Recent Results on Cosmic Reionization from PAPER

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The Radio Universe @ Ger's (wave)-length
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The Donald C. Backer Precision Array for Probing the Epoch of Reionization

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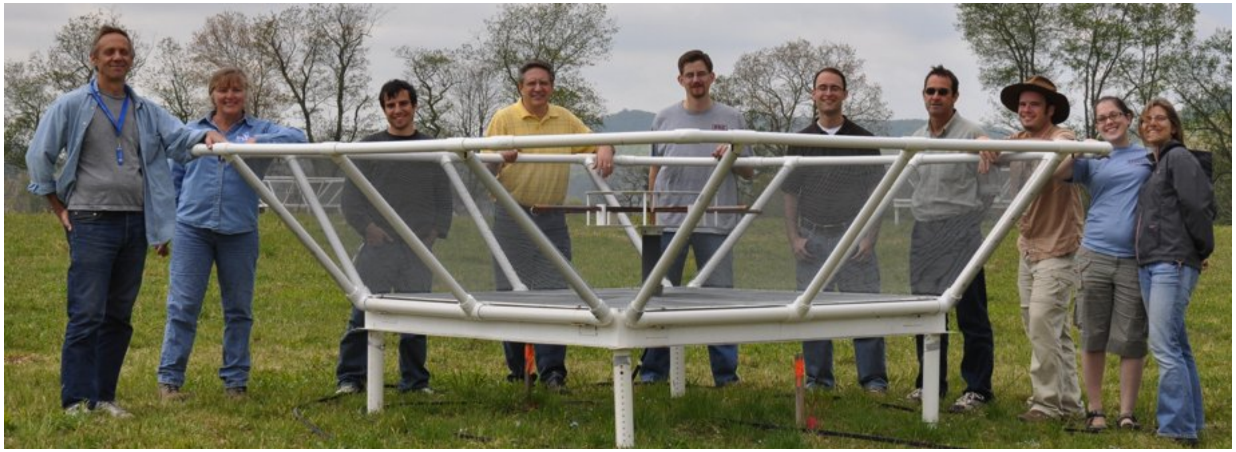


Outline

- The PAPER Experiment
- Recent Results from PAPER
- What Have We Learned From PAPER?
- What Can We Expect From the Next Generation of 21cm Experiments?

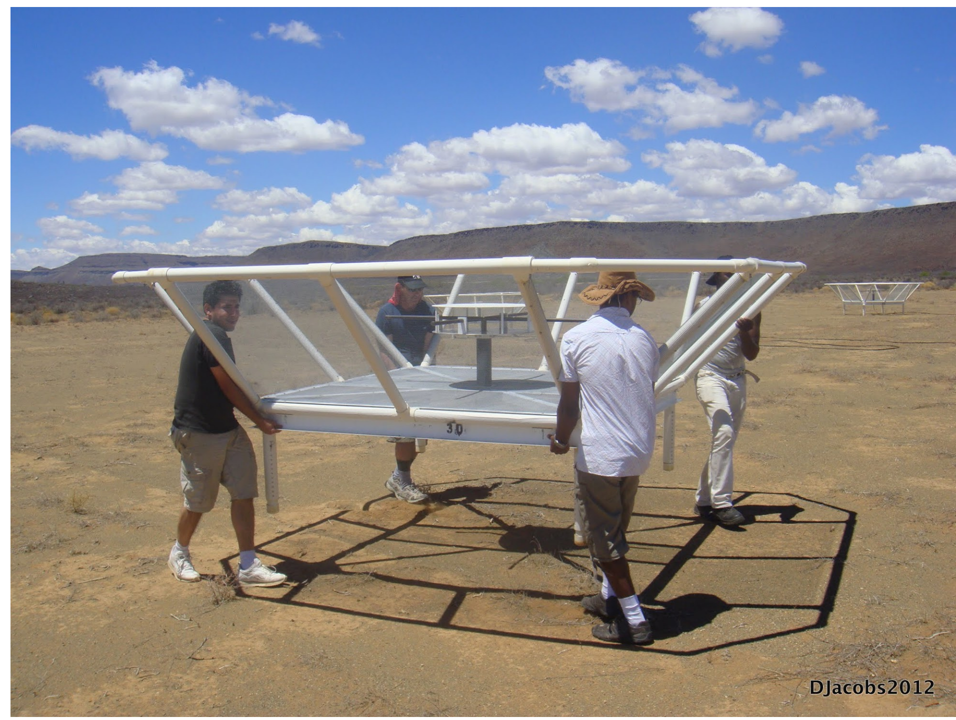
The PAPER Experiment

Design & Status

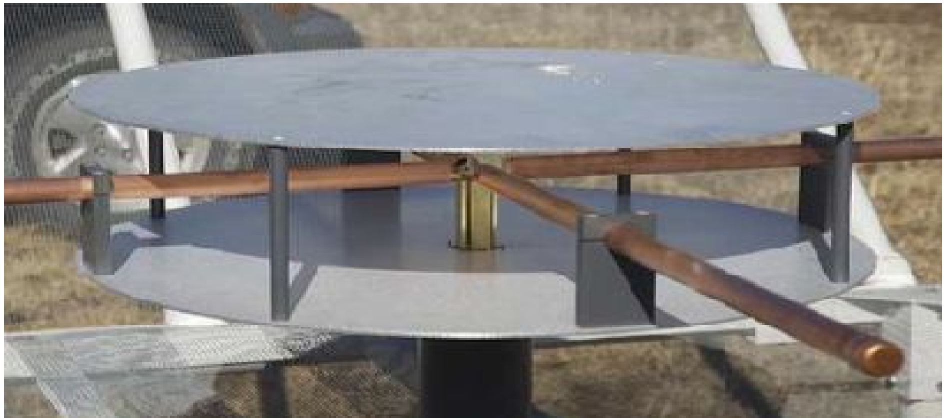
PAPER

Precision Array Probing the Epoch of Reionization

- Array of dual-polarization, non-tracking dipole elements
- Large field of view (~40° FHWM at 150 MHz)
- Instantaneous sensitivity from 100 to 200 MHz ($z \approx 7$-13) in 1024+ frequency channels
- Full correlation of all dipoles (both polarizations) with CASPER FPGA/GPU architecture



Design Rationale



- Single, zenith-phased dipole delivers simple, spatially and spectrally smooth response
- Large instantaneous bandwidth covers wide redshift-range
- Small elements allow for instrument reconfiguration

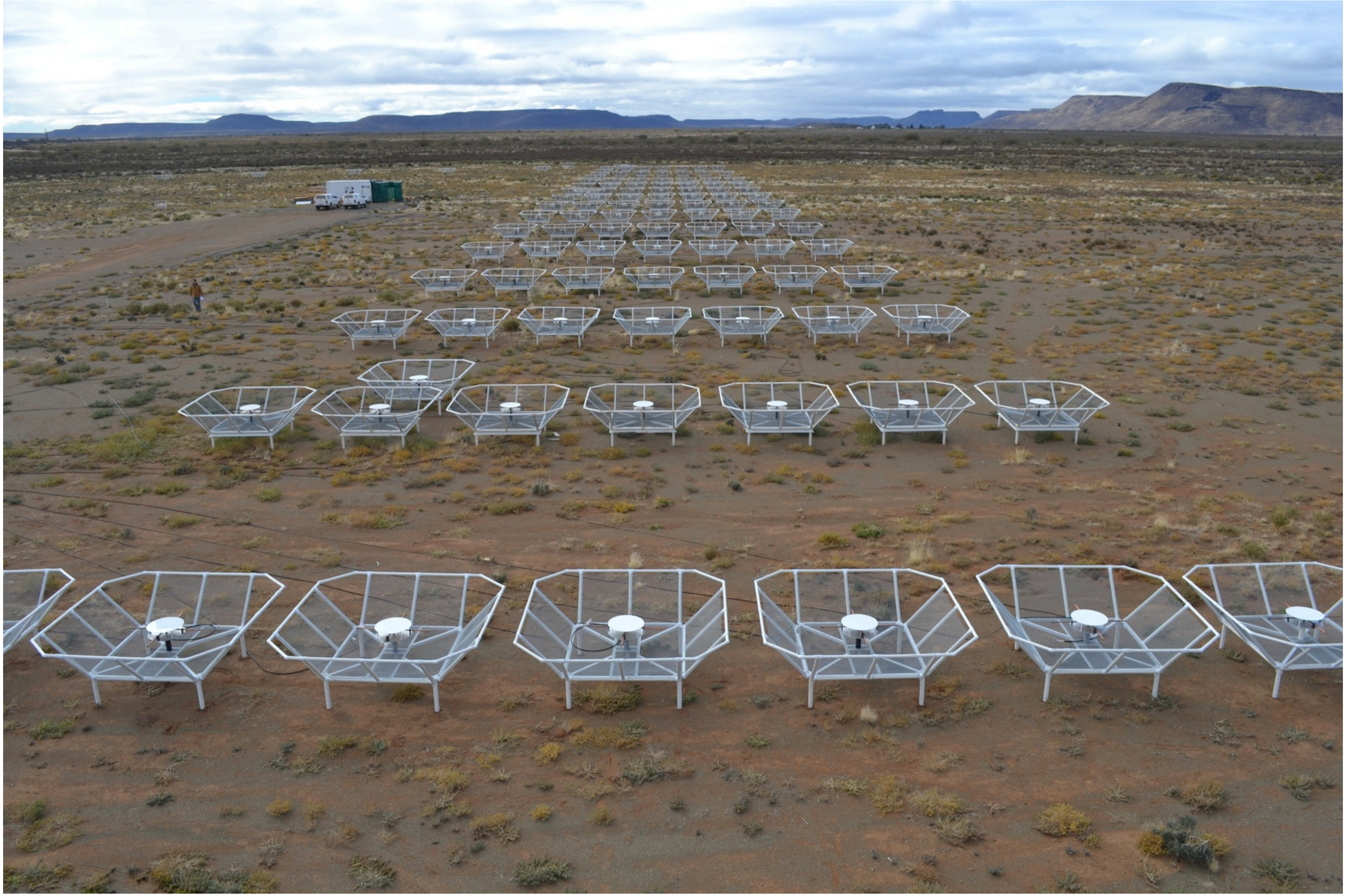
PSA-16 (2009)

PSA-32 (2010)

PSA-64 Minimum Redundancy (2011)

PSA-64 Maximum Redundancy (2011)

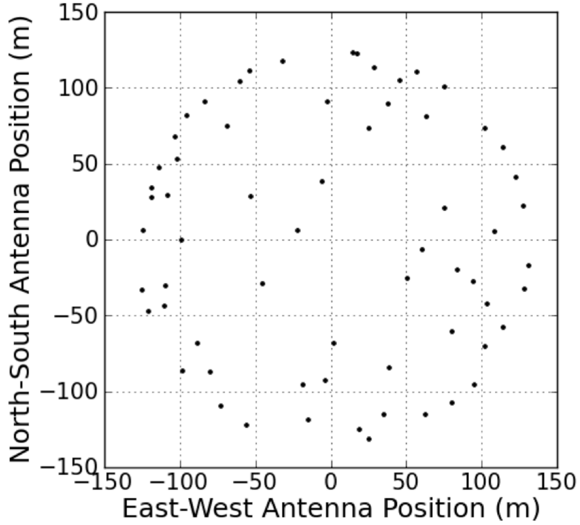
PSA-128 (2013)

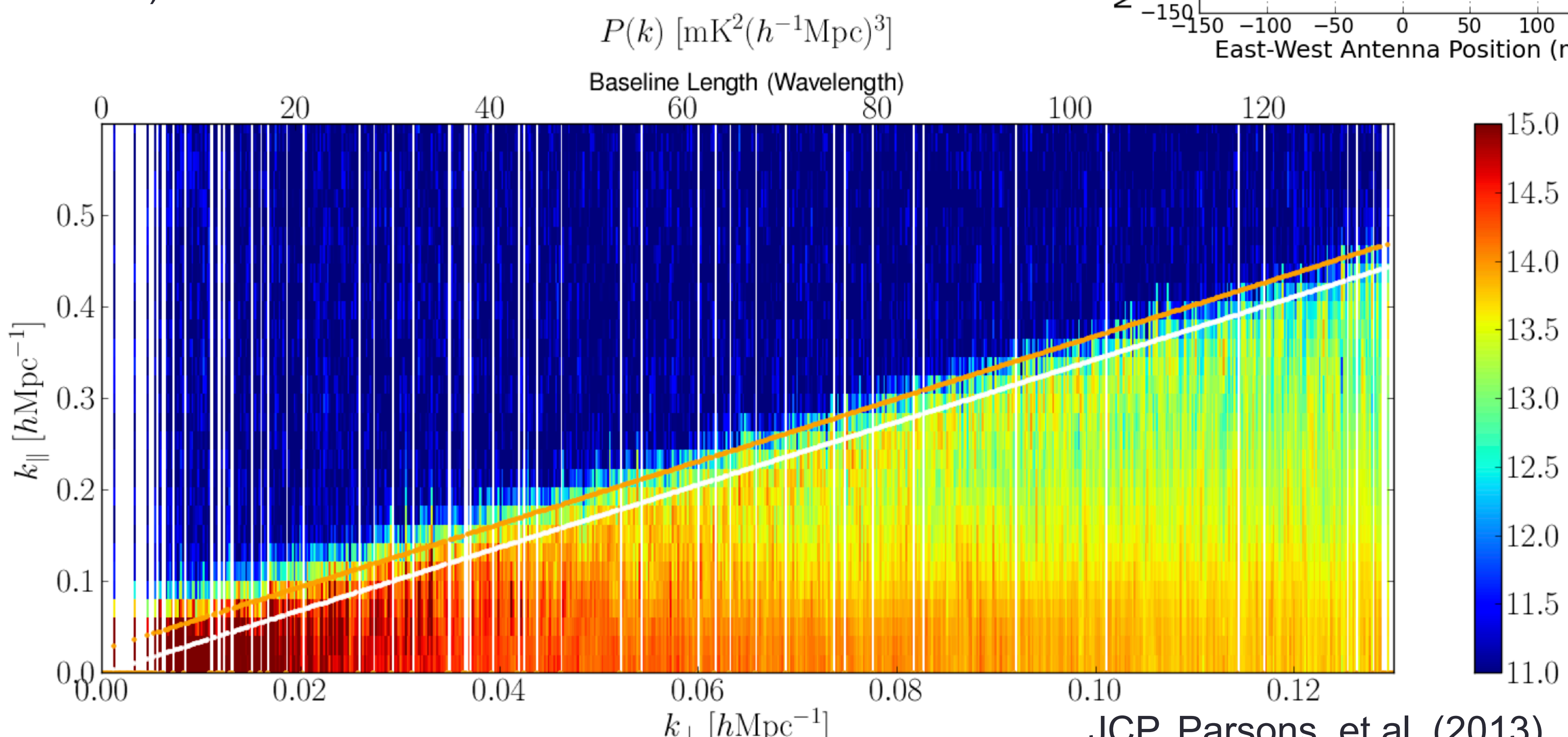


Results

The Wedge

- 4 hours of data from 64-element “imaging” PAPER array in SA
- Power spectra formed from subsequent time samples of each baseline
- Confirms predictions (e.g. Datta et al. 2010; Vedantham et al. 2012; Morales et al. 2012; Parsons, JCP, et al. 2012b; Trott et al. 2012)

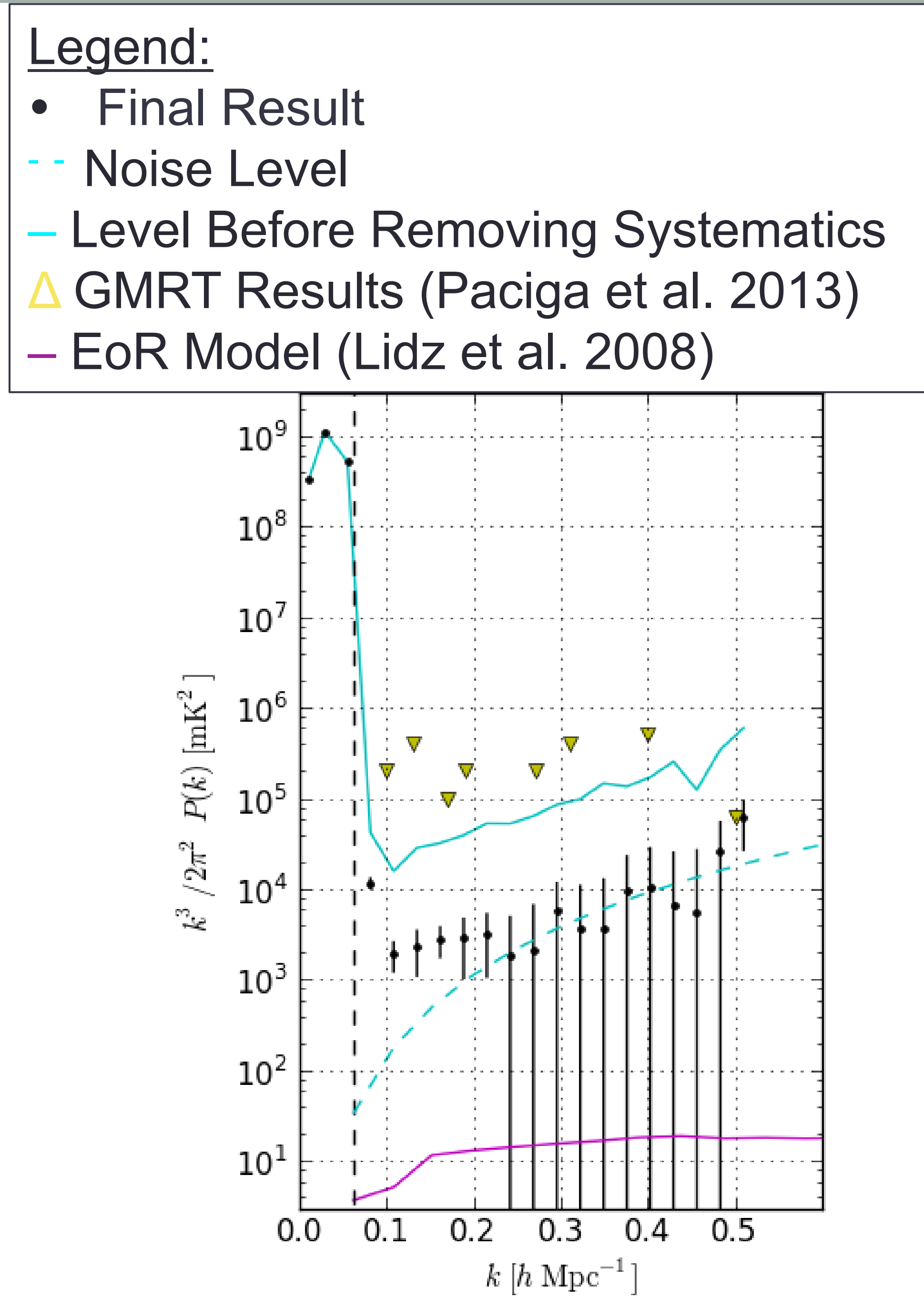




JCP, Parsons, et al. (2013)

Long Integration

- 55 days of dual-polarization, 32-element “maximum redundancy” PAPER in SA
- 10 MHz band @ 164 MHz (z = 7.7)
- 3 baseline “types”
- Systematic limited at the lowest k’s

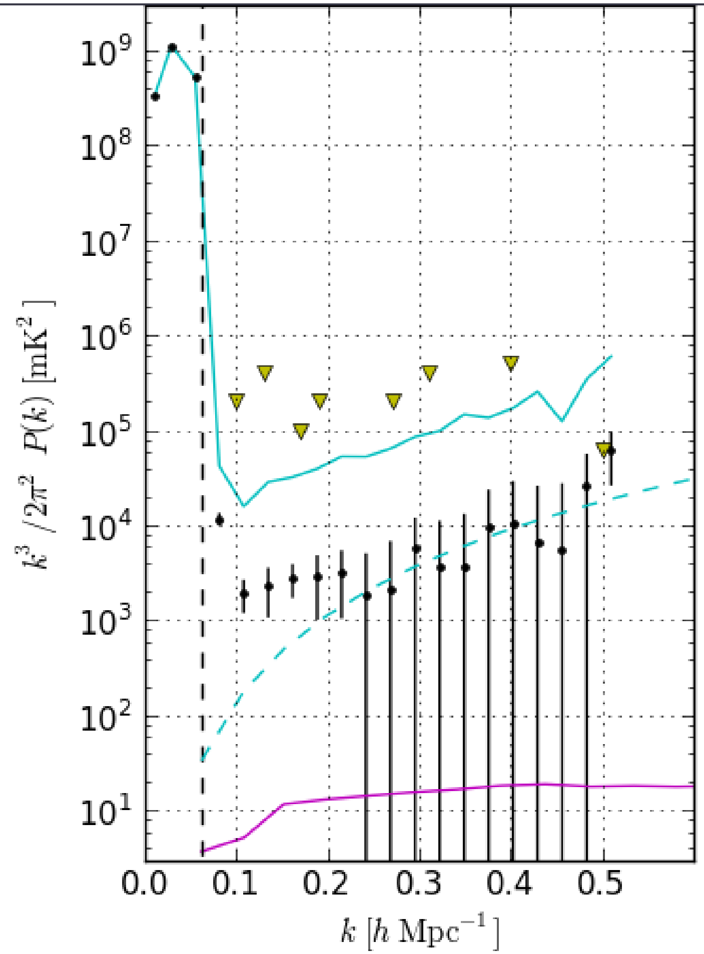


Parsons, Liu, et al. 2013

… An Error

- Normalization error from noise effective bandwidth / windowing function
- Since submission, an additional 60 days of PSA-32 data have been reduced
- Inclusion of additional data leaves bottom line effectively unchanged

Legend:
- • Final Result
- - - Noise Level
- — Level Before Removing Systematics
- Δ GMRT Results (Paciga et al. 2013)
- — EoR Model (Lidz et al. 2008)

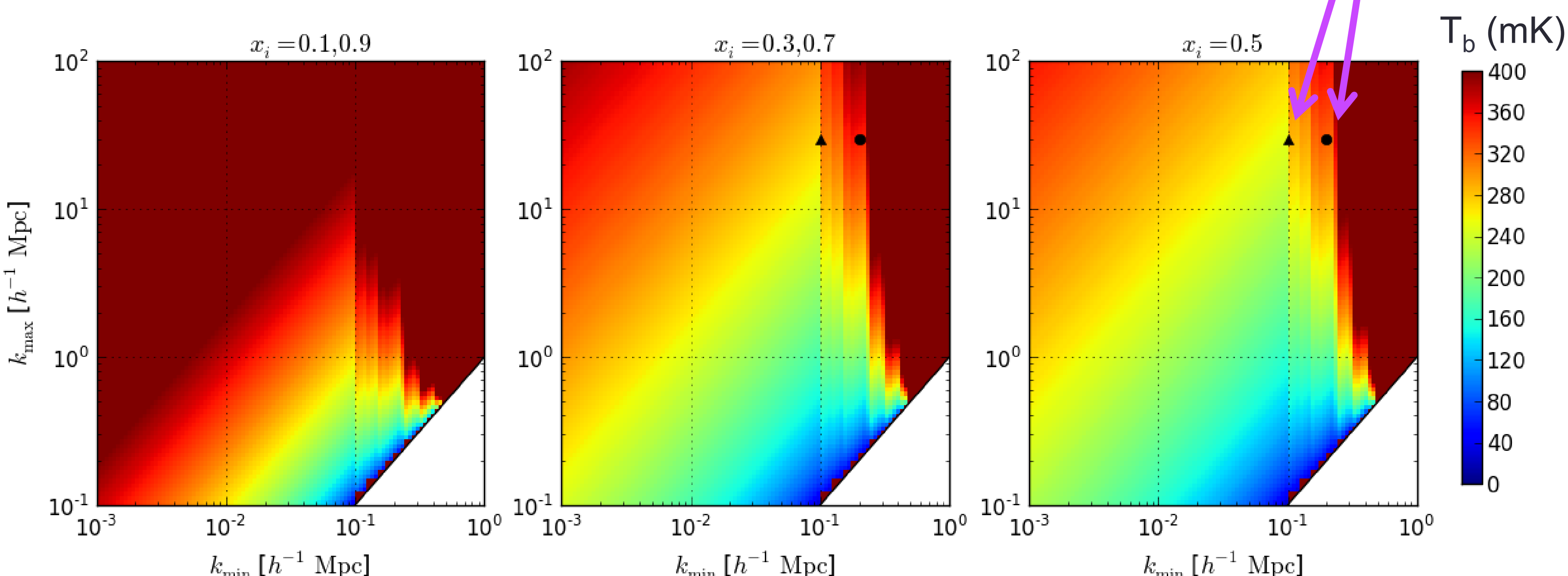


Parsons, Liu, et al. 2013

X-Ray Heating

- Power spectrum measurement can constrain gas temperature
- PAPER measurements generally inconsistent with pure adiabatic cooling of IGM

Fiducial reionization models



Parsons, Liu, et al. 2013

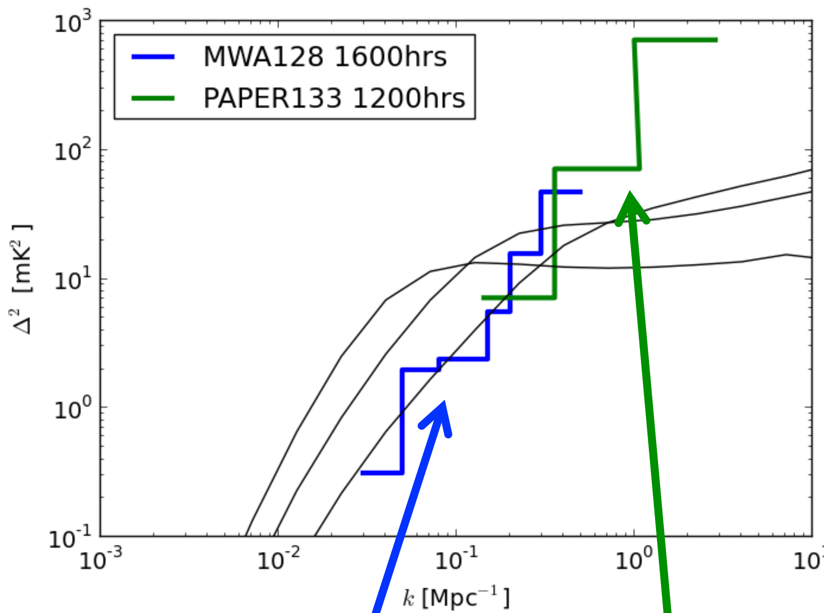
PAPER Prospects

- New data on disk
  - ~120 days of PSA-64 — x 2+
- New deployments
  - PSA-128 beginning observations this winter — x 2+
- New techniques
  - "Aggressive" fringe rate filtering — x 3 – 5
    - Increases SNR
    - "Steers" beam N/S, can help with polarization leakage and other systematics
  - More baselines / earth rotation / partial coherence — x 1.5 – 2
  - Multi-frequency and full-Stokes analyses

≈ x 20 - 50

Reminder: Foregrounds Affect Sensitivity

- PAPER-133 and MWA-128 have comparable noise levels
- Difference in detection significance primarily attributable to *foreground removal* models
- Sparse PAPER array will likely not allow for foreground removal
- If one cannot "work within the wedge," the sensitivity of all first generation experiments will be small



Parsons, JCP, et al. 2012b
(predicted 2σ non-detection)

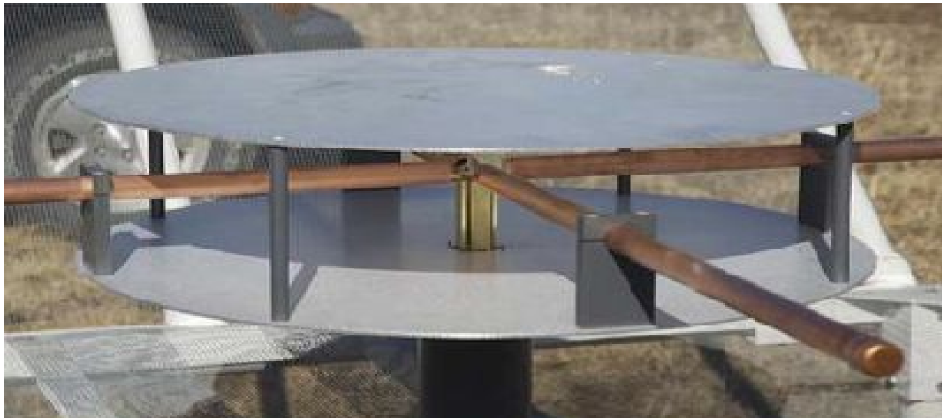
Beardsley et al. 2013
(predicted 14σ detection)

What Have We Learned From PAPER?

Design Rationale: Revisited

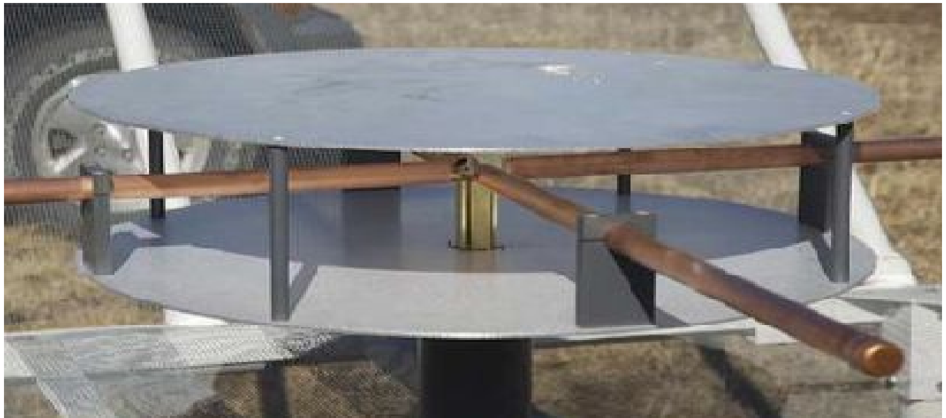
- Single, zenith-phased dipole delivers simple, spatially and spectrally smooth response
- Large instantaneous bandwidth covers wide redshift-range
- Small elements allow for instrument reconfiguration

Design Rationale: Revisited (I)



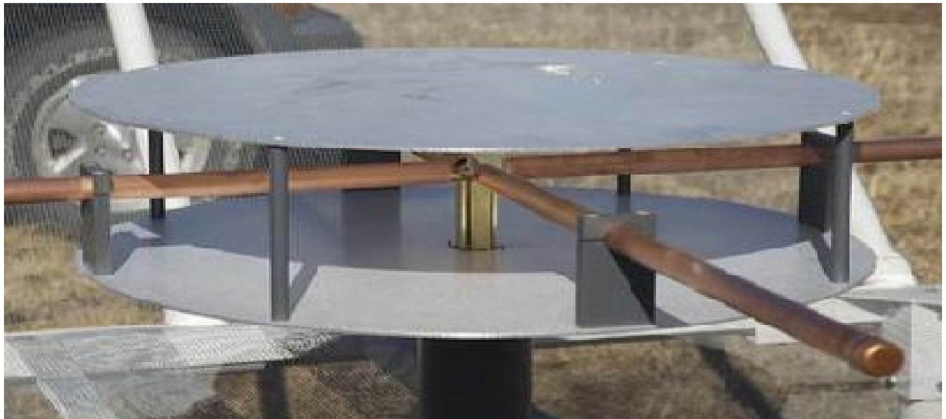
- Single, zenith-phased dipole delivers simple, spatially and spectrally smooth response
- *Lesson*: spectral smoothness is important for keeping the EoR window free of foregrounds, but PAPER is **over-specced**, at the expensive of sensitivity

Design Rationale: Revisited (II)



- Large instantaneous bandwidth covers wide redshift-range
- *Lesson*: having a large available bandwidth drastically aids foreground removal from EoR window
  - PAPER uses its full 100 MHz band to “CLEAN” foregrounds out from each 8 MHz cosmological band

Design Rationale: Revisited (III)



- Small elements allow for instrument reconfiguration
- *Lesson*: Redundant baseline configurations have several powerful benefits for power spectrum studies
  - Increase power spectrum sensitivity
  - Facilitate calibration
  - Separate residual systematics from sky-signal
  - Polarization problems…

Lesson: Polarization

- PAPER "naïvely" combines linearly polarized *visibilities* to make Stokes I
  - Sparse *uv* coverage prohibits beam correction
- xx/yy beam asymmetries create polarization leakage
- Faraday rotated spectra create frequency structure in Stokes I
- Updated Moore et al. 2013 models (to agree with measurements from Bernardi et al. 2013) place PAPER polarization leakage estimates around EoR signal level

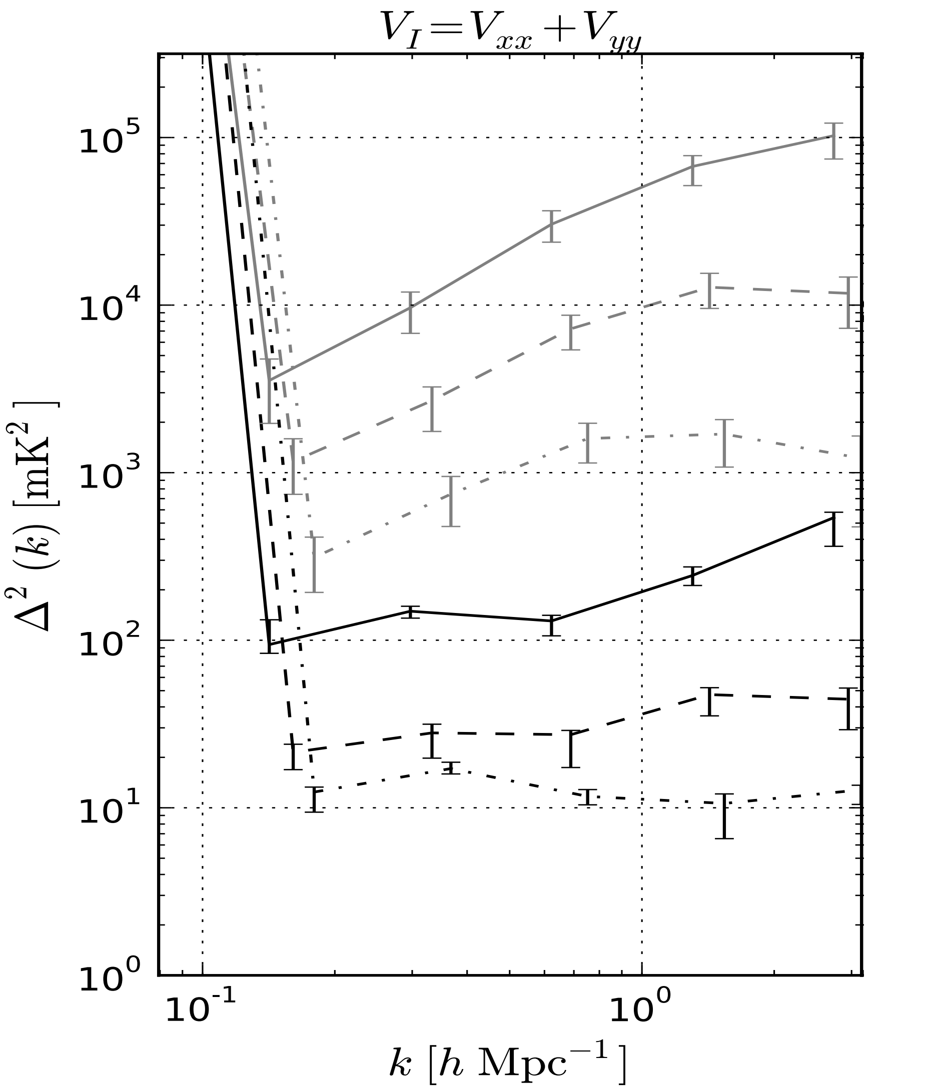
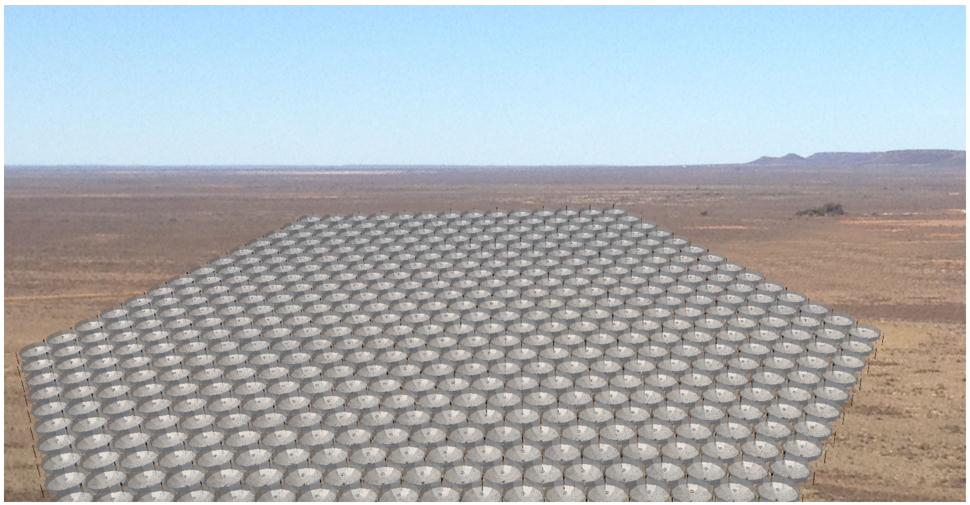


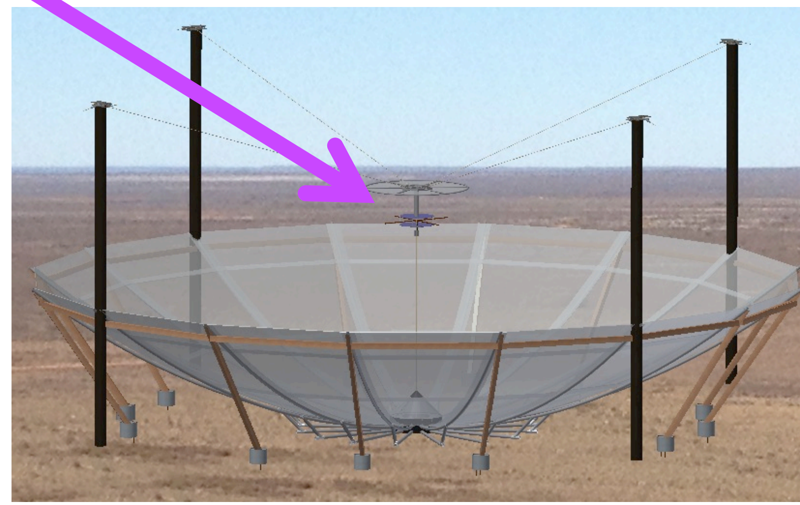
Figure updated from Moore, Aguirre, et al. 2013

What Can We Expect From the Next Generation of 21 cm Experiments?

HERA (Hydrogen Epoch of Reionization Array)

PAPER Dipole

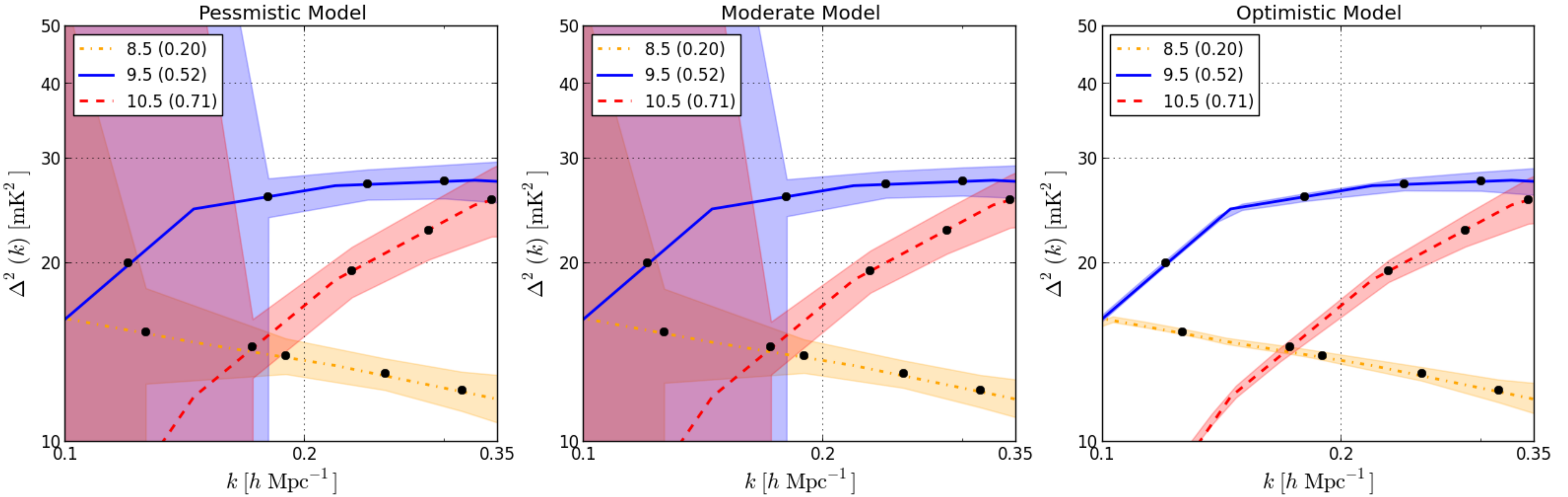




- 14 m reflector design significantly boosts PAPER dipole collecting area, better polarization properties
- Short focal length keeps reflections to delays below *k*-modes of interest
- Dense array allows for imaging and improved foreground removal techniques

“HERACLES” Prototype Testing Underway

Next Generation EoR Science



- HERA-like sensitivity delivers high significance (> 30σ) detection of 21 cm power spectrum across a wide range of redshifts
  - Generic for a very wide range of EoR models
  - Drastic improvements if foreground subtraction recovers modes inside the wedge

JCP, Liu, Dillon et al. arXiv:1310.7031

Conclusions

- PAPER experiment is still continuing: 64 and 128 element data sets will improve current upper limits
    - Improvements will come on the analysis front as well
- PAPER has already resulted in a number of valuable lessons:
    - Array redundancy is a powerful tool for increasing power spectrum sensitivity and diagnosing (and removing) systematics
    - Wide instantaneous bandwidth extremely useful for foreground removal
    - Spectral smoothness valuable, but needs to be balanced versus collecting area
- HERA synthesizes lessons from PAPER and MWA to deliver a new class of EoR science

Thanks