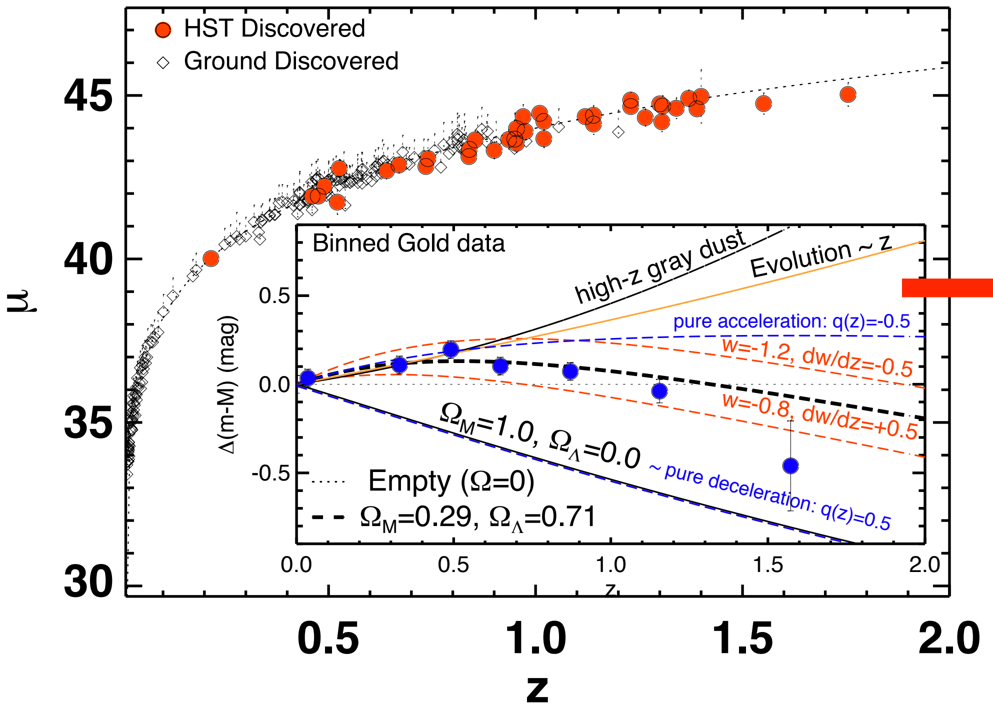
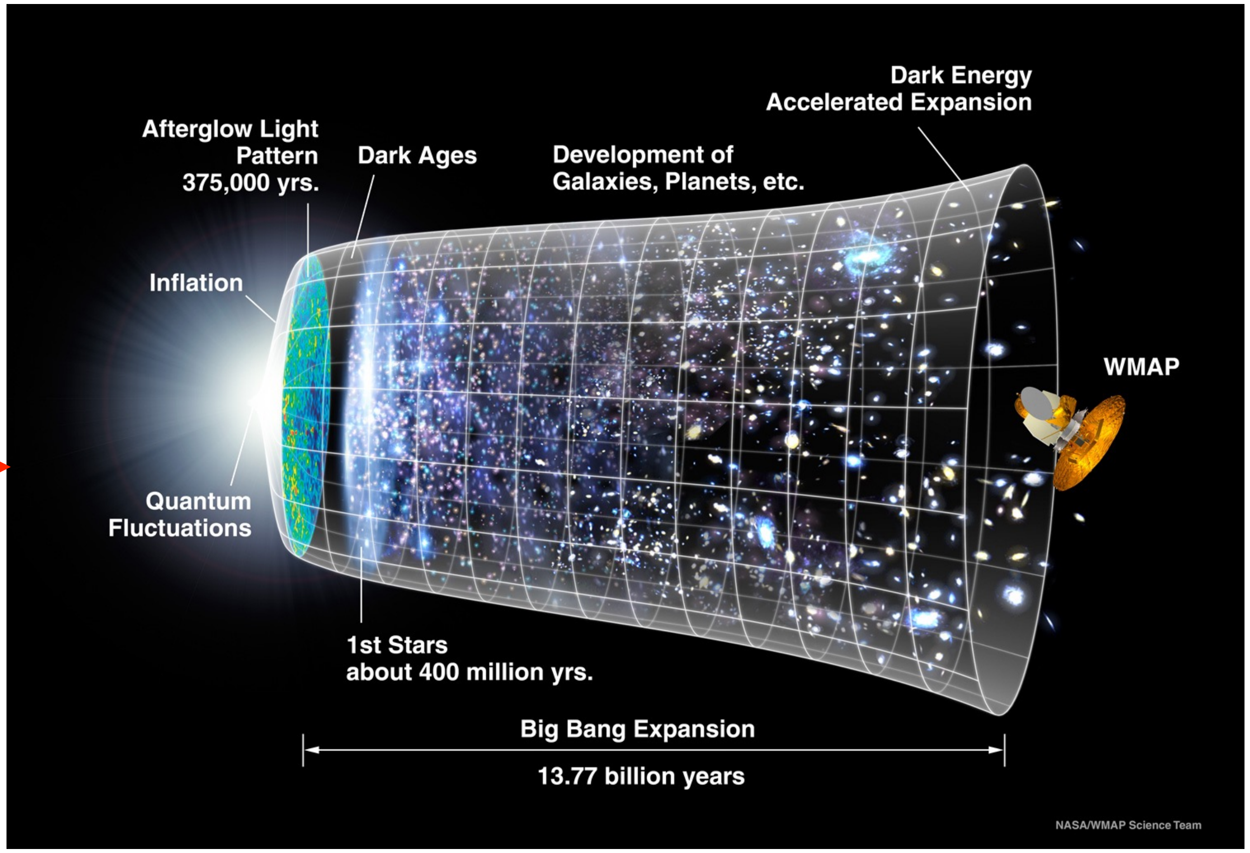
Probing Dark Energy with CHIME

Richard Shaw

a place of mind
THE UNIVERSITY OF BRITISH COLUMBIA

Dark Energy





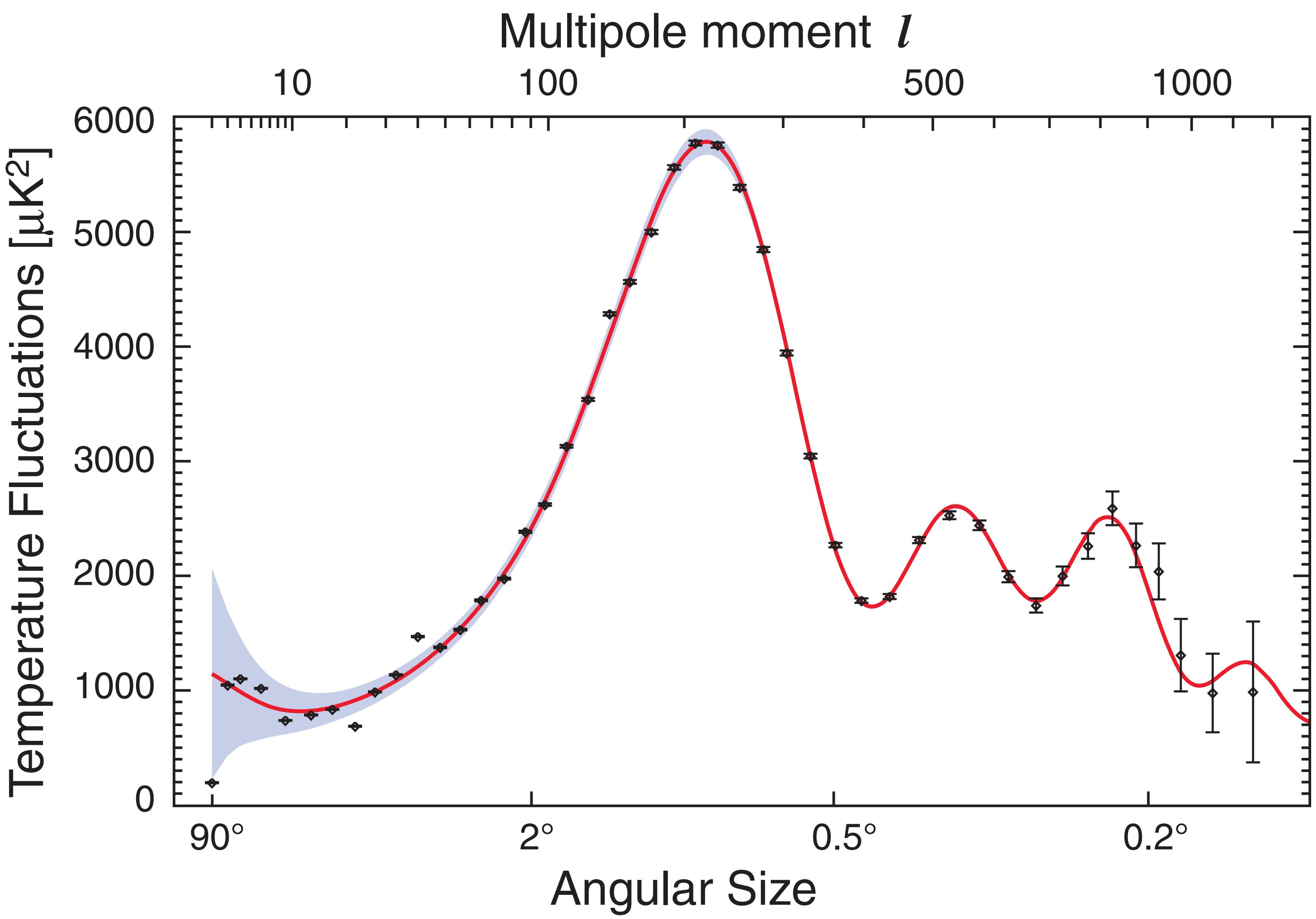
- Accelerating Universe explained by dark energy, substance with negative pressure $p/\rho = w < -1/3$ changes the expansion

$$H(z)^2 \approx \Omega_m(1+z)^3 + \Omega_{DE} \exp\left[\int_0^z (1+w(z))\frac{dz}{1+z}\right]$$

Baryon Acoustic Oscillations

- Sounds waves propagating in the early Universe. Leave acoustic peaks in the CMB
- Weaker imprint left in the matter distribution
- Gives a standard (statistical) ruler

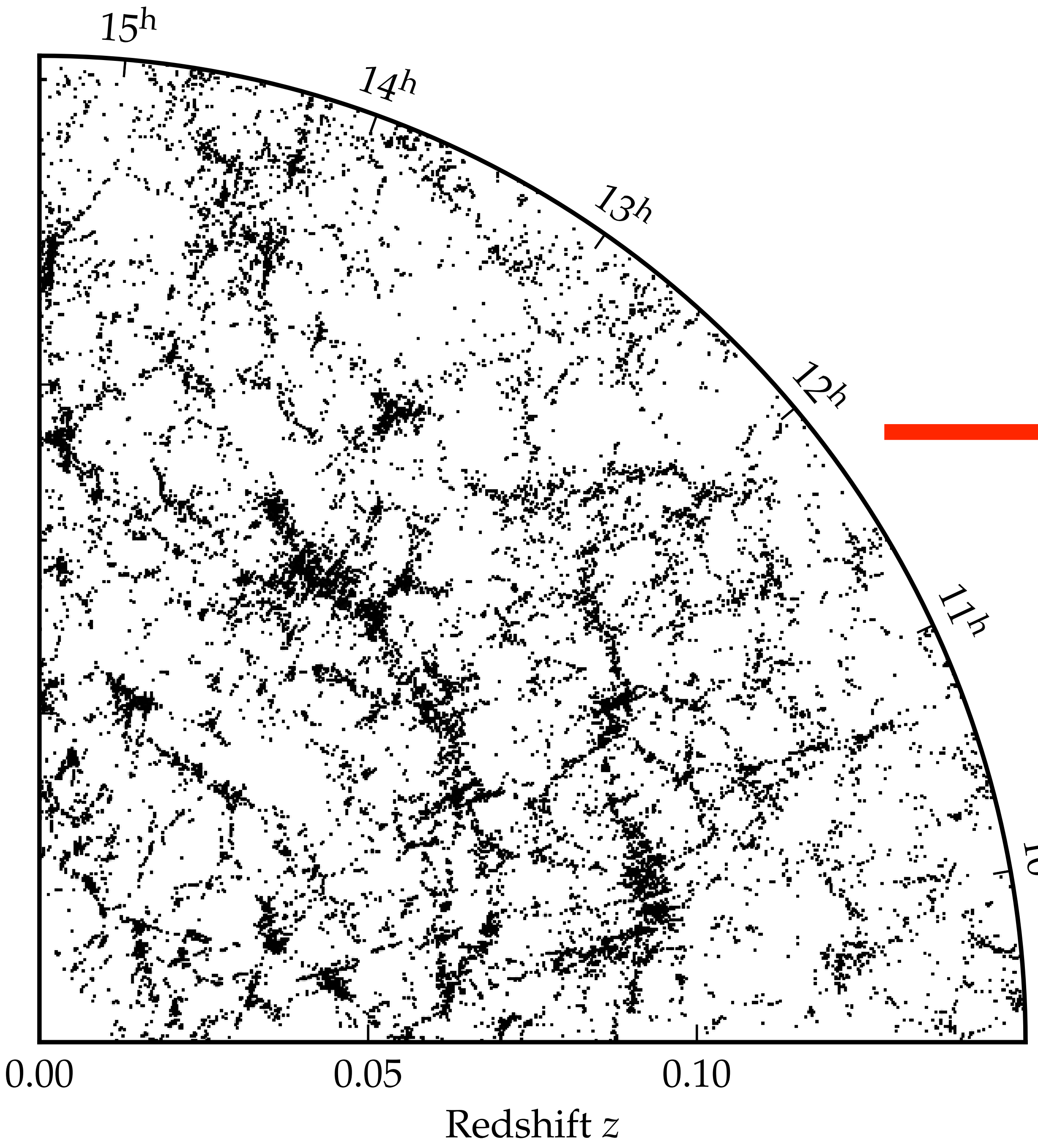
CMB angular power spectrum



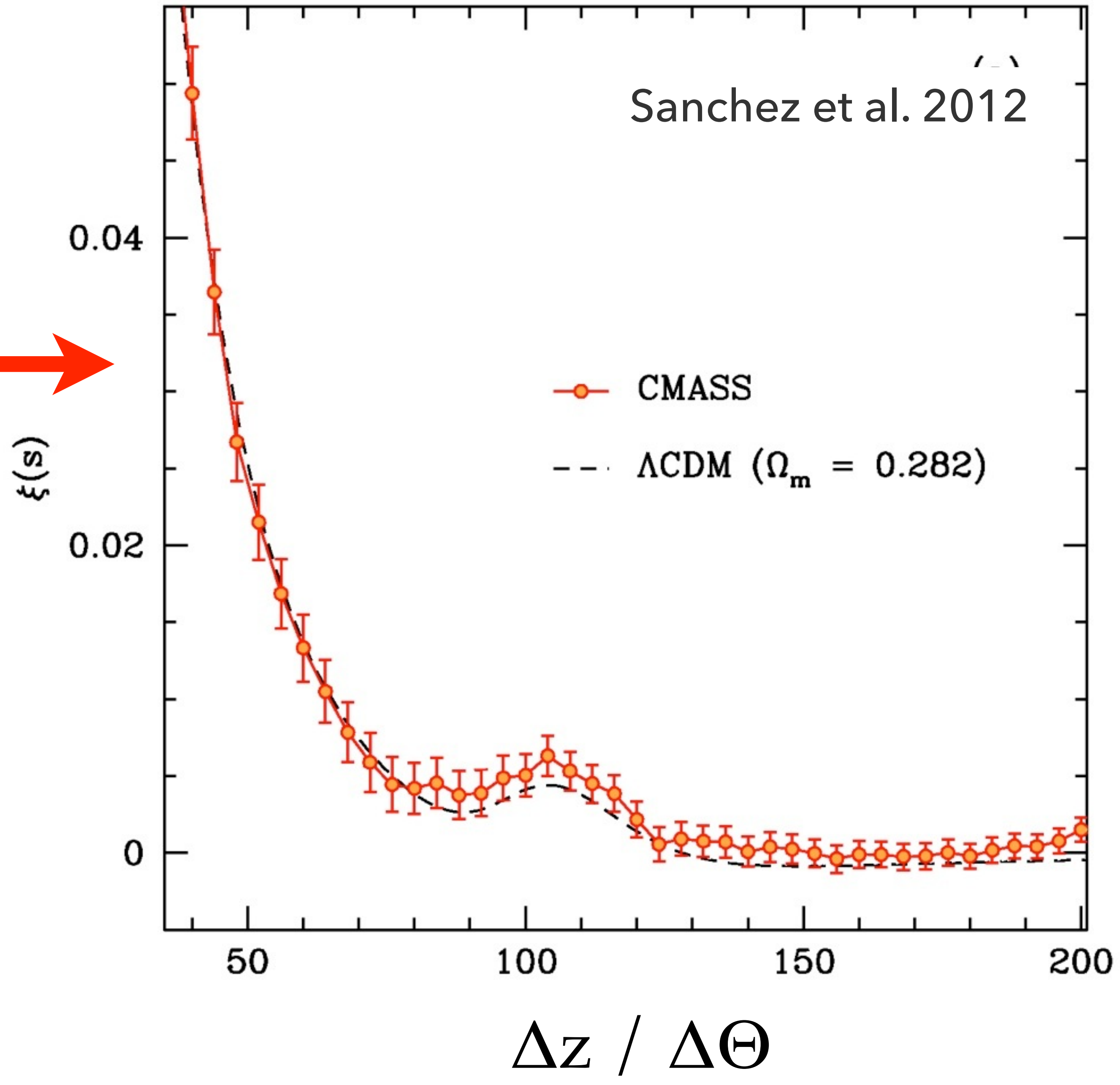
$$r_s = \int_0^{\tau_*} c_s d\tau \sim 100\, h^{-1}\,\mathrm{Mpc}$$

Known from CMB

Galaxy redshift surveys

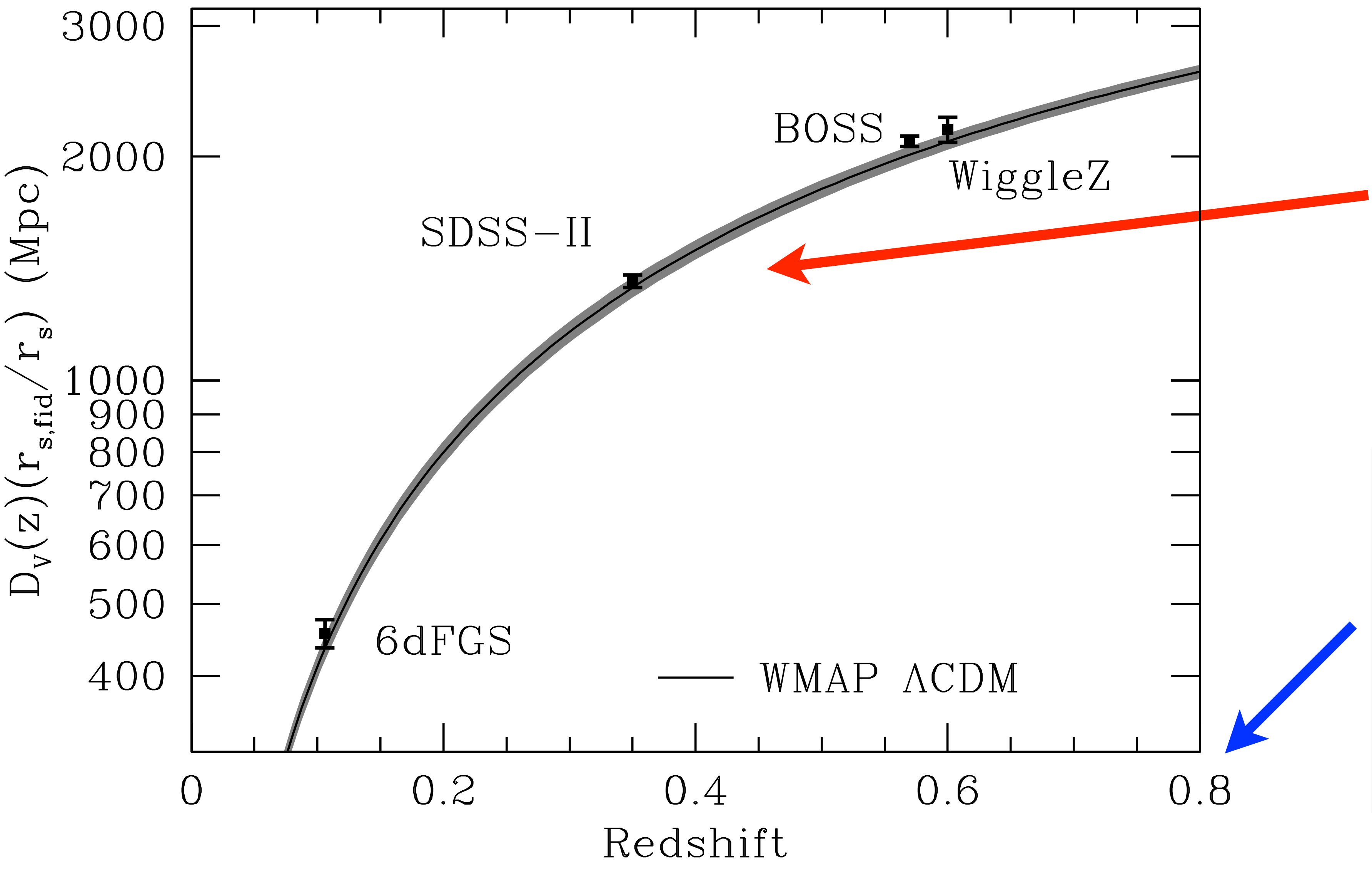


Galaxy Correlation Function


Sanchez et al. 2012

$$r_s = \Delta\theta \, d_A(z) \qquad r_s = \frac{c\Delta z}{H(z)}$$

Baryon Acoustic Oscillations



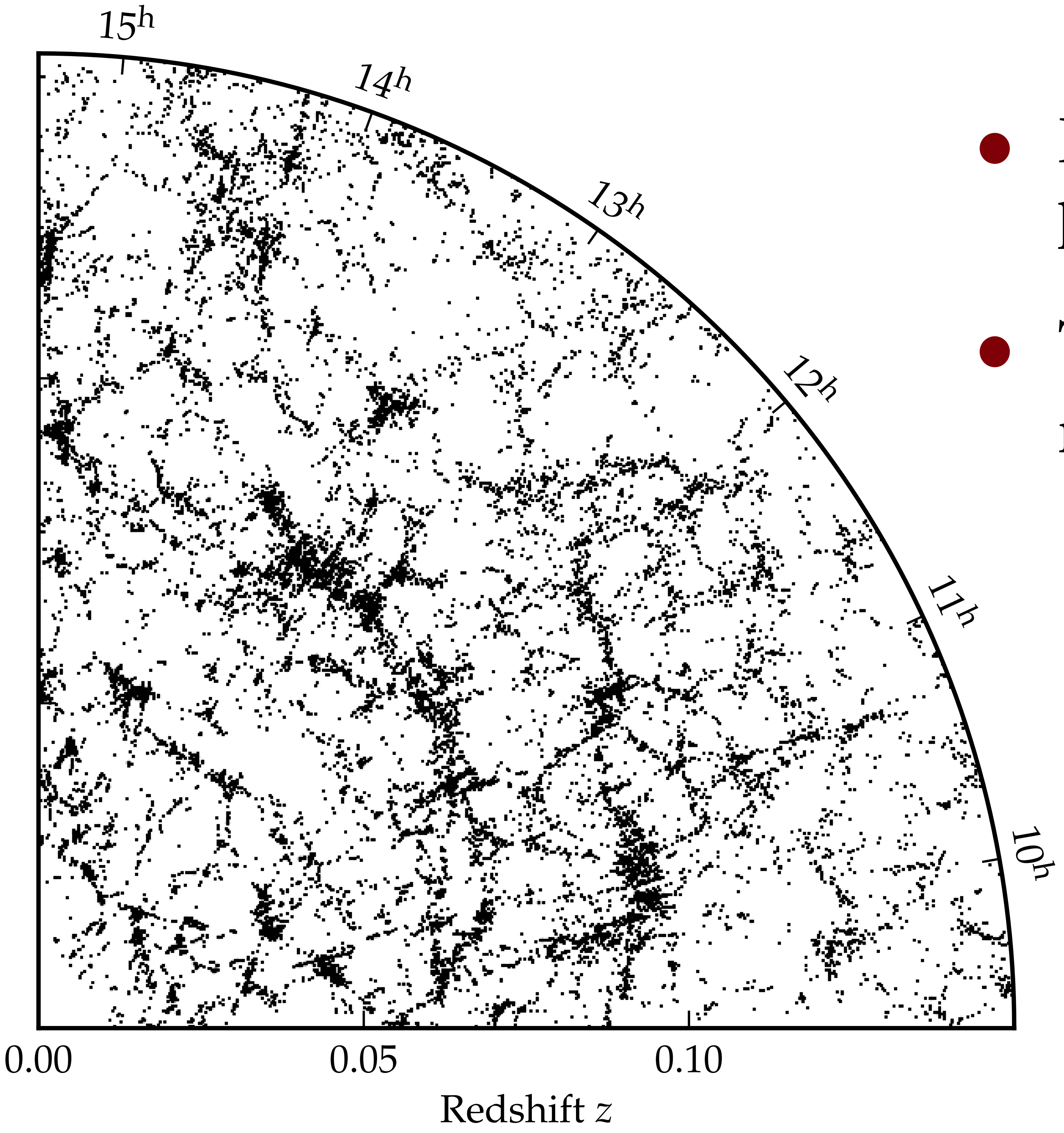
Shape of this curve given by expansion history/ contents of the Universe. Tells us about Dark Energy

Like to be able to measure this at higher redshifts z~1-2. Optically this is difficult - the "redshift desert"

- Potentially 21cm could extend this to higher redshifts

Anderson et al. 2012, http://arxiv.org/pdf/1105.2862

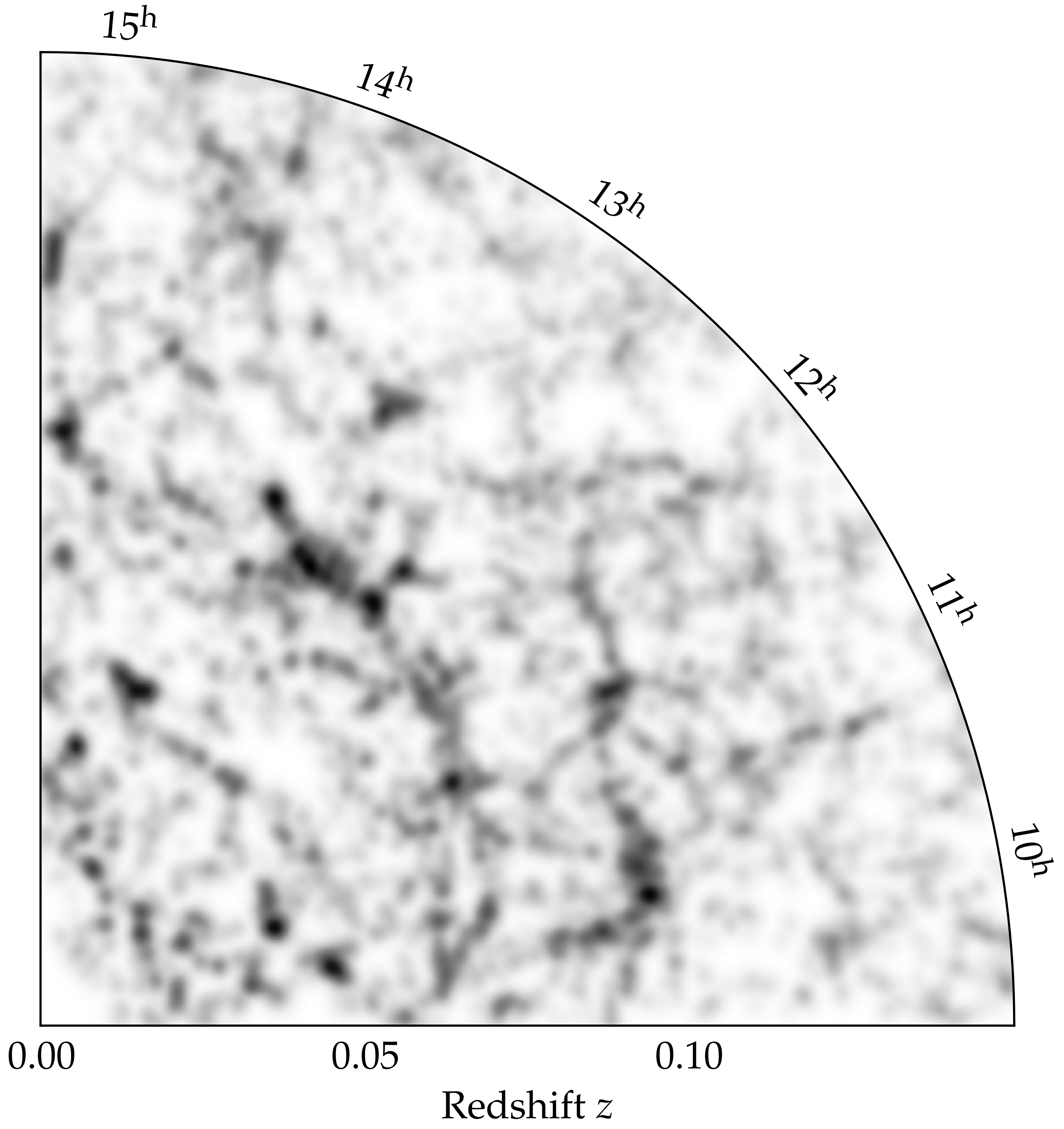
Galaxy Redshift Survey



- Detect all galaxies with high significance.
- Take spectra to determine redshift

Only interested in large scales

21cm Intensity Mapping

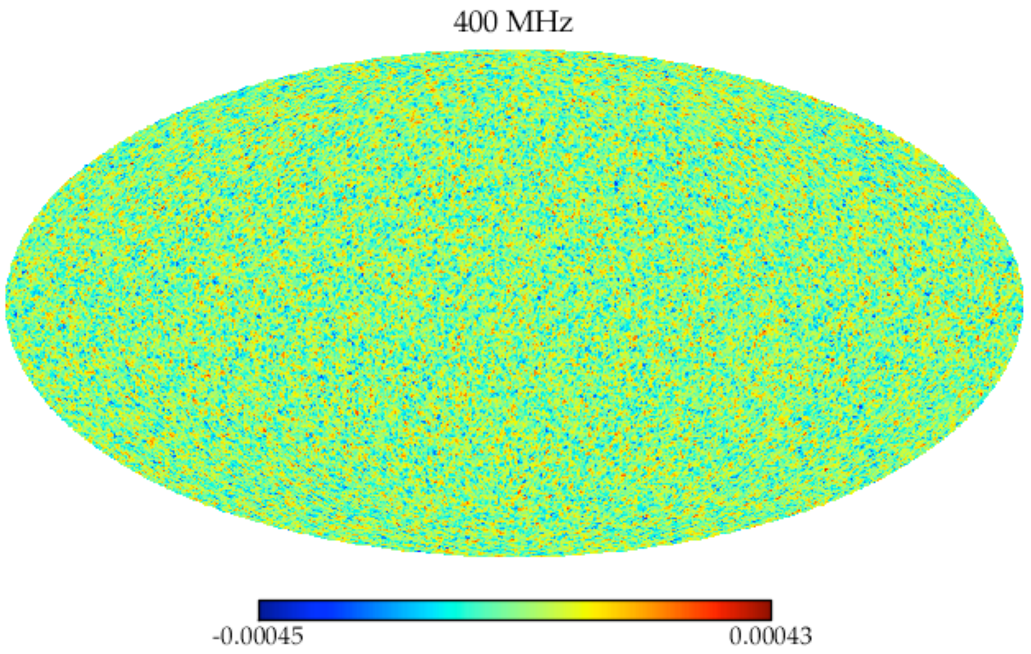


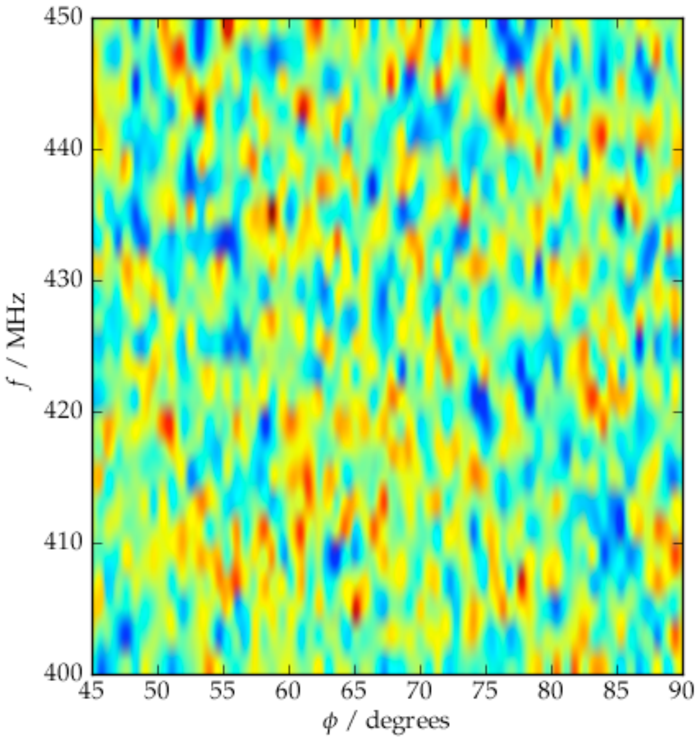
- Observe galaxies with 21cm line
- Automatically gives redshift

Don't need to resolve individual galaxies

Chang et al, 2008; Wyithe and Loeb 2008

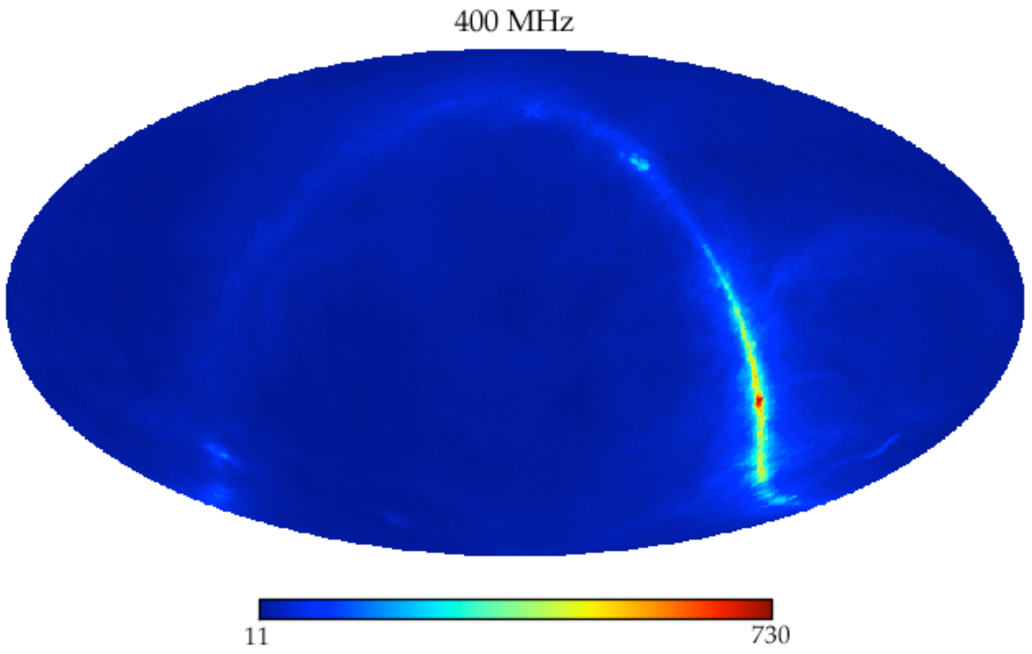
Why are 21cm observations hard?

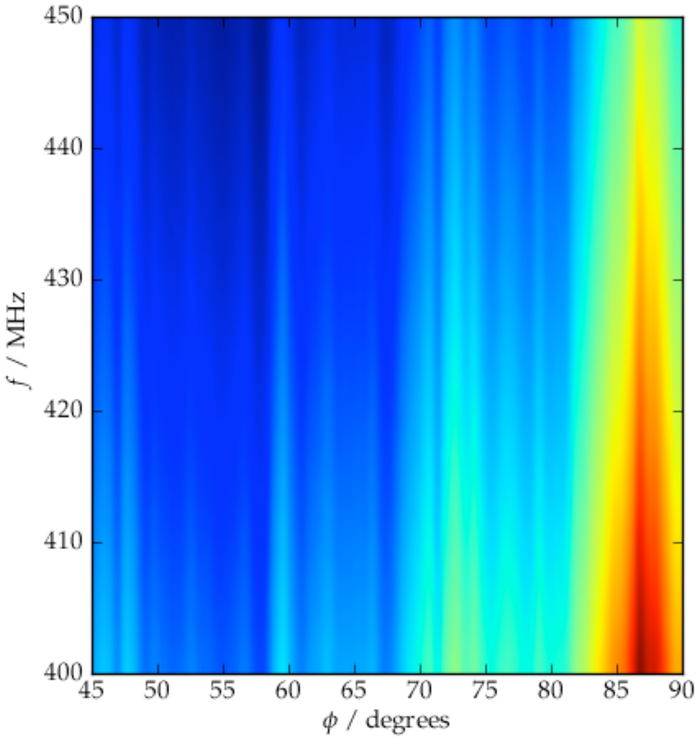




Cosmological
21cm Signal ~ 1mK

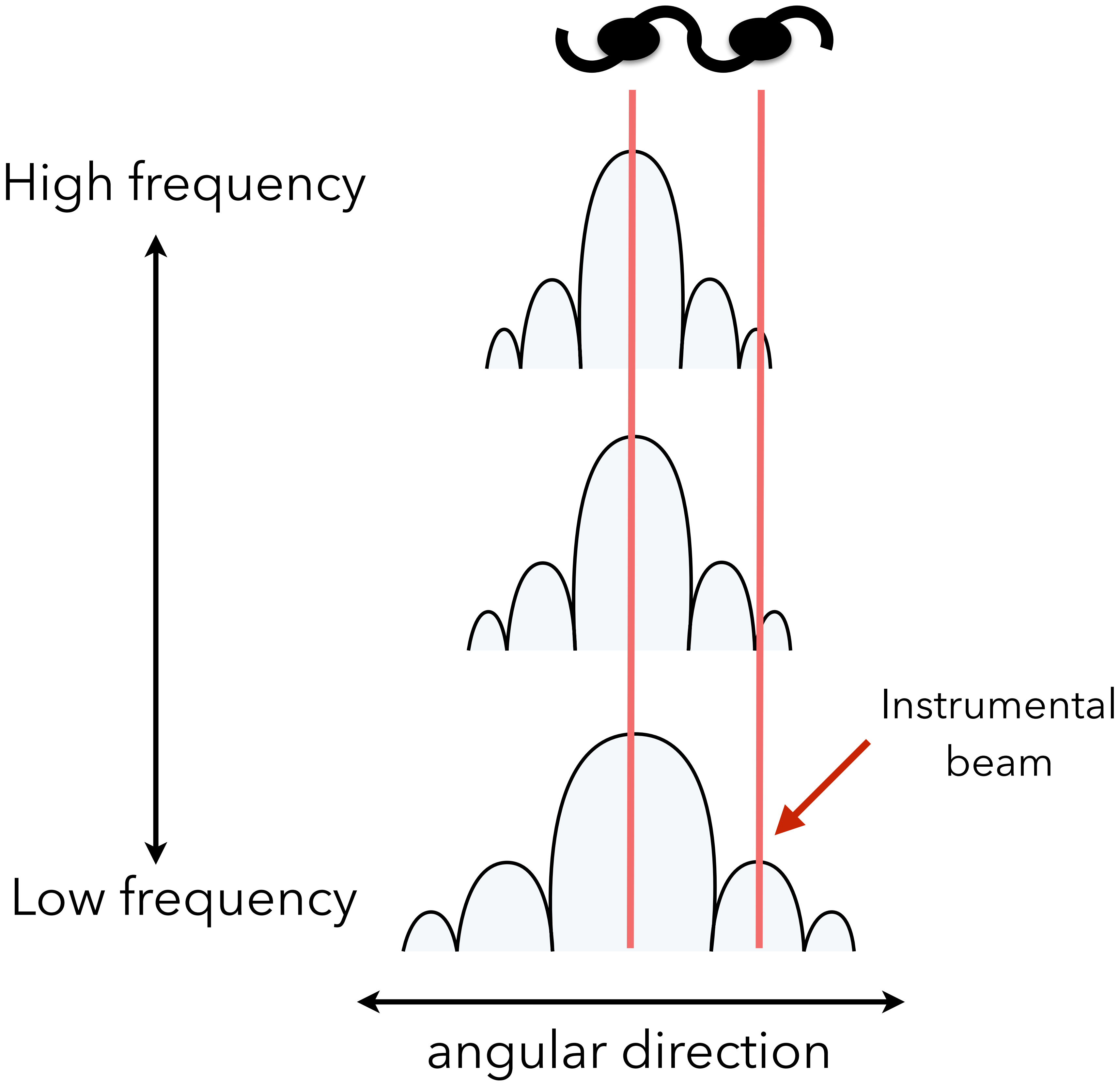
Remove smooth frequency modes





Galaxy: up to 700K

Issue 1: Mode mixing

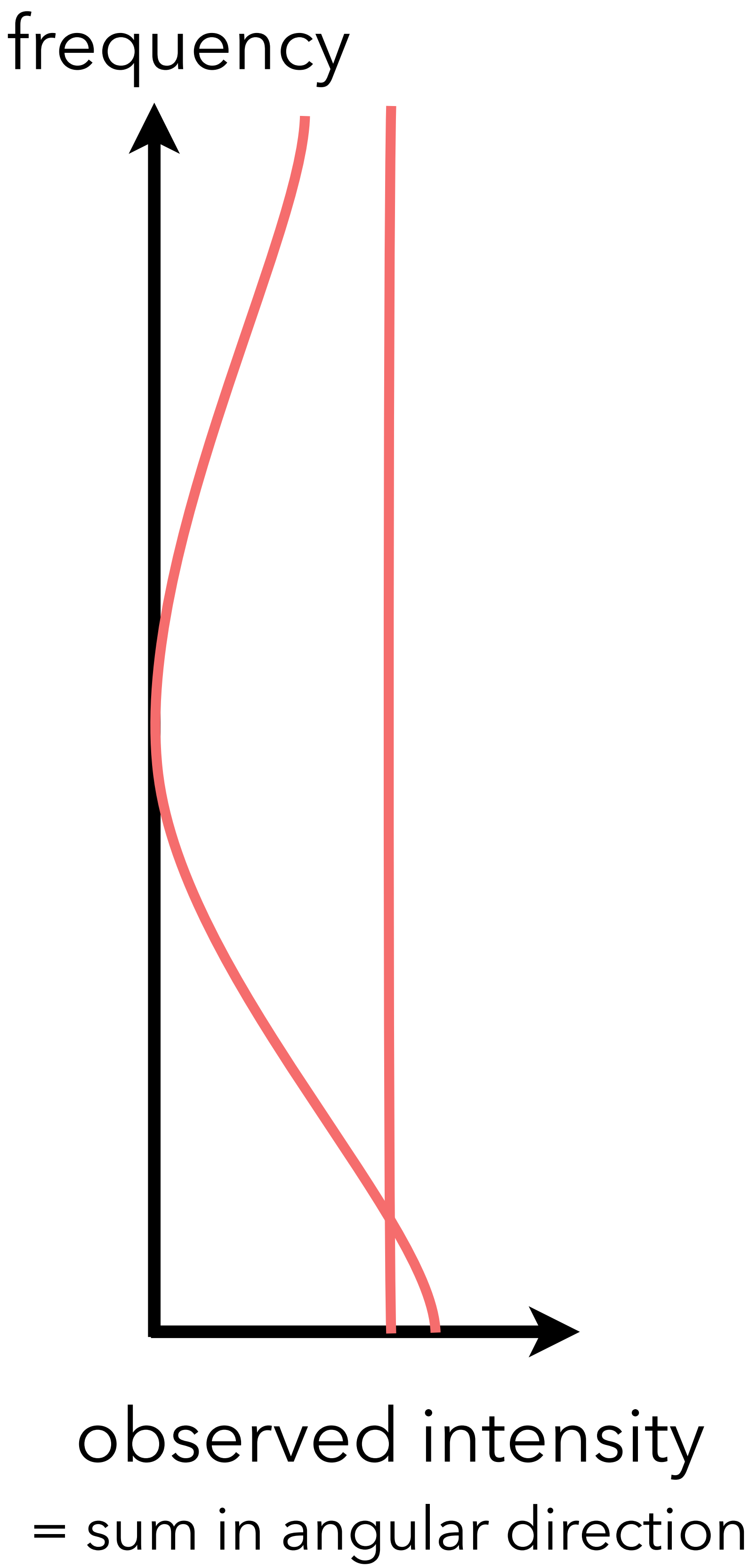


High frequency

Low frequency

Instrumental beam

angular direction



frequency

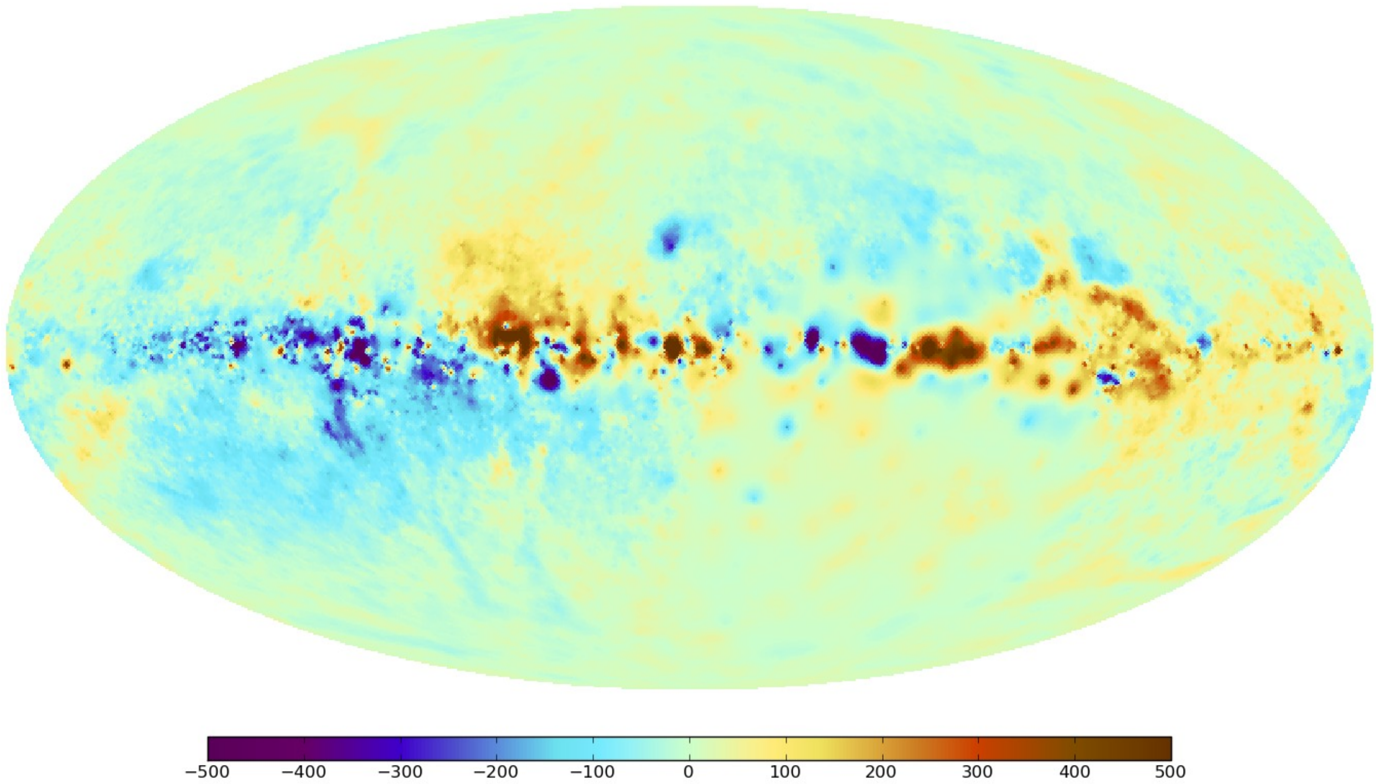
observed intensity

= sum in angular direction

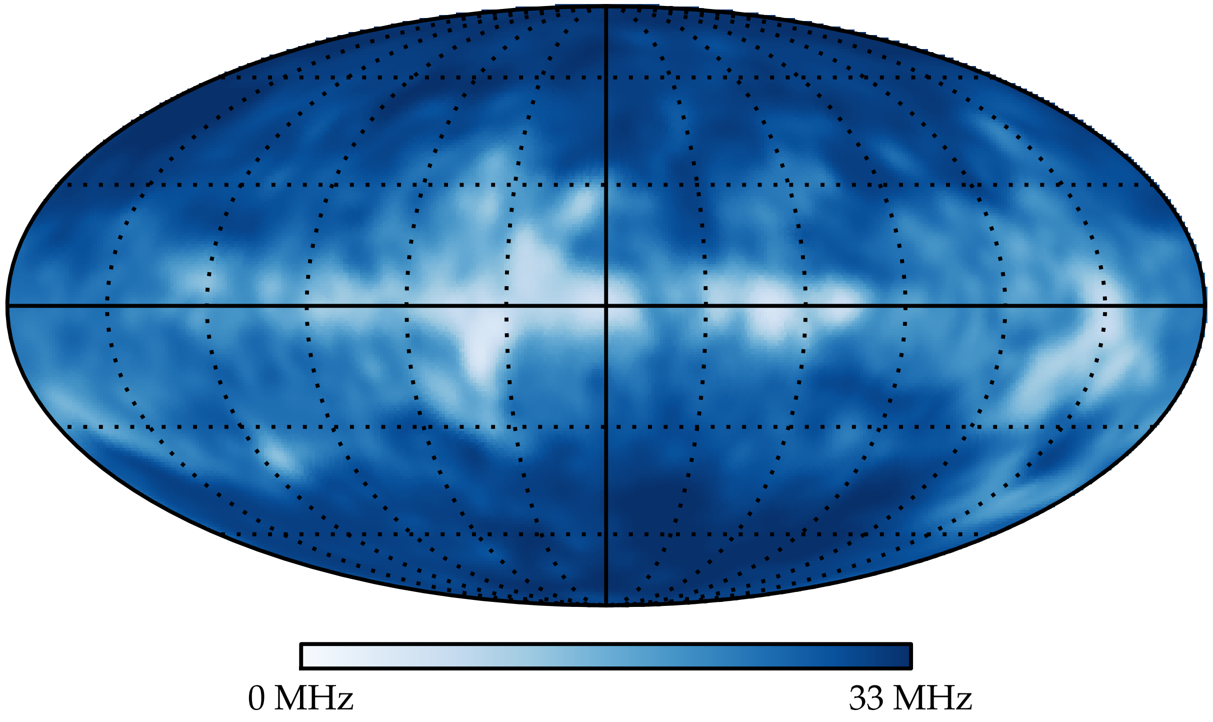
Issue 2: Polarised Foregrounds

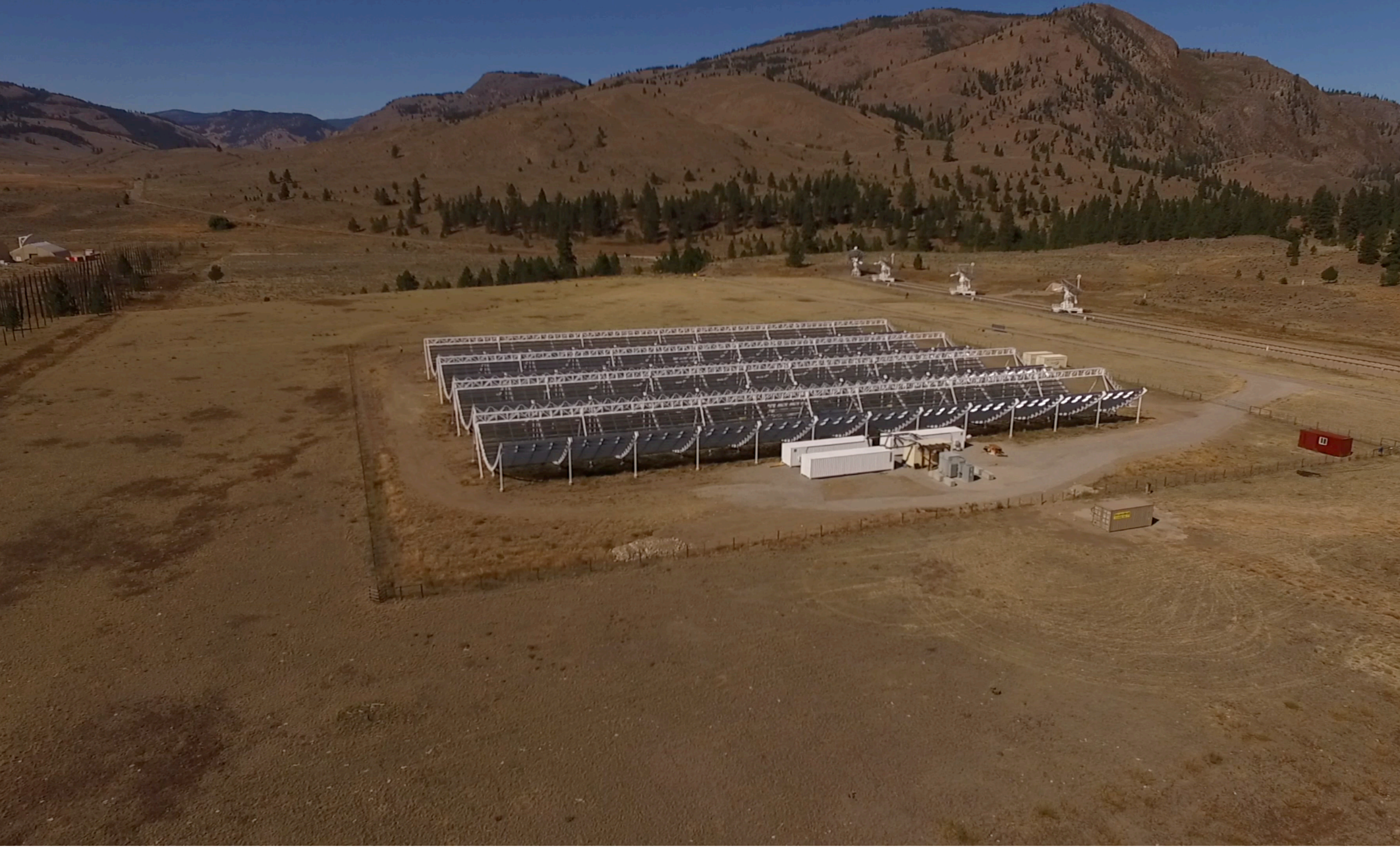
- Synchrotron is highly polarised (fraction ~0.5)
- Faraday rotation changes polarisation angle with frequency $\sim \mathrm{RM}\ \lambda^2$
- Instrumental polarisation leakage causes it to mix P->I

Rotation measure through our galaxy (Oppermann et al., 2012)



Correlation length from simulation





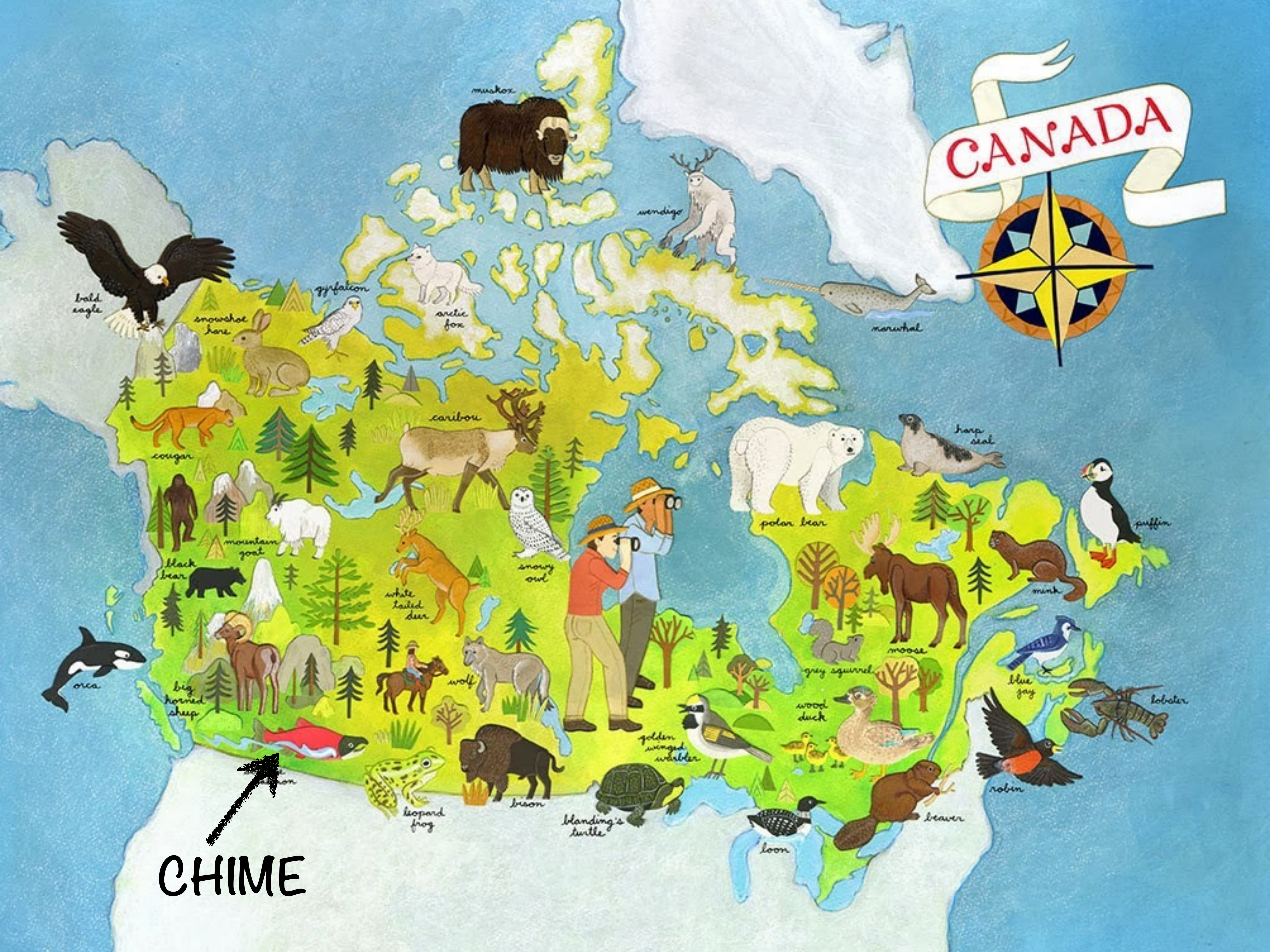
McGill

UBC

DRAO NRC·CNRC

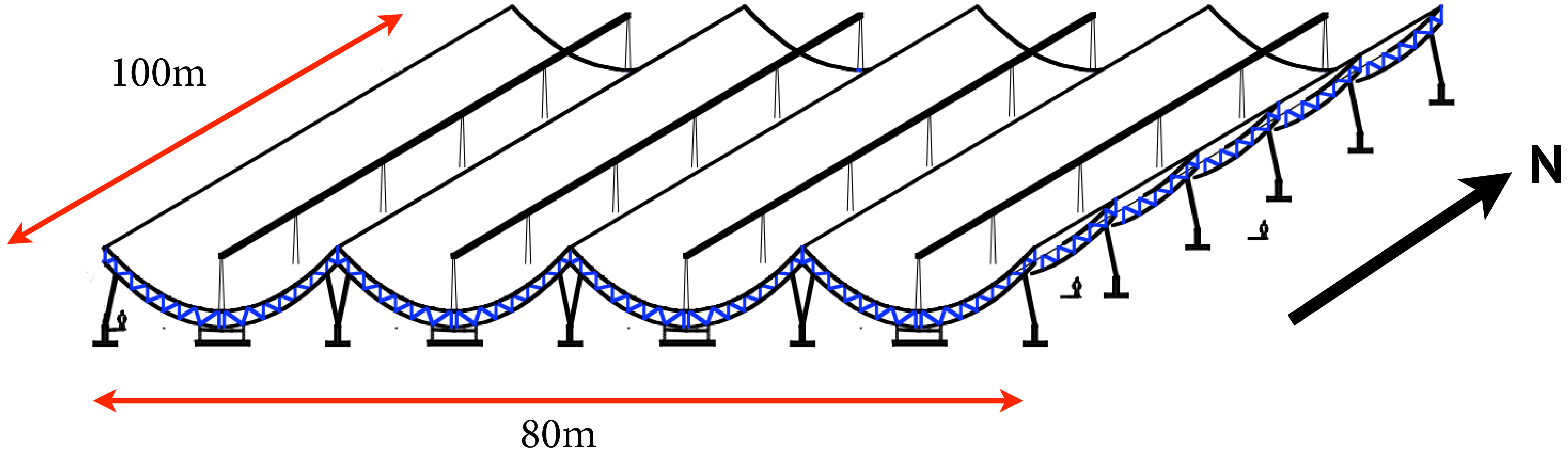
UNIVERSITY OF TORONTO

chime

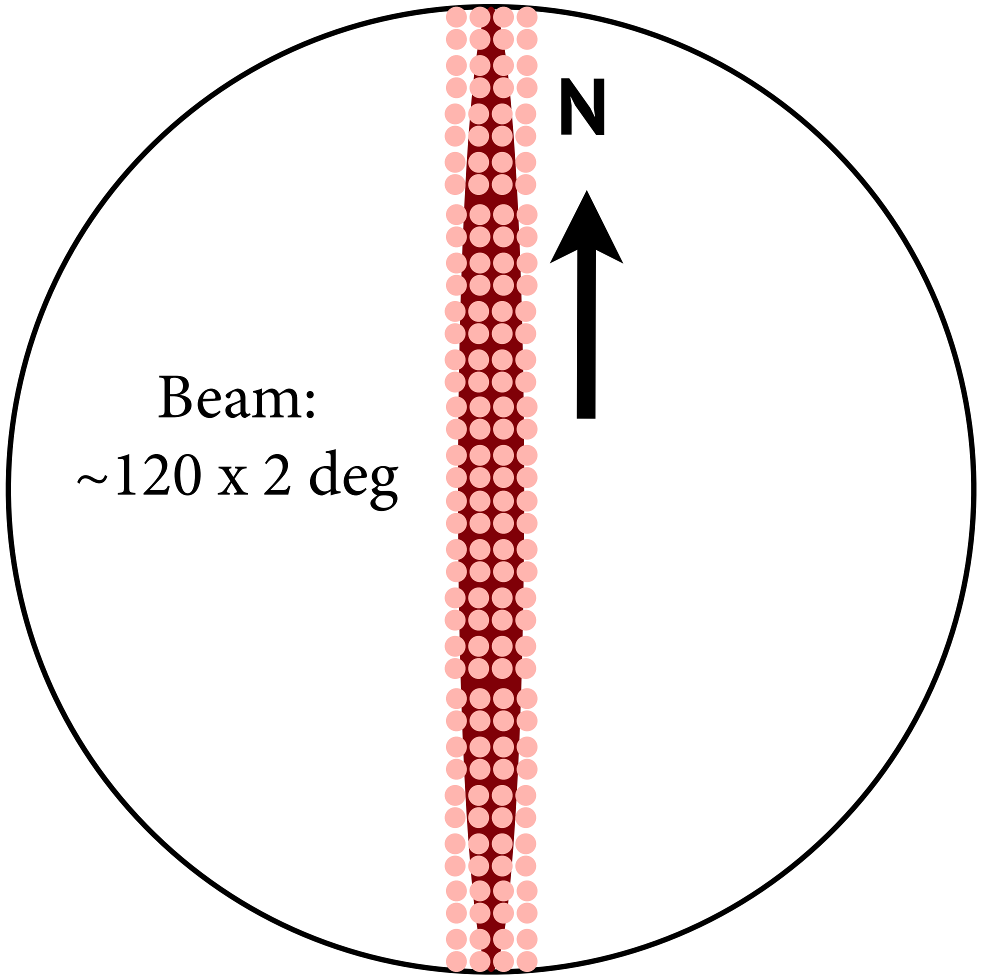

CANADA
muskox
wendigo
narwhal
bald eagle
gyrfalcon
snowshoe hare
arctic fox
cougar
caribou
harp seal
polar bear
puffin
mountain goat
black bear
white tailed deer
snowy owl
mink
moose
grey squirrel
blue jay
lobster
orca
big horned sheep
wolf
wood duck
golden winged warbler
robin
leopard frog
bison
blanding's turtle
loon
beaver

CHIME

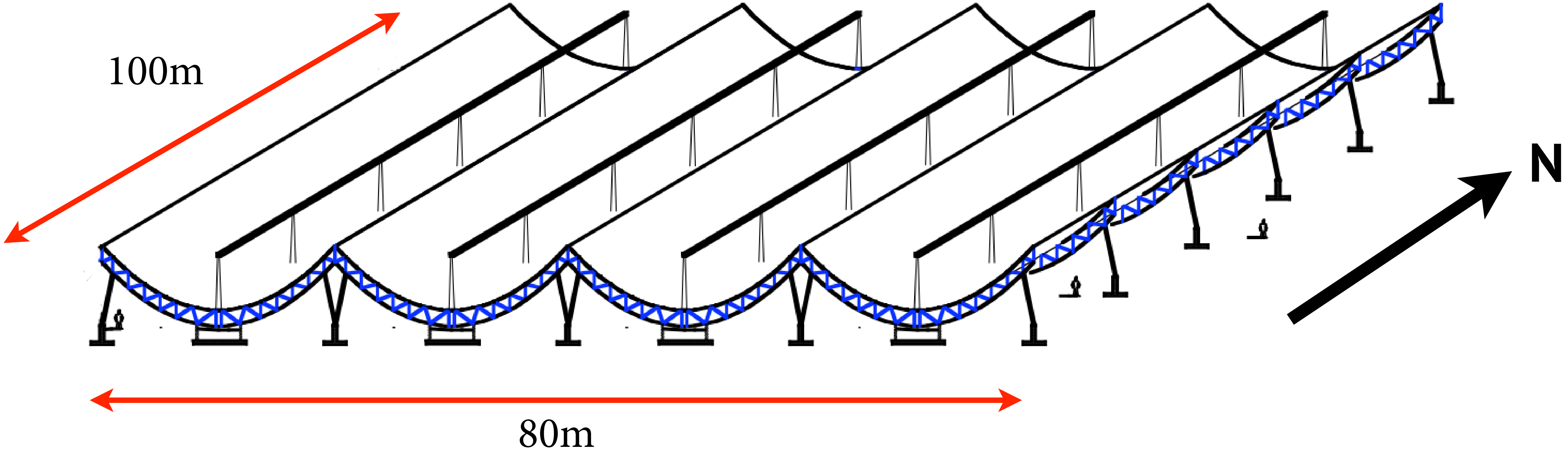
CHIME Overview



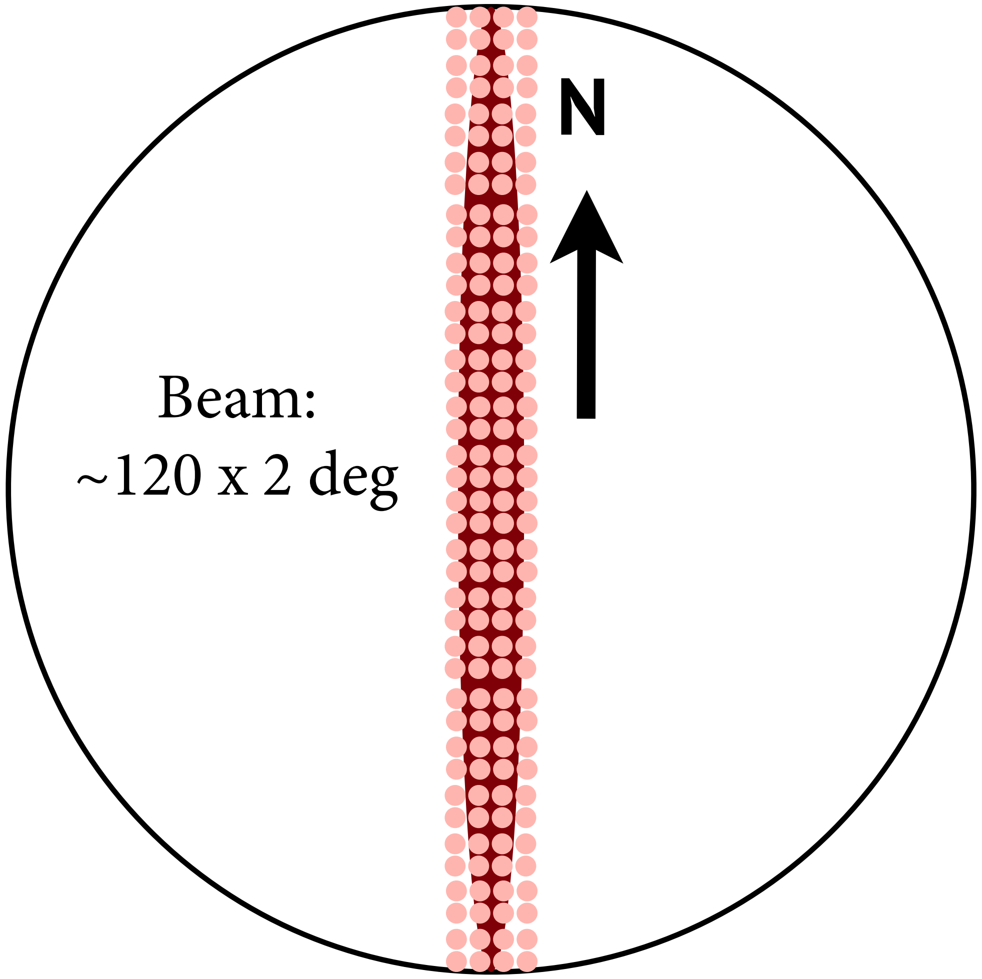
- 120 x 2 degree FoV
- 7x511 beams = 15 arcmin resolution
- Transit radio interferometer
  - Observe between 400-800 MHz
  - 1024 dual pol antennas ($T_{recv} = 50K$)
- Located at DRAO in BC
- Observations started March 2018



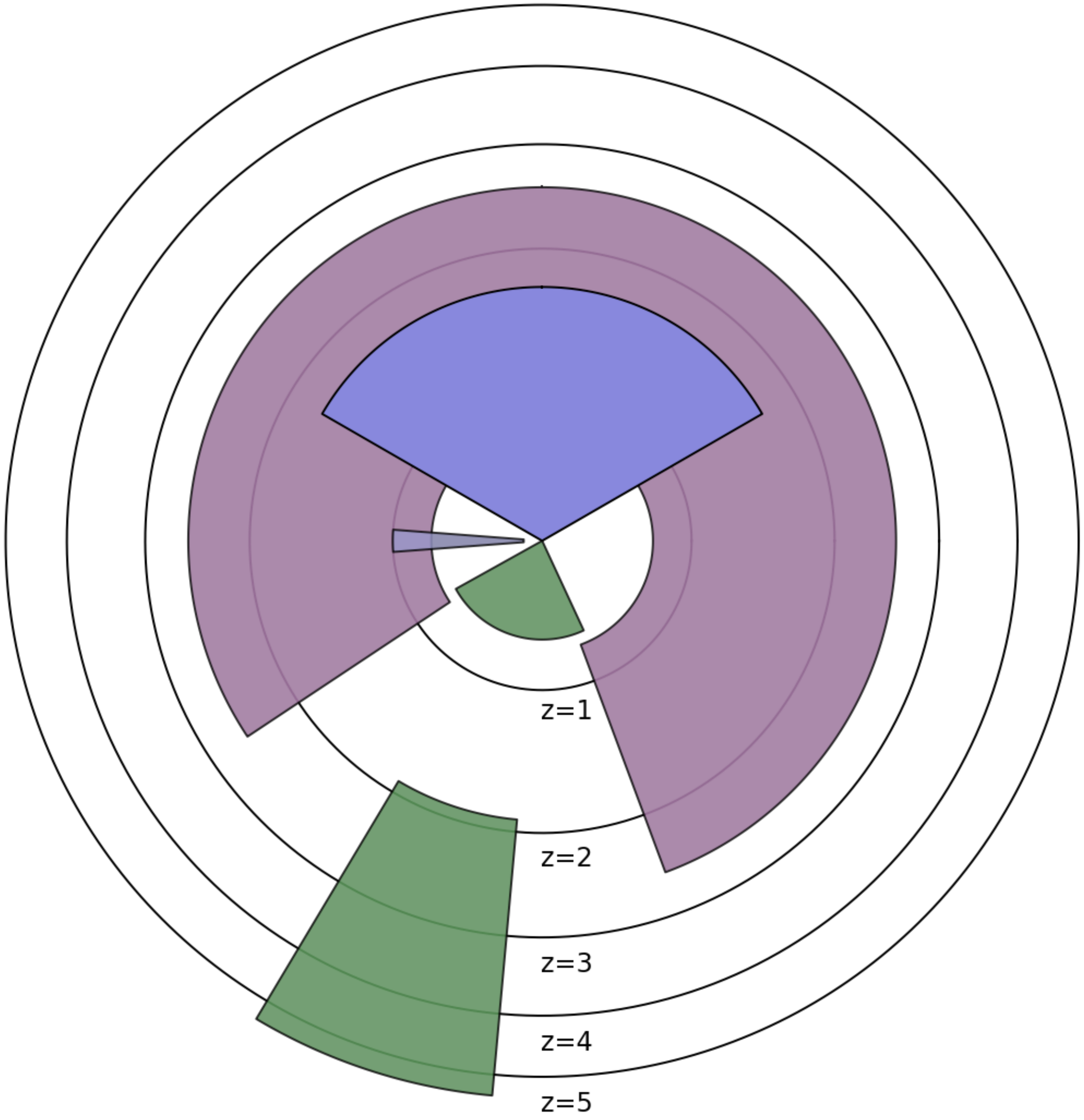
CHIME Overview



- Science Goals
  - **Intensity mapping for BAOs**
  - Fast Radio Bursts
  - Pulsar observations



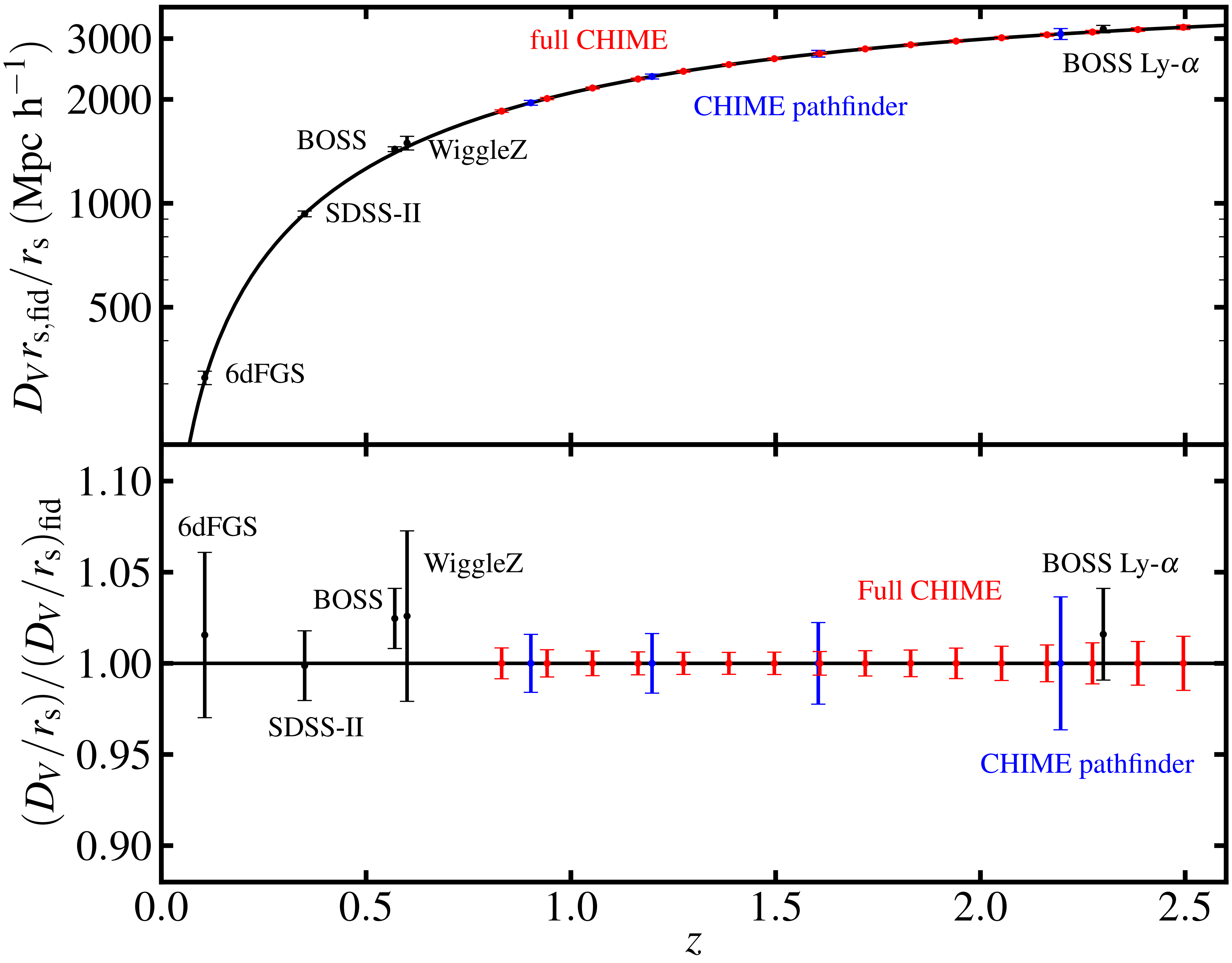
Survey Volume



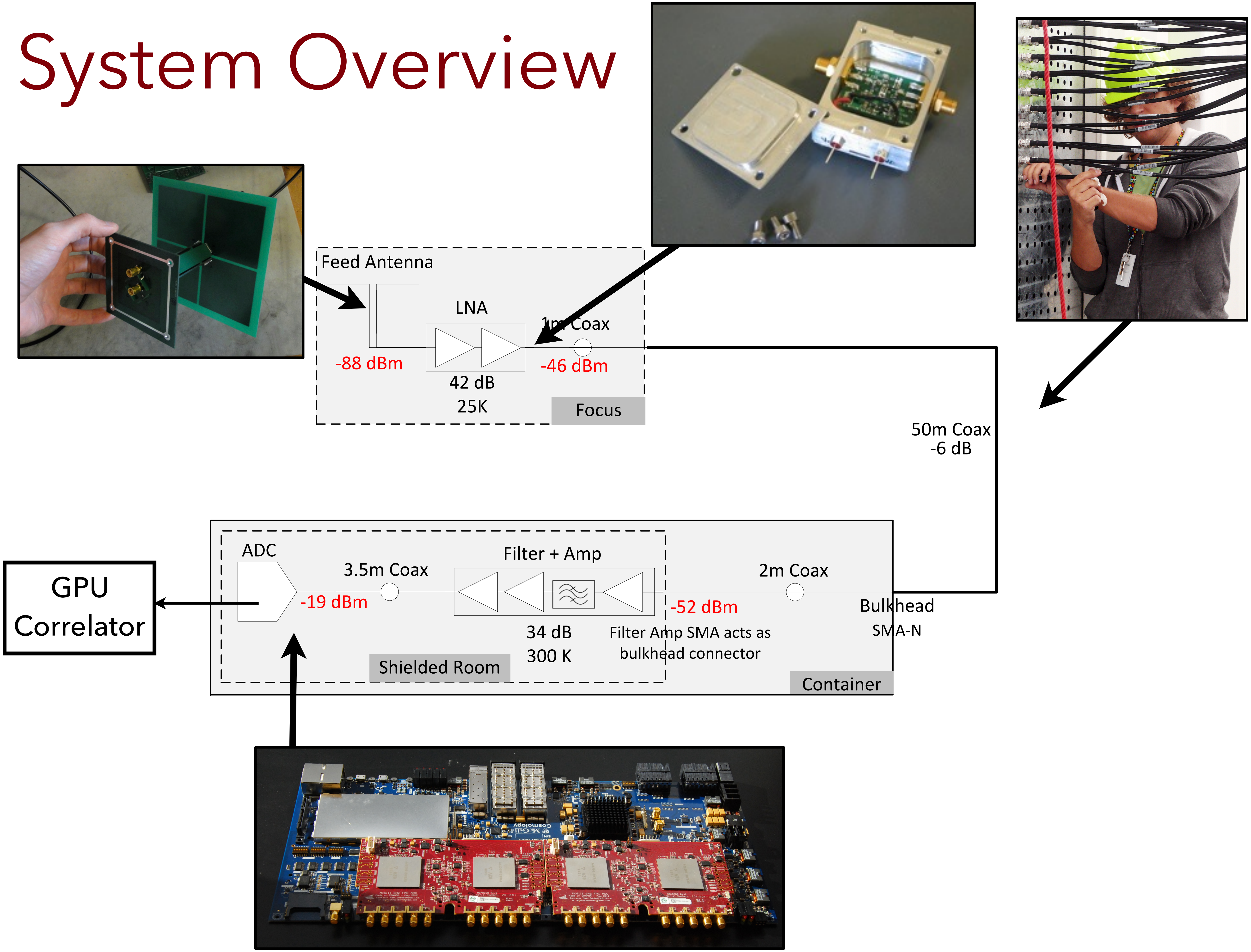
- 🟪 WiggleZ: 1.2 (h^{-1} Gpc)^3
- 🟩 BOSS
    - LRG: 5.3 (h^{-1} Gpc)^3
    - Lyα: 37 (h^{-1} Gpc)^3
- 🟪 CHIME: 203 (h^{-1} Gpc)^3
- 🟦 DESI ELG: 50 (h^{-1} Gpc)^3

Scaled such that:
area of patch=volume of survey

BAO Forecasts



System Overview



Feed Antenna

LNA

1m Coax

-88 dBm

-46 dBm

42 dB

25K

Focus

50m Coax
-6 dB

ADC

3.5m Coax

Filter + Amp

2m Coax

-19 dBm

-52 dBm

Bulkhead
SMA-N

34 dB
300 K

Filter Amp SMA acts as
bulkhead connector

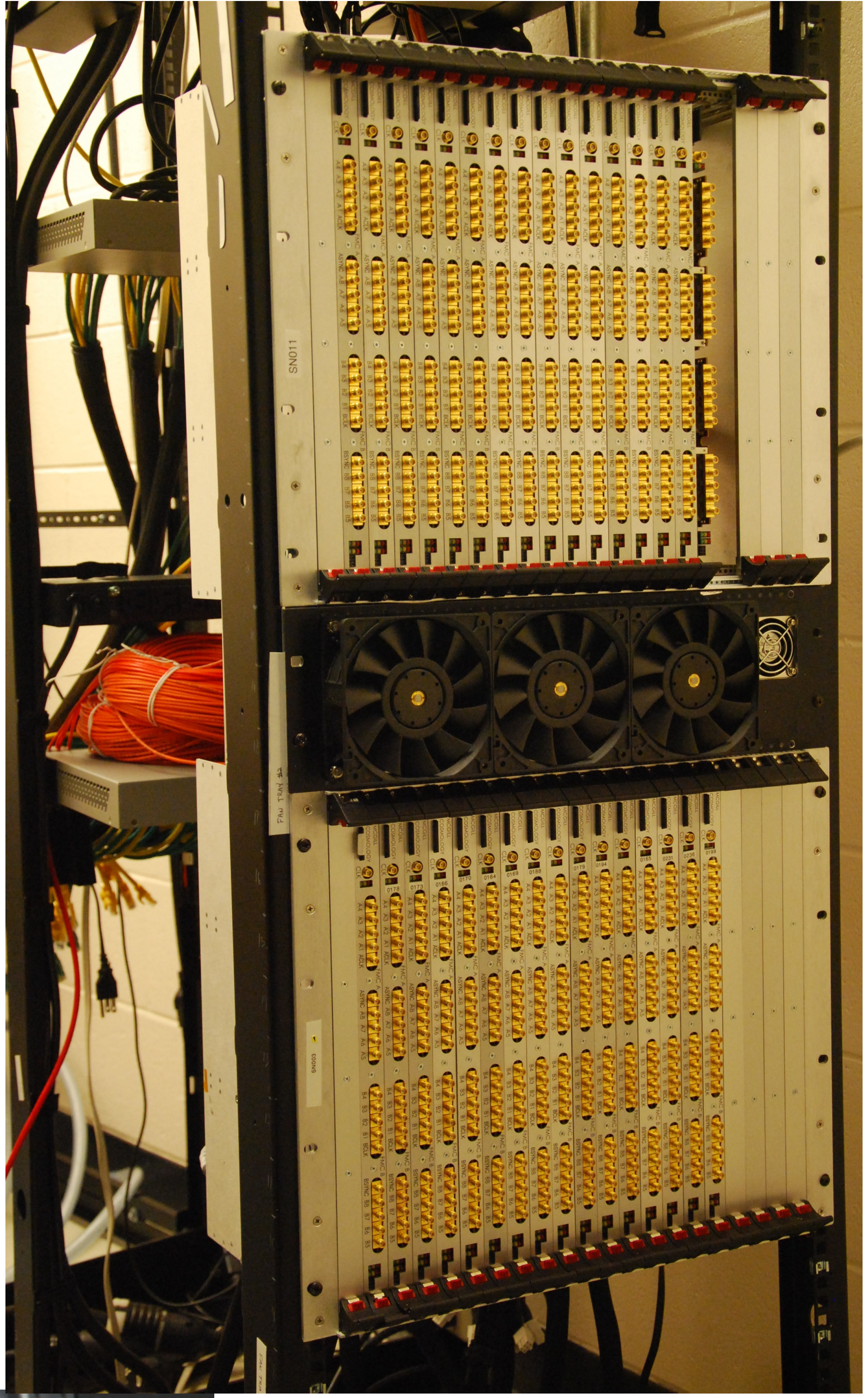
Shielded Room

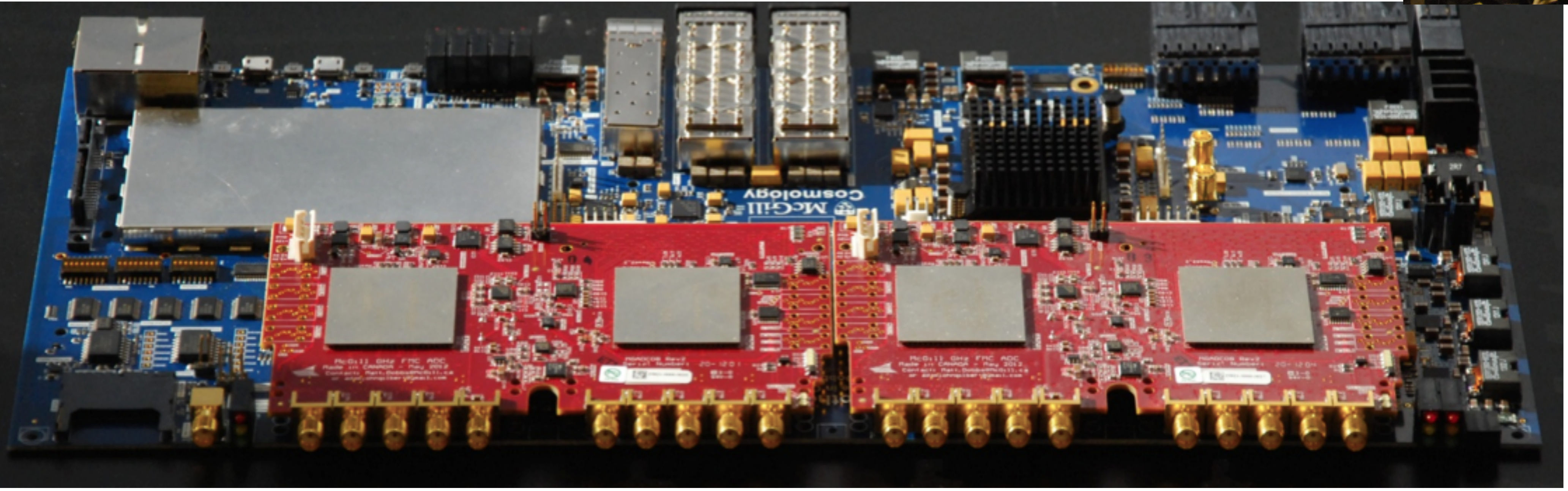
Container

GPU
Correlator

Correlator: F-engine

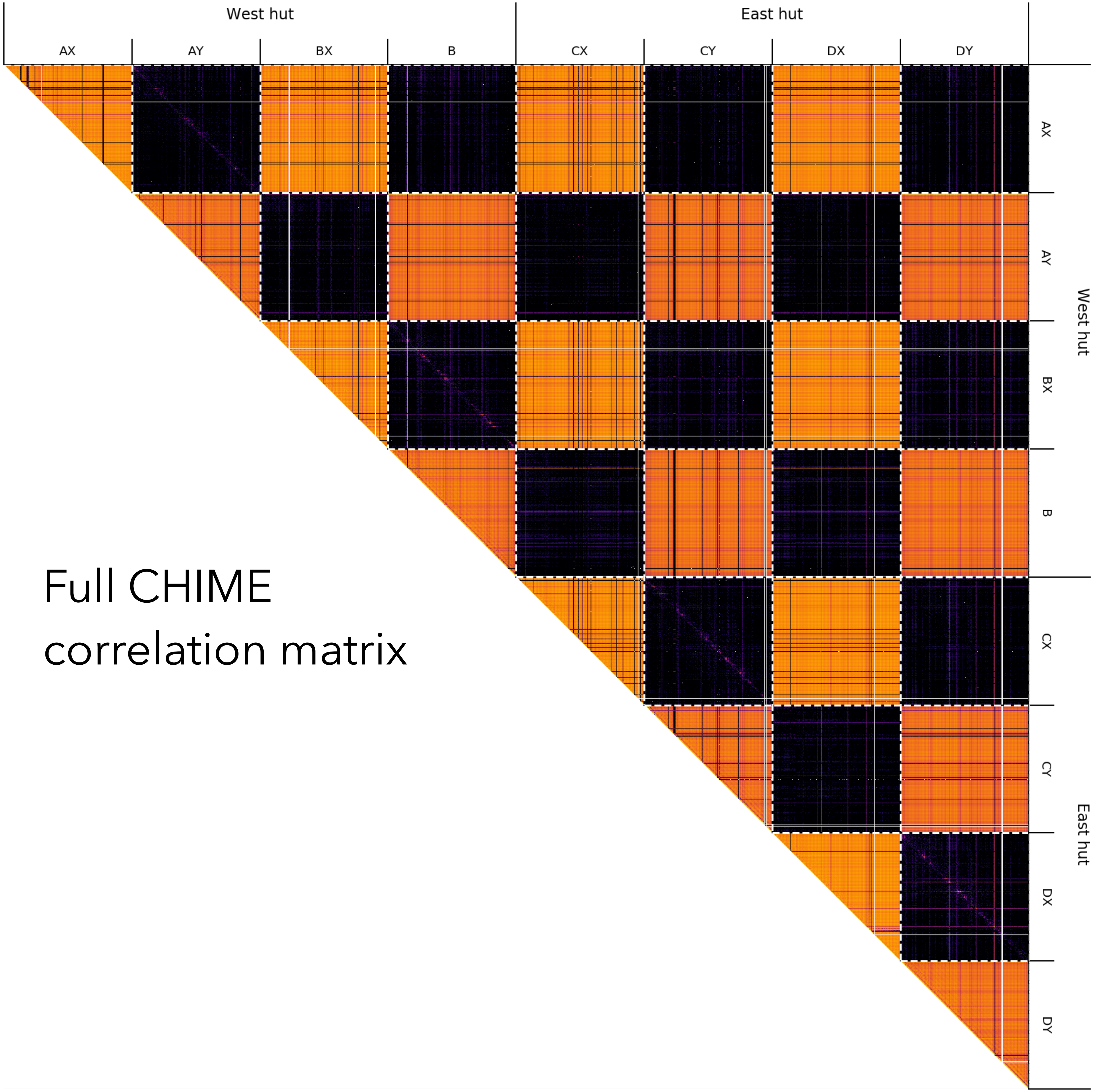
- Uses ‘ICE’ boards developed by team at McGill
- Signal from each antenna is sampled at 800 MHz
    - Each board processes, 16 inputs @ 8 bits **96 Gb/s**
    - CHIME has 128 boards **13 Tb/s**
- Raw time stream turned into frequency channels on FPGAs



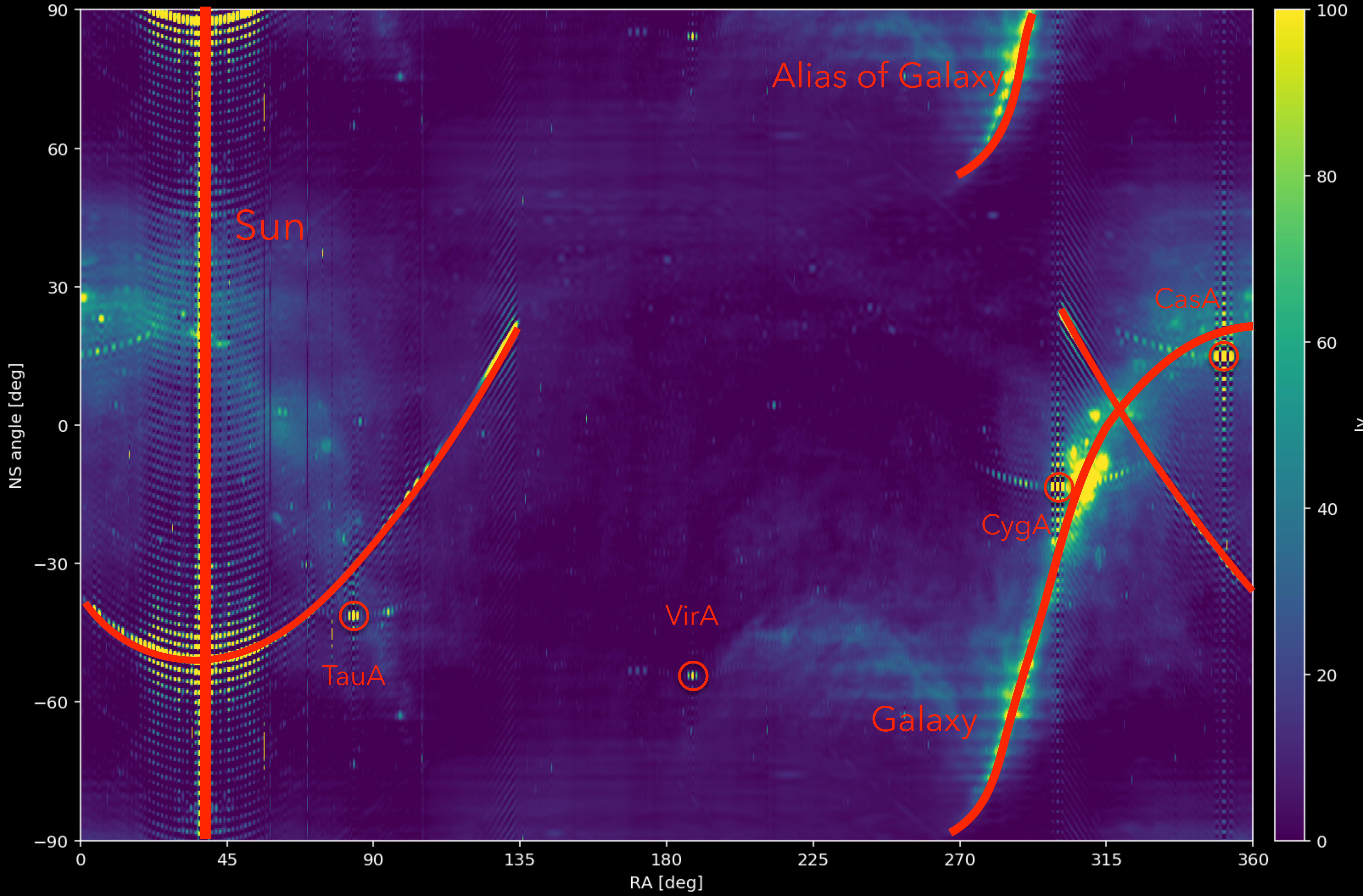


Correlator: X-engine

- Full pairwise multiplication then accumulation in time
- Computationally hard (**1.6 Peta M/s**)
  - ALMA ~ 0.25 PetaM/s
  - Use GPUs (1024 AMD Fiji cores)
  - Efficient: ~**50 GigaOP/W**
  - Built by Keith Vanderlinde at University of Toronto

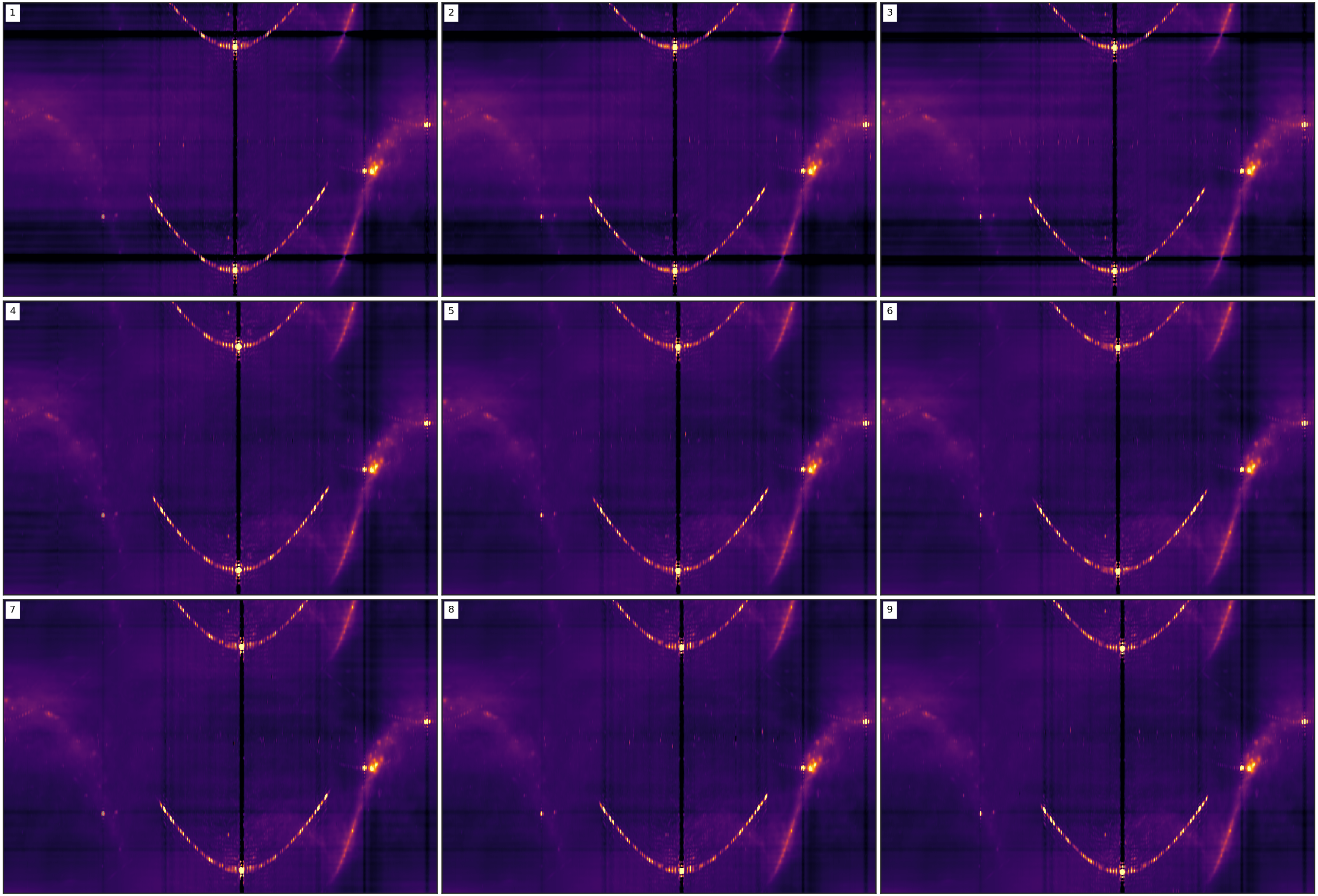


Full CHIME
correlation matrix



Map uses 10^{-6} of all CHIME data collected so far

Map from Seth Siegel

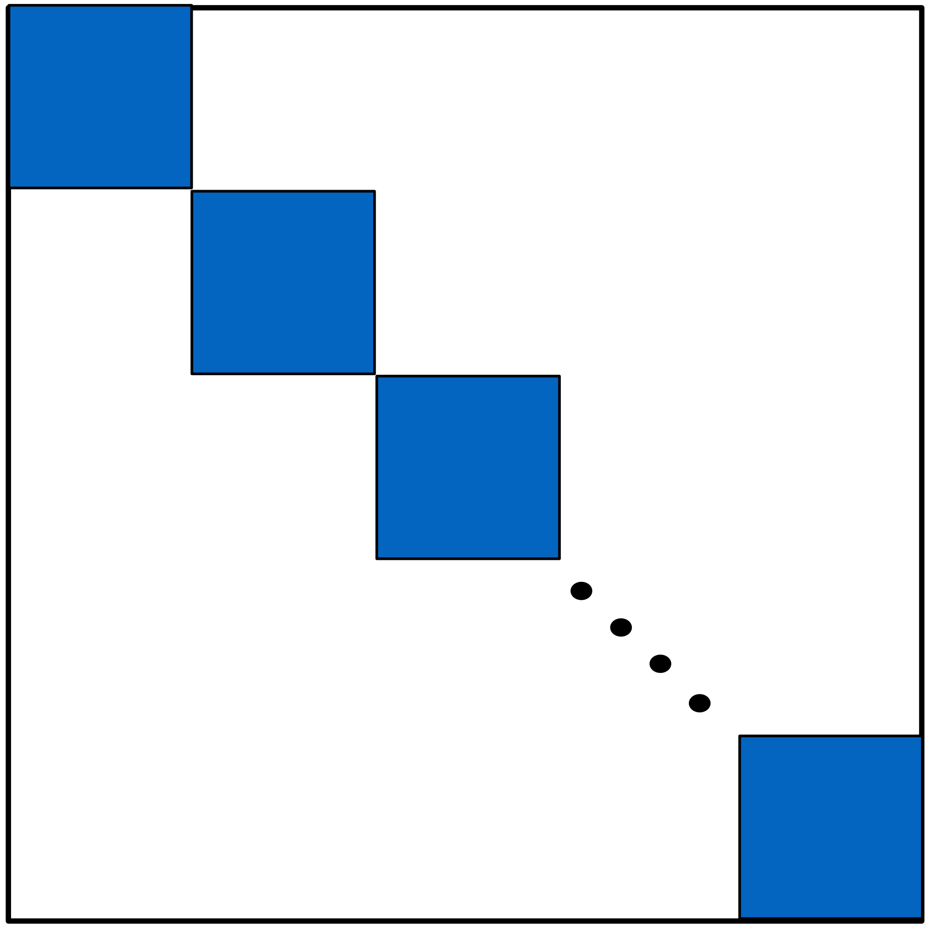

1
2
3
4
5
6
7
8
9

Data deluge

- Data volume
  - Easy(ish) problem to solve
  - CHIME pathfinder ~32k pairs, 1k freq, 20s sampling (**~1 TB/day**)
  - CHIME ~2M pairs, 10s sampling (**~210 TB/day**)
  - Nearly lossless compression (***bitshuffle***) ~ 4x
  - Collapse redundant pairs (lossy) ~50x; total (~ 360 TB/year)
- Degrees of freedom
  - 10^3 frequency channels, 10^4 unique baselines, 10^3 independent time samples per day; **total 10^{10}** correlated degrees of freedom
  - Need an efficient analysis, how optimal can this be?
  - Most analysis needs at least a covariance matrix (~10^{10} per side)

Finding sparsity

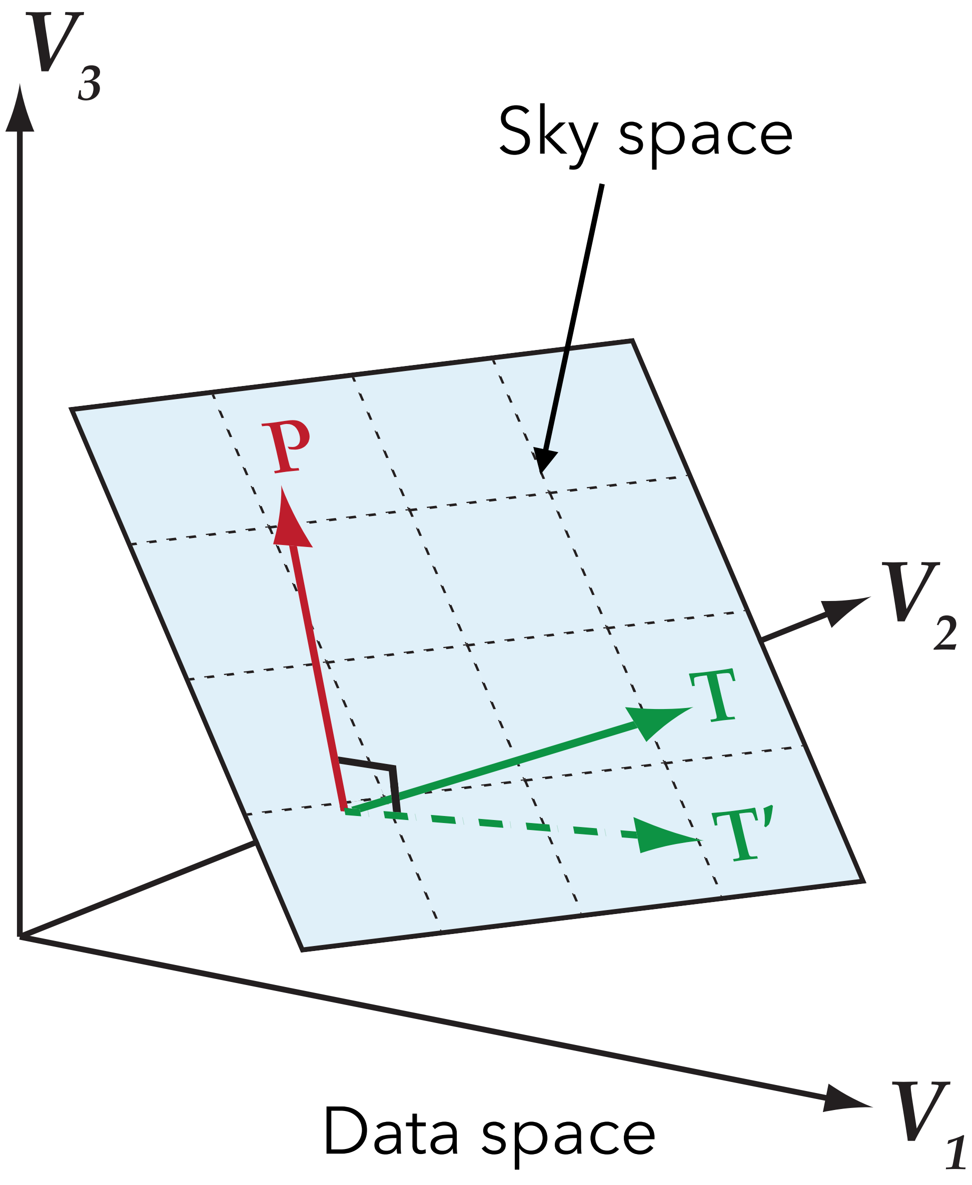
- For transit telescopes like CHIME we can make assumption about *stationarity* of noise in time.
- Implies there is a basis where statistics are block diagonal
  - Around 1000 separate blocks
  - Decomposition is now on 1000 matrices, each 1000 times smaller.
  - Saves factor of **10^6** in computation



Shaw et al. 2014, arXiv:1302.0327

Finding sparsity

- We have more measurements than there are degrees of freedom
  - Some combinations contain no information about the sky. Full of noise!
- To compress our data we can explicitly remove these
  - Per frequency SVD of telescope model to find modes
  - Reduce degrees of freedom by ~10x



Shaw et al. 2015, arXiv:1401.2095

m-mode analysis

- Require/exploit stationarity on the sidereal day.
- Gives ***m*-mode formalism** (*arXiv:1302.0327; arXiv:1401.2095*)
  - Transit telescopes only *(stationary noise)*
  - Naturally full sky, wide-field, and ***exact*** *(no UV plane)*
  - Breaks problem into statistically independent modes *(efficient)*
- Measurement is linear mapping for each mode:

$$\mathbf{v} = \mathbf{B}\,\mathbf{a} + \mathbf{n}\,.$$

  - Discrete, finite number of degrees of freedom
  - Maps between spherical harmonic and visibilities for each m

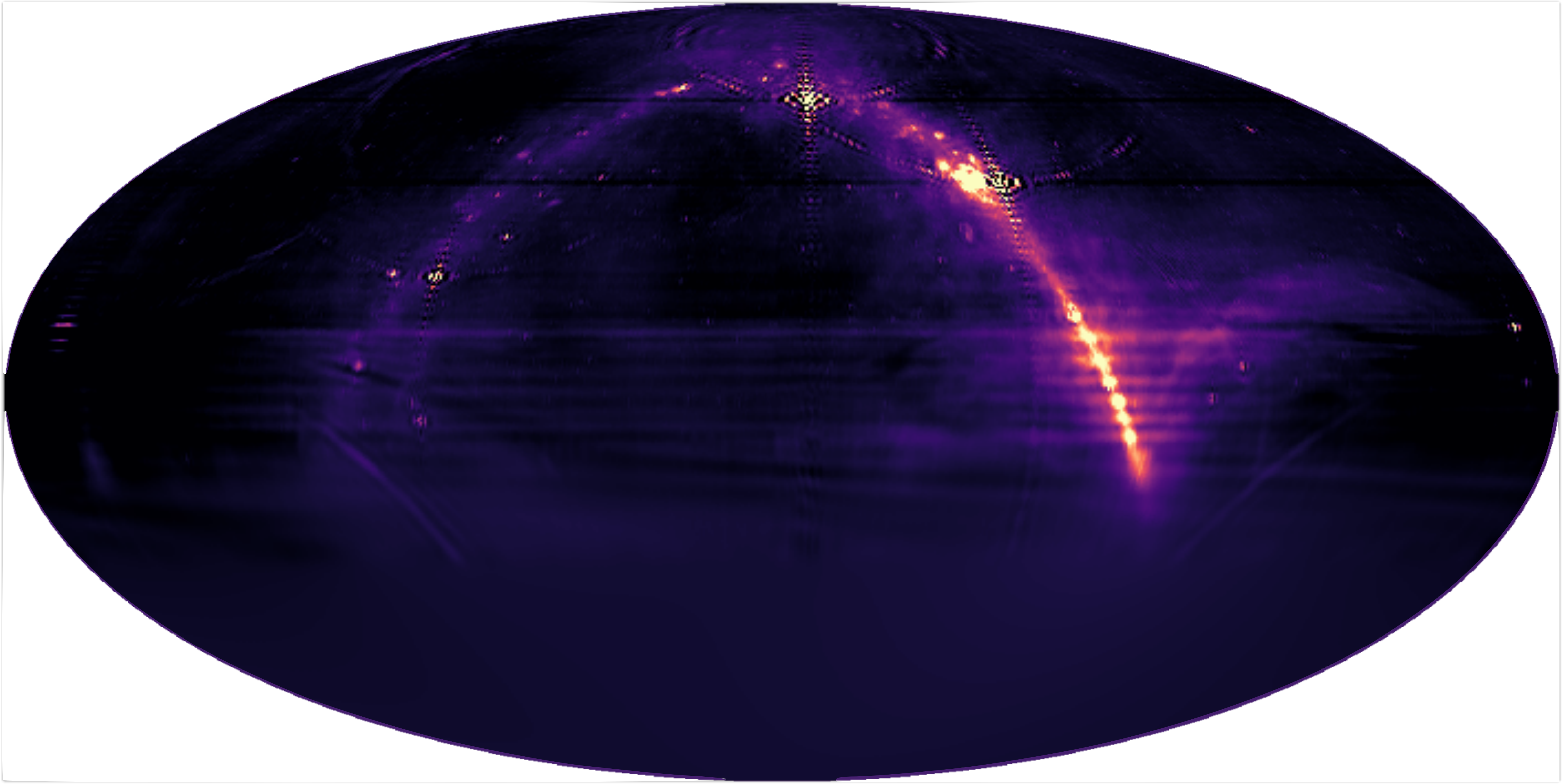
m-mode Imaging

- For our restricted domain (transit telescopes), we can solve the problem optimally
- How do we make an image of the sky? Use standard tools of signal processing:
  - Wiener Filter *(Bayesian expectation)*

$$\hat{\boldsymbol{a}}_{\mathrm{W}} = (\mathbf{S}^{-1} + \mathbf{B}^{\dagger}\mathbf{N}^{-1}\mathbf{B})^{-1}\mathbf{B}^{\dagger}\mathbf{N}^{-1}\boldsymbol{v}$$

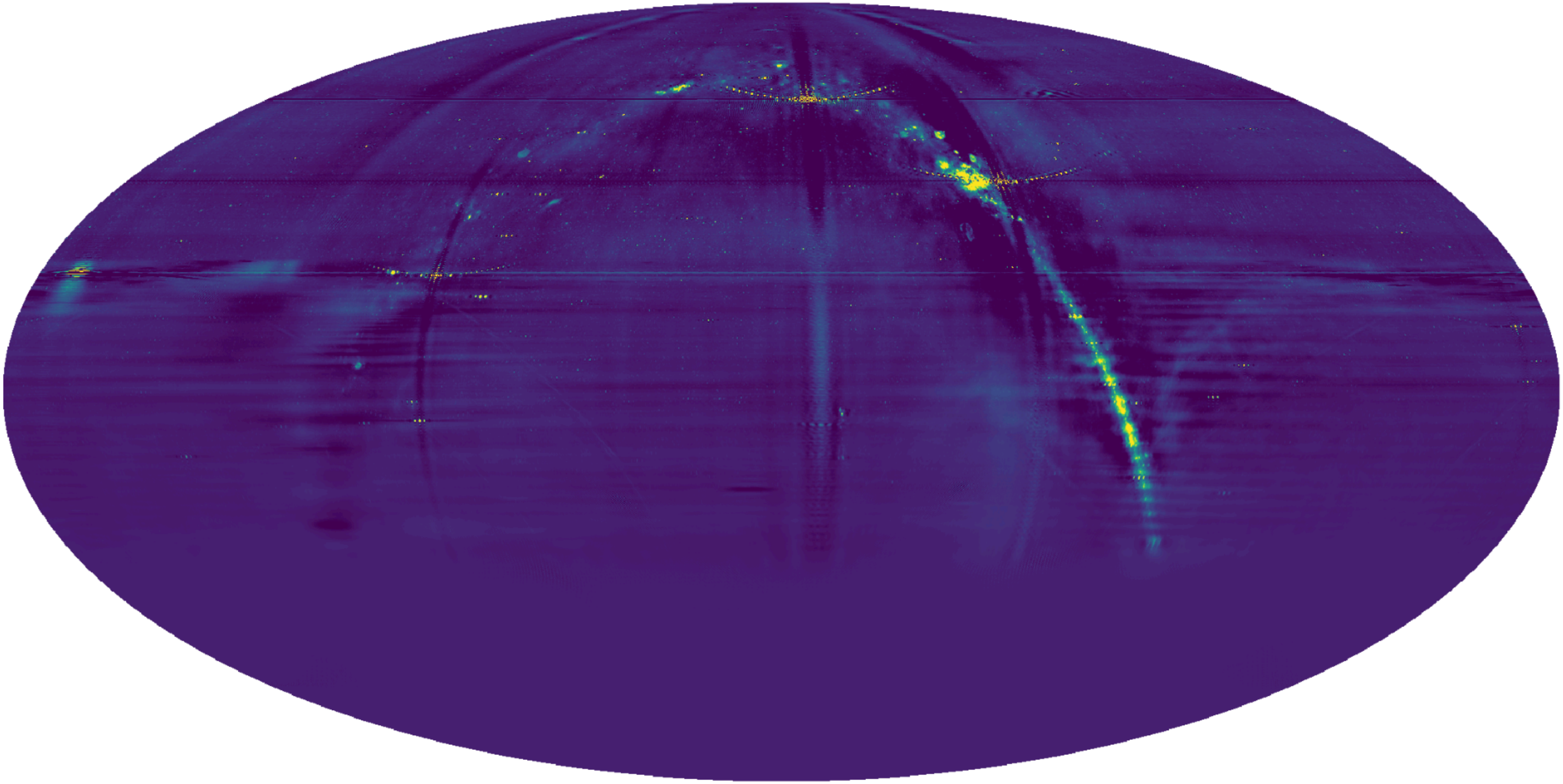
- Conceptually straightforward. Deals naturally with all full sky effects, polarisation etc.
- Evaluate for each of ~10^3 modes independently, saves ~10^6 in computation

M-mode map



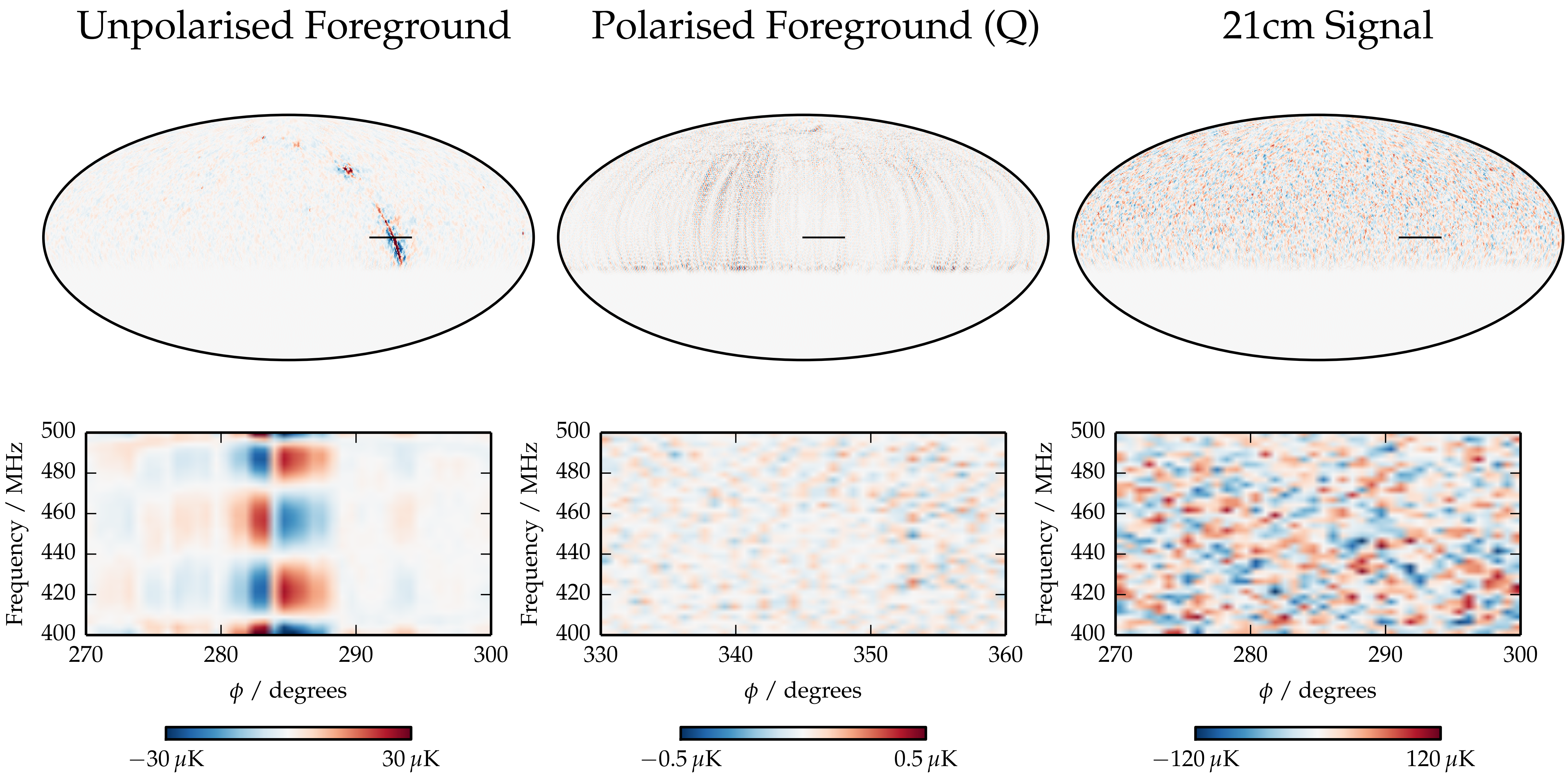
CHIME Pathfinder

M-mode map



CHIME

Foreground Cleaning



Unpolarised Foreground

Polarised Foreground (Q)

21cm Signal

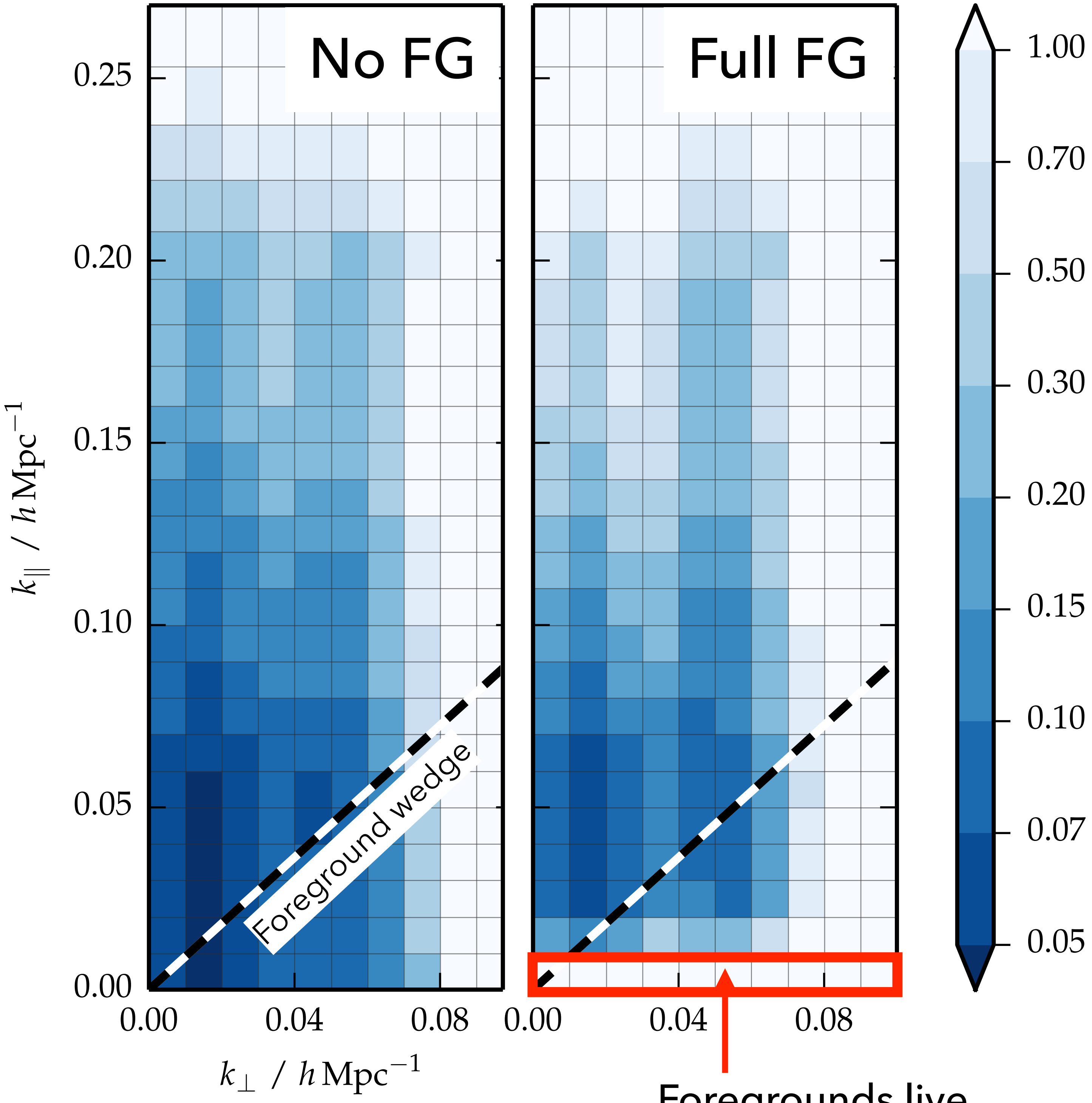
Foreground residuals significantly smaller than signal

Foreground Removal

- KL filter method for for optimal foreground removal
- Requires simultaneous deconvolution of all baselines, frequencies and times
- Computationally challenging — need to exploit sparsity in our data (Shaw et al. 2014, 2015)

CHIME Pathfinder forecast

Fractional power spectrum errors (blue is better)

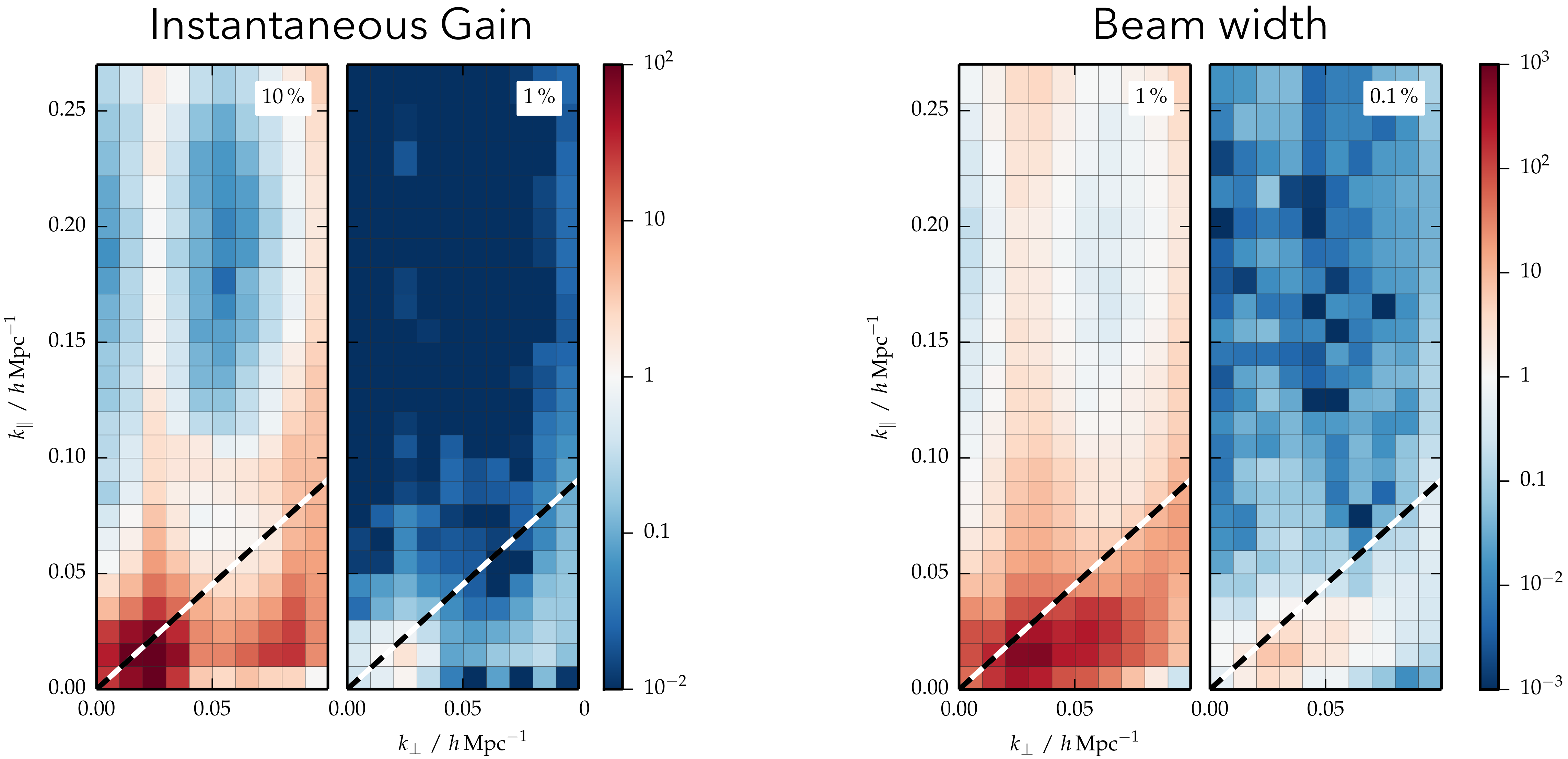


Foregrounds live naturally in here

Shaw et al. 2015, *arXiv:1401.2095*

Calibration requirements

Systematic bias (red > 1σ; blue < 1σ)



Instantaneous Gain

Beam width

Need better than 1% gain calibration: Thermal models (*Sidhant Guliani, Mateus Fandino*); noise injection (*Juan Mena Parra*)

Need to understand beams at 0.1% level: Simulations (*Meiling Deng*); holography (*Alex Hill, Laura Newburgh, Phil Berger*)

Shaw et al. 2015, *arXiv:1401.2095*

Summary

- CHIME will measure BAO from z~0.8 - 2.5
    - Started operating in March 2018
- 21cm observations are hard because of foregrounds
- Foreground cleaning is feasible
    - Need tight control/understanding of calibration, primary beam effects, RFI cleaning/other masking…
- Scope and size of problem needs innovative techniques