Probing Dark Energy with the

Canadian Hydrogen Intensity Mapping Experiment

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UBC a place of mind
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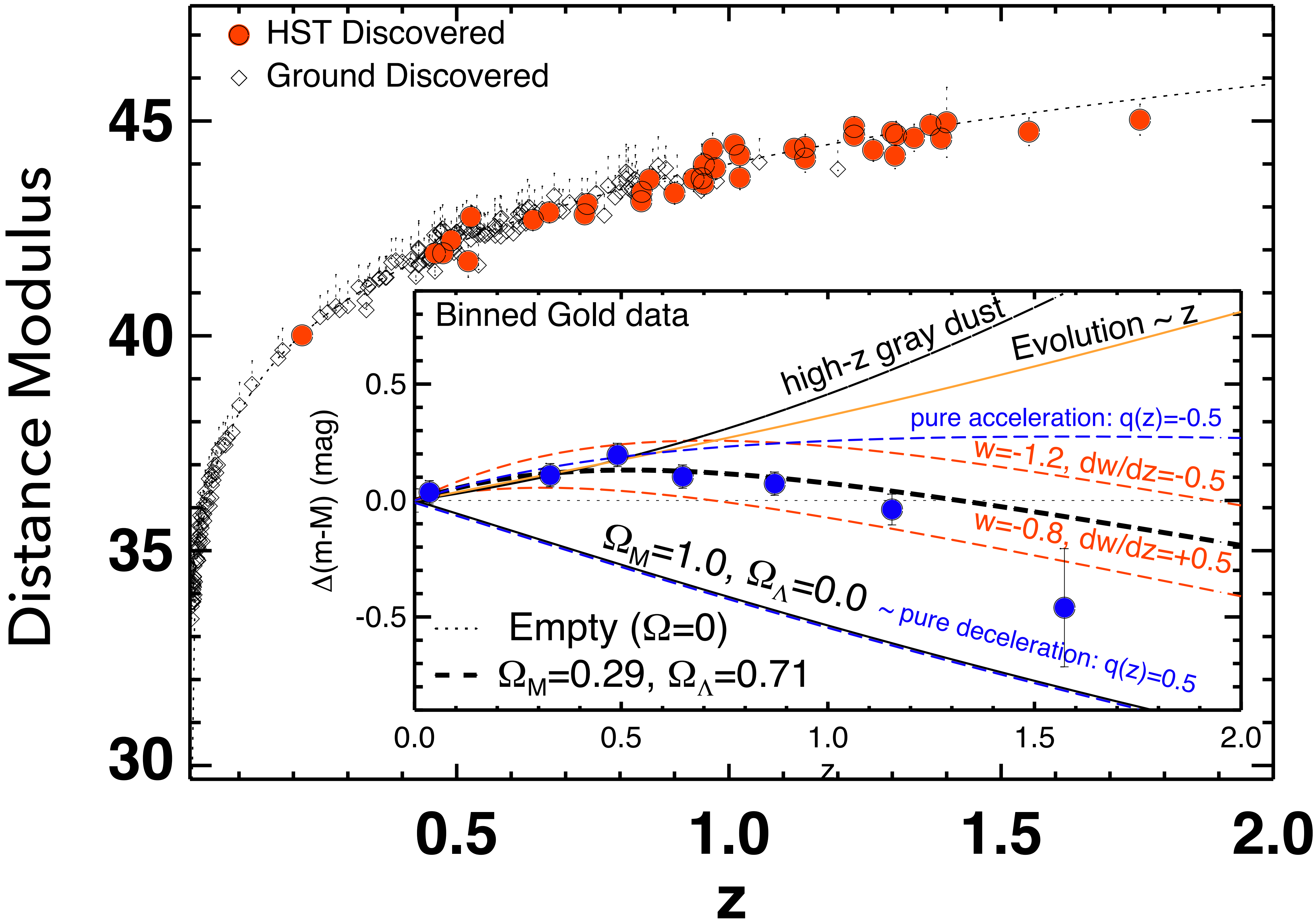
Outline

- Dark Energy, BAOs and Intensity Mapping
- Current and future experiments
- CHIME
- Data analysis/Foreground removal

Accelerating Universe

Luminosity distance
$D_L = (L/4\pi F)^{1/2}$

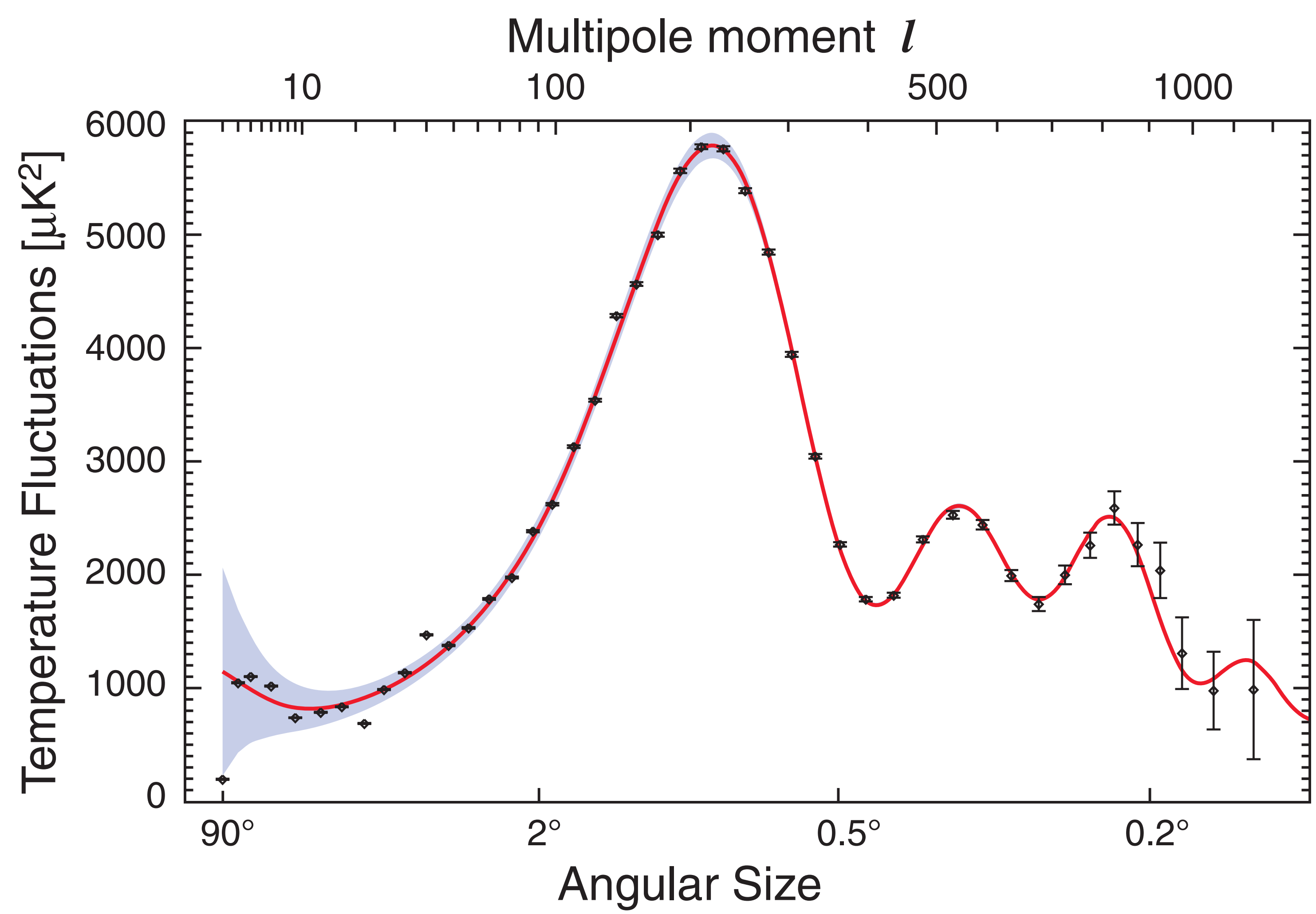


Riess et al. 2007

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



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

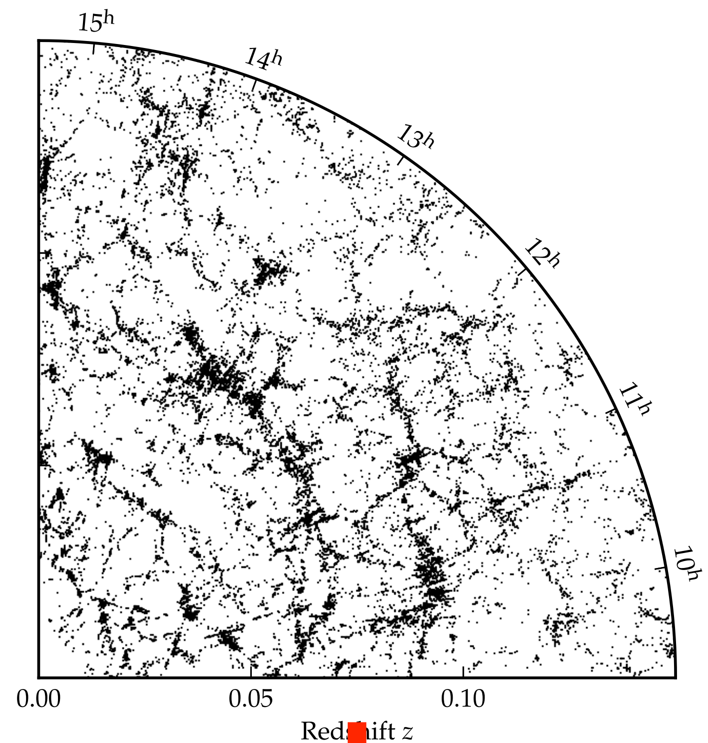
Known from CMB

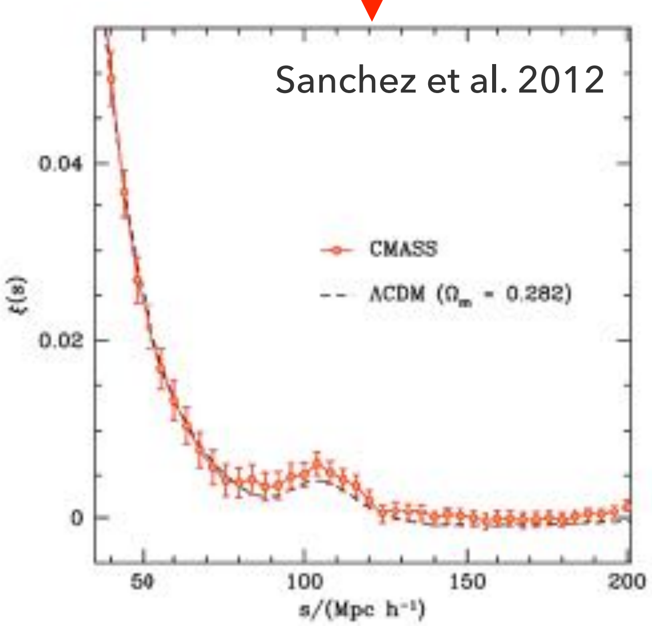
Probing Dark Energy with BAOs

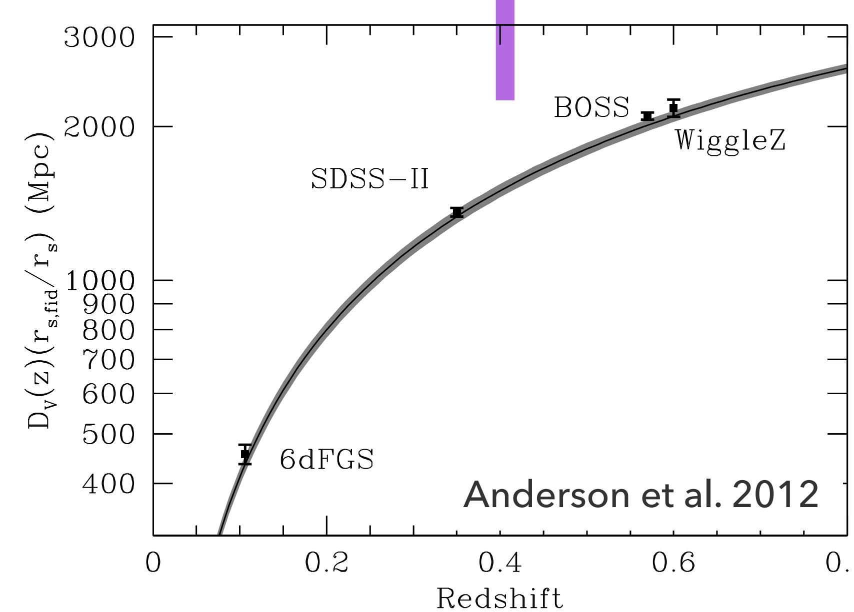
Constraints on theory of dark energy

Friedmann Equation

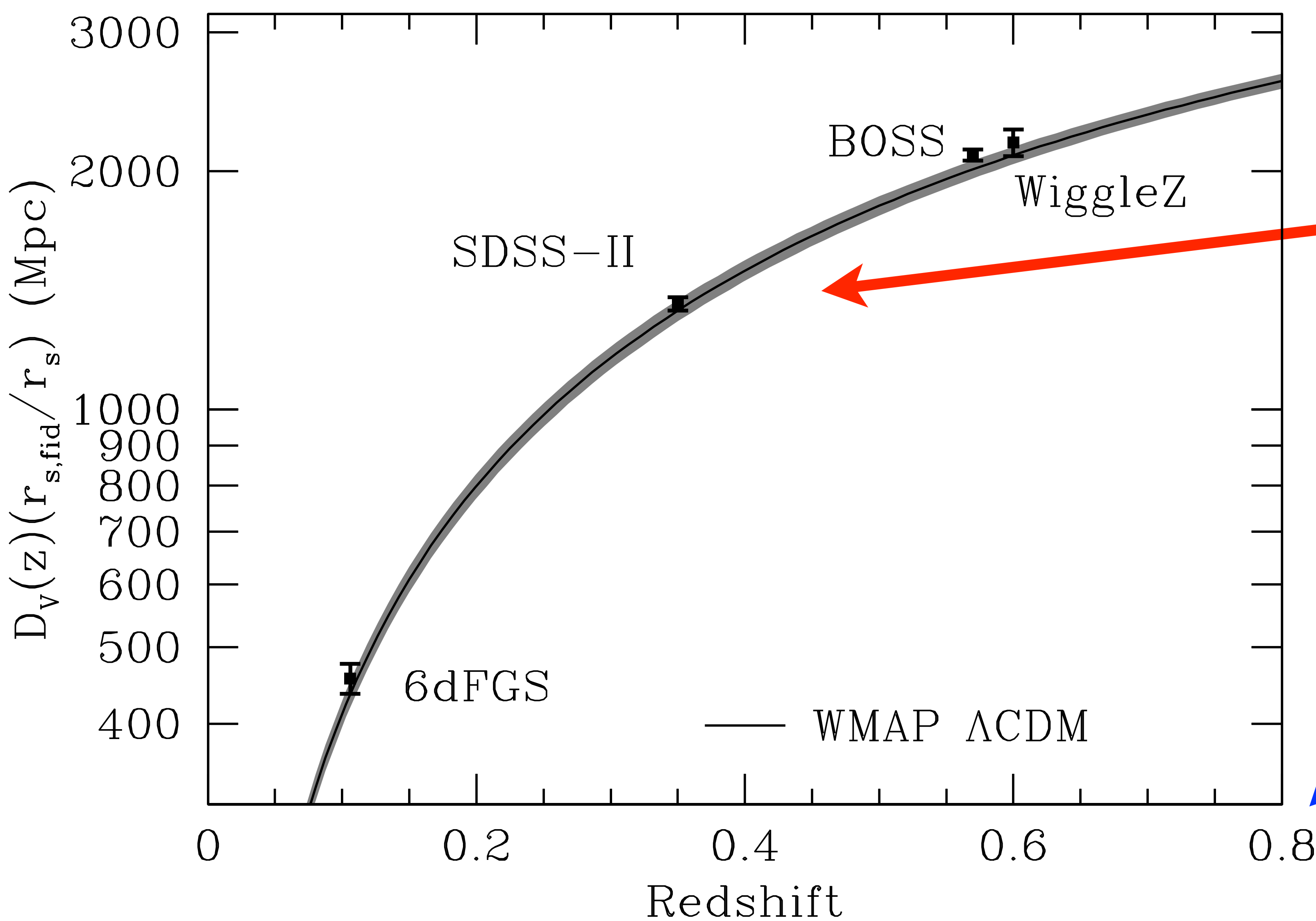
$$H(z)^2 \approx \Omega_m(1+z)^3 + \Omega_{DE} \exp\left[\int_0^z (1+w(z))\frac{dz}{1+z}\right]$$







Baryon Acoustic Oscillations



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

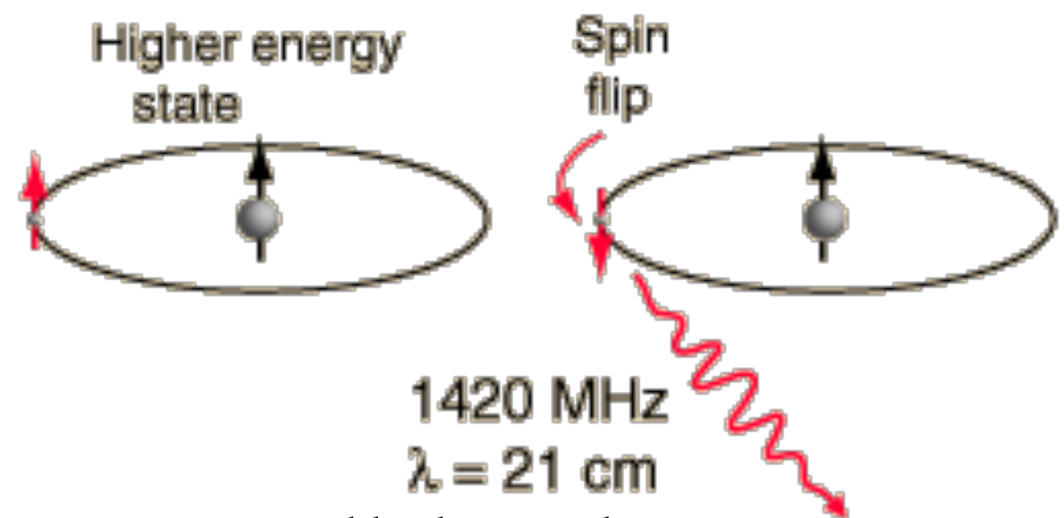
Like to be able to measure this at higher redshifts z~1-2. Optically this is difficult - the “redshift desert”

- Potentially 21cm could extend this to higher redshifts

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

21cm Intensity Mapping

Cosmological 21cm



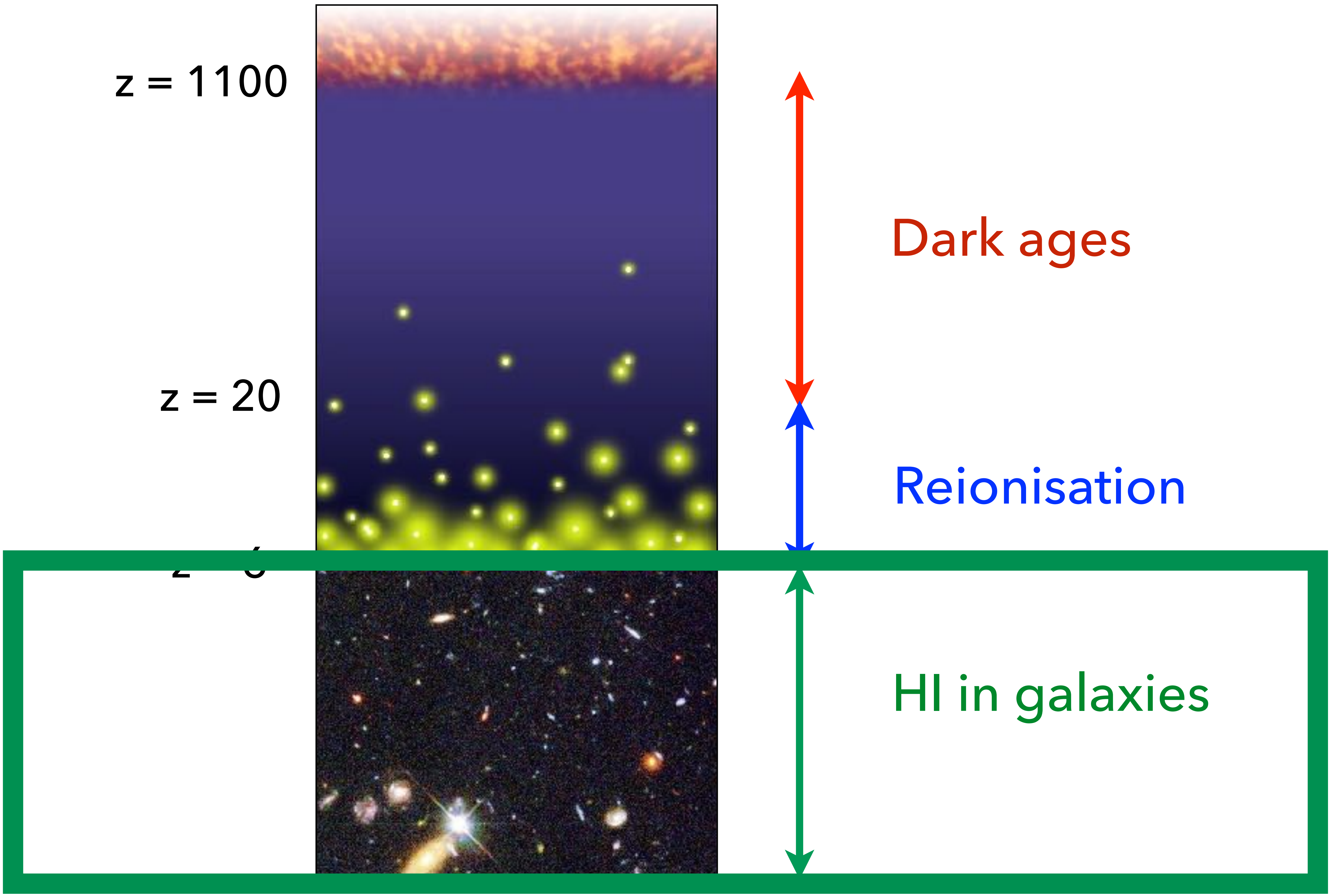
- 21cm line is the transition between parallel and anti-parallel spins of neutral Hydrogen
- The ratio between the two occupancies determines the spin temperature T_S (~ gas temperature)

$$n_1/n_0 = (g_1/g_0)\exp(-T_*/T_S)$$

- We can observe the contrast relative to the CMB

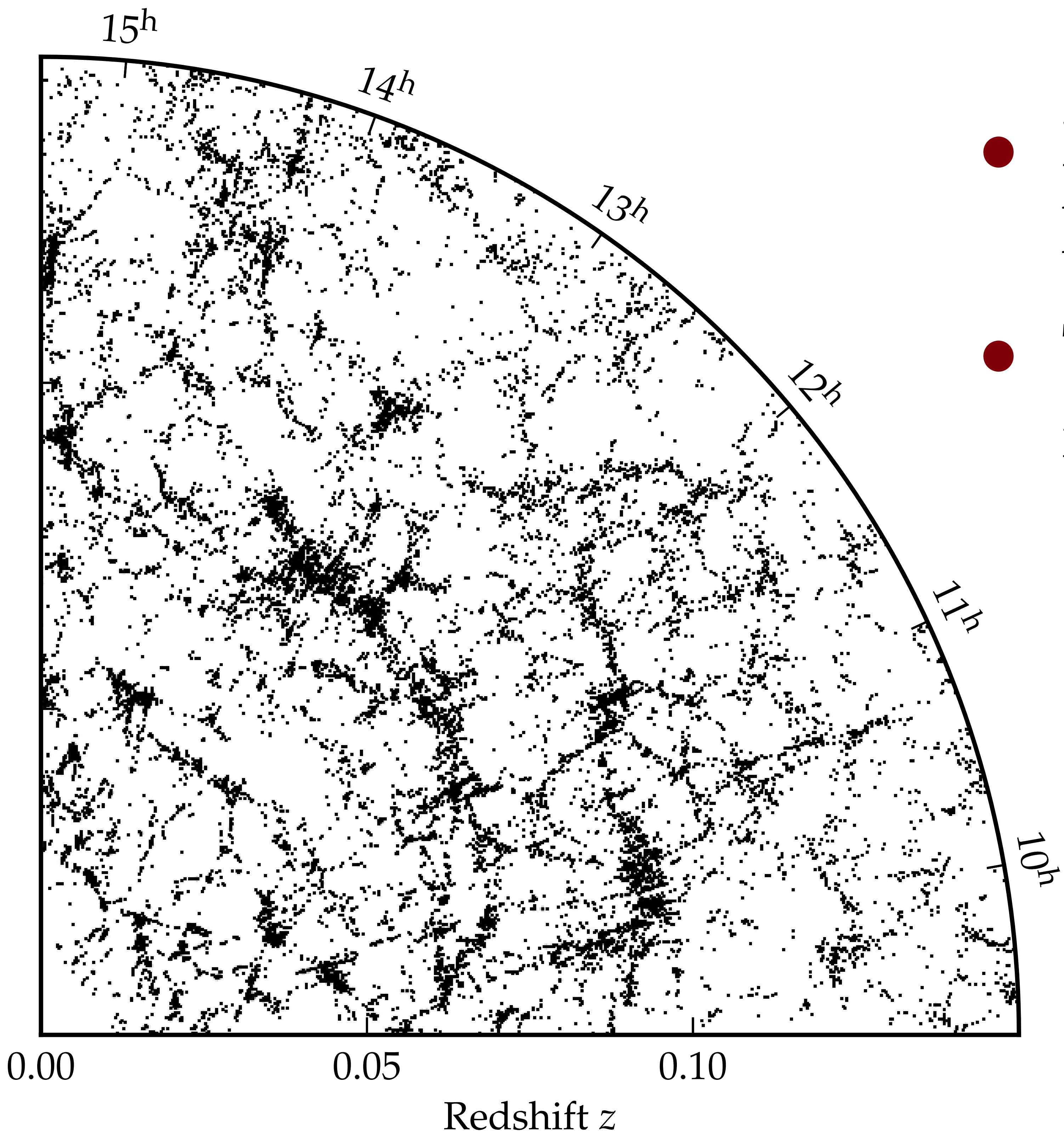
$$\Delta T = 23.8\left(\frac{1+z}{10}\right)^{1/2}\left[1-\bar{x}(1+\delta_x)\right](1+\delta_b)(1-\delta_v)\left[\frac{T_S-T_\gamma}{T_S}\right]\ \mathrm{mK}$$

Hydrogen in the Universe



Djorgovski et al. (Caltech)

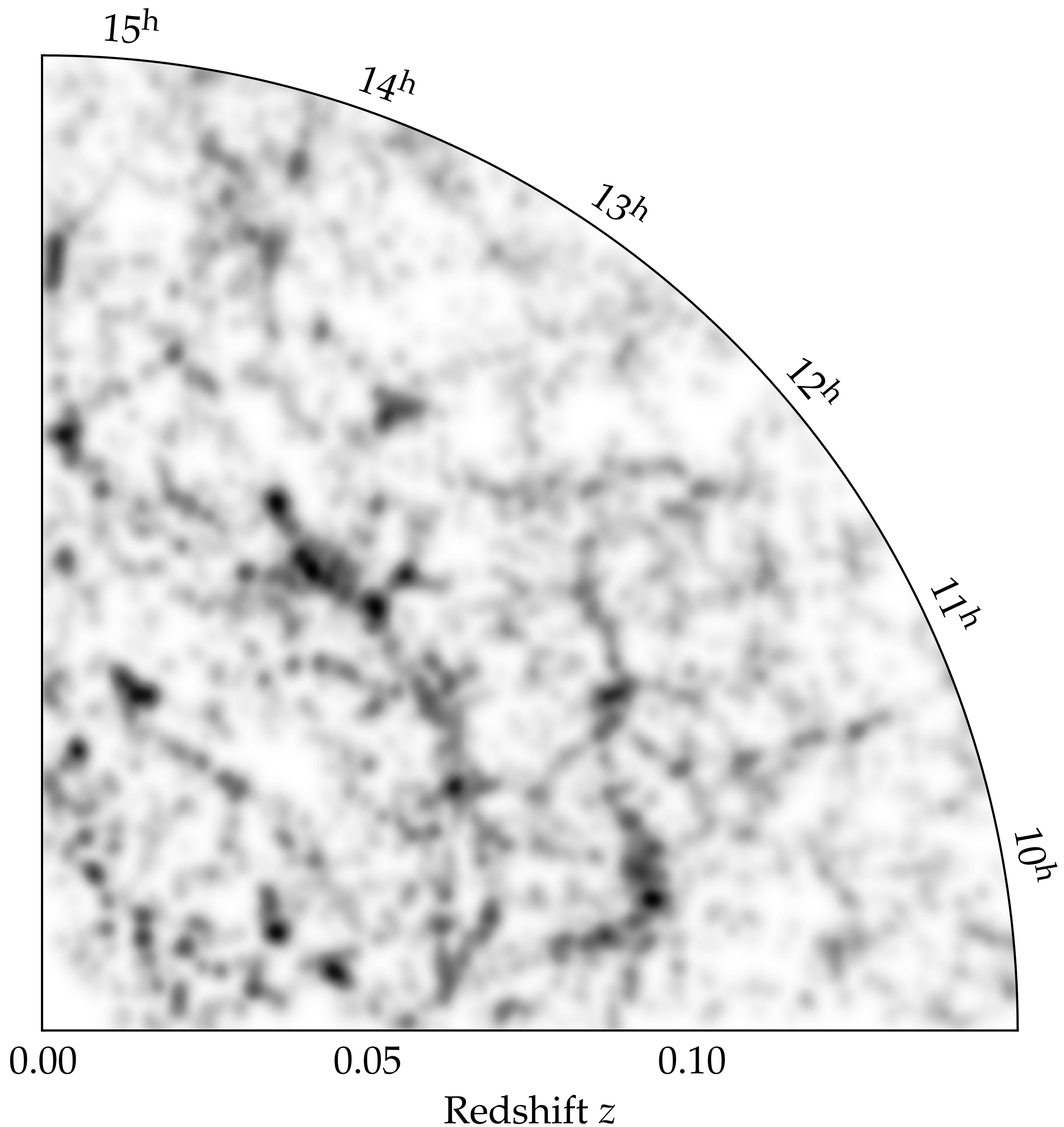
Galaxy Redshift Survey



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

Only interested in large scales

Intensity Mapping



- Observe galaxies with a line transition
- Automatically gives redshift

Don't need to resolve individual galaxies

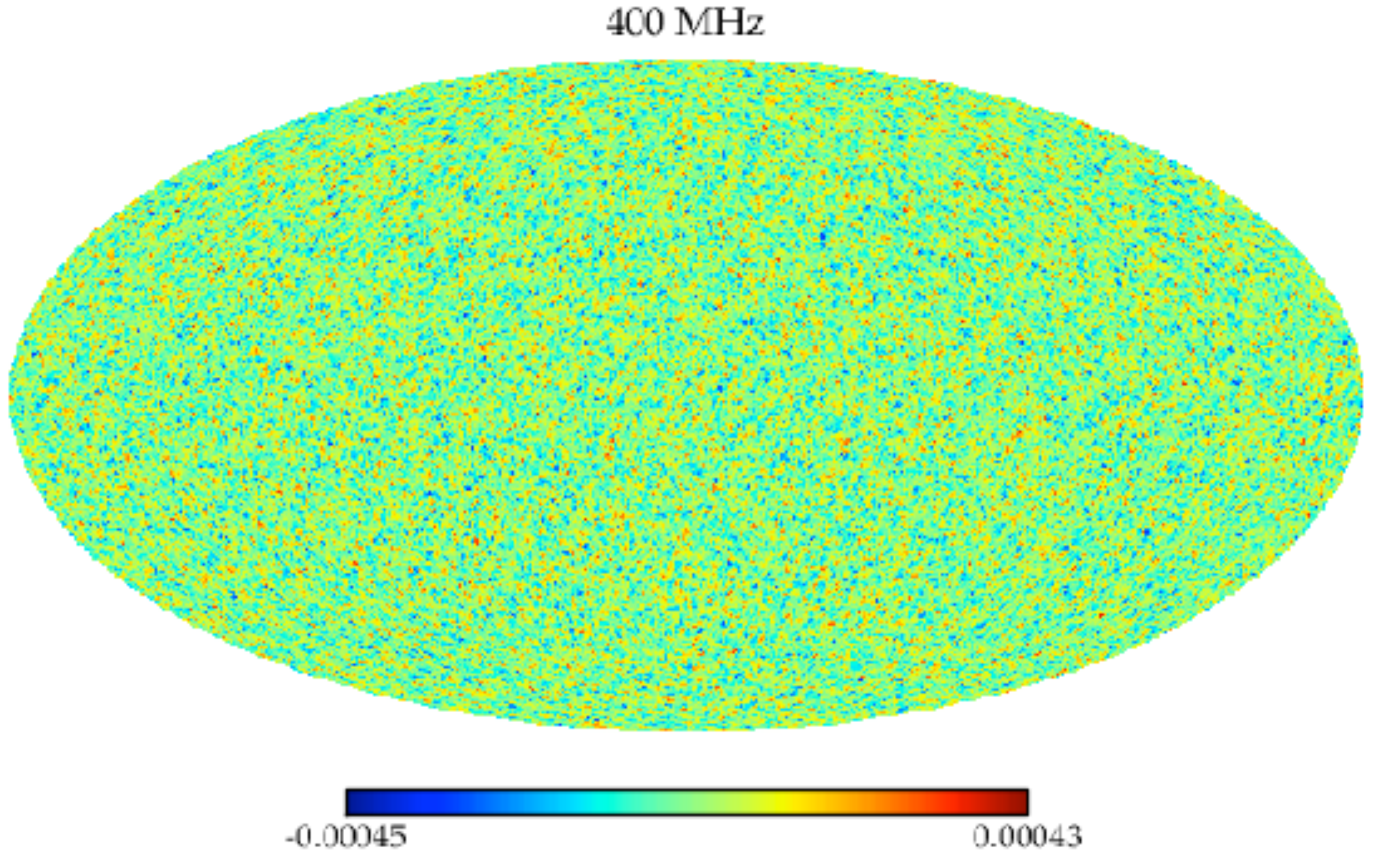
Chang et al, 2008; Wyithe and Loeb 2008

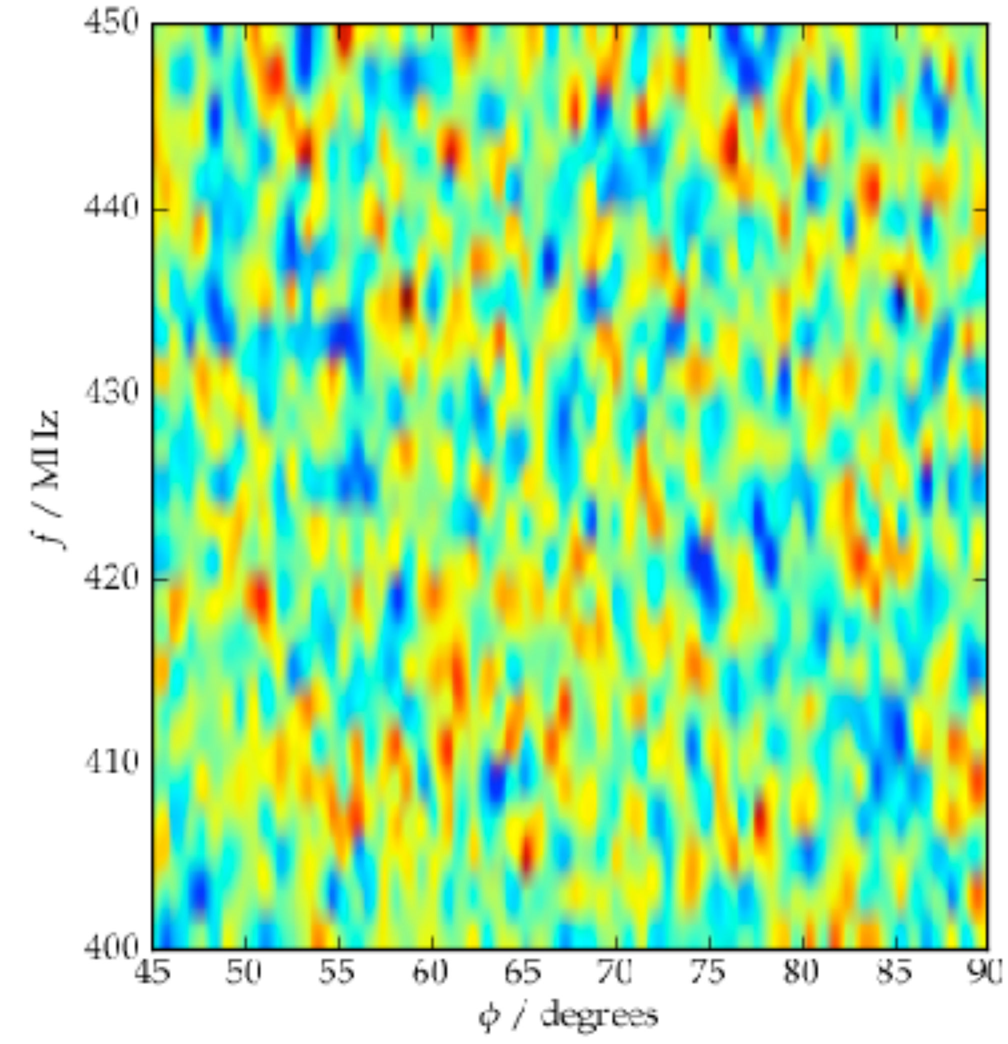
21cm Intensity Mapping

- In 21cm the frequency gives the redshift.
- Observe the diffuse emission from many unresolved galaxies
- Changes the game in telescope design:
  - Previously: large field of view, large collecting area, large angular resolution (SKA?)
  - Now: large field of view, large collecting area, modest angular resolution (compact arrays, single dishes).

Chang, Pen, Peterson and McDonald , 2008, http://arxiv.org/pdf/0709.3672

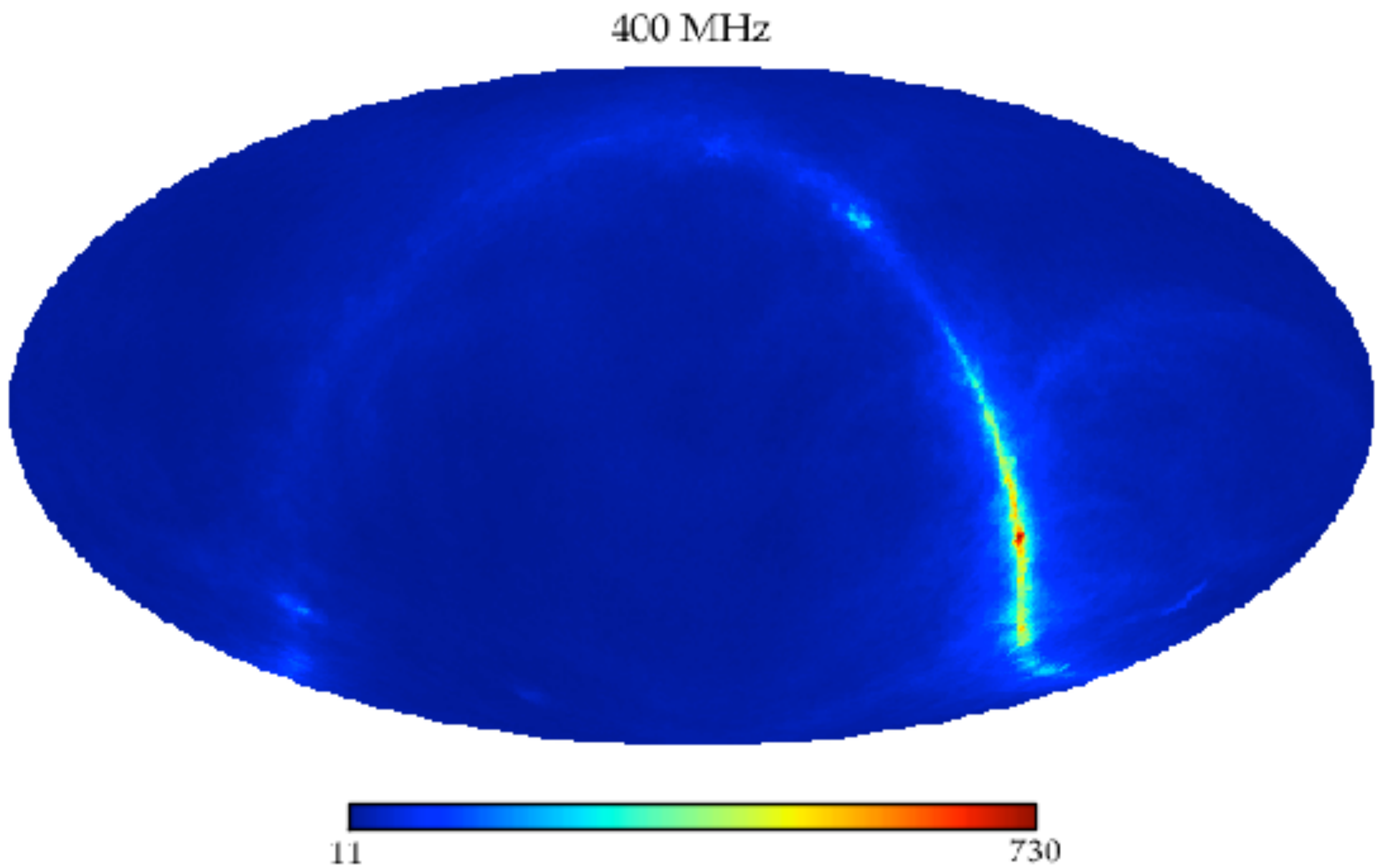
Foreground Challenges

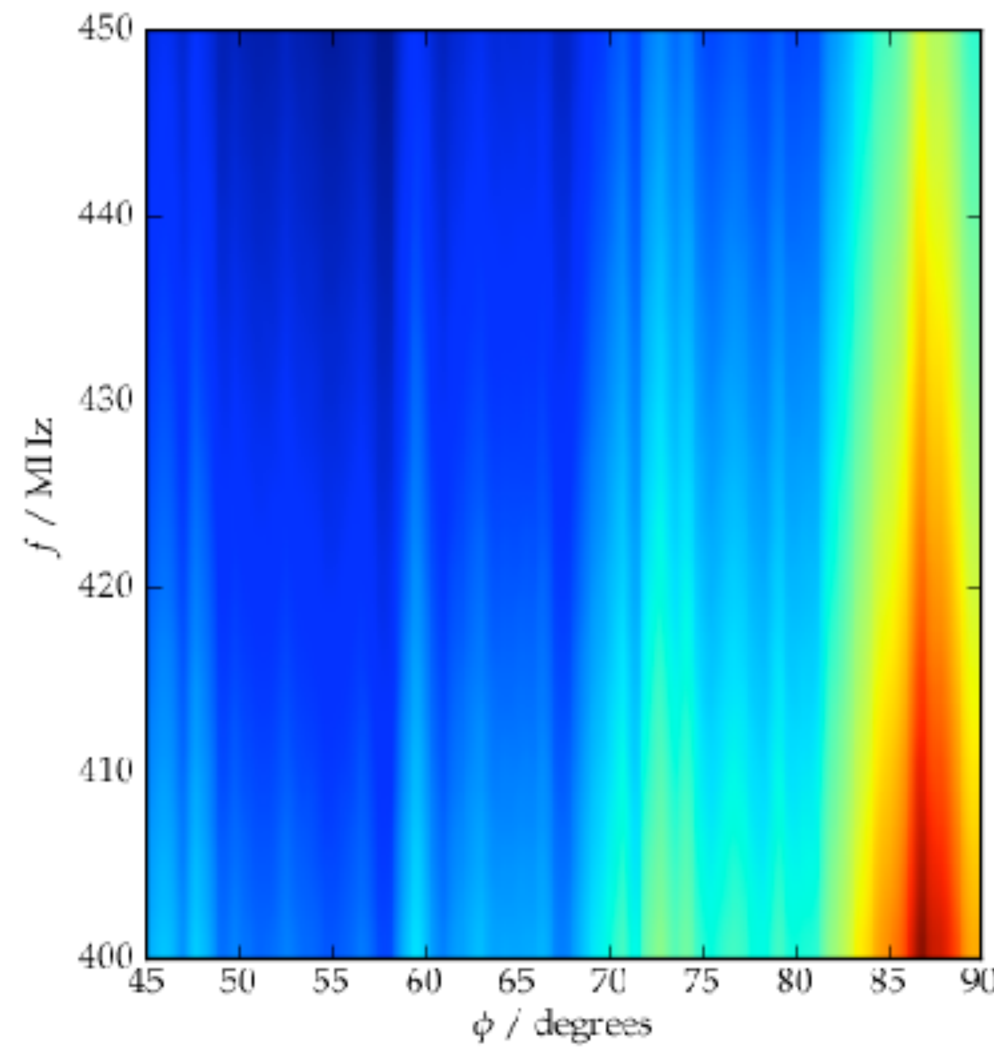




Cosmological 21cm Signal ~ 1mK

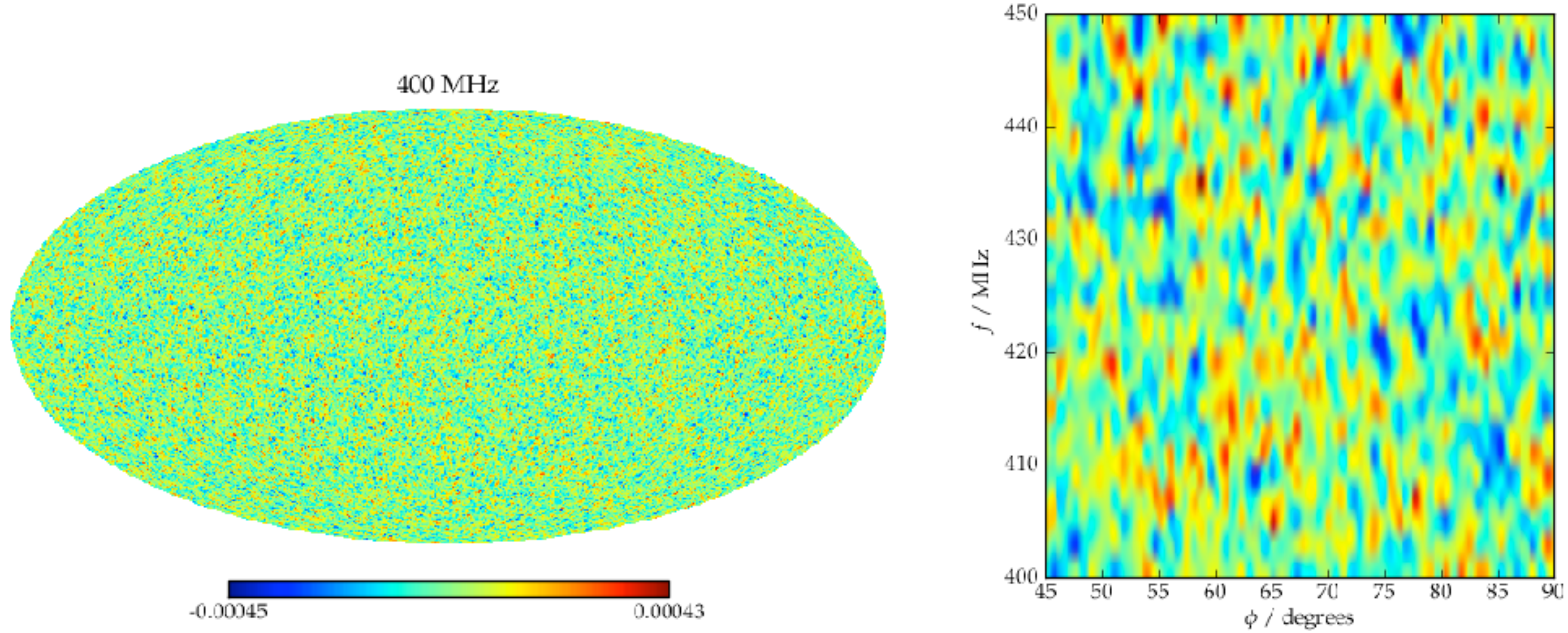
Foreground Challenges





Galaxy: up to 700K

A way out?


400 MHz
-0.00045
0.00043
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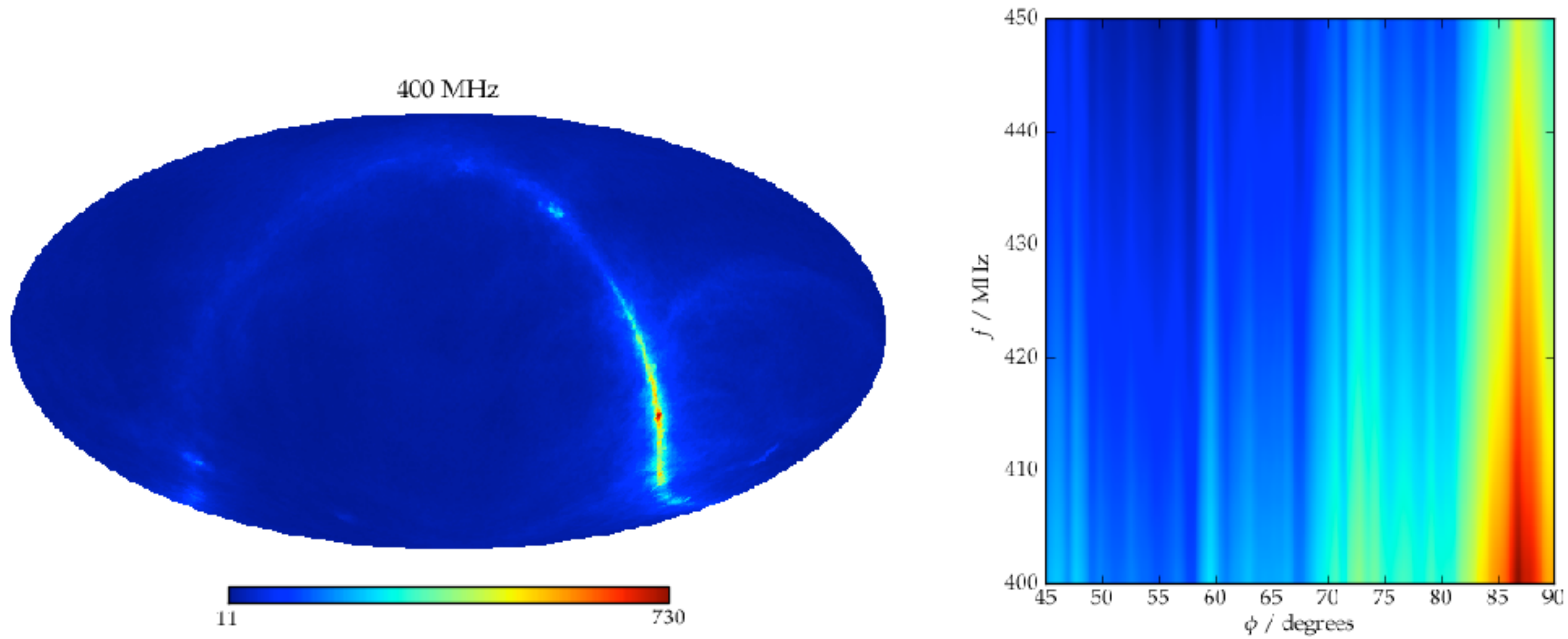
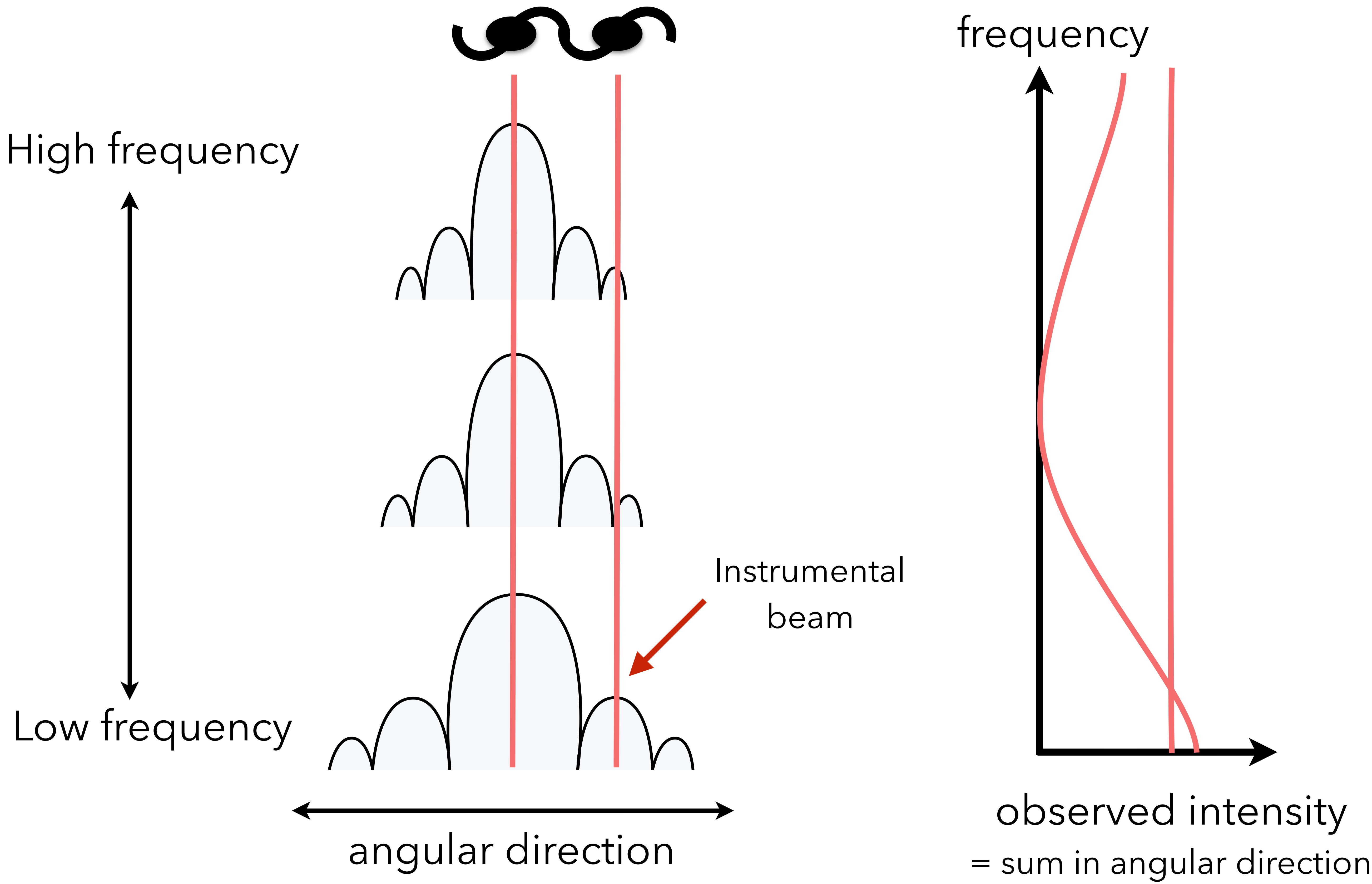
440
430
420
410
400
45 50 55 60 65 70 75 80 85 90
f / MHz
φ / degrees


400 MHz
11
730
450
440
430
420
410
400
45 50 55 60 65 70 75 80 85 90
f / MHz
φ / degrees

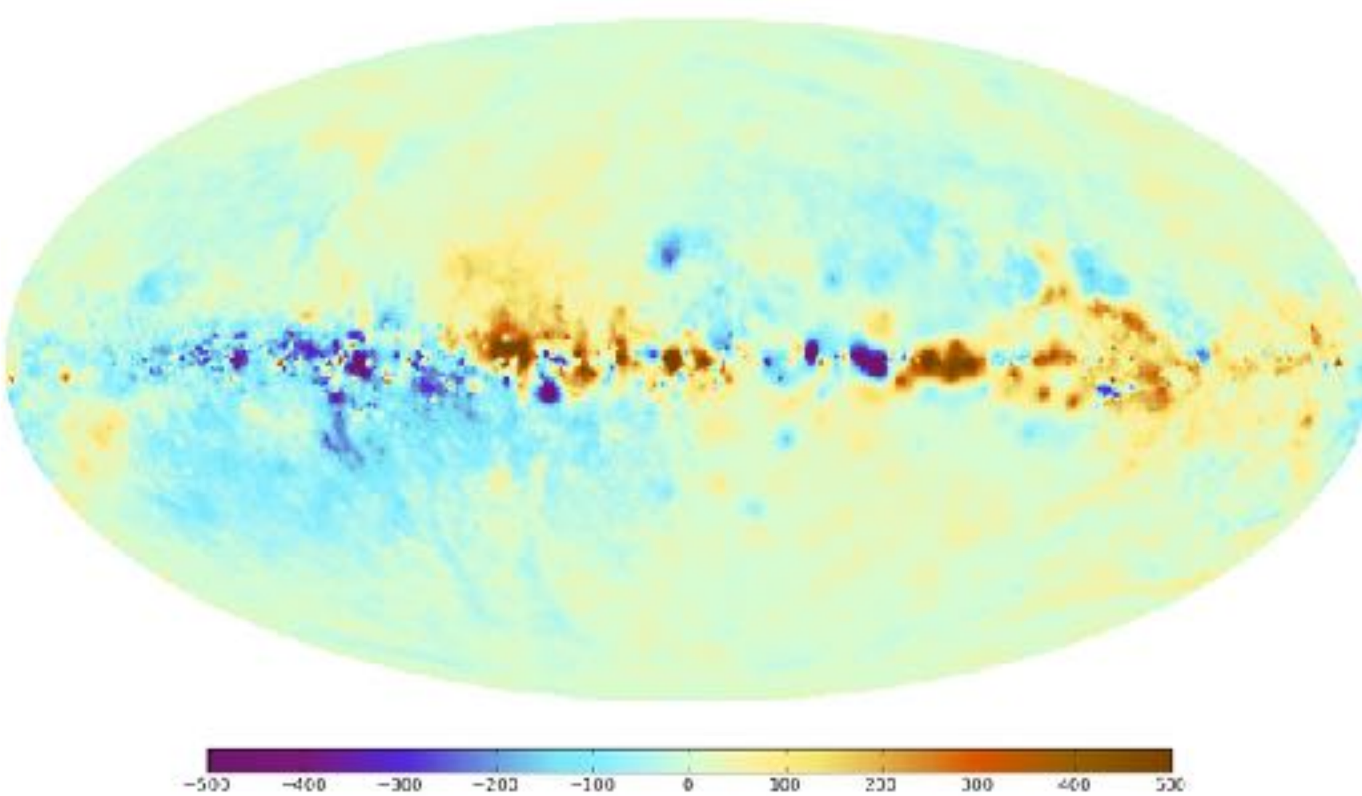
Issue 1: Mode mixing



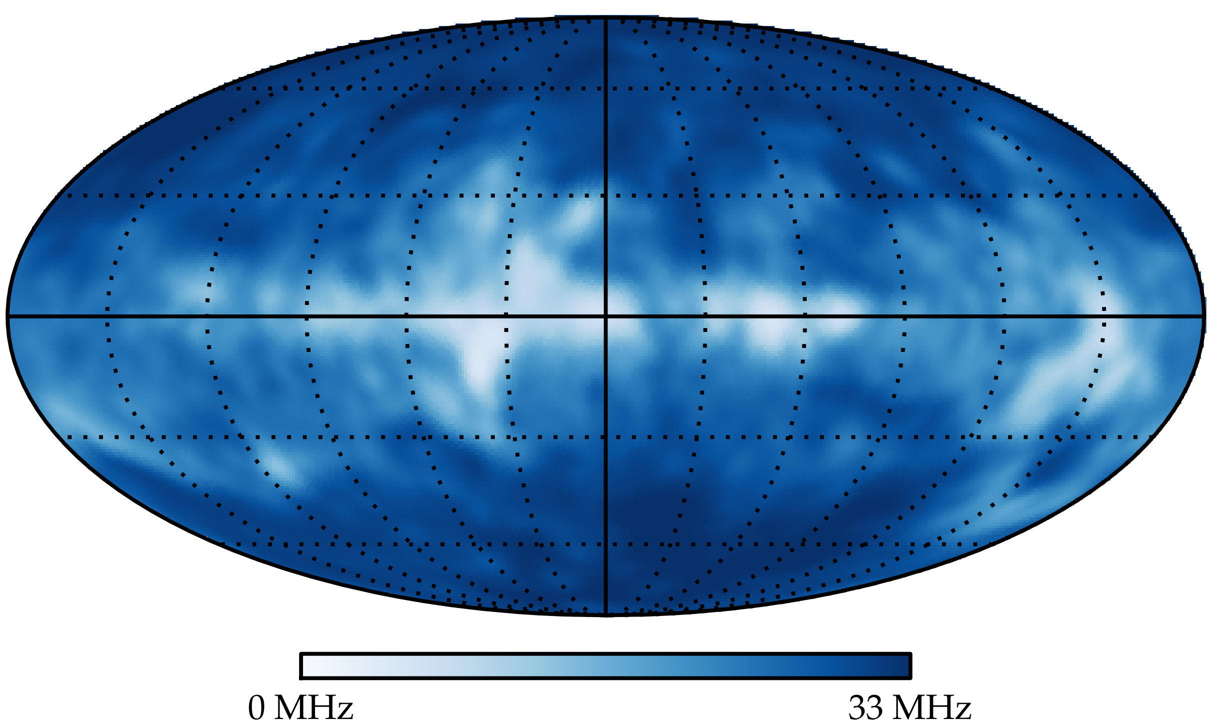
Issue 2: Polarised Foregrounds

- Synchrotron is highly polarised (fraction ~0.5)
- Faraday rotation changes polarisation angle with frequency $\sim \mathrm{RM}\,\lambda^2$
- Galactic emission at different Faraday depths give multiple modes.
- Extent of problem unknown, expected to be worst at intermediate frequencies

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



Correlation length from simulation

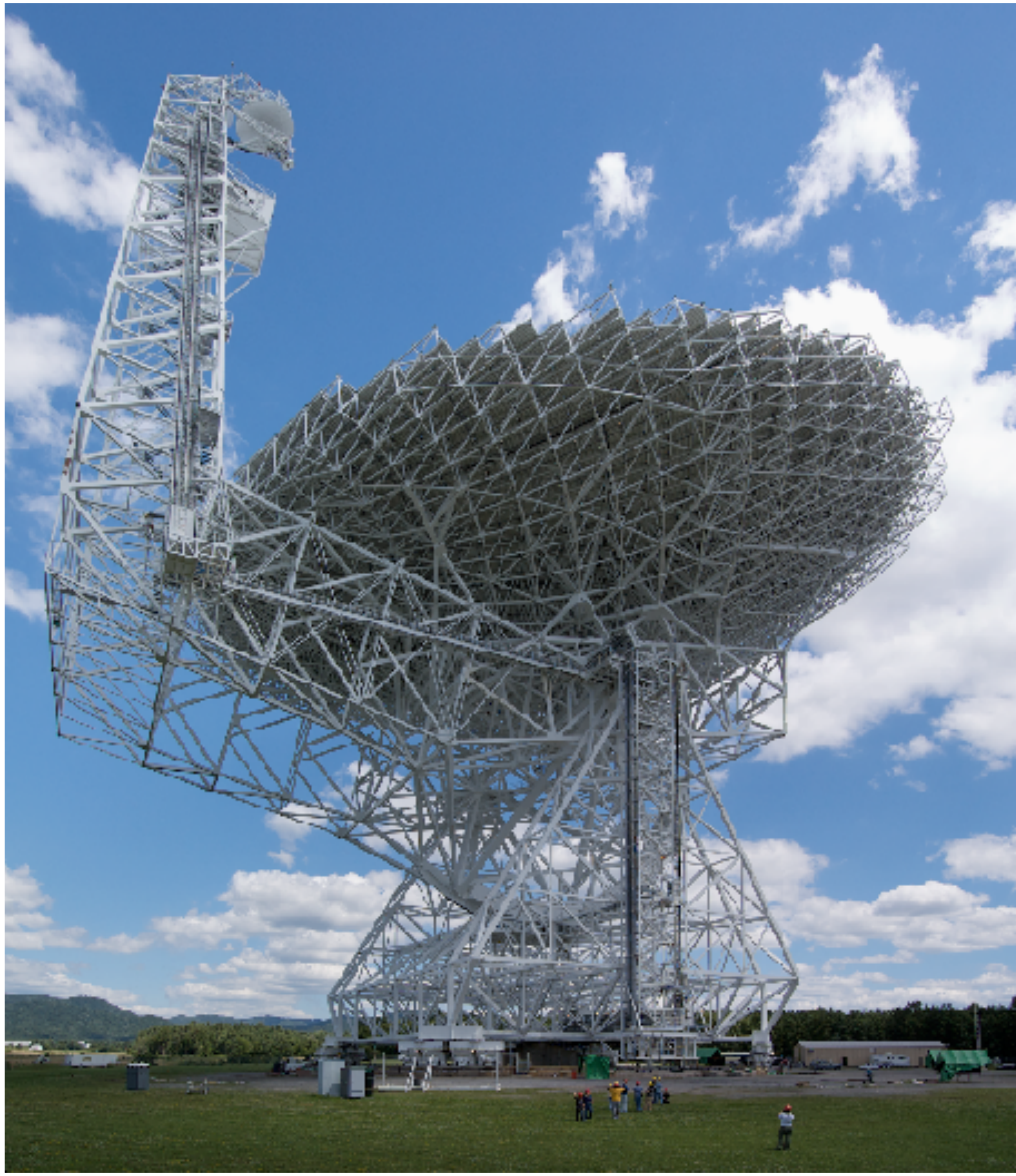


Intensity Mapping at Green Bank

flickr.com/photos/afternoon_sunlight/

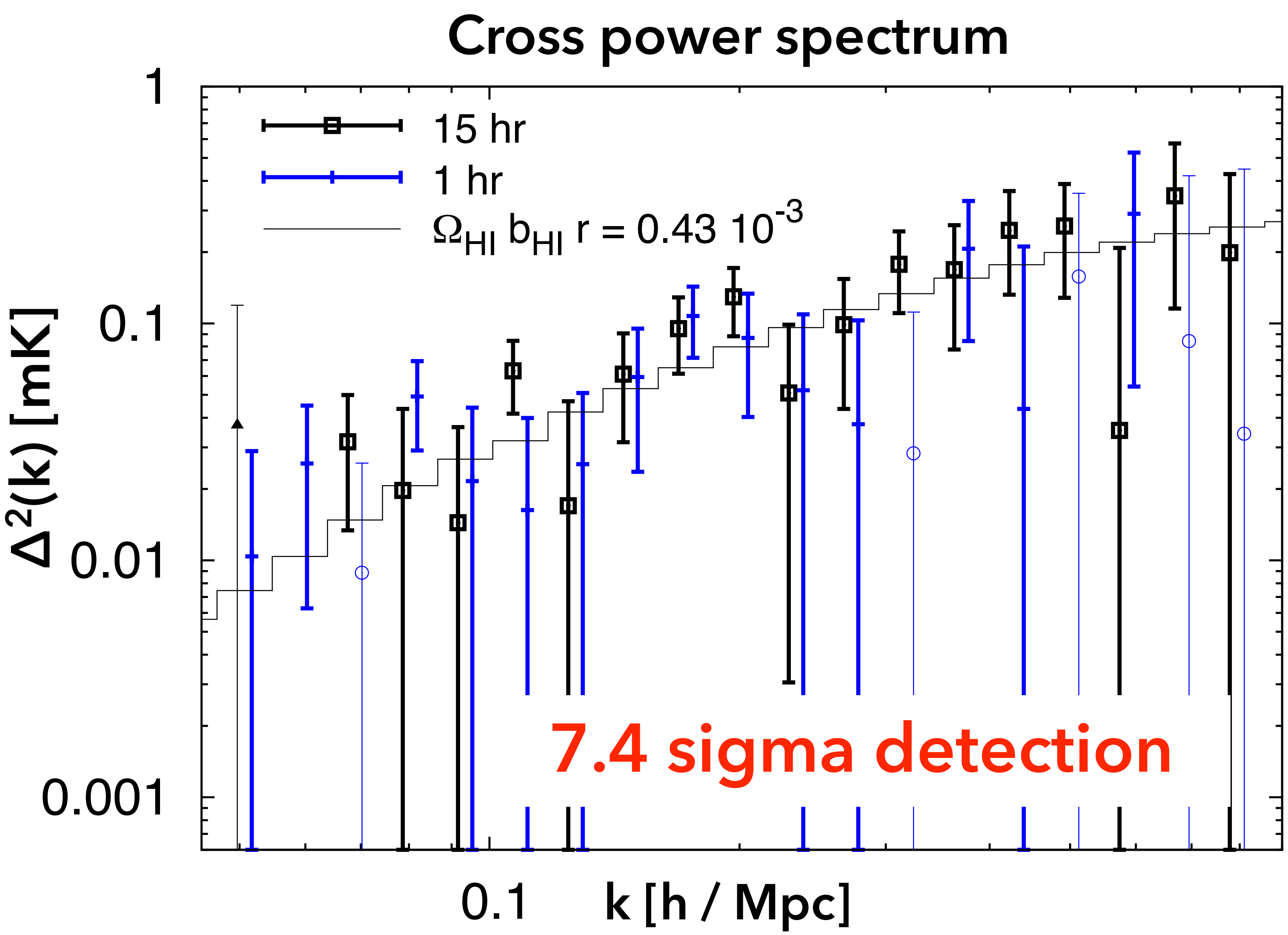
Intensity Mapping with GBT

- Collaboration: CITA, CMU, NRAO, UWisc, NAOC, ASIAA
- 100m telescope (15’ resolution)
- 700-900 MHz (z ~ 0.6 - 1)
- 190 hours observation
- 41 sq deg

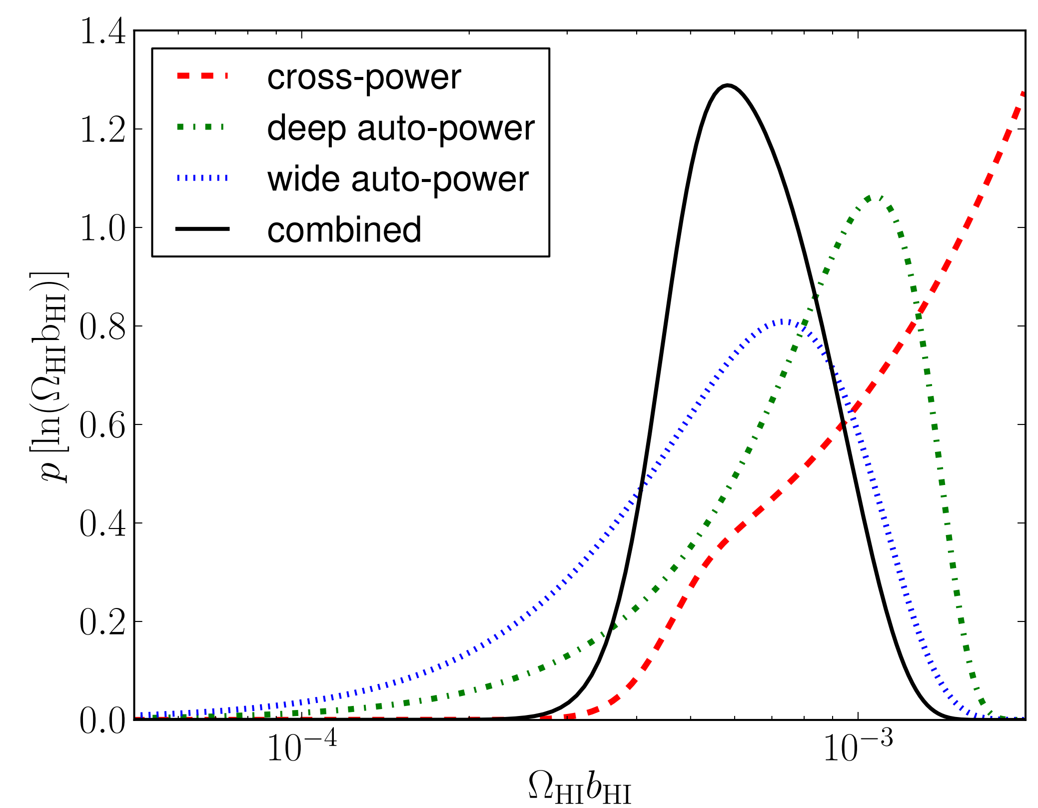


Cross correlation detection

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



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



The Future?

- Work at GBT will continue with the aim of measuring the 21cm *autocorrelation*.
- However, observations like this are slow. To survey the whole sky to this depth ~ 20 years
  - Is there a better way to do this?

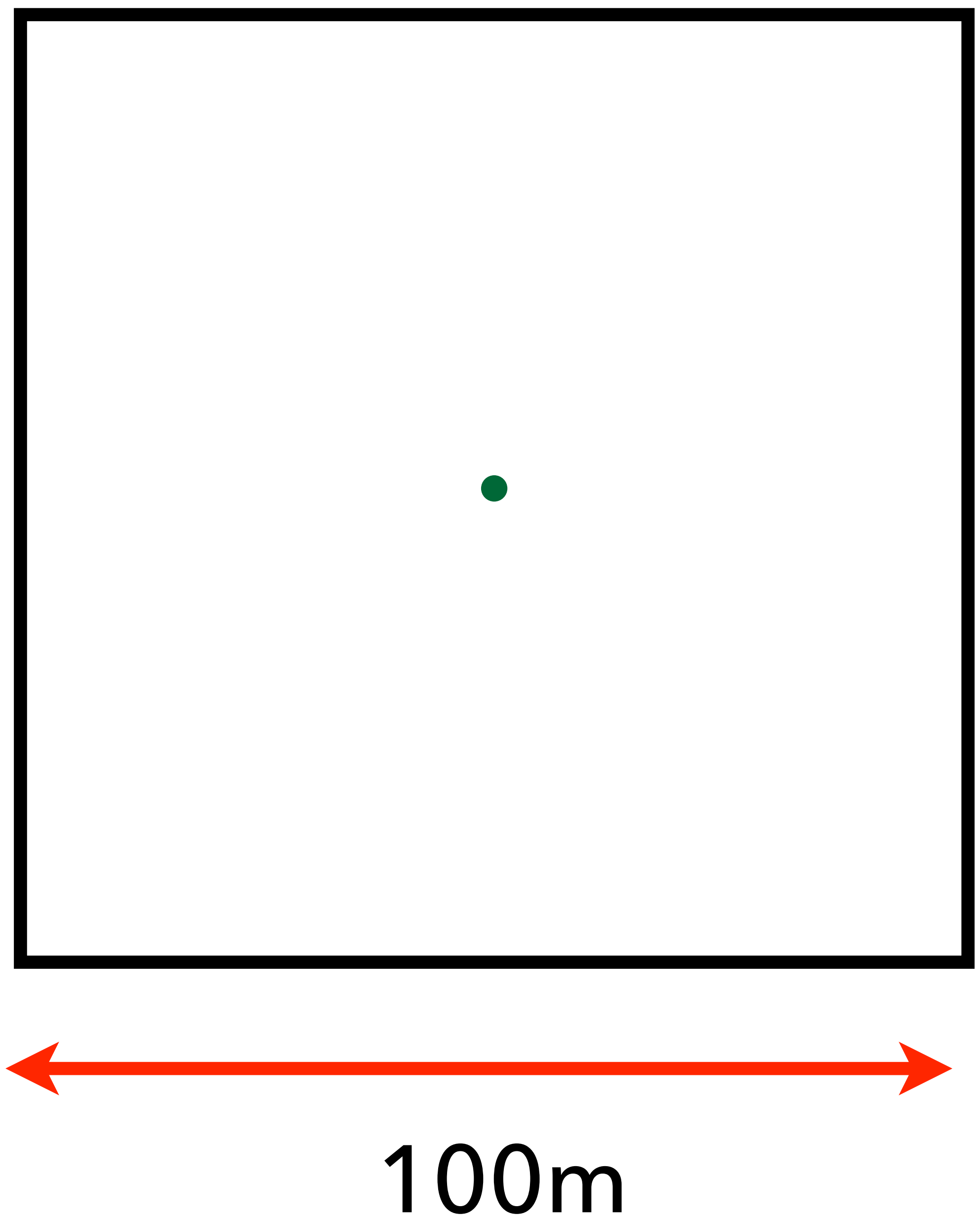
Next Generation Experiments

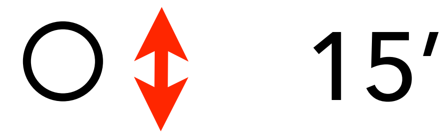
Requirements: Resolution

- Don't need to resolve individual galaxies, but do need sufficient resolution to resolve BAO peak ~ 10 arcmin
- For z~1-3 requires 100m radio telescope (with ~1 MHz freq resolution)

$$\Delta\theta \sim \frac{\lambda}{D}$$

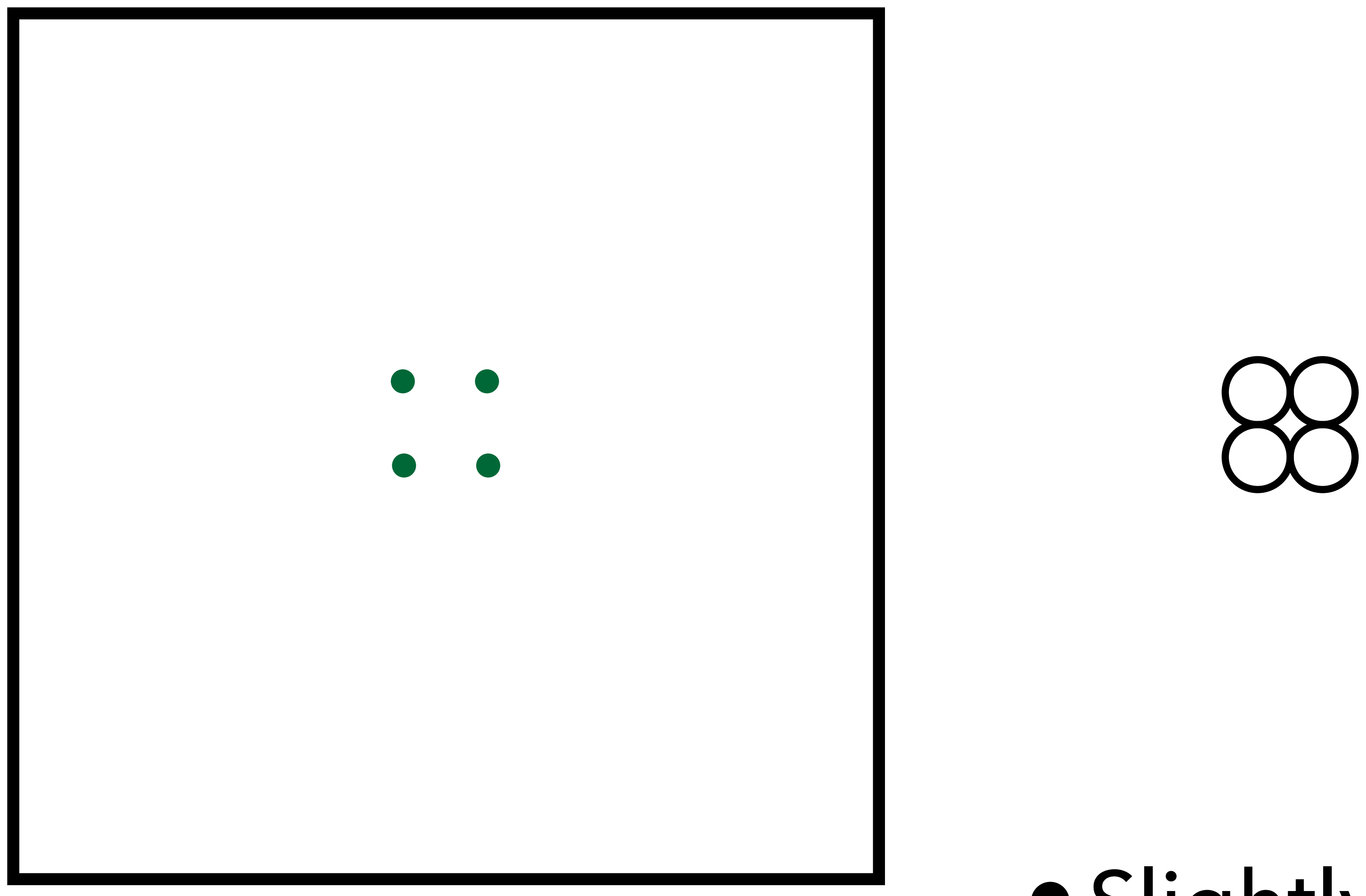
Single Dish





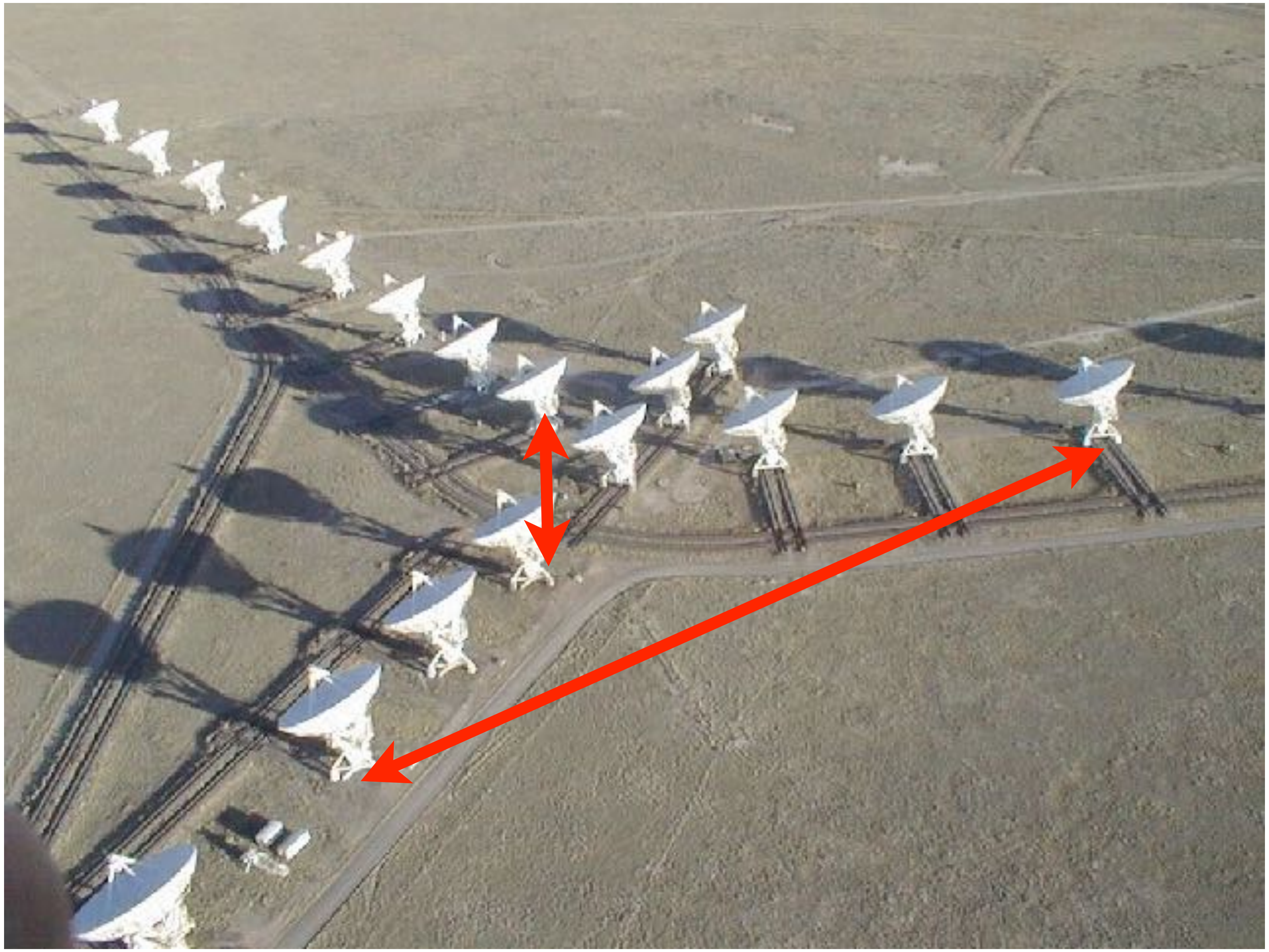
- Slow survey
- Noise: σ_T

Focal Plane Array

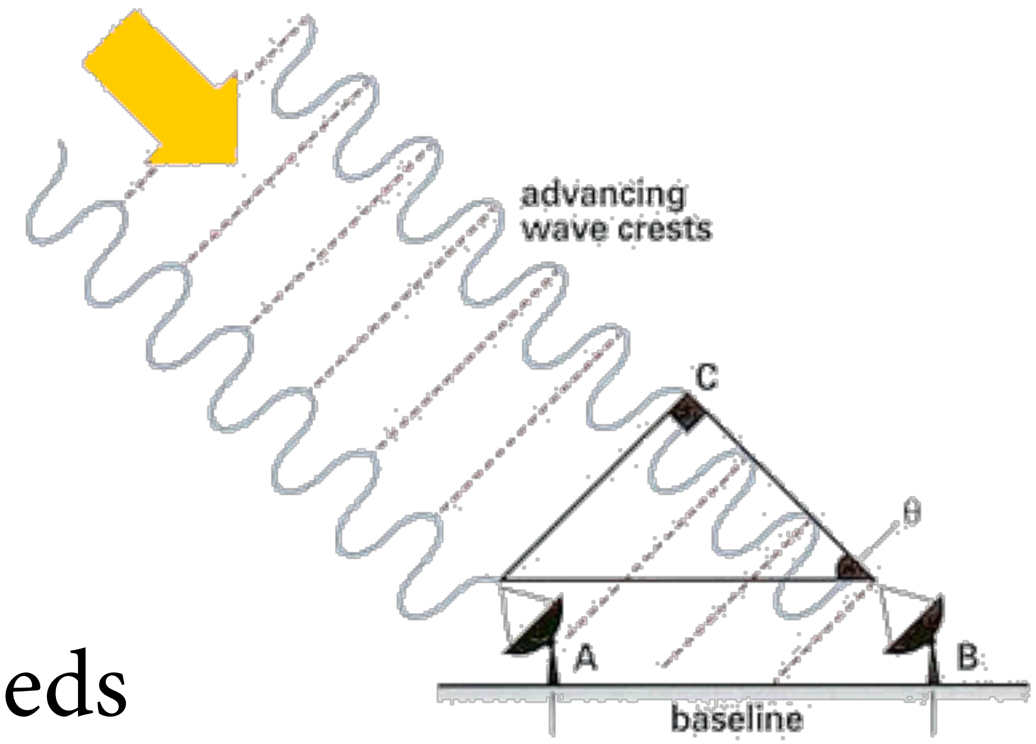


- Slightly offset feeds
- Each beam noise: σ_T
- 4x faster survey

Interferometers



Interferometers



- Complex correlation of two feeds

$$R = \int d^2\hat{\mathbf{n}}\, A^2(\hat{\mathbf{n}})\, e^{2\pi i \hat{\mathbf{n}}\cdot\mathbf{u}}\, I(\hat{\mathbf{n}})$$

- For small parts of sky this is 2d Fourier mode

$$R = \int dl\, dm\, A^2(l,m)\, e^{2\pi i(ul+vm)}\, I(l,m)$$

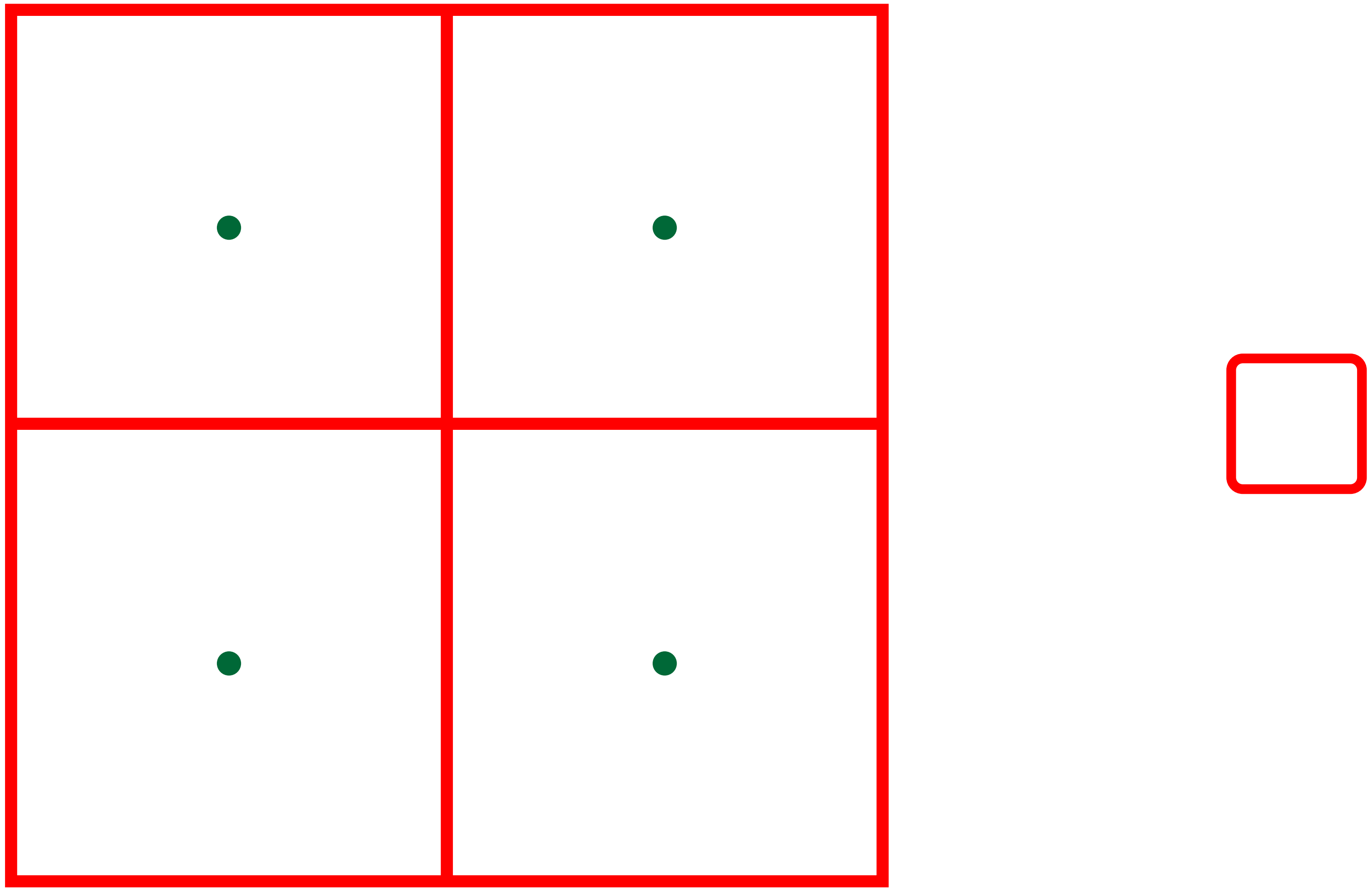
- Imaging: inverse Fourier transform and deconvolution *(on flat sky)*

Interferometers

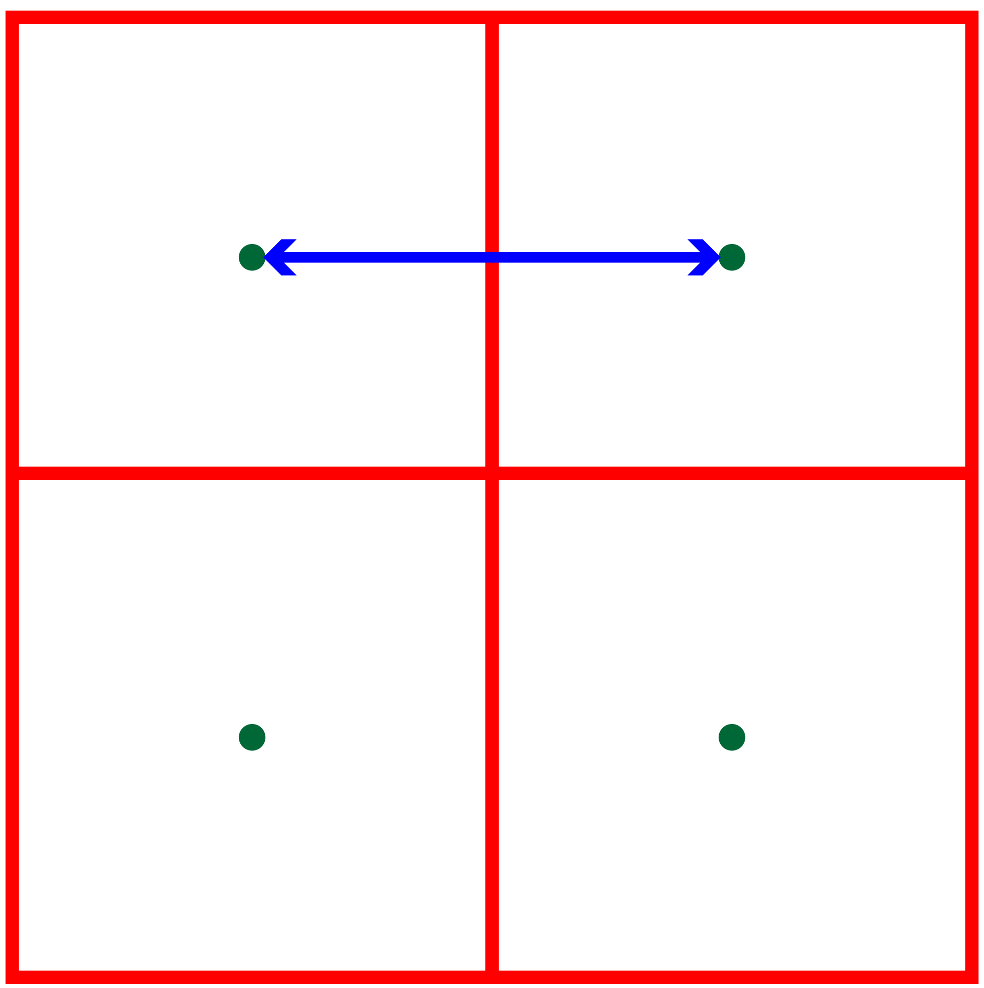
- Traditionally interferometers emphasized high resolution observations of small fields
- We can turn them into high speed survey instruments.
- We need maximal sensitivity to large scales. Means measuring smallest fourier modes (hence many short baselines)

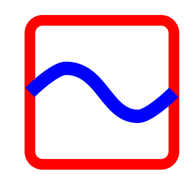
2x2 Interferometer

2x2 Interferometer



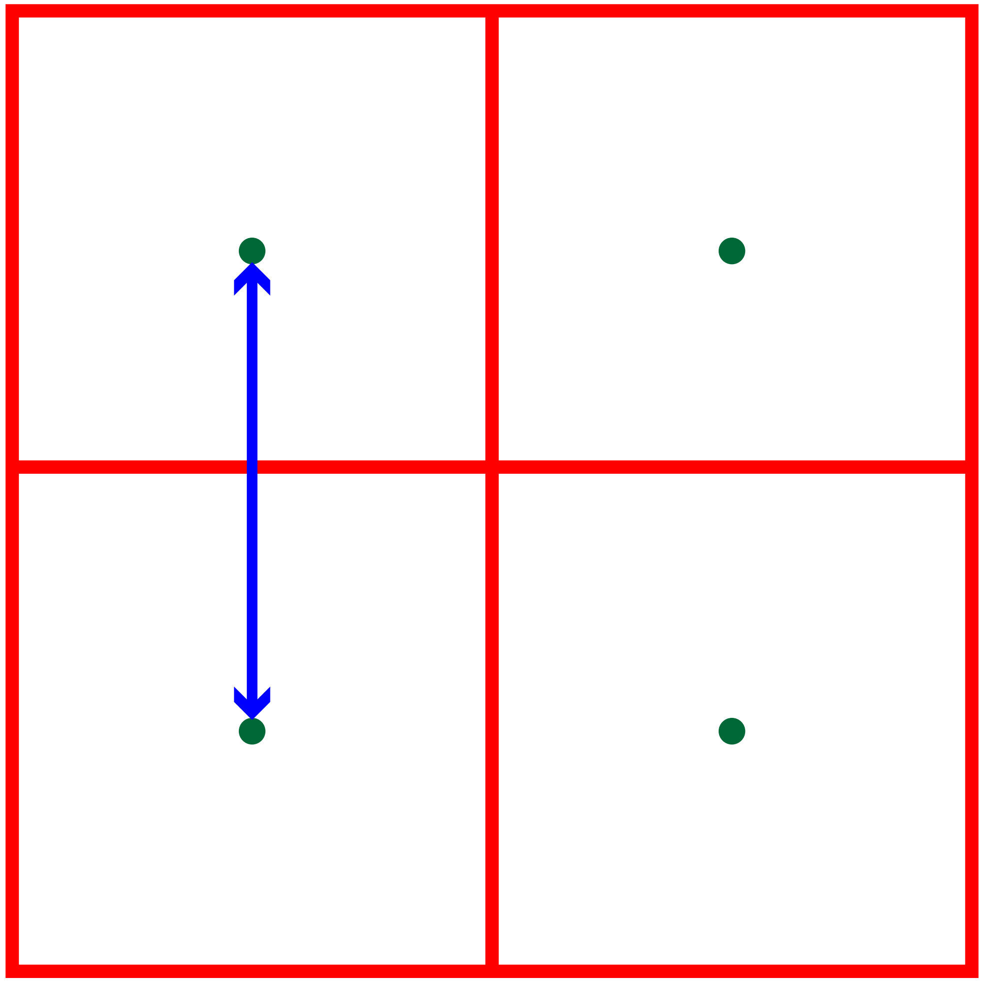
2x2 Interferometer

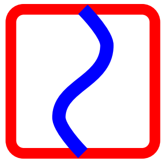




- Measure fourier modes in redbox (primary beam)

2x2 Interferometer





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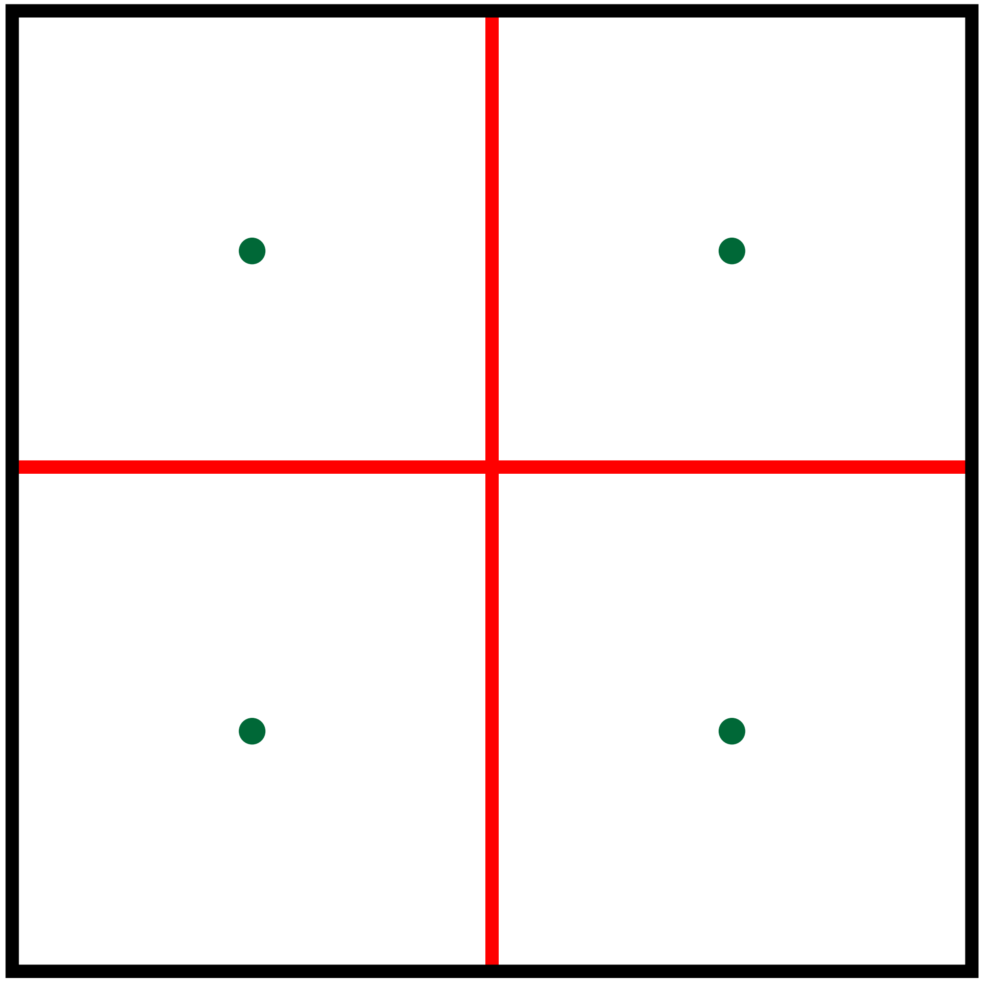
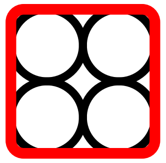
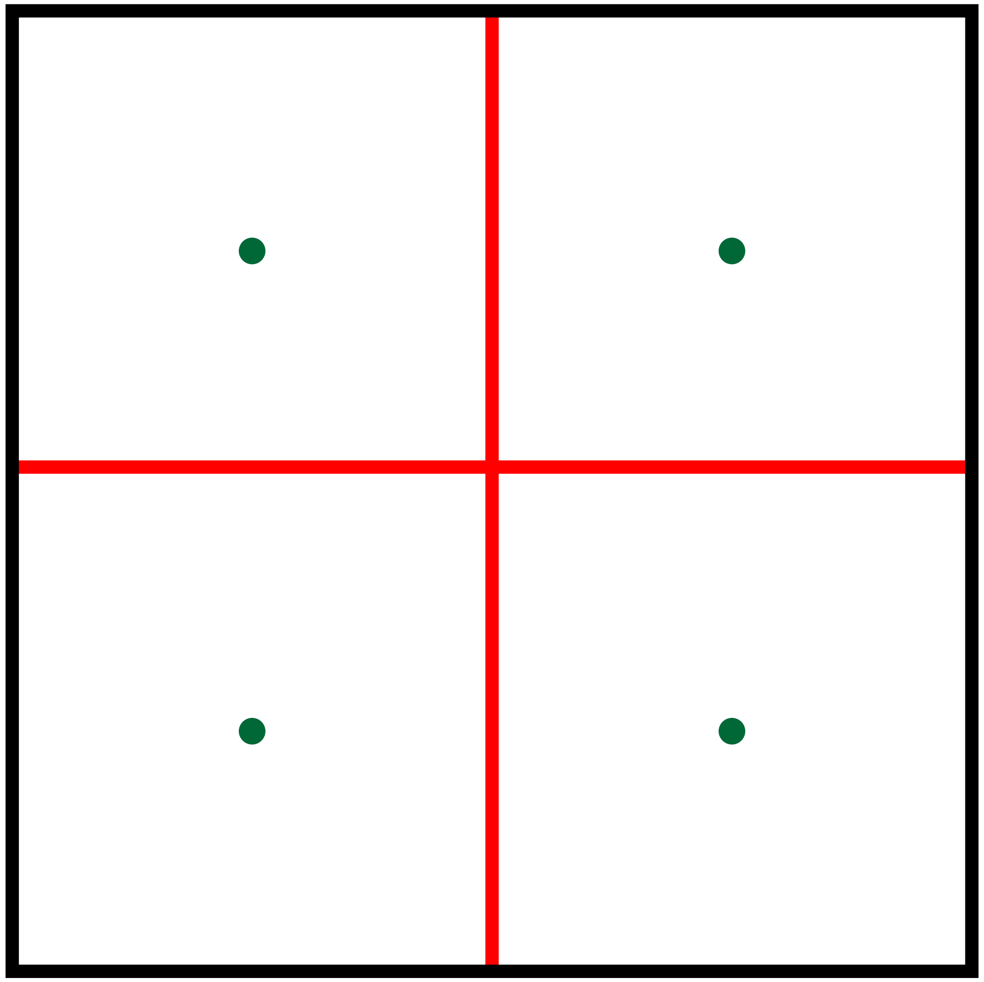
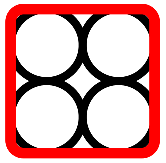




- Linear combinations give independent beams

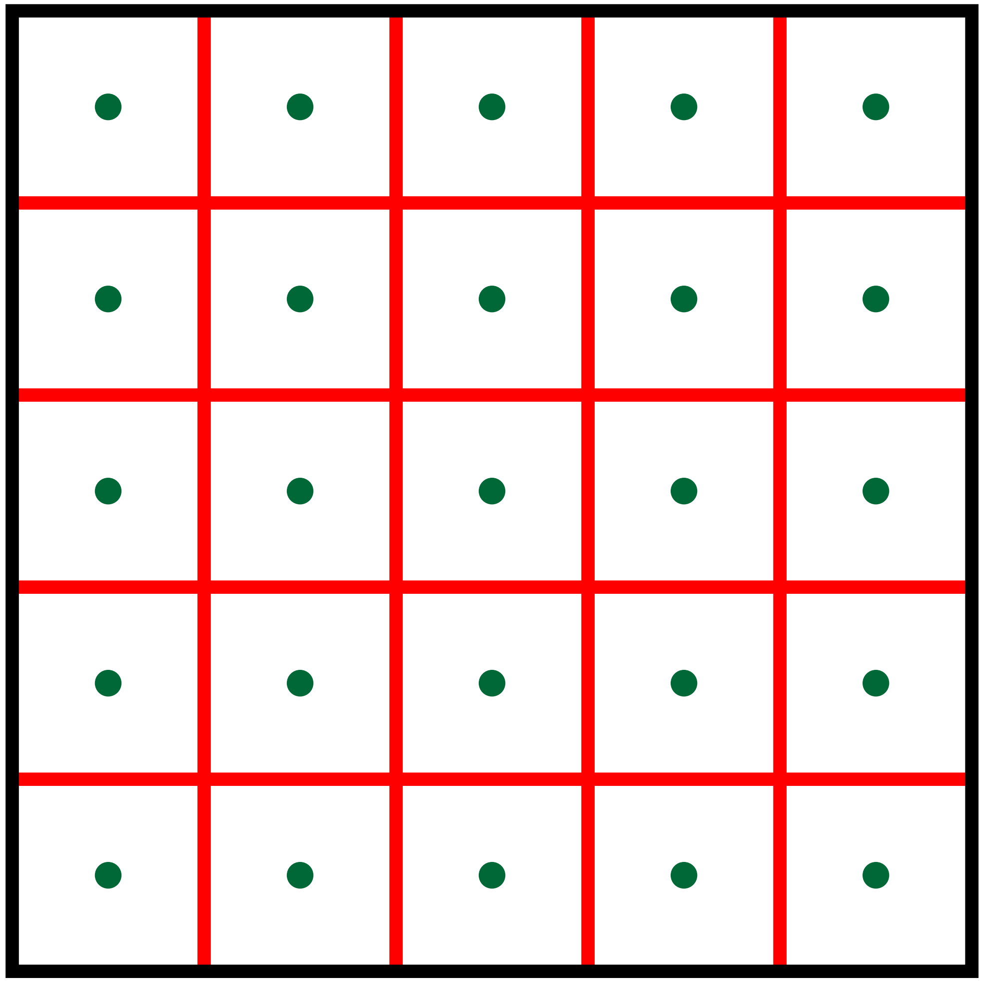
2x2 Interferometer

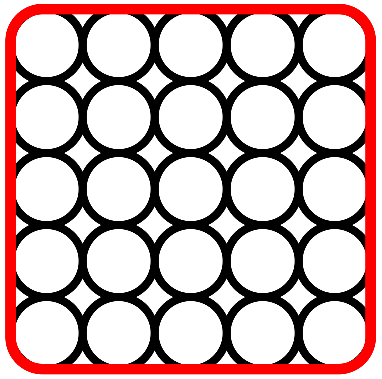




- Each beam has noise σ_T
- 4x faster, with same noise and resolution

5x5 Interferometer





25x faster

Survey Interferometers

- A cheap, scalable way of building large collecting area and angular resolution
- FoV (primary beam) given by size of individual elements
- Resolution determined by total size of array
- Survey speed proportional to N_{feeds}

McGill

UBC

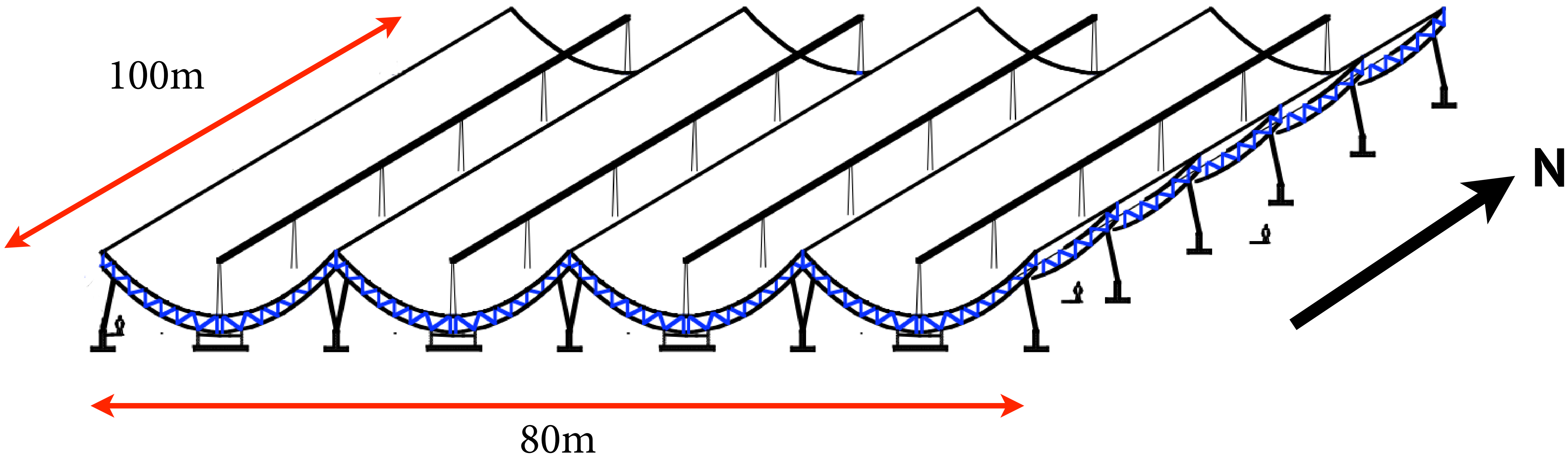
DRAO

NRC · CNRC

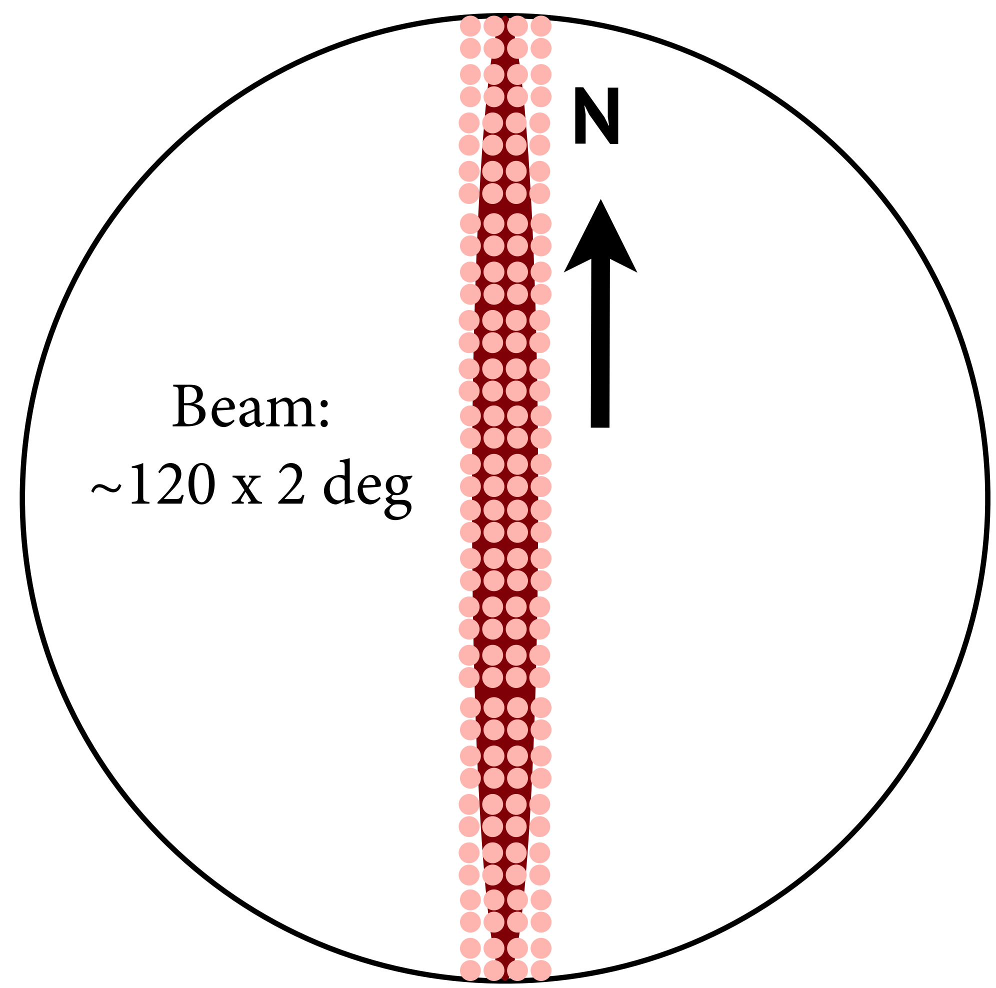
UNIVERSITY OF TORONTO

chime

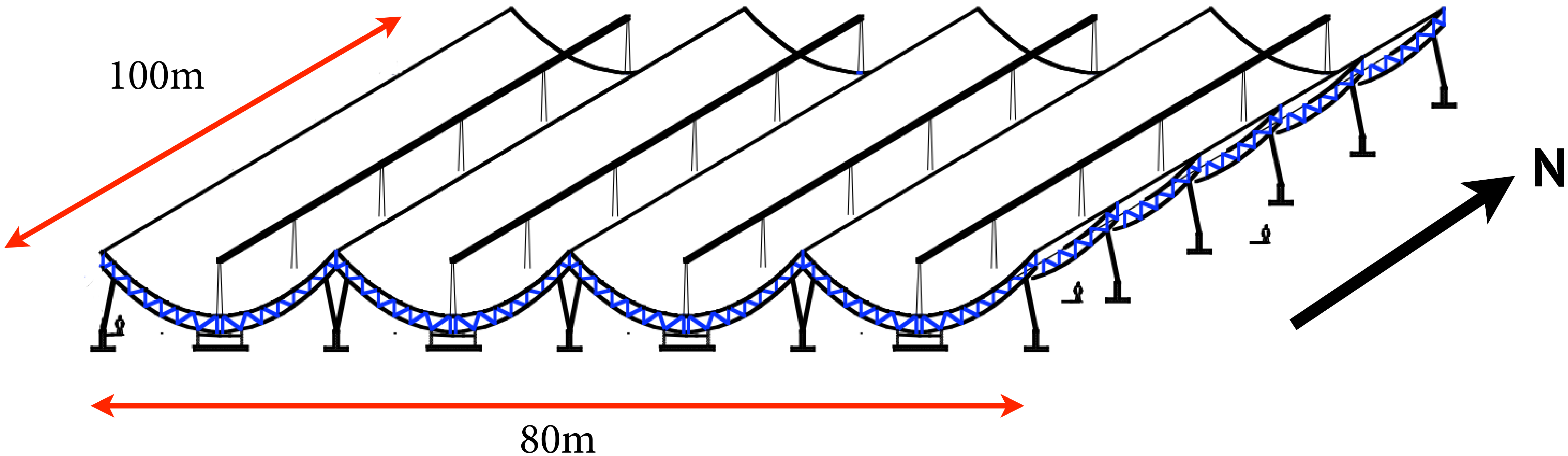
CHIME Overview



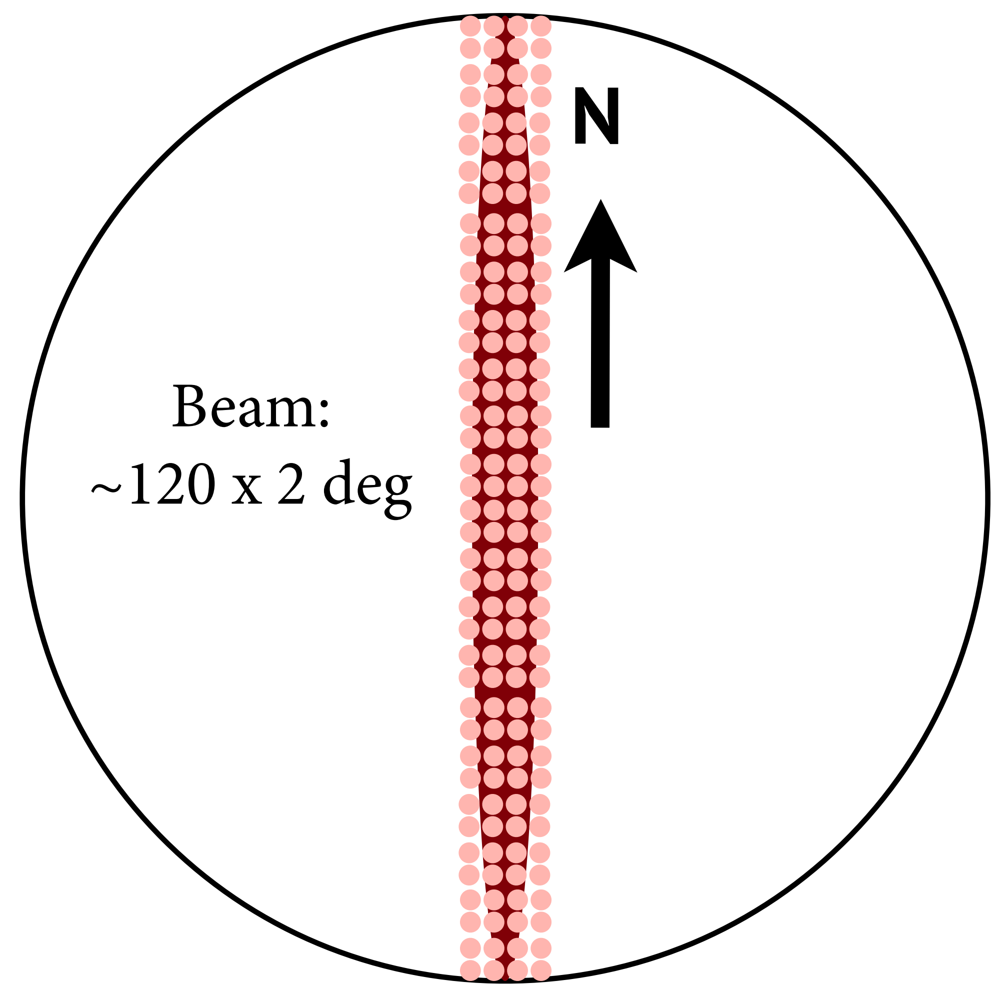
- Located at DRAO in BC
- Transit radio interferometer
  - Observe between 400-800 MHz
  - 0.4 MHz spectral resolution
  - 1024 dual pol antennas ($T_{recv} = 50K$)
- 120 x 2 degree FoV
- 4x256 beams = 15 arcmin resolution

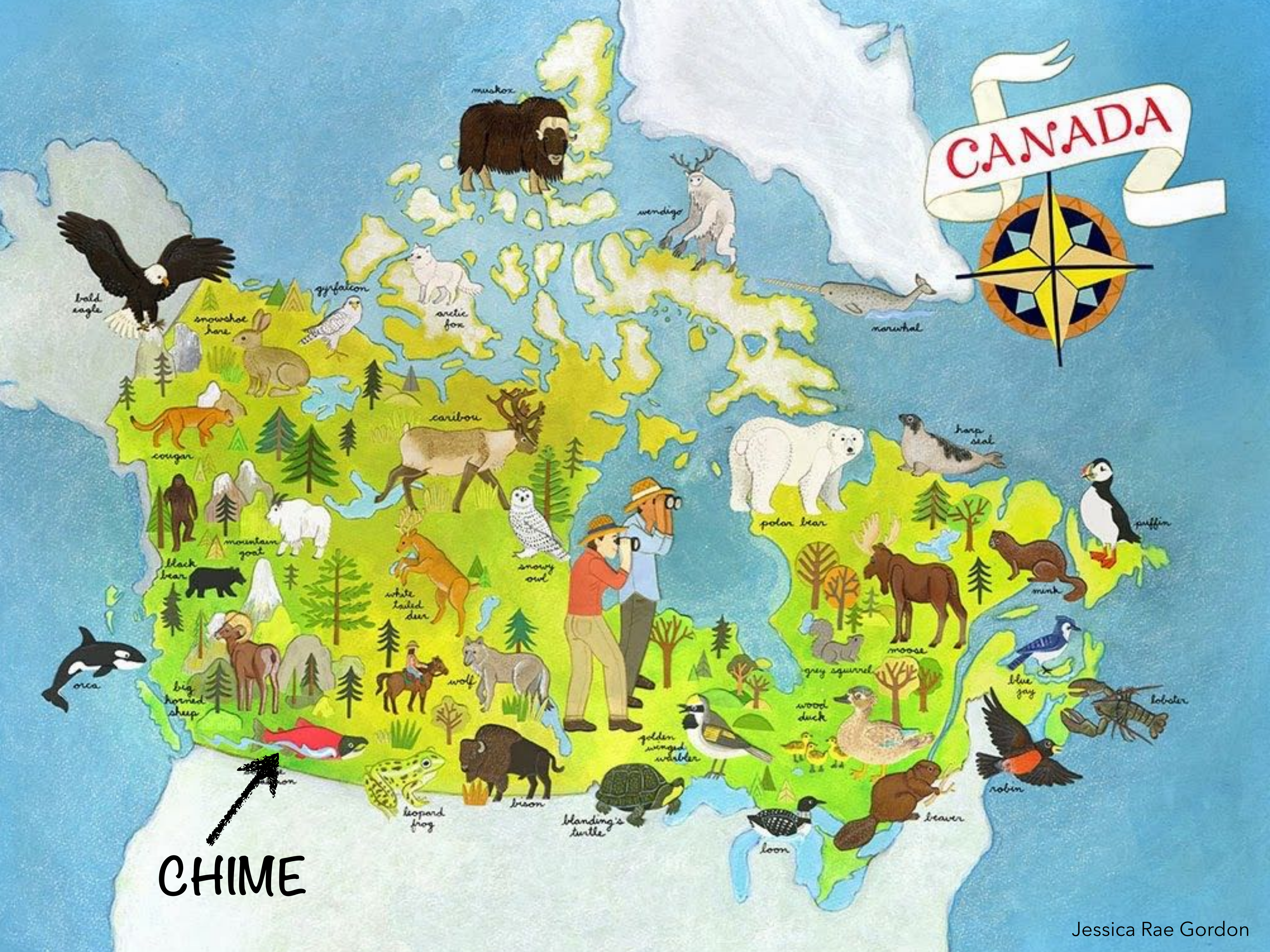


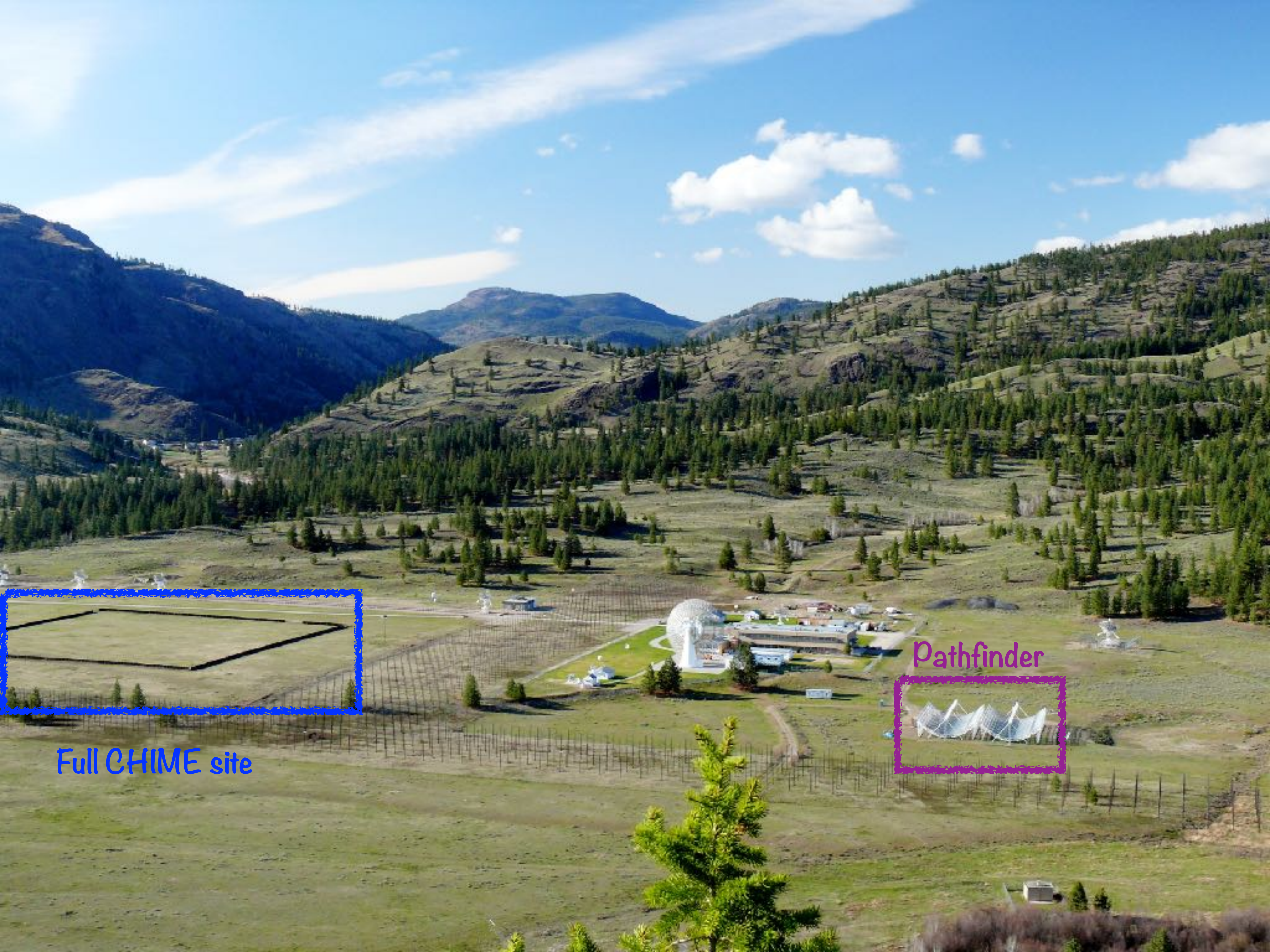
CHIME Overview



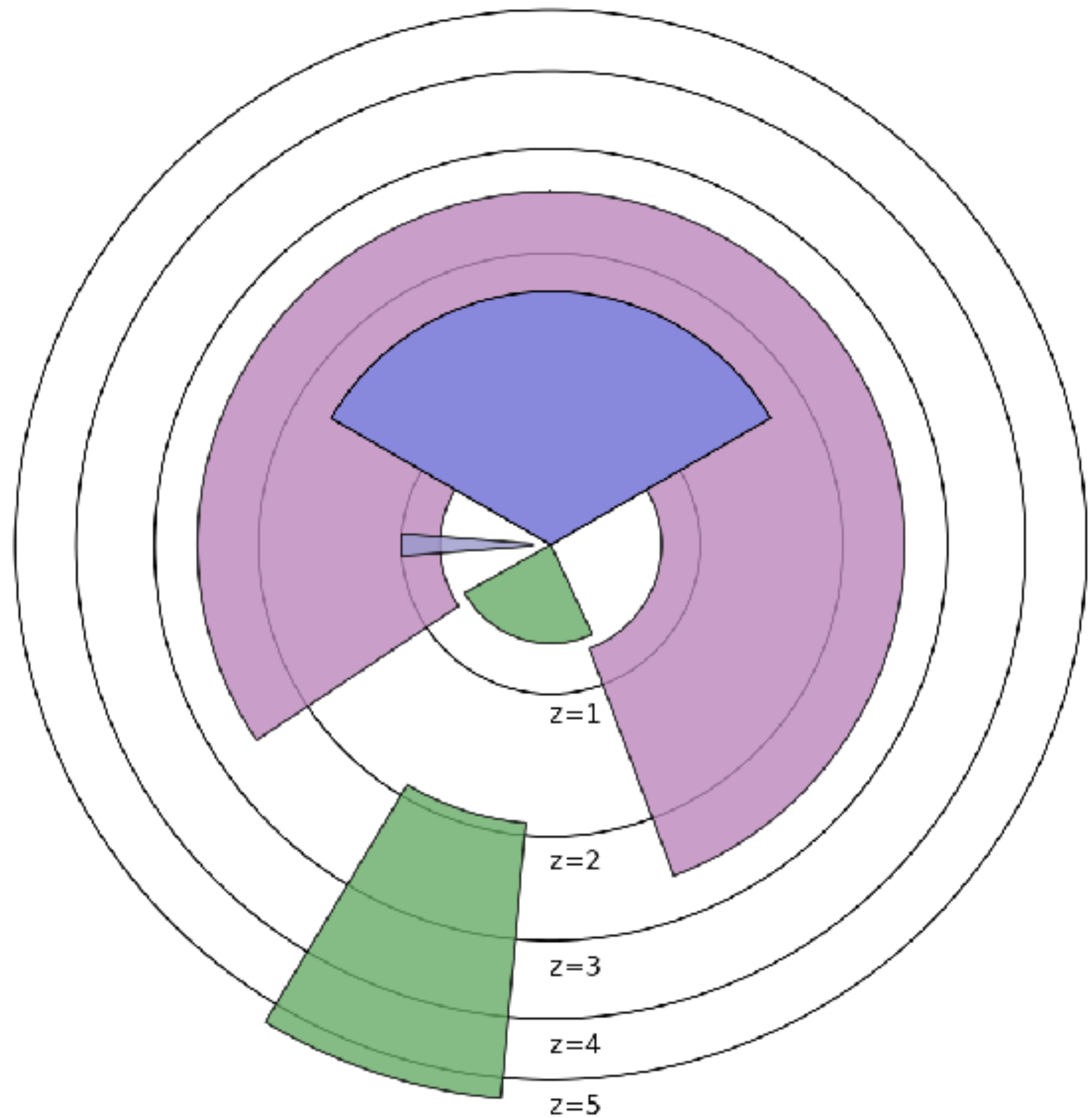
- Science Goals
  - **Intensity mapping for BAOs**
  - Pulsar observations
  - Radio transients




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
orca
big horned sheep
wolf
wood duck
lobster
golden winged warbler
robin
leopard frog
bison
blanding's turtle
beaver
loon
CHIME
Jessica Rae Gordon


Pathfinder
Full CHIME site

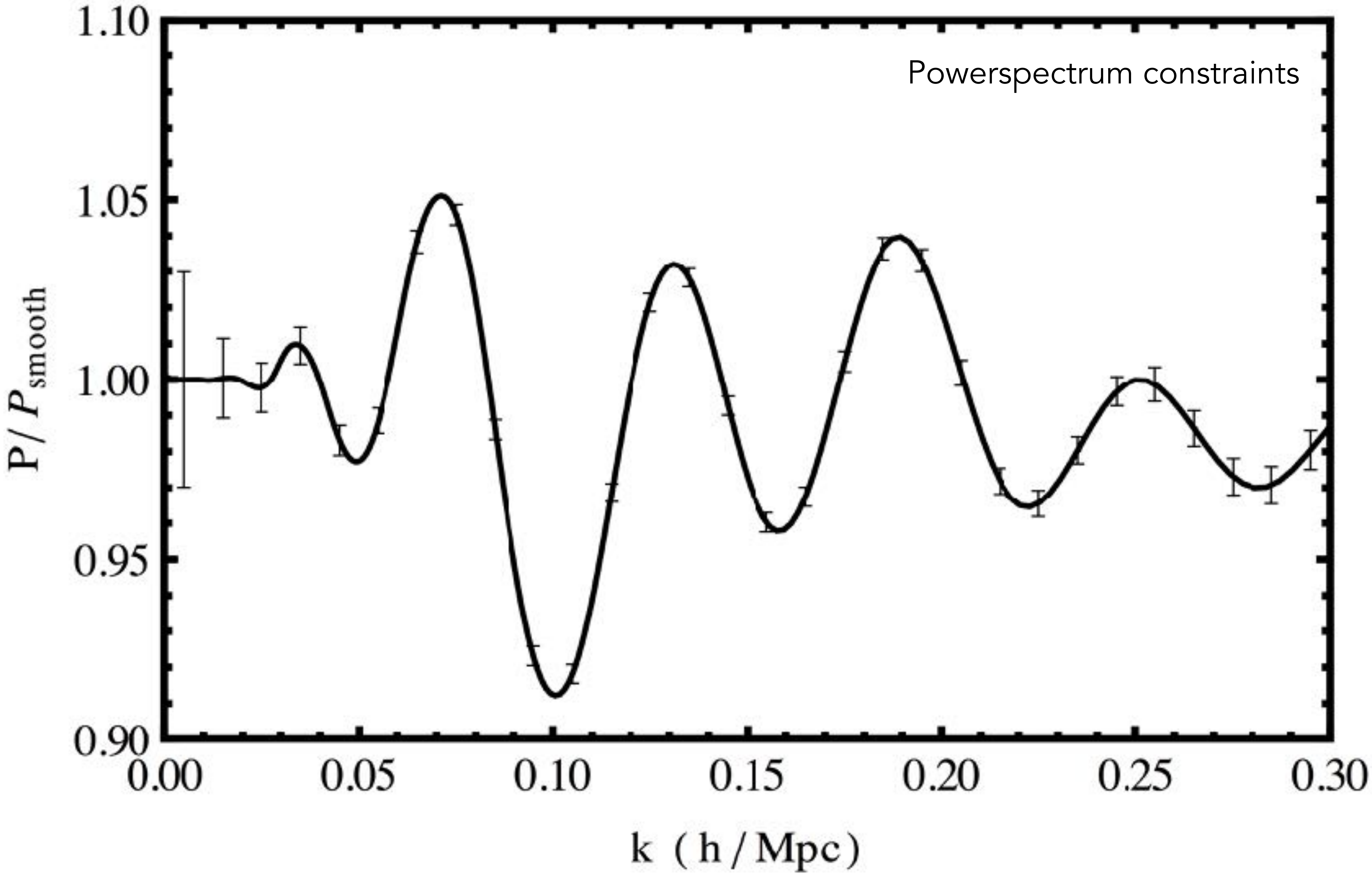
Survey Volume



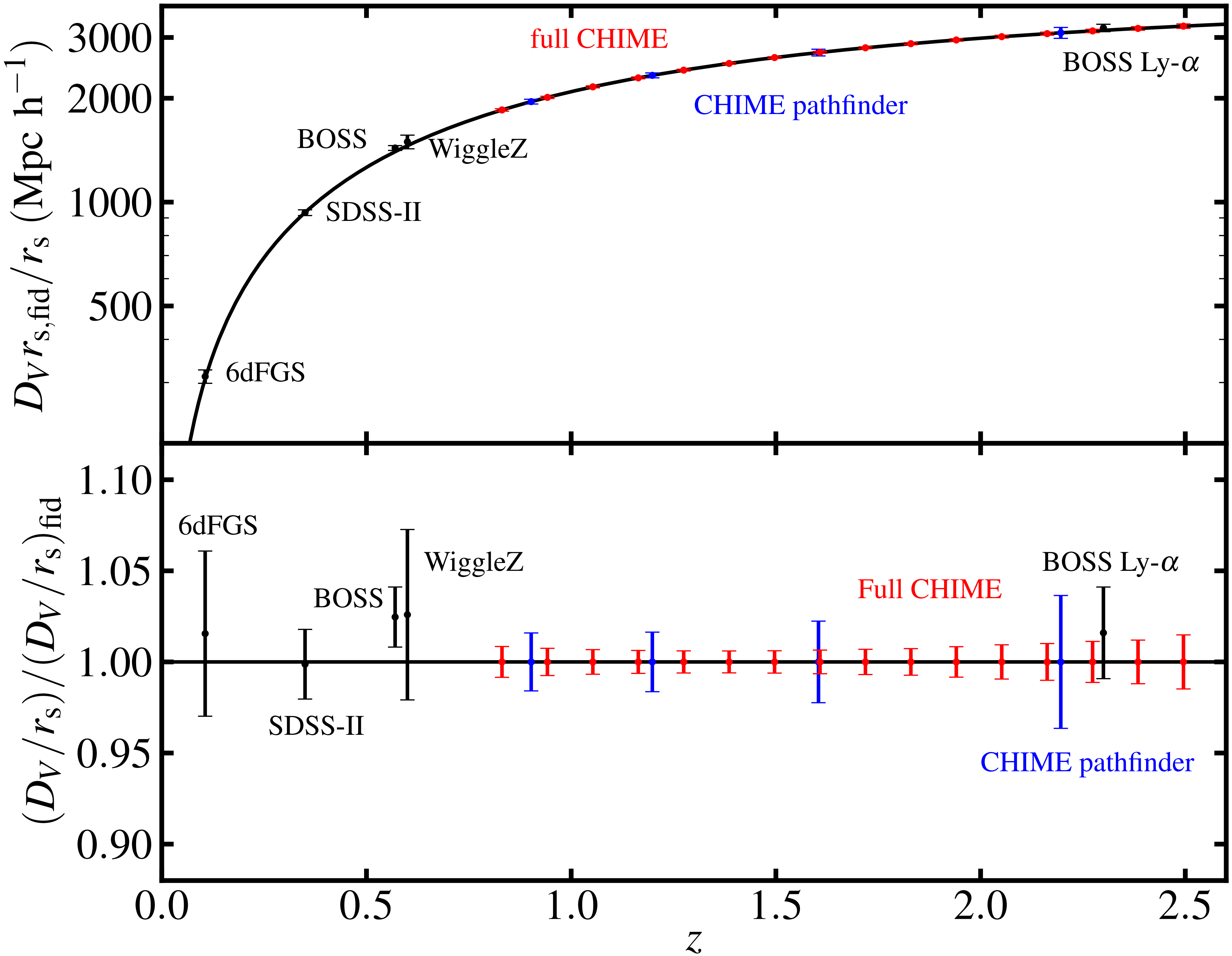
- WiggleZ: 1.2 $(h^{-1}\,\mathrm{Gpc})^3$
- BOSS
  - LRG: 5.3 $(h^{-1}\,\mathrm{Gpc})^3$
  - Lyα: 37 $(h^{-1}\,\mathrm{Gpc})^3$
- CHIME: 200 $(h^{-1}\,\mathrm{Gpc})^3$
- DESI ELG: 50 $(h^{-1}\,\mathrm{Gpc})^3$

Scaled such that:
area of patch=volume of survey

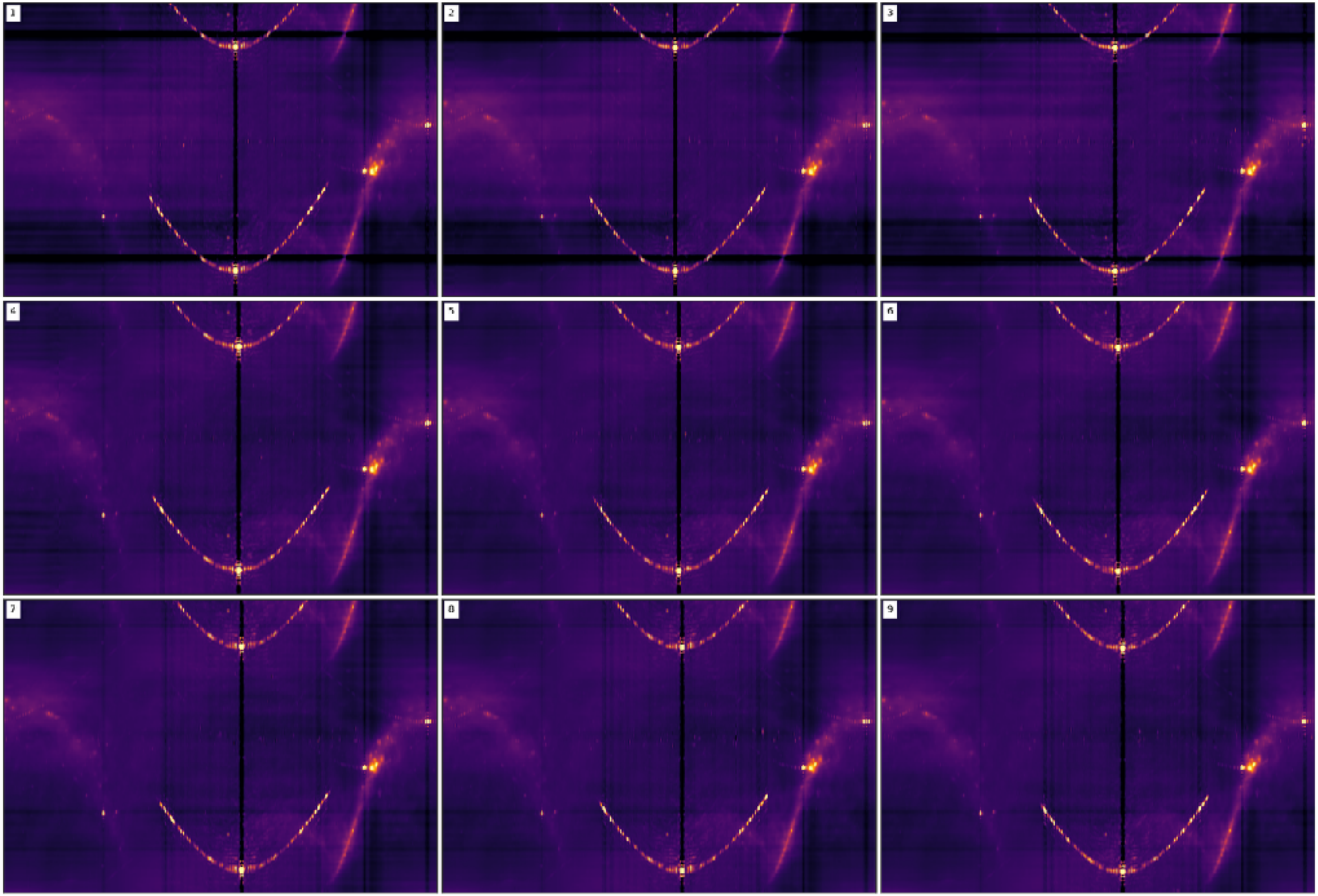
BAO Forecasts



BAO Forecasts



CHIME Pathfinder


1
2
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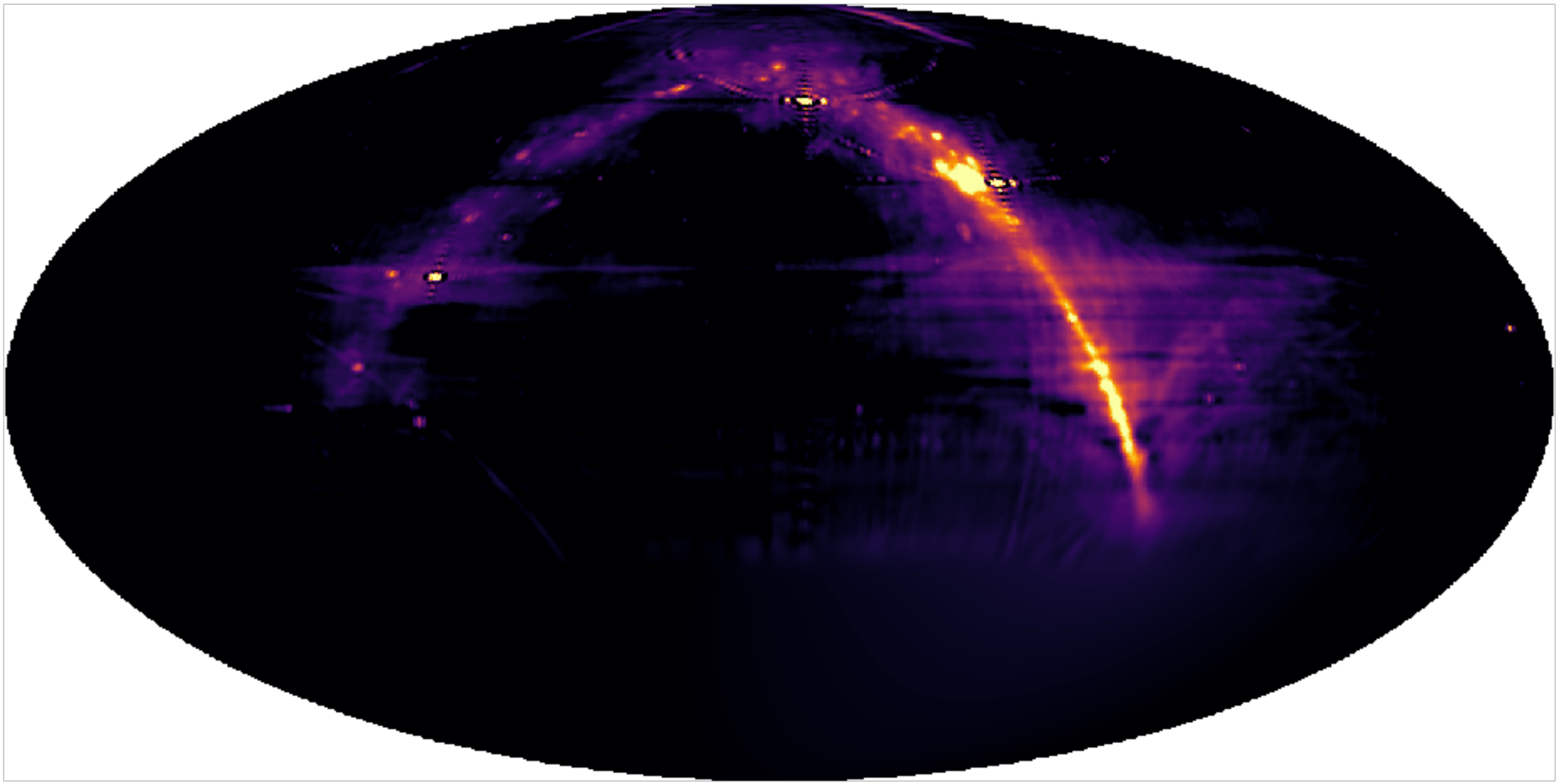
9

Deconvolved Map



711 MHz

Data Analysis with the m-mode formalism

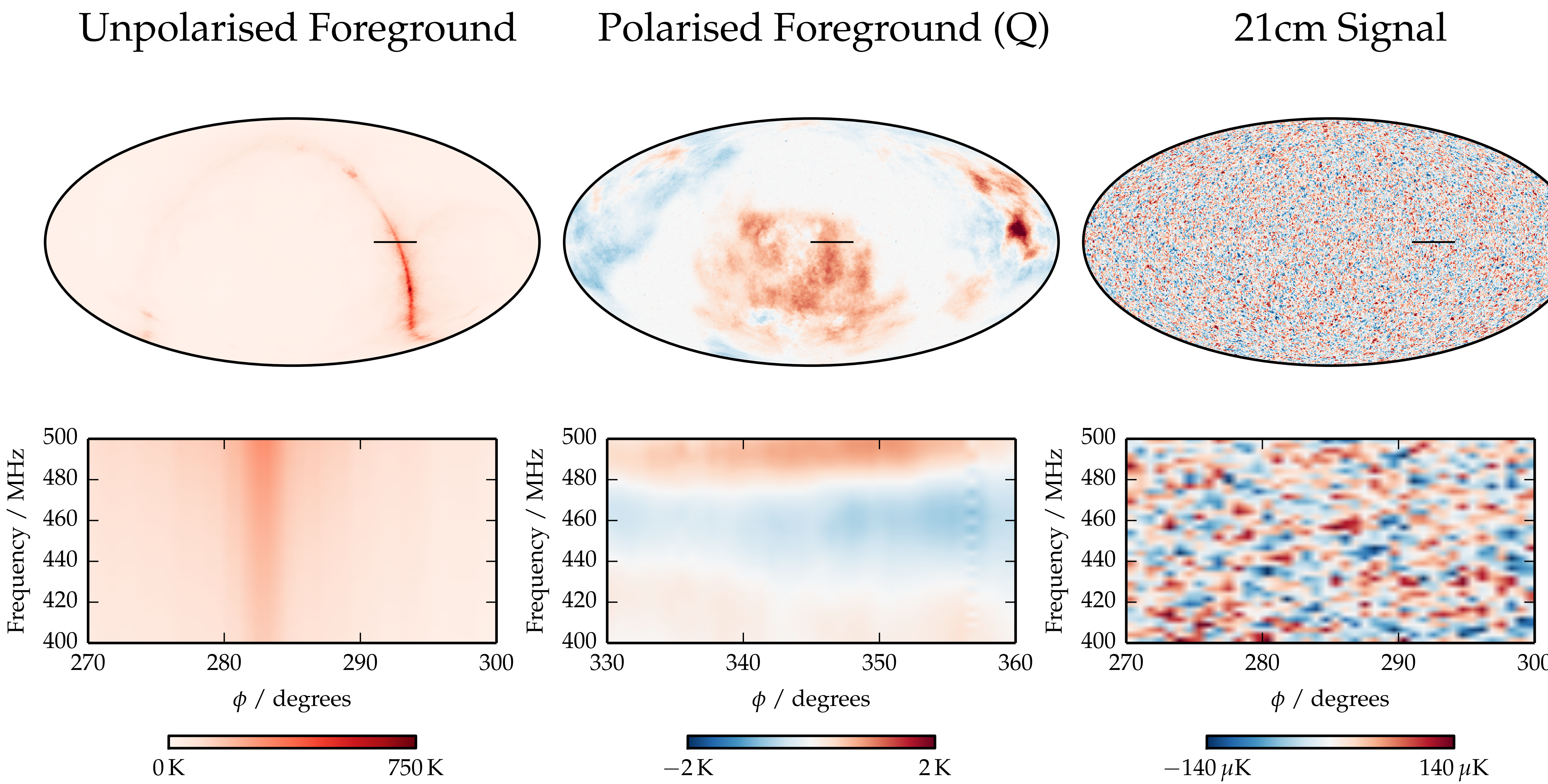
Data Analysis

- Analysis is challenging:
  - Wide field at given instant *(~ 120 x 2 degrees)*
  - Effectively an all sky survey *(3π sr)*
  - Data volume *(>~ 1 TB/day for pathfinder)*
  - Polarisation leakage
  - **Foreground removal** *(> 10^6 times brighter)*

m-mode transform

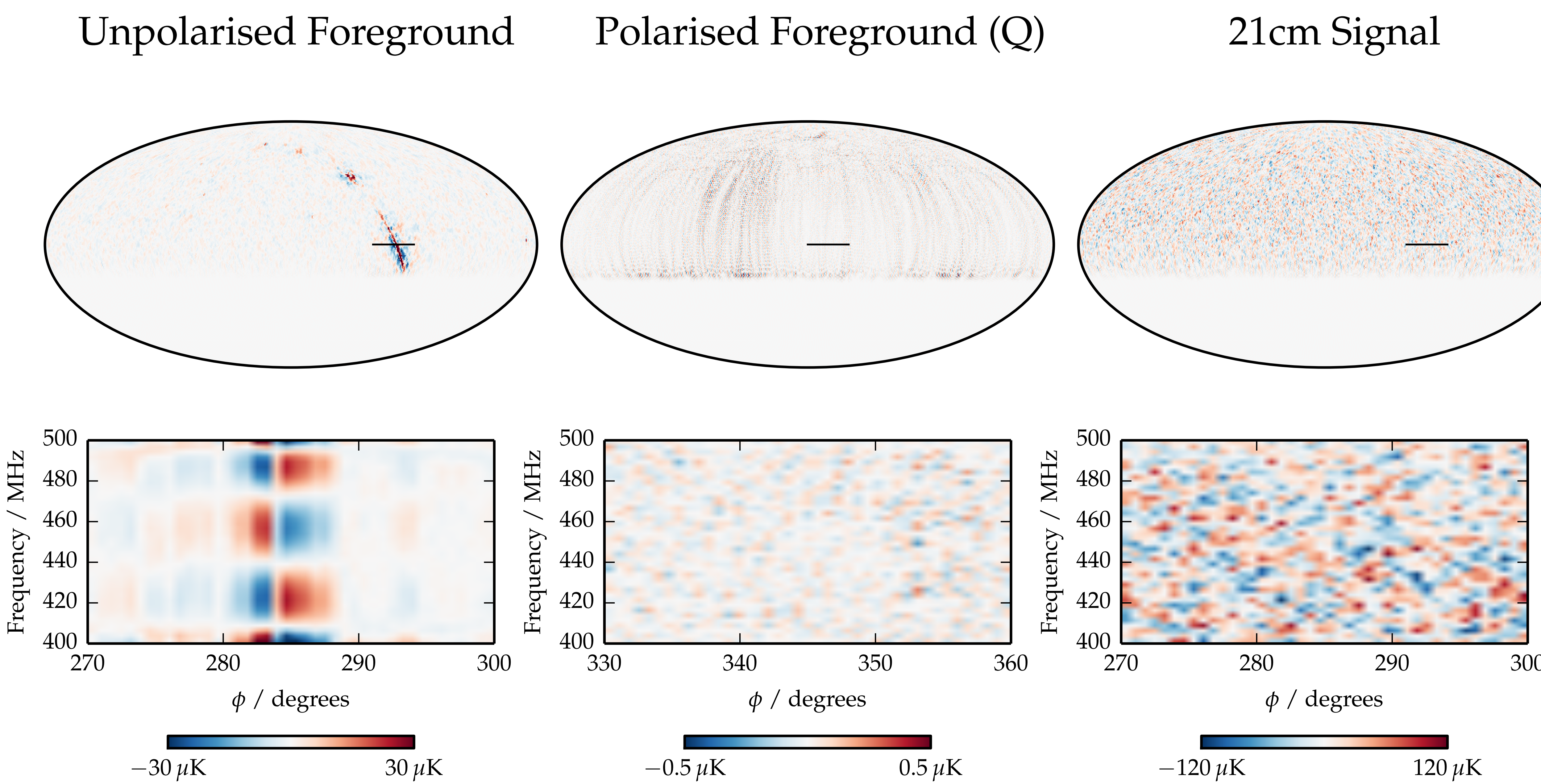
- Developed *m*-mode formalism
  - Transit telescopes only *(stationary noise)*
  - Naturally full sky, wide-field, and ***exact*** *(no UV plane)*
  - Breaks problem into statistically independent modes *(efficient)*
  - Simple linear mapping per mode
  - Published in *arXiv:1302.0327; arXiv:1401.2095*
- Enables an efficient cleaning of foregrounds:
  - Use covariance of data to find a statistical separation (KL Transform/SN eigenmodes)
  - Fully treats mode mixing effects

Foreground Cleaning



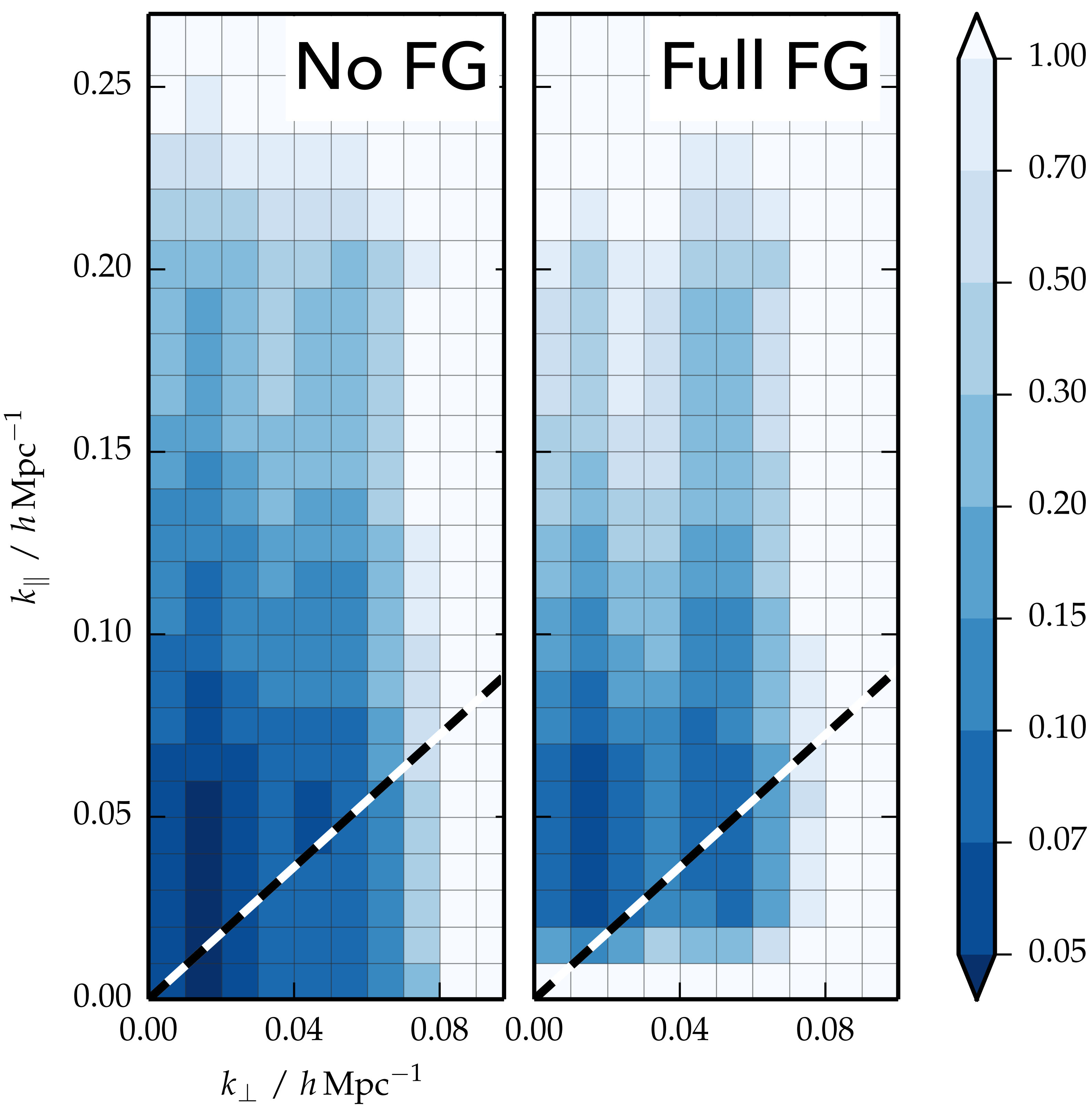
Foregrounds 10^6 times larger than signal

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

Warning: Growth Rate

- Can use redshift space distortions to get access to the growth index $f = \Omega_m^\gamma$
- Problem: we have no direct measurement of the 21cm brightness temperature

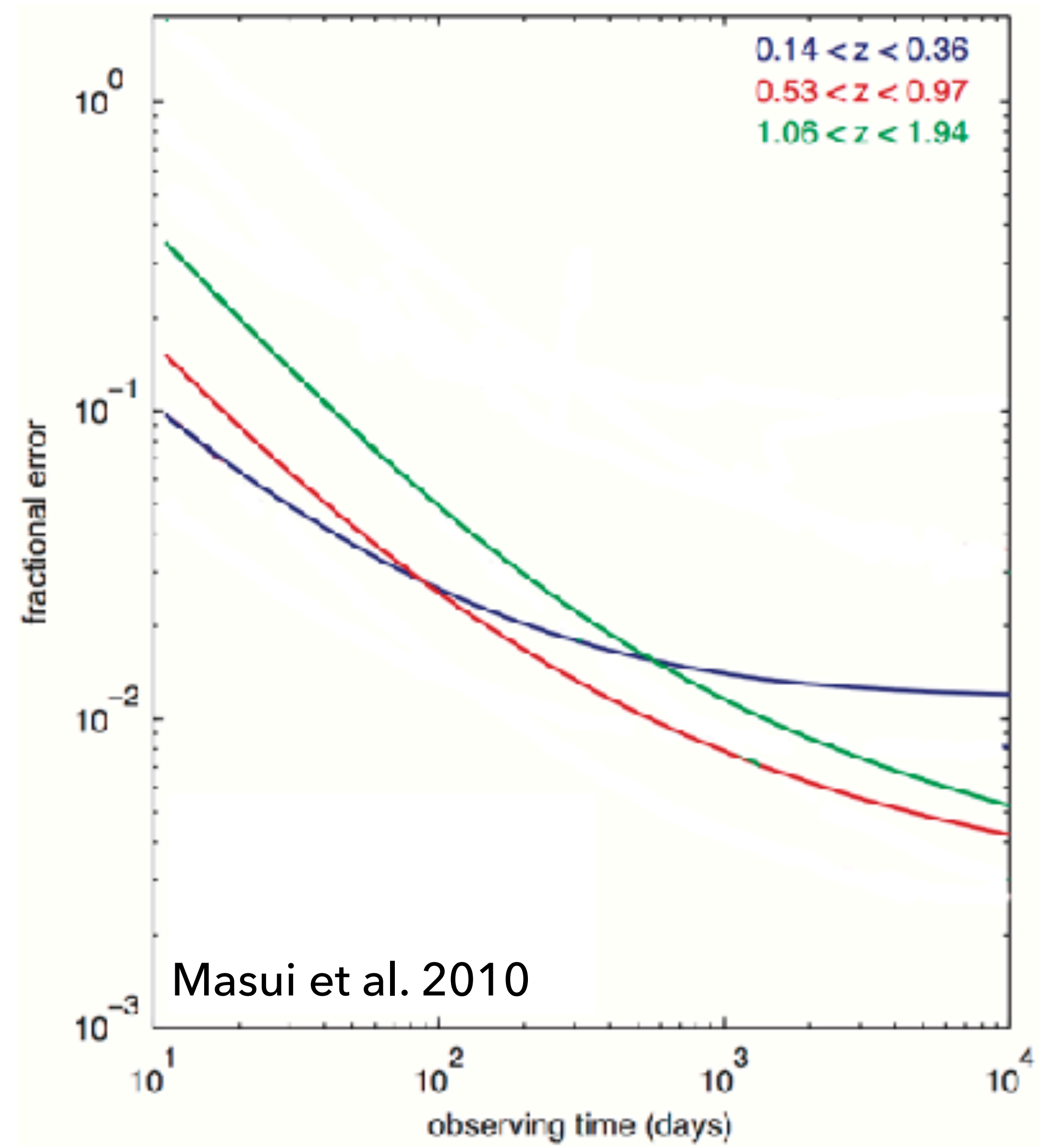
$$P_{21}(\boldsymbol{k}) = \bar{T}_b^2 \left(b + f\mu^2\right)^2 P(k)$$

- Intensity mapping can only measure degenerate combinations:

$$f/b \qquad \bar{T}_b\, f\, \sigma_8$$

- Can we learn these any other way? Sims, global sky experiments, 21cm galaxy surveys?

Fractional Error in f/b

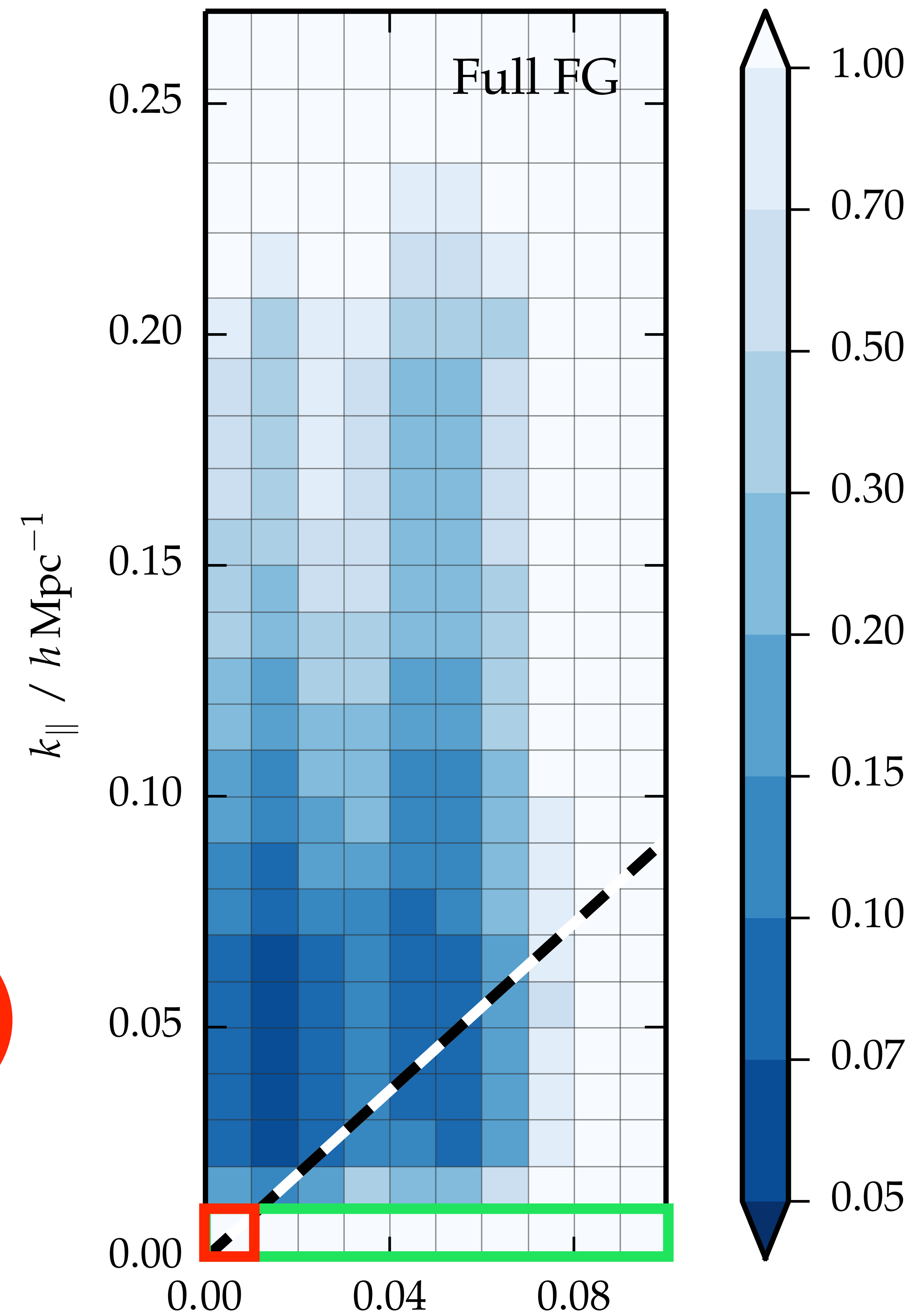


Warning: large scale IM correlation

- Ultra-large scales are a promising regime for tests of gravity (Baker et al., Alonso et al.)
- Use multiple tracers to avoid sample variance (McDonald and Seljak 2009)
- Foregrounds are a huge barrier
    - Cleaning removes the 21 cm signal
    - Without cleaning we get enhanced noise (but not bias)

$$\mathrm{Var}\left(C_\ell^{g,21+fg}\right) = \frac{1}{N} C_\ell^{g} C_\ell^{21+fg}$$

- IM-CMB lensing, IM-CIB similar problems



Summary

- 21cm Intensity Mapping is a promising technique for mapping the Universe and measuring BAOs - foregrounds are challenging
- CHIME Pathfinder is operating, full instrument construction finishing in 2017
- Analysis is fun! Polarised radio sky simulation and 21cm data analysis code all available at:

http://github.com/radiocosmology/