Status of CHIME: The Canadian Hydrogen Intensity Mapping Experiment

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McGill University

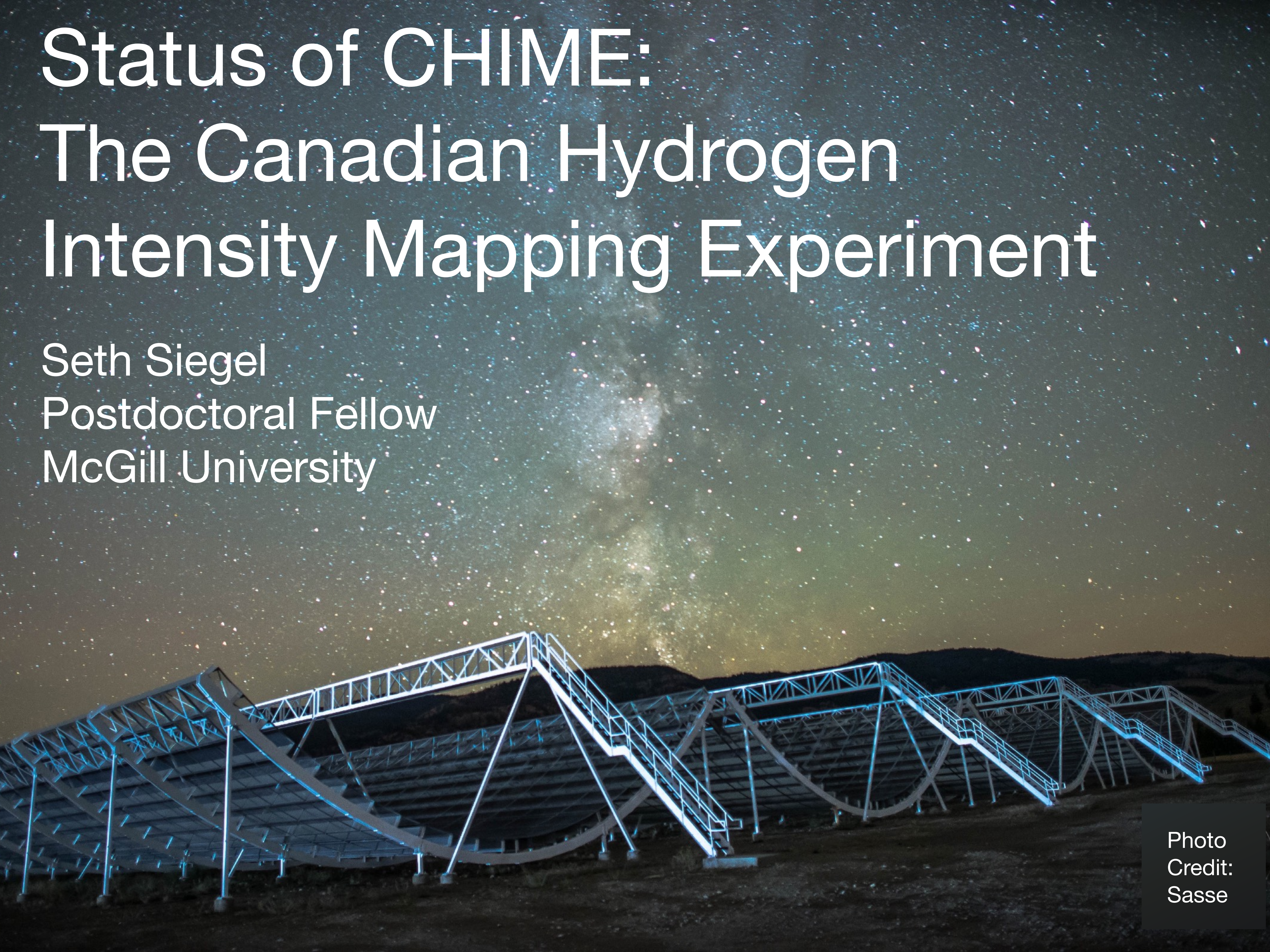


Photo Credit: Sasse

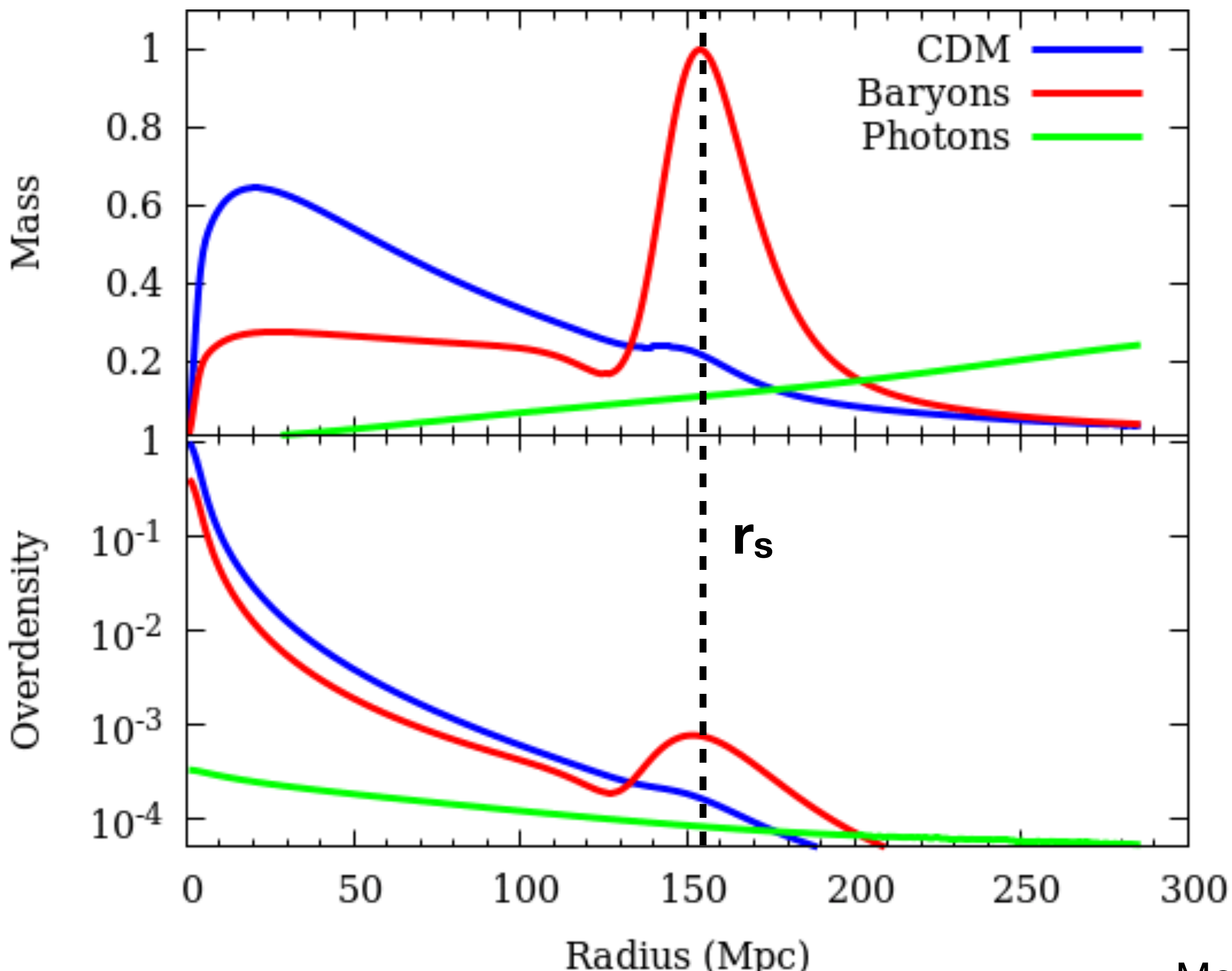
Outline

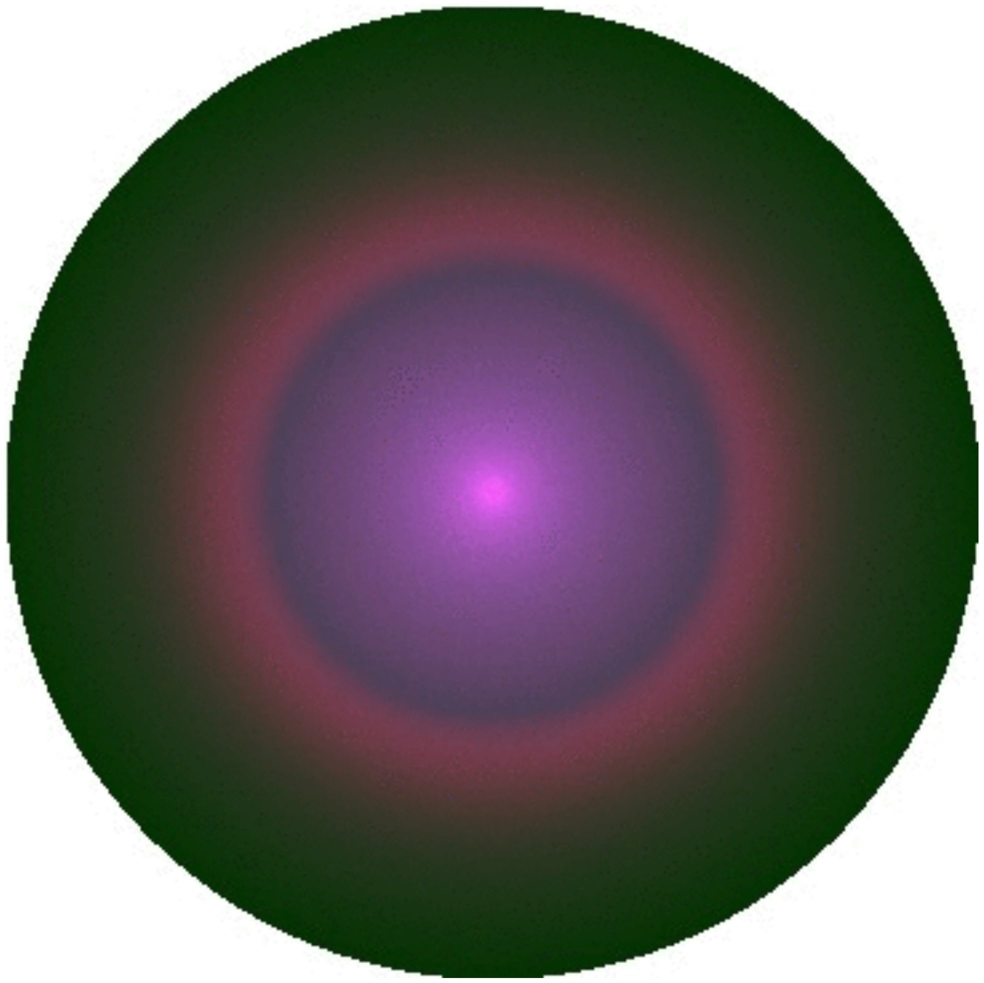
- Description of science goal
  - *Measurement of the Baryon Acoustic Oscillations in the distribution of neutral hydrogen between redshifts 0.8 and 2.5.*
- Virtual tour of CHIME
- Current status and first look at data
- Challenges
  - *Foreground removal*
  - *Instrument characterization*
    - *Complex gain calibration*
    - *Beam calibration*
  - *RFI Excision / Mitigation*
- Forecast on cosmological constraints

Baryon Acoustic Oscillations

Initial density perturbations result in sound waves that propagate in the photon-baryon fluid of the early universe. These are “frozen in” at recombination, leaving acoustic peaks in the CMB and matter power spectrum.

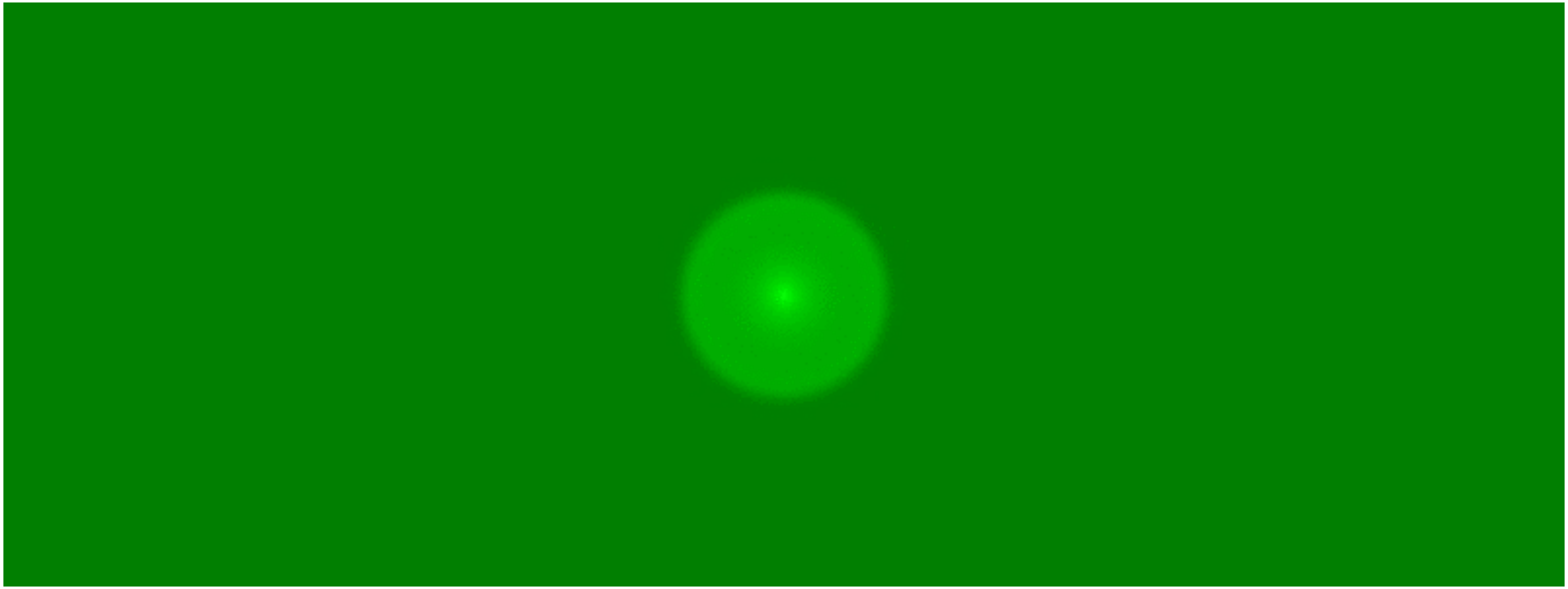
Evolution of a primordial density perturbation





Movies by Adam Hincks: http://adh-sj.info/bao_cmb.php

Baryon Acoustic Oscillations



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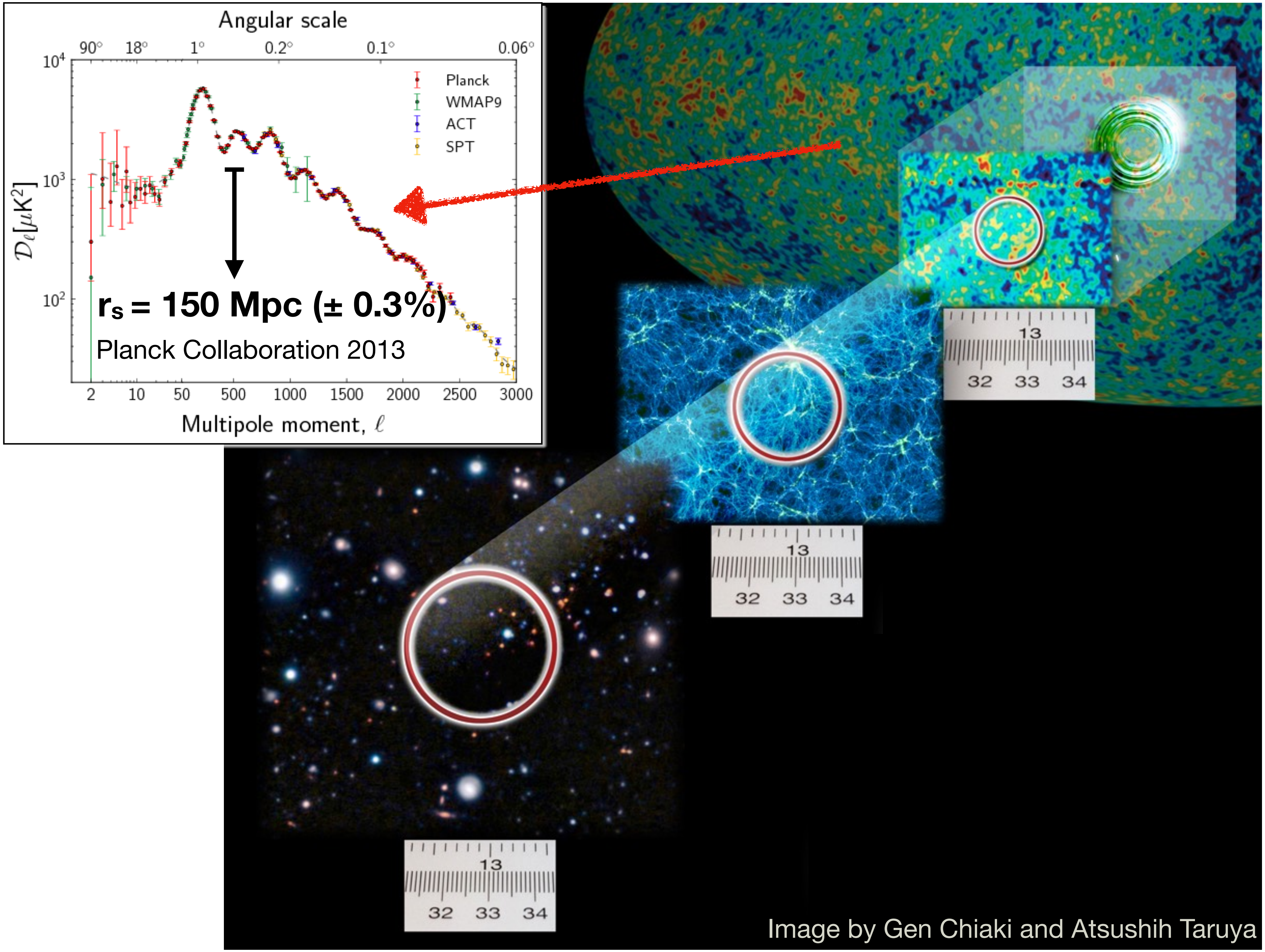
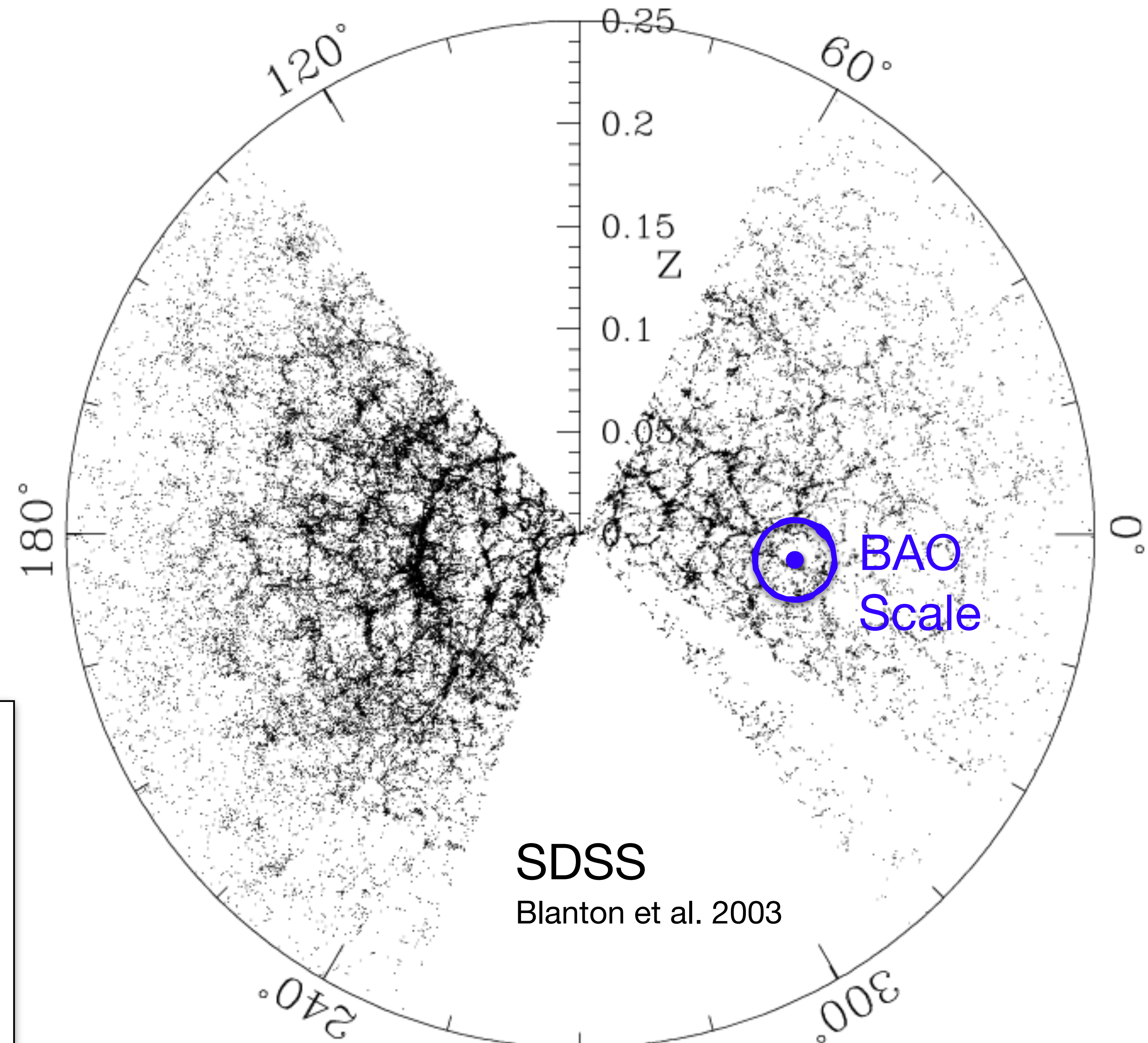
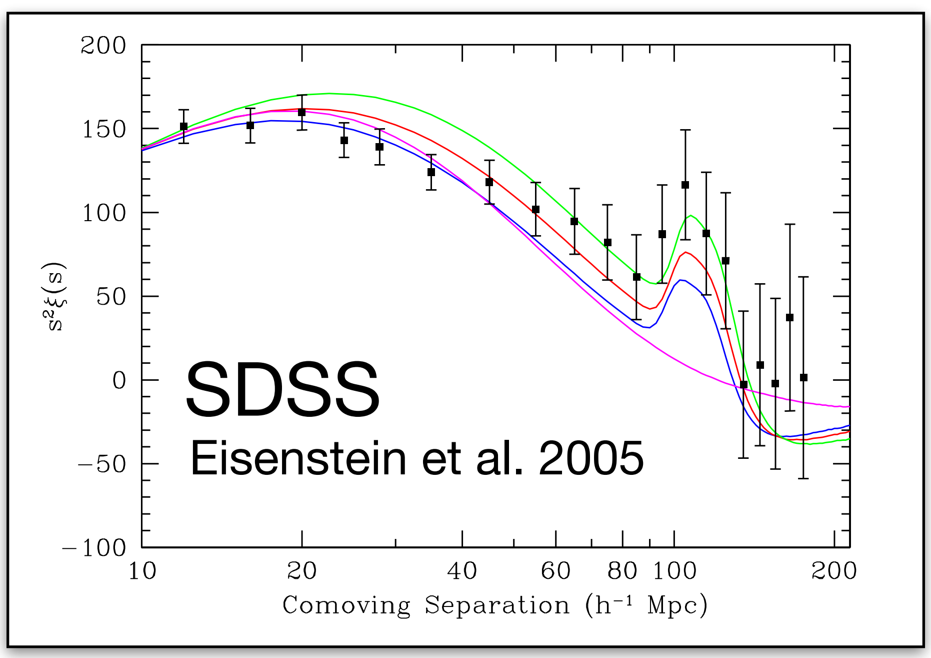
BAO as Cosmological Ruler

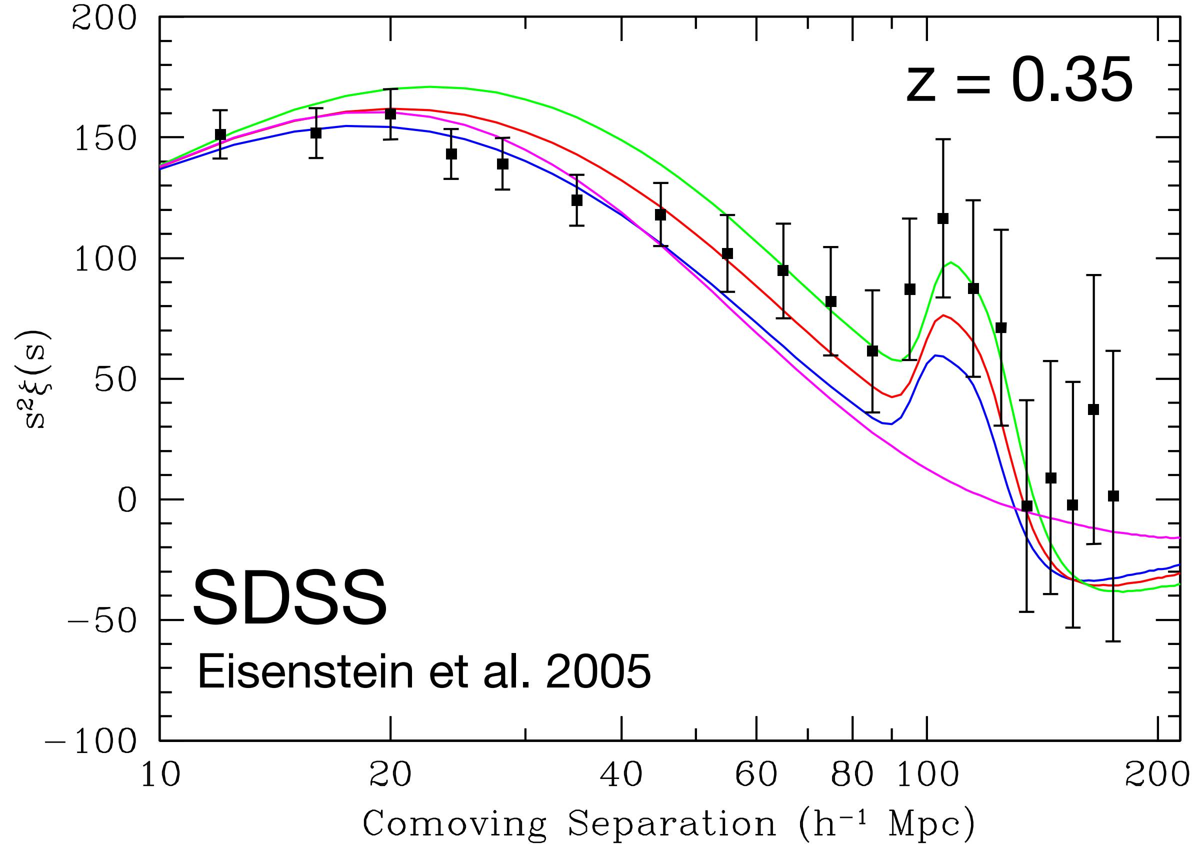


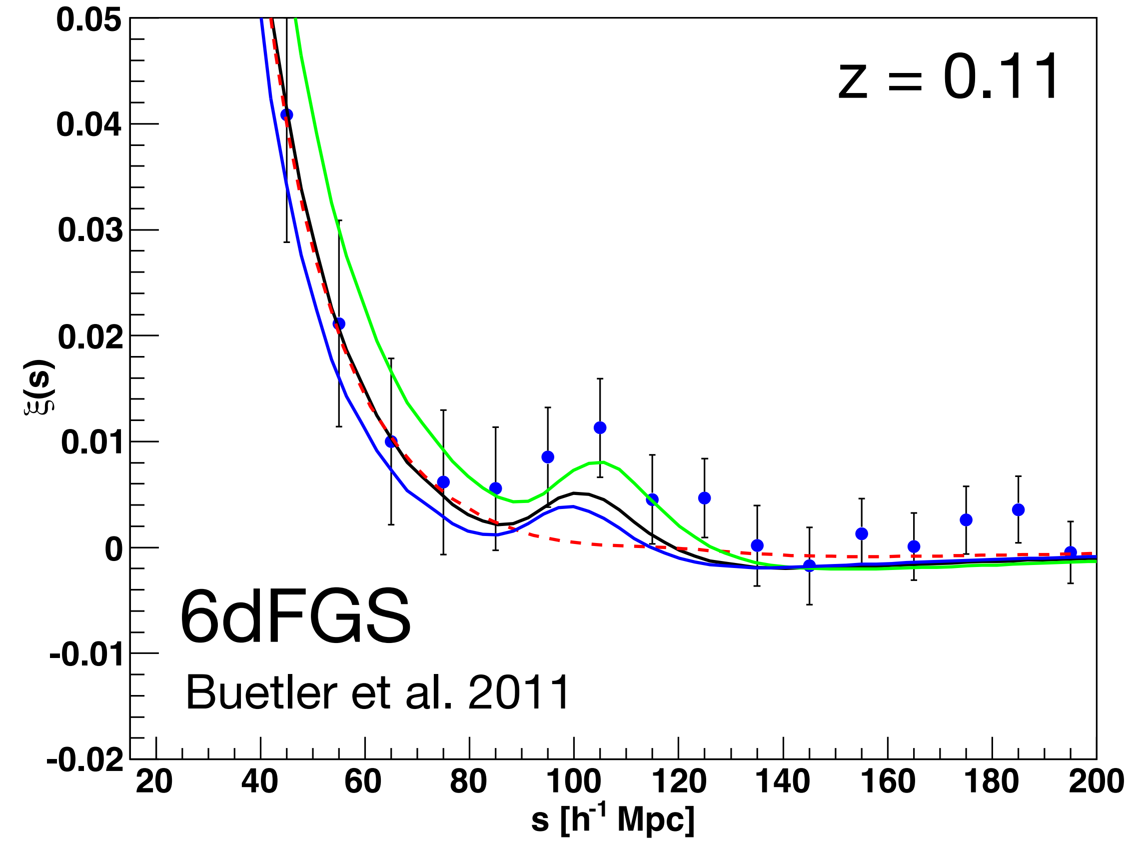
Spectroscopic Galaxy Surveys

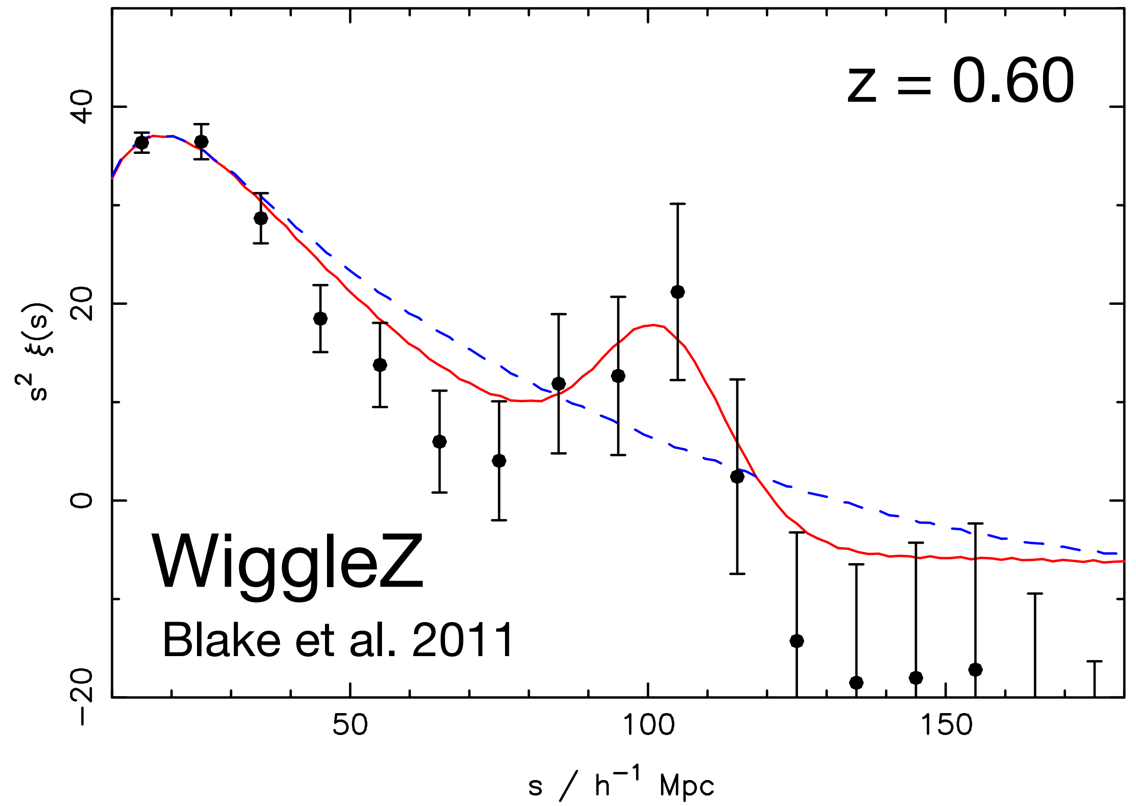


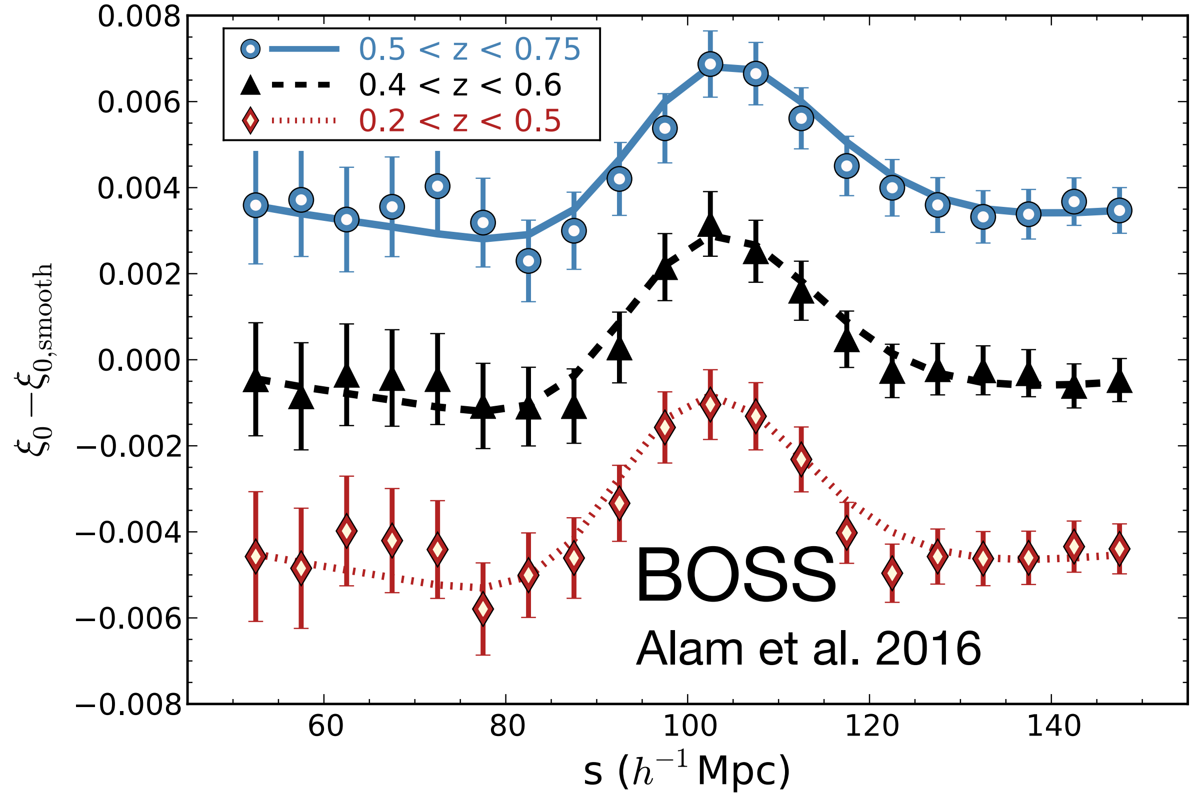


BAO in the Galaxy Correlation Function



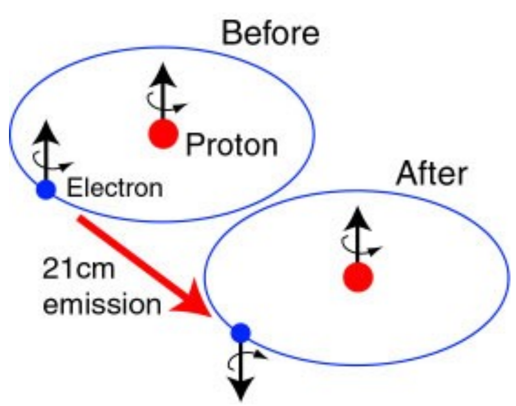


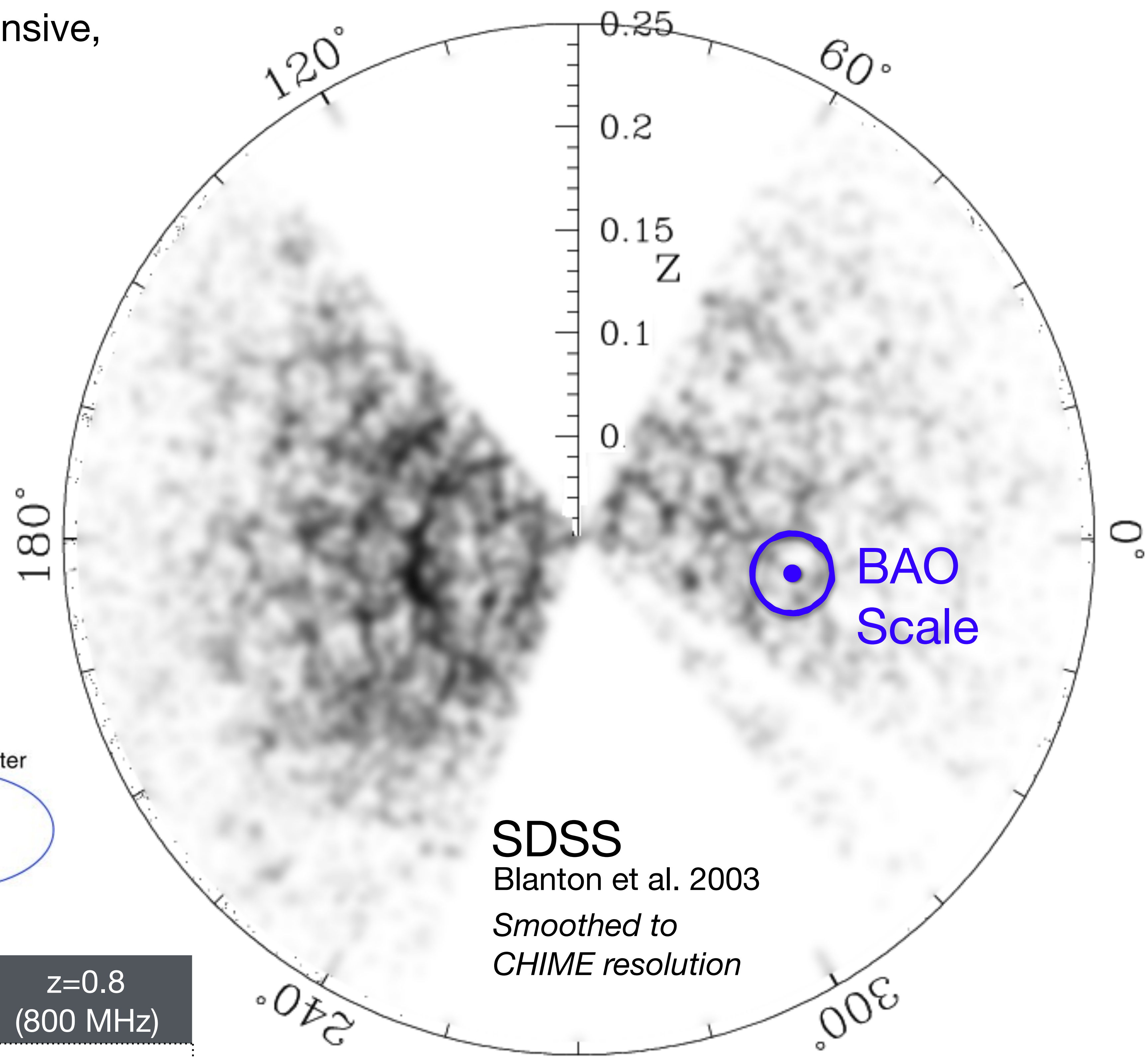




Hydrogen Intensity Mapping

- Spectroscopic galaxy surveys expensive, difficult at high-z
- Interested in much larger scales, do not need to resolve individual galaxies
- Instead, measure the aggregate 21 cm emission from neutral hydrogen
  - Observing frequency maps to redshift slice
  - Probe "redshift desert" (1.4 < z < 2.5)





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Observable	z=2.5 (400 MHz)	z=0.8 (800 MHz)
$\Delta\theta_{BAO}(z) = r_s / D_M(z)$	1.35°	3°
$\Delta z_{BAO}(z) = r_s H(z)/c$	12 MHz	20 MHz

chime

a collaboration between

THE UNIVERSITY OF BRITISH COLUMBIA

UNIVERSITY OF TORONTO

McGill

Dominion Radio Astrophysical Observatory

DRAO

NRC · CNRC

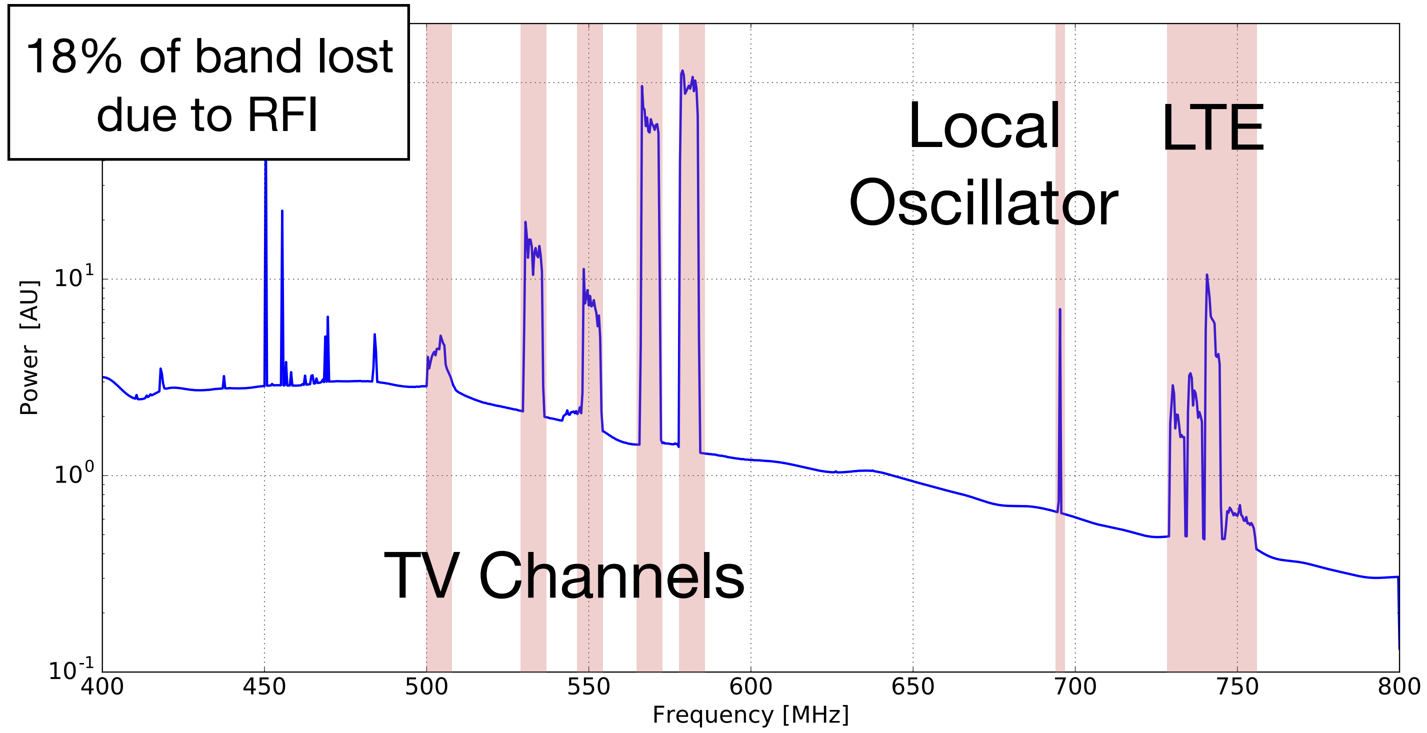
West Virginia University

Yale University

Massachusetts Institute of Technology

Drone Flight Over CHIME

Dominion Radio Astrophysical Observatory

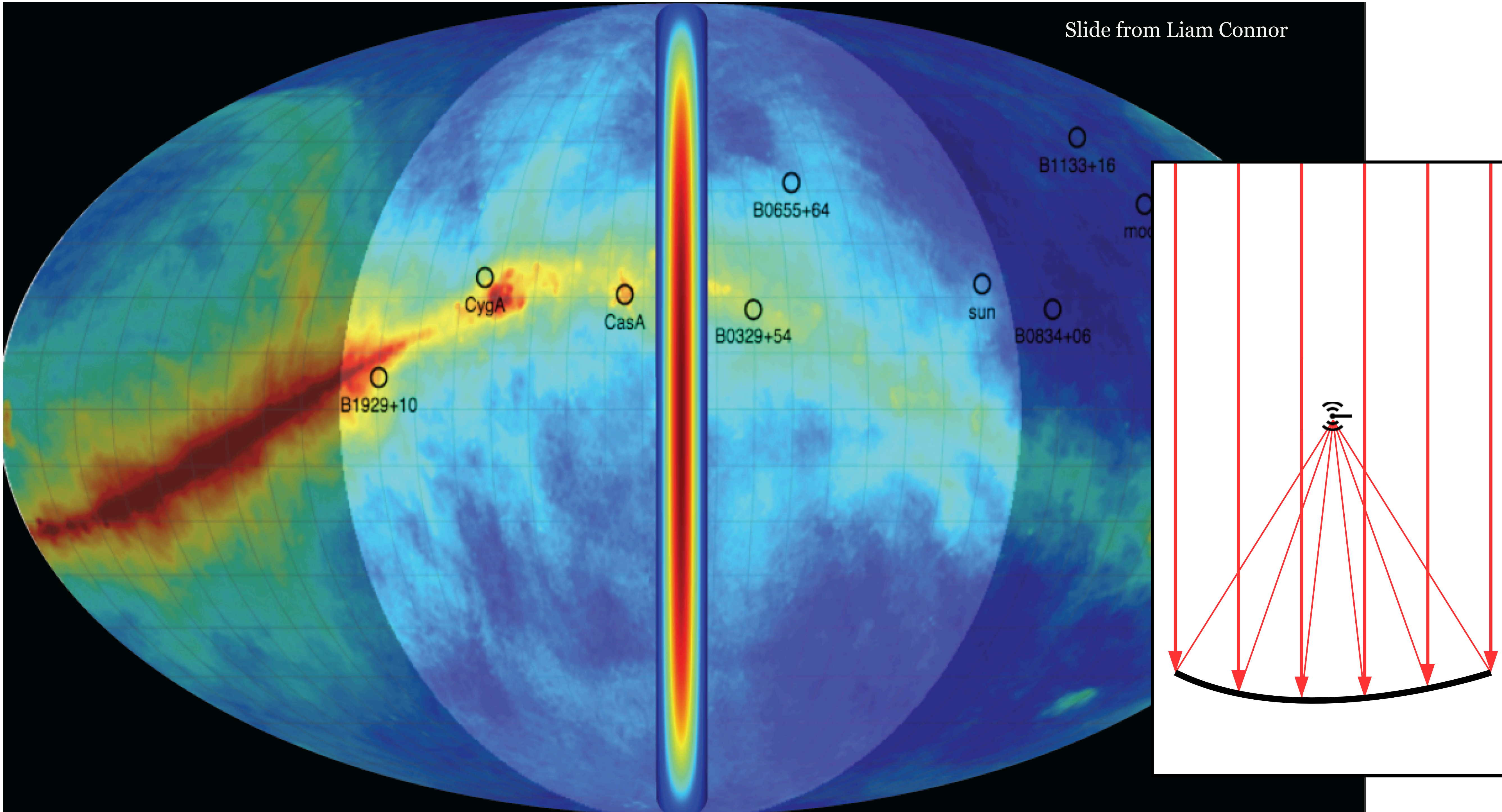


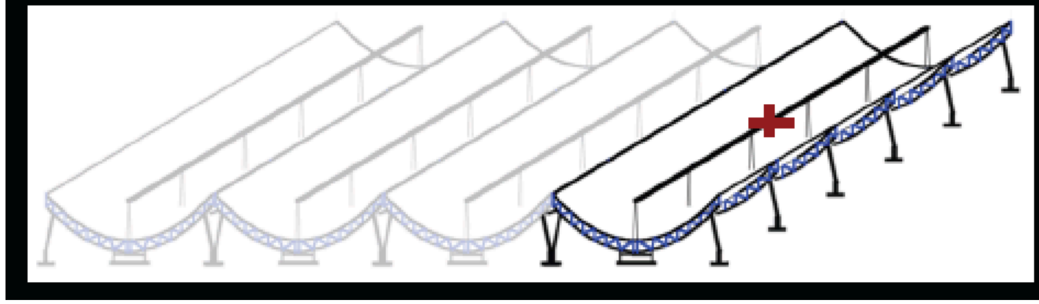
Cylindrical Transit Interferometer

Movie by Peter Klagge

E ⟷ *W*

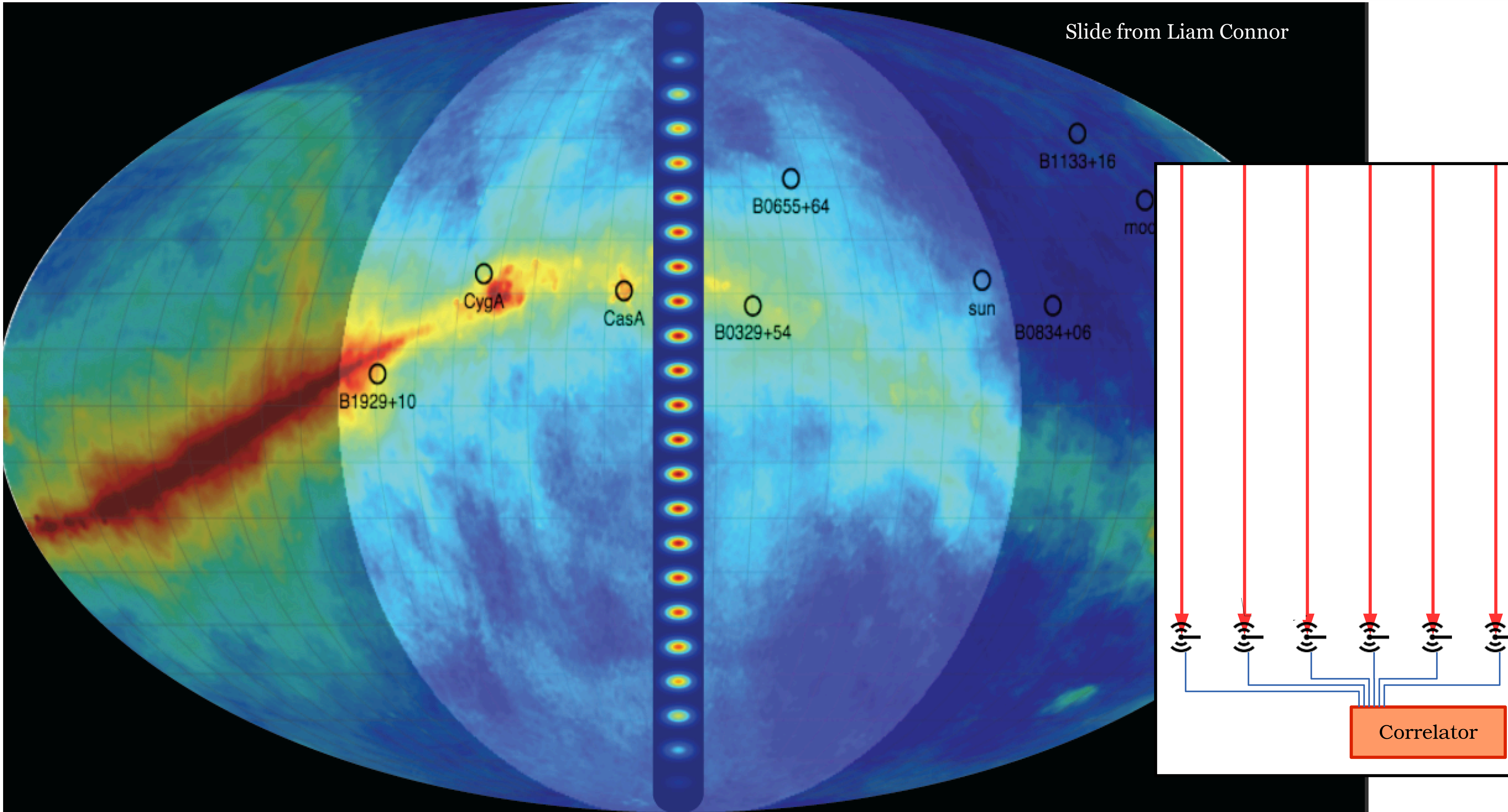
Cylindrical Transit Interferometer

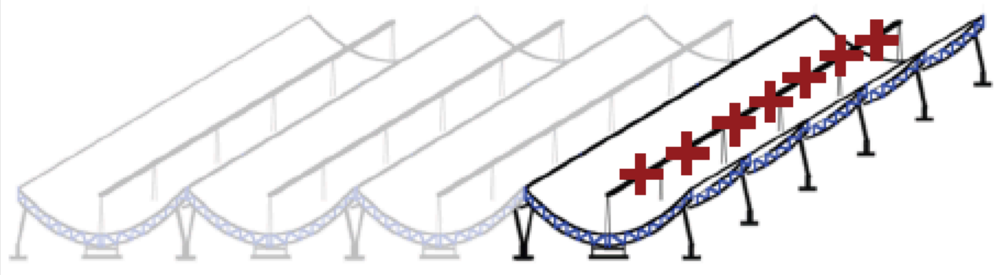




- Cylinder focuses light only in EW direction
- Gives us large FOV

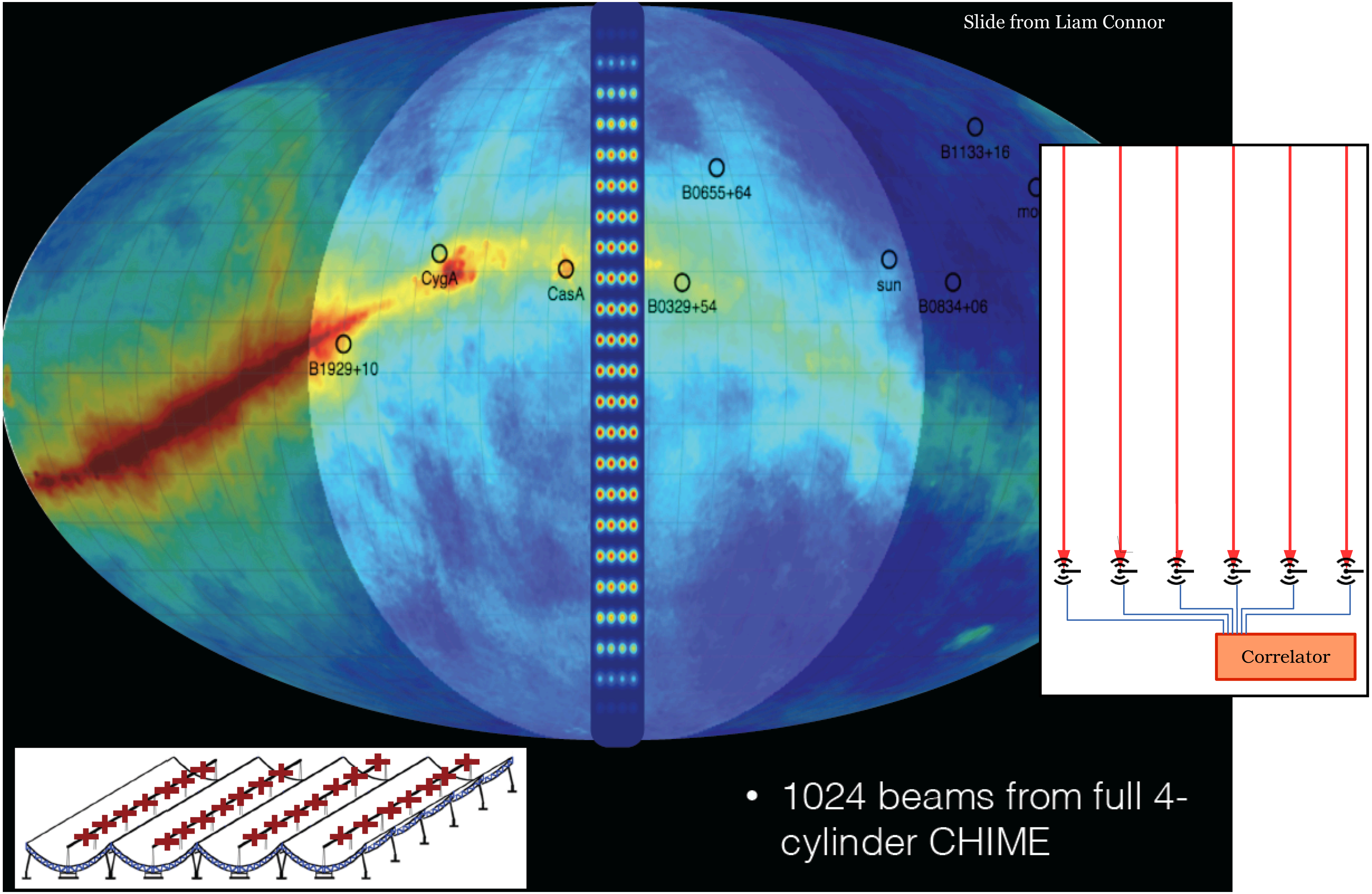
Cylindrical Transit Interferometer





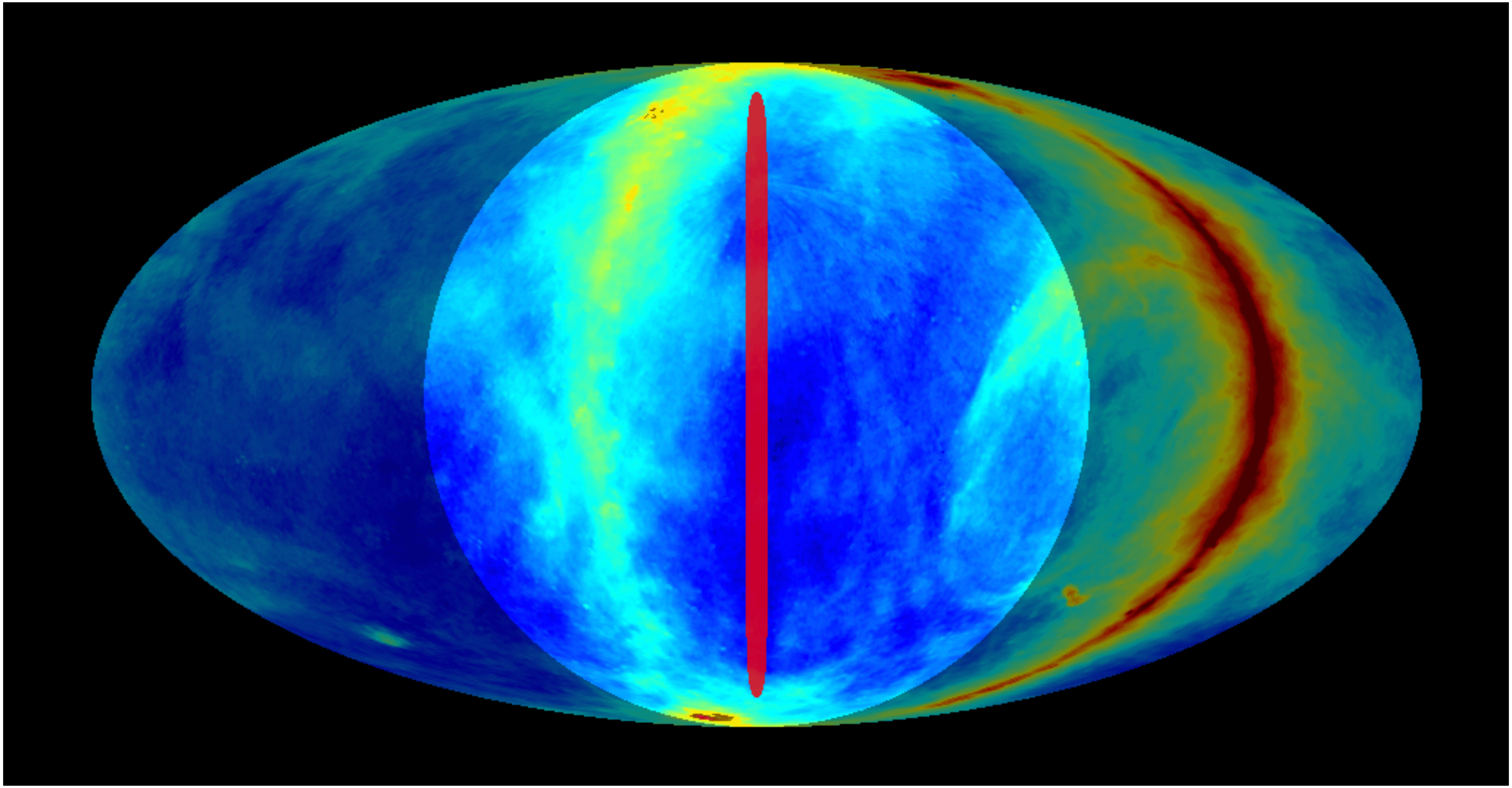
- FFT telescope in NS direction
- 256 beams per cylinder

Cylindrical Transit Interferometer



- 1024 beams from full 4-cylinder CHIME

Cylindrical Transit Interferometer



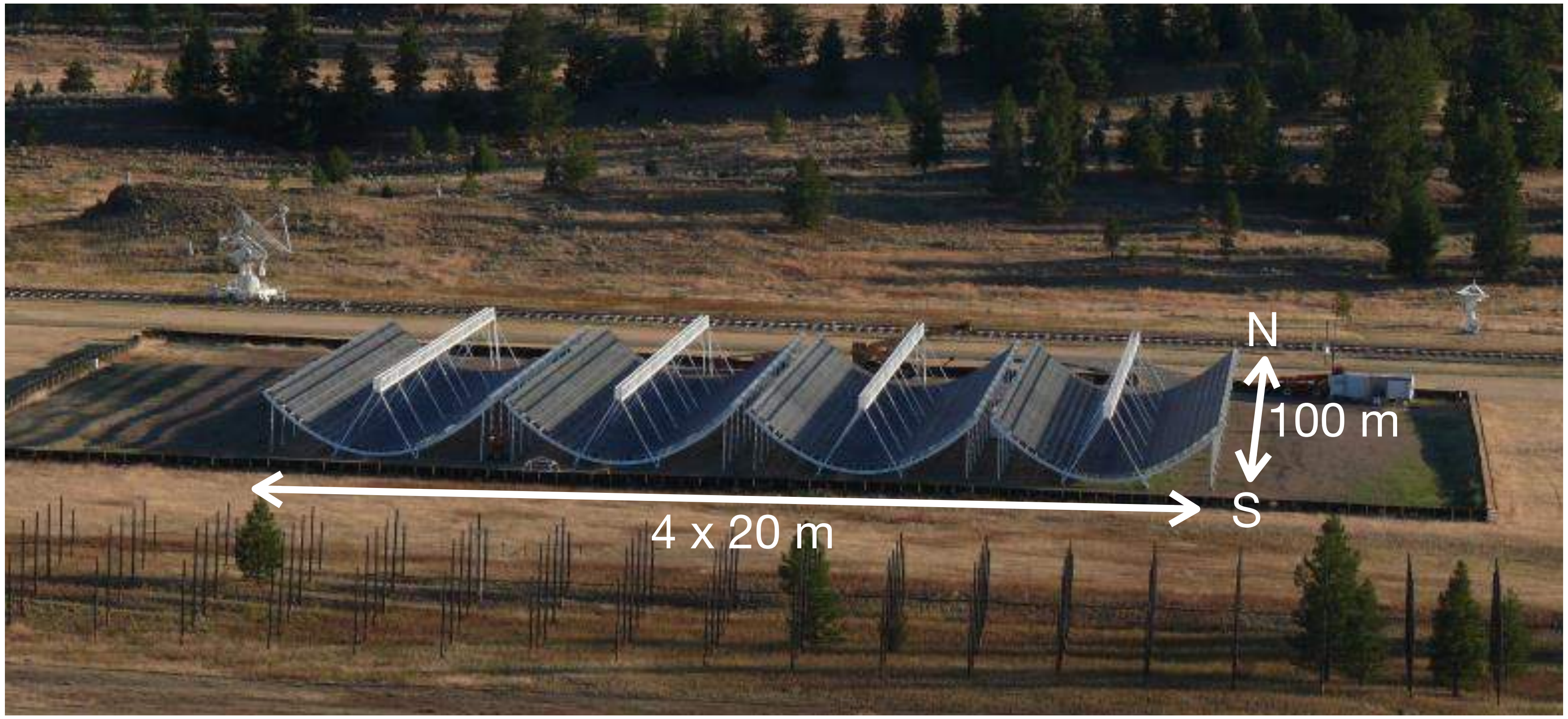
Haslam 408 MHz Map

CHIME Parameters

- 4 cylinders (each 20 m x 100 m)
  - 8,000 m^2 collecting area
- 1024 dual polarization feeds

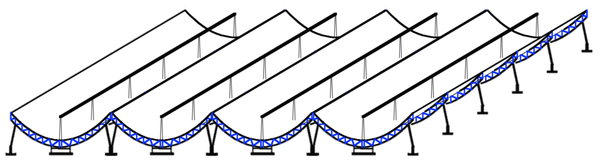
Bandpass	400 MHz	800 MHz
21cm redshift	2.5	0.8
Beam Size	0.52° (45 Mpc)	0.26° (10 Mpc)
E-W FoV	2.5°	1.3°
N-S FoV	~100°	

- 390 kHz frequency resolution
- Maps 1/2 the sky each day
- $T_{receiver}$ = 50 K
- 80 μJy / pixel daily sensitivity
- Collecting data since March.



- **Cosmology**
  - Cosmic variance limited measurement of BAO between z = 0.8 - 2.5
- **Pulsars**
  - Precise timing of known msec pulsars
- **Fast Radio Bursts**
  - Detect on order 10 FRBs per day

Reflector



Reflector

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Analog Receiver Chain

↓

FPGA Digitizer / Channelizer

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GPU Correlator

↓

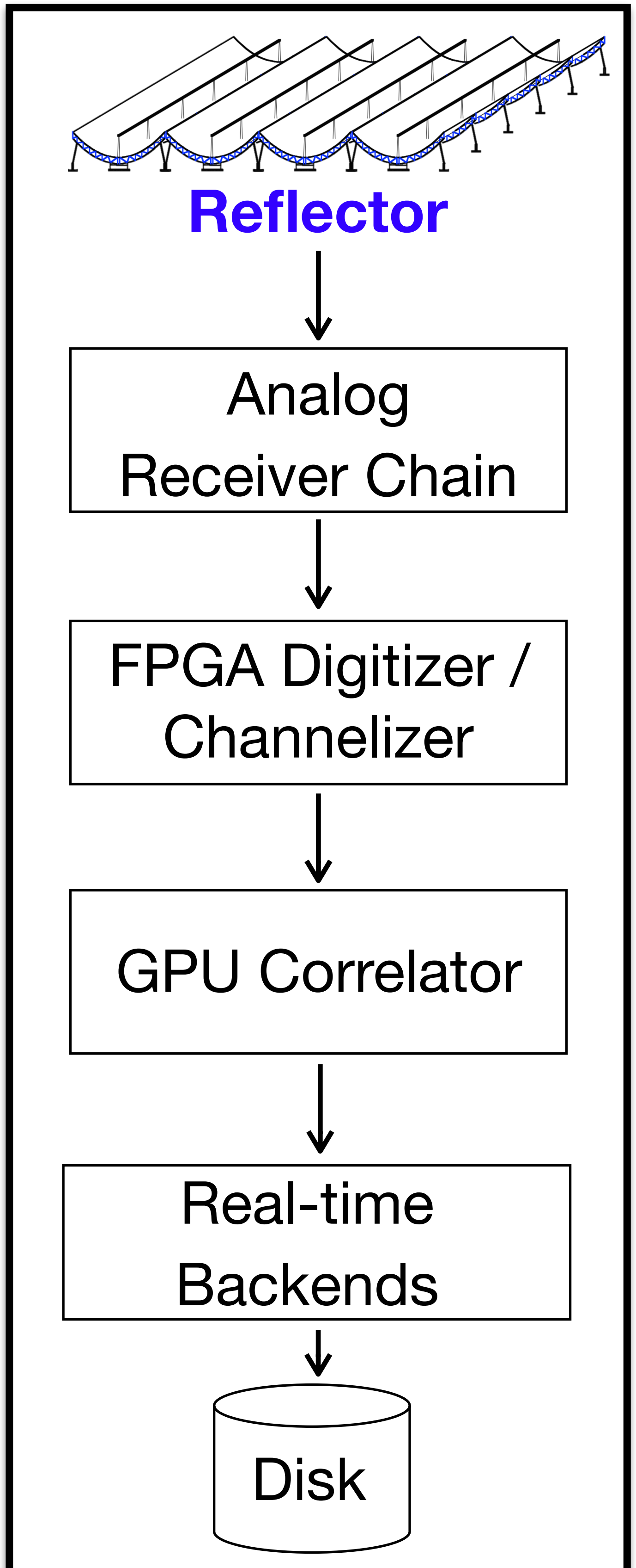
Real-time Backends

↓

Disk

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

Reflector


Reflector
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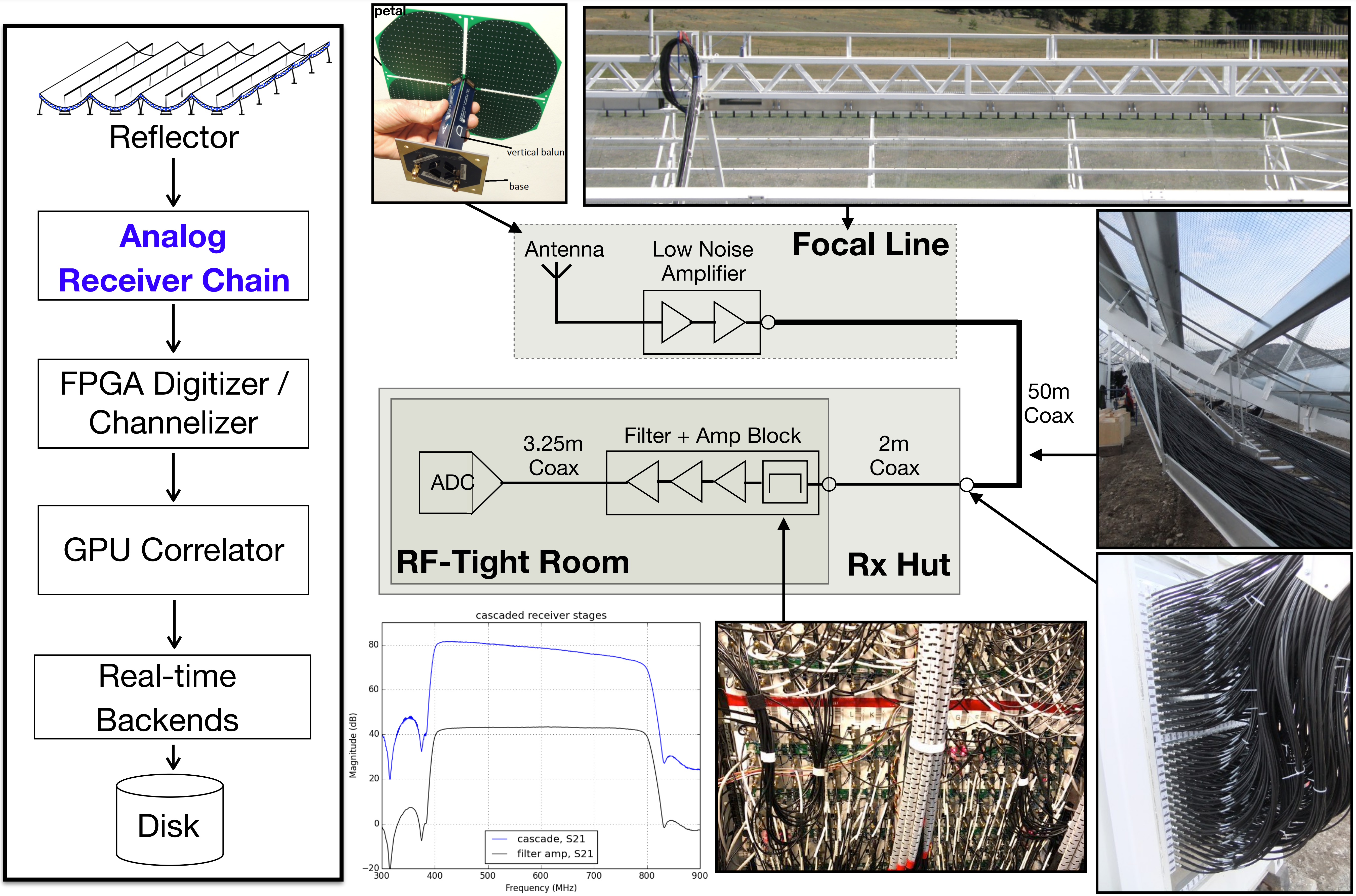
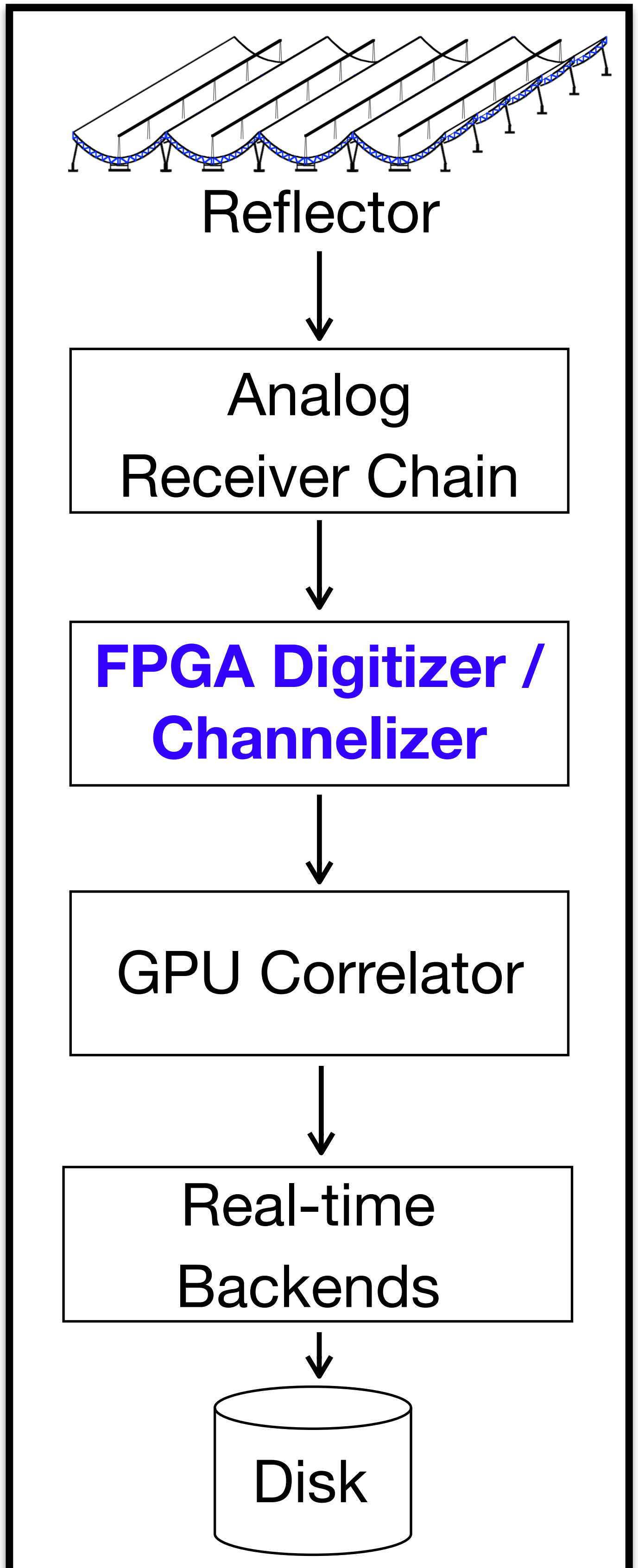
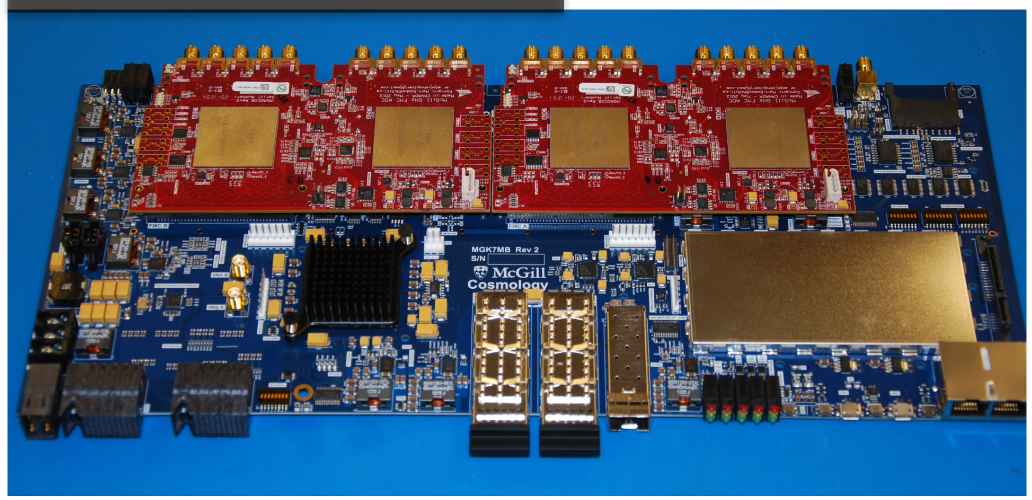
Analog Receiver Chain



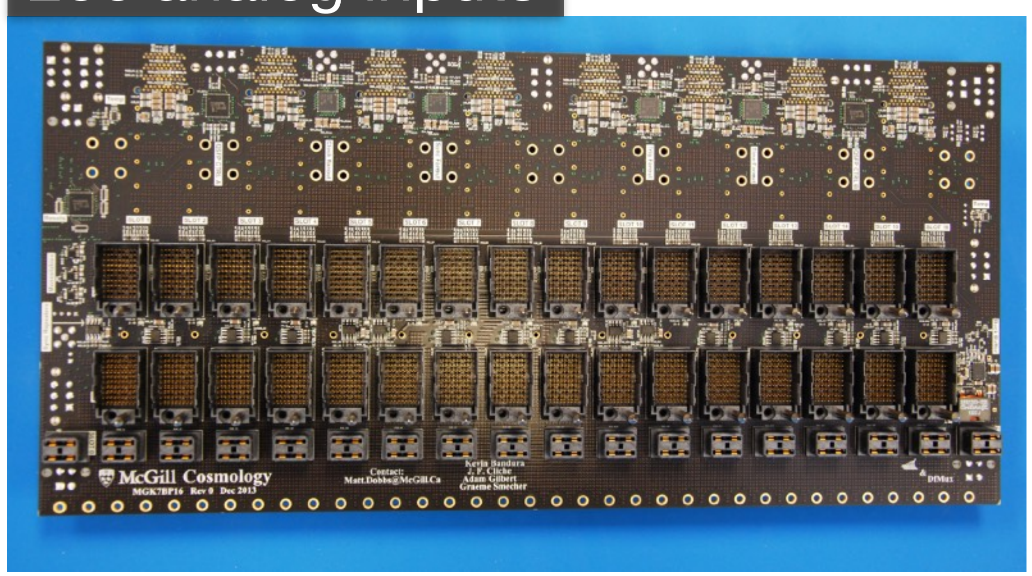
FPGA Digitizer and Channelizer (F-Engine)

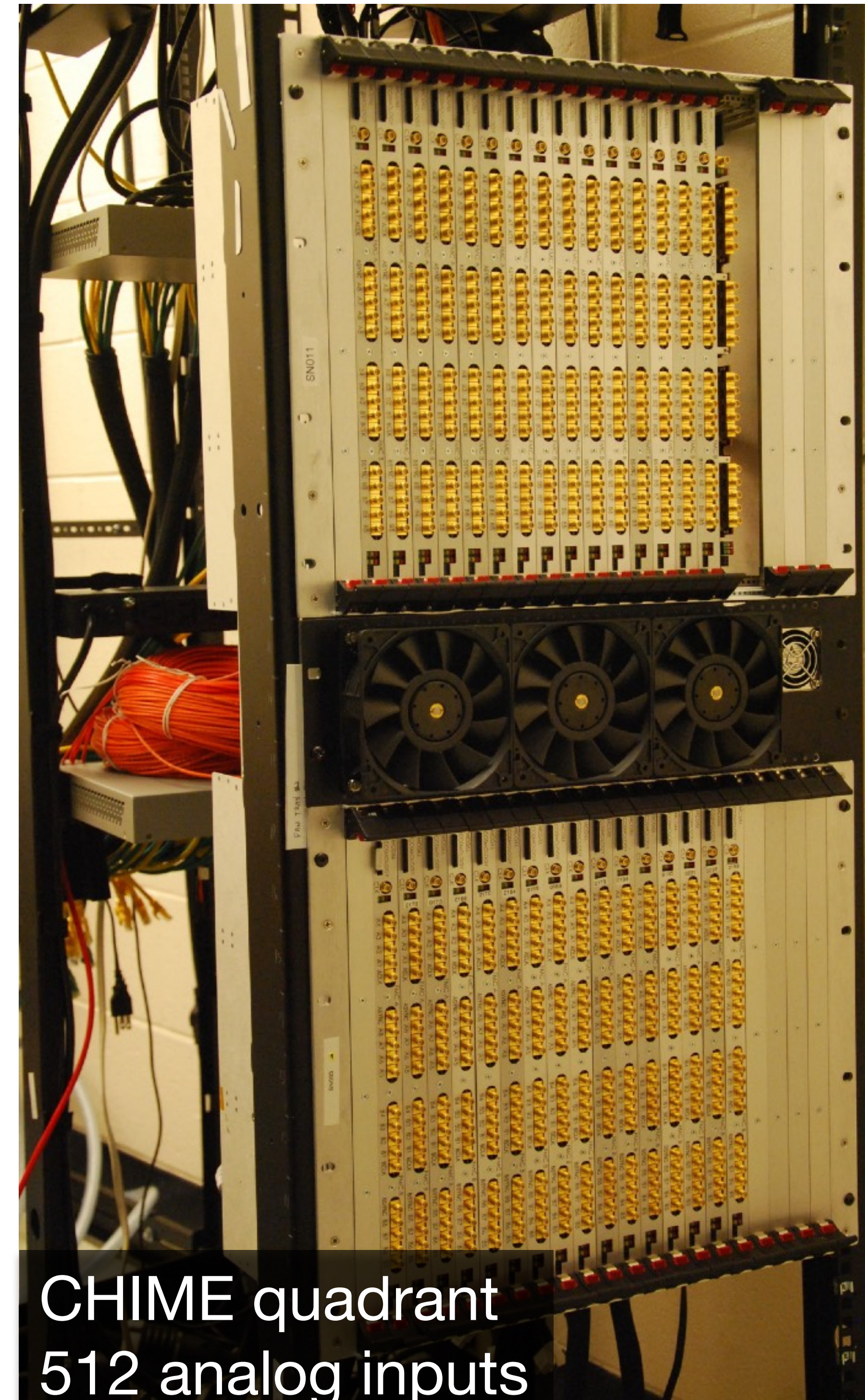


Motherboard
16 analog inputs



Backplane
256 analog inputs

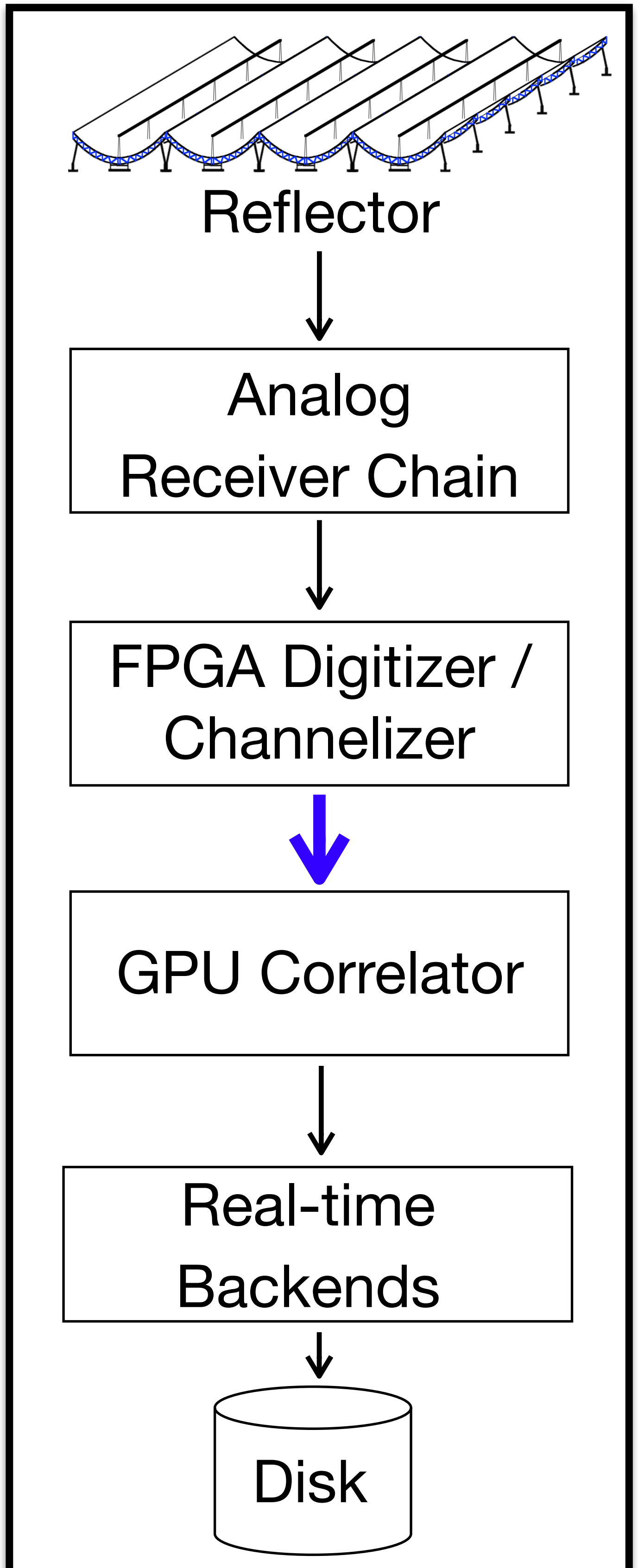


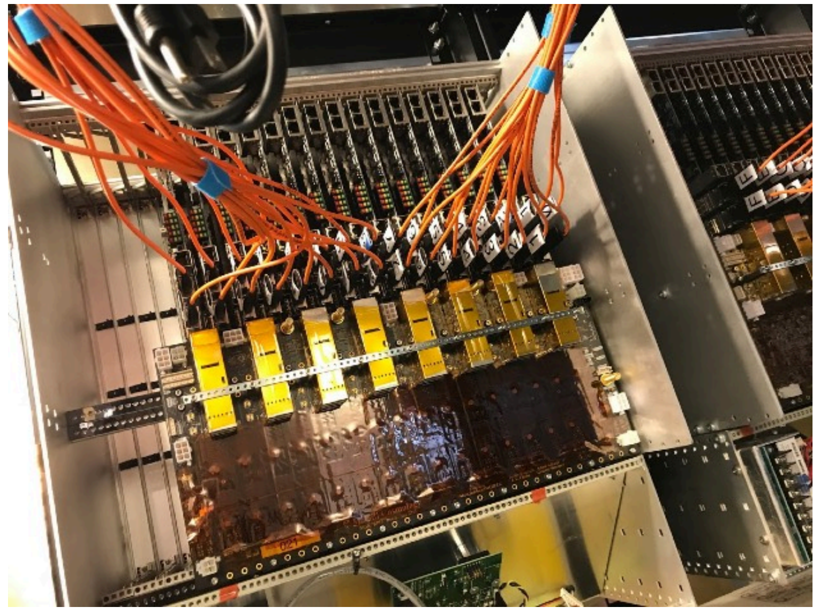


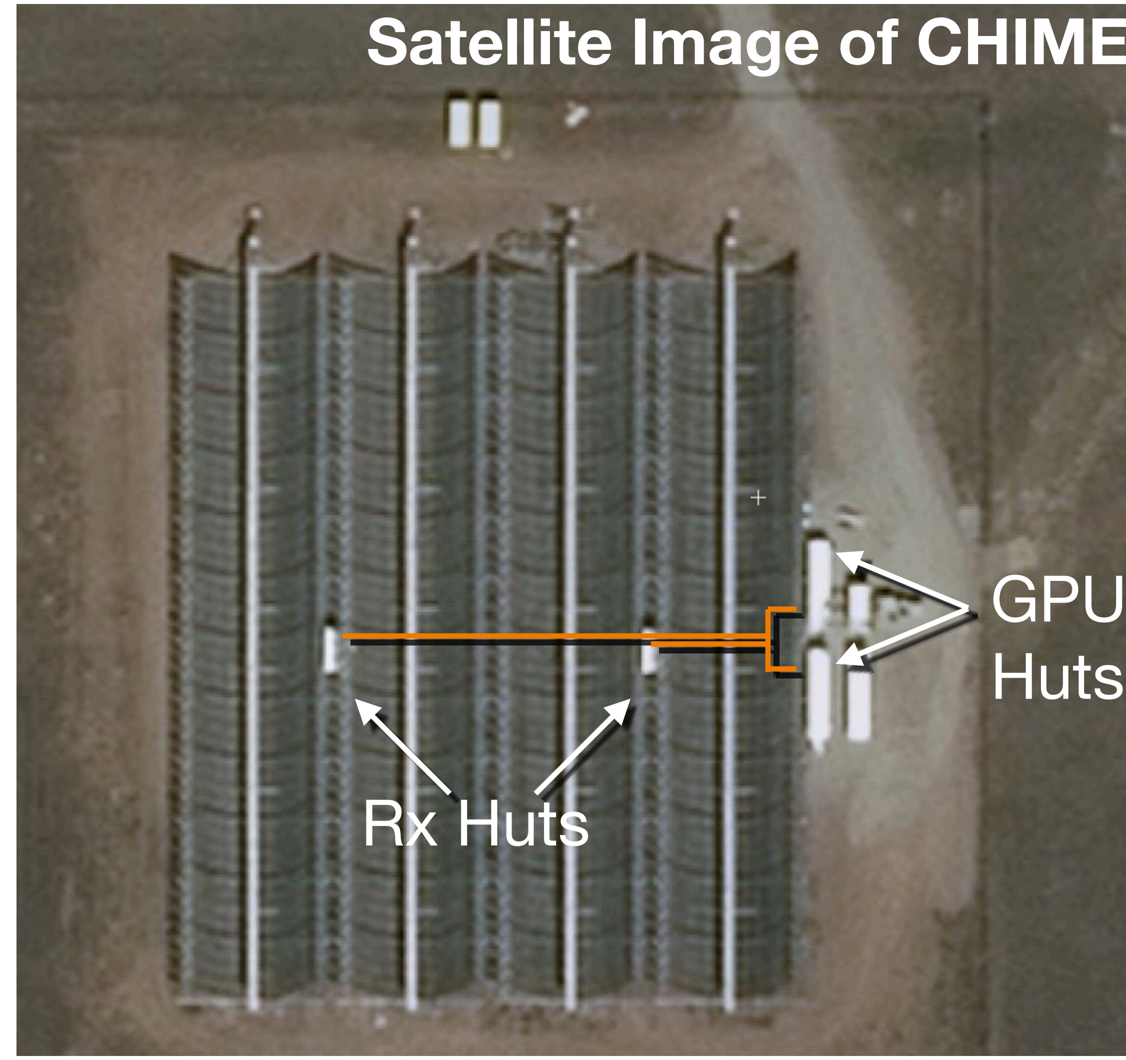
CHIME quadrant
512 analog inputs

Bandura et al. 2016, JAI

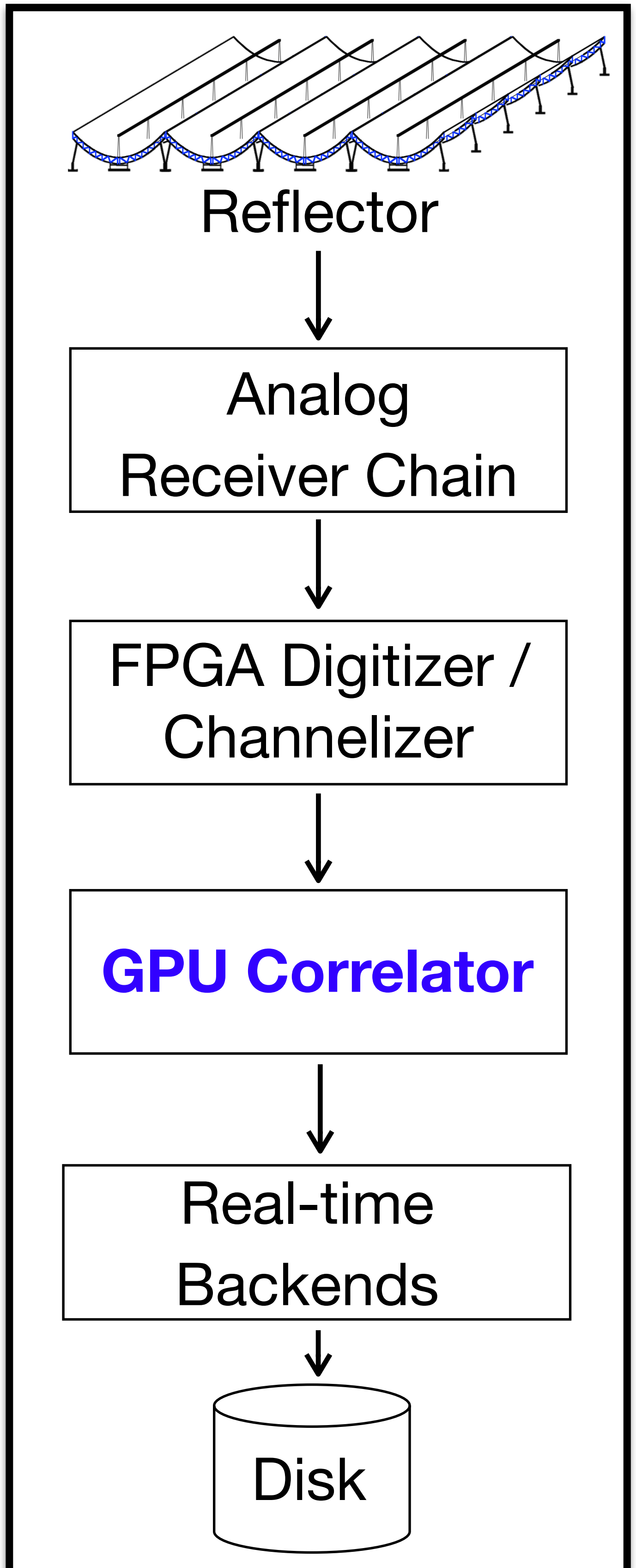
10 Gbit/s Link over Optical Fiber (x1024)

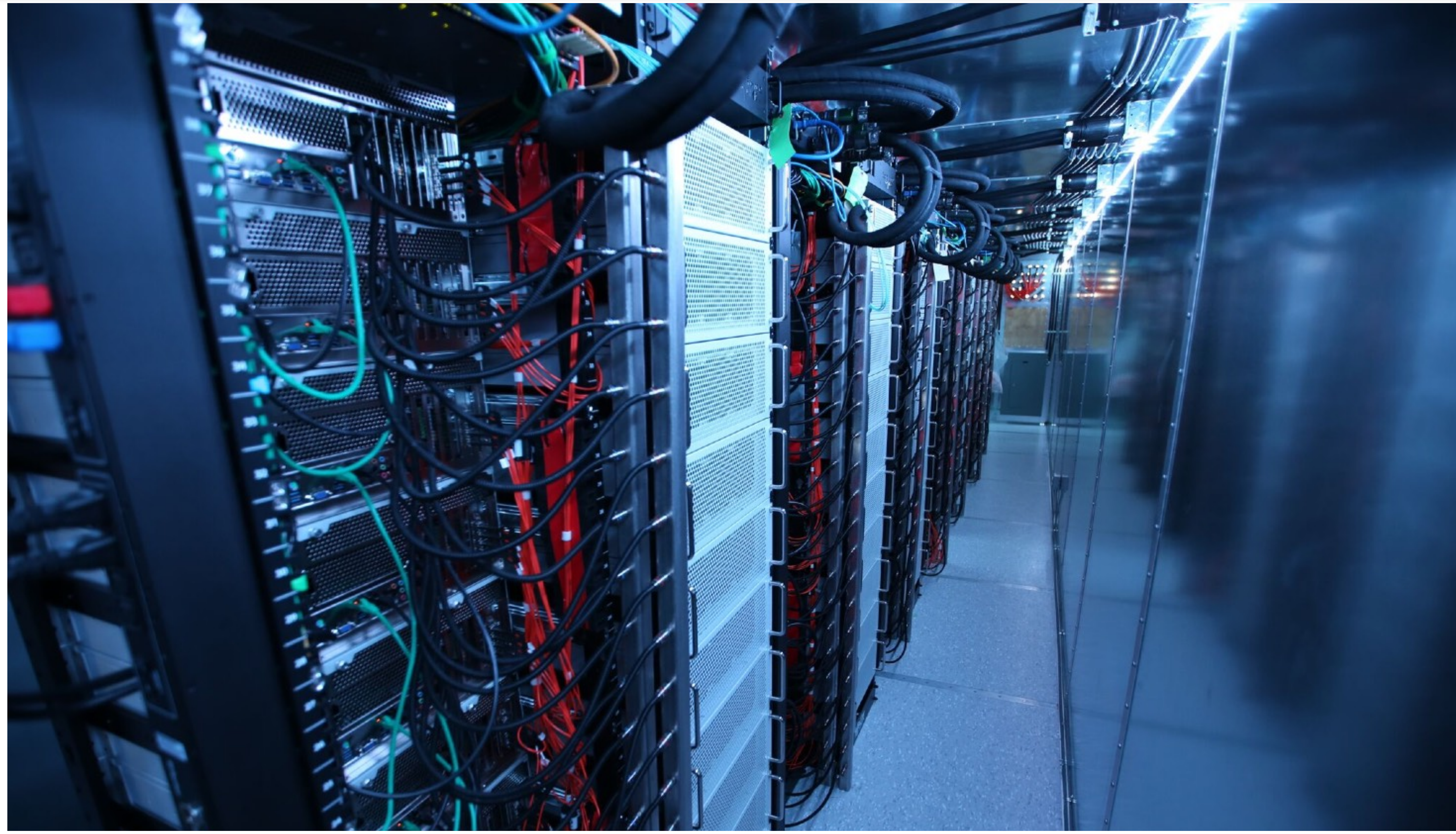




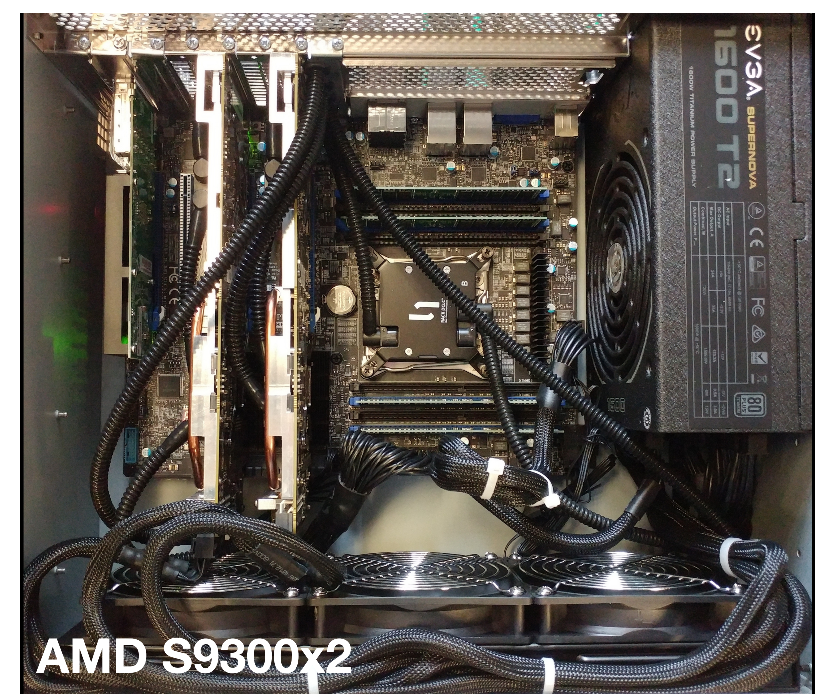


GPU Correlator (X-Engine)

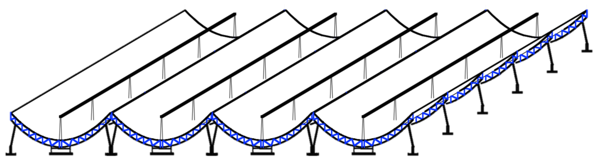





Denman et al. 2015



Backends



Reflector

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Analog Receiver Chain

↓

FPGA Digitizer / Channelizer

↓

GPU Correlator

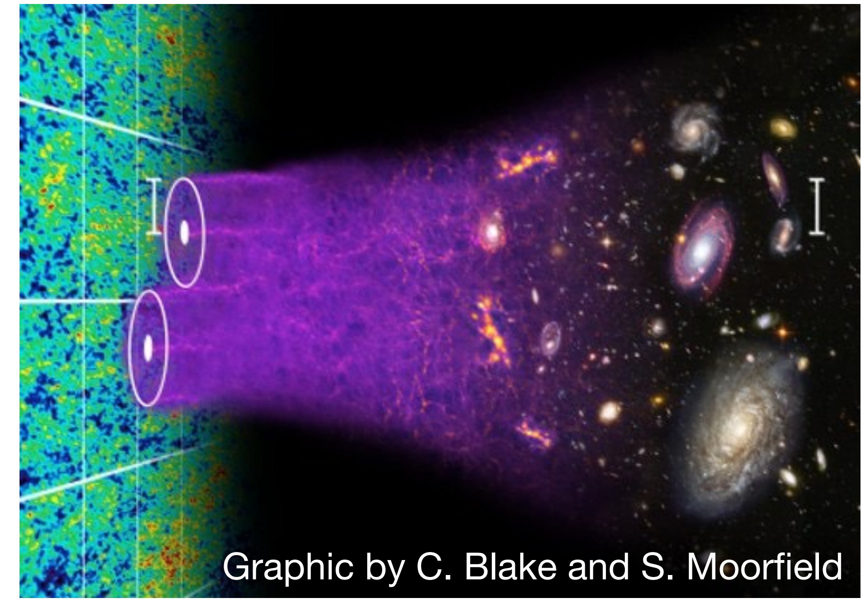
↓

Real-time Backends

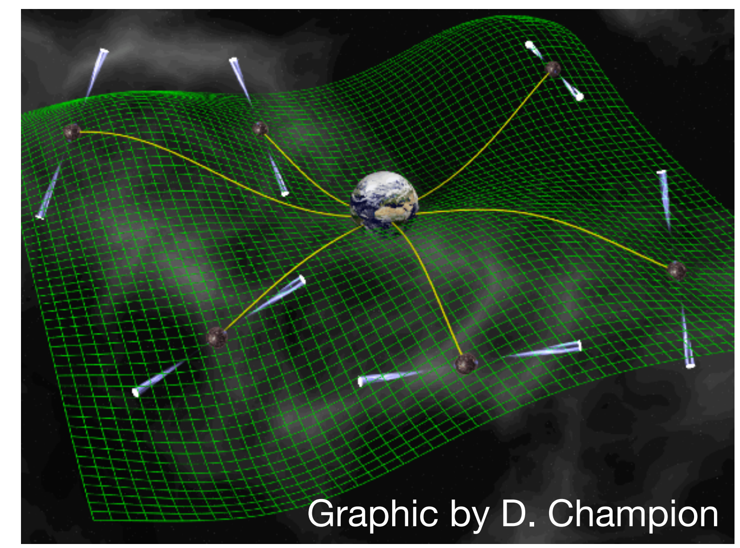
↓

Disk

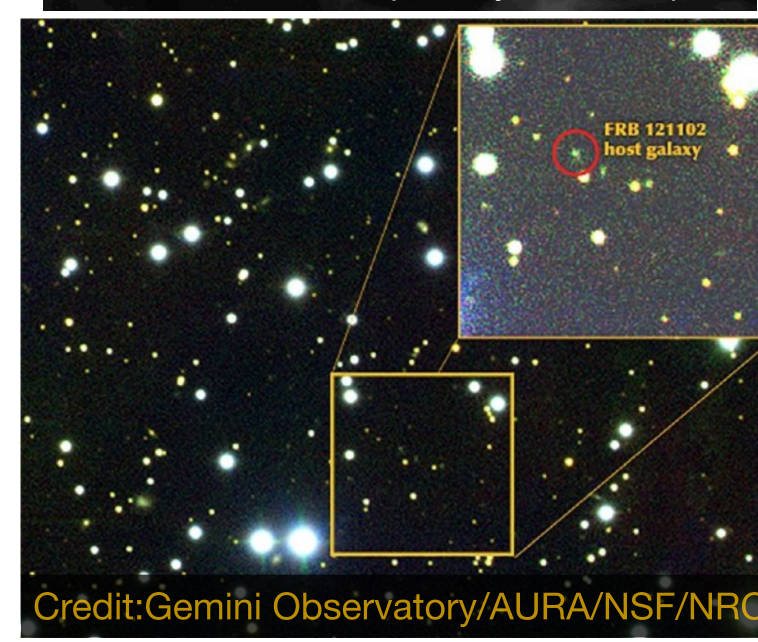
- **Cosmology**
  - Full N^2 visibility matrix
  - 10 sec cadence
  - 135 TB/day
  - Real time flagging and gain calibration
  - Data compression through redundant baselines (0.5 TB/day)
- **Pulsar timing**
  - 10 steerable beams
  - 2.56 μs cadence
- **Fast Radio Burst**
  - 1024 stationary beams
  - 1 msec cadence
  - 16k frequency bins



Graphic by C. Blake and S. Moorfield



Graphic by D. Champion



Credit:Gemini Observatory/AURA/NSF/NRC

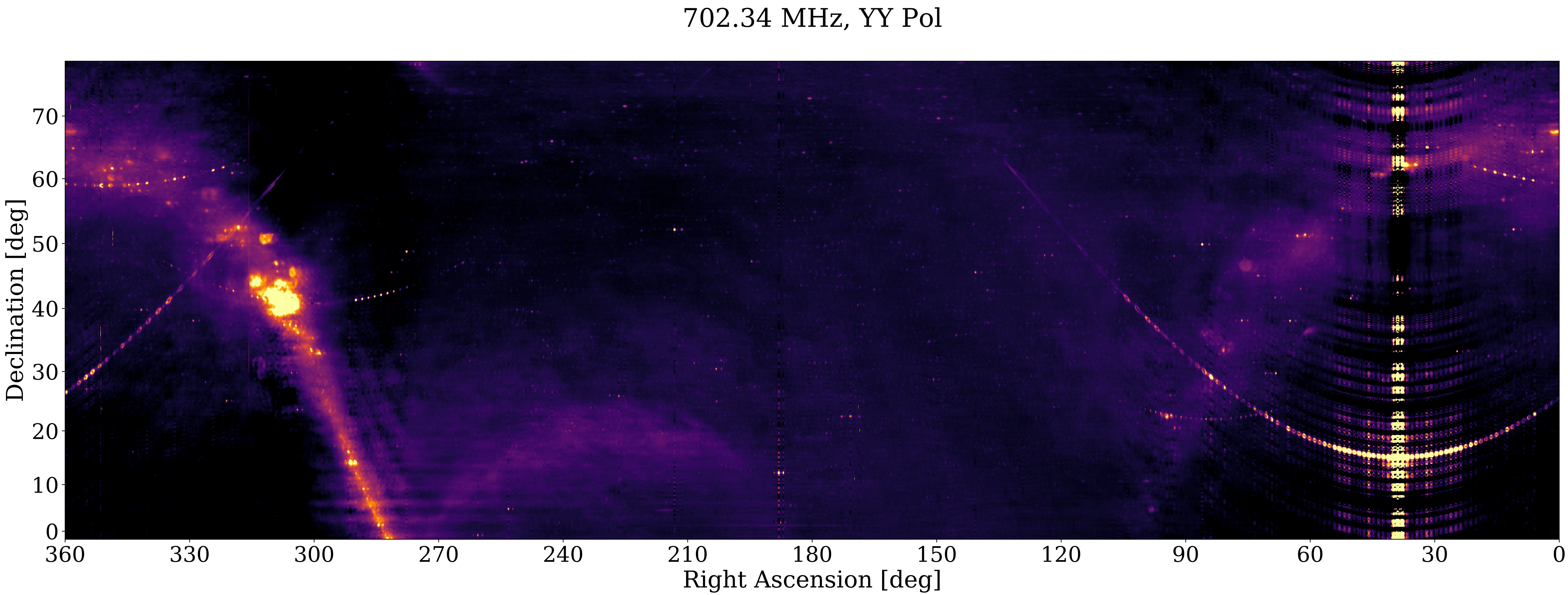
Status

- First light ceremony on September 7, 2017
- Commissioning throughout Winter 2018
- Began collecting science data on March 27, 2018
  - Compression through truncation:
    - Saving 25% of all frequency bins
      - Frequencies with minimal RFI contamination covering 630 - 790 MHz
    - Saving 25% of all baselines
      - $|u_{ew}| \leq 22$m and $|u_{ns}| \leq 20$ m
  - Also writing N^2 data to disk for 4 frequency bins to aid in development of real-time flagging, calibration, and compression algorithms.
- Expect to be at full capacity by October 2018

Efficiency During First Science Run

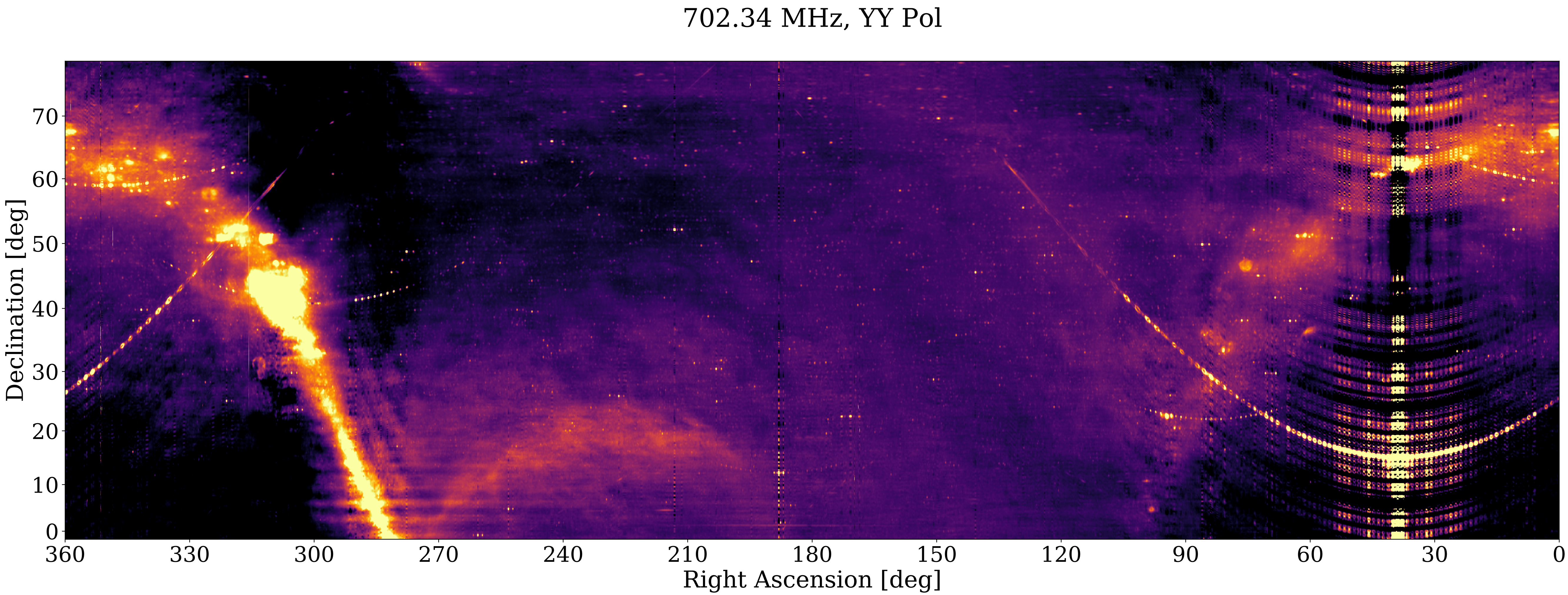
	Number	Total	Fraction
Analog Inputs	1900	2048	93%
Frequency Bins	868	1024	85%
Uptime	49 days	64 days	77%

Radio Sky as seen by CHIME



"Dirty ring map" generated from a single sidereal day of CHIME N^2 data for a single frequency bin and single polarization (0.025% of total data).

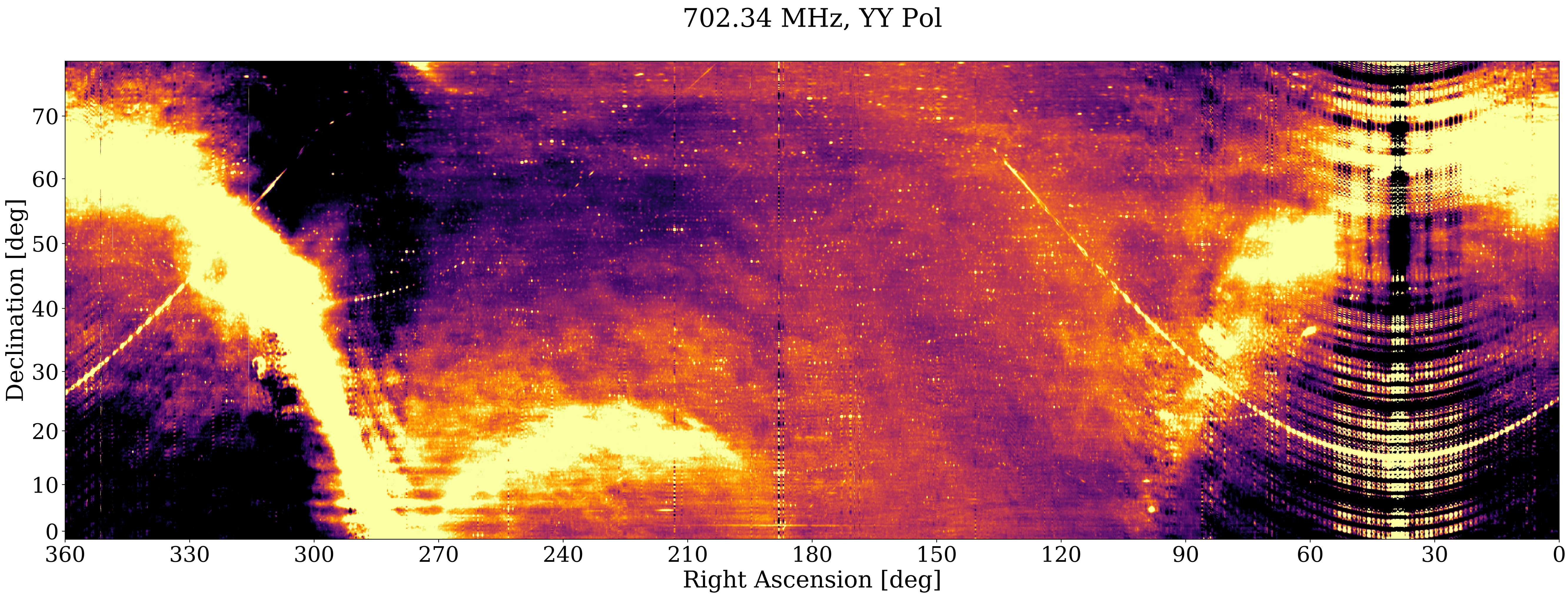
Radio Sky as seen by CHIME



“Dirty ring map” generated from a single sidereal day of CHIME N^2 data for a single frequency bin and single polarization (0.025% of total data).

Color scale compressed by a factor of 2.5.

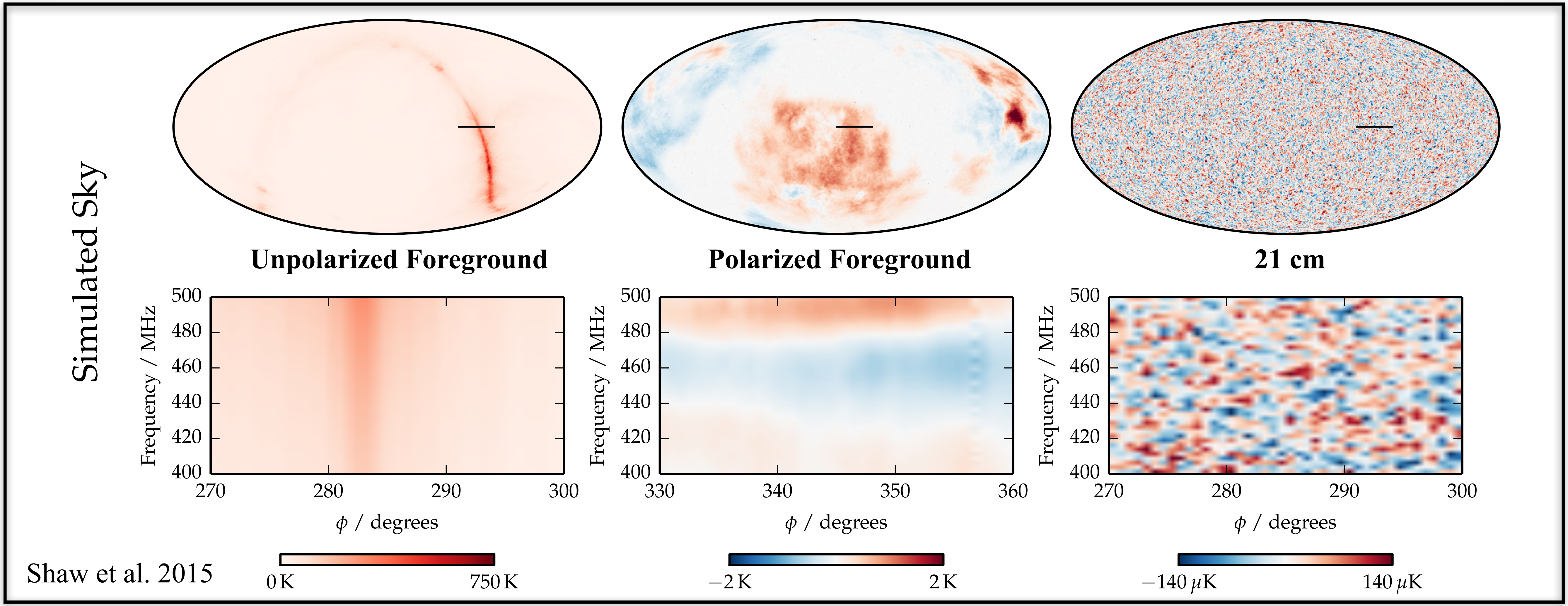
Radio Sky as seen by CHIME



“Dirty ring map” generated from a single sidereal day of CHIME N^2 data for a single frequency bin and single polarization (0.025% of total data).

Color scale compressed by a factor of 10.

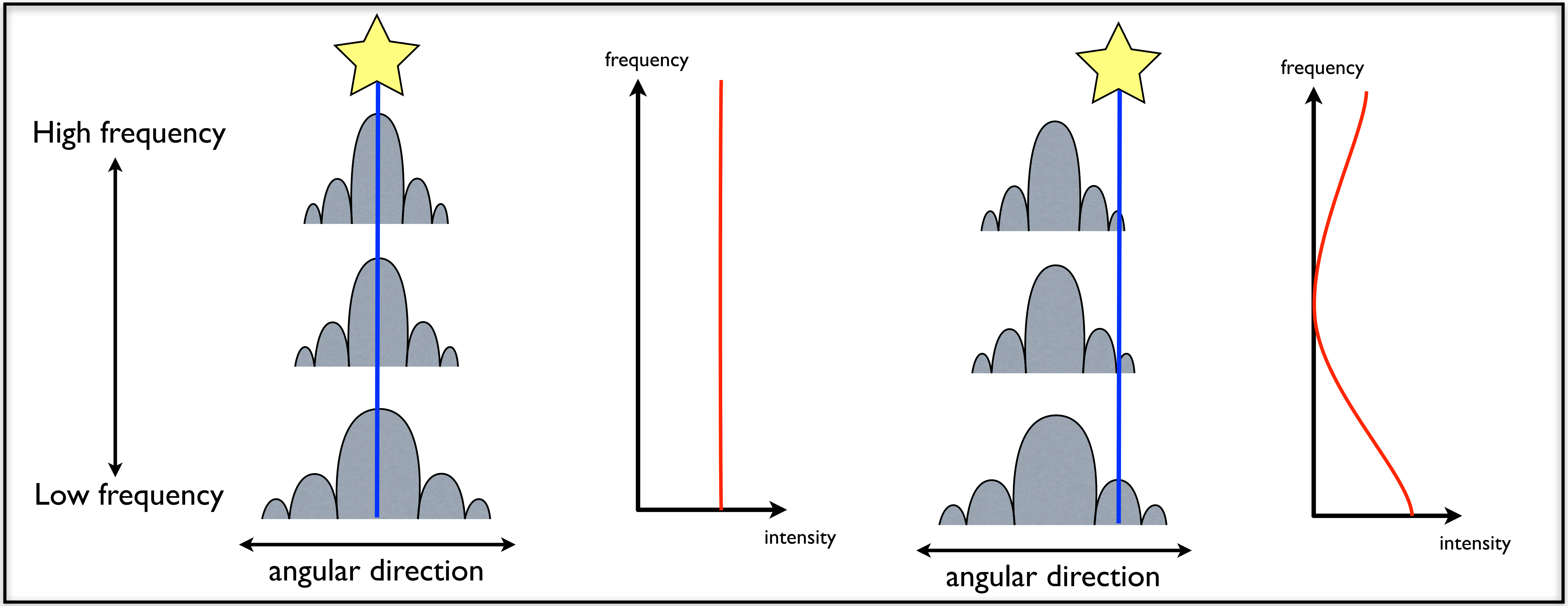
Foregrounds



- Foregrounds are 10^5 times brighter than the 21 cm signal.

- Foregrounds have a smooth spectrum, whereas the 21 cm signal varies rapidly with frequency because it originates from distinct structure along the line-of-sight direction.

Foregrounds



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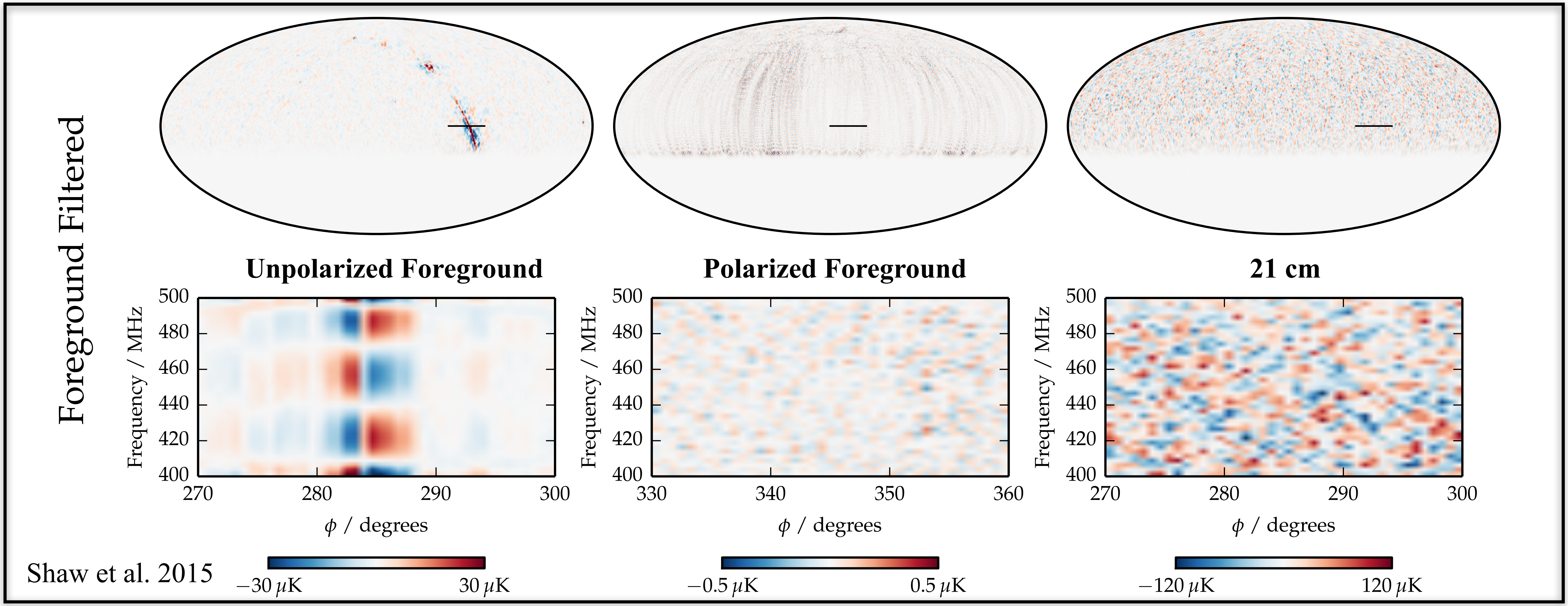
- Unfortunately, frequency dependent instrumental effects convert the bright foreground signal into small-scale spectral structure.

Foregrounds



- Foregrounds are 10^5 times brighter than the 21 cm signal.
- Foregrounds have a smooth spectrum, whereas the 21 cm signal varies rapidly with frequency because it originates from distinct structure along the line-of-sight direction.
- Unfortunately, frequency dependent instrumental effects convert the bright foreground signal into small-scale spectral structure.
- CHIME plans to characterize the transfer function of the instrument and construct optimal Karhunen-Loève filter that rotates measured data into signal/foreground modes.

Calibration Requirements

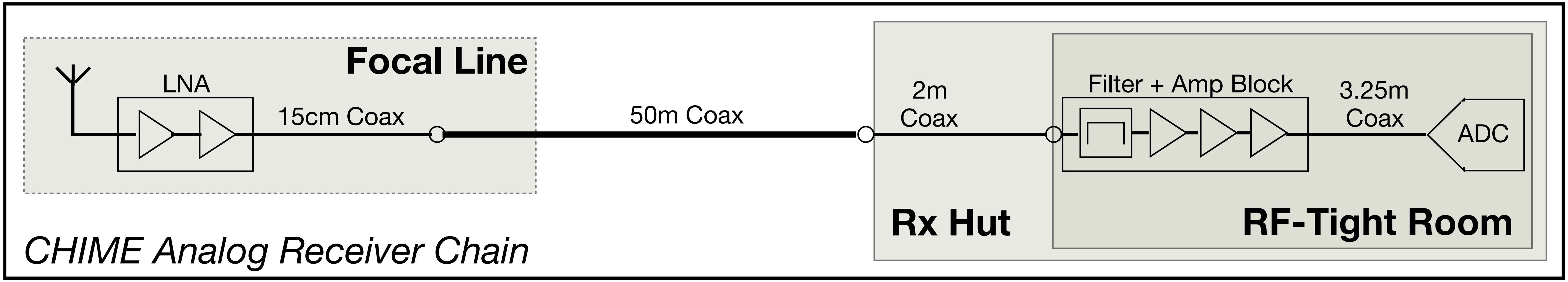
$$V_{ij}(t) =< E_i(t)E_j^*(t) >= g_i(t)g_j^*(t) \int d^2\hat{\mathbf{n}}\, A_i(\hat{\mathbf{n}})A_j^*(\hat{\mathbf{n}})e^{2\pi i\hat{\mathbf{n}}\cdot\mathbf{u}_{ij}}\, T(\hat{\mathbf{n}};t)$$

- **Complex gain calibration:** Need to know complex gain to better than 0.3% on timescales > 1 minute

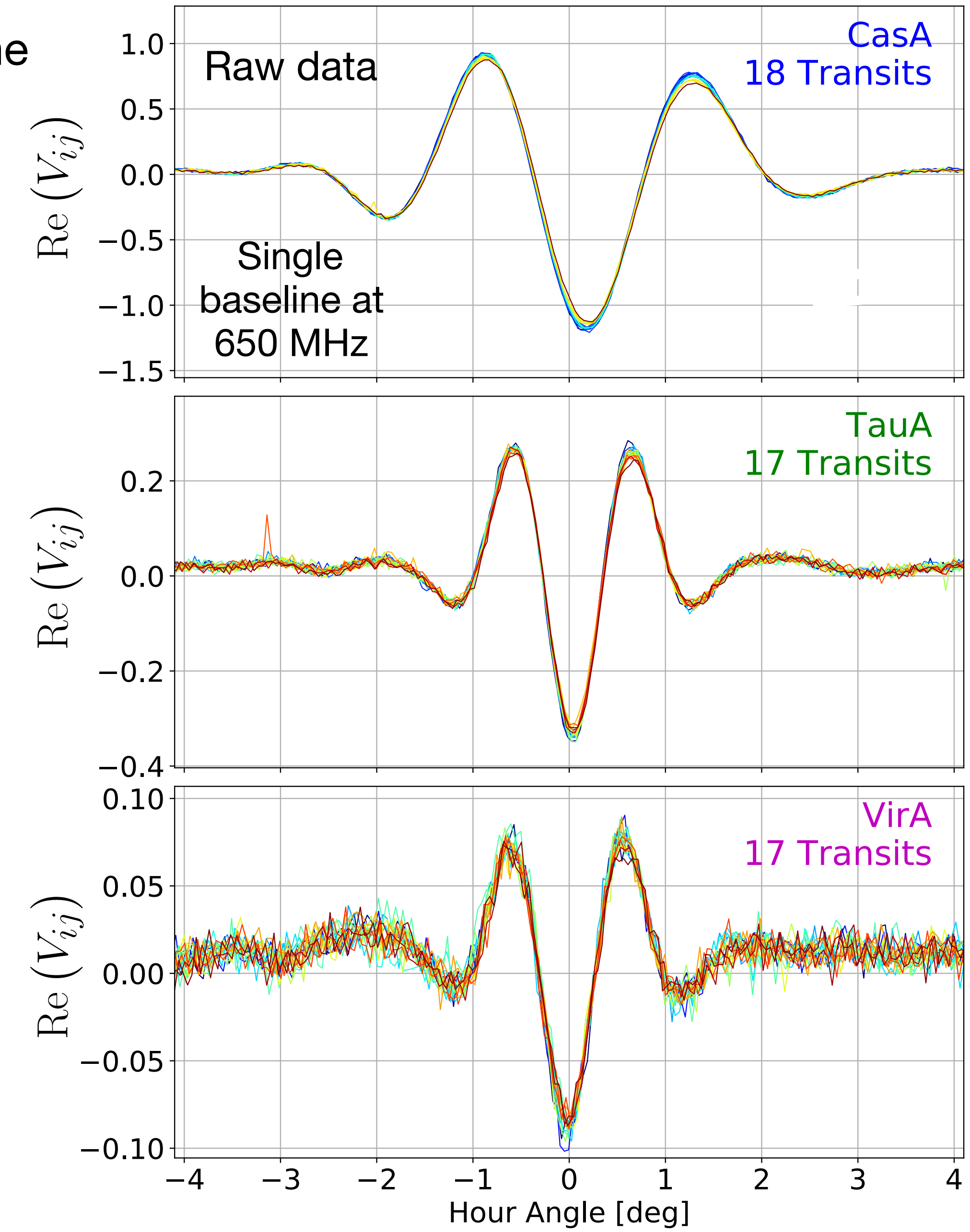
$$V_{ij}(t) =< E_i(t)E_j^*(t) >= g_i(t)g_j^*(t) \int d^2\hat{\mathbf{n}}\, A_i(\hat{\mathbf{n}})A_j^*(\hat{\mathbf{n}})e^{2\pi i\hat{\mathbf{n}}\cdot\mathbf{u}_{ij}}\, T(\hat{\mathbf{n}};t)$$

- **Beam calibration:** Need to know primary beam to better than 0.1%

Complex Gain Calibration



- Currently calibrate complex receiver gain once per sidereal day by using the full visibility matrix to solve for the response of each feed to a stable, radio-bright point source (Cygnus A, Cassiopeia A, or Taurus A).



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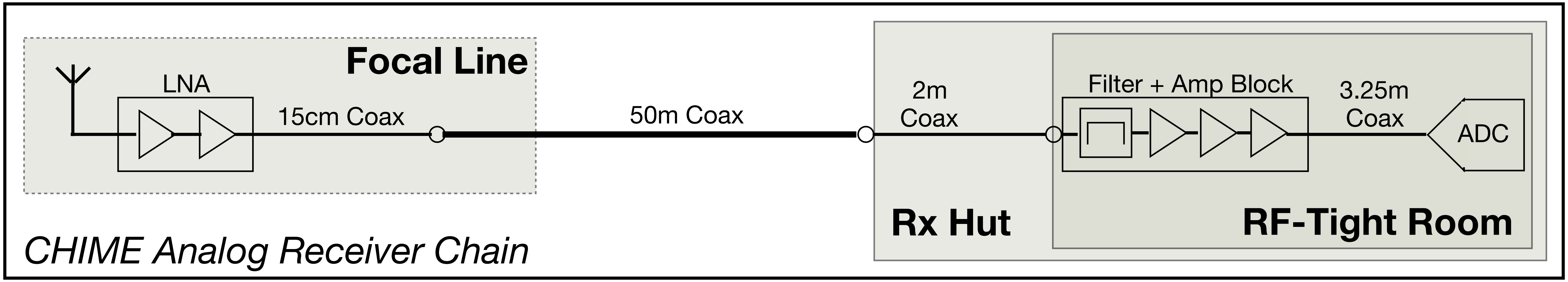

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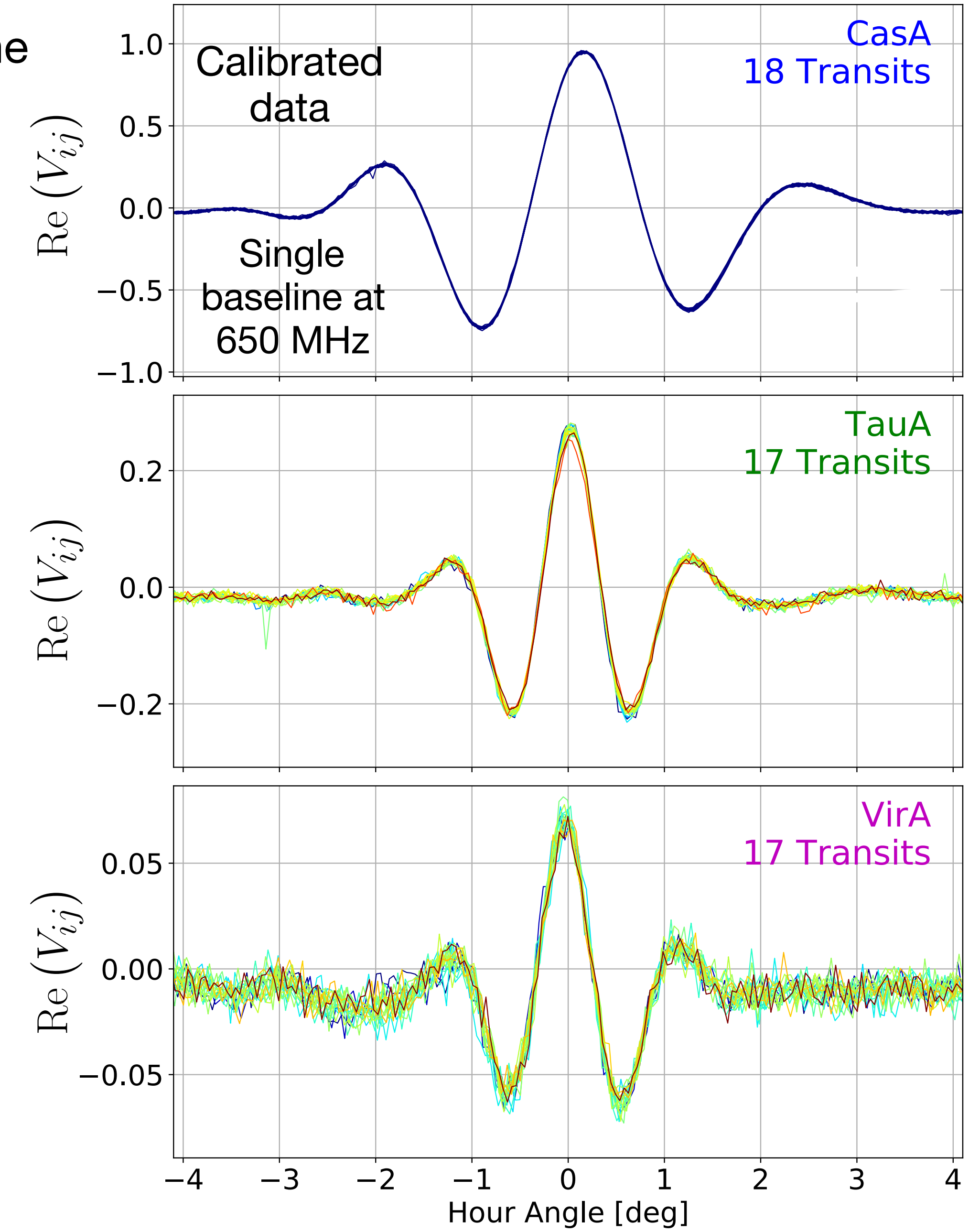
  - Results in amplitude stability at the 1% level and phase stability at the 0.01 radian level.



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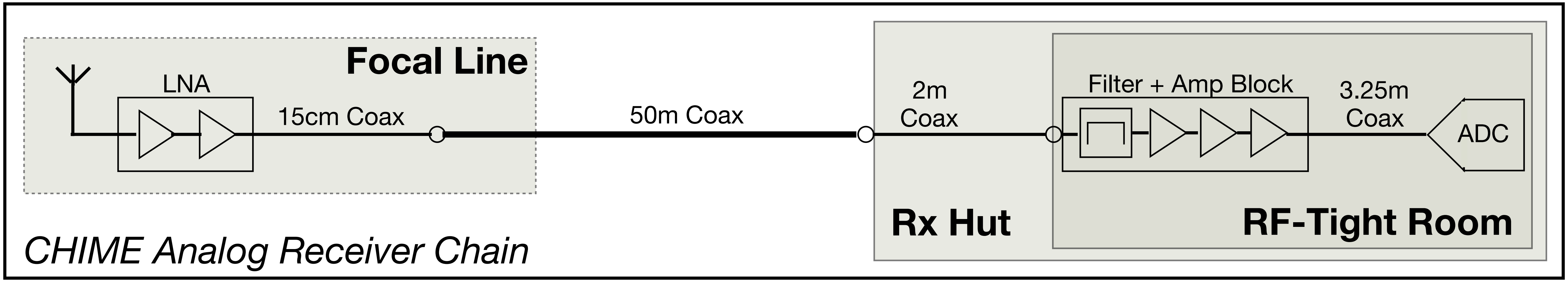

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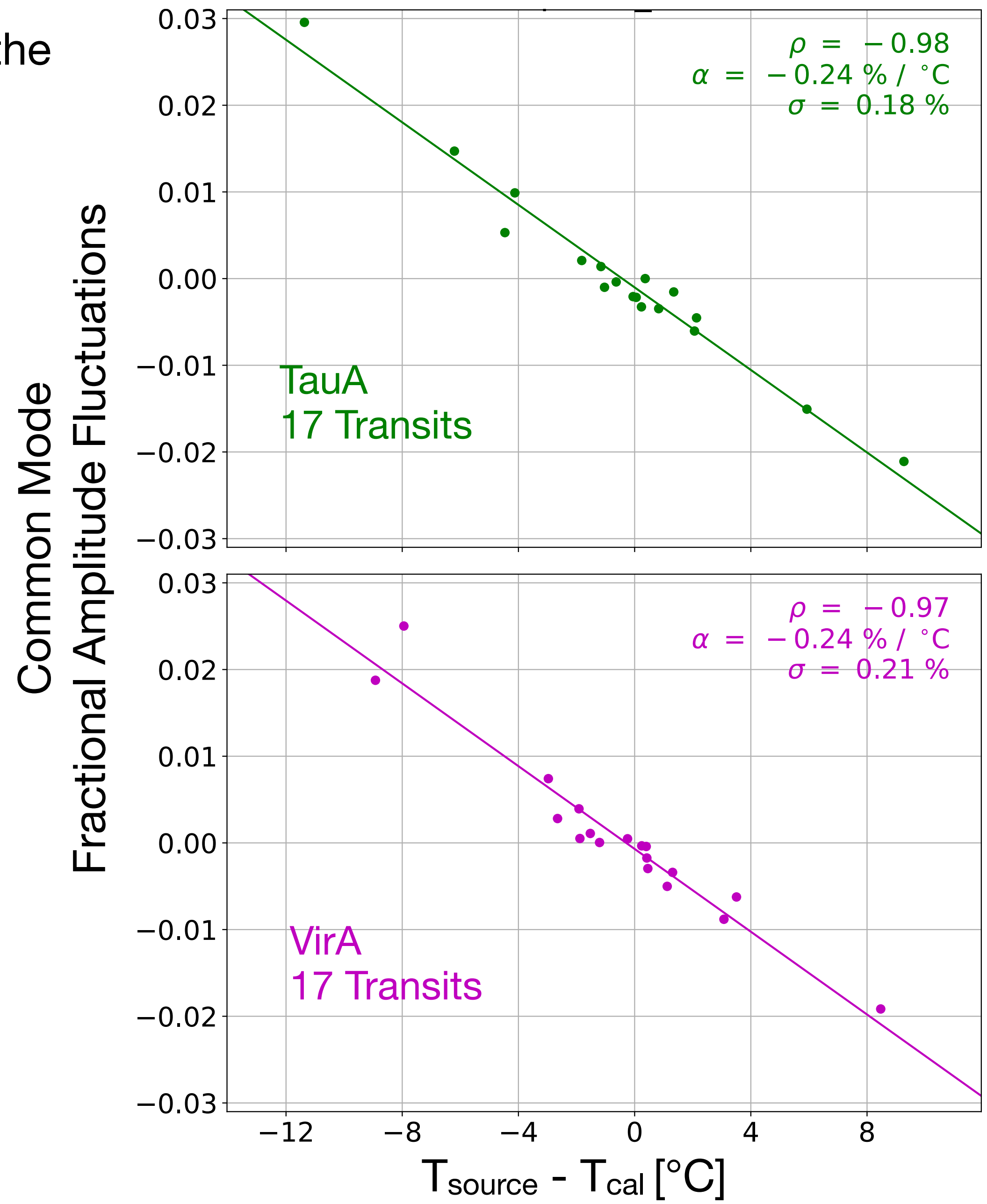
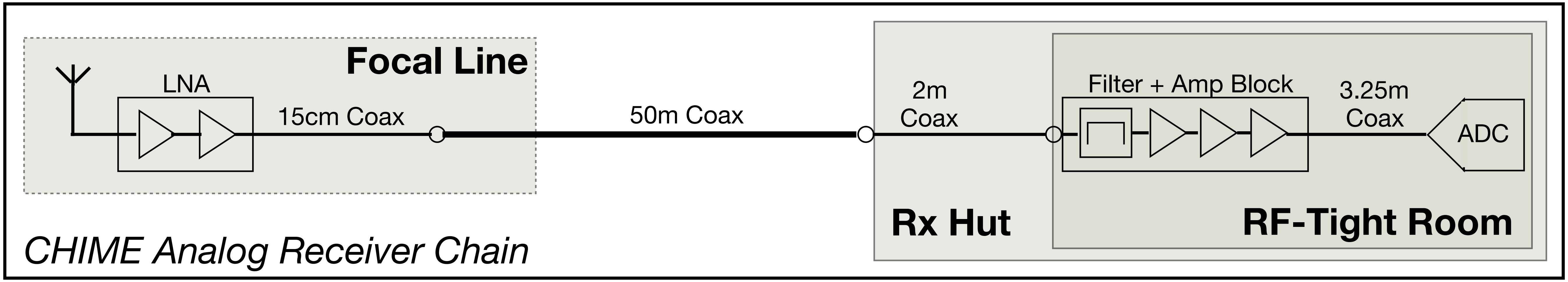
  - Results in amplitude stability at the 1% level and phase stability at the 0.01 radian level.
  - Most of the residual variation observed in amplitude is common mode (across feeds and frequency) and highly correlated with outside temperature.
    - Using a thermal model to interpolate between daily calibrator transits results in amplitude stability at the 0.5% level.



Complex Gain Calibration



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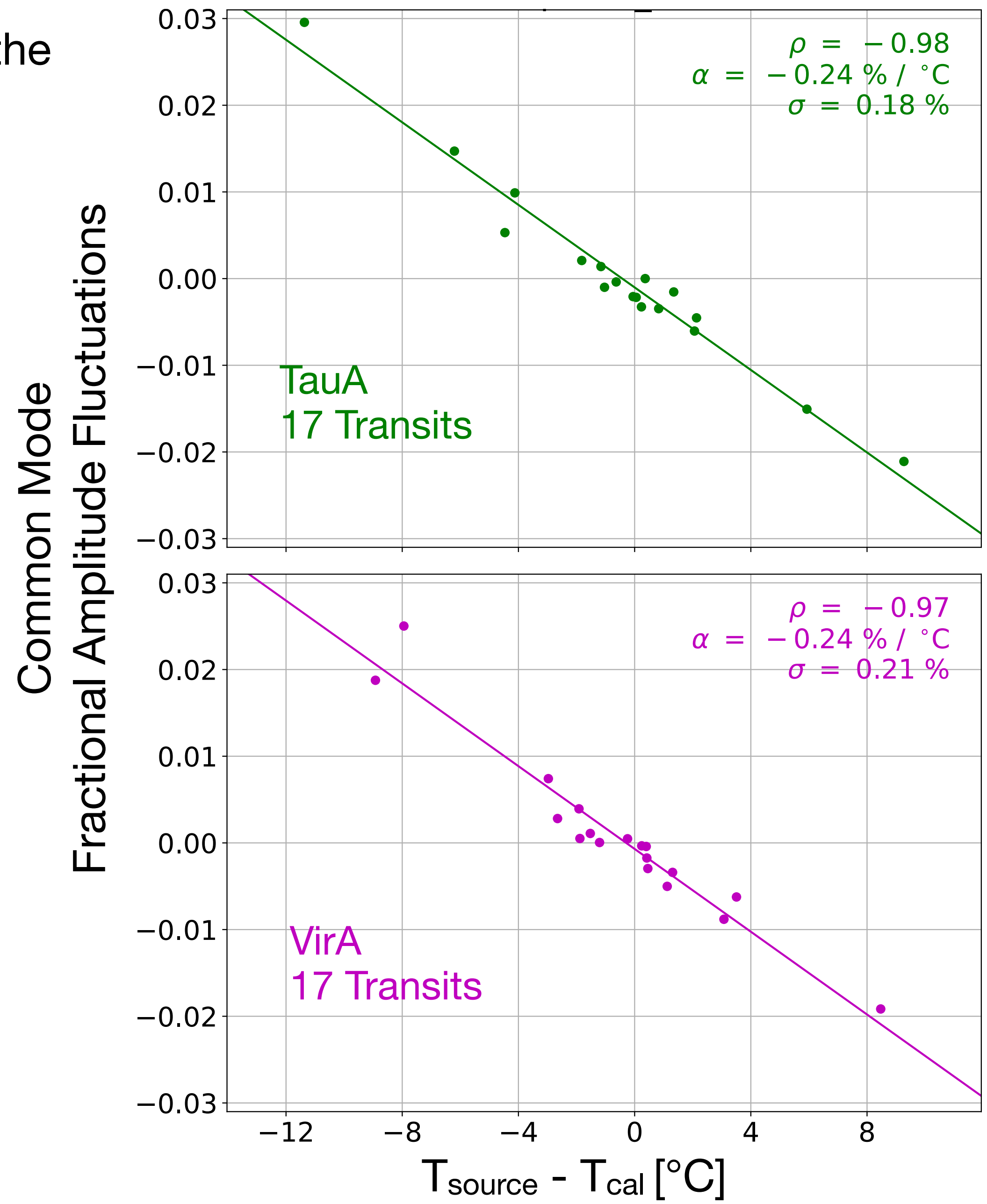
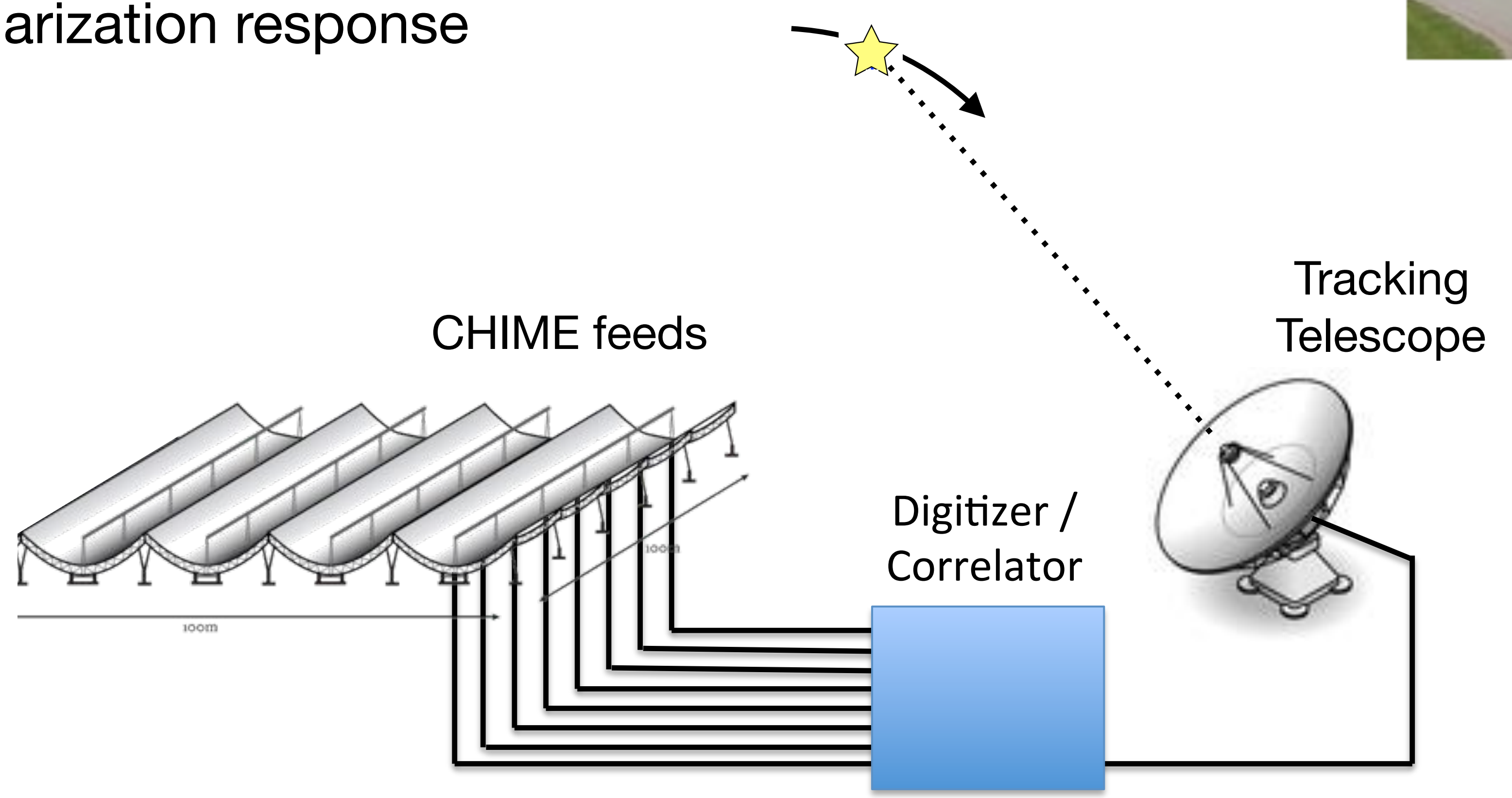


- To ensure systematic errors due to gain fluctuations are negligible compared to statistical errors, we require stability at < 0.3% (amplitude) and < 0.003 radians (phase).
  - Investigating receiver dependent thermal models and broadband signal injection techniques to further improve calibration.

Beam Calibration

- 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)

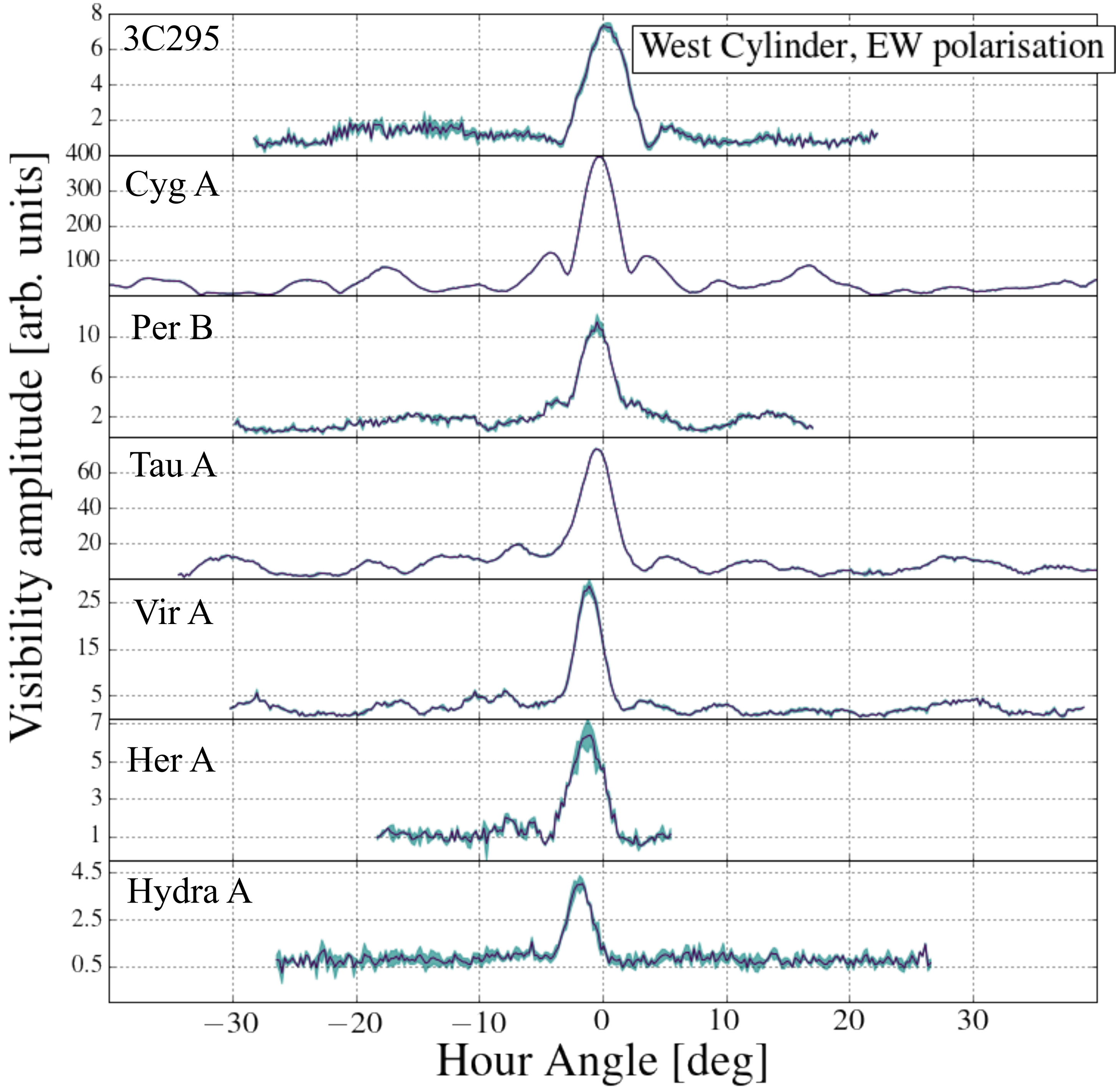
- Pulsar Holography
  - Subtract pulsar ON - pulsar OFF to remove common background sky
  - ~100 msec cadence; implement in GPU
  - Characterize polarization response



Newburgh et al. 2014
Berger et al. 2016

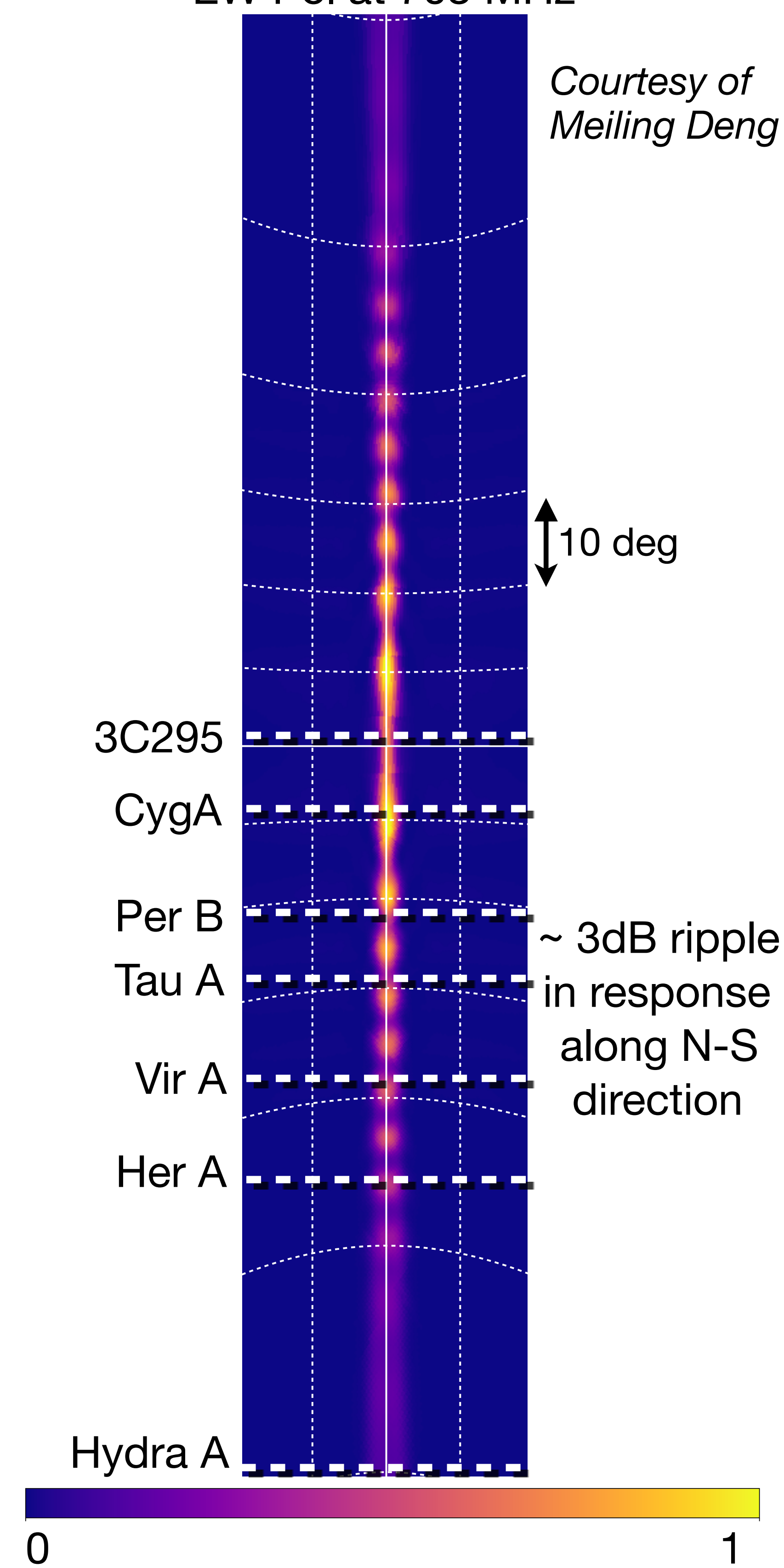
Beam Calibration

Pathfinder holography data
for a single EW Pol Feed



Berger et al. 2016

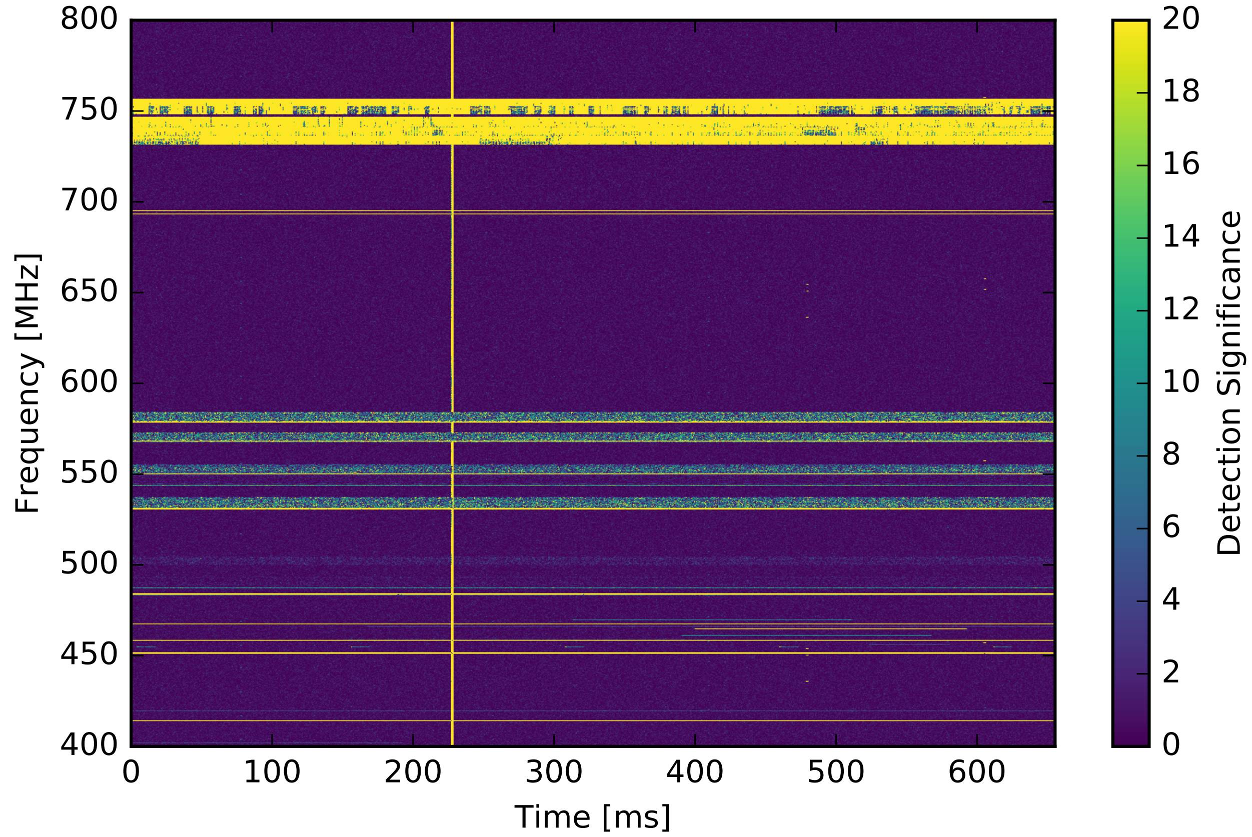
Simulated Beam
EW Pol at 703 MHz

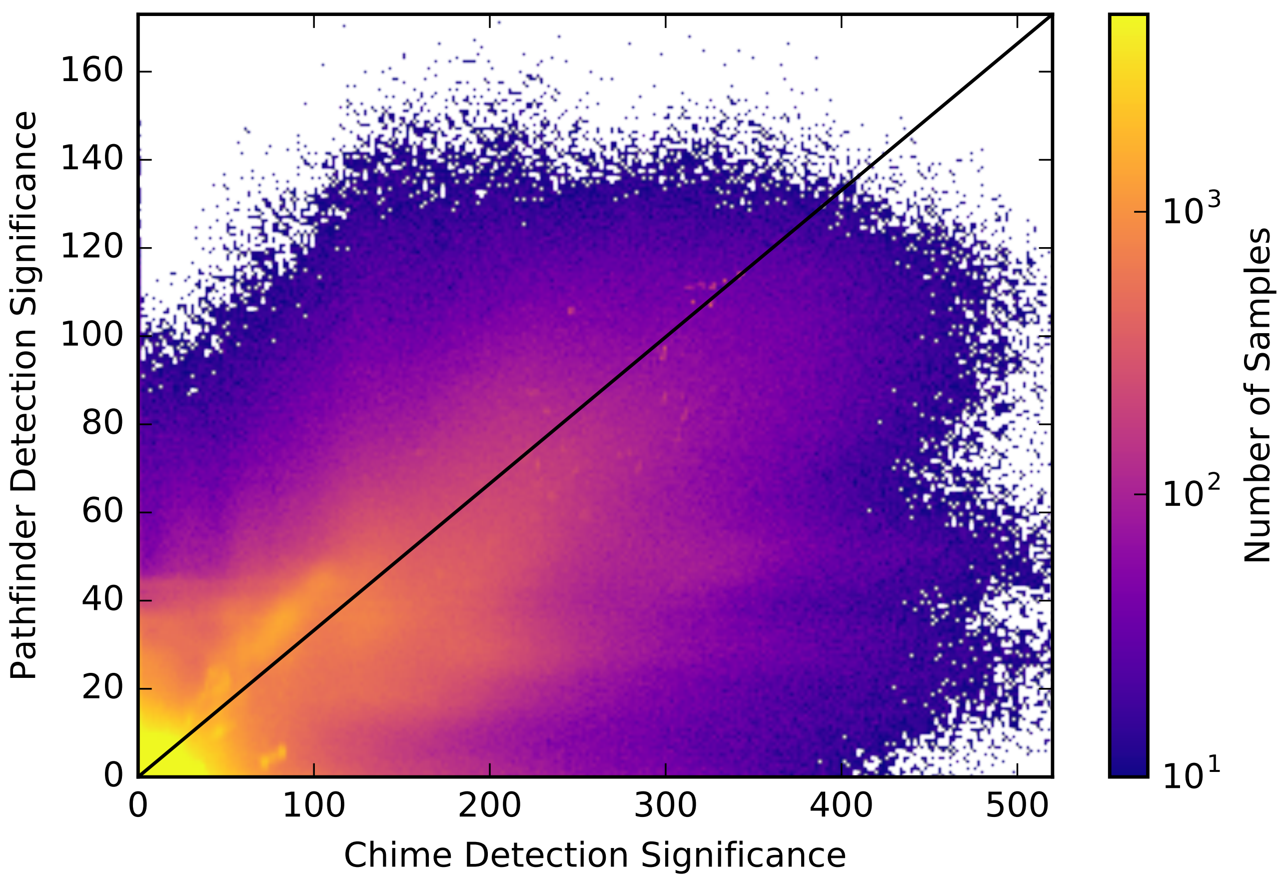


RFI Excision

- Spectral-Kurtosis based implementation of pre-correlation RFI excision using CHIME's GPU backend.
- Increase the sensitivity of the RFI removal by combining samples from CHIME's 2048 independent feeds.
- This extra sensitivity allows for sub-millisecond RFI discrimination to detect quick broadband RFI pulses.
- Comparison with CHIME's pathfinder concludes the discrimination power scales with the size of the array.

Taylor et al. 2018 (in prep)

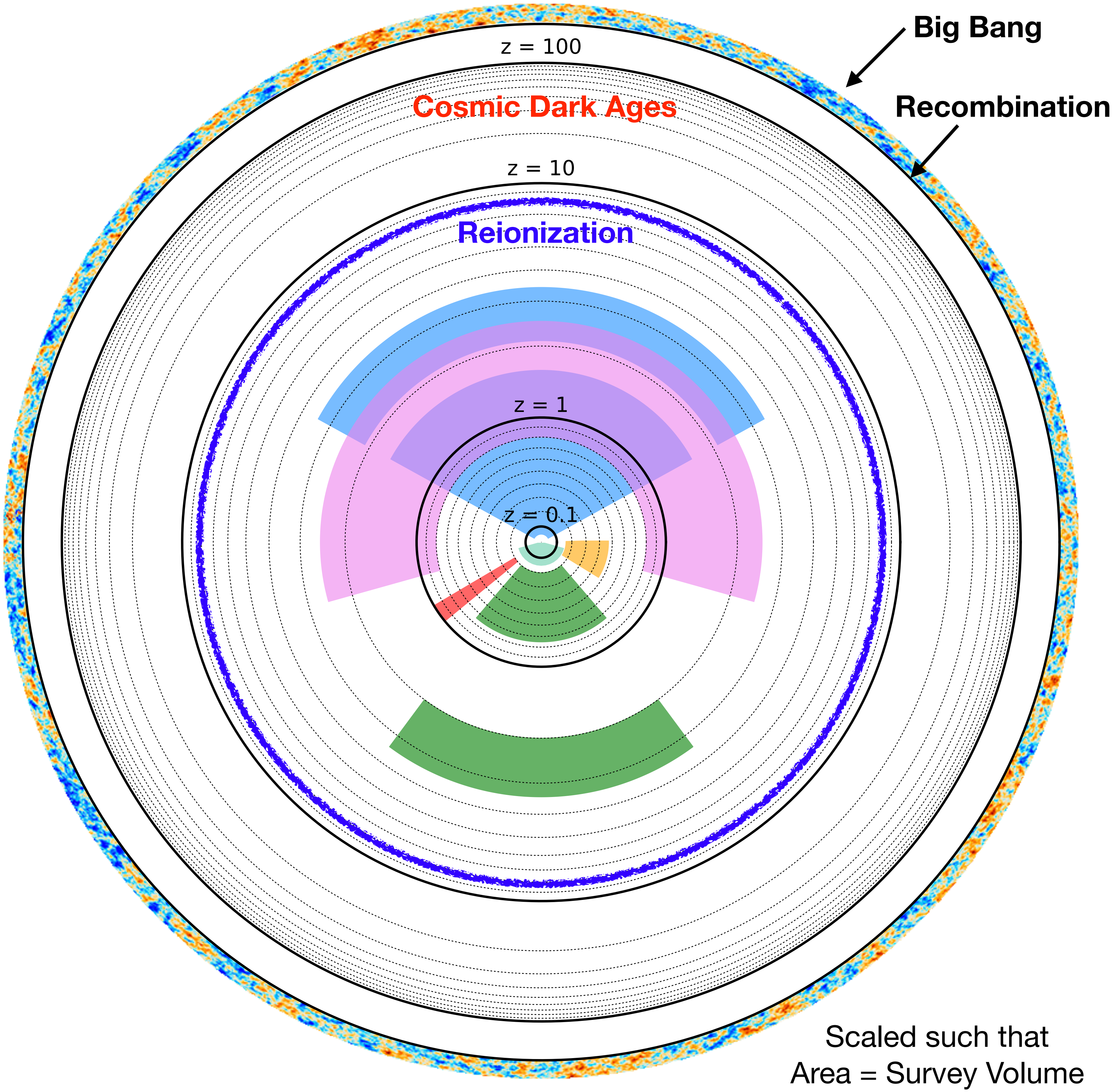




Slide courtesy of Jacob Taylor

Survey Volume

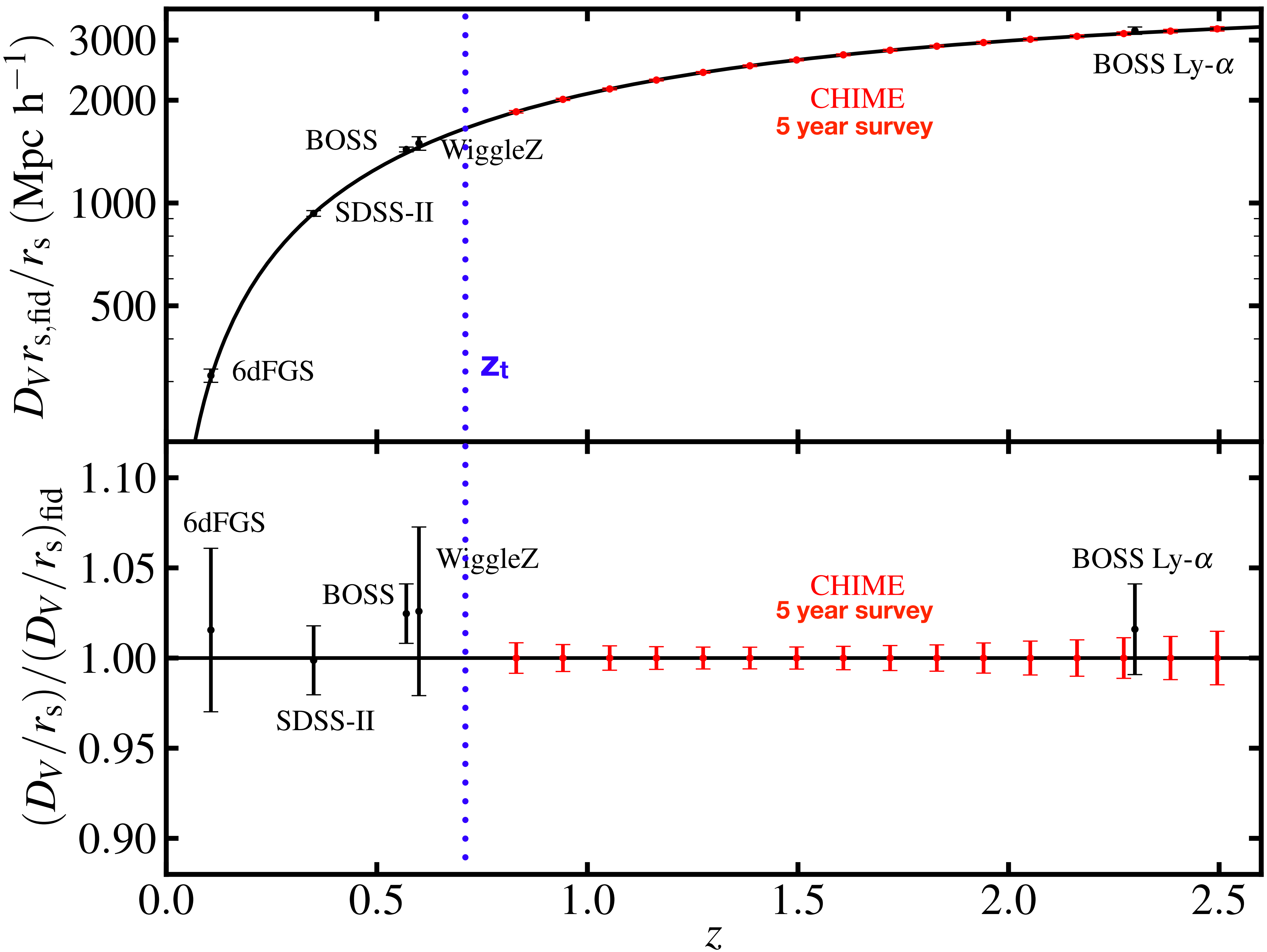
- **SDSS-II**
  - 2.2 Gpc^3
- **6dFGS**
  - 0.4 Gpc^3
- **WiggleZ**
  - 3.8 Gpc^3
- **BOSS**
  - LRG: 20 Gpc^3
  - Ly-α: 150 Gpc^3
- **DESI (2019 - 2024)**
  - LRG/ELG: 140 Gpc^3
  - Ly-α: 230 Gpc^3
- **CHIME (2018 - 2023)**
  - 470 Gpc^3



Scaled such that
Area = Survey Volume

Cosmology Forecast

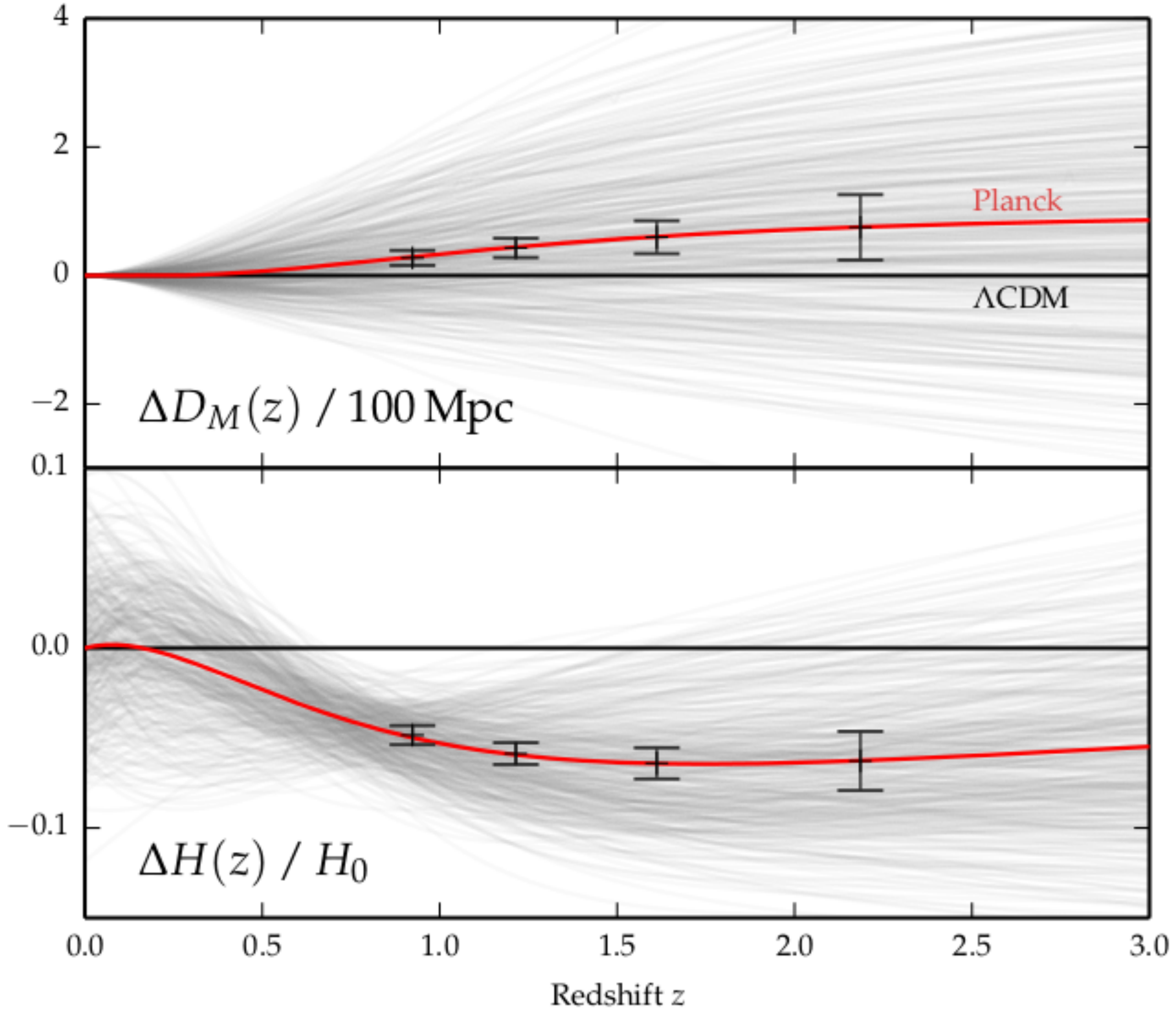
Figure courtesy of Kevin Bandura

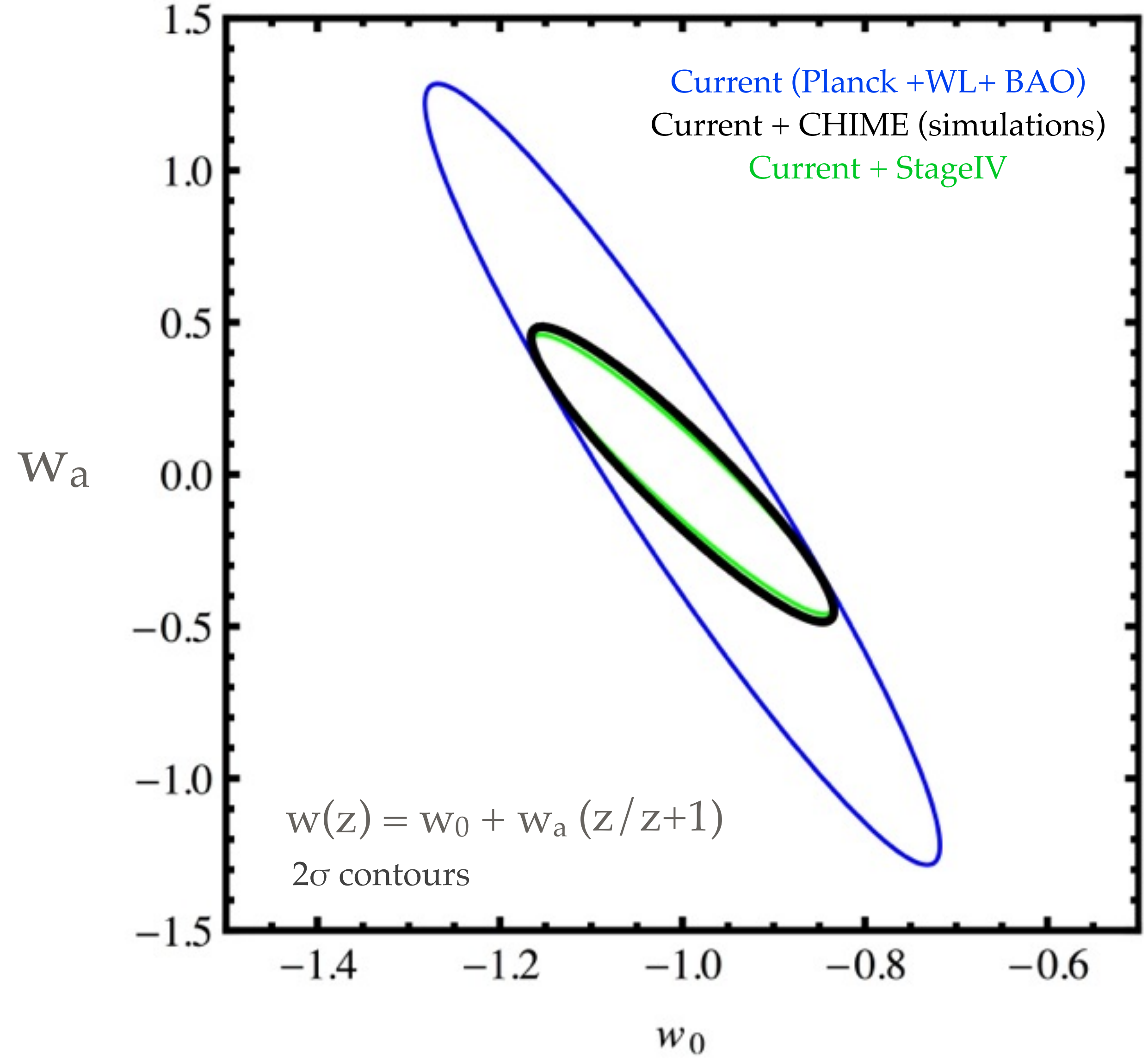


Cosmology Forecast

Dark energy equation of state: w = p / ρ

Figures courtesy of Richard Shaw



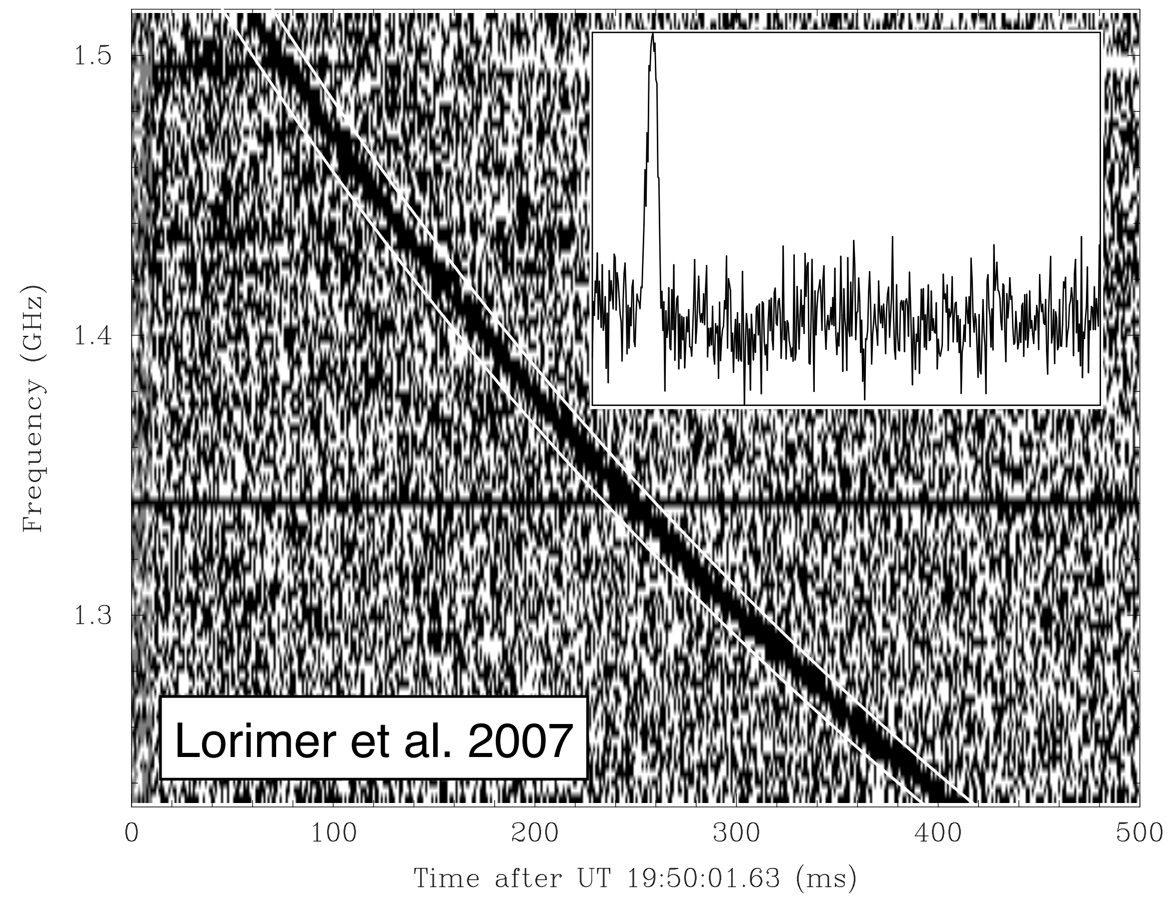


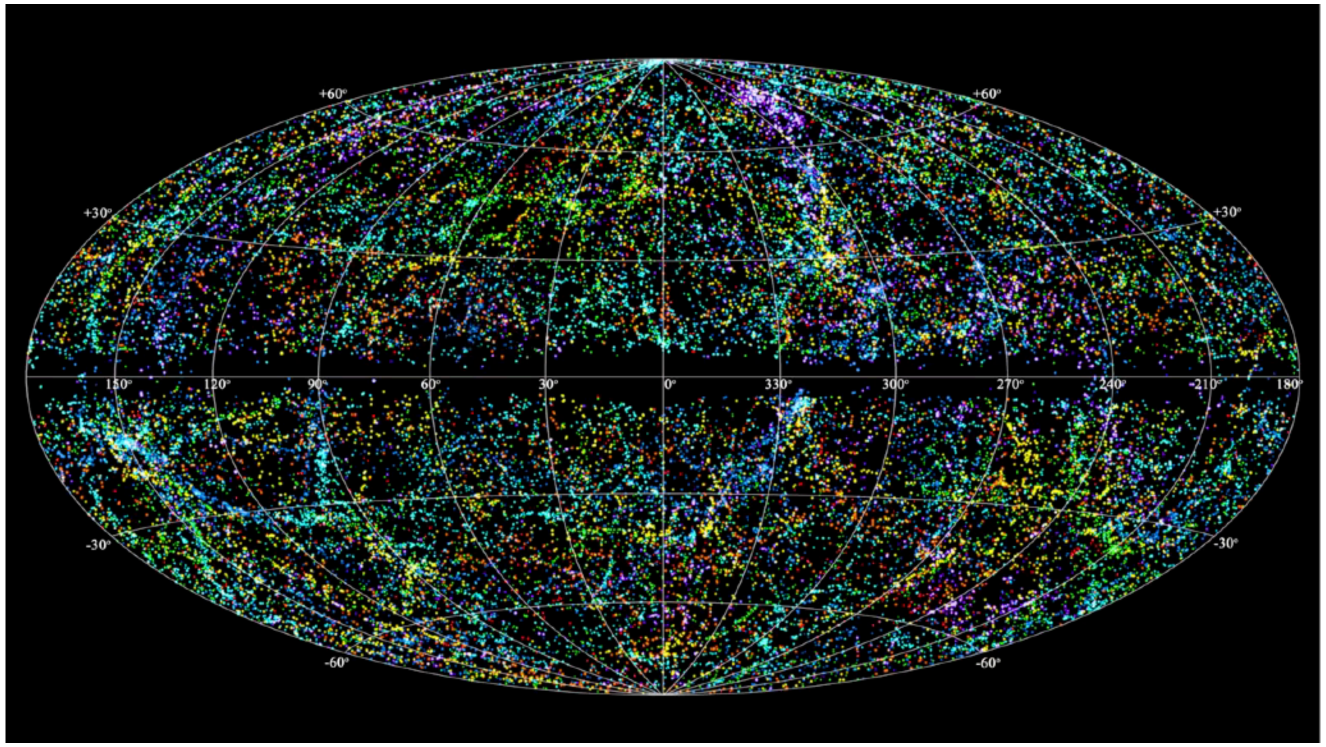
- Lines: Indicate range of (w_0, w_a) allowed by Planck 2013 and Union2.1 SNe data
- Error bars: Predicted 2-year CHIME sensitivity

Constraints on dark energy equation of state competitive with DOE Stage IV experiments (e.g., DESI, Euclid)

Fast Radio Bursts

- Bright bursts of radio emission
- Millisecond timescales
- Very high dispersion measure
  - Located at cosmological distances
- Only **24** have been detected so far
  - Implies there are ~3000 FRBs per sky per day
- One found to repeat, localized to a dwarf galaxy 2.5 billion light-years away (Spitler et al. 2016, Chatterjee et al. 2017, Tendulkar et al. 2017)
- What are they? Lots of theories.
- CHIME expects to detect order 10 per day





Movie by NRAO Outreach: T. Jarrett (IPAC/Caltech) and B. Saxton (NRAO/AUI/NSF)

First Detection of FRBs between 400-800 MHz by CHIME/FRB

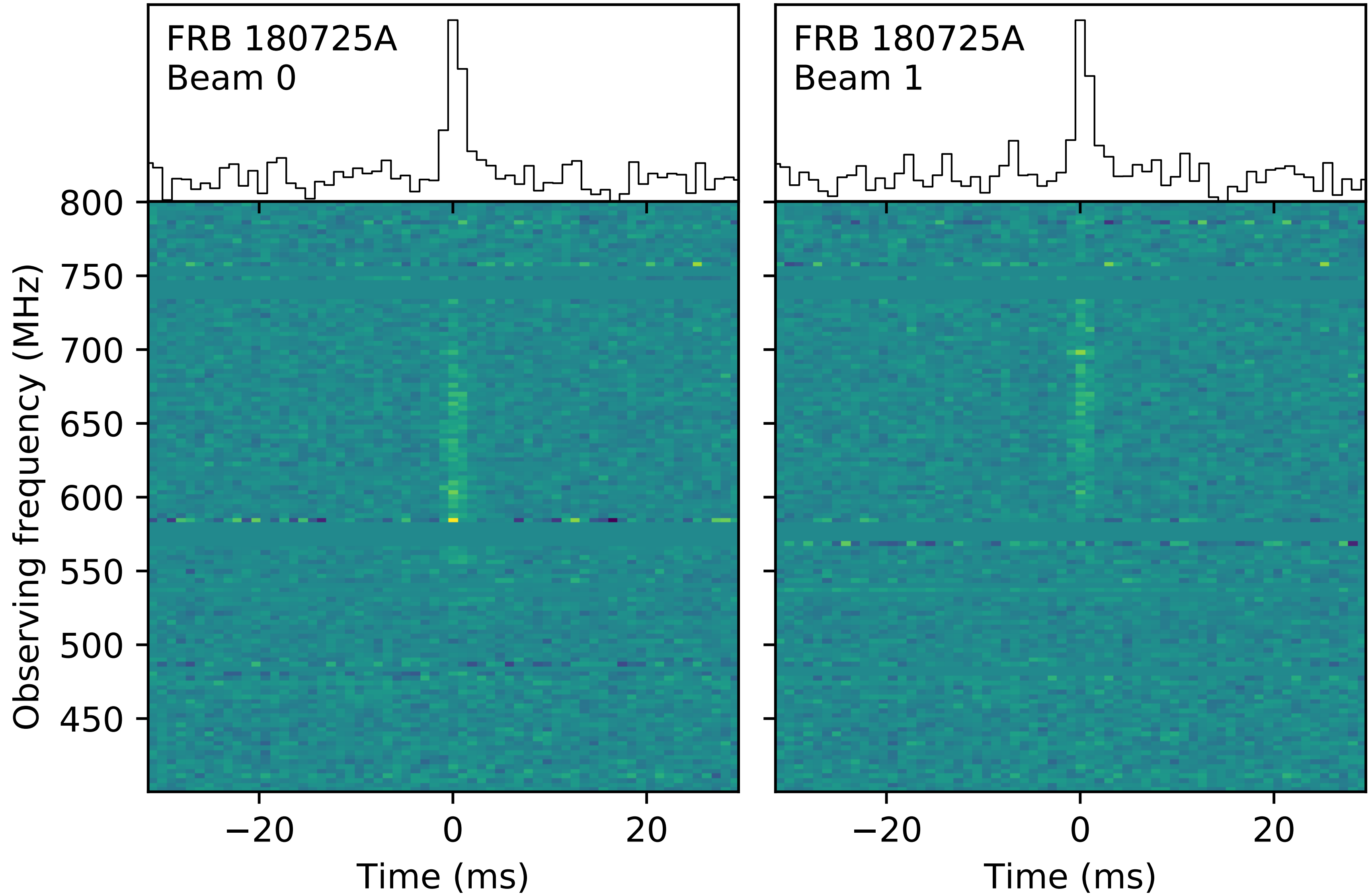


Figure 1: Dynamic spectrum plot after de-dispersion to DM = 716.6 pc cm^{-3}. The time is relative to the topocentric (at 400 MHz) burst peak on 2018 July 25 at 17:59:43.115 UTC. Intensity data for the two beams in which FRB 180725A was detected are shown. These approximately 0.5° wide and circular beams were at RA, Dec = (06:13:54.7, +67:04:00.1; J2000) and RA, Dec = (06:12:53.1, +67:03:59.1; J2000). Some frequency channels with terrestrial radio frequency interference have been zero-weighted.

See Astronomer's Telegram
ATEL #11902

Summary

- CHIME is a dedicated cosmology experiment designed to measure BAO in the large scale distribution of neutral hydrogen between redshifts 0.8 and 2.5.

- Challenges and uncertainties:
  - Foregrounds 10^5 brighter than 21 cm signal.
    - Foreground avoidance and removal are active areas of research:
      - Foreground wedge (Parsons et al. 2012)
      - Karhunen-Loève filter (Shaw et al. 2014, 2015)
    - Will require characterization of the instrument at an unprecedented level.

  - Constraints will depend on HI density and bias of 21 cm sources.
    - Cosmological 21 cm signal detected in cross-correlation at z = 0.8 (Chang et al. 2010, Masui et al. 2013).

- CHIME is currently collecting science data.

- Experiment will reach full capacity by Fall. Survey will last 5 years.
  - Potential to yield Stage IV constraints on dark energy equation of state.

Thank you!

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