21-cm Cosmology at BNL

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KIPAC Tea Talk, SLAC
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Cosmological paradigm

DOE funded cosmological surveys currently come in two varieties:

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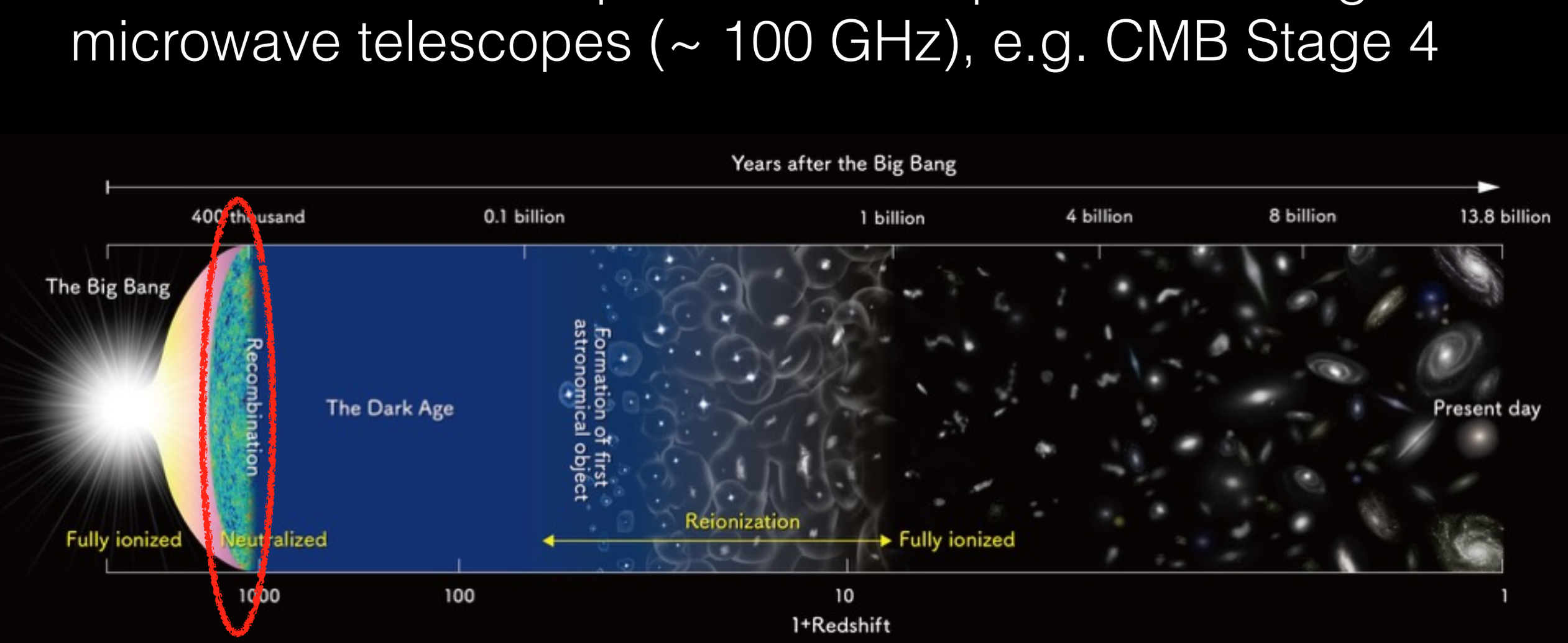
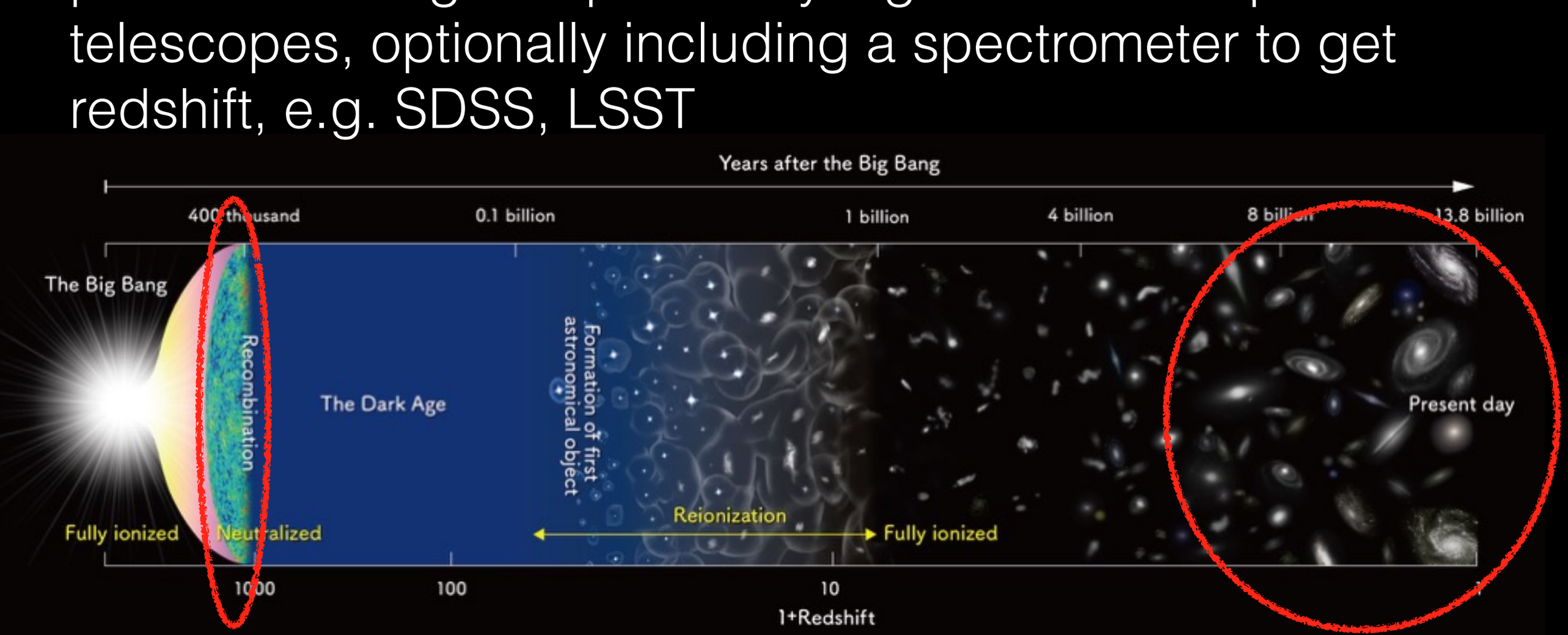
1 - **Cosmic Microwave Background surveys:** uniform, low resolution 2D maps of the CMB produced using microwave telescopes (~ 100 GHz), e.g. CMB Stage 4



Cosmological paradigm

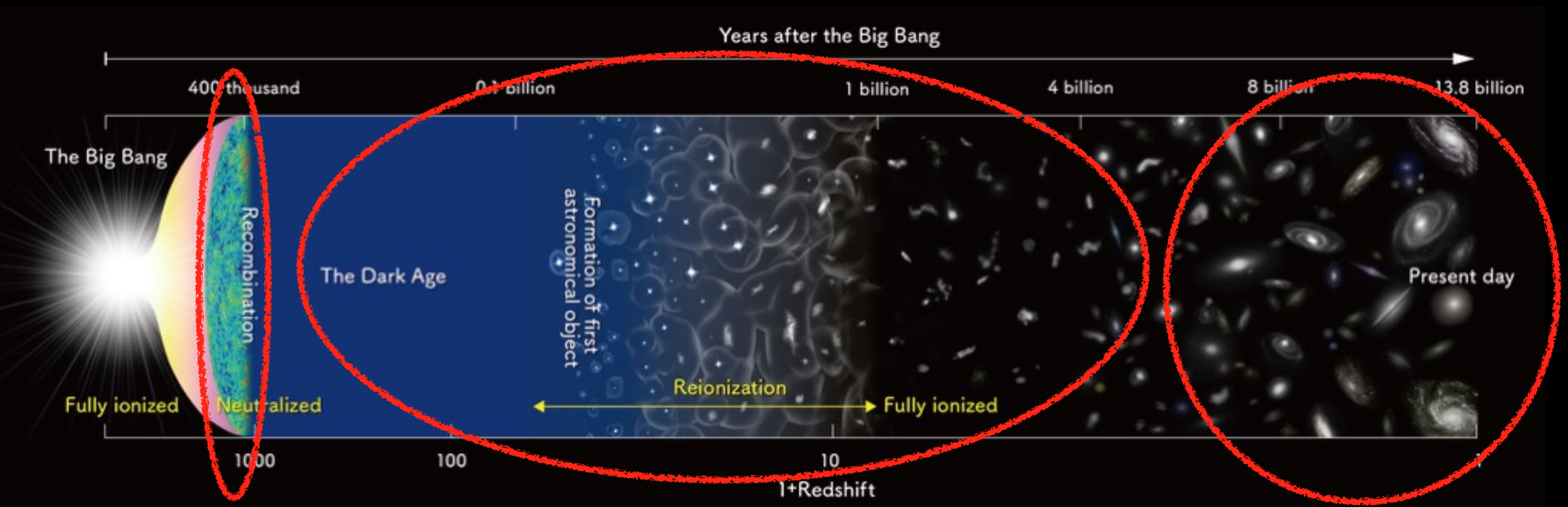
DOE funded cosmological surveys currently come in two varieties:

2 - **Galaxy surveys:** 3D catalogs of individual galaxies produced using comparatively high resolution optical telescopes, optionally including a spectrometer to get redshift, e.g. SDSS, LSST



Cosmological paradigm

How do we map the rest of the Universe, when there are few to no galaxies to measure? Mapping the “dark ages” in particular is the dream — it’s like the CMB in 3D, with pristine primordial fields and everything linear.

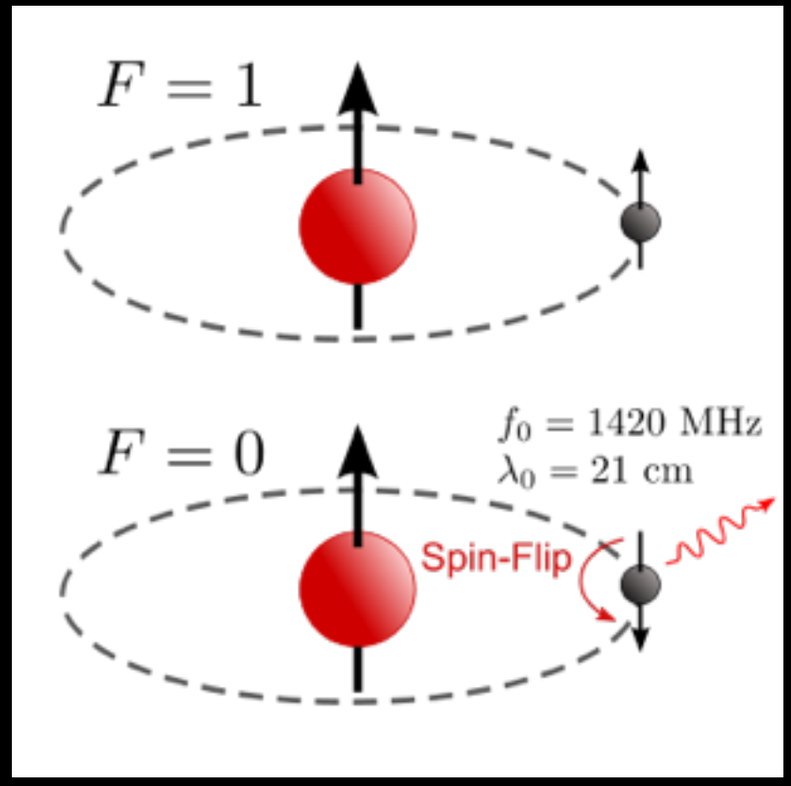


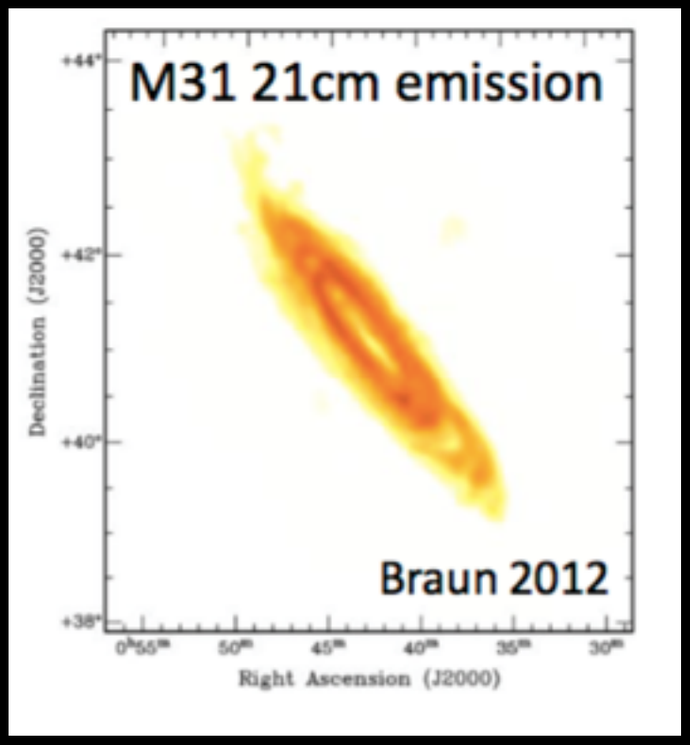
21-cm intensity mapping

Instead of detecting optical starlight from galaxies, detect radio emission from neutral hydrogen. Make low resolution, CMB-like maps of this emission.

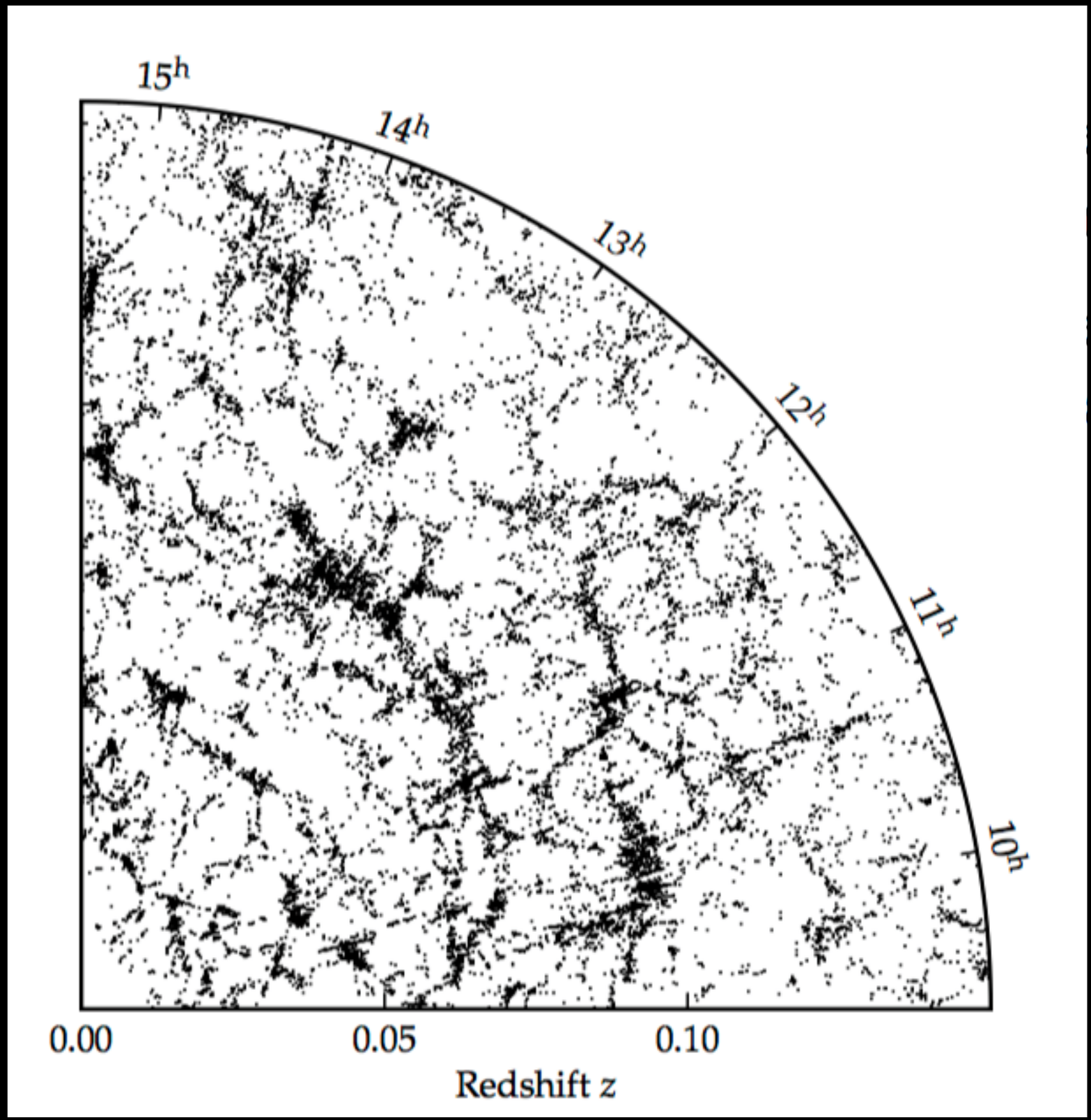
21-cm intensity mapping

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



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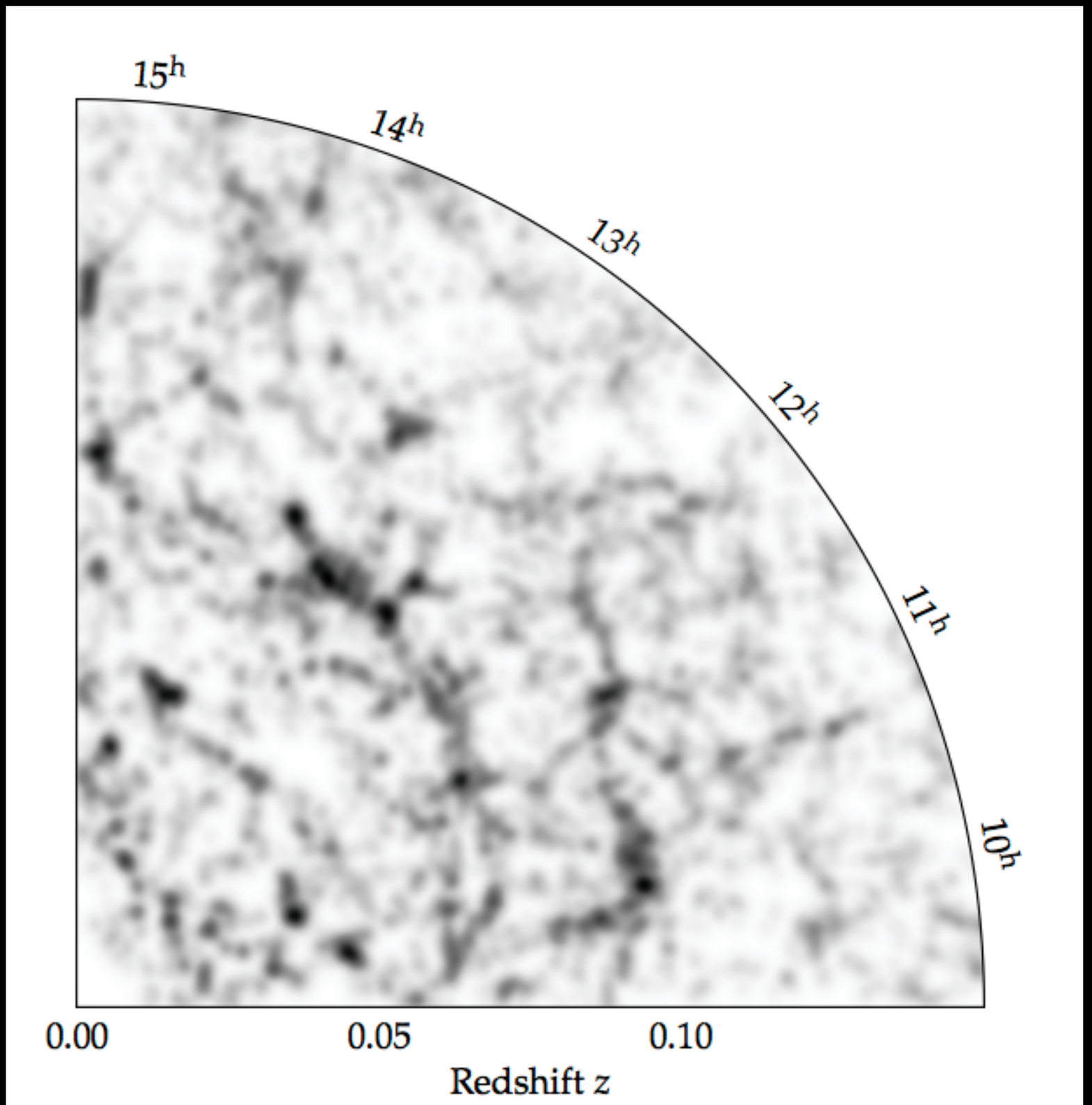
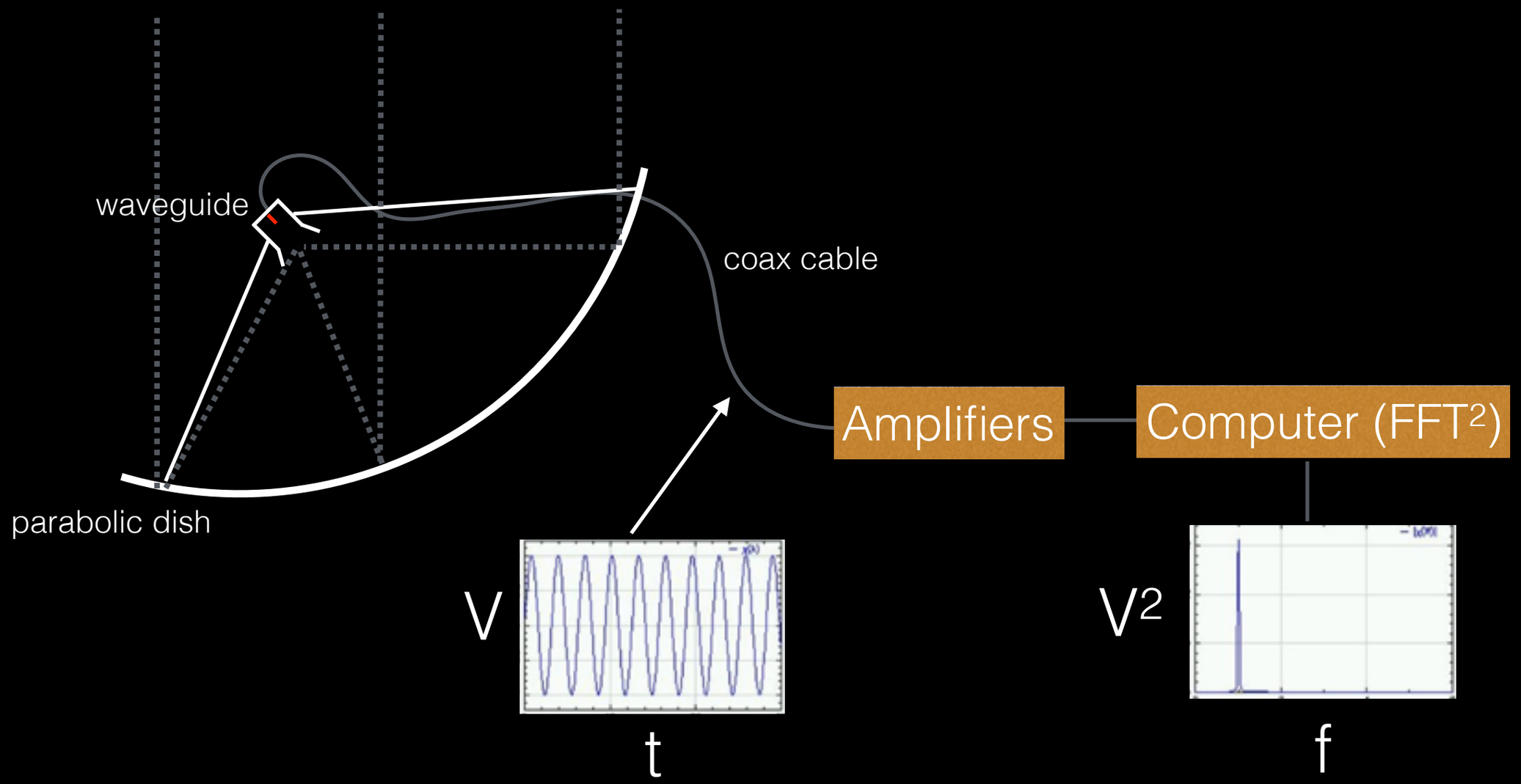


Radio telescopes

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.



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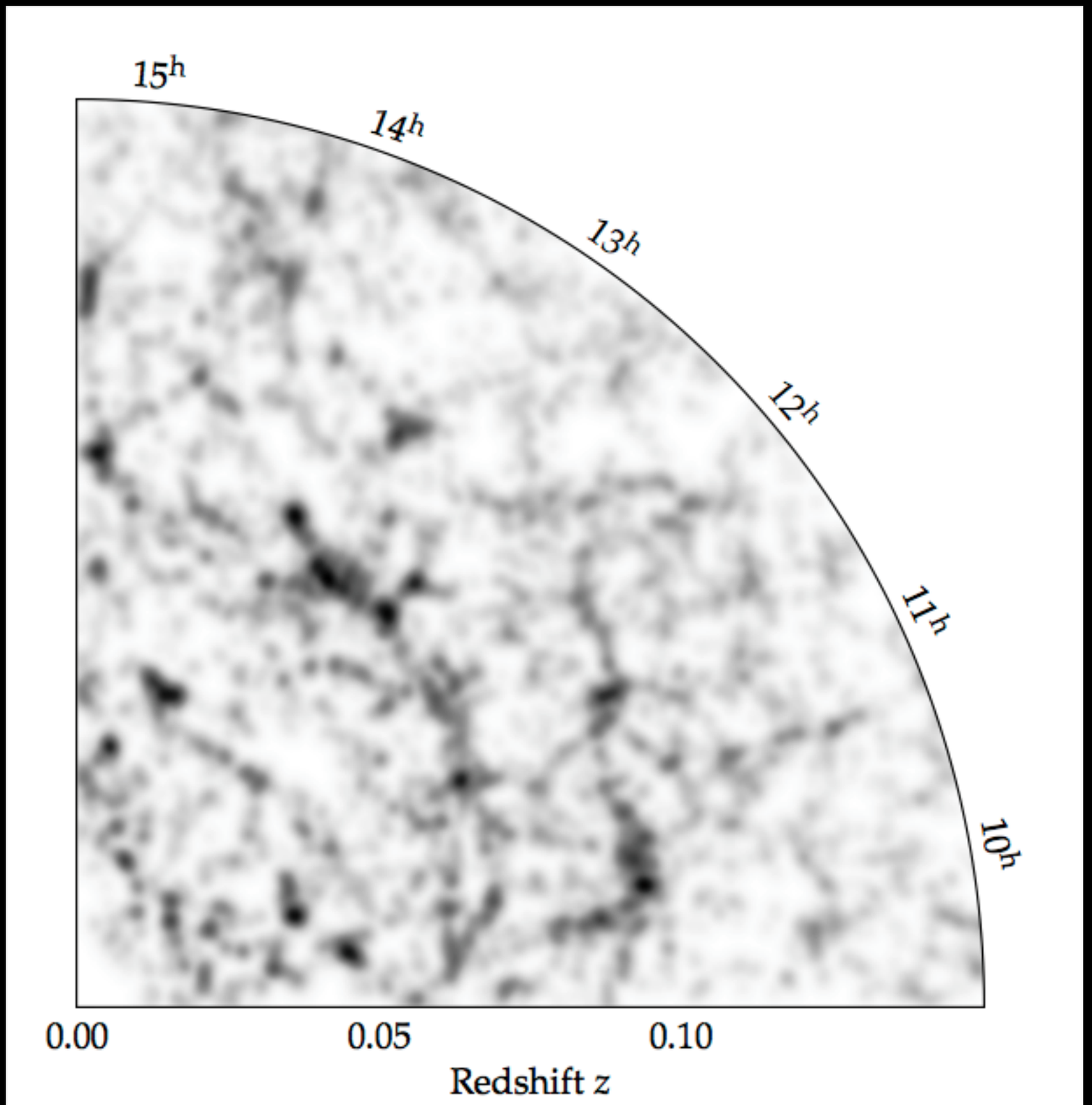

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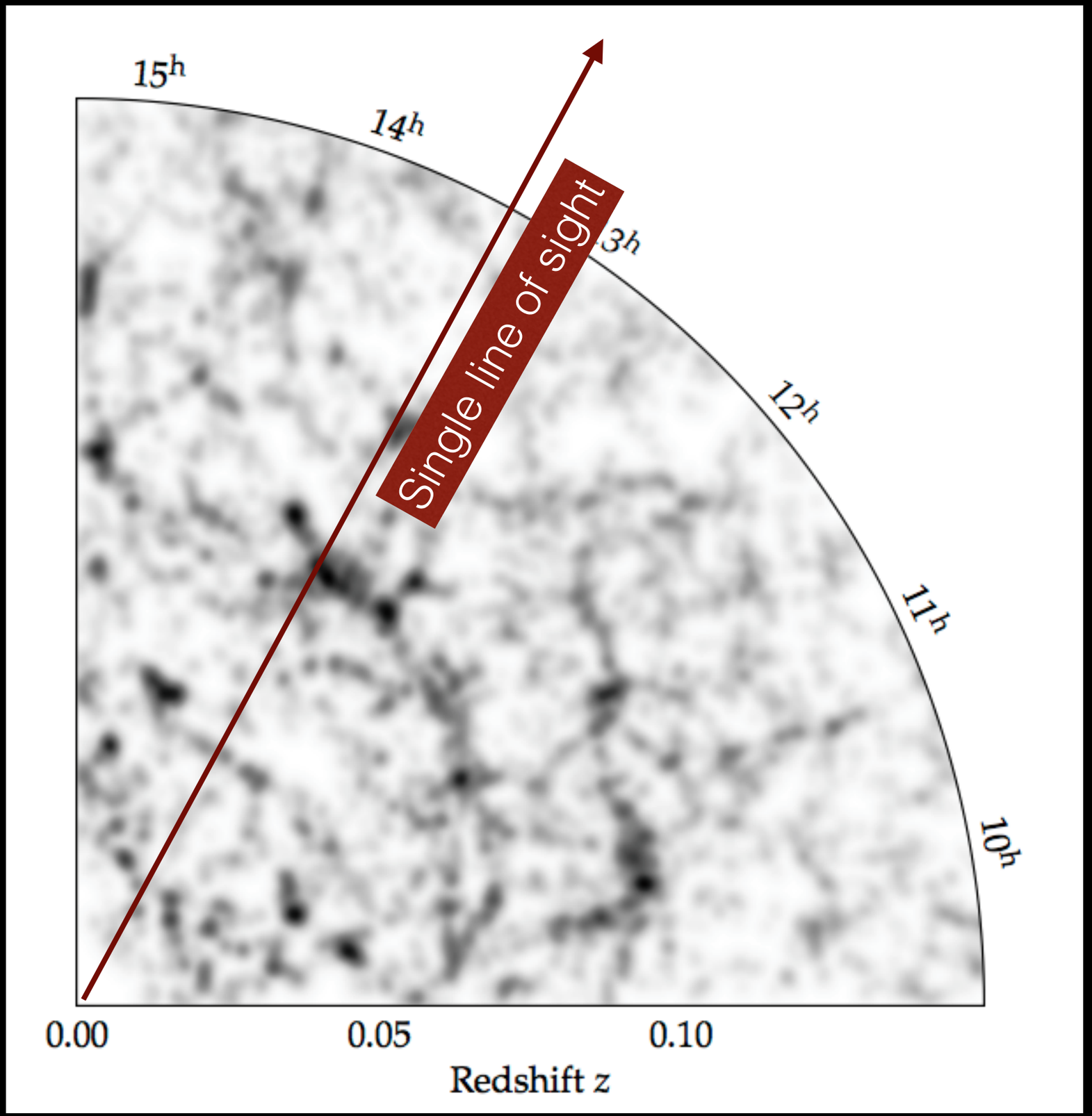

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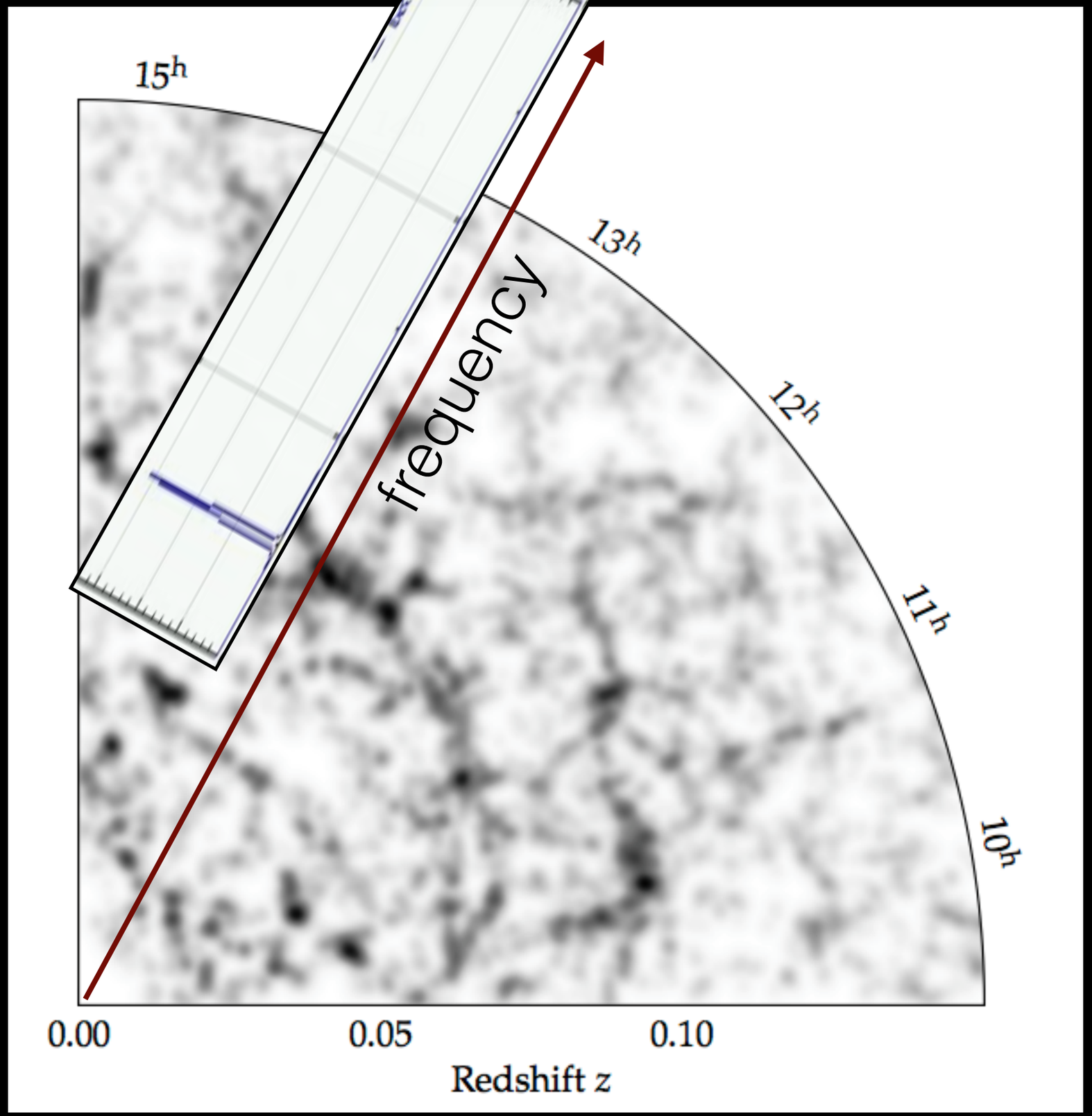

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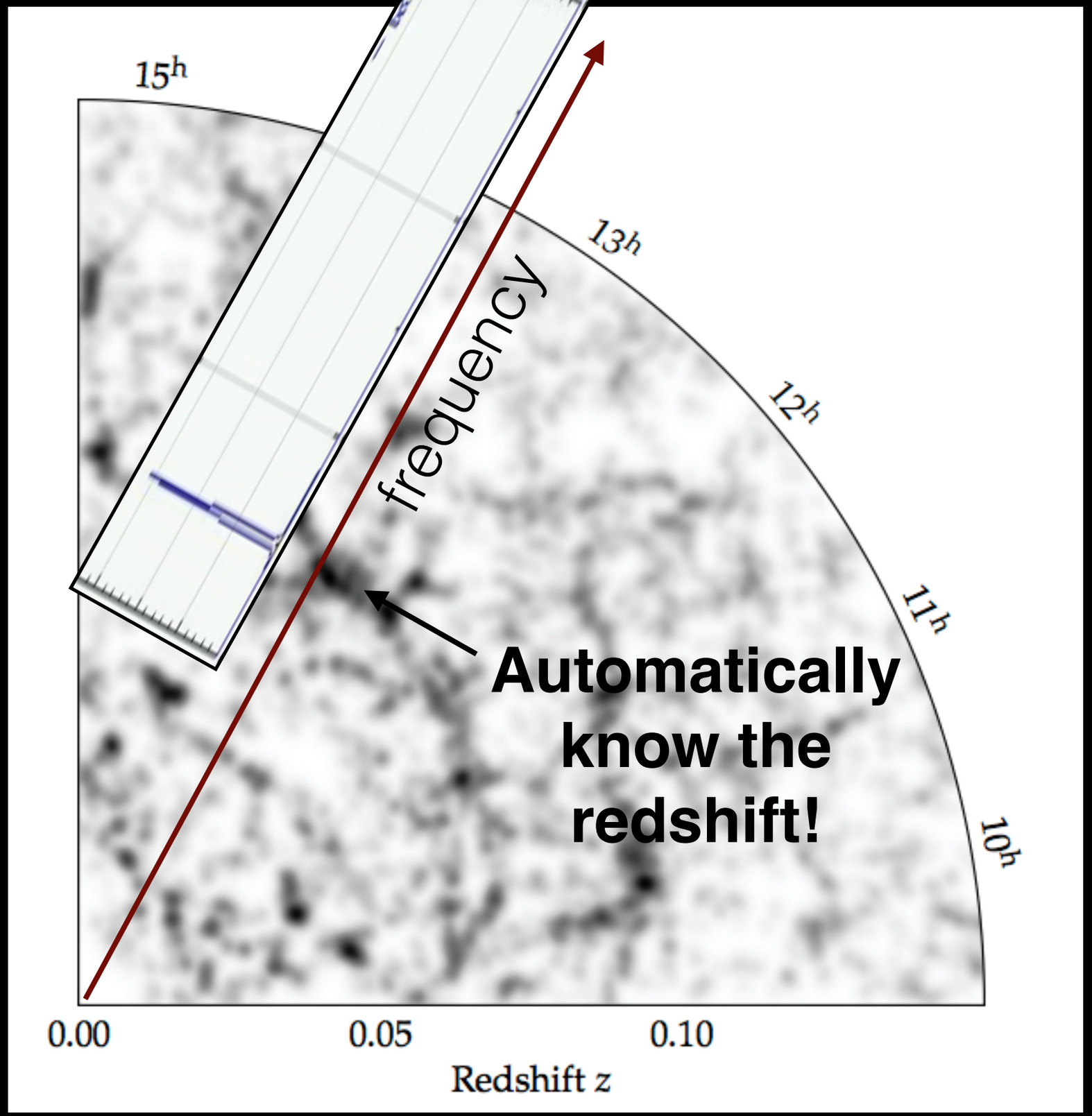
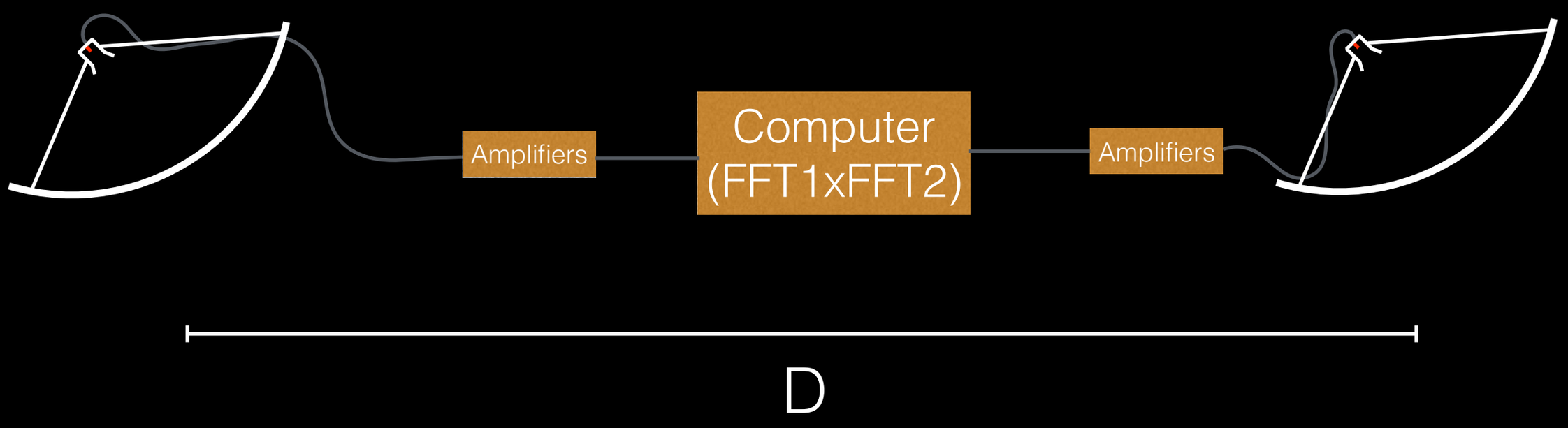


Radio telescopes

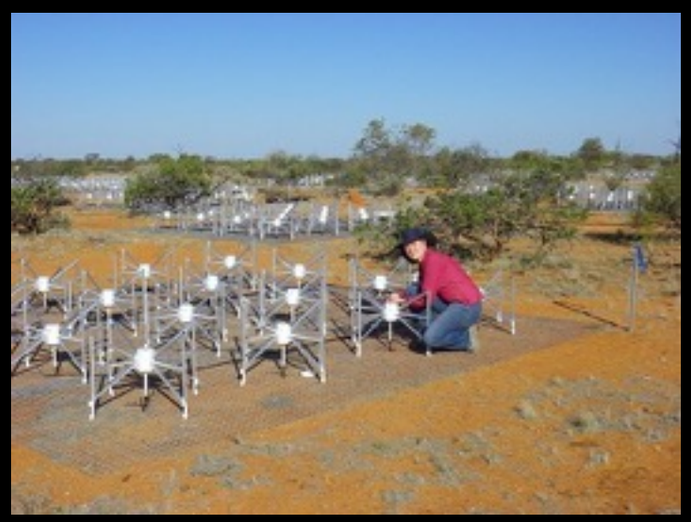
Operate multiple dishes as an interferometer
to increase the effective D and get better
angular resolution.



Current dedicated 21-cm experiments

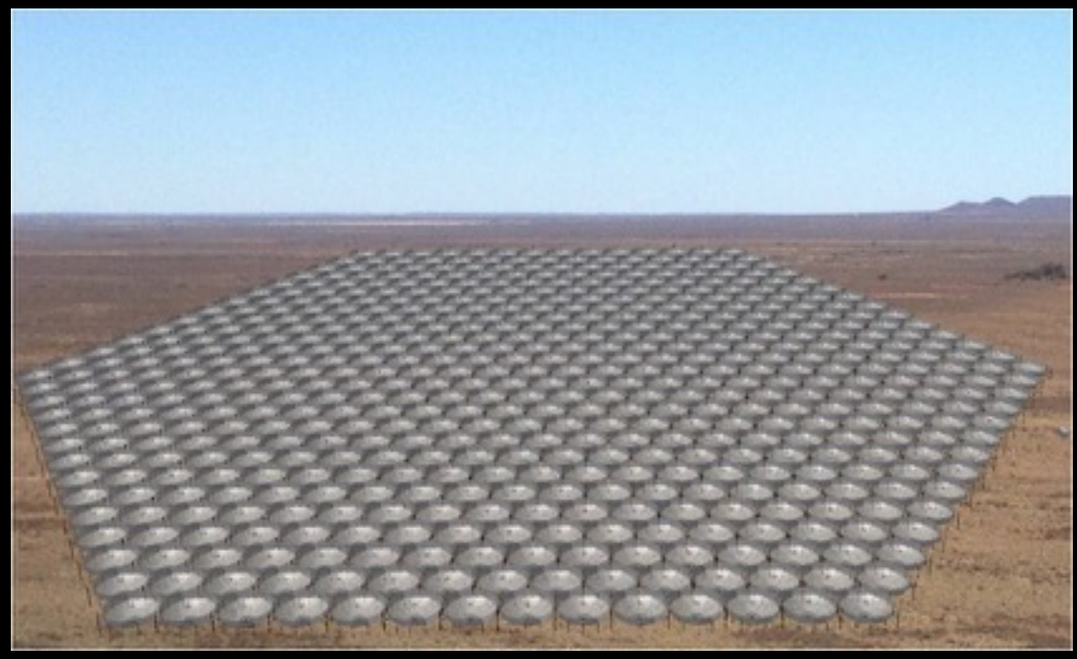
LOFAR

MWA



PAPER

HERA (funded)



CHIME

Current dedicated 21-cm experiments

LOFAR

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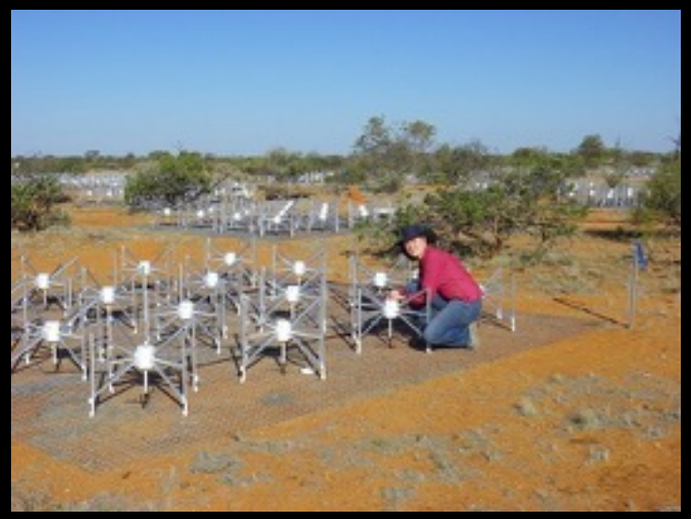

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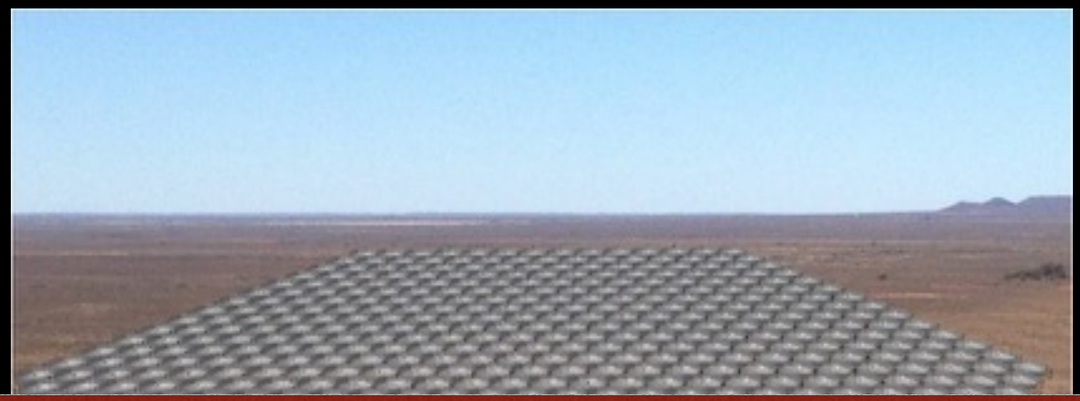
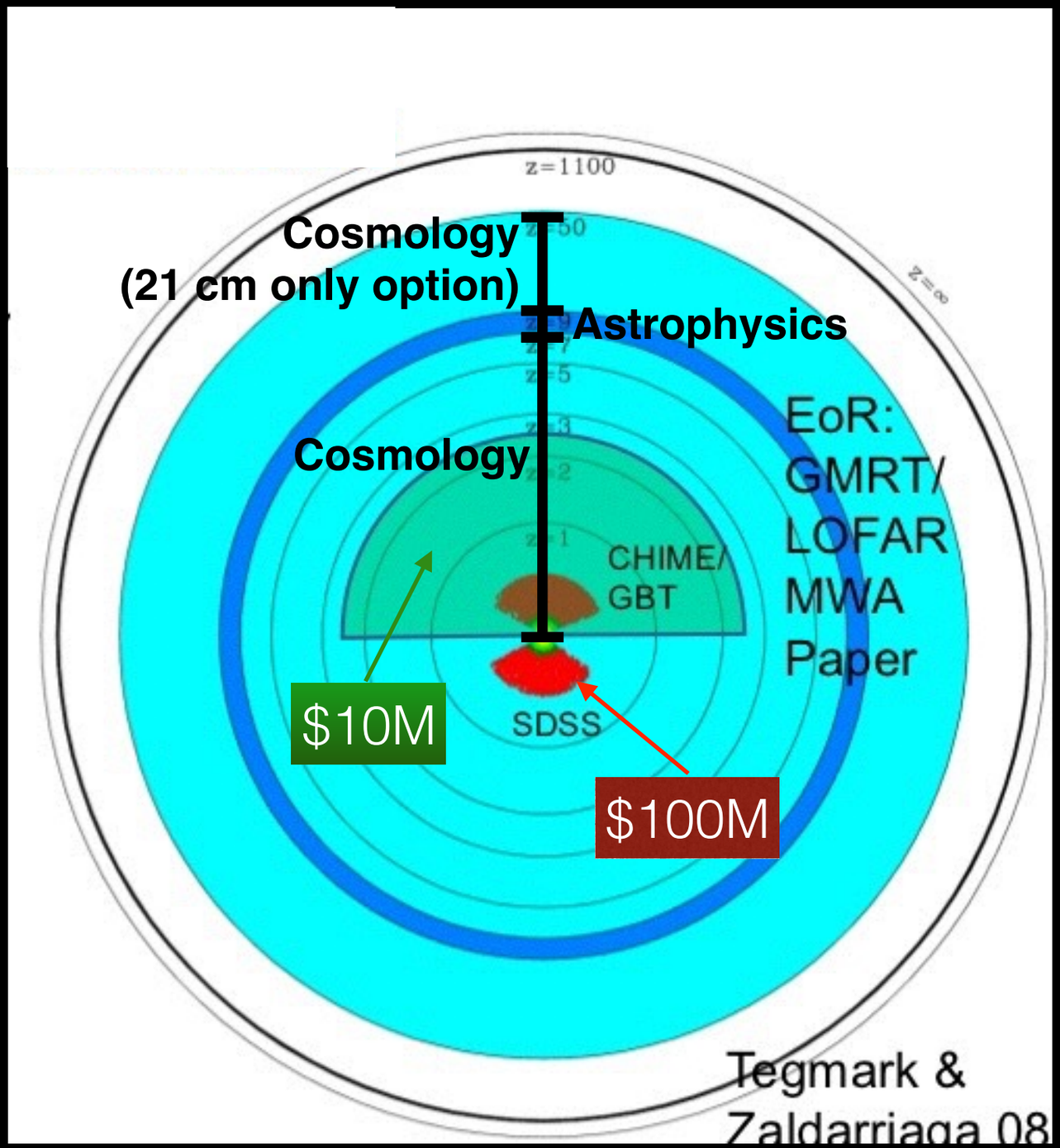


Only CHIME, a Canadian project, is focused on cosmology (BAO) instaead of reionization, z<2.5.

CHIME

Current experiments



Ue-Li Pen

Future of dark energy surveys

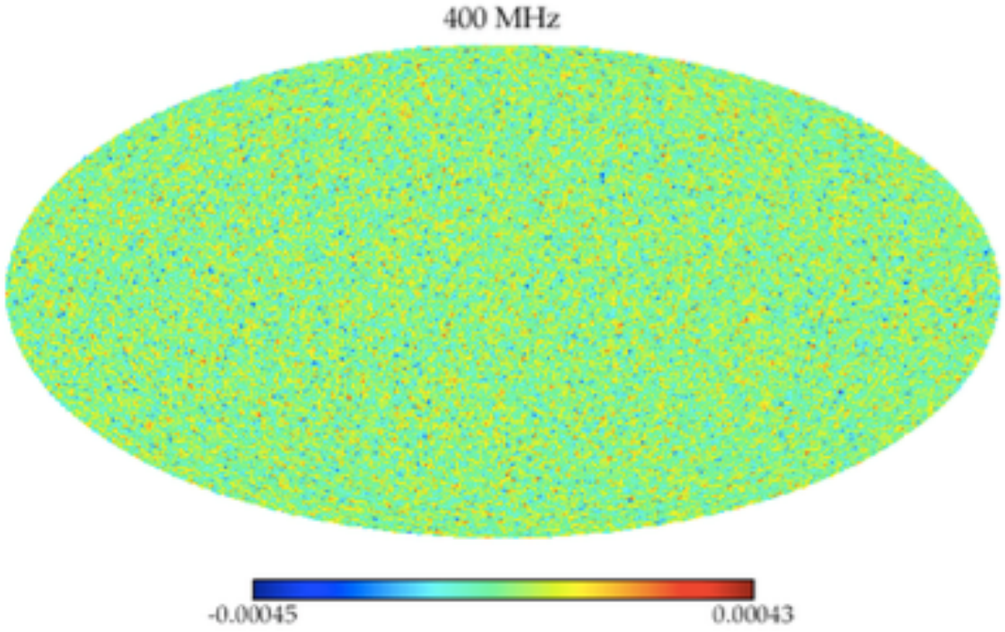
The DOE will fund a Stage IV dark energy survey. An obvious next thing to do is a spectrographic follow up to LSST, but things are starting to get expensive, perhaps $1B scale.

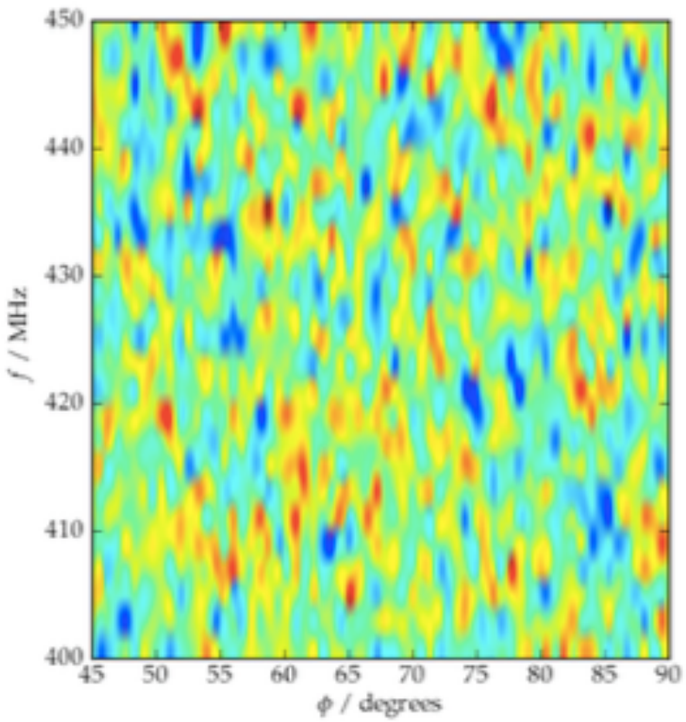
21-cm is identified by the DOE Cosmic Visions Dark Energy panel as one of a few options for a next generation survey.

Why is 21-cm hard? Lots of reasons, but one big one:

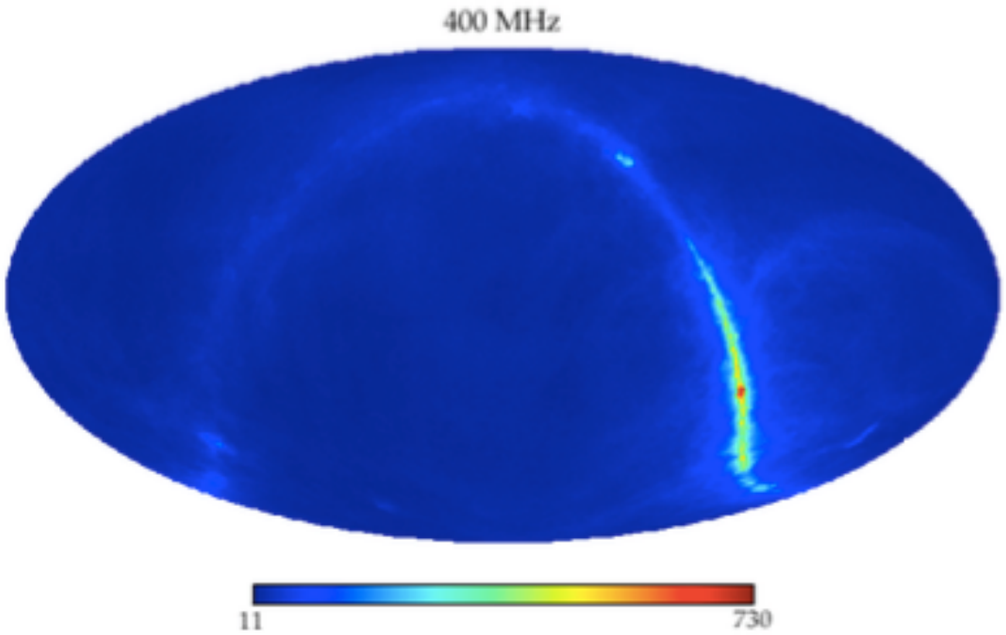
Galactic foregrounds

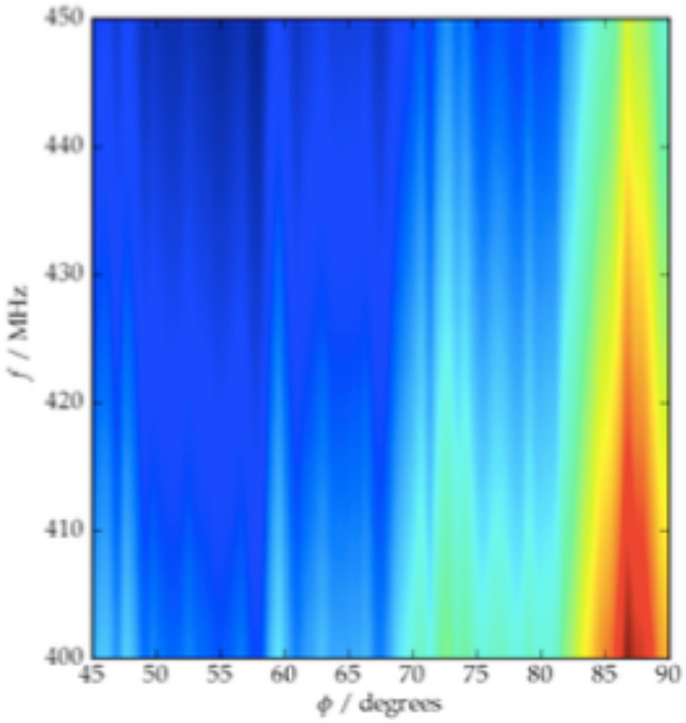
Signal ~1 mK





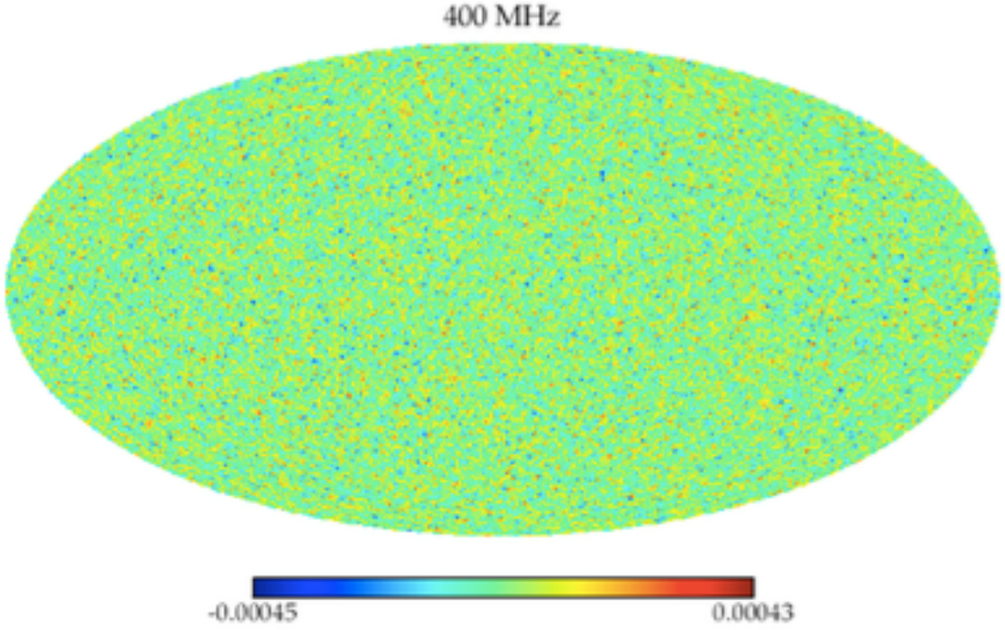
Galactic synchrotron up to 700 K

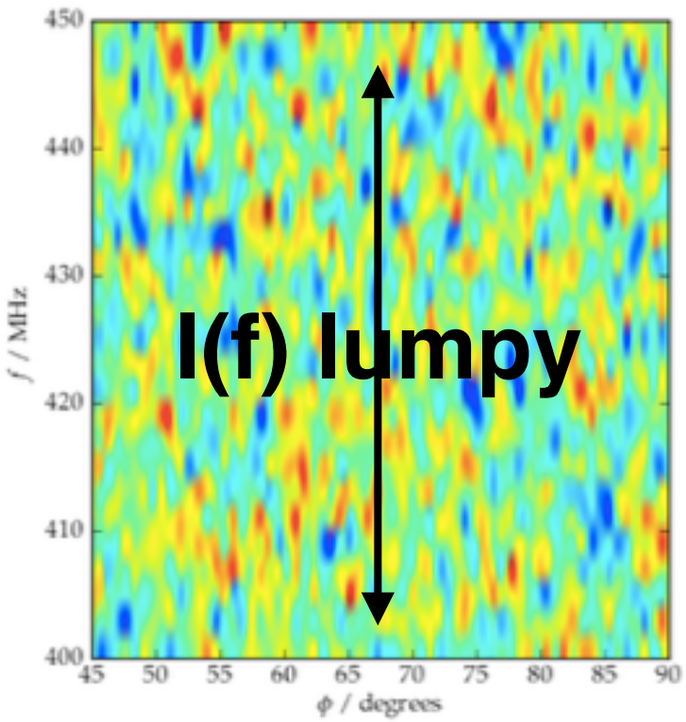




Richard Shaw

Signal ~1 mK





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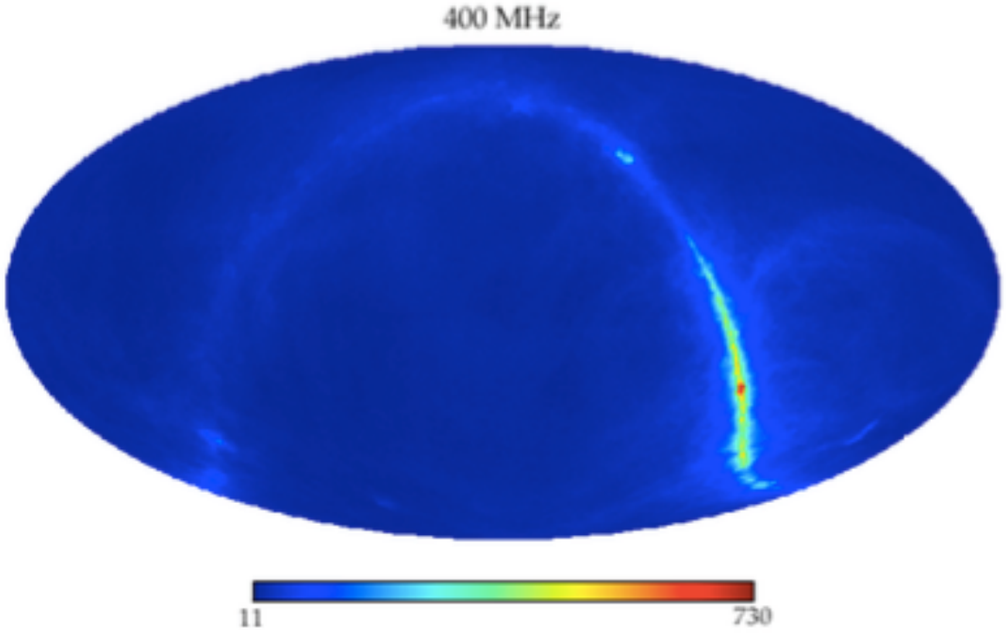
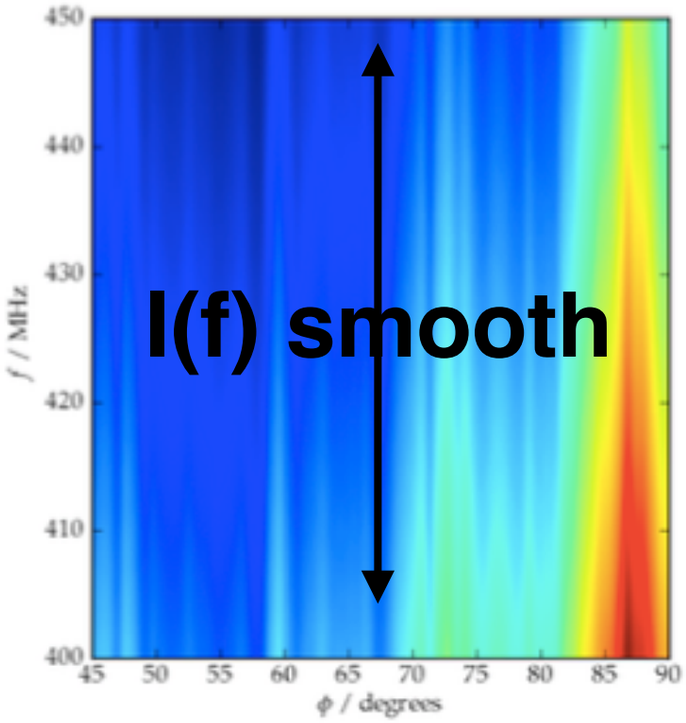


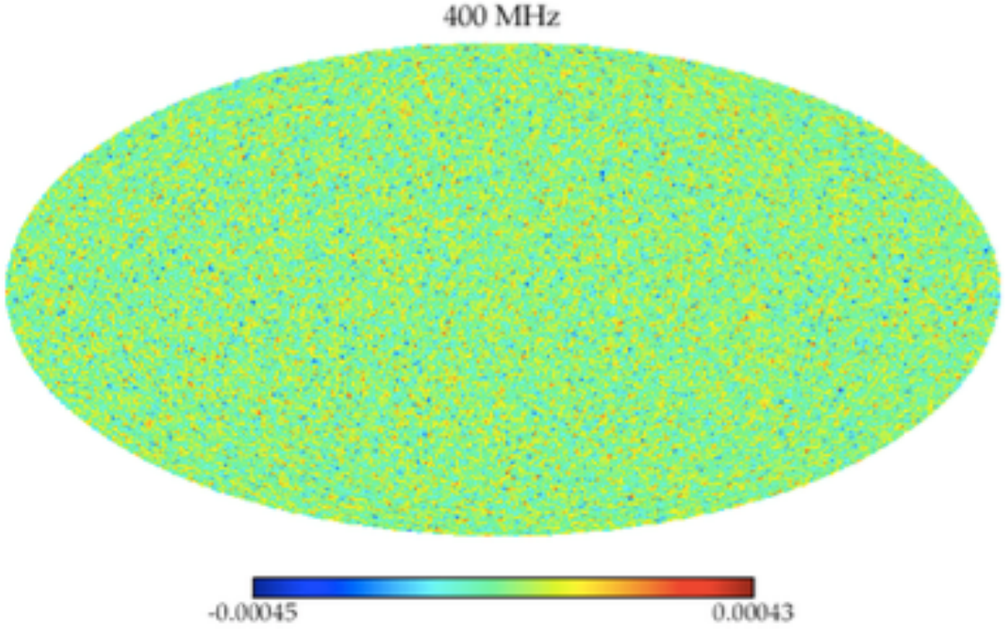


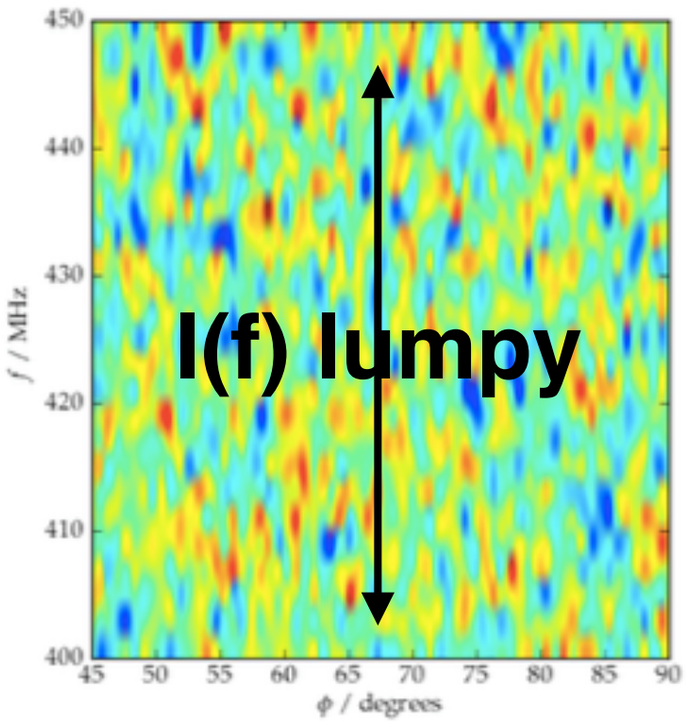
Richard Shaw

Galactic foregrounds

The beam (or point spread function, if you're an optical astronomer) is a function of frequency.

Signal ~1 mK





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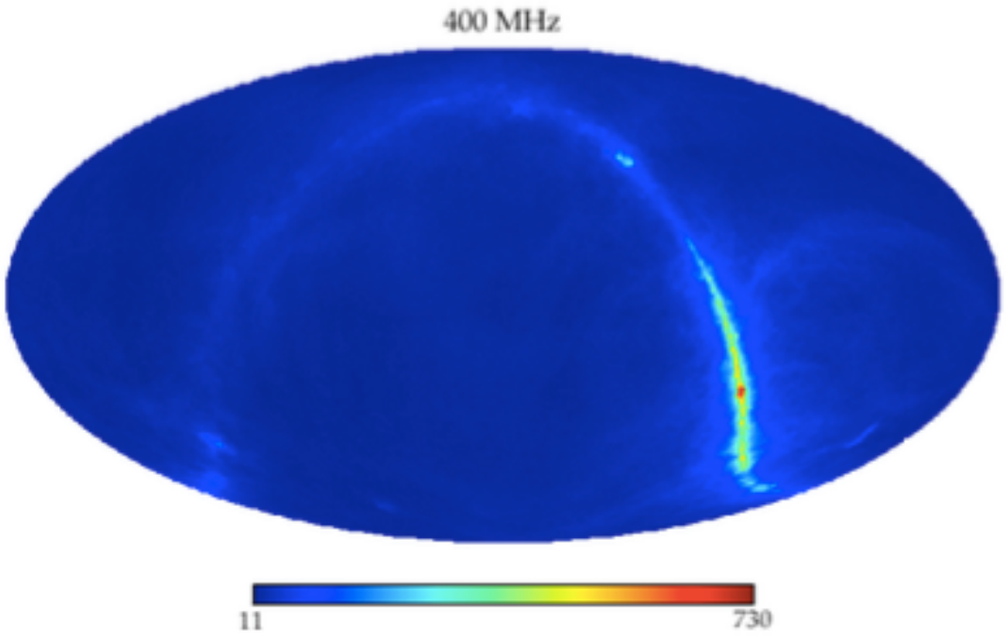

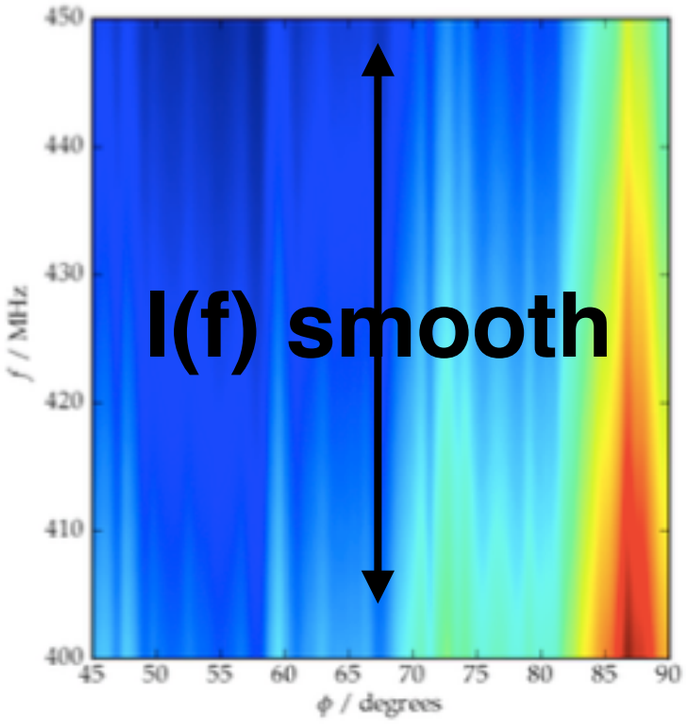

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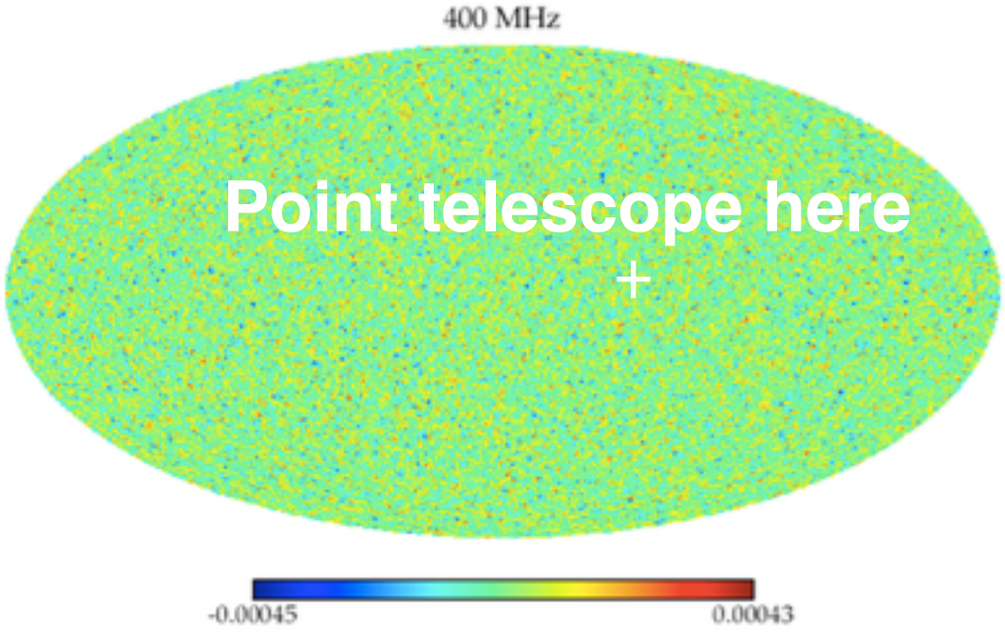

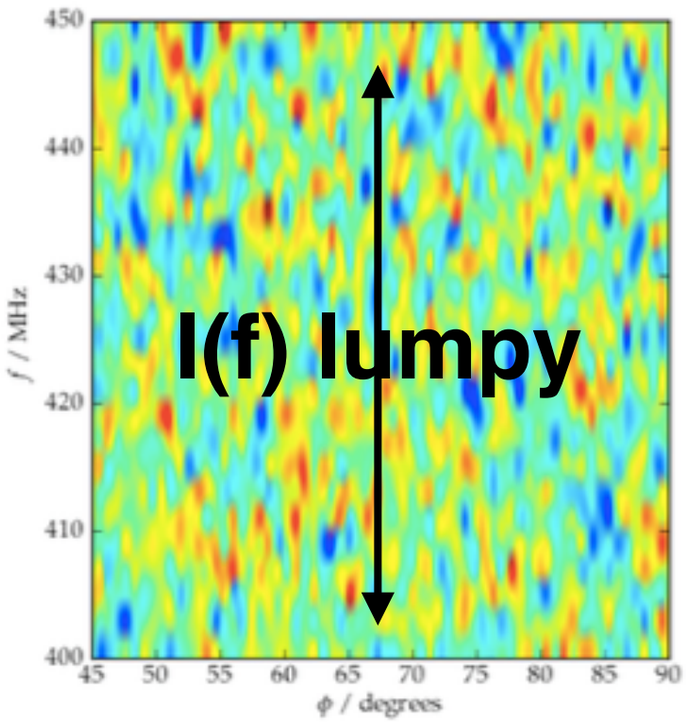

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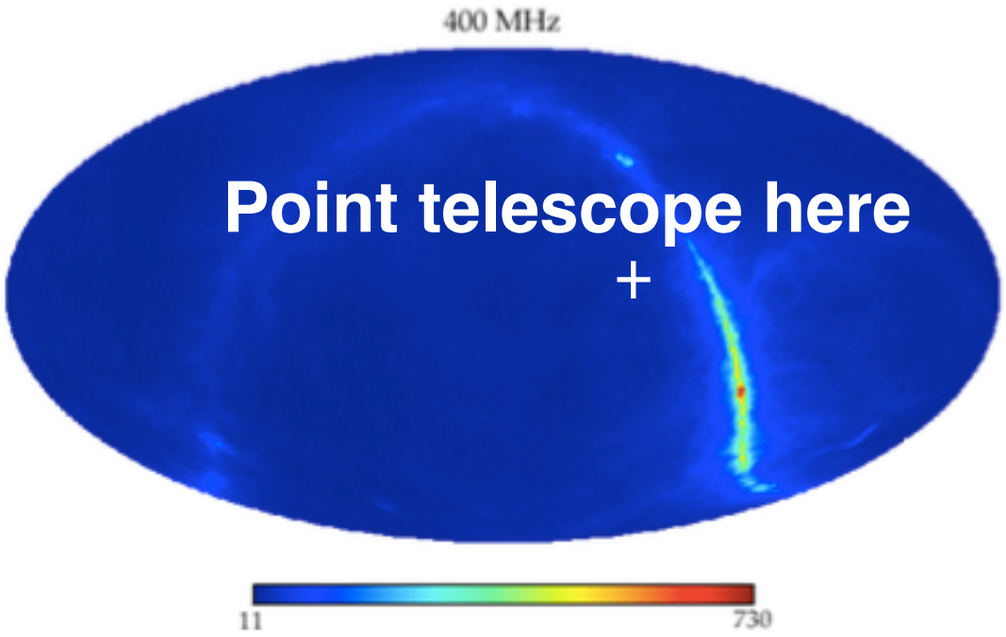

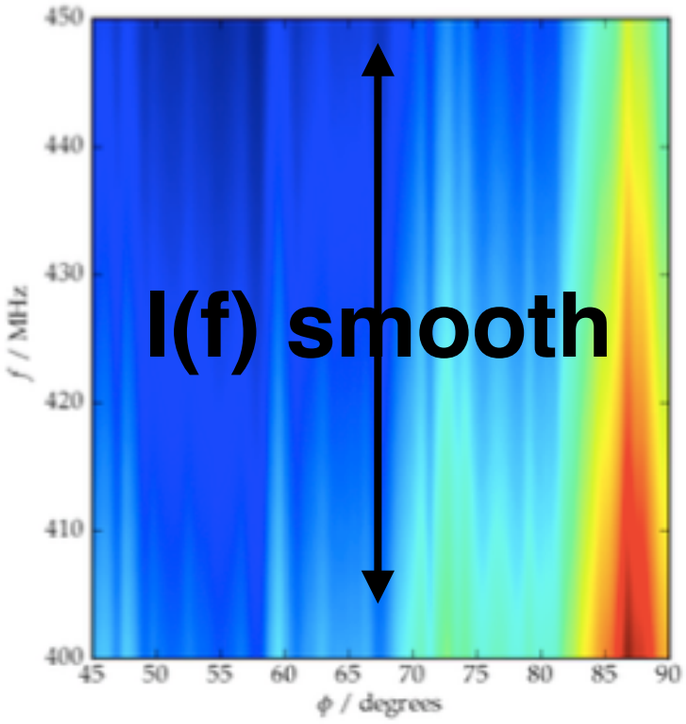

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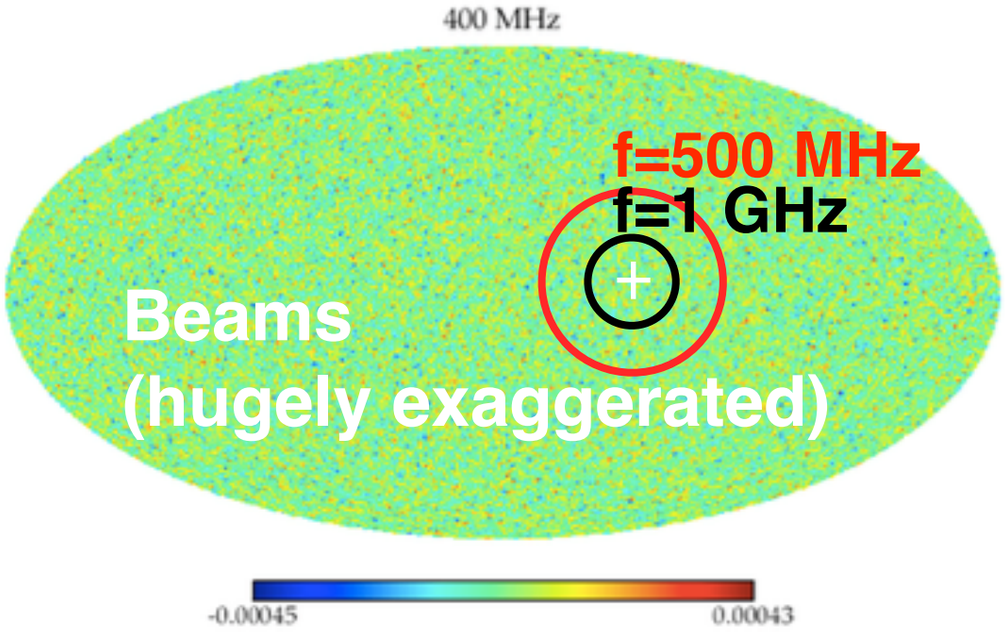

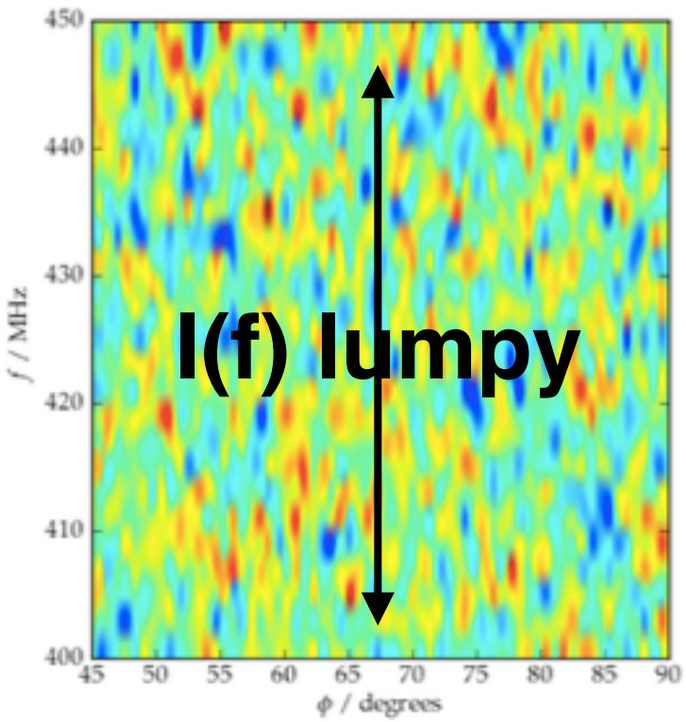

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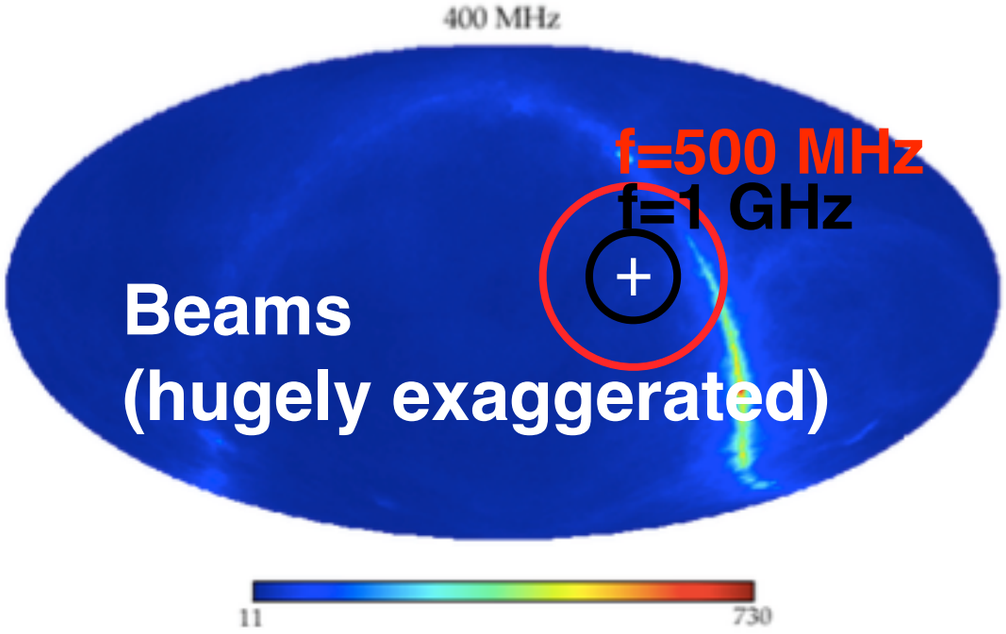

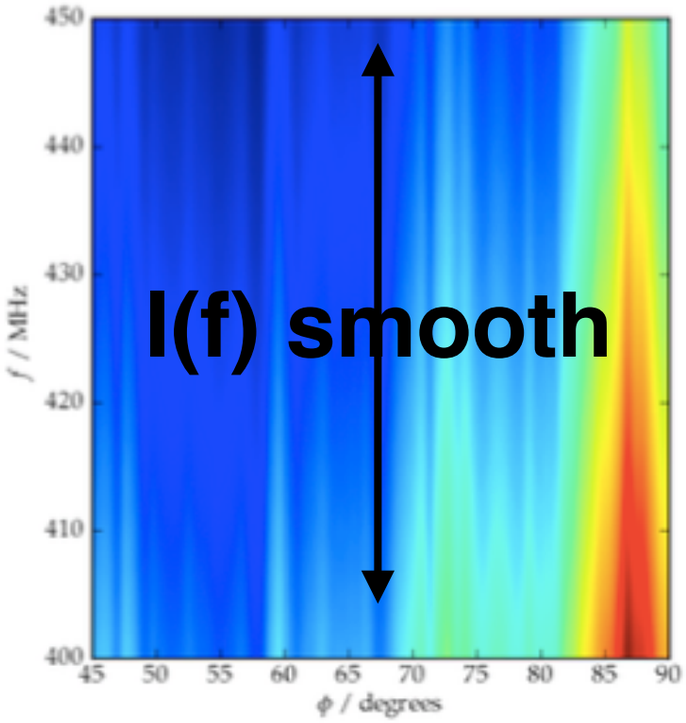

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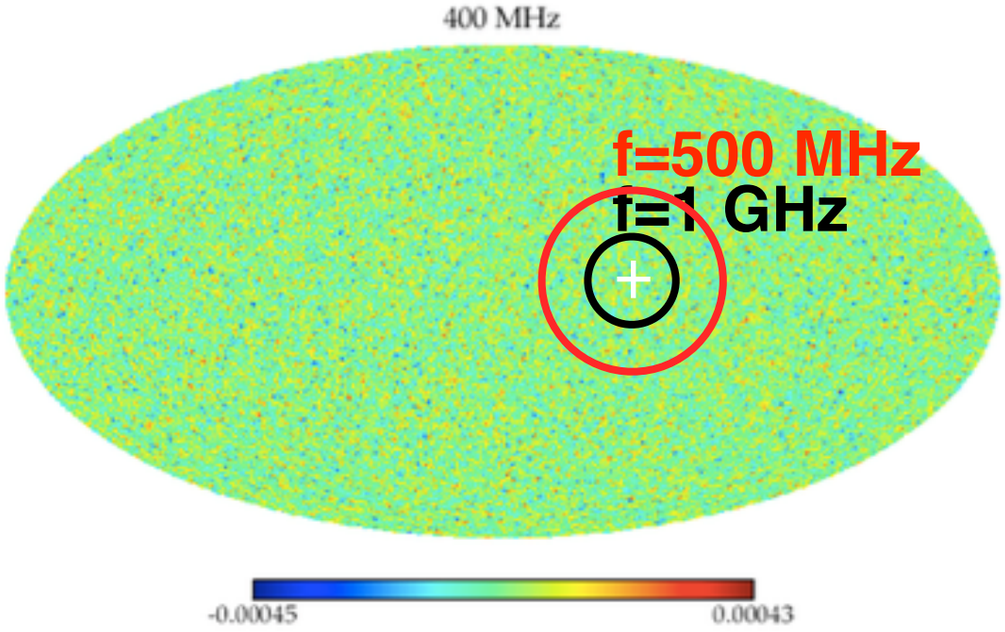

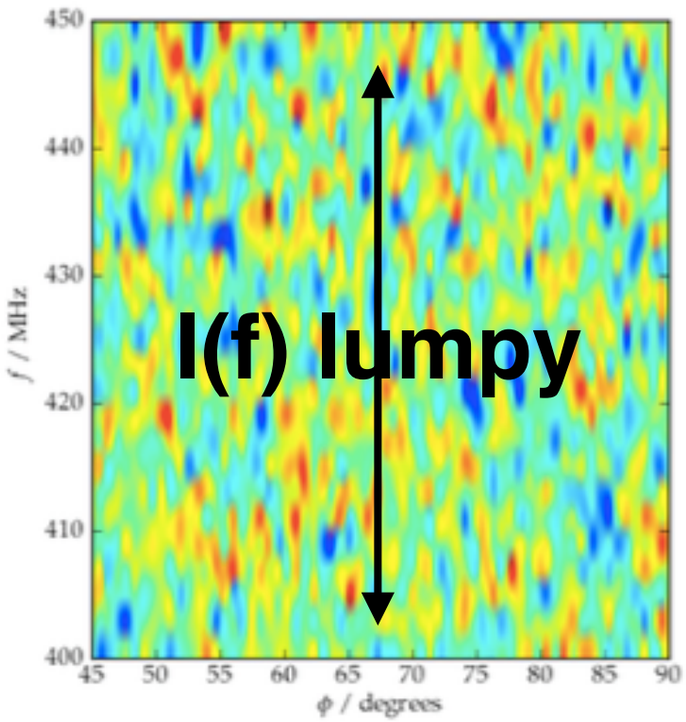

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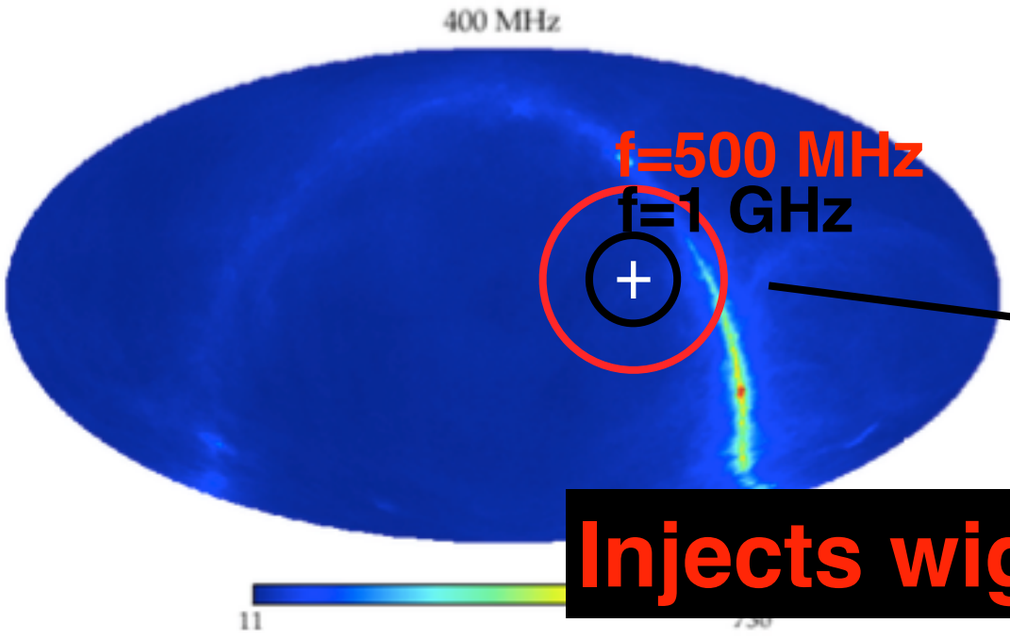
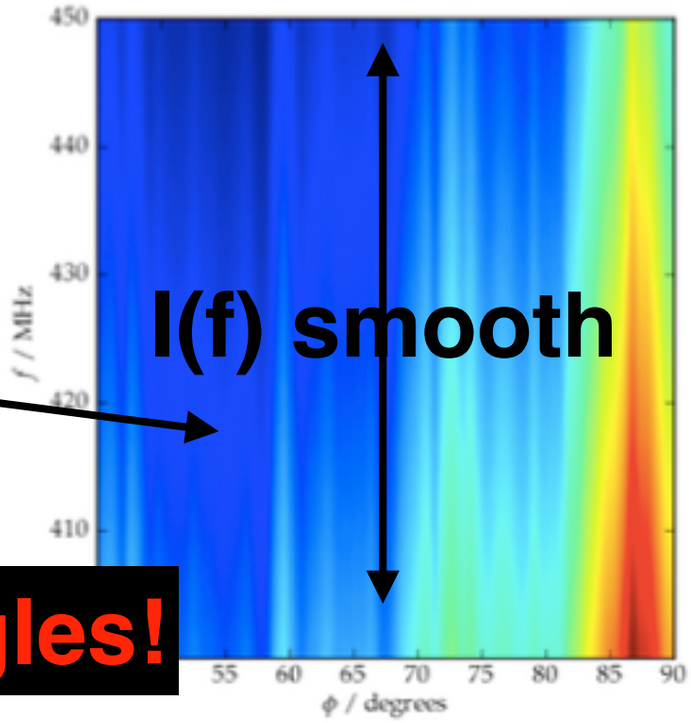


Injects wiggles!



Galactic foregrounds

Need very good control and calibration of telescope beam!

In this sense, “galactic foreground” contamination is actually an ***instrumental systematic*** rather than an astrophysical systematic. This makes it potentially tractable.

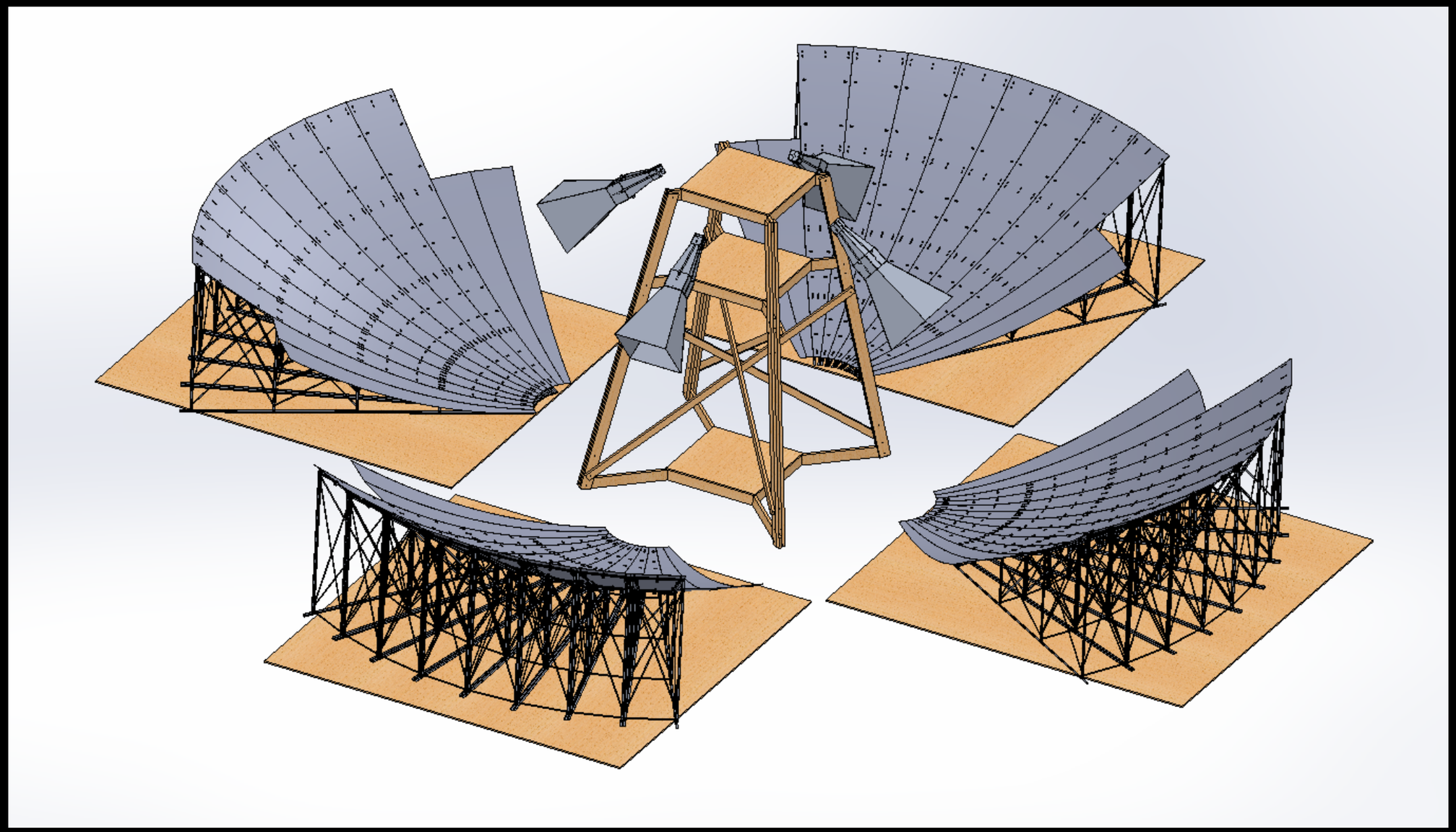
DOE funded 21-cm?

BNL has ~ $1M in LDRD funding to design and build a pathfinder instrument as a prototype that can demonstrate calibration requirements for a DOE funded dark energy survey.

BMX

(baryon mapping experiment)

- Four dish interferometer
- zenith pointing, drift scanning
- 700 - 1500 MHz (z = 0 - 1)
- GPU correlator



BMX

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

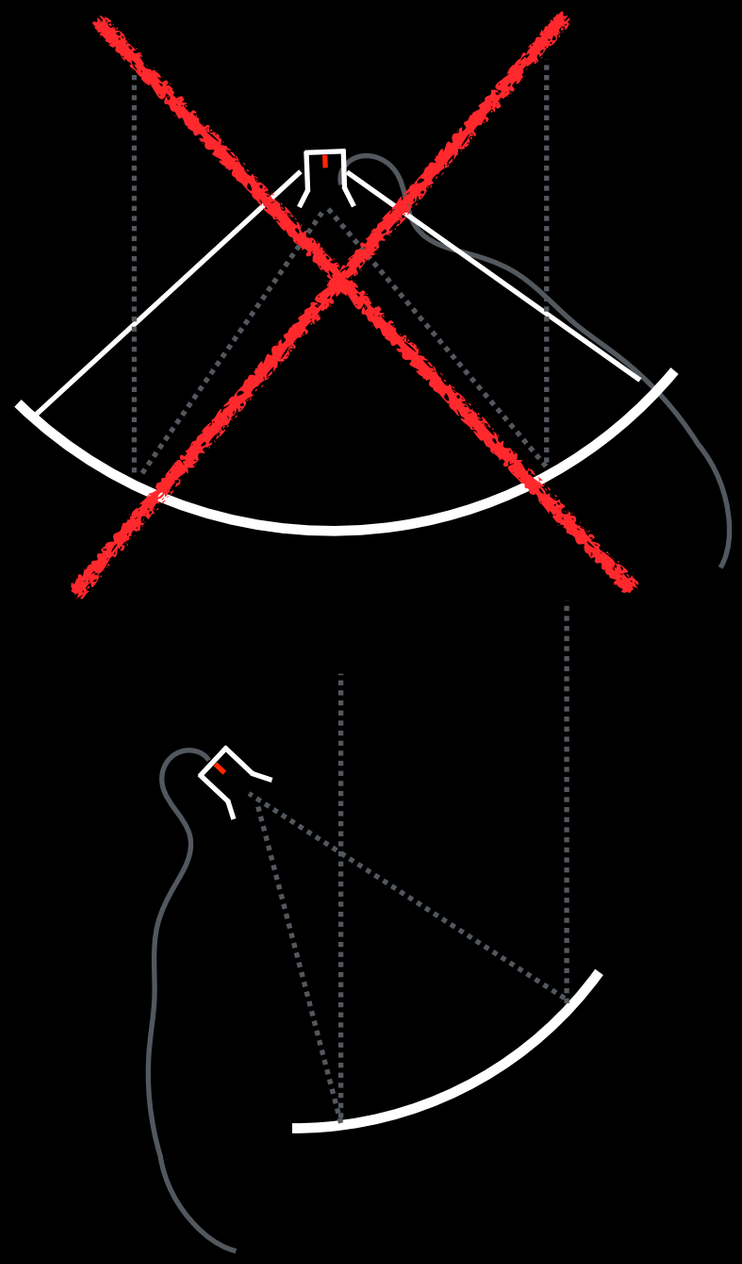
Remington Gerras (undergrad)
Jeff McMahon (prof.)

Evan Arena (undergrad)
Neelima Sehgal (prof.)
William Tyndall (grad)

Hamdi Mani (engineer)
Phil Mauskopf (prof.)

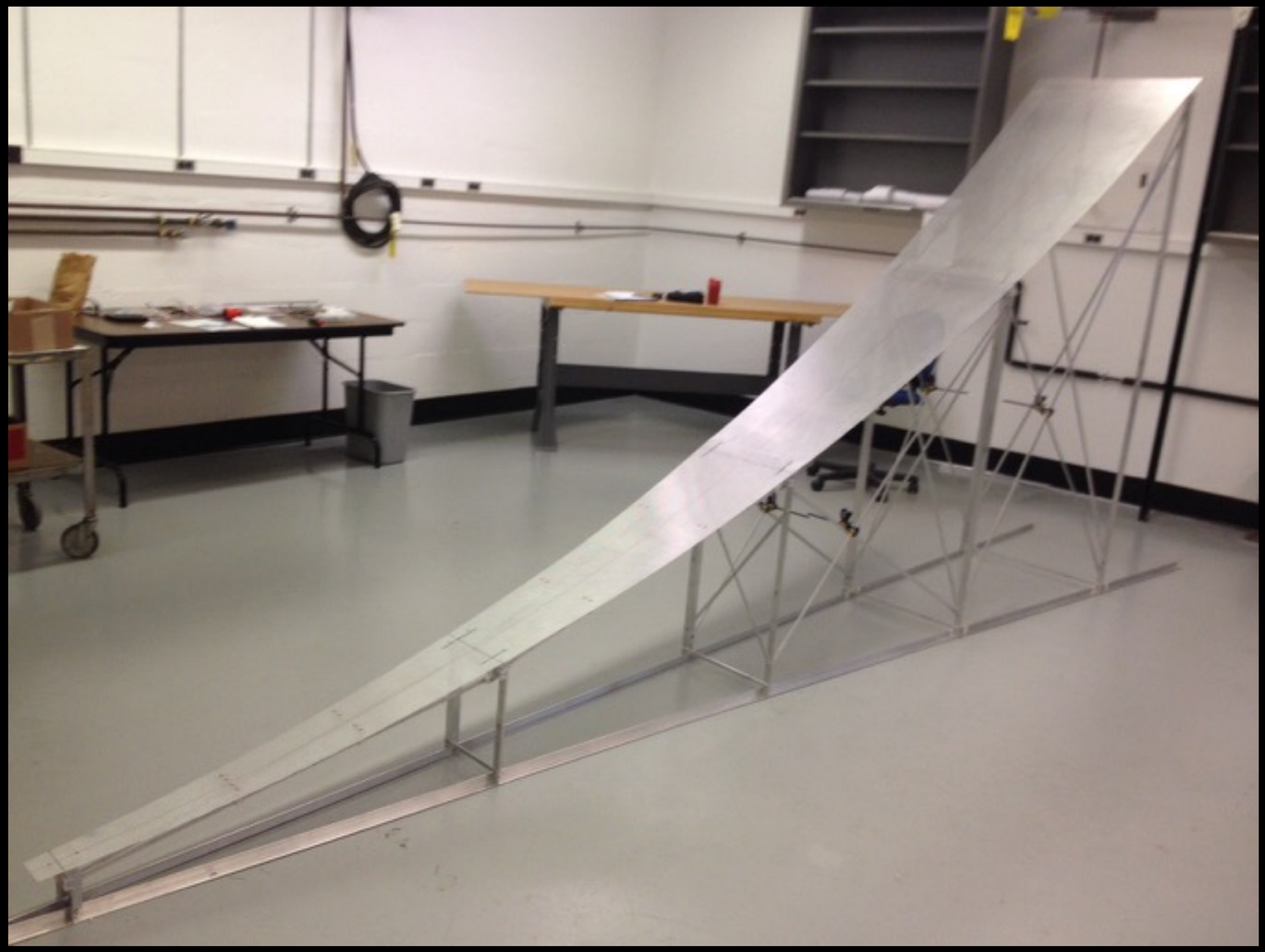
Dish

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



Dish

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!



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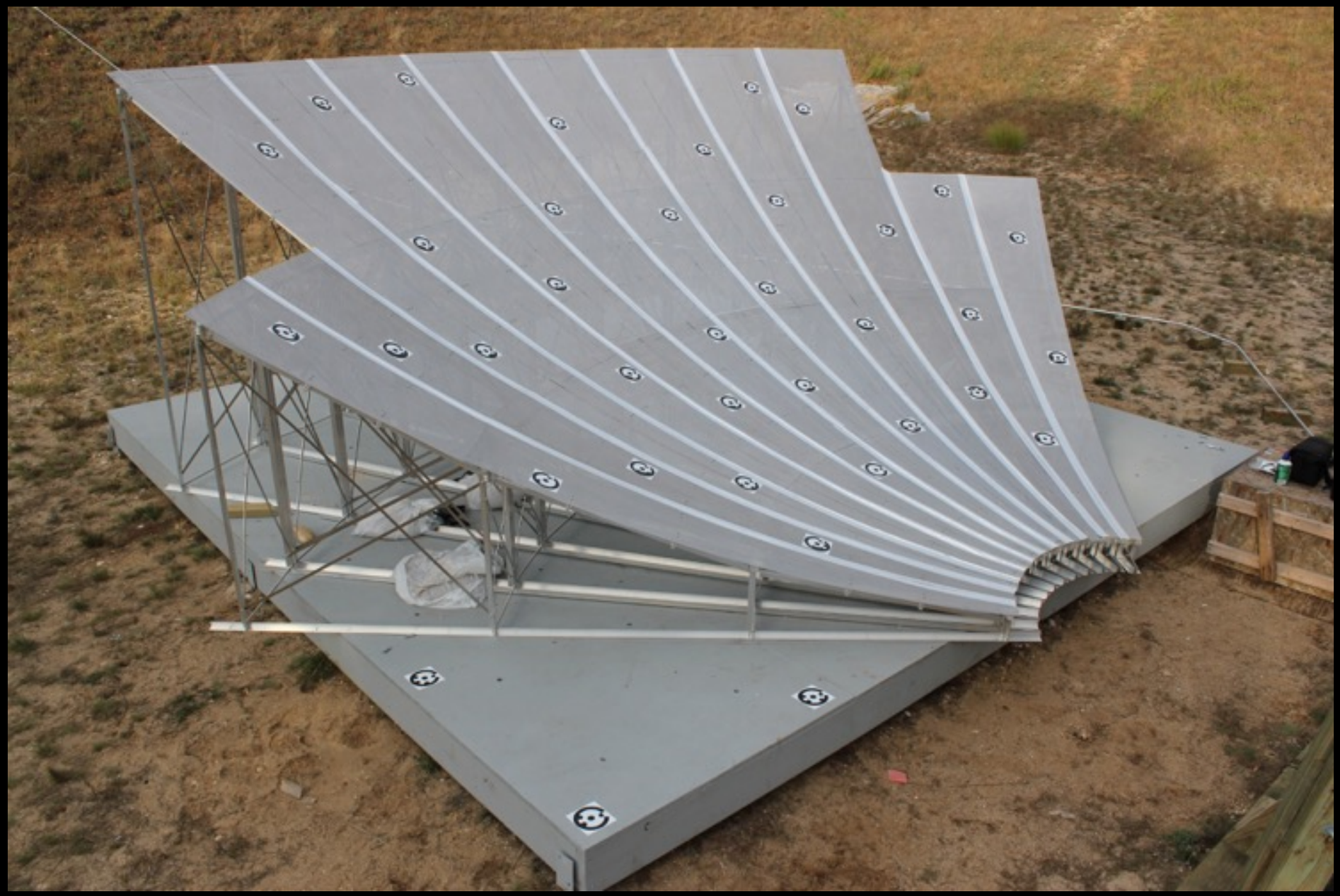
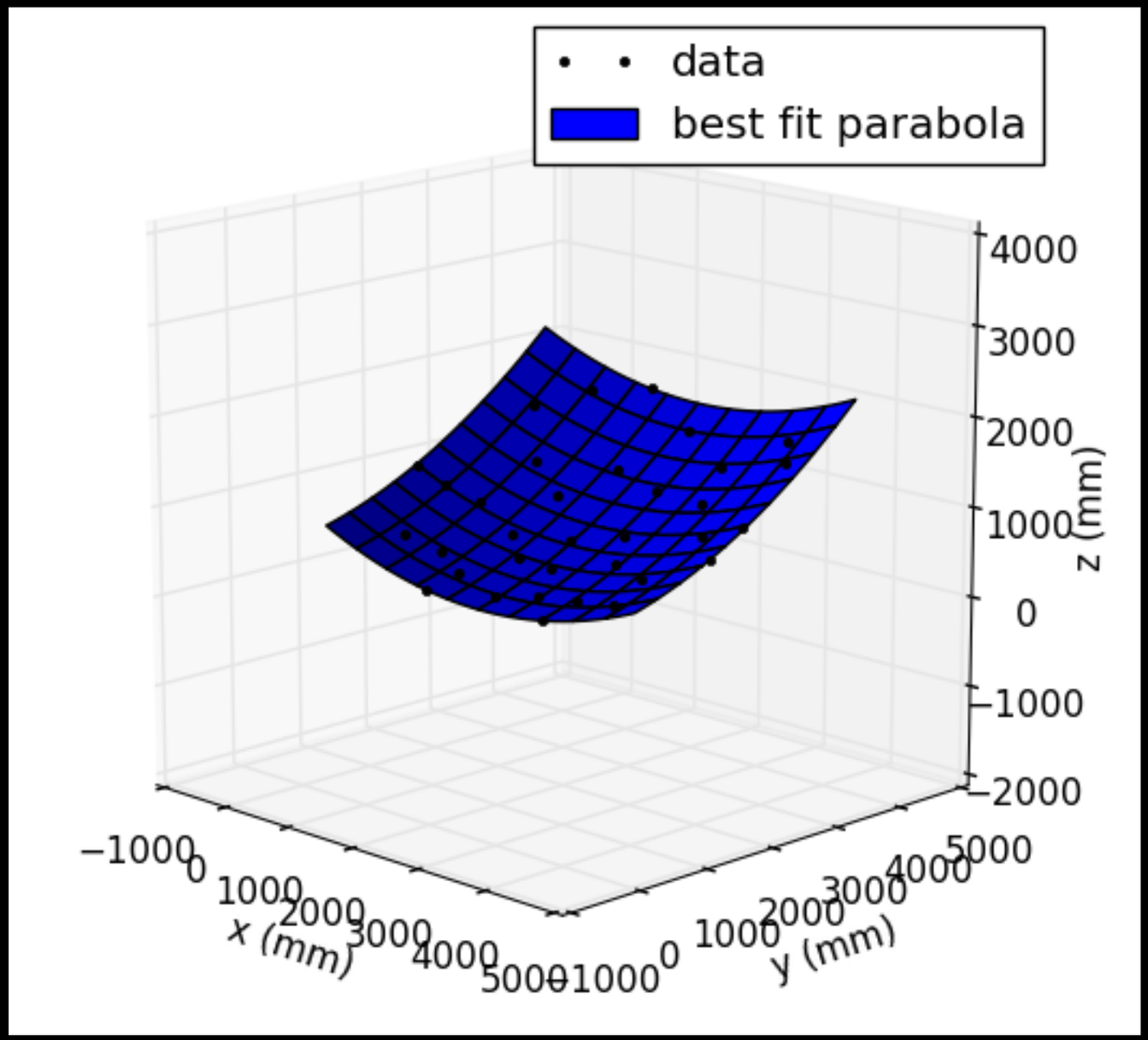


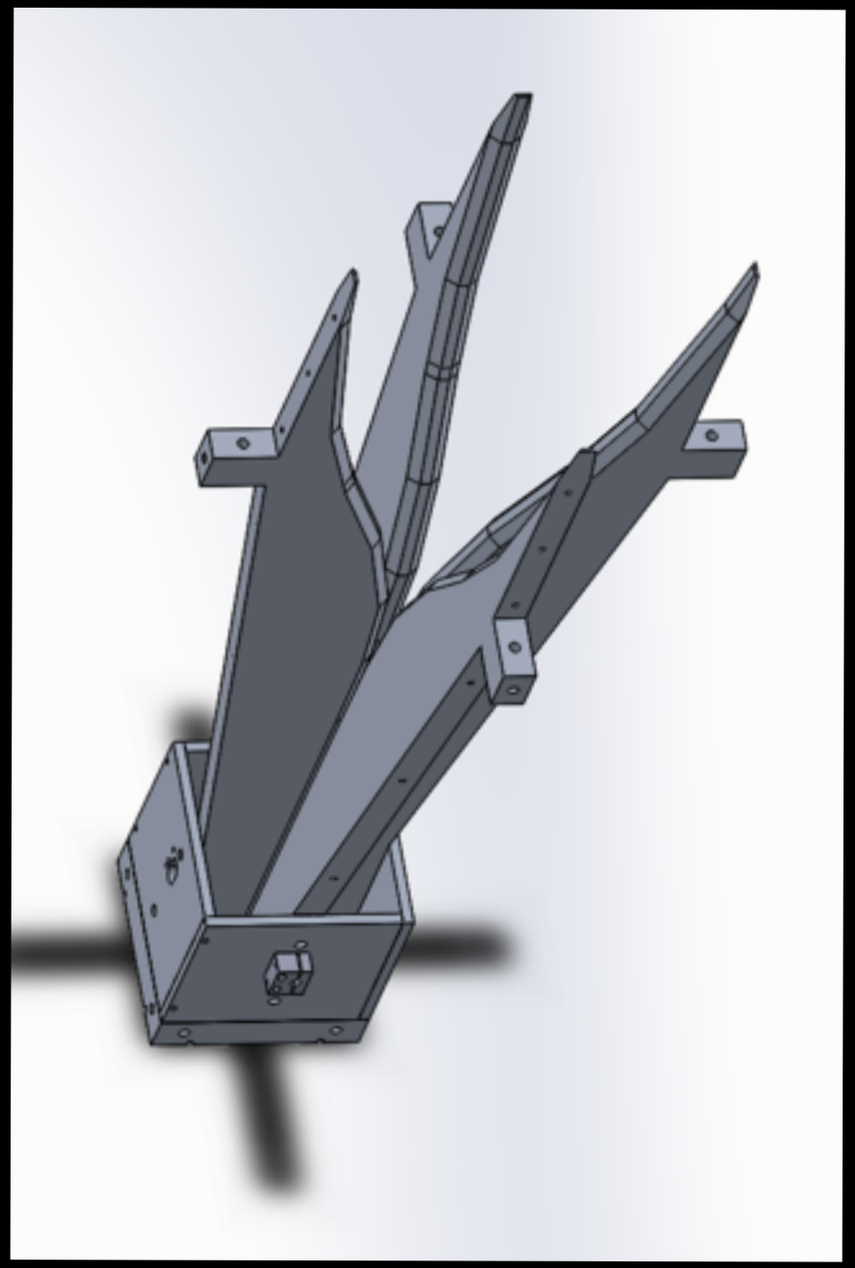
Dish

Surface accuracy ~ few mm

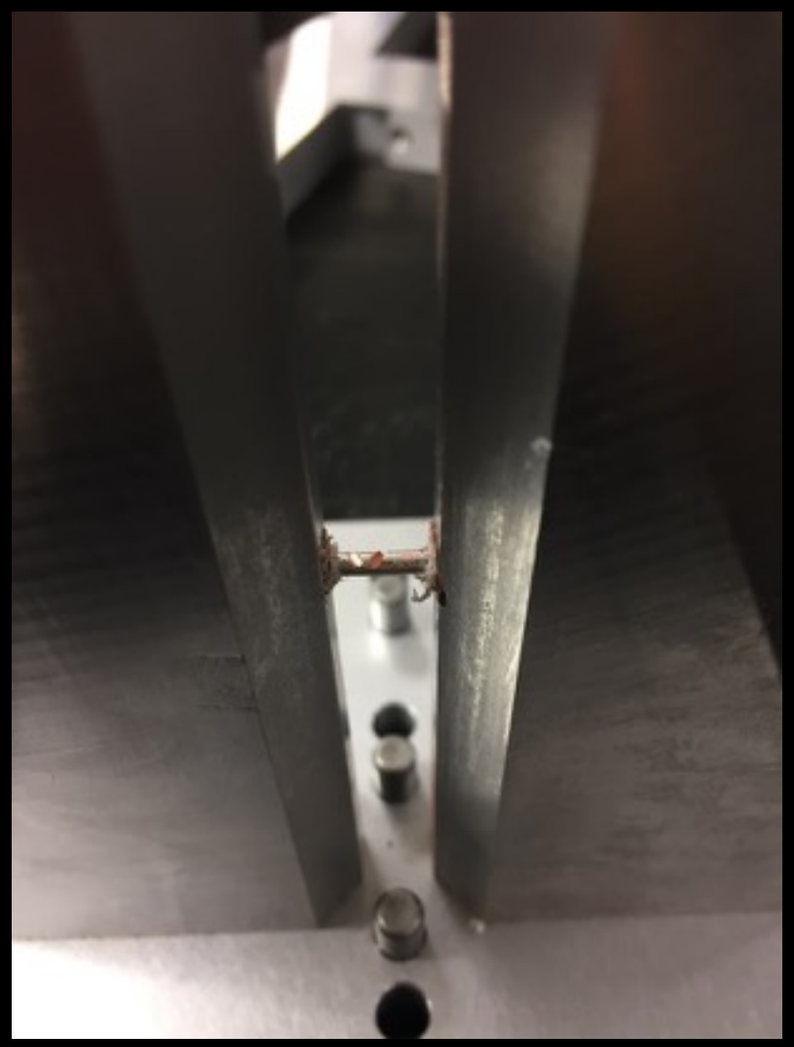


OMT

Octave bandwidth “orthomode transducer” (OMT, splits E-field into orthogonal polarizations) designed using HFSS microwave simulation software, based on scaled up VLA design.

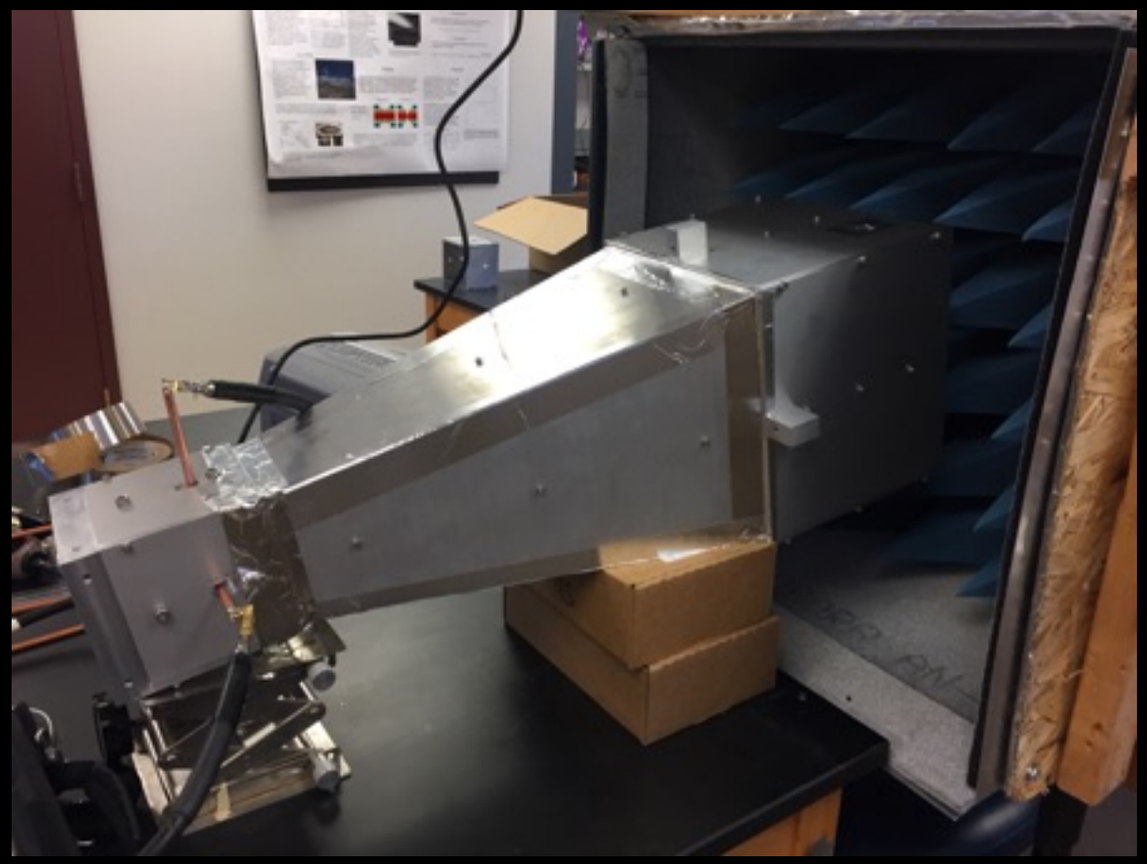


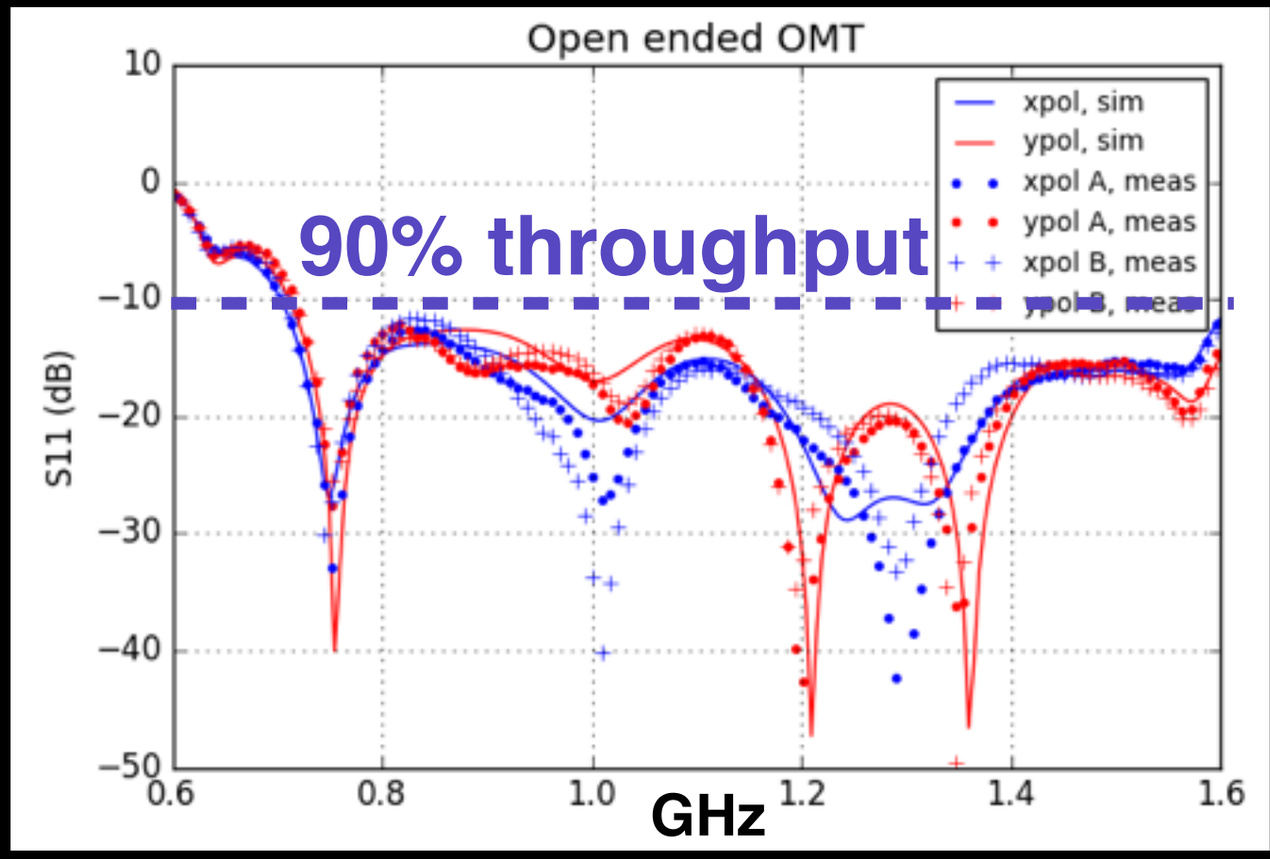
OMT



OMT

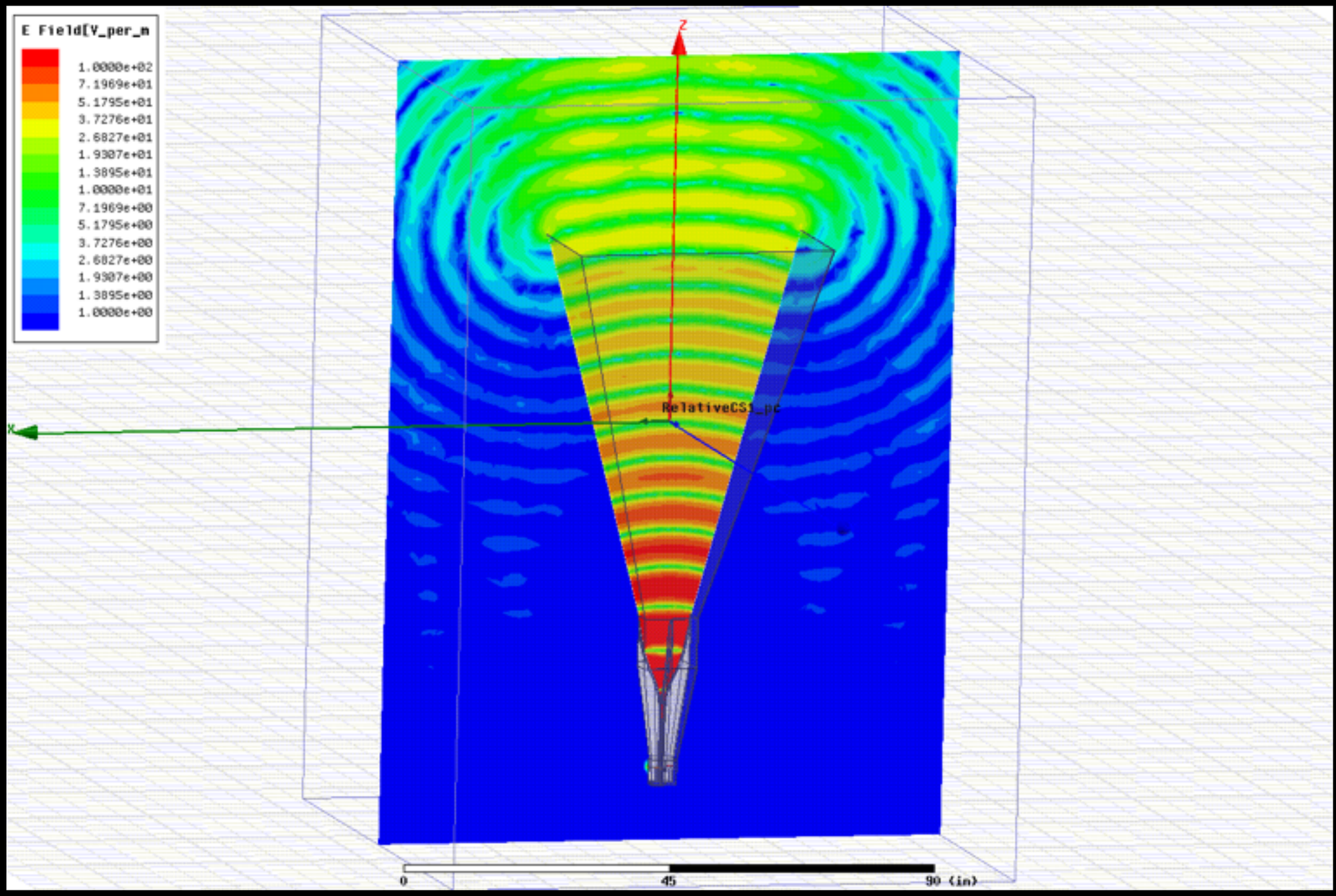
Data matches sims, successful design.





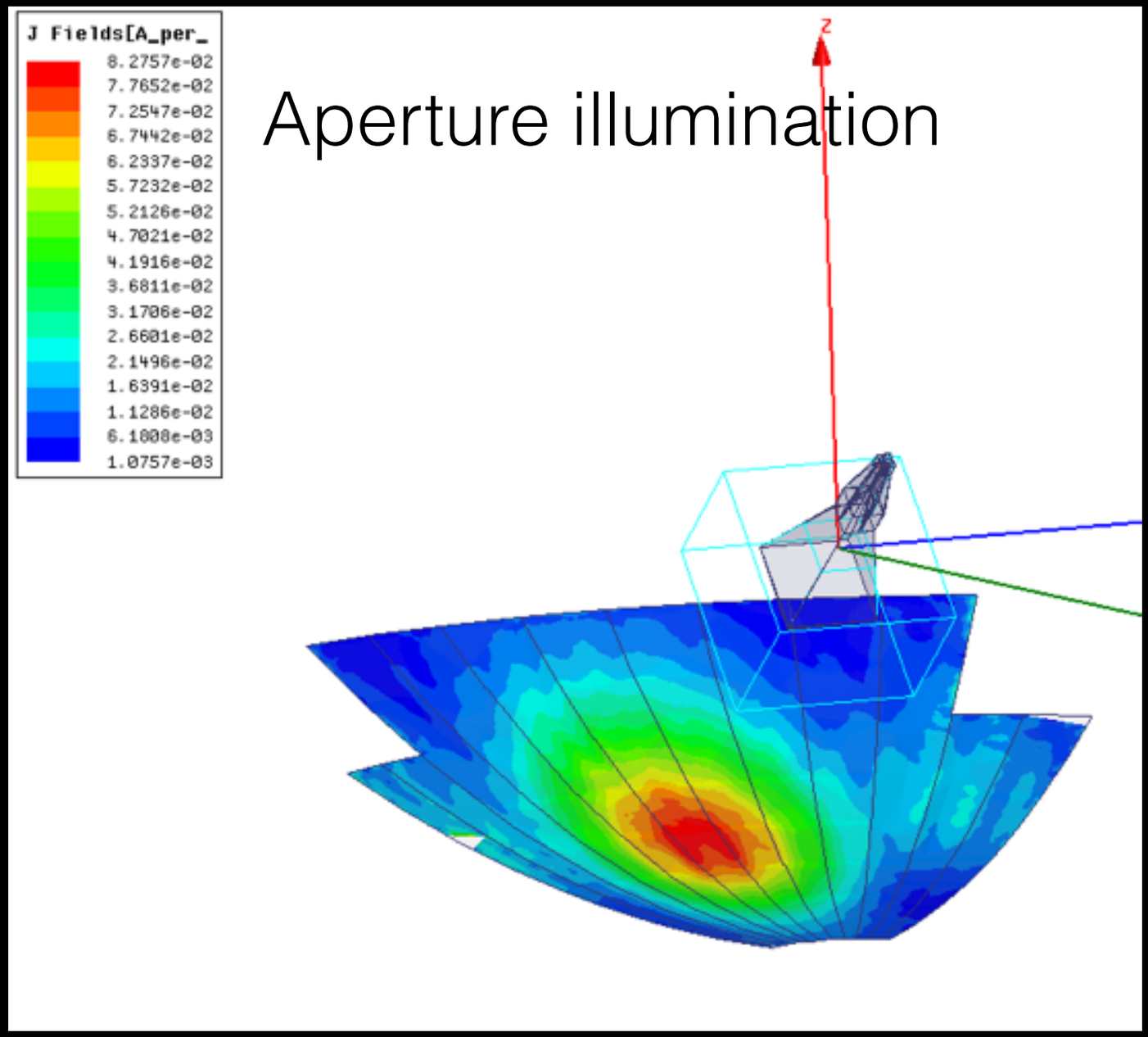
Feed horn

Feed horn defines aperture illumination.



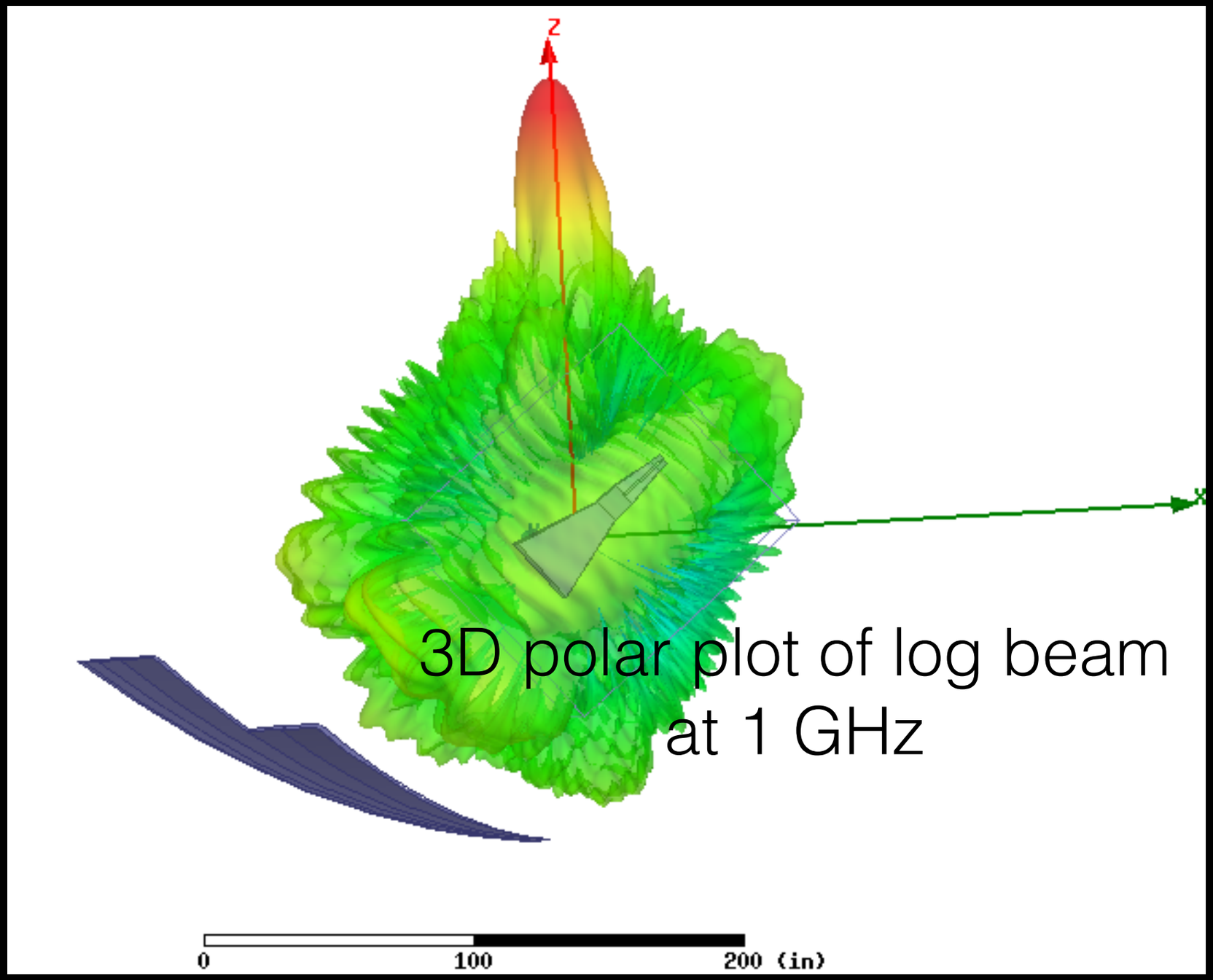
Feed horn

Full end to end beam simulations.



Feed horn

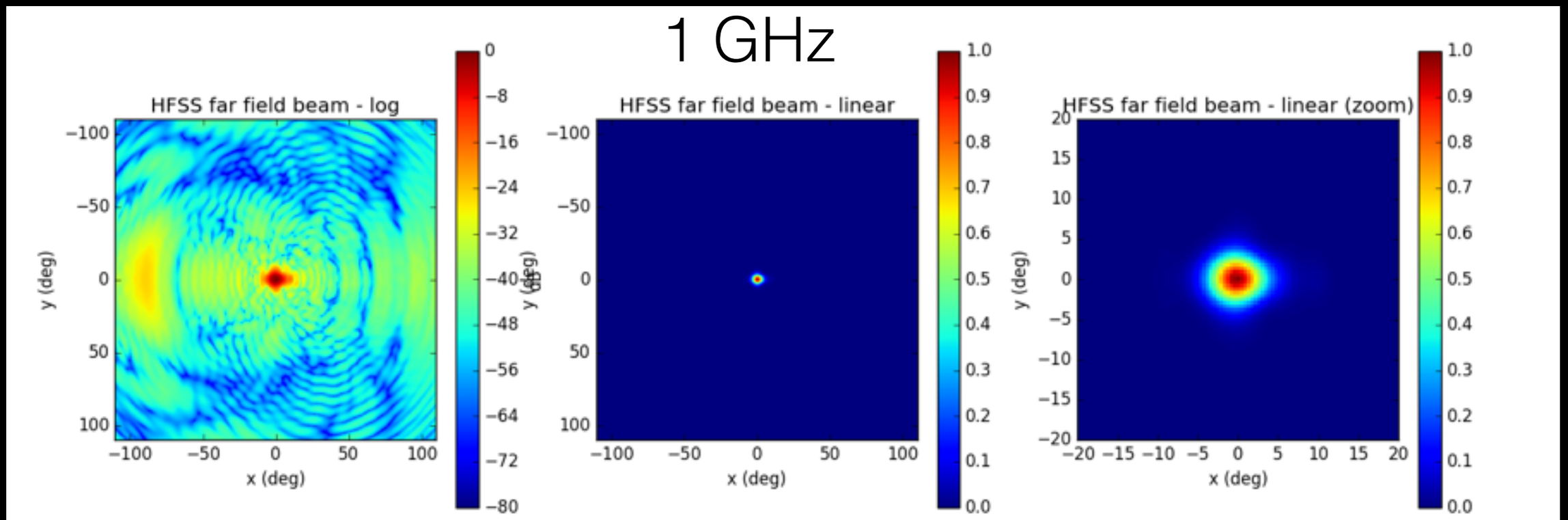
Full end to end beam simulations.



3D polar plot of log beam at 1 GHz

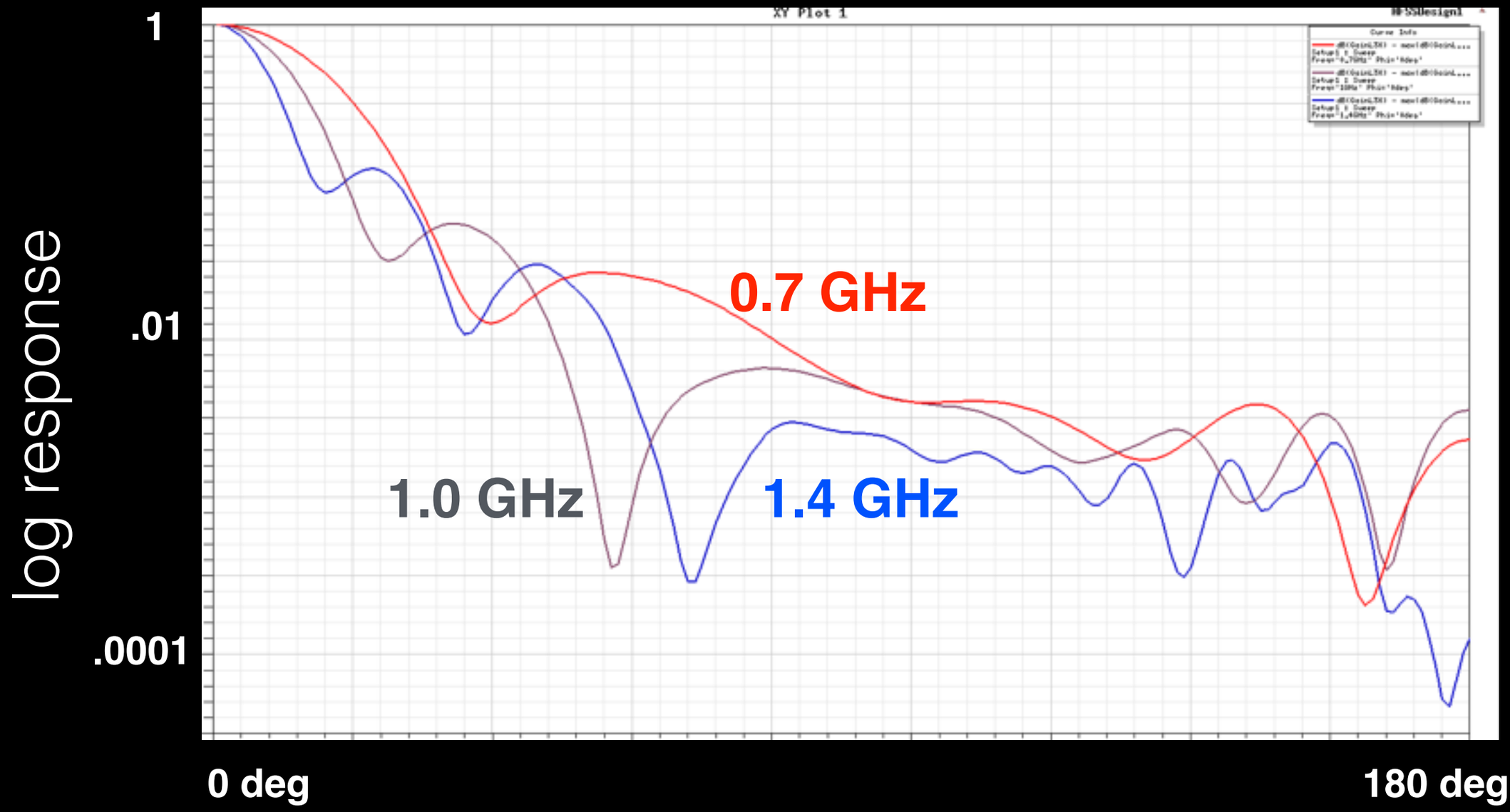
Feed horn

Full end to end beam simulations.



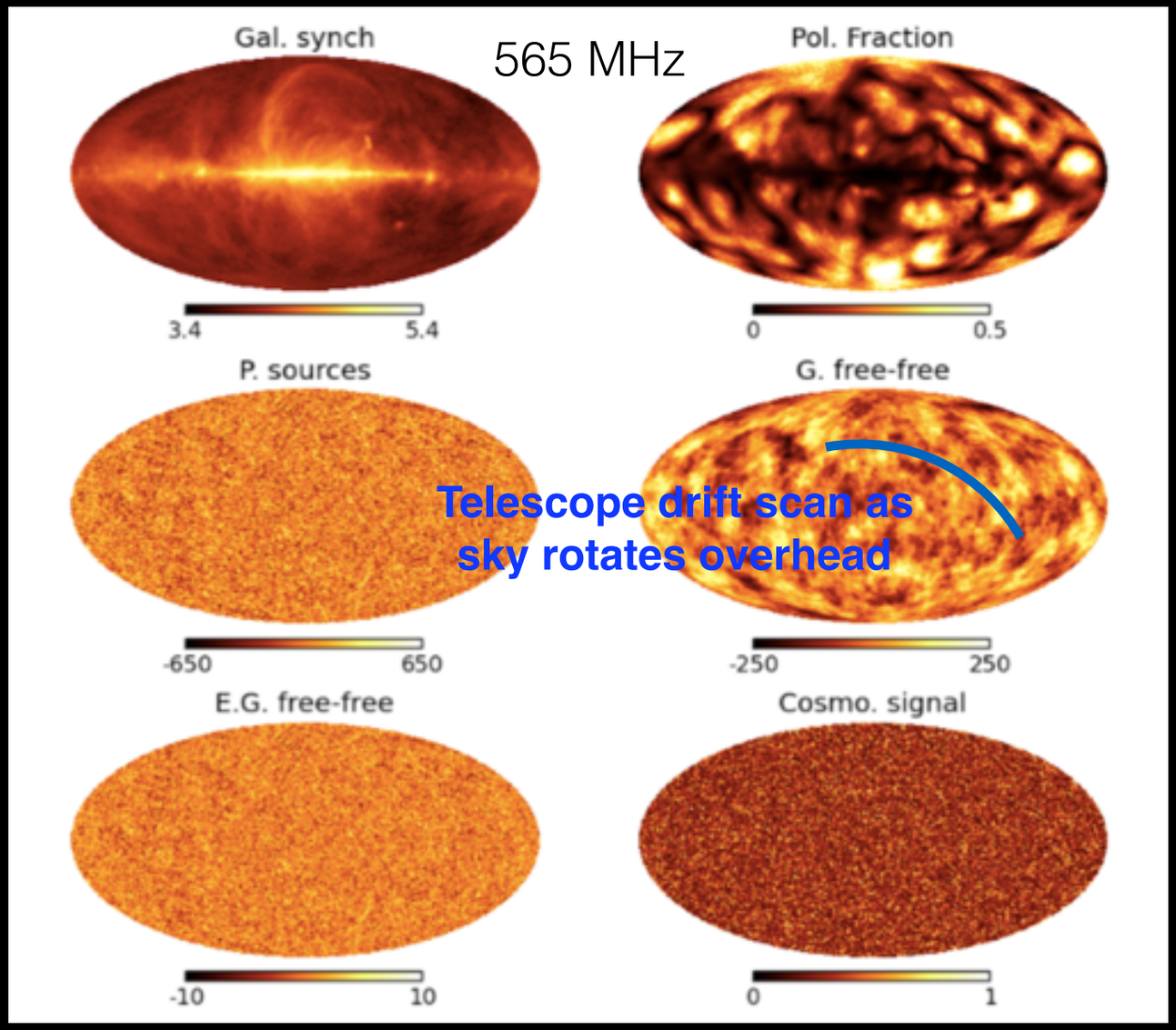
Far field beam

Full end to end beam simulations.



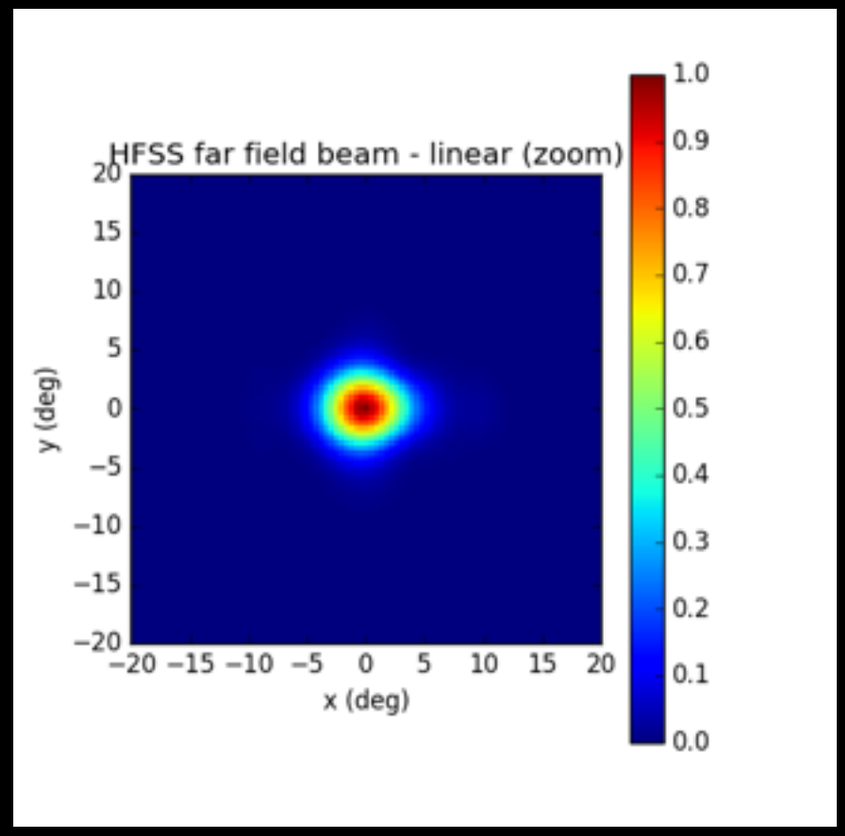
Simulations

Cosmological simulations with realistic instrument beam



CRIME (Alonso, et al., 2014)

Convolve with instrument beam



Simulations

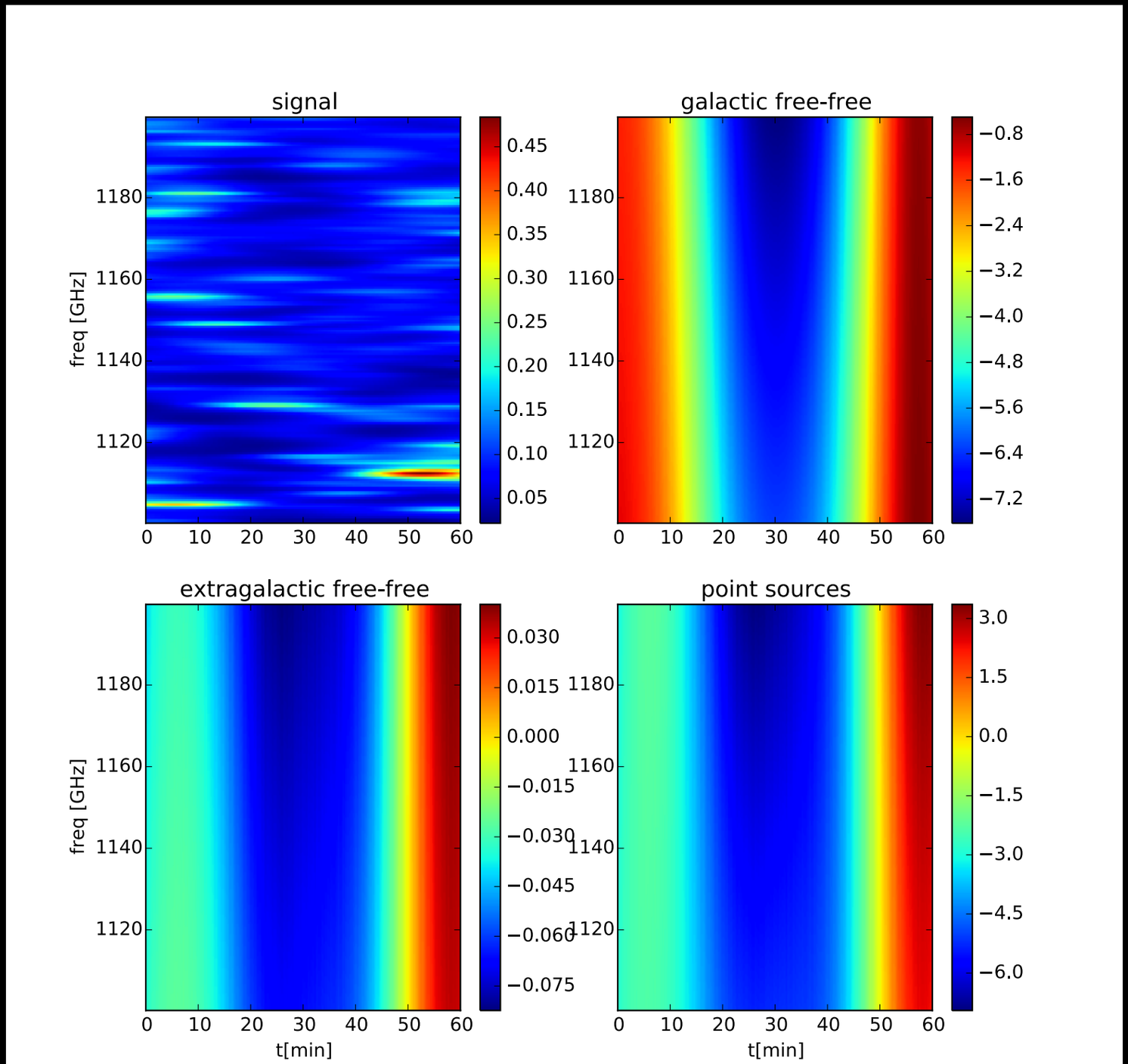
Simulated time ordered data.

Bin into map pixels (really 3D voxels)

Do same to real data.

Compare.

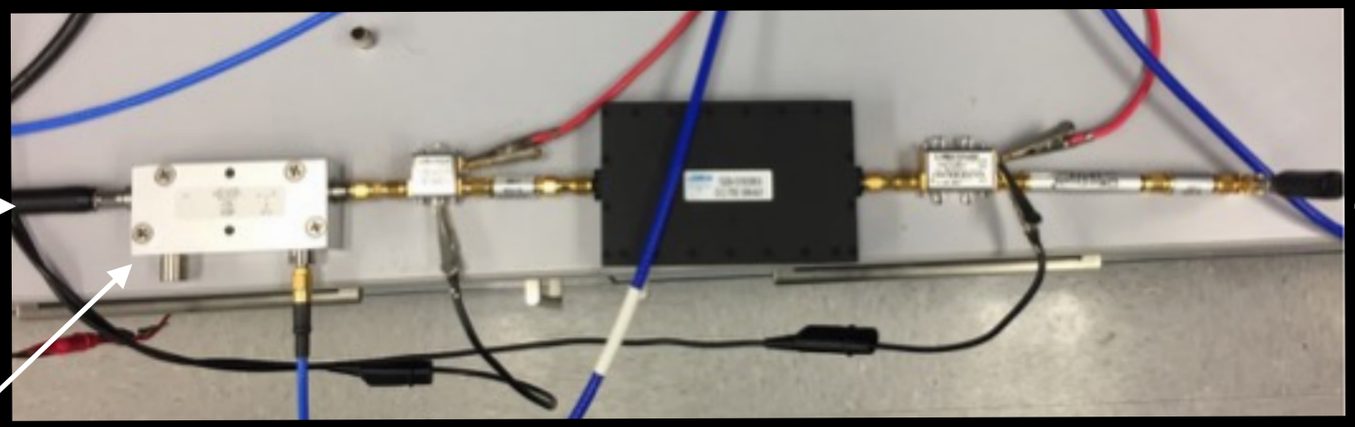
Test systematics mitigation techniques



Front end amplifiers

Front end amplifier chain uses off-shelf components, which are cheap, low noise, and readily available thanks to telecommunications industry.

OMT + horn (tiny signal)



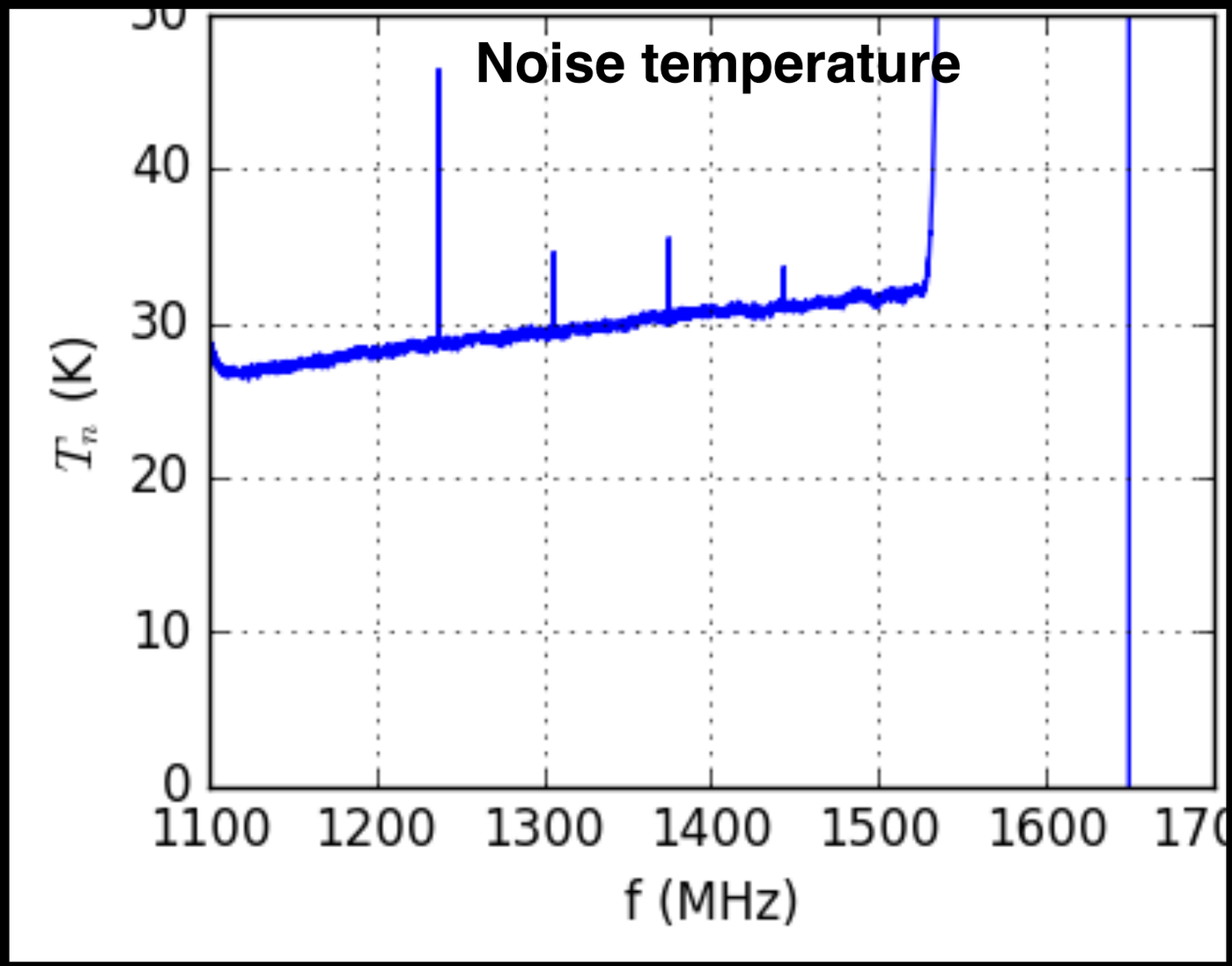
GPU correlator

Low noise amplifiers and filter

30 dB coupler chopped noise diode injection for calibration

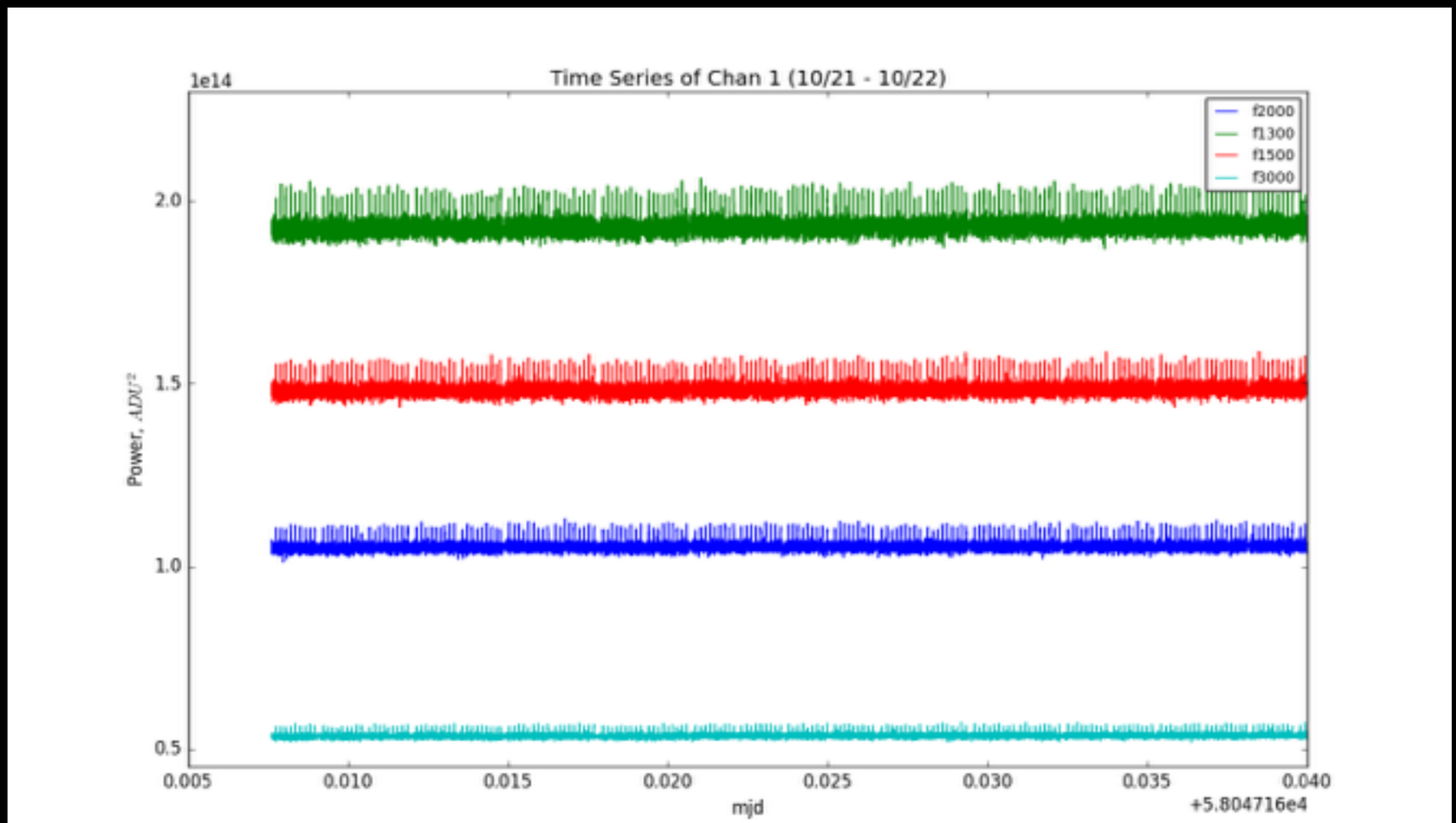
Receiver noise temperature

Achieved receiver noise temperature.



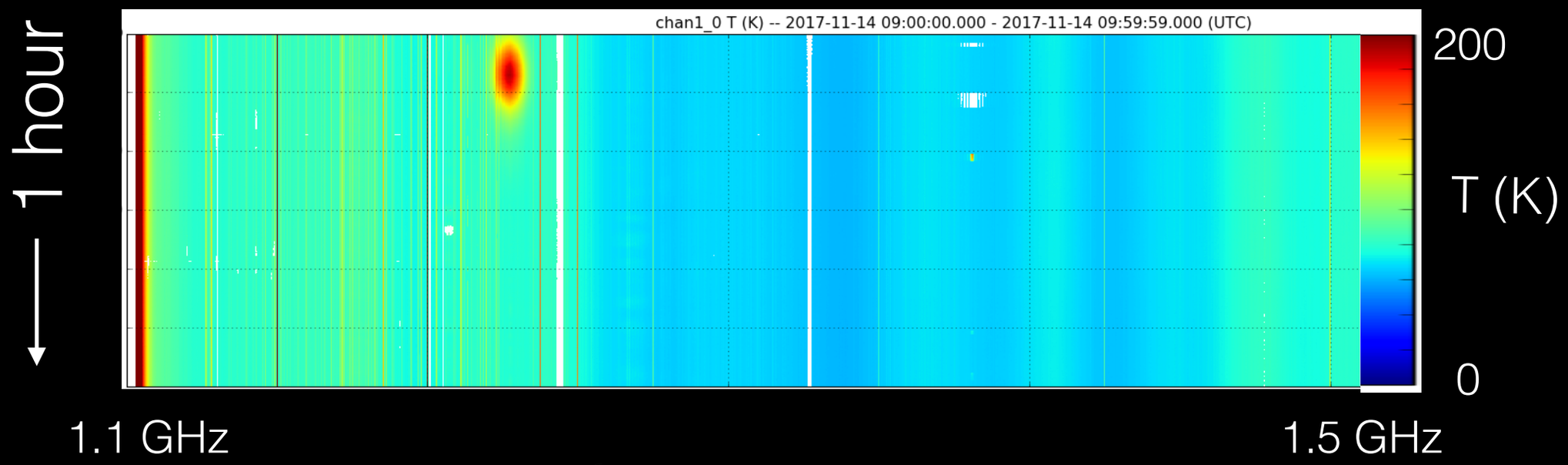
Calibration noise injection

Chopped noise source



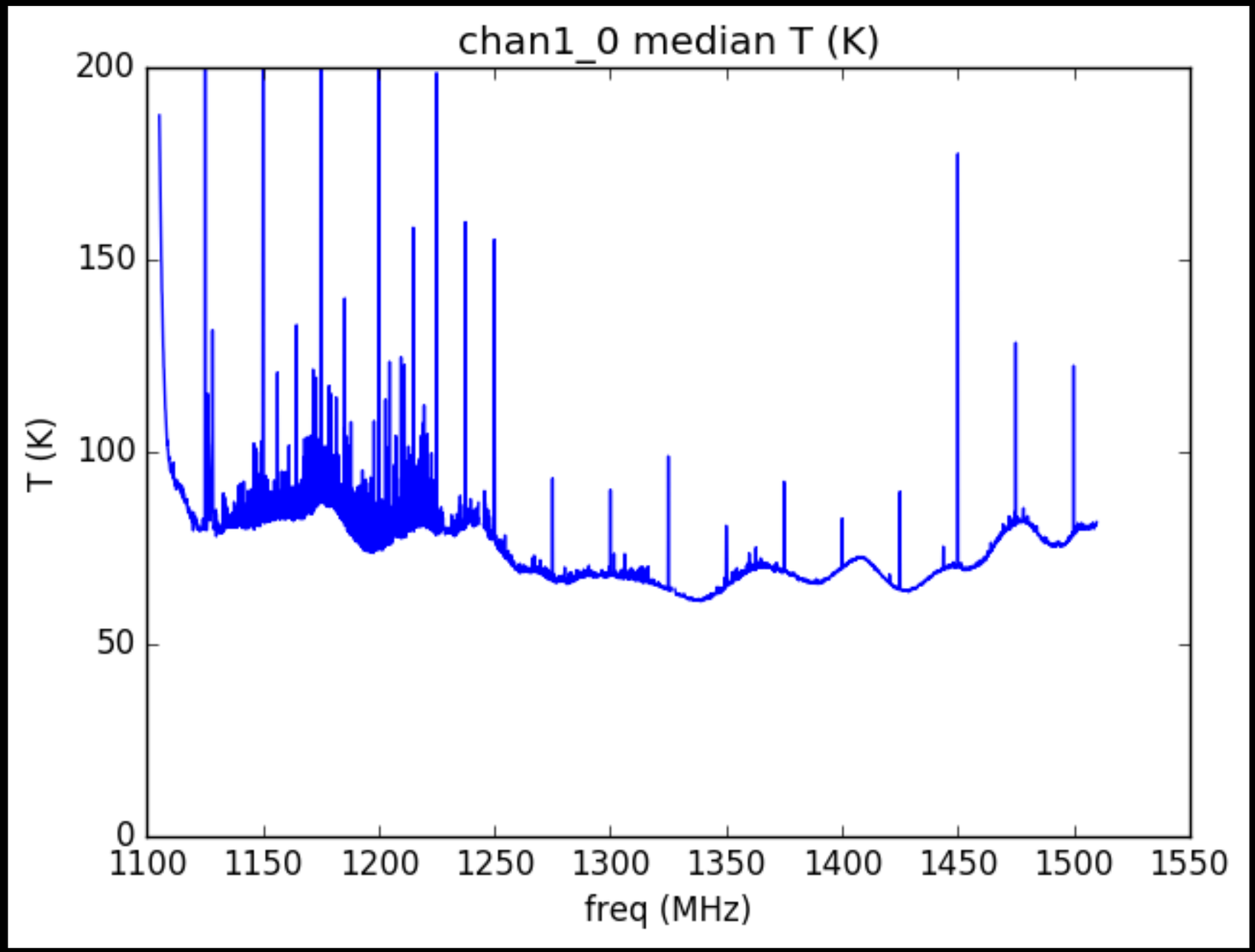
On sky data

Calibrated spectrum as function of time (waterfall plot)



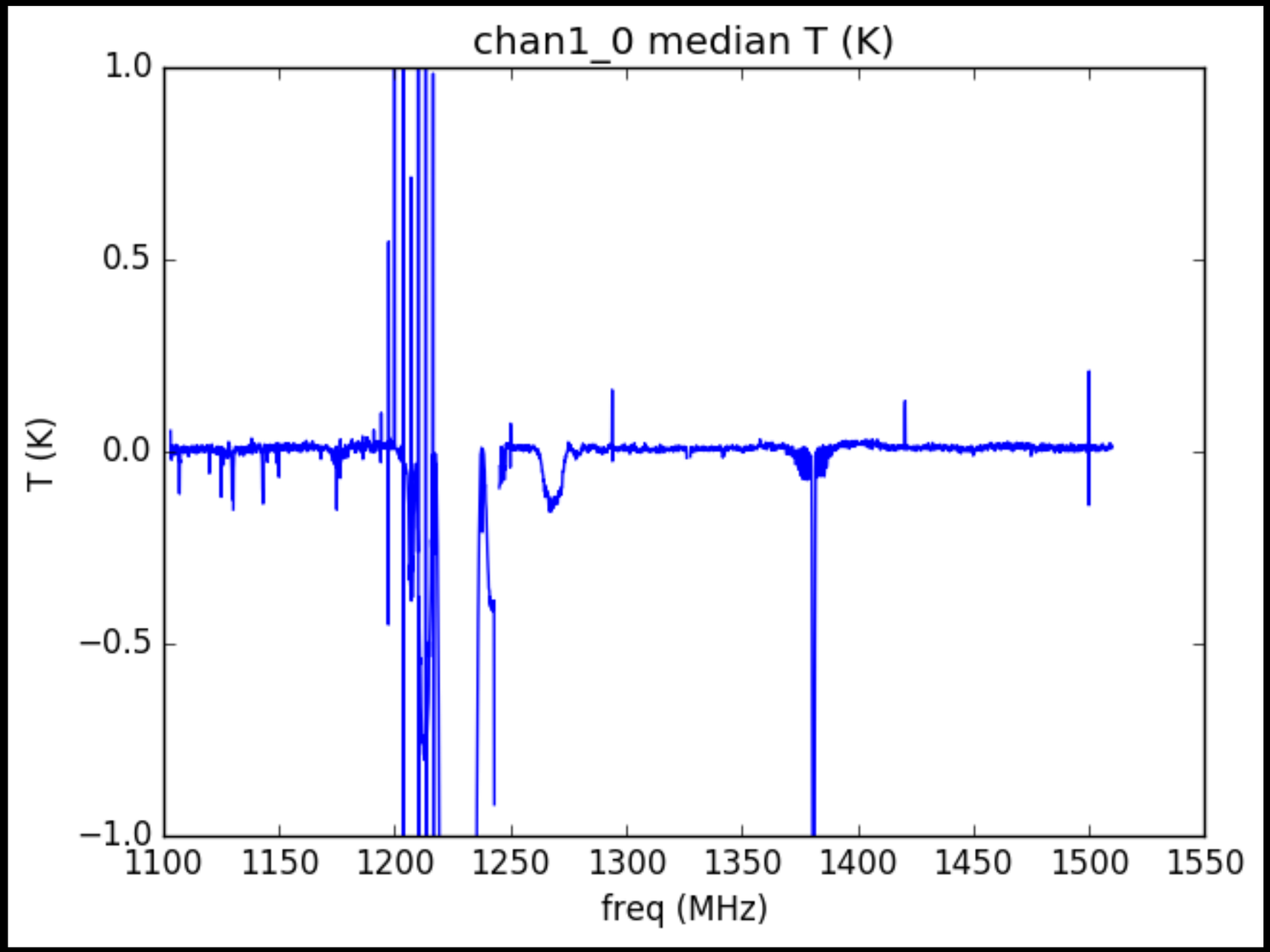
On sky data

Calibrated spectrum, median over 1 hr



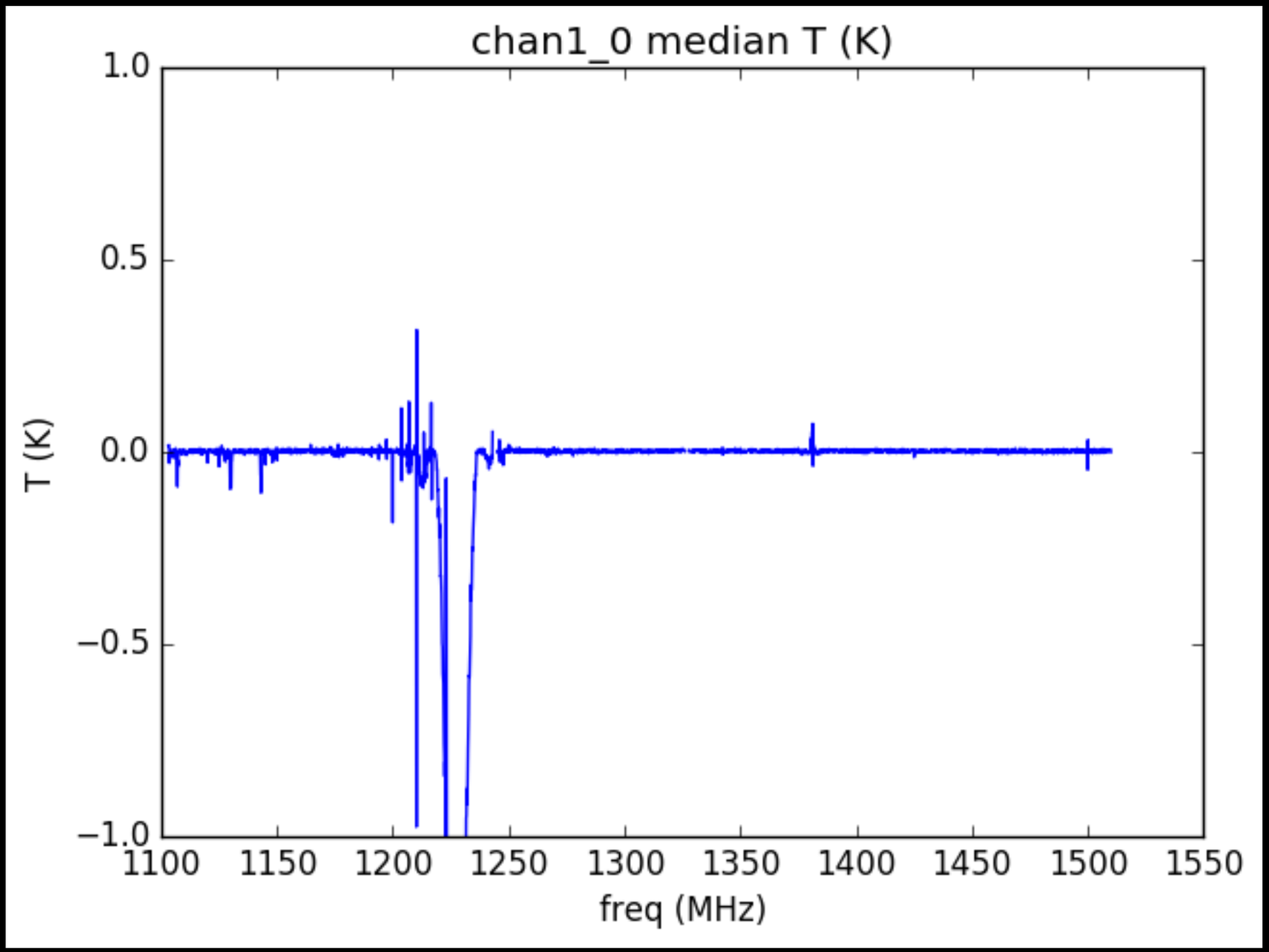
On sky data

Subtract mean over time from each frequency



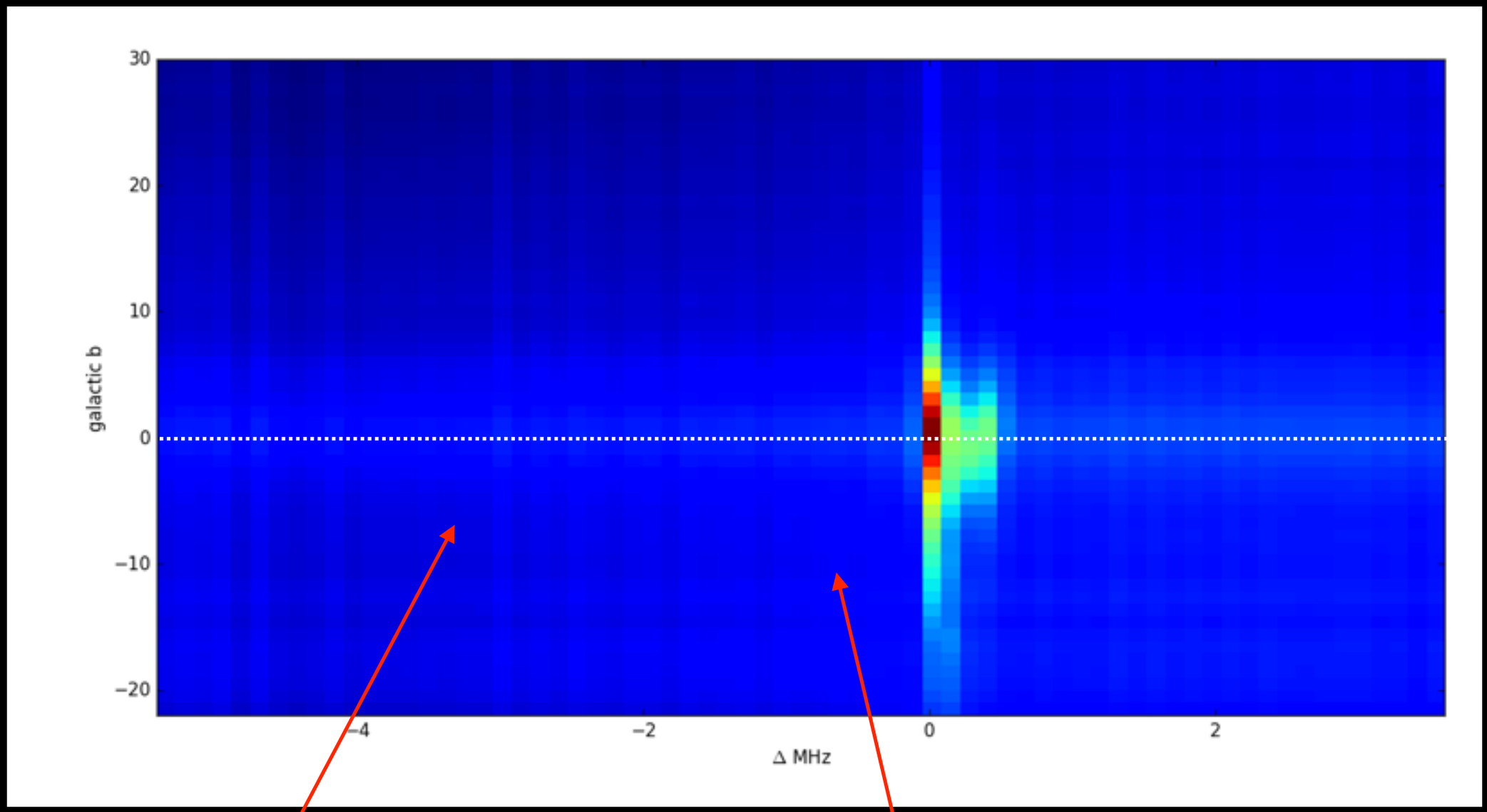
On sky data

Remove first 10 eigenspectra (SVD filtering)



On sky data

Galactic plane passing overhead



galactic synchrotron

galactic 21 cm

Summary