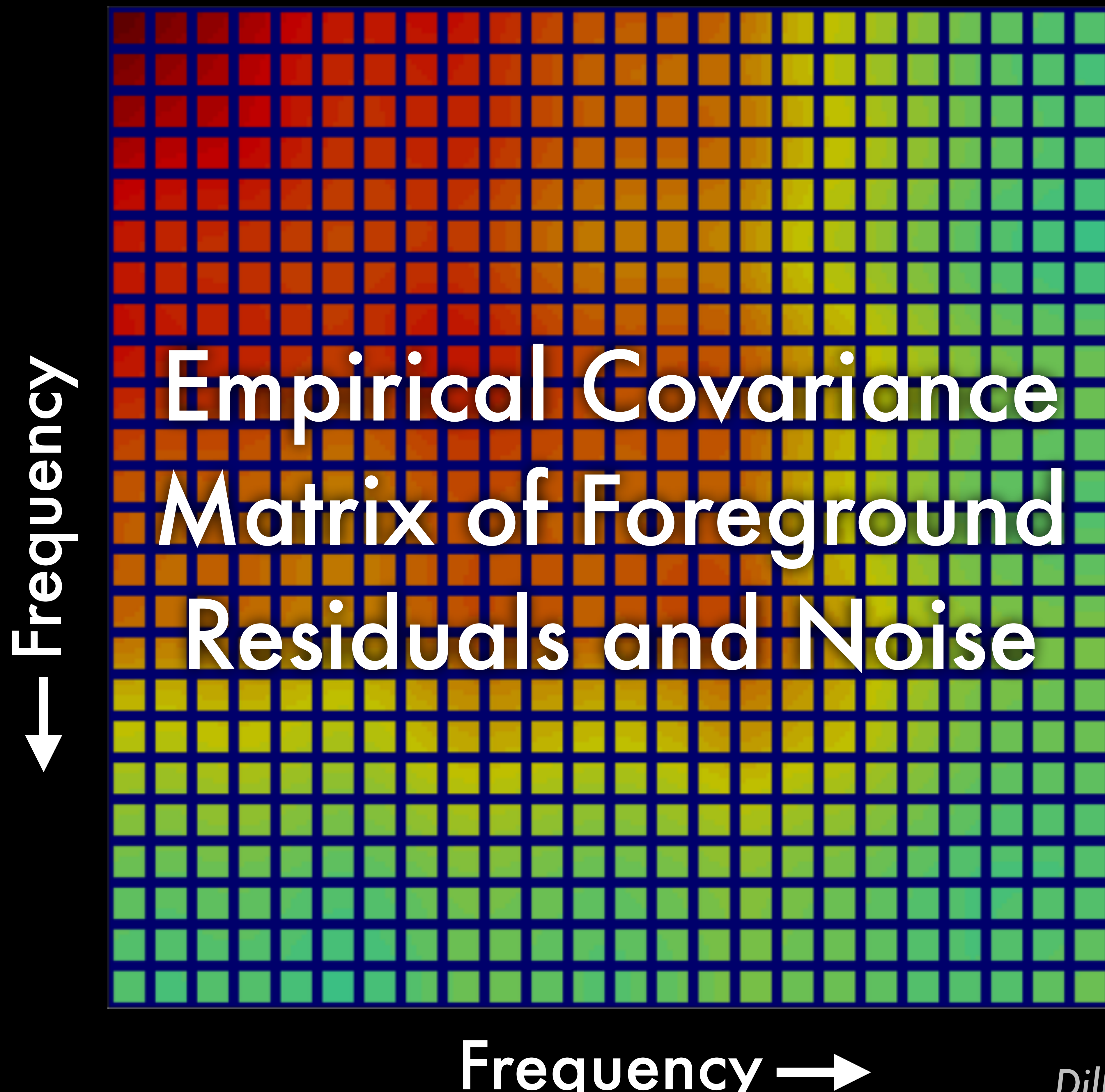
We could try to precisely model our residuals and propagate them to uncertain instrument model…



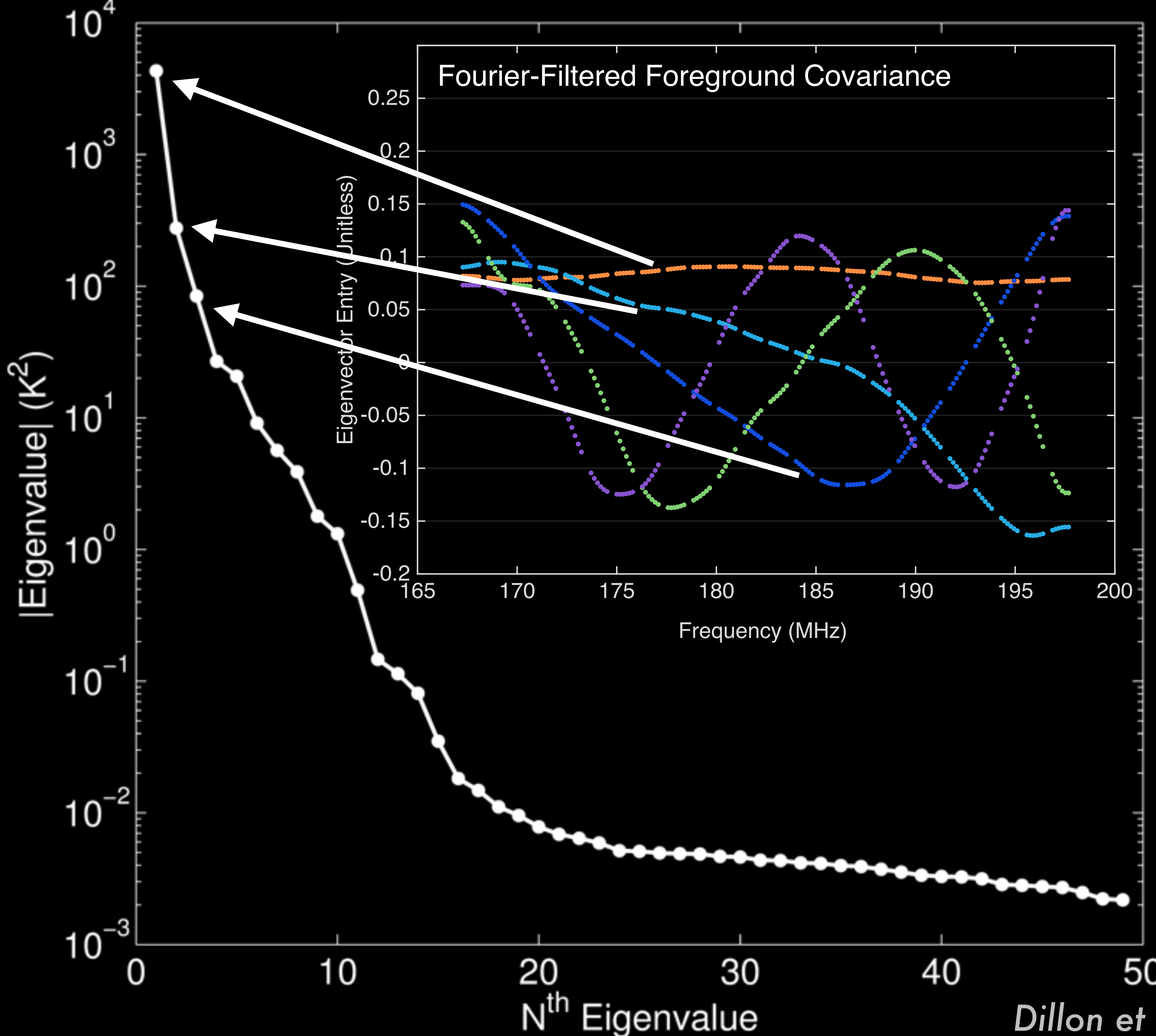
But that's very hard.

Dillon et al. (2013)

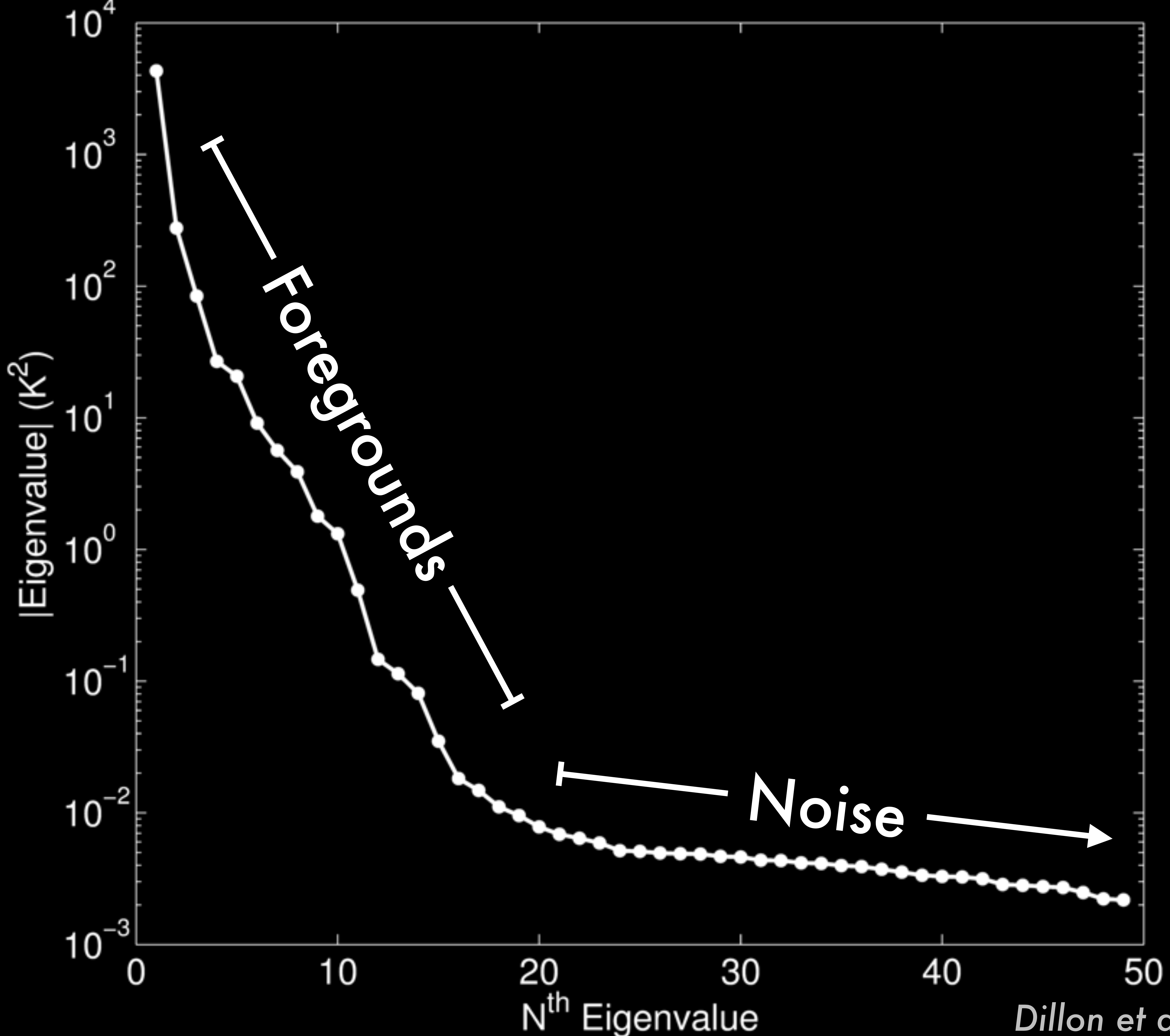
Dillon et al. (2015)



Dillon et al. (2015)

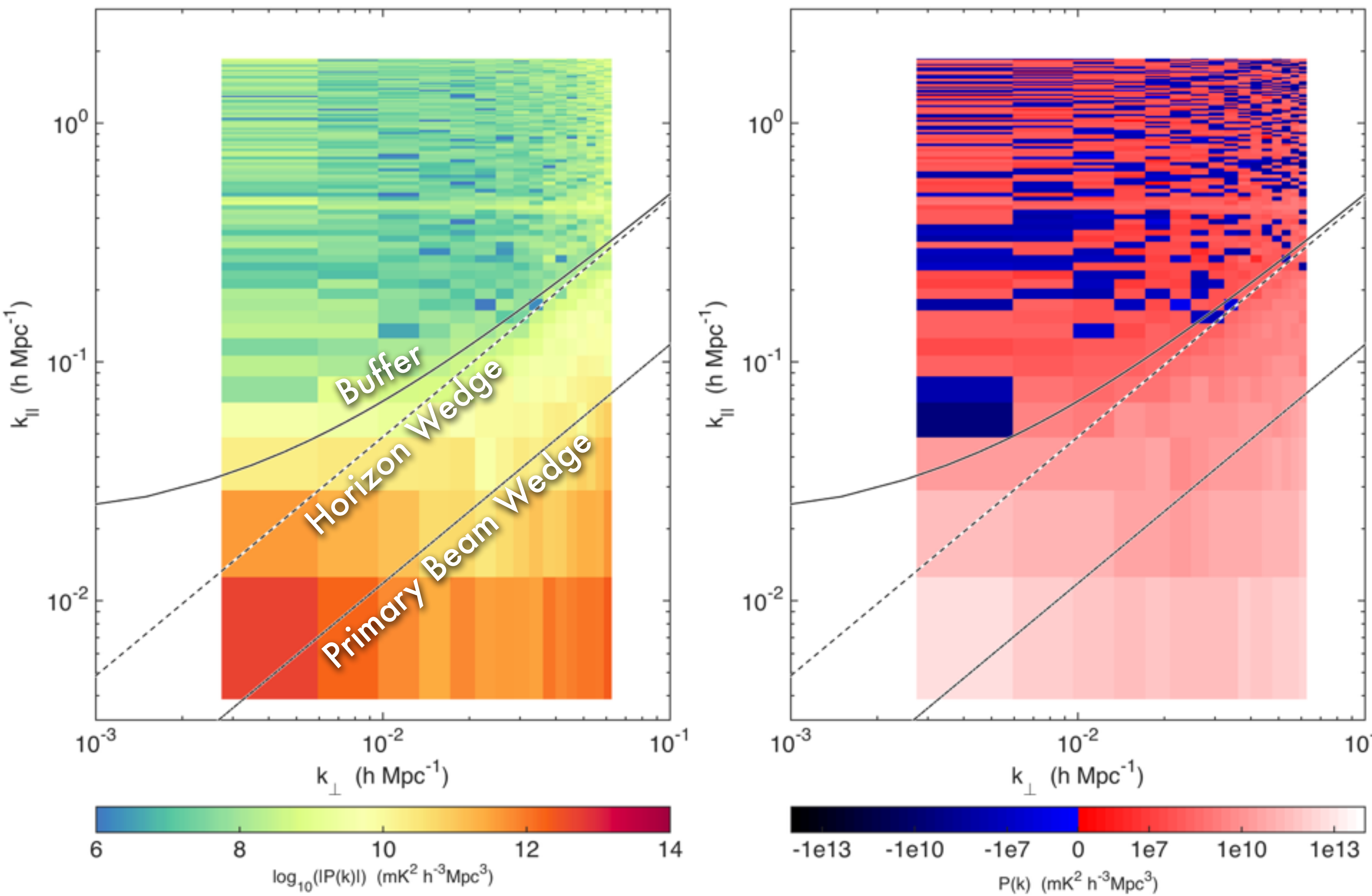


Dillon et al. (2015)



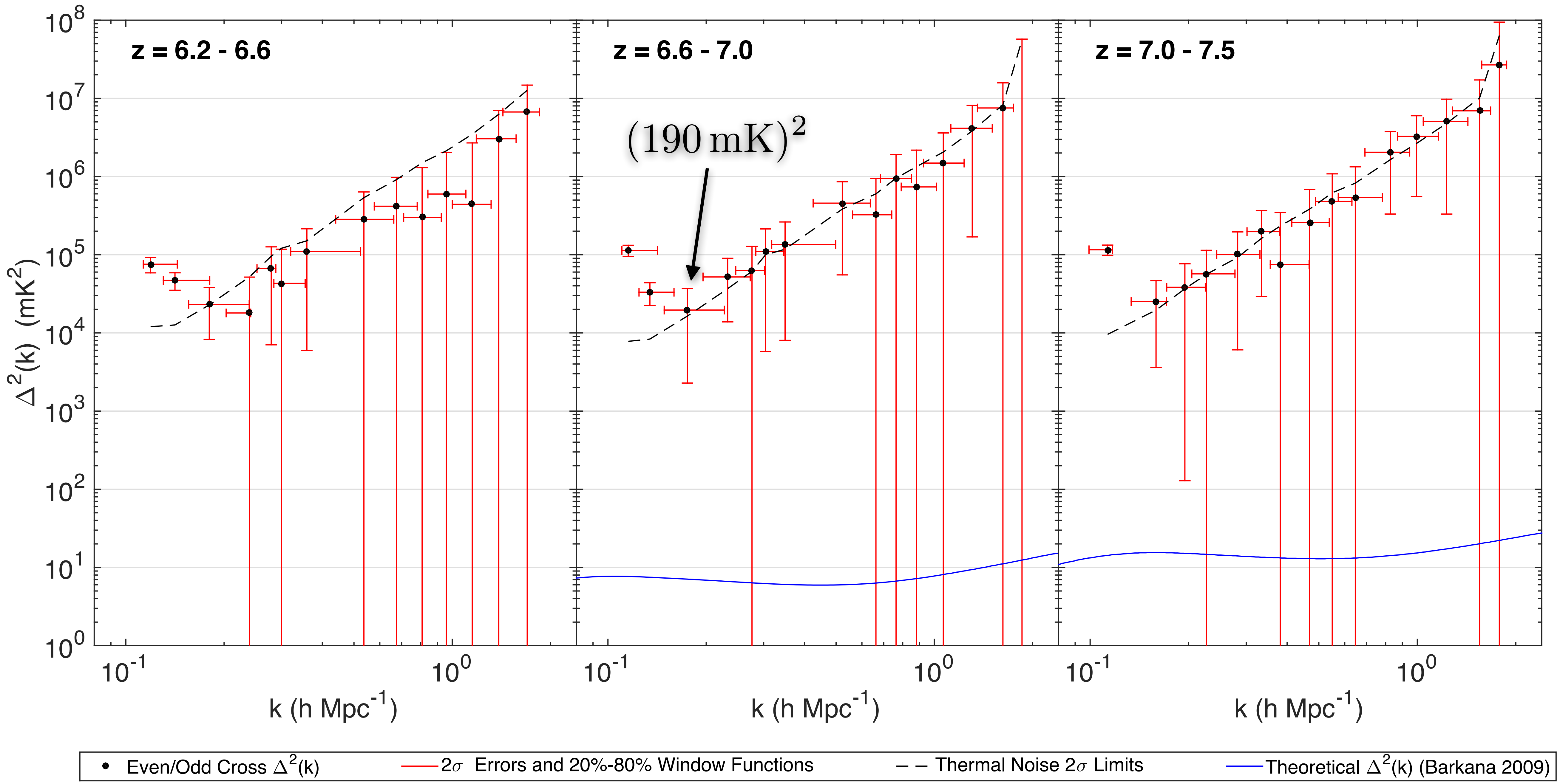
Dillon et al. (2015)

3 Hour MWA Observations at $z \approx 7$



Dillon et al. (2015)

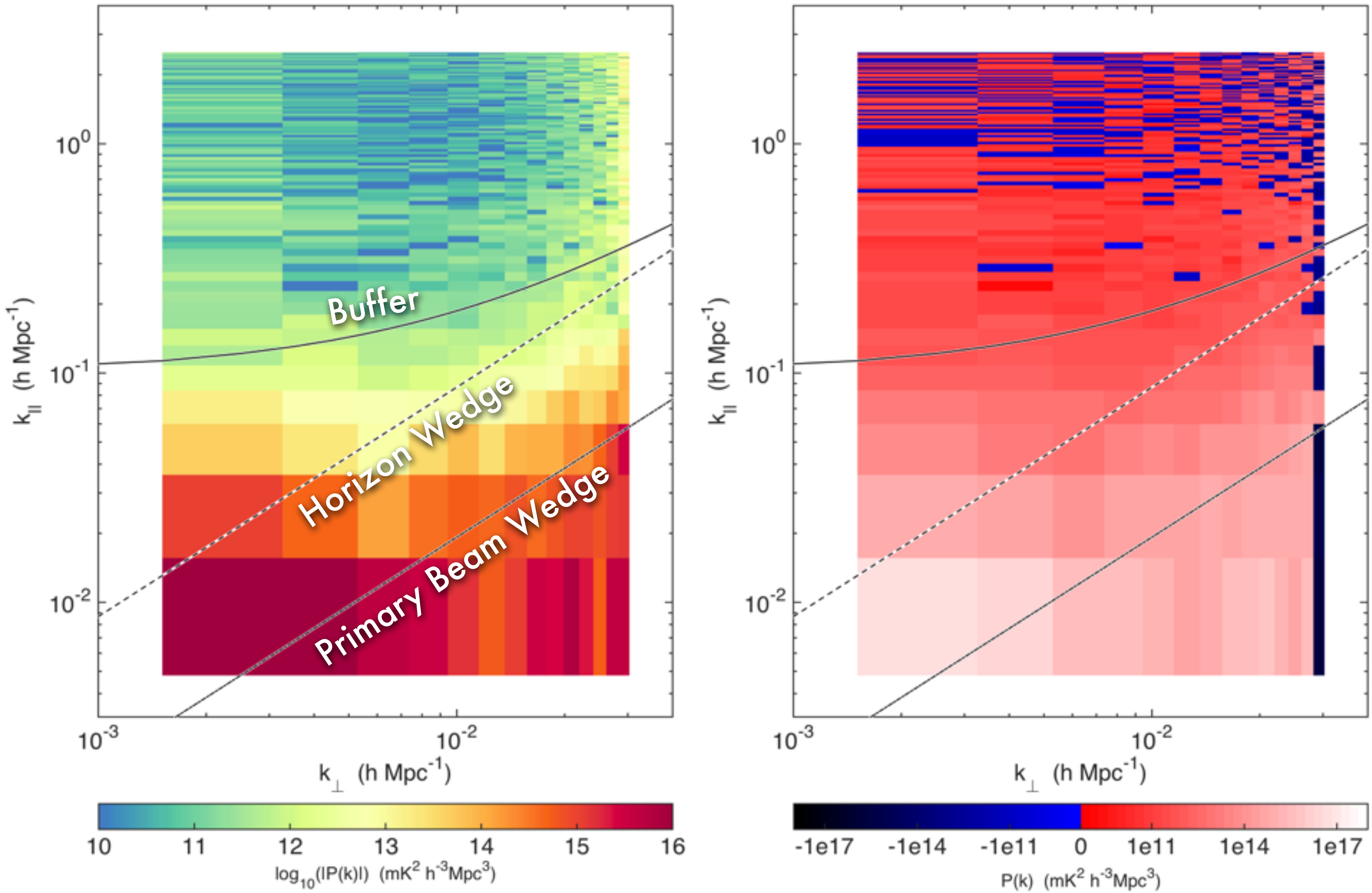
3 Hour MWA Observations at z ≈ 7



Deeper integrations are coming (look for Beardsley et al. and Neben et al. next year.)

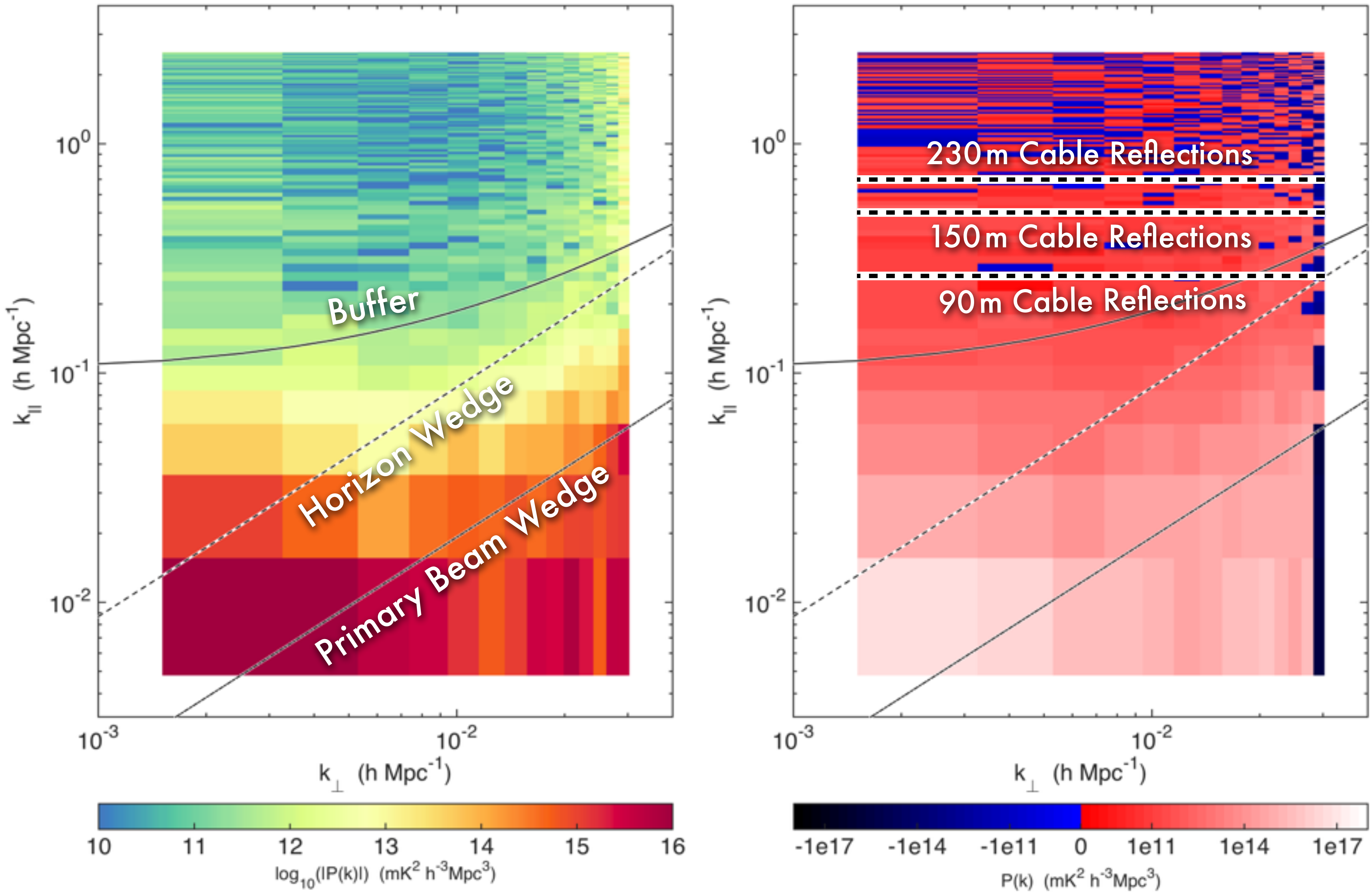
Dillon et al. (2015)

We've also observed at z ≈ 16 to study the EoX.



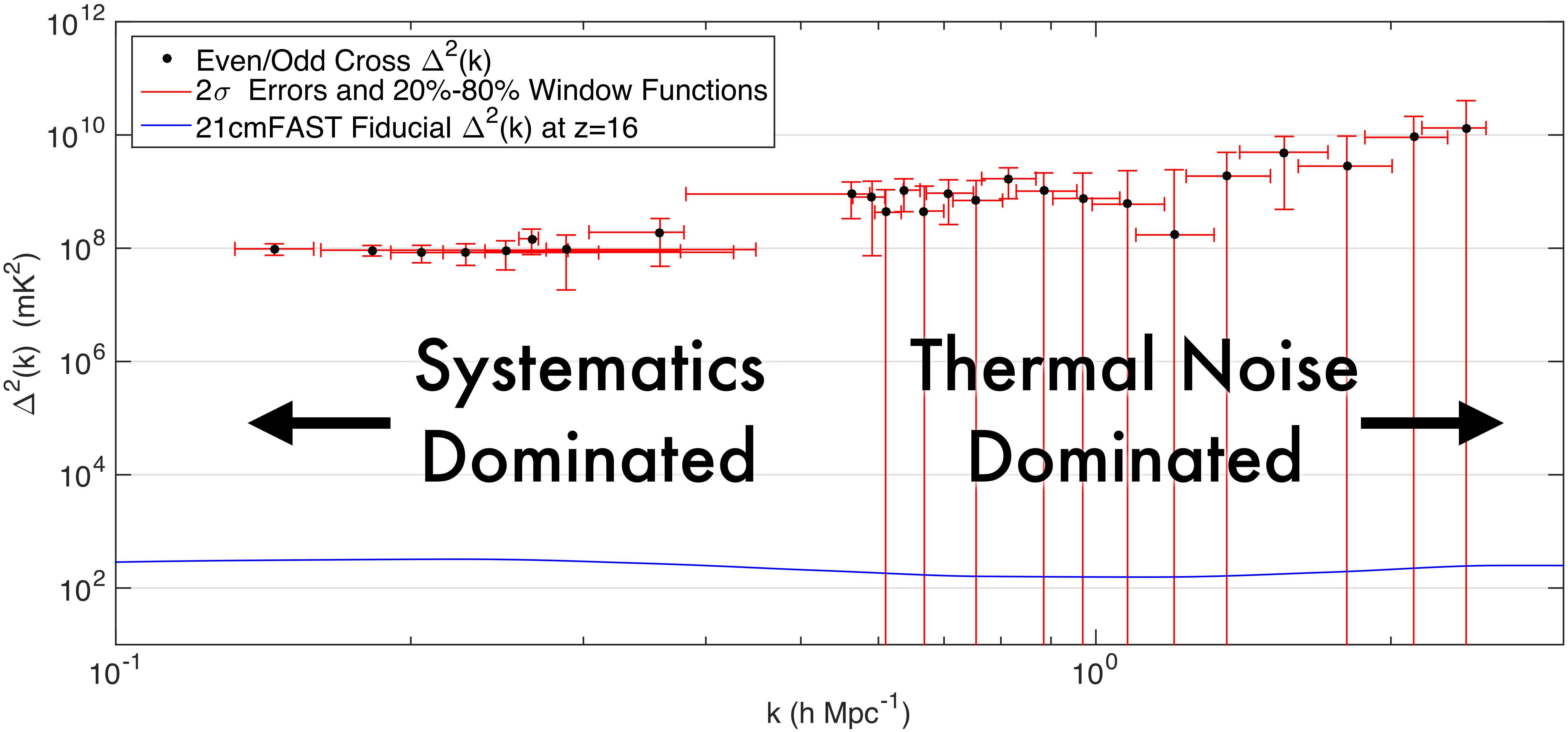
Ewall-Wice, Dillon, et al. (in review)

We're limited by spectral structure in our bandpass.



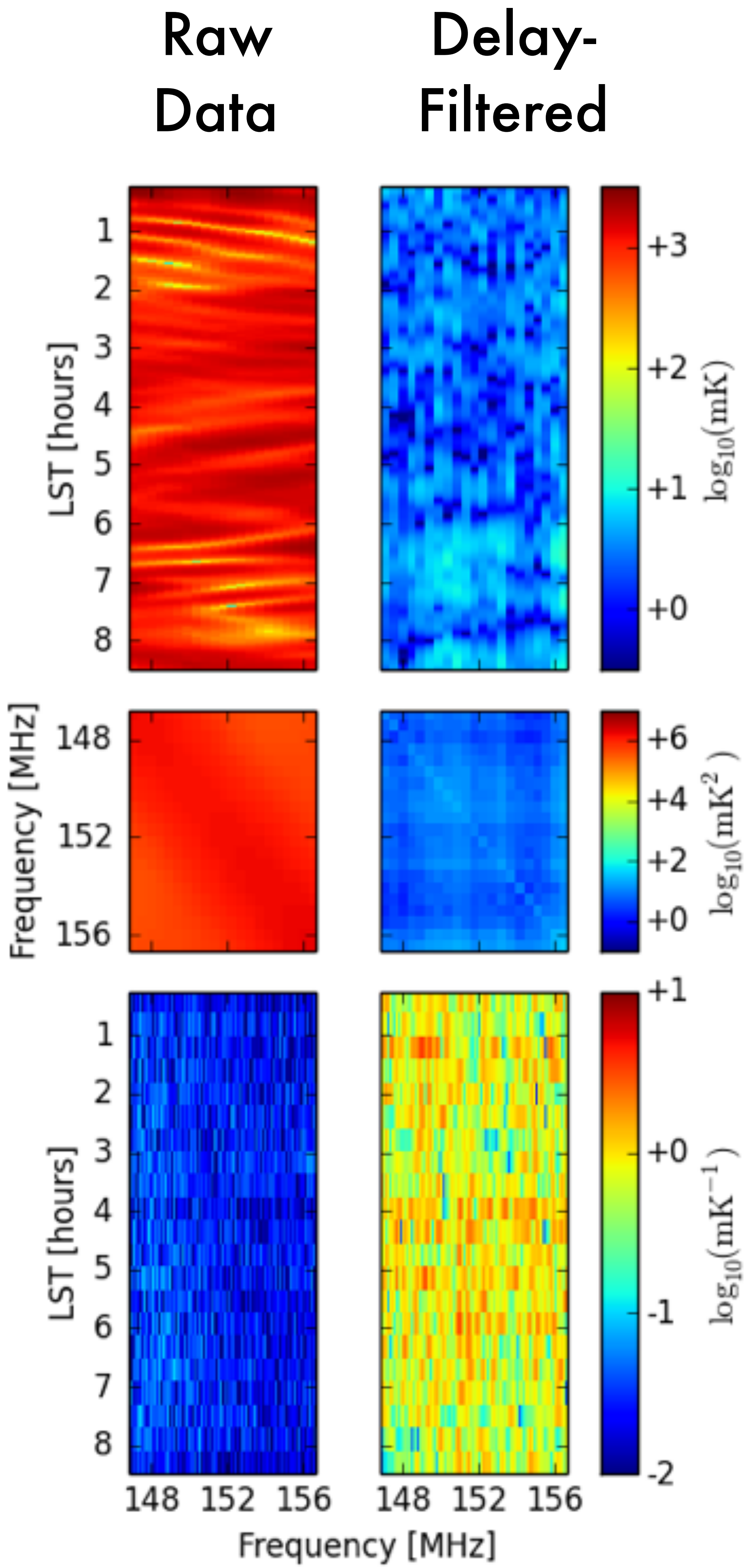
Ewall-Wice, Dillon, et al. (in review)

Even with only a few hours of observation, bandpass structure limits our EoX power spectra.



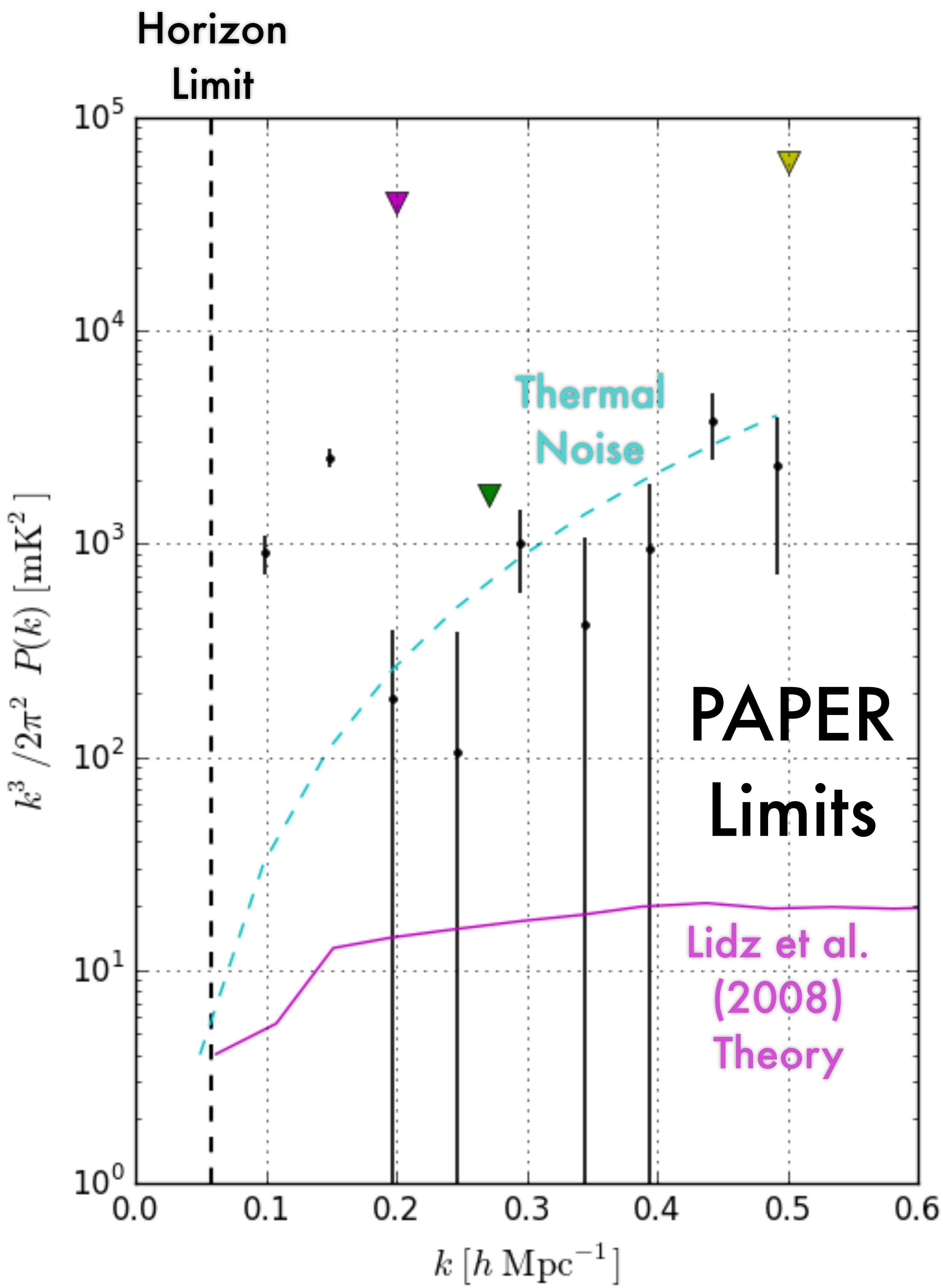
Limits: $2.5 \times 10^7 \text{mK}^2$, 8.3×10^7 mK^2, and 2.7×10^8 mK^2 at z = 12.2, 15.4, and 17.5

Ewall-Wice, Dillon, et al. (in review)



The PAPER team, using a lot more data and the same empirical freq-freq covariance technique to downweight residual spectral structure...

Ali et al. (2015)

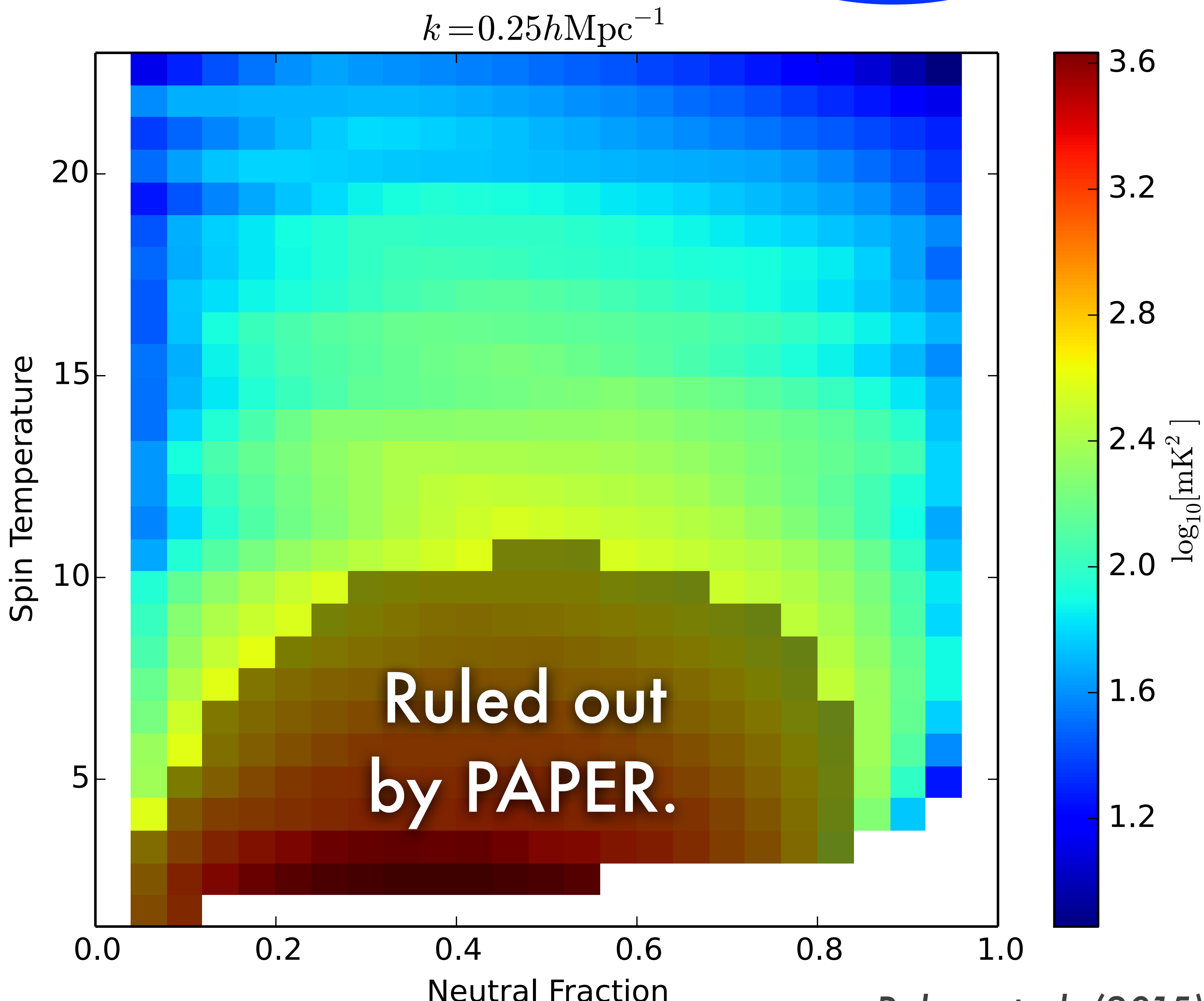


...set the best limits on the 21 cm power spectrum to date: $\Delta^2(k) < (22\text{ mK})^2$ at 2σ, $z = 8.4$, and $0.15 < k < 0.5h\text{ Mpc}^{-1}$.

Ali et al. (2015)

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

PAPER-64 results constrain the IGM spin temperature at z = 8.4.



Pober et al. (2015)

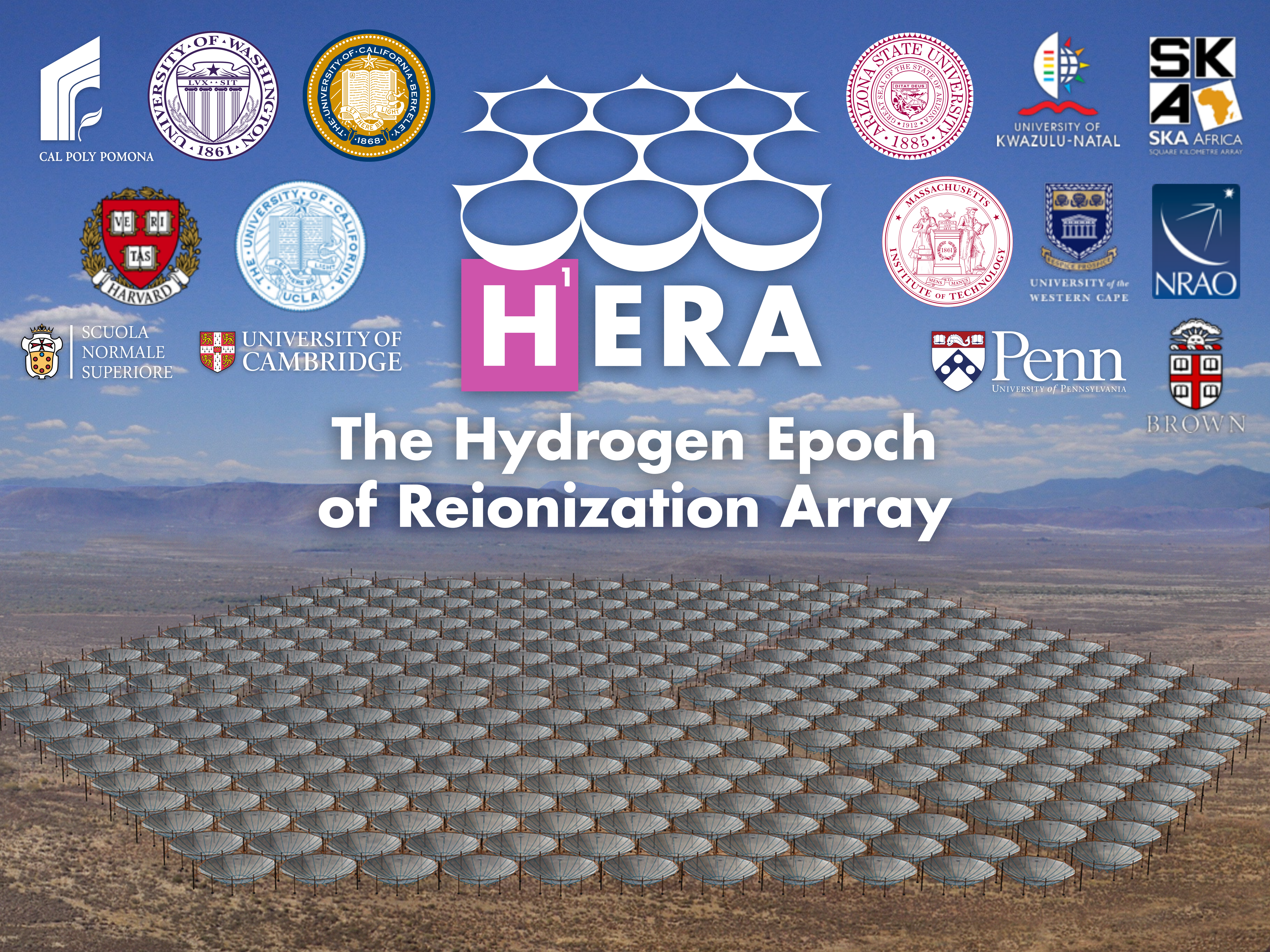
Our upper limits keep marching down...

[REMOVED UNPUBLISHED FIGURE]

(PRELIMINARY)

Kolopanis et al. (in prep.)


We hope for results this year, but that will be it
for PAPER, since PAPER has been replaced by…


CAL POLY POMONA
UNIVERSITY OF WASHINGTON 1861
THE UNIVERSITY OF CALIFORNIA BERKELEY 1868
ARIZONA STATE UNIVERSITY 1885
UNIVERSITY OF KWAZULU-NATAL
SKA AFRICA
SQUARE KILOMETRE ARRAY
HARVARD
THE UNIVERSITY OF CALIFORNIA UCLA
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
UNIVERSITY of the WESTERN CAPE
NRAO
SCUOLA NORMALE SUPERIORE
UNIVERSITY OF CAMBRIDGE
HERA
Penn
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The Hydrogen Epoch of Reionization Array

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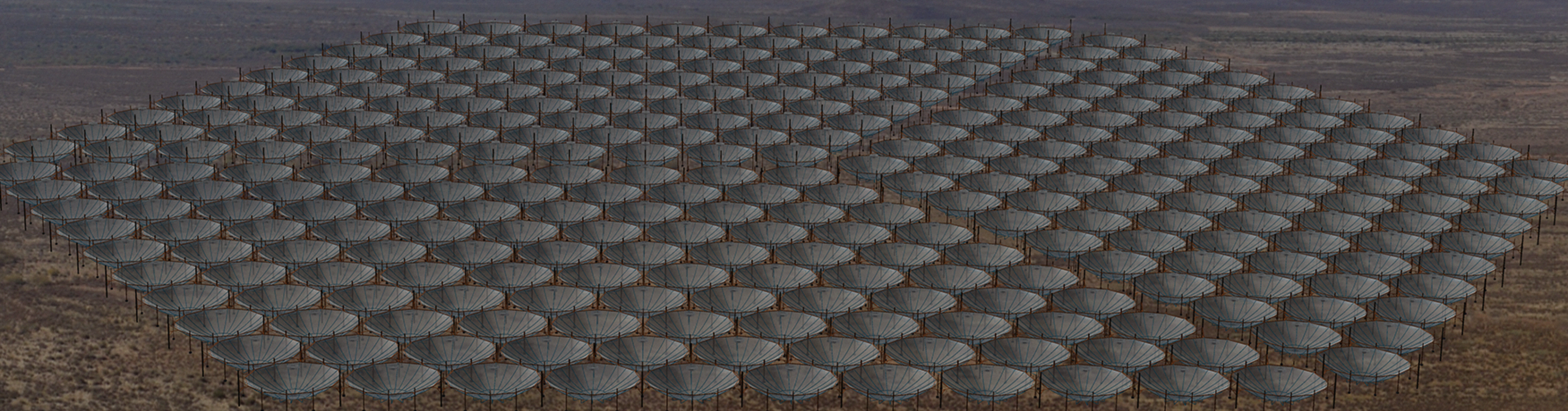
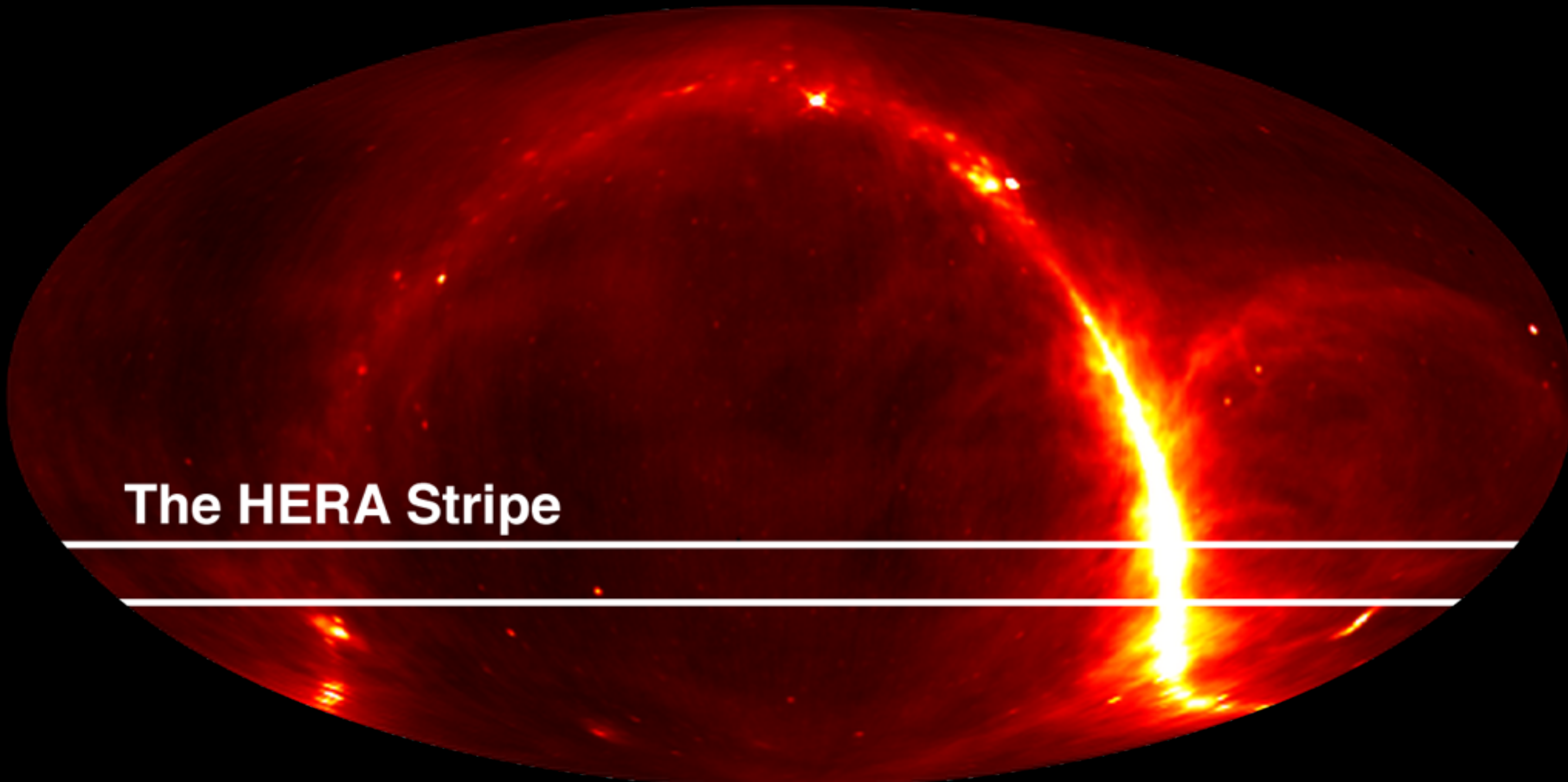
UNIVERSITY of PENNSYLVANIA
BROWN
NSF

HERA will have:

- 350 stationary dishes that vastly increase sensitivity at the cost of field of view.



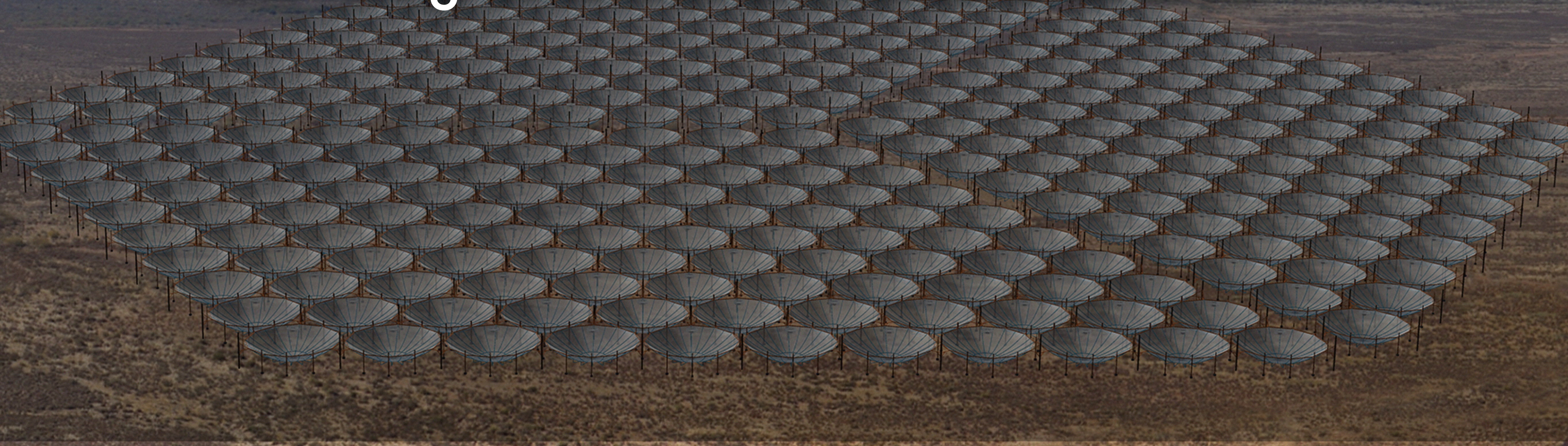

The first 19 HERA elements in are now
being commissioned in South Africa
14 m diameter dishes



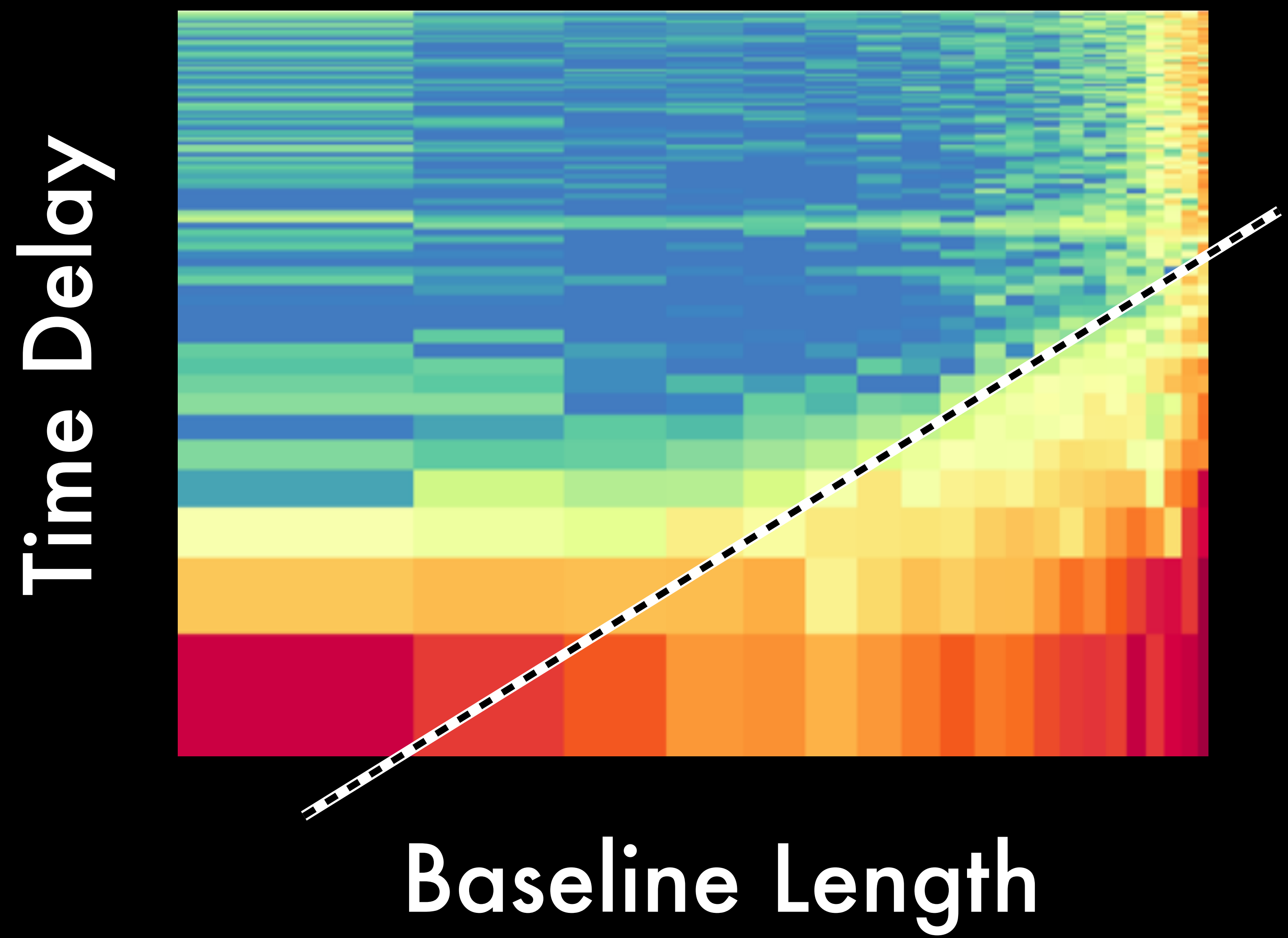
HERA is a drift scan instrument that maps out a stripe of constant declination.

HERA will have:

- 350 stationary dishes that vastly increase sensitivity, at the cost of field of view.
- Compact design with high sensitivity to short, less foreground-contaminated baselines.



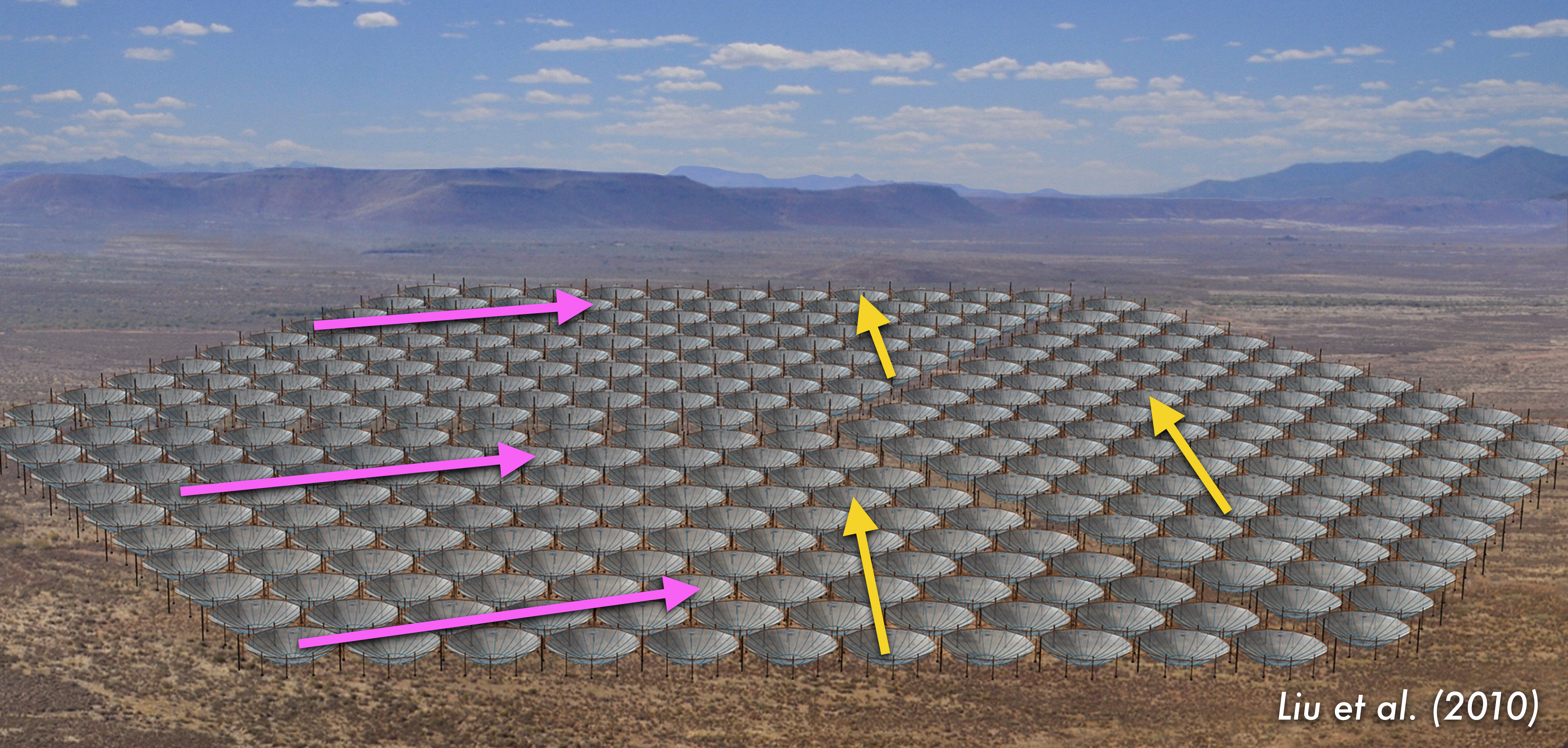
Recall, shorter baselines have "less wedge" in them.



HERA will have:

- 350 stationary dishes that vastly increase sensitivity, at the cost of field of view.
- Compact design with high sensitivity to short, less foreground-contaminated baselines.
- A configuration that enables both precise redundant calibration and widefield imaging.

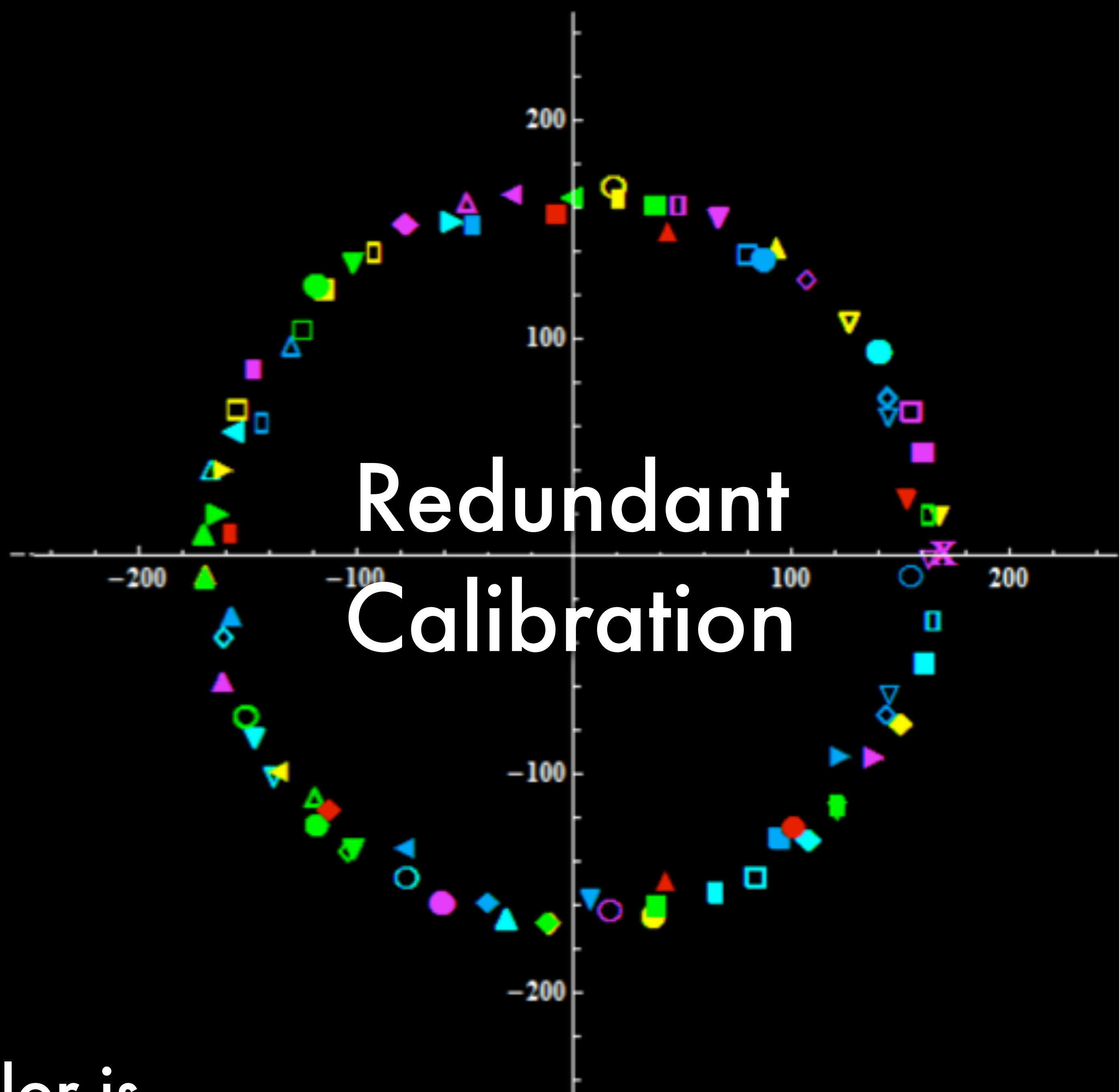
Redundant baselines enable precision calibration without a good sky model.



Liu et al. (2010)

MITEoR: a prototype highly-scalable interferometer for 21 cm cosmology.

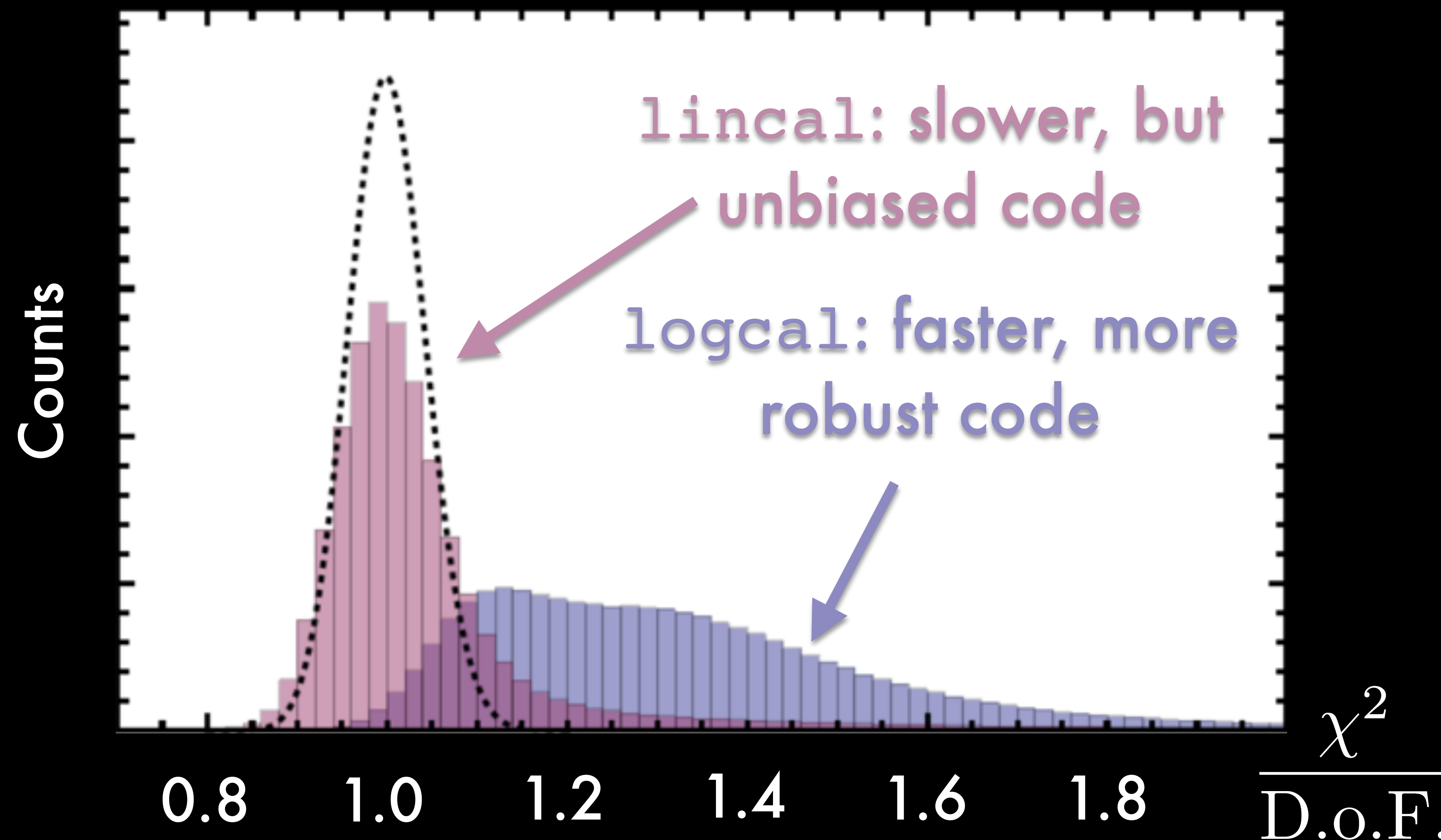
Redundant baselines allow us to quickly and precisely calibrate the amplitudes and phases of every antenna.



Each shape/color is a unique baseline.

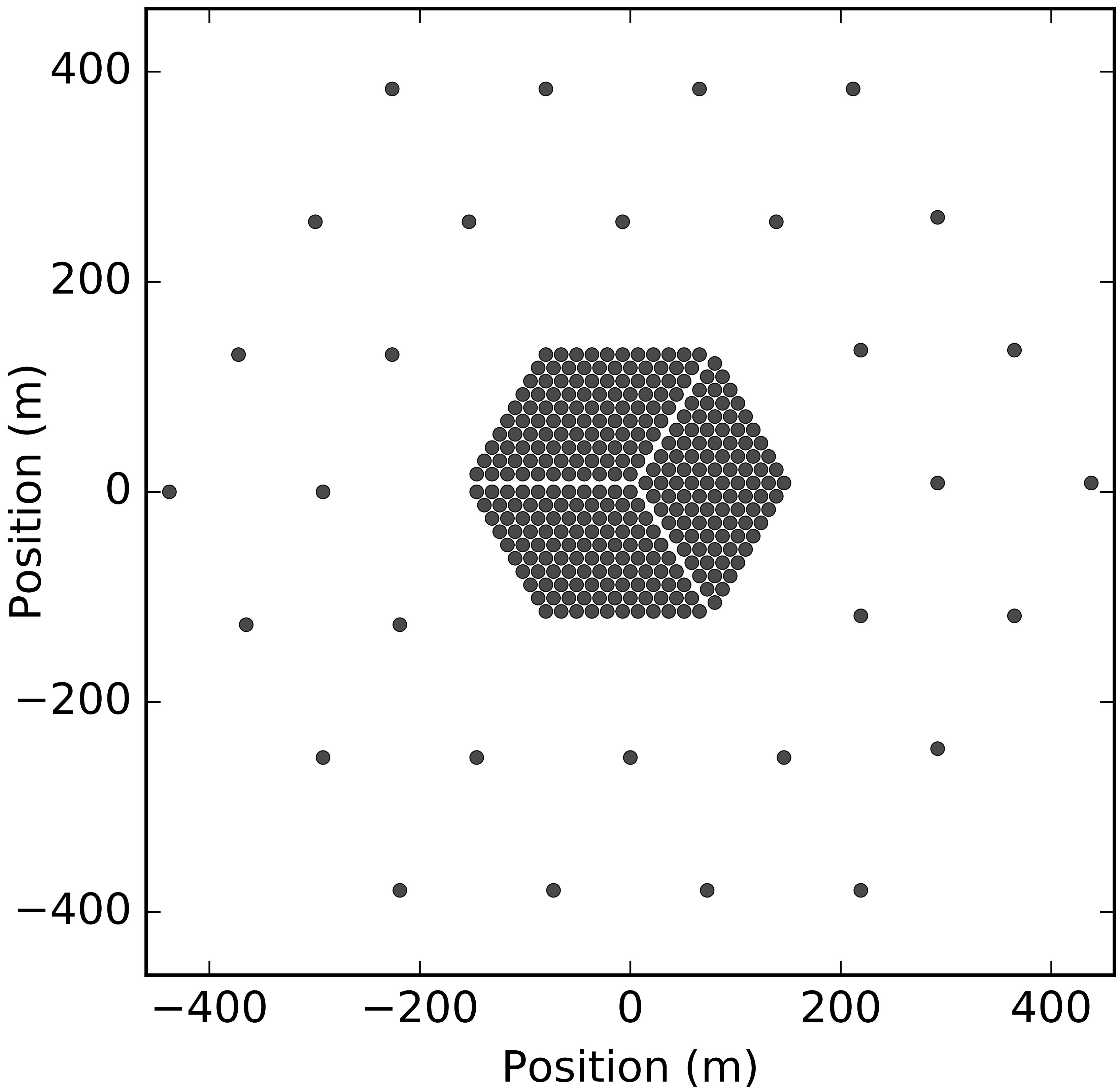
Zheng et al. (2014)

Redundant baselines allow for a quantitative test of calibration and the real-time identification of problems.



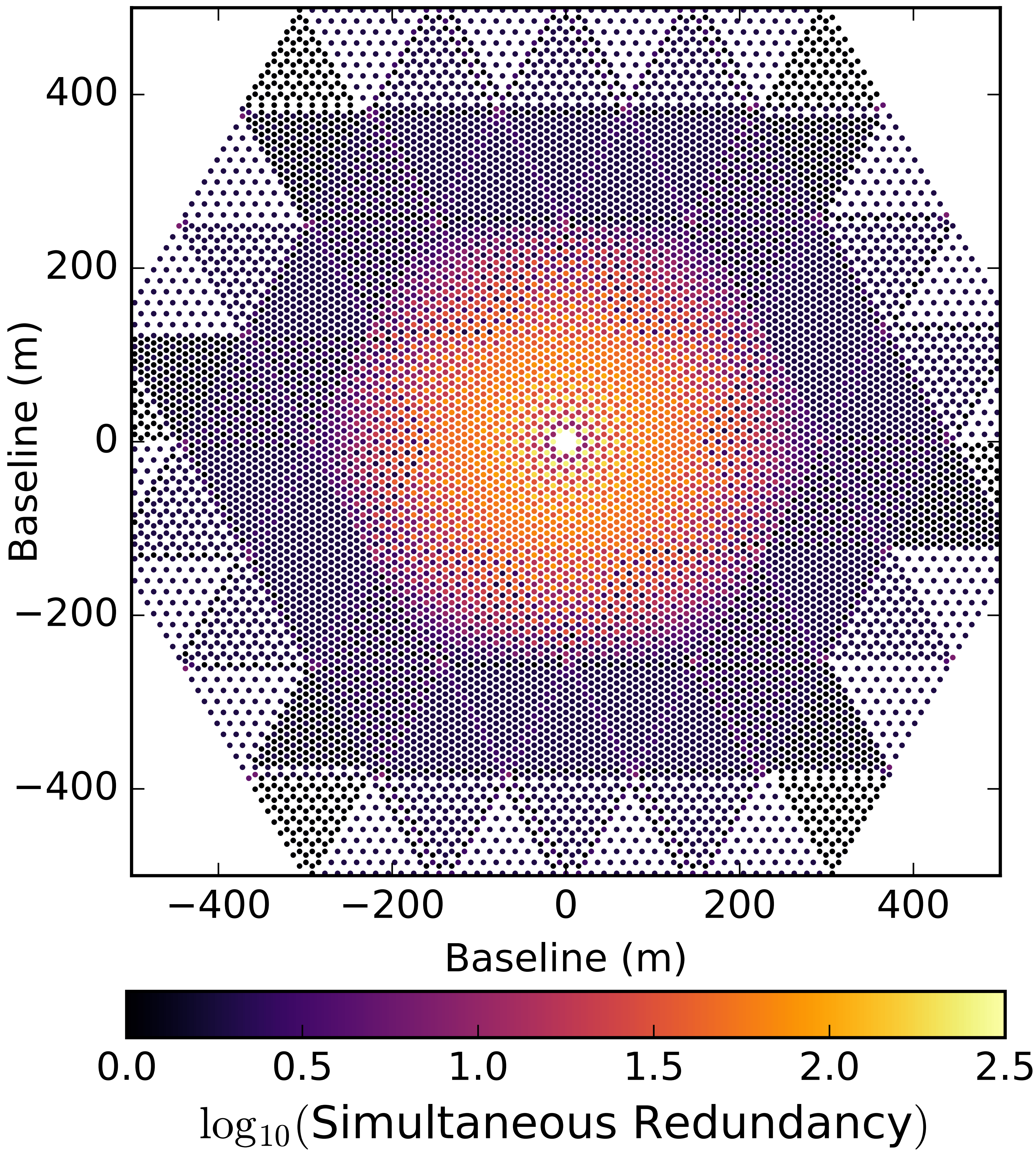
$$\chi^2 = \sum_{\text{all baselines}} \left[(g_i g_j^*) V_{i,j}^{\text{fit}} - V_{i,j}^{\text{measured}} \right] / \sigma^2$$

Zheng et al. (2014)

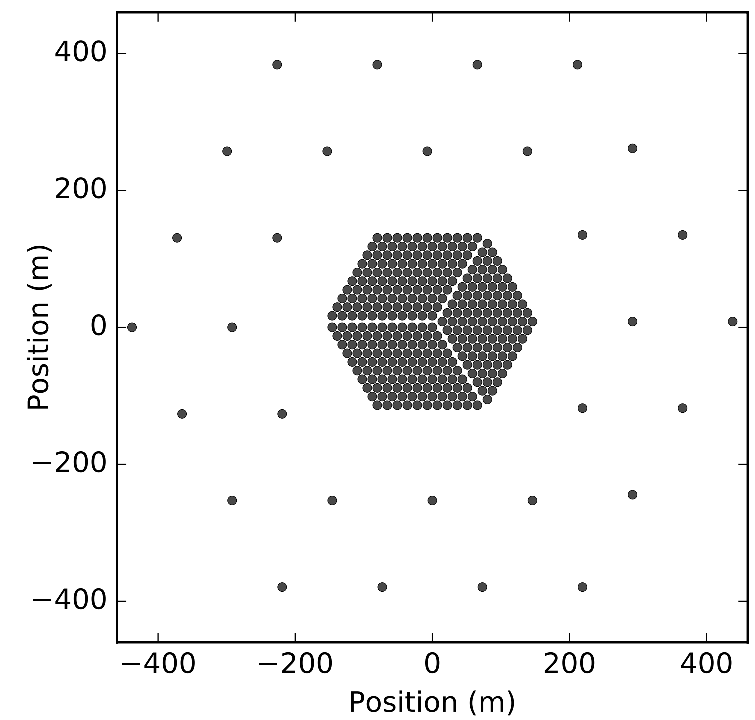


HERA’s split configuration enables

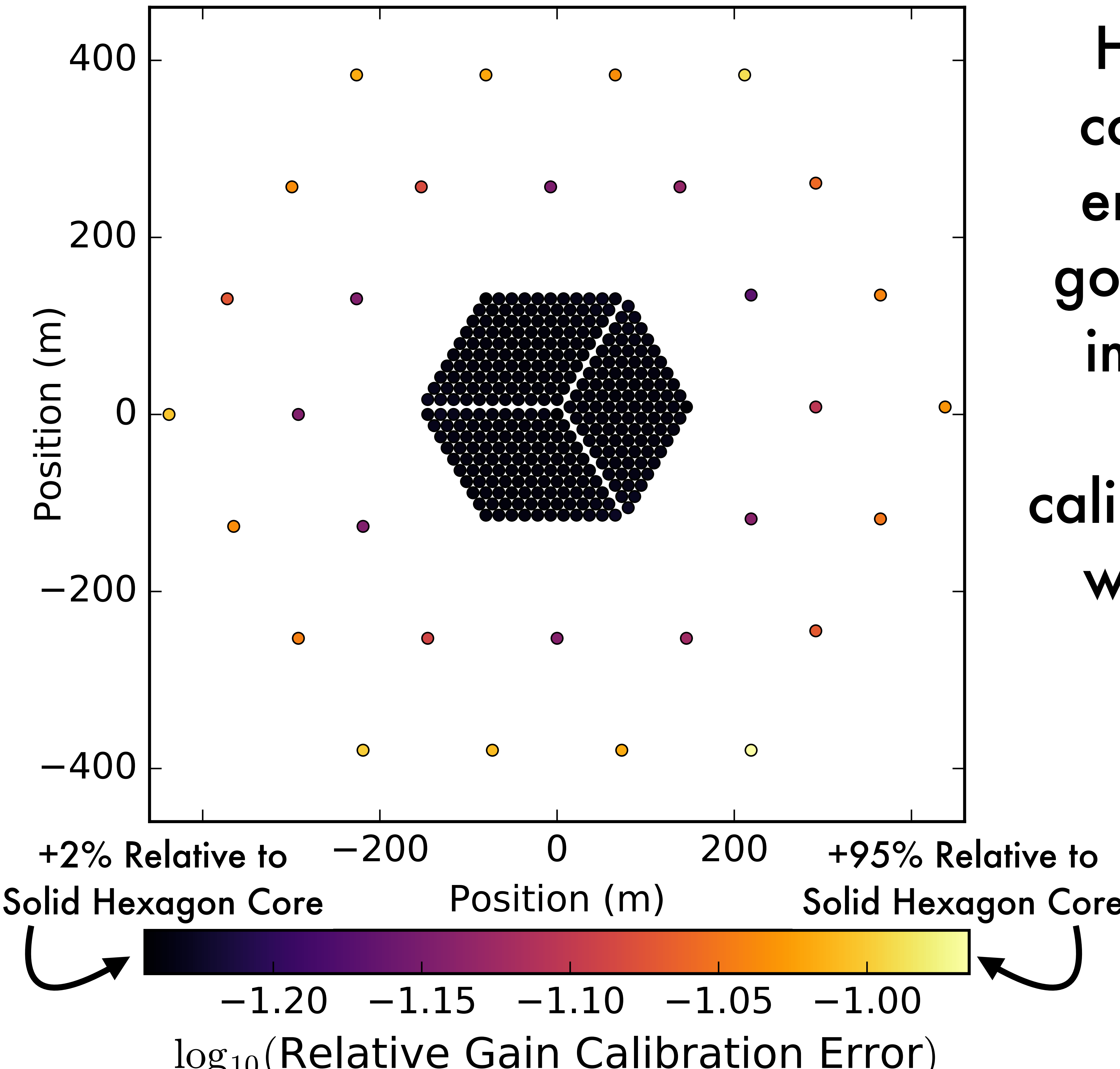
Dillon & Parsons (2016)



HERA's split configuration enables both good widefield imaging



Dillon & Parsons (2016)



HERA's split configuration enables both good widefield imaging and redundant calibration of the whole array.

Dillon & Parsons (2016)

So, what can we expect to learn with HERA?

We'll have the collecting area to confidently detect the EoR.

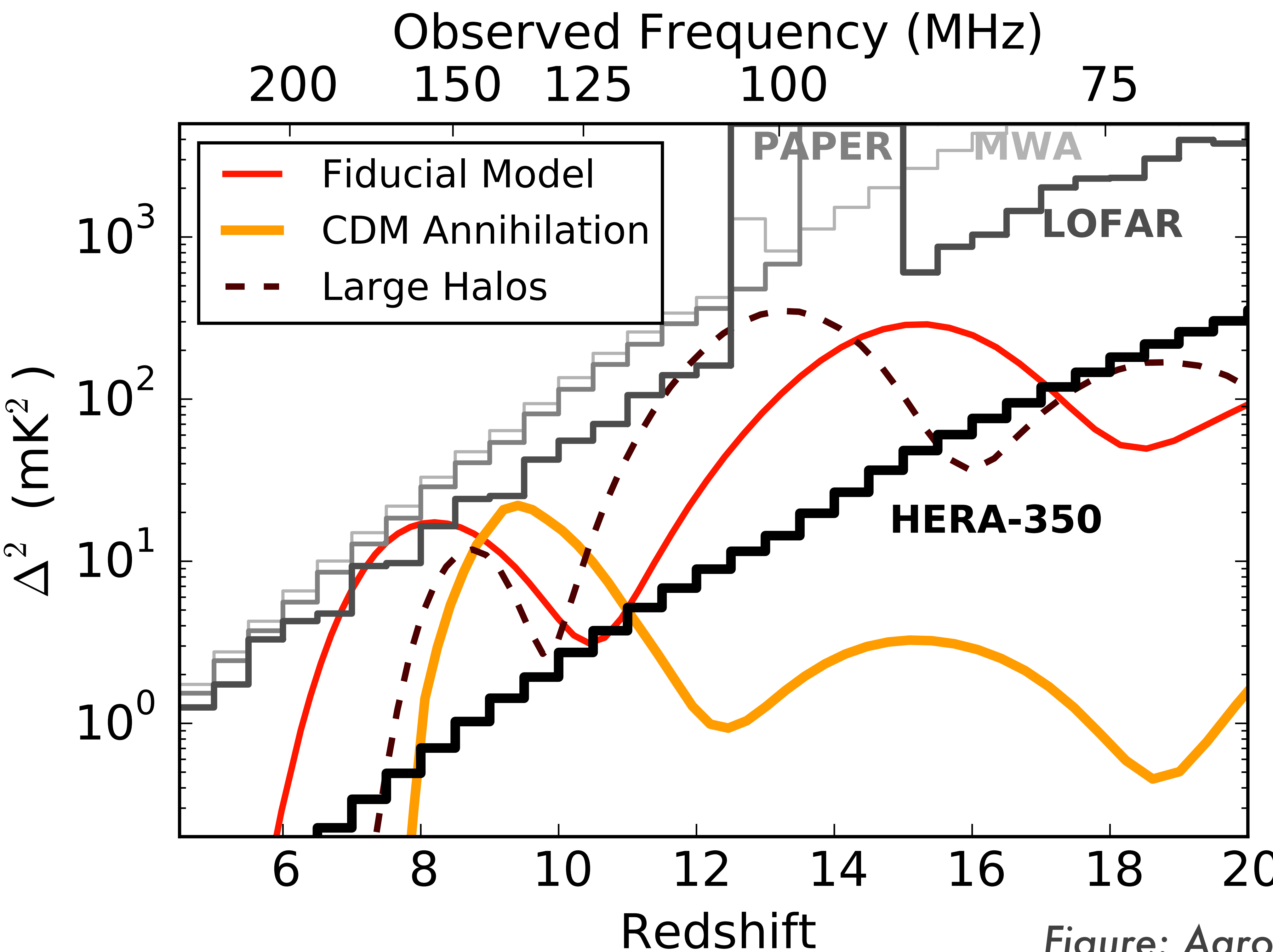
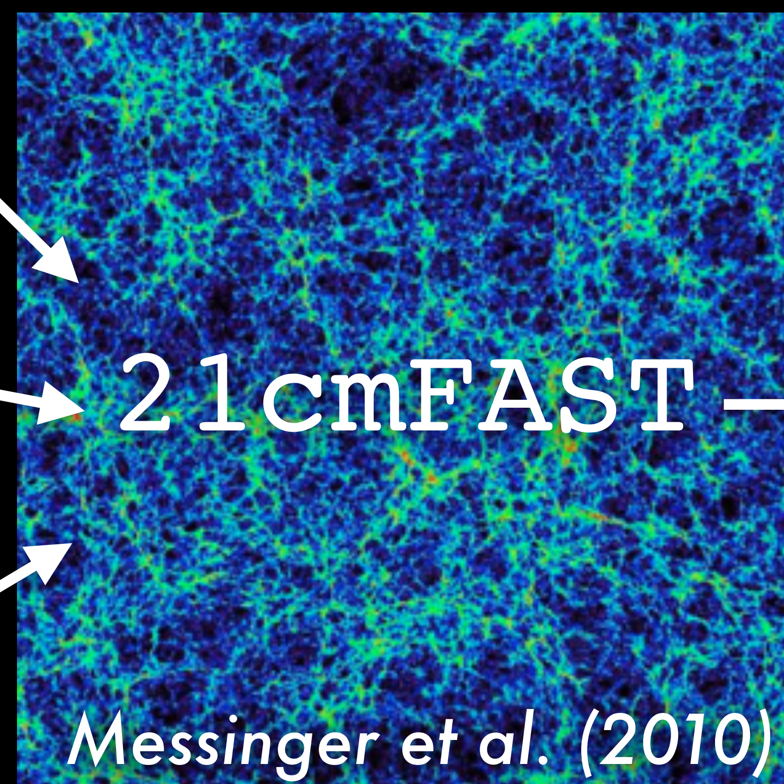
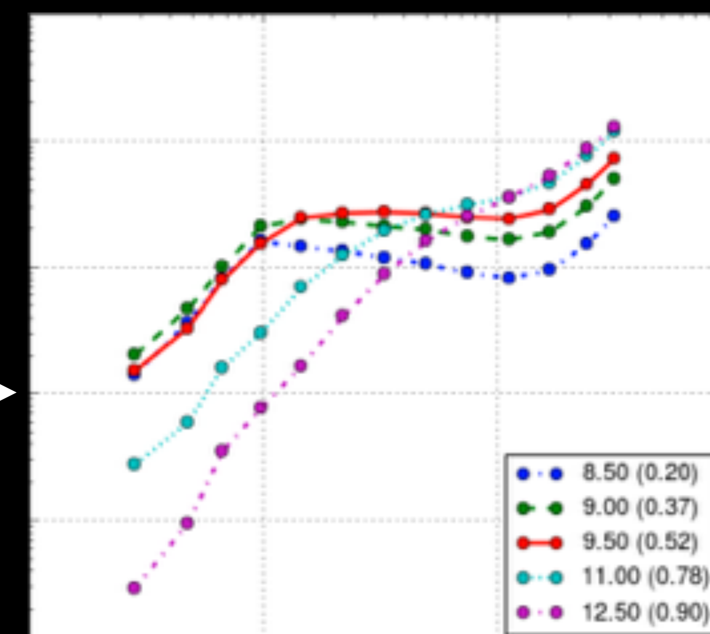


Figure: Aaron Ewall-Wice

And we'll also provide the first tight constraints on the astrophysics underlying reionization.

- ζ: Ionizing efficiency
- R_{mfp}: Mean free path of ionizing photons
- T_{vir}: Minimum virial temperature (and thus mass) of ionizing galaxies

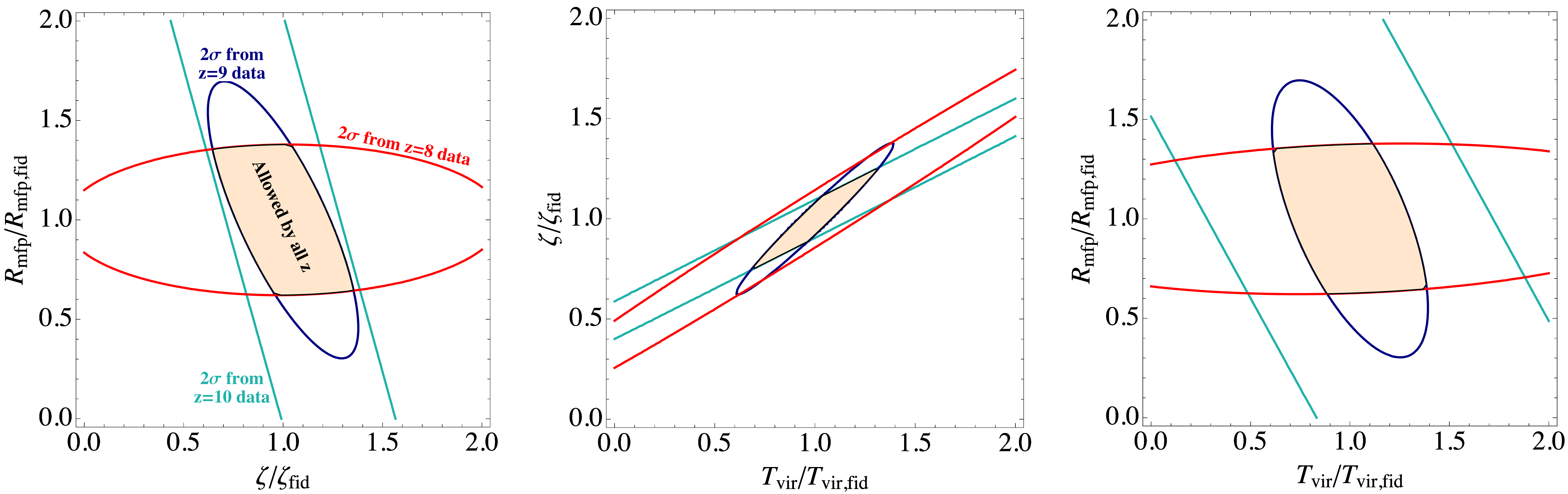




Qualitatively different 1D Power Spectra as a function of k and z

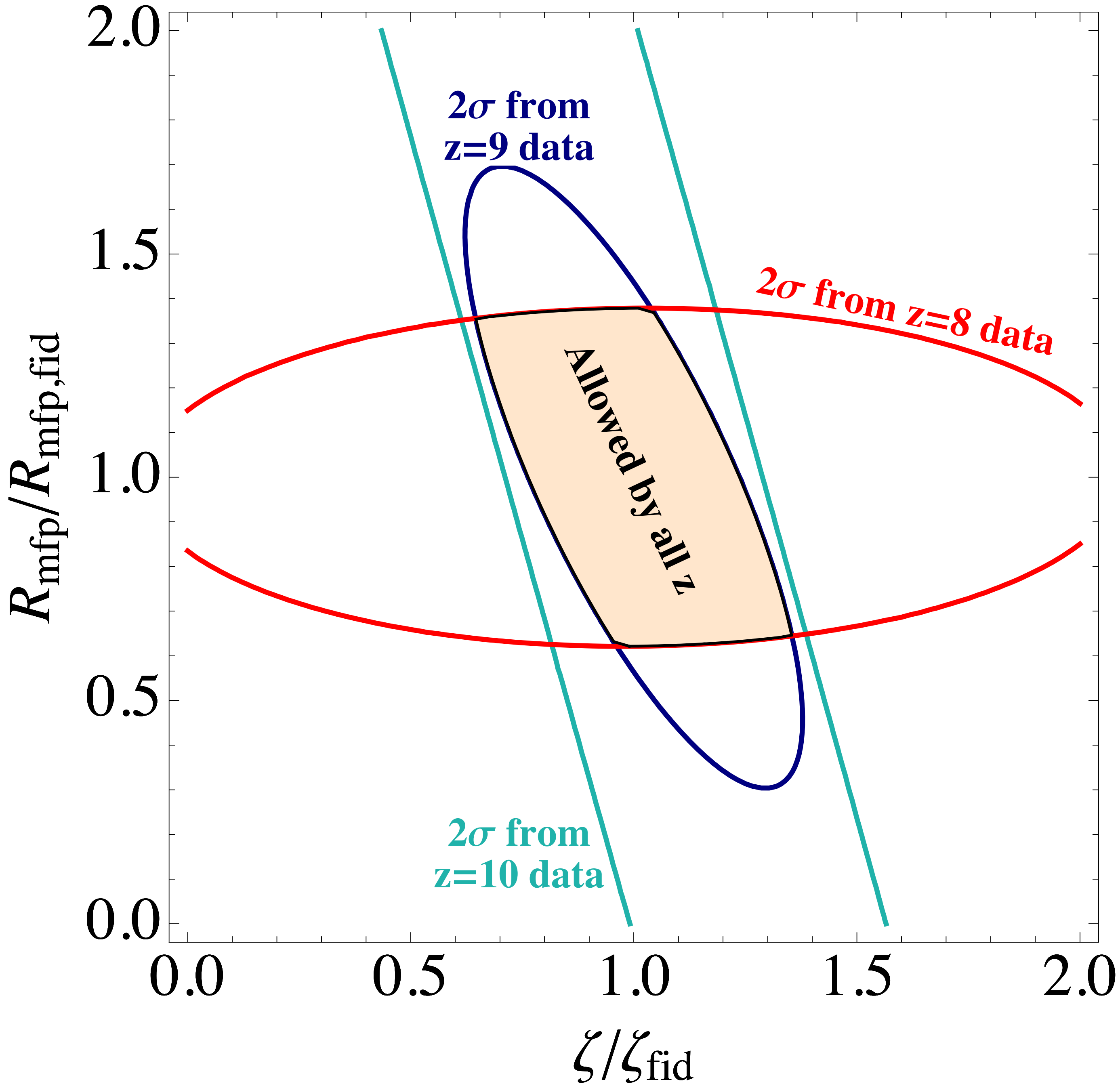
Pober, Liu, Dillon, et al. (2014)

Using a Fisher matrix analysis, we can jointly constrain all three parameters...



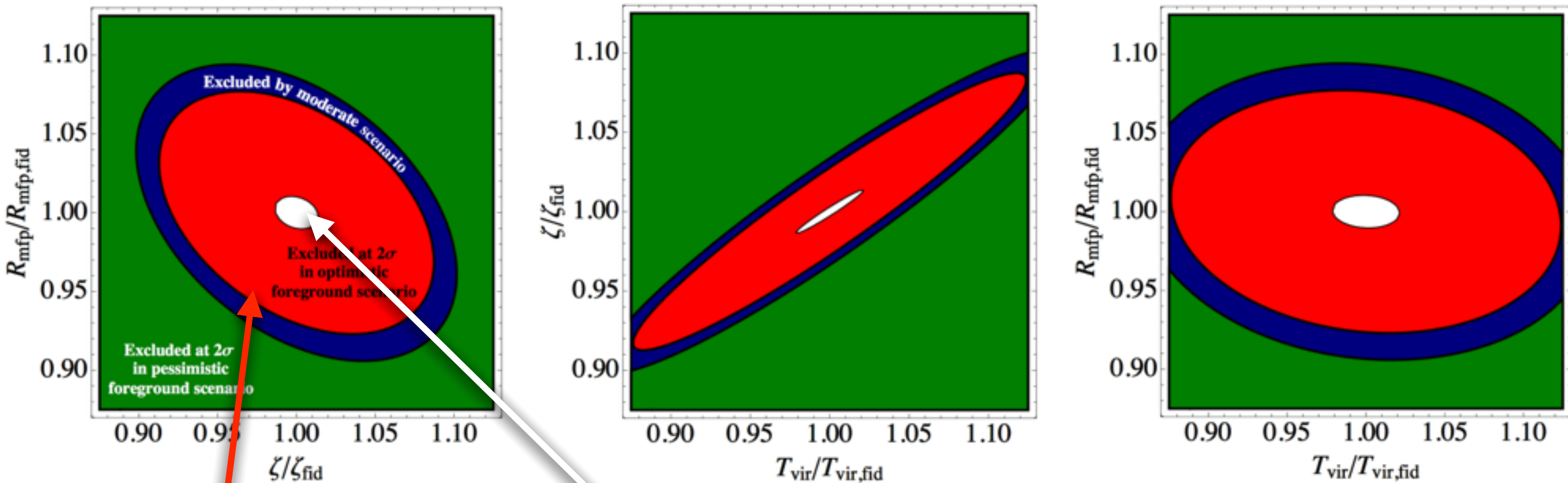
Pober, Liu, Dillon, et al. (2014)

...and break degeneracies using information from multiple redshifts.



Pober, Liu, Dillon, et al. (2014)

We can expect to constrain reionization astrophysics parameters with ~5-10% precision.



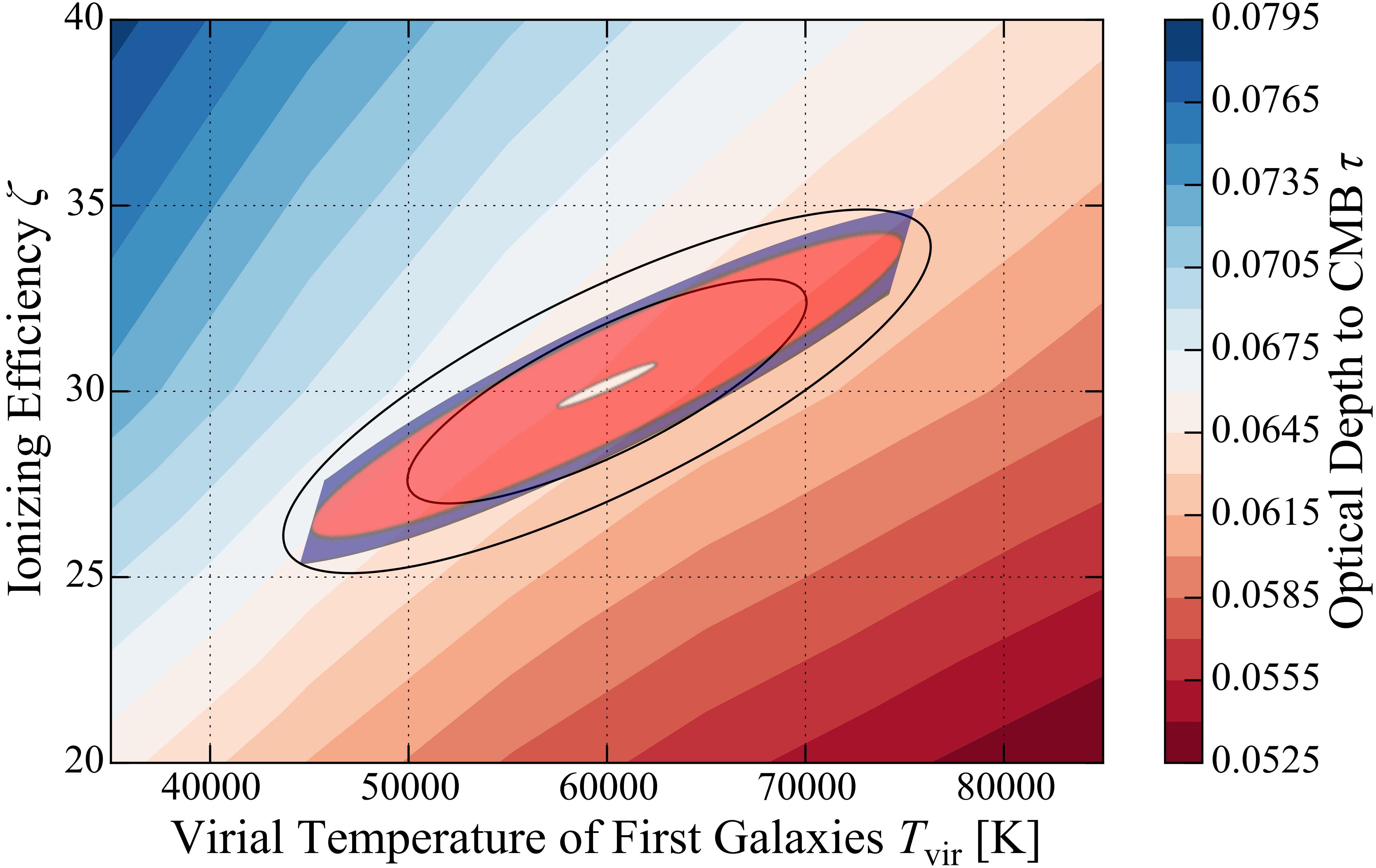
Working inside the EoR window.

Working inside the wedge too.

(These are parameters still unconstrained by an order of magnitude or more.)

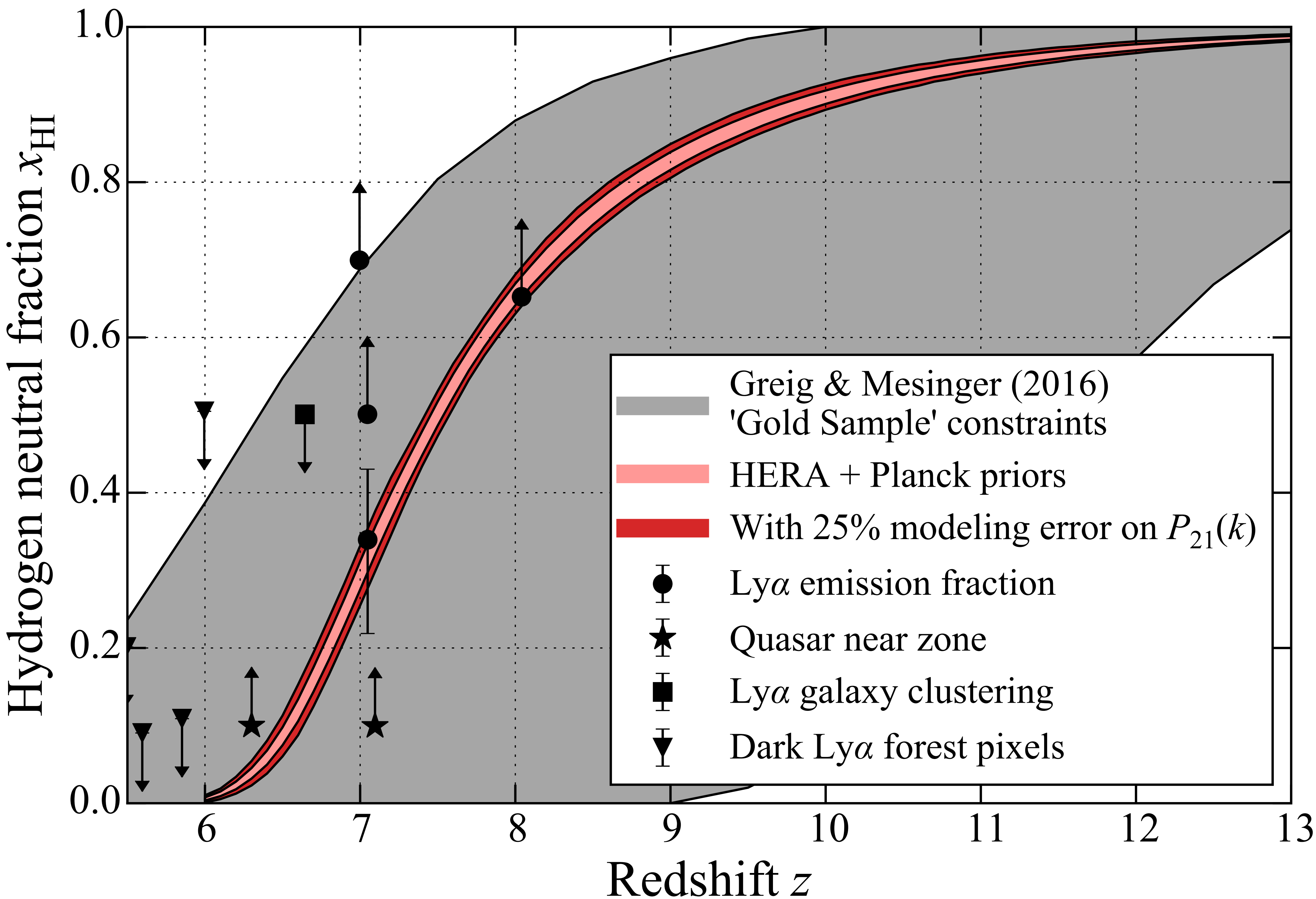
Pober, Liu, Dillon, et al. (2014)

The T_{vir}-ζ degeneracy doesn't strongly affect our measurement reionization history constraints.



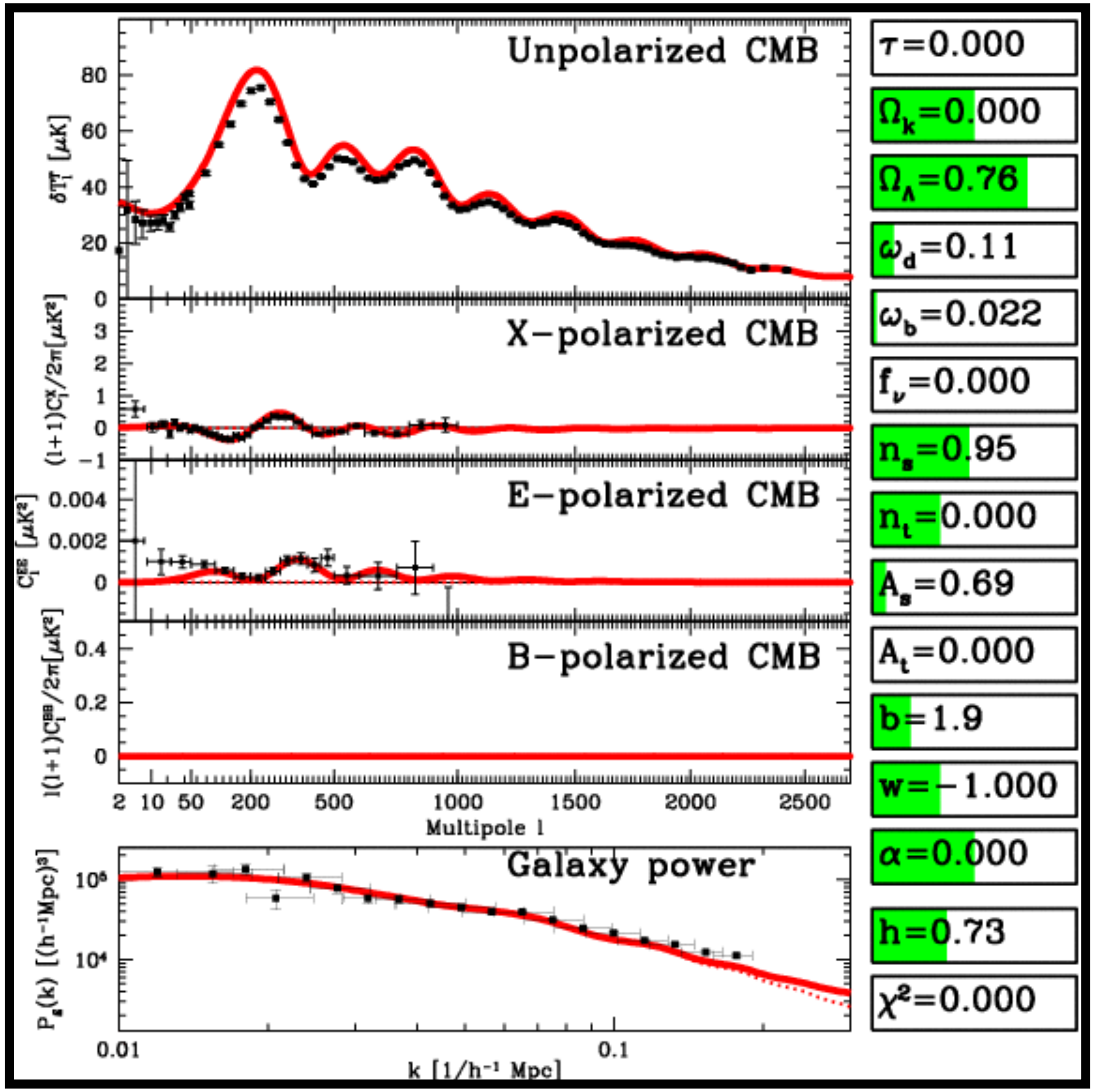
Liu et al. (2016)

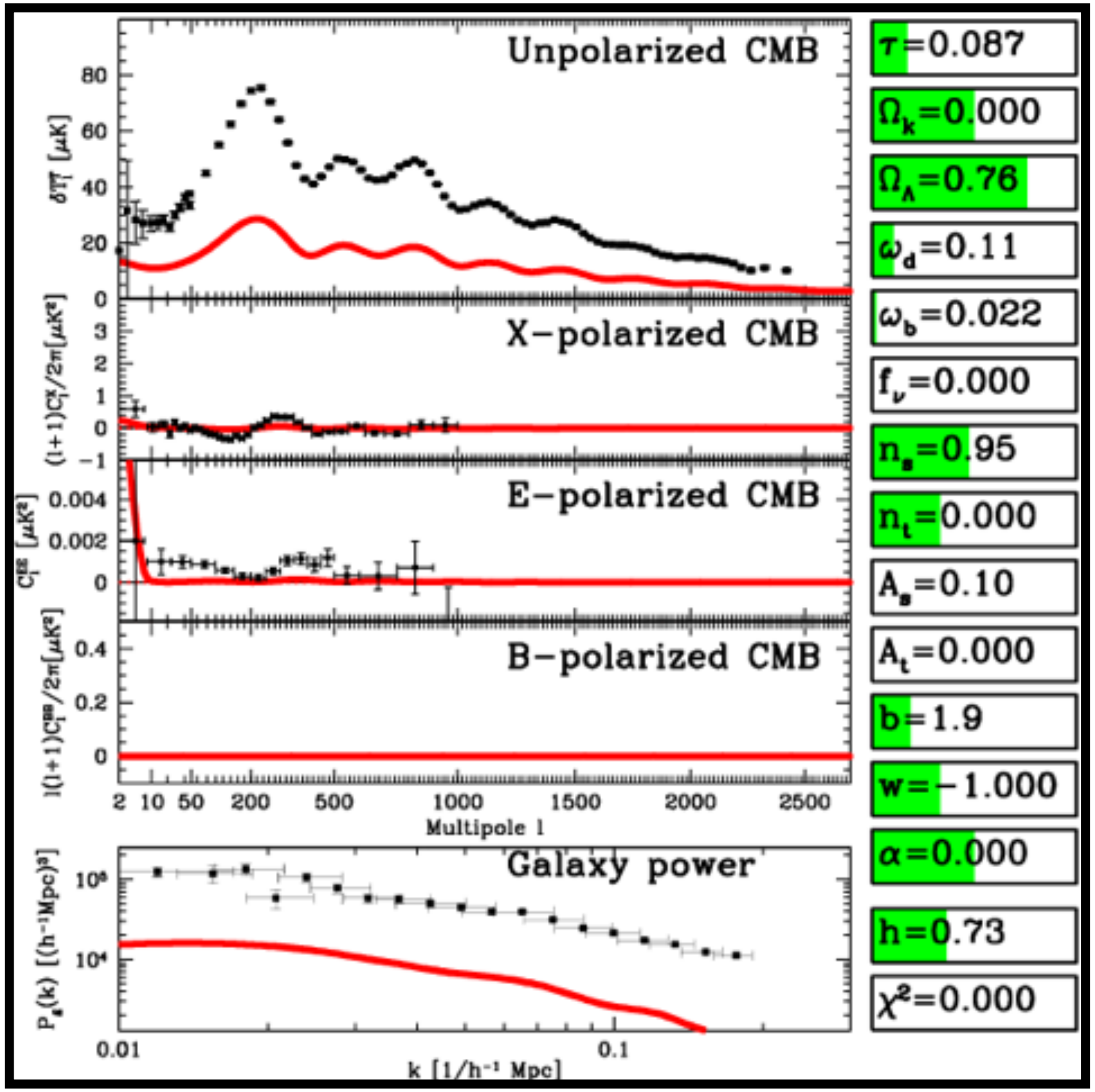
So we can tightly constrain the ionization history of the universe.



Liu et al. (2016)

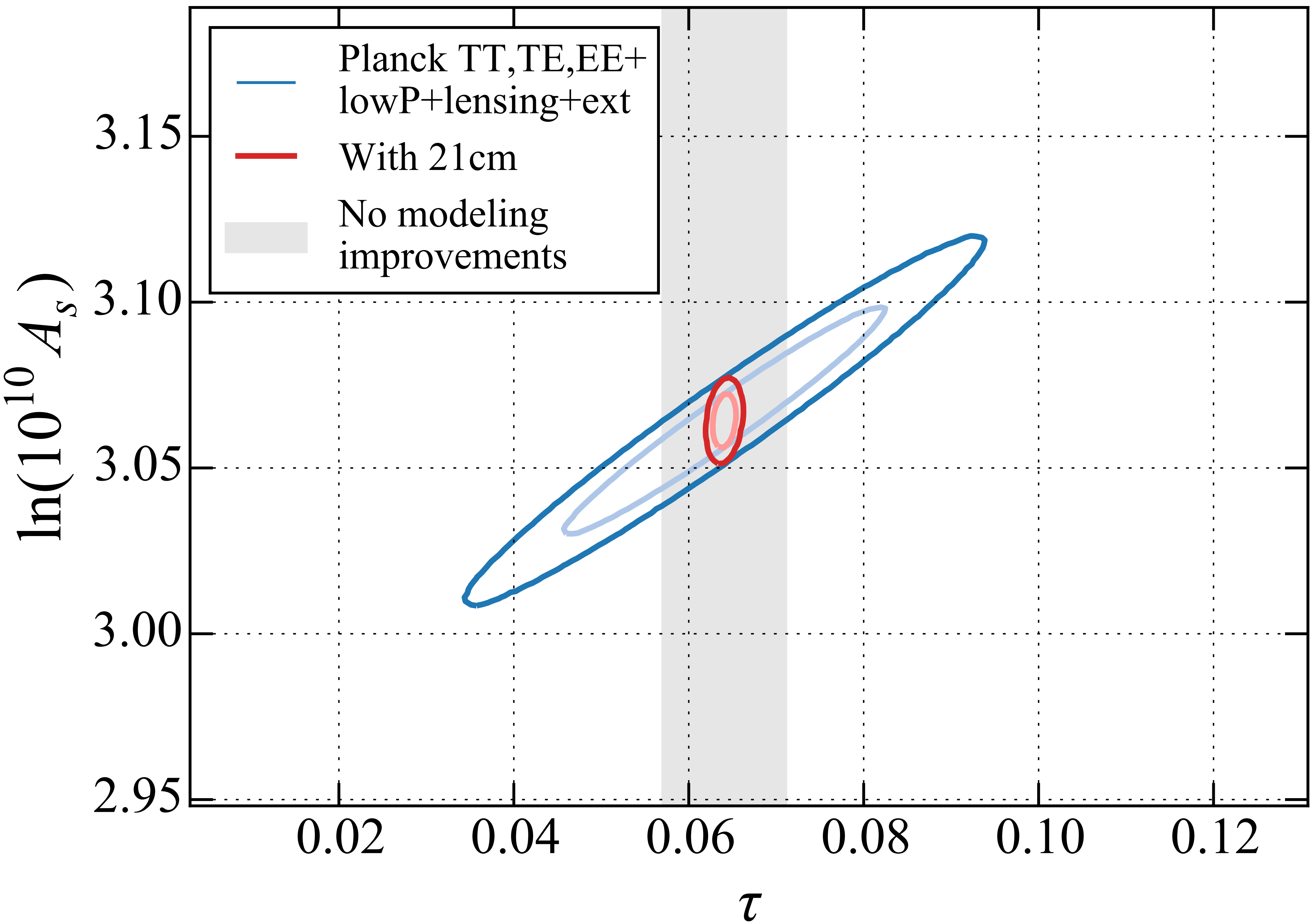
And since τ is degenerate with A_s…





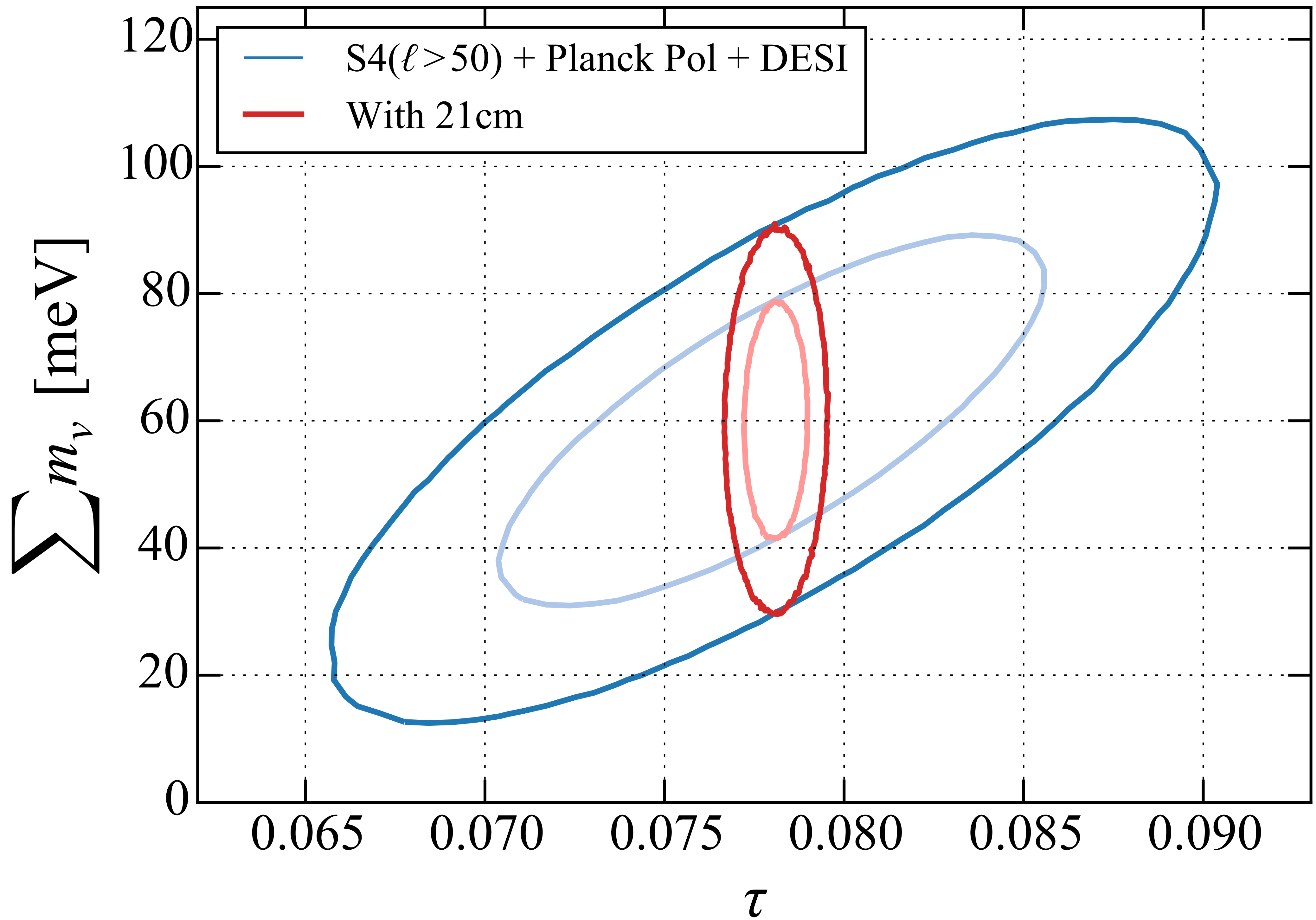
http://space.mit.edu/home/tegmark/movies.html

We'll eliminate τ as a CMB nuisance parameter, improving σ_8 by a factor of 4.



Liu et al. (2016)

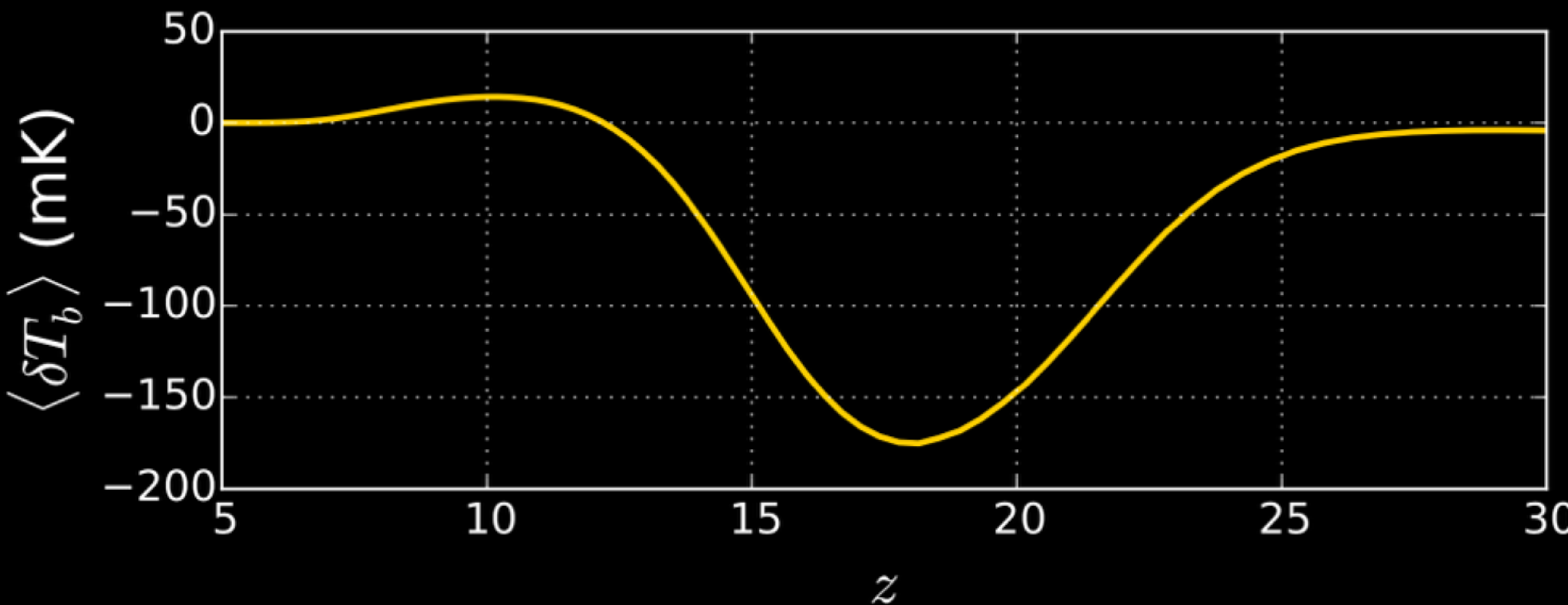
And, perhaps increase the significance of a detection of non-zero Σm_ν with CMB-S4.



Liu et al. (2016)

Before reionization, X-ray heating of the IGM drove spin temperature fluctuations that dominated the 21 cm signal.

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



Ewall-Wice et al. (2015)

If the spin temperature doesn't saturate, we need a joint model for X-ray heating and reionization.

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

$$[\text{X-ray Emissivity}] \propto \alpha_X f_X \left(\frac{\nu}{\nu_{\min}}\right)^{-\alpha_X} \rho_{\mathrm{SFR}}$$

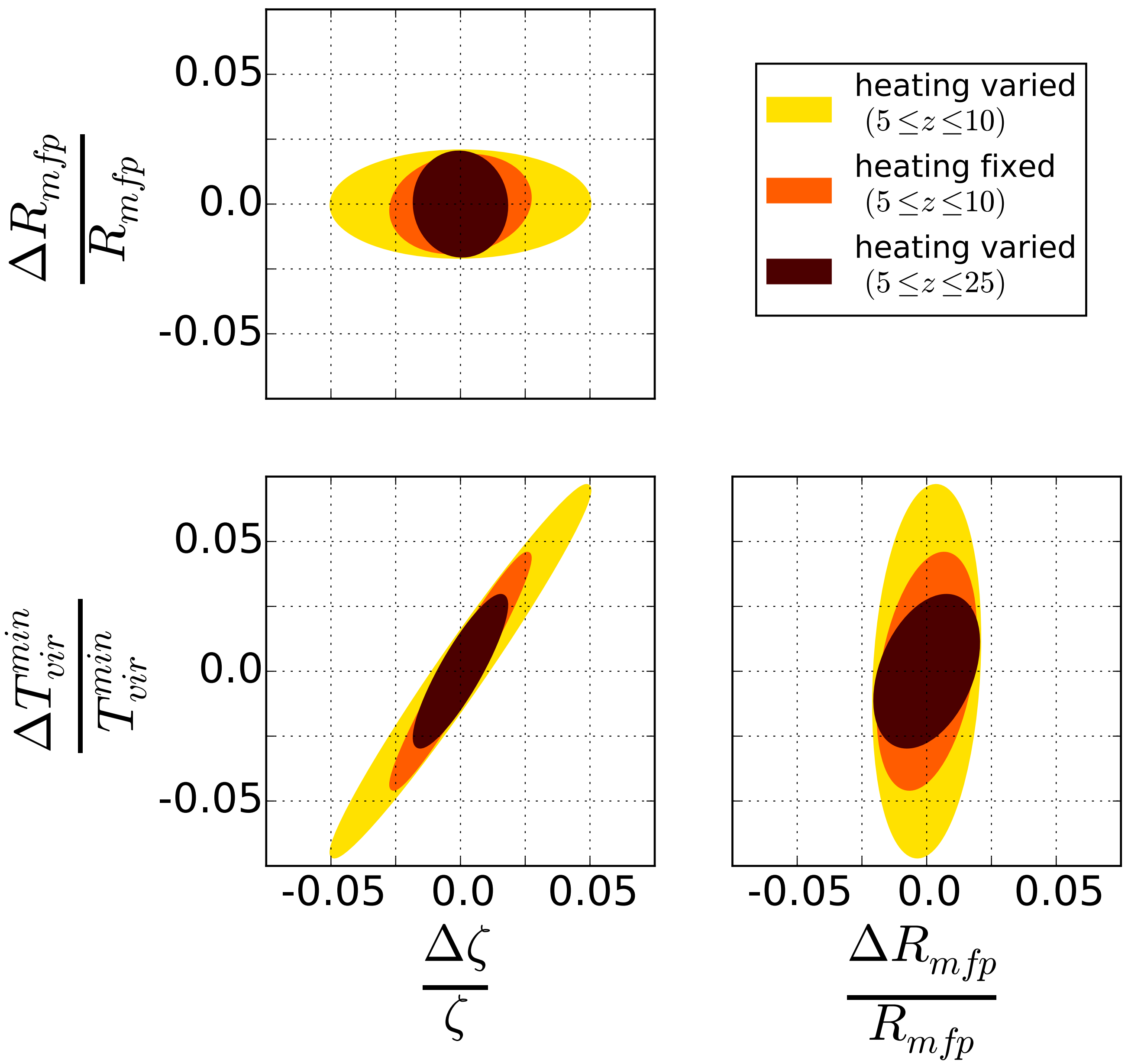
X-ray Efficiency (related to photons per star-forming baryon)

X-ray maximum energy cutoff

X-ray spectral hardness

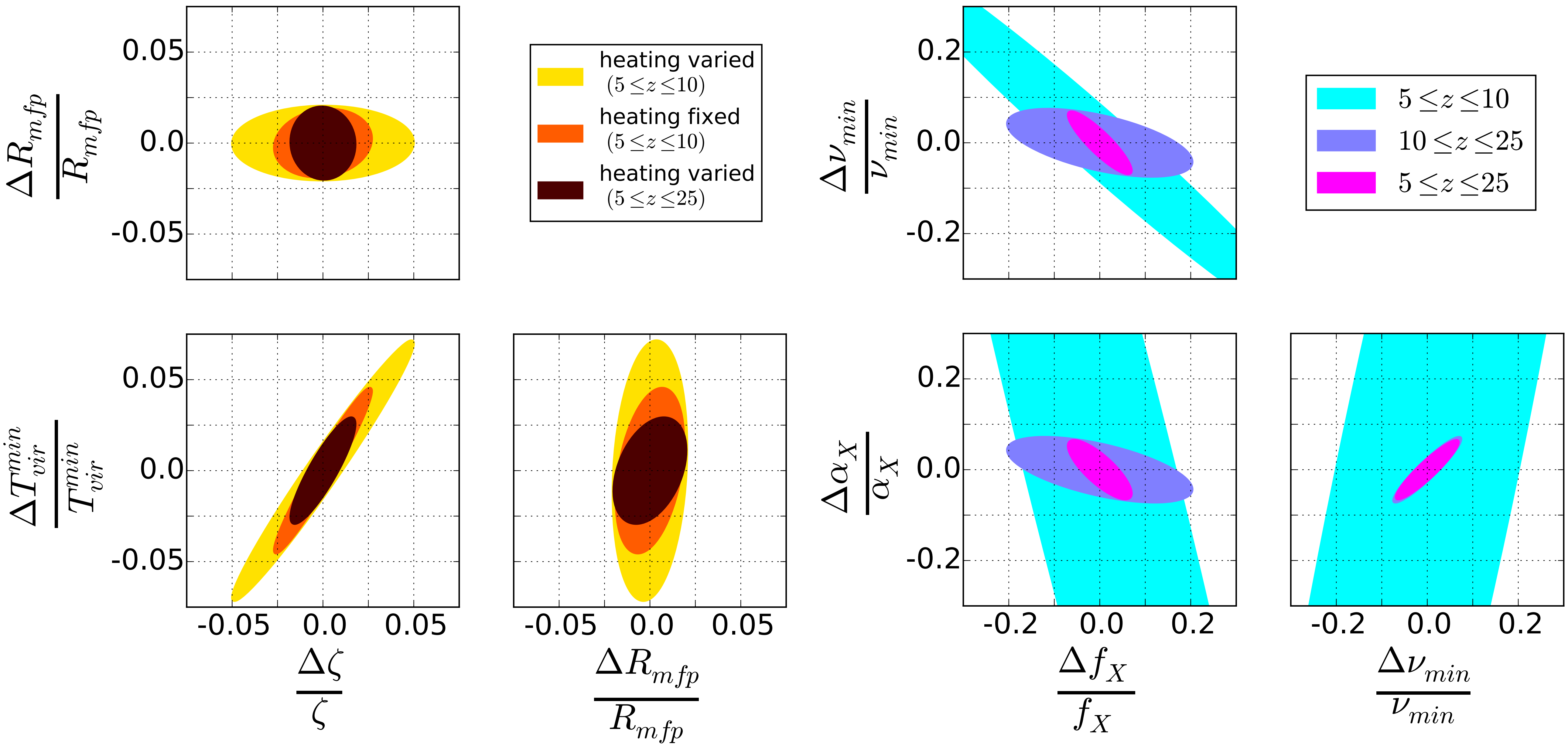
Ewall-Wice et al. (2015)

We do better on reionization parameters if we can measure X-ray heating parameters at high z.



Ewall-Wice et al. (2015)

We do better on X-ray heating parameters if we can measure reionization parameters at low z.



Ewall-Wice et al. (2015)

In Summary

- 21 cm cosmology will open up a huge volume of the universe during the largely unexplored "Cosmic Dawn."
- We've already made great progress avoiding foreground contamination with first generation arrays, setting upper limits with astrophysical implications
- HERA will draw on the lessons of MWA, PAPER, and MITEoR with vastly increased sensitivity to convincingly detect the EoR and tightly constrain the physics behind reionization and the Cosmic Dawn.

Backup Slides

Table 1: Sensitivities (i.e. "number of sigmas") of 21 cm EoR experiments to the reionization model used in Pober et al. (2014).

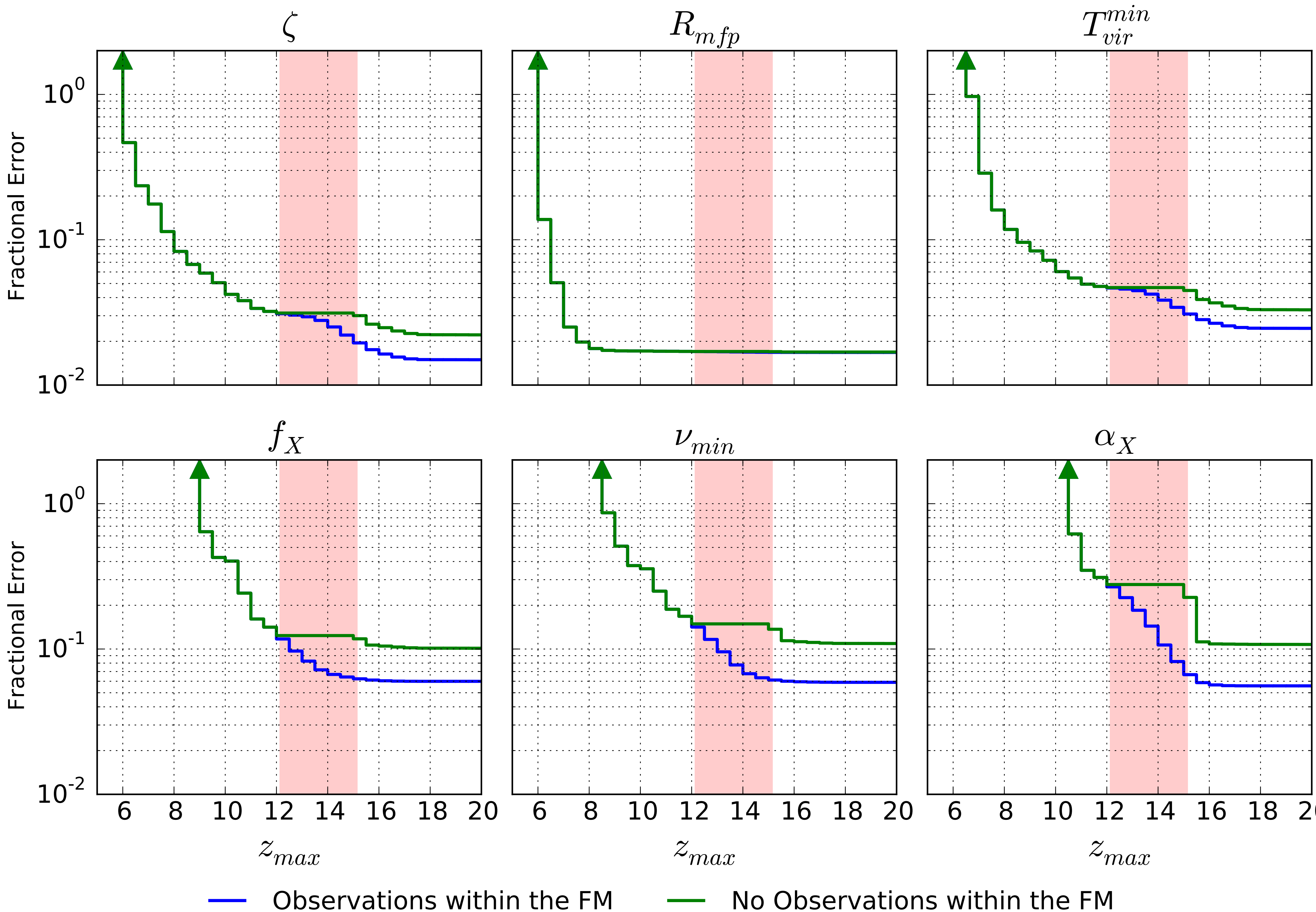
Instrument	Avoidance Drift	Avoidance Track	Subtraction Drift	Subtraction Track
PAPER 128	0.77	—	3.04	—
MWA 128	0.31	0.41	1.63	2.08
LOFAR	0.38	1.06	5.36	9.21
HERA 37	2.75	—	11.73	—
HERA 331	25.53	—	90.76	—
MWA 256[a]	1.02	1.24	5.54	6.51
SKA1 Low[b]	13.44	19.55	109.90	98.15

[a] The "Beardsley" proposed array. The final layout will likely move more antennas from the core to longer distances, reducing the EoR sensitivity of the instrument.

[b] Re-baselined design includes half the number of elements. Note that halving the number of stations removes the need for a redundant core, i.e., the desired SKA element density profile now can be achieved at all radii.

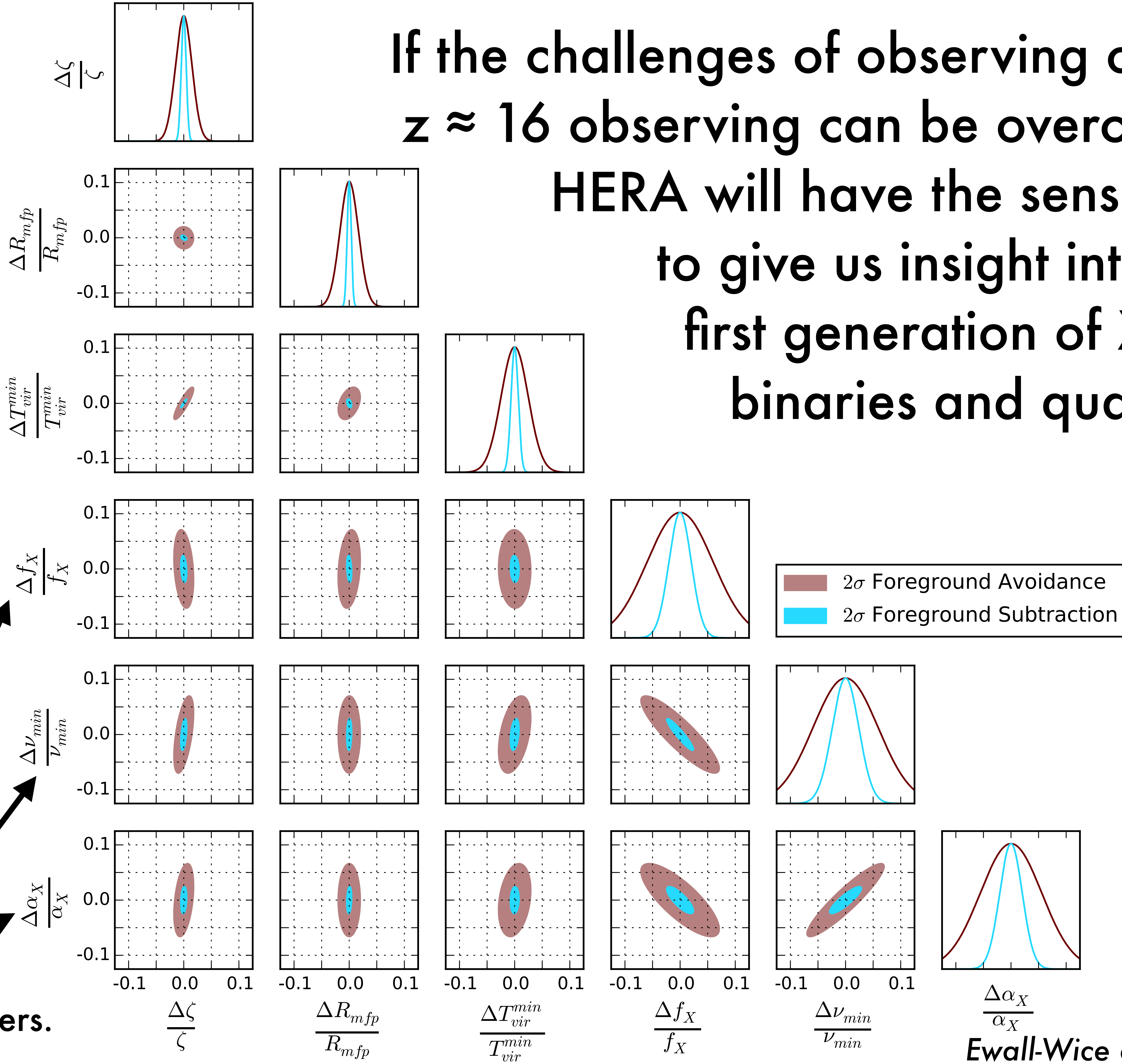
Pober, HERA Memo #4

High-z observations have a lot to tell us about both the reionization and the X-ray heating epoch.



Ewall-Wice et al. (2015)

If the challenges of observing out to z ≈ 16 observing can be overcome, HERA will have the sensitivity to give us insight into the first generation of X-ray binaries and quasars.

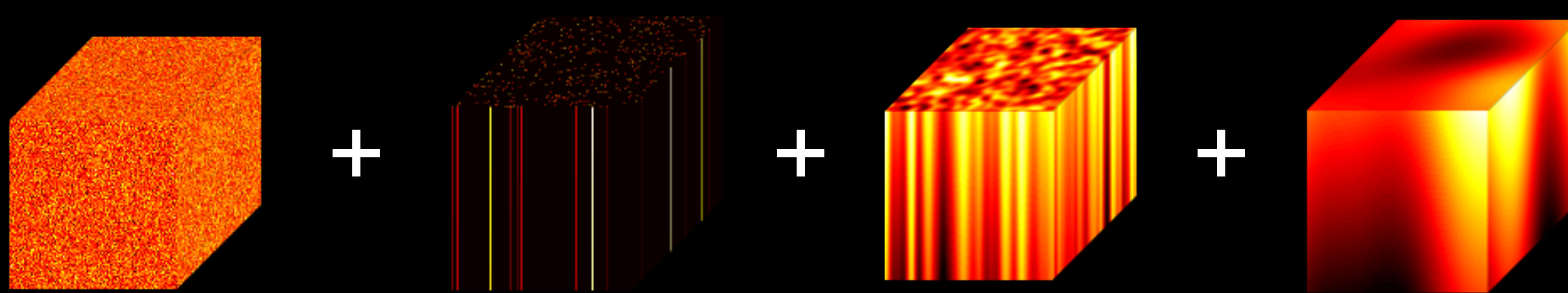


X-ray flux and spectral parameters.

Ewall-Wice et al. (2015)

Fast Power Spectrum Estimation

1. Generate lots of random data cubes from the model covariance, exploiting symmetries



All in O(NlogN)*

Dillon, Liu, & Tegmark (2013)

Fast Power Spectrum Estimation

1. Generate lots of random data cubes from the model covariance, exploiting symmetries

2. Calculate our quadratic estimator

$$q^\alpha \equiv \mathbf{x}^\intercal \mathbf{C}^{-1} \mathbf{Q}^\alpha \mathbf{C}^{-1} \mathbf{x}$$

All in O(NlogN)*

Dillon, Liu, & Tegmark (2013)

Fast Power Spectrum Estimation

1. Generate lots of random data cubes from the model covariance, exploiting symmetries
2. Calculate our quadratic estimator
3. Monte Carlo many quadratic estimators to get error bars and window functions.

Use $\mathrm{Cov}(\mathbf{q}) = \mathbf{F}$

To avoid $F^{\alpha\beta} = \frac{1}{2}\mathrm{tr}\left[\mathbf{C}^{-1}\mathbf{Q}^{\alpha}\mathbf{C}^{-1}\mathbf{Q}^{\beta}\right]$

All in O(NlogN)*

Dillon, Liu, & Tegmark (2013)

Our maps have different statistics than the true sky.

- We need to know $\mathbf{P}$ to estimate power spectra and model foregrounds.
- Nominally, $\mathbf{P}$ maps every point on the true sky to every point in the dirty map at every frequency and knows about every observation...so it's hard to calculate.

Dillon et al. (2014b)

Three ways to make it faster...

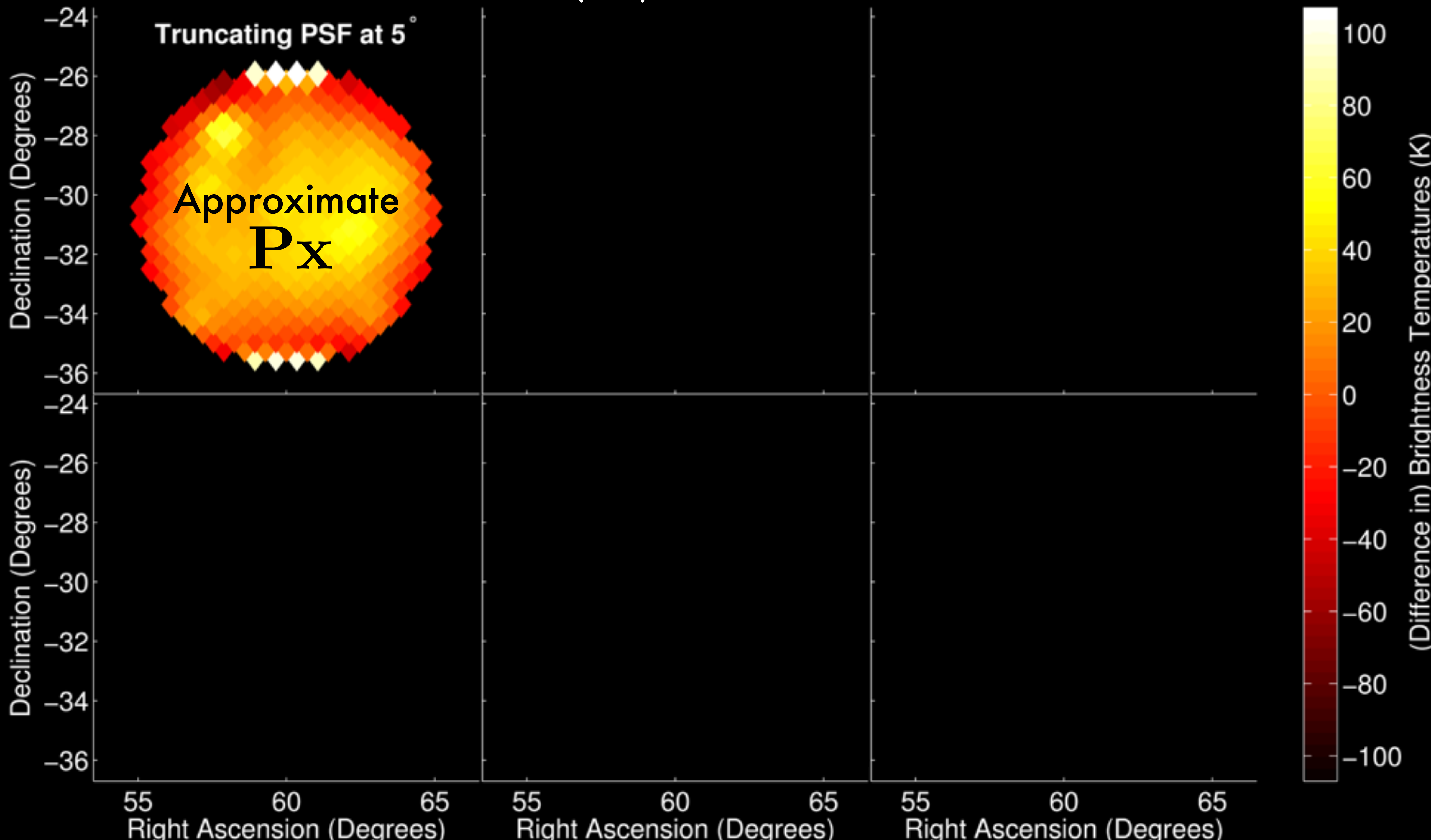
1. Truncating the PSF.
2. Combing together multiple sequential observations.
3. Fitting the PSF's translational variations with low-order polynomials.

All have speed vs. accuracy tradeoffs.

Dillon et al. (2014b)

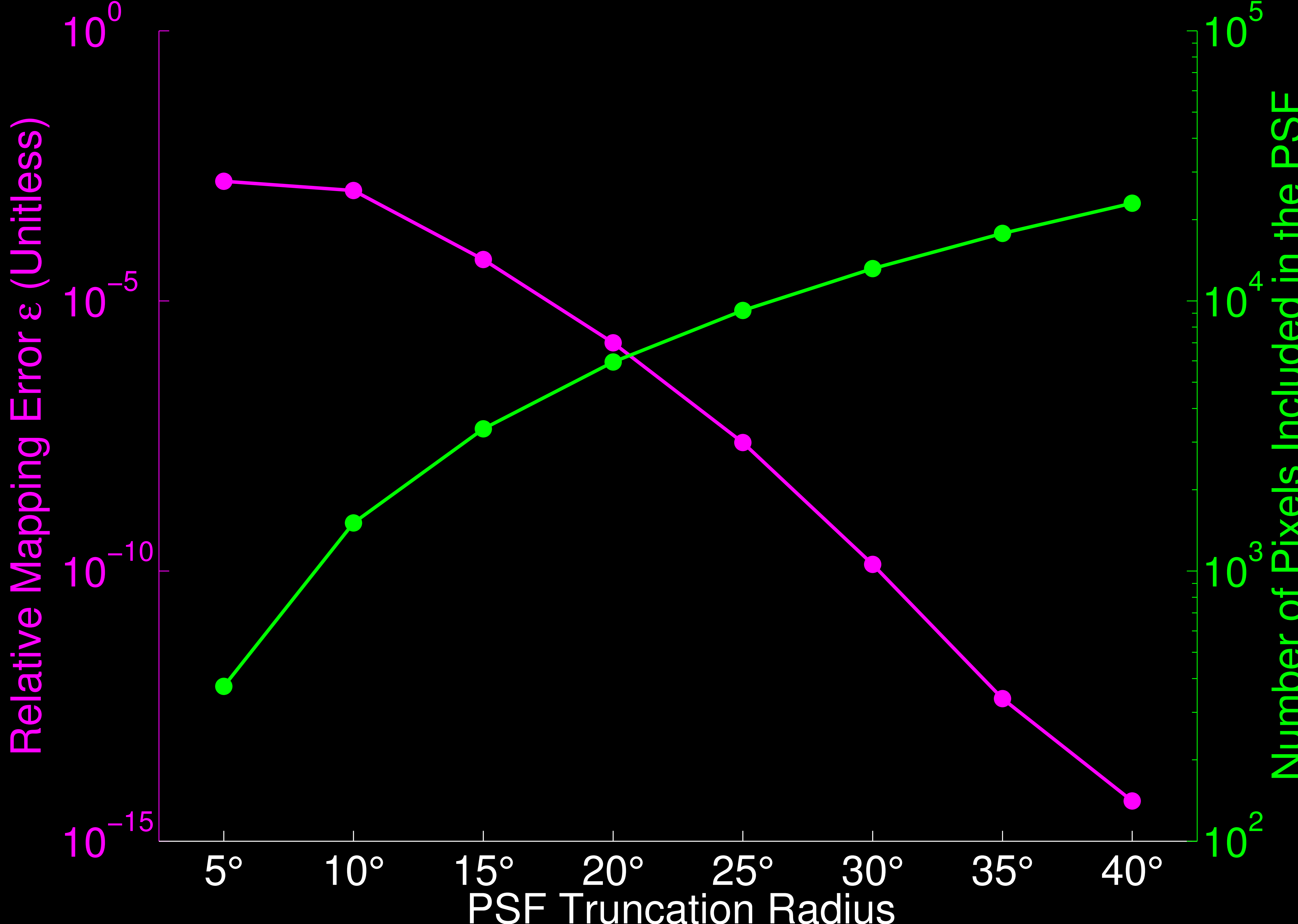
Truncating the PSF trades speed for accuracy.

$$\langle \widehat{\mathbf{x}} \rangle = \mathbf{P}\mathbf{x}$$



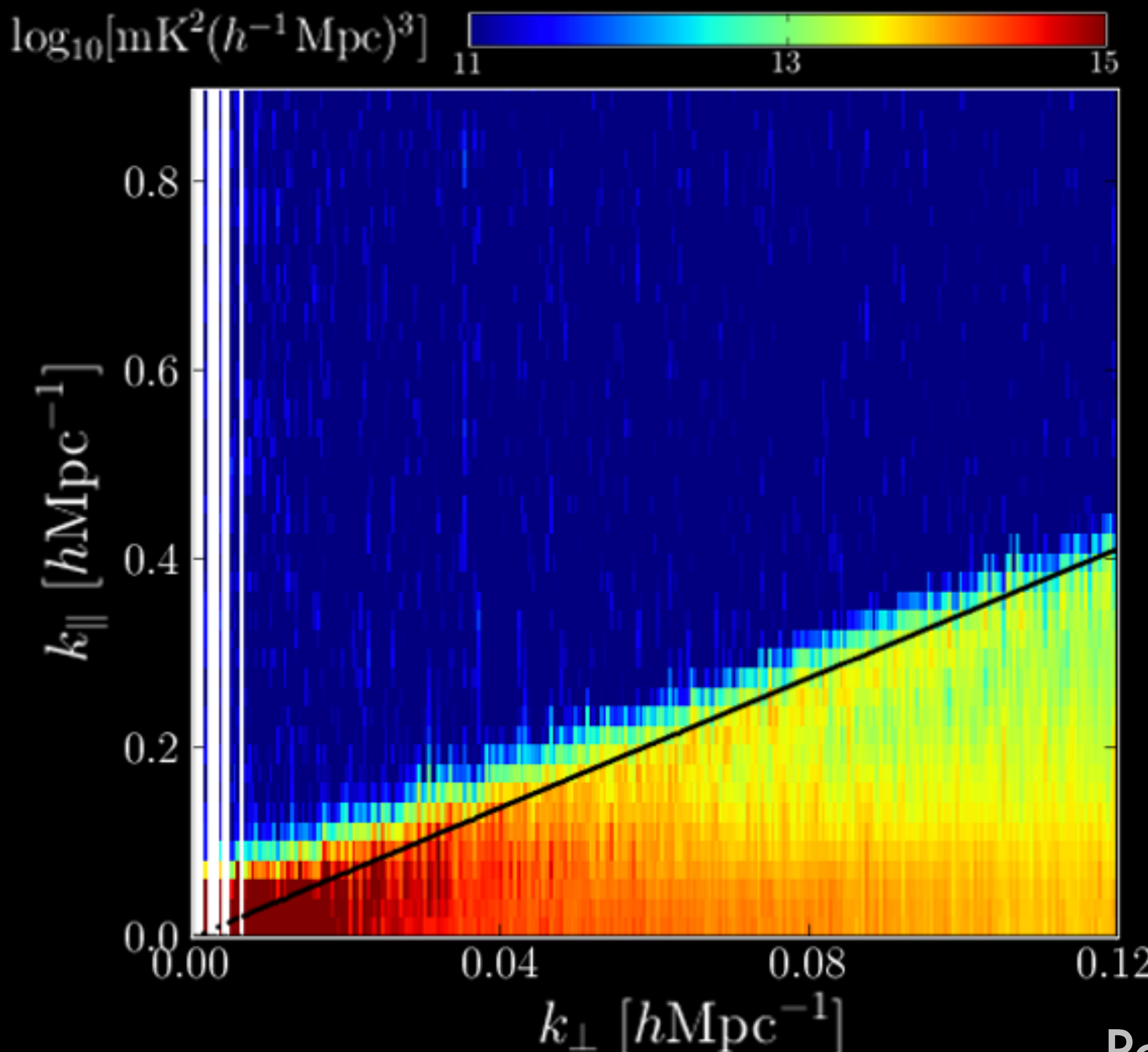
Dillon et al. (2014b)

Truncating the PSF trades speed for accuracy.



Dillon et al. (2014b)

The wedge has been observed to be, as far as we can tell, foreground free.



Pober et al. (2013)

See also Datta et al. (2010) and many others.

We'll begin imaging the EoR directly.

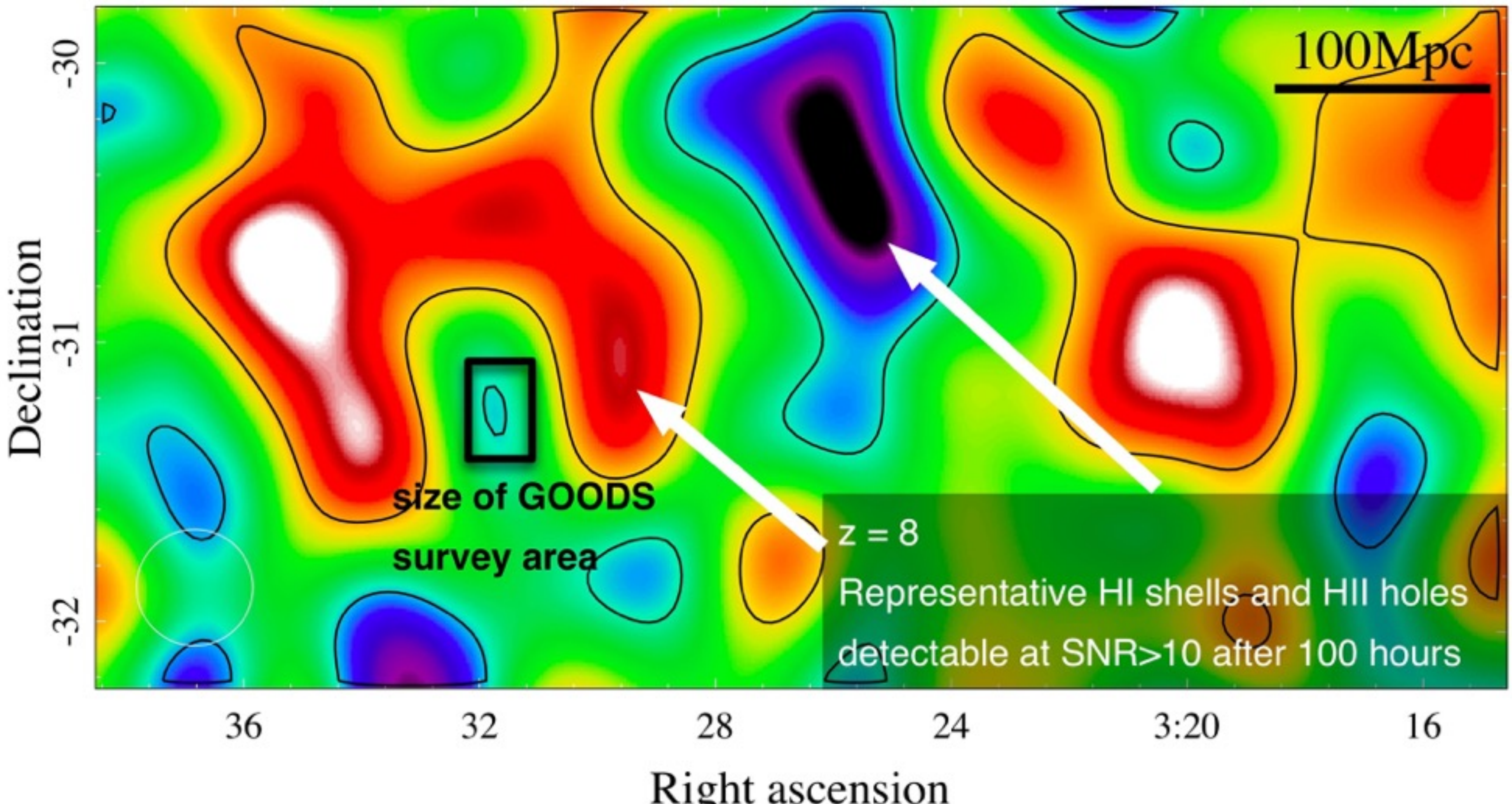


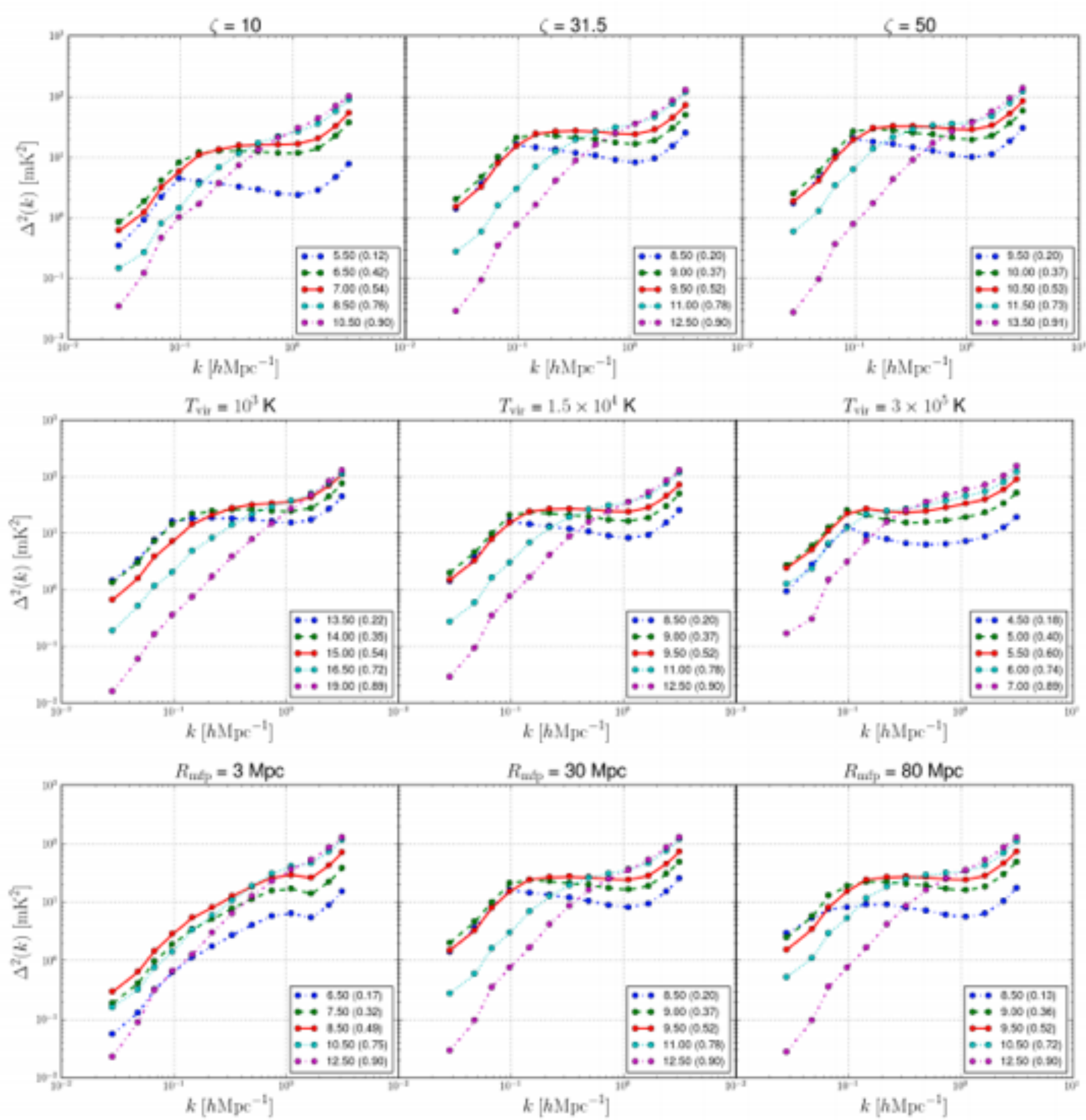
Figure: Danny Jacobs

Varying the reionization parameters yields qualitatively different power spectra.

Varying ζ:

Varying $T_{\rm vir}$:

Varying $R_{\rm mfp}$:



Pober, Liu, Dillon, et al. (2013)