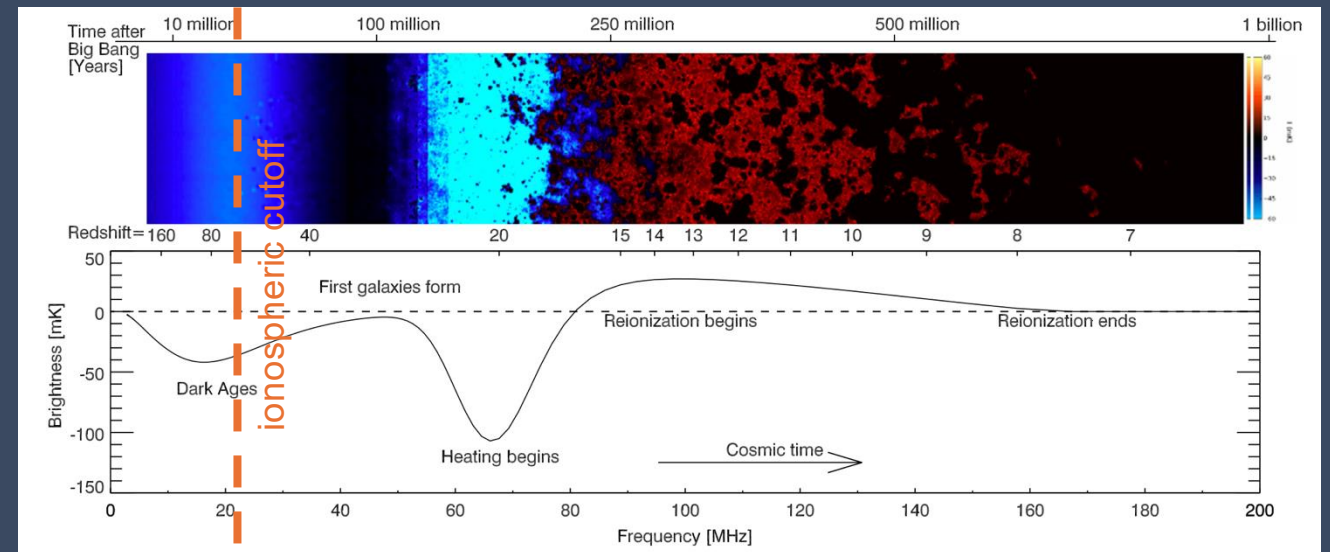


Capabilities Needed for the Next Generation of 21 cm Measurements

Ruby Byrne
Ad ASTRA Workshop
September 2, 2026

WHAT ARE WE TRYING TO DO?

- Measure the 21 cm signal from HI at high redshift
- Measure the "global" (sky-averaged) signal
 - Single-antenna experiments
- Measure fluctuations in the signal
 - Requires resolving spatial structure
 - Interferometric arrays
 - Power spectrum measurement



Source: Pritchard & Loeb 2012

WHAT DO WE MEASURE?

$$\text{data} = \text{instrument} \times (\text{signal} + \text{foregrounds} + \text{RFI})$$

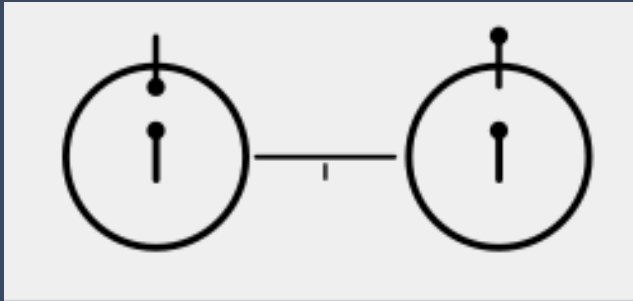
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WHAT DO WE MEASURE?

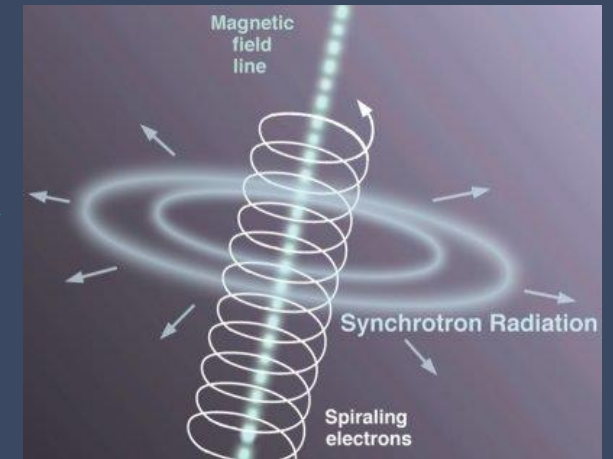
signal + foregrounds

WHAT DO WE MEASURE?



- Line emission
- Variant along the line-of-sight (redshift)
- Global signal has distinct absorption features

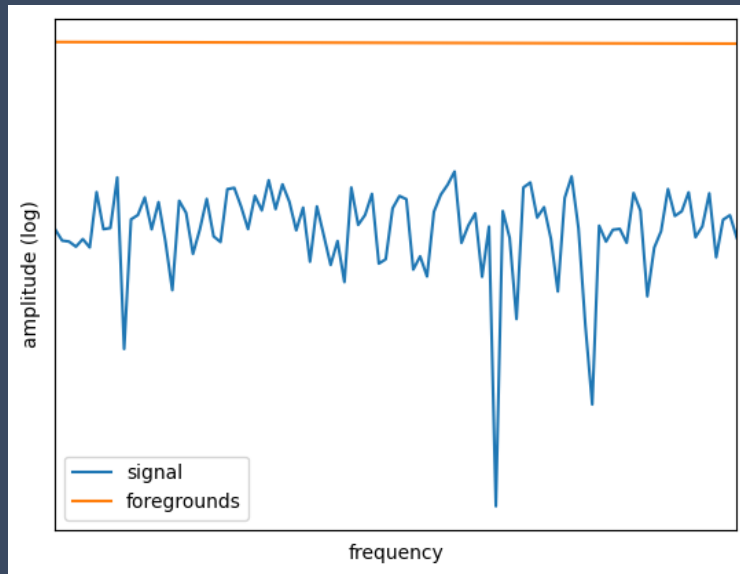
signal + foregrounds



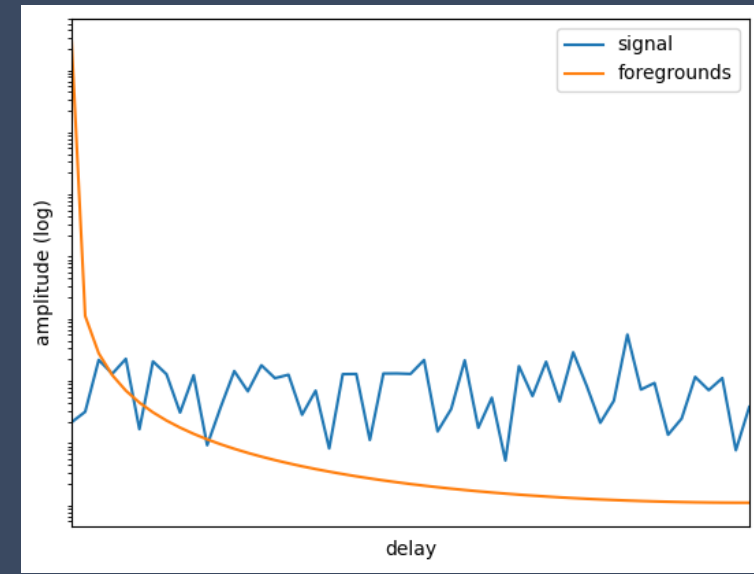
- Synchrotron and free-free emission
- Inherently spectrally smooth
- 4-5 orders of magnitude brighter than the signal

WHAT DO WE MEASURE?

signal + foregrounds

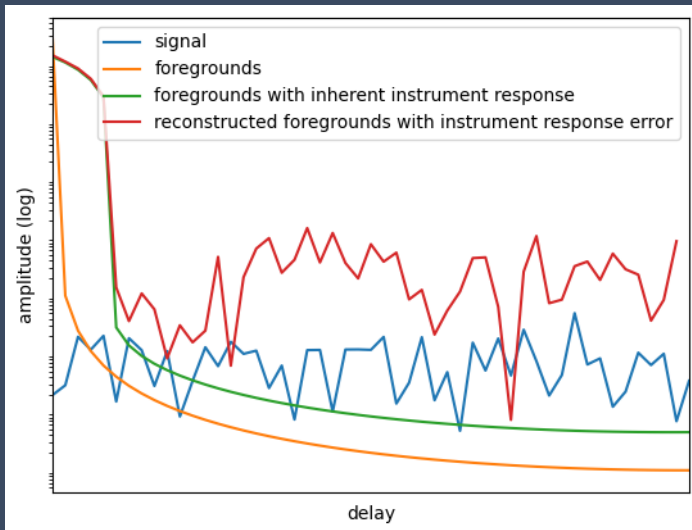


Fourier
Transform



WHAT DO WE MEASURE?

instrument $\times$ (signal + foregrounds)



- Instrument prevents proper separation of the signal and foregrounds
- Instrument response can be arbitrarily complex
 - Direction dependence
 - Frequency dependence

SEPARATING THE INSTRUMENT RESPONSE

1. Control
2. Model
3. Calibrate

SEPARATING THE INSTRUMENT RESPONSE

1. Control

2. Model

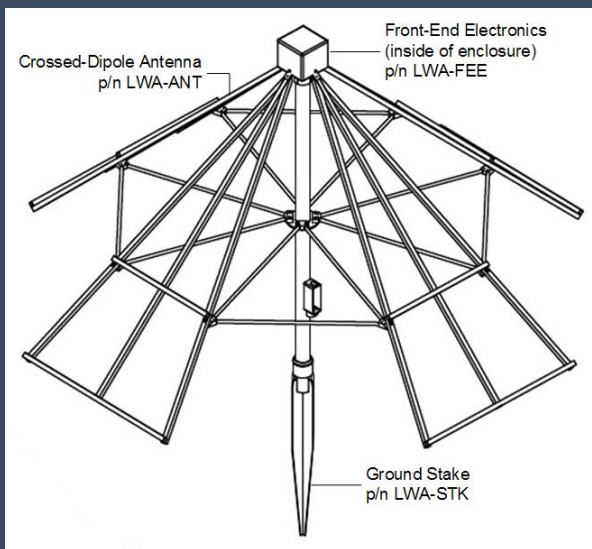
3. Calibrate

CONTROLLING THE INSTRUMENT RESPONSE

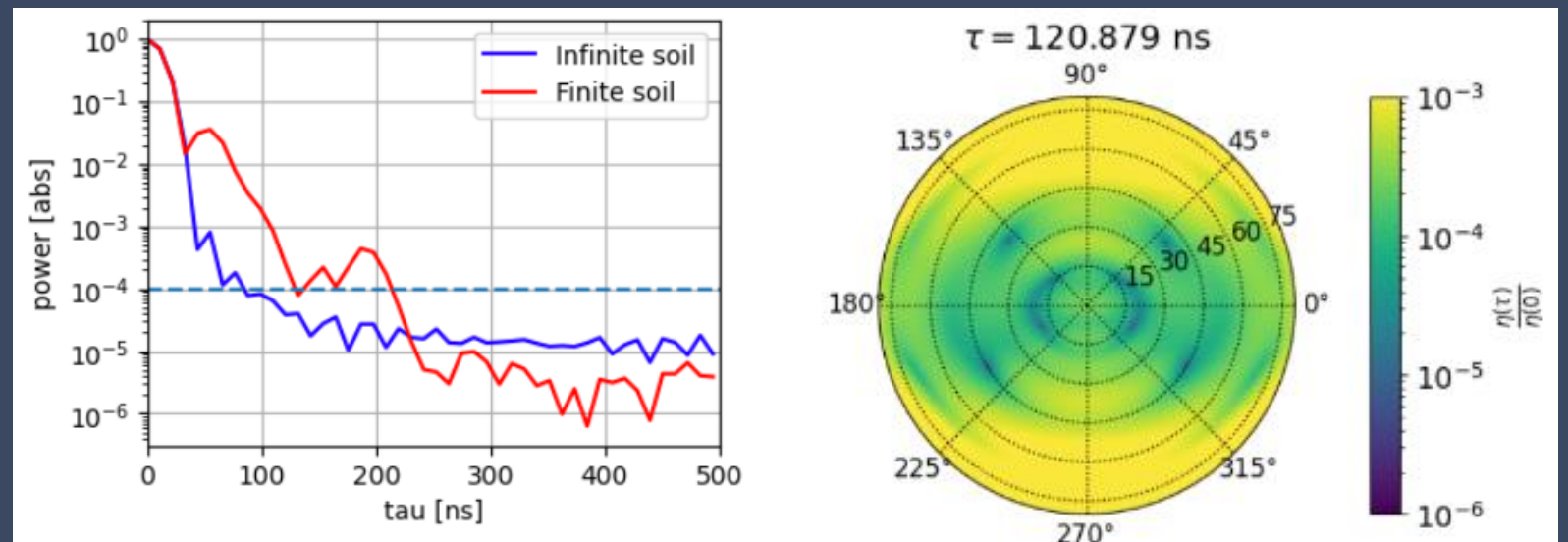
Can we design an instrument that does not mix the signal and foregrounds?

- Antennas with spectrally smooth responses
- Reduced mutual coupling
- Spectrally smooth downstream signal paths

DESIGNING SPECTRALLY SMOOTH ANTENNAS



Spectral performance of an LWA antenna



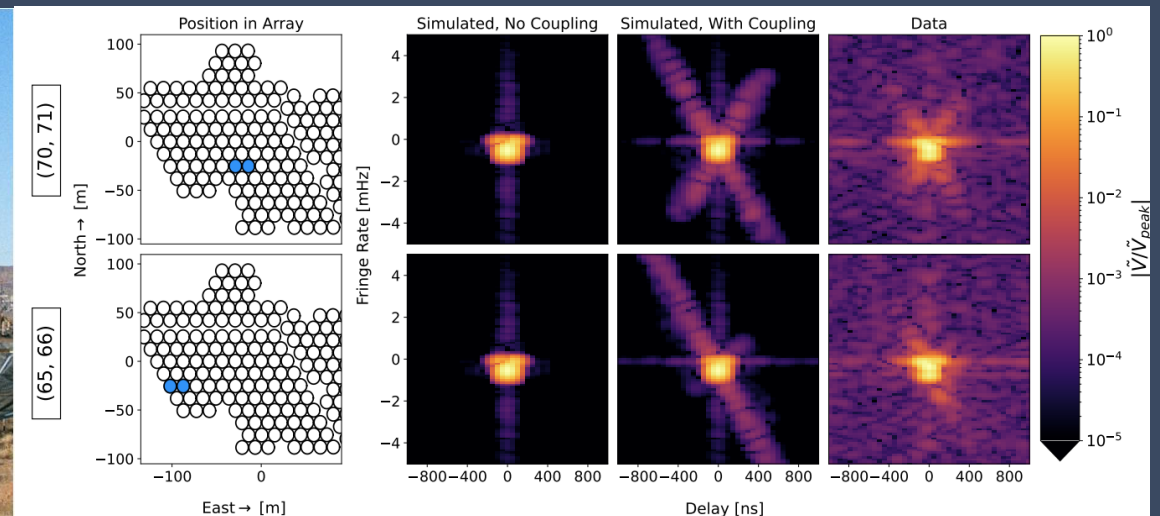
Source: Nivedita Mahesh

CONTROLLING MUTUAL COUPLING

- Mutual coupling perturbs the antenna beam response
- Depends on neighboring antennas and/or features in the environment
- Highly dependent on the instrument design
 - Antenna locations
 - Beam response profile
 - Impedance matching and re-radiation power



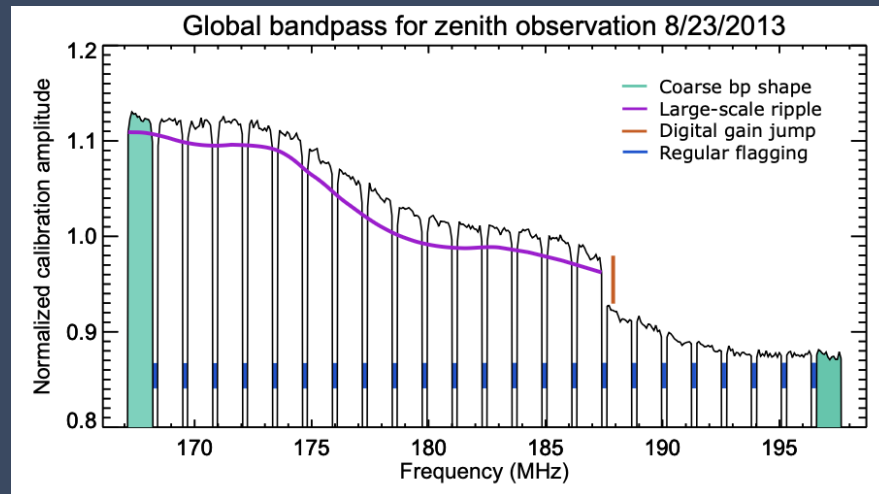
Mutual coupling in HERA (Rath+ 2024)



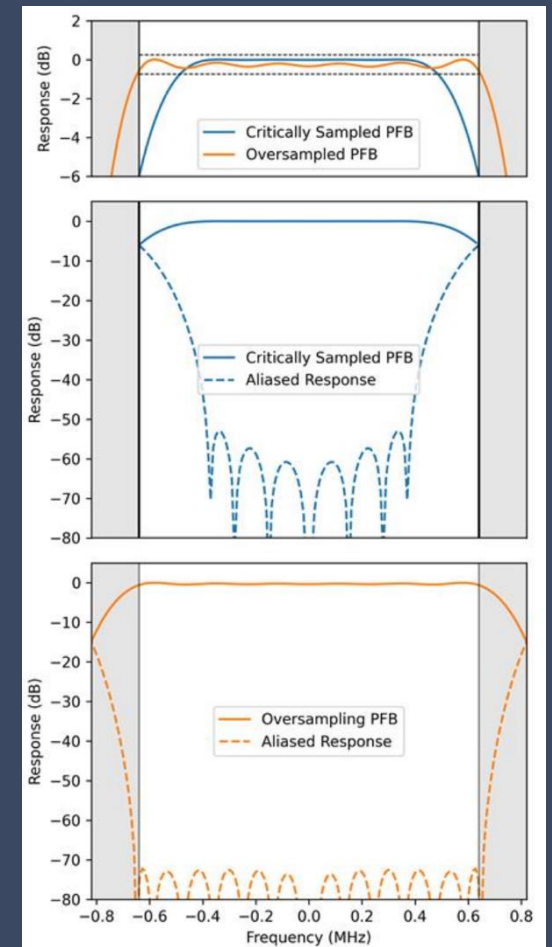
BUILDING SPECTRALLY SMOOTH SIGNAL PATHS

- MWA discovered spectral features from:
 - cable reflections
 - critically sampled polyphase filter bank (corrected in the Phase III instrument upgrade)
 - frequency-dependent digital gain

MWA Phase II Bandpass Response, Before Upgrade



Barry 2018

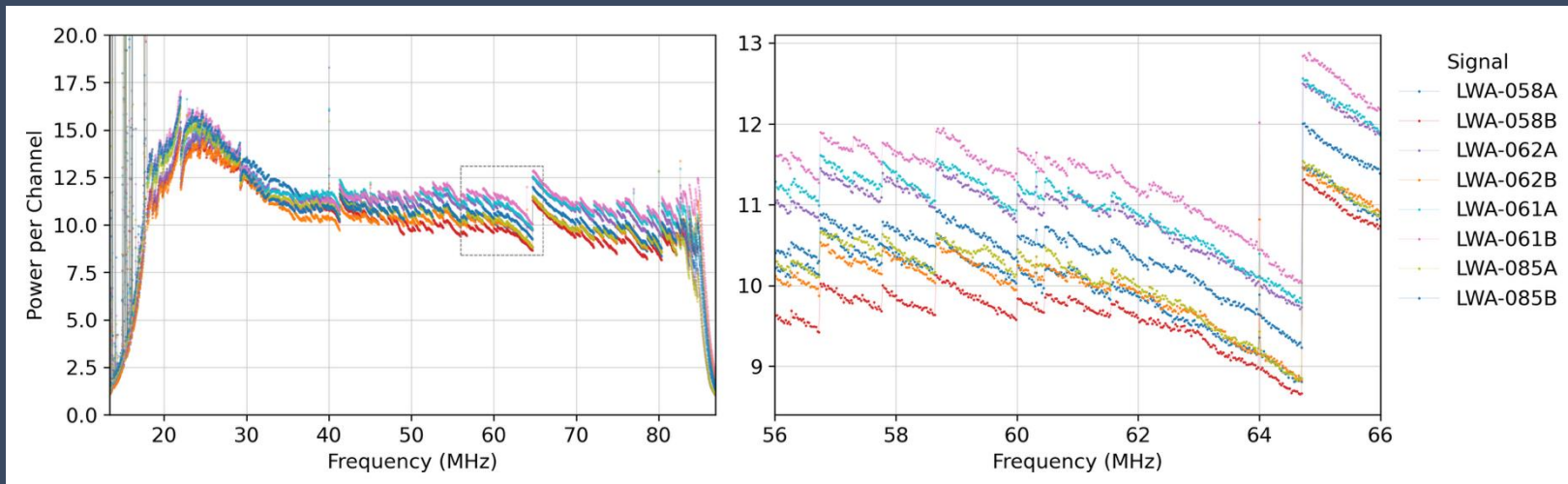


Tingay+ 2026

BUILDING SPECTRALLY SMOOTH SIGNAL PATHS

- MWA discovered spectral features from:
 - cable reflections
 - critically sampled polyphase filter bank (corrected in the Phase III instrument upgrade)
 - frequency-dependent digital gain
- OVRO-LWA discovered spectral features from digital whitening

OVRO-LWA Bandpass Response, Before Whitening Mitigation



Byrne+ 2026

SEPARATING THE INSTRUMENT RESPONSE

1. Control

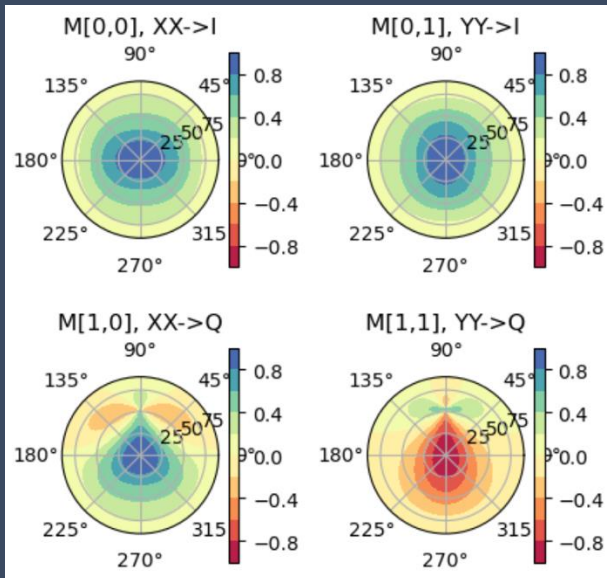
2. Model

3. Calibrate

MODELING THE INSTRUMENT AND FOREGROUNDS

1. Detailed Electromagnetic Beam Simulations

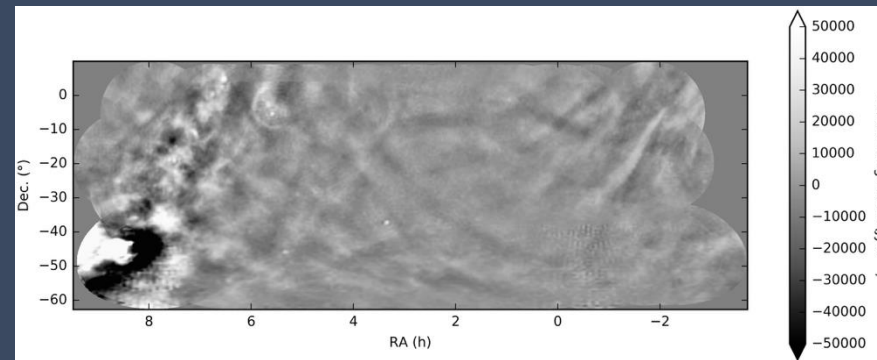
Simulated LWA Mueller matrix elements



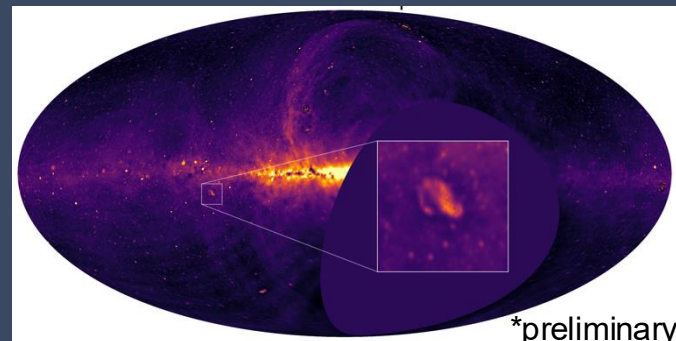
Source: Ruby Byrne and Nivedita Mahesh

2. Foreground Mapping

Mapping diffuse foregrounds with the MWA (Byrne+ 2021)



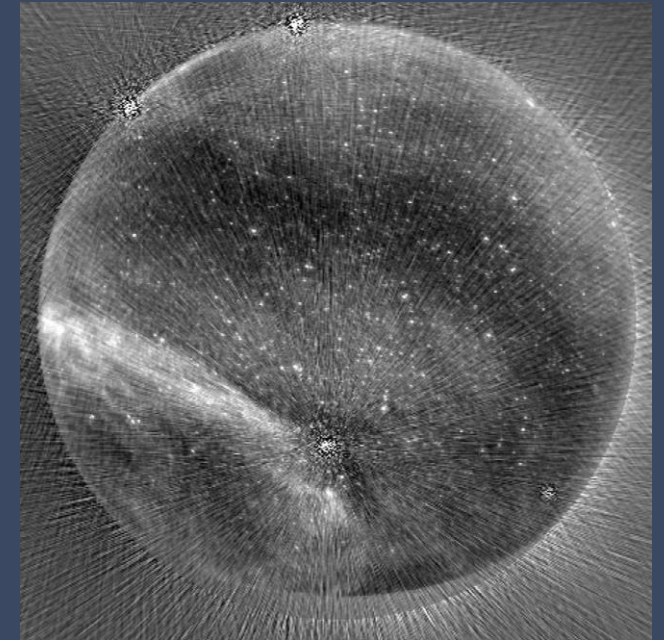
M-mode mapping with the OVRO-LWA (Xander Hall)



*preliminary

3. Full Instrumental Forward Modeling

Simulated OVRO-LWA foreground signal, with FFTVis (Cox+ 2025)



SEPARATING THE INSTRUMENT RESPONSE

1. Control

2. Model

3. Calibrate

PRECISION CALIBRATION

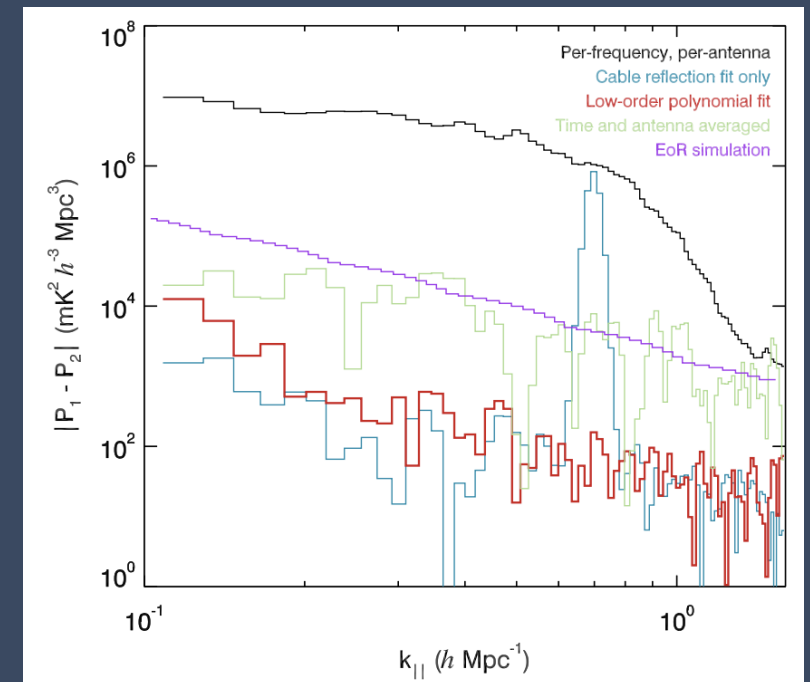
What we know doesn't work (well enough):

- Standard radio astronomy calibration based on the brightest astrophysical sources
 - Low-level sky model incompleteness produces spectral error (e.g. Barry+ 2016)
- Redundant calibration
 - No spectral improvement over standard sky-based calibration (Byrne+ 2019)
 - Could be susceptible to beam variations due to mutual coupling
- Direction-dependent calibration with no regularization across frequency
 - Fitting too many parameters risks signal loss (Patil+ 2016)
 - We cannot calibrate the modes we aim to measure

The path forward:

- Advanced statistical calibration frameworks, including:
 - CALAMITY (Ewall-Wice+ 2022) performs a joint fit of the foregrounds and instrument
 - DWCal (Byrne 2022) downweights sky model error
- Physically-informed calibration regularization
 - Fit as few parameters as possible
 - Rely on accurate modeling instead of in-situ calibration

Simulated calibration error (Barry+ 2016)



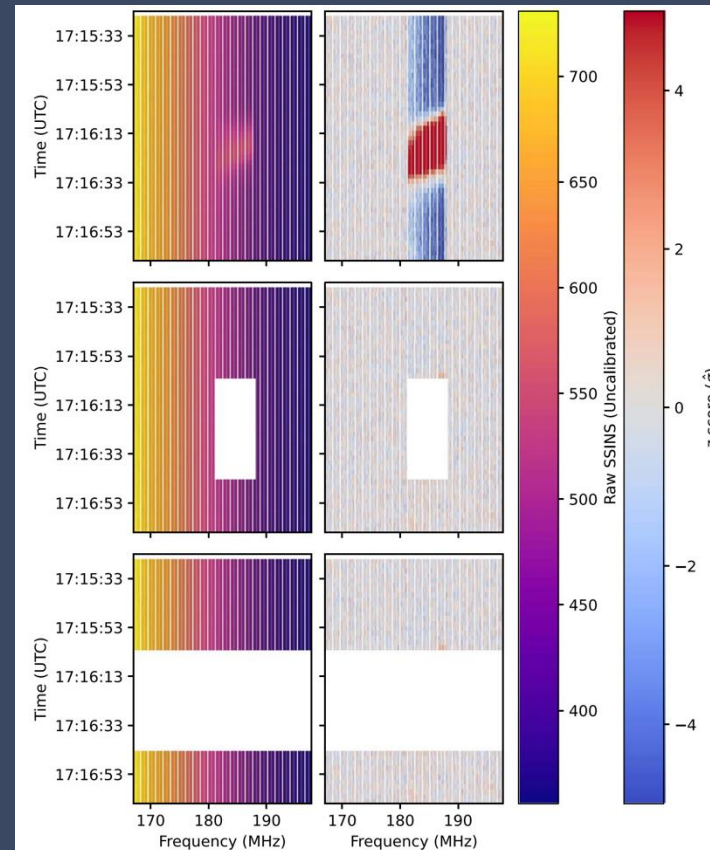
WHAT ABOUT RFI?

$$\text{data} = \text{instrument} \times (\text{signal} + \text{foregrounds} + \text{RFI})$$

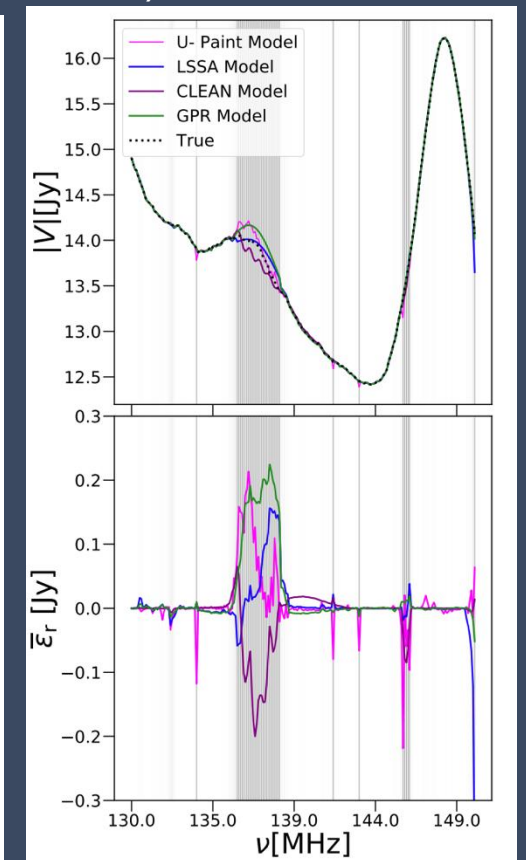
RFI MITIGATION

- Ultra-faint RFI that lies below detection thresholds contaminates 21 cm measurements (Wilensky+ 2023)
- We require advanced detection and flagging algorithms
- Flagging itself contaminates 21 cm measurements; inpainting provides some imperfect mitigation (Pagano+ 2023)
- RFI excision can lead to extreme data loss (>50% data exclusion even in RFI-quiet environments like the MWA site; Wilensky+ 2023)

RFI detection in MWA data using SSINS (Wilensky+ 2023)



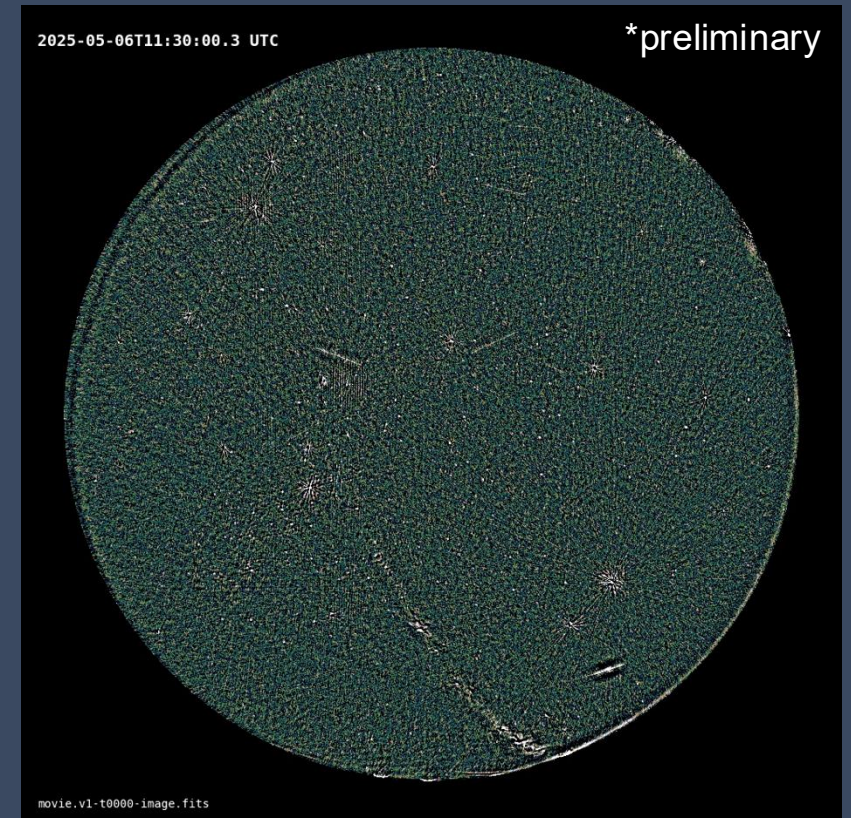
RFI inpainting for HERA data (Pagano+ 2023)



THE WORSENING RFI ENVIRONMENT

- Proliferation of satellite constellations increase RFI through:
 - In-band emission
 - Unintended out-of-band emission, particularly at low frequencies
 - Reflections
- Lunar farside missions benefit from RFI shielding

Mean-subtracted images from the
OVRO-LWA



Source: Gregg Hallinan

CONCLUSIONS

- Principal challenge is separating the faint 21 cm signal from foregrounds, RFI, and instrumental effects
- Path forward requires controlling, modeling, and calibrating the instrument response
- RFI is a serious concern and should be avoided (through RFI quiet sites and lunar experiments) and mitigated with next-generation algorithms
- There are many new and emerging technologies for enabling 21 cm cosmology measurements