The Donald C. Backer Precision Array for Probing the Epoch of Reionization (PAPER) and Hydrogen Epoch of Reionization Array(HERA) A Status Update

Science at Low Frequency
UNM
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PAPER & HERA collaboration

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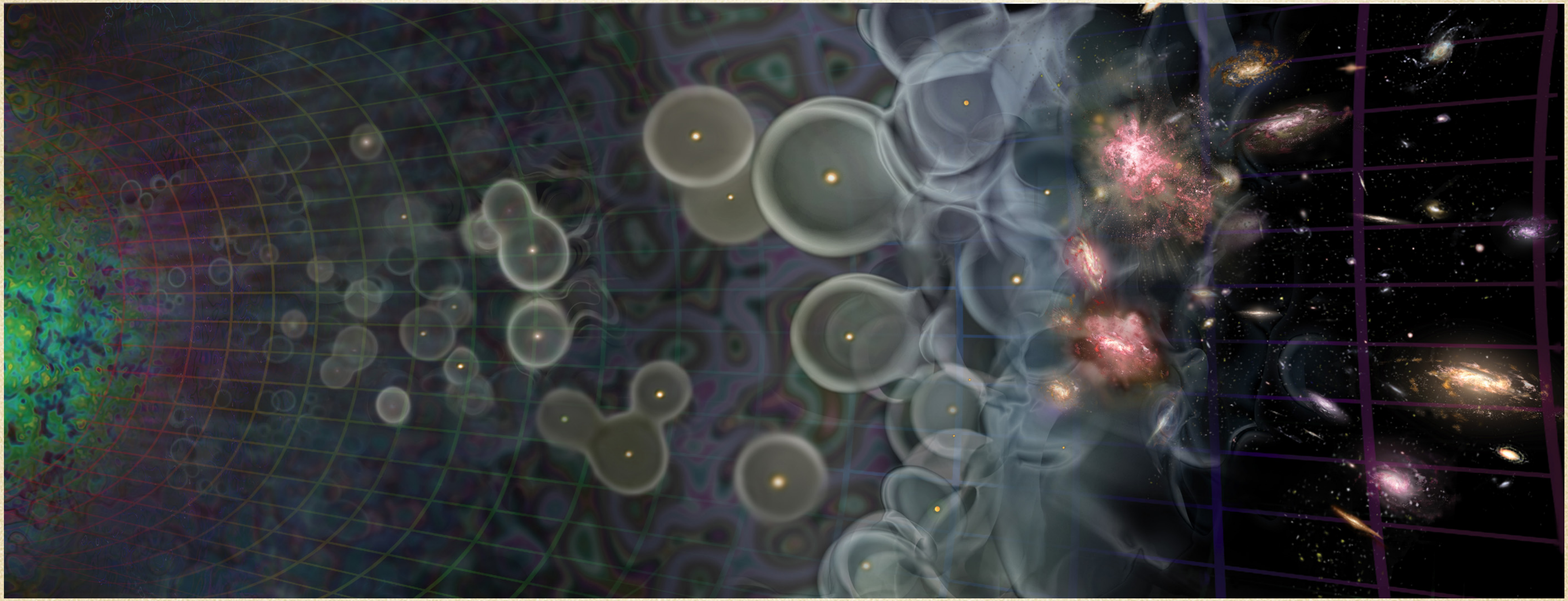
Redshifted 21cm background



$$\Delta T = 23.8 \left(\frac{1+z}{10}\right)^{\frac{1}{2}} \left[1 - \bar{x}_i(1+\delta_x)\right](1+\delta)(1-\delta_v)\left[\frac{T_{\rm s} - T_{\rm CMB}}{T_{\rm s}}\right] \rm{mK},$$

PAPER and HERA

- **Dedicated instruments to probe the power spectrum of redshifted 21cm emission between 100-200MHz (z=7-12)**

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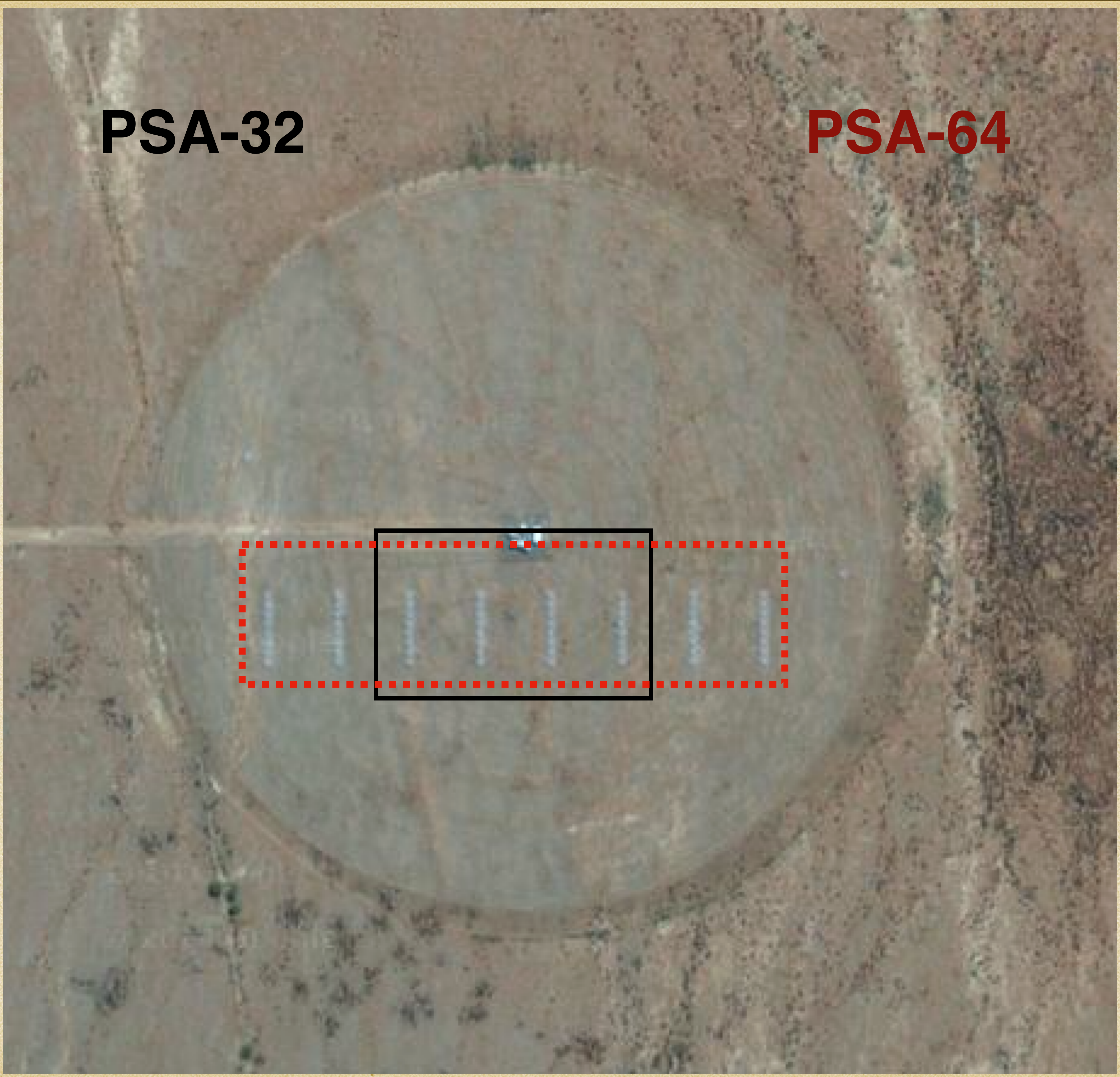
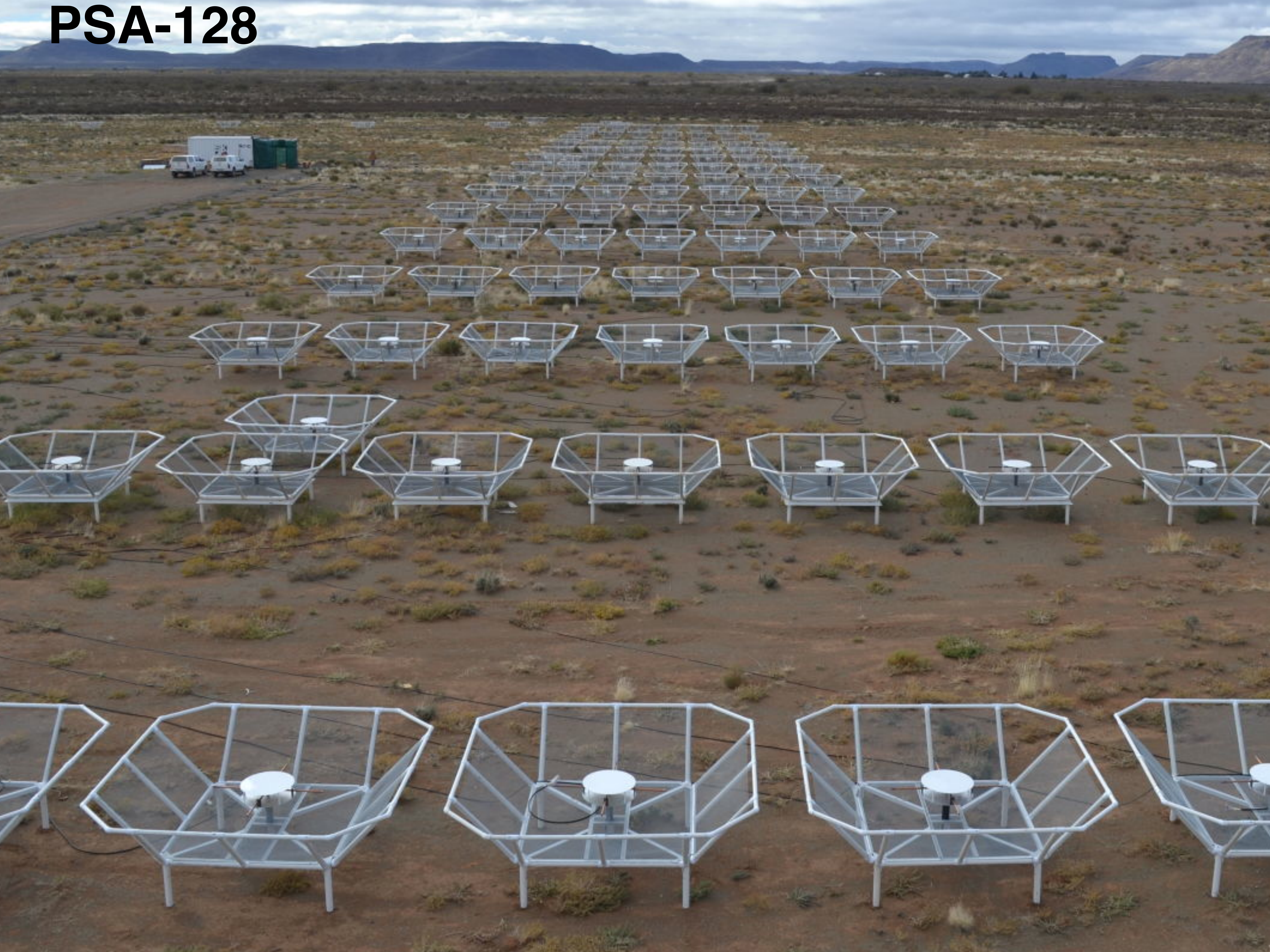
- **Dedicated instruments to probe the power spectrum of redshifted 21cm emission between 100-200MHz (z=7-12)**
- **Stages of incremental development :**
  PAPER-32: Green Bank, WV; Karoo, South Africa
  PAPER-64: Karoo, South Africa
  PAPER-128: Karoo South Africa
- **PAPER is considered to be phase I of its successor HERA which is currently under construction.**

PAPER Antenna


PSA-32
PSA-64

PSA-128



Strategic instrumental and analysis features of PAPER

- High redundancy compact array configuration with redundant baselines
- Such array configuration could be tuned to be directed away from the regions of the uv-plane where foregrounds are brighter and instrumental systematic are more problematic.
- Delay transform technique of foreground removal

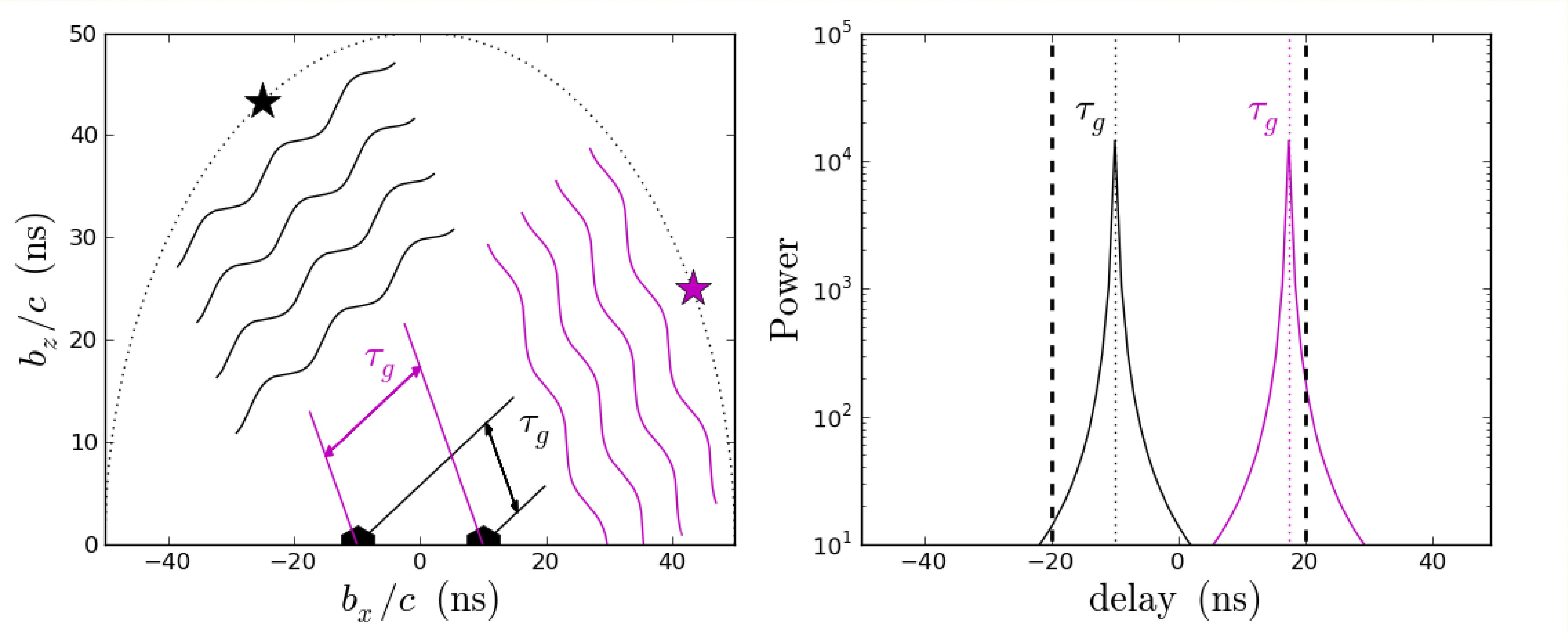
Delay transform technique of foreground suppression

$$\tilde{V}(\vec{b},\tau) = \int\int A(\hat{\theta},\nu) I_{\rm sky}(\hat{\theta},\nu) e^{-\frac{2\pi i \nu \vec{b}\cdot\hat{\theta}}{c}} d\Omega \; e^{+2\pi i \nu \tau} d\nu$$

$$= \int \left[A(\hat{\theta},\tau) * I_{sky}(\hat{\theta},\tau) * \delta(\tau - \frac{\vec{b}\cdot\hat{\theta}}{c}) \right] d\Omega$$

Fourier transform of the complex visibility along frequency axis

Delay transform technique of foreground suppression



The geometric interpretation of the delay spectrum measured by an interferometer.

Left: two sources with identical spectra at differing geometric delays (τ_g) owing to their positions relative to two antennas being correlated.

Right: Fourier transform of the spectrum of each source also enters the delay spectrum centered at the appropriate τ_g

Parsons et al 2012.

Delay transform technique of foreground suppression

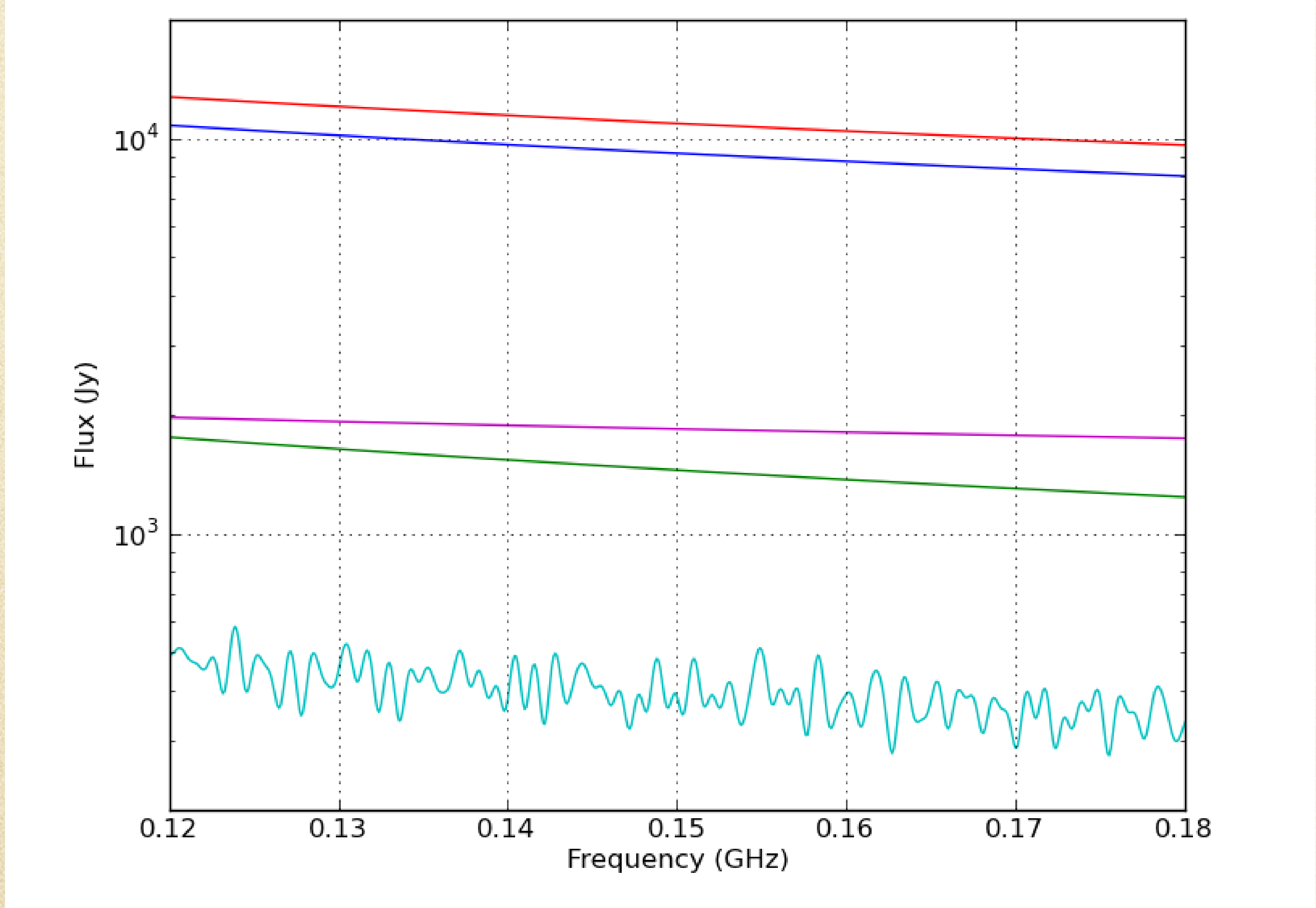
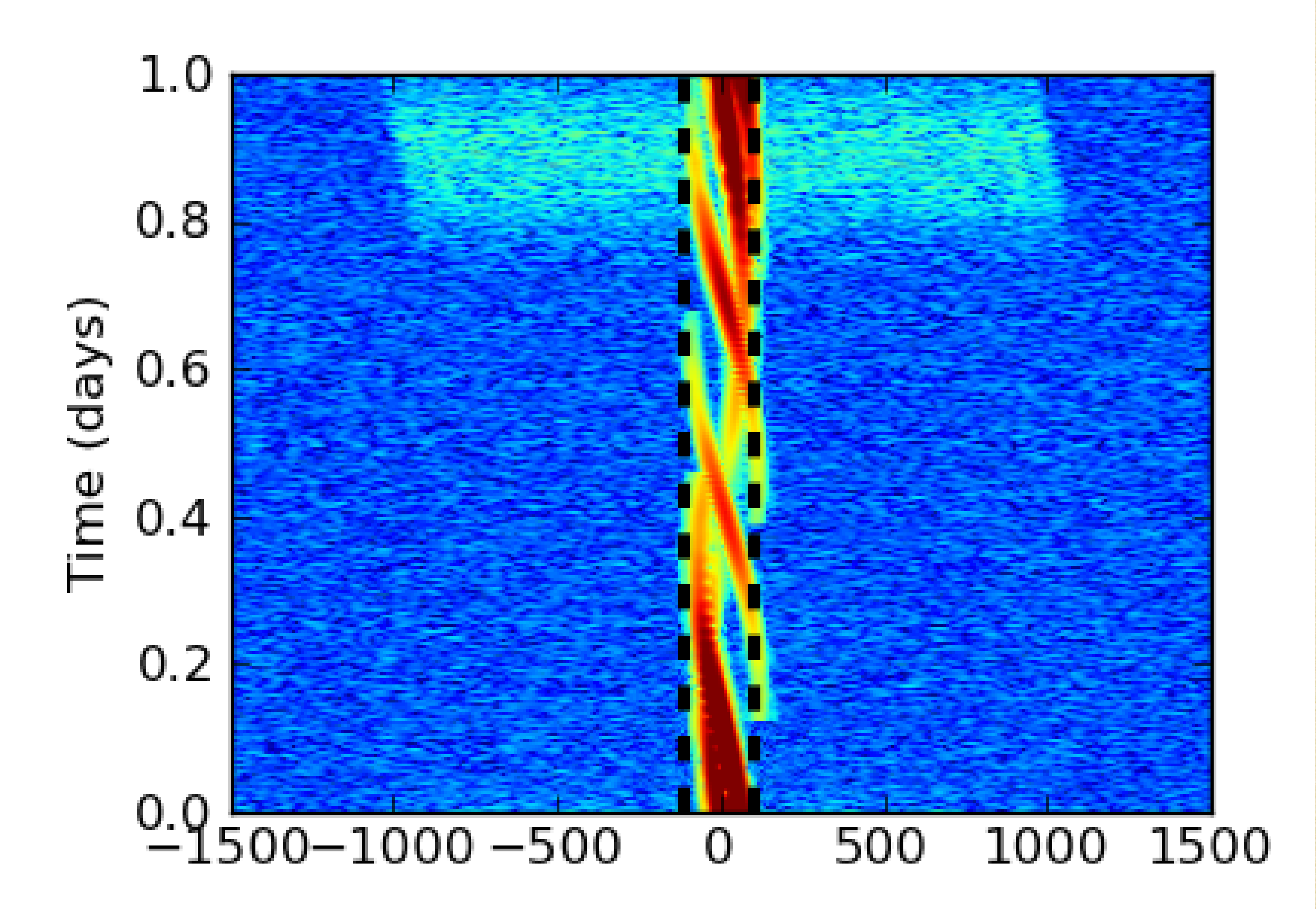


Fig. 2.— The spectra of five sources at random positions on the sky that were used to generate simulated visibilities from which the delay spectra in Figure 3 were calculated, using a model of PAPER's primary beam response. All but one of the sources (cyan) have power-law spectra versus frequency.

Parsons et al 2012.

Delay transform technique of foreground suppression

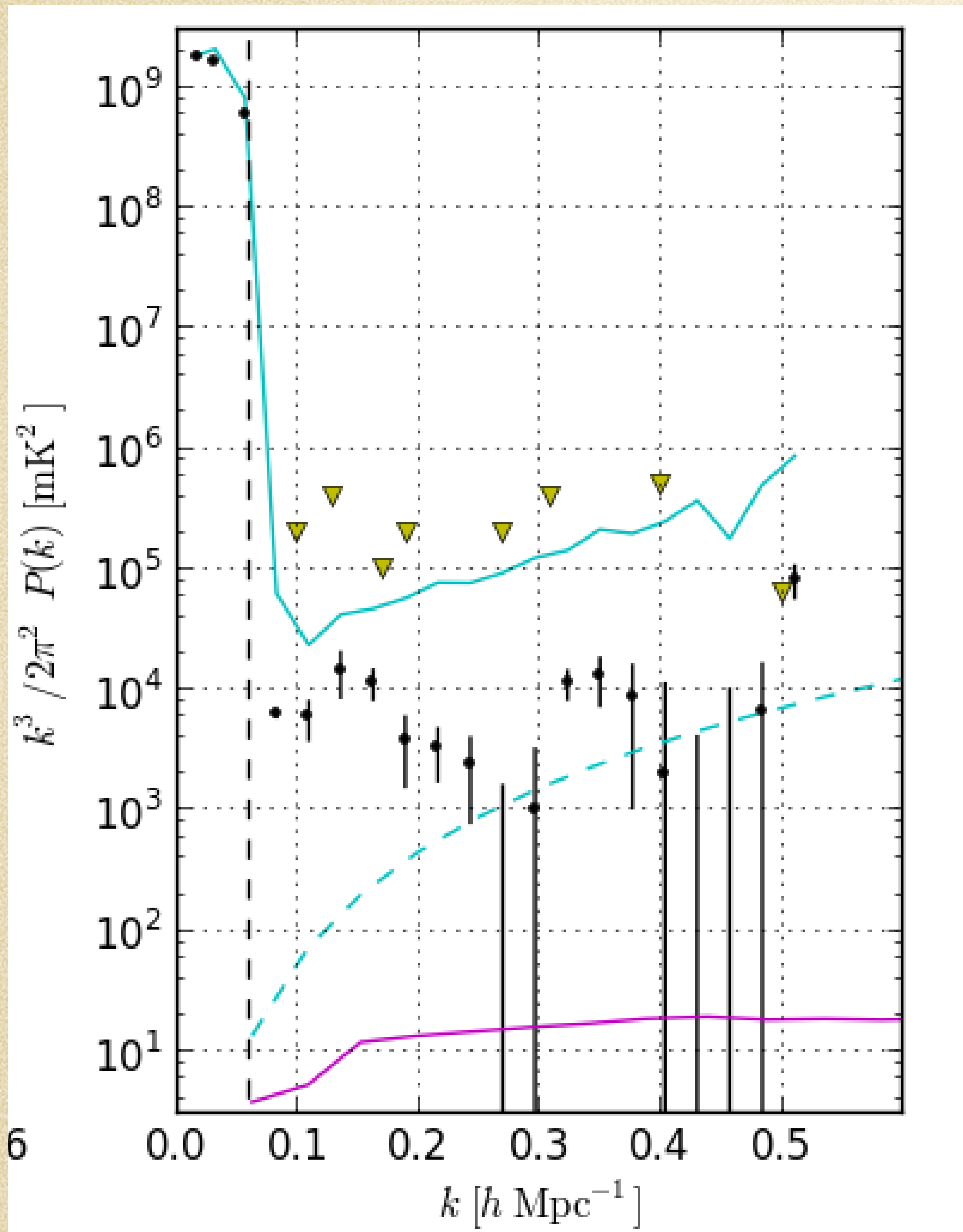


Delay spectrum obtained by Fourier transforming a 60- MHz band centered at 150 MHz for east-west baselines of lengt
meters (16 wavelengths at150 MHz). Emission from sources with power-law spectra remains confined within the horizo
limits. Emission from the source with an fluctuating spectrum extends beyond these limits.

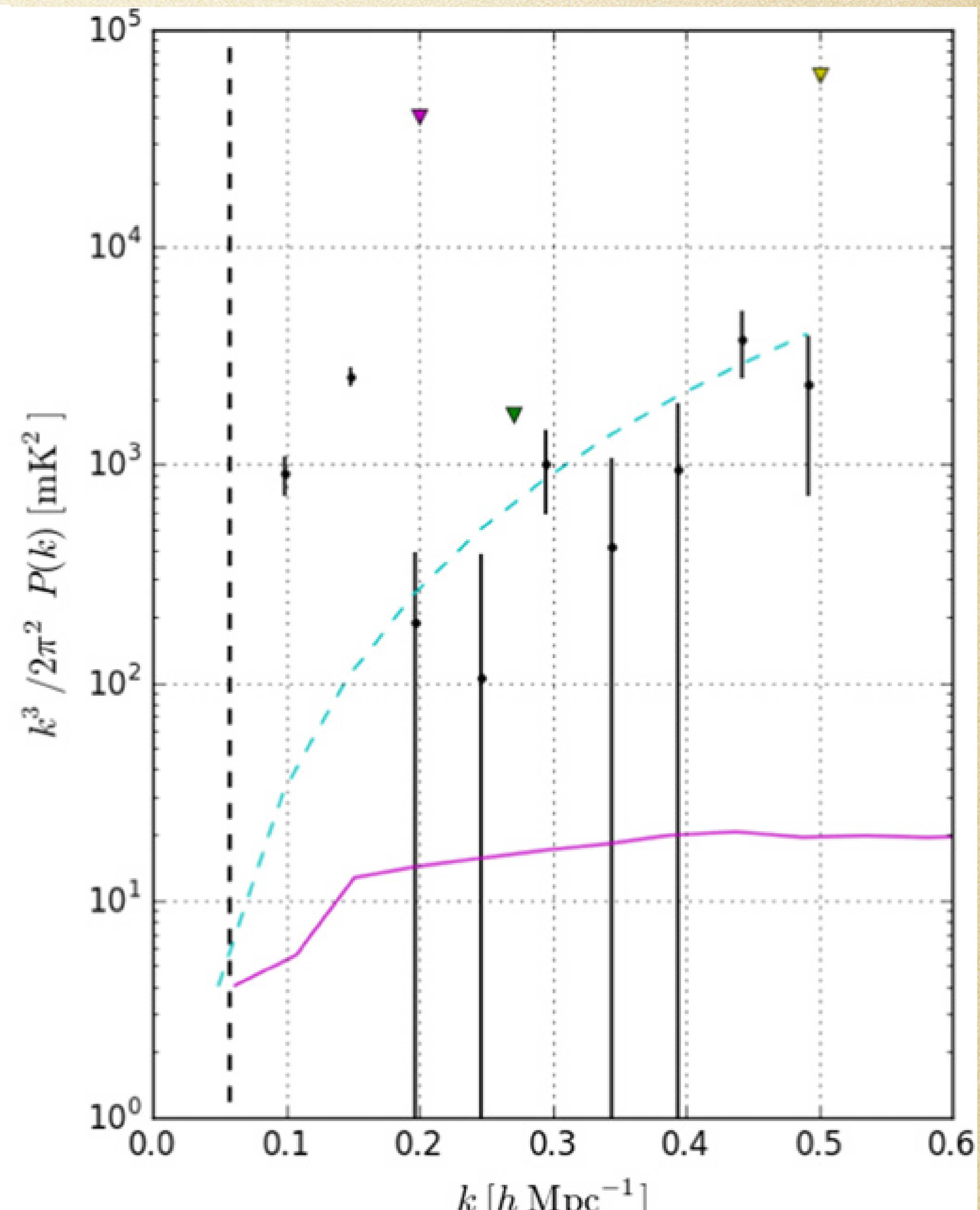
Parsons et al 2012.

Under the assumptions of smooth foreground and instrumental response, PAPER could potentially detect 21cm reionization at an amplitude of 10 mK^2 near $k \sim 0.2h\ Mpc^{-1}$ with 132 dipoles in 7 months of observing.

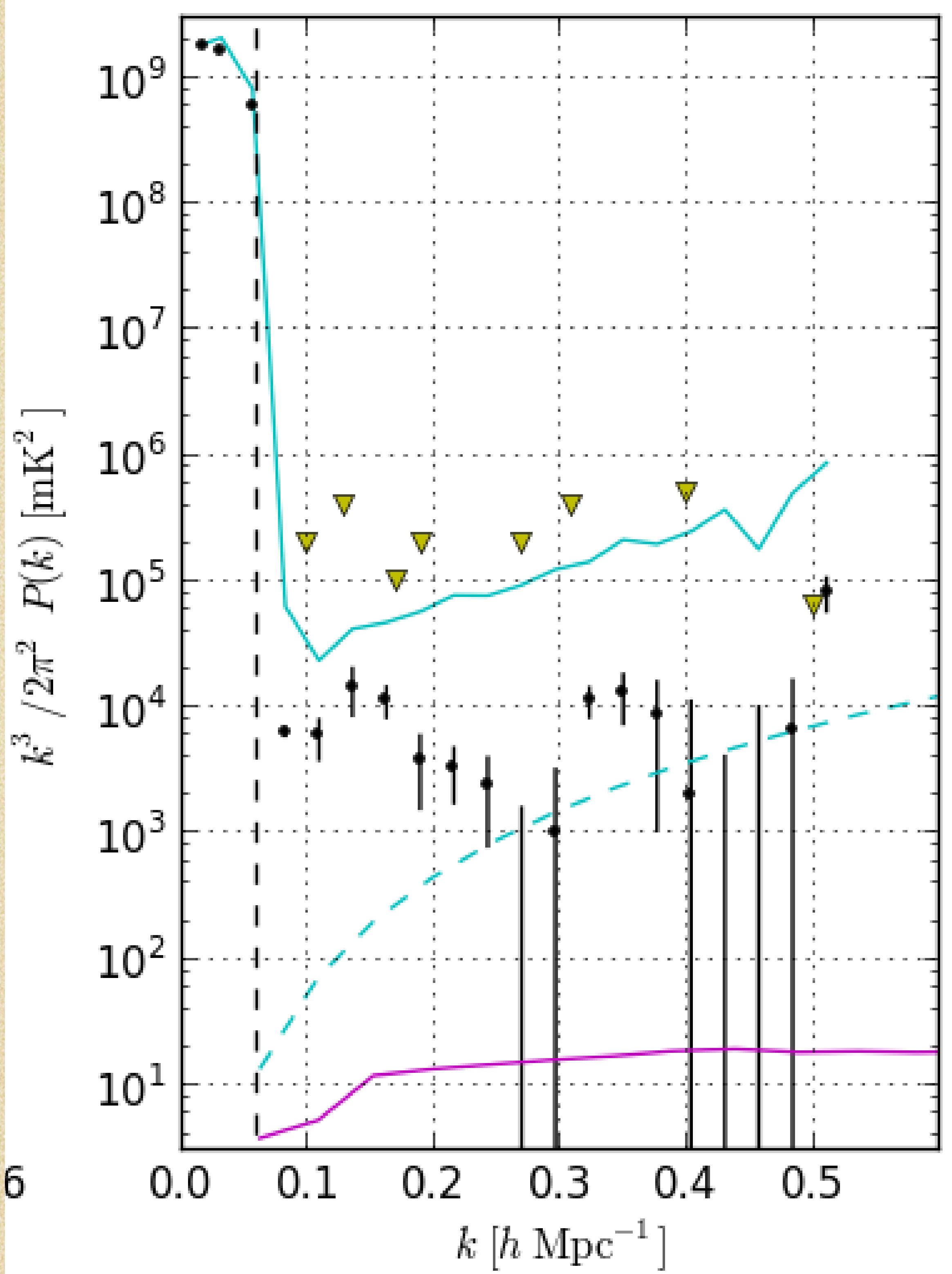
PSA32: Parsons et al. 2014



PSA64: Ali et al. 2015



PSA32: Parsons et al. 2014



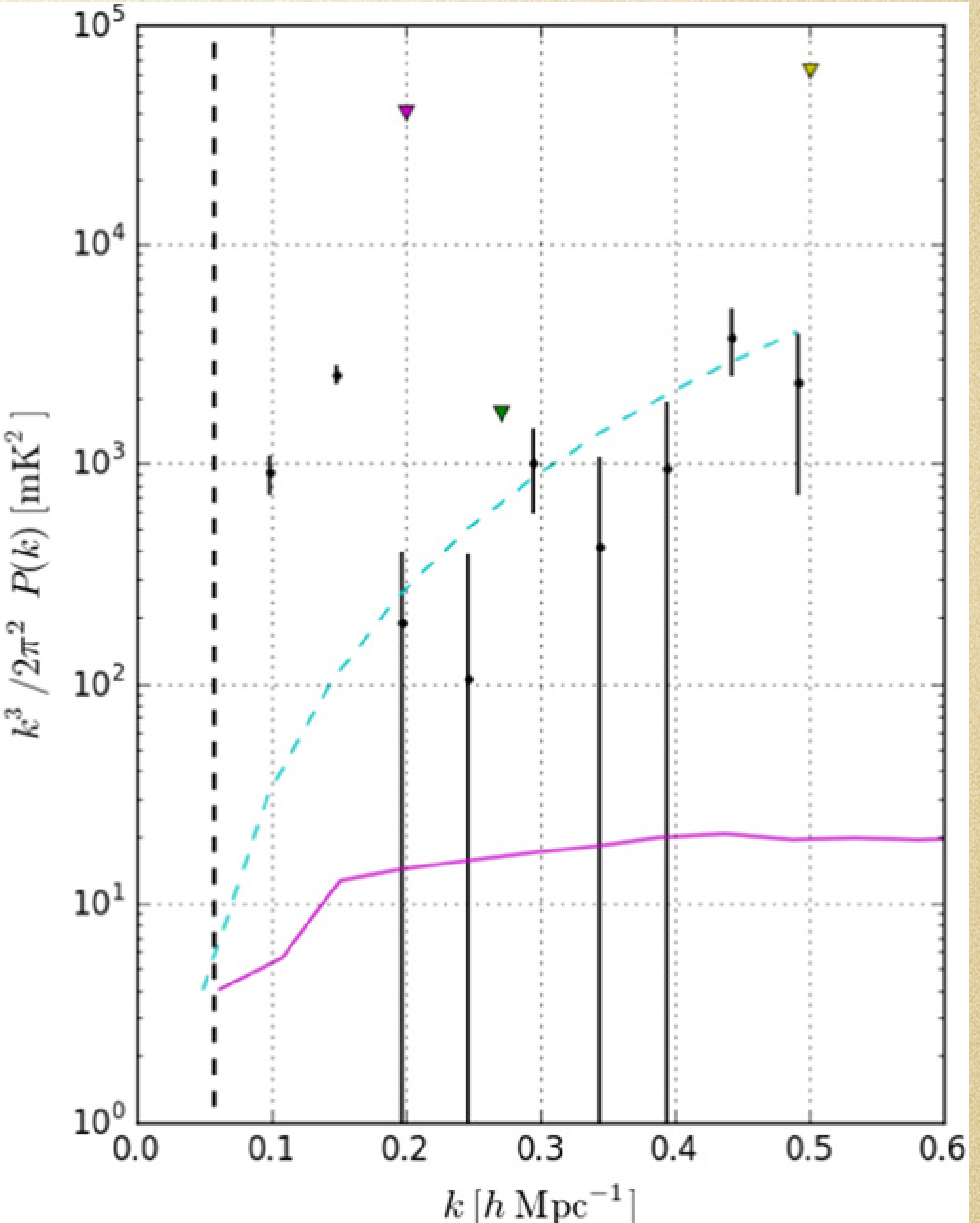
8 order of magnitude foreground suppression

2 sigma upper limit of 41mk^2 (k=0.27hMPc^-1)

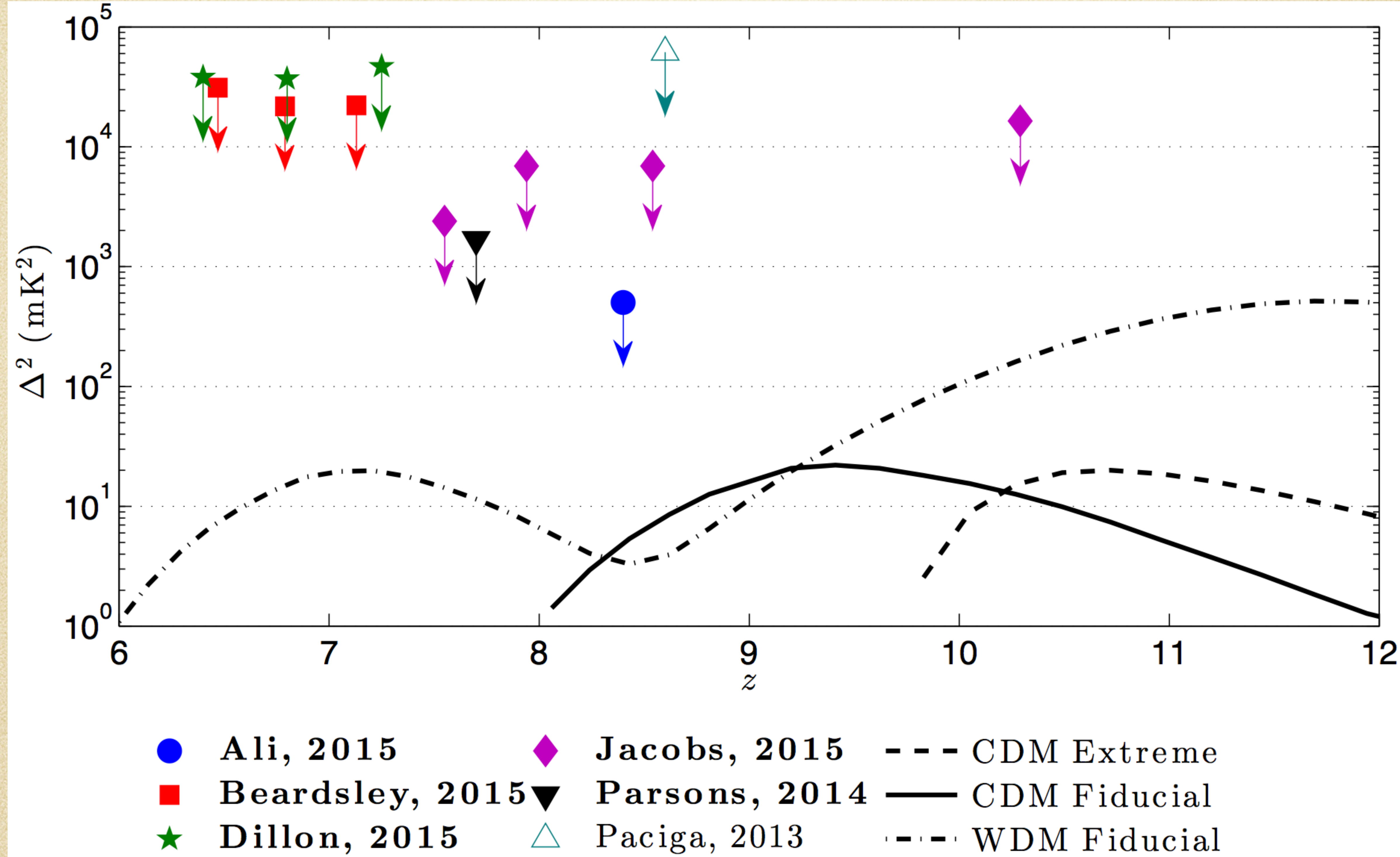
This falls within an order of magnitude of the expected EoR signal

PSA64: Ali et al. 2015

8 order of magnitude foreground suppression
2 sigma upper limit of 22.4mk^2 (0.15<k<0.5hMPc^-1)
Three fold improvement over PSA-32, Parsons et al 2014.



Recent power spectrum measurements

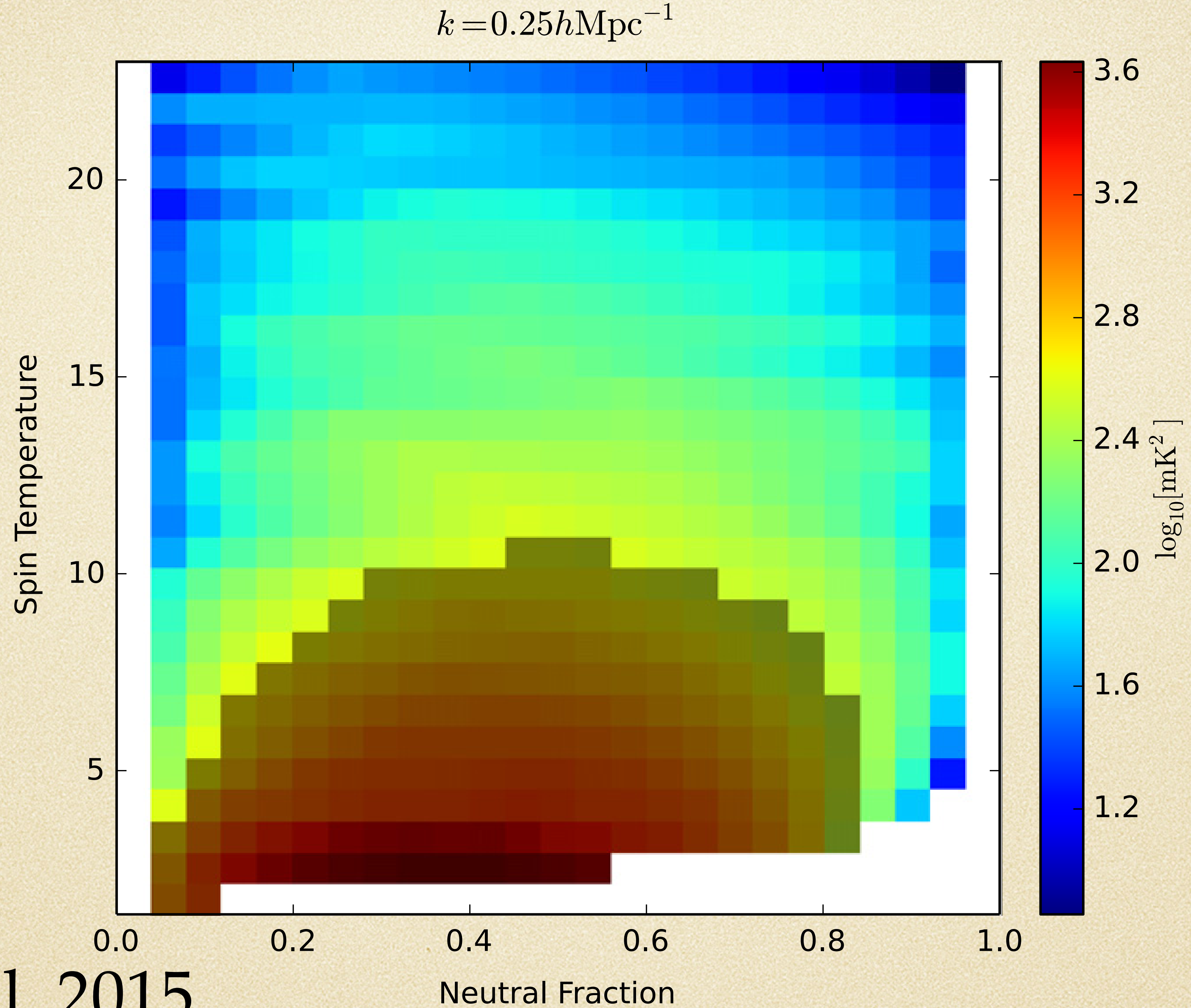


Credit: Adam Beardsley

Science implications

- Heating of the IGM is necessary to conform to the constraints reported in Parsons et al 2014 and Ali et al. 2015. Cold reionization is inconsistent with these power spectrum limits.

Science implications



Pober et al. 2015

Figure 4. Constraints on the IGM spin temperature as a function of neutral fraction based on the 2σ upper limits from the PAPER measurements; regions excluded at greater than 95% confidence are shaded in gray. Plotted is a slice through our 3D (T_s, $x_{\mathrm{H\,I}}$, k) space at the $k = 0.25\ h\mathrm{Mpc}^{-1}$, but the constraints are calculated from the joint likelihood across all k modes measured by PAPER.

HERA: Overview and timeline

- 14m diameter parabolic dishes while delivering an order of magnitude more collecting area per element relative to PAPER.
- Close-packed in a hexagonal grid that maximizes baseline redundancy (Parsons et al. 2012a)

HERA

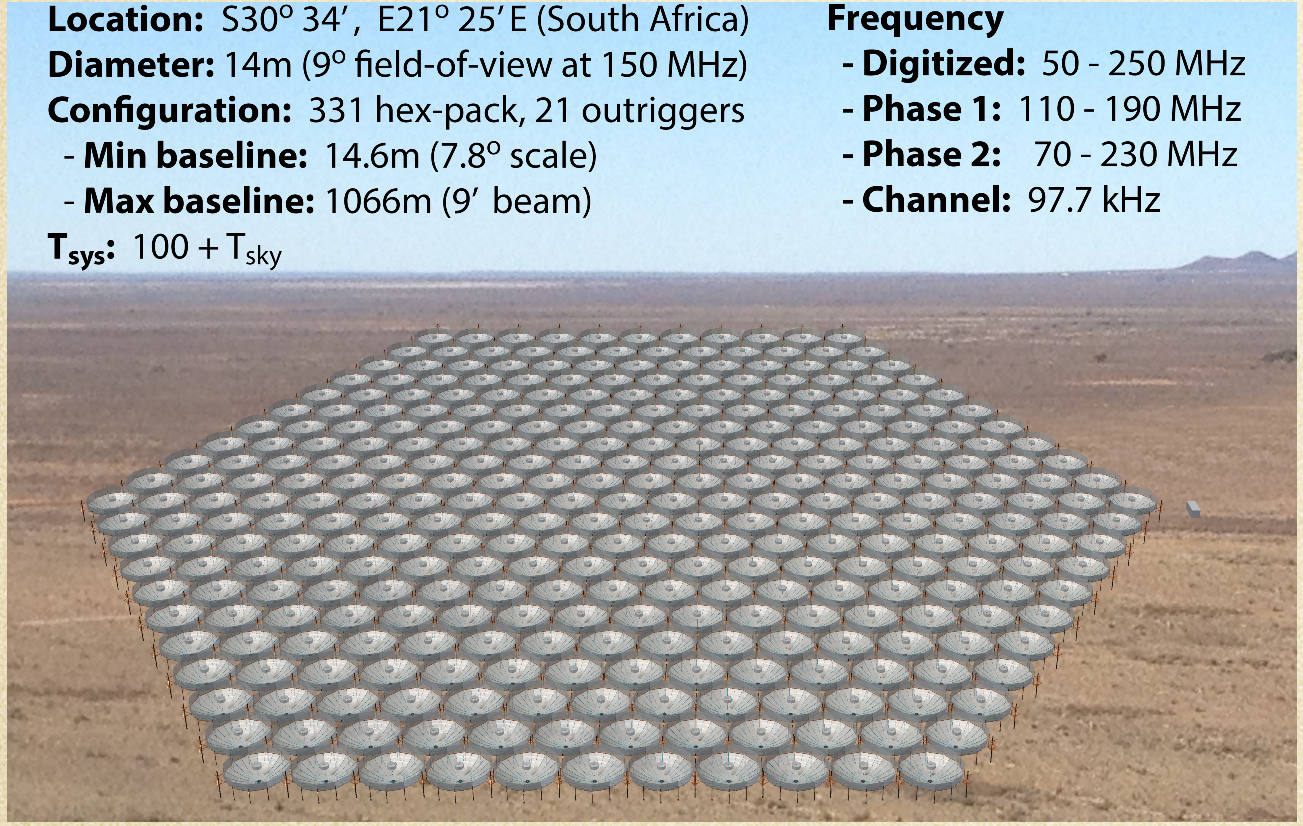
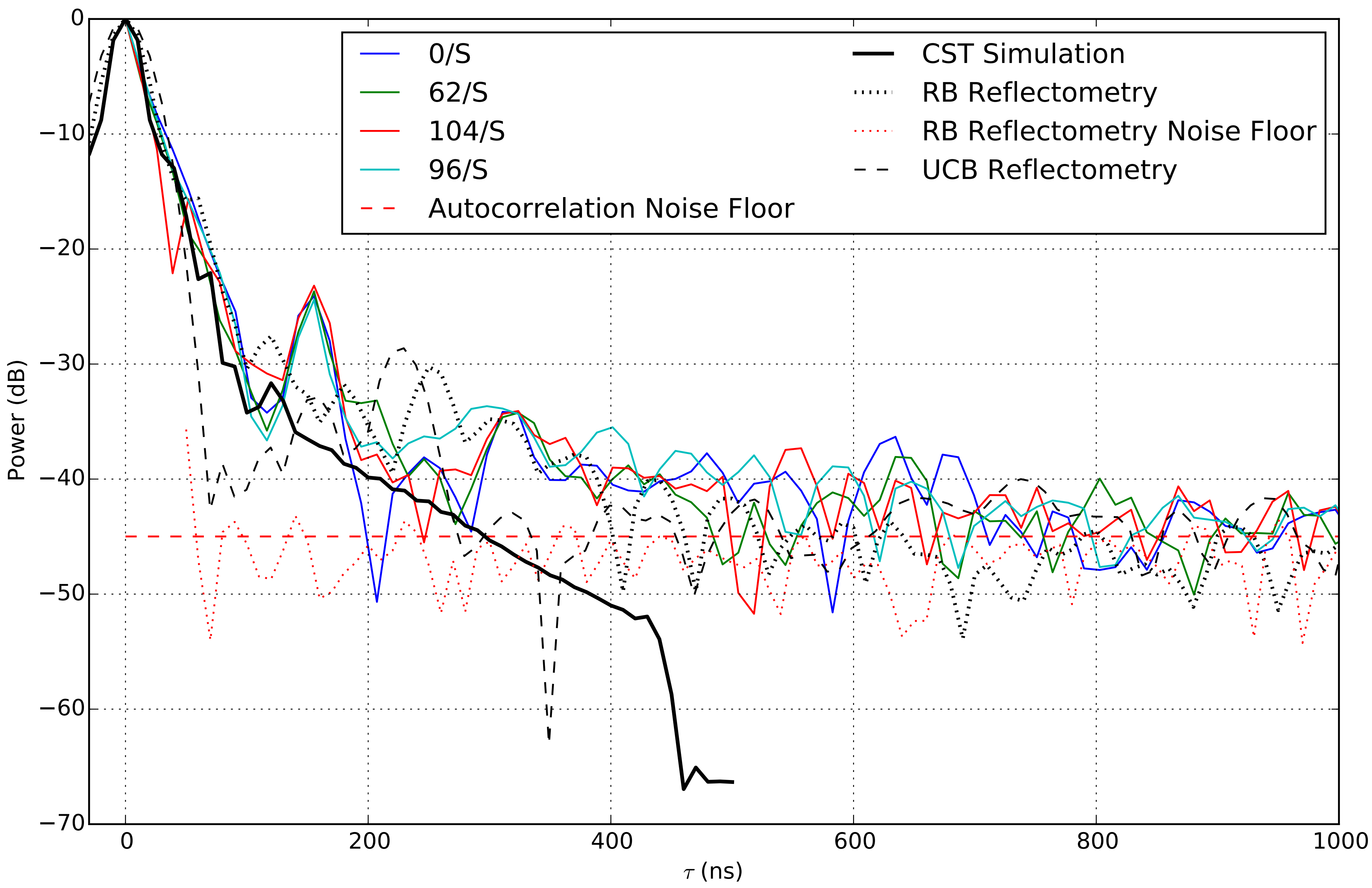


Fig. 8.— Representation of the 331 14-m core elements of the 352 array (left) and the current 19 elements (right). The location is the site of the current PAPER array in the Karoo of South Africa.

HERA First light



HERA

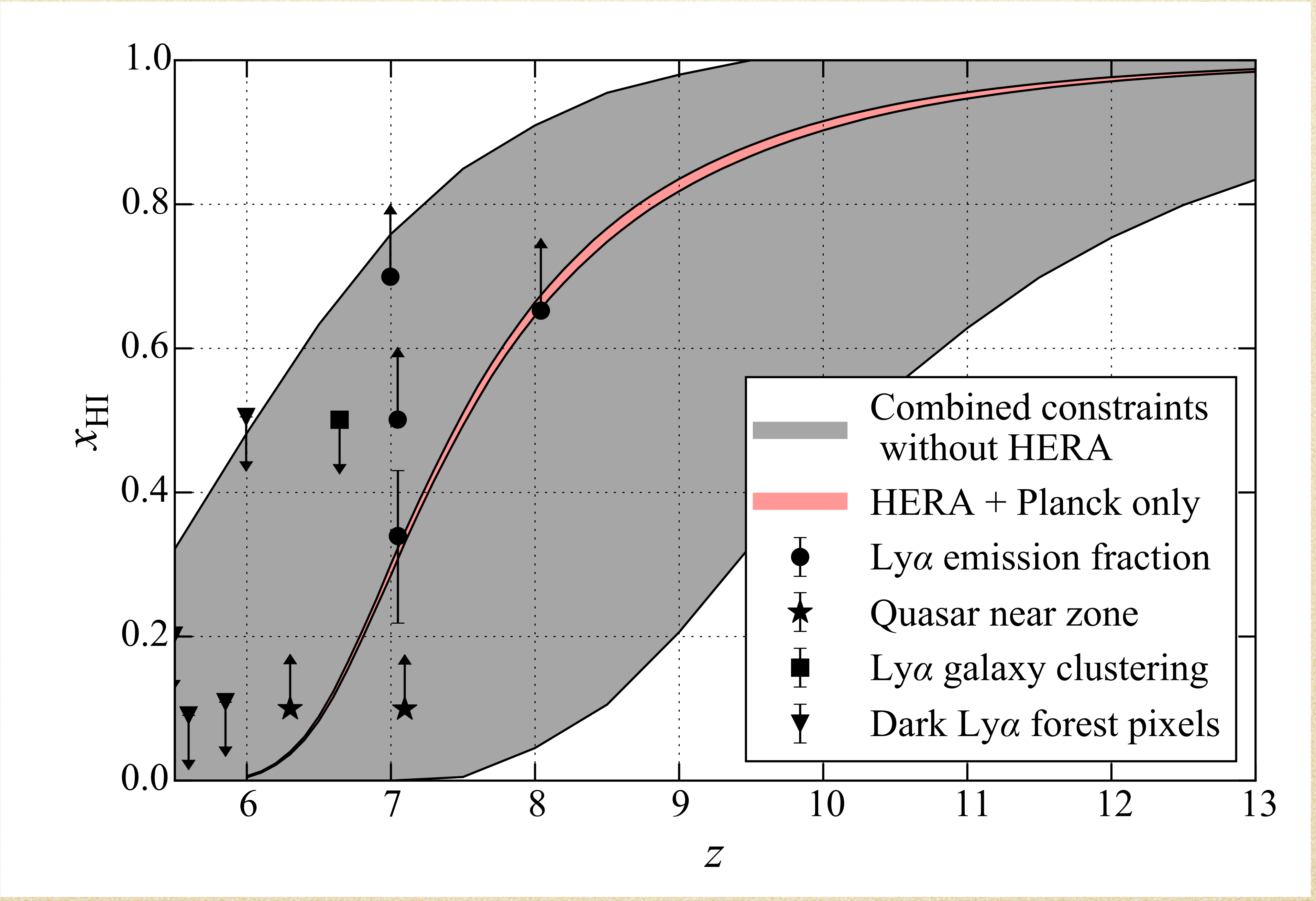
- **Construction of first 19 HERA elements is completed at the PAPER location in Karoo in 2015 and a total of 37 elements would be constructed by 2016 (Already funded).**
- **2016:** System characterization with 37 antennas and expanding to 127
- **2017:** Hardware commissioning and deep foreground survey with 127 and expansion to 271.
- **2018:** Possible detection of the redshifted 21cm power spectrum and buildout to 352.
- **2019:** Observing with HERA 352 and deriving the science implications

HERA

Instrument	Collecting Area (m^2)	Foreground Avoidance	Foreground Modeling
PAPER	528	1.93σ	8.86σ
MWA	896	2.46σ	6.40σ
LOFAR NL Core	35,762	2.76σ	17.37σ
HERA-352	**50,900**	$\mathbf{25.44\sigma}$	$\boldsymbol{87.20\sigma}$
SKA1 Low Core	833,190	97.92σ	284.85σ

Power spectrum signal to noise at z=9.5 from various instruments (Pober et al.)

Current constraints on the ionization history based on high redshift observational probes and 95% confidence region. Expected constraints from HERA, marginalized over cosmological parameters with a prior from Planck showen in red with a 95% confidence limit.



Patra et al. 2015 (soon)

Neben et al. 2015 (sooon)

Thyagarajan et al. 2015 sooon)

Ewal-Wice et al. 2015 (soooooon)

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