Closure phase delay spectrum
A new approach to the first detection of the HI 21cm signal from Cosmic Reionization

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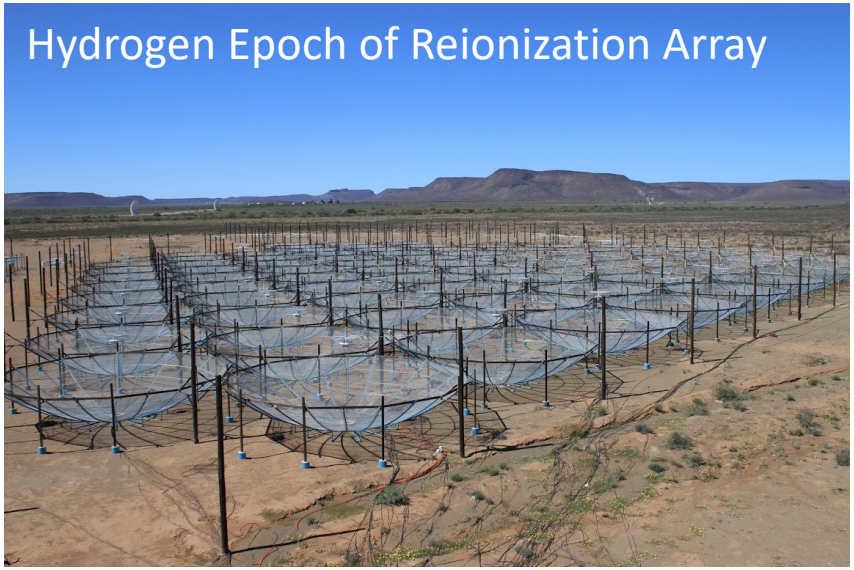
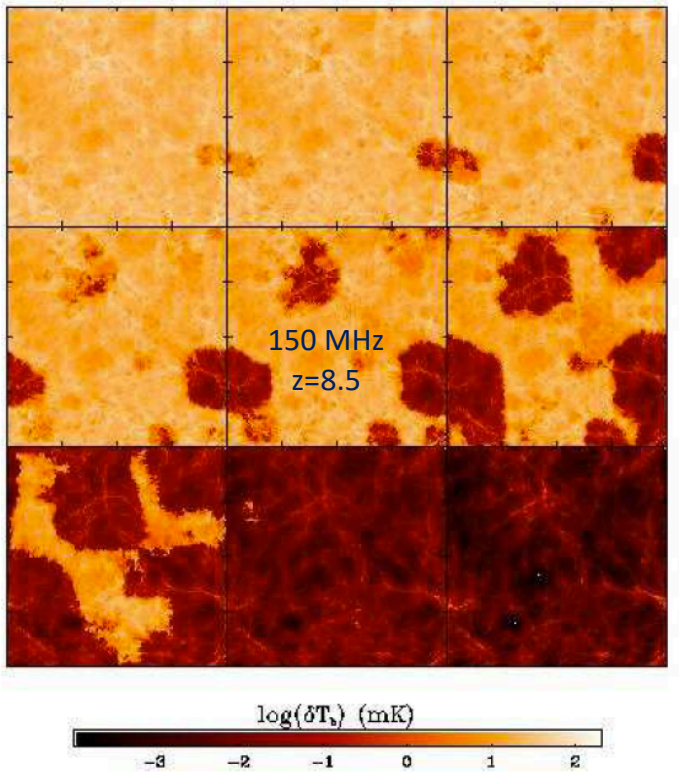




Low frequency: need DNR ~ 10^5

Closure phase: true sky-observable independent of antenna-based gains

INTENSITY DISTRIBUTION ACROSS THE CYGNUS AND CASSIOPEIA SOURCES

R. C. JENNISON 1956

Jodrell Bank Experimental Station, University of Manchester, England

Measurements of the angular distribution of intensity across the intense discrete sources in Cassiopeia and Cygnus have previously been handicapped by lack of knowledge of the phase of the Fourier transform at very long aerial spacings. The technical difficulties of measuring the phase of the transform and also of calibrating the absolute amplitude have been solved by a new technique involving three stations. This method enables the phase to be measured relative to a frame of reference within the source and obviates the need for retaining the phase angles accurately constant on the removal of one of the aerial systems to a new site. The phase measurement is not limited to observations of the central fringe, and useful measurements may be made on all the fringes contained within the aerial polar diagrams.

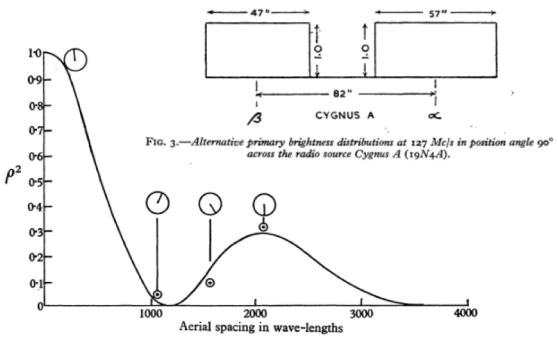
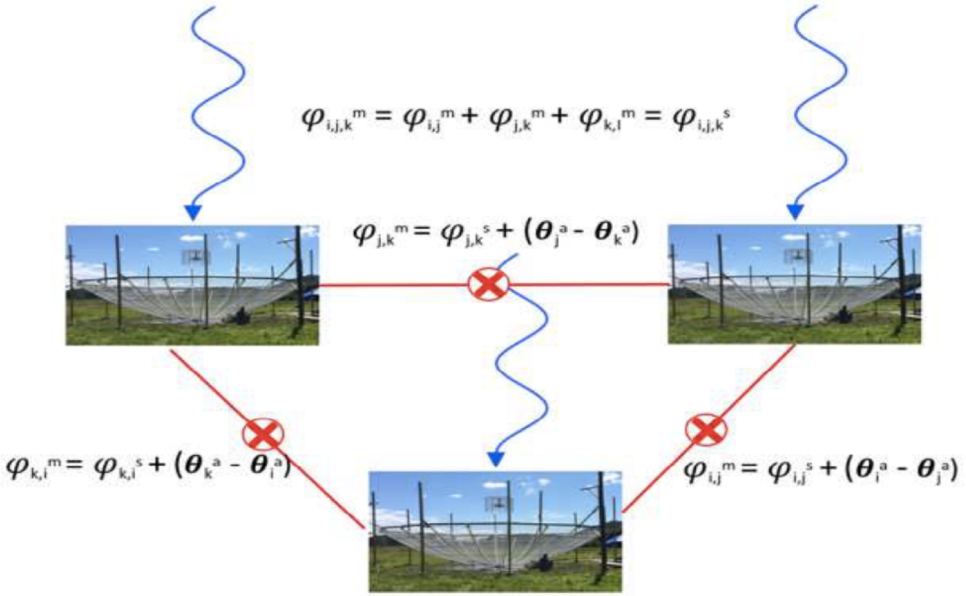


Fig. 3.—*Alternative primary brightness distributions at 127 Mc/s in position angle 90° across the radio source Cygnus A (19N4A).*

Fig. 2. The radio source in Cygnus, variation with base-line of the square of the amplitude of the Fourier transform (full curve) and phase angle, or argument of the Fourier integral (clock faces).



Triple Product or Bispectrum

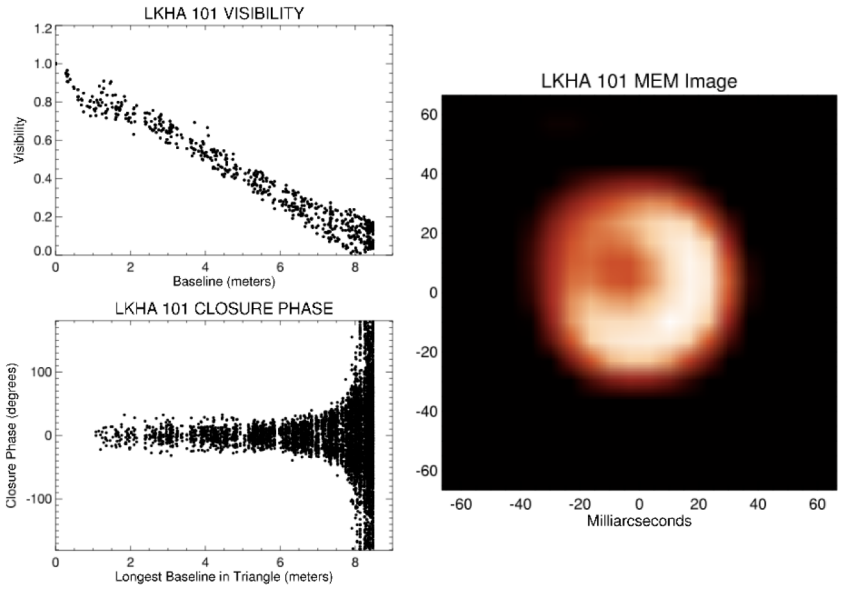
$$V_{i,j}^{m} = G_i G_j^{*} V_{i,j}^{s} = a_i e^{i\theta_i} a_j e^{-i\theta_j} A_{i,j}^{s} e^{i\phi_{i,j}^{s}} \quad + \text{noise}$$

$$C_{i,j,k}^{m} = V_{i,j}^{m} V_{j,k}^{m} V_{k,i}^{m}$$

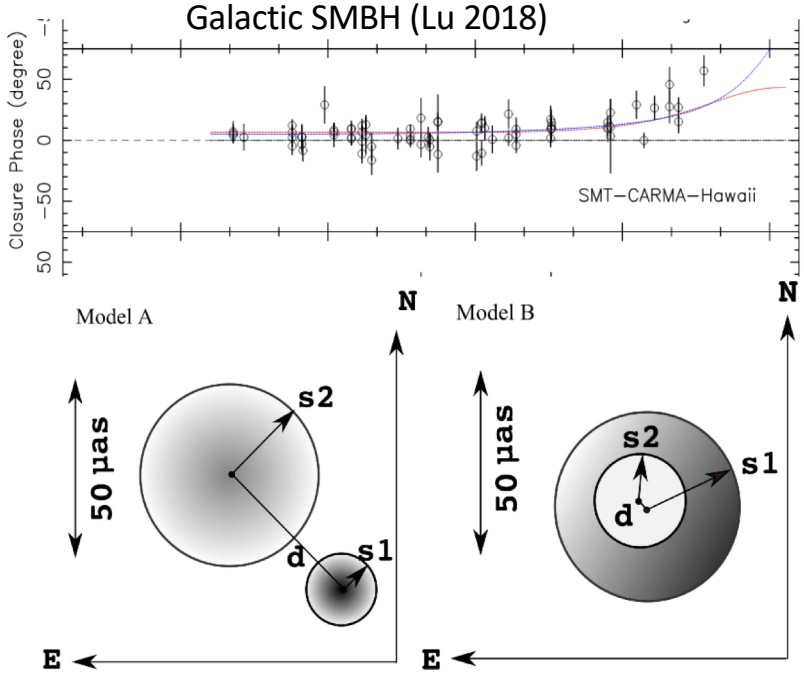
$$\boxed{\phi_{i,j,k}^{m} = \phi_{i,j,k}^{s} \quad + \text{noise}}$$

Closure Phase: determine source structure with an interferometer in conditions when phase calibration is difficult

Optical Interferometry and aperture masking: stellar surfaces (Baldwin 1976; Monnier 2006)



Submm VLBI: EHT and size of the Galactic SMBH (Lu 2018)

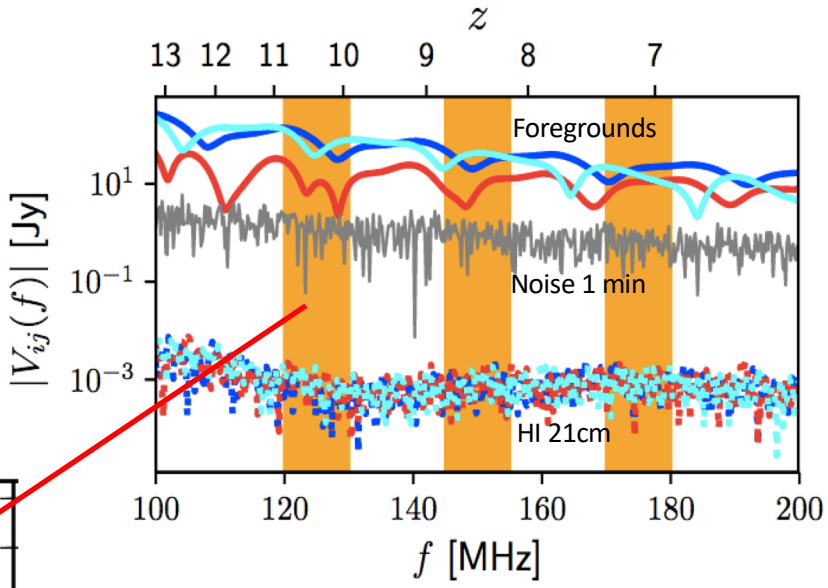


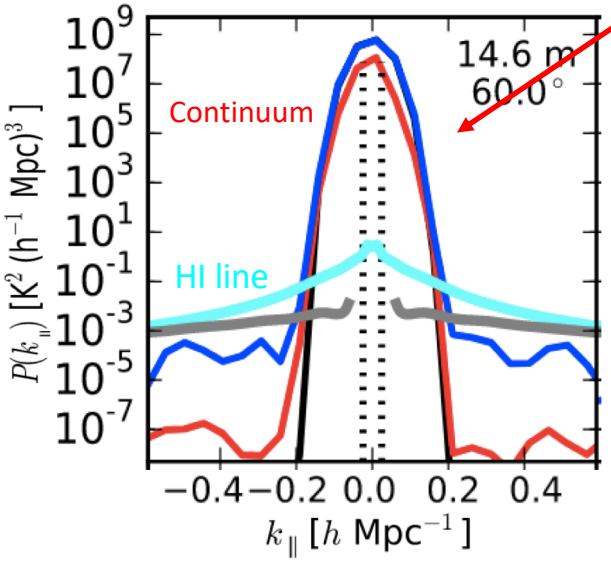
Can we exploit Closure phase in the context HI 21cm cosmology?

Delay spectrum: review

Parsons et al. 2014

- Foregrounds ~ 10^5 x HI
- Freq = LoS distance = k^{-1}
- $F(V_f)^2 \rightarrow P(k)$
- Spectral structure is smooth for foregrounds; noise-like for HI => separate in PS domain at large k



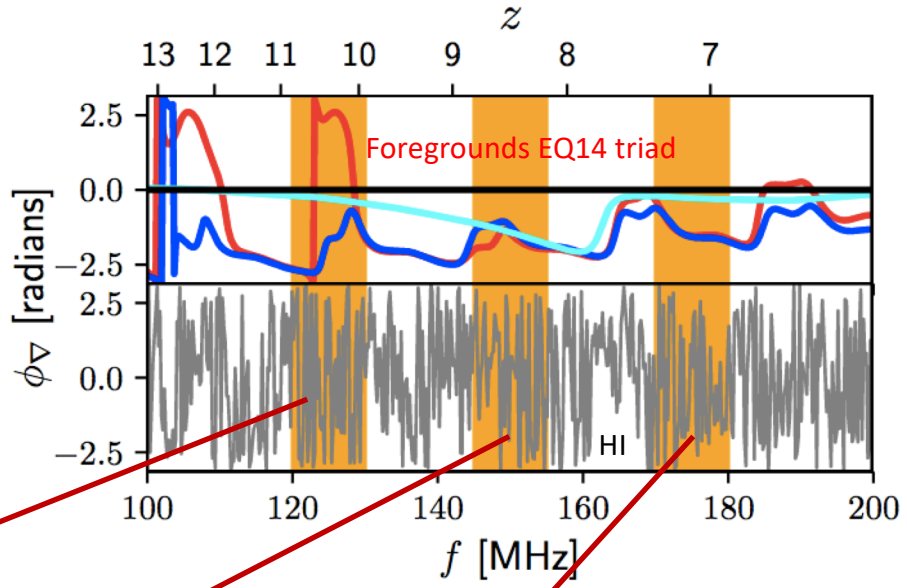


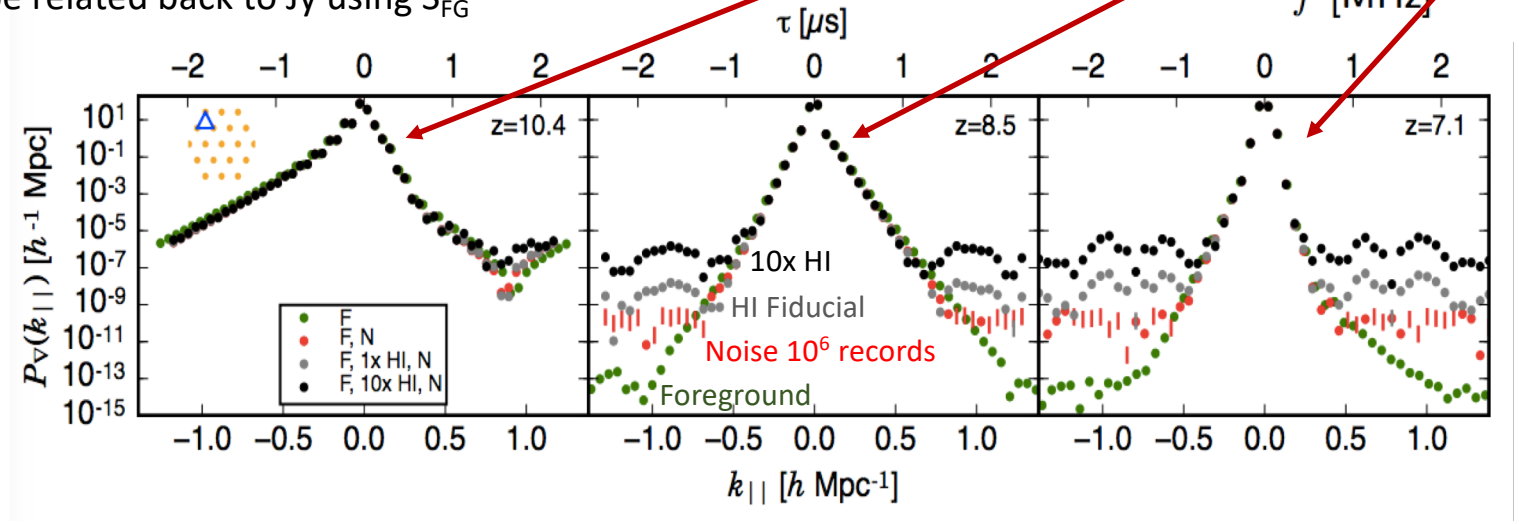
Closure Phase Delay Power Spectrum

Method using PRISim simulations

Thyagarajan et al. PRL, 2018

- Goal: determine *statistics* of HI signal in frequency, not specific spatial structure
- Required PS DNR ~ 10^{10}
- 'Core' of PS due to foreground broadens with more structure FG spec.
- Units? Closure PS ~ measure of S_{FG}/S_{HI}, and hence can be related back to Jy using S_{FG}

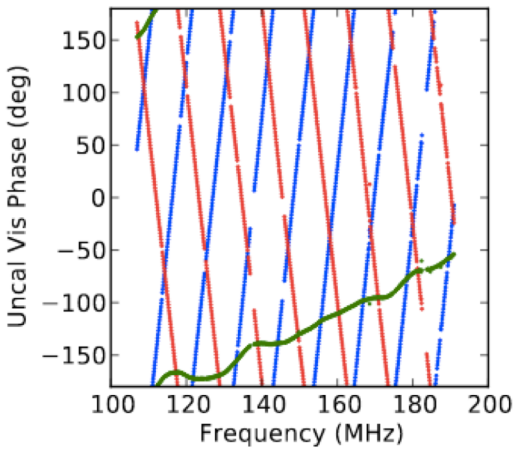


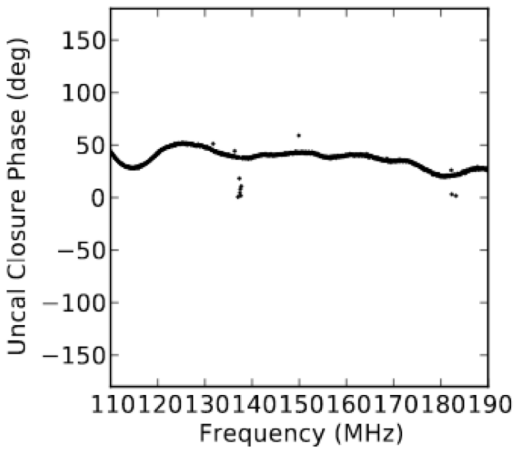


HERA Data of Closure phase: independent of antenna-based gain calibration

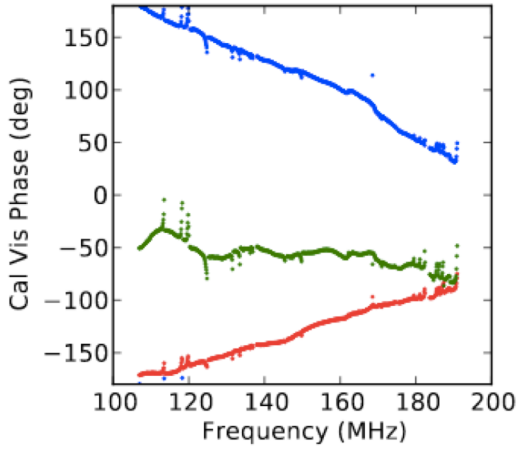
Carilli et al. Radio Science, 2017

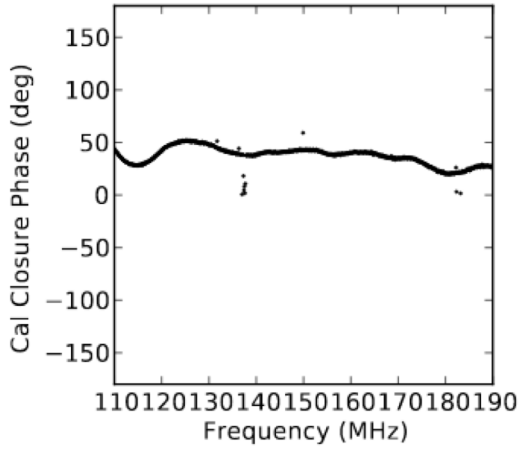
Galactic Center: uncalibrated



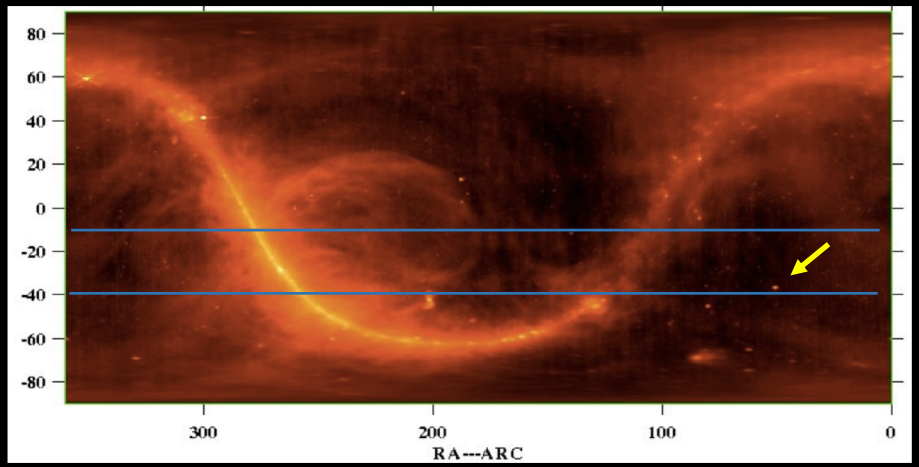


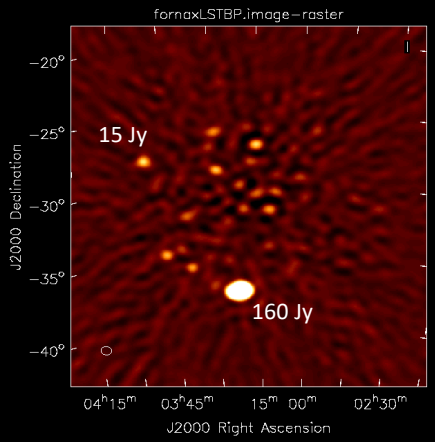
Galactic Center: calibrated

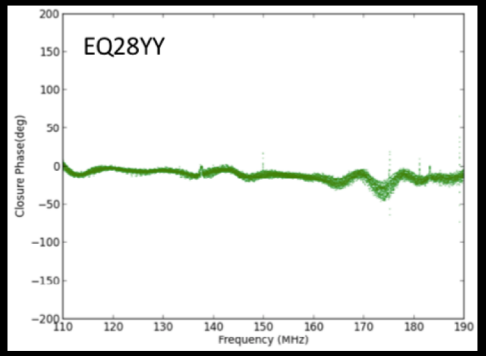




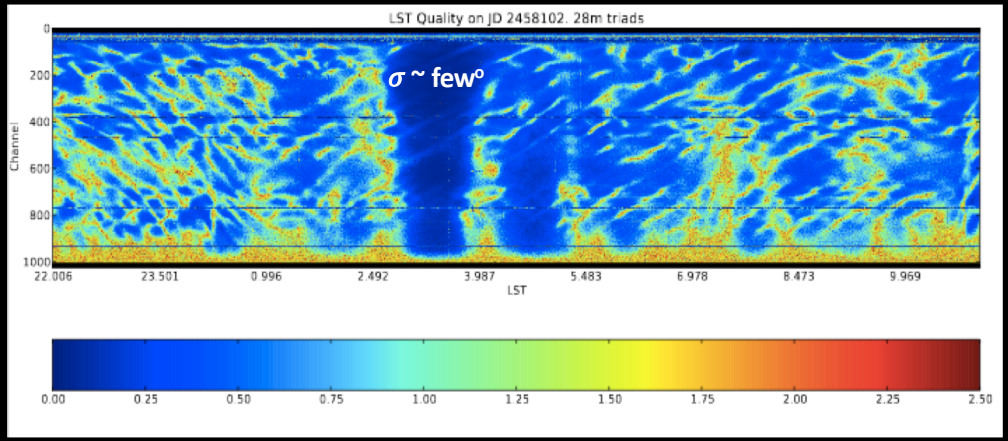
Fornax A: a Gift



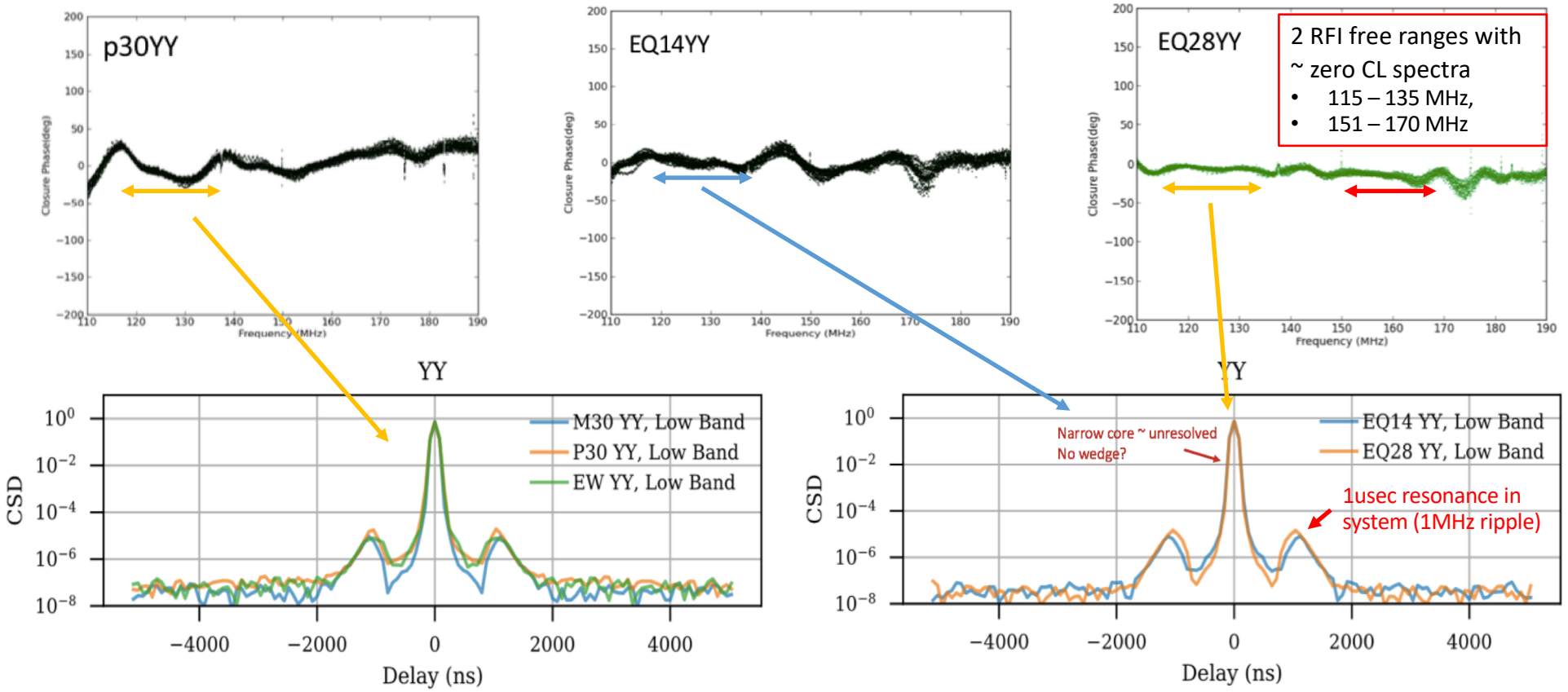




- Dominant point source: $\theta_{cl} \rightarrow 0^o$
- Middle of Cold patch: dec = -37º => 20% PB => 160 Jy (not 700 Jy)
- Improves redundancy
- Easier modeling for PS analysis
- Narrow 'continuum core' of PS

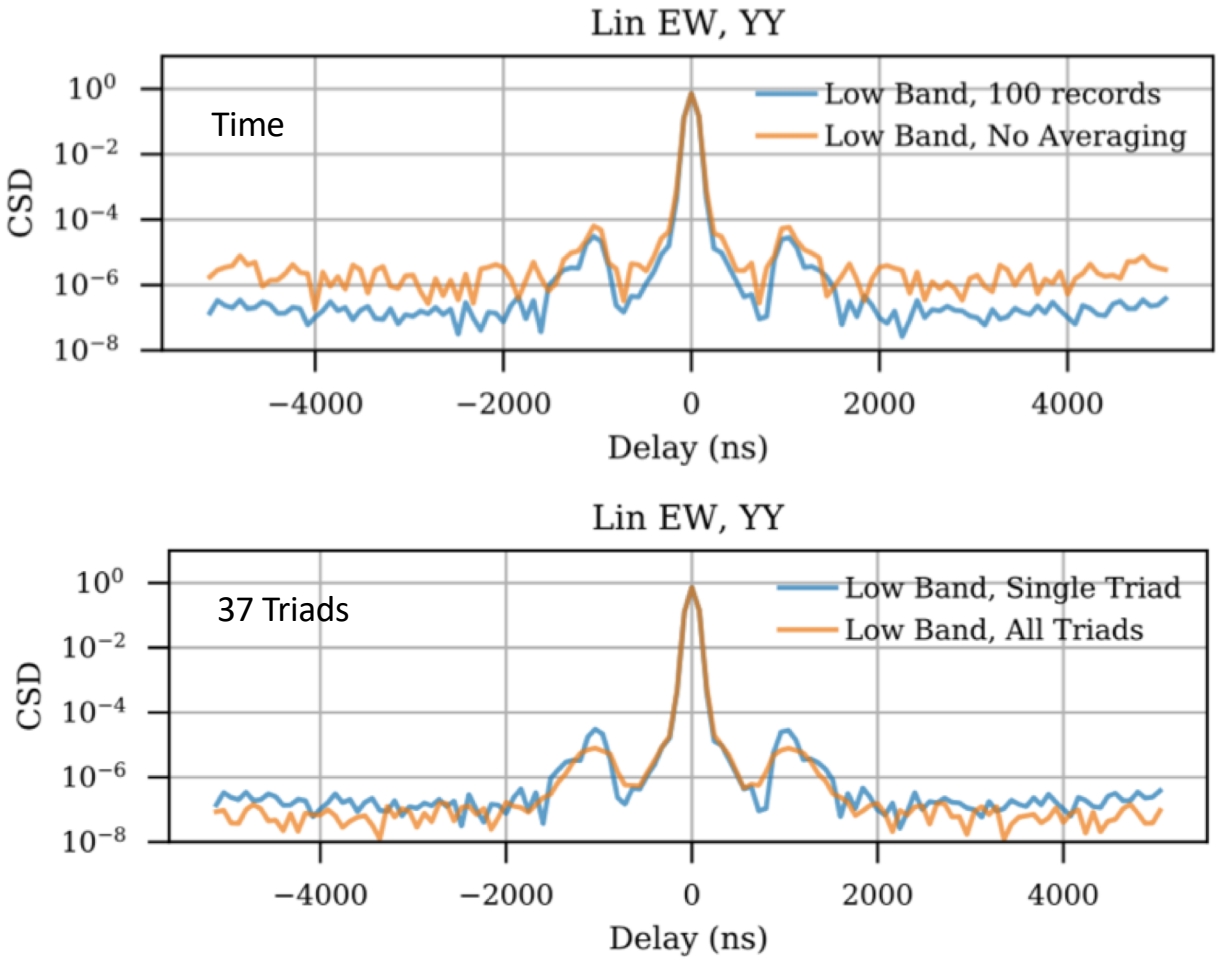


HERA-51 Closure spectra and Power Spectra (uncalibrated data)



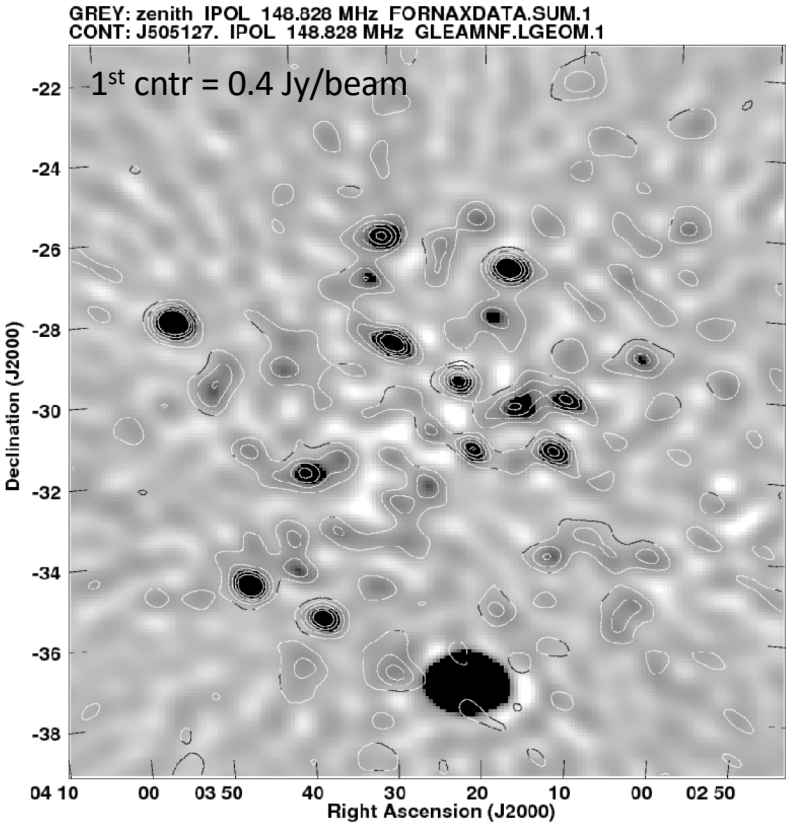
- IDR2 data (18days): 60sec ave of $\boldsymbol{\theta}_{cl}$ bin in LST 1st and 2nd halves, then Xcorr
- Average PS incoherently over +/-10min around Fornax transit, and 34 triads

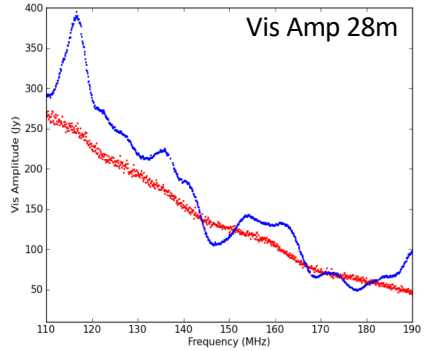
Incoherent averaging of PS

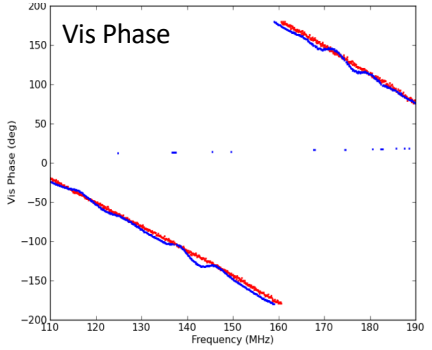


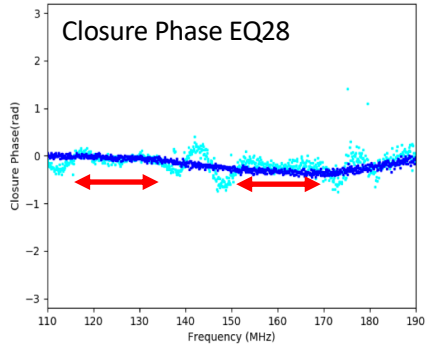
Modeling for quantitative comparison and analysis: confusion limited imaging

- HERA 51 IDR2 LST Binned data w. ‘Kern’ Sky Calibration
- GLEAM sources at 150 MHz: 1300 sources in Primary Beam (100 deg^2) down to 50mJy + CASA
- Syn Beam FWHM ~ 0.55^o
- => 4 sources per syn. beam, or >200 mJy/beam
- Thermal noise ~ 3.3 mJy/beam
- Good agreement model and data =>
  - Model (sources + telescope) provides a good representation of sky seen by HERA
  - Data is finding sources down to confusion limit





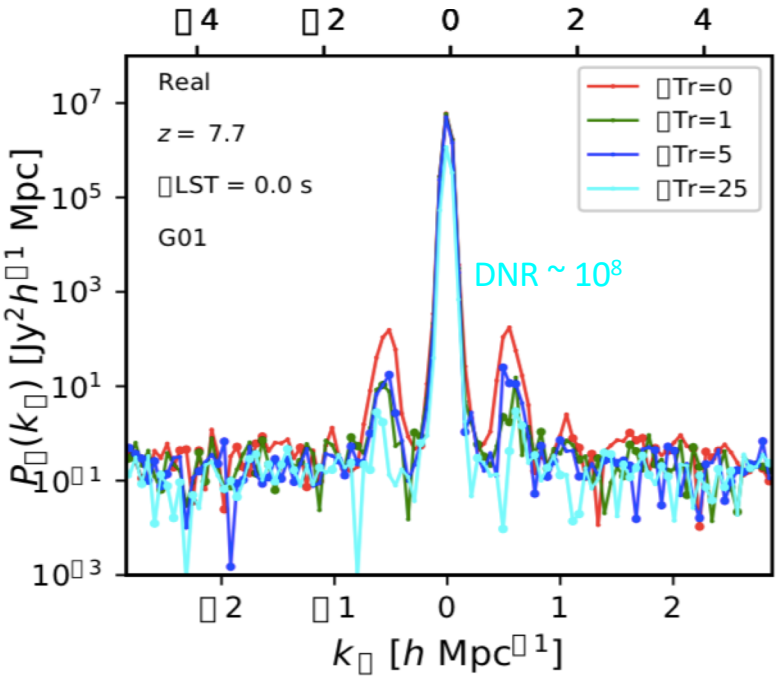




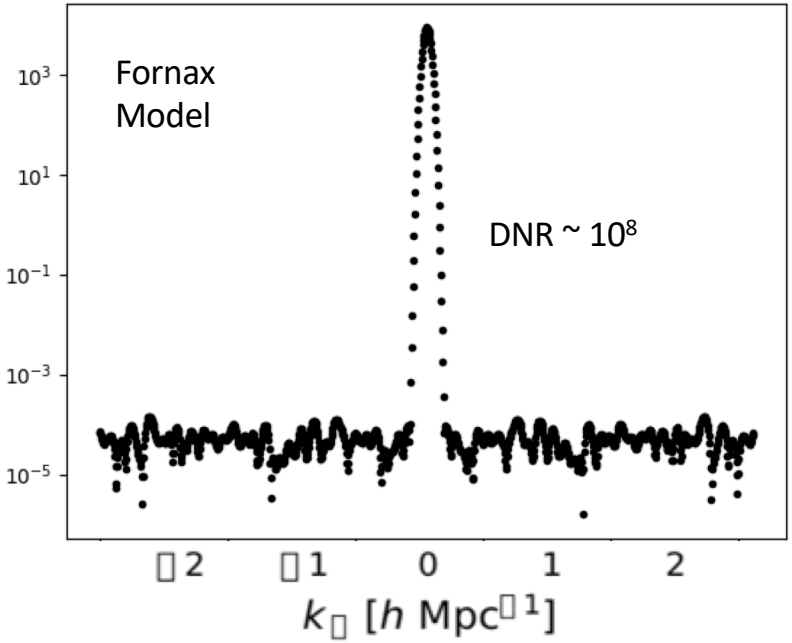
Preliminary ‘calibrated’ power spectrum

HERA-51, 18 days, 34 EQ28 triads, +/-10min around Fornax

- Appears noise limited; unresolved ‘core’
- PS Dynamic range ~ 10^8 (need to get to 10^{10})
- More data: 10x more time, 2pol, different triads
- Next winter: 351 antennas!



- 1usec bump: mitigated with xcorr of selected triads, and/or possibly time averaging. Should not be seen w. new Receivers (?)



Why Closure delay power spectrum?

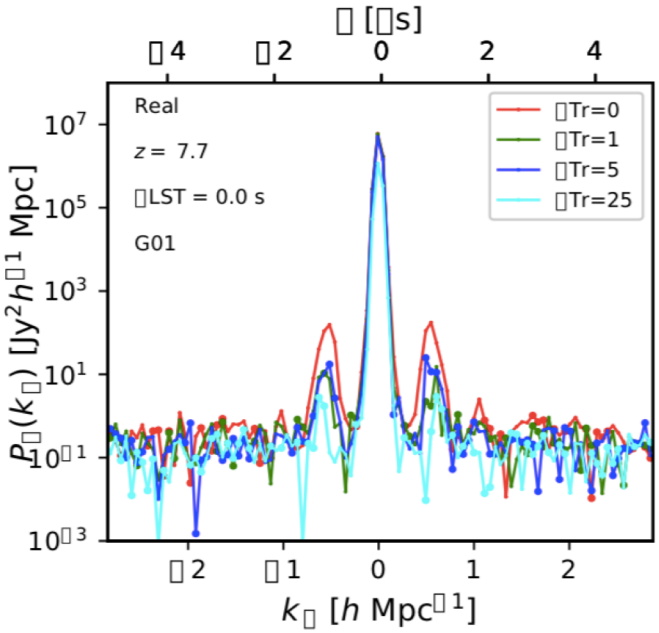
Advantages

- Independent of antenna-based gains, including direction dependent terms common to antennas (=ionosphere)
- Independent and competitive approach (vital check!)
- Extraordinarily simple, fast analysis
- Narrow continuum PS core in Fornax, no wedge

Disadvantage

- Non-closing effects? (if due to PB => broad in frequency?)
- Signal loss in triad xcorr?

Not substitute for long-term goal of direct imaging of HI, but a near-term method to obtain/verify the first statistical detection of HI PS



HERA Closure array diagnostics: redundancy and time variations