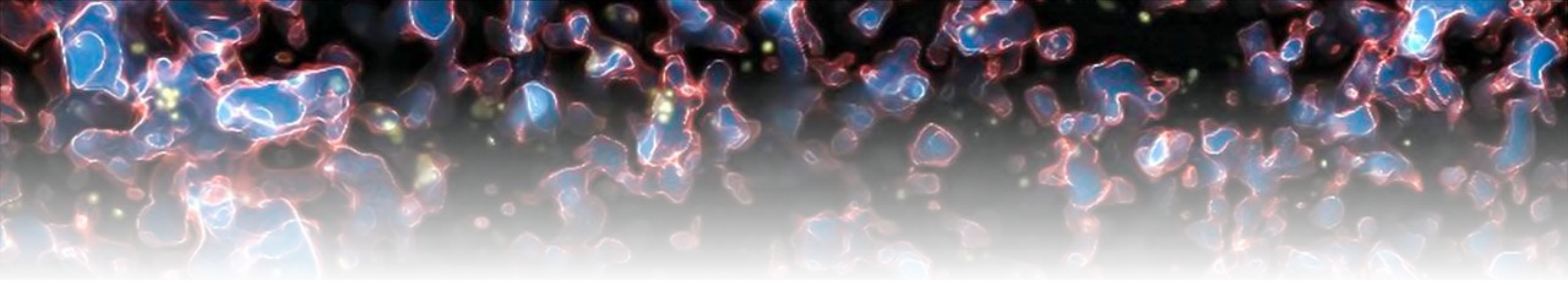

Instrumental Systematics for HERA

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Wisconsin 21 cm Workshop

Preliminaries

• Terminology may be specific to the EoR, but technical challenges are generally similar for low and high-z telescopes

• In some cases (for coupling mitigation), the techniques described assume drift-scan observations

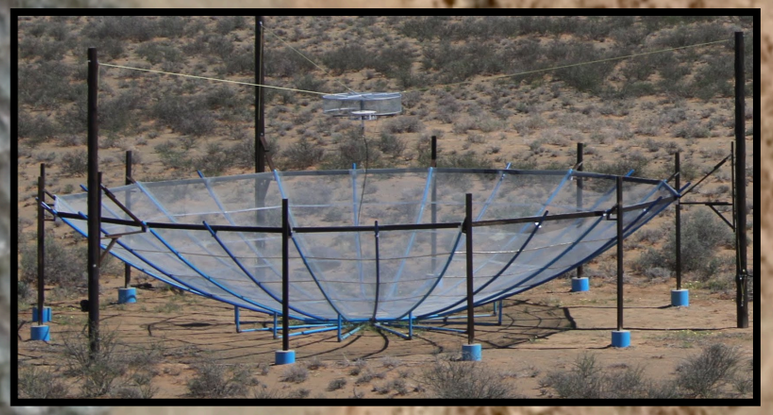
- Calibration -> direction-independent calibration

- “fringe-rate” is the Fourier dual to observing time (e.g. LST)

Hydrogen Epoch of Reionization Array

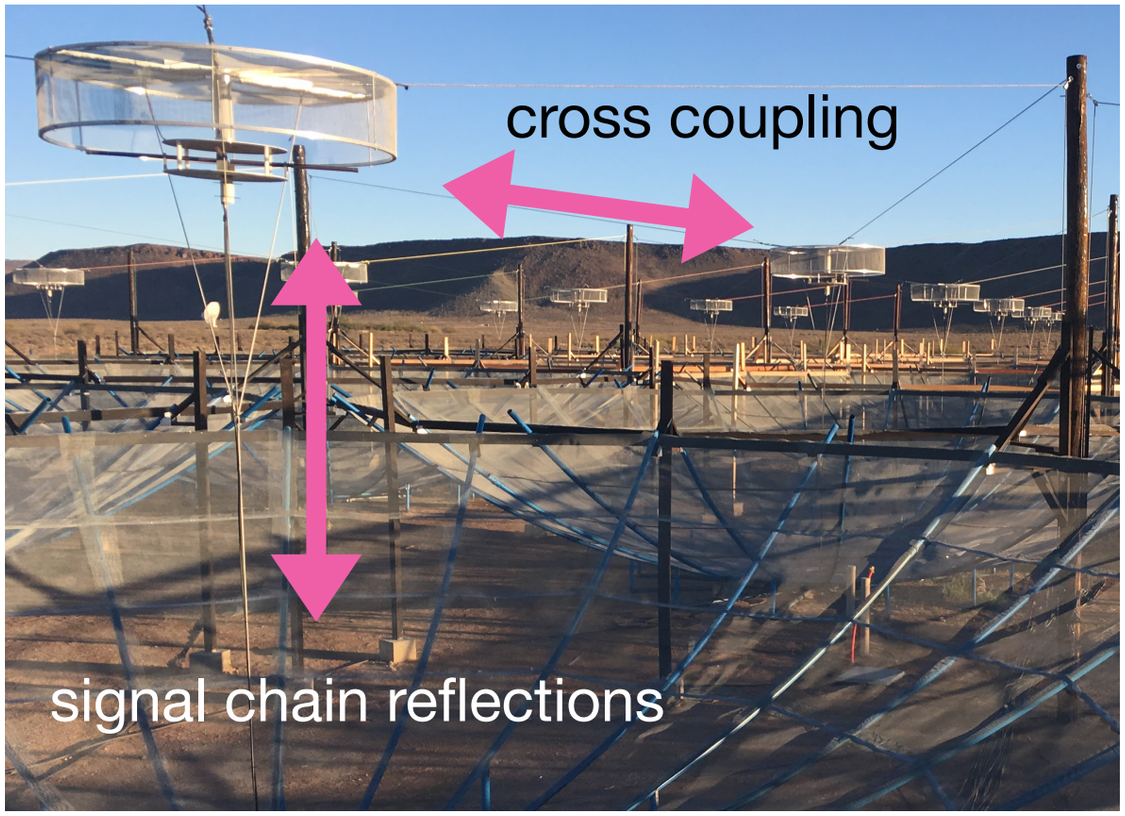
- 350 14-m dishes (0.05 km^2) DeBoer et al. 2017
- Observing 50 - 250 MHz (4.7 < z < 27.4)

300 m



Phase I & II: two distinct telescopes

Phase I dipole with cage
(retired 2018)



150 m coax -> AMP -> 20 m coax

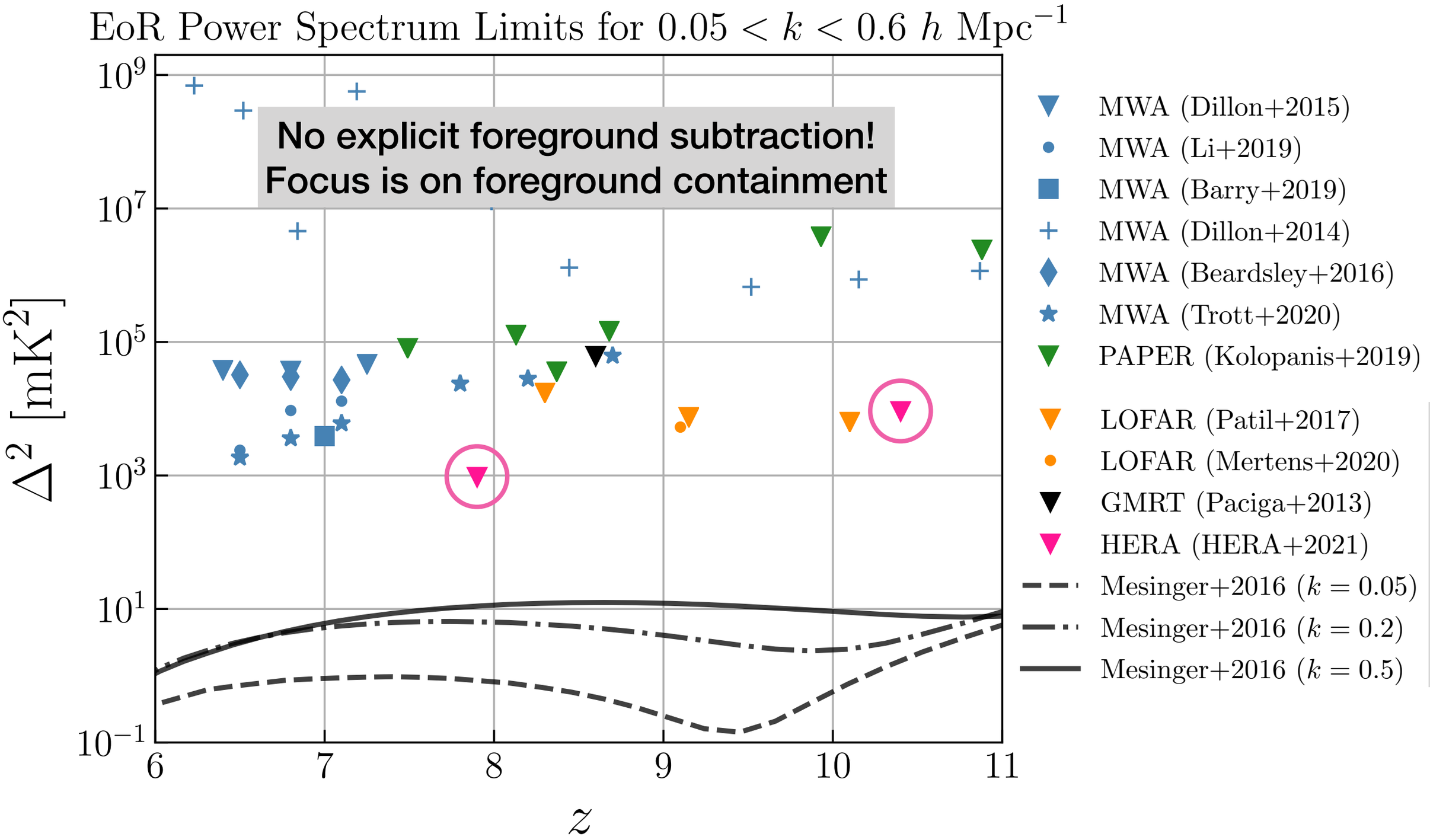
DeBoer et al. 2017, Fagnoni et al. 2019

Phase II Vivaldi w/o cage
(present)

500 m optical fiber

Fagnoni et al. 2021

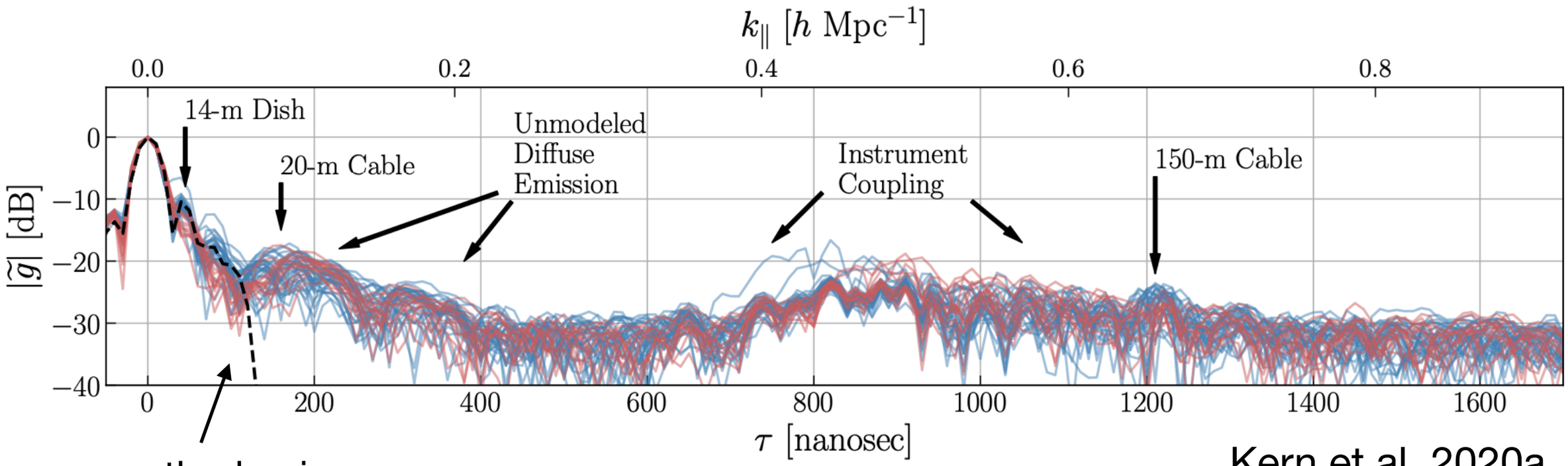
Context: HERA's recent limits (Phase I)



HERA Collaboration 2022a, 2022b

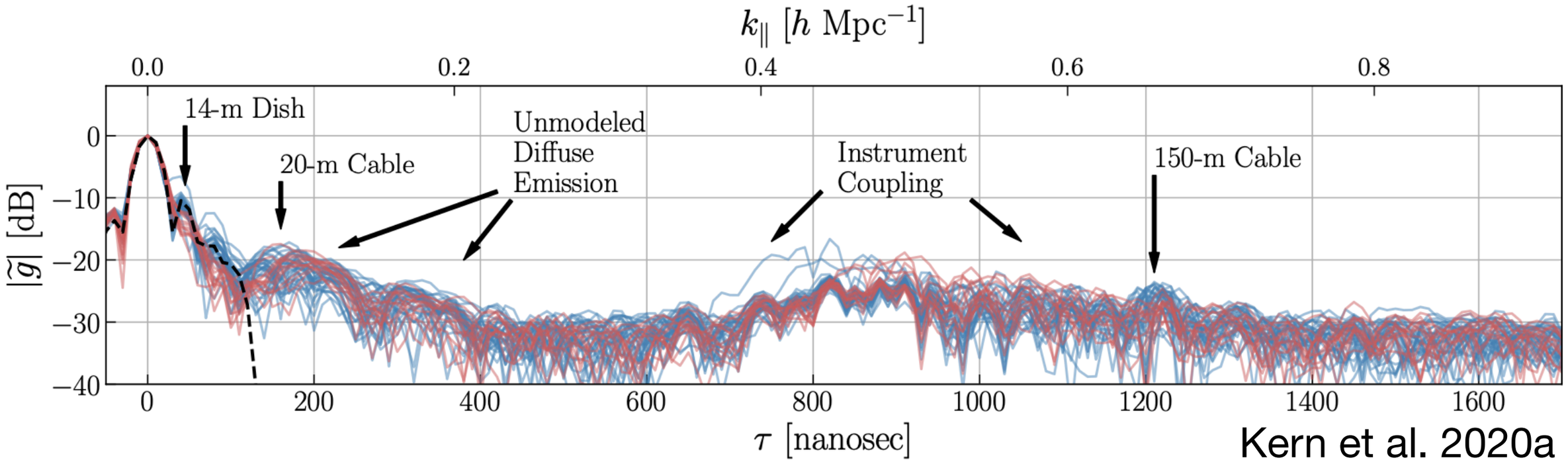
Phase I systematics

Fourier transform of the gains show the limiting systematics



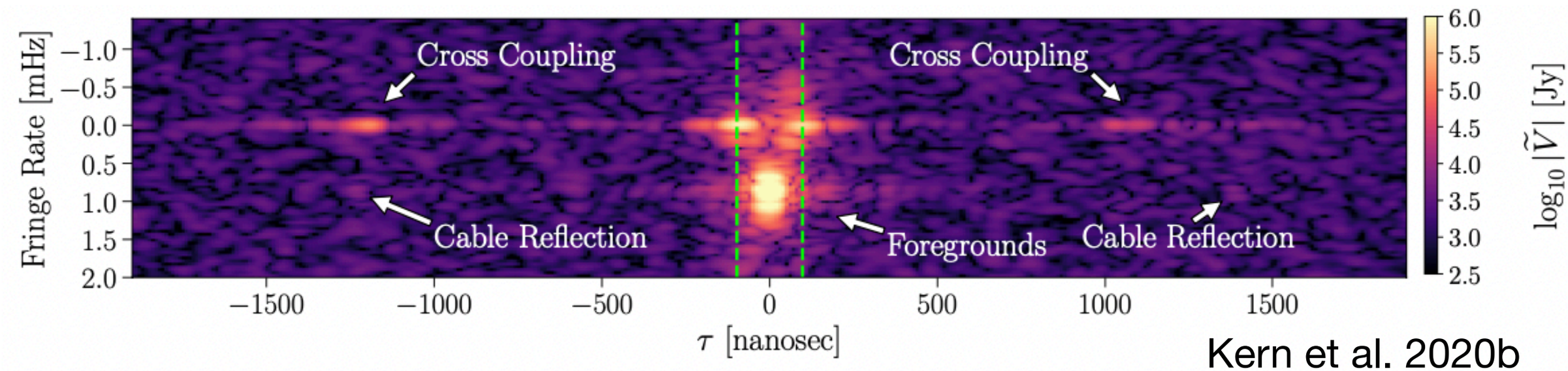
Kern et al. 2020a

Phase I systematics



Kern et al. 2020a

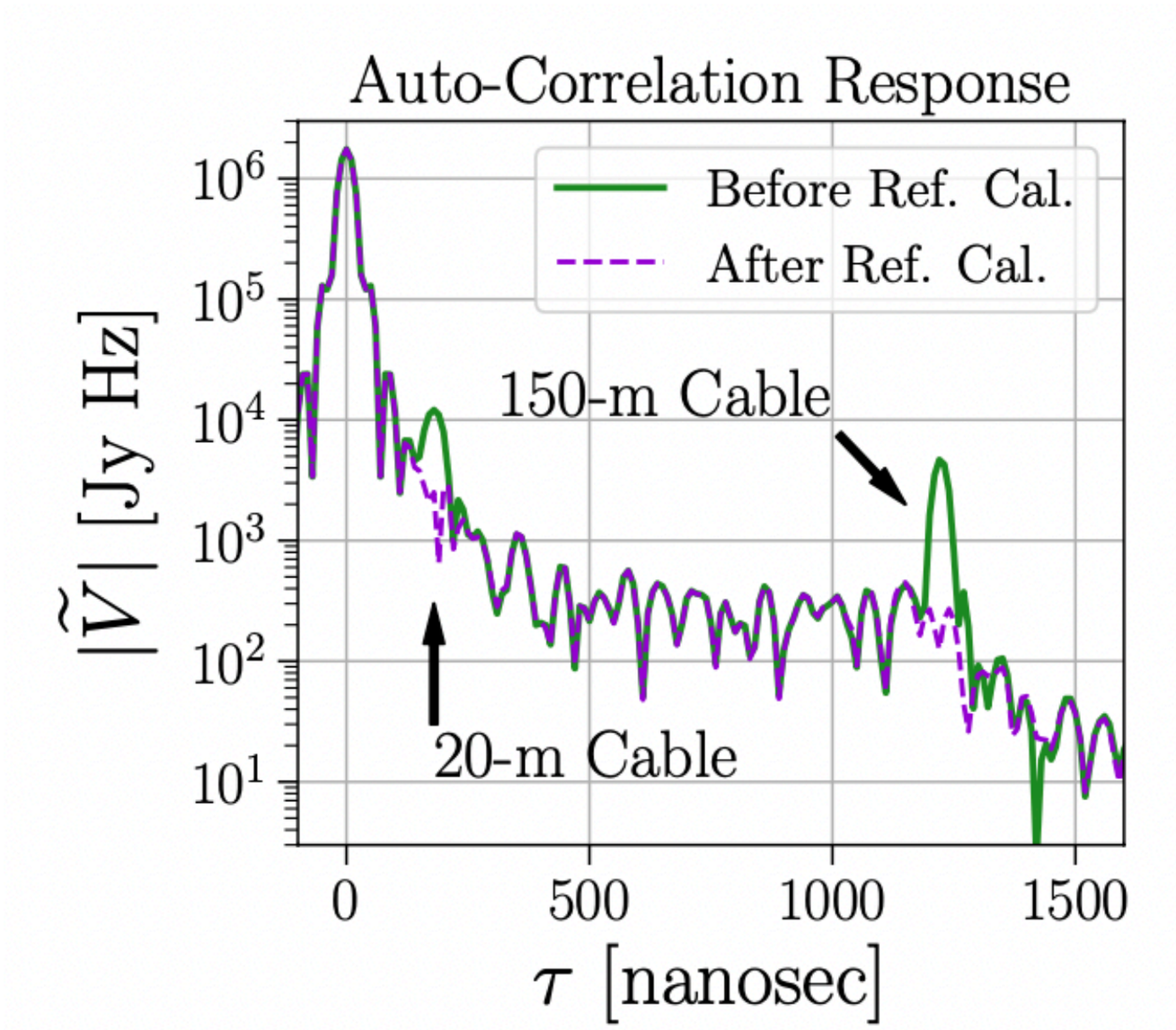
Visibilities show the impact of cross coupling in Phase I



Kern et al. 2020b

Reflections: autocorrelation peak finding

• Derive per-antenna reflection parameters which are combined with the smoothed gains
• Autos have high SNR, and have minimal overlap with cross corrs

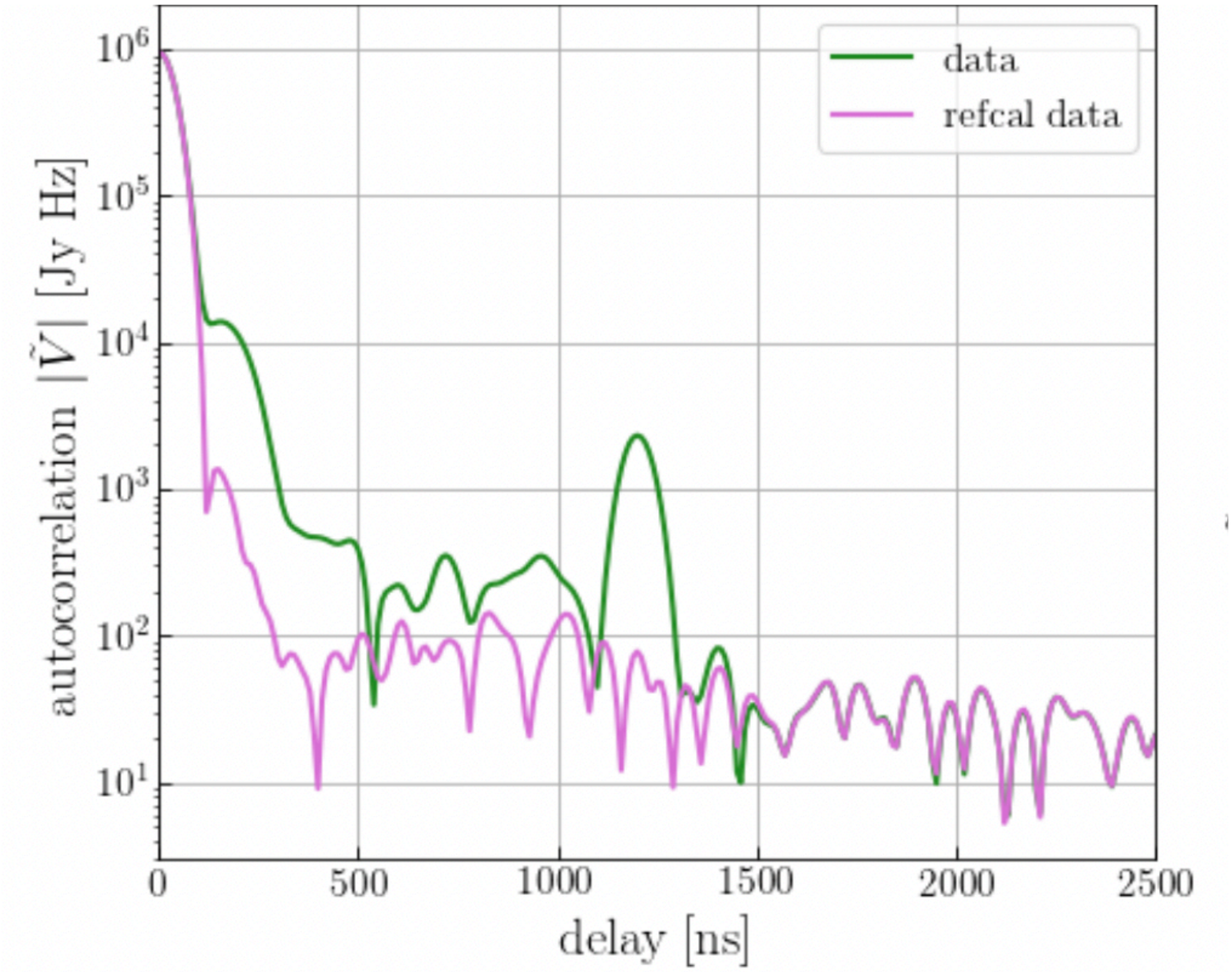


$$A_{11}e^{2\pi i\tau_{11}\nu+i\phi_{11}}$$

Kern et al. 2020b

Reflections: autocorrelation peak finding

- Can include more terms to reduce “shoulder”

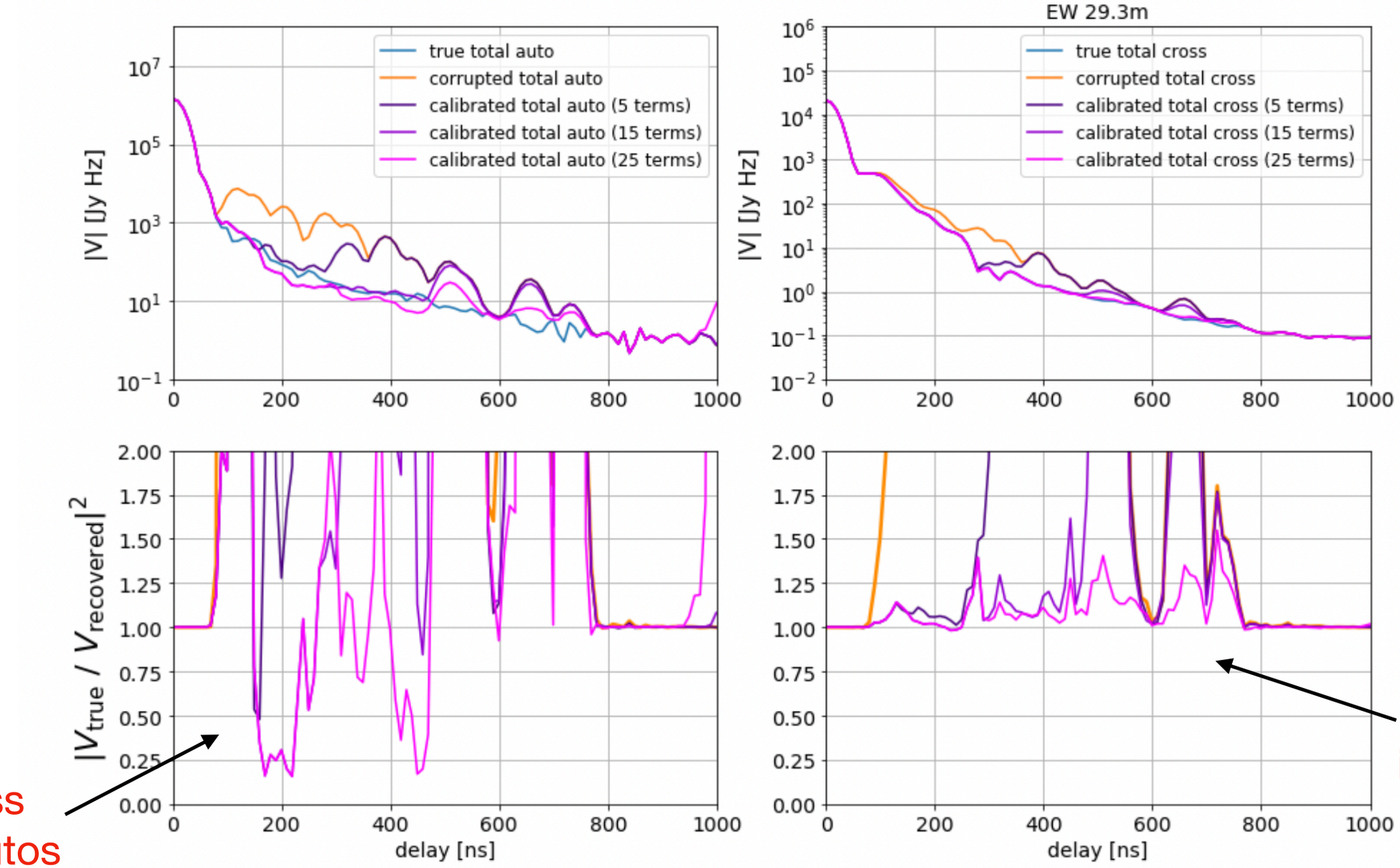


Reflections: autocorrelation peak finding

- Extra degrees of freedom not lossy in cross correlations

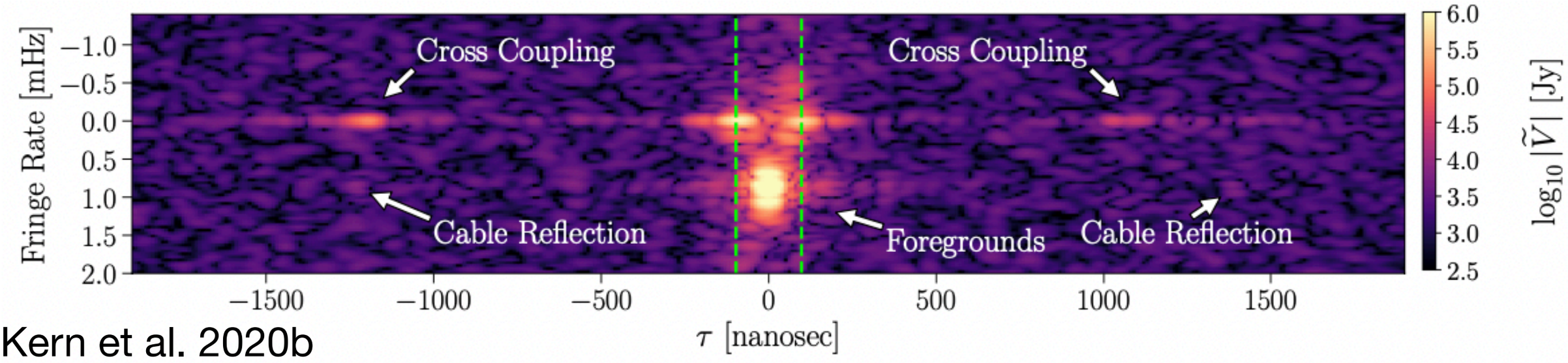
simulated auto correlations

simulated cross correlations



Phase I cross coupling model

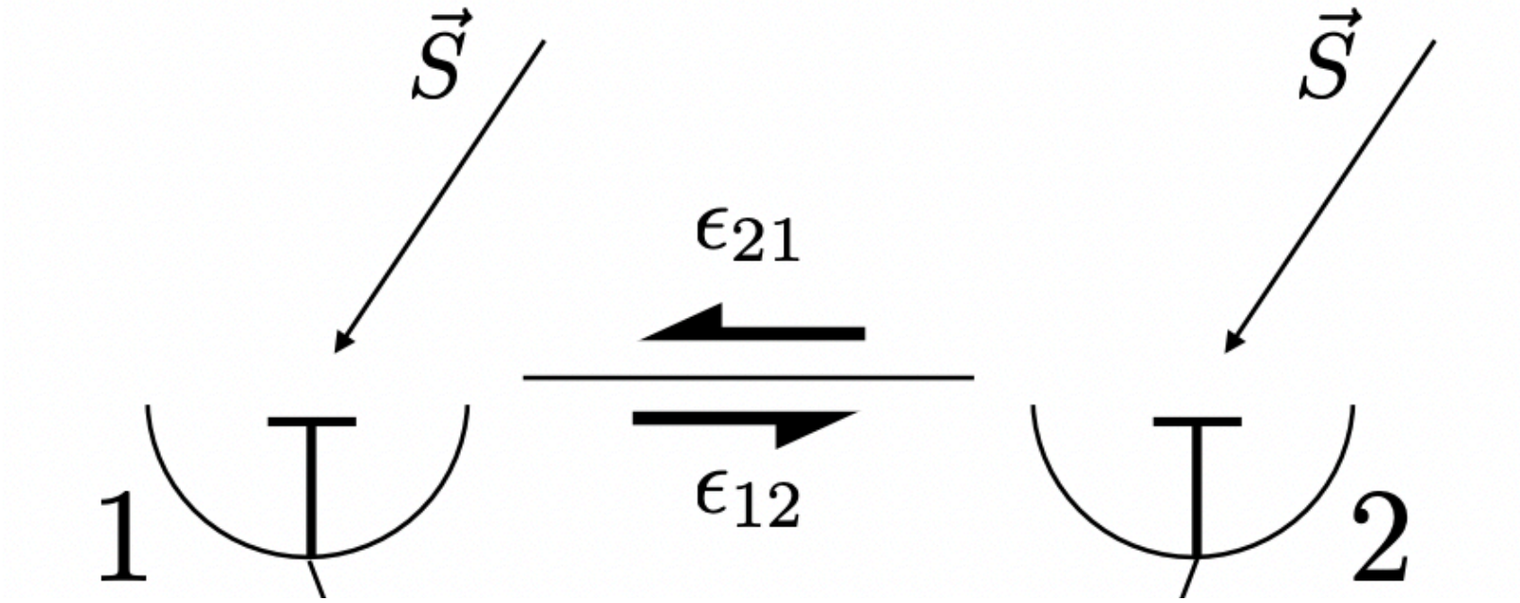
- The coupling systematic in Phase I visibilities is very bright
- Occupies a wide range of delays
- Confined to low fringe-rates



Kern et al. 2020b

Phase I cross coupling model

• The model that describes this is a coupling term in a two-antenna system



Kern et al. 2019

• This creates a copy of the auto-corr in the cross-corr, which explains the low fringe-rate footprint (autos are slowly time variable)

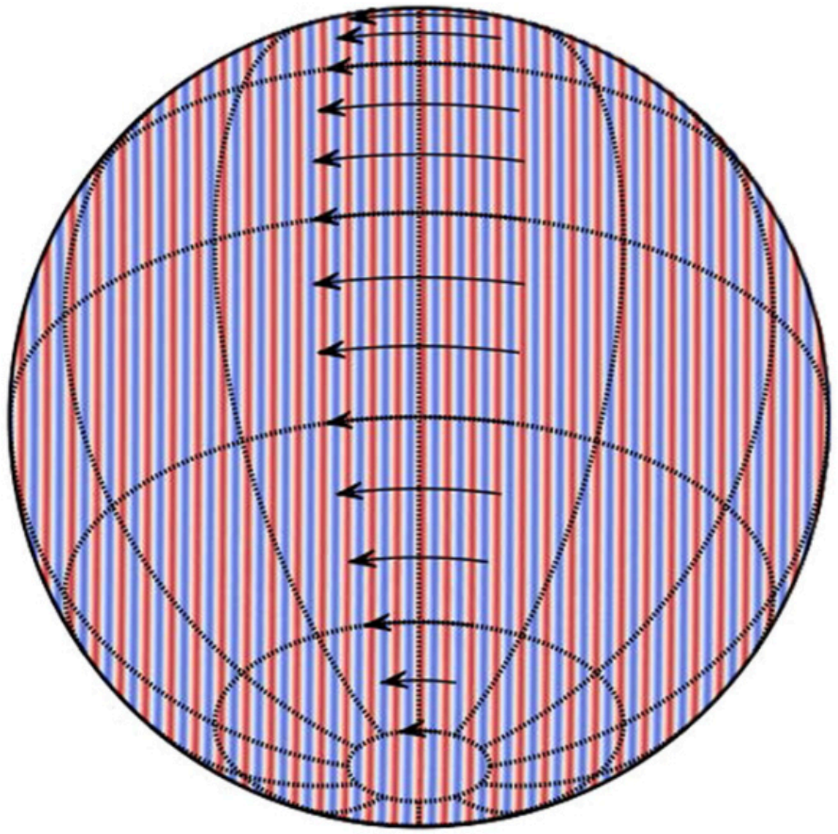
• Culprit was likely a malfunctioning node.

See Kern et al. 2019b (HERA Memo #64) and Dillon et al. 2022 (HERA Memo #104) for more details. See also Fagnoni et al. 2019 for mutual coupling EM sims.

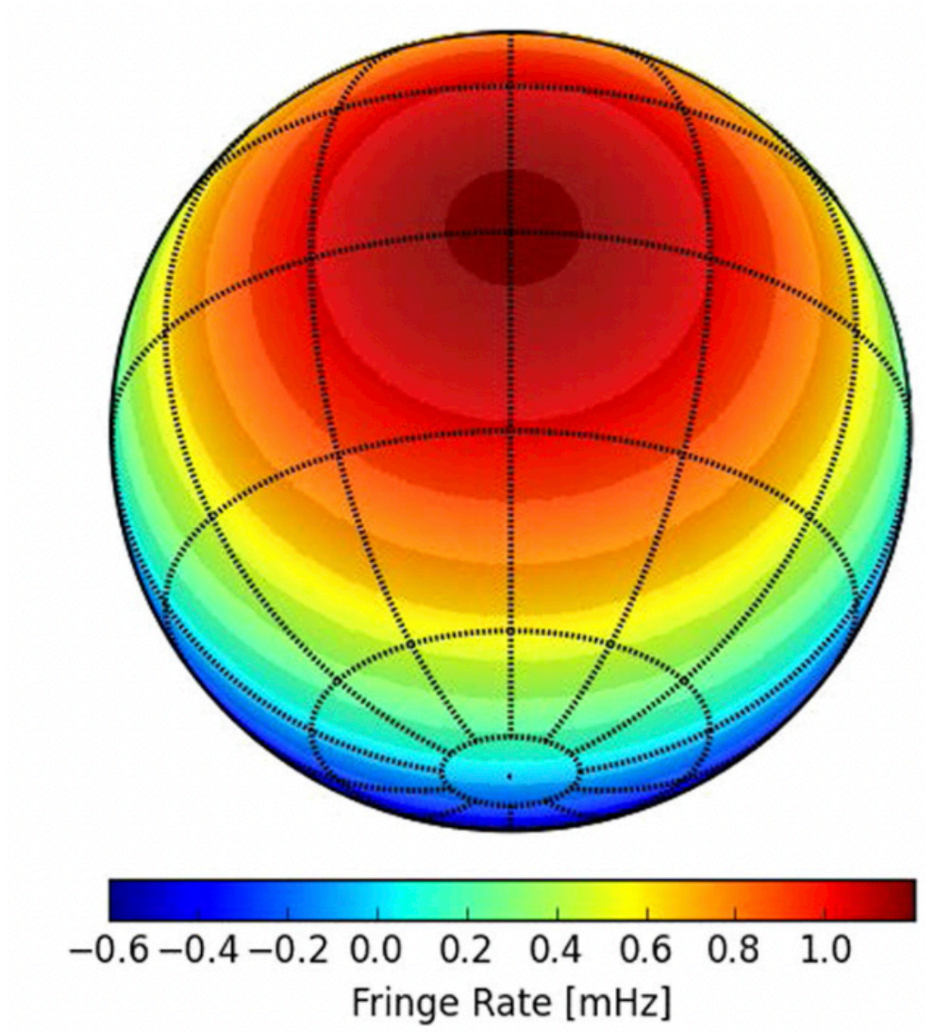
Fringe-rate filtering as a mitigation strategy

• For **drift-scan observations**, the sky moves through the baseline fringes, creating a distinct sinusoidal response

Fringe pattern on the sky for an East-West baseline



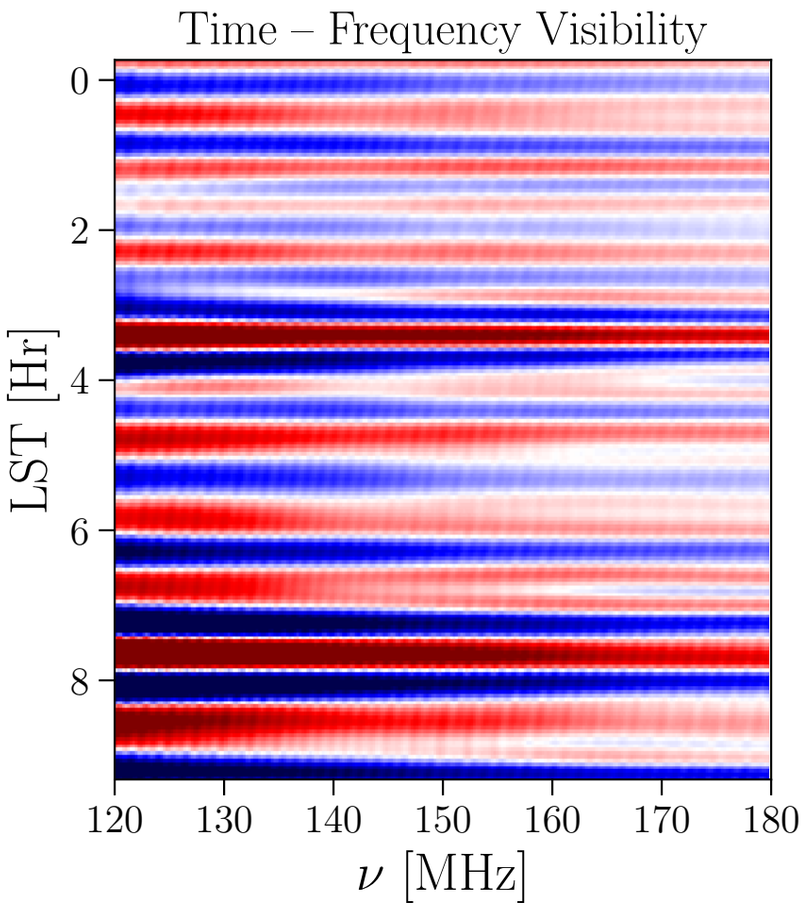
Effective fringe-rate in the visibilities

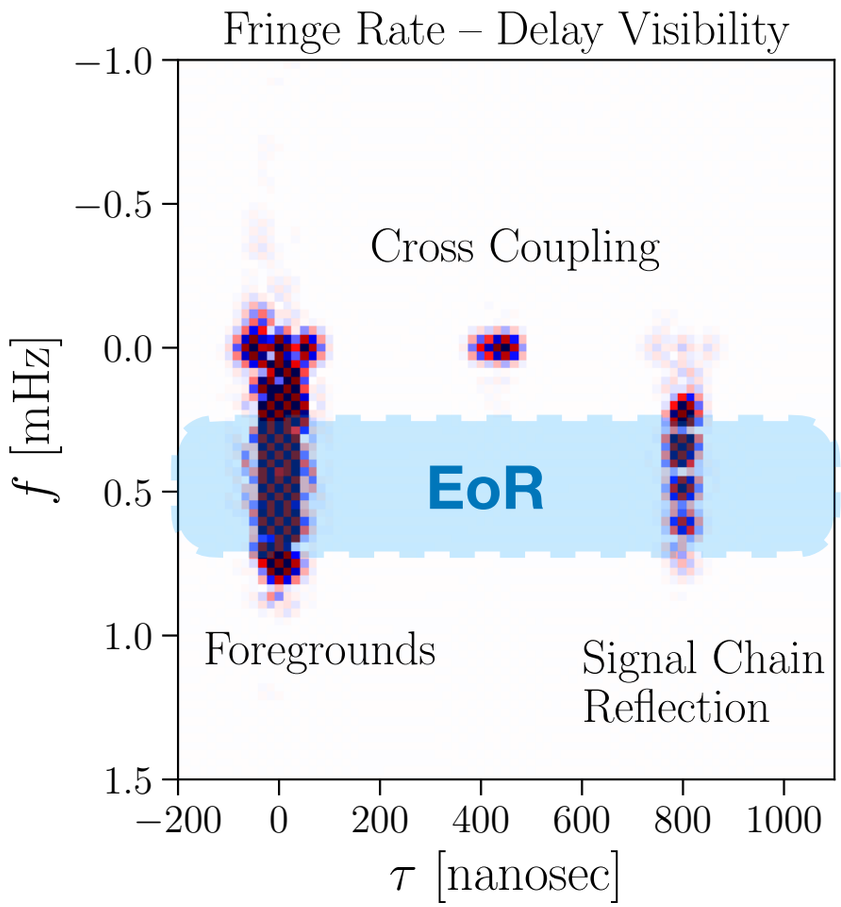


Parsons et al. 2016

Confirming intuition with simulations

Foreground visibility simulation for HERA but with the coupling terms included show expected footprint in fringe-rate & delay space



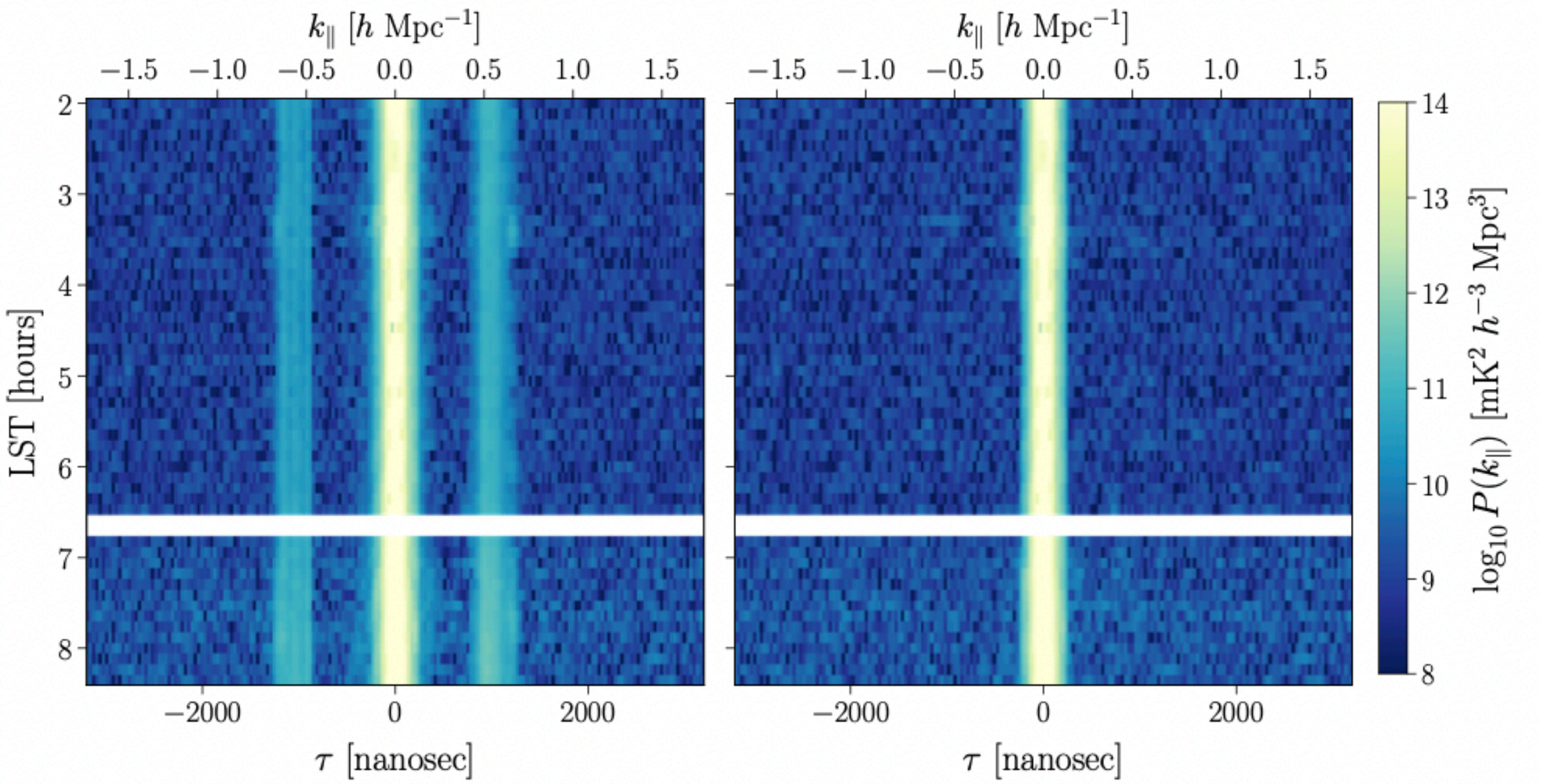


The actual algorithm is a combination of SVD to isolate specific delay modes and GPR to isolate the low-fringe rate modes. See Kern2019 for details.

Kern et al. 2019

Combined result on power spectra

Reflection and cross coupling mitigation enable high dynamic ranges recovery of the noise floor in integrated Phase I data



Kern et al. 2020b

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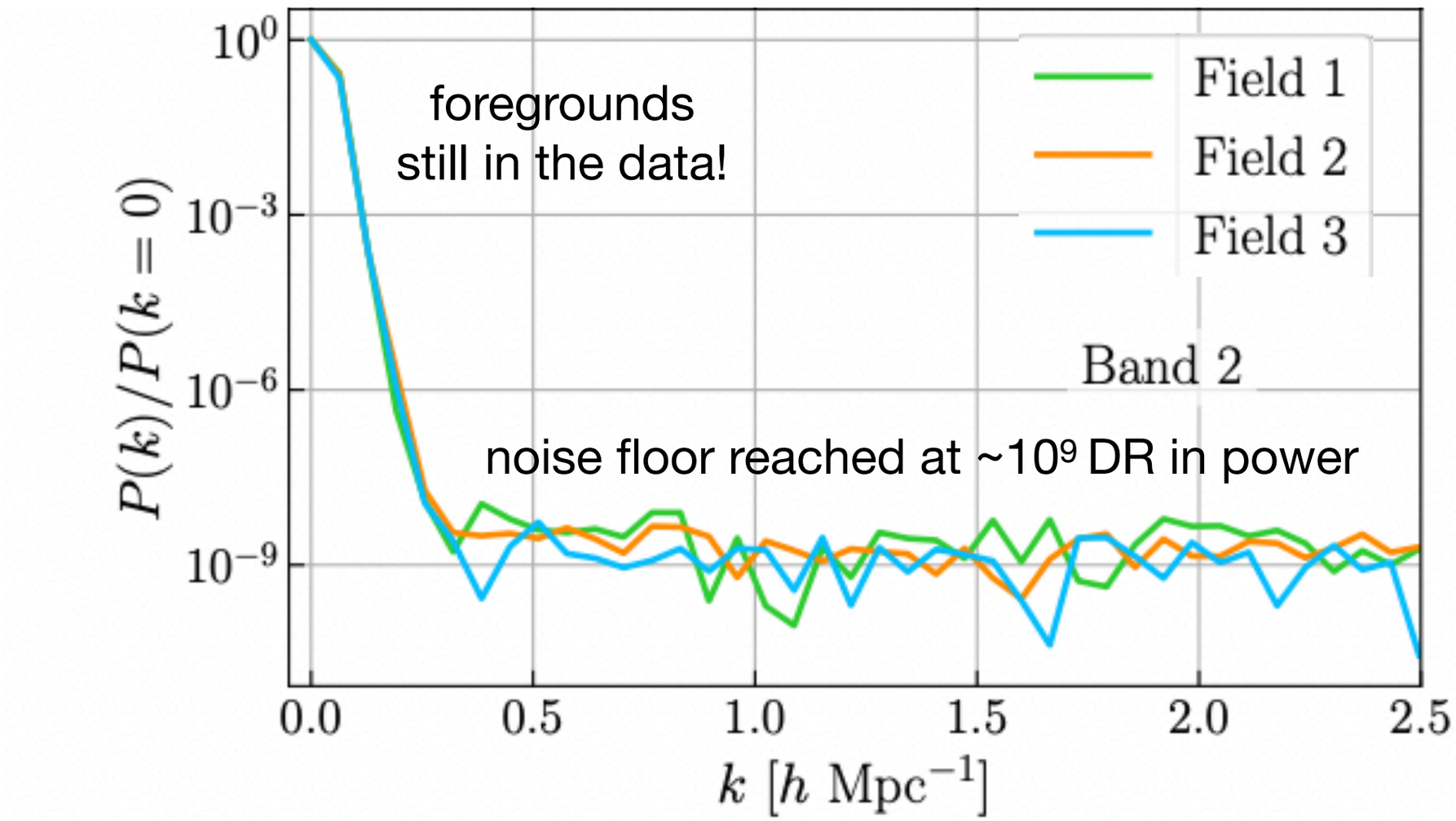
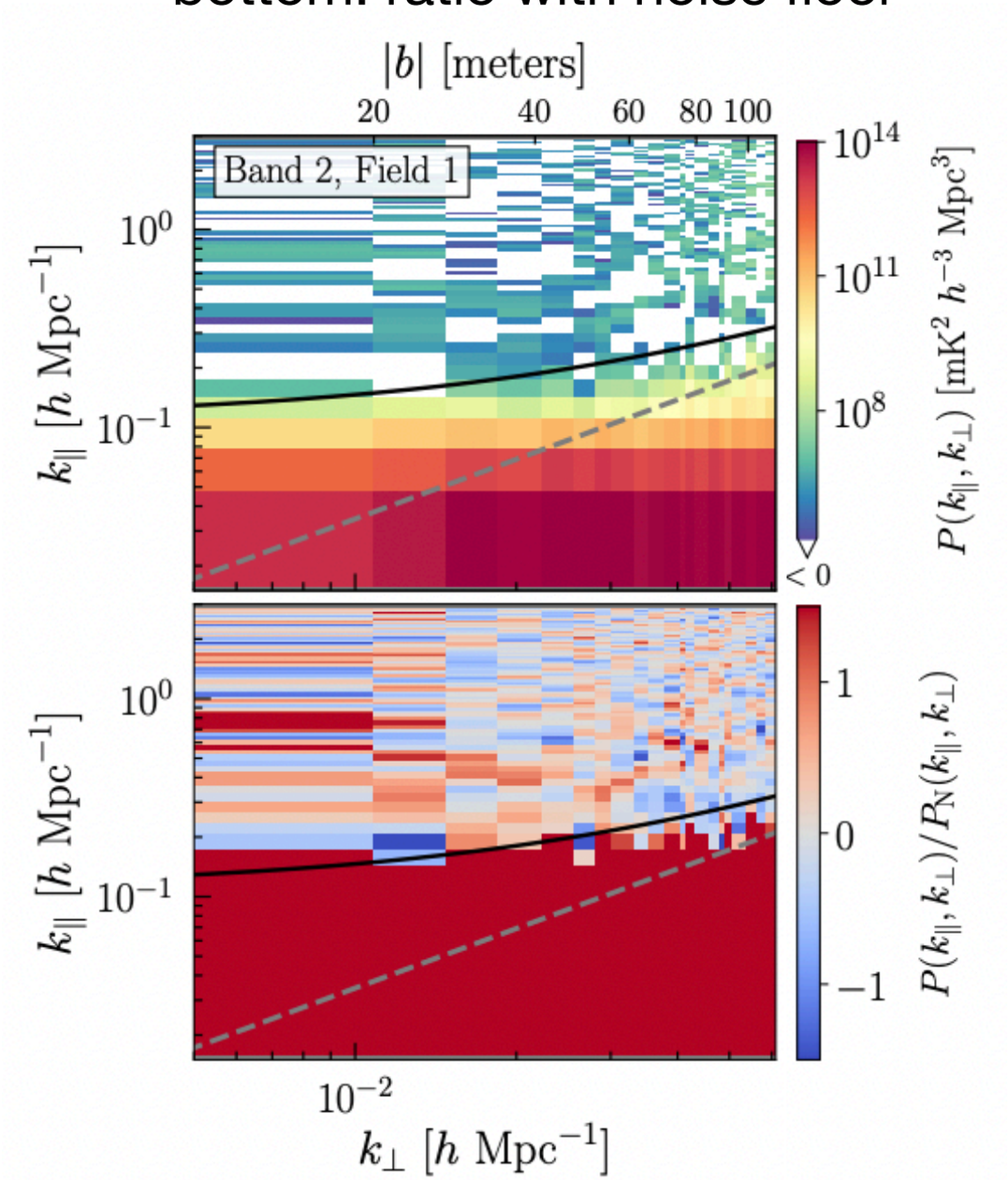


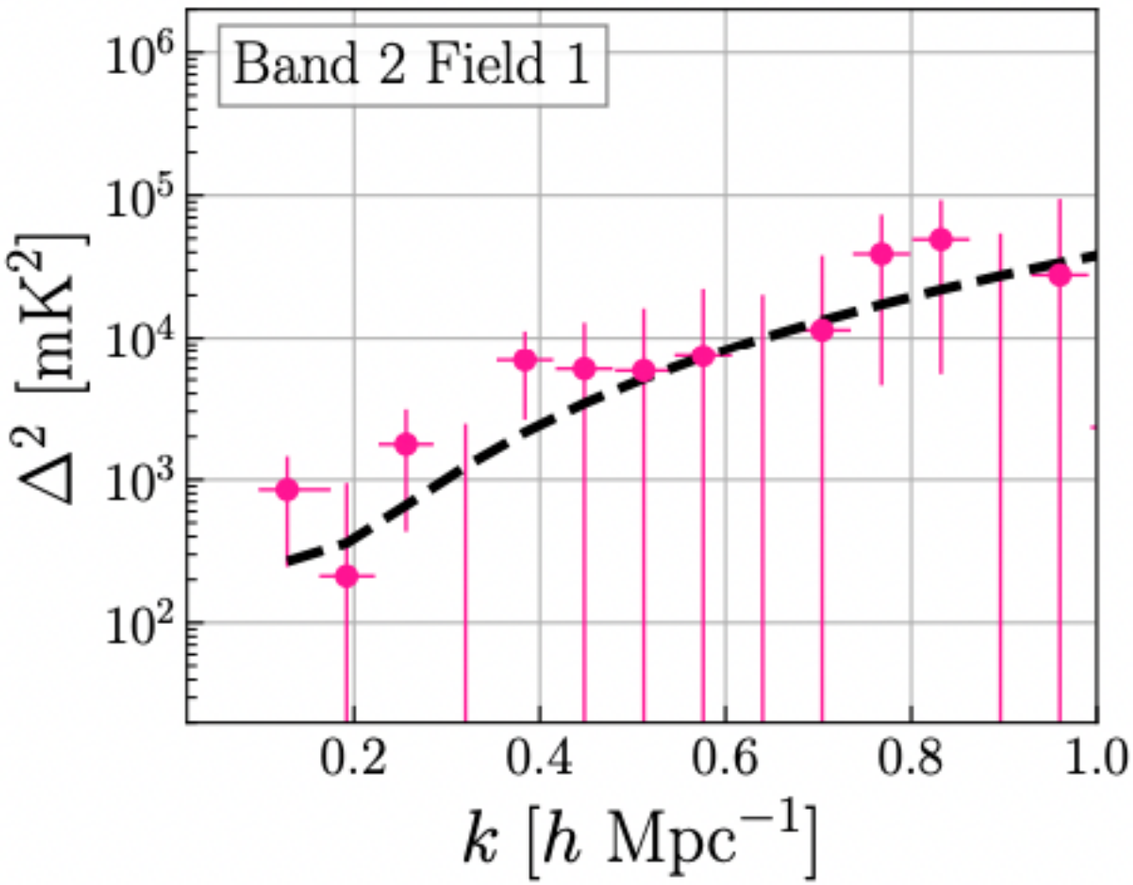
HERA Collaboration 2022a

Largely noise dominated outside wedge

2D power spectra for cleanest field
top: measured power
bottom: ratio with noise floor



1D power spectra yielding new limits
at low k, marginal systematic detections



HERA Collaboration 2022a

Phase II challenges

• No cage means less dish reflections, and no coax means less cable reflections

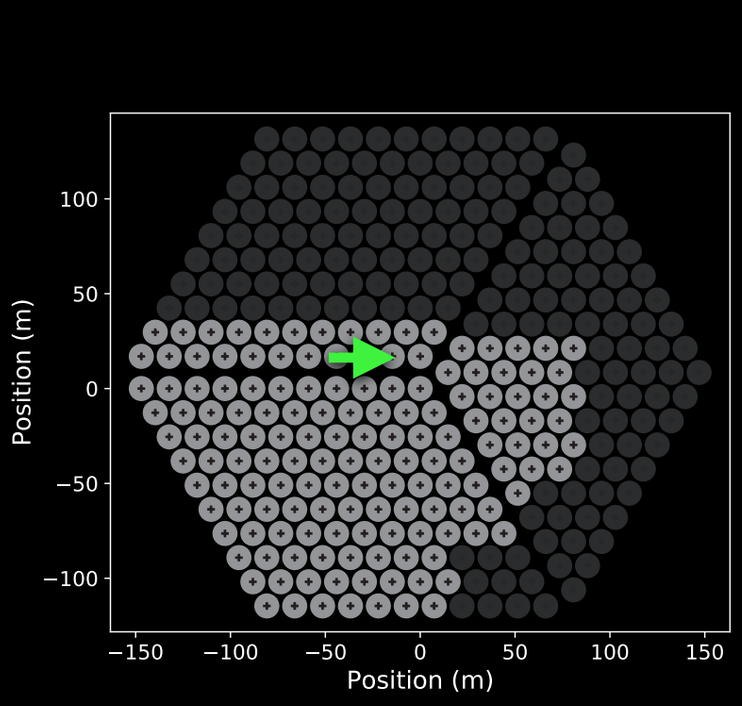
Phase II challenges

• No cage means less dish reflections, and no coax means less cable reflections
• However, Vivaldi structures are more exposed to each other

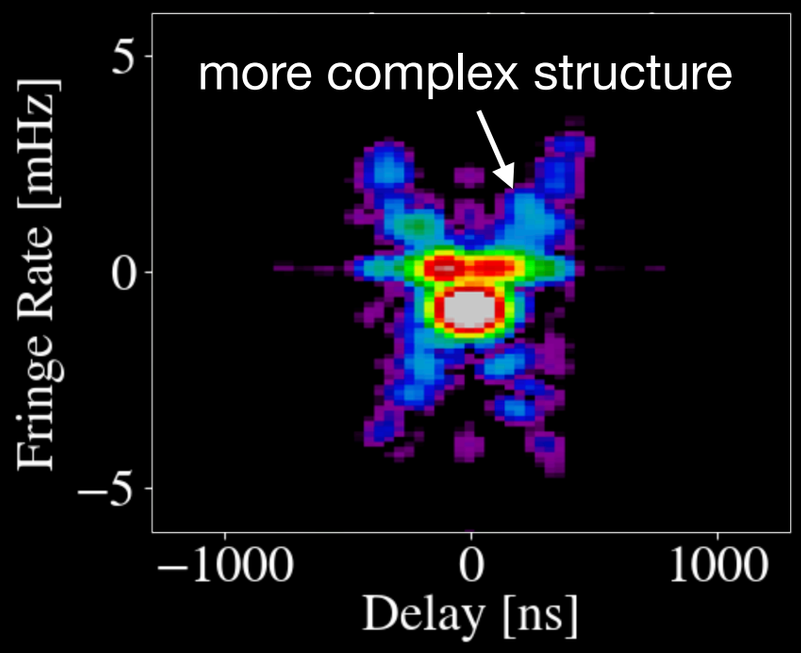
Phase II challenges

• Higher order semi-analytic data model needed when multi-pathway coupling is important

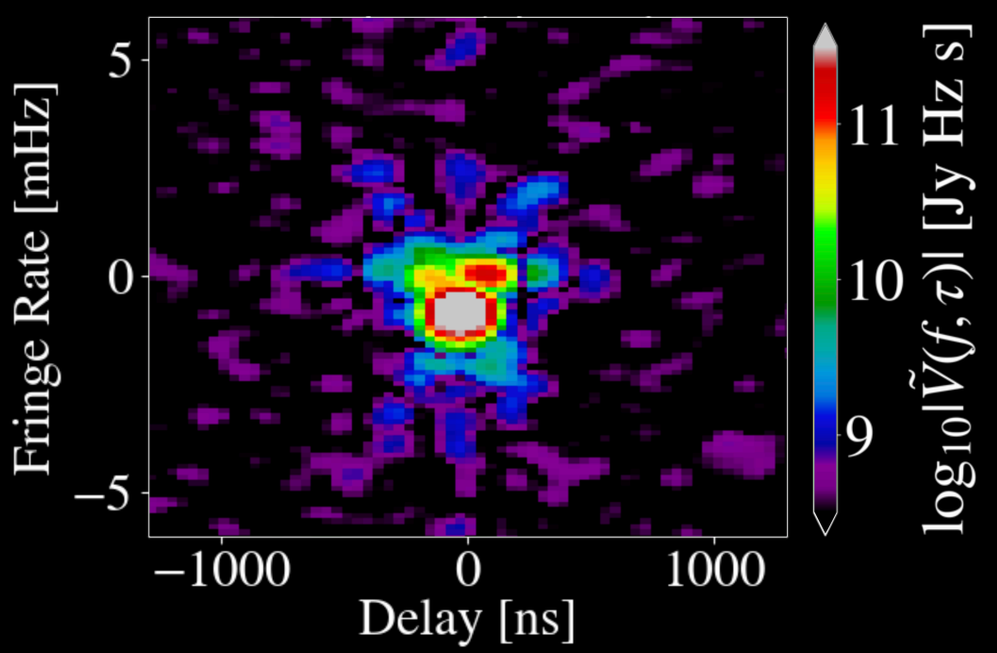
• Aggressive fringe-rate filtering may help but can also be lossy. Currently work in progress.



semi-analytic coupling sims



HERA Phase II data



Josaitis et al. 2022

Summary

• HERA Phase I sees strong reflection and coupling systematics, but have been mitigated by orders of magnitude to yield the most sensitive limits at z~8

• Exploiting time correlations of the systematic with drift-scans has been key to separating cross coupling from the cosmological signal

• HERA Phase II sees less reflections but more complex mutual coupling. Fringe-rate filtering will help but this is work in progress