Probing Dark Energy with the

Canadian Hydrogen Intensity Mapping Experiment

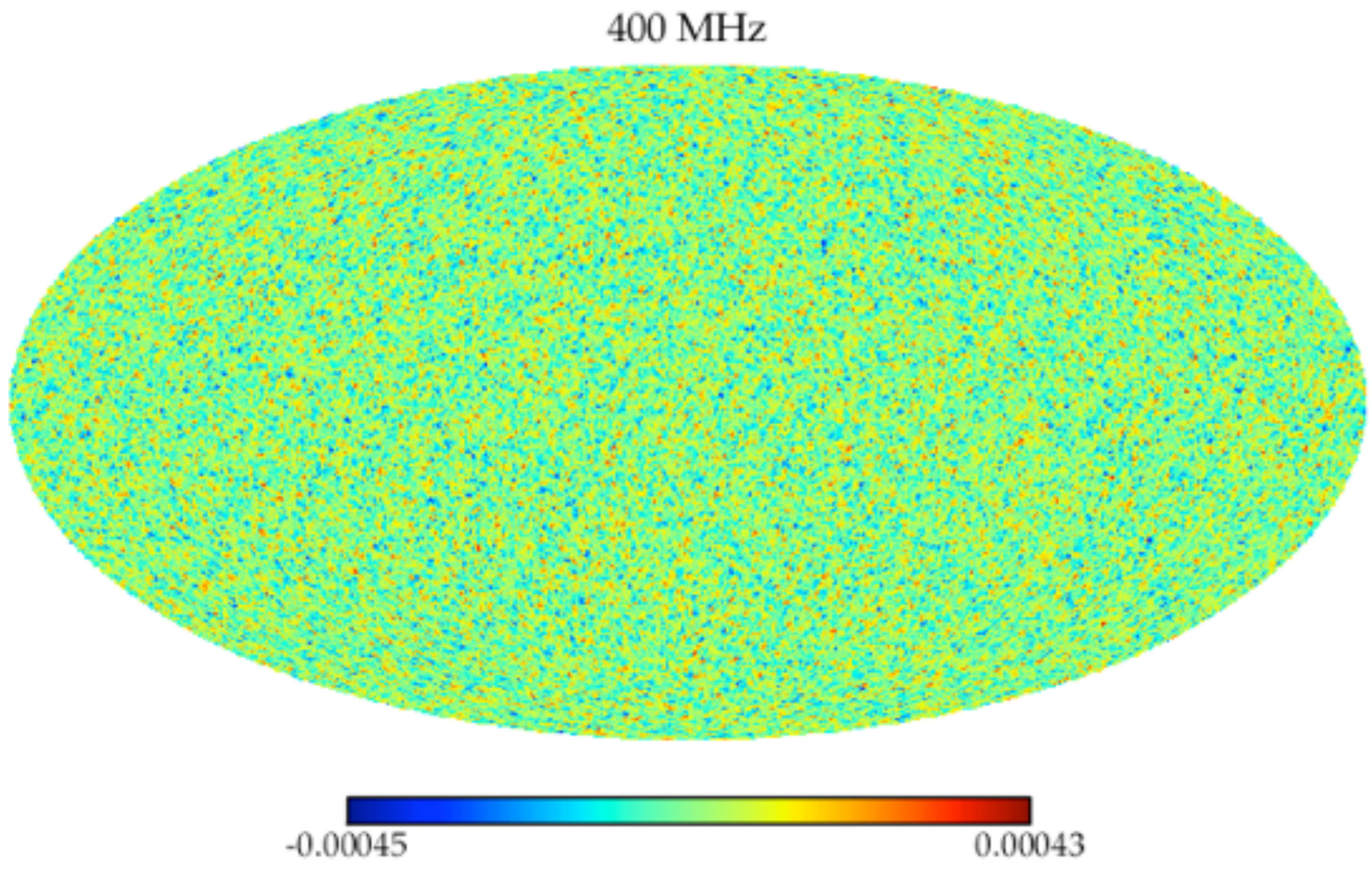
Richard Shaw

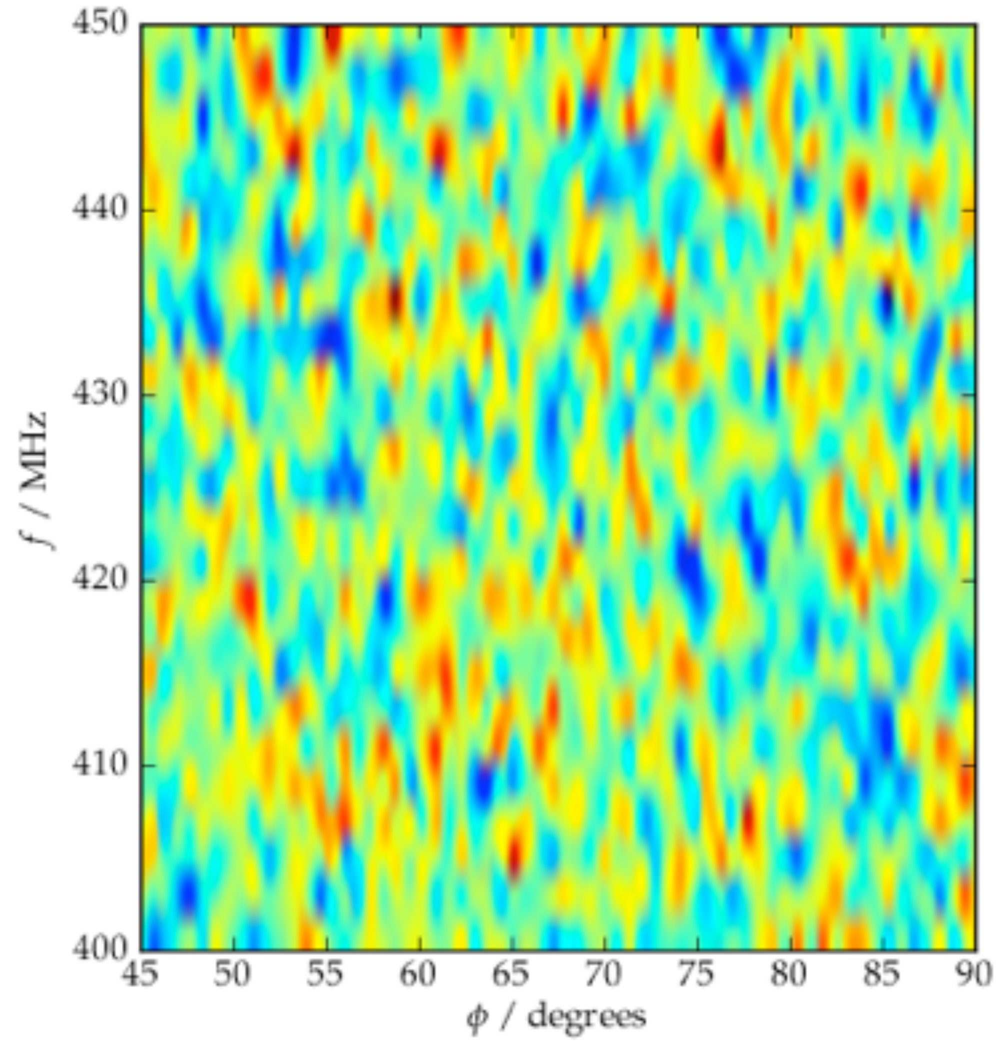
UBC
a place of mind
THE UNIVERSITY OF BRITISH COLUMBIA

Outline

- Brief intro
- CHIME
- Data analysis
  - M-mode transform
  - Map making
  - Foreground removal

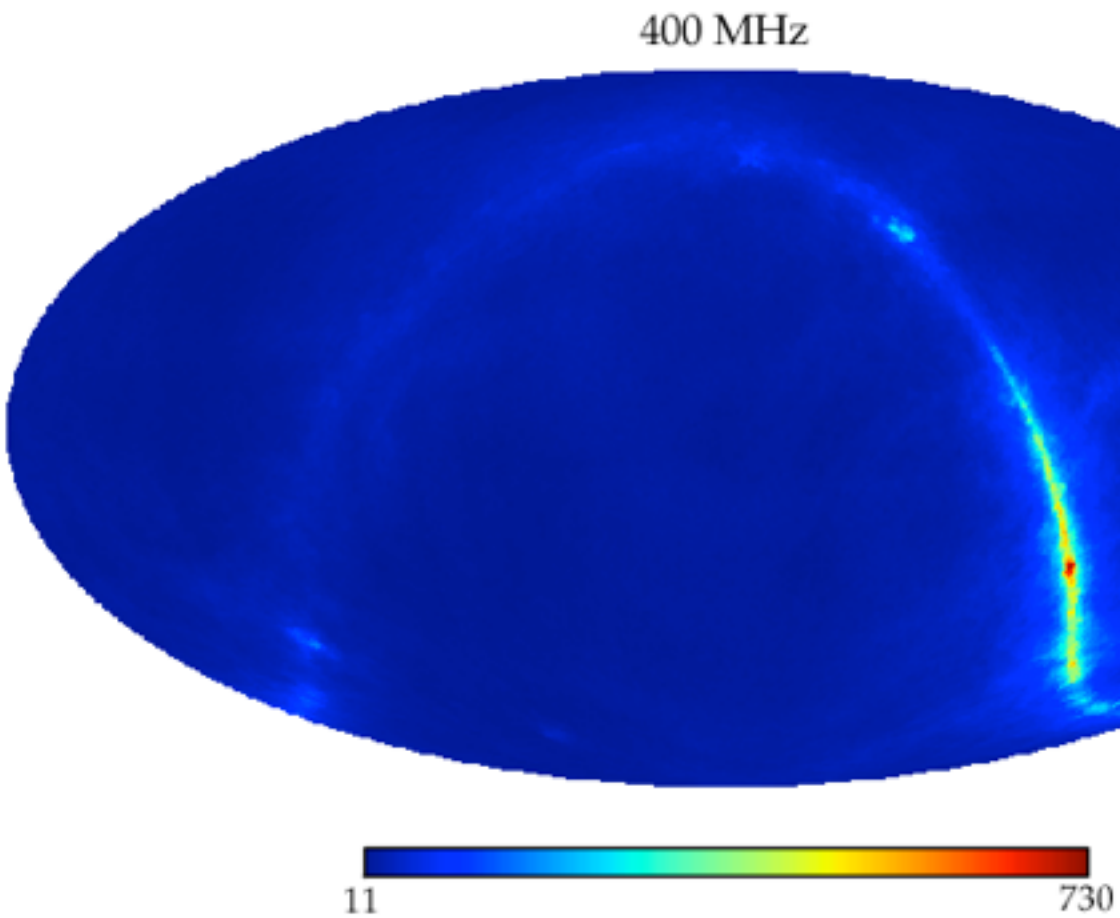
Foreground Challenges

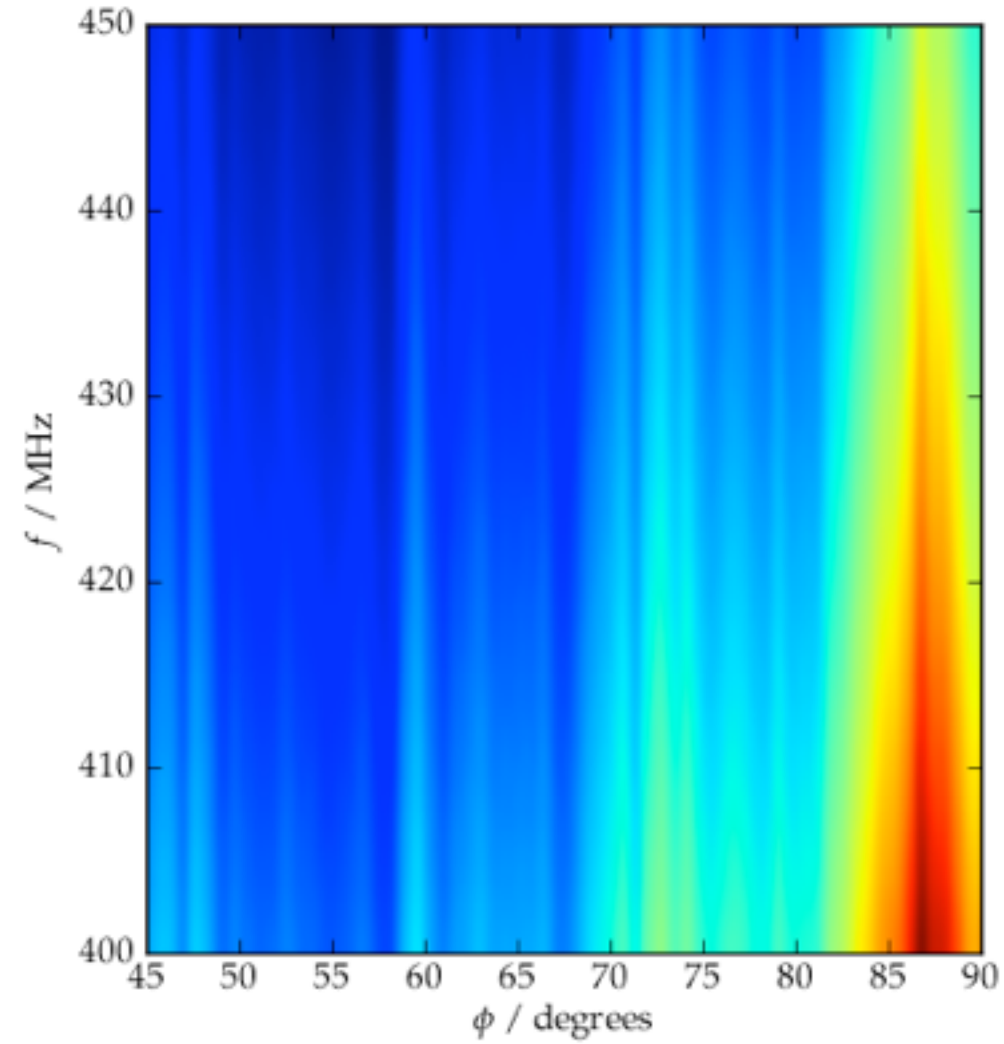




Cosmological 21cm Signal ~ 1mK

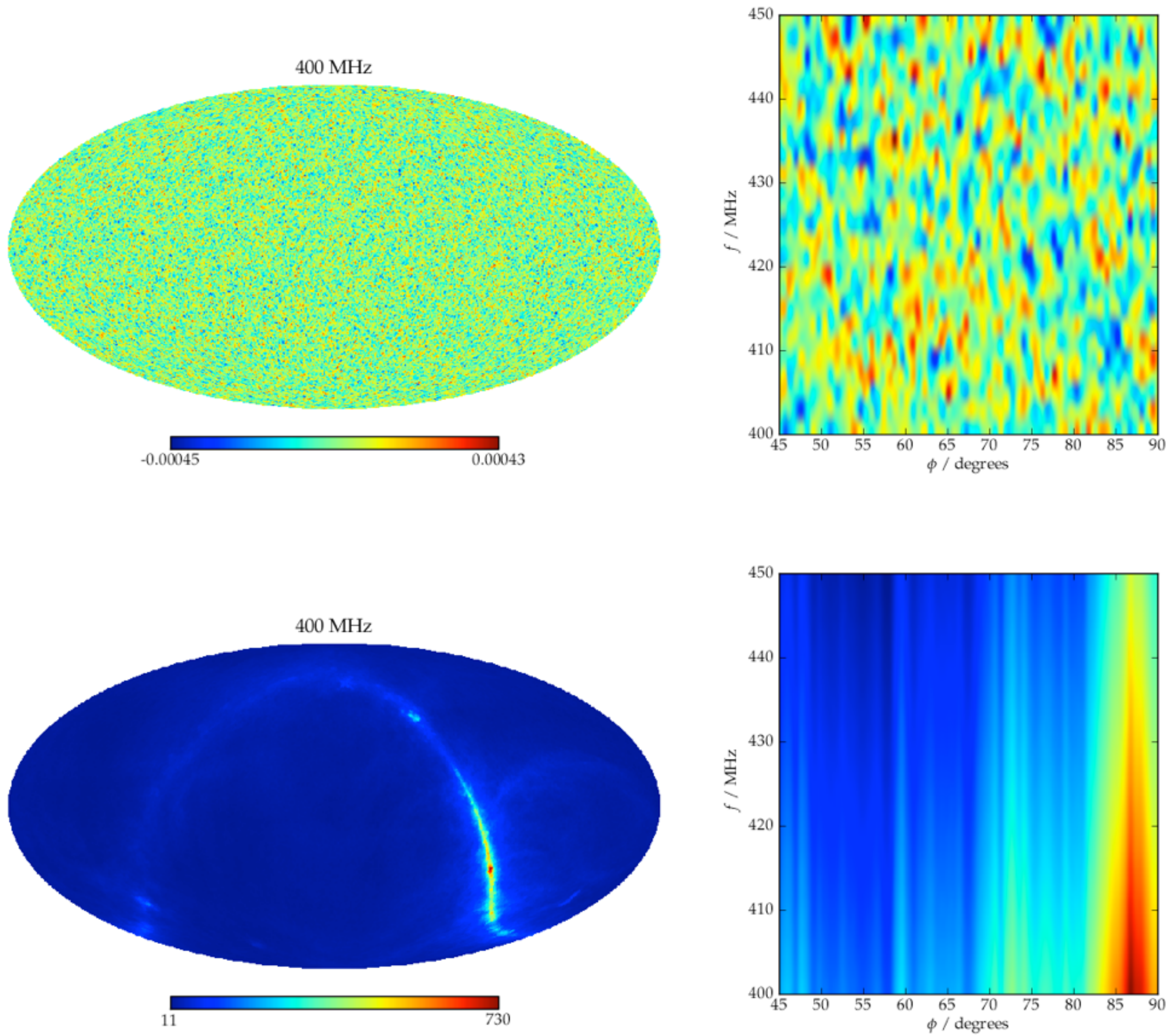
Foreground Challenges



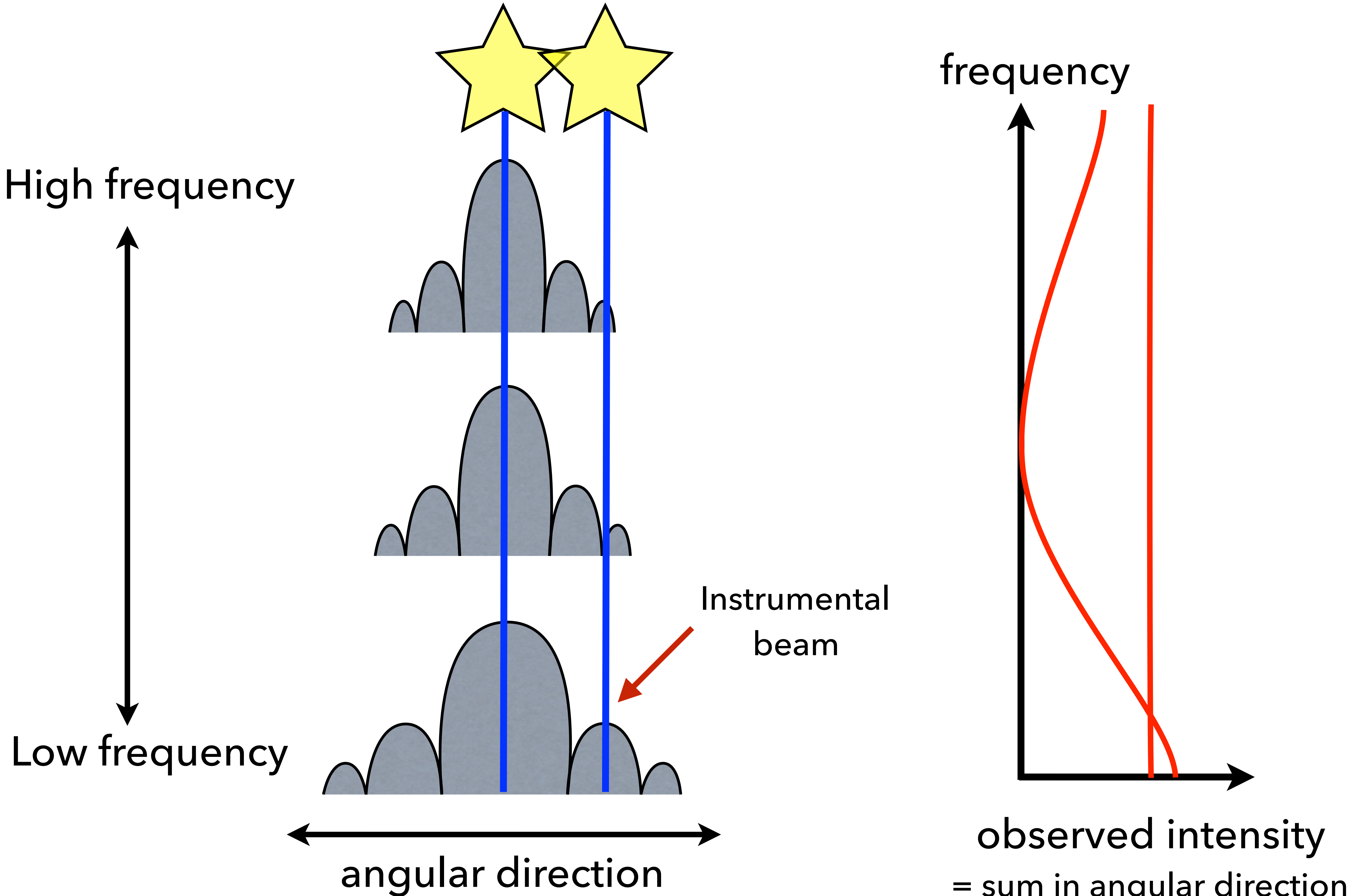


Galaxy: up to 700K

A way out?


400 MHz
-0.00045
0.00043
f / MHz
φ / degrees
400 MHz
11
730
f / MHz
φ / degrees

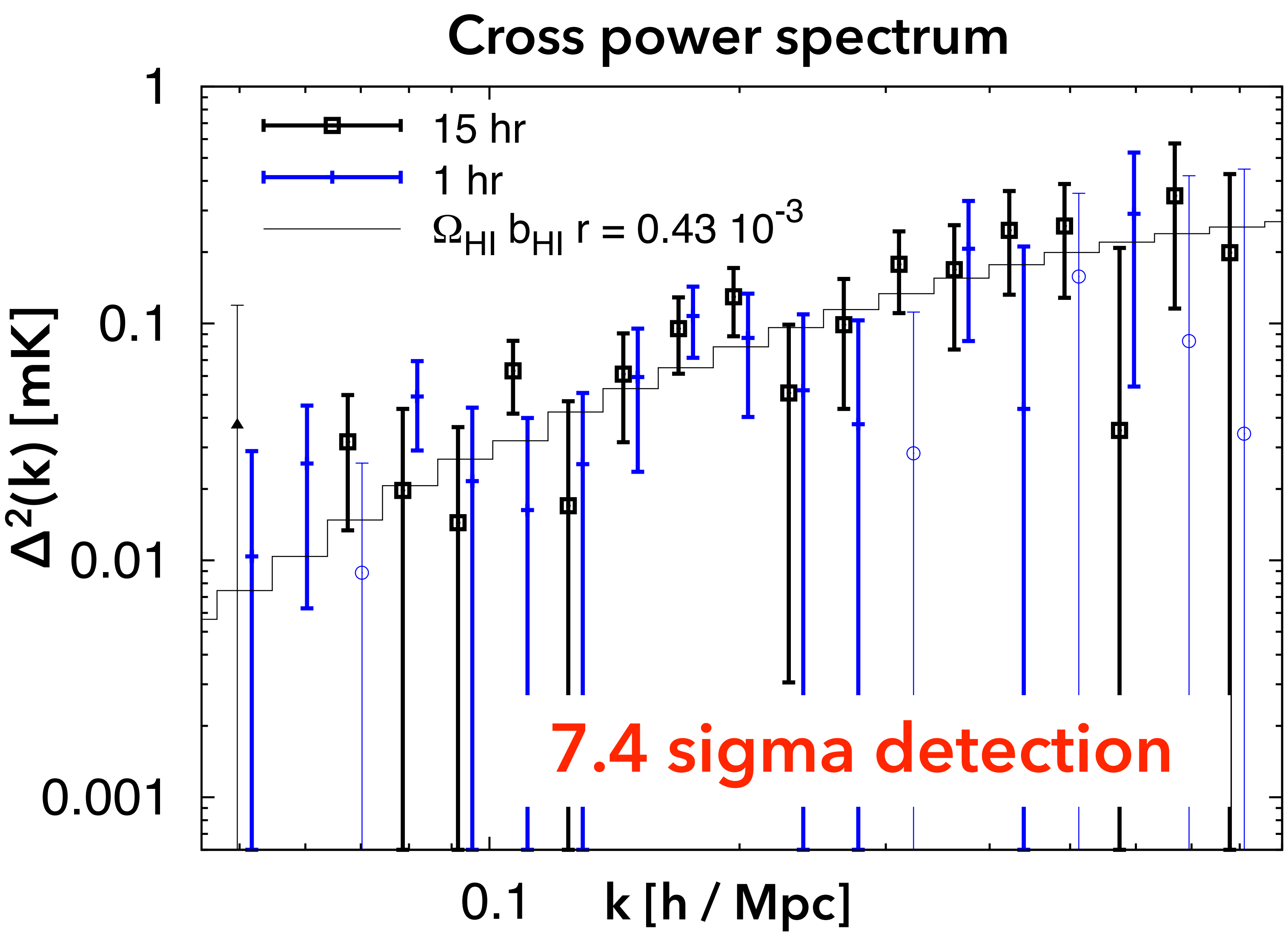
Mode mixing


High frequency
Low frequency
Instrumental
beam
angular direction
frequency
observed intensity
= sum in angular direction

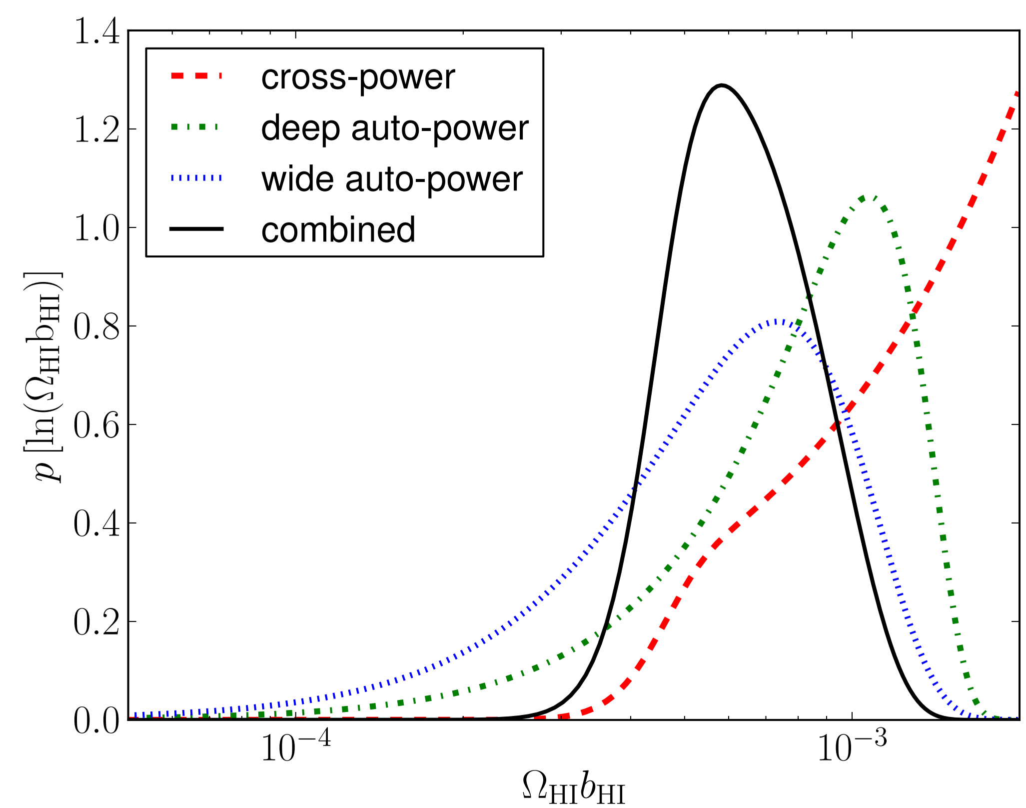

Intensity Mapping at
Green Bank
flickr.com/photos/afternoon_sunlight/

Cross correlation detection

- Correlation with DEEP2 Galaxy survey by Chang et al. (2010) - *avoids foreground problem!*
- Updated using WiggleZ survey (Masui et al. 2012)



$$\Omega_{\rm HI} = [0.62^{+0.25}_{-0.15}] \times 10^{-3}$$

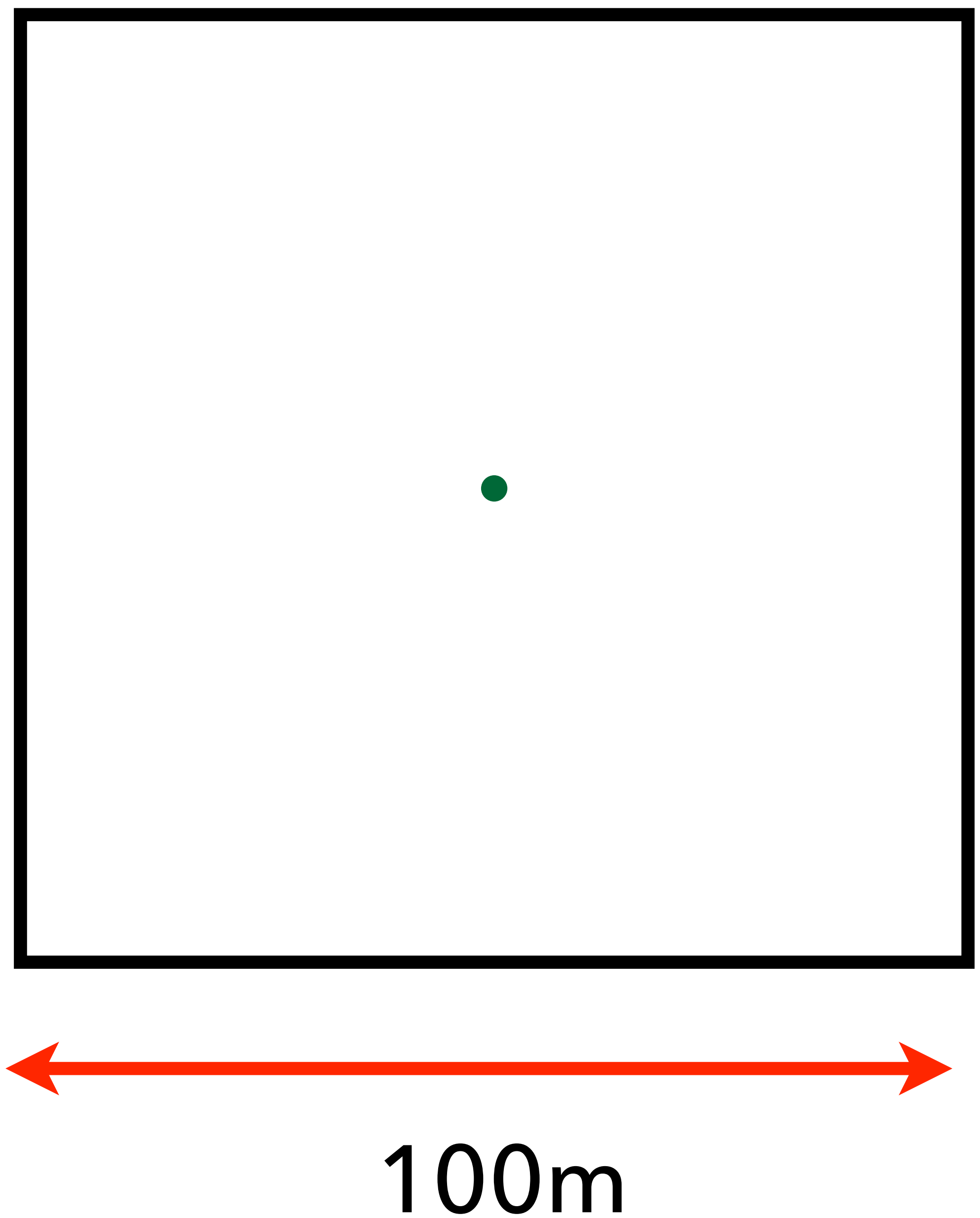


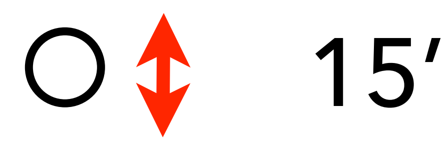
Next Generation Experiments

The Future?

- Observations like this are slow. To survey the whole sky to this depth ~ 20 years
  - Is there a better way to do this?

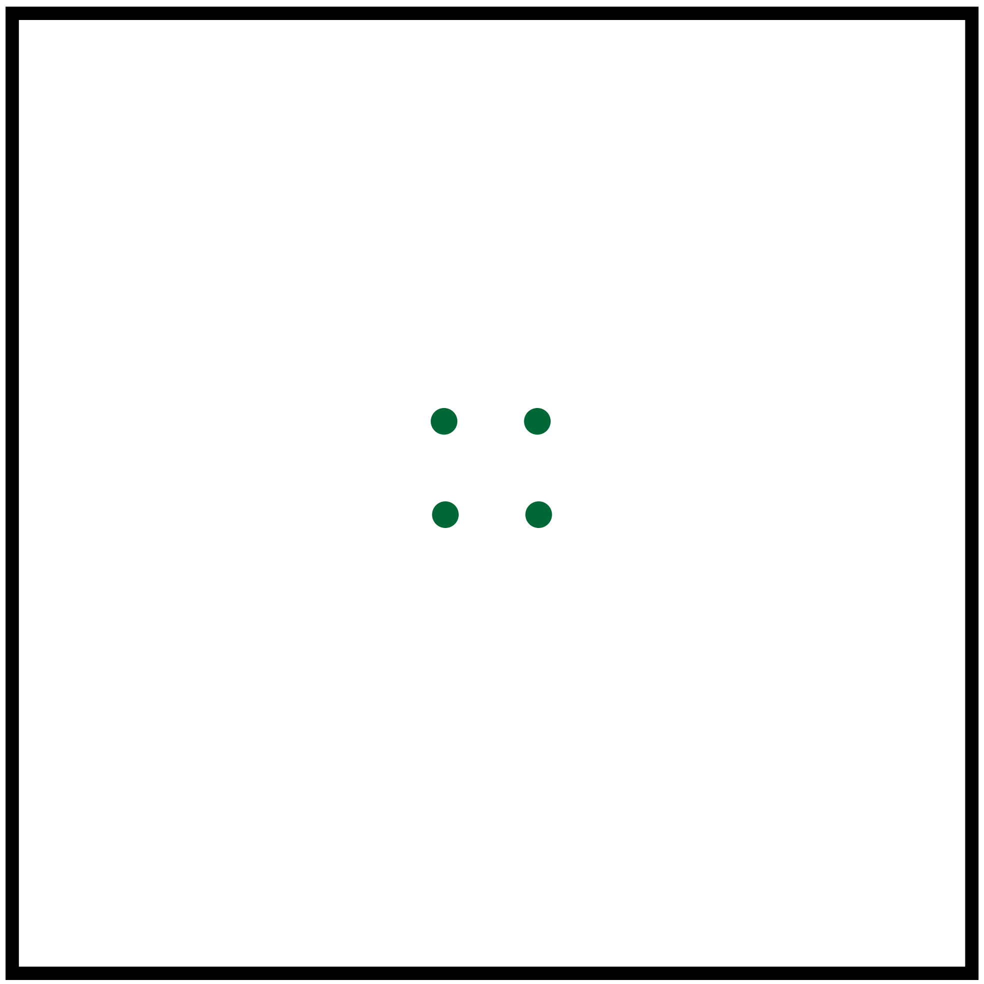
Single Dish

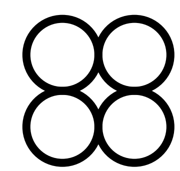




- Slow survey
- Noise: σ_T

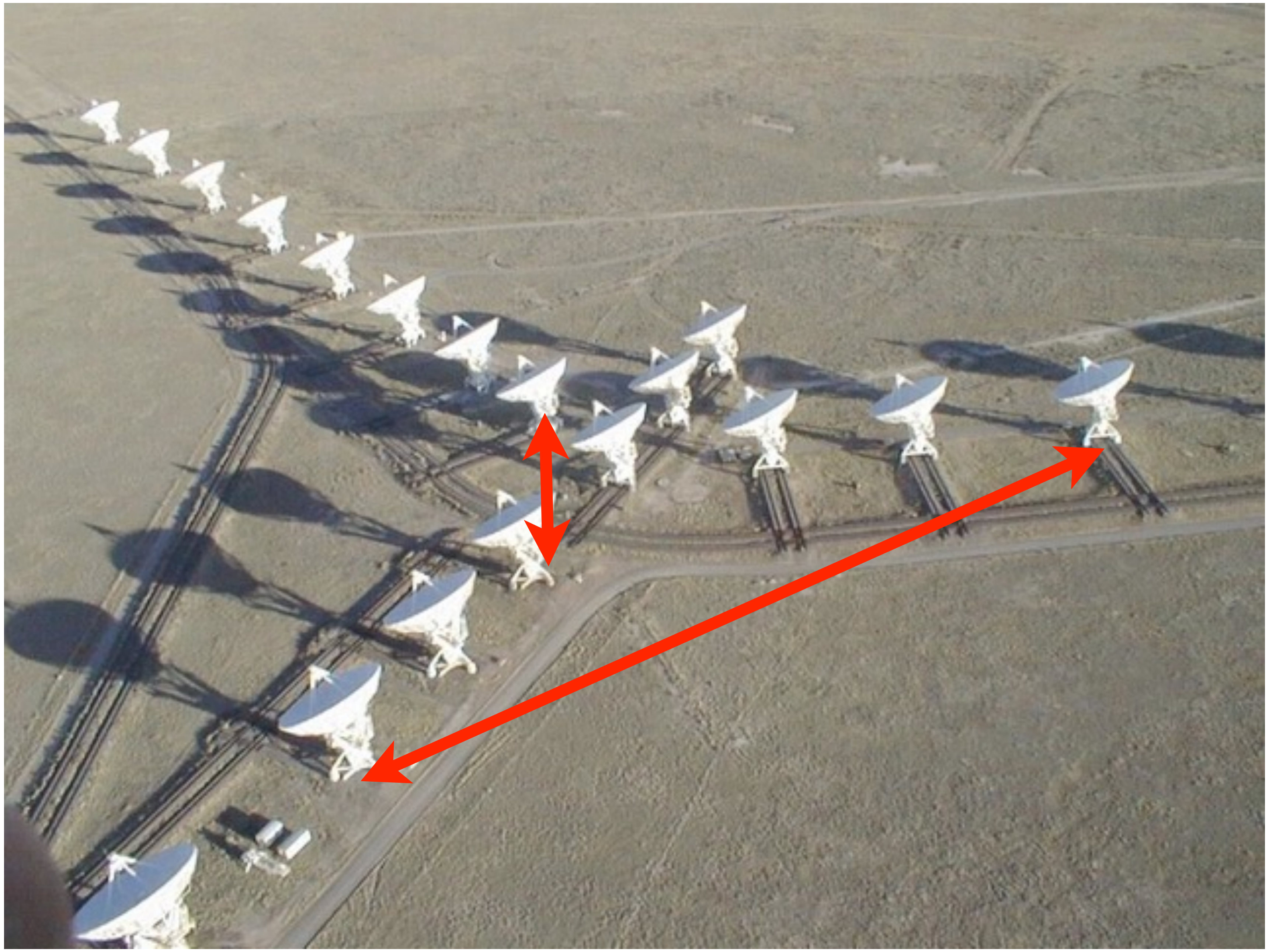
Focal Plane Array





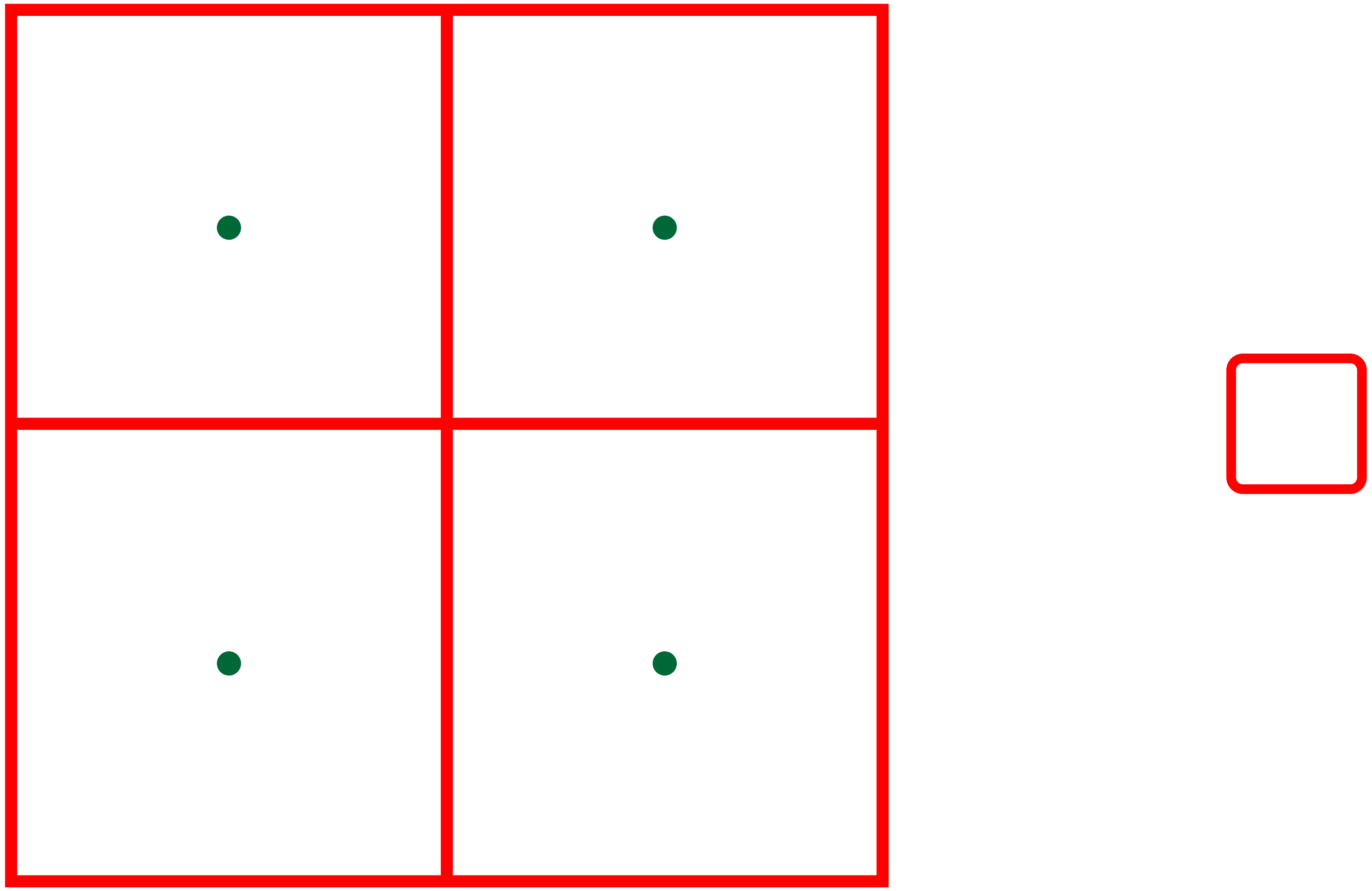
- Slightly offset feeds
- Each beam noise: σ_T
- 4x faster survey

Interferometers



2x2 Interferometer

2x2 Interferometer



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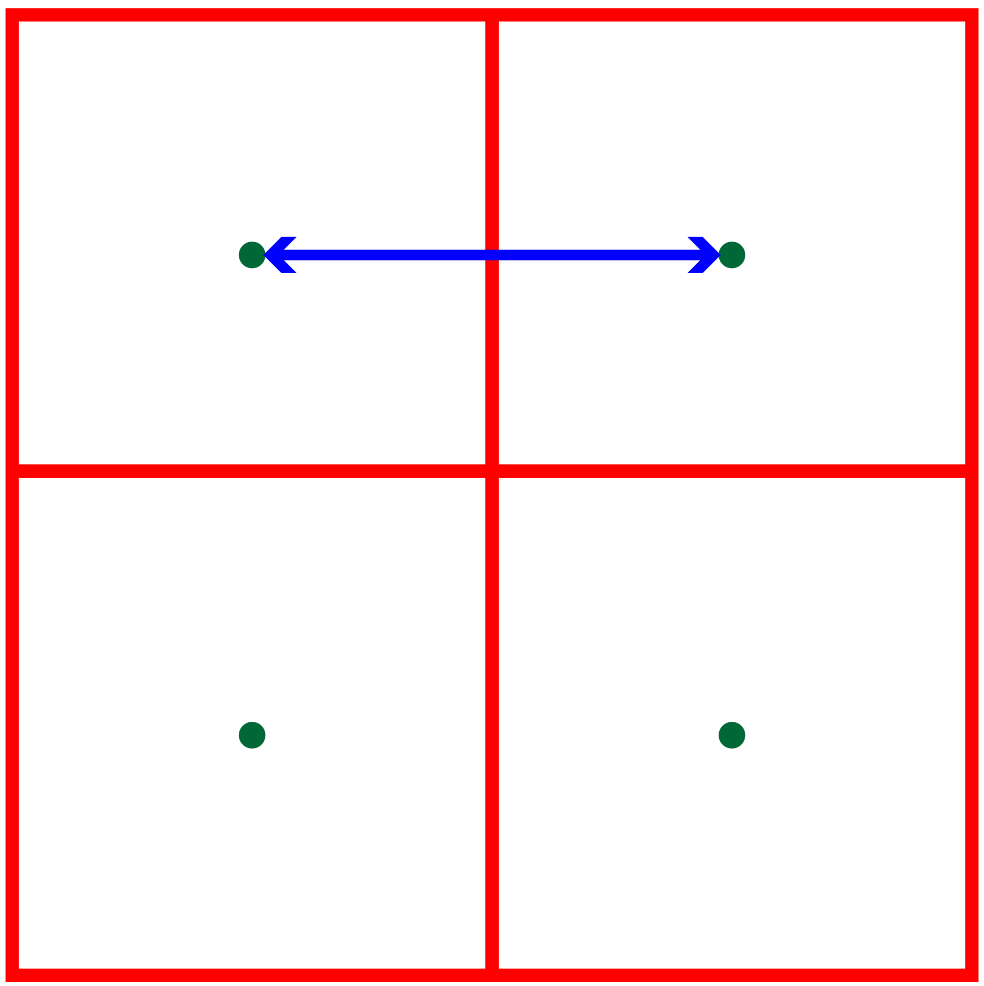
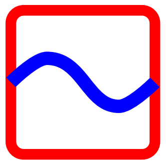
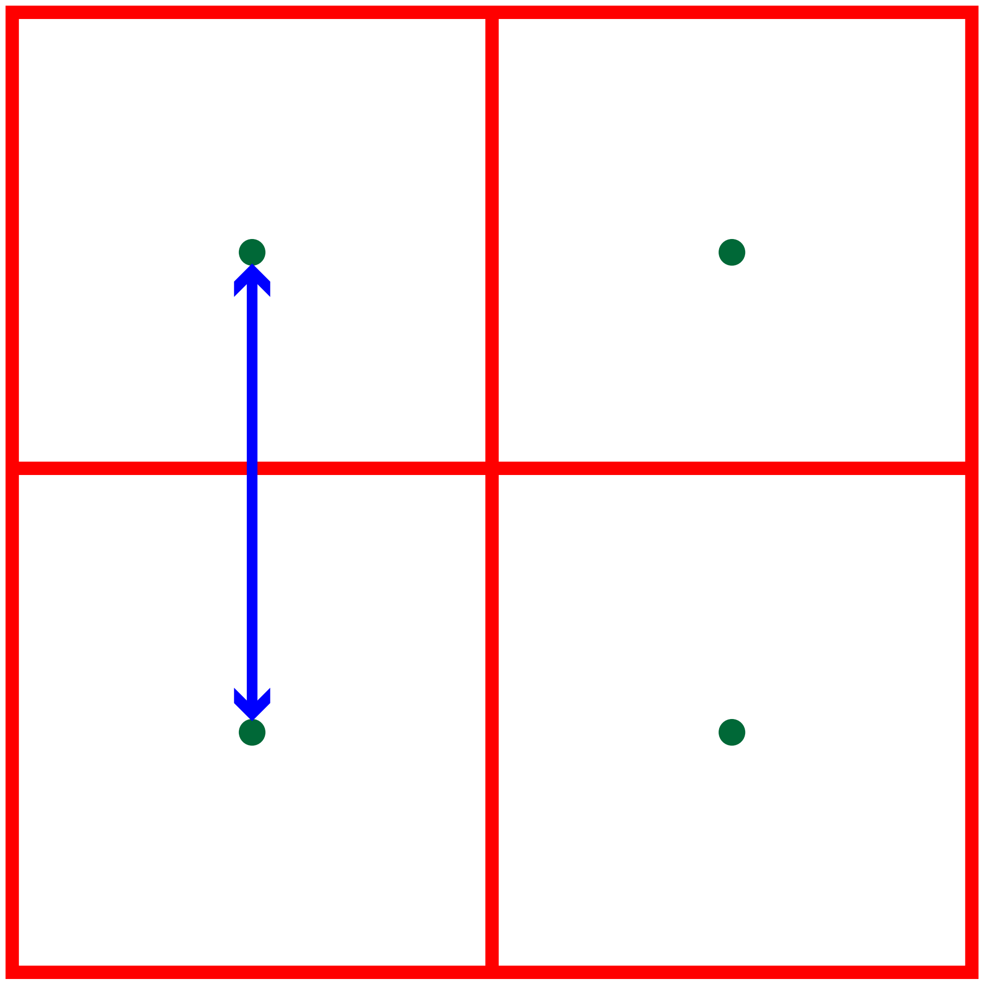
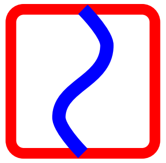




- Measure fourier modes in redbox (primary beam)

2x2 Interferometer





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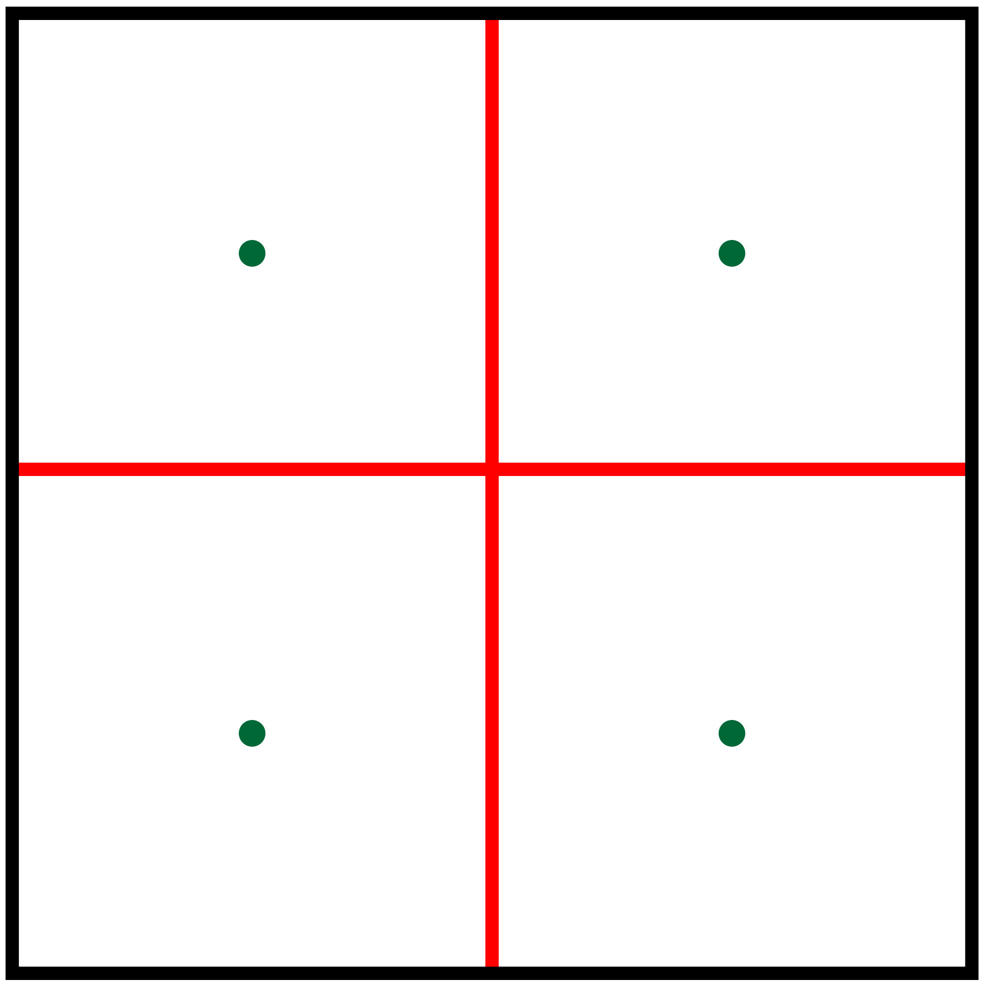
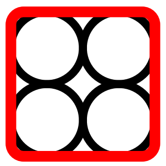
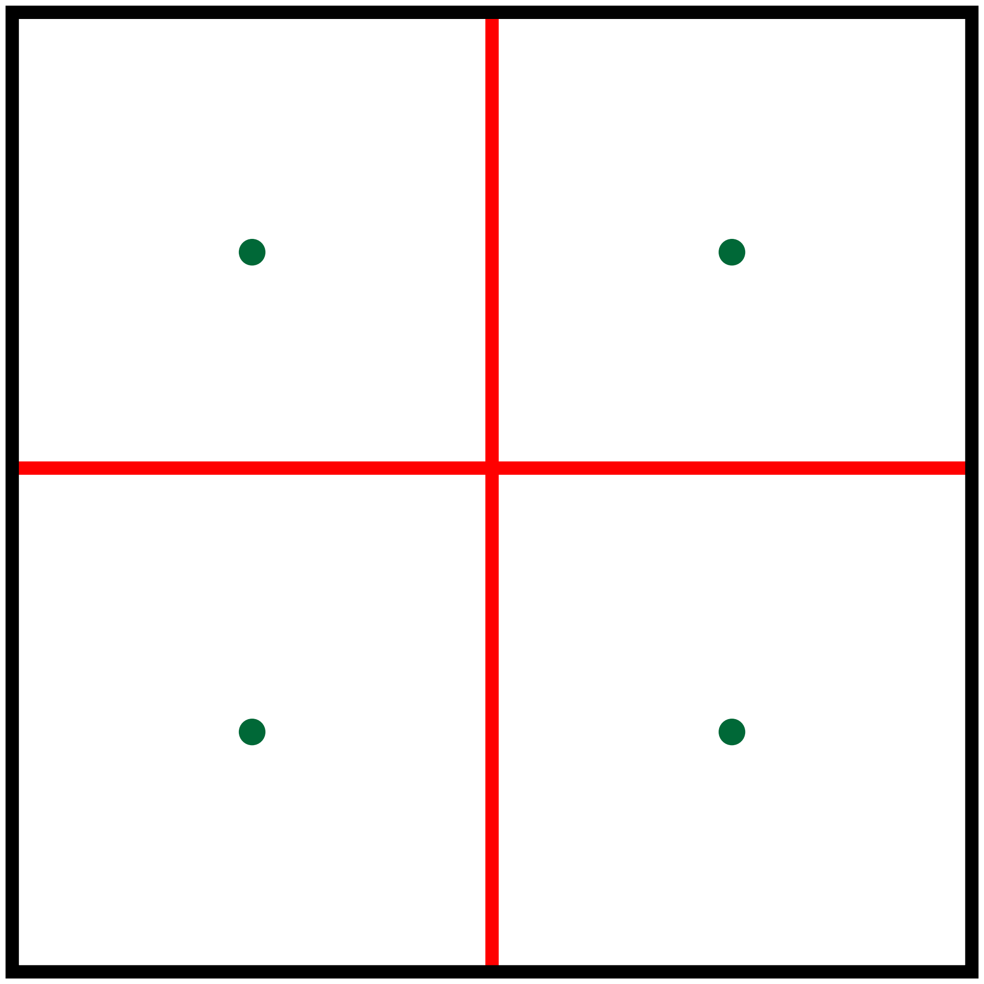
2x2 Interferometer

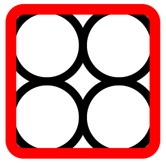




- Linear combinations give independent beams

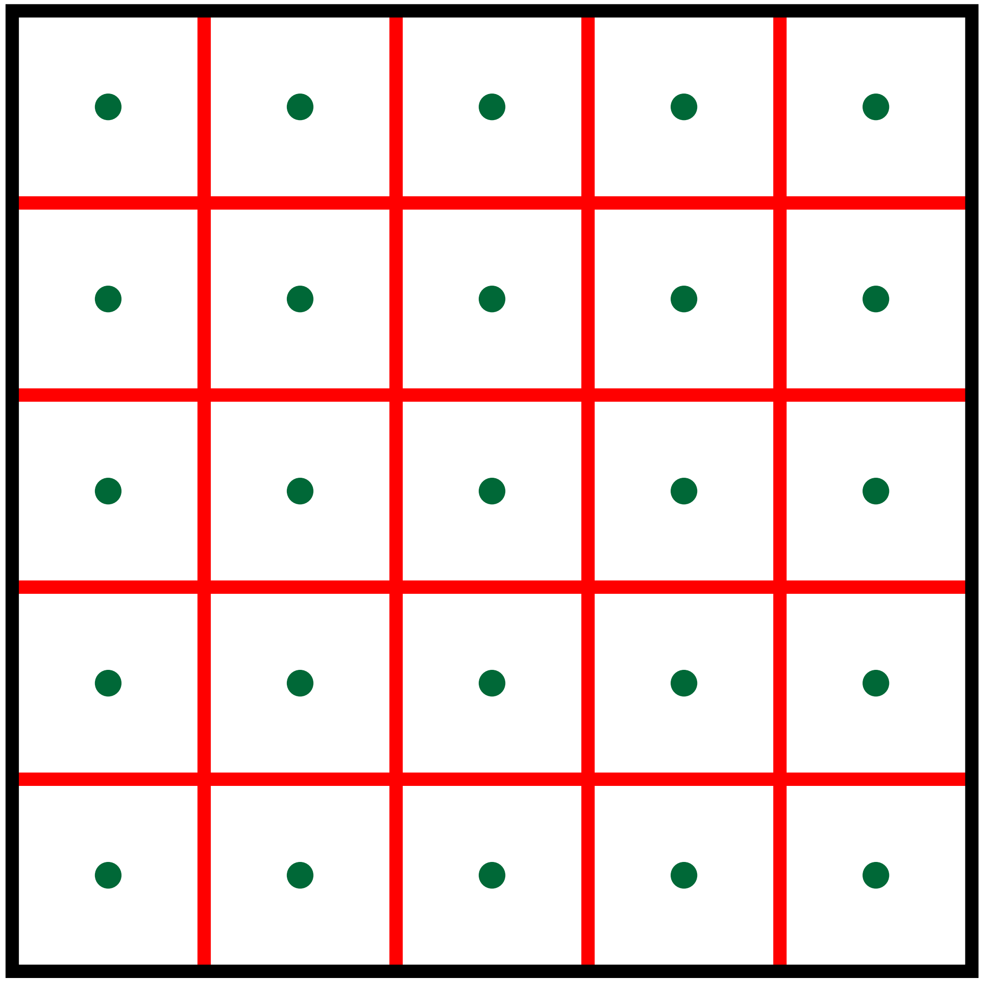
2x2 Interferometer

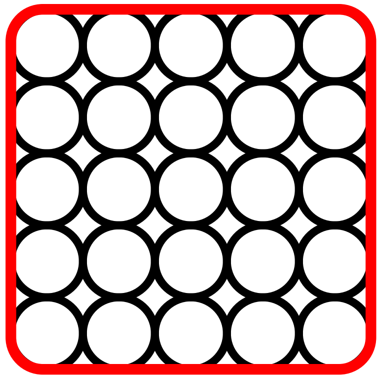




- Each beam has noise σ_T
- 4x faster, with same noise and resolution

5x5 Interferometer





25x faster

McGill

UBC

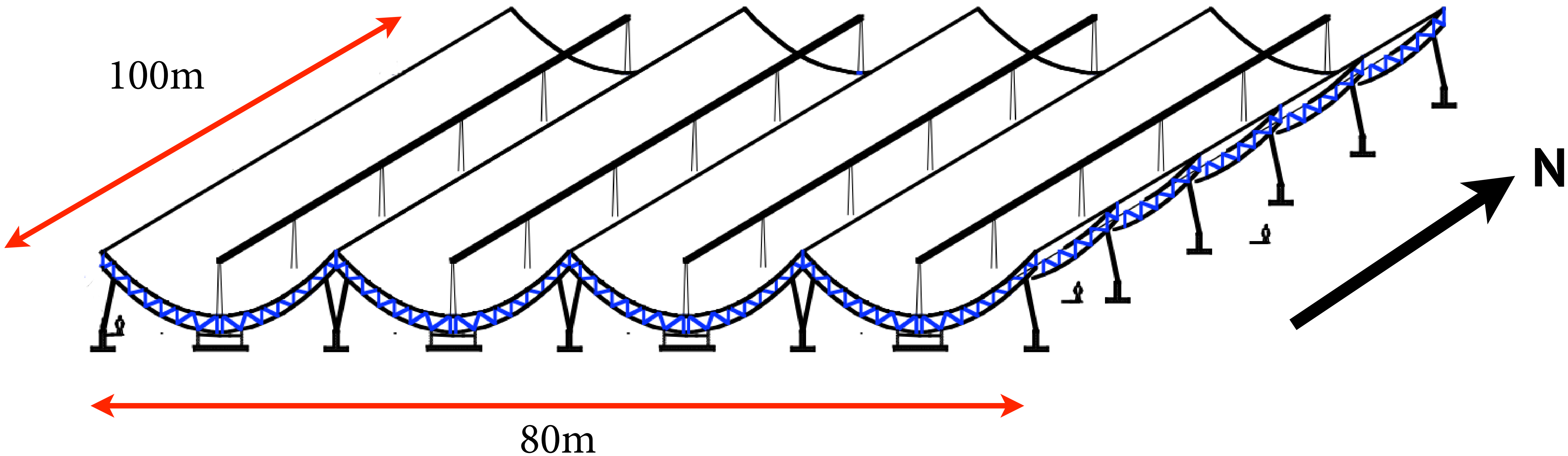
DRAO

NRC · CNRC

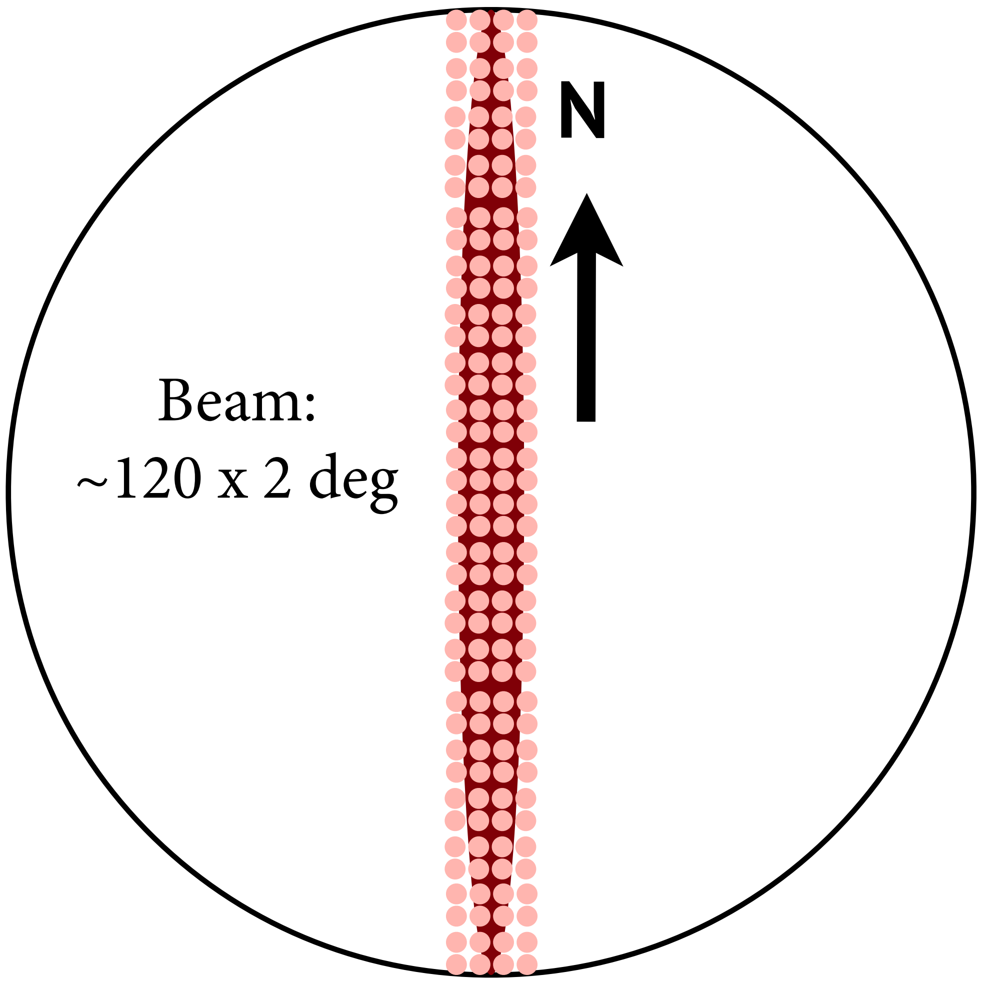
UNIVERSITY OF TORONTO

chime

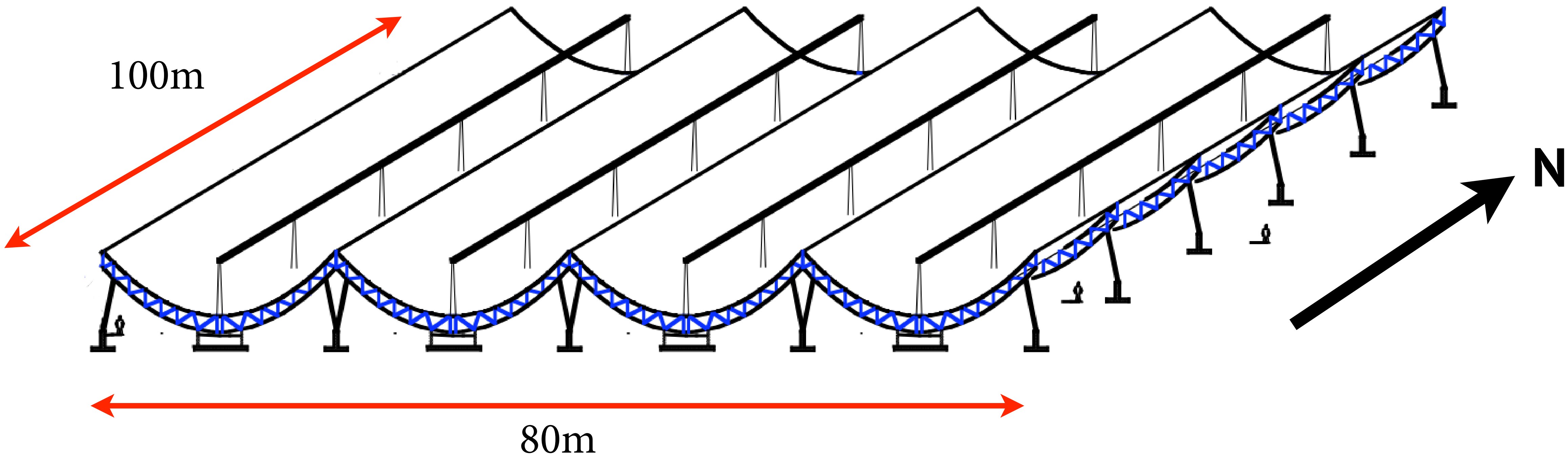
CHIME Overview



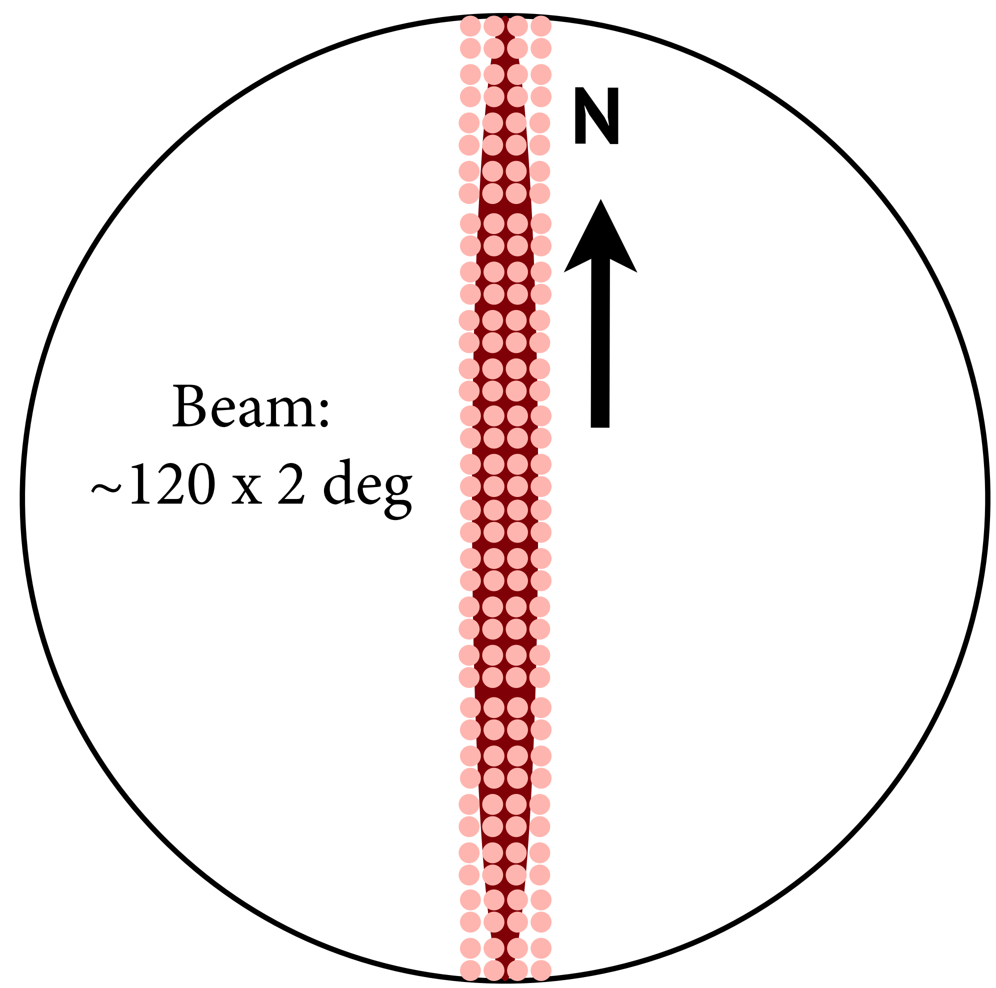
- Located at DRAO in BC
- Transit radio interferometer
  - Observe between 400-800 MHz
  - 0.4 MHz spectral resolution
  - 1024 dual pol antennas (T_{recv} = 50K)
- 120 x 2 degree FoV
- 4x256 beams = 15 arcmin resolution

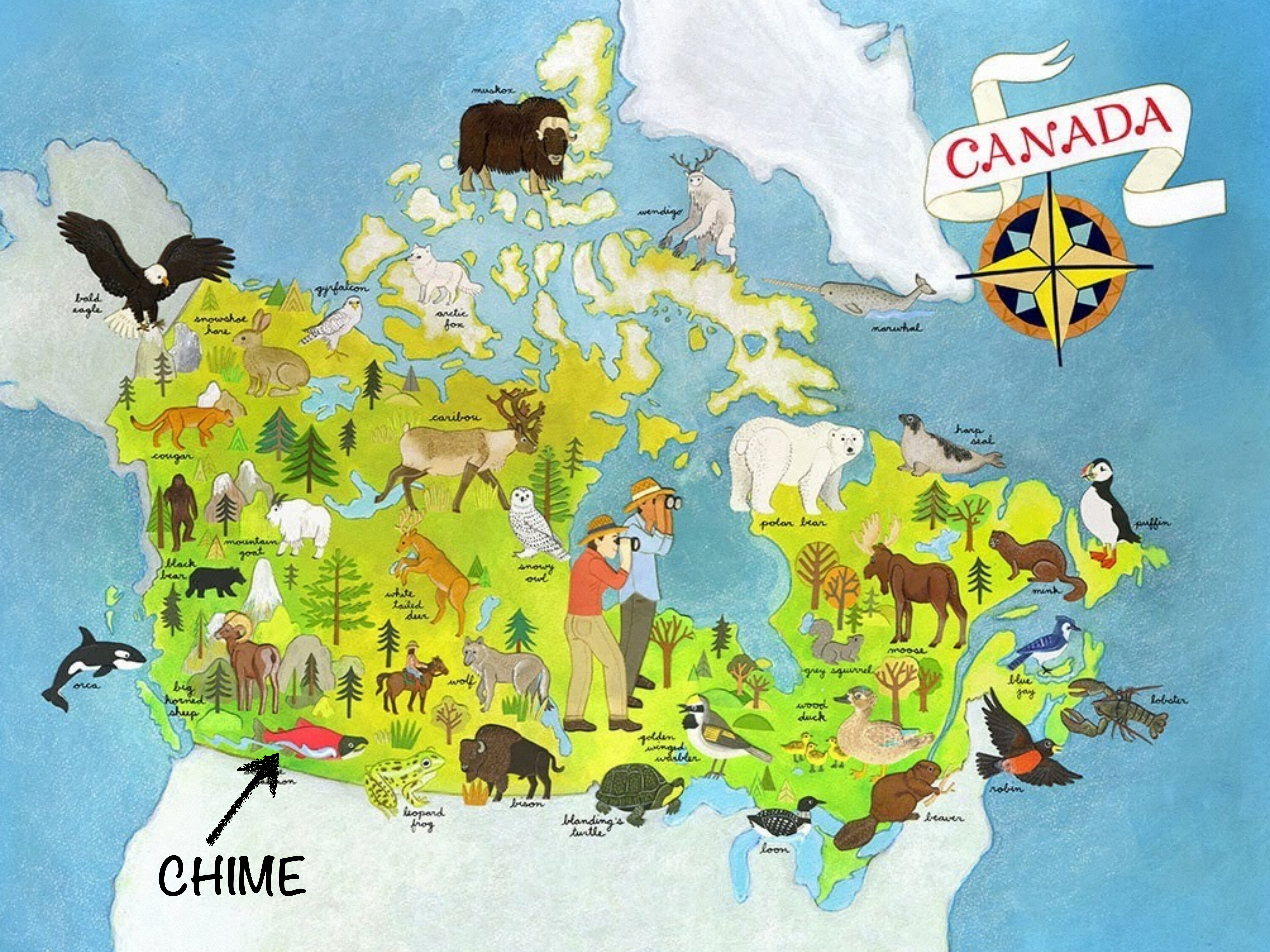


CHIME Overview

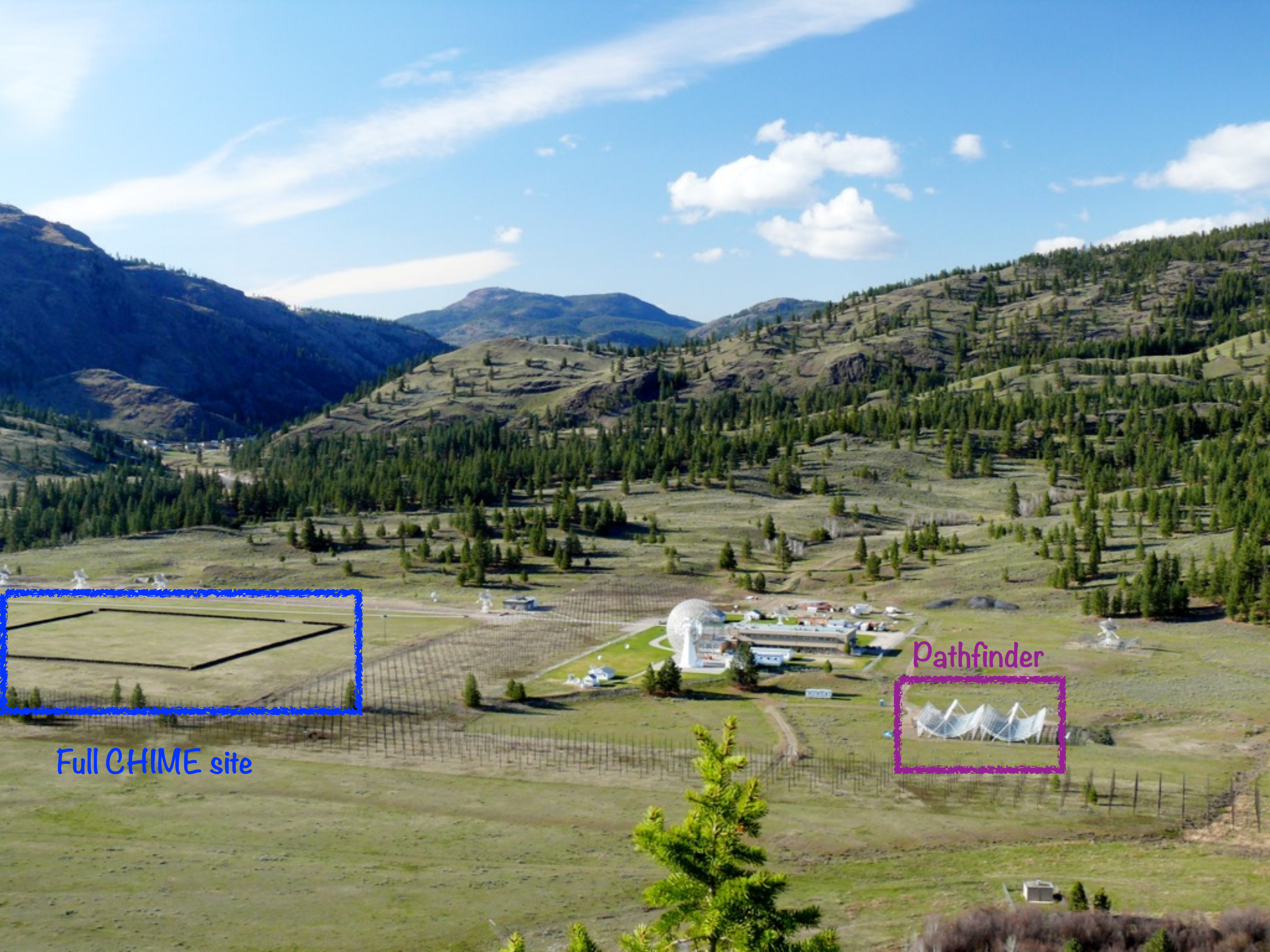


- Science Goals
  - **Intensity mapping for BAOs**
  - Pulsar observations
  - Radio transients
- Fully funded!

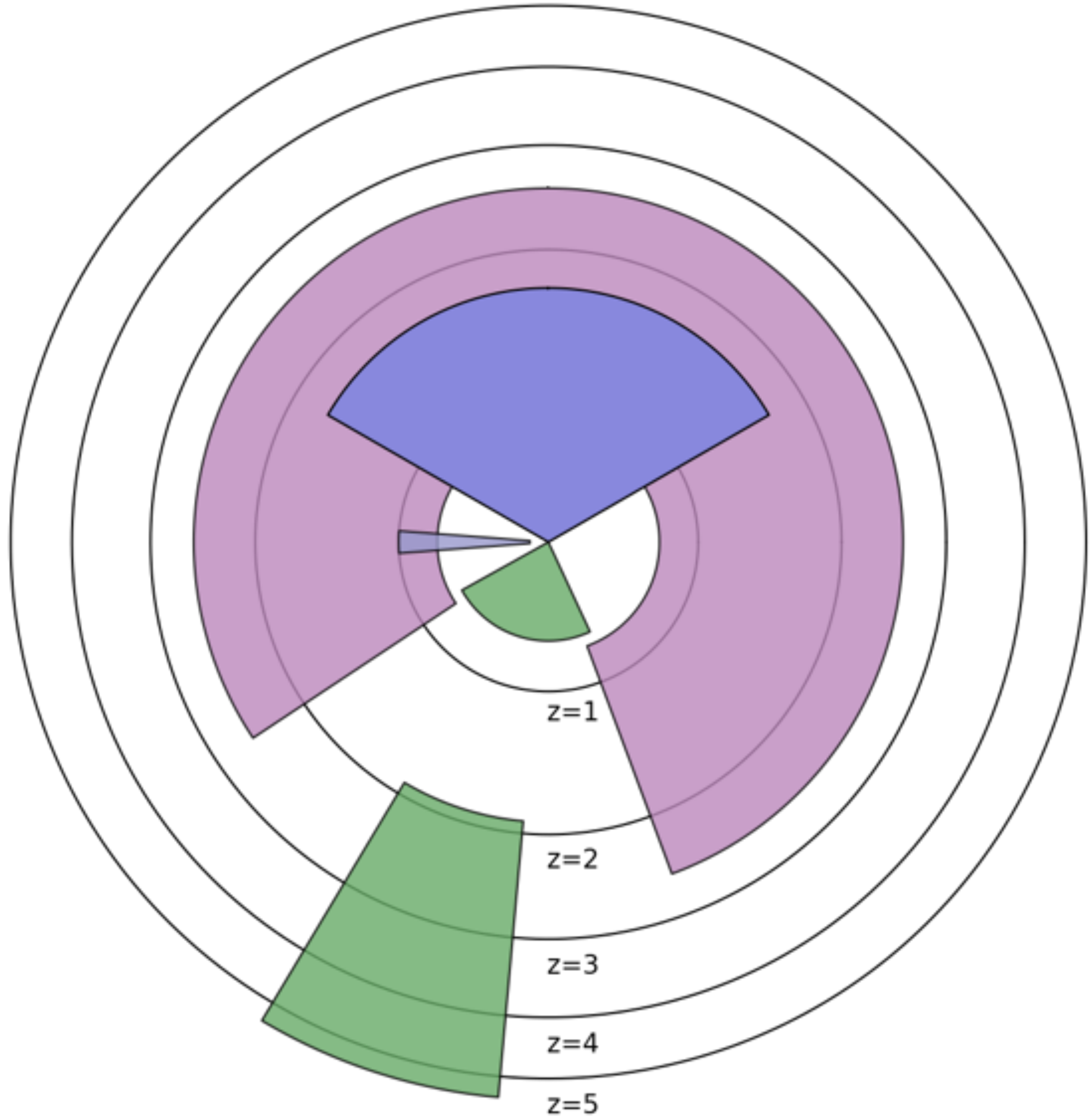



CANADA
muskox
wendigo
bald eagle
gyrfalcon
snowshoe hare
arctic fox
narwhal
caribou
harp seal
cougar
polar bear
puffin
mountain goat
black bear
snowy owl
white tailed deer
mink
moose
grey squirrel
blue jay
lobster
orca
wolf
big horned sheep
wood duck
golden winged warbler
robin
leopard frog
bison
blanding's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


BEAUFORT SEA
BAFFIN SEA
Banks Island
Victoria Island
Somerset Island
Prince of Wales Island
King William Island
Baffin Island
Davis Strait
NUNAVUT TERRITORY
Foxe Basin
ARCTIC CIRCLE
YUKON TERRITORY
NORTHWEST TERRITORIES
Great Bear Lake
Great Slave Lake
Hudson Bay
Labrador Sea
Gulf of Alaska
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
QUÉBEC
NEWFOUNDLAND
NOVA SCOTIA
Queen Charlotte Islands
Vancouver Island
PACIFIC OCEAN
ATLANTIC OCEAN
UNITED STATES
Lake Winnipeg
Calgary
Regina
Winnipeg
OTTAWA
Toronto
Montréal
Québec
Yellowknife
Whitehorse
Iqaluit
Seattle
Kamloops
Kelowna
CHIME
CANADA
0 km 300 600 900 km


Pathfinder
Full CHIME site

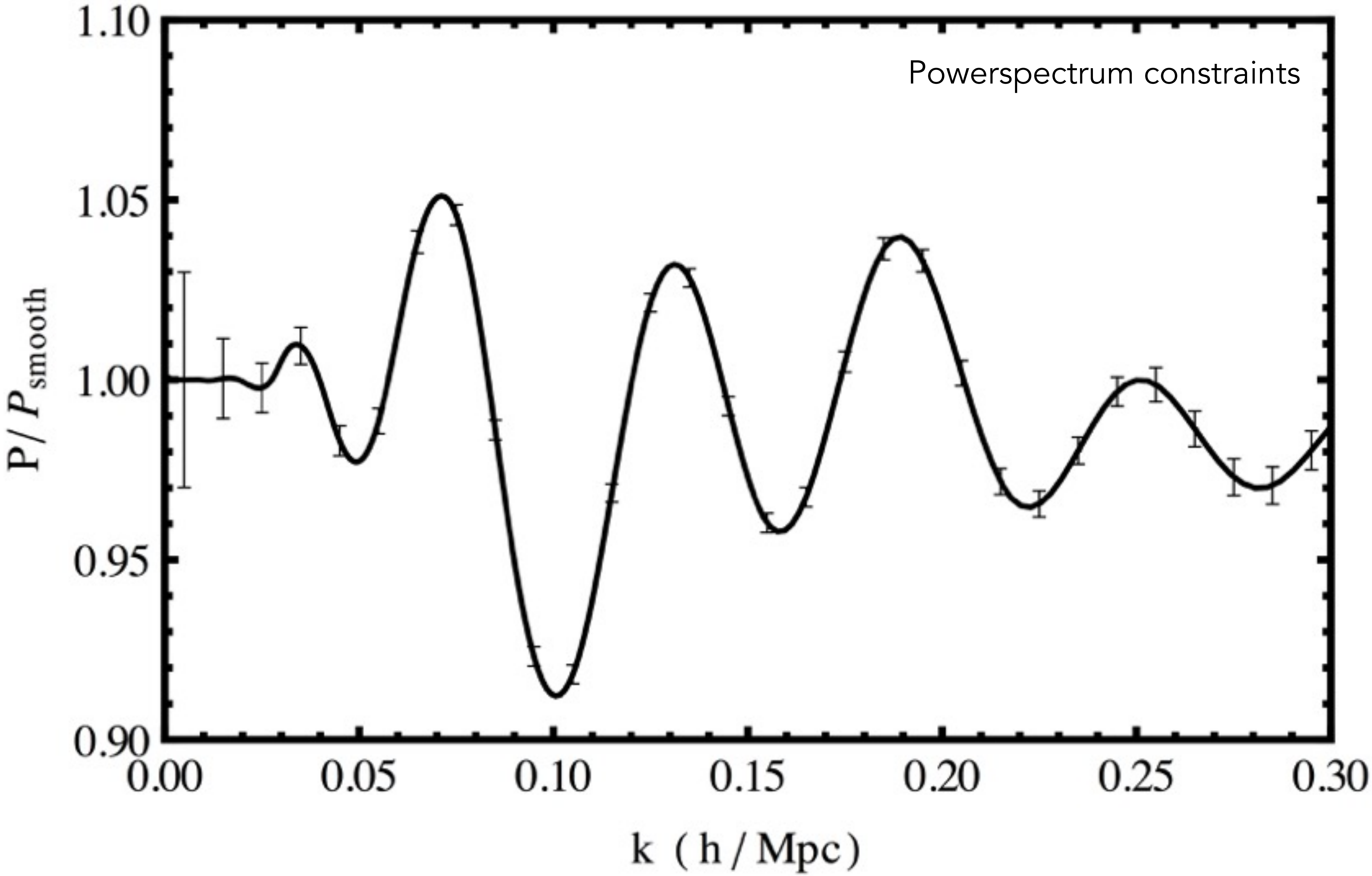
Survey Volume



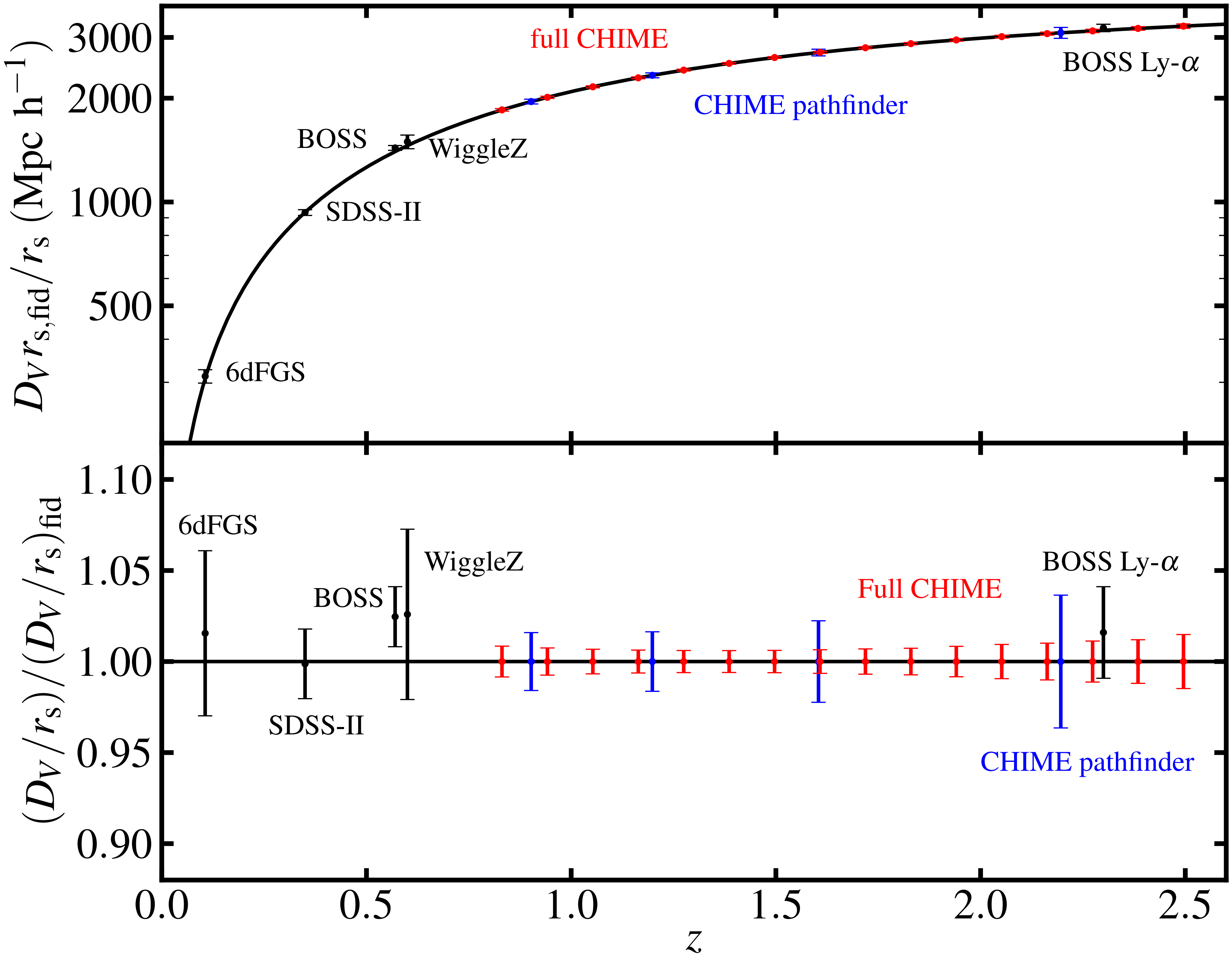
- WiggleZ: 1.2 $(h^{-1}\ \mathrm{Gpc})^3$
- BOSS
  - LRG: 5.3 $(h^{-1}\ \mathrm{Gpc})^3$
  - Lyα: 37 $(h^{-1}\ \mathrm{Gpc})^3$
- CHIME: 203 $(h^{-1}\ \mathrm{Gpc})^3$
- DESI ELG: 50 $(h^{-1}\ \mathrm{Gpc})^3$

Scaled such that:
area of patch=volume of survey

BAO Forecasts



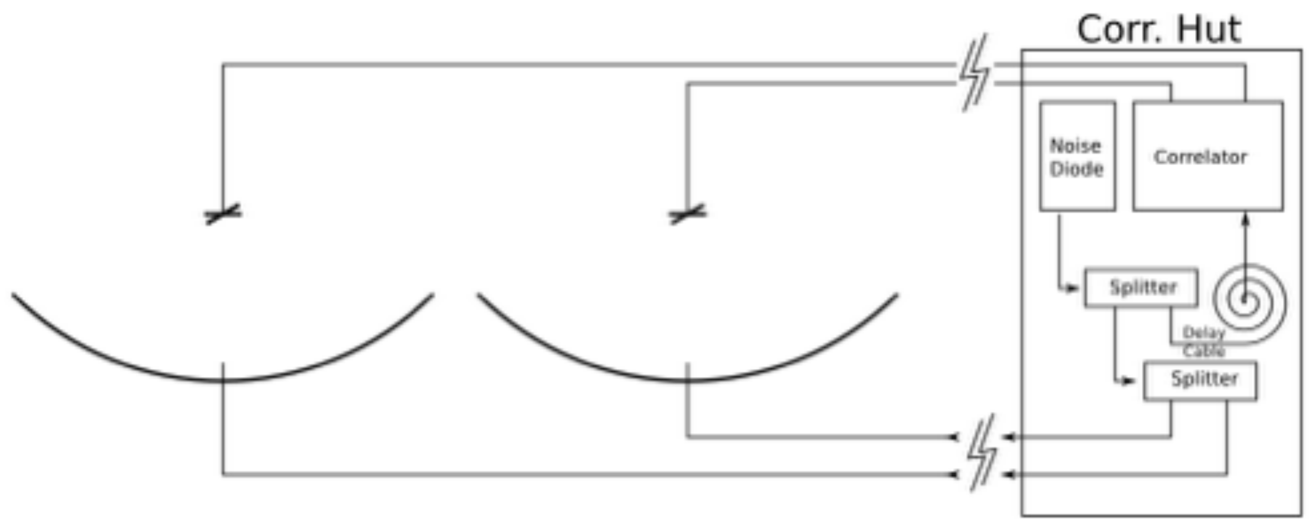
BAO Forecasts



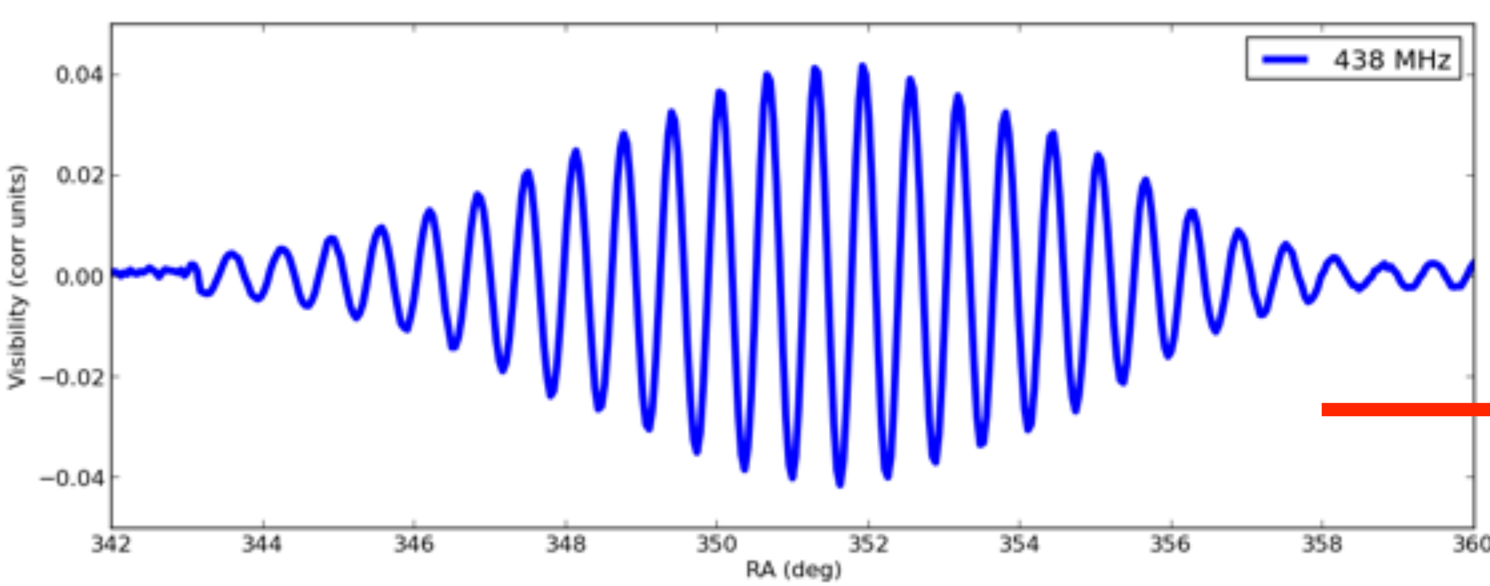
Status: Construction completed!

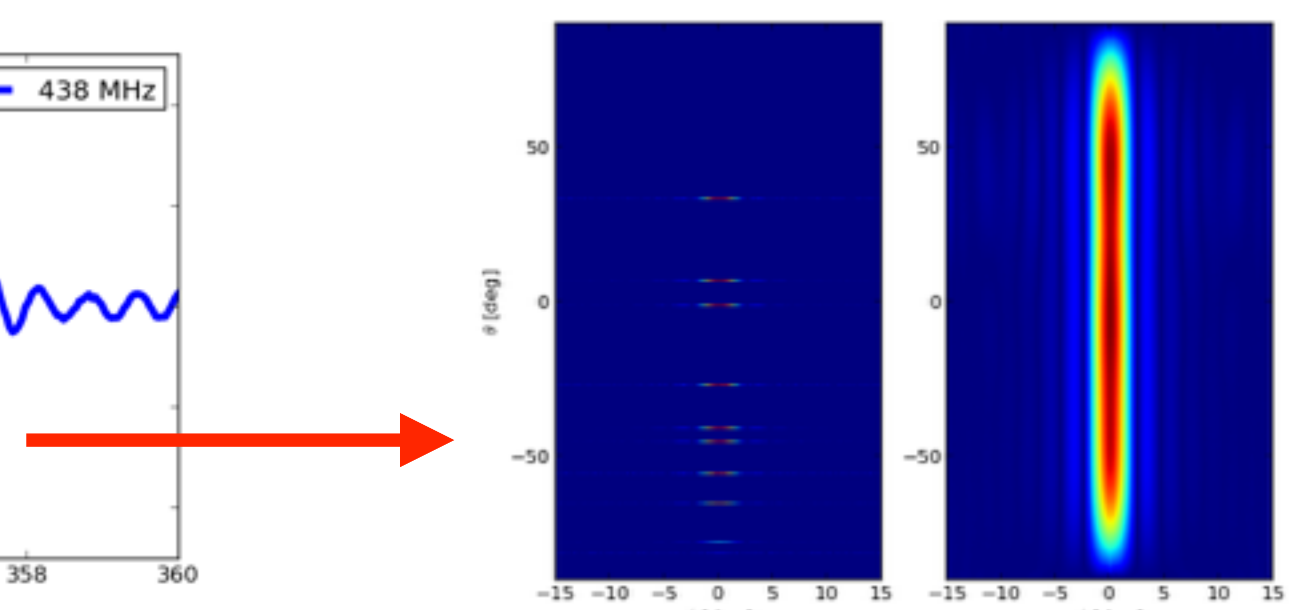
Calibration

- See more in Jon's talk tomorrow….
- Requirements set by ratio of signal to foregrounds ~ 10^{-5}
- Calibration of electric gains (broadband noise injection)



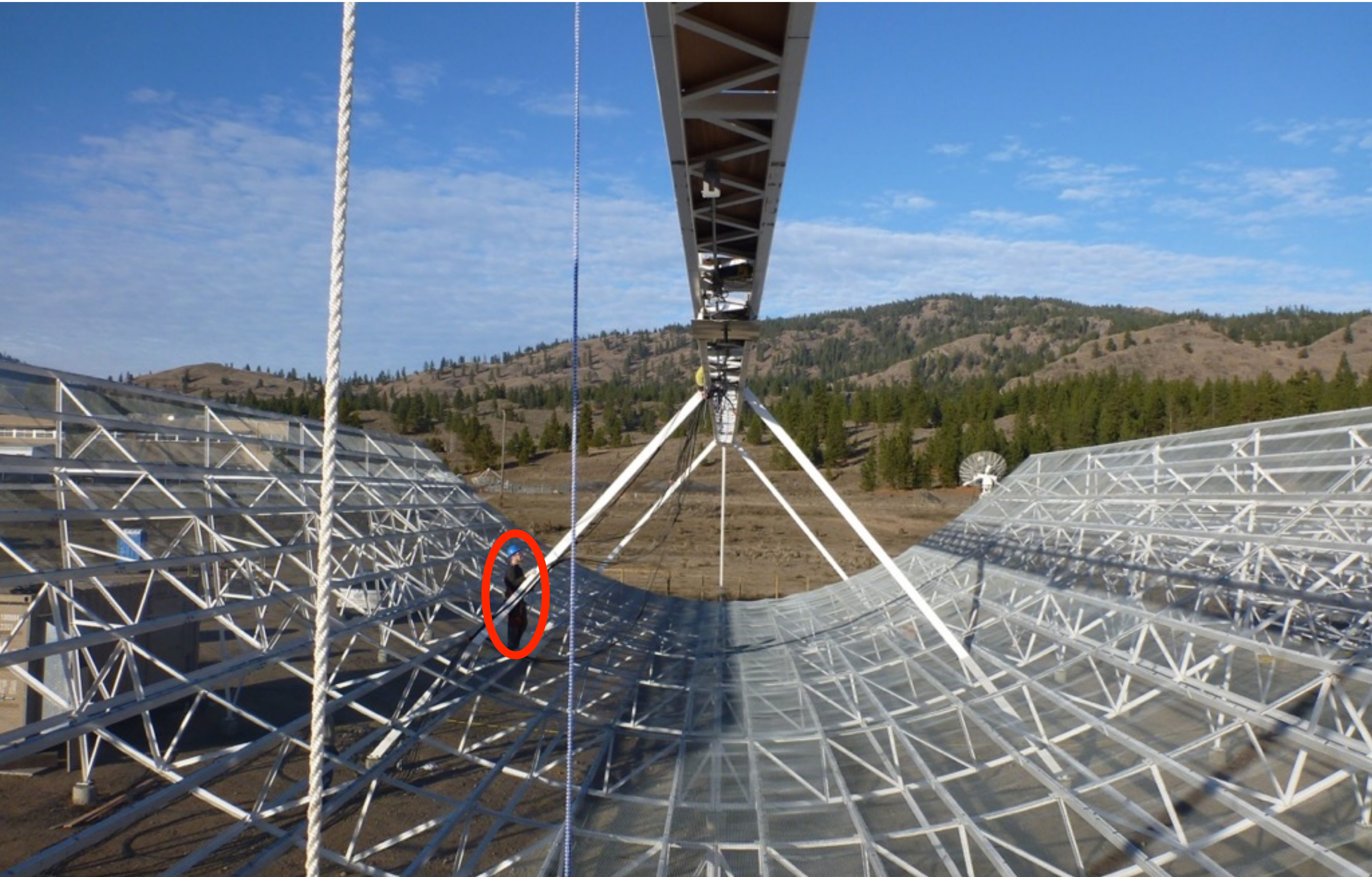
- Calibration of primary beams (pulsar holography…)



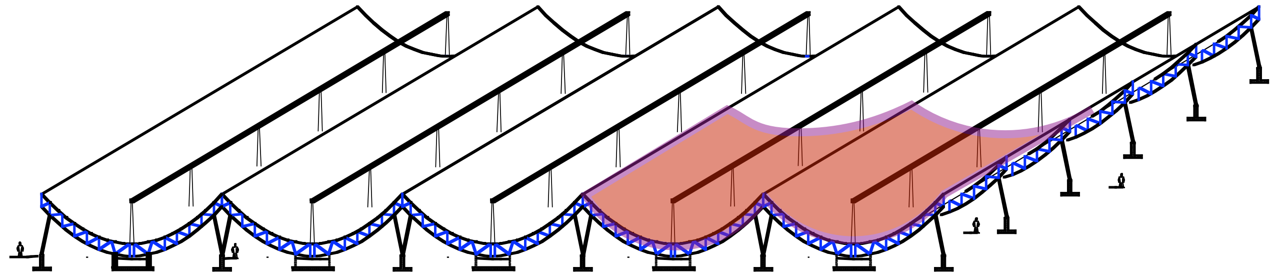


CHIME Pathfinder

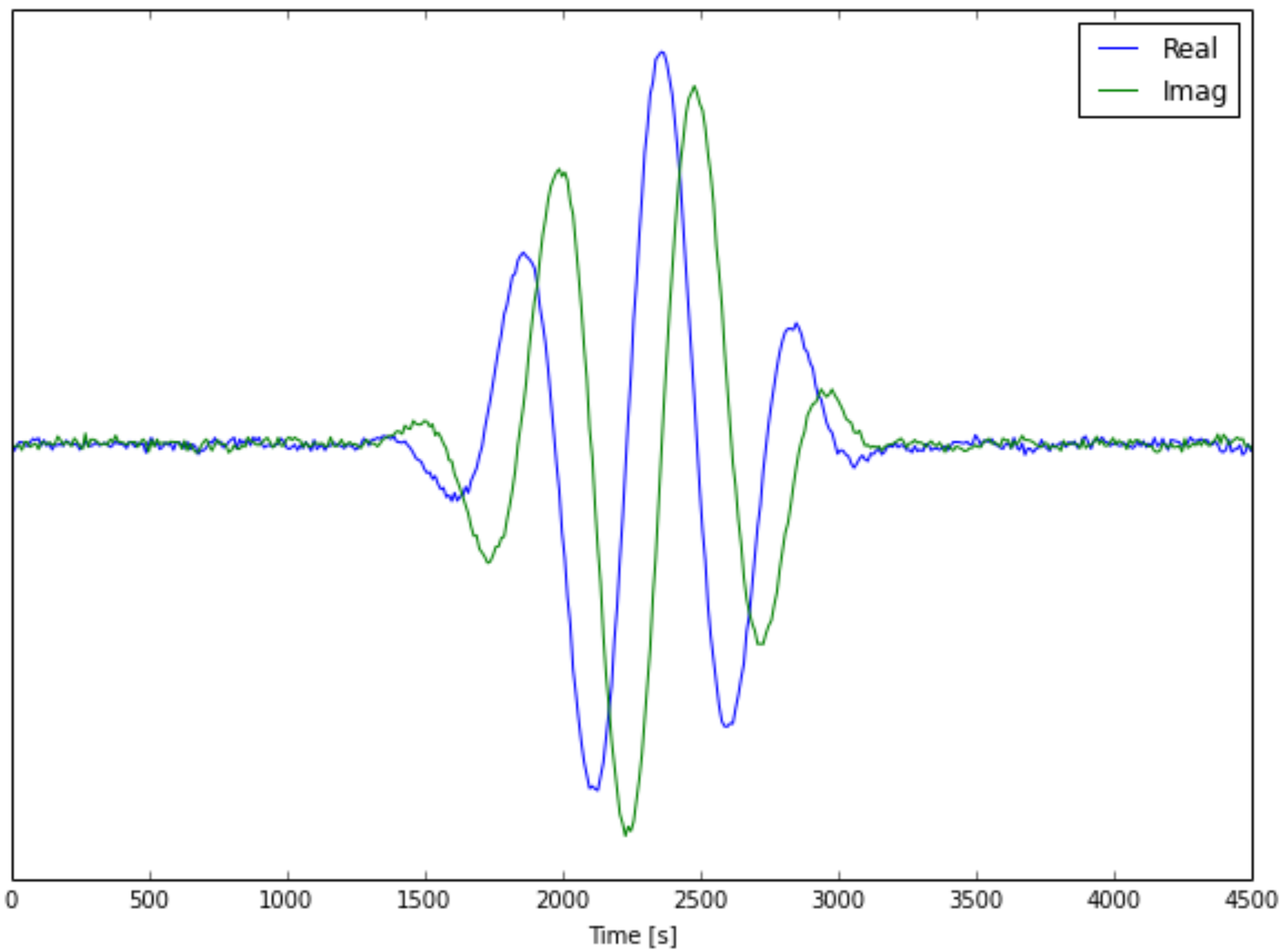
CHIME Pathfinder

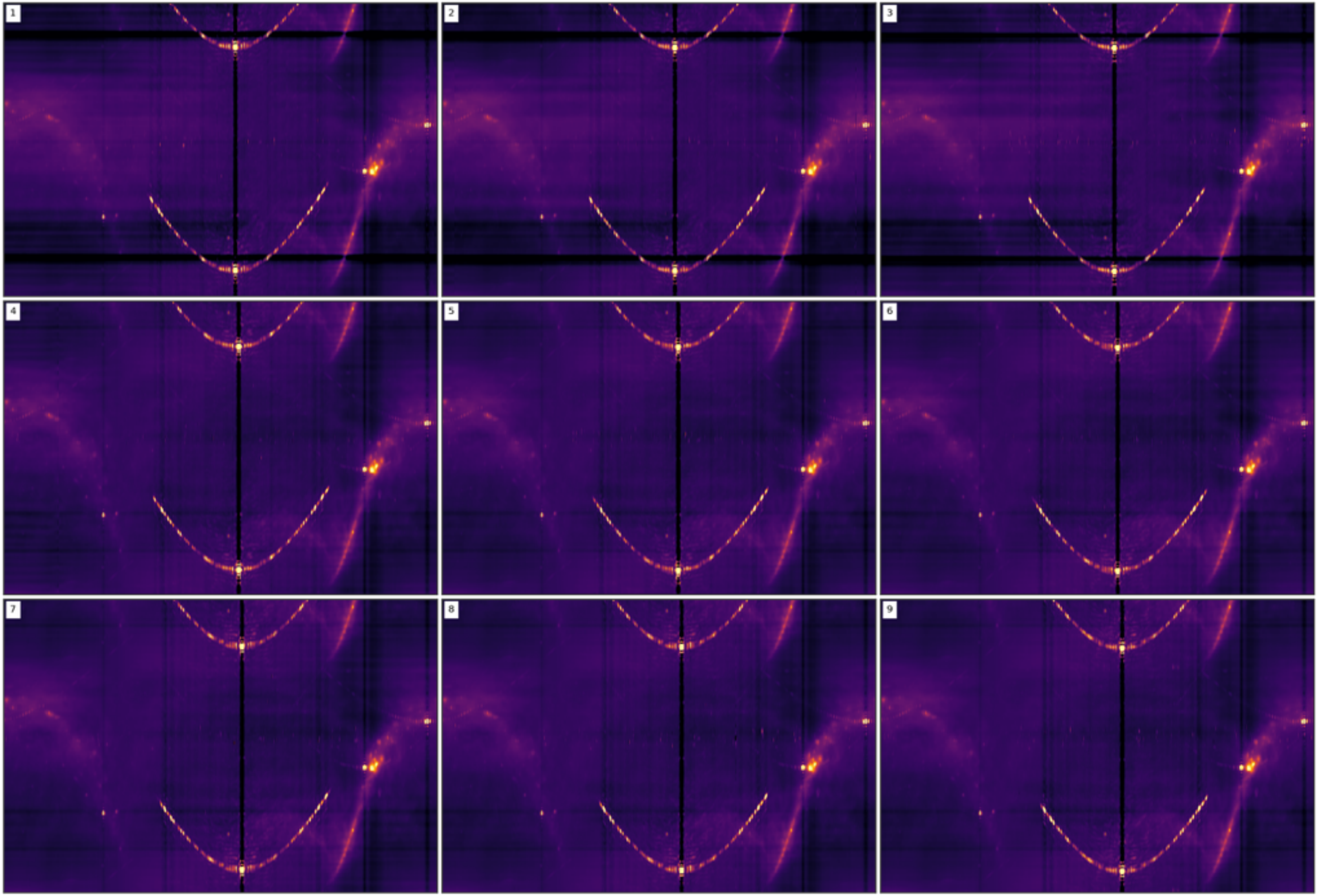


CHIME Pathfinder

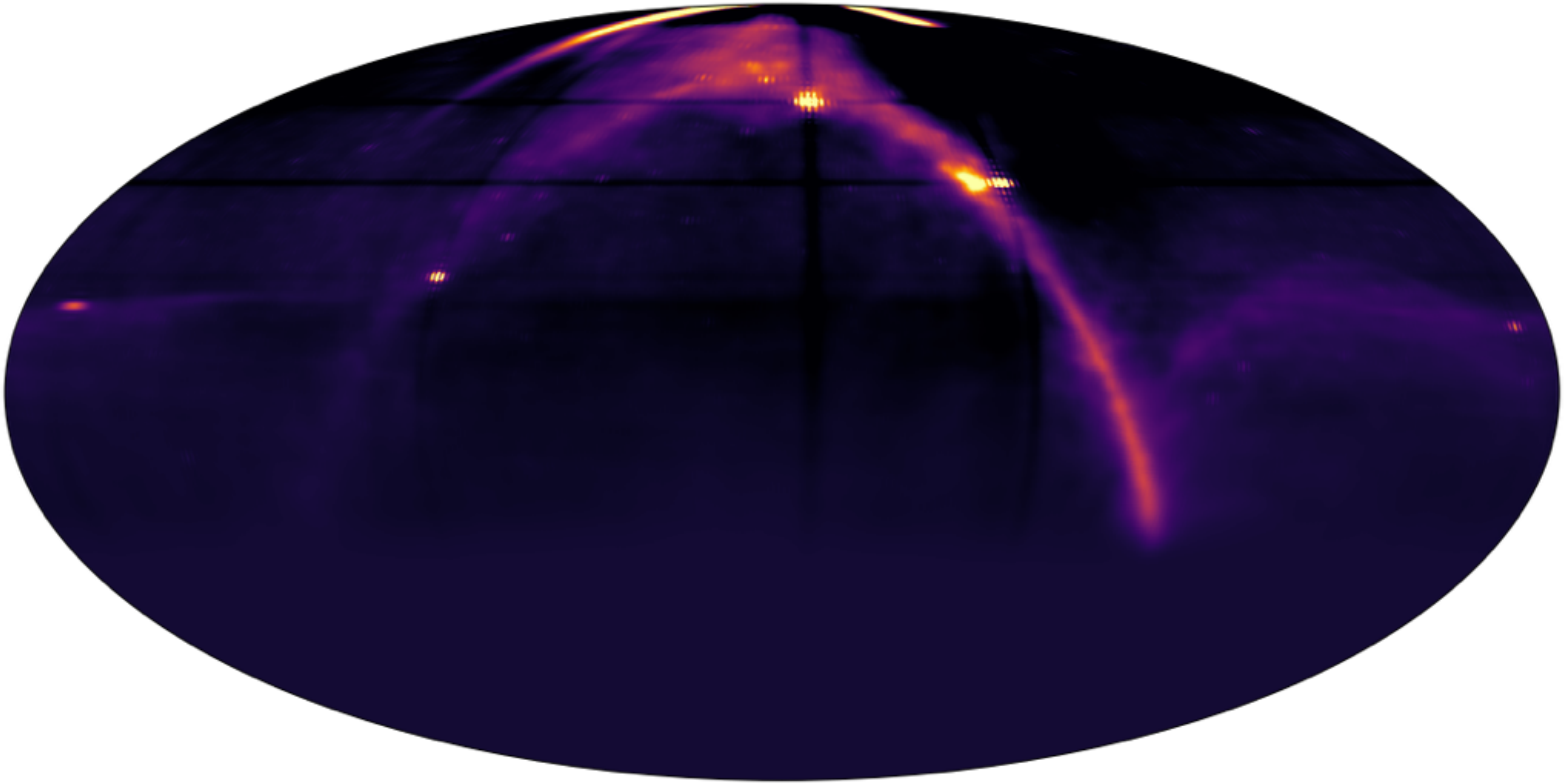


- 2x20m cylinder, 40m long
- First light was late 2013
- Commissioning finished early 2015



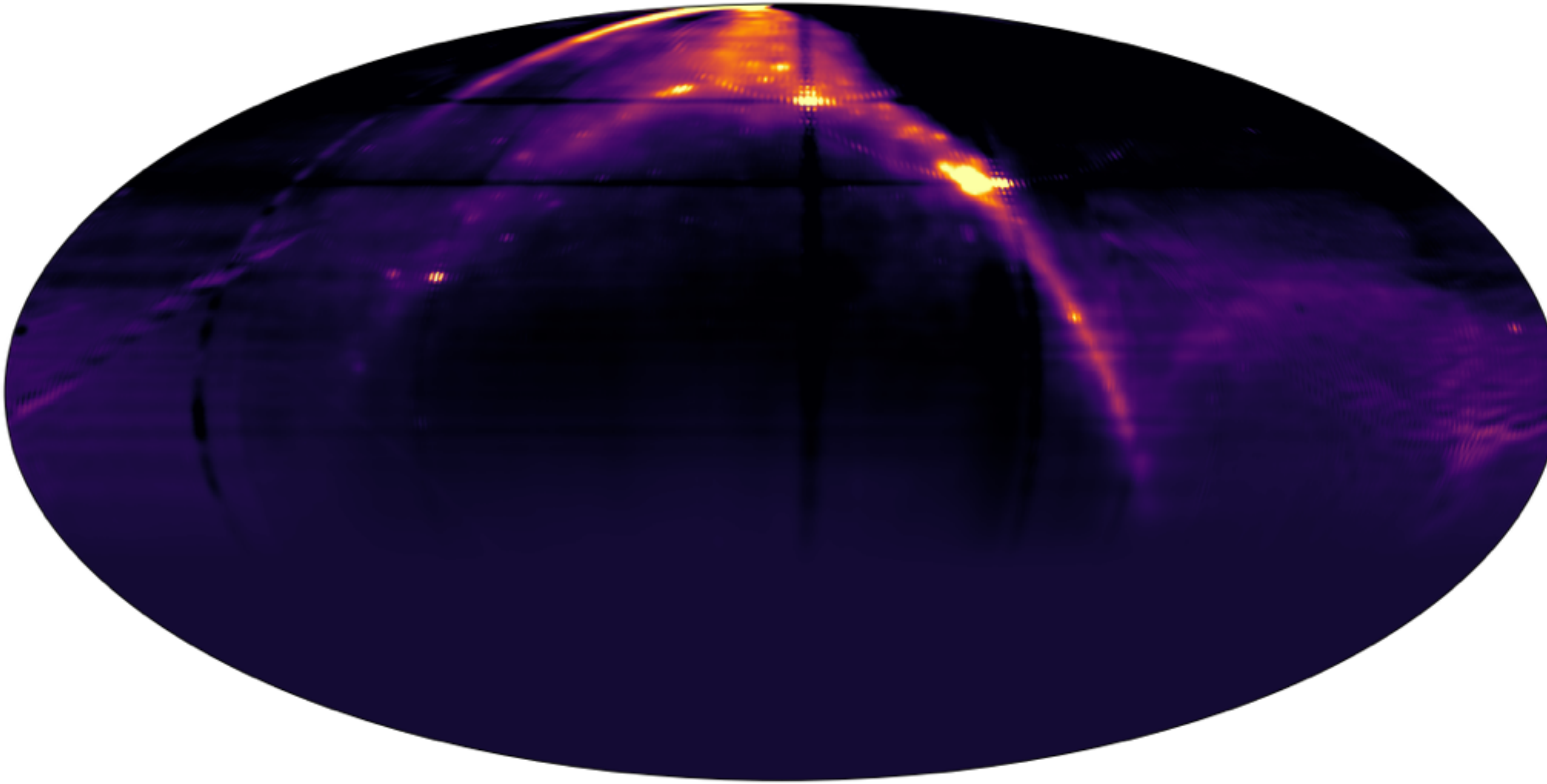

1
2
3
4
5
6
7
8
9

Dirty map



Simulated

Dirty map

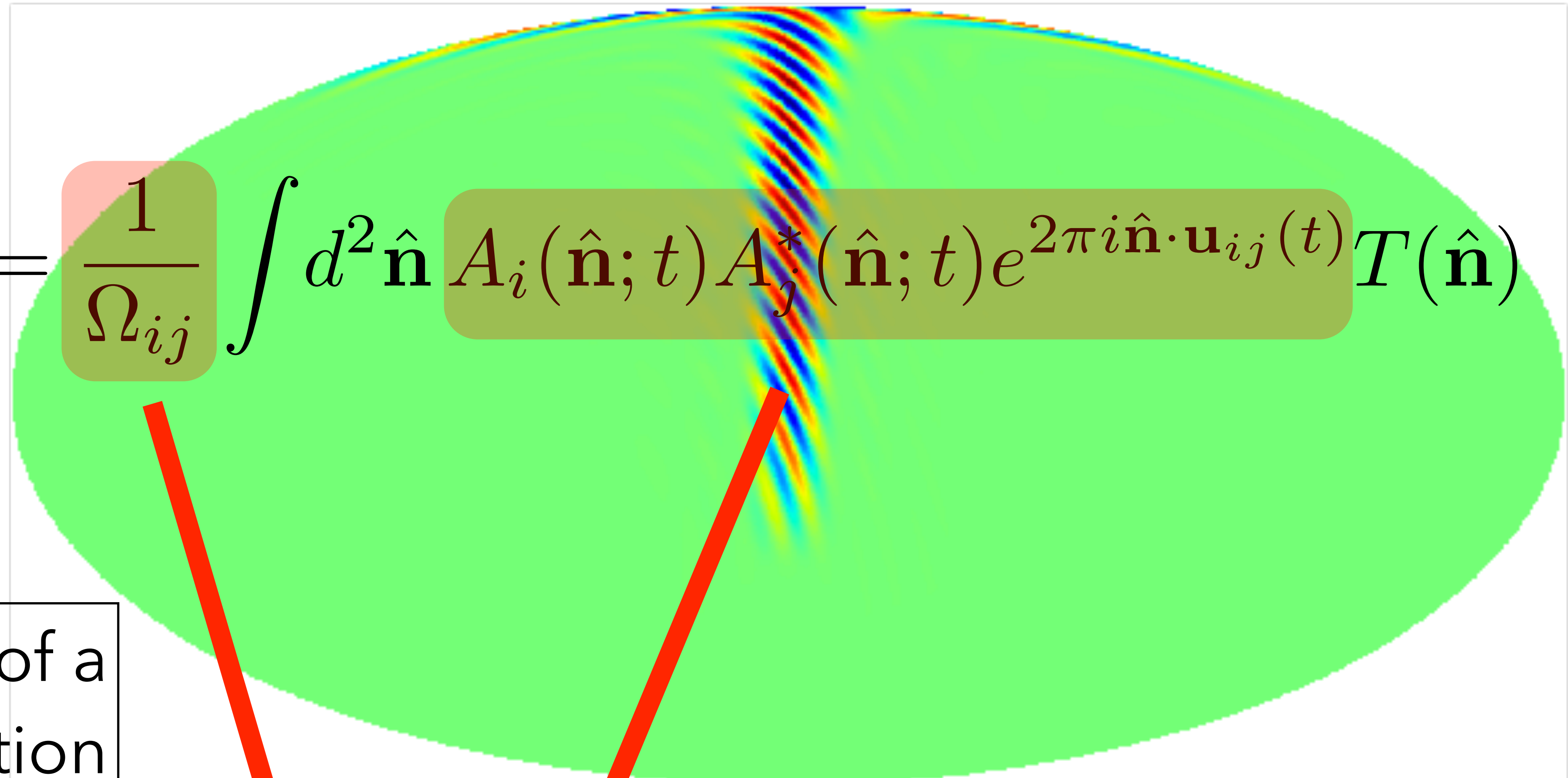


Real

Stack of 10 days data

Data Analysis with the m-mode formalism

Interferometers



$$V_{ij}(t) = \frac{1}{\Omega_{ij}} \int d^2\hat{\mathbf{n}}\, A_i(\hat{\mathbf{n}};t) A_j^*(\hat{\mathbf{n}};t) e^{2\pi i \hat{\mathbf{n}}\cdot\mathbf{u}_{ij}(t)} T(\hat{\mathbf{n}})$$

Write in terms of a transfer function

$$V_{ij}(t) = \int d^2\hat{\mathbf{n}}\, B_{ij}(\hat{\mathbf{n}};t) T(\hat{\mathbf{n}}) + n_{ij}(t)$$

Analysis challenges

- Data size (~ for CHIME):
  - Time samples: ~8000 / day
  - Baselines: ~3000 unique
  - Pixels: ~ 12 x 10^6
  - Frequencies: ~1000
- As a matrix in pixel space **B** ~ 10M x 30M (per frequency)
- Operations (e.g. direct map making are hugely costly)
- Consider other options….

Transit Interferometers

- Timeseries is periodic on the sidereal day $t \to \phi$
  - Apply this restriction and see how the analysis goes.

$$V_{ij}(\phi) = \int d^2\hat{\mathbf{n}}\, B_{ij}(\hat{\mathbf{n}};\phi) T(\hat{\mathbf{n}}) + n_{ij}(\phi)$$

Spherical Harmonic Transform

$$V^{ij}(\phi) = \sum_{lm} B^{ij}_{lm}(\phi) a^T_{lm} + n^{ij}(\phi)$$

Fourier Transform

$$V^{ij}_m = \sum_l B^{ij}_{lm} a^T_{lm} + n^{ij}_m$$

m-mode transform

- Mapping does not mix m's (each is independent)

$$V_m^\alpha = \sum_l B_{lm}^\alpha a_{lm}^T + n_m^\alpha$$

- Write in vector form

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

- Simple, linear mapping from the information on the sky, to the measured degrees of freedom
- Discrete relation, with finite number of degrees, can apply all the standard statistical, signal processing techniques.
- Computationally efficient: For 1000 m's an $O(N^3)$ matrix operation becomes 10^6 times faster

Interferometric Imaging

- Traditional imaging is based around the 2D Fourier Transform approximation to the interferometry equation (only valid on small patches instantaneously)
- Use a series of steps to relax this approximation and increase field of view (w-projection, mosaicking, A-projection)
  - eg. w-term. From non coplanarity of array and sky. Solve by iteratively deconvolving the effects

$$V = \int dx dy A^2(x,y) e^{2\pi i (ux + vy + w\sqrt{1 - x^2 - y^2})} I(x,y)$$

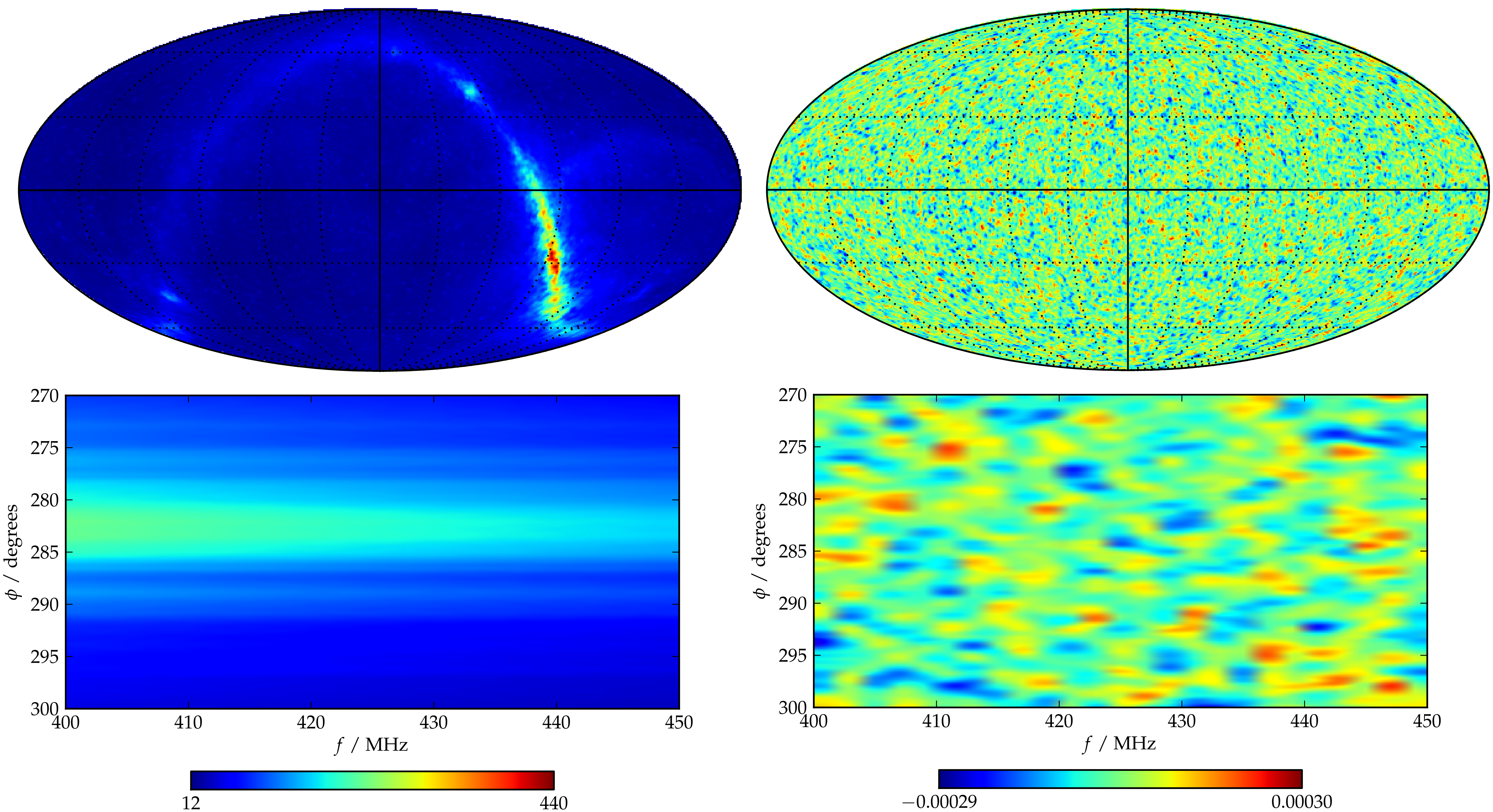
m-mode Imaging

- For our restricted domain (transit telescopes), we can solve the problem exactly.
- Measurement is linear mapping:

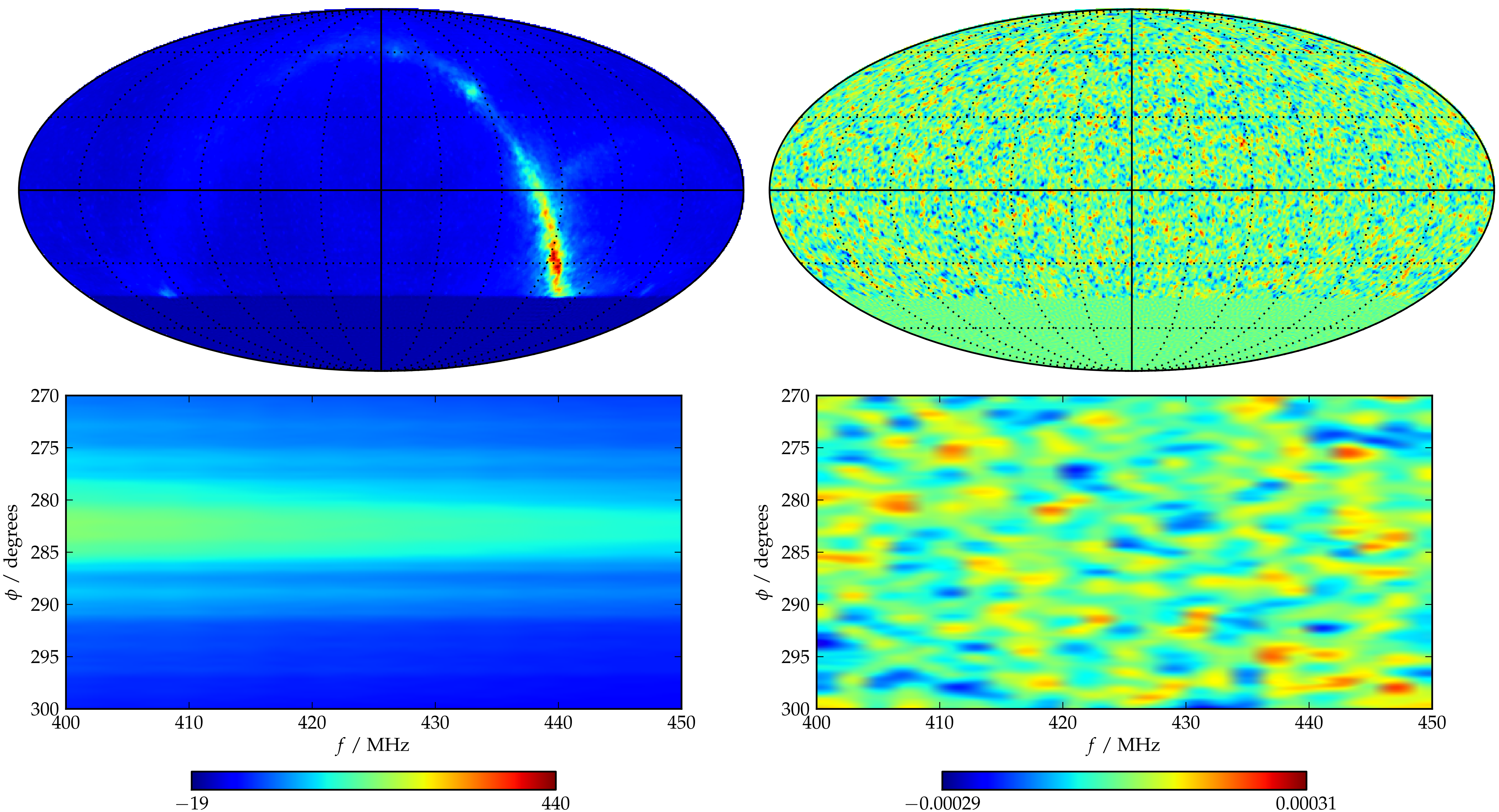
$$\mathbf{v} = \mathbf{B}\,\mathbf{a} + \mathbf{n}\,.$$

- How do we make an image of the sky? Use standard tools of signal processing:
    - Pseudo-inverse to solve and regularize *(Maximum likelihood)*
    - Wiener Filter *(Bayesian expectation)*
- Conceptually straightforward. Deals naturally with all full sky effects, polarisation etc.

Simulated sky



Observed sky (from time stream) $\hat{\mathbf{a}} = \left(\mathbf{N}^{-\frac{1}{2}}\mathbf{B}\right)^{+}\mathbf{N}^{-\frac{1}{2}}\mathbf{v}$

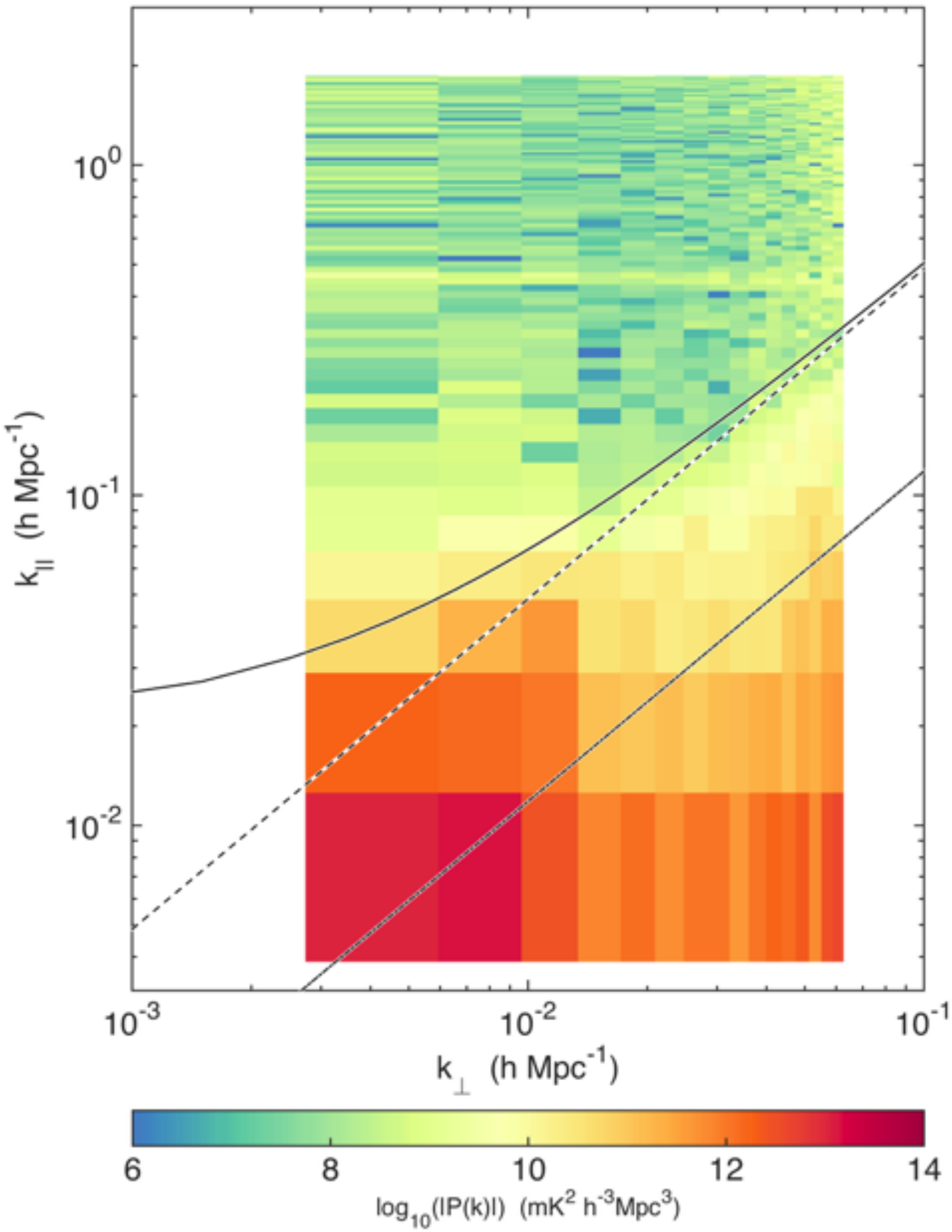


2x15m wide cylinders, 60 feeds, 0.25m spacing 400-600 MHz

Foreground Removal

- Spectral smoothness allows separation of 21cm
  - Measure components and model (Liu, Dillon etc.)
  - Power spectrum removal (Foreground wedge)
  - Delay-space filtering (Parsons et al. 2012)
- Most methods have difficulties:
  - *Mode mixing* of angular and frequency fluctuations by frequency-dependent beams (esp. interferometers)
  - *Robustness* Biasing introduced if foreground model poorly understood (esp. non-gaussianities)
  - *Statistical Optimality* Need to keep track of transformations on statistics, for optimal PS estimation
  - *Polarisation leakage* mixes fluctuations from polarised foreground

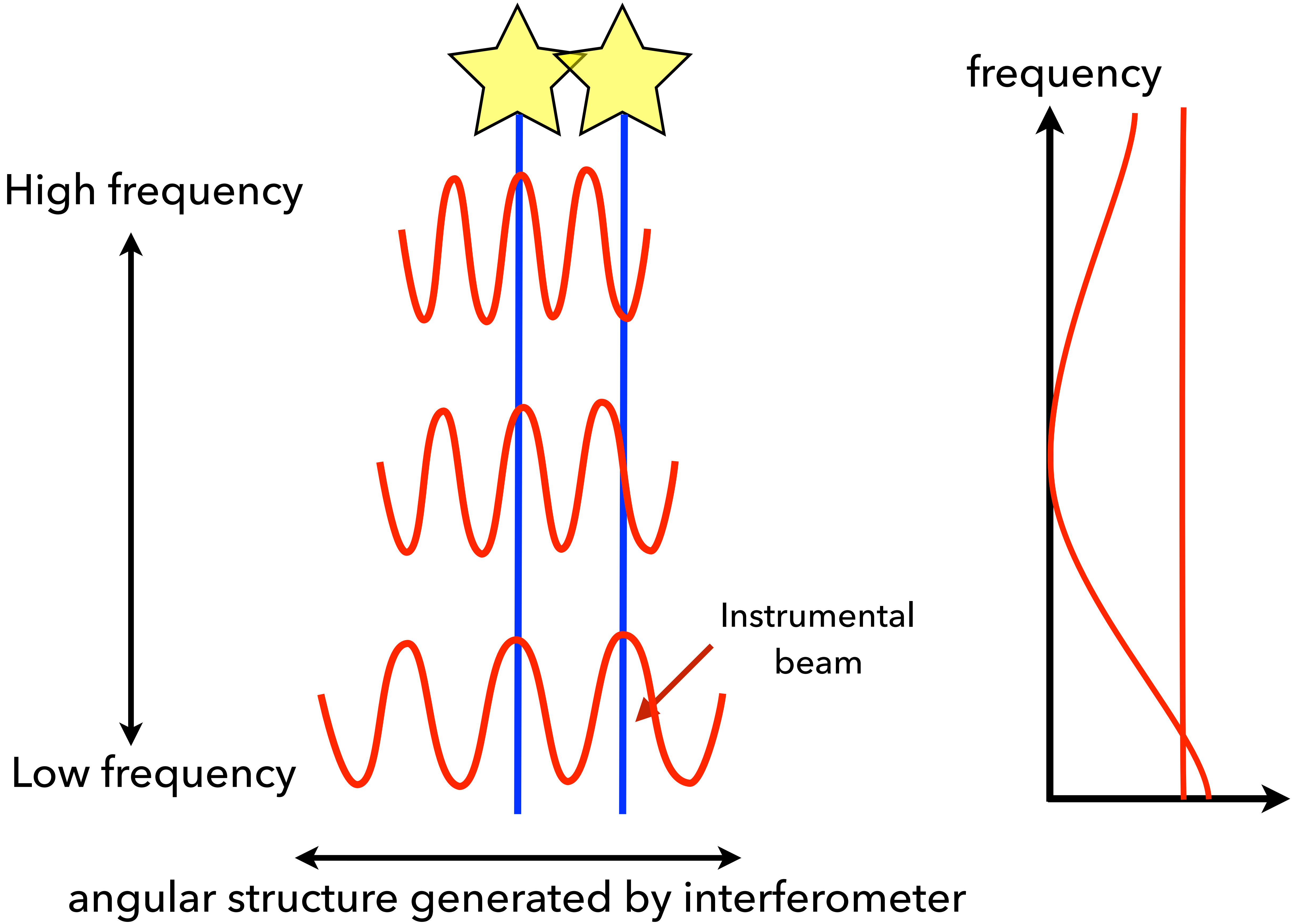
Foreground Wedge



Dillon et al. 2015 (MWA)

- Wedge is caused by mode mixing
- Argument for a smooth primary beam is that foreground power is limited in k_par, for a fixed baseline
- Optimistic:
  - Actual primary beam may not be smooth
  - Polarisation leakage
- Pessimistic too!
  - If we know about the beam we can remove it….

Mode mixing


High frequency
Low frequency
Instrumental
beam
angular structure generated by interferometer
frequency

Karhunen-Loeve Transform

- Old CMB idea - E/B mode separation (Bunn et al. 2003)
- An 'optimal' treatment - m-modes makes it feasible.
- Construct the covariances of the signal and foregrounds in the measured basis

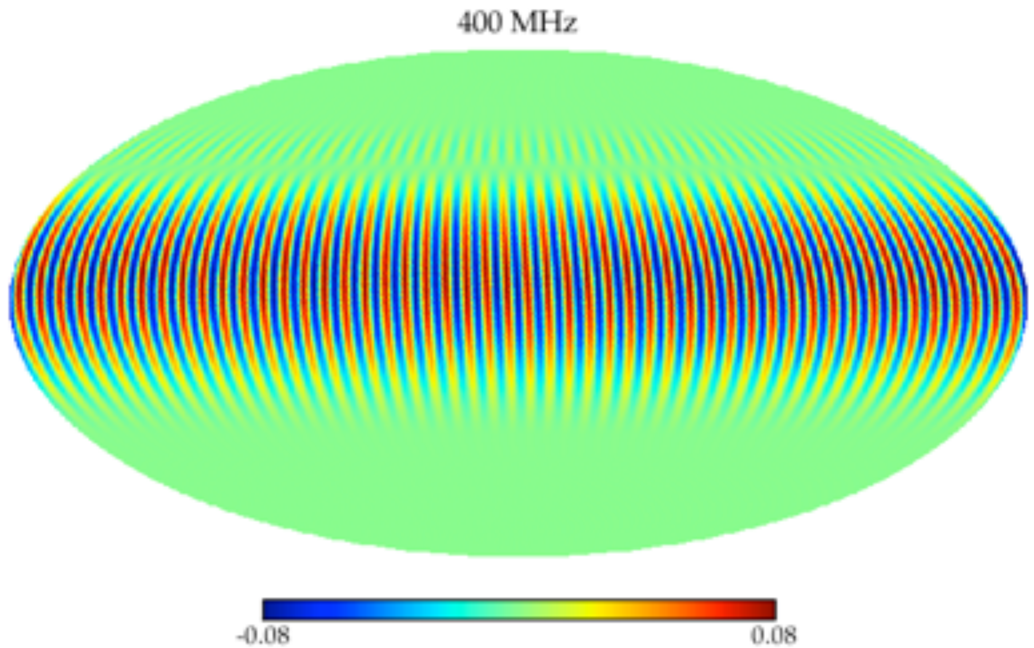
$$\mathbf{S} = \left\langle \mathbf{s}\mathbf{s}^{\dagger} \right\rangle = \mathbf{B} \left\langle \mathbf{a}_s^{*} \mathbf{a}_s^{T} \right\rangle \mathbf{B}^{\dagger} \qquad \mathbf{F} = \mathbf{B} \left\langle \mathbf{a}_f \mathbf{a}_f^{\dagger} \right\rangle \mathbf{B}^{\dagger}$$

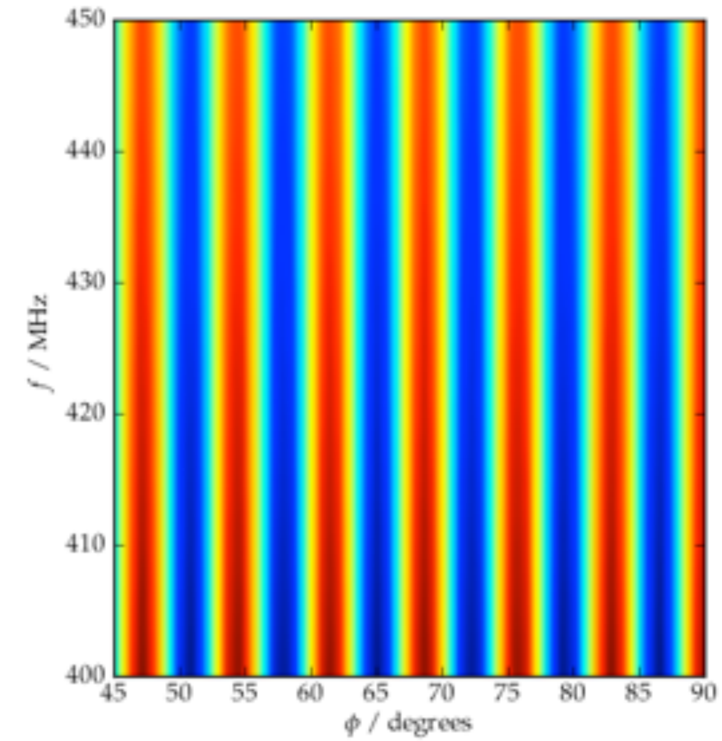
- Jointly diagonalise both (eigenvalue problem)

$$\mathbf{S}\mathbf{x} = \lambda \mathbf{F}\mathbf{x}$$

- Gives a new, uncorrelated basis. Corresponding eigenvalue gives the expected signal to foreground power ratio.

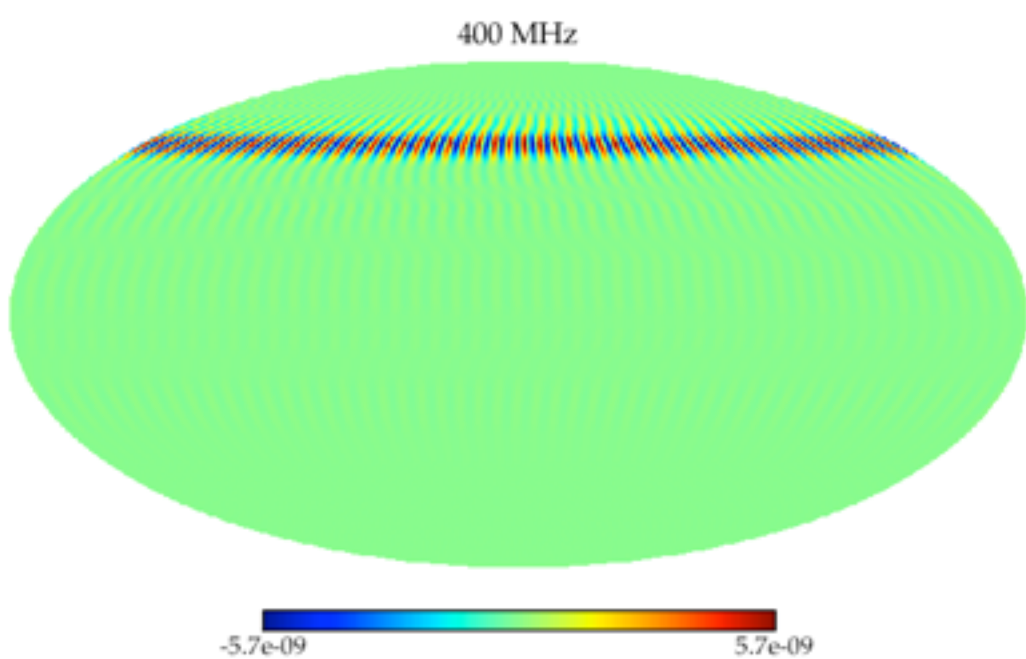
Most foreground

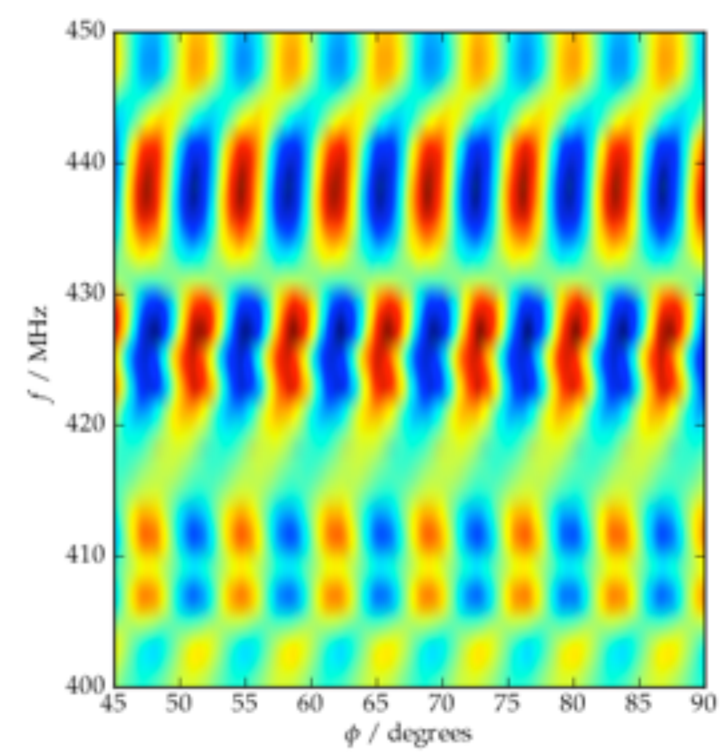




smooth in freq

Most signal





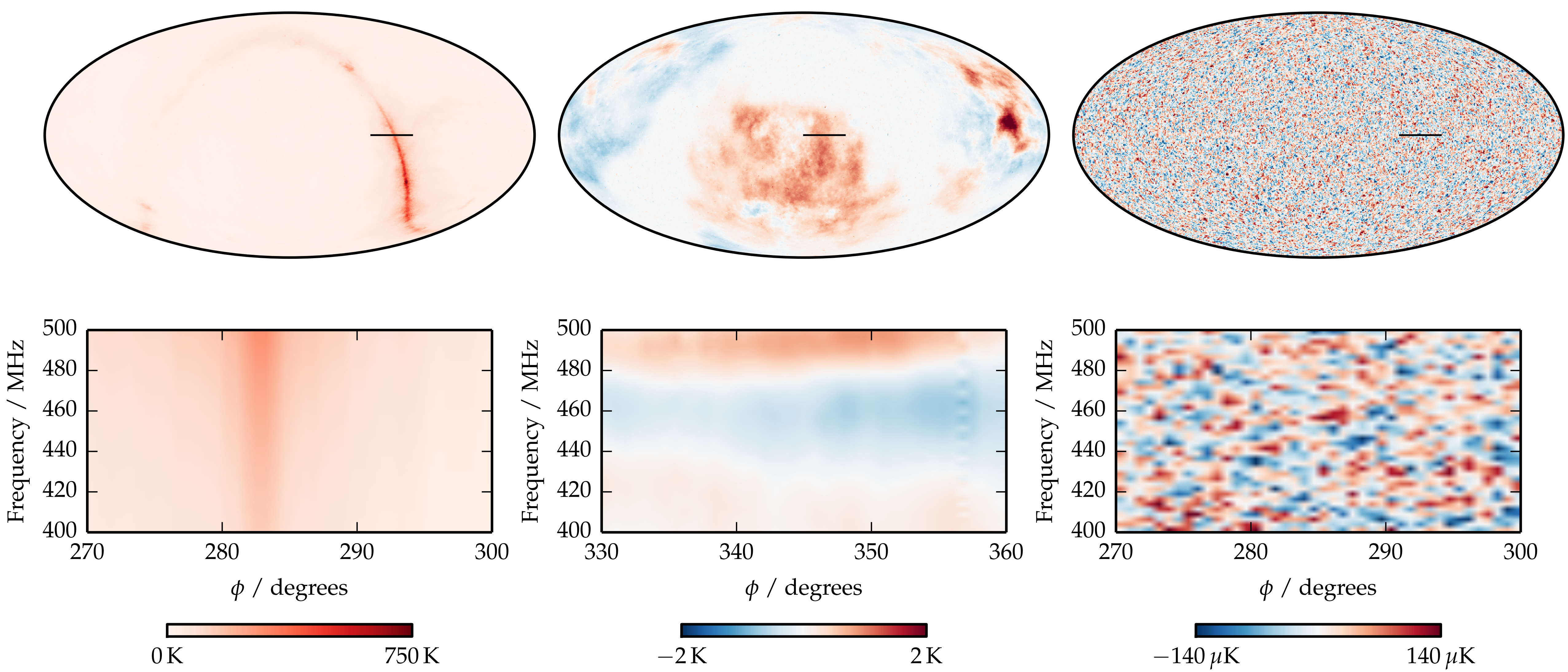
oscillates in freq

Foreground Removal with KLT

- Foreground removal is performed by projecting out modes with low signal-to-foreground ratio.
- Robustness to model uncertainties by choosing a conservatively large threshold; we would prefer to increase our errors bars in order to remove bias.
- Addresses the previous problems
    - Analysis uses all measured data to avoid mode mixing.
    - Can be made arbitrarily robust - increase threshold for removal
    - Linear transformation in the data space, keeps track of statistics

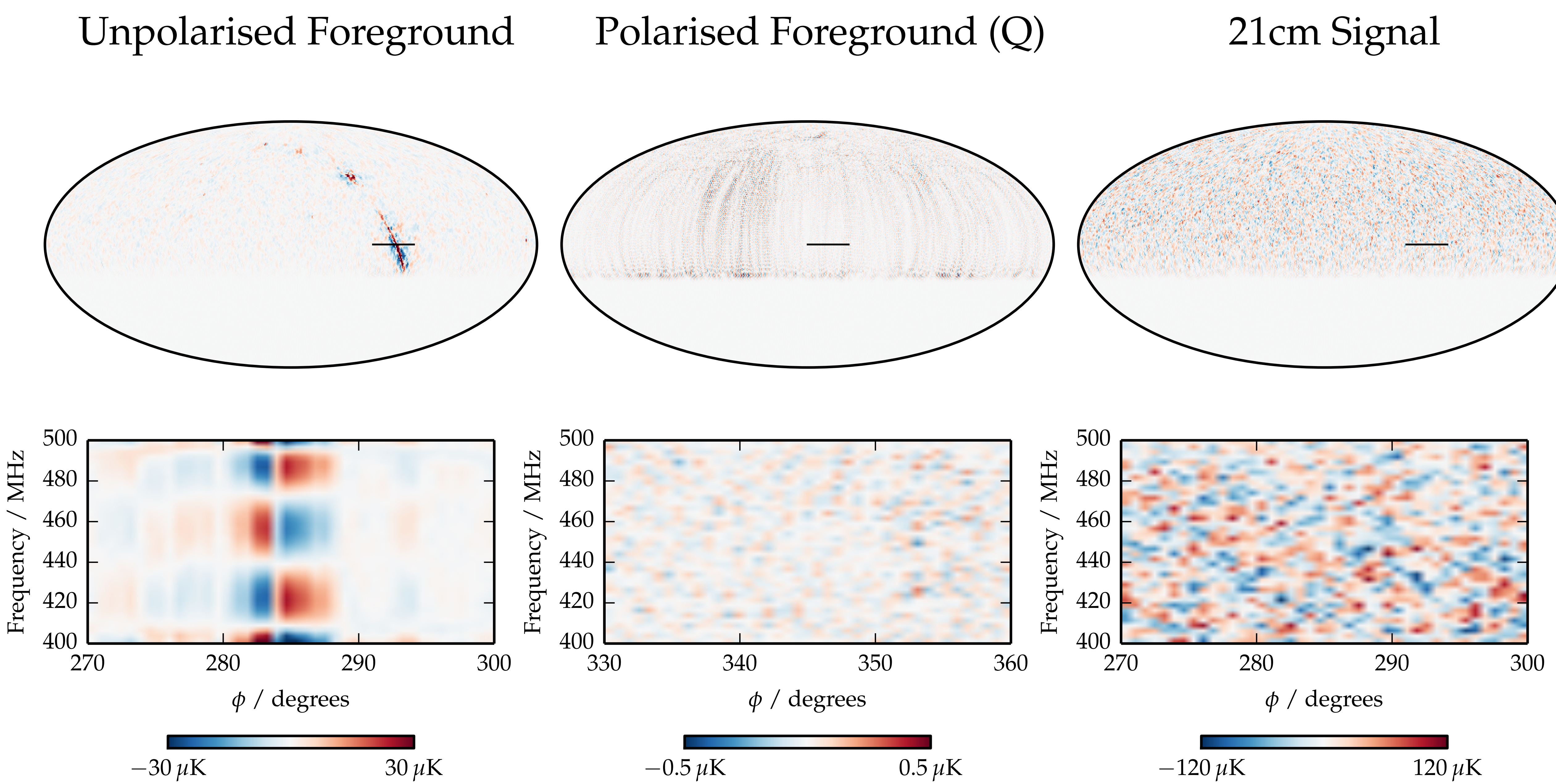
Foreground Cleaning

Unpolarised Foreground | Polarised Foreground (Q) | 21cm Signal



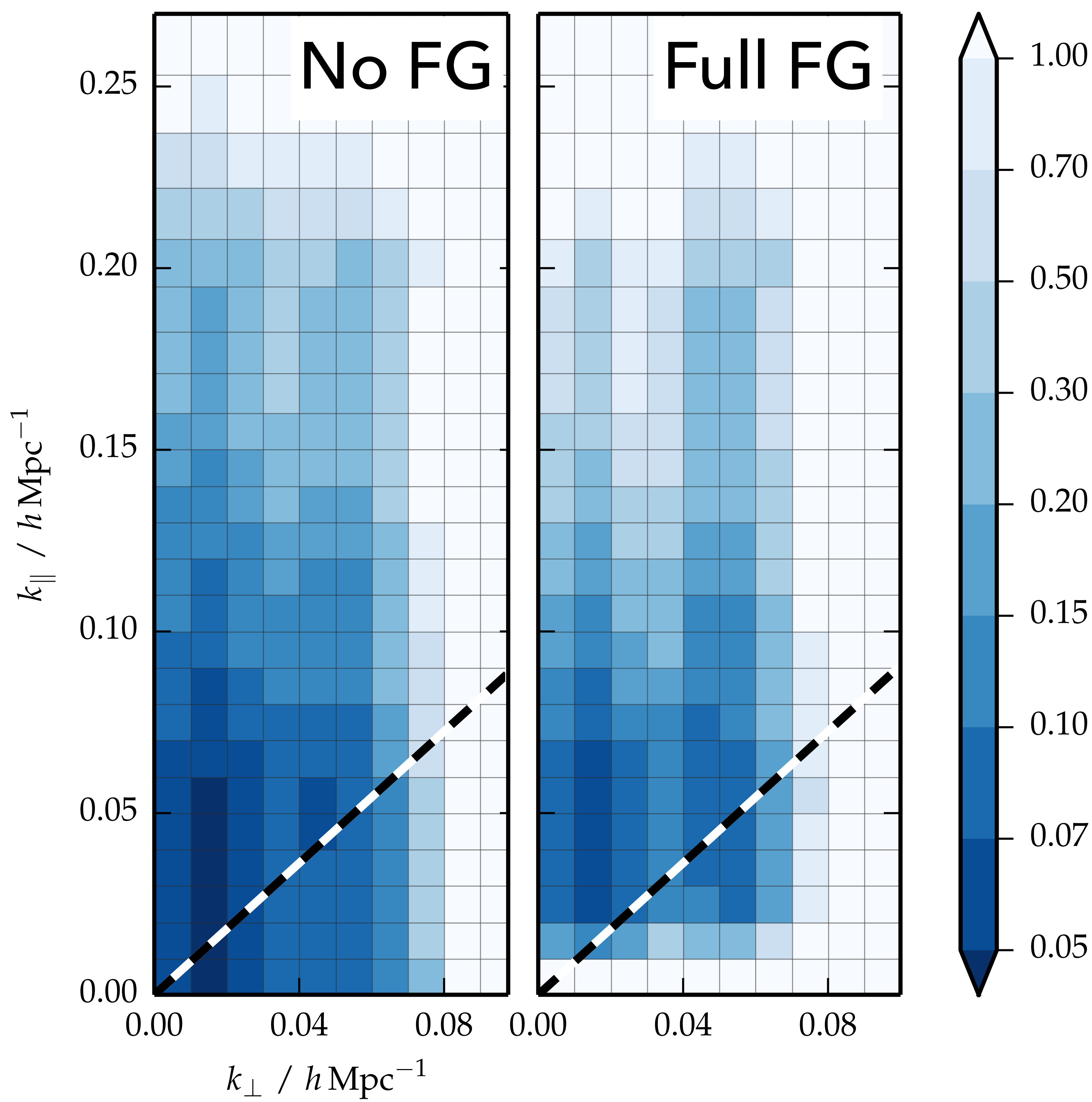
Foregrounds 10^6 times larger than signal

Foreground Cleaning



Foreground residuals significantly smaller than signal

2D Power spectrum Estimation



Fractional power spectrum errors (blue is better)

Subtraction works well into foreground wedge

Summary

- CHIME Pathfinder is operating, full instrument construction finishing in 2016
- Analysis is fun! Polarised radio sky simulation and 21cm data analysis code all available at:

http://github.com/radiocosmology/