21cm Dark Energy Cosmology with CHIME

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@ CIPANP
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"If you cannot measure it, you cannot improve it" - Kelvin

$$\rho = a^{-3(1+w)}$$

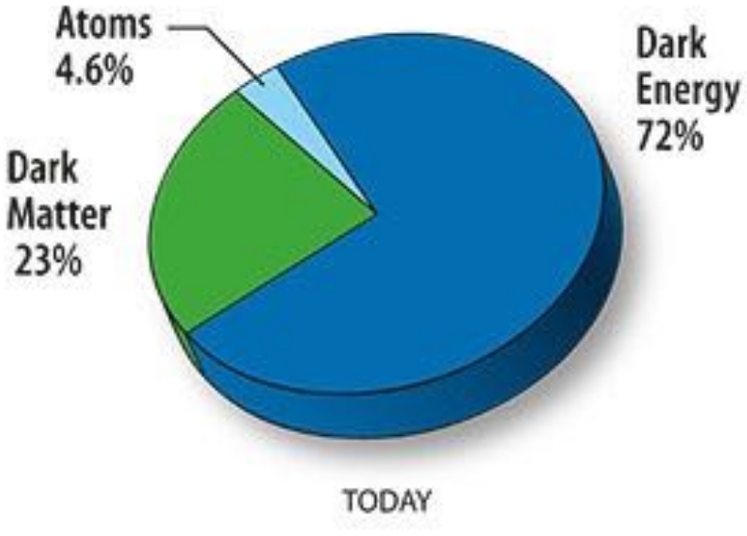
$$\mathrm{P} = w\rho$$

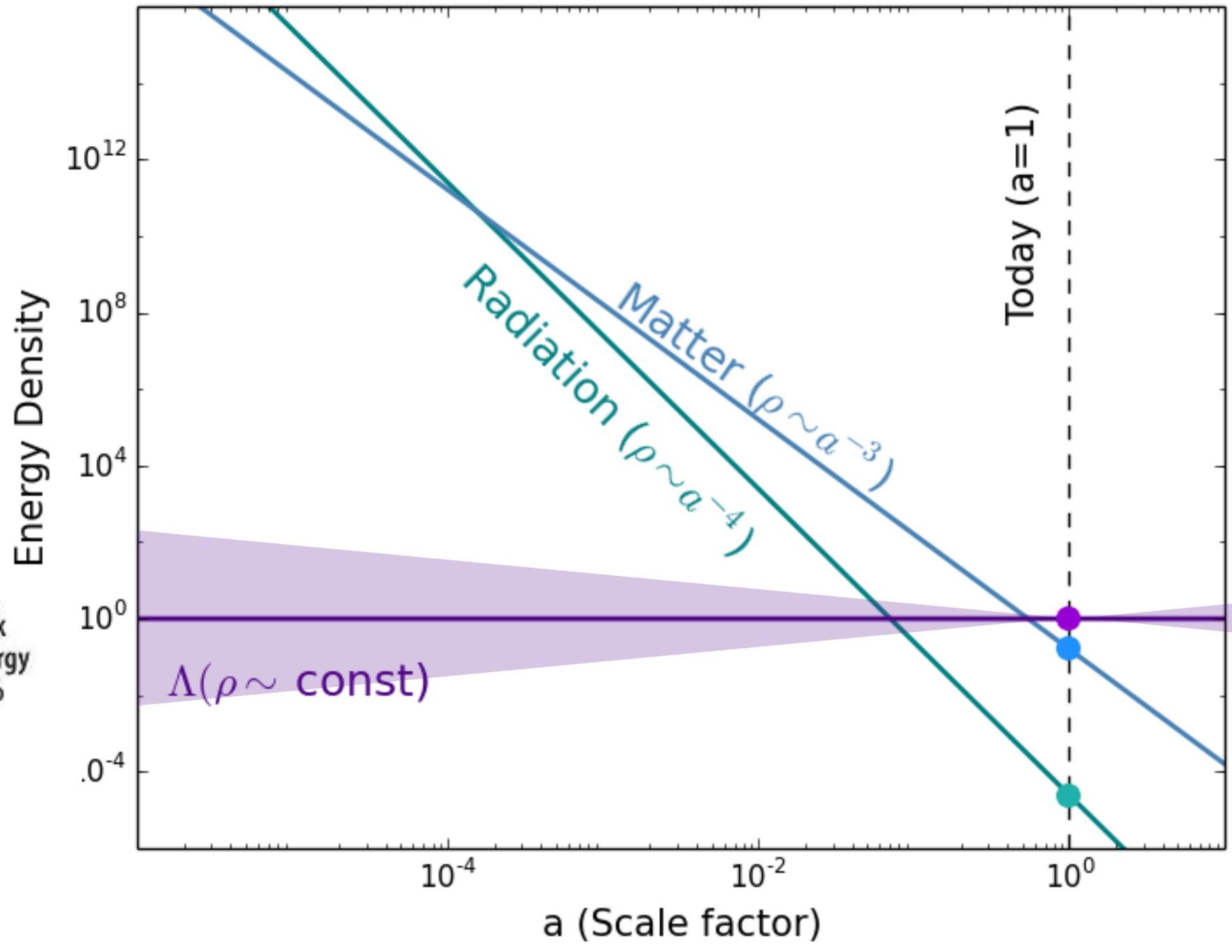
(equation of state)

Best constraint so far:

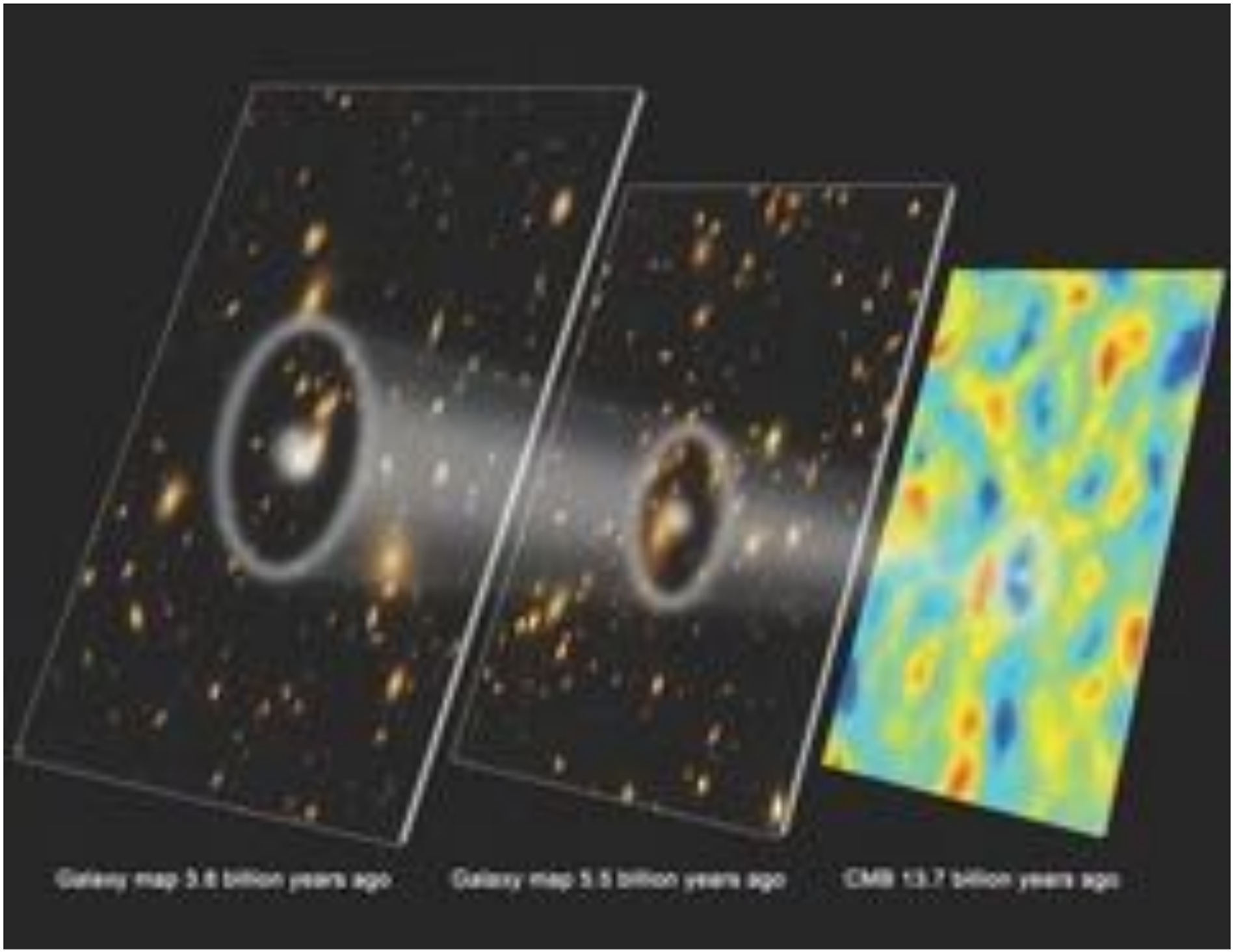
w = -1.06 ± 0.07

(a ~0.6)

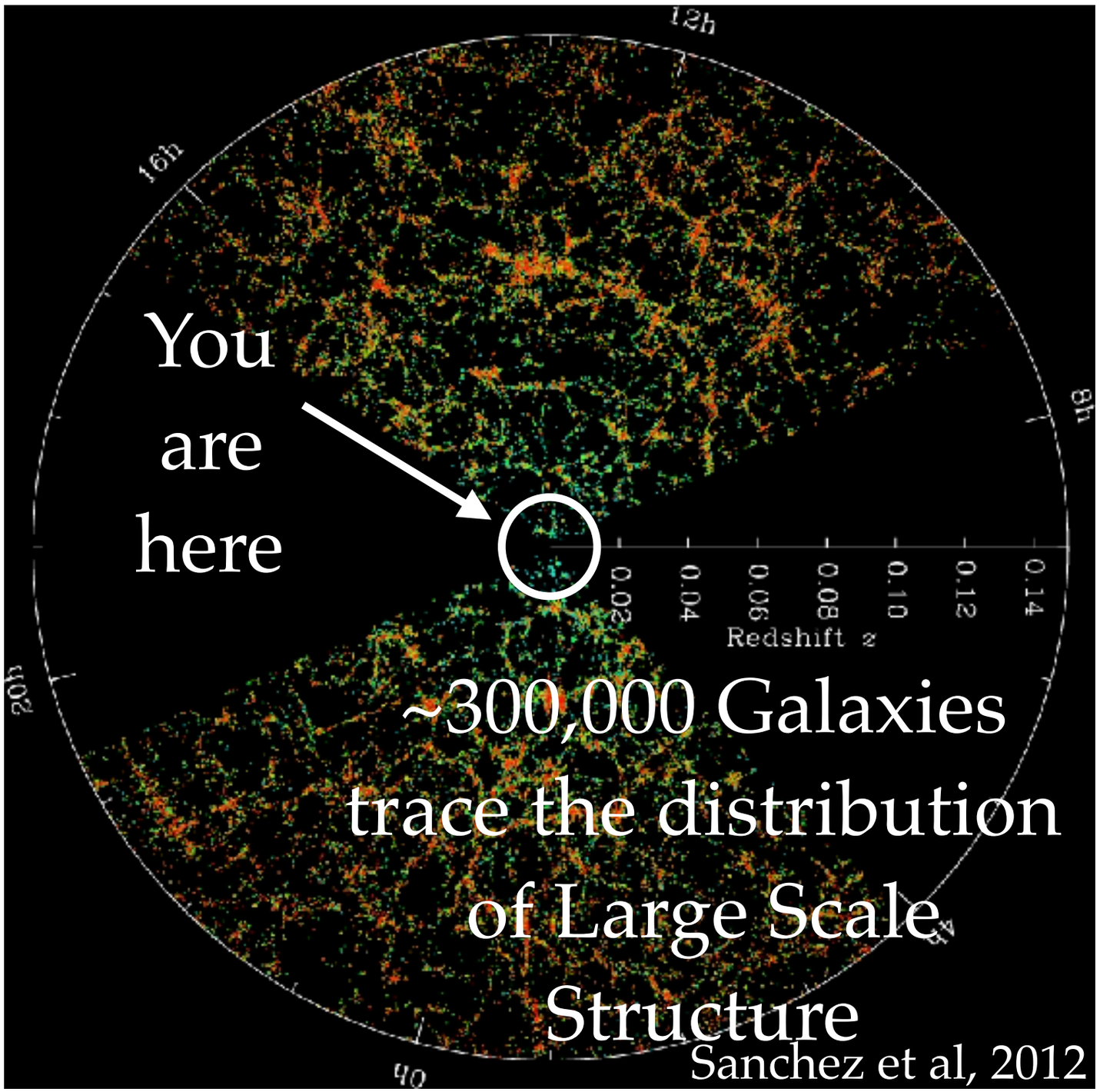




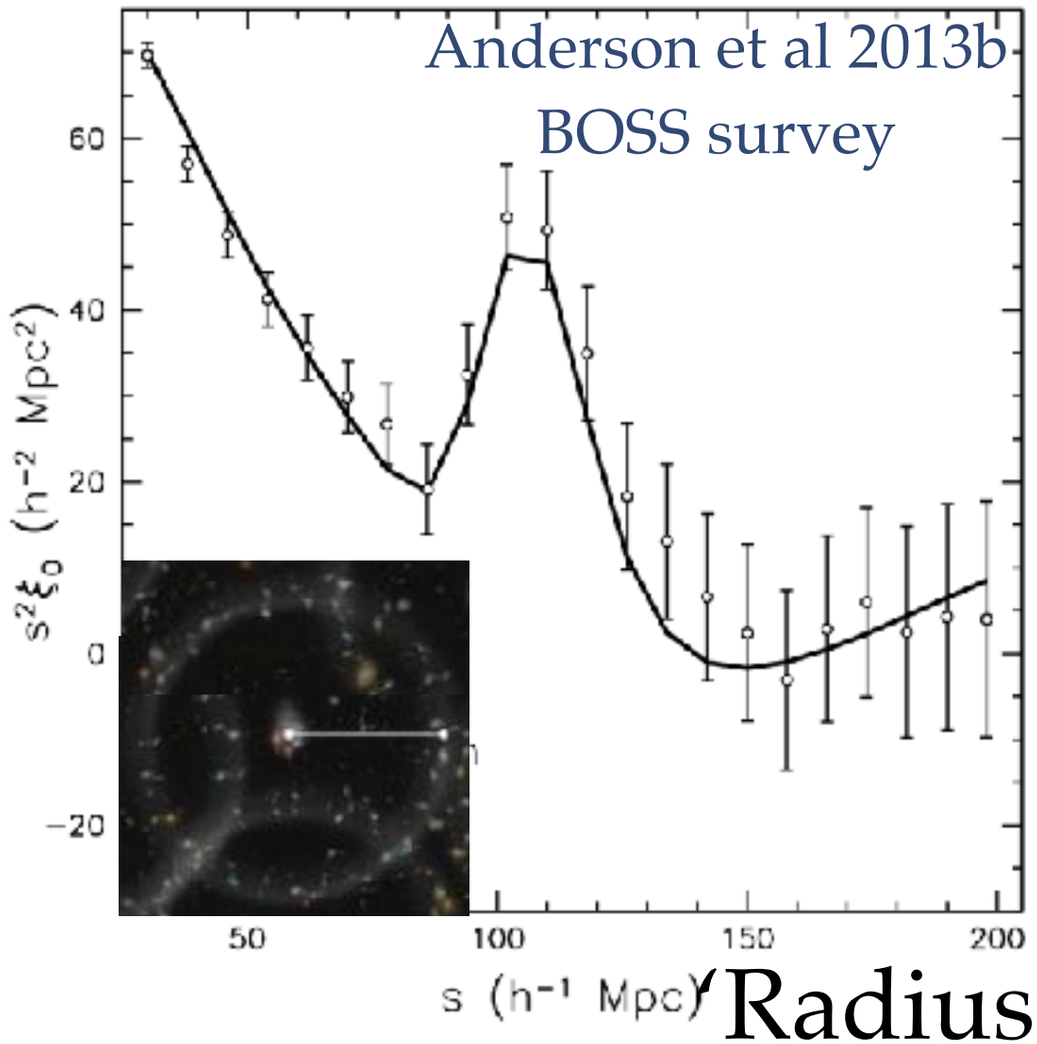
Baryon Acoustic Oscillations (BAO) Standard Ruler



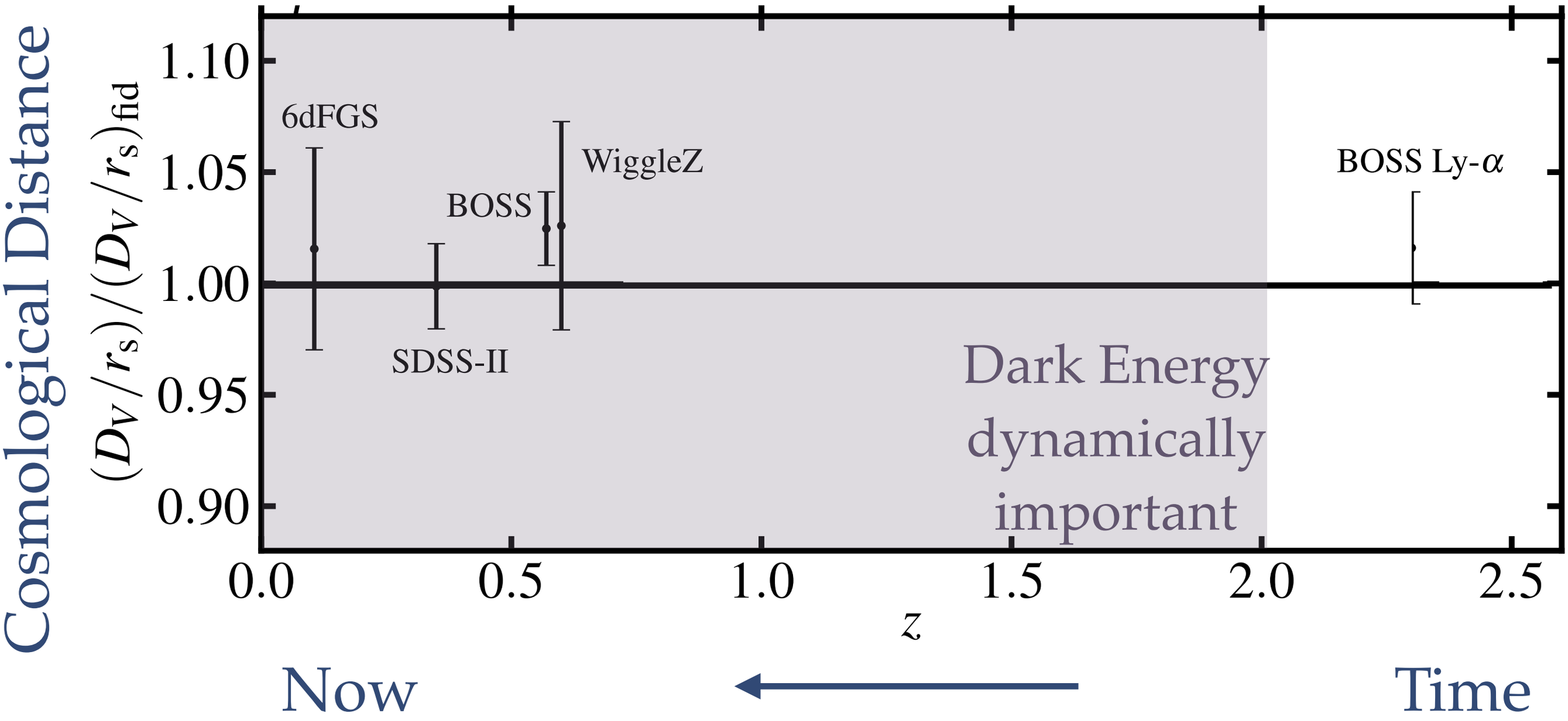
BAO from galaxy surveys



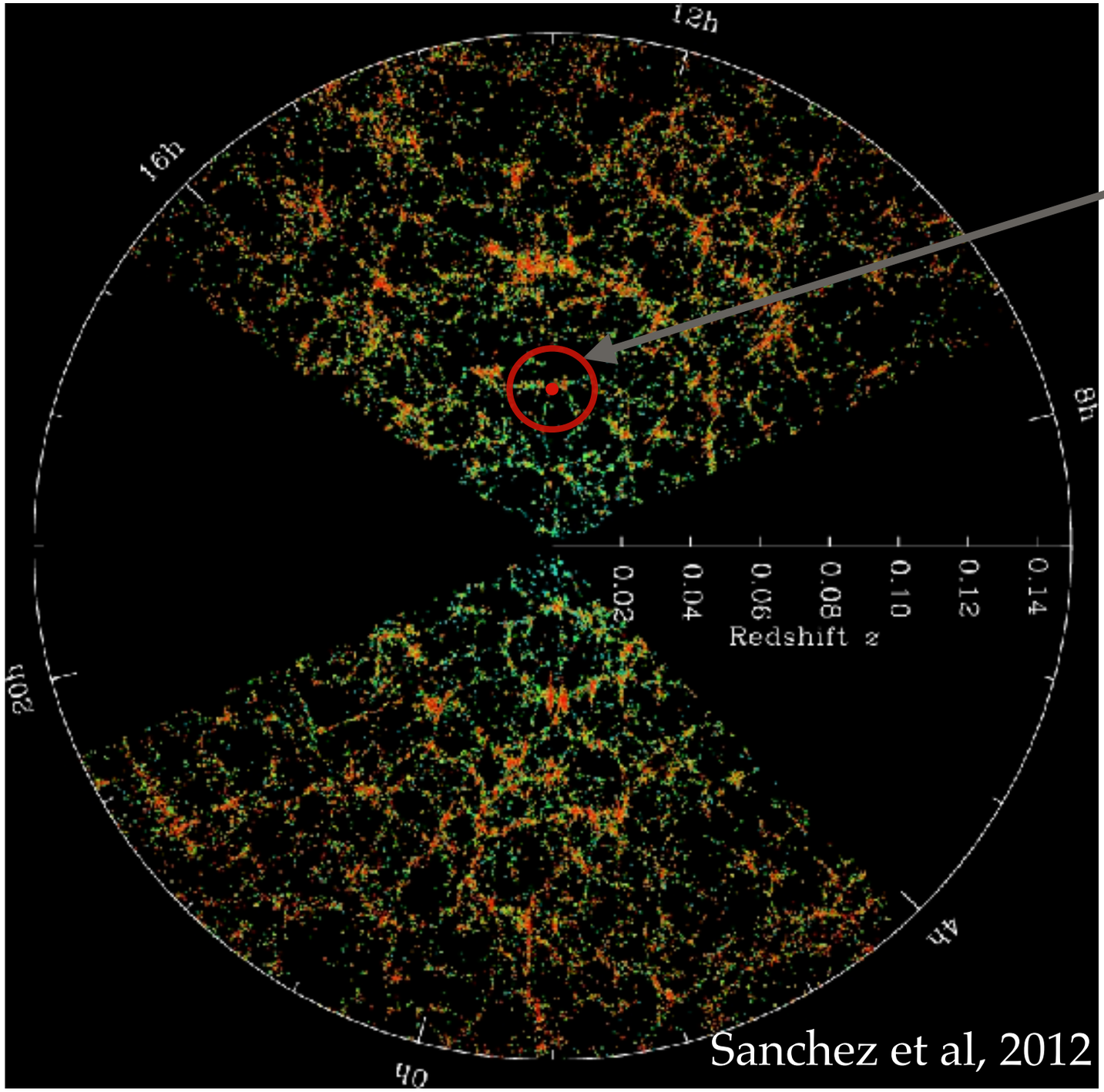
Correlation function



How are we doing so far (BAO probes)?



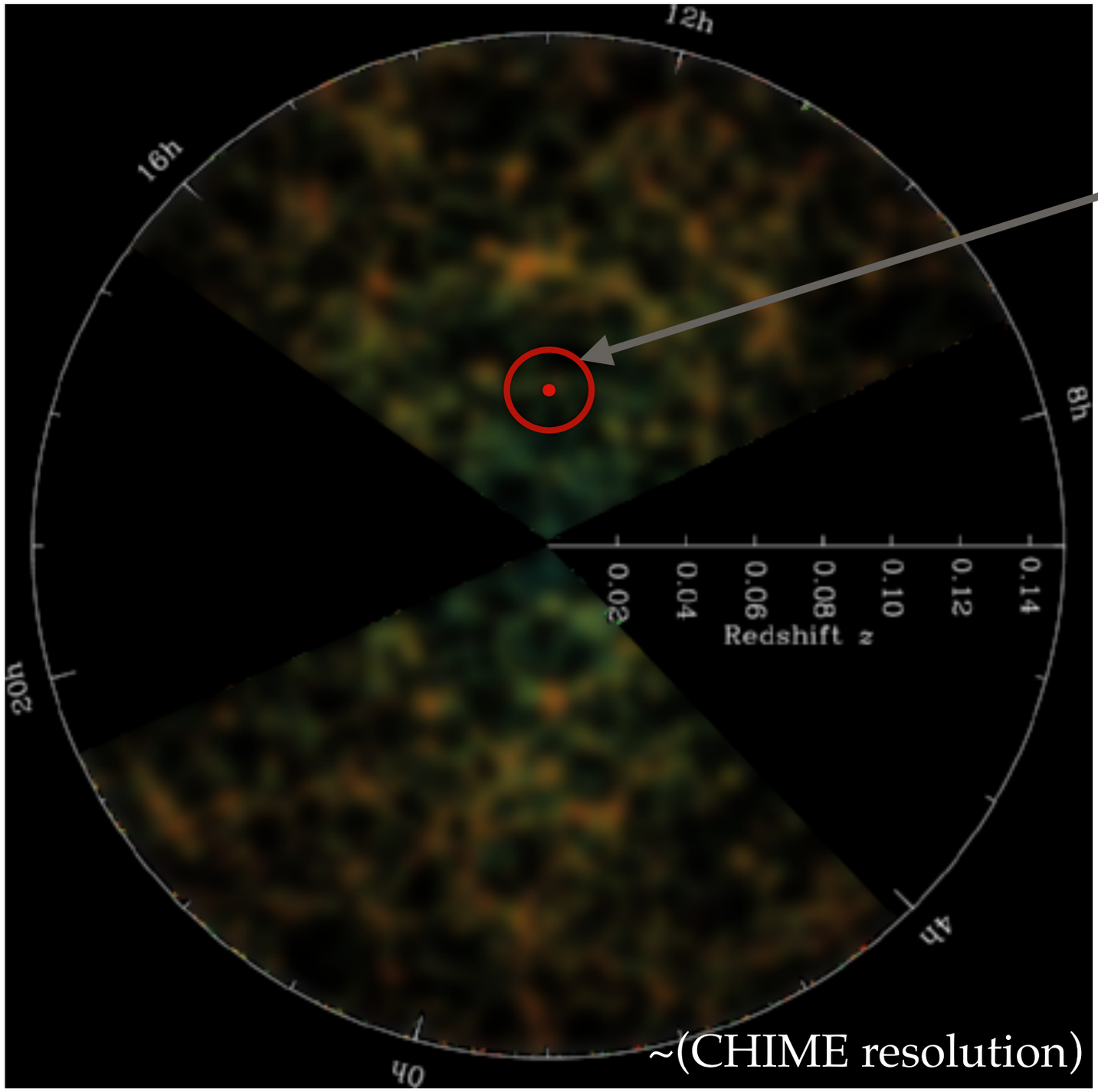
The scale of interest is *Large*…



150 Mpc
radius

Sanchez et al, 2012

So we don't need to resolve individual galaxies

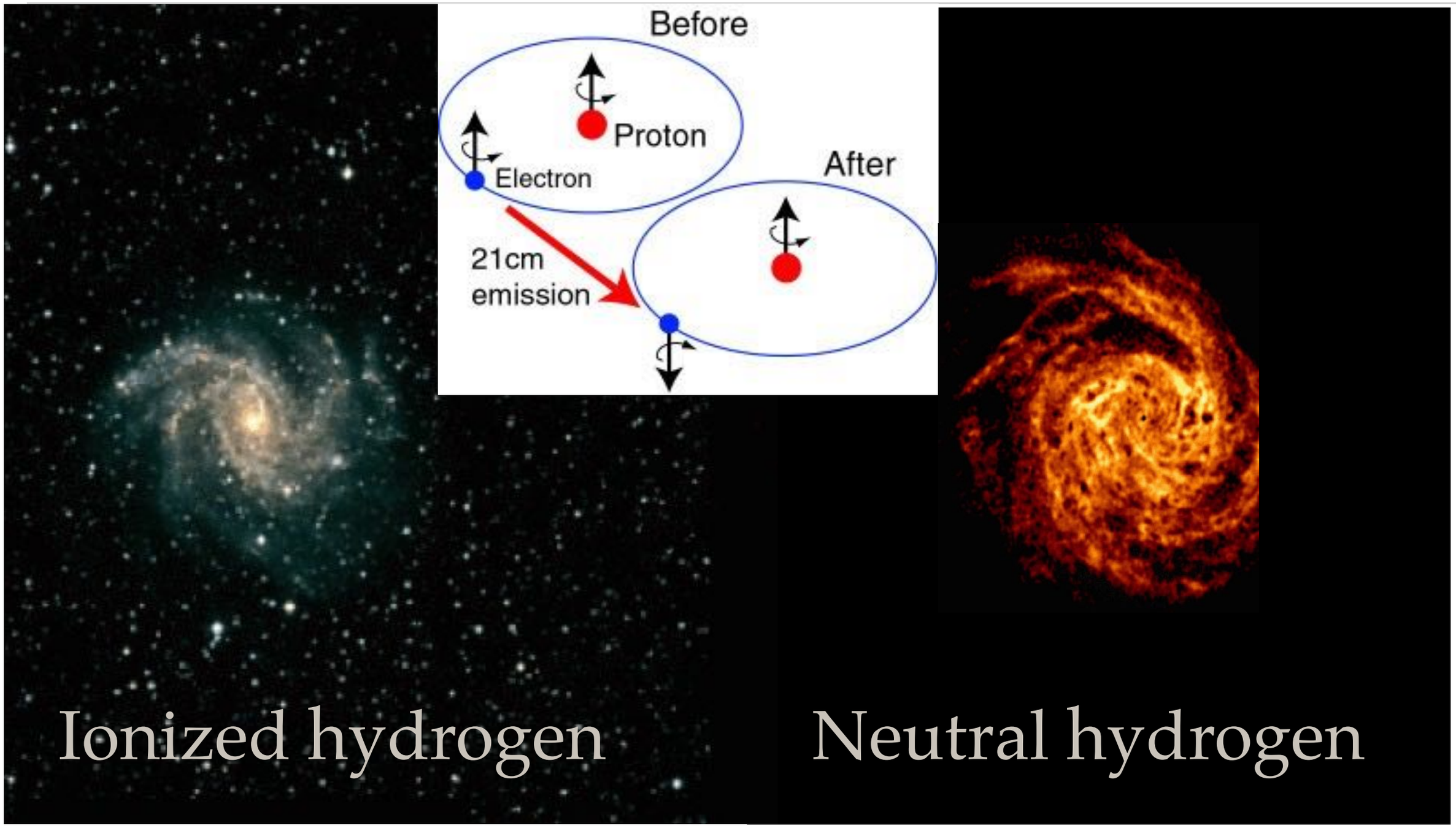


150 Mpc radius

<u>DO</u> need:

- Traces matter distribution
- Redshift information (time)

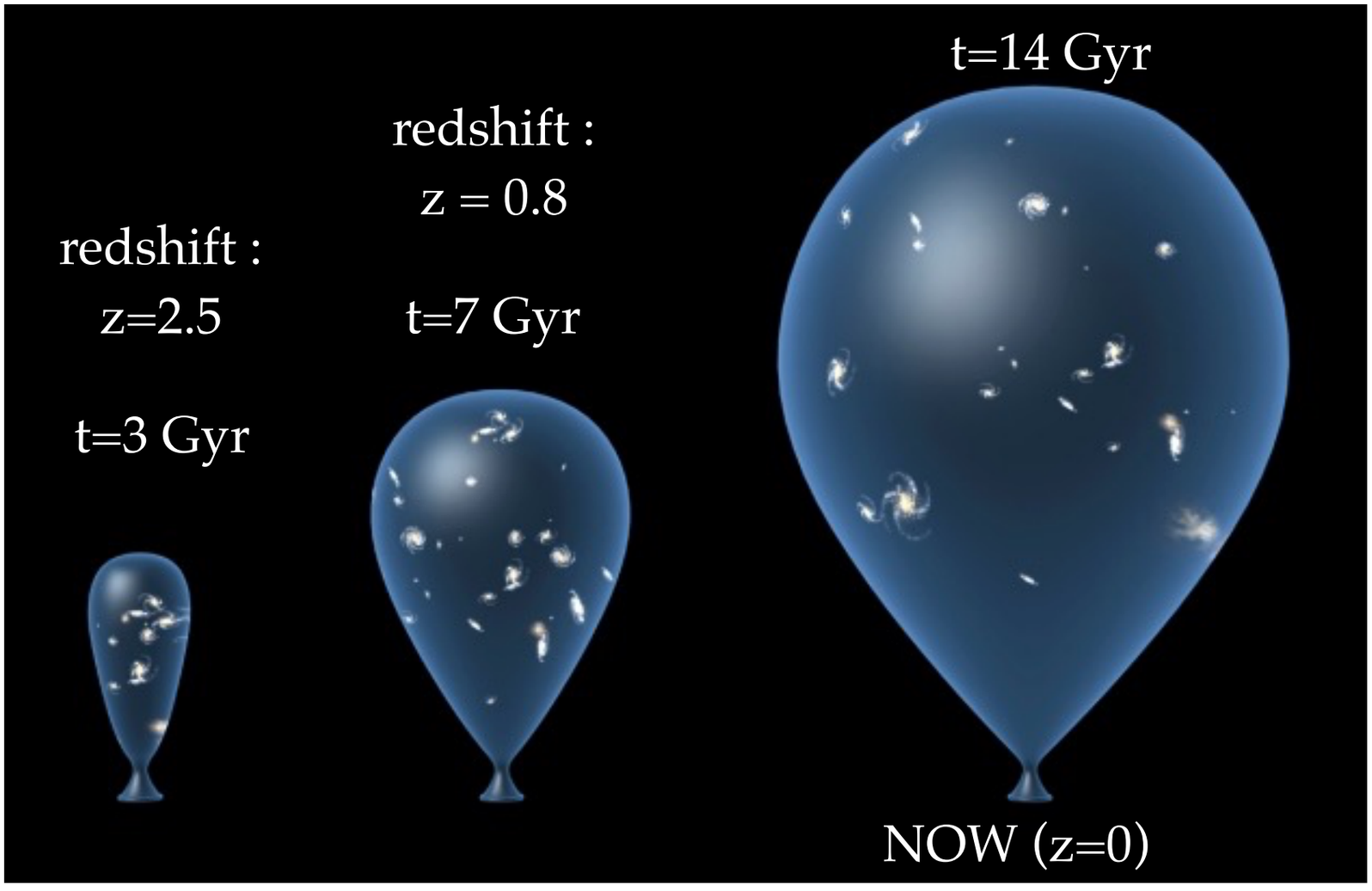
Hydrogen Intensity Mapping



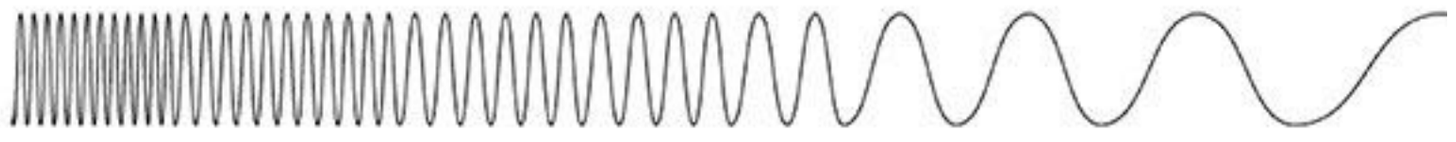
Credit: T. Oosterloo

Same Galaxy — Neutral Hydrogen in un-ionized bubbles, supported within galaxies

What do I build?

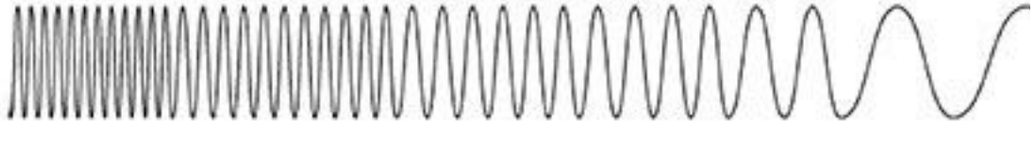


Radio astronomy



21cm

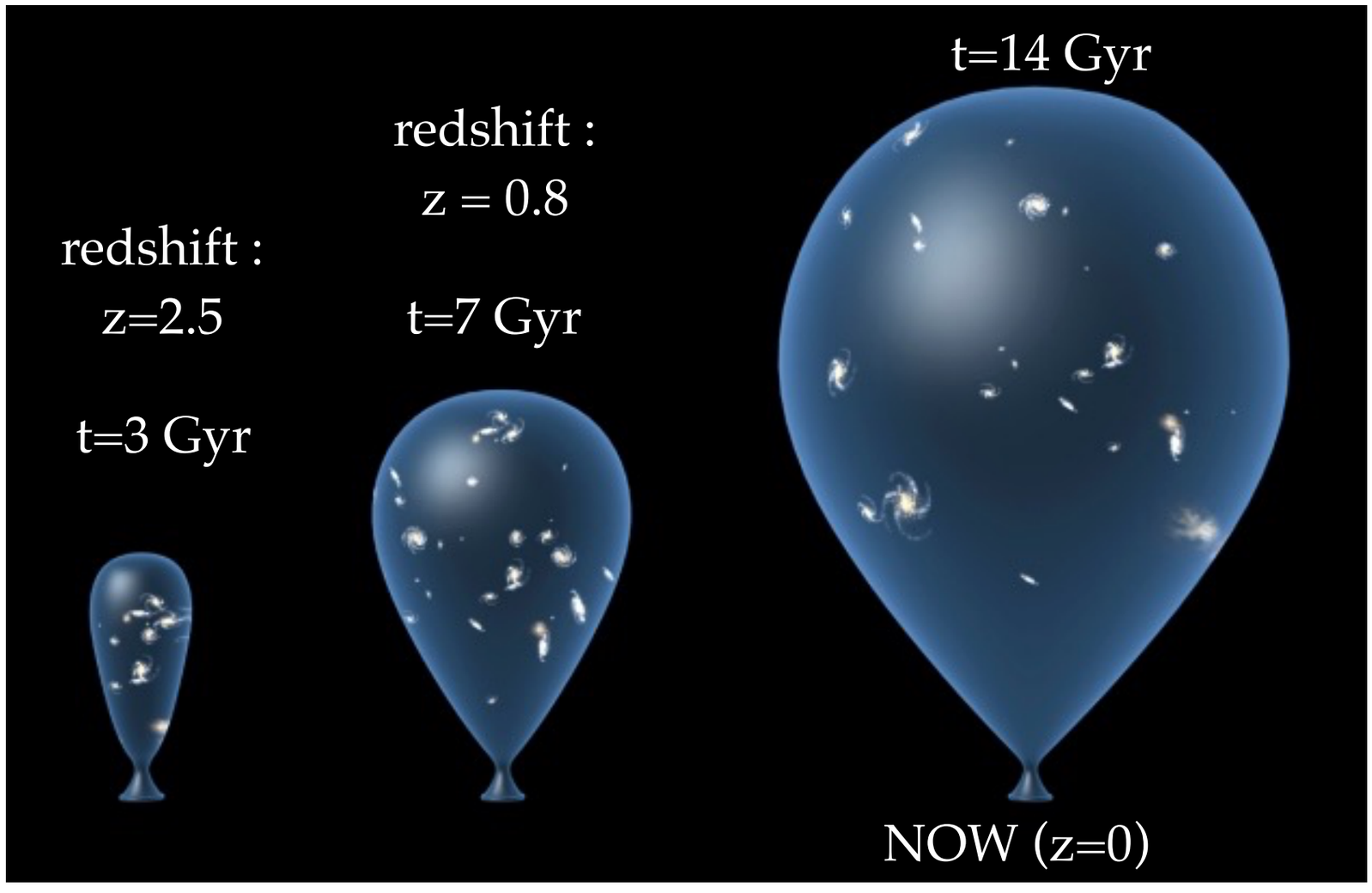
75cm (400 MHz)



21cm

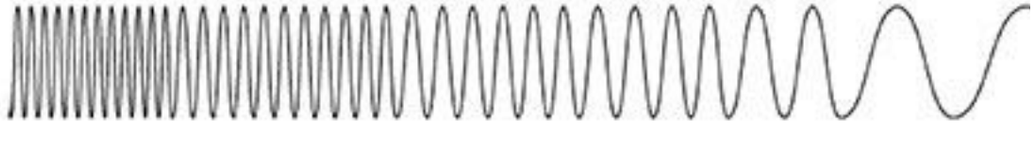
38cm (800 MHz)

What do I build?



z~0.8 HI has been detected in cross-correlation (GBT and WiggleZ/ Deep2)

21cm



38cm (800 MHz)

The Canadian Hydrogen Intensity Mapping Experiment (CHIME)

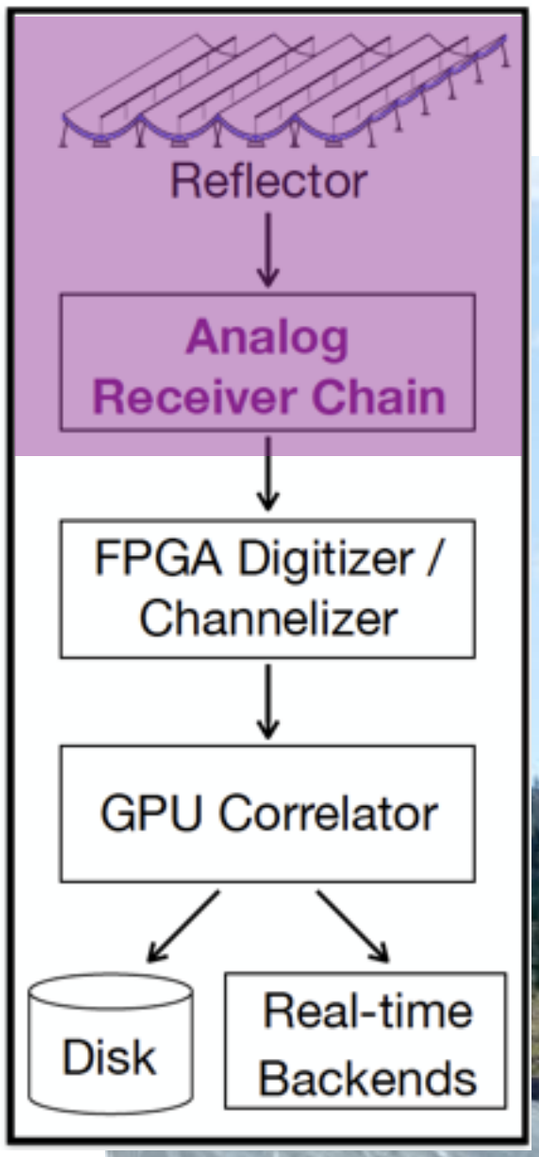
- 4 cylinders: 20m x 100m
- 1024 dual-polarization feeds
- 400-800MHz
- First light ceremony was Sept 7, 2017!

The Canadian Hydrogen Intensity Mapping Experiment (CHIME)

The Canadian Hydrogen Intensity Mapping Experiment (CHIME)

Credit: Peter Klages

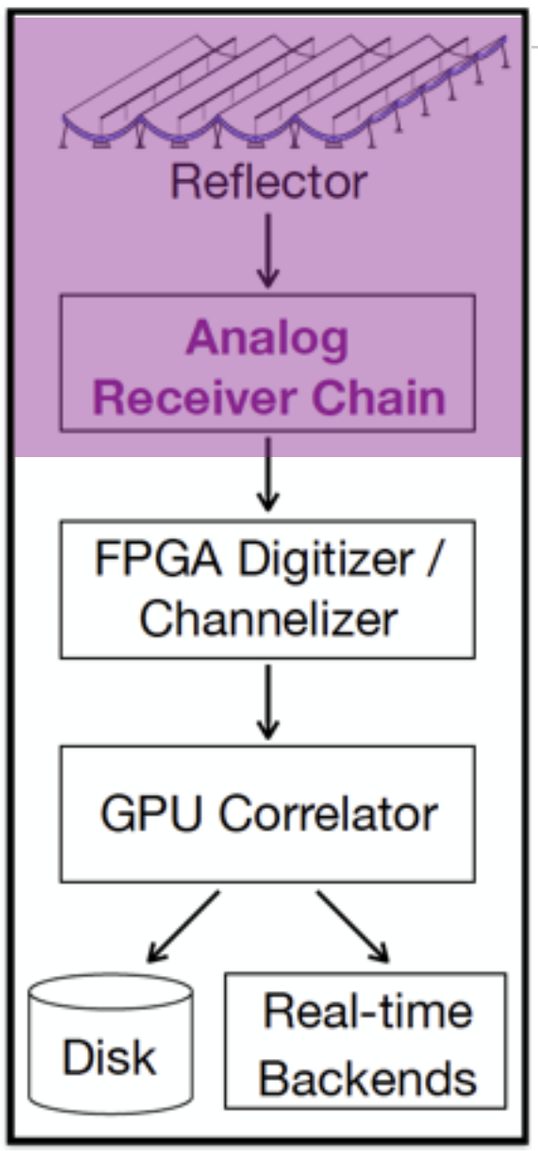
Front End: Reflector + Feeds

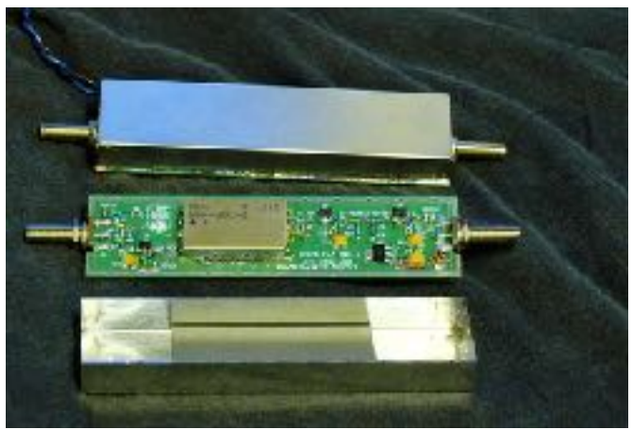


Deng et al, 2014

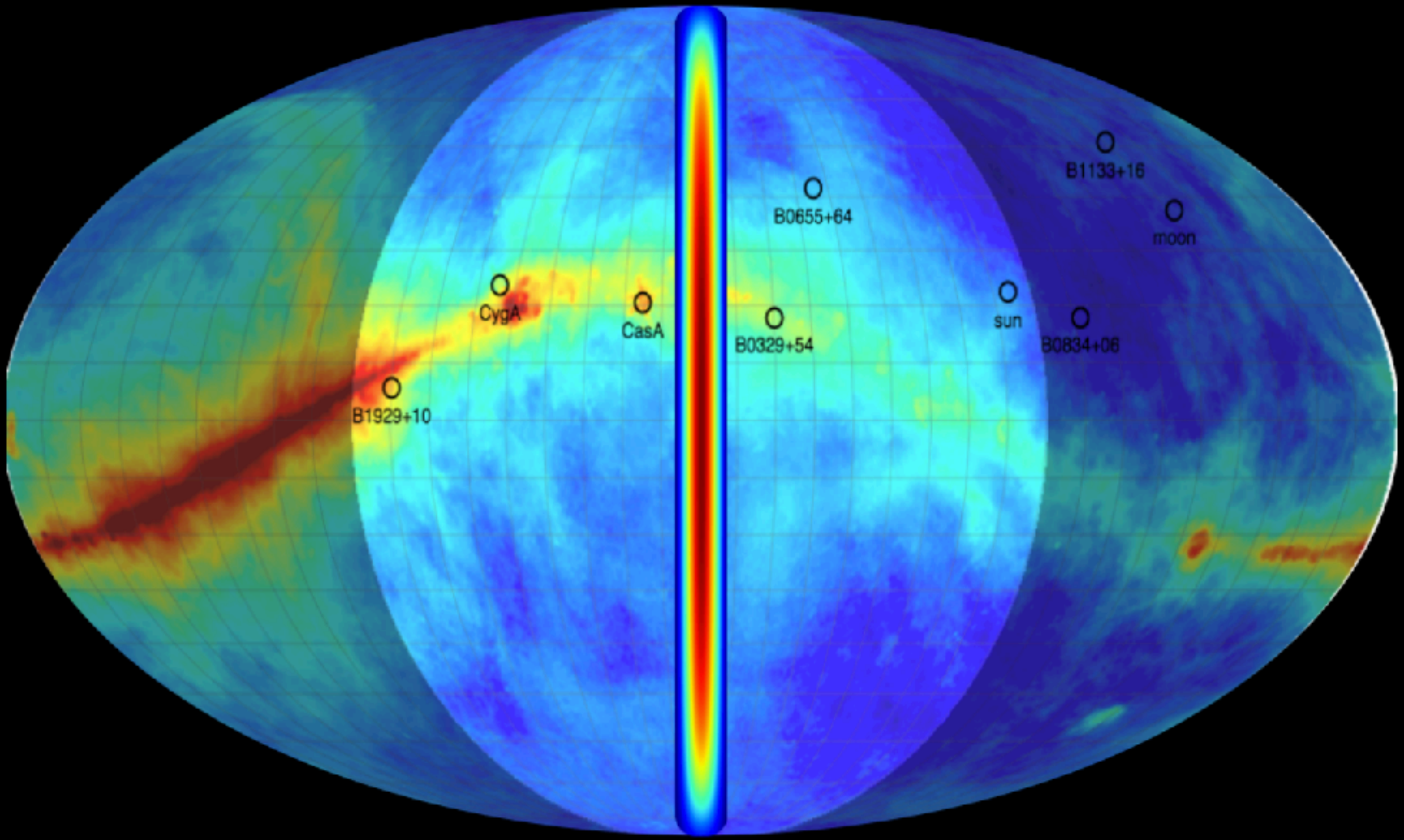
(Canadian Minister of Science for scale)

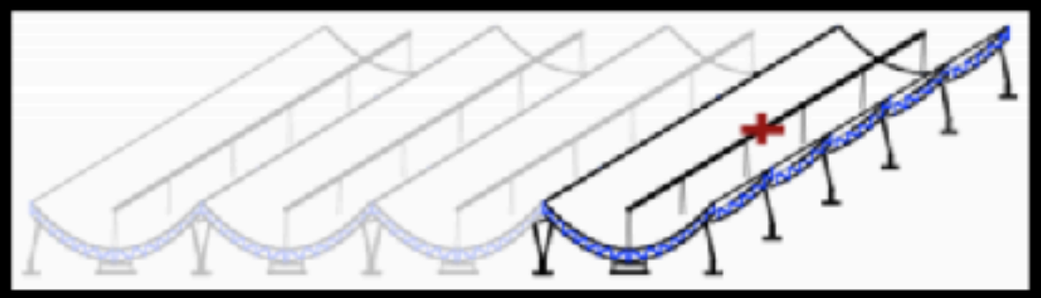
Front End: Filter Amplifiers





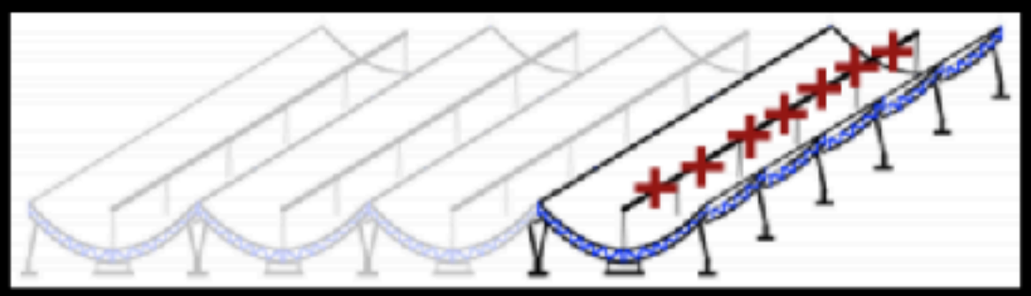
Shipping container



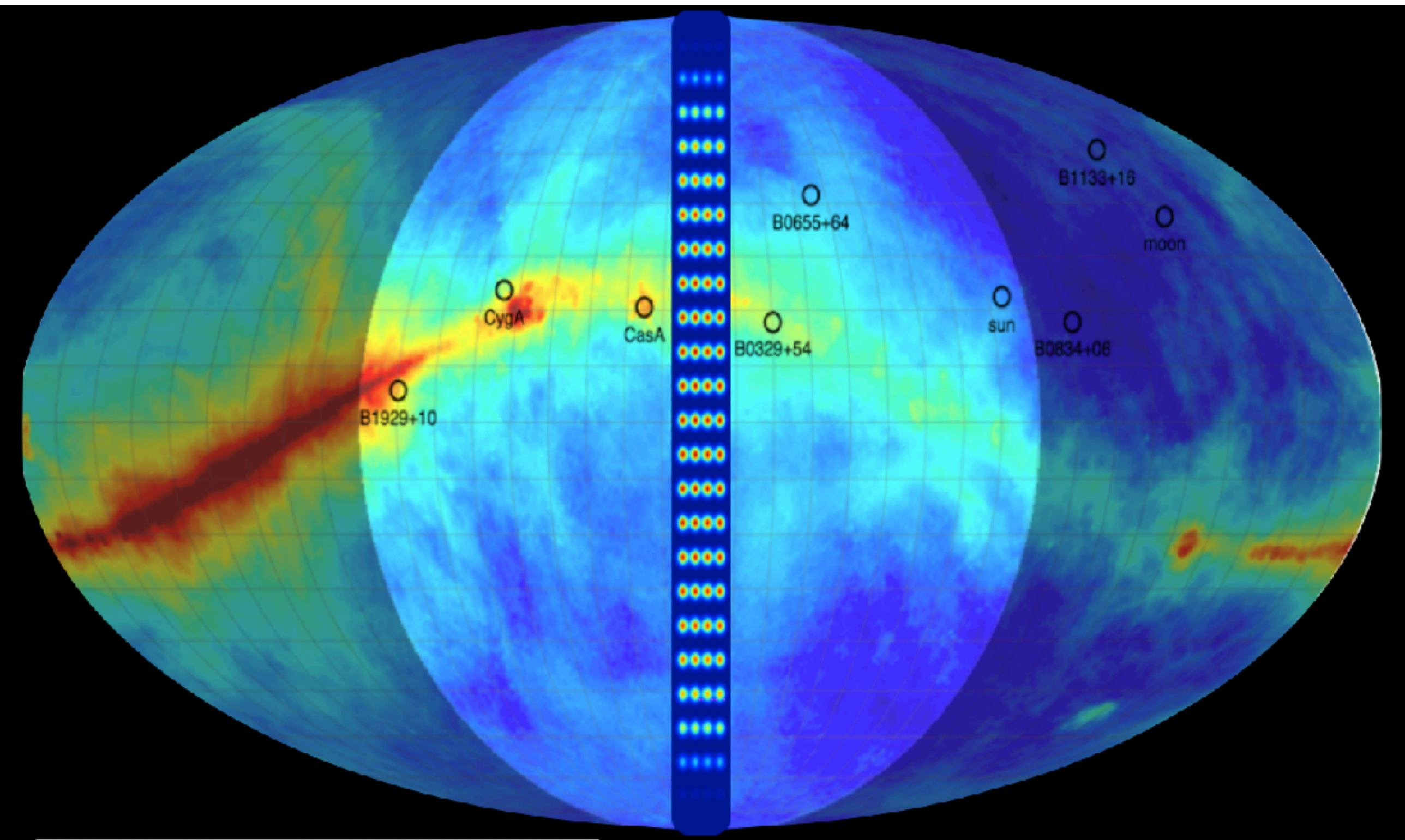


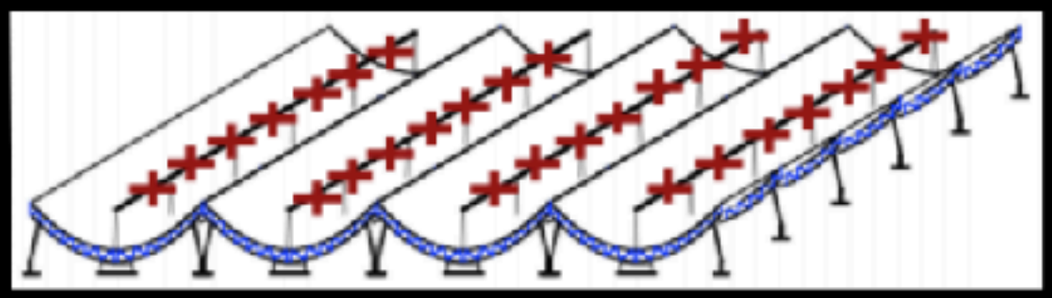
slide: Liam Connor

B1133+16
B0655+64
moon
CygA
CasA
sun
B0329+54
B0834+06
B1929+10



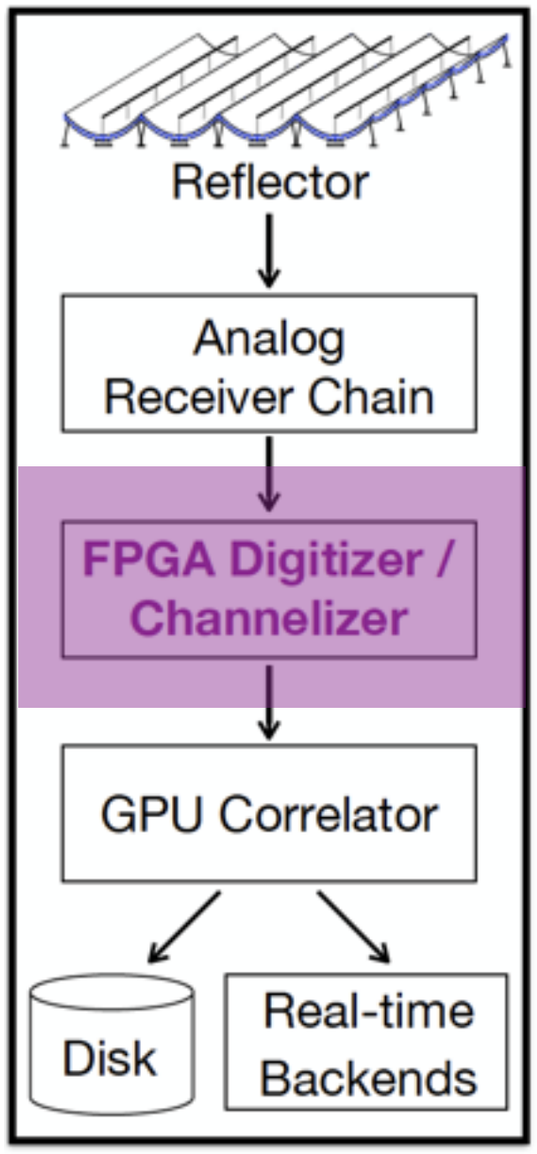
slide: Liam Connor

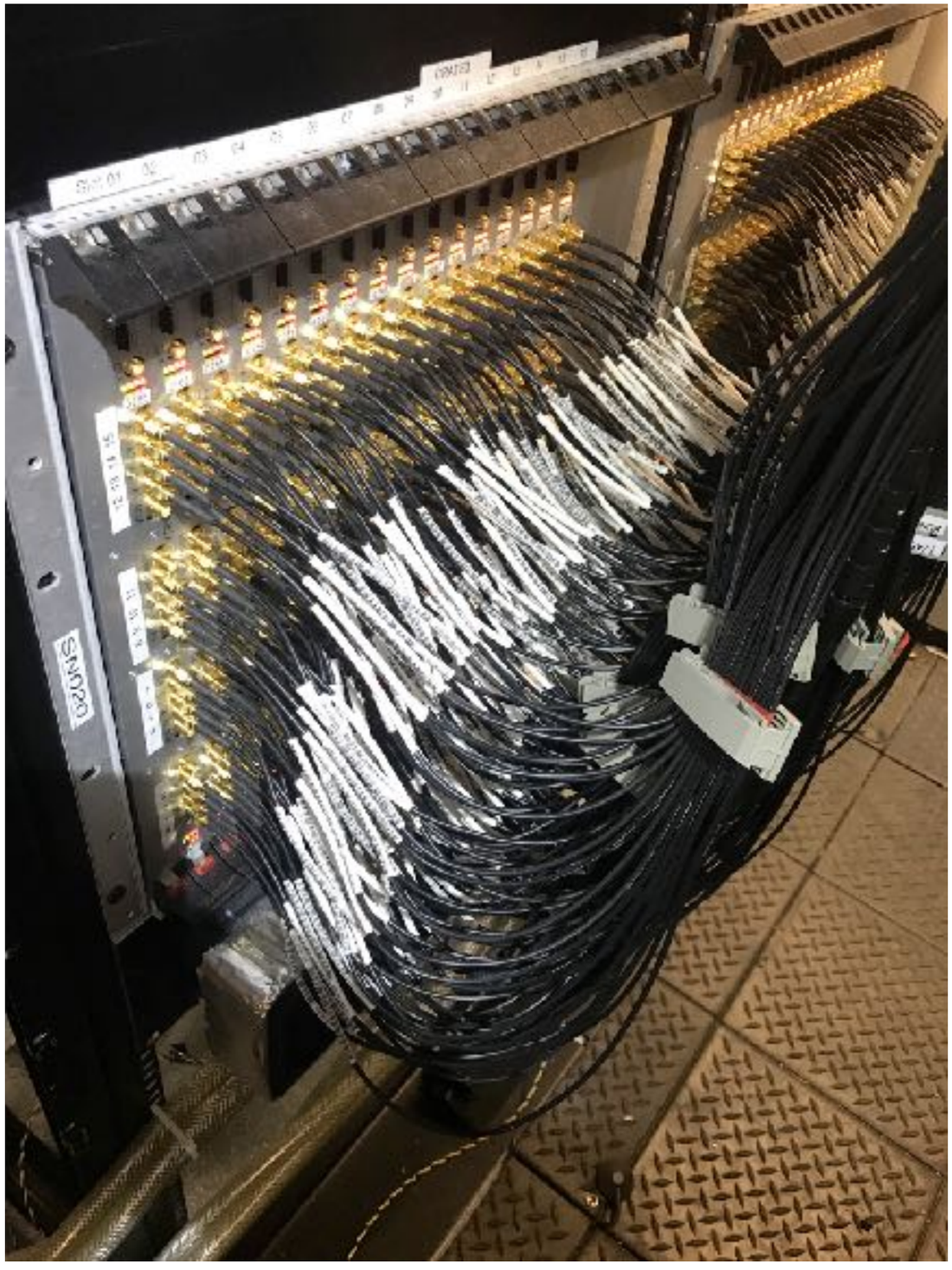




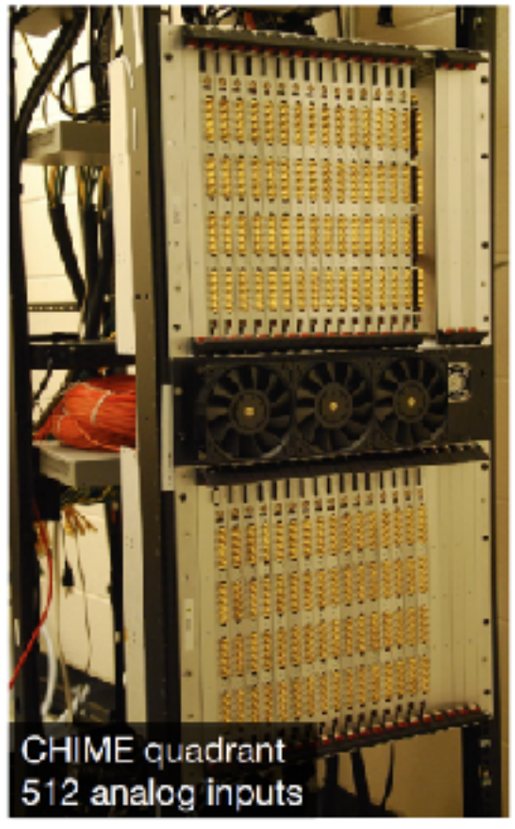
slide: Liam Connor

F in FX

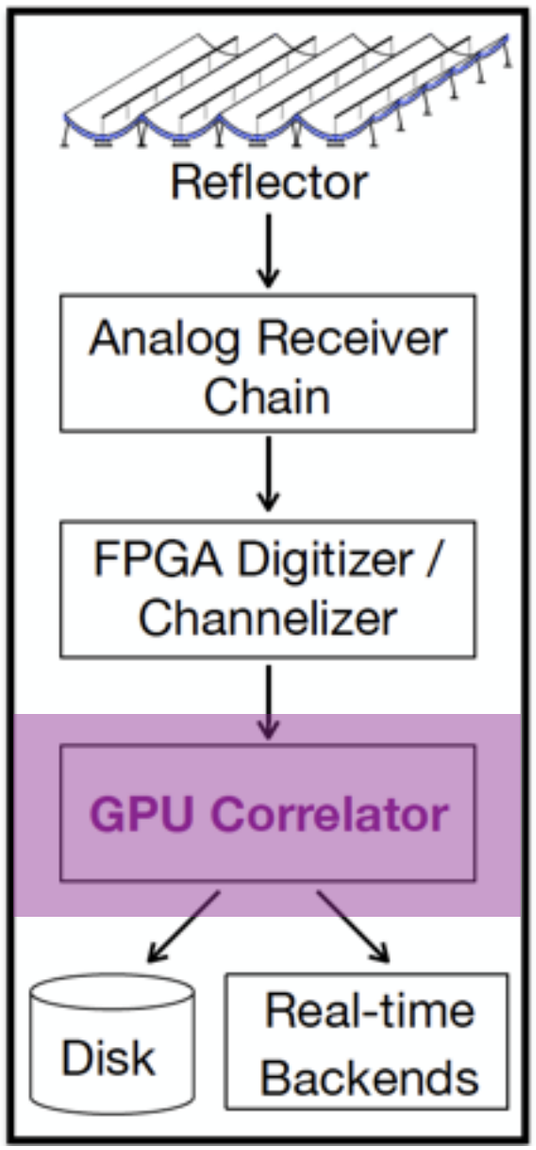


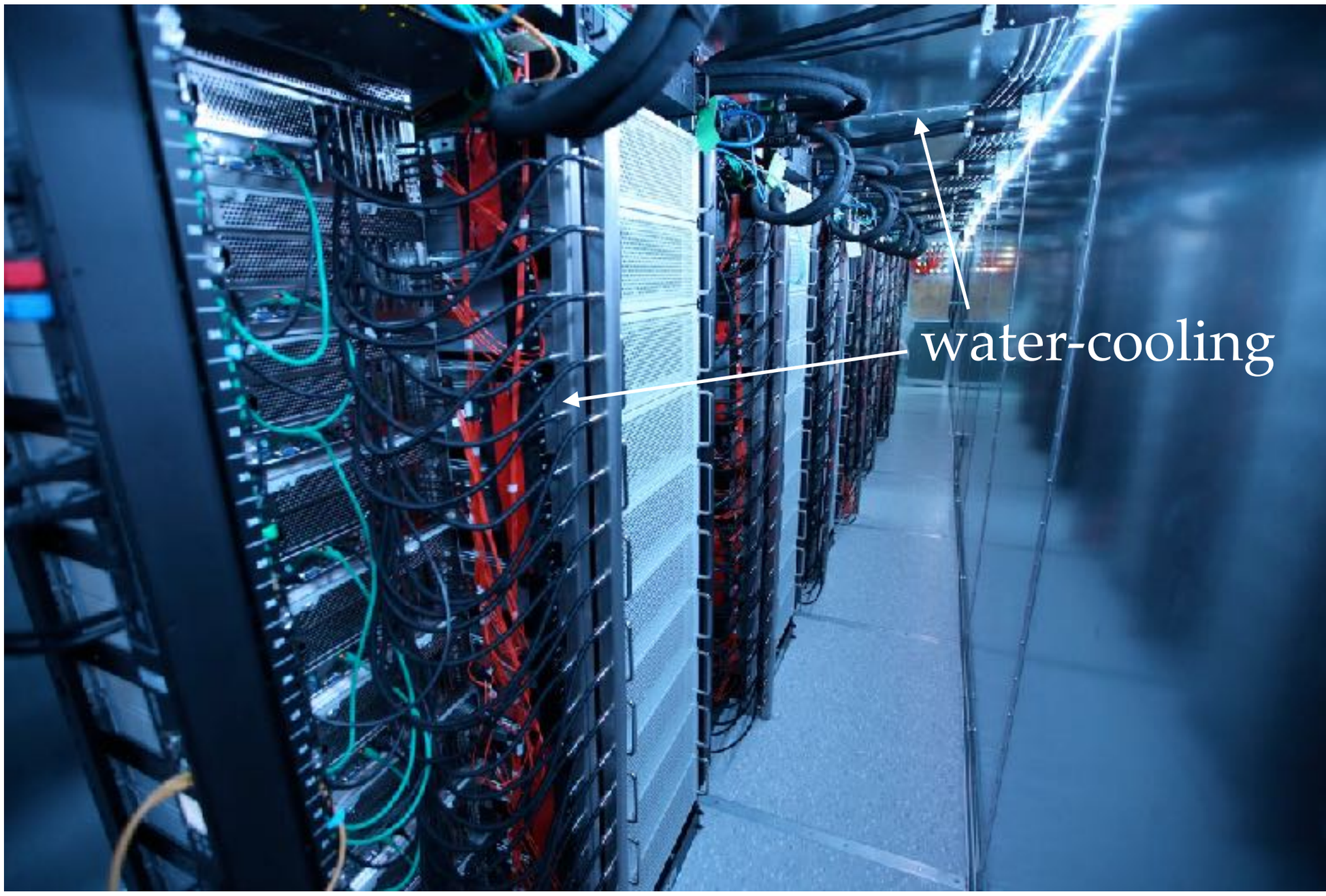


Digitizes and channelizes: each channel does a small FFT and produces 1024 frequencies per spatial input



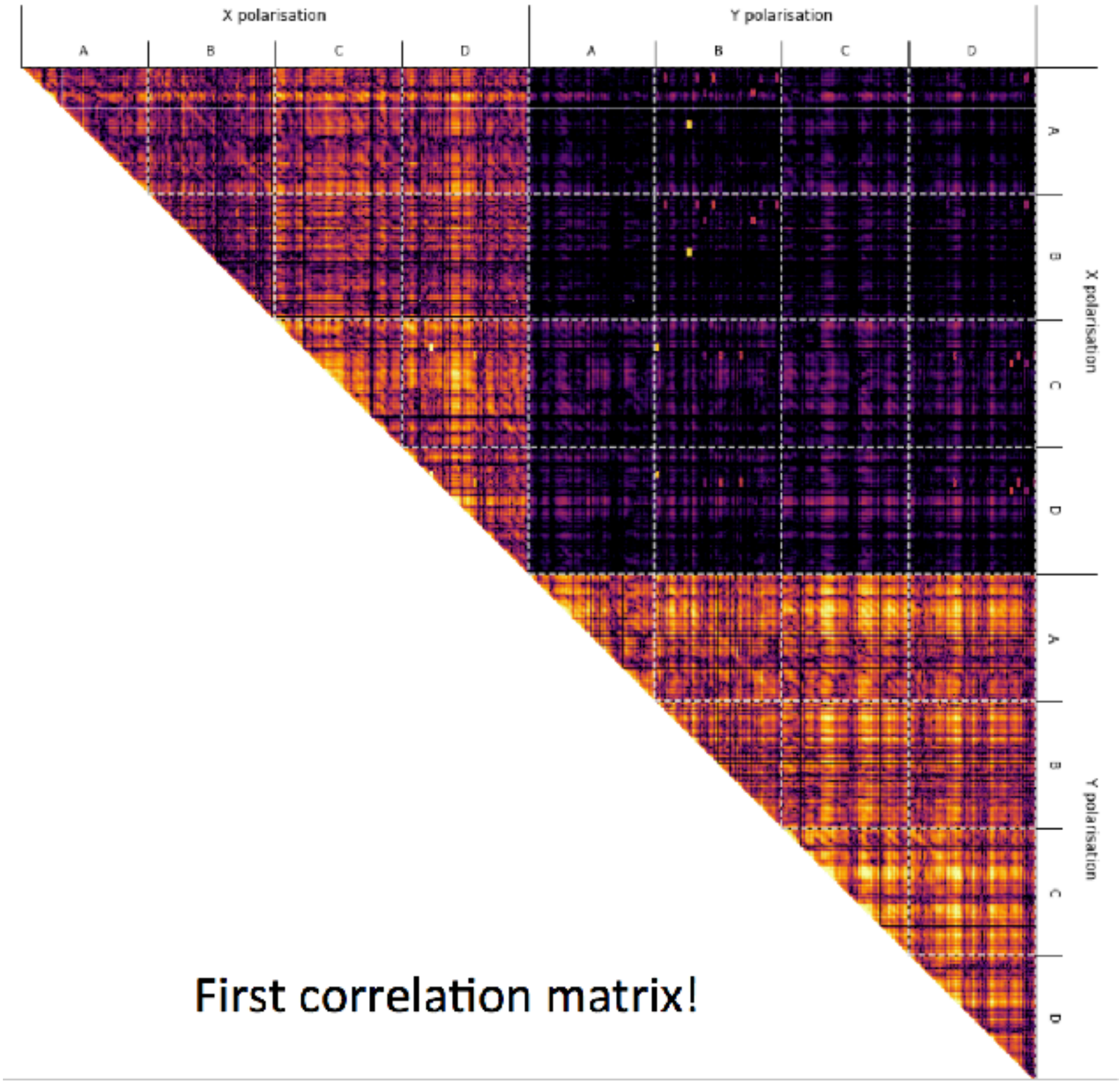
X in FX


Reflector
Analog Receiver Chain
FPGA Digitizer / Channelizer
GPU Correlator
Disk
Real-time Backends

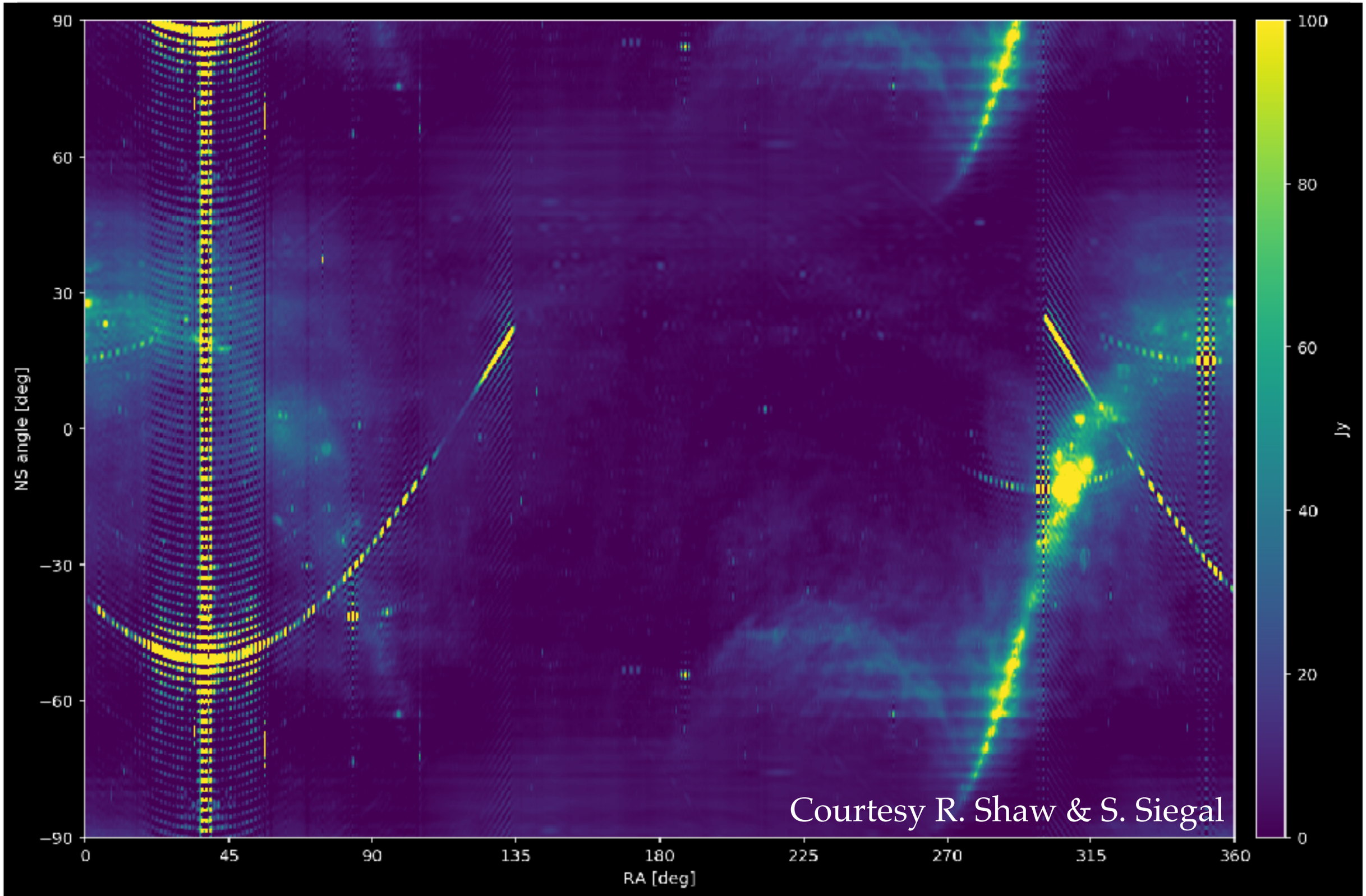

water-cooling

CHIME - it lives!

2048 x 2048:
We make
1024 of these
(1 per
frequency)
every 10s



CHIME - it lives!



If you're going to try cross-country skiing,

start with a small country

- (Anonymous)

CHIME Pathfinder

- Pathfinder is a test-bed
  - 2 shorter cylinders (20m x 40m)
  - 128 dual-pol feeds
  - See Bandura et al 2014 (arXiv 1406.2288) for more instrument details
  - Fielded and taking data!

LIMITS ON THE ULTRA-BRIGHT FAST RADIO BURST POPULATION FROM THE CHIME PATHFINDER

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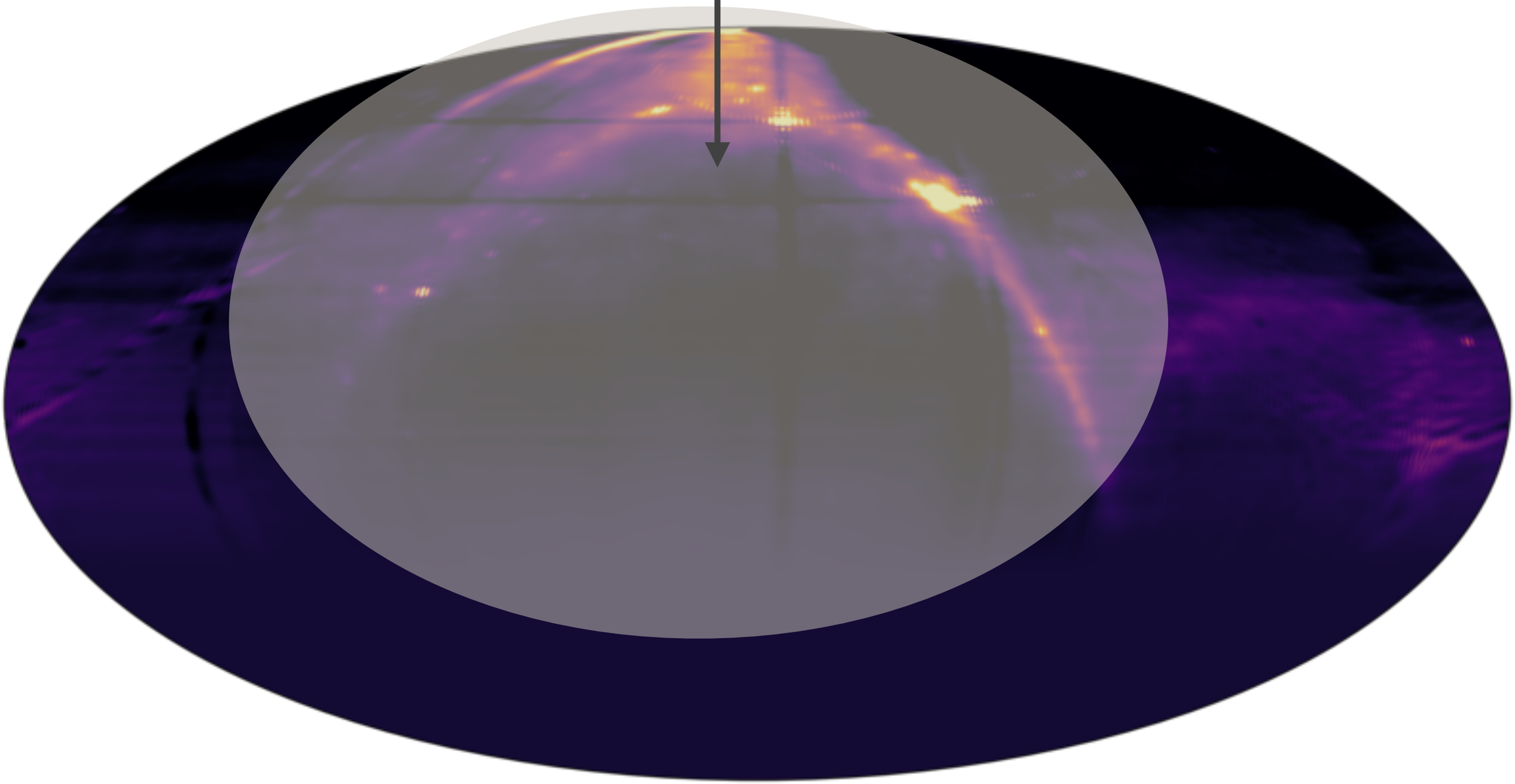
ABSTRACT

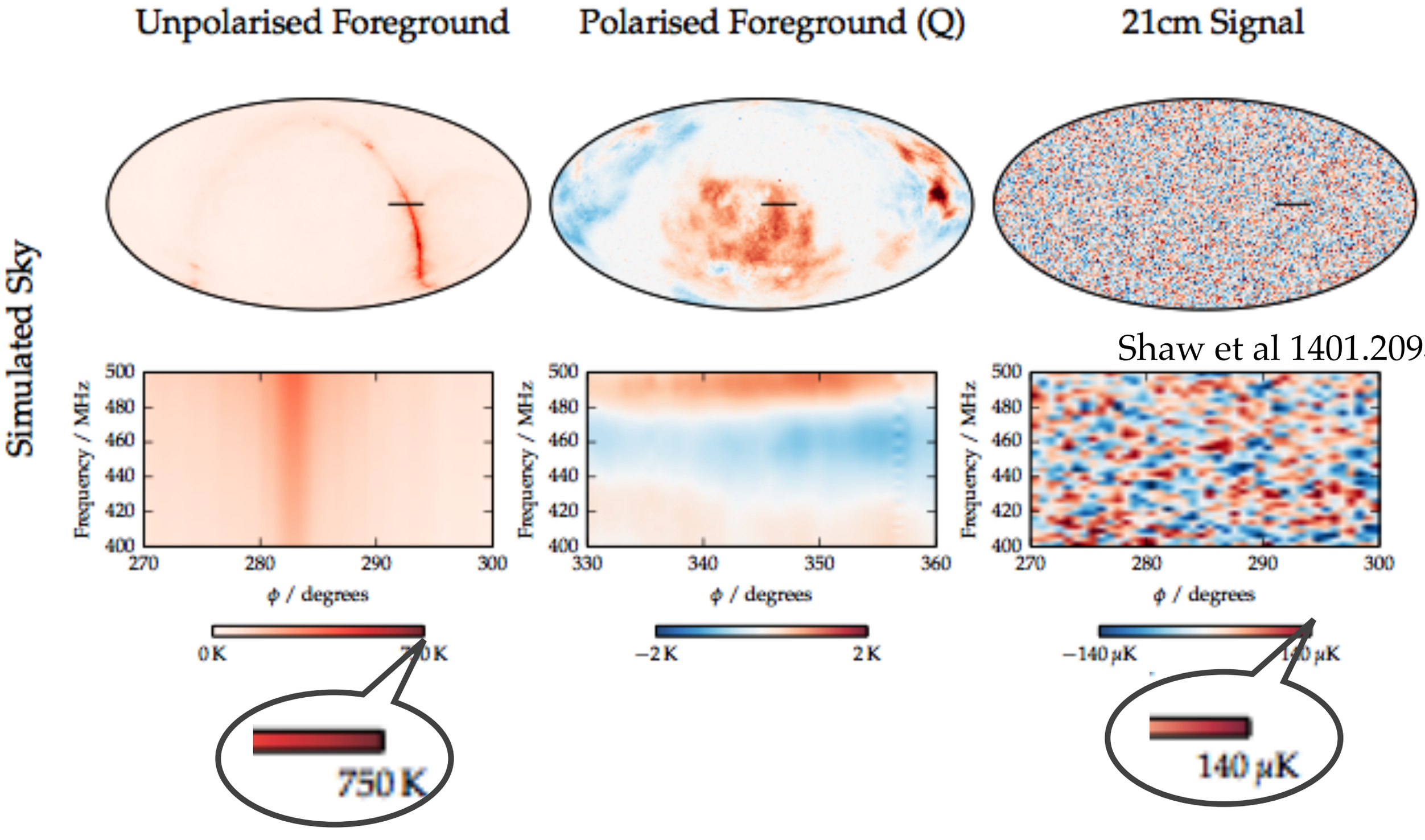
We present results from a new incoherent-beam Fast Radio Burst (FRB) search on the Canadian Hydrogen Intensity Mapping Experiment (CHIME) Pathfinder. Its large instantaneous field of view (FoV) and relative thermal insensitivity allow us to probe the ultra-bright tail of the FRB distribution, and to test a recent claim that this distribution's slope, $\alpha \equiv -\frac{\partial \log N}{\partial \log S_\nu}$, is quite small. A 256-input incoherent beamformer was deployed on the CHIME Pathfinder for this purpose. If the FRB distribution were described by a single power-law with $\alpha = 0.7$, we would expect an FRB detection every few days, making this the fastest survey on sky at present. We collected 1268 hours of data, amounting to one of the largest exposures of any FRB survey, with over $2.4 \times 10^5\,\mathrm{deg}^2\,\mathrm{hrs}$. Having seen no bursts, we have constrained the rate of extremely bright events to $< 13\,\mathrm{sky}^{-1}\,\mathrm{day}^{-1}$ above $\sim 220\sqrt{(\tau/\mathrm{ms})}$ Jy ms for τ between 1.3 and 100 ms, at 400–800 MHz. The non-detection also allows us to rule out $\alpha \lesssim 0.9$ with 95% confidence, after marginalizing over uncertainties in the GBT rate at 700–900 MHz, though we show that for a cosmological population and a large dynamic range in flux density, α is brightness-dependent. Since FRBs now extend to large enough distances that non-Euclidean effects are significant, there is still expected to be a dearth of faint events and relative excess of bright events. Nevertheless we have constrained the allowed number of ultra-intense FRBs. While this does not

The Galaxy



Credit: Richard Shaw

We have some ~~problems~~ challenges…



Shaw et al 1401.2095

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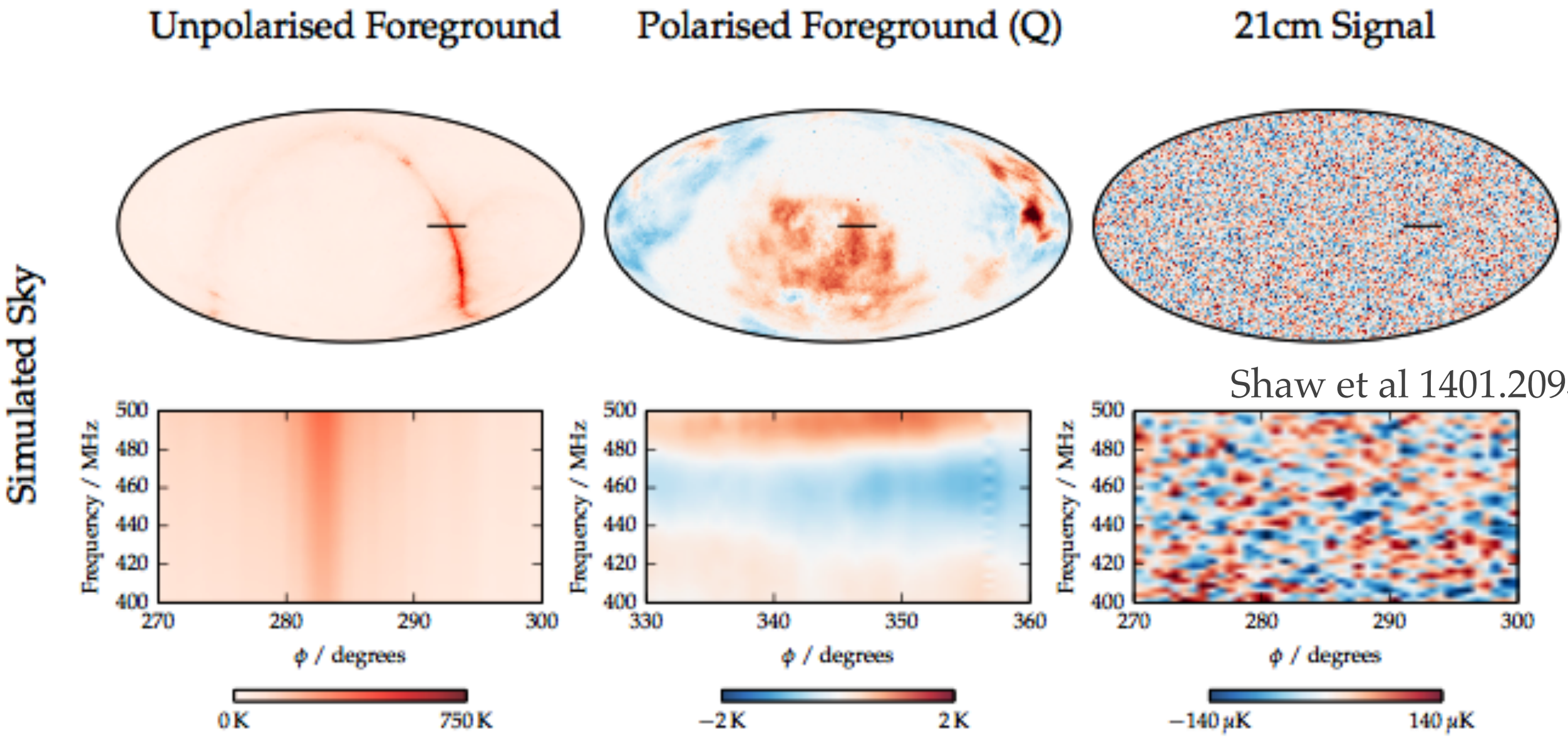
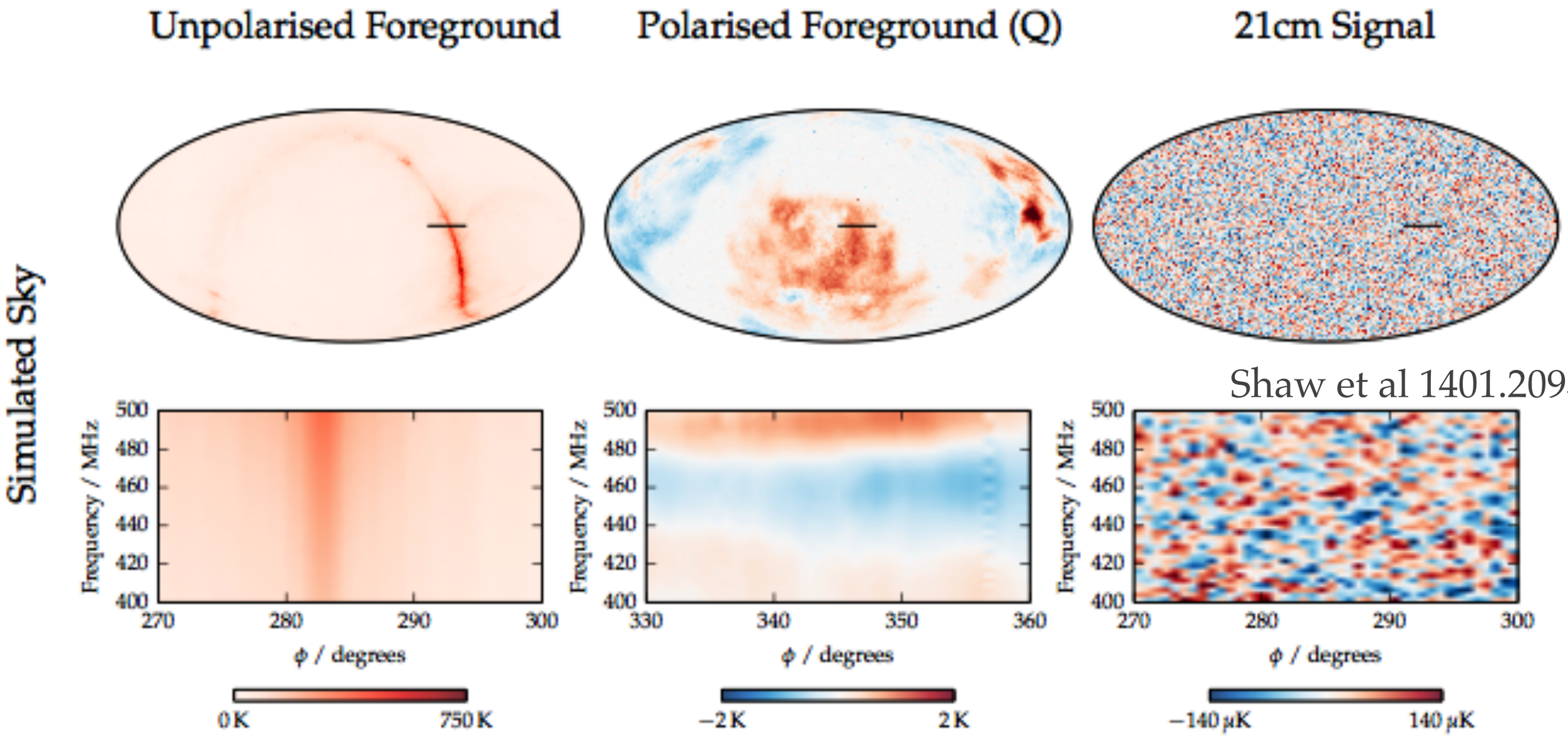


Shaw et al 1401.2095

Require: <1% gain error
<0.1% beam error
} LBN et al, 2014

We have some ~~problems~~ challenges…



Shaw et al 1401.2095

Require: <1% gain error

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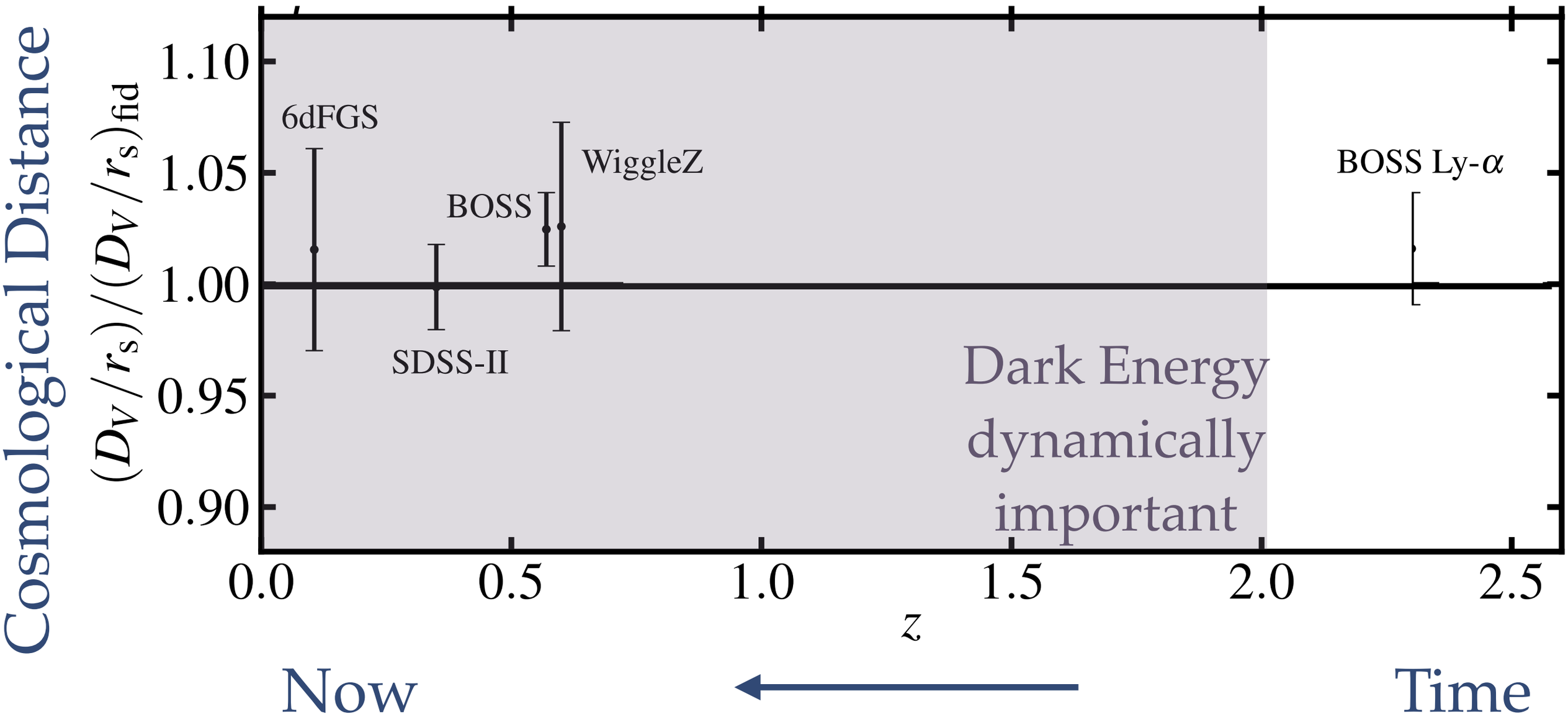
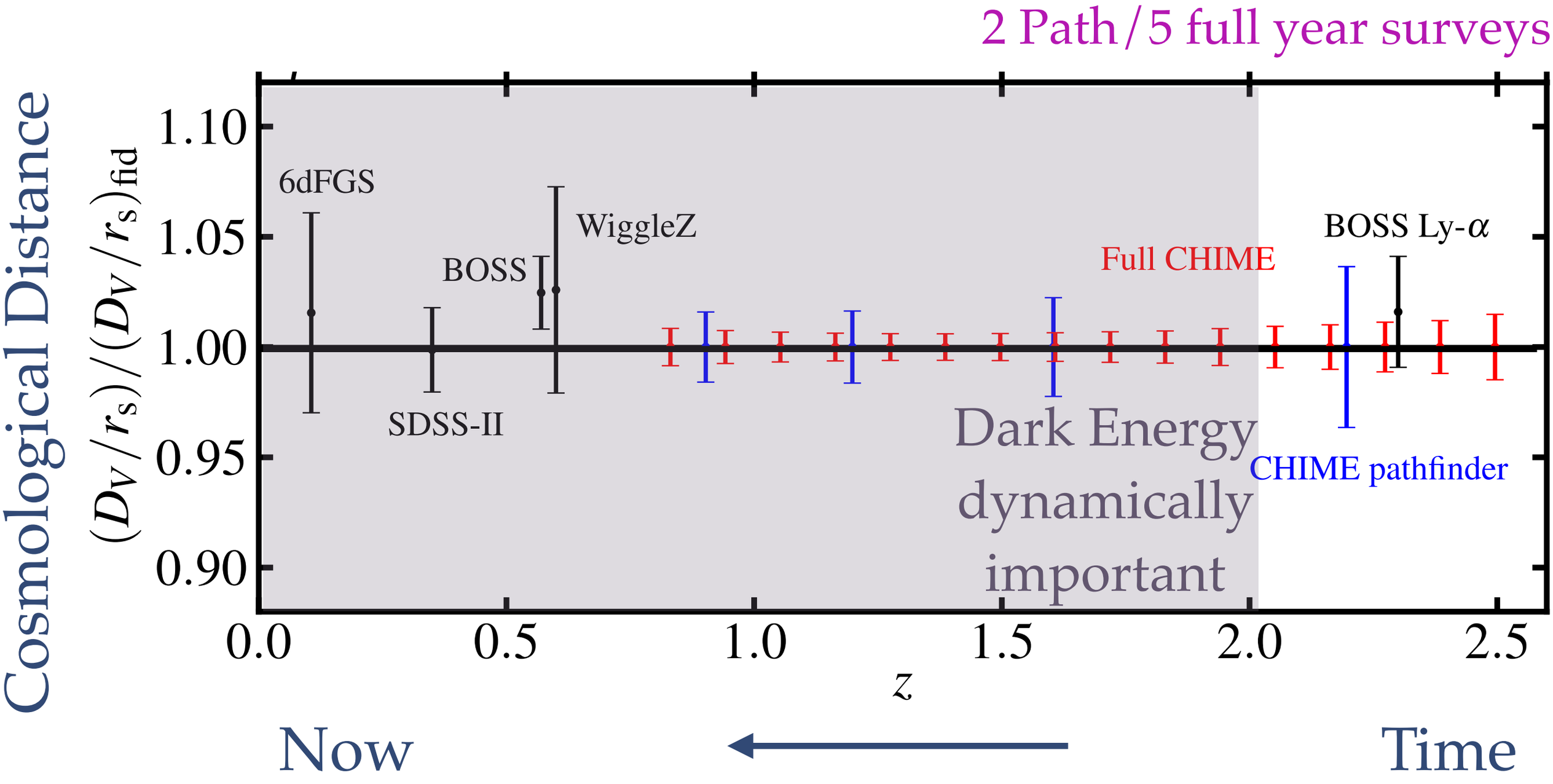
} LBN et al, 2014

Current state-of-the-art



Current state-of-the-art

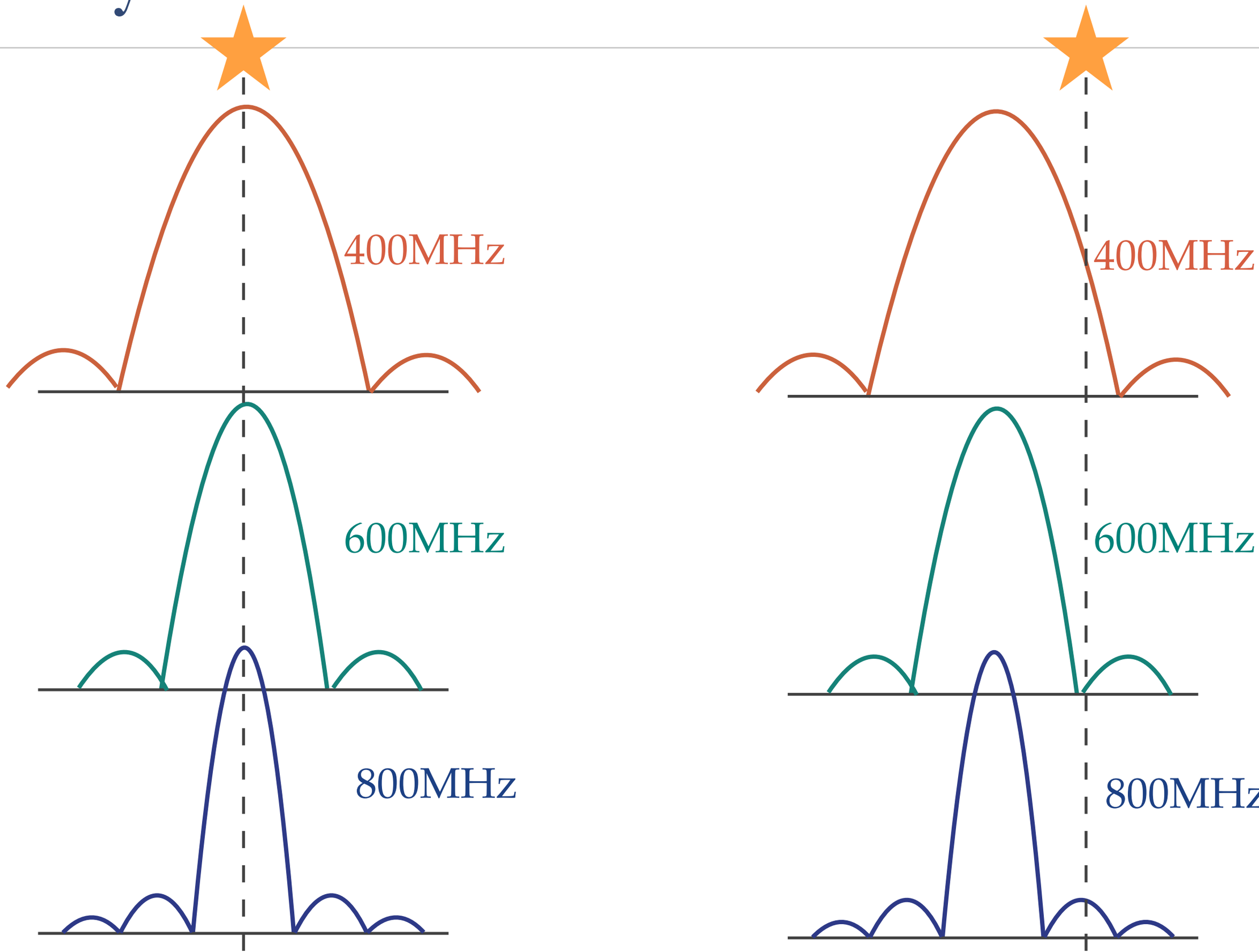


Summary

- Pathfinder has >2 years of ‘data in the can’
- CHIME is nearing the end of its commissioning, have ~1 month of stable data in the can
- Busy analyzing data!

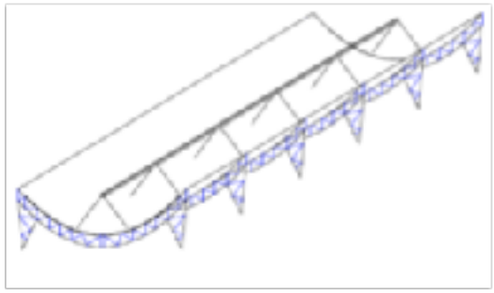
Backup

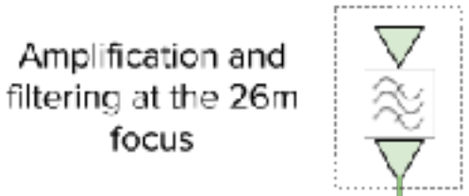
Why Do We Have to Know the Beams?



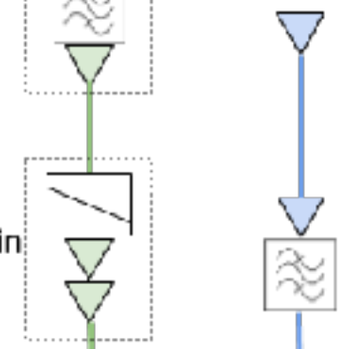
Beam map with Holography

Tracking dish





Amplification and filtering at the 26m focus

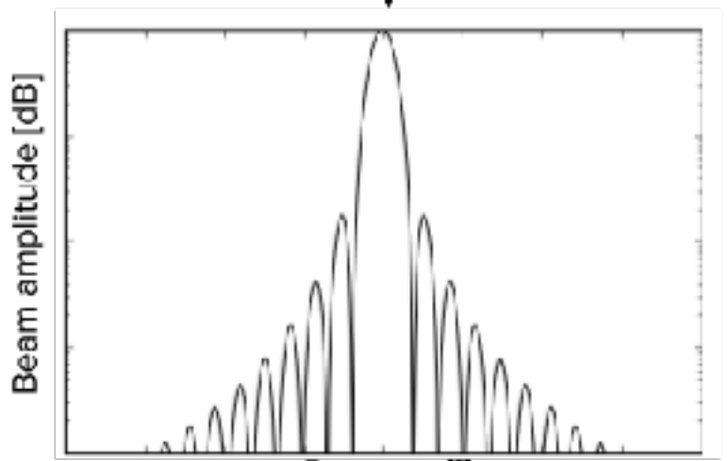


Amplification at the CHIME focus

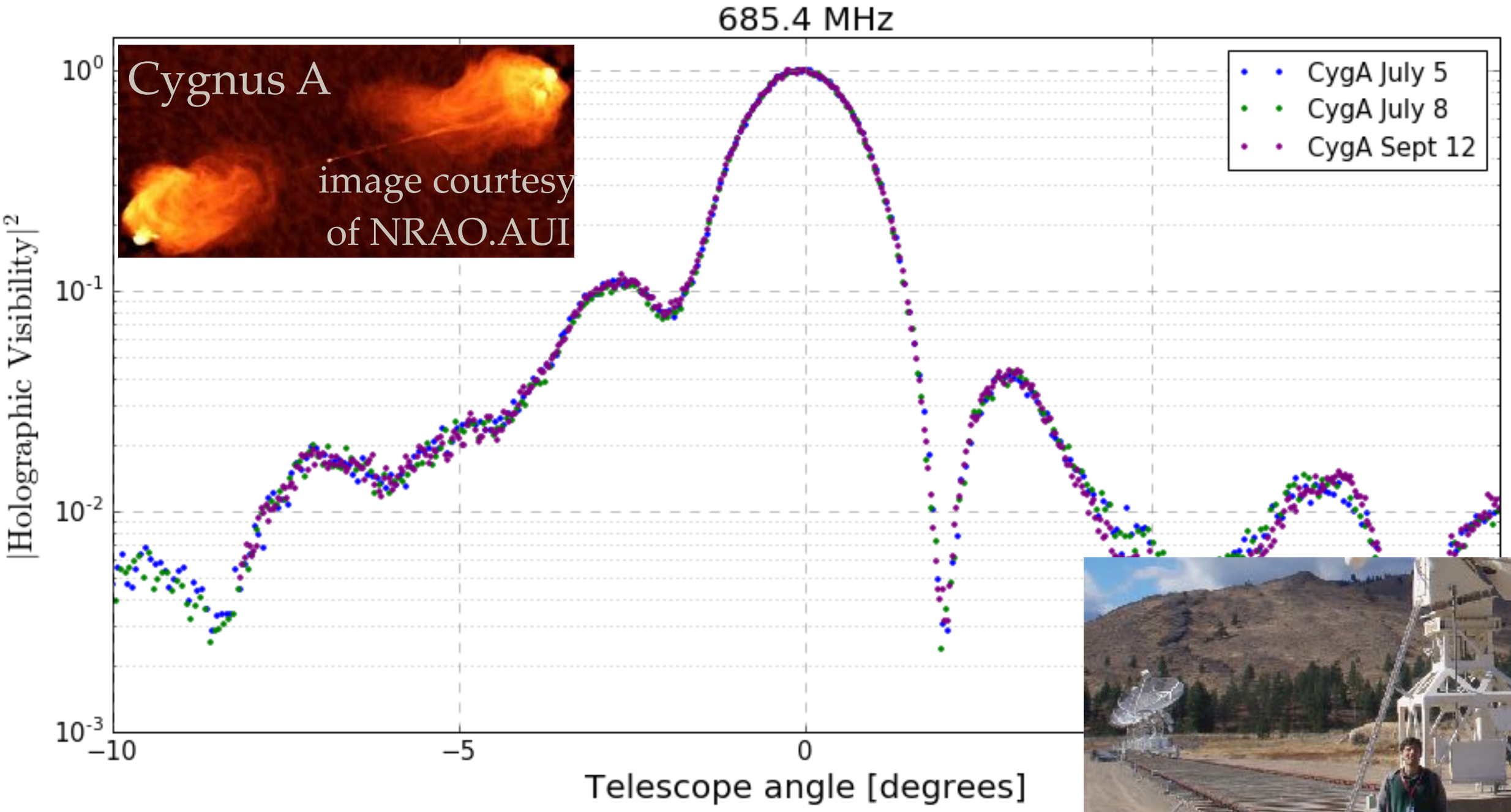
Amplification and signal equalization in the 26m control room

Amplification and filtering at CHIME

Digitization and correlation in the CHIME correlator

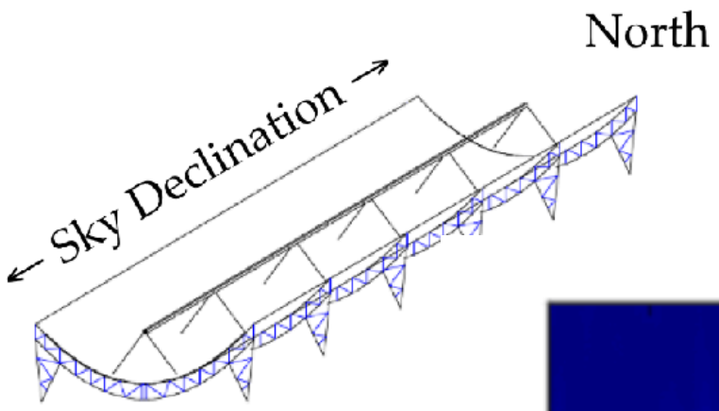


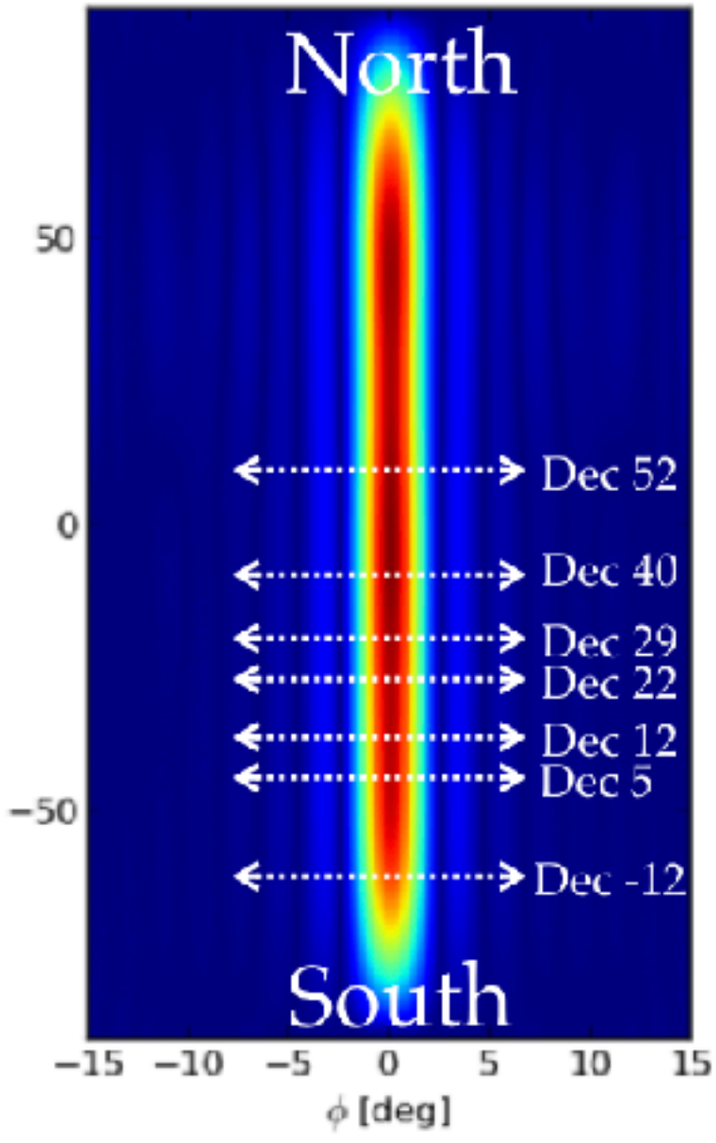
Holographic beam scans from CygA



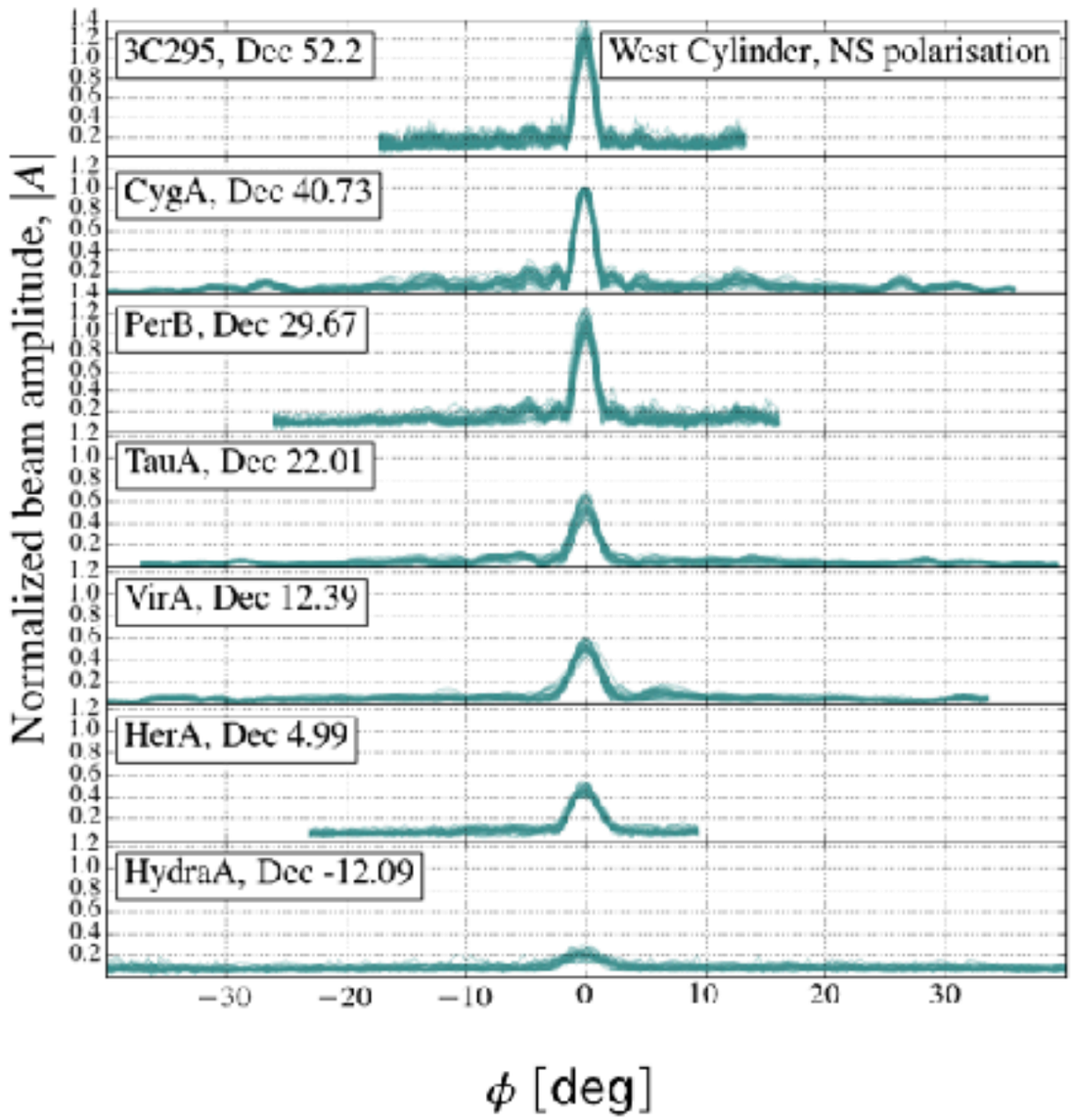
Analysis by grad student Phil Berger

Holographic beam scans from multiple sources

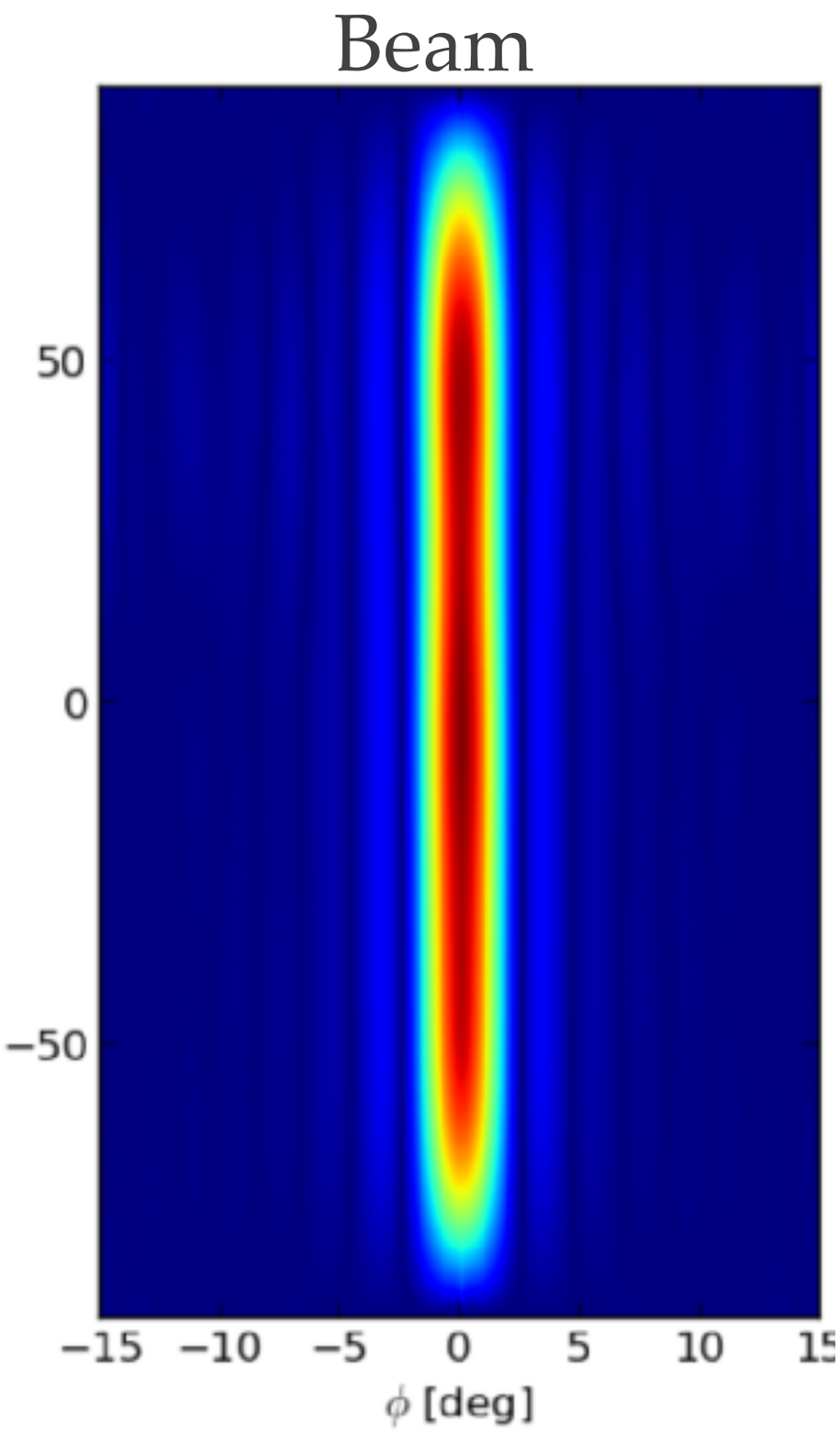


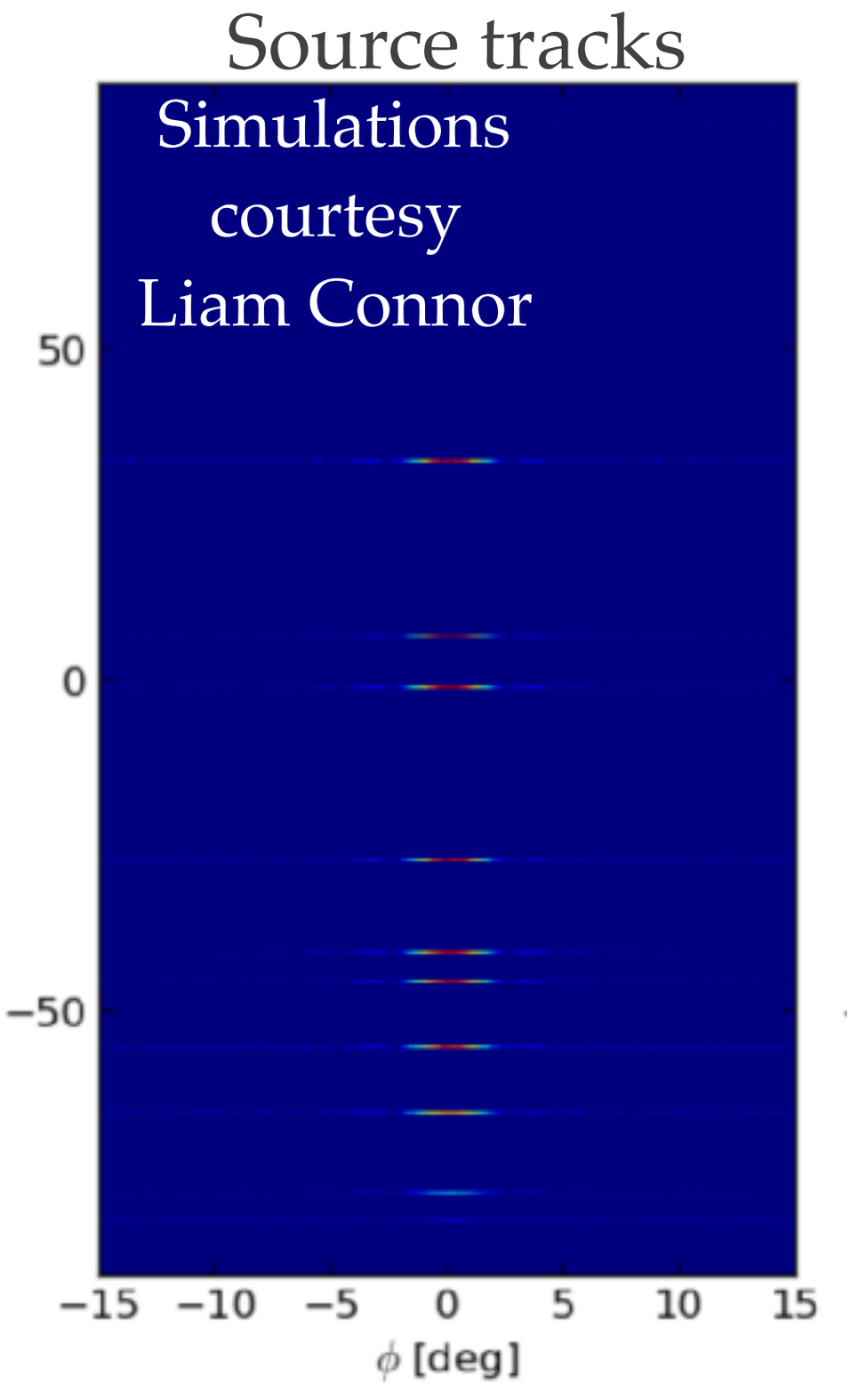


Berger et al 2016



Building up a beam map

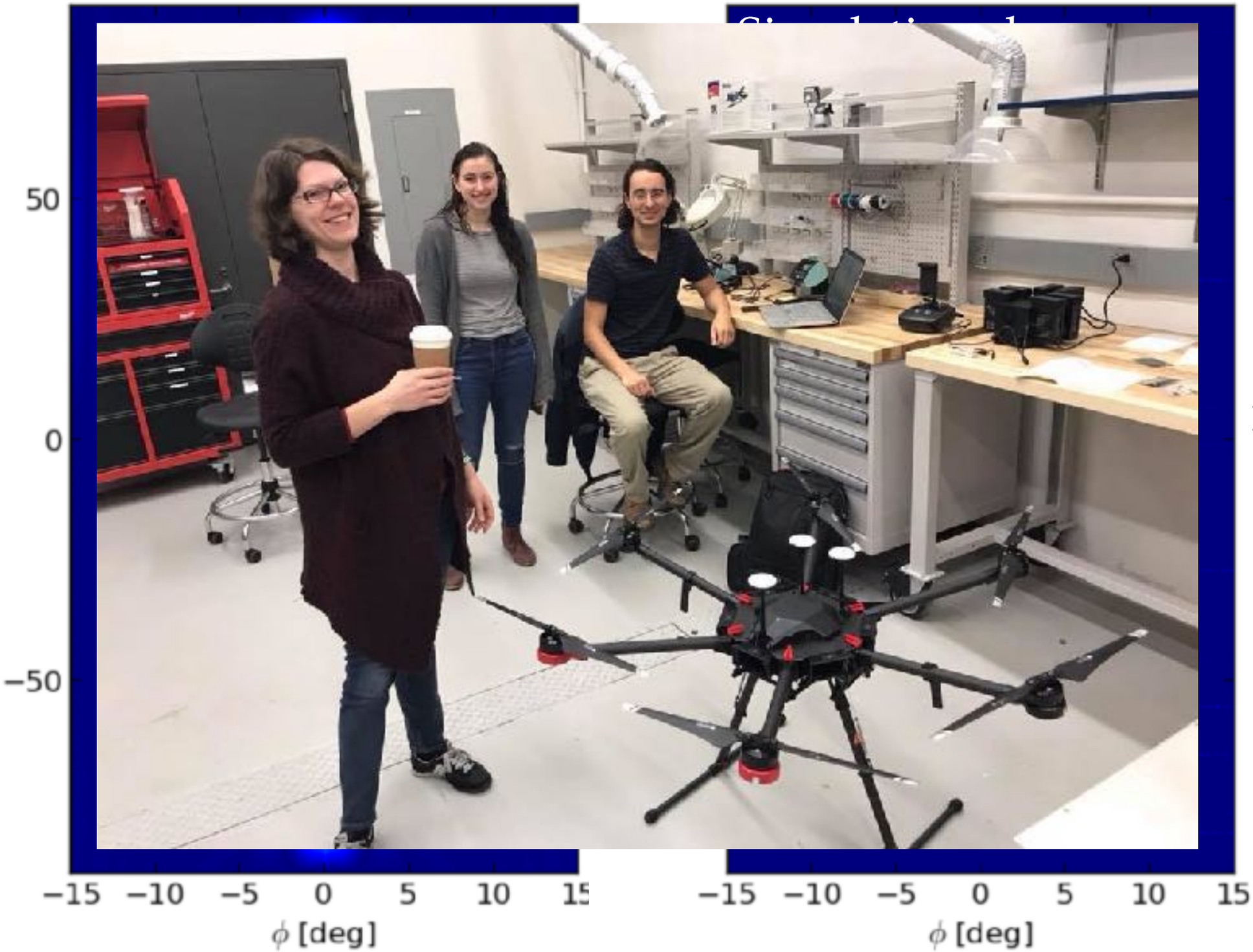




Building up a beam map

Beam

Pulsar tracks

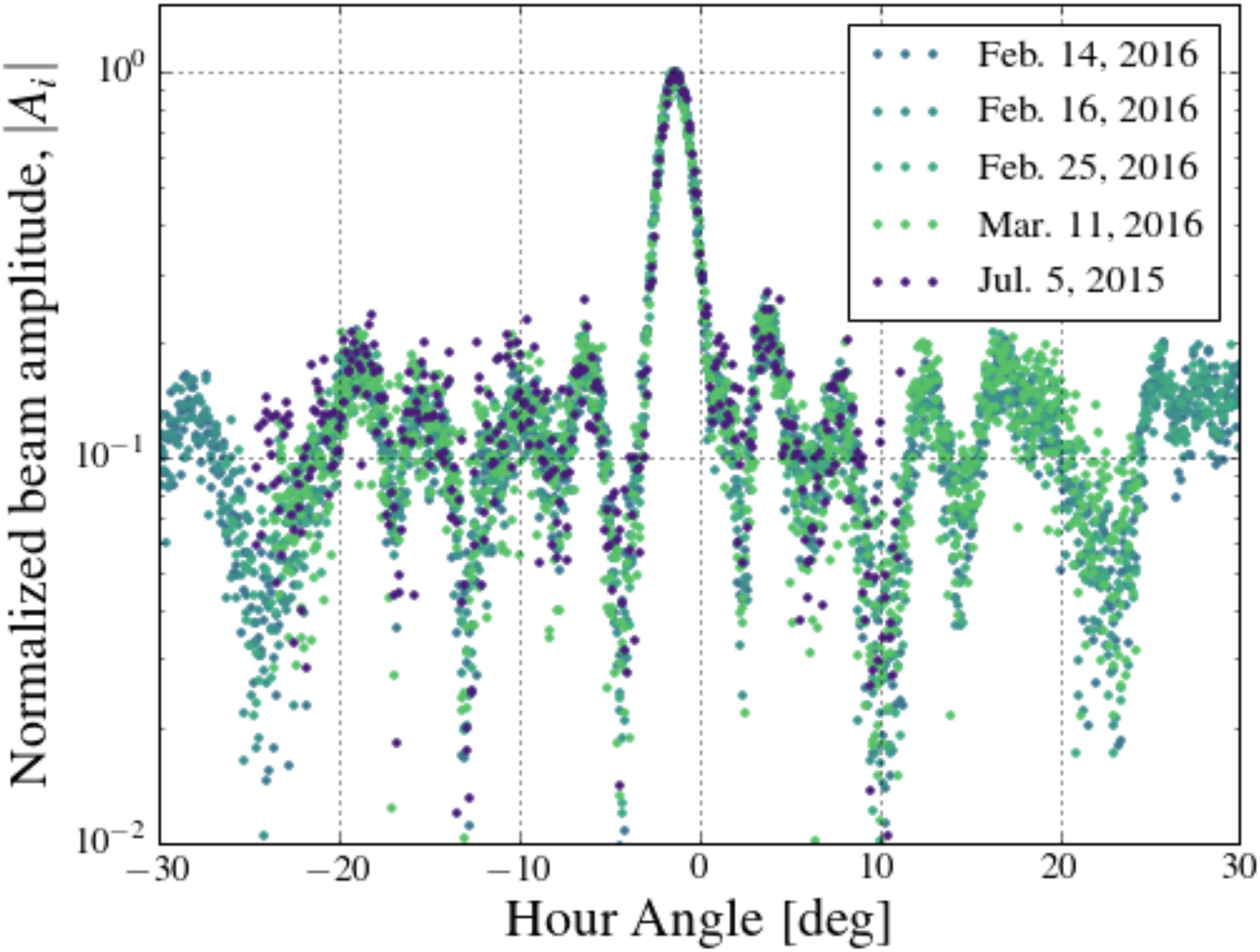


Actually mapping the NS beam …. Drones!

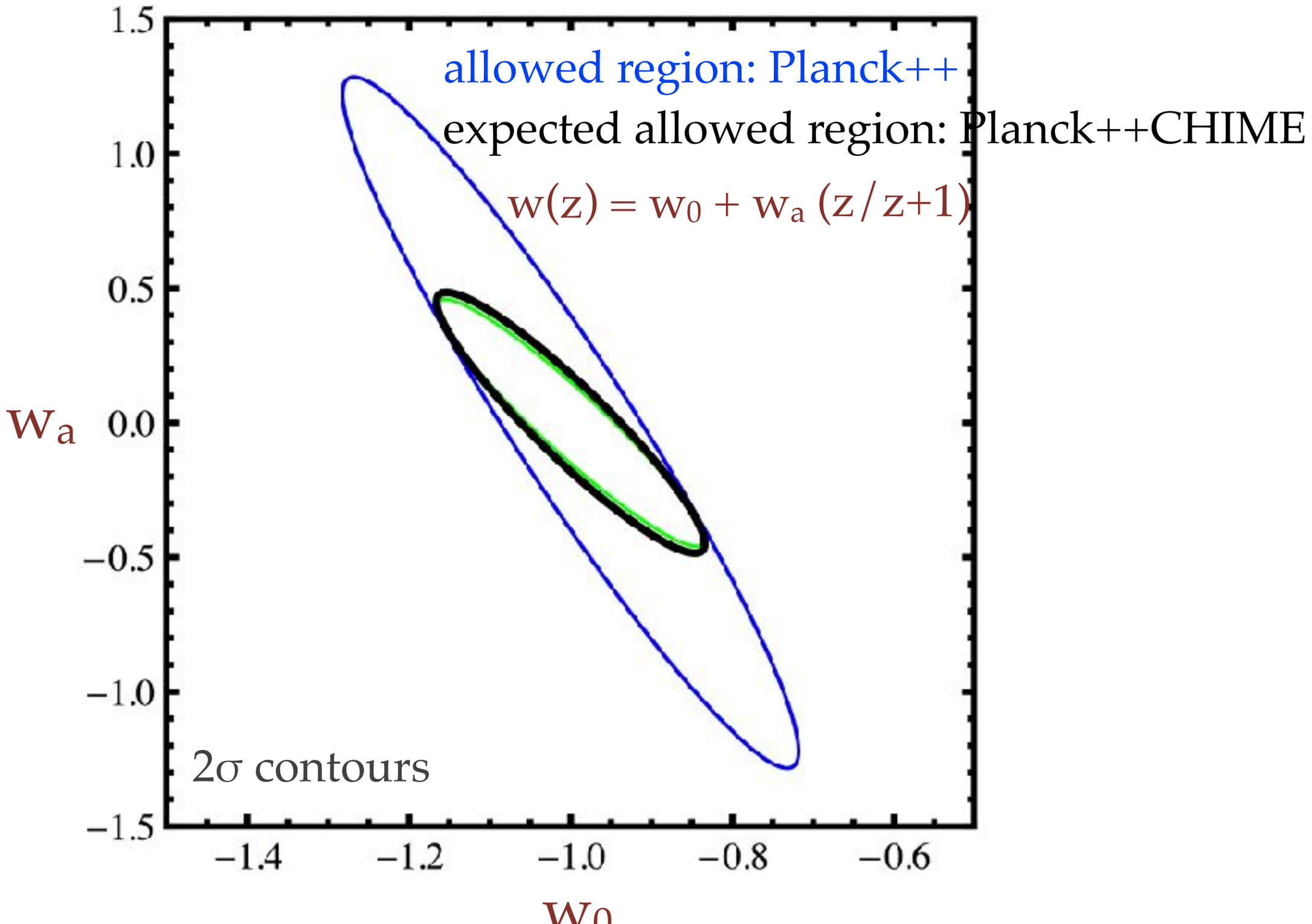
Some fun (non Cosmology) numbers

- >110km of coaxial cable
- 135TB/day (we compress via redundant baselines to a mere 0.5TB/day)
- 13Tb/s of data across correlator backplane (6Tb/s total global cellphone traffic in 2014)
- 6.7POps (6x ALMA)
- >100 cows

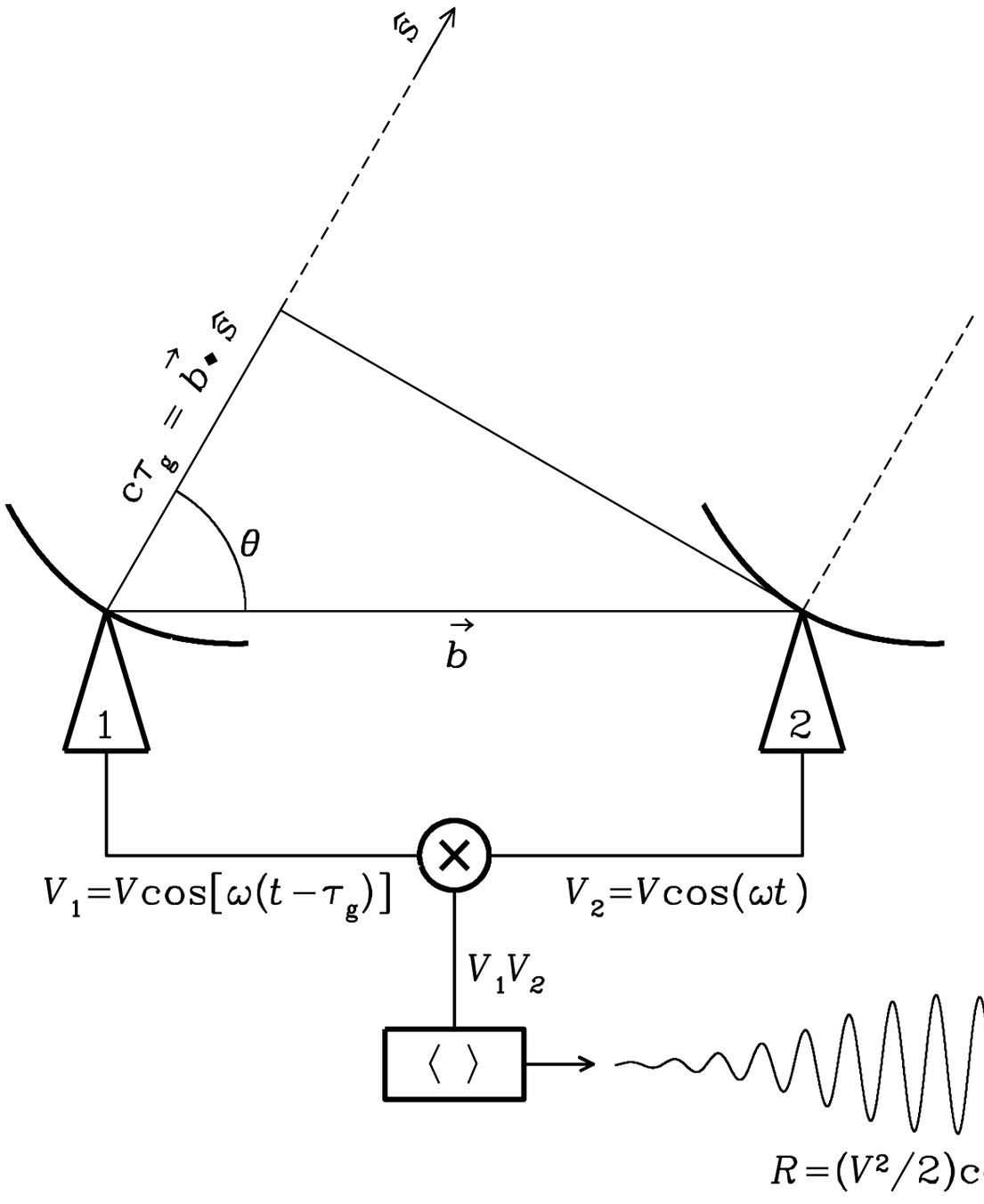
Current Beam Measurements

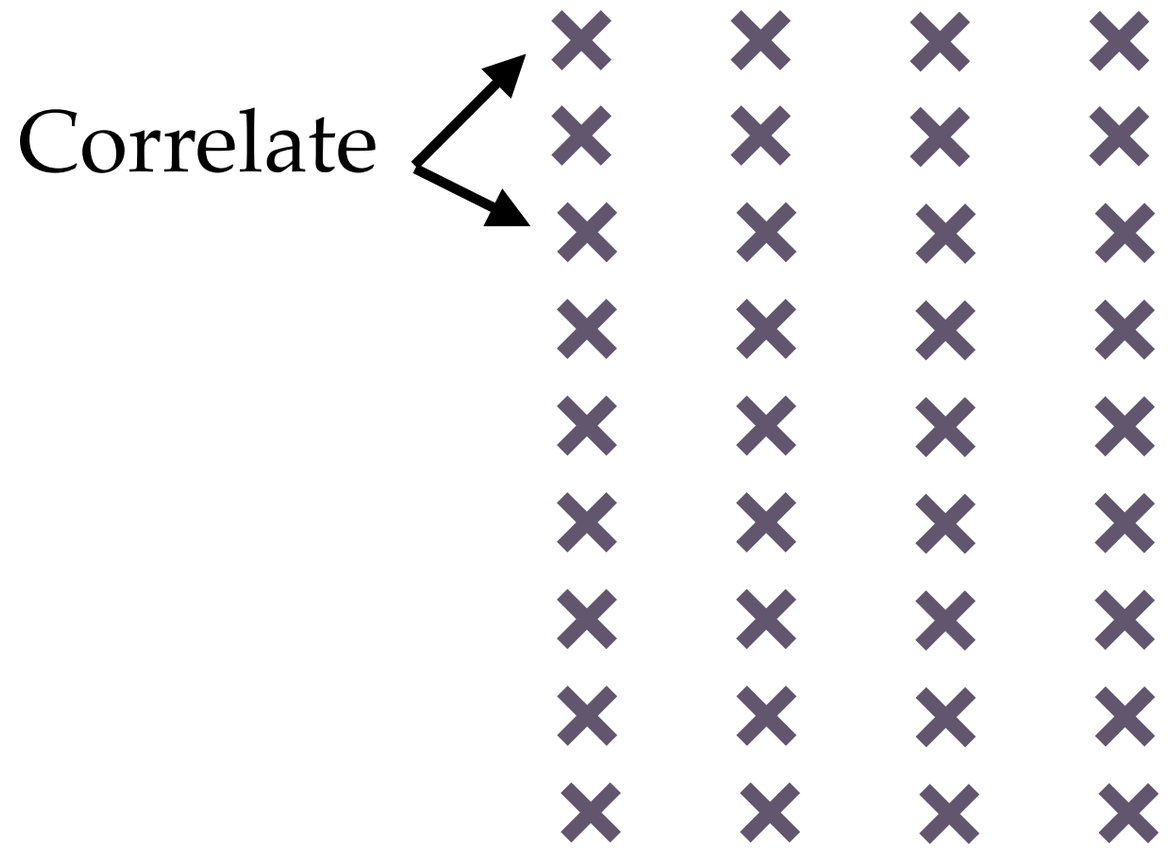


CHIME : A 21cm Stage 4 Dark EnergyExperiment



A Fast Fourier Transform Interferometer





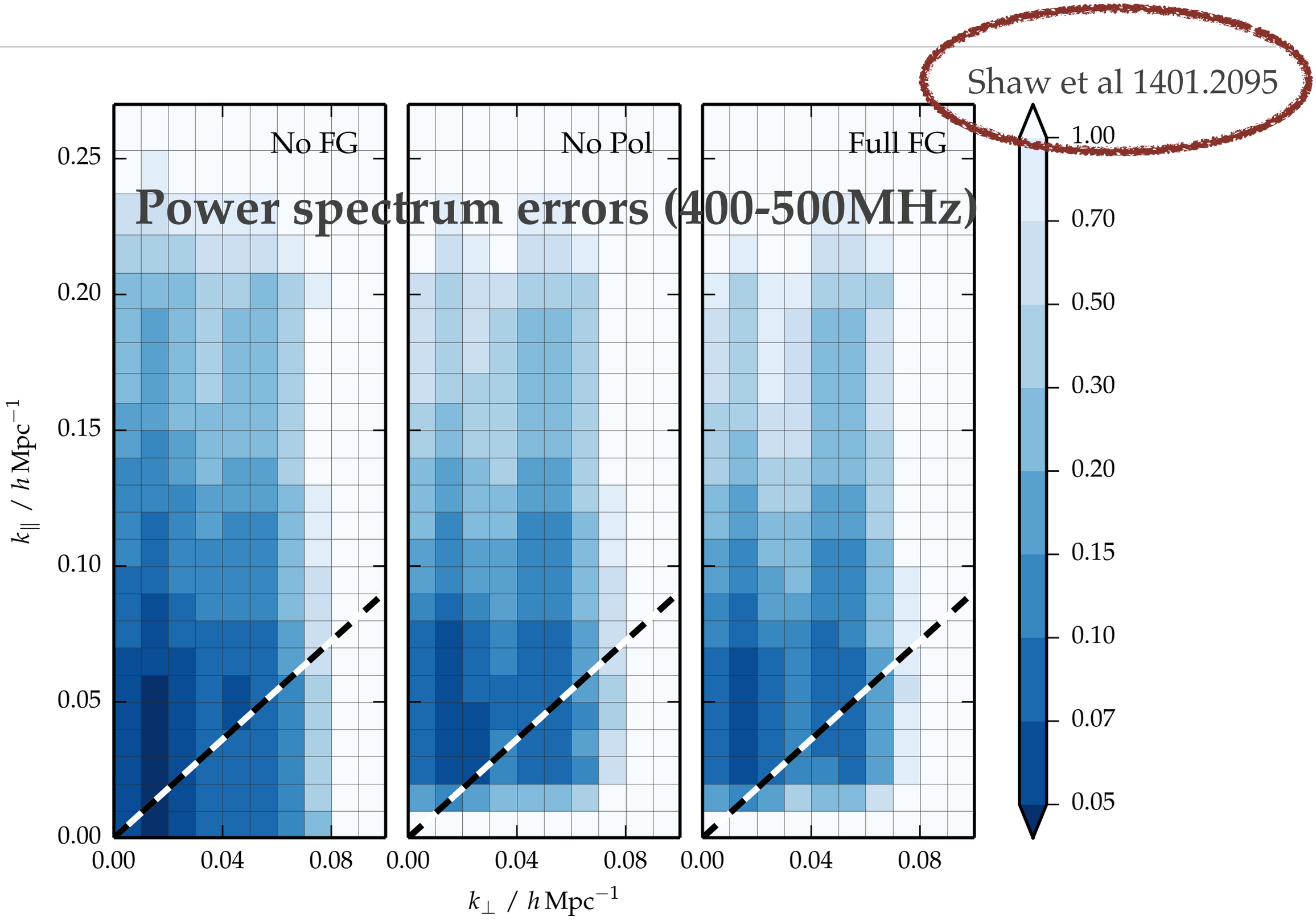
'FFT Telescope':

Regular correlation: ~ N^2

DFFT correlation: ~NlogN

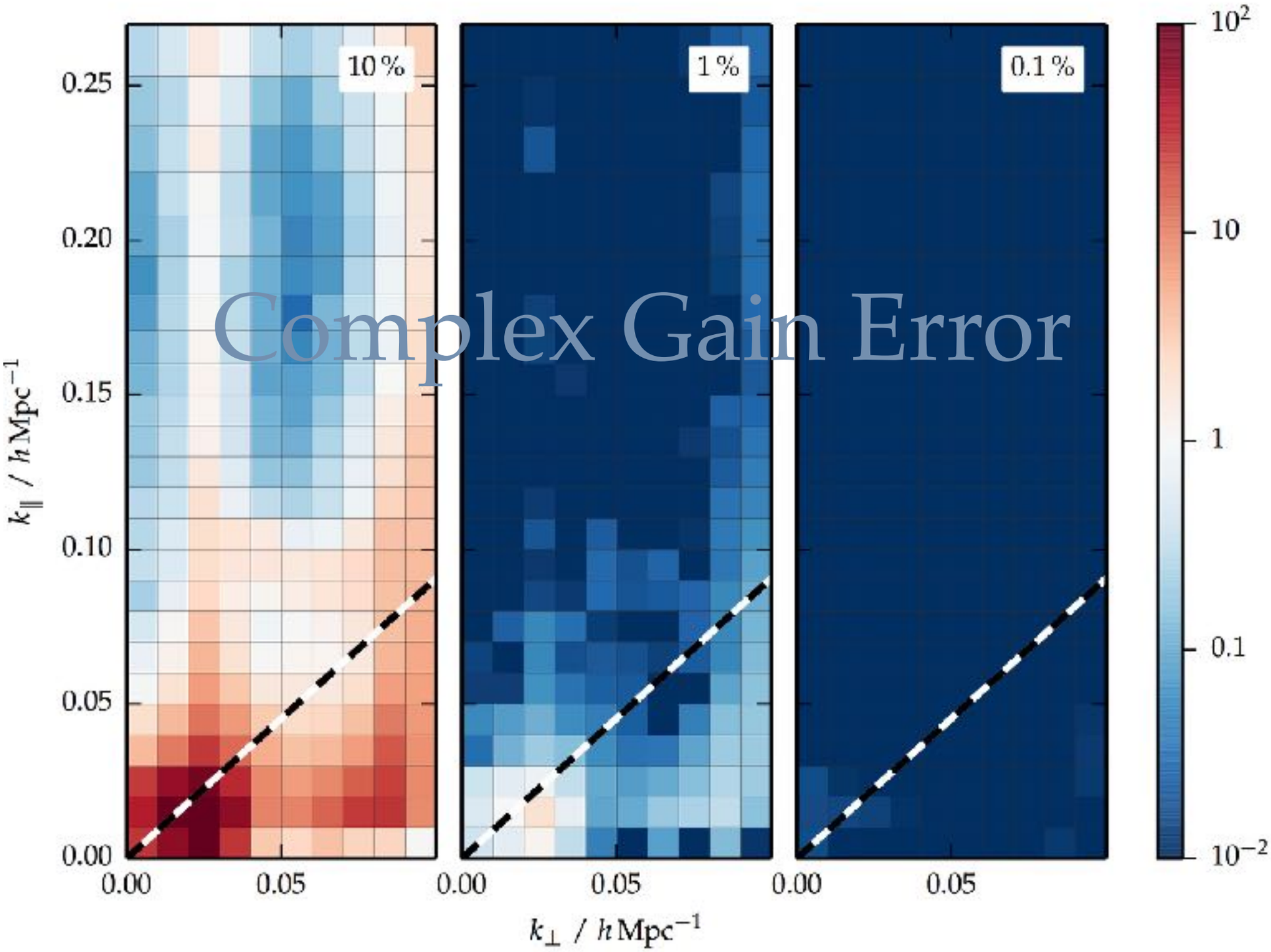
(Tegmark and Zalarriaga, 2008)

Can remove them!



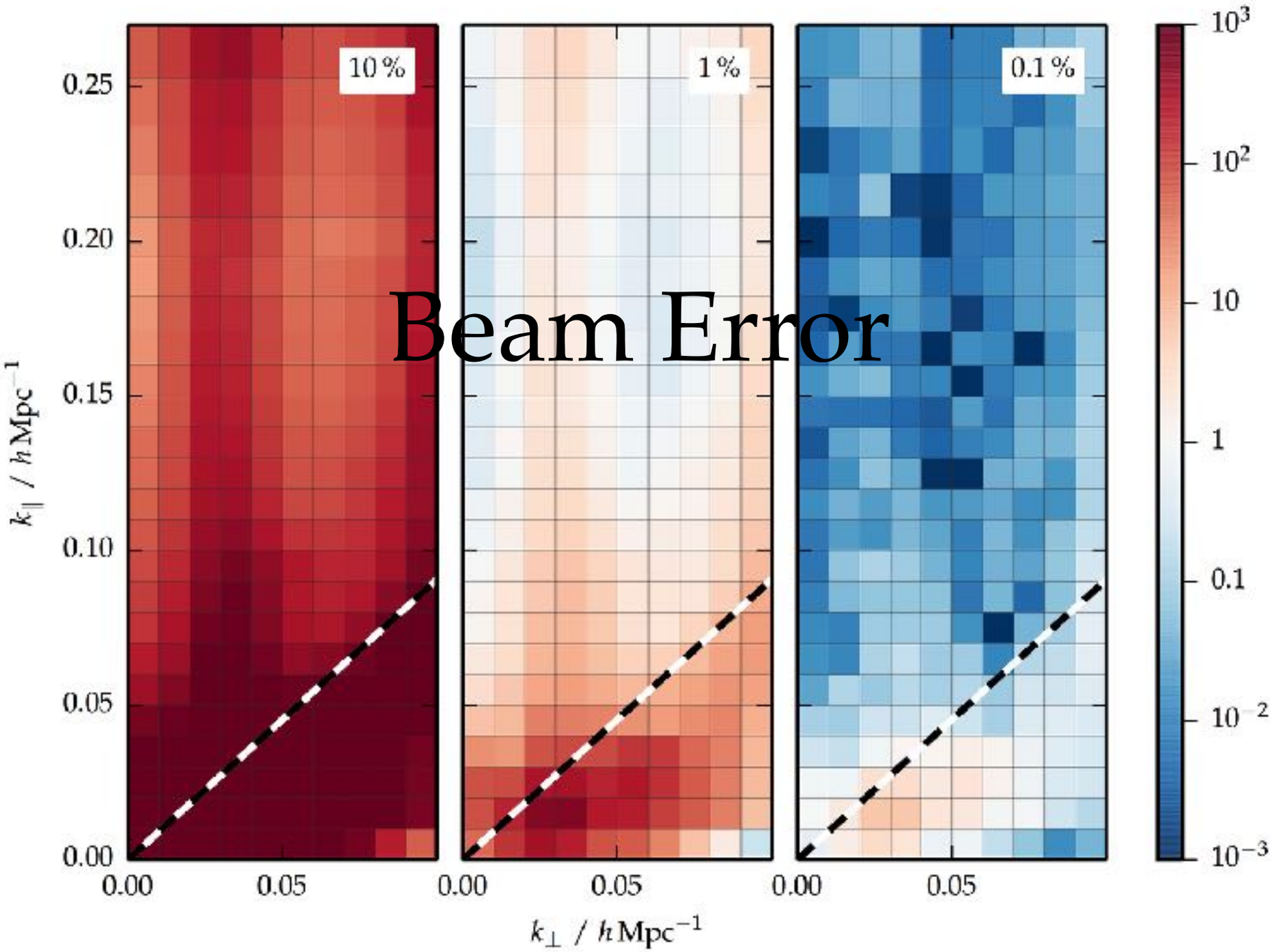
(As long as we know our instrument)

Shaw et al 1401.2095



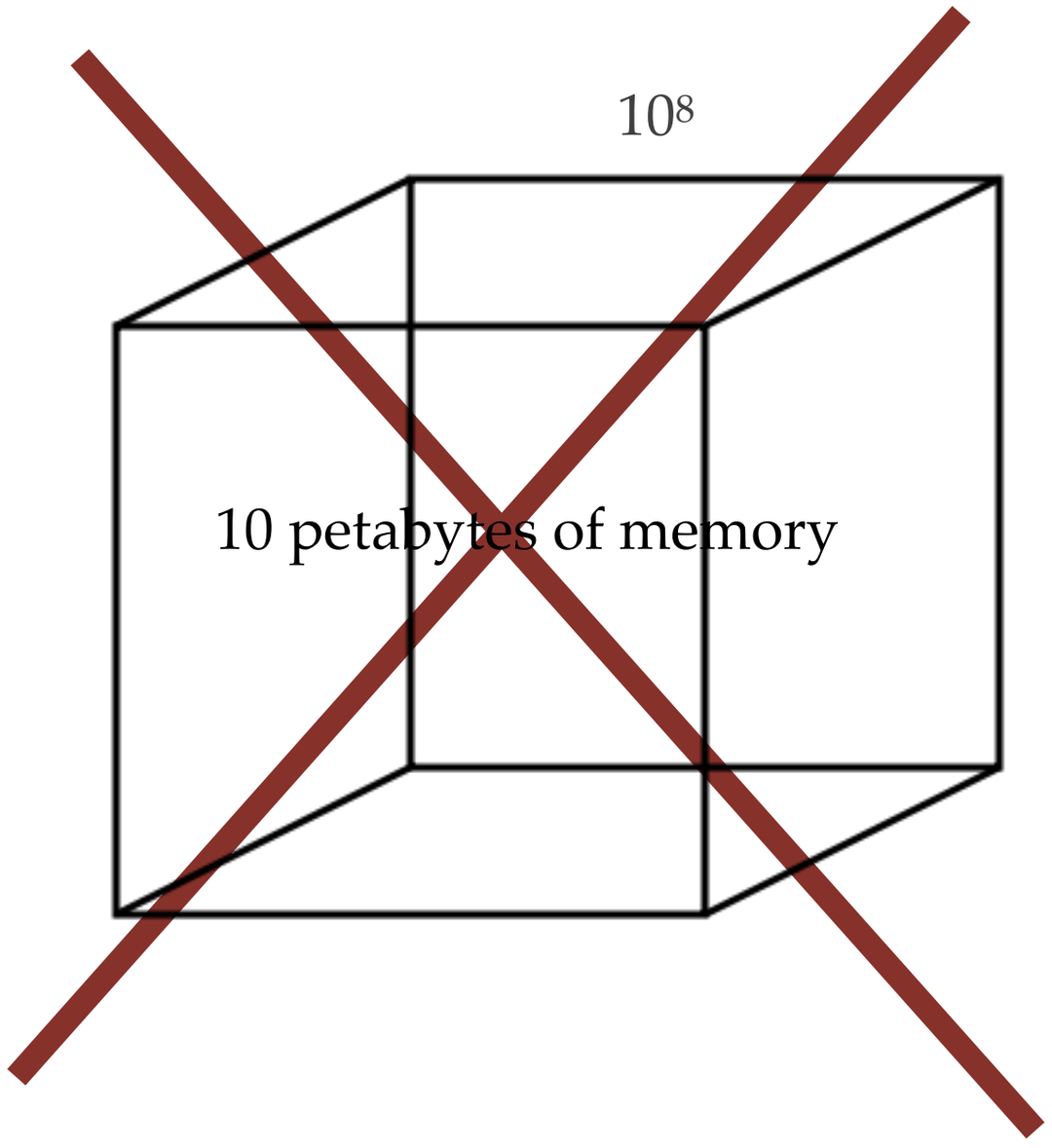
(As long as we know our instrument)

Shaw et al 1401.2095



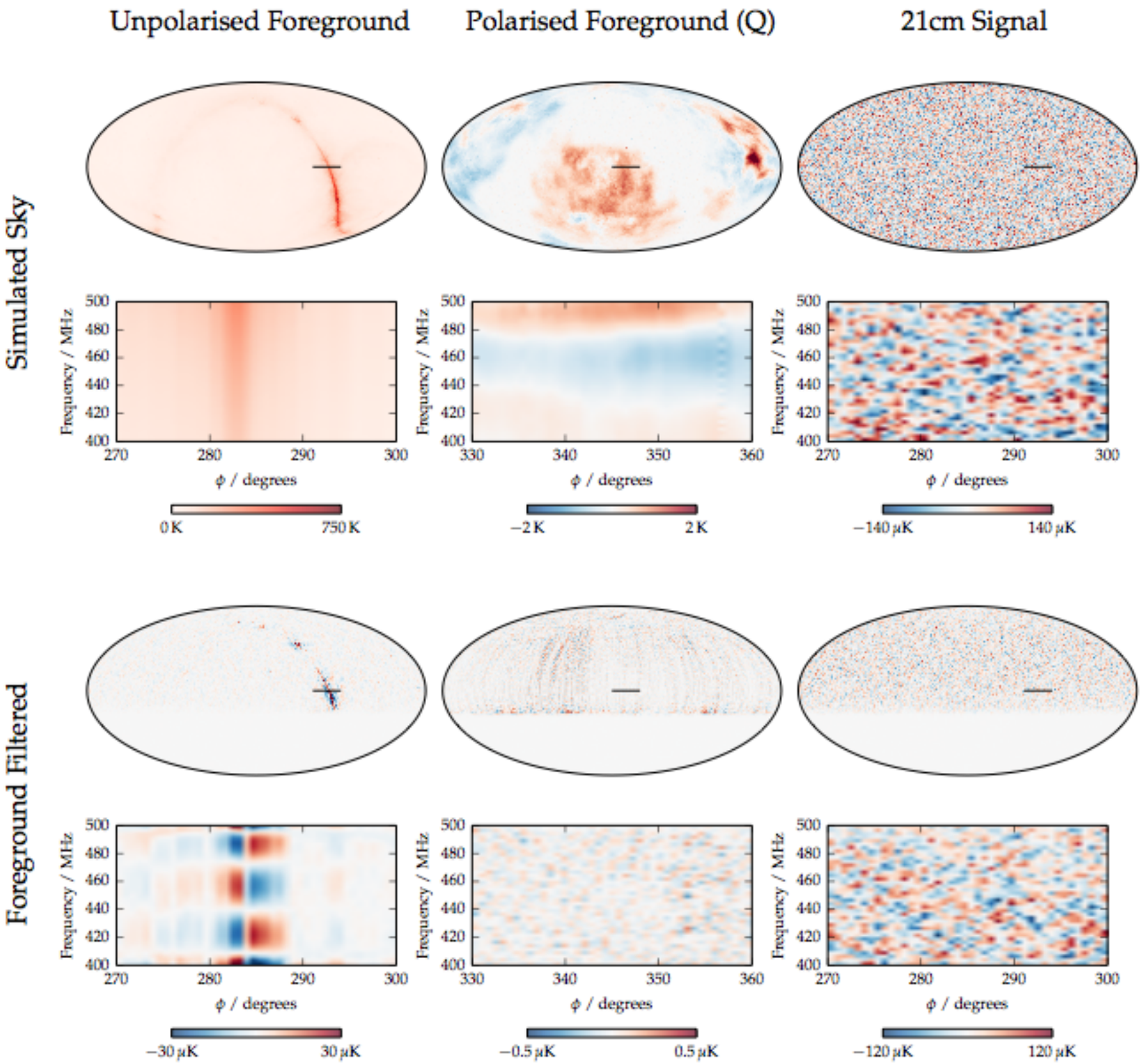
Foreground Removal?

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



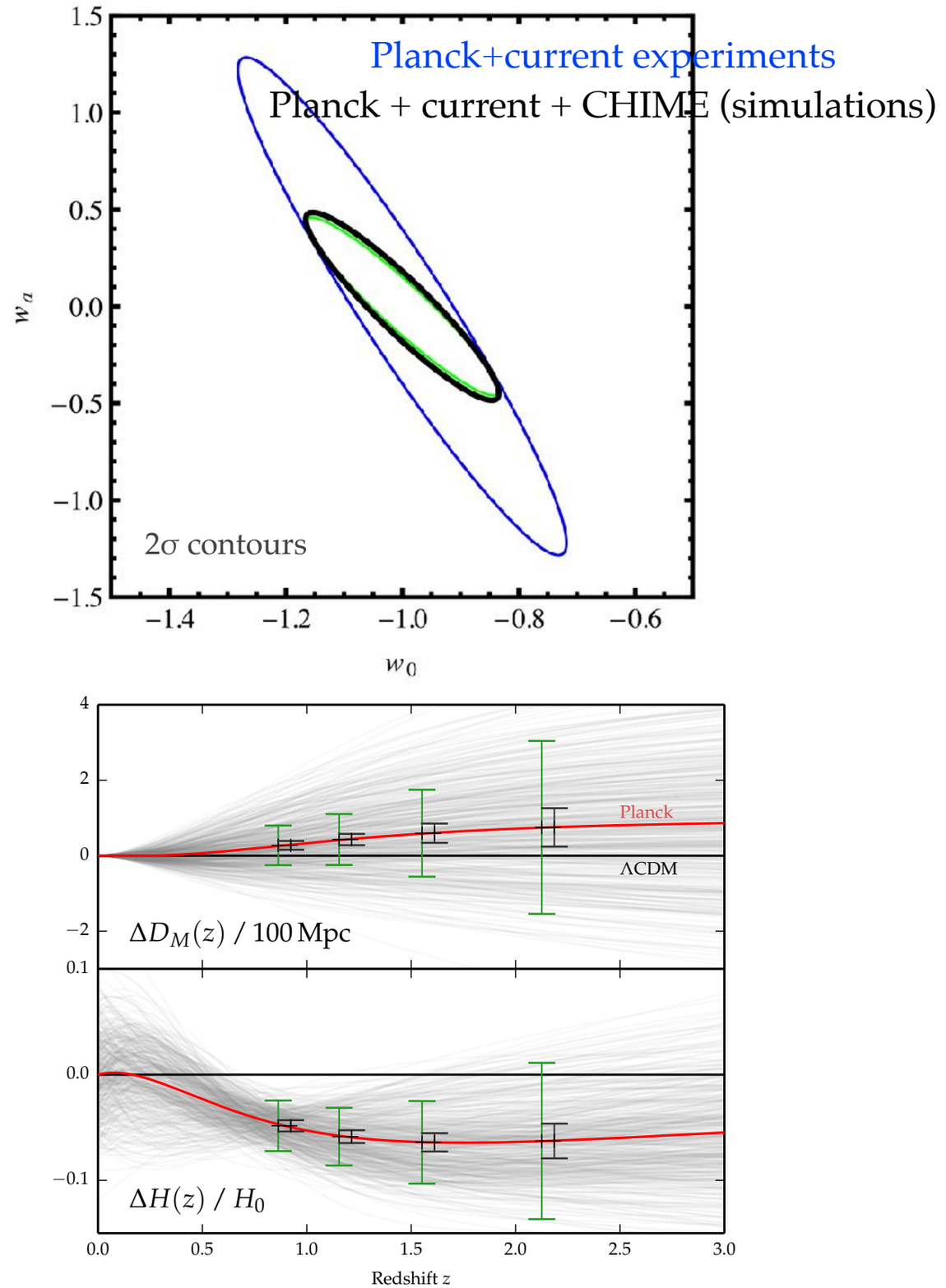
Solution: M-Modes

- 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



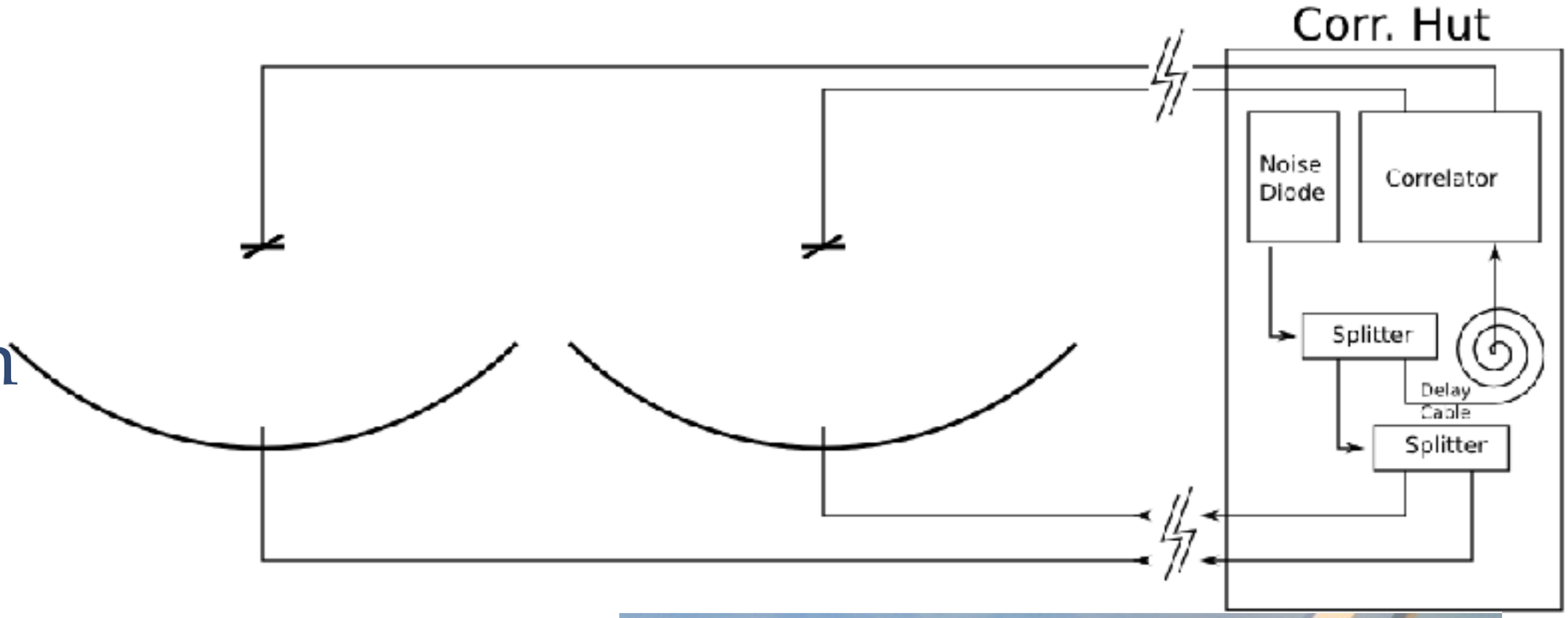
CHIME Forecasts

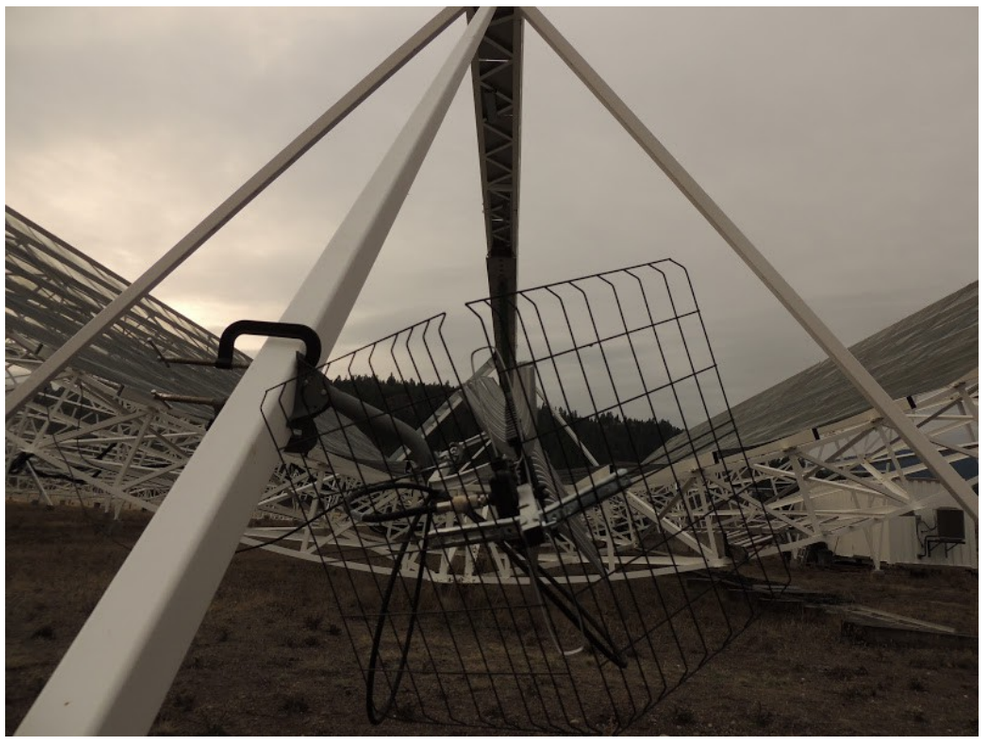
- Can do science with the pathfinder
- Full CHIME breaking ground this summer, anticipate 5 years of data
- 0.52 - 0.26 deg beamsize (400-800MHz)
- 10 - 45 Mpc resolution (400-800)
- 50K, 2K/Jy, 1.5uJy/pixel final sensitivity (50uJy/pixel daily),

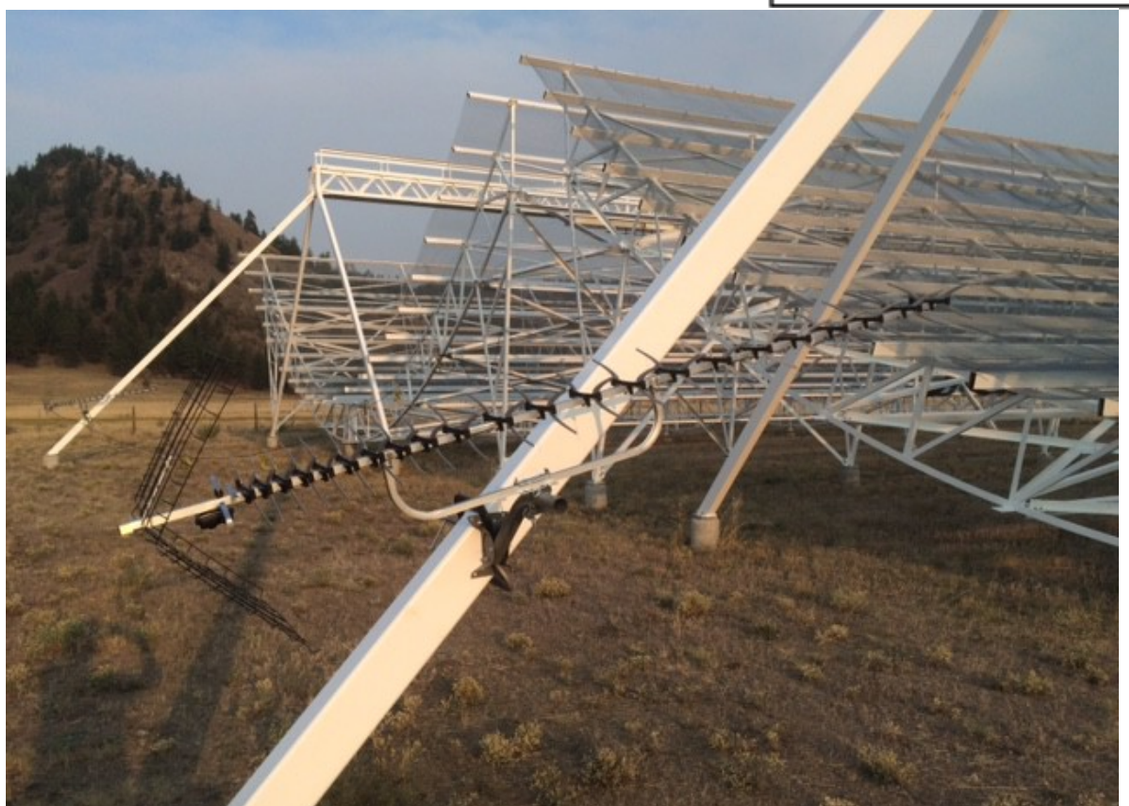


Calibration: Gain and Phase

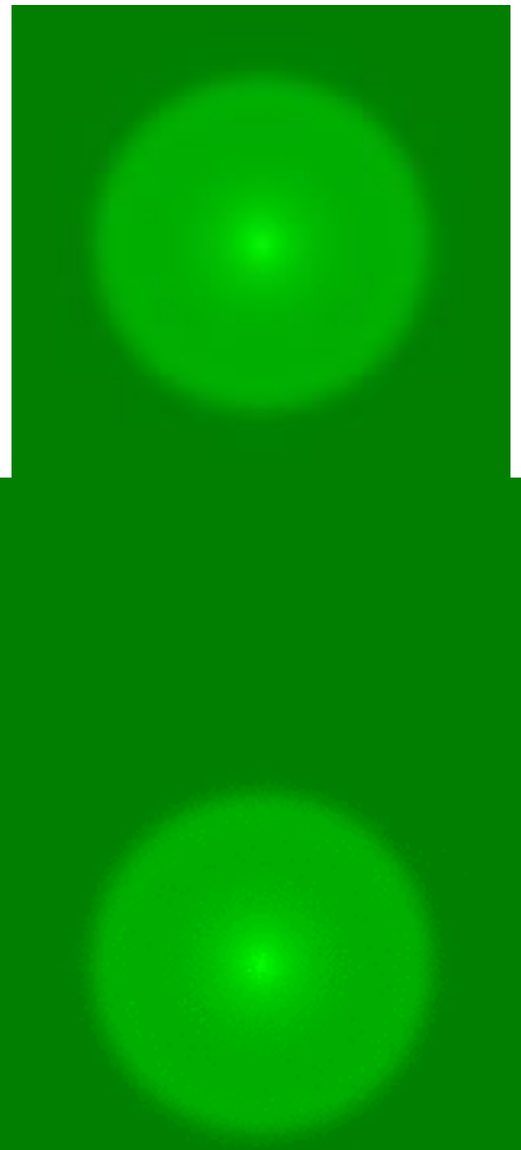
Noise Rigidization





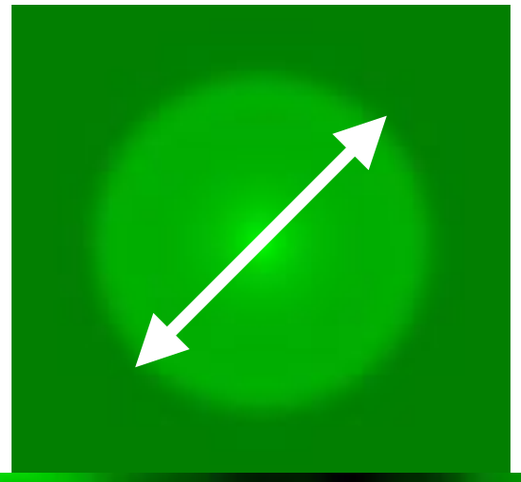


It's a statistical statement



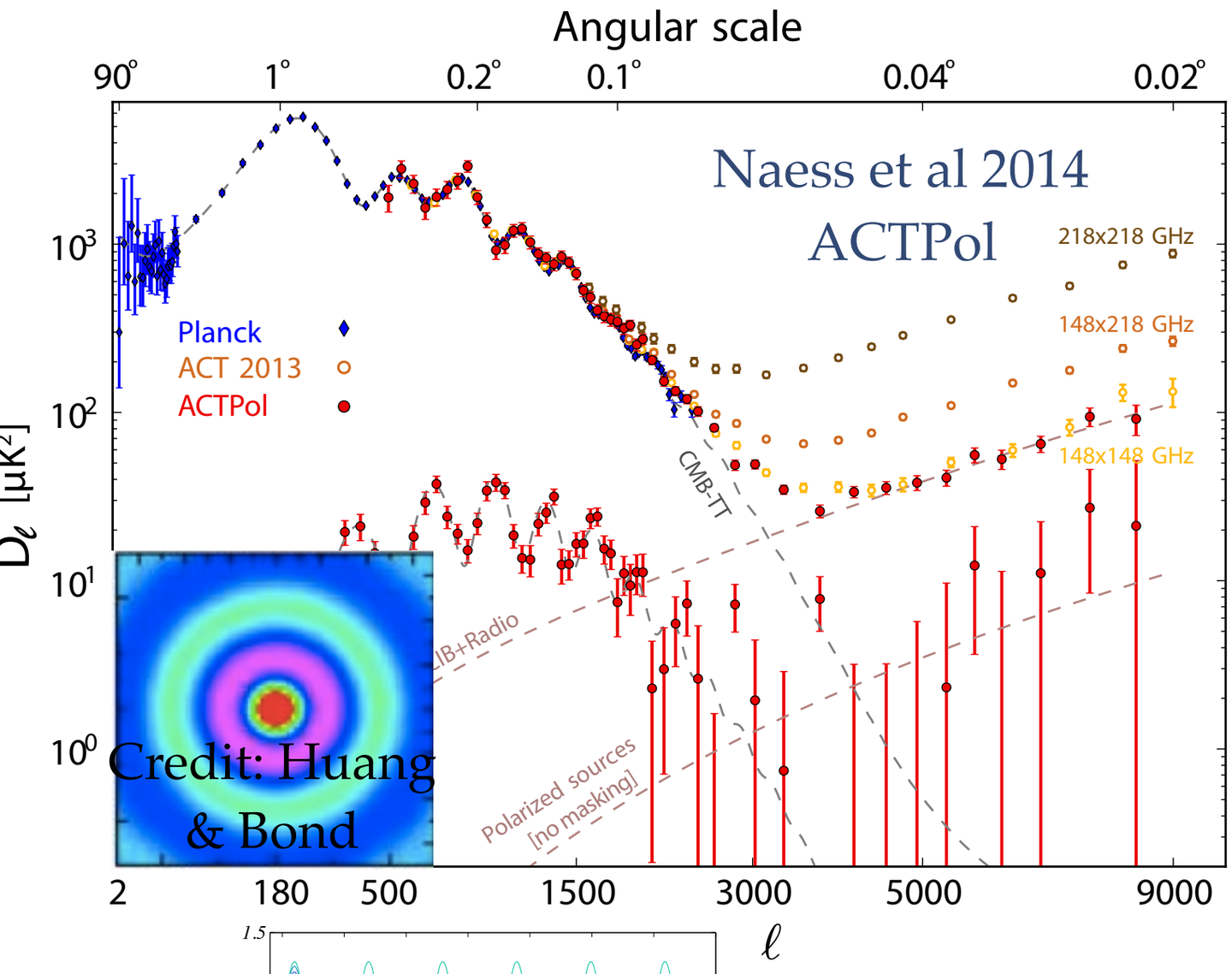
Credit: A. Hincks

It's a statistical statement

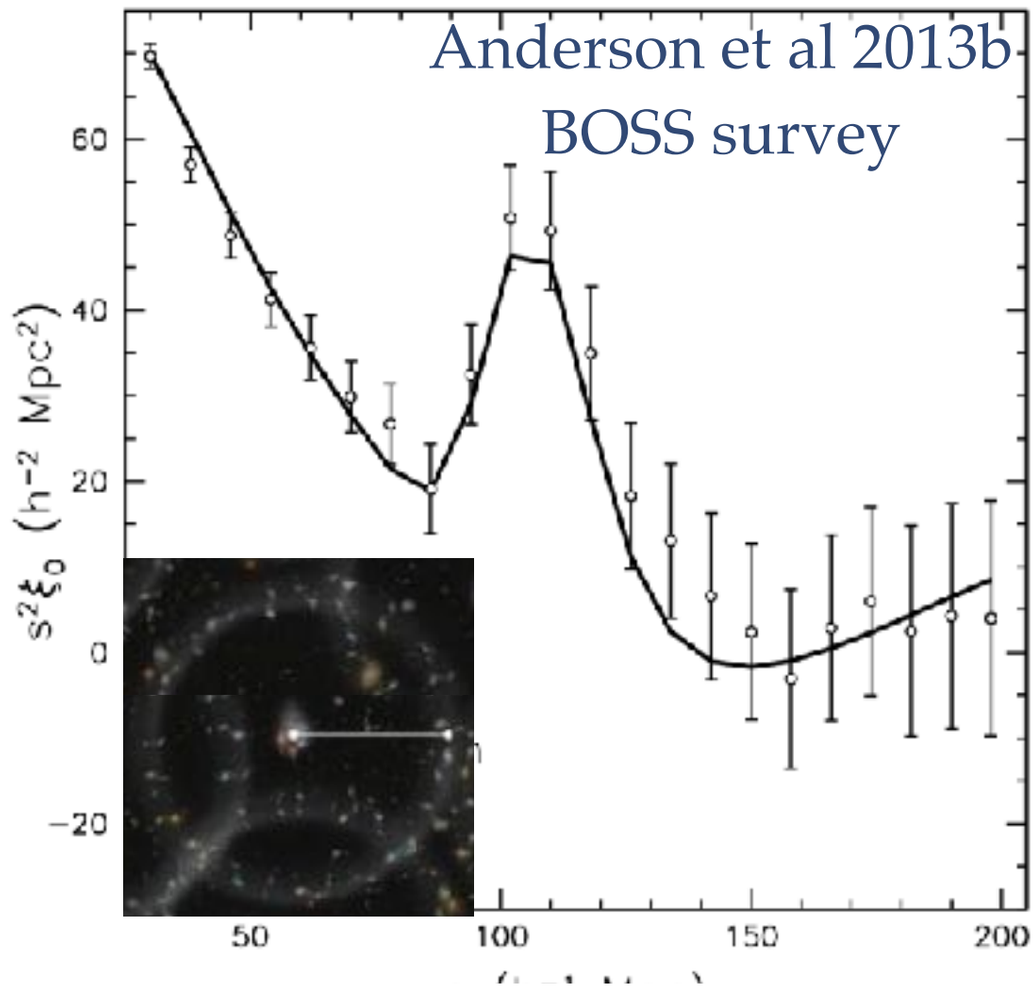


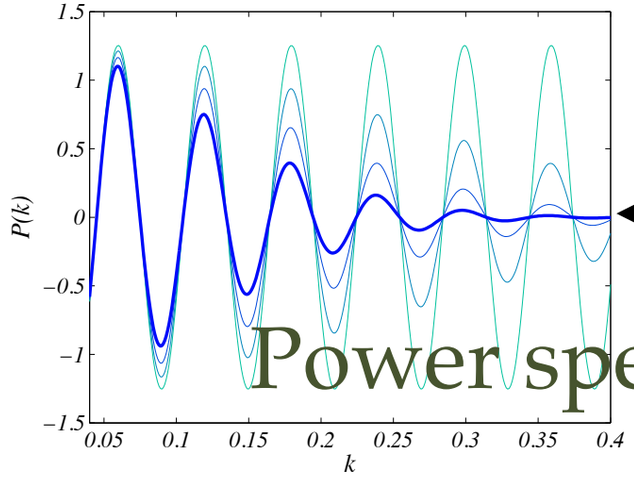
Credit: A. Hincks

(aside)



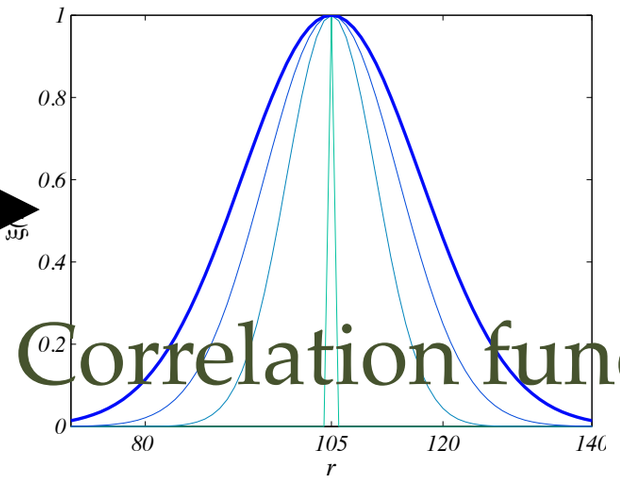
Credit: Huang & Bond





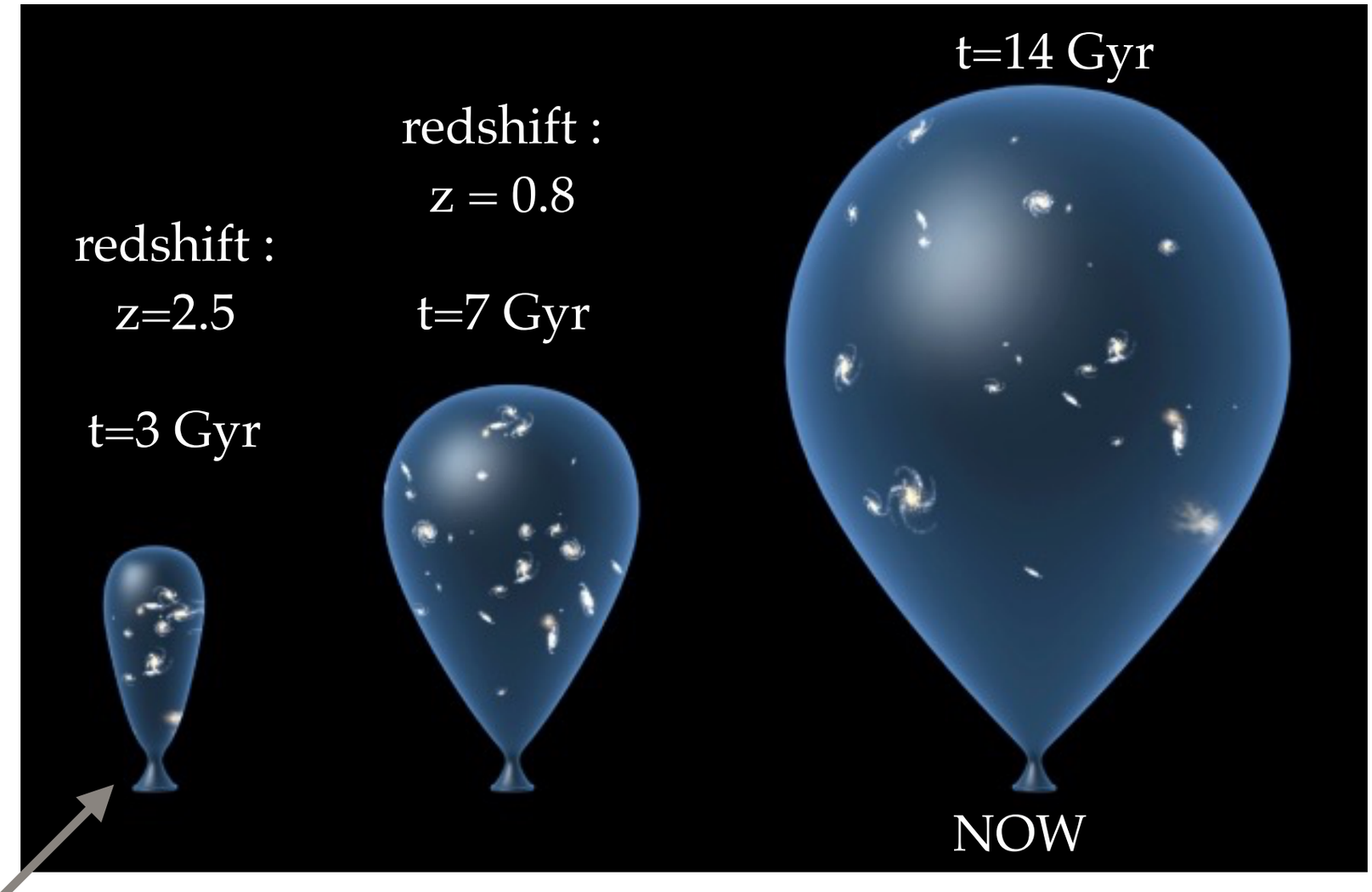
Power spectrum

(Fourier pair)



Correlation function

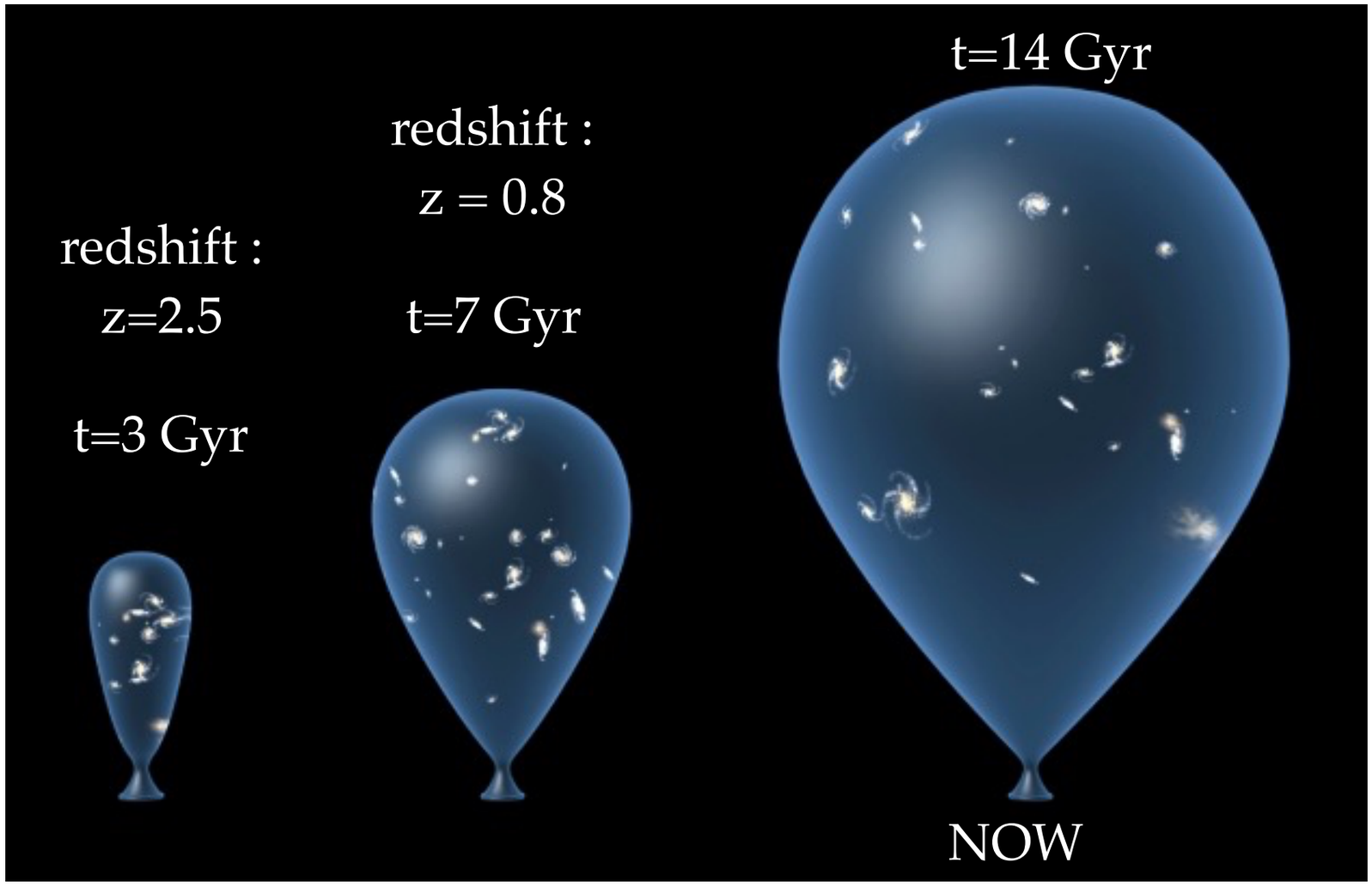
What do I build?



sources fainter,
BAO smaller

Requires highest sensitivity, highest telescope resolution

What do I build?



75cm

50 Mpc $\Longleftrightarrow$ ~0.5 degrees

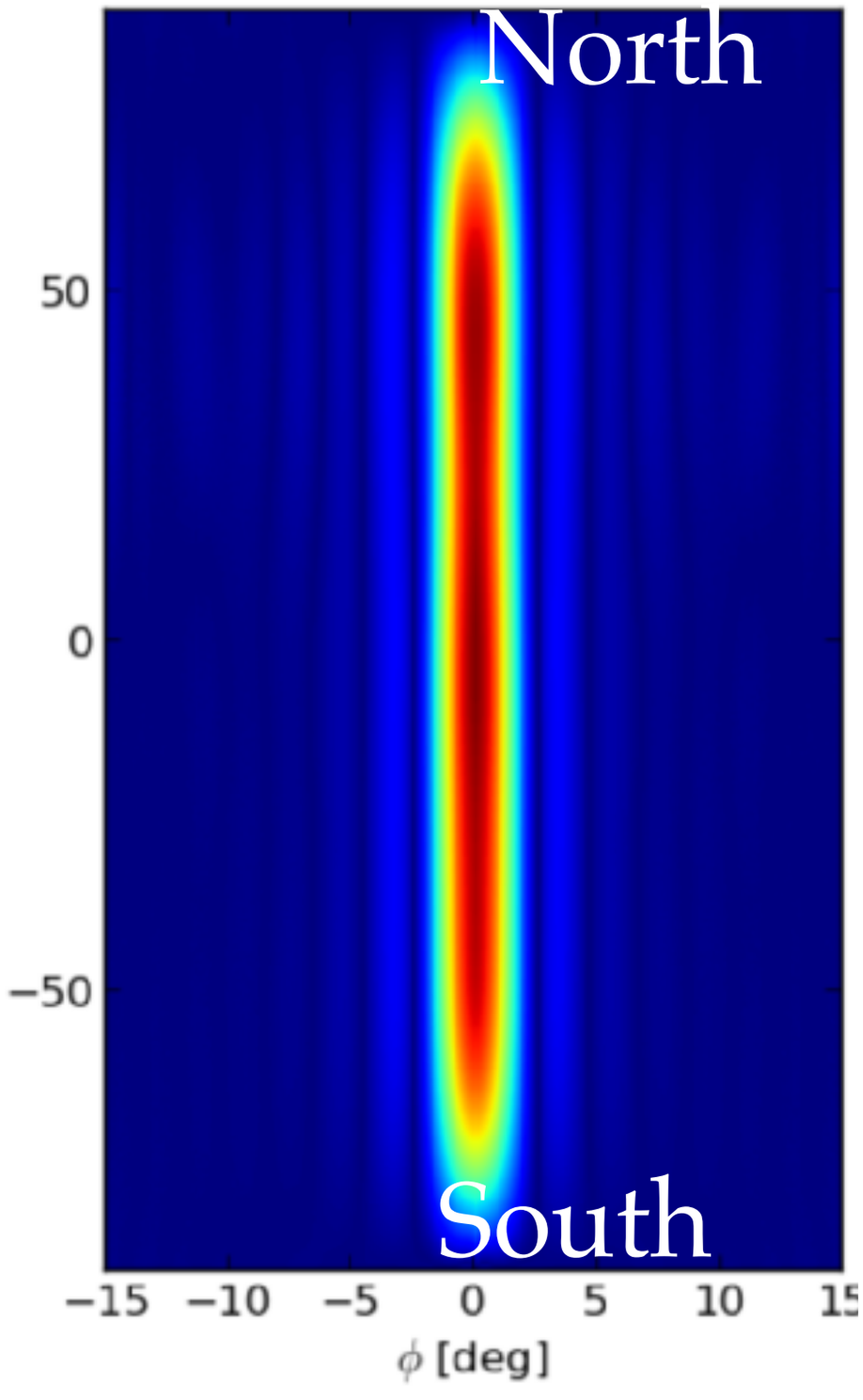
Resolution~λ/D -> 80m dish!

Signal level: ~100μK, need:

1) ~ 1000 detectors
2) a lot of collecting area
3) low noise

What does this look like?

Beam



Pulsar tracks