Radio cosmology at BNL and Stony Brook

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SB Grad Student Seminar, May 5, 2017

Cosmological paradigm

Cosmological paradigm

The standard cosmological paradigm is an expanding Universe containing dark energy (Λ) and cold dark matter, plus a little regular matter, i.e. baryons.

"ΛCDM"

Cosmological paradigm

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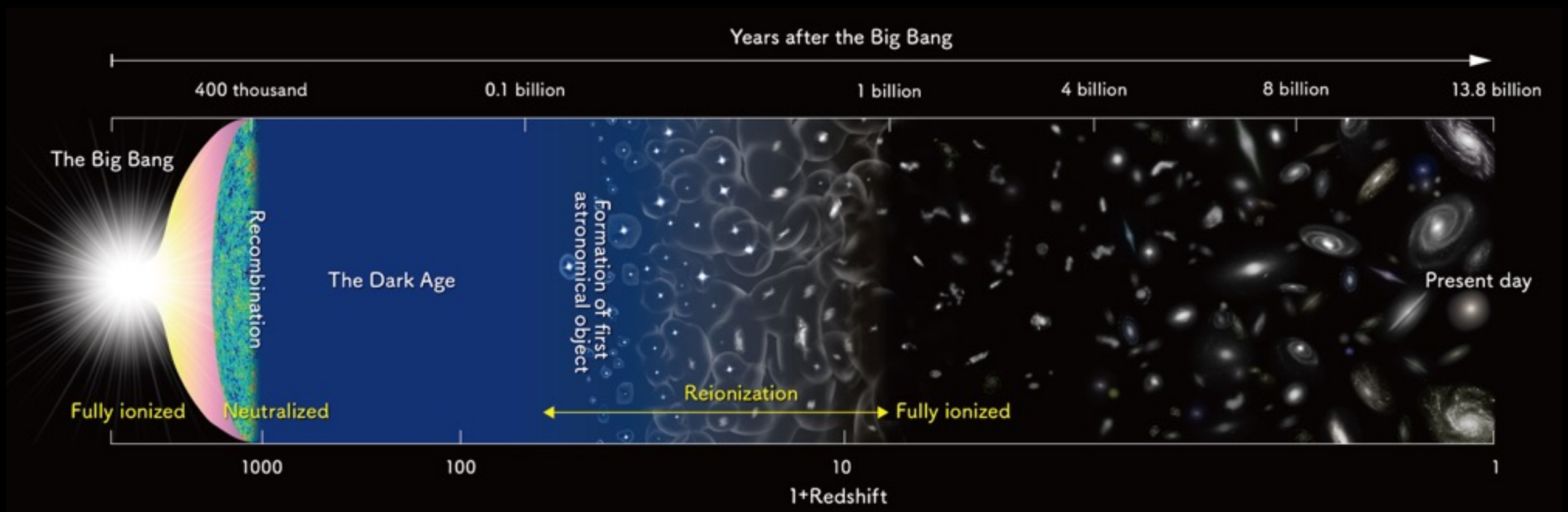
"ΛCDM"

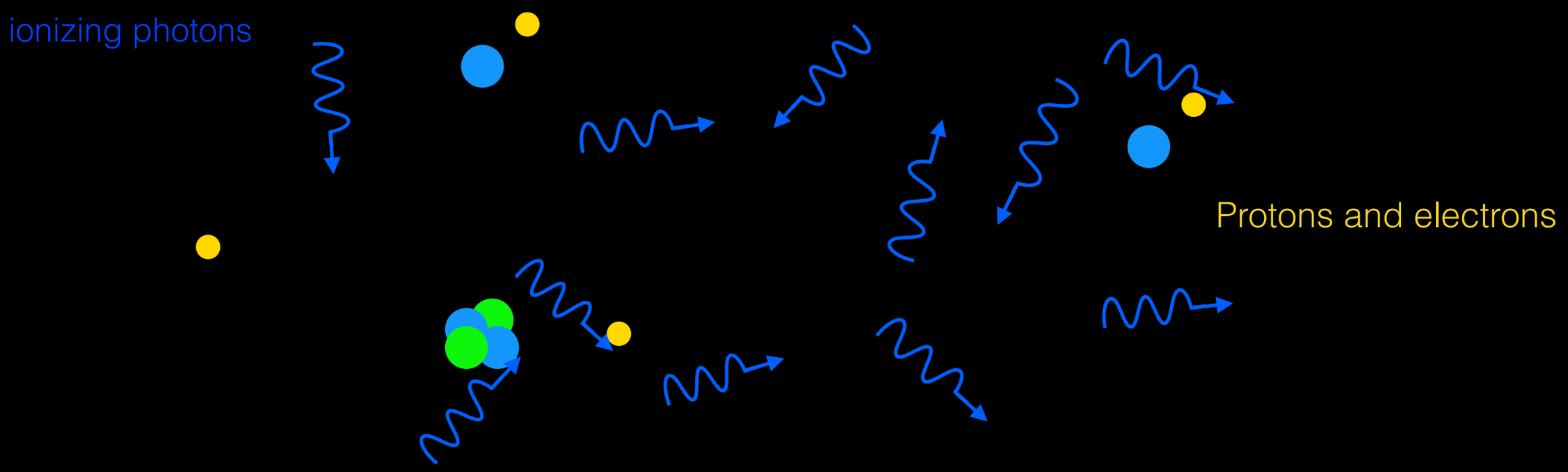
If the Universe is expanding, then it used to be smaller, denser, and hotter.

Cosmological paradigm



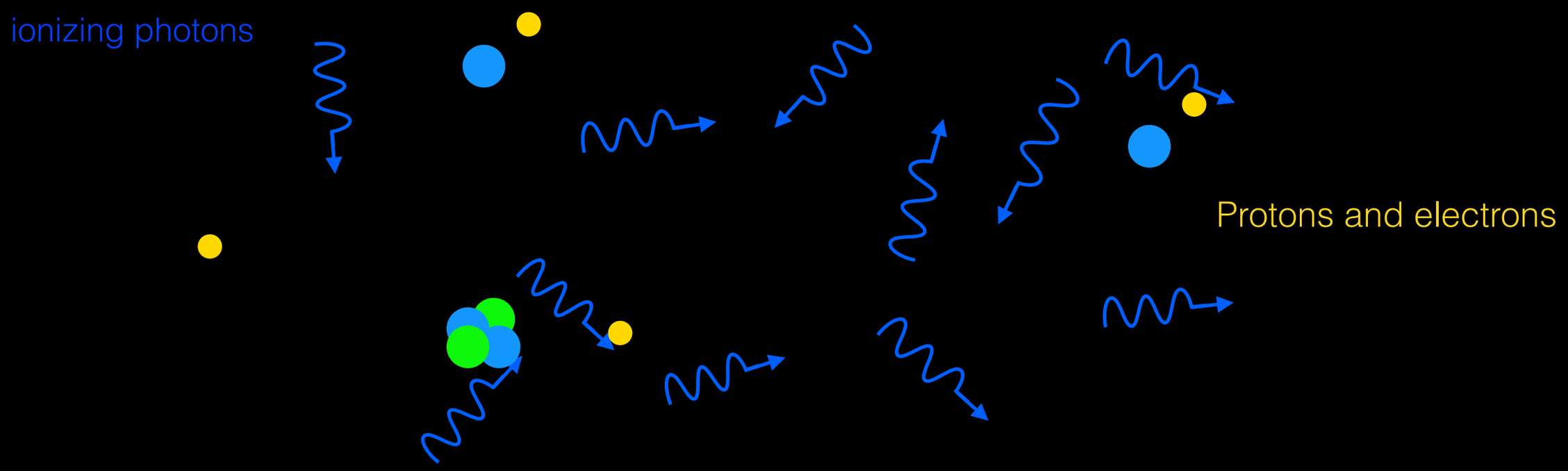
Thermal history of the Universe

The universe at **high** (>3000 K) temperature:
hydrogen and helium plasma + photons = the “photon/baryon fluid”



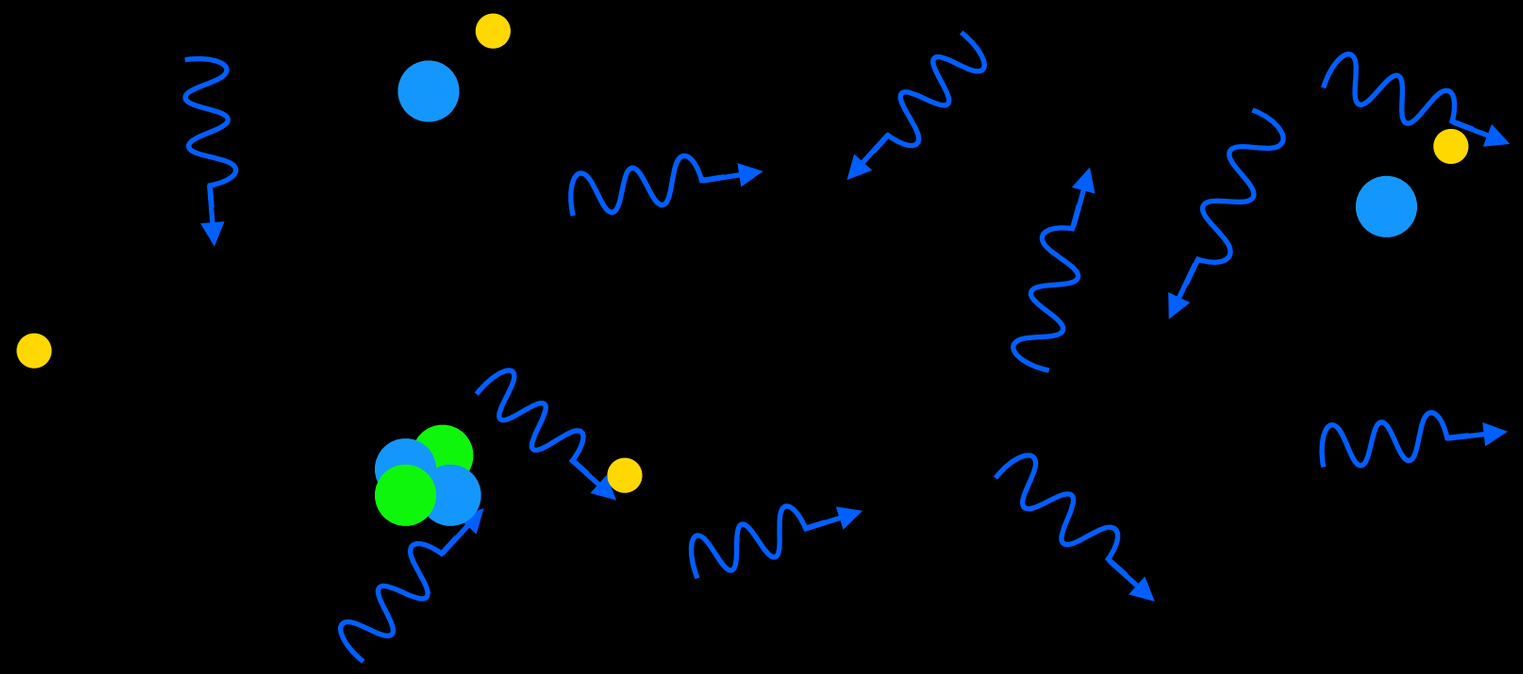
Thermal history of the Universe

Free electrons have a high cross section to photons. Neutral hydrogen atoms do not. Efficient Thompson scattering makes the plasma opaque and photons tightly coupled to baryons.



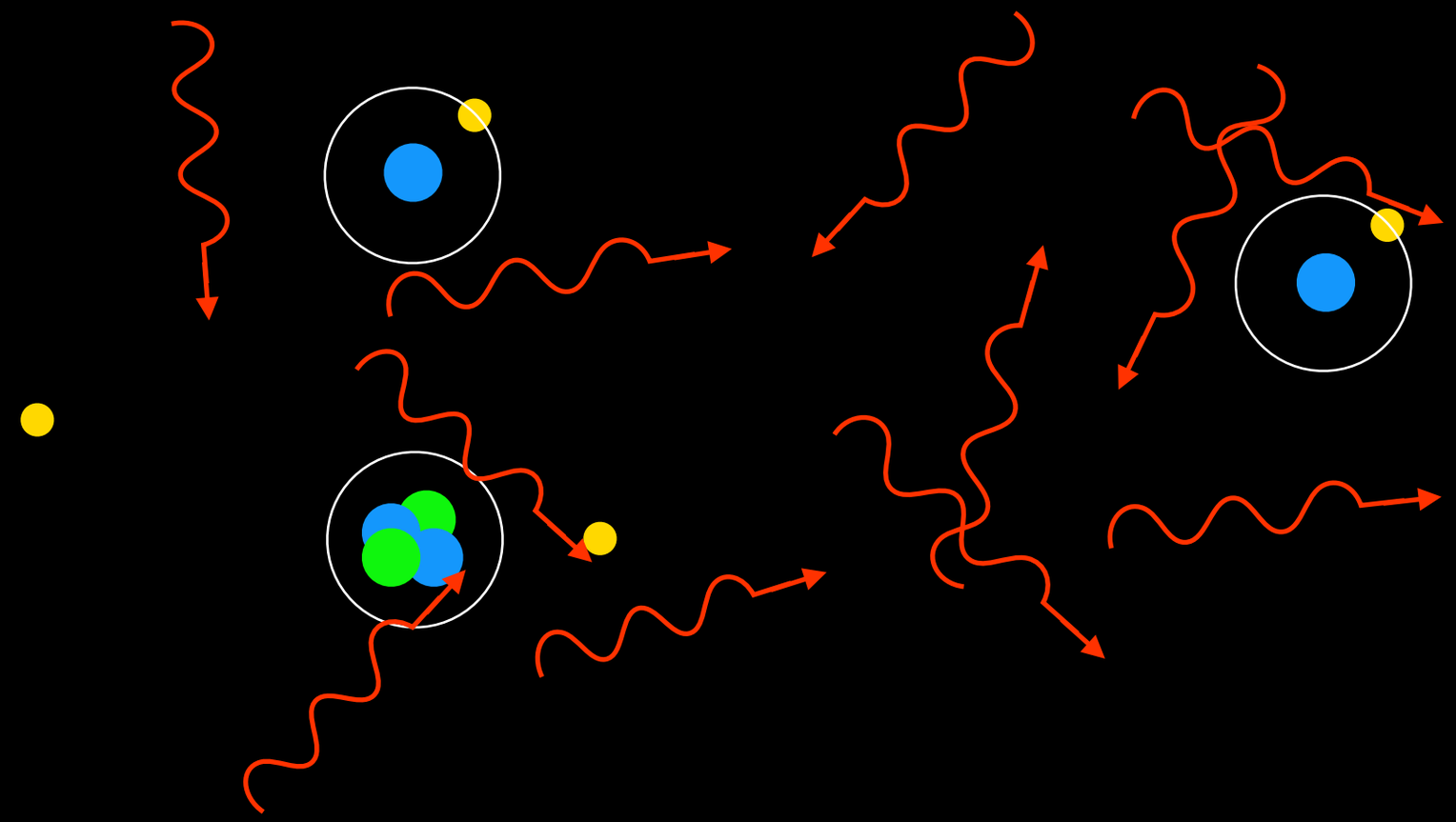
Thermal history of the Universe

Going forward in time…



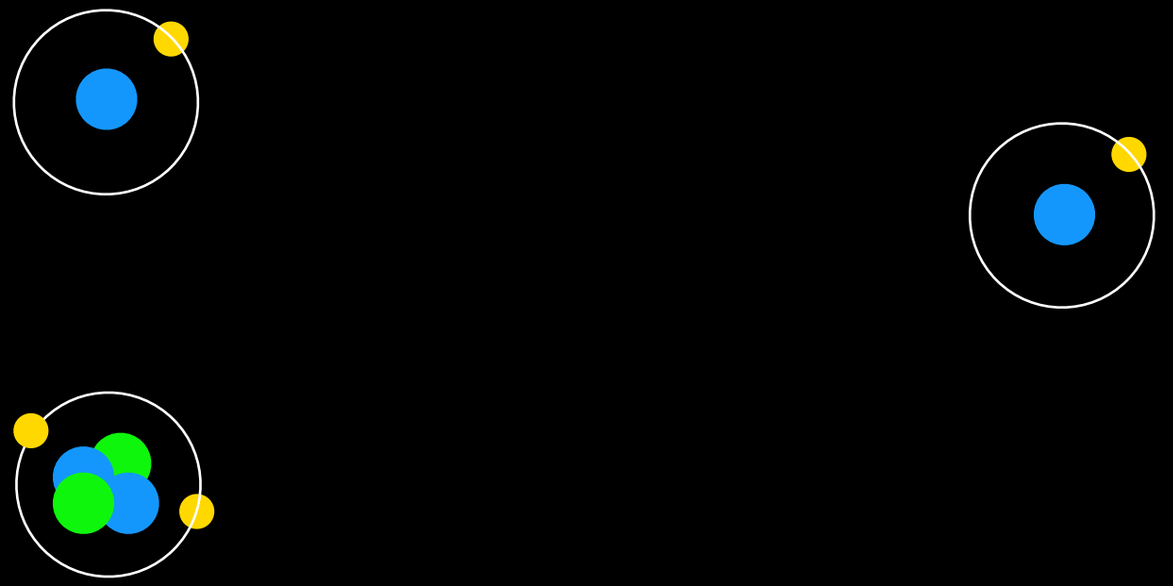
Thermal history of the Universe

Going forward in time, when the Universe cools to ~3000 K, the protons and electrons “recombine,” and the photons travel unimpeded through space.



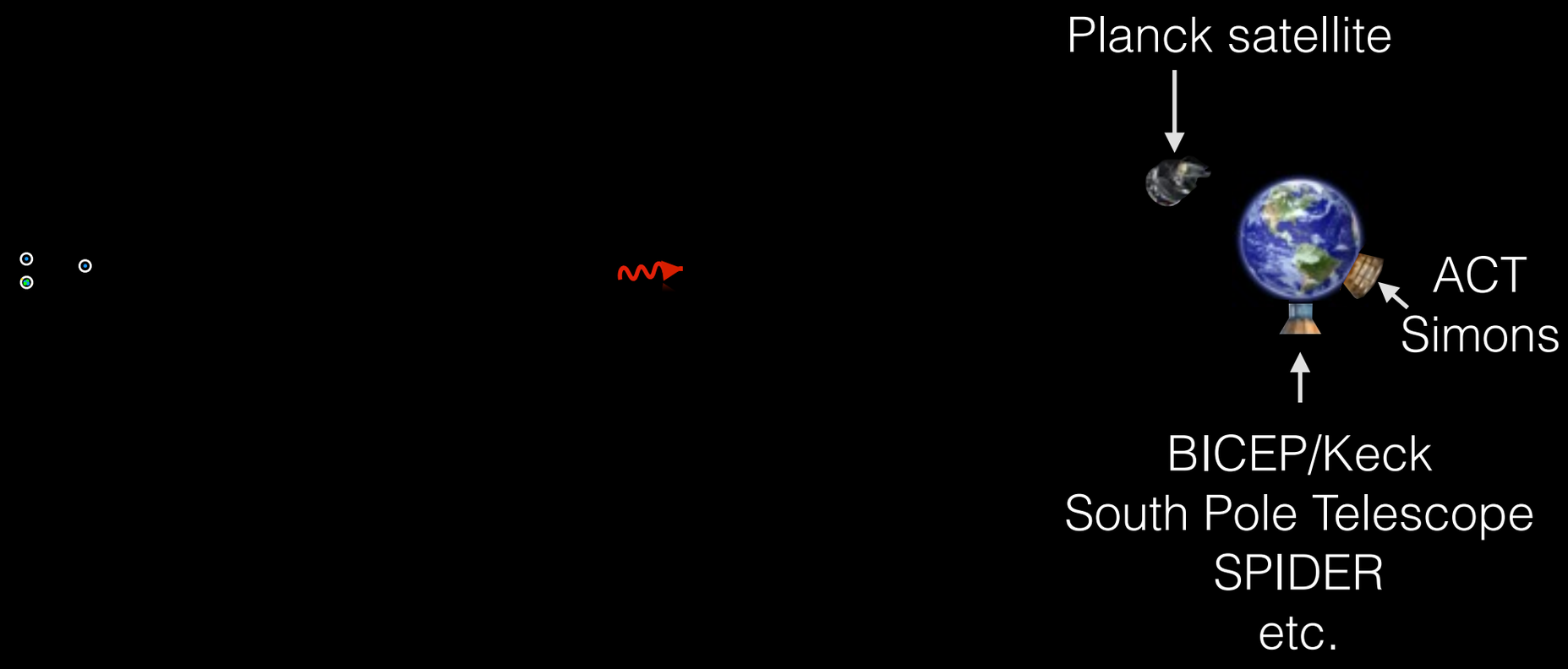
Thermal history of the Universe

The photons heading in the right direction find their way to Earth.



Cosmic Microwave Background

The photons heading in the right direction find their way to Earth.

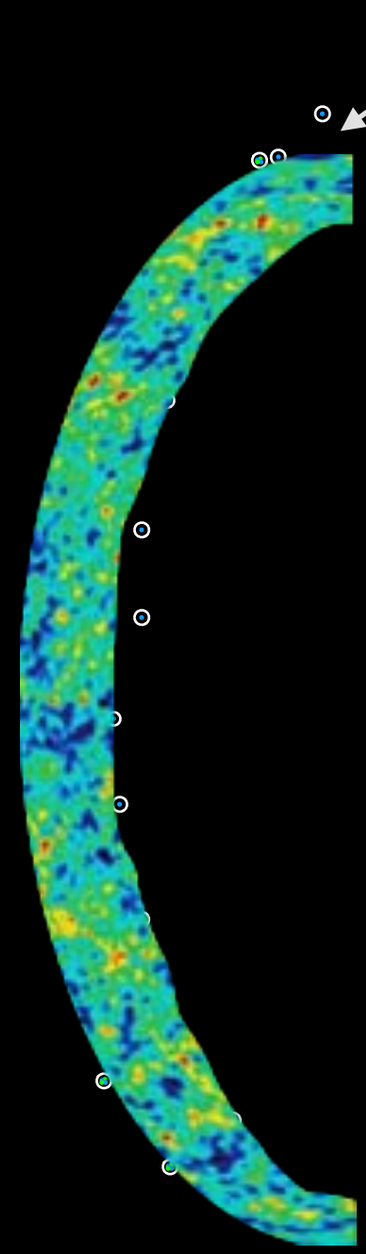


Cosmic Microwave Background

This is the Cosmic Microwave Background!

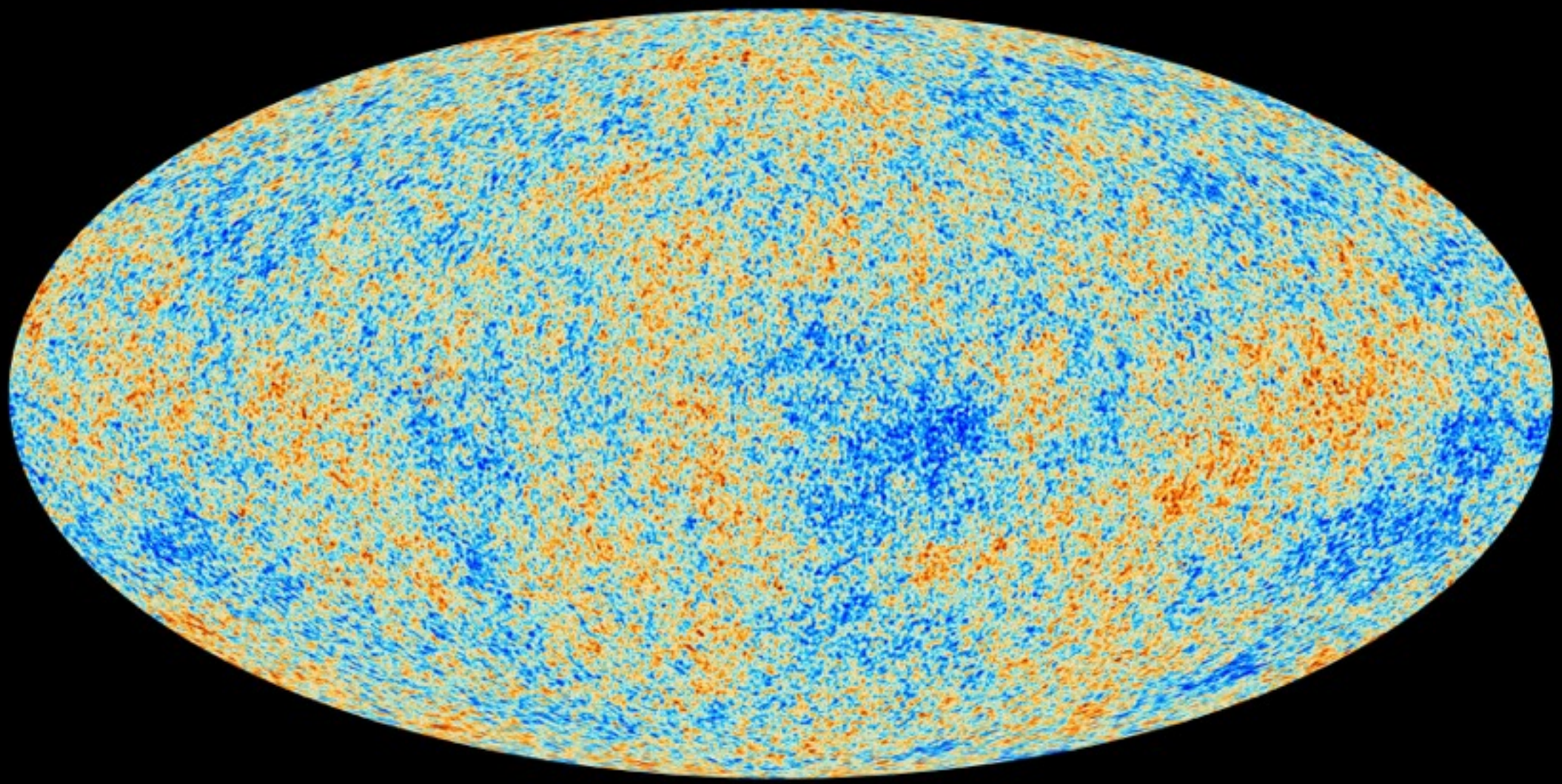
The fluctuations in intensity (anisotropy) trace the fluctuations in the density of the Universe.

$$\frac{\delta I}{I} \propto \frac{\delta \rho}{\rho} \sim 10^{-5}$$



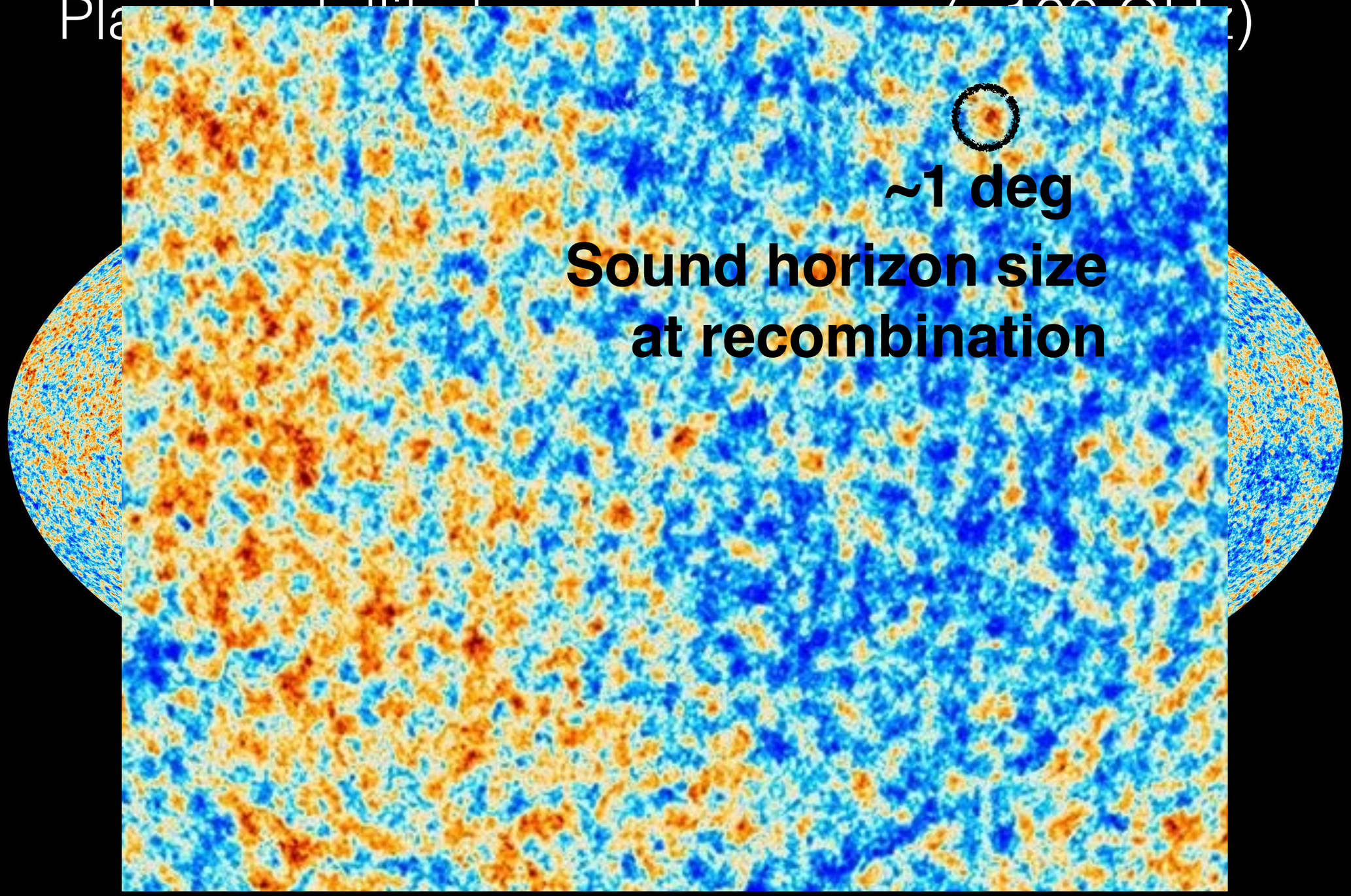
Cosmic Microwave Background

Planck satellite temperature map (~100 GHz)



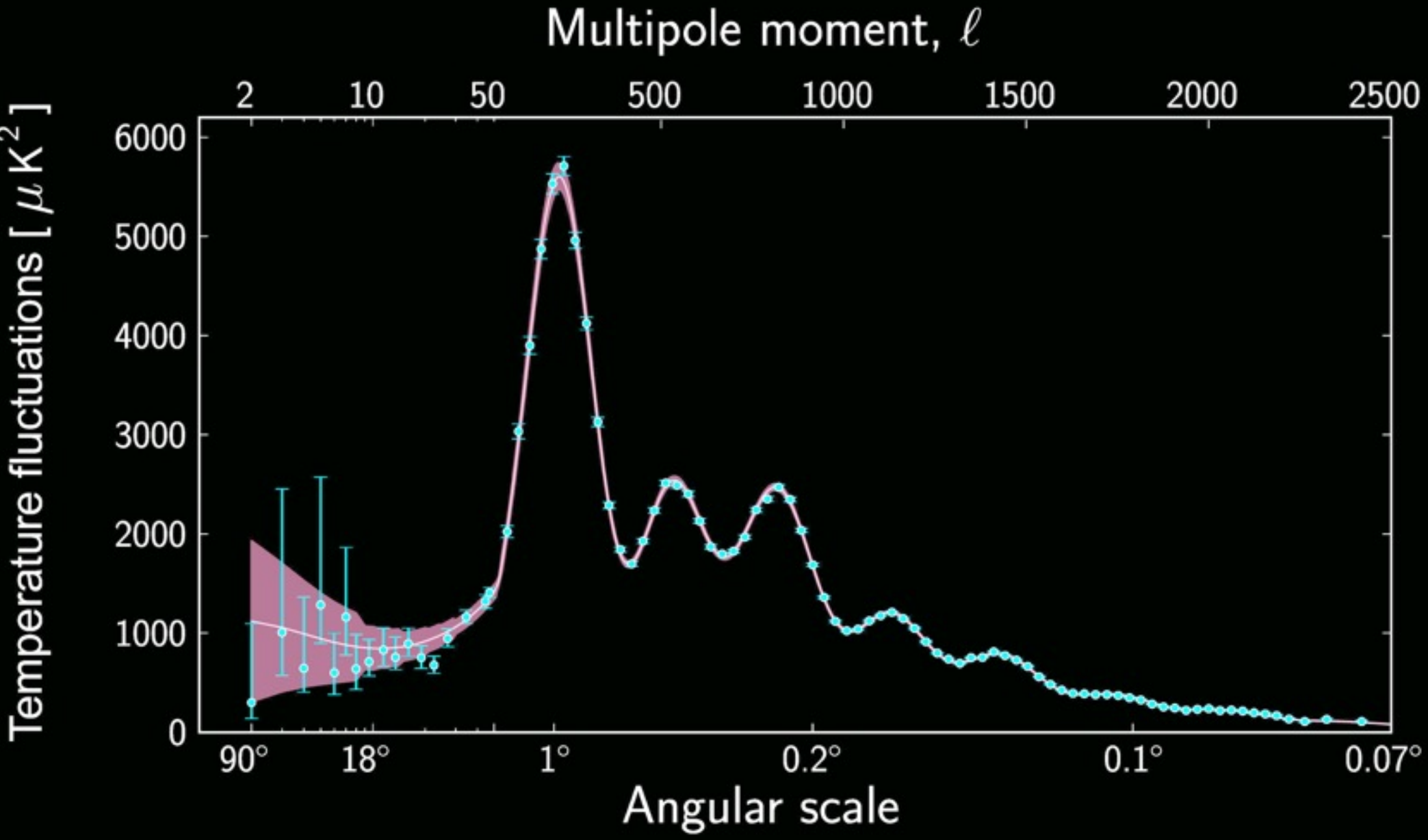
Cosmic Microwave Background

Pla (~100 GHz)



Cosmic Microwave Background

Planck temperature “angular power spectrum”



Planck Collaboration & ESA

Angular Power Spectrum

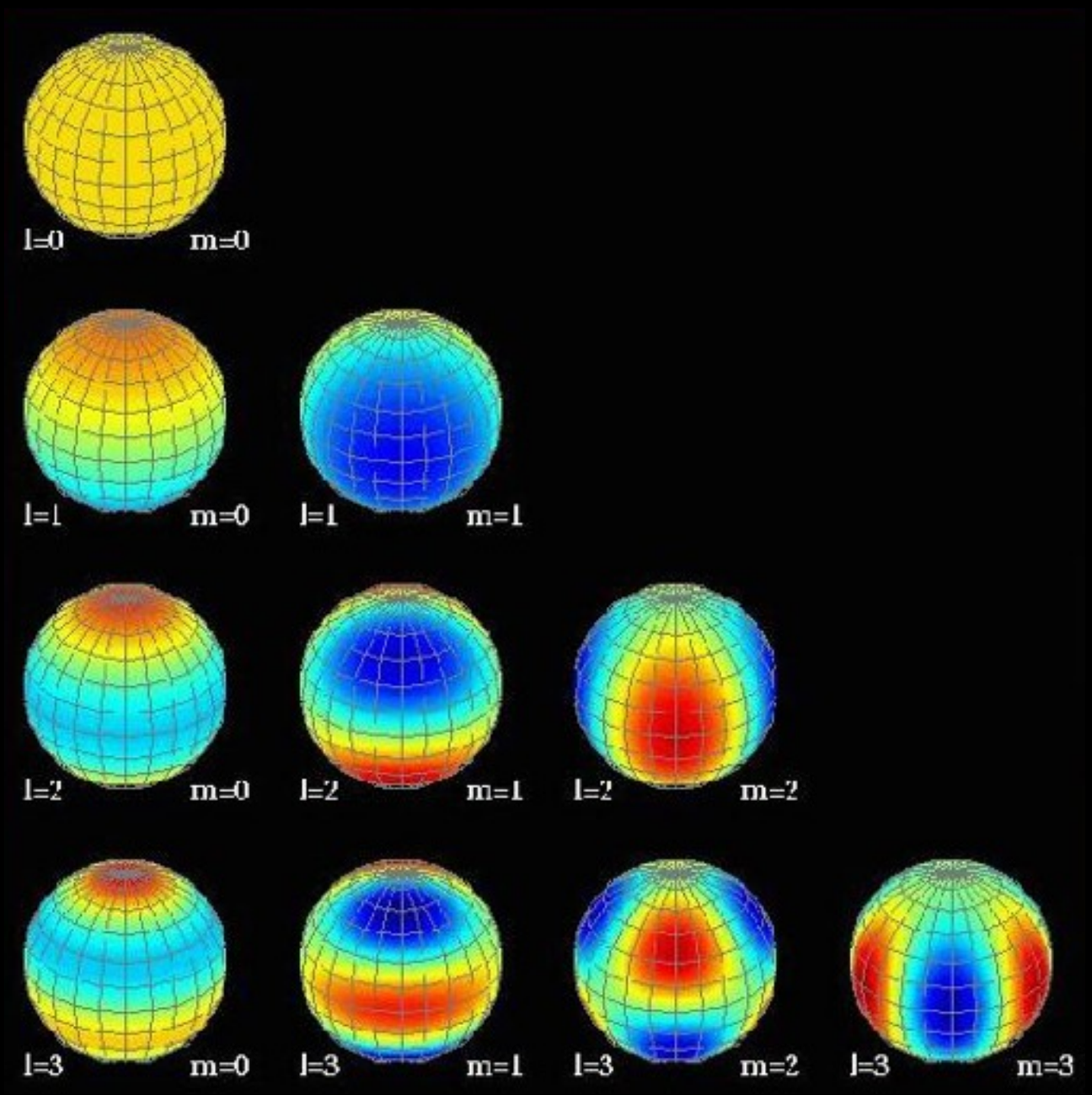
$$T(\theta,\Phi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{+\ell} a_{\ell,m}\, Y_{\ell,m}(\theta,\Phi)$$

$\ell = 0$

$\ell = 1$

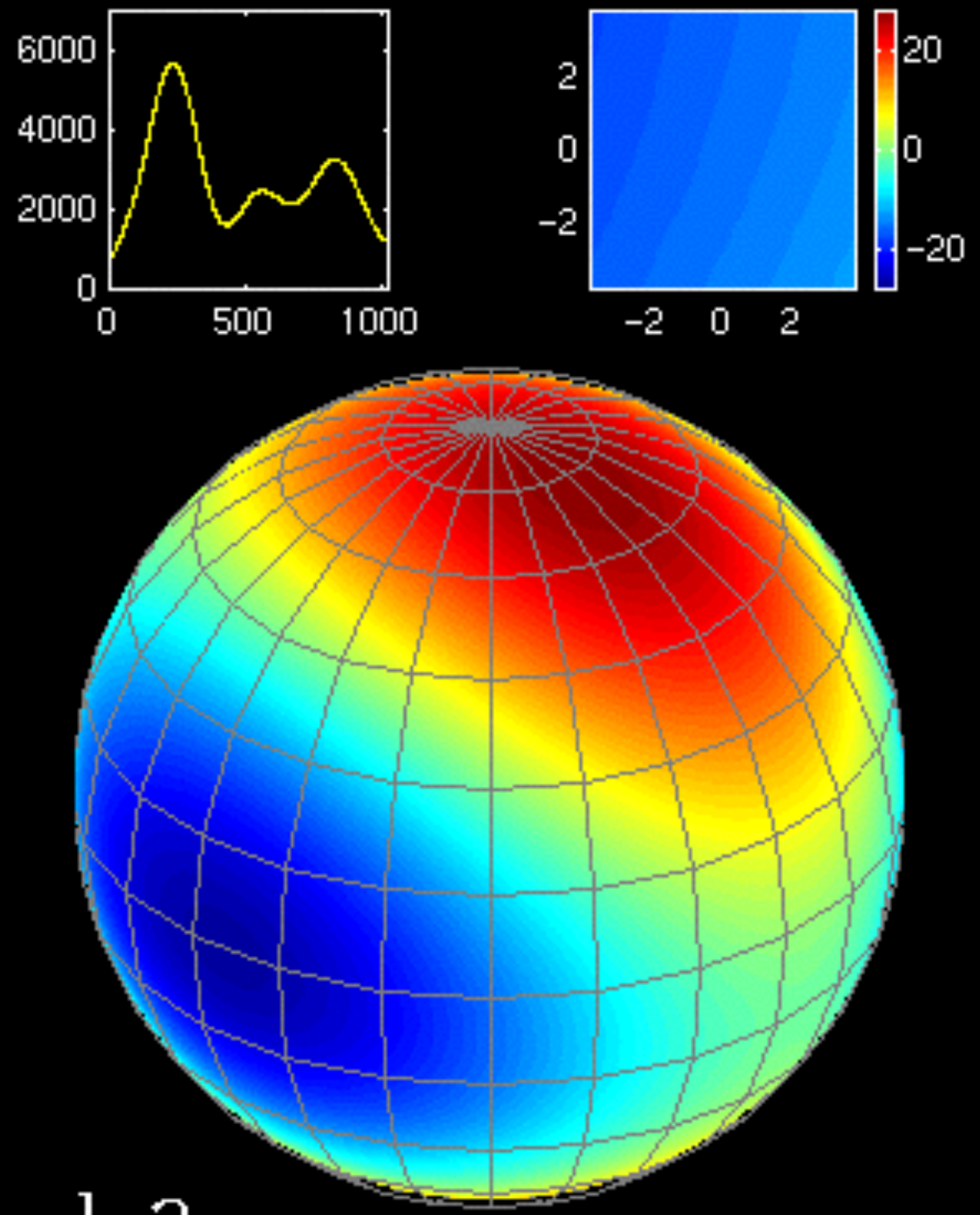
$\ell = 2$

$\ell = 3$



courtesy Clem Pryke

Angular Power Spectrum



courtesy Clem Pryke

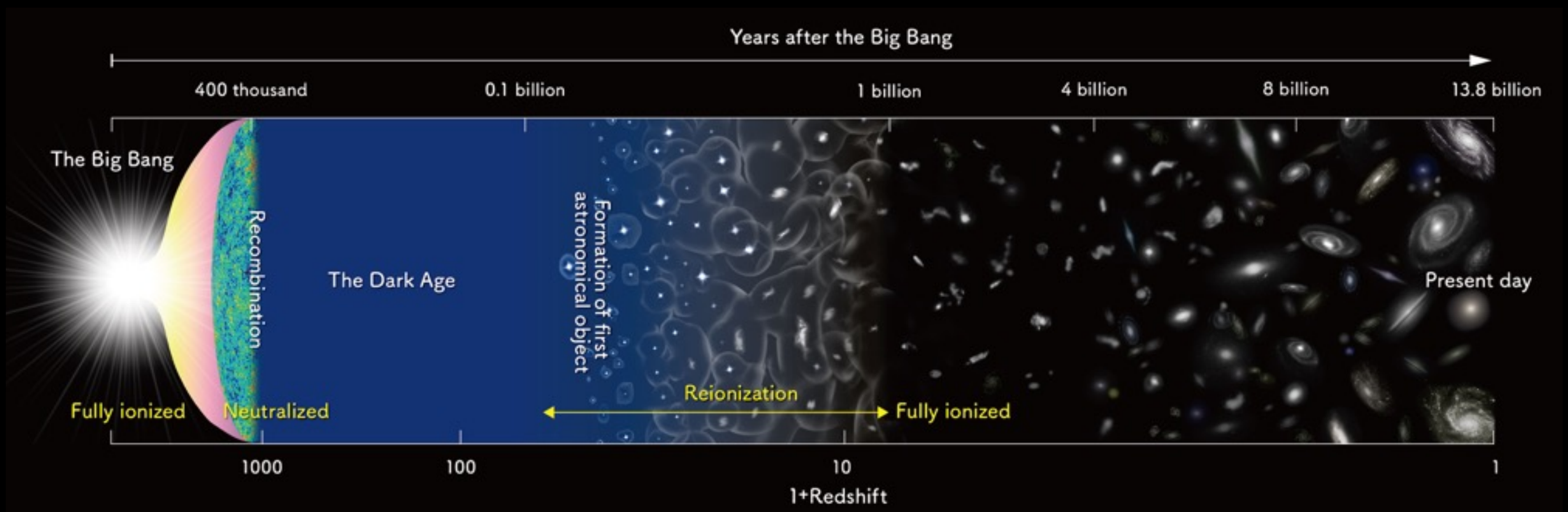
Cosmic Microwave Background

But this is only a 2D slice of the large scale structure of the universe at relatively early times.

The CMB is cosmic variance limited in temperature, so cannot provide any more information. (Polarization still has some ways to go.)

Would like to map out structure on other 2D slices — that is, in a 3D volume. Lets us get better statistics and lets us directly measure time evolution.

Cosmological paradigm



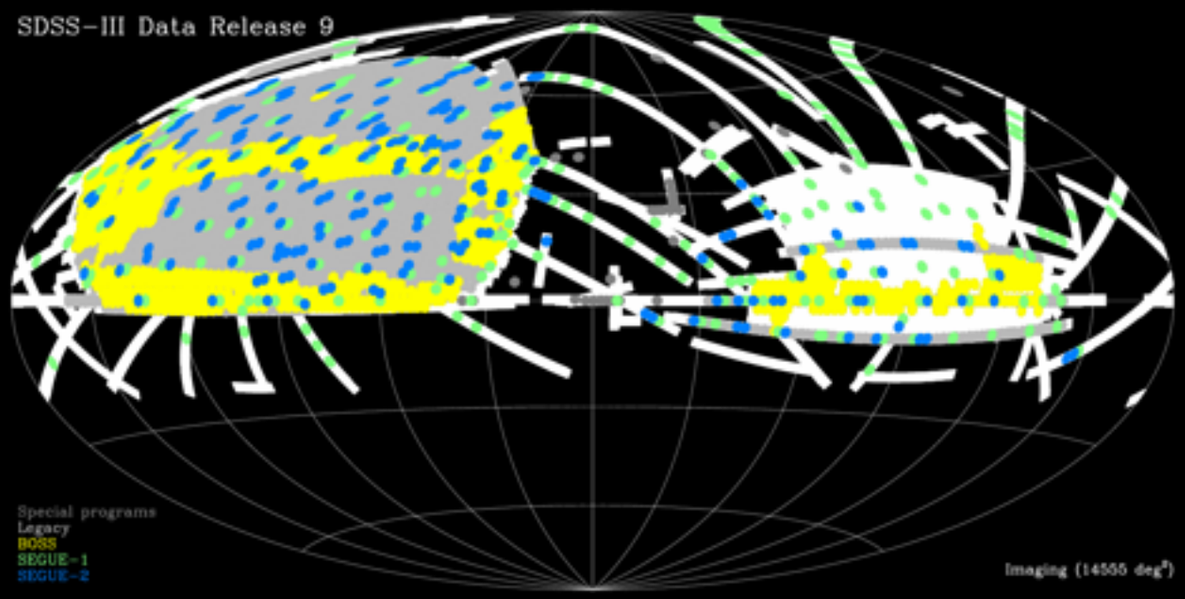
Volume mapping

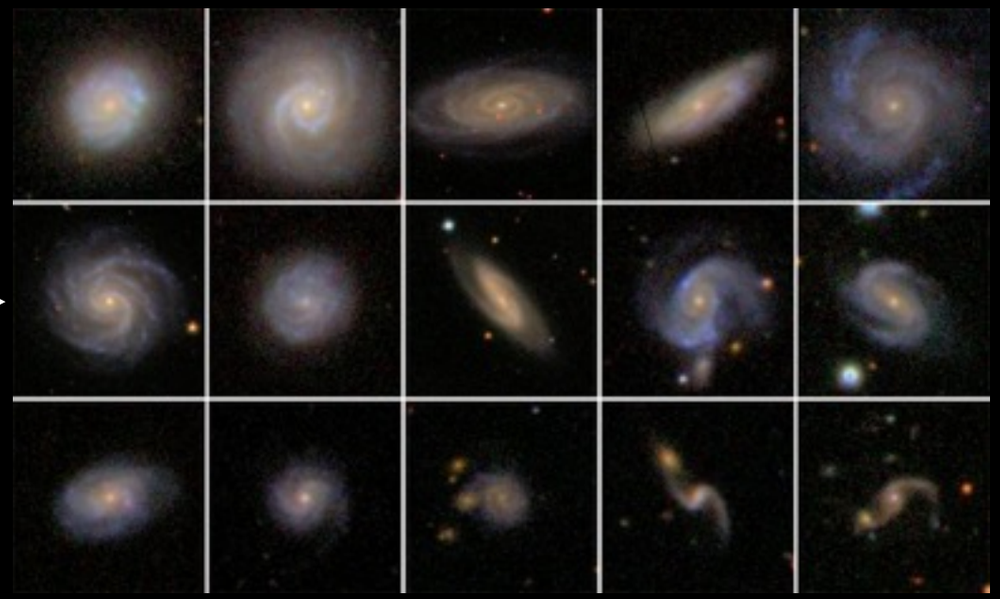
- Option 1: Find individual galaxies. Measure each one's position on the sky and redshift.

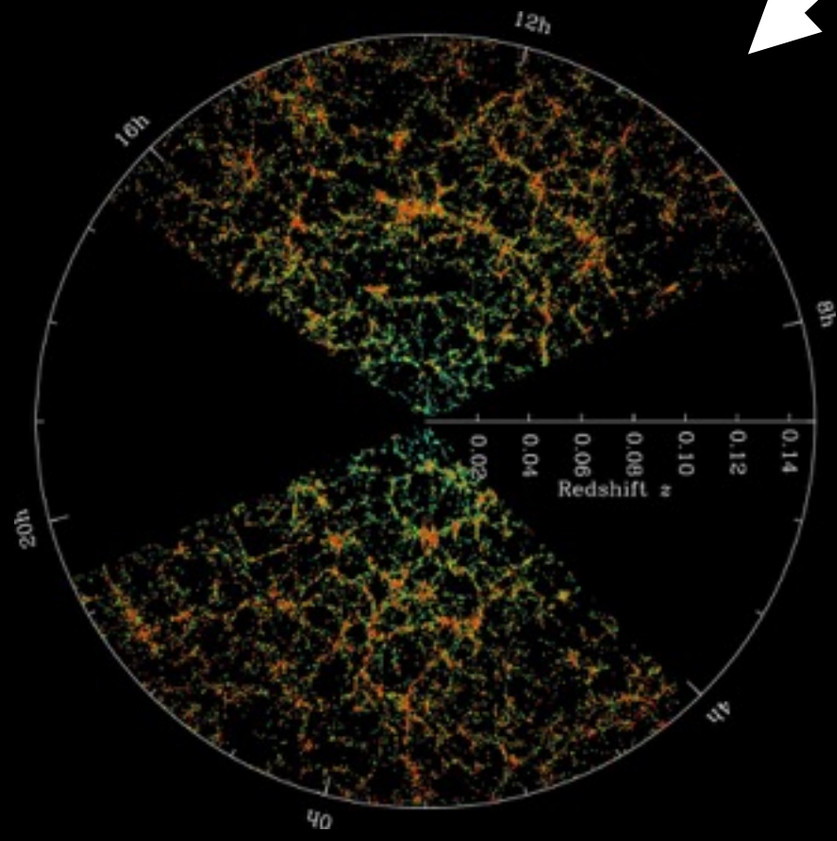
Volume mapping

Sloan Digitial Sky Survey (2000 - present)

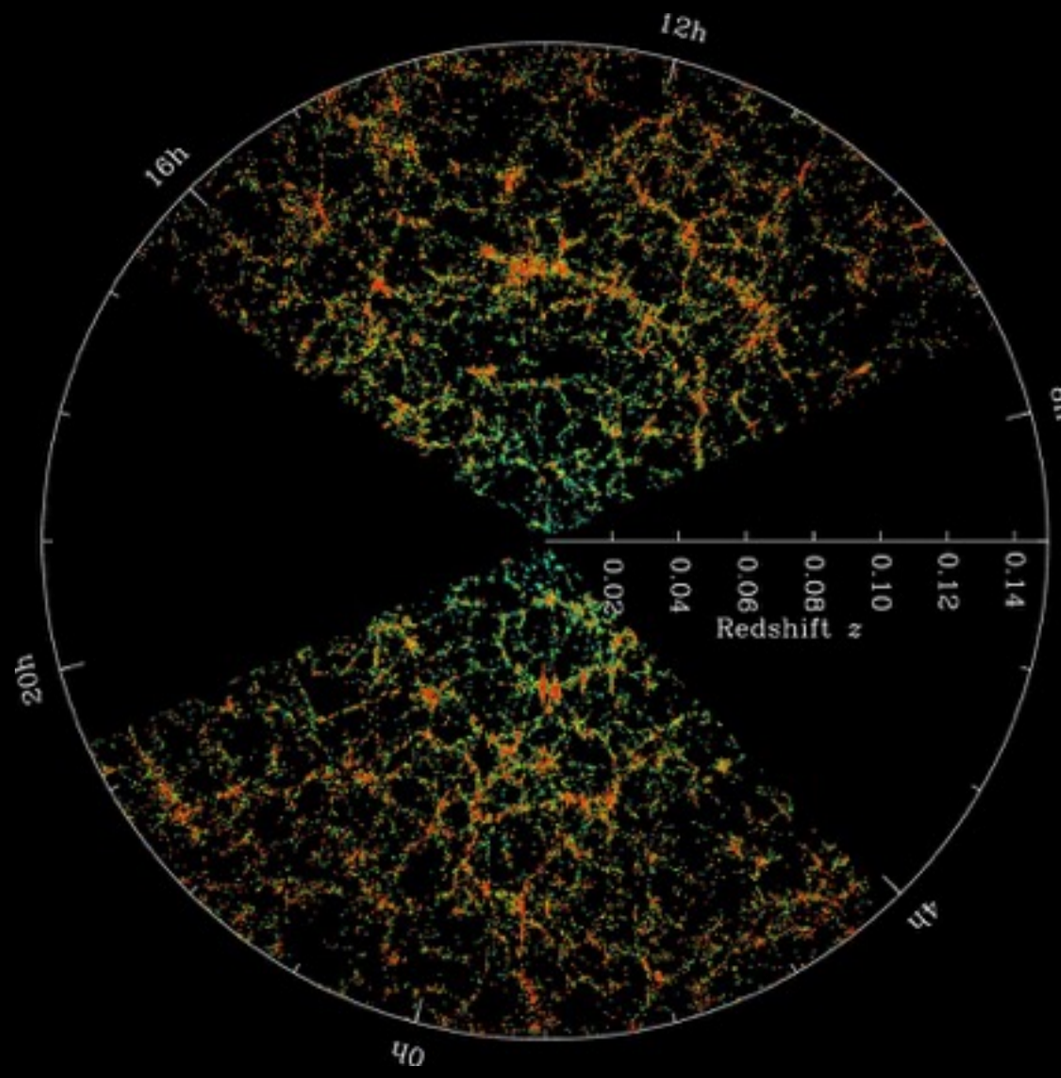
Volume mapping



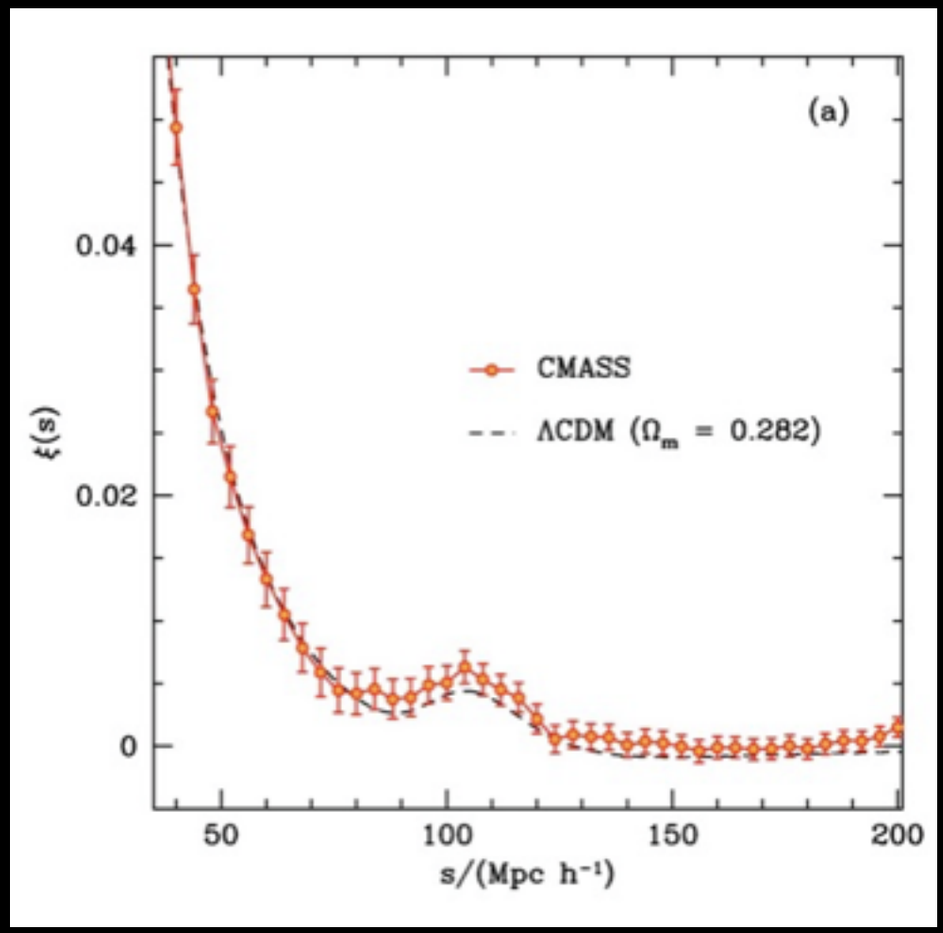




Baryon Acoustic Oscillations

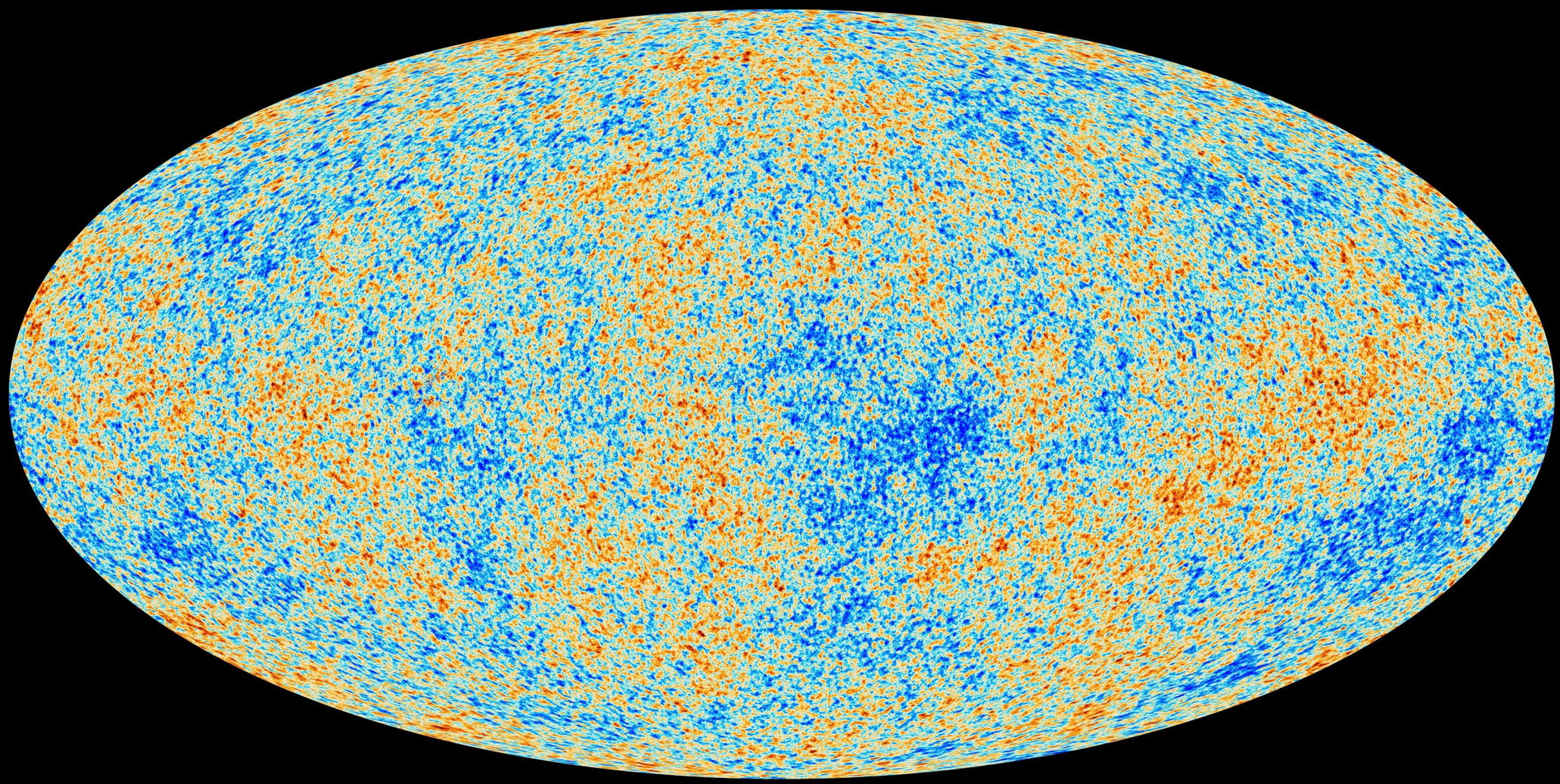


2-point correlation function

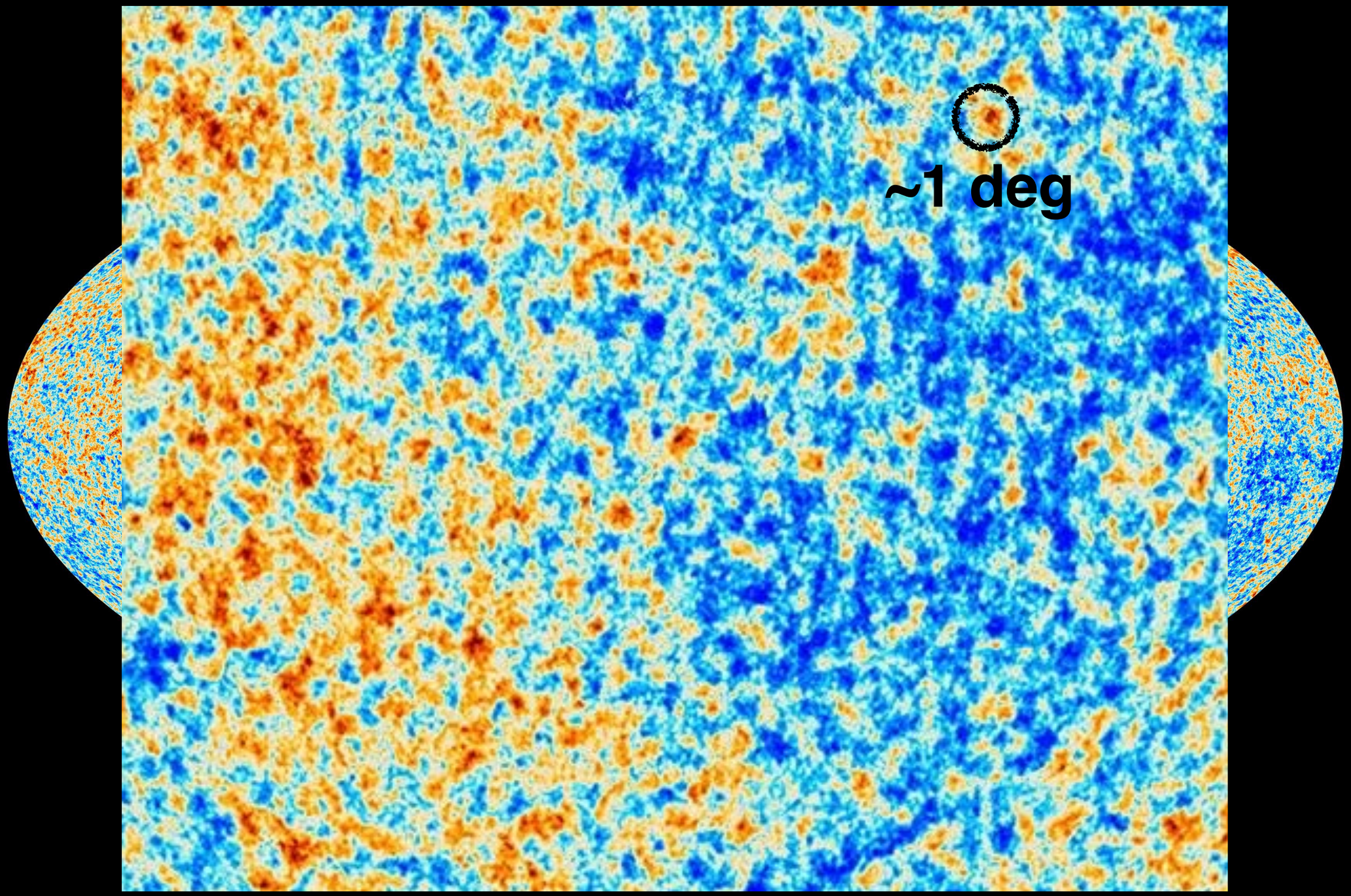


Sanchez et al, 2012

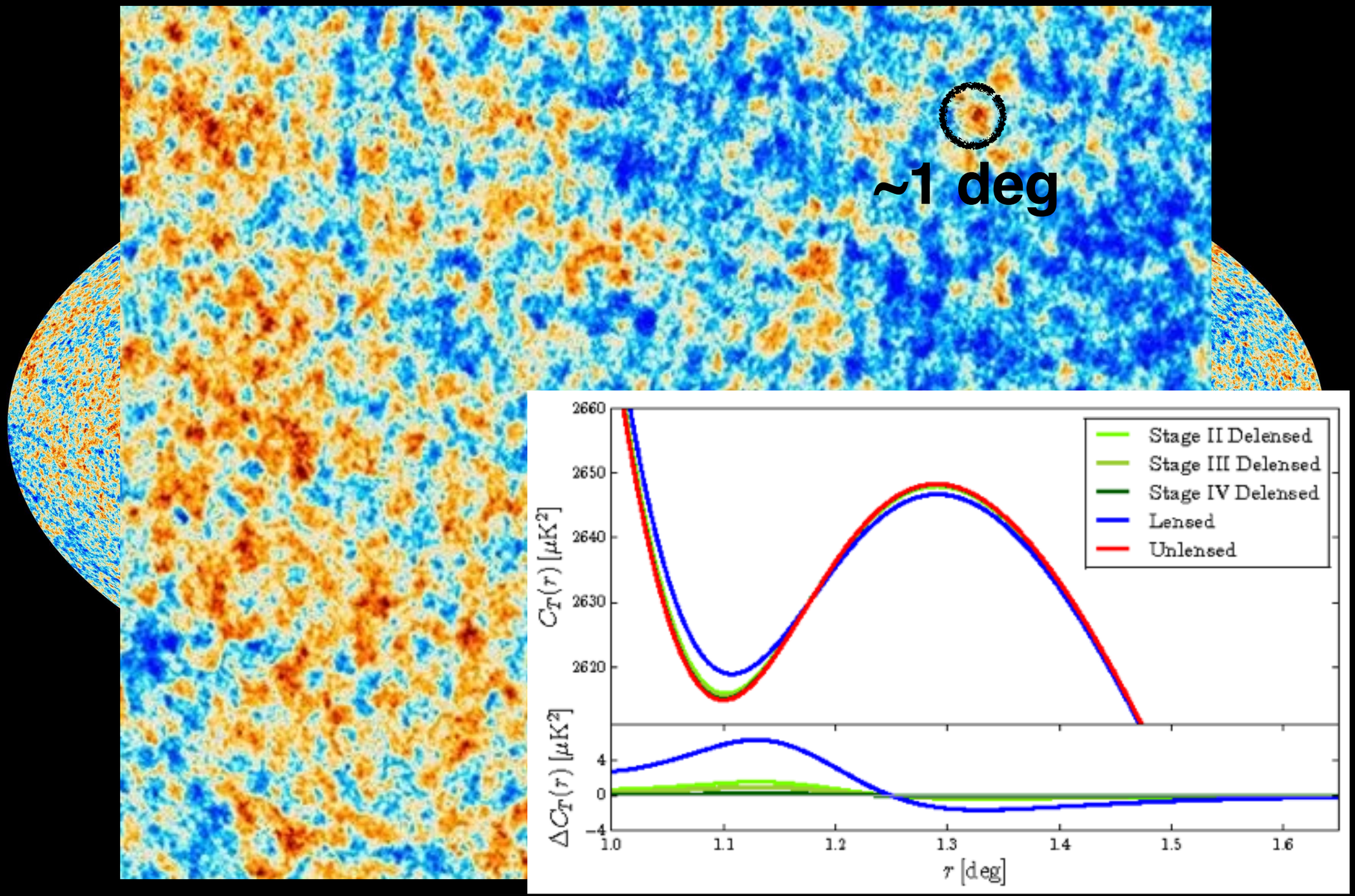
Baryon Acoustic Oscillations



Baryon Acoustic Oscillations



Baryon Acoustic Oscillations

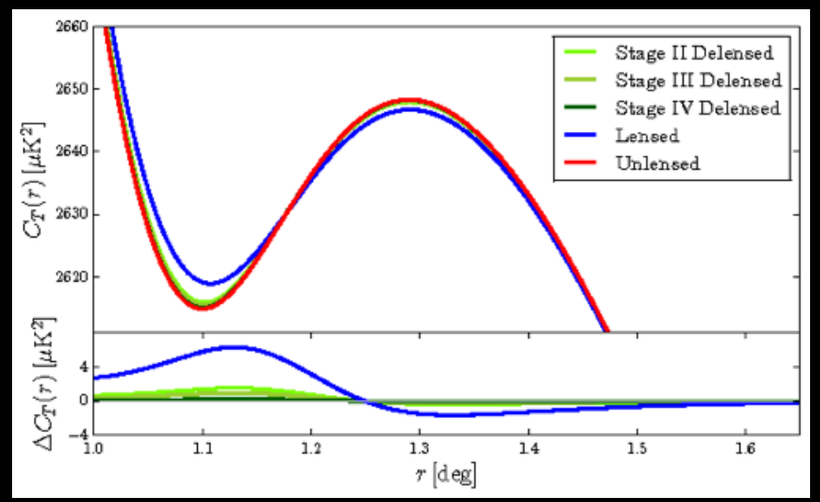


Green, D (2016)

Baryon Acoustic Oscillations

Real space

CMB



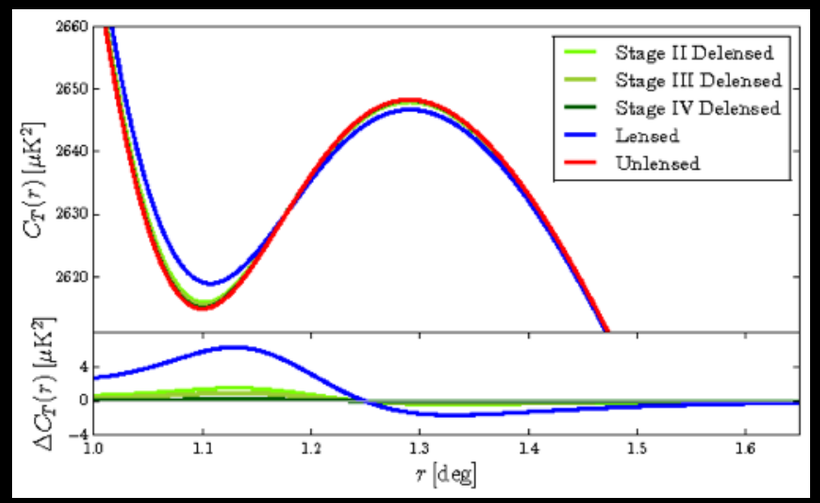
Green, D (2016)

Baryon Acoustic Oscillations

Real space

Fourier space

CMB



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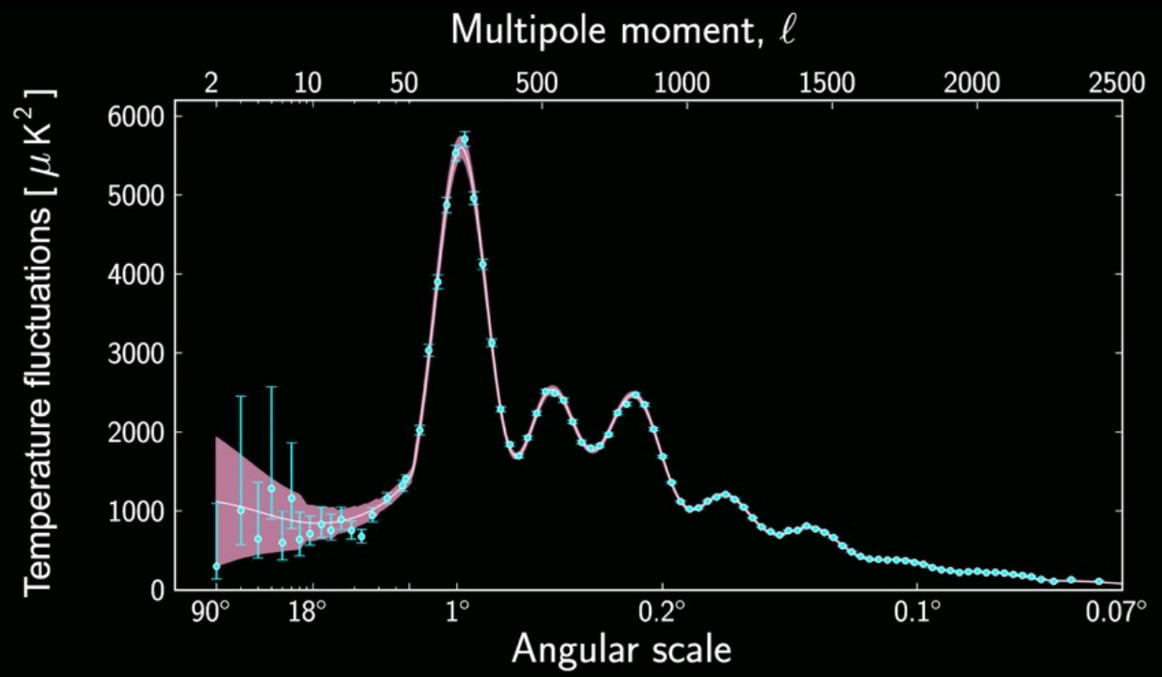

Baryon Acoustic Oscillations

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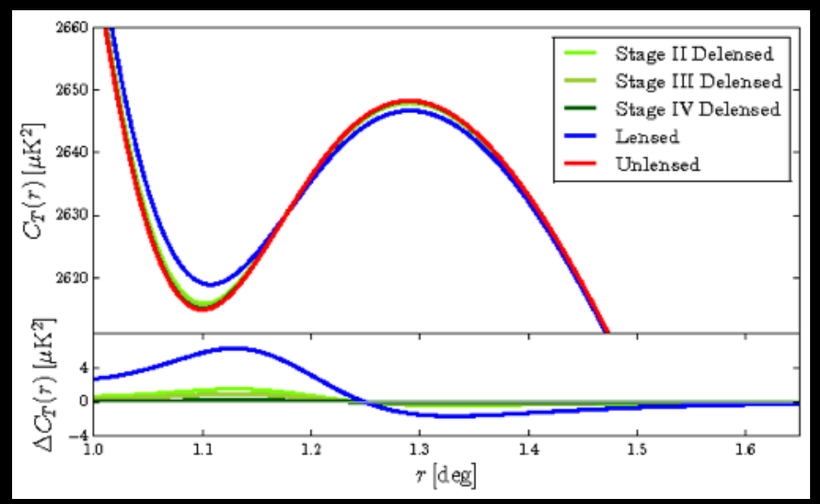
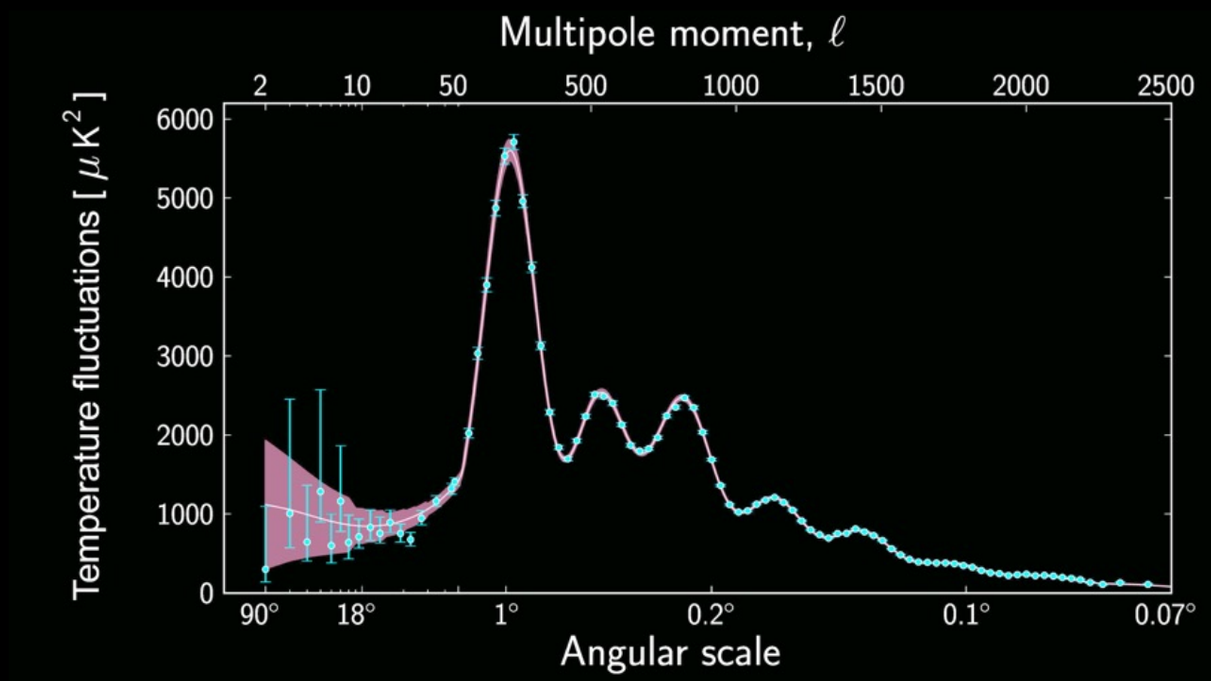
Fourier space

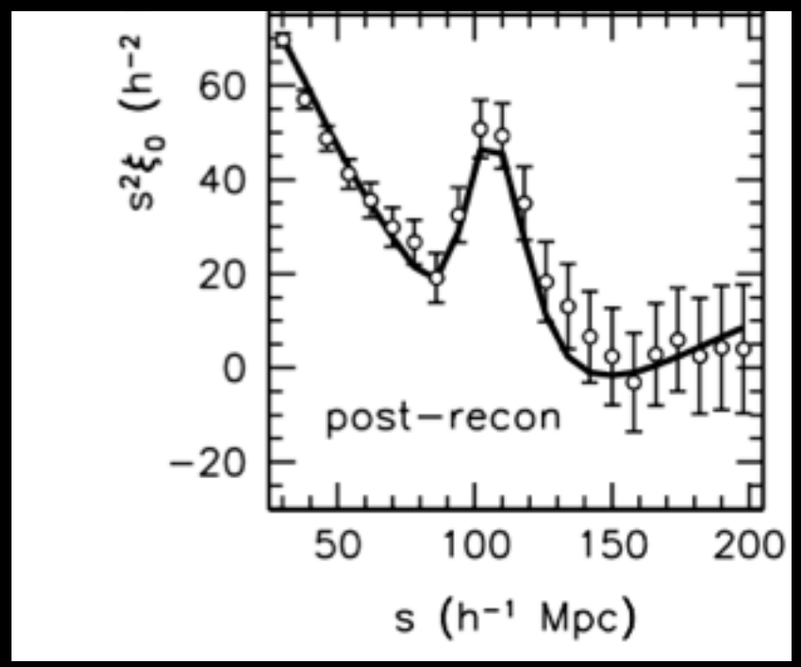
CMB



Green, D (2016)



SDSS



Anderson, et al (2013)

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Fourier space

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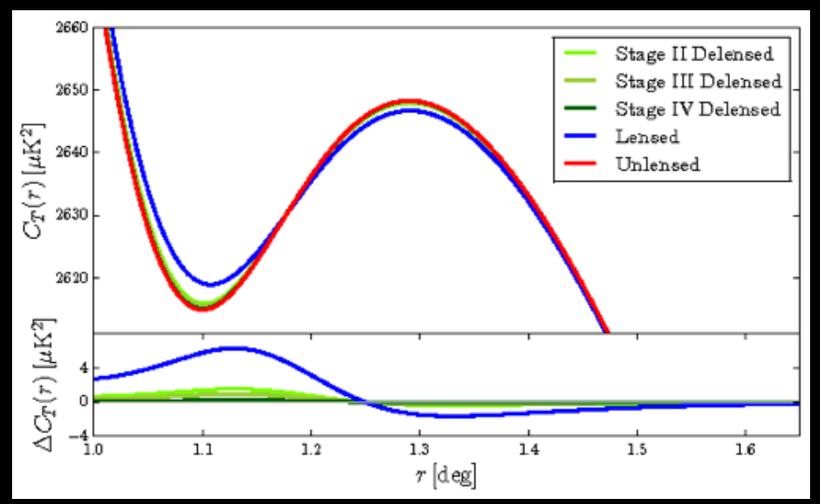
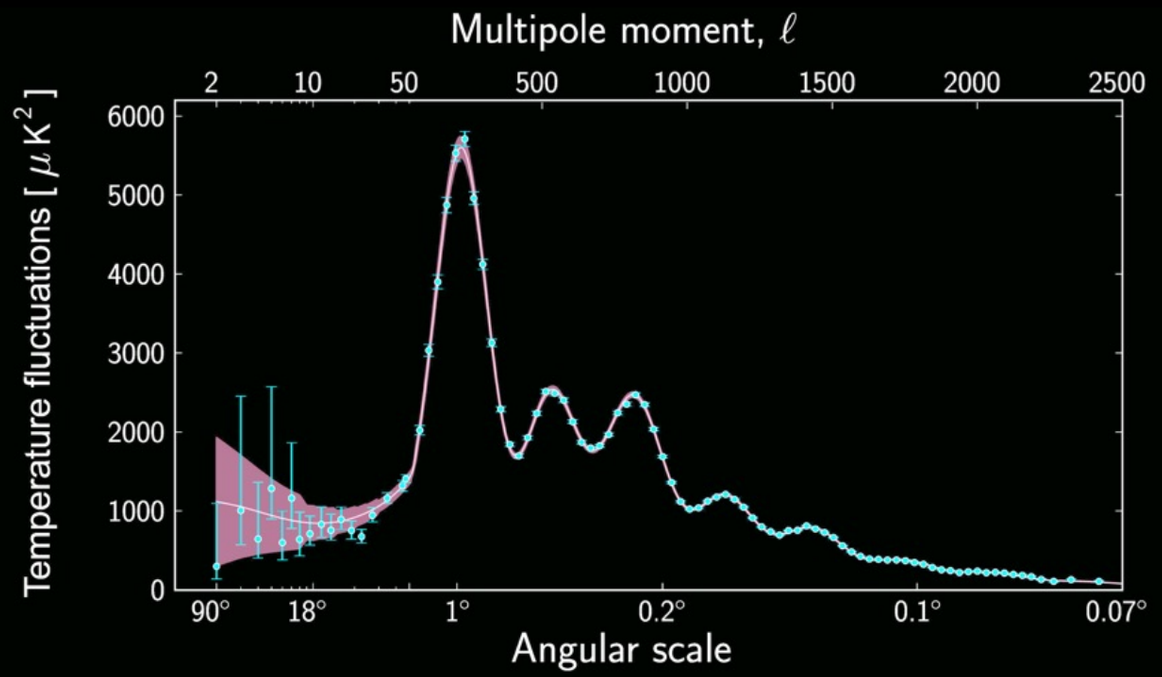
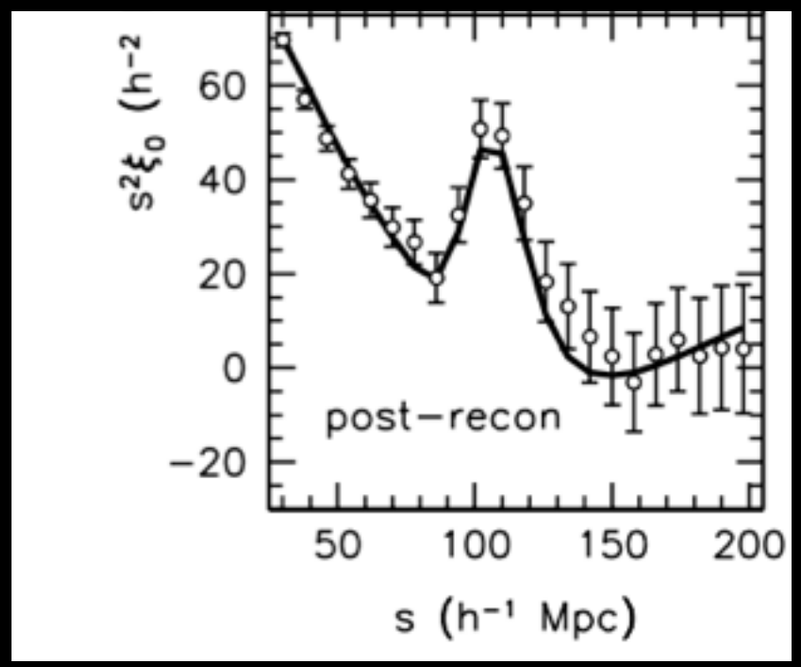


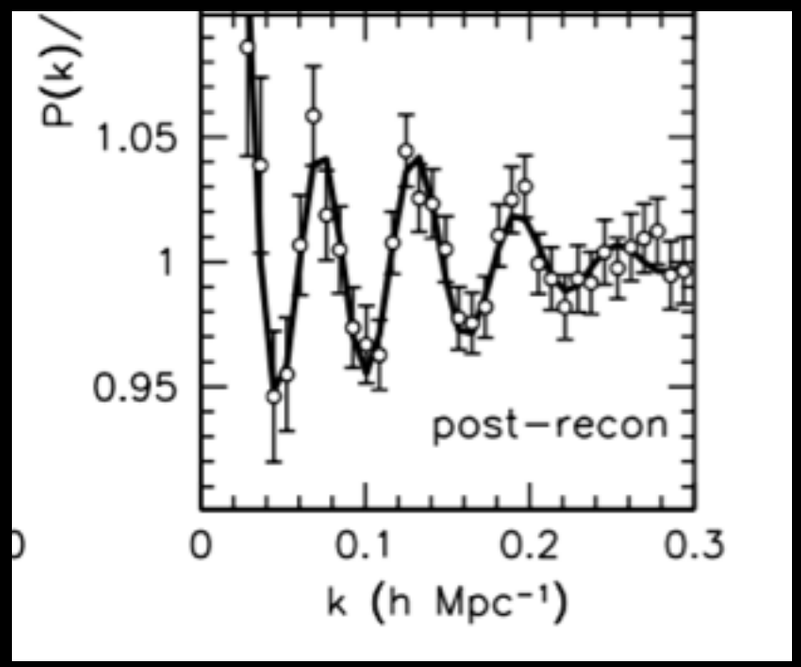
Green, D (2016)



SDSS



Anderson, et al (2013)



Baryon Acoustic Oscillations

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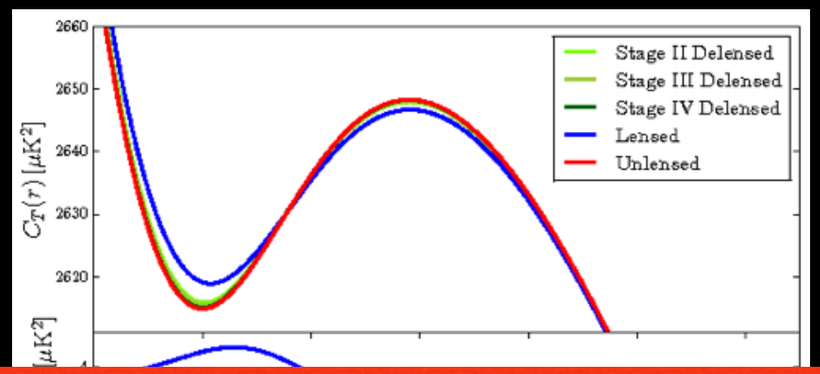
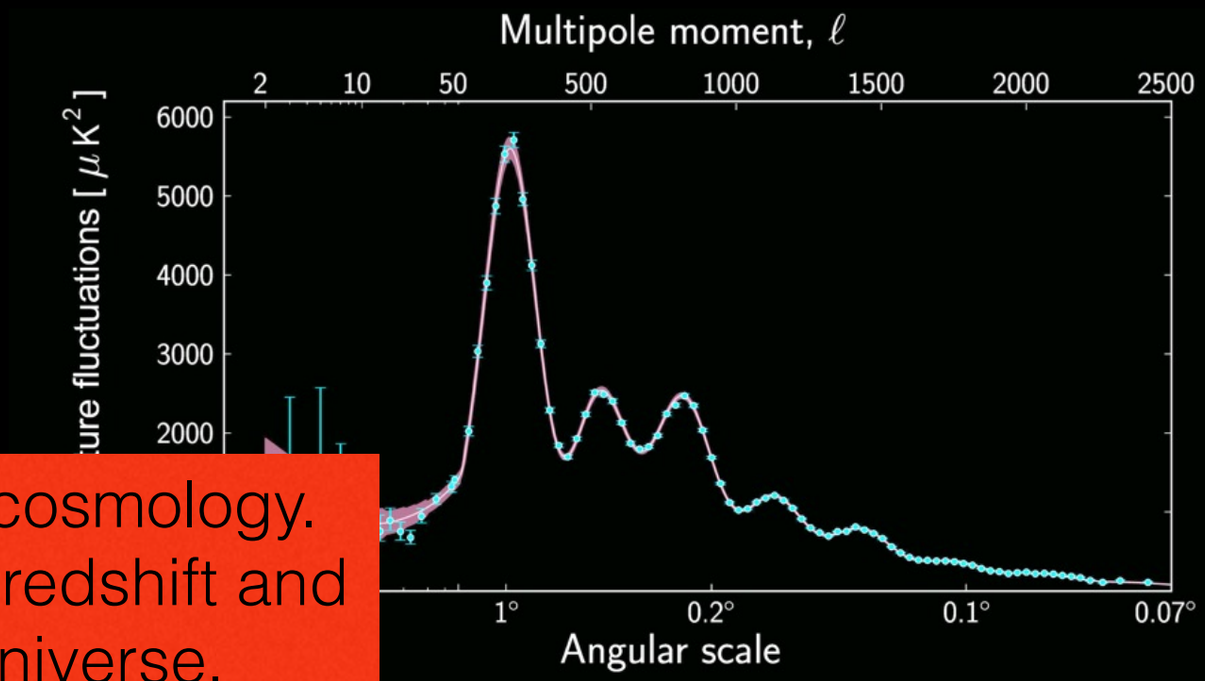
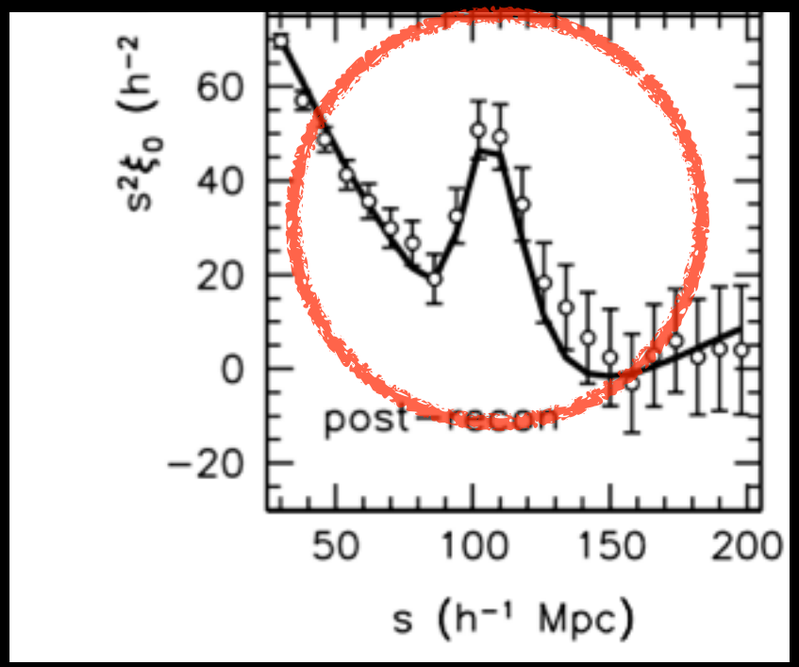
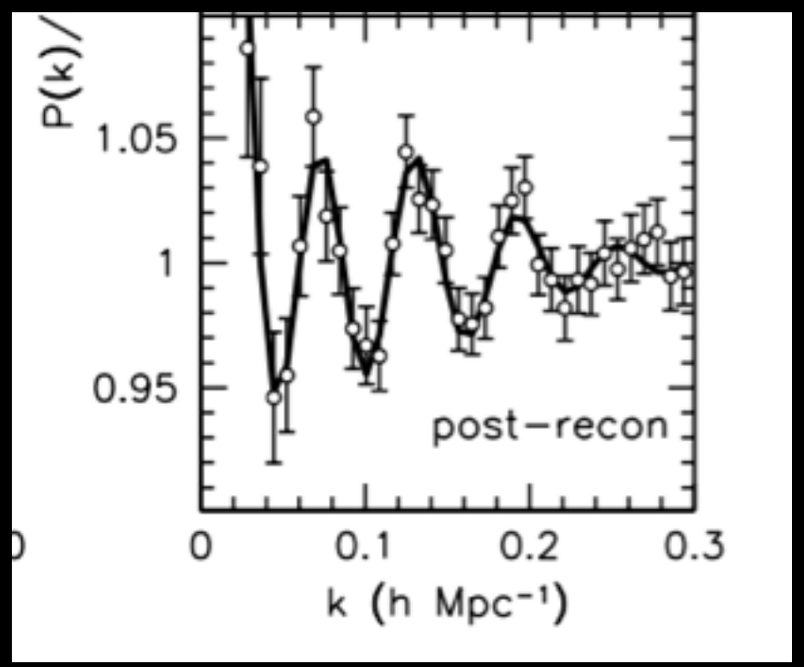




Standard length scale ("ruler") for cosmology. Map out angular size as function of redshift and measure expansion history of universe.

SDSS





Anderson, et al (2013)

Baryon Acoustic Oscillations

- Recall Hubble's law: v = H0 * D
- Redshift is an observable and gets you radial velocity, v. Distance to an object, D, is very hard to measure, especially as D gets large. But with it, can measure H as a function of redshift, i.e. expansion history of universe.
- Measuring the apparent brightness of supernova "standard candles" is one way to get D — led to the discovery of accelerated expansion. But supernovae are plagued by astrophysical systematics (e.g. dust, not actually standard, etc.)
- Measuring the apparent angular size of the BAO "standard ruler" similarly gets D, and has the advantage of being relatively free of systematics.

Baryon Acoustic Oscillations

BAO is considered the cleanest way to measure the expansion history of the universe.

The “Dark Energy surveys” you hear about can target BAO if they can measure redshifts, but measuring spectra is more difficult and more expensive than taking pictures.

Volume mapping

SDSS (2000 -)

DES (2012 -)

DESI (2019 - 2024)

LSST (2022 -)

Volume mapping

SDSS (2000 -)

DES (2012 -)

DESI (2019 - 2024)

LSST (2022 -)

Volume mapping

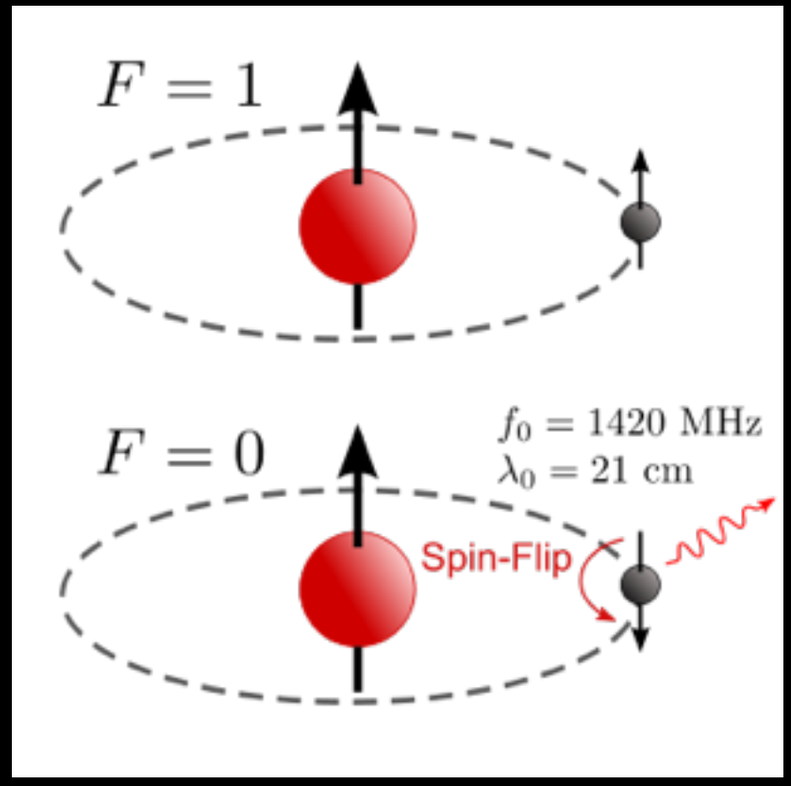
The DOE will fund a next generation (“Stage IV”) dark energy survey. An obvious next thing to do is a spectrographic follow up to LSST, but things are starting to get expensive!

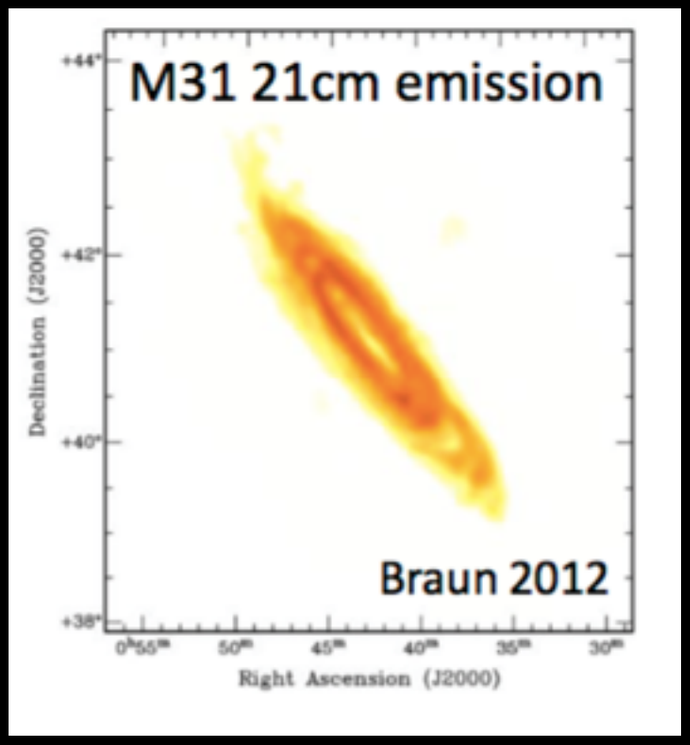
21-cm intensity mapping

Option 2: Instead of detecting optical starlight from galaxies, detect radio emission from neutral hydrogen.

21-cm intensity mapping

Neutral hydrogen has a line at **1.4 GHz (21 cm)** from a hyperfine transition. Galaxies have neutral hydrogen in abundance. Observe them at radio frequencies.

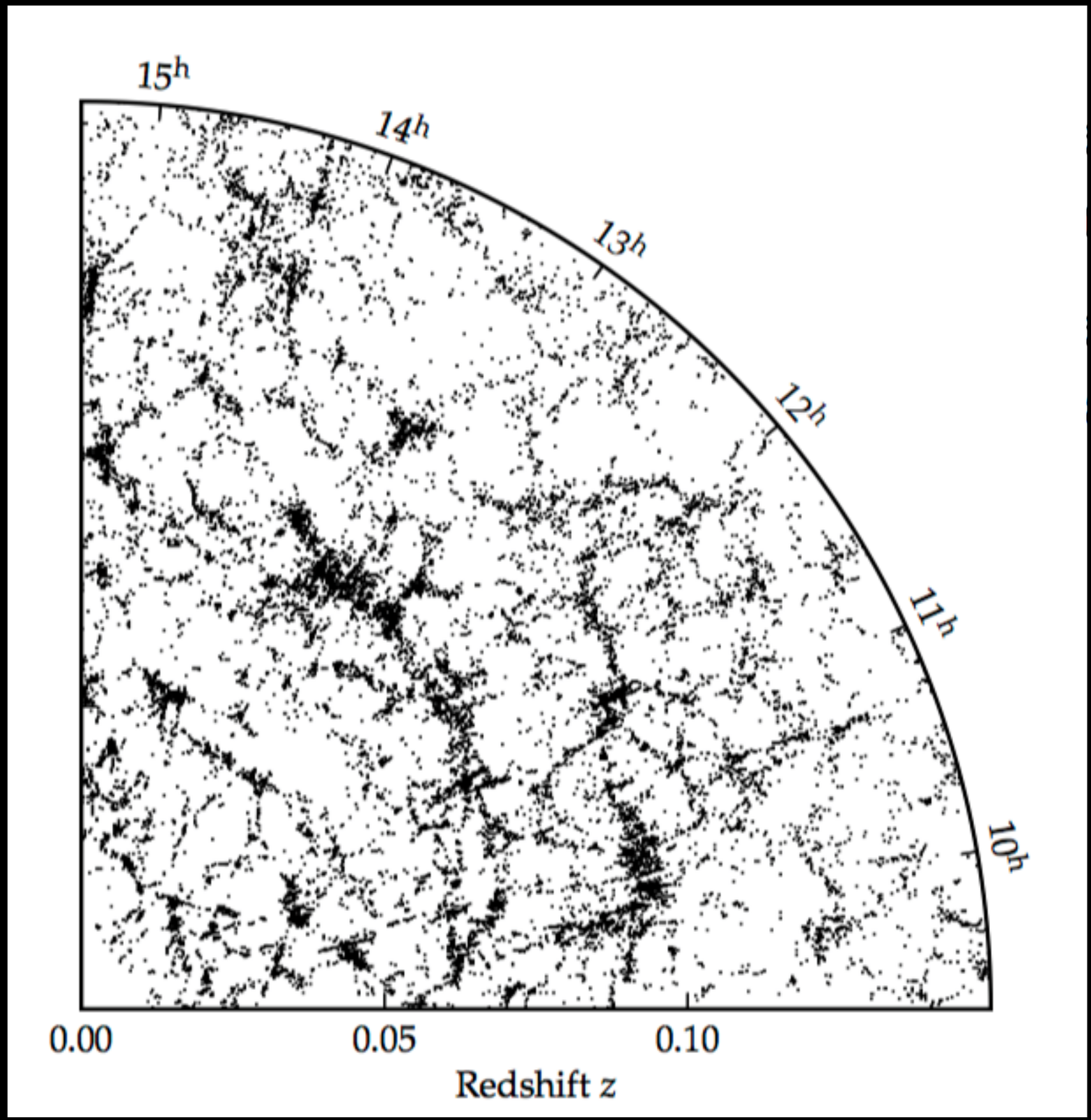




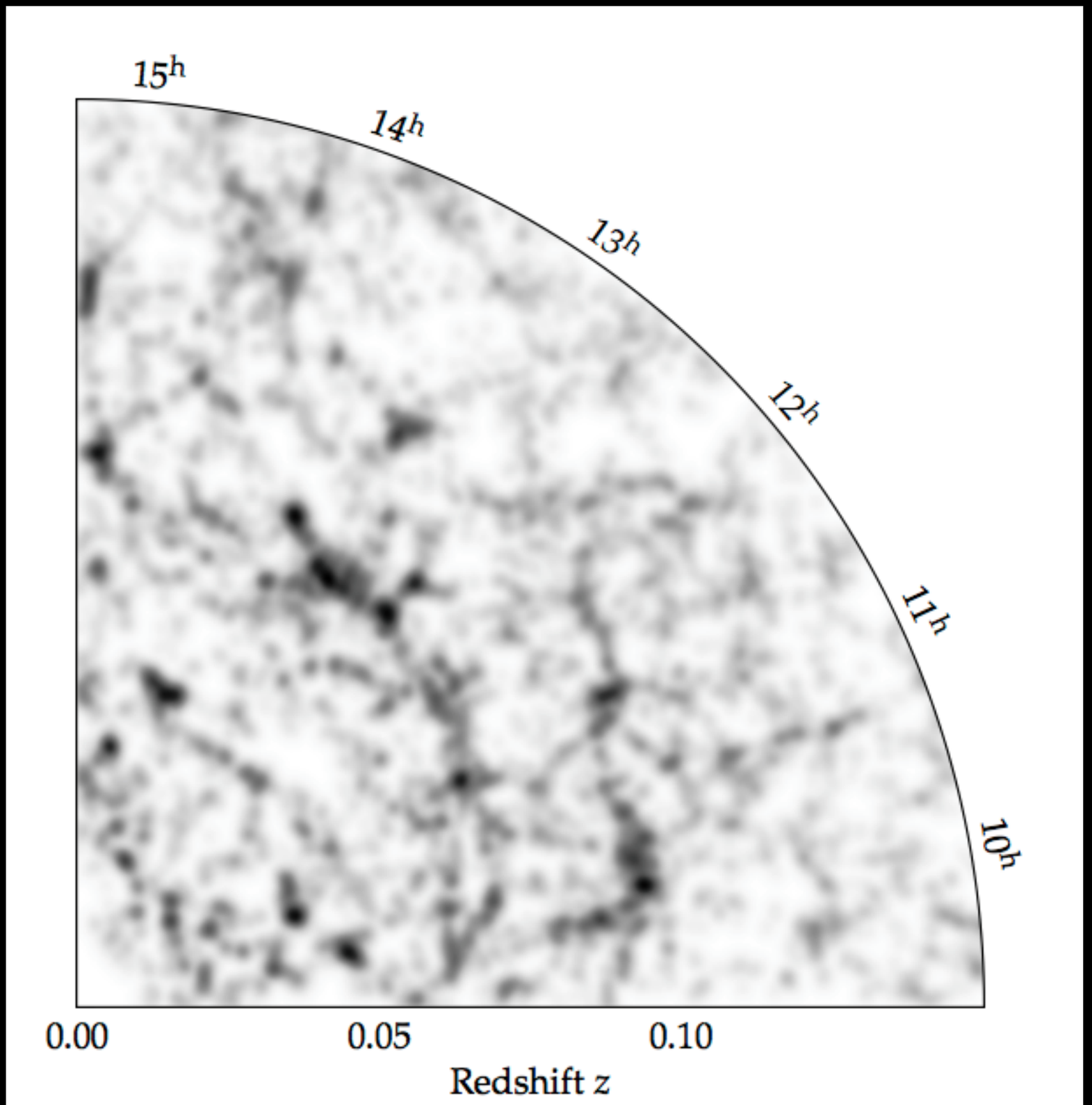
21-cm intensity mapping

- Angular resolution of a telescope ~λ / D, where λ is the wavelength and D is the telescope aperture diameter.
- Angular resolution will be poor relative to an optical telescope. But who cares? We're not astronomers, we don't care about individual galaxies.

21-cm intensity mapping

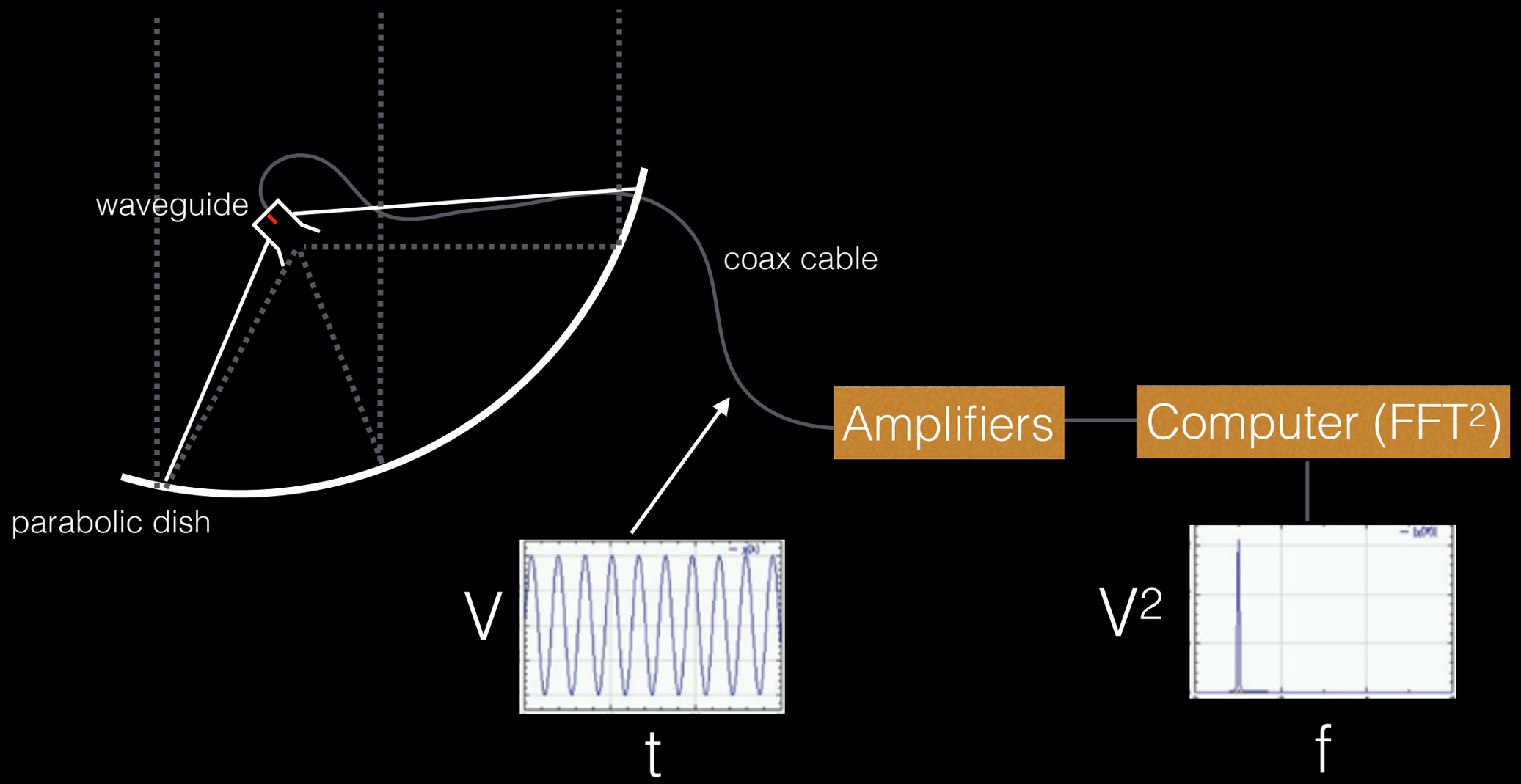


21-cm intensity mapping

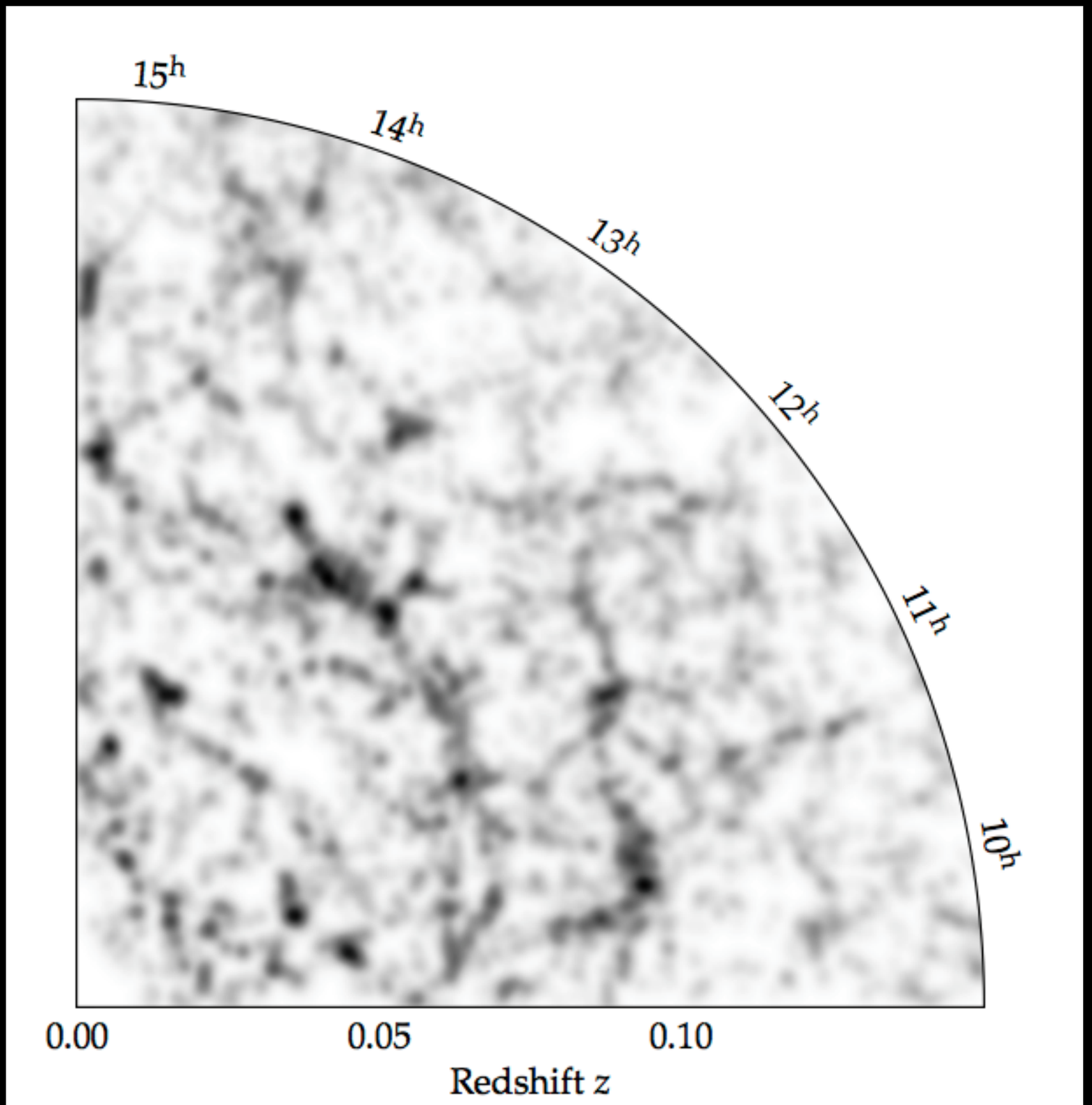


Radio telescopes

At frequencies < few GHz, one can just directly sample the electric field, Fourier transform, and square to get I(nu).
Automatically get high resolution mapping of structure along the line of sight.



21-cm intensity mapping



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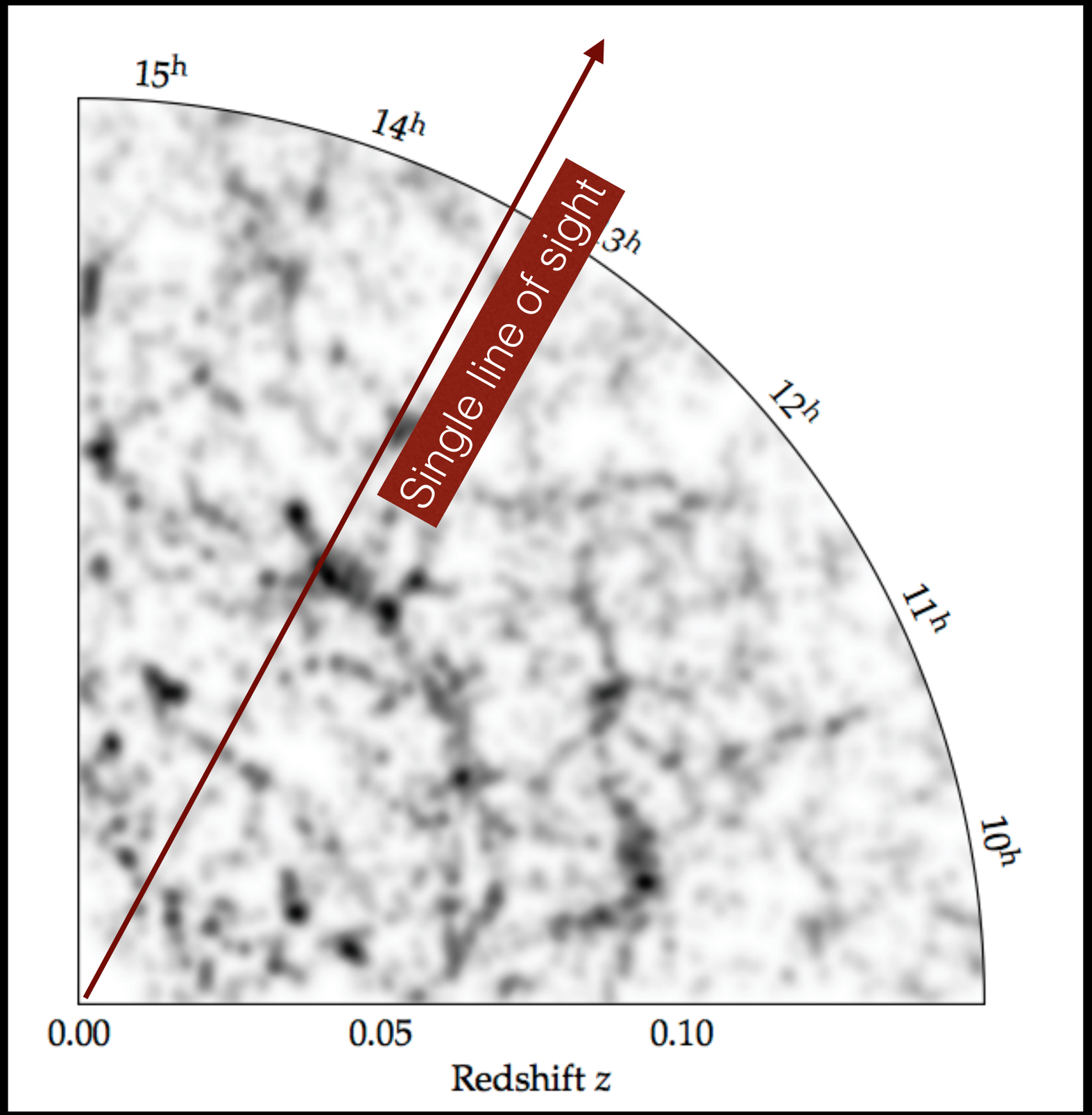

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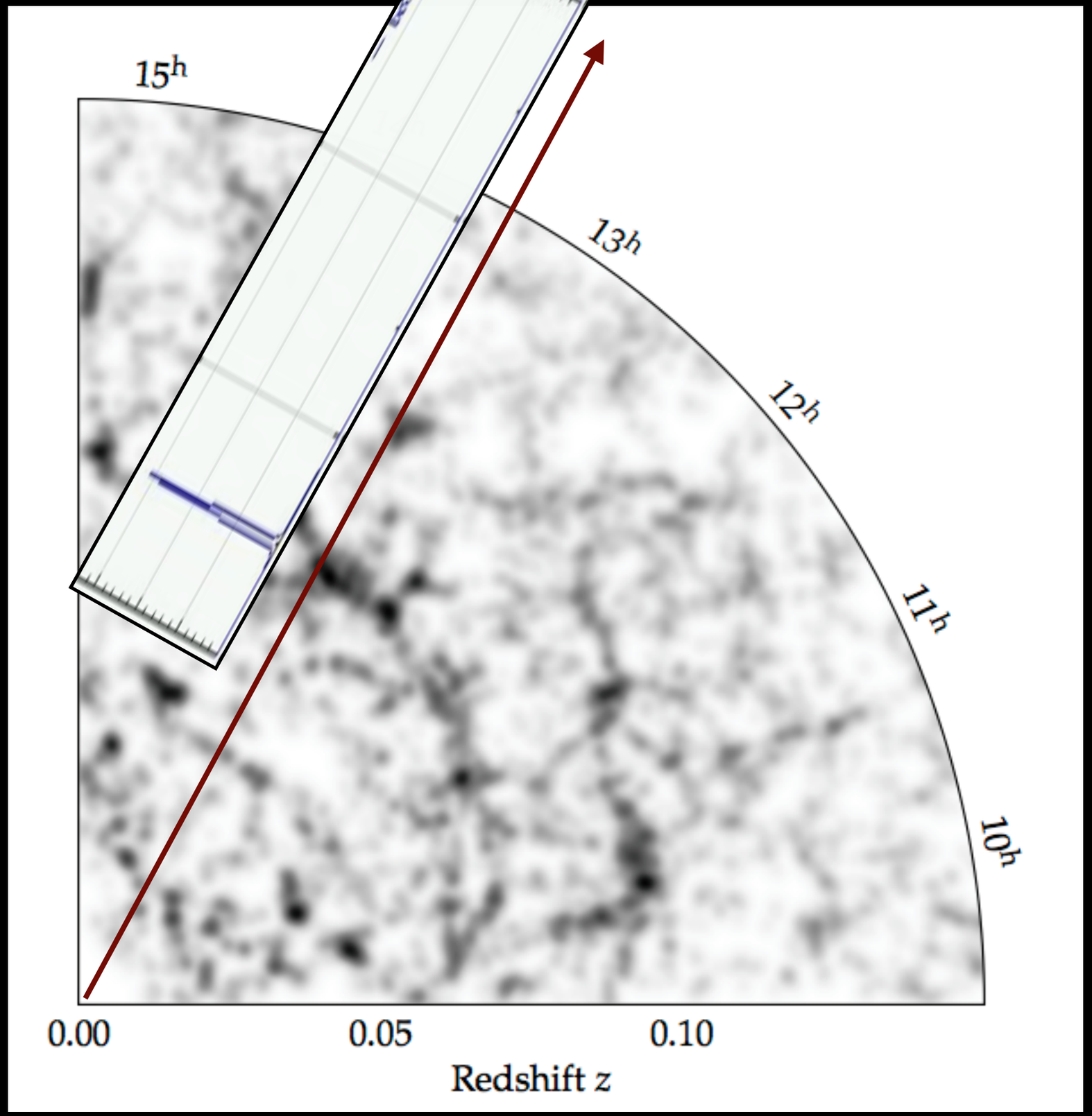
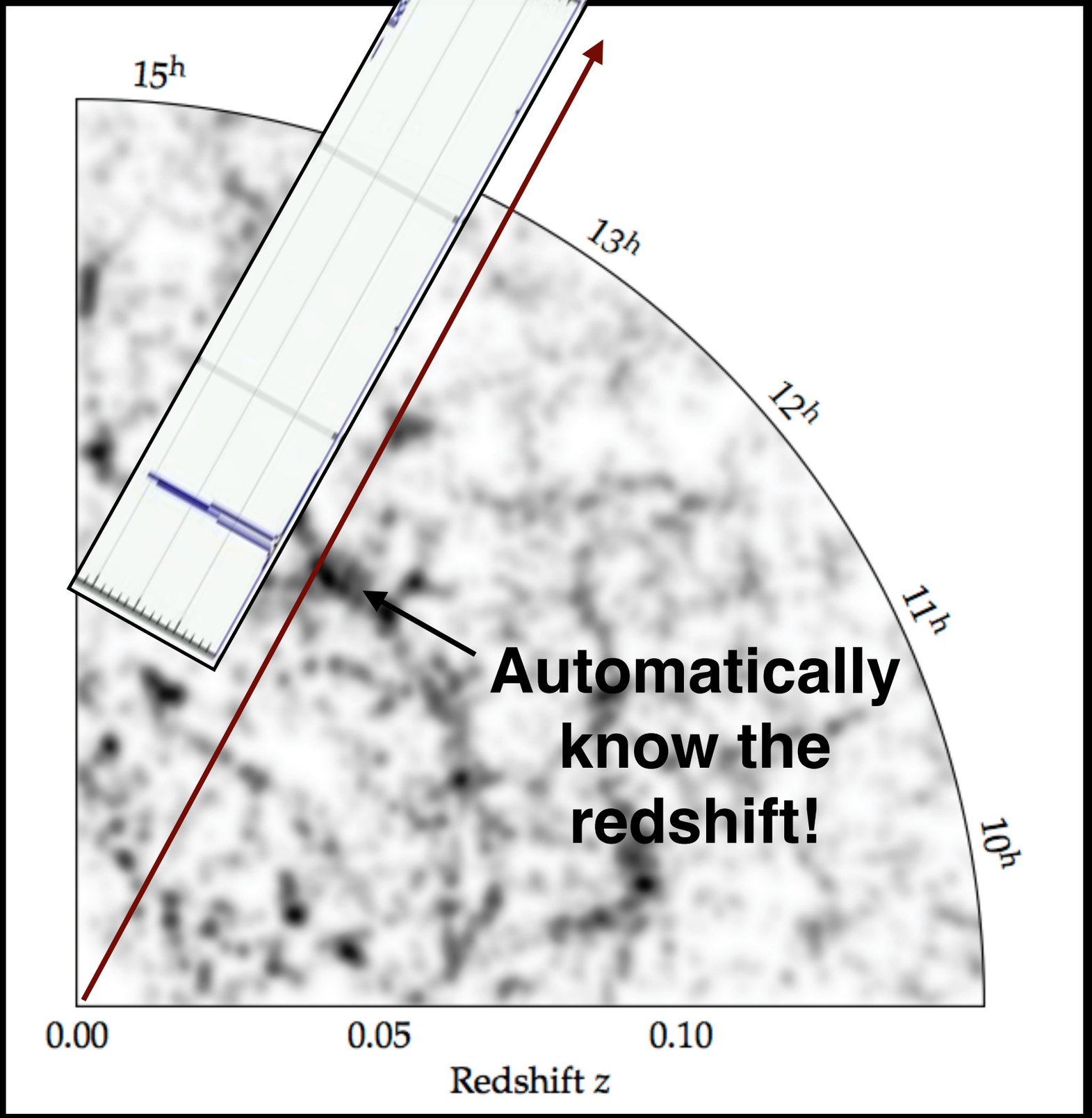
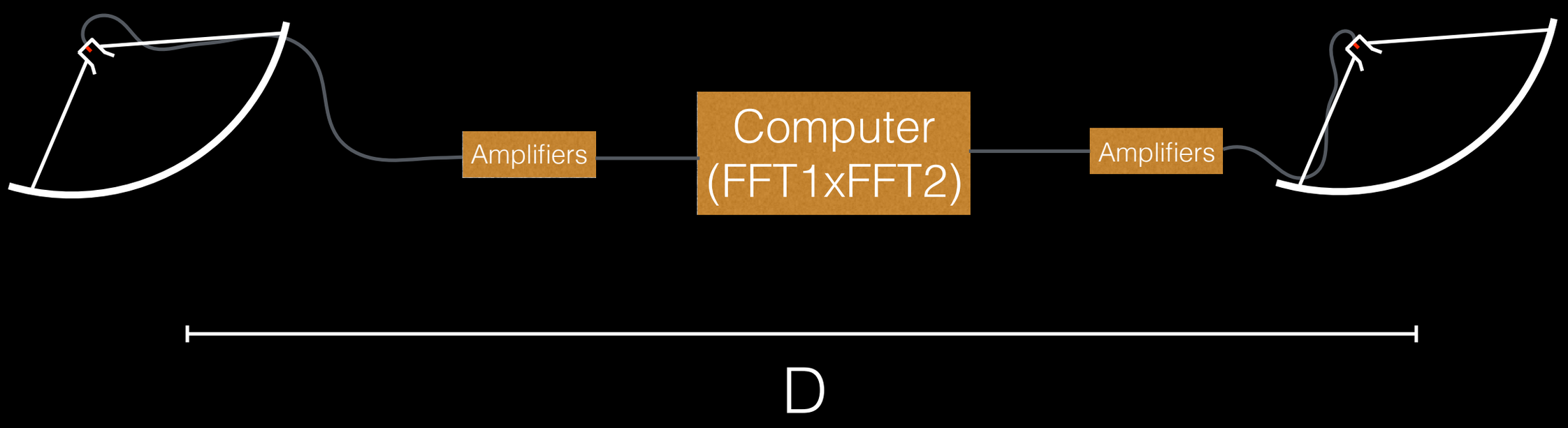


21-cm intensity mapping



Radio telescopes

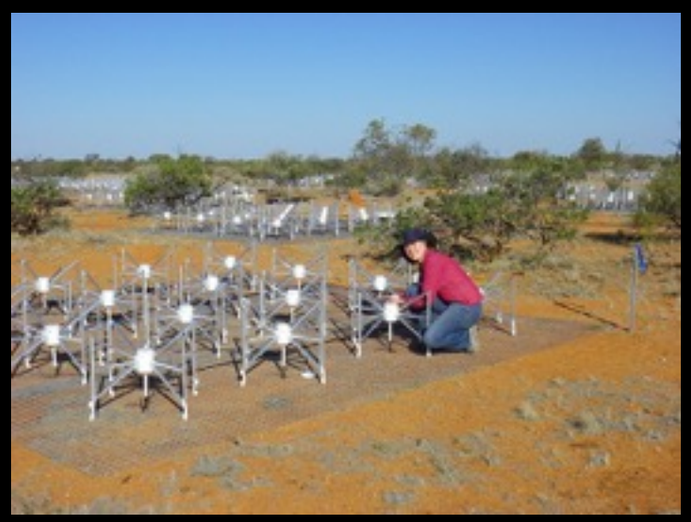
Operate multiple dishes as an interferometer
to increase the effective D and get better
angular resolution, i.e. perpendicular to the
line of sight



Current experiments

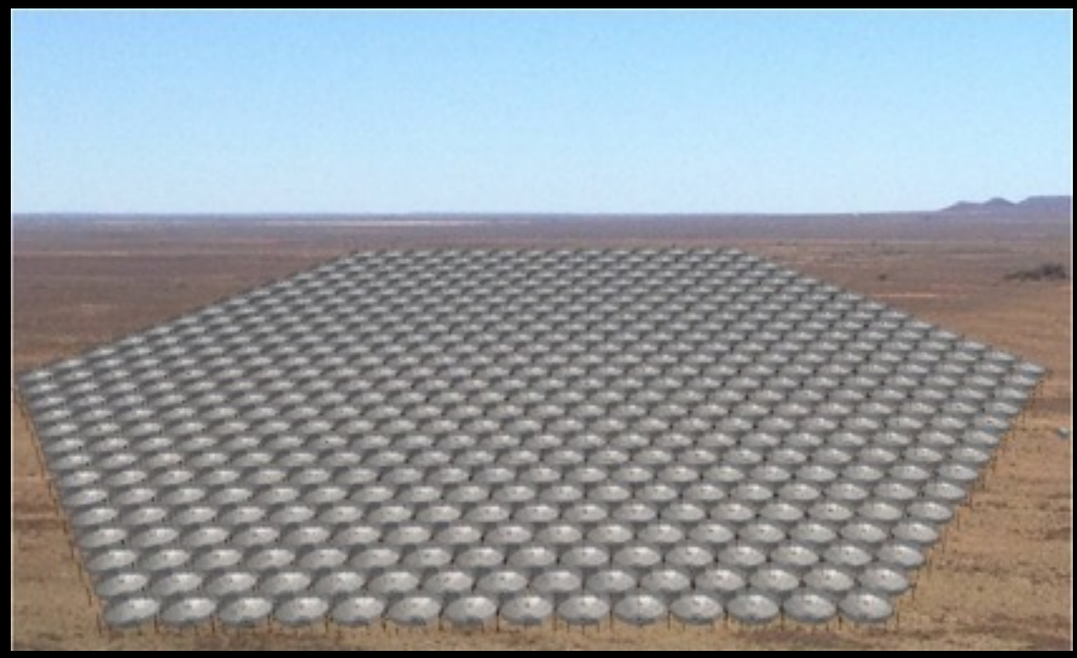
LOFAR

MWA



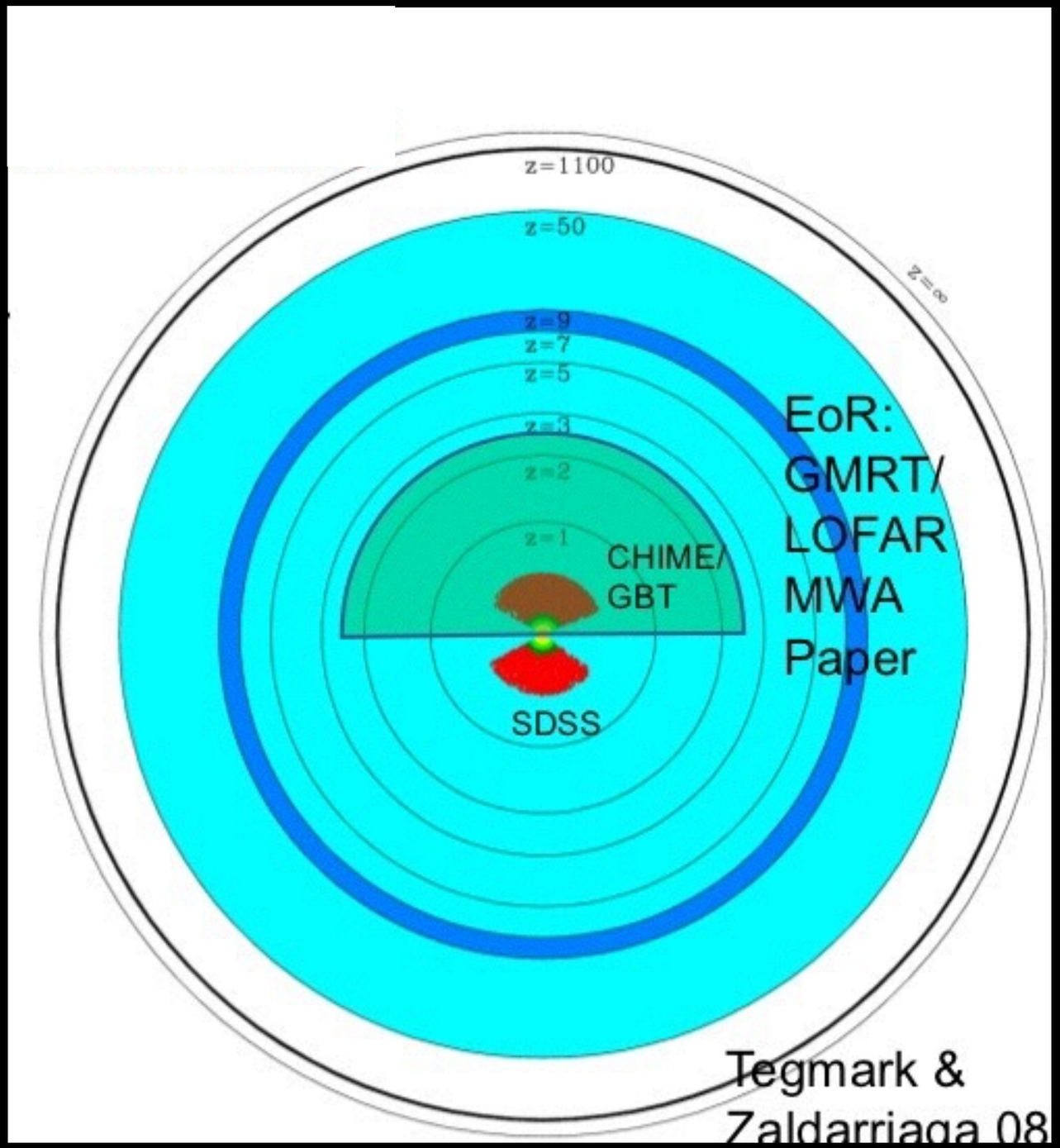
PAPER

HERA (funded)



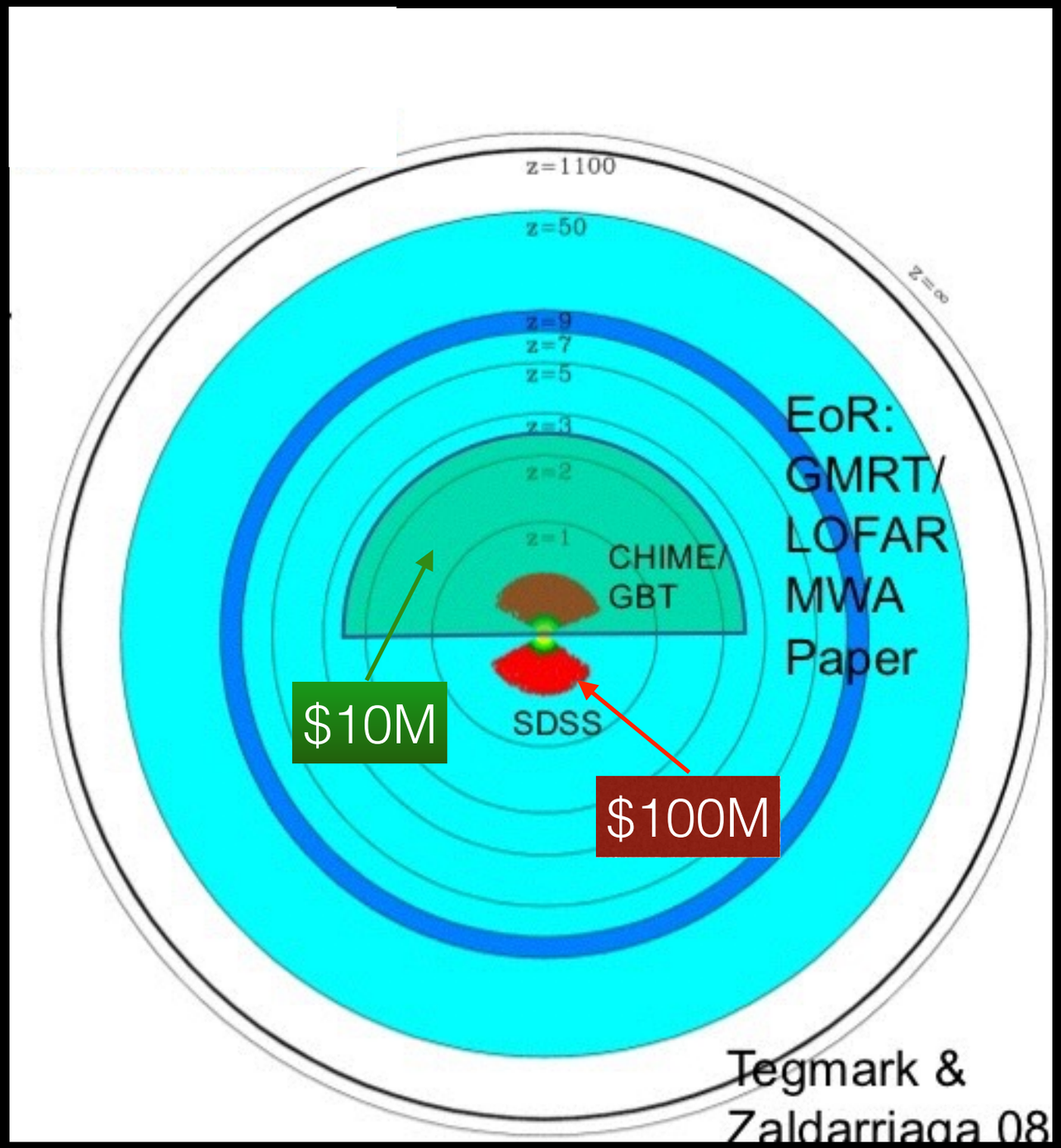
CHIME

Current experiments



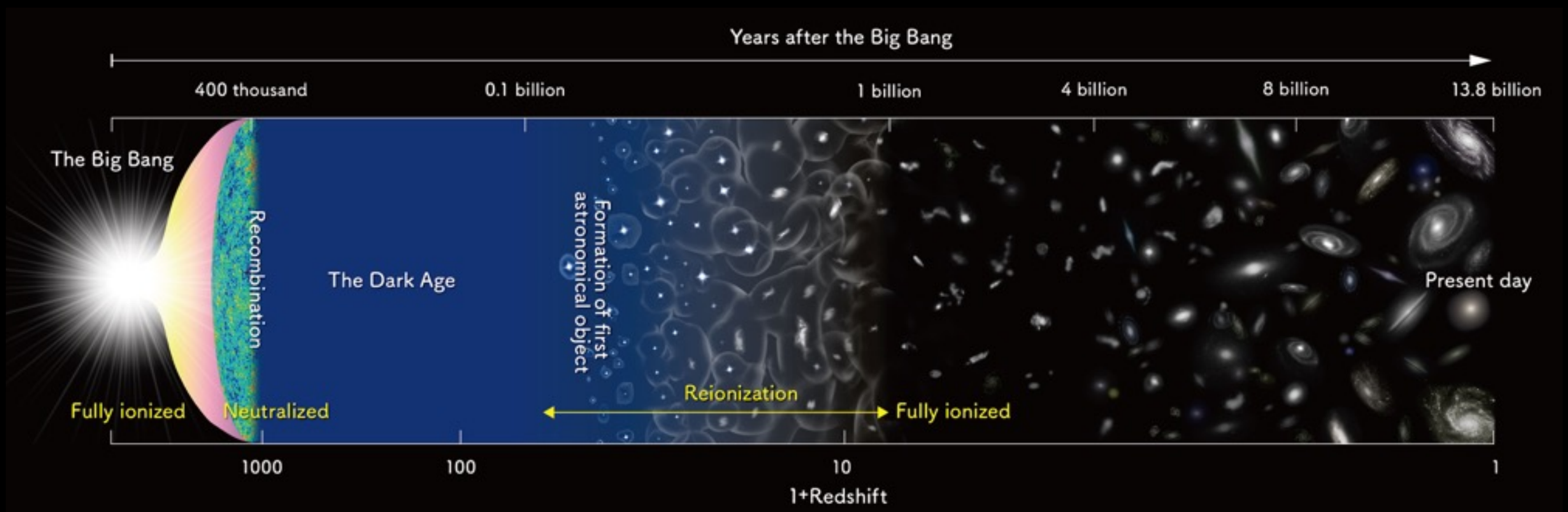
Ue-Li Pen

Current experiments

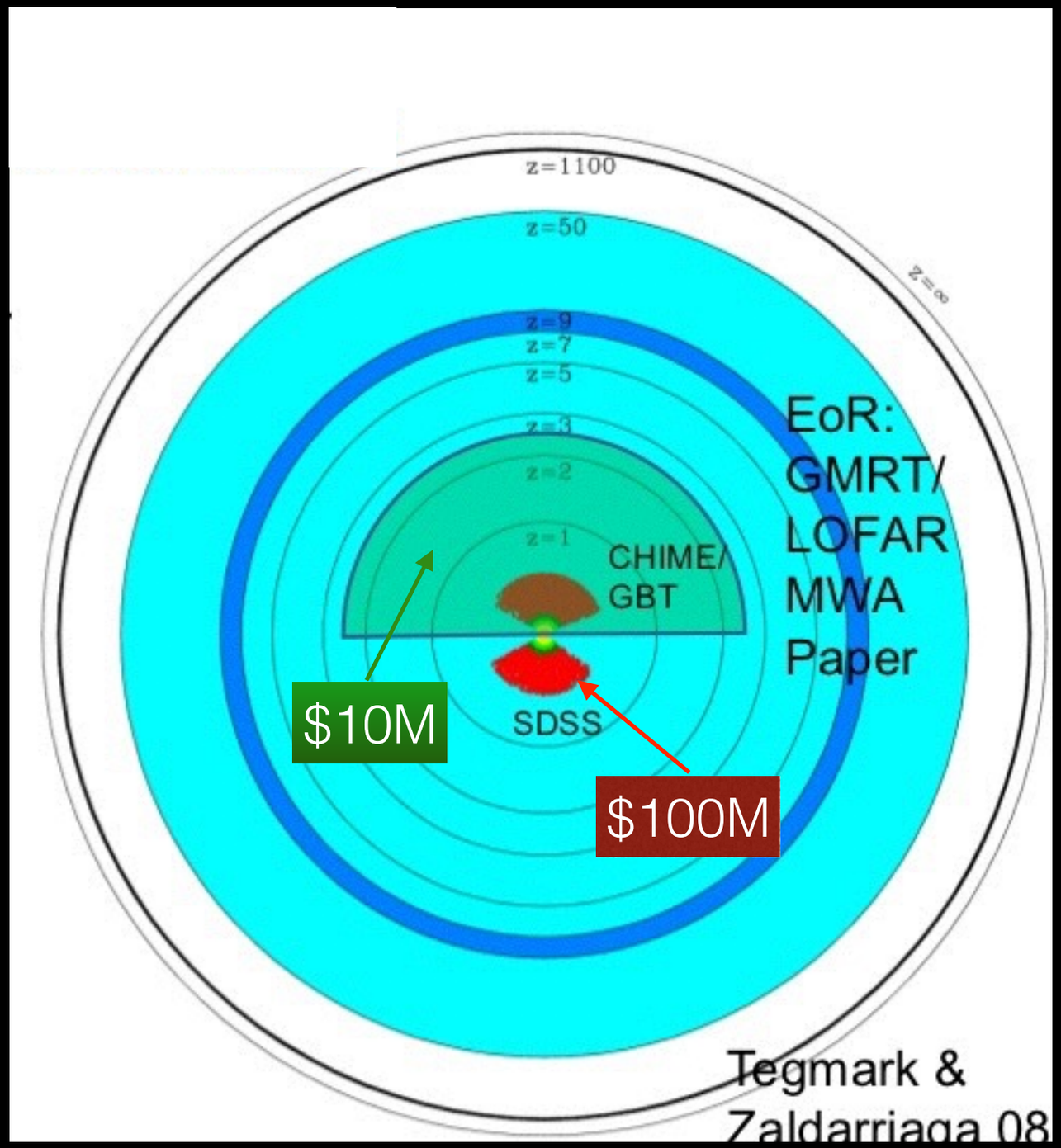


Ue-Li Pen

Cosmological paradigm

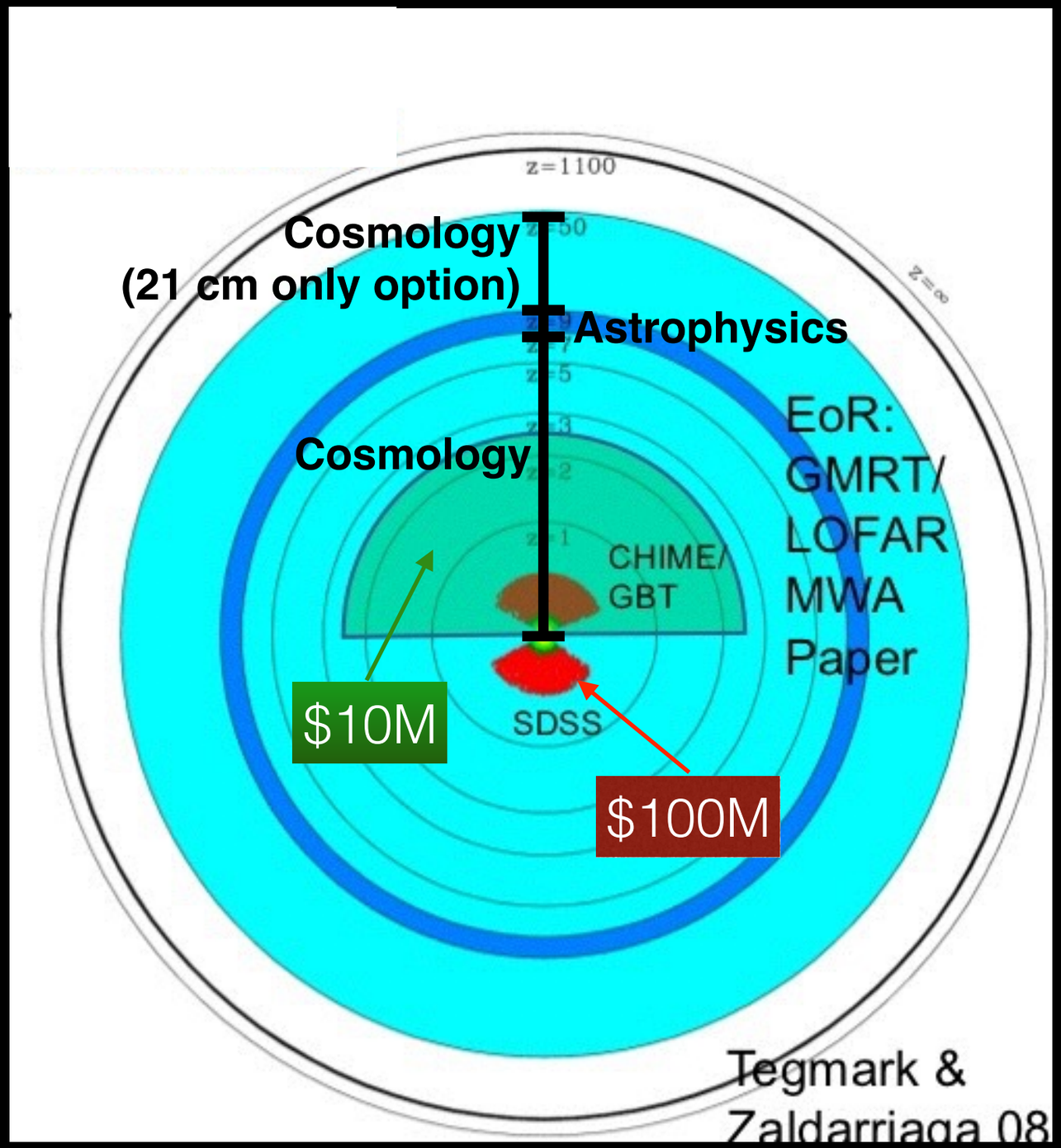


Current experiments



Ue-Li Pen

Current experiments

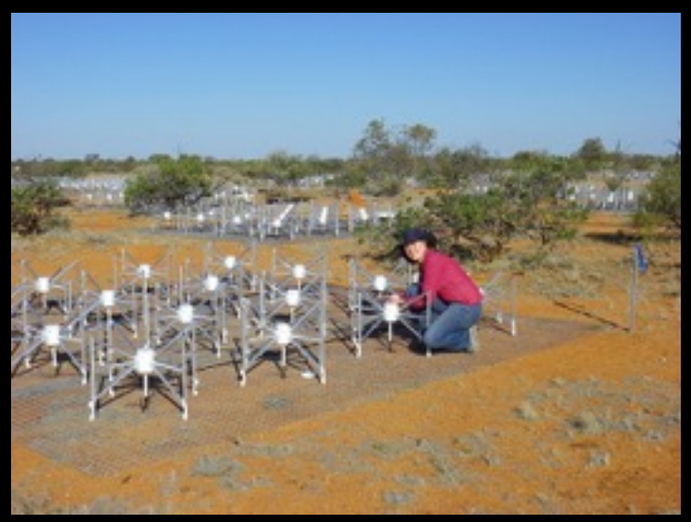


Ue-Li Pen

Current experiments

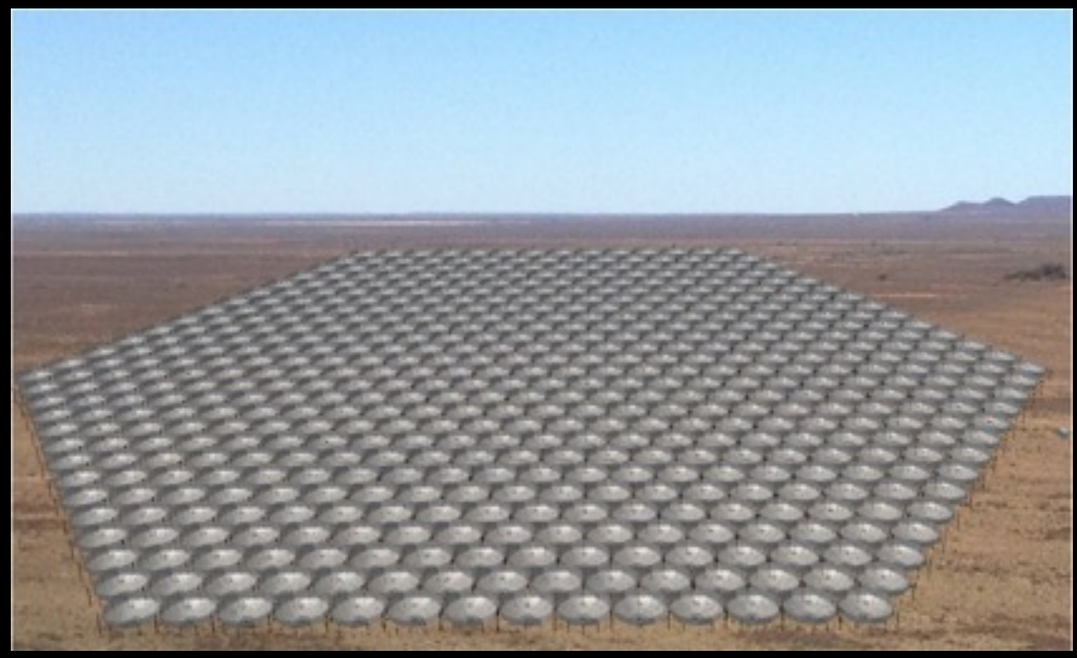
LOFAR

MWA



PAPER

HERA (funded)

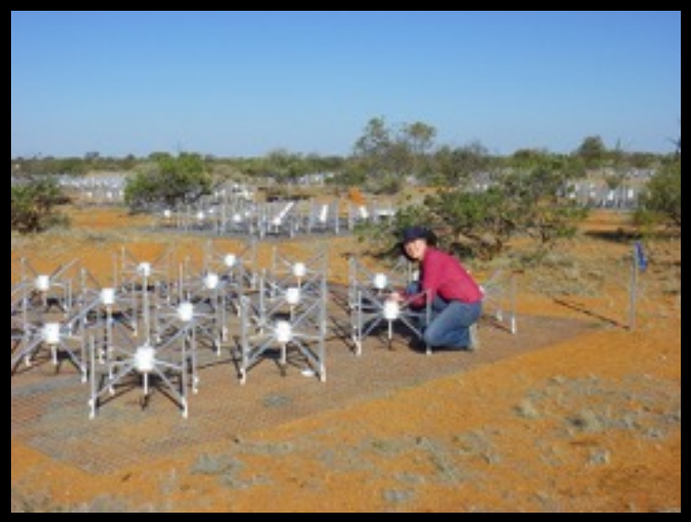


CHIME

Current experiments

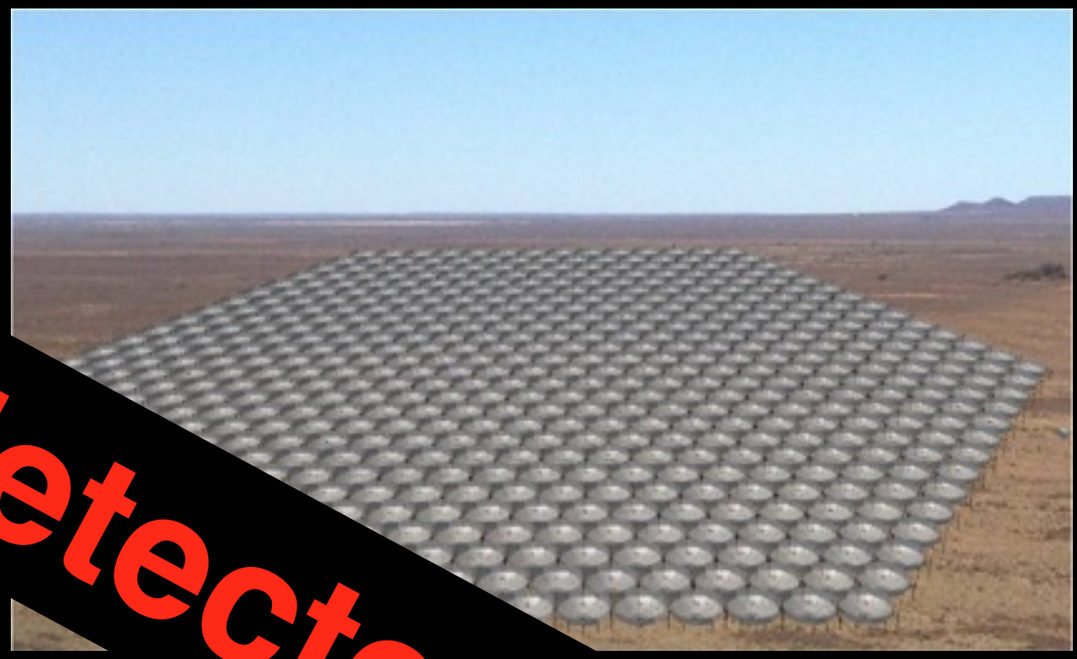
LOFAR

MWA



PAPER

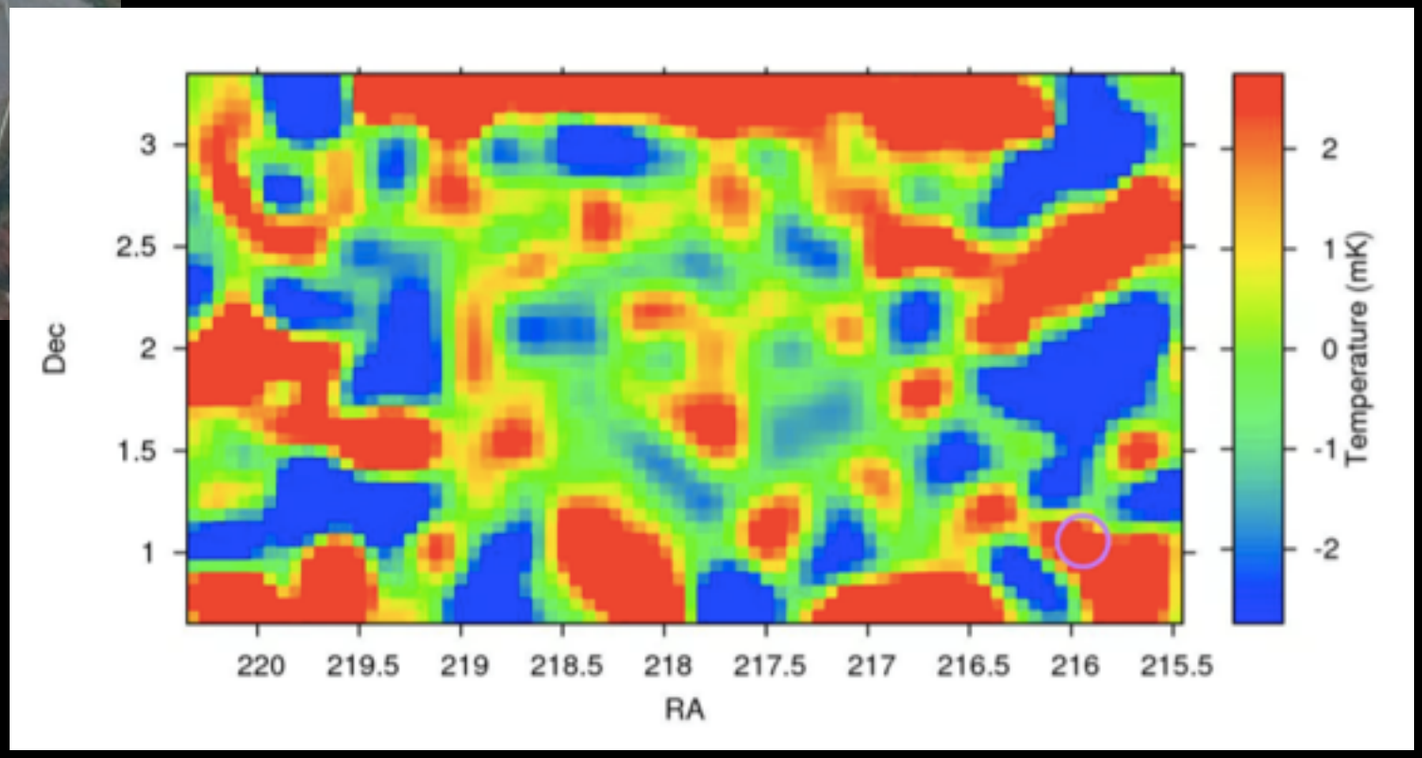
HERA (funded)



Have not detected 21- cm

Current experiments

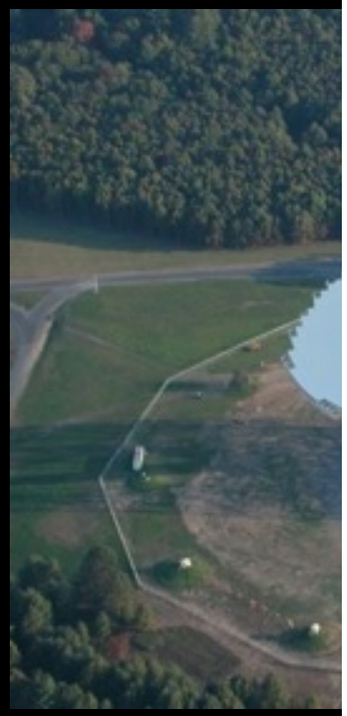
Only one statistical detection of 21-cm at cosmological distances! (In cross correlation with SDSS, using Green Bank Telescope.)

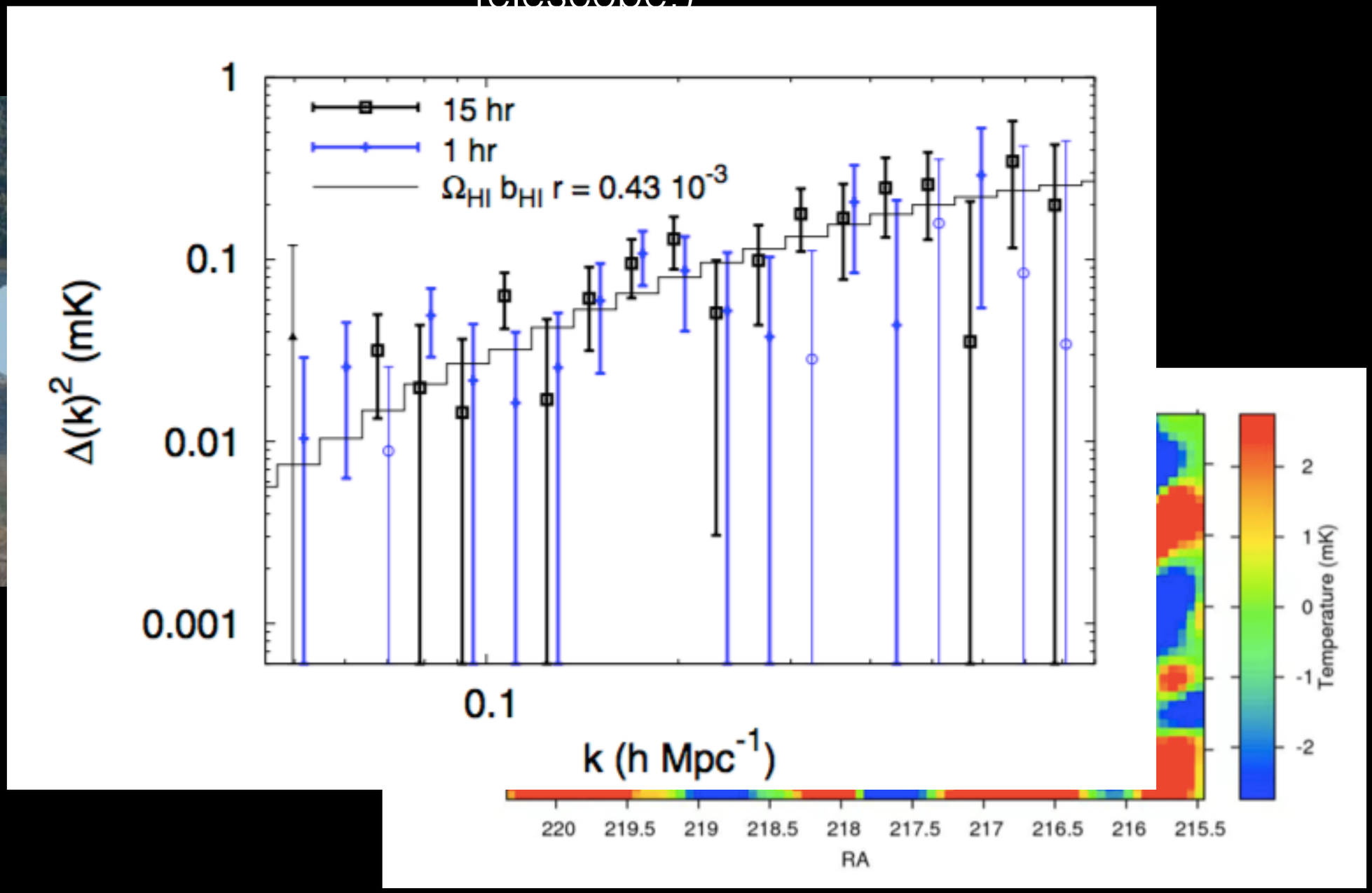


Masui, et al (2012)

Current experiments

Only one statistical detection of 21-cm at cosmological distances! (In cross correlation with SDSS, using Green Bank Telescope.)



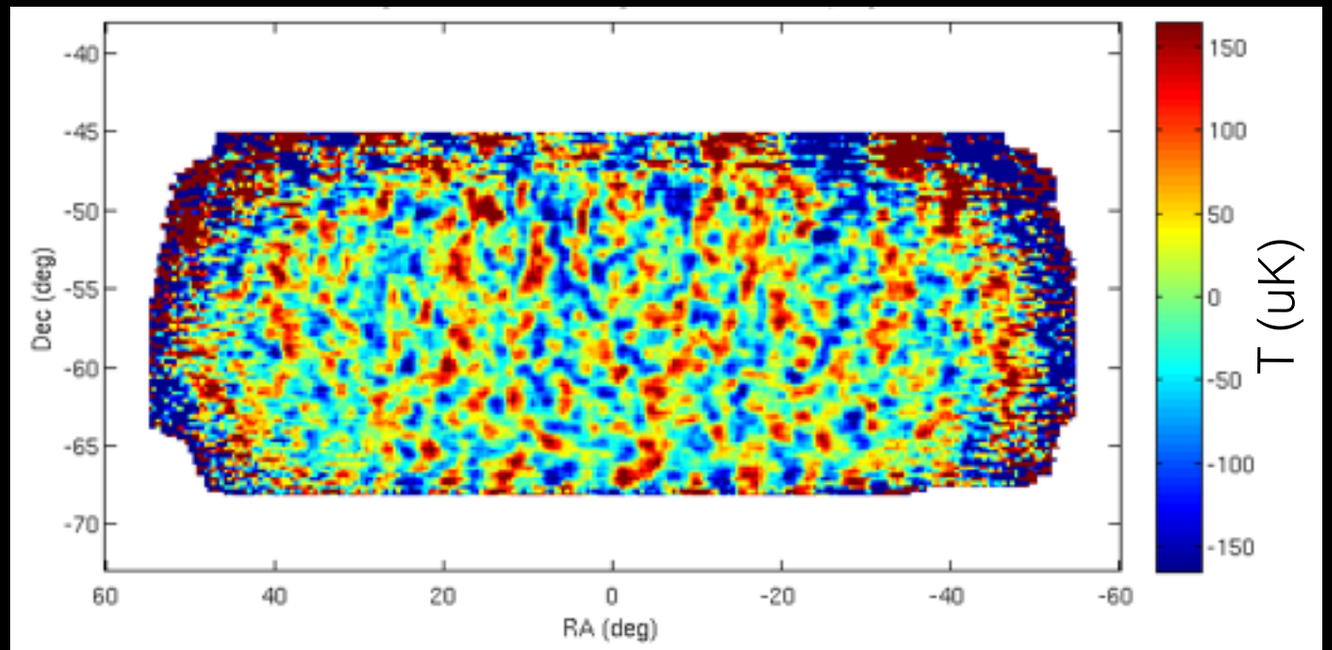


Masui, et al (2012)

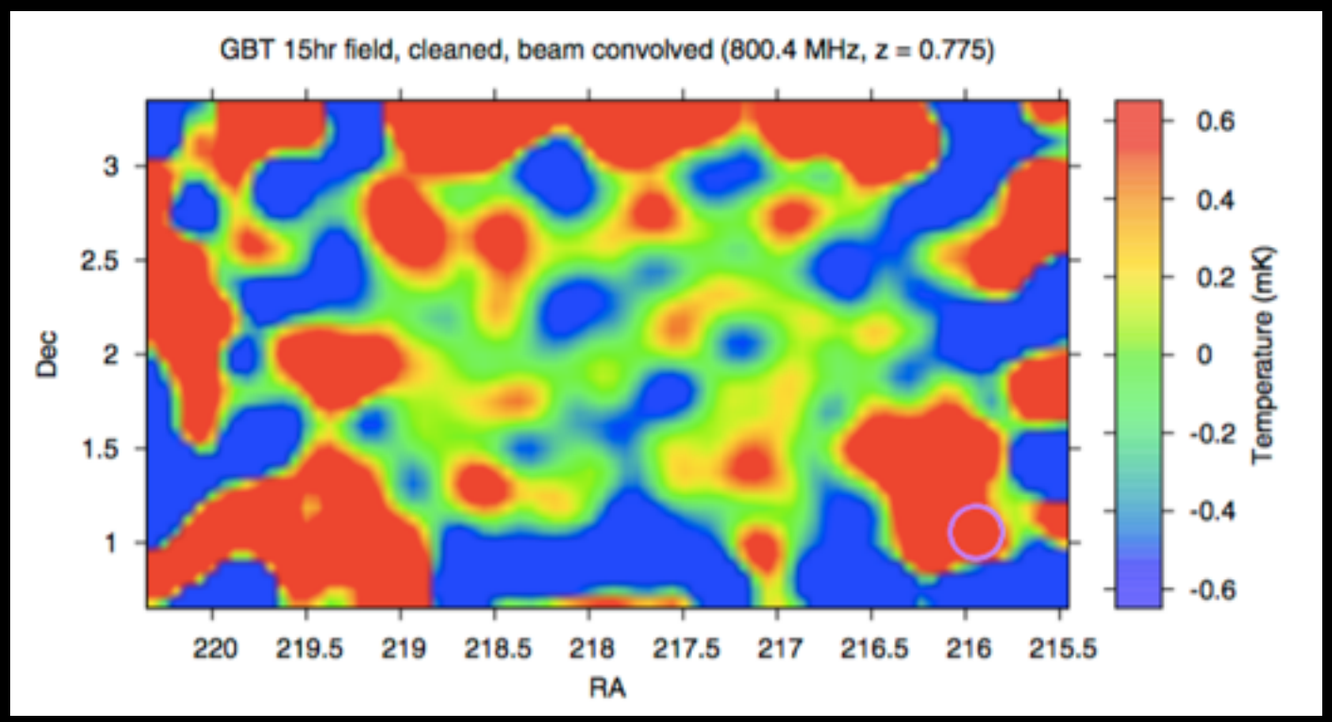
Current experiments

Looks like a CMB map! Statistical measurement, like CMB, means doing large scale structure without seeing any galaxies!

BICEP/Keck
200-240 GHz



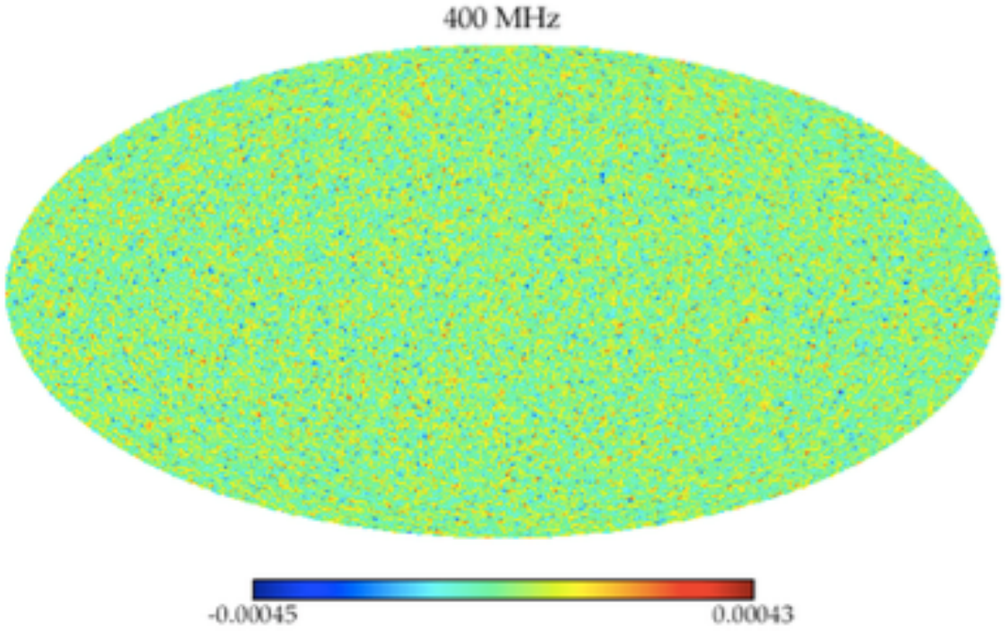
GBT 800.4 MHz

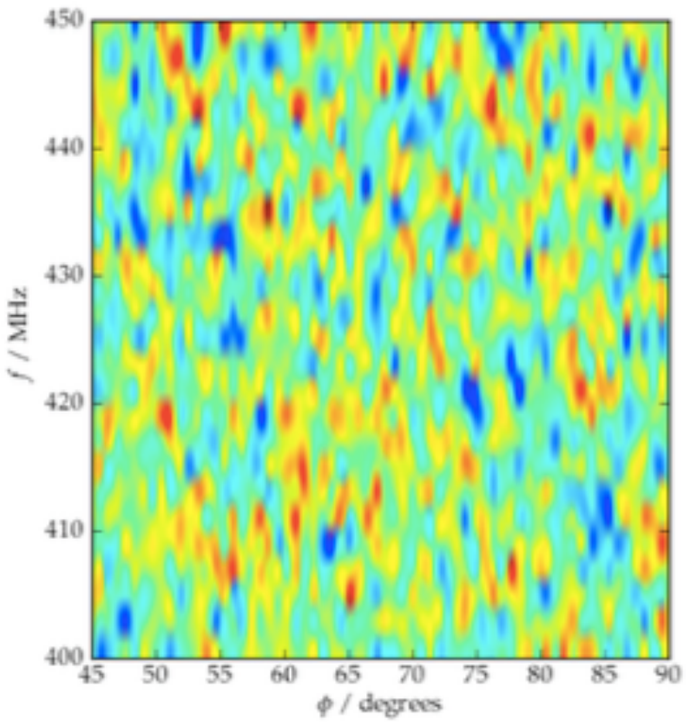


Current experiments

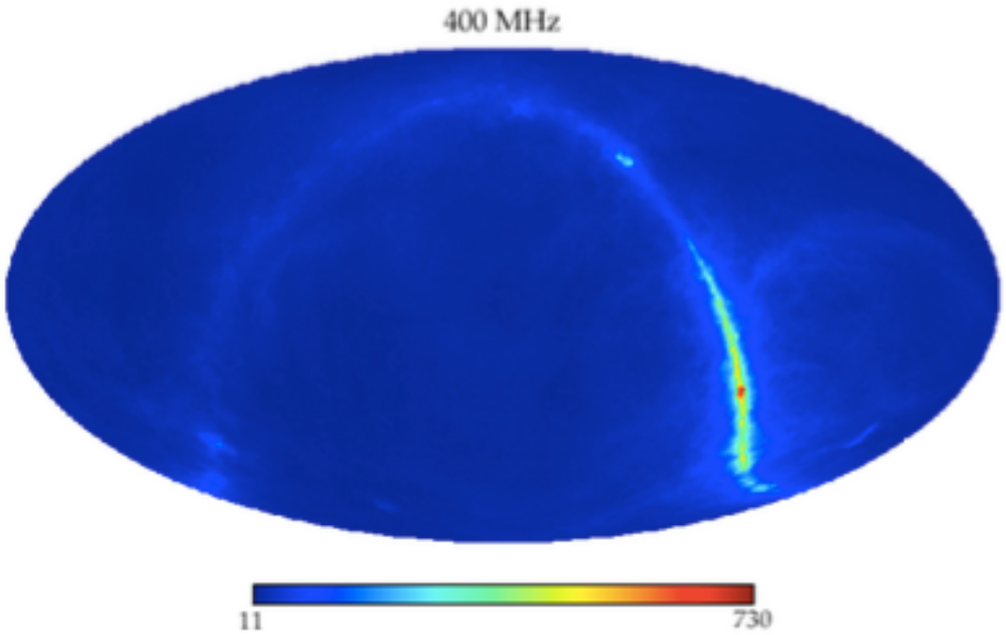
Why is this so hard? Lots of reasons, but one big one:
Galactic foregrounds

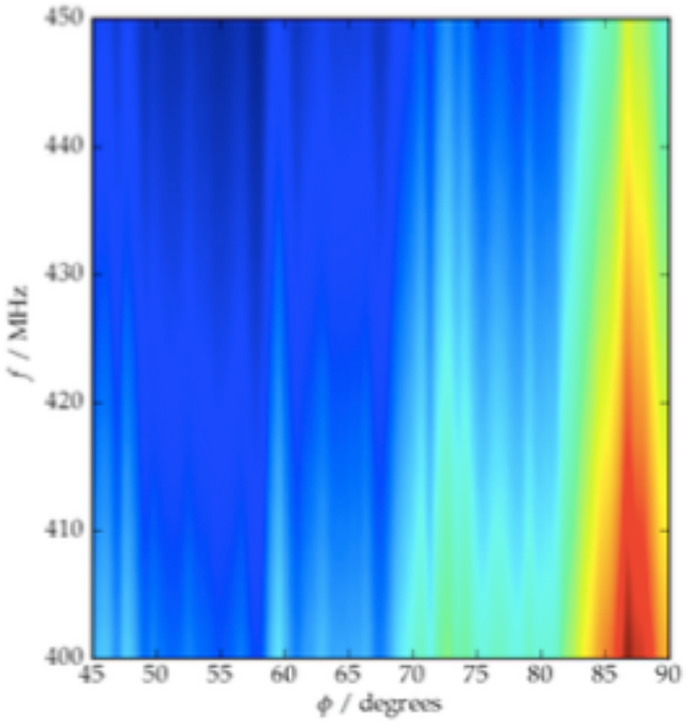
Signal ~1 mK





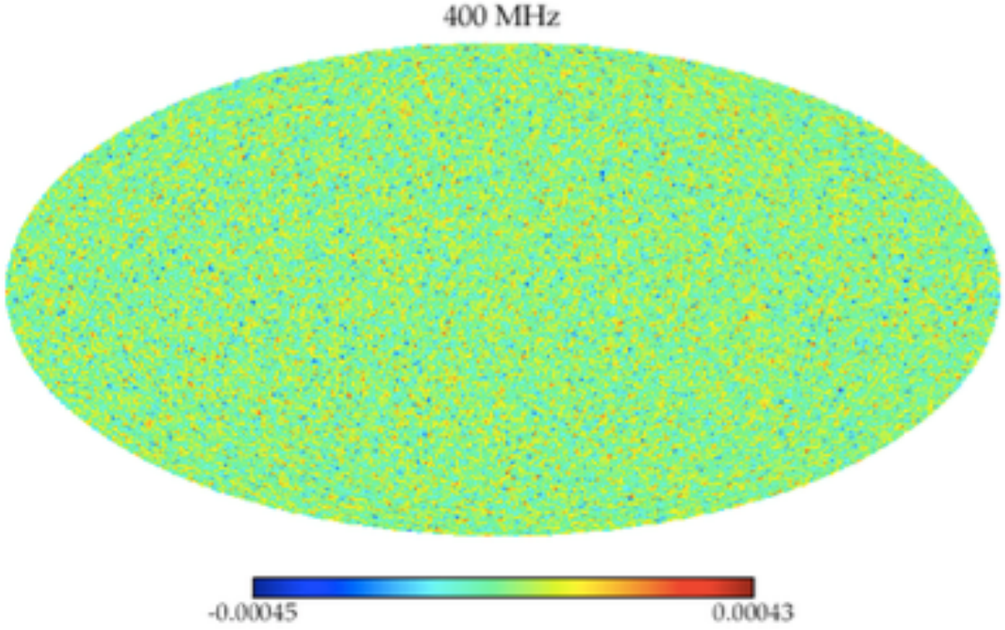
Galactic synchrotron up to 700 K

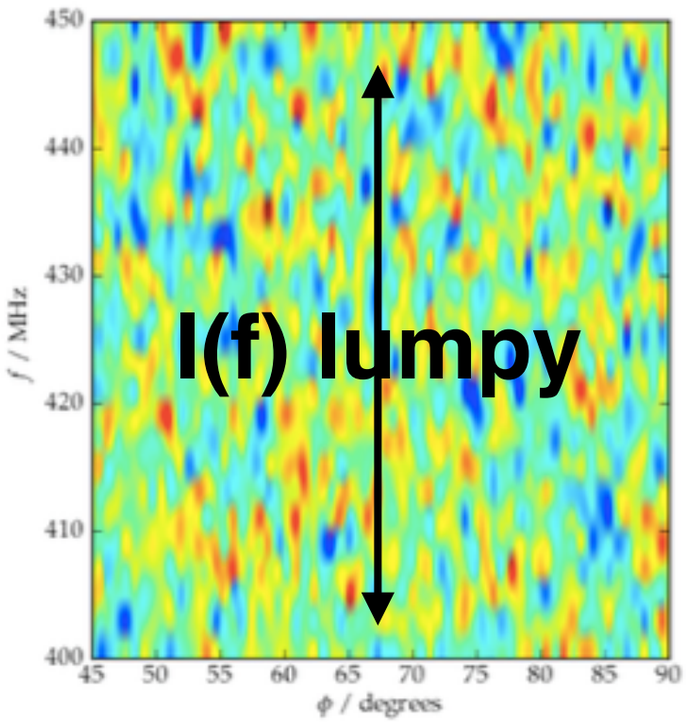




Richard Shaw

Signal ~1 mK





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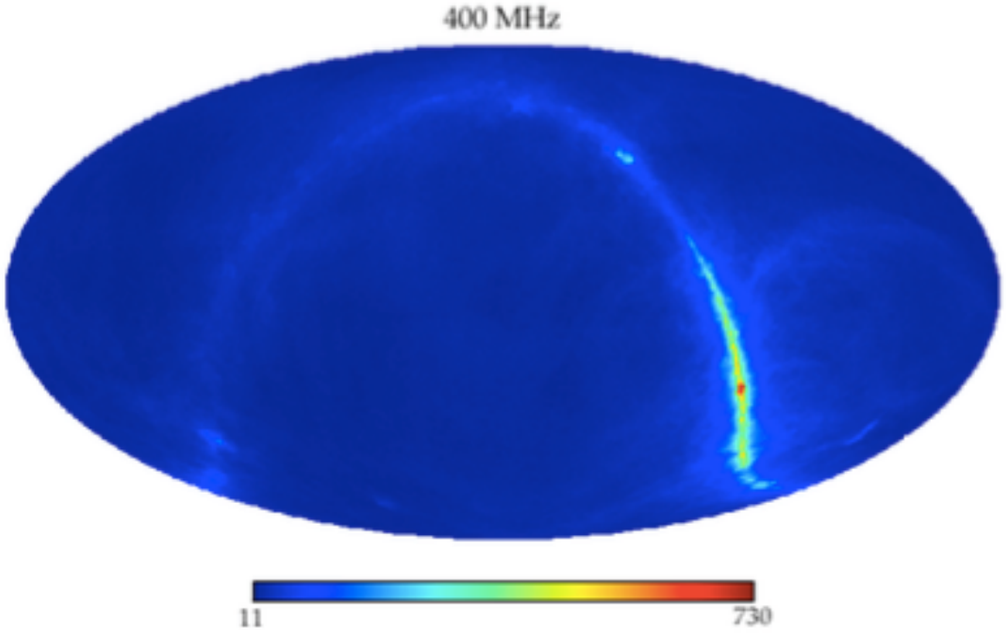
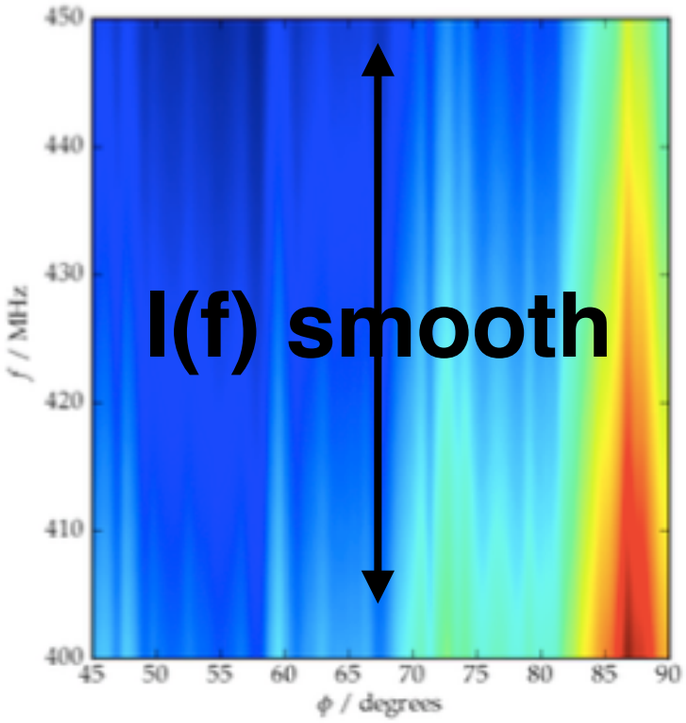




Richard Shaw

Galactic foregrounds

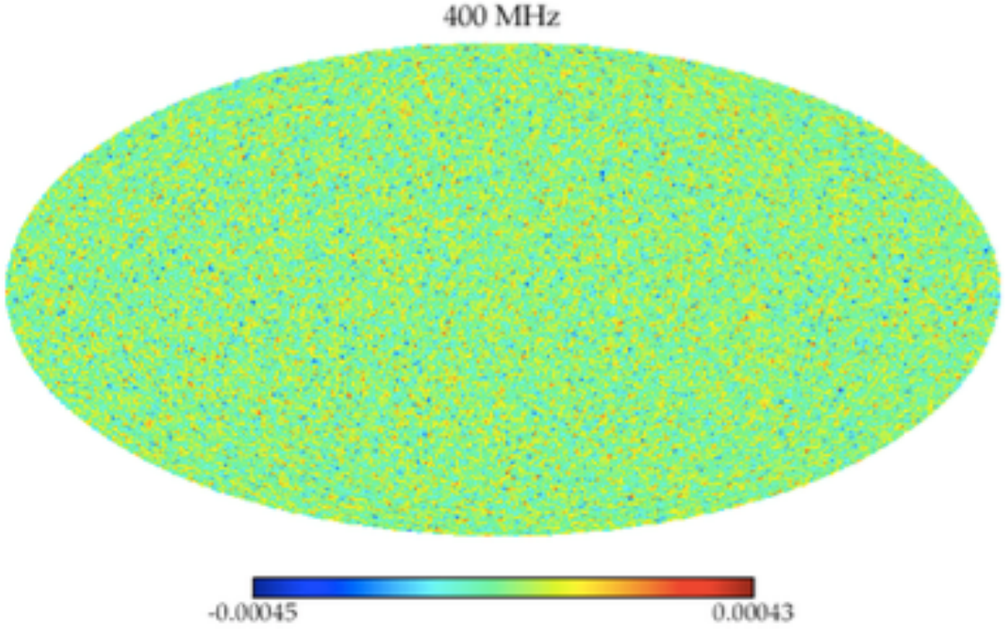
A telescope measures the sky intensity averaged over an area defined by the telescope's angular response. The response is called the "point spread function" if you're an optical astronomer or the "beam" if you're a radio astronomer.

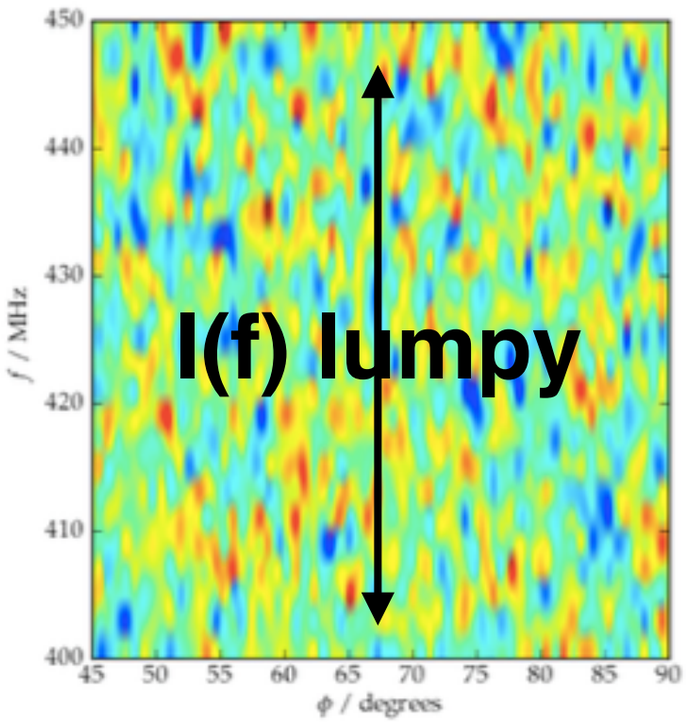
This is why images of stars don't appears as infinitely small point sources in telescopic images, and is what sets the angular resolution of 21-cm and CMB maps.

Galactic foregrounds

The beam is a function of frequency.

Signal ~1 mK





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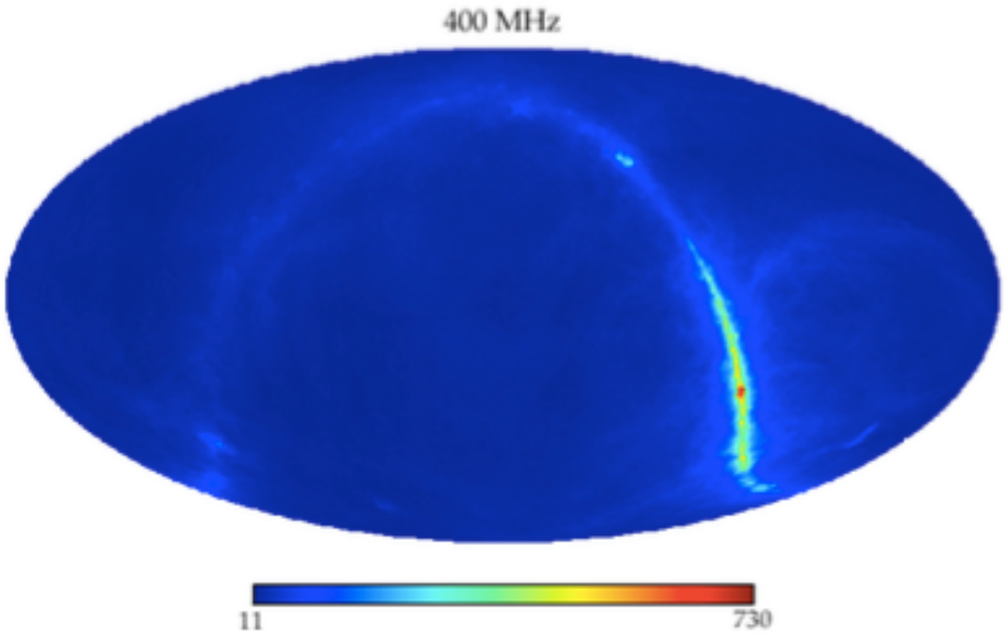

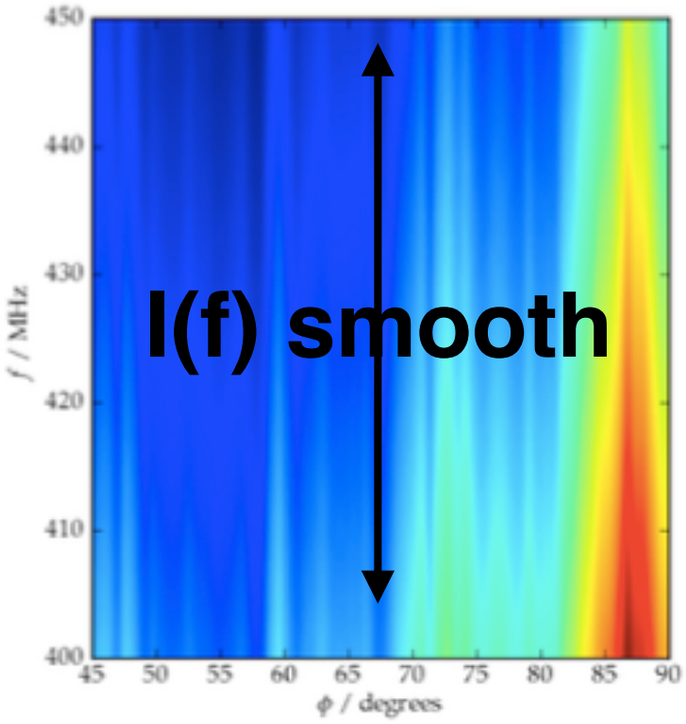

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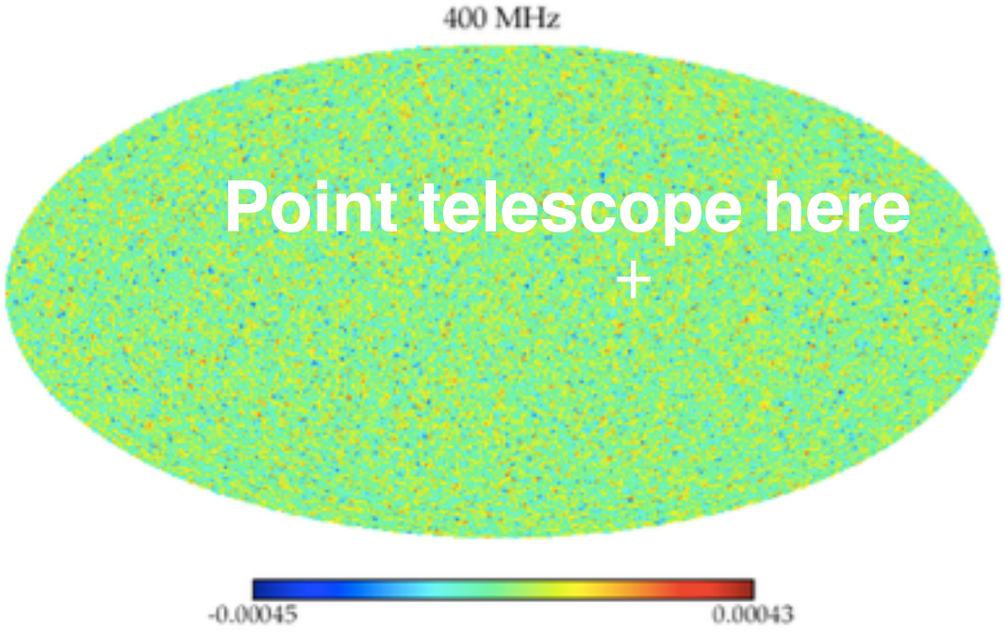

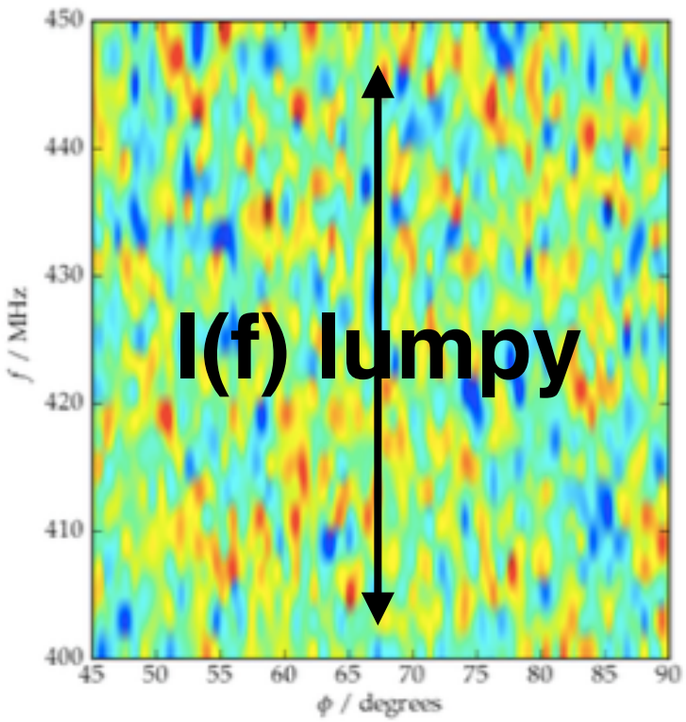

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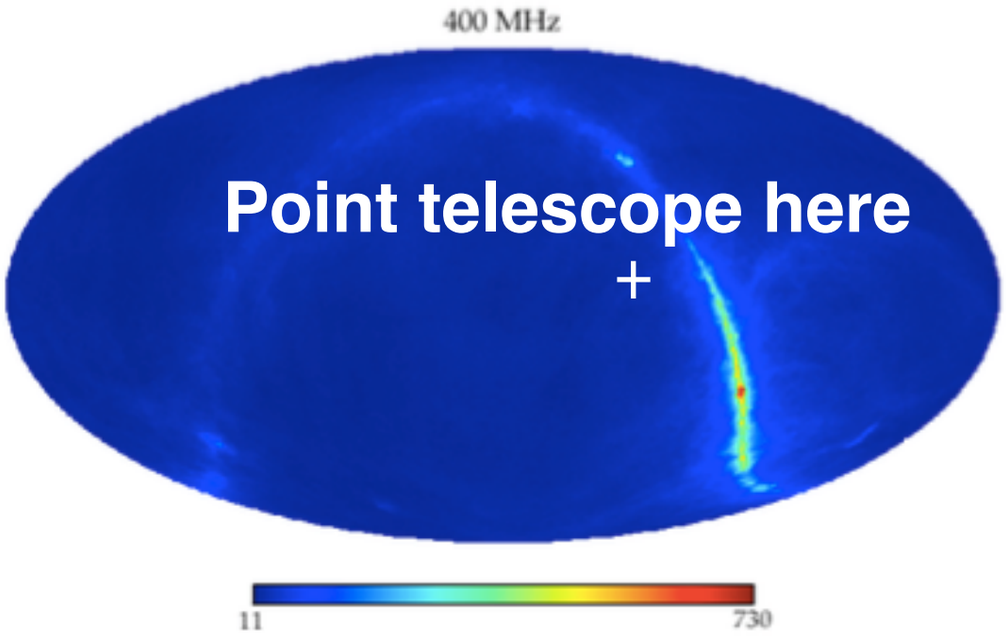

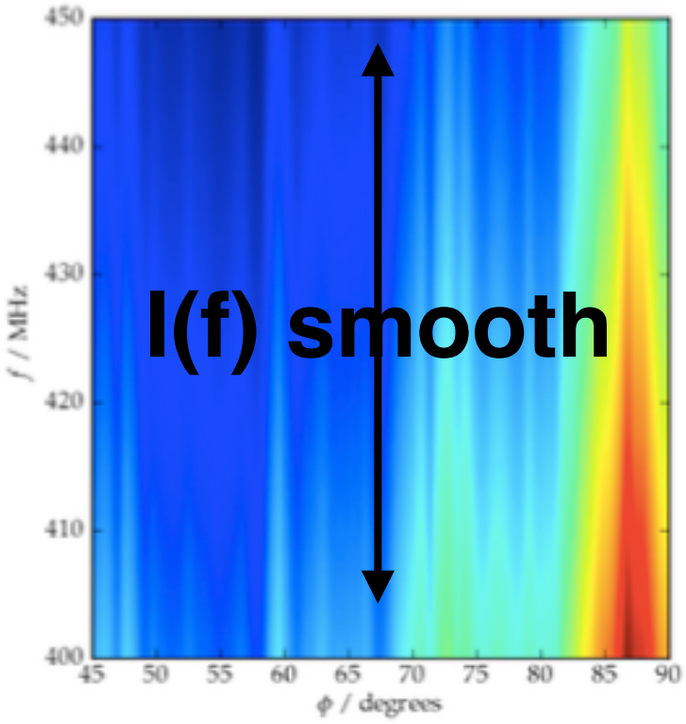

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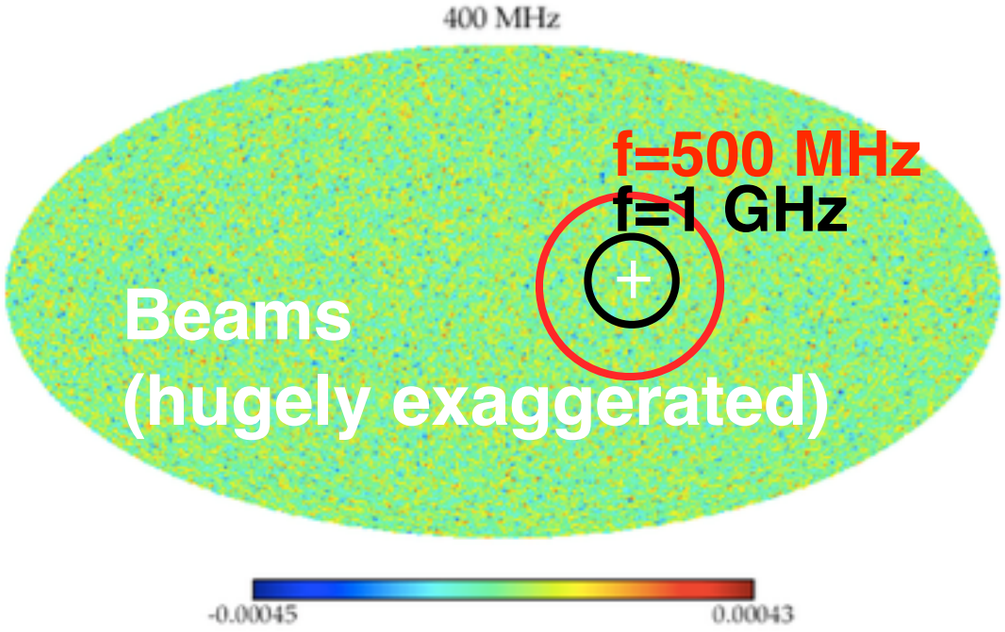

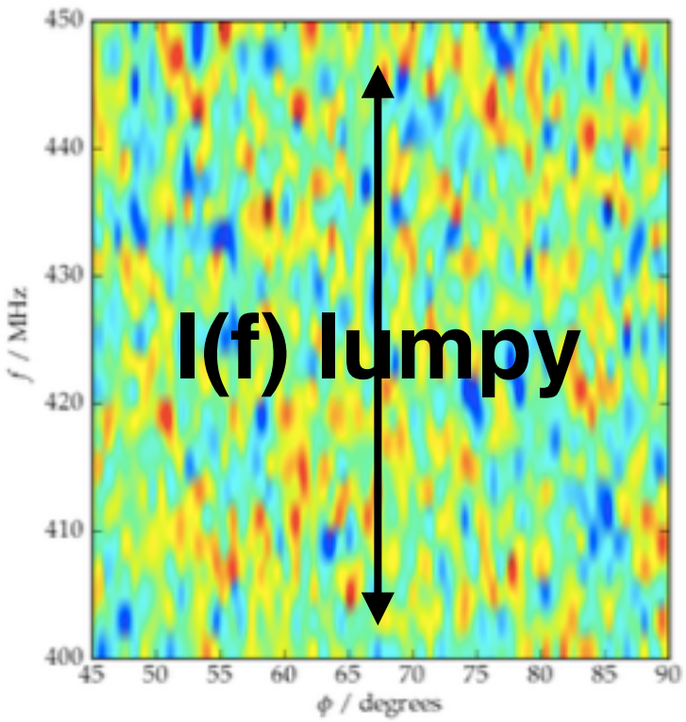

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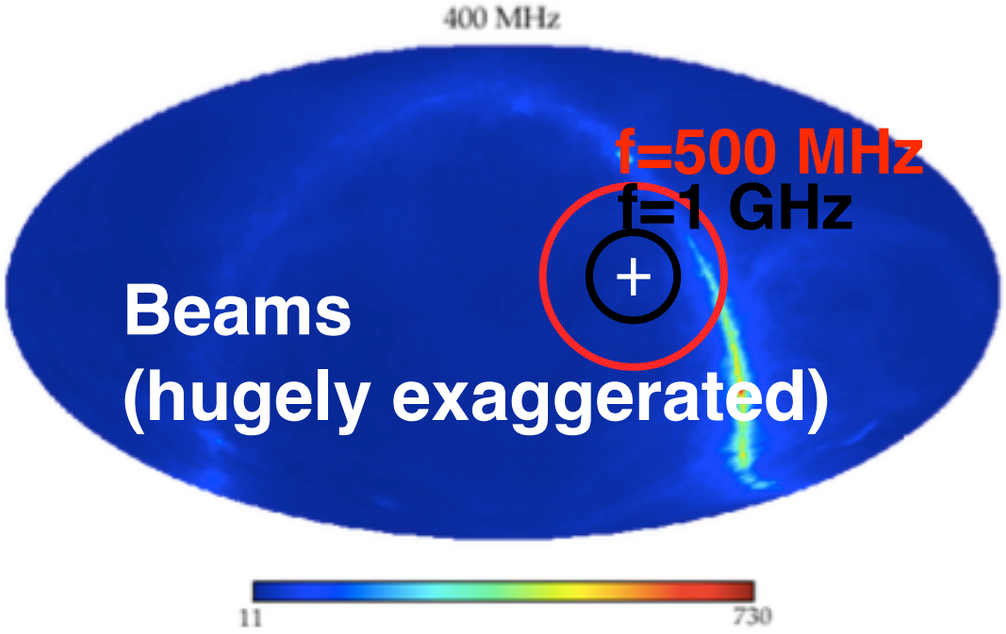

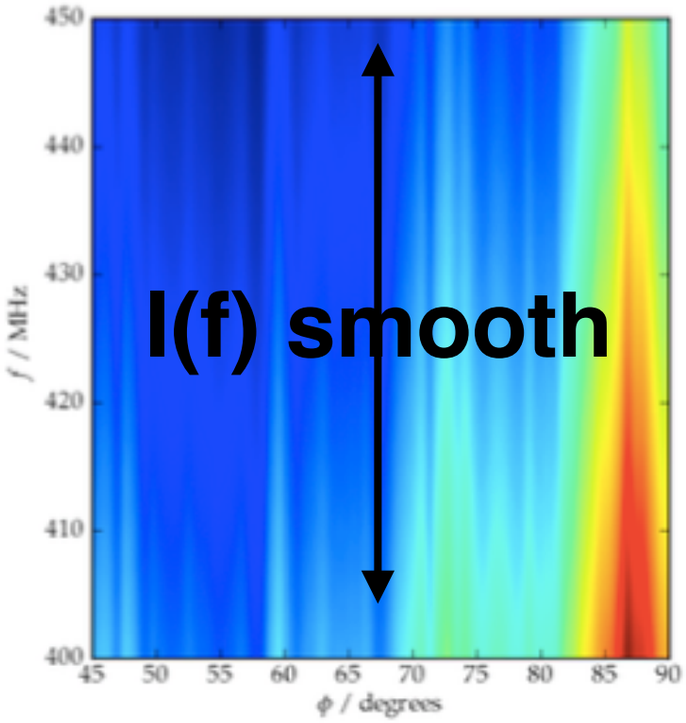

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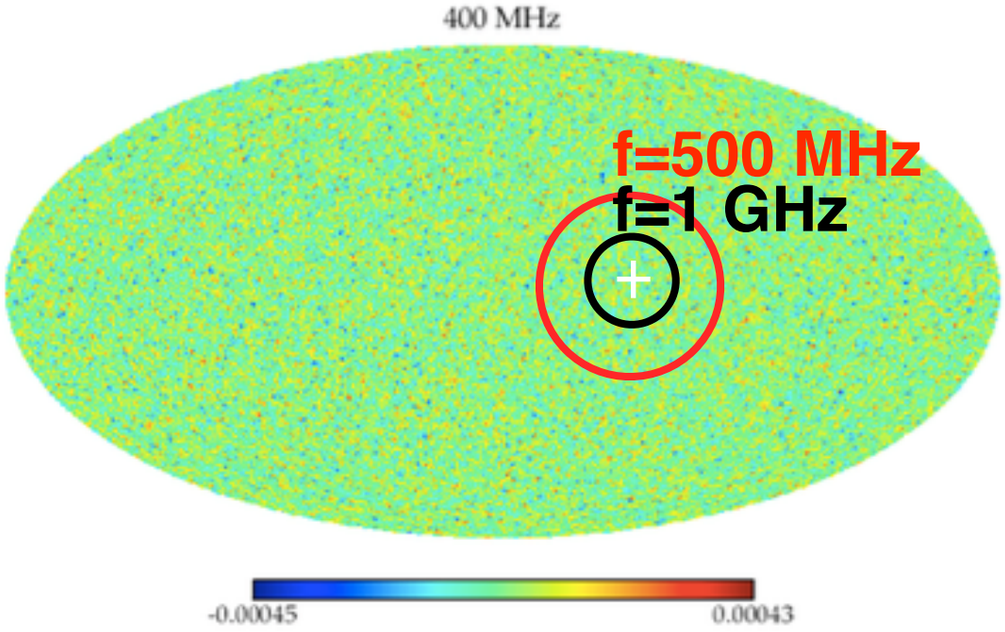
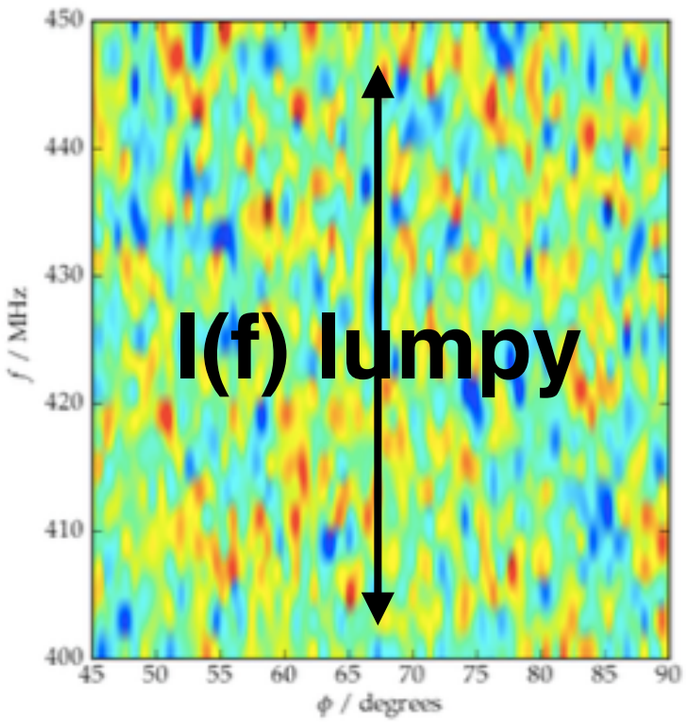
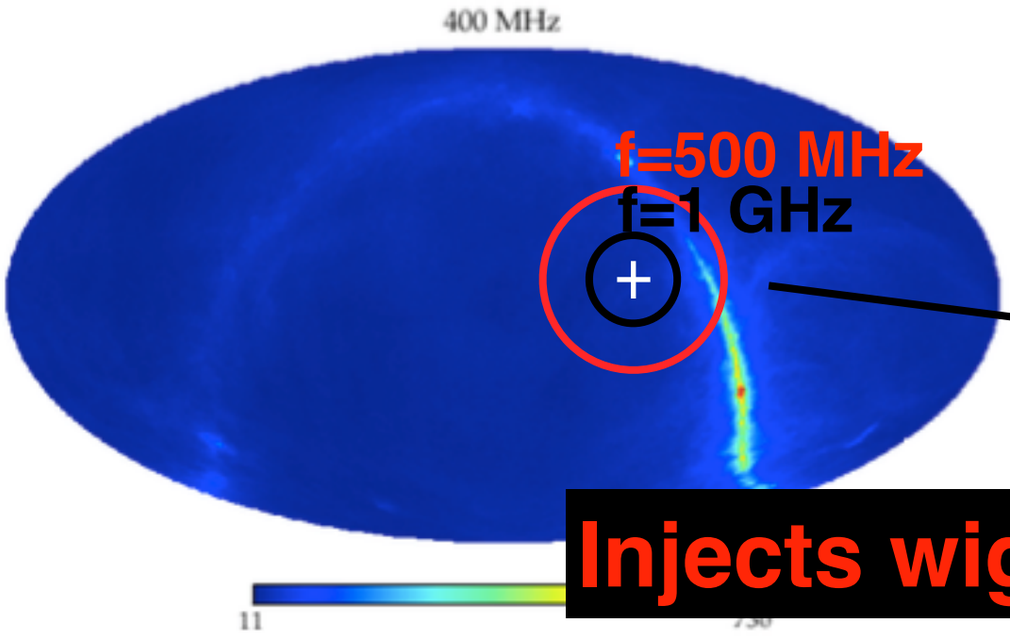
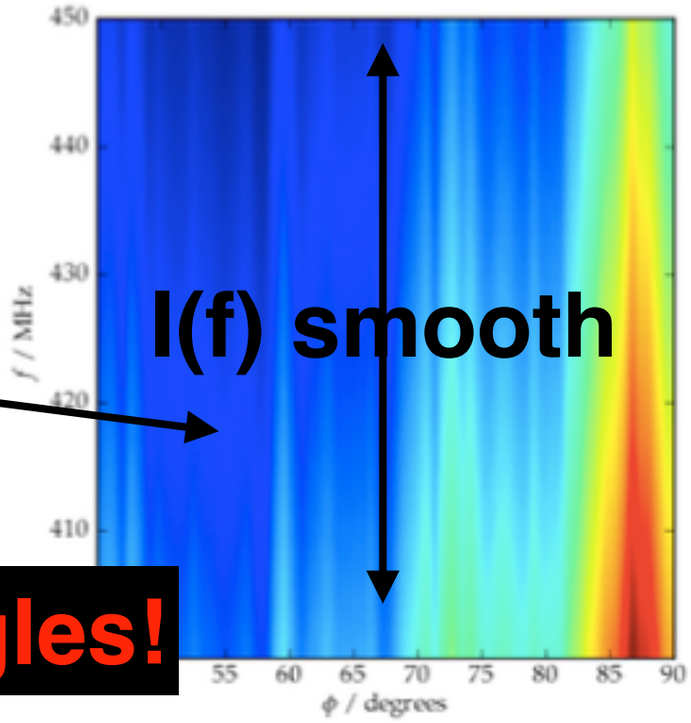




Galactic synchrotron up to 700 K



Injects wiggles!



Galactic foregrounds

Need very good control and calibration of telescope beam! This is the number one challenge for 21-cm surveys.

BNL and Stony Brook

- Recall that CHIME (Canadian funded) costs $10M and is competitive with $100M scale DOE funded Dark Energy optical surveys like SDSS/BOSS and DES/DESI.

- What if you spent $100M on a 21-cm survey?

BNL and Stony Brook

- BNL has is putting together a pathfinder instrument to measure 21-cm at $z < 1$.
- Idea is to detect of 21-cm at cosmological distances with an easily replicated (i.e. cheap) instrument.
- In doing so, will develop the science case for a large scale, DOE funded survey.

BMX

Justine Haupt (engineer)
Paul O'Connor (scientist)
Chris Sheehy (Goldhaber fellow)
Anže Slosar (scientist)
Paul Stankus (scientist)

Remington Gerras (undergrad)
Jeff McMahon (prof.)

Evan Arena (undergrad)
Neelima Sehgal (prof.)

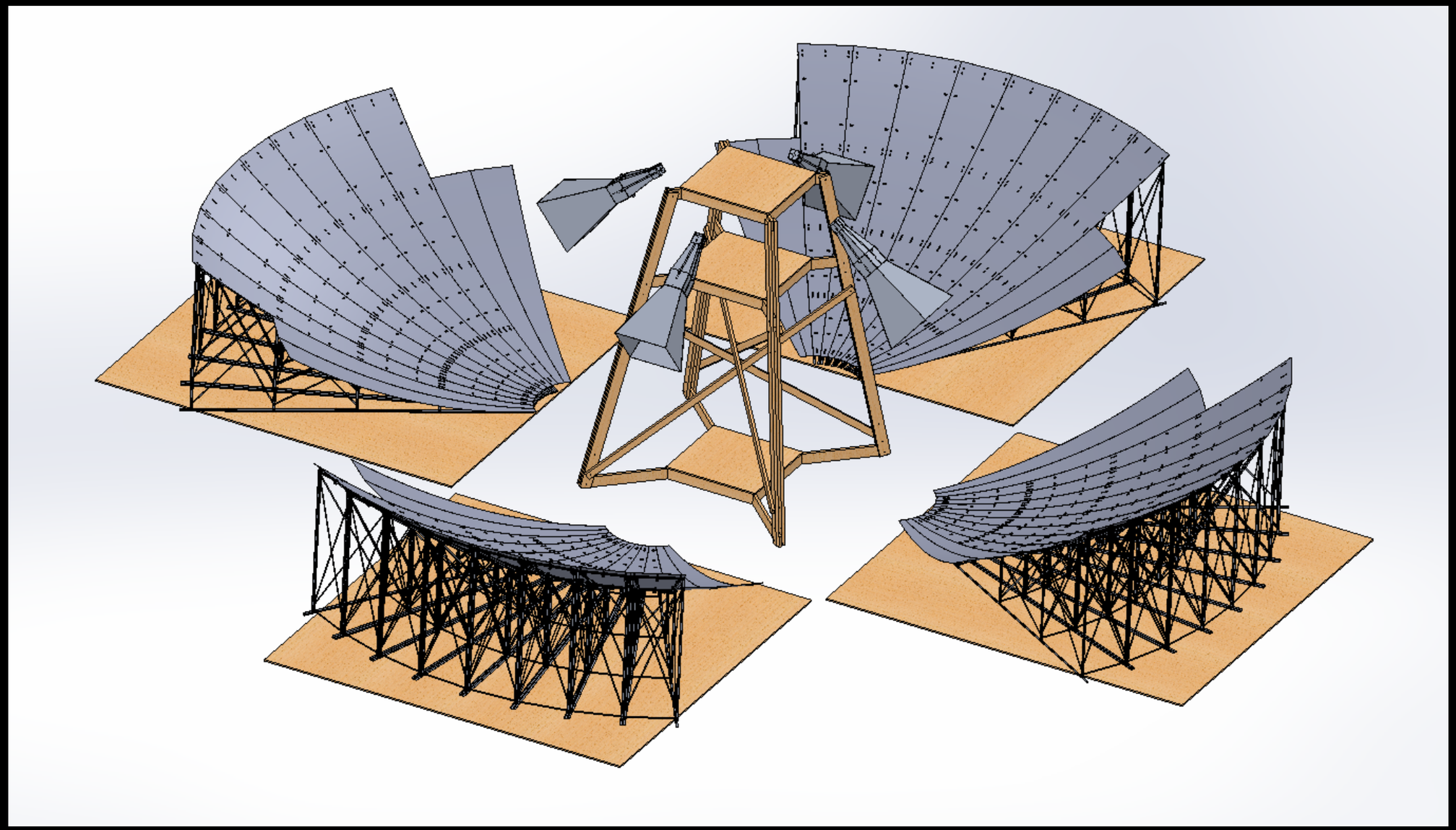
Hamdi Mani (engineer)
Phil Mauskopf (prof.)

BMX

We need a grad student!

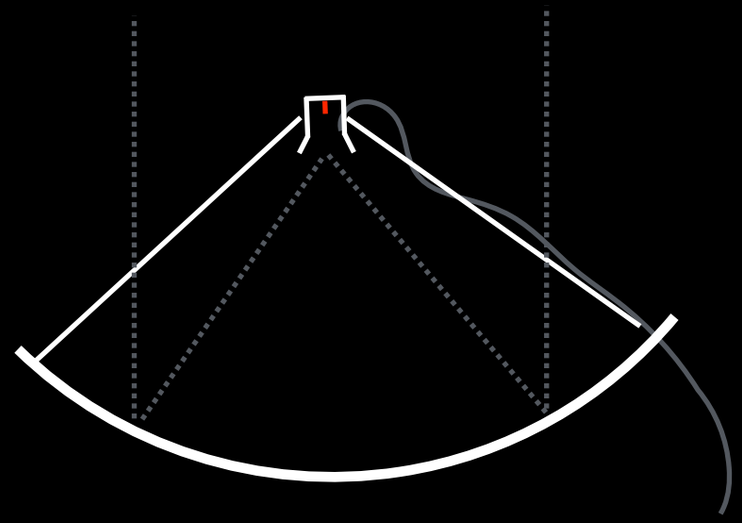
BMX

- Four dish interferometer
- 700 - 1500 MHz (z = 0 - 1)
- GPU correlator



BMX

Off axis parabola for beam purity (reduces scattering off struts holding feed)



BMX

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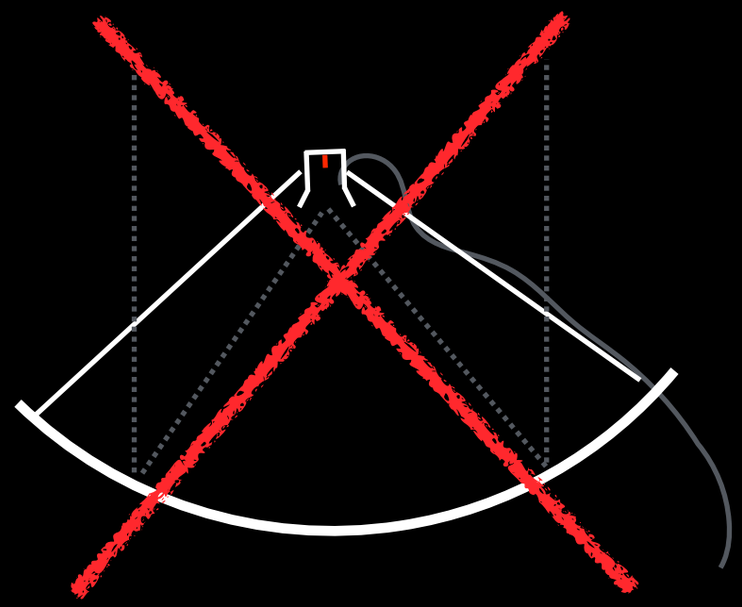
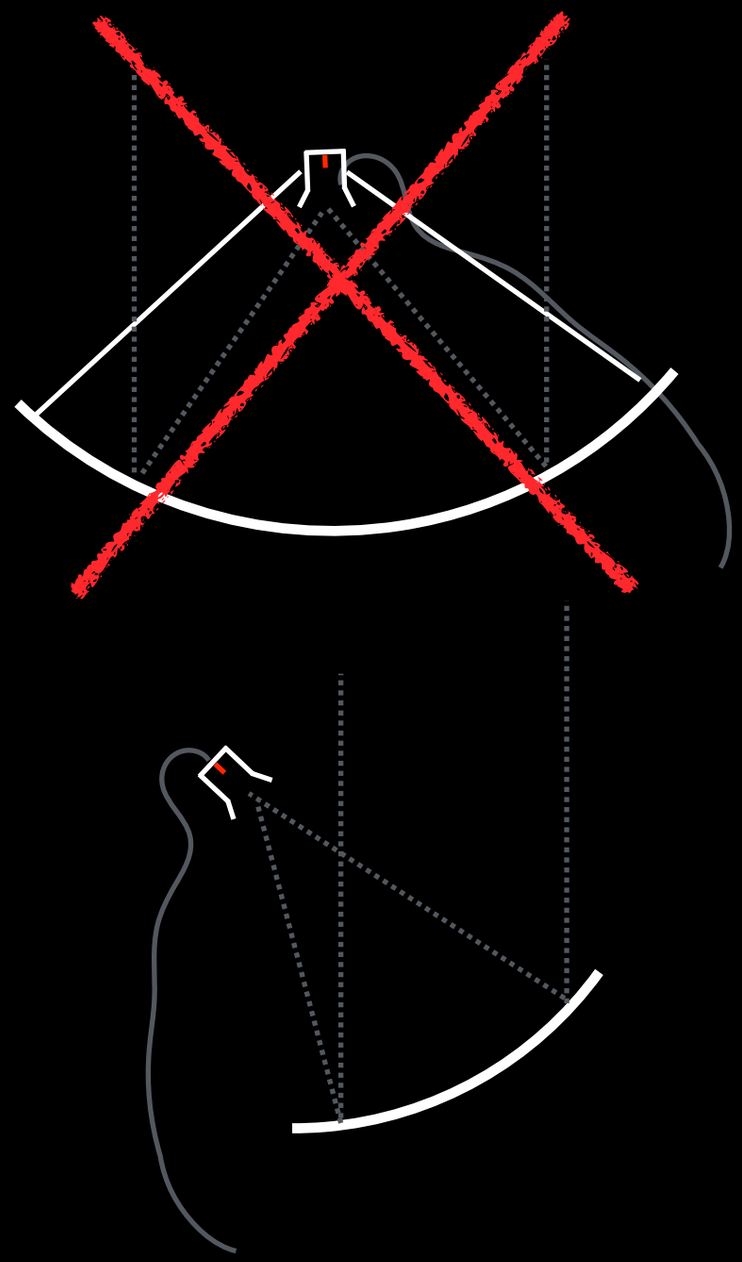


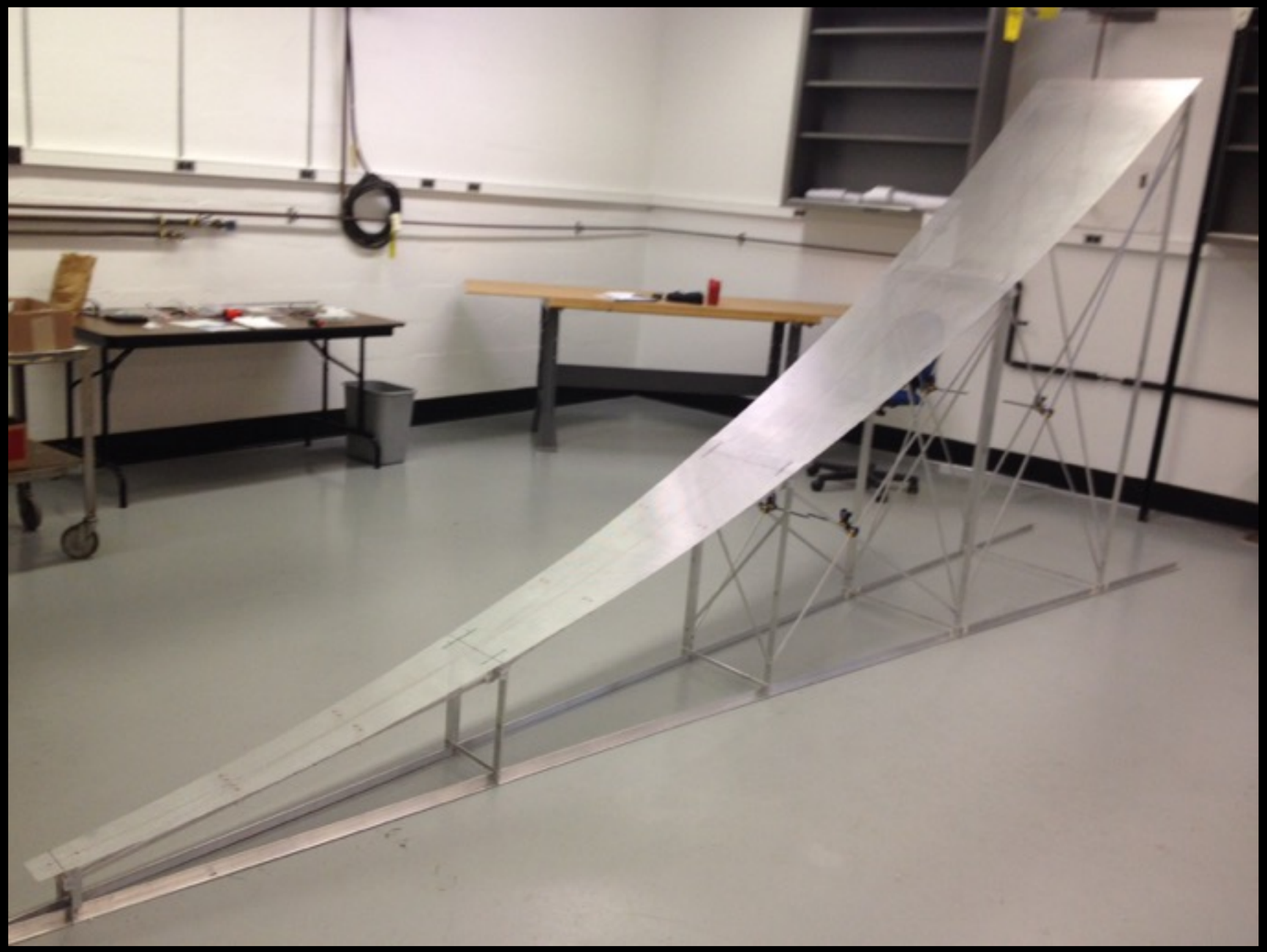
BMX

Off axis parabola for beam purity (reduces scattering off struts holding feed)



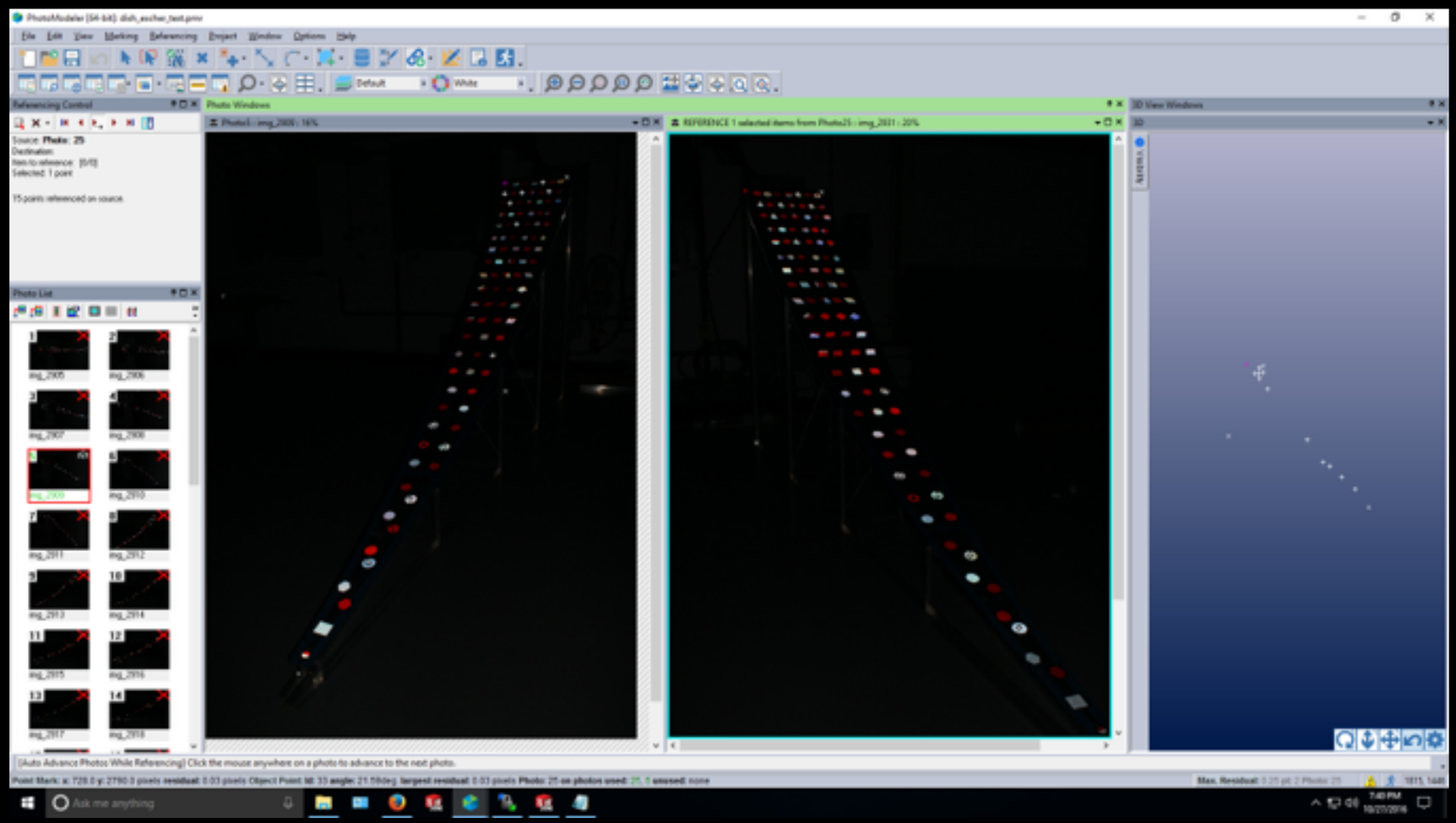
BMX

Clever design for ease of manufacturing: flat sheets roll out into a single “petal.” Only complicated parts are 3D printed to define dish height and join petals. Cheaply replicable for a large array!



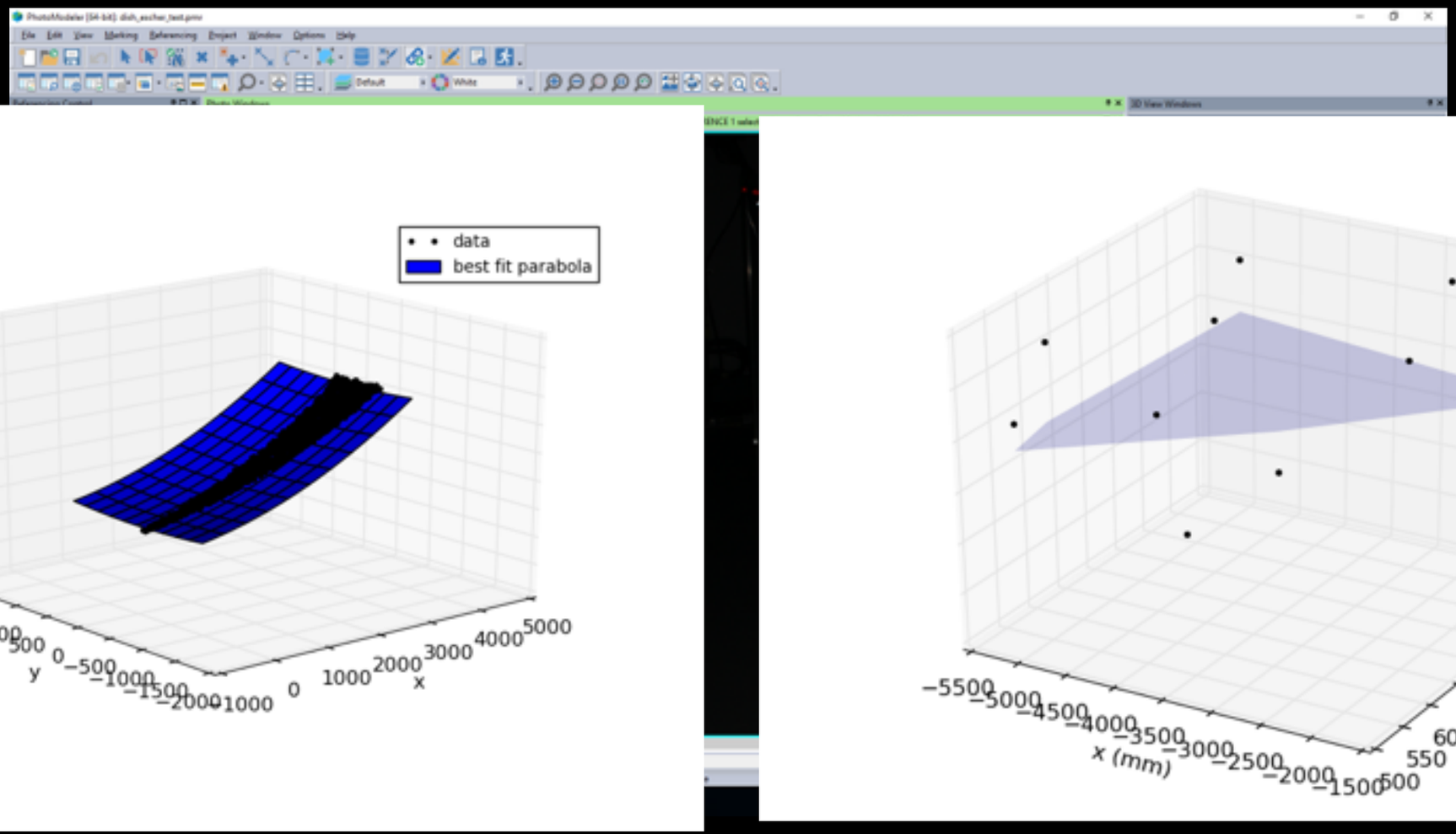
BMX

Using photogrammetry techniques to measure dish surface in 3D using photos and reflective markers.



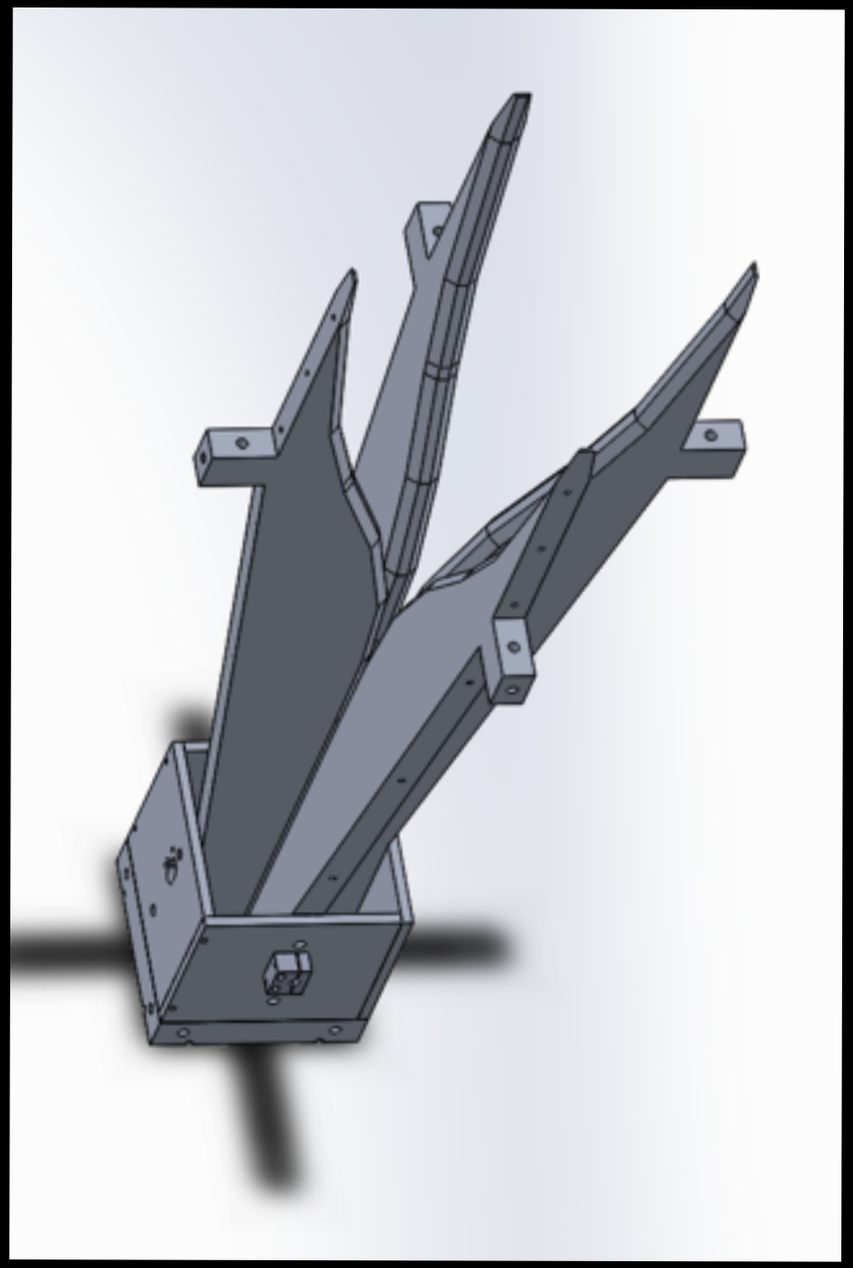
BMX

Developing photogrammetry techniques to measure dish surface in 3D using photos and reflective markers.



BMX

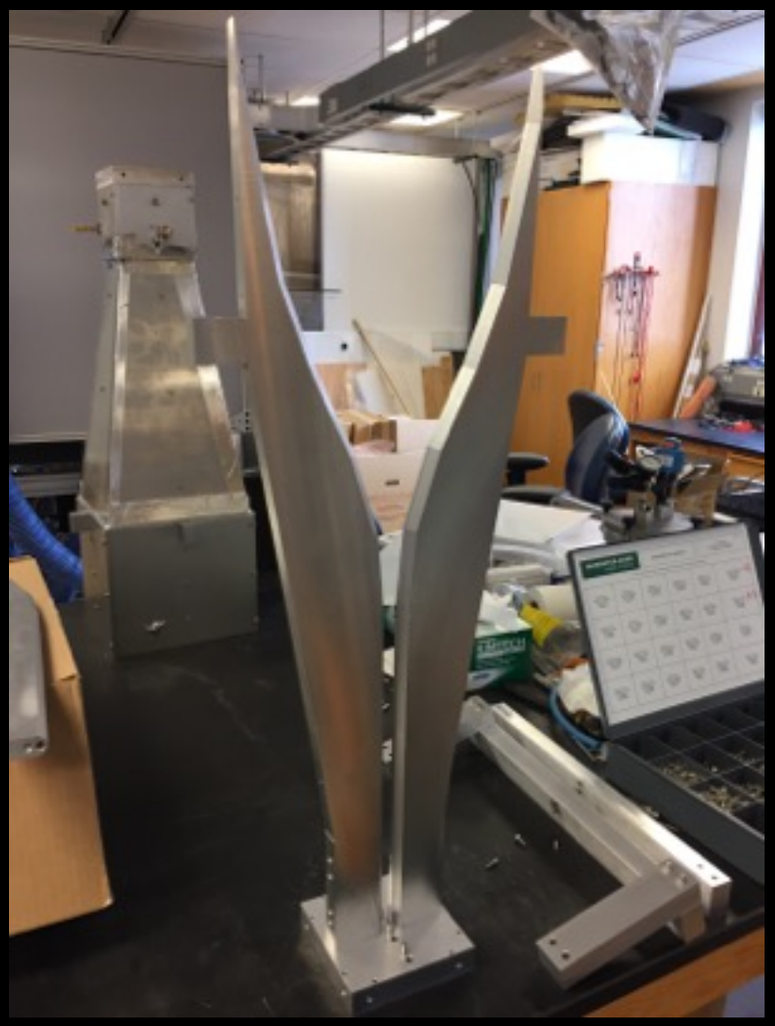
Design feed horn and “orthomode transducer” (OMT, splits E-field into orthogonal polarizations) using state of the art microwave simulation software.

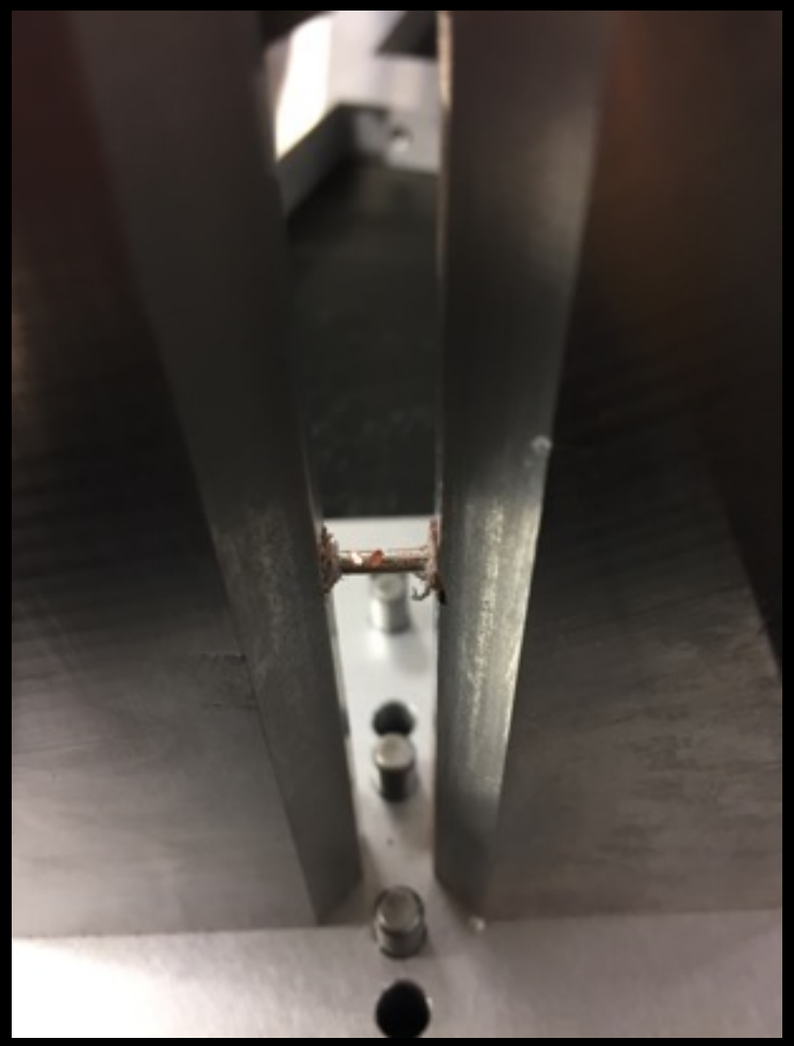


3D CAD design

BMX

Design feed horn and “orthomode transducer” (OMT, splits E-field into orthogonal polarizations) using state of the art microwave simulation software.





In the lab at U Michigan

BMX

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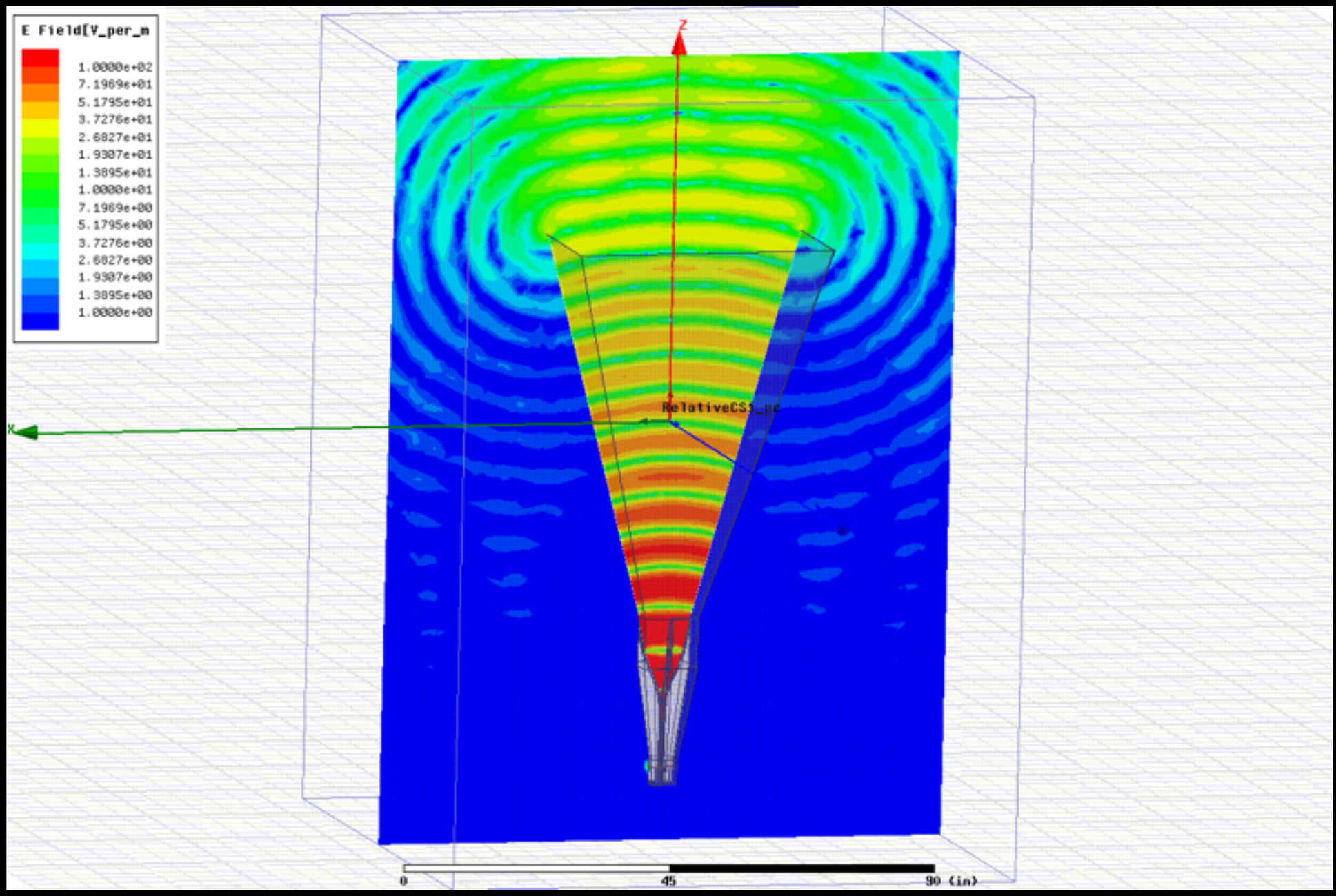
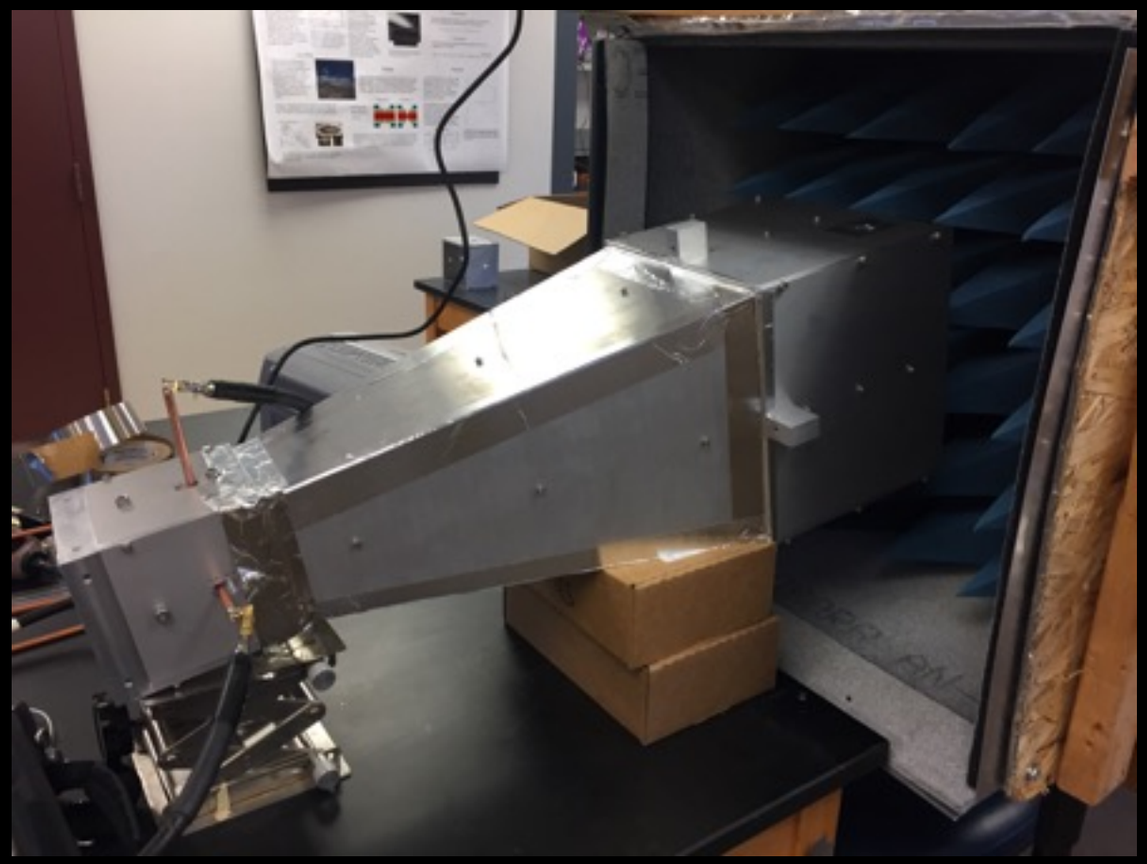
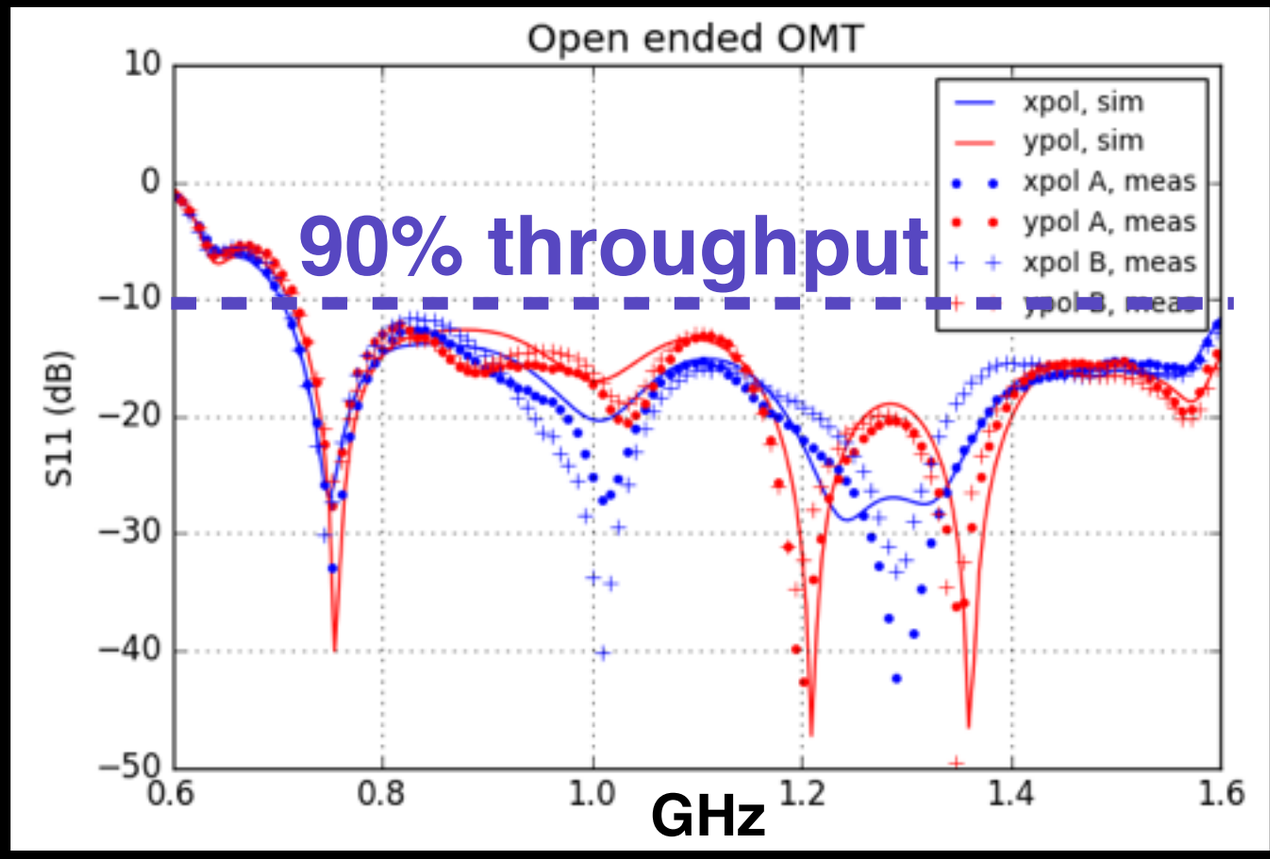


BMX

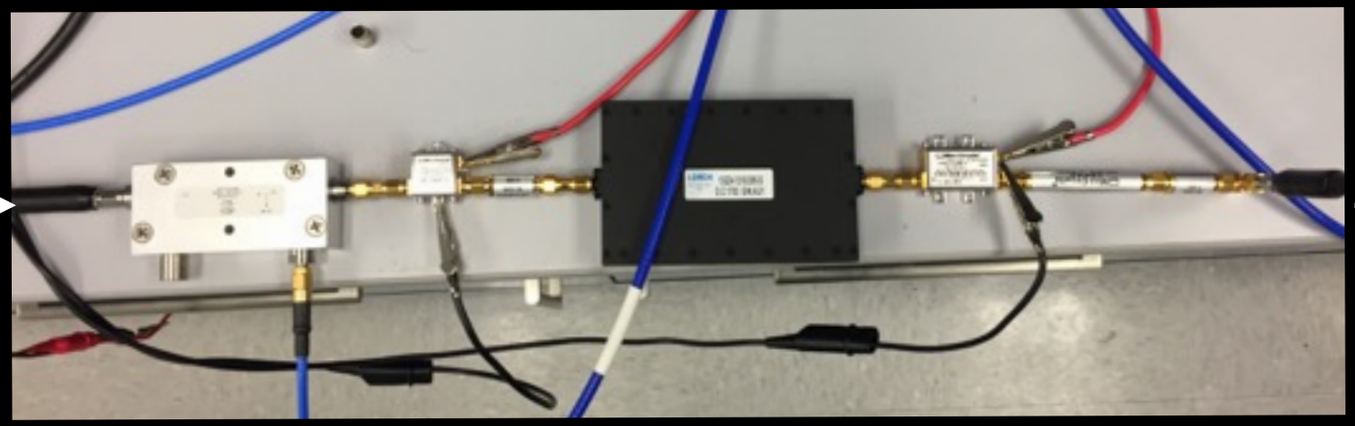
Data matches sims, successful design.





BMX

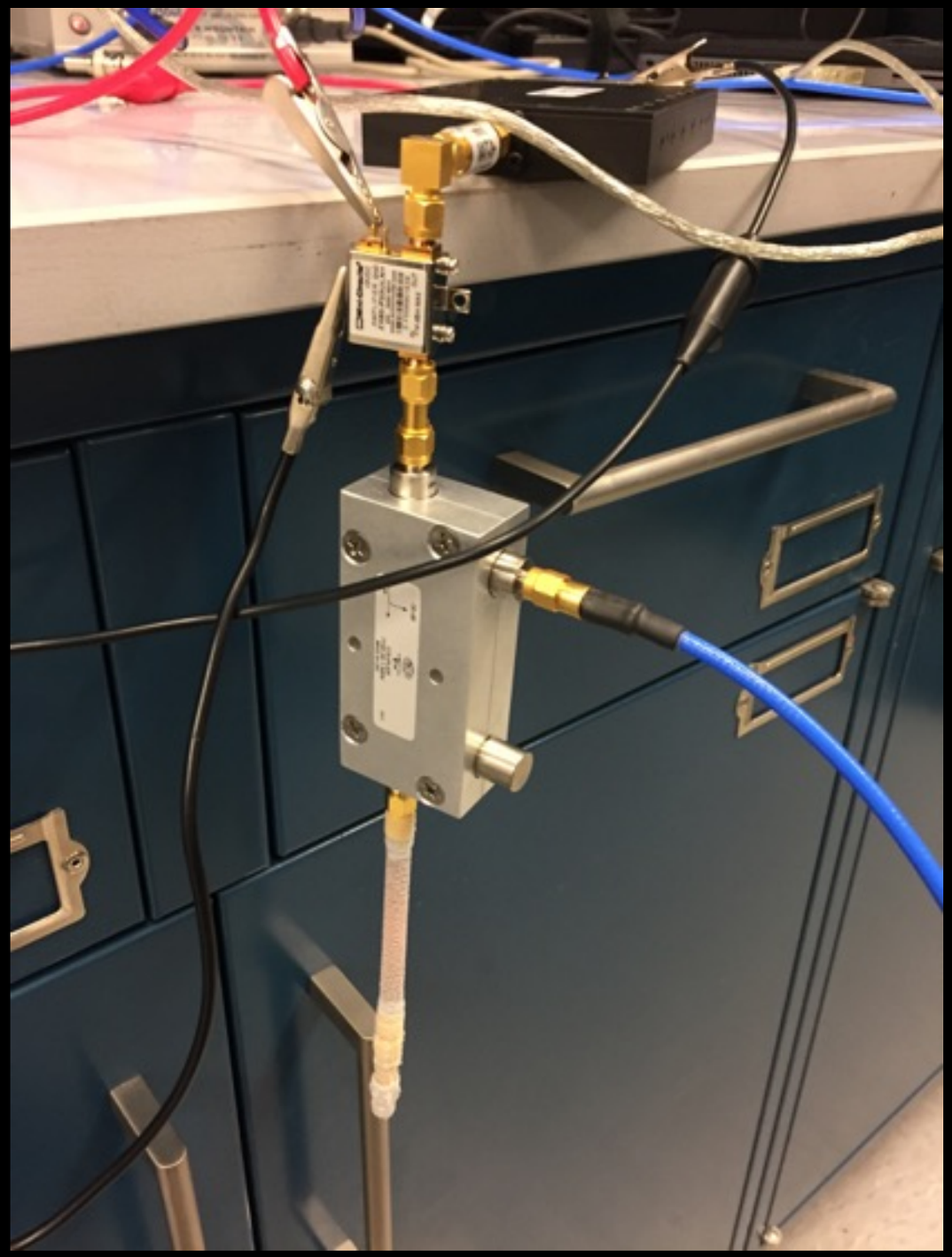
Front end microwave amplifier design. Learn what's on the top of all those cell towers!

OMT + horn (tiny signal) →  → GPU correlator

Low nosie amplifiers and filter

BMX

Calibrate spectrometer and measure noise temperature with Liquid nitrogen



BMX

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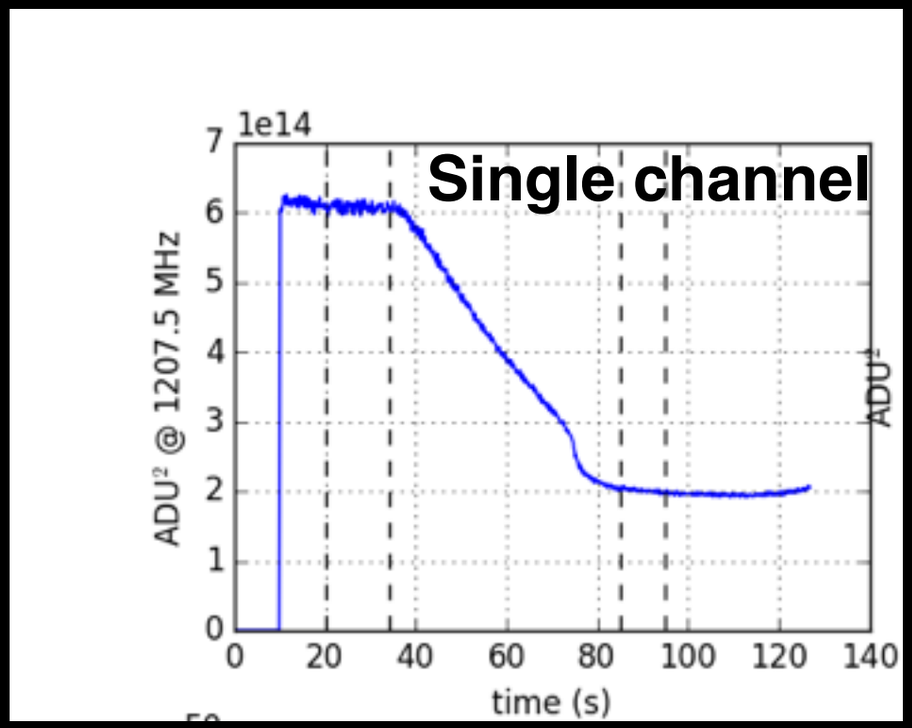

BMX

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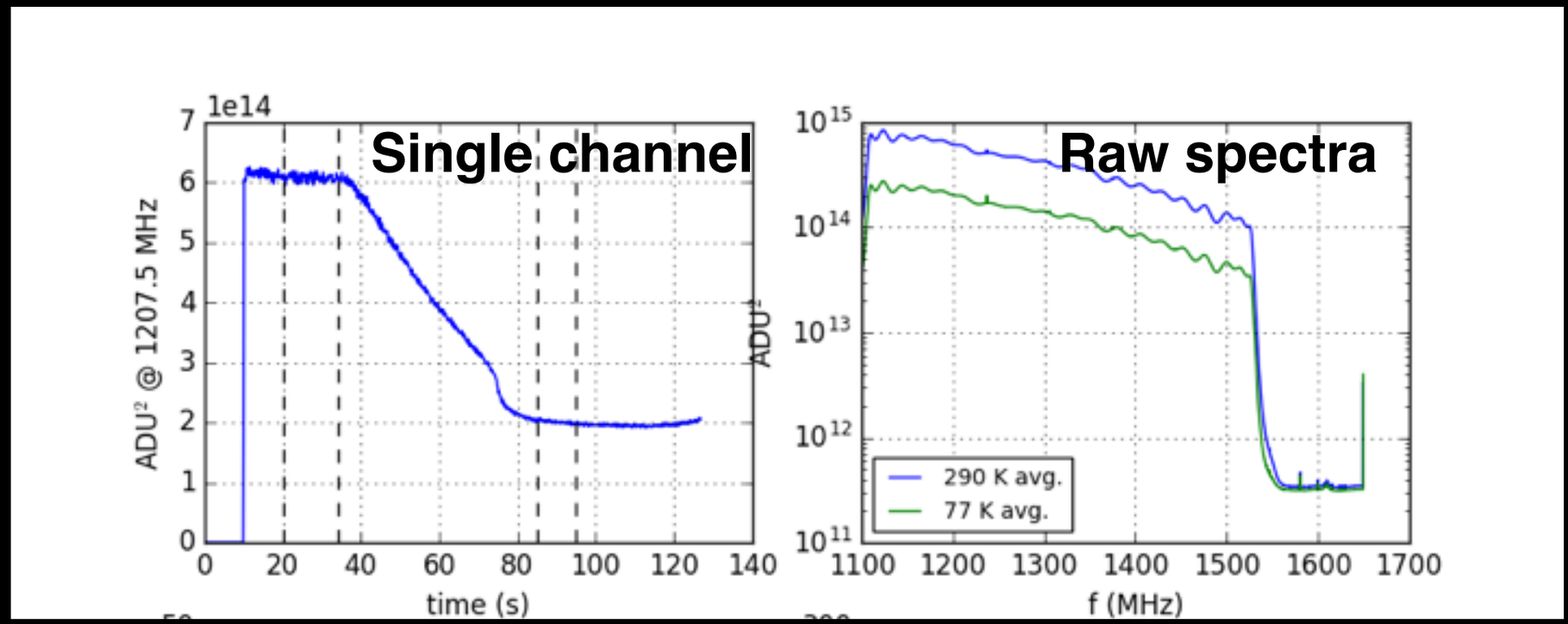
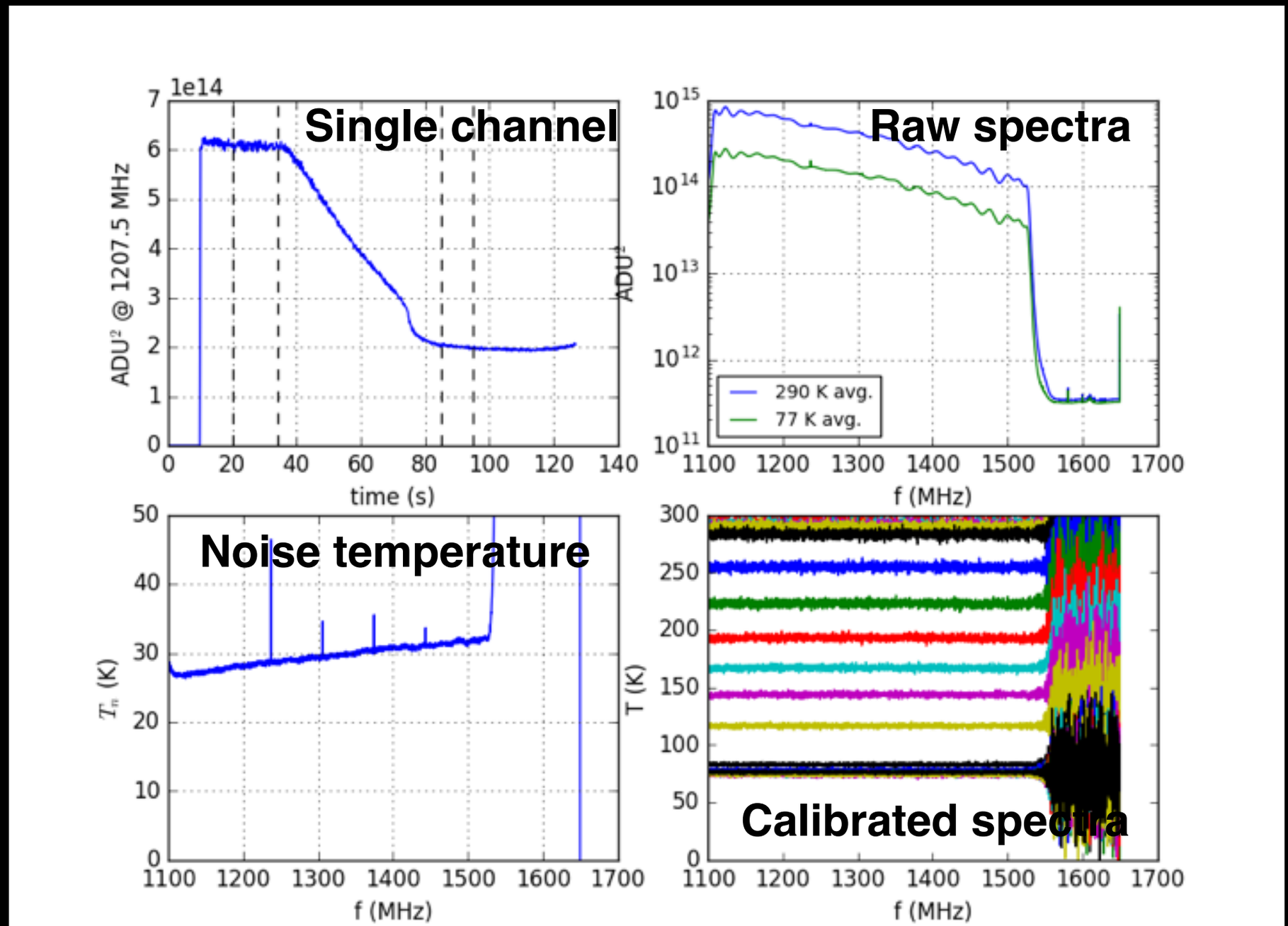


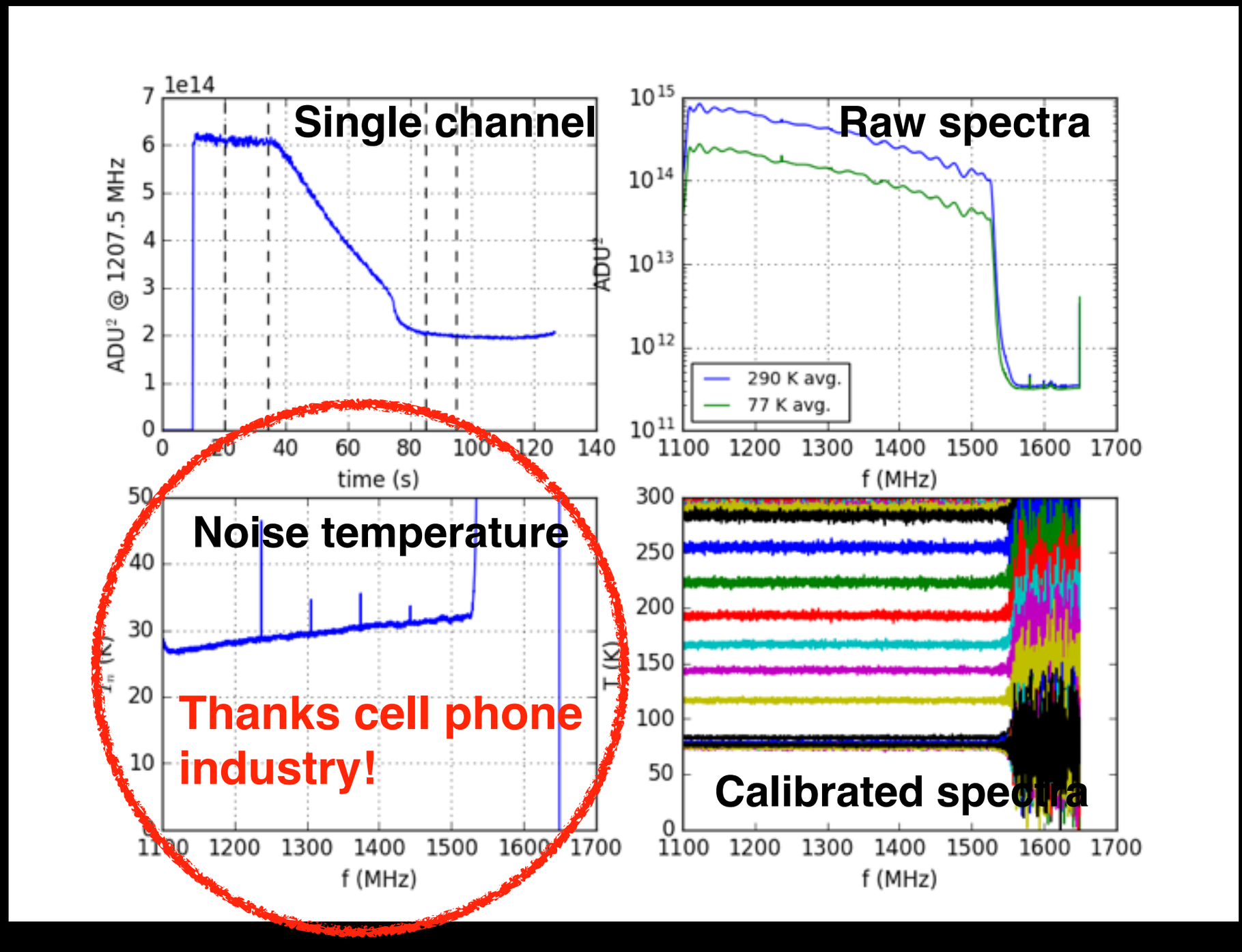
BMX

Calibrate spectrometer and measure noise temperature with Liquid nitrogen



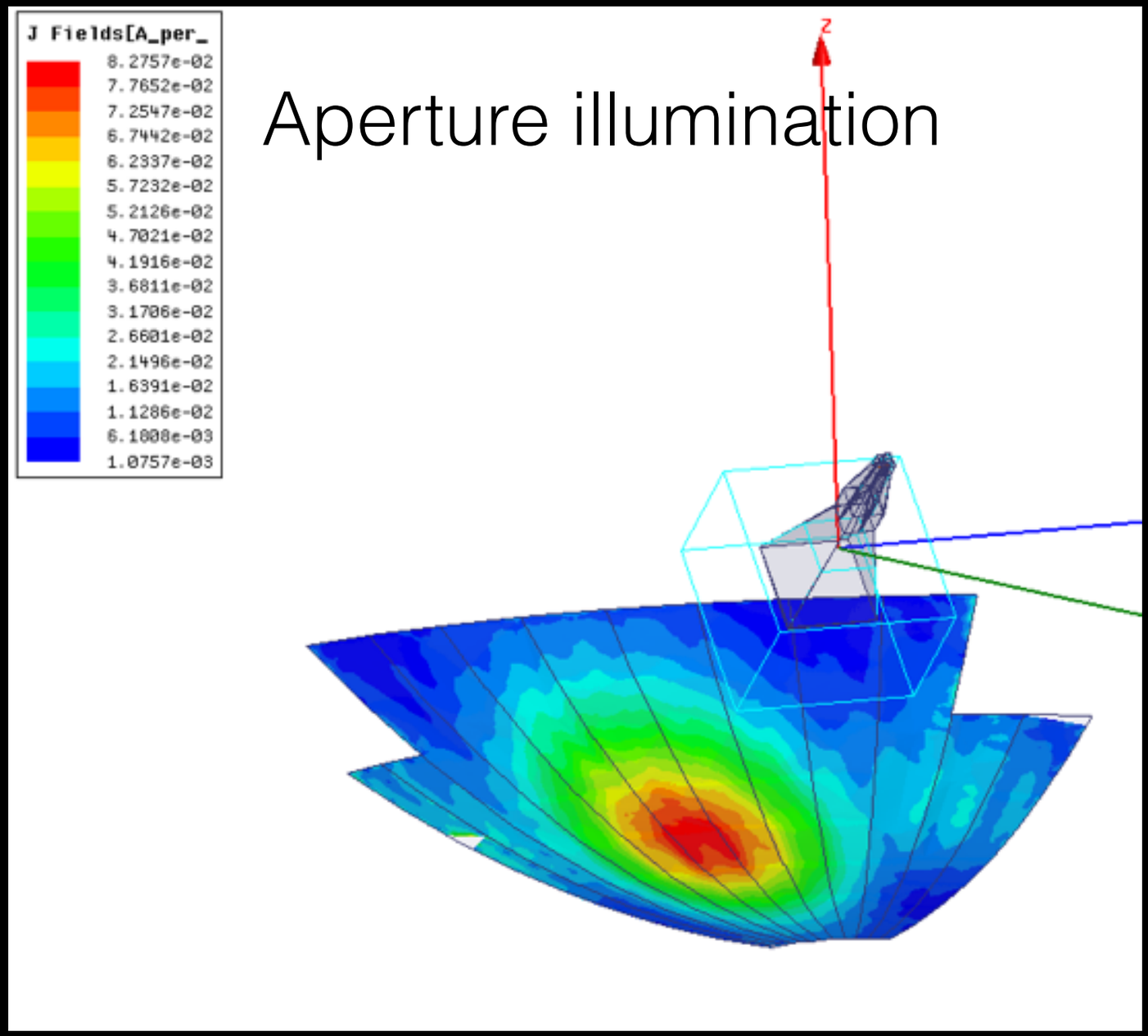
BMX

Calibrate spectrometer and measure system noise temperature with Liquid nitrogen



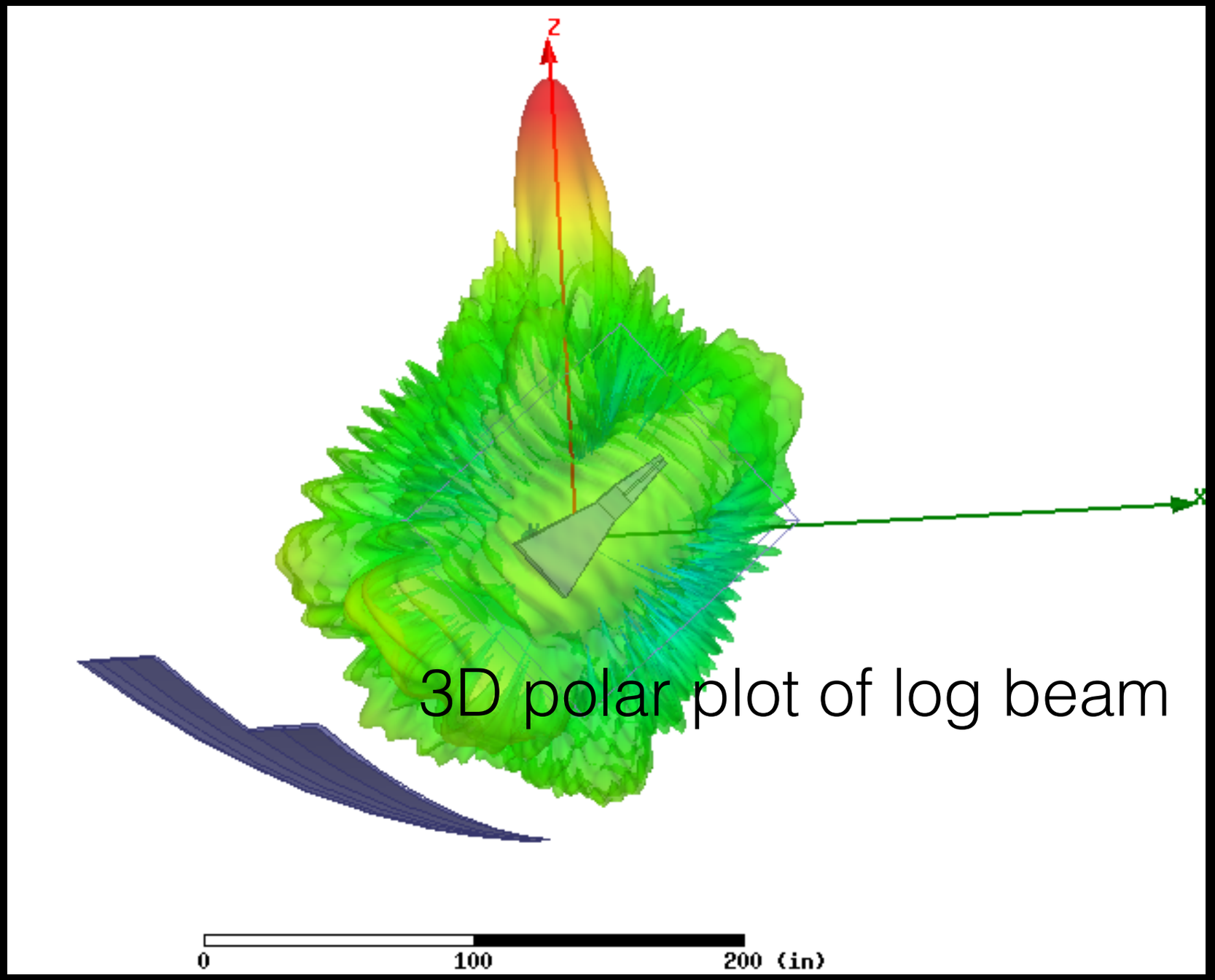
BMX

Full end to end beam simulations.



BMX

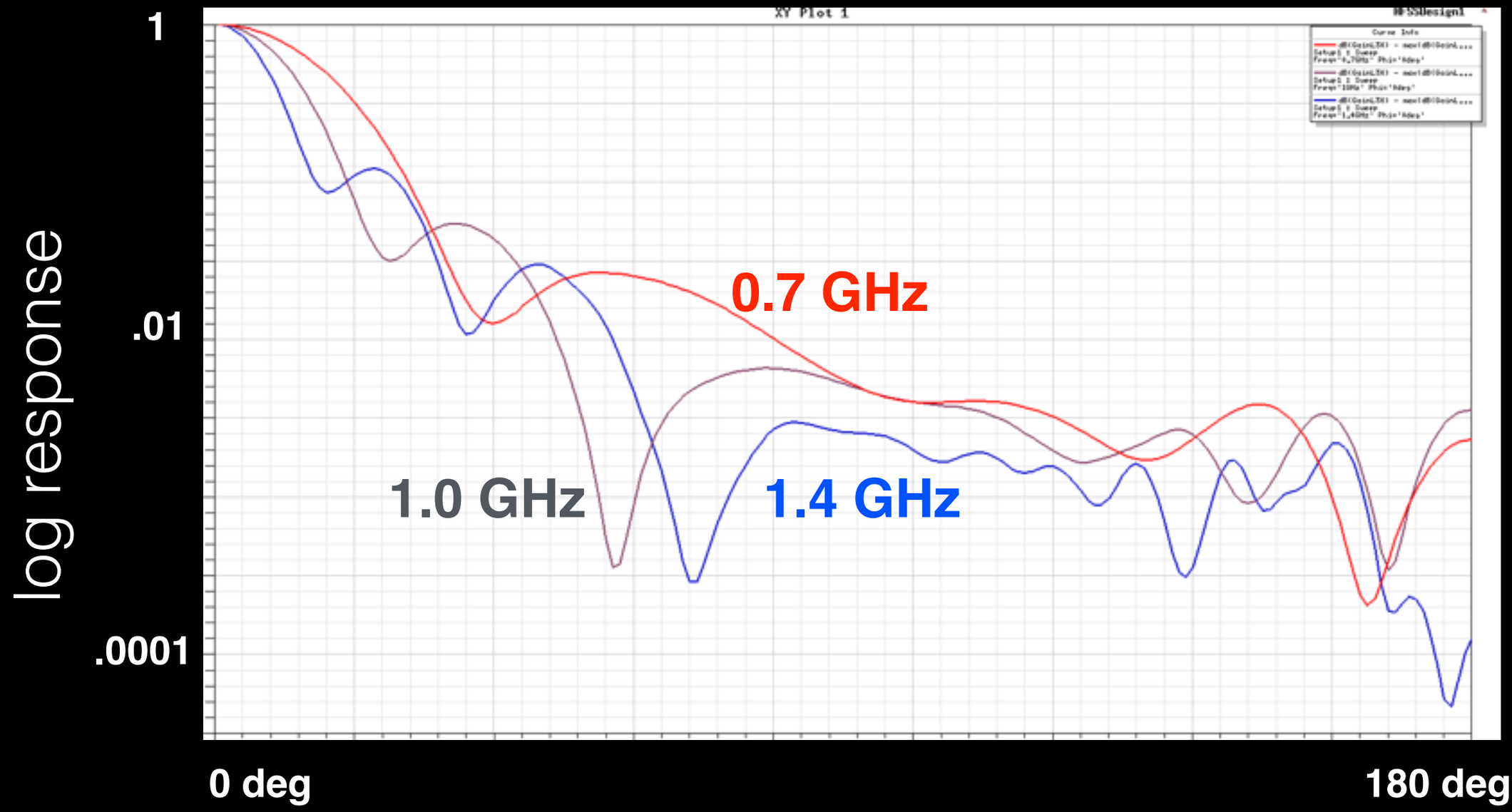
Full end to end beam simulations.



3D polar plot of log beam

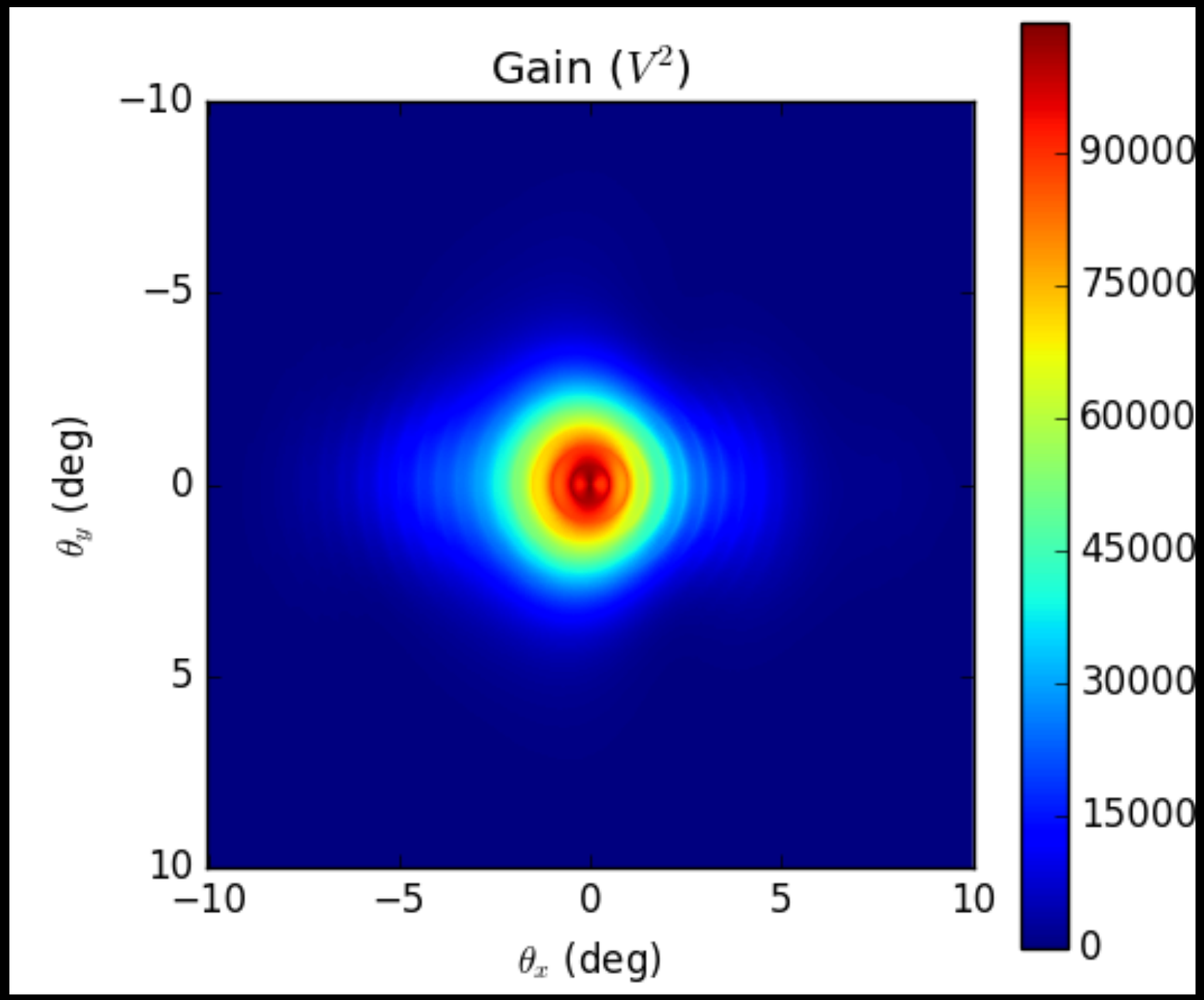
BMX

Full end to end beam simulations.



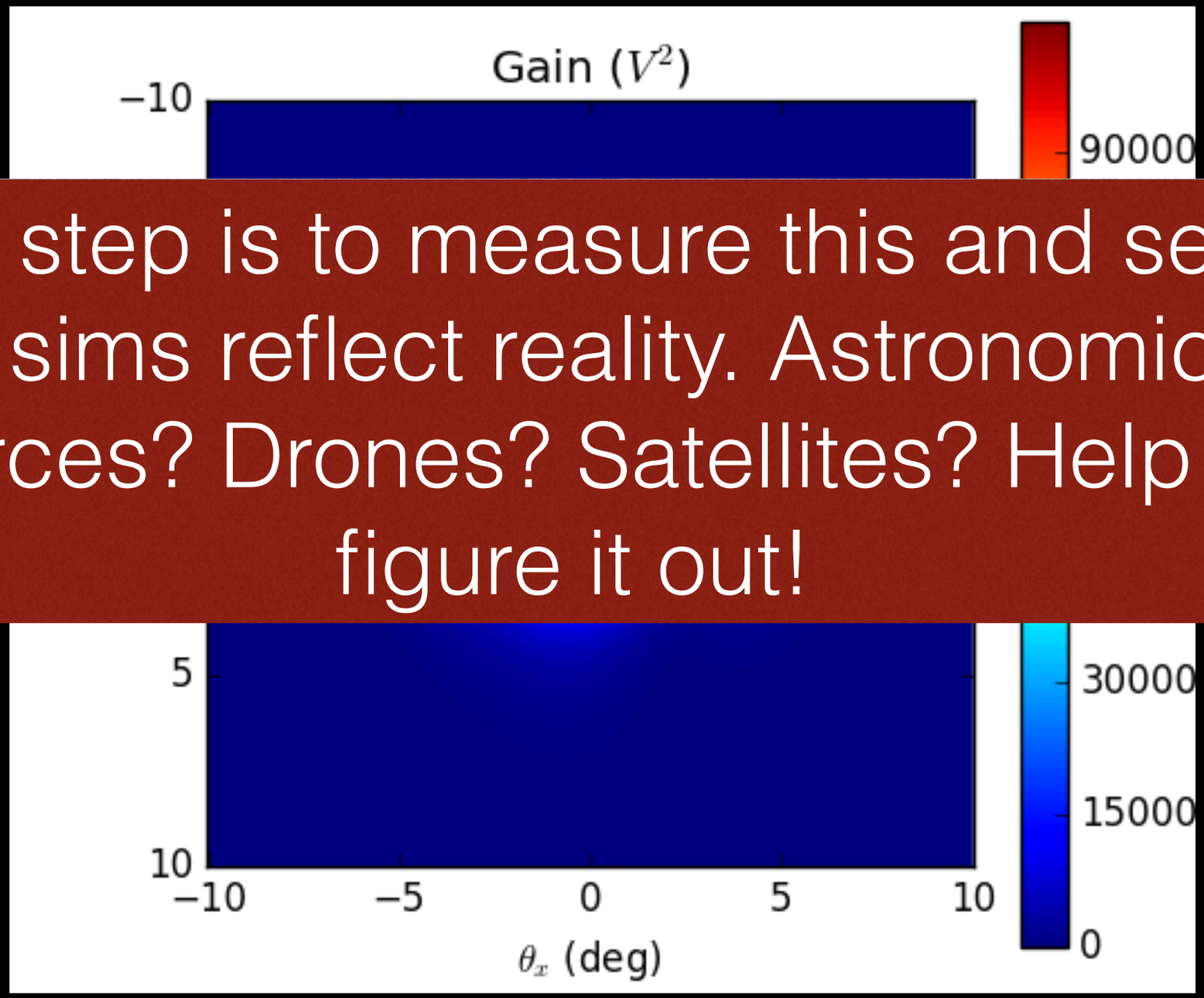
BMX

Full end to end beam simulations.



BMX

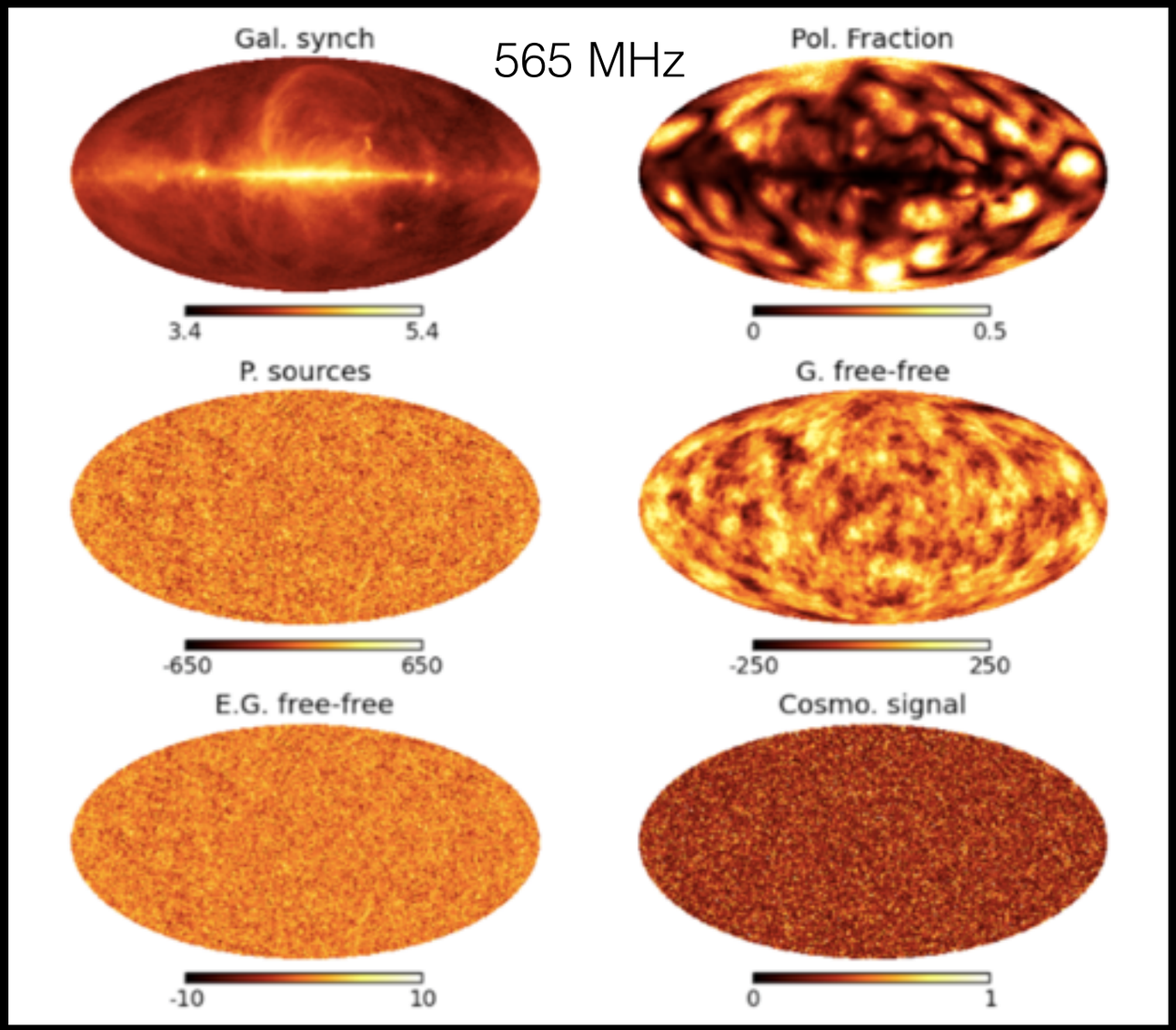
Full end to end beam simulations.



Next step is to measure this and see if our sims reflect reality. Astronomical sources? Drones? Satellites? Help us figure it out!

BMX

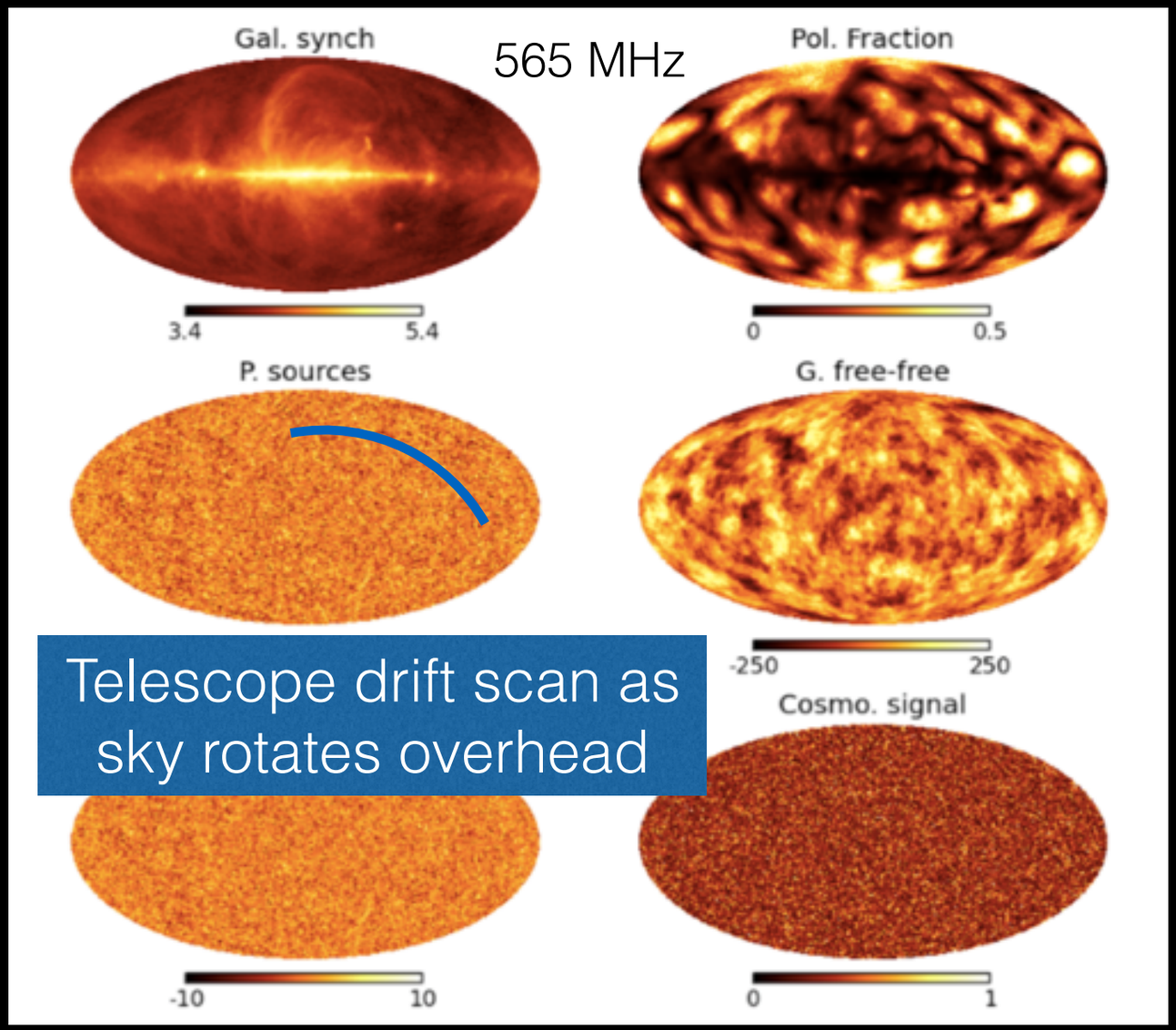
Cosmological simulations with realistic instrument: python pipeline in progress!



CRIME (Alonso, et al., 2014)

BMX

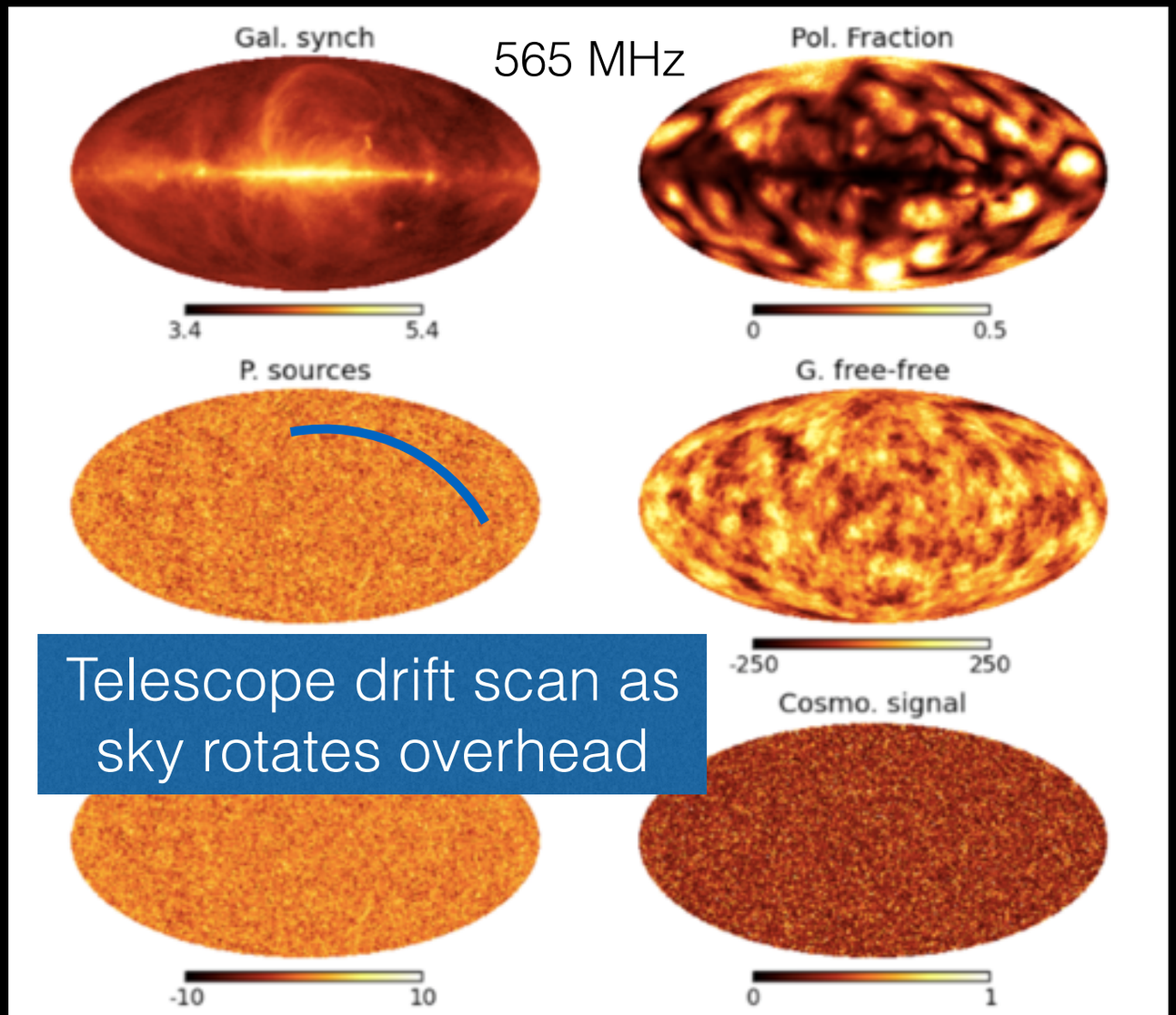
Cosmological simulations with realistic instrument: python pipeline in progress!



CRIME (Alonso, et al., 2014)

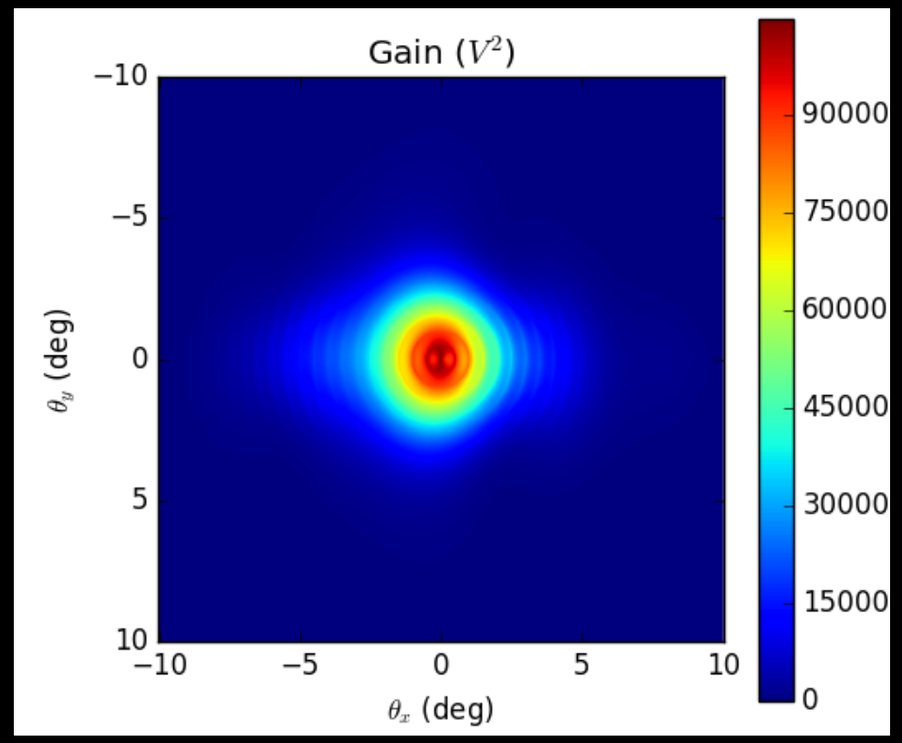
BMX

Cosmological simulations with realistic instrument: python pipeline in progress!



CRIME (Alonso, et al., 2014)

Convolve with instrument beam



BMX

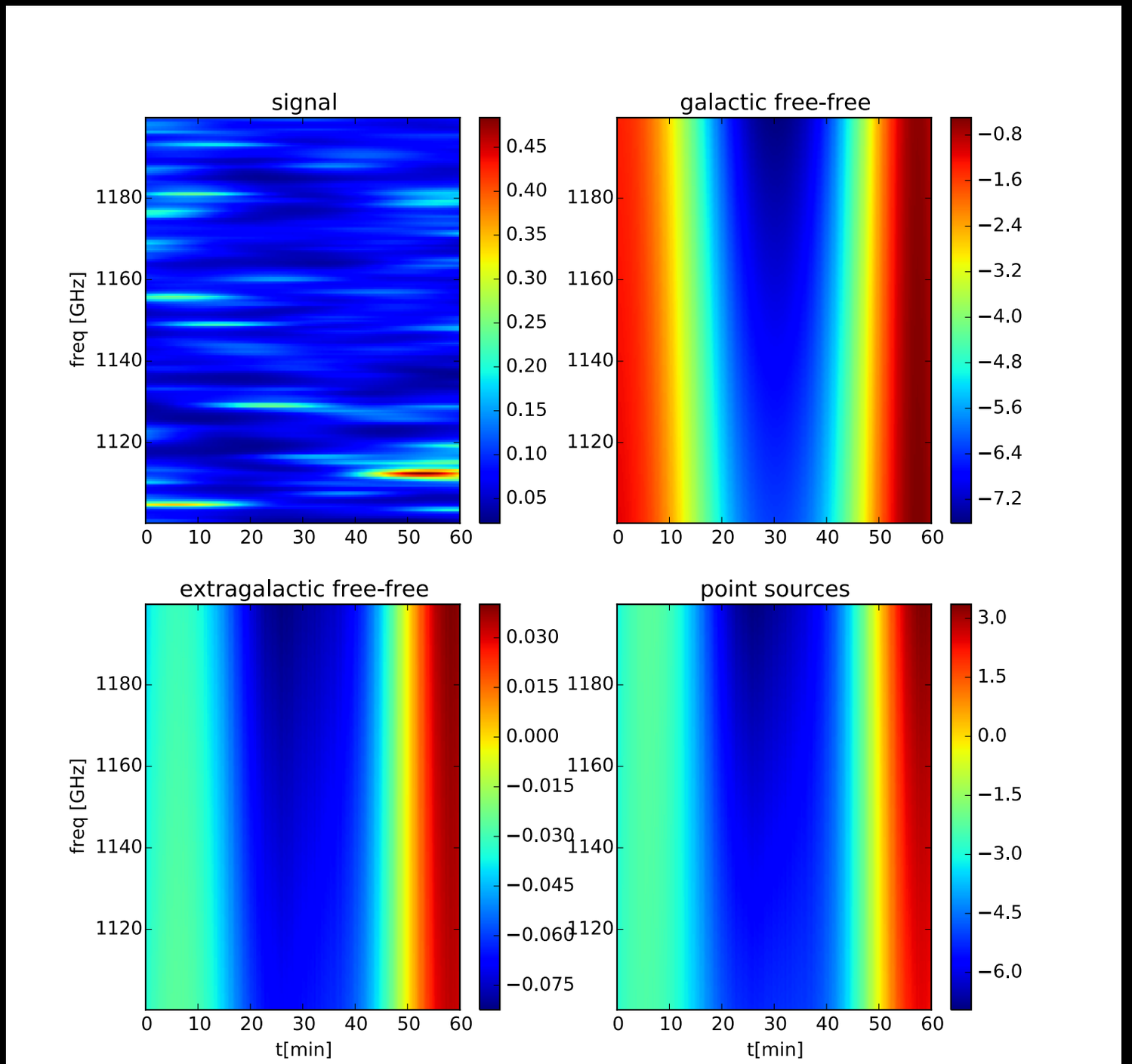
Simulated time ordered data.

Bin into map pixels (really 3D voxels)

Do same to real data.

Compare.

Publish.



BMX

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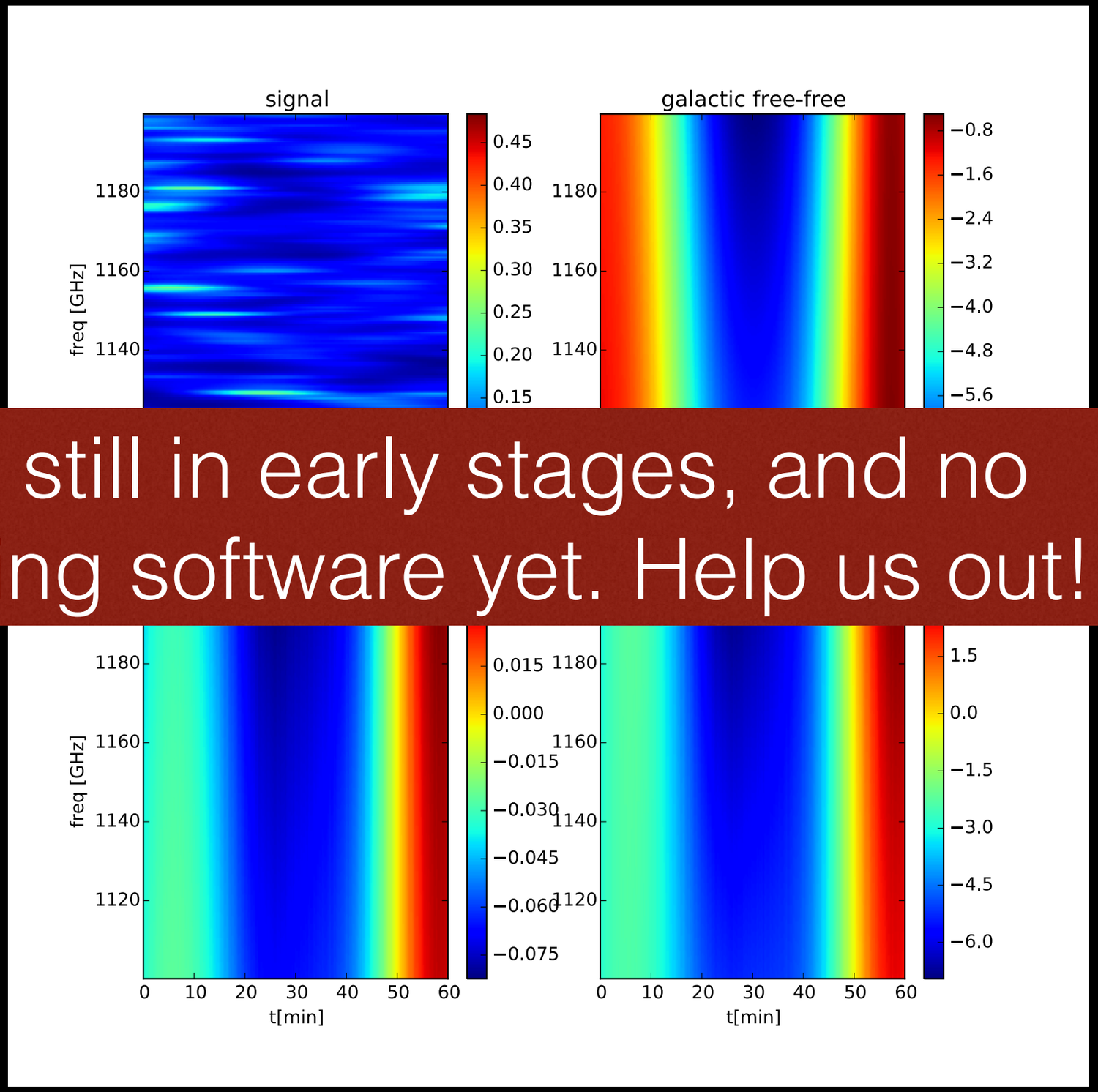


Pipeline still in early stages, and no map making software yet. Help us out!

BMX

Lastly, what can we ultimately do with a DOE funded 21-cm survey? We don't fully know! (Constraints on non-Gaussianity? Lensing? Extra relativistic species?)

Anže Slosar is coordinating the DOE Cosmic Visions 21-cm working group and producing Fisher forecasts that will inform the entire community. This still needs a lot of work and will be very visible.

BMX

What aspects can you get involved in?

As many as you want. We need help with everything. This is a lot like the CMB's early days, before excessive specialization. Much less "theory / experiment" divide, just do whatever needs to happen to get a result.

- Instrument design and engineering. (It's fun.)
- Physically building the thing, making it work, and calibrating it.
- Simulation and data analysis pipeline development (in python), leading to final maps and mock observations
- Cosmological analysis of the data
- Forecasting for next generation DOE dark energy surveys.

BMX

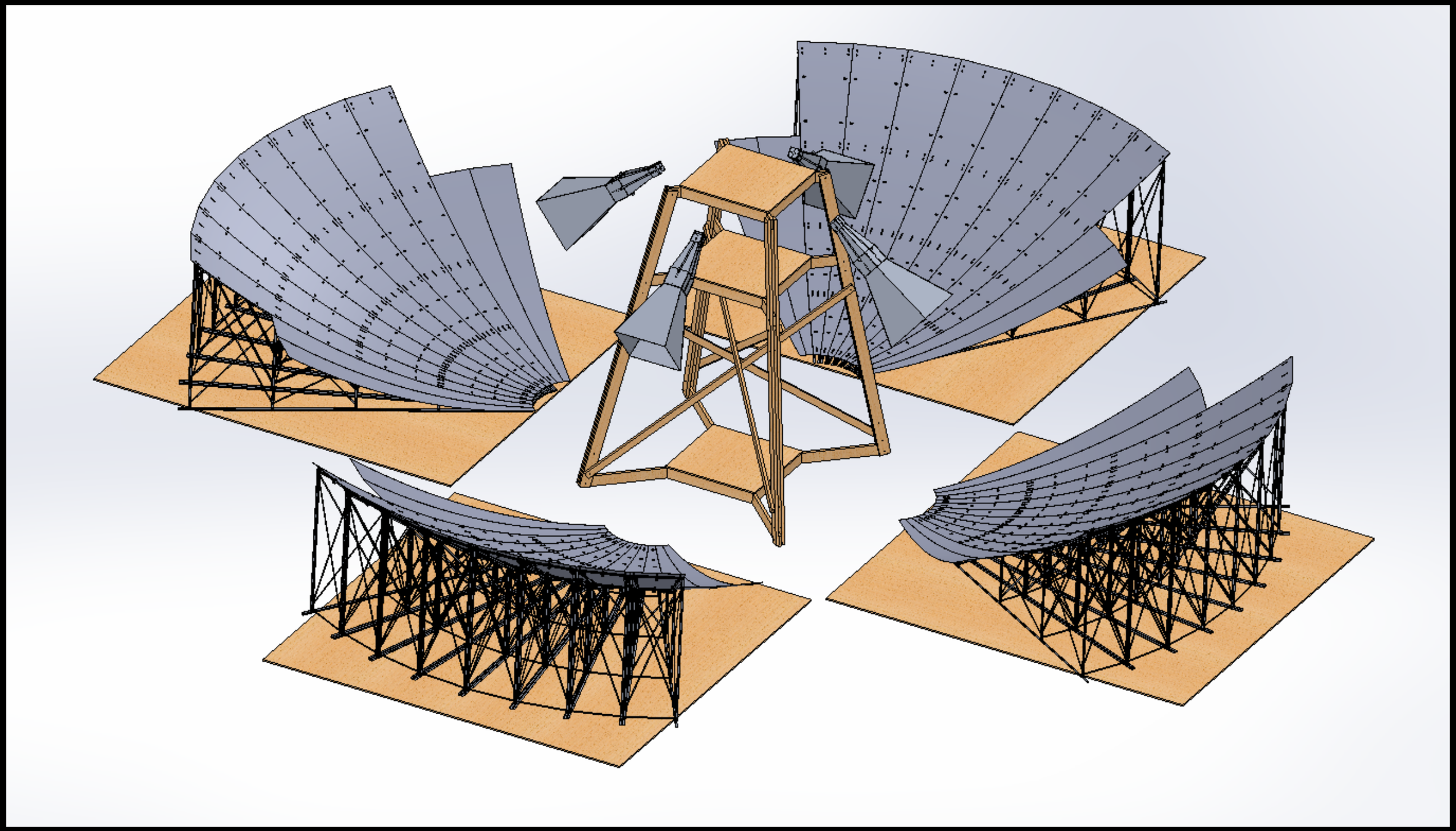
If you want to get involved:

Contact either me (Chris Sheehy, csheehy “at” bnl.gov)

or Neelima Seghal (neelima.sehgal “at” stonybrook.edu)

Thanks!

BMX



Thanks!