Expanding the frontiers of detecting structures from cosmic reionization using redshifted 21 cm experiments

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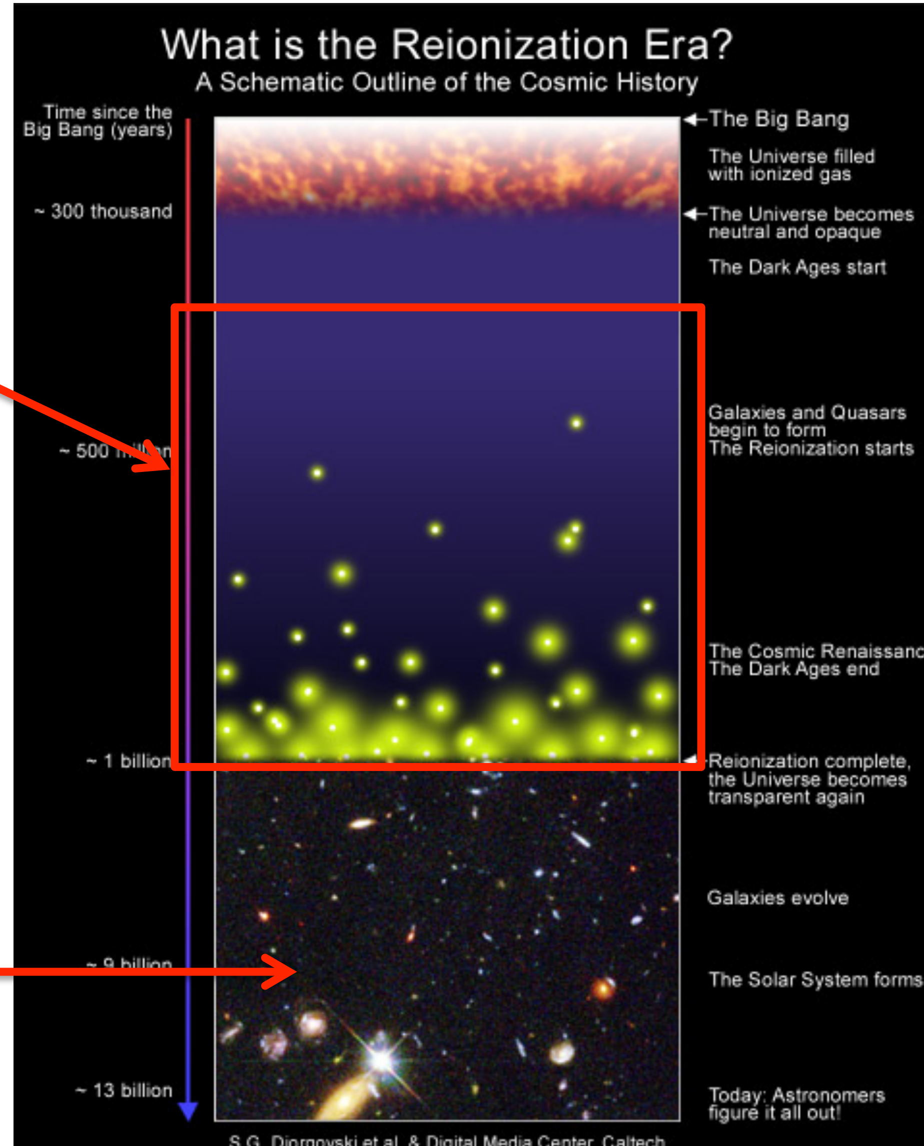
HERA+

Why EoR? Why low radio frequency?

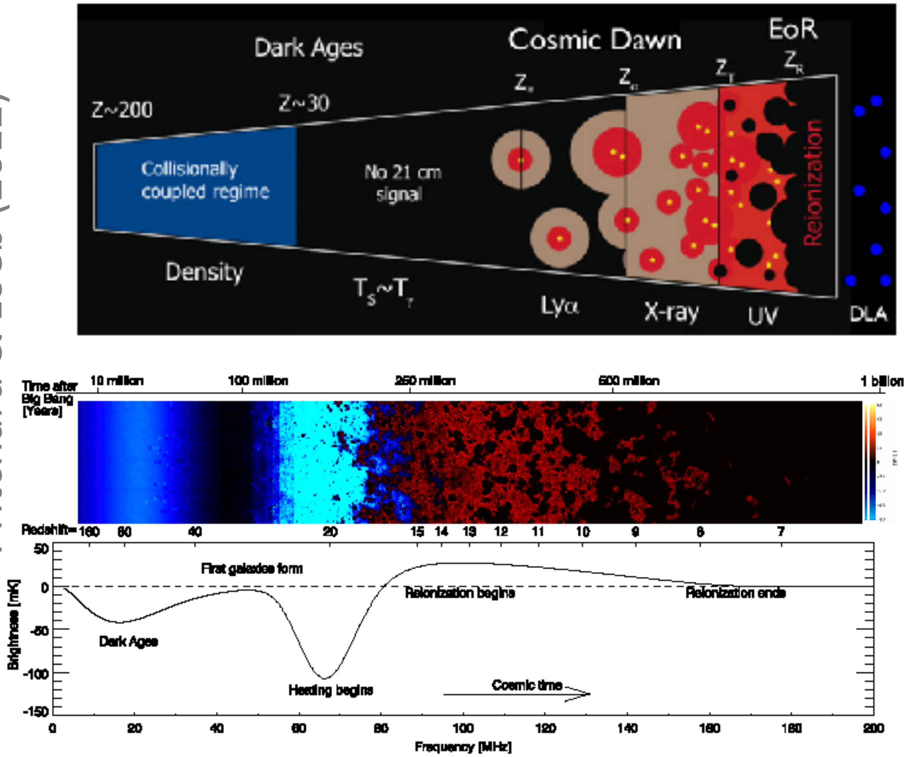
- First stars and galaxies
- Phase transformation: neutral to fully reionized
- Large scale structure
- Redshifted 21cm – direct probe of neutral Hydrogen in the EoR

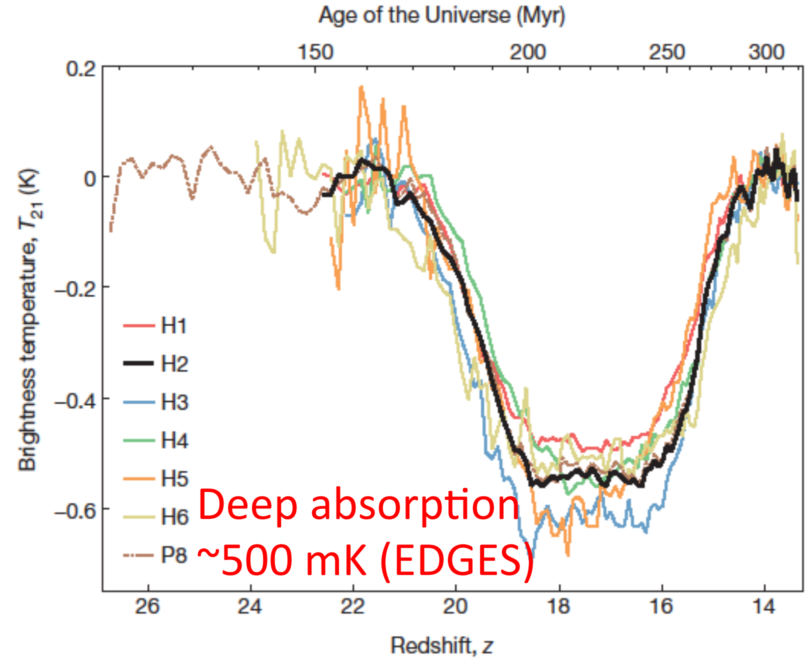
Foreground Challenge



Evolution of Cosmic HI Brightness Temperature Monopole

Pritchard & Loeb (2012)





Deep absorption ~500 mK (EDGES)

Bowman et al. (2018)

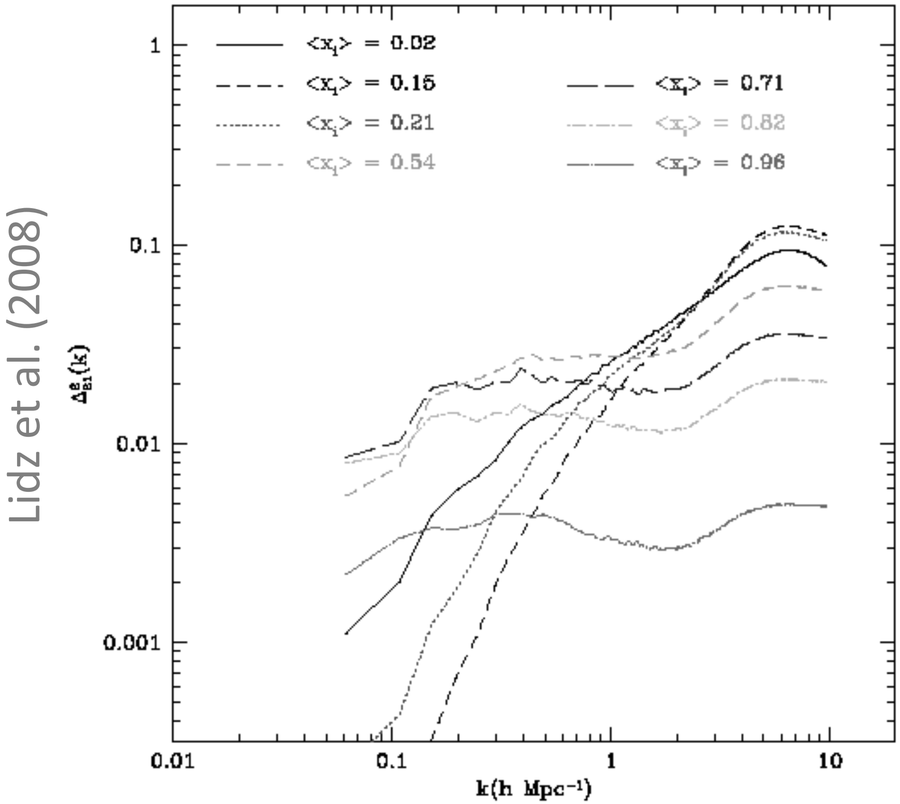
Exotic physics at play?

- Cooling of Tk by scattering of Dark Matter Particles ? (Barkana 2018)
- Excess background radiation from BH growth? (Ewall-Wice et al. 2018)

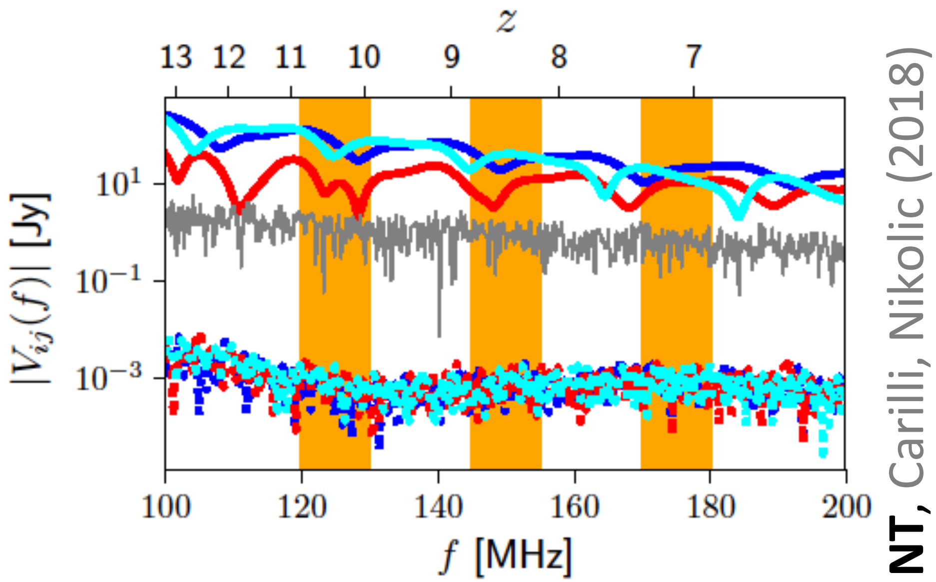
Wide range of astrophysical processes responsible for the evolutionary behavior:

- Compton scattering couples T_s to T_k and T_{CMB}
- Decoupling from T_{CMB} leads to absorption as T_s follows T_k (adiabatic cooling)
- Further expansion makes collisional coupling ineffective, T_s follows T_{CMB}
- First stars form, Lyα recouples T_s to T_k (follows adiabatic cooling)
- Lyα and X-rays heating raises T_k above T_{CMB} (signal in emission = EoR)

Cosmic Reionization Spatial Fluctuations



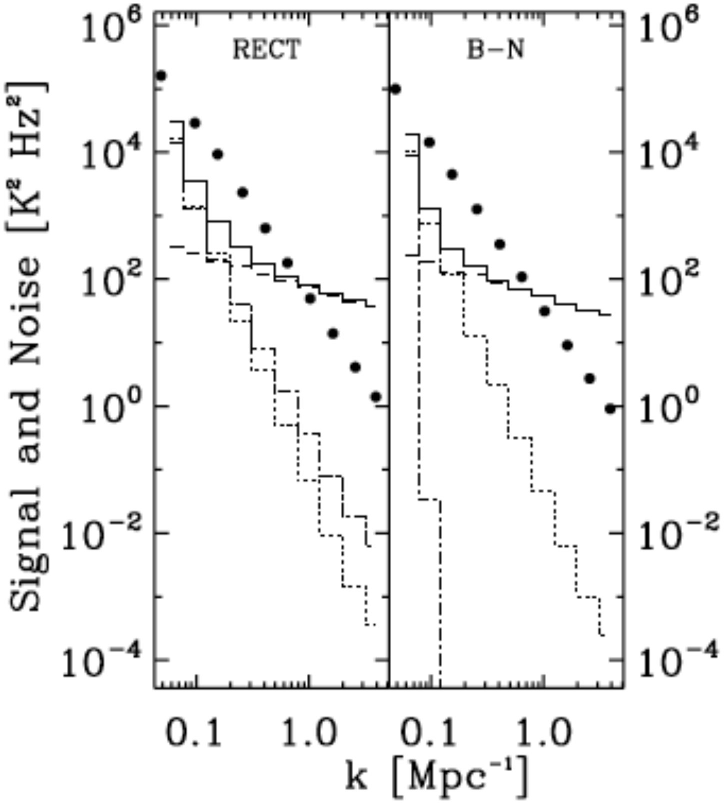
- Evolution of power spectrum reveals nature of ionizing objects
- The astrophysics causing evolution of structures
- Seeds of large-scale structure formation



- Foregrounds are ~10^5 brighter than EoR HI signal
- Foregrounds are spectrally smooth
- EoR HI signal is faint but has fine spectral structure in contrast to bright foregrounds
- Number of instruments – MWA, LOFAR, HERA, PAPER, SKA – designed to detect EoR spatial fluctuations using spectral contrast (statistically using power spectrum)

Expectations and Results from First-generation Instruments

NT+ (2013)



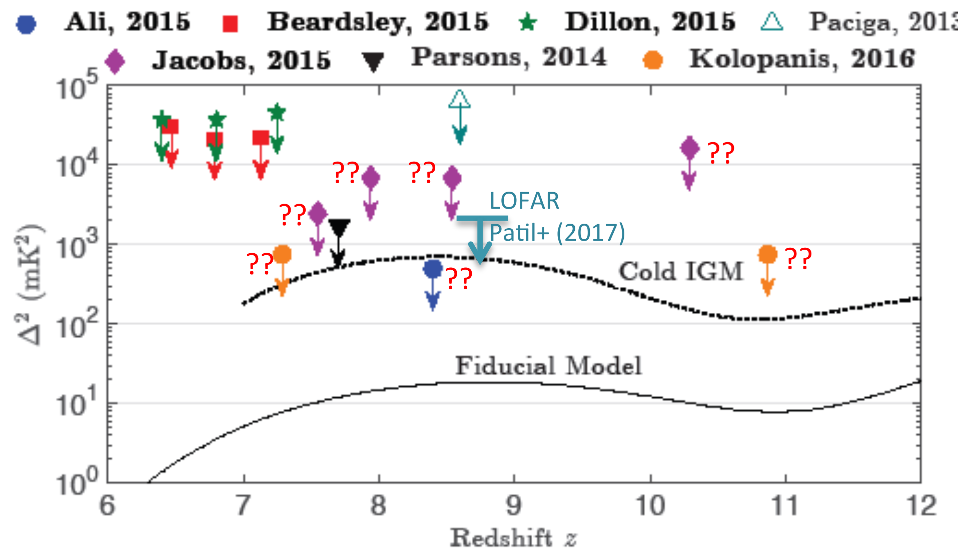
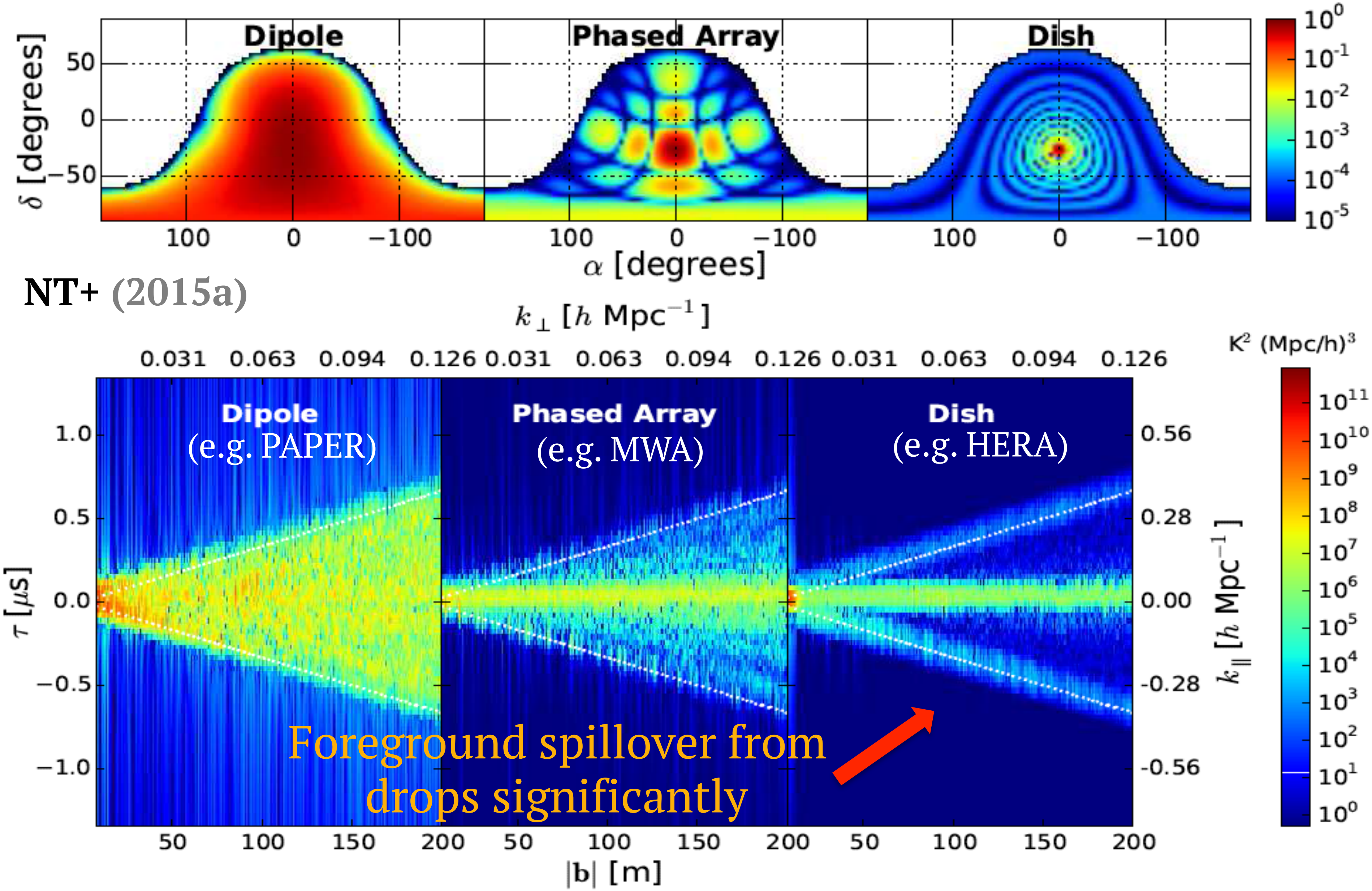


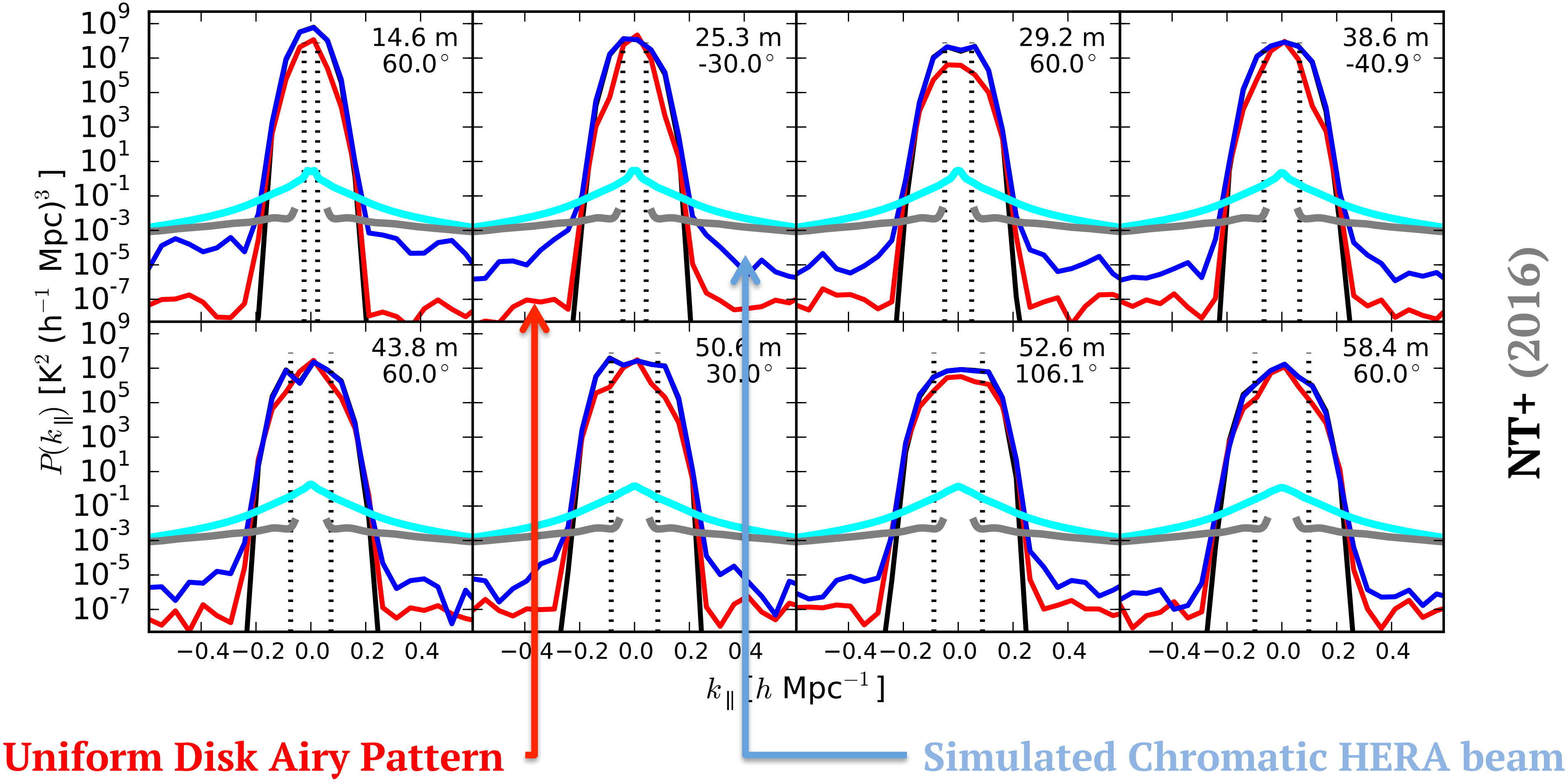
Image: Matt Kolopanis

- >10-sigma statistical detection expected with ~1000 hours data
- Currently limited by foregrounds and instrument systematics. e.g. PAPER64 - Ali et al. 2015, Pober et al. 2015, Cheng et al. 2018 (in prep); MWA – Dillon et al. 2013, Beardsley et al. 2016; LOFAR - Patil et al. 2017

Mitigation of systematics via Aperture Shape



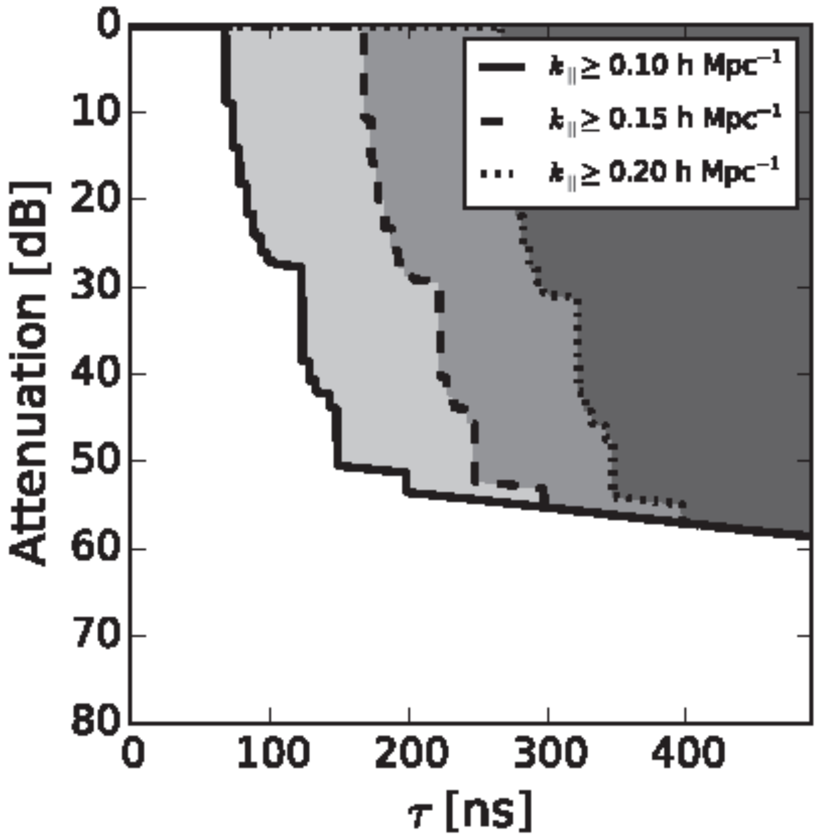
Effects of Beam Chromaticity



- Differences seen only due to spectral differences in Antenna beam
- Beam chromaticity worsens foreground contamination
- HERA aiming for such a robust element design

Design Specs on Reflections in Instrument

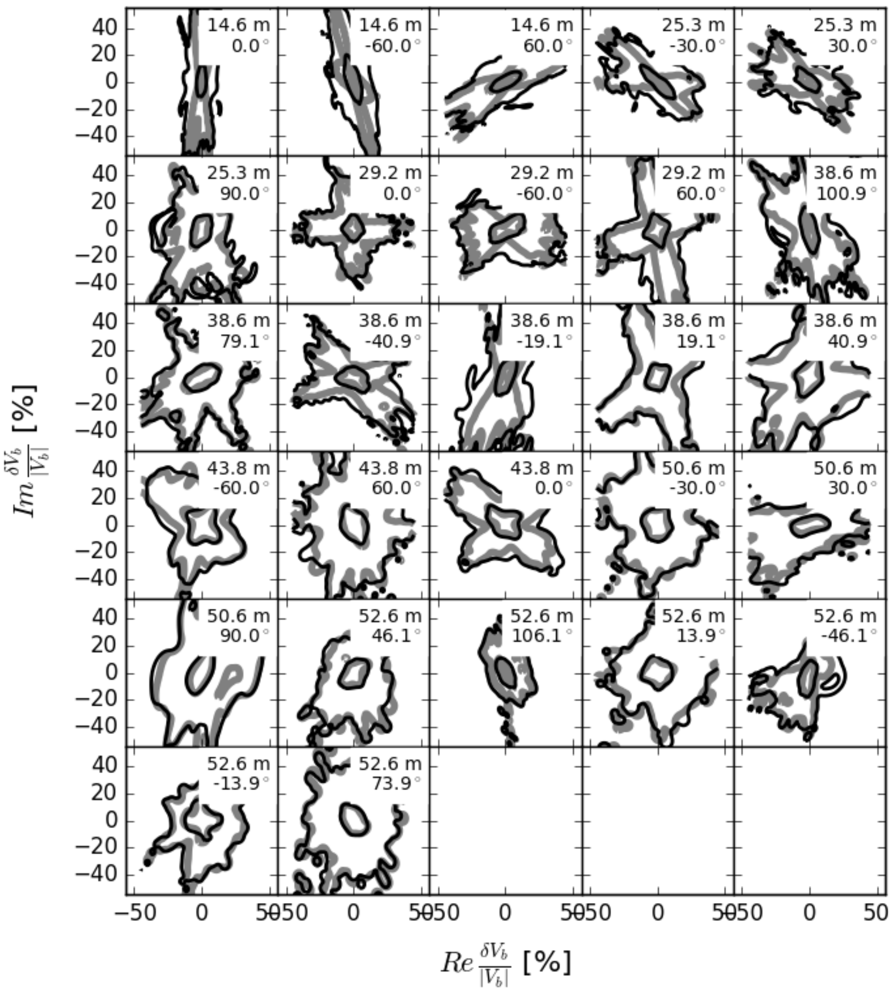
Dish-Feed Reflections



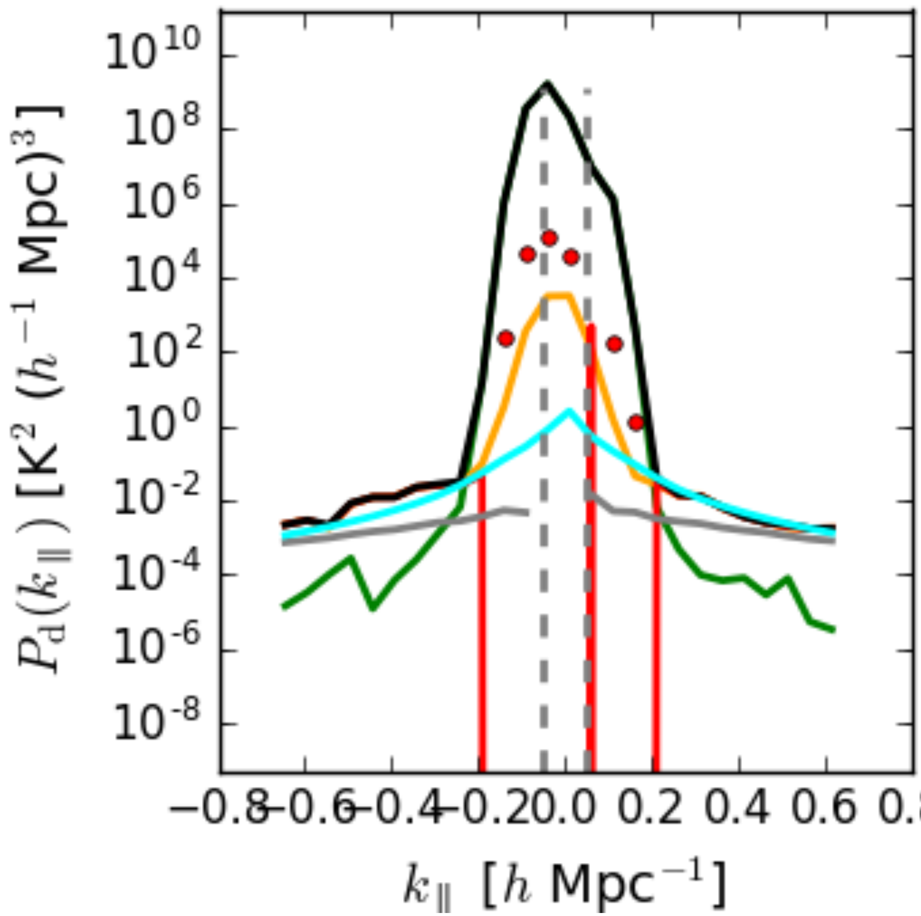
NT+ (2016)
Ewall-Wice et al. (2016)
Neben et al. (2016)
Patra et al. (2016)
DeBeor et al. (2016)

- Reflections inevitable in electrical systems
- Reflections extend foregrounds and contamination in delay spectrum
- Require reflected foregrounds to be below HI signal levels
- HERA will aim for these specs
- Similar study is ongoing for SKA1-low

Effects of Antenna Position Errors



NT+ (in prep.)

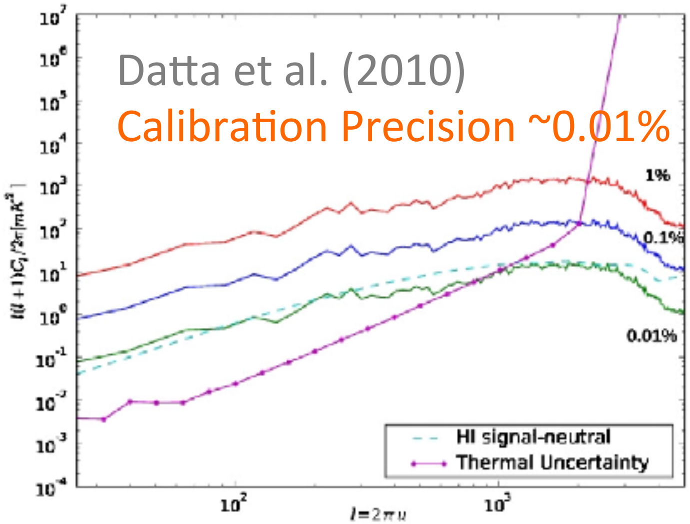


Deviation from redundancy quickly introduce undesirable levels of spectral structure

Analysis Challenges

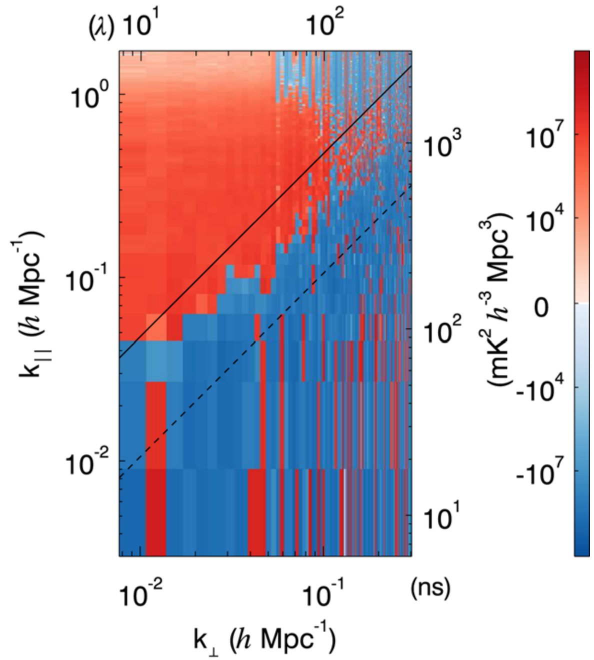
- Calibration Accuracy
- Foreground mitigation without signal loss
- Precise Instrument Knowledge
- Precise knowledge of foregrounds
- Polarization Leakage compounded with wide-field effects?
- Antenna-to-antenna variations in beam and signal path?
- Avoid introducing spectral artifacts

Calibration Challenges



Datta et al. (2010)

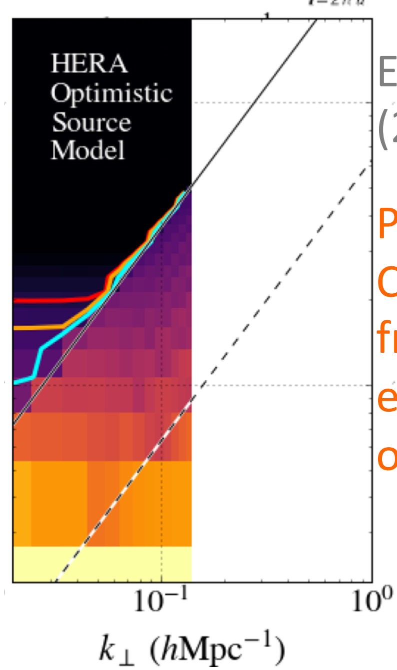
Calibration Precision ~0.01%



Barry et al. (2016)

Calibration Precision ~10^{-5}

Thorough knowledge of foregrounds required to achieve this precision



Ewall-Wice et al. (2017)

Power Spectrum Contamination from calibration errors in an optimistic case

Similar conclusions from …

- Trott & Wayth (2016) for MWA and SKA
- Patil et al. (2017) for LOFAR
- …
- Sophisticated strategies being developed for redundant polarization calibration for HERA (Dillon et al. 2017)

Interferometric Solution to Calibration Woes

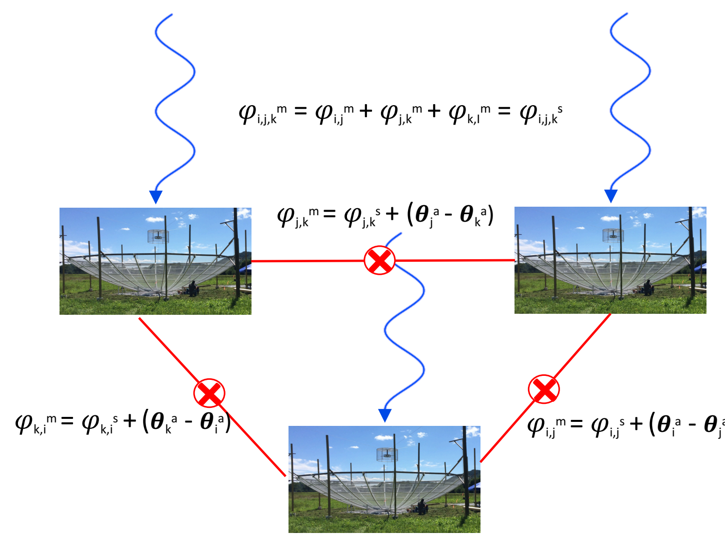
- Phase of bi-spectrum (closure phase)

$$B_\Delta(f) = V_{ab}(f)\, V_{bc}(f)\, V_{ca}(f)$$

$$V_{ab}^{\mathrm{m}}(f) = g_a(f)\, g_b^*(f)\, V_{ab}^{\mathrm{T}}(f) + V_{ab}^{\mathrm{N}}(f)$$

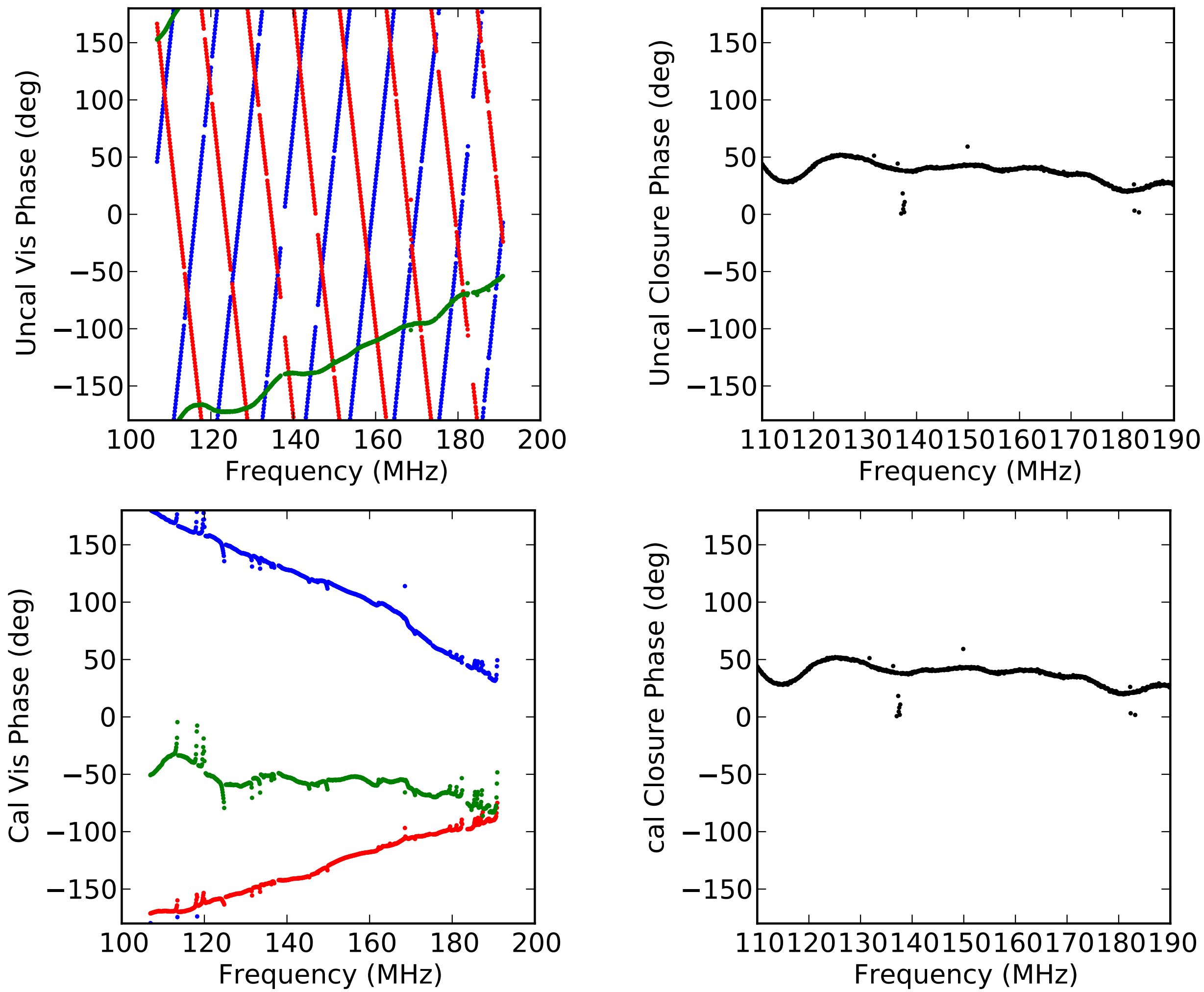
$$\phi^{\mathrm{m}}_{i,j,k} \quad = \phi^{\mathrm{s}}_{i,j} + (\theta_i - \theta_j) + \phi^{\mathrm{s}}_{j,k} + (\theta_j - \theta_k) + \phi^{\mathrm{s}}_{k,i} + (\theta_k - \theta_i) + \phi^{\mathrm{n}}_{i,j,k} \; = \phi^{\mathrm{s}}_{i,j,k} + \phi^{\mathrm{n}}_{i,j,k}$$

Used in radio interferometry since 1950s



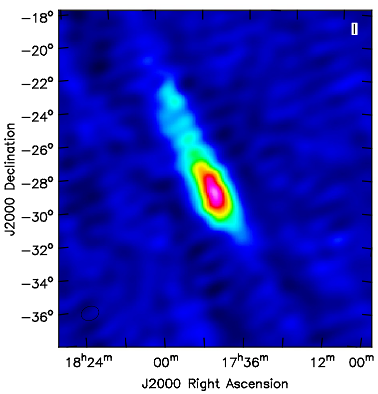
Carilli, Nikolic, **NT** et al. (2018)

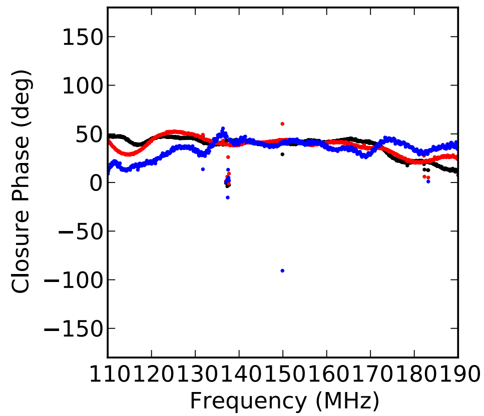
Bi-spectrum Phase Independent of antenna calibration and its errors

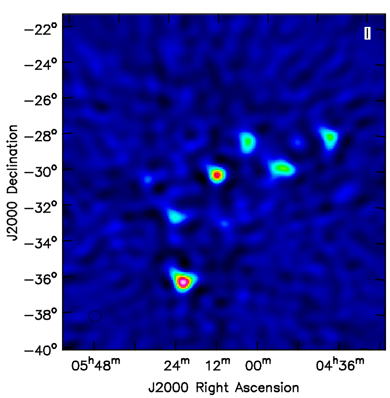


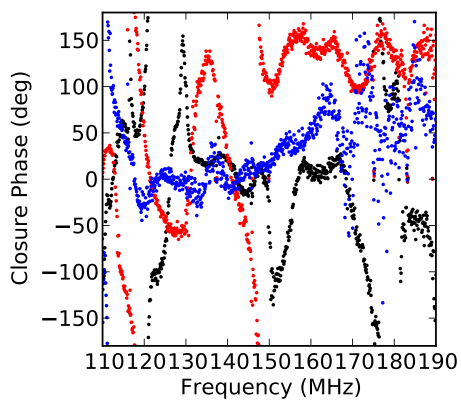
Carilli, Nikolic, **NT** et al. (2018)

Bi-spectrum phase fluctuations depend on S/N

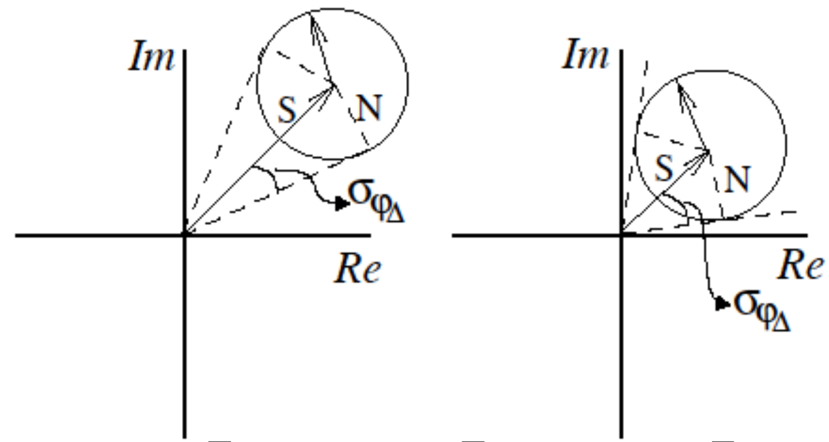








Carilli, Nikolic, **NT** et al. (2018)

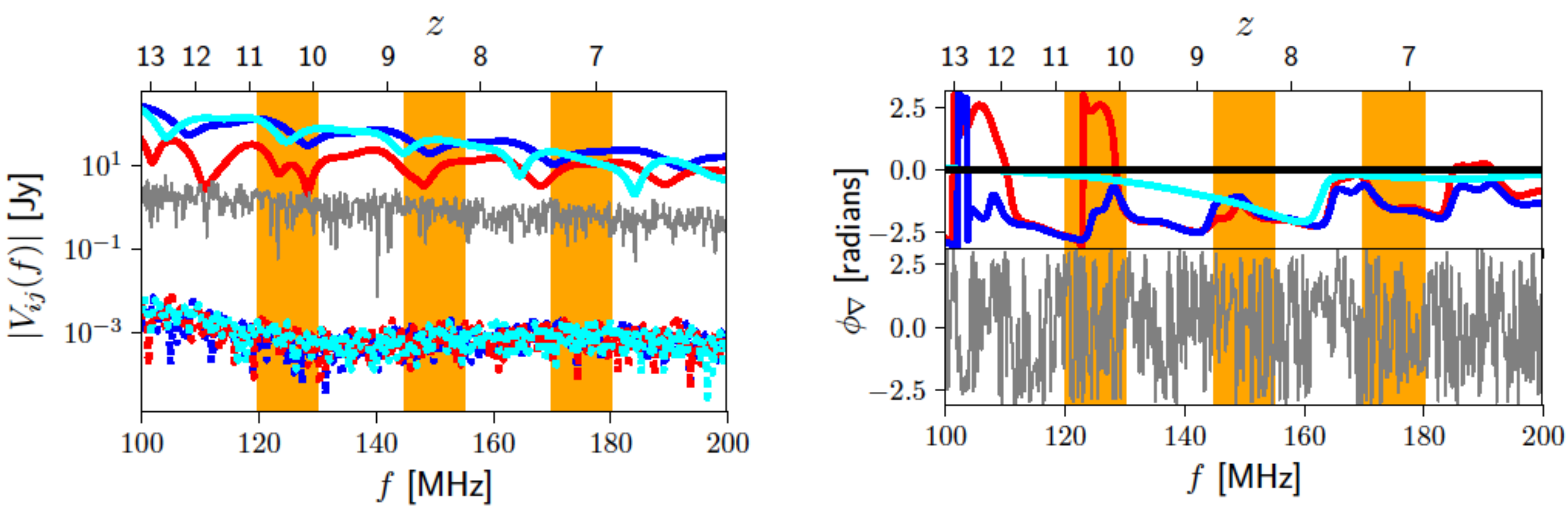


$$\sigma^2_{\phi^{\rm m}_\Delta} = (\sqrt{2}\,\rho^{\rm N}_{ab})^{-2} + (\sqrt{2}\,\rho^{\rm N}_{bc})^{-2} + (\sqrt{2}\,\rho^{\rm N}_{ca})^{-2}$$

NT, Carilli, Nikolic (2018)

Gaussian distribution
width = 1/SNR
(for high SNR)

Why Bi-spectrum Phase for EoR?



$$\phi_\Delta^{\mathrm{m}} = \left(\phi_\Delta^{\mathrm{F}} + \delta\phi_\Delta^{\mathrm{H\,I}}\right) + \delta\phi_\Delta^{\mathrm{N}}$$

$$\sigma^2_{\phi_\Delta^{\mathrm{m}}} = (\sqrt{2}\,\rho_{ab}^{\mathrm{N}})^{-2} + (\sqrt{2}\,\rho_{bc}^{\mathrm{N}})^{-2} + (\sqrt{2}\,\rho_{ca}^{\mathrm{N}})^{-2}$$

$$\sigma^2_{\phi_\Delta^{\mathrm{m}}} = (\sqrt{2}\,\rho_{ab}^{\mathrm{H\,I}})^{-2} + (\sqrt{2}\,\rho_{bc}^{\mathrm{H\,I}})^{-2} + (\sqrt{2}\,\rho_{ca}^{\mathrm{H\,I}})^{-2}$$

Noise/FG

Sufficient Averaging and Noise Reduction

EoR HI/FG

NT, Carilli, Nikolic (2018)

Bi-spectrum Phase Delay Spectrum

$$\xi_\Delta = e^{i\phi_\Delta} = e^{i\phi_{ab}}\, e^{i\phi_{bc}}\, e^{i\phi_{ca}}$$

Delay Spectrum of Bi-Spectrum Phase:

$$\Xi_\Delta(\tau) = \int \xi_\Delta(f)\, W(f)\, e^{i2\pi f\tau}\, \mathrm{d}f,$$

$$\Xi_\Delta(\tau) = \Xi_{ab}(\tau) \star \Xi_{bc}(\tau) \star \Xi_{ca}(\tau) \star \mathcal{W}(\tau)$$

FG wedge * FG wedge * FG wedge * Spec. Window

Triply convolved FG wedge

$$|\tau_\mathrm{F}| \lesssim \frac{|\boldsymbol{b}_{ab}| + |\boldsymbol{b}_{bc}| + |\boldsymbol{b}_{ca}|}{c} + \frac{1}{B_\mathrm{eff}}$$

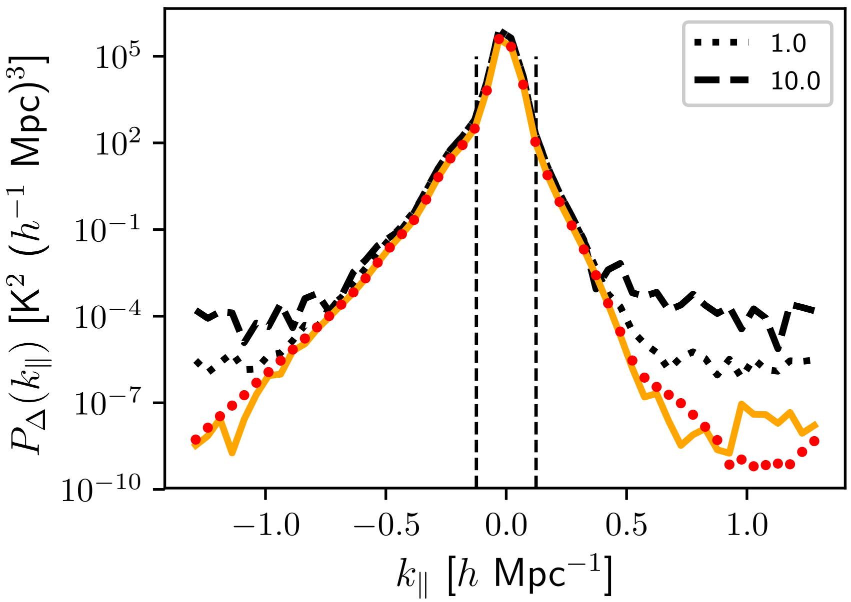
$$P_\nabla(k_\parallel) \equiv \mathfrak{Re}\left\{\Xi_\nabla(\tau)\, \Xi^*_{\nabla'}(\tau)\right\} \left(\frac{\Delta D}{B^2_\mathrm{eff}}\right)$$

Not same as cosmological bi-spectrum analysis

- Bi-spectrum is non-zero for Gaussian field
- Isotropic fluctuations average to zero over different triads of k-modes
- We consider only bi-spectrum phase
- We average different triads only in power spectrum of bi-spectrum phase

Detection of EoR HI Fluctuations

NT, Carilli, Nikolic (2018)



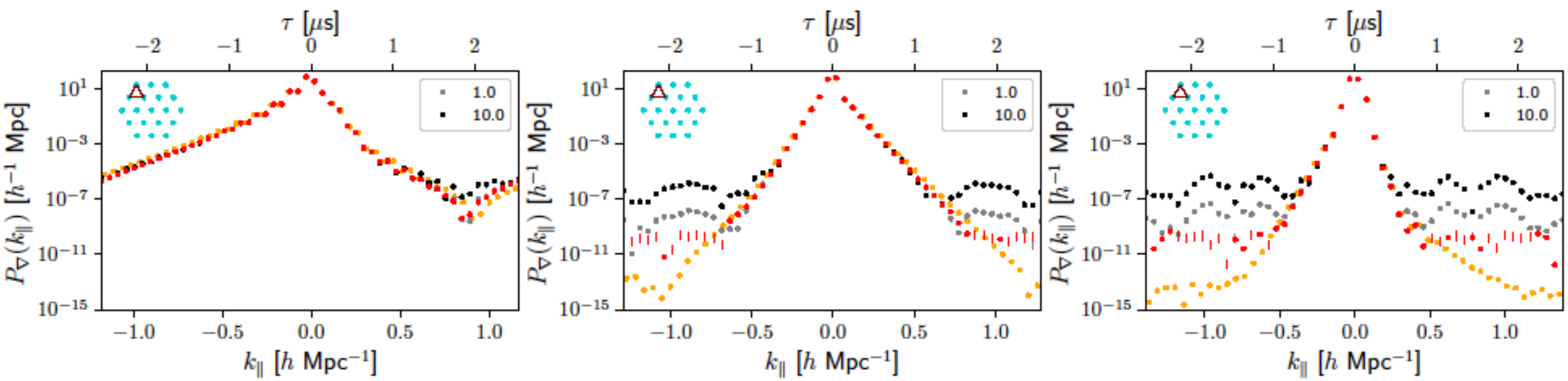
Detection:

- EoR HI signal may be detectable at $k_{||} > 0.5$ h Mpc^{-1}
- Separation measures line-continuum ratio

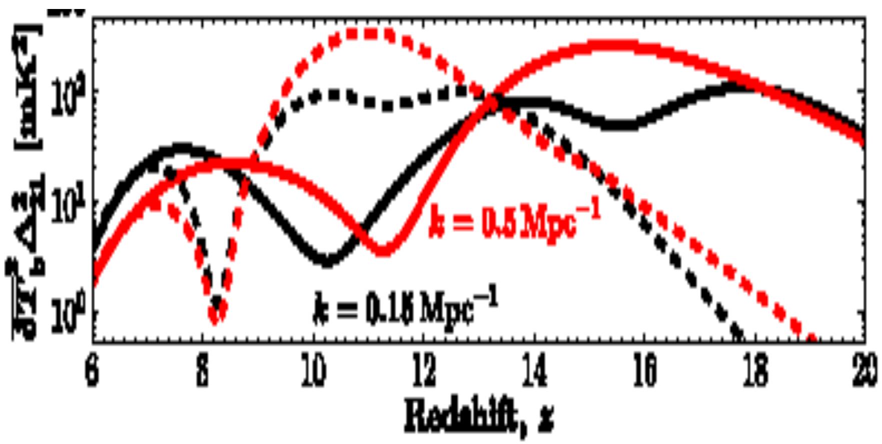
$$\sigma^2_{\phi^{\rm m}_\Delta} = (\sqrt{2}\,\rho^{\rm HI}_{ab})^{-2} + (\sqrt{2}\,\rho^{\rm HI}_{bc})^{-2} + (\sqrt{2}\,\rho^{\rm HI}_{ca})^{-2}$$

Evolution of EoR HI Fluctuations

NT, Carilli, Nikolic (2018)



(a) 125 MHz sub-band ($z \approx 10.4$) (b) 150 MHz sub-band ($z \approx 8.5$) (c) 175 MHz sub-band ($z \approx 7.1$)



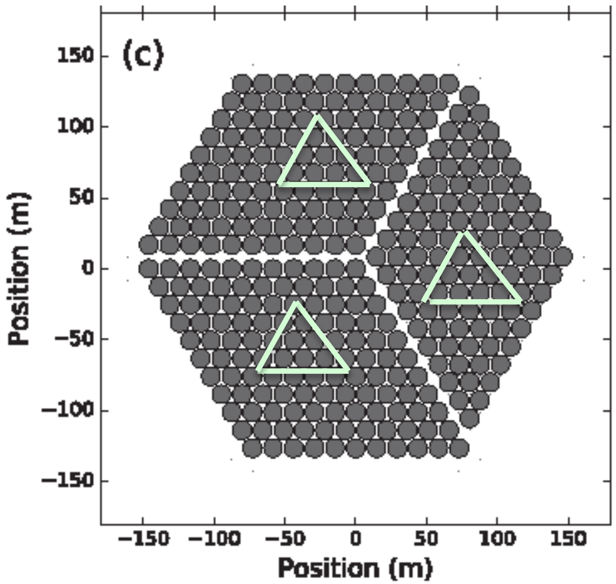
Greig & Mesinger (2017)

EoR HI Brightness Temperature, Var($dT_b^{HI}(z)$)

- Separation yields EoR/FG ratio in different bands (redshifts)
- If FG model known, Var($dT_b^{HI}(z)$) can be estimated
- 10^{-5} precision not required

Challenges & Prospects

✓ Redundancy



Dillon & Parsons (2016)

✓ Averaging LST across nights

✓ Filter dominant FG bi-spectrum phase

✓ Combine k-modes (cylindrical and spherical) optimally

✓ Combine data incoherently in power spectrum

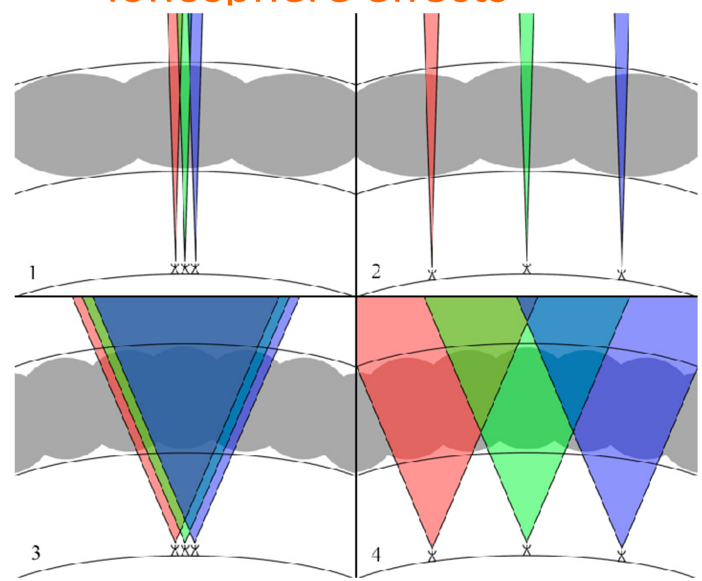
X Baseline-dependent gains

$$V_{ab}^{\mathrm{m}}(f) = \quad g_{ab}\; g_a(f)\, g_b^*(f)\, V_{ab}^{\mathrm{T}}(f)$$

X Direction-dependent gains

X Cross-polarization gains

X Long baseline wide-field ionosphere effects



Intema et al. (2009)

X Non-redundancy (technically not a showstopper)

Prospects with HERA

- HERA-47 in one season has > 2 million, 1-min measurements of ~30 triads in 14.6 m equilateral triad class in 150 nights, 8 hr/night
- Data sufficient to comment on whether systematic-limited or noise-limited
- Independent approach to EoR detection – complementary to existing approaches

Summary

- Systematics are the biggest challenge to EoR and low frequency experiments - HERA, SKA, MWA, PAPER, LOFAR

- Bi-spectrum phase avoids antenna calibration issues
- Worst Case: Can't be much worse than now, understand instrument systematics and limitations
- Best case: Can be much better and avoid big calibration systematics - maybe upper limits on Var($dT_b^{HI}(z)$) ??
- HERA-47 can indicate position on "worst-to-best" scale

- PRISim – high precision simulator for wide-field radio interferometry – https://github.com/nithyanandan/PRISim