Recent Results on Cosmic Reionization from PAPER

Jonathan Pober, UC Berkeley

Reionization in the Red Centre
07/17/13

The Donald C. Backer Precision Array for Probing the Epoch of Reionization

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- Pat Klima
- Nicole Gugliucci
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- Jonathan Pober
- Zaki Ali
- Dave DeBoer
- Dave MacMahon
- Adrian Liu
- Gilbert Hsyu

<u>U. Pennsylvania</u>

- James Aguirre
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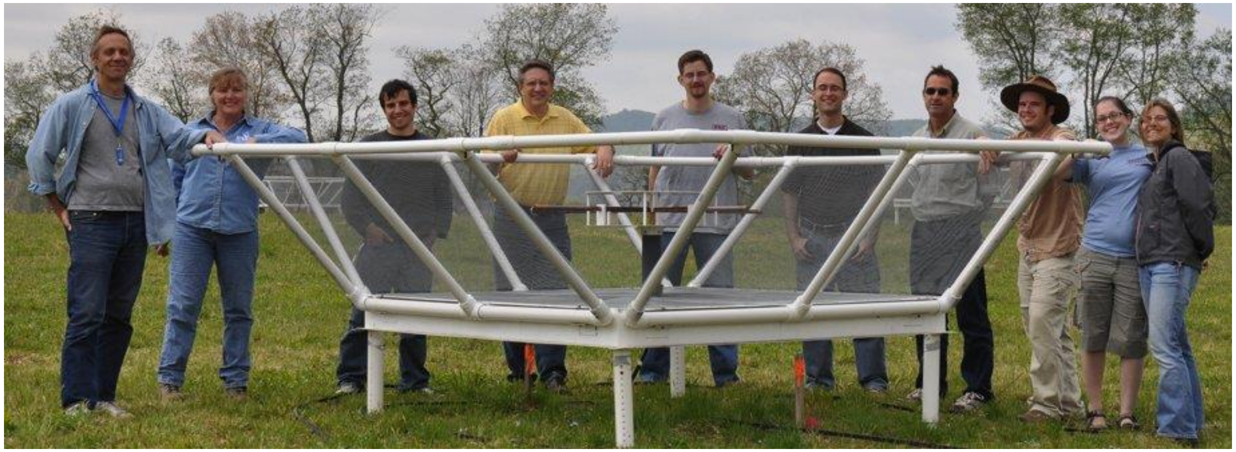
- Daniel Jacobs

<u>South Africa</u>

- Carel van der Merwe
- Jason Manley
- William Walbrugh



Outline

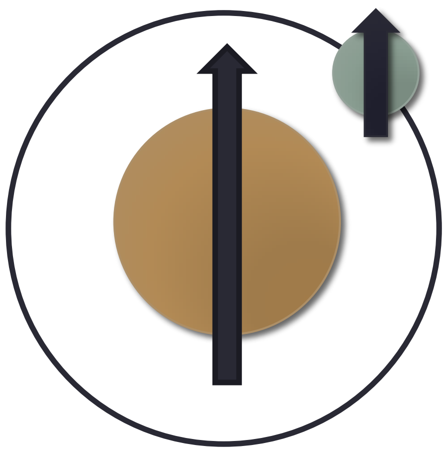
- 21cm Cosmology and the Epoch of Reionization
- The PAPER Experiment Design
- The PAPER Approach (explained graphically)
- Recent Results from PAPER
  - Measurements of foregrounds
  - Constraints on the EoR Power Spectrum
- Future Prospects and Conclusions

21cm Cosmology

Scientific Motivation and Techniques

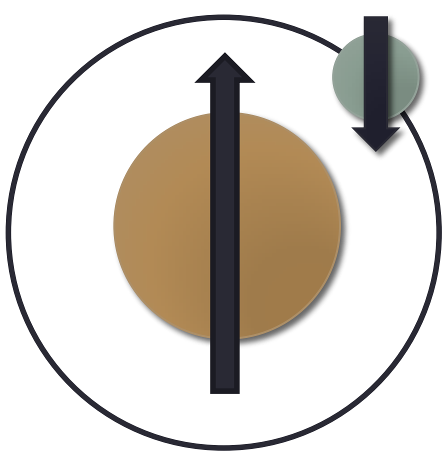
Hydrogen

- The most abundant element in the universe
  - 75% of all baryons by mass



- Ionization potential of 13.6 eV

- Hyperfine splitting energy differential of 5.9×10^{-6} eV
  - ν = 1420 MHz
  - λ = 21 cm
  - T = 0.068 K



- Describe relative population of hyperfine state with spin temperature:

$$\frac{n_1}{n_0} = \left(\frac{g_1}{g_0}\right) e^{(-T_*/T_S)}$$

Fluctuations

- Spatial variations in T_s, x_{HI}, and δ all source brightness temperature fluctuations around the global signal

- Describe spatial fluctuations in Fourier space with power spectrum

Epoch of Reionization

$$\delta T_b \approx 9 x_{HI} (1+\delta)(1+z)^{1/2} \left[1 - \frac{T_g(z)}{T_S}\right]\left[\frac{H(z)/(1+z)}{dv_{\parallel}/dr_{\parallel}}\right] mK$$

- UV photons from first galaxies reionize intergalactic hydrogen
- 21cm can measure:
  - Duration and timing of EoR
  - Clustering of ionizing sources

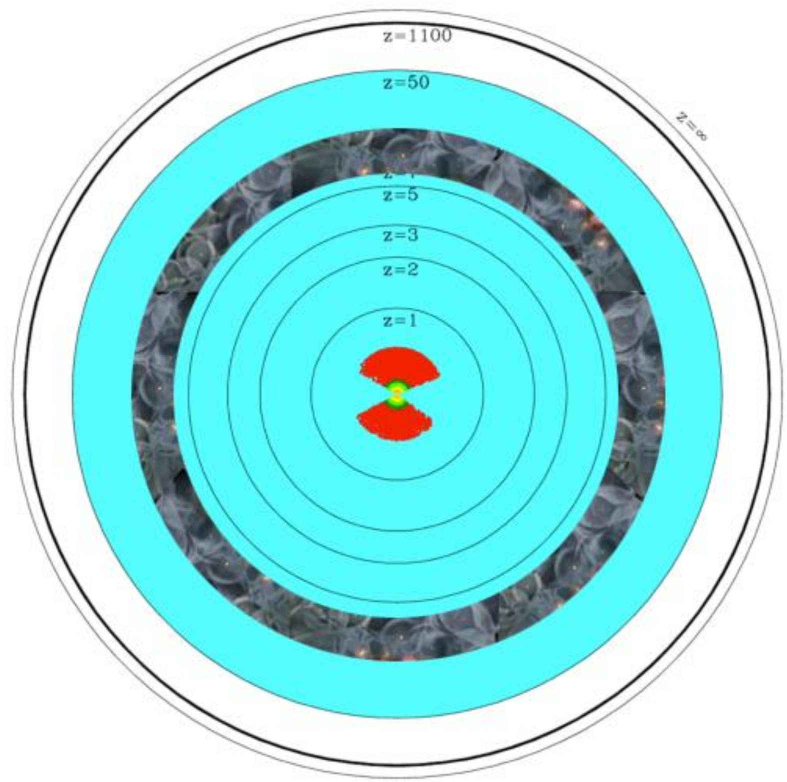
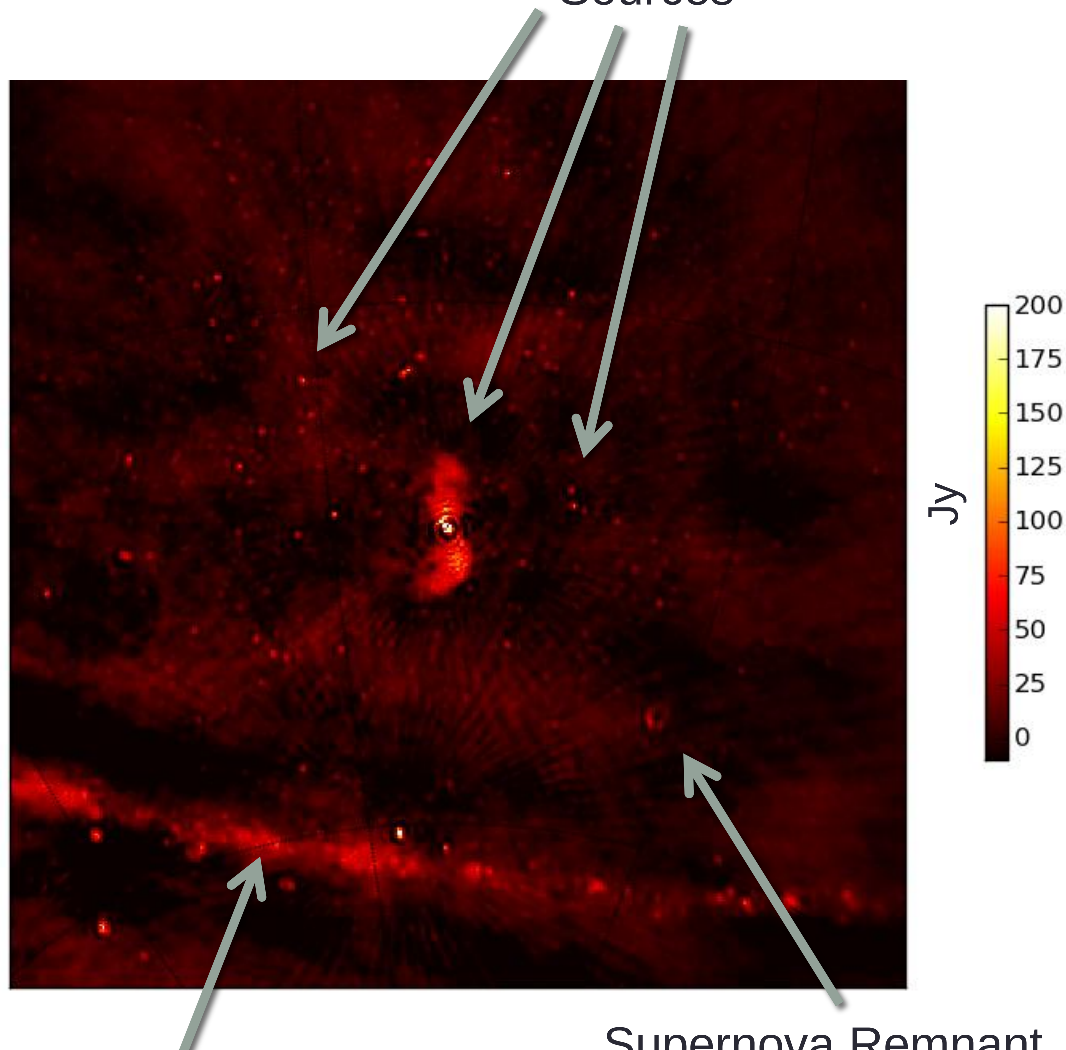


Figure adapated from Mao et al. (2008), Podevin illustration in Scientific American

Detecting the Signal

- Signal is faint
  - Long integrations and large collecting areas required
- Foregrounds are orders of magnitude brighter
  - Separate from 21cm signal using **spectral smoothness**



The PAPER Experiment

Design, Status and Results

PAPER

Precision Array Probing the Epoch of Reionization

- Array of dual-polarization, non-tracking dipole elements
- Sensitivity from 110 to 180 MHz ($z \approx 7$-12) in 1024+ frequency channels
- Full correlation of all dipoles with CASPER FPGA/GPU architecture
- Store all raw visibilities for later analysis

Deployments

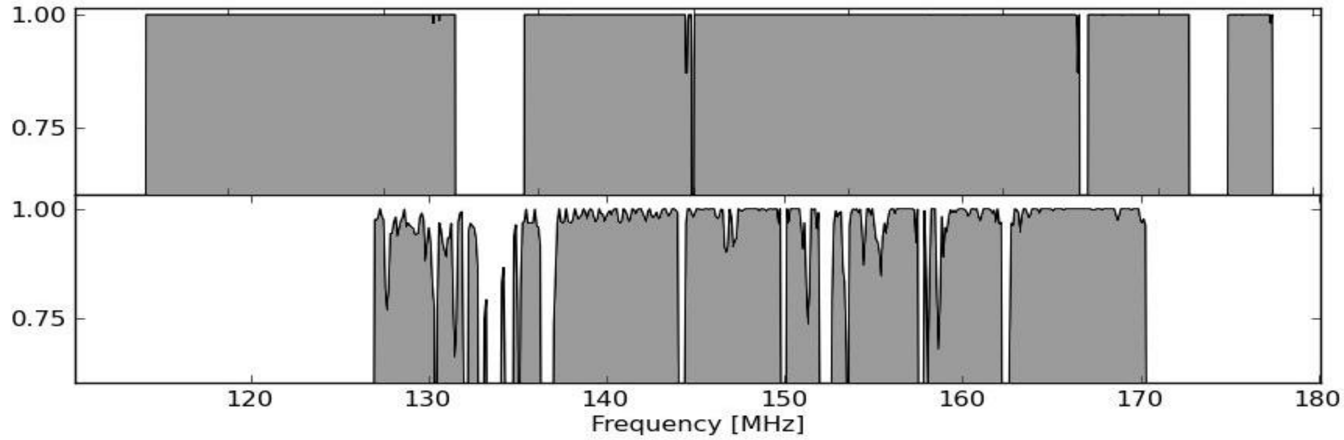
- PGB-4: 2004
- PGB-8: 2006
- PGB-16: 2008
- PGB-32: 2010

- **PSA-16: 2009**
- PSA-32: 2010
- PSA-64: 2011
- (PSA-128: 2013)

RFI Flagging

Unflagged

Flagged



South Africa

Green Bank

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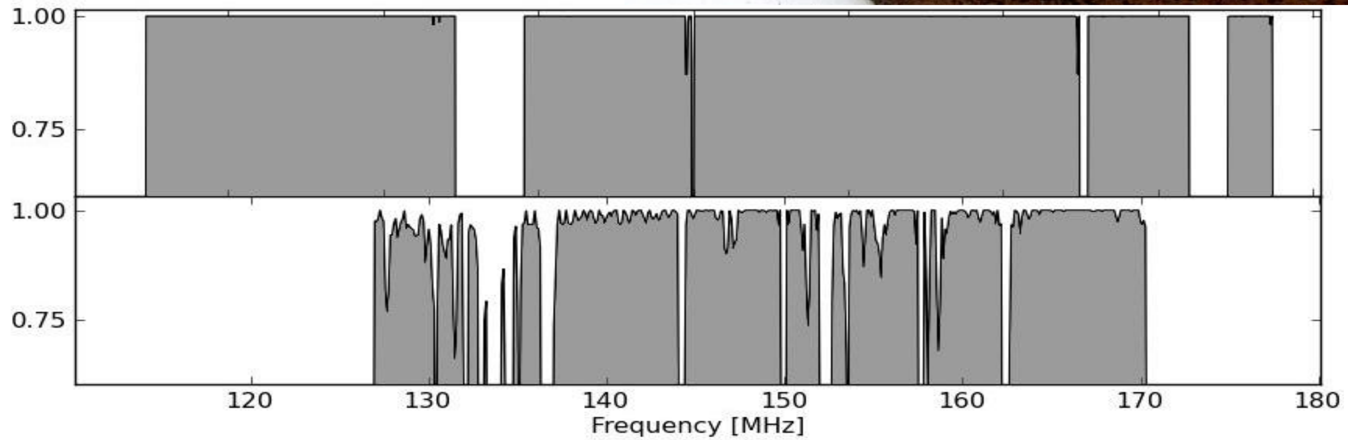

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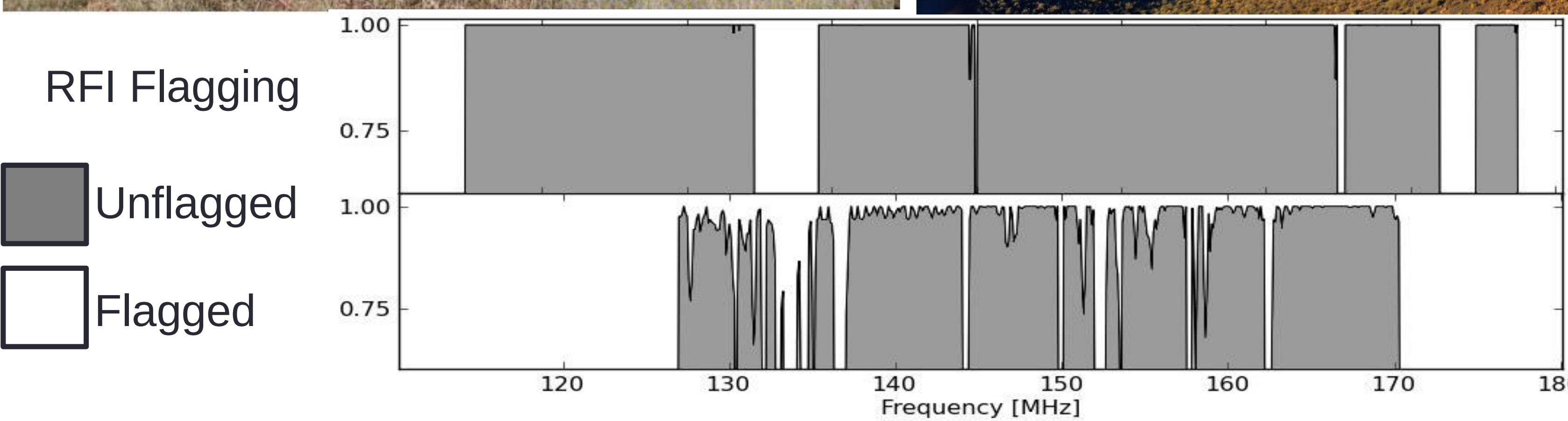

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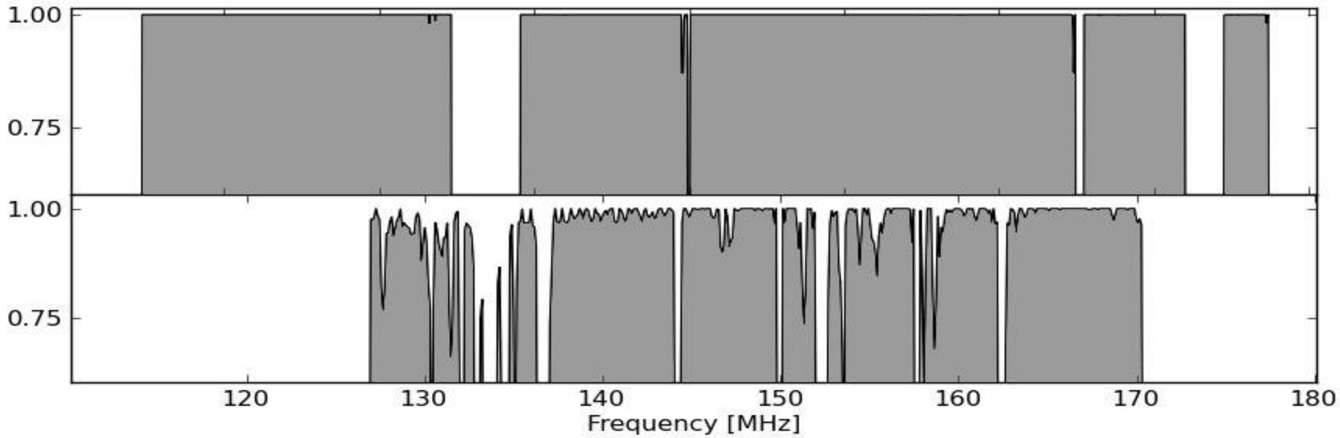

South Africa

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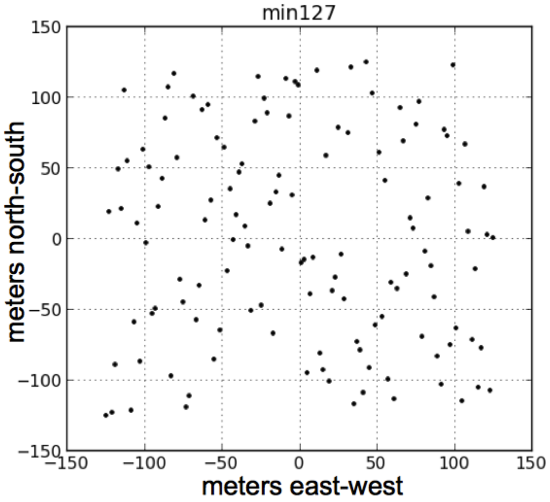
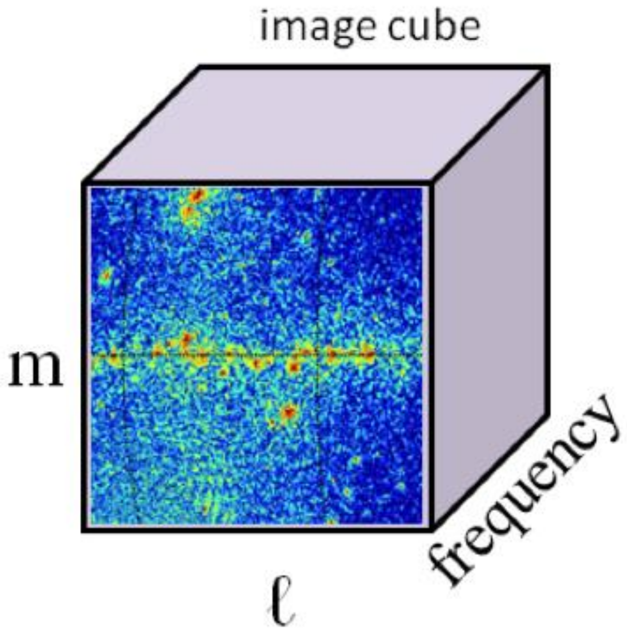
The PAPER Approach

Redundancy and the "Delay Spectrum"



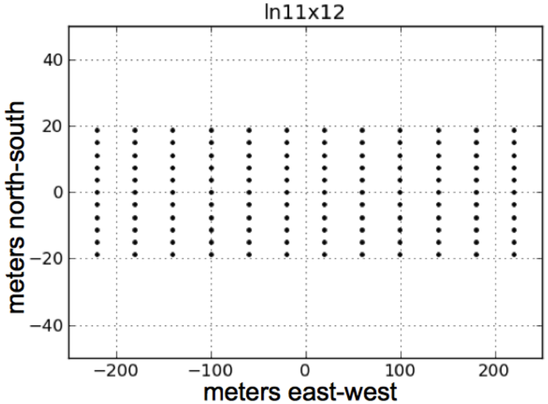
“Minimum Redundancy” Array

Parsons, JCP, et al. (2012a)



u,v: interferometer sampling plane

m, ℓ: sky plane



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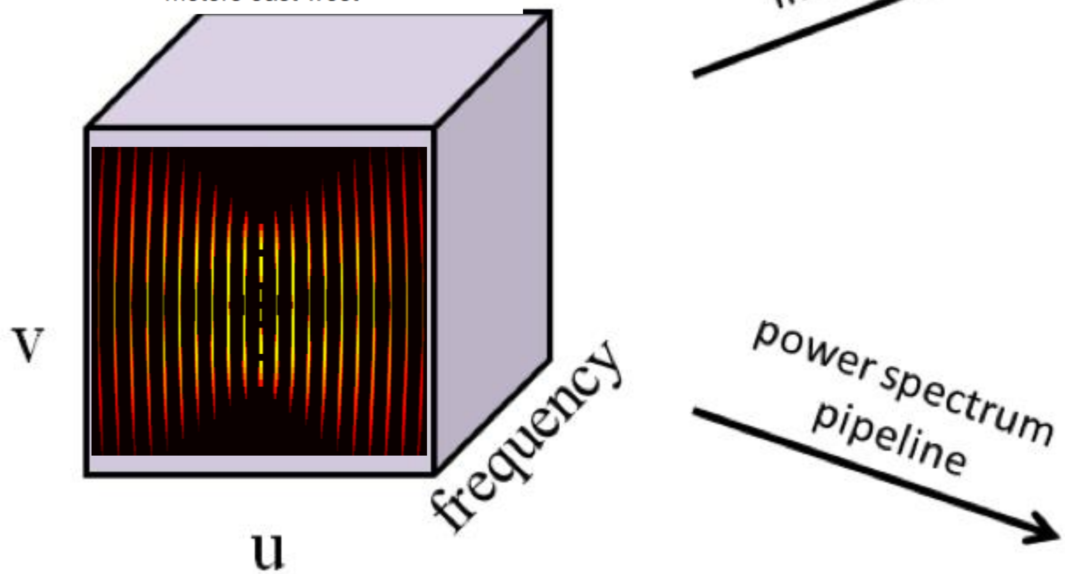

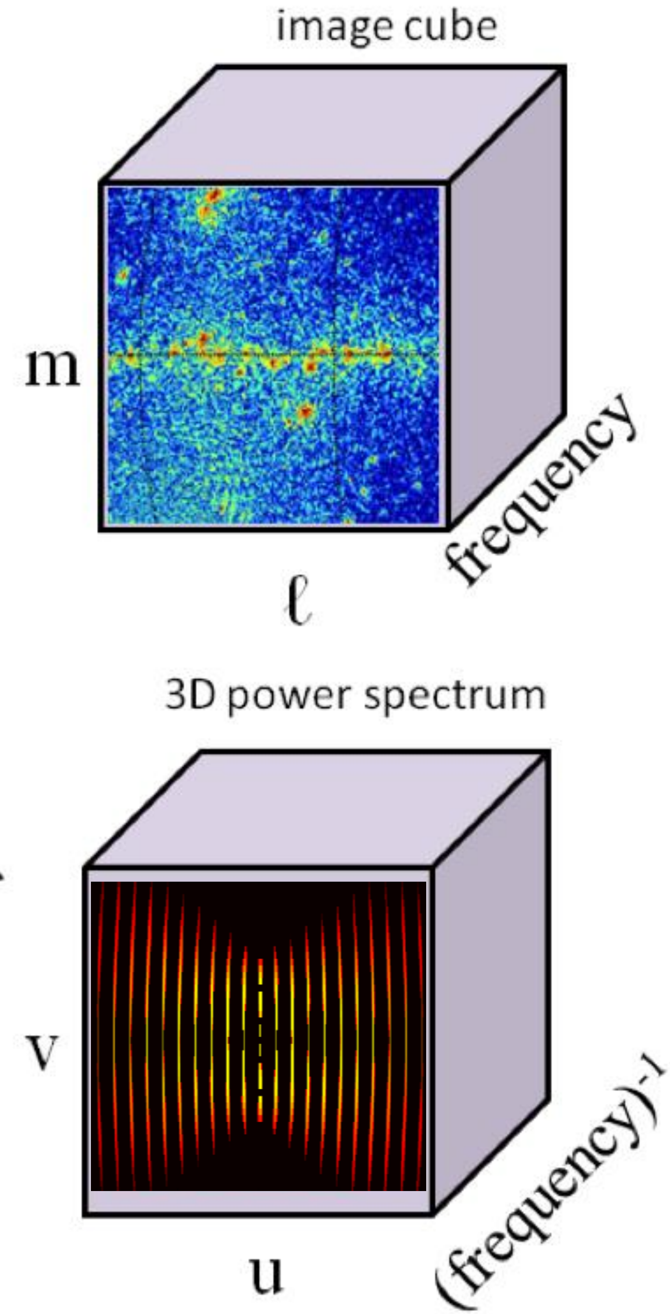

u,v: interferometer sampling plane

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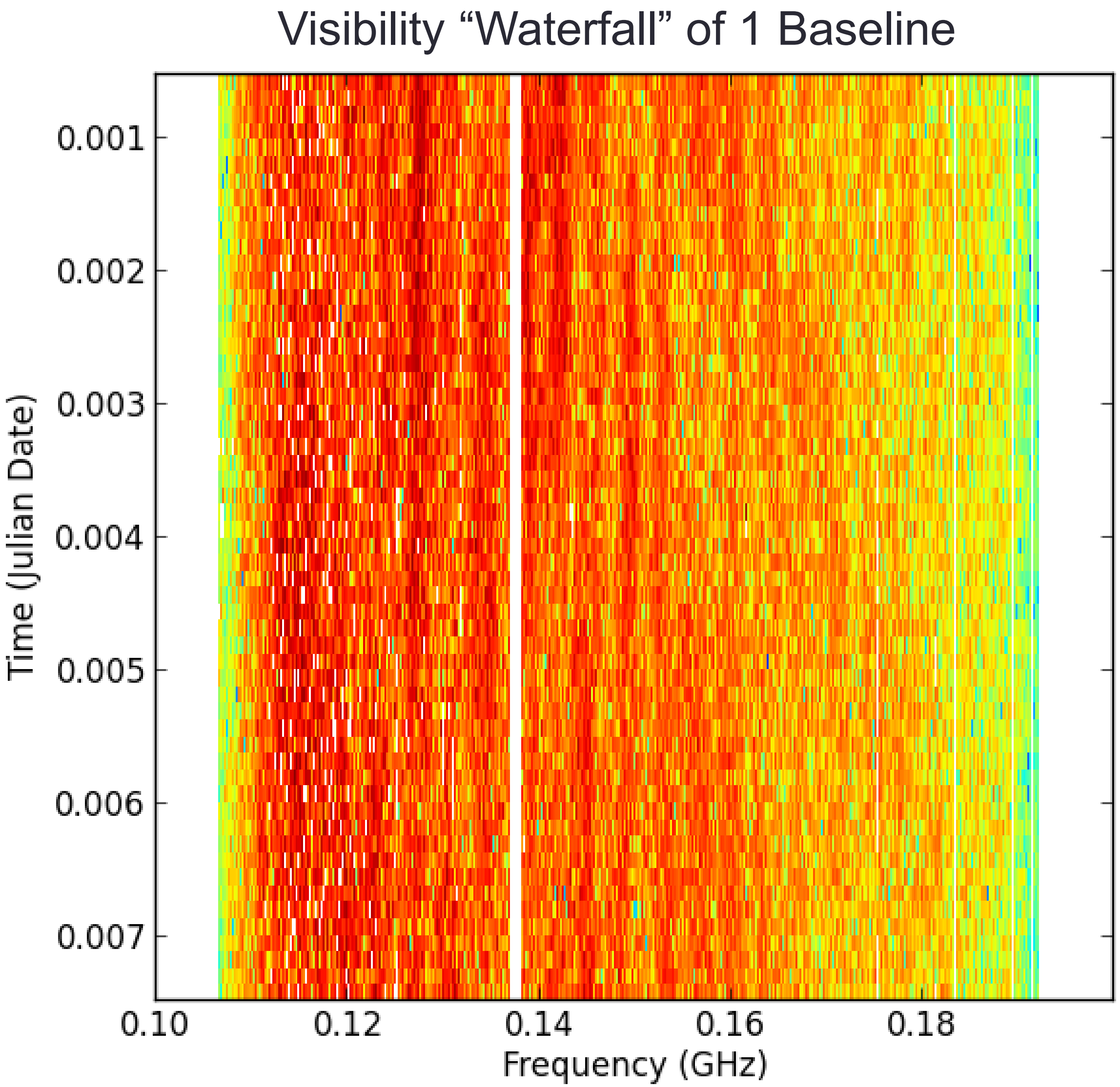
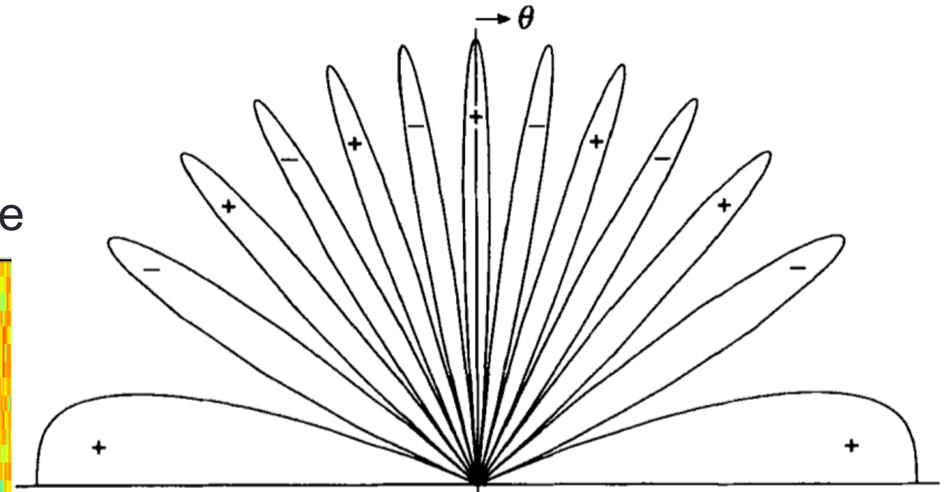
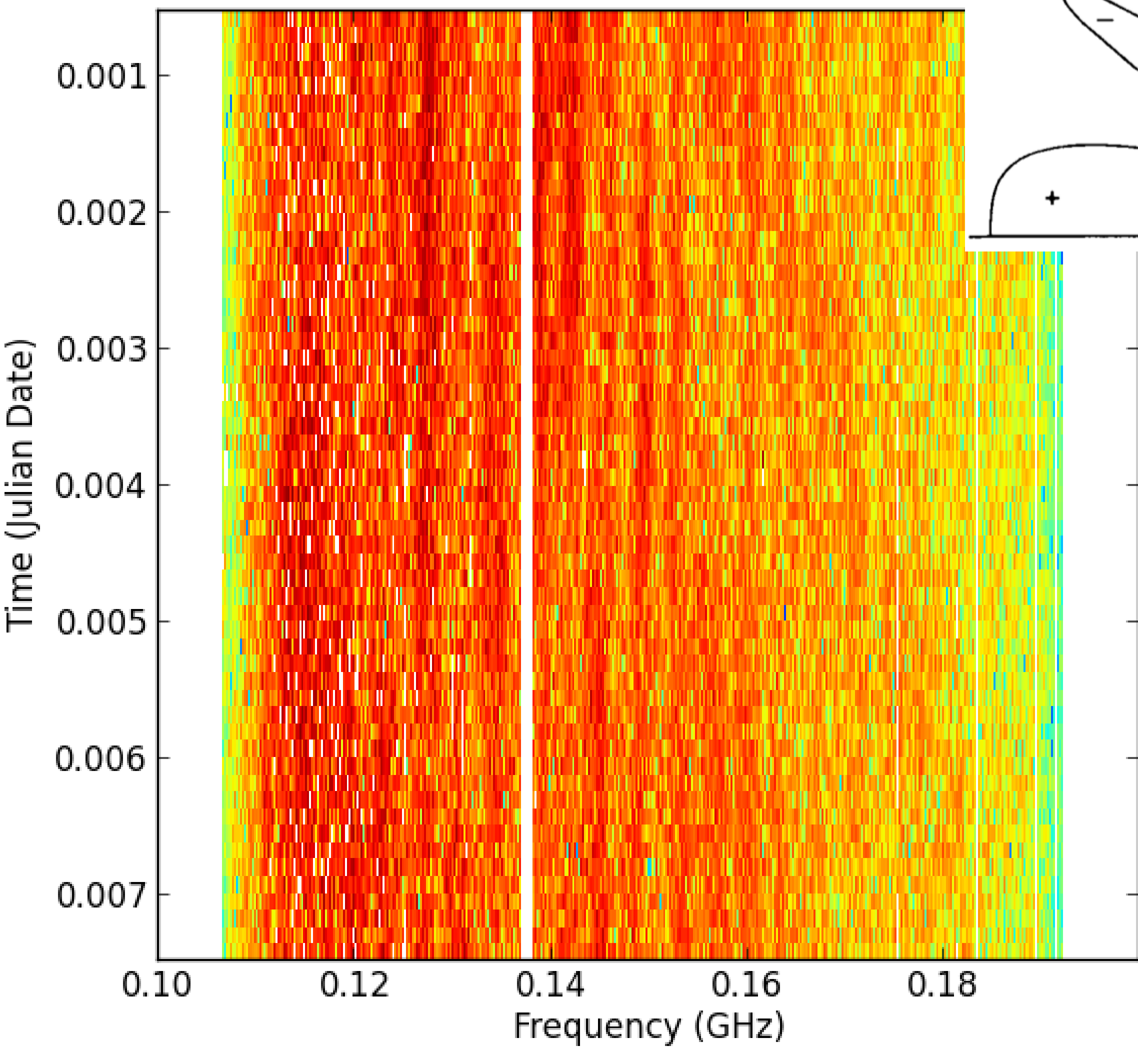
A Pictorial View of the PAPER Pipeline



(Image: Thompson, Moran & Swenson)



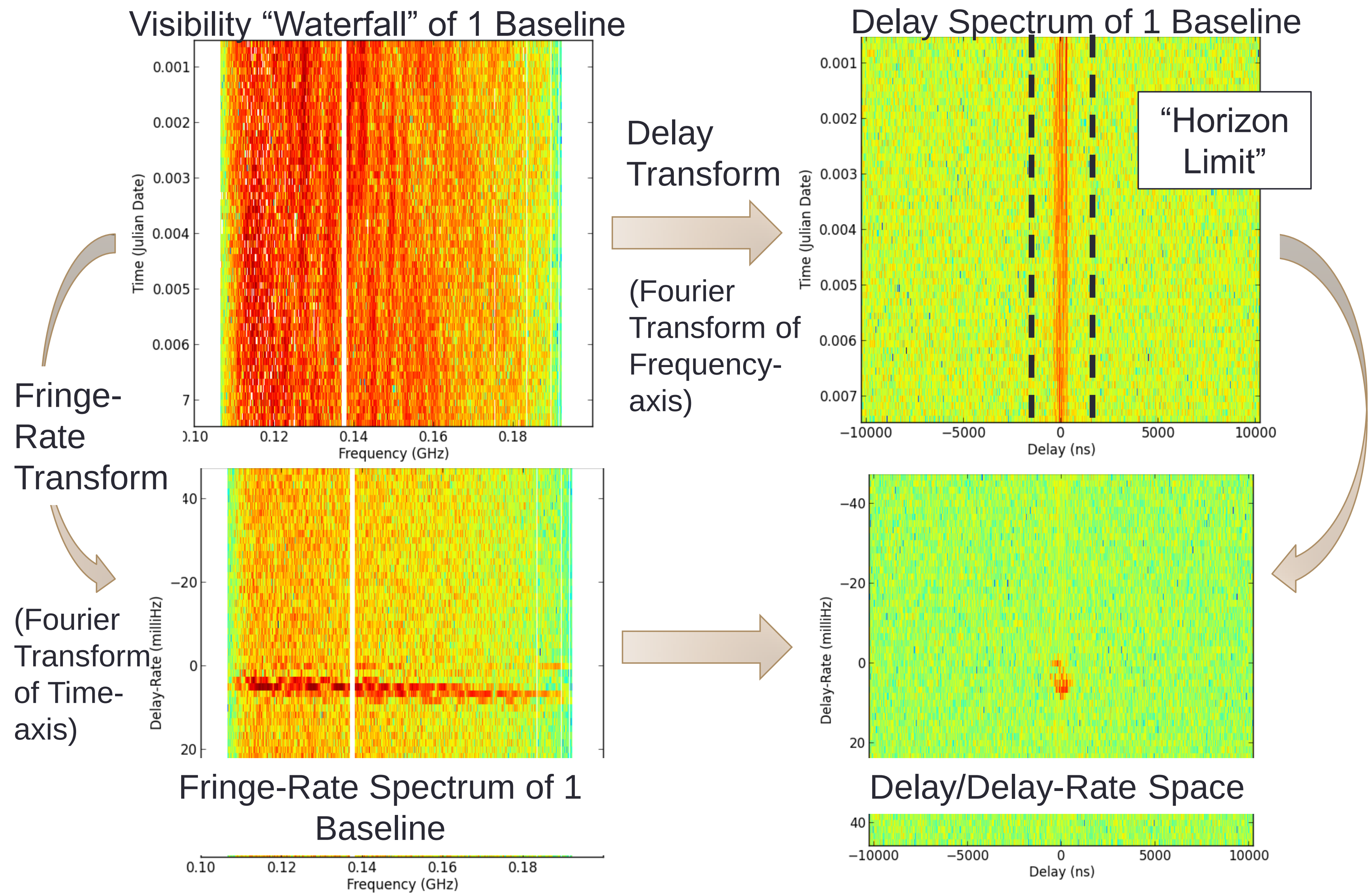
Visibility “Waterfall” of 1 Baseline



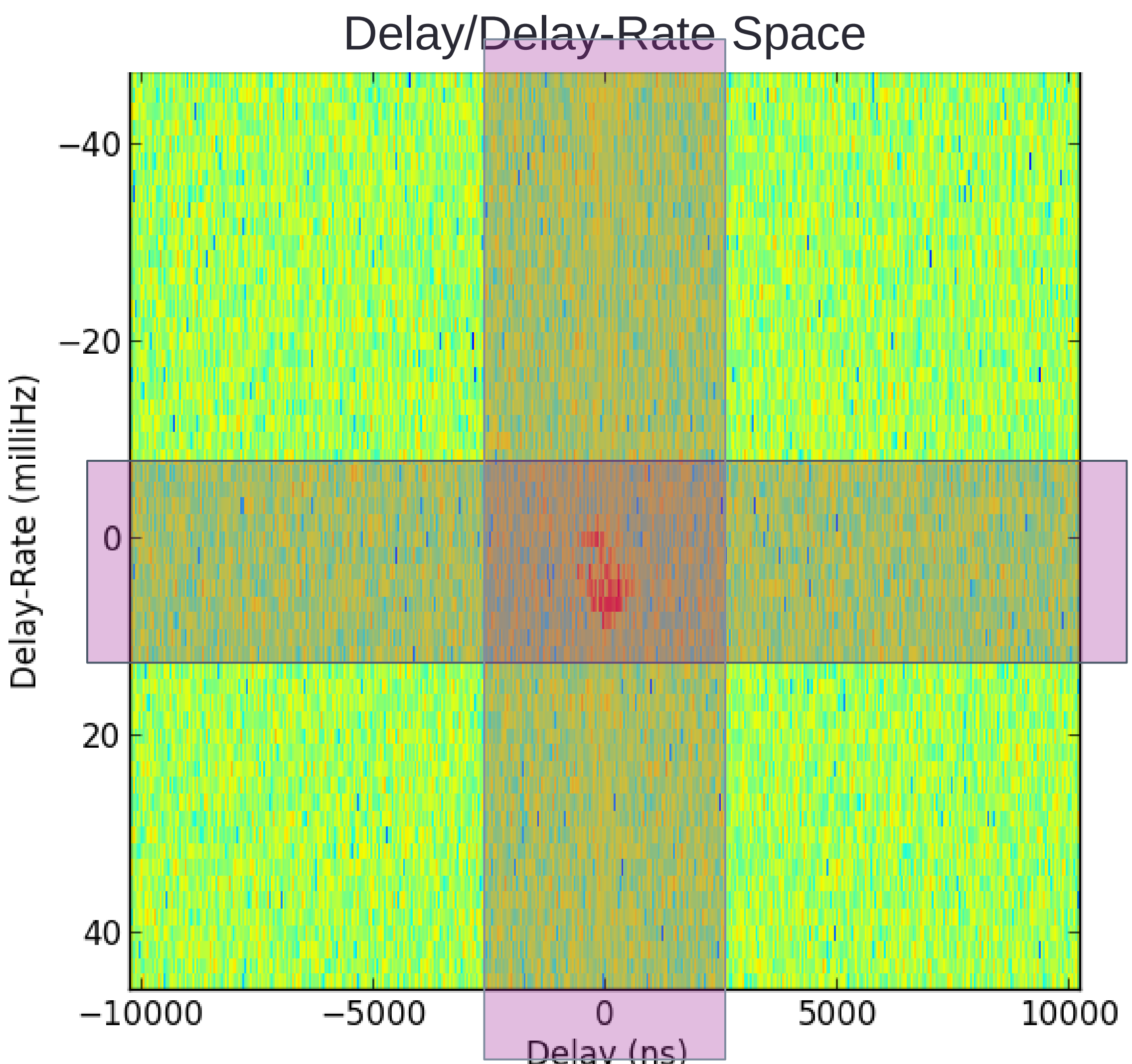
- Why are there fringes vs. frequency?
- *Baseline length (in wavelengths) is frequency dependent*

- Why are there fringes vs. time?
- *Drift scanning telescope means sources move through fringe pattern*

Delay/Delay-Rate Transforms (Parsons & Backer 2009)



Data "Compression"



Parsons, Liu, et al. (2013)

- DDR space divides into regions with delays/delay rates "on" and "off" sky
- Retain only "on" sky portions
- Be conservative with delays (they will be your $k_{||}$ modes)
- Potential for further benefit by weighting delay rates "on"-sky

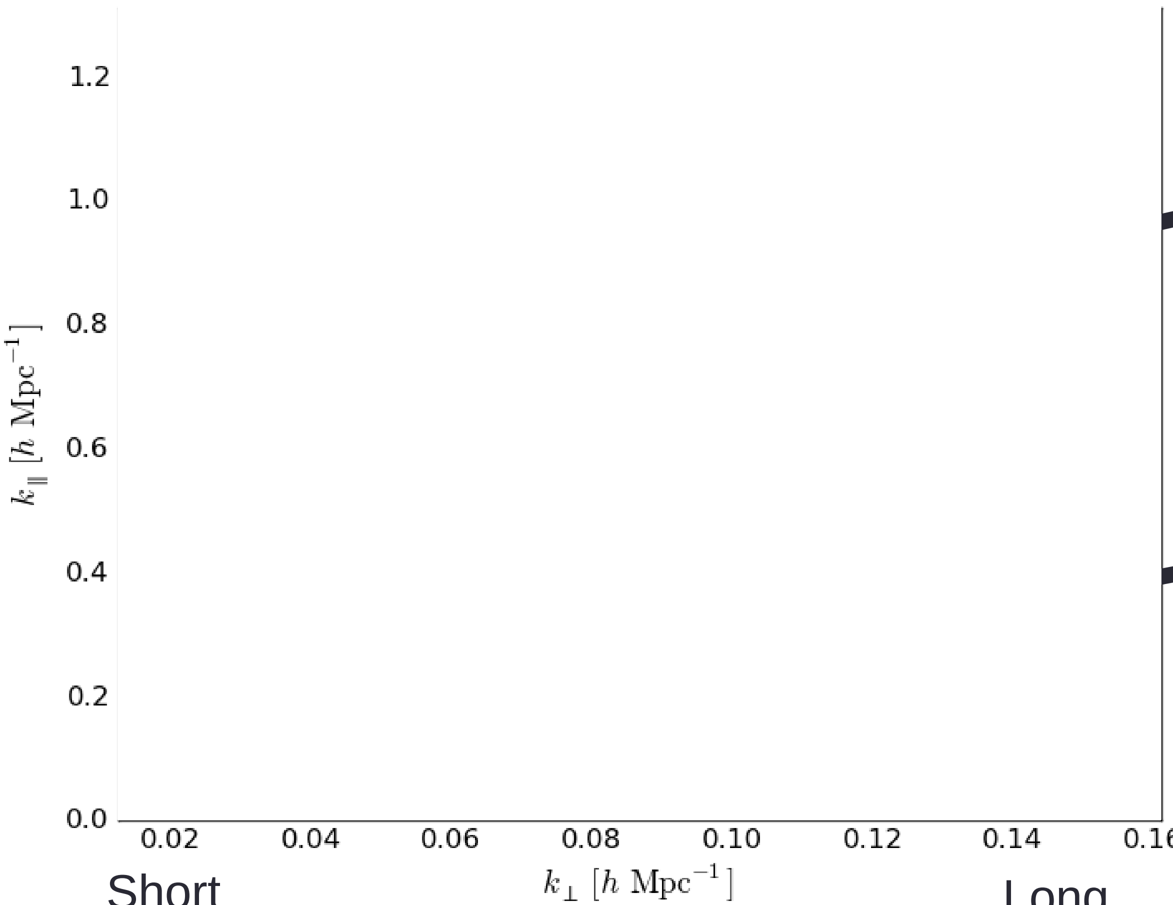
From Delay-Space to P(k)

$$P(k_{\|}, k_{\wedge}) \quad \mu \quad \left|\tilde{V}(t, |\vec{u}|)\right|^2$$

(Parsons, JCP, et al. 2012b)

$\Delta^2(k_{\|}, k_{\perp})$

Delay (FT of Frequency)



Short

Long

Baseline Length

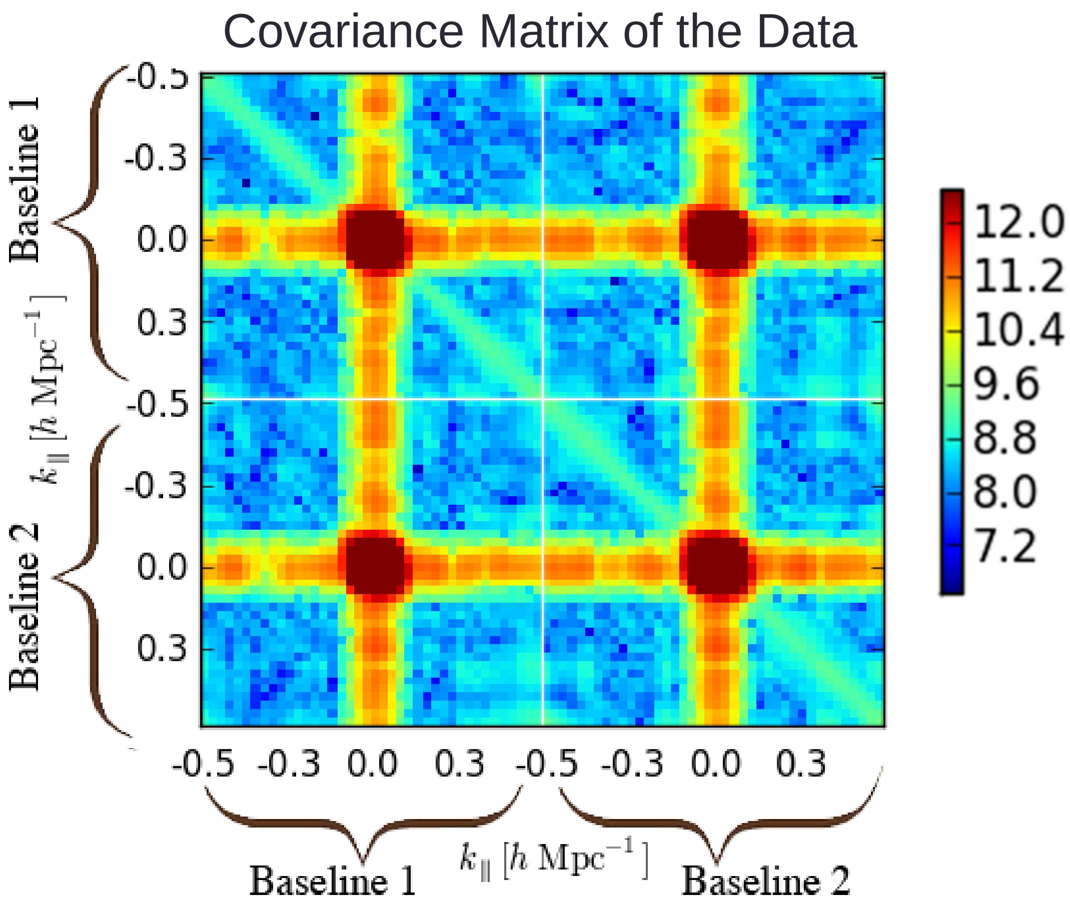
EoR "Window"

Foregrounds

Parsons, JCP, et al. 2012b
Datta et al. 2010
Vedantham et al. 2012
Morales et al. 2012
Trott et al. 2012

Cleaning up the Power Spectrum

$$P(k_{\parallel}, k_{\perp}) \propto \left| \tilde{V}(t, |\vec{u}|) \right|^2$$



- Cross-multiply redundant, but independent samples
  - Time (JCP, Parsons, et al. 2013)
  - Redundant baselines (Parsons, Liu, et al. 2013)

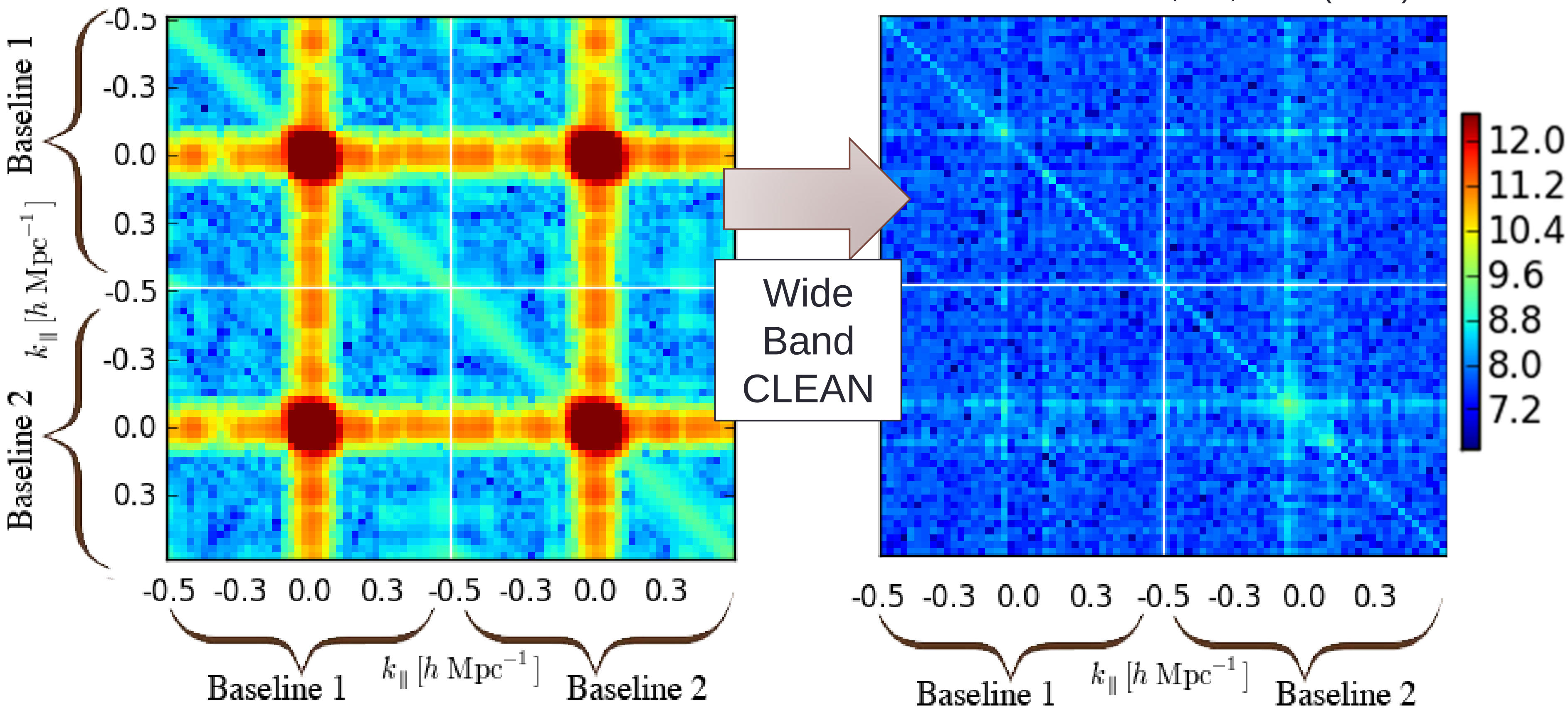
Parsons, Liu, et al. (2013)

Cleaning up the Power Spectrum

$$P(k_{\|}, k_{\perp}) \propto \left|\tilde{V}(t, |\vec{u}|)\right|^2$$

Covariance Matrix of the Data

Parsons, Liu, et al. (2013)



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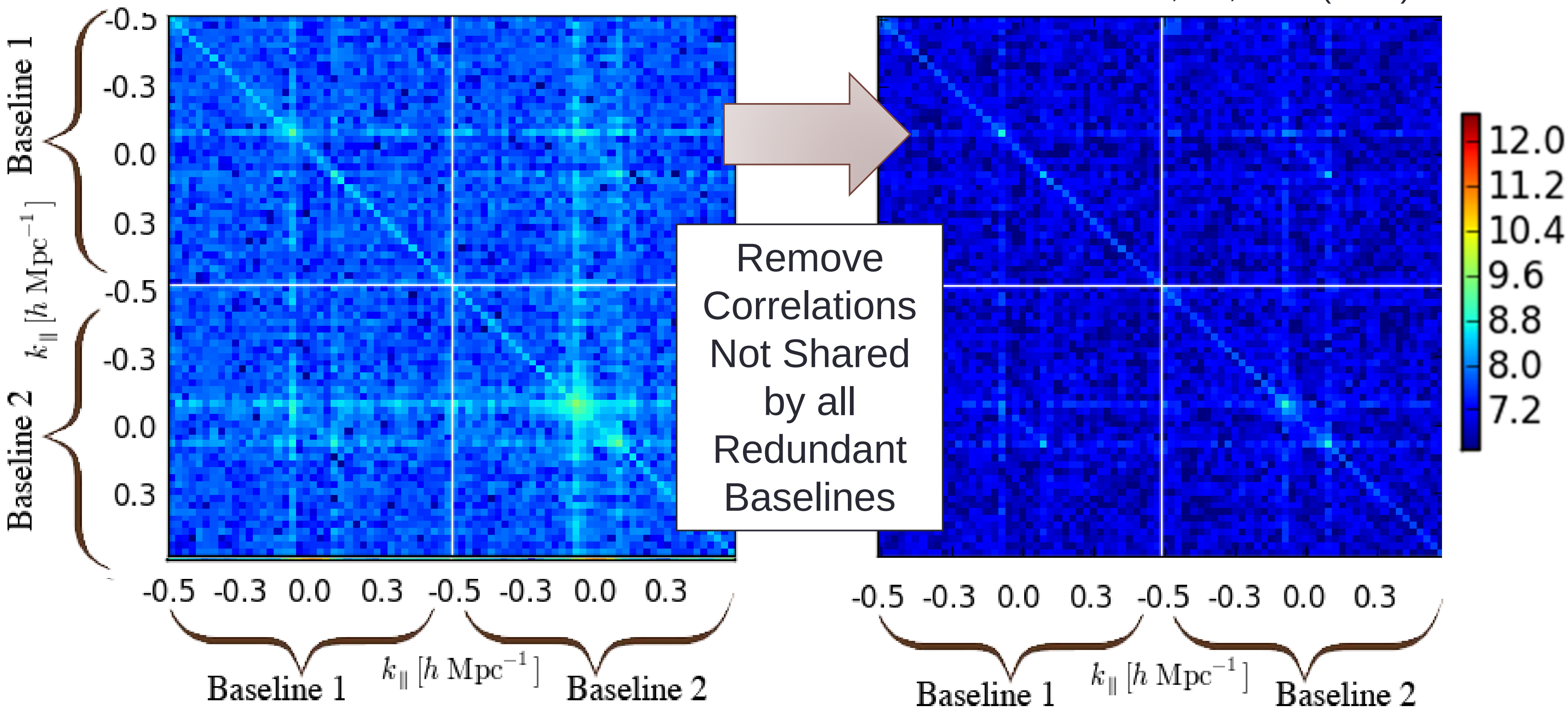


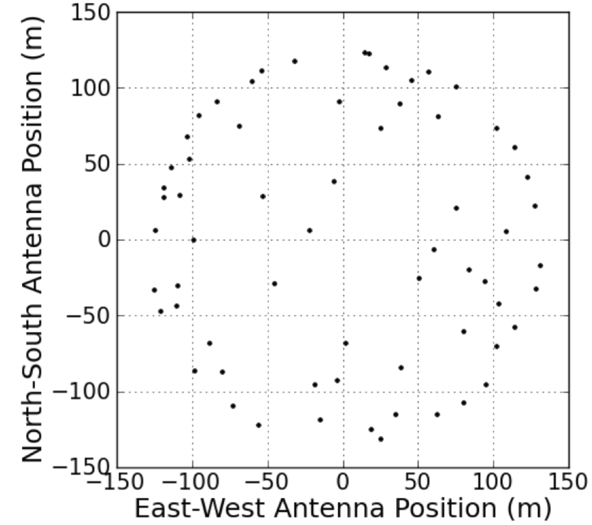
The PAPER Approach: Take Home Points

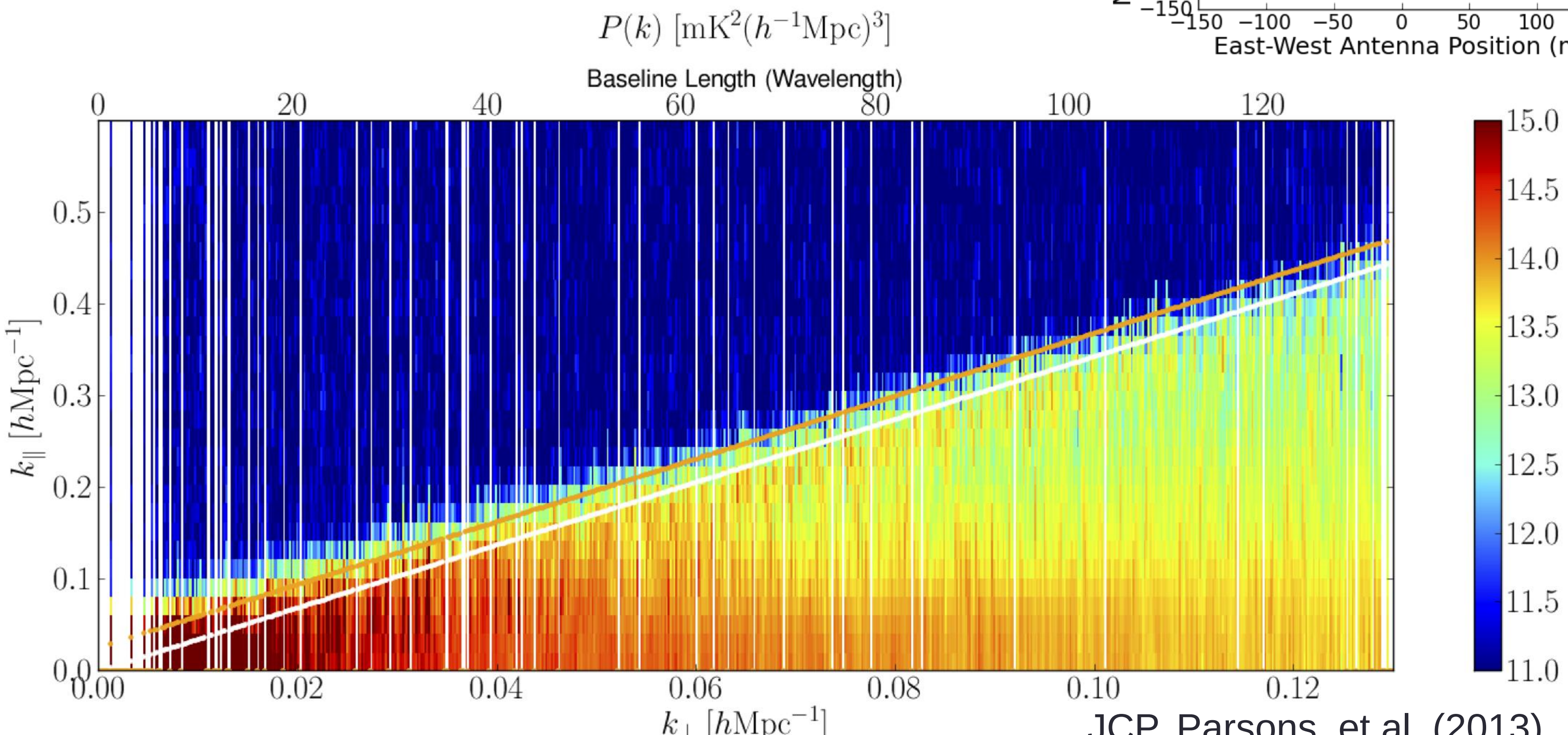
- Redundant baselines
  - Increase power spectrum sensitivity
  - Facilitate calibration
  - Separate residual systematics from sky-signal
- Wide-bandwidth invaluable for foreground CLEANing/modeling
- Forgoing modes within the horizon greatly reduces calibration challenge (see Adrian's talk this afternoon)

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
- Delay spectrum approach yields extremely clean EoR window

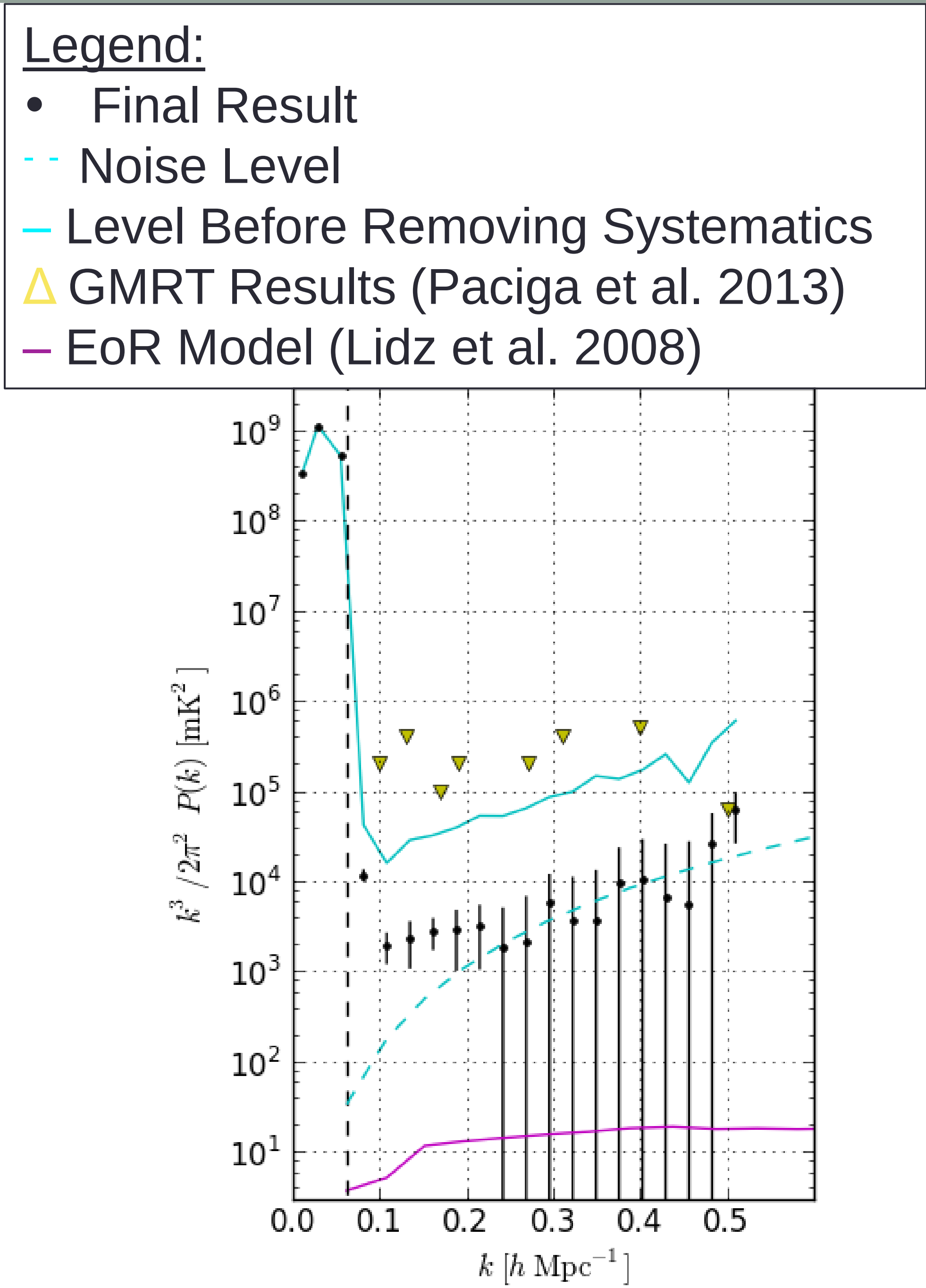




JCP, Parsons, et al. (2013)

Long Integration

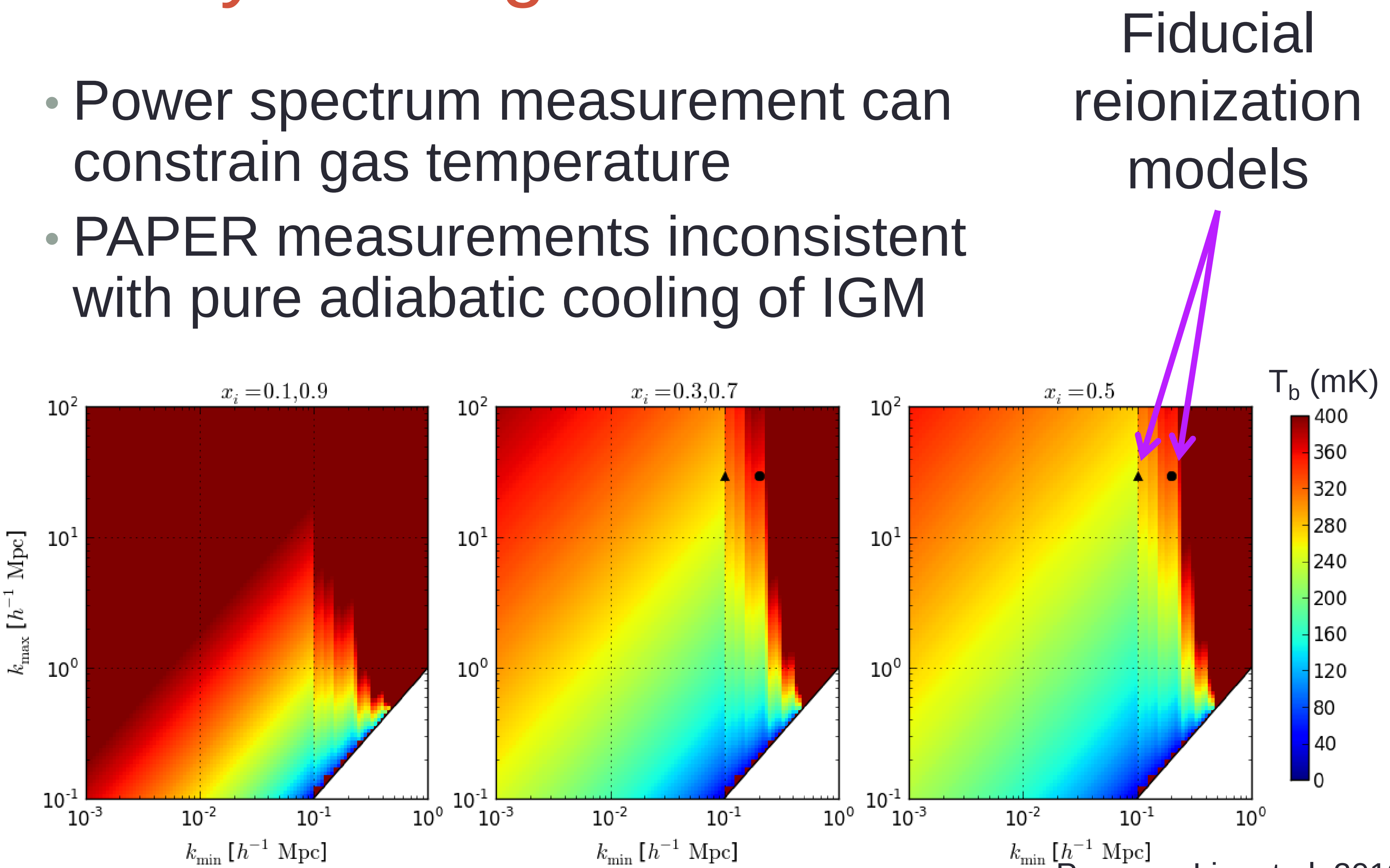
- 55 days of dual-polarization, 32-element “maximum redundancy” PAPER in SA
- 10 MHz band @ 164 MHz (z = 7.7)
- 3 baseline “types”
- Systematic limited at the lowest k’s



Parsons, Liu, et al. 2013

X-Ray Heating

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



Parsons, Liu, et al. 2013

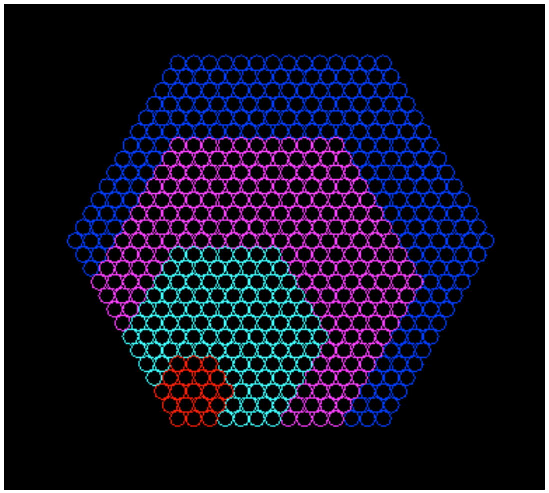
Conclusions

PAPER Prospects

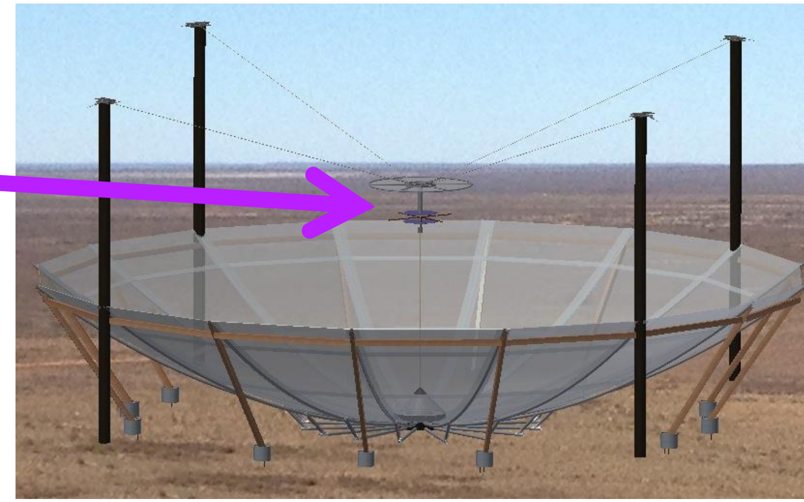
- New data on disk
  - ~50 more days of PSA-32 — x 1 - 2
  - ~120 days of PSA-64 — x 2+
- New deployments
  - PSA-128 beginning observations this fall — x 2+
- New techniques
  - "Aggressive" fringe rate filtering — x 3 - 5
    - Increases SNR
    - "Steers" beam N/S, can help with polarization leakage
  - More baselines / earth rotation synthesis — x 1.5 - 2
  - Multi-frequency and full-Stokes analyses

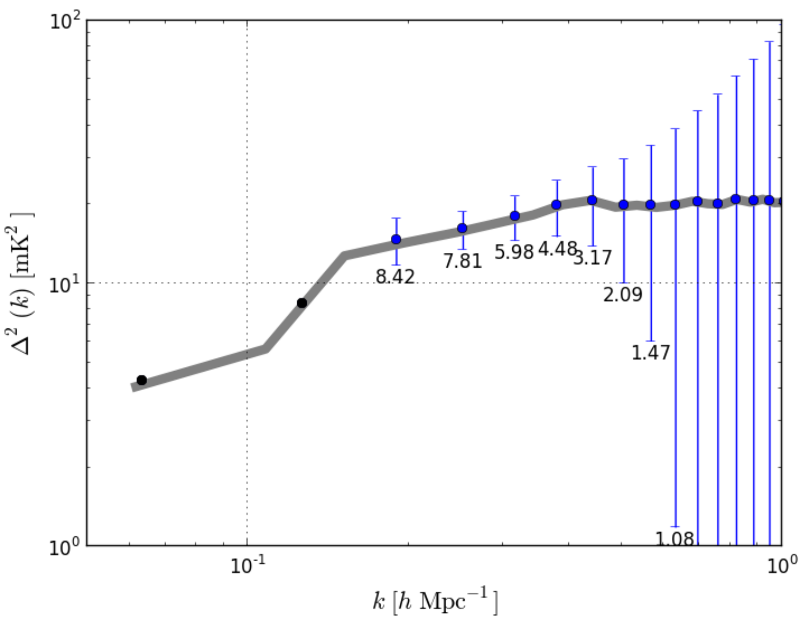
≈ x 20 - 80

HERA (Hydrogen Epoch of Reionization Array)



PAPER Dipole





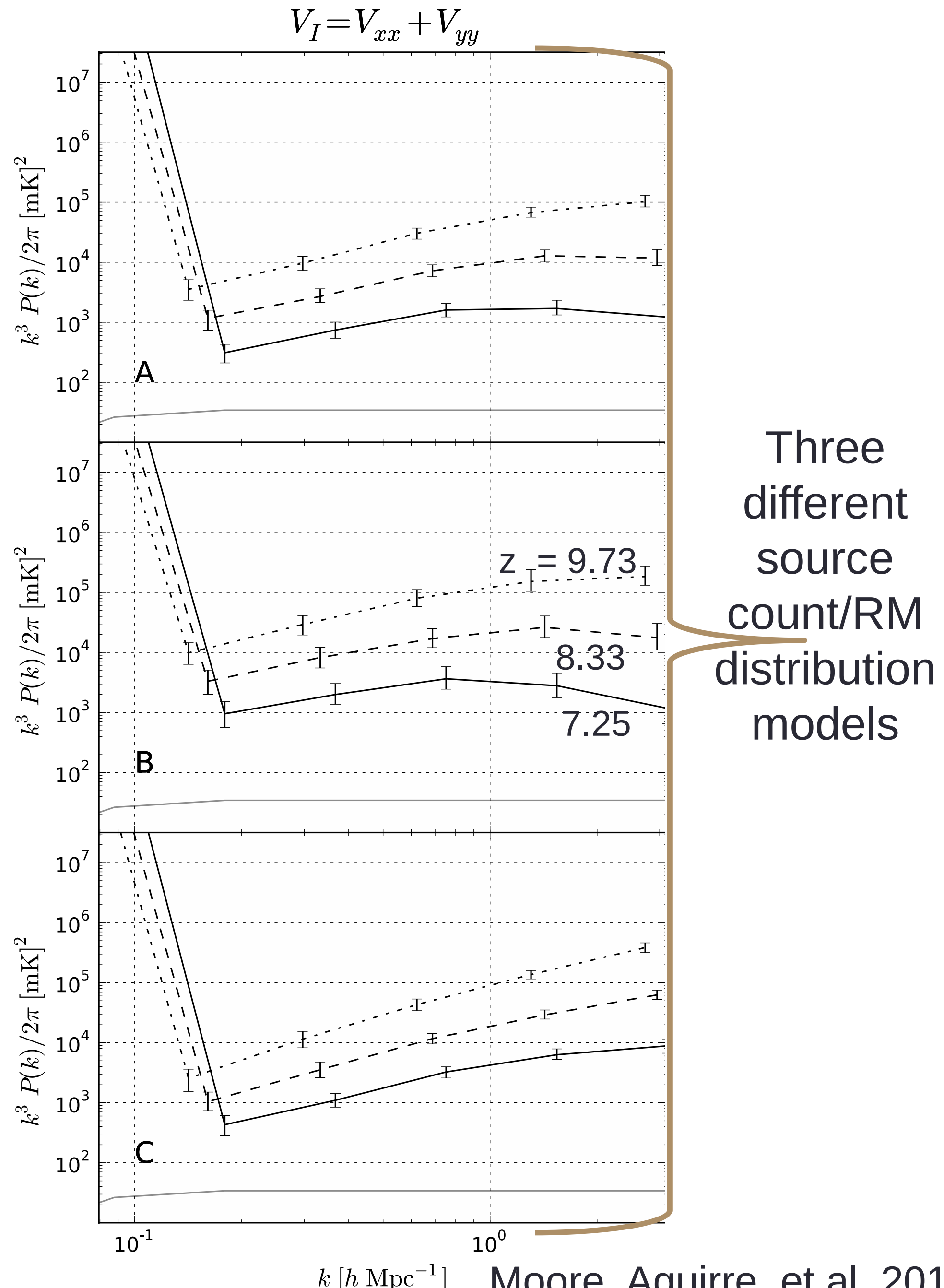
- 14m reflector design significantly boosts PAPER dipole collecting area, better polarization properties
- Short focal length keeps reflections to delays below k-modes of interest
- 547 element sensitivity (left) opens door to next generation EoR science
- Dense array allows for imaging and advanced foreground removal techniques

THANKS

Extra Slides

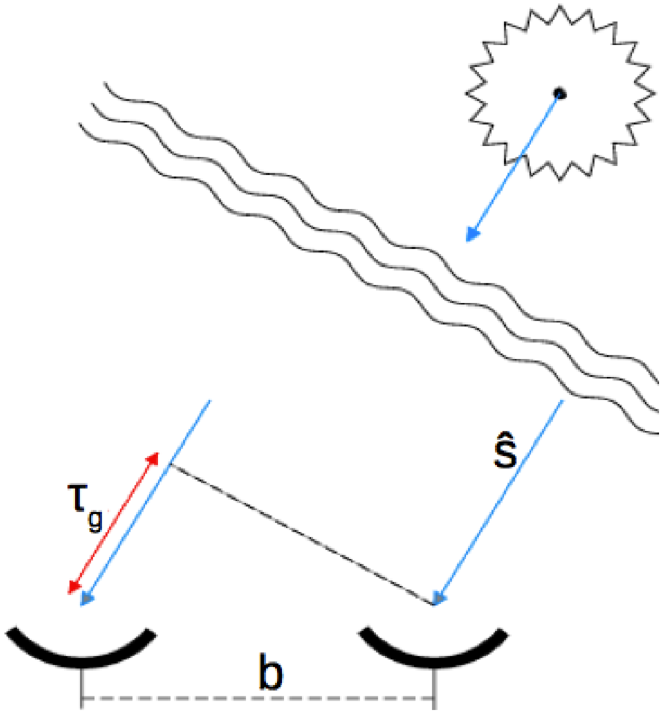
Polarization

- 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
- Some models approach levels already ruled out by PAPER observations/ Bernardi et al. 2013



Moore, Aguirre, et al. 2013

The Delay Transform



$$V(u,v) = \int dl\,dm\,A(l,m)\,I(l,m)\,e^{-2\pi i(ul+vm)}$$

$$\tau_g = \frac{\vec{b}\cdot\hat{s}}{c} = \frac{1}{c}(b_x l + b_y m)$$

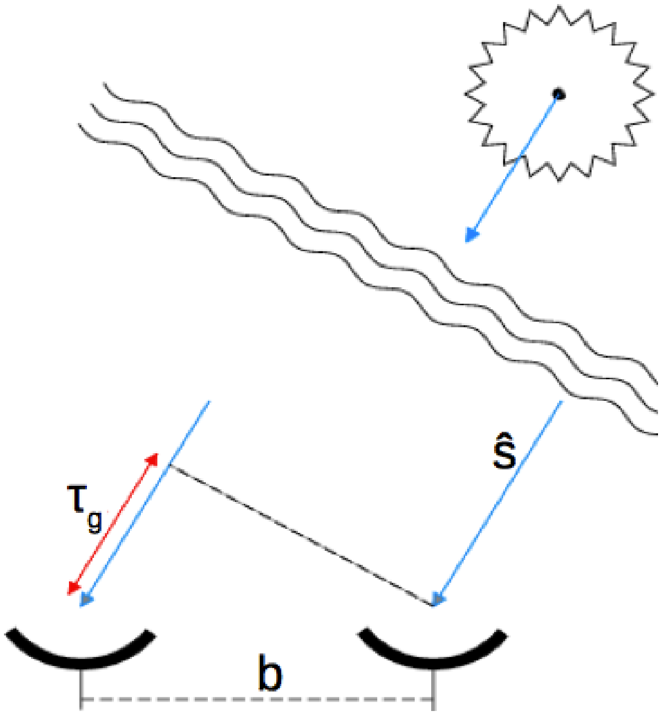
$$\vec{u} = (u,v) = \frac{\nu\vec{b}}{c}$$

$$V(\nu) = \int dl\,dm\,A(l,m,\nu)\,I(l,m,\nu)\,e^{-2\pi i\nu\tau_g}$$

$$\tilde{V}_b(\tau) = \int dl\,dm\,d\nu\,A(l,m,\nu)\,I(l,m,\nu)\,e^{-2\pi i\nu(\tau_g-\tau)}$$

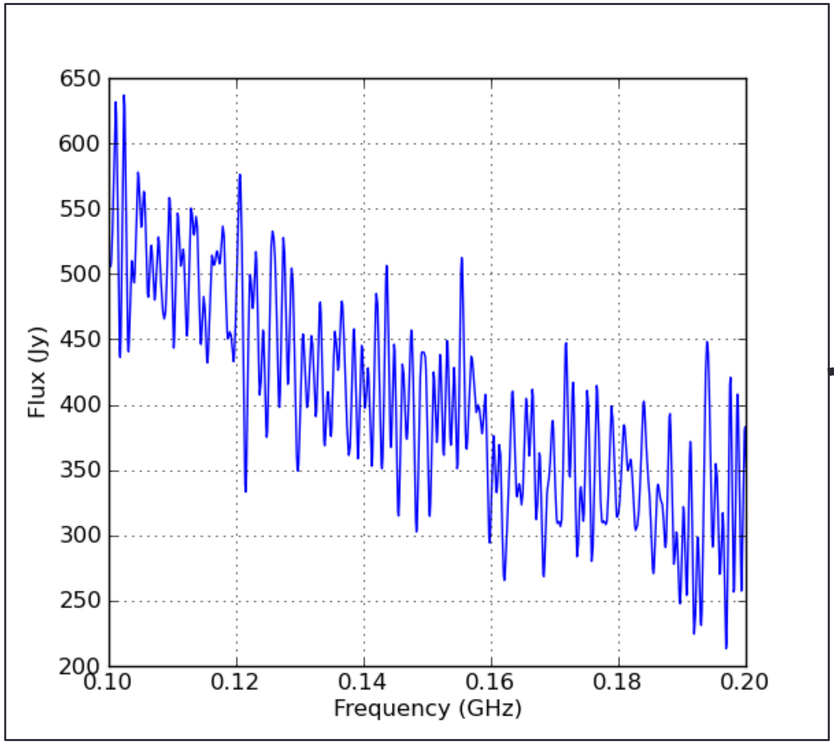
$$\tilde{V}_b(\tau) = \int dl\,dm\left[\tilde{A}(l,m,\tau) * \tilde{I}(l,m,\tau) * \delta_D(\tau_g-\tau)\right]$$

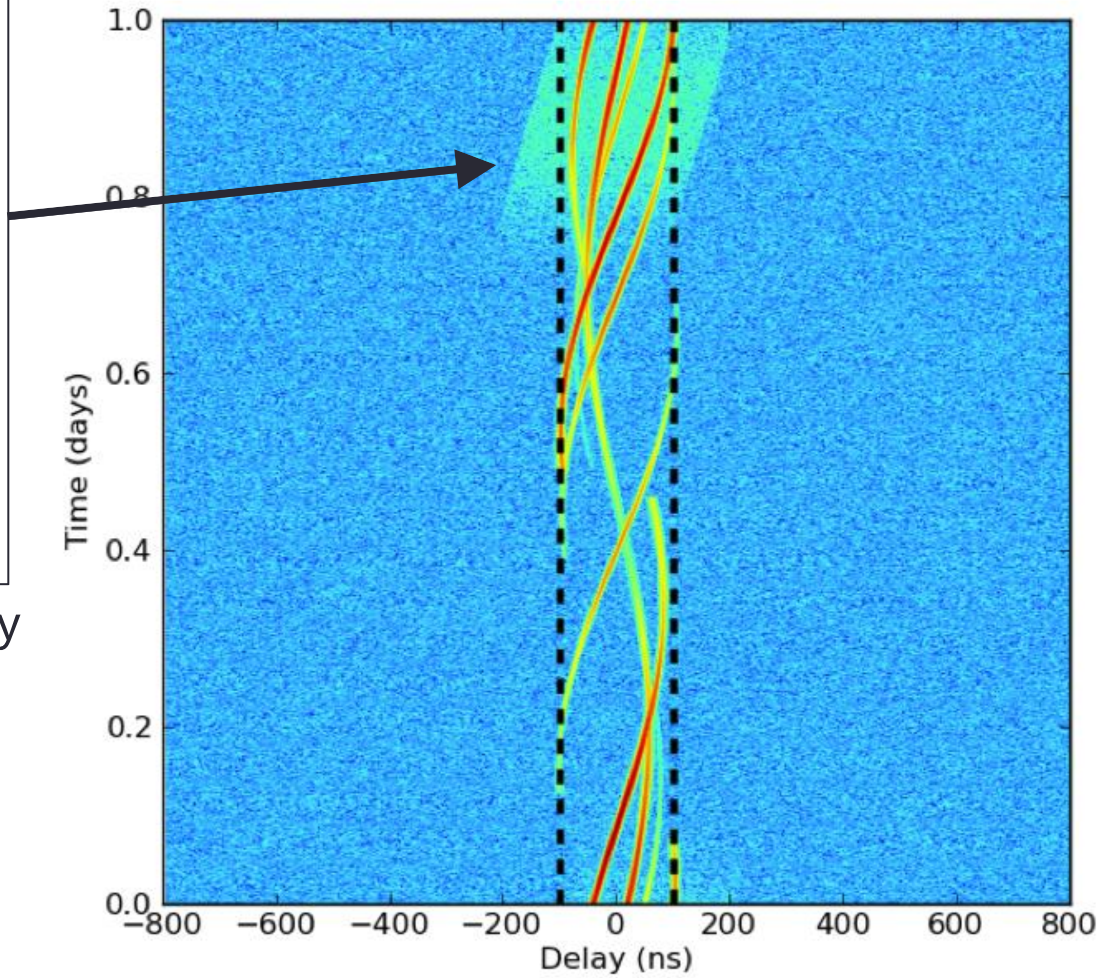
The Delay Transform



- Fourier transform vs. frequency of one baseline is *delay transform*
- Sources on the sky map to a geometric delay, convolved with a kernel that is the FT of their spectrum
- 1D per baseline “imaging”

Avoiding Foregrounds in Delay Space

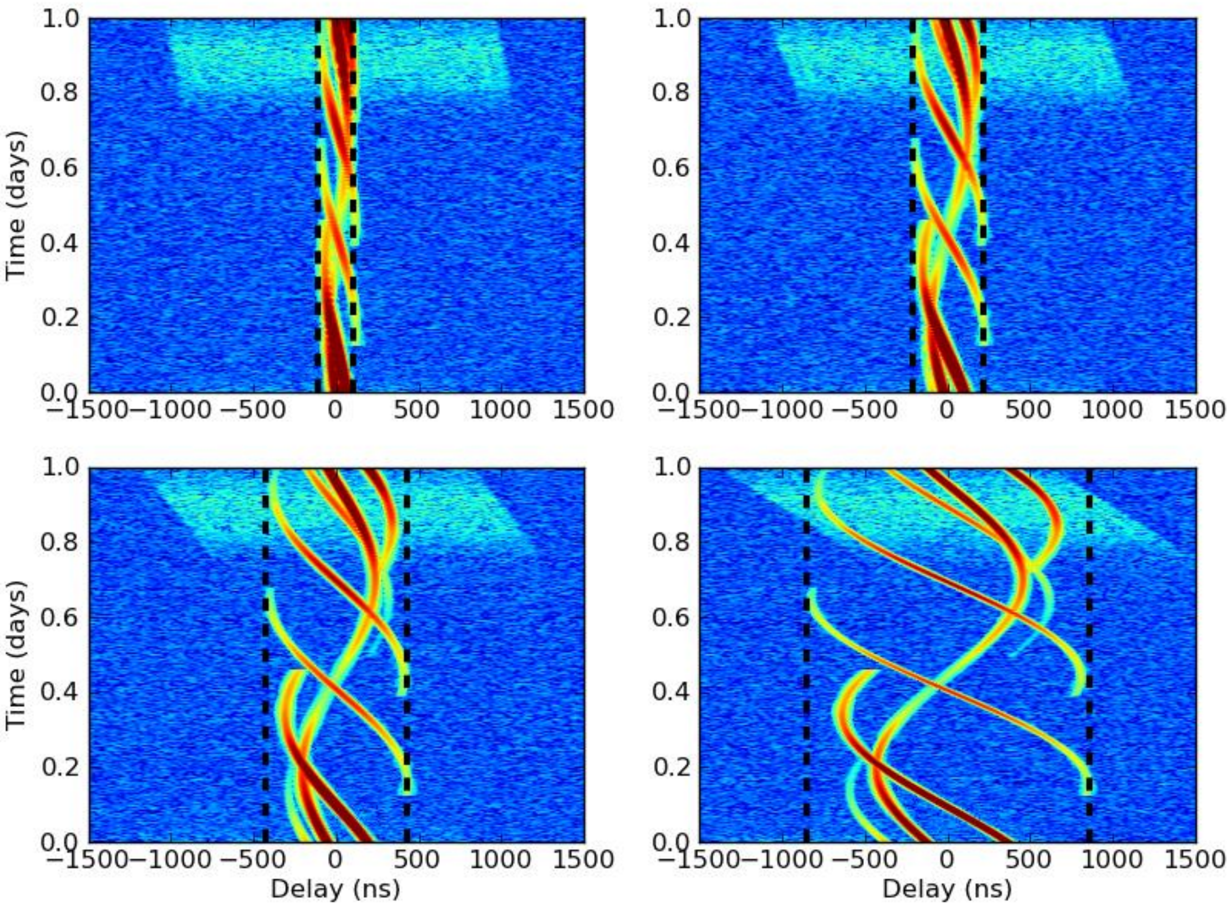




- Horizon imposes **maximum** delay
- Smooth spectrum sources stay within this boundary
- Un-smooth sources have sidelobes that extend beyond horizon

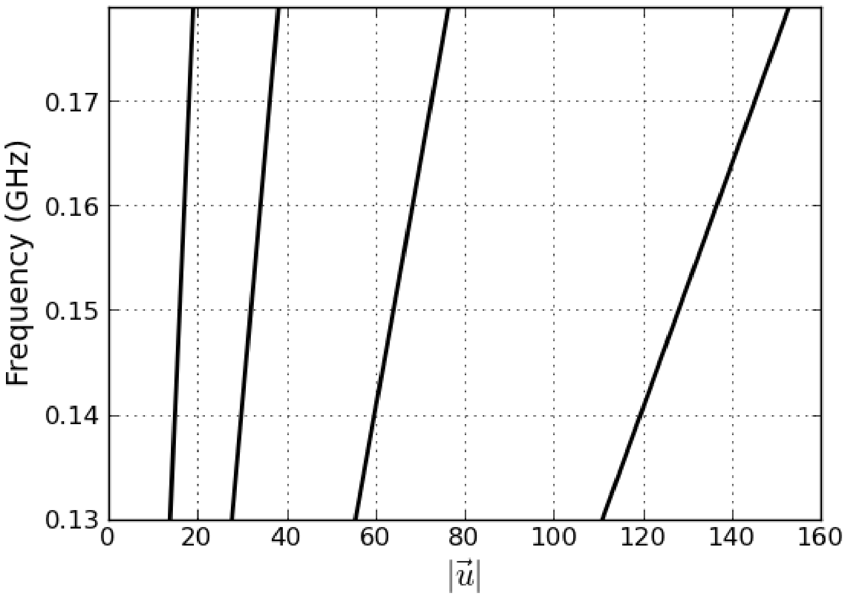
Avoiding Foregrounds in Delay Space II

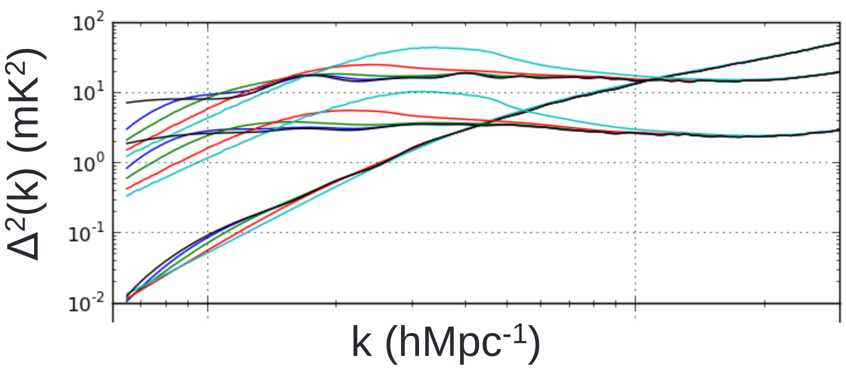
- Maximum delay is baseline length dependent
- Shorter baselines can access more of 21cm signal
- Free to maximize number of short baselines!



Parsons, JP, et al. (2012b)

Mapping Delay Space to k-space



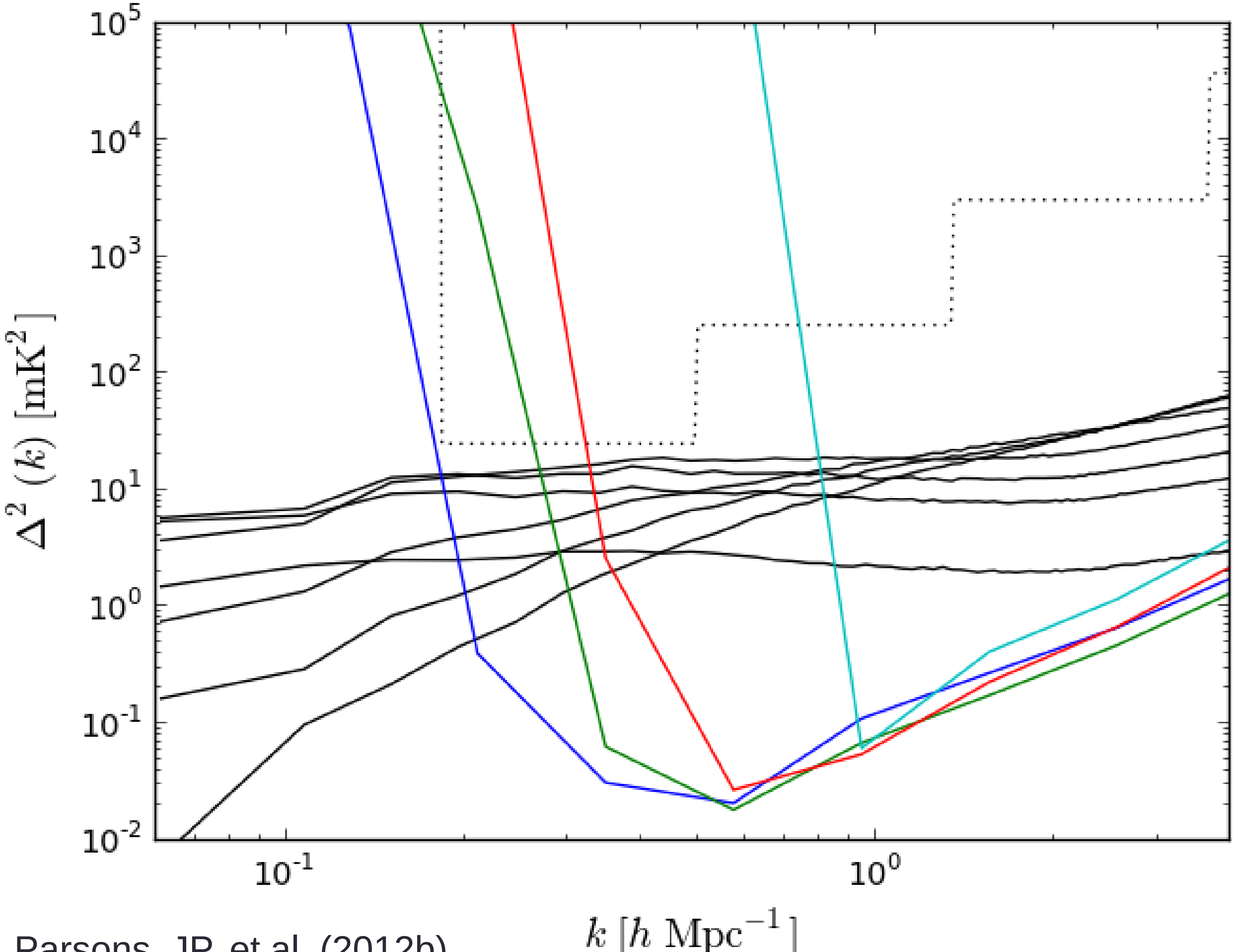


Effect of mode mixing on power spectra measured 16λ, 32λ, 64λ, 128λ baseline

- Delay-space is not a perfect match to cosmological k-space
  - A baseline samples different transverse modes as a function of frequency
- How bad is the effect of "mode-mixing"?
- With short baselines and small-bandwidths, you can get away with it!
  - Short baselines already desirable for foreground isolation
  - Small-ish (8 MHz) bandwidths already necessitated by cosmology

Parsons, JP, et al. (2012b)

Delay Spectrum Technique: Predictions



Parsons, JP, et al. (2012b)

Legend

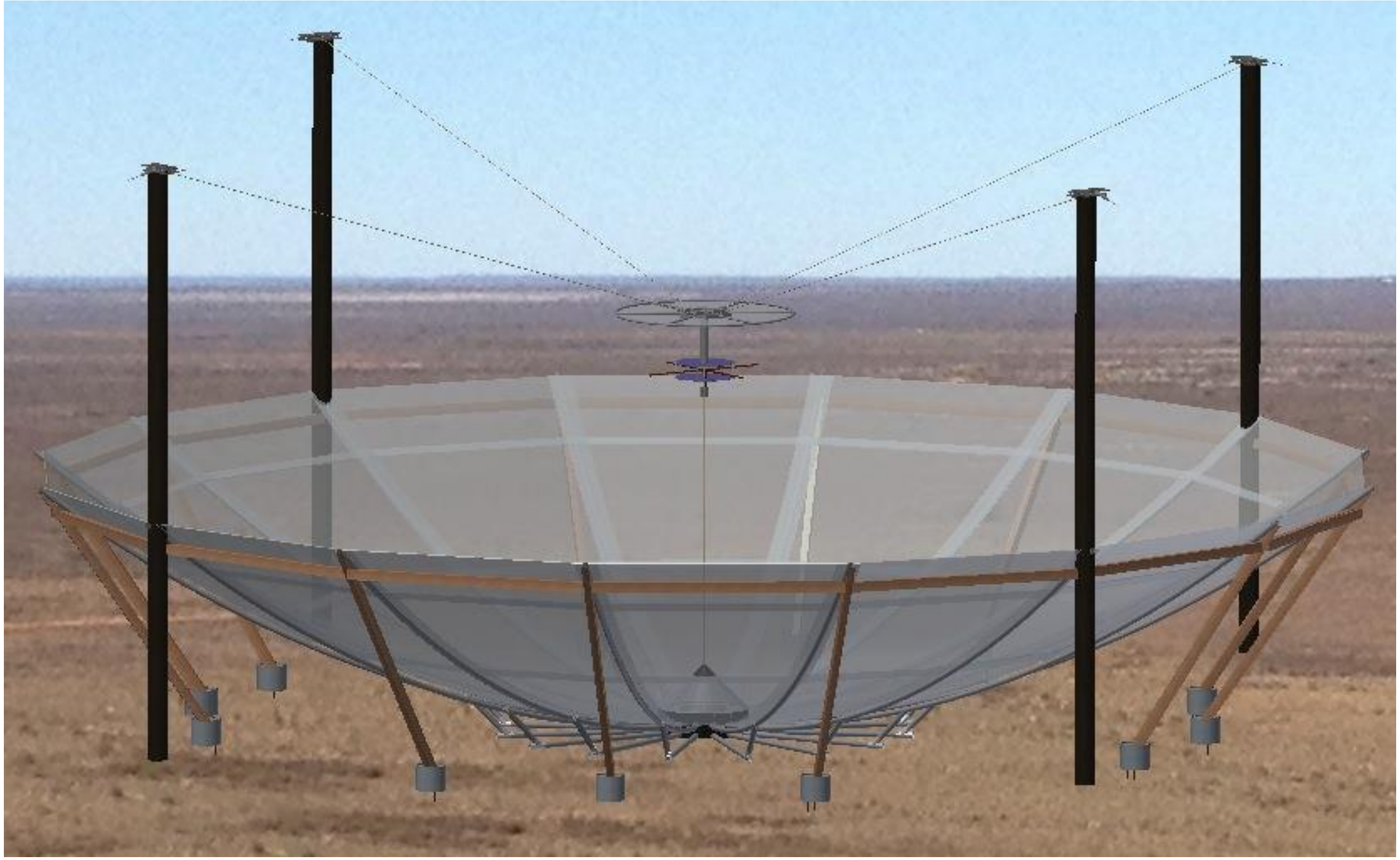
- Dotted: PAPER-128 sensitivity
- Solid black: Lidz et al. 2008 EoR power specta vs. <x_i>
- Solid colors: Maximum k-mode foreground contamination for 16λ, 32λ, 64λ, 128λ baseline

HERA-576 Parameters

Parameter	Value	Units	Description
N	576		Number of Antennas
d	14	m	Antenna Diameter
f/d	0.32		Focal Length (fractional)
Ω_{P}	0.026	sr	Field of View (power)
Ω_{PP}	0.013	sr	Field of View (power^2)
Ω_{eff}	0.052	sr	Field of View (sensitivity)
B_{samp}	0–250	MHz	Sampled Frequency Range
B_{corr}	100	MHz	Correlated Bandwidth
Config.	24×24		Square Grid Antenna Configuration
f/f_0	$1.5 \cdot 10^5$		Redundancy Metric (Parsons et al. 2012a)
A	0.09	km^2	Total Collecting Area
θ	15	arcmin	Angular Resolution (150 MHz)
b_{max}	500	m	Maximum Baseline
T_{sys}	500	K	System Temperature
t_{obs}	120	days	Observing Time
t_{day}	6	hrs	Observing Time Per Day
Δ^2_{N}	1.6	mK^2	Expected Noise Level ($k = 0.2h$ Mpc^{-1})
SNR_{21}	11.7σ		Expected Detection Significance (Lidz et al. 2008, $x_i = 0.5$, 150 MHz)

The HERA Dish

- 14m diameter, 4.5m focal height, zenith-pointing
- Confines reflections to delays < 50 ns, ensuring smooth frequency response for foreground suppression
- Dish diameter minimizes cost for sensitivity, given the foreground removal specification



HERA Signal Flow

- Short analog signal chain minimizes reflection timescales
- New CASPER board digitizes 0-250 MHz, hosts correlator F-engine, transmits selected 100-MHz via 10GbE optical links
- 42 GPU-accelerated servers act as correlator X-engines (night) and data compression engines (daytime)