21cm Cosmology with the Canadian Hydrogen Intensity Mapping Experiment (CHIME)

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Cosmo 2014

Photo credit:
K Vanderlinde

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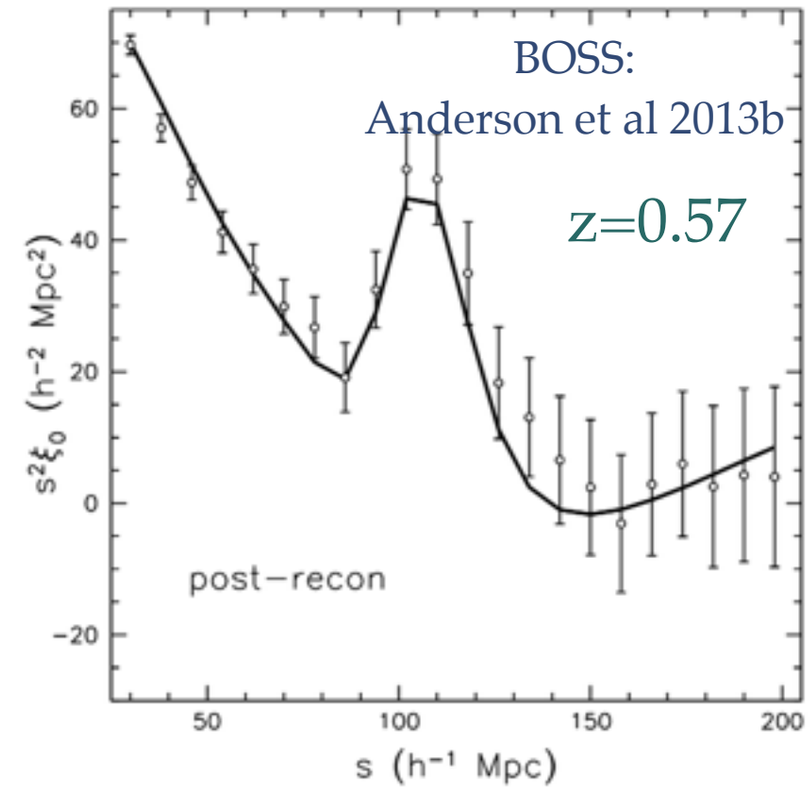
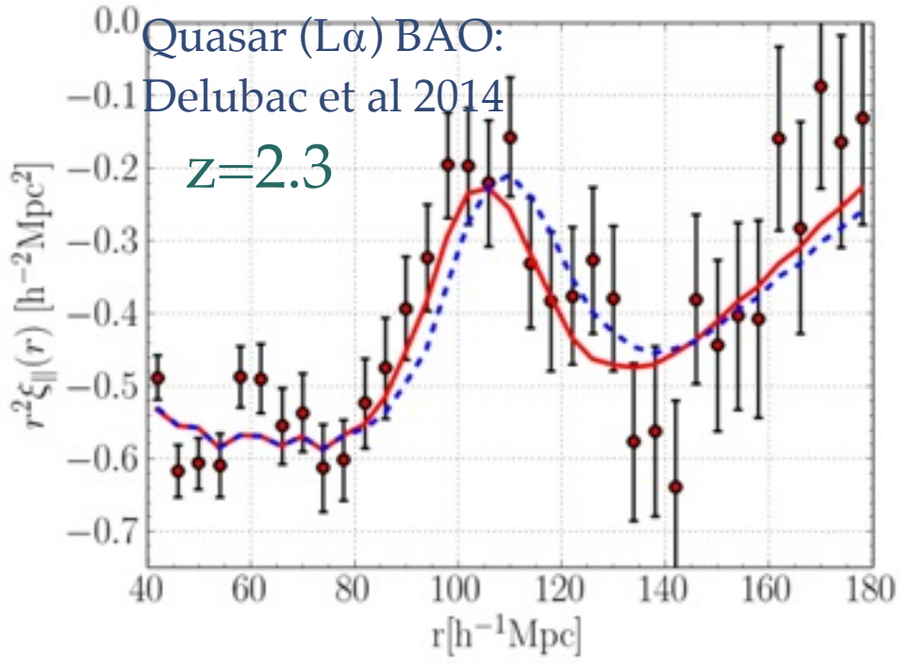
NRC · CNRC

BAO : Probe of Dark Energy

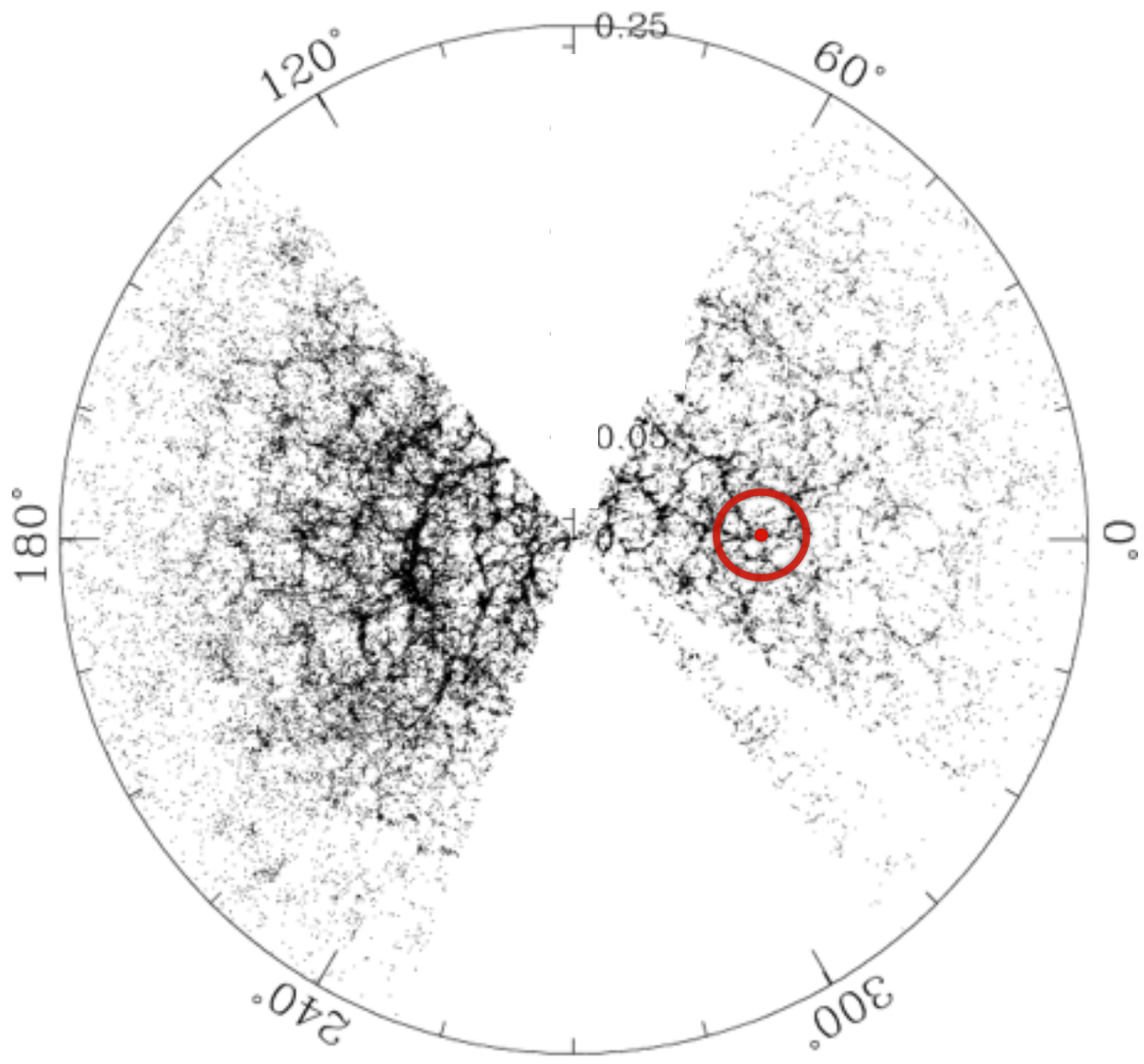
- BOSS galaxy survey: 7σ detection of BAO, w= -1.06± 0.07
- BOSS Quasar Lα: ~2.5σ discrepancy from best-fit Planck
- Measurements to fill in this redshift desert
  - Deep optical surveys (e.g. DESI)
  - And …. a different way?





Galaxy Mapping

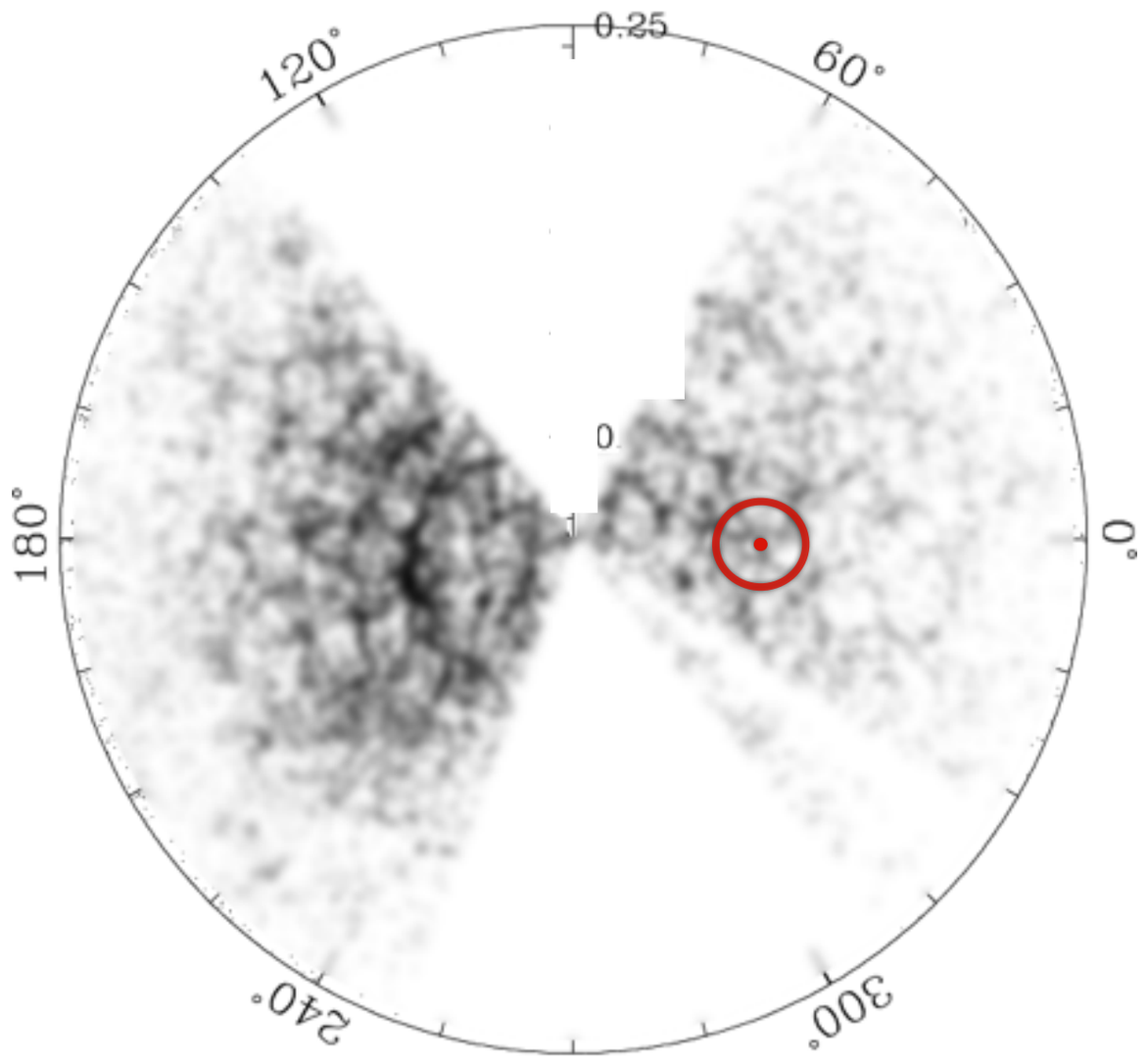
- The scale of interest is large (~150 Mpc)



SDSS DR7 (Blake et al 2011)

Intensity Mapping

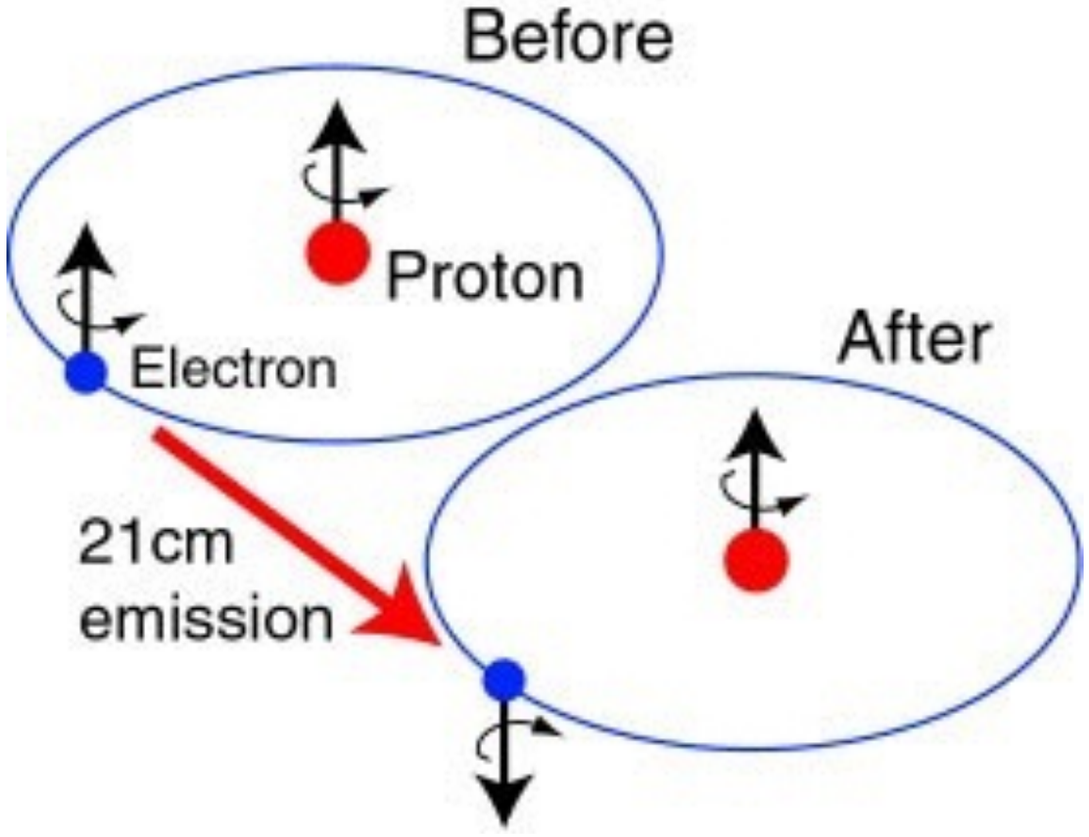
- So we don’t really need to resolve individual galaxies, DO need:
  - Traces dark matter distribution
  - Redshift information



(CHIME resolution)

Hydrogen Intensity Mapping

- Neutral hydrogen has characteristic emission from its hyperfine transition → Redshift information for free!

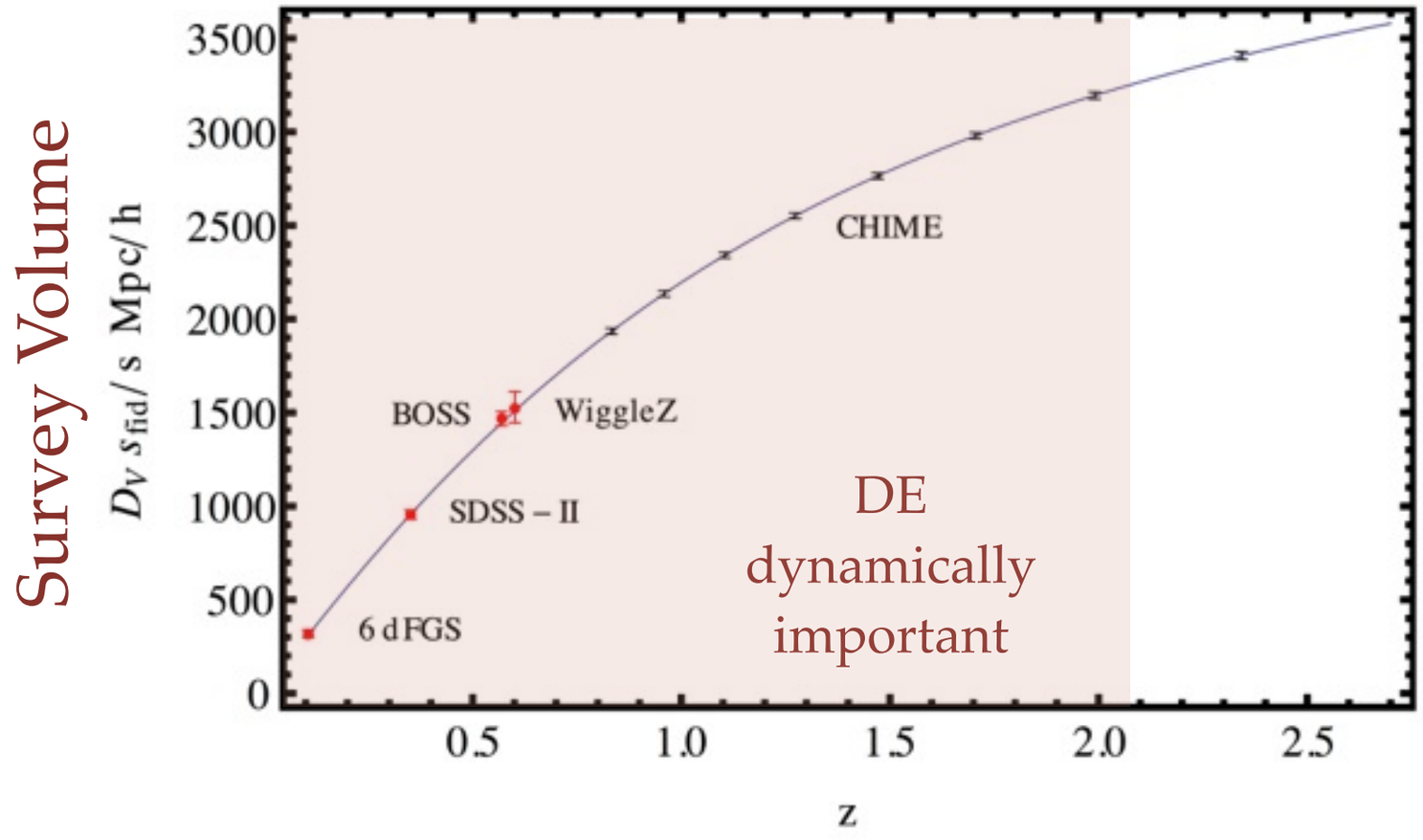


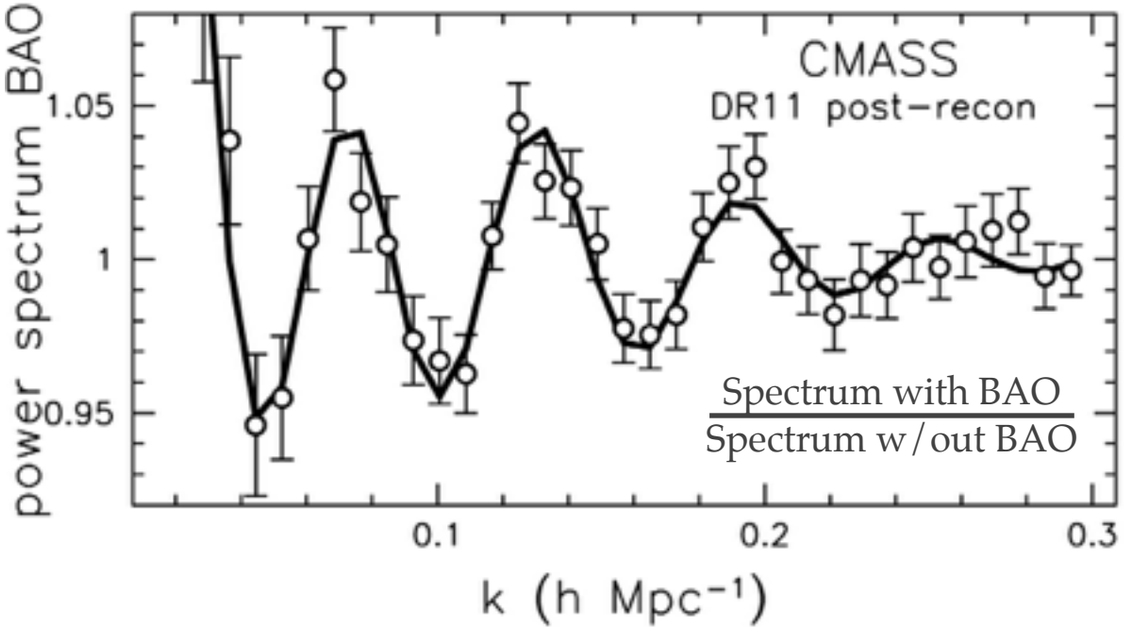
21cm @ z=0.8 :: 37cm ~ 800MHz

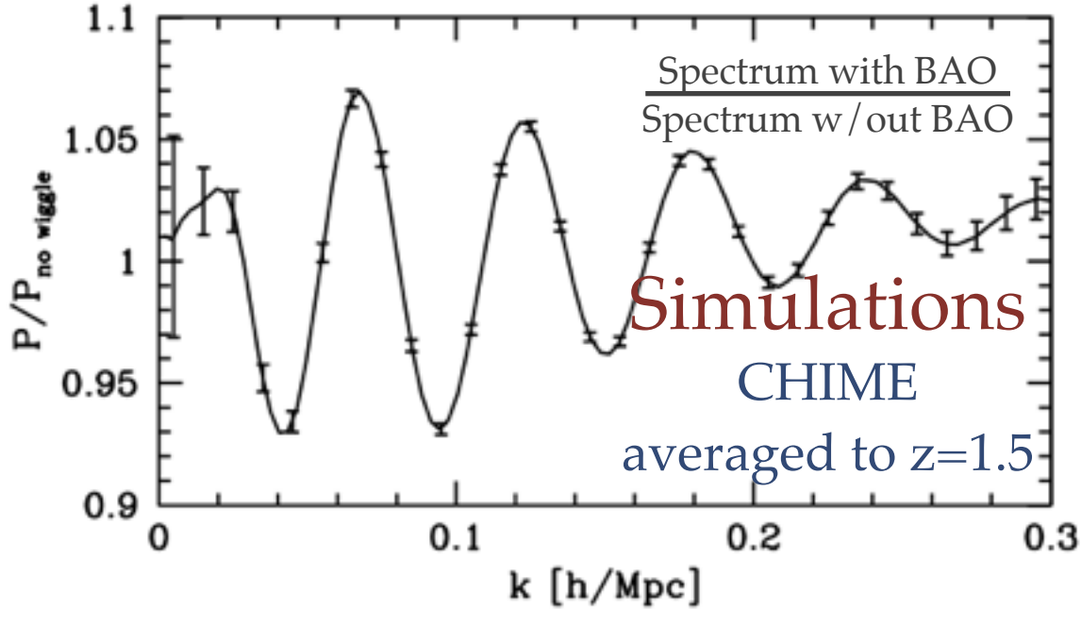
21cm @ z=2.5 :: 74cm ~ 400MHz

CHIME : A 21cm **Dark Energy** Experiment

- Error bars scale with survey volume

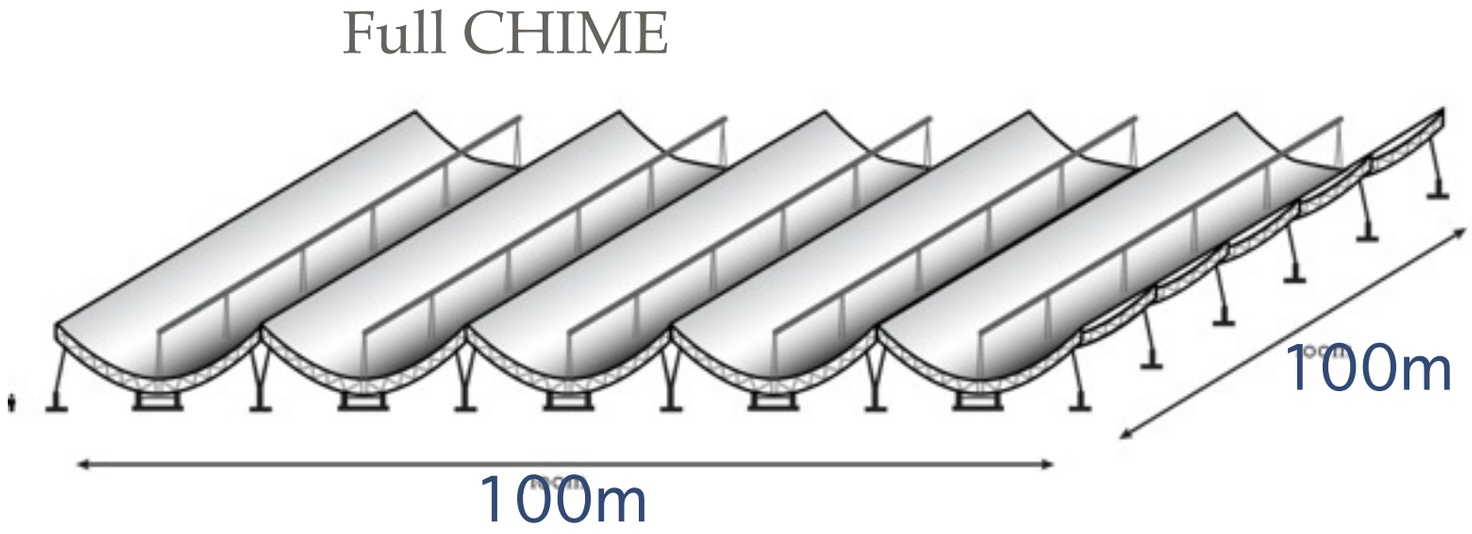






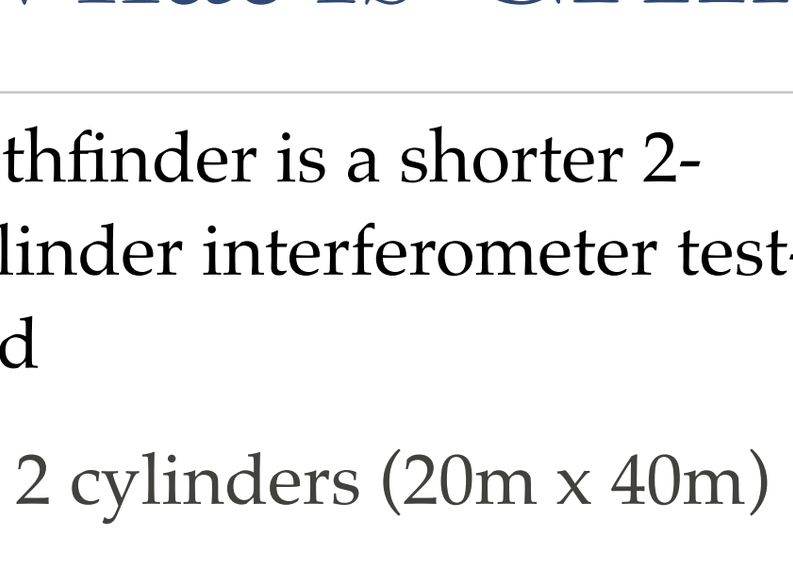
What is CHIME, anyway

- CHIME is a stationary transit interferometer with
  - 5 cylinders (20m x 100m)
  - 1280 dual-pol feeds total
  - 400—800 MHz
    - See Bandura et al 2014 (arXiv 1406.2288) for more instrument details
- Measures the entire available sky in a day (~3/4 of the sky)
- Fourier Transform telescope (Tegmark & Zaldarriaga 2008)
  - Grided layout allows DFT: $N^2 \rightarrow N \log(N)$

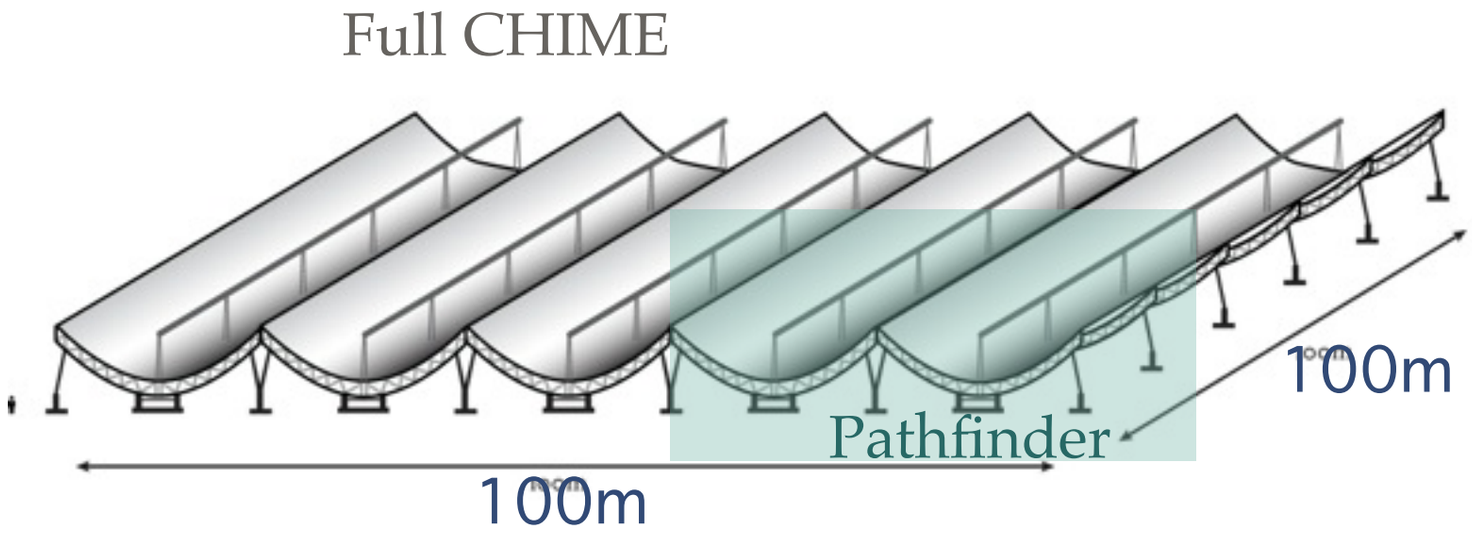


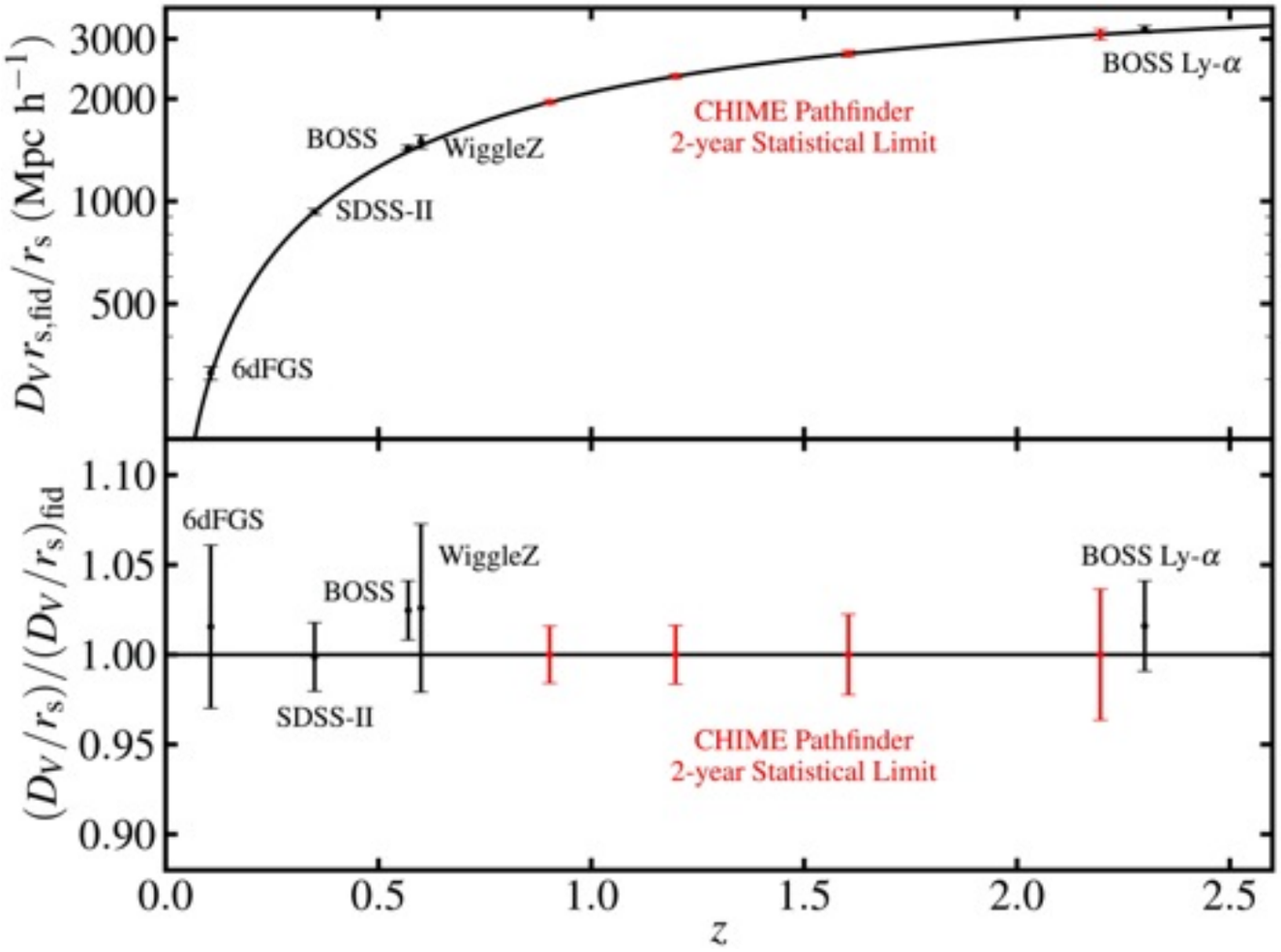
What is CHIME Pathfinder, anyway

- Pathfinder is a shorter 2-cylinder interferometer test-bed
  - 2 cylinders (20m x 40m)
  - 128 dual-pol feeds
- Can also do science
- Fielded!



First Light! (Cas A)

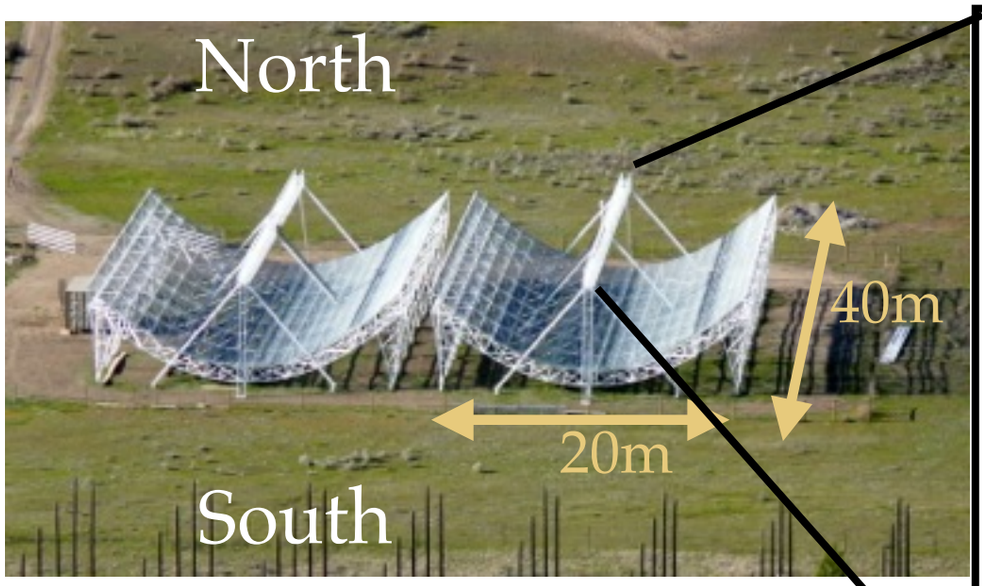




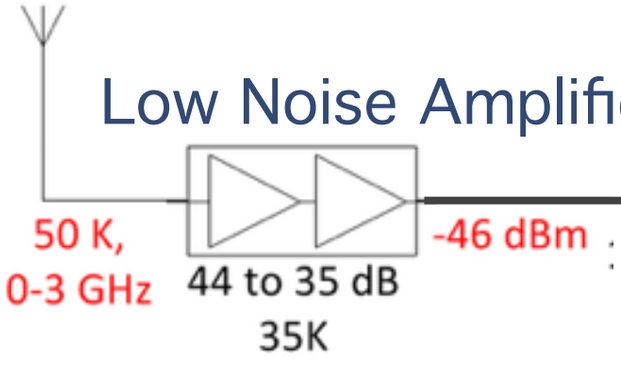
CHIME Site

- At the Dominion Radio Astrophysical Observatory (Penticton, BC):
  - located in a legally protected radio-quiet valley for reduced radio interference from civilization

Analog Chain

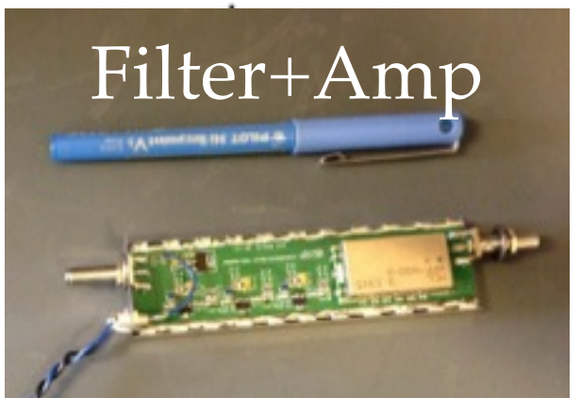


Cylinder+Feed



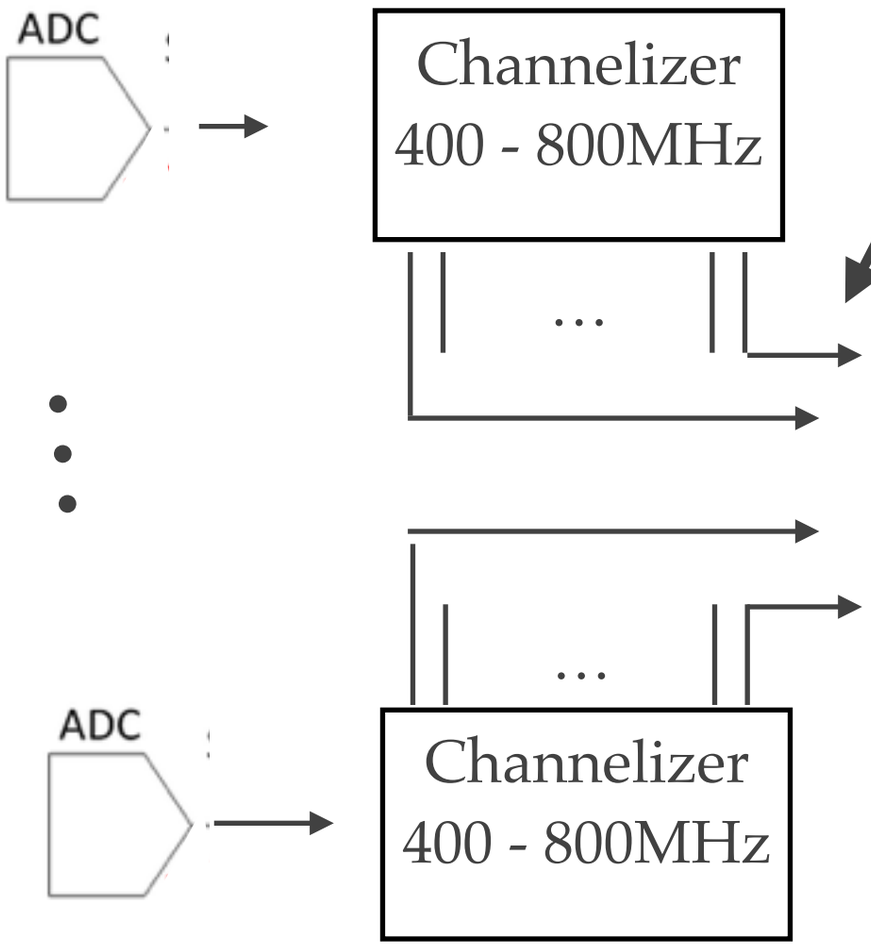
(a lot of) Coax

Filter + Amplifier



Digitization + Correlation

Pathfinder with 256 inputs:
16 FPGA channelizer cards
x
16 inputs per card



FFT ~2ms time sample to 400-800 MHz

Pathfinder: 125GByte/s
Full CHIME : 1 TByte/s !

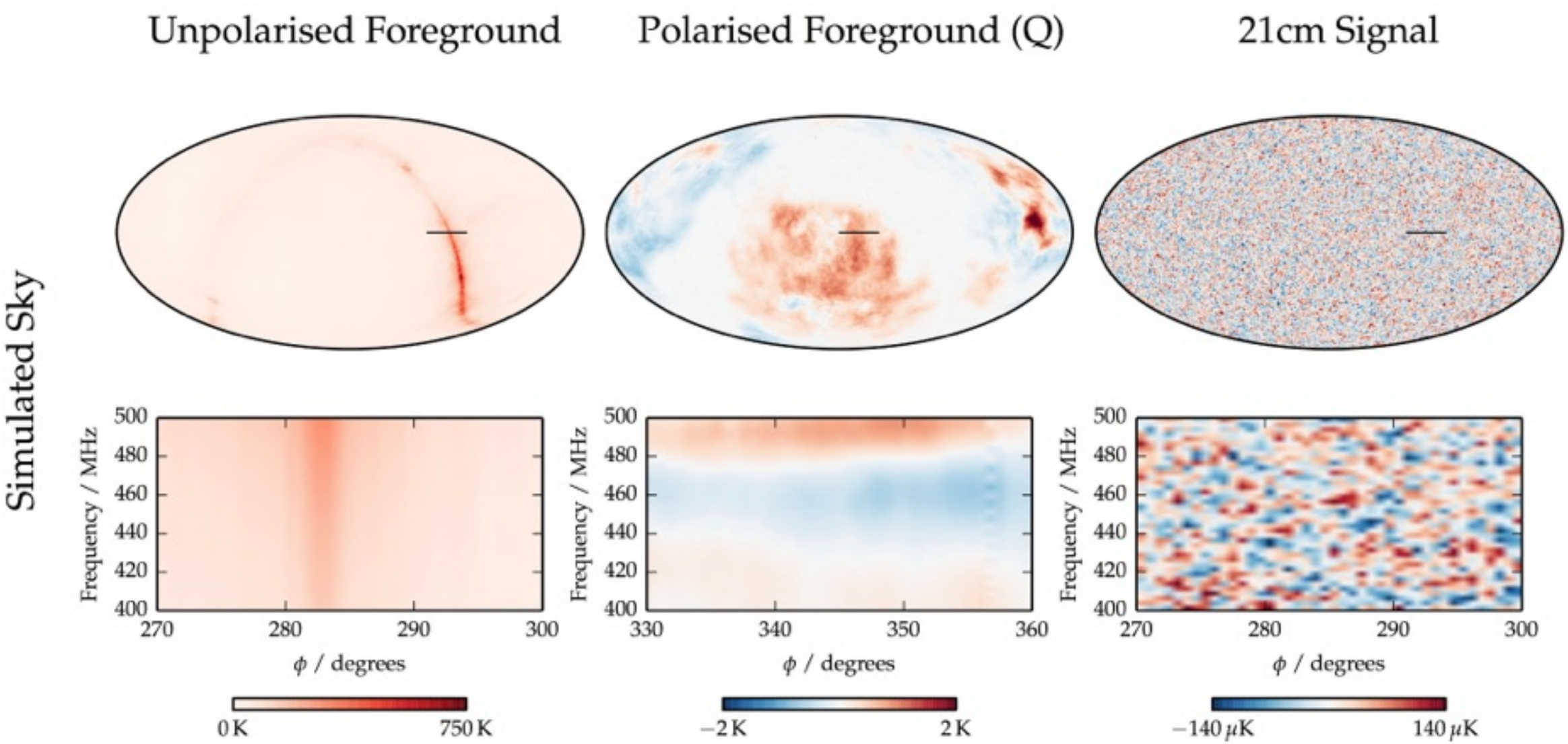
Pathfinder:
16 graphics cards (GPU) hosts
Correlate inputs and average

Pathfinder data rate: ~100 Mbit/s averaging for 30s

By now you're wondering

- Why hasn't someone done this before?
  - We need a very large, very fast correlator
- What aren't you telling me?
  - Assumption of hydrogen tracing structure?
    - Chang et al 2010, Nature 466: 473; Masui et al 2013, arxiv 1208.0331
- Do you have foregrounds?
  - Do we ever
- How well do we have to calibrate our instrument?
  - Really, really well

Foregrounds

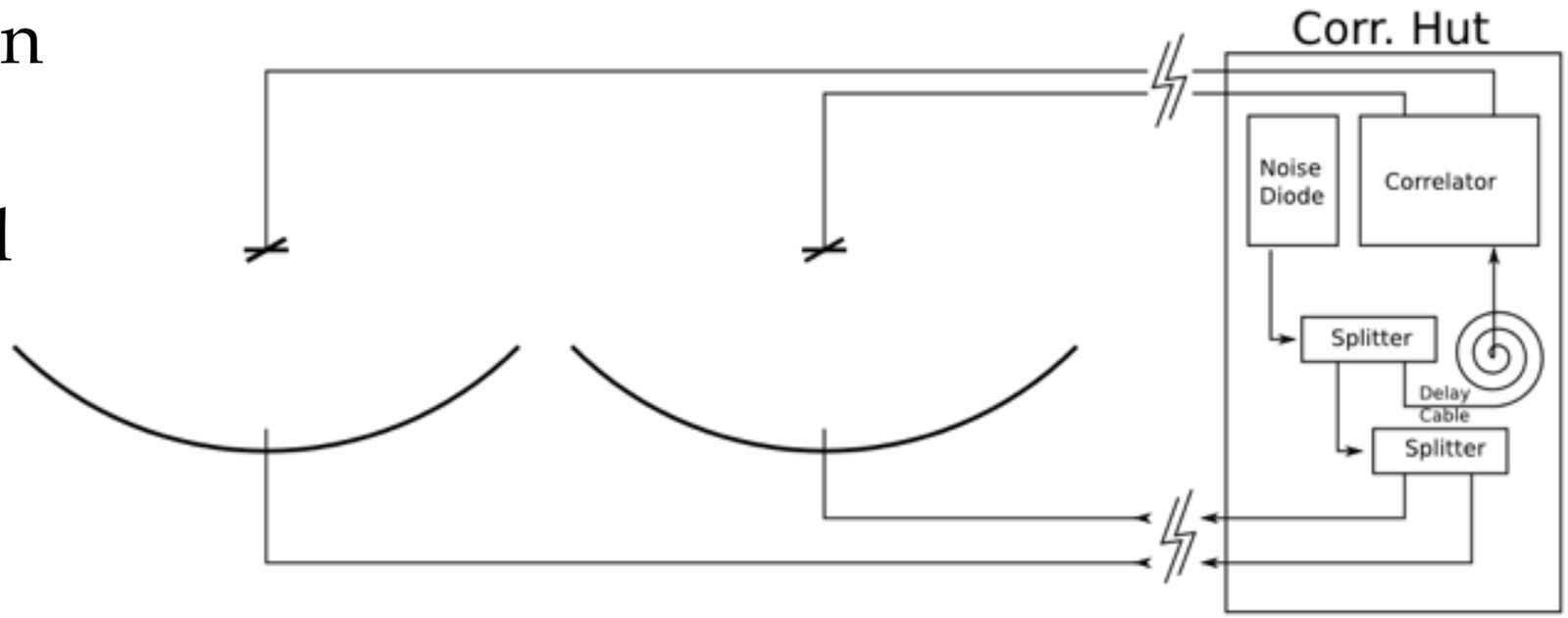


Shaw et al 2014

- Foregrounds are 10^6 x larger than our signal, but spectrally smooth
- Filtering scheme presented in Shaw et al (arXiv 1401.2095)

Calibration

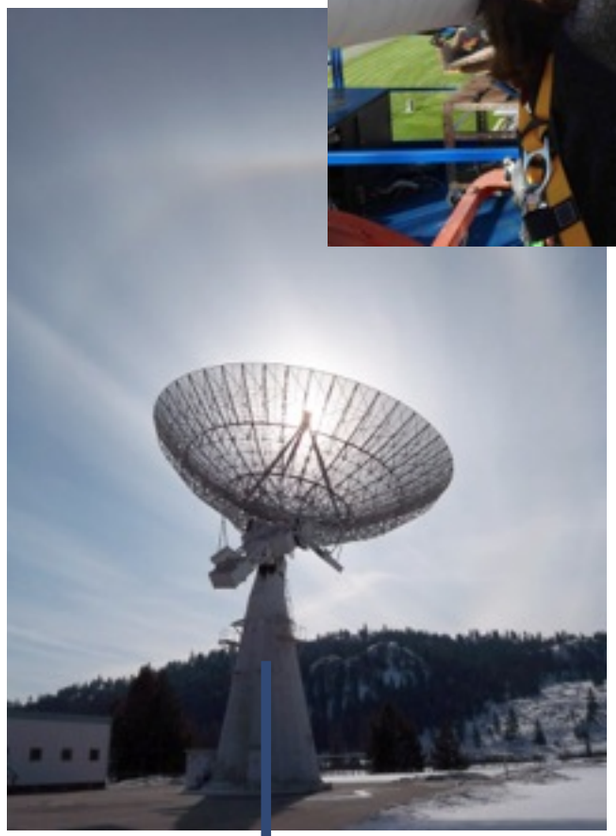
- Noise Rigidization: gain +phase solution from inserting a known (and separately digitized) noise signal
- Redundant Baselines: gain+phase solution from numerous identical baselines



Noise Rigidization: current achieving ~ -25dB gain calibration with our ‘hacked together’ system, not far from our requirement of -30dB

Calibration

- Beam Calibration: simultaneously measure pulsars with CHIME and the DRAO 26m telescope
- See Newburgh et al 2014 (arXiv 1406.2267) for more calibration details



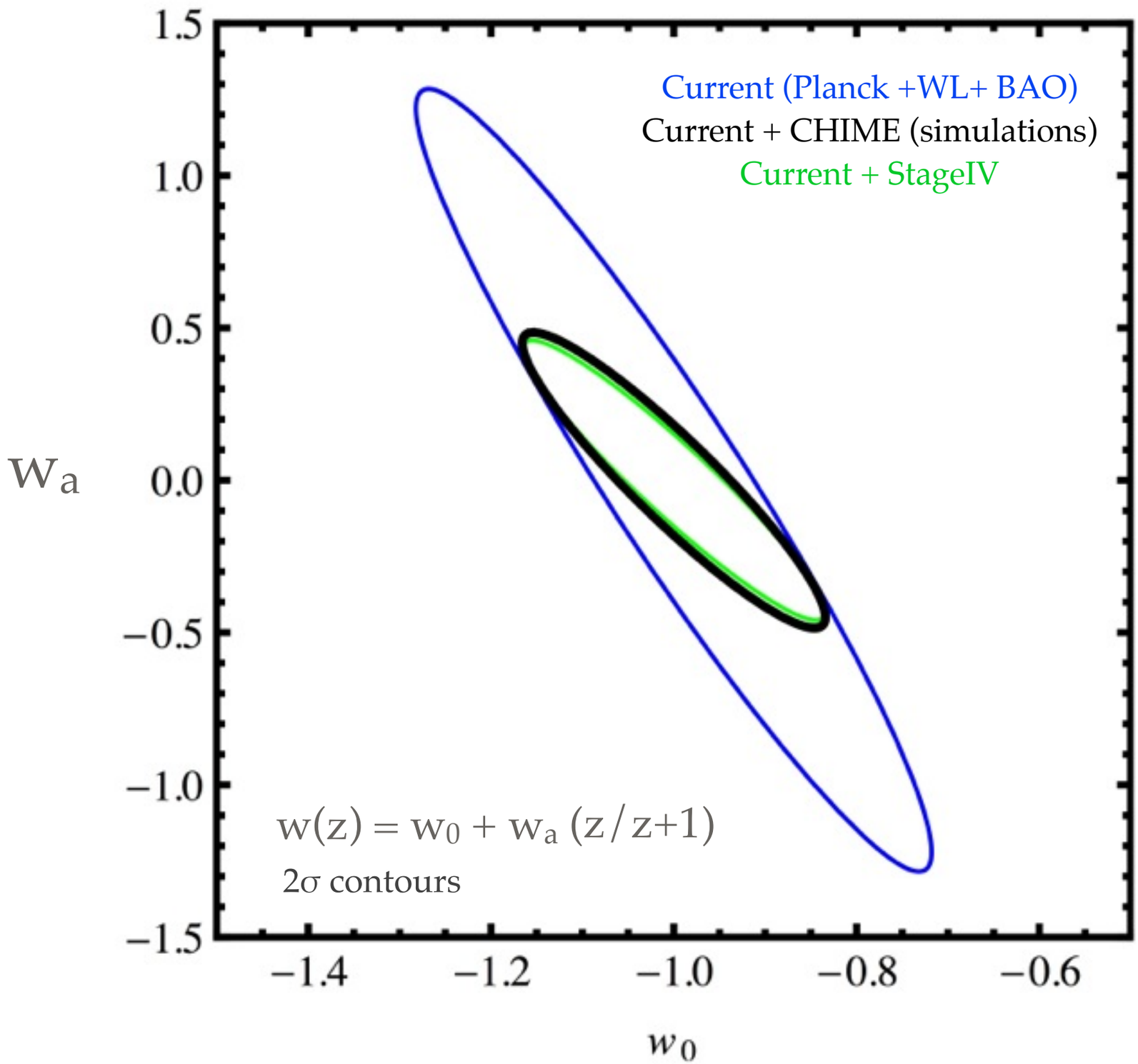
very long coax cable

Status & Summary

- CHIME will map neutral hydrogen at redshifts z~0.8 - 2.5
- Instrument resolution optimized for BAO measurements
- 5 years of CHIME data will make cosmic variance limited measurement of BAO to explore the nature of dark energy
- CHIME and Pathfinder fully funded
  - (portion of the) Pathfinder array taking data
  - Breaking ground for CHIME this year

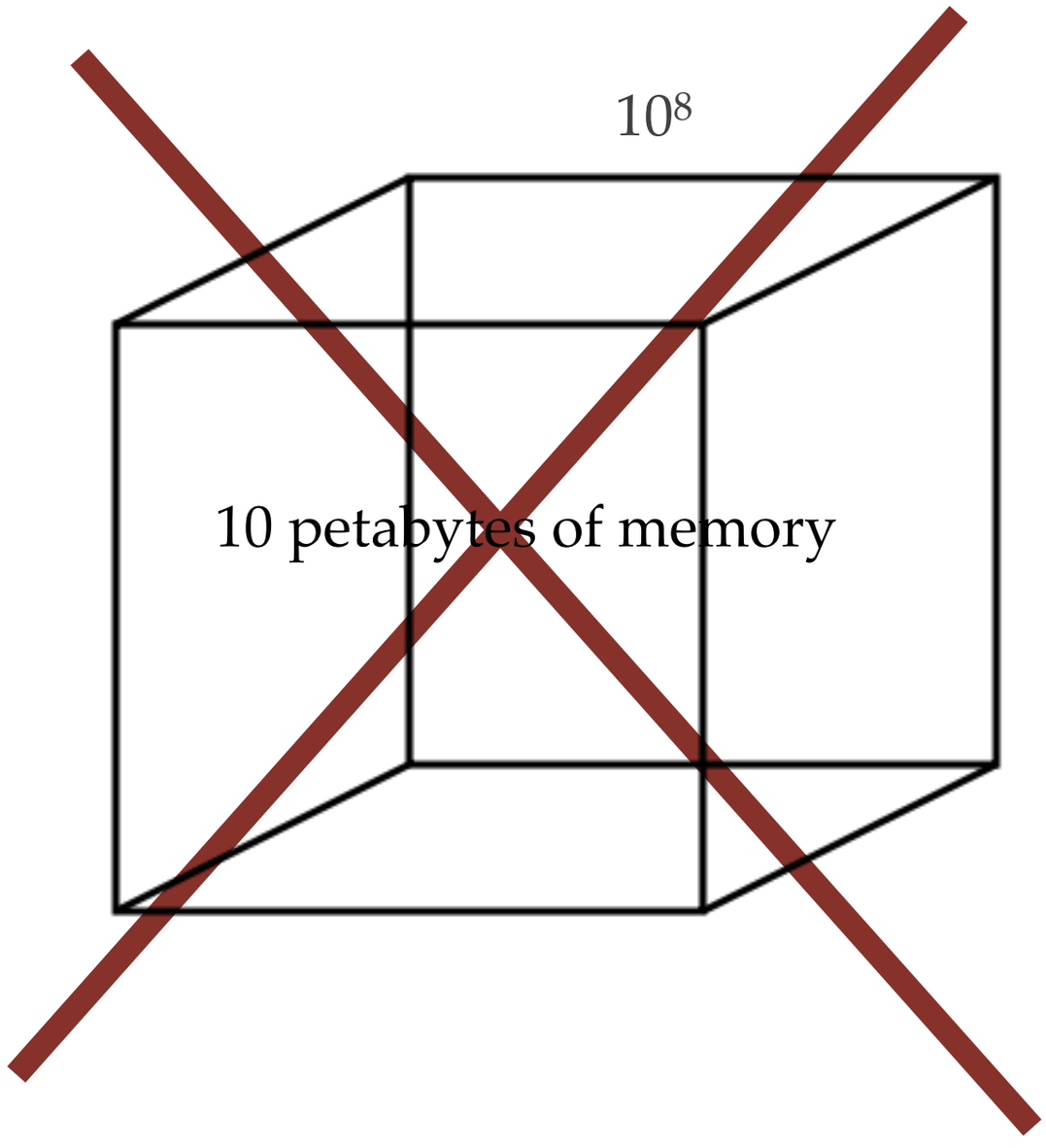
Thanks!

CHIME : A 21cm **Dark Energy** Experiment



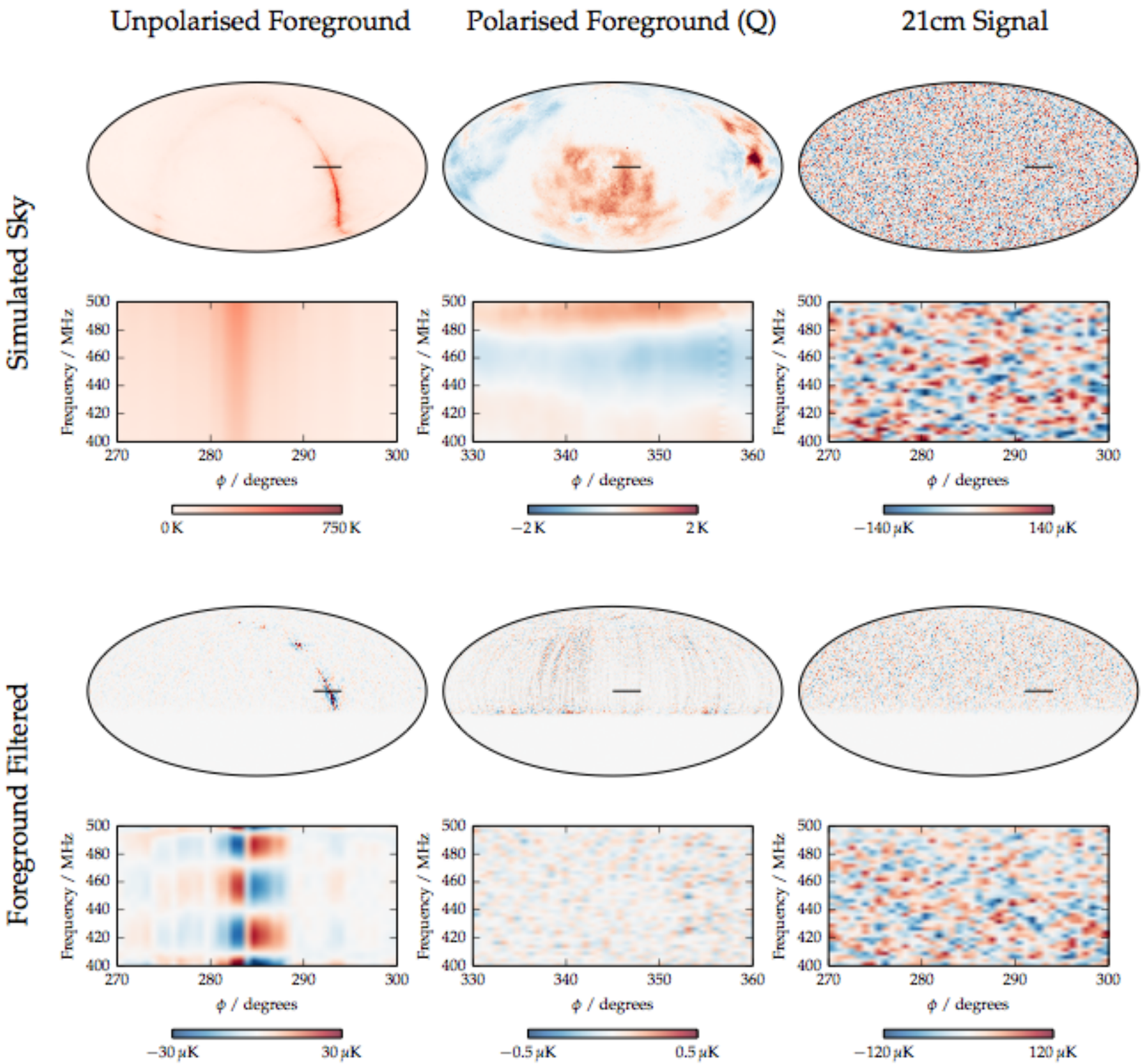
Foreground Removal?

- Foregrounds are highly correlated
  - Can change basis into one where that is more apparent with the Karhunun-Loeve transform
- But, this requires covariance matrices:



Solution: M-Modes

- Data has periodicity in sky angle (ϕ), encouraging an additional spherical harmonic: m (Shaw et al 1302.0327 & 1401.2095)
- M-modes are statistically independent
- We must know the gain, phase, and polarized beam shape of the instrument to ~0.1% (!) to remove foregrounds



CHIME Forecasts

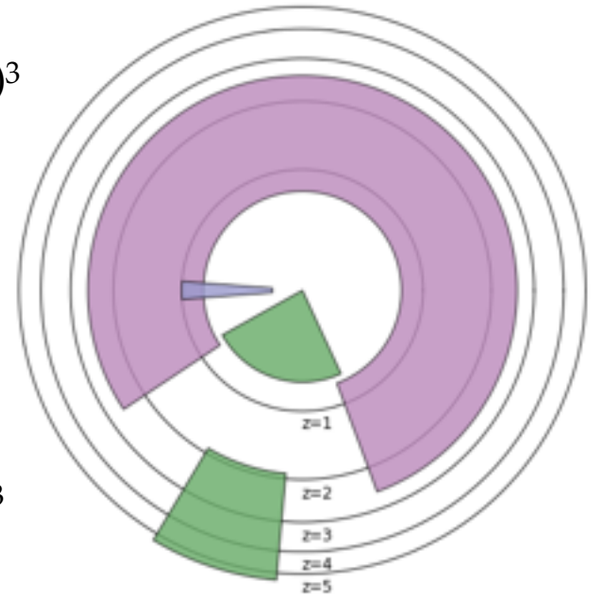
WiggleZ : 1.2 $(h^{-1}\ Gpc)^3$

BOSS

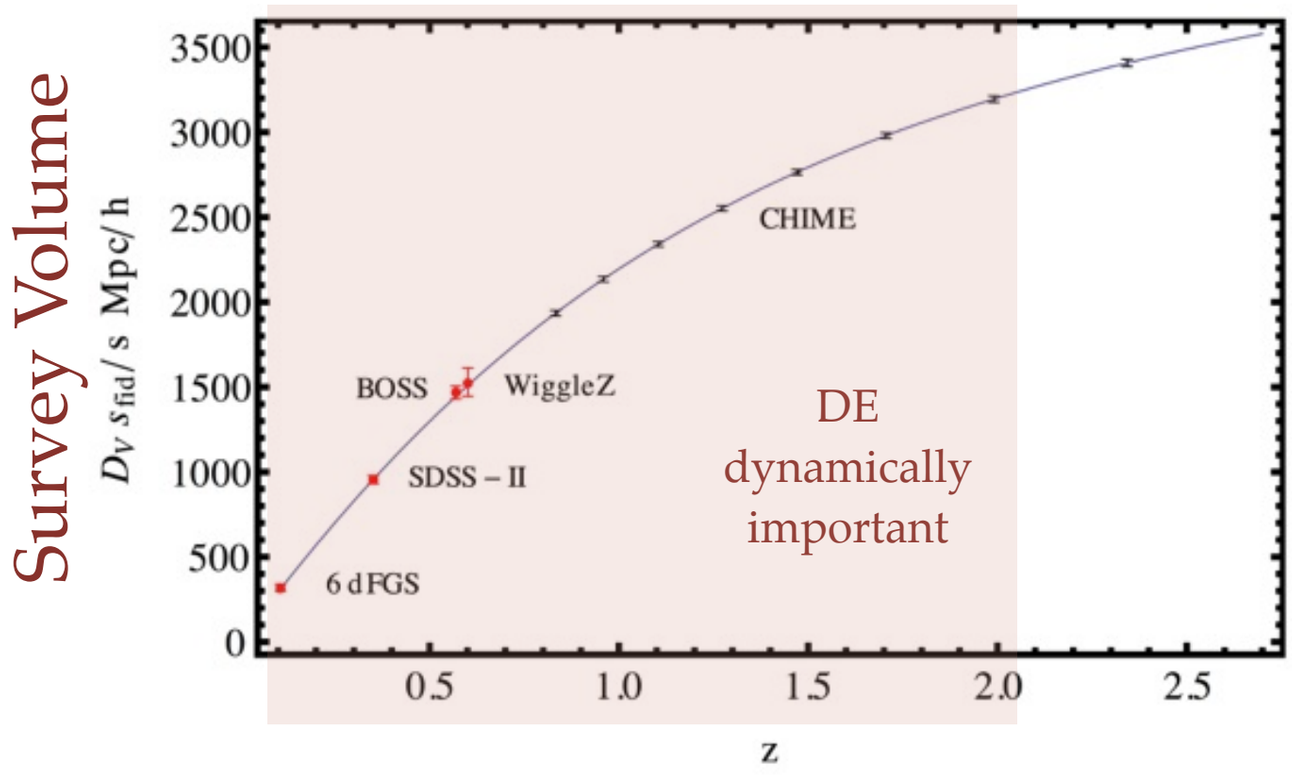
LRG: 5.3 $(h^{-1}\ Gpc)^3$

LyA: 37 $(h^{-1}\ Gpc)^3$

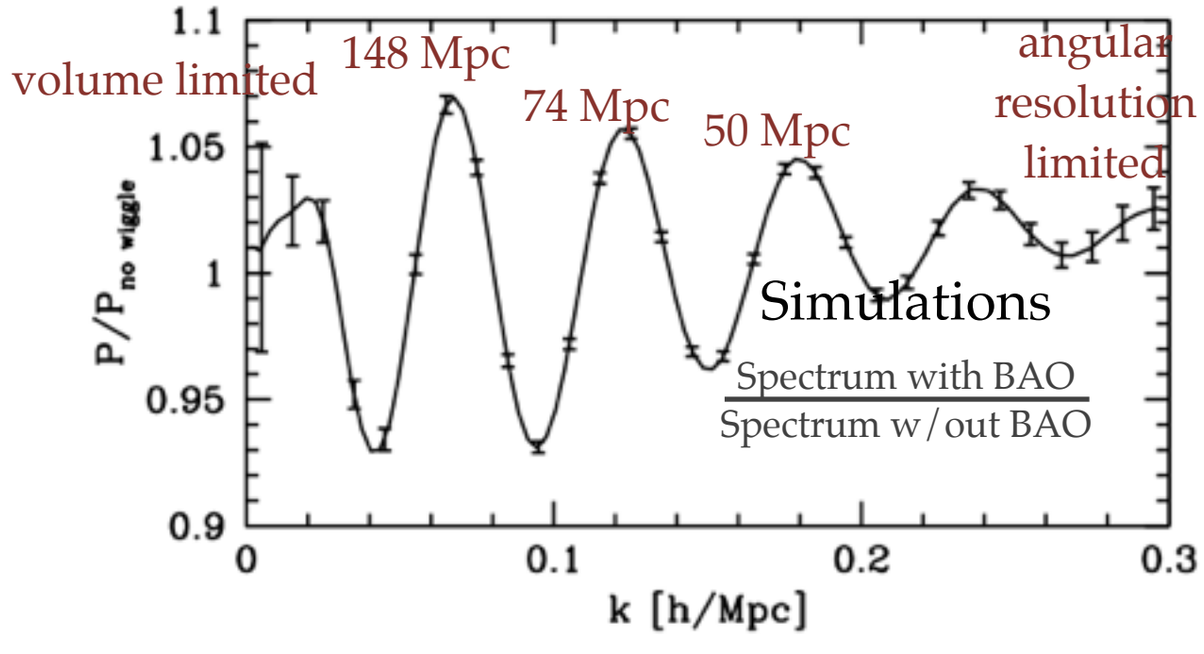
CHIME: 203 $(h^{-1}\ Gpc)^3$



(scaled such that
area of patch = volume of survey)

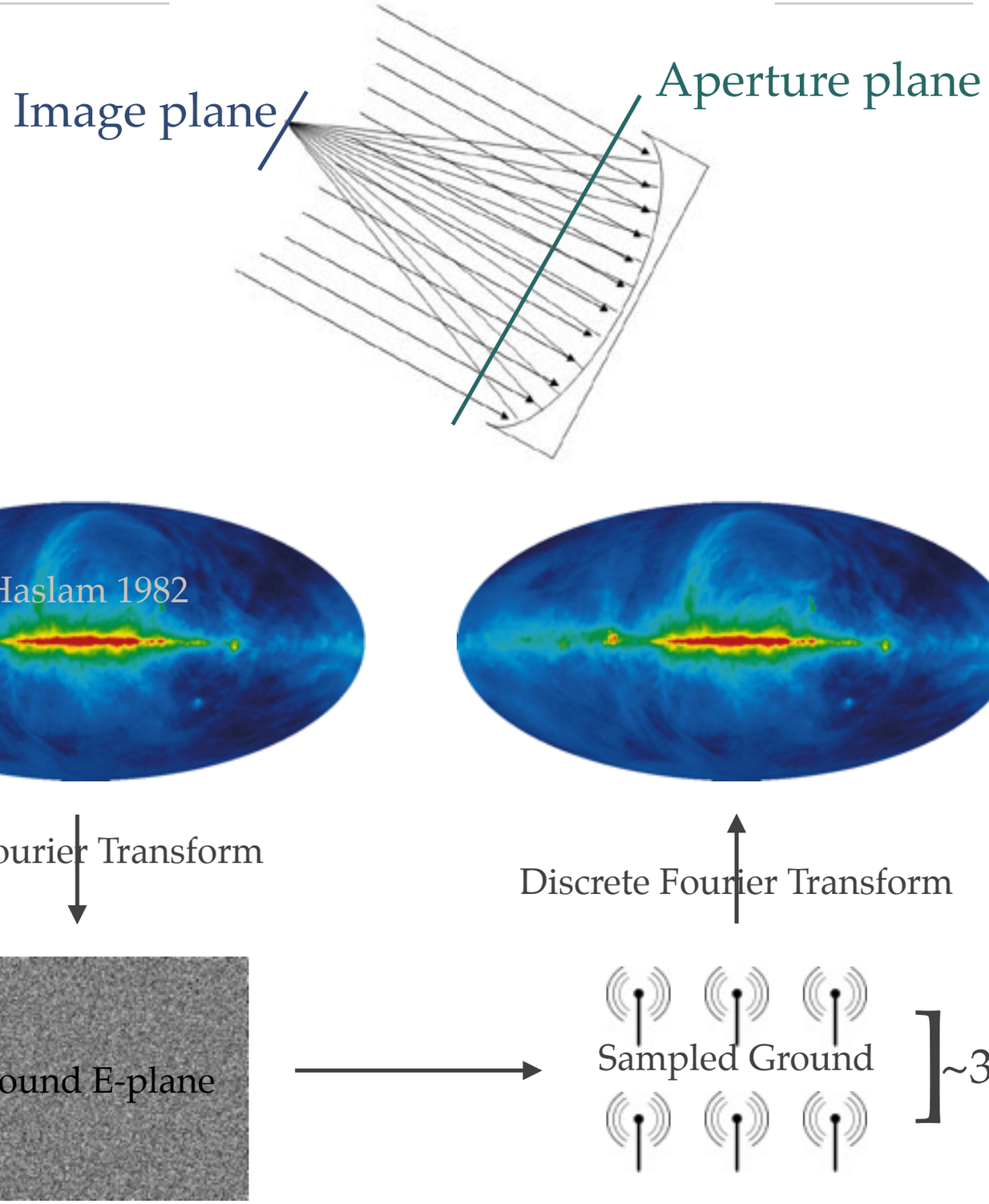


- Anticipated sensitivity for two years of data (projected to a single redshift z=1.5)

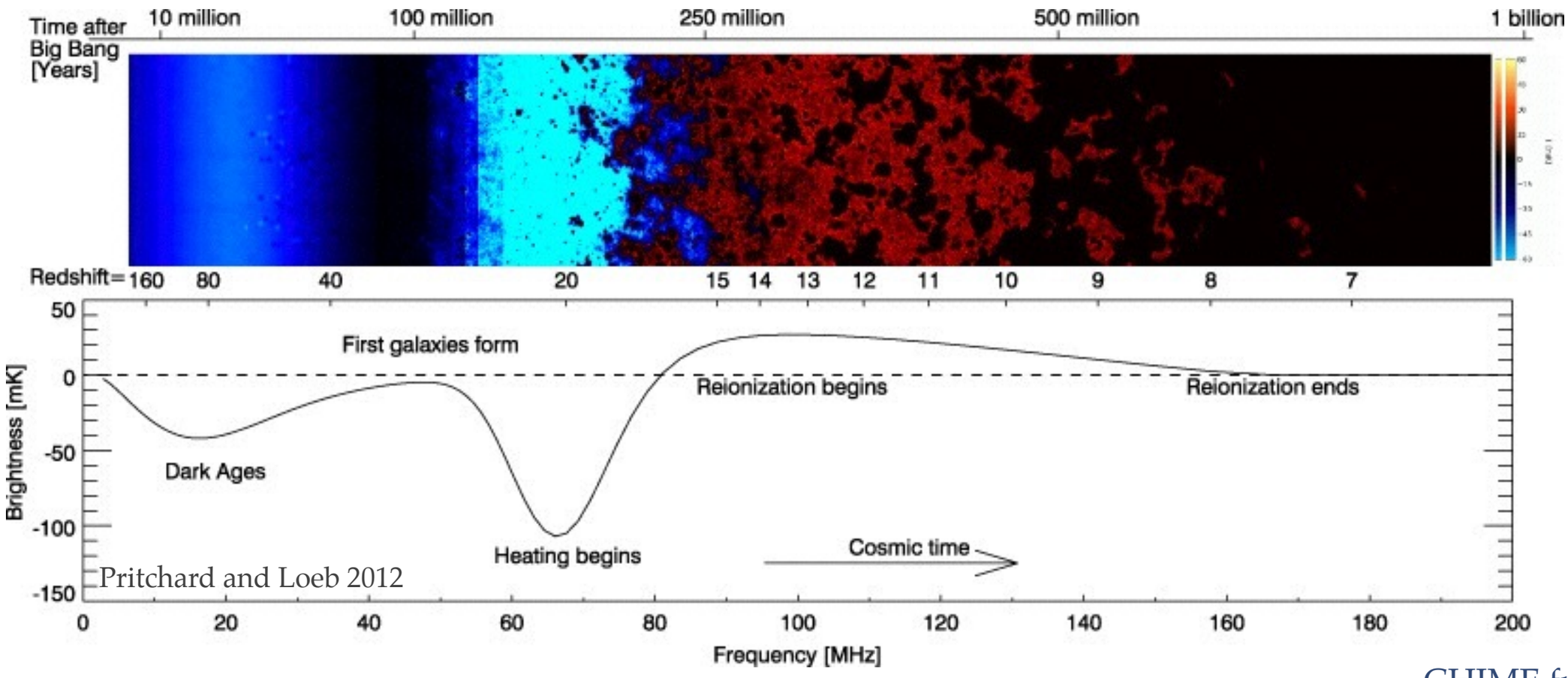


Digital Telescope

- In a traditional telescope, the image is the fourier transform of the aperture
- CHIME grid of antennas is our aperture plane, and instead of having a reflector/lens do our FT, we will use our grid of beams to do a Discrete Fourier transform
  - Assumes we can beam-form
  - Reduces computation from N^2 to NlogN (D^4 to D^2 logD)
  - See Tegmark & Zaldarriaga 2009



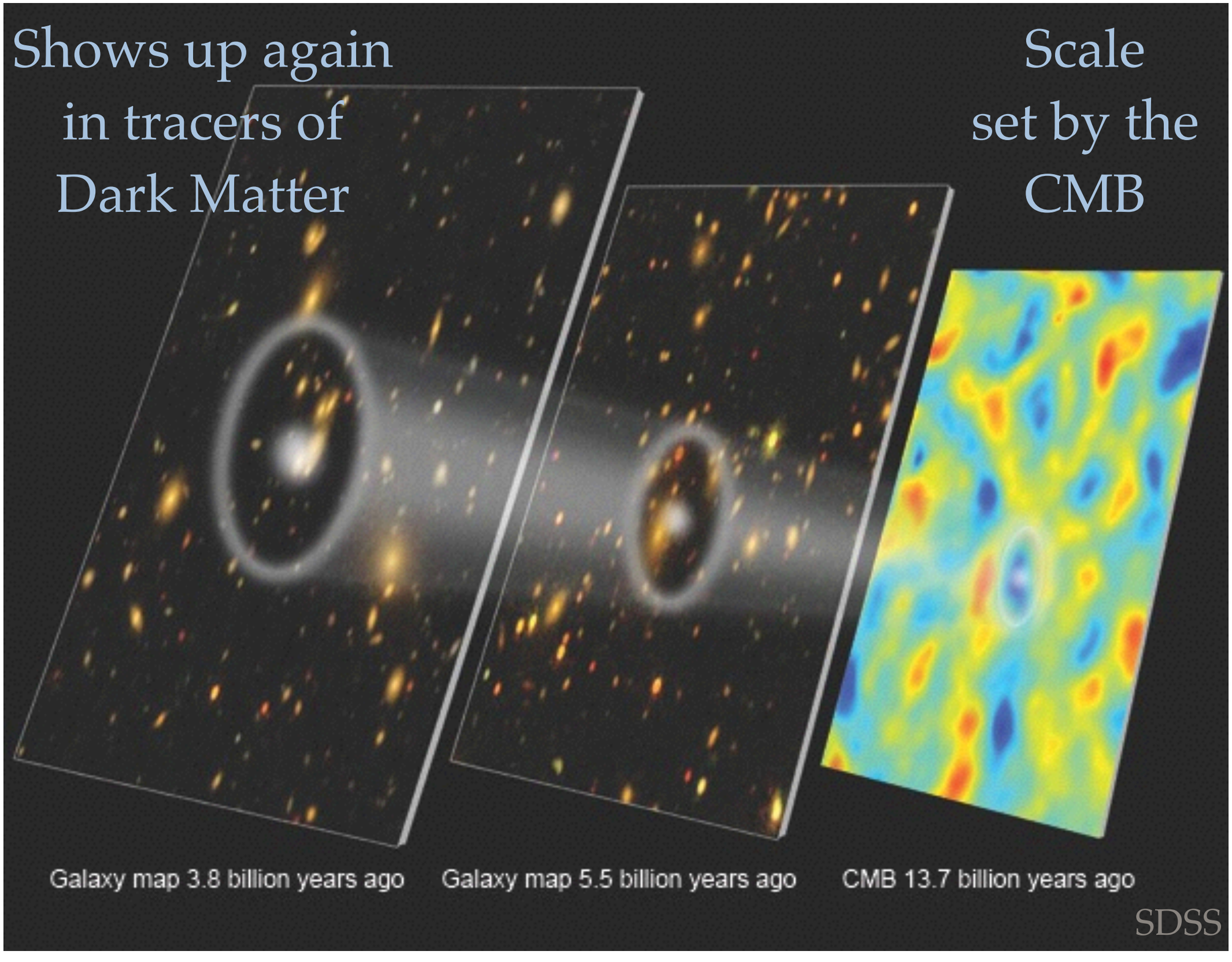
21cm Cosmology is not just CHIME



CHIME frequency range isn't even on this plot!

- 'Epoch of Reionization"
  - measure neutral hydrogen at very high redshift
  - first galaxies
  - this is the primary science goal for many different experiments: EDGES, PAPER, MWA, GBT, GMRT, etc
  - It is in the set of science goals for SKA

Baryon Acoustic Oscillations (briefly)



CHIME Auxiliary Science

- We will make daily maps of ~3/4 of the sky. This leads to a variety of auxiliary science goals:
  - pulsars : dispersion measures for pulsar searches/timing
  - bursts for LIGO coincidence searching
  - SN1a progenitors in radio
  - radio transients
  - magnetic fields
  - galactic weather