Status of CHIME Intensity Mapping

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Photo Credit: Sasse

Outline

- Description of CHIME
- Current status and look at data
- Challenges
  - *RFI Excision*
  - *Instrument characterization*
    - *Beam calibration*
    - *Complex gain calibration*
  - *Foreground removal*
- Forecast on cosmological constraints

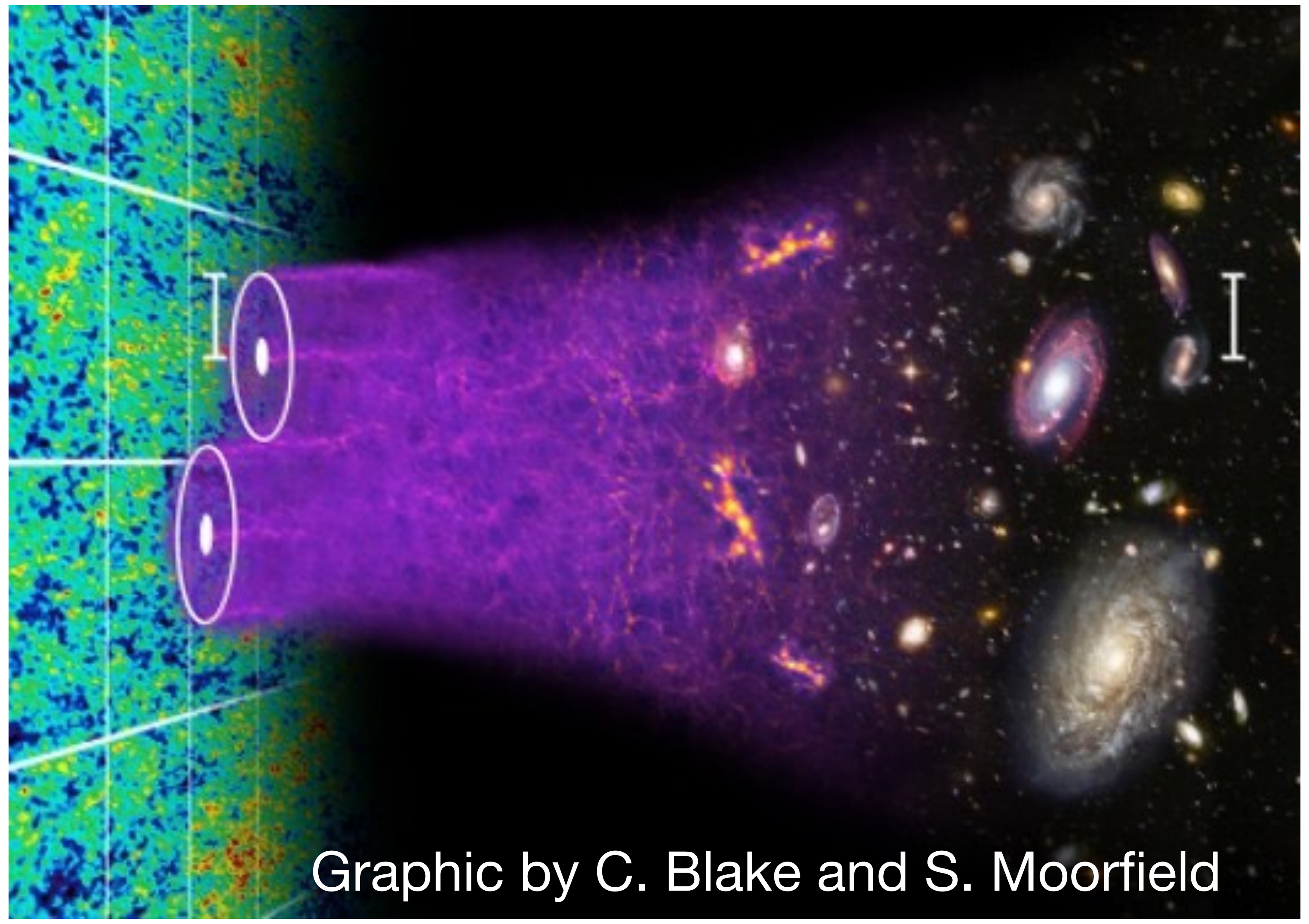
Baryon Acoustic Oscillations (BAO)

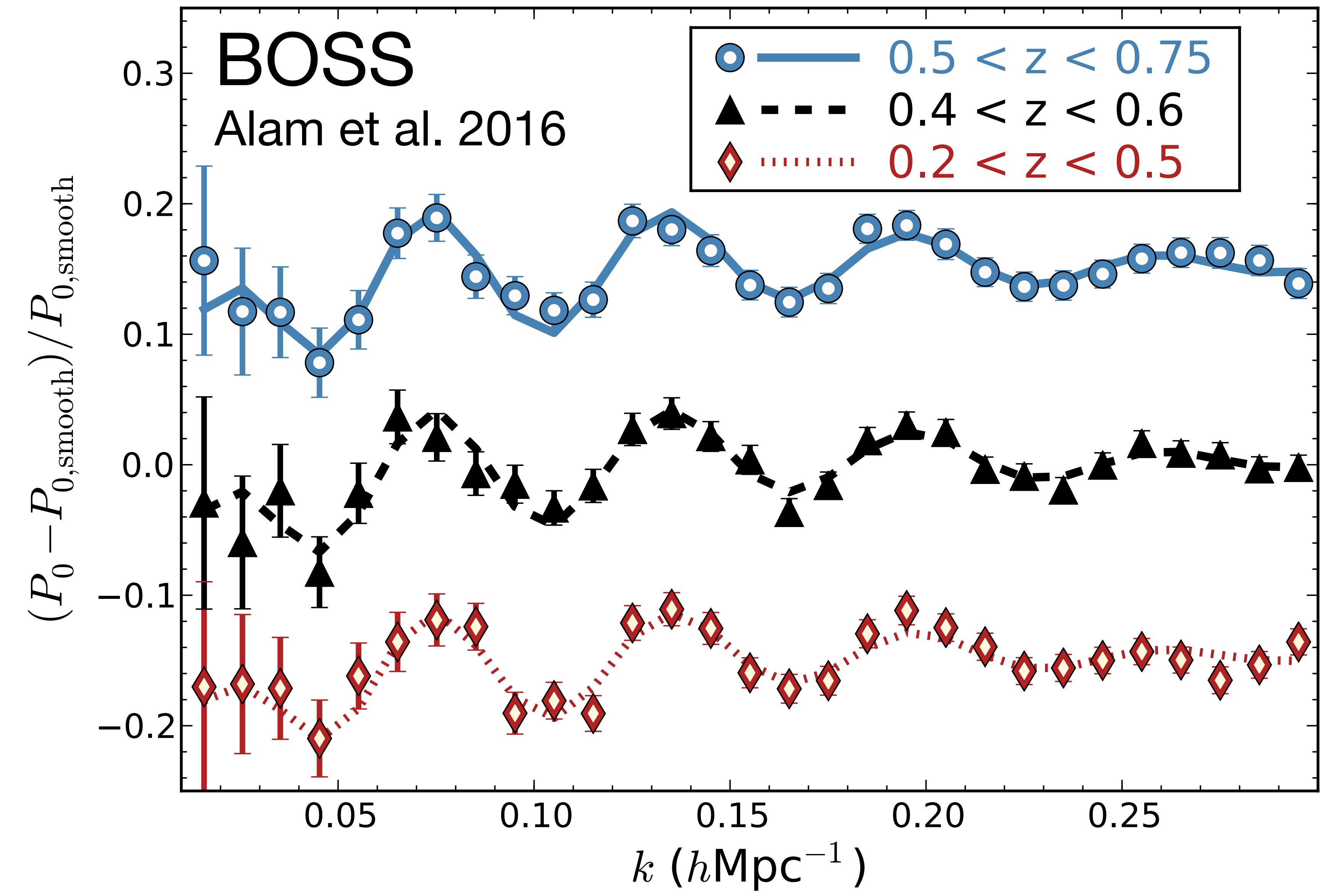
- Measure power spectrum of the 21cm emission from neutral hydrogen between redshift 0.8 and 2.5
  - Corresponds to radio frequencies between 800 and 400 MHz

- Extract the scale of the BAO in the angular and line of sight direction
  - $\Delta\theta_{bao}(z) = r_s / D_M(z)$
  - $\Delta z_{bao}(z) = r_s H(z)/c$

- Constrain the distance-redshift relation over period of universe's history not accessible by current spectroscopic galaxy surveys

- Learn something about dark energy


Graphic by C. Blake and S. Moorfield



Instrument Considerations

- Map a large volume
- Choose angular and frequency resolution to measure third BAO peak
- Maximize sensitivity to these scales
- Limit cost

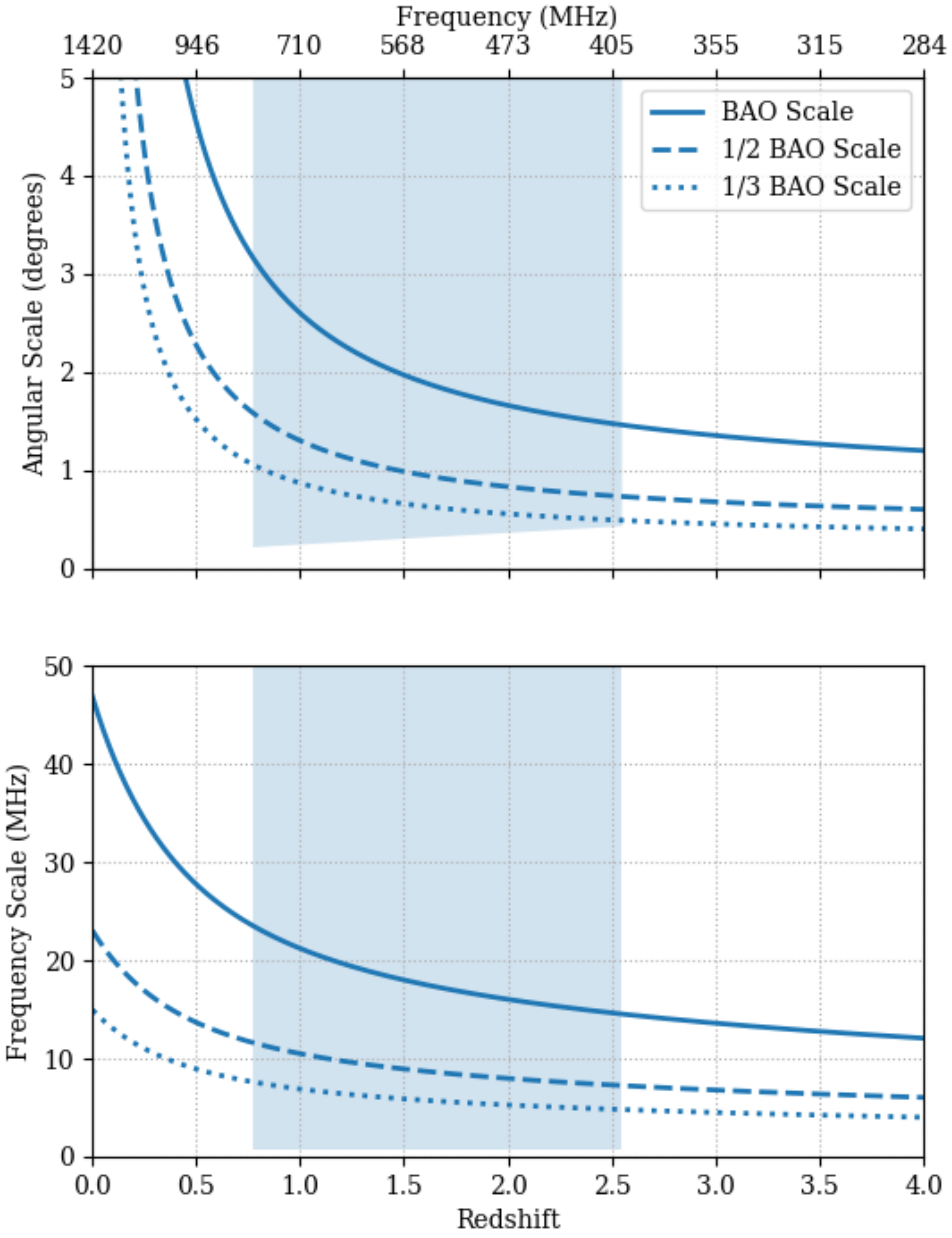


Figure courtesy of Dallas Wulf

chime

a collaboration between

THE UNIVERSITY OF BRITISH COLUMBIA

UNIVERSITY OF TORONTO

McGill

Dominion Radio Astrophysical Observatory
NRC · CNRC

with partners at

Yale University

West Virginia University

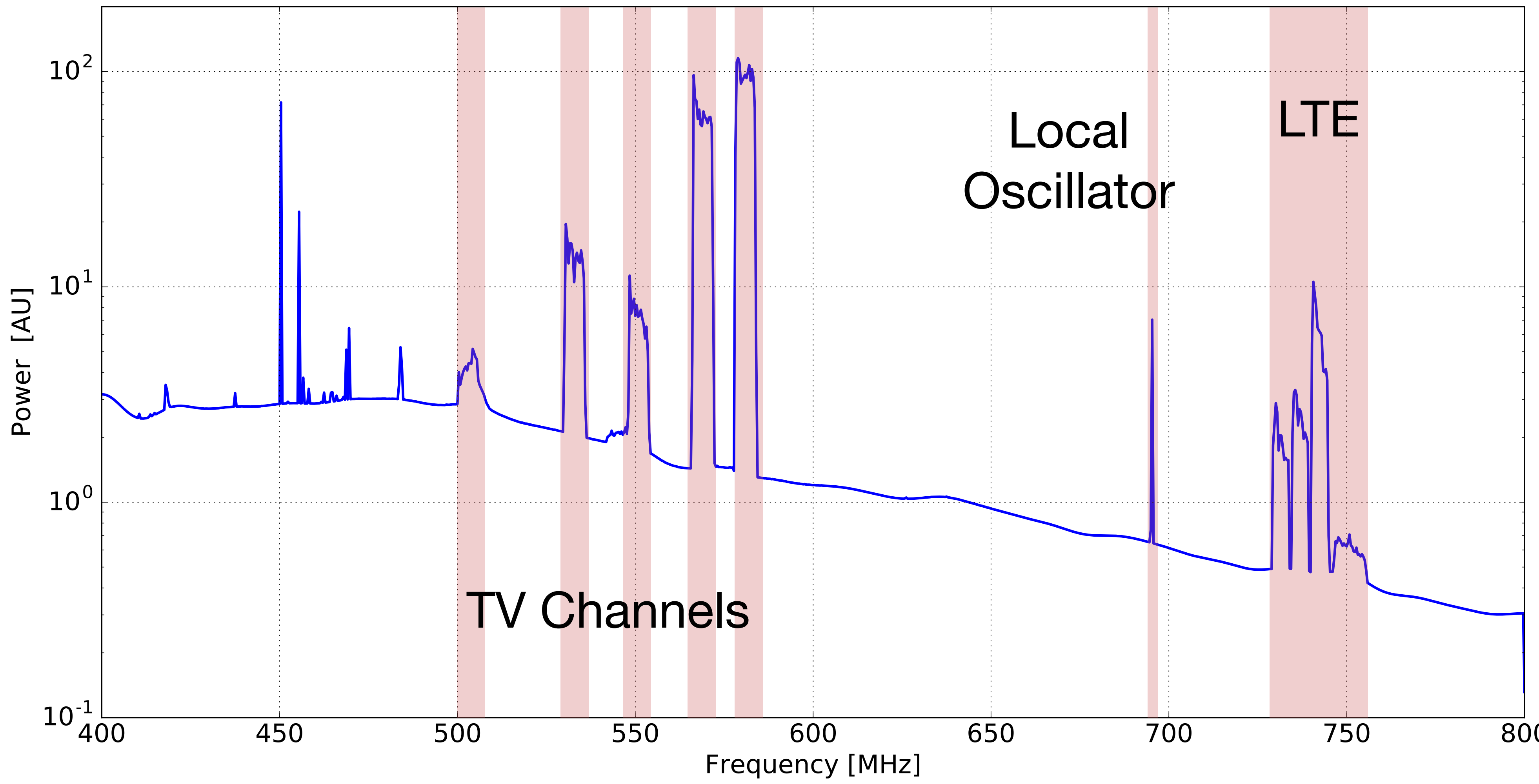
PERIMETER INSTITUTE

Massachusetts Institute of Technology

NRAO

Drone Flight Over CHIME

Dominion Radio Astrophysical Observatory

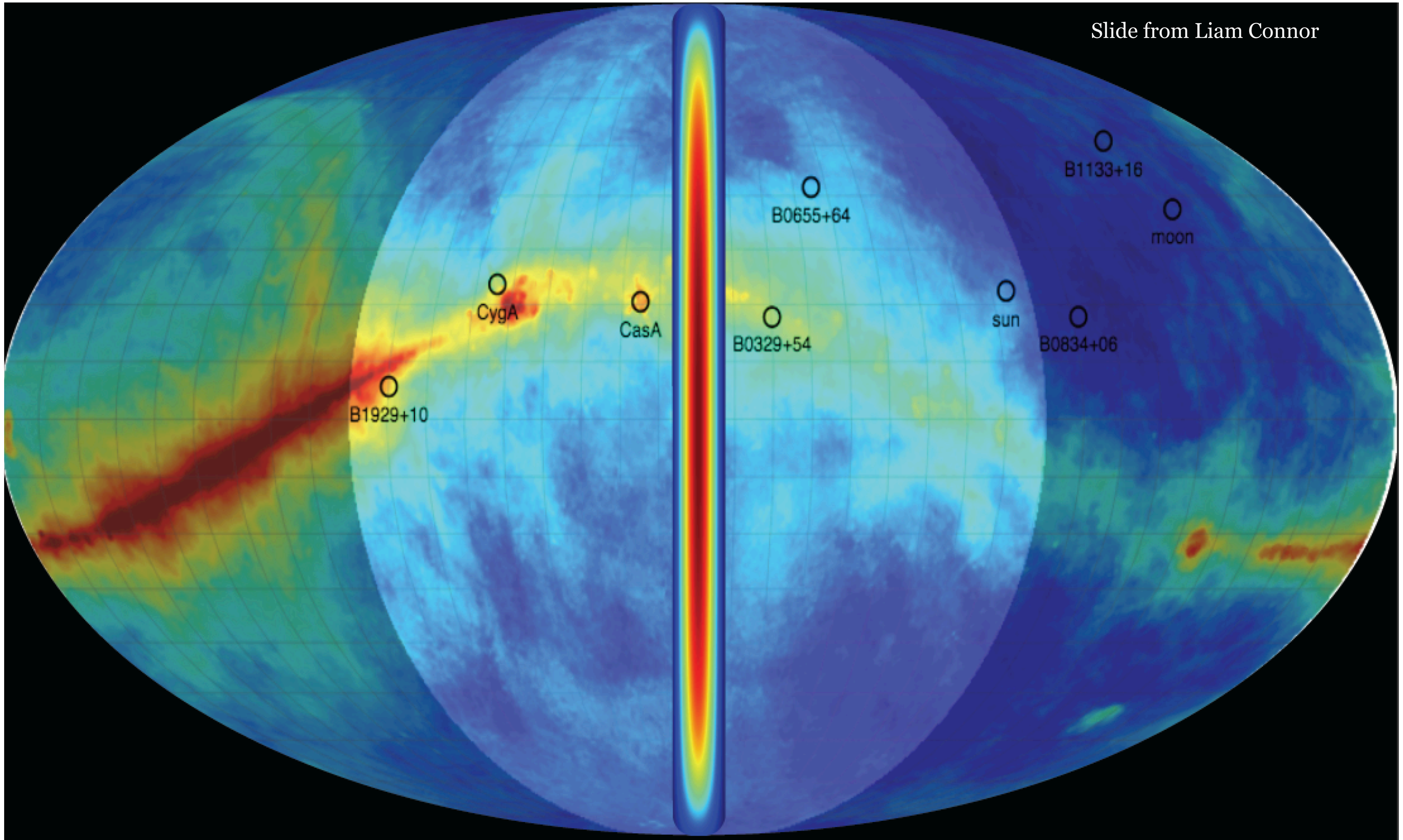


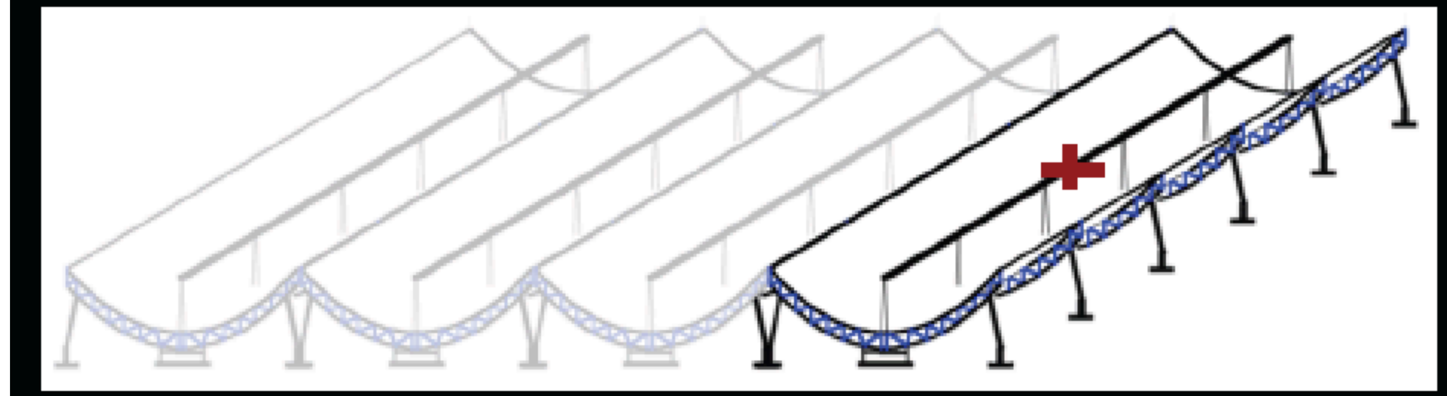
≈ 25% of band masked due to persistent RFI

Cylindrical Transit Interferometer

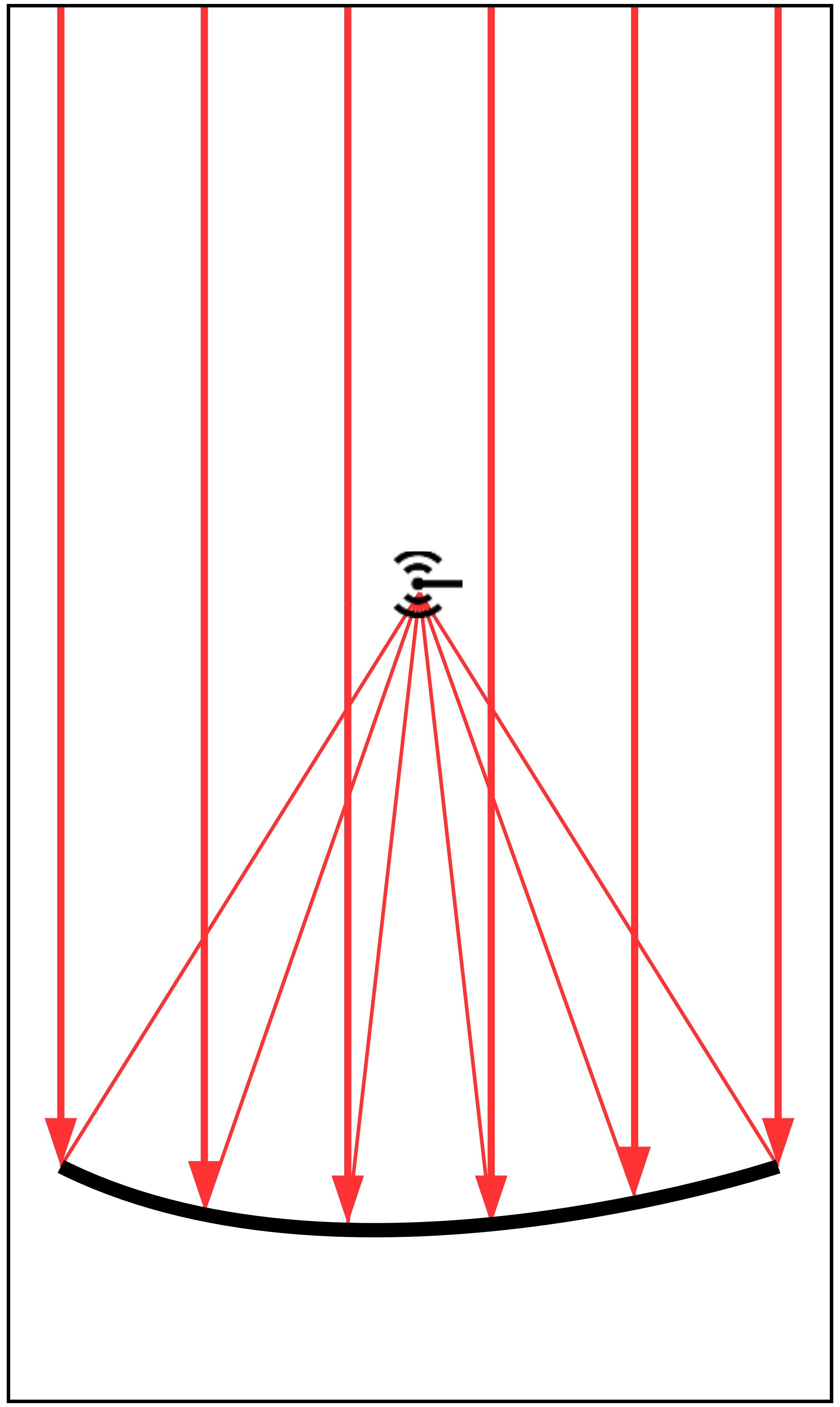
Movie by Peter Klagge

Cylindrical Transit Interferometer

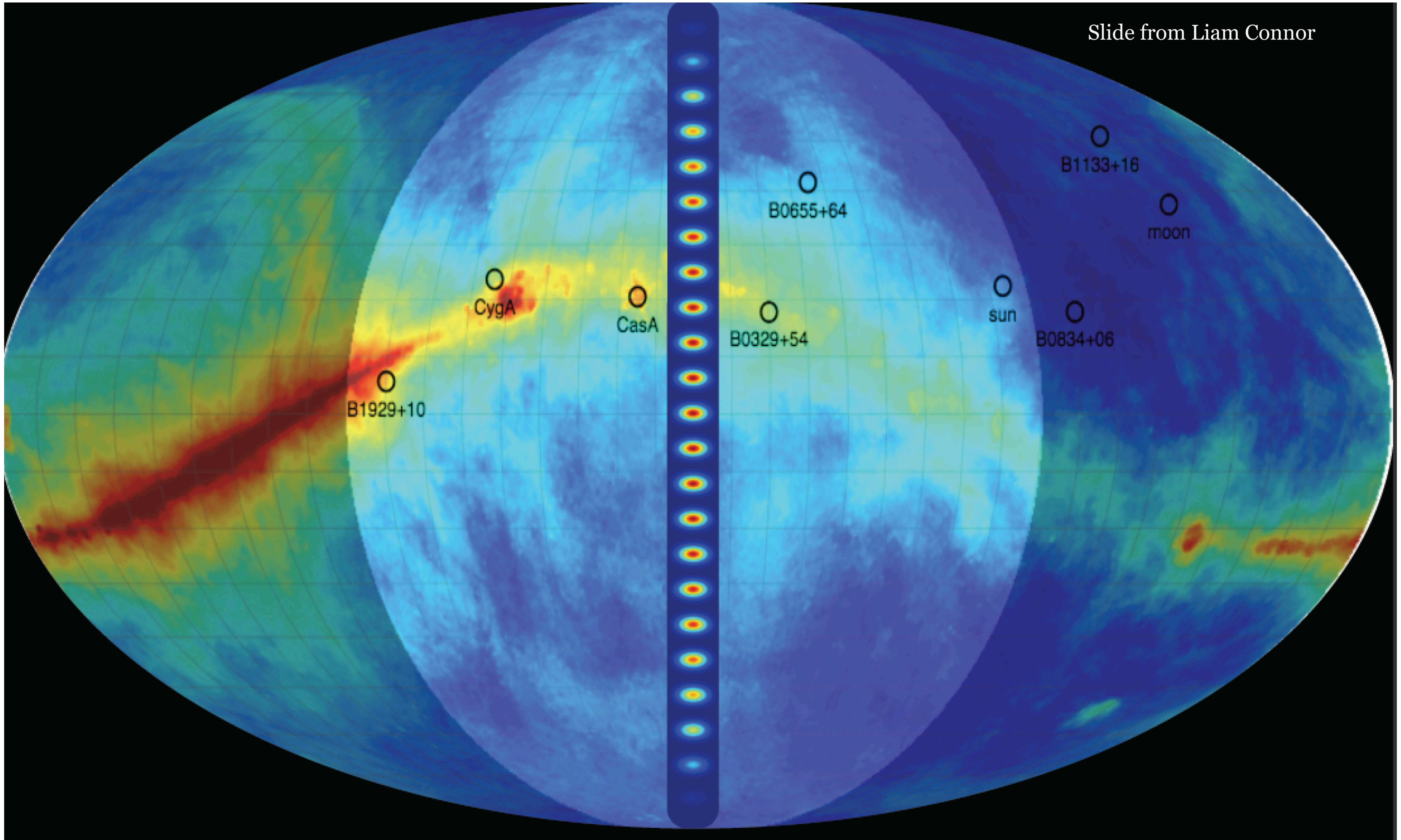


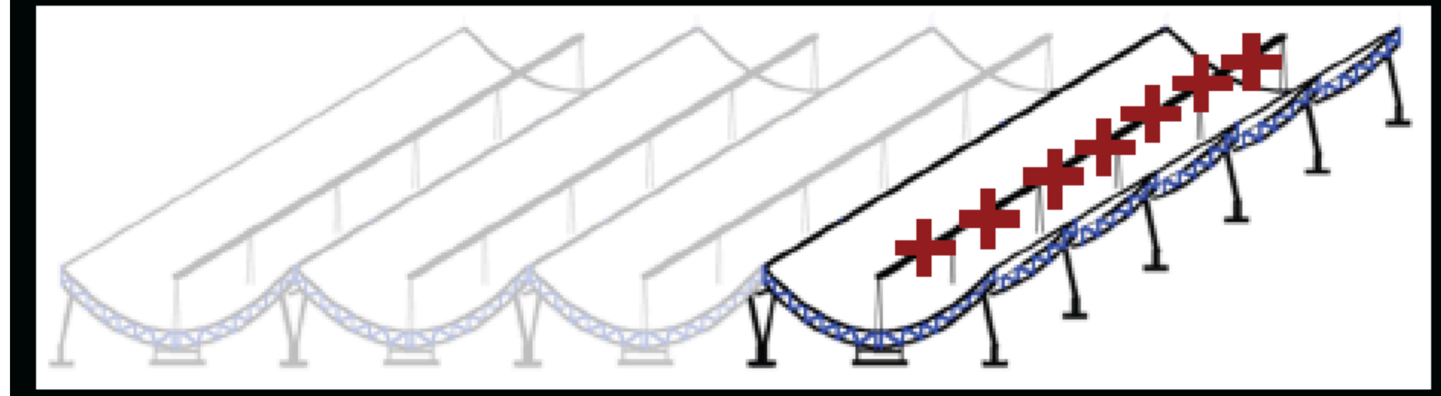


- Cylinder focuses light only in EW direction
- Gives us large FOV

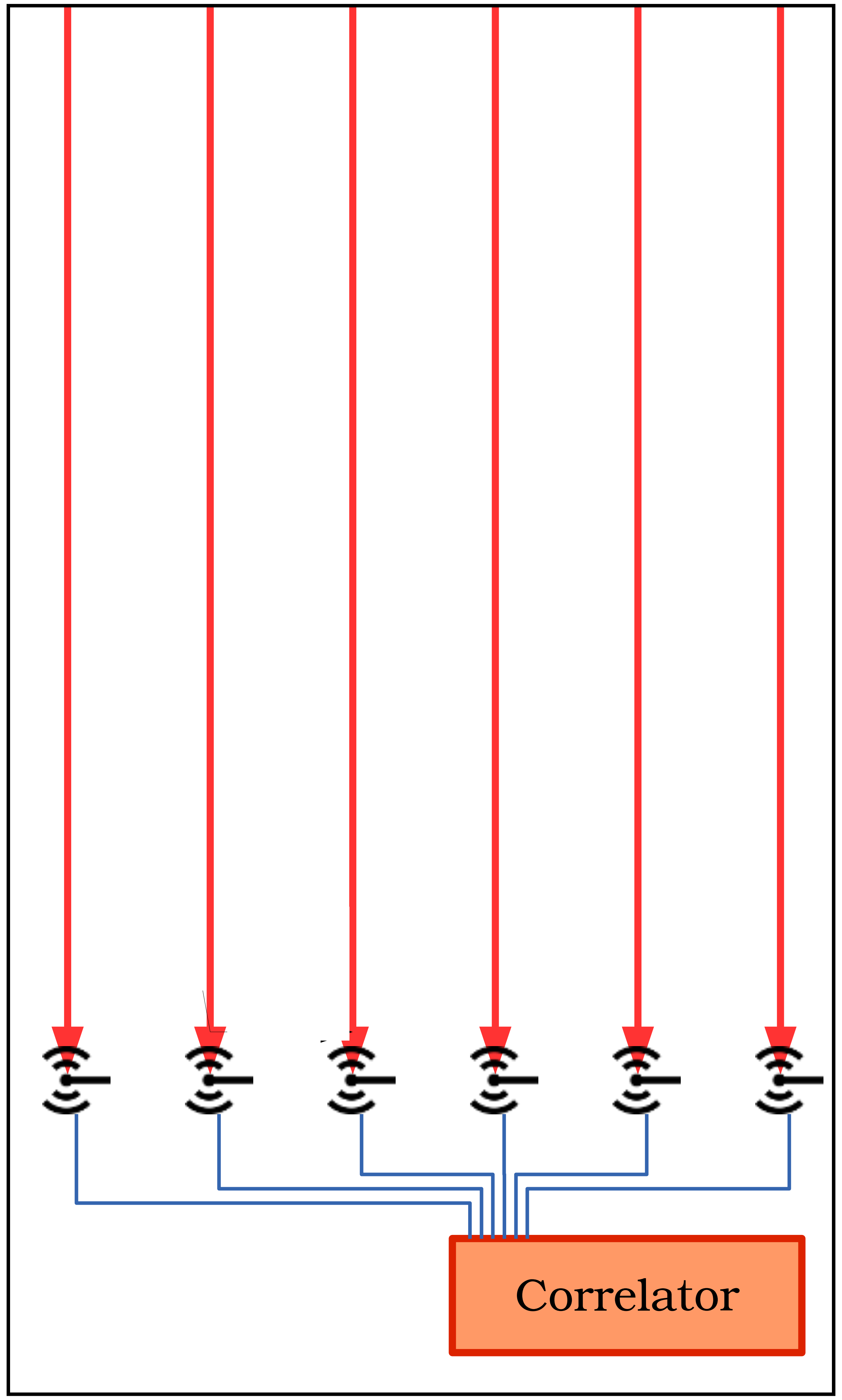


Cylindrical Transit Interferometer

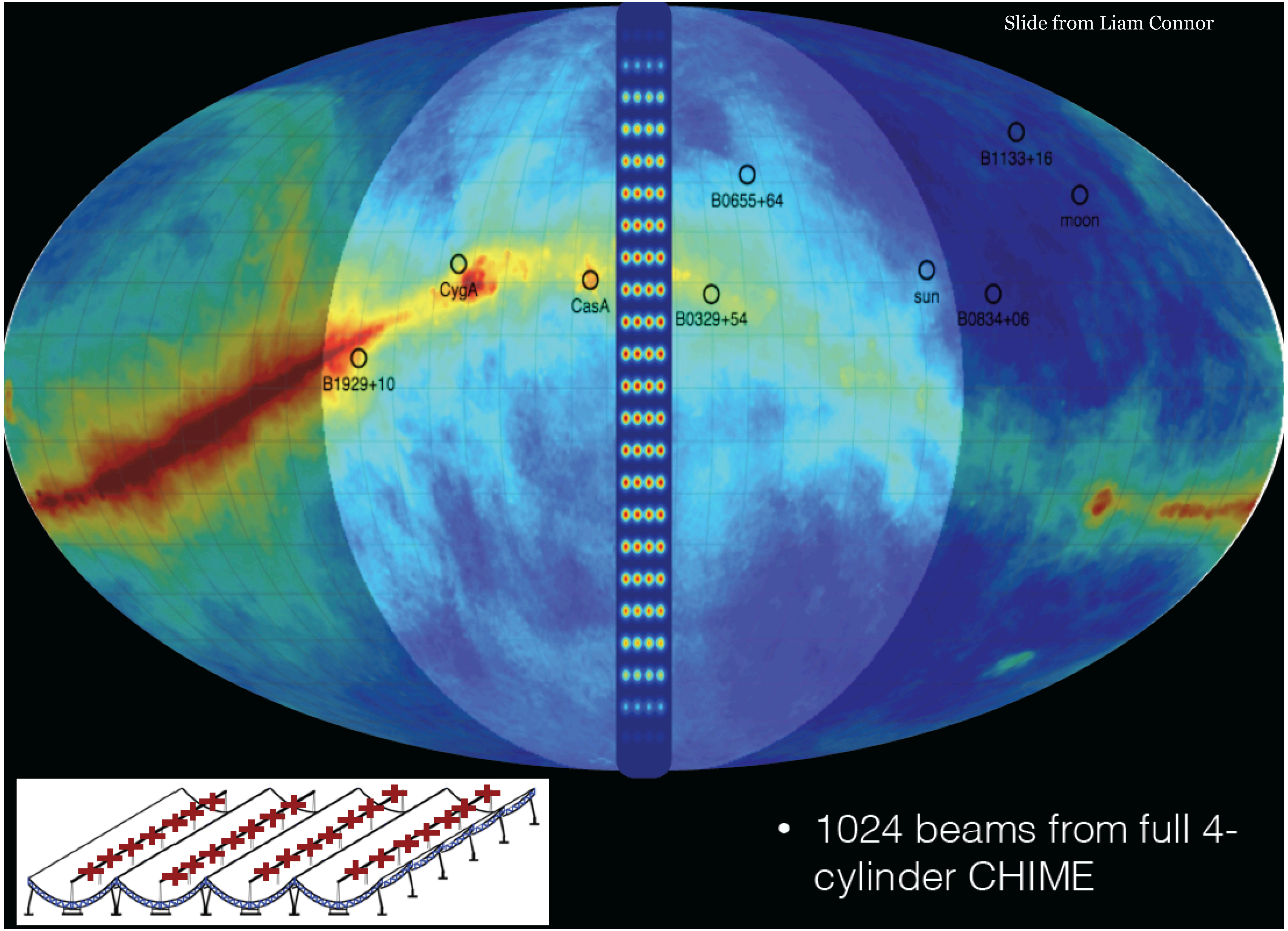




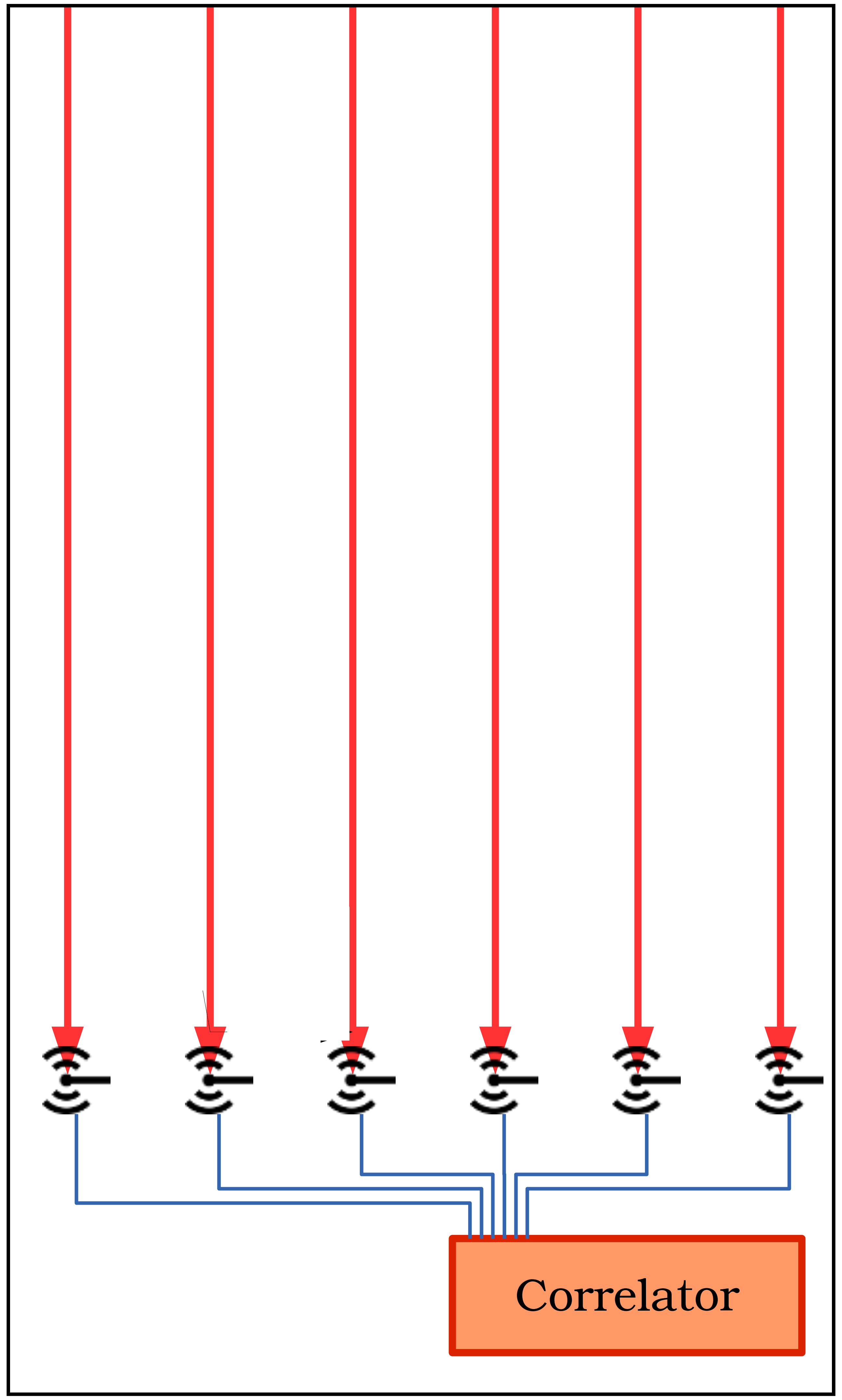
- FFT telescope in NS direction
- 256 beams per cylinder



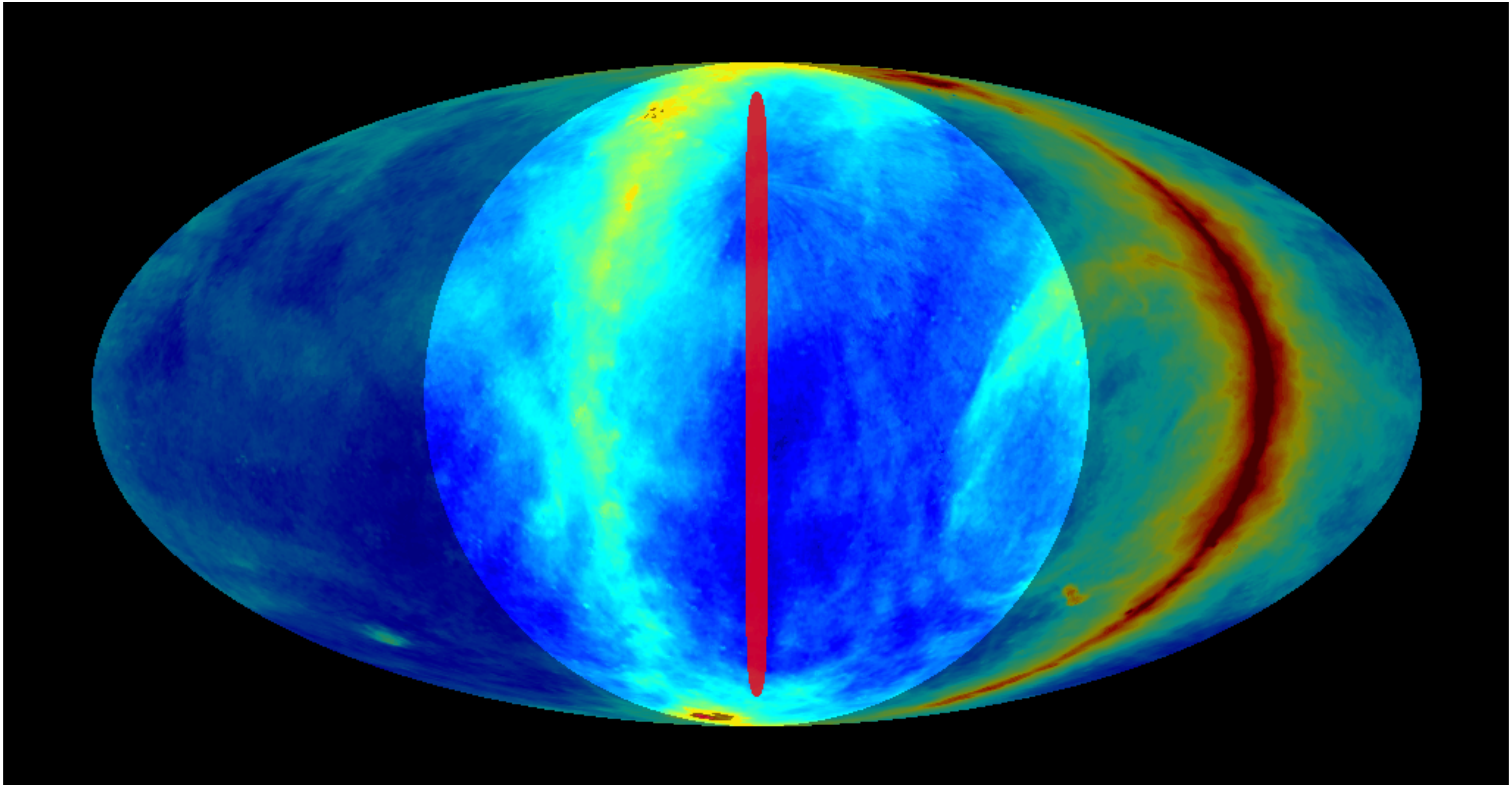
Cylindrical Transit Interferometer



- 1024 beams from full 4-cylinder CHIME



Cylindrical Transit Interferometer



Haslam 408 MHz Map

CHIME Science Objectives

chime

Hydrogen Intensity Mapper

Measure baryon acoustic oscillations in the distribution of neutral hydrogen between z = 0.8 - 2.5.

Constrain dark energy.

Fast Radio Burst Detector

Detect large sample of FRBs.

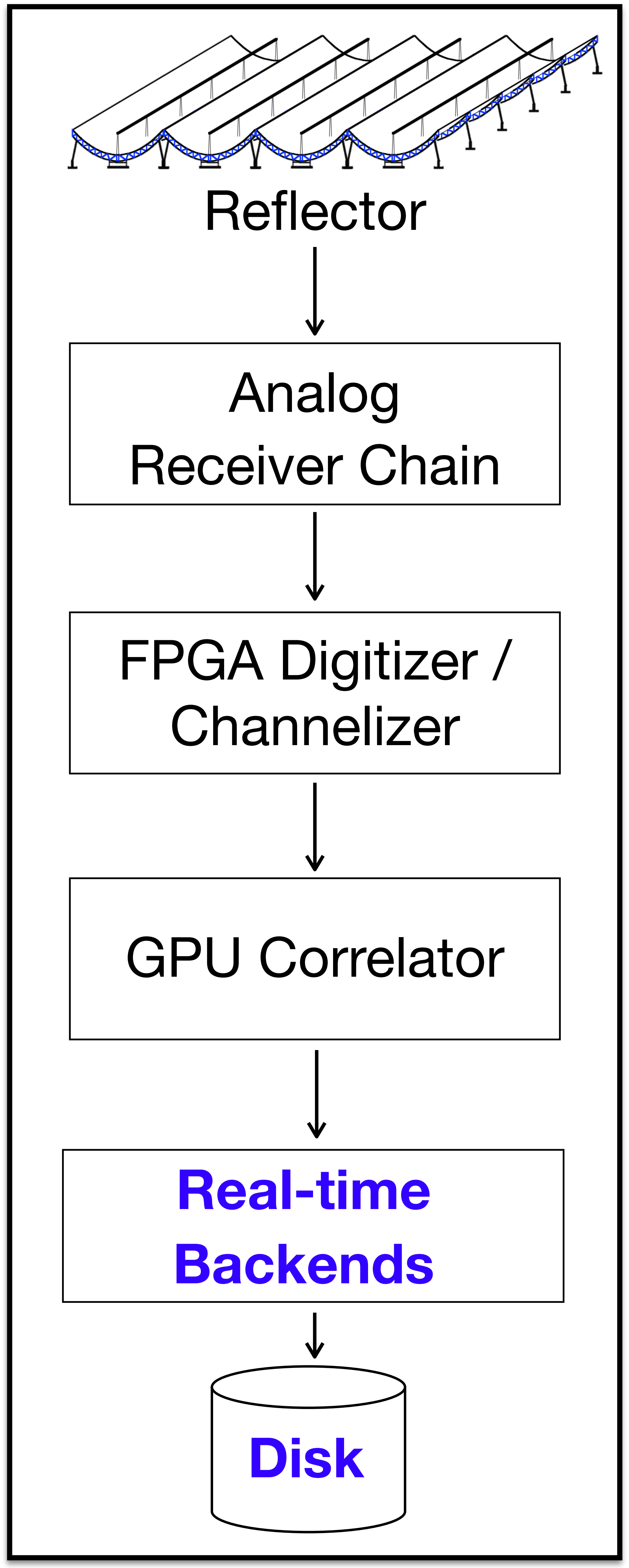
Constrain properties and origins of FRBs.

Pulsar Monitor

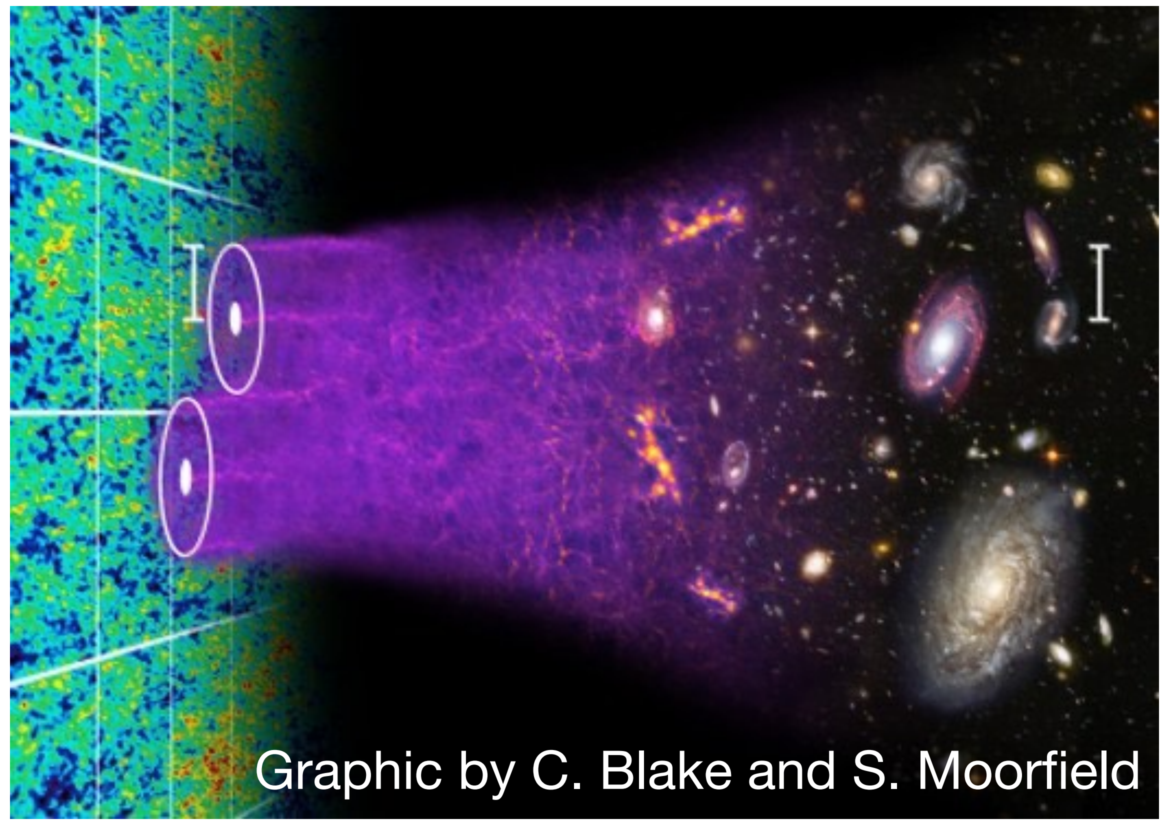
Provide near daily timing data on all northern hemisphere pulsars.

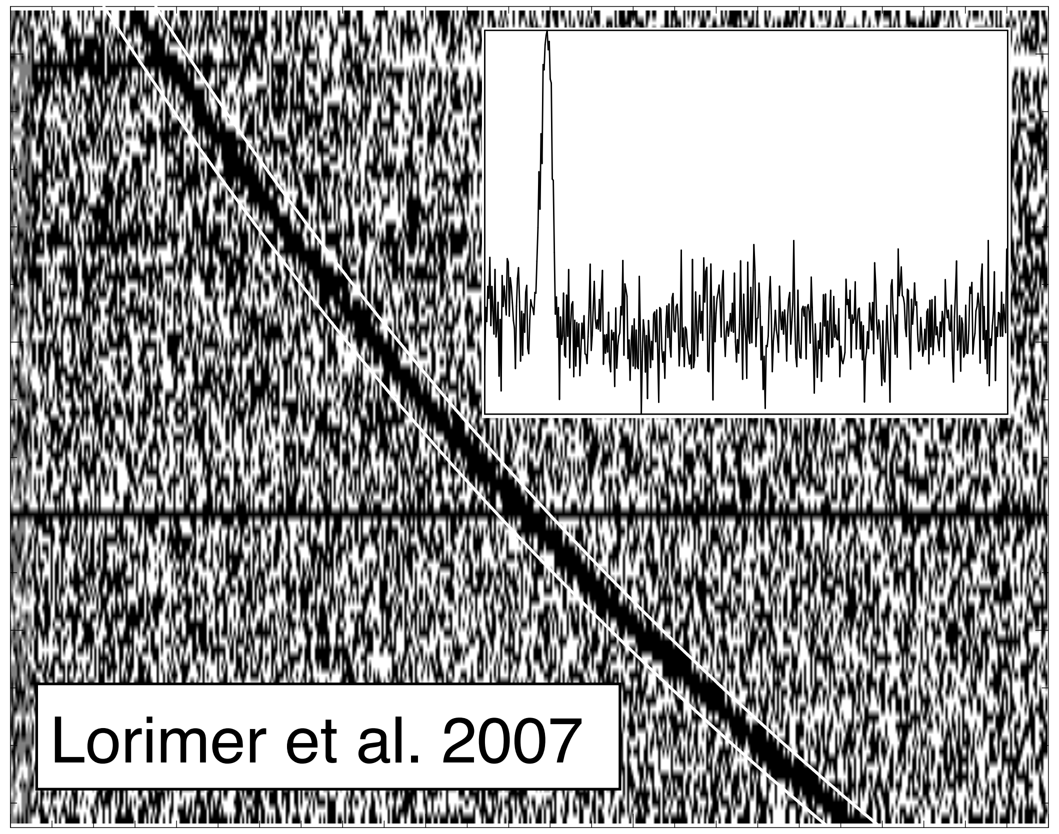
Measure pulsar properties and improve constraints on gravitational waves.

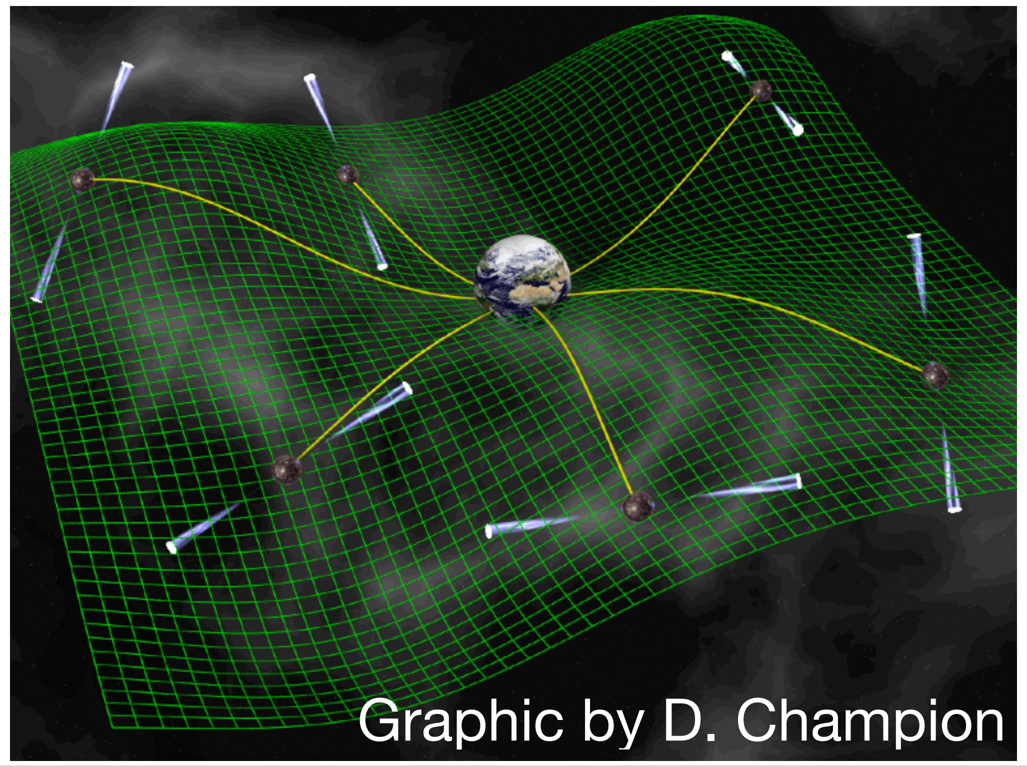
CHIME Science Backends



- **Cosmology**
  - Full N^2 visibility matrix
  - 10 sec cadence
  - 210 TB/day
  - Real-time flagging and gain calibration
  - Data compression through redundant baselines (1.0 TB/day)
- **Fast Radio Bursts**
  - 1024 stationary beams
  - 1 msec cadence
  - 16k frequency bins
- **Pulsar timing**
  - 10 steerable beams
  - 2.56 μs cadence


Graphic by C. Blake and S. Moorfield

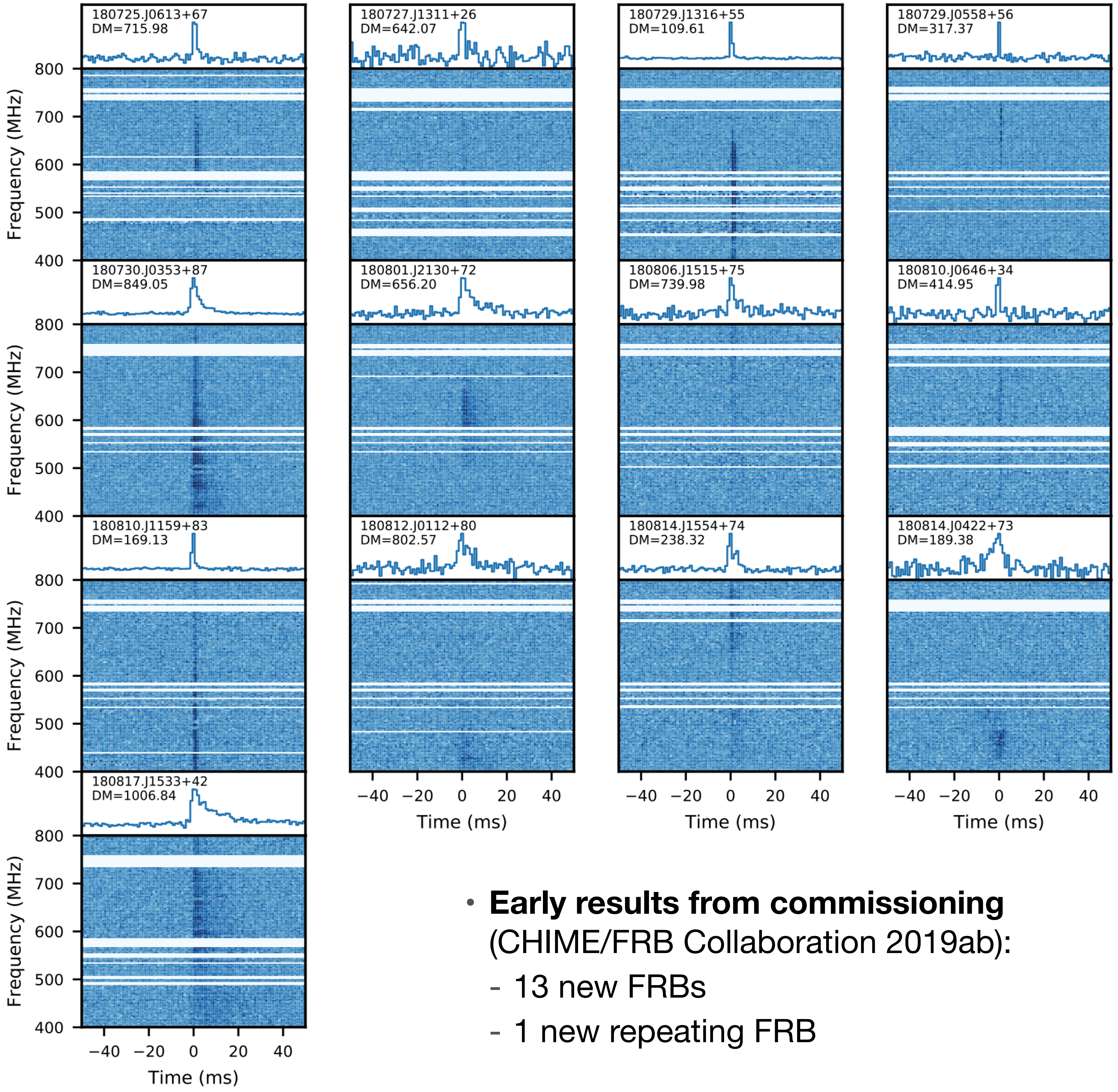

Lorimer et al. 2007


Graphic by D. Champion

Status (Cosmology Backend)

- **Sep 7, 2017:** First light ceremony
- **Sep 2018:** Reached full capacity. Compress data by averaging redundant baselines.
- **Past 2 Years**: Acquiring data roughly 80% of the time.
- Downtime is primarily due to software upgrades. Some notable upgrades have included:
  - Pulsar gating
  - Fast-cadence (msec) RFI excision
  - Fast-cadence (10 sec) gain updates
  - Frequency remapping (send the RFI contaminated frequencies to non-operational GPU nodes)
- As of 2020-07 we have acquired 540 days of data total. Significant fraction flagged due to sun (50%) and rain (10-20%). Have acquired between 130-200 days worth of clean, night-time data.
- **In progress:**
  - Calibrate instrument transfer function and characterize systematics
  - Remove foregrounds
    - Use methods that do not require a beam model to start
  - Measure the cosmic 21cm signal in cross-correlation with quasar catalogs from the Sloan Digital Sky Survey

Results from CHIME/FRB



- **More recently:**
  - Detection of original repeater (Josephy et al. 2019)
  - Detection of 8 new repeaters (CHIME/FRB Collaboration 2019c)
  - Detection of 9 new repeaters (Fonseca et al. 2020)
  - Bright millisecond burst from a Galactic Magnetar (CHIME/FRB Collaboration 2020a)
  - Periodic activity from an FRB (CHIME/FRB Collaboration 2020b)

- **In progress:**
  - Catalog of hundreds of new FRBs

- **Early results from commissioning** (CHIME/FRB Collaboration 2019ab):
  - 13 new FRBs
  - 1 new repeating FRB

Radio Sky as Seen by CHIME

Averaging ~50 Nights of Data

“Dirty” maps of the northern sky between 800 and 400 MHz.
Constructed from YY visibilities, averaging each LST bin over 50 nights.

RFI Excision

Three stages of RFI excision:

- **0.66 msec cadence (real-time pipeline)**

  Spectral kurtosis based implementation of pre-correlation RFI excision using CHIME’s GPU backend.

  See Taylor et al. 2018

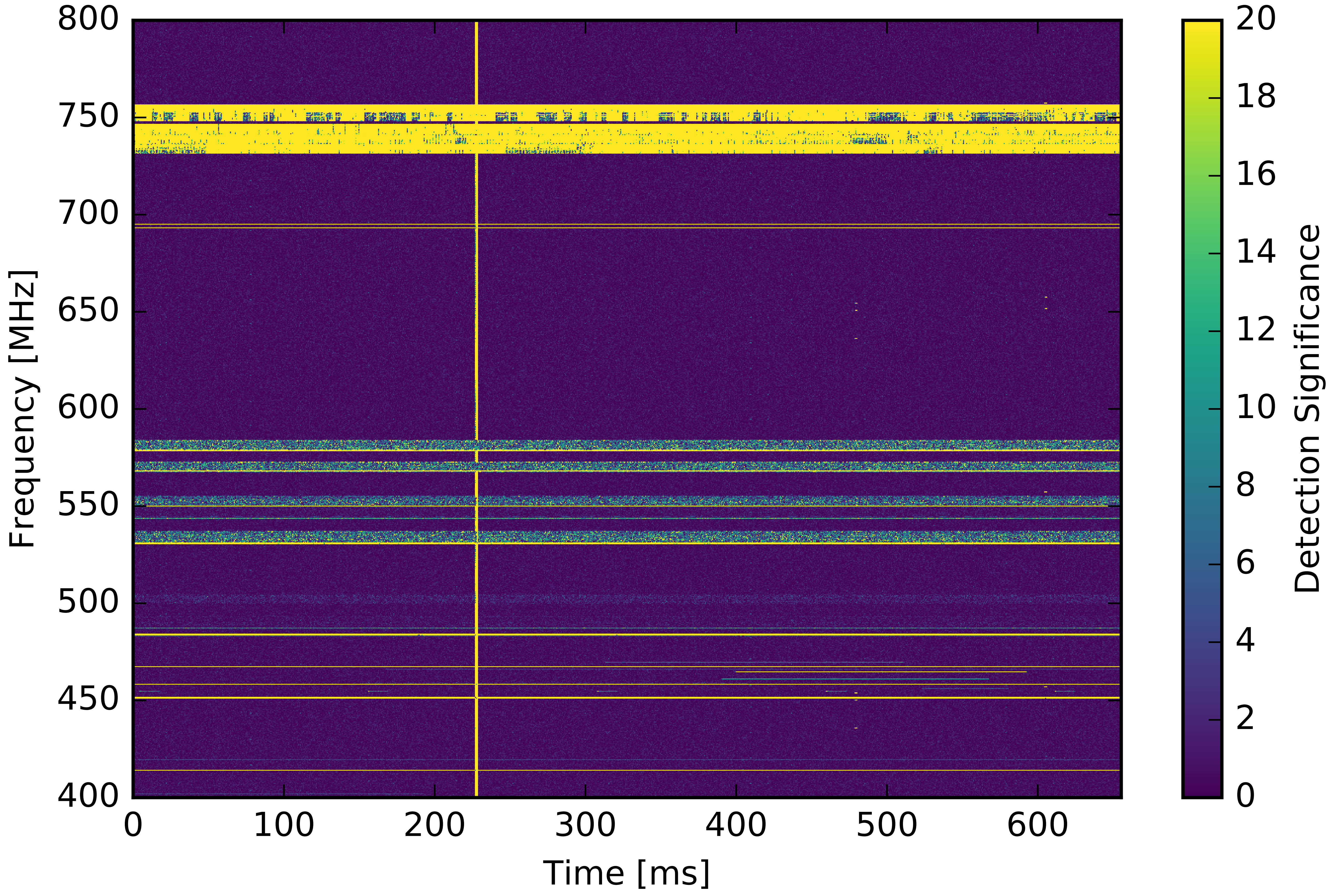
- **31 msec cadence (real-time pipeline)**

  Also uses the spectral kurtosis values but sensitive to lower-power, longer-duration events.

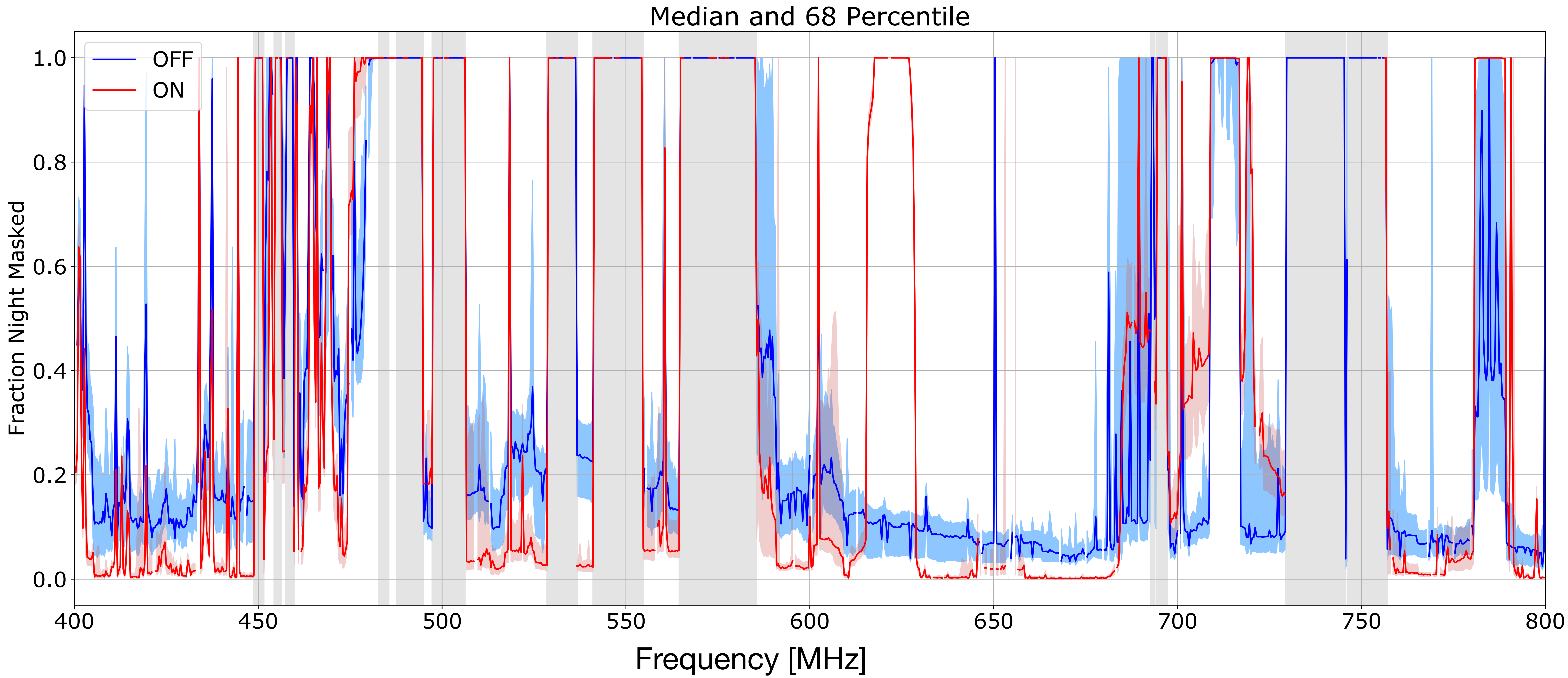
- **10 sec cadence (offline pipeline)**

  Apply SumThreshold outlier detection to sample variance of the visibilities averaged over all baselines and normalized by expectation based on radiometer equation.

Figure from Taylor et al. 2018



RFI Excision



Fraction of night-time data masked by pipeline due to RFI. Shown is the median value over many nights.

Blue: 200 nights between Jan-Sep 2019 when real-time RFI excision was off
Red: 30 nights in Jun 2020 when real-time RFI excision was on

Calibration Challenges

- Instrument chromaticity converts spatial variations in the bright, spectrally smooth foregrounds into spectral variations.

- CHIME plans to characterize the transfer function of the instrument and construct optimal Karhunen-Loève (KL) filter that rotates measured data into signal/foreground modes. (Shaw et al. 2014/15)

- **Beam calibration:**

$$V_{ij}(t) = < E_i(t)E_j^*(t) > = g_i(t)g_j^*(t) \int d^2\hat{\mathbf{n}}\ A_i(\hat{\mathbf{n}})A_j^*(\hat{\mathbf{n}})e^{2\pi i\hat{\mathbf{n}}\cdot\mathbf{u}_{ij}}\ T(\hat{\mathbf{n}};t)$$

Need to measure FWHM of primary beam pattern to better than 0.1%

Evidence for time-variable beams and baselines i.e., $A_i(\hat{\mathbf{n}},t)$ and $\hat{\mathbf{u}}_{ij}(t)$

- **Complex gain calibration:**

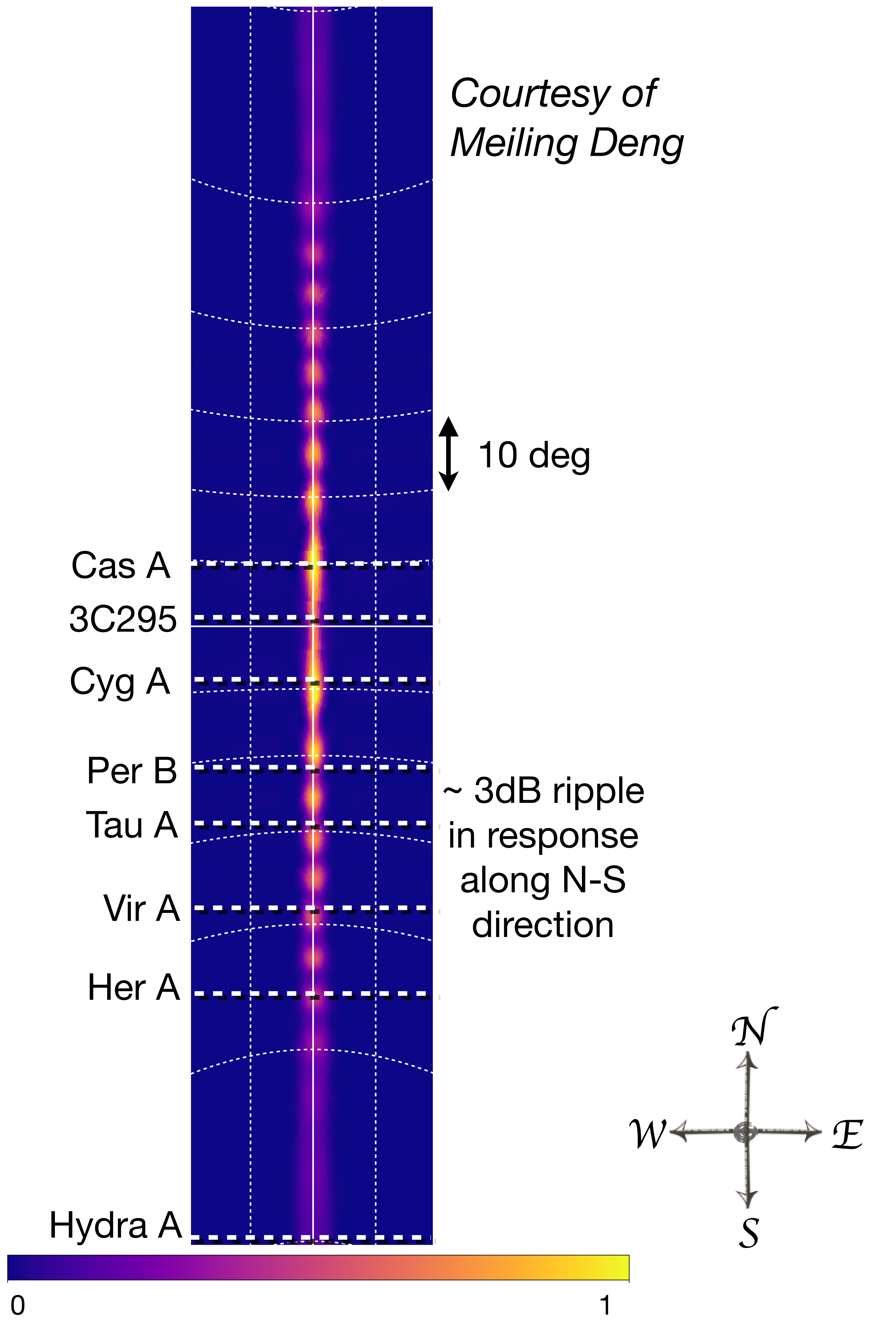
$$V_{ij}(t) = < E_i(t)E_j^*(t) > = g_i(t)g_j^*(t) \int d^2\hat{\mathbf{n}}\ A_i(\hat{\mathbf{n}})A_j^*(\hat{\mathbf{n}})e^{2\pi i\hat{\mathbf{n}}\cdot\mathbf{u}_{ij}}\ T(\hat{\mathbf{n}};t)$$

Need to measure complex gain to better than 0.7% (amplitude) and 0.007 rad (phase) on timescales > 1 minute

Beam Calibration

- **Measurements:**
  - CHIME x 26m holography
    - Radio-bright point sources (~10)
    - Pulsars (~10)
  - CHIME stacked visibilities
    - Radio-bright point sources (~30)
    - Sun
    - Full sky maps
- **Modeling:**
  - Simple physics-based coupling / reflection model
  - Data-driven model
    - Fit SVD modes from sun measurements to all other measurements

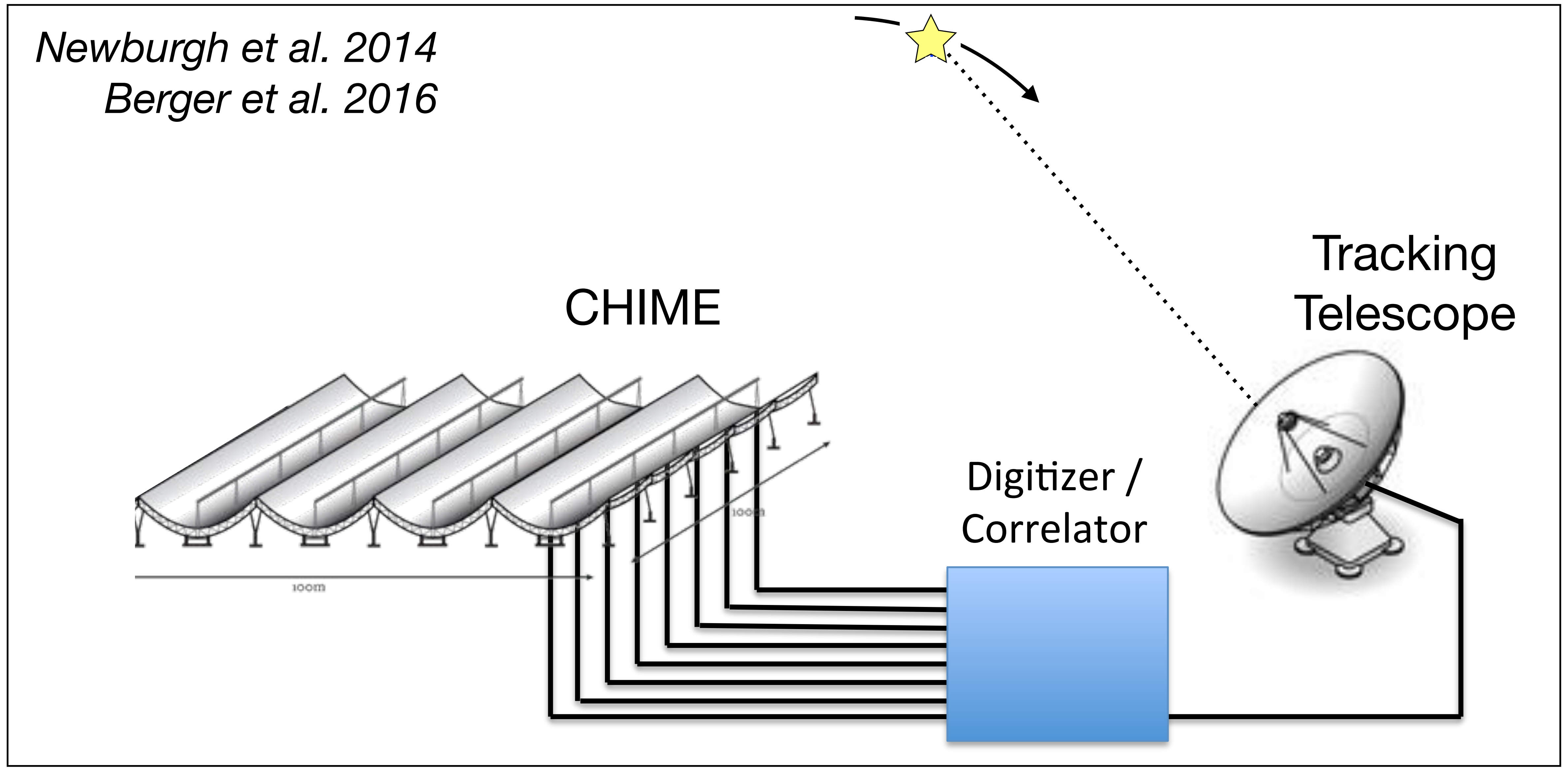
Simulated Beam
EW Pol at 703 MHz



Beam Calibration via Holography

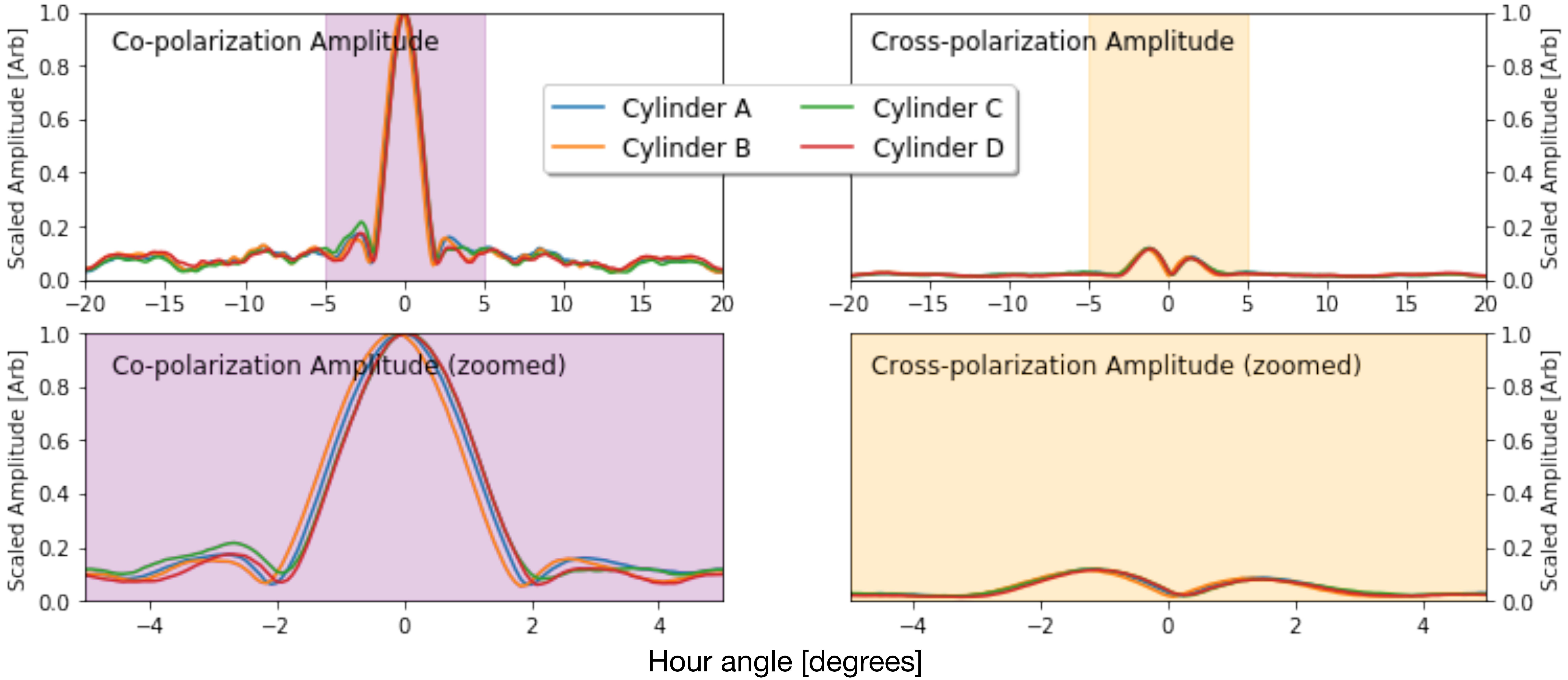
- Point Source Holography
  - Track radio-bright point source with John Galt 26m telescope as it drifts through the beam of the CHIME feeds
  - Correlate signal from 26m with signal from every CHIME feed
    - Extracts point source signal modulated by CHIME beam (plus any common background sky)

- Pulsar Holography
  - Subtract pulsar ON - pulsar OFF to remove common background sky
  - Implemented in GPU. Can gate on 30 msec cadence.
  - Characterize polarization response



Example Holographic Beam Measurements

Figure courtesy of Laura Newburgh

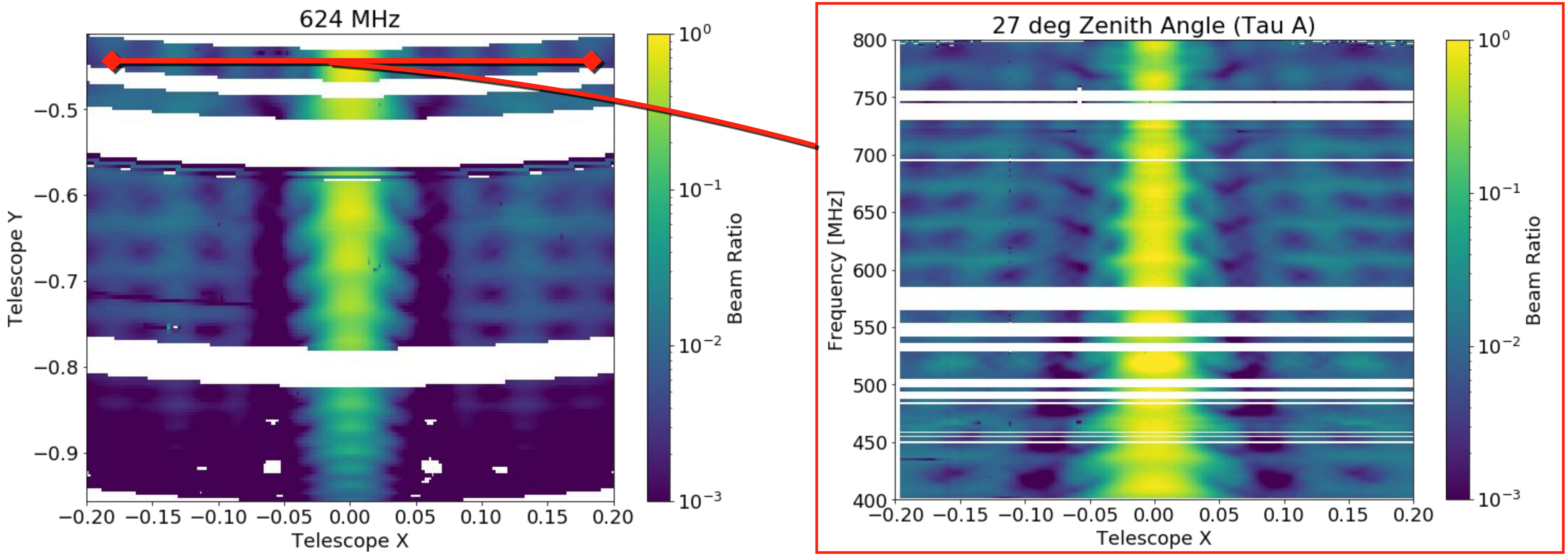


Holographic measurement of a Cyg A transit between the 26m at DRAO (tracking) and CHIME at 717 MHz. Shown is the median amplitude over all Y polarisation feeds on each of the 4 cylinders. Left is co-polar, right is cross-polar. Data is normalized by the peak co-polar response.

Currently have in hand 10-100 observations of each of the 10 brightest radio point source and 1-20 observations of each of the 10 brightest pulsars.

Beam Calibration via Sun

- Pros:
  - Extremely bright (>100 kJy) providing high signal-to-noise, even in sidelobes
  - Maps out -23.5° to 23.5° in declination every 6 months
- Cons:
  - Time-variable flux
  - Causes additional complex gain instability
  - Extended (0.5-1.0° diameter)



Work by Dallas Wulf

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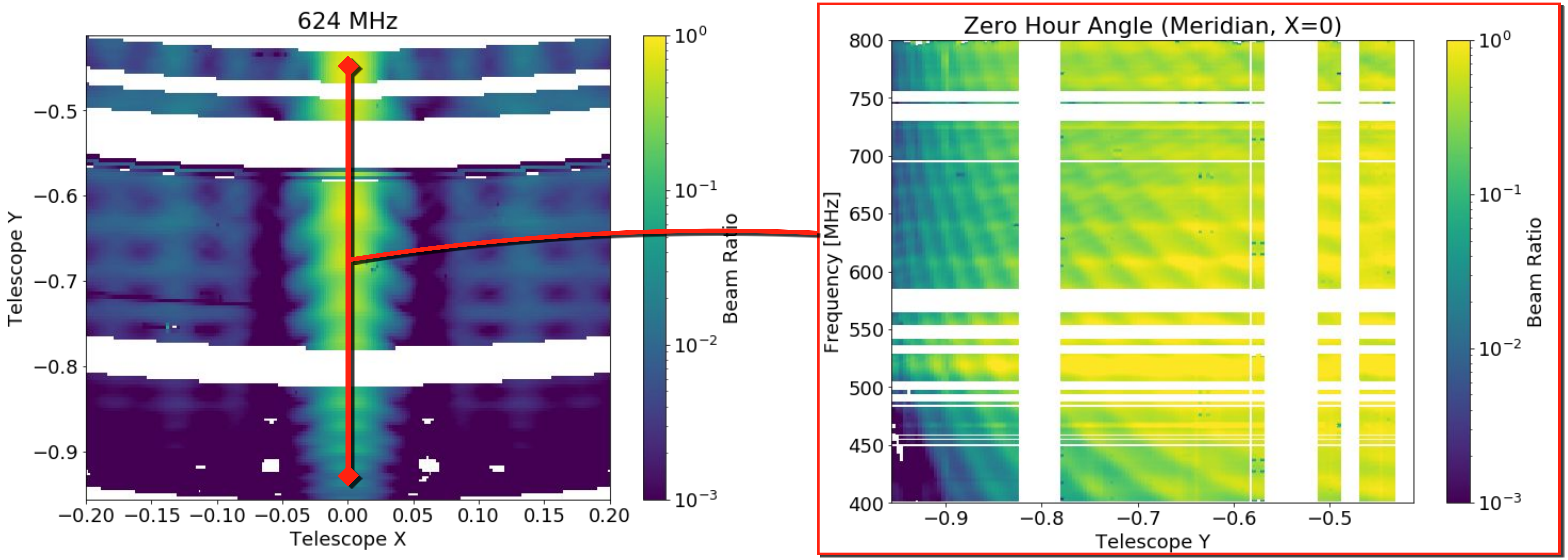
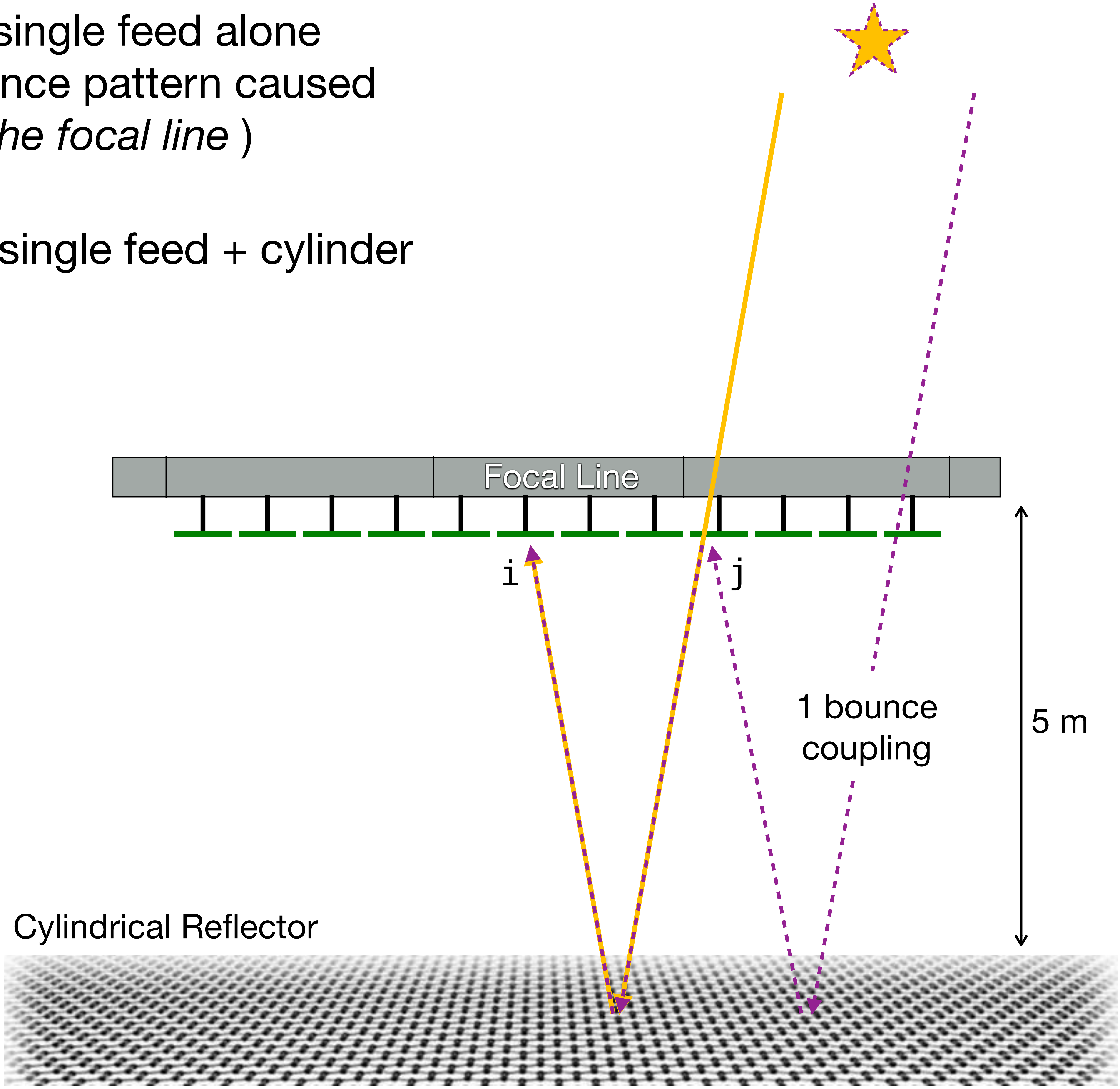


Work by Dallas Wulf

Modeling the North-South Beam

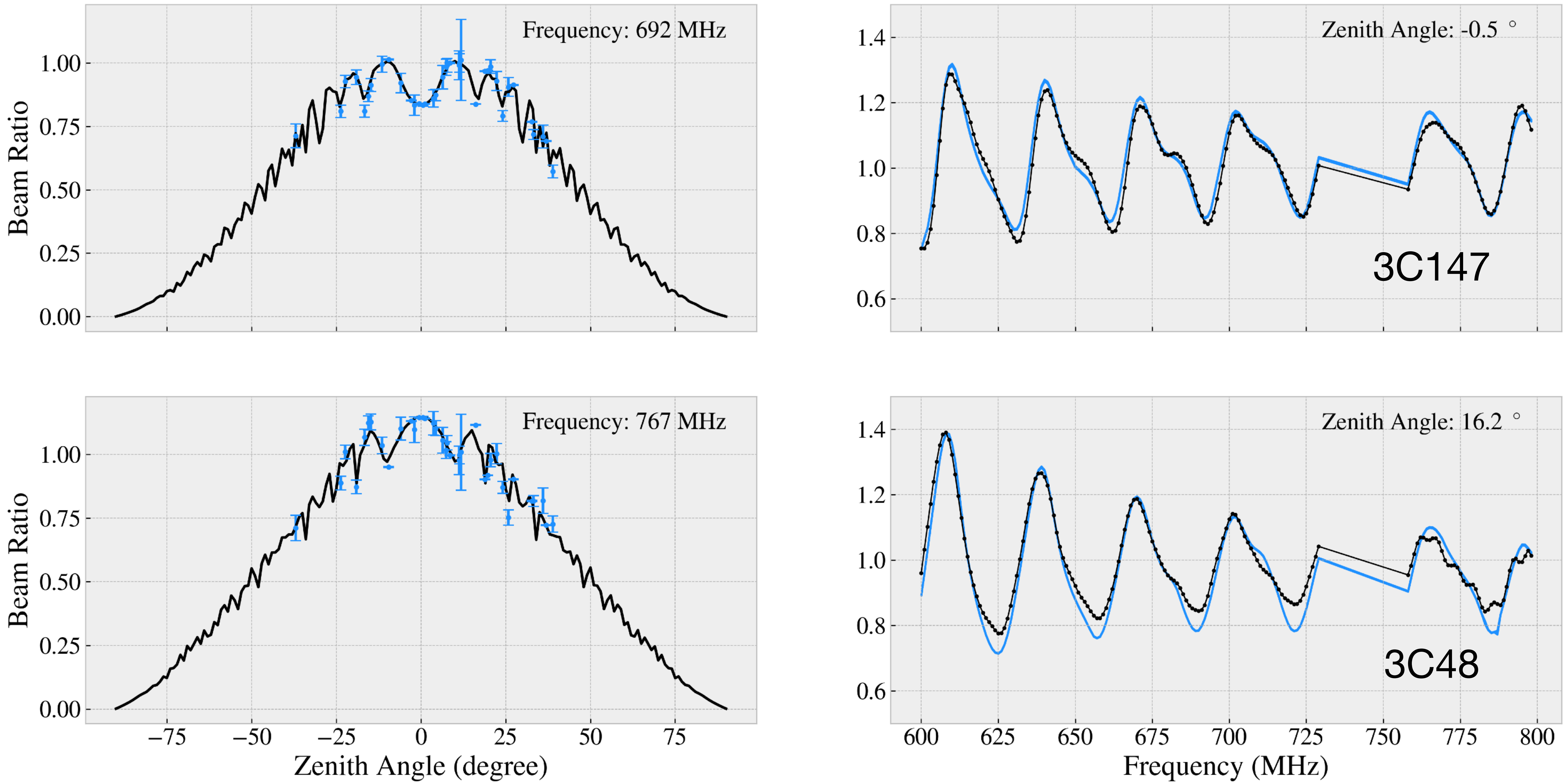
- The north-south beam of CHIME is the response of a single feed alone on the cylinder (base beam) modulated by an interference pattern caused by coupling between feeds (… *and also reflection off the focal line*)
- Base beam obtained from CST+GRASP simulation of single feed + cylinder
- Assume 4 coupling paths with known delay
- For each path, parametrize:
  - Dependence of coupling on frequency
  - Dependence of coupling on feed separation
- ~25 model parameters
- Fit to spectrum of ~35 radio-bright sources.

  Obtained by beamforming CHIME visibilities to source location and dividing by the expected source flux from literature.



Modeling the North-South Beam

Figure courtesy of Saurabh Singh



Data in **blue**. Current best-fit model in **black**.

Left: Peak response as a function of zenith angle for 2 frequencies.

Right: Peak response as a function of frequency for 2 zenith angles.

Complex Gain Calibration (Amplitude)

- Determine gain for each feed and frequency from an eigen-decomposition of the N^2 visibility matrix during transit of a radio-bright point source (Cyg A, Cas A, Tau A, or Vir A).

- Calibrate once per day. Use variations in these point-source gains over sidereal days to characterize instrument stability and calibrate thermal regression models.

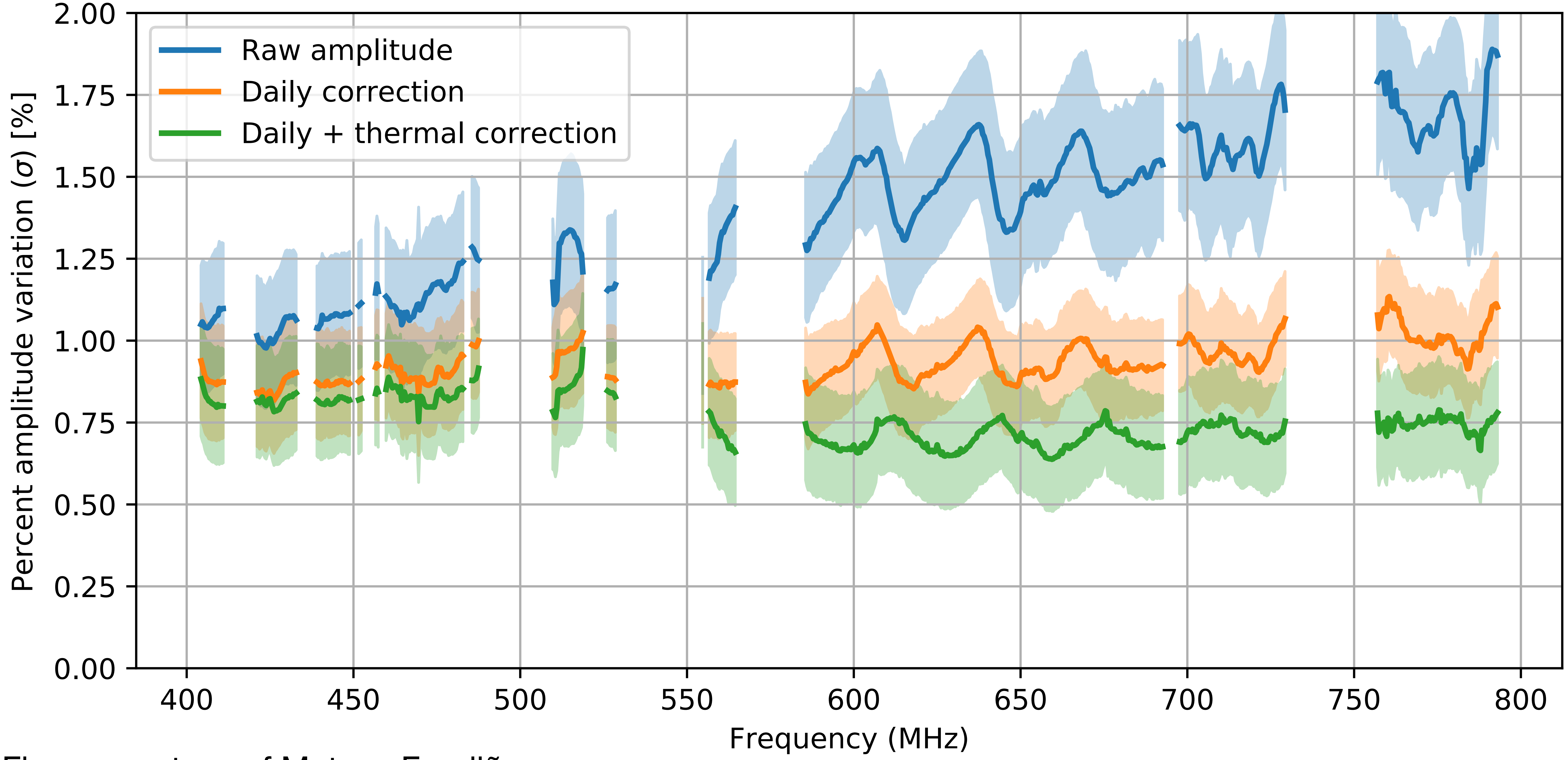
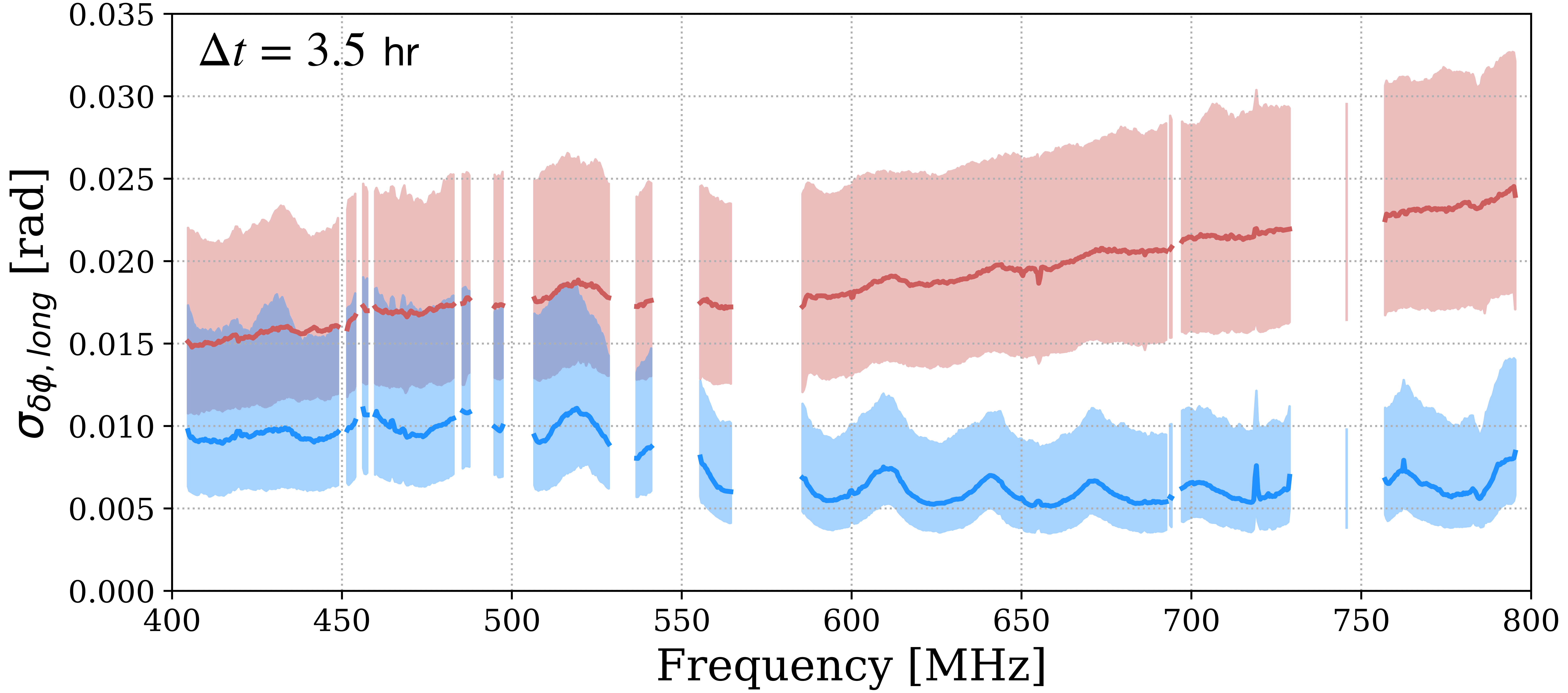


Figure courtesy of Mateus Fandiño.

Standard deviation of the fractional amplitude variations determined from 94 Cas A transits, 89 Cyg A transits, 76 Tau A transits.

Complex Gain Calibration (Phase)

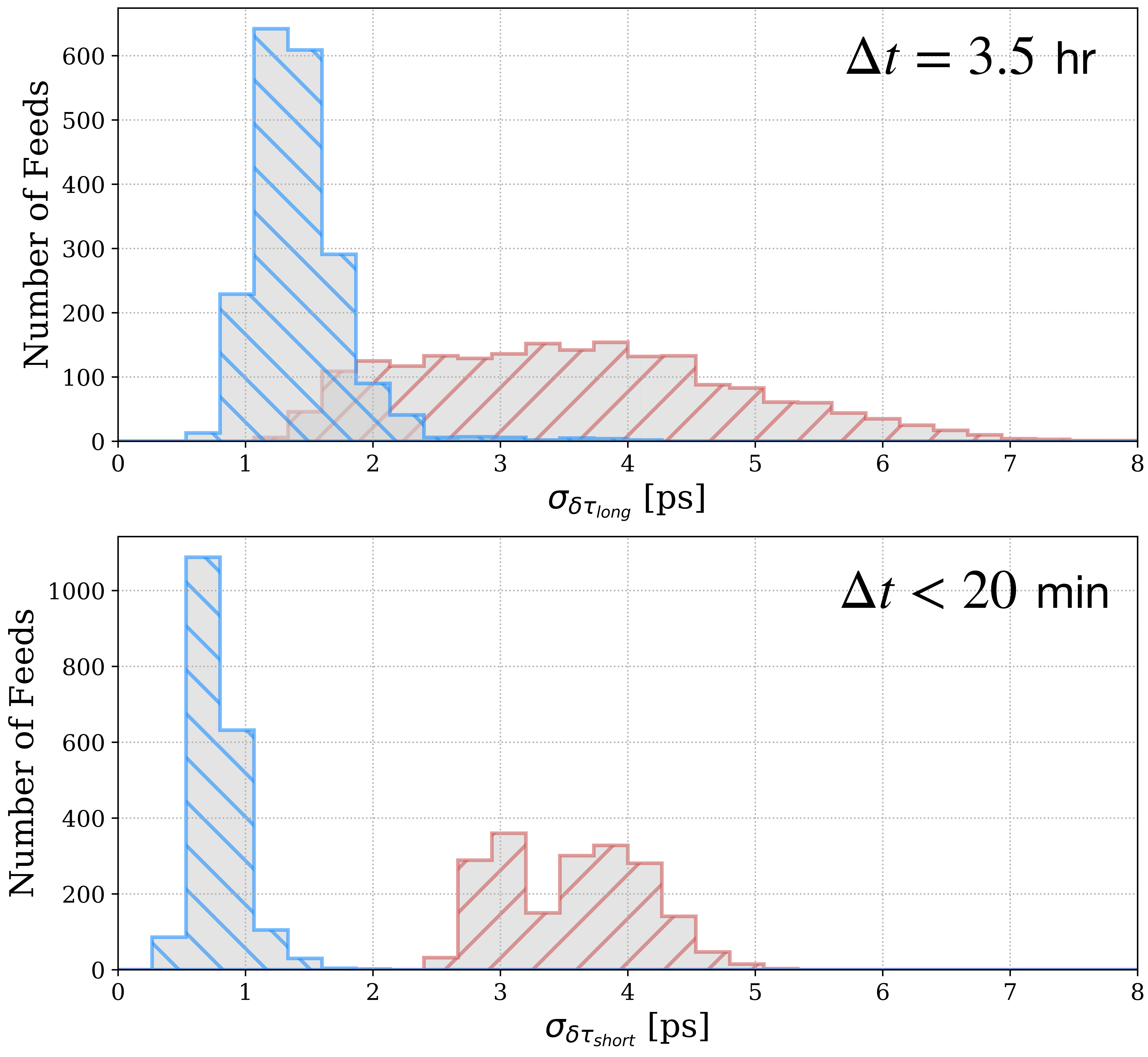


Red: Standard deviation of phase of 74 Cas A transits after daily calibration with Cyg A.

Blue: Standard deviation of phase residuals after subtracting variations that scale linearly with frequencies, i.e.,

$$\delta\phi_i(t,\nu) = 2\pi\nu\delta\tau_i(t) + \delta\phi_i^r(t,\nu)$$

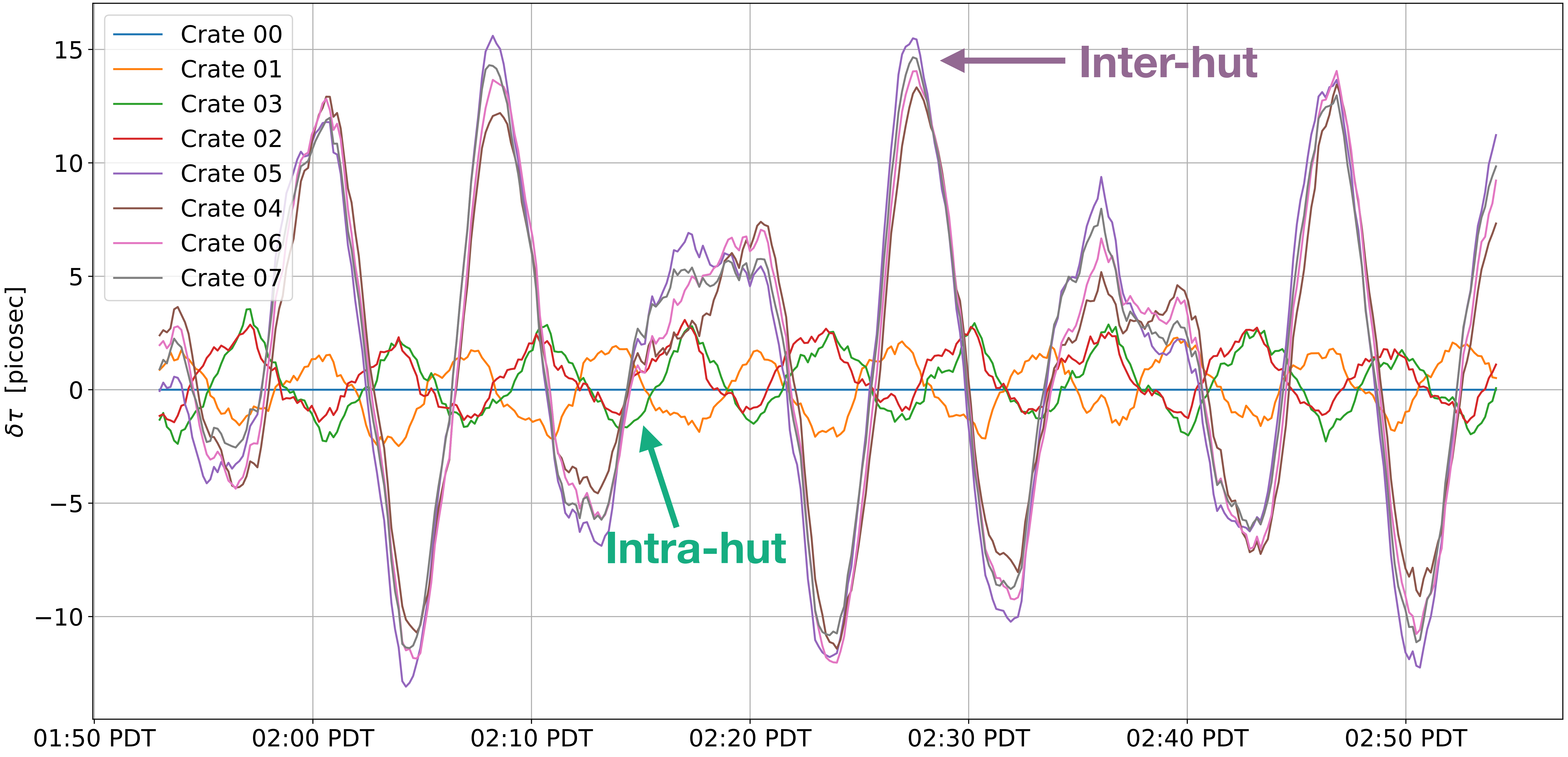
Complex Gain Calibration (Delay)



- Developed multiple linear regression model that relates measured delay variations to noise source and temperature sensor data.
- Coefficients calibrated using gains inferred from transit of 4 brightest point sources.
- Noise source and temperature sensor data then used to correct visibilities in between point source transits.
- Model corrects for:
  - Drift between copies of the 10 MHz clock supplied to different ADCs
  - Thermal expansion of the focal line
  - Thermal susceptibility of the outside portion of the analog chain (primarily coaxial cables)

Realistic Simulations of Complex Gain Errors

- Simulate complex gain errors with realistic correlations across feed, frequency, and time
  - Drift between copies of the 10 MHz clock
  - Differences in thermal susceptibility of coaxial cables
  - Differences in temperatures of coaxial cables



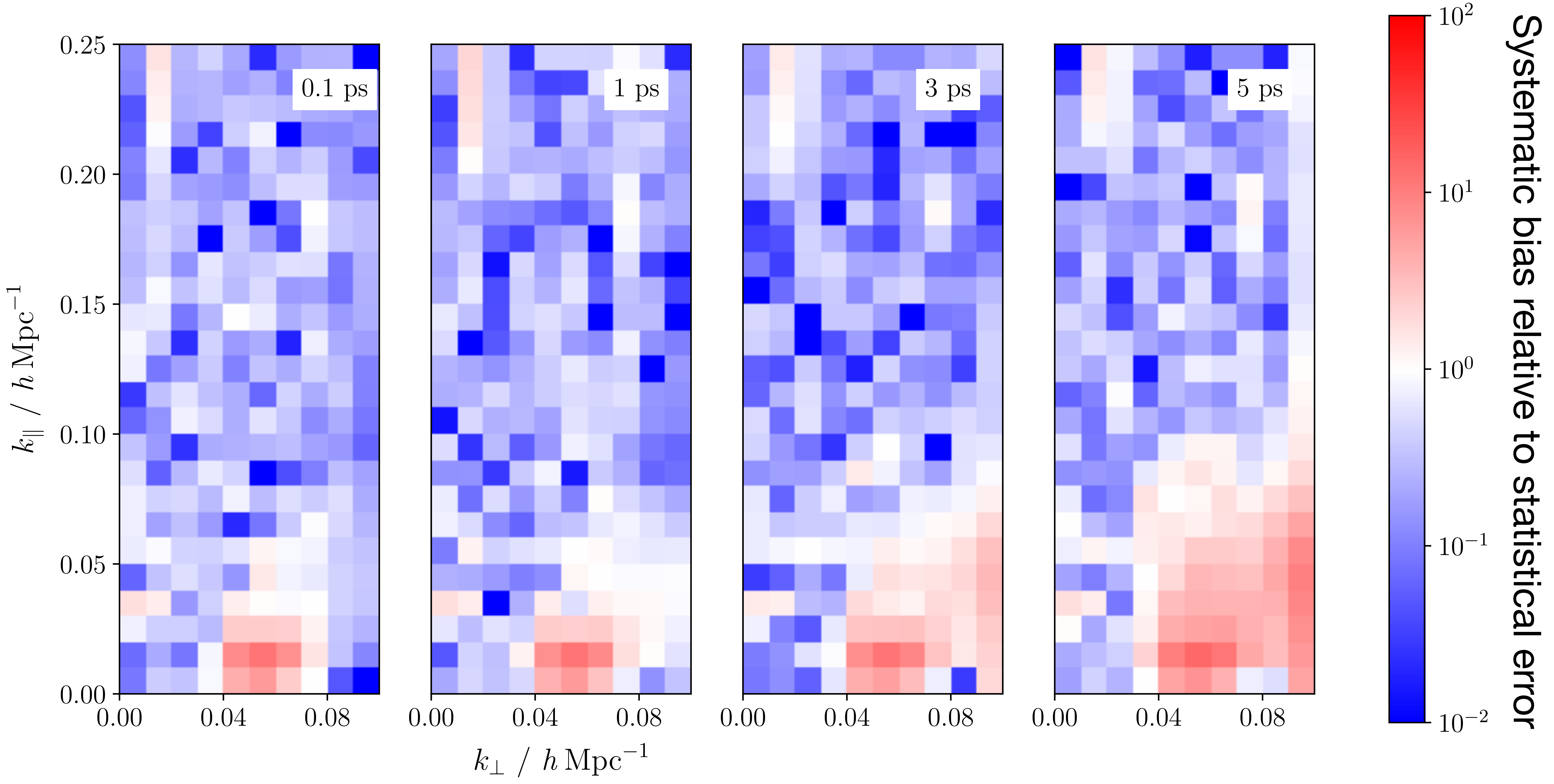
Drift between copies of the 10 MHz clock as measured by a broadband noise source connected to each FPGA crate.

Significant variations on 5-10 minute timescales corresponding to chiller cycle.

The two receiver huts are at different temperatures. Relative delay between ADCs in different huts is much larger than between ADCs in same hut.

Realistic Simulations of Complex Gain Errors

- Process the miscalibrated data through foreground filtering (KL) pipeline and determine if recovered power spectrum is biased.



Bias in power spectrum due to realistic drift in the 10 MHz clock (for pathfinder-like telescope in the 400-500 MHz band)

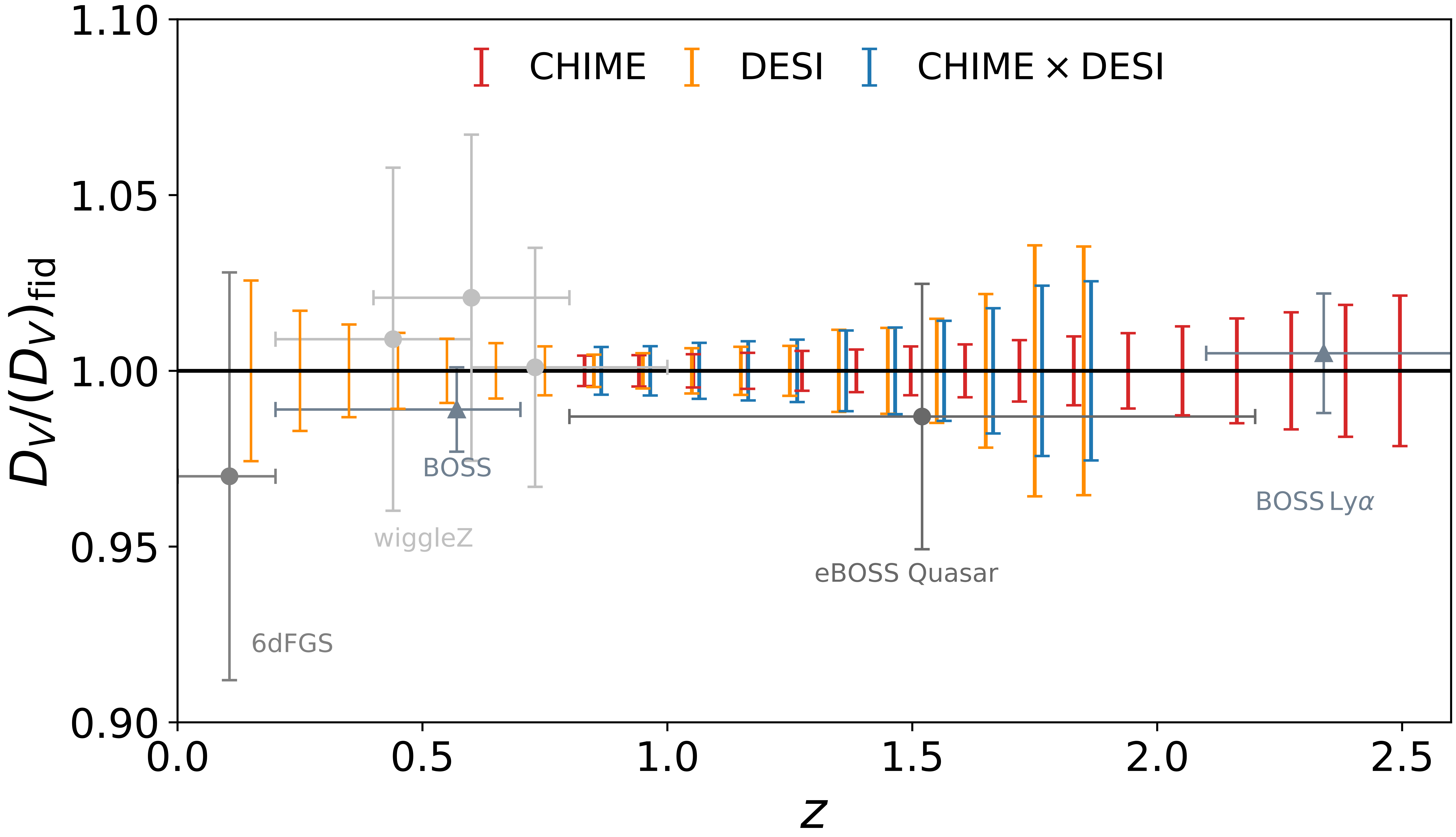
Work by Carolin Höfer

Foreground Filtering

- Pursuing several techniques for foreground filtering
  - Delay space filter
    - Remove modes with low delay, threshold set per baseline
  - SVD filter
    - Remove the most correlated modes
    - Apply in (frequency, beamformed pixel) basis
    - Apodize the visibilities in the N-S direction prior to beamforming to reduce the frequency dependence in the map at the expense of resolution
  - Karhunen-Loève (KL) filter
    - Remove modes with low S/F ratio
    - Recent improvements in pipeline enable 3 cylinder telescope.
  - Hybrid SVD + KL filter
    - First apply SVD filter to blindly remove the brightest foreground modes
    - Next apply KL filter to optimally filter what's left
    - Currently testing viability in simulations

Cosmology Forecast

Figure courtesy of Tianyue Chen



Cosmology Forecast

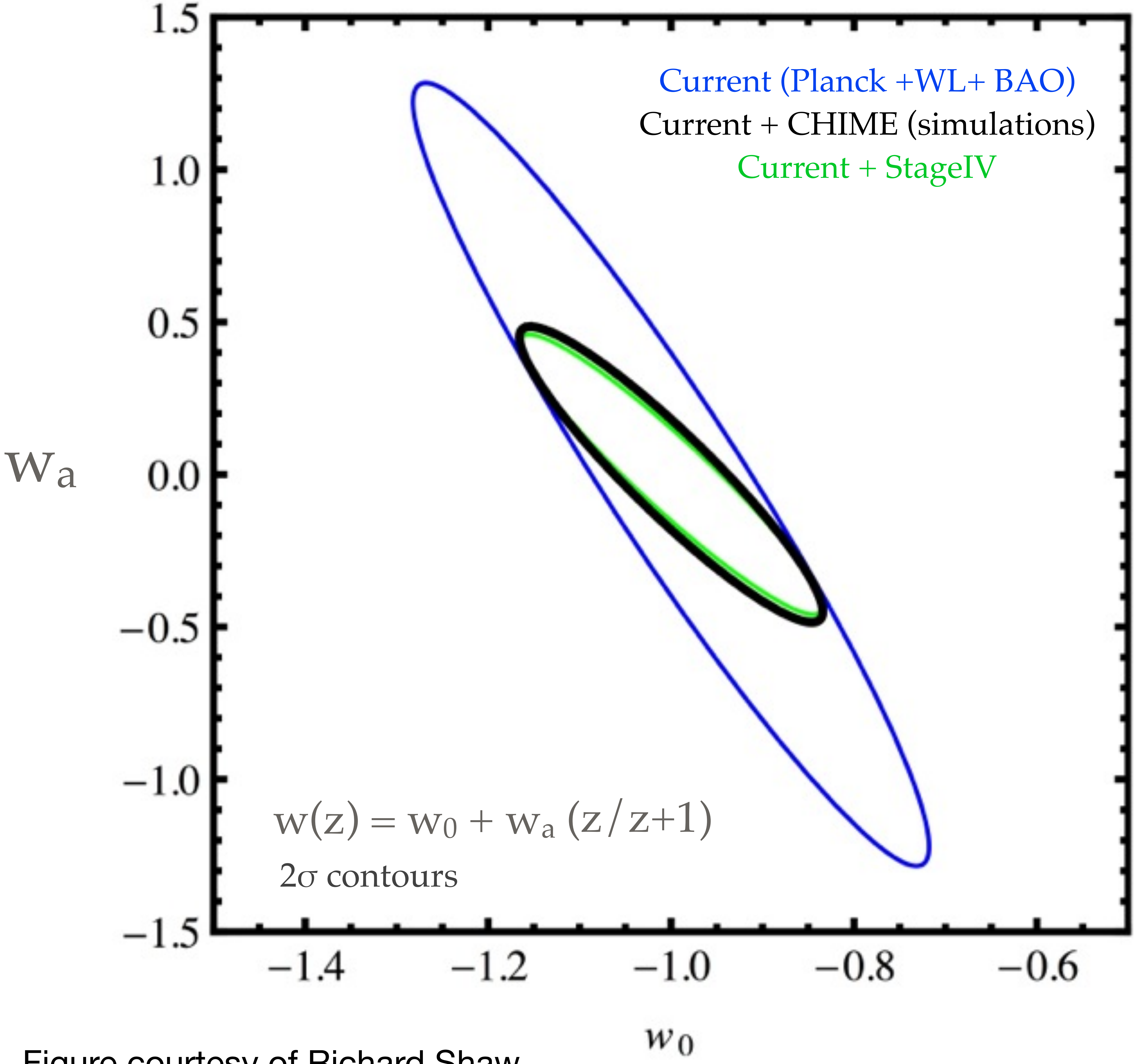


Figure courtesy of Richard Shaw

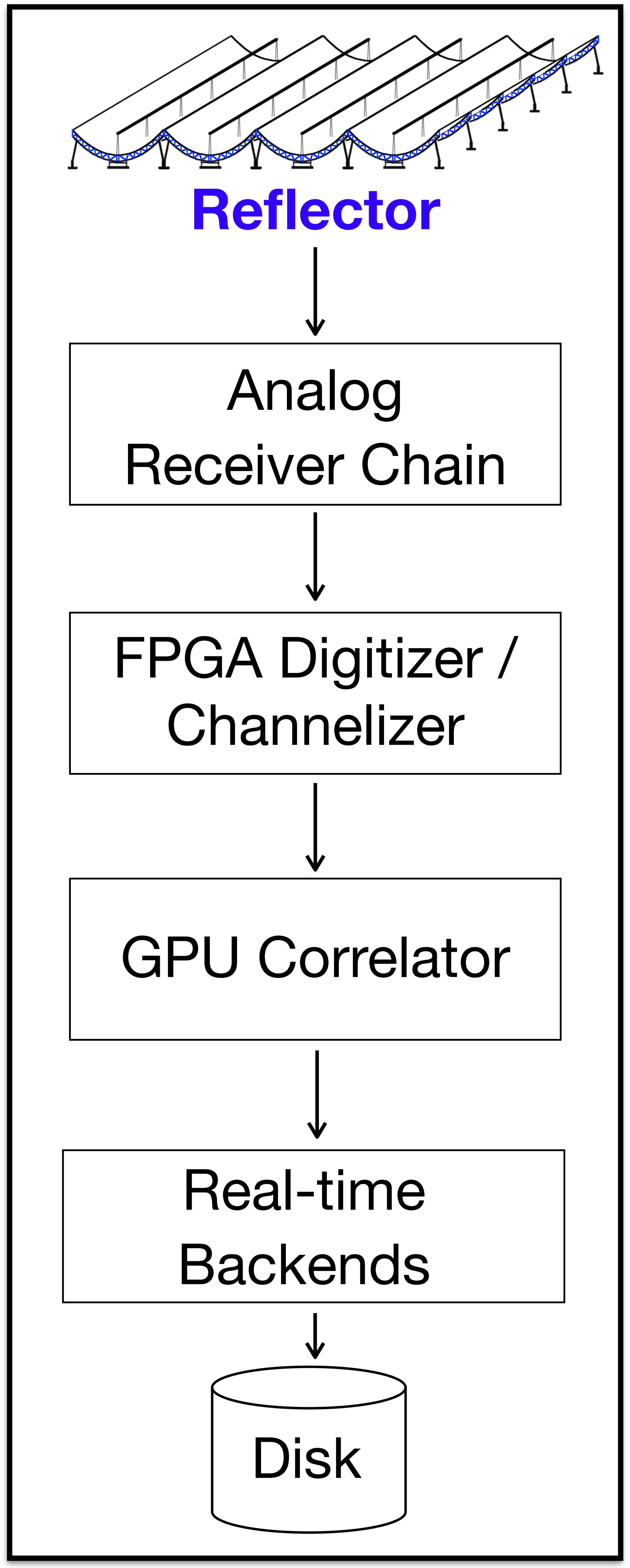
Constraints on dark energy equation of state $w = p/\rho$ from 5 year survey competitive with DOE Stage IV experiments (e.g., DESI, Euclid)

Thank you!

Check out our website at: www.chime-experiment.ca

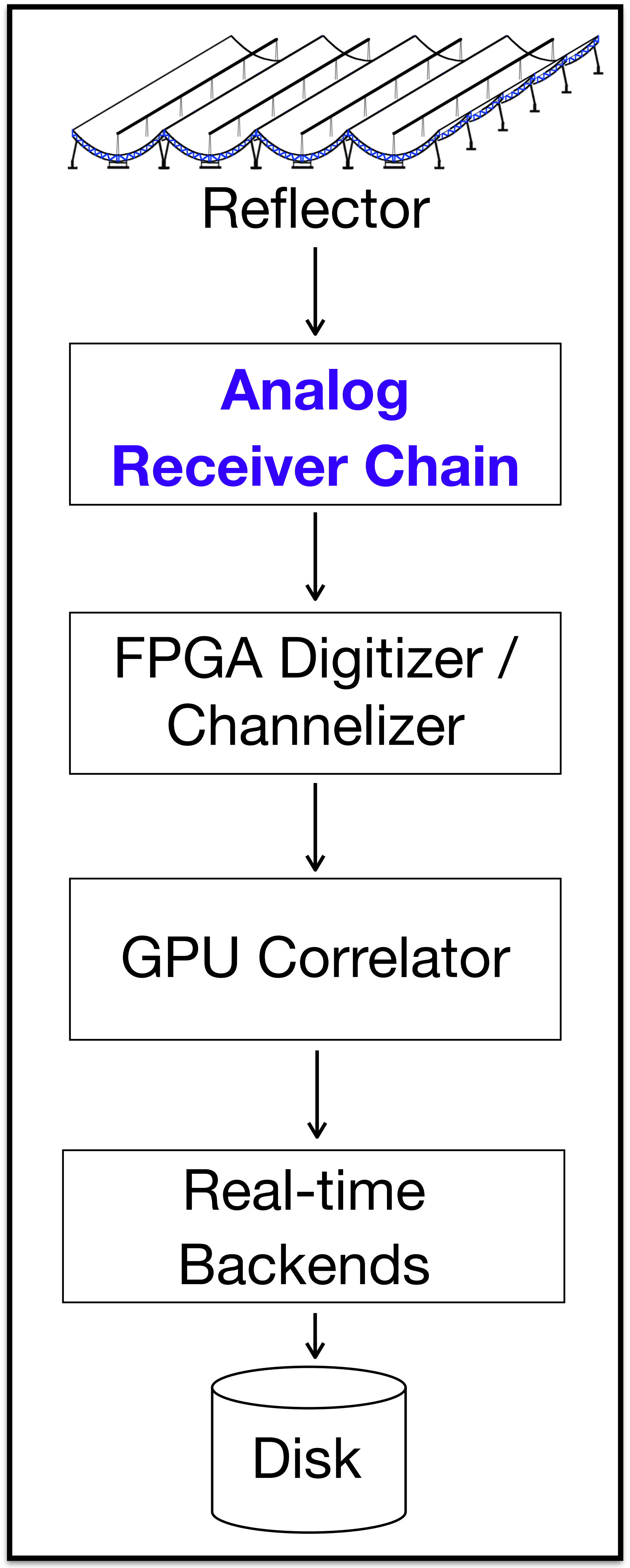
Additional Slides

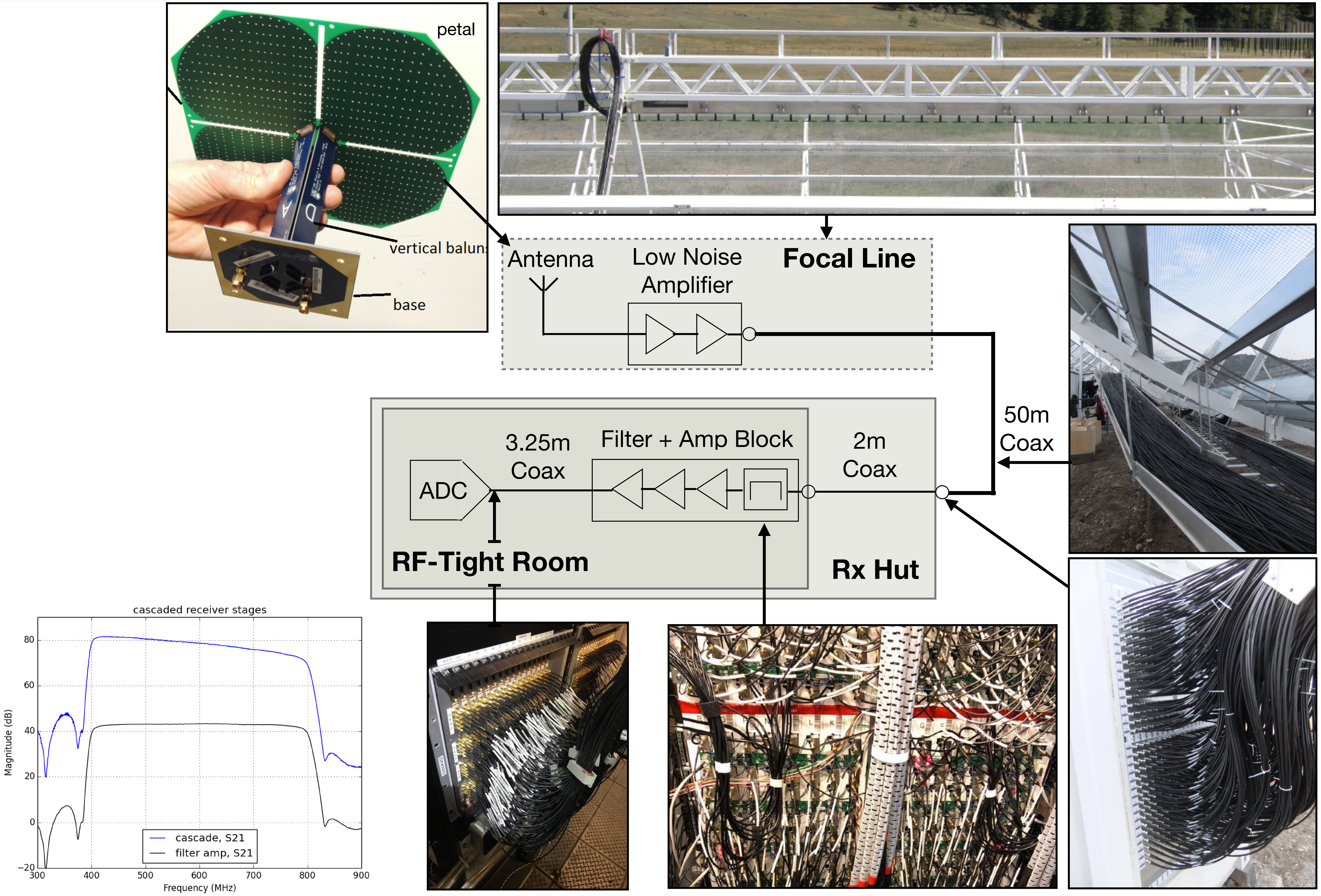
Reflector



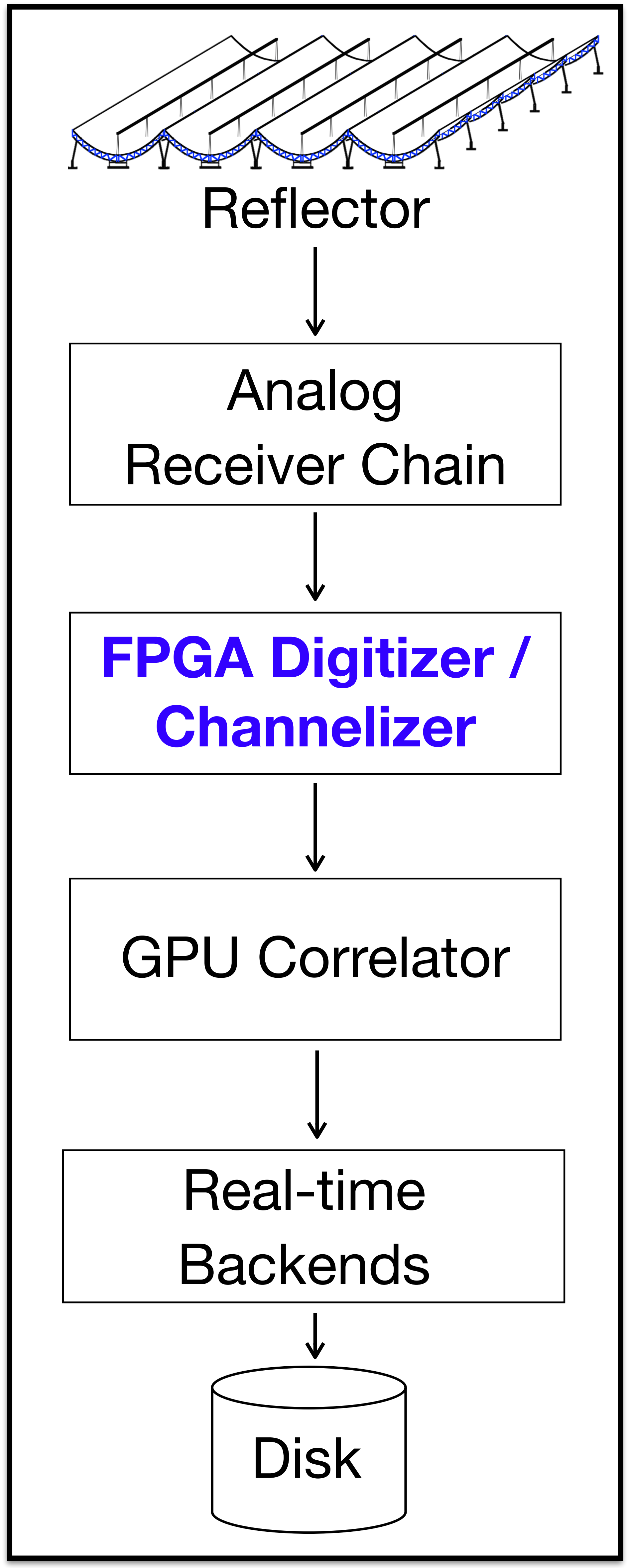
UBC graduate student Meiling Deng
who led design of CHIME cloverleaf antennas

Analog Receiver Chain

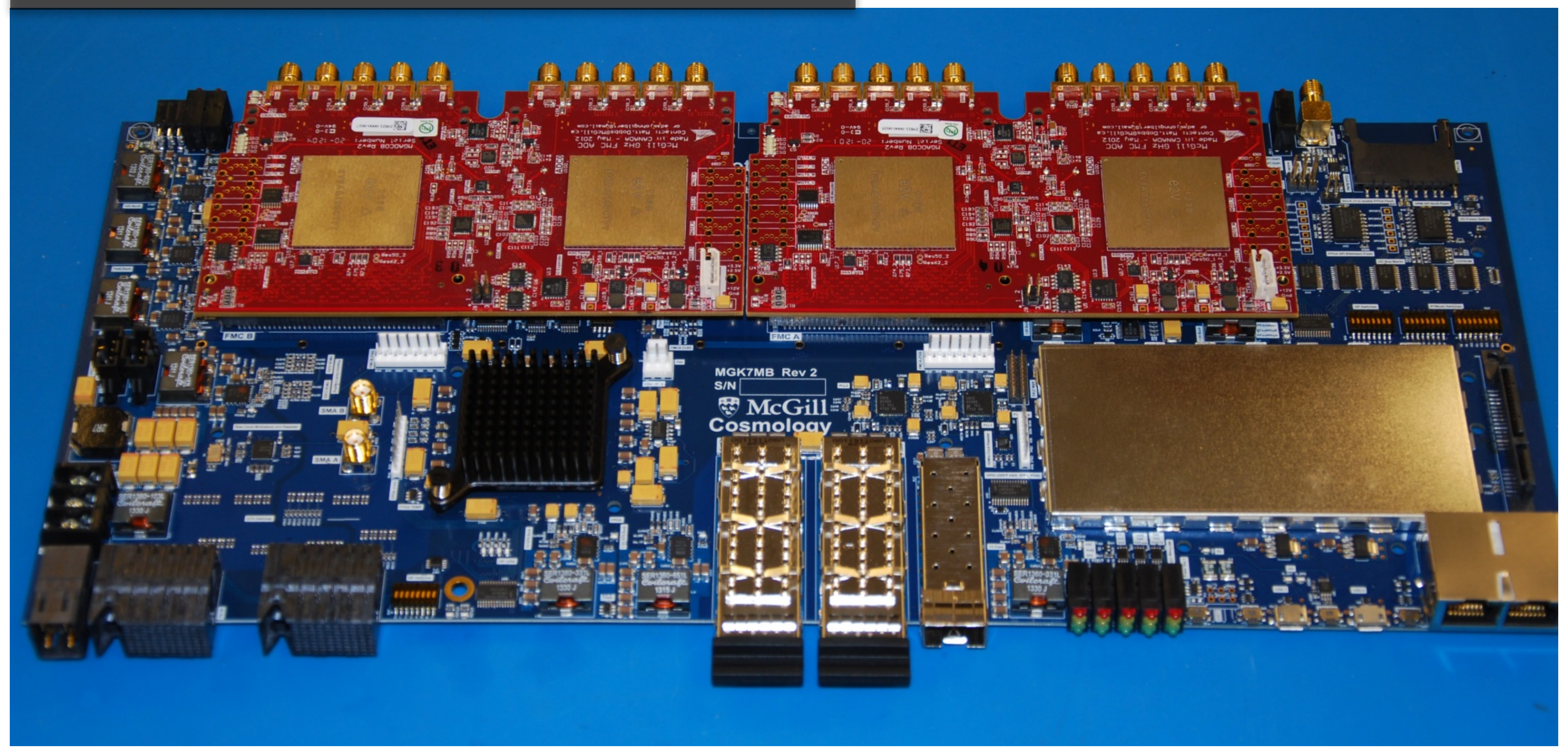




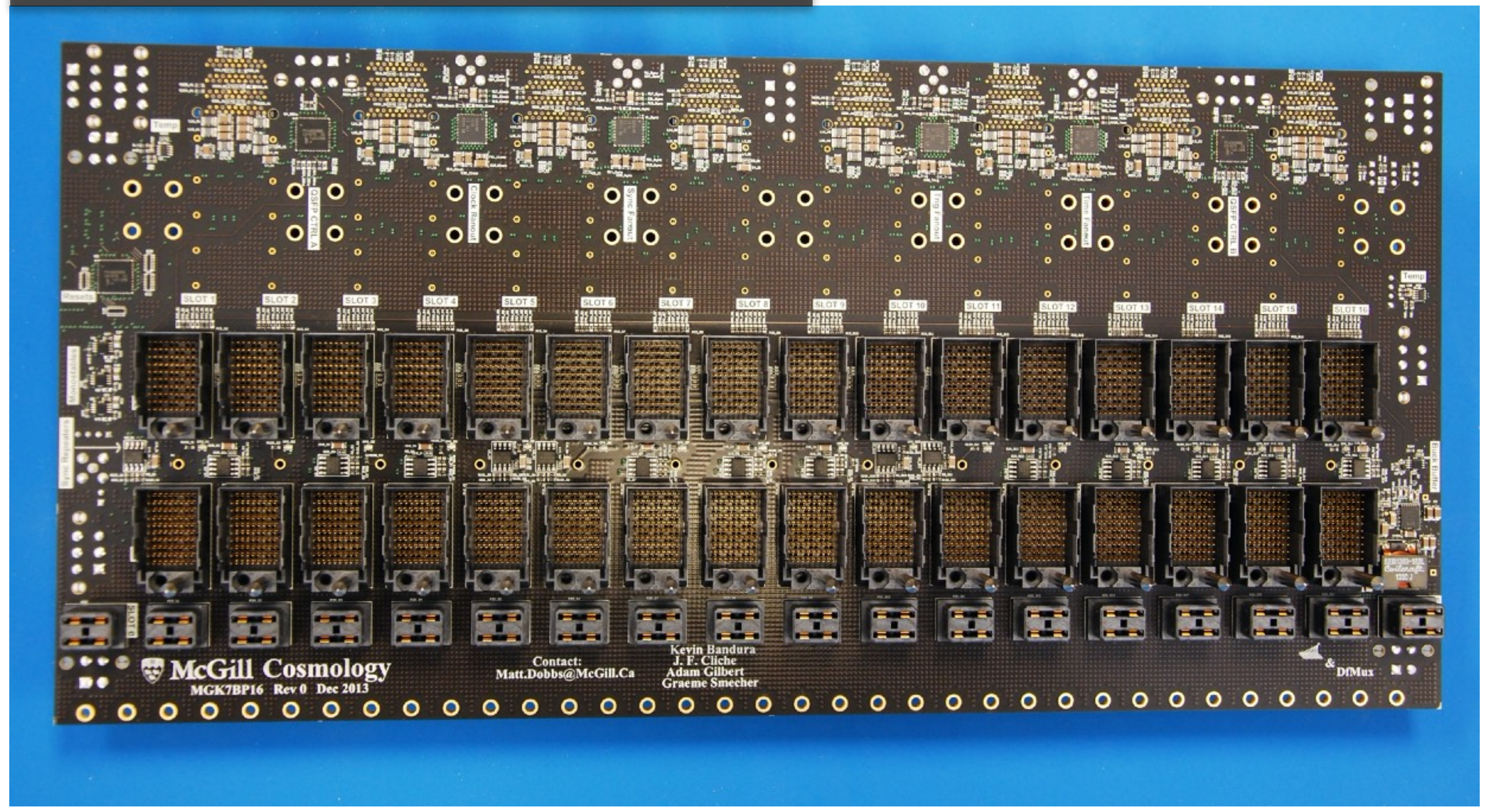
FPGA Digitizer and Channelizer (F-Engine)

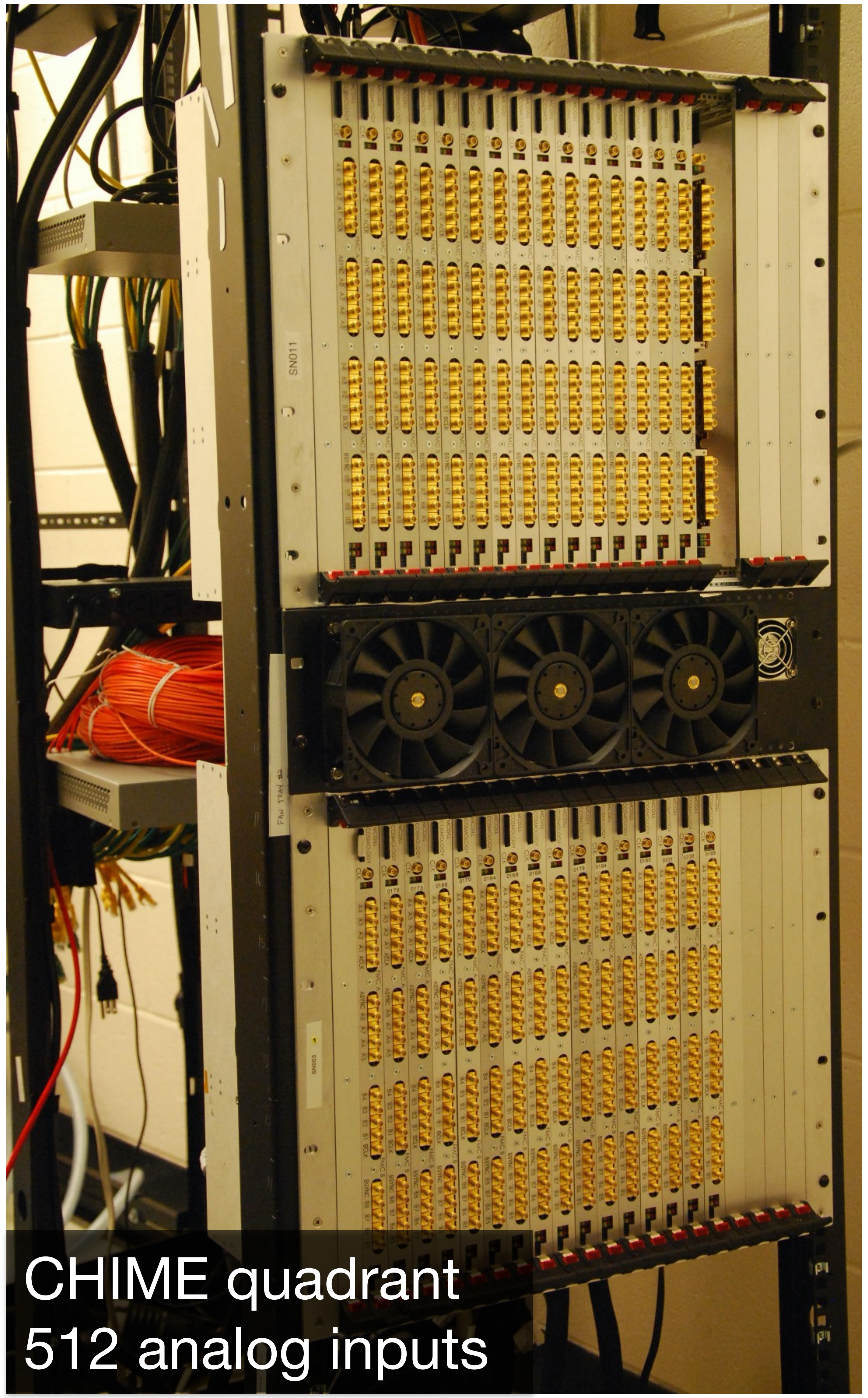


Motherboard
16 analog inputs



Backplane
256 analog inputs





Bandura et al. 2016, JAI

GPU Correlator (X-Engine)