Single-Dish Continuum

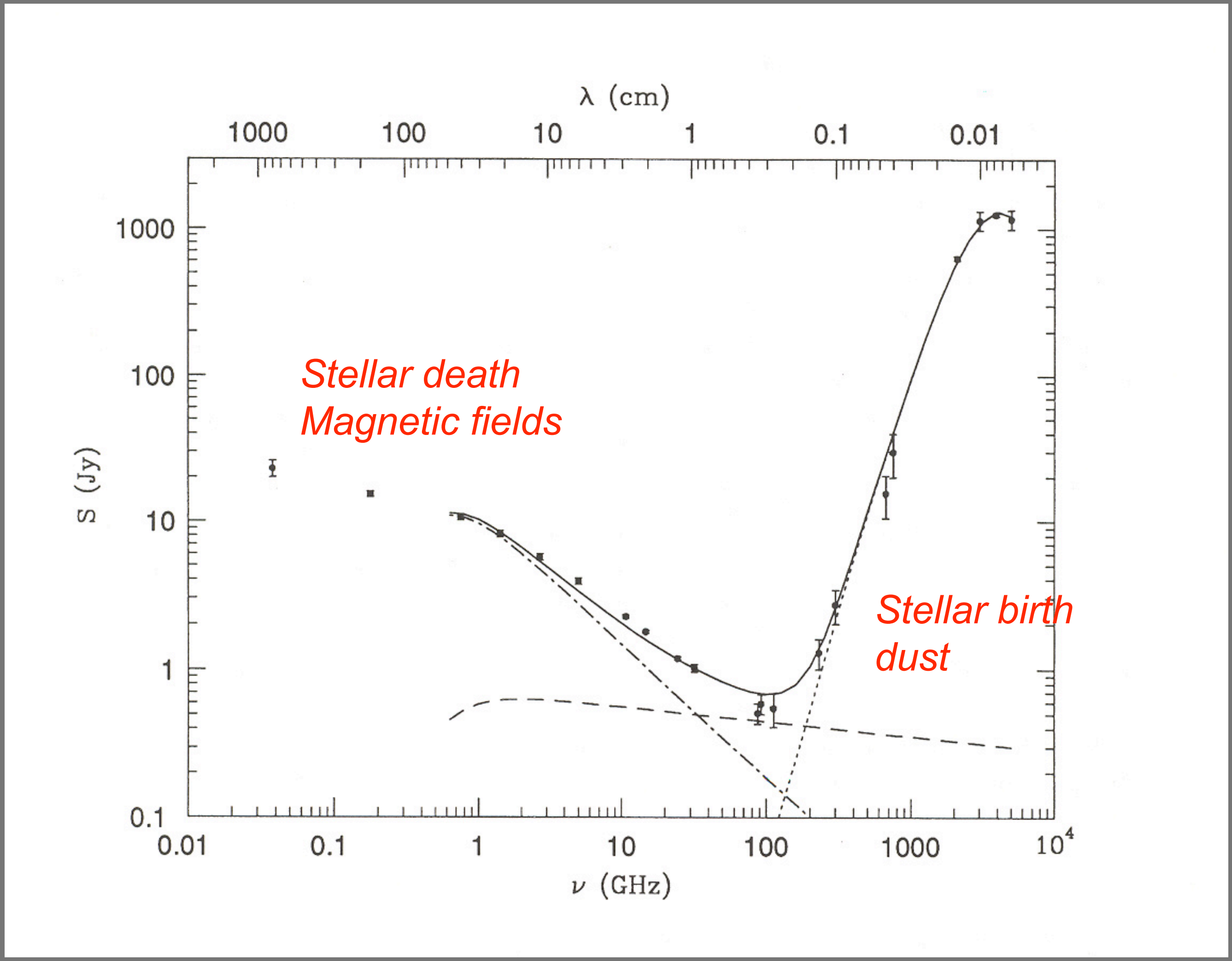
- *Continuum emission mechanisms & science*
- *Issues*
  - *Confusion*
  - *gain fluctuations*
  - *atmosphere*
- *Receiver architectures & observing strategies*
- *The future: large arrays*

Brian Mason (NRAO)

NRAO/NAIC Single-Dish Summer School

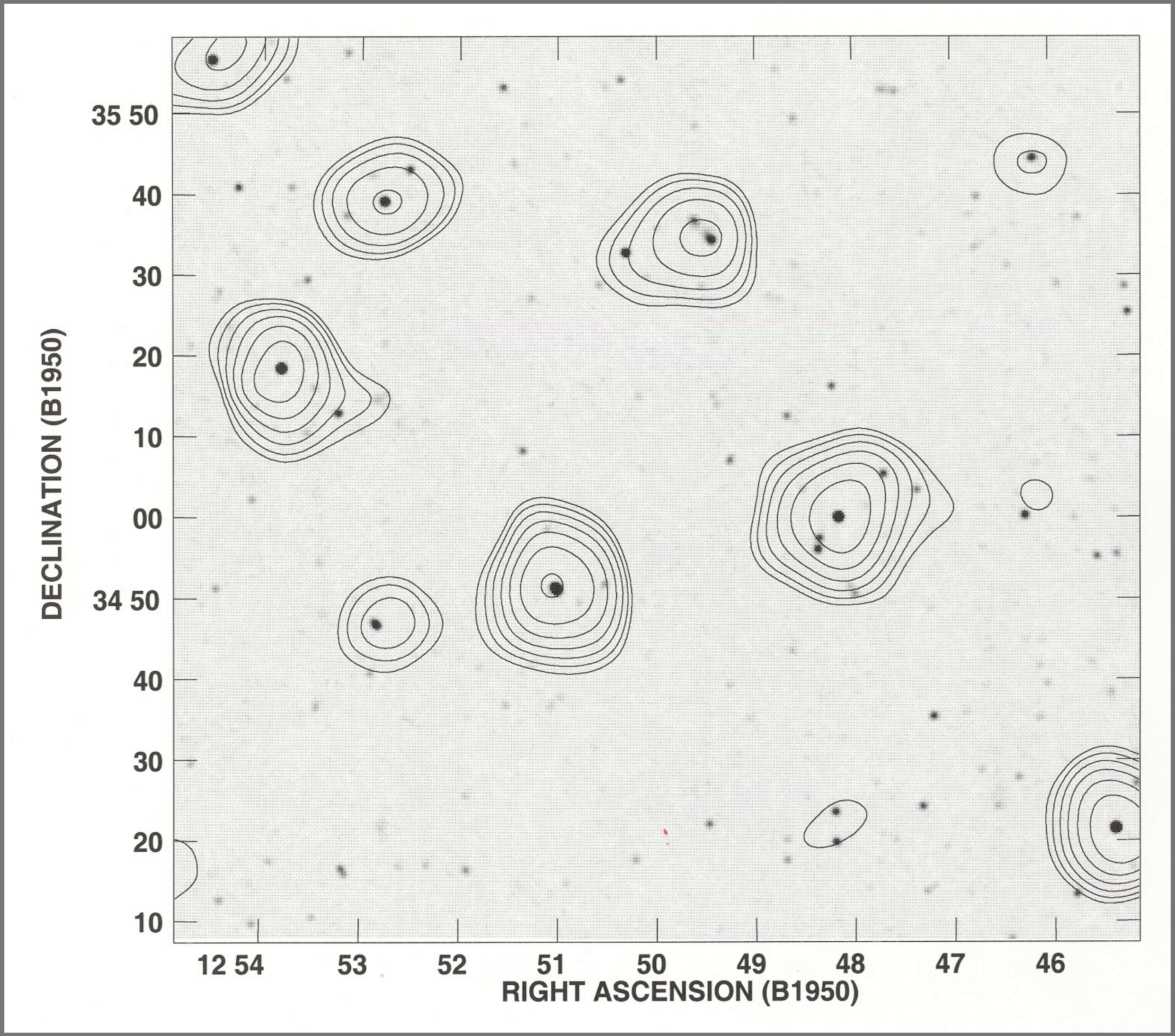
July 10, 2007

M82
Synchrotron (dash-dot curve), free-free (dashes), and dust (dots) emission typical of spiral galaxies



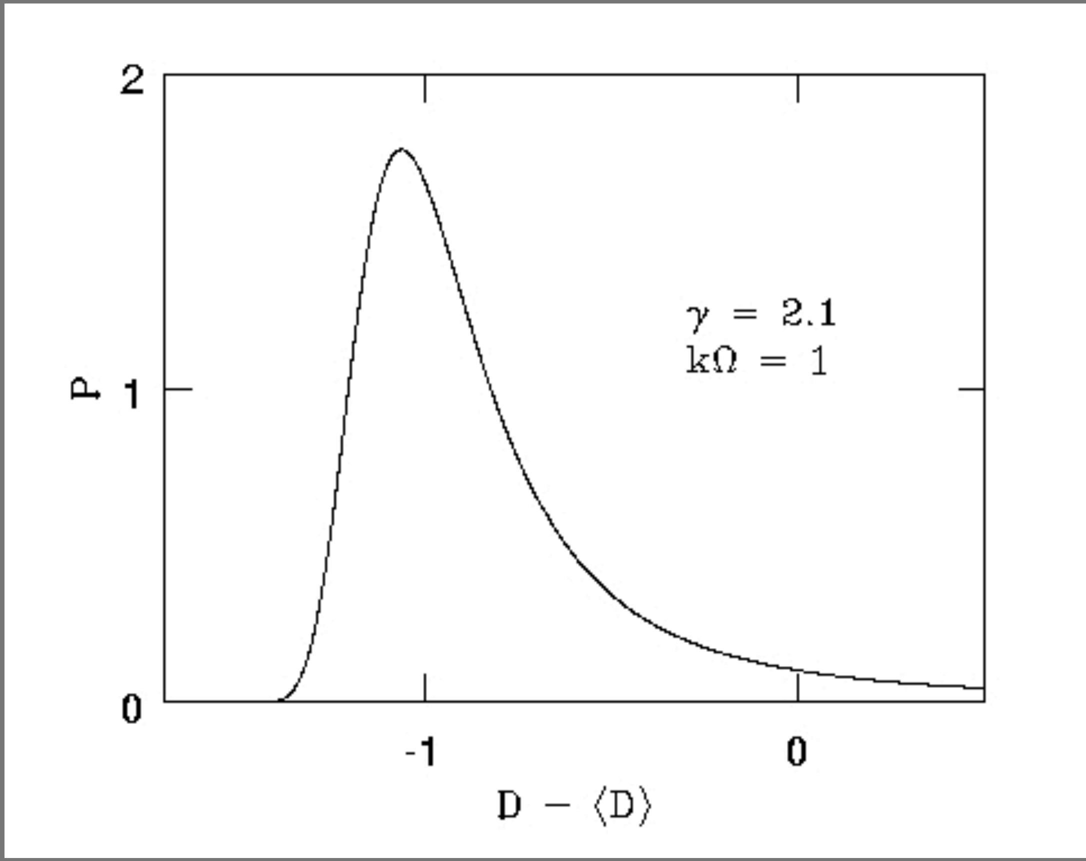
See Condon (1992, ARA&A)

The Sky Isn't Empty: Confusion



NVSS (45 arcsec FWHM) grayscale under GB6 300' (12 arcmin FWHM) contours illustrates source blending

The confusion amplitude P(D) distribution [for $n(s) = kS^{-2.1}$]



Euclidean:

$\gamma = -2.5$

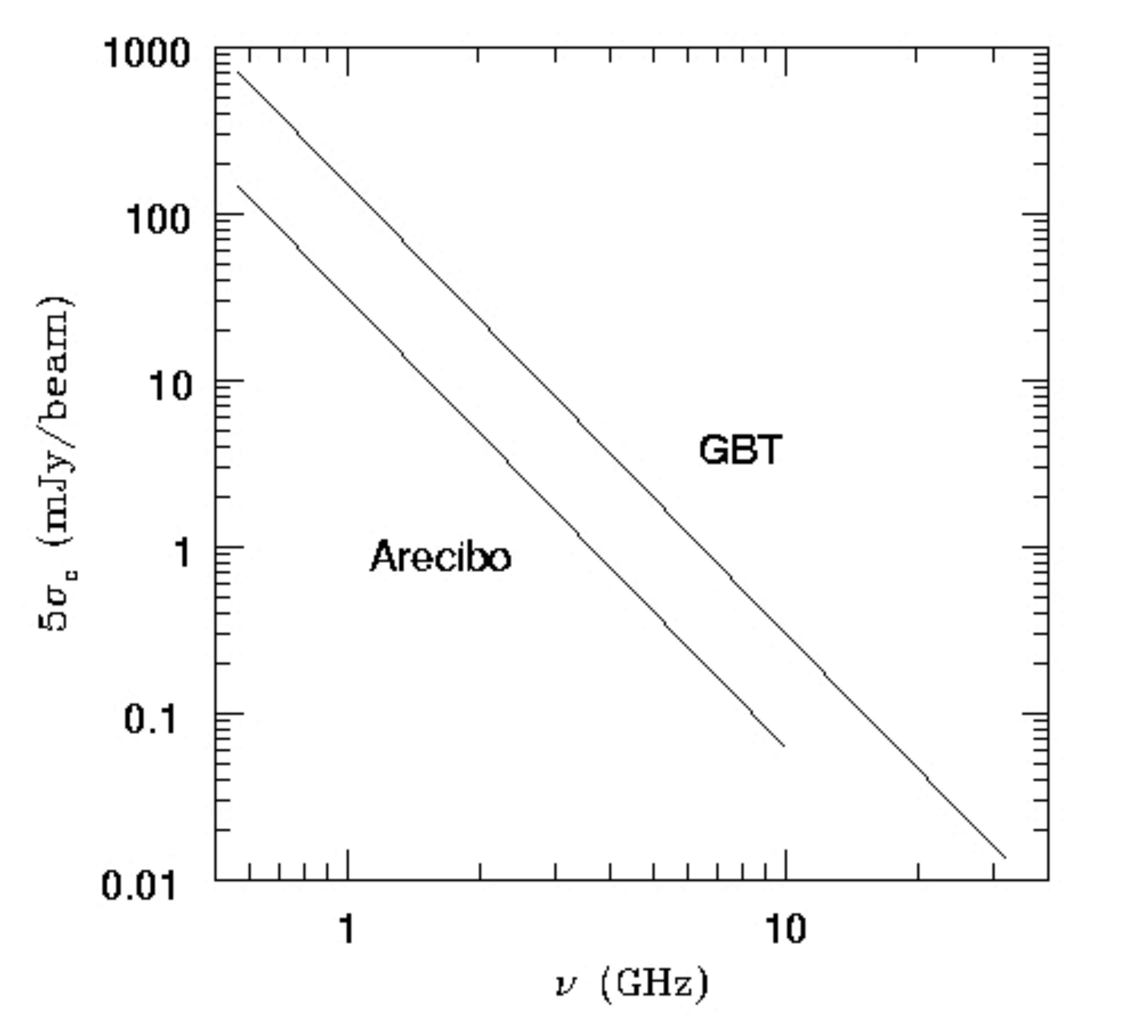
D = image brightness (e.g., Jy/beam)

D = 0 mean is not a good baseline; use
running median instead

Long tail --> use at least 5 sigma threshold (src/30 beams)

Condon (1974); Scheuer (1956)

The 5σ extragalactic confusion limits for Arecibo (d = 220 m) and the GBT (d = 100 m).



Random Noise

The Radiometer Equation:

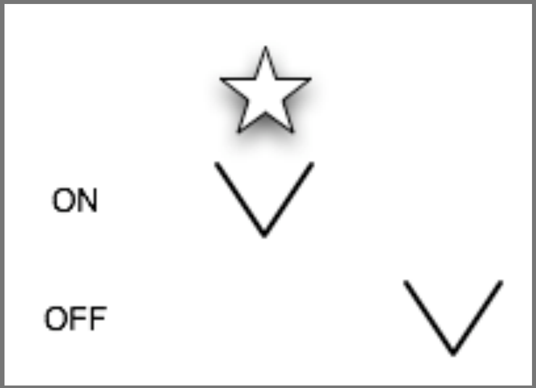
$$\Delta T = \frac{T_{sys}}{\sqrt{t \Delta \nu}}$$

SNR of a continuum measurement can be made higher by increasing the bandwidth of the measurement.

Radiometer equation for a real receiver

$$\sigma = T_{\mathrm{s}} \left[\frac{1}{B\tau} + \left(\frac{\Delta G_{\mathrm{r}}(f)}{G_{\mathrm{r}}} \right)^2 + \left(\frac{\Delta T_{\mathrm{s}}(f)}{T_{\mathrm{s}}} \right)^2 \right]^{1/2}$$

A Simple Picture of Gain Fluctuations



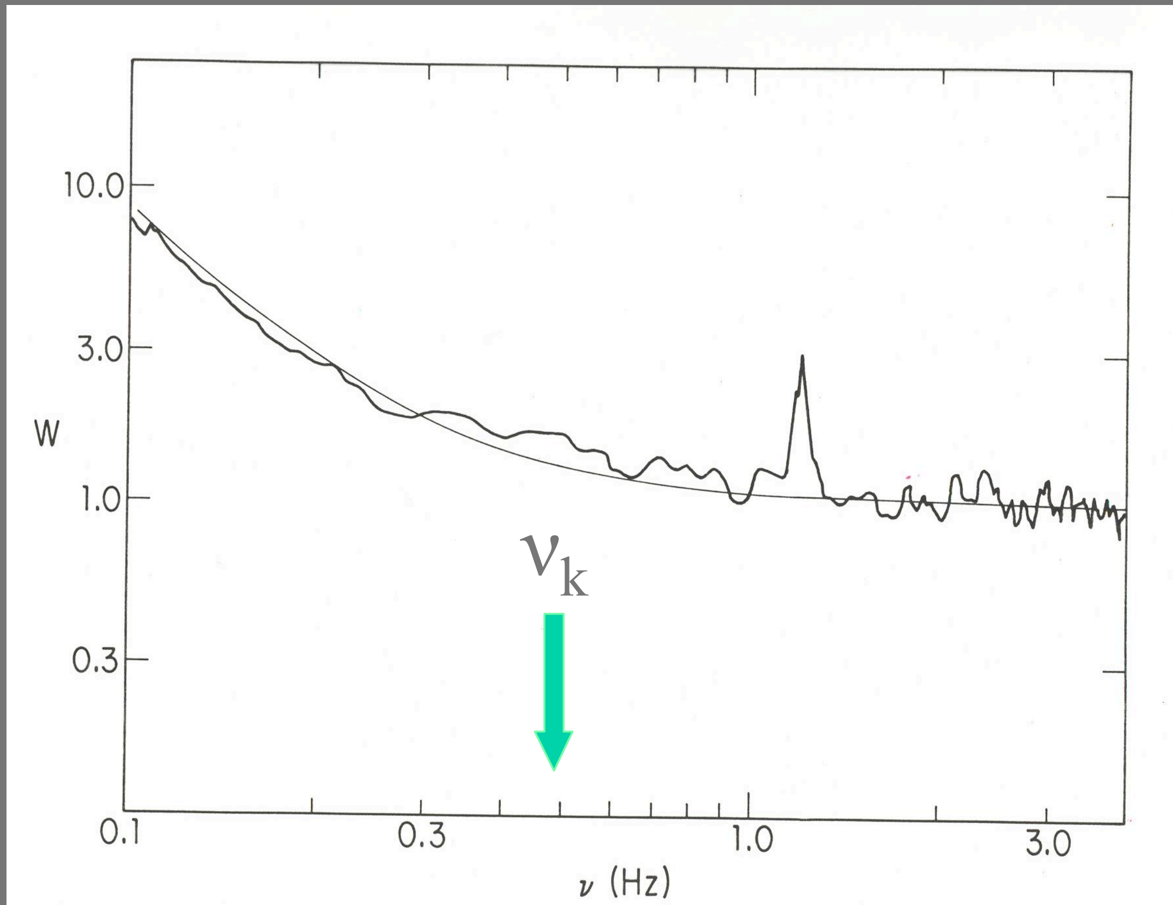
$$G(t_1)\{T_{SRC} + T_{RX} + T_{ATM}\}$$

$$G(t_2)\{T_{RX} + T_{ATM}\}$$

$$On - Off = G(t_1)T_{SRC} + \Delta G(T_{RX} + T_{SKY})$$

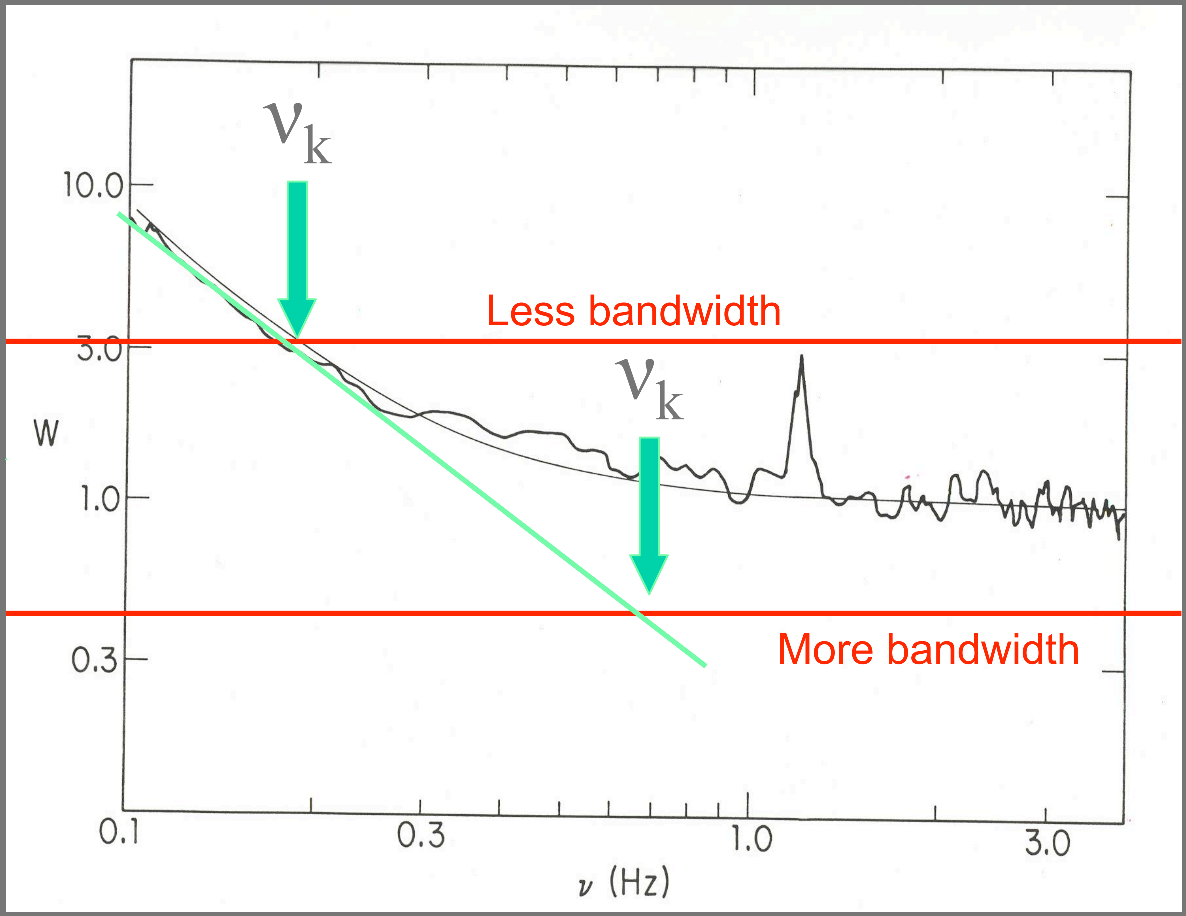
How fast does G(t) vary?

Postdetection power spectrum showing 1/f noise at low frequencies and refrigerator microphonics near 1.2 Hz.



Use $\tau < 1/(2\pi\nu_k)$: on-the-fly mapping, Dicke switching, …

Postdetection power spectrum showing 1/f noise at low frequencies and refrigerator microphonics near 1.2 Hz.



Use $\tau < 1/(2\pi\nu_k)$: on-the-fly mapping, Dicke switching, …

Characteristic Timescales for Broadband Measurements

Gain fluct. In coherent amplifiers: 100+ Hz

- *receiver architecture*

•incoherent (bolometer) detectors: 0.1-10 Hz

•atmosphere

- *chopping or rapid scanning*

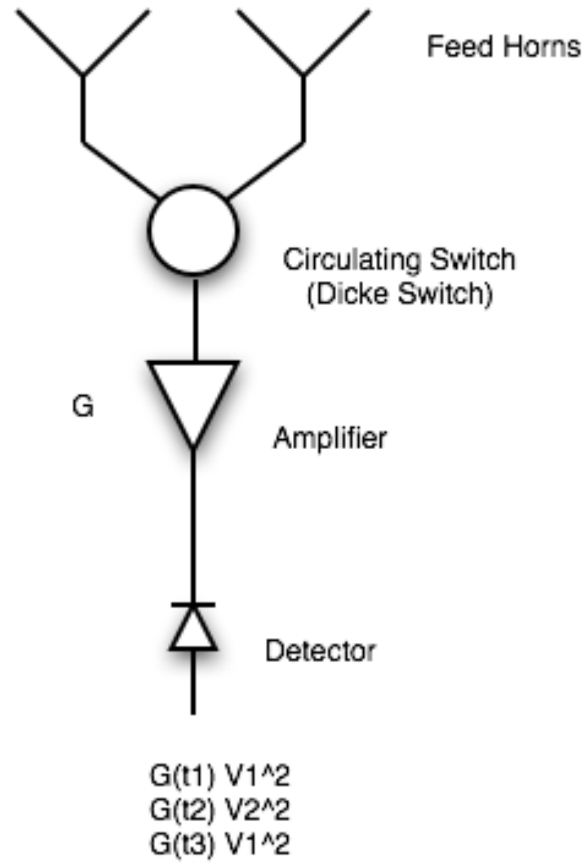
For more details see instrumentation sections of

•Radio Astronomy by L. Krauss

•Tools of Radio Astronomy by Rohlfs & Wilson

Dicke-Switching Receiver

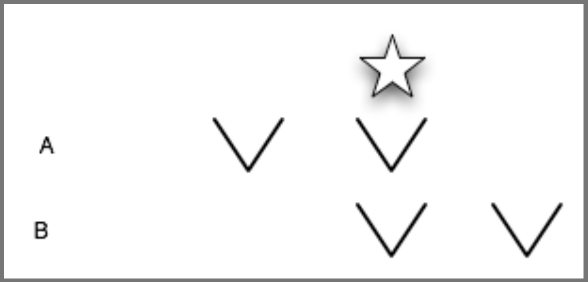
- Rapidly alternate between feed horns to achieve theoretical noise performance
- Only spend 50% of time on source
- Differencing adds another Sqrt(2) to the noise level
- Requires
  - Switch before unstable components (e.g., HEMT amplifier)
  - Closely balanced Trx/gains before switch



$$\Delta P = G(V_1^2 - V_2^2)$$

Higher-Order Differences: Symmetric Nodding

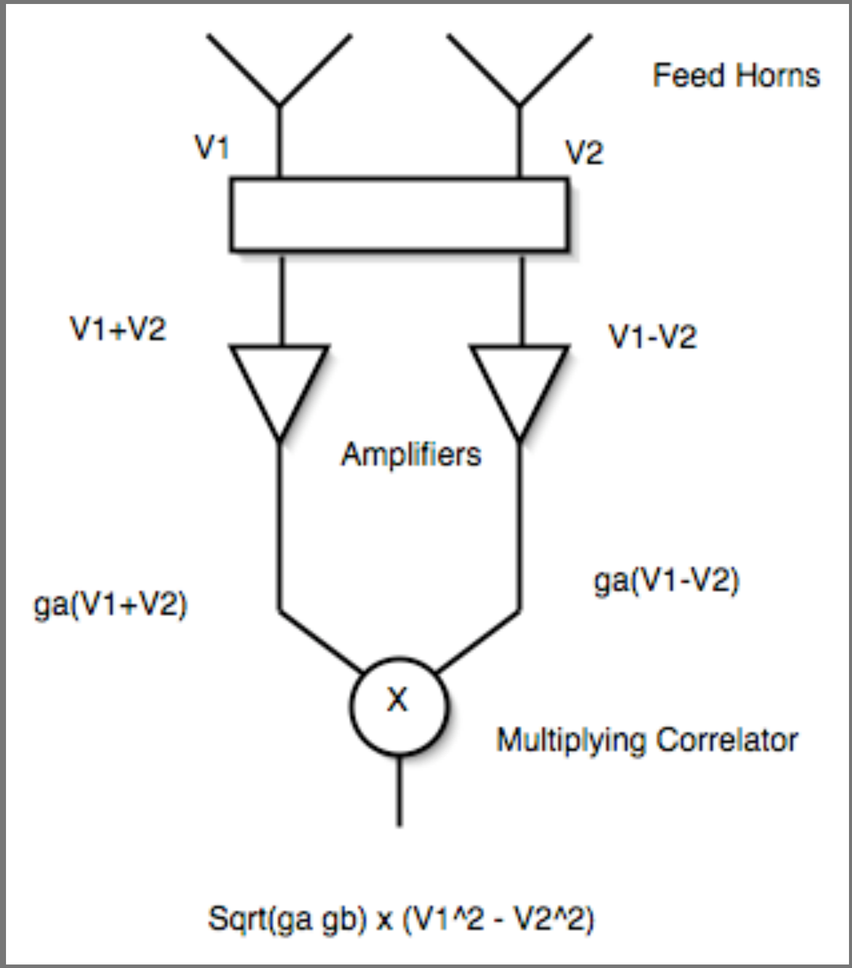
- For sensitive photometry, one level of differencing is usually not enough
  - Gradient in sky emission, or with time
  - Dual-feed systems: Slight differences in feedhorn gains or losses



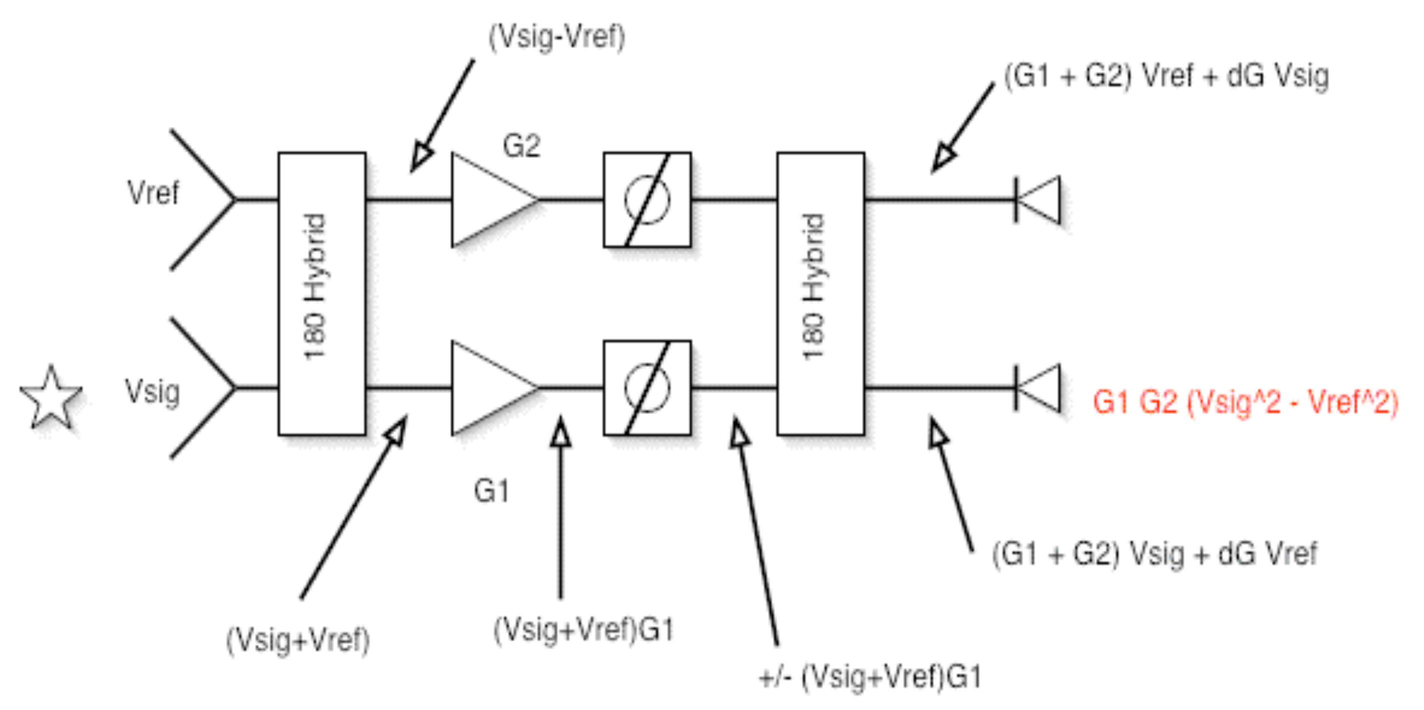
Correlation Receiver

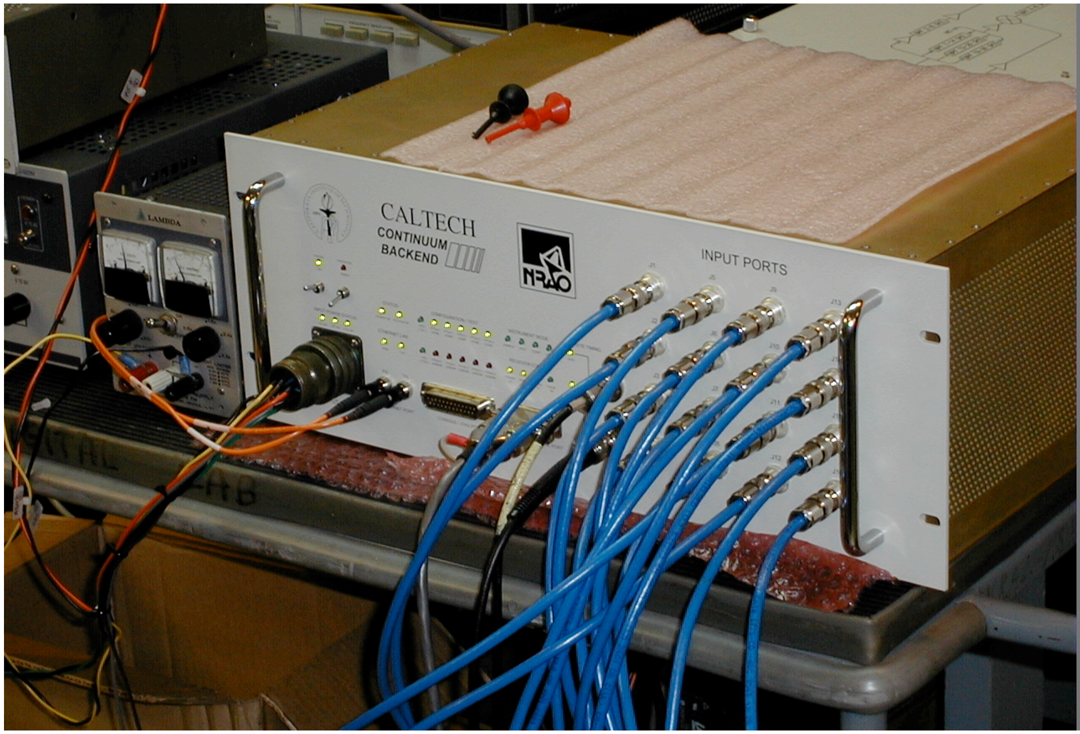
Always looking at both source & reference: only lose one sqrt(2) for differencing

Receiver noise is uncorrelated and drops out.



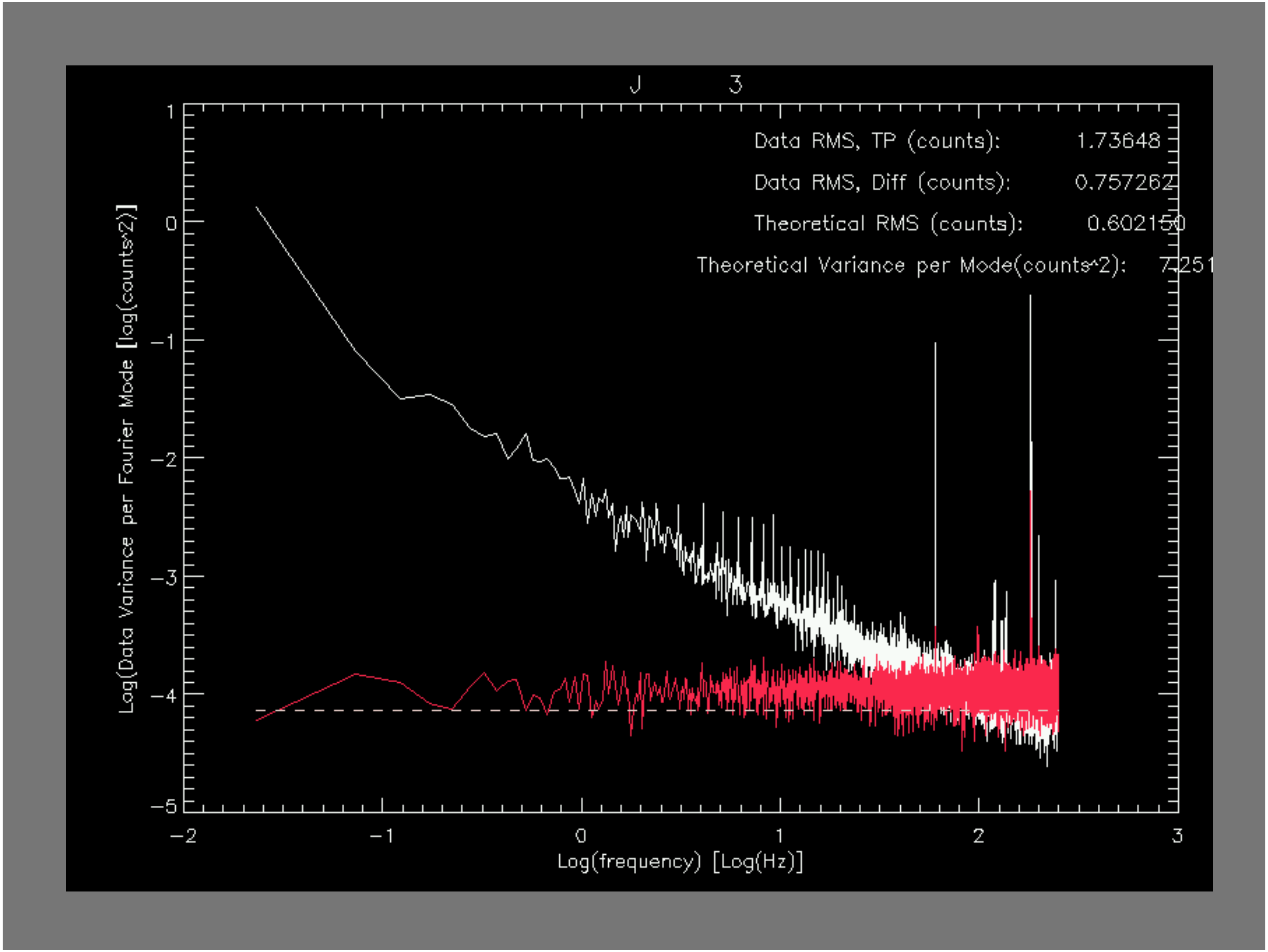
Also useful for spectroscopy (ZSPEC)





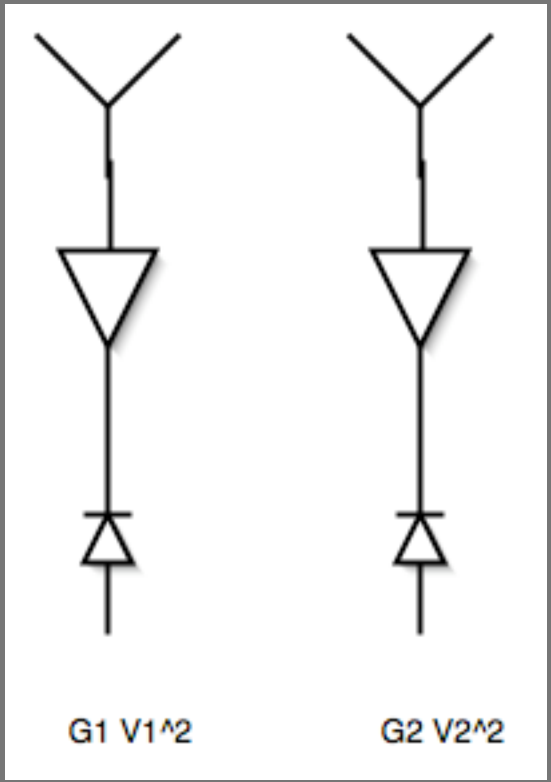
Gives radiometer equation for 10s of seconds.

Other GBT receivers are total power (few to 50 x radiometer equation in 1 second).



J 3
Data RMS, TP (counts): 1.73648
Data RMS, Diff (counts): 0.757262
Theoretical RMS (counts): 0.602150
Theoretical Variance per Mode(counts^2): 7.251
Log(Data Variance per Fourier Mode [log(counts^2)])
Log(frequency) [Log(Hz)]

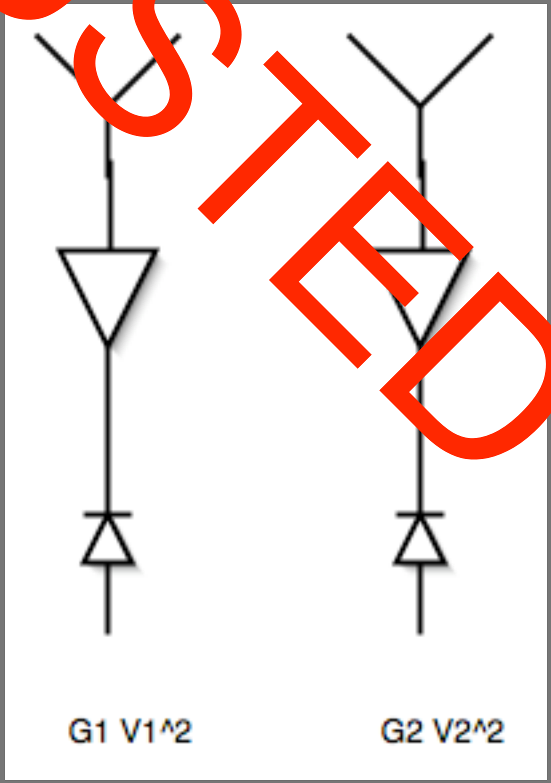
Common Myth: You beamswitch to cancel the atmosphere



$$A - B = G_1 T_{SRC} + \Delta G(T_{RX} + T_{SKY})$$

Common Myth: You beamswitch to cancel the atmosphere

BUSTED



$$A - B = G_1 T_{SRC} + \Delta G(T_{RX} + T_{SKY})$$

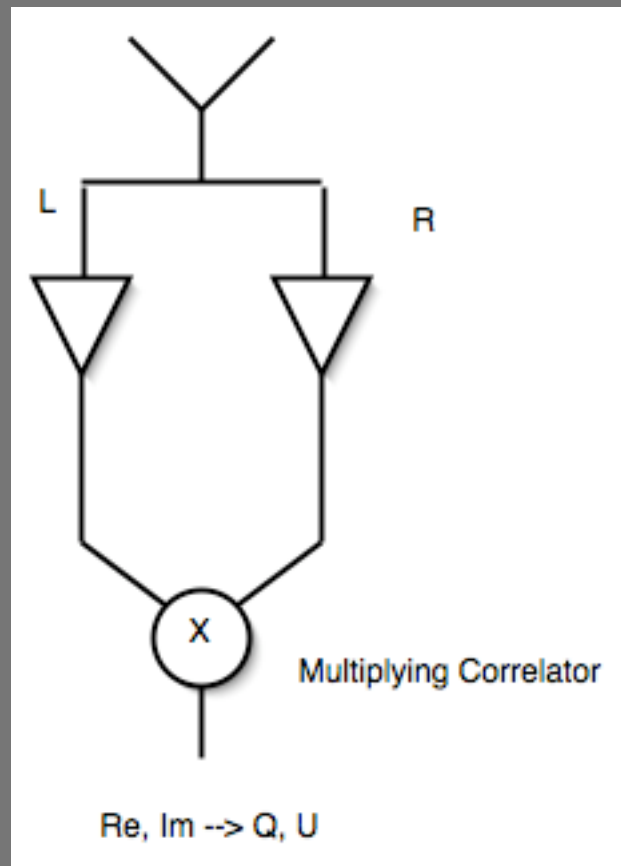
Correlation Polarimeter

$$I = L^2 + R^2$$

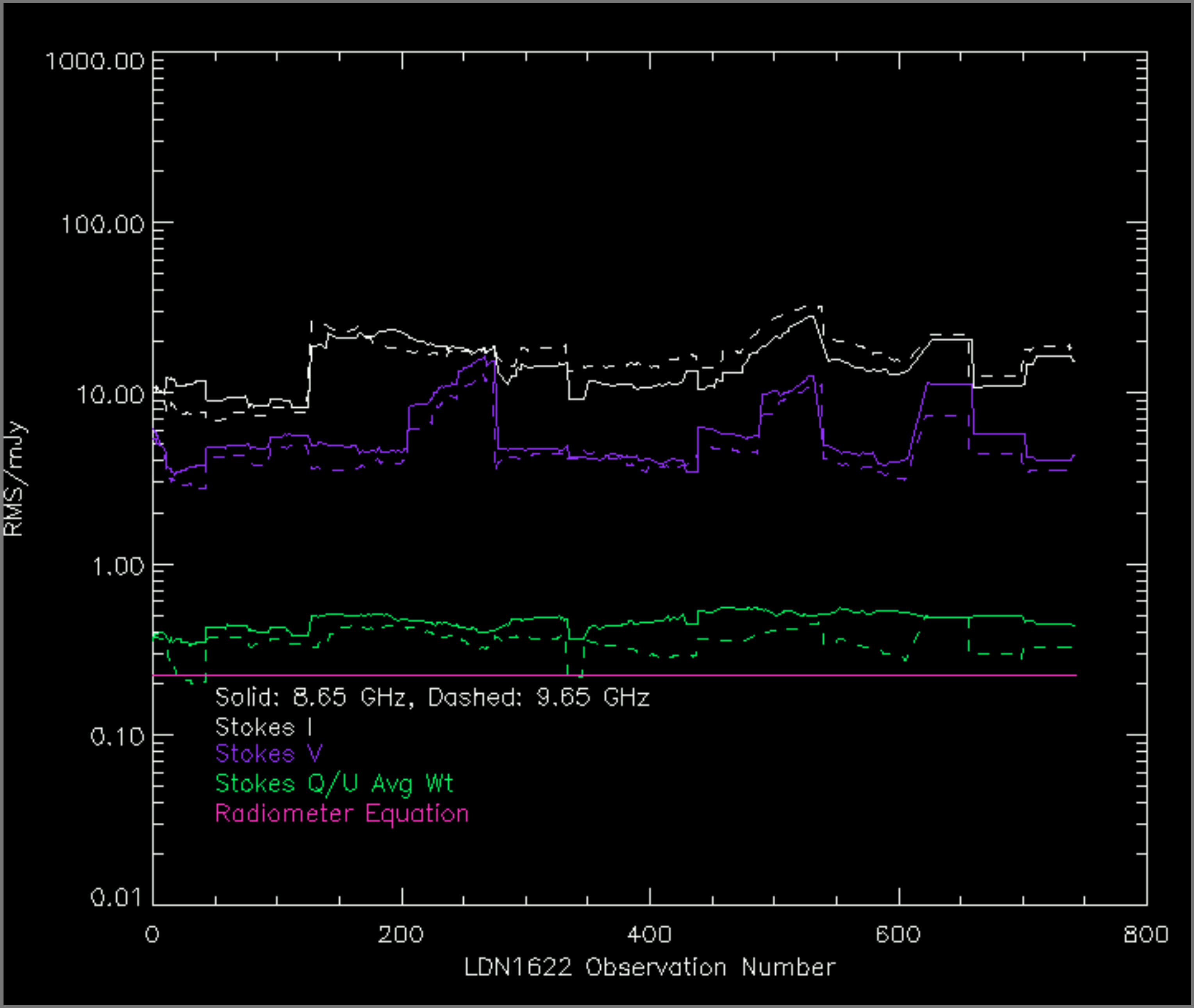
$$V = L^2 - R^2$$

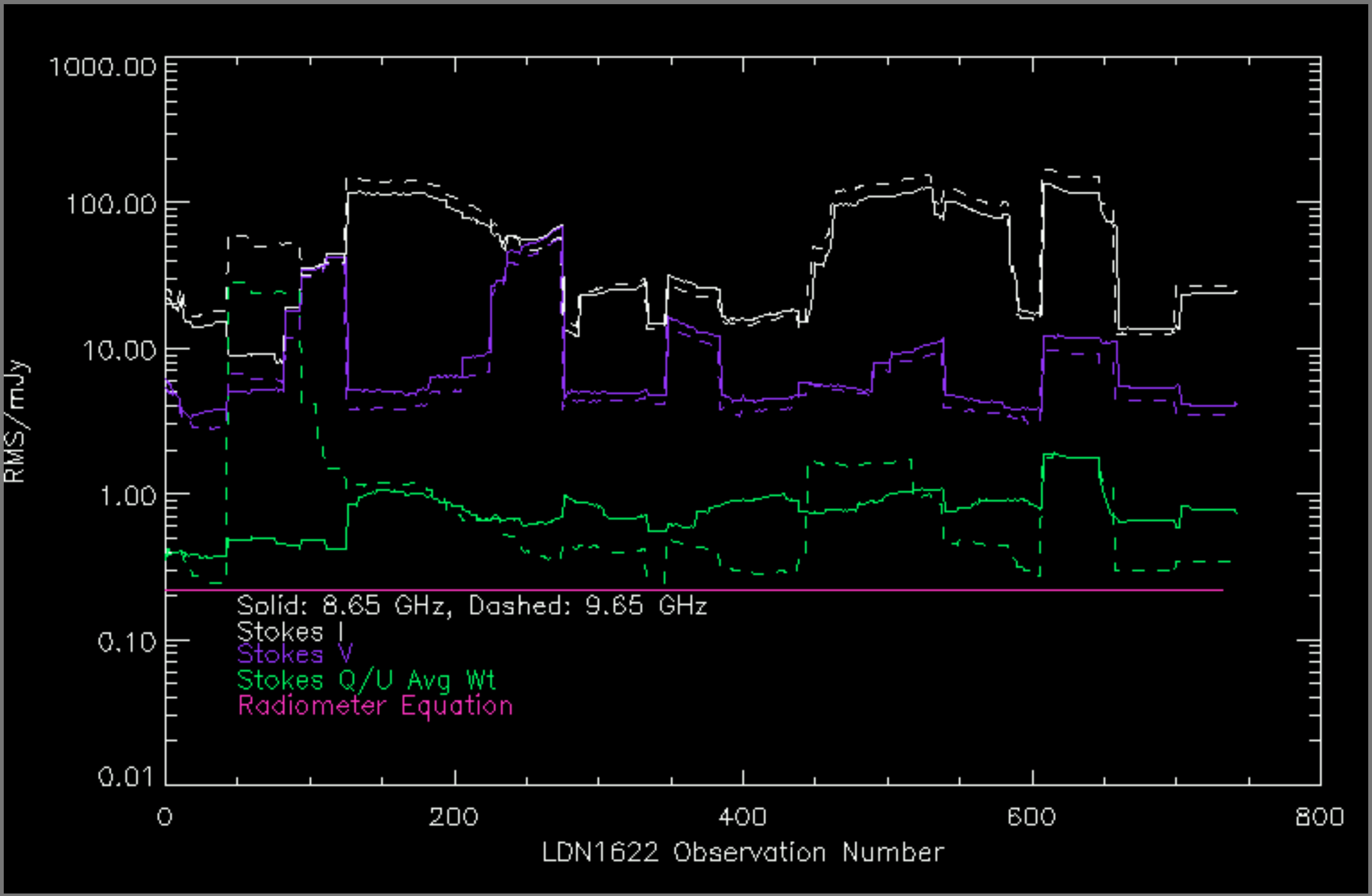
$$Q = -\mathrm{Re}(< LR >)$$

$$U = \mathrm{Im}(< LR >)$$



See talk by Carl Heiles

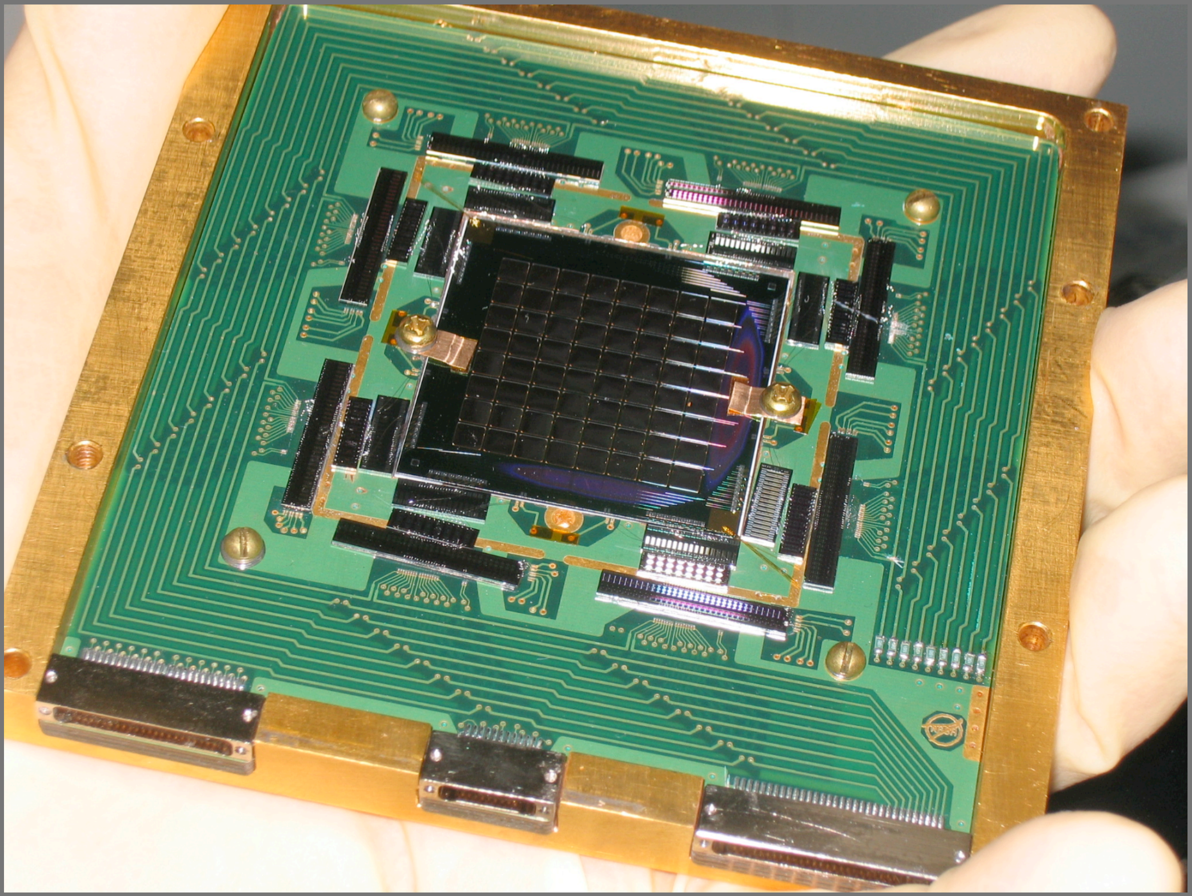

1000.00
100.00
10.00
1.00
0.10
0.01
RMS/mJy
0
200
400
600
800
LDN1622 Observation Number
Solid: 8.65 GHz, Dashed: 9.65 GHz
Stokes I
Stokes V
Stokes Q/U Avg Wt
Radiometer Equation



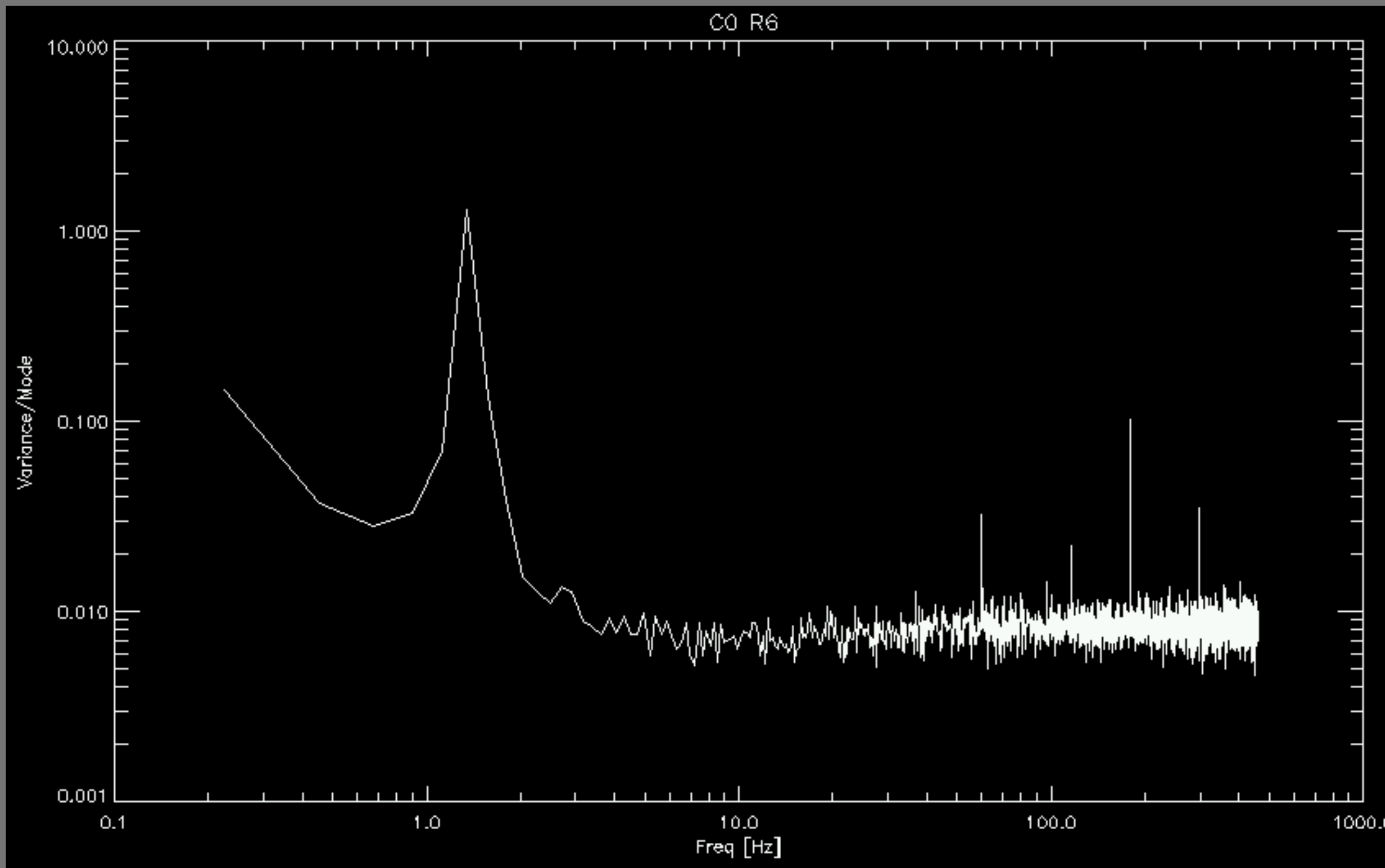
Measure your uncertainties from the scatter in the data!

Bolometers

Bolometer detectors
• *Incoherent*; measure total power
• Very broad bandwidths possible; approach quantum - limited noise.
• Can be built in very large-format arrays!

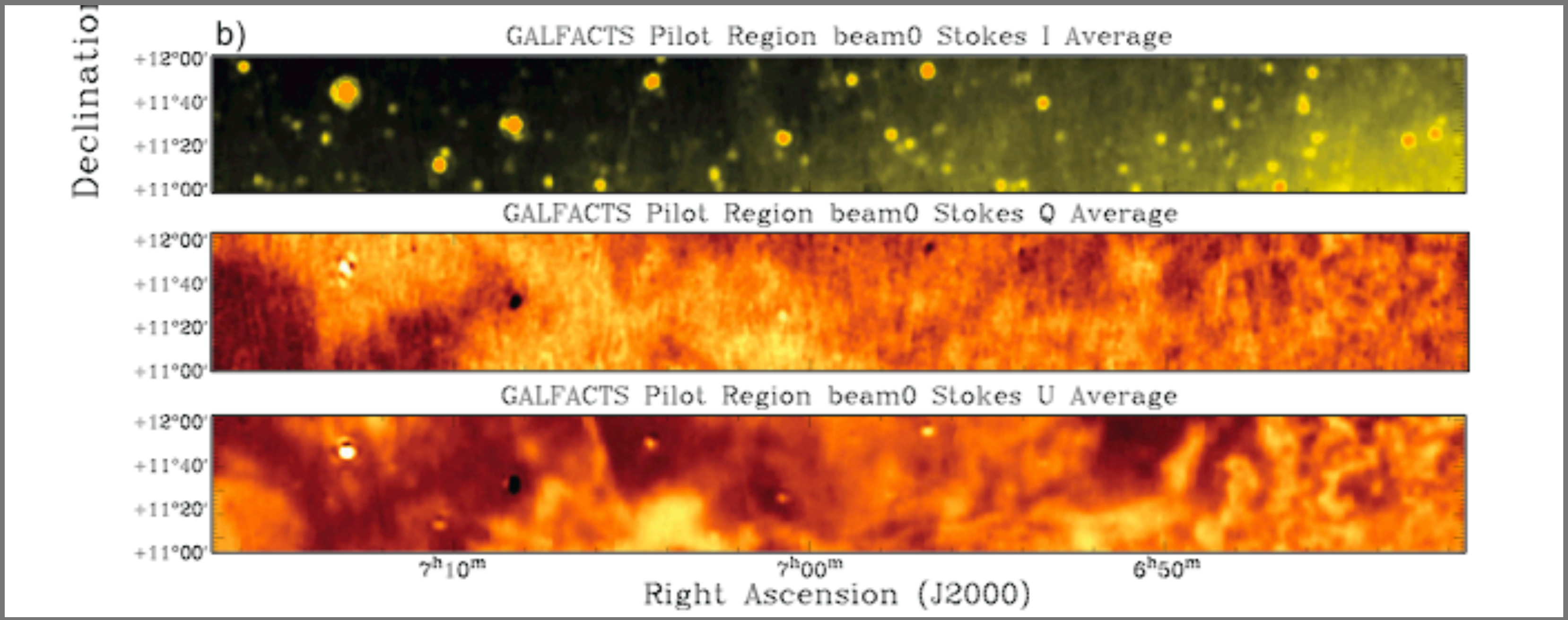


MUSTANG Detector Array


C0 R6
Variance/Mode
10.000
1.000
0.100
0.010
0.001
0.1
1.0
10.0
100.0
1000.0
Freq [Hz]

The Future: Array Receivers

ALFA



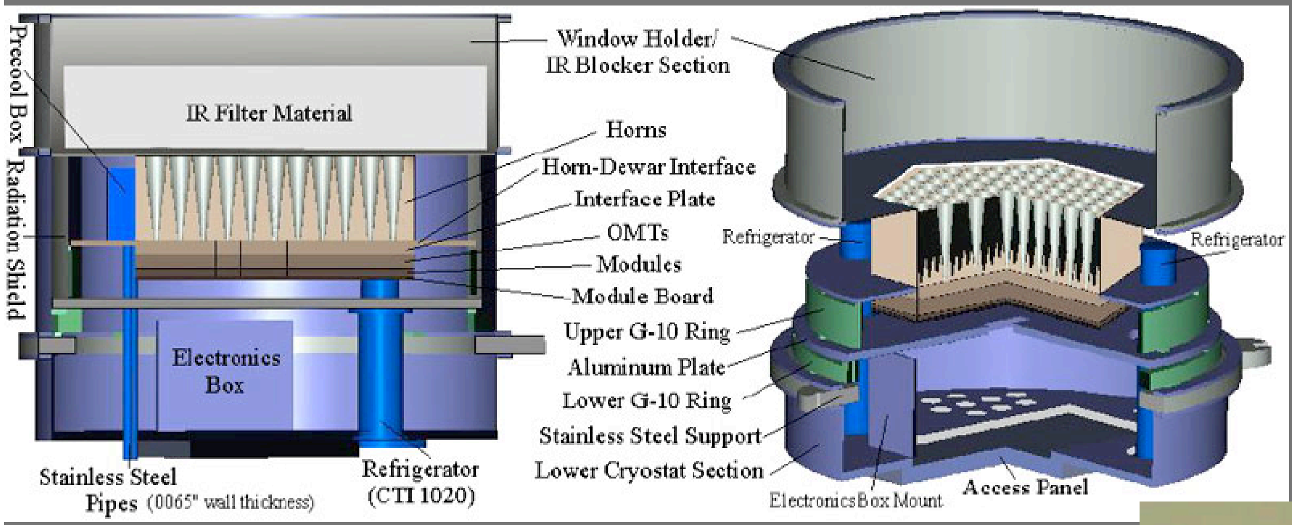
ALFA on Arecibo

7-element λ = 21 cm coherent array, 3 arcmin resolution

GALFACTS:full-Stokes , sensitive, high-resolution survey of 12,000 deg^2

Galactic magnetic fields, ISM, SNR, HII regions, molecular clouds …

MMIC Arrays

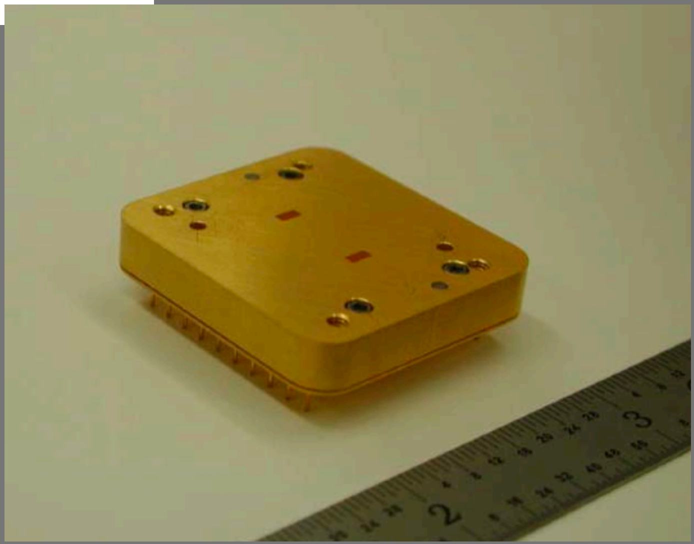


QUIET

- 91 pixels
- 90 GHz
- integrated, mass-producable "receiver on a chip" (MMIC)

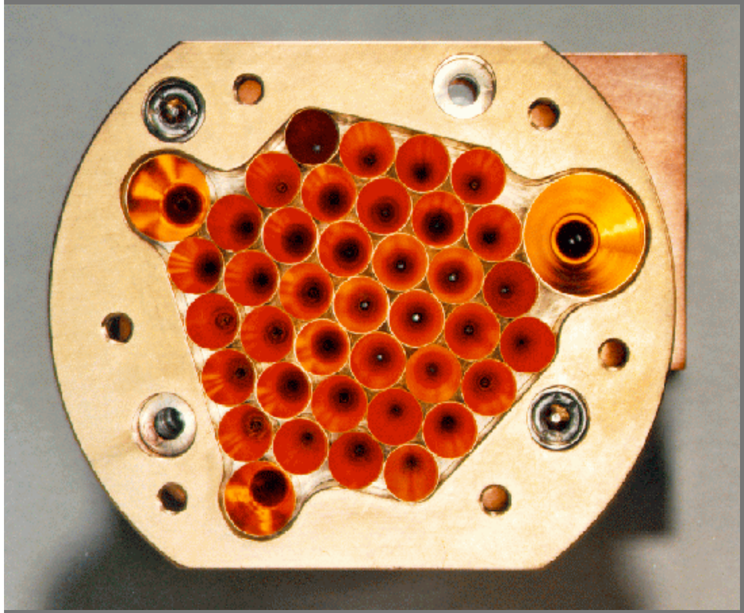
OCRA

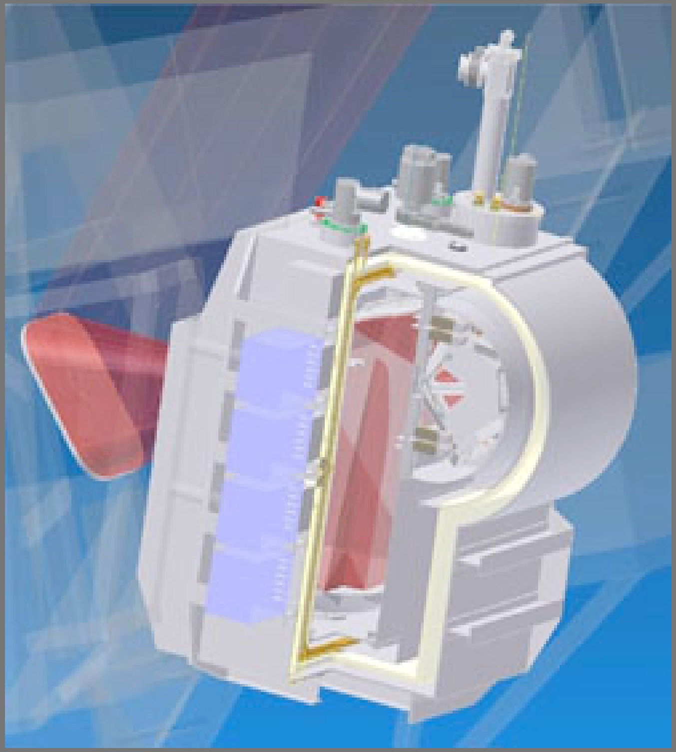
- 1-cm Receiver Array
- Under construction at Jodrell Bank, initially for Torun 30m telescope
- 16 --> 100 pixels
- correlation architecture



T. Gaier (JPL)

Sub-millimeter





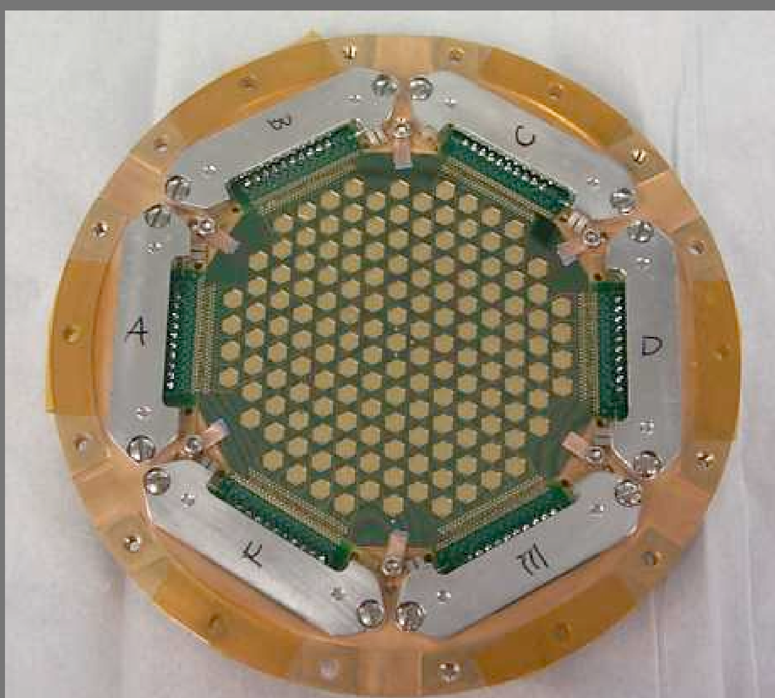
Sub-mm Common User Bolometer Array (SCUBA)
- JCMT (15m)
- 37 pixels at 850um, 91 at 450 um

SCUBA-2
- JCMT (15m)
- ~10,000 pixels!
- SQUID-MUX'd TES bolometers (CCD-like)
- First light expected soon!

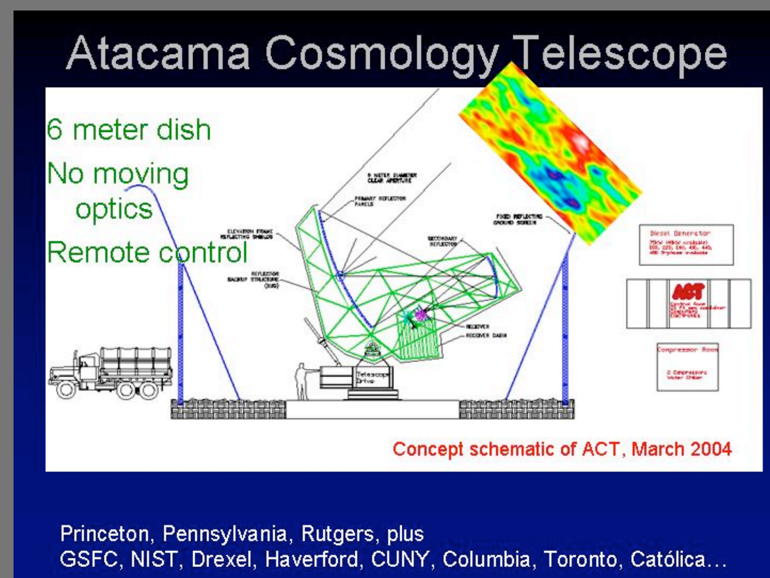
Also: SHARC-II on CSO, 384 pixels at 350 um

Millimeter

Bolocam/AZTEC
- 1-2 mm
- 144 pixels
- CSO (10m) & LMT (50m)



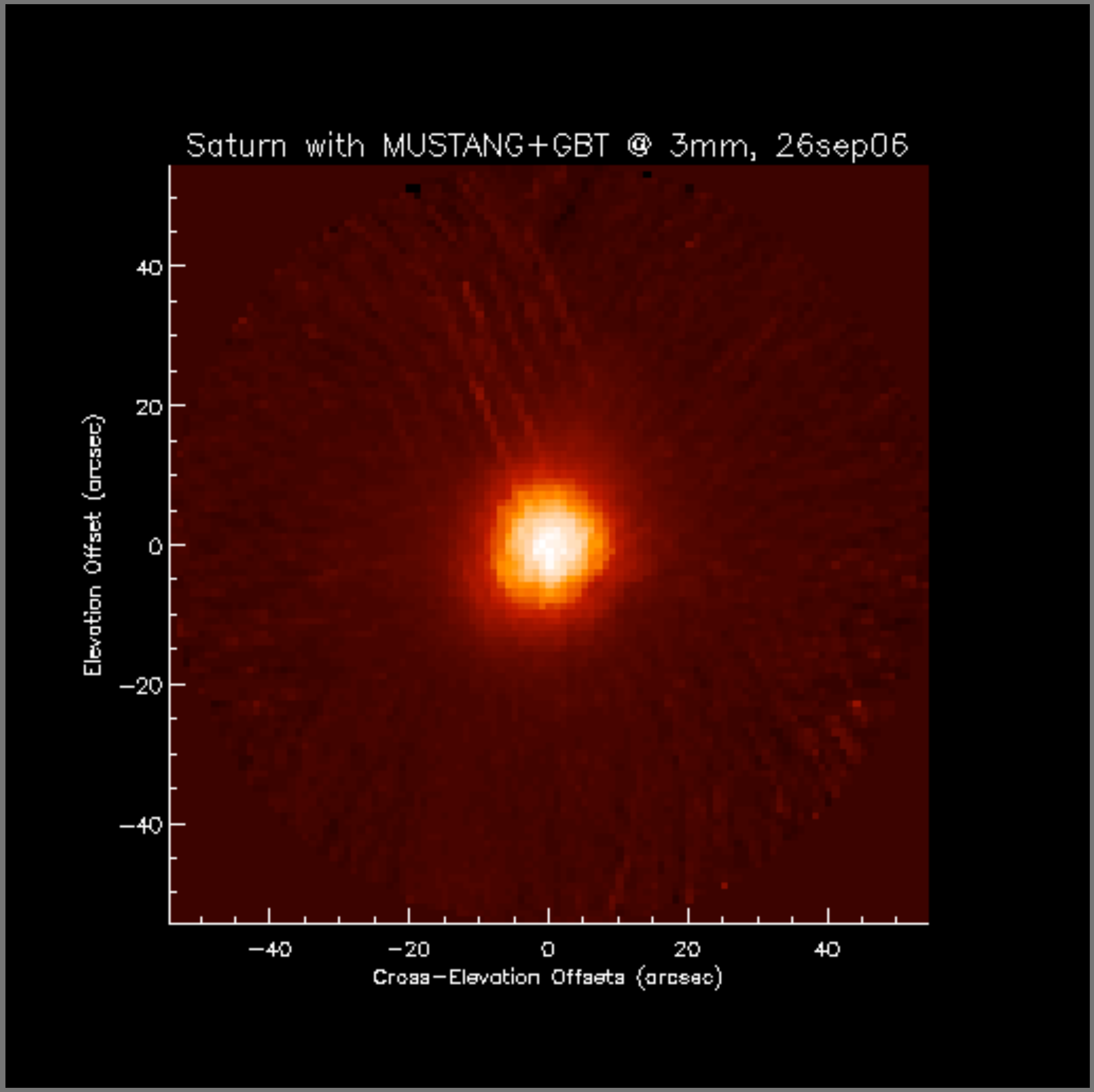
ACT (6m) , SPT (10M)
- 1-2 mm
- Large Area Surveys (SZ) - 1000s of deg^2
- few 1000 detectors

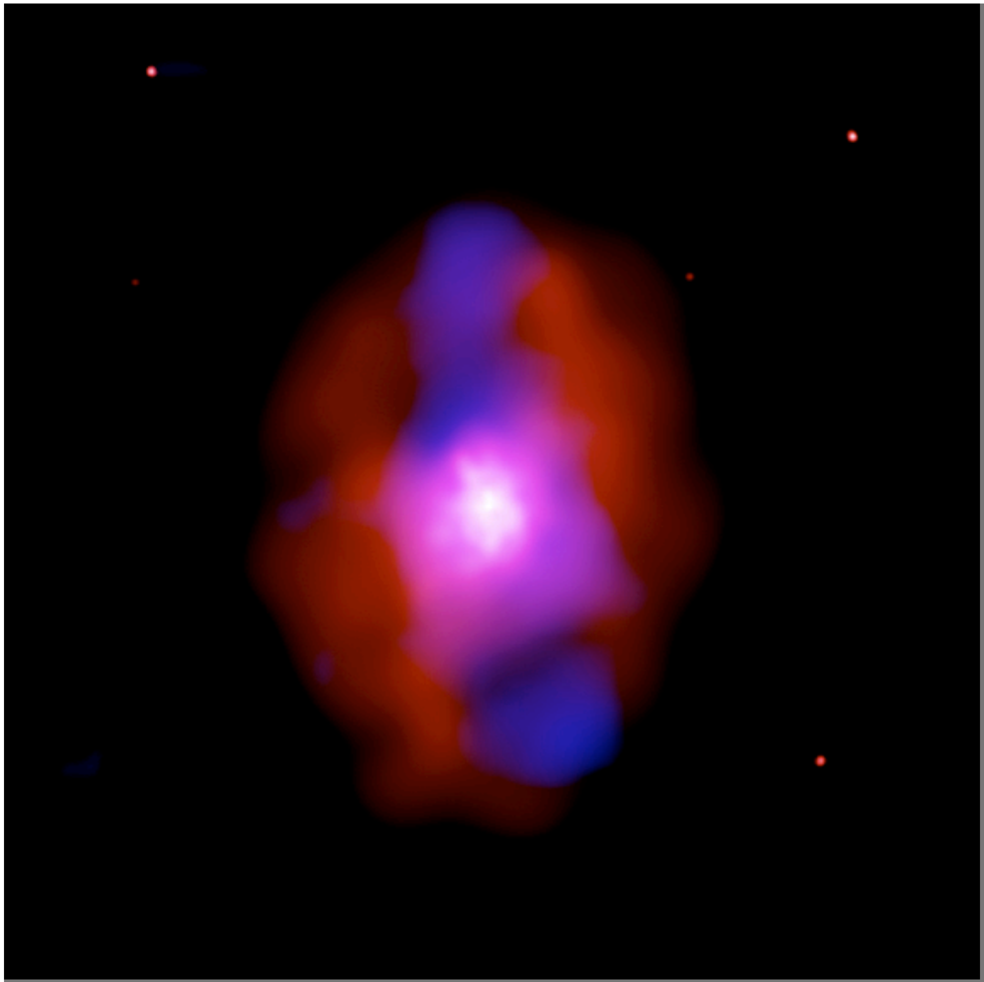


Also IRAM 30m, APEX

Multiplexed SQUID/TES Array for Ninety Gigahertz (MUSTANG)

- 8x8, multiplexed TES array
- Bandpass 86-94 GHz initially
- Fully sampled focal plane (8” fwhm beams, 4” beam spacing
    - All technologies suitable for a much larger bolometer array
- Achieved first light on the GBT in Fall 2006; will be a proposable facility instrument


Saturn with MUSTANG+GBT @ 3mm, 26sep06
Elevation Offset (arcsec)
40
20
0
−20
−40
−40
−20
0
20
40
Cross−Elevation Offsets (arcsec)



MS0735.6+7421
McNamara et al. 2005, Nature
(Chandra/VLA composite)

MUSTANG Science

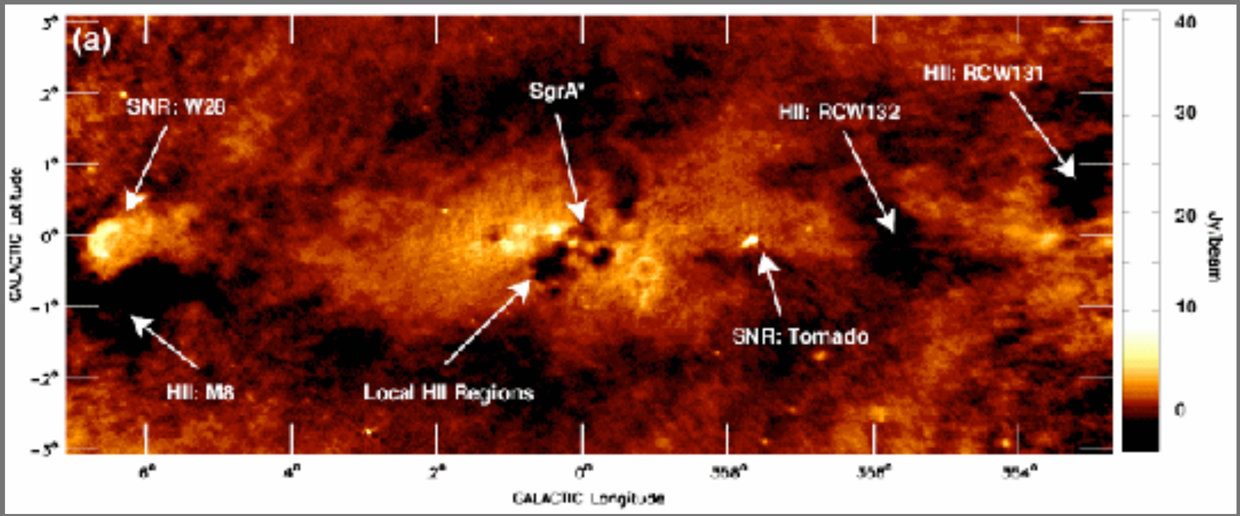
- High resolution SZ (bubbles, shocks, cooling flows, etc.)
- High-z galaxies
- Protostellar clouds
- PMS stars & debris-disk systems

- *First light: Fall 2006*
- *Commissioning, GBT surface improvements, early science 2007-2008*
- *Facility instrument: Fall/winter 2009*

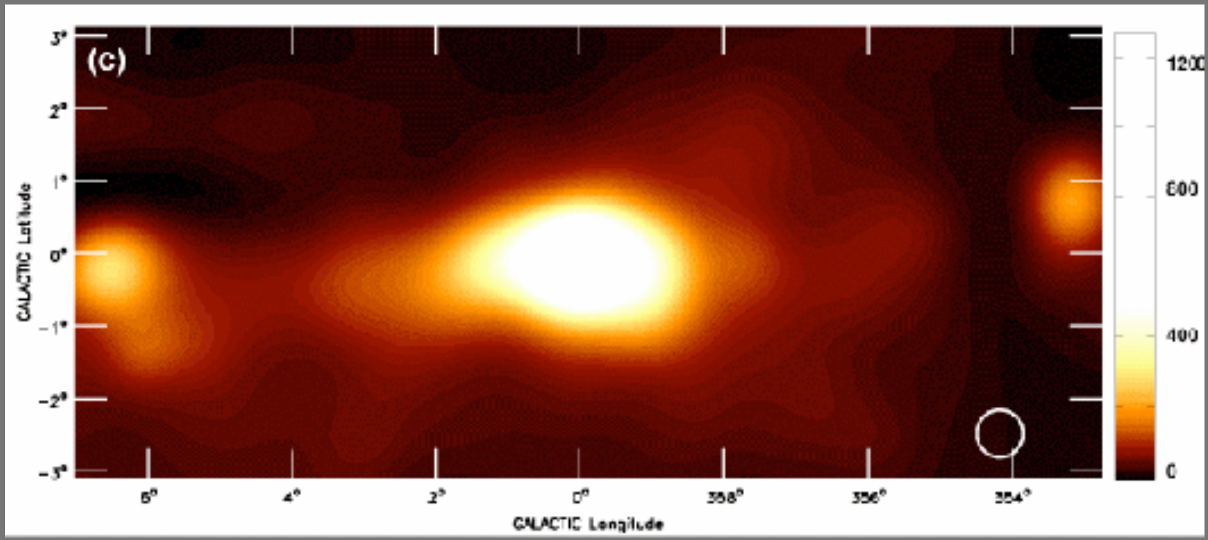
END

75 & 300 MHz continuum emission from the Galactic Center: A diffuse Halo around SgrA*

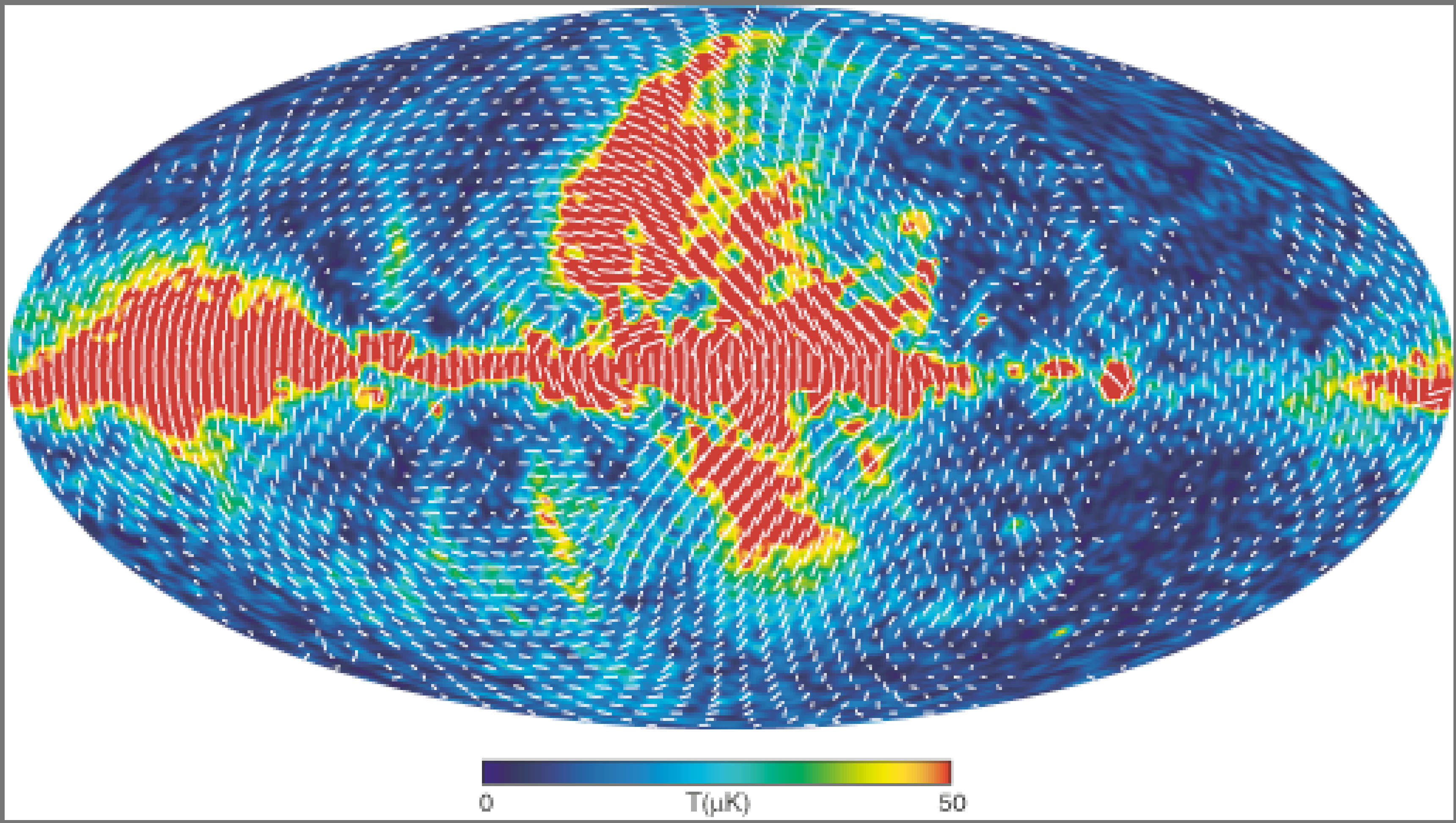
75 MHz, VLA:



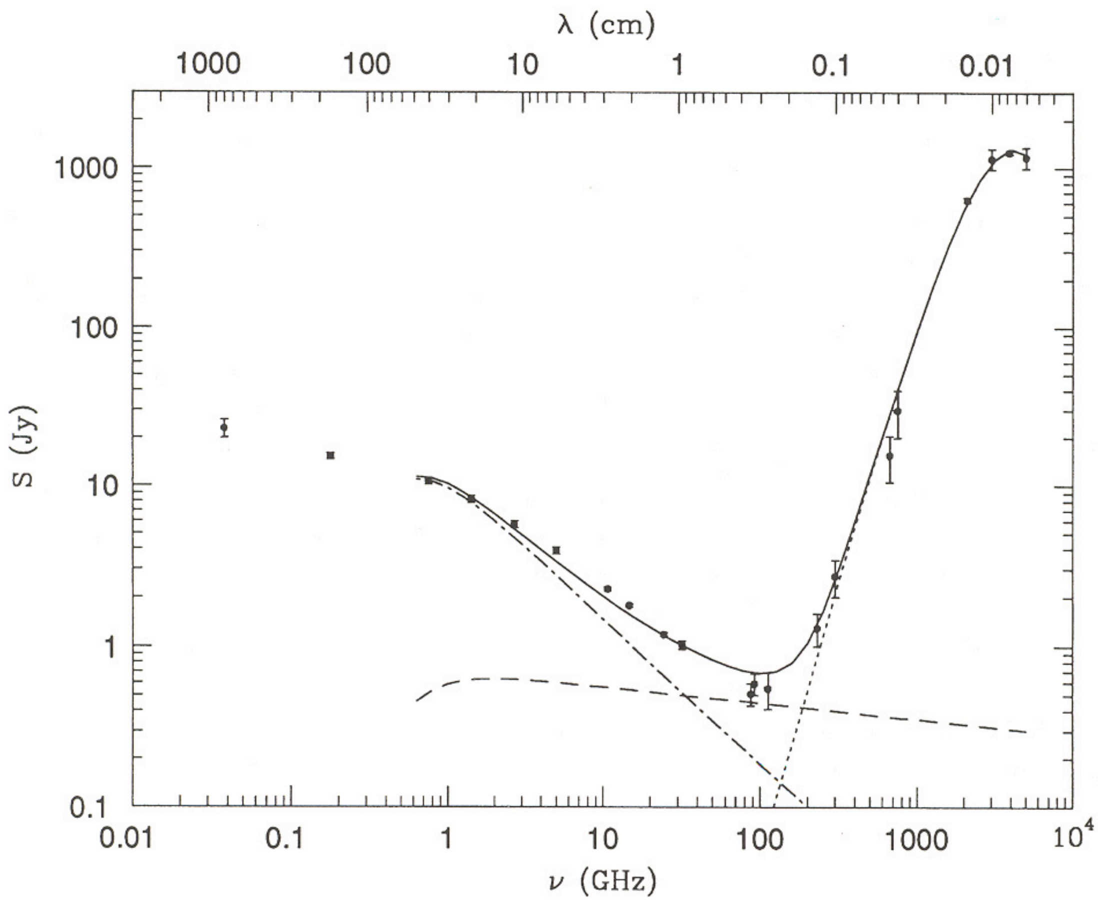
330 MHz, GBT:



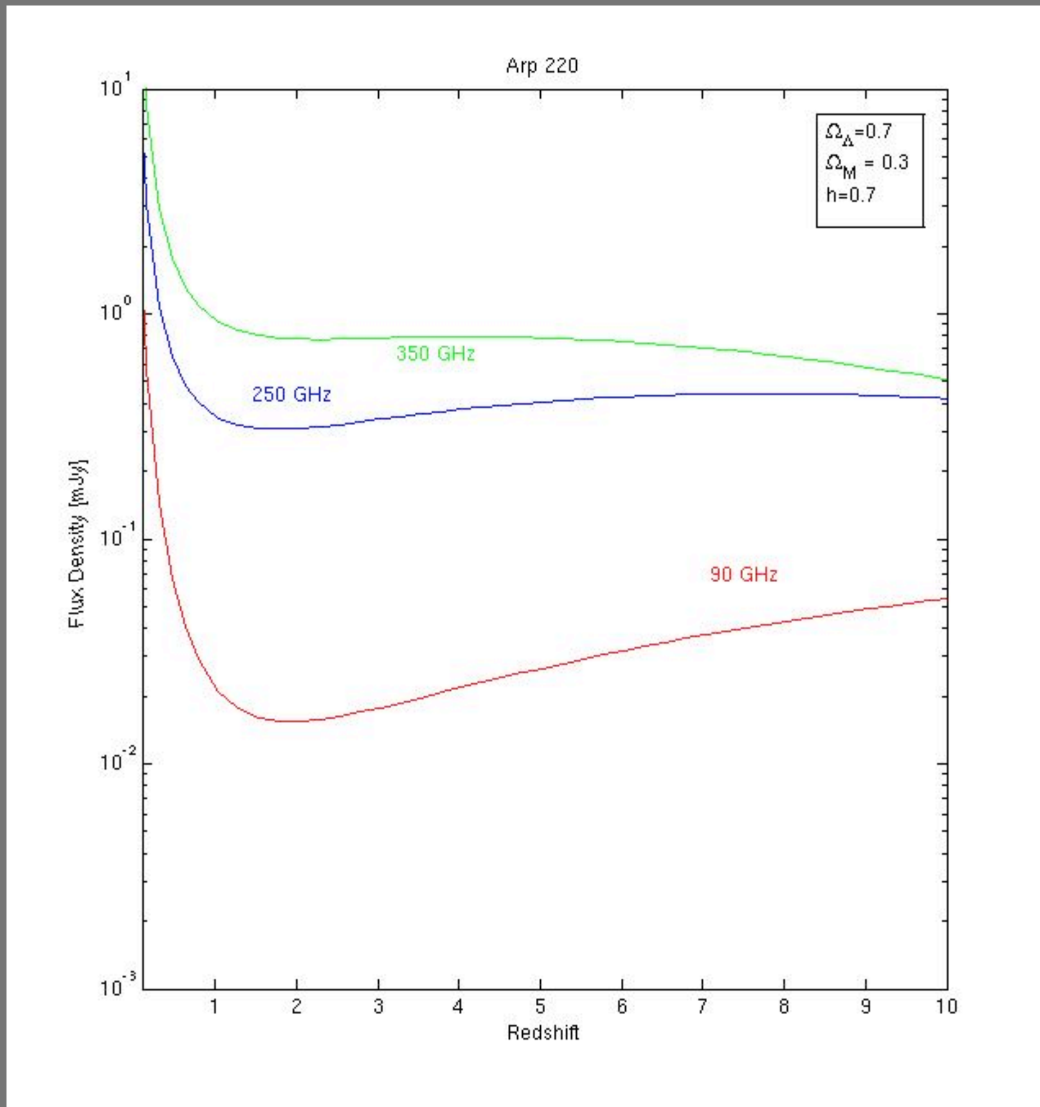
LaRosa, Brogan et al. (2005)



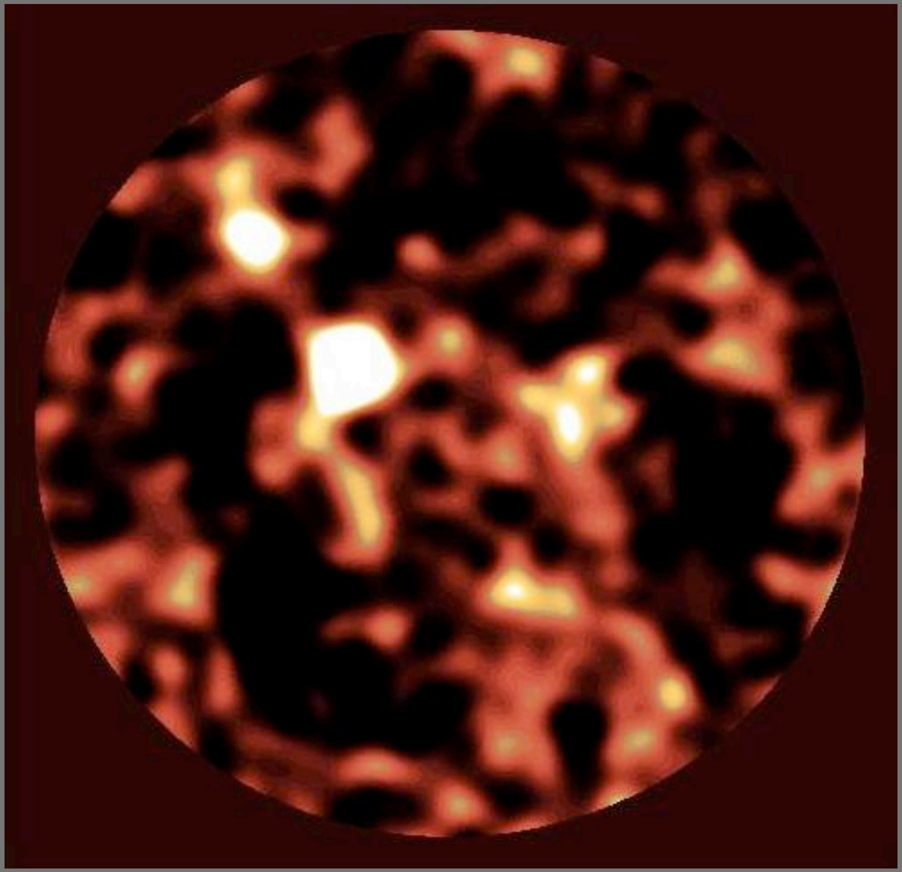
Linear polarization of the sky at 20 GHz (WMAP)


λ (cm)
1000
100
10
1
0.1
0.01
S (Jy)
1000
100
10
1
0.1
0.01
0.1
1
10
100
1000
10^4
ν (GHz)

Dust emission at high redshifts



Dust emission at high redshifts



- Discovered an abundant population of submm galaxies at z~1-3

- confusion limited

HDF-- Hughes et al. (1998)

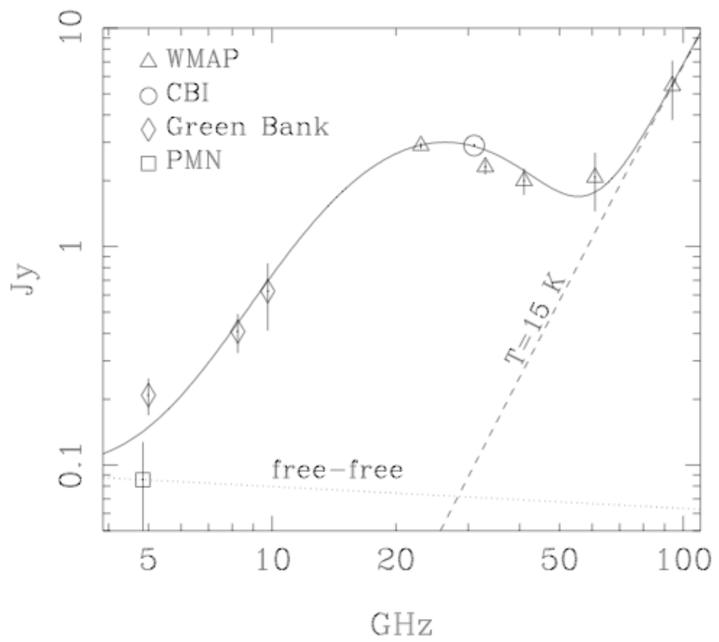


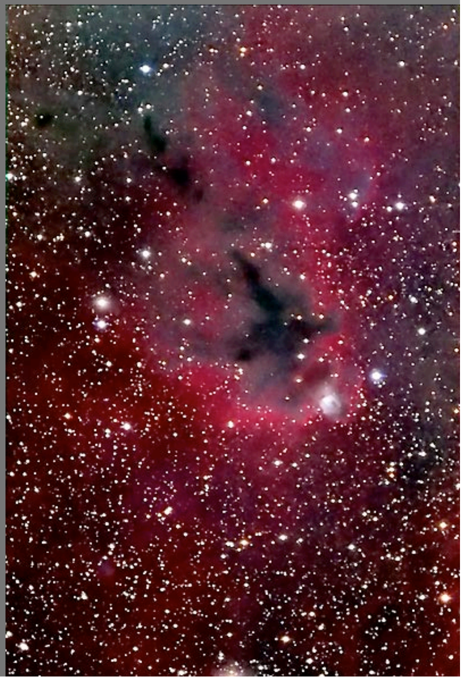
FIG. 10.—SED of LDN 1622. The solid line shows a fit to the data, composed of a free-free component, a modified blackbody at 15 K with a 1.7 emissivity index representative of traditional dust emission, and the Draine & Lazarian (1998b) spinning dust emissivities.

Spinning Dust

Newly discovered, often dominant emission mechanism at cm wavelengths

Electric dipole emission from small, spinning dust grains

Casassus et al. (2006)



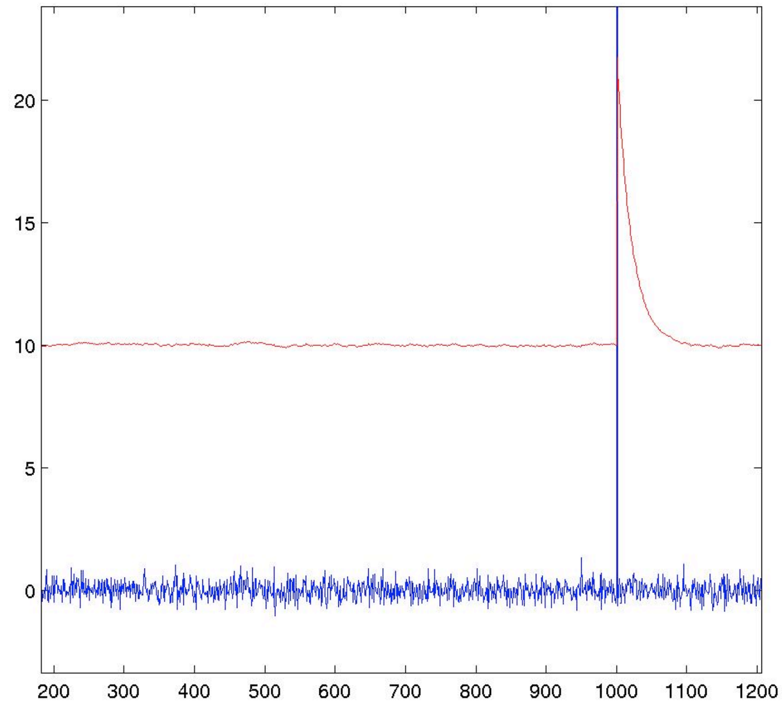
Diffuse, extended signals--discovered by, and best studied with, single dishes (or extremely compact interferometers)

END

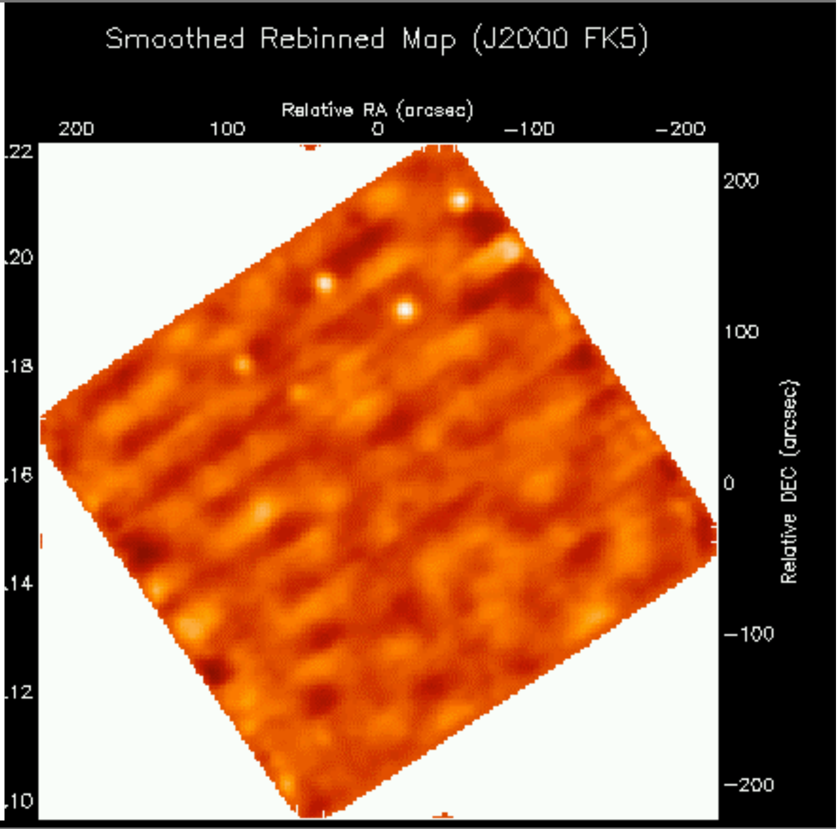
The Basic Problem

Simulations courtesy
Of E. Chapin & D. Hughes (IANOE)

Bolometer Timestreams



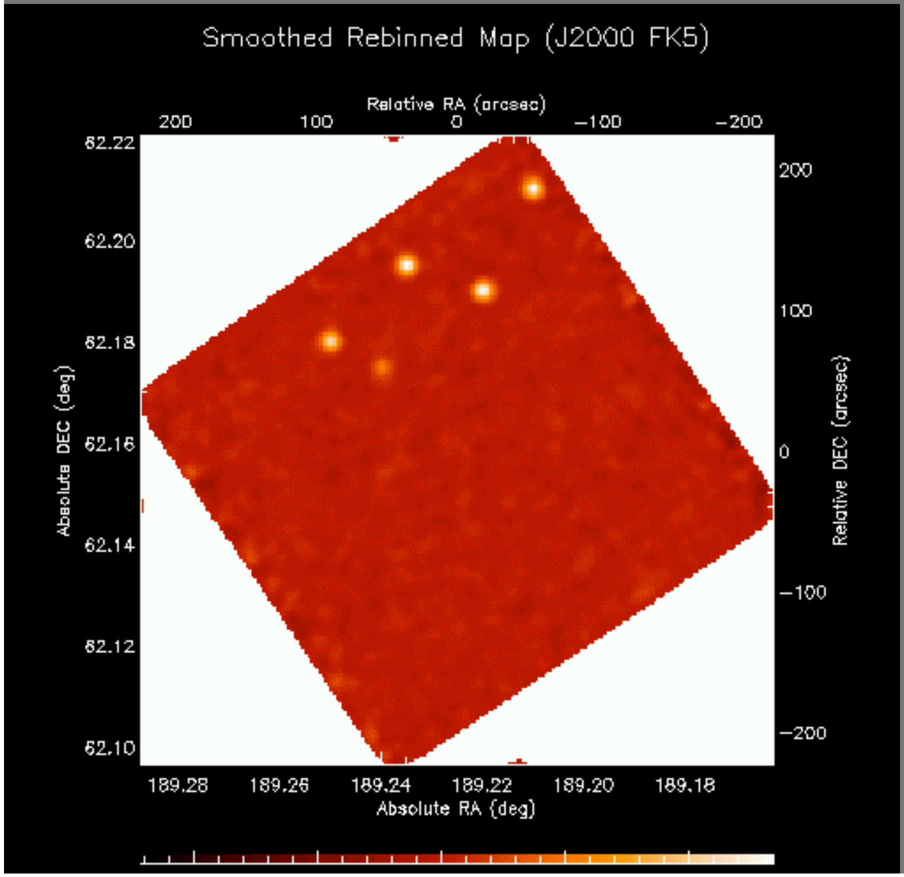
Image



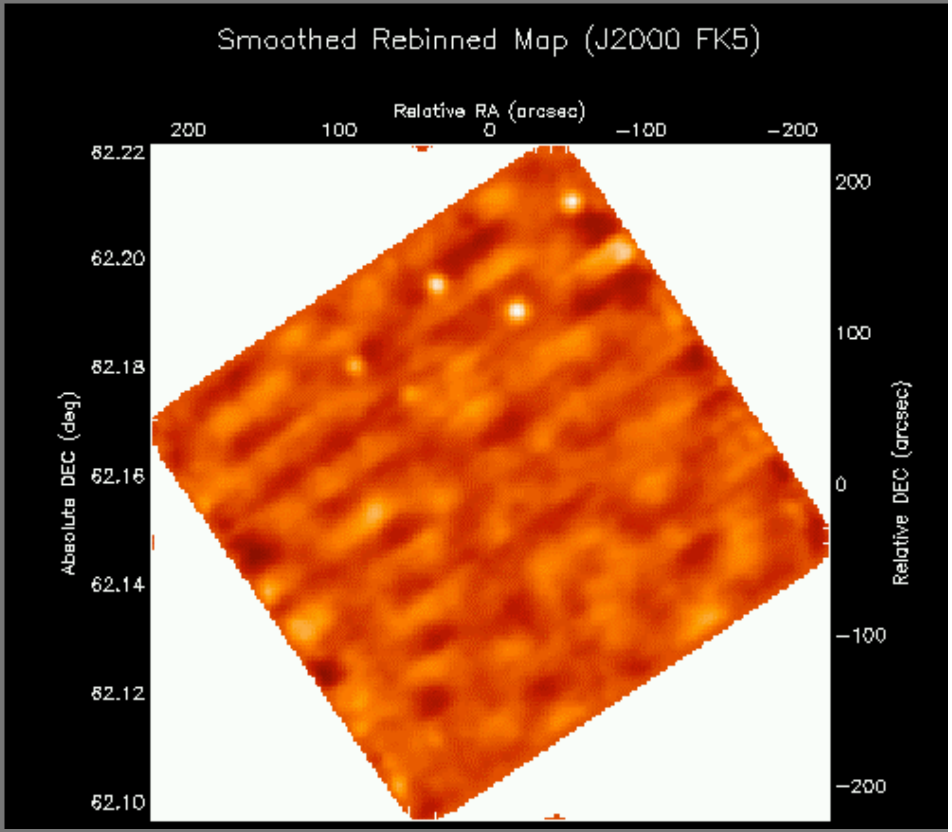
SD Continuum Maps are Often Limited by Systematics not Noise

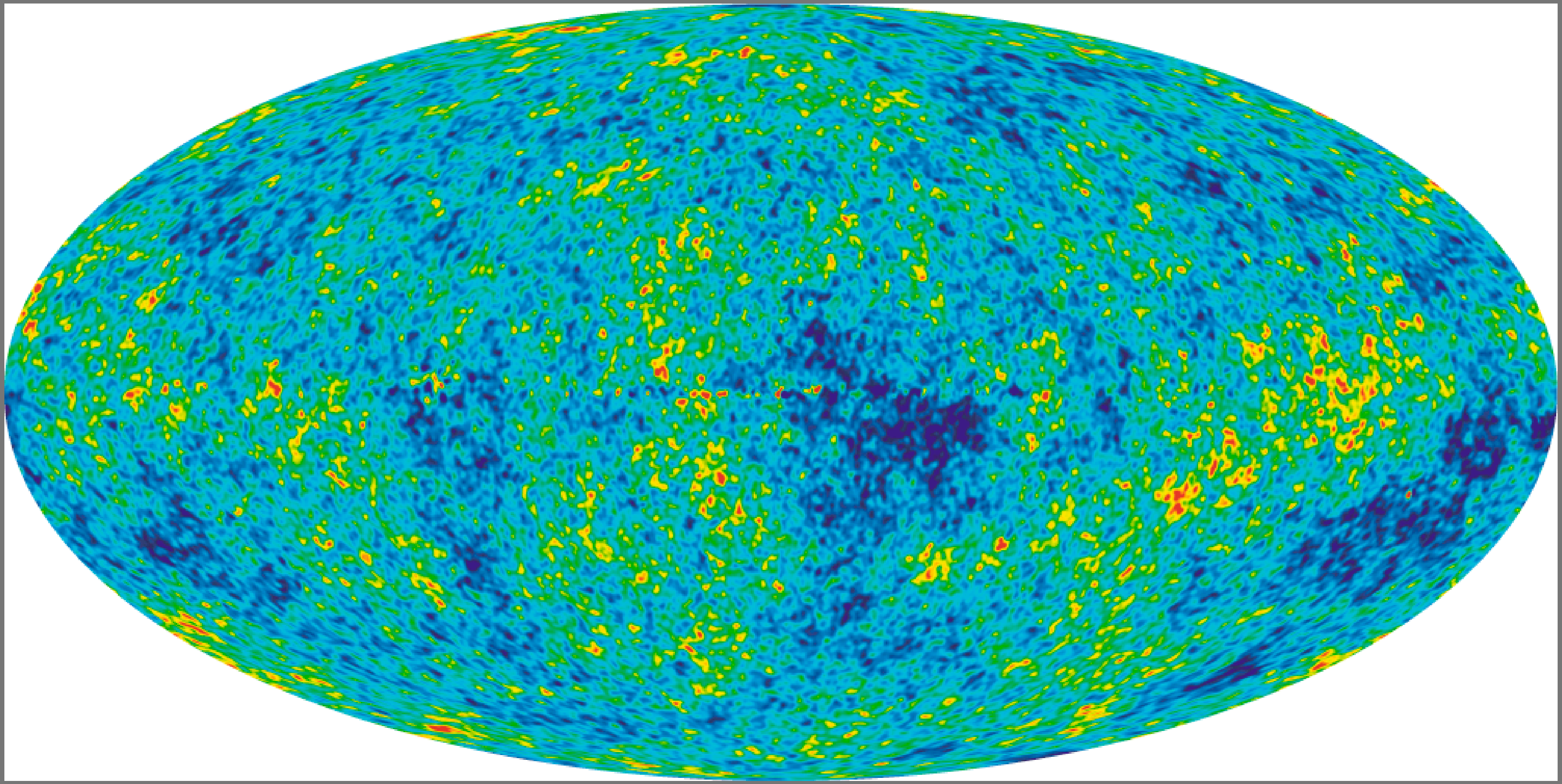
→ATMOSPHERE
→ RELATIVE GAINS

Penn Array simulation: 5'x5', no atmosphere (thermal noise only)

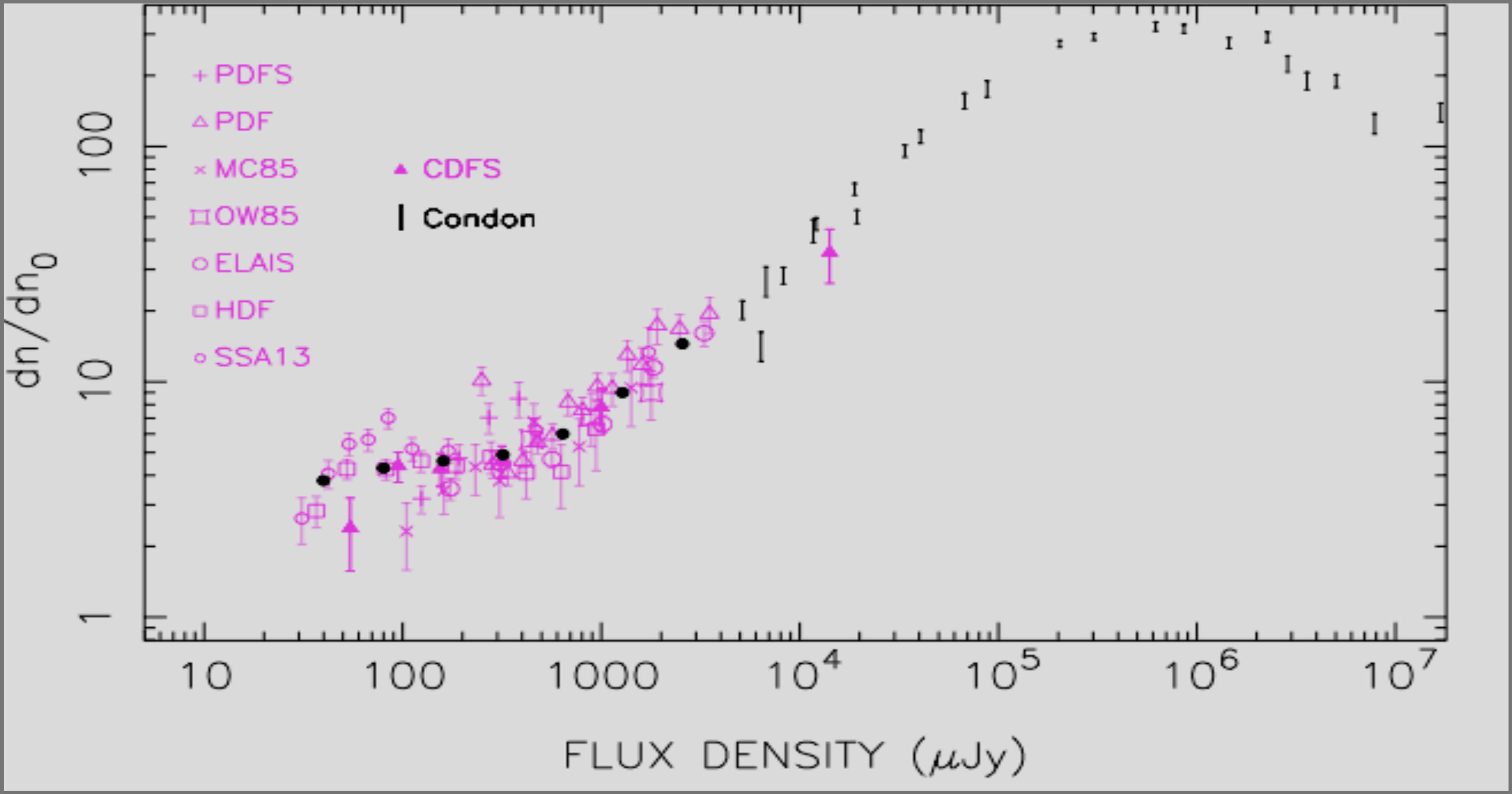


Same simulation with atmosphere, standard reduction (subtract baseline, grid onto sky)

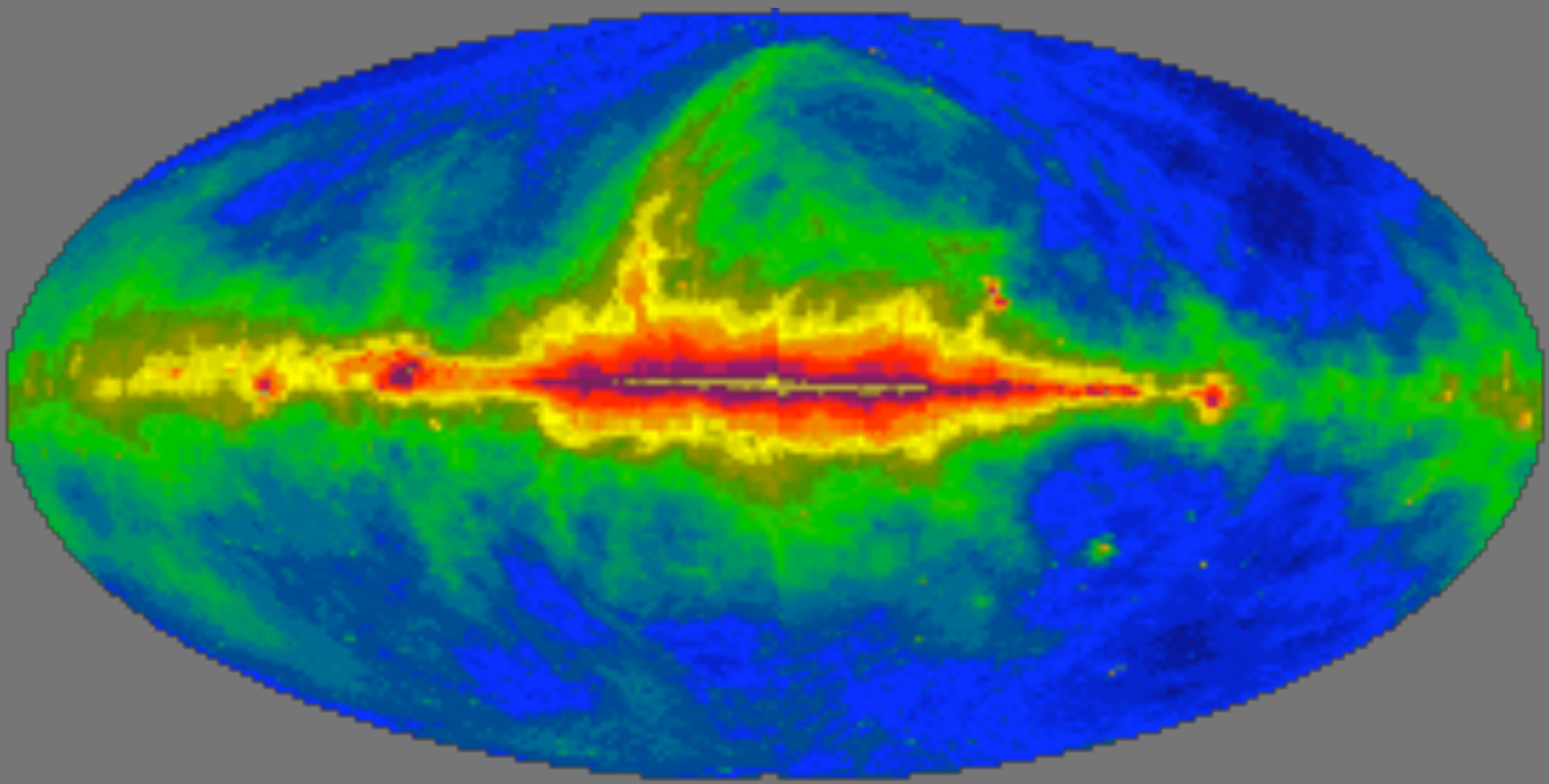




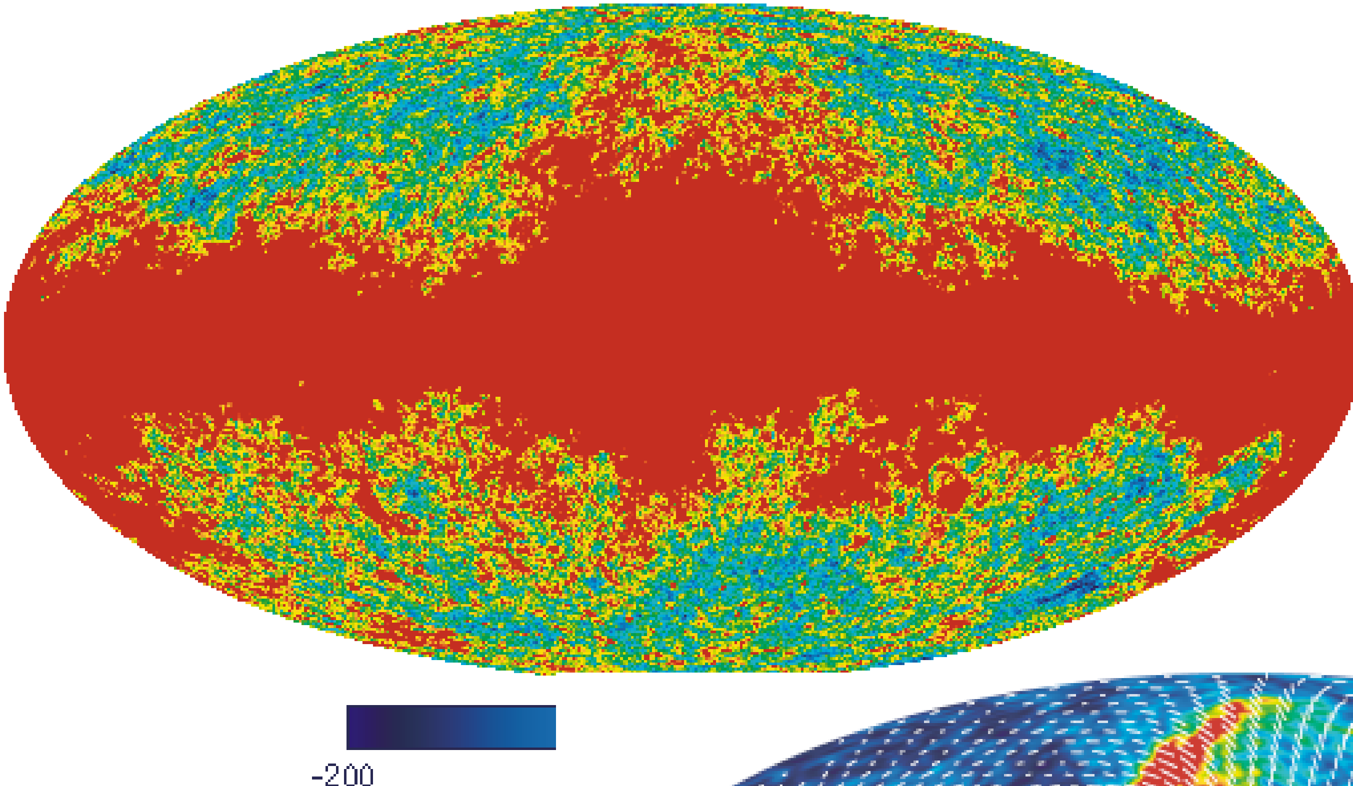
Extragalactic Radio Sources

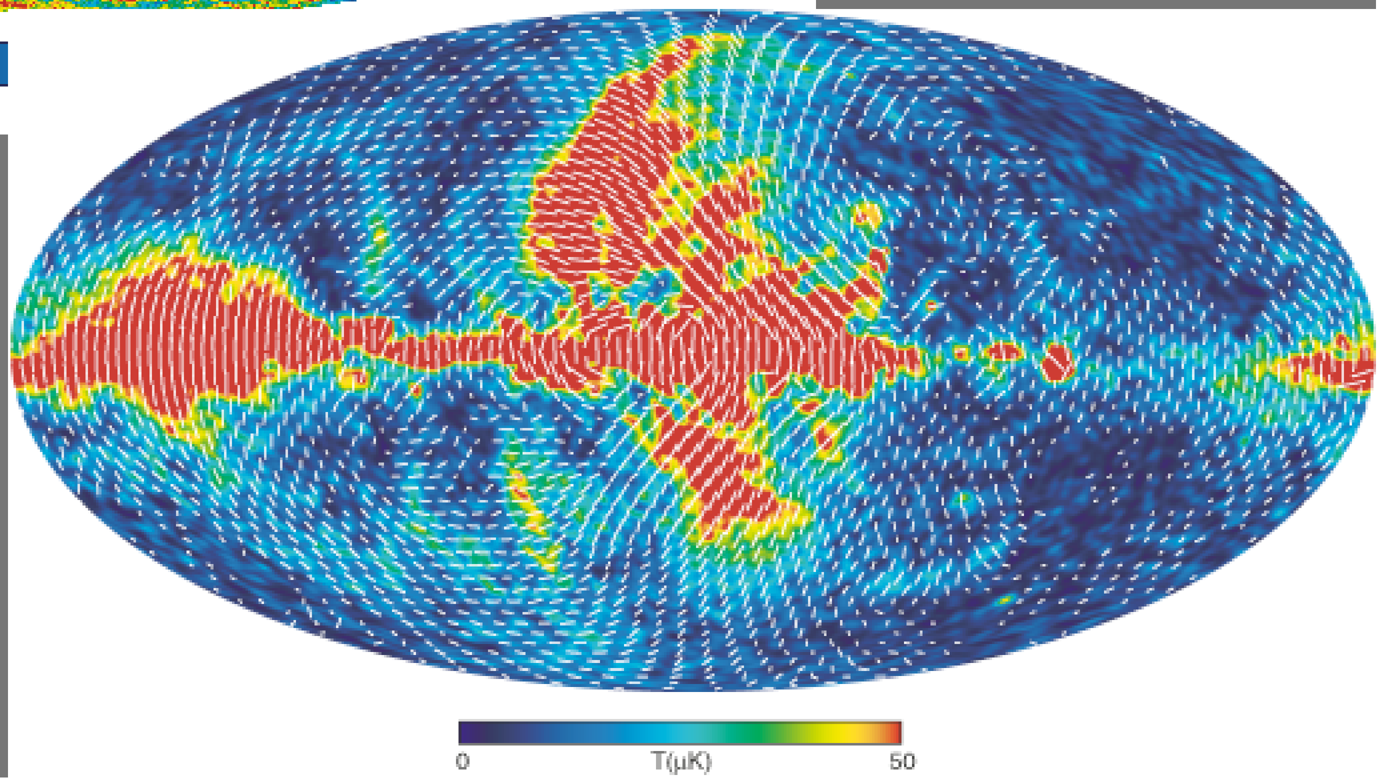


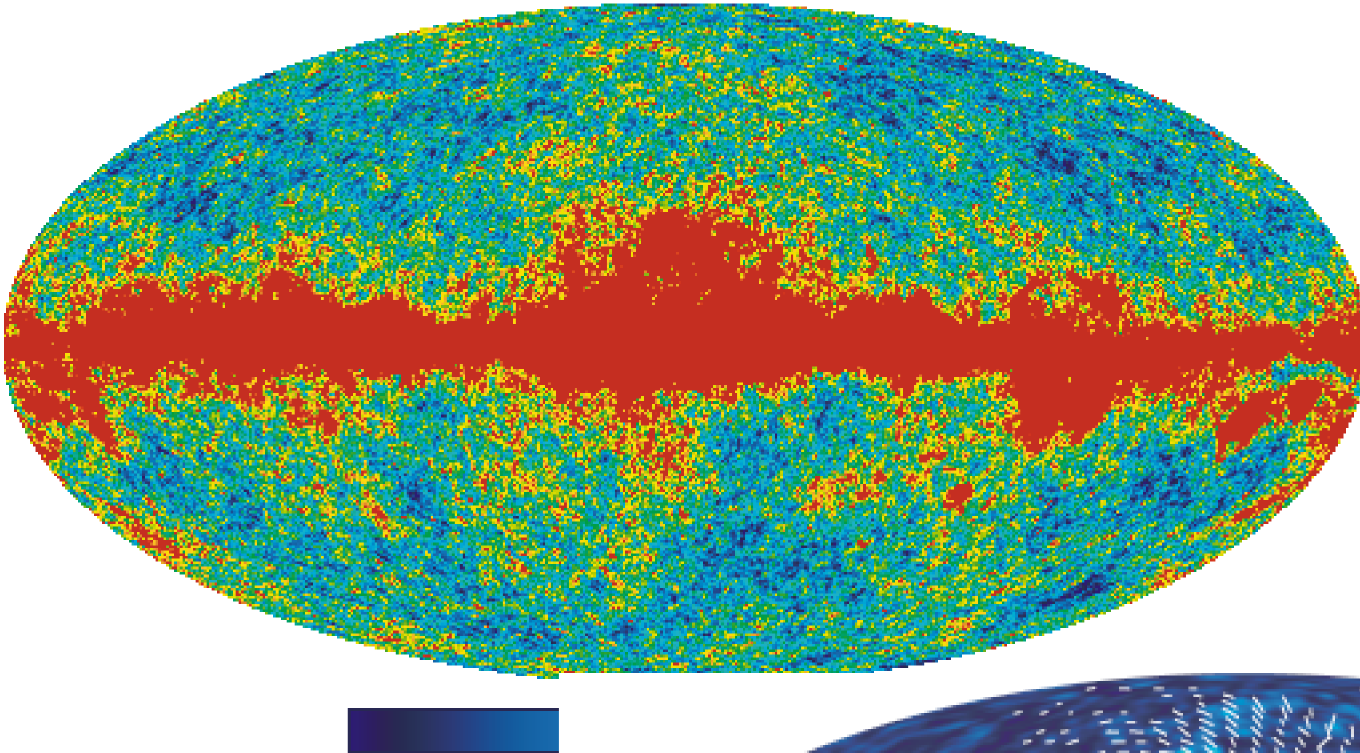
408 MHz continuum emission from our Galaxy

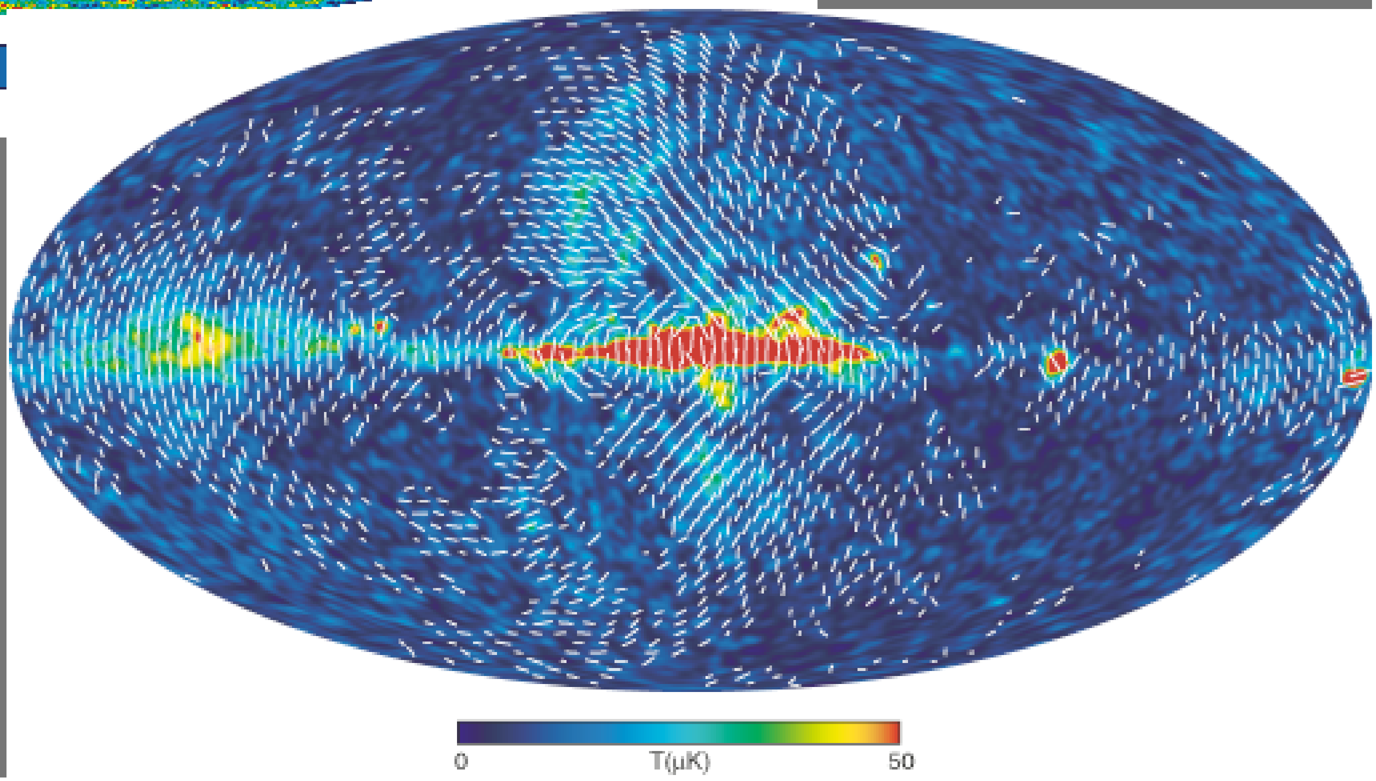


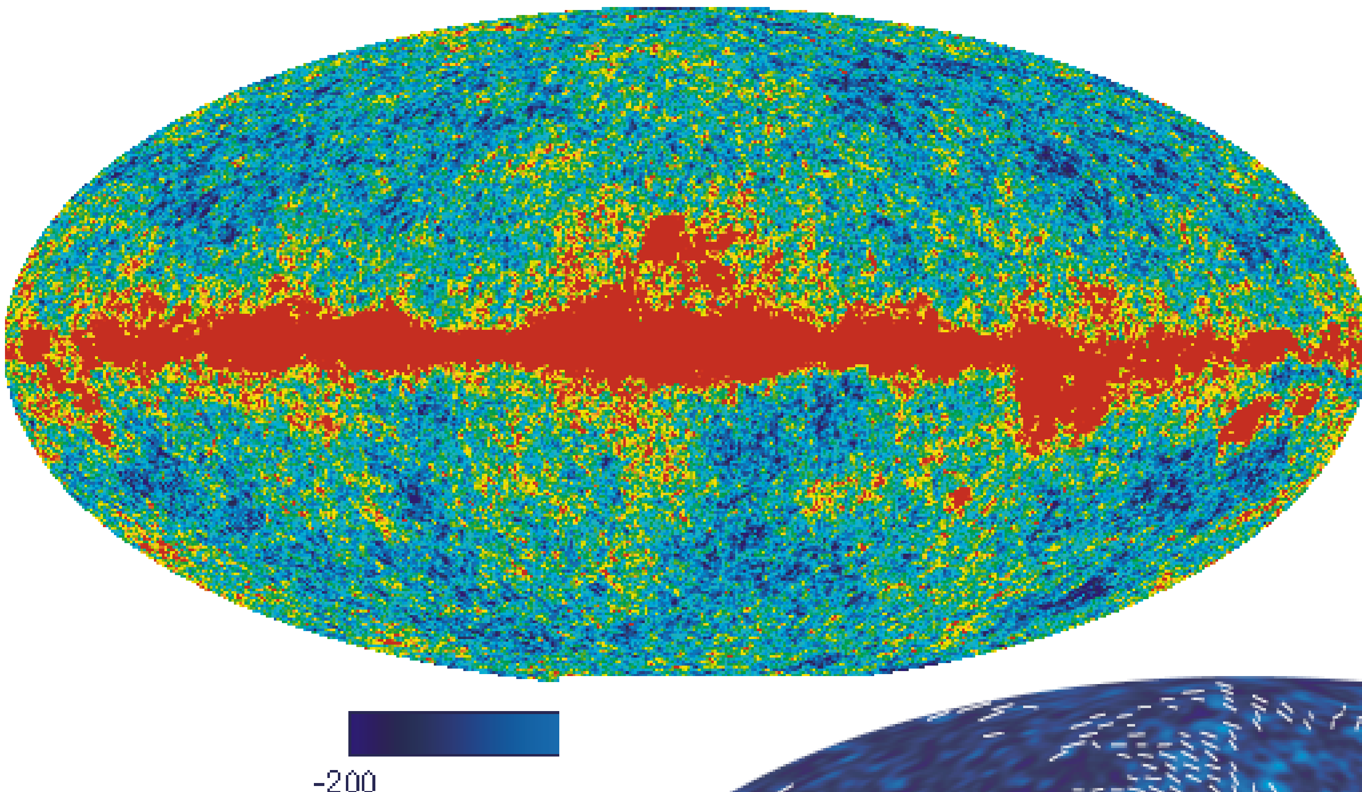
Haslam et al., 1982

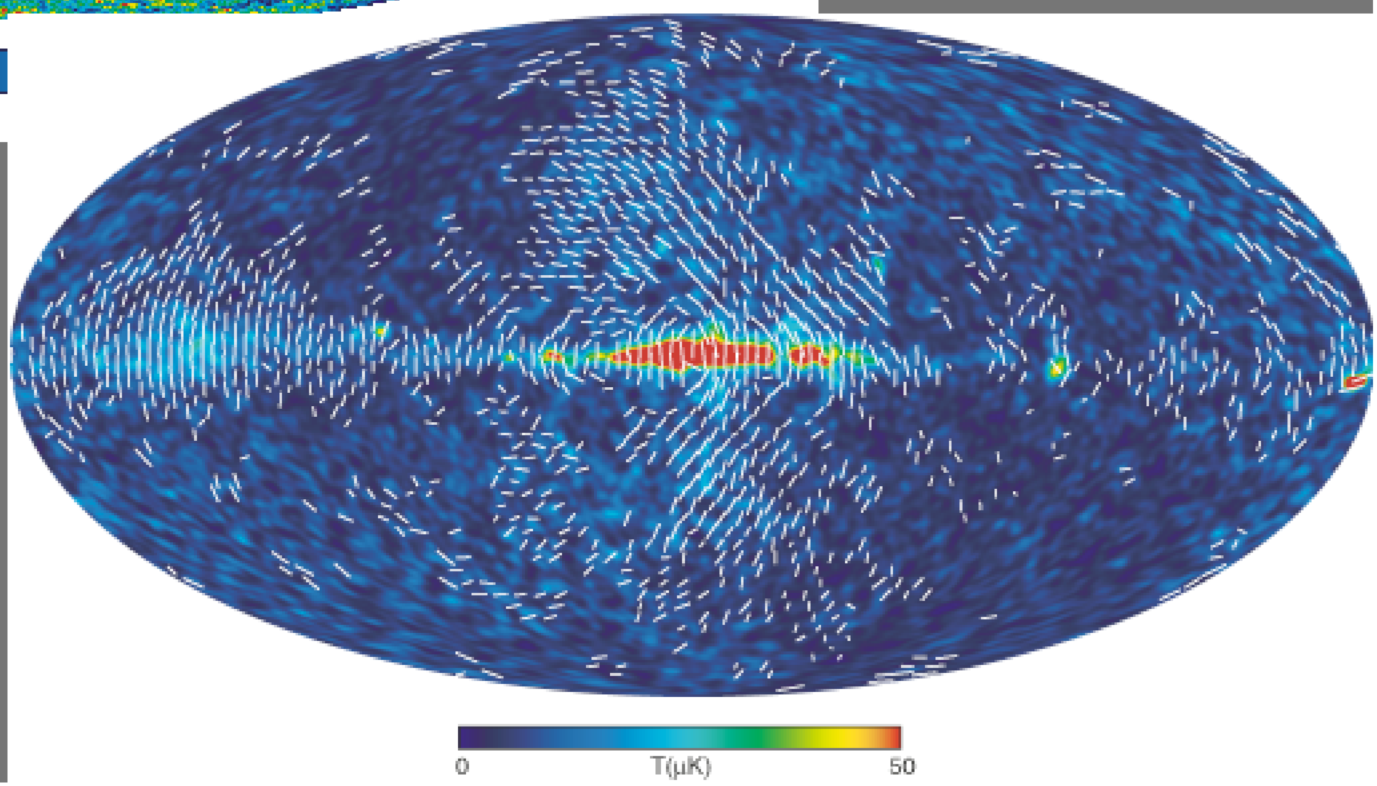

-200


0
T(μK)
50

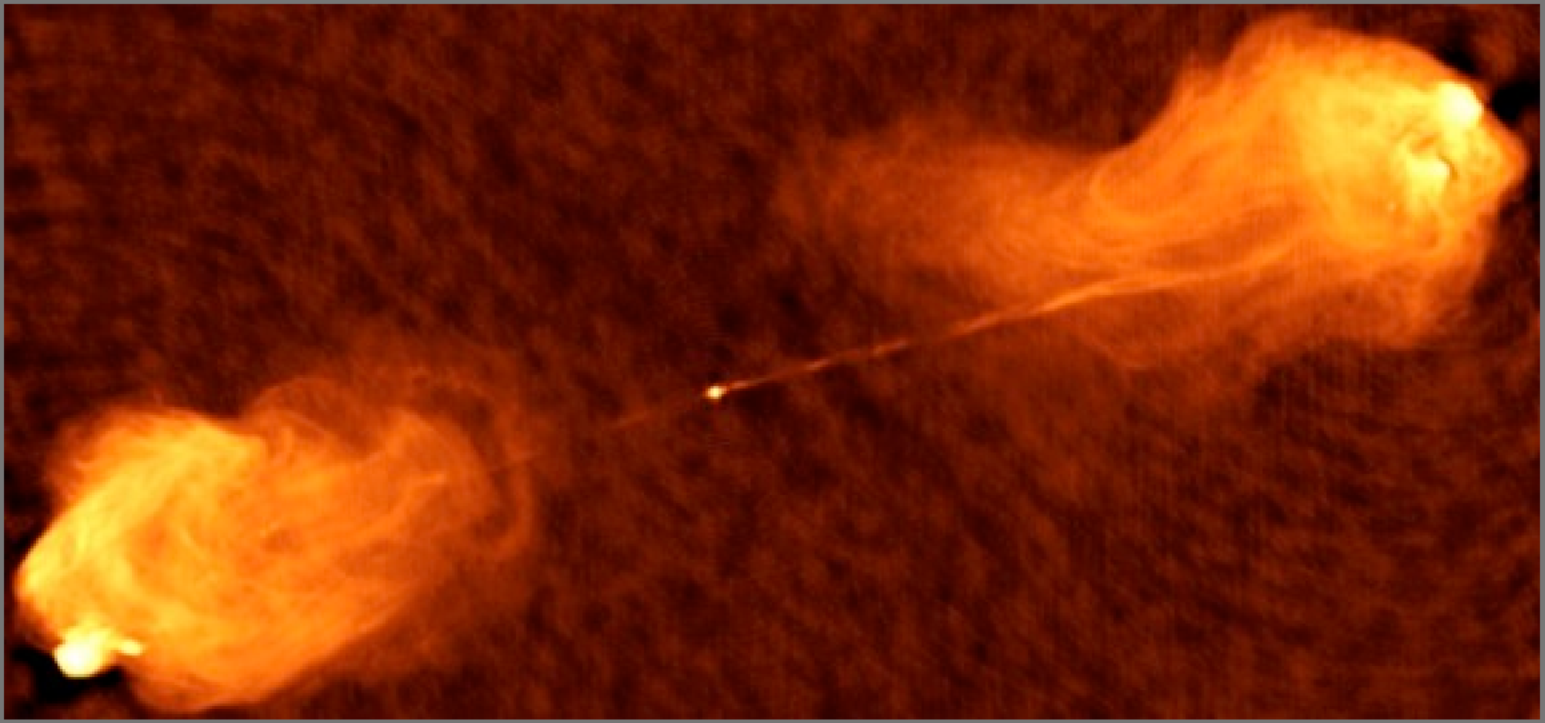

-200


0
T(μK)
50

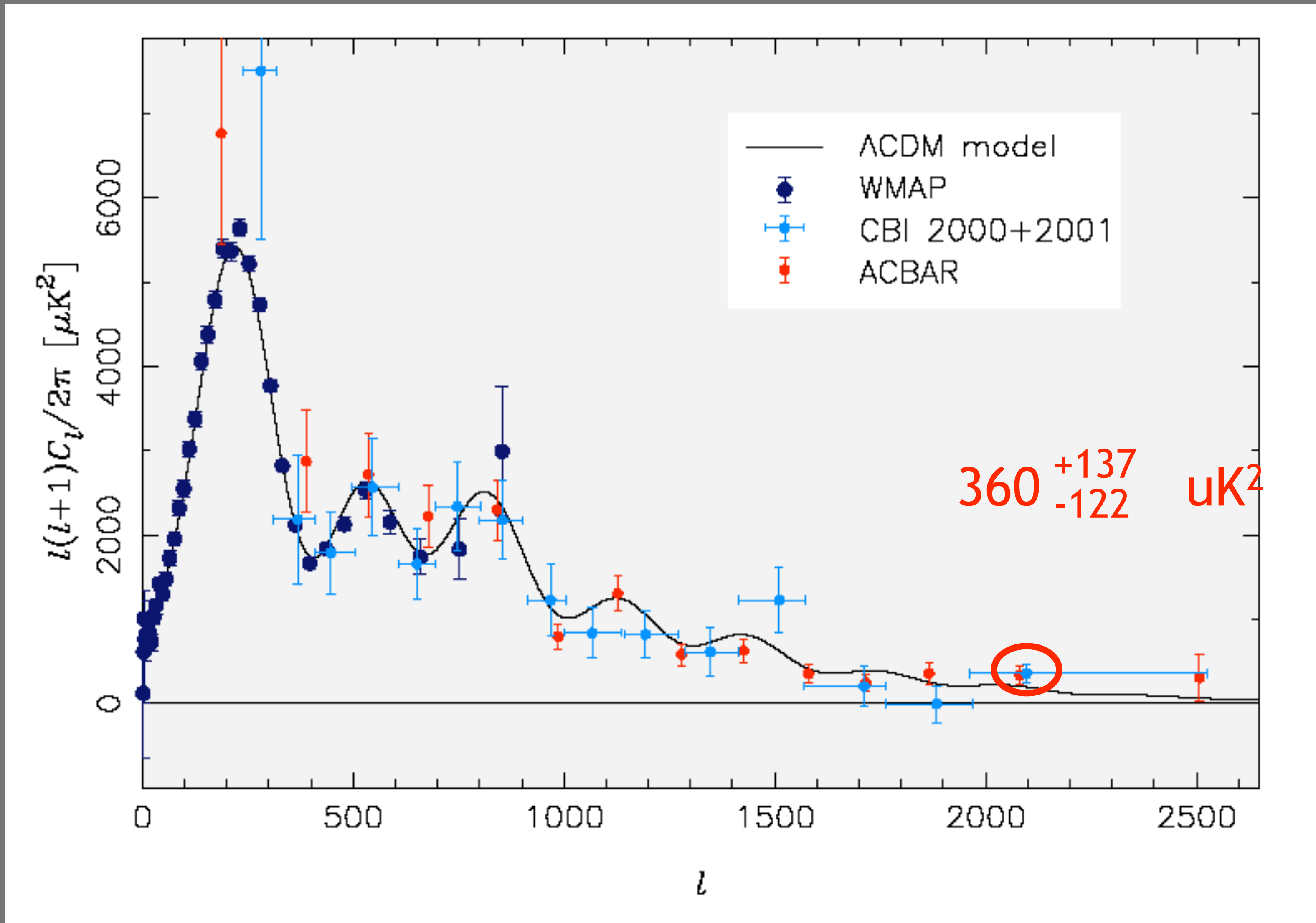

-200


0
T(μK)
50

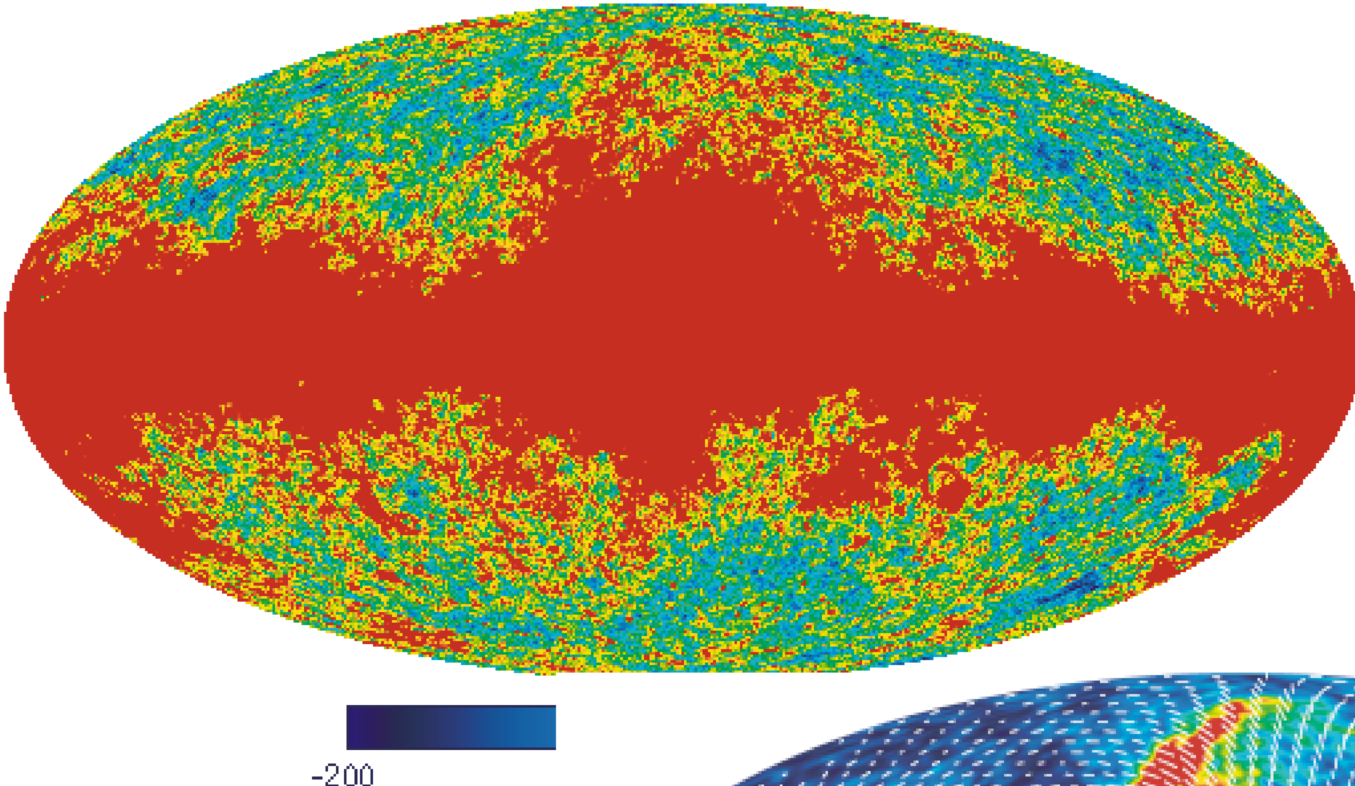
Active Galactic Nuclei & Quasars



Cygnus A -- Perley, Carilli, & Dreher (1984)



Readhead, Mason et al. 2004



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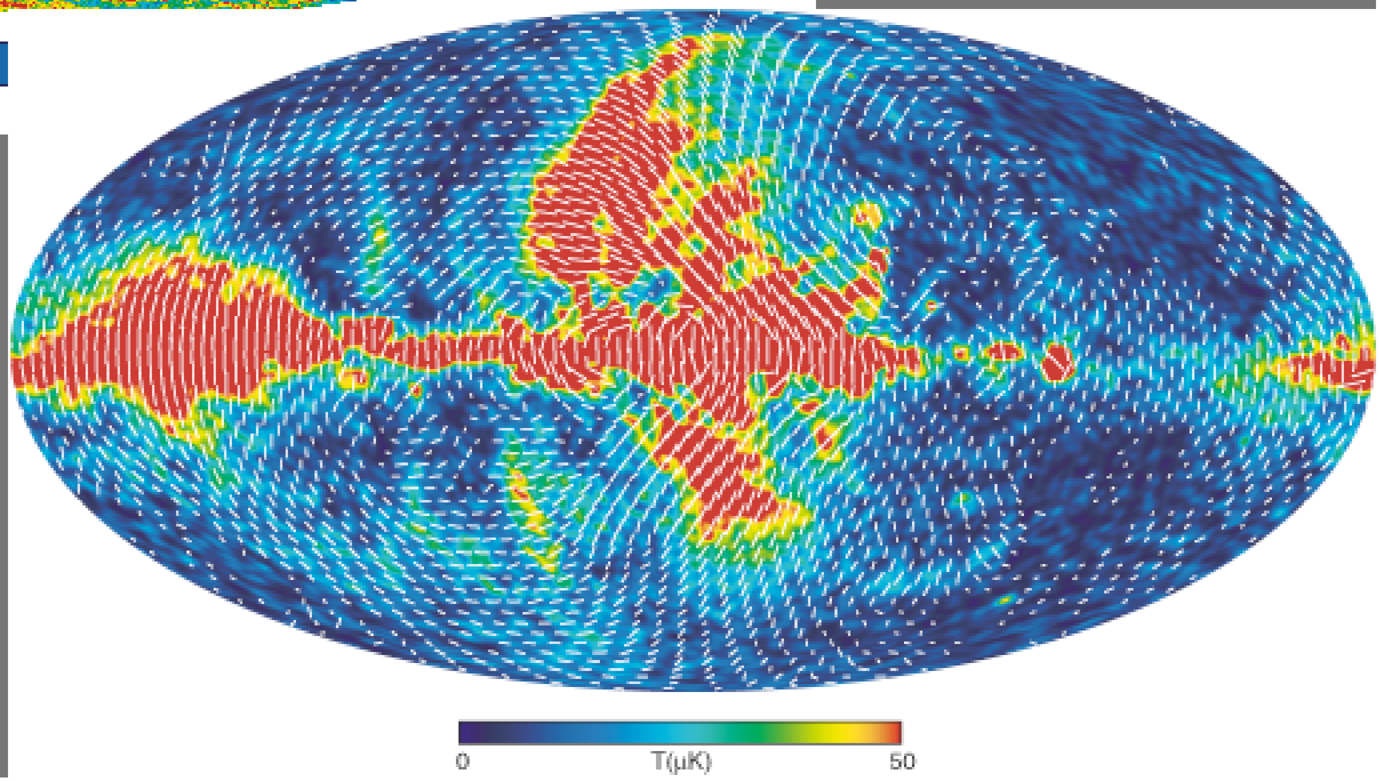
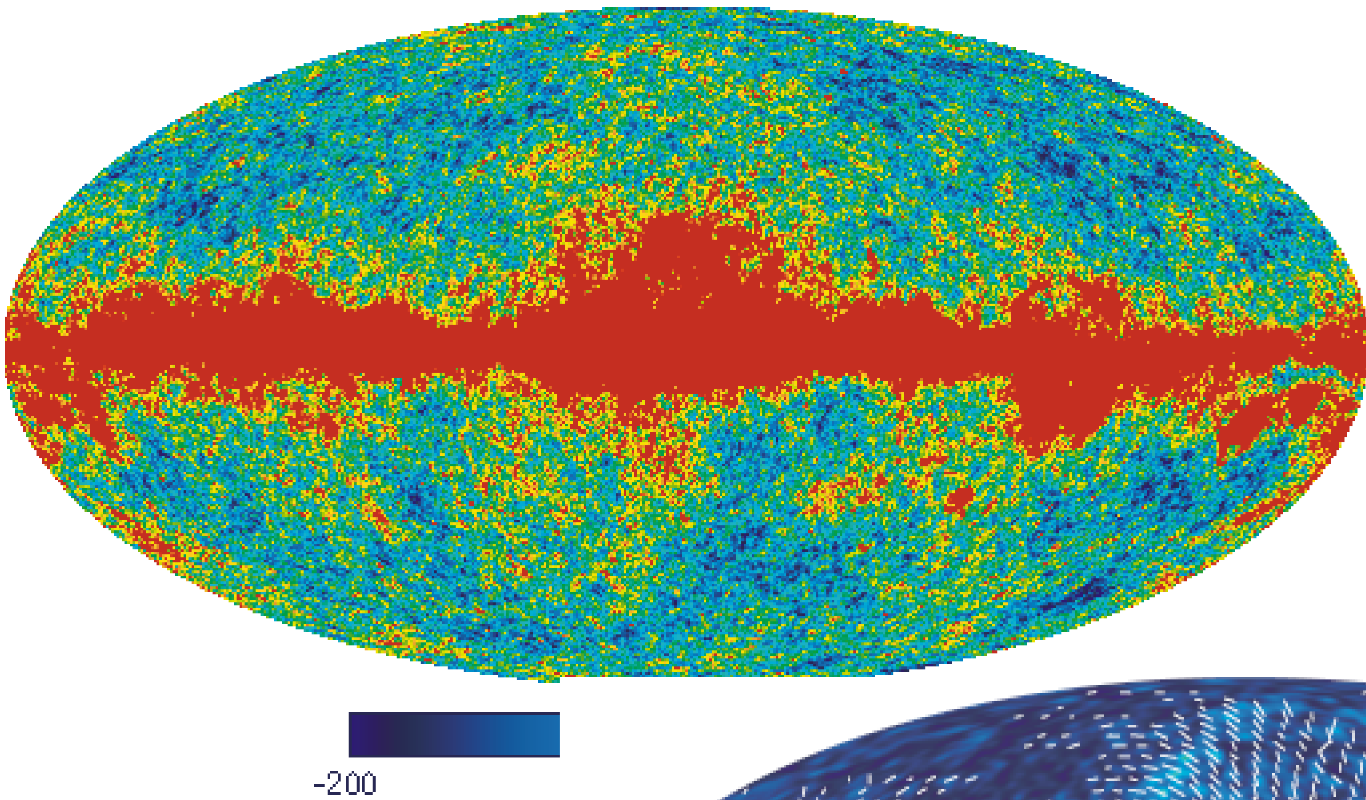


0
T(μK)
50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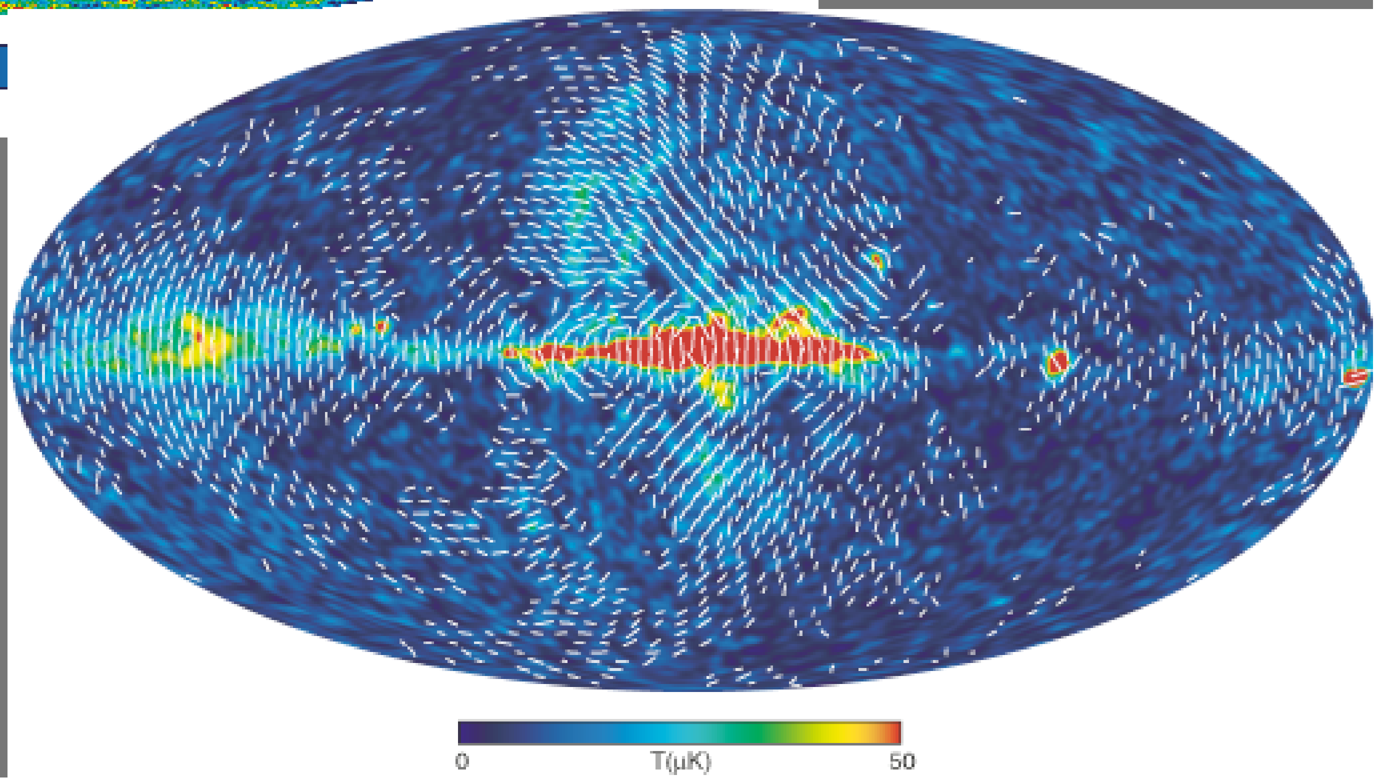
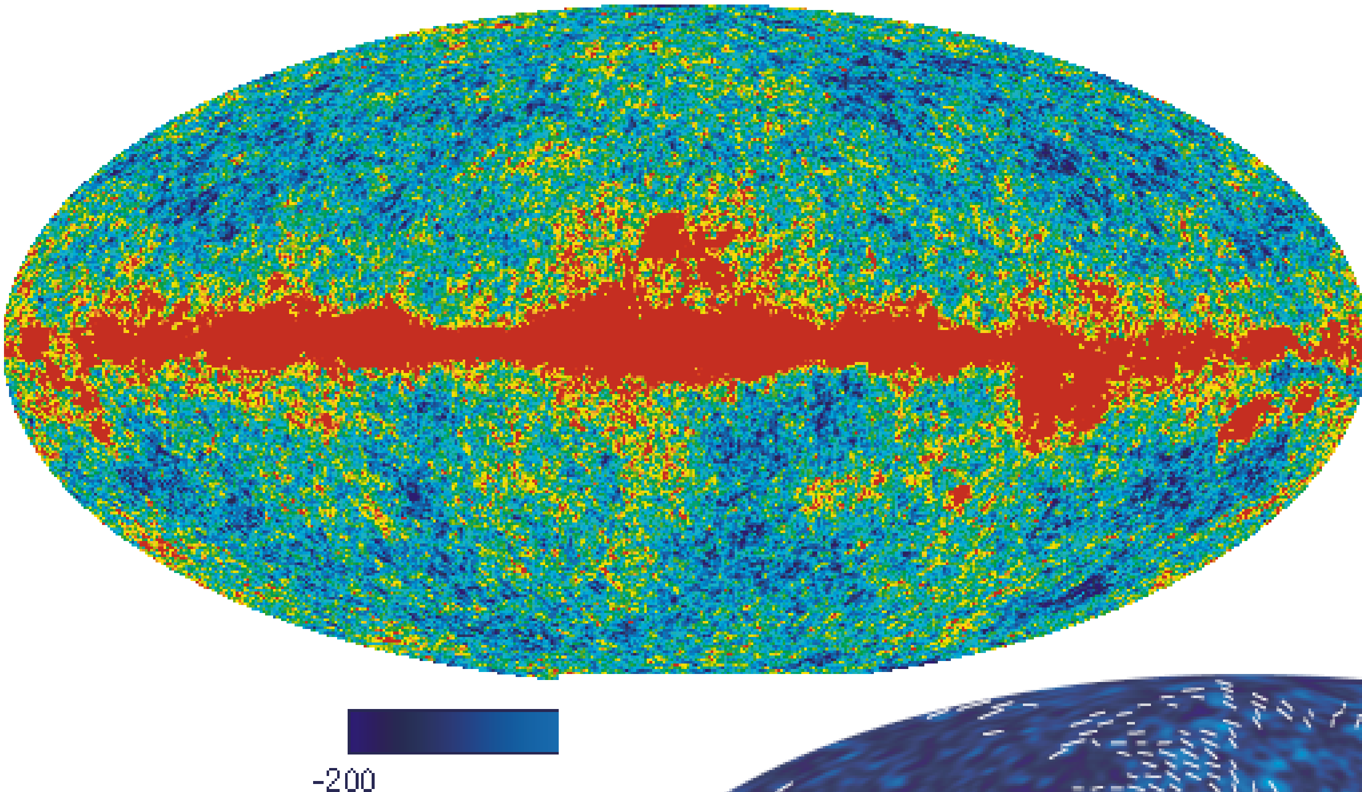

0
T(μK)
50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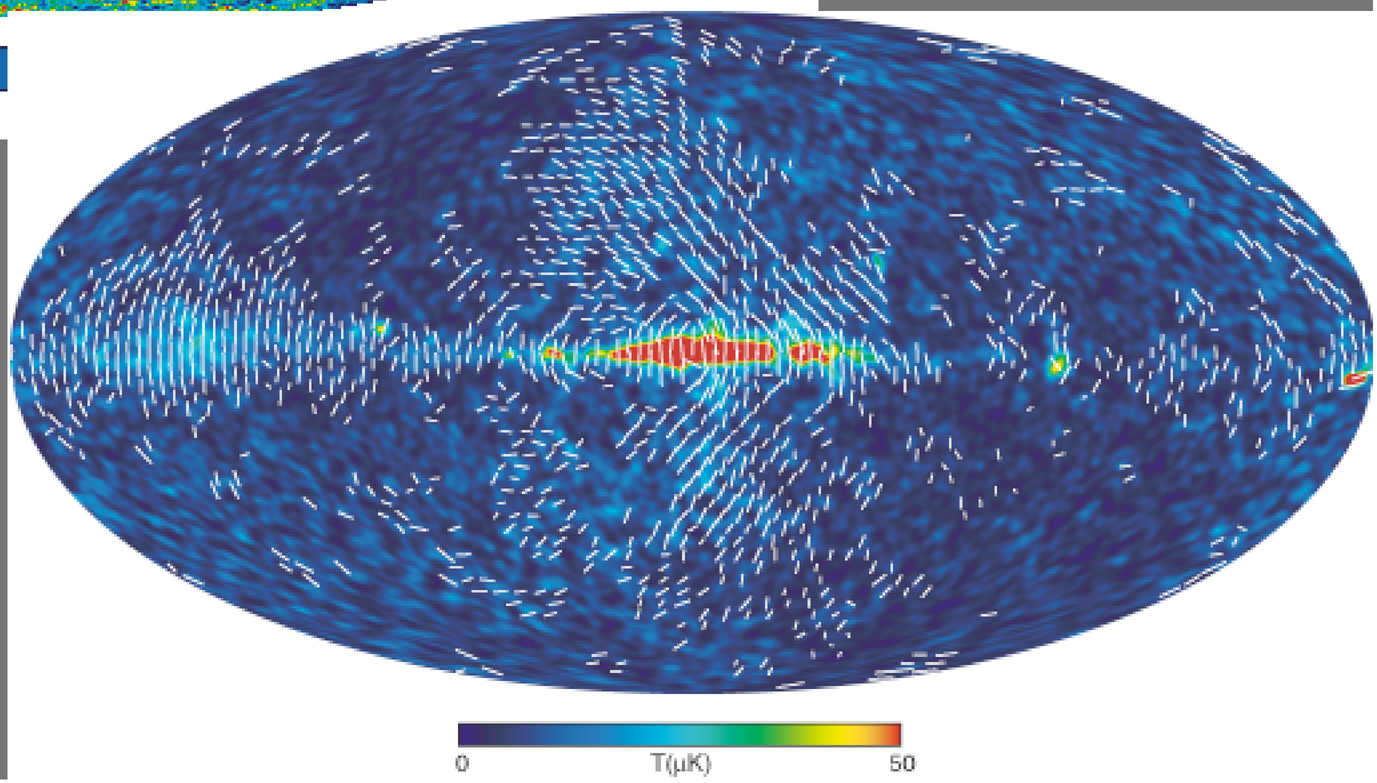
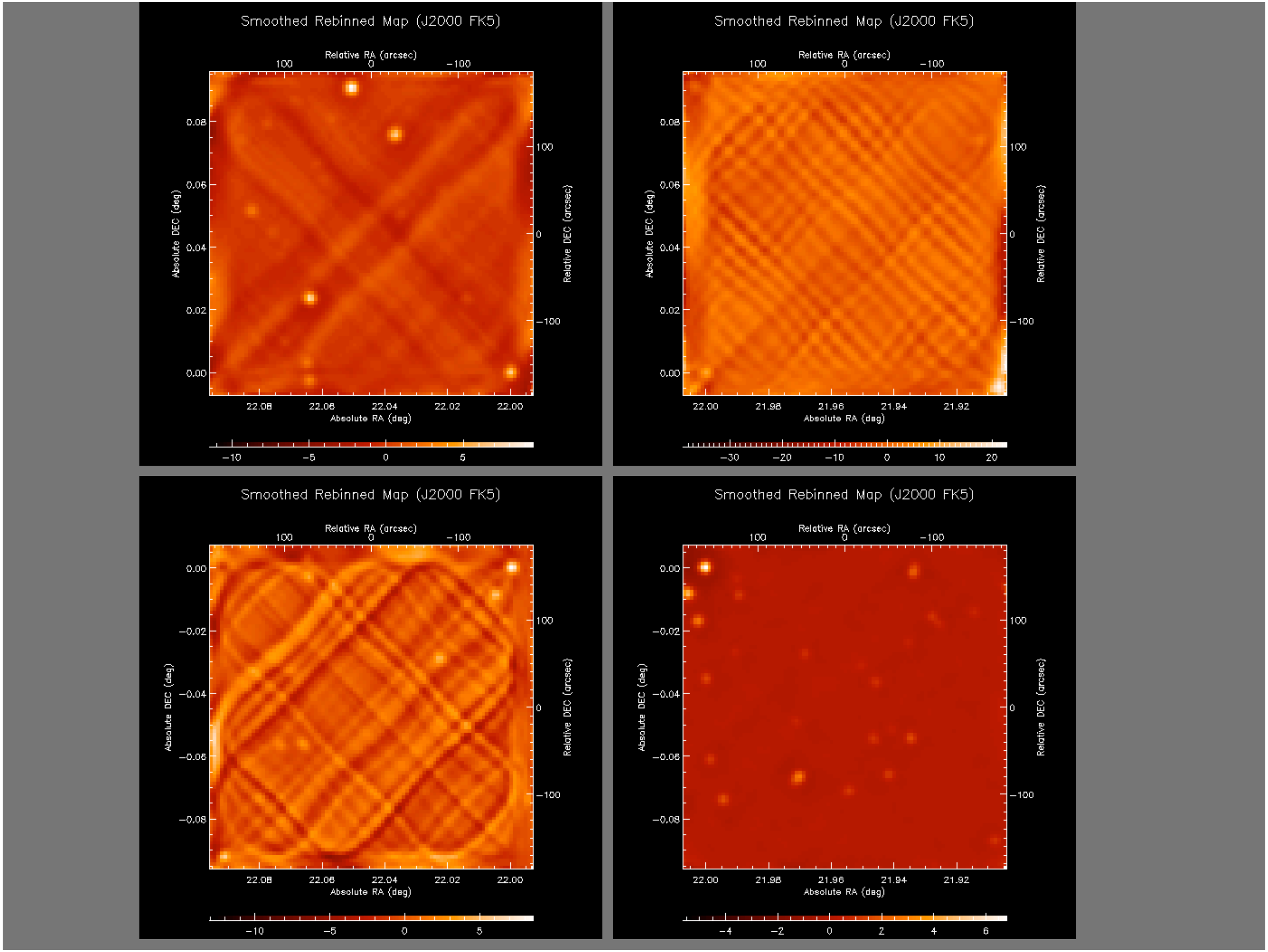

0
T(μK)
50

Continuum Mapping

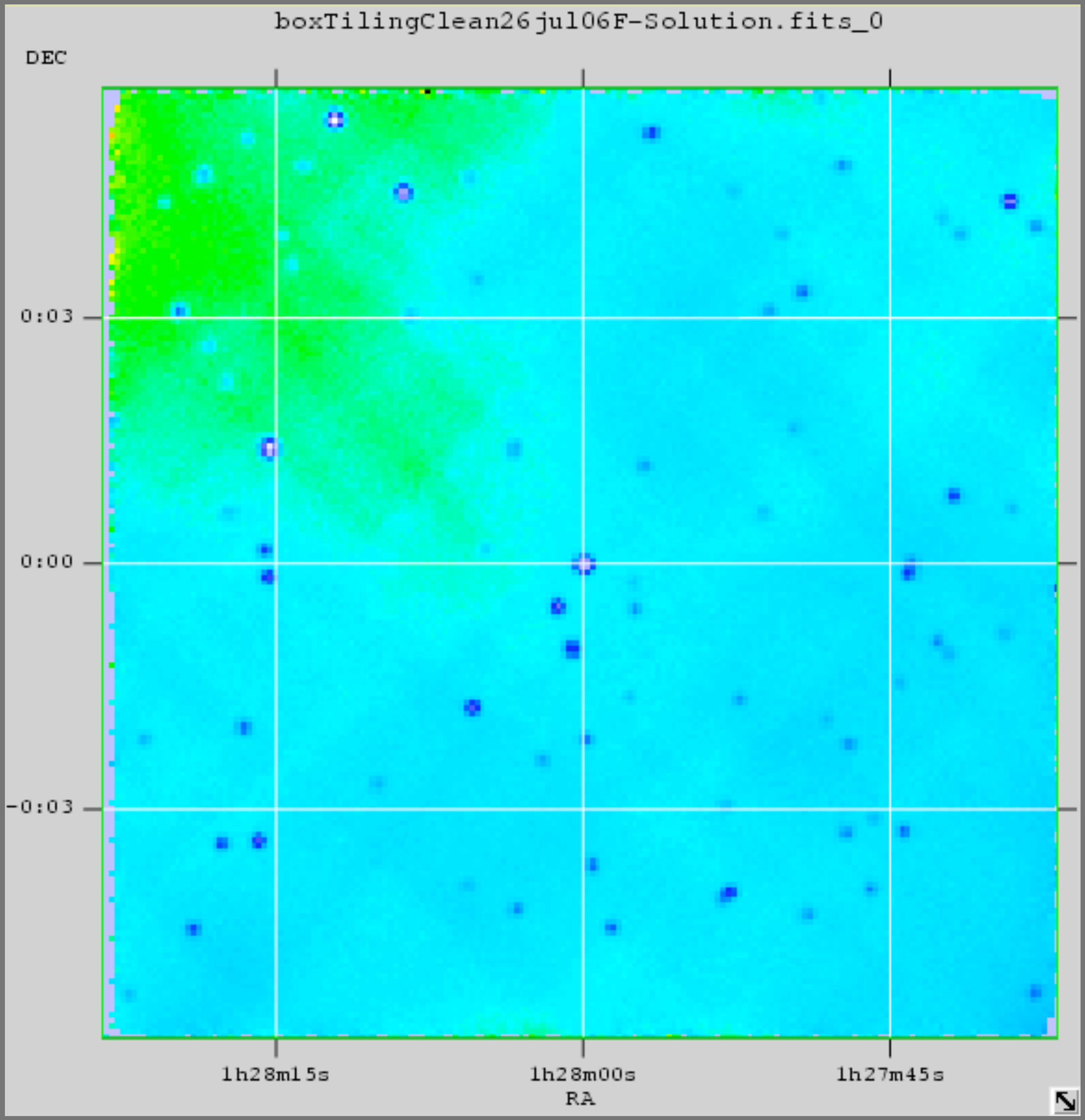
- If High sensitivity or extended structures aren't sought, simple approaches will work (total power receiver; subtract a polynomial or median-filter baseline & grid residuals onto sky)
- Otherwise systematics must be removed, and this often removes some astronomical information as well
  - Eg, map made with a dicke switching system
- How to deal with this?
  - Emerson, Klein, & Haslam (1972): directly deconvolve beam switch.
    - Switch multiple angles (chopping system) or parallactic angle rotation allows most of the lost information to be regained
  - Iterative schemes (single-dish CLEAN-- Bill Cotton's OBIT)
  - Brute-force least-squares & variants thereof
    - Used for WMAP & other CMB experiments
    - Implemented in IDL for SHARC-II, NICMOS-- See Fixsen, Moseley, & Arendt (2000)

$$\vec{d} = A\vec{m}$$

$$\vec{m} = (A^T A)^{-1} A^T \vec{d}$$


Smoothed Rebinned Map (J2000 FK5)
Relative RA (arcsec)
Absolute RA (deg)
Absolute DEC (deg)
Relative DEC (arcsec)
Smoothed Rebinned Map (J2000 FK5)
Relative RA (arcsec)
Absolute RA (deg)
Absolute DEC (deg)
Relative DEC (arcsec)
Smoothed Rebinned Map (J2000 FK5)
Relative RA (arcsec)
Absolute RA (deg)
Absolute DEC (deg)
Relative DEC (arcsec)
Smoothed Rebinned Map (J2000 FK5)
Relative RA (arcsec)
Absolute RA (deg)
Absolute DEC (deg)
Relative DEC (arcsec)

- Spectral Lines arise from the quantization of energy levels in atoms and molecules. These give rise to fairly sharp, distinct (dnu/nu << 1) features in the frequency domain
- Macroscopic bodies and unbound particles, in contrast, usually give rise to frequency spectra which vary quite slowly (continuum)



To separate astronomy signal from systematics, an appropriate scan pattern is necessary

- Scan or chop speed t_scan < t_systematics
    - 100s Hz (Rx gain for coherent system)
    - 0.1 - few Hz (sky)
- Resample the same patch of sky in different ways (e.g., basketweaving)