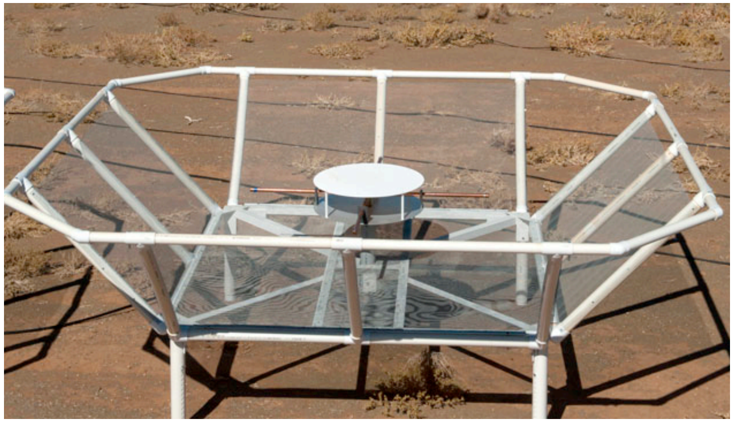
# How a “1-year project” became my last 3 years of grad school

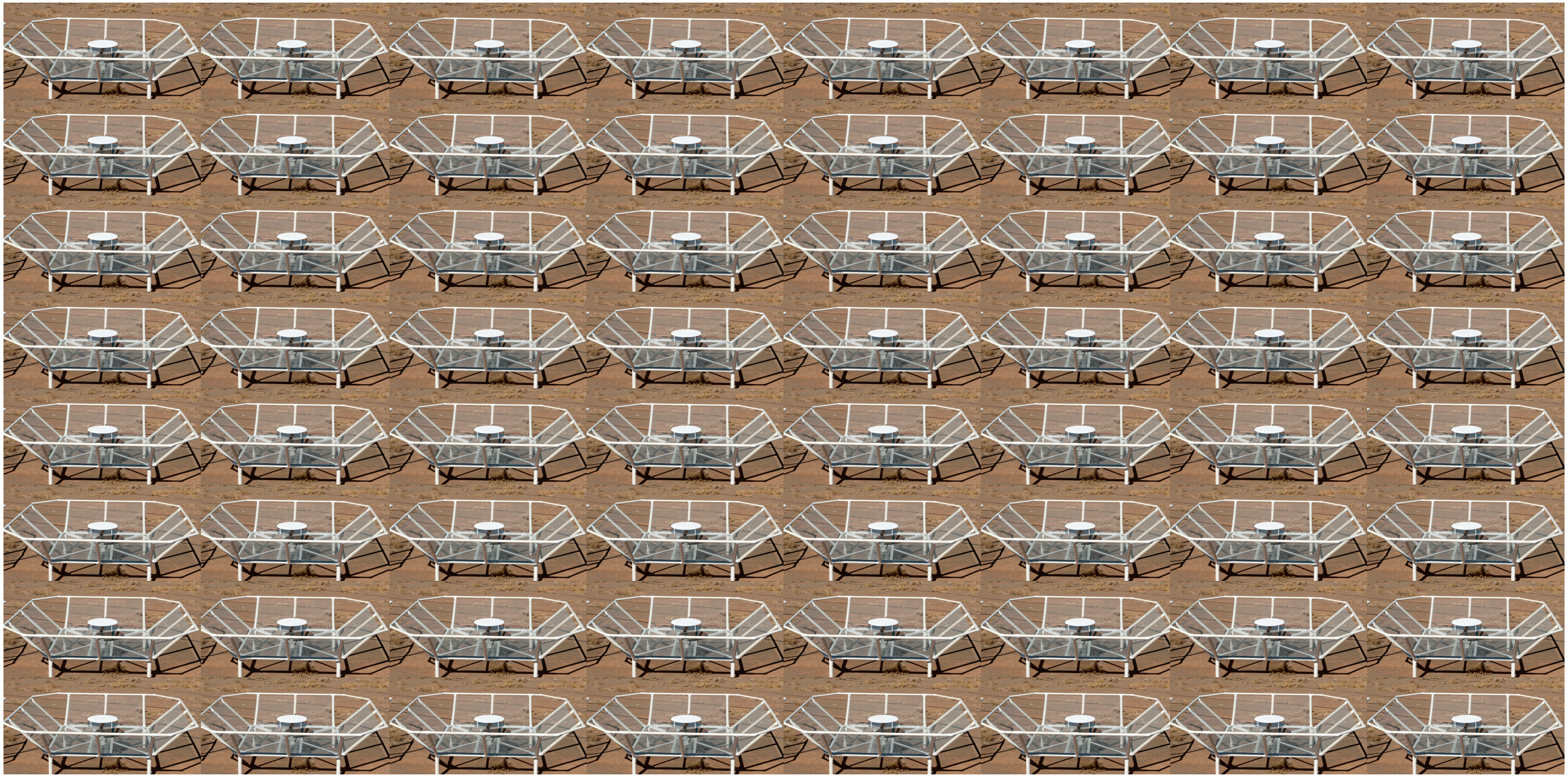
21cm Power Spectrum Analysis is Really Hard

21cm Power Spectrum Lessons:
Updated Results from the PAPER Experiment

Carina Cheng
UC Berkeley

# The Story





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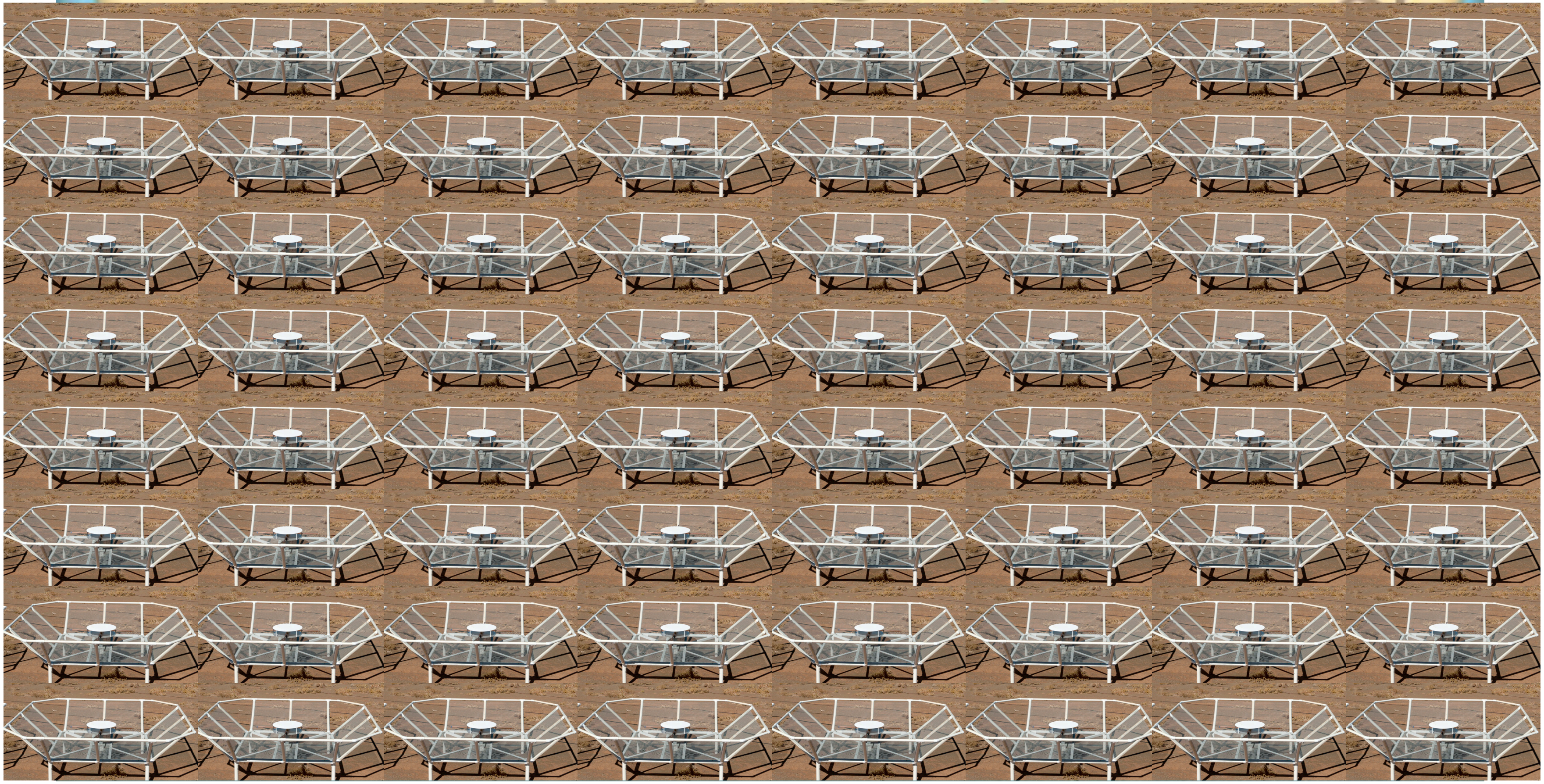

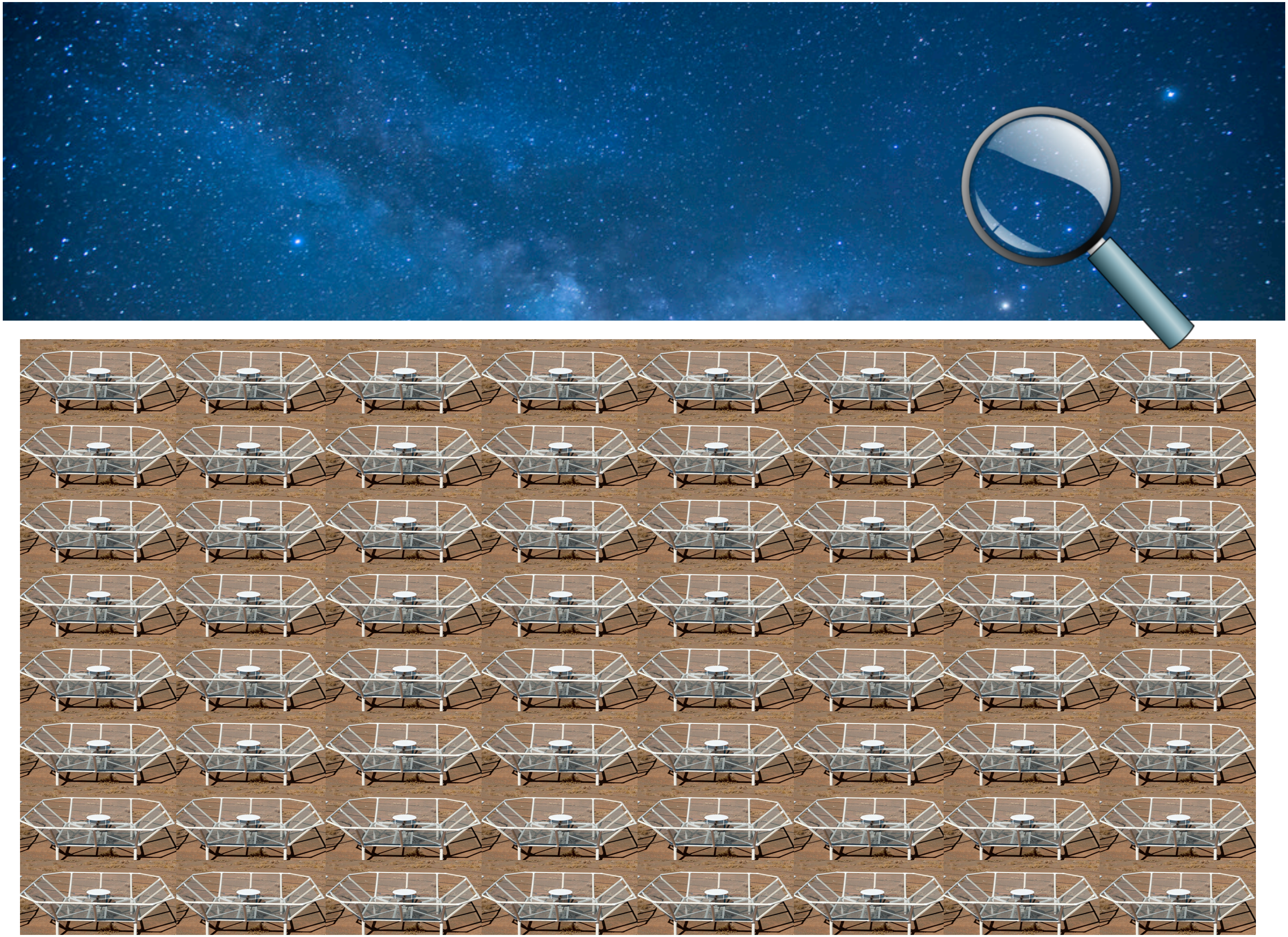


x 64

# The Story

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PAPER-64 CONSTRAINTS ON REIONIZATION: THE 21 cm POWER SPECTRUM AT $z = 8.4$

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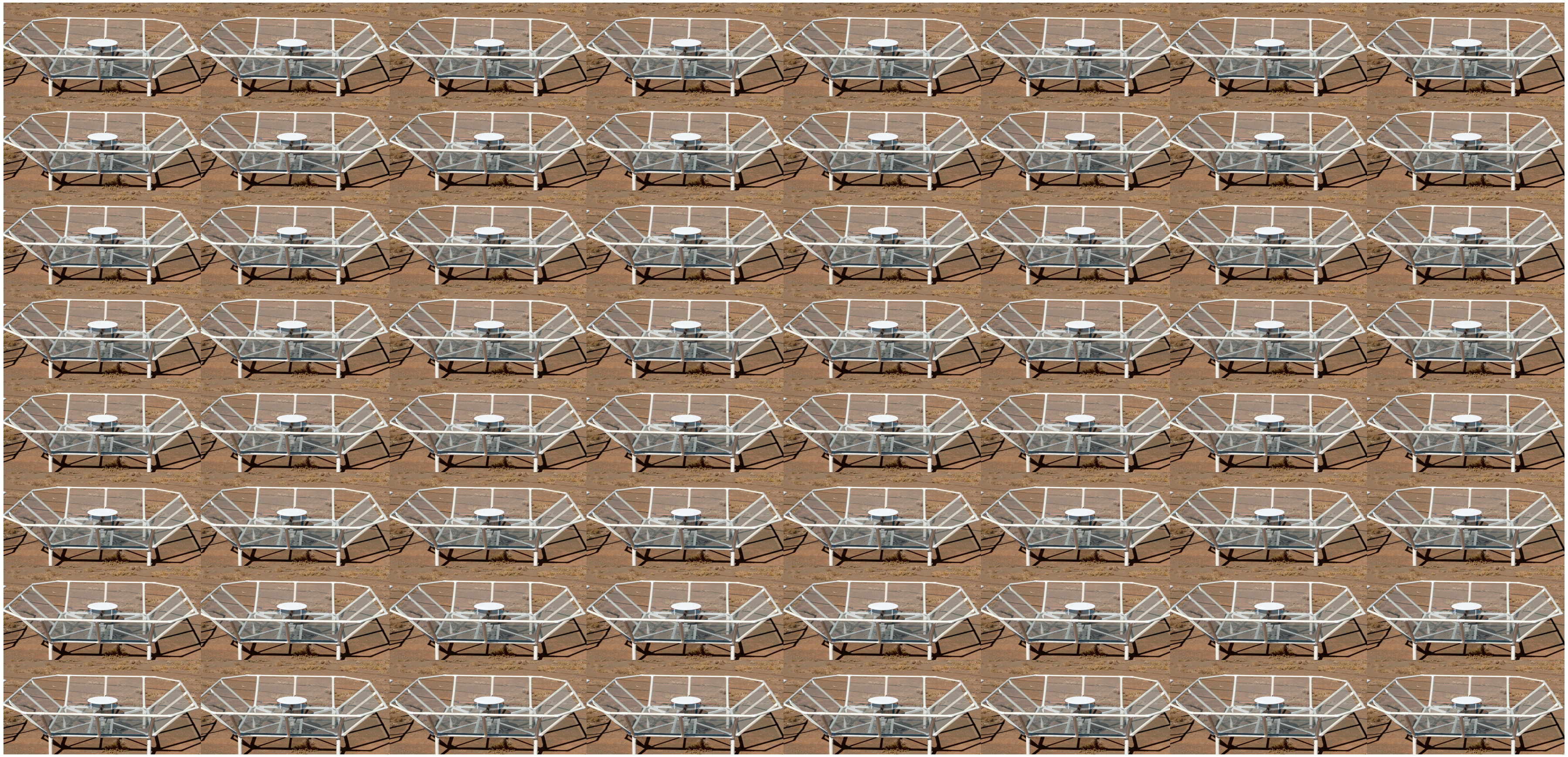
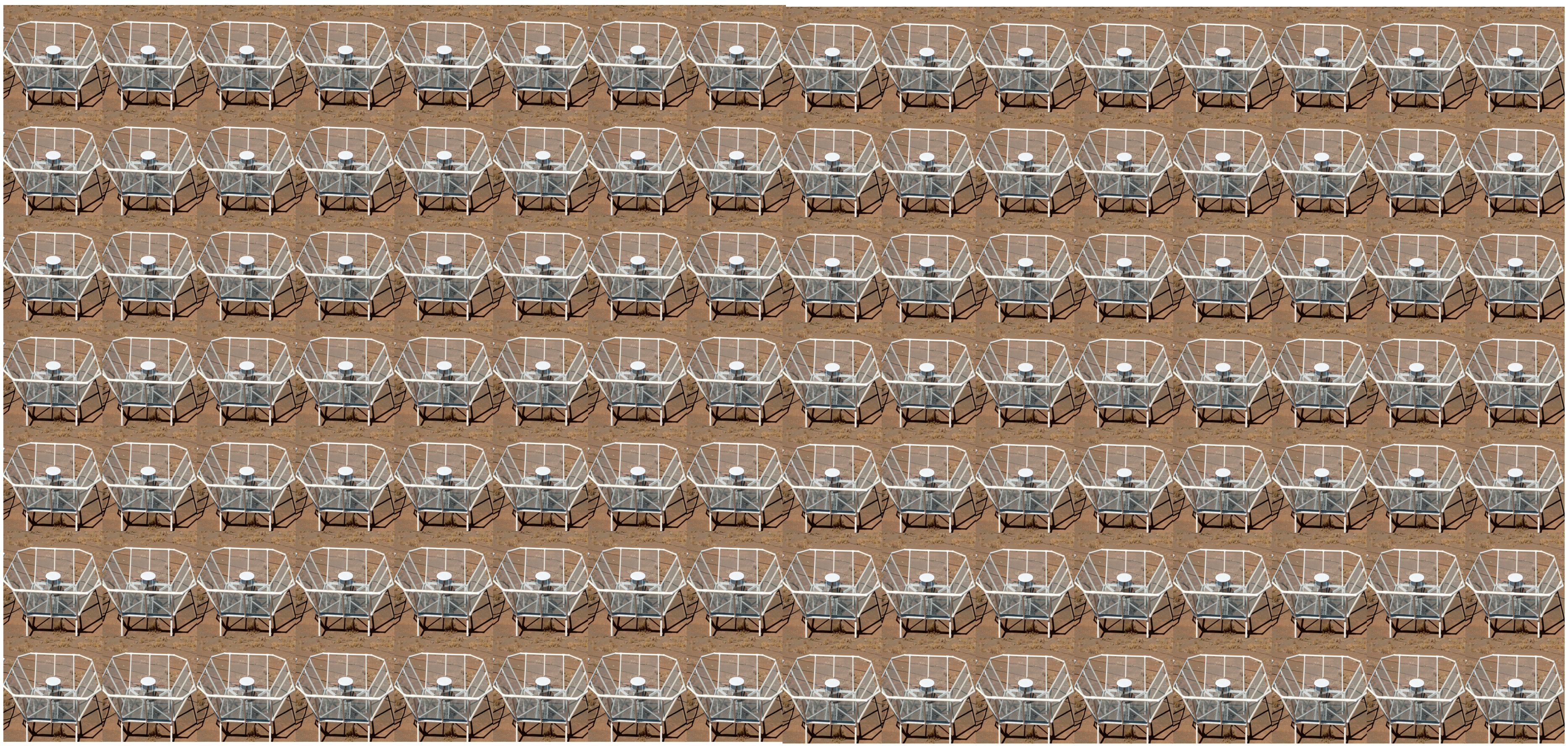
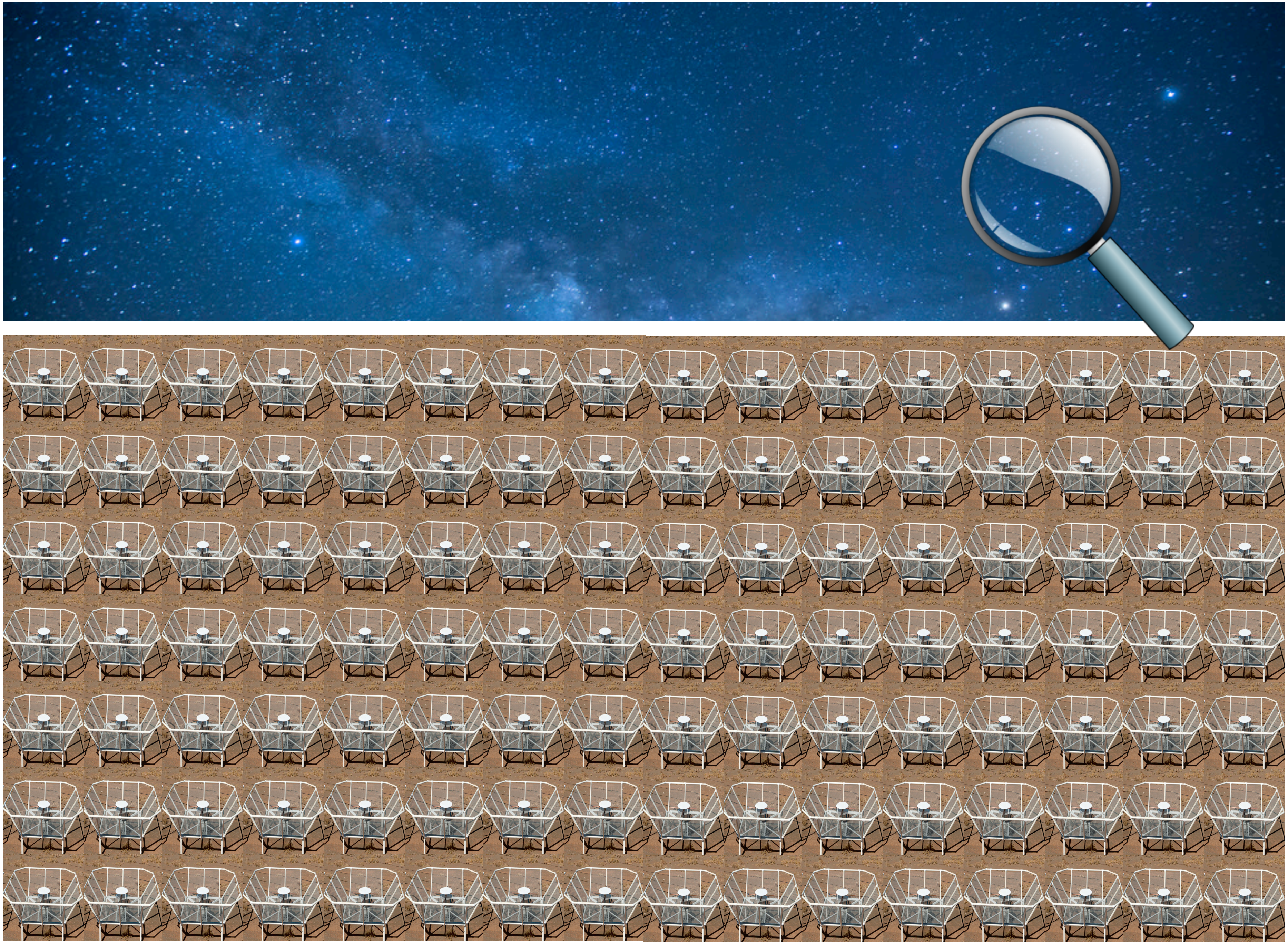
ABSTRACT

In this paper, we report new limits on 21 cm emission from cosmic reionization based on a 135 day observing campaign with a 64-element deployment of the Donald C. Backer Precision Array for Probing the Epoch of Reionization in South Africa. This work extends the work presented in Parsons et al. with more collecting area, a longer observing period, improved redundancy-based calibration, improved fringe-rate filtering, and updated power-spectral analysis using optimal quadratic estimators. The result is a new $2\sigma$ upper limit on $\Delta^2(k)$ of $(22.4\ \text{mK})^2$ in the range $0.15 < k < 0.5h\ \text{Mpc}^{-1}$ at $z = 8.4$. This represents a three-fold improvement over the previous best upper limit. As we discuss in more depth in a forthcoming paper, this upper limit supports and extends previous evidence against extremely cold reionization scenarios. We conclude with a discussion of implications for future 21 cm reionization experiments, including the newly funded Hydrogen Epoch of Reionization Array.

*Key words:* cosmology: observations – dark ages, reionization, first stars – early universe – instrumentation: interferometers – intergalactic medium








x 128

???


x 64

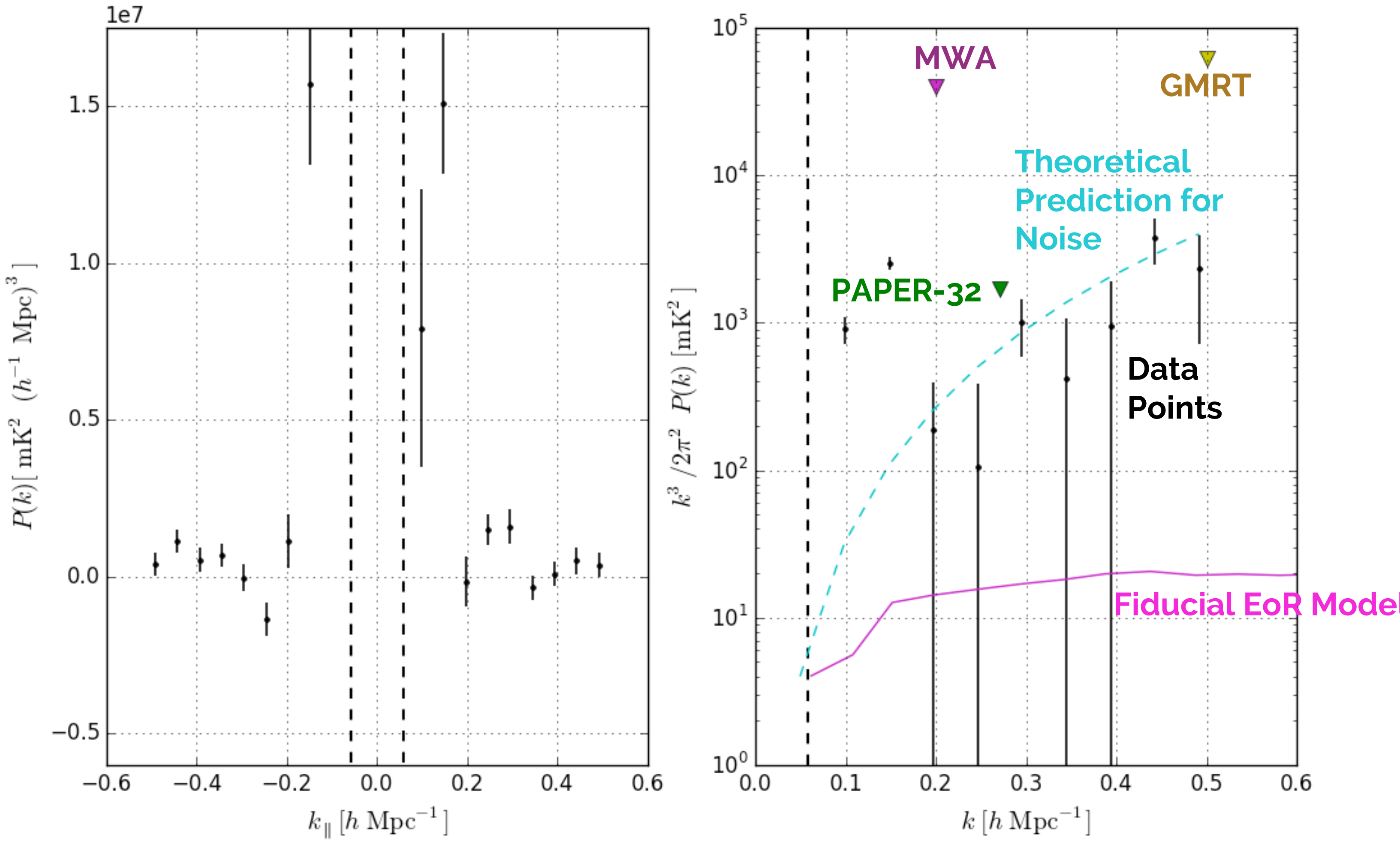
# Outline

- Introduction
- PAPER-64 Results & Status of Field
- Reasons for Revision
- Updated PAPER-64 Results

# Precision Array for Probing the Epoch of Reionization

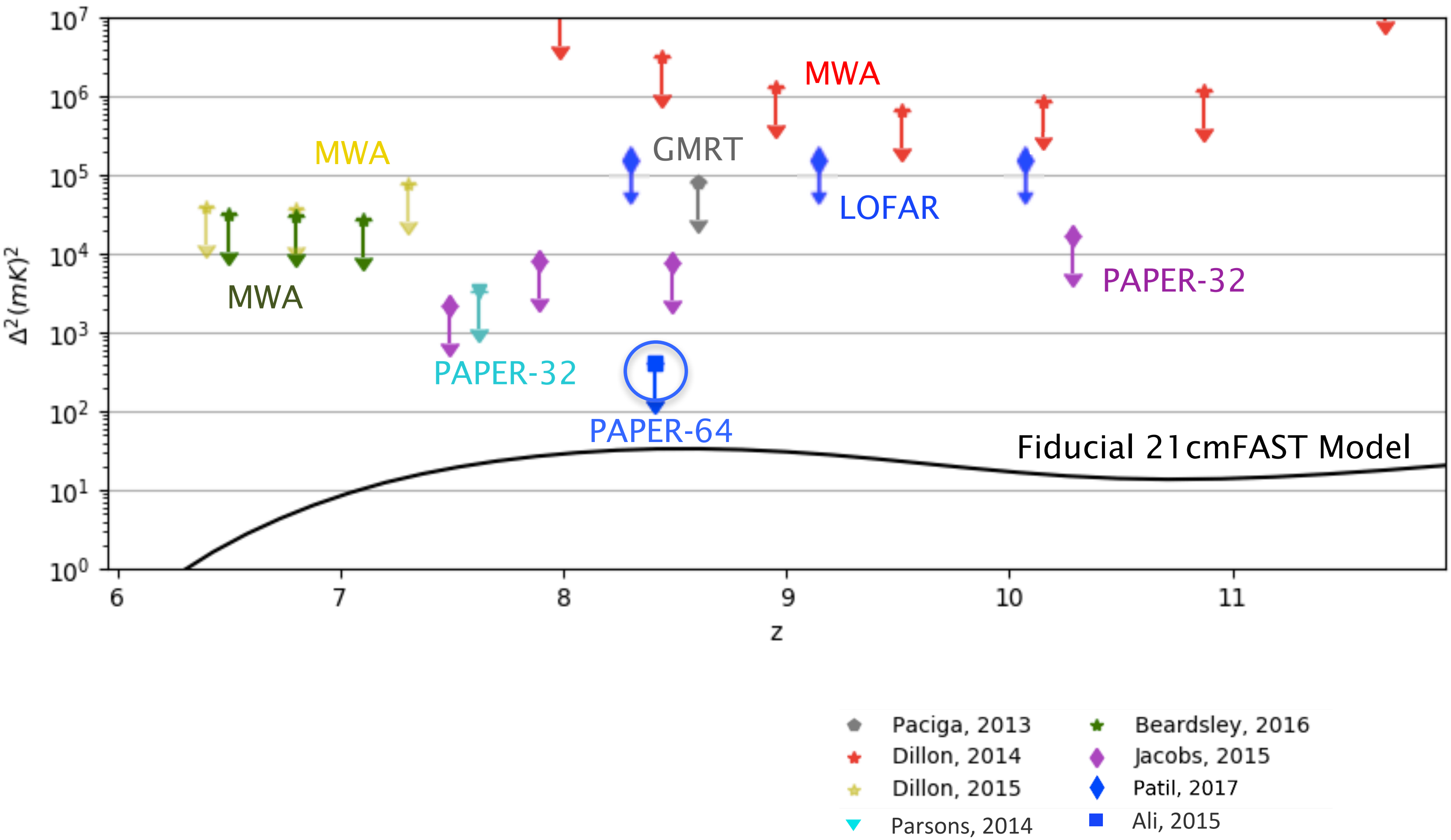
- Interferometer located in the Karoo Desert, South Africa
- EoR experiment (100-200MHz)
- PAPER-64: 2012-2013
- PAPER-128: 2013-2015
- Main challenge: foregrounds & systematics are ~$10^4$-$10^5$ times brighter than the predicted EoR signal
- One PAPER technique to increase sensitivity: *fringe-rate filtering*

# Original PAPER-64 Results (z = 8.4)




Ali et al. (2015)

# Status of Field



# # Low Quality Pic, High Quality People

Aaron Parsons
PI of PAPER and HERA

Danny Jacobs
ASU

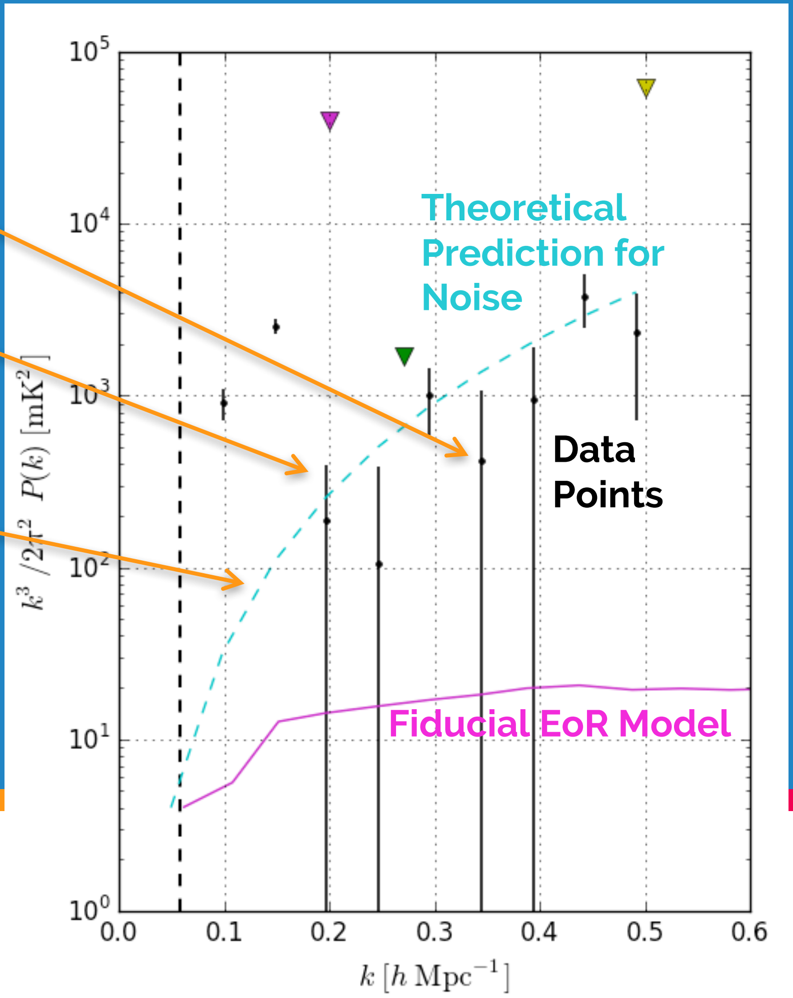
Matt Kolopanis
ASU

Saul Kohn
U. Penn.


- Zaki Ali
- Gianni Bernardi
- Adrian Liu
- Ridhima Nunhokee
- Jonathan Pober
- others

# Reasons for Revision

1) Under-estimated signal loss
2) Under-estimated errors
3) Under-estimated theoretical prediction of noise




Ali et al. (2015)

# Signal Loss

- Lesson #1: Signal loss can result when weighting data using empirically-derived covariances

Fourier-Transforms along frequency

Inverse Covariance

$$\hat{p}_\alpha \propto \mathbf{x}^\dagger \mathbf{C}^{-1} \mathbf{Q}_\alpha \mathbf{C}^{-1} \mathbf{x}$$

Data

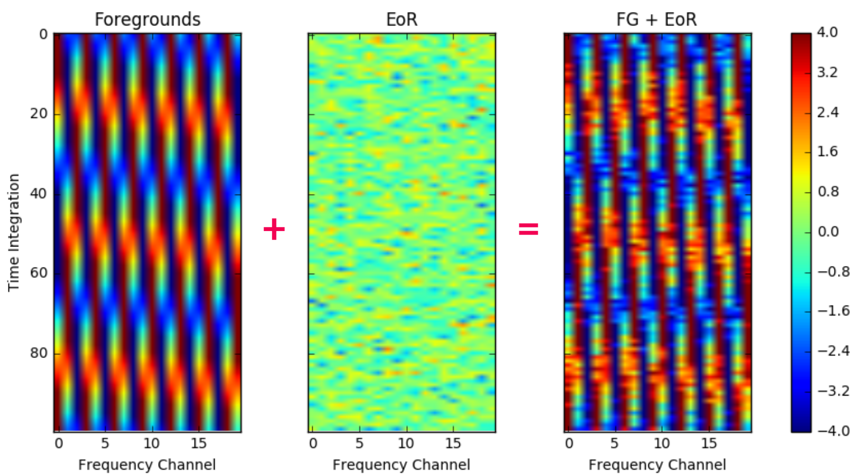
$$\hat{\mathbf{C}} \equiv \langle \mathbf{x}\mathbf{x}^\dagger \rangle_t$$

time

Liu and Tegmark (2011)

# Signal Loss

- Lesson #1: Signal loss can result when weighting data using empirically-derived covariances



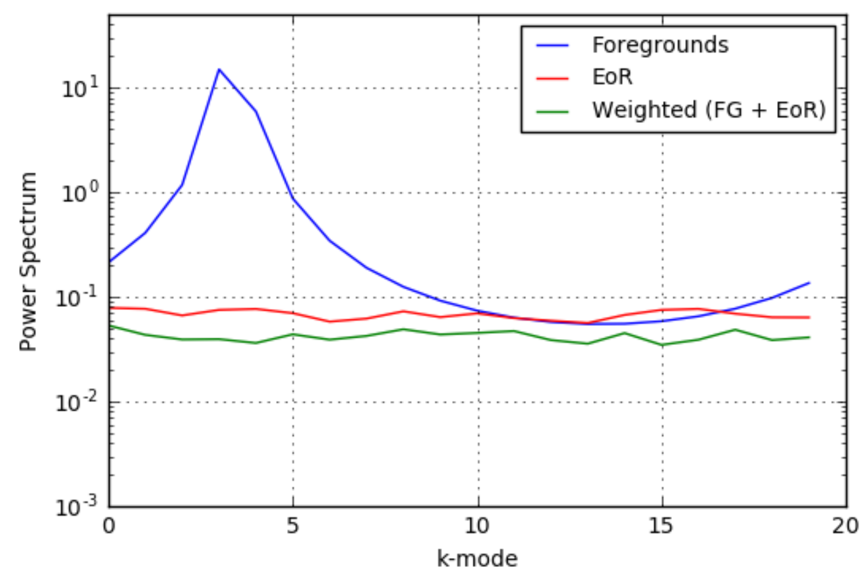

Toy Model:

**x** = foregrounds + mock EoR

$$\hat{\mathbf{C}} \equiv \langle \mathbf{x}\mathbf{x}^{\dagger} \rangle_t$$

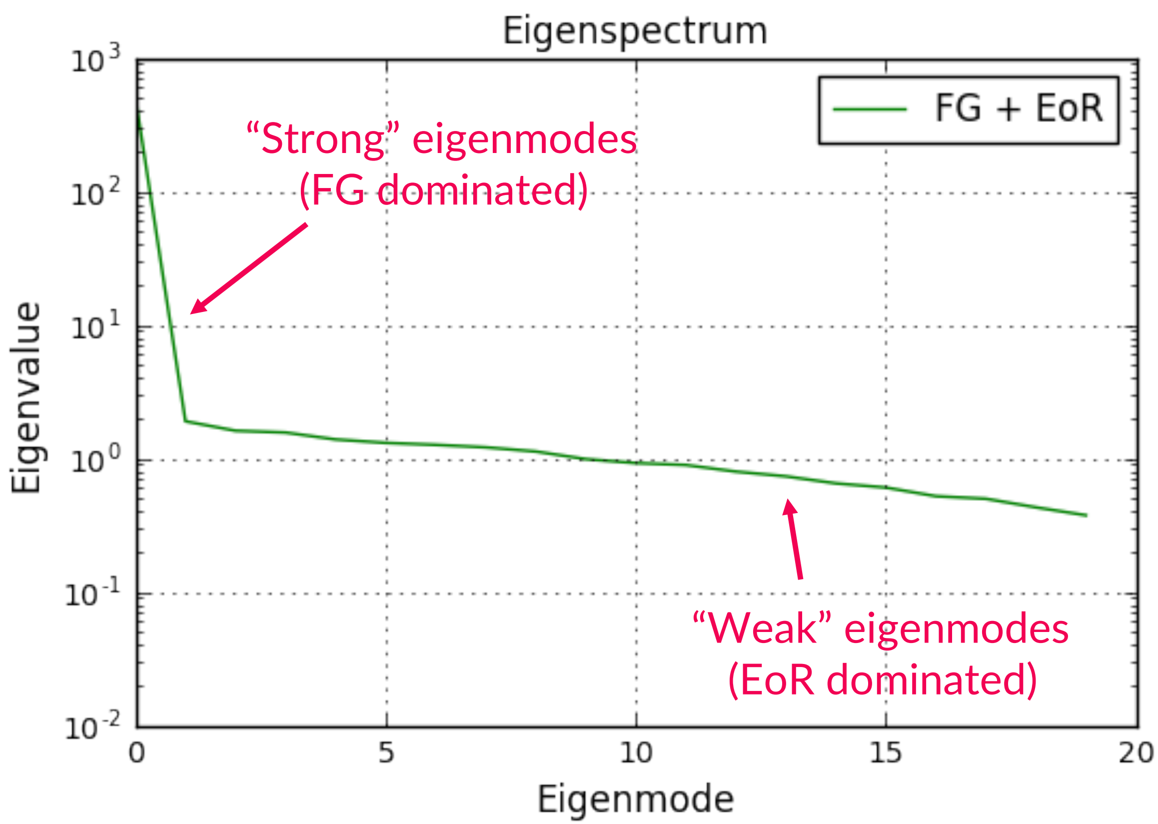
$$\hat{p}_{\alpha} \propto \mathbf{x}^{\dagger}\mathbf{C}^{-1}\mathbf{Q}_{\alpha}\mathbf{C}^{-1}\mathbf{x}$$

Cheng et al., *in prep*



# Signal Loss

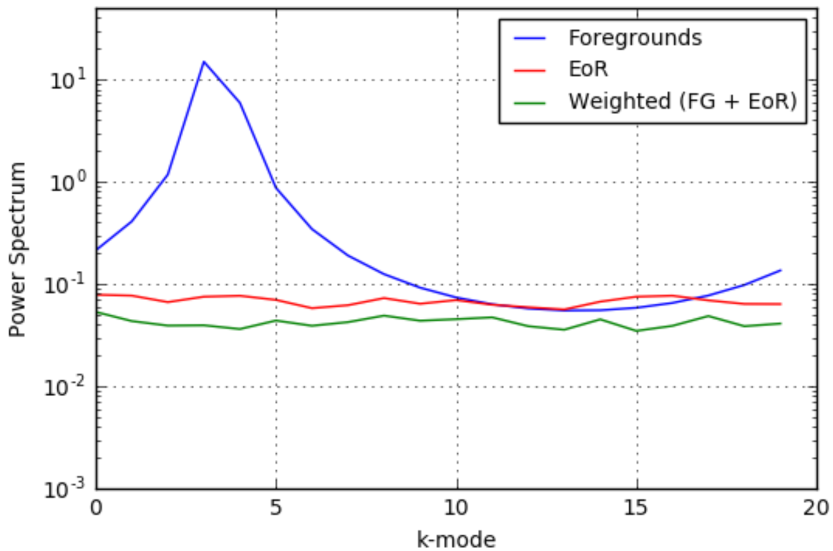
- Lesson #1: Signal loss can result when weighting data using empirically-derived covariances



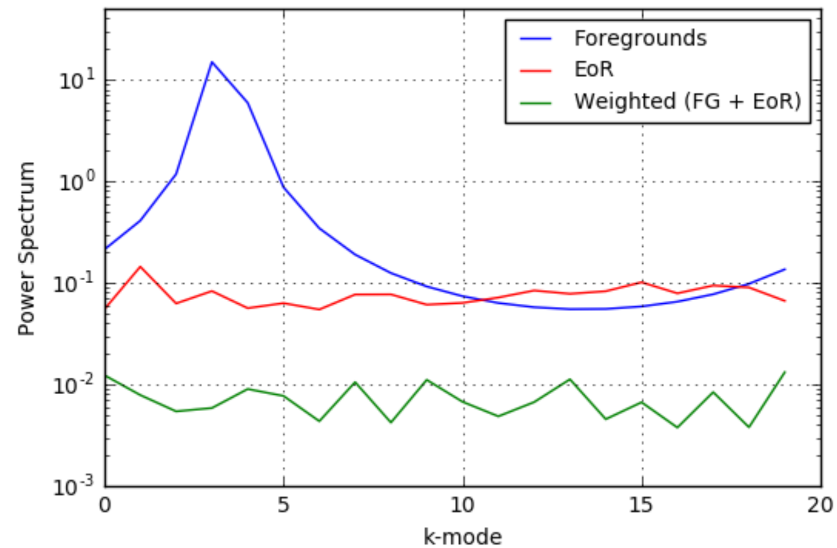

Cheng et al., *in prep*

# Signal Loss

- Lesson #2: Signal loss is magnified if data has a reduced number of independent samples




Original Toy Model
$N_{eff}$ = 100




Time-Averaged Toy Model
$N_{eff}$ = 25

Cheng et al., *in prep*

# Signal Loss

▷ Lesson #3: Signal loss can be quantified with injection/recovery simulations, but not with EoR-only simulations

Data EoR

$$\mathbf{r} = \mathbf{x} + \mathbf{e} \qquad \hat{\mathbf{C}} = \langle \mathbf{r}\mathbf{r}^{\dagger} \rangle$$

$$P_{in} \propto \mathbf{e}^{\dagger}\mathbf{I}\mathbf{Q}\mathbf{I}\mathbf{e}$$

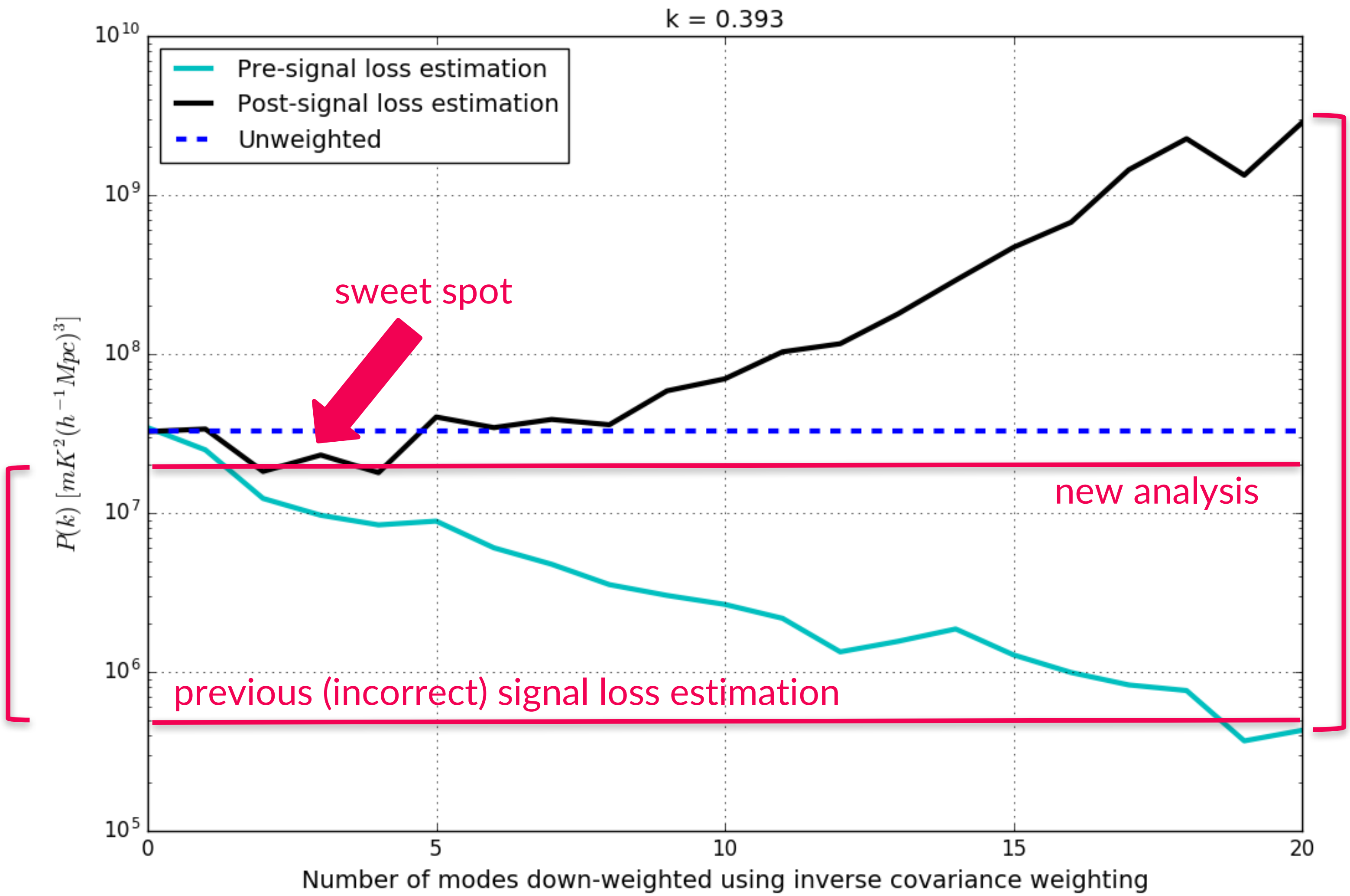
"Input" = unweighted PS of EoR-only

~~$$P_{out} \propto \mathbf{e}^{\dagger}\hat{\mathbf{C}}^{-1}\mathbf{Q}\hat{\mathbf{C}}^{-1}\mathbf{e}$$~~

"Output" = weighted PS of EoR-only

**This overestimates $P_{out}$ (underestimates signal loss) because it does not take into account FG-EoR correlations!**

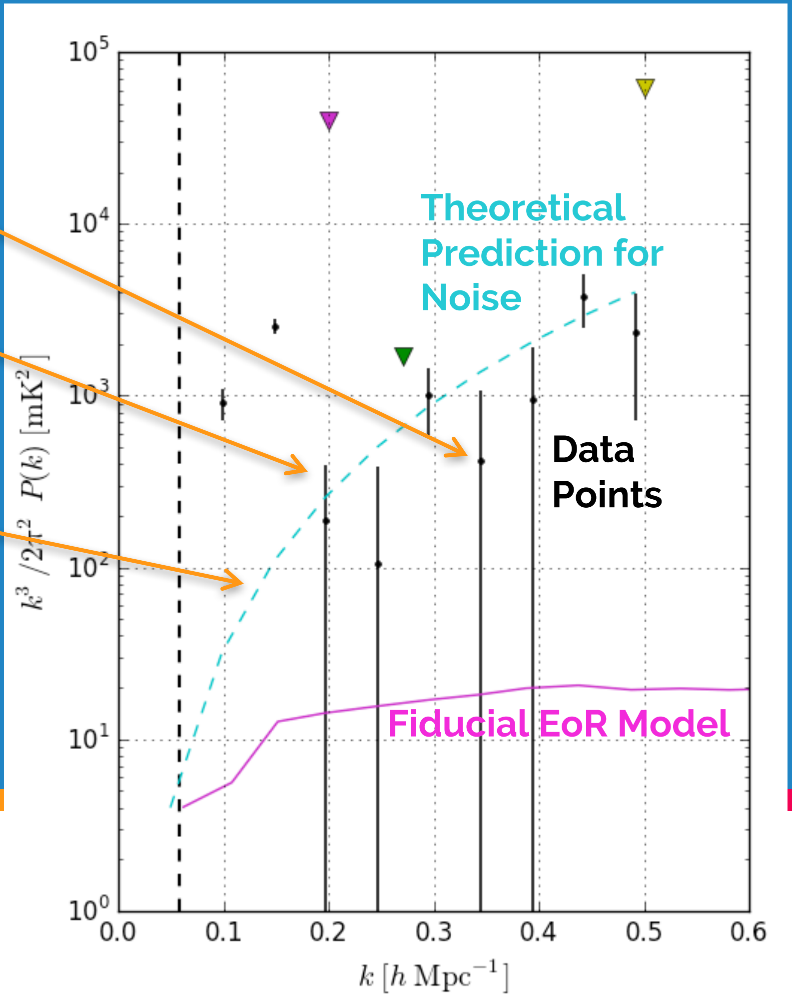
# Signal Loss in PAPER-64




Cheng et al., *in prep*

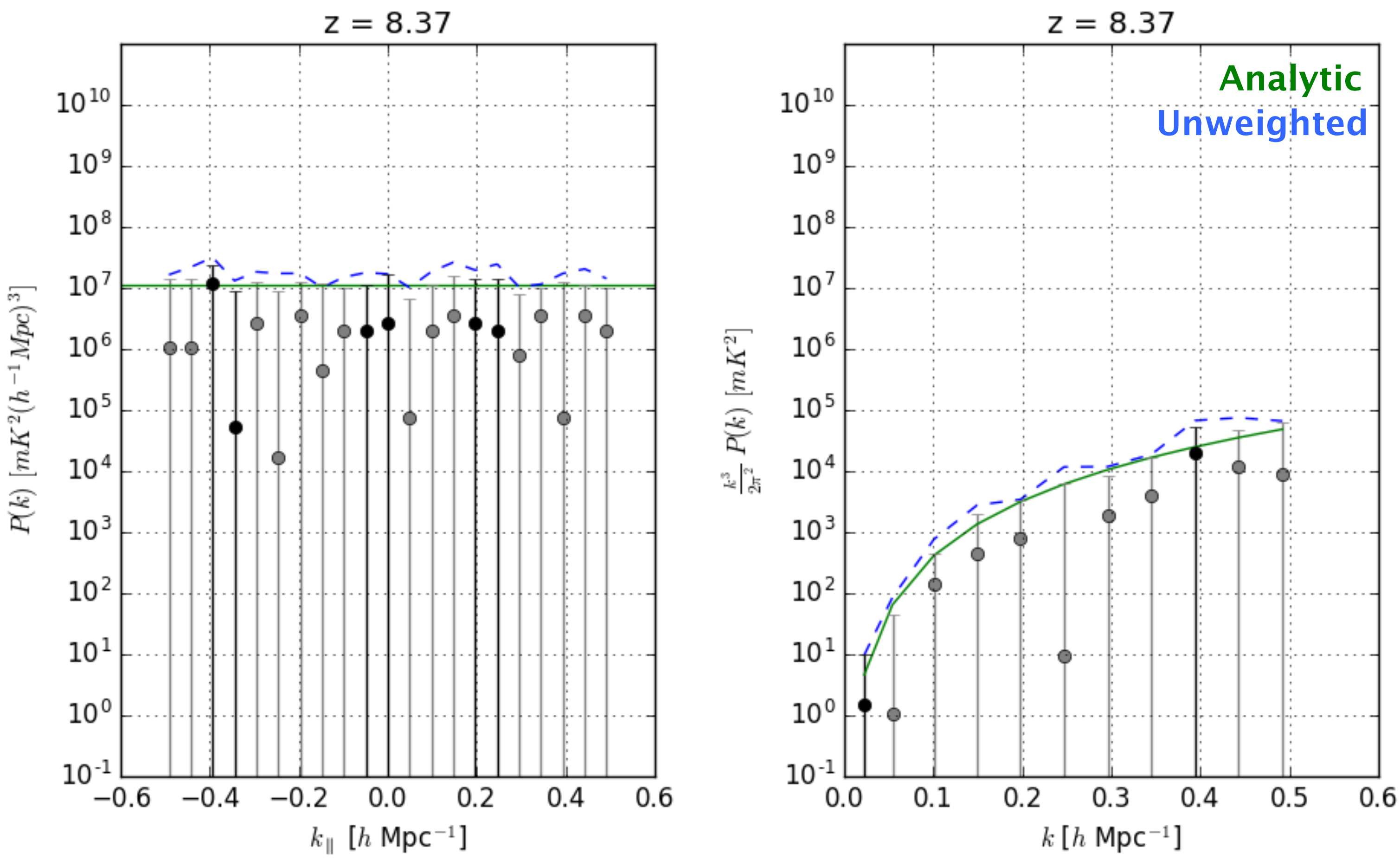
# Reasons for Revision

1) **Under-estimated signal loss**
2) **Under-estimated errors**
3) **Under-estimated theoretical prediction of noise**



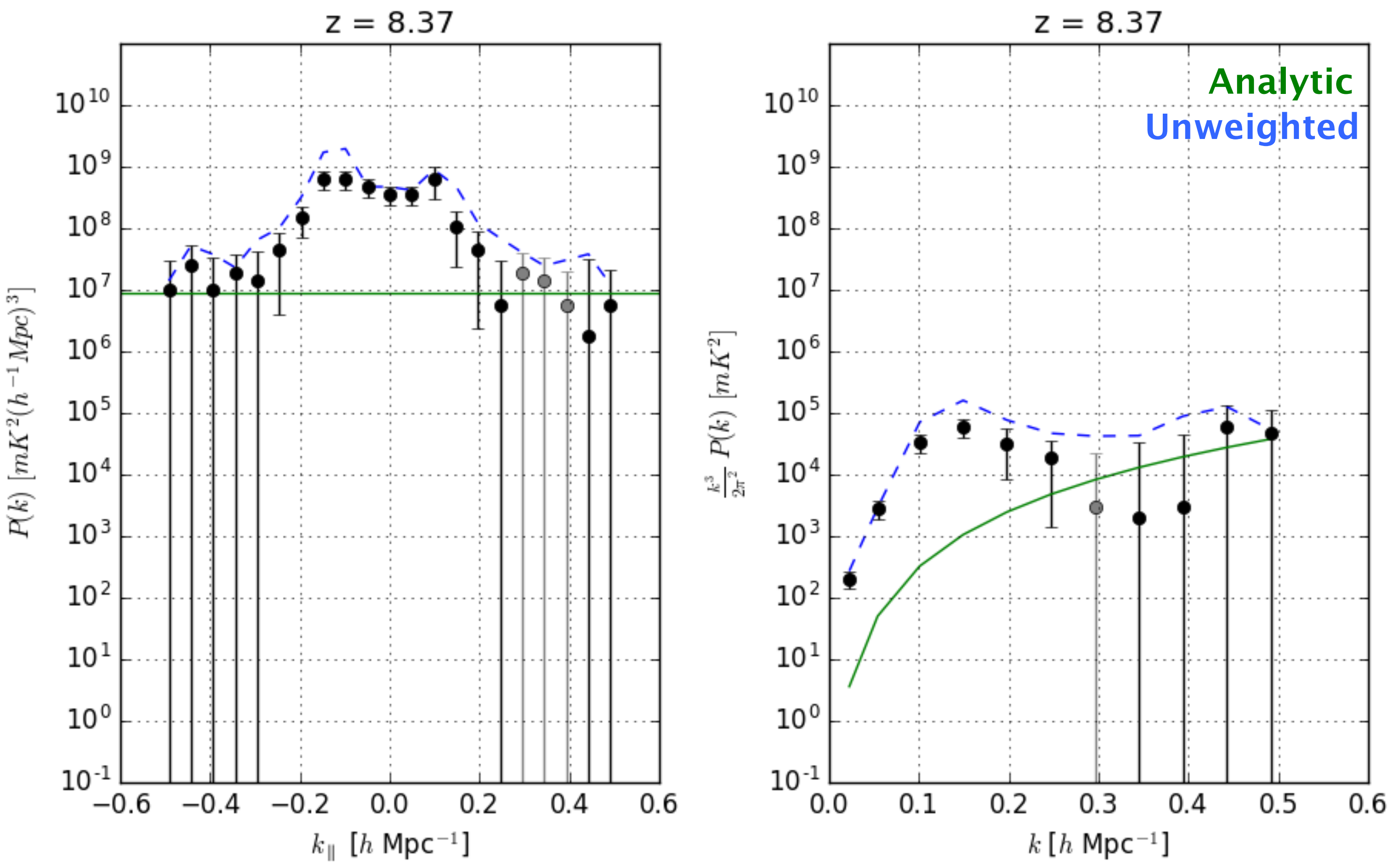

Ali et al. (2015)

# Verifying with Noise Simulations




Cheng et al., *in prep*

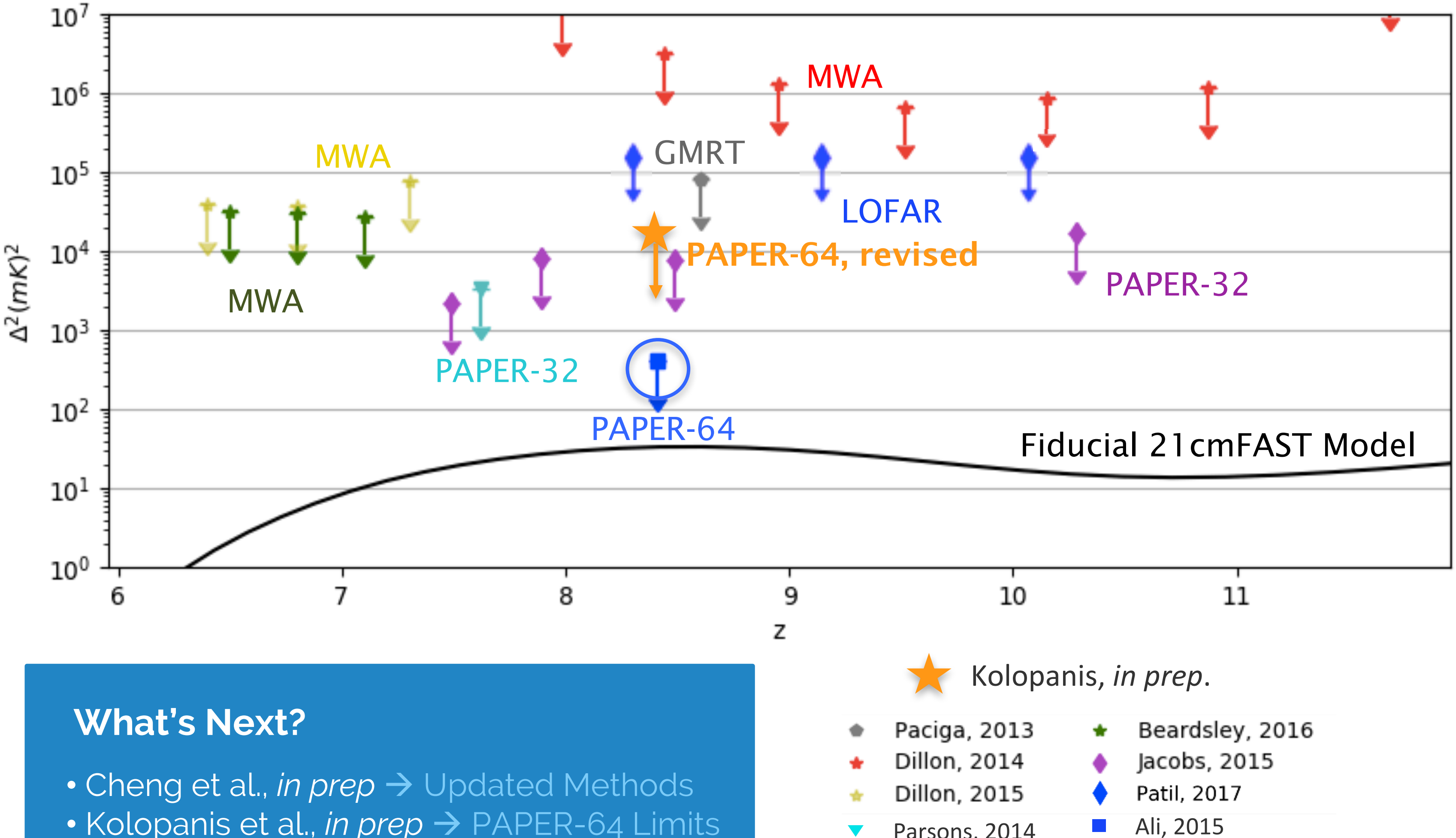
# PAPER-64 Revised Power Spectrum
# One baseline type only




Cheng et al., *in prep*

# Status of Field (revised)






**What's Next?**

- Cheng et al., *in prep* → Updated Methods
- Kolopanis et al., *in prep* → PAPER-64 Limits

# 21cm Power Spectrum Analysis is Really Hard

… but we've come a long way in our understandings, we're on much firmer ground for future analyses, and it only cost me one gray hair (so far).

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Updated Results from the PAPER Experiment~~

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# Thanks!

## Questions?

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