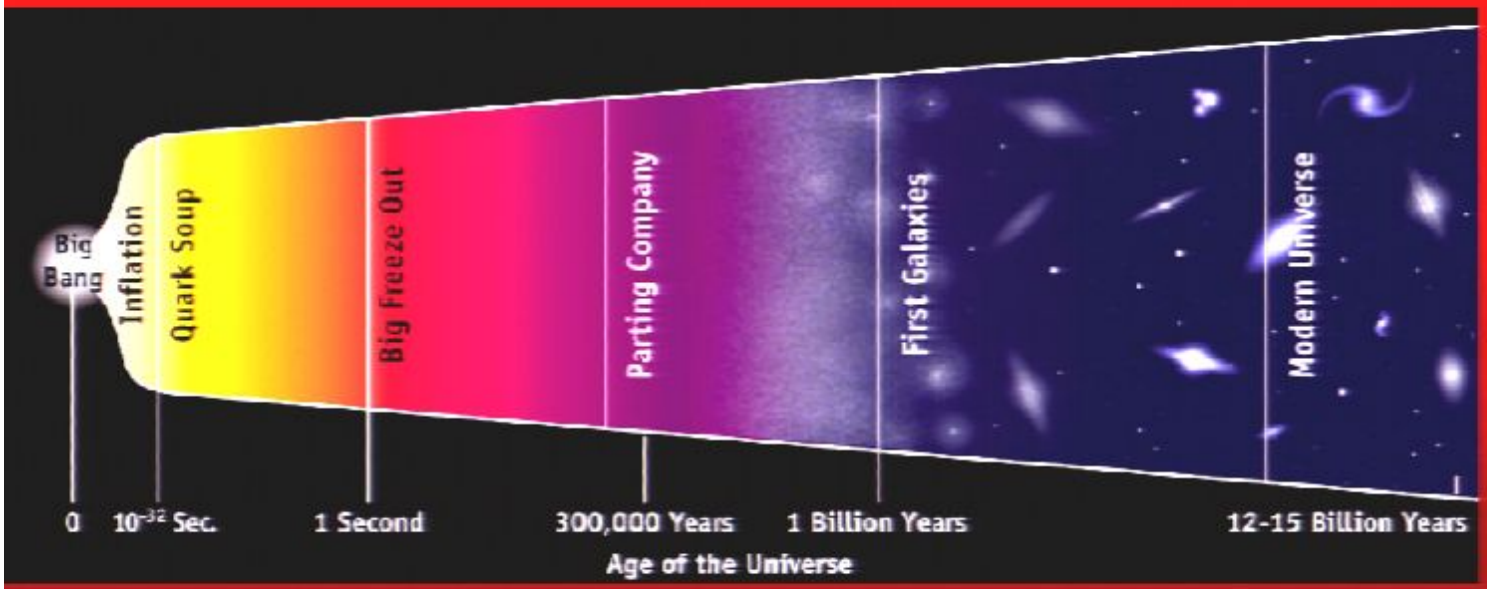
Title: New CMB Polarization Results From QUaD

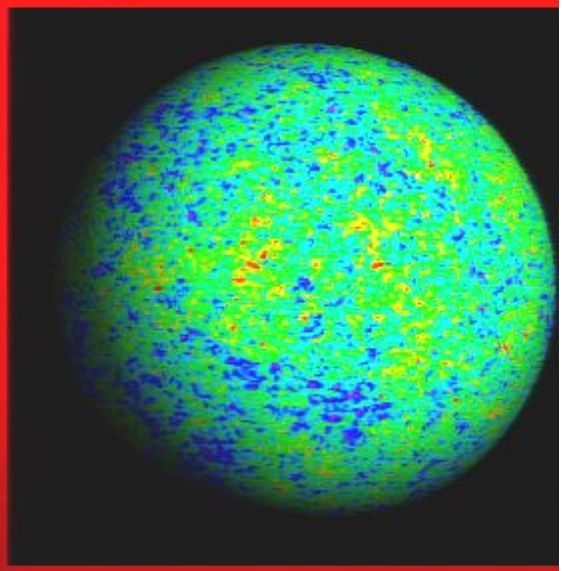
Date: Sep 23, 2008 02:00 PM

URL: http://pirsa.org/08090022

Abstract: The QUaD experiment has recently released CMB polarization results at el>200 which are the most sensitive to date. The predicted series of peaks in the EE spectrum are shown to be present for the first time while BB remains undetectable. After briefly reviewing the motivation for polarization measurements I will move on to the experiment, observations, analysis technique and the final results. Finally I will mention on-going efforts to detect gravitational wave B modes.

The Cosmic Microwave Background





- As we look out into space we look back into time
- Most ancient light "last scattered" at 400,000 years
  - ► Before that Universe was hot opaque plasma
  - ► Expansion of Uni. has stretched it to microwaves
- Unevenness of CMB gives us density structure on a sphere cut through the infant Universe
  - ► Number of "blobs" of different sizes depends on properties of our Universe

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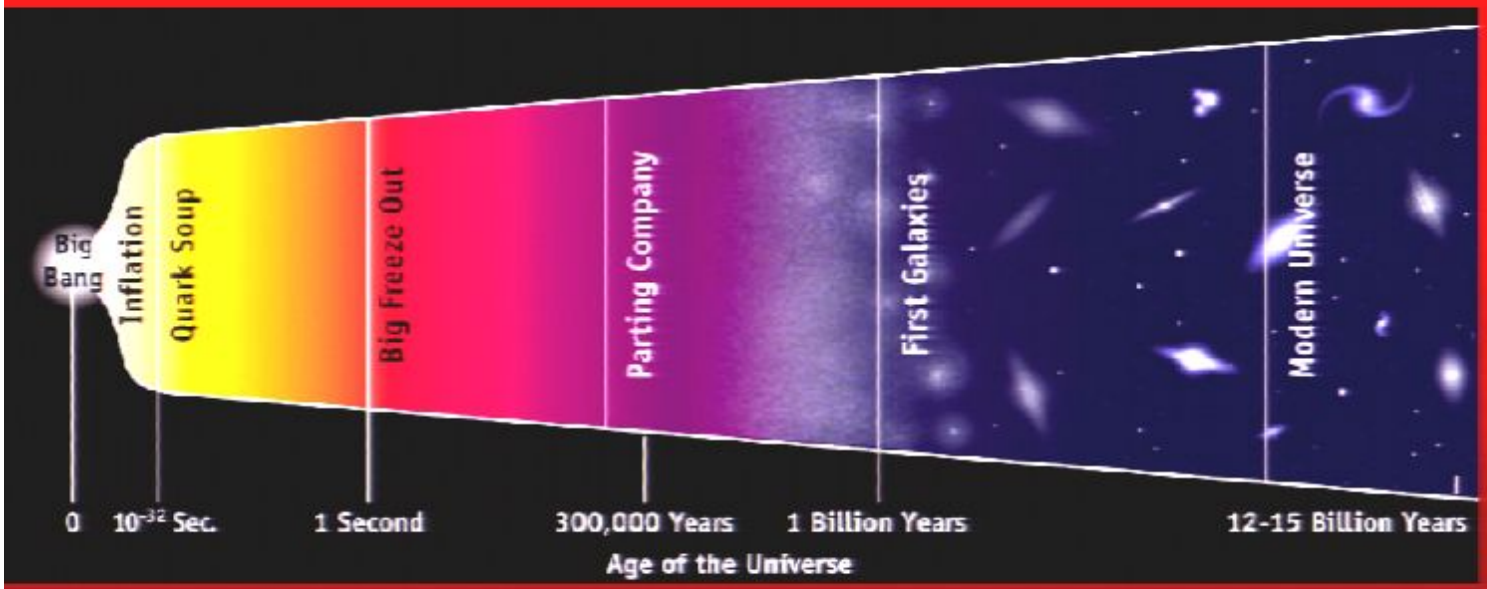

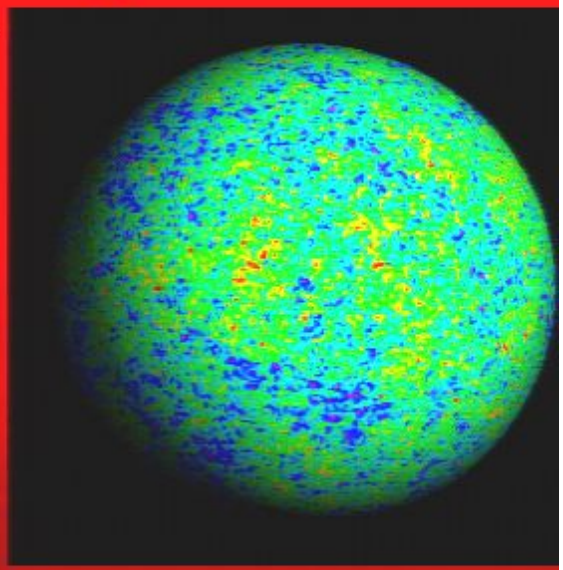

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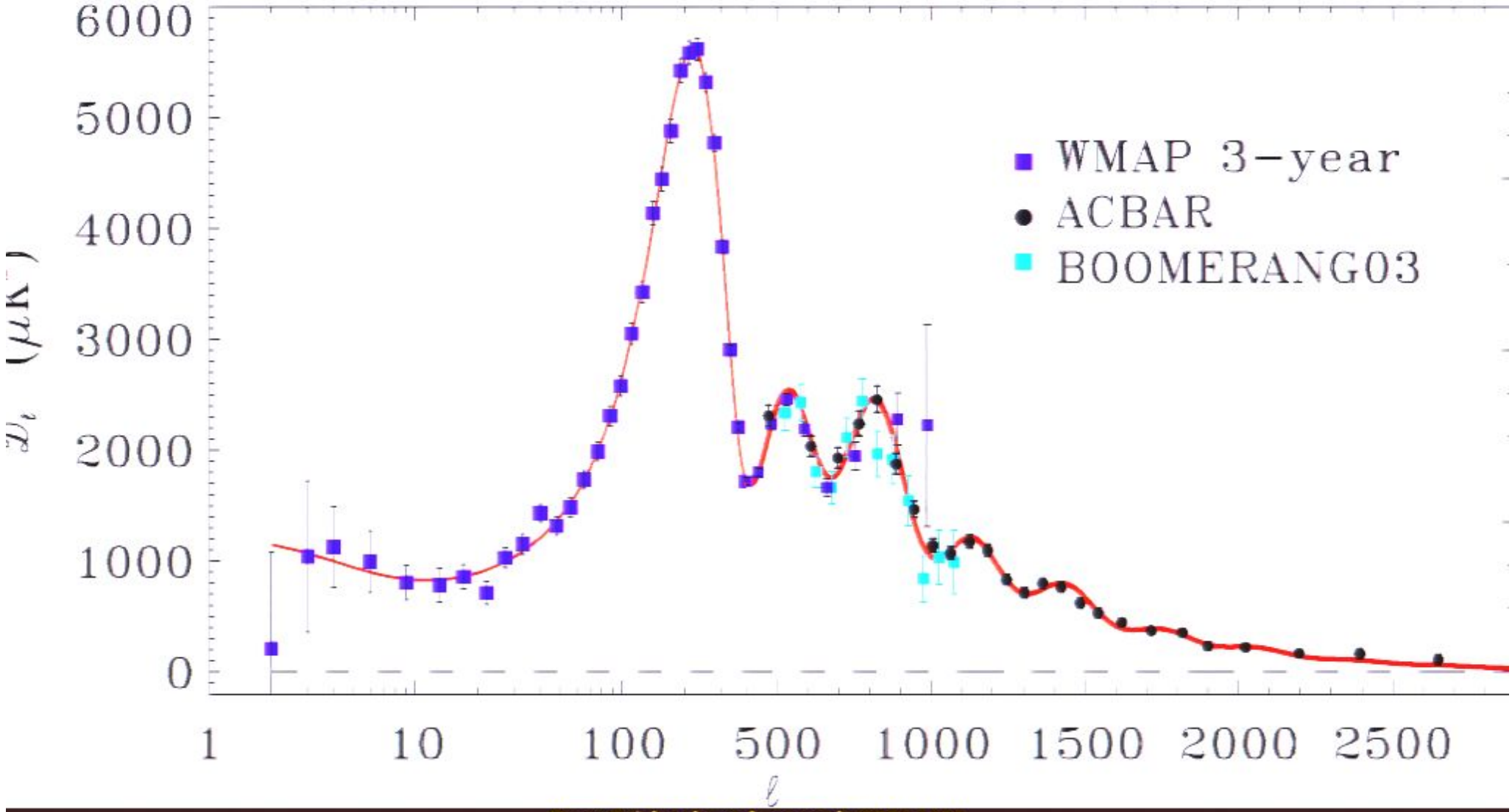
Current Total Intensity (T) Results



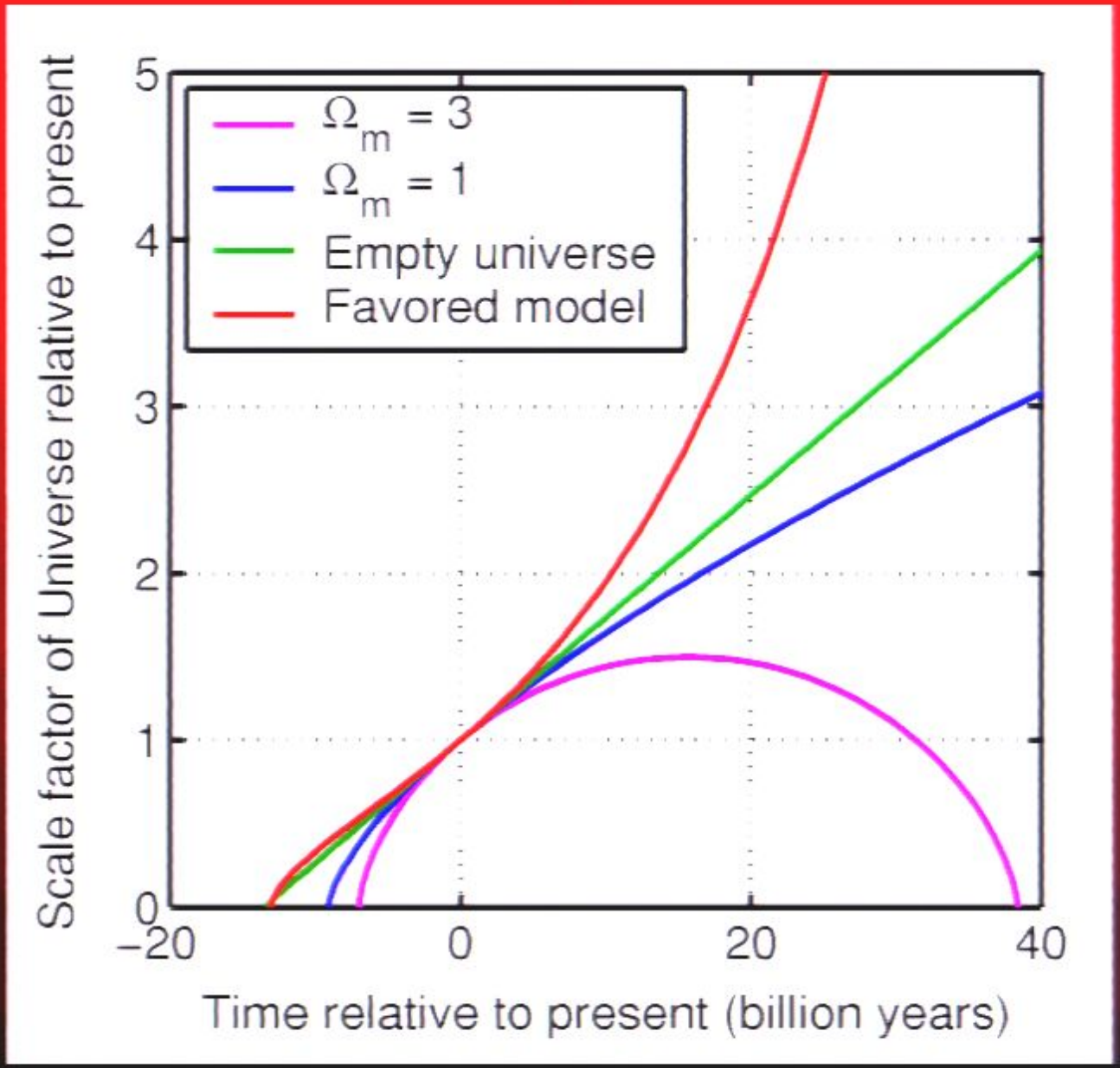
From Reichardt et al, astro-ph/0801.1491

Beautiful confirmation of predicted acoustic oscillations in plasma...

Glorious/Absurd Modern Cosmology

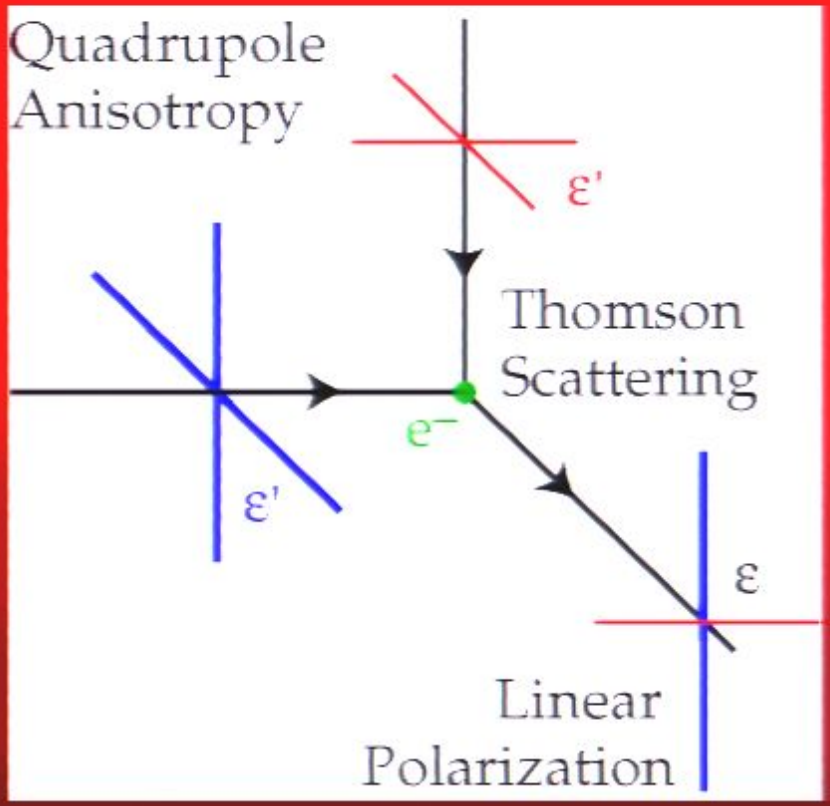
- Prediction/observation of acoustic peaks in T spectrum an incredible scientific result!
- Supernova data also indicates accelerating expansion
- In fact many kinds of data all fit with the "Standard Cosmological Model"
- But a hopelessly incomplete model with uncomfortable consequences
  - Contains "made up" elements like dark matter/energy
    - Need to check the paradigm every way we can!

Expansion History of the Universe



Does this seem likely?

CMB pol. generated at last scattering

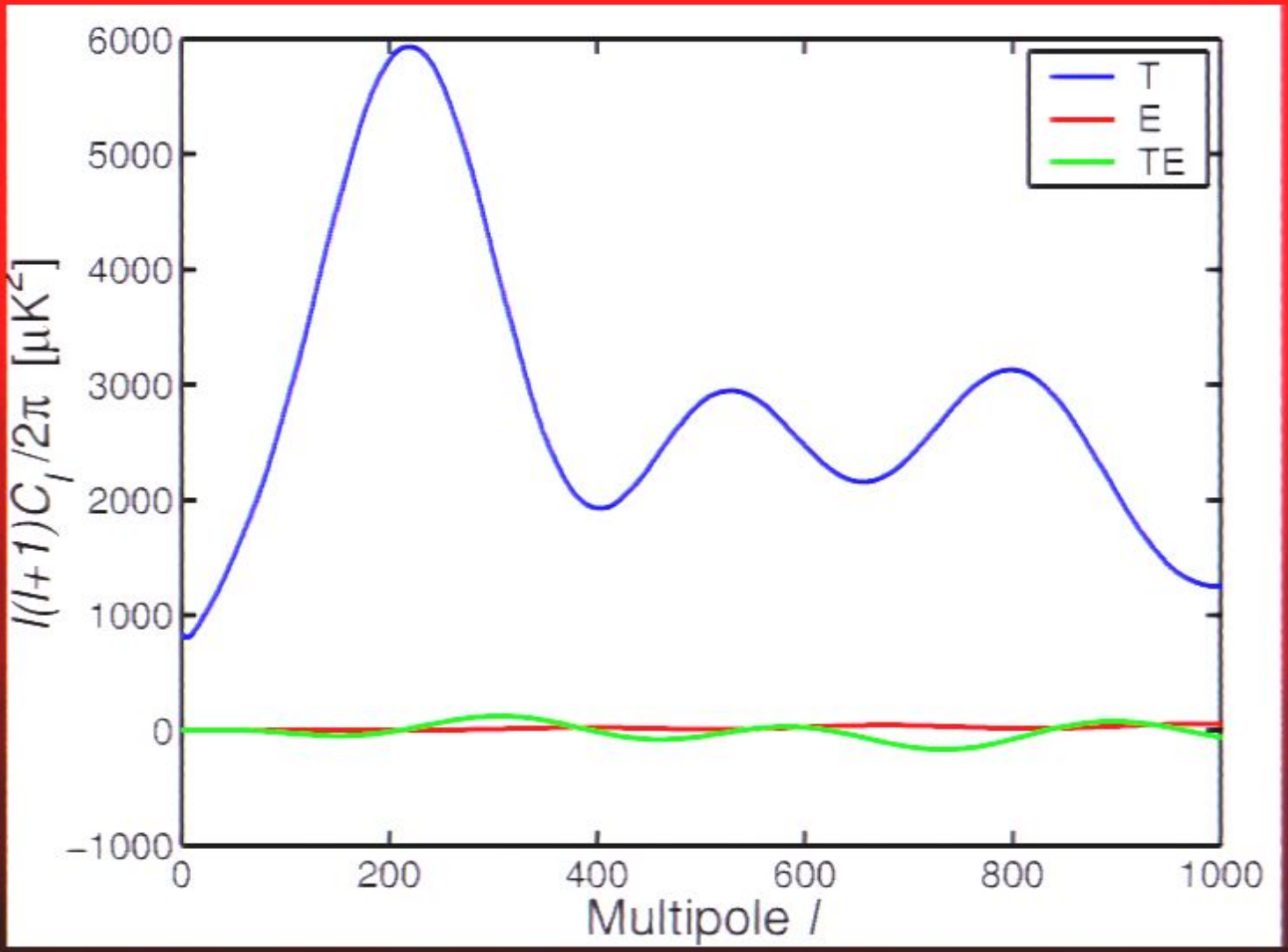


- If electrons are exposed to incoming radiation which has a quadrupole moment the re-radiated light will be (partially) polarized.
- At CMB last scattering quadrupole generated by Doppler shift in rest frame of moving material.

"First Order" Polarization of the CMB

- Density perturbations at last scattering produce T anisotropy.
- Material flowing along gradients in the density field
  - Resulting polarization pattern aligned with its gradient (E-modes) and has zero curl (B-modes).
  - Since density perturbations produce the motions there is TE cross correlation.
- Given T spectrum and standard cosmological model can predict expected E and TE spectra.
  - ...if measurements don't match the whole framework falls apart! - Critical test!

T, E and TE on the same linear y-axis

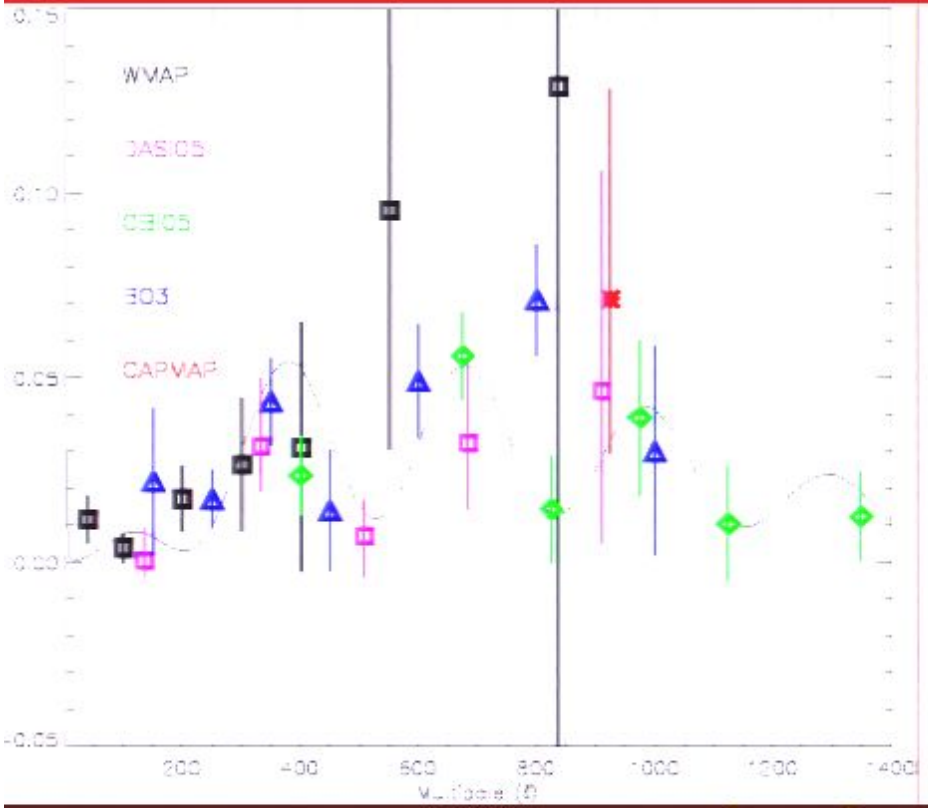


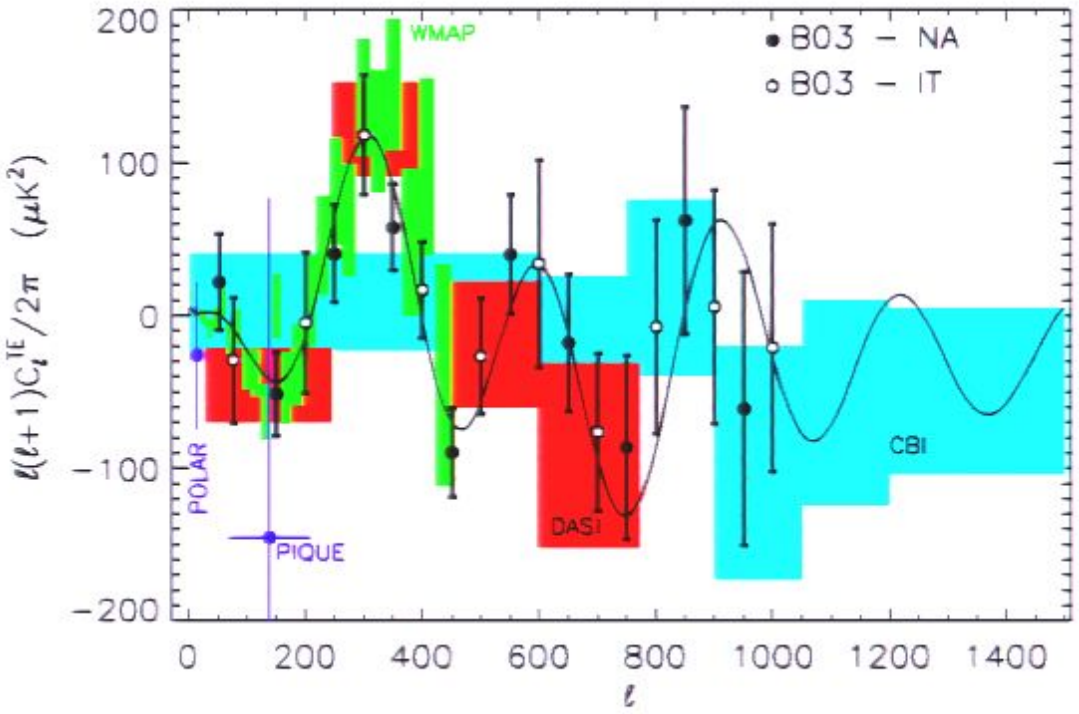
- Polarization less than 1% (in power units)
- A long struggle to get to the required sensitivity…

The DASI Interferometer

- First detection of CMB polarization in 2002
  - "5 sigma" result versus no pol. model
  - E consistent with expected amplitude, B consistent with zero.

Pre QUaD Polarization Results





From Page et al, astro-ph/0603450 and Piacentini et al, astro-ph/0507507

- As of 18 months ago evidence for EE peaks still very sketchy...

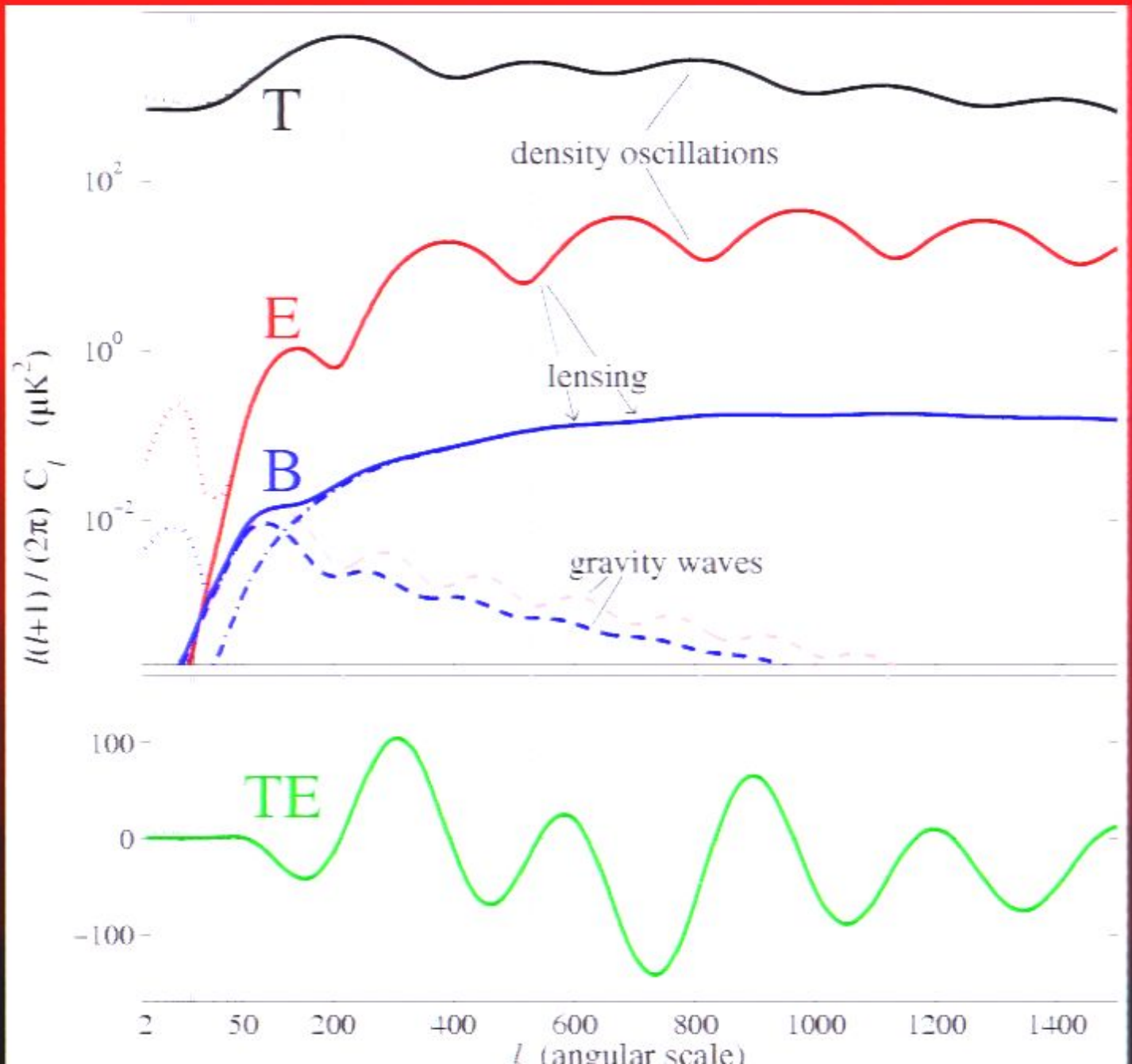
"Second Order" Polarization of the CMB

- Lensing by large scale structure between last scattering and us distorts the polarization pattern...
  - mixes E into B to a small extent.
    - Called "Lensing B-modes"

- Gravity waves propagating through the primordial plasma add to all spectra...
  - based on existing T data we know contribution small.
    - Called "Gravity Wave B-modes"

- When Universe re-ionizes additional scattering occurs
  - generates extra large scale anisotropy.
    - Called "Re-ionization Signature"

Location of "Second Order" Pol. Effects



Why Make Further Measurements?

- At $l>150$
  - Refine measurements of E and TE to further test paradigm
  - Try to detect lensing B to get info on neutrinos and dark energy
- At $30<l<150$
  - Try to detect gravity wave B
- At $l<30$
  - Refine measurements of E and TE to constrain re-ionization
  - Try to detect gravity wave B

Higher ell E/TE Any Help to Parameters?

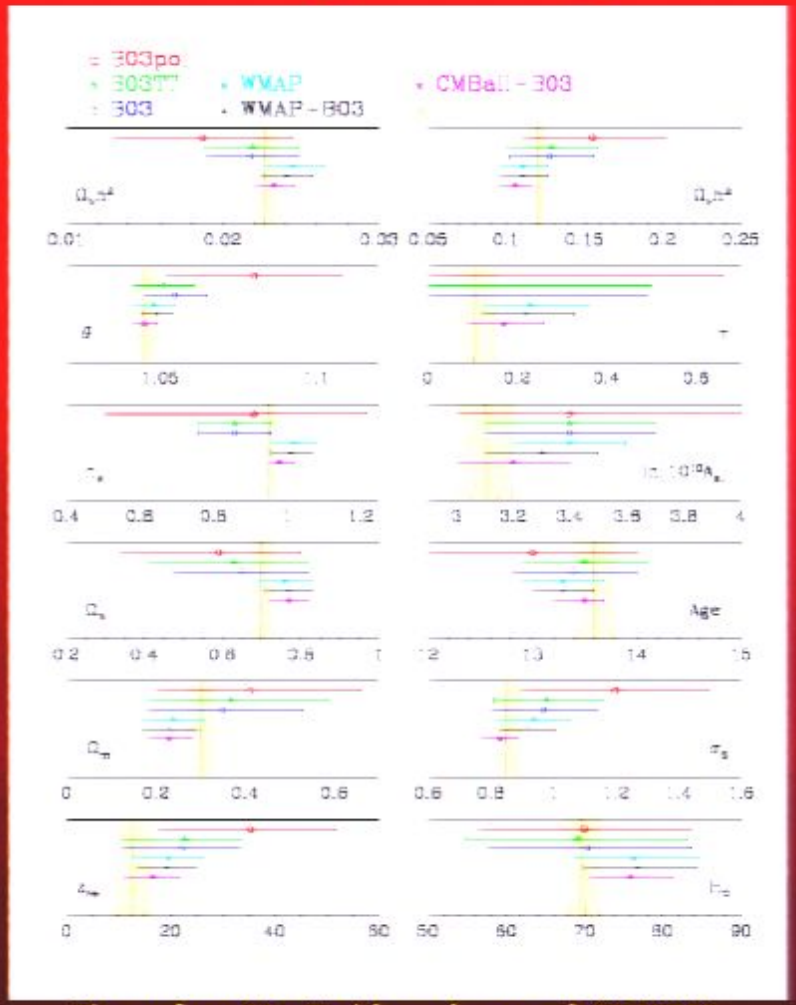


Figure from MacTavish et al, astro-ph/0507503

- Without extremely high precision pol. data doesn't improve cos. par. constraints for conventional models
  - Green to blue from adding E&TE info

What QUaD Is

History of QUaD

- Once upon a time a collaboration called QUEST:
  - Caltech (JPL) provide bolometers
  - Stanford provide focal plane and integrate receiver
  - Cardiff provide mirrors, cryostat
- In early 2003 receiver under construction but problems getting money to deploy...

- At that time DASI starting on final season
  - Suggestion to put QUEST receiver on DASI mount
  - Collaborative proposal to NSF submitted mid 2003
  - Funded early 2004 - experiment deployed late 2004!

- QUaD = QUest And Dasi

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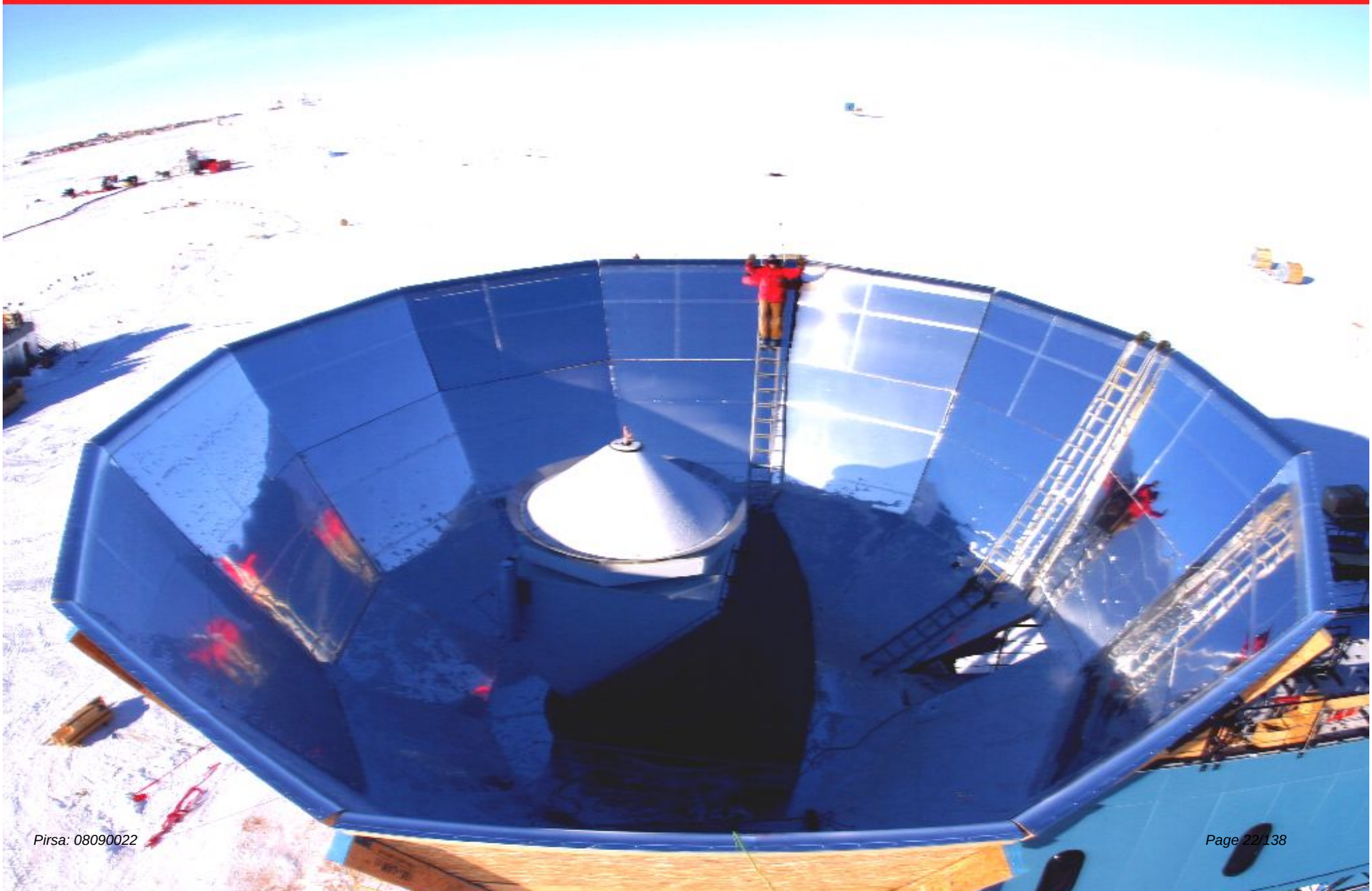
QUaD Collaboration

- Stanford: Sarah Church (PI), Jamie Hinderks (NASA Goddard), Ben Rusholme (IPAC), Keith Thompson, Melanie Bowden (industry), Ed Wu
  - ► Focal plane design, receiver integration, readout electronics, analysis
- Caltech/JPL: Andrew Lange (co-PI), Jamie Bock, John Kovac, Ken Ganga (APC/CNRS)
  - ► Detectors, calibration sources & methods
- Chicago: Clem Pryke (co-PI), Robert Friedman, John Carlstrom, Tom Culverhouse, Erik Leitch (JPL), Robert Schwarz (South Pole)
  - ► Mount, foam cone, DAQ, observations, analysis
- Cardiff: Walter Gear (PI), Simon Melhuish (Manchester), Lucio Piccirillo (Manchester), Peter Ade, Mike Zemcov (Caltech), Nutan Rajguru (UCL), Angiola Orlando (Caltech), Abi Turner, Sujata Gupta
  - ► Cryostat, mirrors, fridge, cal source, analysis
- Edinburgh: Andy Taylor, Michael Brown (Cambridge), Patricia Castro (Lisbon), Yasin Memari
  - ► Analysis
- Maynooth: Anthony Murphy, Creidhe O'Sullivan, Gary Cahill
  - ► Optics design

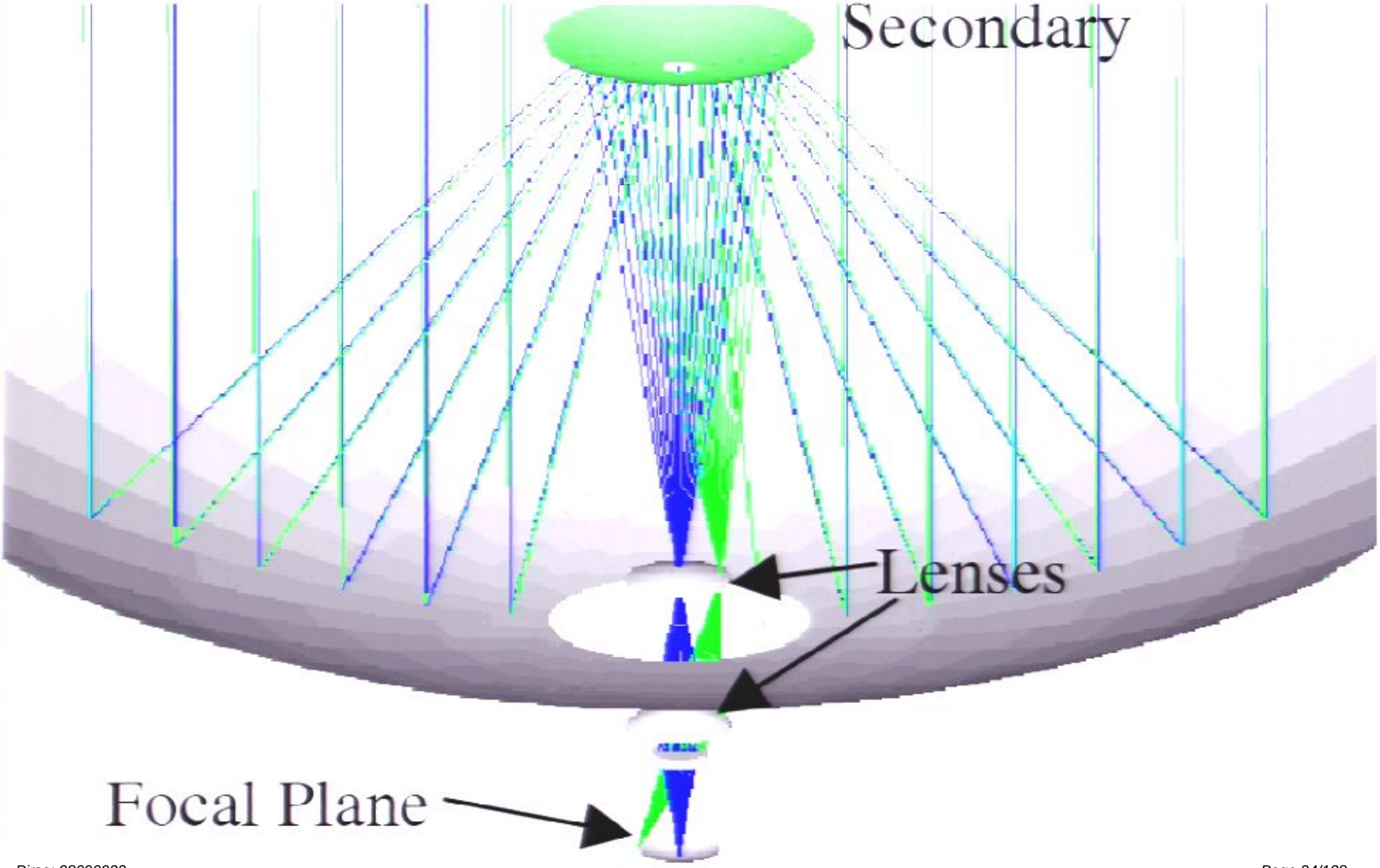
QUaD at South Pole Feb 2005



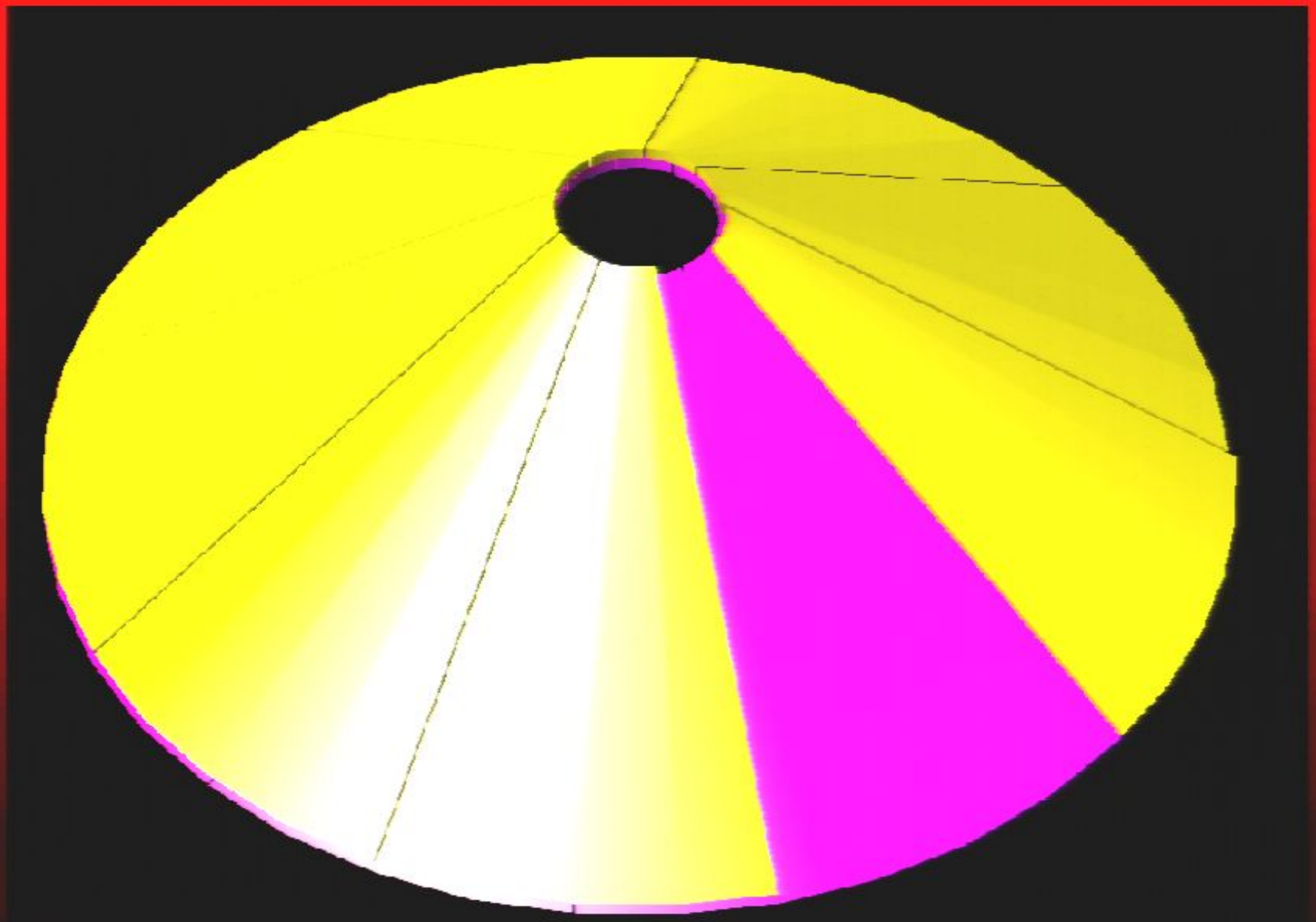
The QUaD Telescope

- 2.6 meter Cassegrain radio telescope attached to front of DASI mount (3rd axis preserved)
- 31 pixel polarization sensitive bolometer camera (PSBs), no internal pol modulator (waveplate)
- Secondary supported on foam cone - aperture blockage small and uniform
- DASI tower, equipment room, drive system, DAQ system re-used.
- Ground shield extended

Optical Path

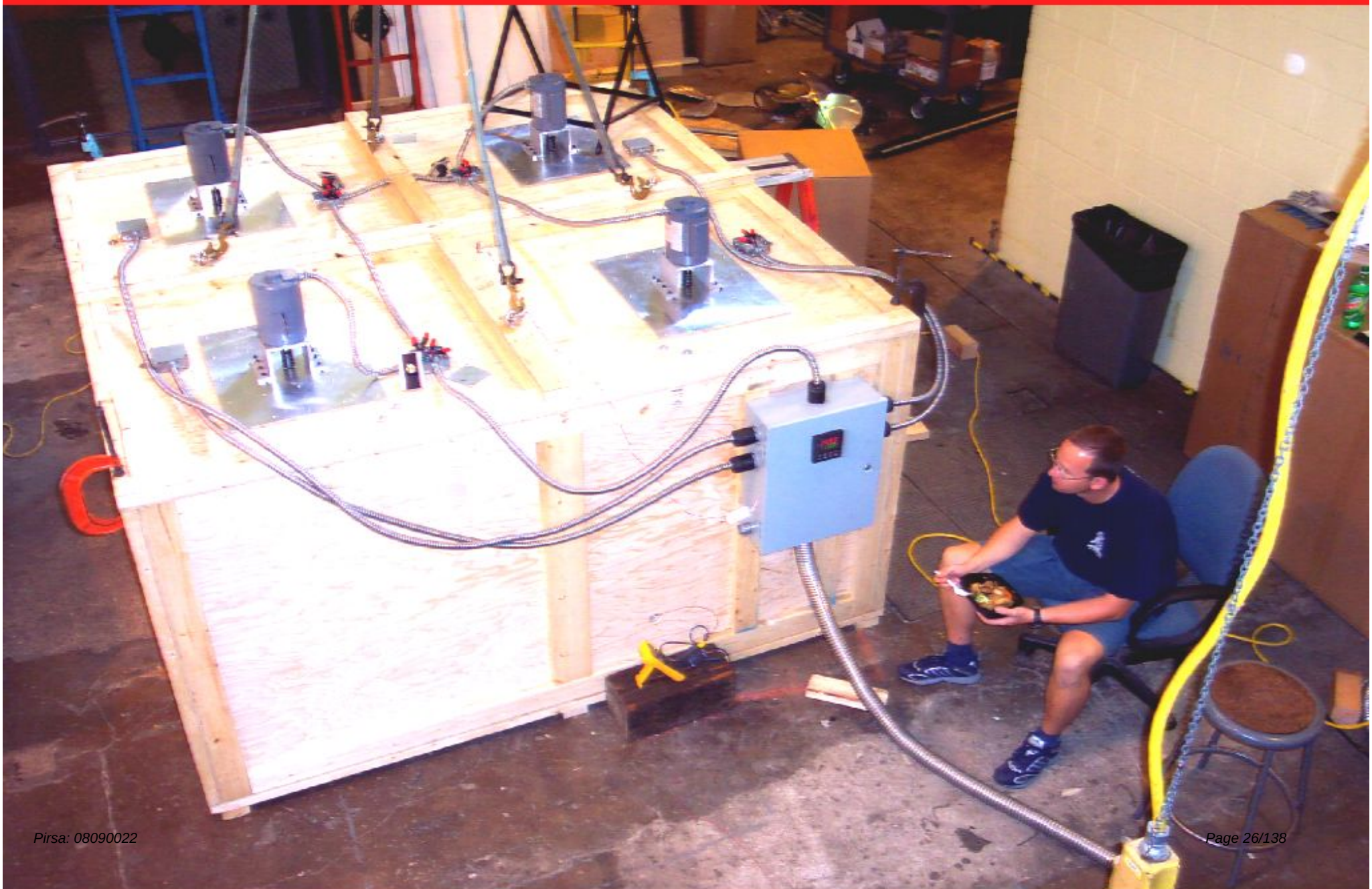


Foam Cone Concept



Foam only manufactured in 6x3' flat sheets

Thermoforming Oven

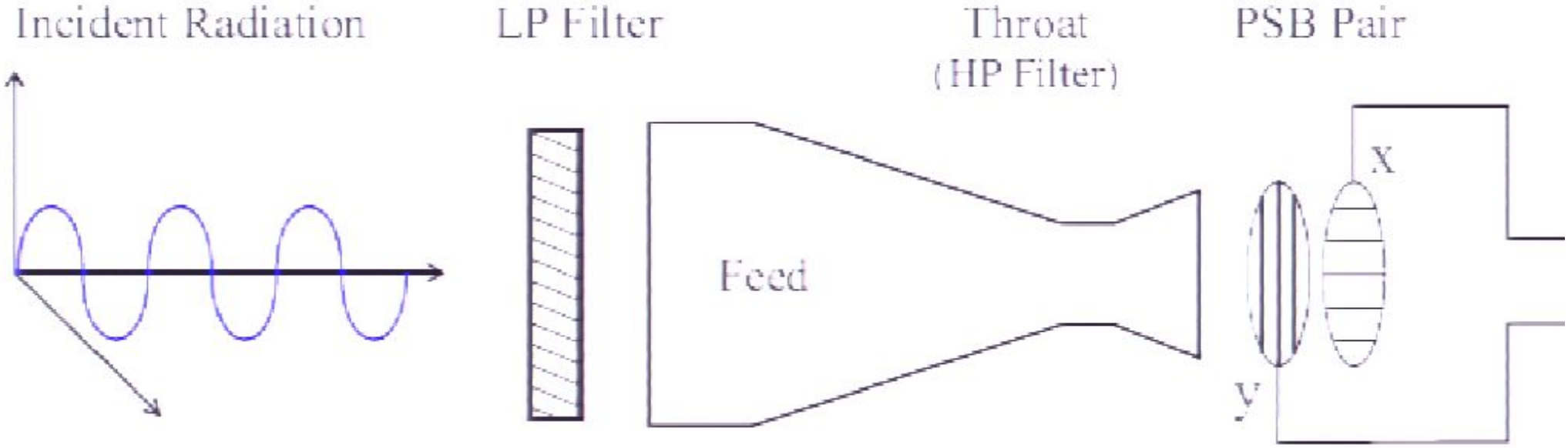


Full Size Form and Foam Trimming

Receiver Focal Plane

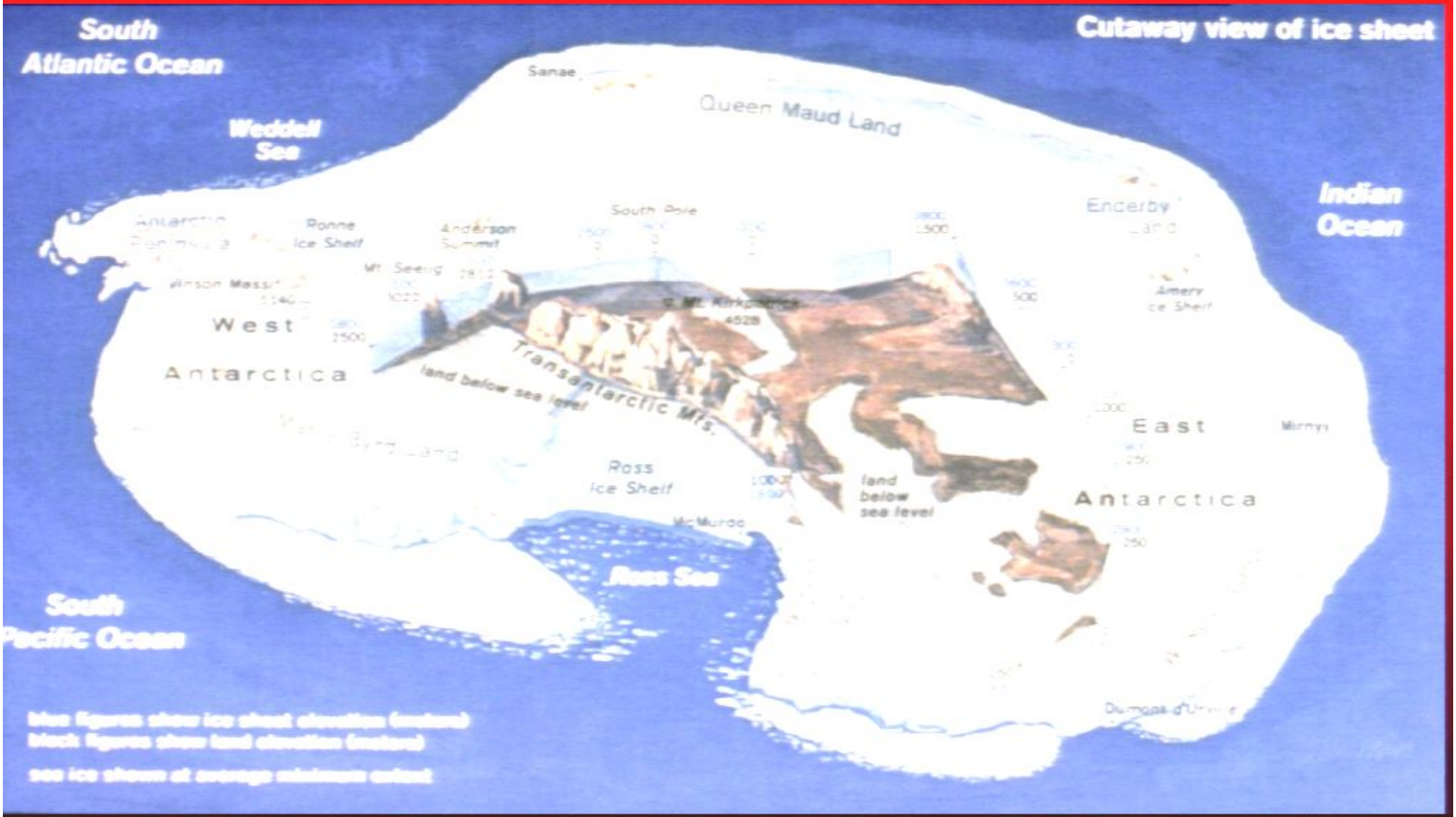
12 feeds @ 100GHz (6 arcmin), 19 @150GHz (4 arcmin)

Polarization Sensitive Bolometers



- Two orthogonal absorber grids read out independently
  - Sum measures total intensity
  - Difference measures polarization
- 12 pairs @ 100GHz, 19 pairs @ 150GHz

Antarctic Continent



Larger than the US - Ice sheet two miles thick!

Clem at the Actual South Pole

Nothing Out There...

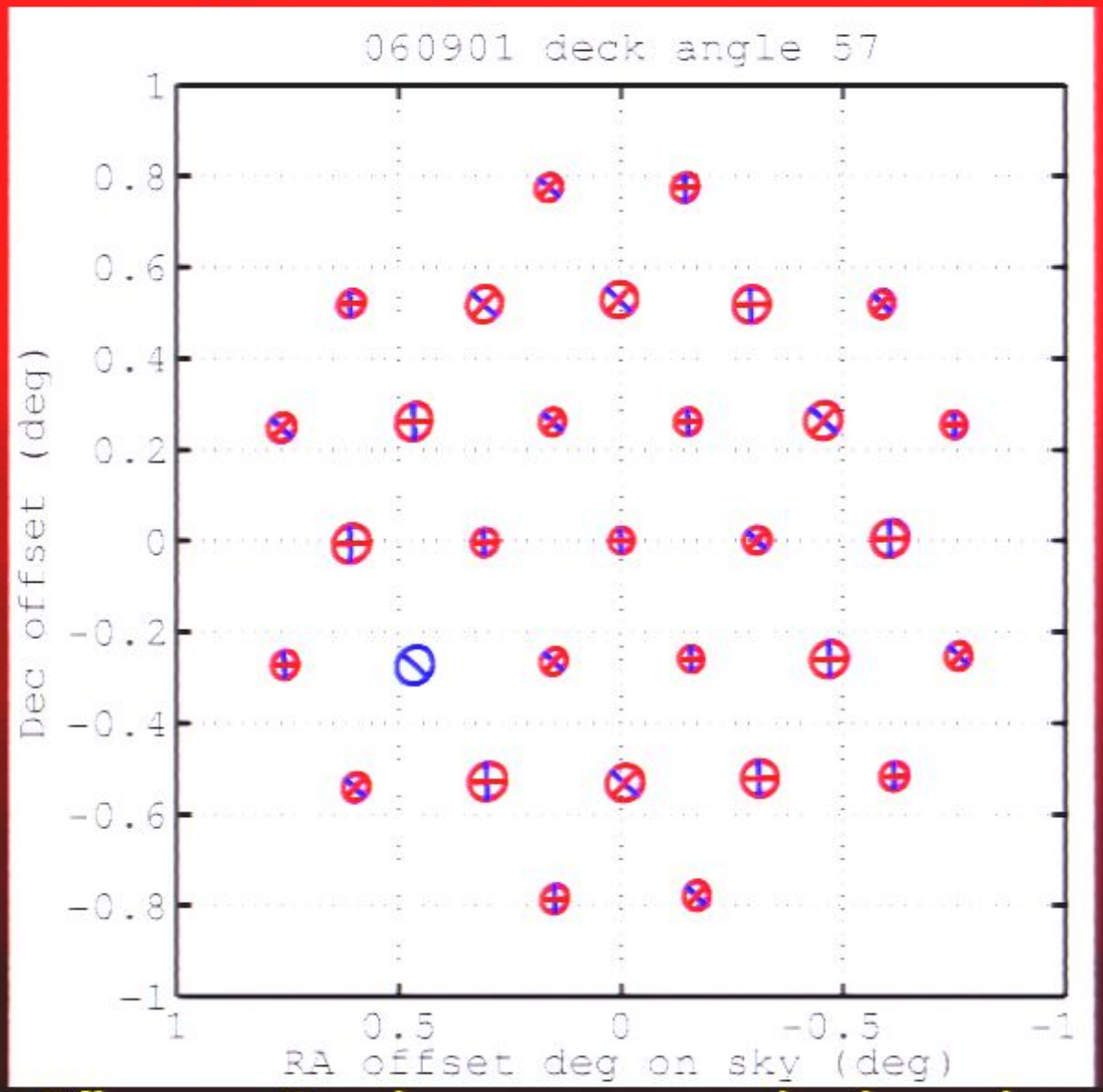
Why at the South Pole?

- Very cold, and high altitude
  - Very low atmospheric moisture.
    - Atmos. *nearly* transparent to microwaves
- Atmosphere extremely stable (no daily sunrise/set)
- No Sun for 6 months of the year:
  - Work on instrument in summer.
  - Observe in winter.
- Fields remain at constant elevation angle
  - and superb low foreground sky available at high el!
- Existing infrastructure and logistics.

How QUaD Works

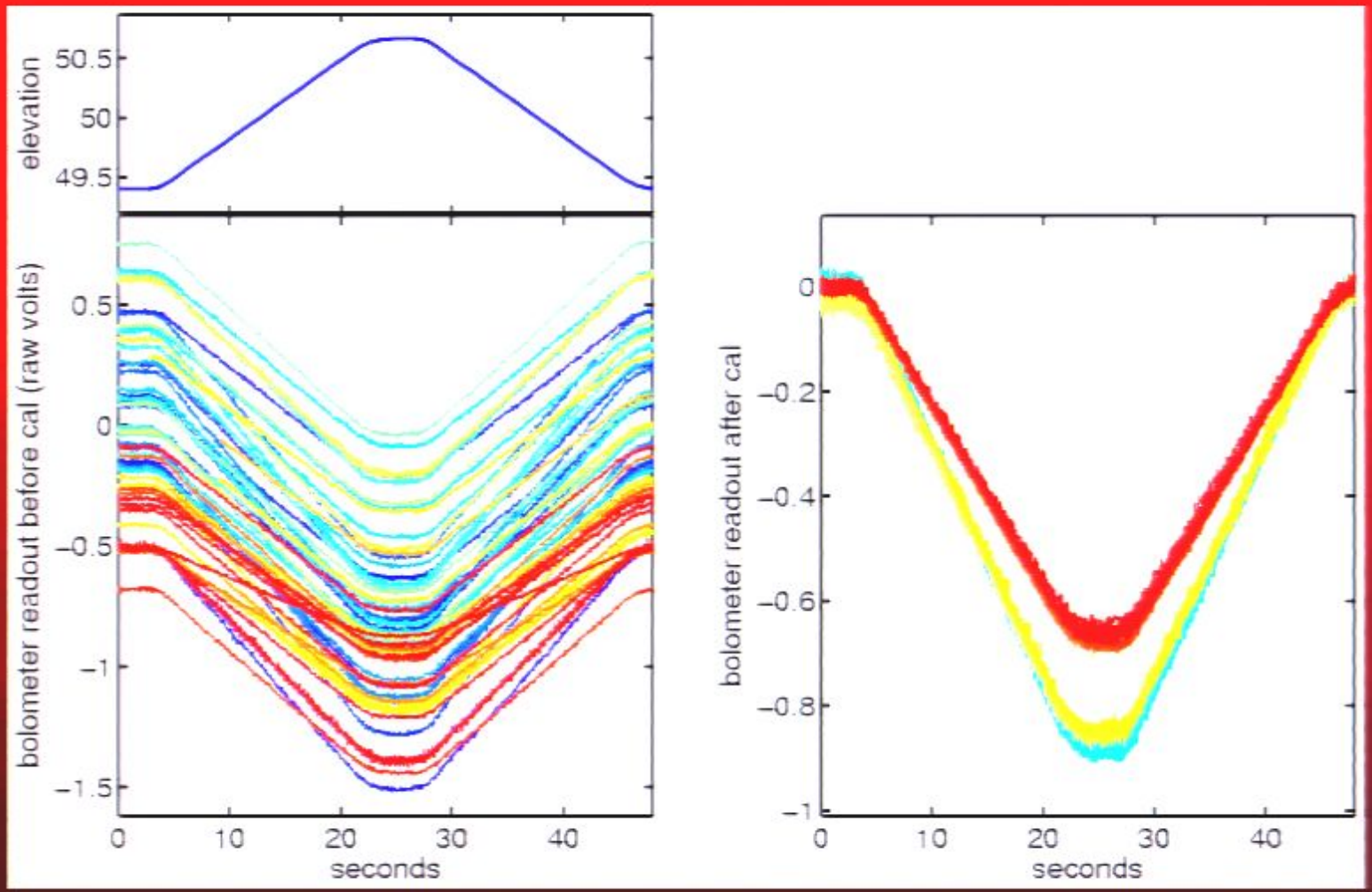
- Bolometer temperature coupled to temperature of incoming radiation from small "spots" on the sky
- Whole telescope moves (scans), sweeping the set of pencil beams around on the sky
- We read out the *changing* bolometer temperature as a function of pointing position - called timestream data...
  - any change in bolometer temperature appears in readout...
    - need an outrageously stable system!

Array Projected on Sky



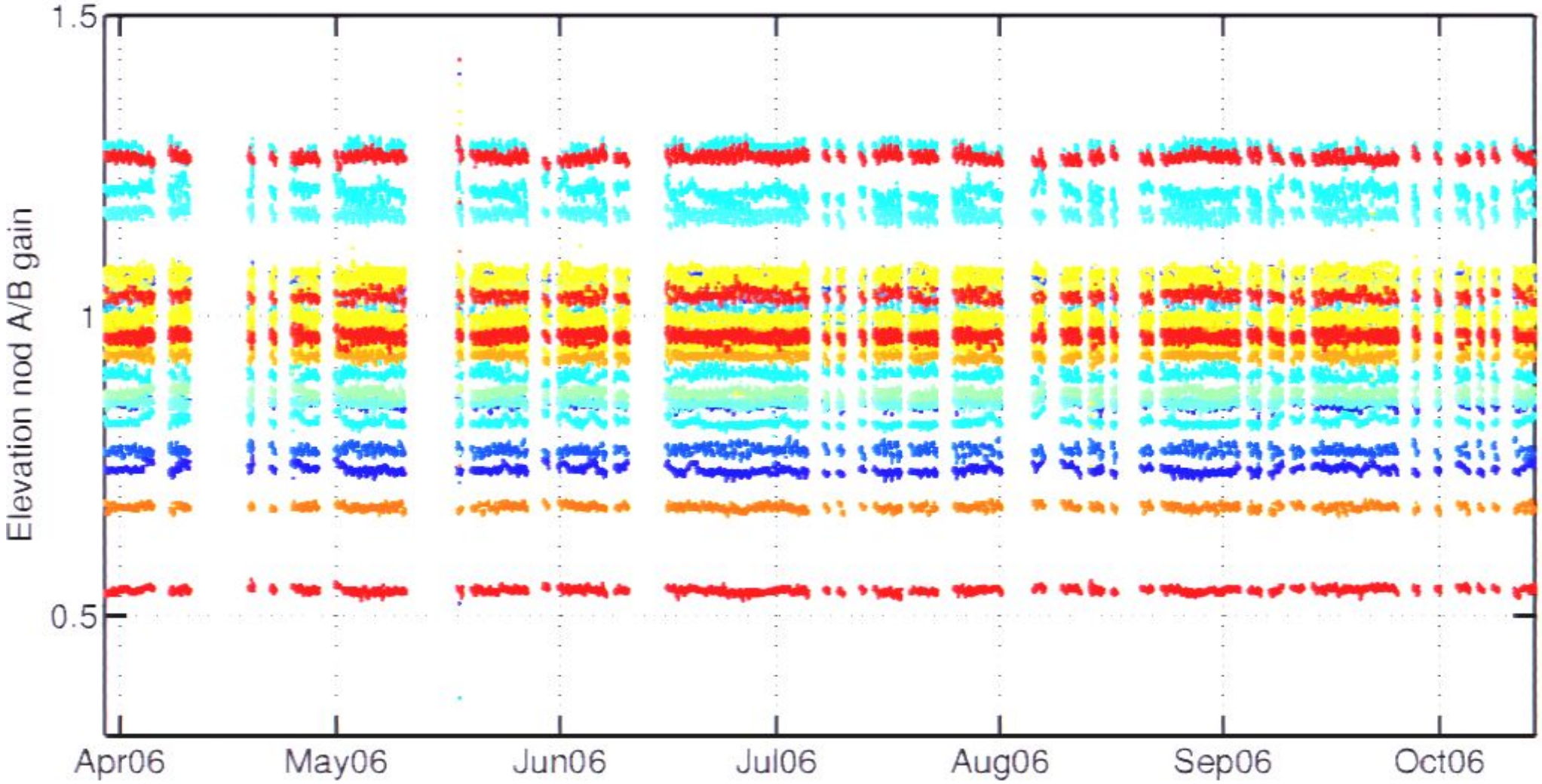
2 orientation "flavors", plus rotate whole telescope around line of sight by 60 deg

Relative Gain Cal



- Before can take pair diff. need to adjust relative gain
  - "Nod" the telescope in elevation to inject large signal from atmospheric gradient

Excellent A/B Gain Stability

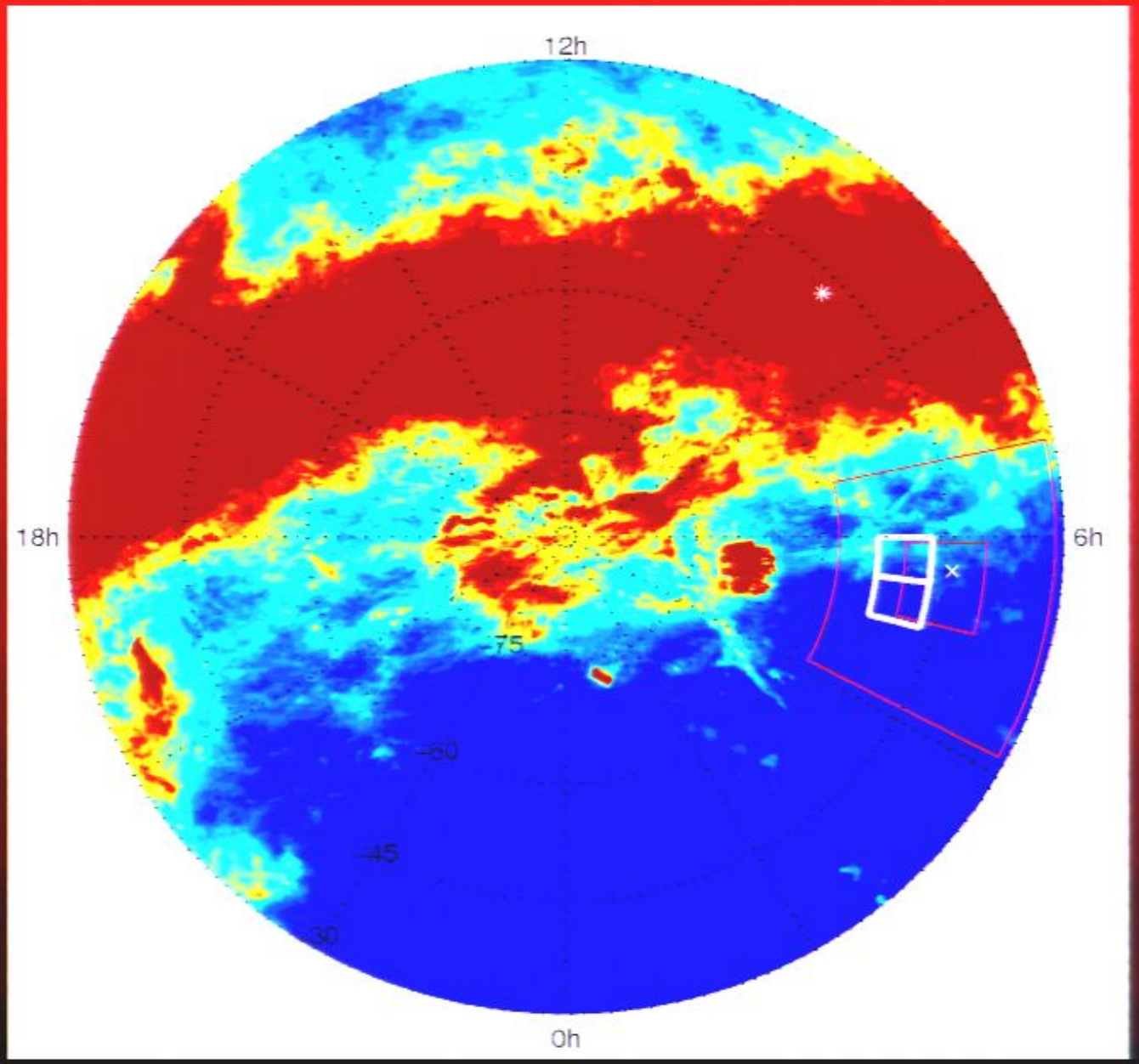


- Pair gain ratio is stable to <1% rms over full season!
  - and fluctuations average down...

QUaD Observing Strategy

- Telescope scans 7.5 deg in azimuth as modulation on top of sky track (at Pole sky rotates around zenith)
- Scan 5 times out and back - then step in el by 0.02 deg and repeat.
  - Build simple raster map - no cross linking!
  - Scan at 0.25 deg/sec putting ell range 200 to 2000 at 0.1 to 1Hz in timestream.
- One run per day starting always at same LST
  - (Start as observing field clears lab building)
- Cal, 8 hours CMB, cal, rotate telescope, cal, 8 hours CMB, cal (and 5 hour fridge cycle)

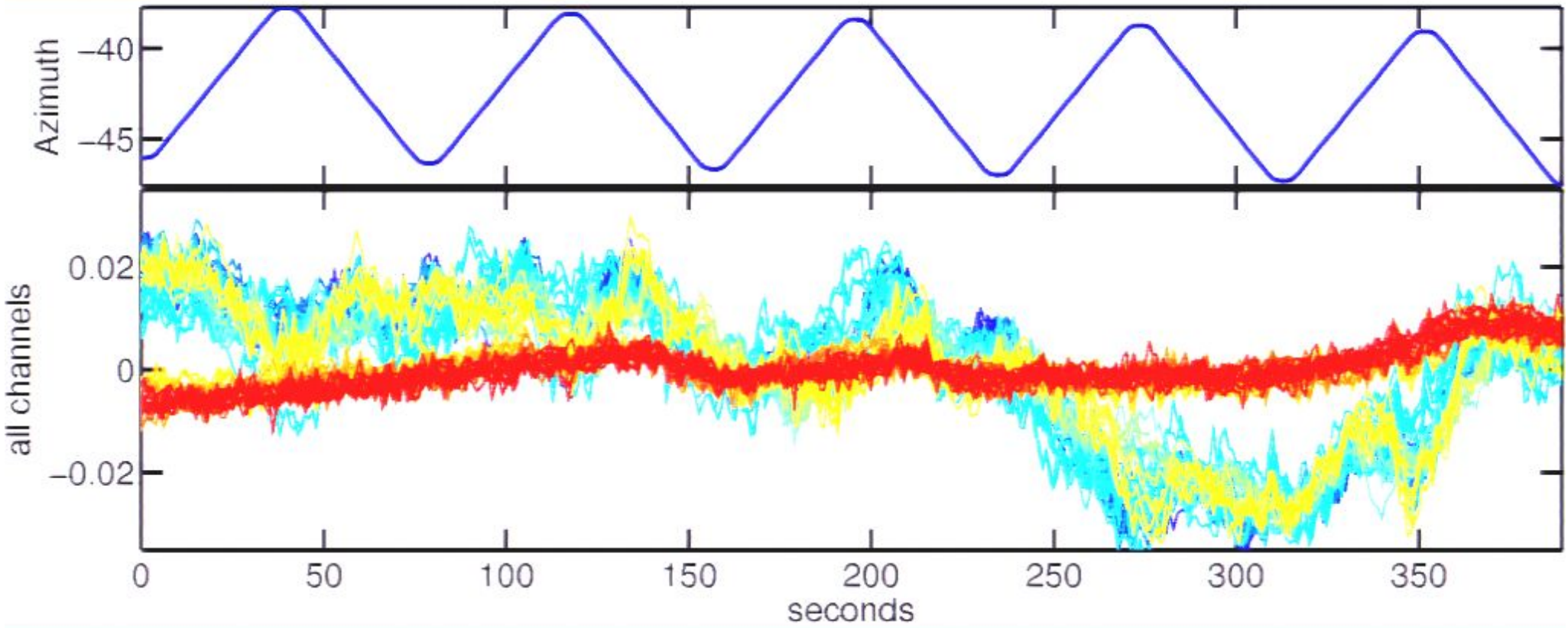
Location of QUaD Field



FDS dust prediction @ 150GHz around SCP, linear color scale 0 to 100uK (heavily saturated),

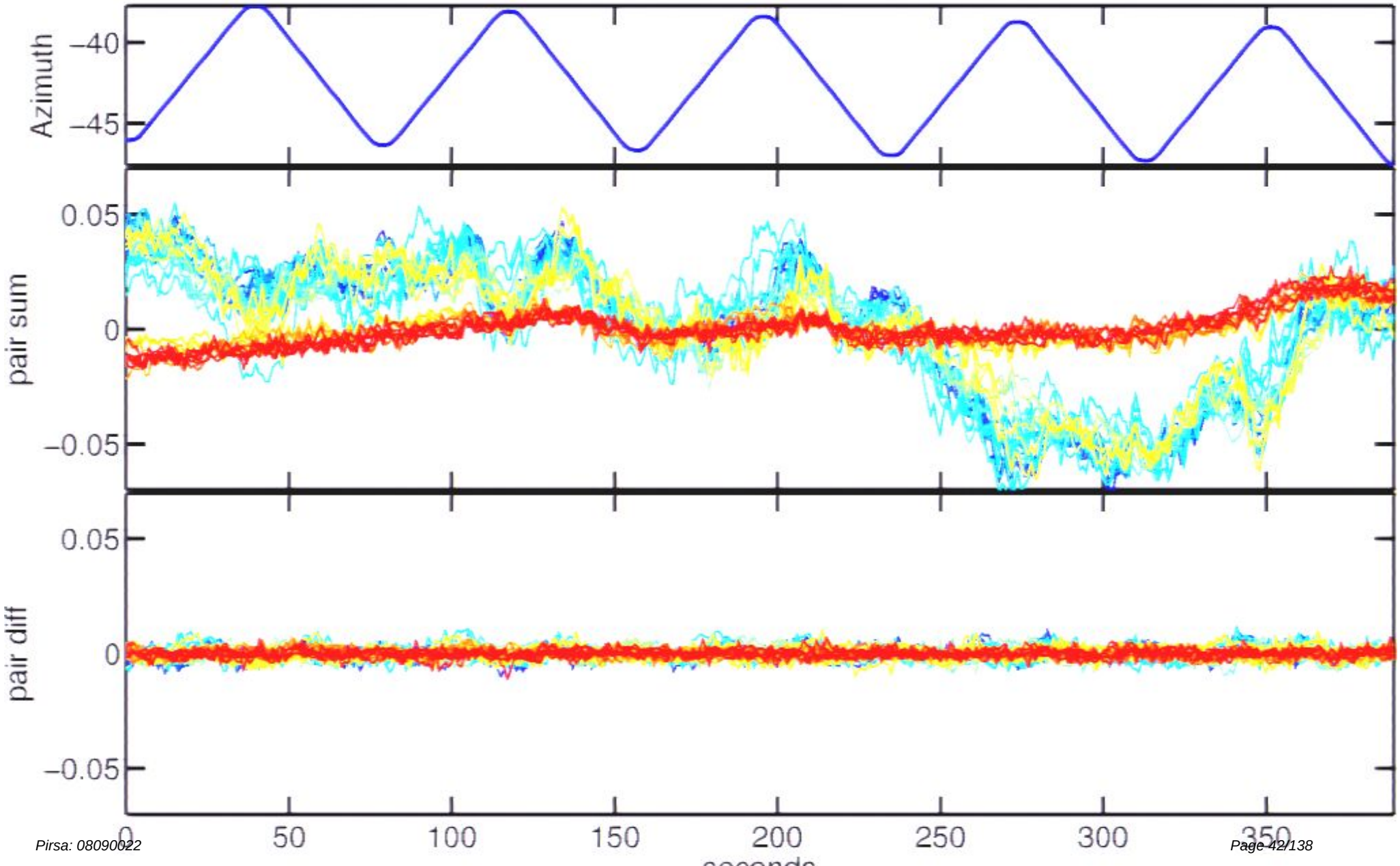
From Timestream to Maps

A raw scan set



(Well actually deconvolved, low-passed, deglitched, downsampled, relative gain calibrated)

...pair sum/difference...



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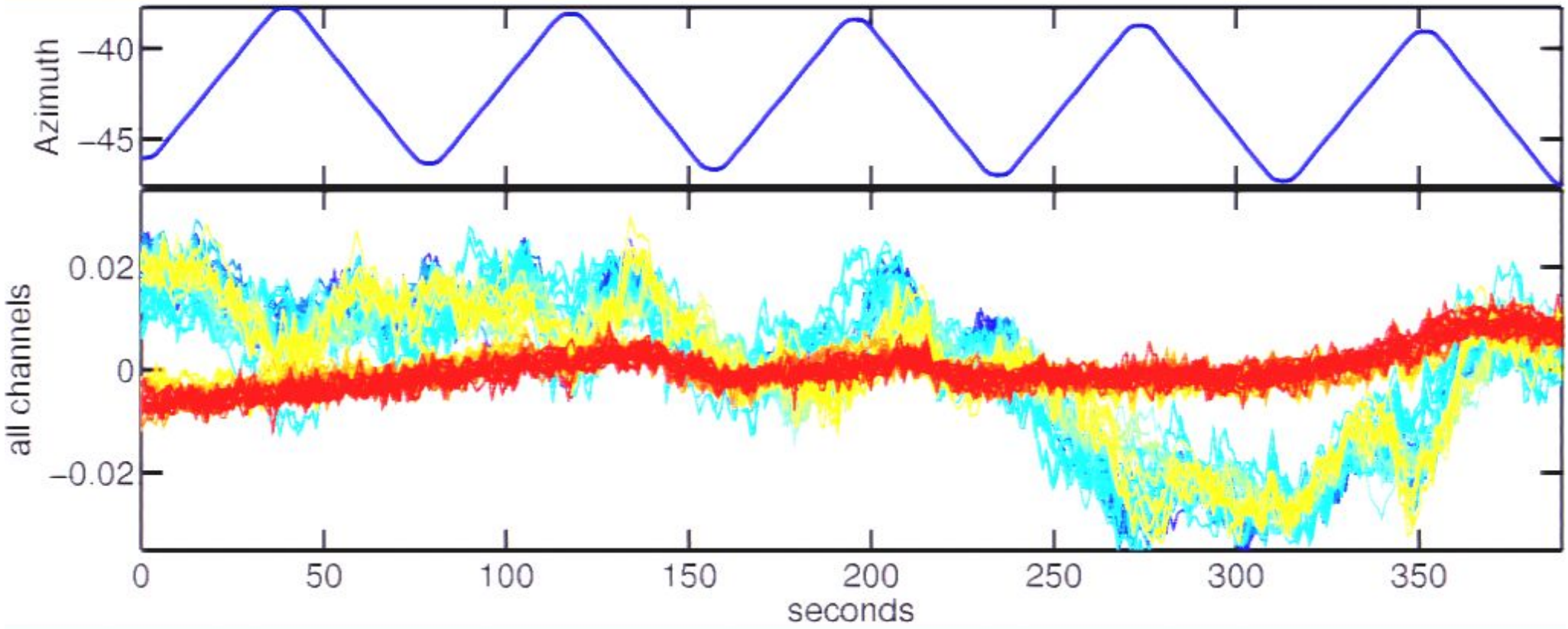

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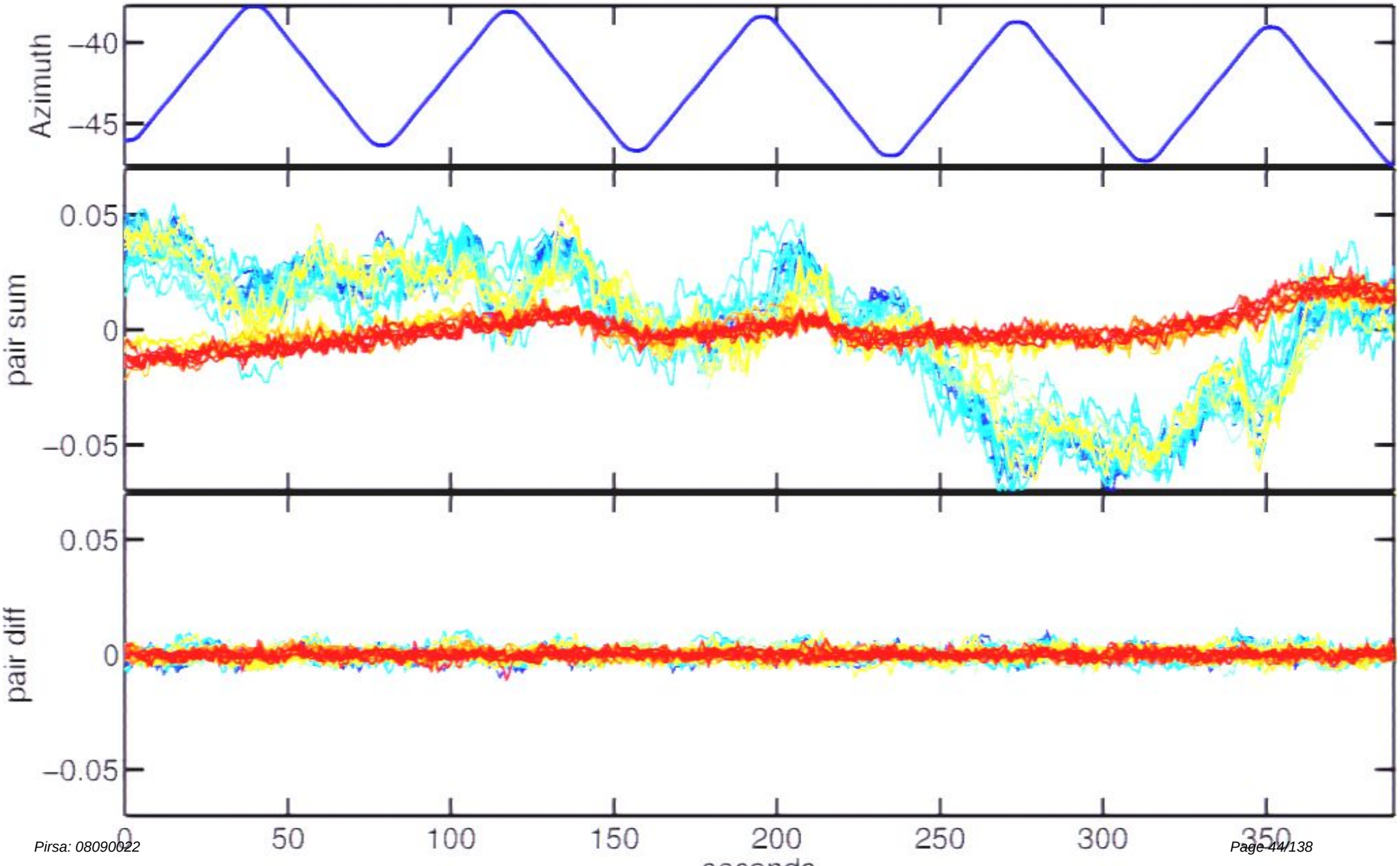
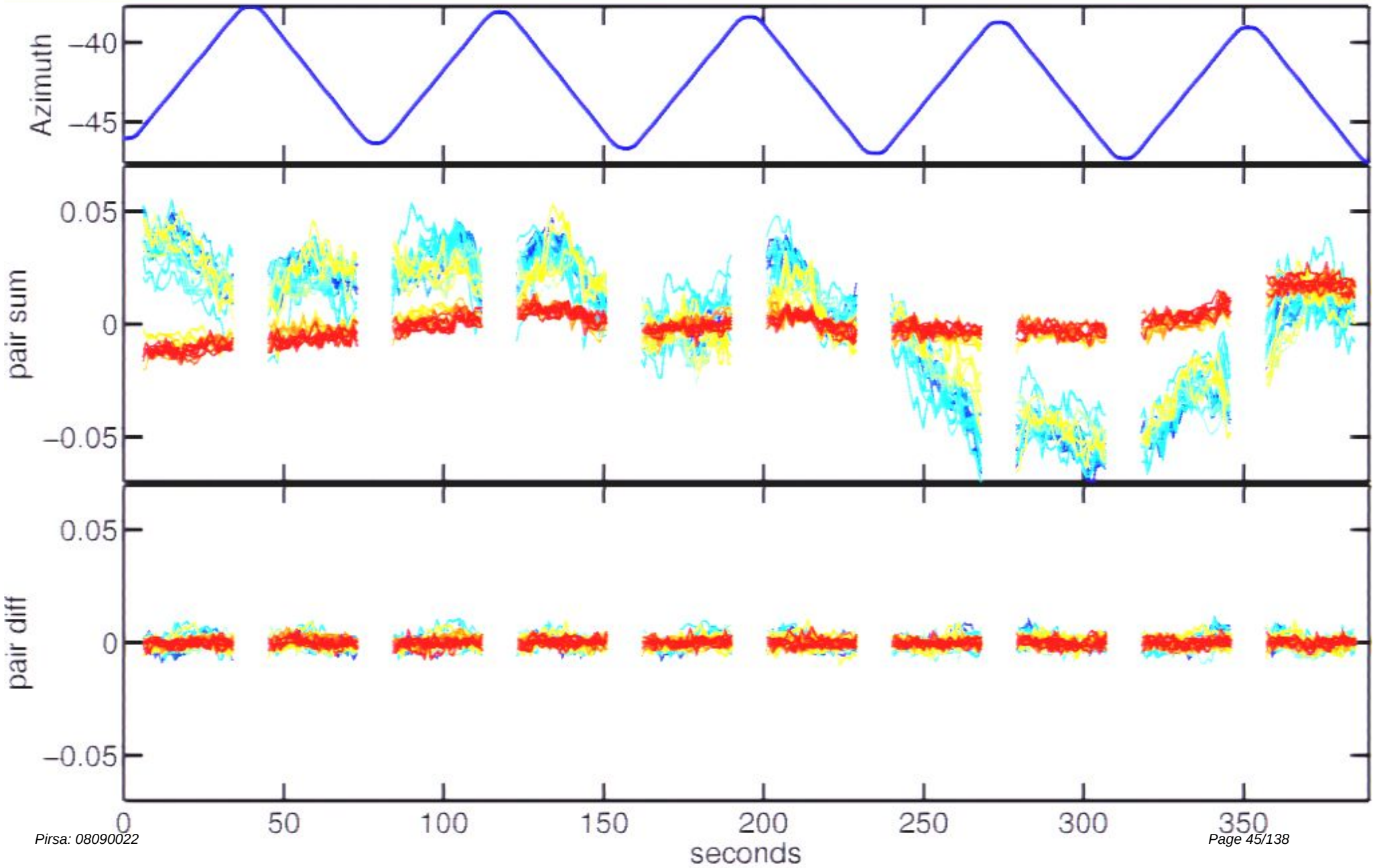
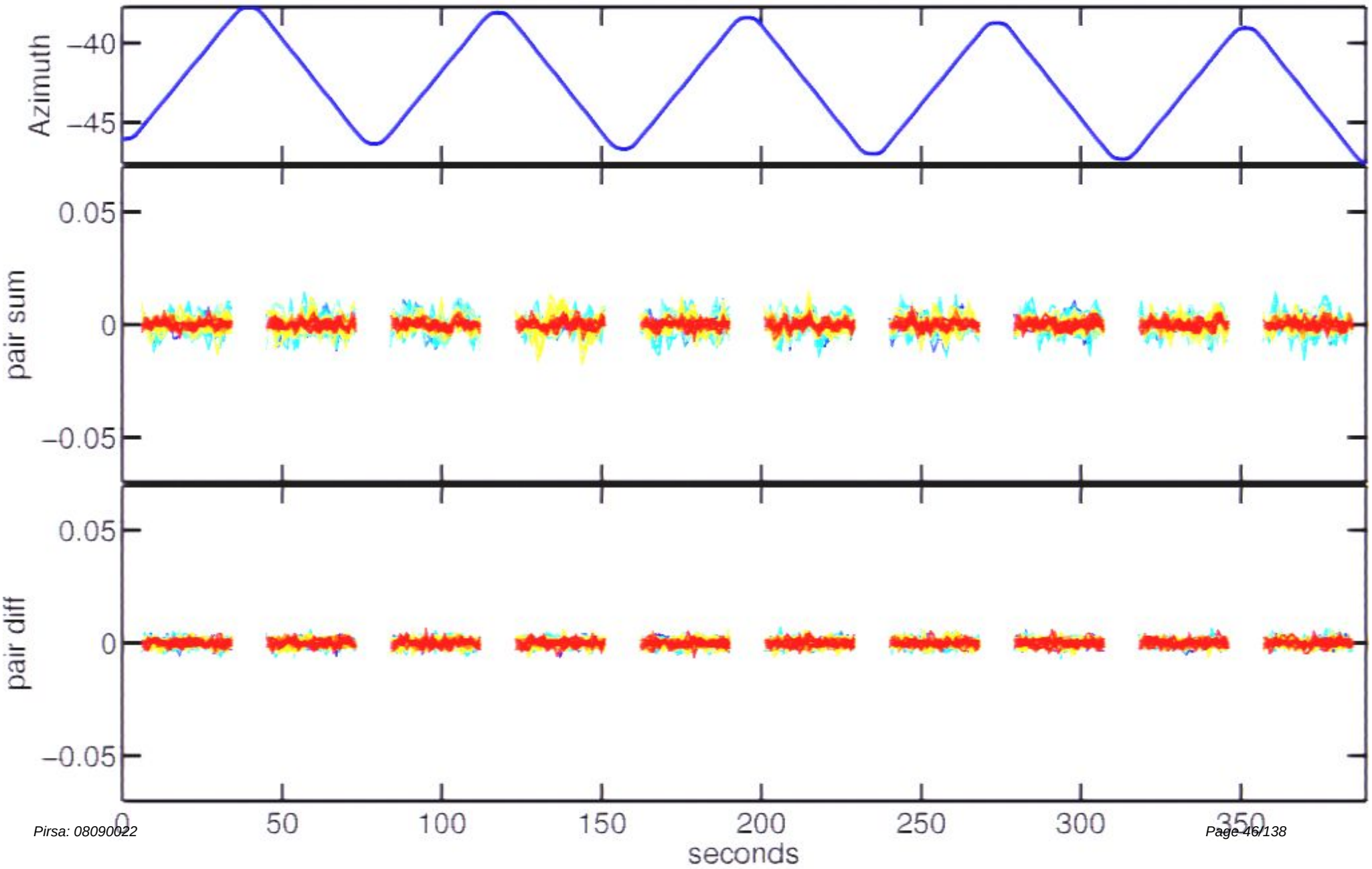
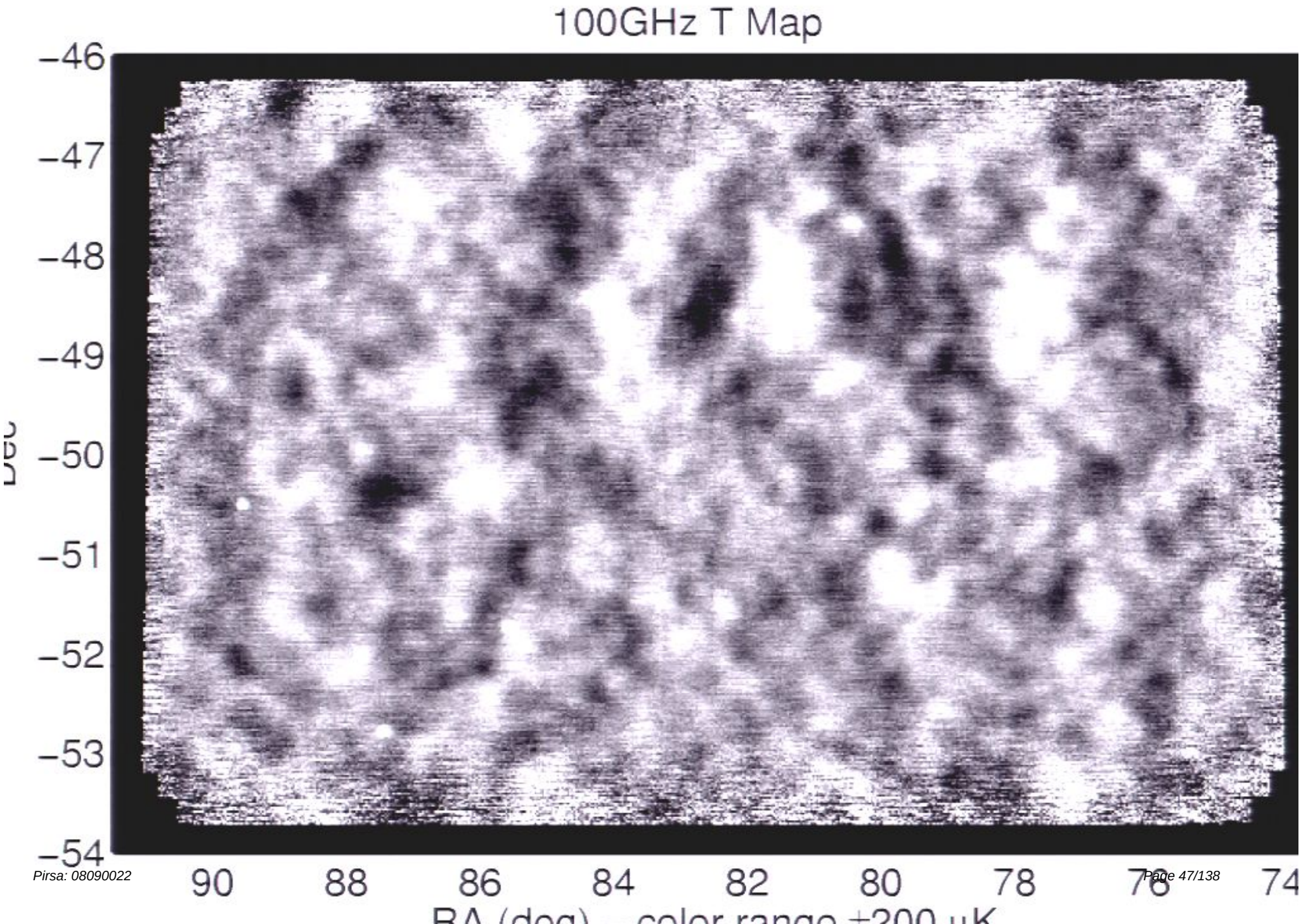


...cut to "half-scans"...



...remove 3rd order polynomials...




100GHz T Map
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Dec
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74
RA (deg) color range ±200 μK

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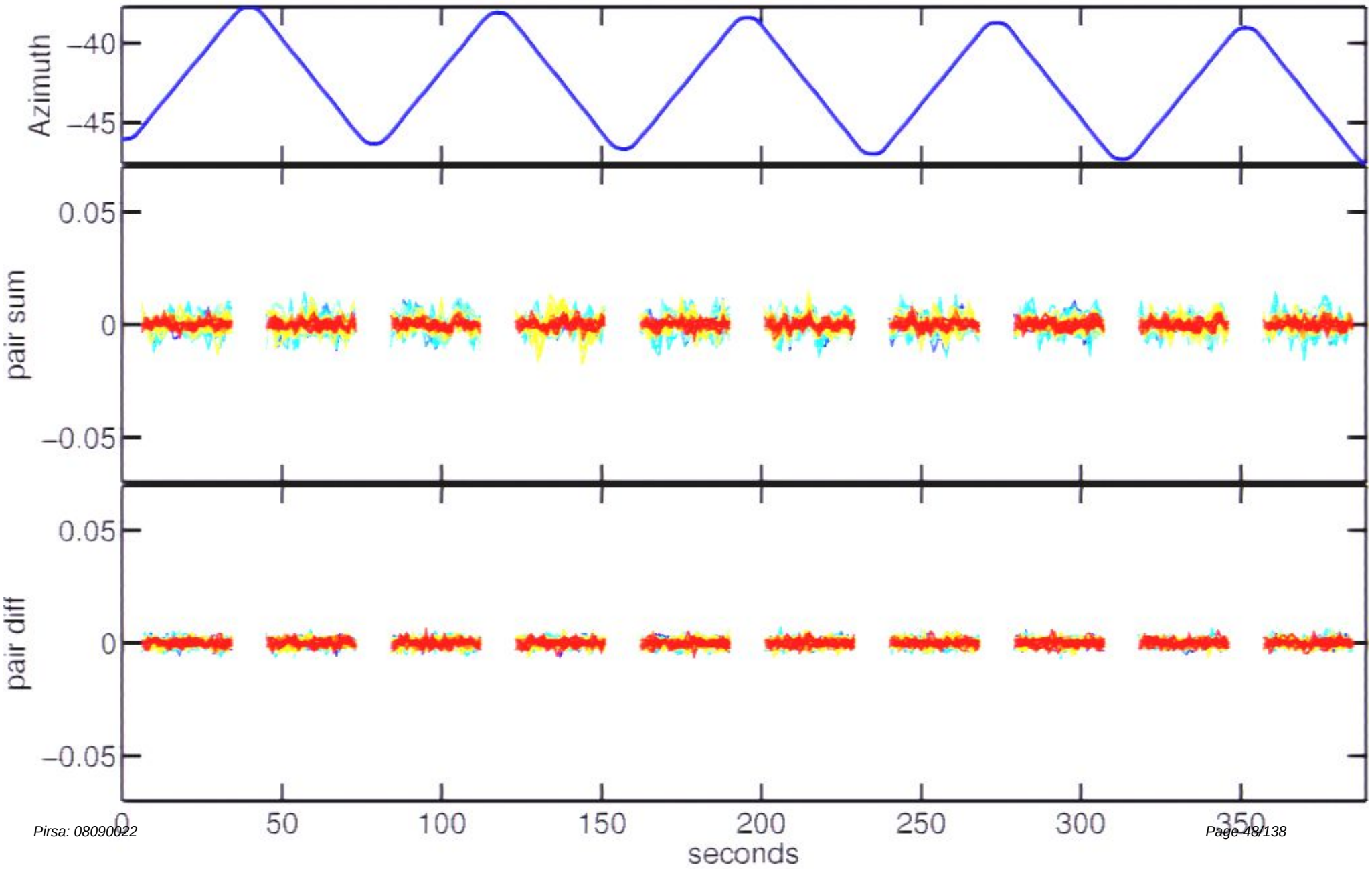

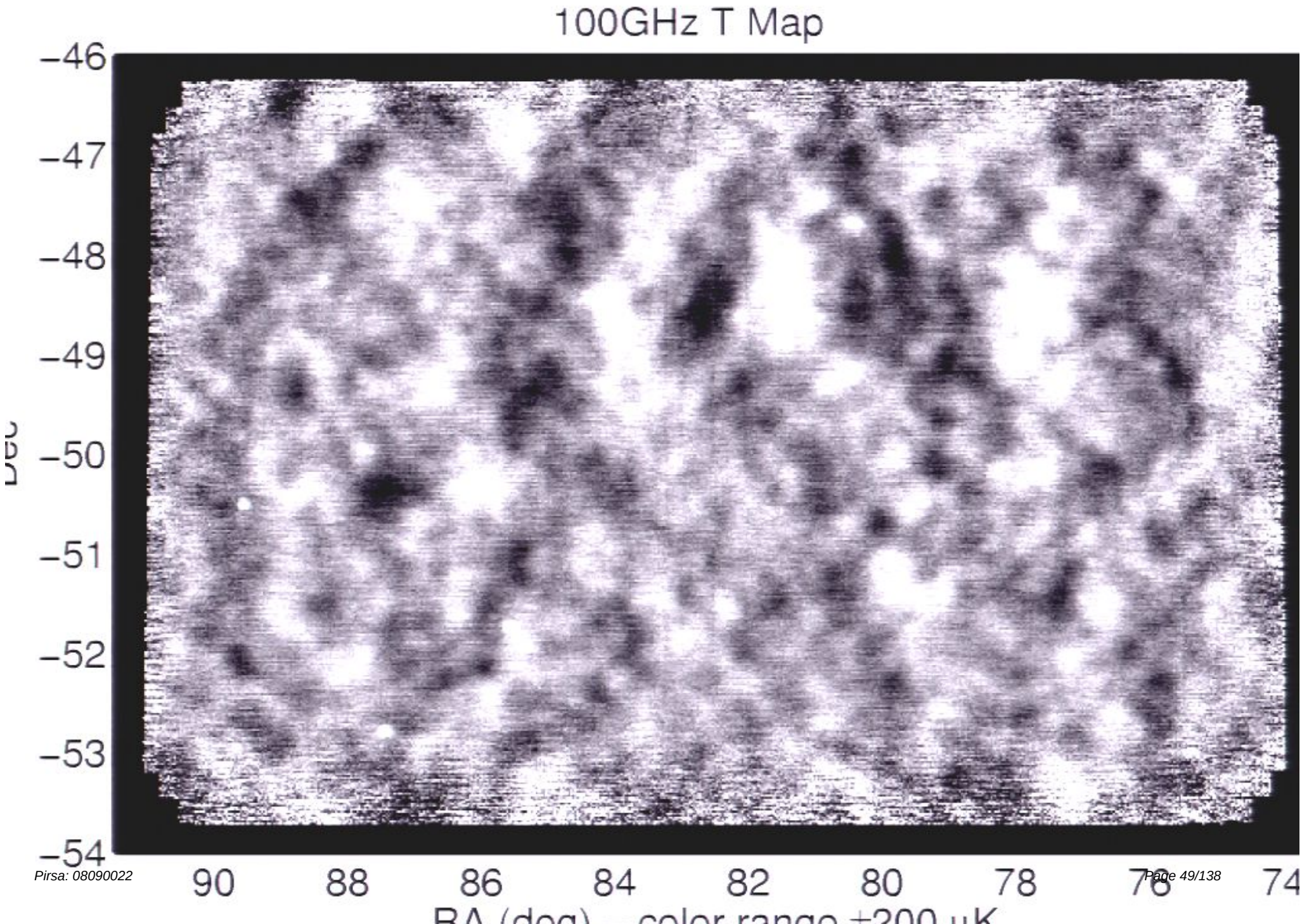
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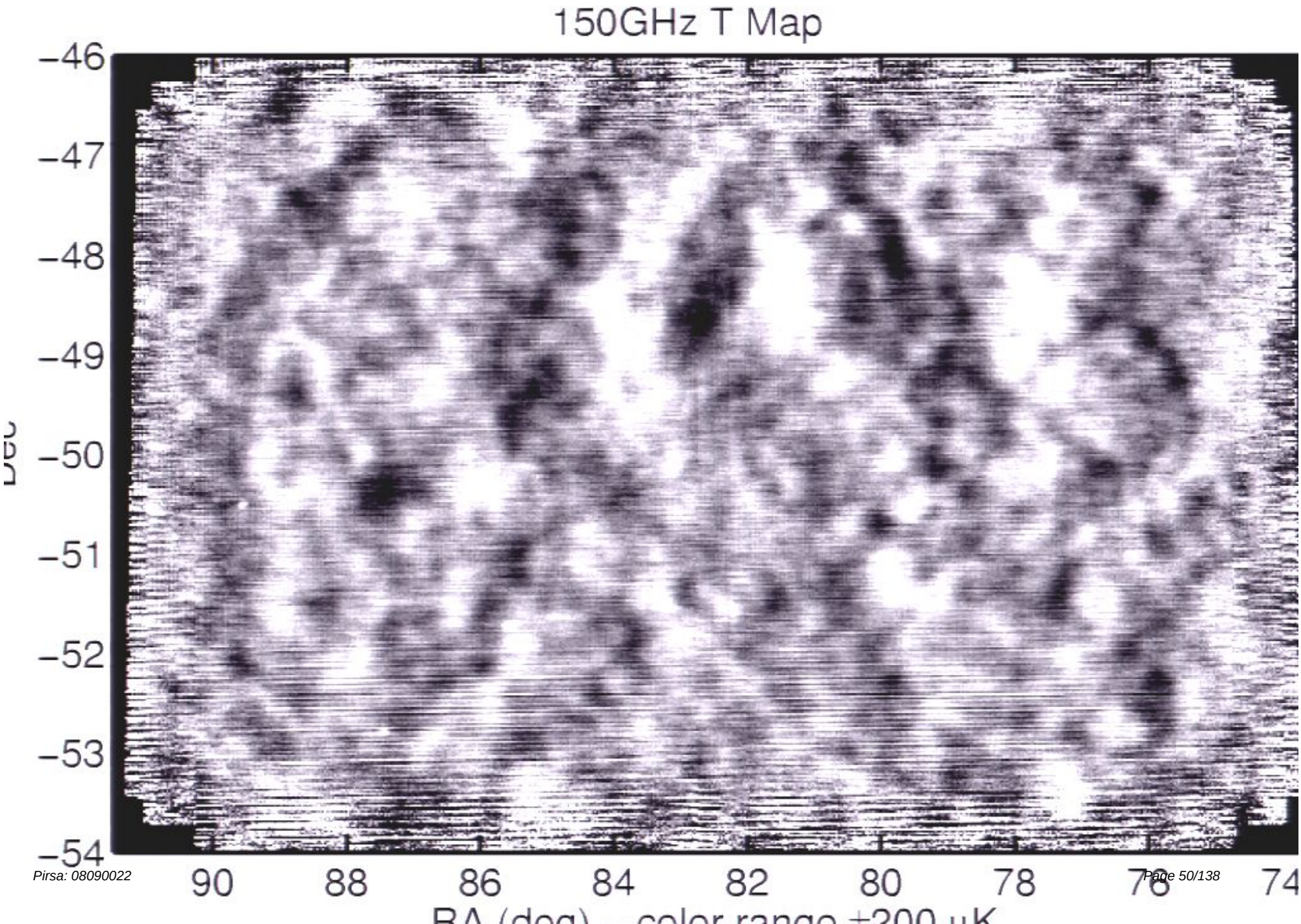
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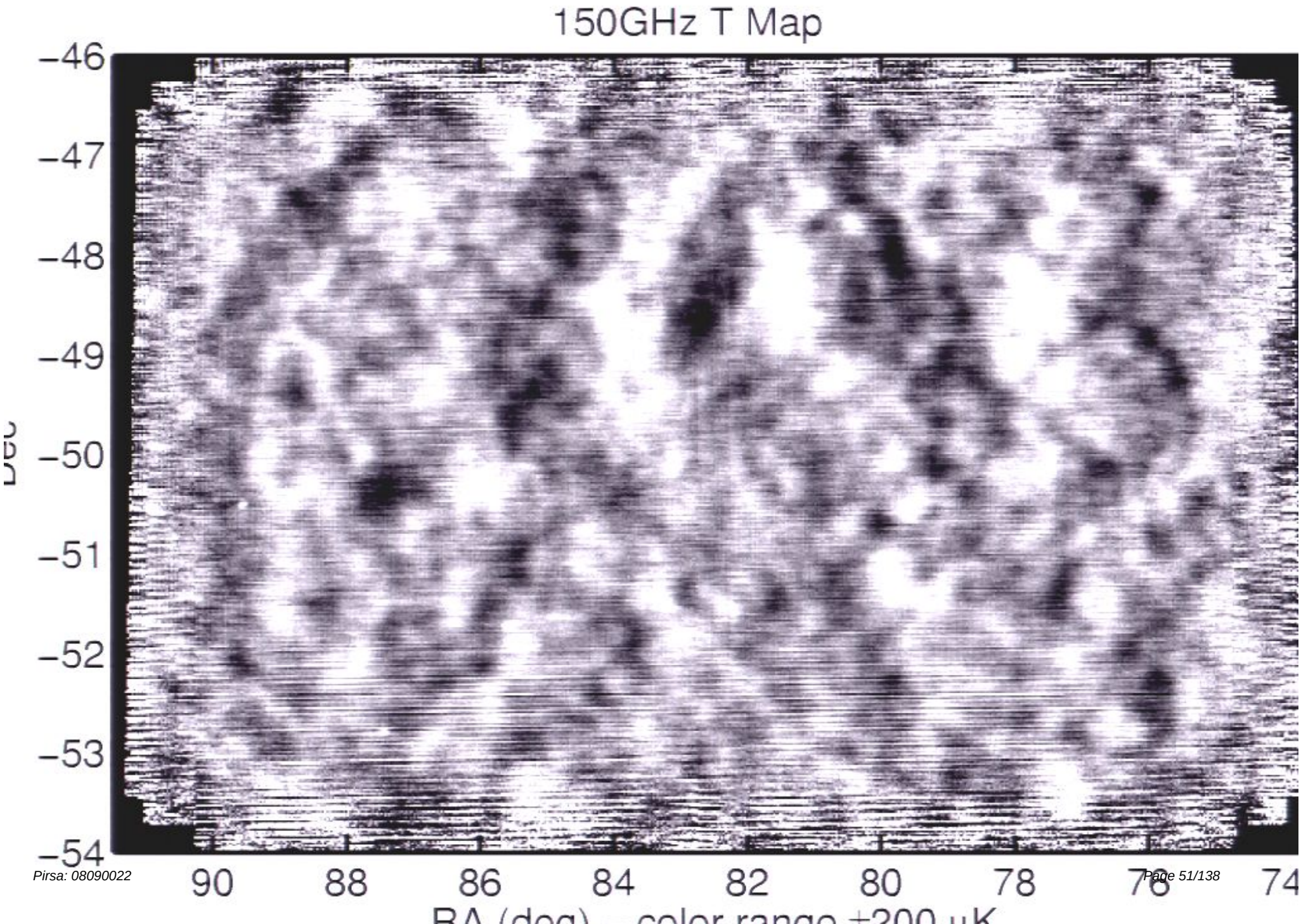
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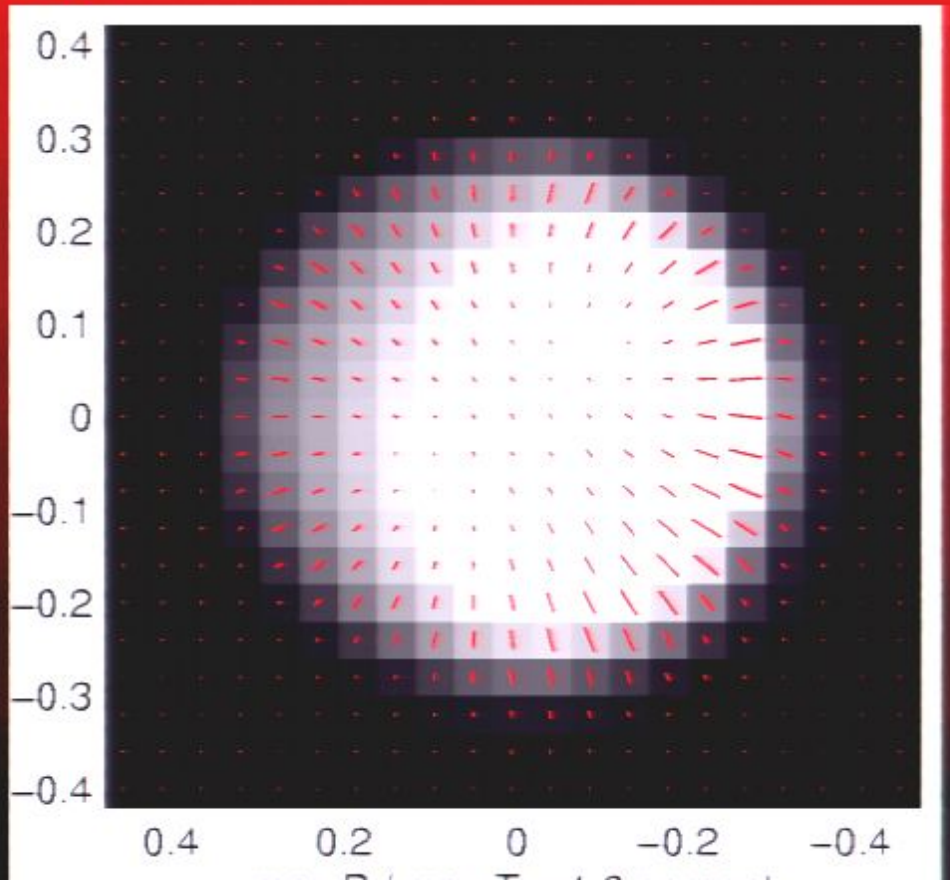
Constructing Polarization Maps

- To go from pair diff timestream to pol. maps (Q/U) need to know orientation of bolometer pairs as projected on sky
  - Confirmed very close to design values using external source.
- Complete pipeline confirmed by mapping Moon
  - (has weak radial polarization pattern due to scattering as radiation exits lunar surface)



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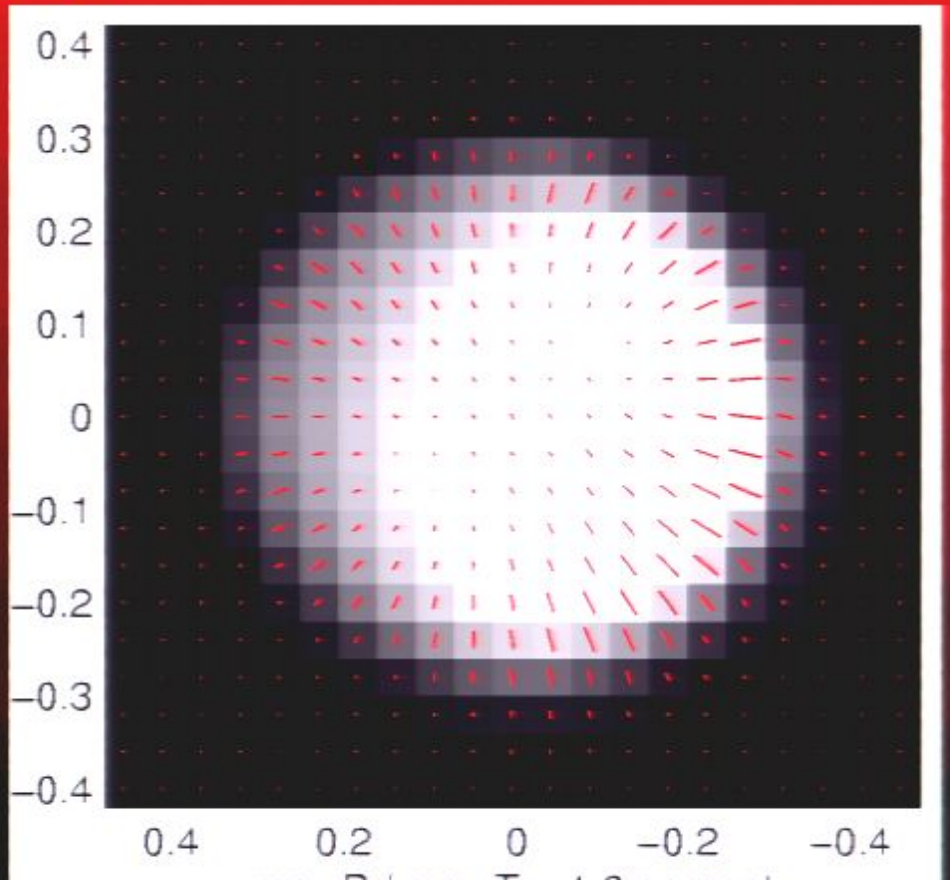

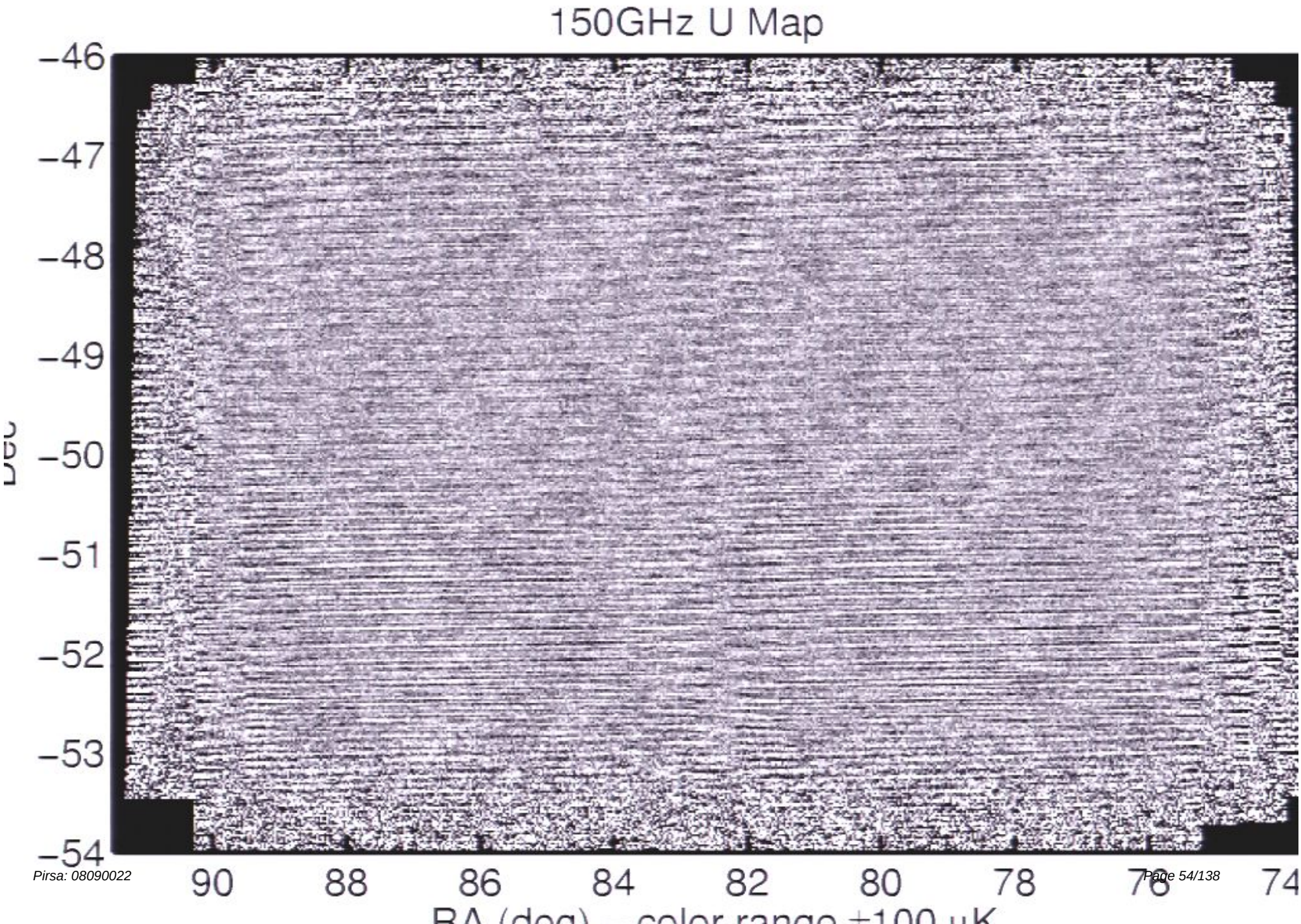
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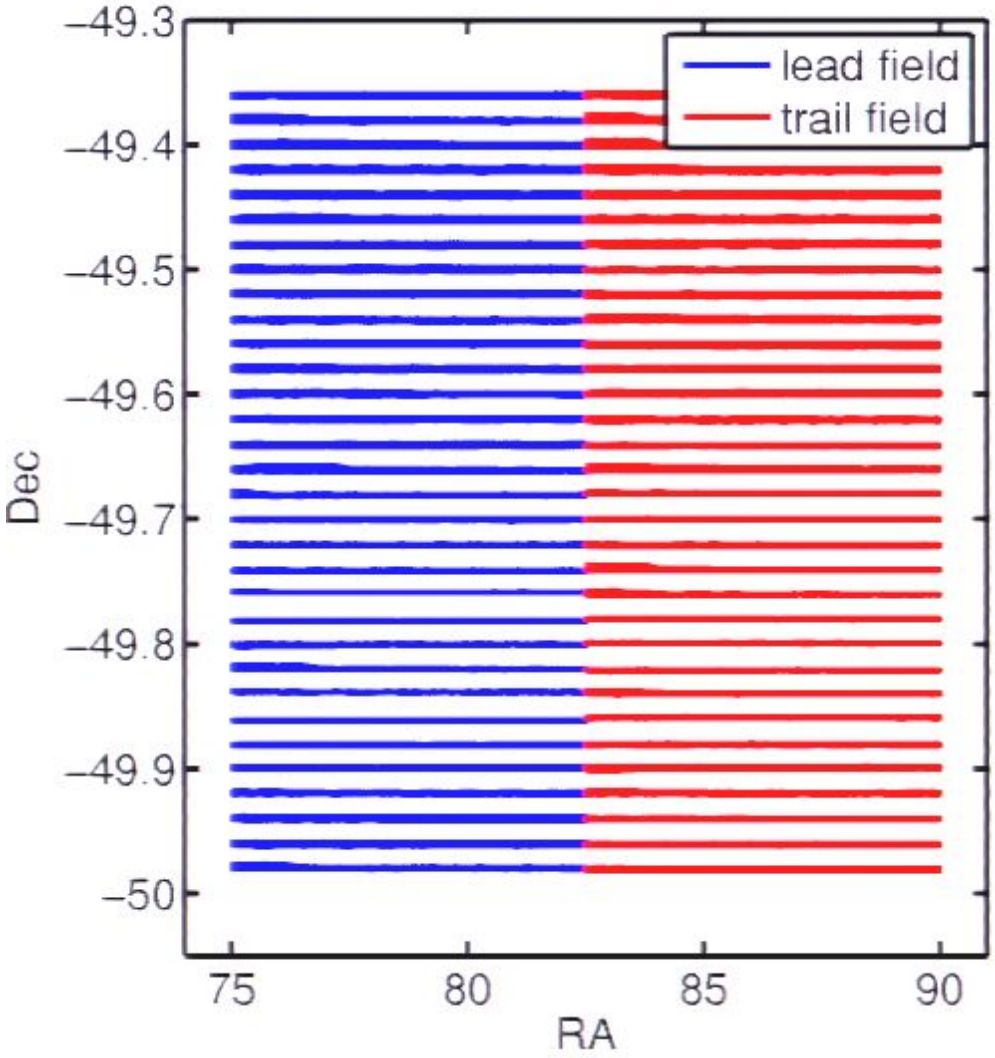
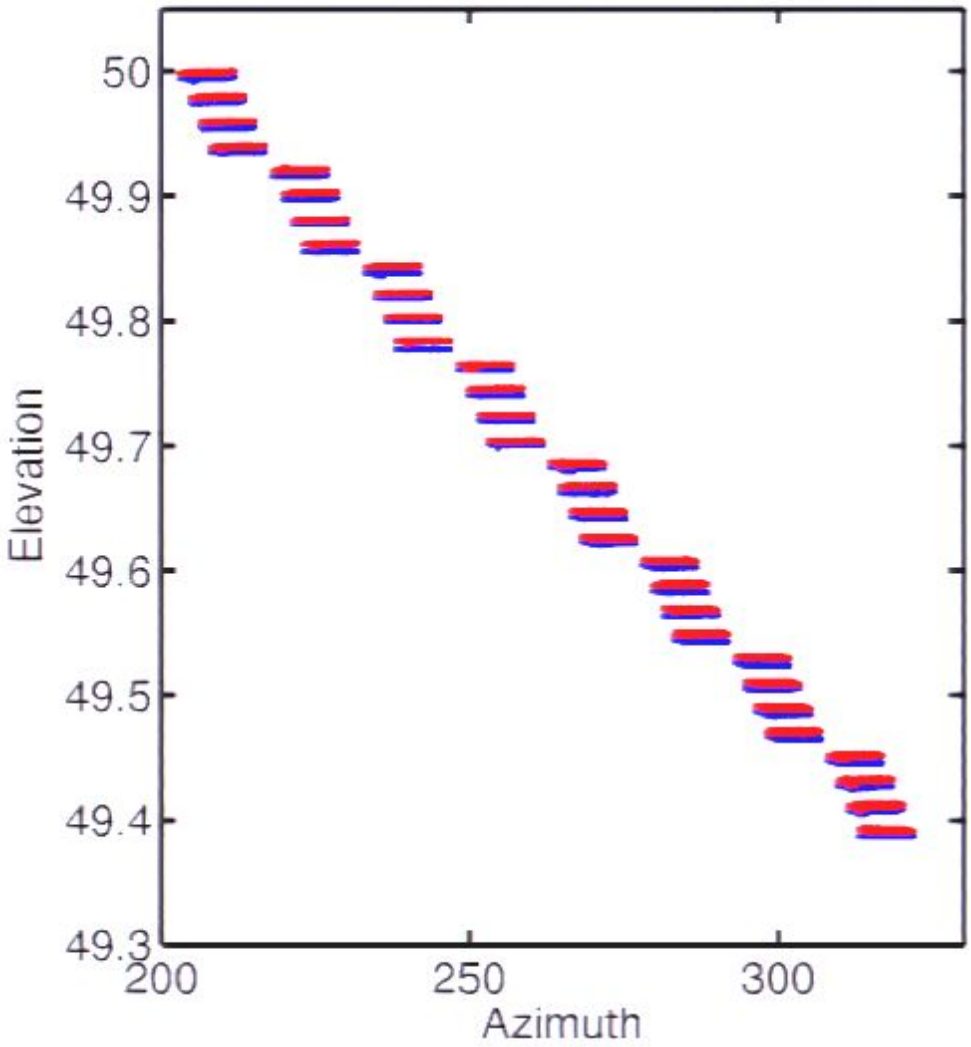
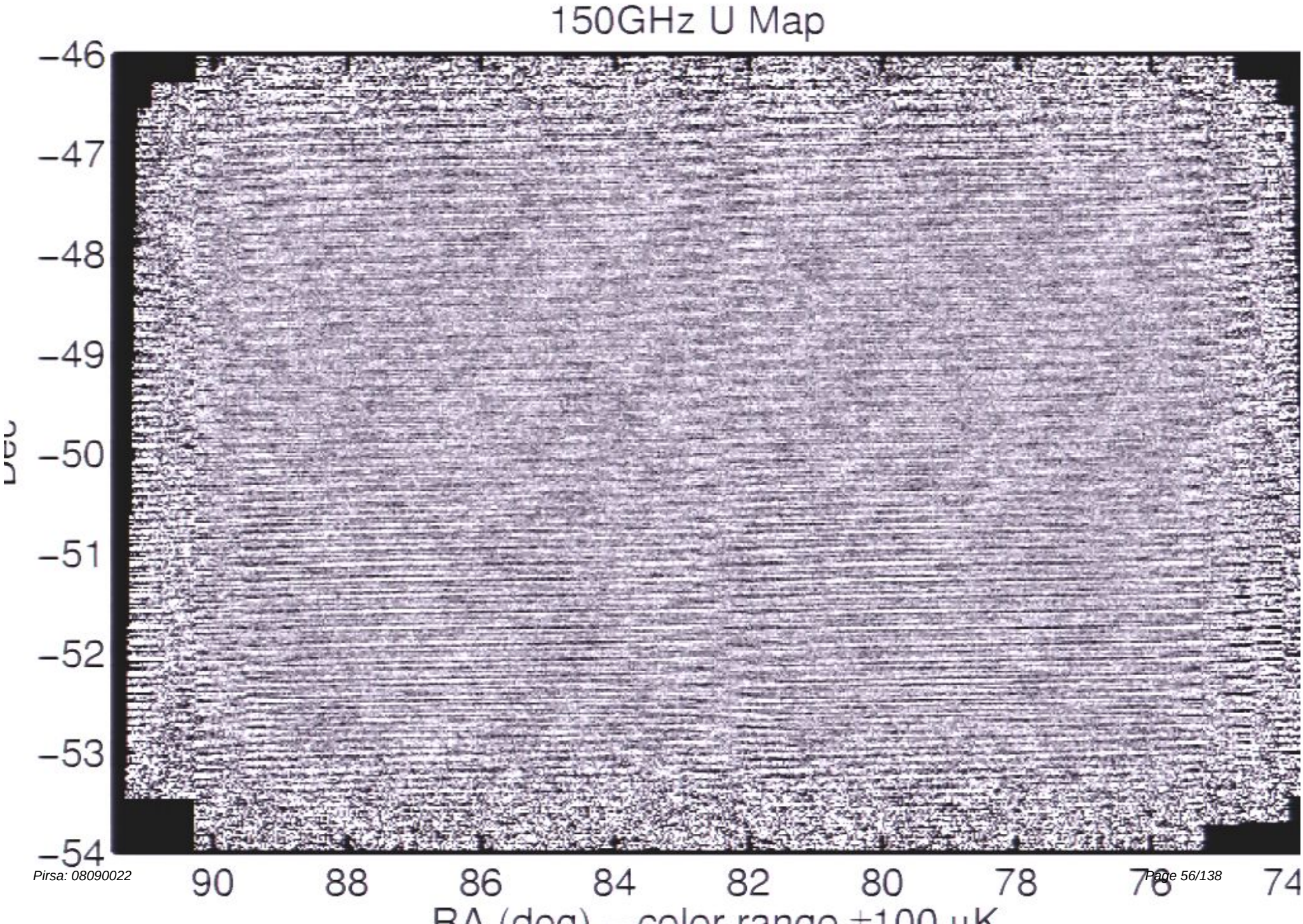
Lead/Trail Mapping





- Scan two sub-fields separated by 0.5hr in RA
  - Sky signal different - ground signal same


150GHz U Map
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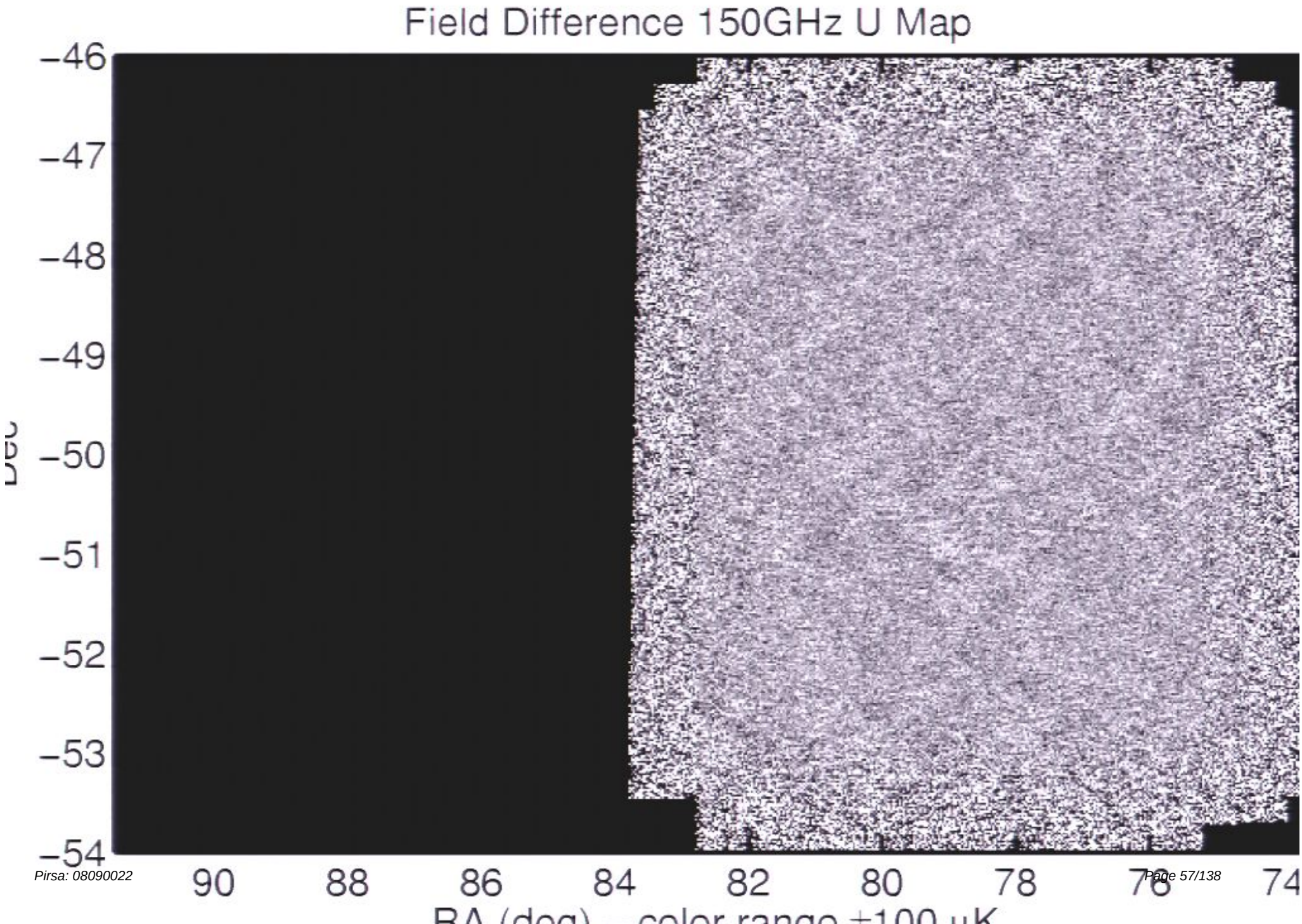
RA (deg) color range ±100 μK


Field Difference 150GHz U Map
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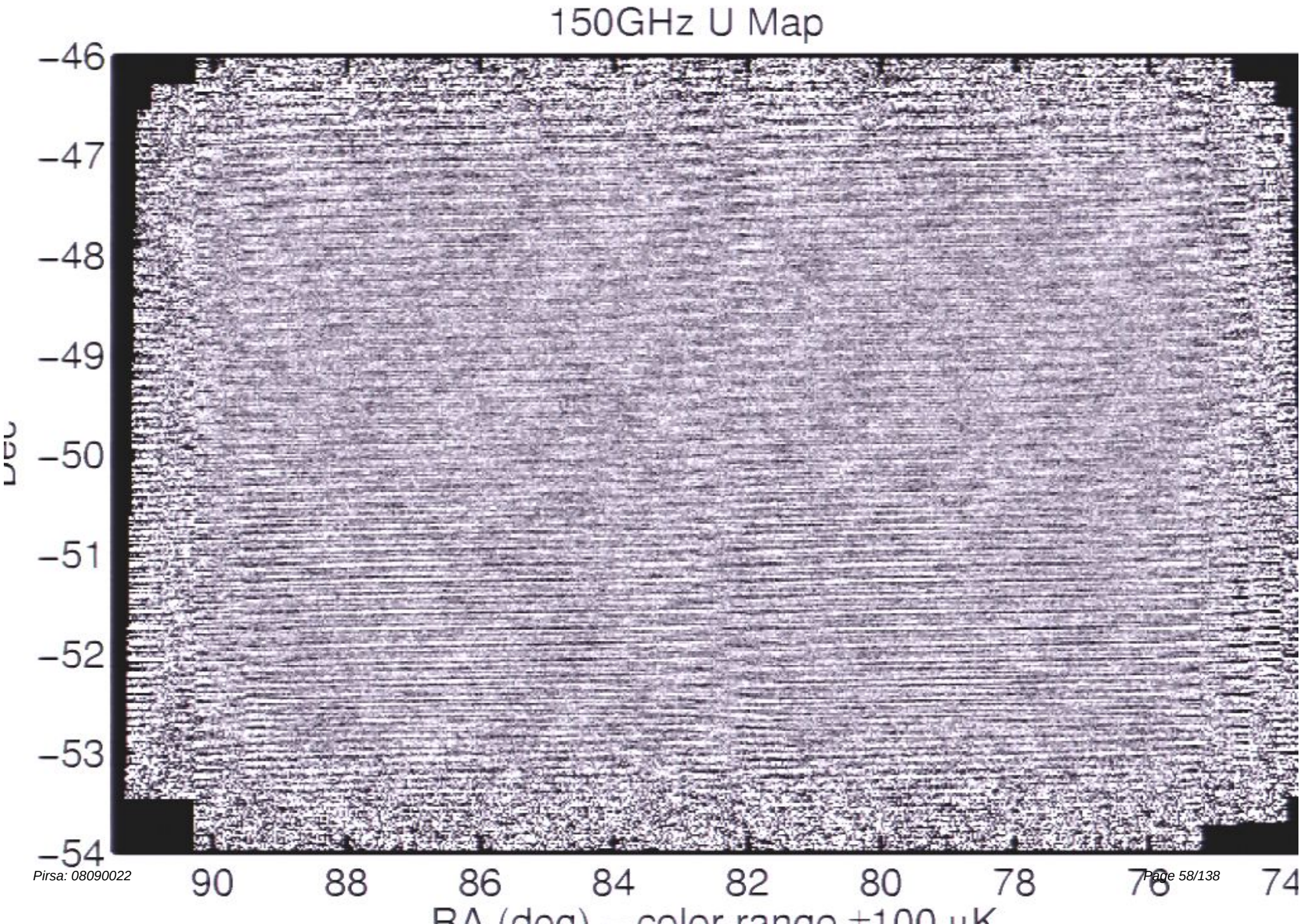
RA (deg) color range ±100 μK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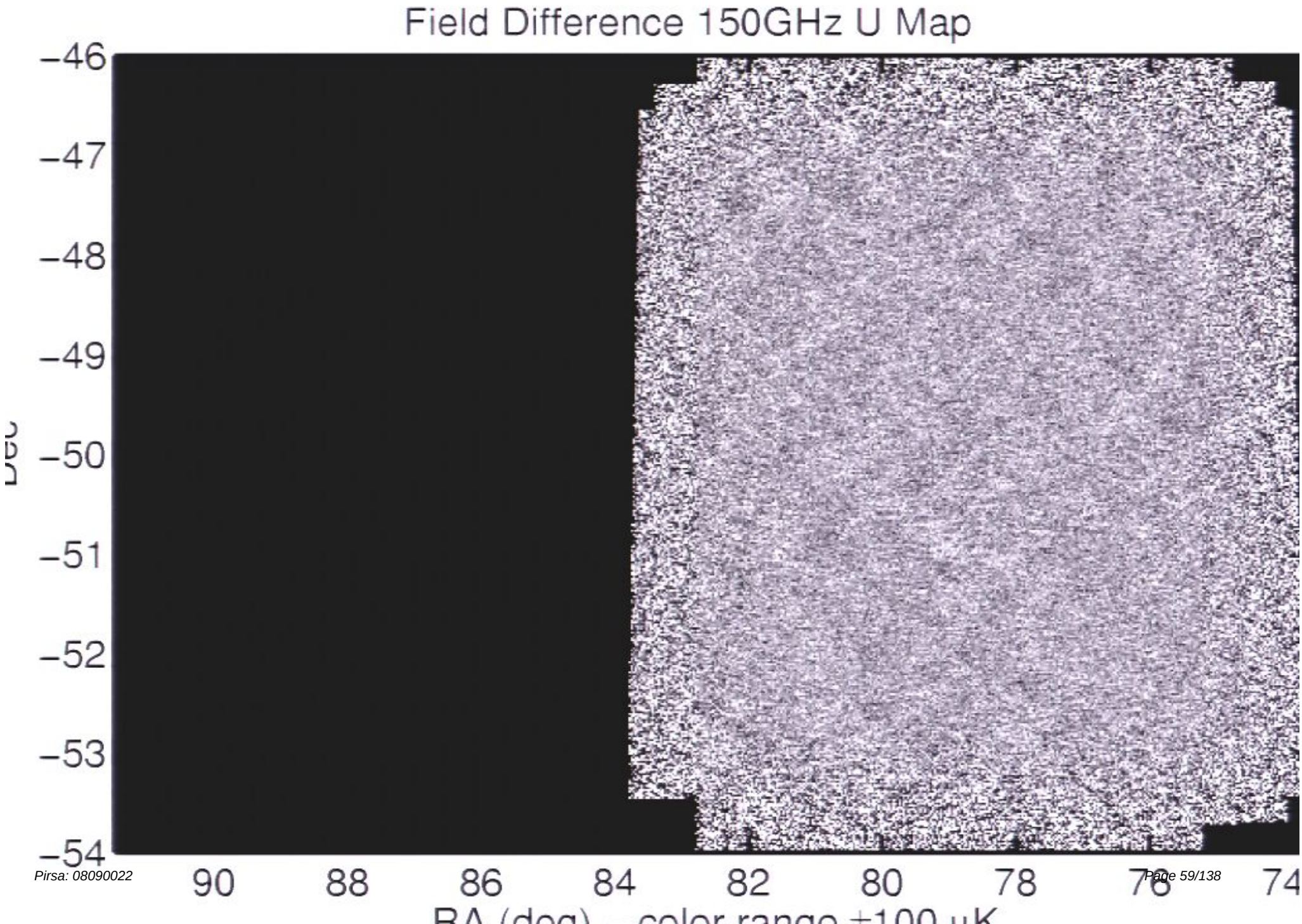
RA (deg) color range ±100 μK


Field Difference 150GHz U Map
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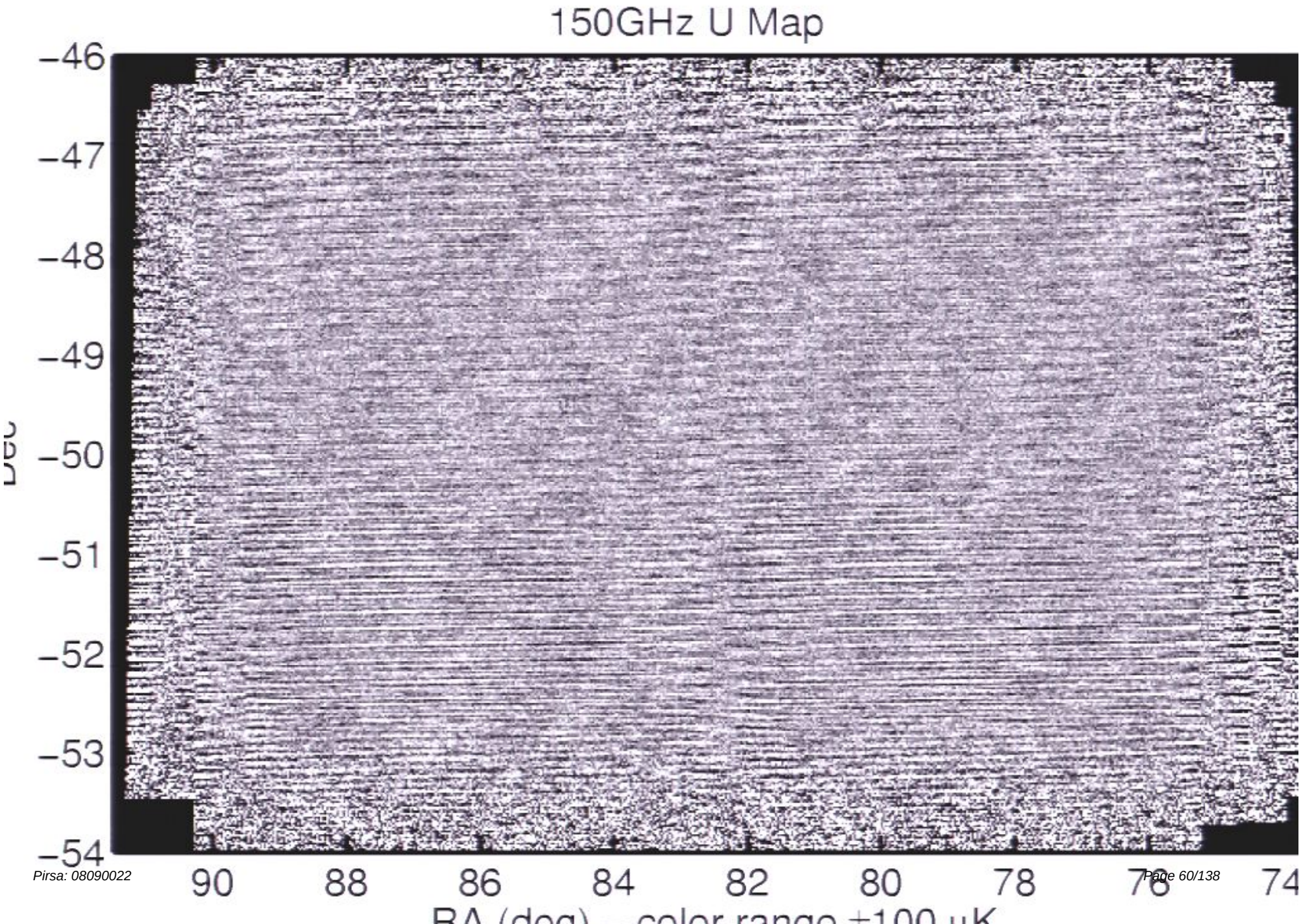
RA (deg) color range ±100 μK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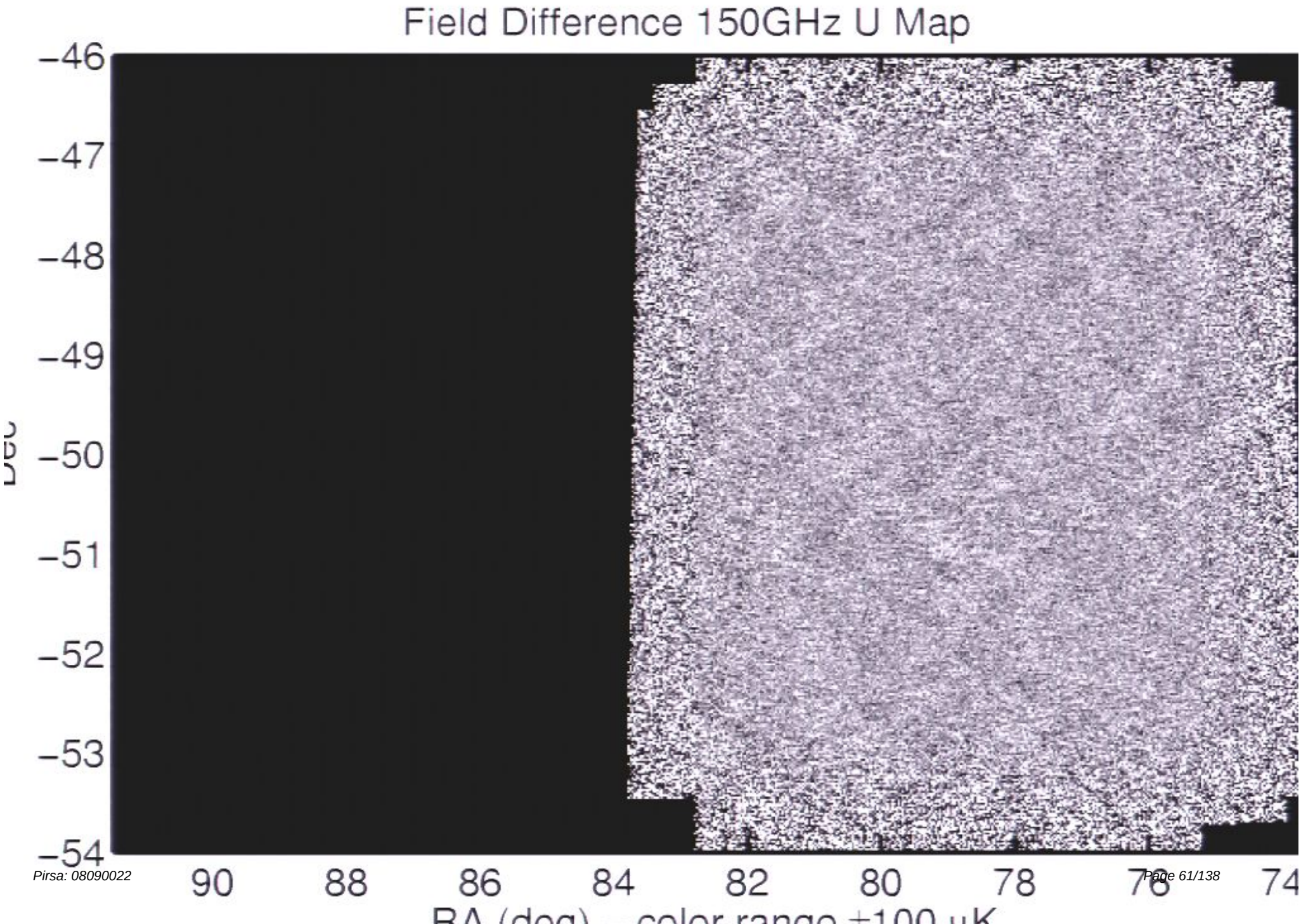
RA (deg) color range ±100 μK


Field Difference 150GHz U Map
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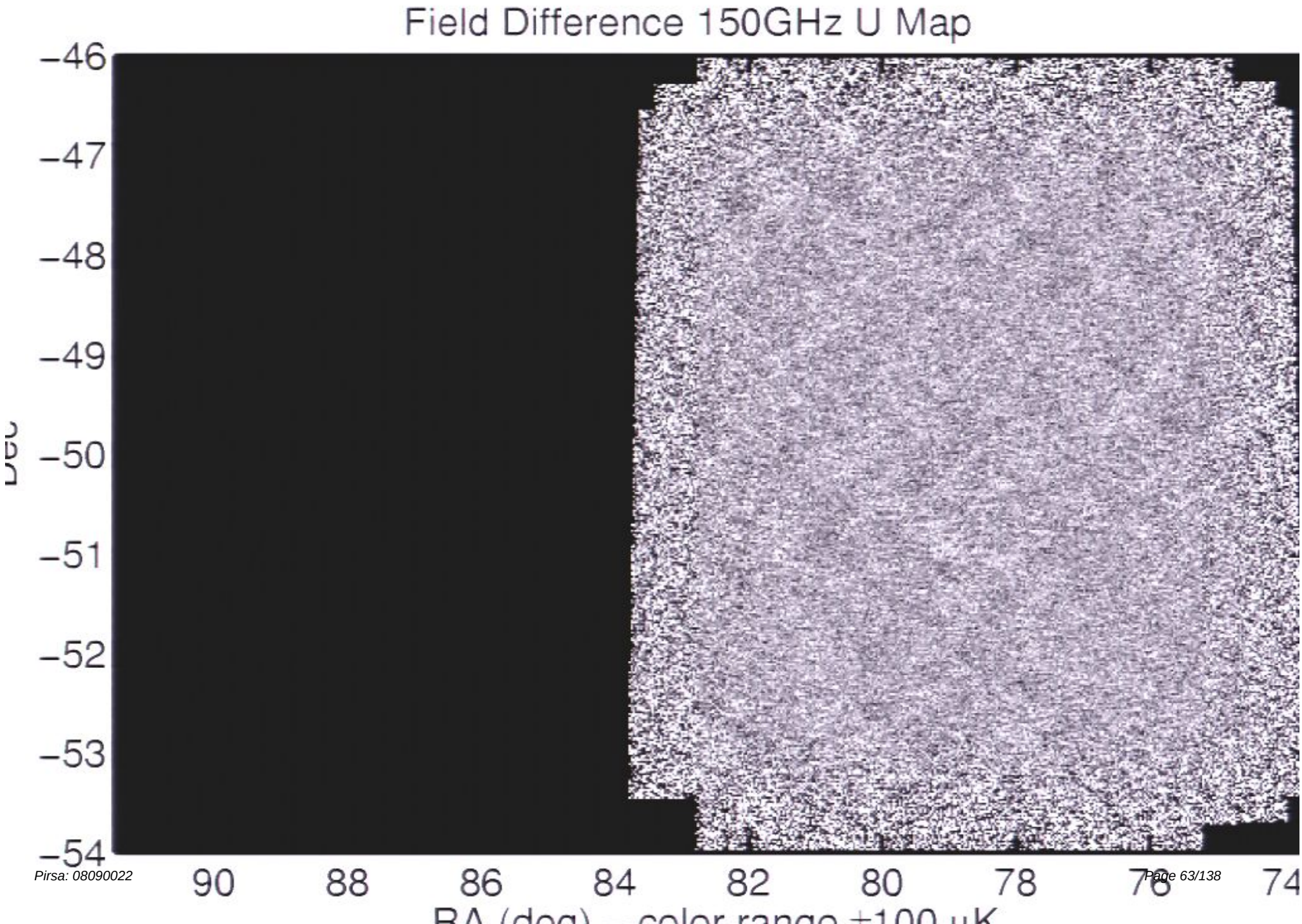
RA (deg) color range ±100 μK

Map Based Jackknifes

- An internal consistency check

- To confirm data is uncontaminated (after field diff) split into approx. equal subsets which should contain identical sky signal, but likely different false signal:
  - "Deck jack" - different azimuth range (different ground) with 60 deg rotation about line-of-sight
  - "Scan jack" - forward versus backwards scans
  - "Season jack" - first/second halves of data
  - "Focal plane jack" - bolo pair orientation groups

- Make maps using each half of data
  - Subtract the maps - result should just be noise...


Field Difference 150GHz U Map
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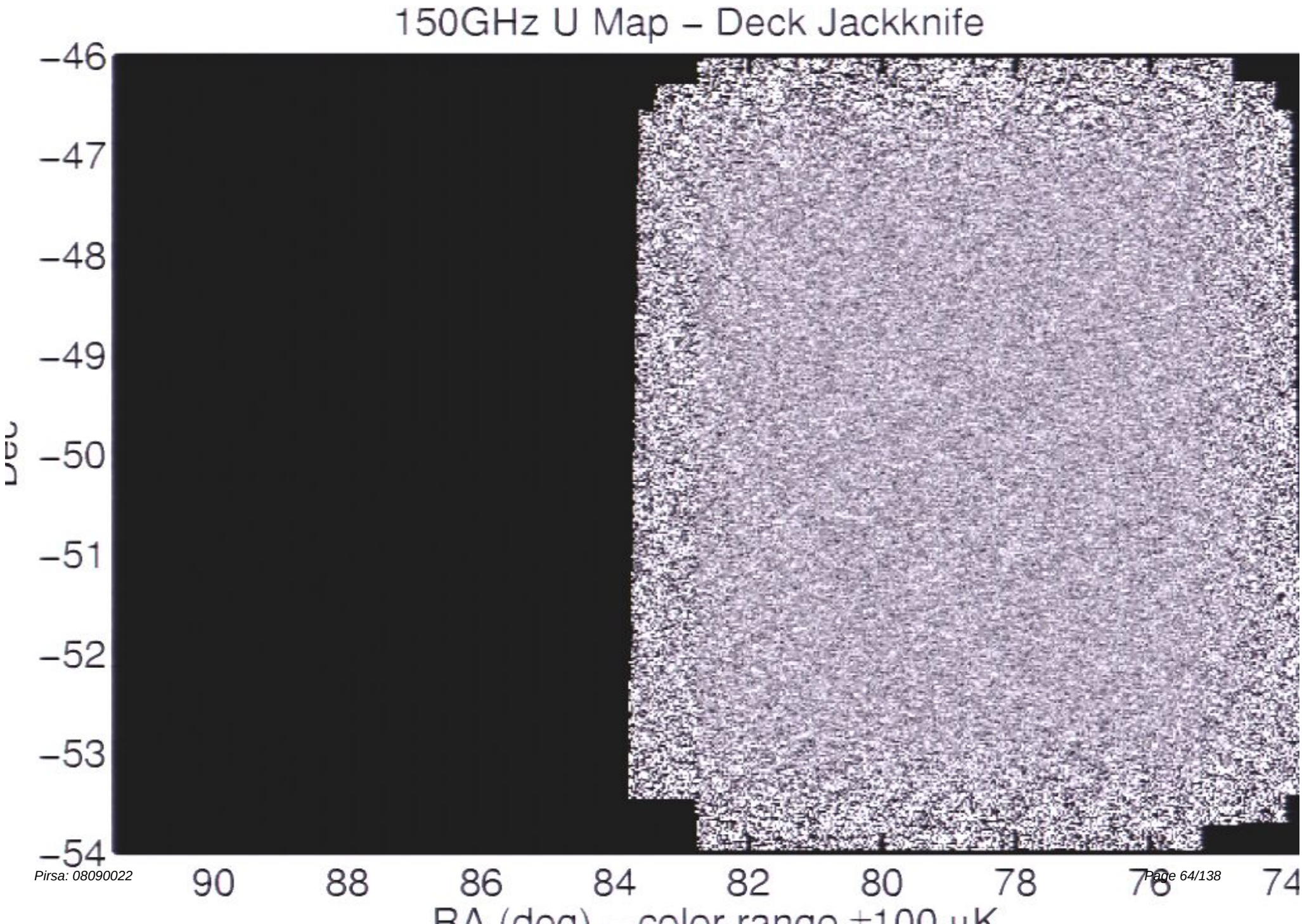
RA (deg) color range ±100 μK


150GHz U Map – Deck Jackknife
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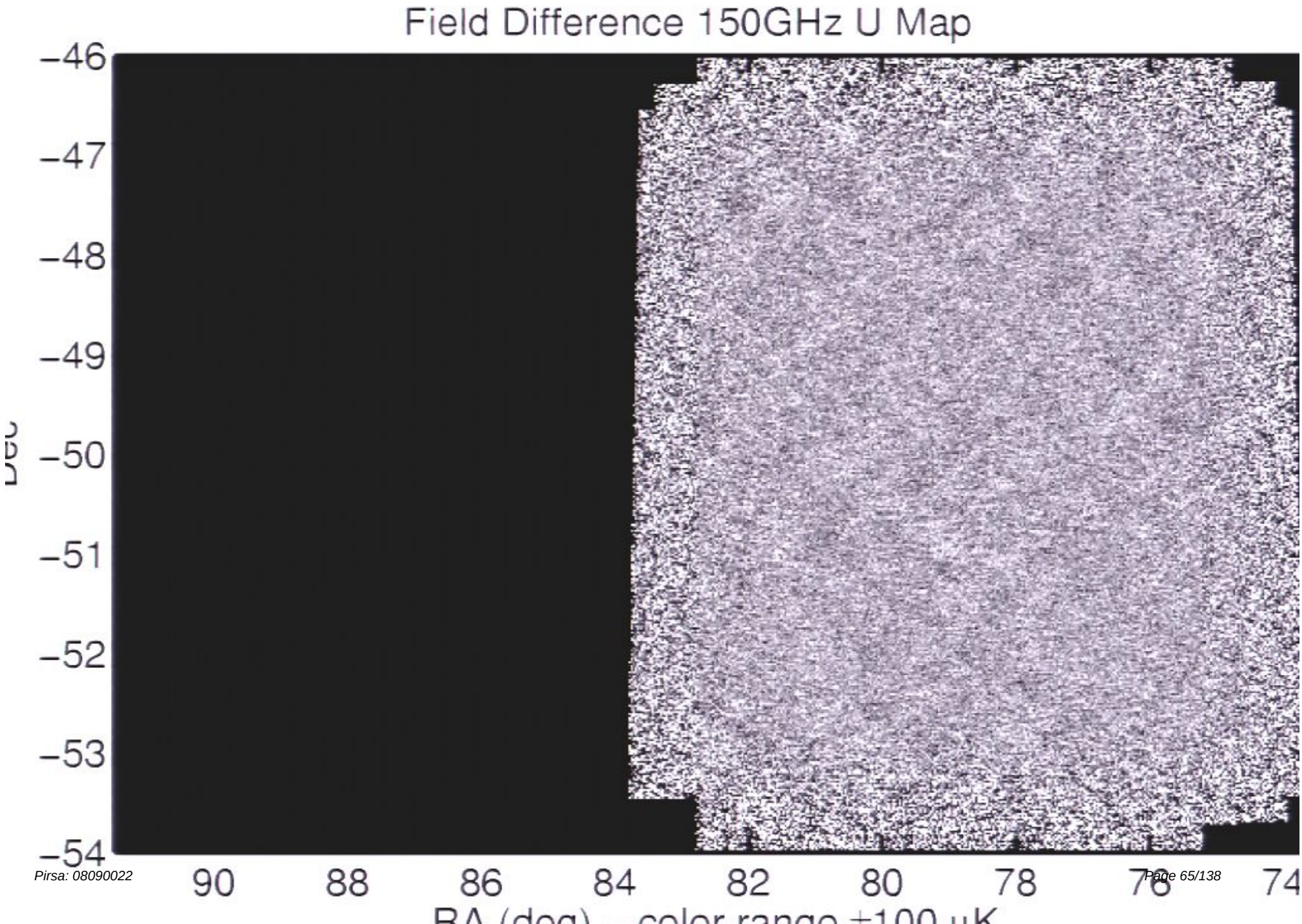
RA (deg) color range ±100 μK


Field Difference 150GHz U Map
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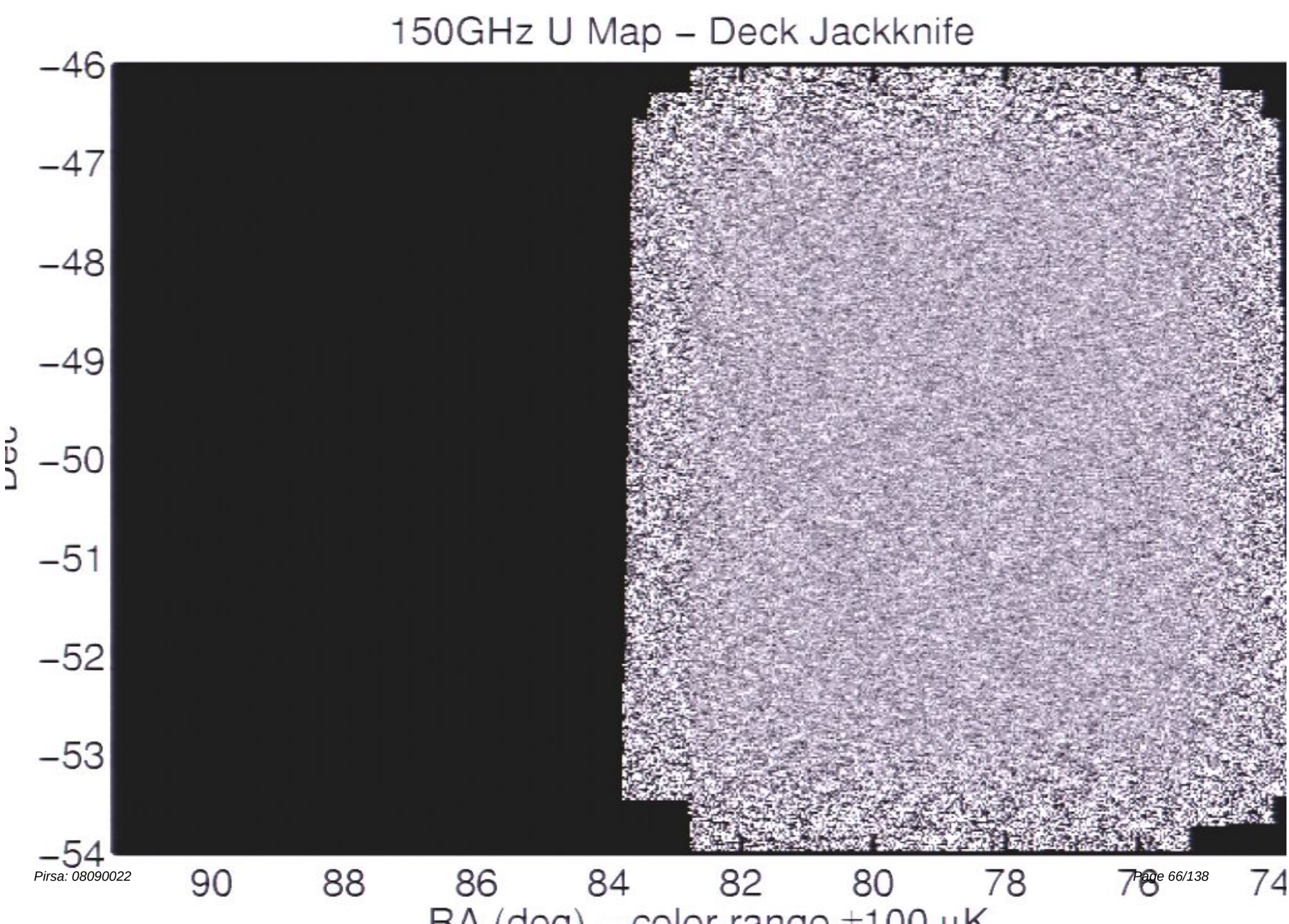
RA (deg) color range ±100 μK


150GHz U Map – Deck Jackknife
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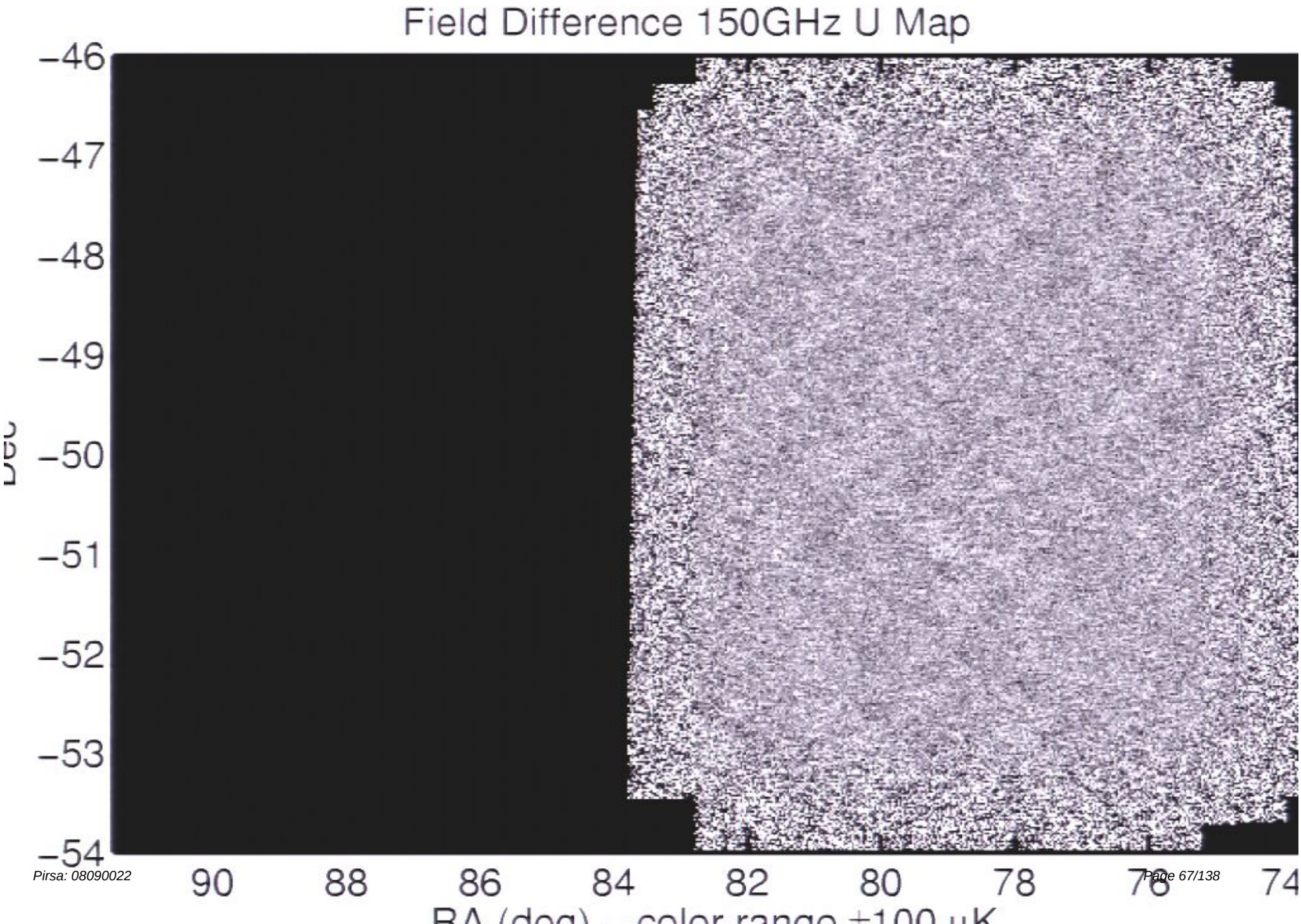
RA (deg) color range ±100 μK


Field Difference 150GHz U Map
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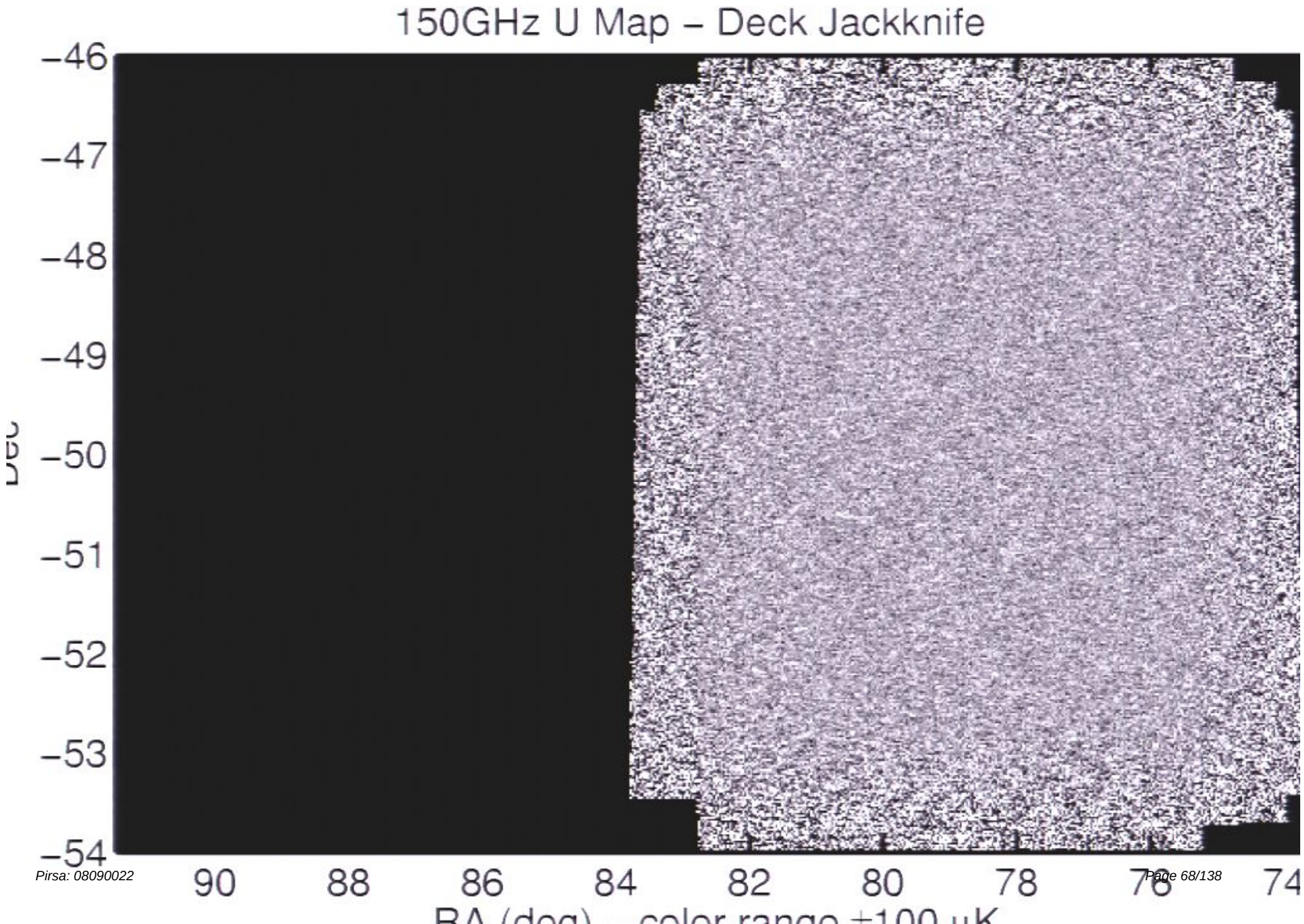
150GHz U Map – Deck Jackknife
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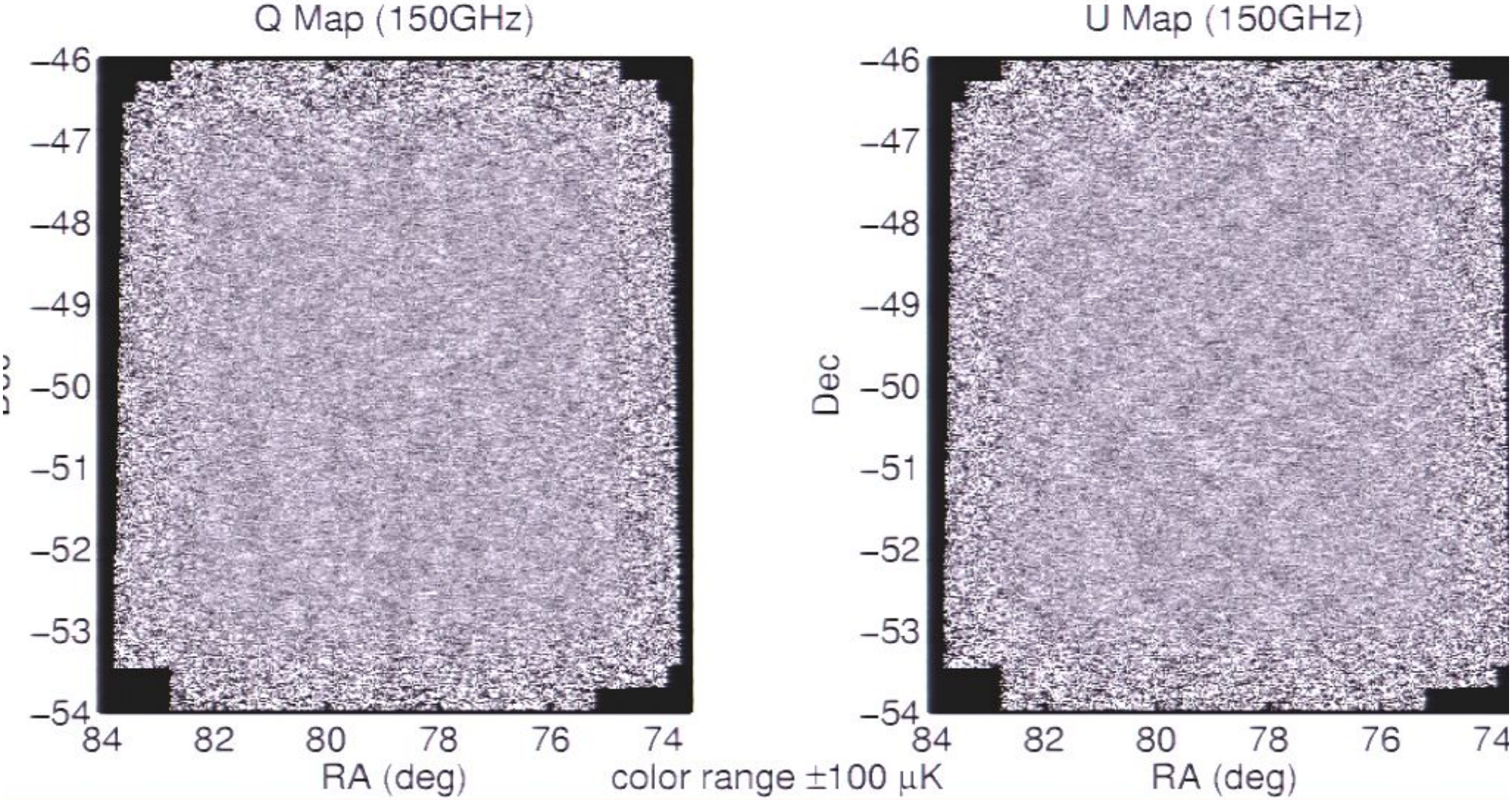
RA (deg) color range ±100 μK

From Maps to Power Spectra

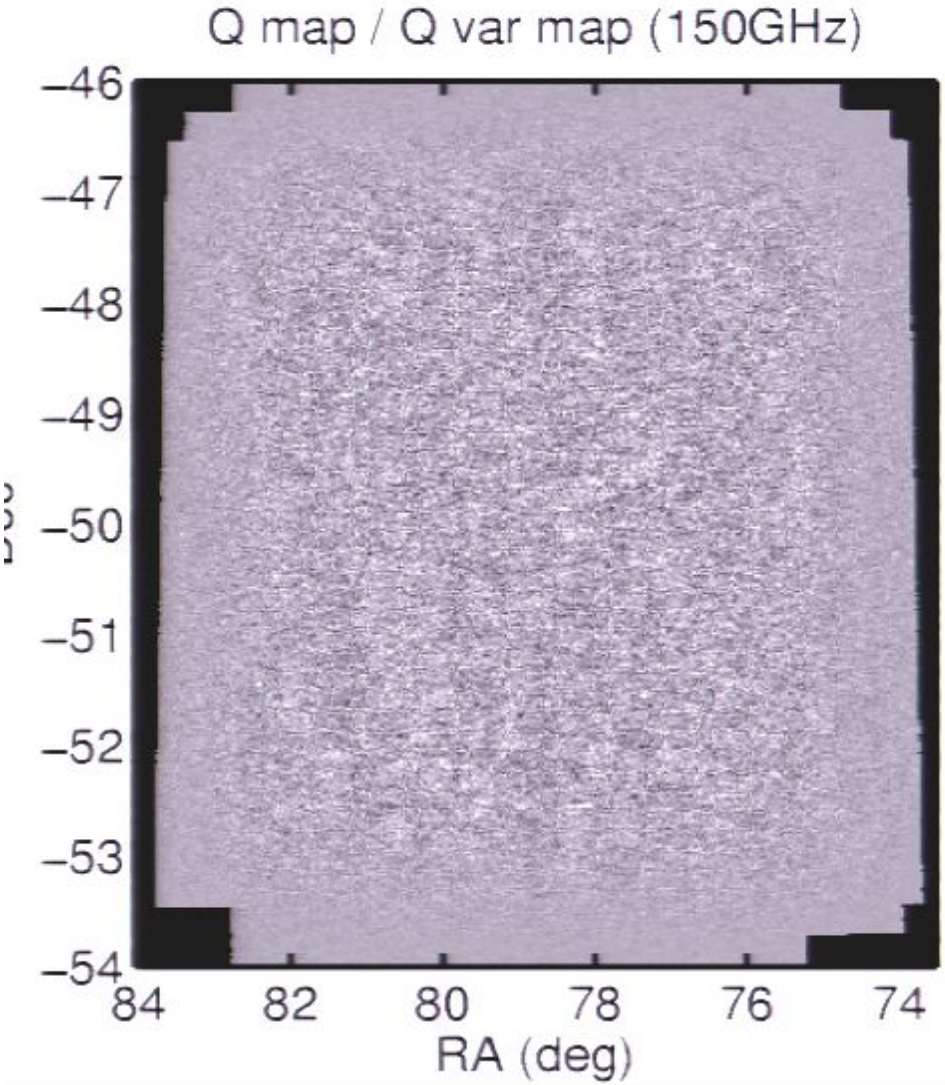
From Maps to Power Spectra

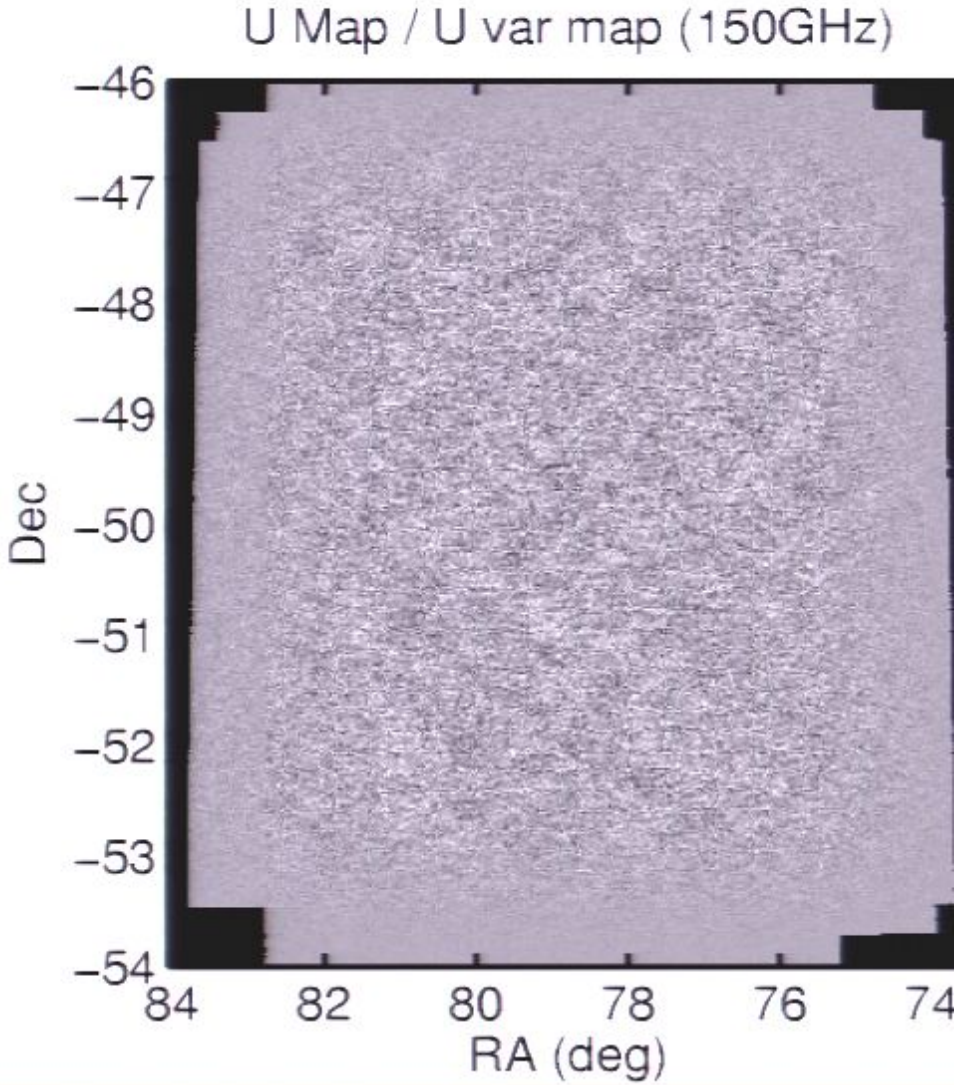
Take the Q/U maps...



How to make CMB power spectra step by step with pictures...

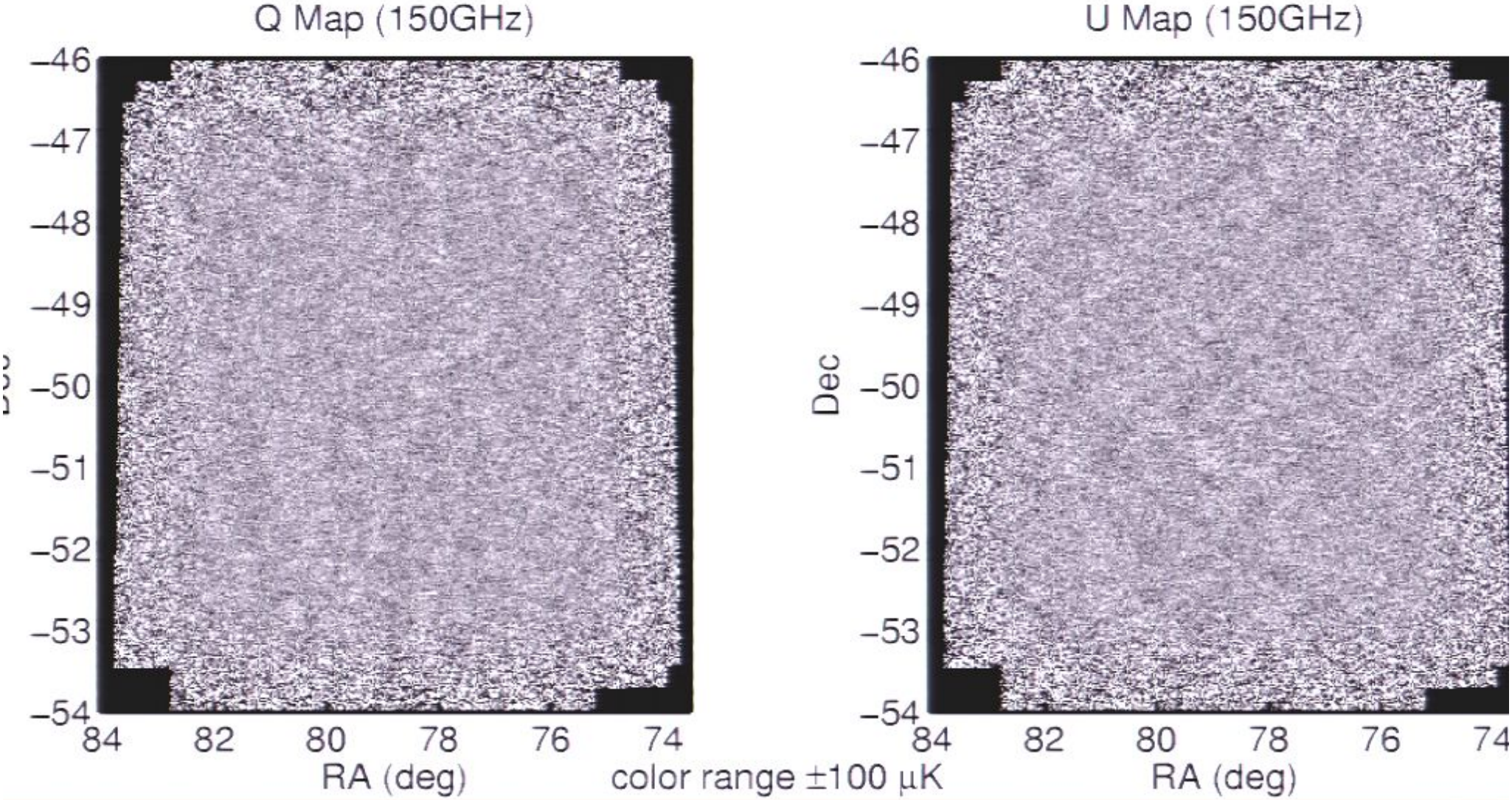
...appodize...





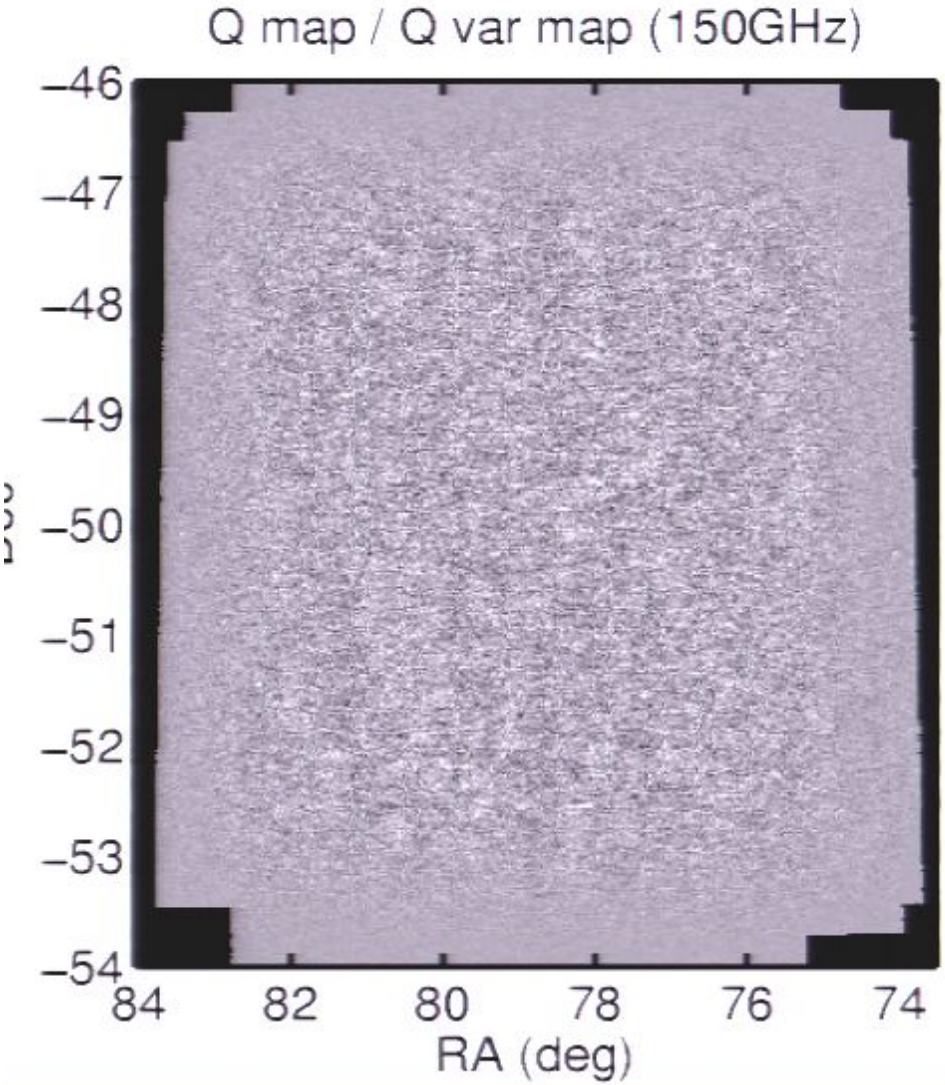
Divide signal map by variance map

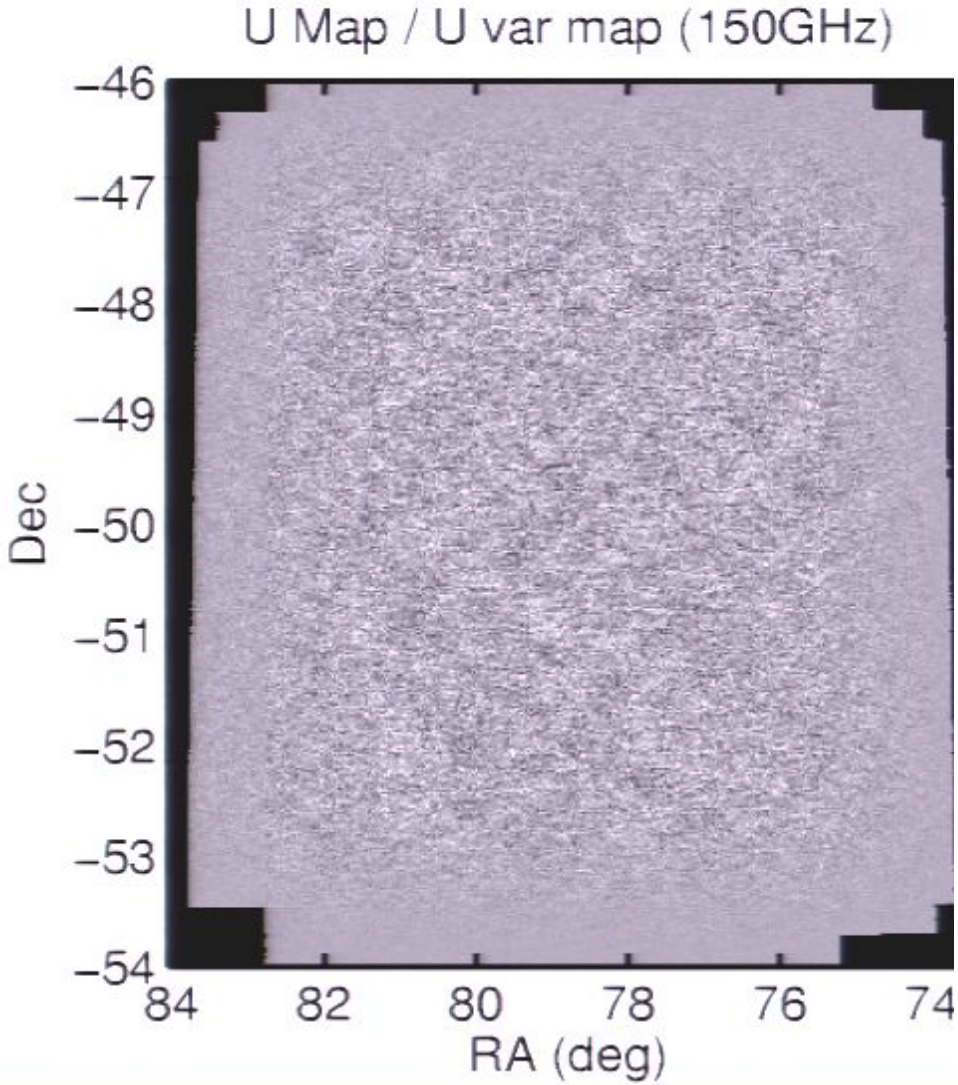
Take the Q/U maps...



How to make CMB power spectra step by step with pictures...

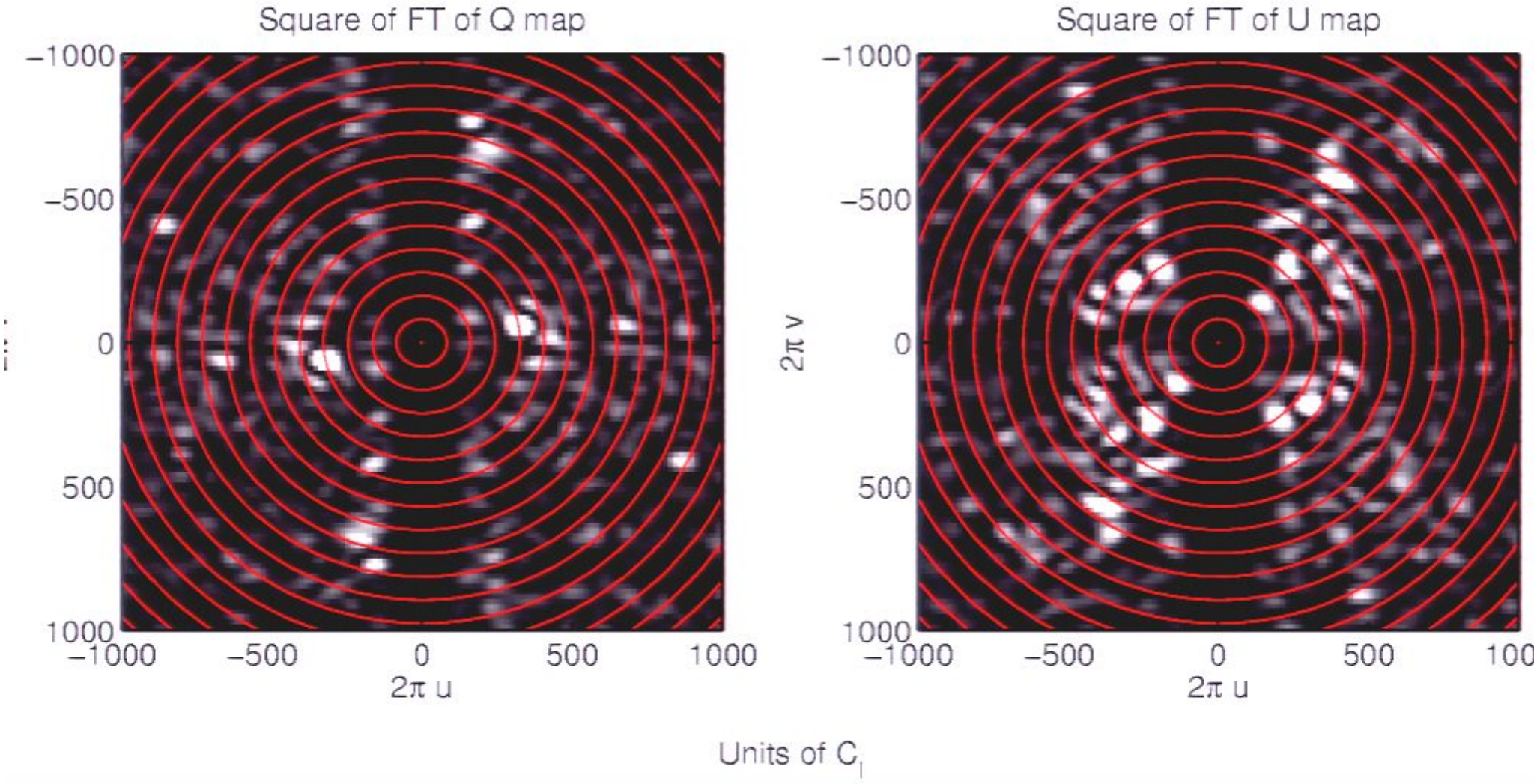
...appodize...





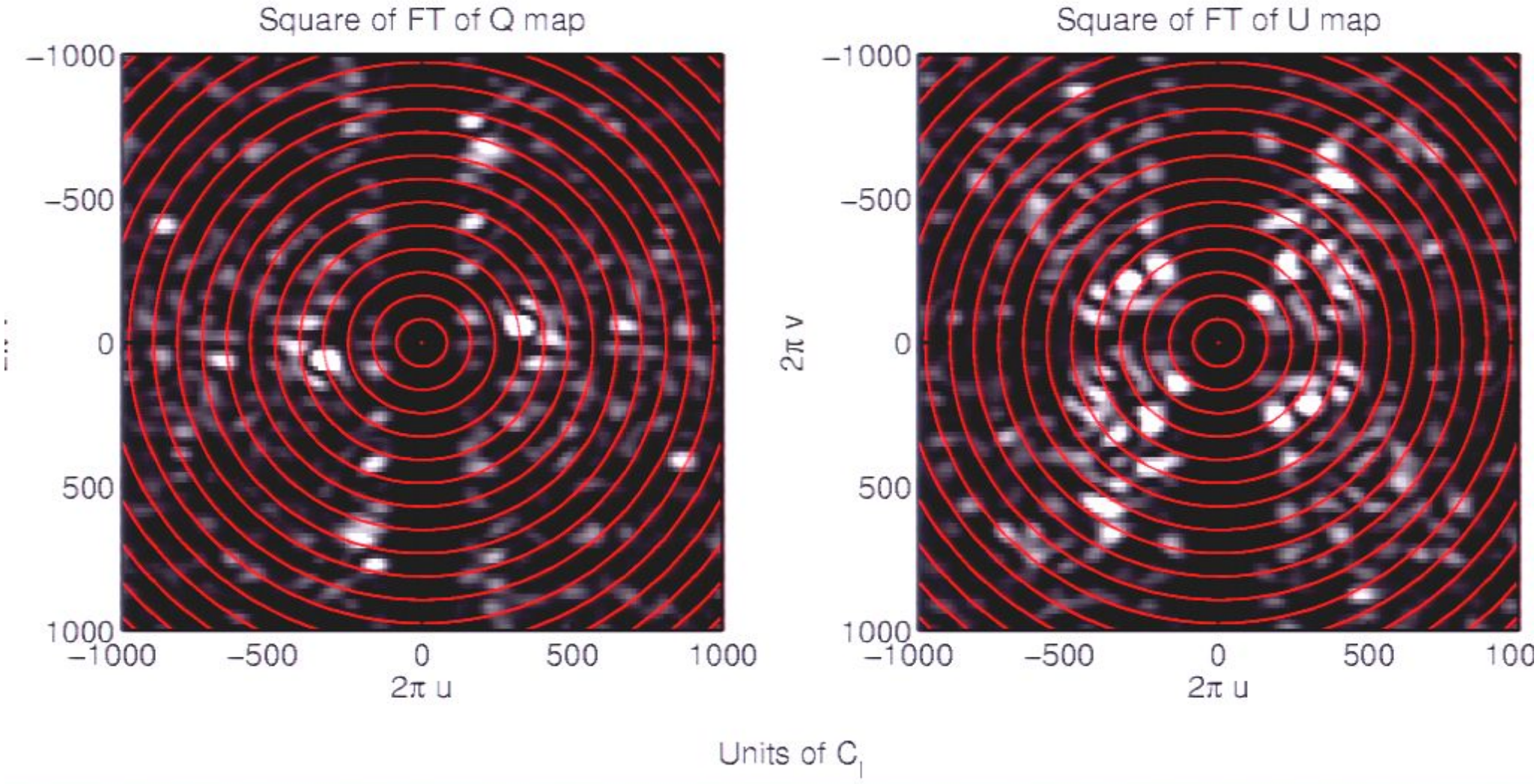
Divide signal map by variance map

...Fourier transform and square...



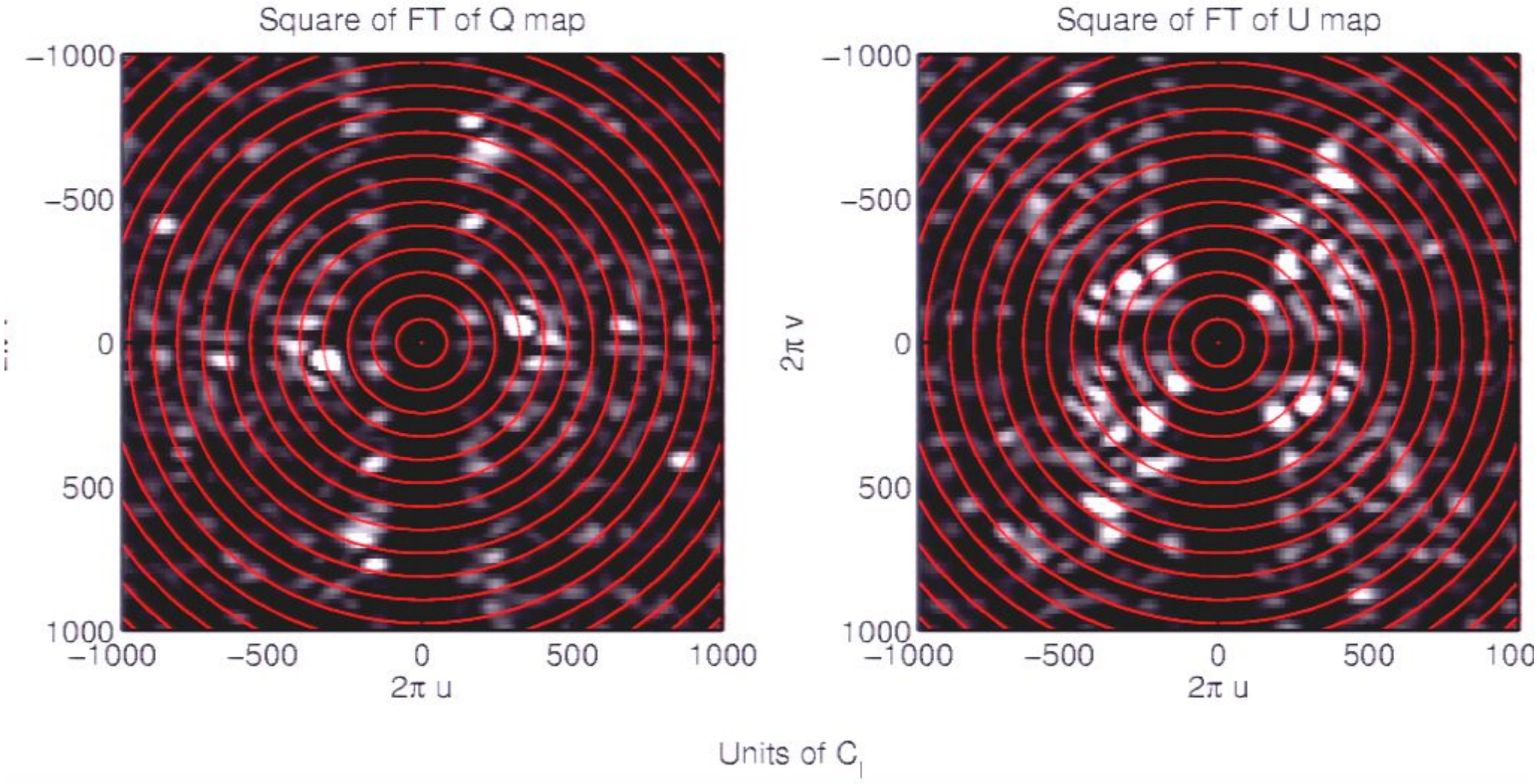
(Dark stripe along y-axis is due to half-scan polynomial filtering)

...Fourier transform and square...



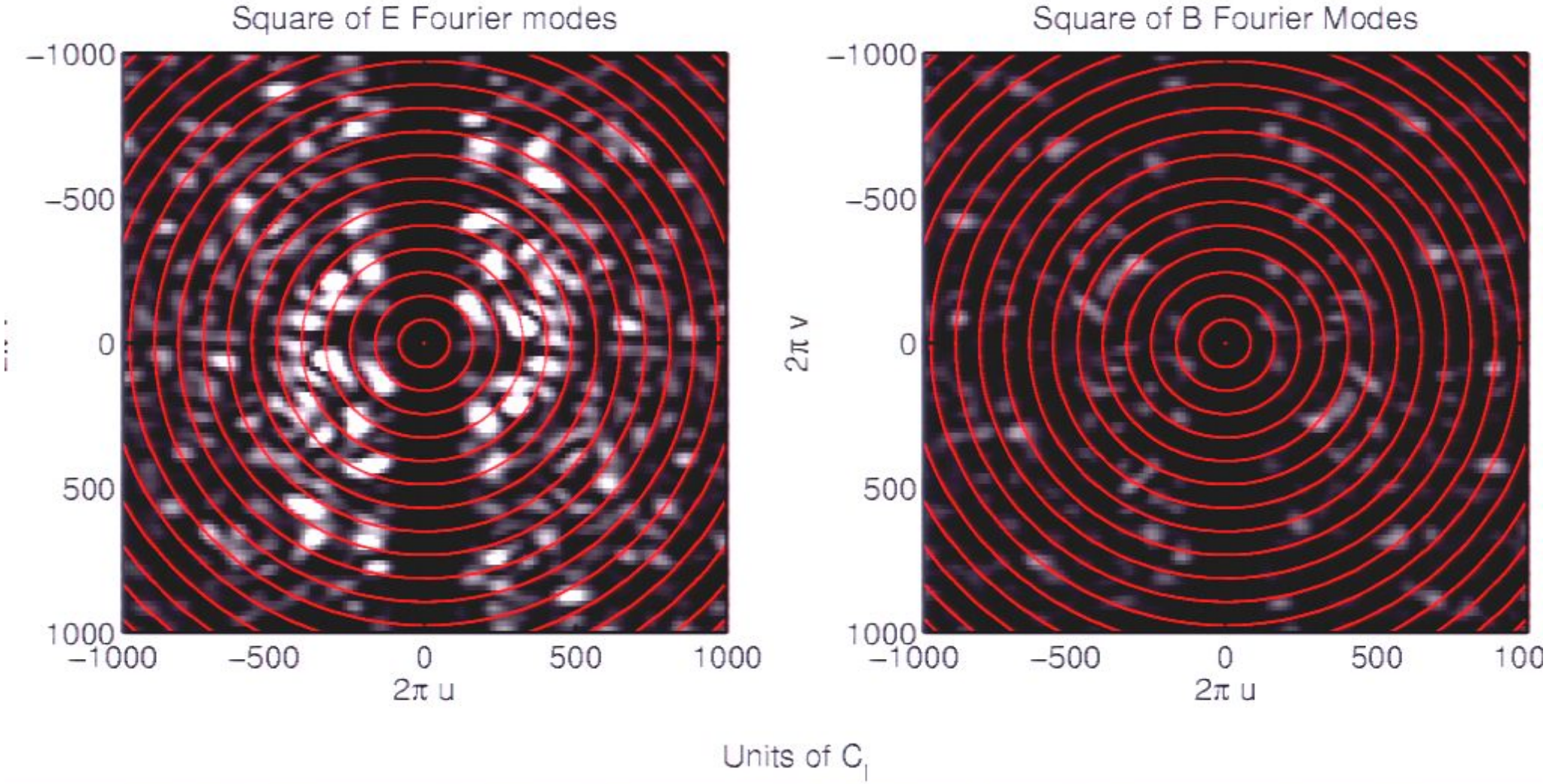
(Dark stripe along y-axis is due to half-scan polynomial filtering)

...Fourier transform and square...



(Dark stripe along y-axis is due to half-scan polynomial filtering)

...go from Q/U to E/B...

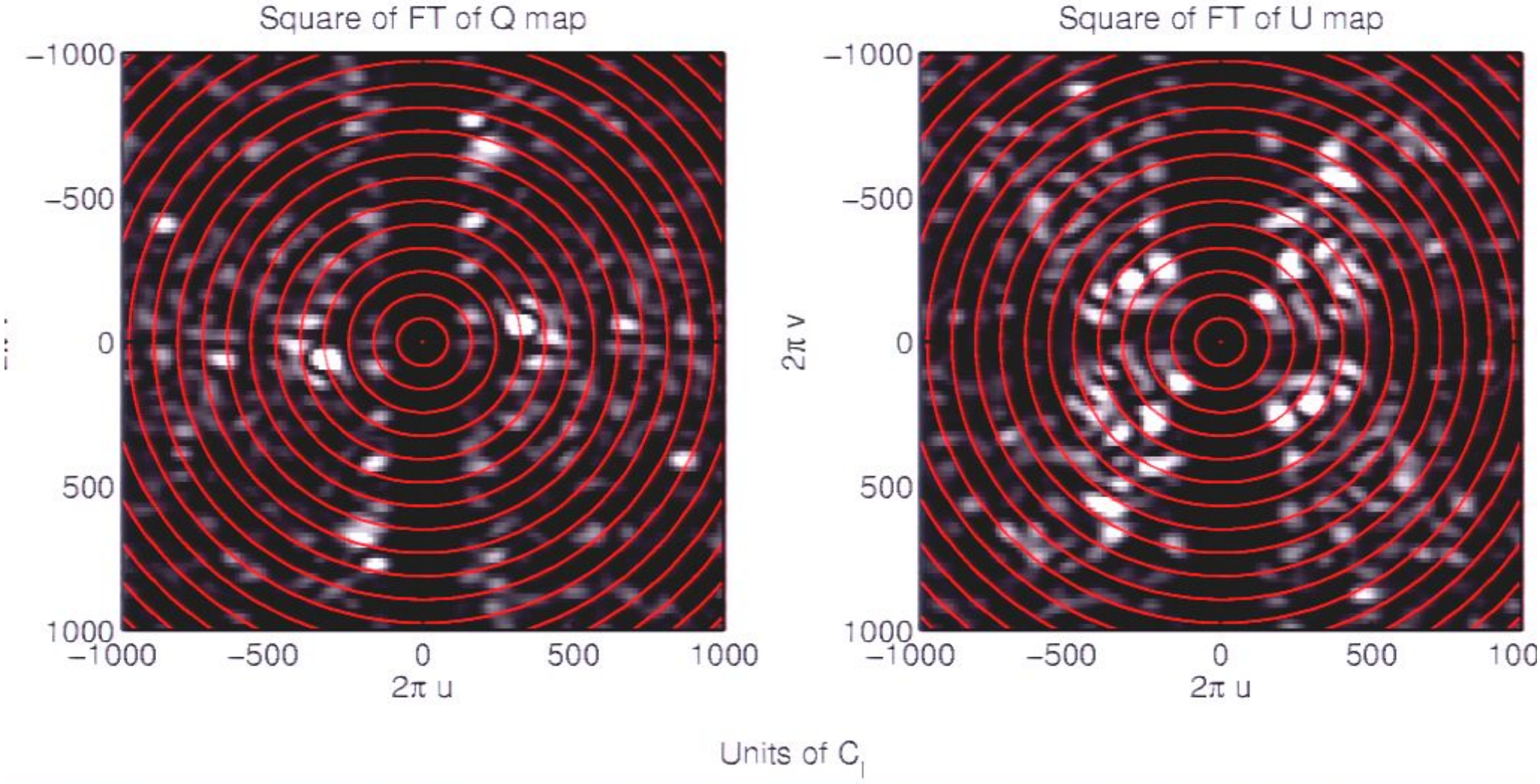


$$\chi = \arctan 2(v,u) - \pi/2$$

$$E = +Q\cos 2\chi + U\sin 2\chi$$

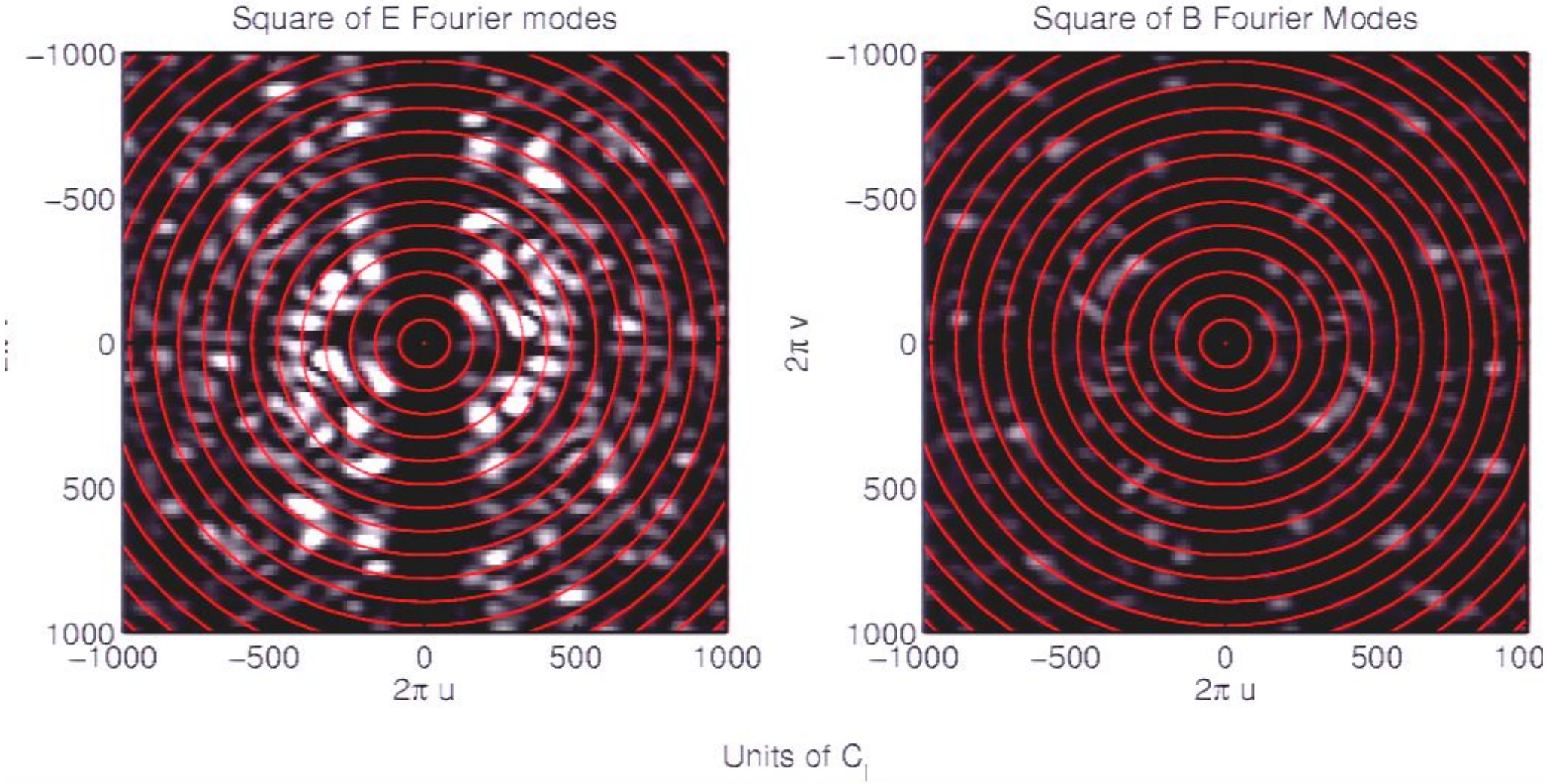
$$B = -Q\sin 2\chi + U\cos 2\chi$$

...Fourier transform and square...



(Dark stripe along y-axis is due to half-scan polynomial filtering)

...go from Q/U to E/B...

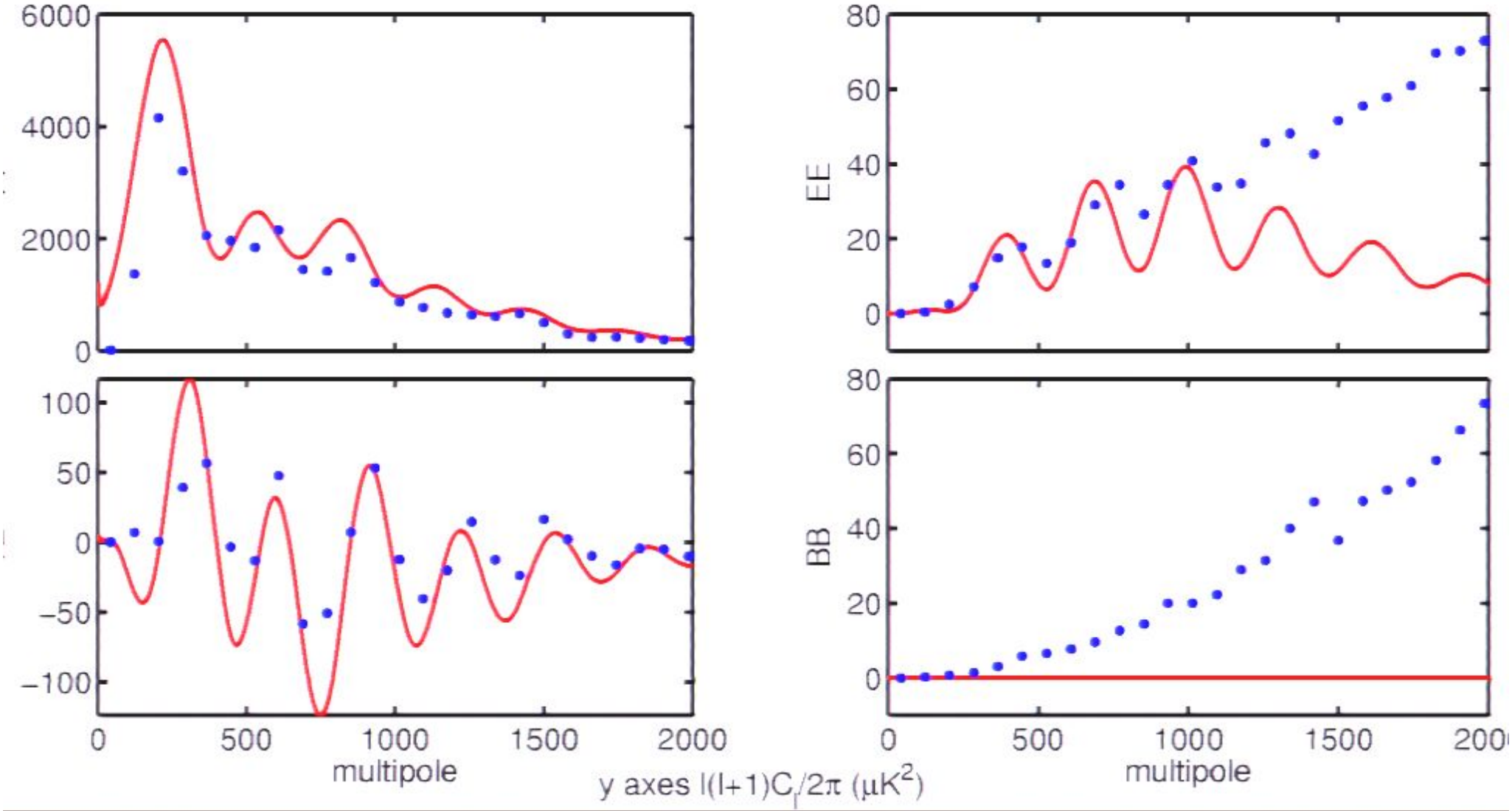


$$\chi = \arctan 2(v,u) - \pi/2$$

$$E = +Q\cos 2\chi + U\sin 2\chi$$

$$B = -Q\sin 2\chi + U\cos 2\chi$$

..mean in annuli is raw power spectrum

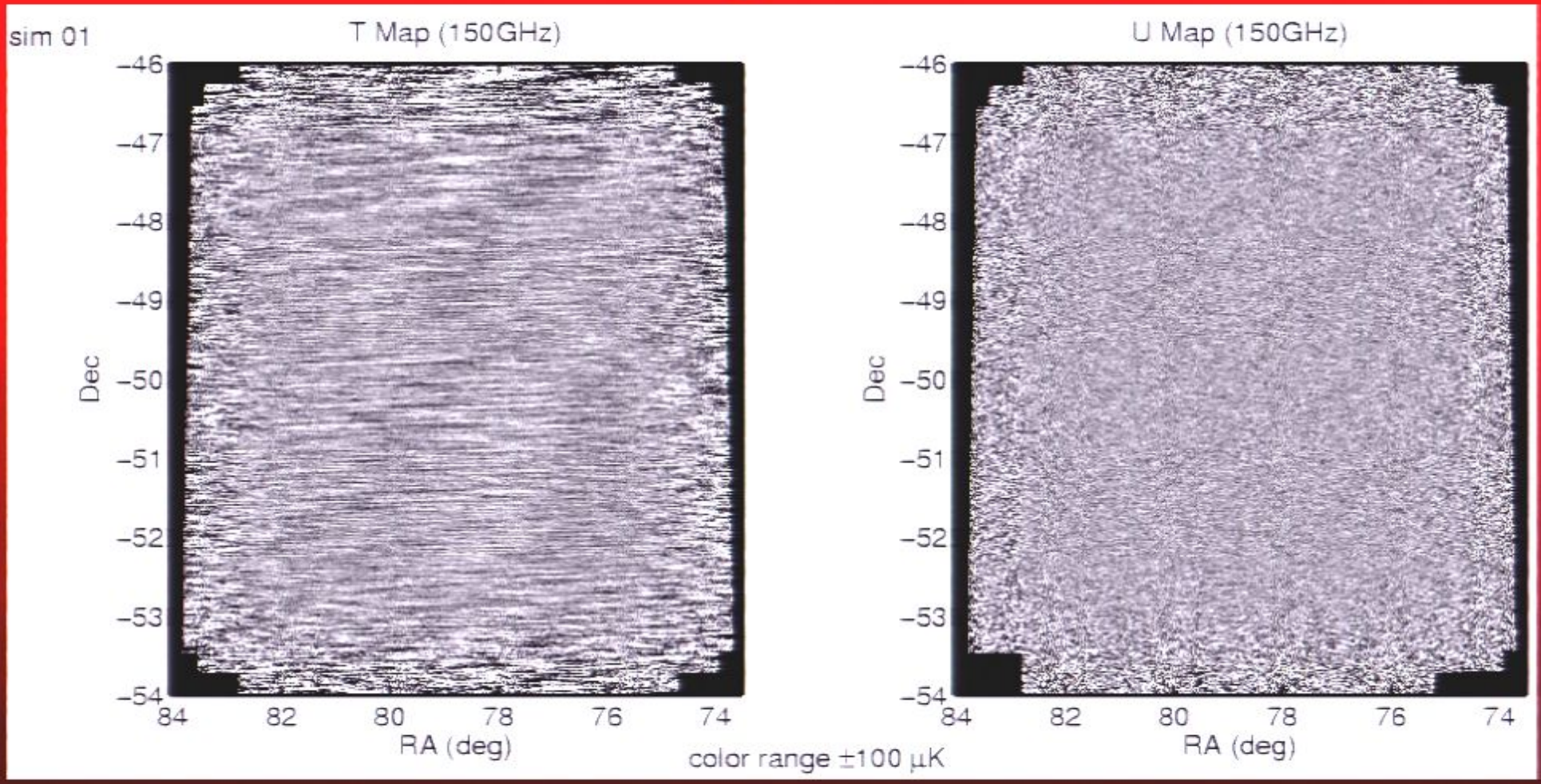


Now need to correct for noise and filtering/beam...

Simulation Based Analysis

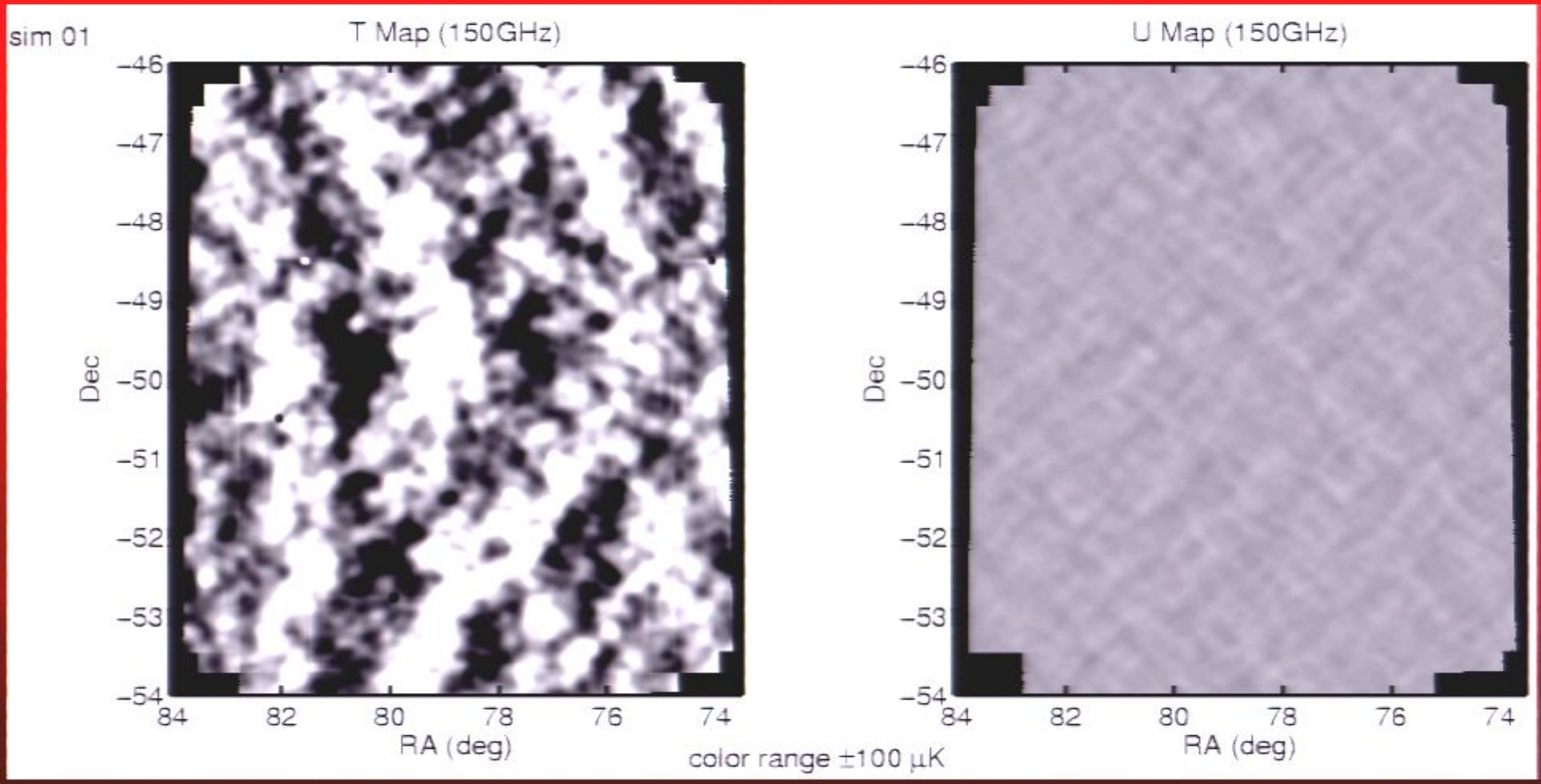
- Noise is complex -
  - non-white with strong correlations between channels.
- Filtering of sky pattern is complex -
  - only scan in one direction and no DC sensitivity.
- Derive corrections empirically using simulations -
  - generate full timestream level simulations of signal and noise and process identically to real data.

Noise only sim maps



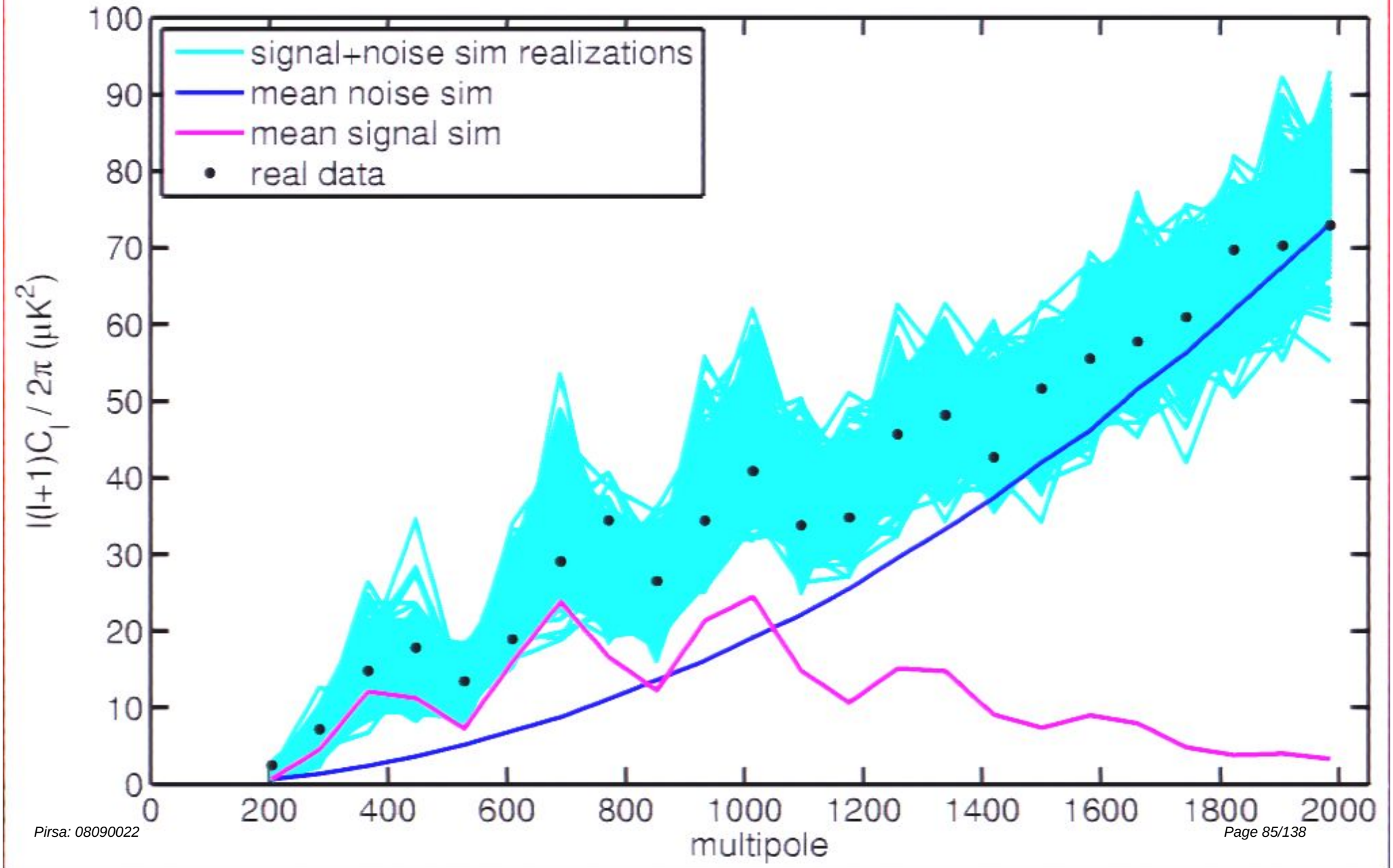
- Make noise only sim maps using same code as used for real data

Signal only sim maps

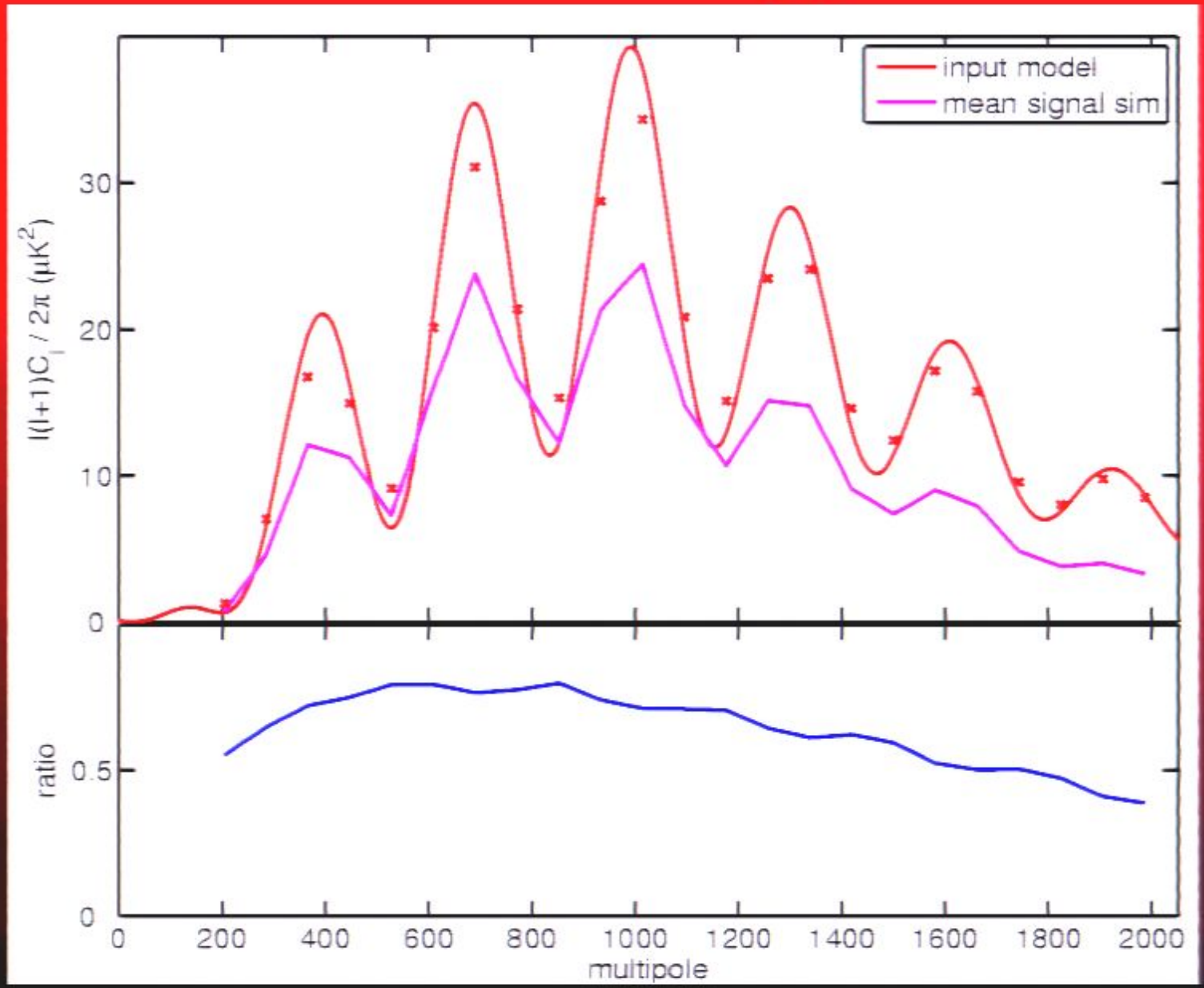


- Generate LCDM sky realizations (using synfast from Healpix)
  - Convolve with beams and re-sample timestream
- Make signal only sim maps using standard code
  - (including polynomial half-scan filtering)

Real and Sim Raw EE Spectra

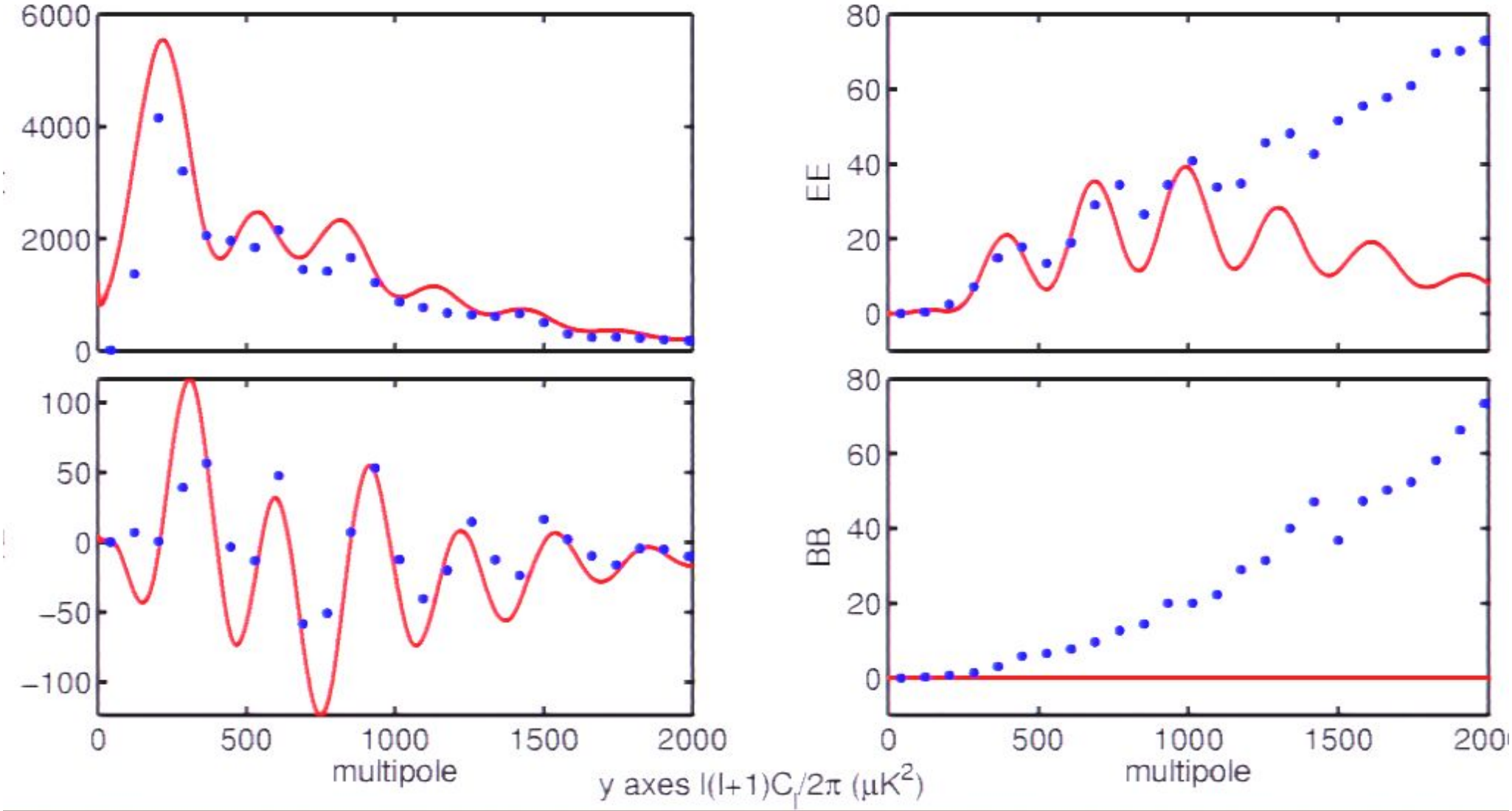


Measure Filter/Beam Suppression Factor



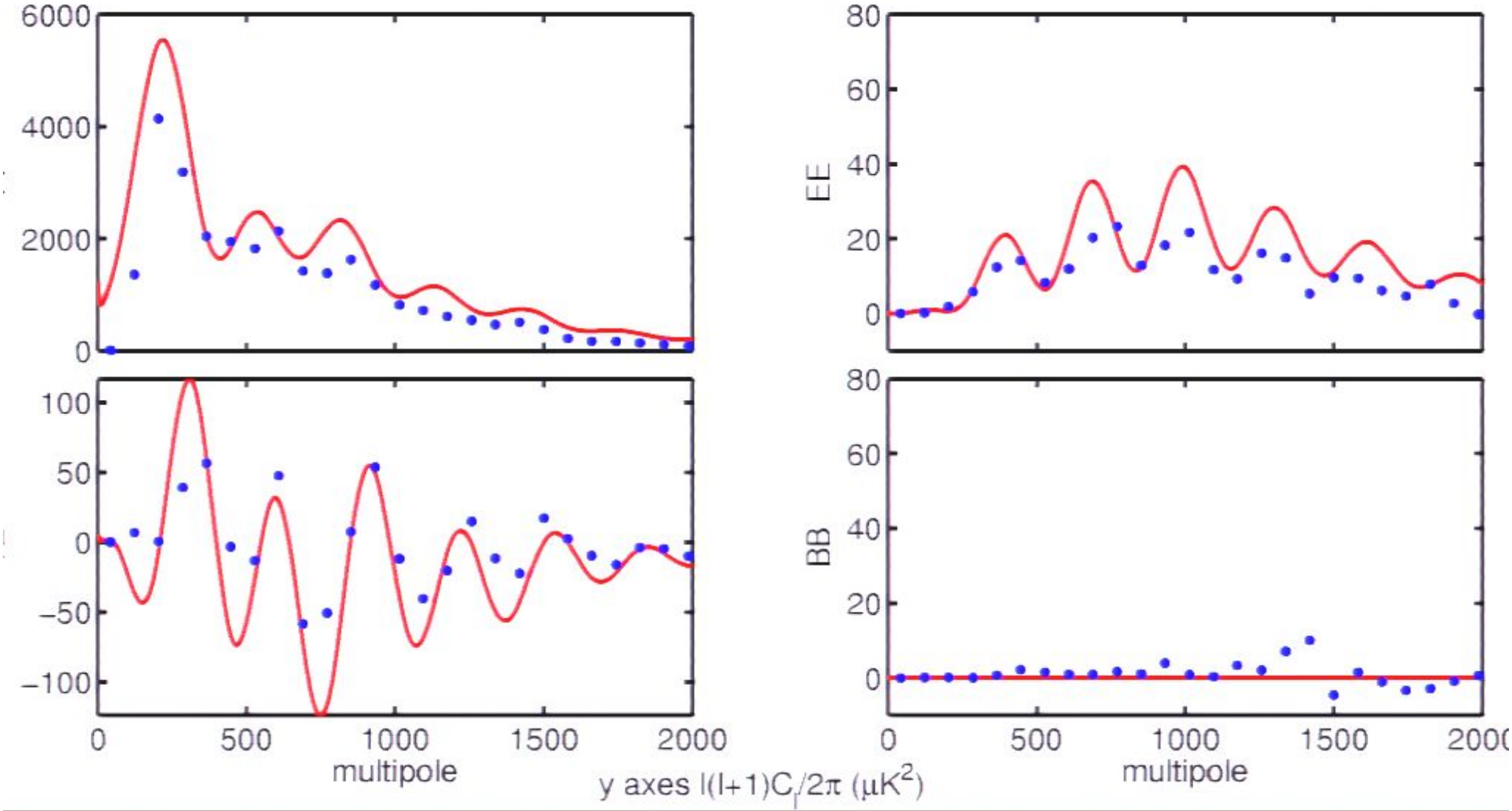
Divide real spectra by suppression factor to correct

Correcting the Real Spectra - Stage 1



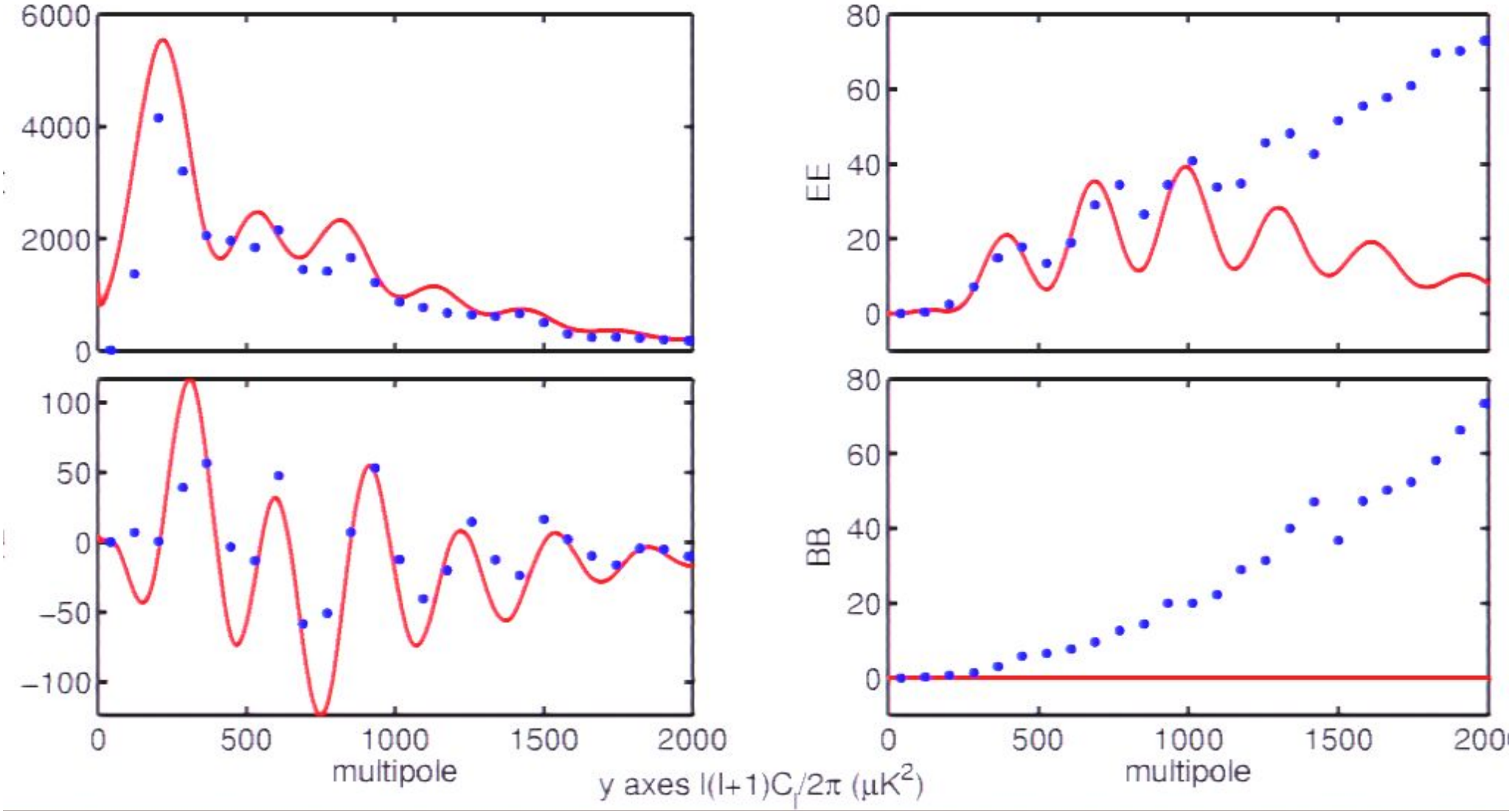
Raw Spectra

Correcting the Real Spectra - Stage 2

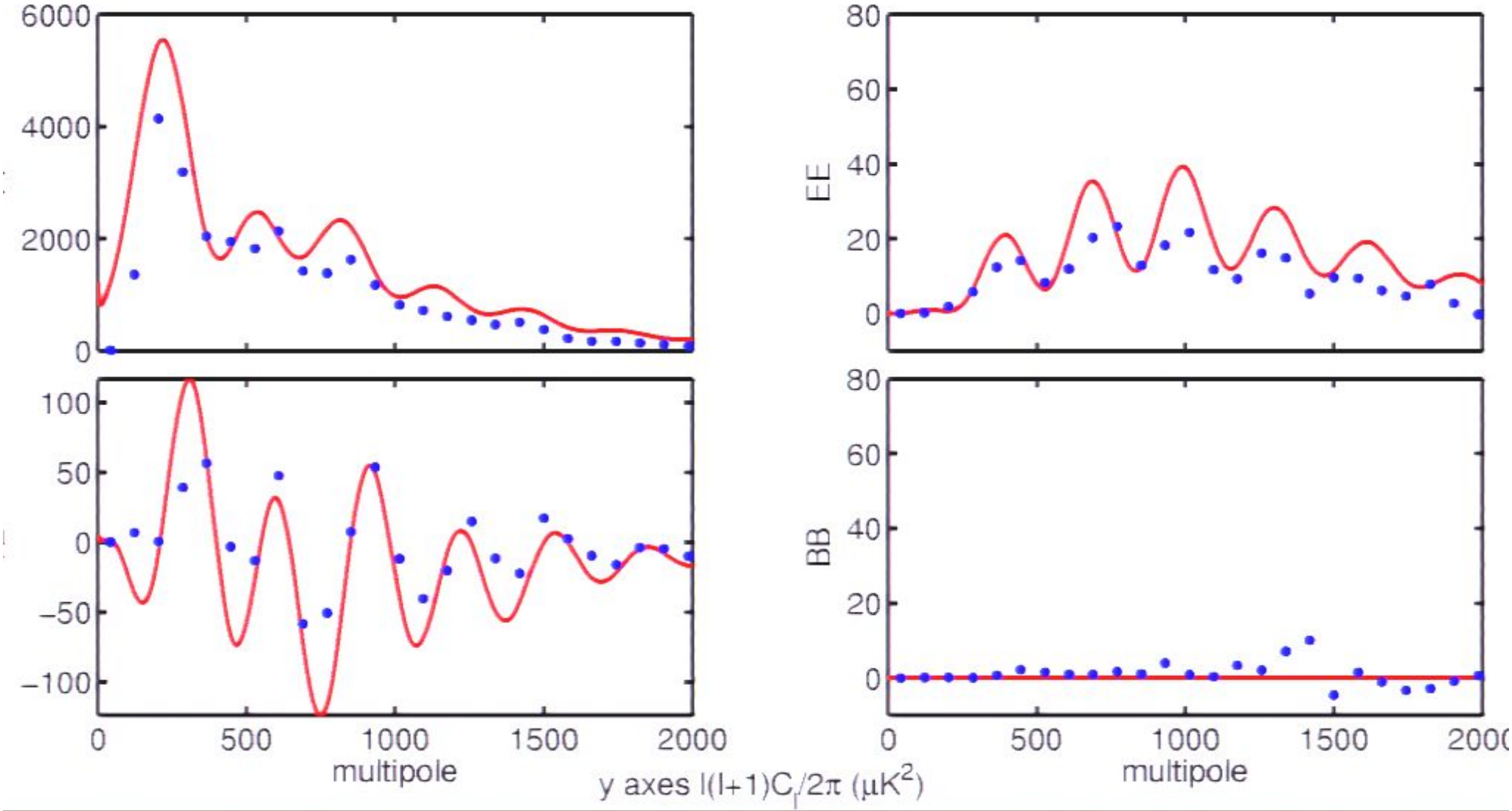


Subtract the noise

Correcting the Real Spectra - Stage 1

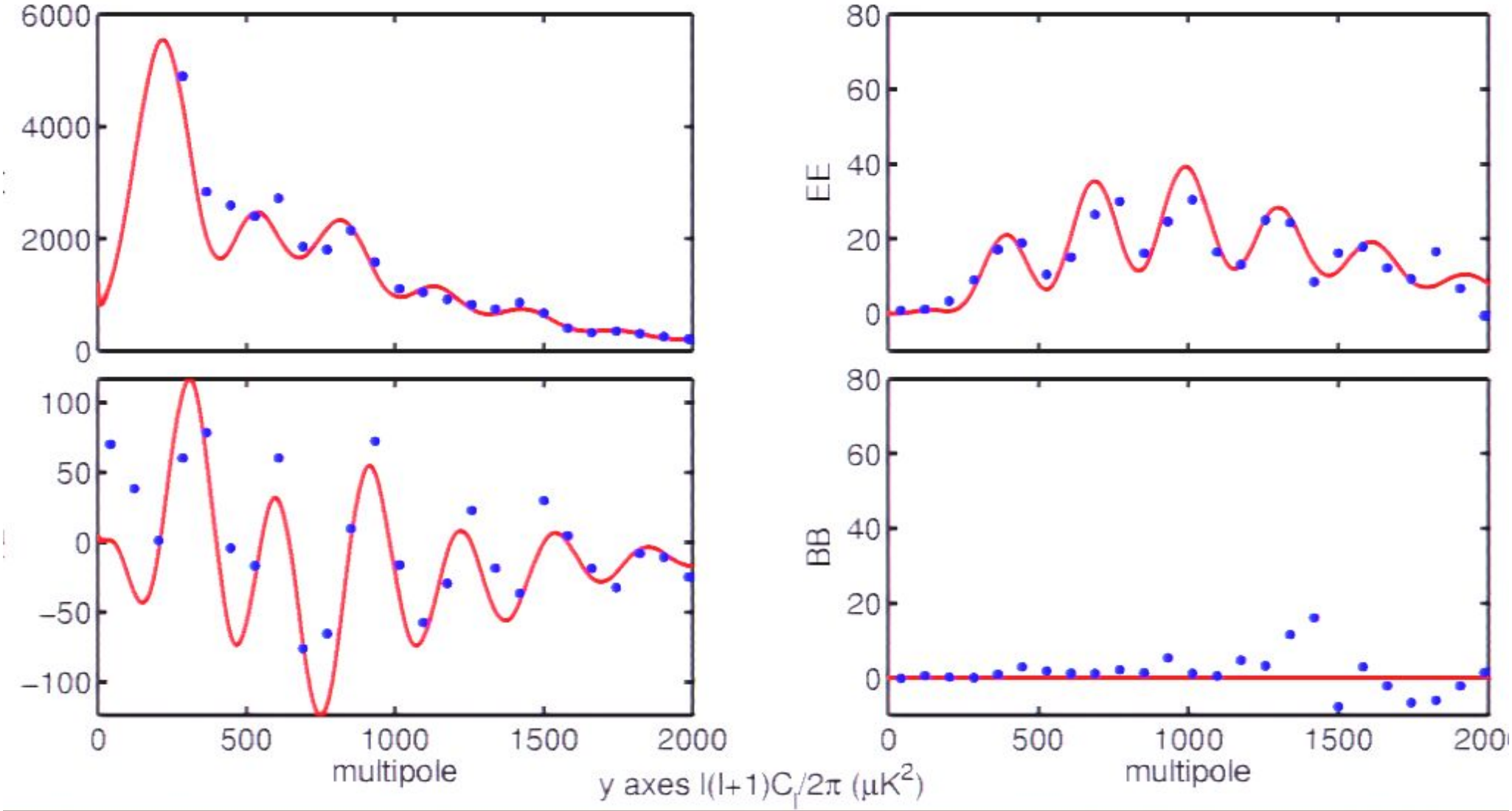


Correcting the Real Spectra - Stage 2



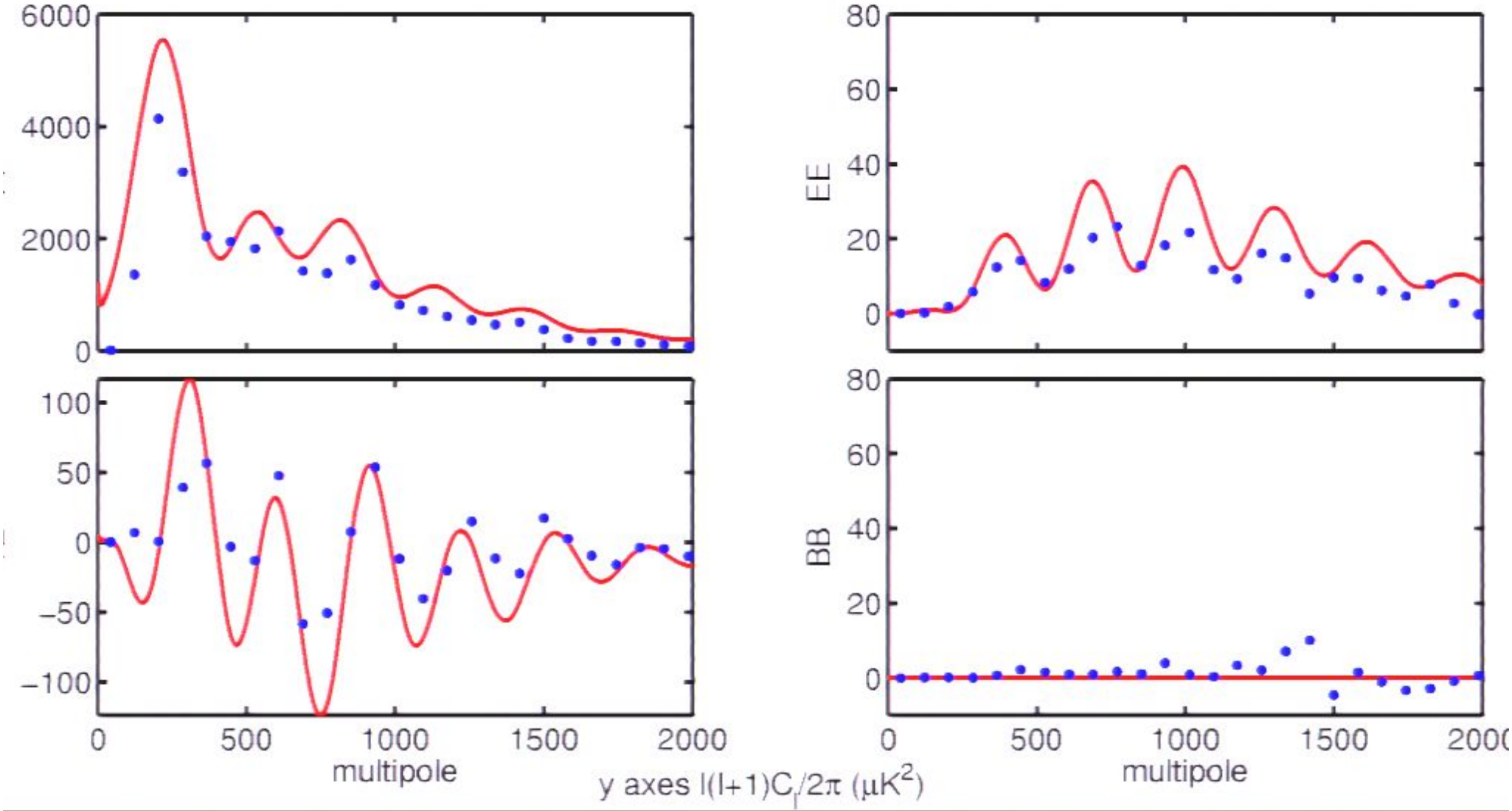
Subtract the noise

Correcting the Real Spectra - Stage 3



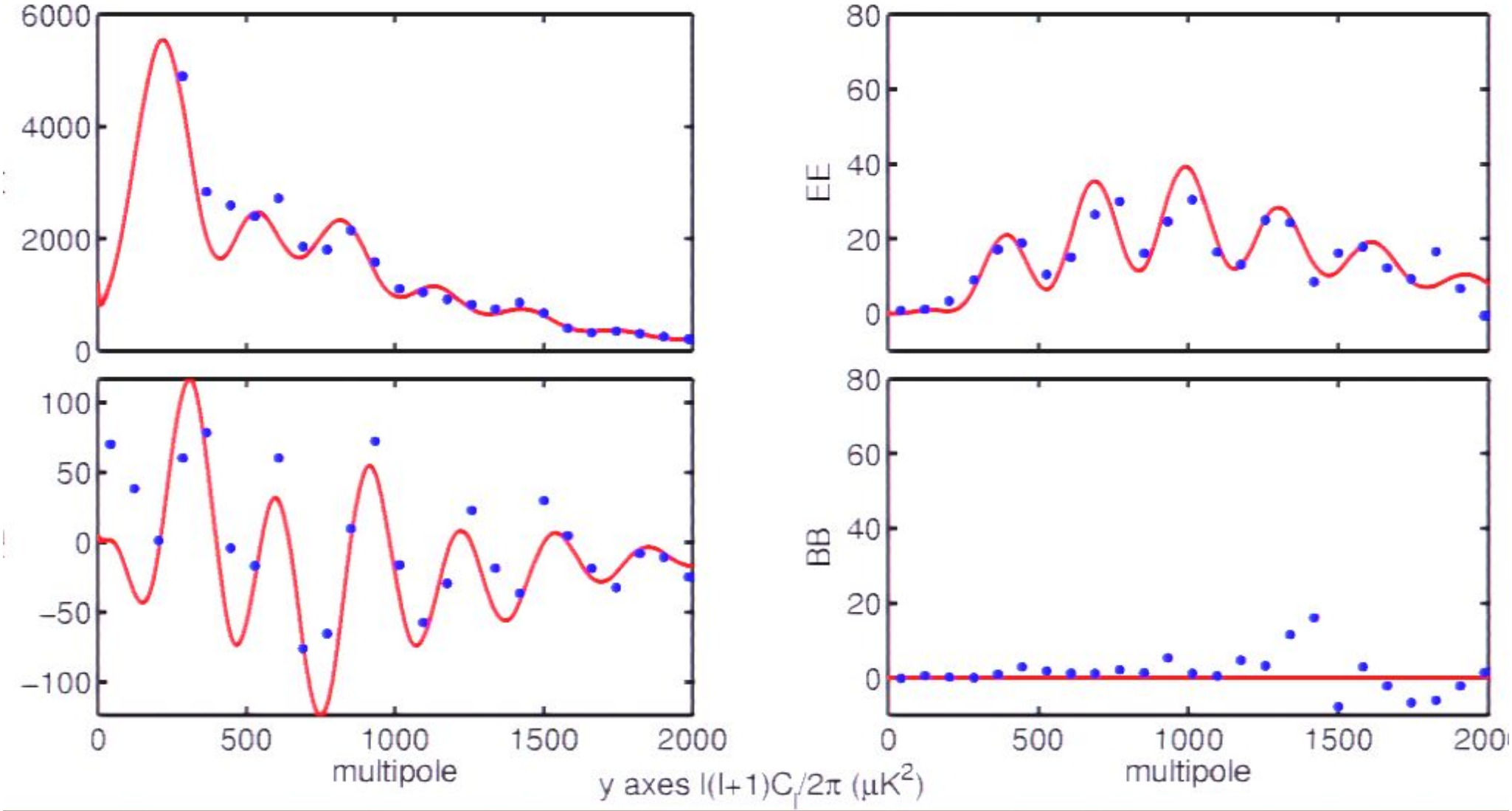
Correct for filter/beam Suppression

Correcting the Real Spectra - Stage 2



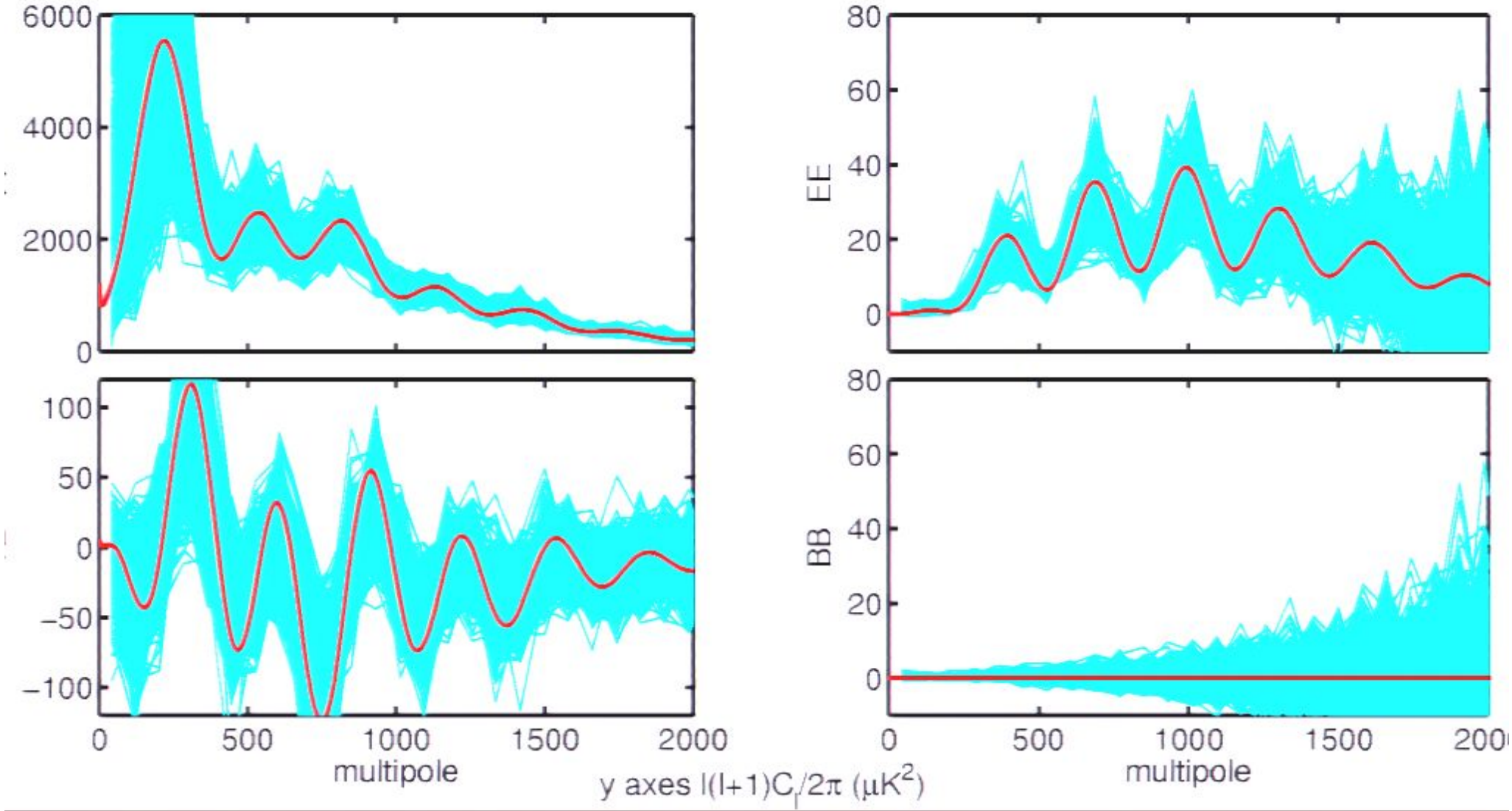
Subtract the noise

Correcting the Real Spectra - Stage 3



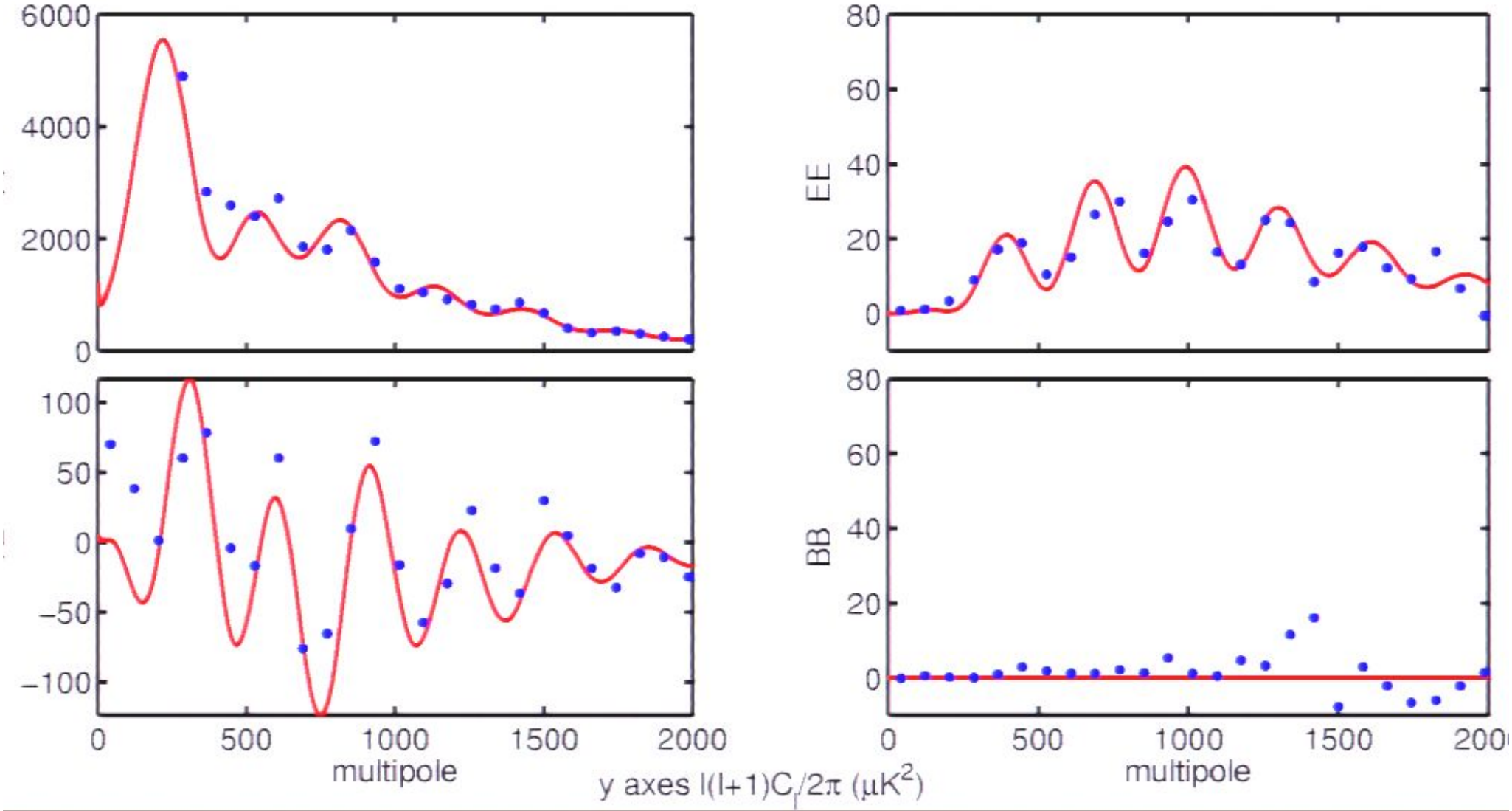
Correct for filter/beam Suppression

Estimate error bars using sig+noi sims.



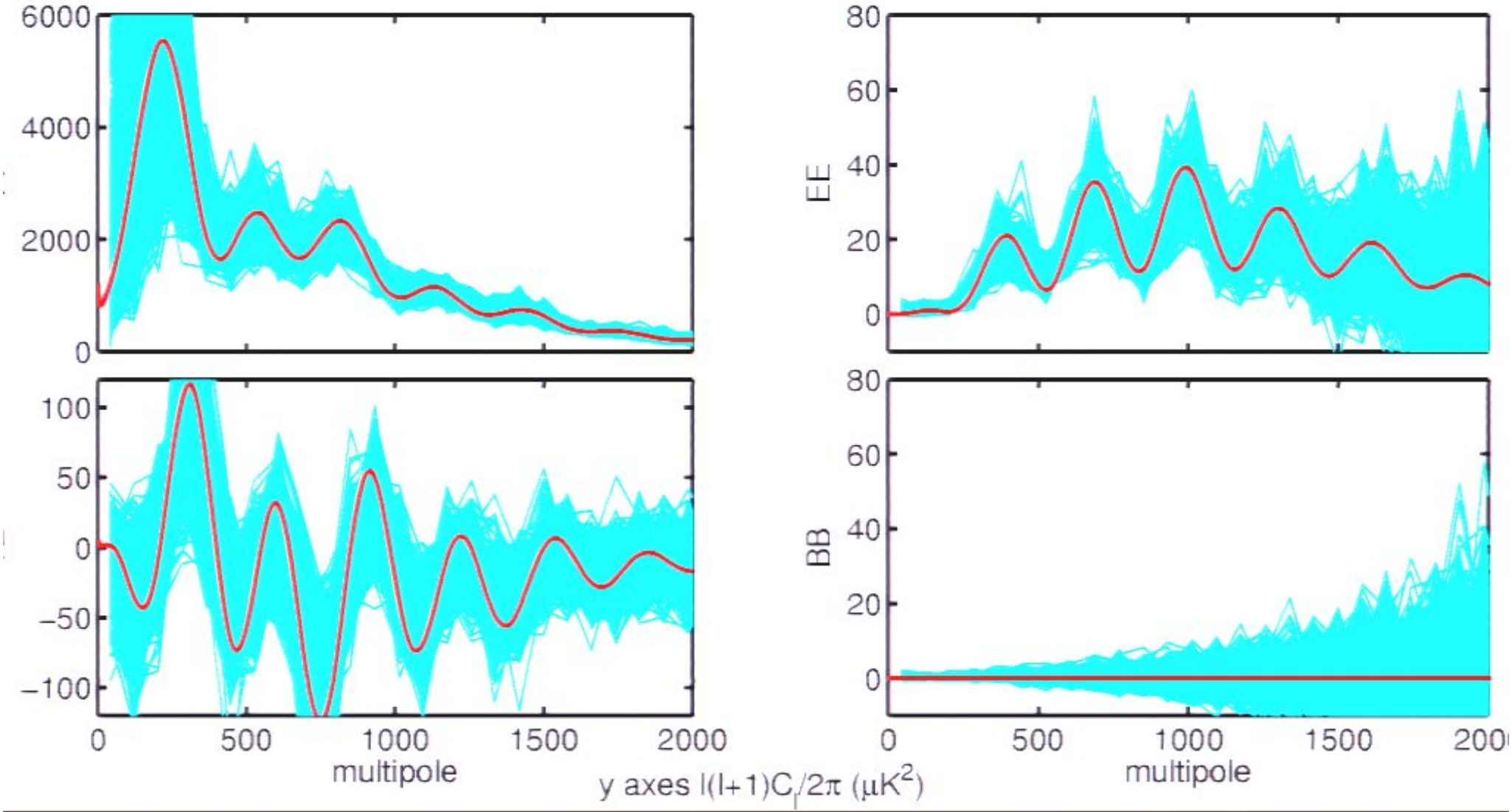
Warning: error bars only correct if cosmology assumed in sims is close to reality...

Correcting the Real Spectra - Stage 3



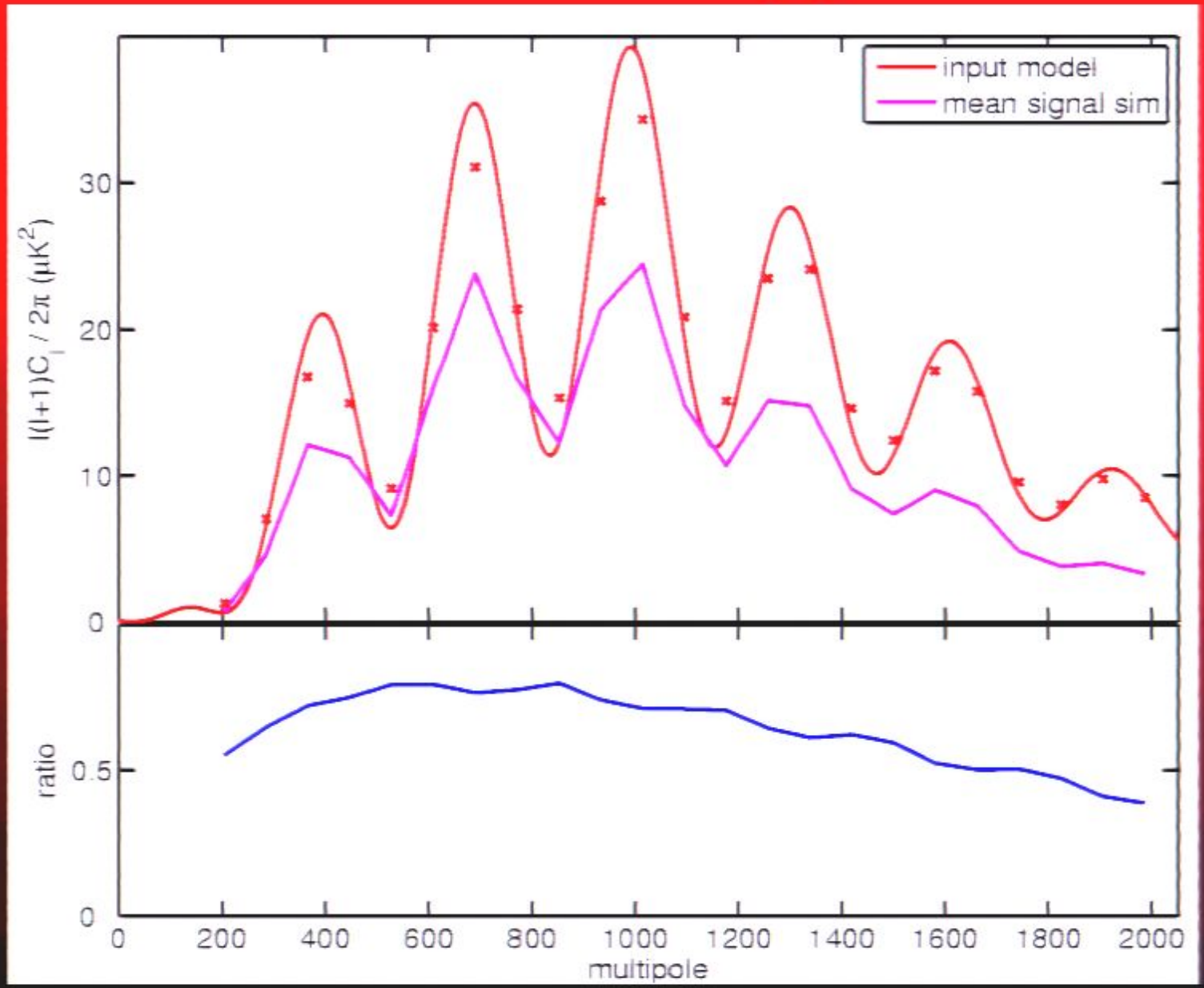
Correct for filter/beam Suppression

Estimate error bars using sig+noi sims.



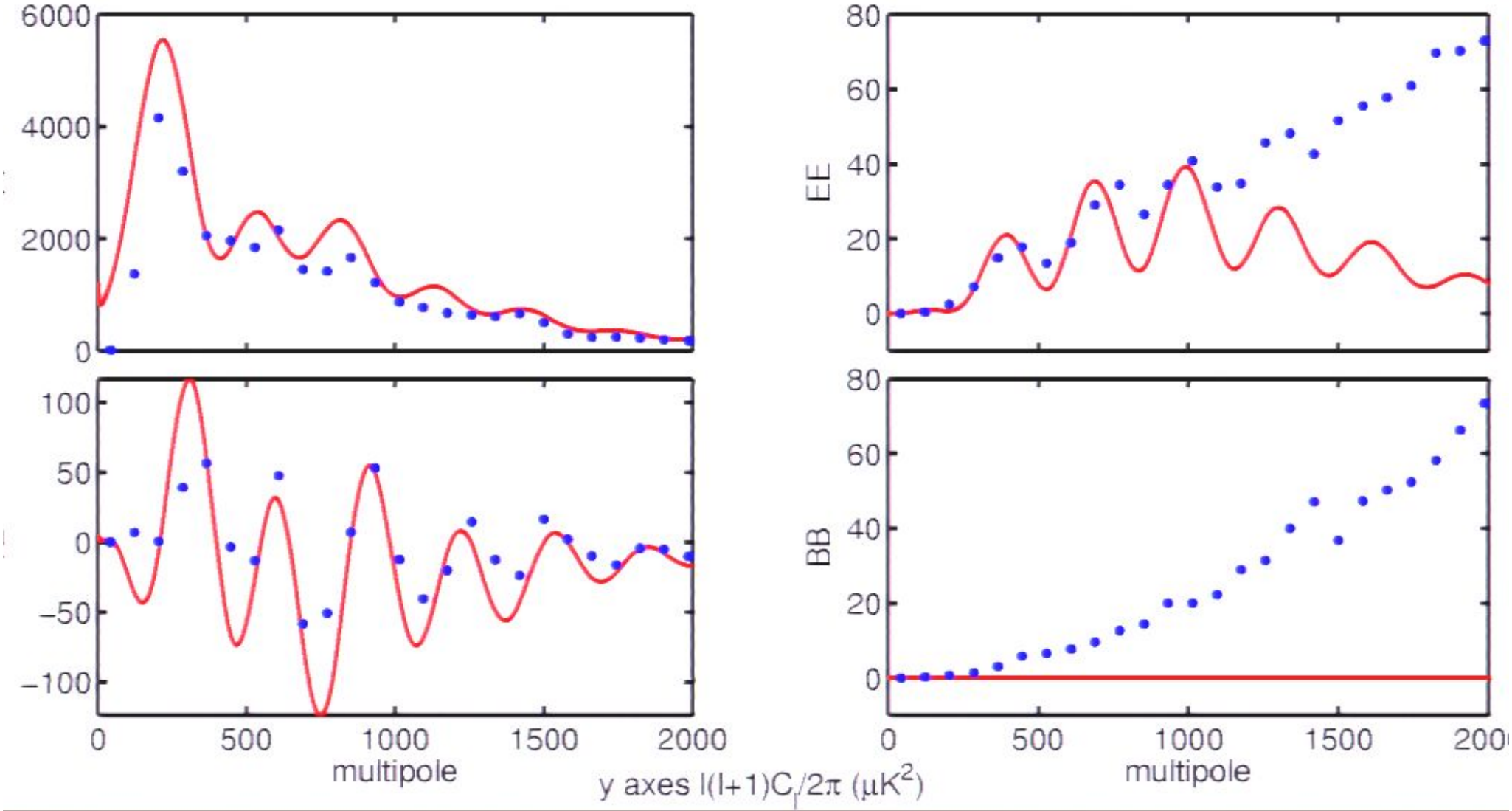
Warning: error bars only correct if cosmology assumed in sims is close to reality...

Measure Filter/Beam Suppression Factor



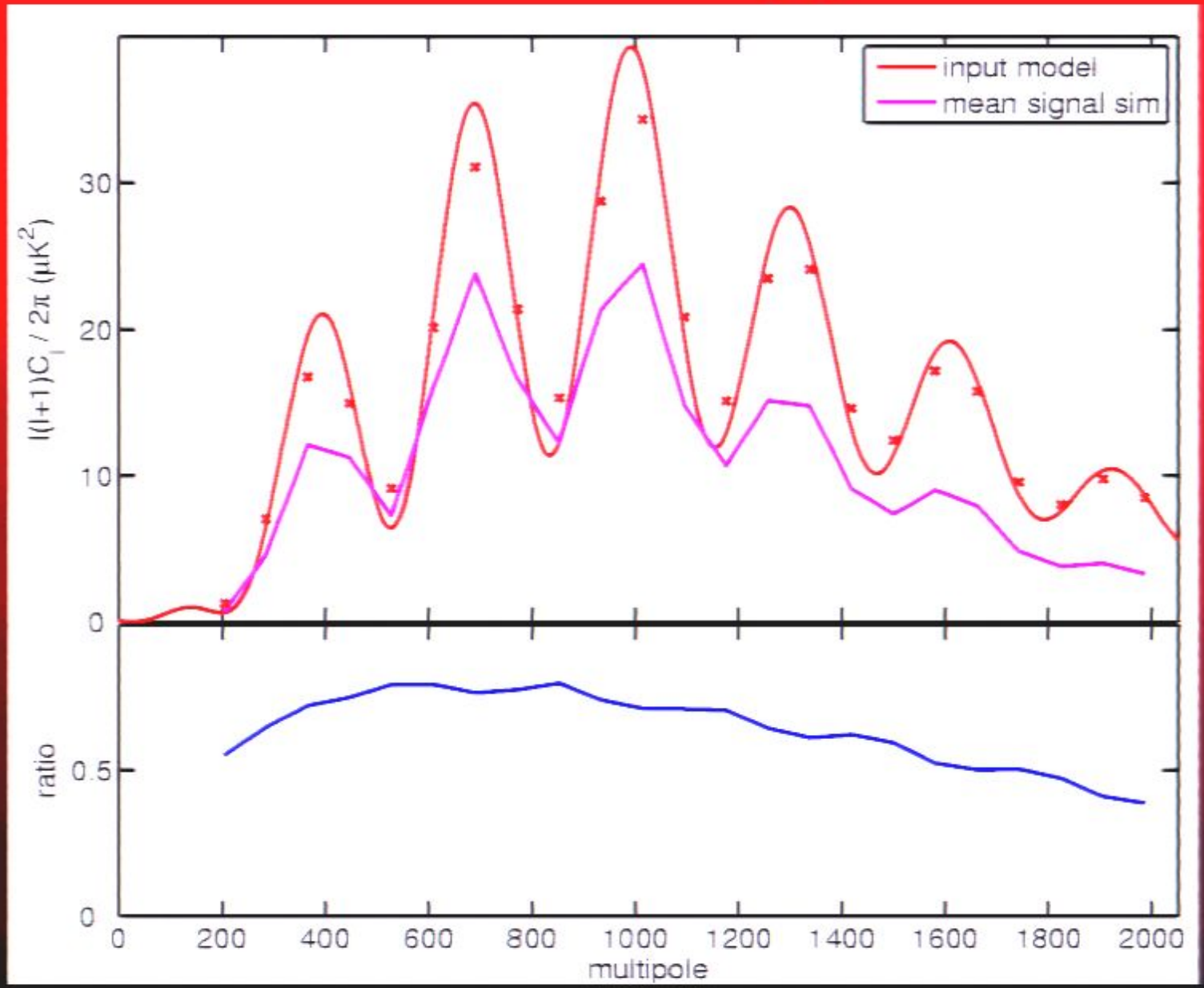
Divide real spectra by suppression factor to correct

Correcting the Real Spectra - Stage 1



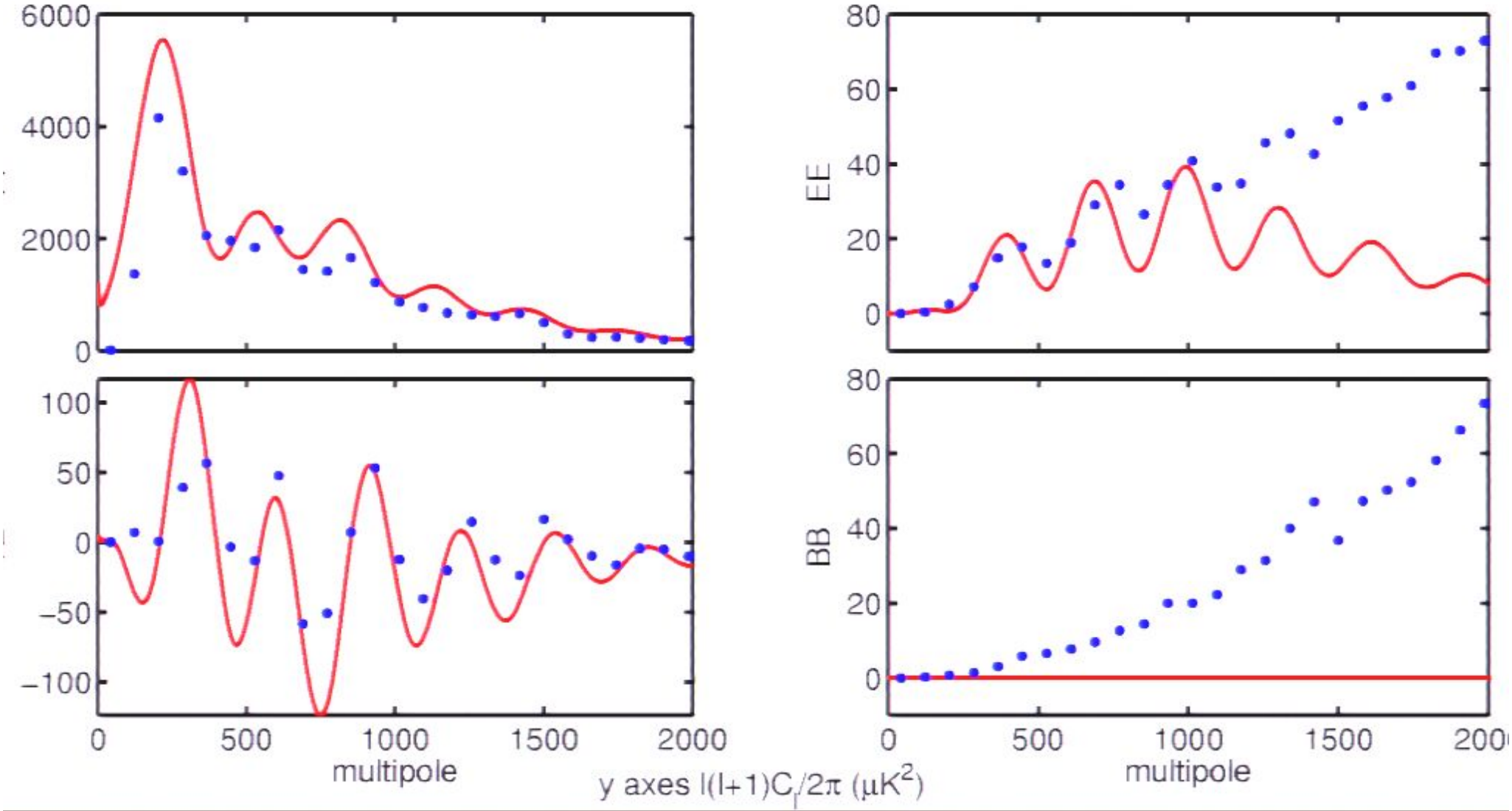
Raw Spectra

Measure Filter/Beam Suppression Factor

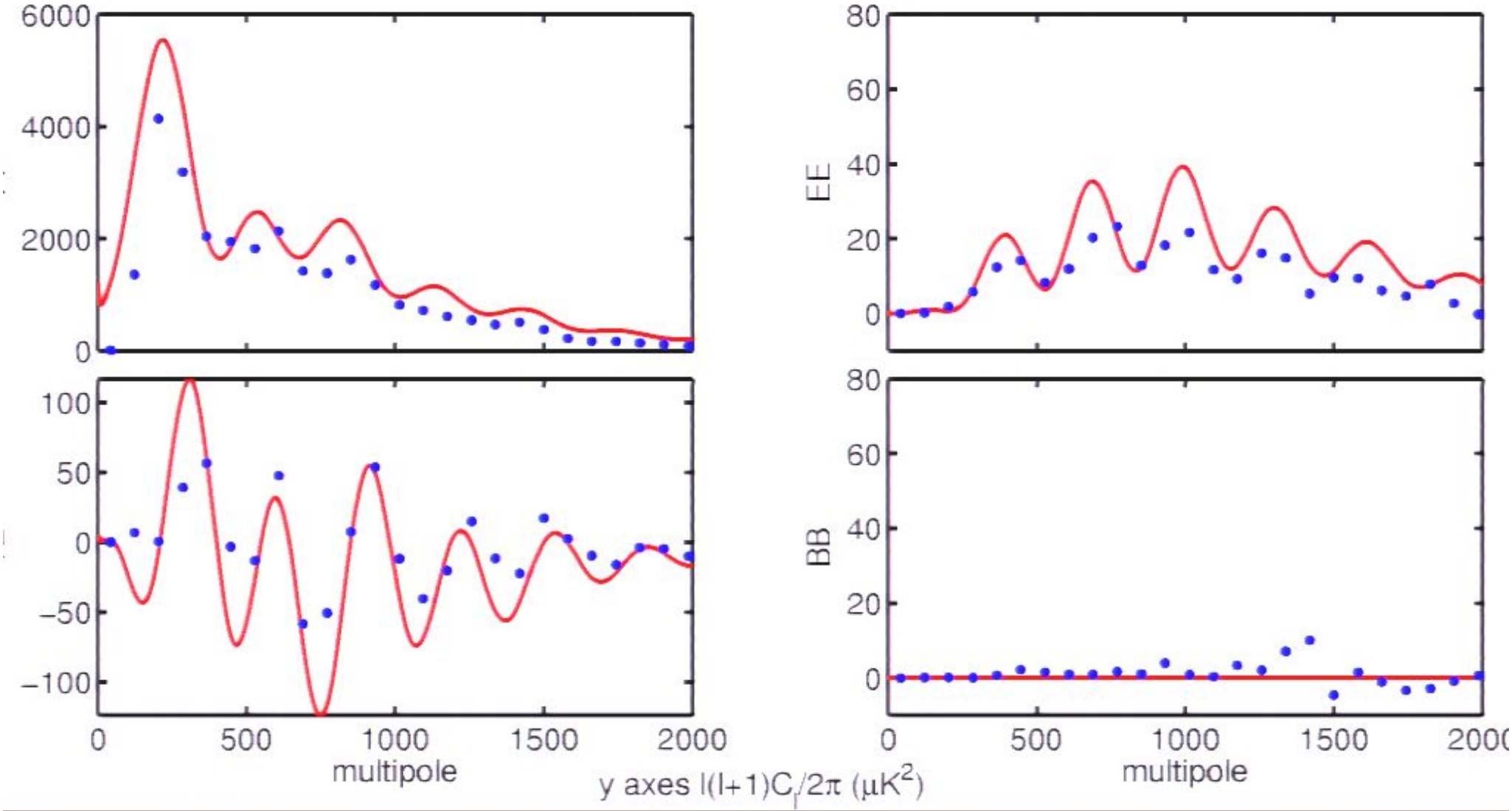


Divide real spectra by suppression factor to correct

Correcting the Real Spectra - Stage 1

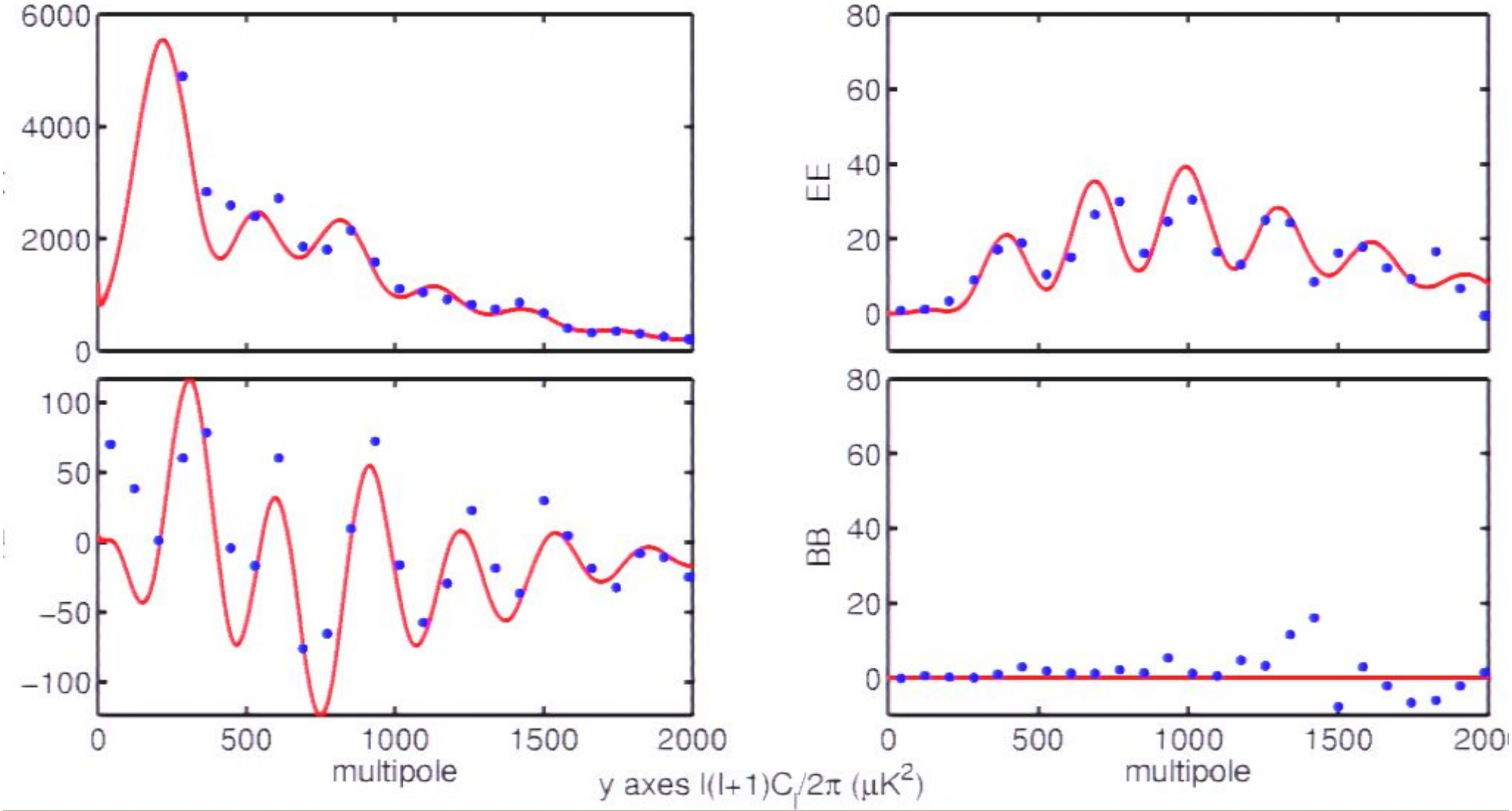


Correcting the Real Spectra - Stage 2



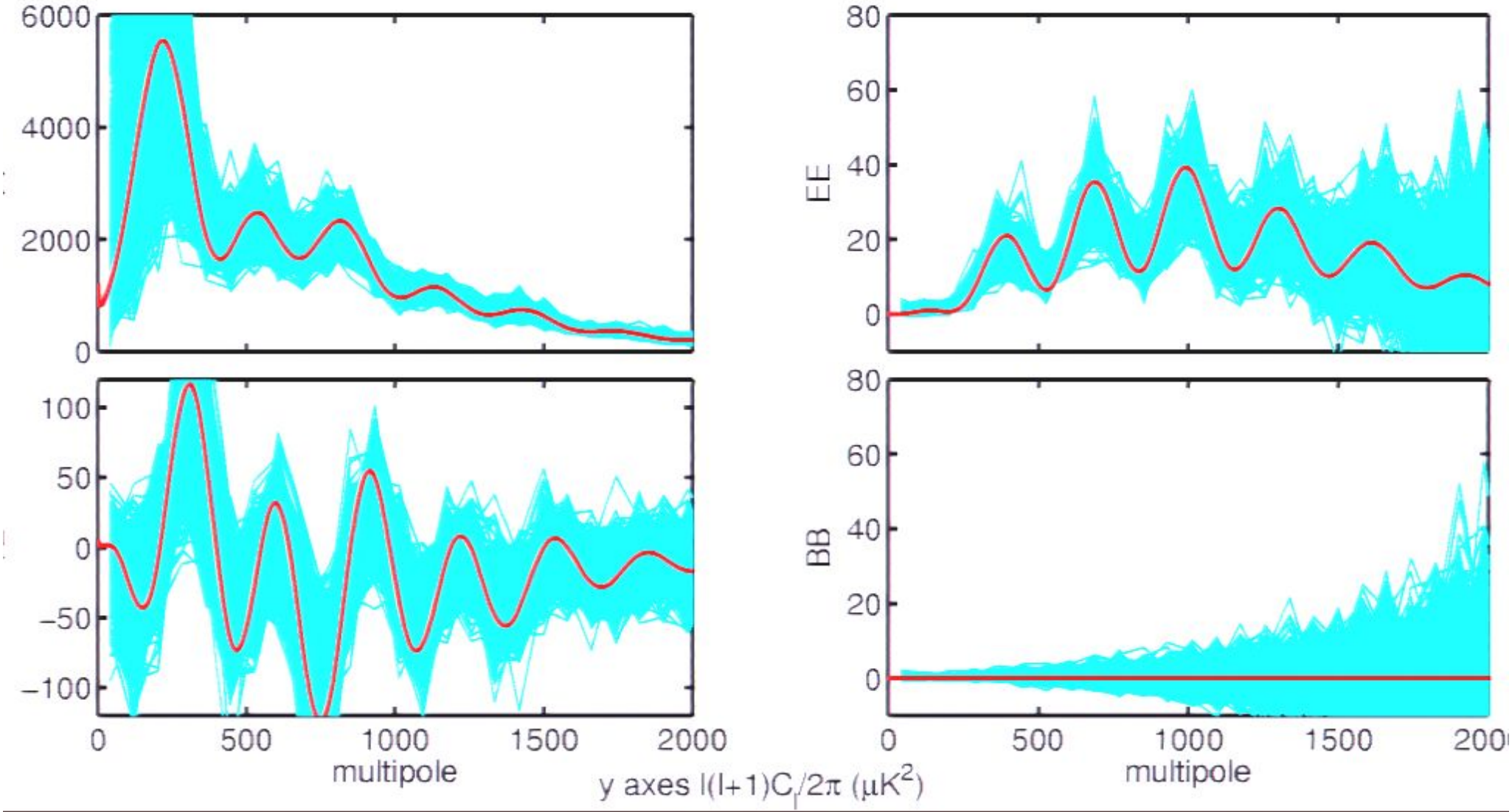
Subtract the noise

Correcting the Real Spectra - Stage 3



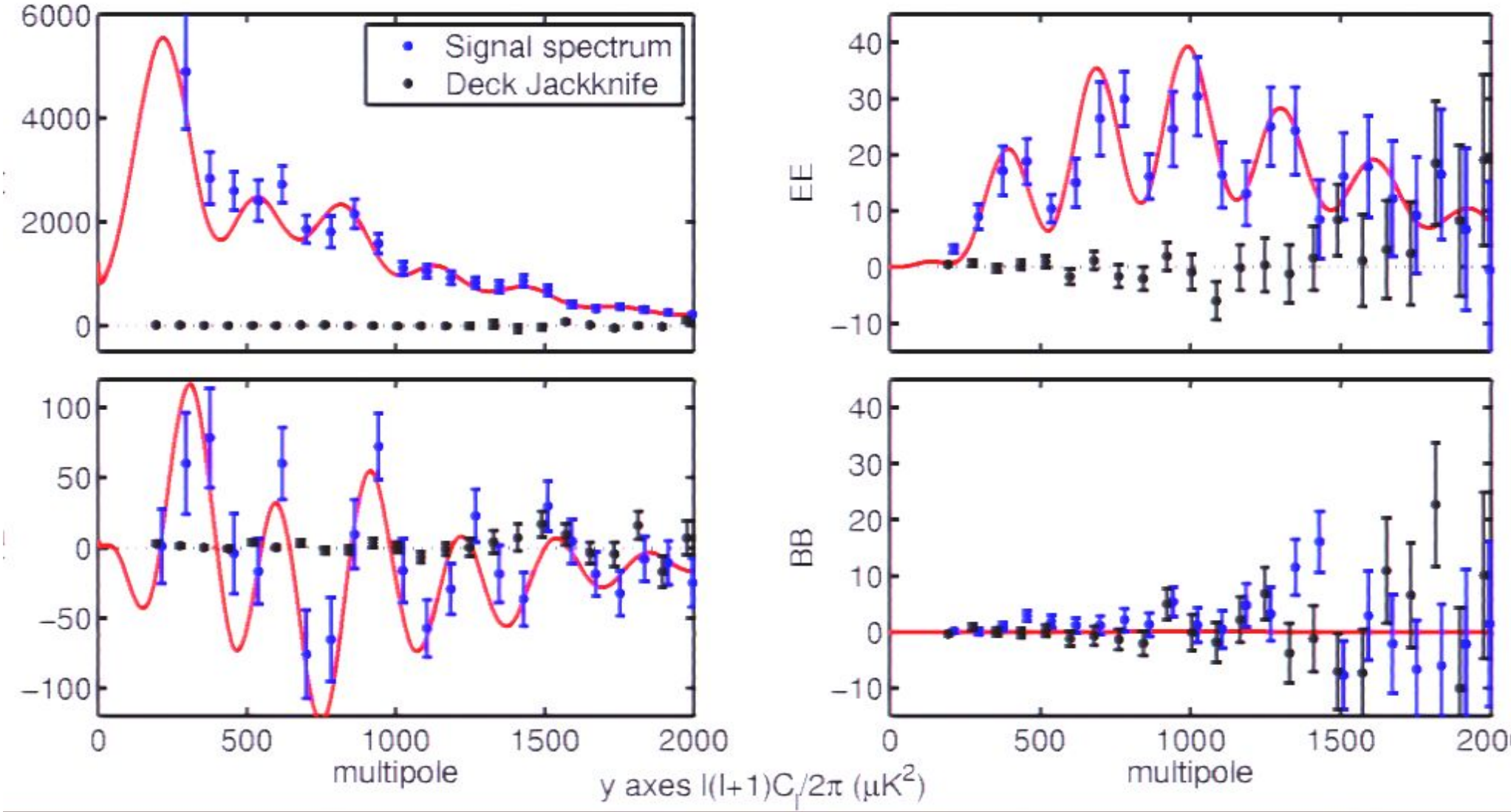
Correct for filter/beam Suppression

Estimate error bars using sig+noi sims.



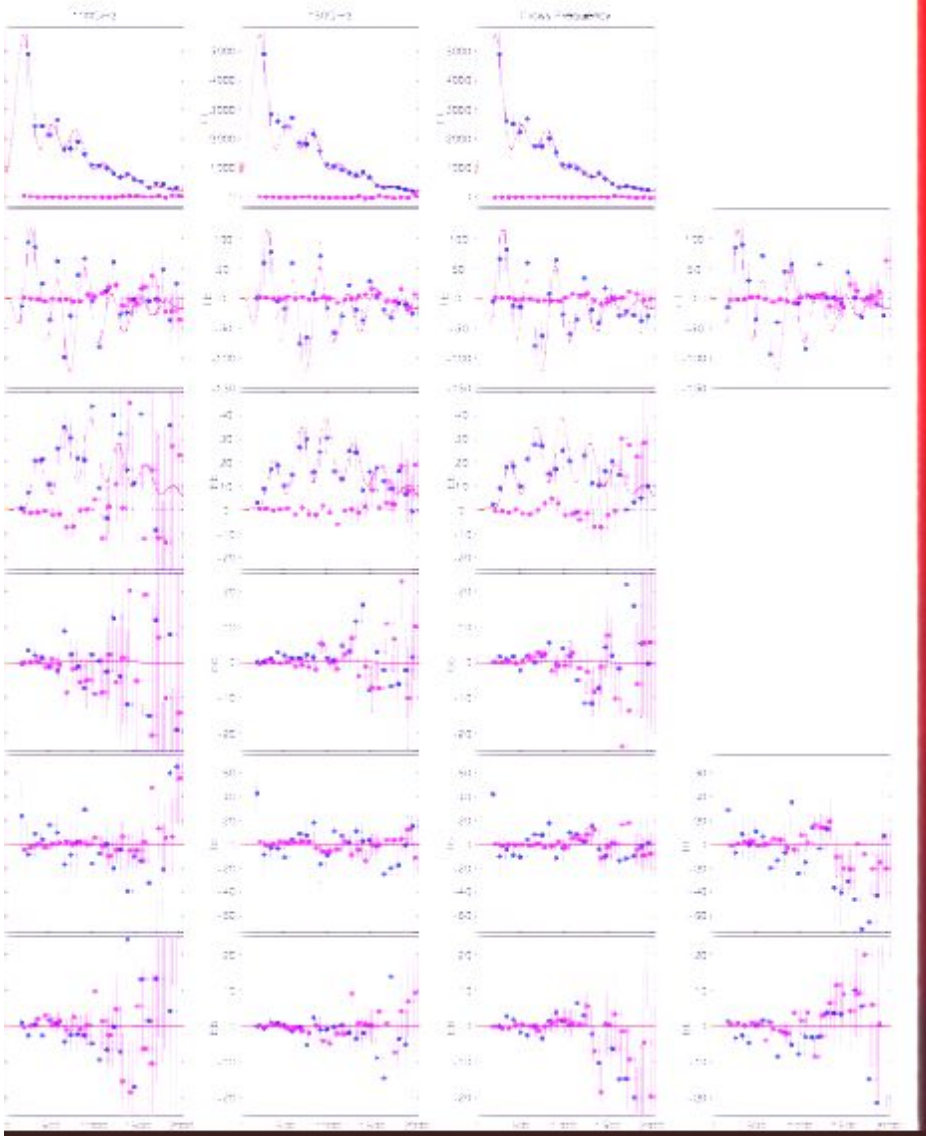
Warning: error bars only correct if cosmology assumed in sims is close to reality...

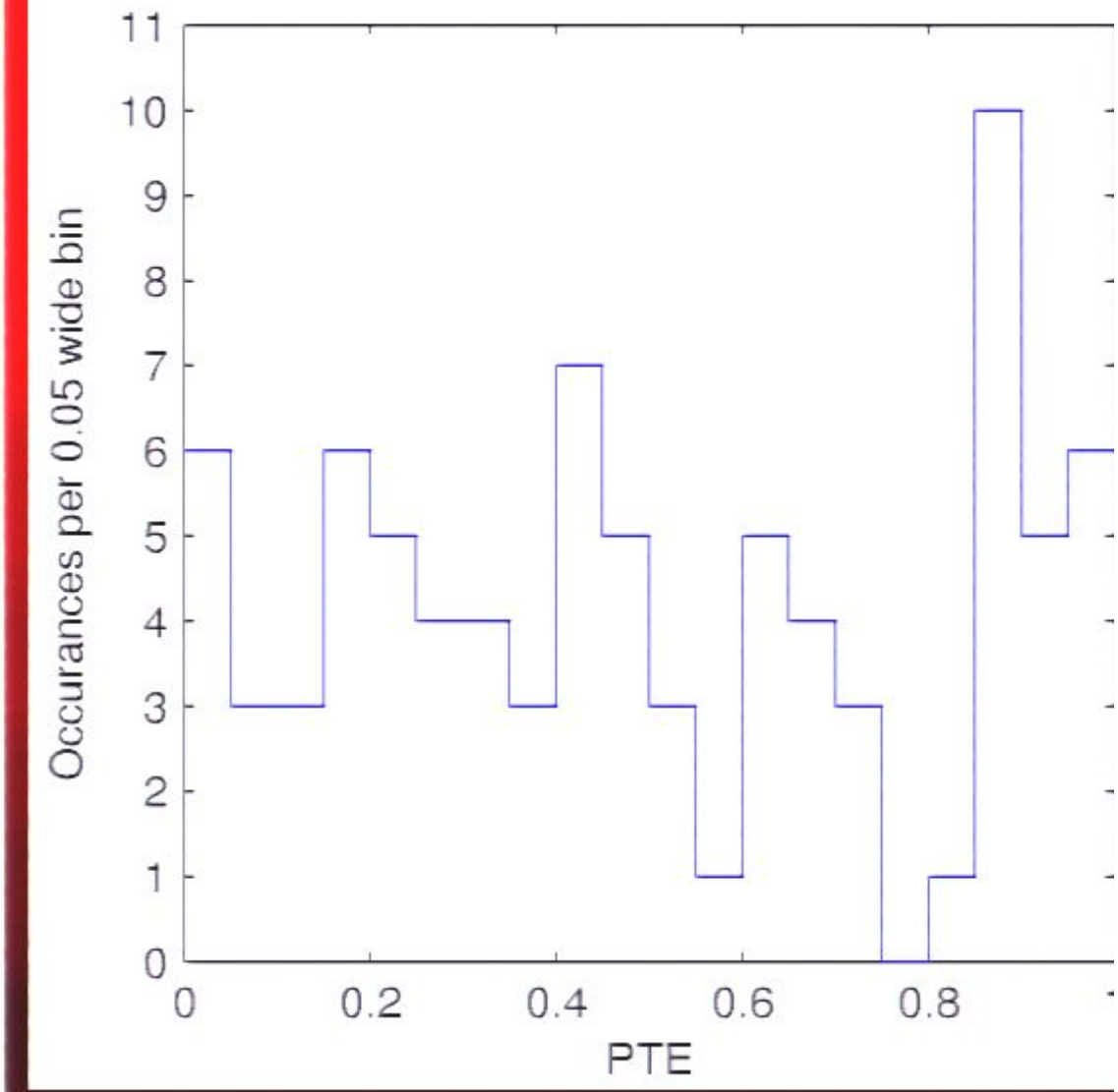
150GHz Corrected Spectra



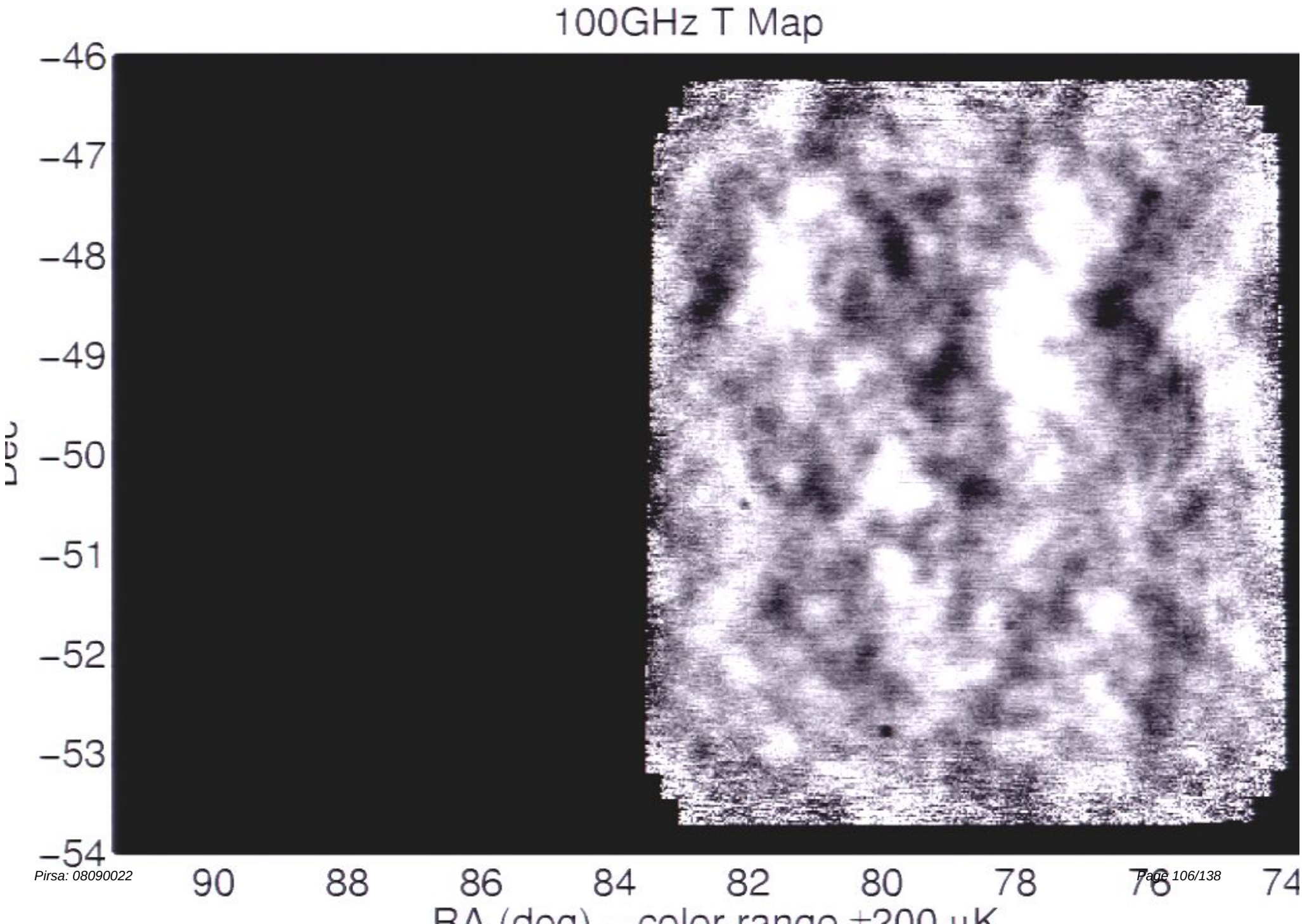
- Signal to noise high! (except BB)
  - No obvious jackknife cancellation failure...

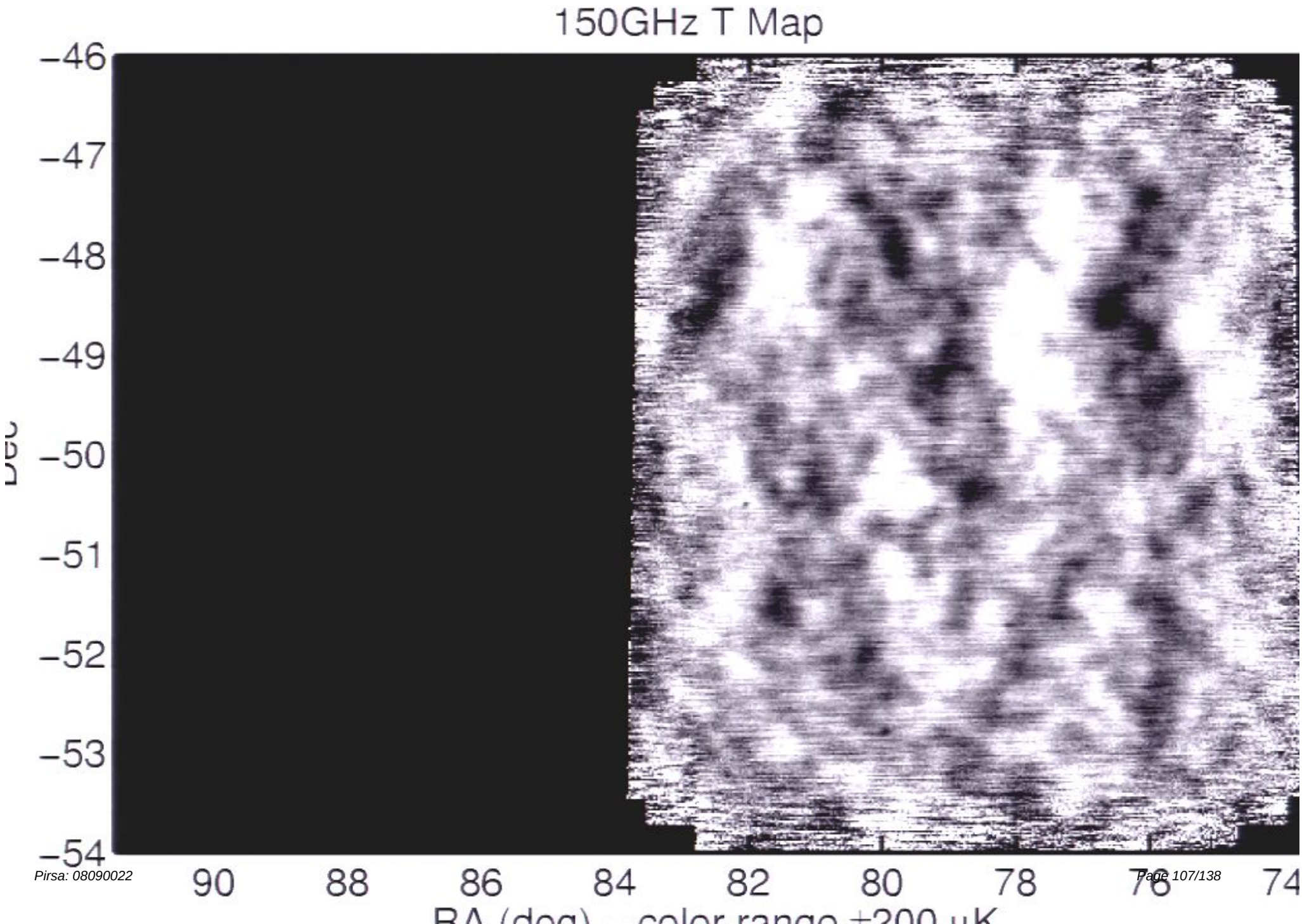
Battery of Jackknife tests

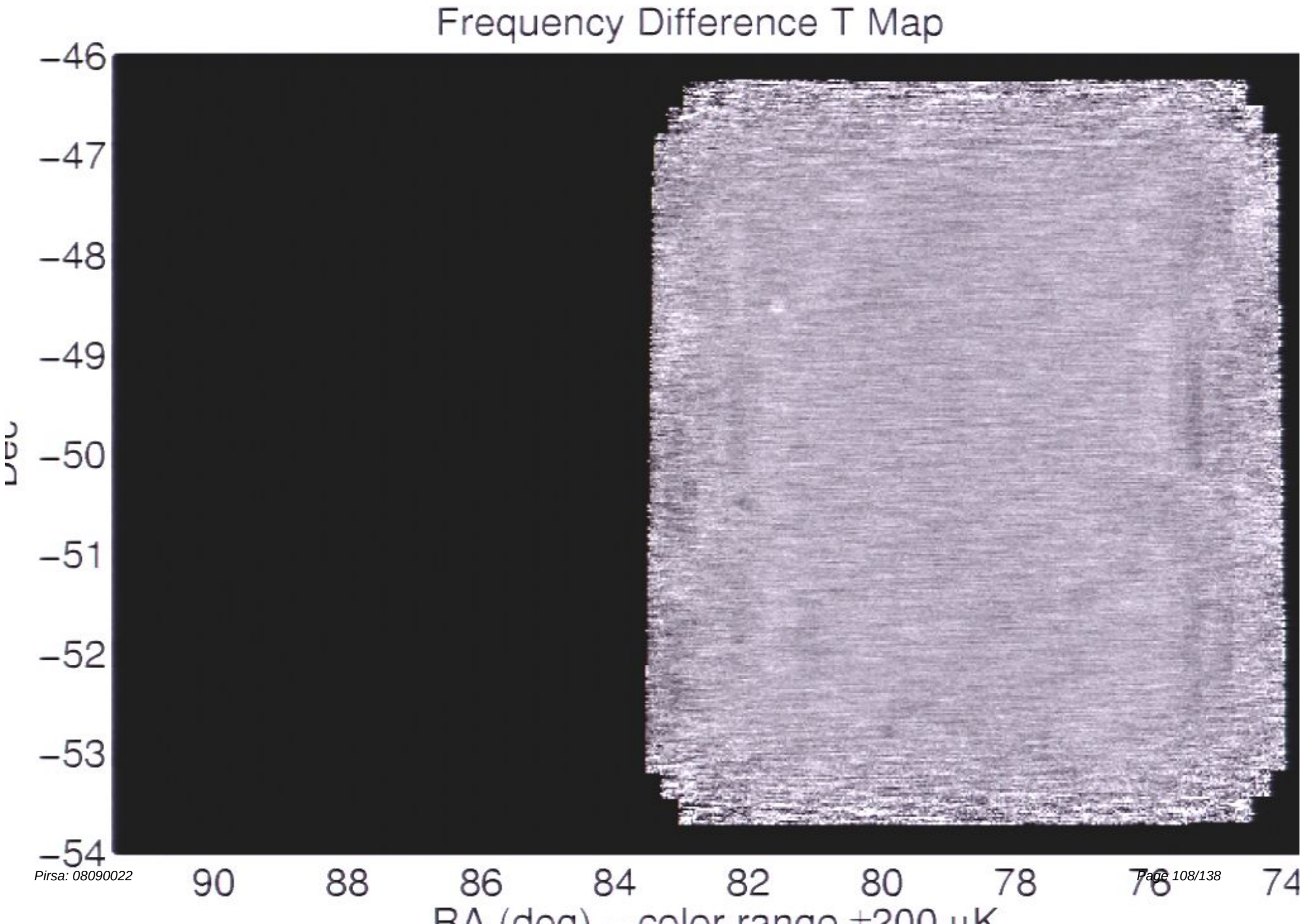




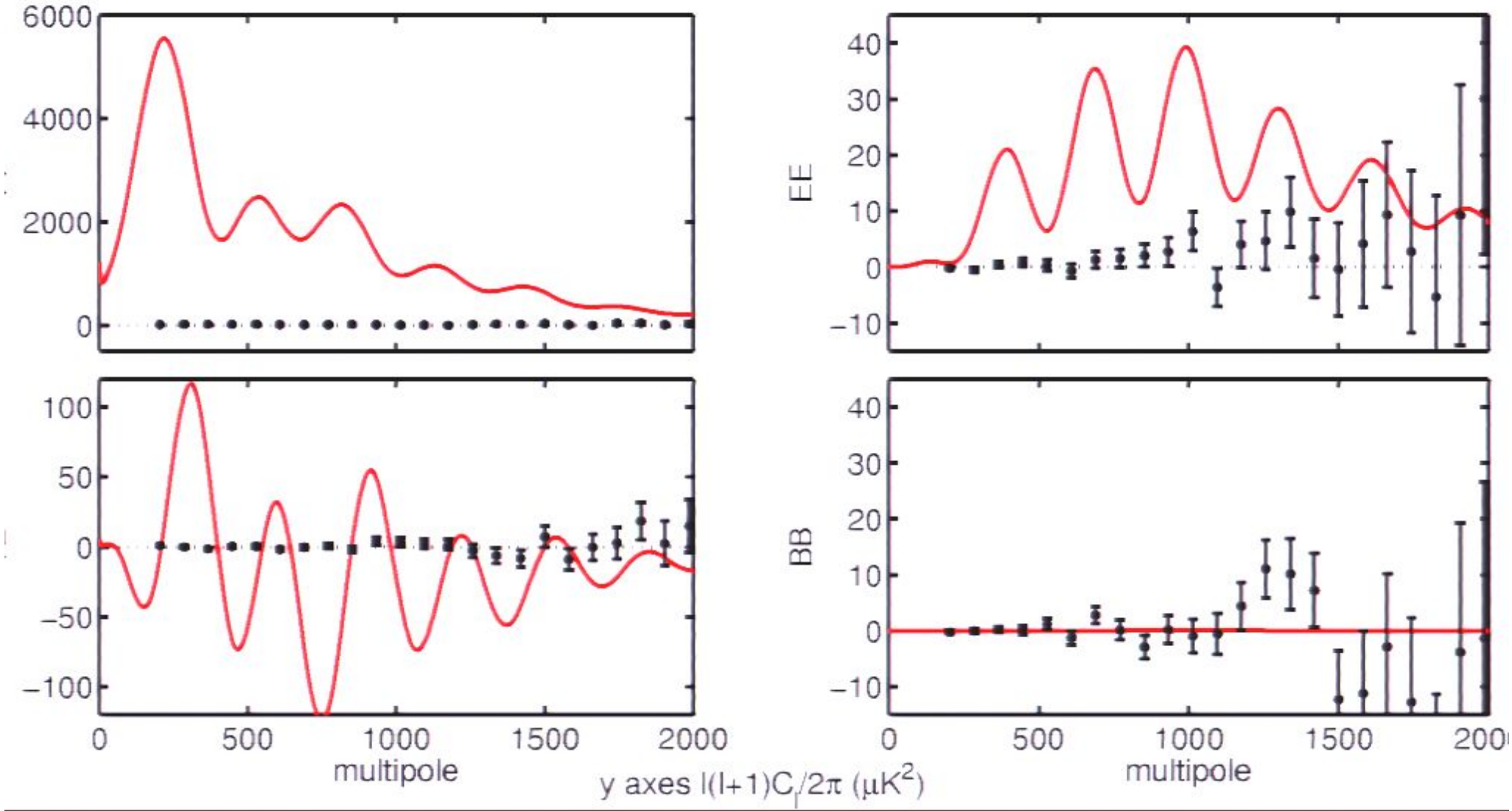
Take χ^2 of each jackknife spectrum → Convert to Probability To Exceed (PTE) → Should be flat distribution


100GHz T Map
−46
−47
−48
−49
−50
−51
−52
−53
−54
Dec
90
88
86
84
82
80
78
76
74
RA (deg) color range ±200 μK


150GHz T Map
−46
−47
−48
−49
−50
−51
−52
−53
−54
Dec
90
88
86
84
82
80
78
76
74
RA (deg) color range ±200 μK


Frequency Difference T Map
−46
−47
−48
−49
−50
−51
−52
−53
−54
Dec
90
88
86
84
82
80
78
76
74
RA (deg) color range ±200 μK

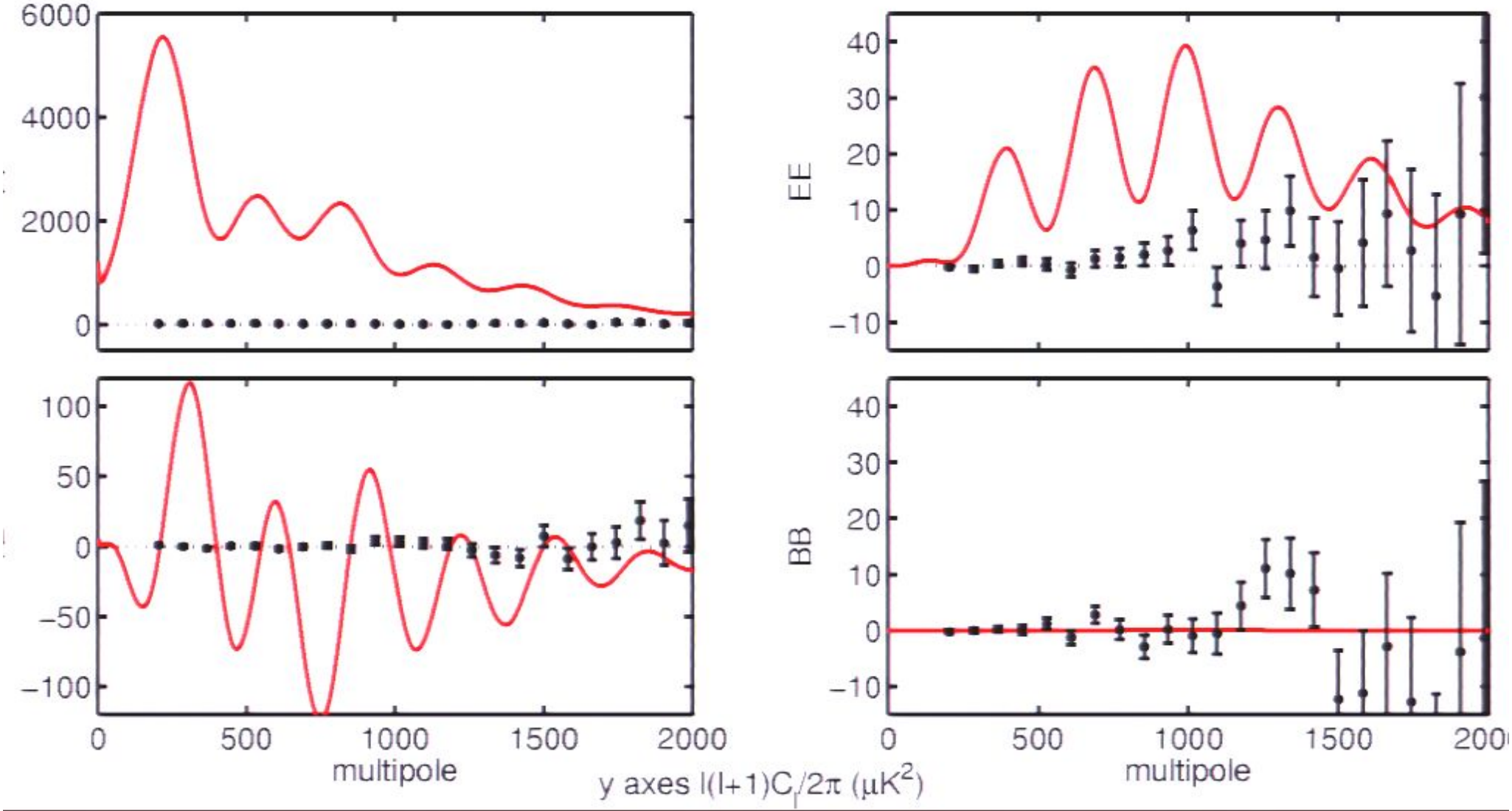
Frequency Difference Spectra



Tests if pattern identical at each freq.
(both freq. abs. cal'ed against same B03 150GHz map)

Examination of Final Results

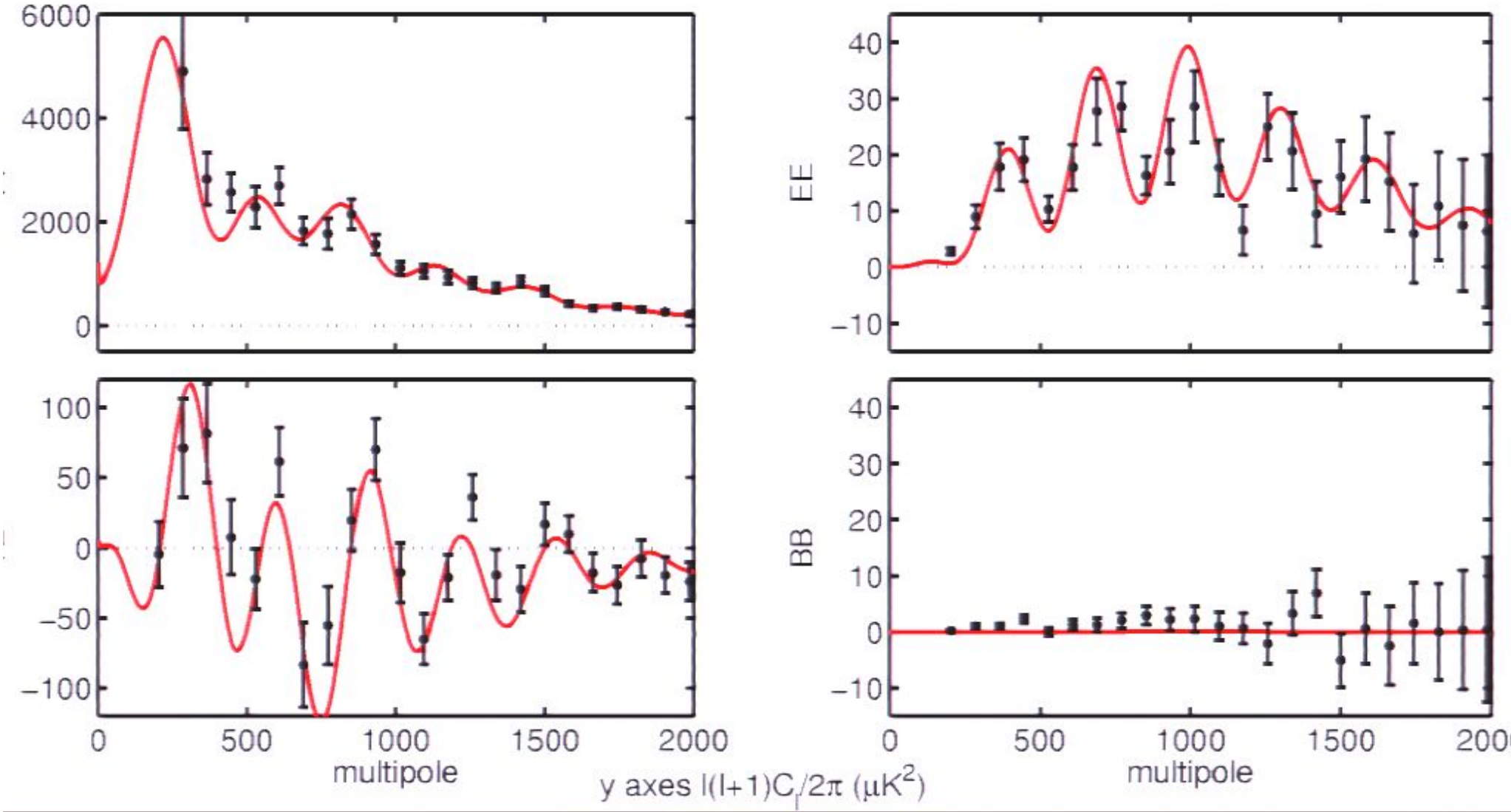
Frequency Difference Spectra



Tests if pattern identical at each freq.
(both freq. abs. cal'ed against same B03 150GHz map)

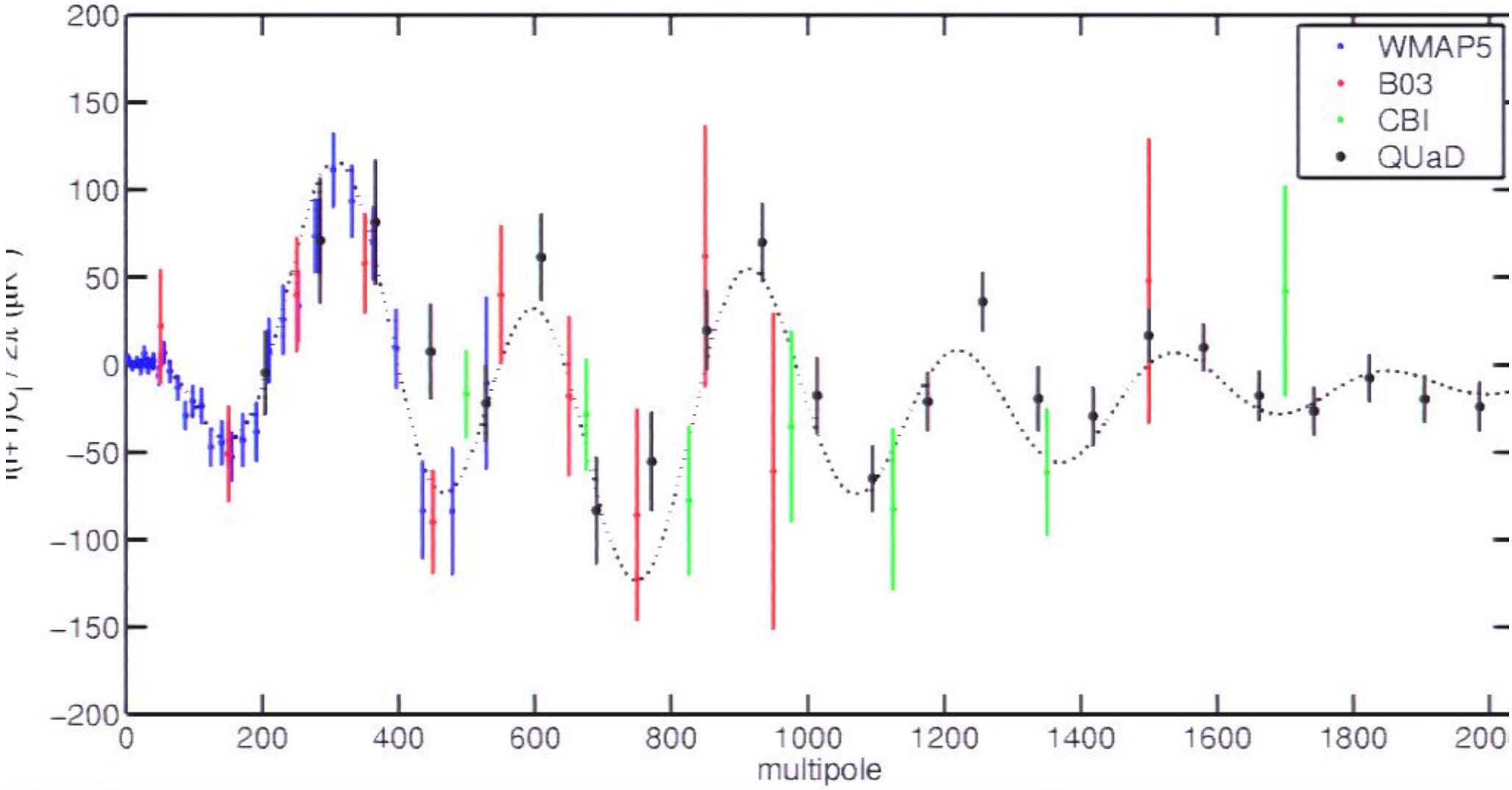
Examination of Final Results

Combined 100/150/cross Spectra



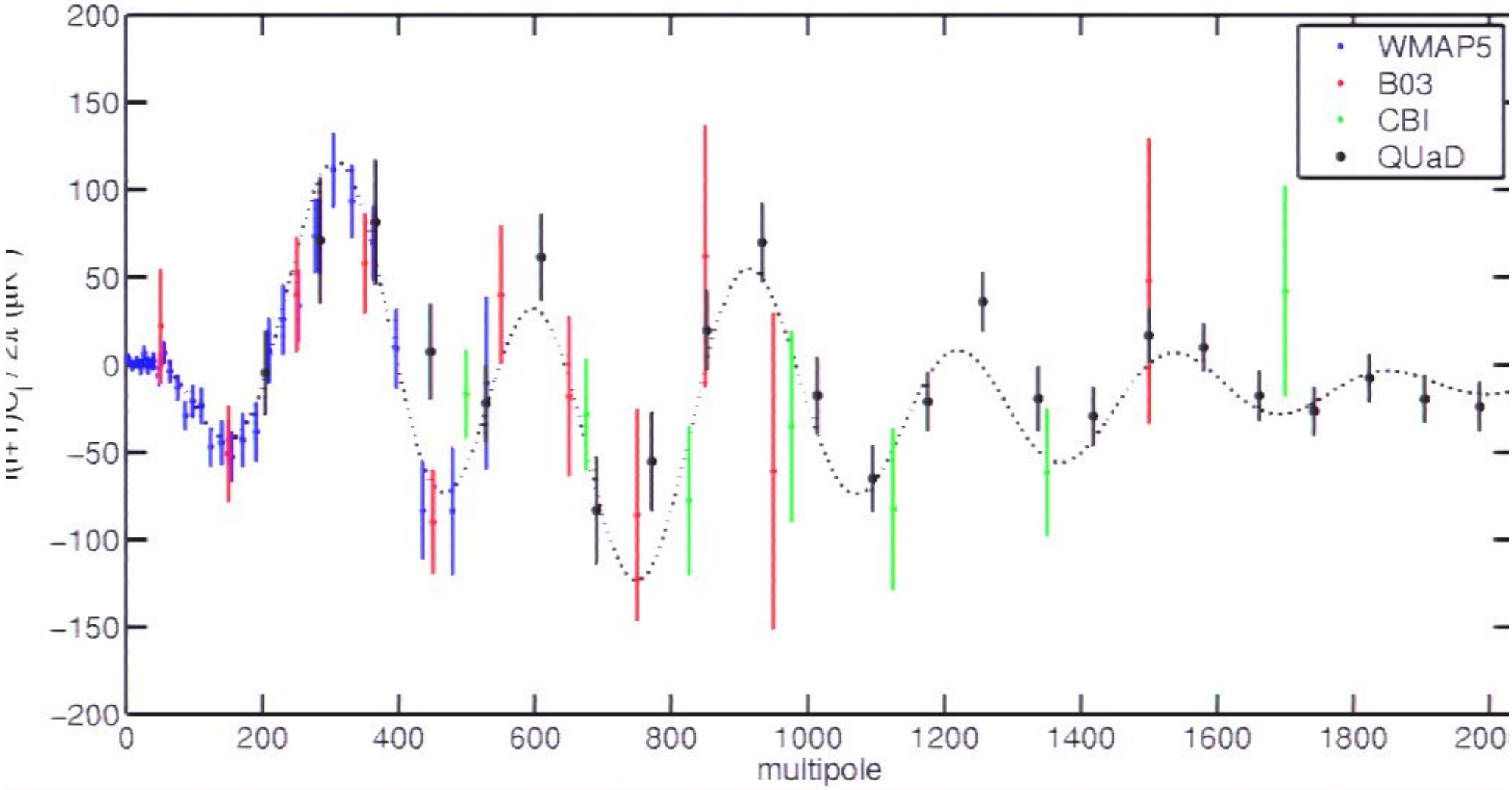
(Only slightly better than 150GHz alone)

TE Compared to Other Experiments



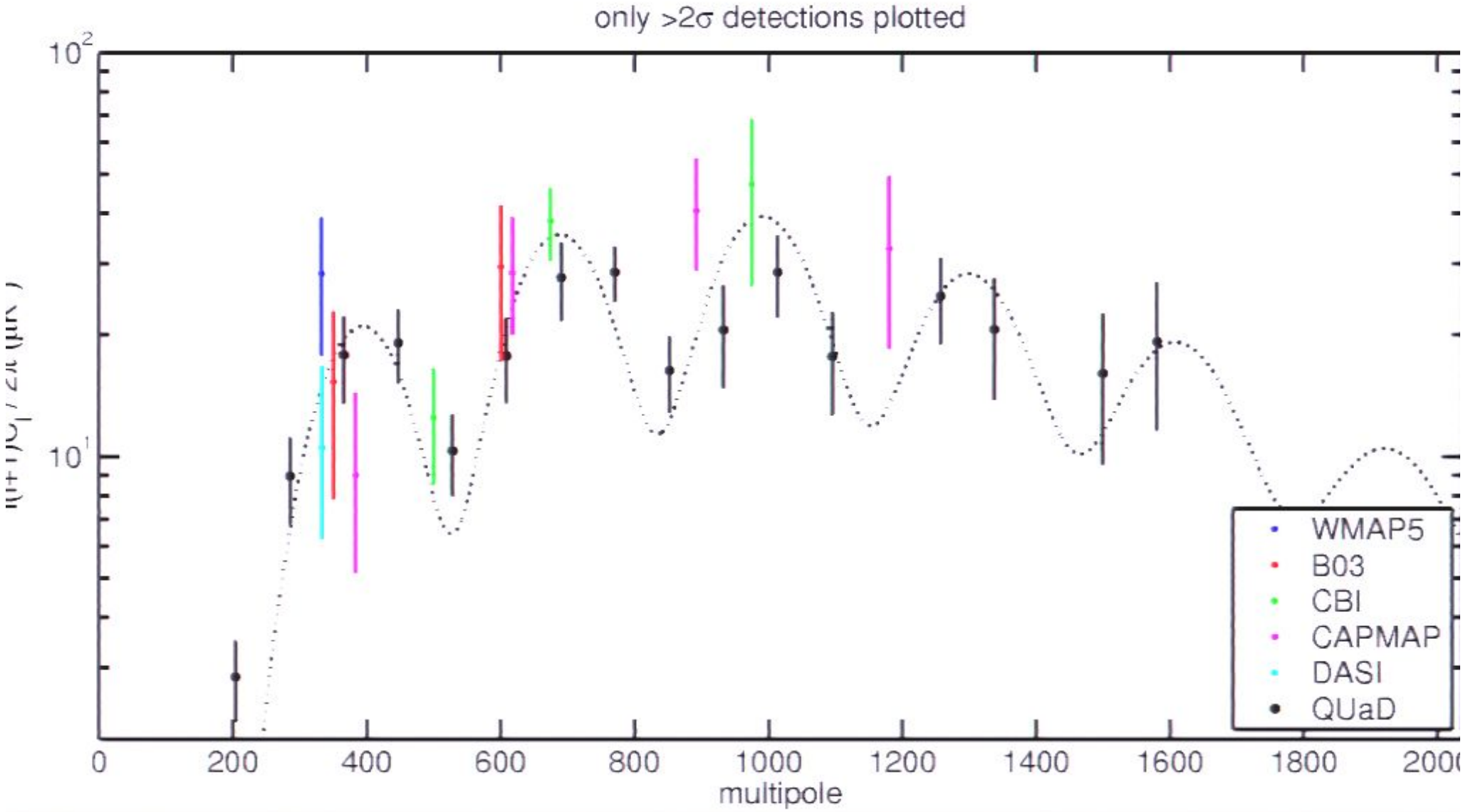
QUaD improves over previous at higher ell

TE Compared to Other Experiments



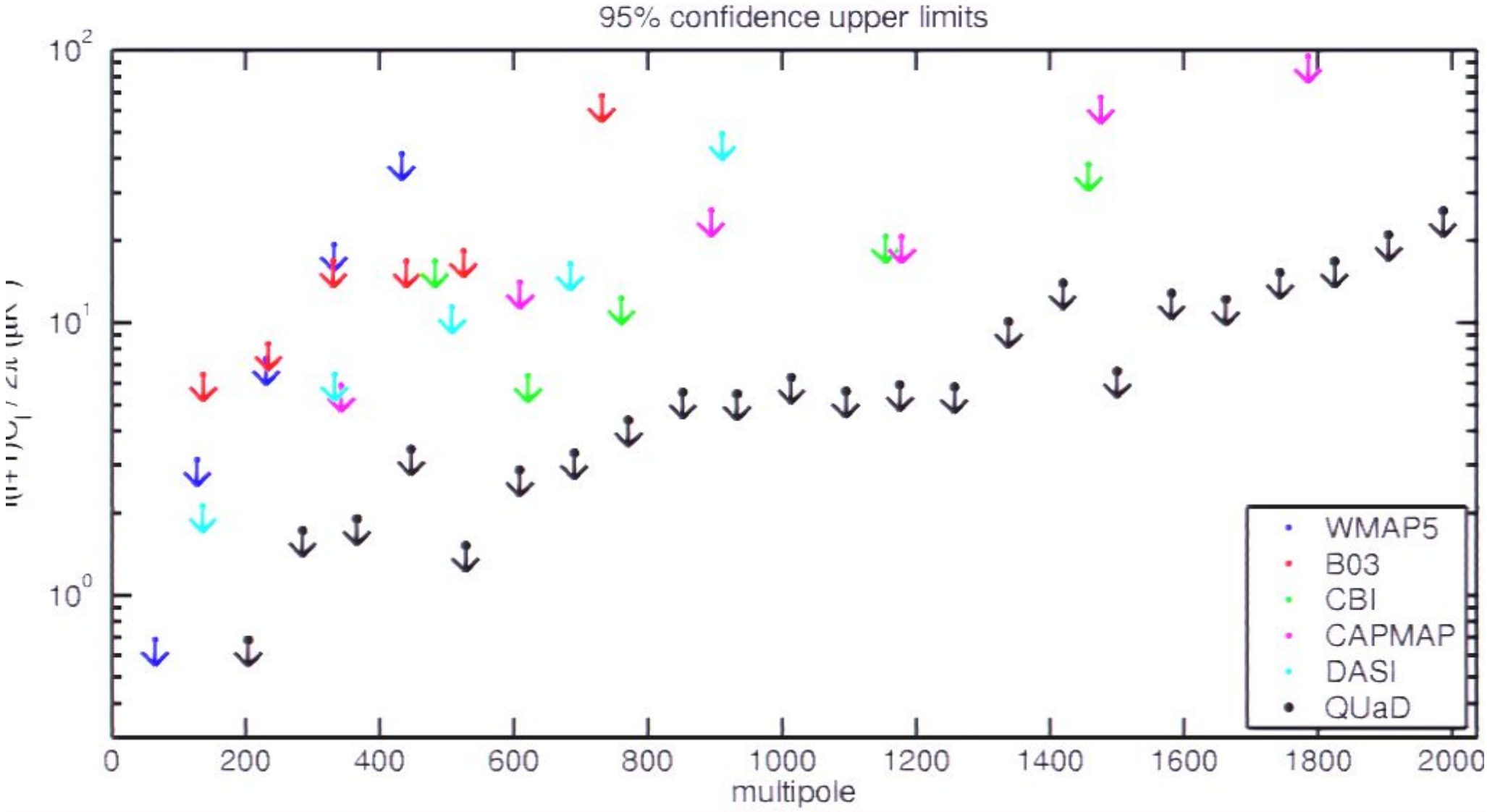
QUaD improves over previous at higher ell

EE Compared to Other Experiments



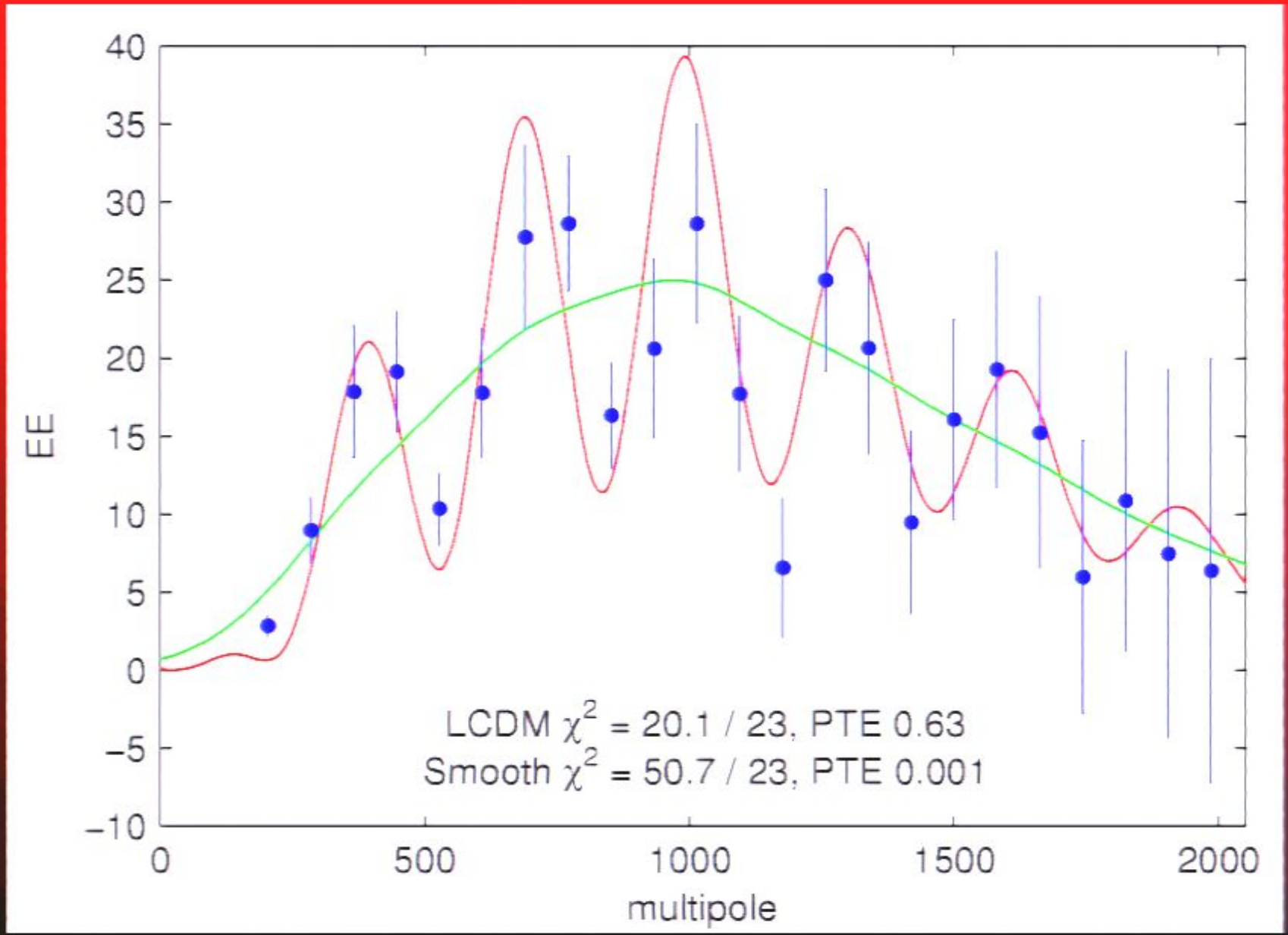
QUaD detects a series of peaks for the first time...

BB Compared to Other Experiments



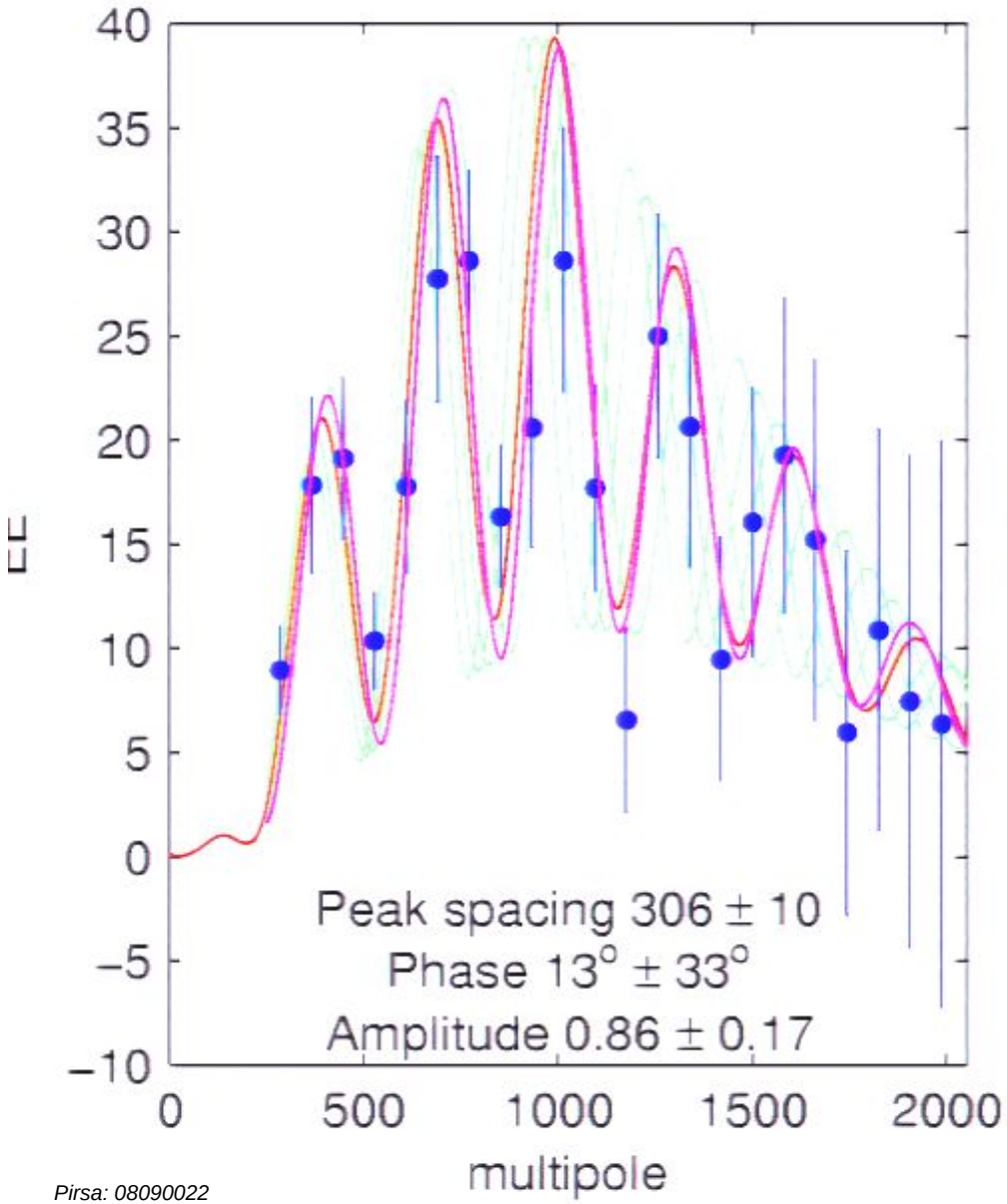
QUaD pushes well below previous results - but still a long way to go to lensing B-modes

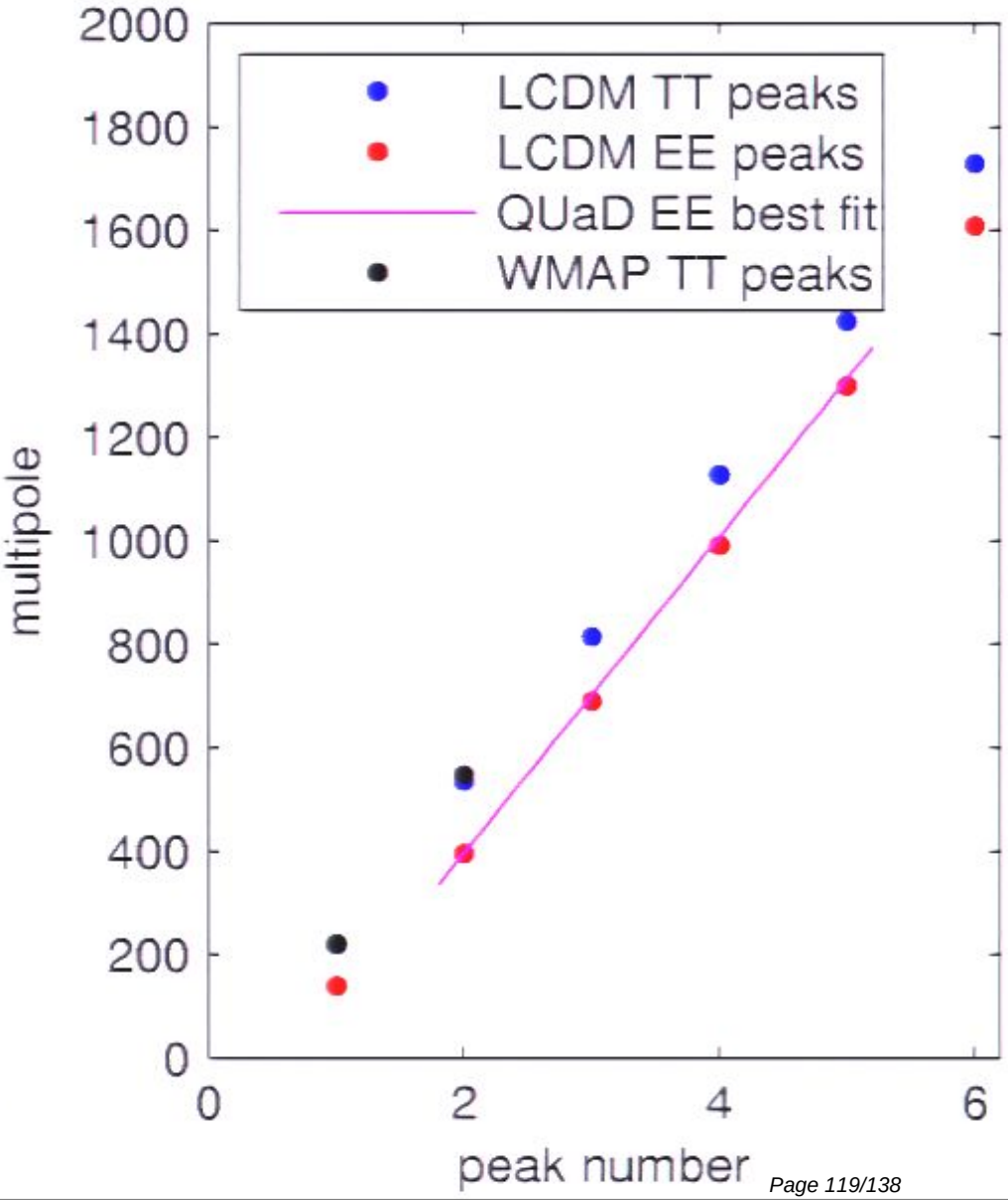
Does the EE Spectrum Have Peaks?



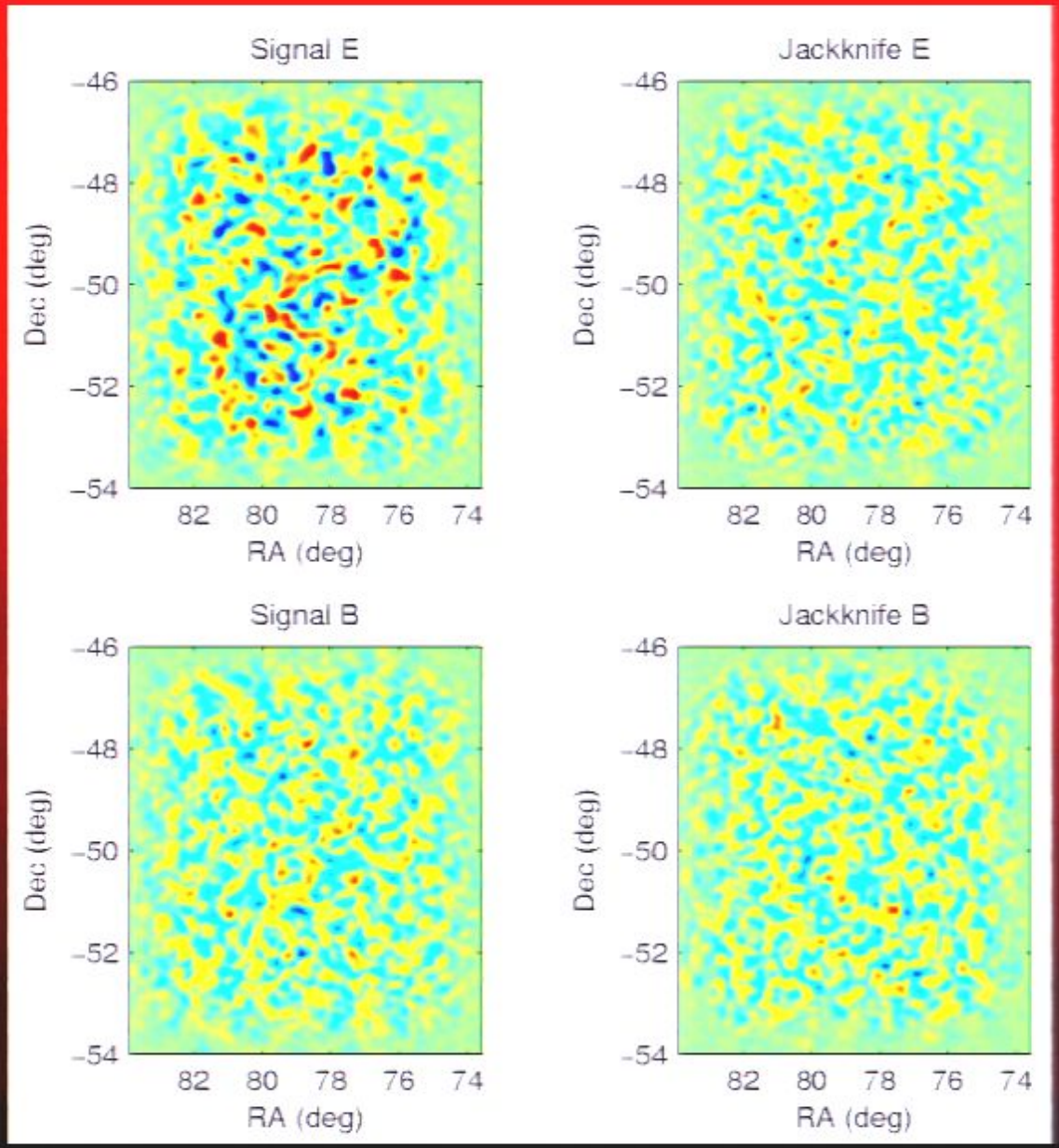
Chance that true spectrum is smooth is 1 in a 1000

What is the EE Peak Spacing/Phase?





E/B Maps



For fun after Q/U->E/B go back to map space

Lessons from QUaD

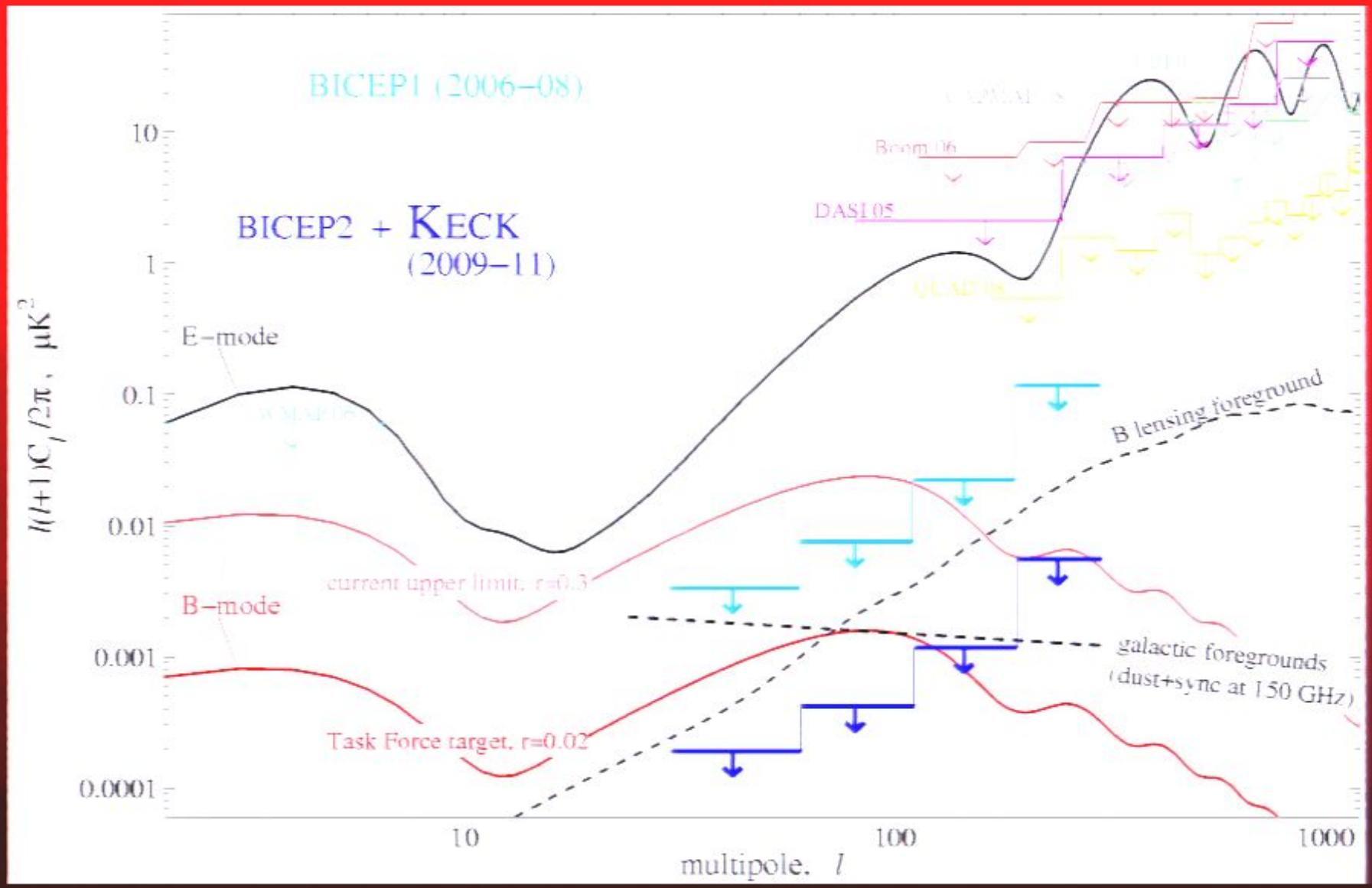
- A ground based CMB polarimeter can have excellent stability
  - Direct pair difference worked
  - Half wave plate modulation was not required
  - Cross linking of map not needed
- Simple Fourier based analysis has proven to be adequate
- By far the biggest problems have been detector weirdness and good old fashioned sidelobe pickup
  - Moon!

- (Caveat: obviously the above are shown to be true only for the specific configuration and sensitivity of QUaD)

QUaD Conclusions

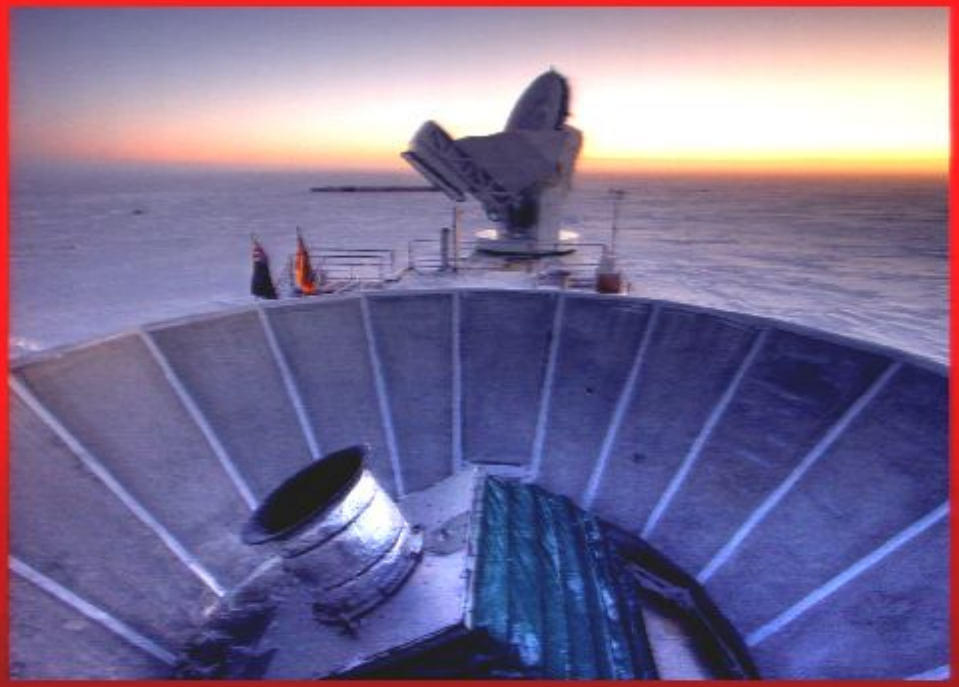
- QUaD was decommissioned last fall after three seasons of operation
- New results paper out
  - Pryke el al - http://arxiv.org/abs/0805.1944
- Results:
  - Improve considerably over previous pol. results (for l>200)
  - Are consistent with LCDM - no B-modes yet...
- The polarization signal cancels under frequency jackknife
  - No evidence for foregrounds

The Quest for Gravity Wave B-Modes



Health warning: theorists refuse to say how small this signal may be!

QUaD's Sister - BICEP



- BICEP is essentially QUaD without the primary and secondary mirrors - "Telescope in a can" approach for excellent systematic control, modularity and low cost
  - all cold optics and black fore-baffle
    - super low sidelobes
  - downside is big beam - 0.9/0.6 deg @ 100/150GHz

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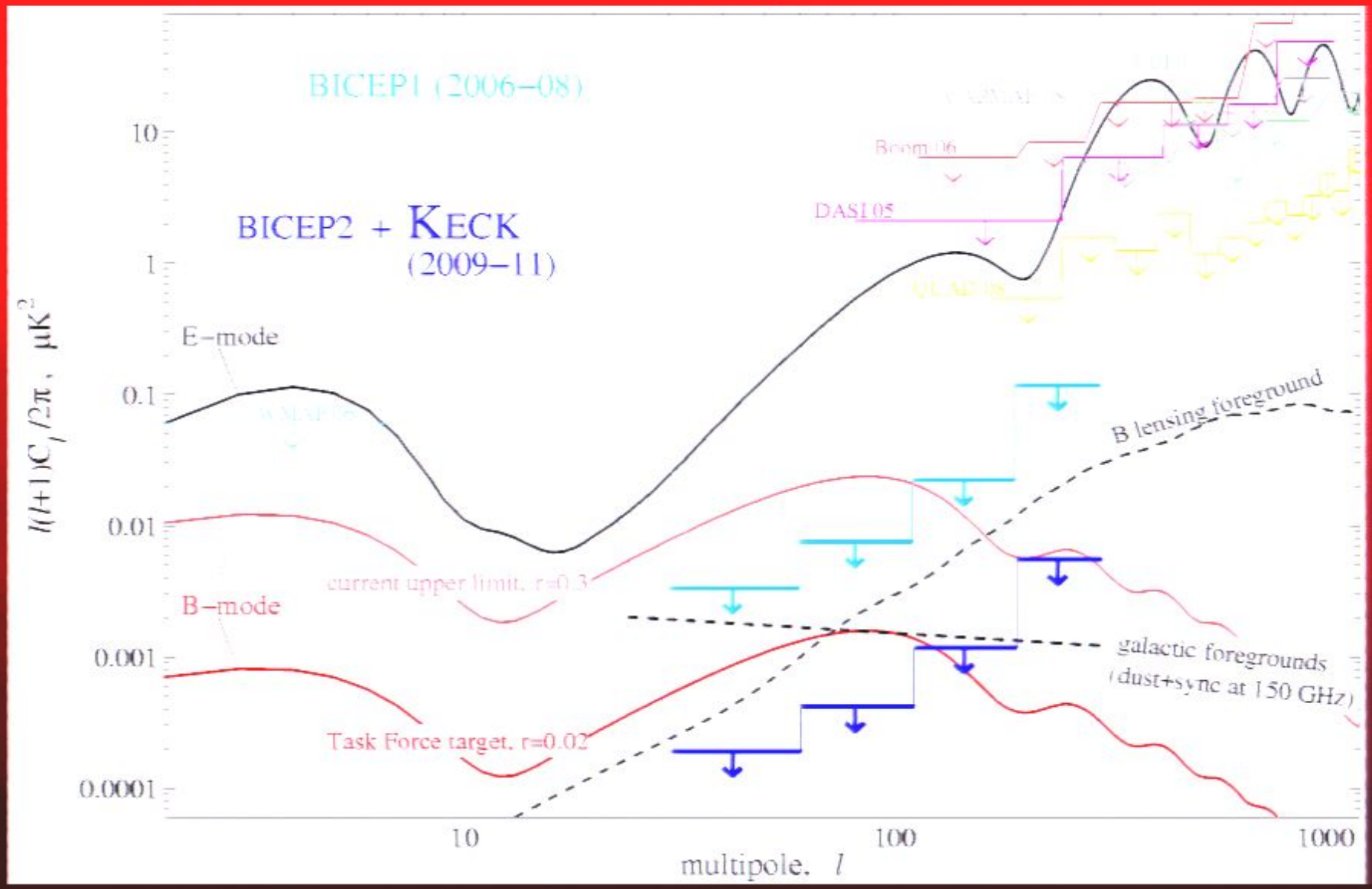

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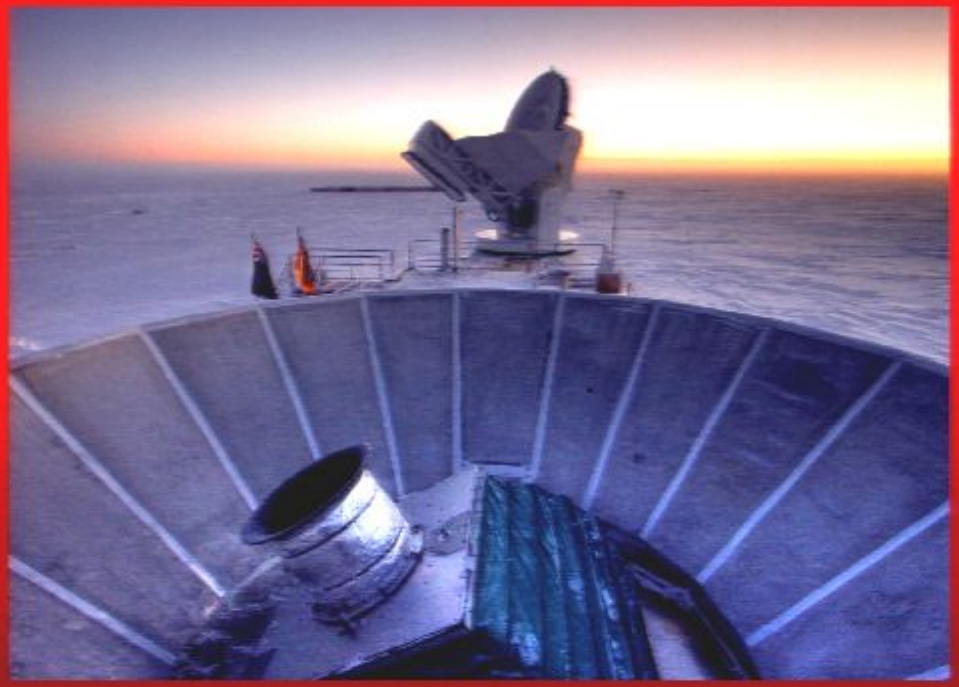

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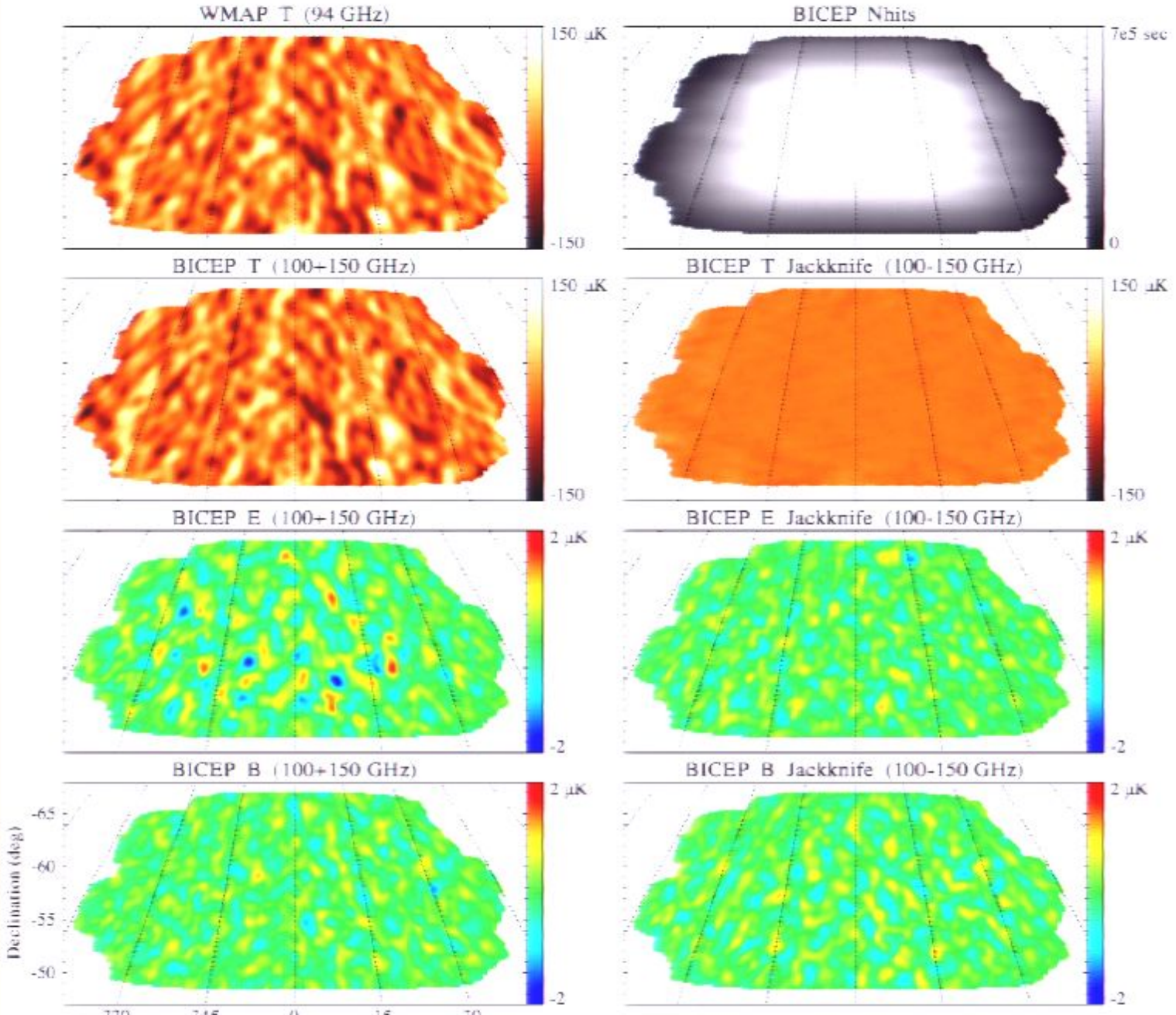
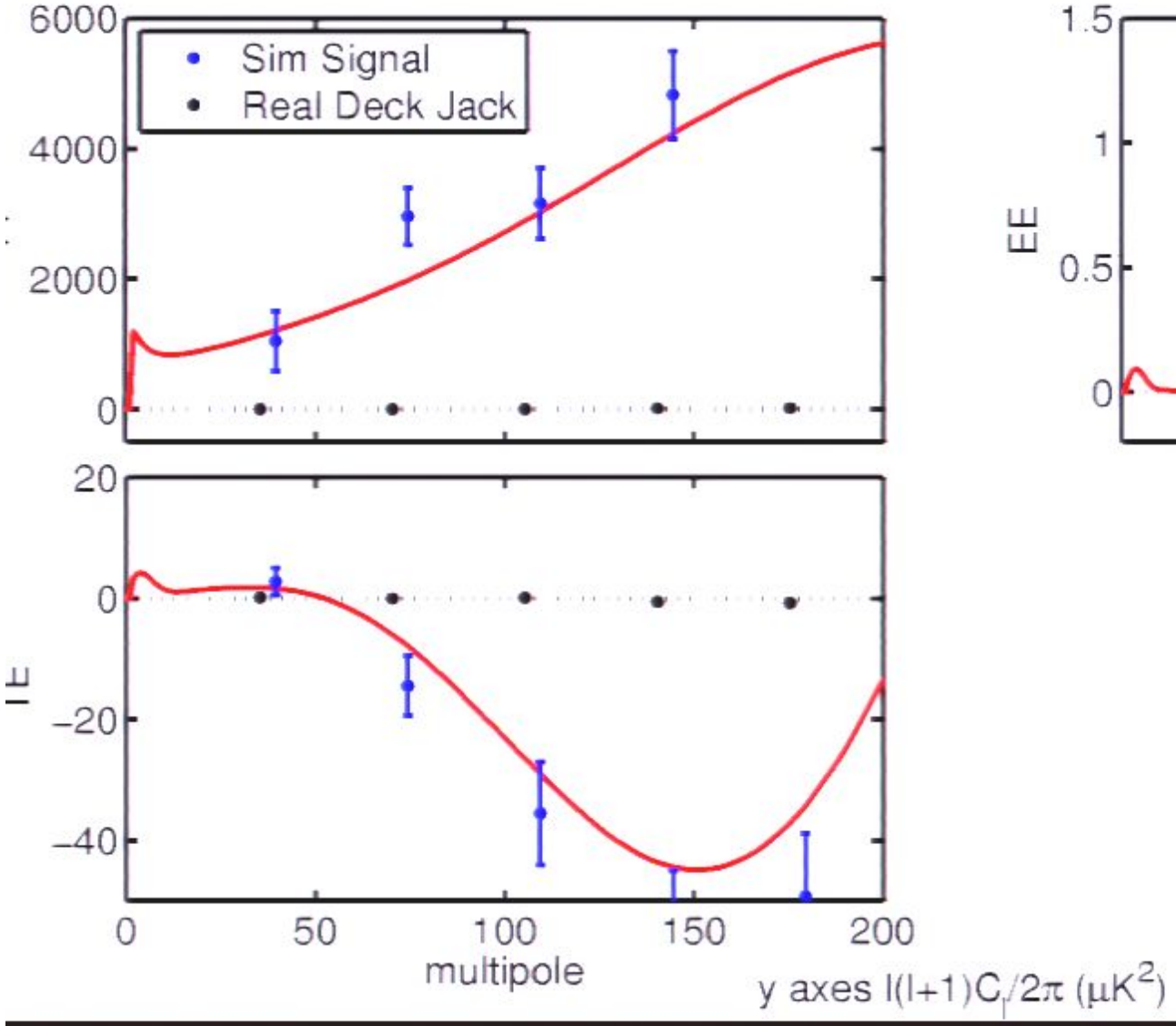
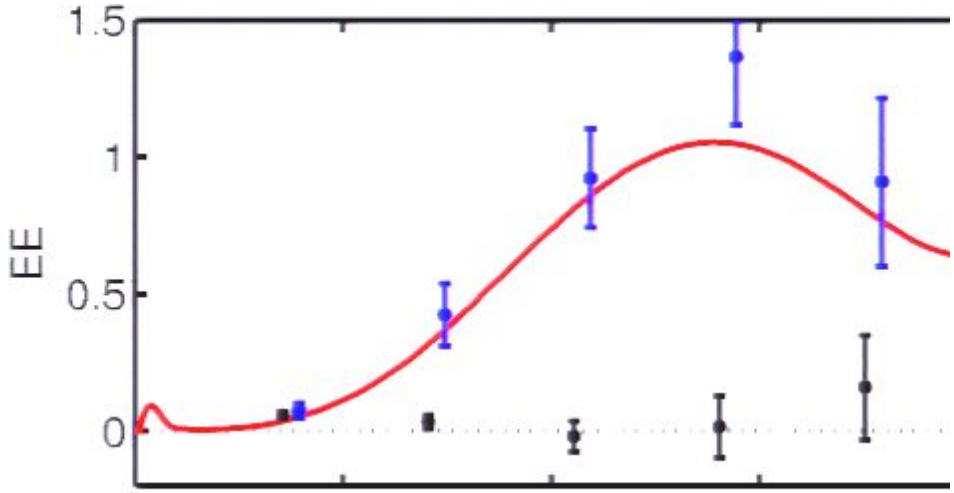
BICEP Maps


WMAP T (94 GHz)
150 μK
-150
BICEP Nhits
7e5 sec
0
BICEP T (100+150 GHz)
150 μK
-150
BICEP T Jackknife (100-150 GHz)
150 μK
-150
BICEP E (100+150 GHz)
2 μK
-2
BICEP E Jackknife (100-150 GHz)
2 μK
-2
BICEP B (100+150 GHz)
2 μK
-2
BICEP B Jackknife (100-150 GHz)
2 μK
-2
Declination (deg)
-65
-60
-55
-50

Sim and Jackknife BICEP Spectra



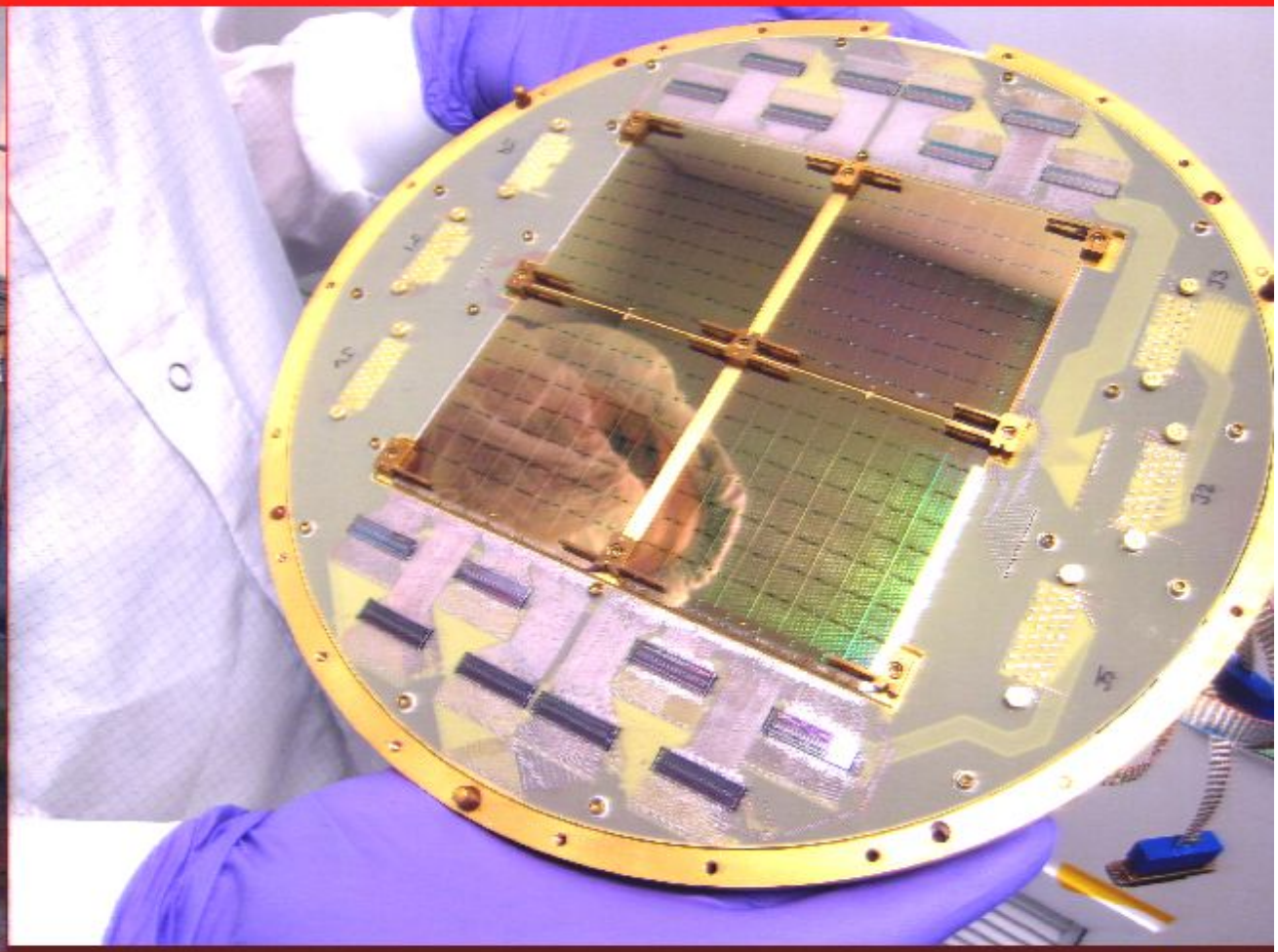


y axes $l(l+1)C_l/2\pi$ (μK^2)

BICEP1 analysis in advanced state (Denis Barkats / Cynthia Chang)

BICEP2 Under Construction

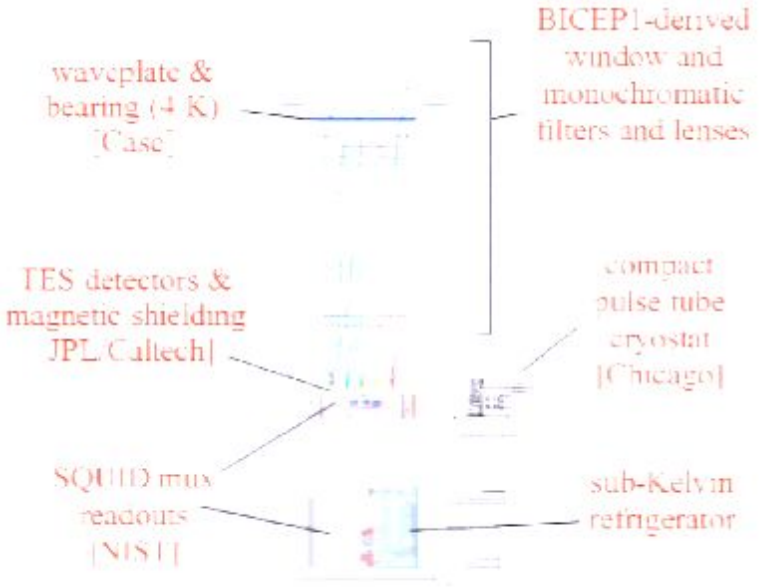
BICEP2 Under Construction



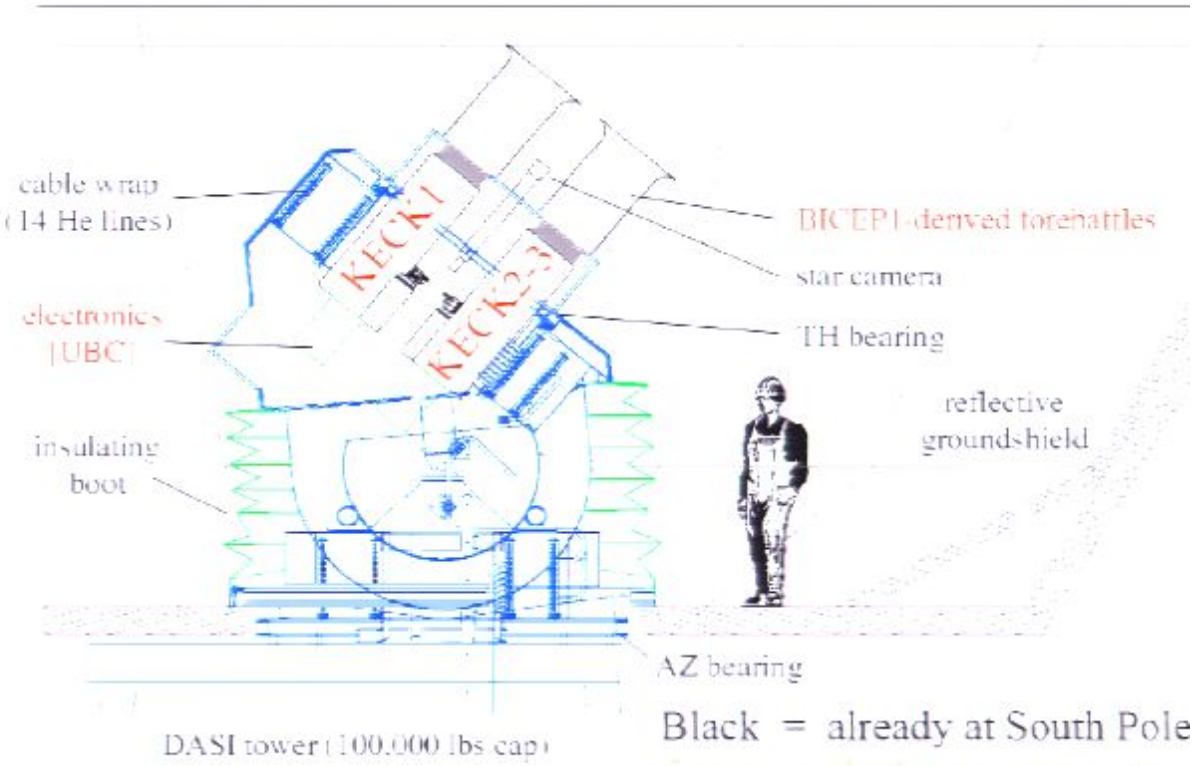
- 256 dual pol pixels (antenna coupled)
- Now under integration at Caltech
- Will deploy to Pole fall 2009

B-mode Array on the DASI Platform

KECK:



KECK1.2.3



DASI tower (100,000 lbs cap)

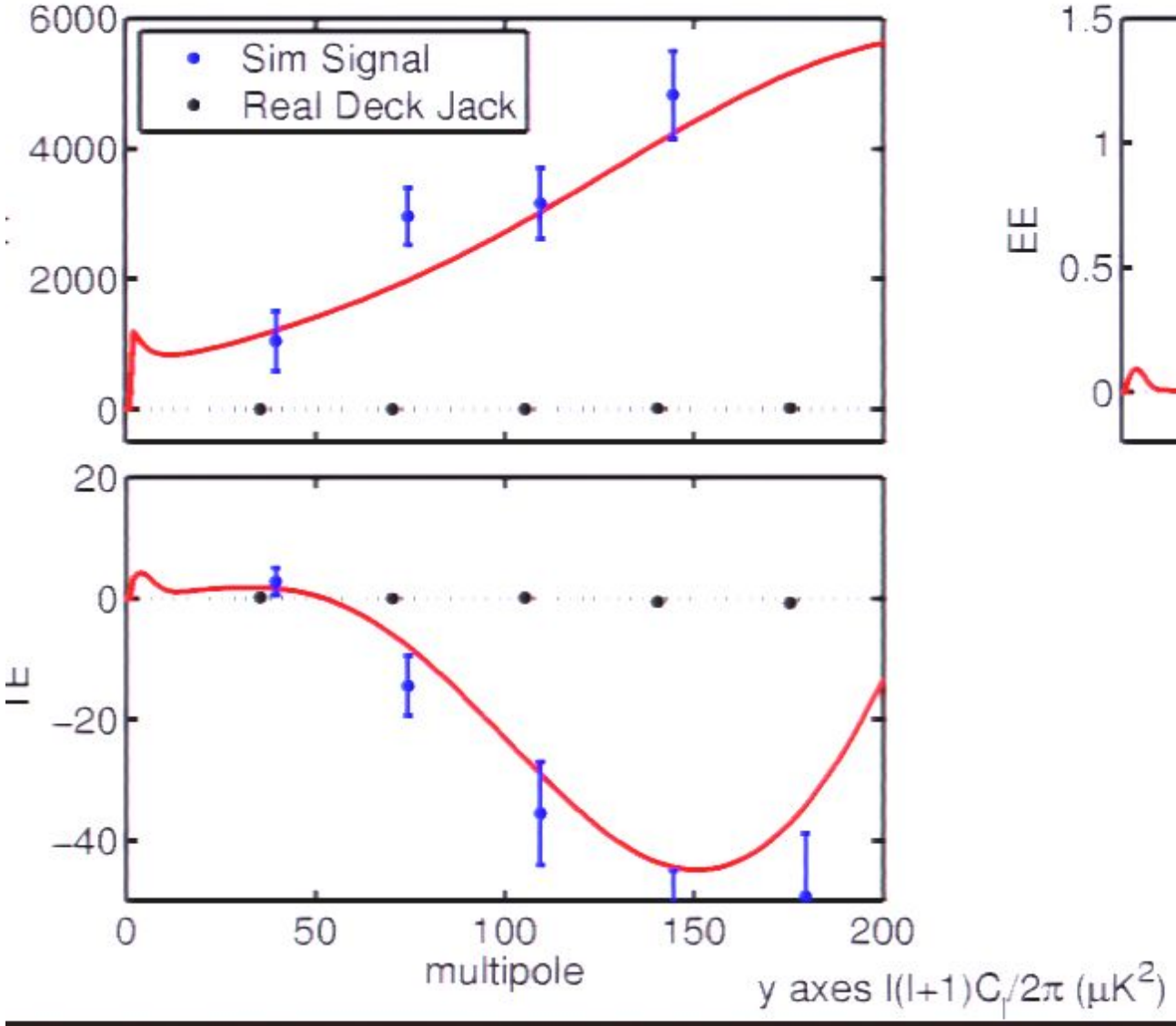
Black = already at South Pole

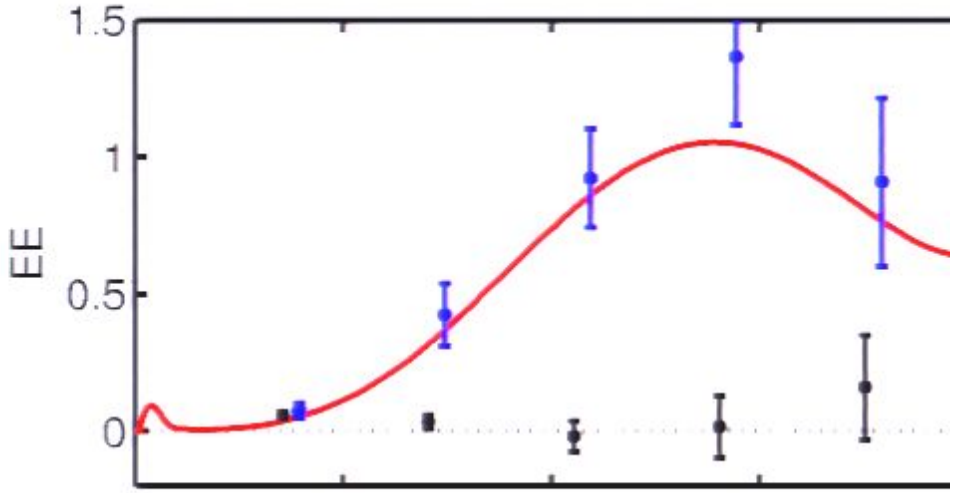
Green = [illegible] this year

Red = this proposal

- First three receivers funded by NSF/Keck
- Will deploy fall 2010
- Ultimately up to six at a mix of frequencies

Sim and Jackknife BICEP Spectra





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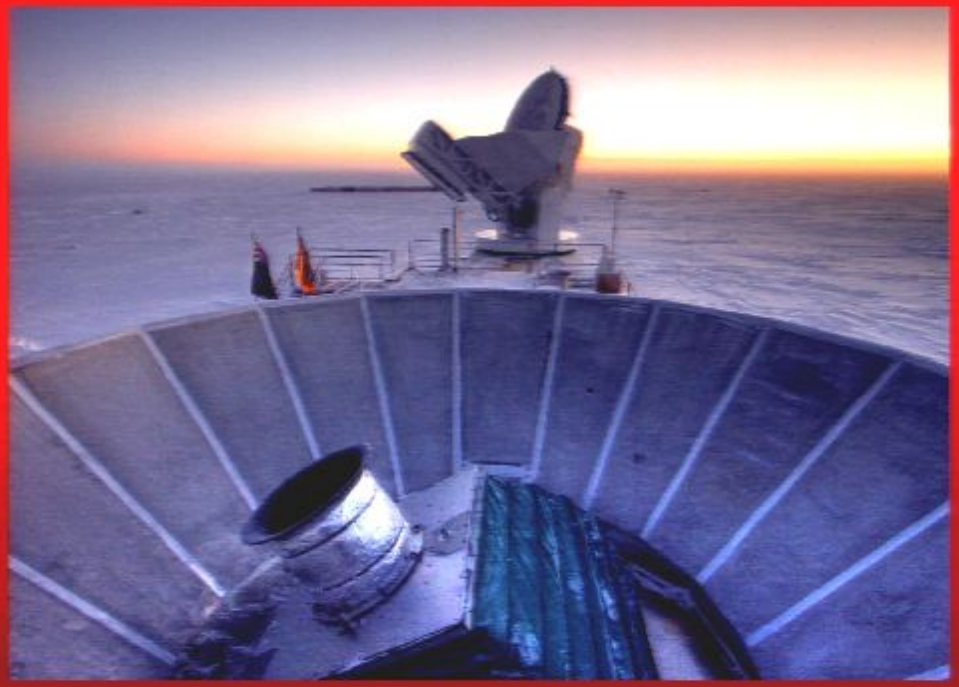
BICEP1 analysis in advanced state (Denis Barkats / Cynthia Chang)

QUaD's Sister - BICEP



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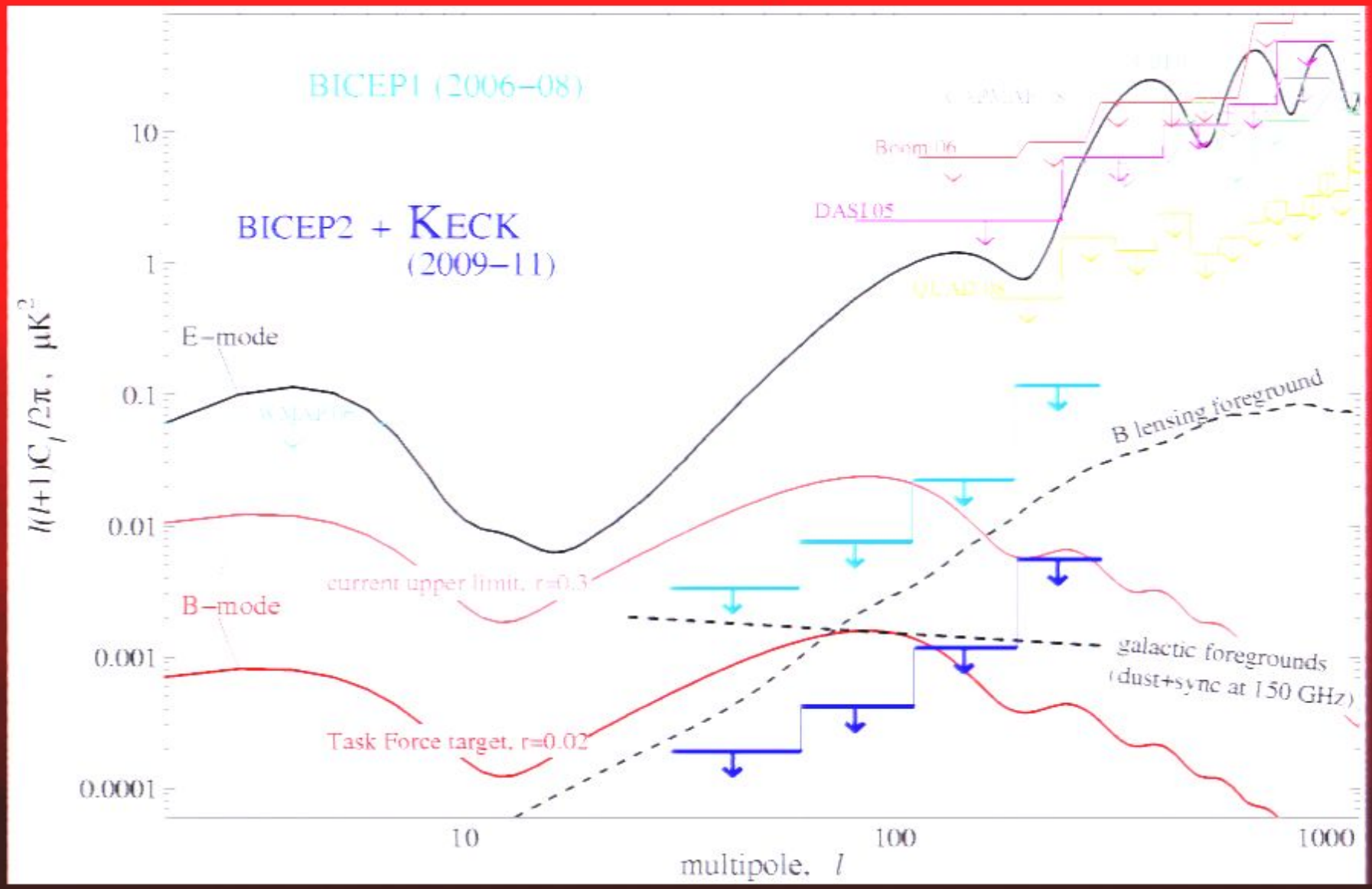
The Quest for Gravity Wave B-Modes



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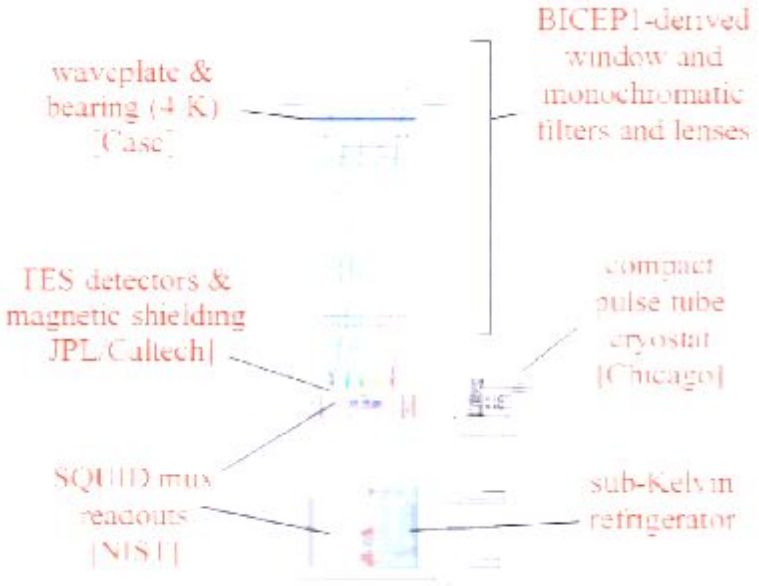
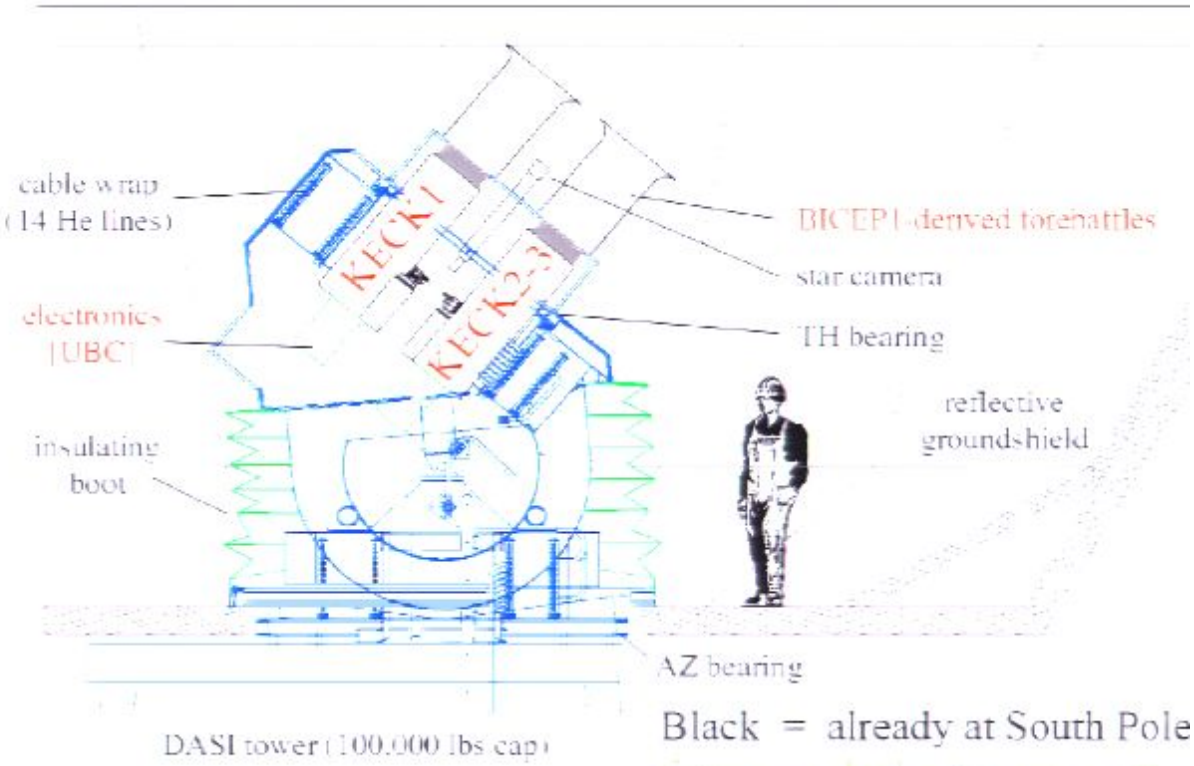
B-mode Array on the DASI Platform

KECK:



KECK1.2.3



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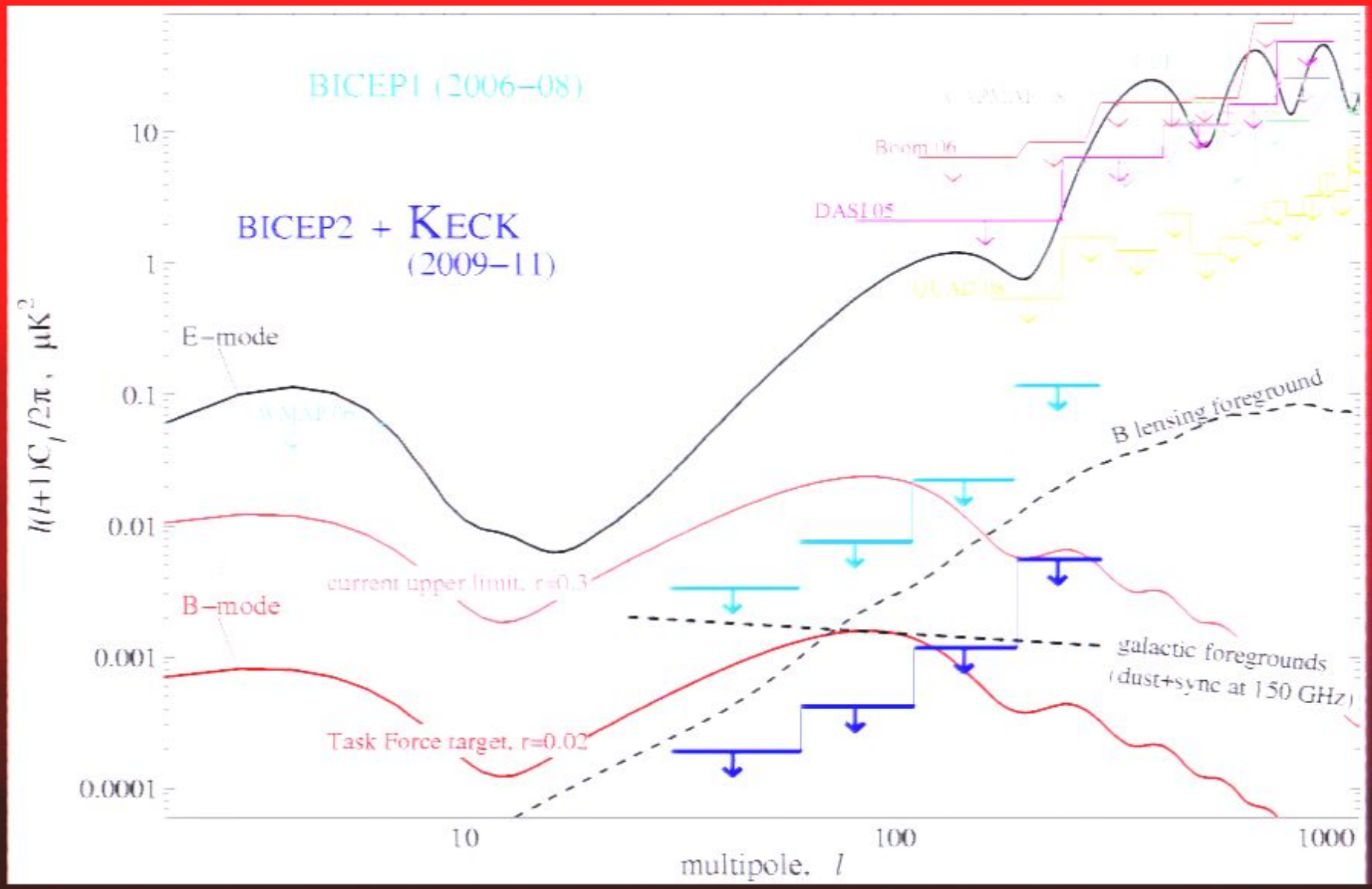
The Quest for Gravity Wave B-Modes



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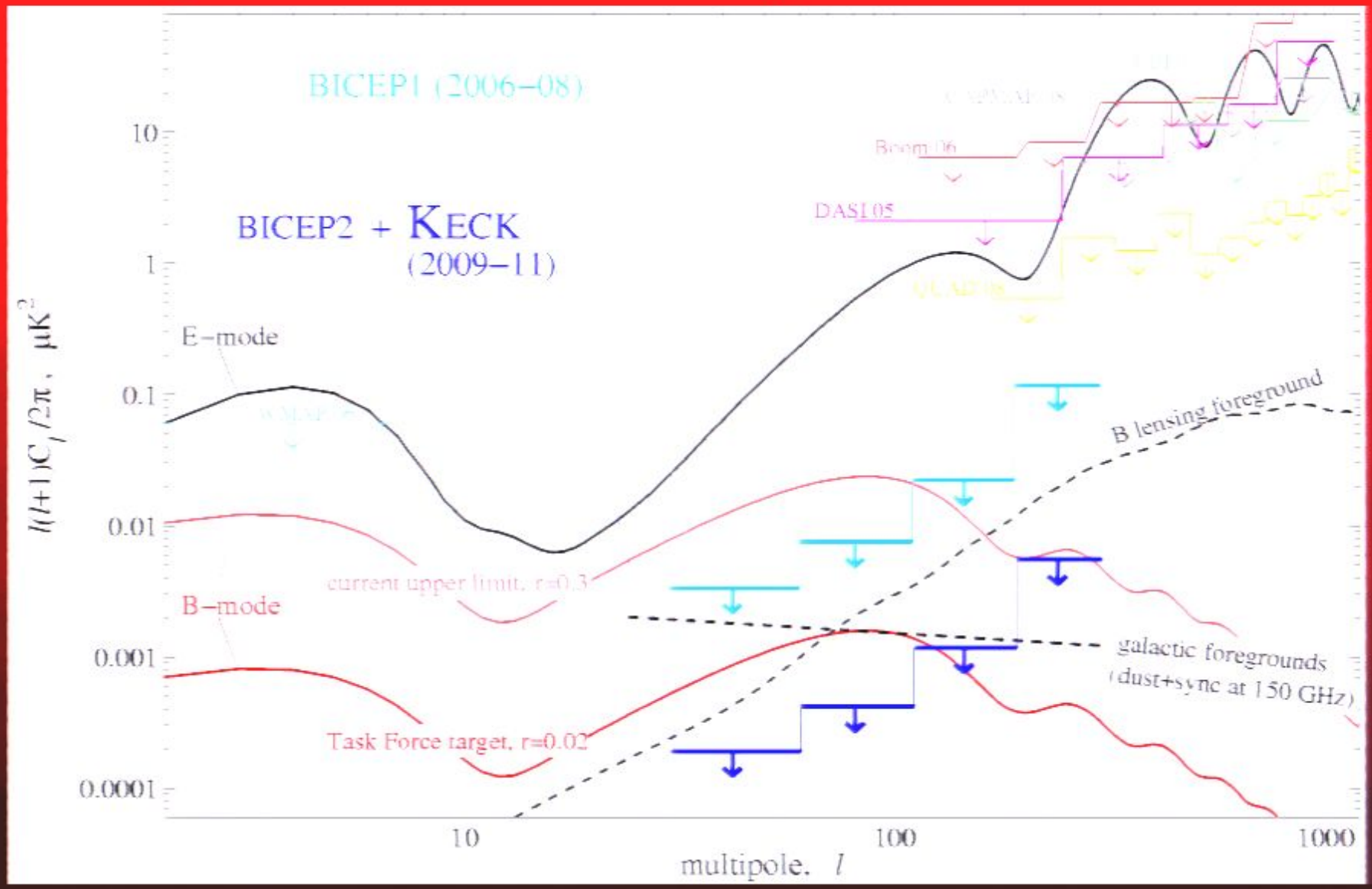
BICEP/BICEP2/Keck-Array Conclusions

- Aggressive "get there first" program
  - Can we show that gravity wave B-modes exist?
    - If they do expensive experiments become justifiable...
- "Foreground avoidance" strategy
  - Observe the cleanest 2% of the sky and target l=70 bump
  - Use multi frequency to push below r=0.03
- Caltech/Chicago + others collaboration
  - Chicago responsible for cryostat, mount, analysis...

The Quest for Gravity Wave B-Modes



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