CMB Interferometry

Jonathan Sievers (CITA), with liberal poaching from Steve Myers, rick Perley, NrAO ppt's...

(NB: my keyboard is broken, so apologies in advance for misspellings, odd capitalizations, missing r's...)

World seems to be split into two camps. radio astronomers, and those who aren't really sure what it is we're actually doing.

Lots of jargon in radio astronomy. If I break into some without defining, please stop me.

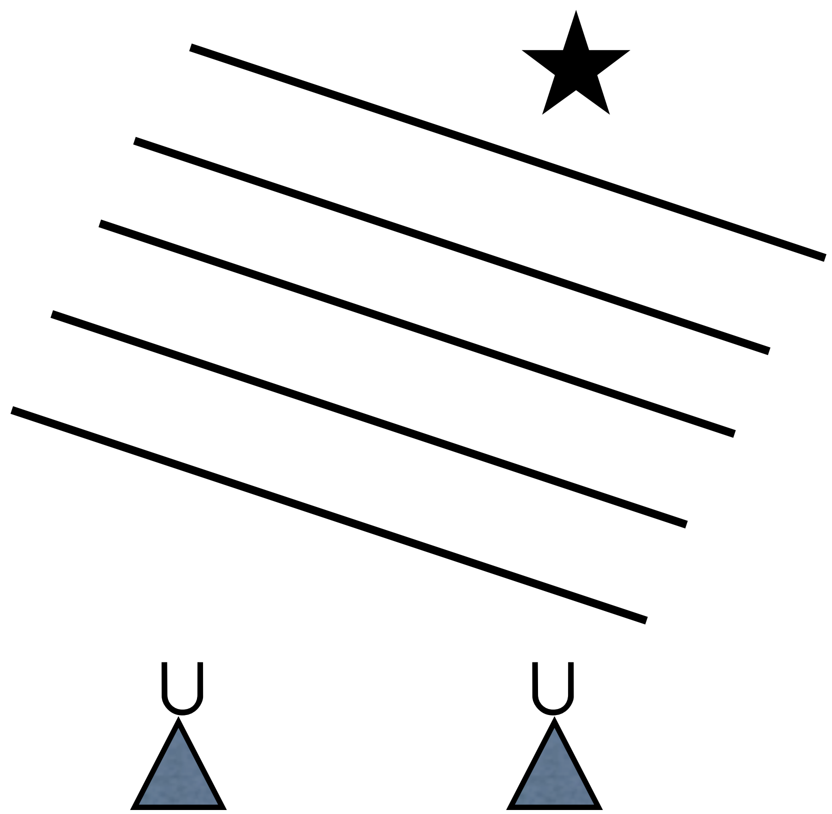
Outline, Fundamentals of radio astro.

- What does a point source look like to a pair of antennas?
- What does an extended source look like?
- What happens with lots of detectors?
- What happens when we hook them to telescopes?
- What if we want a larger area?
- What are effects of finite banwidth?

What Is This Visibility Thing?

- Simplest case: two (almost) monochromatic detectors pointed at the sky.
- Measure *product* of *electric fields* of the detectors.
- Time average of product is a visibility. It depends on relative spacing of detectors, sky brightness, etc.
- Product of electric fields is a power, total power proportional to bandwidth, gives rise to one of the more notorious units - the Jansky. 1 Jy = 10^{-23} erg/cm^2/s/hz.

Visibility, cont'd...
Signal from a point source



Source puts out plane waves of radiation. Telescopes see the same signal, with a phase lag set by path length difference between the two antennae.

$V = \langle E_1^* E_2 \rangle = I_0 \exp(2\pi i \boldsymbol{\theta} \cdot \mathbf{u})$

$\boldsymbol{\theta}$=angle on sky of source

$\mathbf{u}$=separation of antennae, wavelengths

Visibility, cont'd... Signal from an extended source

For one source: $V=\langle E_1^* E_2\rangle = I_0 \exp(2\pi i \boldsymbol{\theta}\cdot\mathbf{u})$

For many sources, if they don't know about each other, electric fields are incoherent, so visibilities add. In that case, visibility becomes integral over the response from one source:

$$V(\mathbf{u})=\int\int I_0(\boldsymbol{\theta})\exp(2\pi i\boldsymbol{\theta}\cdot\mathbf{u})d^2\boldsymbol{\theta}$$

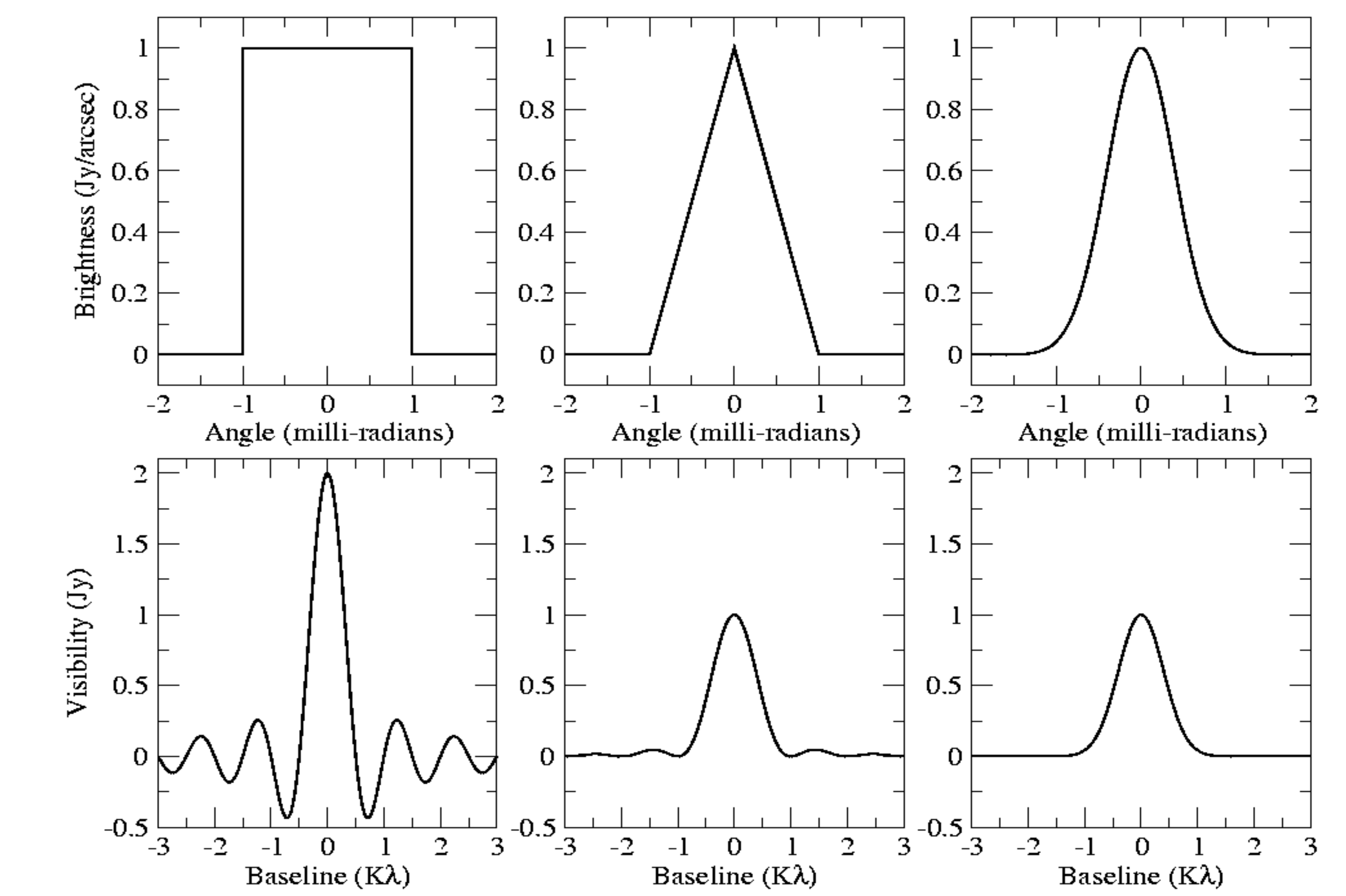
This is simply the 2-D Fourier transform of the sky, evaluated at the antenna separation (the "baseline") in wavelengths. The components of the baseline vector are standardly denoted by (u,v), hence the UV plane.

Visibilities Directly Measure Sky FT

- If we had perfectly dense sampling, would simply take inverse FT of UV plane (also called the aperture plane) to get sky map. However, we never have perfect sampling, so must interpolate to guess unmeasured modes. Lots of algorithms for doing this (clean, multi-scale clean, MEM...)
- Straight FT of UV plane gives "dirty" map.
- For CMB power spectrum, we don't really want the map. We want the FT of the sky - what the interferometer was measuring all along!
- For CBI power spectrum pipeline, we never make a sky-plane map. Just work directly with visibilities.

Examples of Visibility Functions

- Top row: 1-dimensional even brightness distributions.
- Bottom row: The corresponding real, even, visibility functions.



Some Quick Vis. to remember

- A point source at the pointing center is constant and real for all visibilities.
- An off-center point source has constant amplitude, but ramping phase along direction of offset.
- A Gaussian blob transforms to a Gaussian, whose width in $\mathbf{u}$ is 1/width of blob on sky.
- A plane-wave on the sky is a δ-function in UV plane. Wavelength is $2\pi/|\mathbf{u}|$, direction is angle($\mathbf{u}$).

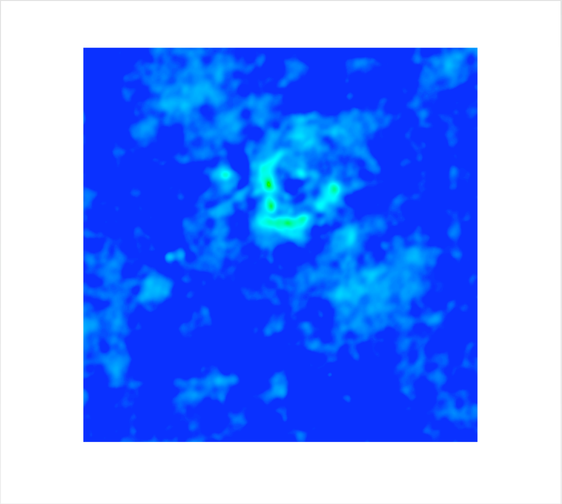
Many Dishes

- More baselines means more knowledge of UV plane, better pictures, etc.
- Correlate every pair of antennas. Number of baselines goes like n(n-1)/2, so can quickly get expensive. Noise in each baseline generally independent.
- Digital correlation: VLA has 27 dishes, current 50 MHz bandwidth, 2 pol. =(27*26/2)*5e7*4=70 billion correlations/s. CBI has 13@10 GHz = nearly one trillion. For this reason, many correlators still analog.
- EVLA major upgrade to VLA, biggest part improving correlator (plus lots of other goodies).

Optics: holes in a mask (poached nrao)

Double number of holes from frame to frame:

- 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024



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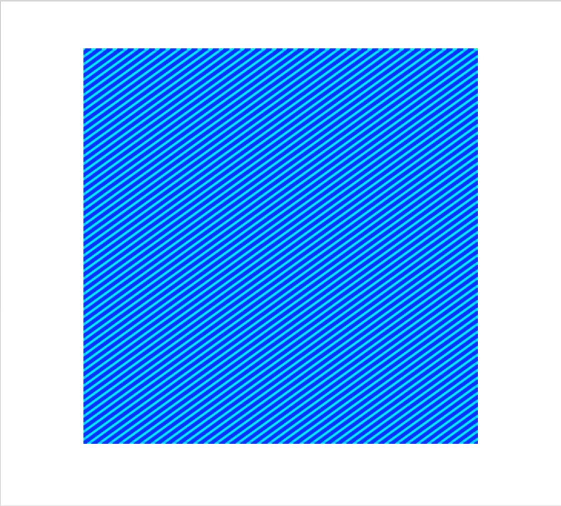

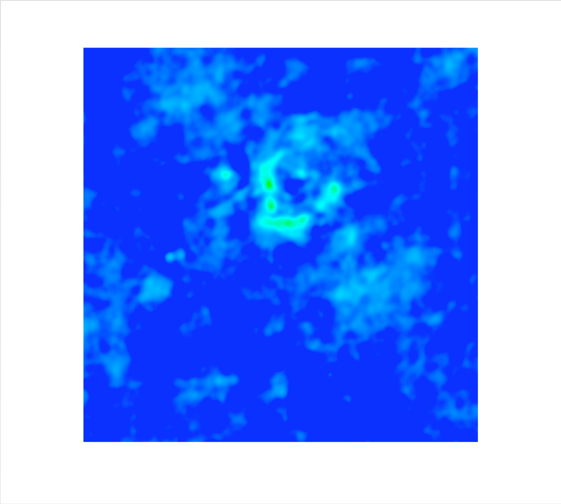

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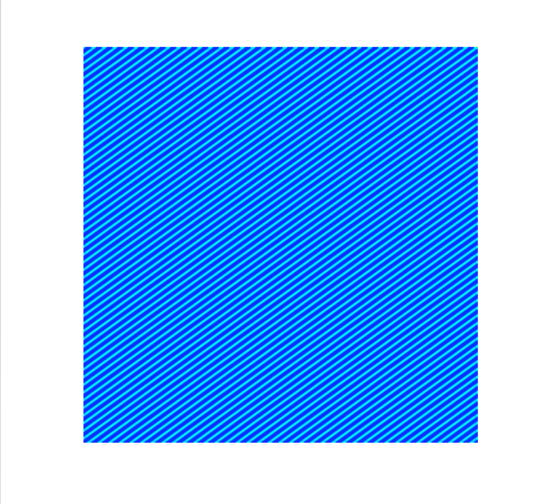

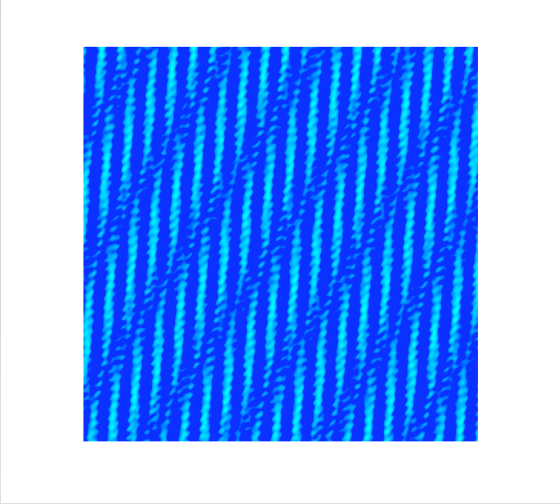

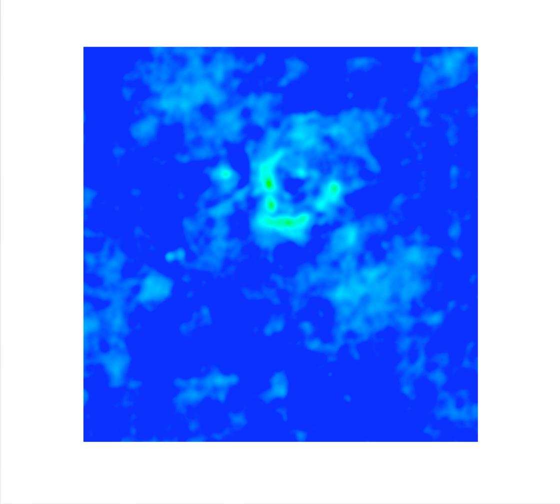

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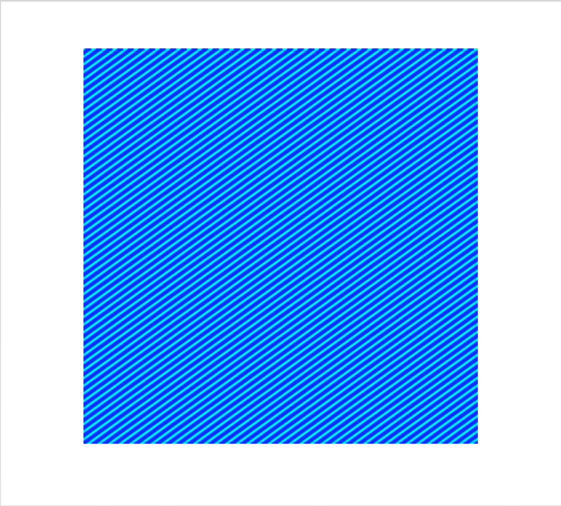

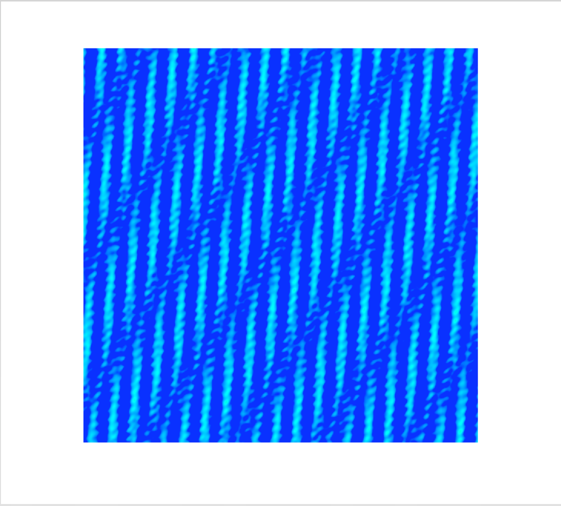

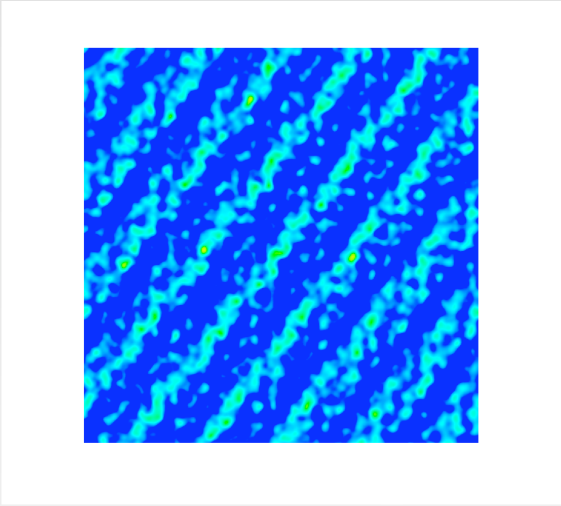

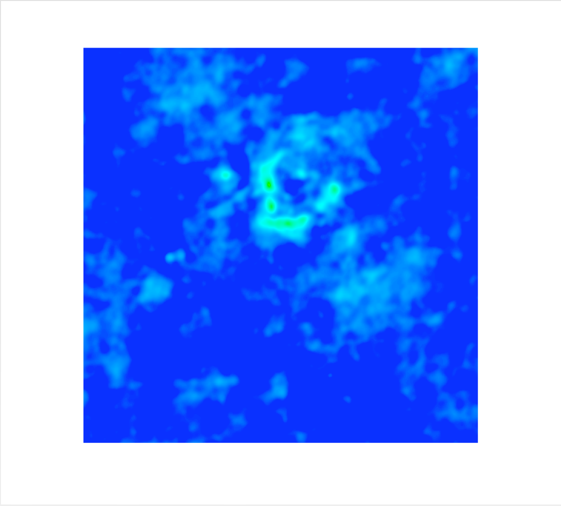

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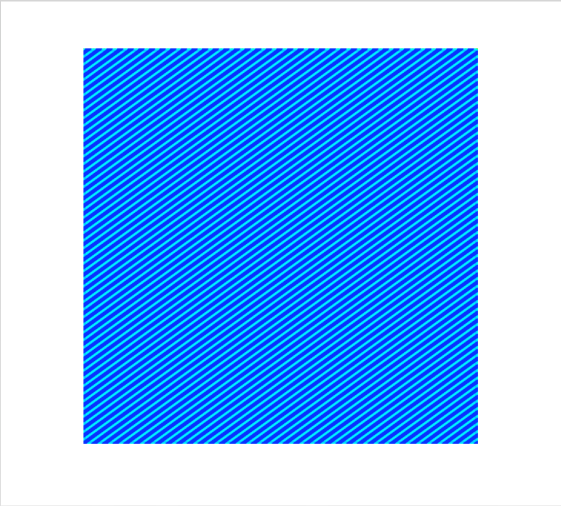

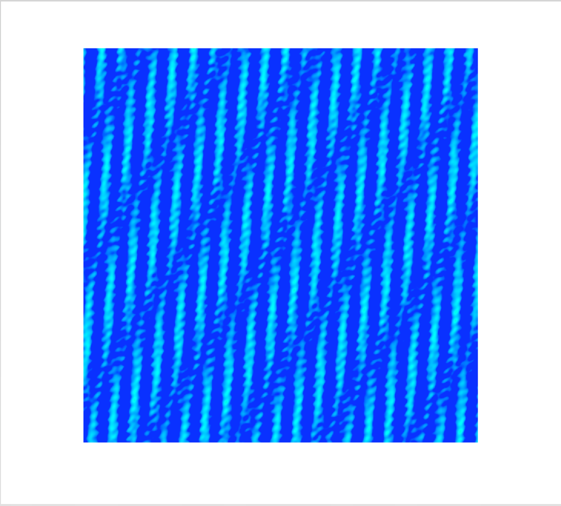

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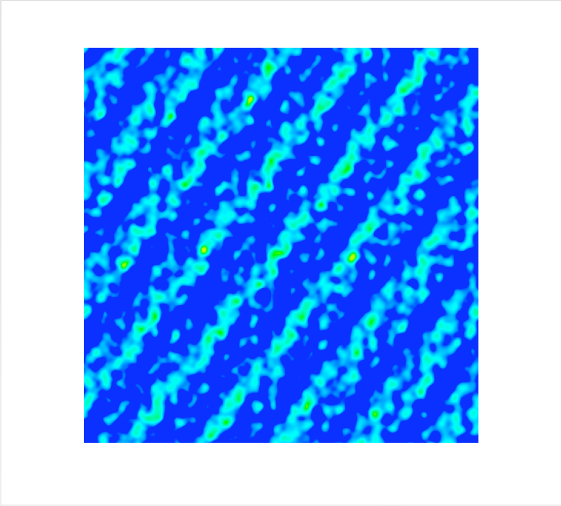

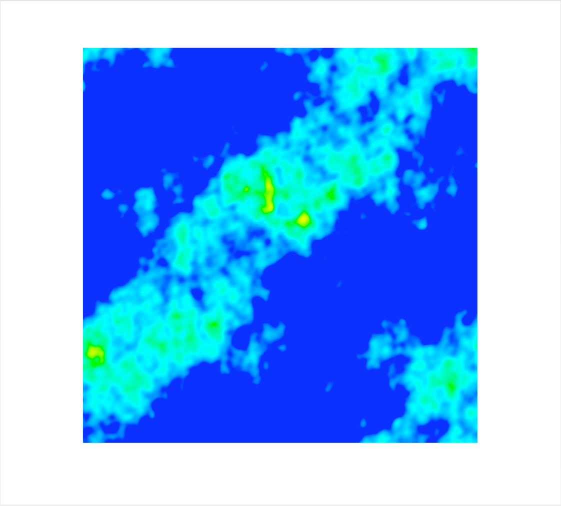

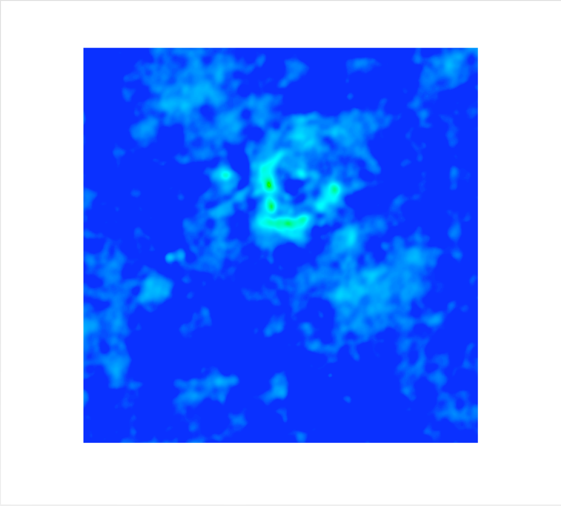

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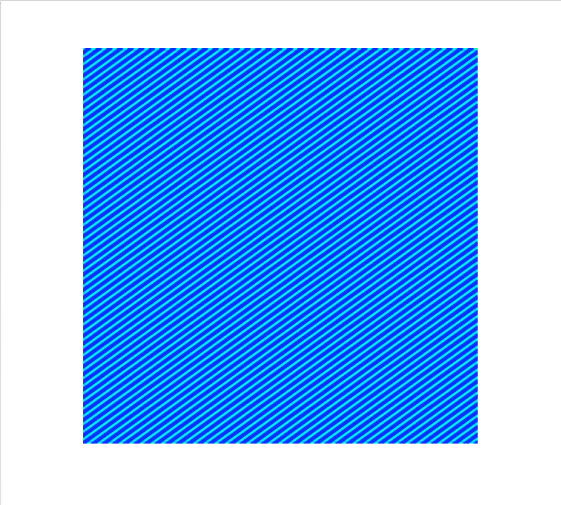
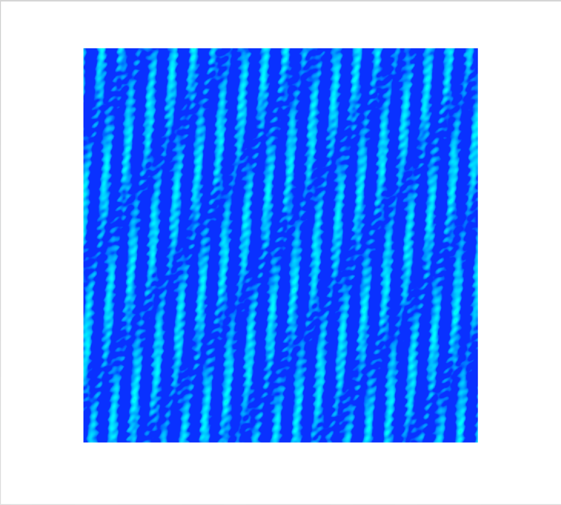
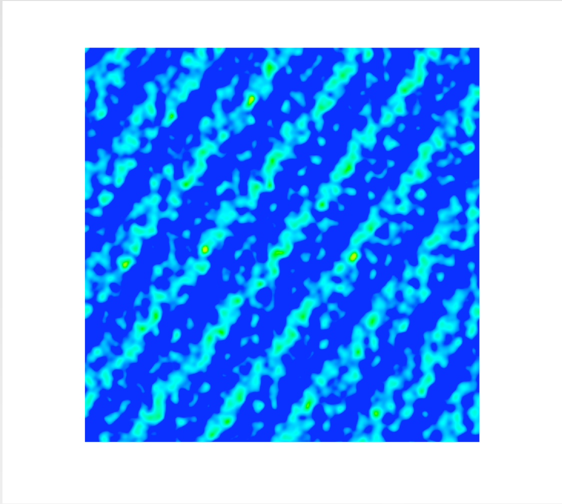
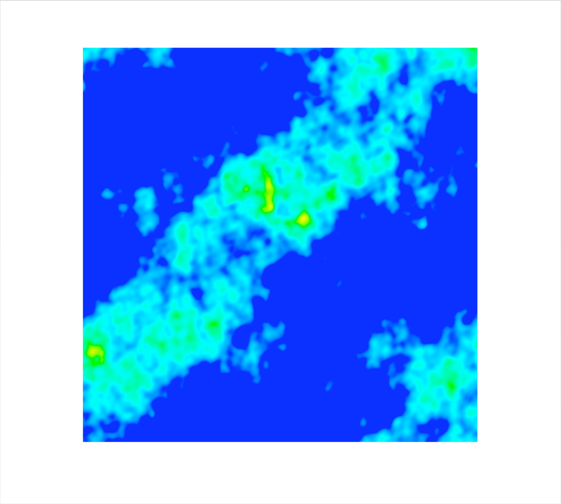
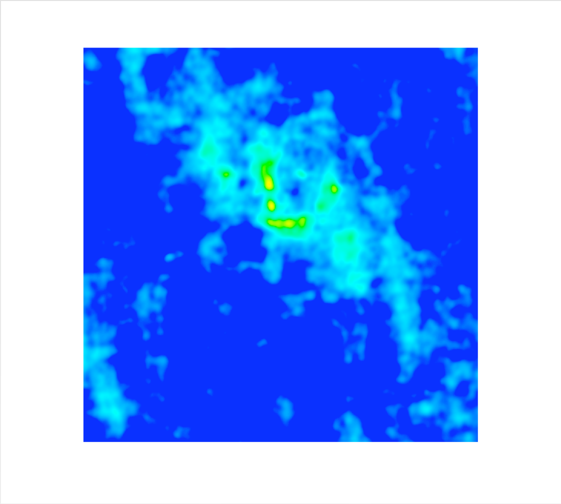
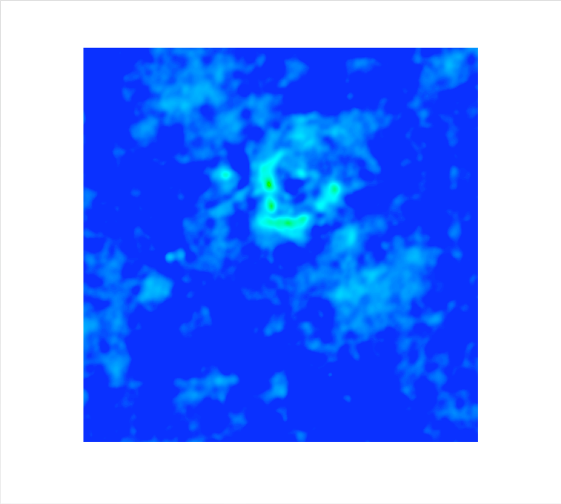

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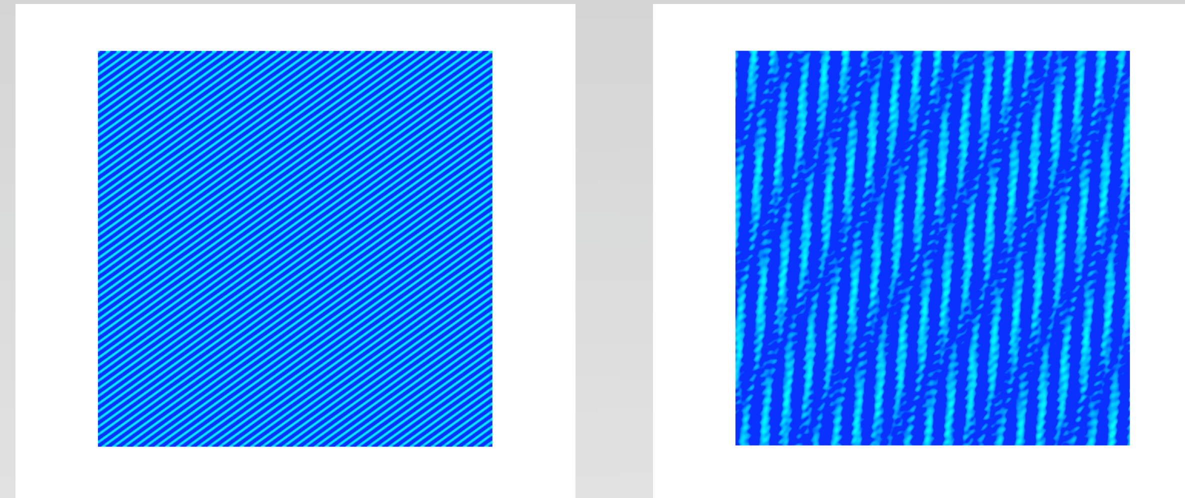

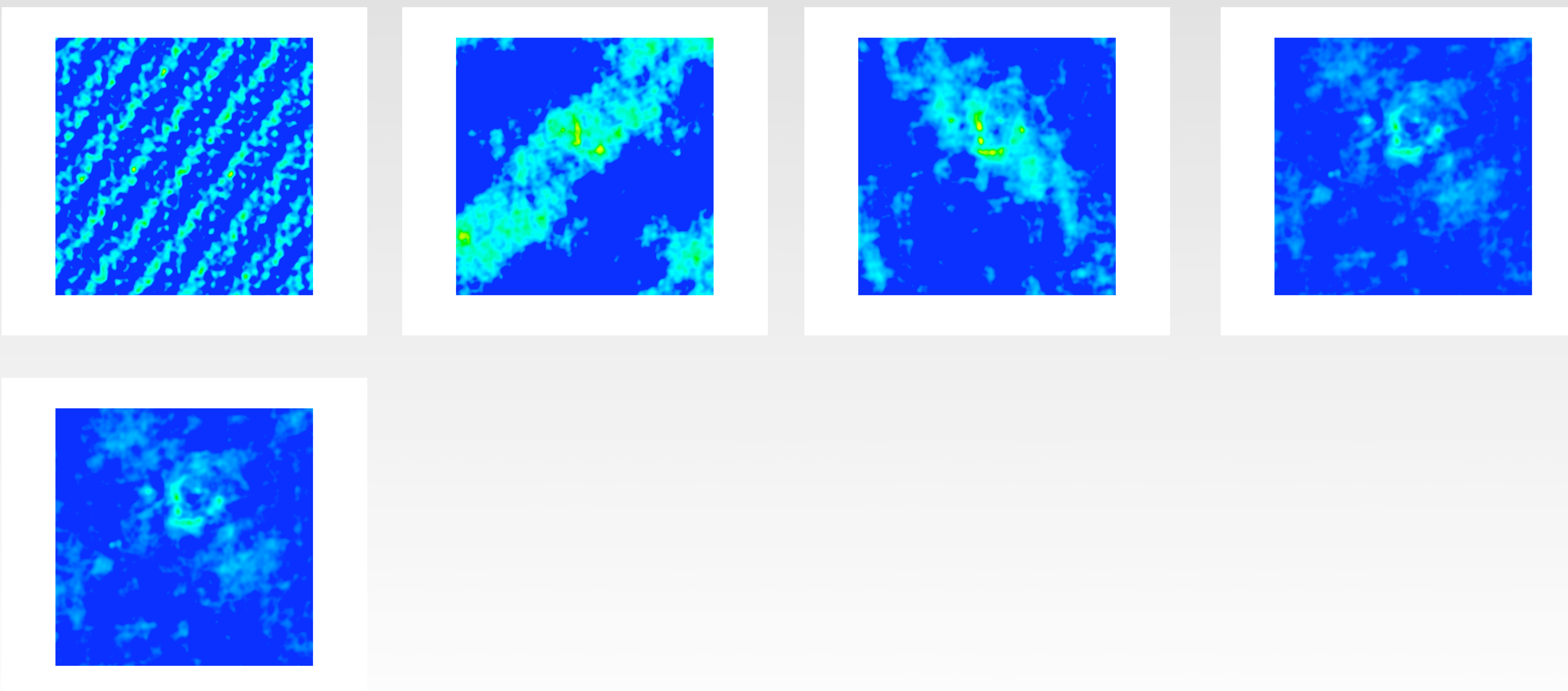

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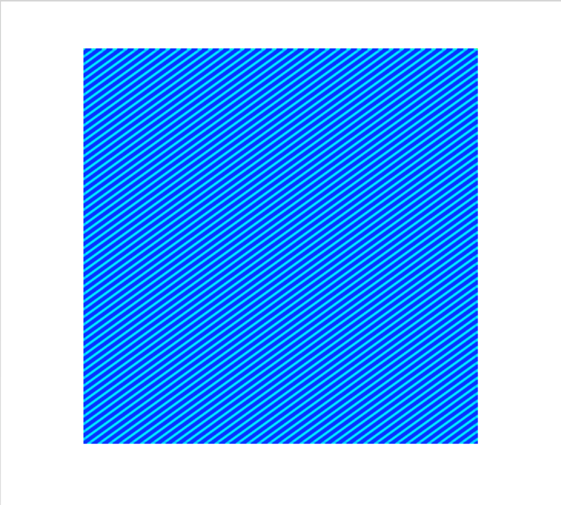
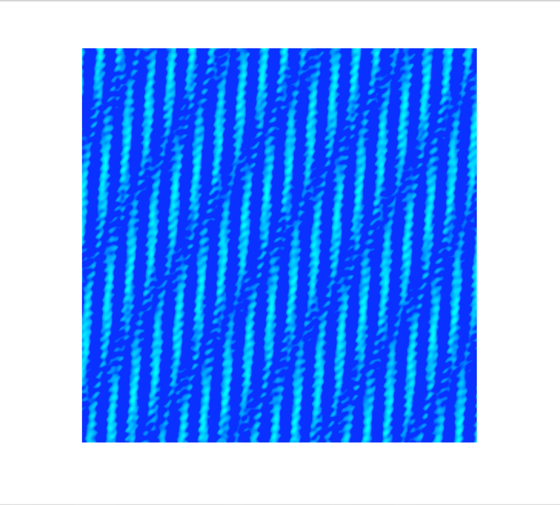
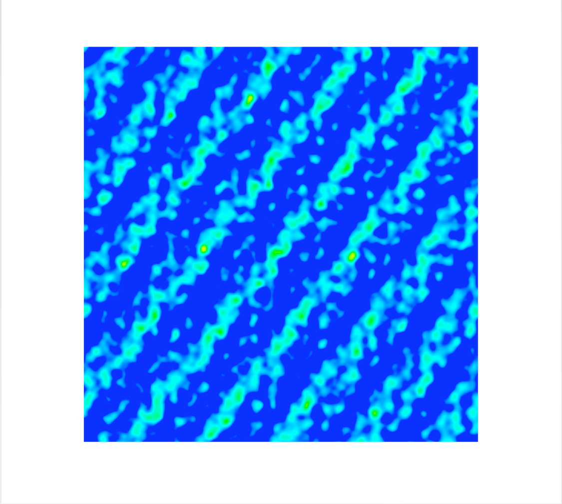
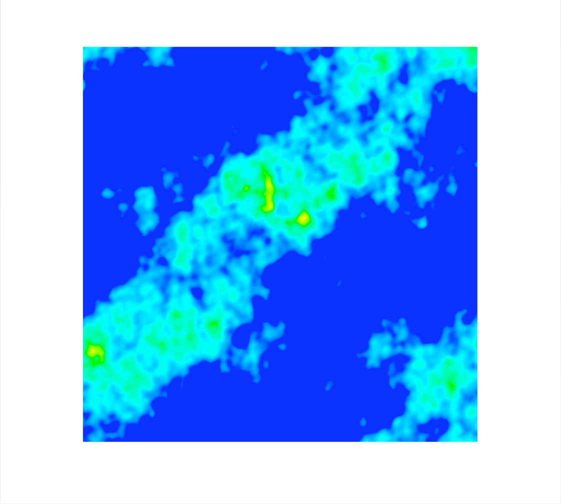
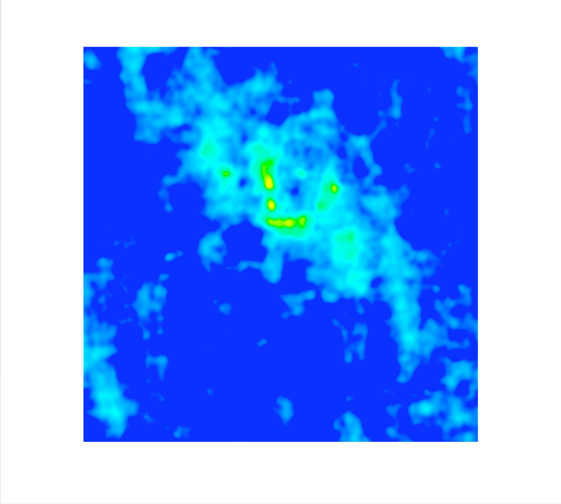
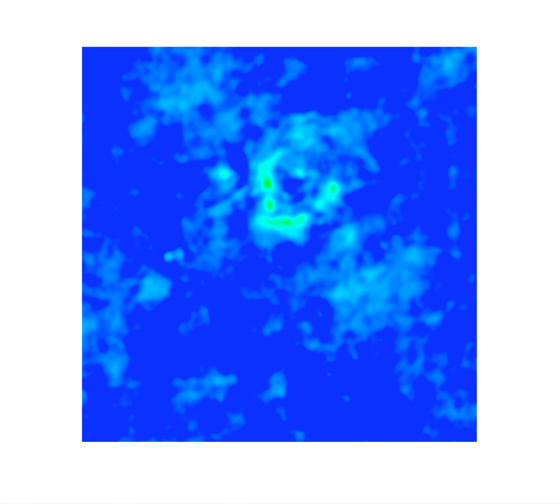
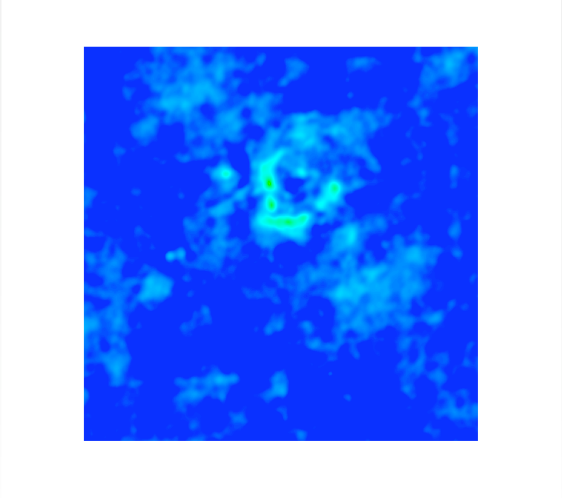
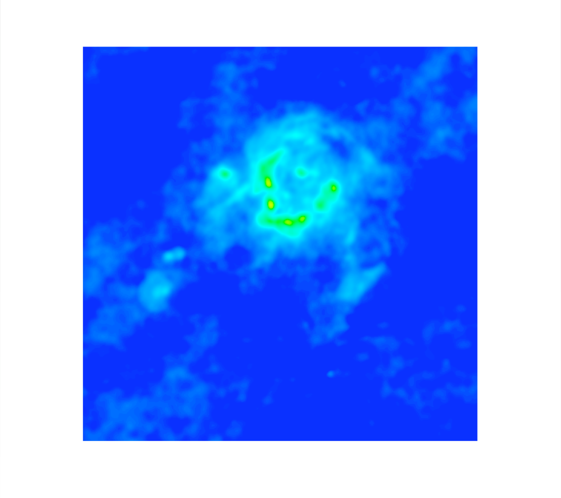

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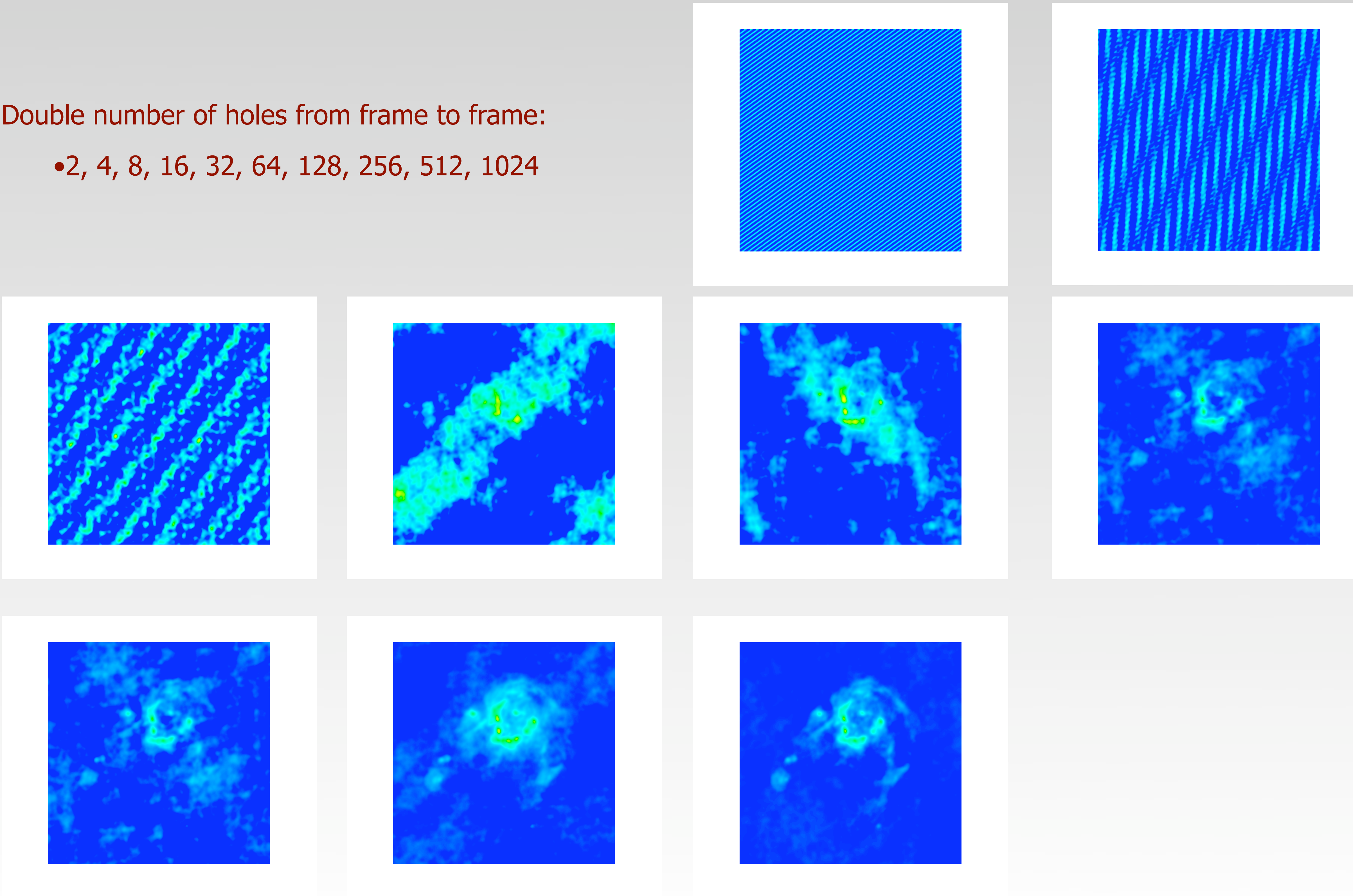

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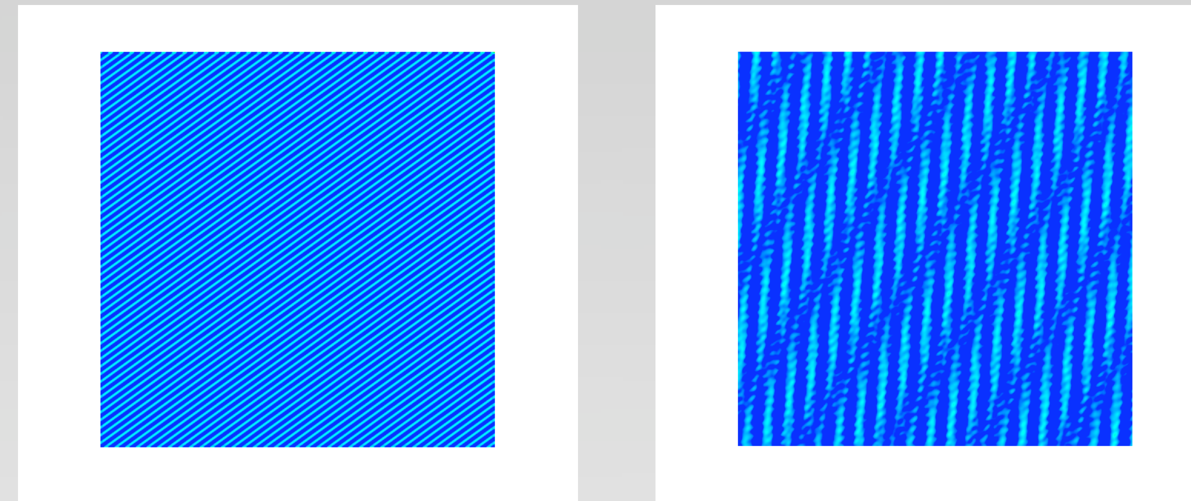
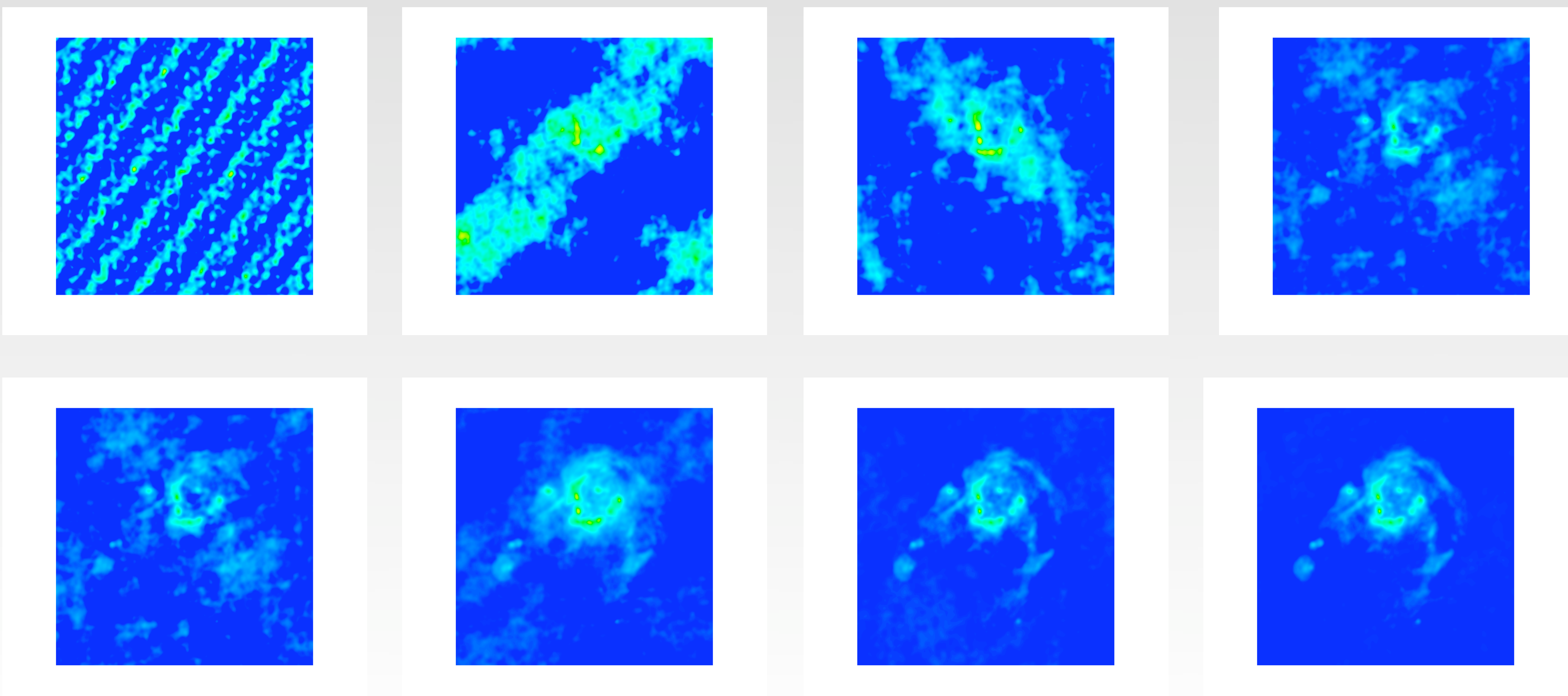
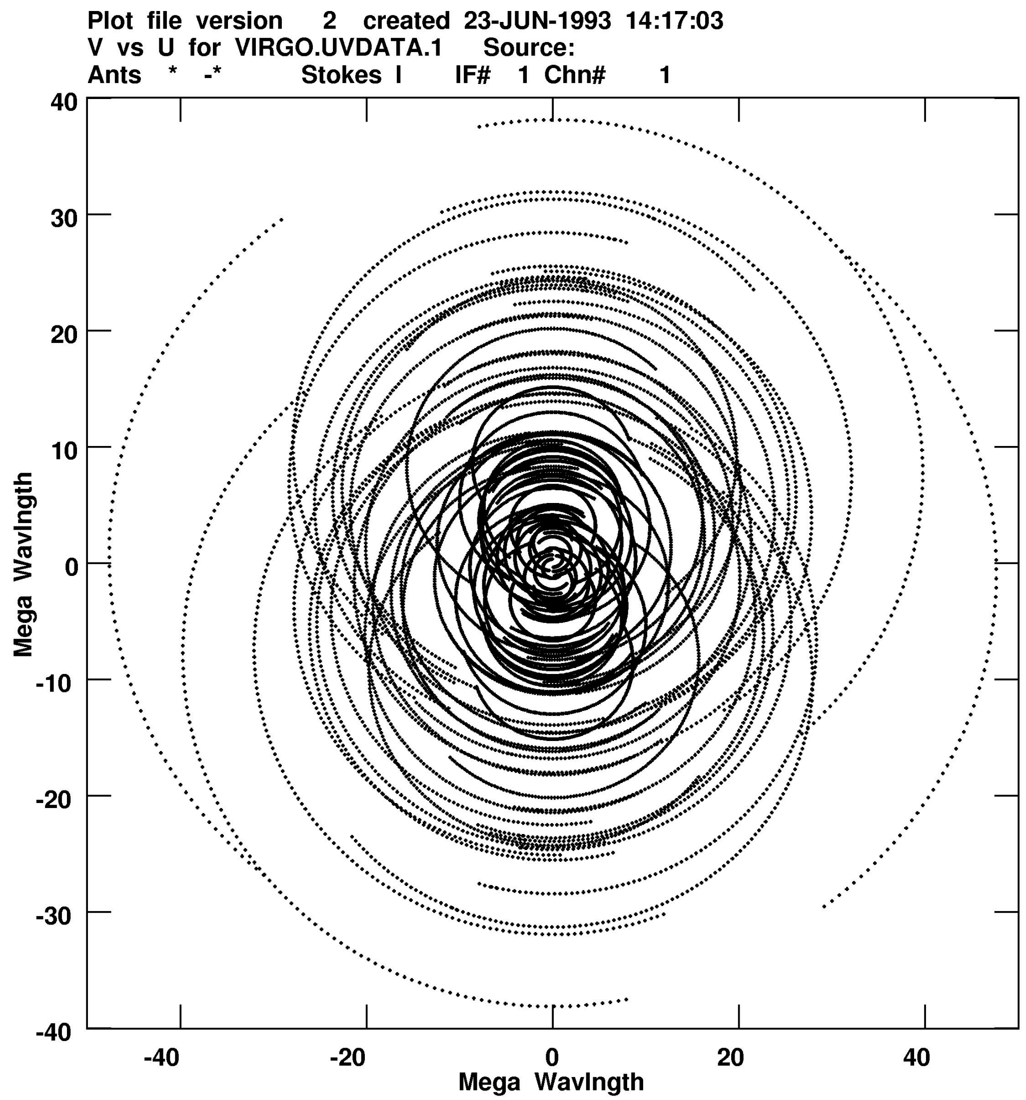
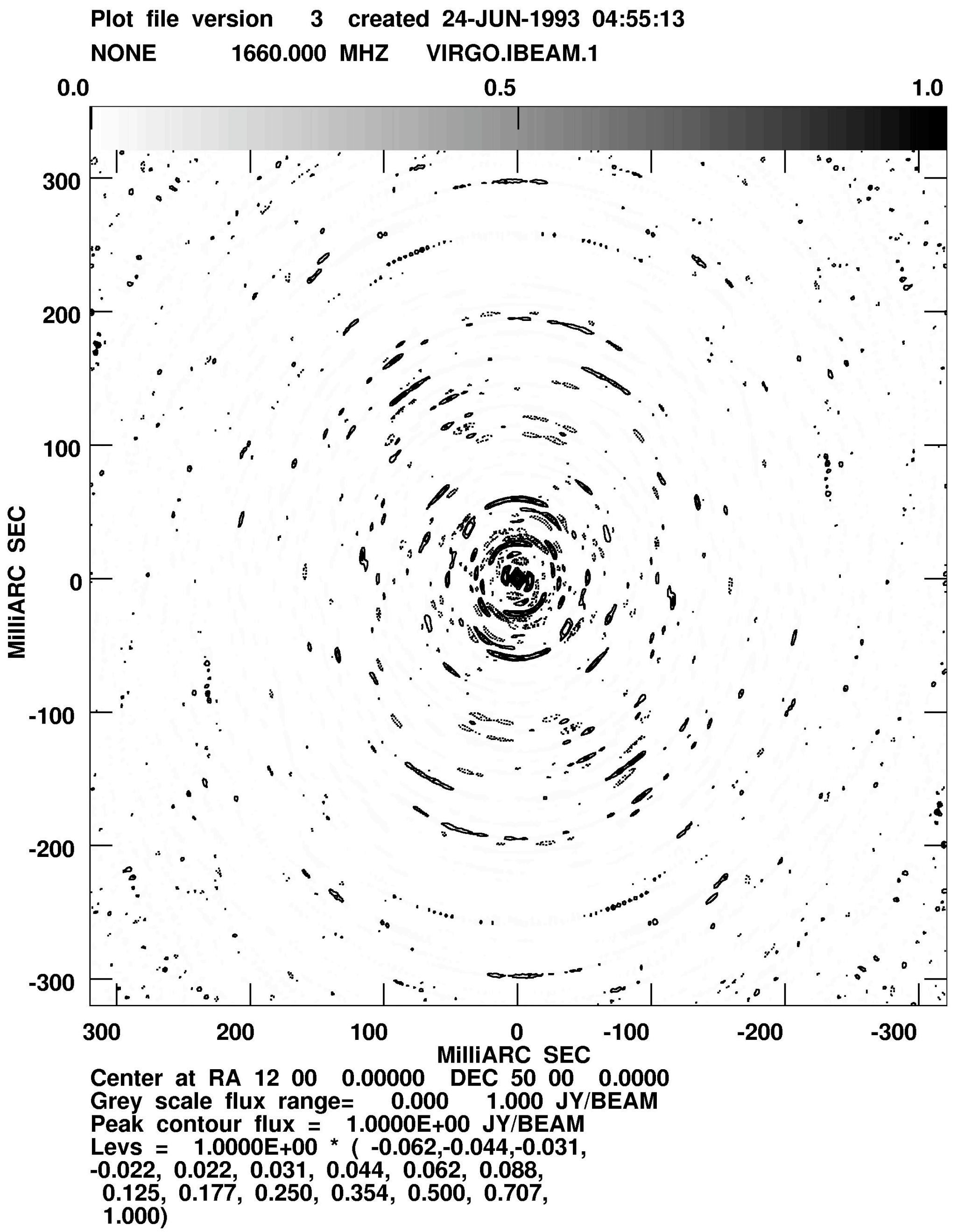




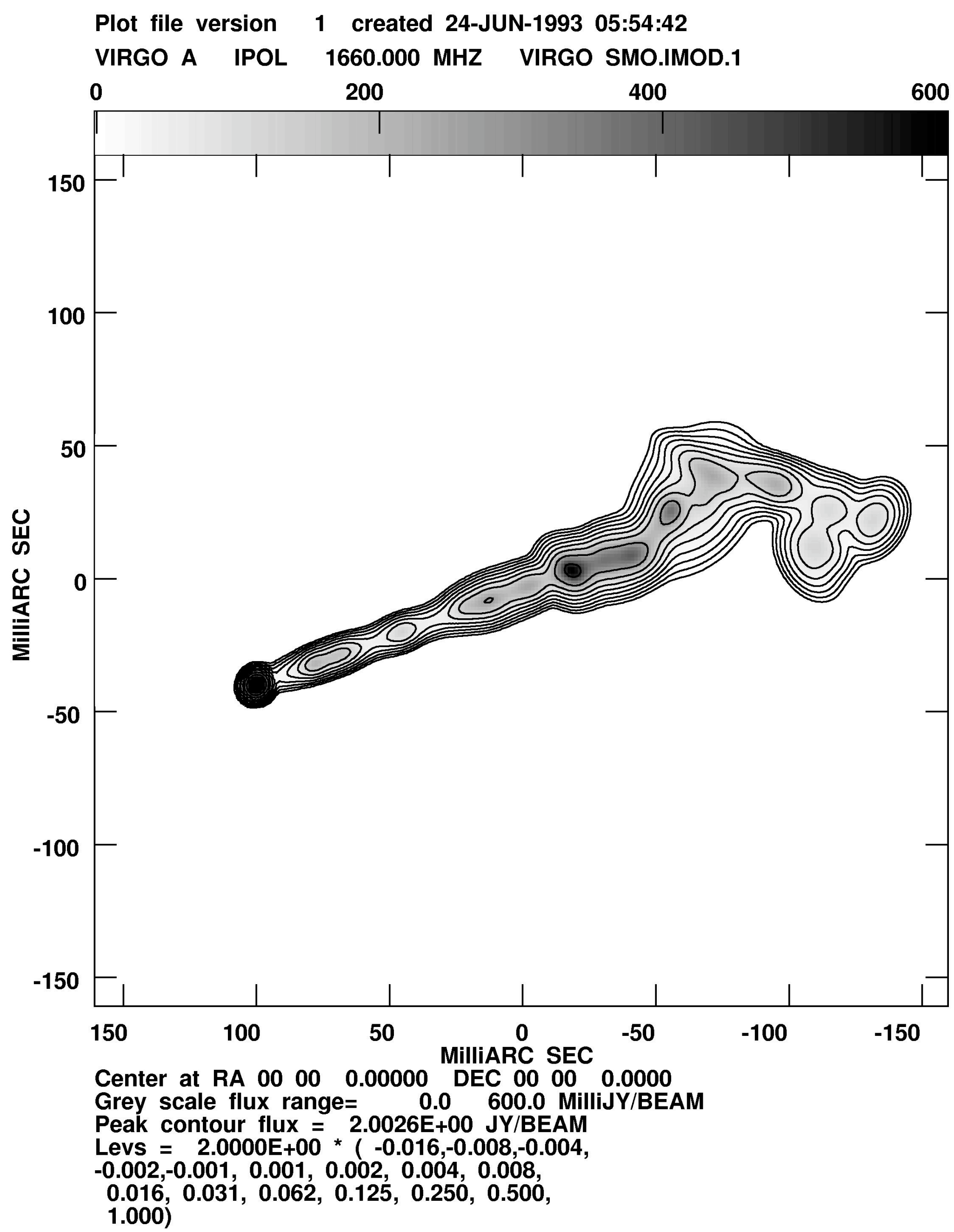
UV Sampling ⇔Point Spread Function

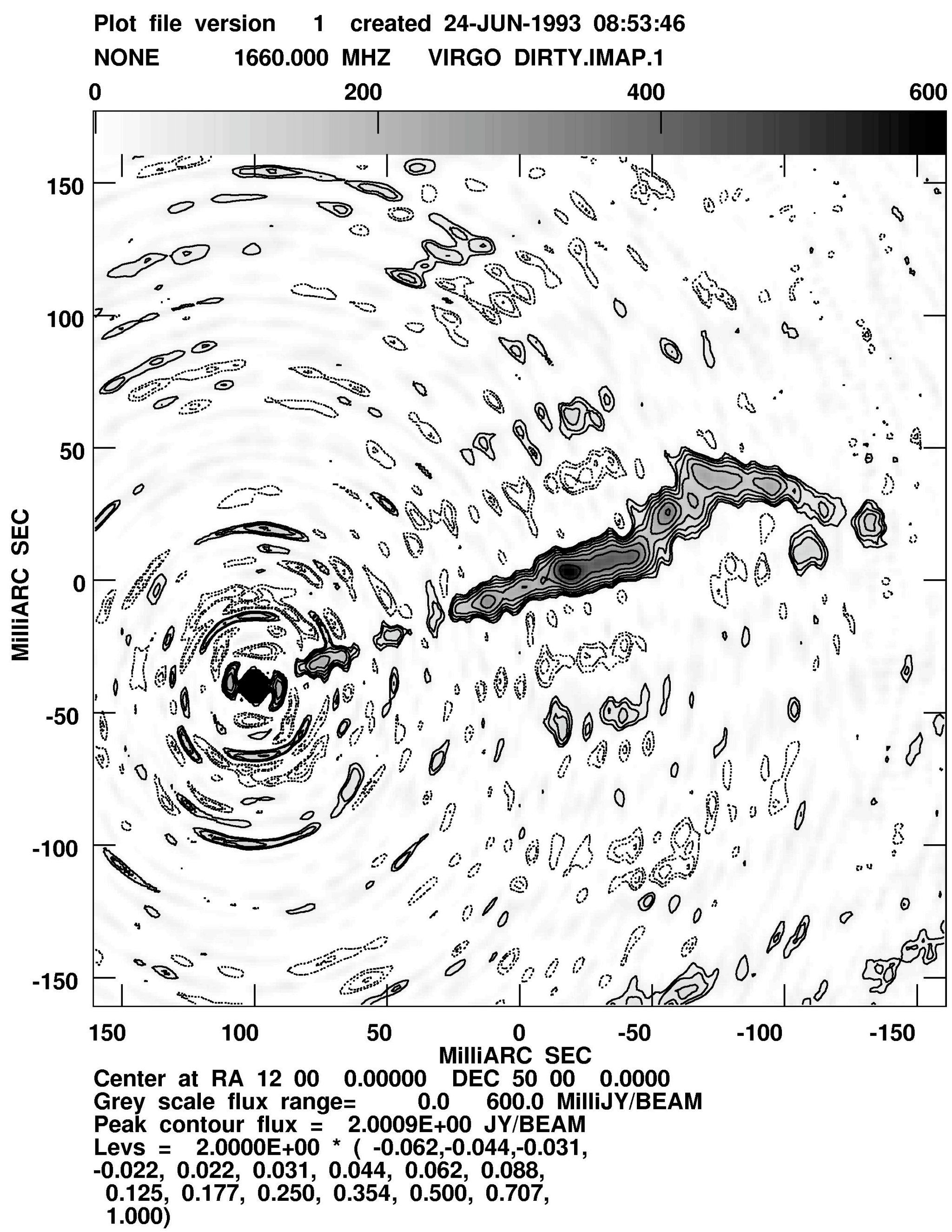


For most arrays, UV coverage filled out by rotation of the Earth, hence the loops.

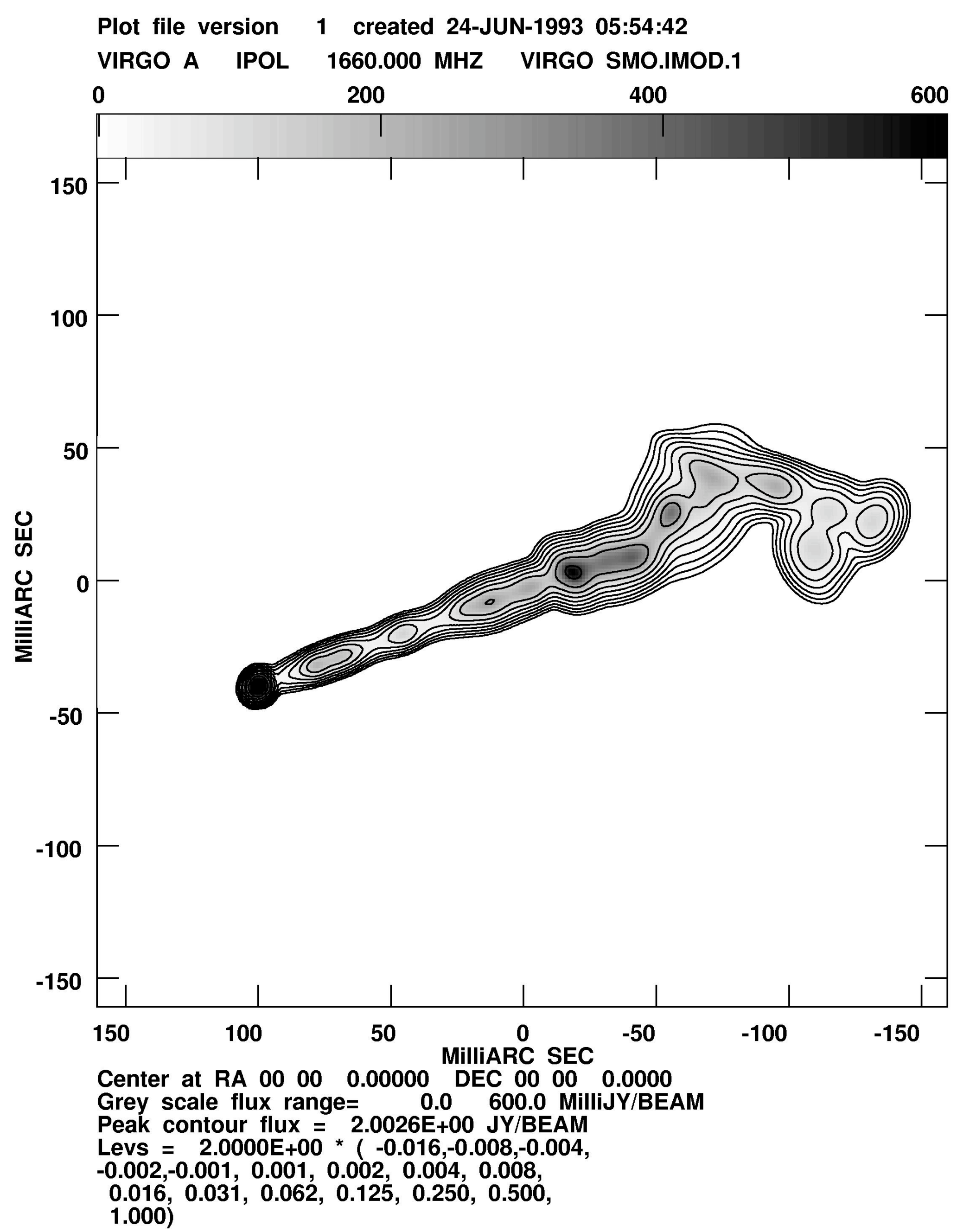


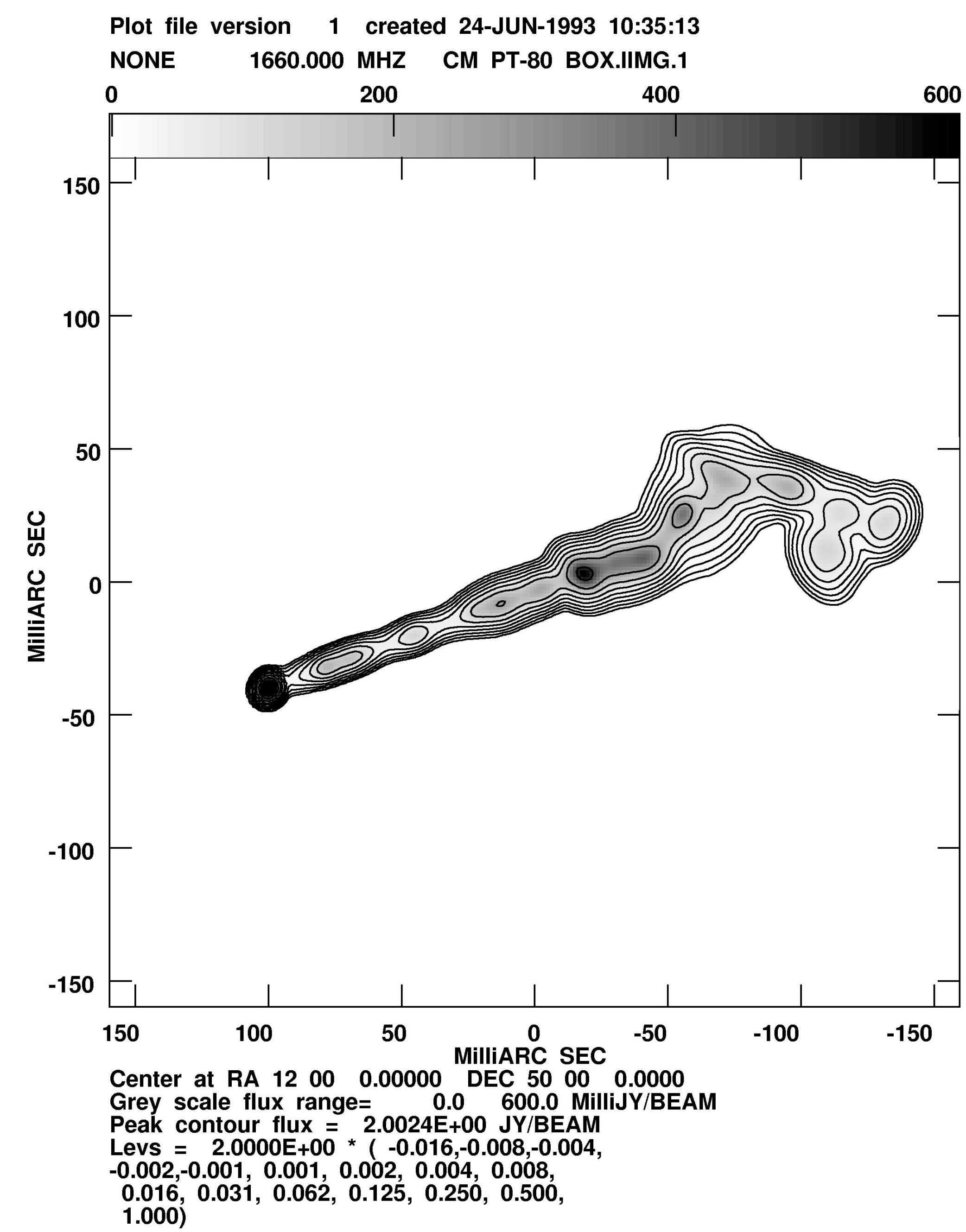
Original model and Dirty image





Original model and best image





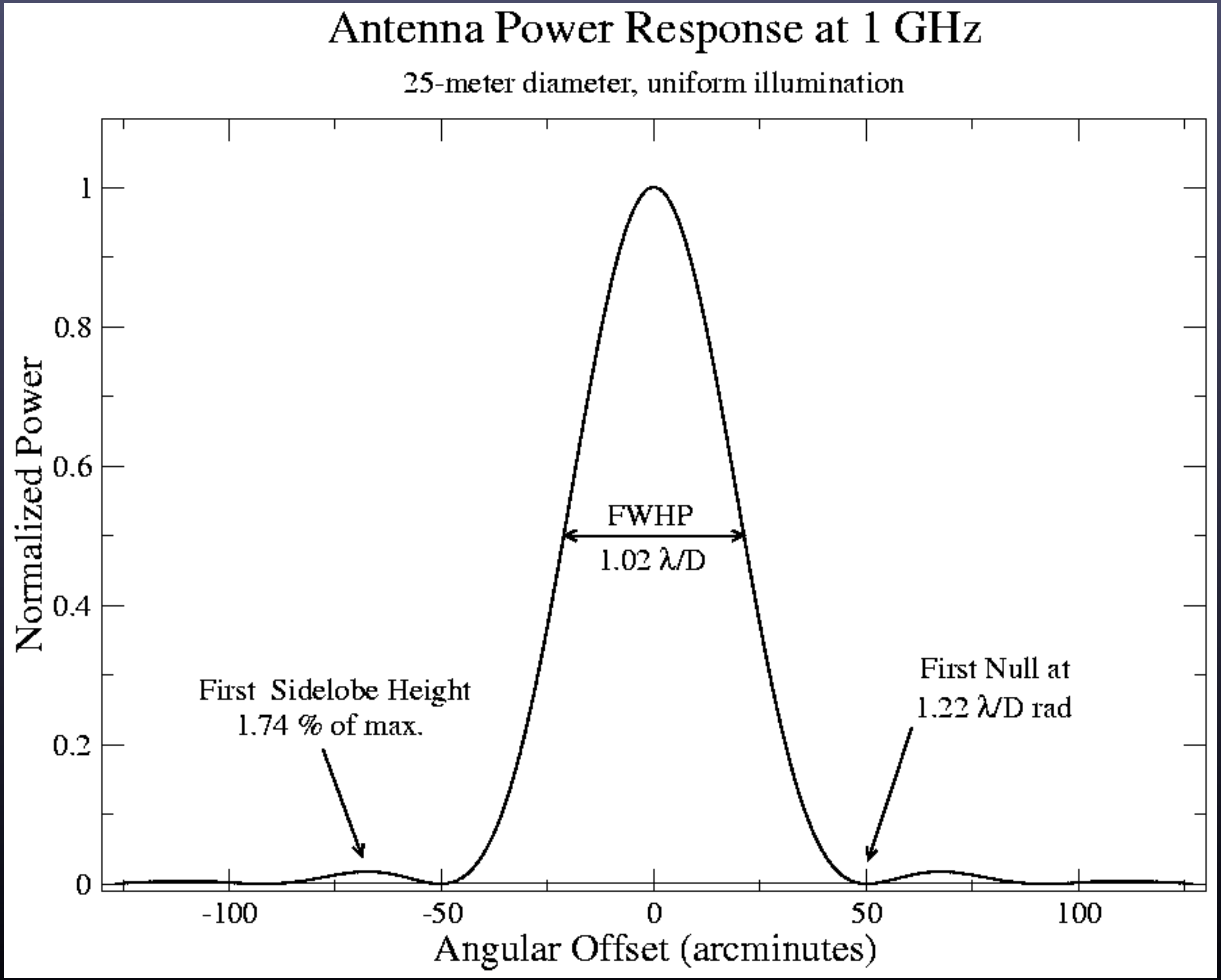
Visibilities From Dishes

- Detectors hooked up to telescopes, the dishes only see part of the sky. So, a visibility doesn't just see put sine wave.
- Seeing small patch of sky means Fourier resolution goes down. Quantitatively, what happens?
- Electric field at detector is coherent sum of fields across dish, intensity response of this is then FT of dish pattern.
- Visibilities have this squared, since pattern comes in twice.

The Standard Parabolic Antenna Response

The power response of a uniformly illuminated circular parabolic antenna of 25-meter diameter,
at a frequency of 1 GHz.

(Stolen, Perley)

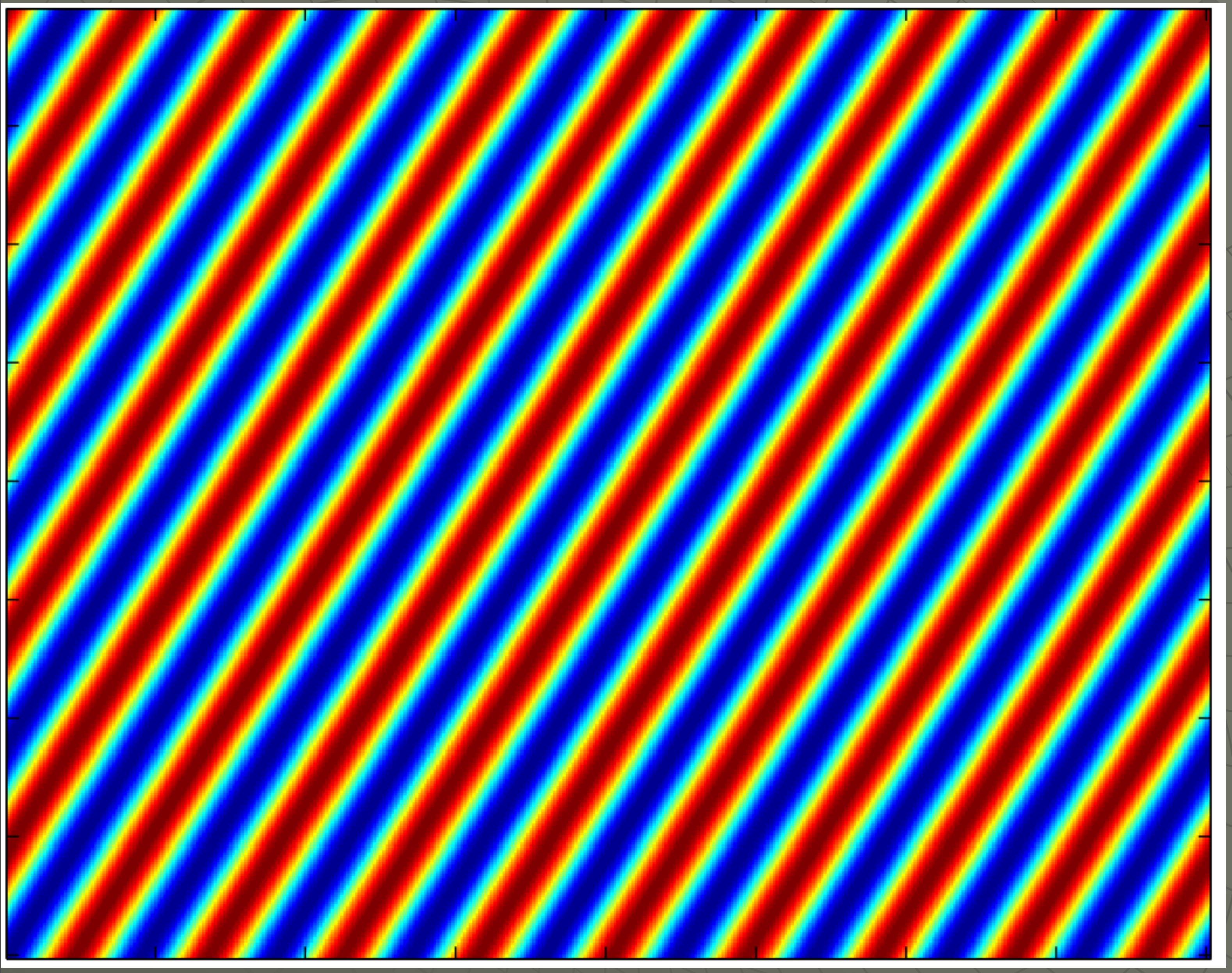


Dishes, cont'd

- Have two beams. #1 - Primary beam is set by the single dish response. We will never see anything far outside the primary beam.
- #2 - Synthesized beam is FT of visibility pattern. Typically, have many of these across primary beam.
- For power spectrum, want to know primary beam in Fourier space. Beam on sky is square of intensity beam, which is FT of the dish illumination. FT of square of FT is autocorrelation of original thing. Just smear dish by itself to give response in Fourier space!
- Big dishes smear by a lot, so bad Fourier resolution, but good sensitivity. Small dishes have large fields of view, hence good Fourier resolution.

Single Baseline Reponse

Big dishes means small piece of sky -> *big beam* in Fourier space.
Position sampled in Fourier space set by dish separation.



Response on sky

FT of sky response

Single Baseline Reponse

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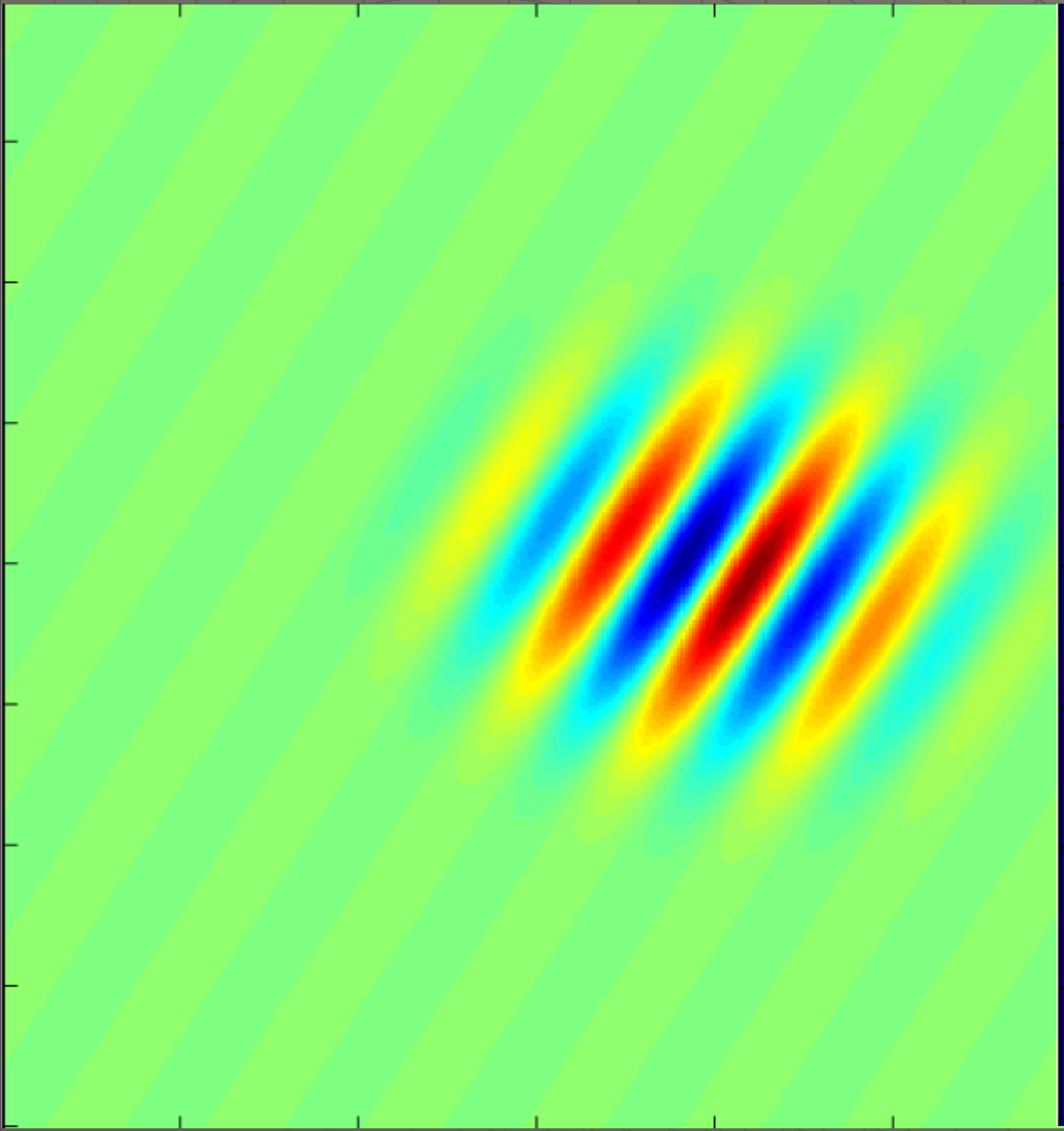
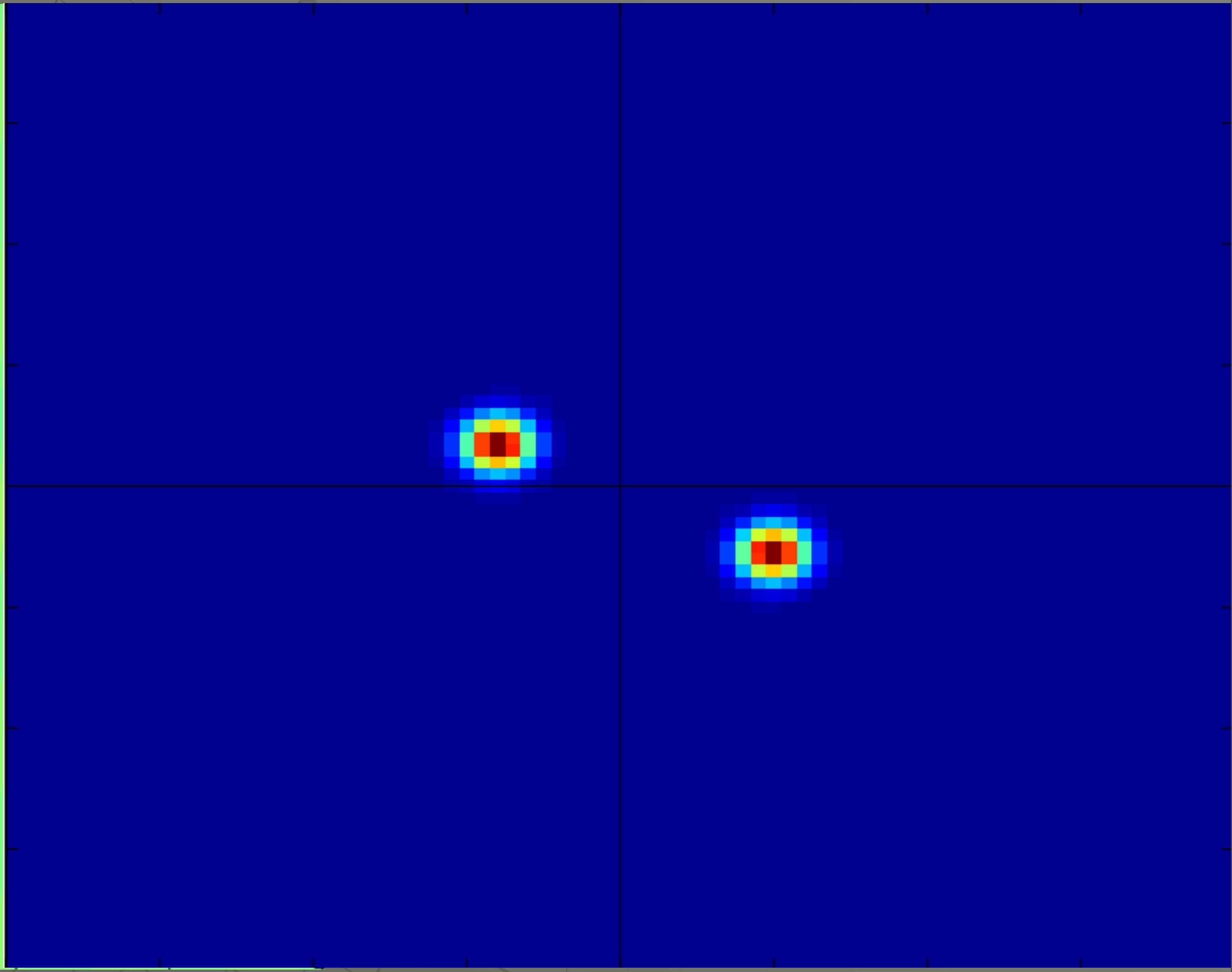


Response on sky



FT of sky response

Single Baseline Reponse

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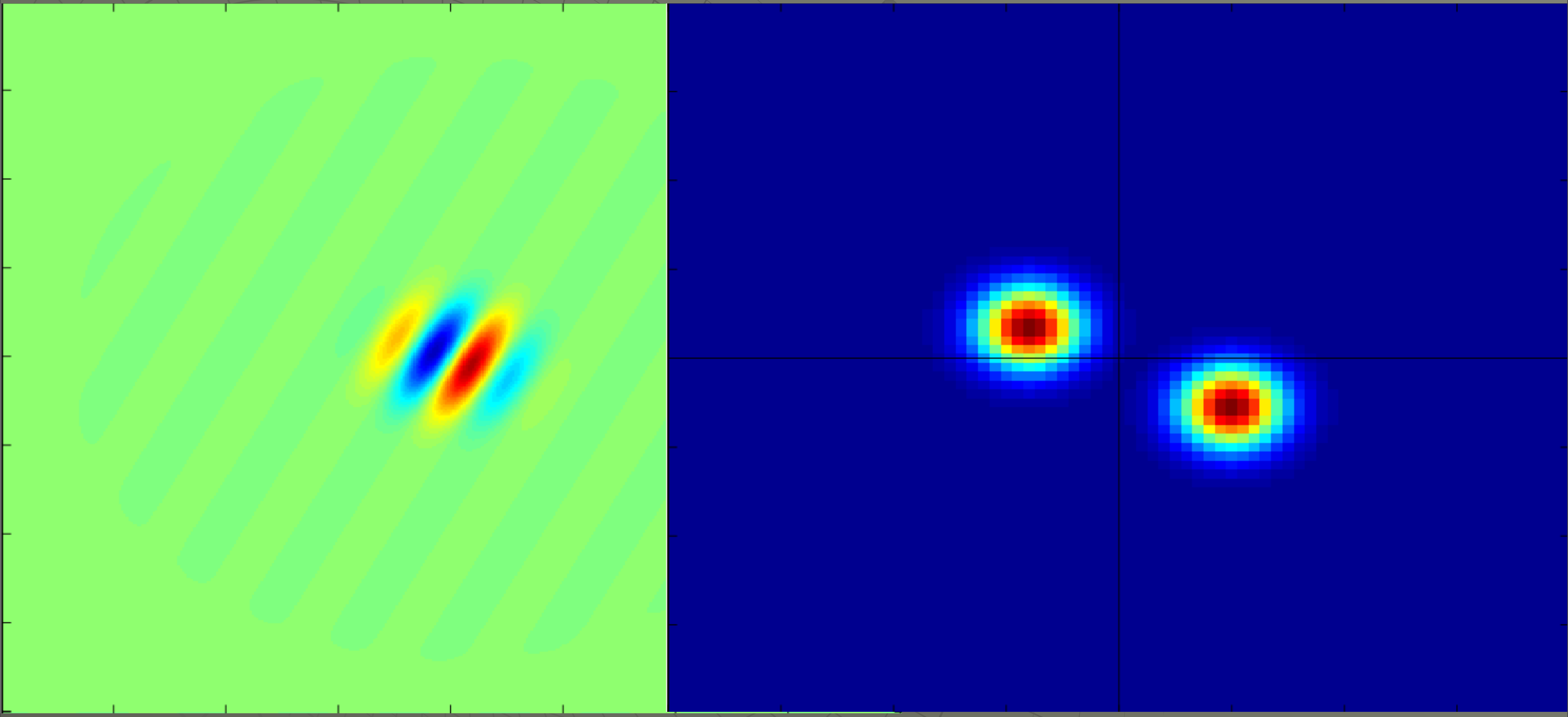


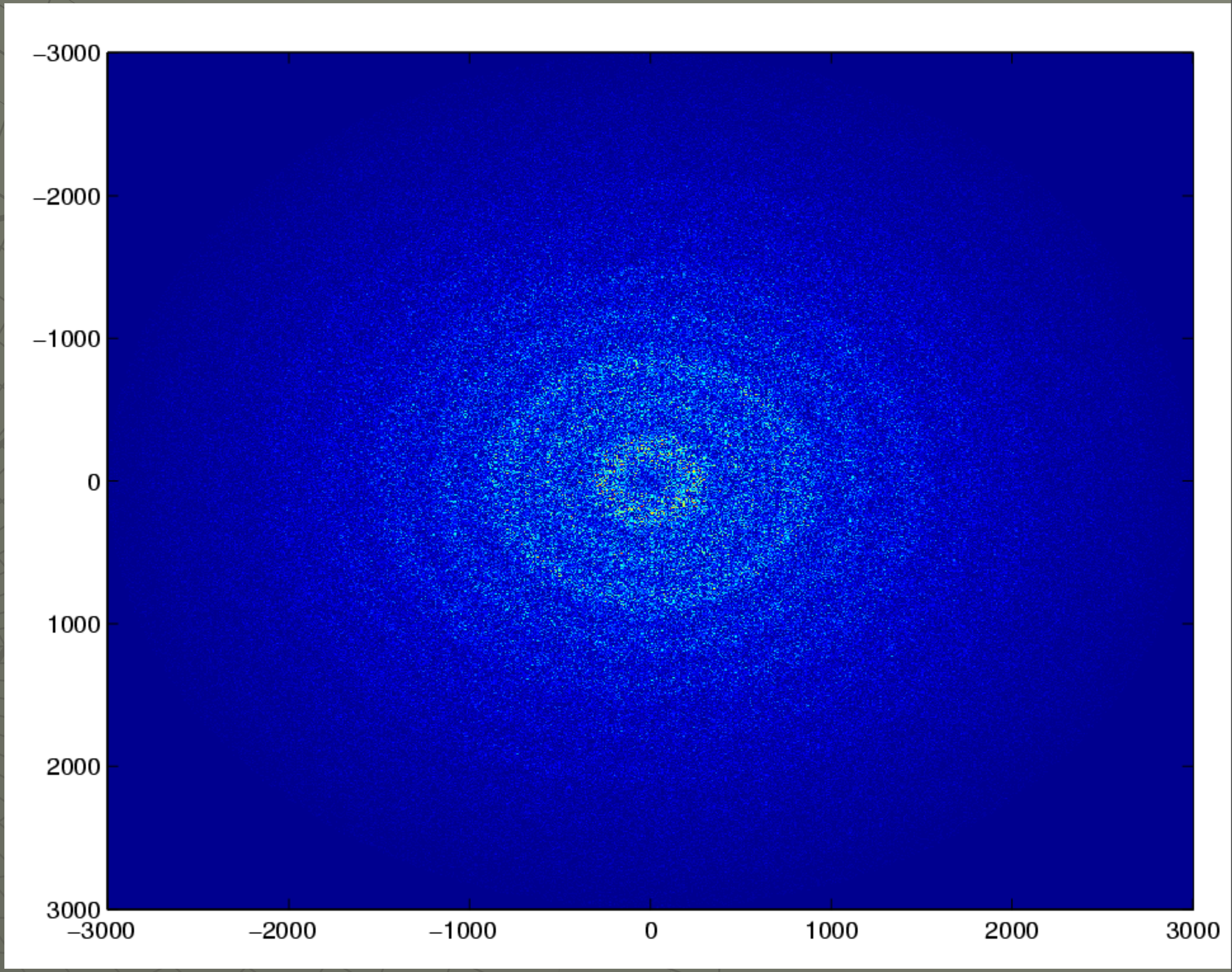
Response on sky

FT of sky response

PS Fundamentals - What we want to measure.

In Fourier space, we expect random, uncorrelated noise with rings of high/low amplitude.

Power Spectrum is variance of random field in rings of ***k***.



PS Fundamentals - What we want to measure.

In Fourier space, we expect random, uncorrelated noise with rings of high/low amplitude.

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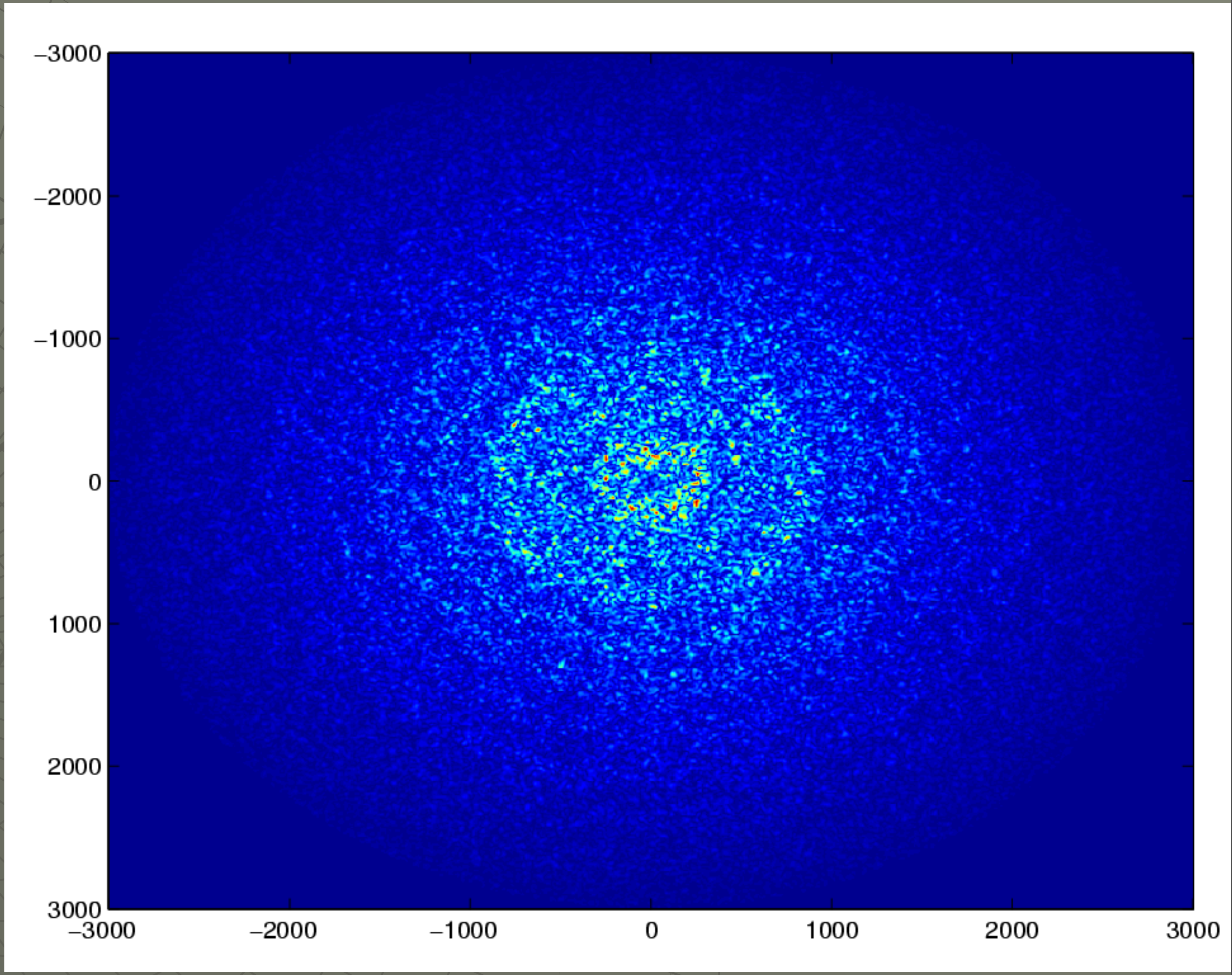
Small piece of sky = smoothing of Fourier plane. Leads to worse resolution and fewer independent waves measured.



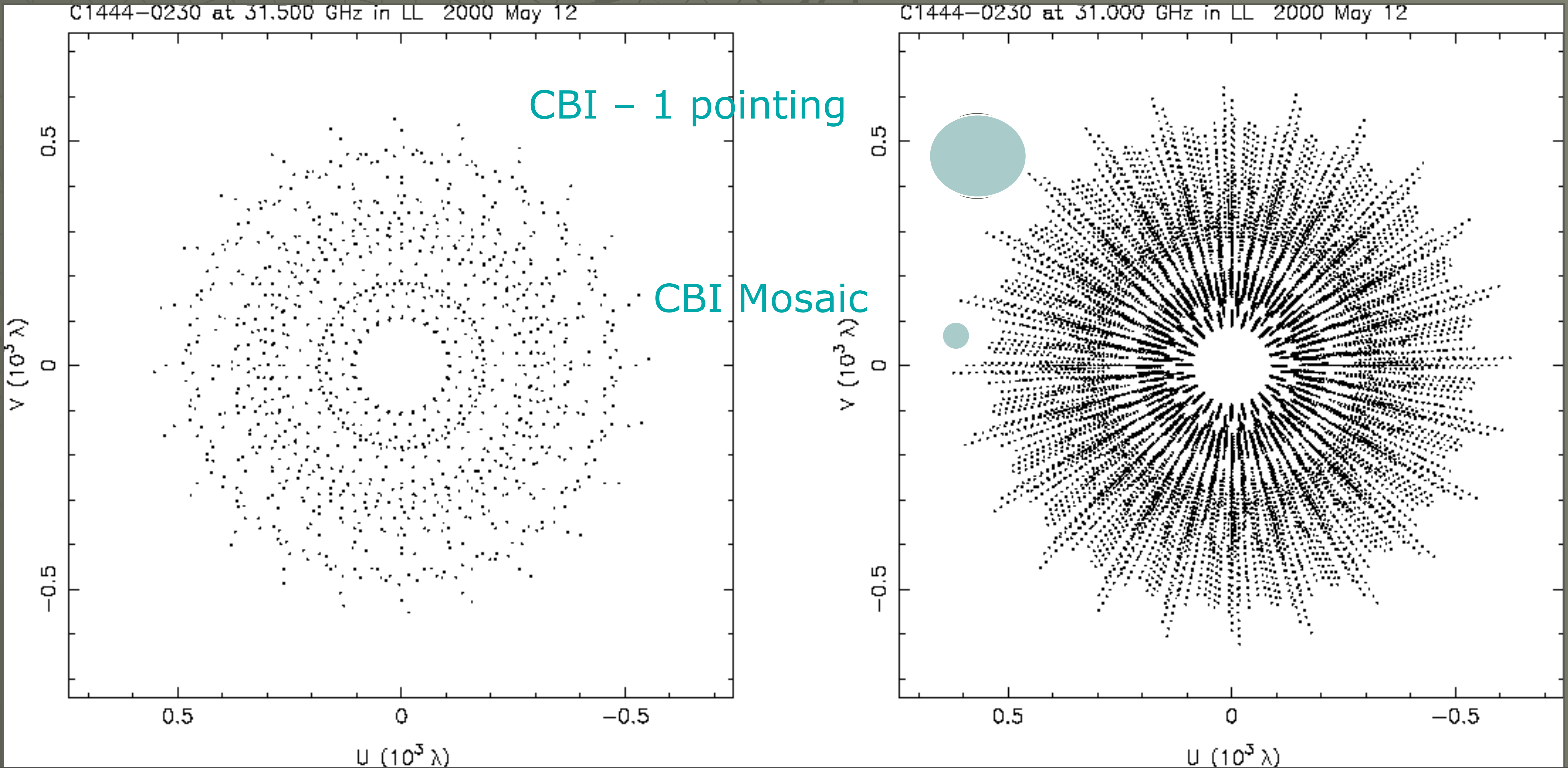
Mosaicing

- Big signal comes from having big dishes, but UV resolution is crappy. Solution: mosaicing.
- What mosaicing buys you: Fourier resolution is FT of area covered, so measure more modes, plus can resolve structure in power spectrum.
- What mosaicing doesn't buy you: ell coverage. The visibilities are instrinsically insensitive to low-ell (relative to dish size) modes. You will never get those modes with the interferometer.
- For this reason, a mosaiced interferometric map will never look like a total-power map on scales comparable to an larger than the primary beam. (again, tricks exist)

UV coverage with mosaic beam

Can get Fourier plane (also called *UV* plane by radio astronomers) resolution back by *mosaicing* – surveying a larger region of sky.

CBI has very dense uv coverage – measure all modes available to us.



Mosaic Phases

- If I point somewhere else, the UV coordinate is the same, however clearly the visibility is different.
- So, can't directly combine data from the different pointings in a mosaic.
- For power specrum, we scatter visibilities onto a grid, apply phase gradient set by pointing location. Gives pretty much optimal power spectrum.

Sometimes Missing Modes is Good!

- Any signal on scales larger than the primary beam gets thrown out - gets rid of most atmosphere, for instance.
- Any constant (or slowly varying) signals get tossed out - clears out many instrumental systematics.
- Gain fluctuations only hit visibilities, not total power, so they are a minor issue.
- Upshot: interferometers are very stable and resistant to systematic.

Sensitivity

- What is temperature at detector (T_{ant}), relative to temperature of structure? This is the fundamental question.
- One way: number of ripples a baseline sees is roughly dish size/separation. Will have roughly that many blobs (for a random field) along each stripe, adding incoherently. So, have # of stripes squared independent blobs, square root of that says sensitivity *per baseline* falls like dish-to-uv ratio.
- Could break up each dish into *n* smaller dishes. Then get n^2 as many baselines, for a wash - sensitivity set by collecting area. However, field of view larger, so we've actually won.
- radiometer equation: $\delta T/T=1/\sqrt{(Bt)}$, T=system temperature (noise), B=bandwidth, t=observing time, δT=measurement accuracy. $\delta T/T_{ant}$ is fractional measurement error.
- Compact arrays are most sensitive.

The Effect of Bandwidth.

Real interferometers must accept a range of frequencies (amongst other things, there is no power in an infinitesimal bandwidth)! So we now consider the response of our interferometer over frequency.

To do this, we first define the frequency response functions, G(ν), as the amplitude and phase variation of the signals paths over frequency.

Then integrate:

$$V = \frac{1}{\Delta\nu} \int_{\nu-\Delta\nu/2}^{\nu+\Delta\nu/2} I_\nu(\mathbf{s}) G_1(\nu) G_2^*(\nu) e^{2\pi i\nu\tau_g} \, d\nu$$

The Effect of Bandwidth.

If the source intensity does not vary over frequency width, we get

$$V = \iint I_\nu(\mathbf{s})\,\mathrm{sinc}(\tau_g \Delta\nu)\, e^{-2i\pi\nu_0\tau_g}\, d\Omega$$

where I have assumed the G(ν) are square, real, and of width $\Delta\nu$. The frequency ν_0 is the mean frequency within the bandwidth.

The fringe attenuation function, sinc(x), is defined as:

$$\mathrm{sinc}(x) = \frac{\sin(\pi x)}{\pi x}$$

$$\approx 1 - \frac{(\pi x)^2}{6} \qquad \text{for } x \ll 1$$

The Bandwidth/FOV limit

This shows that the source emission is attenuated by the function sinc(x), known as the 'fringe-washing' function. Noting that $\tau_g \sim (B/c) \sin(\theta) \sim B\theta/\lambda\nu \sim (\theta/\theta_{res})/\nu$, we see that the attenuation is small when

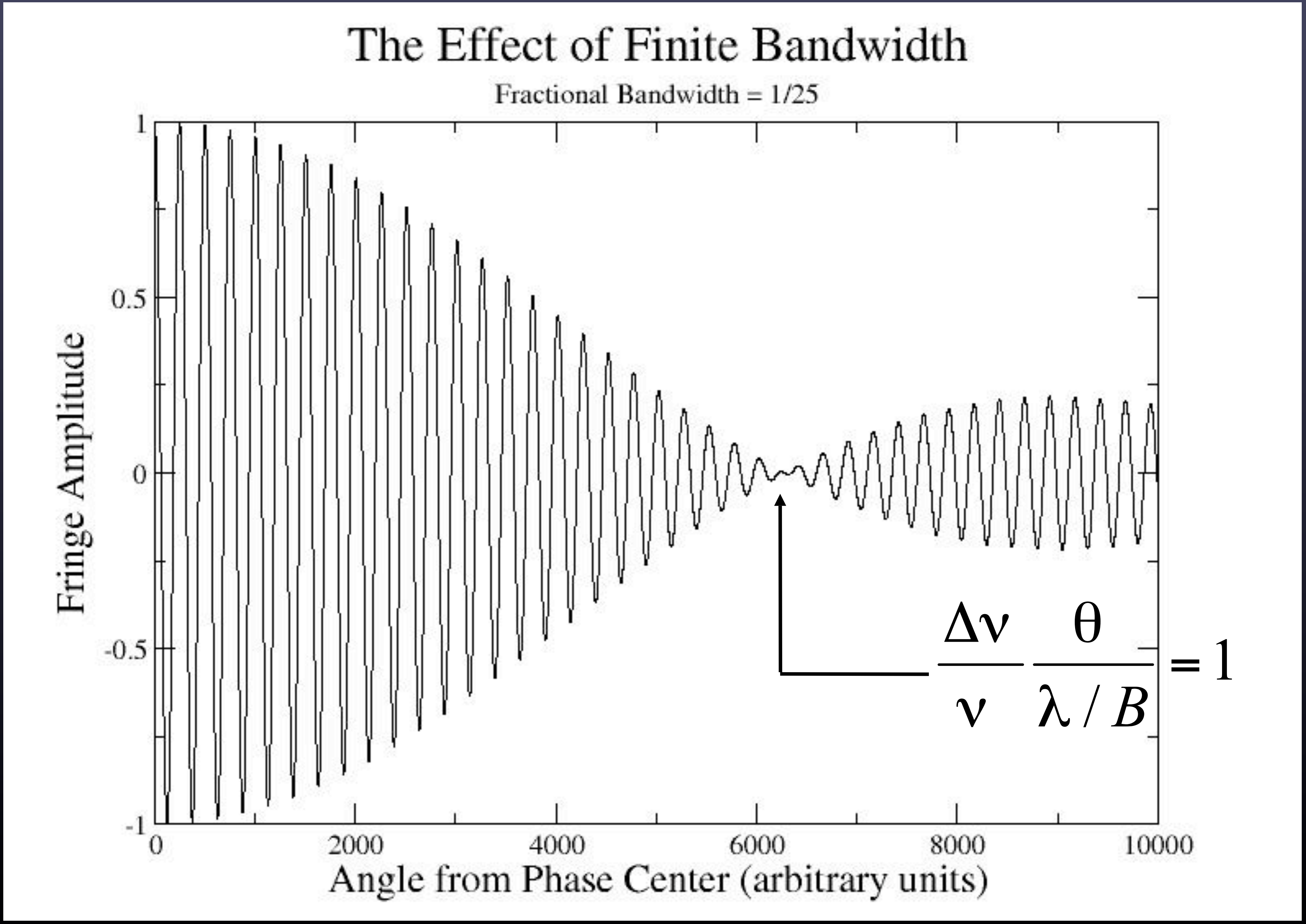
$$\frac{\Delta\nu}{\nu}\frac{\theta}{\theta_{res}} << 1$$

The ratio $\Delta\nu/\nu$ is the fractional bandwidth. The ratio θ/θ_{res} is the source offset in units of the fringe separation, λ/B.

In words, this says that the attenuation is small if the fractional bandwidth times the angular offset in resolution units is less than unity. Significant attenuation of the measured visibility is to be expected if the source offset is comparable to the interferometer resolution divided by the fractional bandwidth.

Bandwidth Effect Example

Finite Bandwidth causes loss of coherence at large angles, because the amplitude of the interferometer fringes are reduced with increasing angle from the delay center.



Summary of Basics

- Interferometer measures FT of sky over a patch set by the antenna pattern of the dishes.
- Because interferometers don't measure all spatial modes, making maps is an art. However, data lives natively in Fourier plan, has a simple relation to power spectrum.
- Sensitivity generally lower than equivalent total-power experiment because visibilities average over structures.
- Stability is generally much better.
- For PS work, generally cover large areas to beat down cosmic variance, ell resolution. Not for ell range.
- Generally need lots of frequency channels. CBI uses 10, big projects can use hundreds to thousands.

The Cosmic Background Imager

The Cosmic Background Imager is…

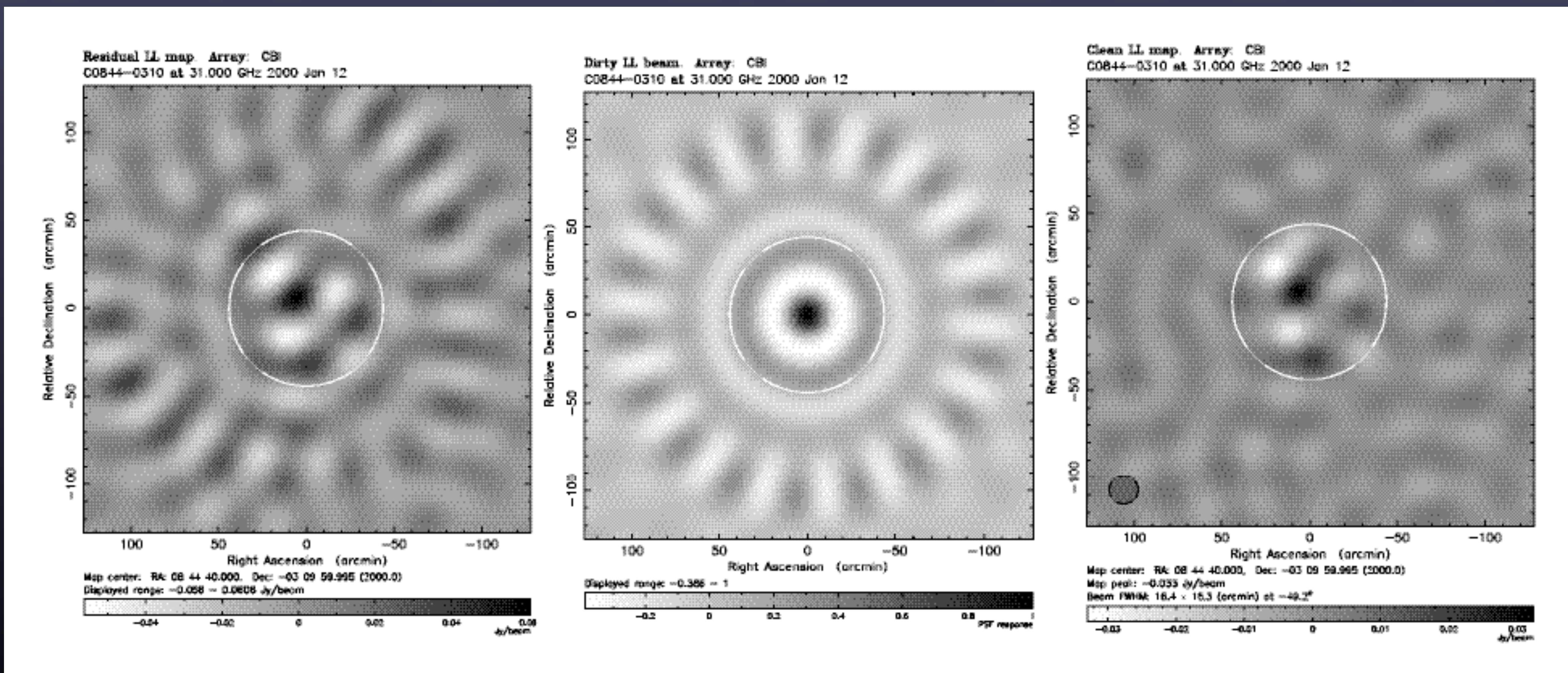
- 13 90-cm Cassegrain antennas
  - 78 baselines
- 6-meter platform
  - Baselines 1m – 5.51m
  - <u>reconfigurable</u>
- 10 1 GHz channels 26-36 GHz
  - HEMT amplifiers (NRAO)
  - Tnoise 8K, Tsys 15 K
- Single polarization (R or L)
  - U. Chicago polarizers < 2% leakage
- Analog correlators
  - 780 complex correlators
  - pol. product RR, LL, RL, or LR
- Field-of-view 44 arcmin
  - Image noise 4 mJy/bm 900s
- Resolution 4.5 – 10 arcmin

CMB Interferometer – the CBI

- Antennas fixed to <u>3-axis</u> platform (alt, az, deck)
  - rotate deck to rotate baselines ➔ telescope rotation synthesis!

CBI Beam

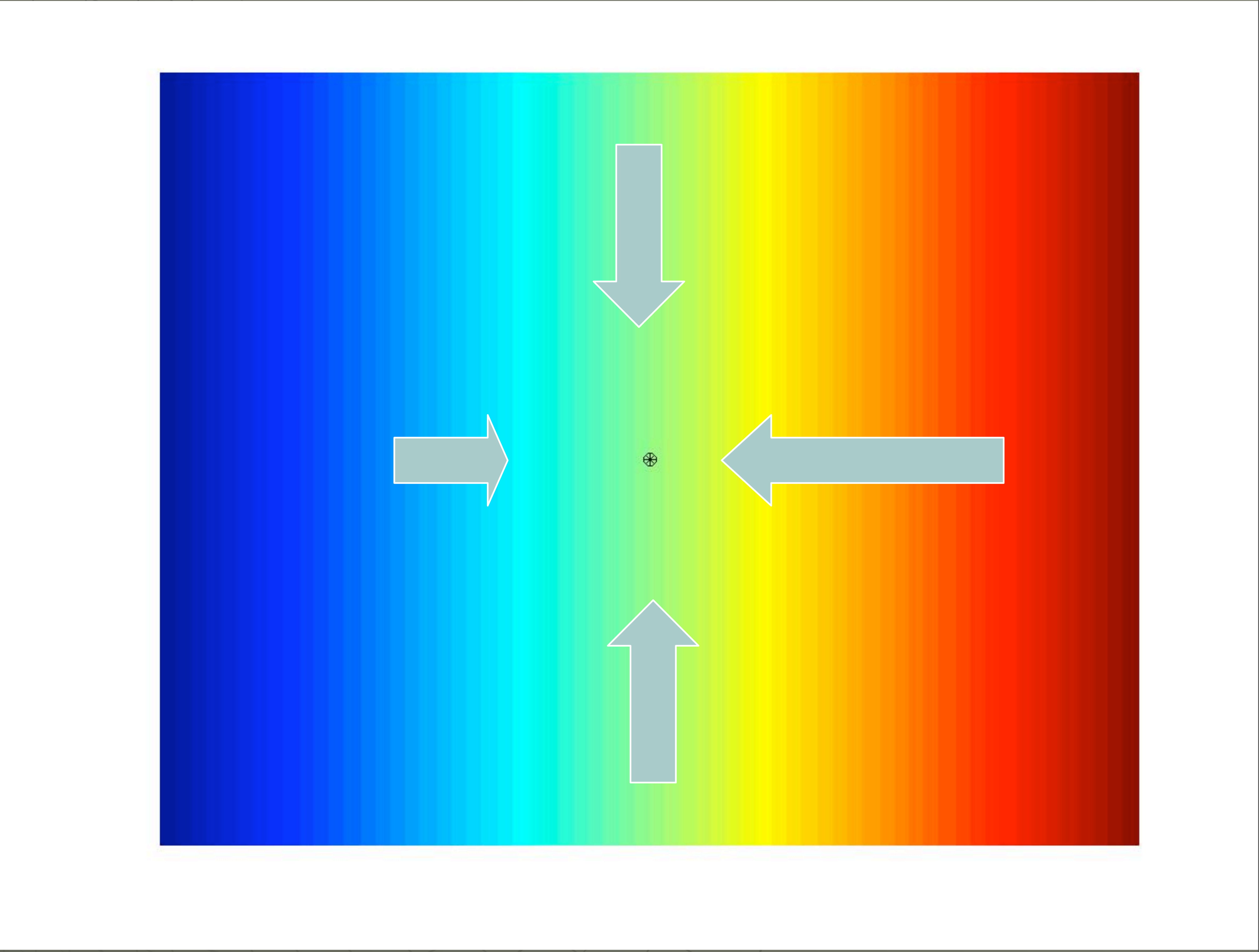
- Rotate pointing platform to fill in *uv* coverage
  - Beam nearly circularly symmetric



Dipole Gives No Pol'n

How does an electron jiggle in a radiation field?

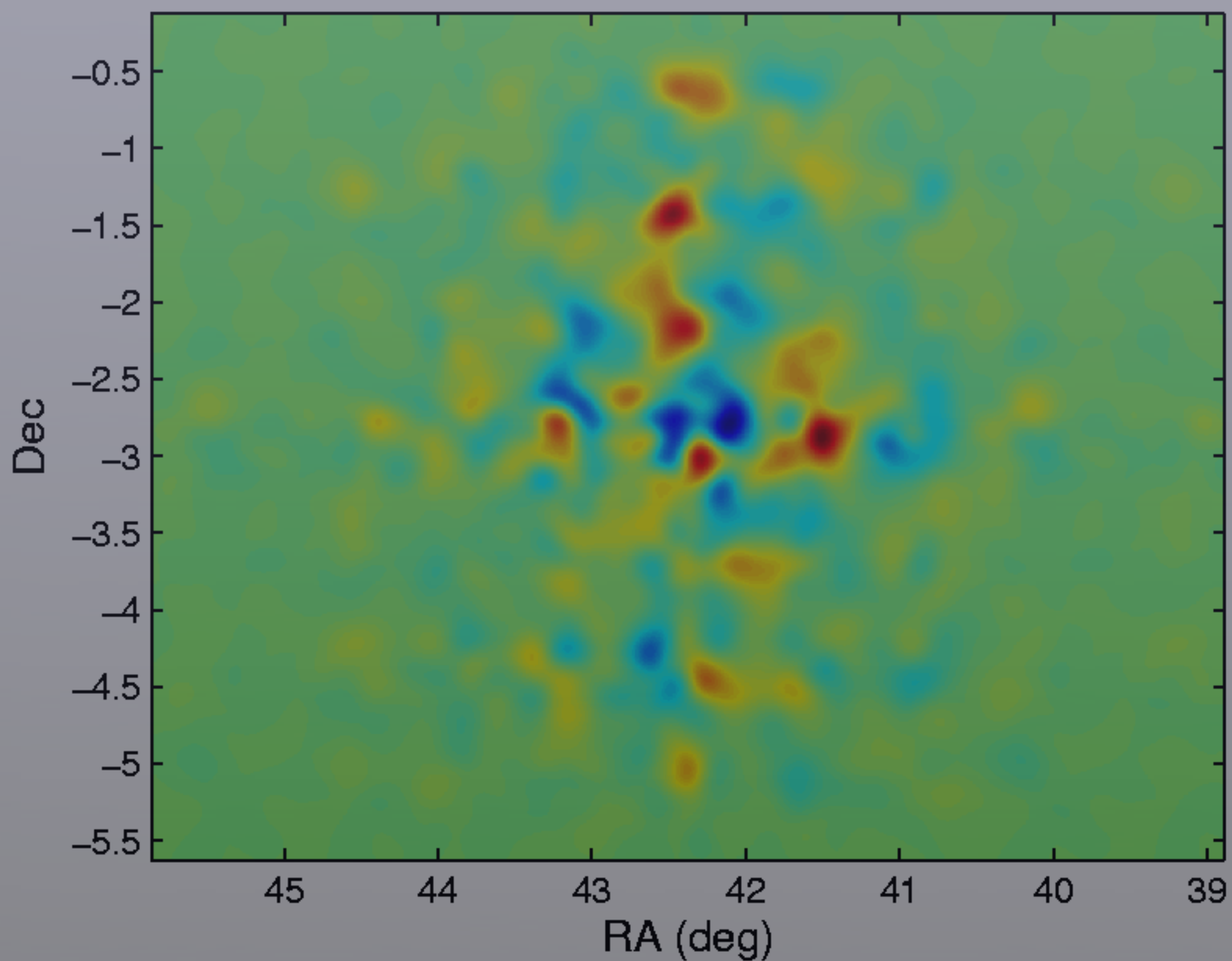
- No net extra radiation from left/right or top/bottom, so no polarization
- Doppler shift makes dipole pattern, so moving electron in an isotropic field has no polarization.



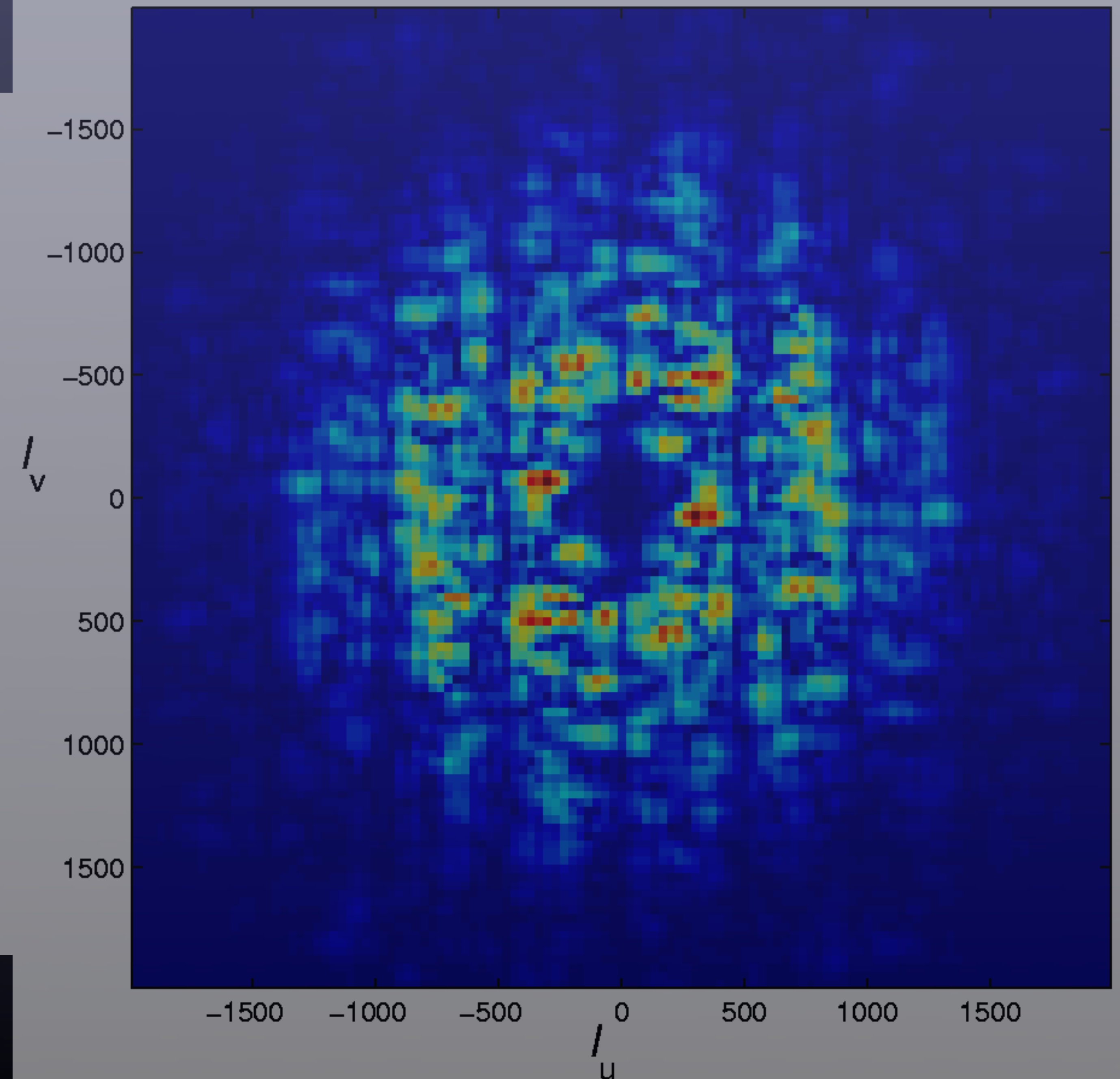
ℓ-space maps

- use gridded visibilities to reconstruct T,E,B in ℓ-space

CBI 02h 6x6 field T mosaic

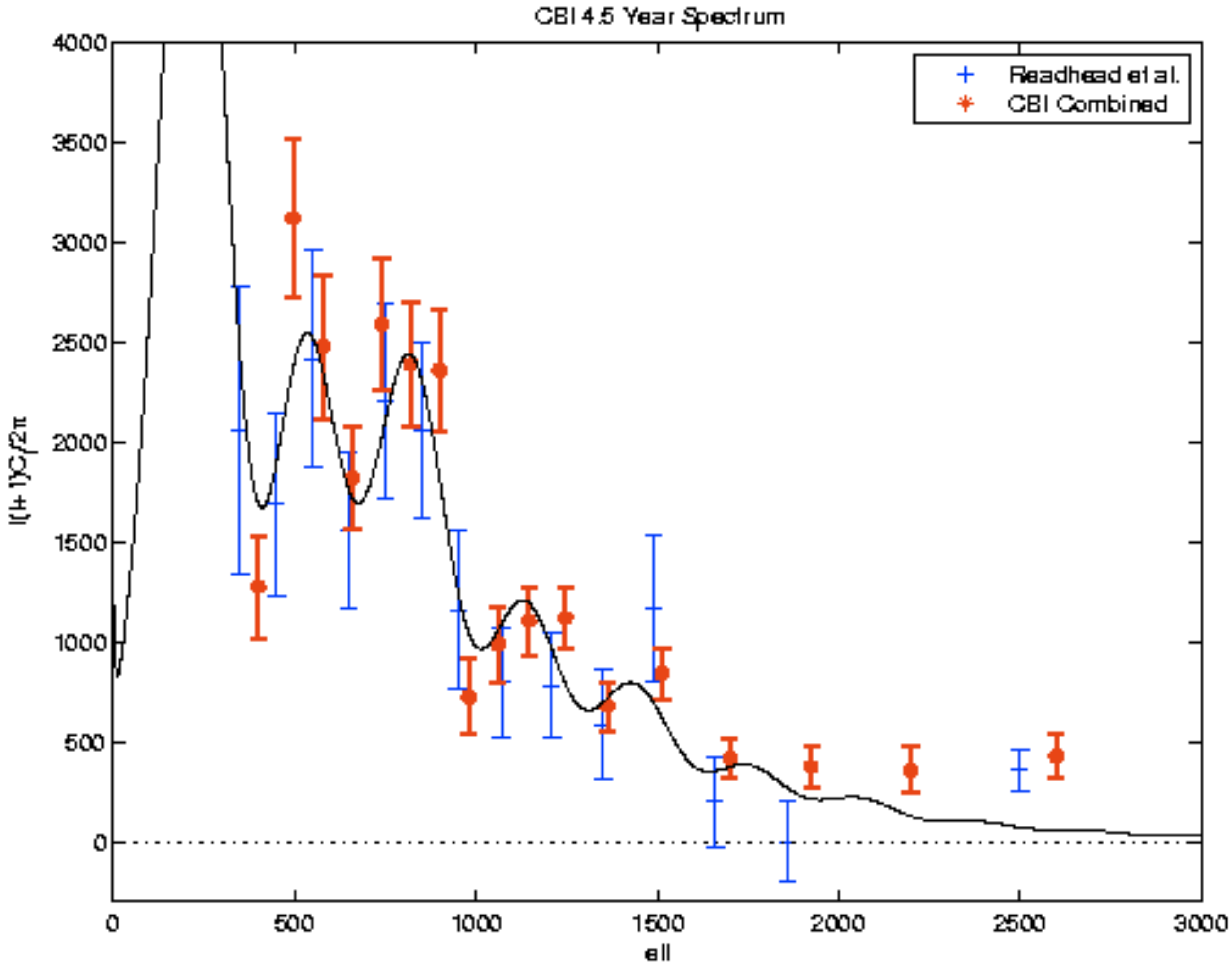


T image ⇔ $\ell\, T_\ell$



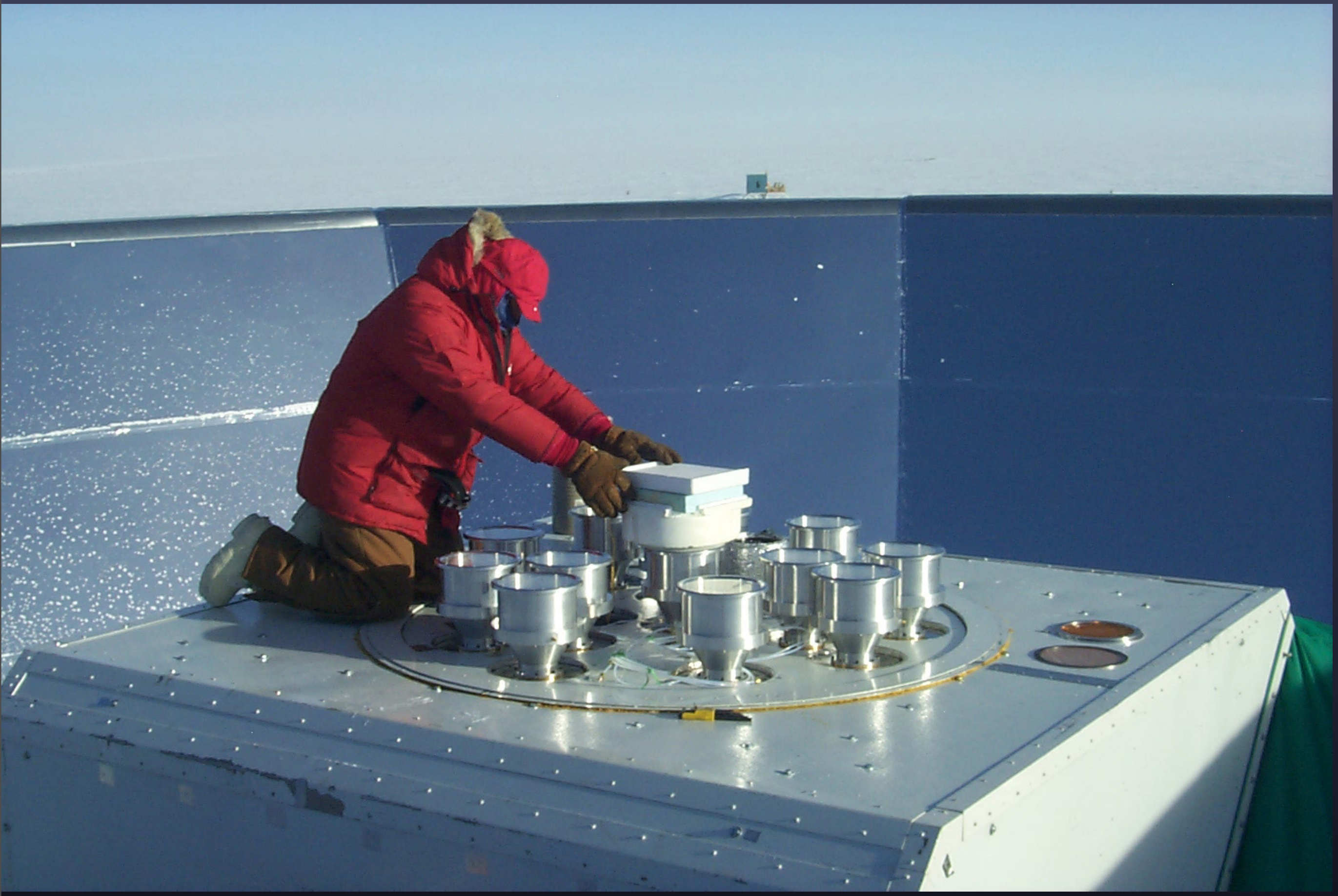
ℓ -space CLEAN deconvolved!

New CBI Spectrum!



Other CMB Interferometers: DASI, VSA

- DASI @ South Pole



- VSA @ Tenerife

Also CAT, BIMA, Ryle, MINT
Future: Amiba, SZA, ALMA?

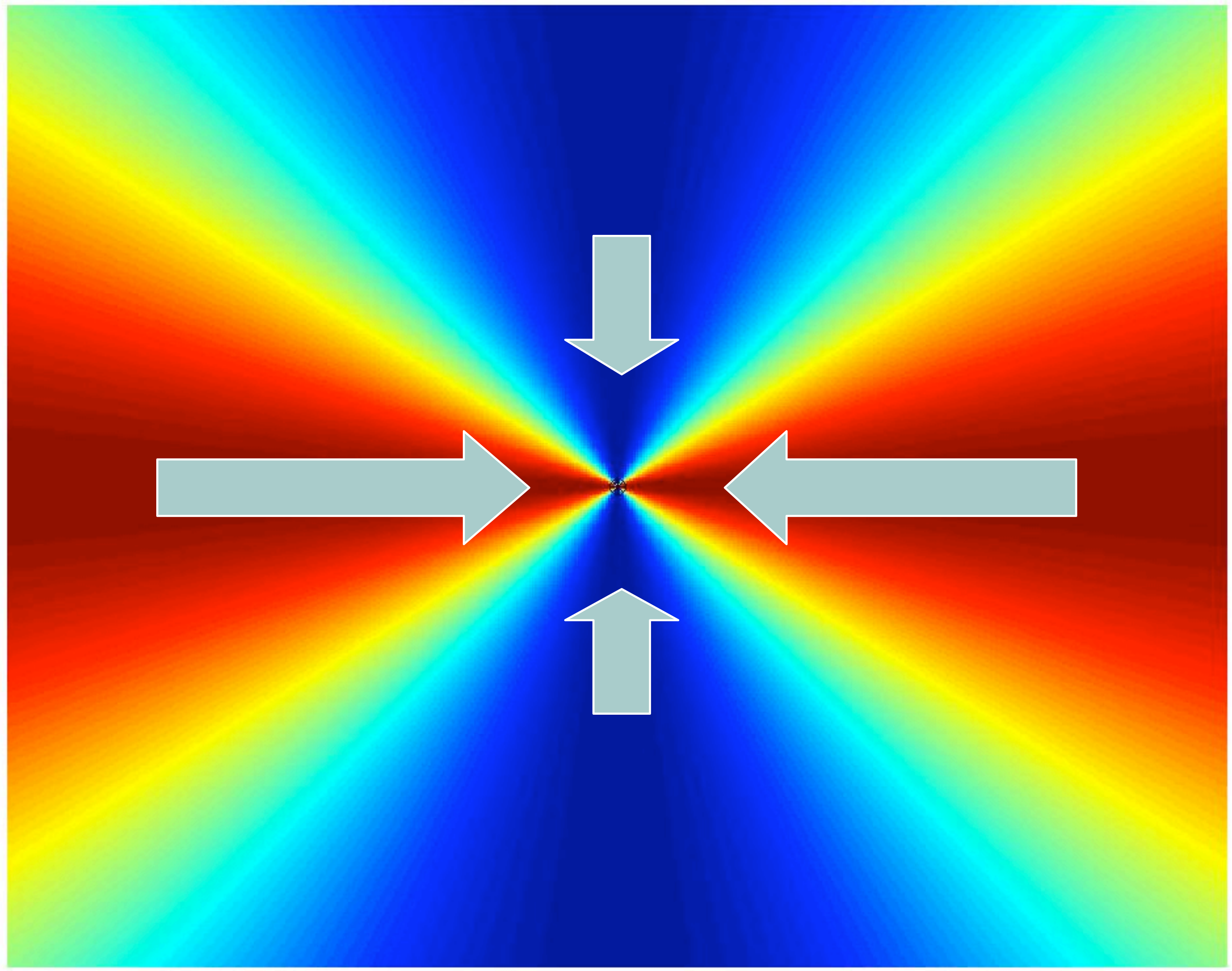
CMB Polarization

CMB is polarized. What's going on?

Anisotropic intensity scattering gives linear polarization (why you may have polarized sunglasses).

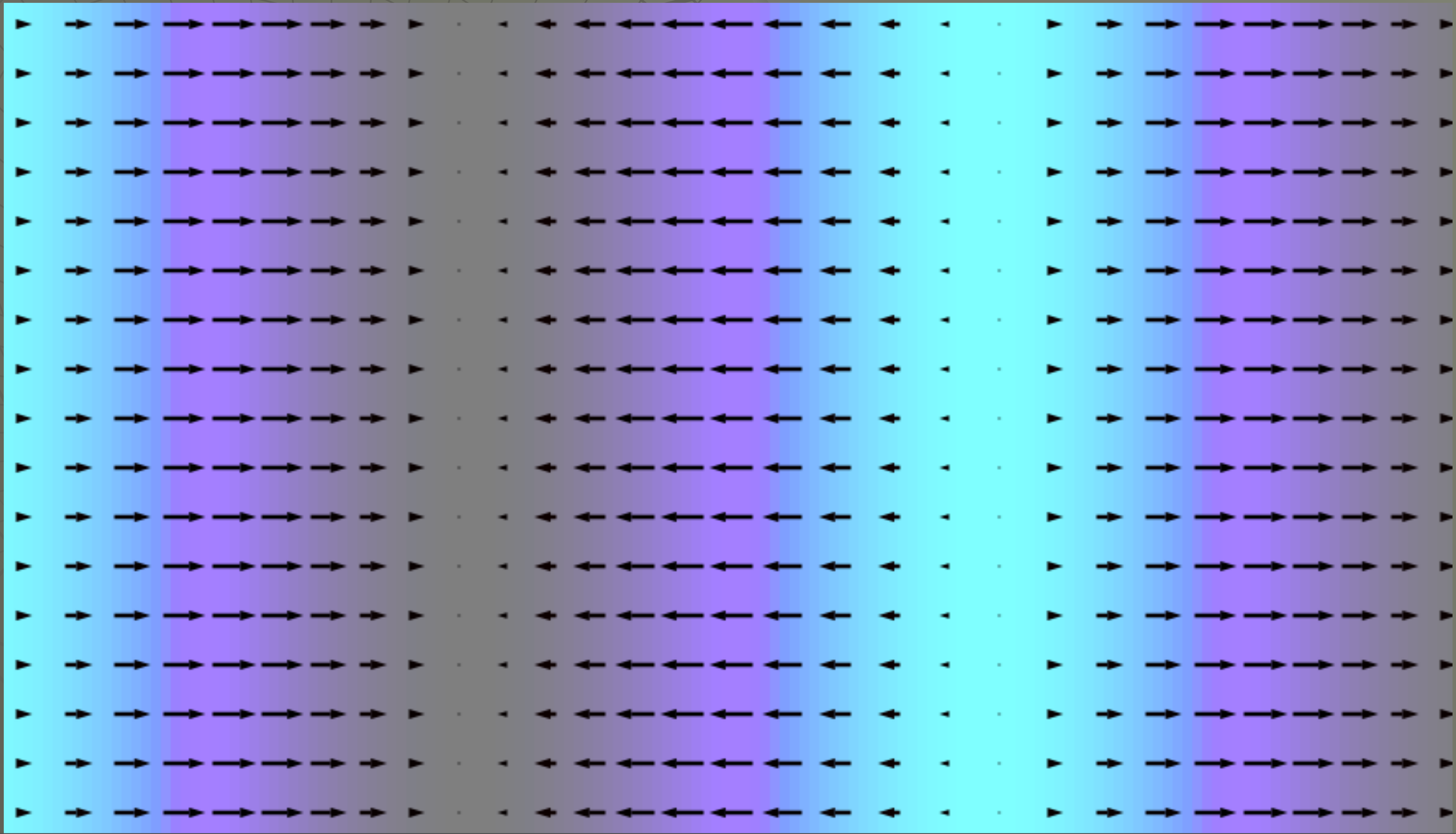
Quadrupole

- More radiation from left/right than top/bottom. Electron moves up/down, and so scattered radiation is polarized.



Polarization

If the flow is converging, electron moves perp. to *k*. If diverging, electron moves parallel to *k*. *But it never moves at an angle*. This is E-mode polarization (B-mode is the polarization tilted by 45 degrees for the same *k*). E peaks where velocity is maximum and overdensity zero, so E out of phase with intensity spectrum. Also, waves at neither density nor velocity null give rise to T and E, causing a correlation.



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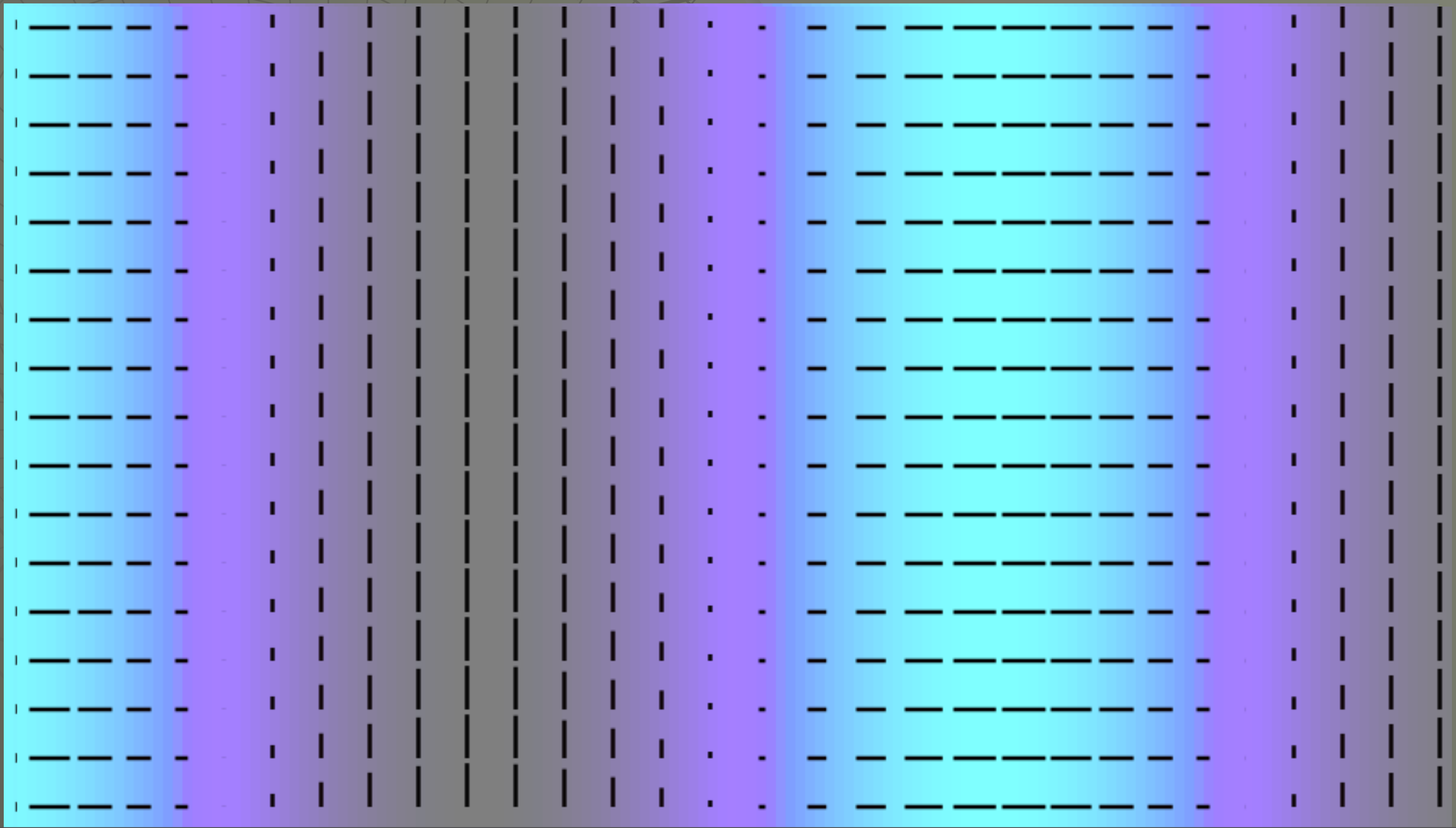

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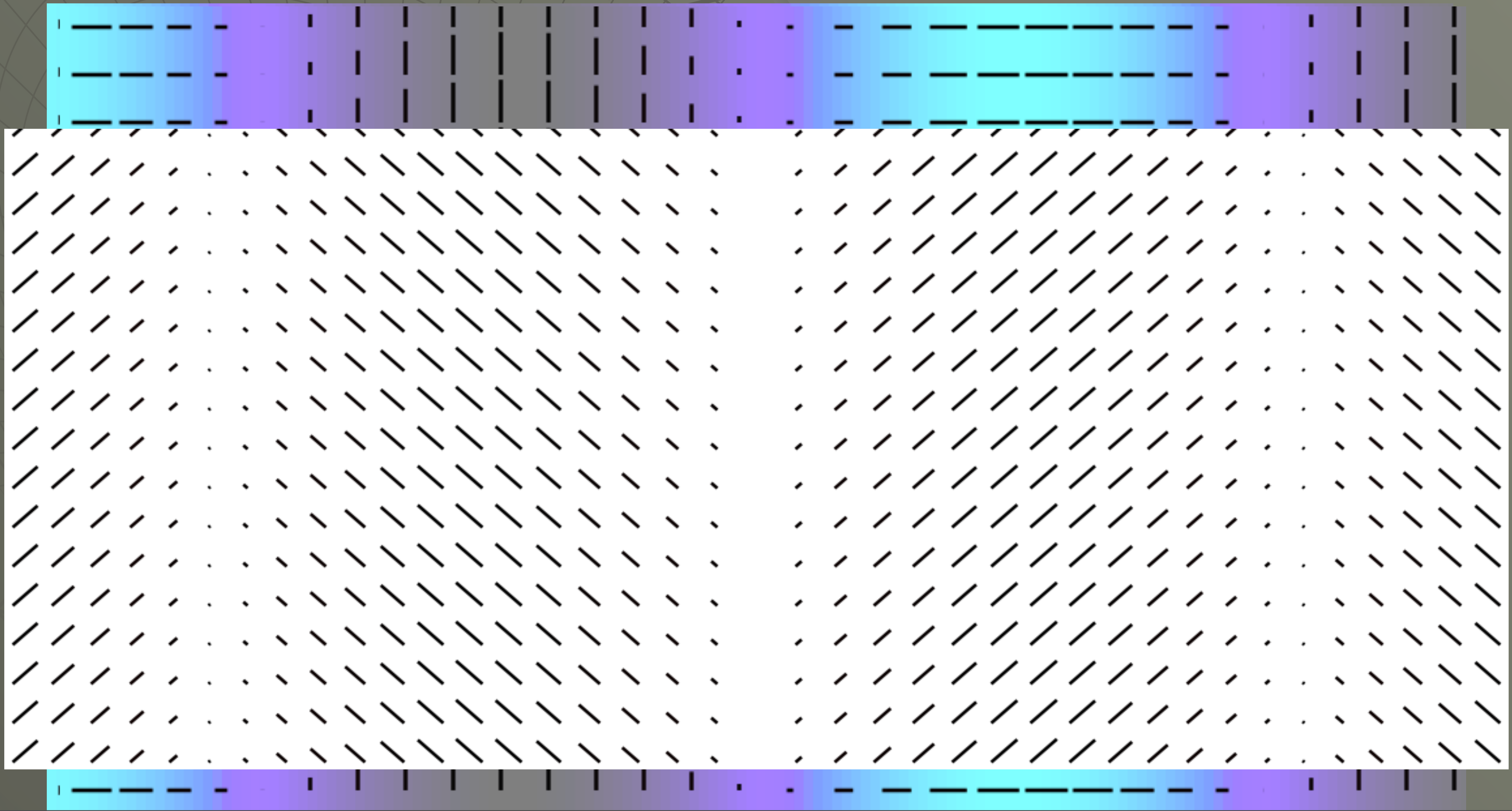


Polarization – Stokes parameters

- CBI or VLA receivers can observe RCP or LCP
  - cross-correlate RR, RL, LR, or LL from antenna pair
- Correlation products (RR,LL,RL,LR) to Stokes (I,Q,U,V) :

$$\begin{pmatrix} \langle e_R \, e_R^* \rangle \\ \langle e_R \, e_L^* \rangle \\ \langle e_L \, e_R^* \rangle \\ \langle e_L \, e_L^* \rangle \end{pmatrix} = \begin{pmatrix} I + V \\ (Q + iU) e^{-i2\theta} \\ (Q - iU) e^{i2\theta} \\ I - V \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 1 \\ 0 & e^{-i2\theta} & ie^{-i2\theta} & 0 \\ 0 & e^{i2\theta} & -ie^{-i2\theta} & 0 \\ 1 & 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

- note – similar relation for XY feeds

E and B modes

- Decomposition into E and B Fourier modes:

$$\widetilde{Q}(\mathbf{v}) + i\,\widetilde{U}(\mathbf{v}) = \left[\widetilde{E}(\mathbf{v}) + i\,\widetilde{B}(\mathbf{v})\right] e^{i2\div_{\mathbf{v}}}$$

$$\widetilde{E}(\mathbf{v}) + i\,\widetilde{B}(\mathbf{v}) = \left|\widetilde{P}(\mathbf{v})\right| e^{i2\left[\phi(\mathbf{v}) - \div_{\mathbf{v}}\right]}$$

$$\chi_{\mathbf{v}} = \tan^{-1}\left(v/u\right)$$

E : ϕ-χ=0,π/2

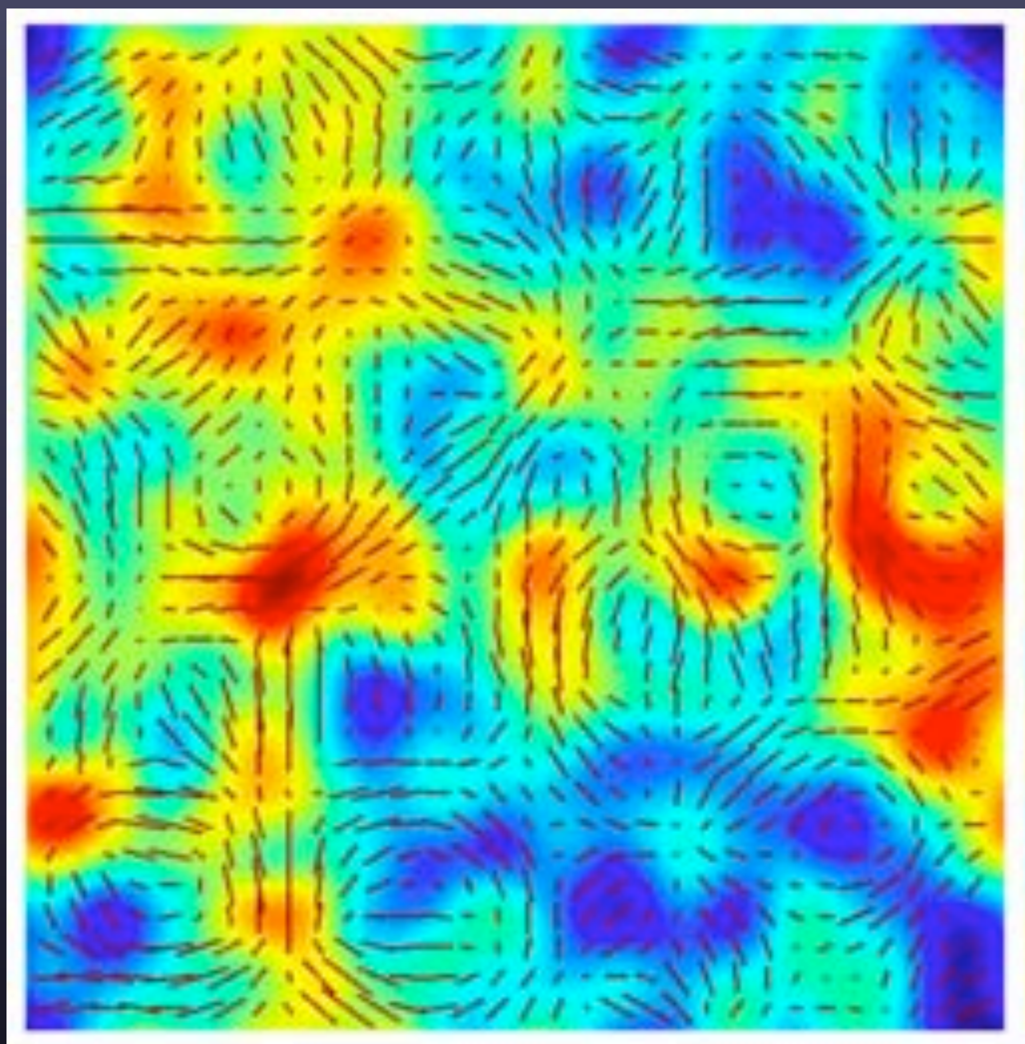
B : ϕ-χ=$\pm\pi$/4

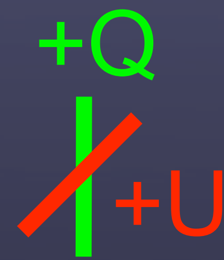
E and B measure alignment of plane-wave polarization with wave vector

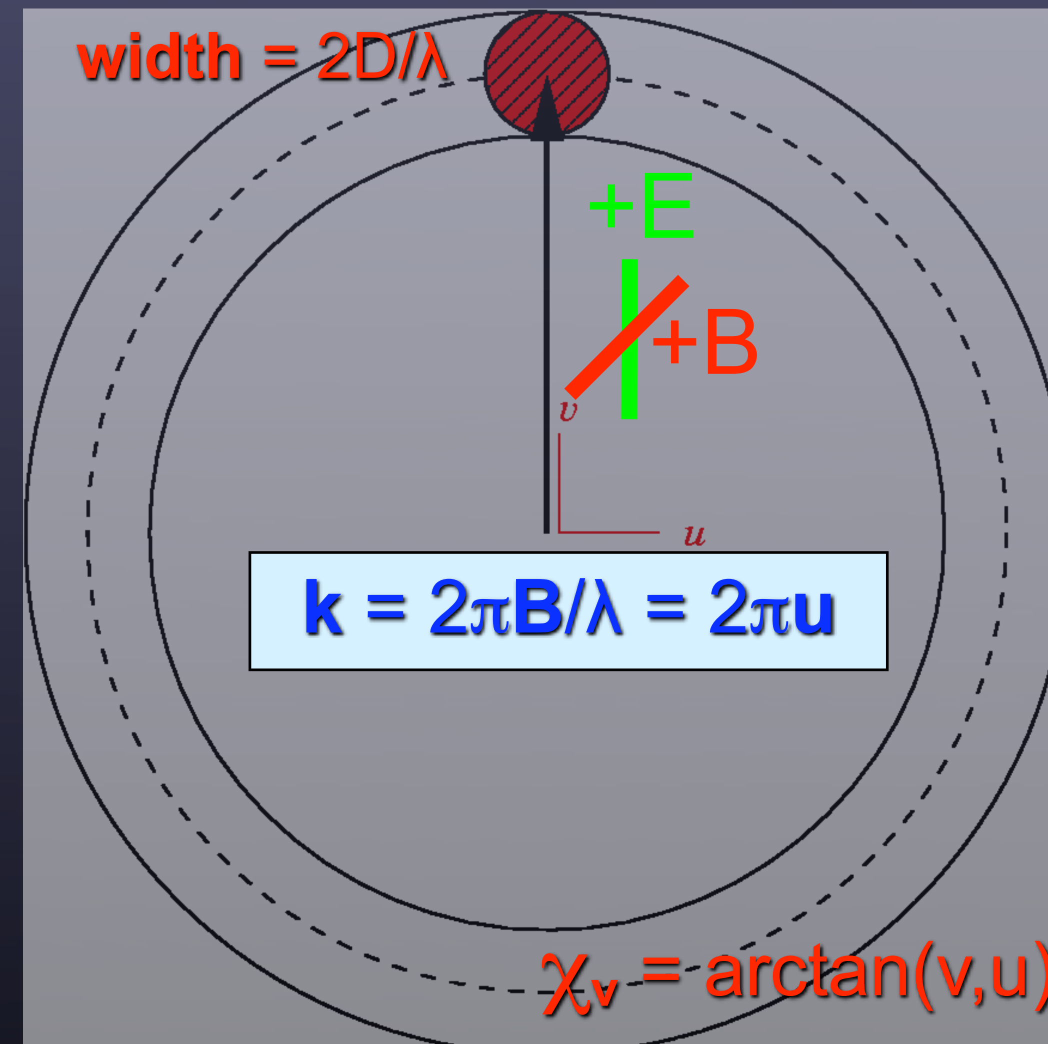
Q,U Cartesian vs. E,B polar coordinate frame in uv-plane

Polarization Interferometry : E & B

Stokes Q,U in image plane transform to E,B in uv-plane







$$Q + i\,U = [\,E + i\,B\,]e^{i2\chi_v}$$

$$V_k^{RL}(\mathbf{u}_k) = \int d^2\mathbf{u}\,\widetilde{A}_k^{RL}(\mathbf{u}_k - \mathbf{u})[\widetilde{E}(\mathbf{u}) + i\,\widetilde{B}(\mathbf{u})]\,e^{i2(\chi_v - \chi_k)}\,e^{2\pi\, i\mathbf{u}\cdot\mathbf{x}_k}$$

RL interferometer “directly” measures E & B in Fourier domain!

E & B Mode Images

Grid visibilities into ℓ-space estimators (e.g. Myers et al. 2003).

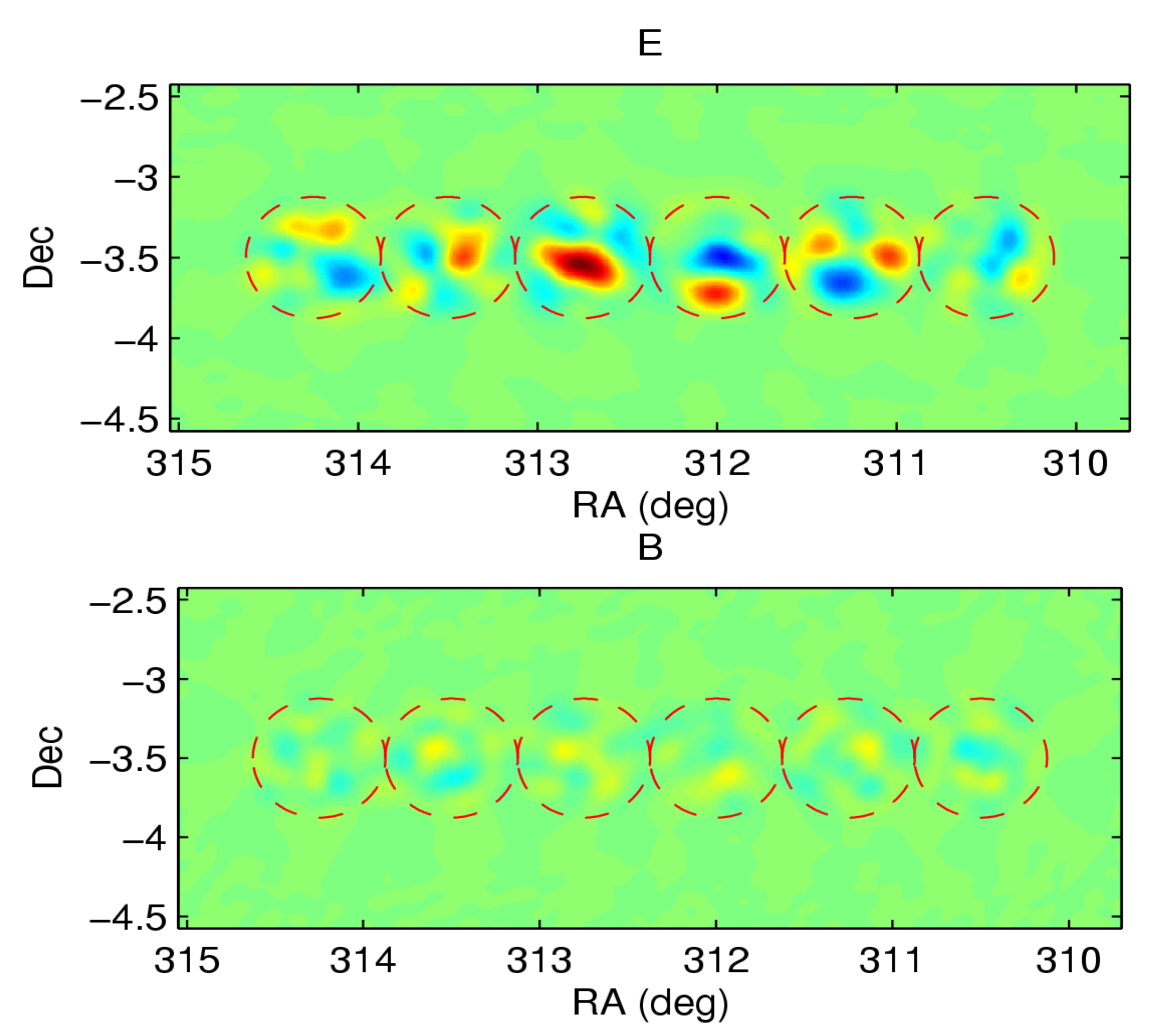
Variance of E in raw data 2.45 times B (ℓ<1000). B is consistent with noise.

Mixing between E,B Is ~5% in power.

NOTE: <u>Peaks in E/B are not peaks in P!</u>

Sievers et al. 2007

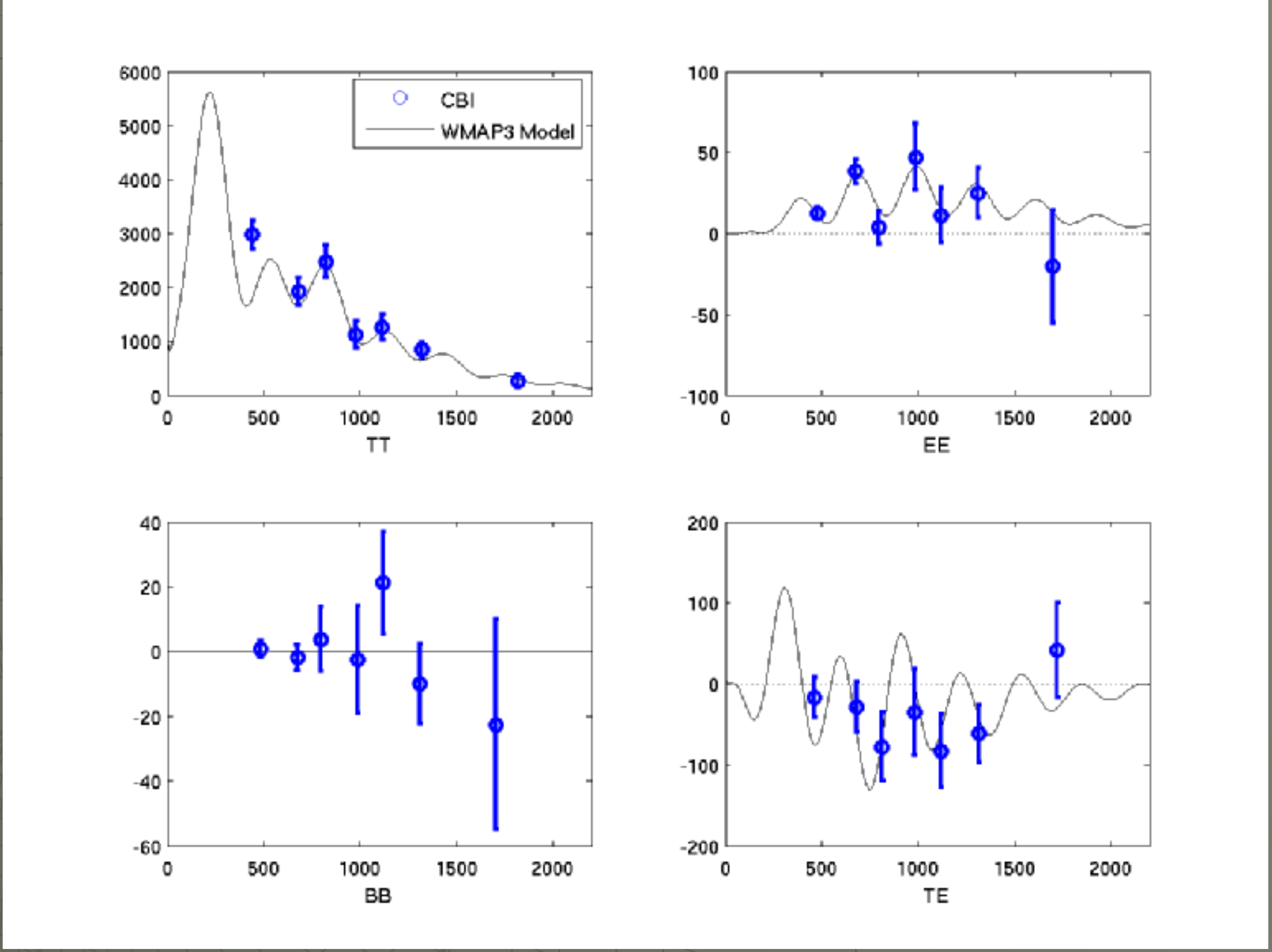
CBI 20h strip: gridded FT($E + i\,B$) transformed to image



Very Clean Exp’t

CBI polarization. Required virtually no filtering/ cleaning. Note axes on EE/BB 50-100x smaller than TT. Black curves *prediction* from WMAP TT.

Amplitude vs. (all) TT prediction:
TT=1.12+/-0.05
EE=1.02+/-0.14
TE=1.02+/-0.24
BB=0.22+/-1.55
(BB=μK)



JLS et al. astro-ph/ 0509203

Polarization Summary

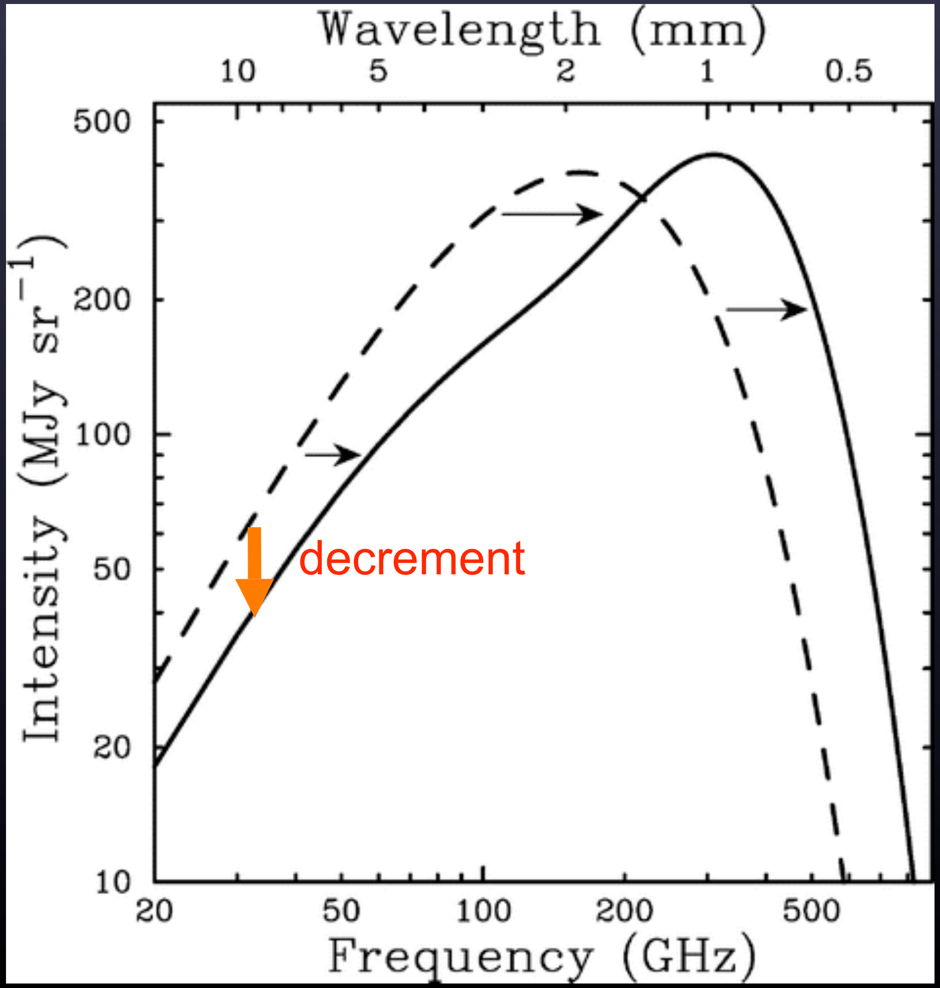
- CMB is polarized. For a given plane wave, we expect statistics of polarization along/perpenicular to wave vector (E-mode) to differ from statistics of pol’n tilted 45 to wave vector (B-mode).
- Interferometer measures things that are simply related to E and B. Can trivially make maps that have E and not B in them.
- We never subtract two large quantities - again, stability to gain fluctuations. Extremely useful.
- Stability/direct E/B measurement meant fast data analysis - 5 months from last pol’n data to astro-ph, vs. typically years for total power expts.

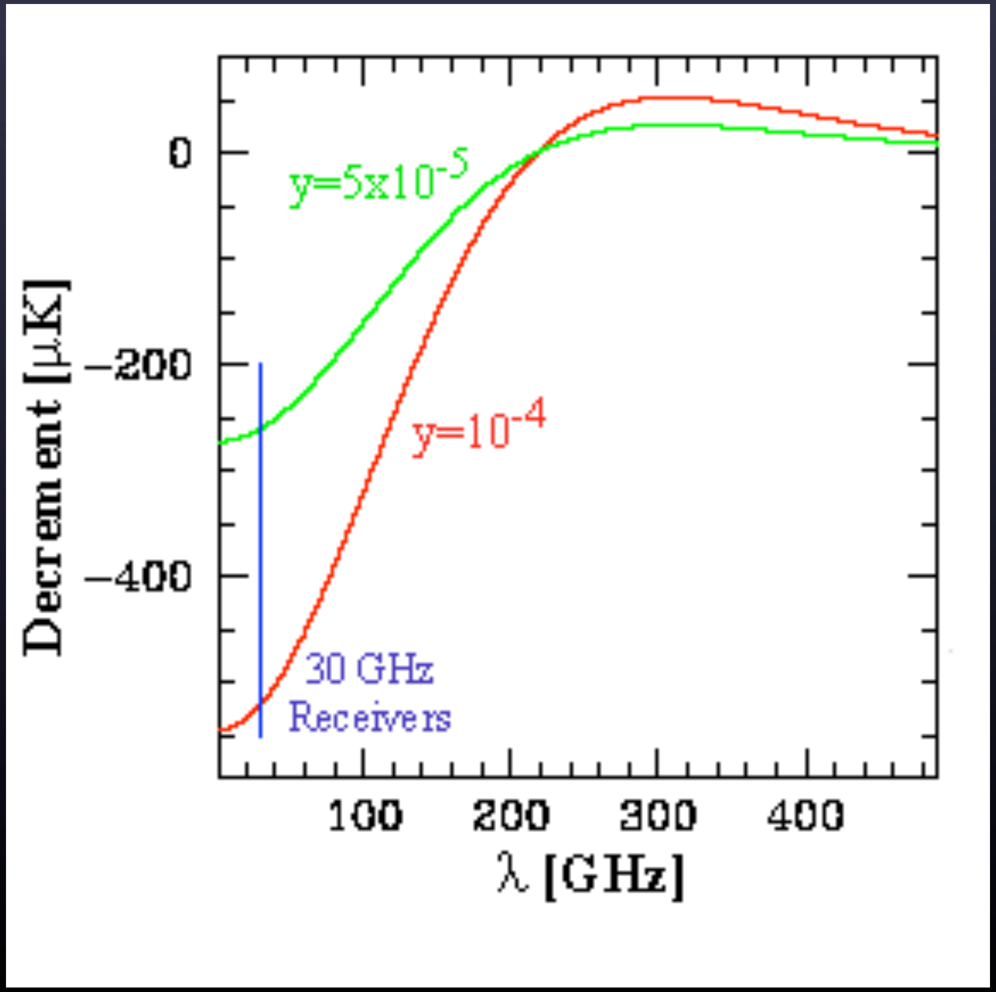
Some More Interferometer Pros:

- Generally, don’t need to scan to reject atmosphere. So, much easier to sit and stare at a point on the sky.
- Stability means long integrations aren’t much more difficult than short ones.
- Generally easier to calibrate and measure beams than for total power. (synthesized beam set by antenna locations, which hopefully aren’t moving)
- So, interferometers good for measuring targeted objects, especially if they are relatively bright.
- Makes interferometers excellent choice for observing --

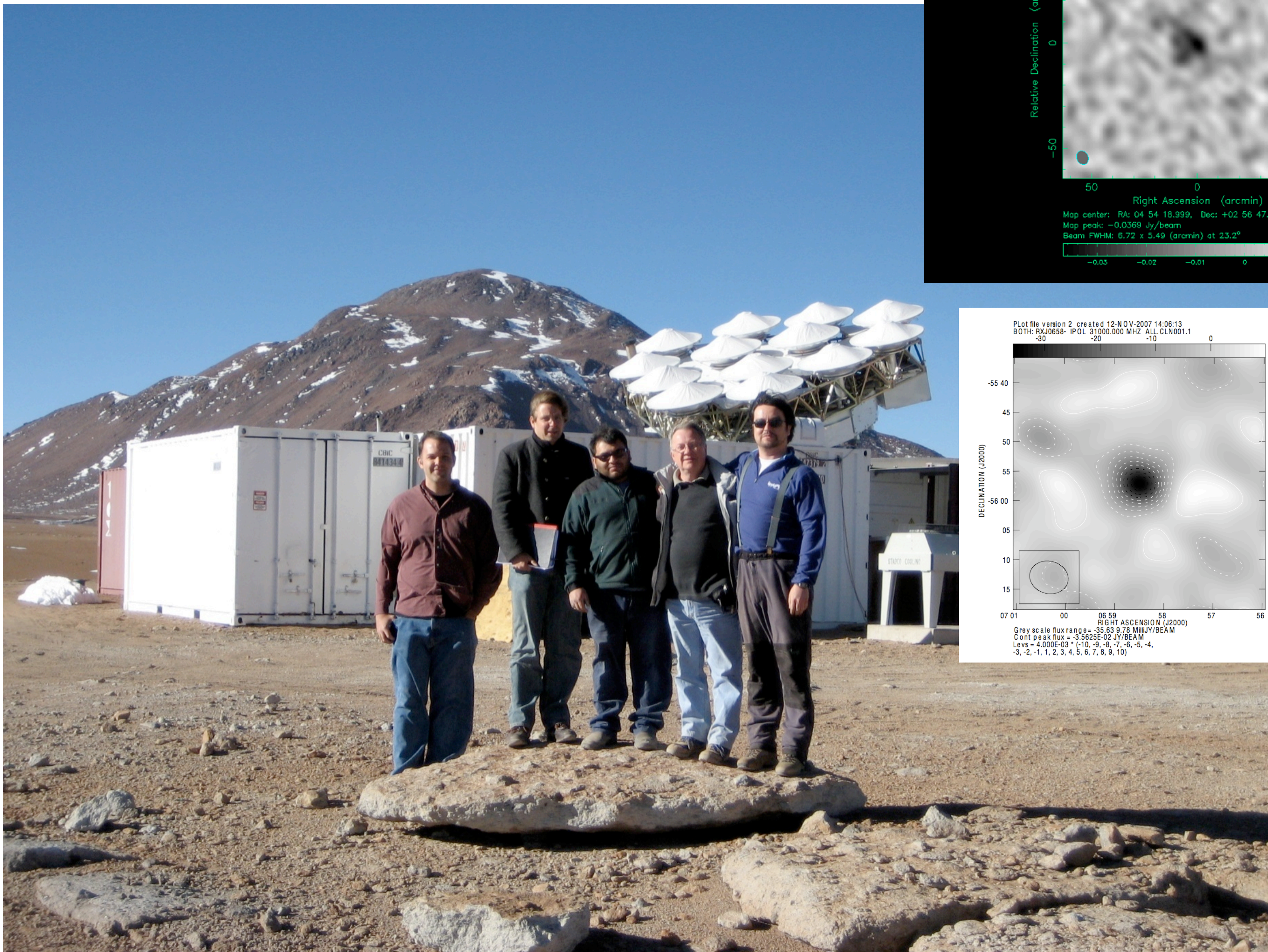
The SZE

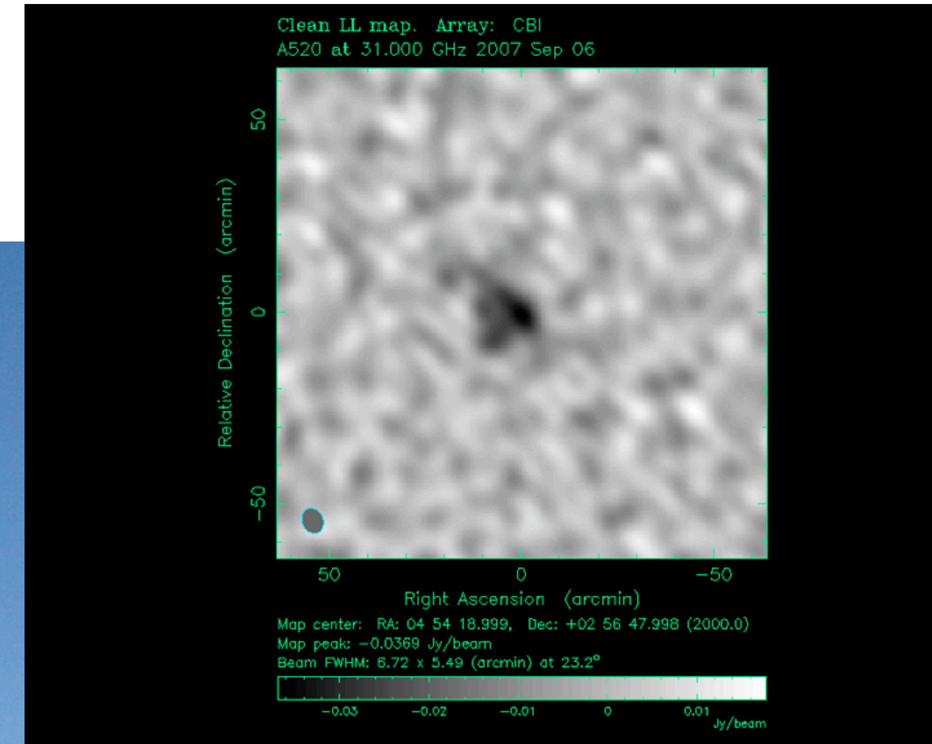
- The Sunyaev-Zeldovich Effect
  - Compton upscattering of CMB photons by keV electrons
  - decrement in I below CMB thermal peak (increment above)
  - negative extended sources (absorption against 3K CMB)
  - massive clusters mK, but shallow profile $\theta^{-1} \rightarrow$ -exp(-v)



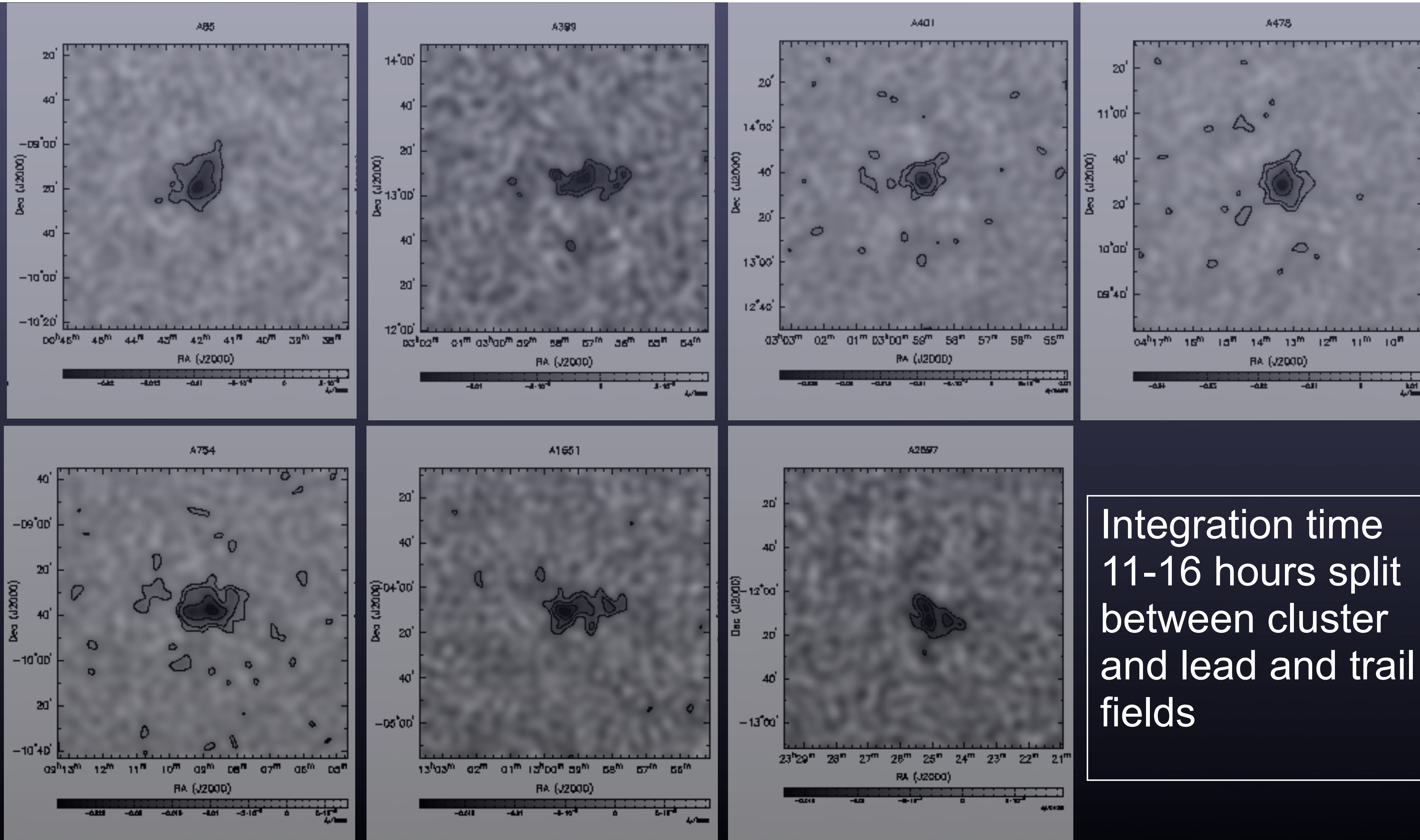


CBI2@5080m


PLot file version 2 created 12-NOV-2007 14:06:13
BOTH: RXJ0658- IPOL 31000.000 MHZ ALL.CLN001.1
-30
-20
-10
0
DECLINATION (J2000)
-55 40
45
50
55
-56 00
05
10
15
07 01
00
06 59
58
57
56
RIGHT ASCENSION (J2000)
Grey scale flux range= -35.63 9.78 MilliJY/BEAM
Cont peak flux = -3.5625E-02 JY/BEAM
Levs = 4.000E-03 * (-10, -9, -8, -7, -6, -5, -4,
-3, -2, -1, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10)


Clean LL map. Array: CBI
A520 at 31.000 GHz 2007 Sep 06
Relative Declination (arcmin)
50
0
−50
Right Ascension (arcmin)
Map center: RA: 04 54 18.999, Dec: +02 56 47.998 (2000.0)
Map peak: −0.0369 Jy/beam
Beam FWHM: 6.72 x 5.49 (arcmin) at 23.2°
−0.03
−0.02
−0.01
0
0.01
Jy/beam

CBI SZ cluster gallery



Integration time 11-16 hours split between cluster and lead and trail fields

Udomprasert, Mason, Readhead, & Pearson 2004, *ApJ.*, **615**, 63-81

Interferometers and the SZE

- Most SZ detections have come from interferometers. Easy for them to throw most of their sensitivity on the cluster.
- CBI has several dozen at this point, ovro/bima and SZA (both Carlstrom) have many dozen.
- Single frequency, large scales, CMB is largest noise.
- Would like to combine frequencies for CMB rejection, different arrays for angular scale coverage.
- CBI gets a good detection on a reasonably bright (500 uK) cluster in a few hours.

Down the road...

- QUIET is array of correlating detectors, will be observing CMB on CBI mount in matter of months.
- ALMA is the big daddy - esp. if gets 30 GHz system, will clean up on clusters.
- High-z 21cm being done with interferometers (lofar, gmrt, mwa...)
- Further down the road, SKA (square kilometer array) will do insane things.

Summary

- Interferometers directly measure the Fourier Transform of the sky, smoothed by the primary beam.
- Many pros: instrumental stability, rejection of atmosphere/systematics, clean polarization measurement.
- Two main cons: sensitivity (since visibilities average over structure) and difficulty/cost of n2 correlations for huge arrays (though cost coming down?).
- Interferometers well suite for measuring Sunyaev-Zelovich effect.
- By far best way for high resolution longwards of optical-type wavelengths. Several major interferometric arrays underway.

Possible Discussion Topics

- Gridding mosaiced visibilities onto a single plane
- Maximum likelihood powe spectrum estimation
- Dealing with point sources in the data
- Mapmaking techniques

CBI *uv* coverage

- 78 baselines and 10 frequency channels = 780 instantaneous visibilities

1 channel, 15° deck rotations

10 channels – fill in radially