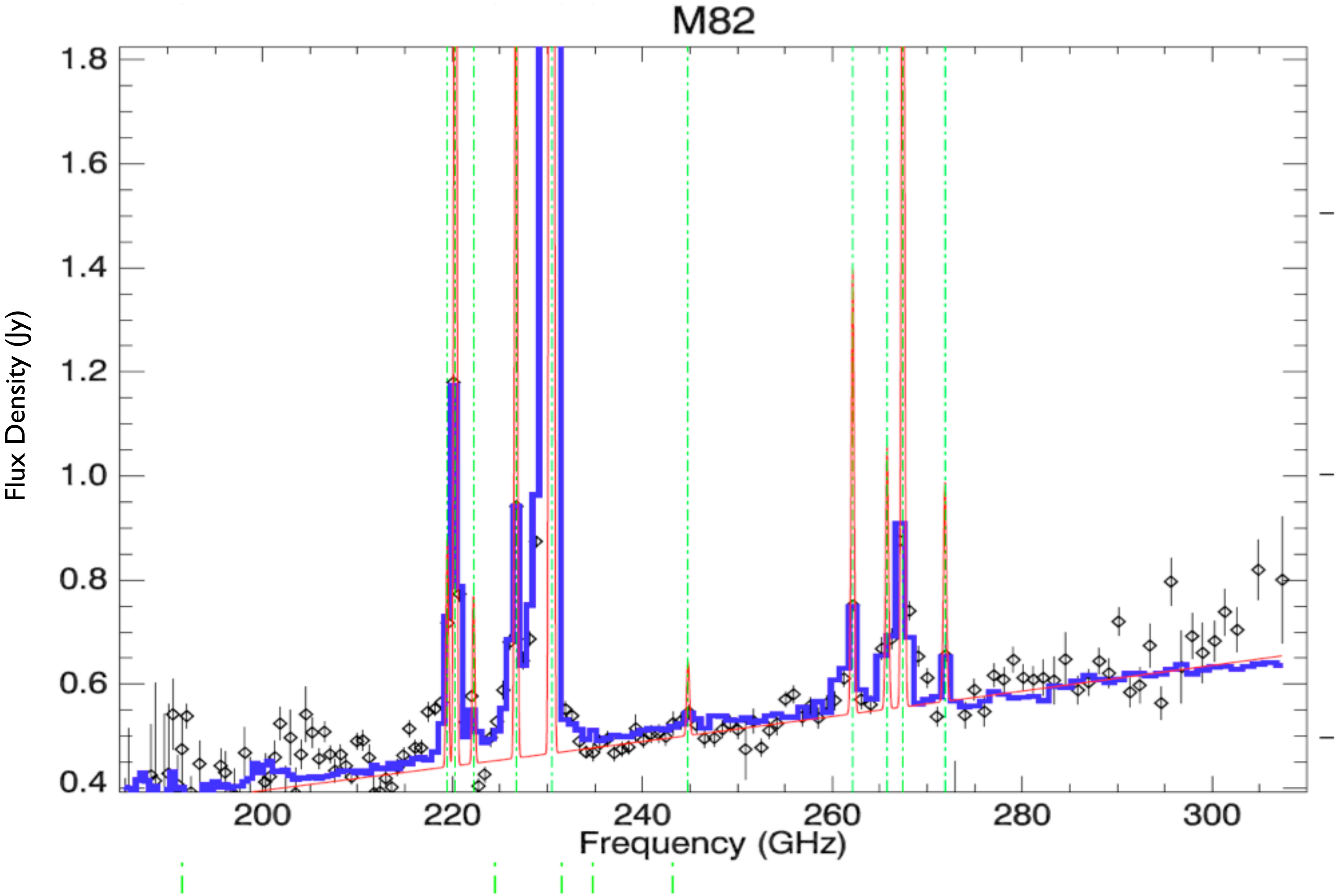
Single-Dish Continuum

- Continuum Emission Mechanisms & Science
- Issues
  - Confusion
  - gain fluctuations
  - atmosphere
- Receiver architectures & observing strategies
- Calibration

Brian Mason (NRAO)
NRAO/Arecibo Single-Dish Summer School
July 6, 2015

What do we mean by “continuum”?



ZSPEC (Caltech Submillimeter Observatory)
Naylor et al. (2010)

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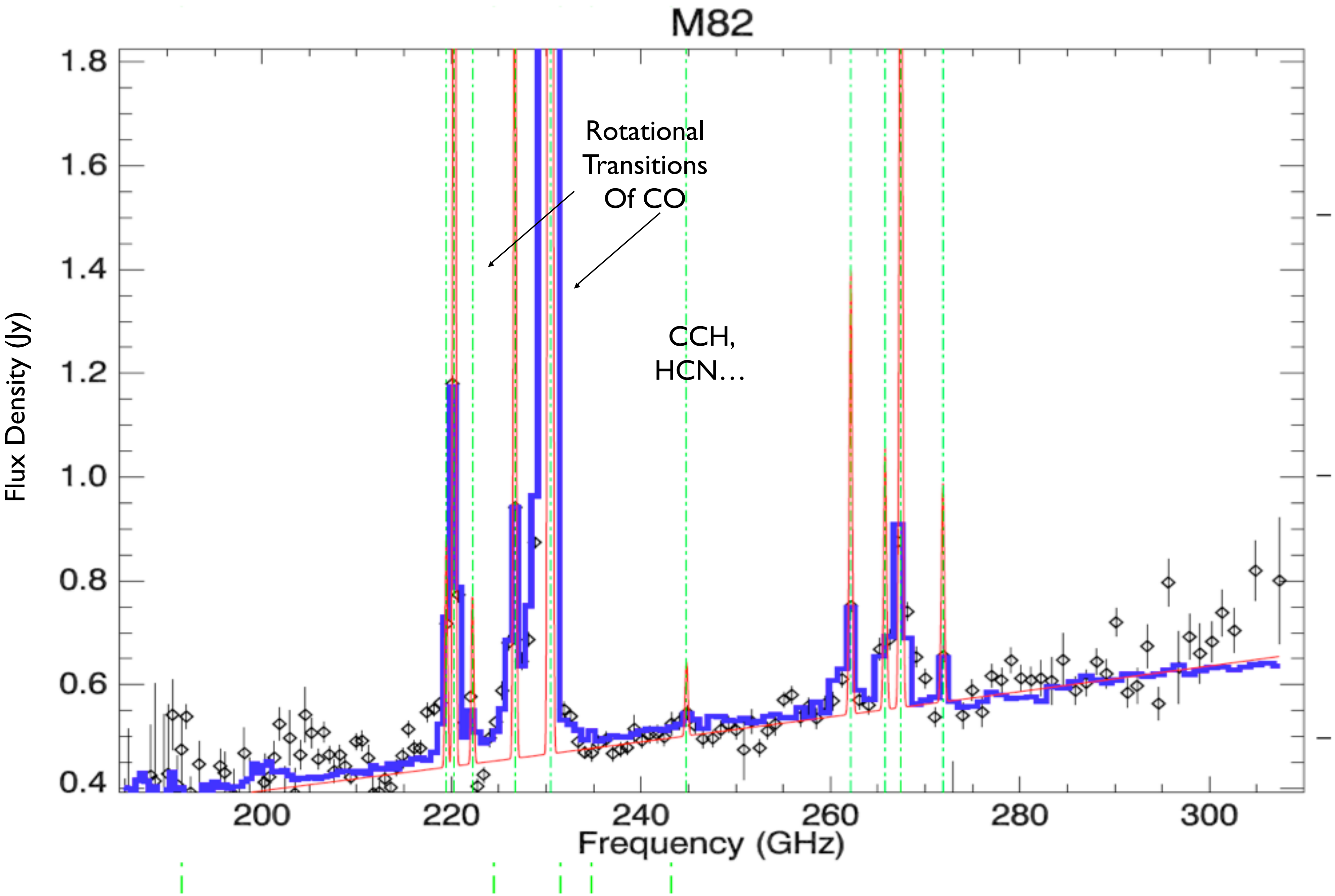

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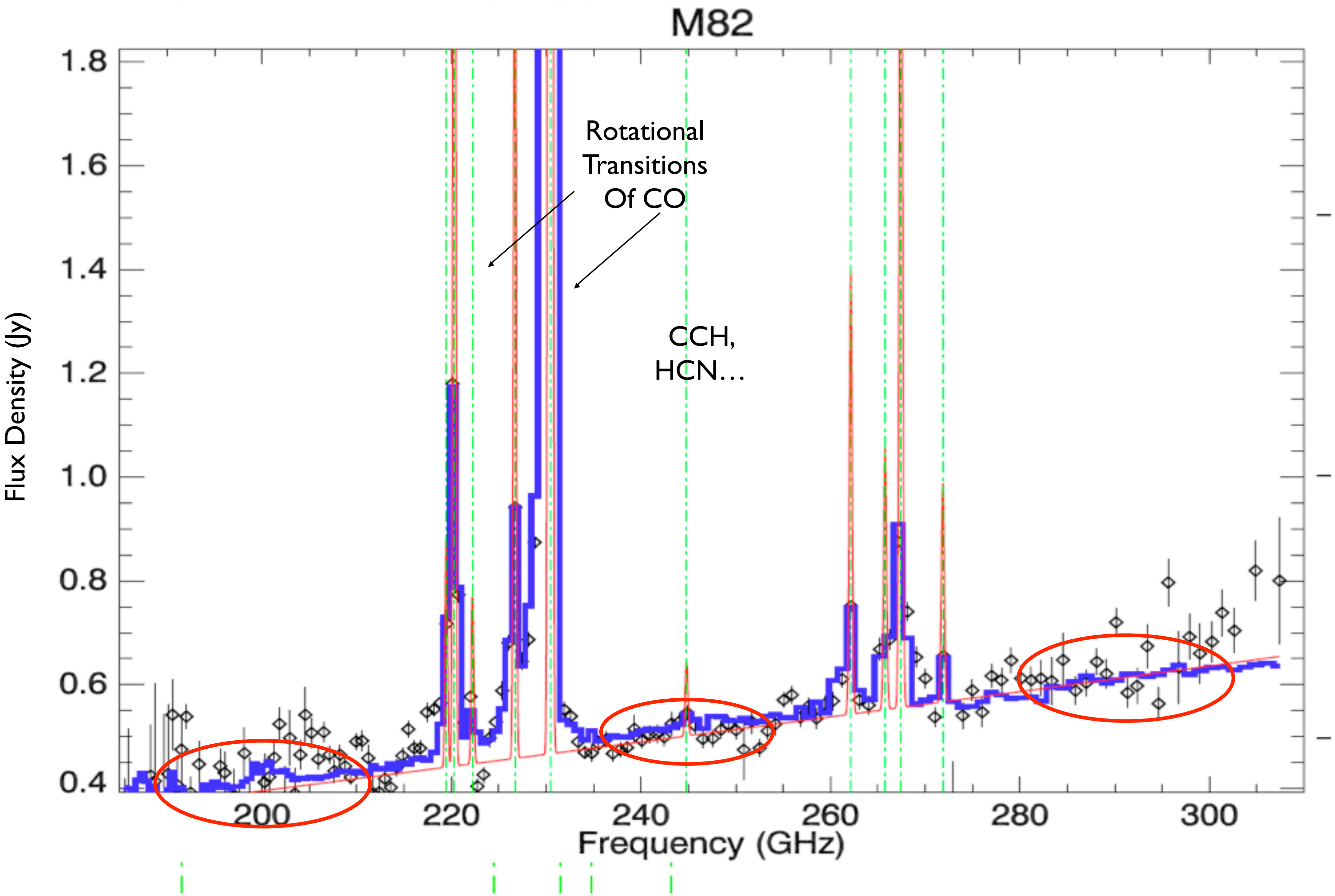

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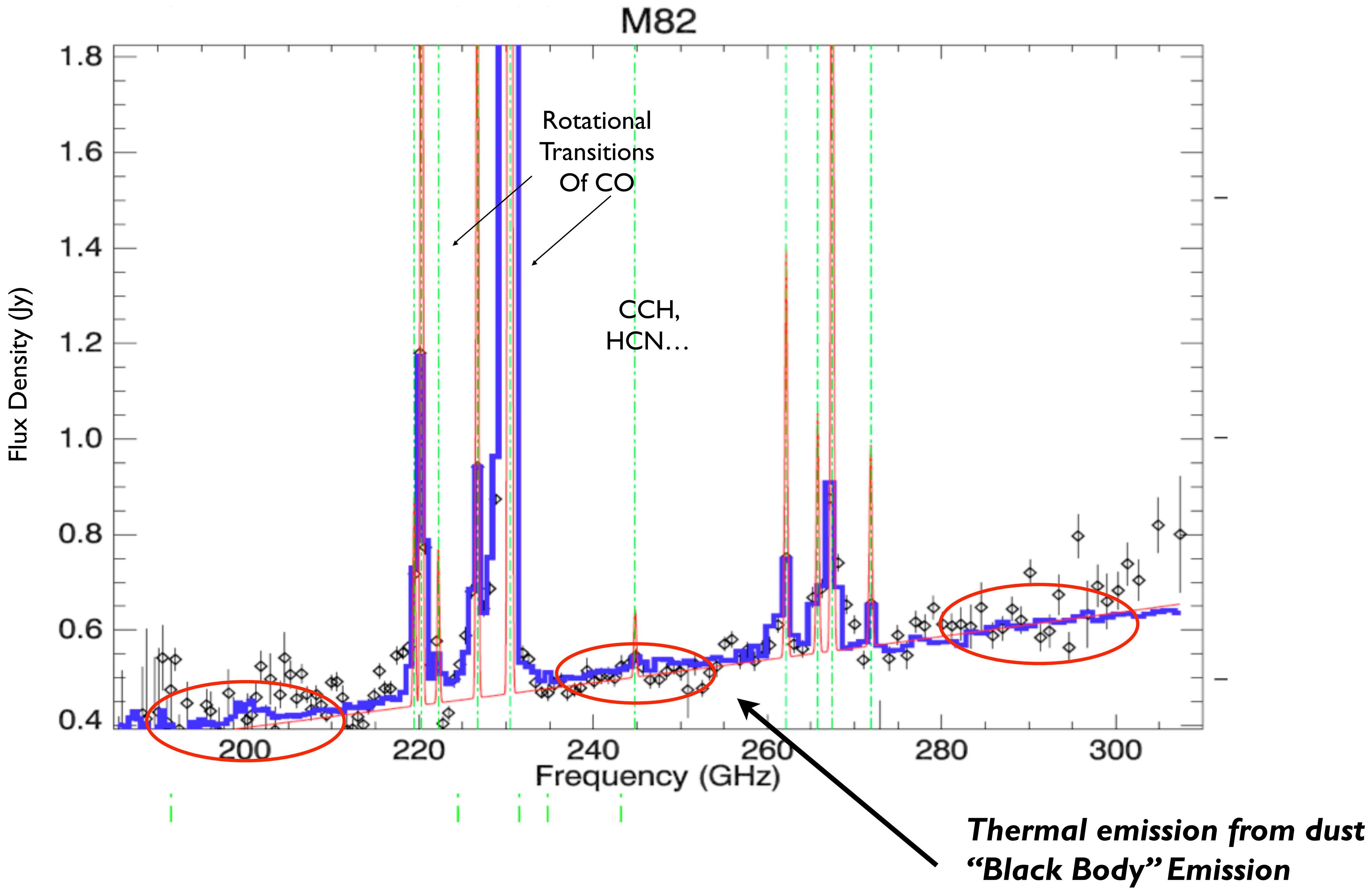

Thermal emission from dust "Black Body" Emission

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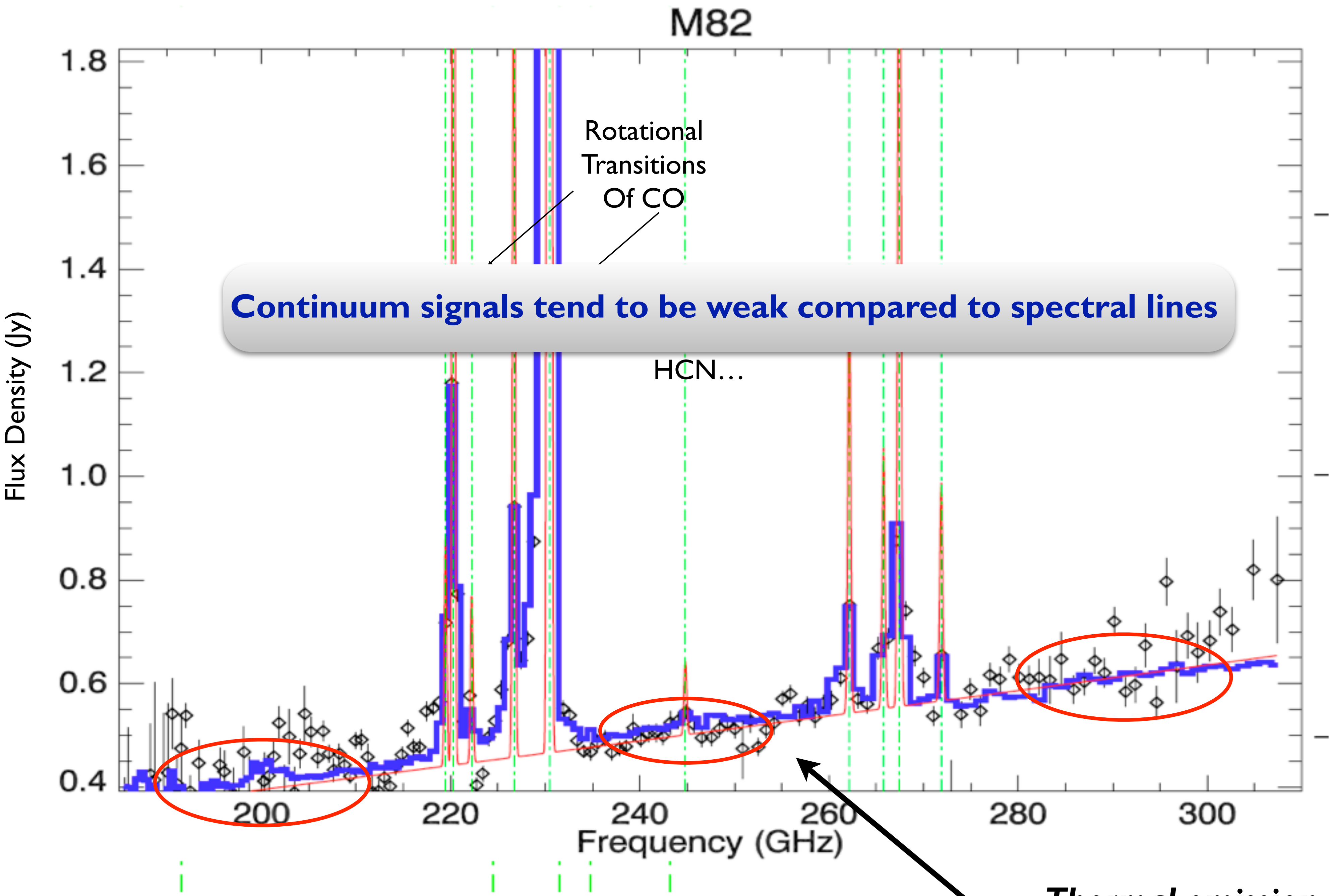


Rotational Transitions Of CO

Continuum signals tend to be weak compared to spectral lines

HCN…

Thermal emission from dust
"Black Body" Emission

ZSPEC (Caltech Submillimeter Observatory)
Naylor et al. (2010)

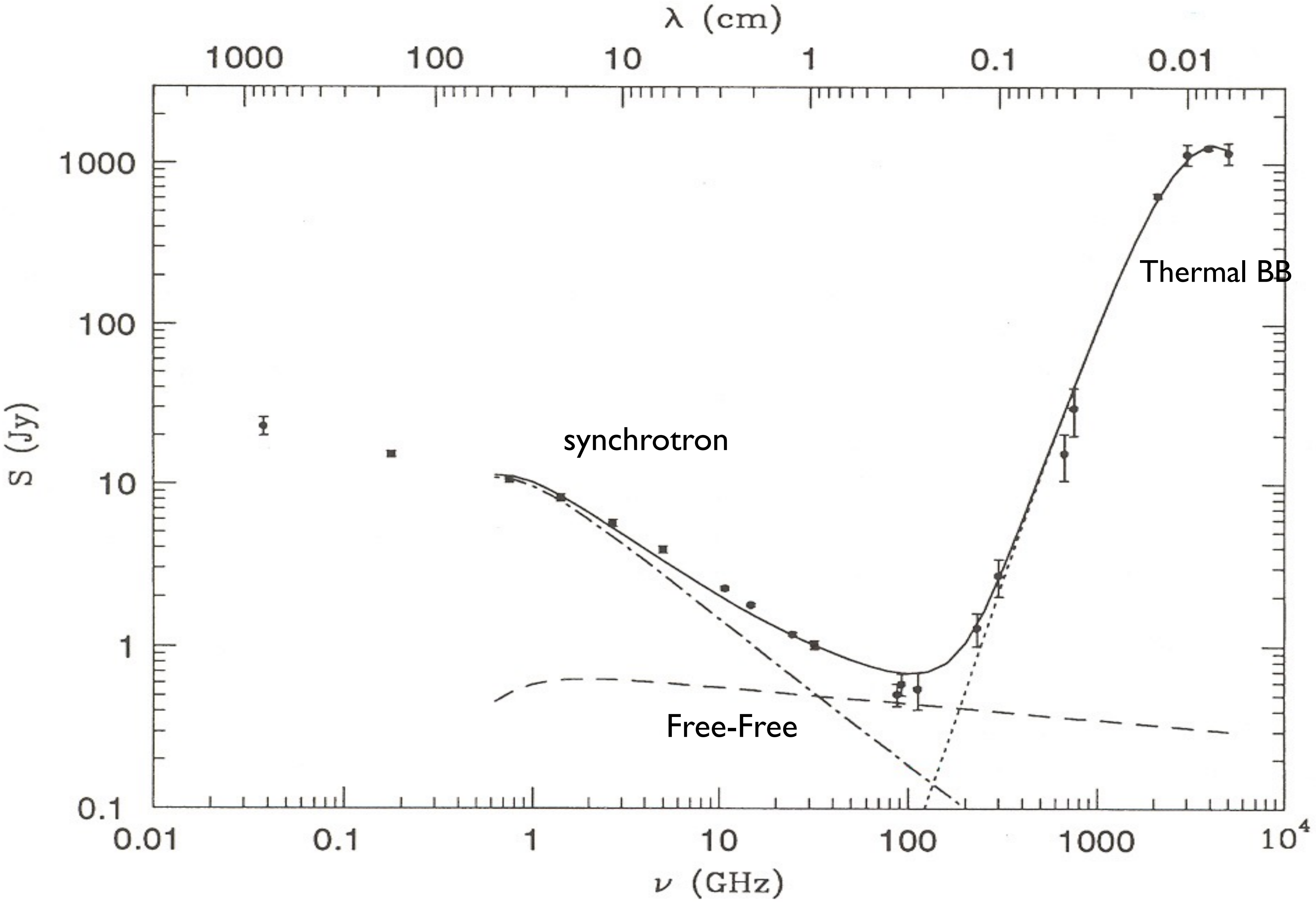
Signal Strength & Noise

But we can make our measurements much more sensitive by measuring the signal over a very broad bandwidth

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

much of this talk will be about overcoming the practical challenges in doing so.

Emission Mechanisms: THE SPECTRUM OF CONTINUUM EMISSION FROM A TYPICAL GALAXY (M82)



Thermal BB

synchrotron

Free-Free

See Condon (1992, ARA&A)

Synchrotron Emission

- Radiation due to the acceleration of relativistic charged particles in a magnetic field

- Observed spectrum is simply related to the energy spectrum of the charged particles (generally declining with frequency)

$$N(E)dE = N_0\, E^{-A} \quad \longleftrightarrow \quad I_\nu(\nu) = I_0 \left(\frac{\nu}{\nu_0}\right)^{-\alpha}$$

$$\alpha = (A-1)/2 \sim 0.7$$

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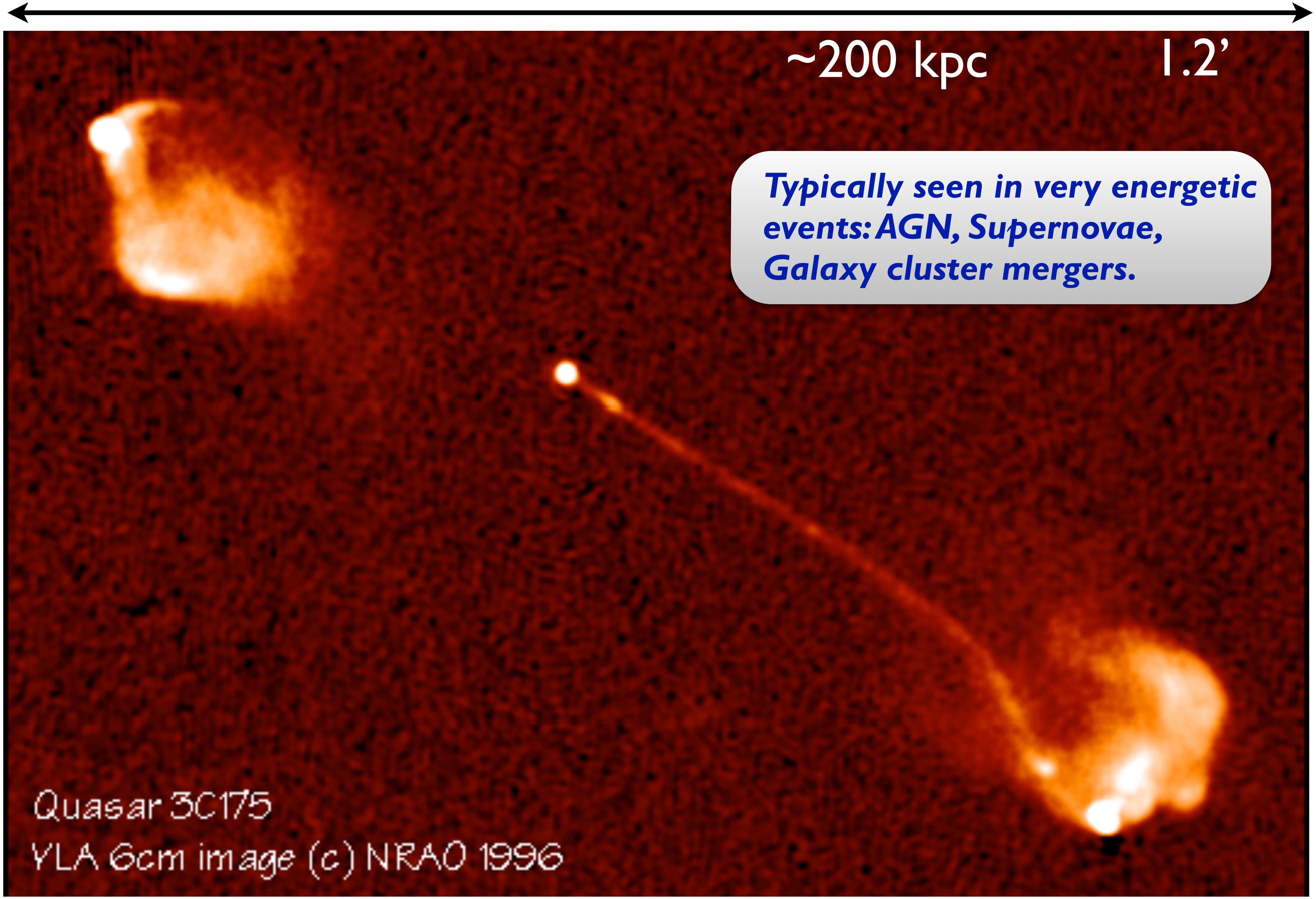
$$N(E)dE = N_0\, E^{-A} \quad \longleftrightarrow \quad I_\nu(\nu) = I_0 \left(\frac{\nu}{\nu_0}\right)^{-\alpha}$$

- More energetic particles lose their energy more rapidly resulting in the spectrum to *become steeper with time*

$$\frac{dE}{dt} \propto -B^2 E^2$$

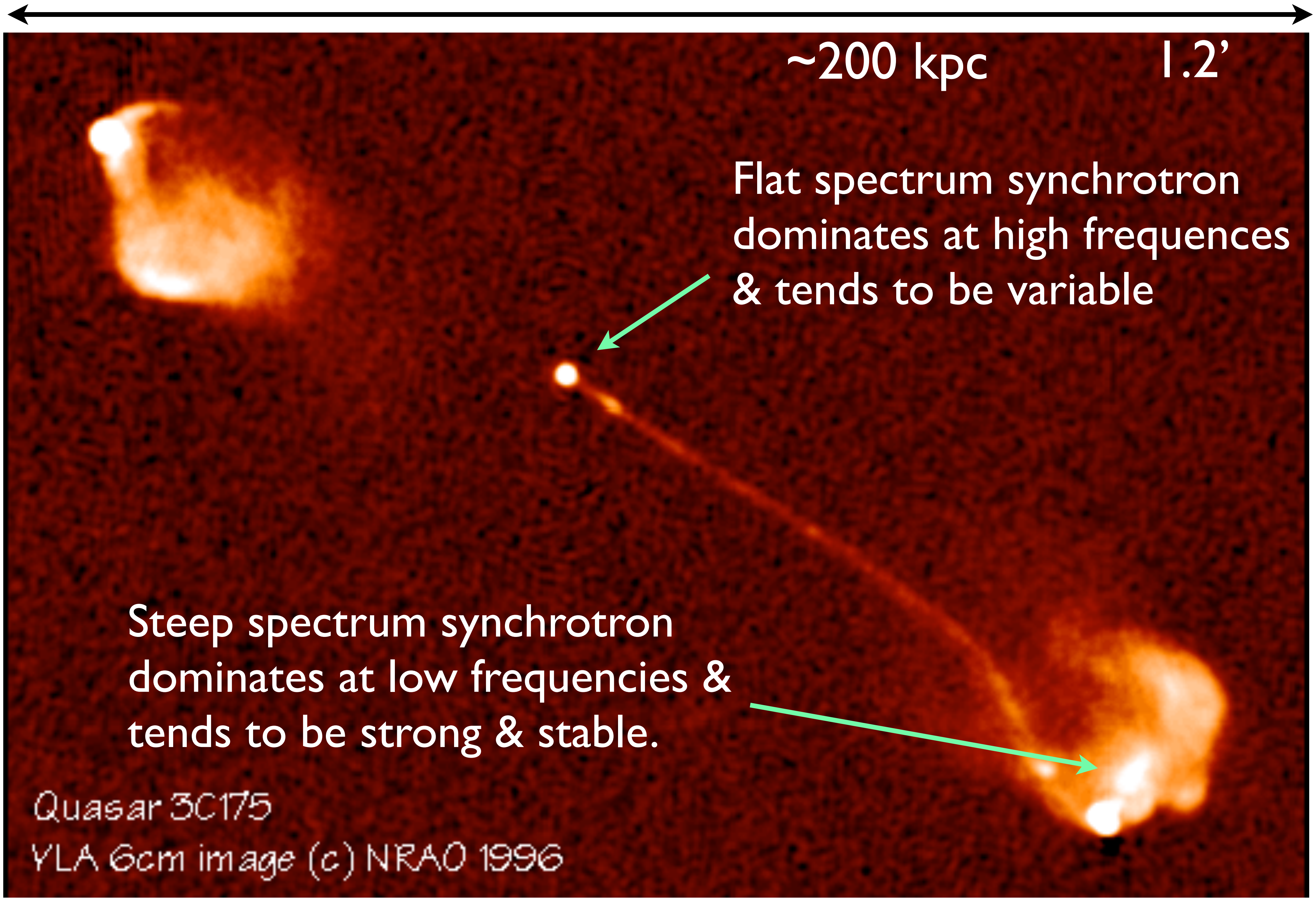
  - *To maintain a shallow spectrum synchrotron spectrum requires a constant supply of "fresh", high-energy particles.*

Synchrotron Emission: Astrophysical Context



Typically seen in very energetic events: AGN, Supernovae, Galaxy cluster mergers.

Synchrotron Emission: Astrophysical Context



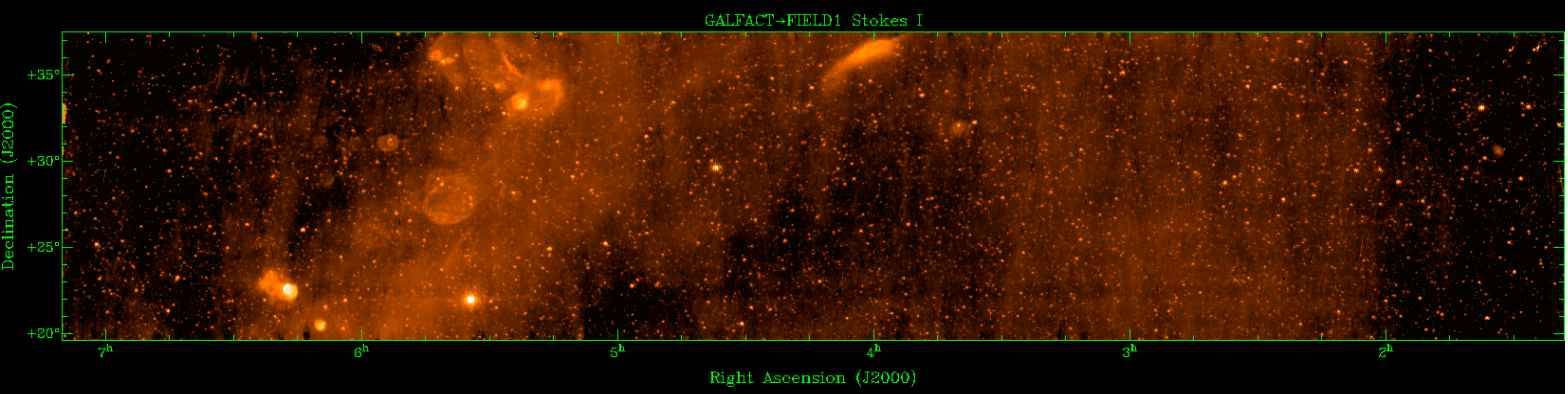
Flat spectrum synchrotron dominates at high frequences & tends to be variable

Steep spectrum synchrotron dominates at low frequencies & tends to be strong & stable.

Quasar 3C175
VLA 6cm image (c) NRAO 1996

Synchrotron Polarization

- ***Synchrotron radiation is inherently linearly polarized***
  - bears imprint magnetic fields *in situ*, as well as along L.O.S. (Faraday Rotation)
- ***GALFACTS***: Full-Stokes, all-Arecibo-sky, continuum survey; 300 MHz bandwidth
  - Science:
    - Uncover new, low-surface brightness supernova remnants & HII regions
    - Measure the properties & effects of the Galactic magnetic field in a wide range of environments
    - Thermal-nonthermal separation of low-*b* Galactic continuum emission.
    - Foreground removal for *Planck* (CMB intensity & Polarization).



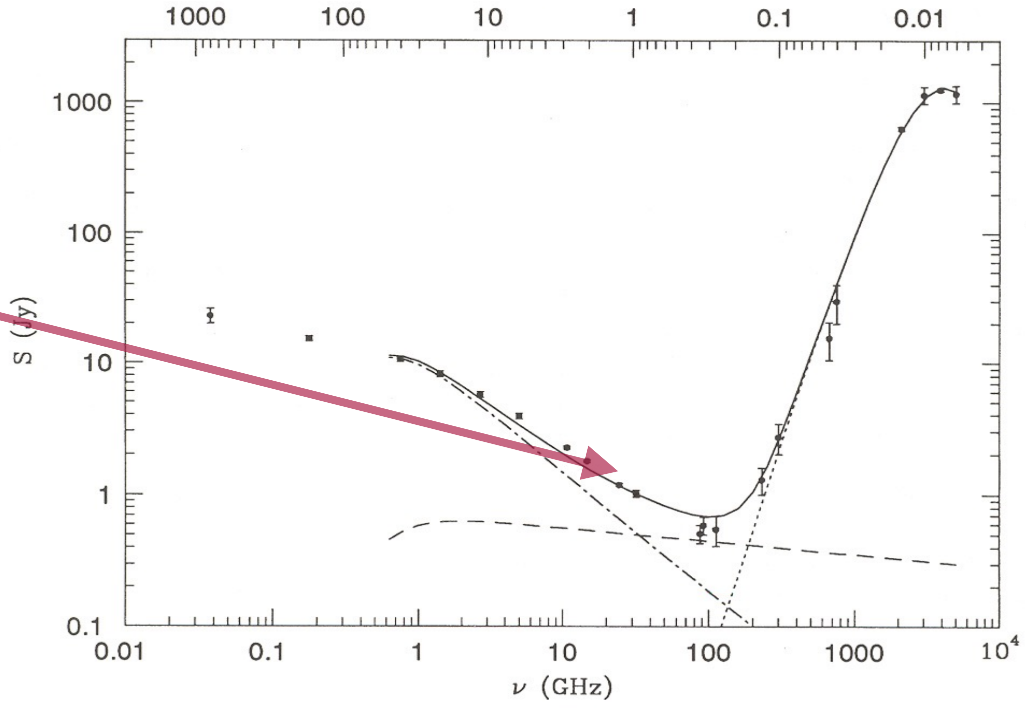
Free-Free Emission

- Bremmstrahlung radiation of thermal, ionized electrons "richocheting" off of ions

$$\epsilon^{ff} \sim n_e n_i \sqrt{T}$$

- At cm wavelengths, generally approximately flat spectrum (optically thin)

$$I_\nu \propto \nu^{-0.2}$$



Typically seen in moderately energetic environments (e.g., HII regions around massive stars, stellar and protostellar winds)

Thermal (“Black Body”) Emission

$$I_\nu(T,\nu) = \frac{2k_B T}{\lambda^2}\frac{x}{e^x - 1} \qquad x = \frac{h\nu}{kT}$$

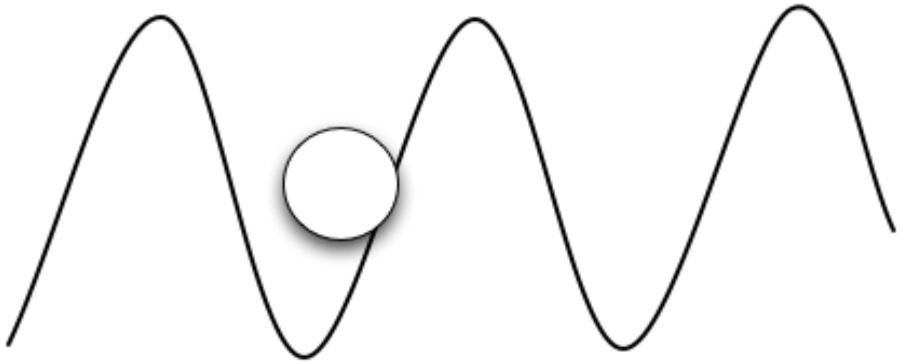
$$\text{Dusty Galaxy}: T \sim 30\,\text{K} \rightarrow \lambda_{peak} = 170\,\mu\text{m} \;\; (x << 1)$$

$$\text{CMB}: T = 2.725\,\text{K} \rightarrow \lambda_{peak} = 1.9\,\text{mm}$$

A means to study thermal material (mass, temperature, particle sizes). Does not require the matter to be ionized / charged. Pervasive but often difficult to detect at cm wavelengths.

"Grey Body" Emission

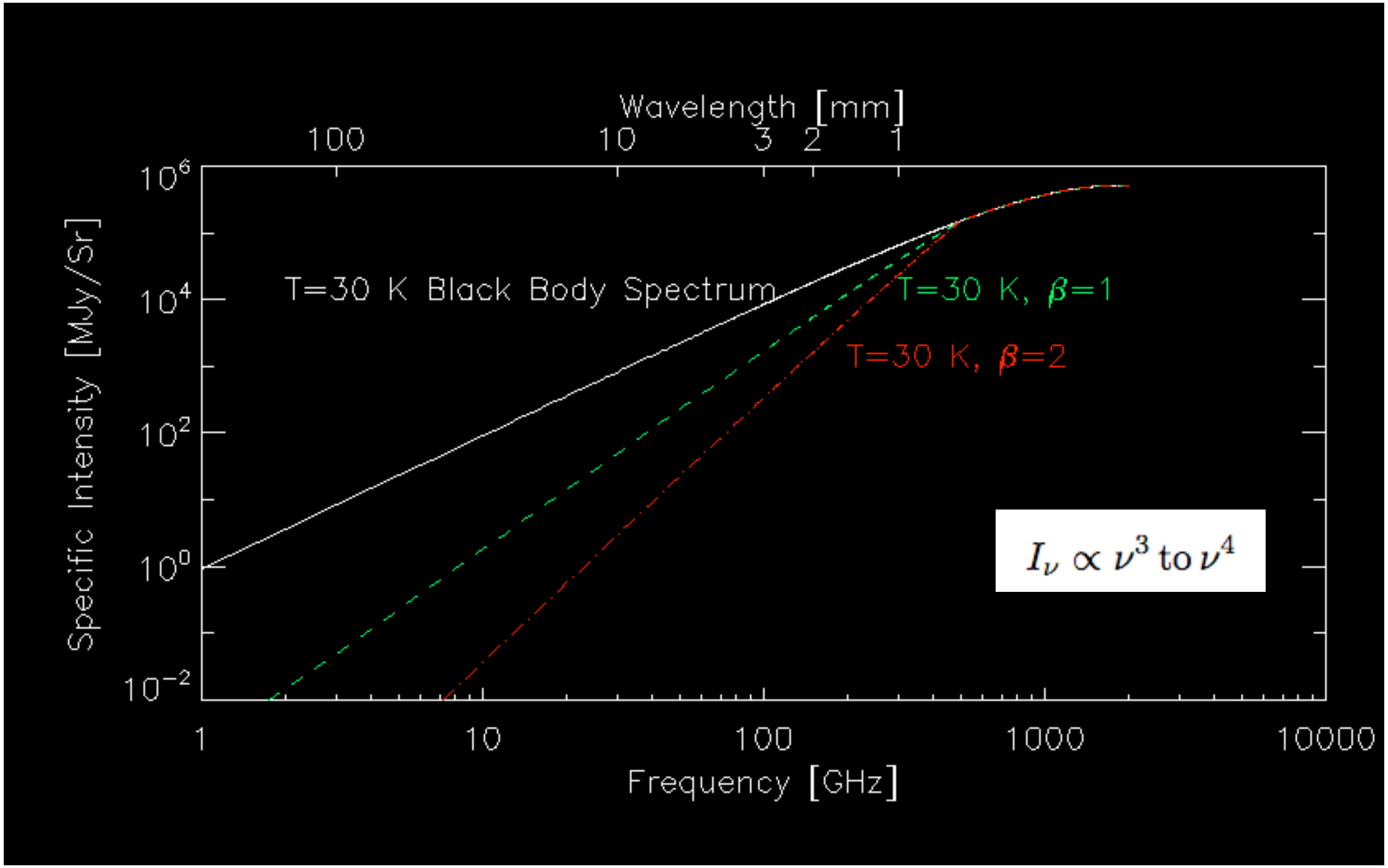
In the cm & mm, "black bodies" are often not efficient radiators



$$
\begin{aligned}
I_\nu &= I_{\nu,BB} \times \epsilon_{rad} \\
&\approx I_{\nu,BB} \qquad (\lambda < \lambda_o) \\
&\approx I_{\nu,BB} \times \left(\frac{\lambda_o}{\lambda}\right)^\beta \quad (\lambda > \lambda_o)
\end{aligned}
$$

where typically $0.5 < \beta < 2$

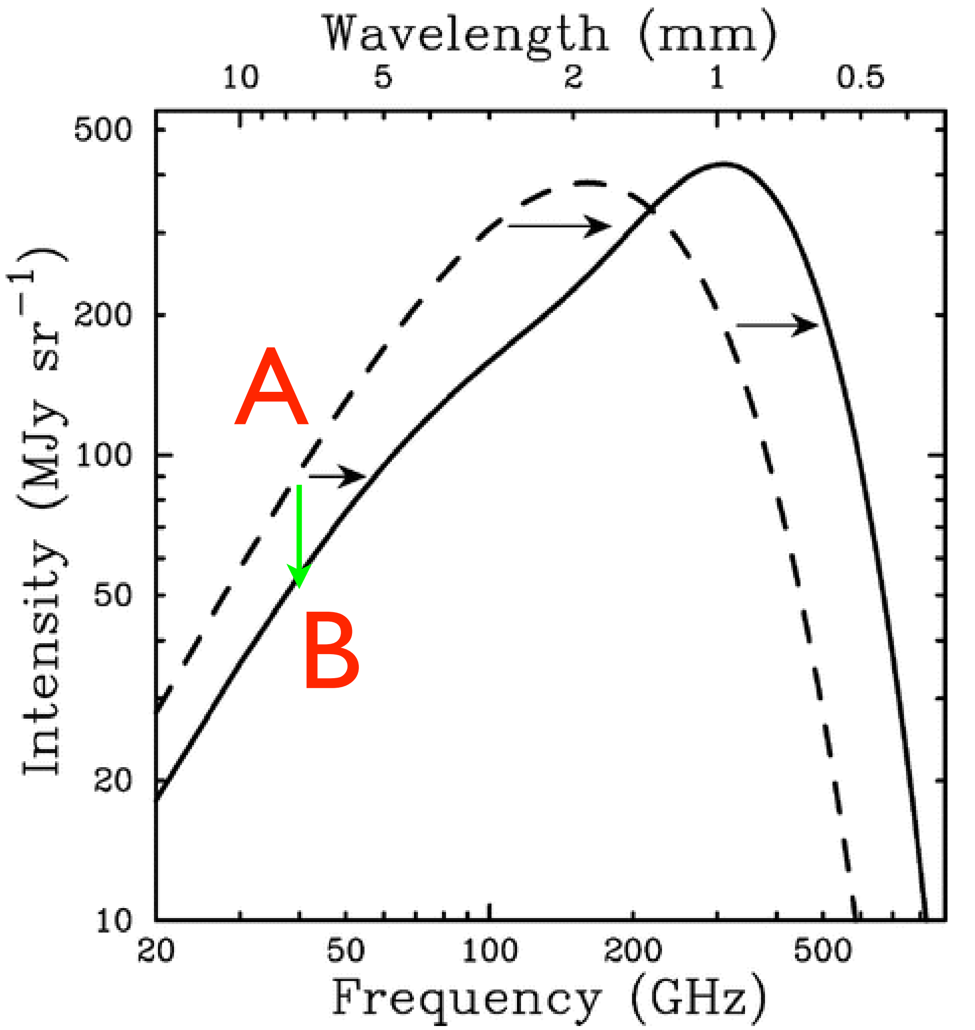
“Grey Body” Emission



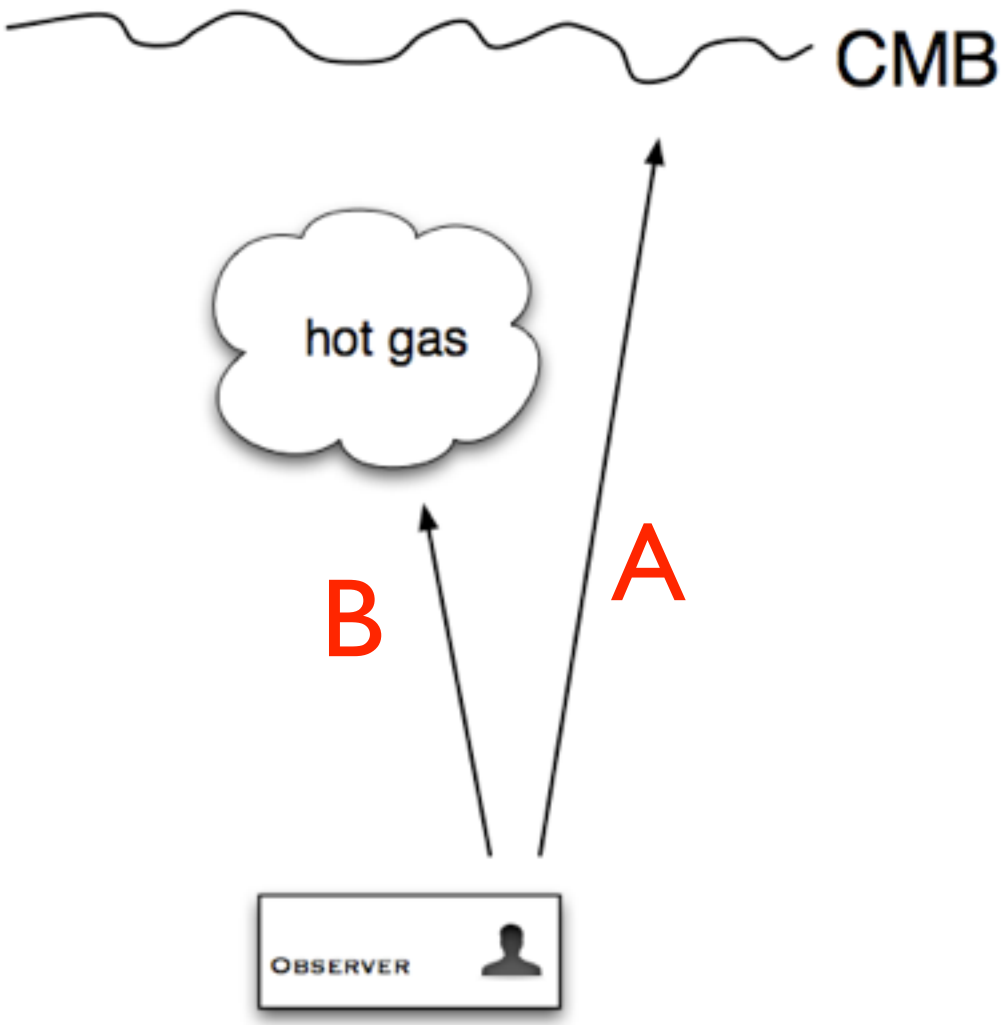
$I_\nu \propto \nu^3$ to ν^4

Sunyaev-Zel'dovich Effect

A spectral distortion in the CMB caused by scattering off of hot electrons



Carlstrom, Holder & Riess (2002)



At the (radio) frequencies most sensitive to the SZE from the ground, it appears as a decrement, i.e., a shadow

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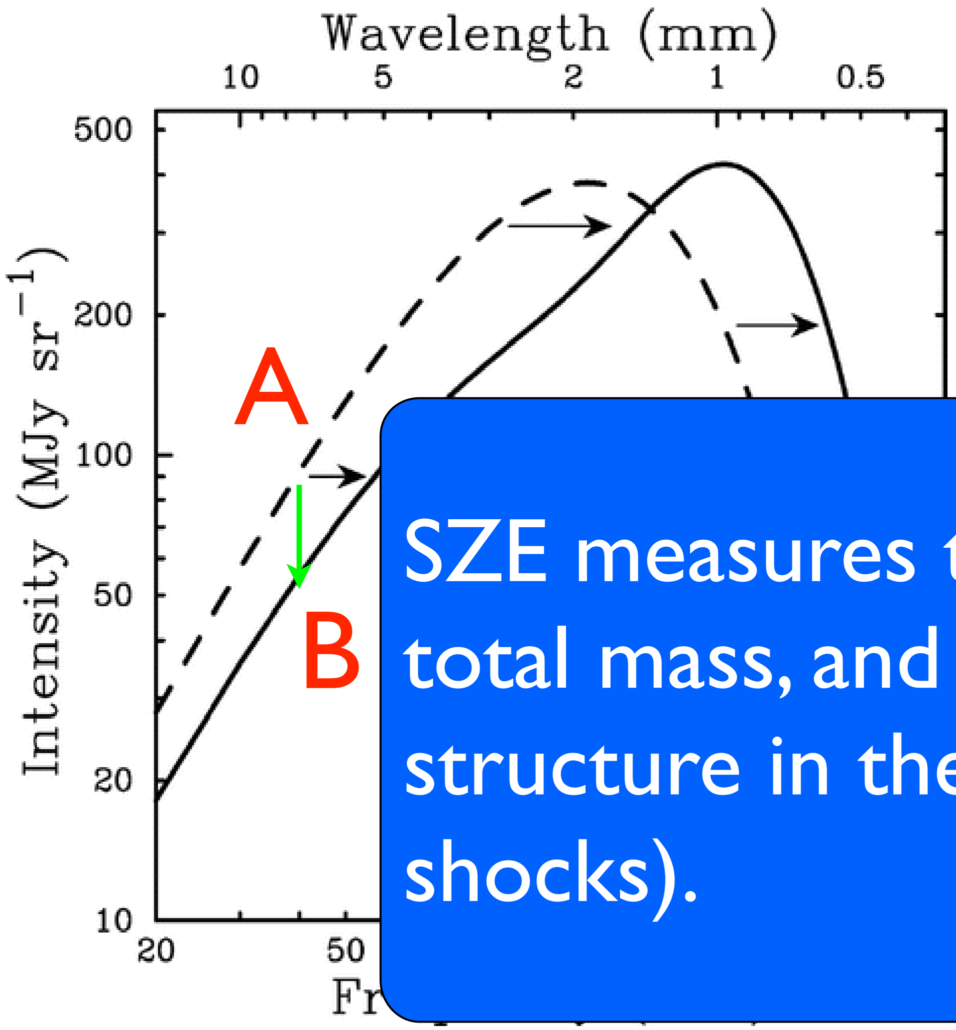
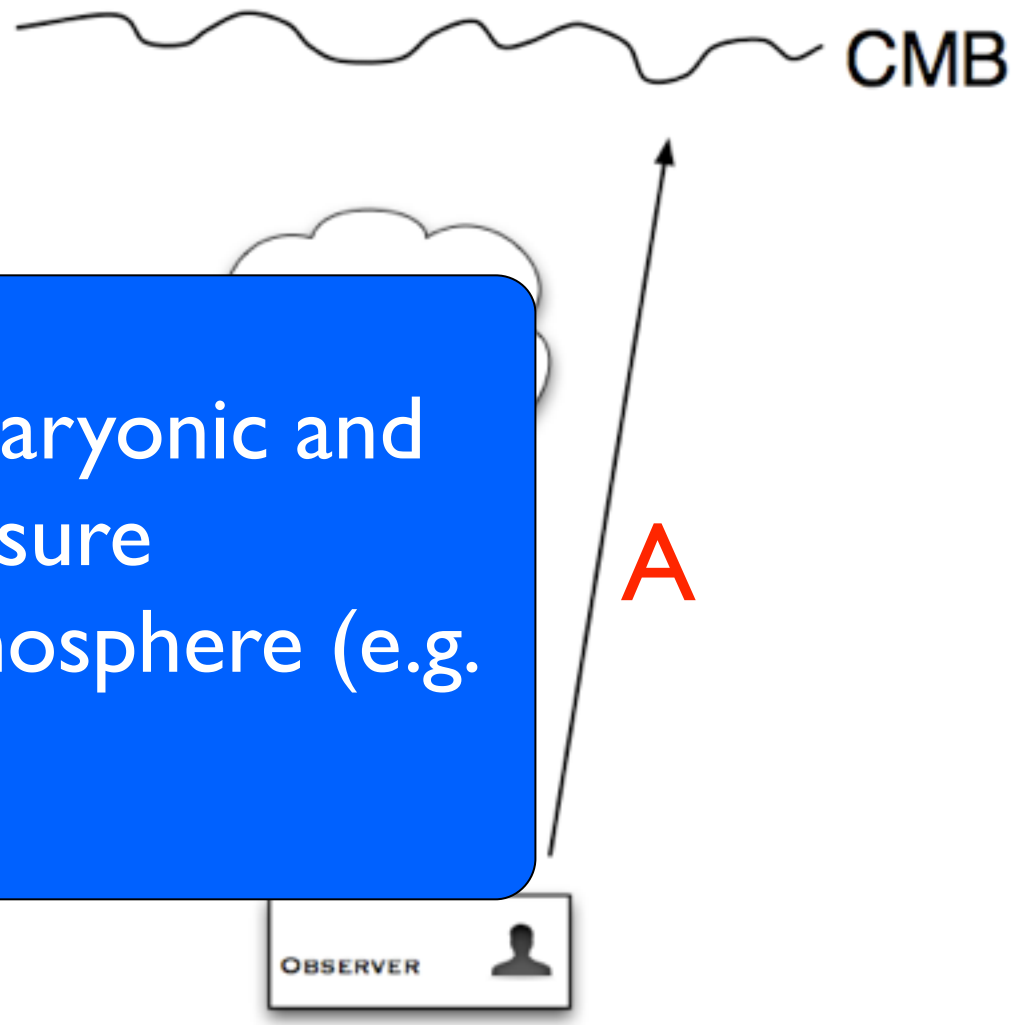


Carlstrom, Holder & Riess (2002)

SZE measures the cluster baryonic and total mass, and probes pressure structure in the cluster atmosphere (e.g. shocks).



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MUSTANG-1 SZE Rogue's Gallery

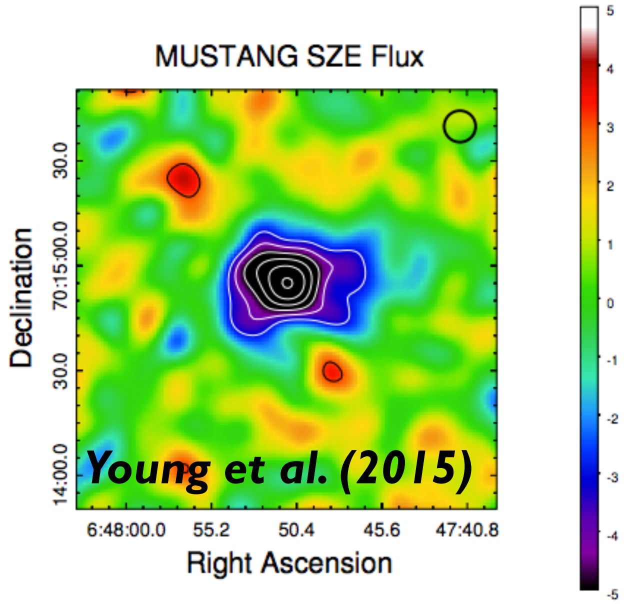
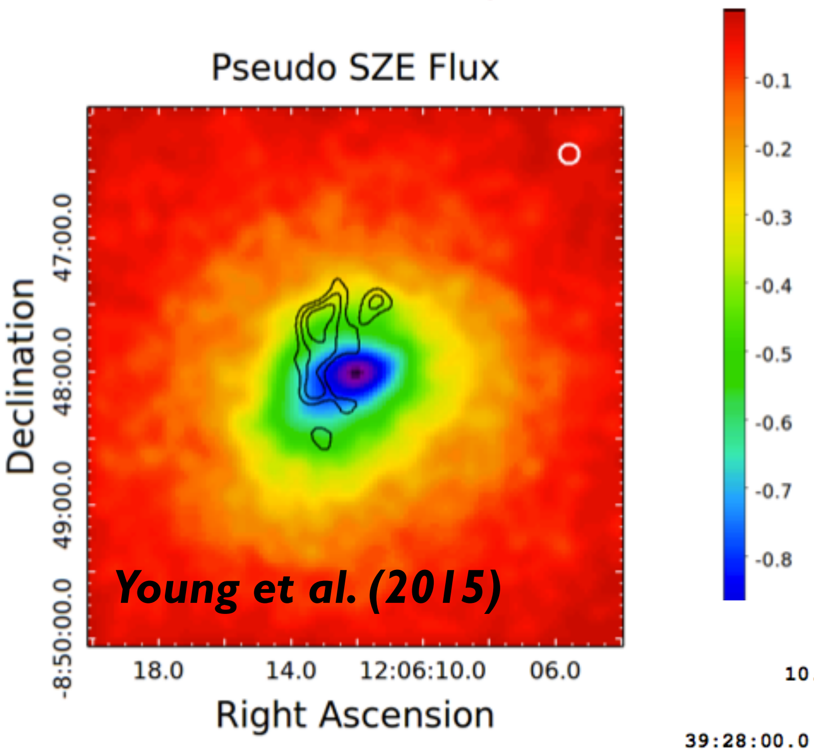
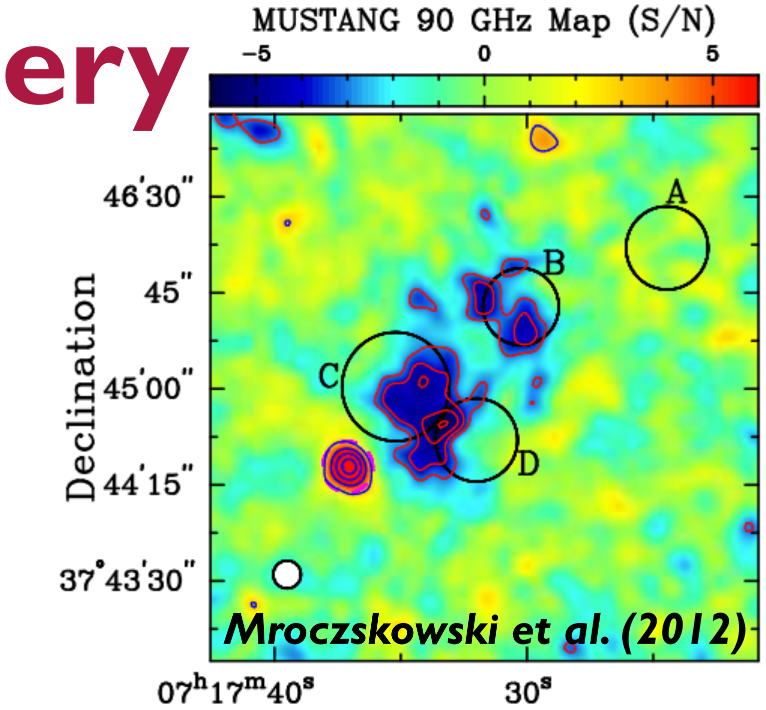
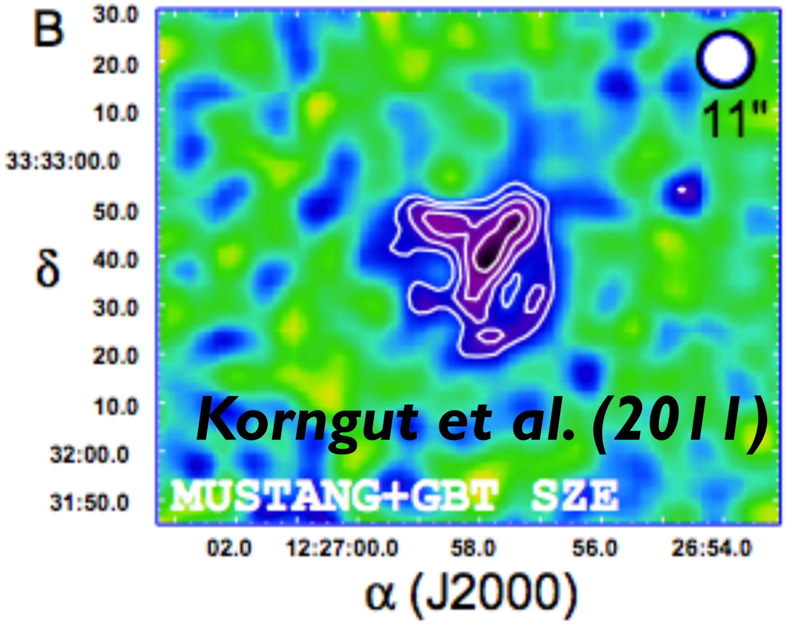
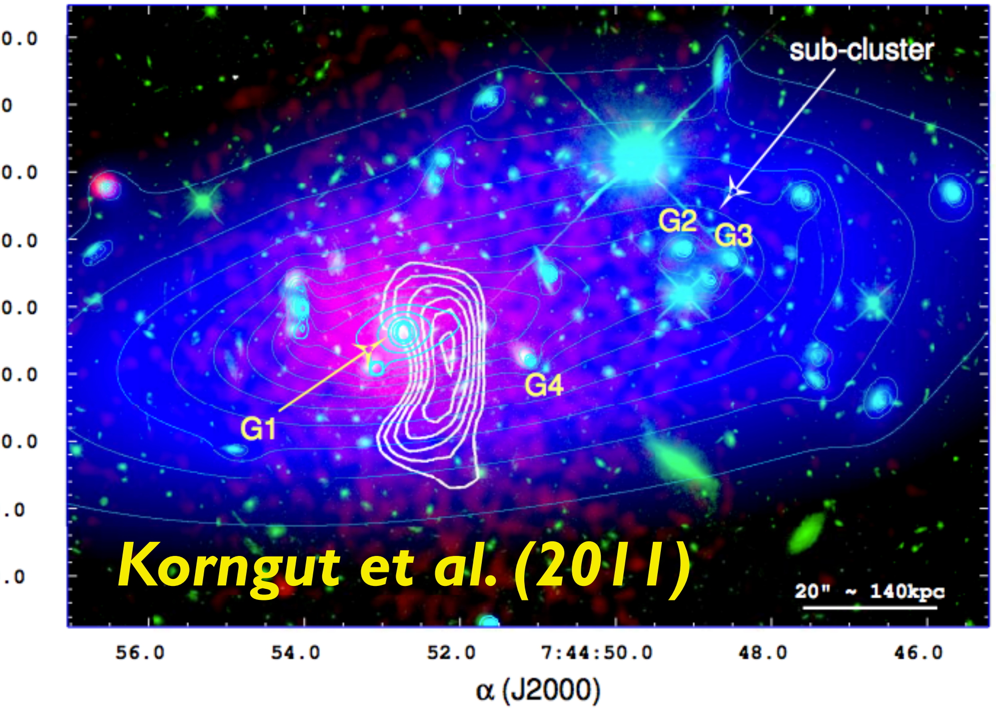


Figure 4. MUSTANG SZE S/N map of MACS J0647.7+7015 smoothed with the 9″ beam represented by the black circle in the upper right. Contours are shown in increments of 1-σ beginning at 3-σ for SZE decrement (white) and positive flux (black).









Comprehensive analysis of 14 clusters in C.Romero (in prep)

MUSTANG-1 SZE Rogue's Gallery

MUSTANG-2

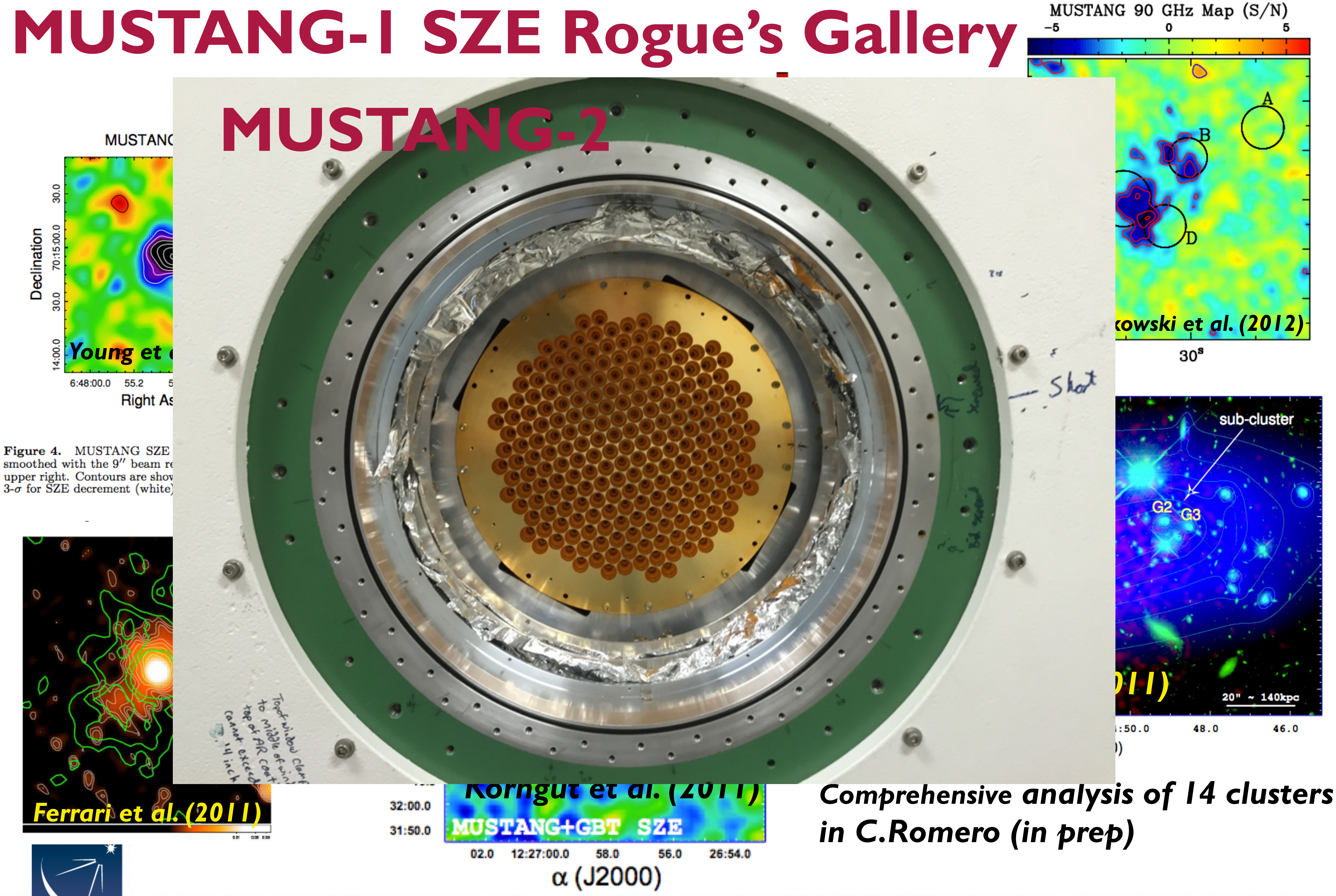


Figure 4. MUSTANG SZE
smoothed with the 9″ beam re
upper right. Contours are show
3-σ for SZE decrement (white)

Comprehensive analysis of 14 clusters in C.Romero (in prep)

Challenges

"Lacking the rapid time variability of pulsars and ... narrow spectral signatures ... astronomical **continuum sources are distinguishable from receiver baseline drifts, atmospheric emission fluctuations, ground radiation, and each other only by their positions on the sky**. These competing "signals" often exceed radiometer noise .... In addition, telescope gain uncertainties and pointing errors affect even strong sources. The continuum observer must understand both these **noiselike** and **intensity-proportional** errors to obtain the best possible data and to make reliable error estimates for measured source parameters."

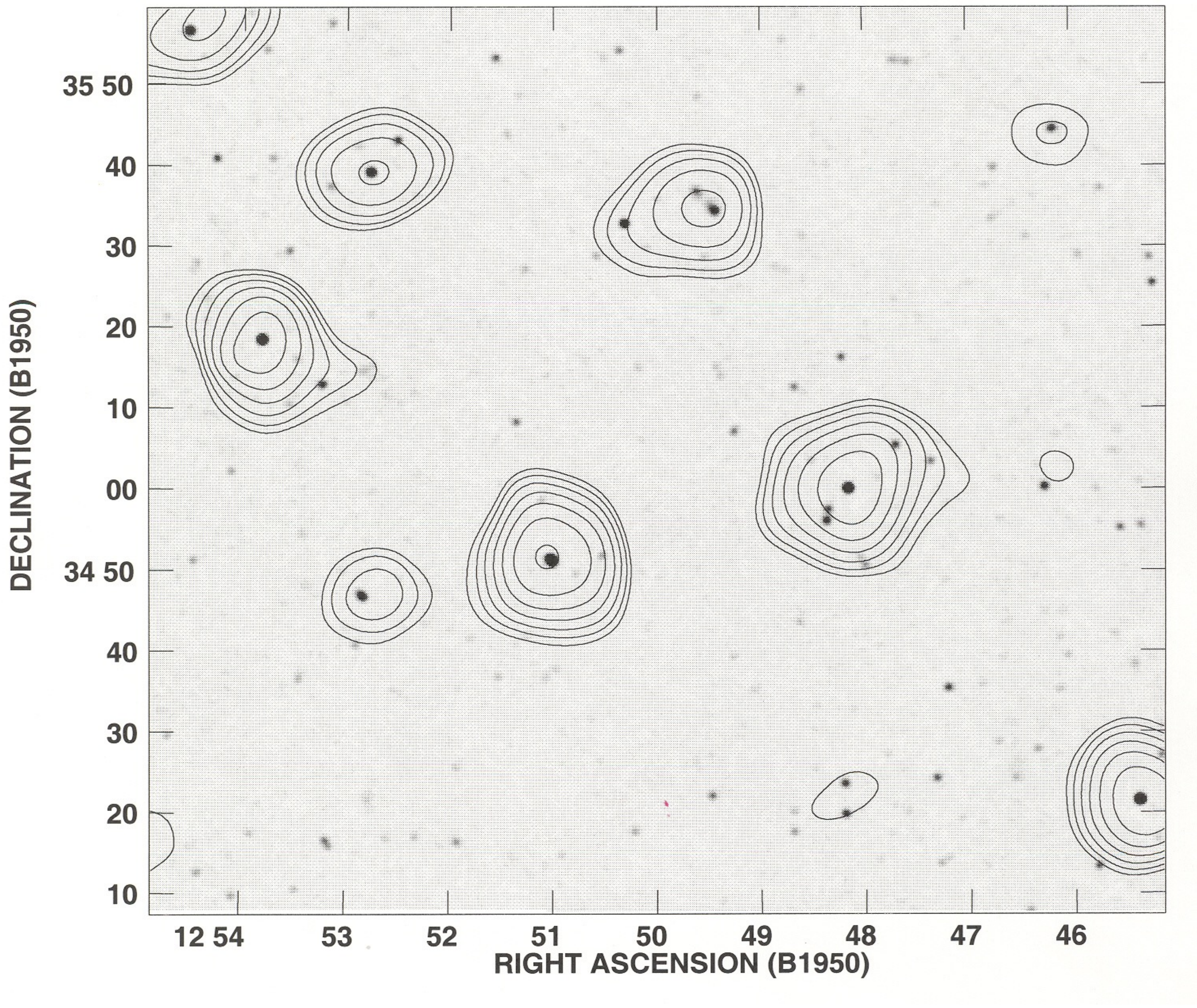
-J.Condon, Single Dish School Procedings

1. Pointing
2. Confusion
3. Gain & Atmosphere fluctuations
4. Receiver Architecture

Issue #1: Telescope Pointing

- Residual, time-varying pointing errors can introduce artifacts in your map near bright sources.
- Repeatable pointing errors are typically accounted for in the telescope pointing model
- Non-repeatable pointing errors
  - thermal: timescale ~1 hour (night vs day).
- Solution: Monitor a pointing calibrator

Issue #2: The Effect of Extragalactic Sources (Radio)



GB6 300' (12 arcmin FWHM) contours

NVSS (45 arcsec FWHM) grayscale

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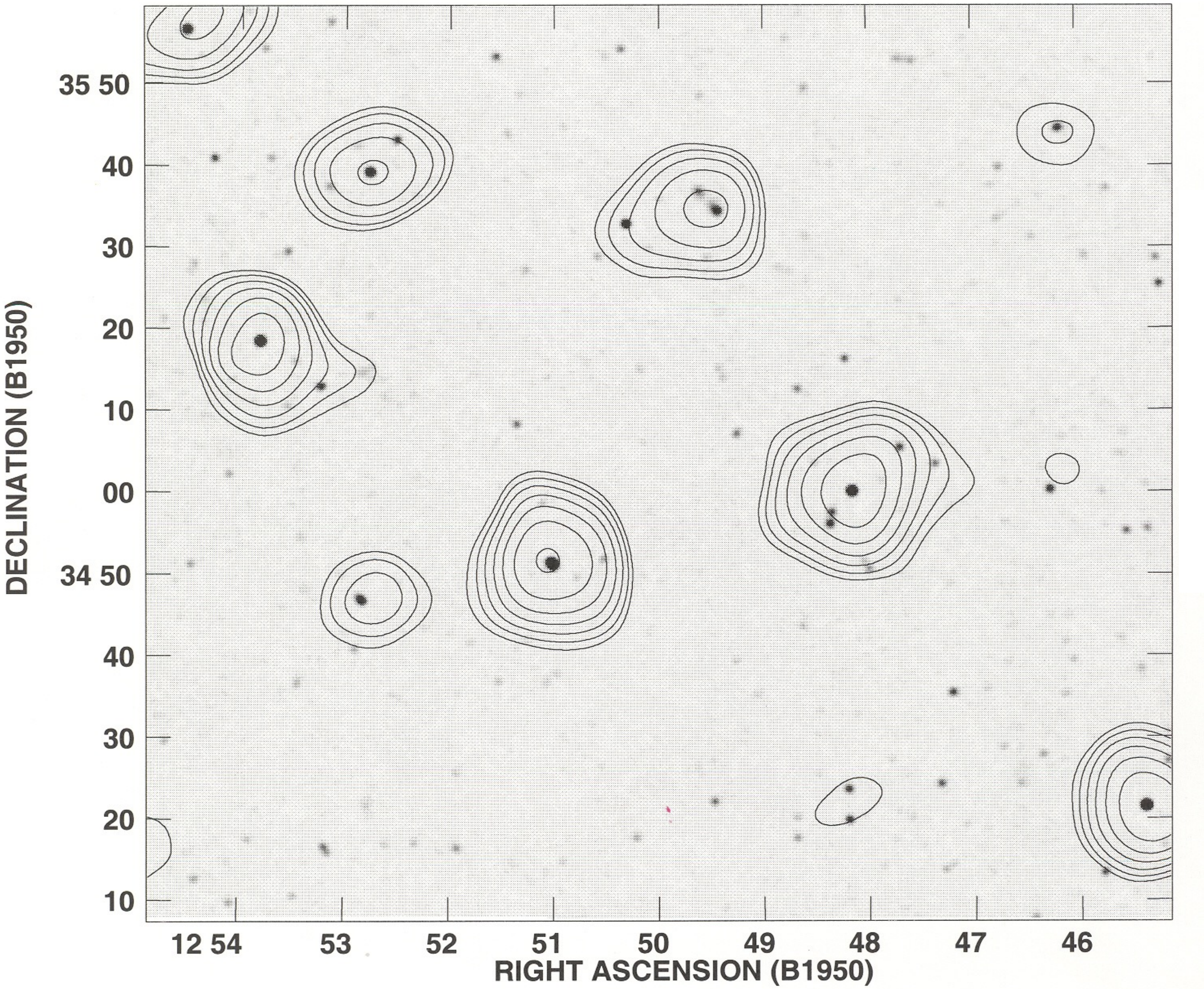
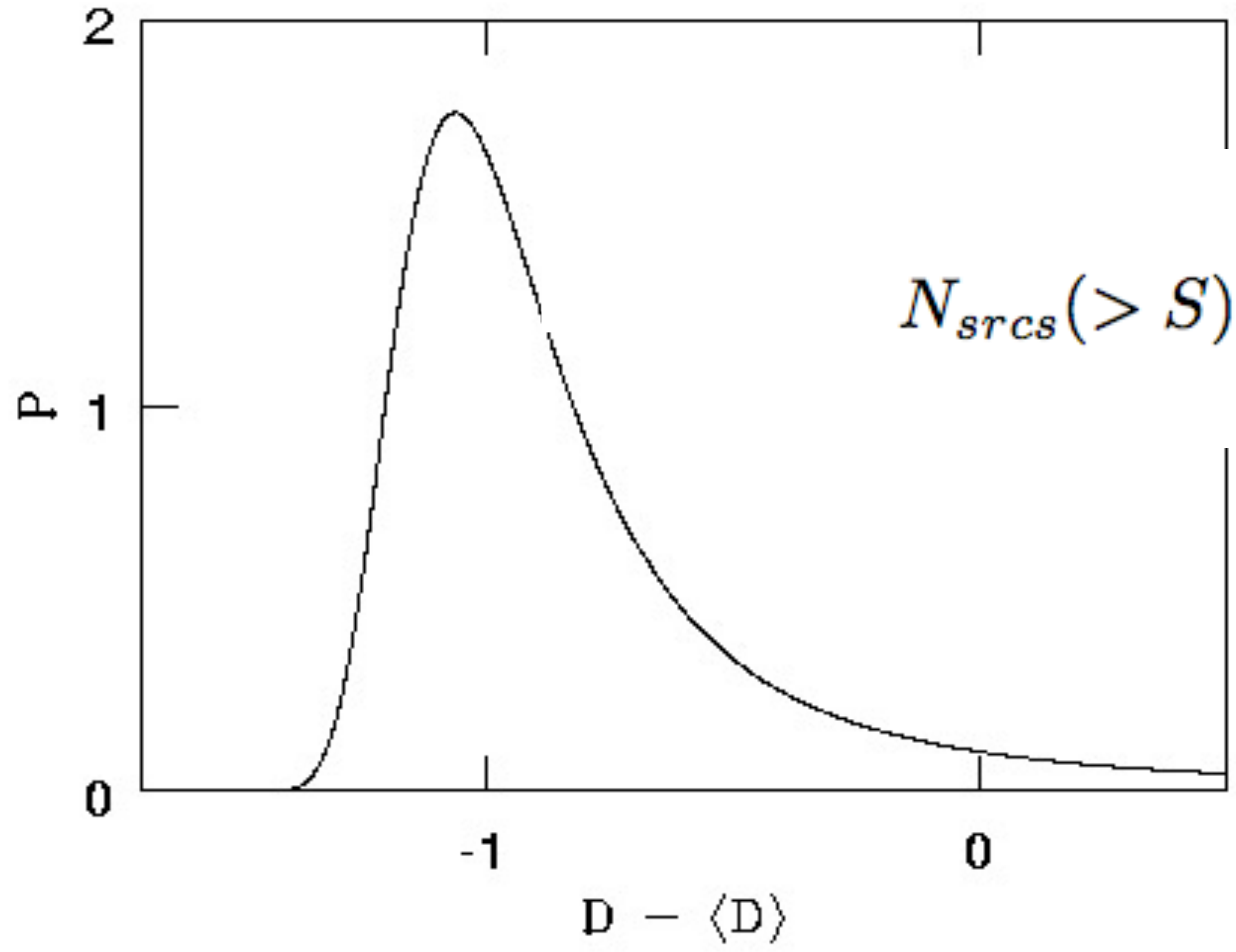


$$\frac{\sigma_{conf}}{\mathrm{mJy/bm}} \sim S_\nu \, \Omega_{bm}$$

$$\sim \nu^{-0.7} \frac{1}{\nu^2}$$

$$\sim \nu^{-2.7}$$

Distribution of Unresolved Source Residuals

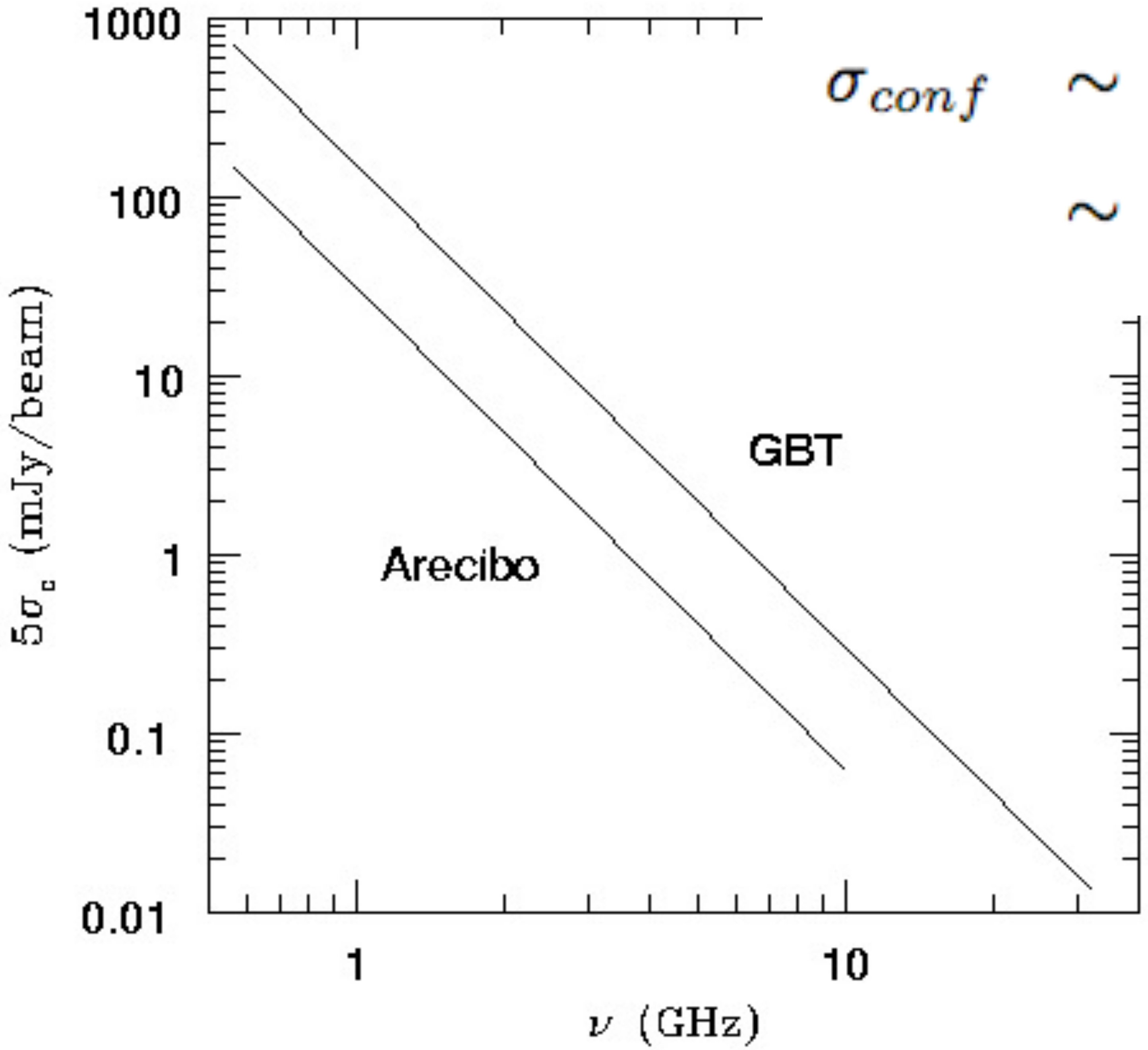


$$N_{srcs}(>S) = N_o \left(\frac{S}{S_o}\right)^{-0.7}$$

Condon (1974); Scheuer (1956)

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

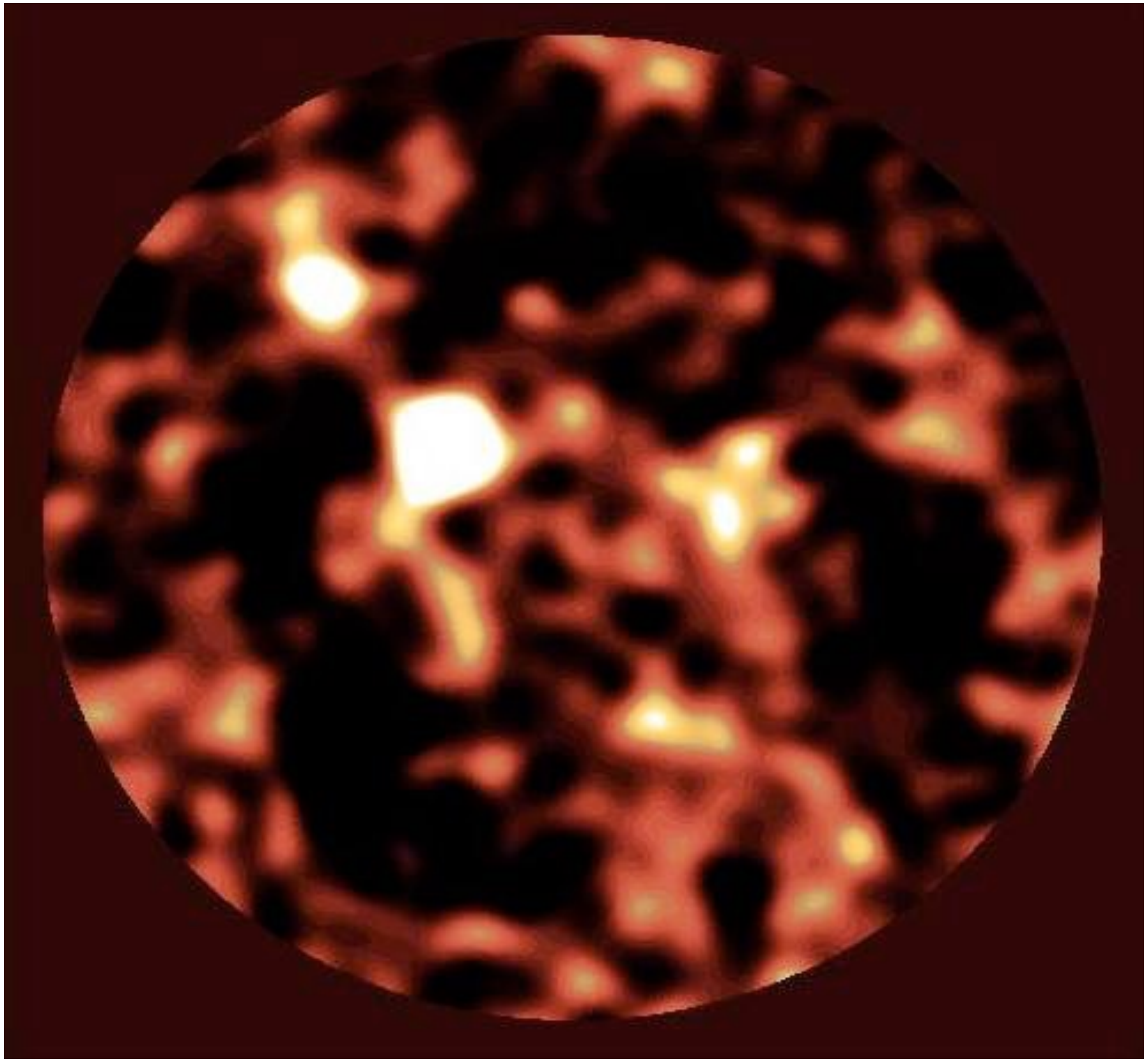
5σ extragalactic confusion limits for Arecibo (d = 220 m) and the GBT (d = 100 m).



$$\sigma_{conf} \sim 50\,\mathrm{mJy}\left(\frac{\nu}{\mathrm{GHz}}\right)^{-2.7}$$
$$\sim 0.1\,\mathrm{mJy}\,(@10\,\mathrm{GHz})$$

This noise won't go down if you integrate for longer!

The Effect of Extragalactic Sources (mm/submm)



Hubble Deep Field-- Hughes et al. (1998)

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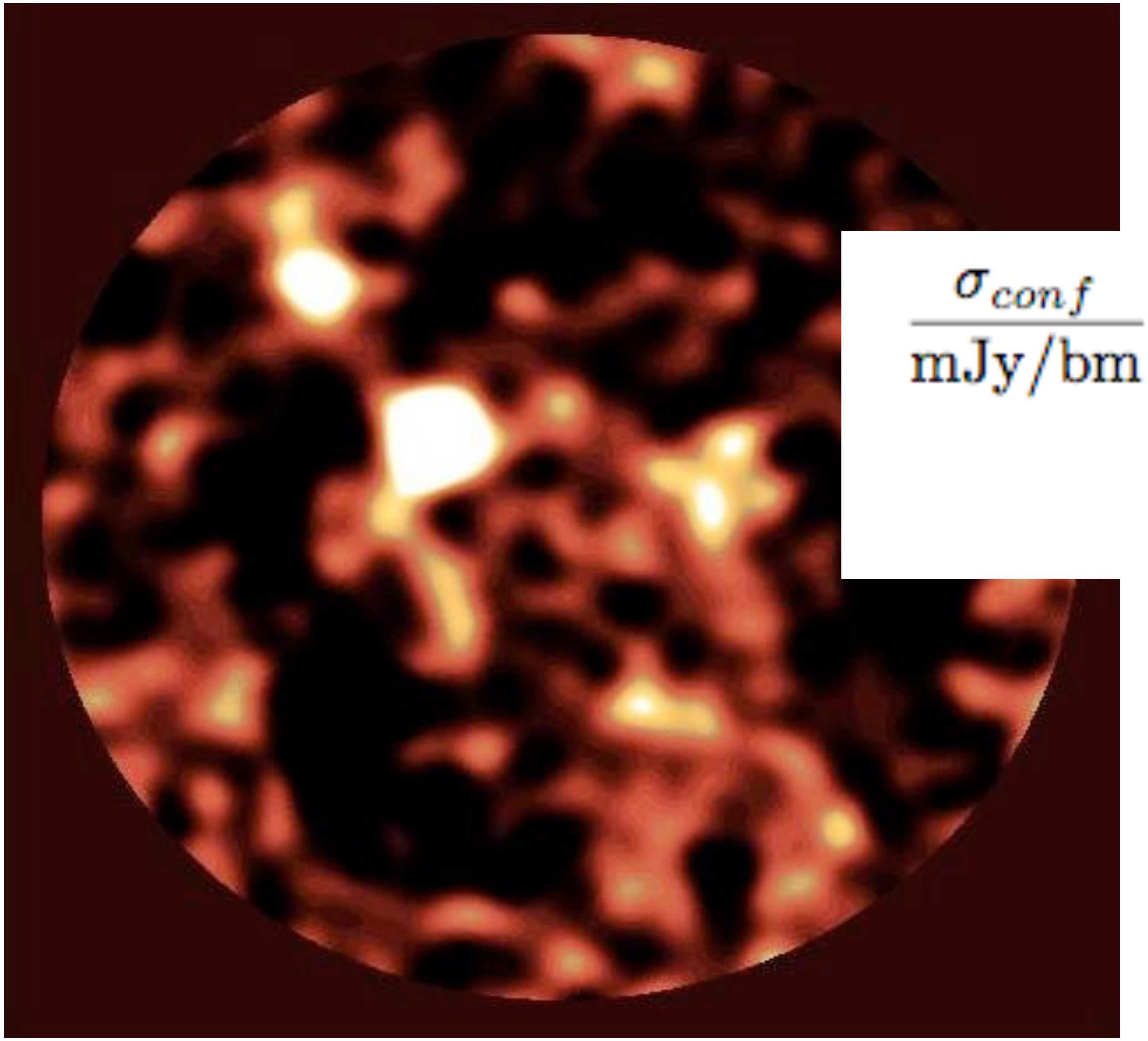


$$\frac{\sigma_{conf}}{\mathrm{mJy/bm}} \sim S_\nu\,\Omega_{bm} \sim \nu^3\,\frac{1}{\nu^2}$$

see also Blain et al. 2002

Hubble Deep Field-- Hughes et al. (1998)

Solutions:

1) be aware and plan accordingly

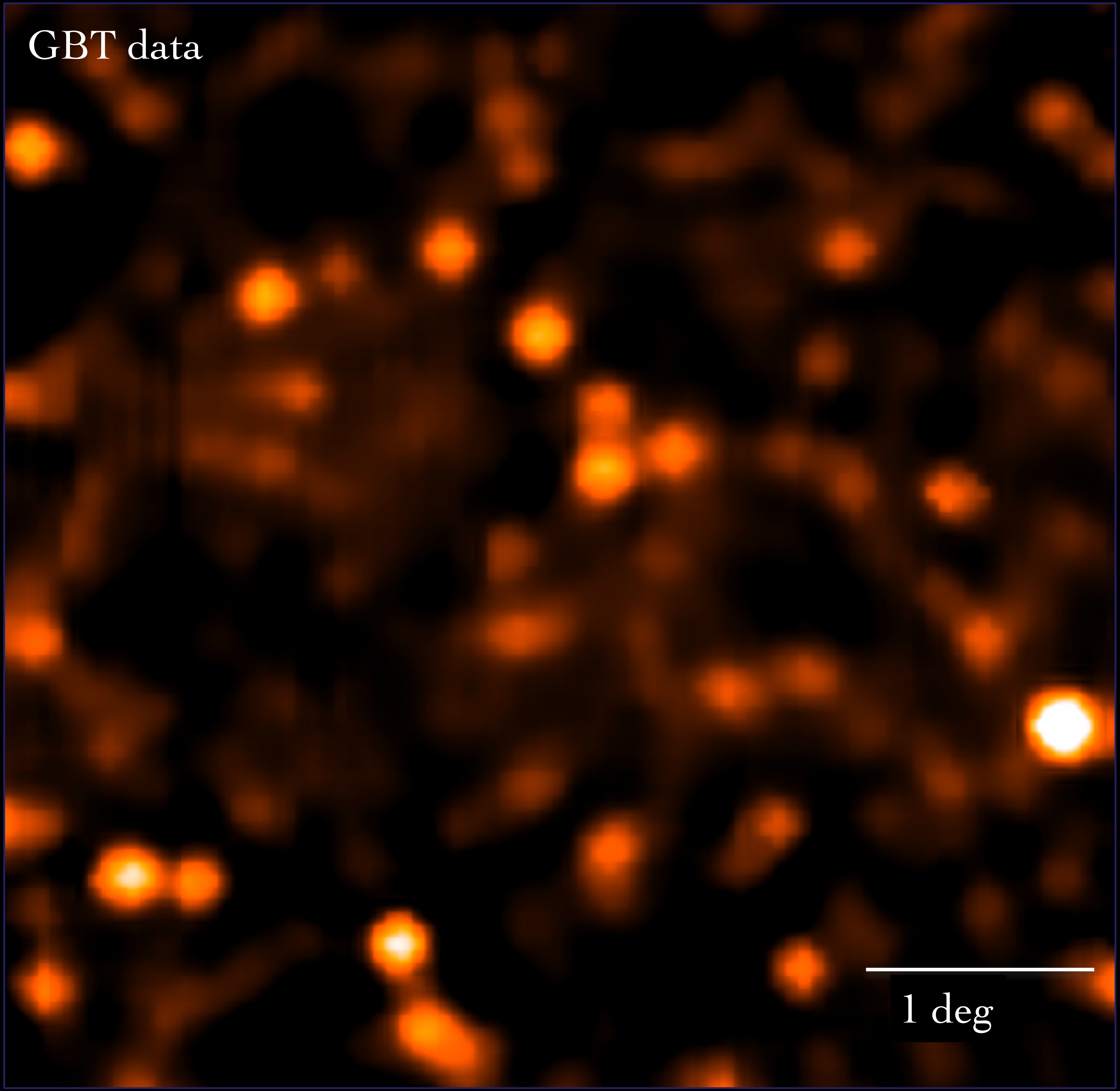
2) there are sometimes pre-existing large area surveys which can be used to identify sources and reduce confusion

NRAO VLA Sky Survey (NVSS): 1.4 GHz

GB6: old 300'+7-beam receiver, 5 GHz

AT20G: southern-sky, 20 GHz

Deep radio map of Draco dSphs



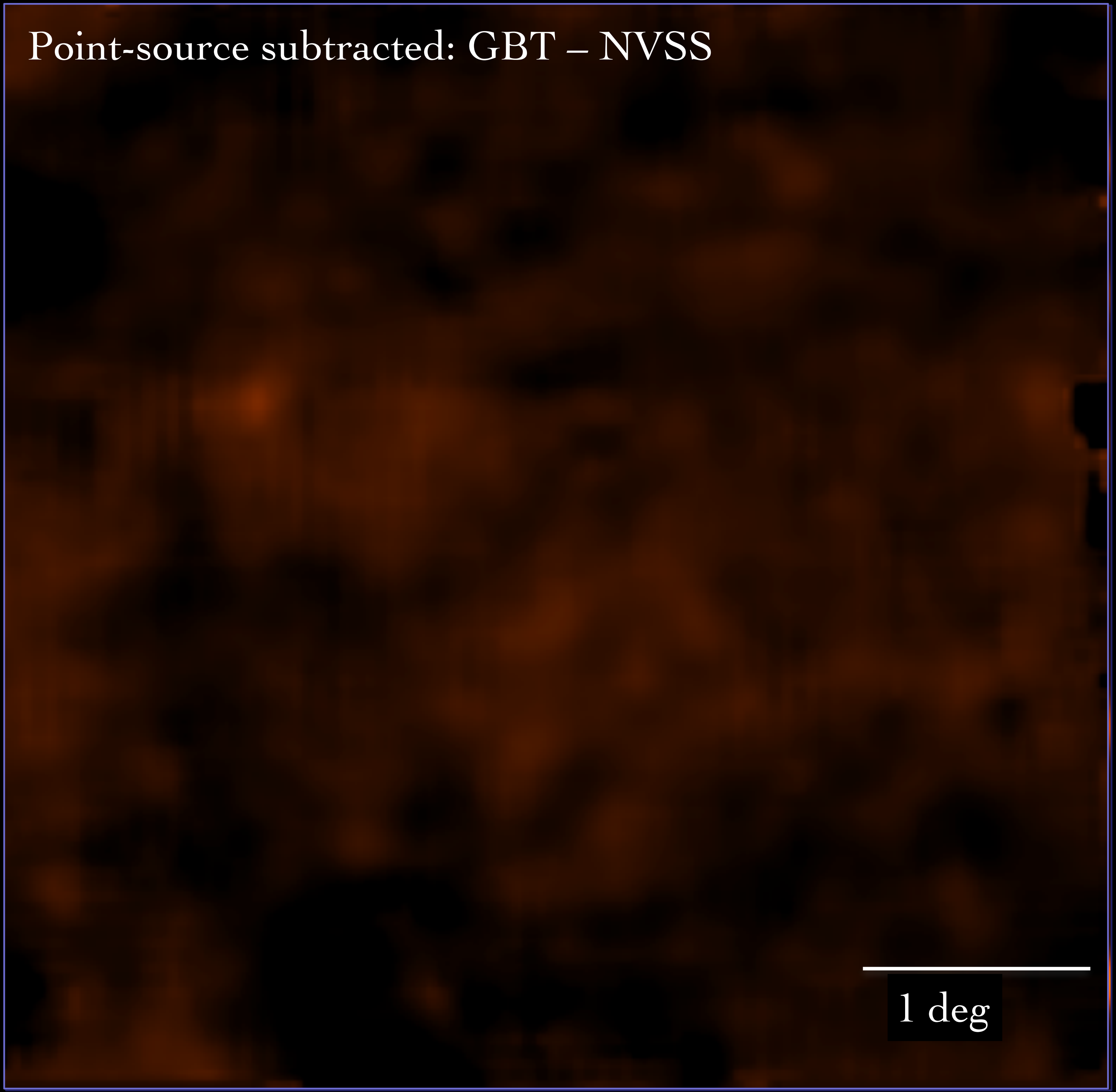
Spekkens+ 2013

4 deg x 4 deg

L-band (1.4 GHz)
-same frequency as NVSS

Stokes I

Deep radio map of Draco dSphs



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Issue #3: Gain Fluctuations

Extra Noise Term

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

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

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

Issue #3: Gain Fluctuations

Radiometer Equation

$$\frac{\Delta T}{T_{sys}} = \sqrt{\frac{1}{\Delta\nu\,\tau}}$$

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Radiometer Equation

Extra Noise Term

$$\frac{\Delta T}{T_{sys}} = \sqrt{\frac{1}{\Delta\nu\,\tau}} \rightarrow \sqrt{\frac{1}{\Delta\nu\,\tau} + \left(\frac{\Delta G}{G}\right)^2}$$

$$\frac{\Delta G}{G} \sim 10^{-3}\,@\,1\,\mathrm{Hz}$$

Limiting the useful RF bandwidth to ~ 1 MHz in one second, compared to many GHz in principle available.

This is a big problem! (see Rx architectures)

Issue #4: Atmospheric Emission

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

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

$$On - Off = G\Delta T_{SKY}$$

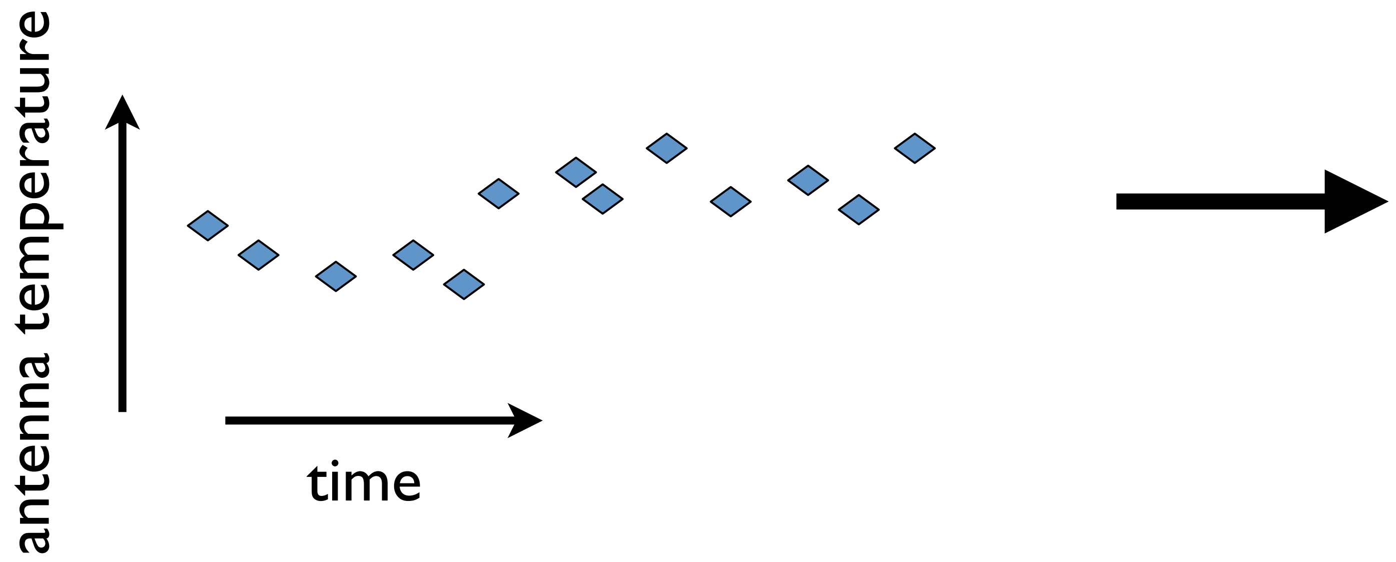
Issue #4: Atmospheric Emission

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

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

$$On - Off = G\Delta T_{SKY}$$

How fast do G(t), T_{ATM}(t) vary, and what is the character of the variations?

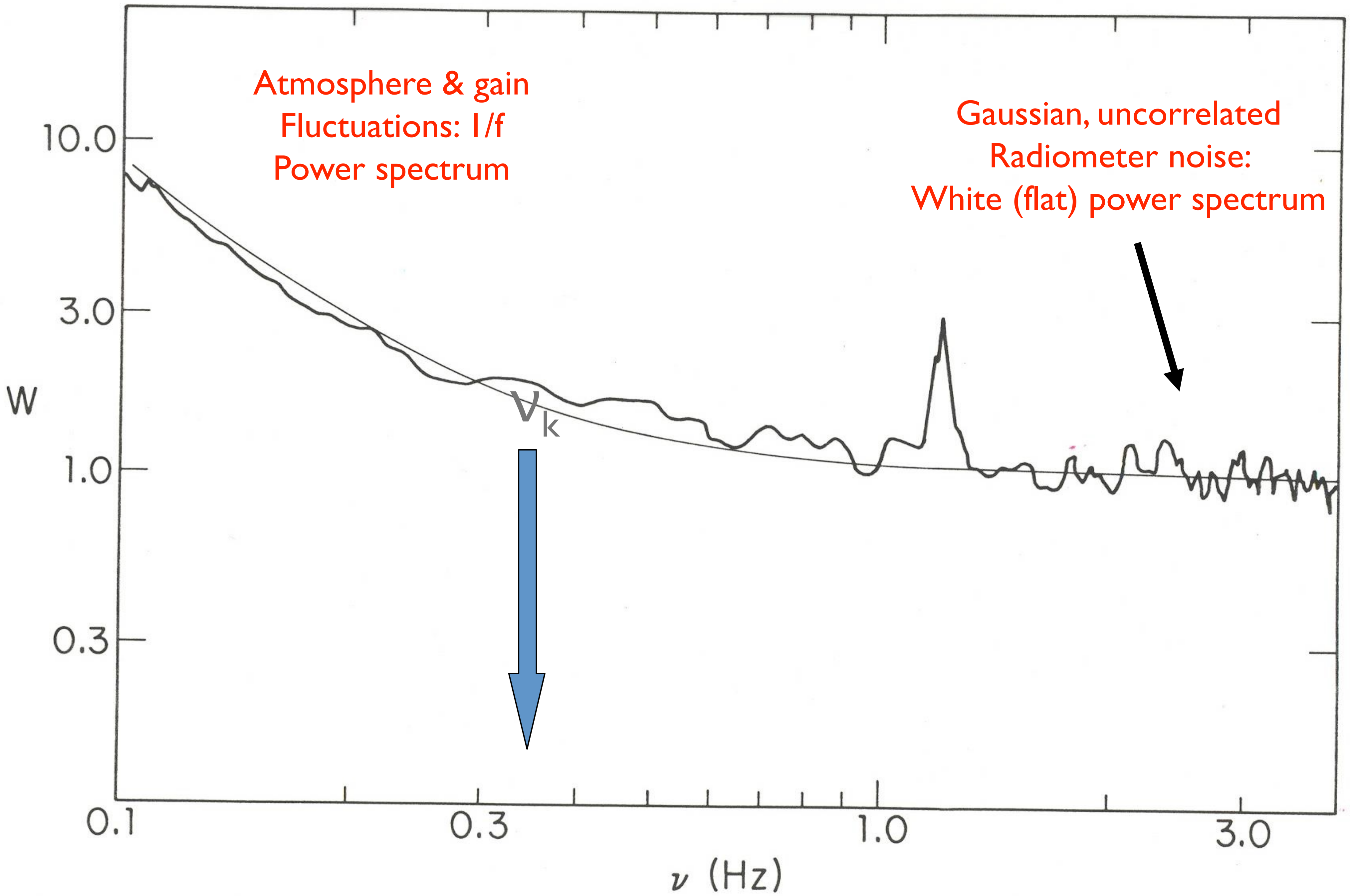


Fourier transform to characterize noise

Receiver (radiometer) noise is "white": stationary fuzz.

Both gain fluctuations and atmospheric fluctuations tend to show erratic, long-term drift ("1/f noise").

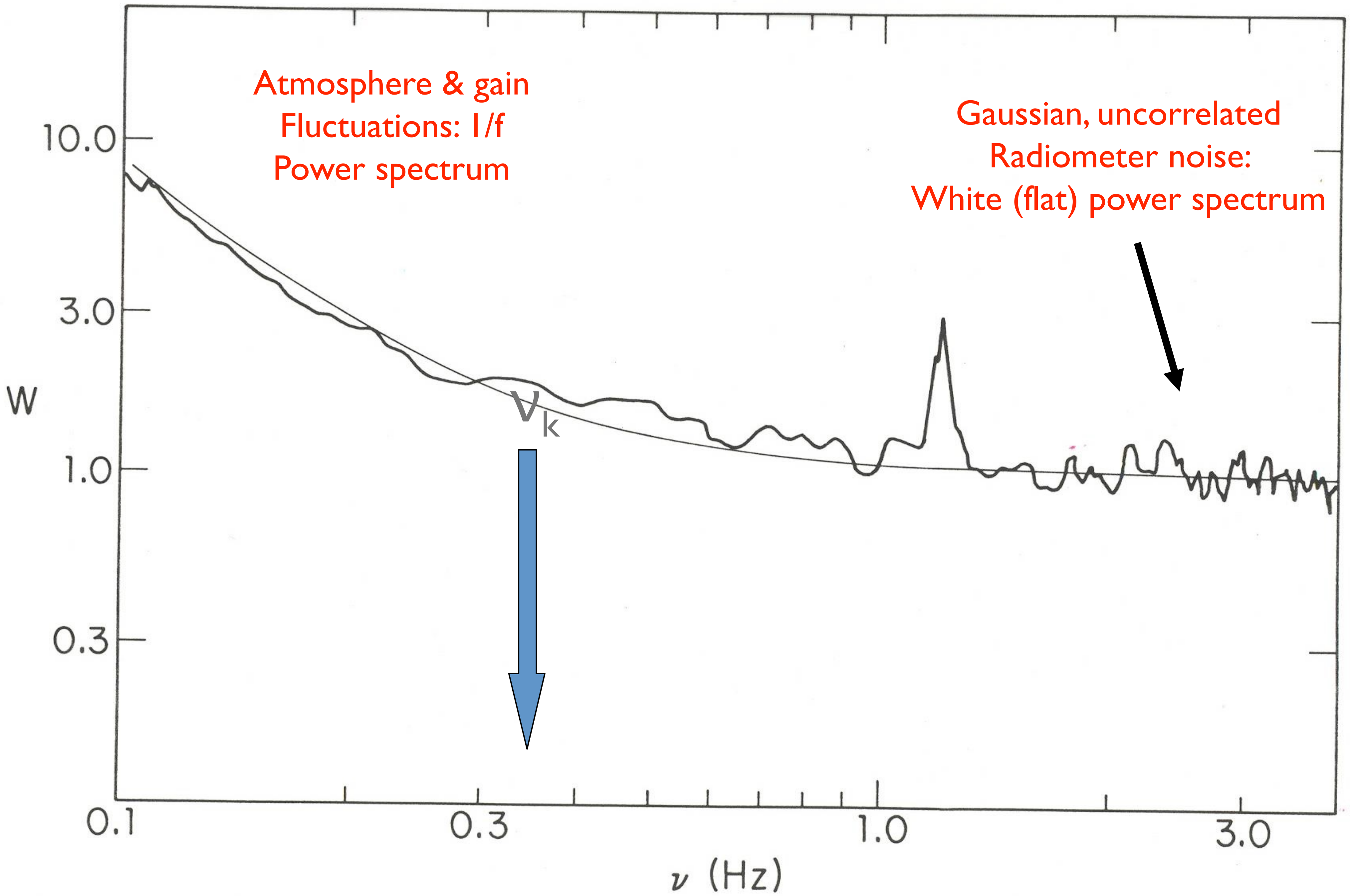
Postdetection power spectrum of the receiver output



Atmosphere & gain
Fluctuations: 1/f
Power spectrum

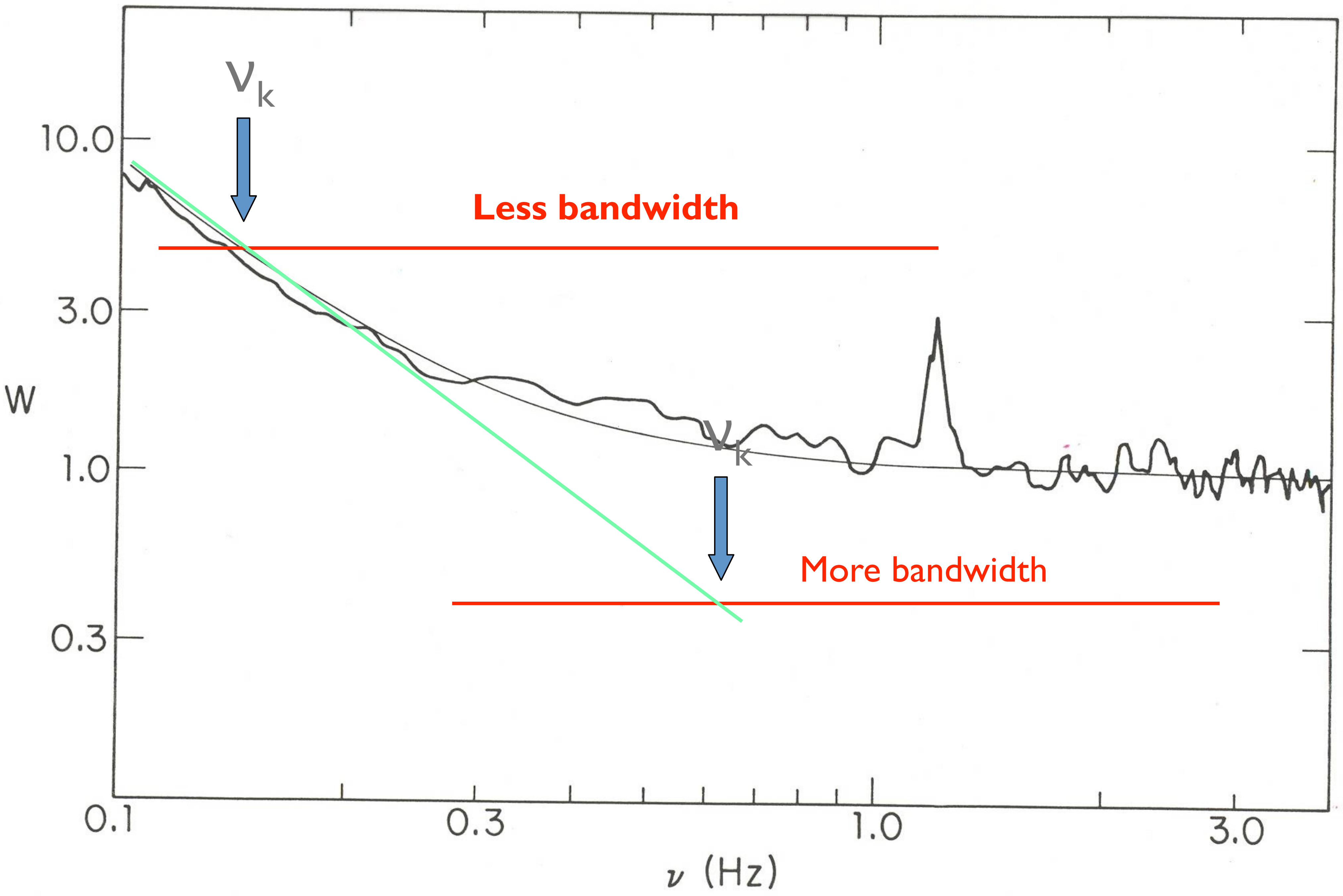
Gaussian, uncorrelated
Radiometer noise:
White (flat) power spectrum

Postdetection power spectrum of the receiver output



Modulate the sky signal faster than this characteristic timescale (nod telescope, chop subreflector, beamswitch receiver beams, scan the telescope) to eliminate the extra noise in your measurement.

Postdetection power spectrum of the receiver output



Characteristic Timescales for Broadband Measurements

- Atmosphere 0.1-few Hz
  - chopping (secondary/tertiary) or rapid scanning
  - “common mode” subtraction for imaging arrays
- Gain & offset fluctuations for coherent amplifiers: very instrument-dependent; can be 100s of Hz
  - receiver architecture:
  - -switching (dicke switch, correlation radiometer)
  - -build a stable receiver!
- Bolometers are typically more stable: gain & offset fluctuations ~1 Hz

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AKA beam switching, differencing...

Dicke-Switching Receiver

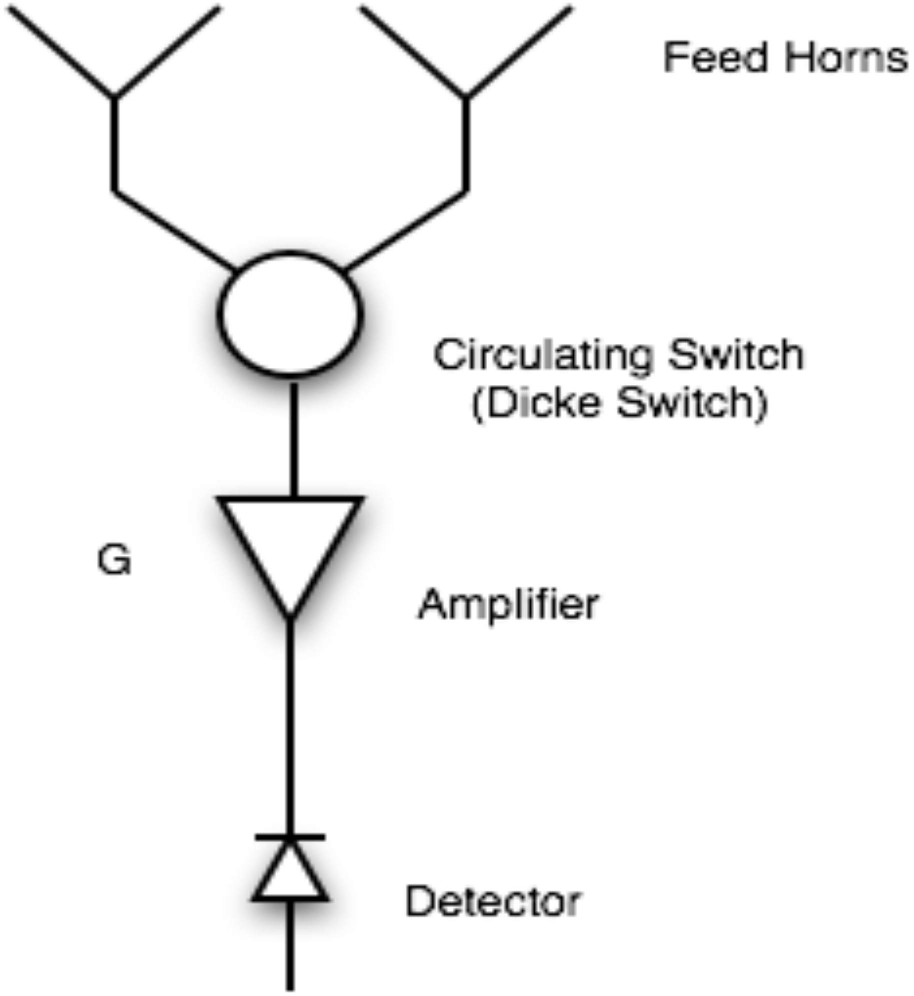
Rapidly alternate between feed horns to achieve theoretical noise performance.

$$G\{T_{SRC} + T_{RX} + T_{ATM}\}$$

$$G\{T_{RX} + T_{ATM}\}$$

$$On - Off = GT_{SRC} + (\Delta G = 0)(T_{RX} + T_{SKY})$$

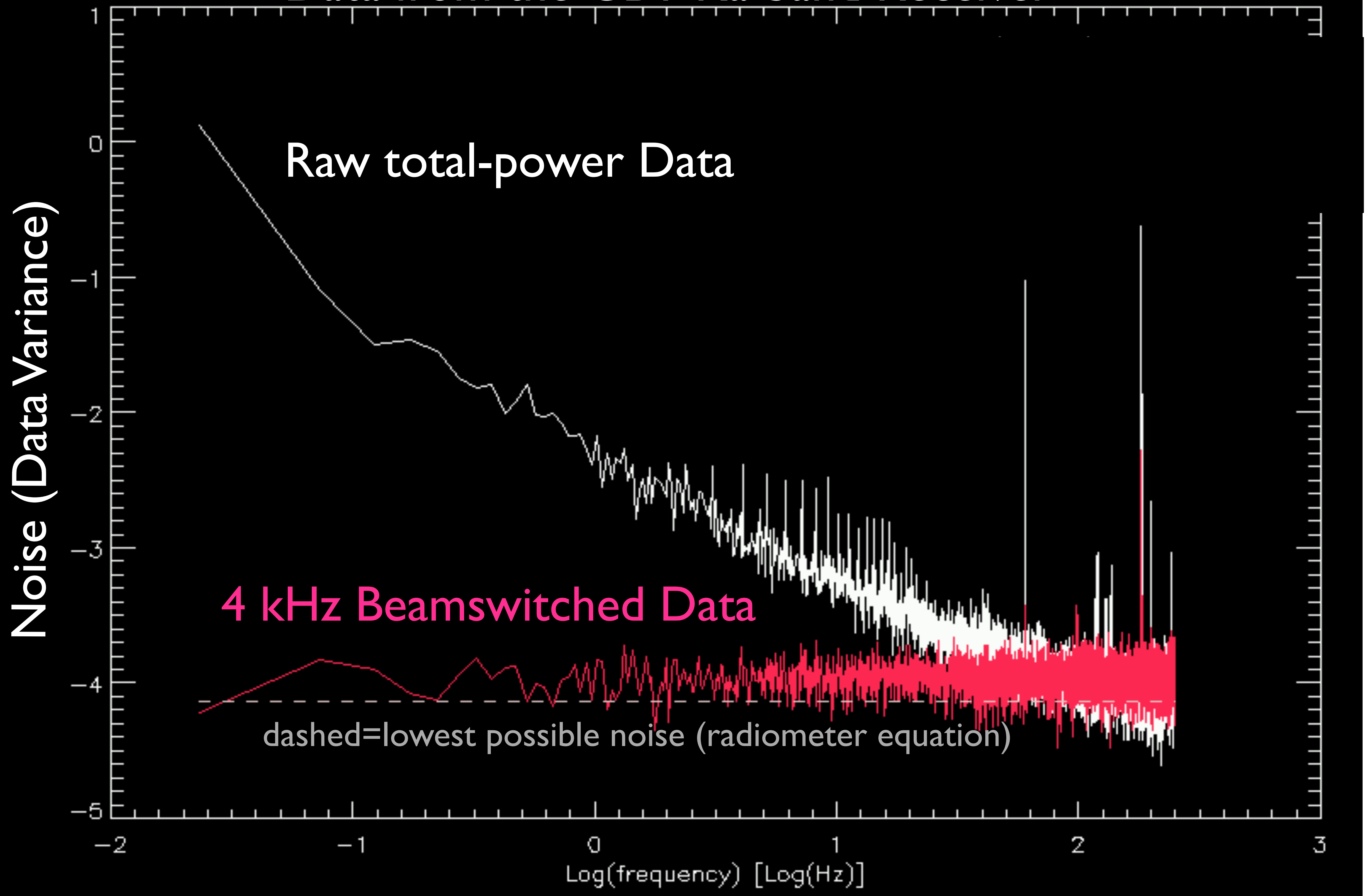
For $T_{SRC} << T_{SYS}$ gain fluctuations don't contribute significantly to the noise



G(t1) V1^2
G(t2) V2^2
G(t3) V1^2
.
.

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

Data from the GBT Ka-band Receiver



Raw total-power Data

4 kHz Beamswitched Data

dashed=lowest possible noise (radiometer equation)

The Price of Beam Switching

- Depends on the type of Observation
  - Photometric (targetted Nod): possibility of confusion in the off-source (reference) positions; no image to check your assumptions.
  - Mapping: loss of some spatial frequency information, much of which can be restored by deconvolution techniques (Emerson Klein & Haslam or EKH; MEM; etc.).

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- Sqrt(2) to 2 in RMS Noise for a given integration time
  - you spend half your observing time looking away from your source

$$\Delta T = T_{sys,on} - T_{sys,off}$$

$$RMS(\Delta T) = \sqrt{2} \times RMS(T_{sys,on})$$

$$= \sqrt{2}\frac{T_{sys,on}}{\sqrt{\Delta\nu\,\tau_{on}}} = \frac{2 \times T_{sys,on}}{\sqrt{\Delta\nu\,\tau_{total}}}$$

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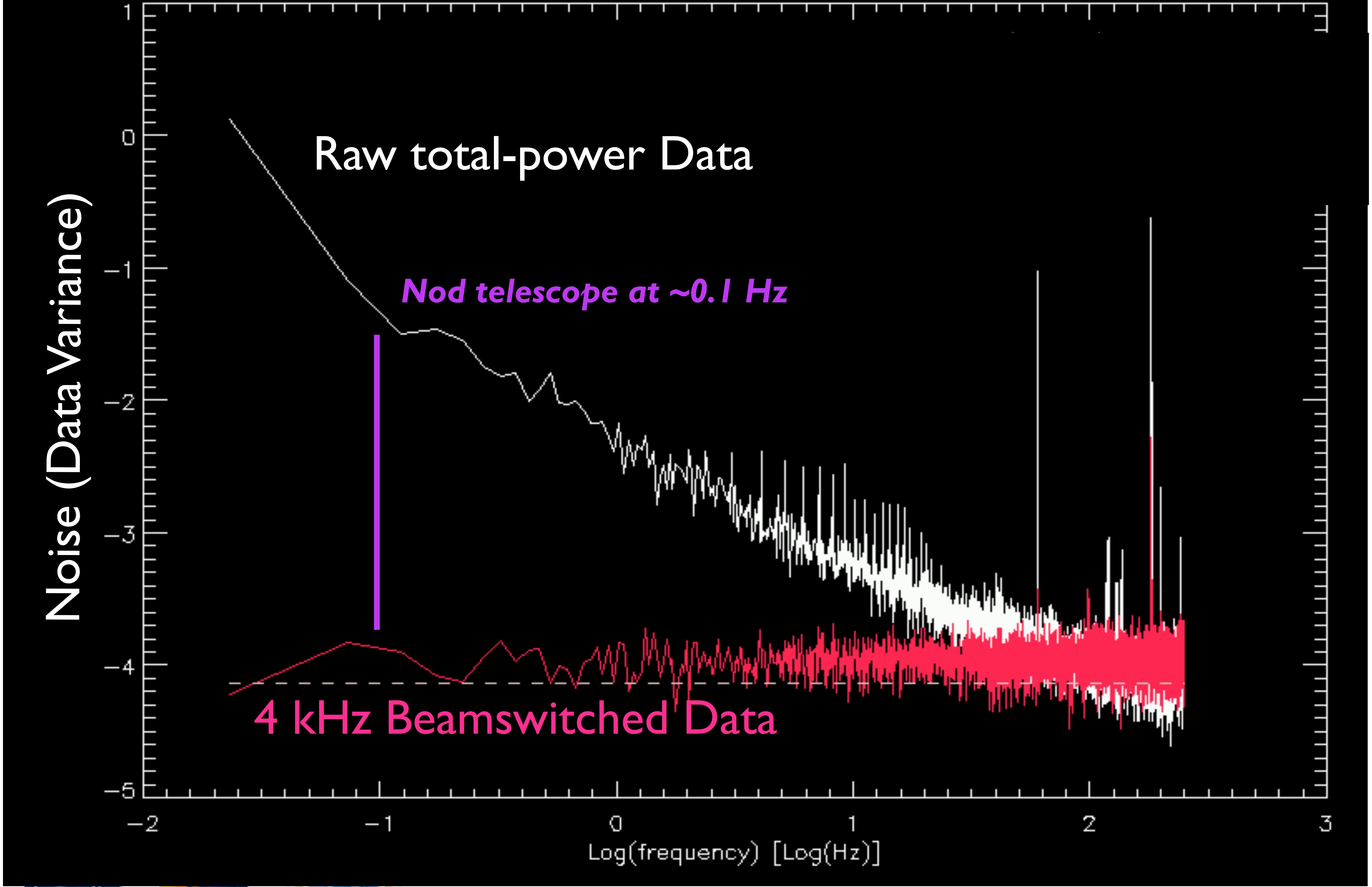
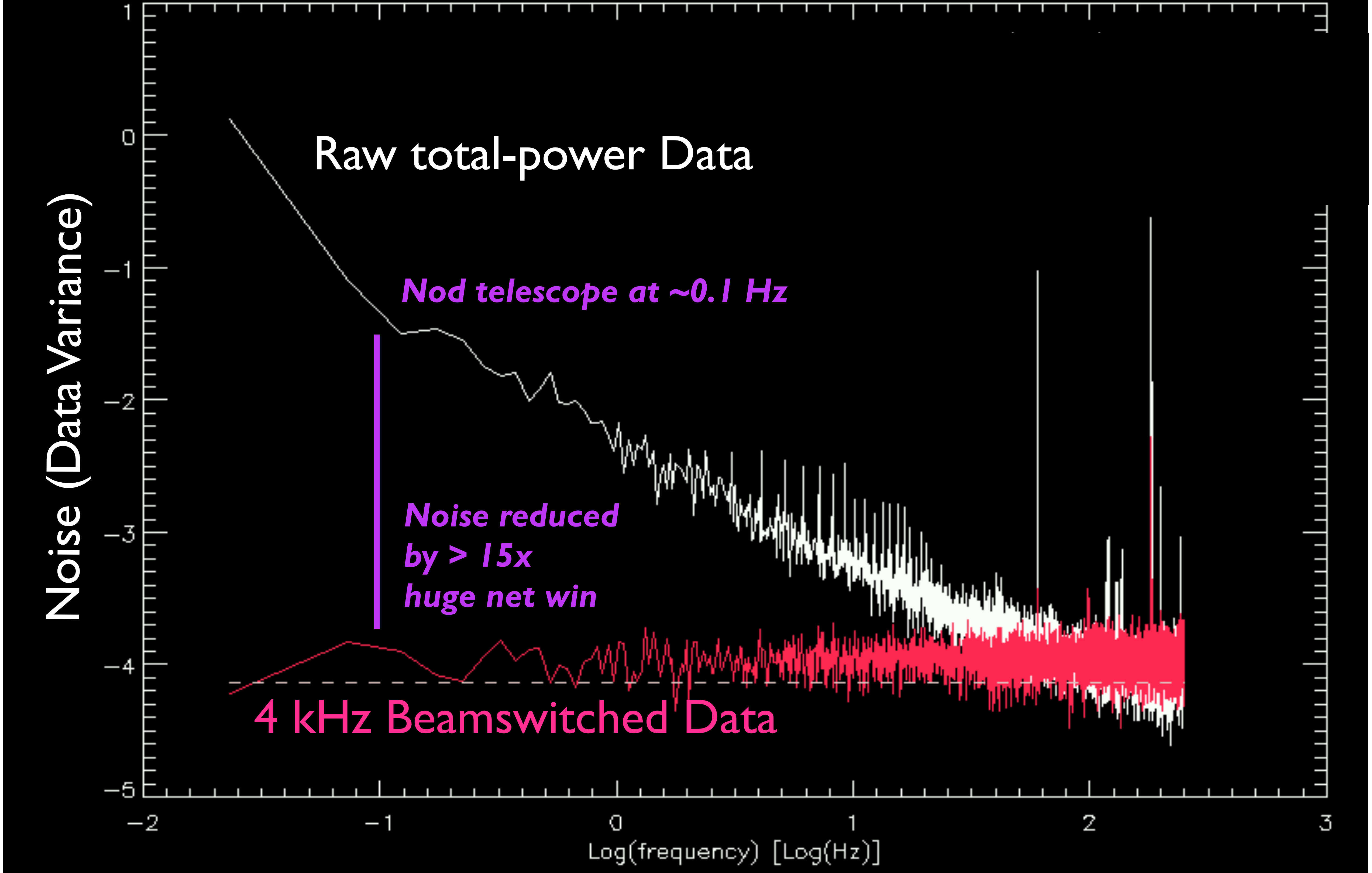
Sqrt(2) can be gotten back with other architectures: continuous comparison/ correlation radiometers; pseudo-correlation radiometers, correlation polarimeters, etc.

$$= \sqrt{2}\frac{T_{sys,on}}{\sqrt{\Delta\nu\,\tau_{on}}} = \frac{2\times T_{sys,on}}{\sqrt{\Delta\nu\,\tau_{total}}}$$

Data from the GBT Ka-band Receiver



Data from the GBT Ka-band Receiver



Raw total-power Data

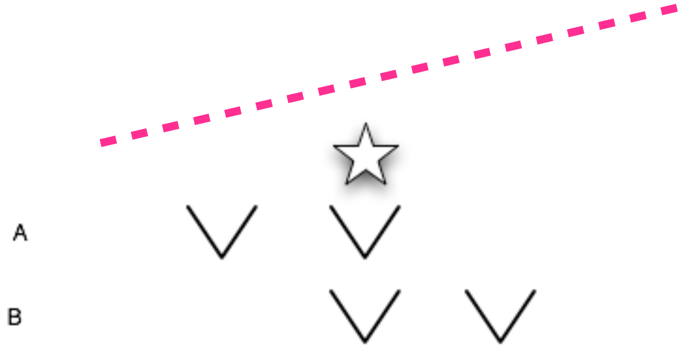
Nod telescope at ~0.1 Hz

Noise reduced by > 15x huge net win

4 kHz Beamswitched Data

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



$$\begin{aligned} A &= F_1 - F_2 &&= -S_{src} + \Delta \\ B &= F_1 - F_2 &&= S_{src} + \Delta \\ (A - B)/2 & &&= S_{src} \end{aligned}$$

***Only penalty is slew time**

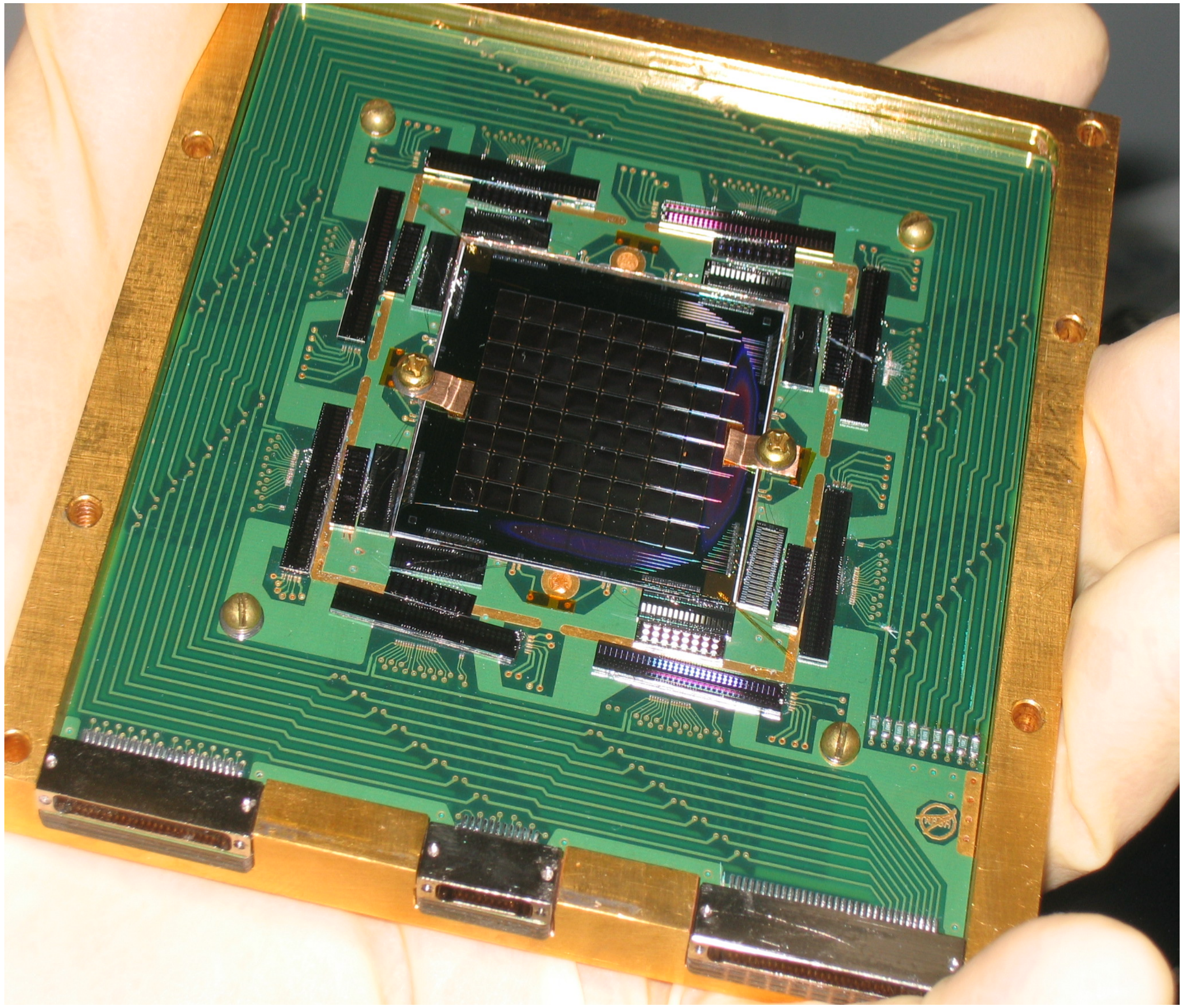
Generalizes to yet higher order schemes (eg, symmetric double-nod)

Bolometer Arrays

- Large-N
- Large Bandwidth
- Low intrinsic noise is possible ("Background Limited" Performance)

$$T_{sys} = T_{sky} \sim 25\,\mathrm{K}$$

- More stable (knee ~ 1 Hz vs 100s of Hz)



MUSTANG (Δν=18 GHz)

Absolute Calibration

What is the specific intensity at a given point in the sky in real units: Watts/Hz/m^2/Sr.

Relative calibration is a routine application of continuum measurements: "Flux Calibration"

-In each observing session measure a standard flux calibrator of known flux density (e.g., Baars et al. 1977)

But how do we know the flux density of these sources?

Absolute Calibration (1960s)

Findlay, Hvatum & Waltman (1965)

Absolute Calibration (1960s)

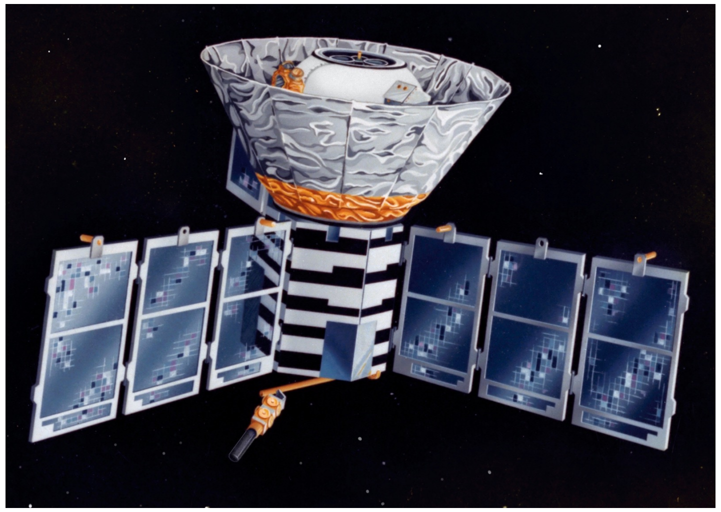
Measure one bright source accurately (in an absolute sense)

Transfer to fainter, more numerous, more useful sources by accurate *relative* measurements

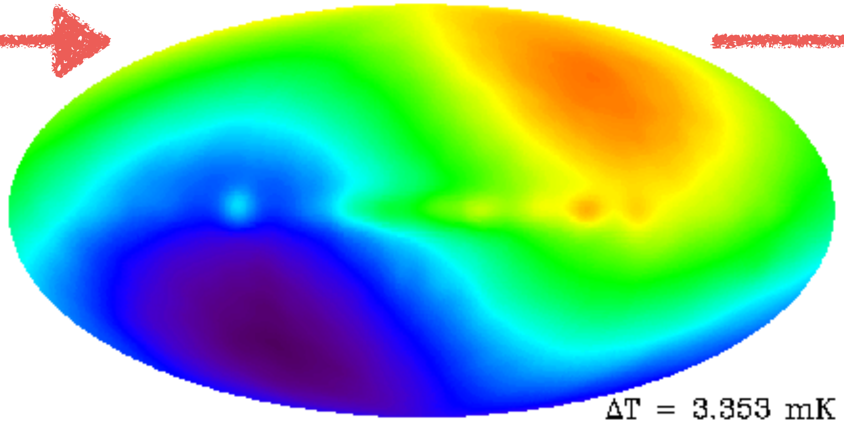
- usually with a larger telescope

Findlay, Hvatum & Waltman (1965)

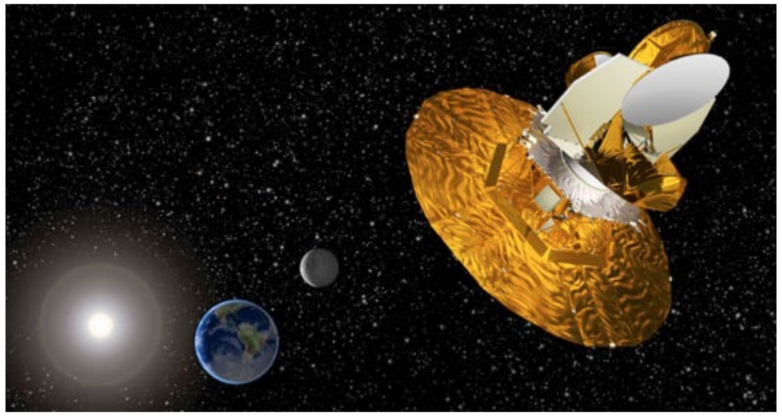
Absolute Calibration (today)



COBE



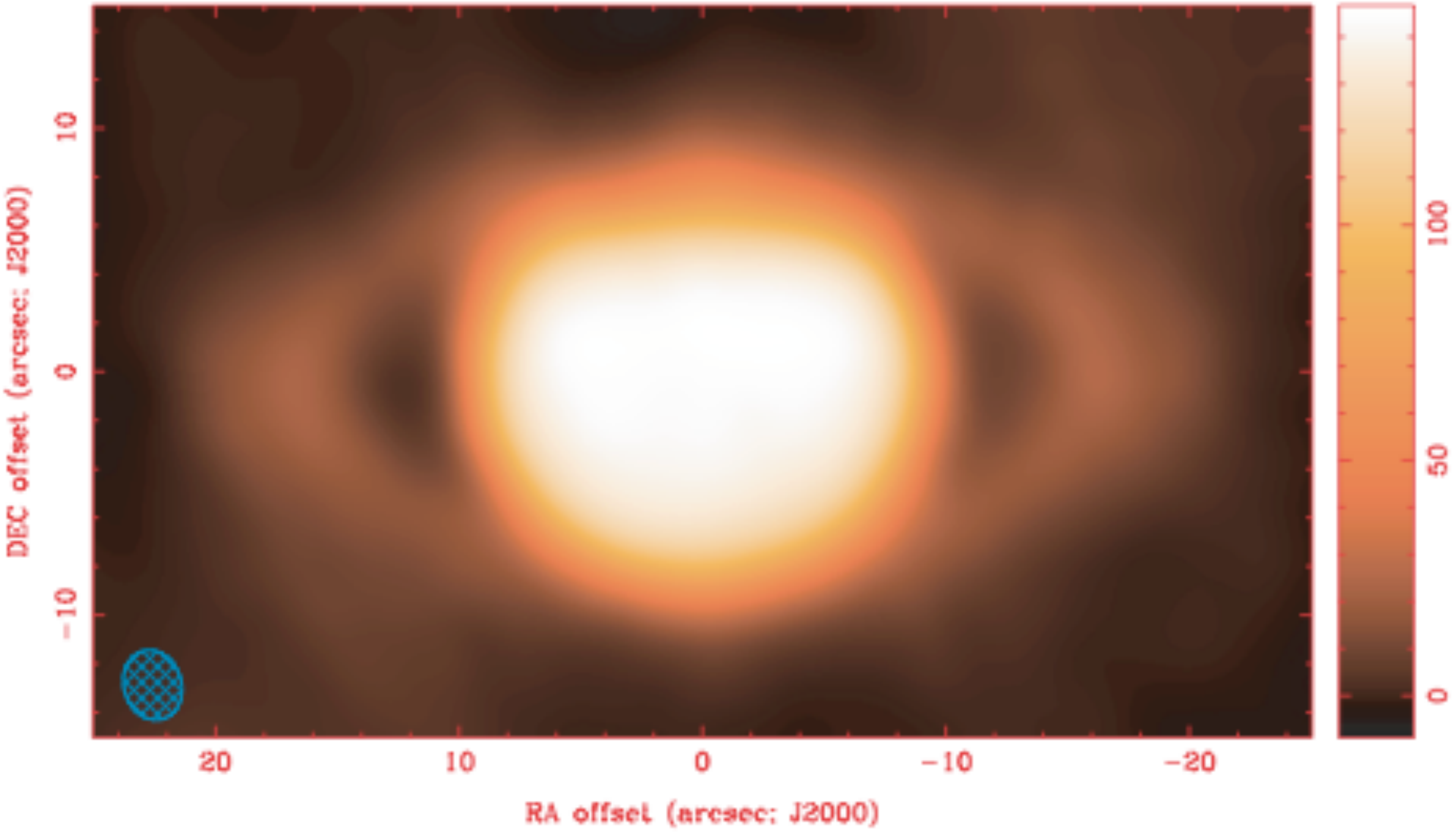
CMB Dipole
(3.347 +/- 0.008) mK



WMAP … < 1% planetary brightness temperature measurements

(Weiland et al. 2011)

3.0 mm



Dunn et al. 2005

- slightly elliptical orbit
- surface brightness of martian surface is not constant
    - varying visibility of polar cap

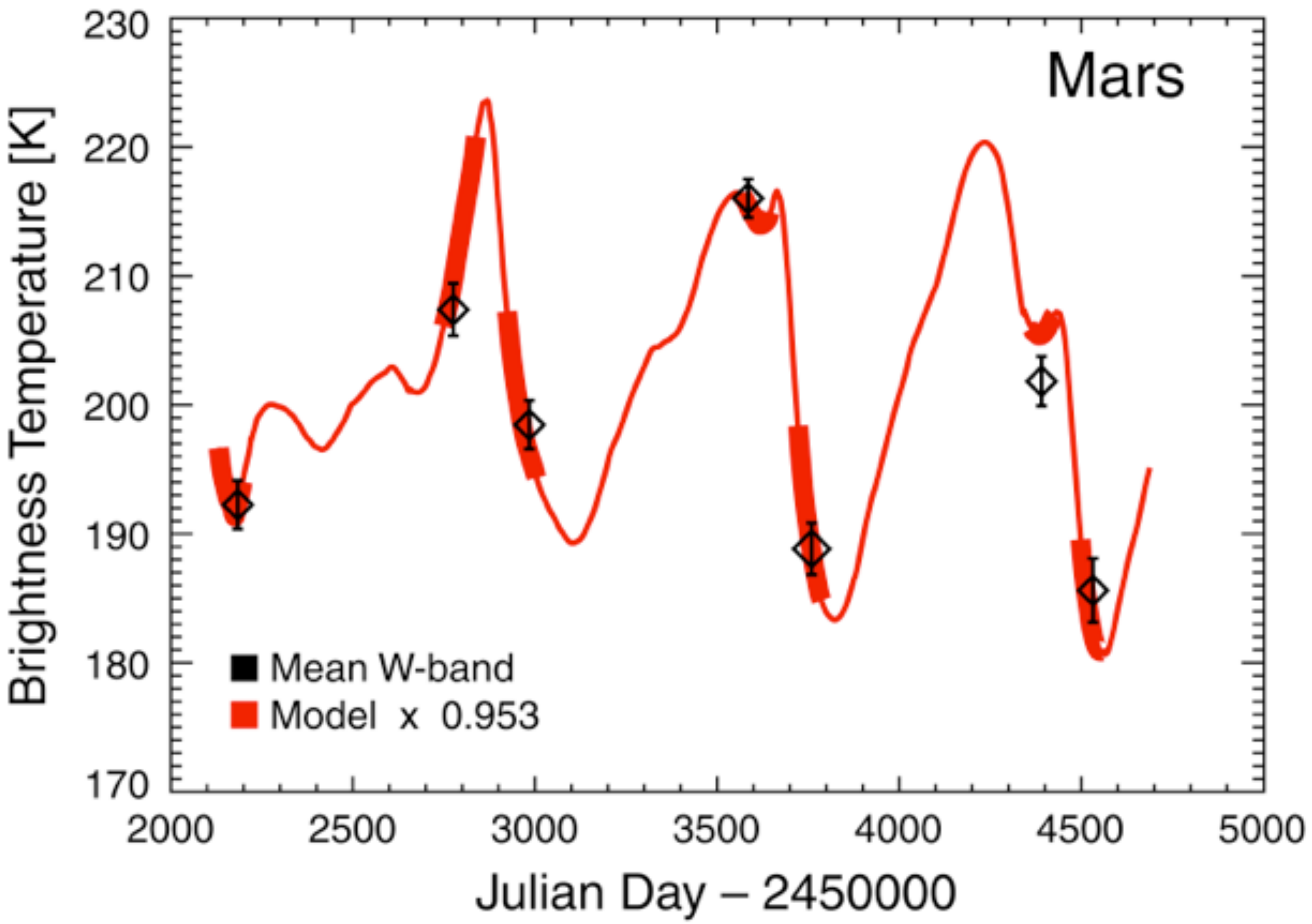
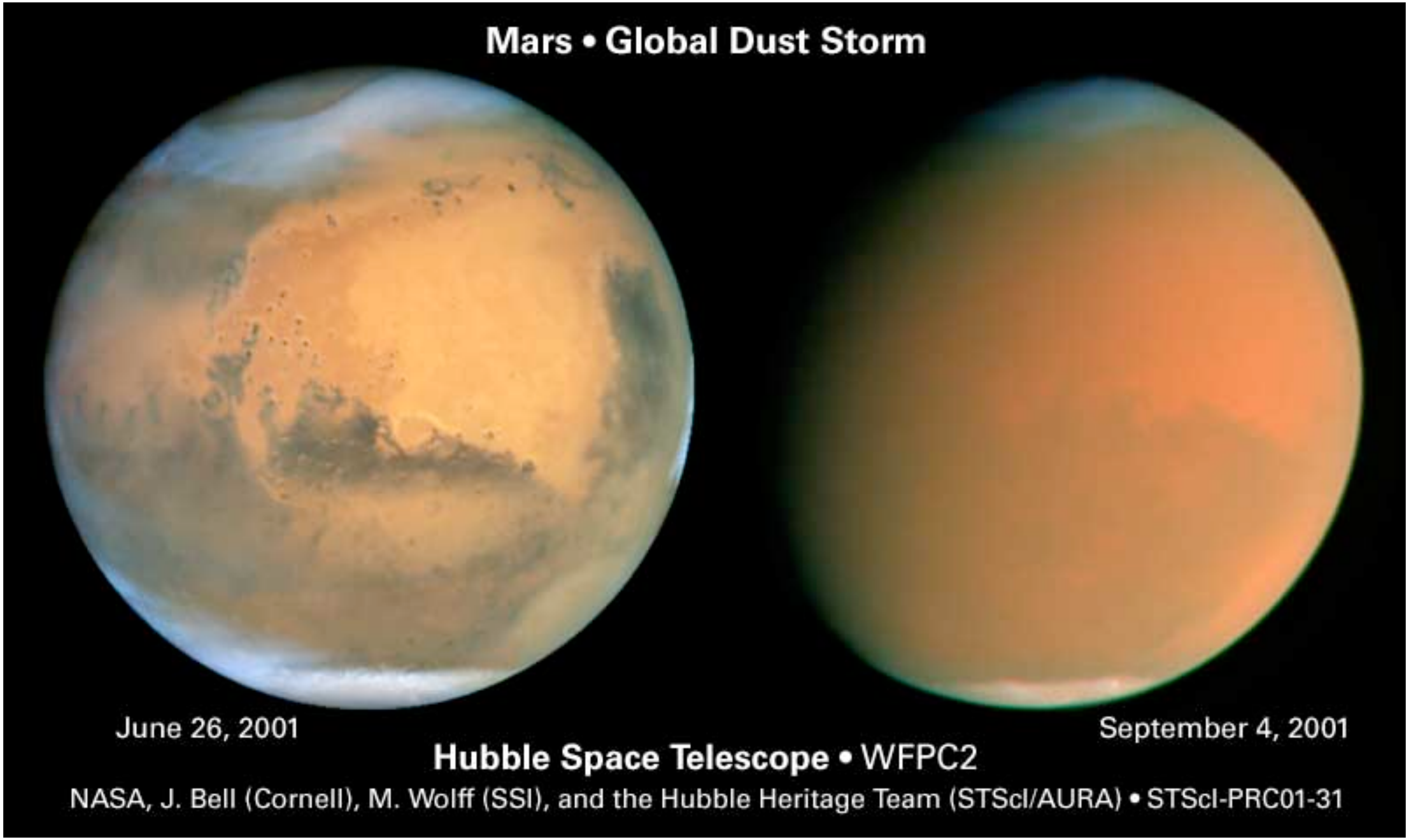
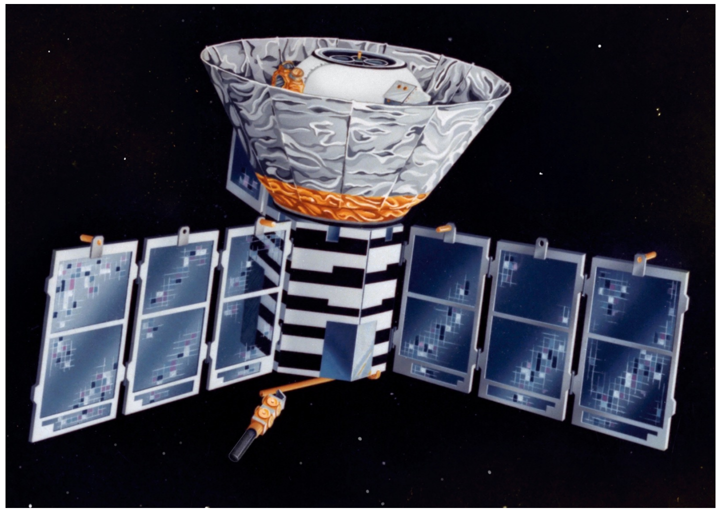


Fig. 3.— Comparison of *WMAP* W-band seasonal averages (black diamonds; Table 6) to the Mars model of Wright (1976, 2007). The *WMAP* observations have been corrected to absolute brightness. Model values (red line) have been rescaled by a factor of 0.953 to bring them into overall agreement with the observations; thick portions of the line indicate observing seasons. Data quality masking can skew the mean times of observations from the mean of the seasonal interval, as is evident in the second observing season.

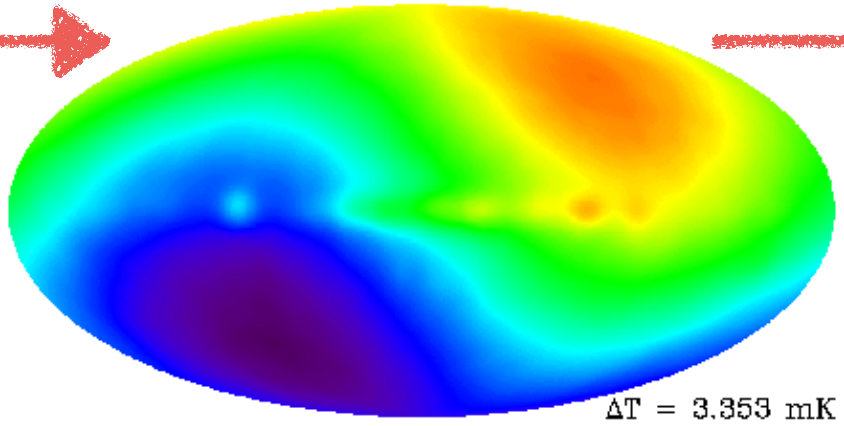
Weiland et al. 2010
Model of Ned Wright


Mars • Global Dust Storm
June 26, 2001
September 4, 2001
Hubble Space Telescope • WFPC2
NASA, J. Bell (Cornell), M. Wolff (SSI), and the Hubble Heritage Team (STScI/AURA) • STScI-PRC01-31

Absolute Calibration (today)



COBE



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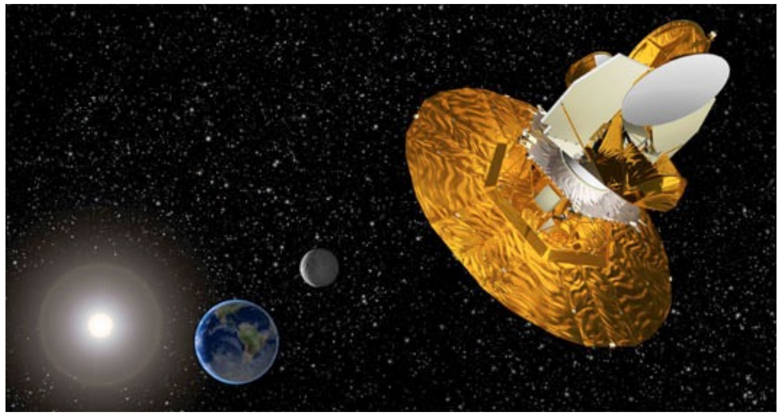

WMAP … < 1% planetary brightness temperature measurements

(Weiland et al. 2011)

See Perley & Butler (2014) and Partridge et al. (2015), who leverage these onto standard radio (cm) calibrator sources [5% abs. accuracy in the 1 to 50 GHz range]