Measuring the 21cm Power Spectrum at Low-z with CHIME

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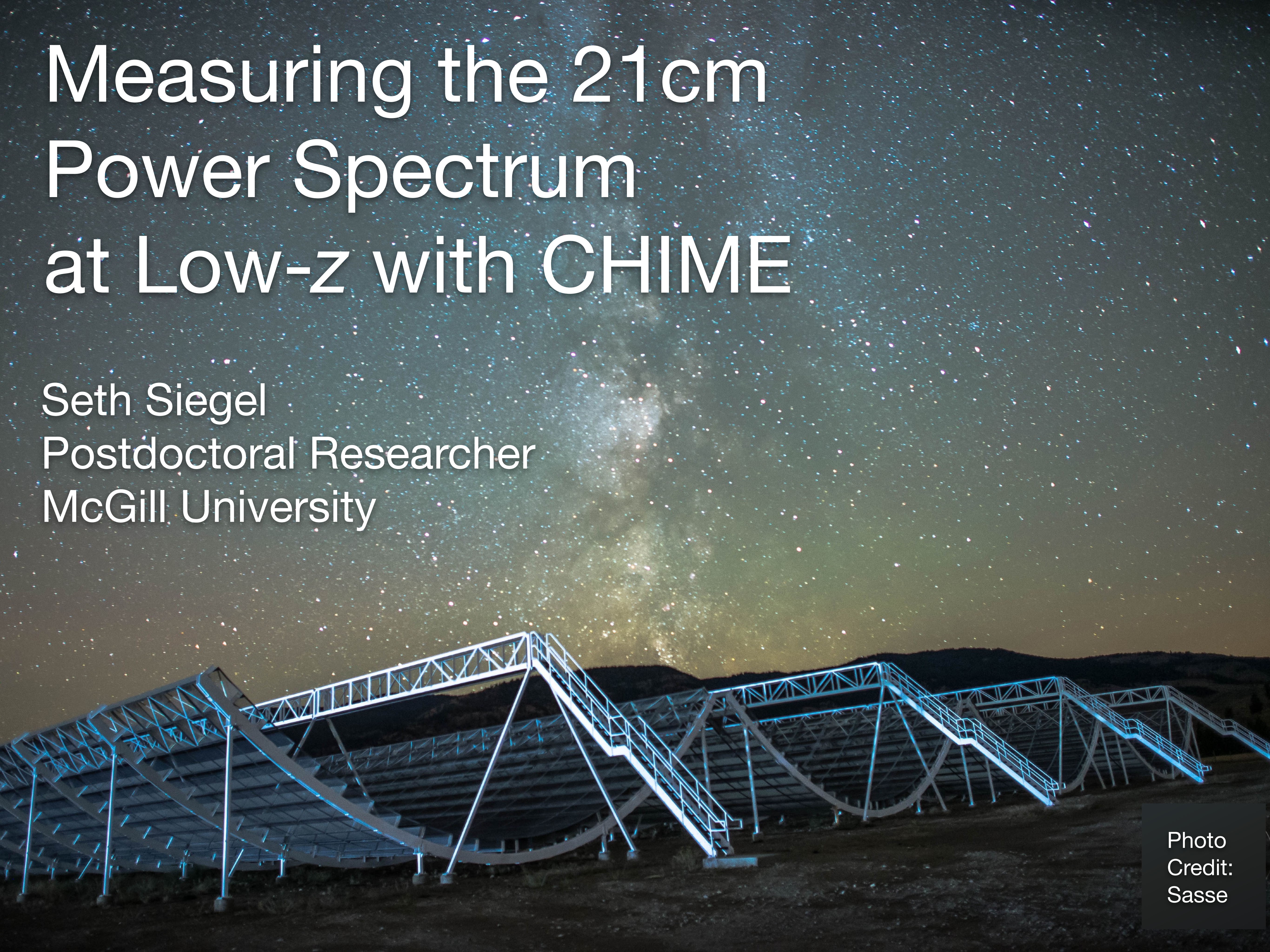


Photo Credit: Sasse

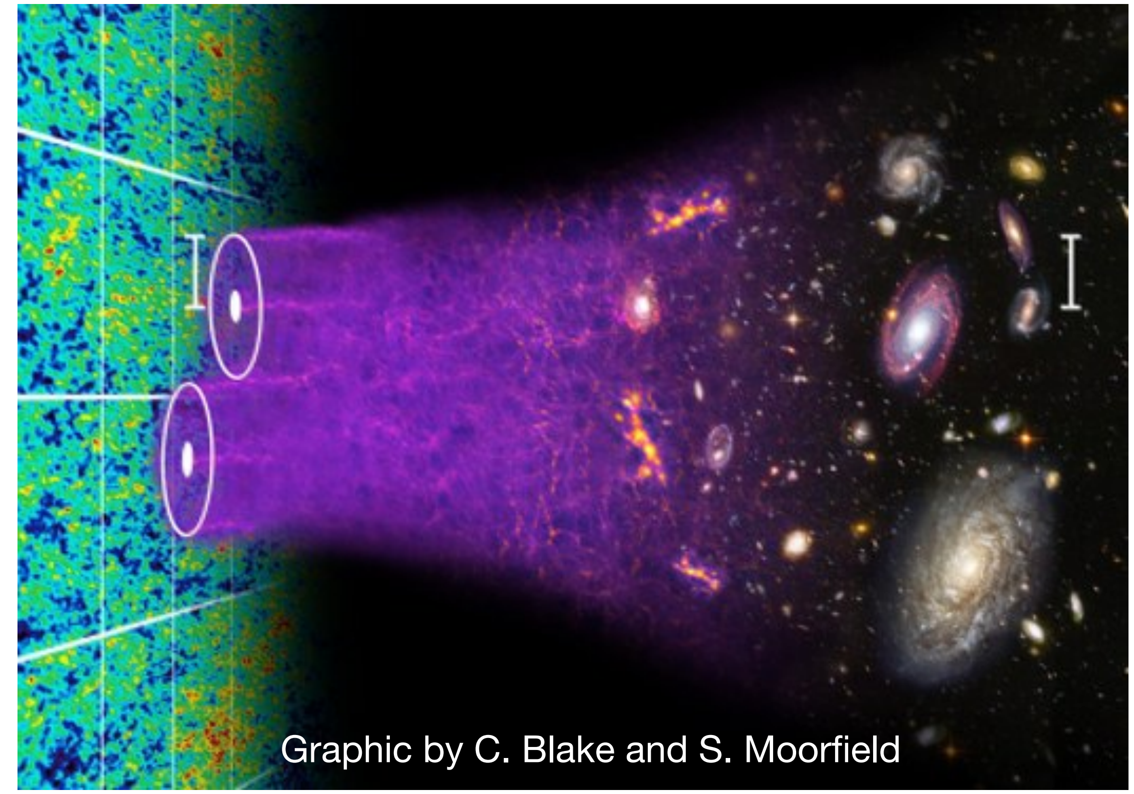
Baryon Acoustic Oscillations (BAO)

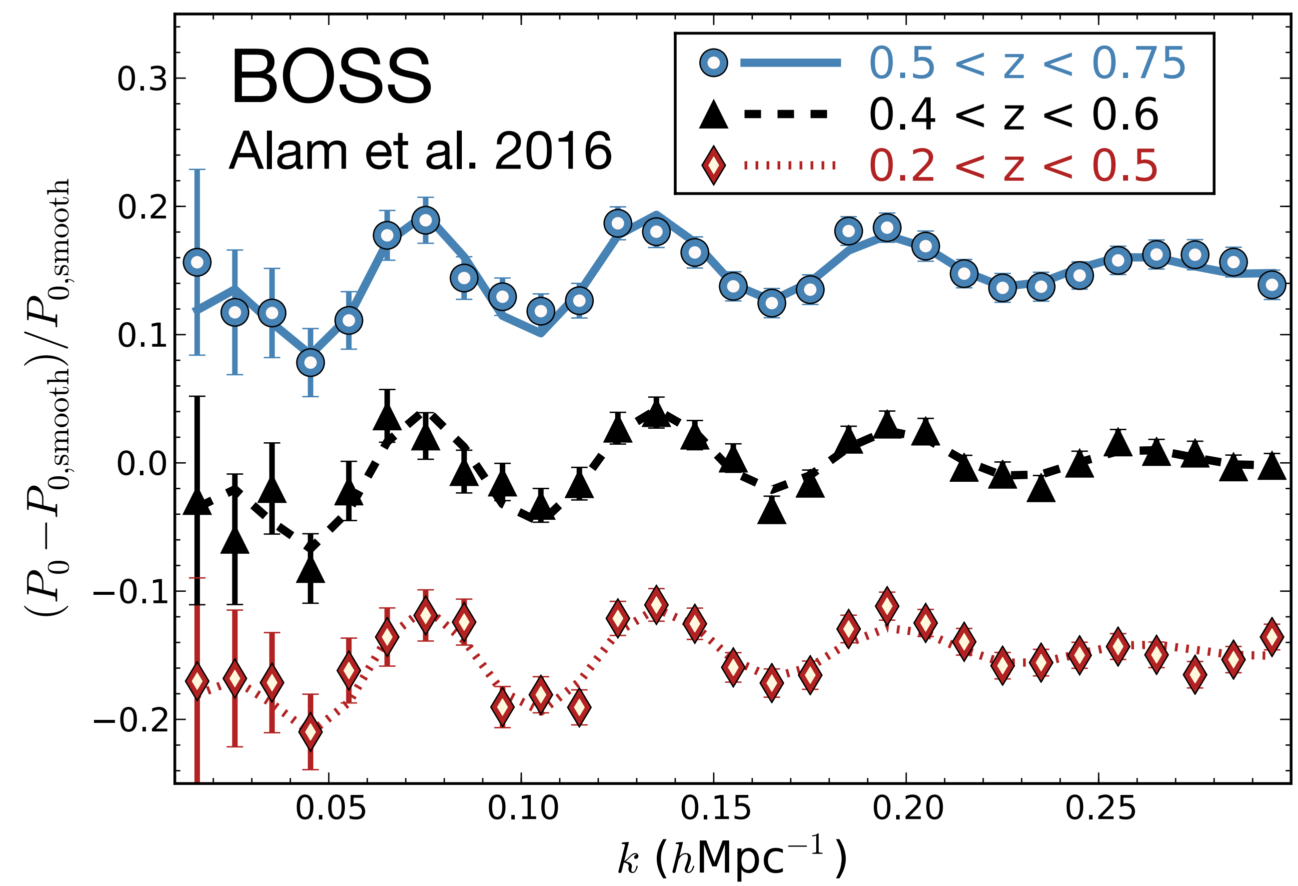
- Measure power spectrum of the 21cm emission from neutral hydrogen between redshift 0.8 and 2.5
  - Corresponds to radio frequencies between 800 and 400 MHz

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

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

- Learn something about dark energy





Instrument Considerations

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

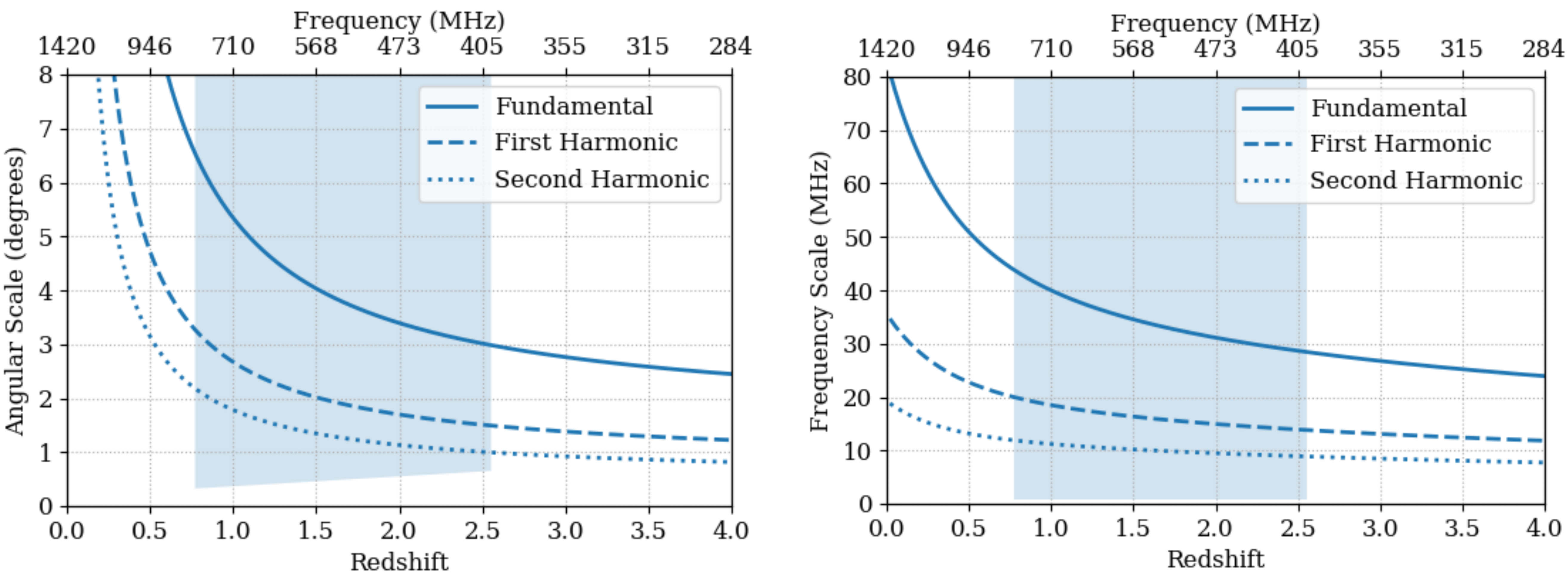


Figure courtesy of Dallas Wulf

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

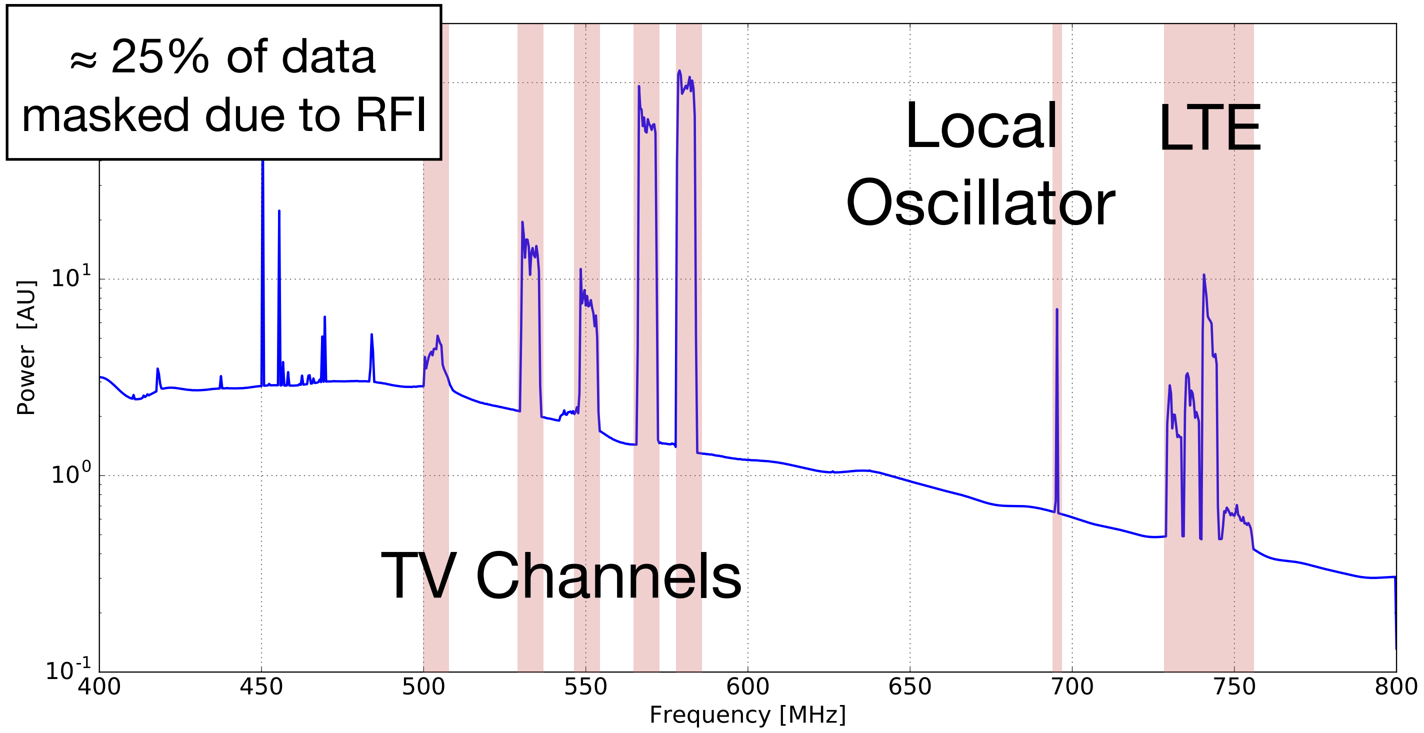
Massachusetts Institute of Technology

PERIMETER INSTITUTE

NRAO

Drone Flight Over CHIME

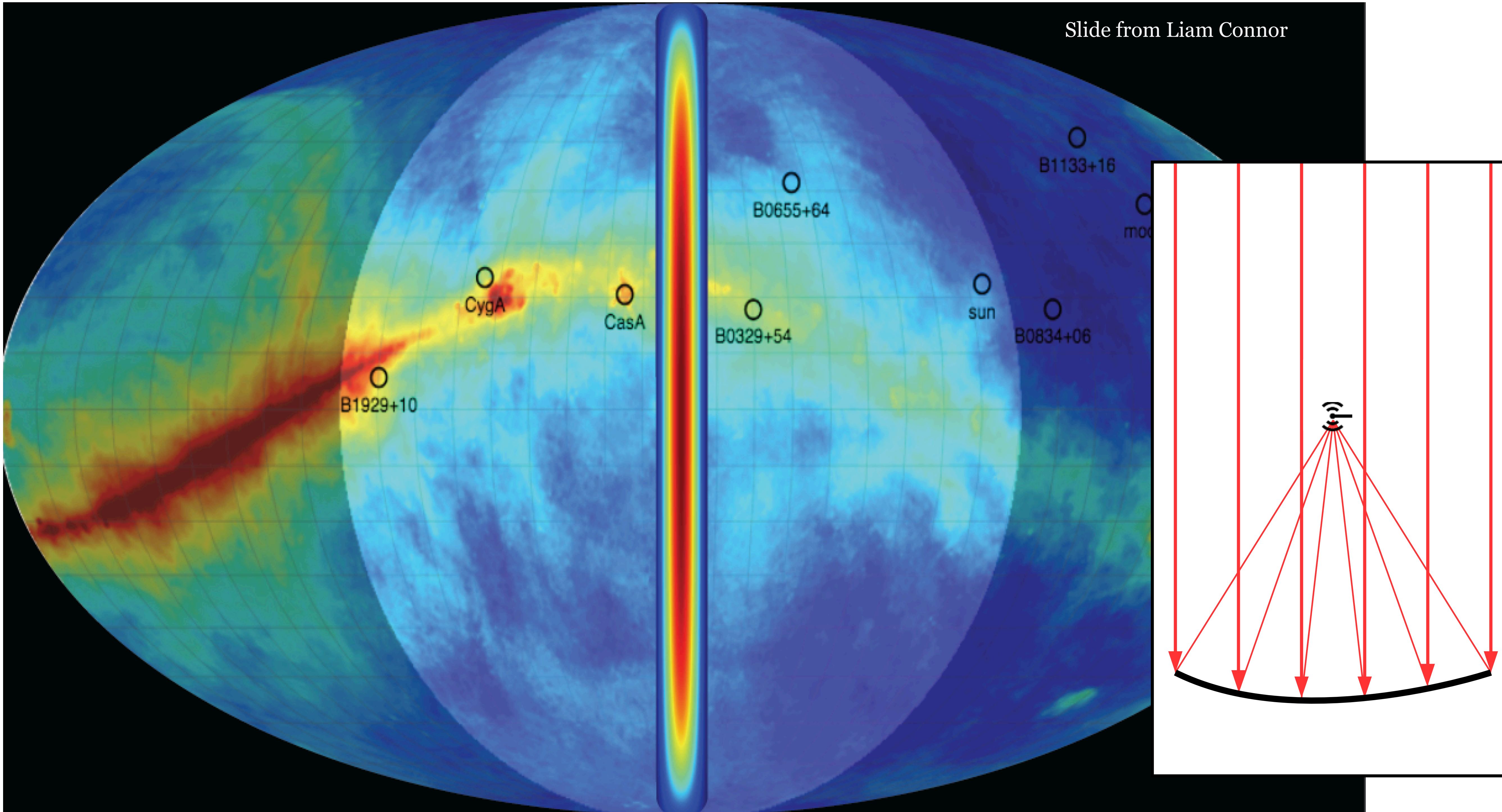
Dominion Radio Astrophysical Observatory

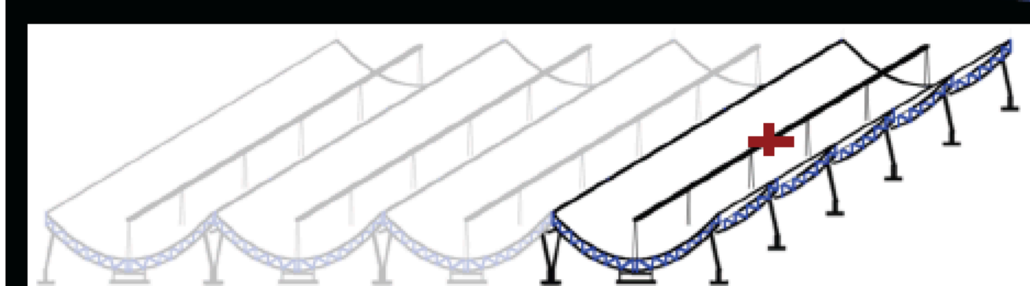


Cylindrical Transit Interferometer

Movie by Peter Klagge

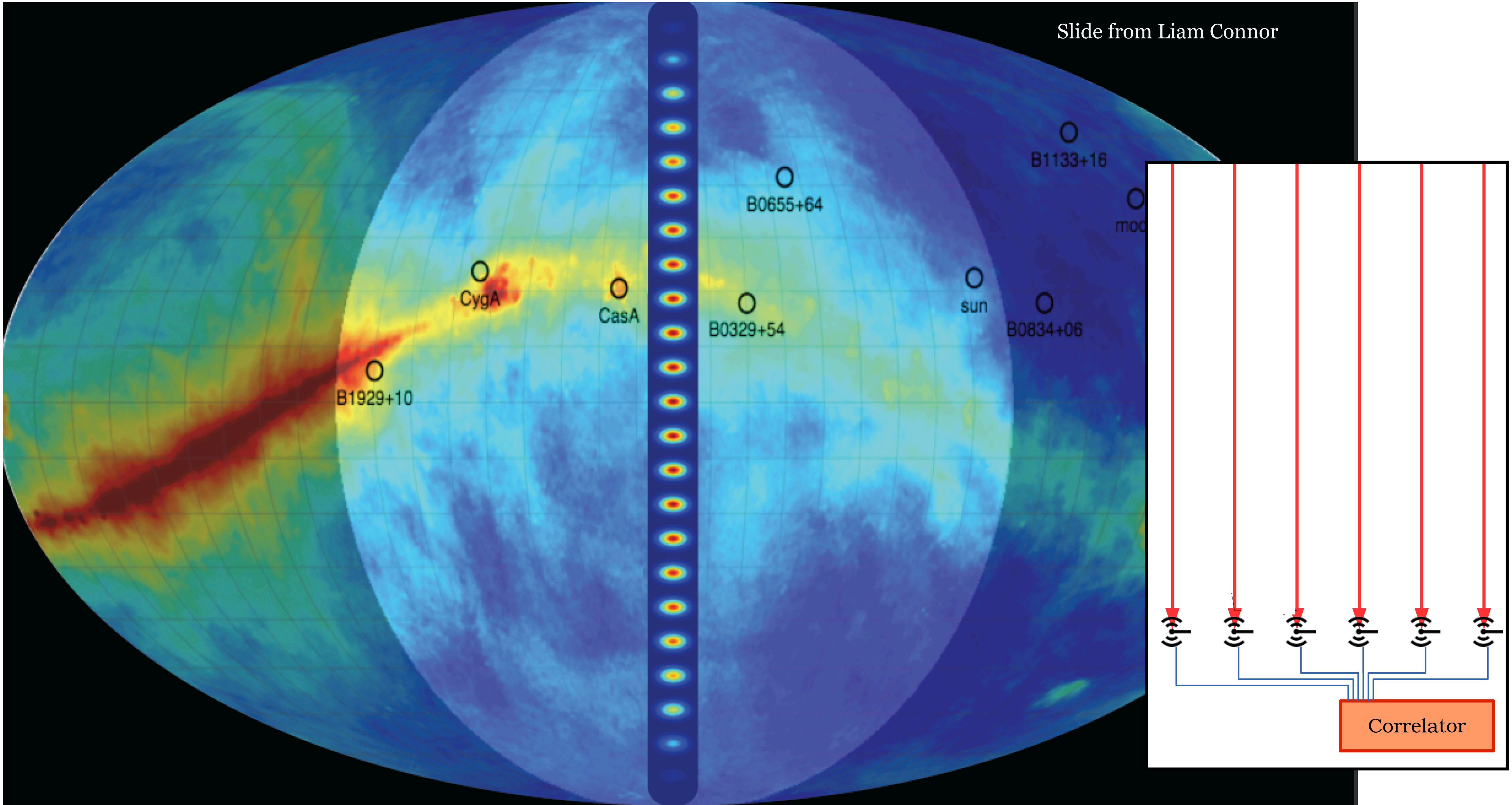
Cylindrical Transit Interferometer

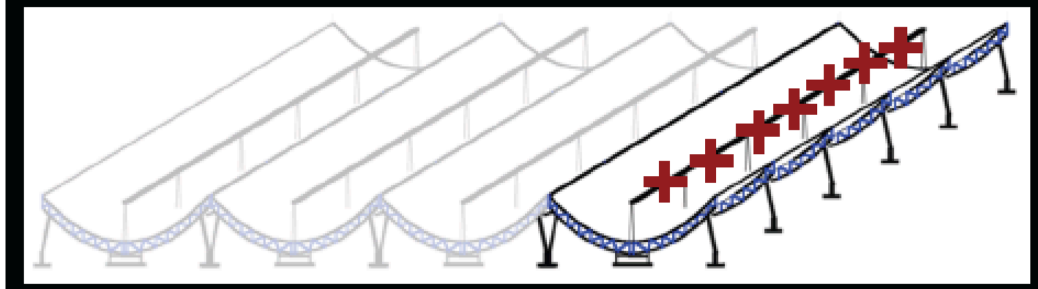




- Cylinder focuses light only in EW direction
- Gives us large FOV

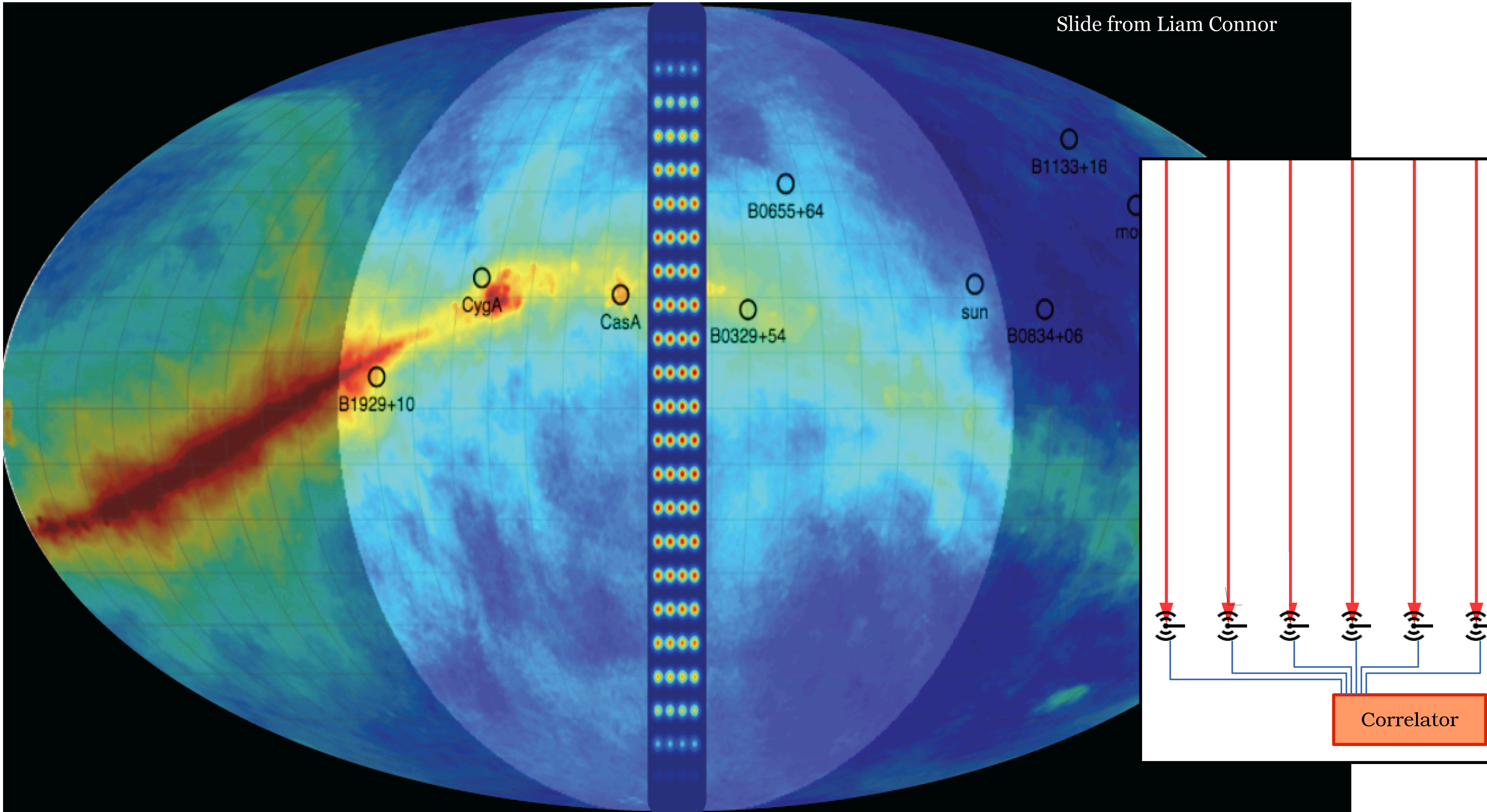
Cylindrical Transit Interferometer

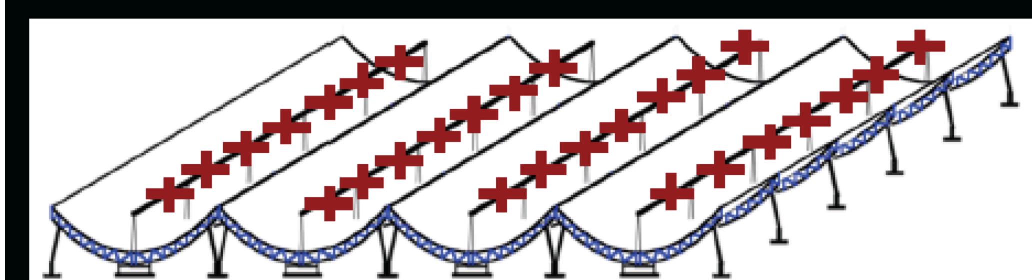




- FFT telescope in NS direction
- 256 beams per cylinder

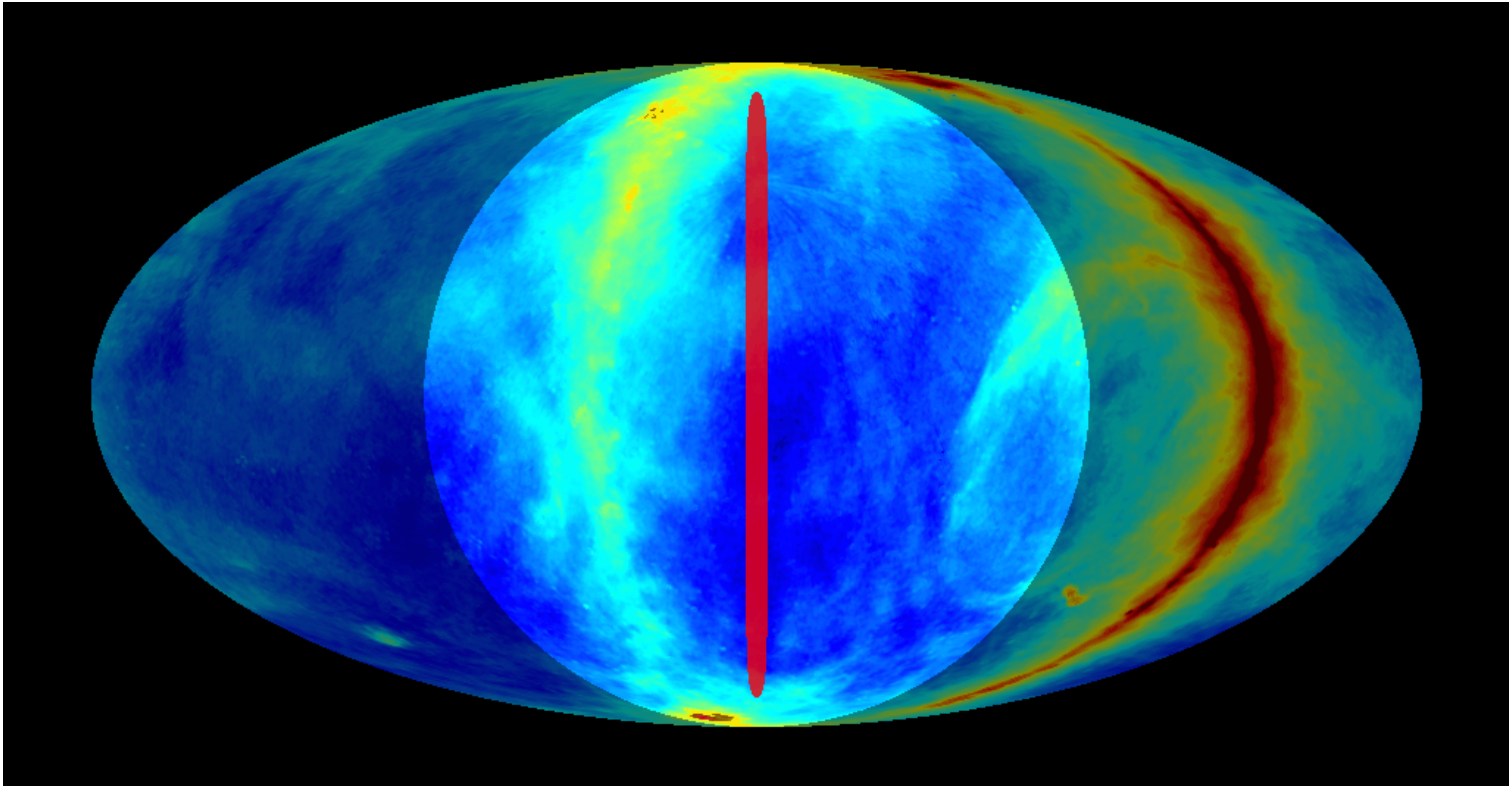
Cylindrical Transit Interferometer





- 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.

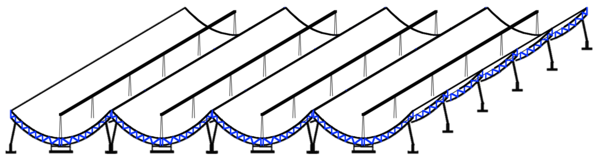
Constrain properties and origins of FRBs.

Pulsar Monitor

Provide near daily timing data on all northern hemisphere pulsars.

Measure pulsar properties and improve constraints on gravitational waves.

CHIME Science Backends



Reflector

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Analog Receiver Chain

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FPGA Digitizer / Channelizer

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GPU Correlator

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Real-time Backends

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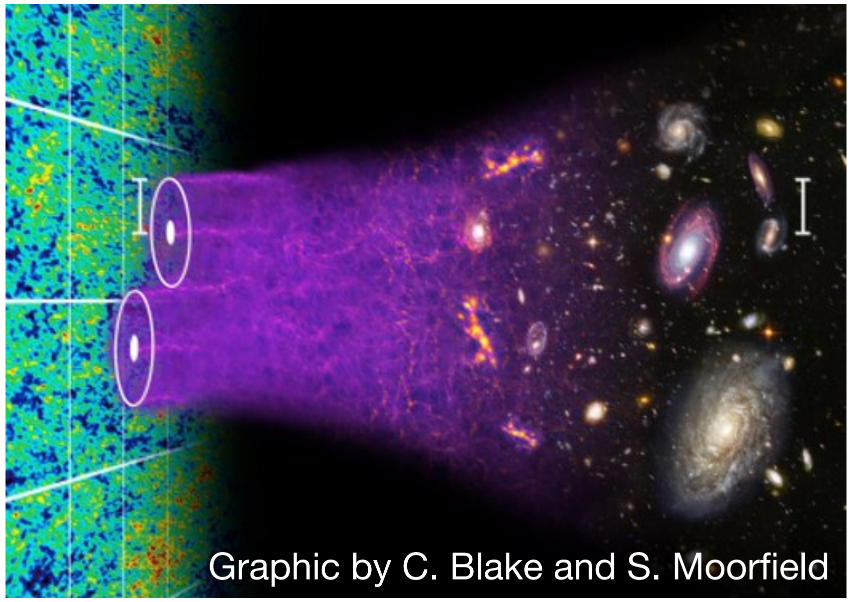
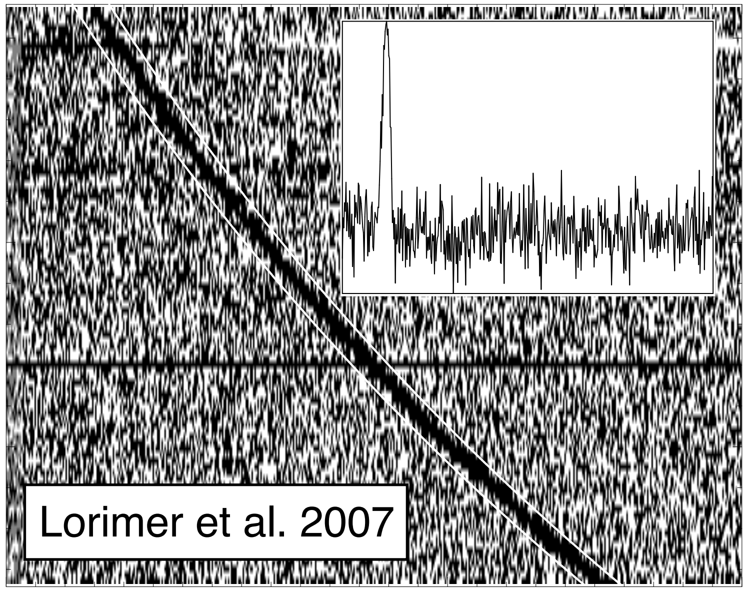
Disk

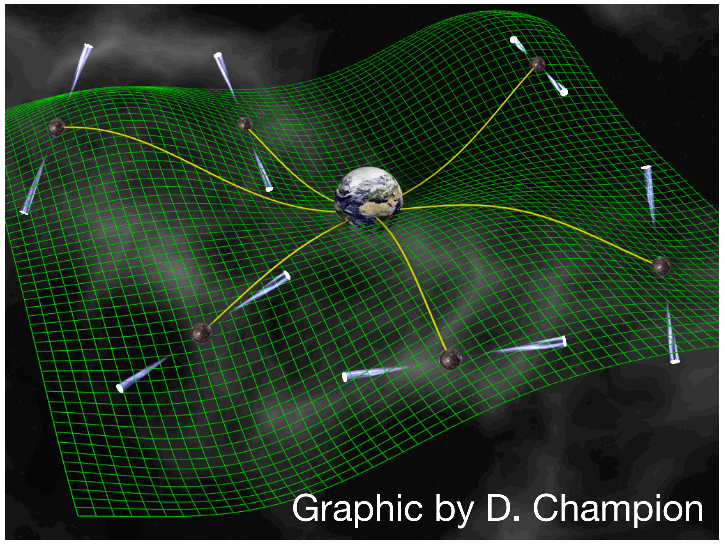
- **Cosmology**
  - Full N^2 visibility matrix
  - 10 sec cadence
  - 210 TB/day
  - Real-time flagging and gain calibration
  - Data compression through redundant baselines (1.0 TB/day)
- **Fast Radio Bursts**
  - 1024 stationary beams
  - 1 msec cadence
  - 16k frequency bins
- **Pulsar timing**
 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



Graphic by C. Blake and S. Moorfield



Lorimer et al. 2007

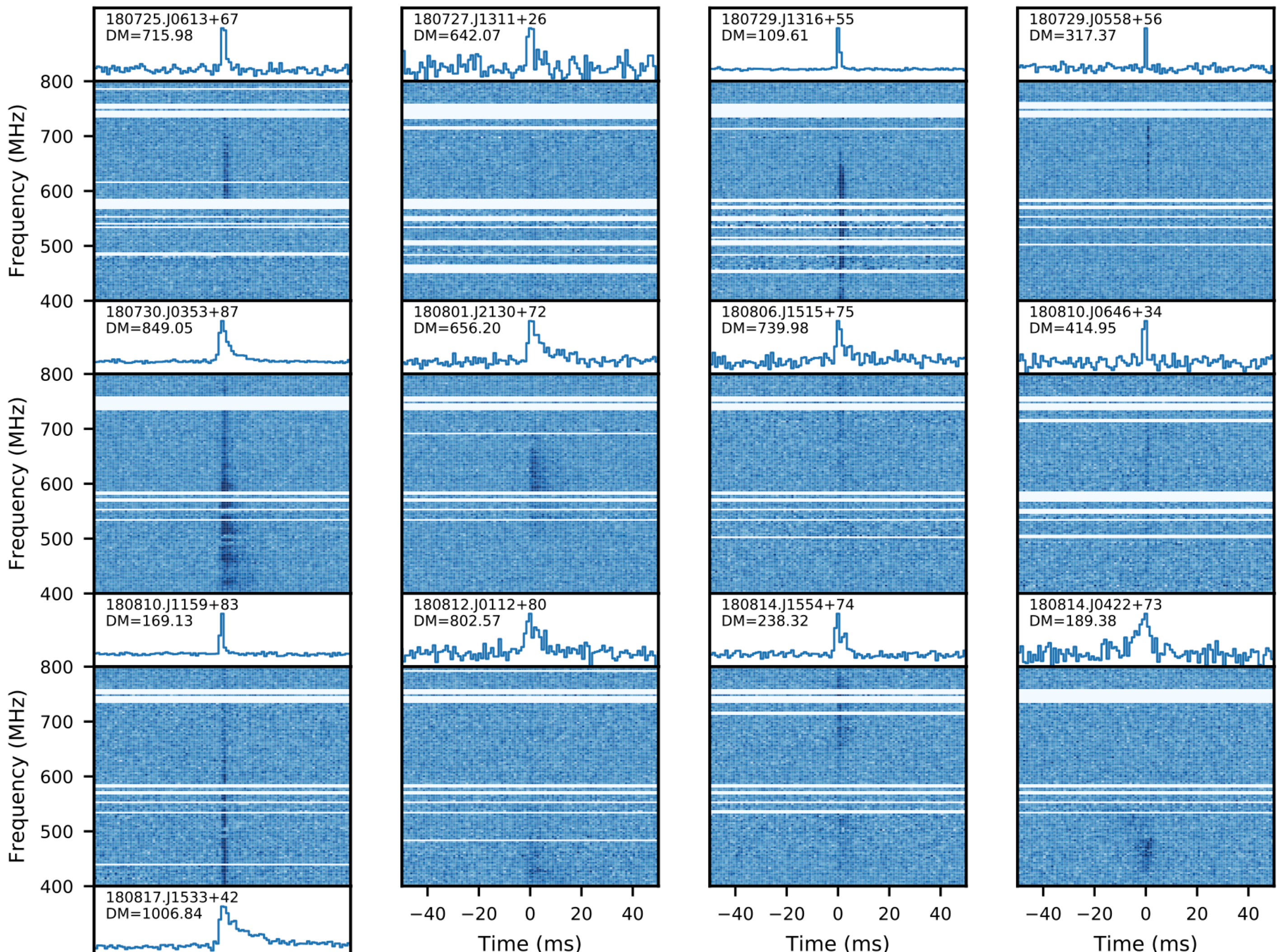


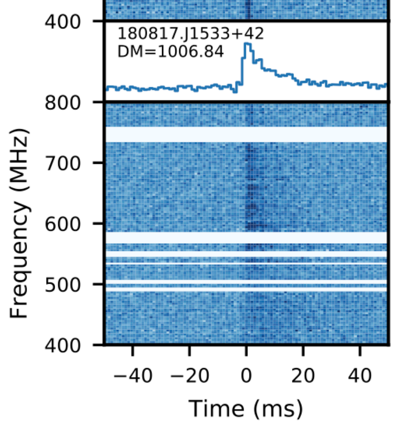
Graphic by D. Champion

Status (Cosmology Backend)

- **September 7, 2017:** First light ceremony
- **September 2018:** Reached full capacity
  - Compression through averaging redundant baselines.
- Since then we have been writing data to disk roughly 75% of the time. Downtime primarily due to software upgrades.
- **Next steps**
  - Mask RFI, calibrate instrument transfer function, and characterize systematics
  - Remove foregrounds
    - Pursue methods that do not require a beam model to start
      - Delay space filtering (remove low delay modes or “foreground wedge”)
      - SVD (remove the modes that are most correlated in frequency-pixel basis)
  - Measure the cosmic 21cm signal in cross-correlation with quasar catalogs from the Sloan Digital Sky Survey

Results from CHIME/FRB





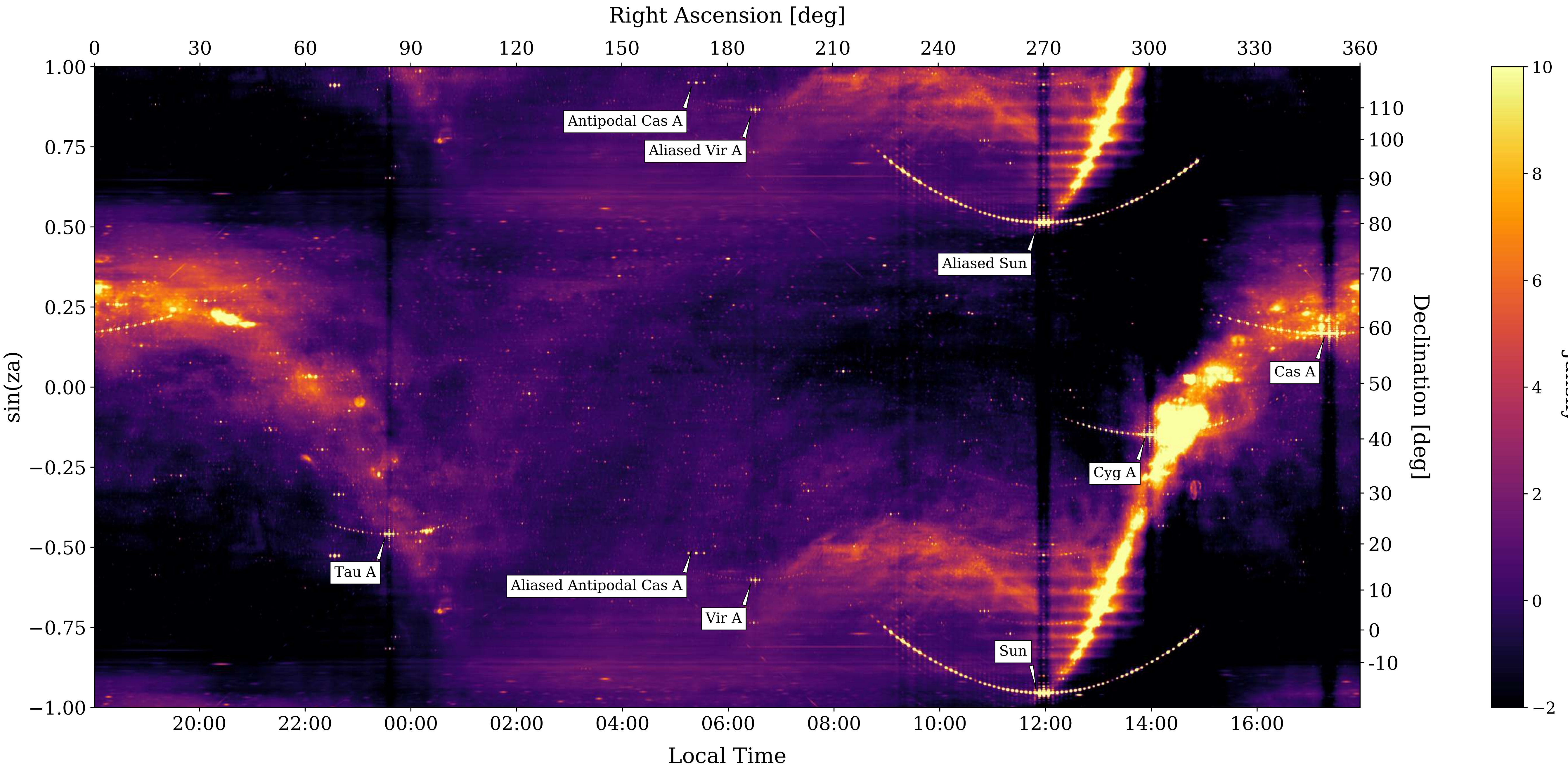
- **Early results from commissioning** (CHIME/FRB Collaboration 2019ab):
  - 13 new FRBs
  - 1 new repeating FRB

February 14 2019

- **More recently**
  - Detection of original repeater (Josephy et al. 2019)
  - Detection of 8 new repeaters (CHIME/FRB Collaboration 2019c)

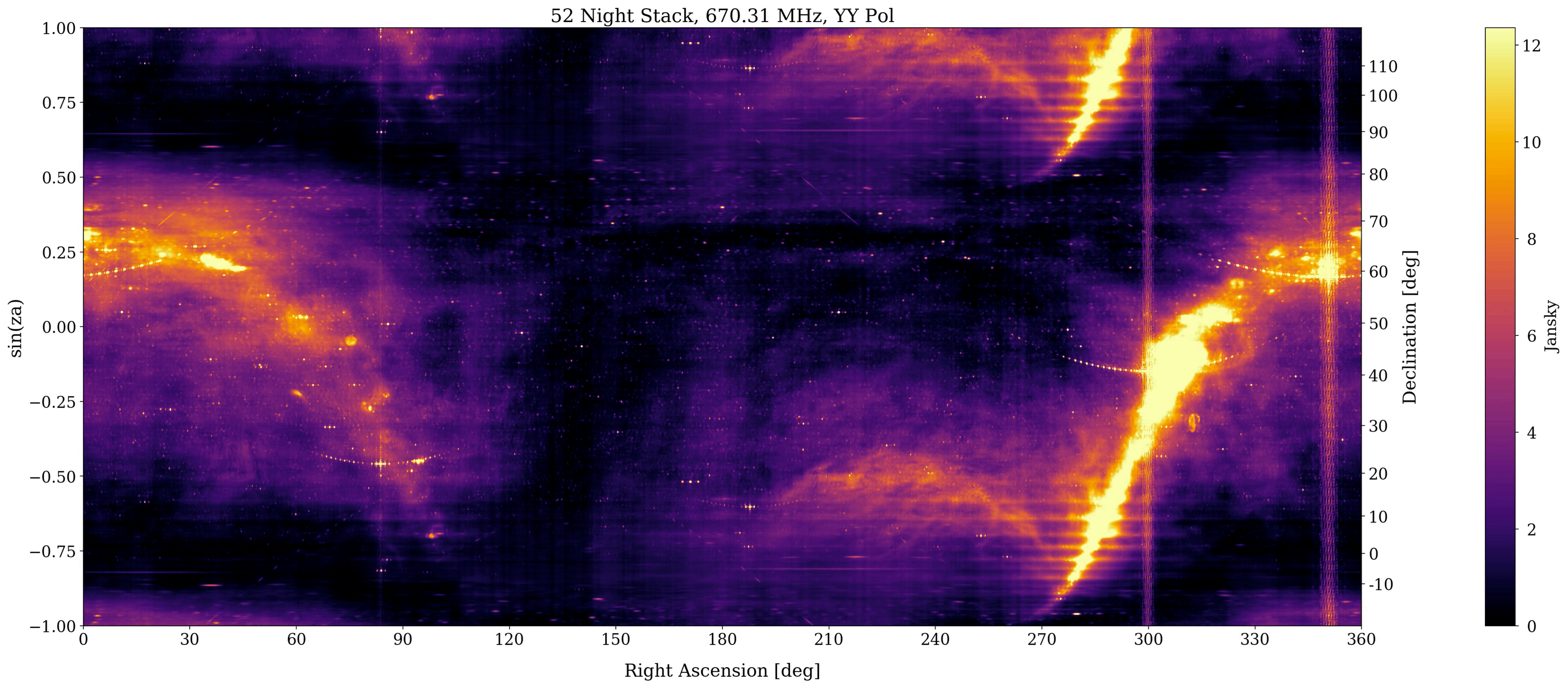
- **In progress:** Catalog of hundreds of new FRBs

Radio Sky as Seen by CHIME



"Dirty" map of the northern sky at 670 MHz (0.39 MHz wide channel).
Constructed from YY visibilities collected over single day (2018-12-21/22).

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.

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%

- **Complex gain calibration:**

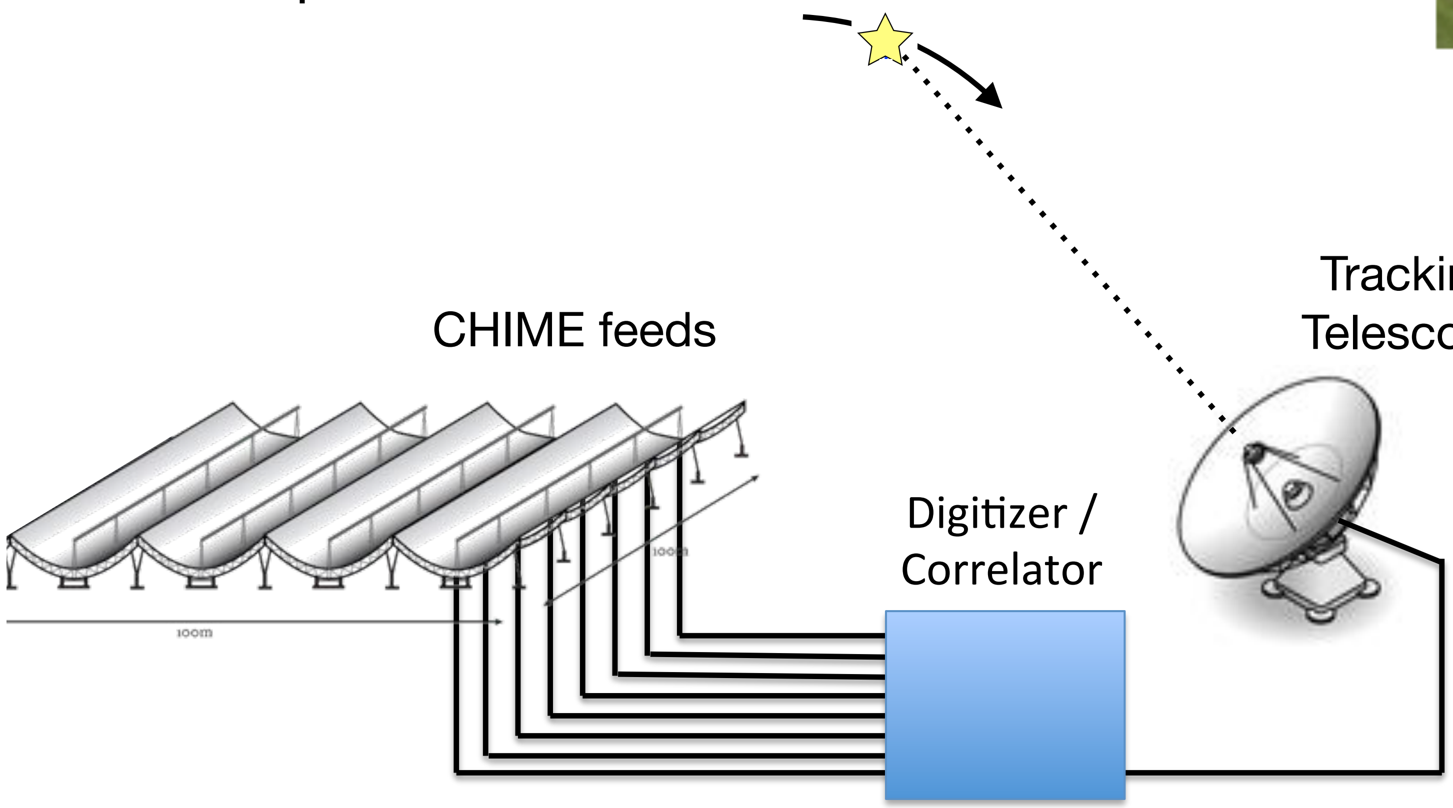
$$V_{ij}(t) = < E_i(t) E_j^*(t) > = g_i(t) g_j^*(t) \int d^2\hat{\mathbf{n}}\, A_i(\hat{\mathbf{n}}) A_j^*(\hat{\mathbf{n}}) e^{2\pi i \hat{\mathbf{n}} \cdot \mathbf{u}_{ij}}\, T(\hat{\mathbf{n}}; t)$$

Need to measure complex gain to better than 0.3% on timescales > 1 minute

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)

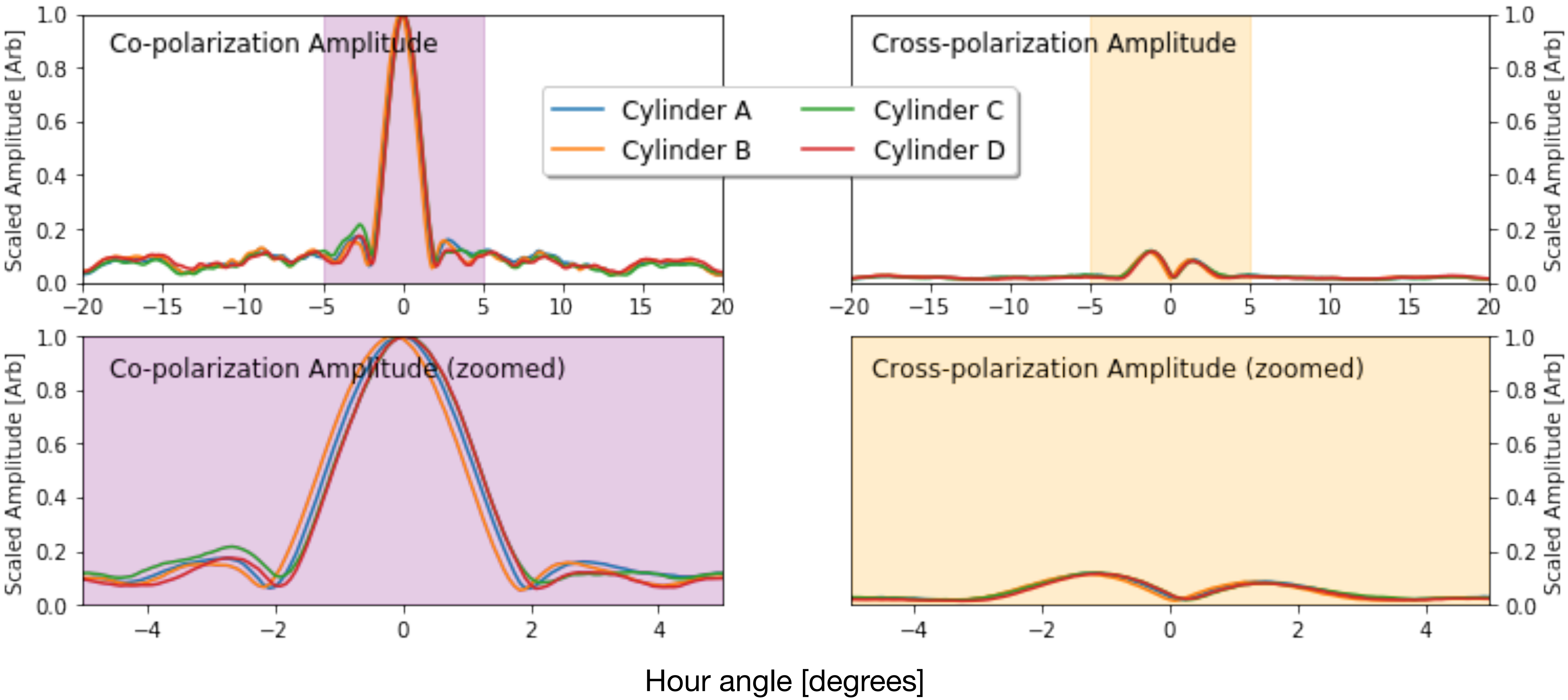
- Pulsar Holography
  - Subtract pulsar ON - pulsar OFF to remove common background sky
  - Implemented in GPU. Can gate on 30 msec cadence.
  - Characterize polarization response



Newburgh et al. 2014
Berger et al. 2016

Example Holographic Beam Measurement

Figure courtesy of Laura Newburgh



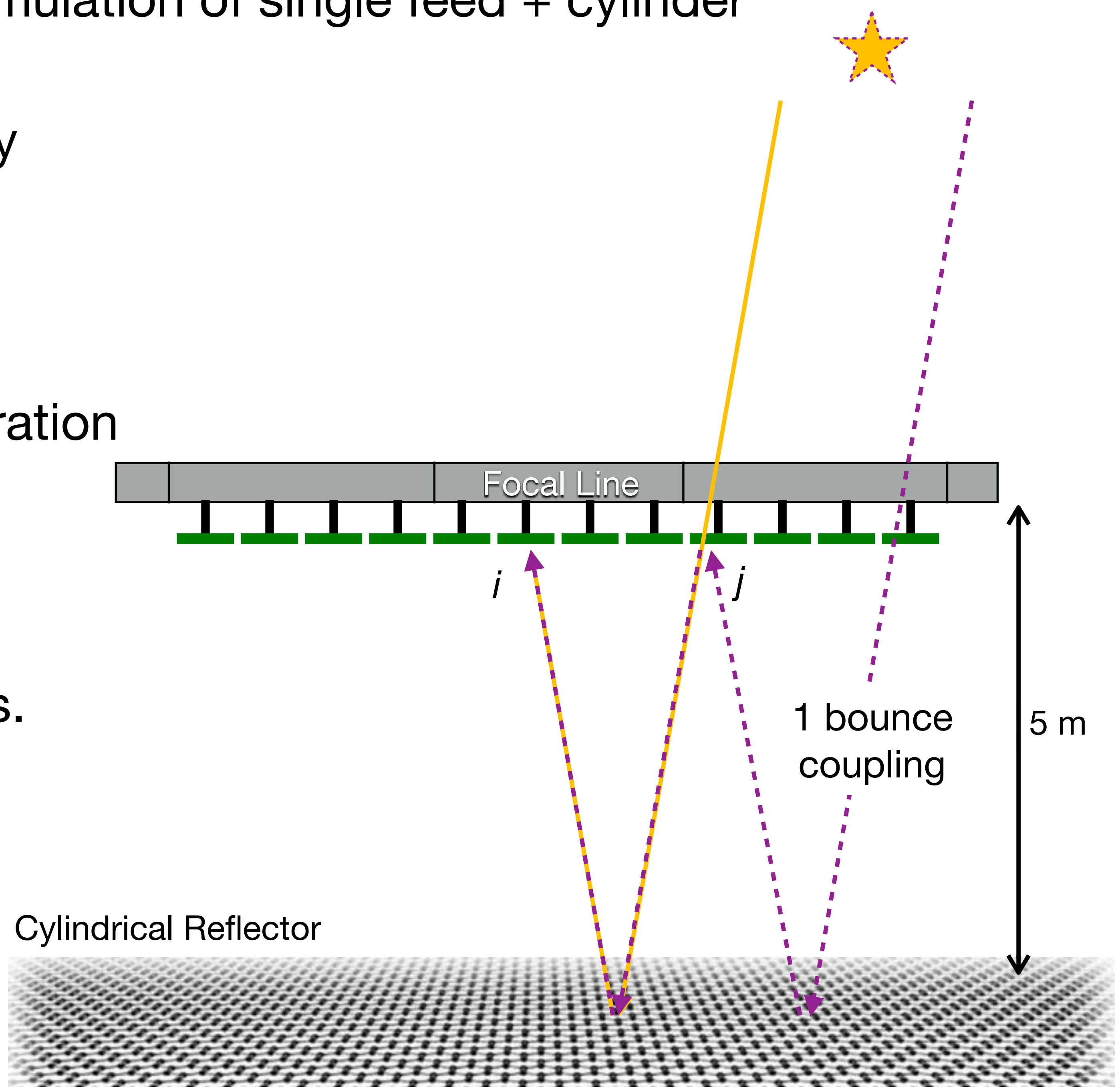
Holographic measurement of a Cyg A transit between the 26m at DRAO (tracking) and CHIME at 717 MHz. Shown is the median amplitude over all Y polarisation feeds on each of the 4 cylinders. Left is co-polar, right is cross-polar. Data is normalized by the peak co-polar response.

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.

Modelling 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
- 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.

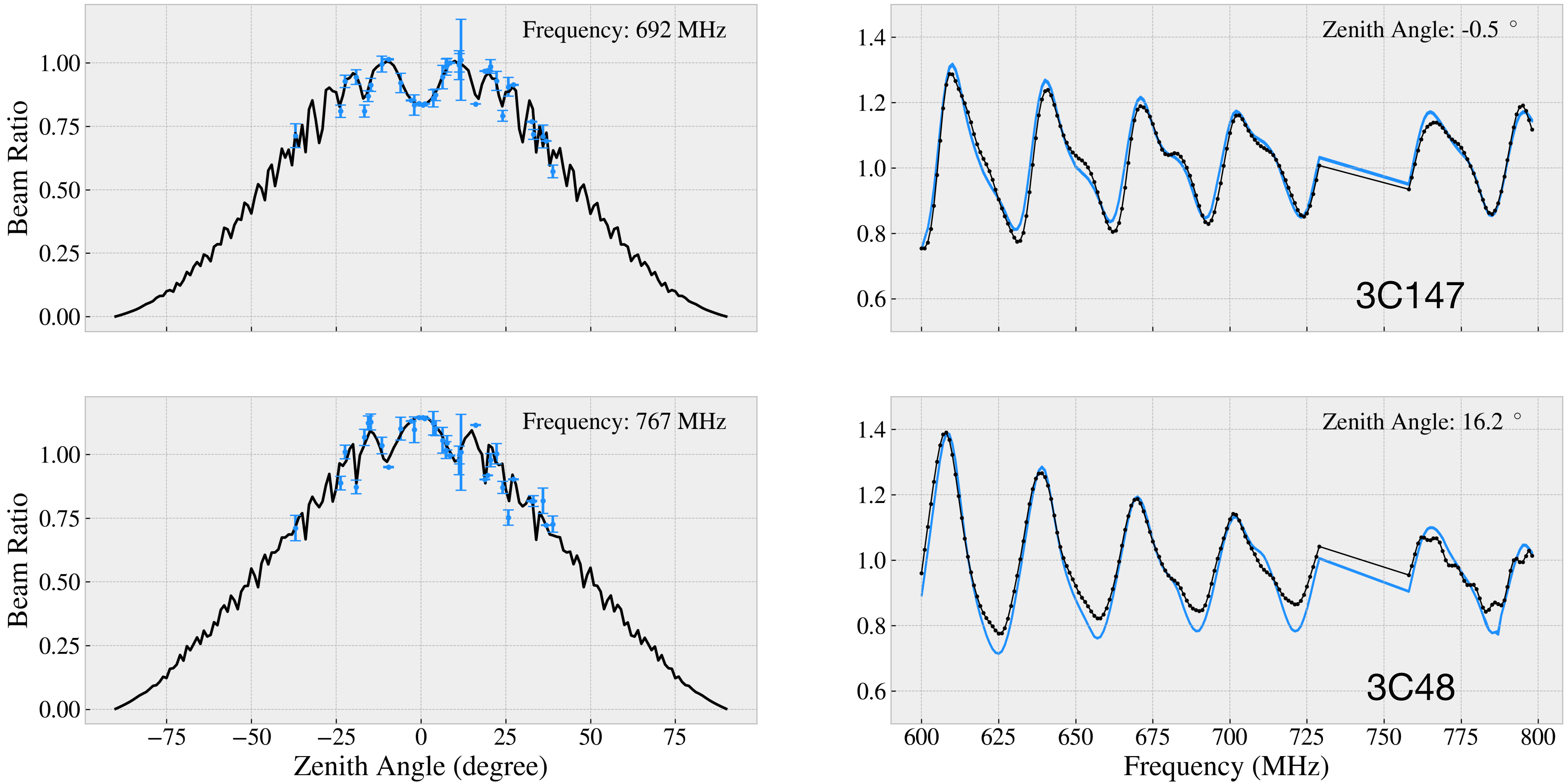
  Obtained by beamforming visibilities to source location and dividing by the expected source flux from literature.



Modelling the North-South Beam

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

Figure courtesy of Saurabh Singh

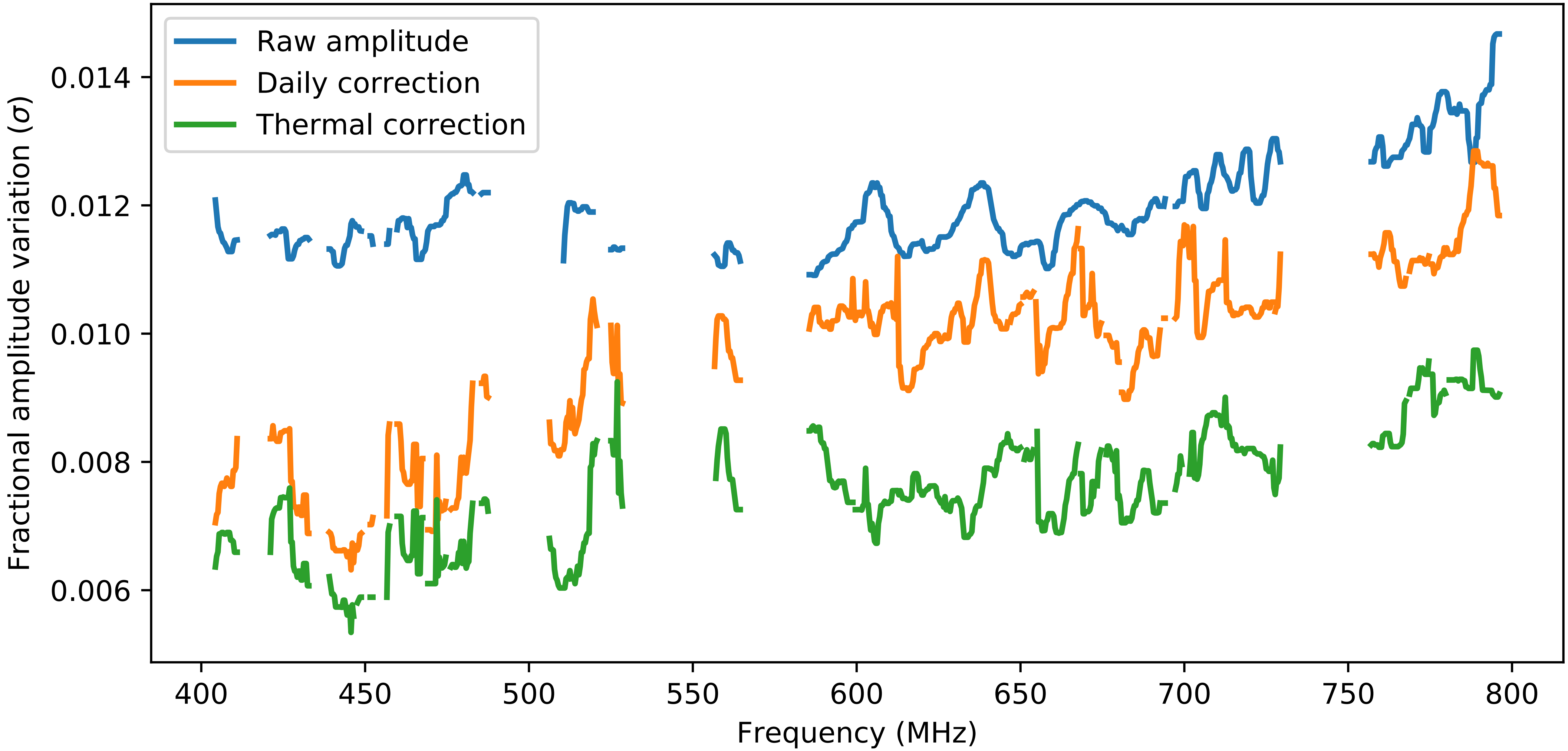


Left: Peak response as a function of zenith angle for 2 frequencies.

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

Complex Gain Calibration

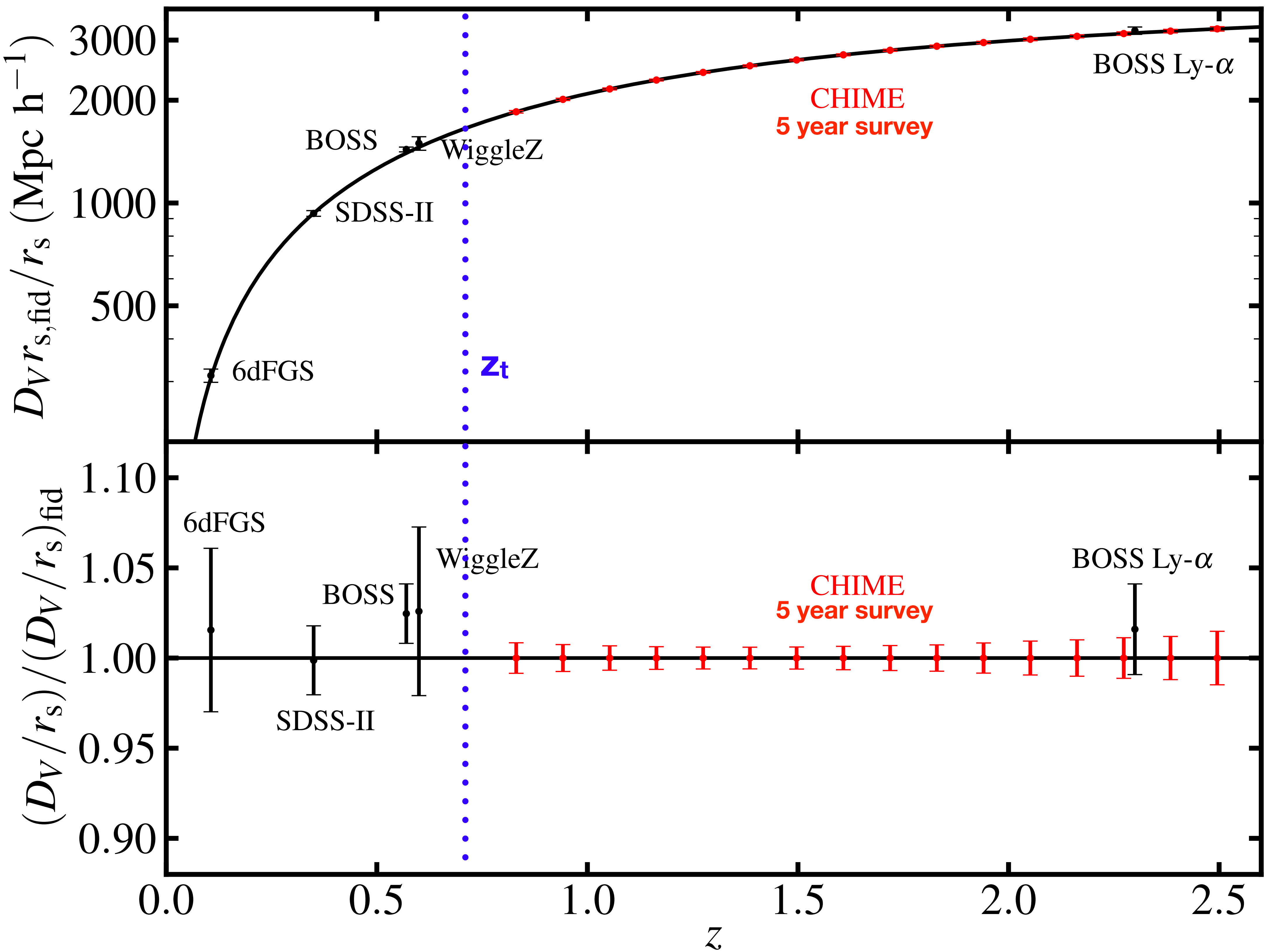
Figure courtesy of Mateus Fandino



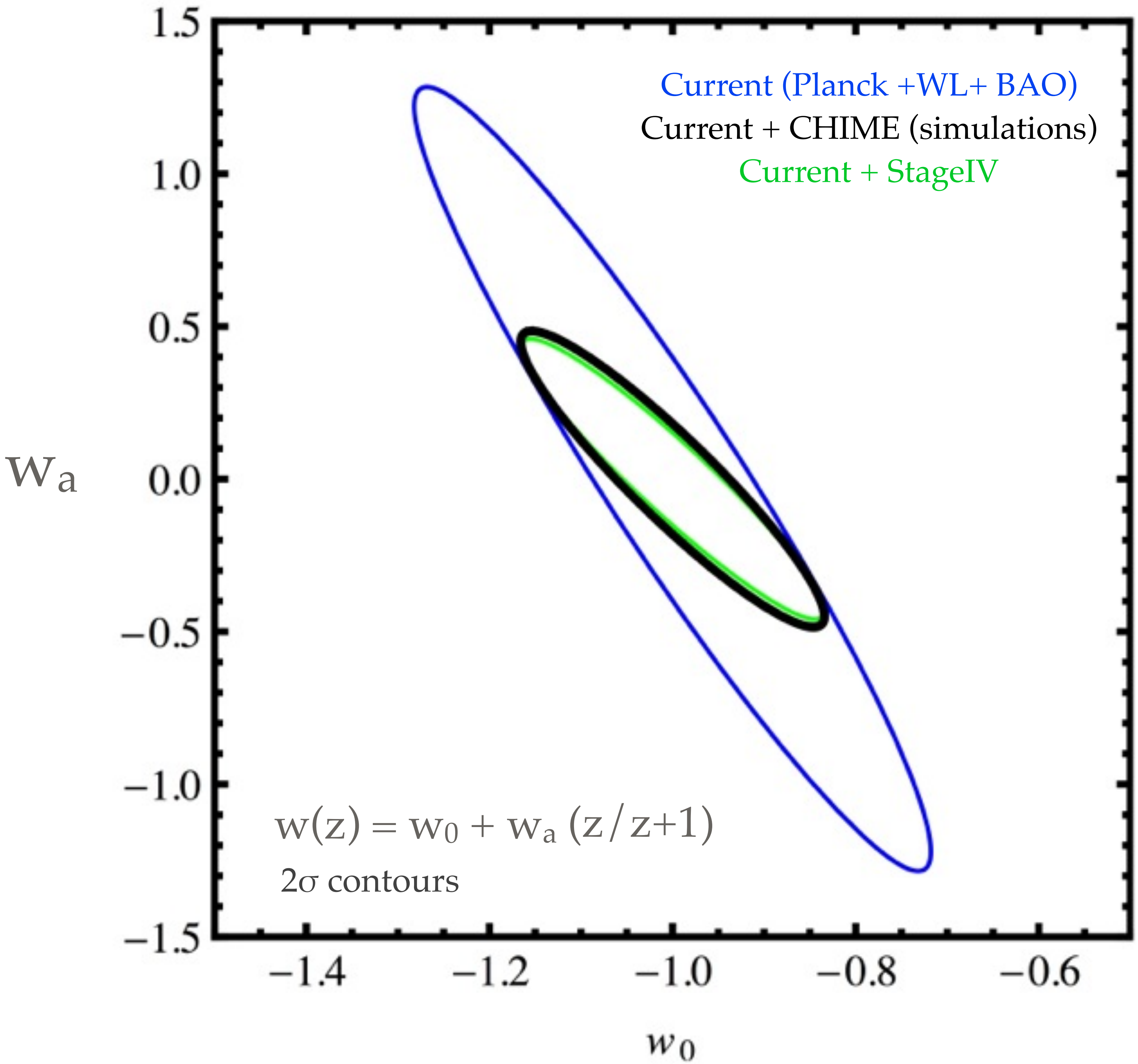
Common mode amplitude stability. Raw, after daily calibration, and after daily calibration and correction based on outside temperature.

Cosmology Forecast

Figure courtesy of Kevin Bandura



Cosmology Forecast



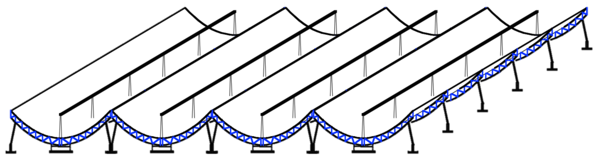
Constraints on dark energy equation of state $w = p / \rho$ from 5 year survey competitive with DOE Stage IV experiments (e.g., DESI, Euclid)

Figure courtesy of Richard Shaw


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

Additional Slides

Reflector



Reflector

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Analog Receiver Chain

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FPGA Digitizer / Channelizer

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GPU Correlator

↓

Real-time Backends

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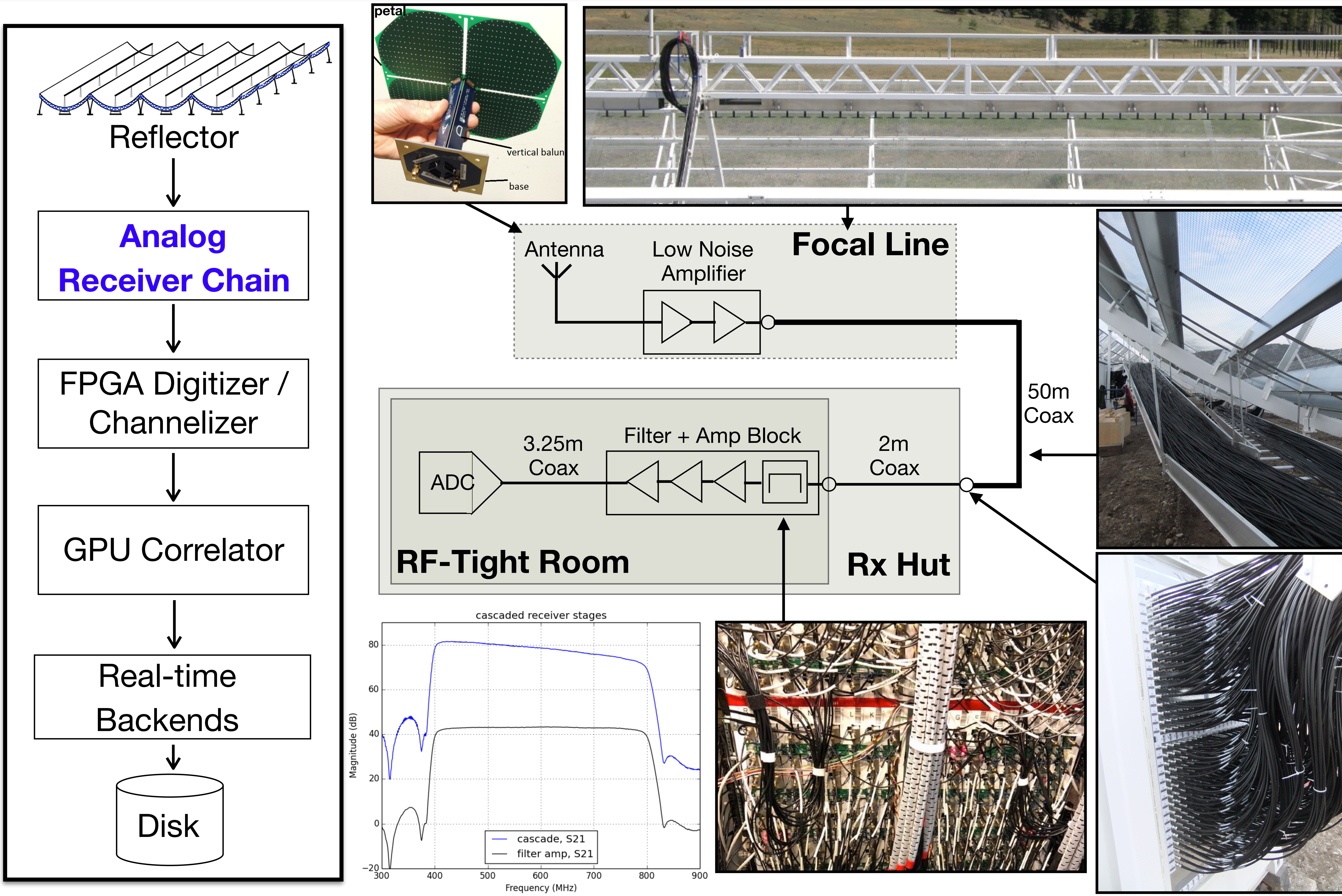
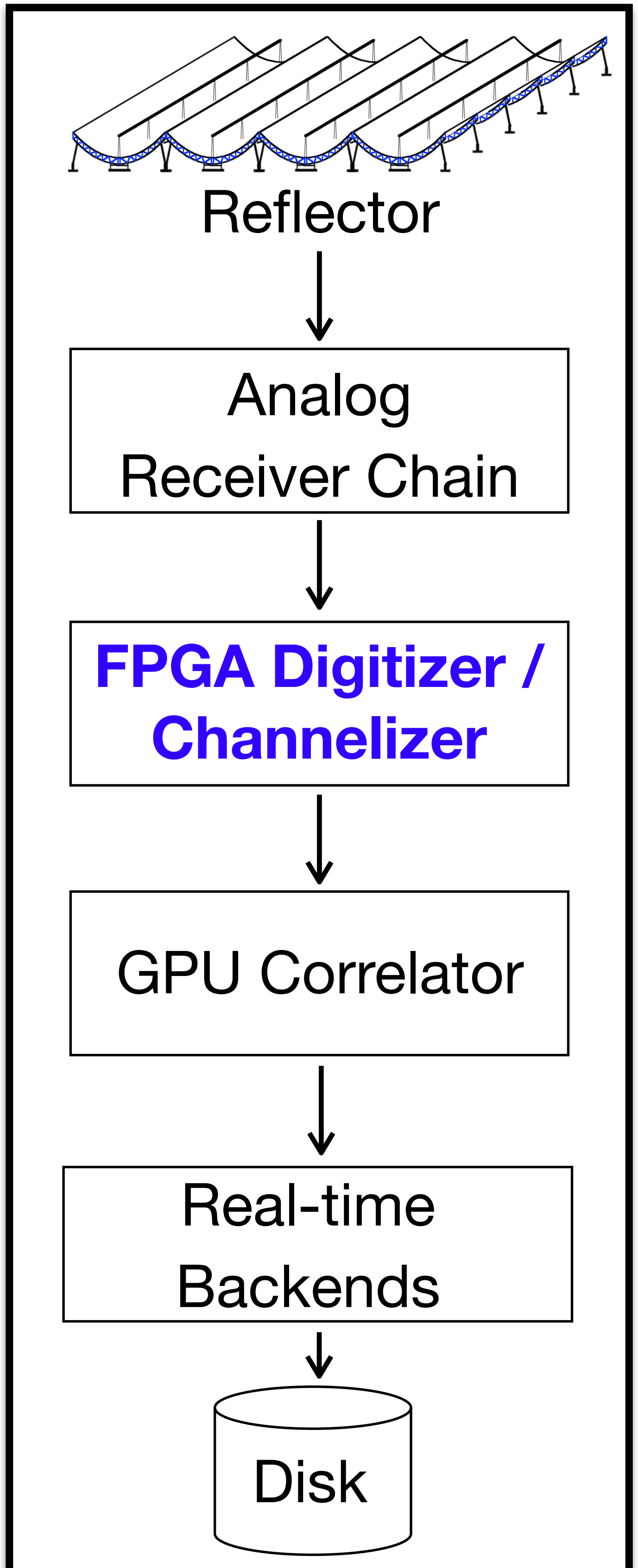
Disk

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

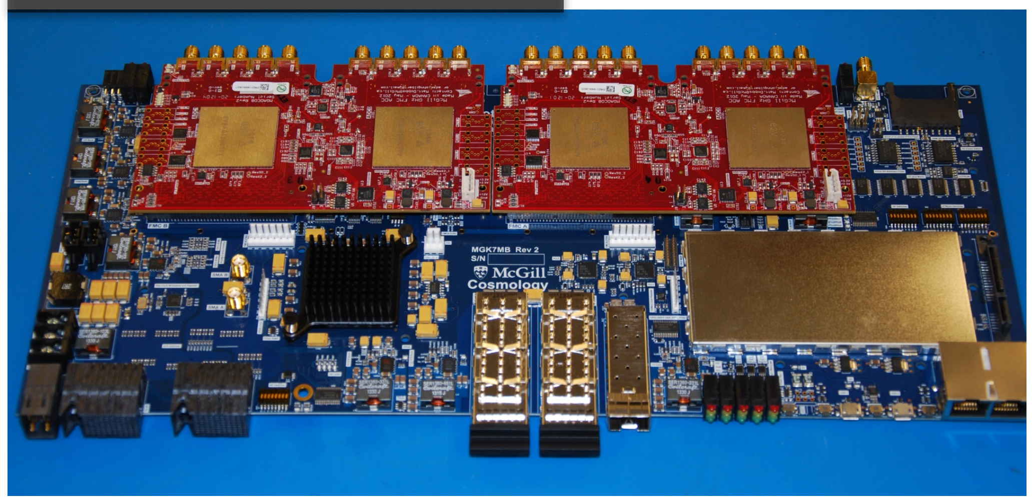
Analog Receiver Chain



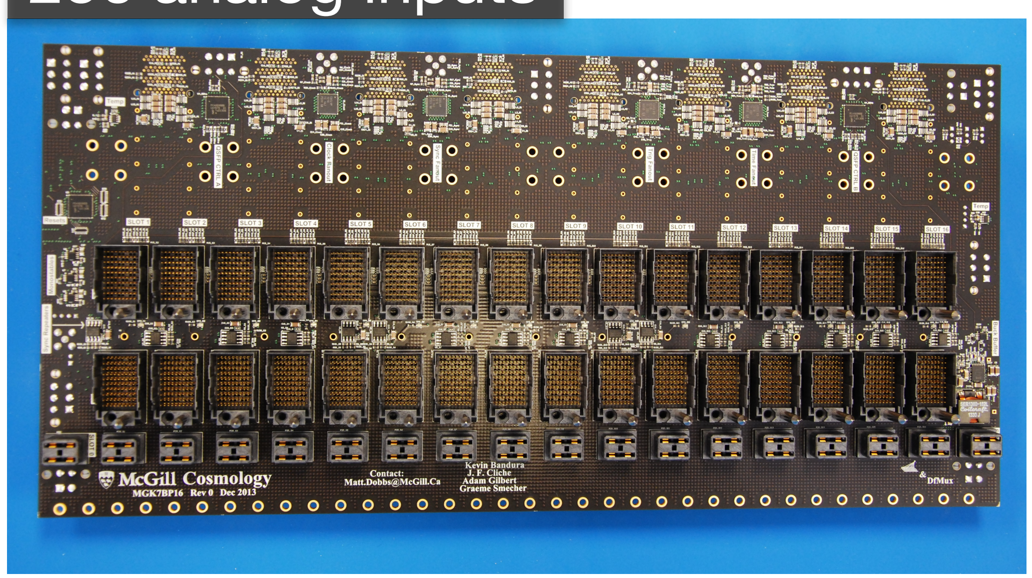
FPGA Digitizer and Channelizer (F-Engine)

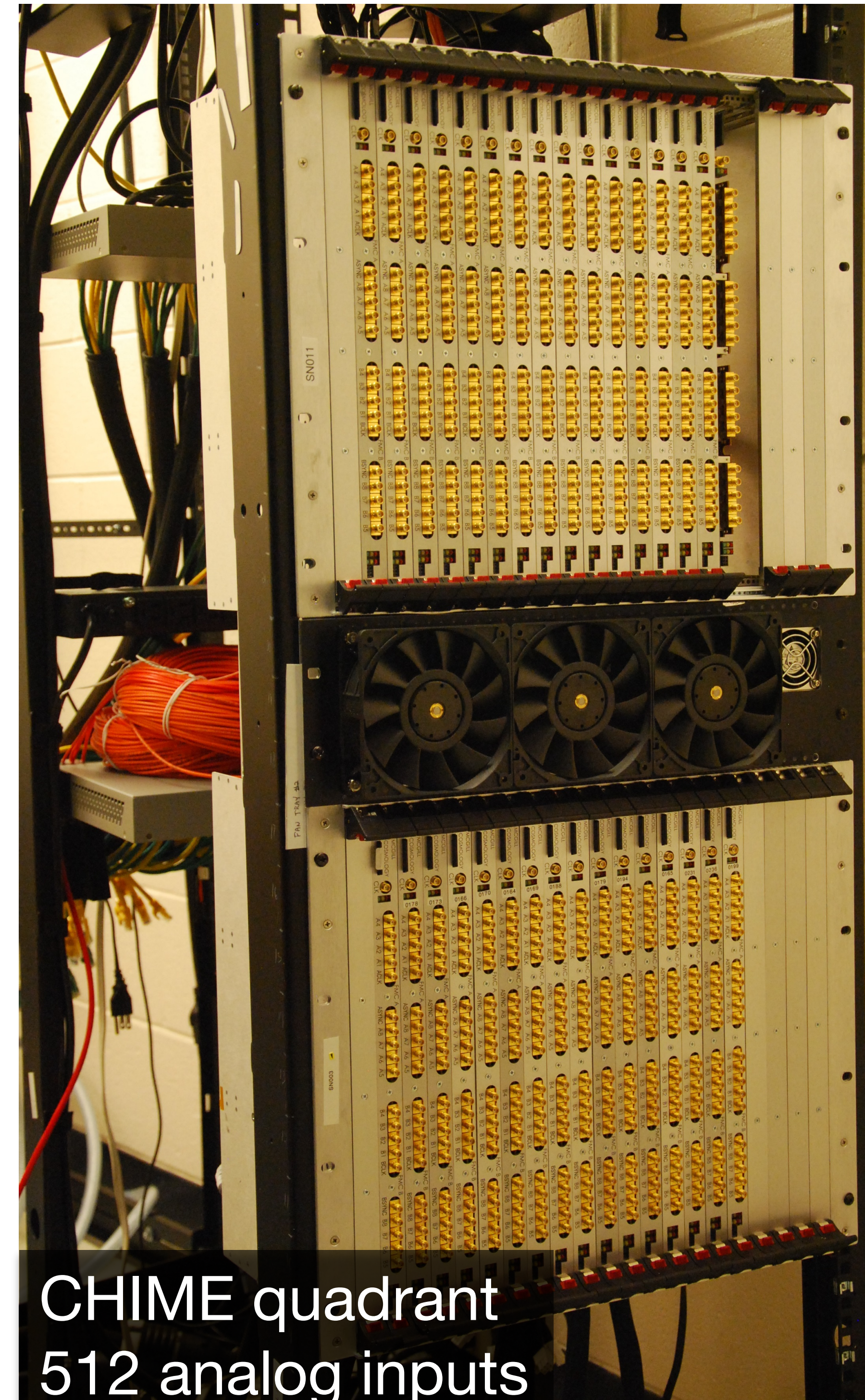


Motherboard
16 analog inputs



Backplane
256 analog inputs

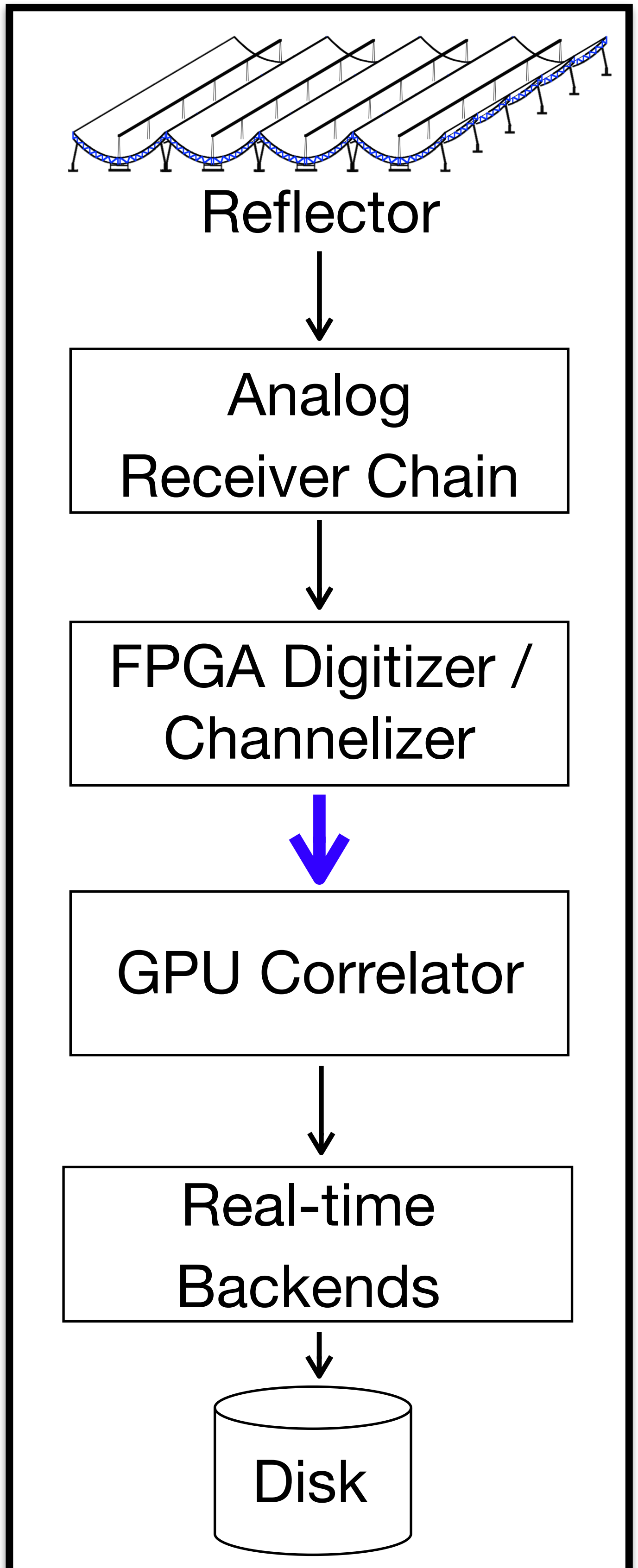


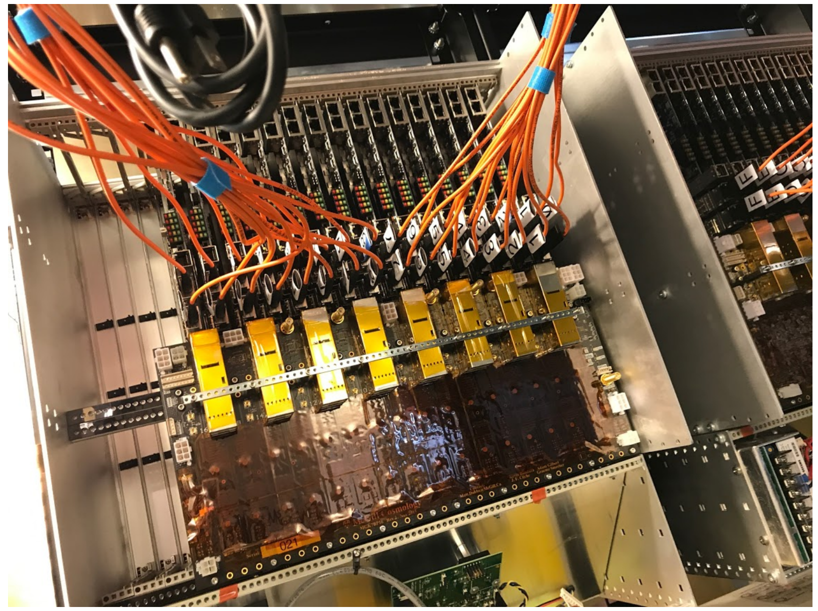


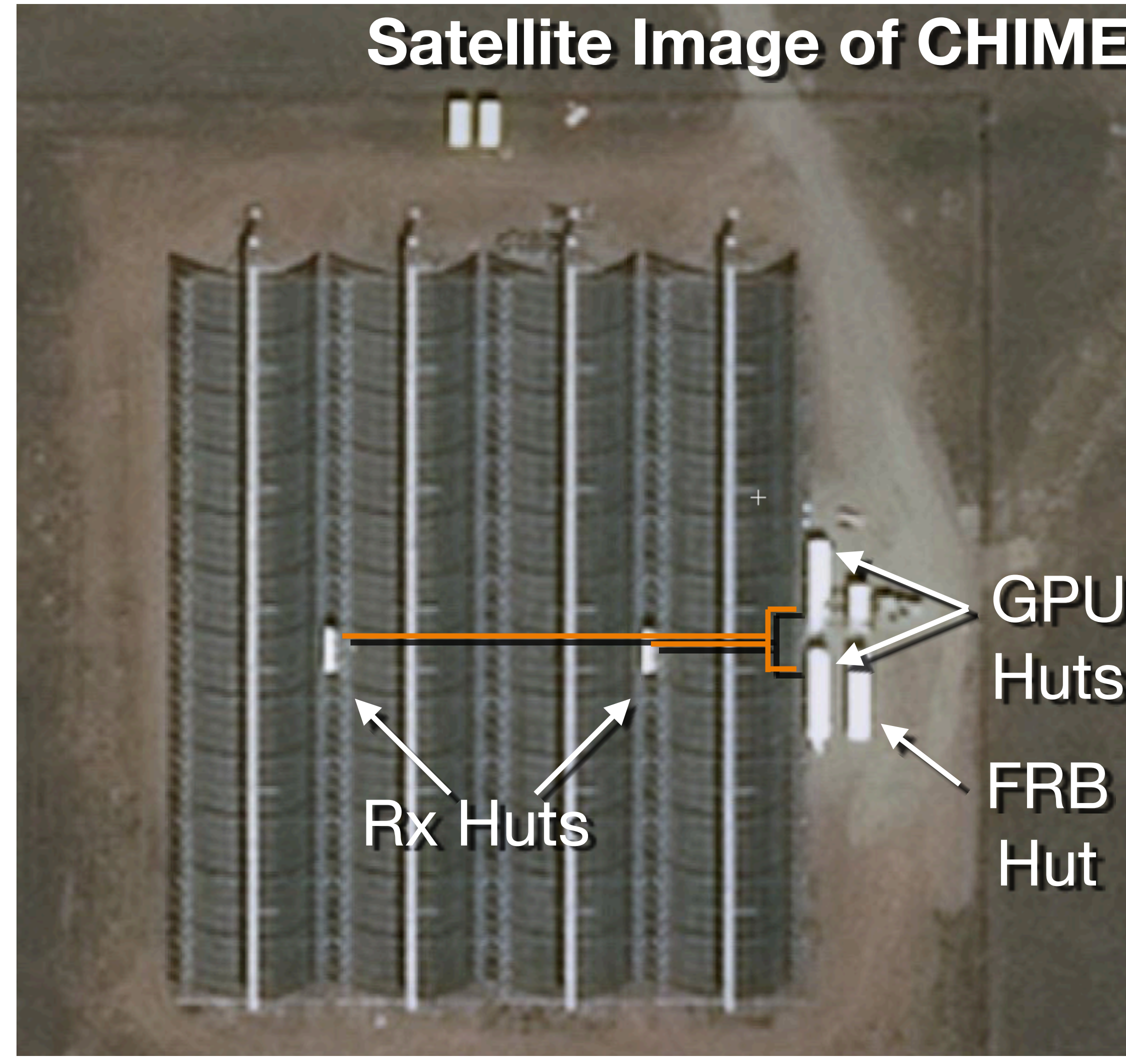
CHIME quadrant
512 analog inputs

Bandura et al. 2016, JAI

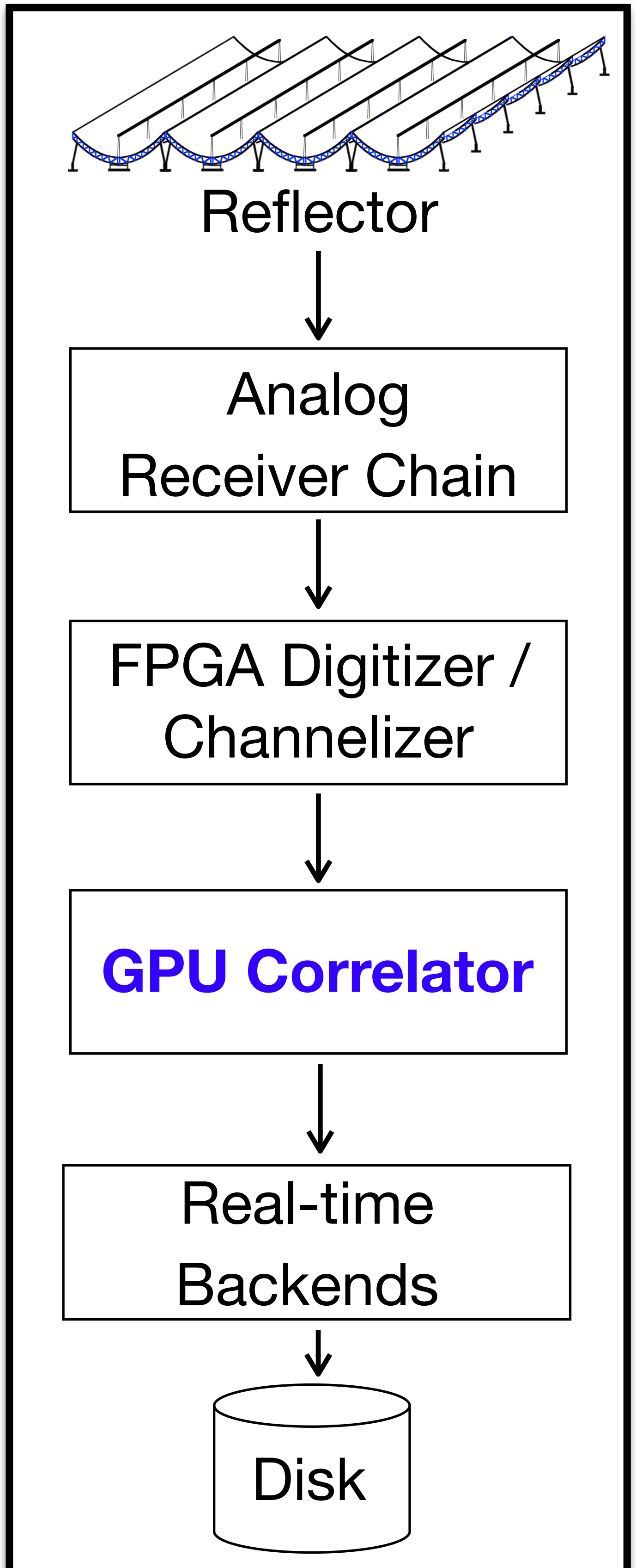
10 Gbit/s Link over Optical Fiber (x1024)







GPU Correlator (X-Engine)



Denman et al. 2015