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

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21cm Power Spectrum Analysis is Really Hard

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~~Updated Results from the PAPER Experiment~~

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How a "1-year project" became my last 3 years of grad school

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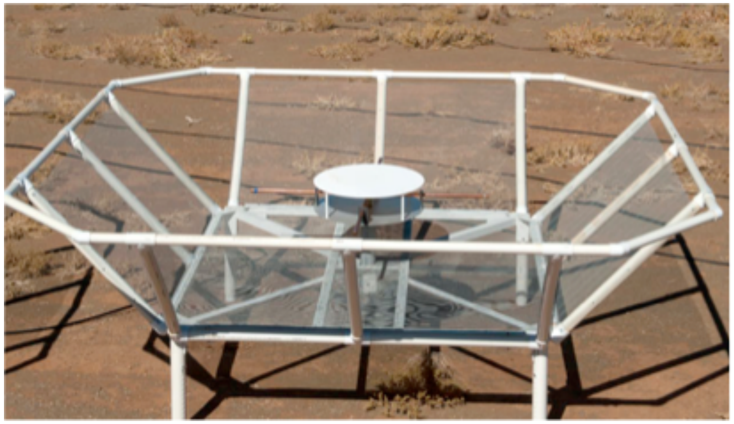
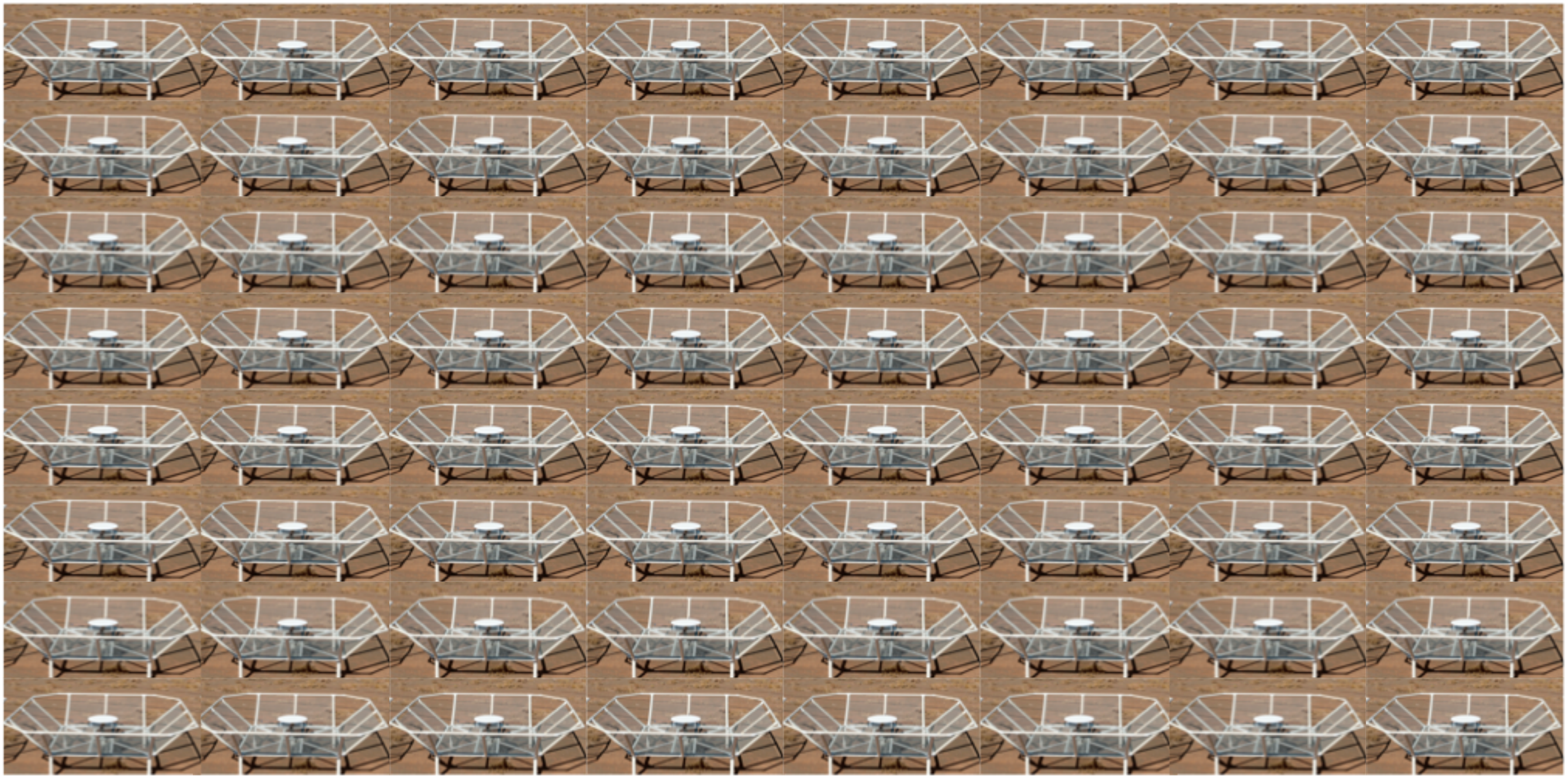
The Story



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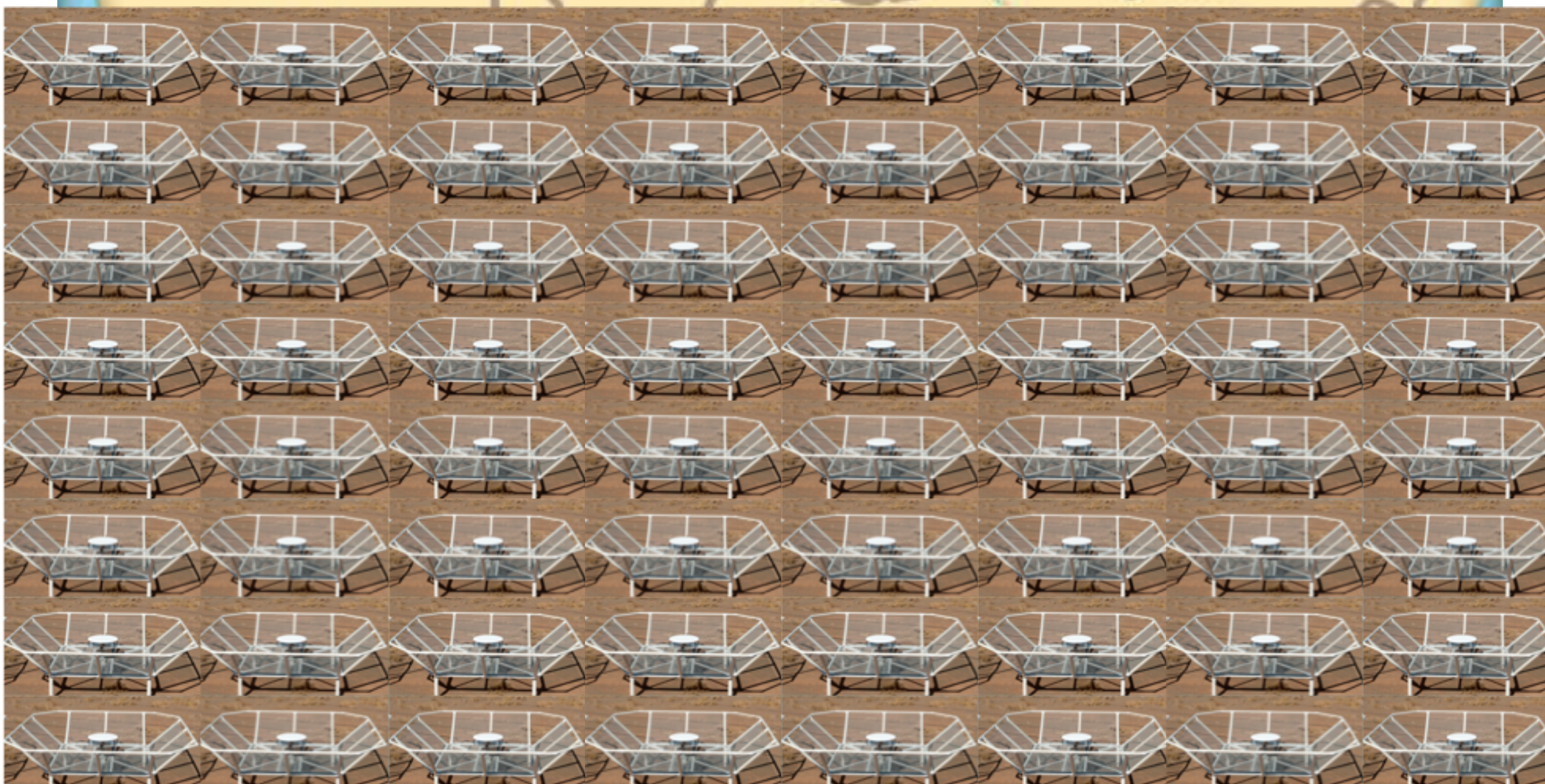

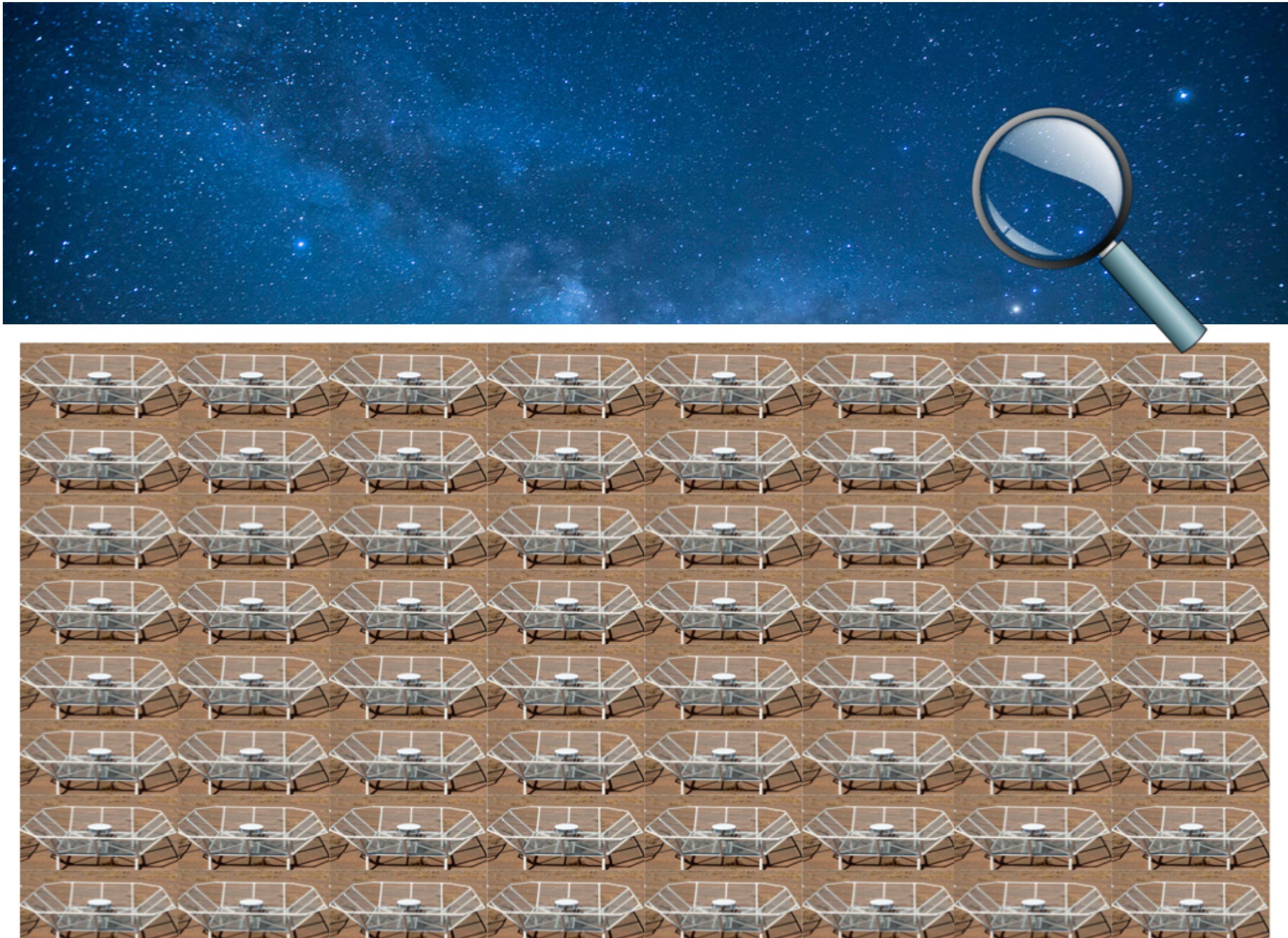


x 64

The Astrophysical Journal, 809:61 (21pp), 2015 August 10 doi:10.1088/0004-637X/809/1/61

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

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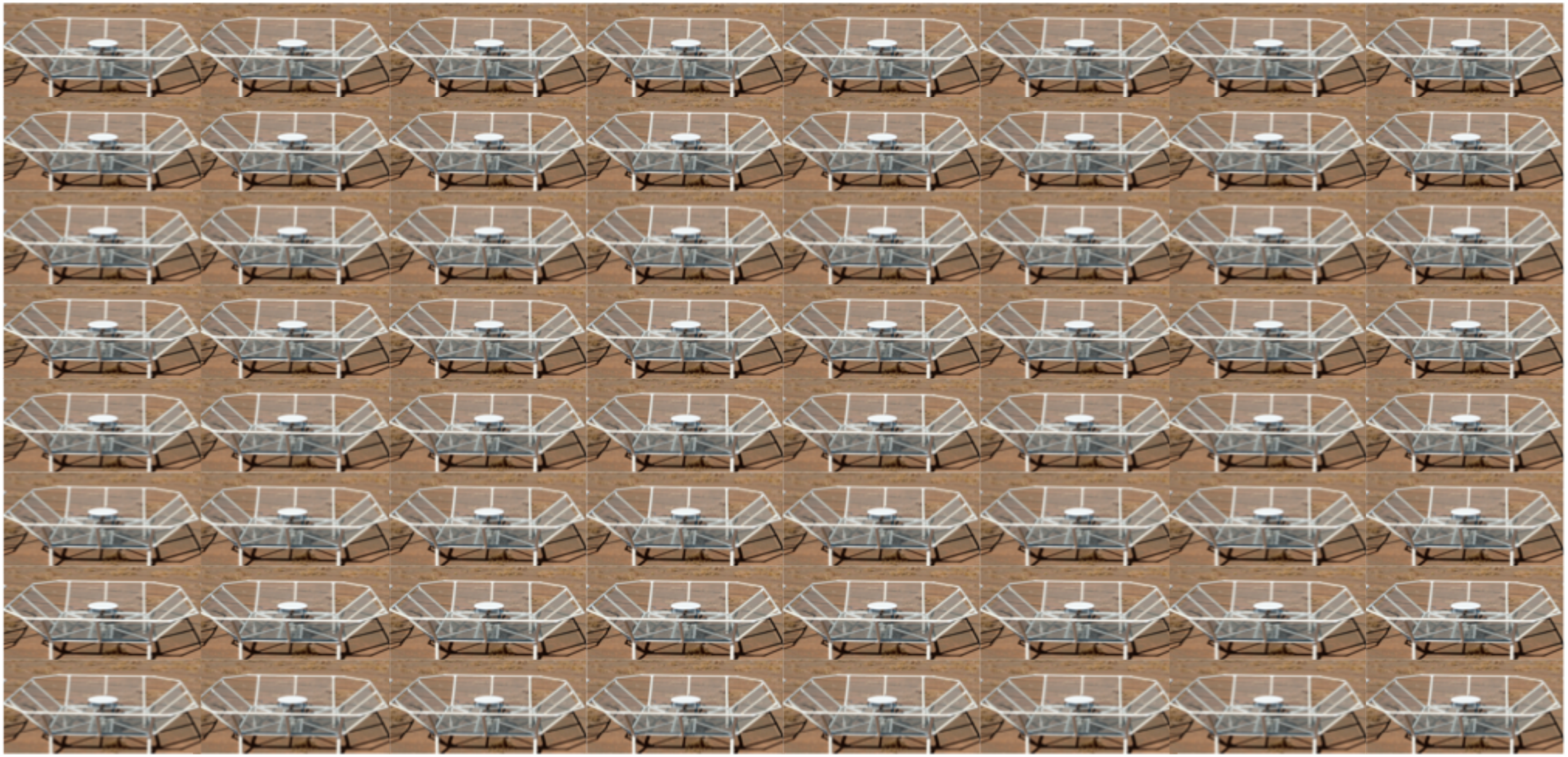
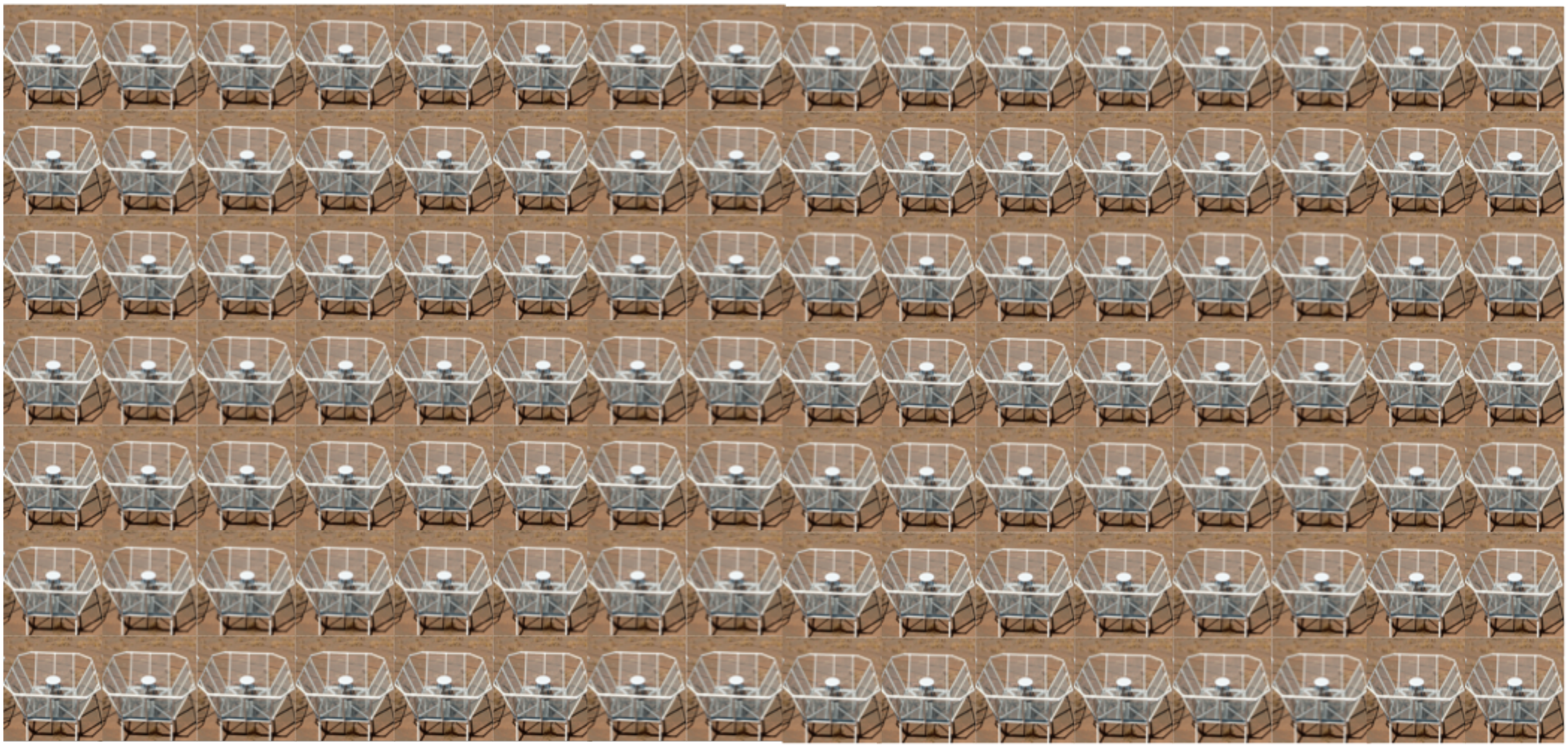
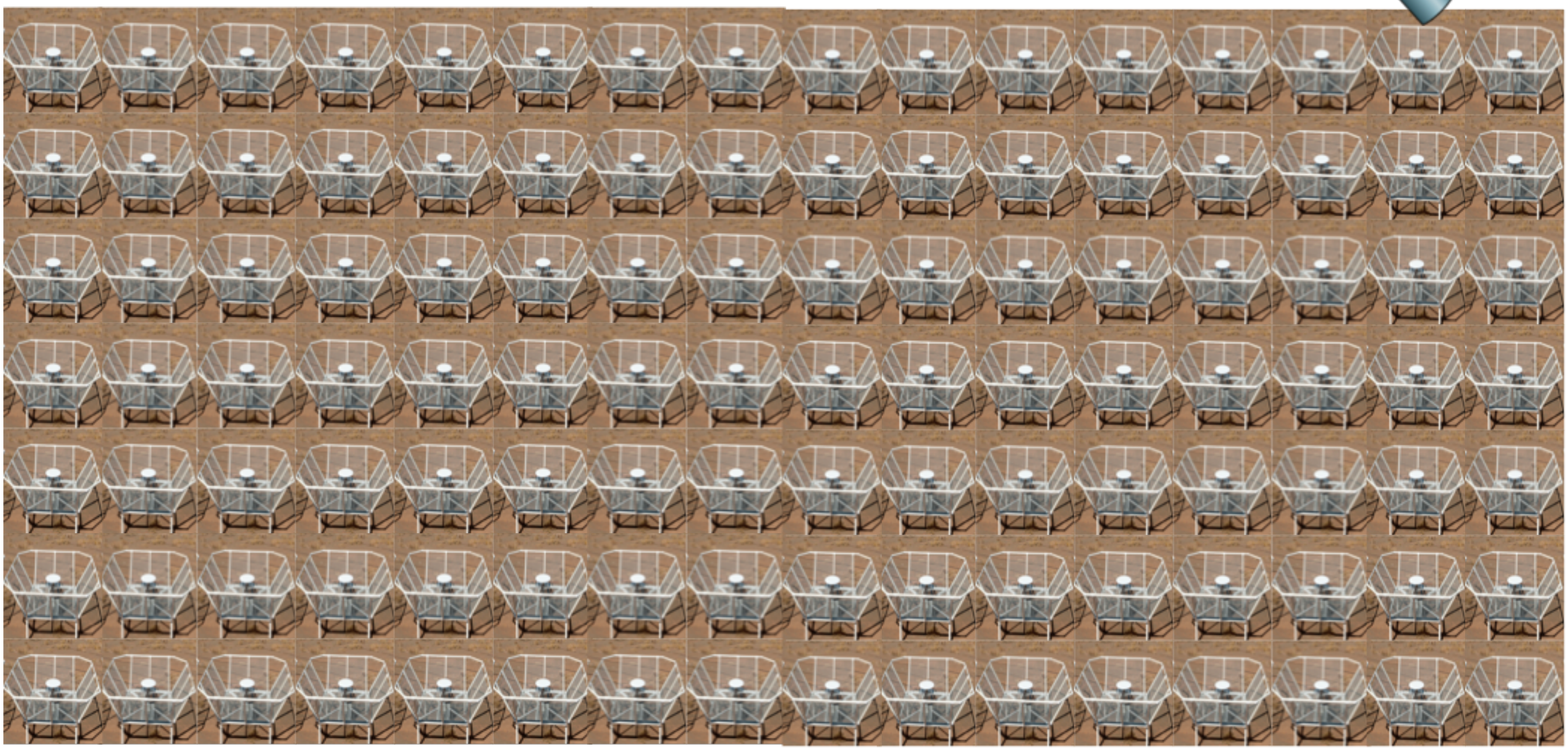
ABSTRACT

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 2σ upper limit on $\Delta^2(k)$ of $(22.4\,\mathrm{mK})^2$ in the range $0.15 < k < 0.5h\ \mathrm{Mpc}^{-1}$ 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

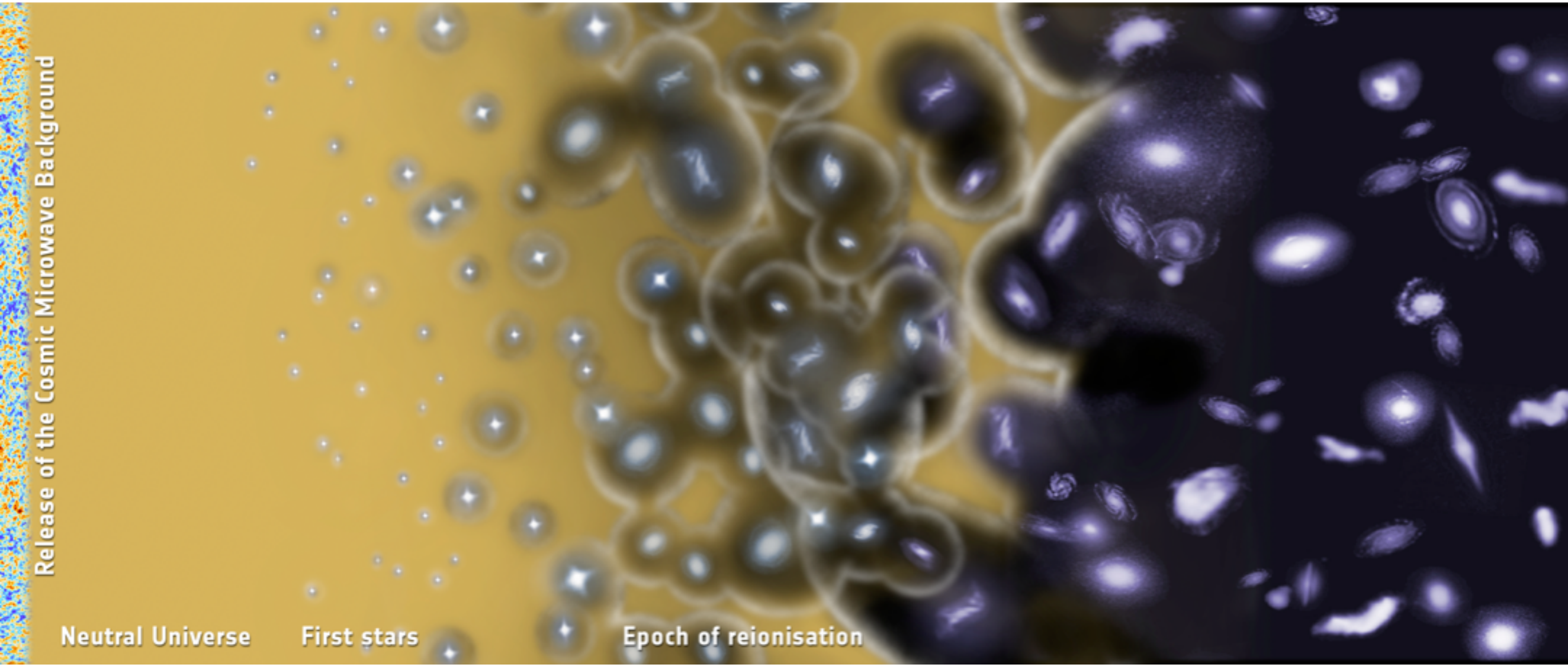
???


x 64

Outline

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

Epoch of Reionization

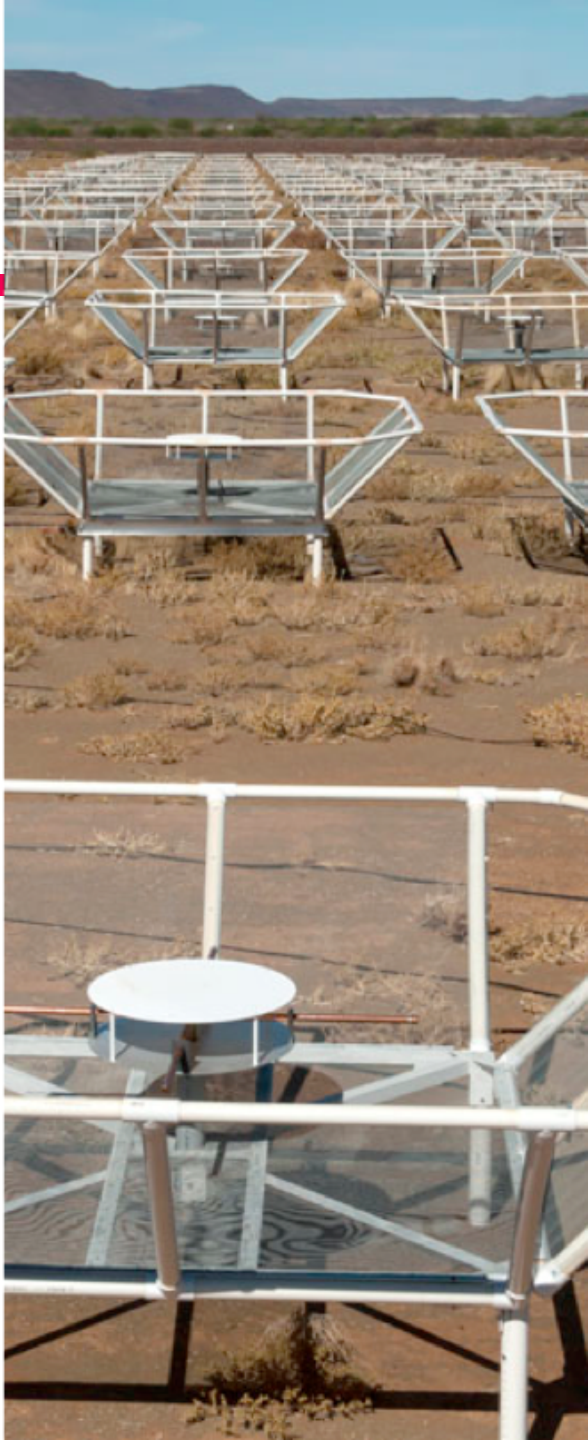


z = 6-12

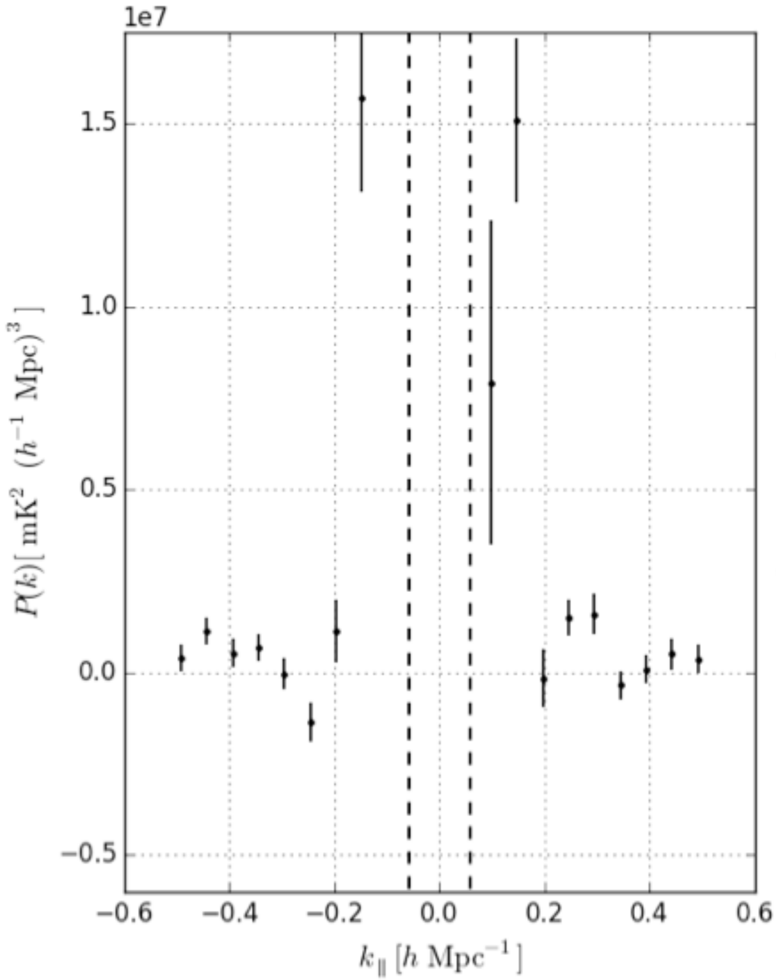
100-200 MHz

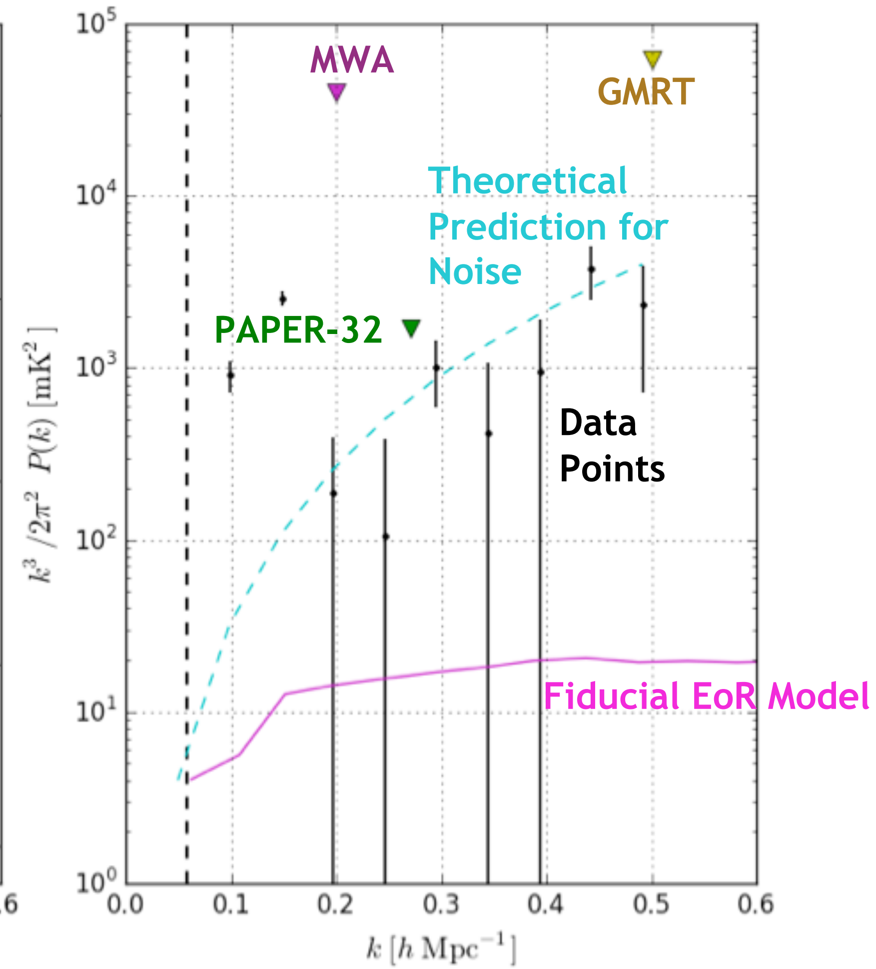
Precision Array for Probing the Epoch of Reionization

- Interferometer located in the Karoo Desert, South Africa
- 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*



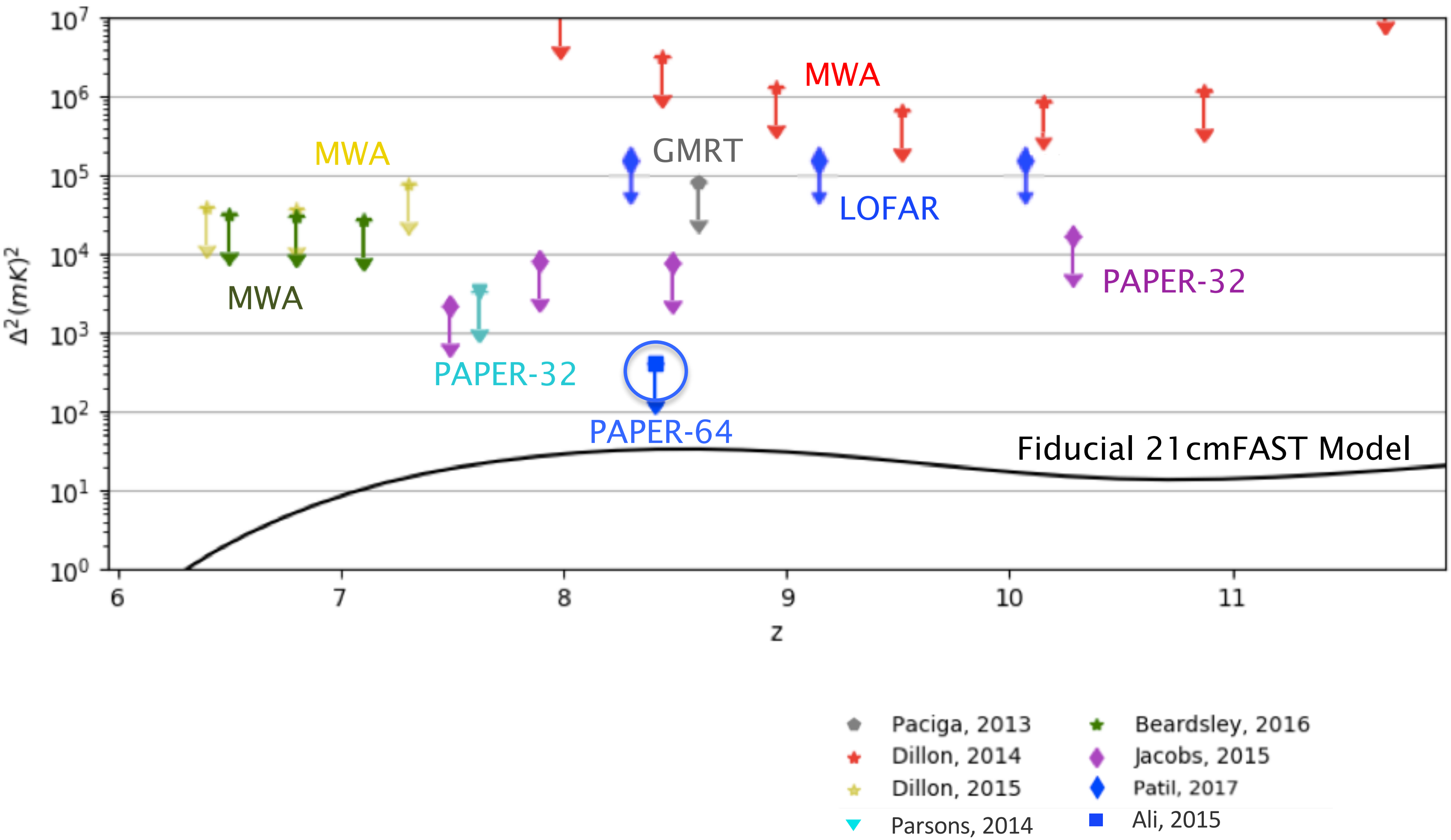
Original PAPER-64 Results (z = 8.4)





Ali et al. (2015)

Status of Field



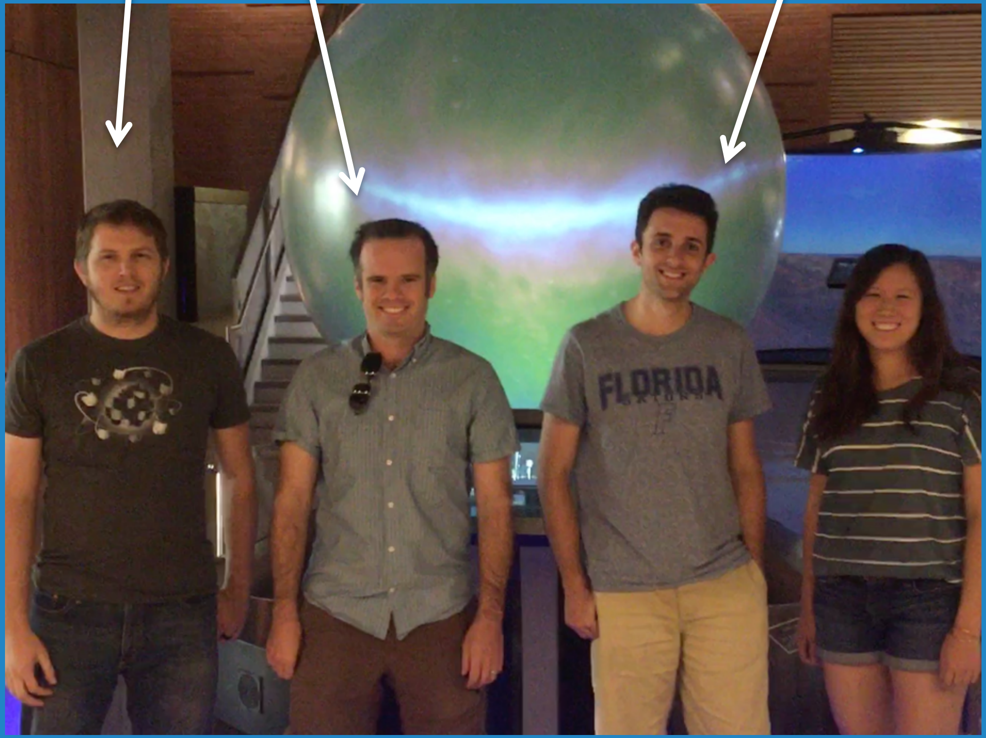
Low Quality Pic, High Quality People

Aaron Parsons
PI of PAPER and HERA

Danny Jacobs
ASU

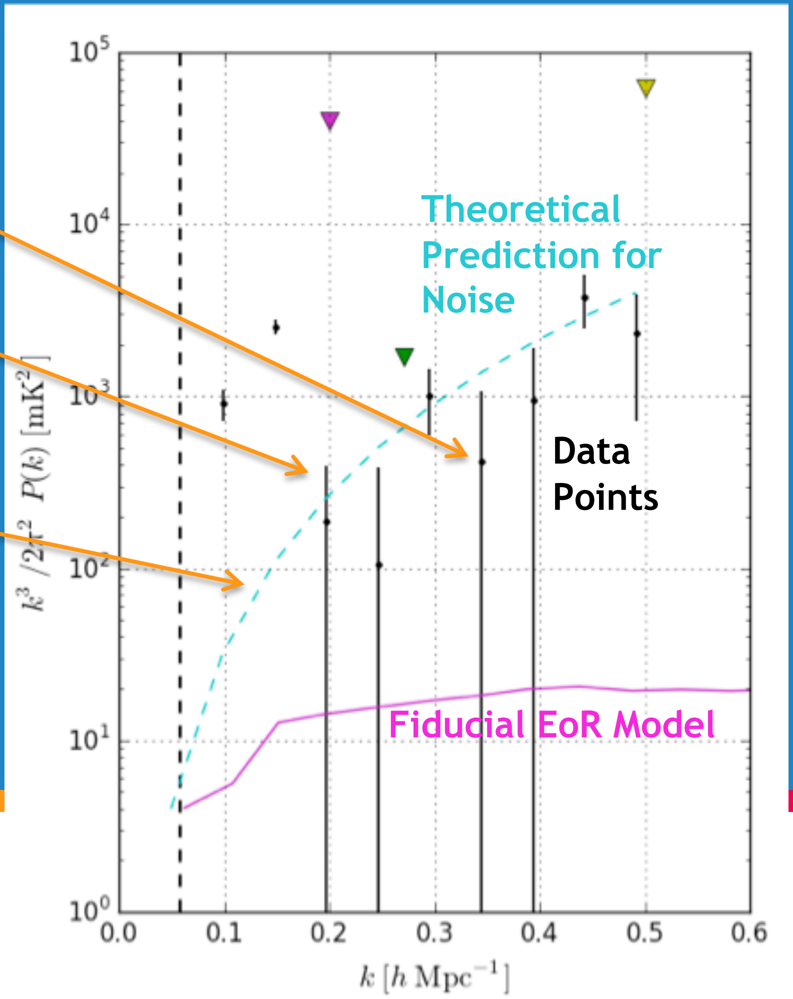
Matt Kolopanis
ASU

Saul Kohn
U. Penn.



Reasons for Revision

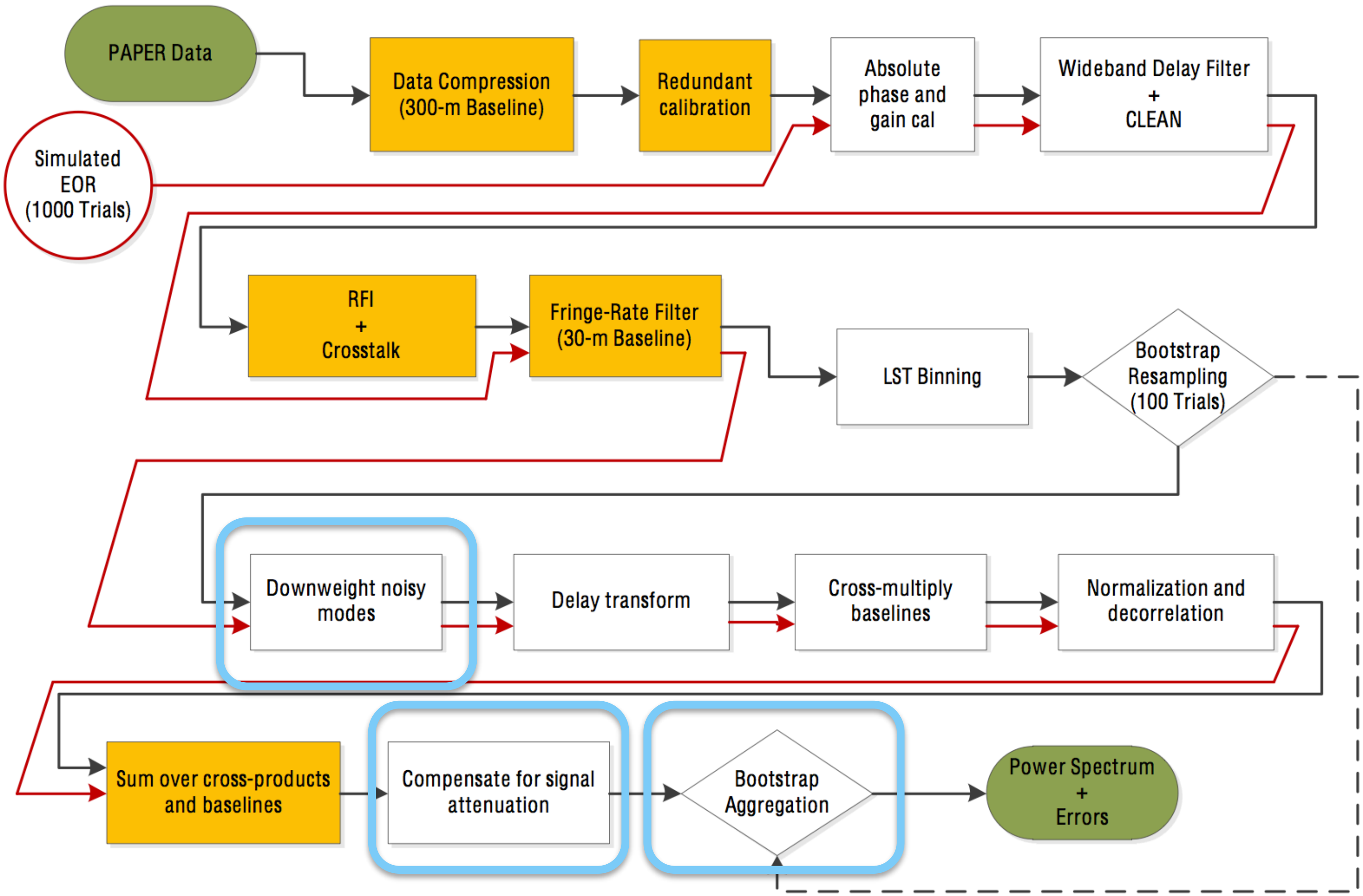
1) Under-estimated signal loss
2) Under-estimated errors
3) Under-estimated theoretical prediction of noise



Ali et al. (2015)

PAPER-64

= revised steps



Ali et al. (2015)

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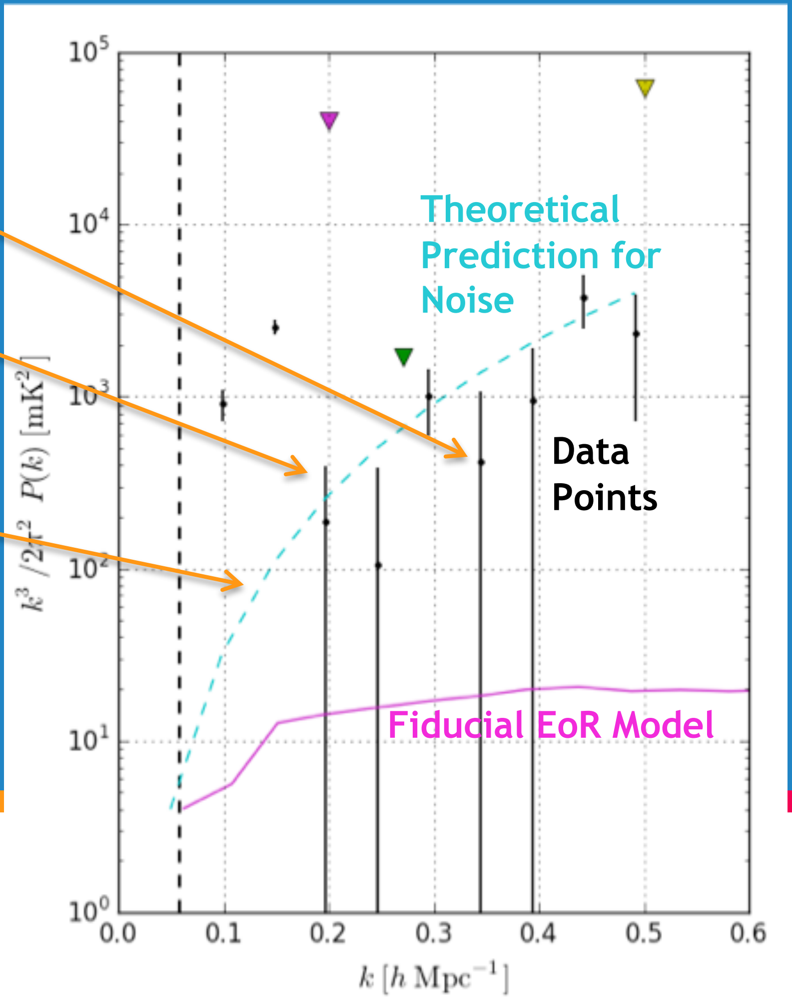


Ali et al. (2015)

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

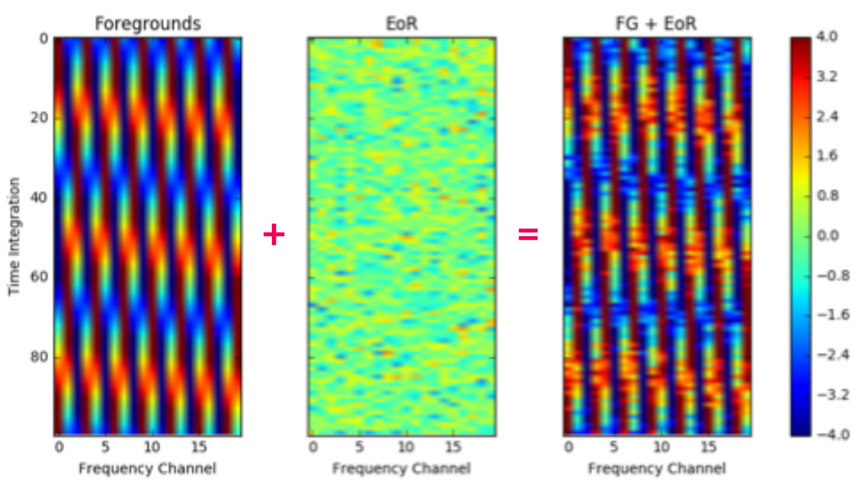
$$\hat{\mathbf{C}} \equiv \langle \mathbf{x}\mathbf{x}^\dagger \rangle_t$$

time

Liu and Tegmark (2011)

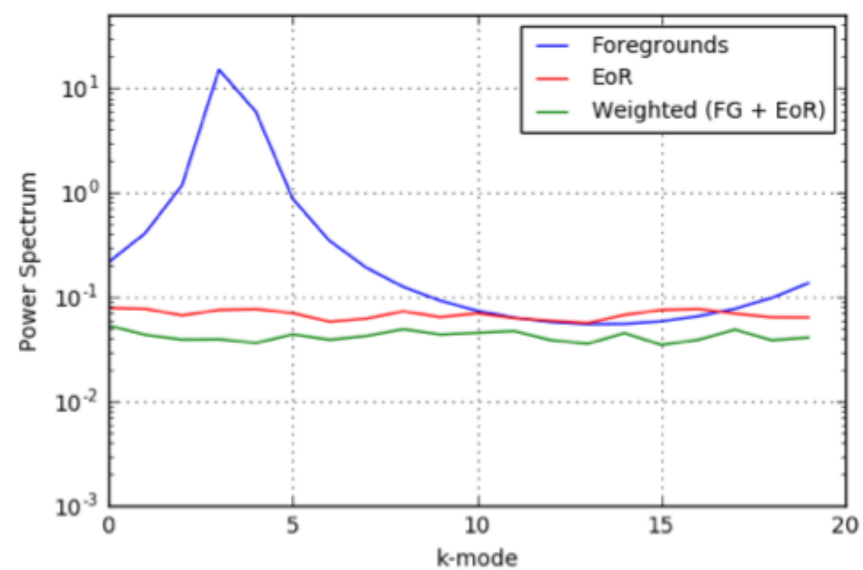
Signal Loss

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



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

Cheng et al., *in prep*



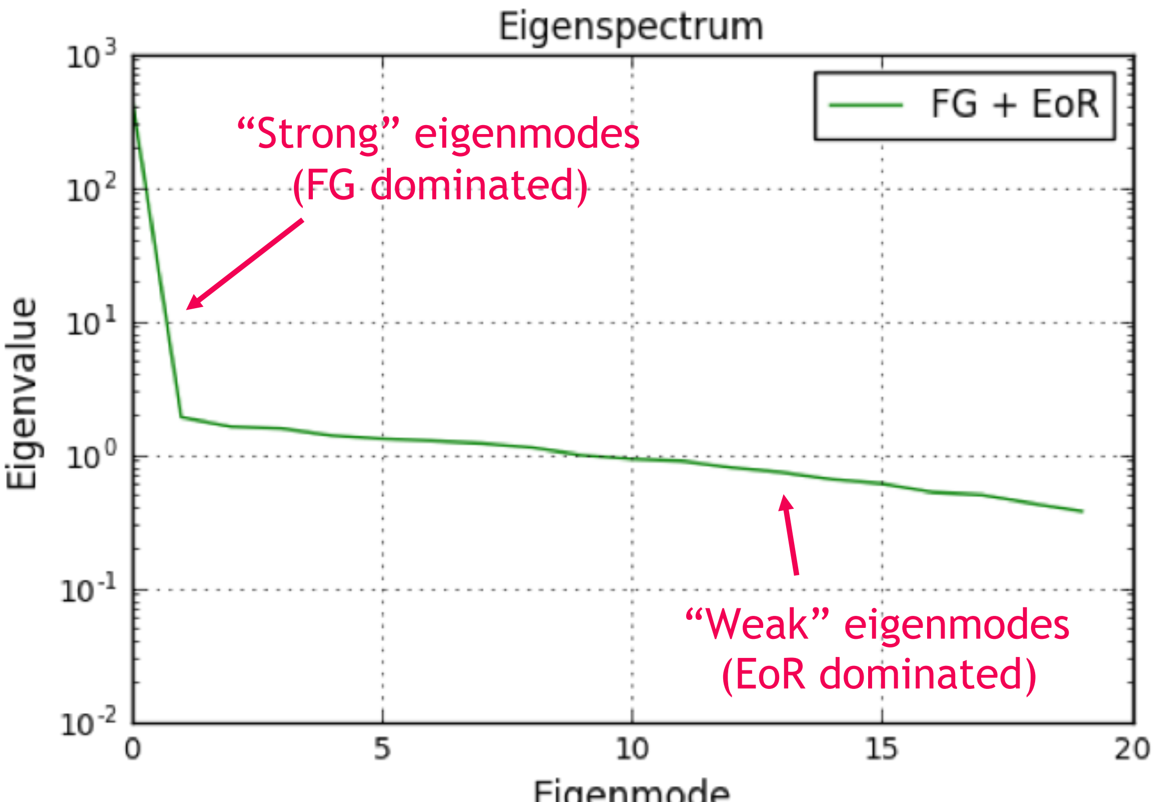
Toy Model:

$\mathbf{x}$ = foregrounds + mock EoR

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

Signal Loss

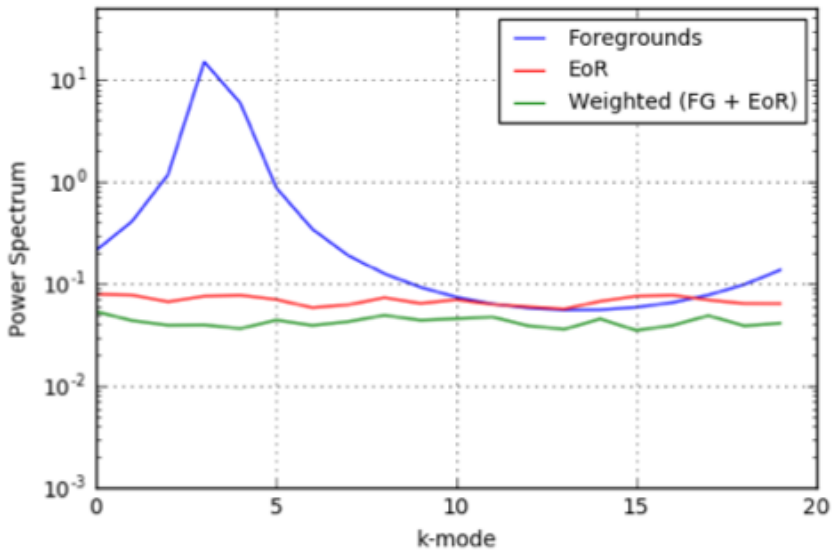
- Lesson #1: Signal loss can result when weighting data using empirically-derived covariances



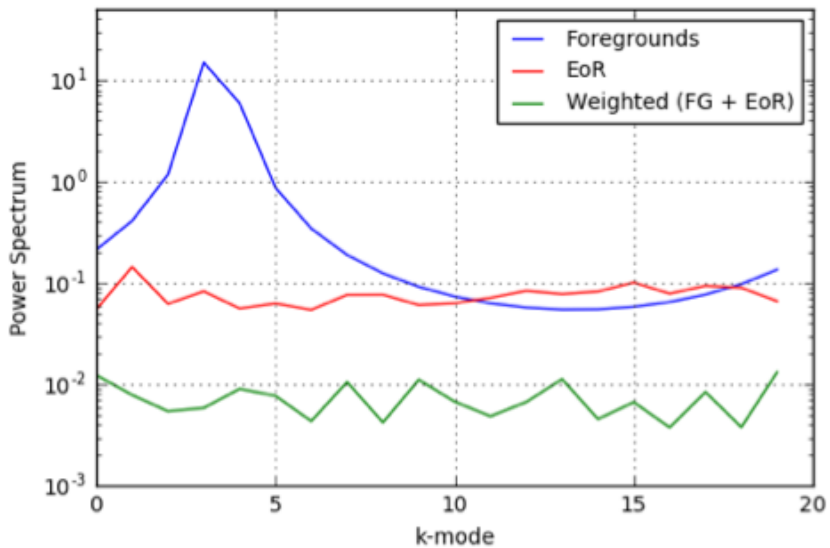
Cheng et al., *in prep*

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

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

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

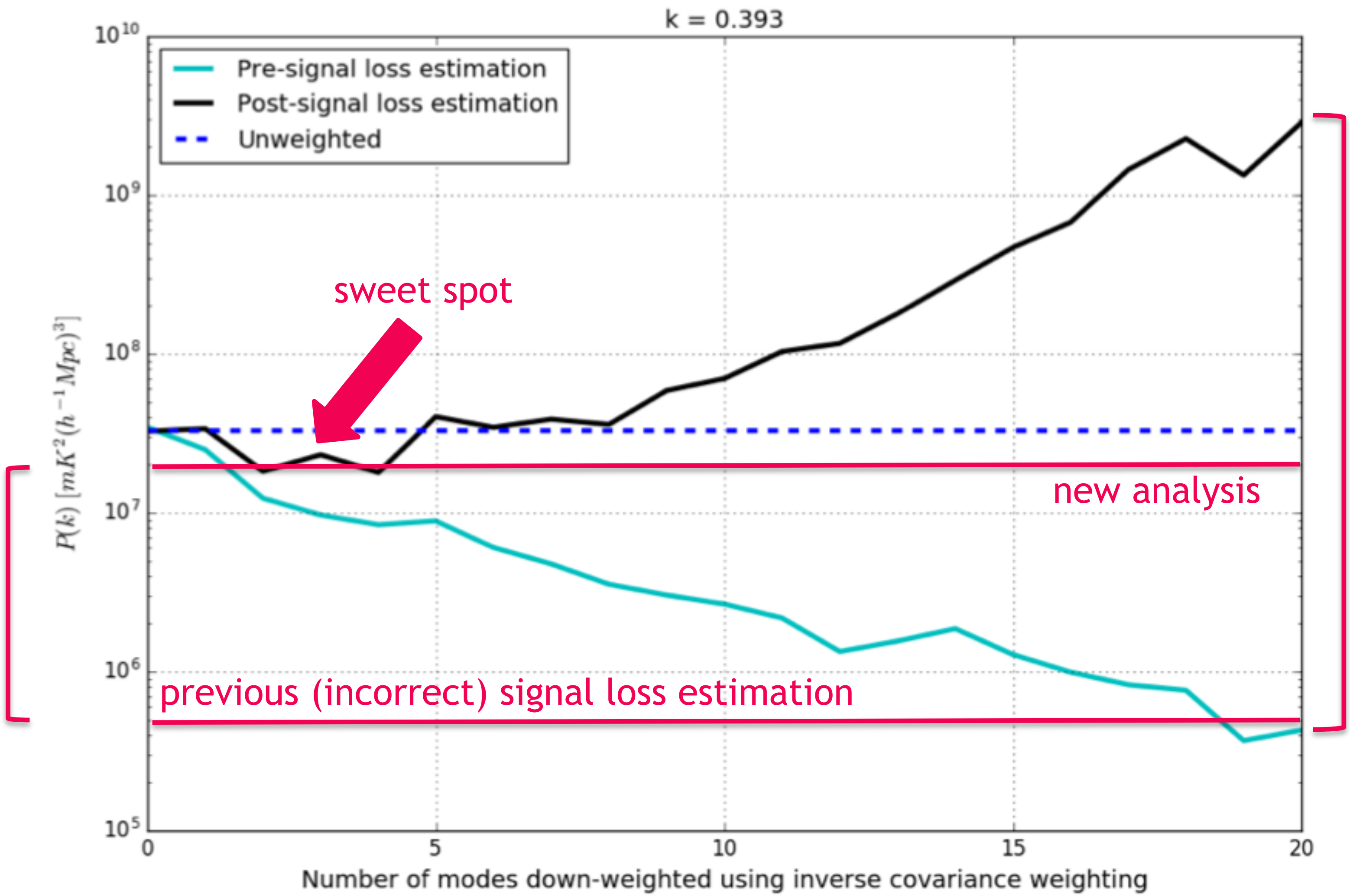
"Input" = unweighted PS of EoR-only

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

"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
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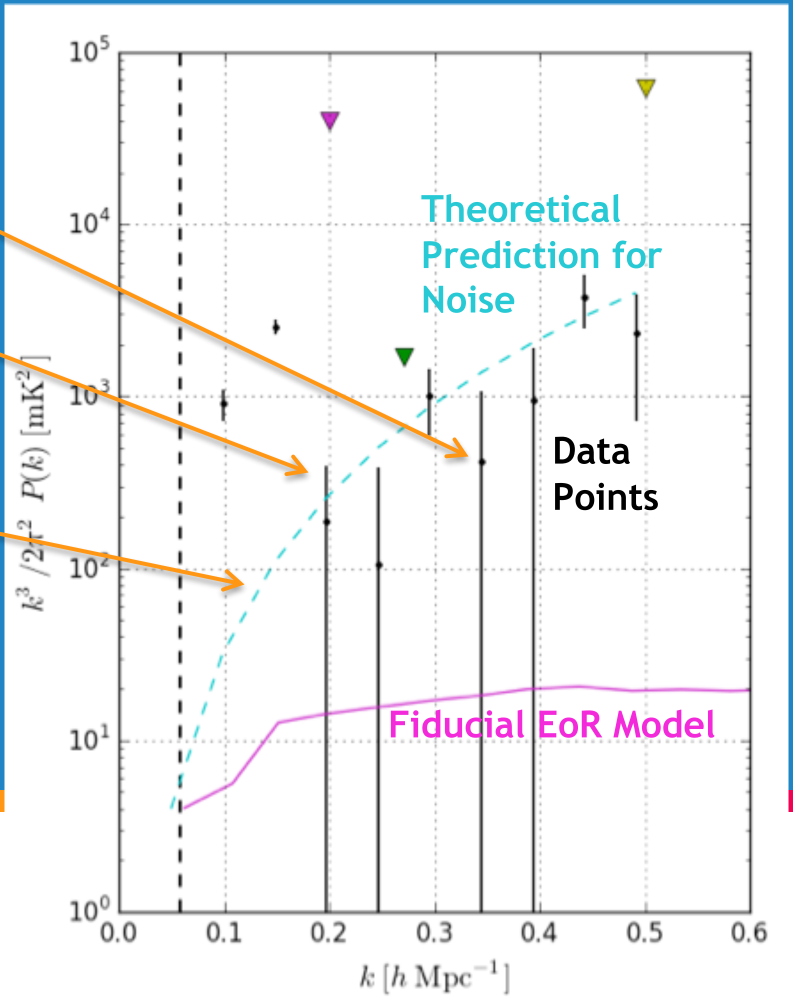
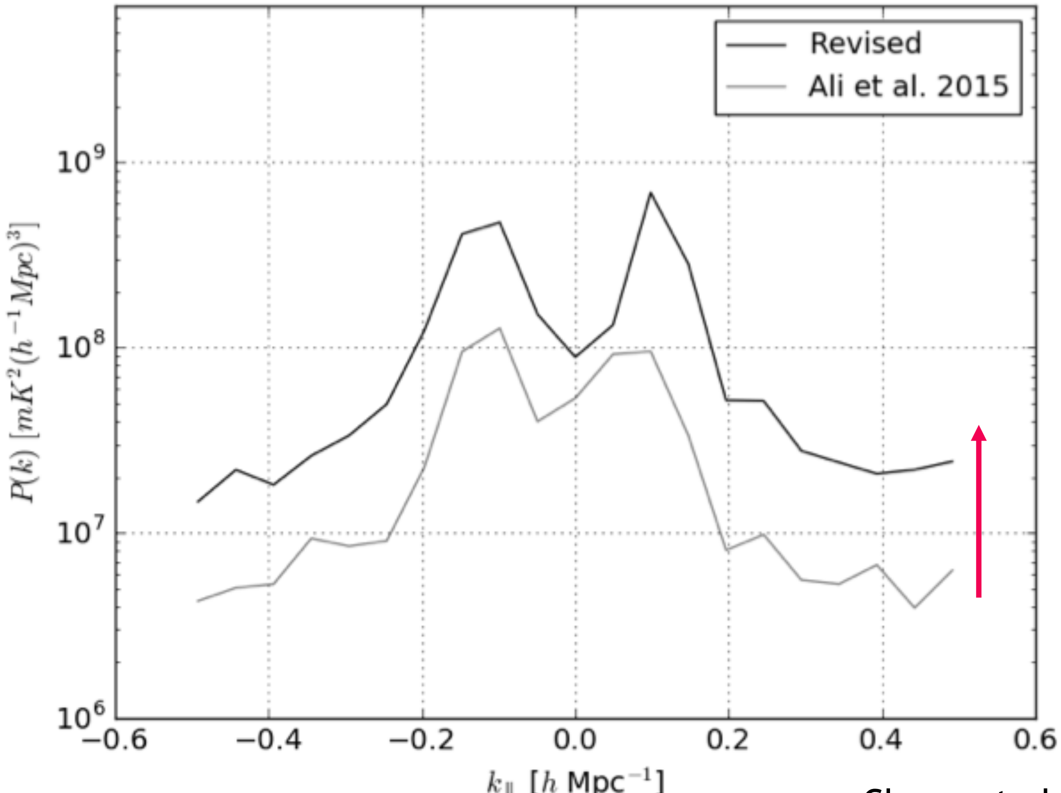
3) Under-estimated theoretical prediction of noise



Ali et al. (2015)

Error Estimation

- Errors can be under-estimated by bootstrapping correlated data



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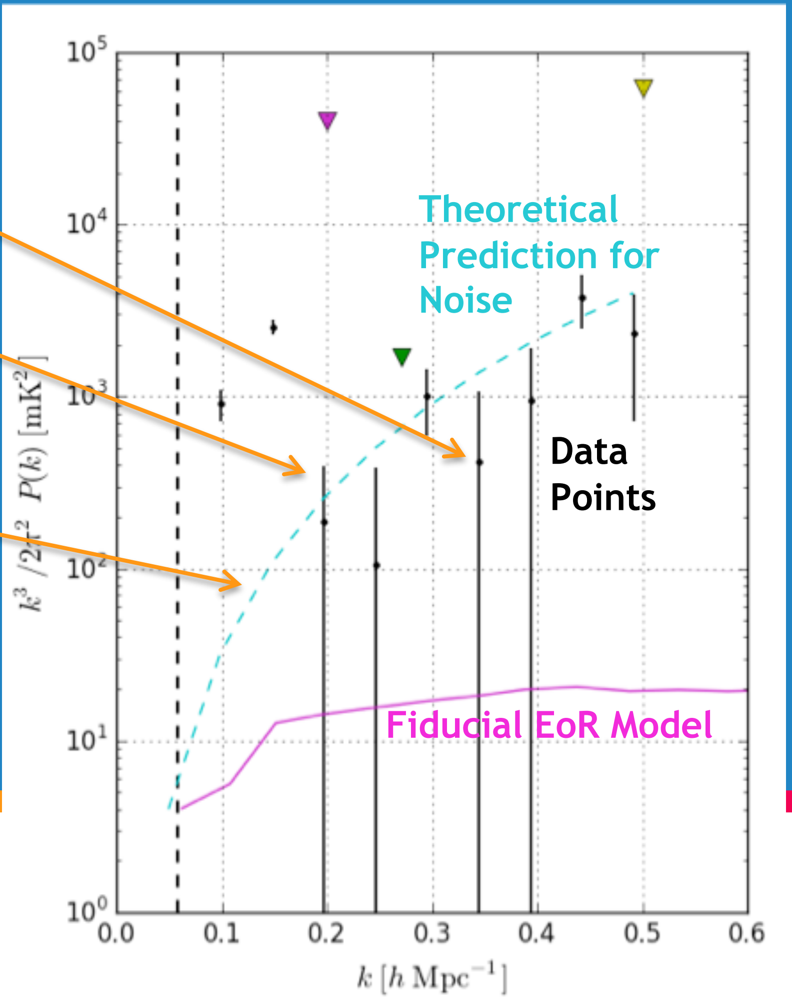
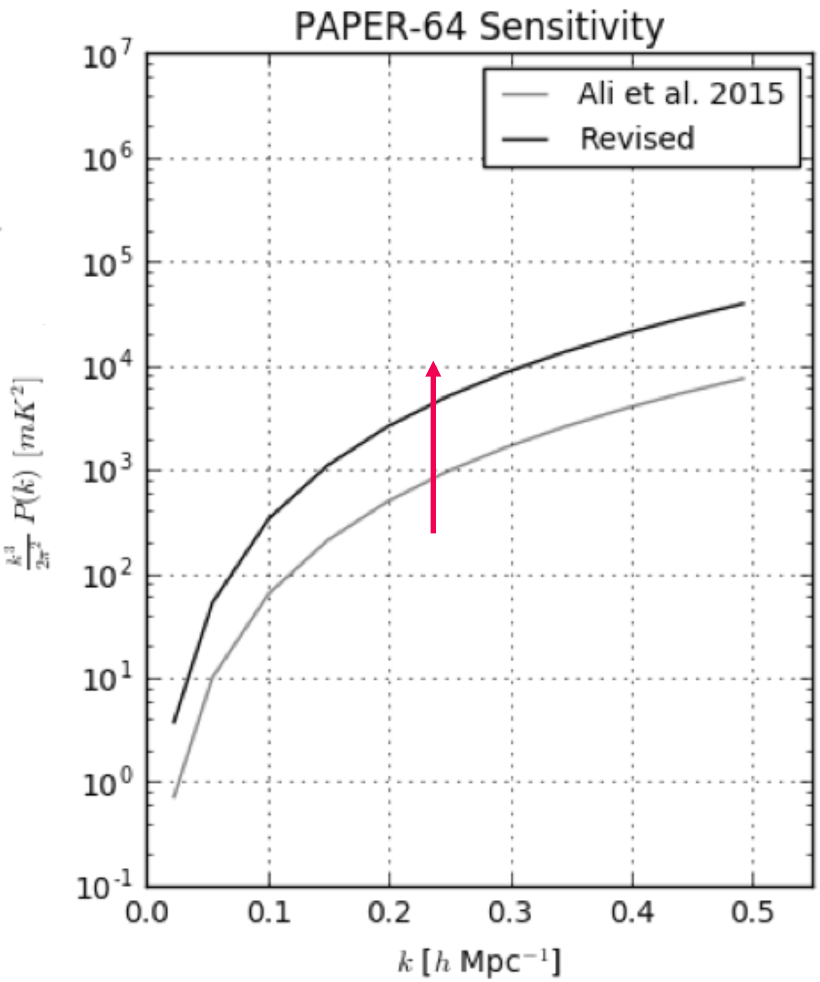


Ali et al. (2015)

Theoretical Prediction of Noise

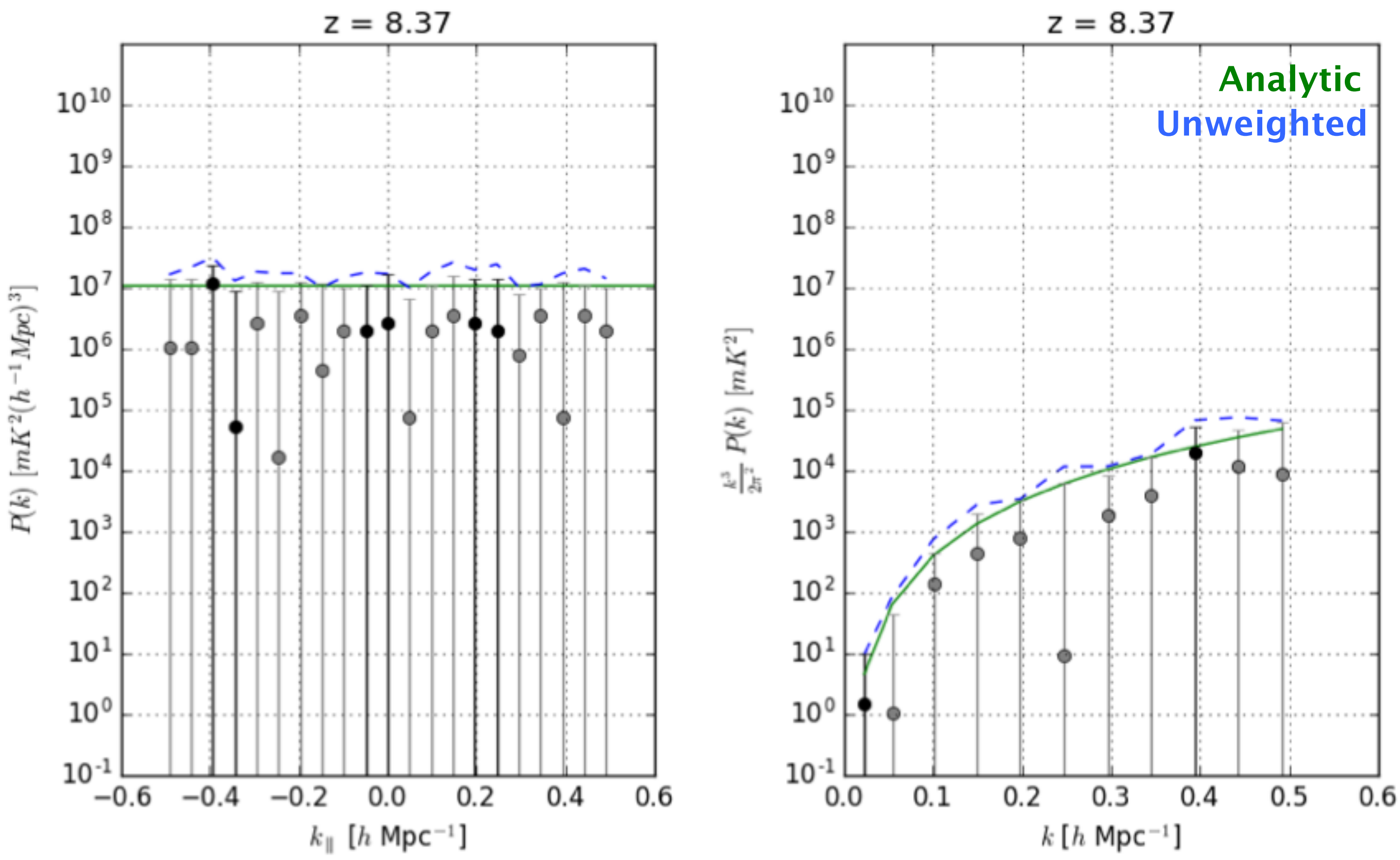
$$p(k) = \frac{X^2 Y \boxed{\Omega_{eff}} \boxed{T^2_{sys}}}{\sqrt{2N_{lsts}N_{seps}}\, t_{int} \boxed{N_{days}} \boxed{N_{bls}} N_{pols}}$$

these factors changed



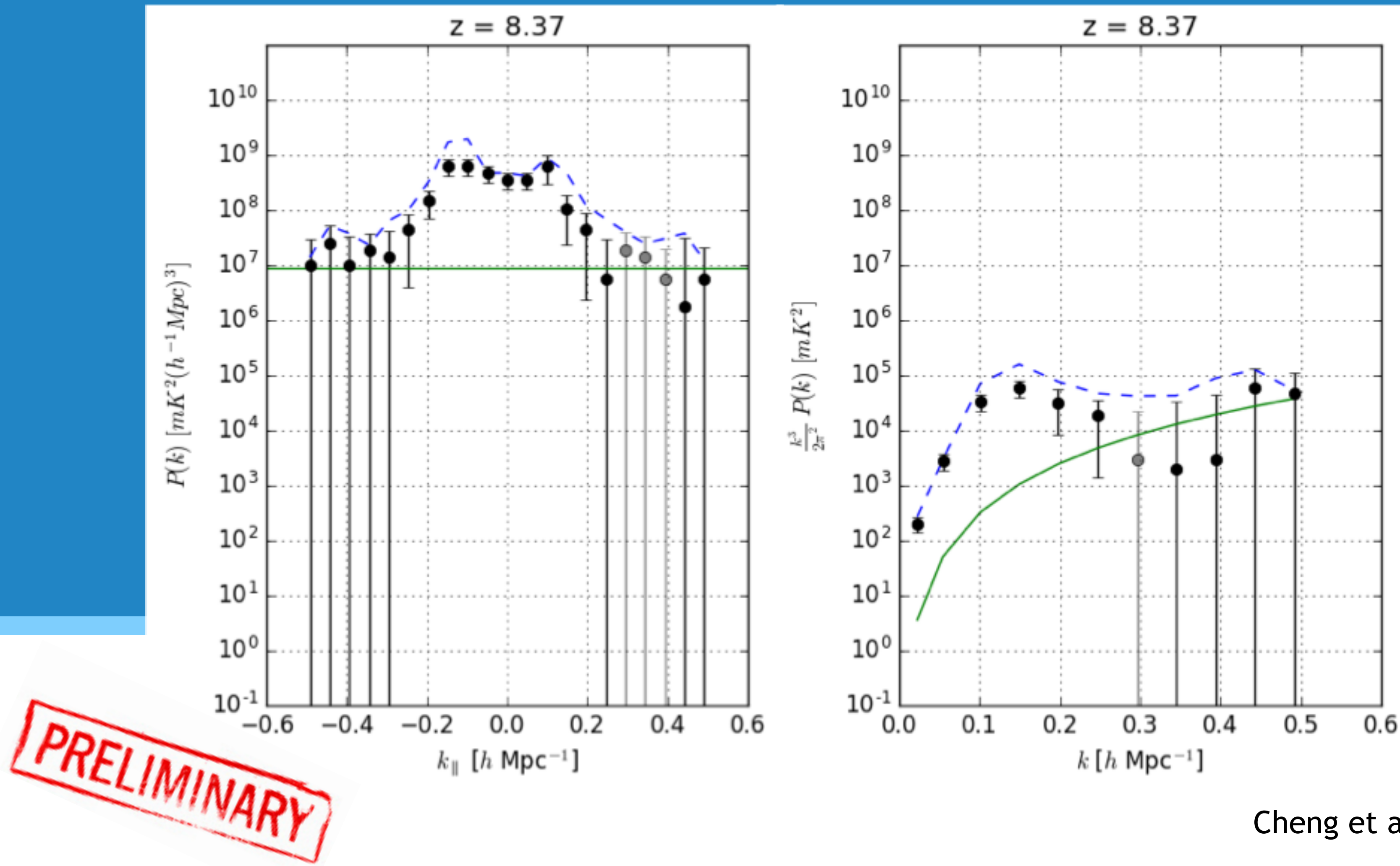
Cheng et al., *in prep*

Verifying with Noise Simulations



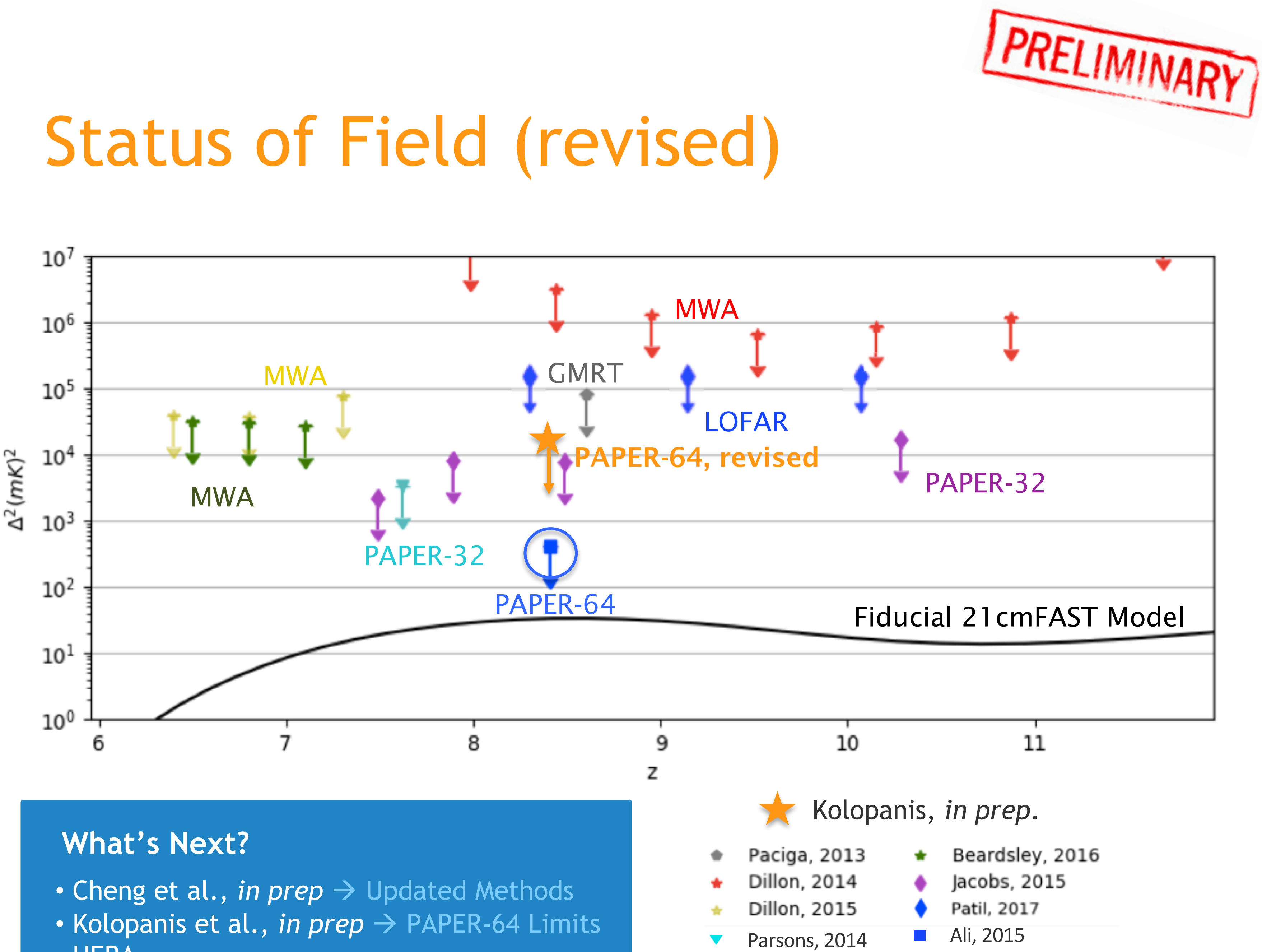
Cheng et al., *in prep*

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
- HERA

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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Thanks!

Questions?

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