Novel interferometric approaches to probe large-scale structures in the early Universe using redshifted 21 cm

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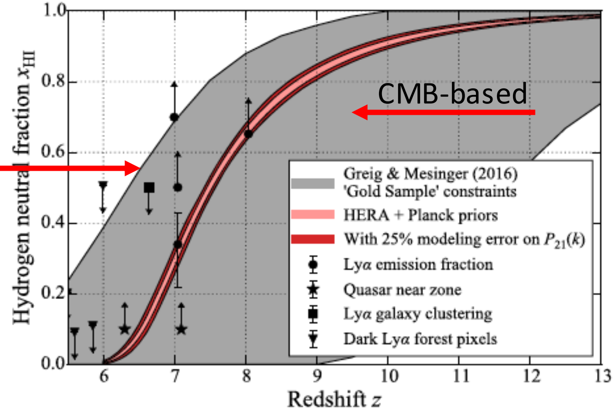
+

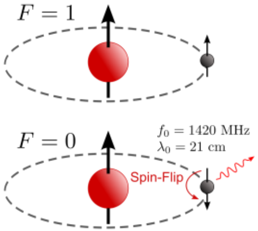
HERA Collaboration

I acknowledge the Traditional Owners of the land, sea and waters, of the area that we live and work on across Australia. I acknowledge their continuing connection to their culture and pay my respects to their Elders past and present.

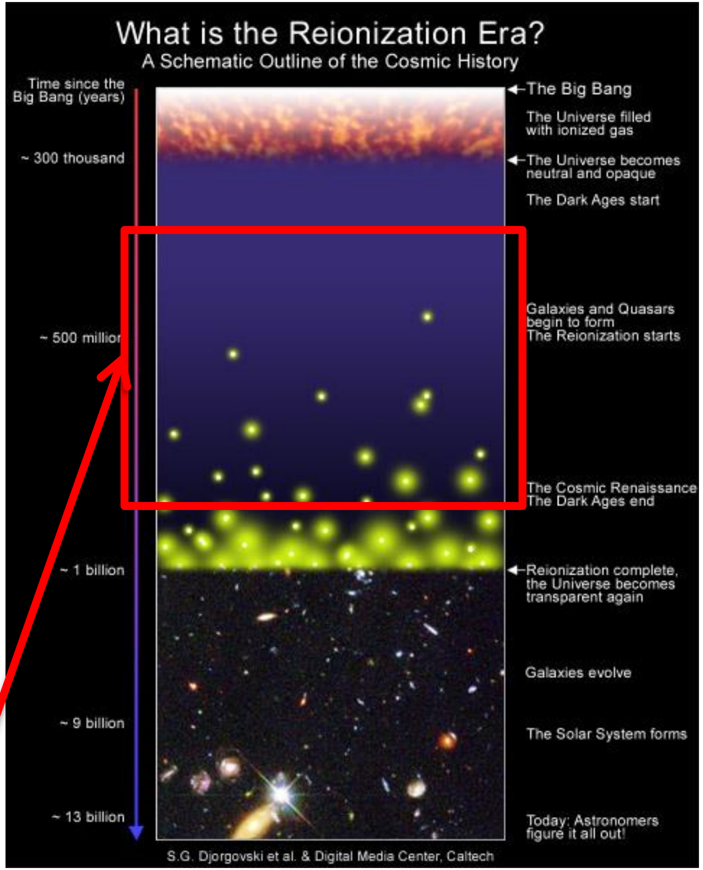
Probing early Universe using Neutral Hydrogen

Quasars

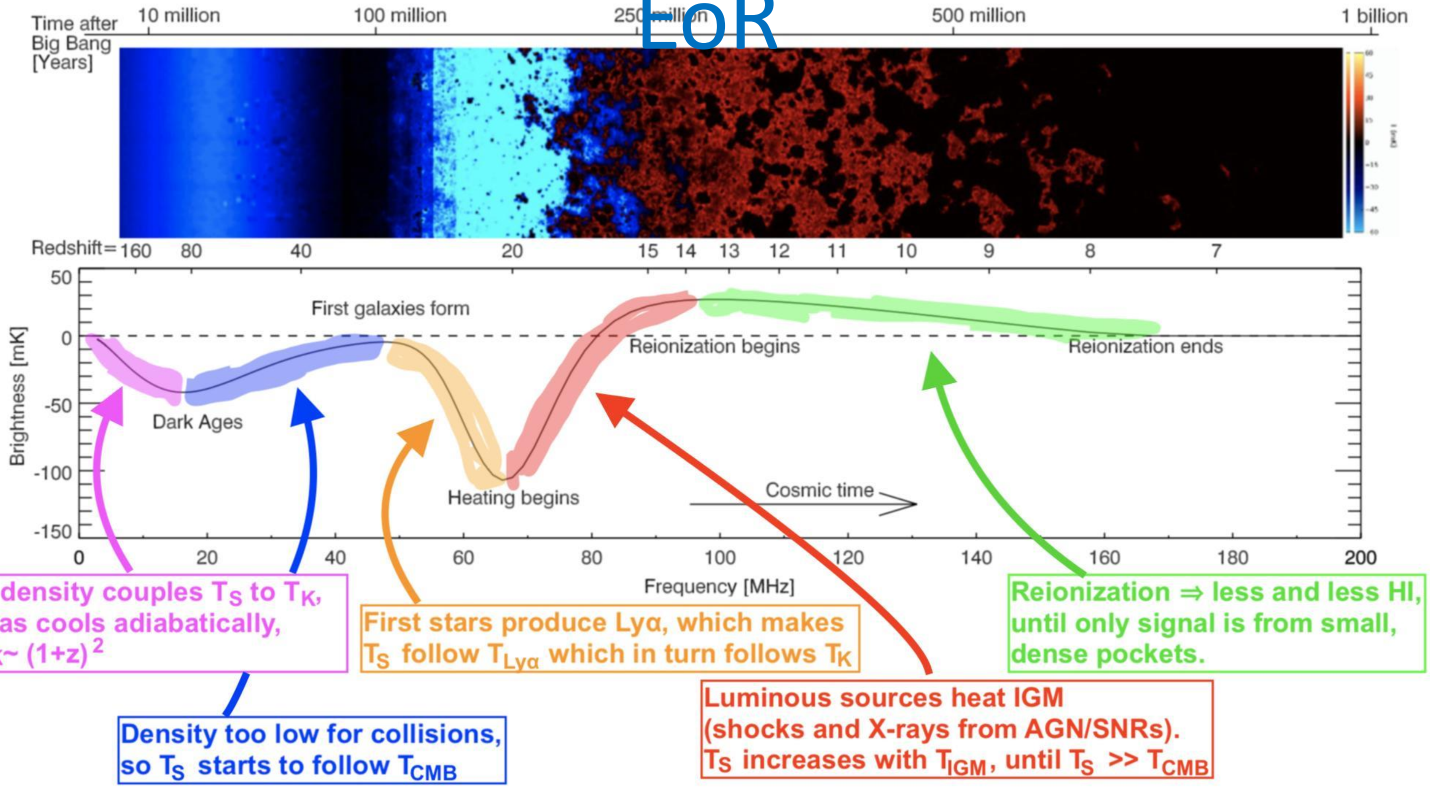




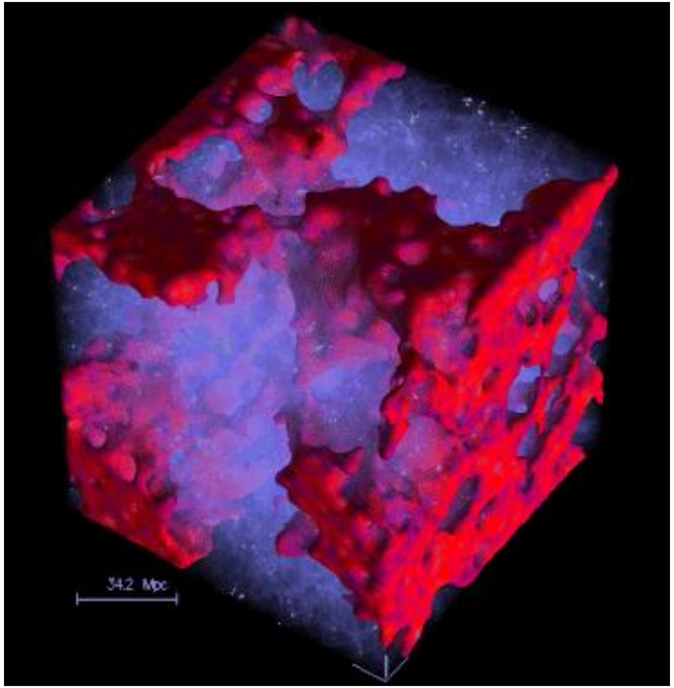
Redshifted 21cm – direct probe of neutral Hydrogen in the EoR (50 – 200 MHz)

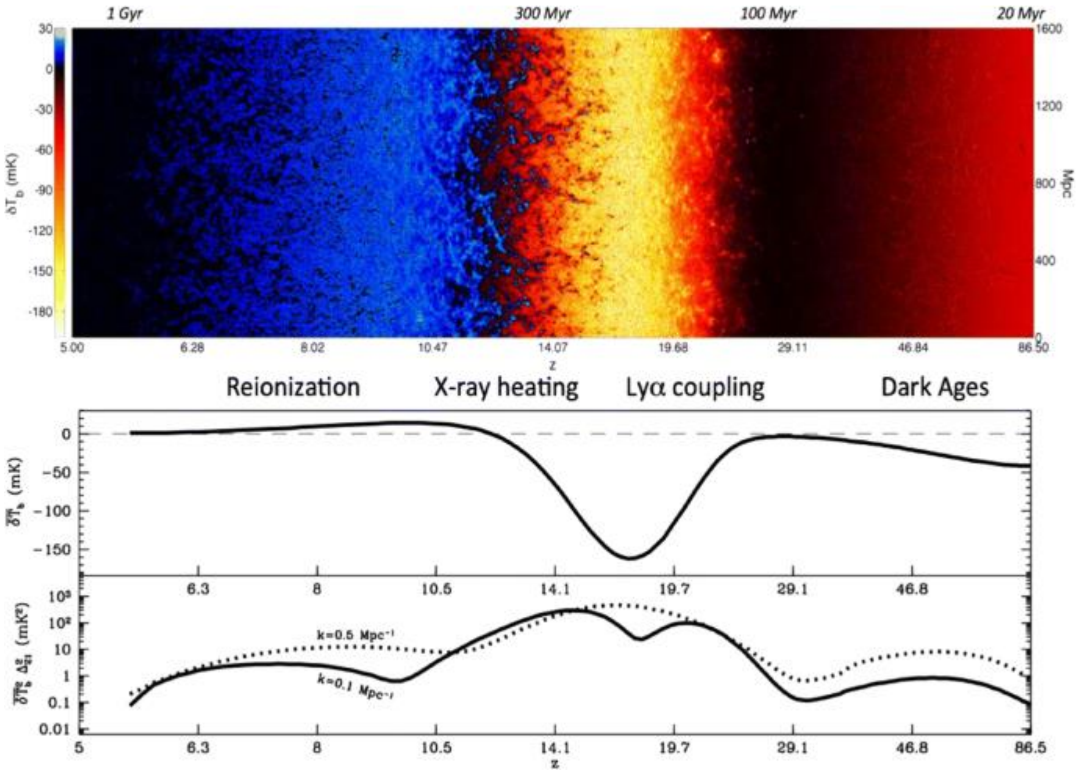


Sky-averaged 21cm signal from the EoR



EoR fluctuations using redshifted 21 cm line



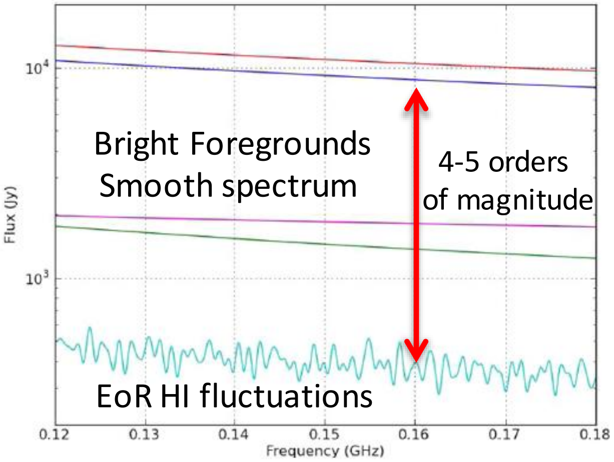


Mesinger+2016

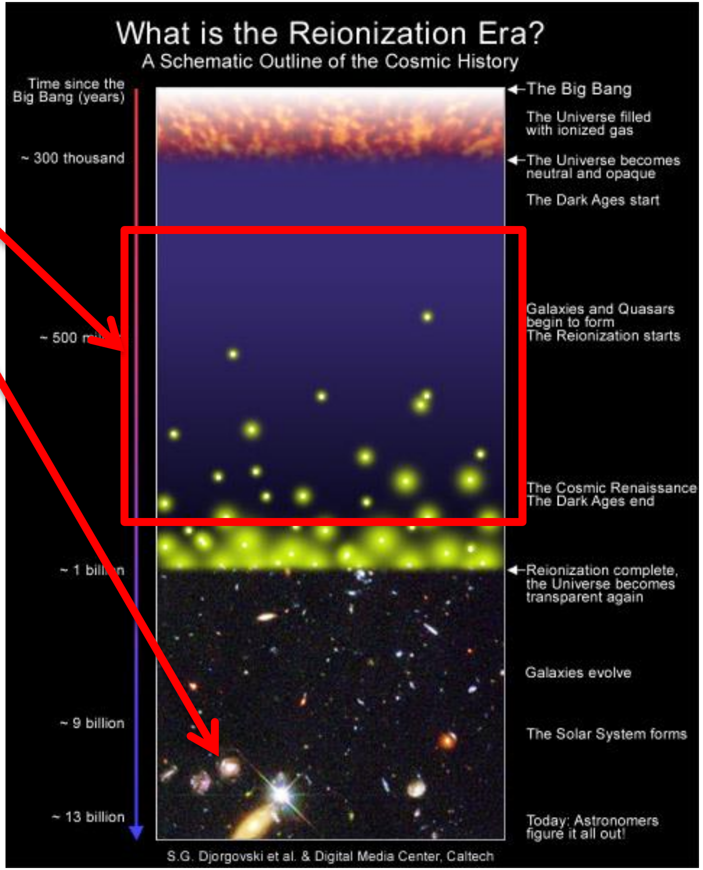
EoR fluctuations using redshifted 21 cm line

- Redshifted 21cm – direct probe of neutral Hydrogen in the EoR (50 – 200 MHz)

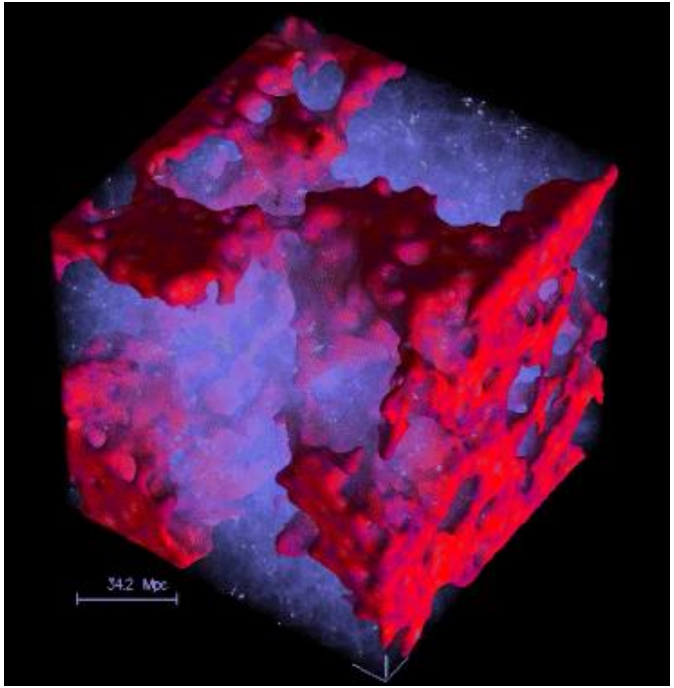
Bright Synchrotron Foregrounds



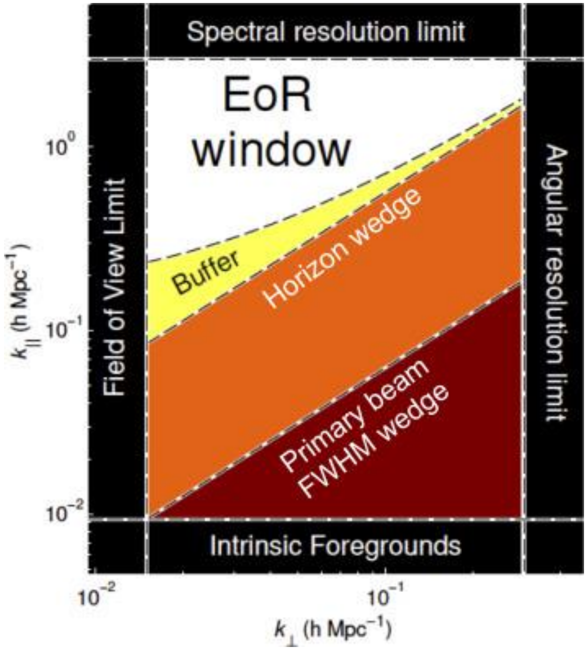
Parsons et al. (2012)



EoR 21cm fluctuations



Inadequate sensitivity for 3D tomography

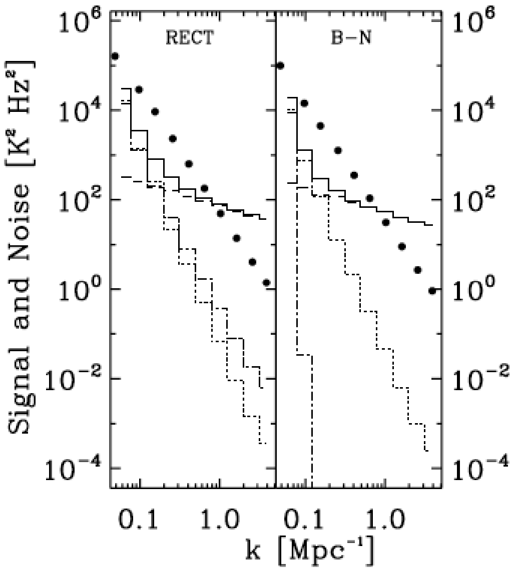


Statistical Power Spectrum using spatial Fourier transform possible

Expectations/Results from First-generation

>10-sigma statistical detection
expected with ~1000 hours data

Thyagarajan et al. (2013)



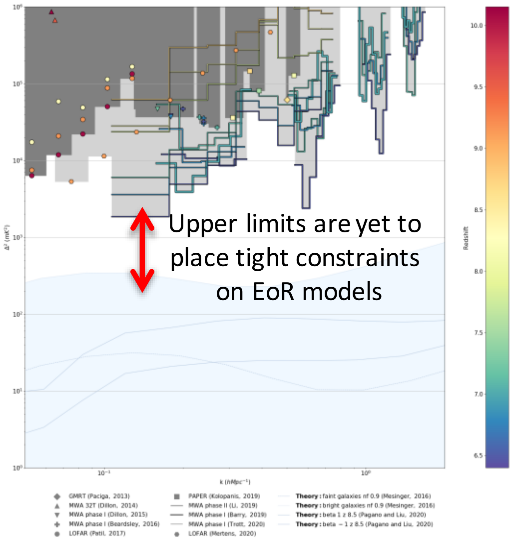
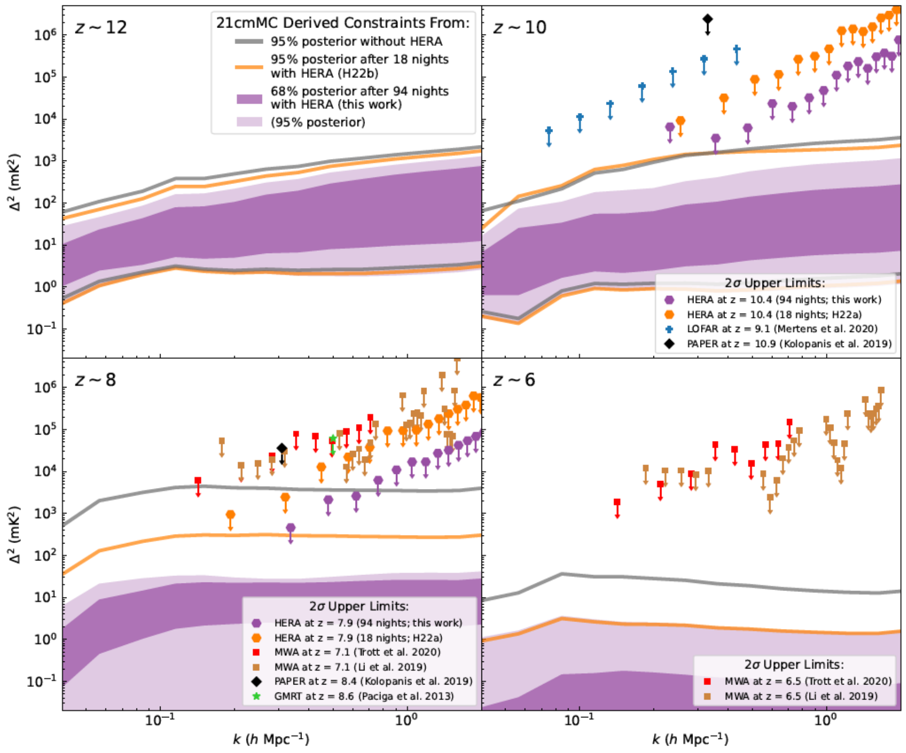


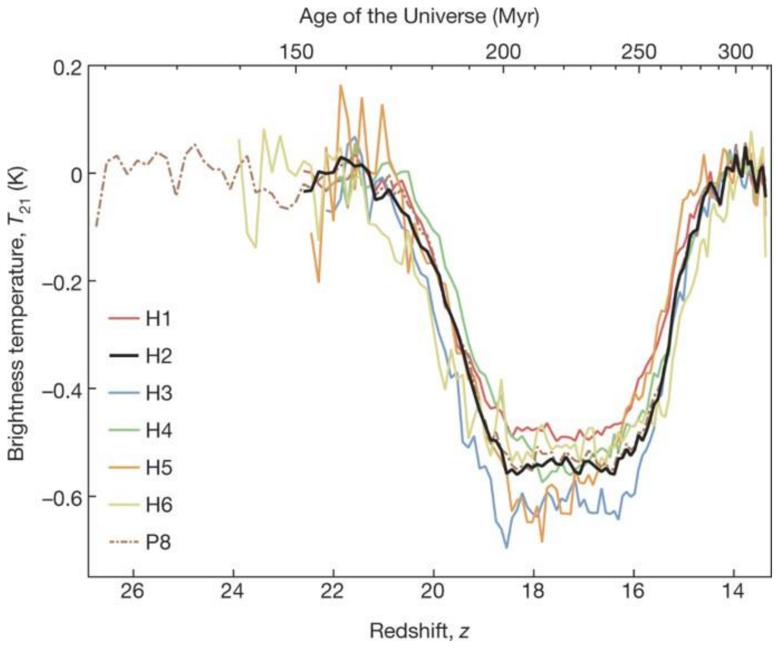
Image credit: https://github.com/EoRImaging/eor_limits

Currently limited by foregrounds and instrument systematics.

PAPER64 - Kolopanis et al. 2019, Cheng et al. 2018
MWA – Dillon et al. 2014, Beardsley et al. 2016, Barry et al. 2019, Li et al. 2019
LOFAR - Patil et al. 2017, Mertens et al. 2020
OVRO-LWA – Eastwood et al. 2019

Very recent results from HERA





HERA Collaboration (2022) at odds with

Bowman et al. (2018)

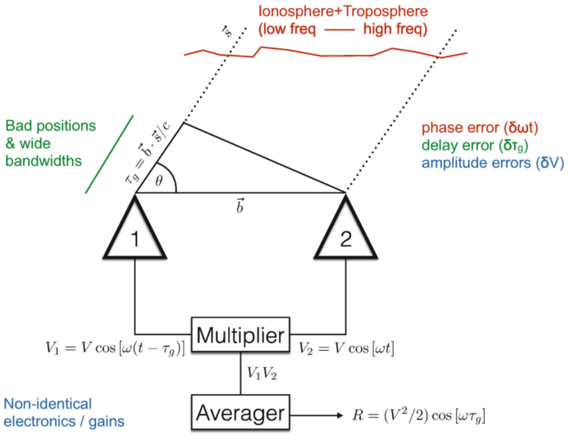
Challenges

- Knowledge and behavior of foregrounds – point sources and diffuse emission
- Control of wide-field "pitchfork" effects
- Careful aperture design
- Control of antenna beam chromaticity
- Control of reflections in instrument
- Control of antenna positions
- Careful system design

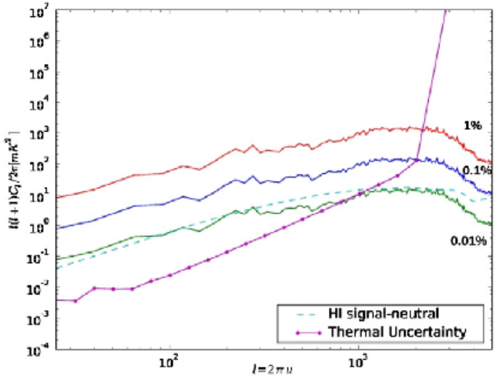
And more challenges

- Calibration Accuracy
- Precise Instrument Design & Knowledge
- Polarization Leakage compounded with wide-field effects?
- Recombination lines ignored?
- Antenna-to-antenna variations in beam and signal path?
- Need for confirmation from independent techniques
- Cross-correlation with other approaches

Calibration Challenges



$$\mathcal{V}^{m}_{i,j} = G_i G_j^* \mathcal{V}^{s}_{i,j} + N_{i,j}$$



Datta et al. (2010)

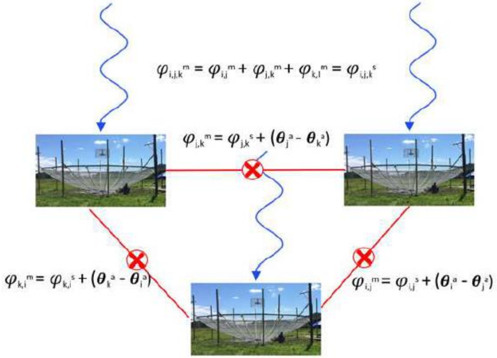
Calibration Precision ~10^{-5}

Thorough knowledge of foregrounds and instrument required to achieve this precision

Similar conclusions from …

- Trott & Wayth (2016) for MWA and SKA
- Patil et al. (2017) for LOFAR
- …
- Sophisticated calibration strategies are required (Dillon et al. 2017; Orosz et al. 2018; Byrne+ 2020)

Interferometric Solution to Calibration Woes



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

Phase of bi-spectrum (closure phase)

$$\mathcal{V}^{\rm m}_{i,j} = G_i G_j^* \mathcal{V}^{\rm s}_{i,j} + N_{i,j}$$

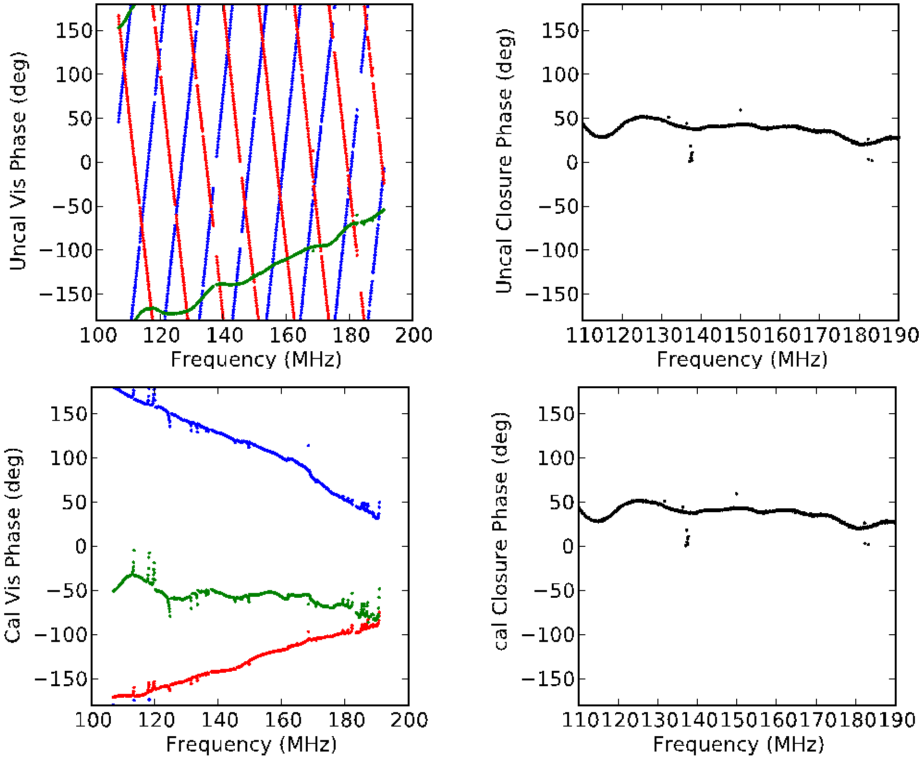
$$C^{\rm m}_{i,j,k} = \mathcal{V}^{\rm m}_{i,j} \mathcal{V}^{\rm m}_{j,k} \mathcal{V}^{\rm m}_{k,i}$$

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

Used in radio interferometry since 1950s

Jennison (1958)

Closure Phase Independent of antenna calibration and its errors



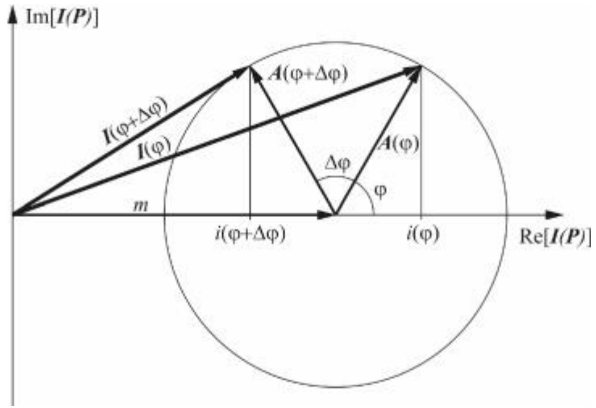
Carilli, Nikolic, **NT** et al. (2018)

Small Perturbations to Closure Phase

$$\delta\theta_0 \approx \frac{|Z_1|}{|Z_0|}\sin(\theta_1 - \theta_0) = \Im\left\{\frac{Z_1}{Z_0}\right\}$$

EoR HI

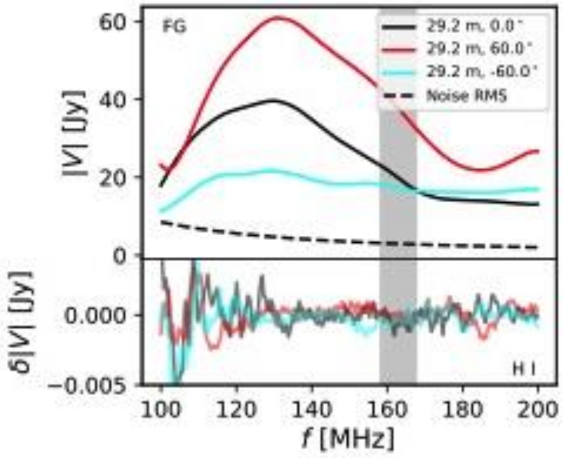
Foregrounds



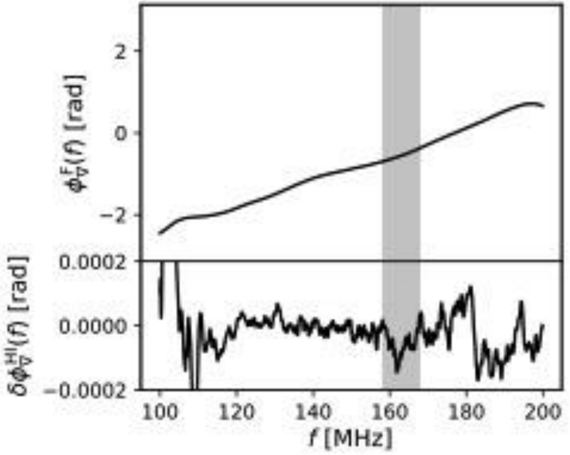
Thyagarajan+ (2018)
Thyagarajan & Carilli (2020): PRD, 102, 022001

Closure phase spectrum

Visibility Fluctuations



Closure Phase Fluctuations

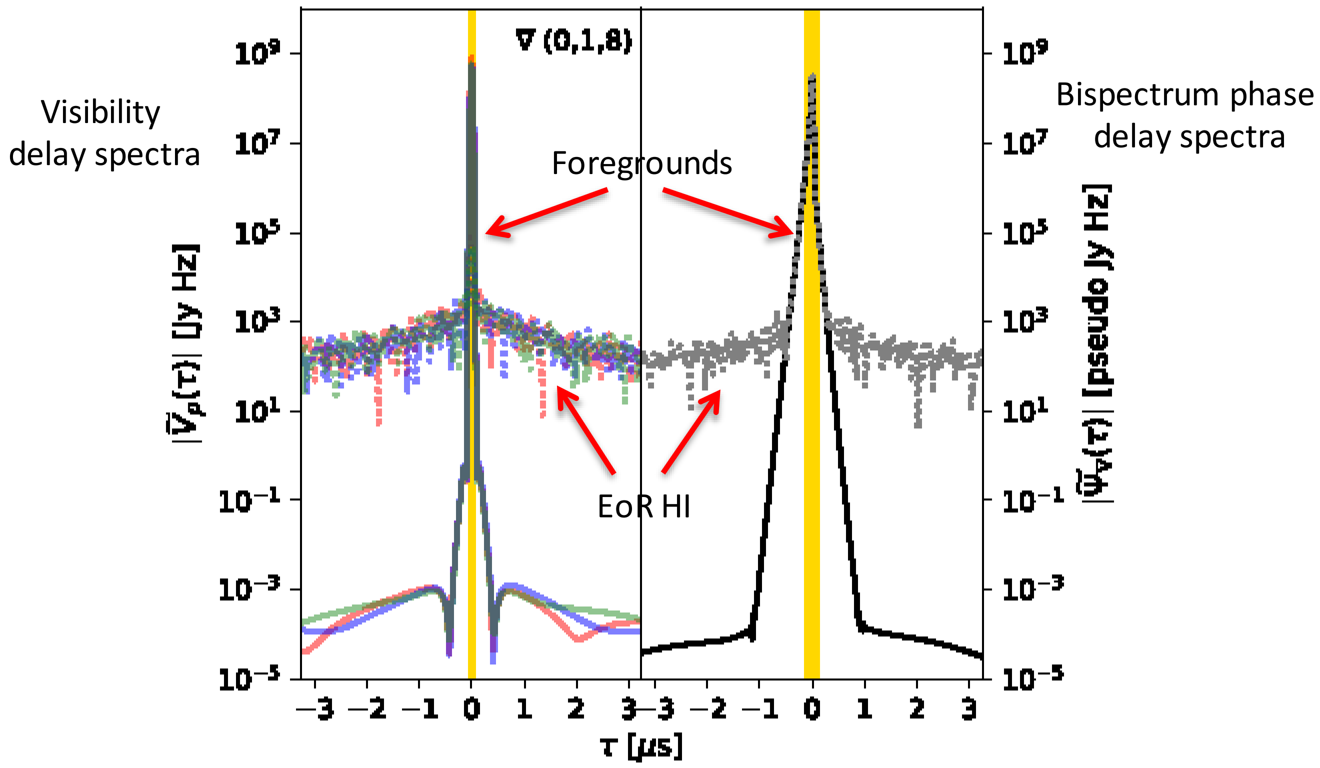


Thyagarajan et al. (2020): PRD 102, 022002

Good correspondence between fluctuations.

Shape, Dynamic range, Sensitivity, etc.

Fluctuations in Visibility vs. Bispectrum Phase (Realistic GLEAM foreground + 21cmfast EoR HI)

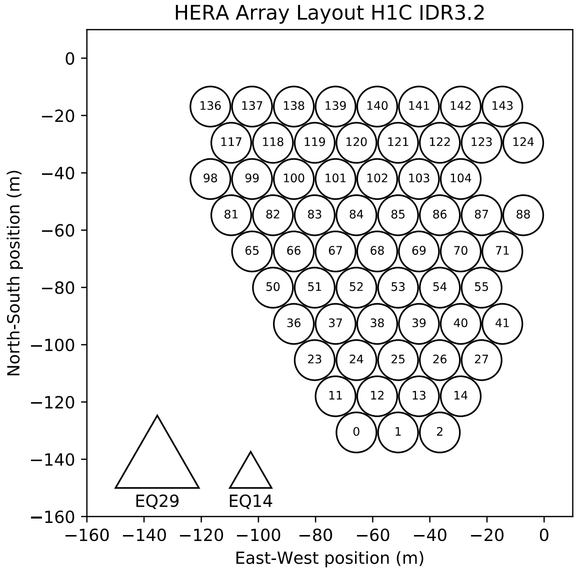


Thyagarajan & Carilli (2020): PRD, 102, 022001

Data

- Small subset of HERA data from first observing season in 2018
- 61 dishes in total (50 good ones selected for analysis)
- 2 fields (Fornax A transit and J0136-30)
- 31 triads (29.2m equilateral)
- 2 fields x 18 nights x 22 min x 31 triads x 2 pol
- Data is essentially raw and uncalibrated
- Visually low-RFI spectral window (ΔB~10 MHz around 163 MHz) but no RFI flagging except median filtering (so RFI may still be present)

HERA layout



HERA Data Analysis Approach

- Data analysis paralleled by forward modeling
- Models verified to match data to first order using visibilities, images, etc. (Carilli, **NT**, et al. 2020)
- Set up expectations with standard delay spectrum approach as reference
- Same mathematical formalism as in delay spectrum approach
- Analysis with and without assumption of redundancy in triad measurements

Models (from PRISim)

Thyagarajan et al. (2020): PRD 102, 022002

HERA Instrument

- 61 dishes matching data
- Identical Beams: Fagnoni et al. 2019
- On-site layout (including non-redundancy)
- Effective Area: 100 m^2 in the spectral window

Foregrounds

- 30 deg. of GLEAM (J0136-30 field)
- 30 deg. Of GLEAM + Fornax A (Fornax field) from Byrne/FHD
- No diffuse emission due to large uncertainties

EoR HI

- 21cmFAST lightcone cubes
- 'Faint Galaxies' from Greig & Mesinger 2017
- Original 1.6 Gpc (~10 deg.) smoothed to 14' angular resolution and tiled to 30 deg on each side.

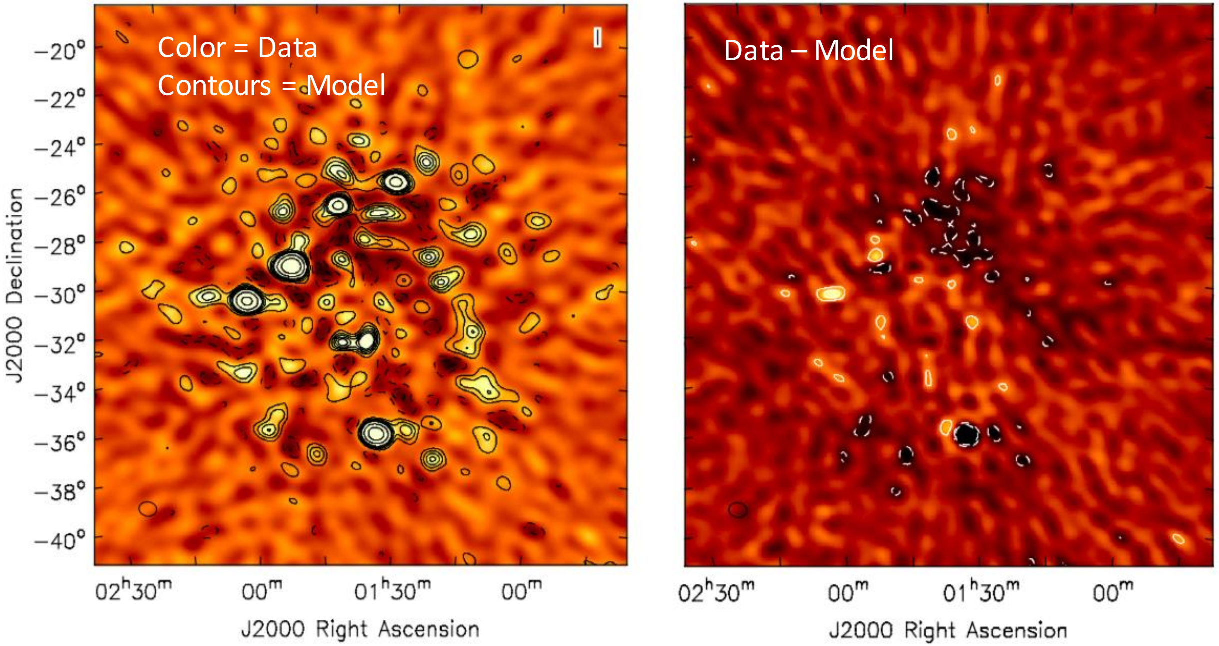
Noise

- $T_{sys} = T_{rx} + T_{ant}(f_0)\,(f/f_0)^{\alpha}$, f_0=150 MHz
- T_{rx} = 162 K, $T_{ant}(f_0)$ = 200K, $\alpha = -2.55$
- Consistent with HERA memos 59-60
- Still some uncertainty but not significant for this amount of data.

PRISim – simulator for wide-field radio interferometry

https://github.com/nithyanandan/PRISim

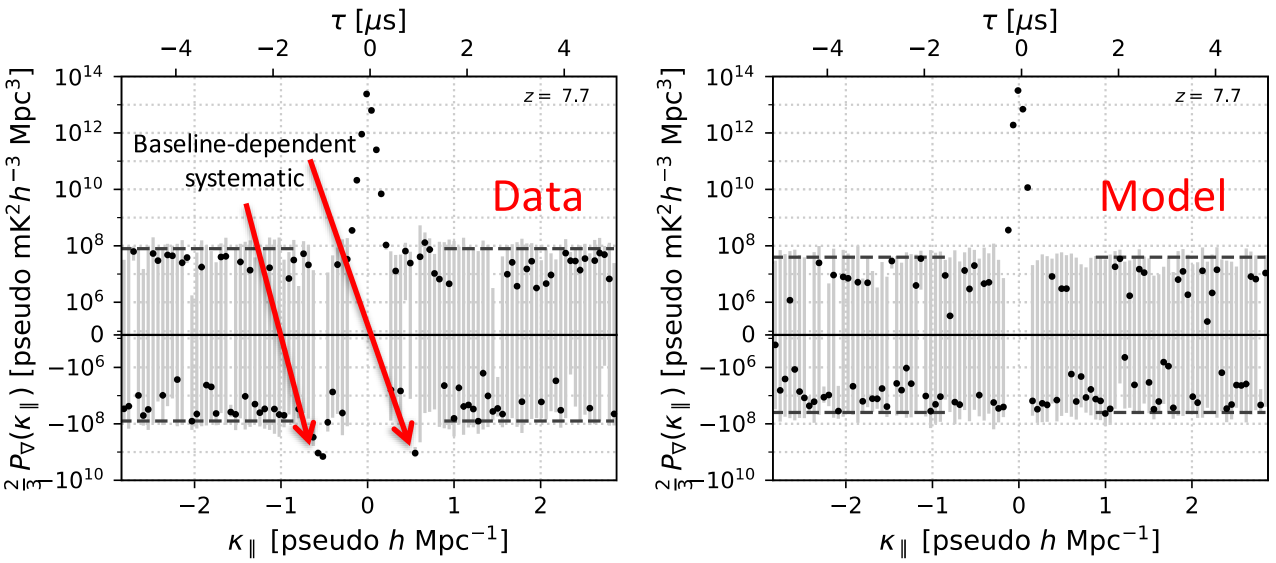
Model – Data Agreement



Carilli, **NT**, et al. 2020

- Good agreement model and data to in-beam confusion limit
- Difference large scale residuals => Diffuse Galactic Emission (not in model)

Results on J0136-30 field

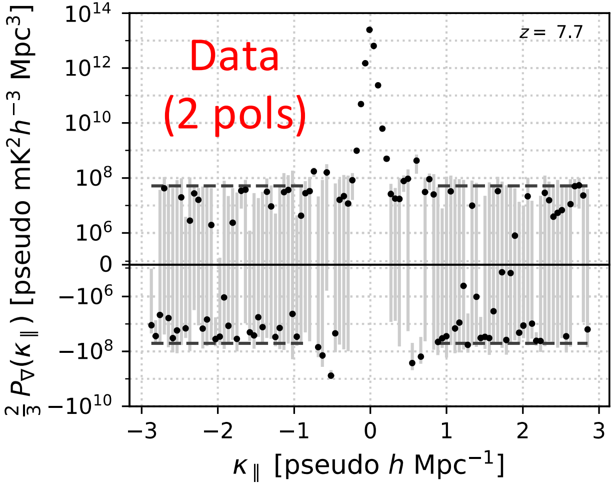


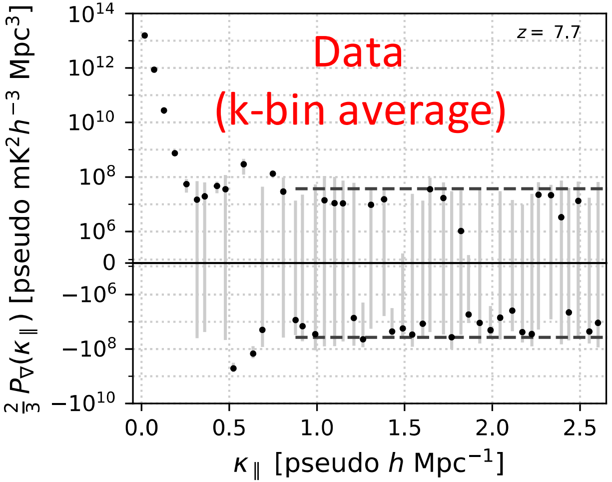
(a) Data

(b) Model

Thyagarajan & Carilli (2020): PRD, 102, 022002

Incoherent Averaging in Power





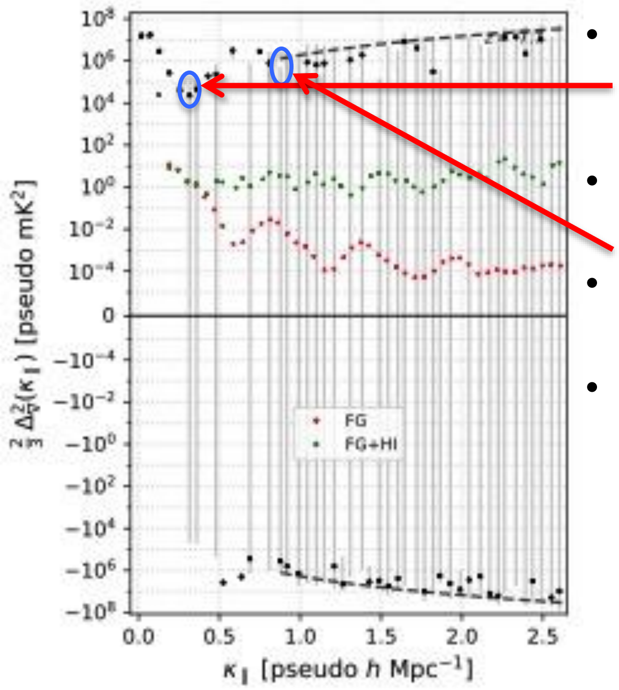
Average over polarizations

Average over k-bins

Thyagarajan & Carilli (2020): PRD, 102, 022002

- Average over polarizations and k-bins each improve noise floor by a factor 1.4
- The baseline-dependent systematic bump at $k_{||} = 0.5$ h Mpc^{-1} is reduced
- Room for improvement with more data

Power Spectrum Results



- $\Delta^2 <$ (316 pseudo-mK)^2 ($k_{||}$ = 0.33 h/pseudo-Mpc) but surrounded by systematic-limited bins
- $\Delta^2 <$ (1000 pseudo-mK)^2 ($k_{||}$ = 0.875 h/pseudo-Mpc) surrounded by noise-limited bins
- Dynamic range between FG peak and HI power similar to standard delay PS
- Still a long way to go but hoping good quality data with HERA will get us to interesting constraints (improved results coming soon!)

Thyagarajan & Carilli (2020): PRD, 102, 022002

Summary

- Independent approach and constraints using bispectrum phase
- Bypasses the important problem of antenna-based calibration systematics but other systematics may remain
- Simple analysis using simple delay/Fourier-domain techniques on raw, uncalibrated data
- Dynamic range for spectral distinction is similar to standard approaches
- Using a subset of data and corresponding forward-models, we've shown it to be data-limited
- High quality data with full HERA season 1 data will definitely improve sensitivity by a factor of ~30-90 towards making interesting constraints (even if not an outright detection)

References:

Thyagarajan, Carilli, Nikolic (2018), PRL, 120, 251301

Carilli, Nikolic, Thyagarajan, et al. (2018), Radio Science, 53, 845

Thyagarajan & Carilli (2020), PRD, 102, 022001

Thyagarajan et al. (2020), PRD, 102, 022002

Carilli, Thyagarajan, et al. (2020), ApJS, 247, 67