Calibrating the CHIME beam with radio holography

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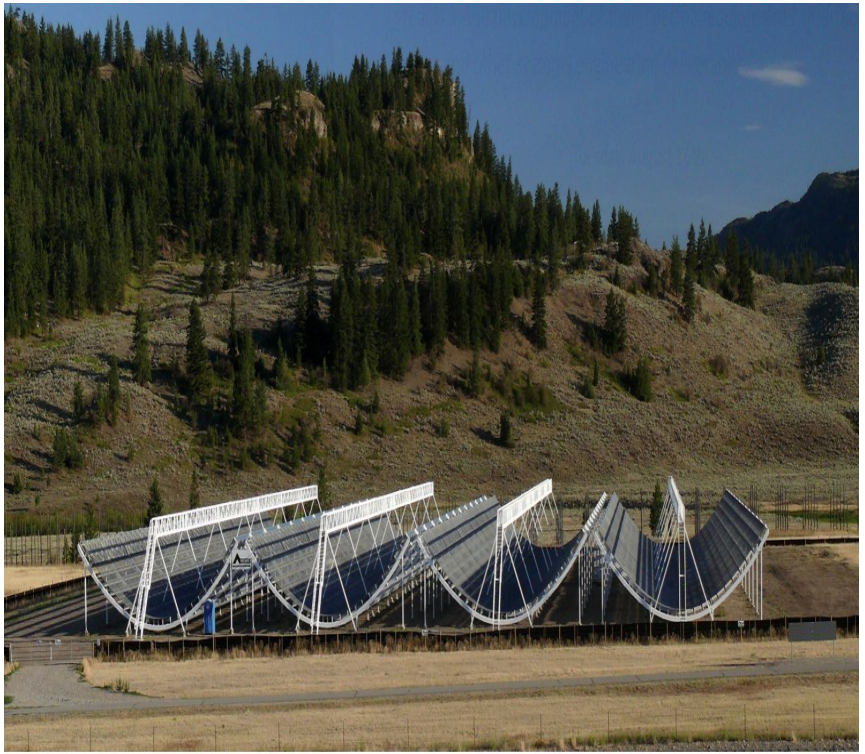
for
The CHIME Collaboration

CHIME: The Canadian Hydrogen Intensity Mapping Experiment

- Compact interferometer
  - Observing from DRAO in BC, Canada
  - 4 cylinders, 20m x 100m w/ 256 dual-pol feeds (X, Y)
  - 400-800 MHz, 21cm redshifts 0.8-2.5
  - arXiv: 2201.07869



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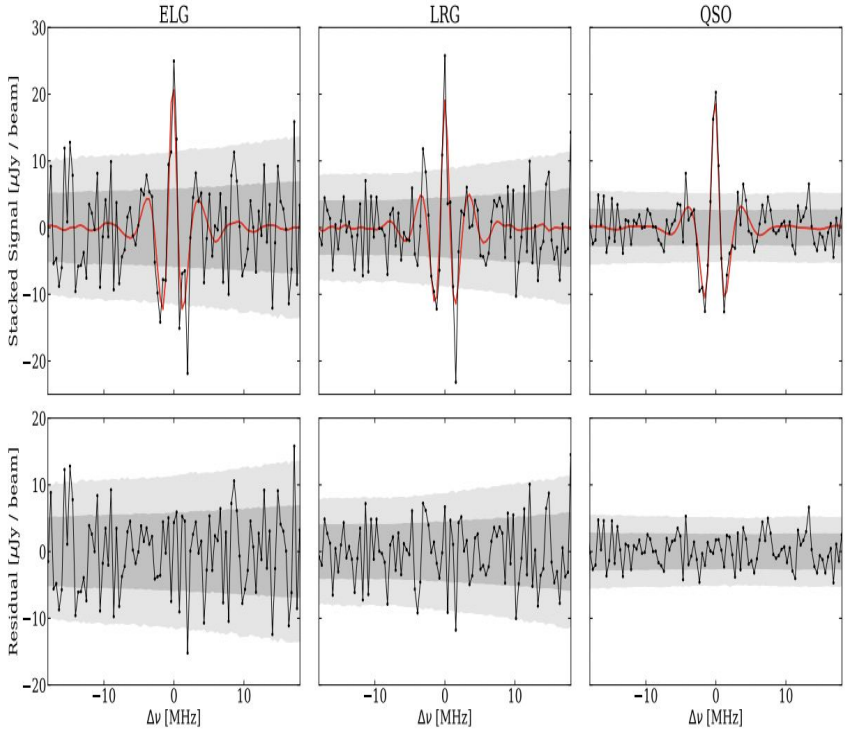
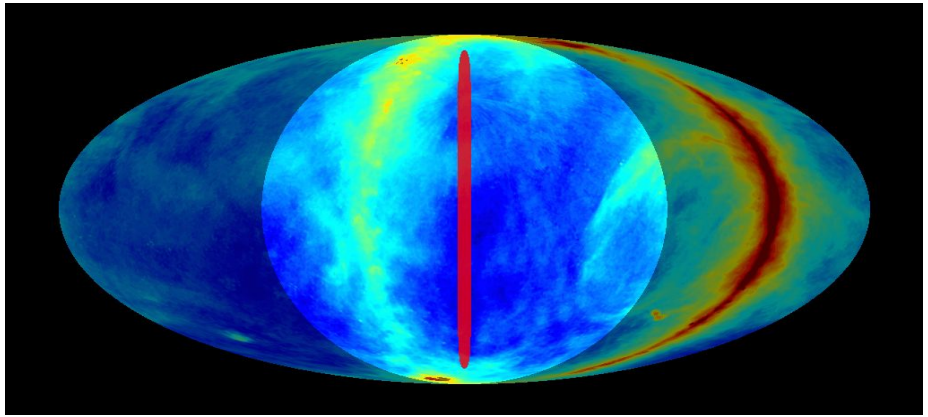
- Targeting 21cm emission in galaxies to constrain dark energy (BAO)
- First results: detection of 21cm in cross-correlation with eBOSS
  - 7.1σ LRG, 5.7σ ELG, 11.1σ QSO
  - arXiv:2202.01242
- arXiv:2201.11822 for solar beam measurements



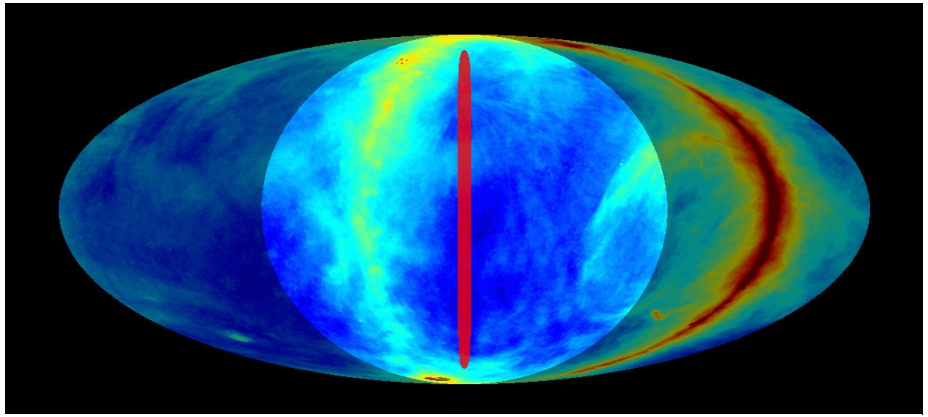
The beam response

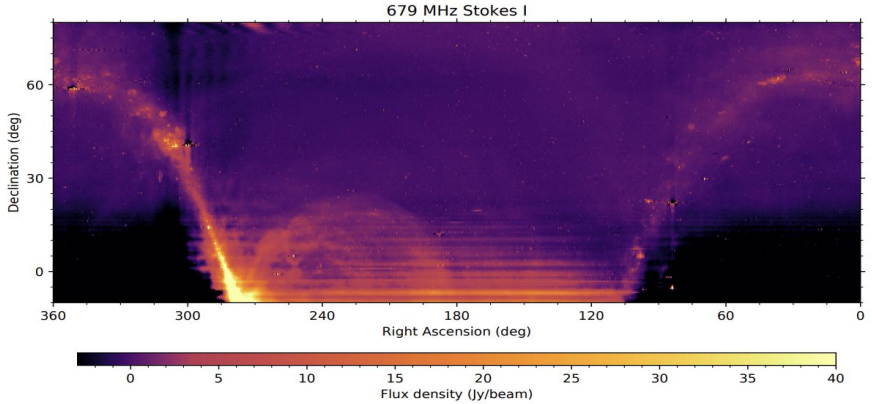


- Cylindrical telescope -> “hot dog” beam
  - Instantaneous FoV a narrow (few degrees) strip stretching horizon-to-horizon

Animation by Liam Connor

The beam response





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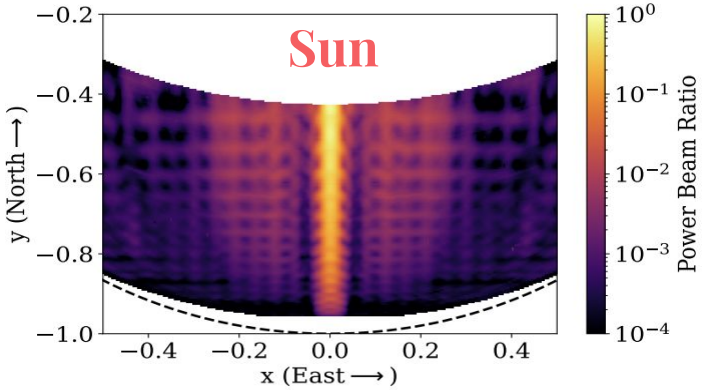
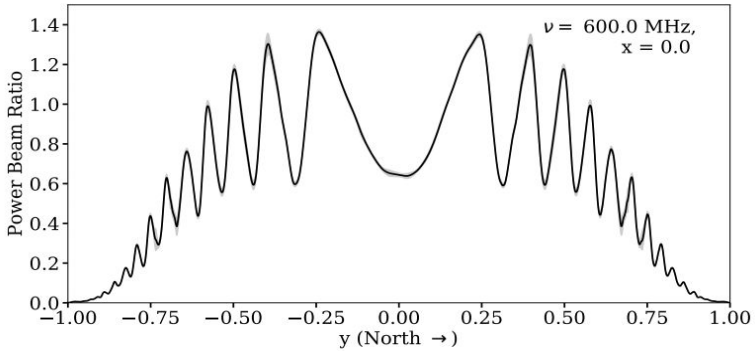
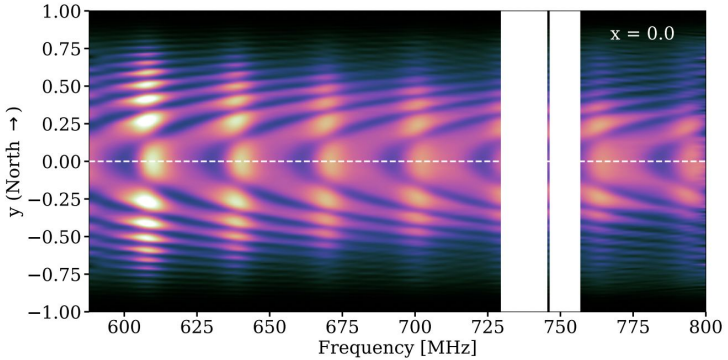




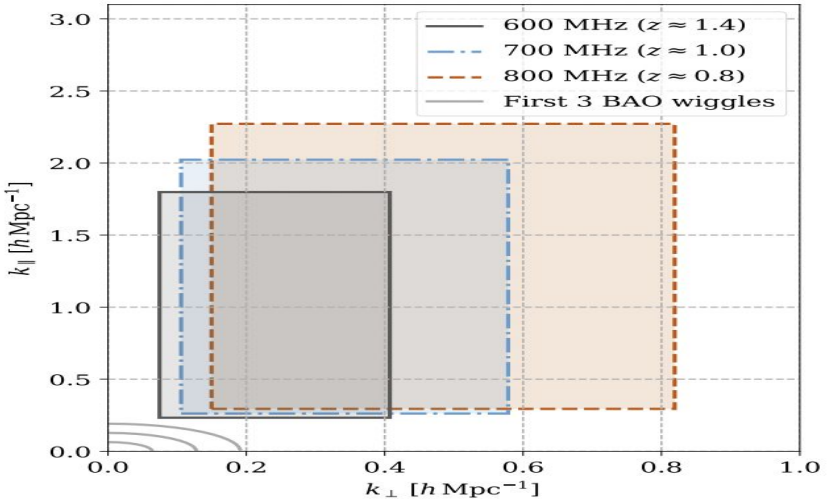
- Beam has complicated structure over several dimensions
- Understanding of the beam shaped by complementary datasets

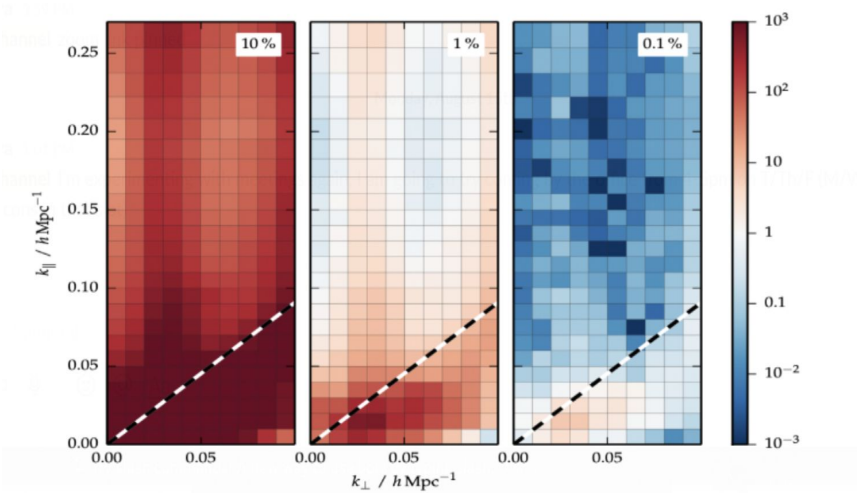
Point-source sky



The foreground challenge and beam calibration requirements

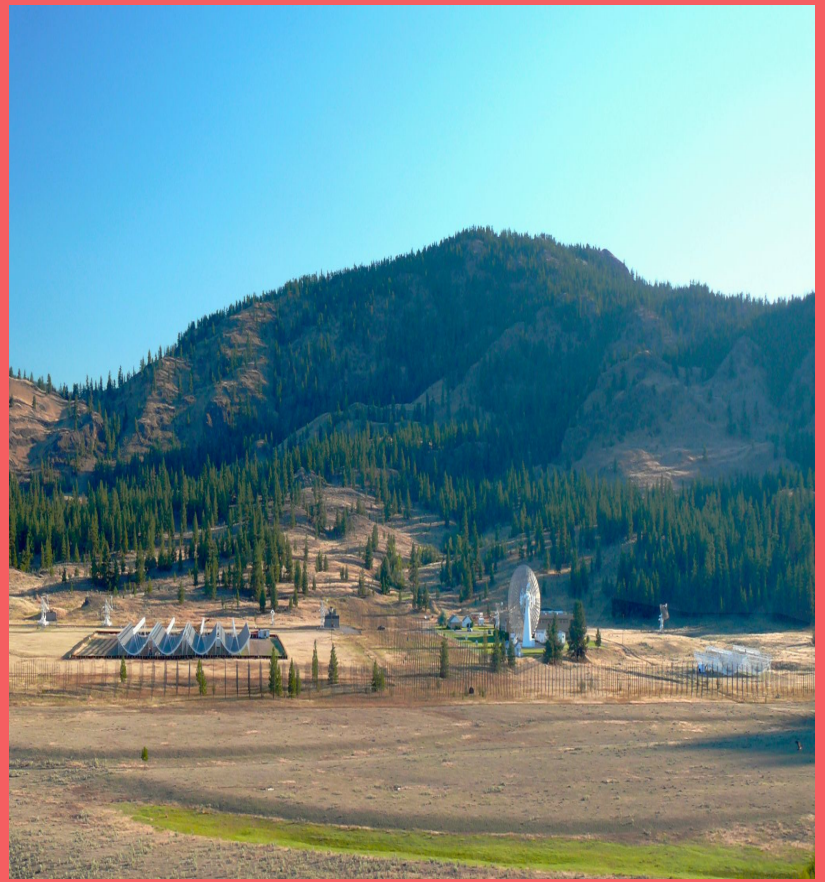
- Shaw et al. (2015): Even limiting instrument uncertainty to per-feed beam-widths can bias power spectrum
- Meanwhile, foreground filtering scheme used in x-correlation analysis throws away BAO scales

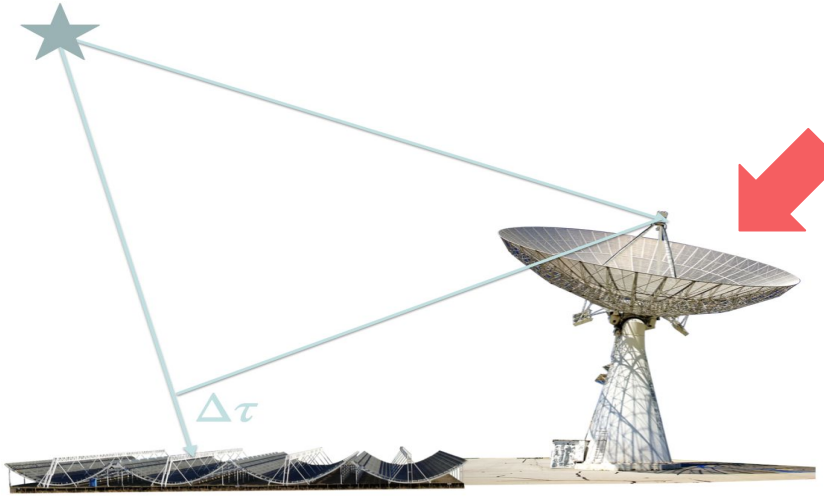




arXiv: 2202.01242

Beam calibration with holography

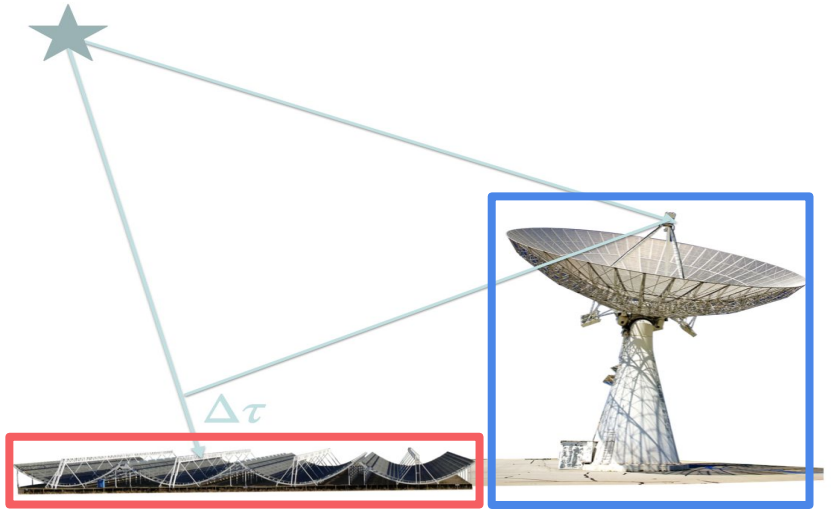




DRAO's 26m John Galt Telescope

arXiv: 2207.13876

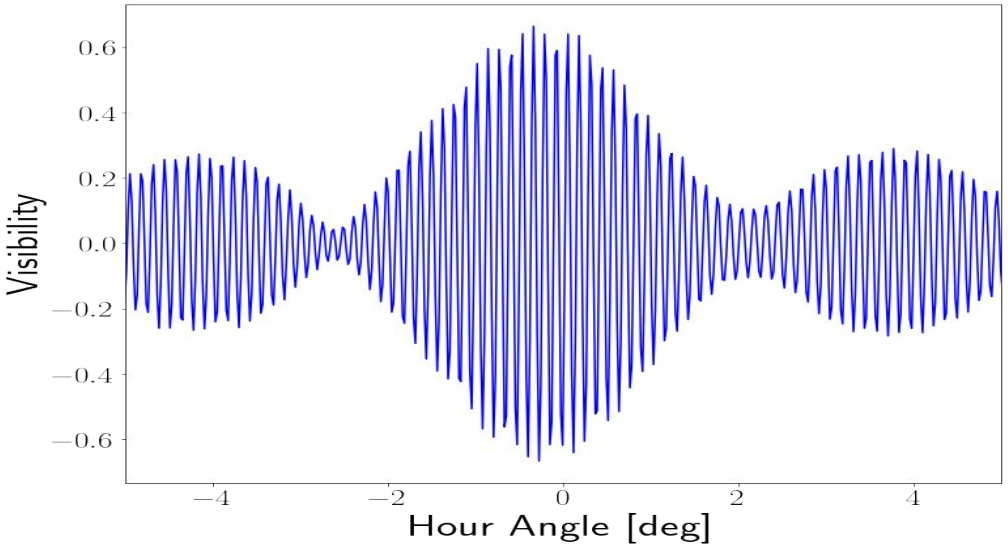
- Interferometric measurement
  - Antenna under test - CHIME
  - Reference antenna - DRAO's 26m (equipped w/ dual-pol CHIME feed)
  - Observing common source - bright radio sources observable from DRAO



$$V_{26,i} = A_i(\mathbf{n}_{ps})\, A_{26}\, T(\mathbf{n}_{ps})\, e^{2\pi\nu\Delta\tau} + n_{26,i}$$

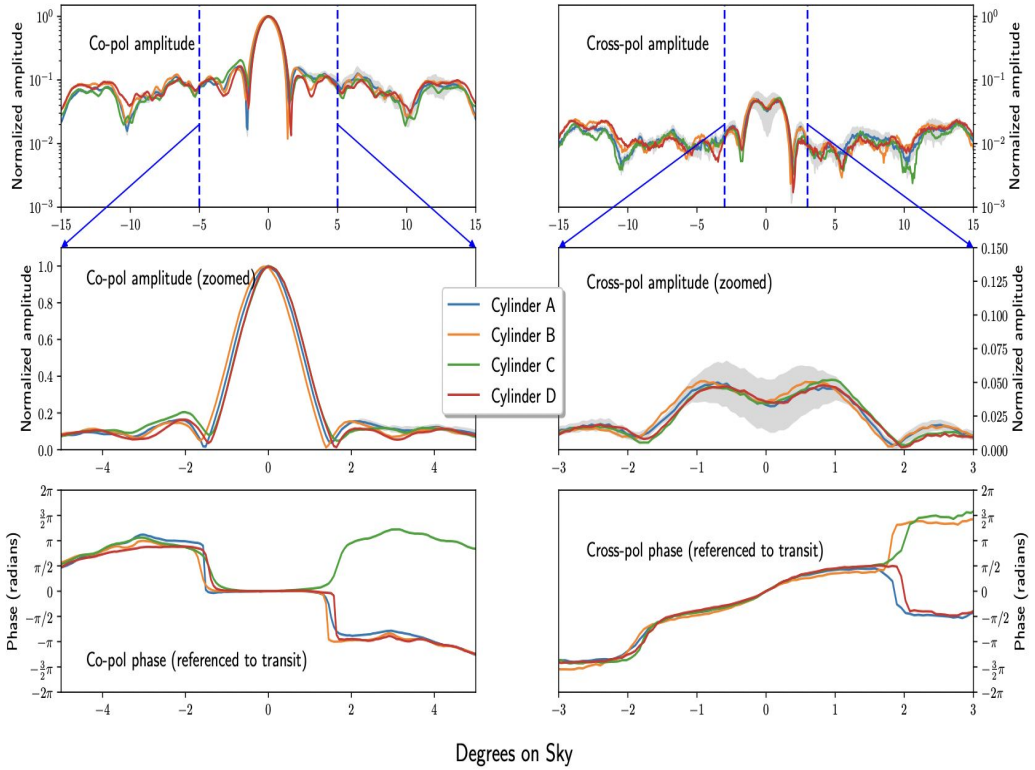
$$V_i \star V_{26} =$$

in YY, XX (“co-pol”), XY, YX (“cross-pol”)



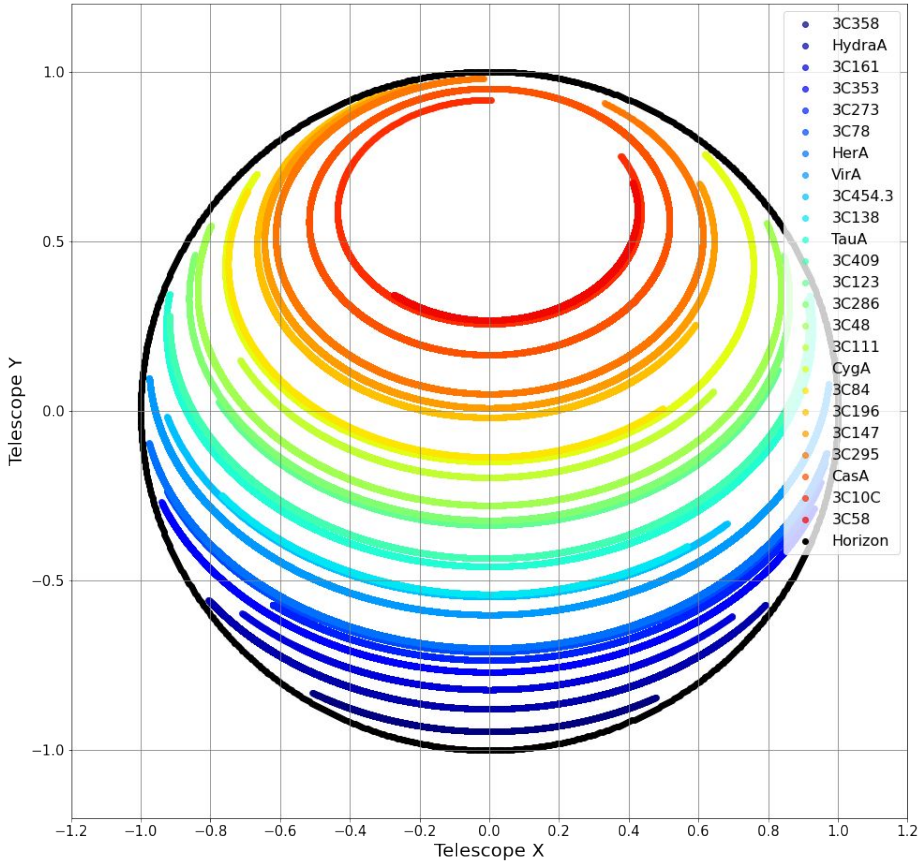
Advantages of holography

- Provides the beam response of all feeds
  - Assess array non-redundancy
  - Access individual feed polarization properties
- Only retains what correlates between CHIME and 26m's much smaller FoV
  - Avoid confusion noise floor far out in sidelobes
- Interferometric measurement - amplitude and phase
  - Can study aperture field



The dataset

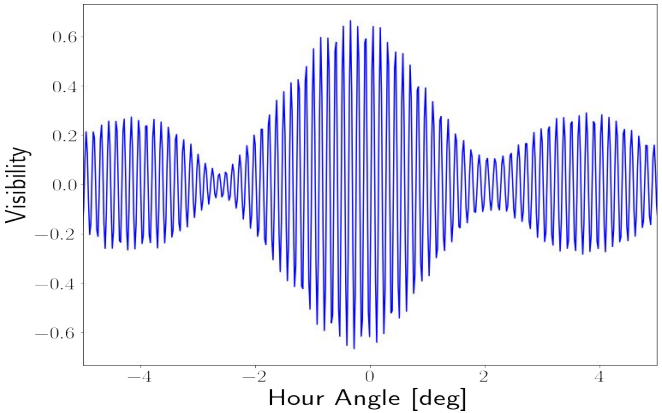
- To date, over 1800 observations
  - of 24 sources
  - spanning declinations -21 to +65 degrees



Raw holography → Fringestopping, decorrelation correction → Stacking → Stacks

$$V_{26,i} = A_i(\mathbf{n}_{\mathrm{ps}})A_{26}T(\mathbf{n}_{\mathrm{ps}})e^{2\pi\nu\Delta\tau}$$

$$A_i(\nu, \theta, \phi)$$



From data to beam

with Tristan Pinsonneault-Marotte

Raw holography → Fringestopping, decorrelation correction → Stacking → Stacks

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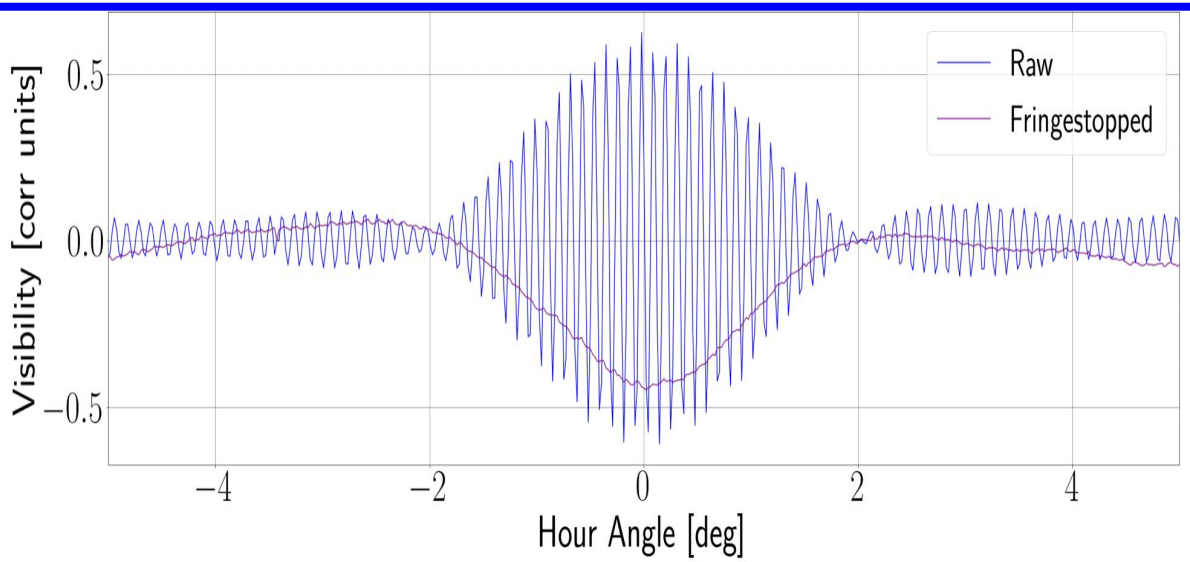
Fringestopping



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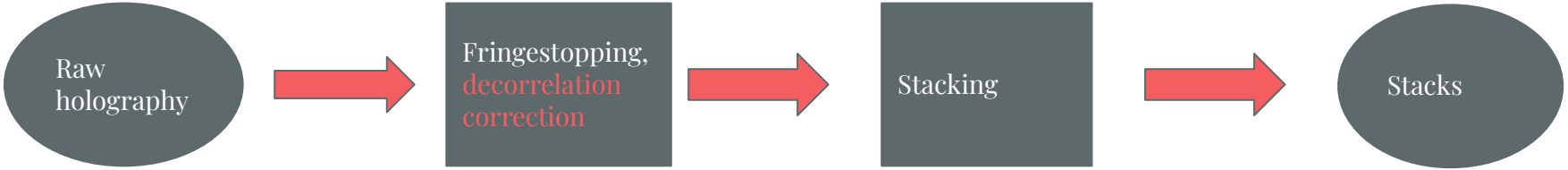
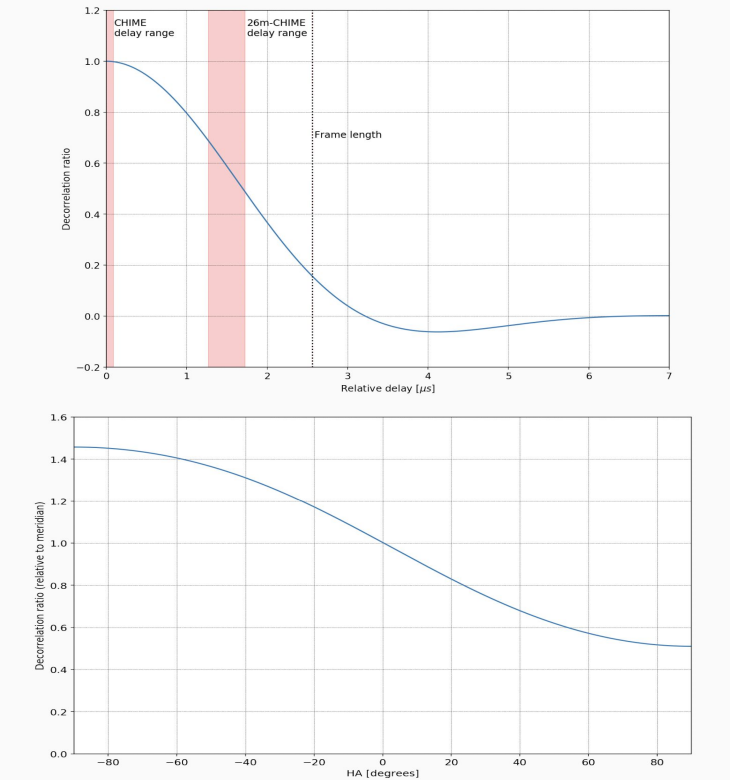
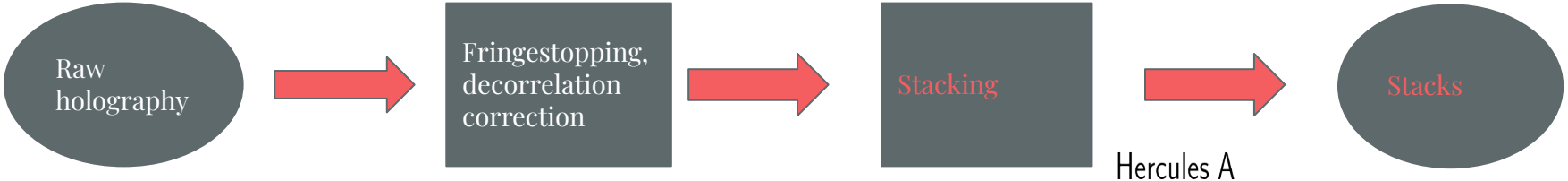


Decorrelation correction

- Delay between input signals -> signal loss
- 26m is connected to CHIME correlator via > 300 m of coax
  - Delayed by ~ 1 μs, correlation frames are 2.56 μs
  - + changing geometric delay causes hour-angle dependent signal loss

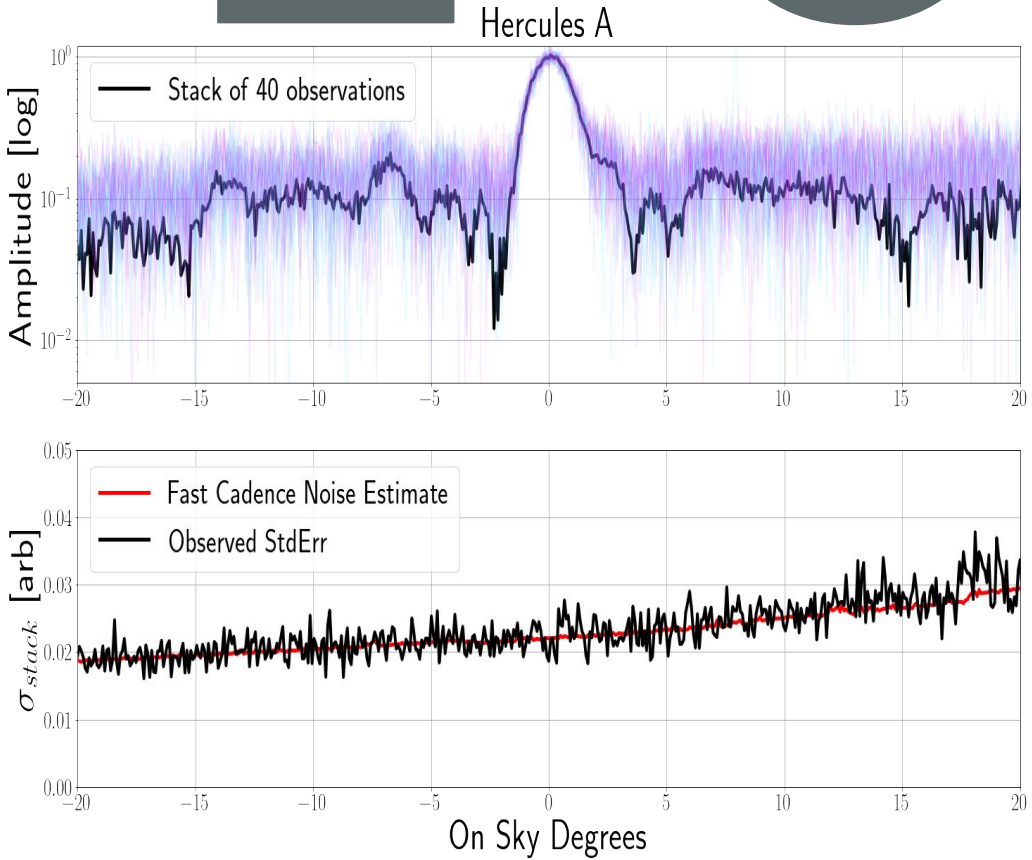


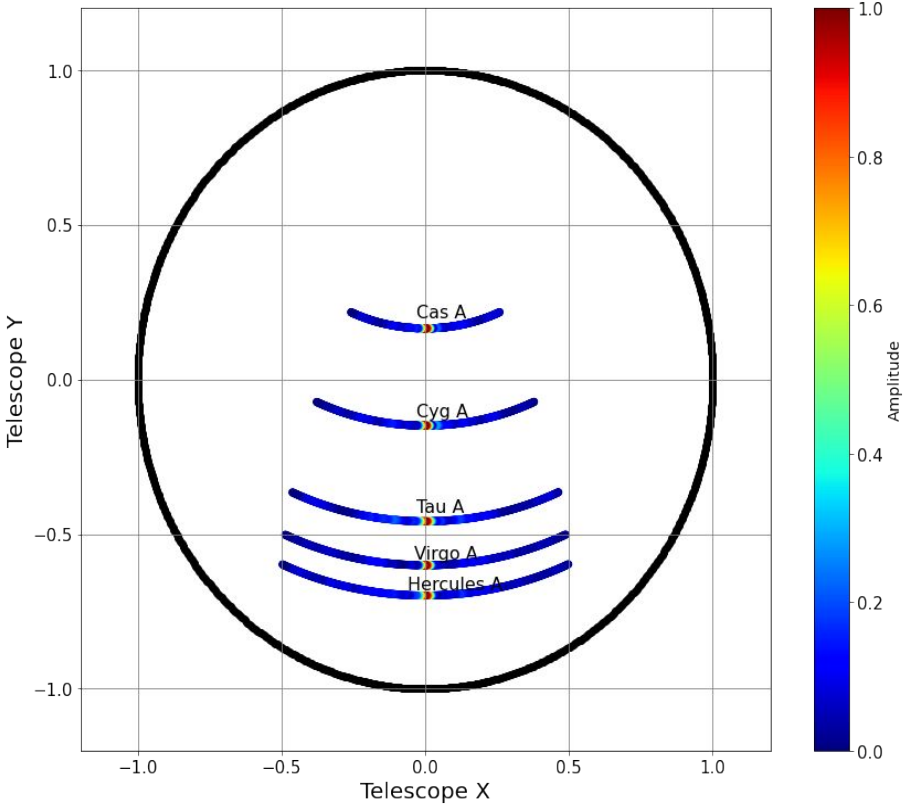
Courtesy Richard Shaw, Tristan Pinsonneault-Marotte

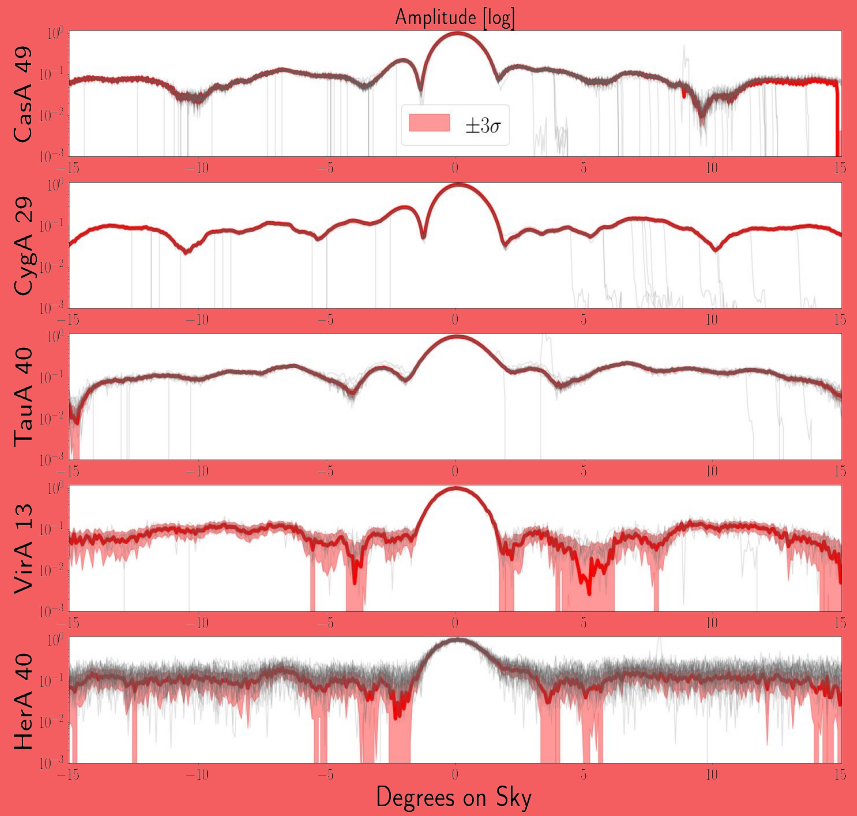


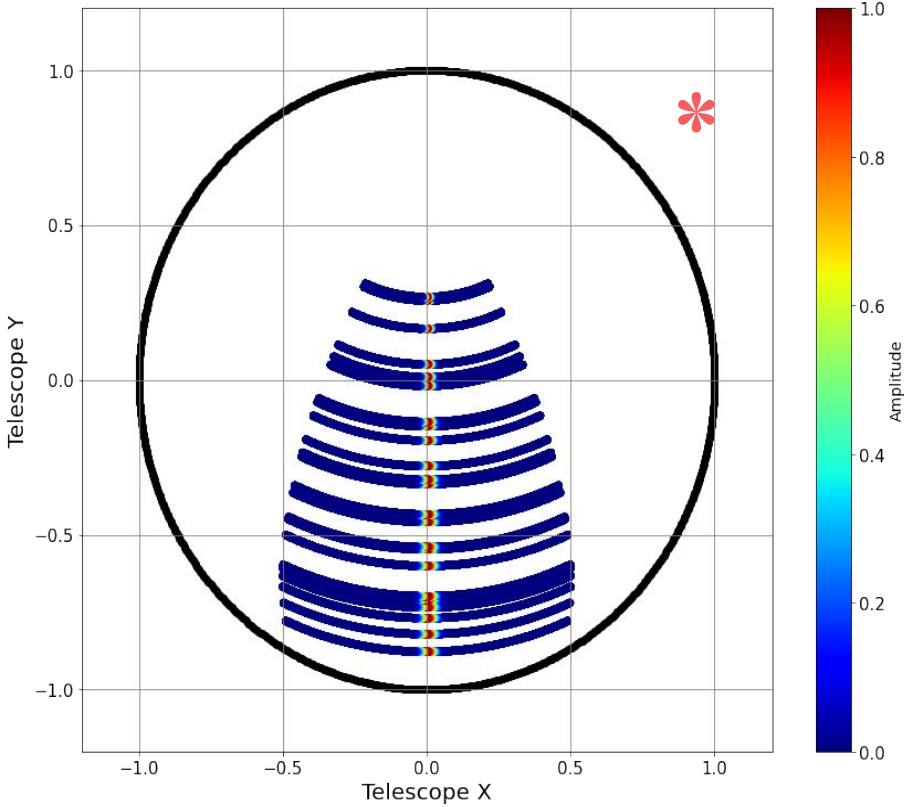
Stacking

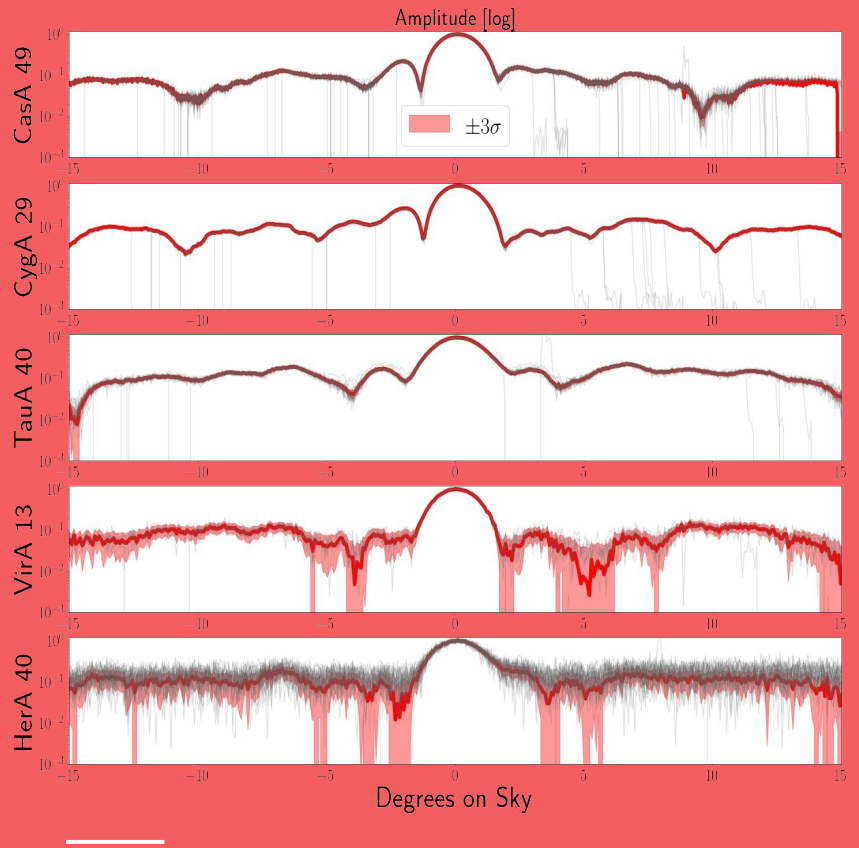
Coadding over redundant observations to integrate down noise




Cas A
Cyg A
Tau A
Virgo A
Hercules A
Telescope X
Telescope Y
Amplitude
1.0
0.8
0.6
0.4
0.2
0.0
1.0
0.5
0.0
−0.5
−1.0

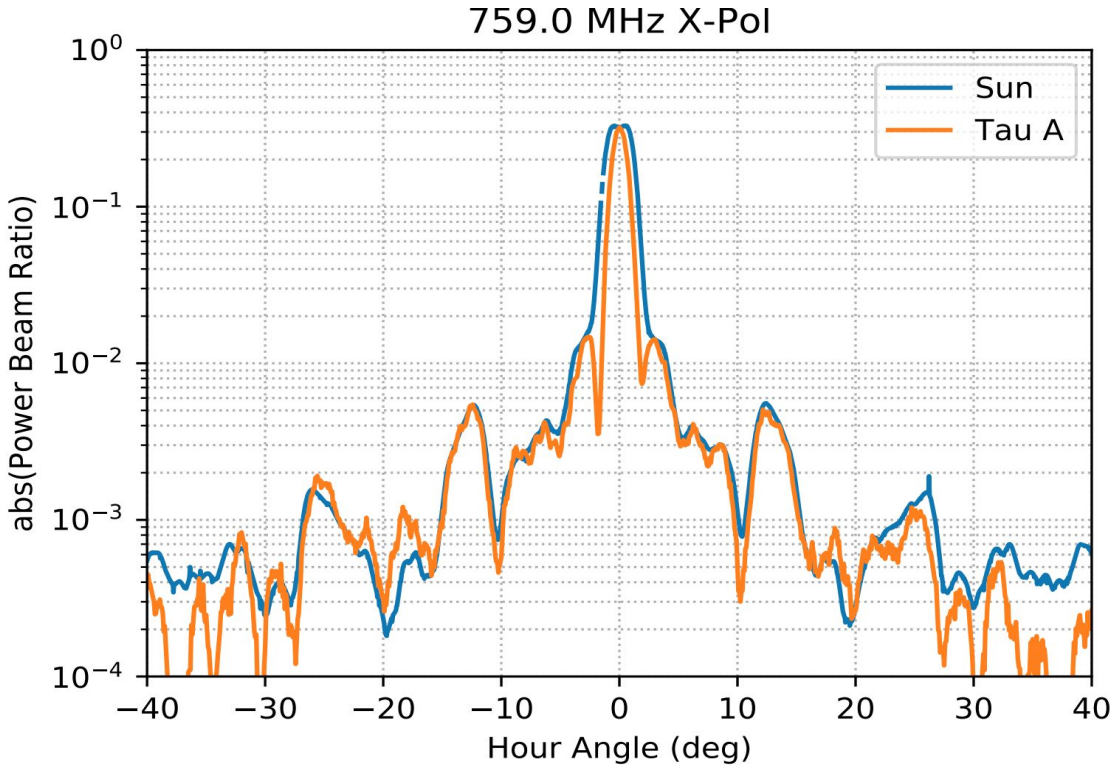

Amplitude [log]
CasA 49
CygA 29
TauA 40
VirA 13
HerA 40
±3σ
Degrees on Sky





*with a completely processed dataset

A mystery solved by holography

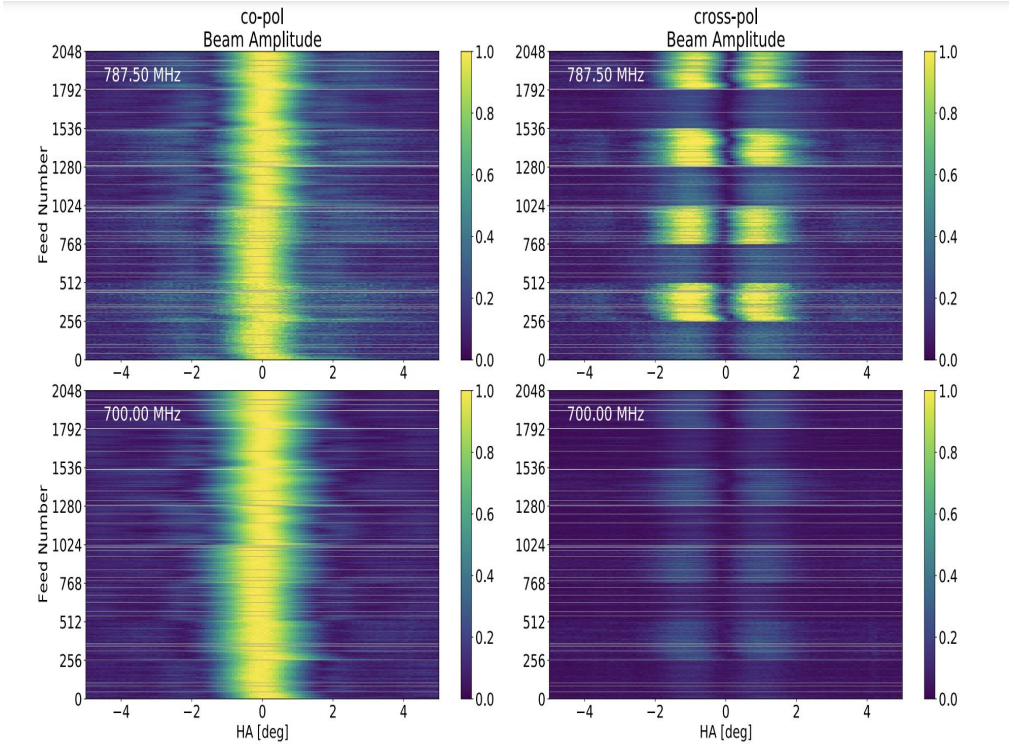


Courtesy Dallas Wulf

- Tau A holography vs. a measurement of the beam using the Sun, @ same declination
- At a handful (~5 channels) of frequencies and some southern declinations, seems to miss a dip in the middle of the CHIME beam

A mystery solved by holography

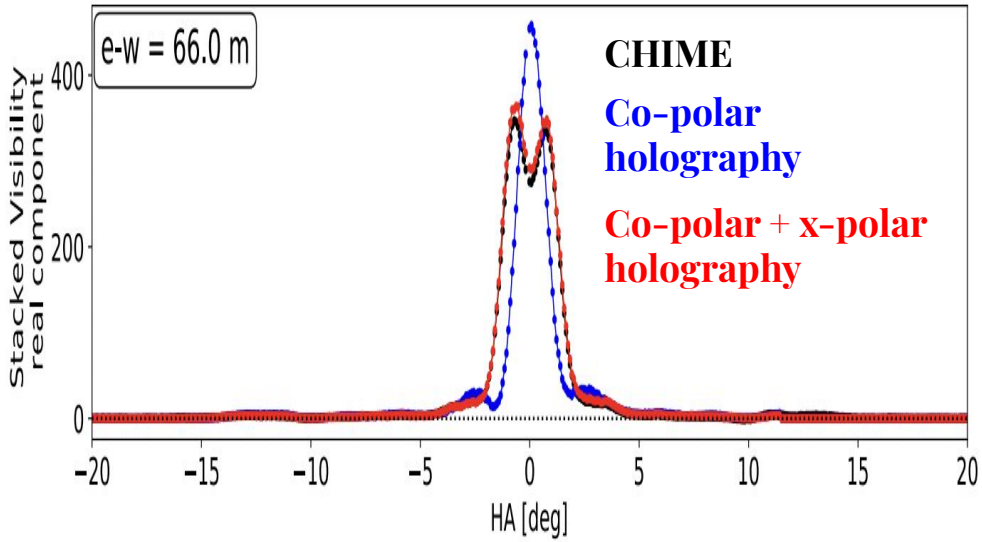
- Cross-polar holography at these same declinations and frequencies is abnormally high



Courtesy Seth Siegel

A mystery solved by holography

- When the polarization information provided by holography is properly taken into account, the datasets match
- High amplitude of cross-polar holography implies CHIME has high polarization leakage @ those decs and freqs
  - Still under investigation



Courtesy Seth Siegel

Summary

- CHIME will trace the evolution of the BAO scale to measure the expansion history from redshift 2.5 to 0.8
  - Constraining models of dark energy
- Our expected beam calibration requirements to successfully filter foregrounds are strict
- Meeting this challenge with holography, among other methods
- Holography offers our best view of the far sidelobes across the Northern sky and is currently the only method for studying feed-level effects
- Large dataset in can to-be-processed
- Comparison with other beam measurements has taught us about our instrument

Thank you!