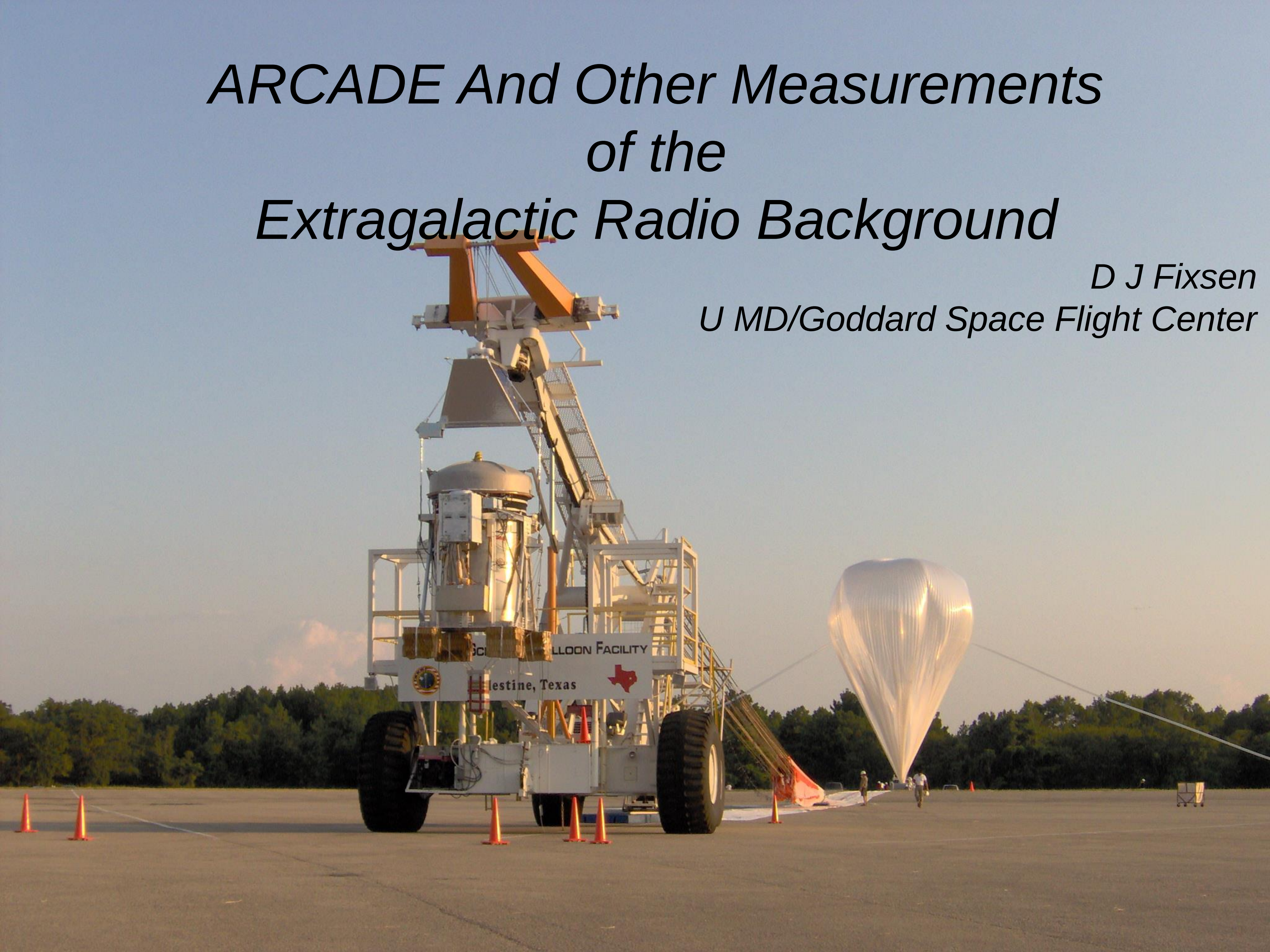
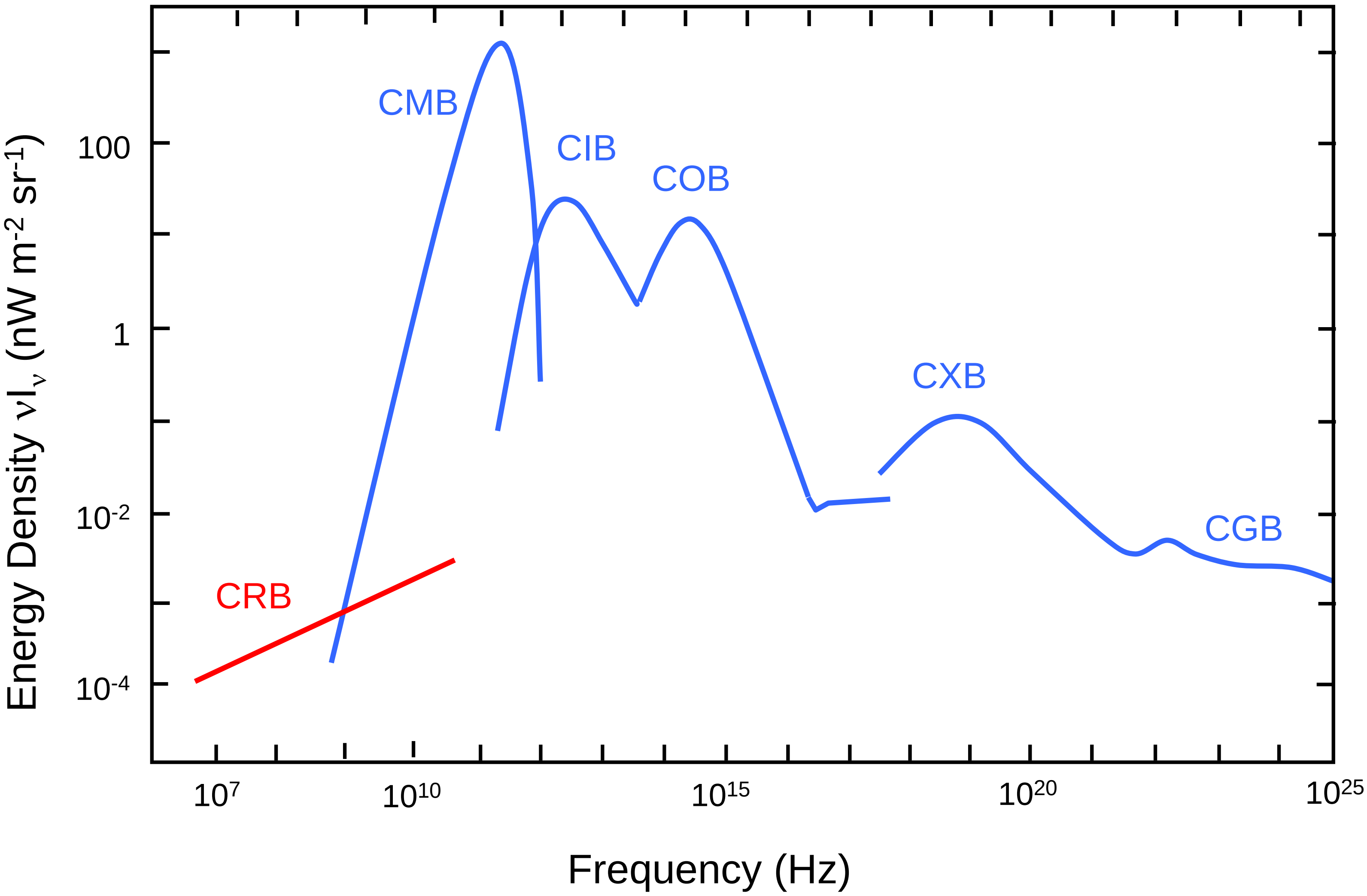
# *ARCADE And Other Measurements of the Extragalactic Radio Background*

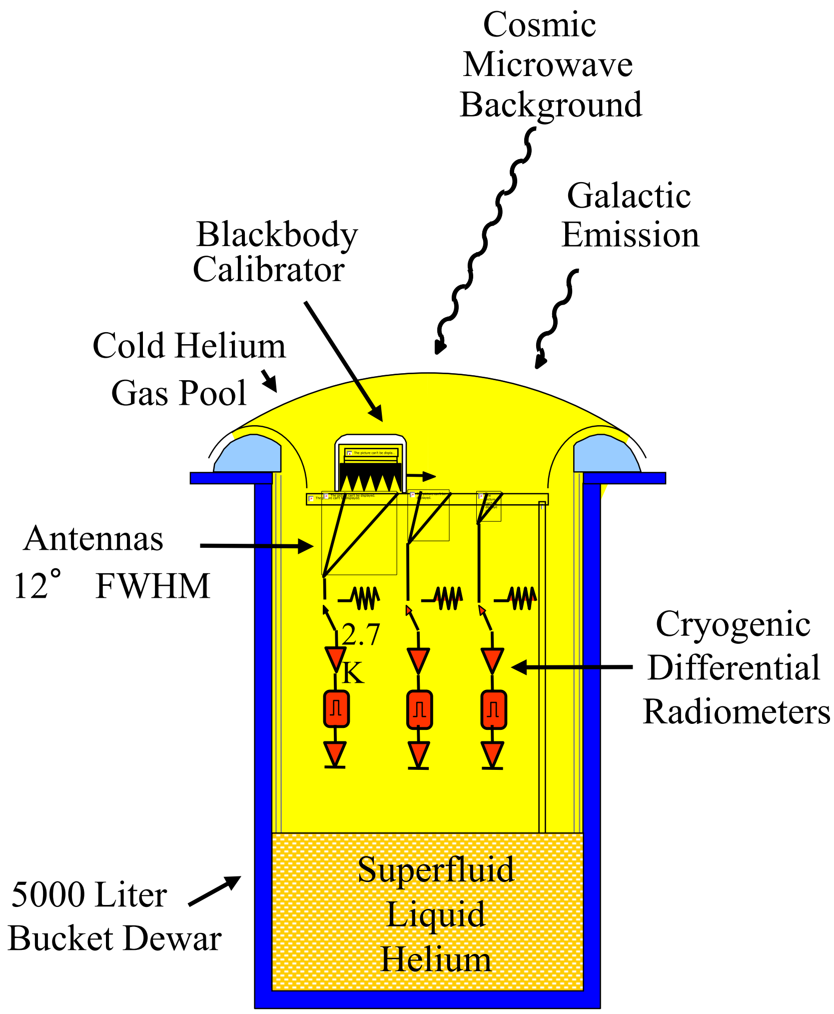
*D J Fixsen*
*U MD/Goddard Space Flight Center*



# Cosmic Radio Background



# ARCADE Concept

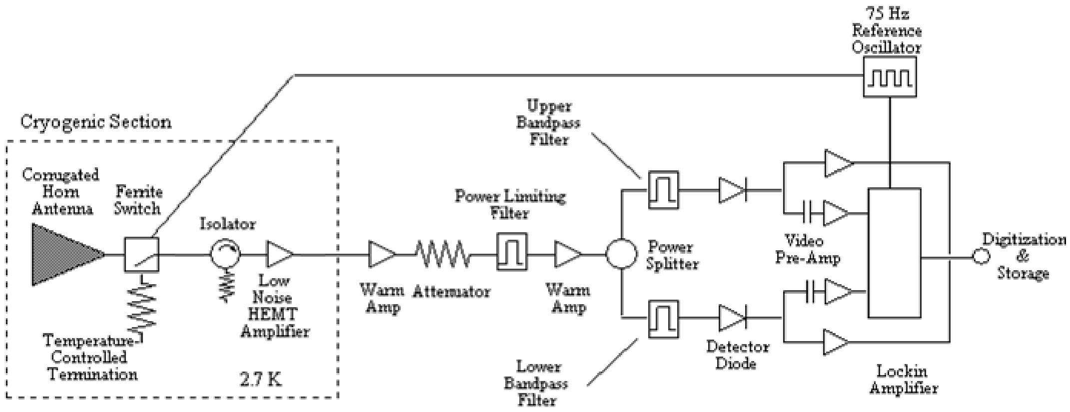


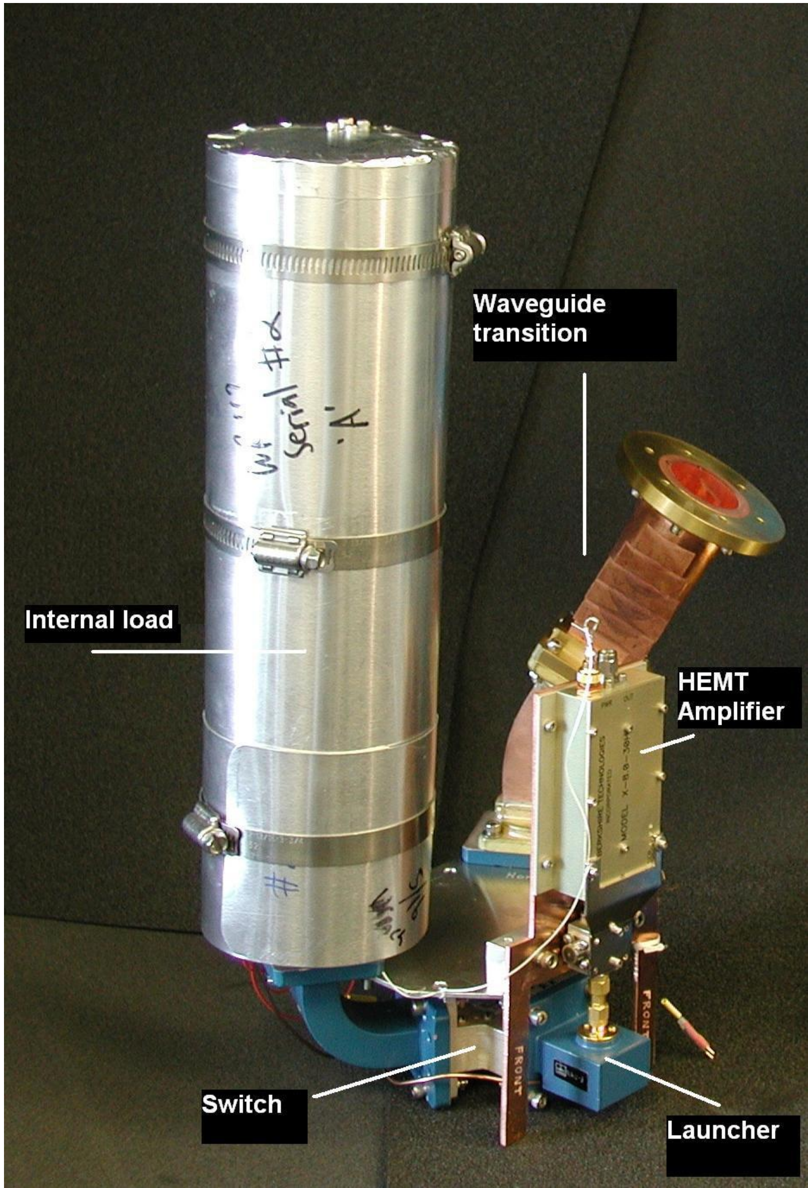

## Systematics, Not Sensitivity!

- Double-Nulled Design
  - Adjust reference load to null antenna signal
  - Adjust calibrator to null sky signal
  - Measure small differences about null
- Calibrator: Cold and Black
  - Absorption ε > 0.9999 across band
  - Adjust temperature to match sky
  - Read temperature from embedded thermometers
- Eliminate emission from warm objects
  - Instrument isothermal with 2.7 K CMB
  - Balloon eliminates atmospheric emission
  - Open aperture -- no windows (!)

**Double-Nulled, Cryogenic, and Isothermal**

# Cryogenic Radiometers




Six frequency bands: 3, ~~5~~, 8, 10, 30, 90 GHz

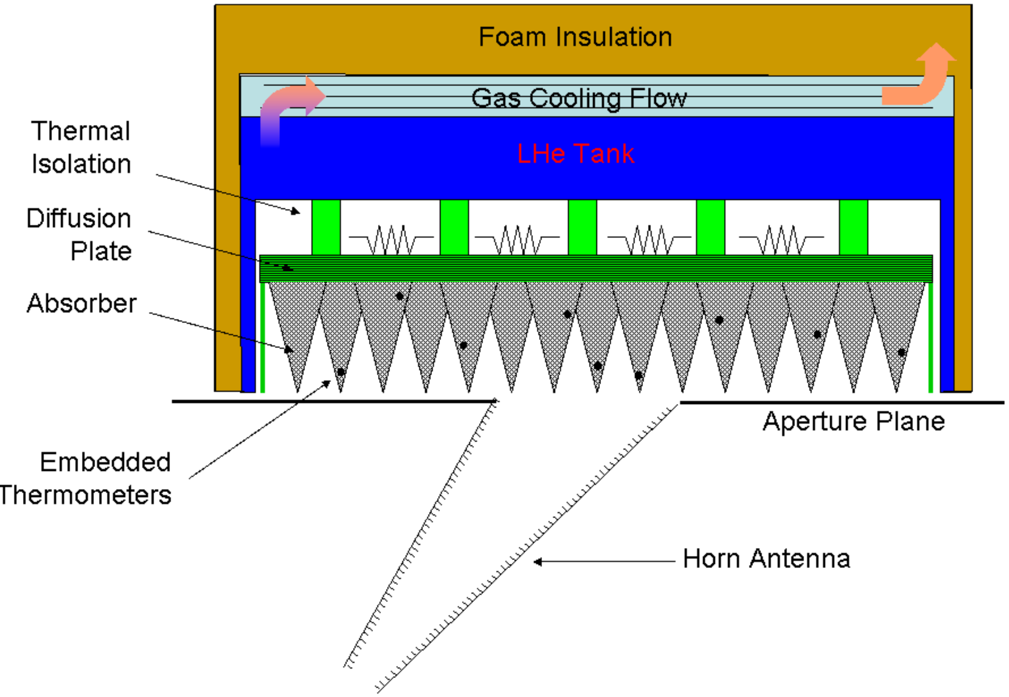
Chop between horn and load at 75 Hz

Load functions as transfer standard, but is black enough ($\varepsilon$>0.999) for absolute reference

External calibrator ($\varepsilon$>0.99997) nulls any remaining instrument asymmetry and provides absolute temperature scale

*ARCADE is a thermal experiment, not a radiometric experiment!*

# External Blackbody Calibrator

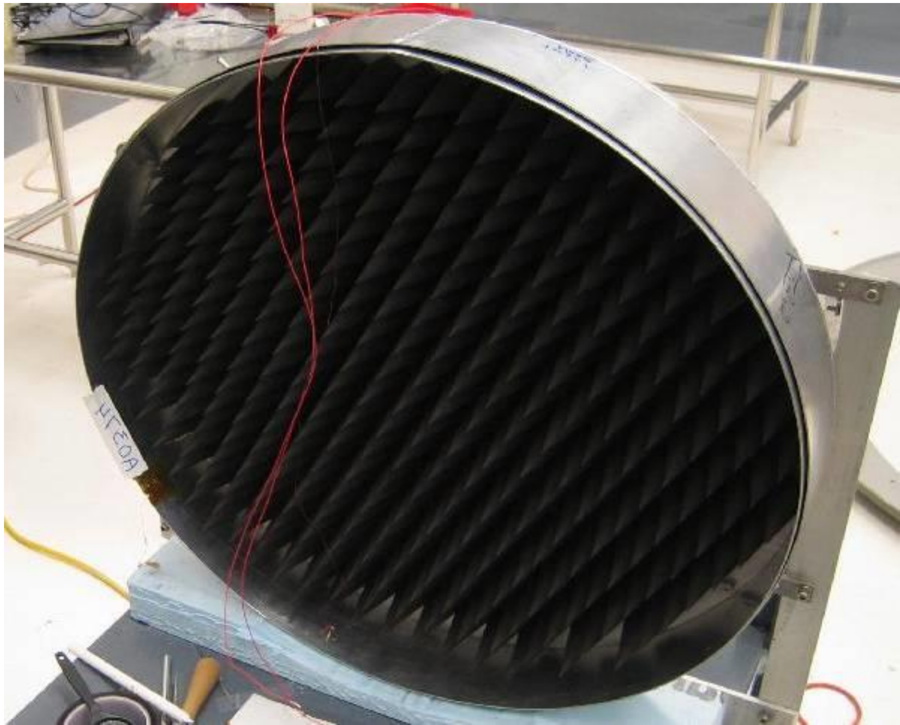



## Radiometric Performance

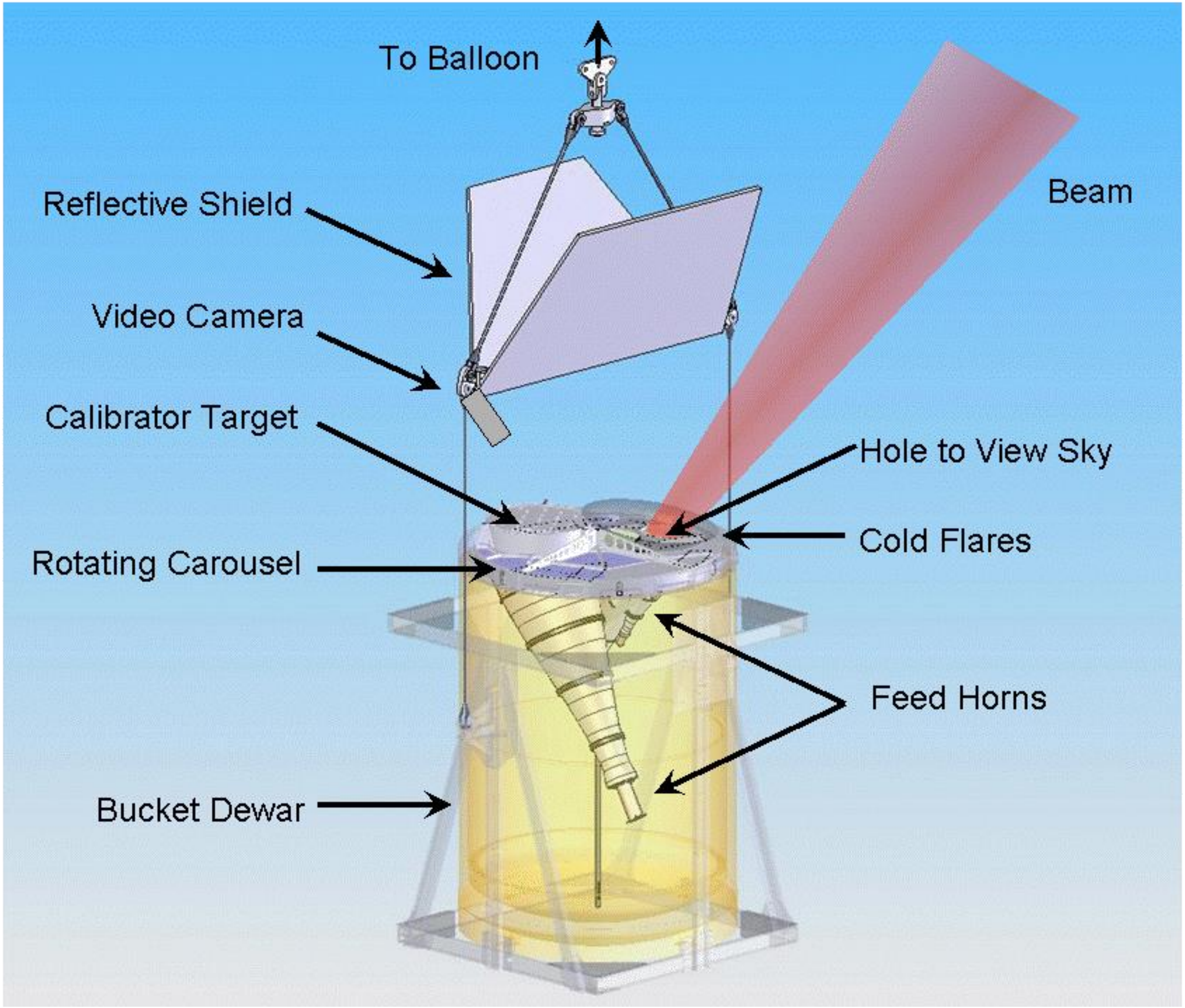
- 298 Absorbing cones
- Absorption > 0.99997 with height < $\lambda$

## Thermal Performance

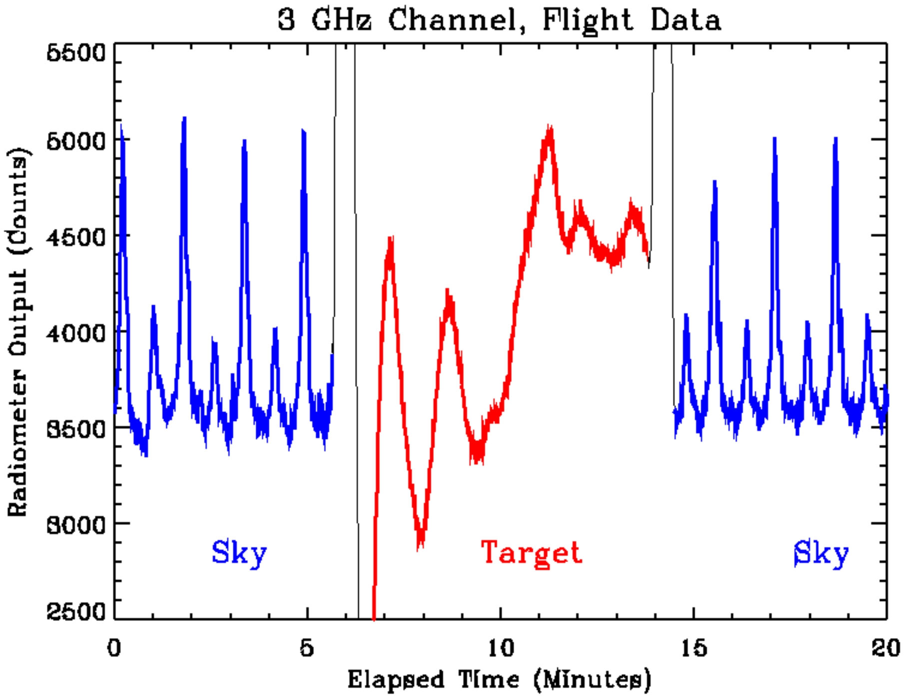
- LHe tank for thermal isolation
- Temperature controlled near 2.7 K
- 26 embedded thermometers
- Absolute scale verified via $\Lambda$ transition



# Payload Schematic



# Sky-Calibrator Comparison




Successful thermal operations

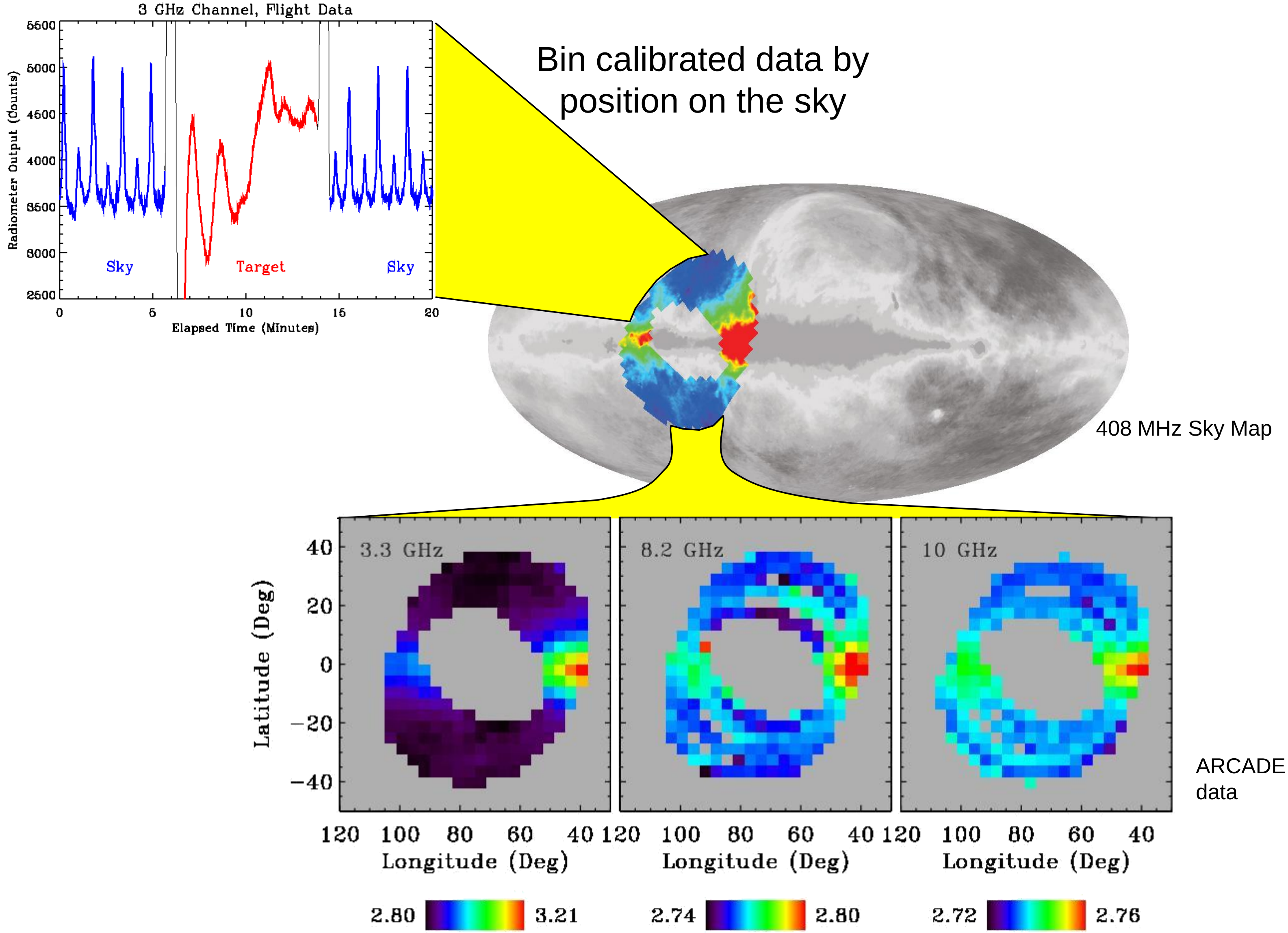
- Calibrator brackets sky temp
- Instrument nulled to < 0.1 K
- 8 sky/calibrator comparisons per band
- Stable "transfer standard"

*Linear instrument model allows interpolation of sky temperature*

Error Budget at 3.15 GHz

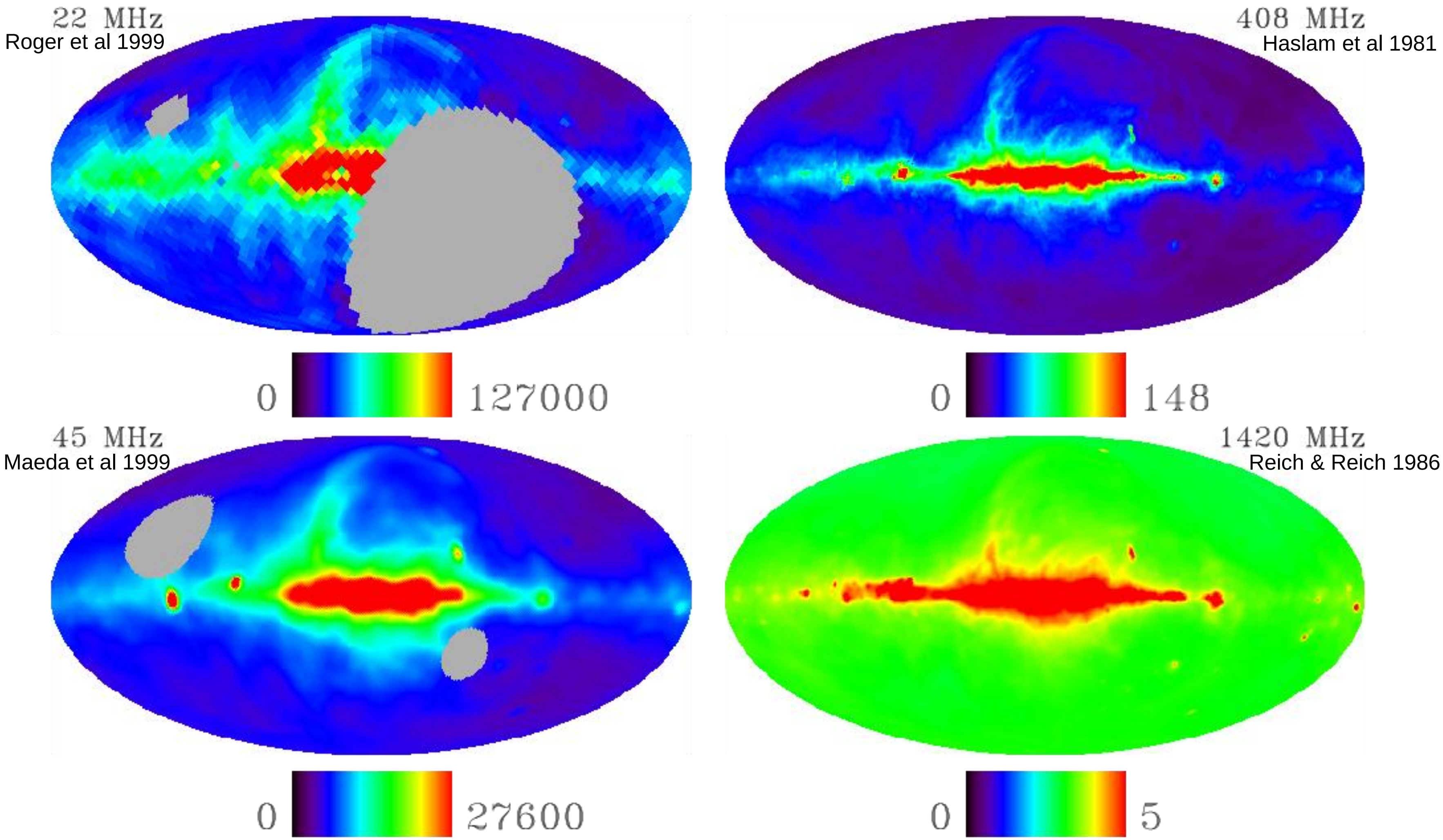
| **Effect** | **Uncertainty (mK)** |
|---|---|
| Instrument Emission | 3.2 |
| Calibrator Gradients | 6.7 |
| Thermometer Calibration | 1.0 |
| Atmosphere | 0.2 |
| **Total** | **7.5** |

# Binned Sky Temperatures



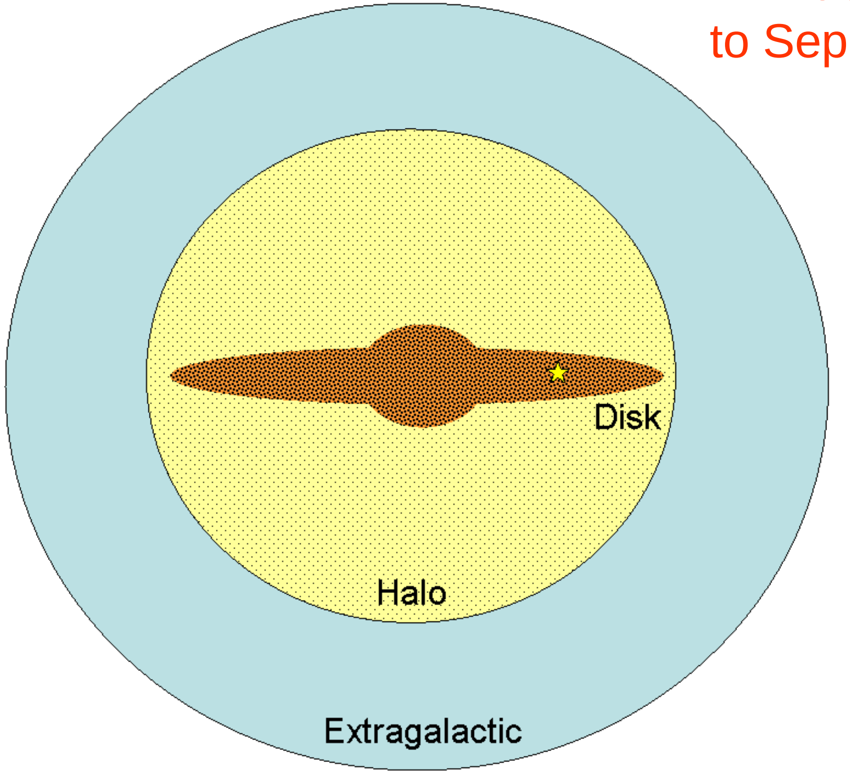

Subtract Galactic emission to search for extragalactic residual

# Low-Frequency Radio Surveys



# Galactic vs Extragalactic Emission

Problem: Can't Use Frequency Dependence
to Separate Galactic From Extragalactic Emission




I. Spatial Morphology

- Dominant plane-parallel disk
- Compare radio emission to Galactic latitude

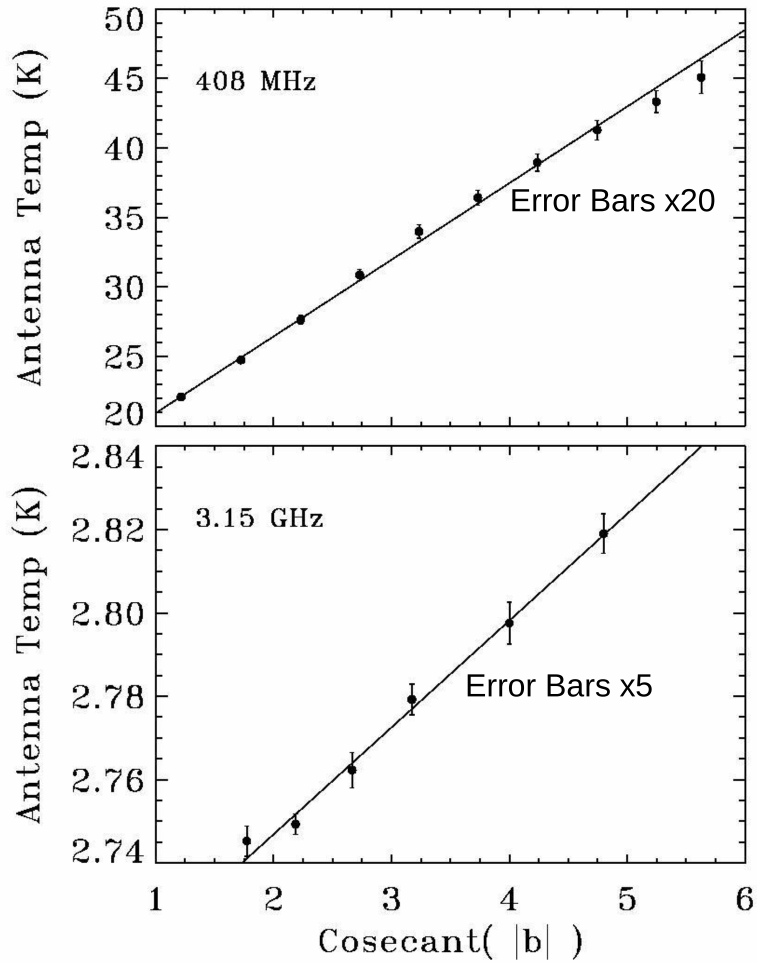
II. Line Emission

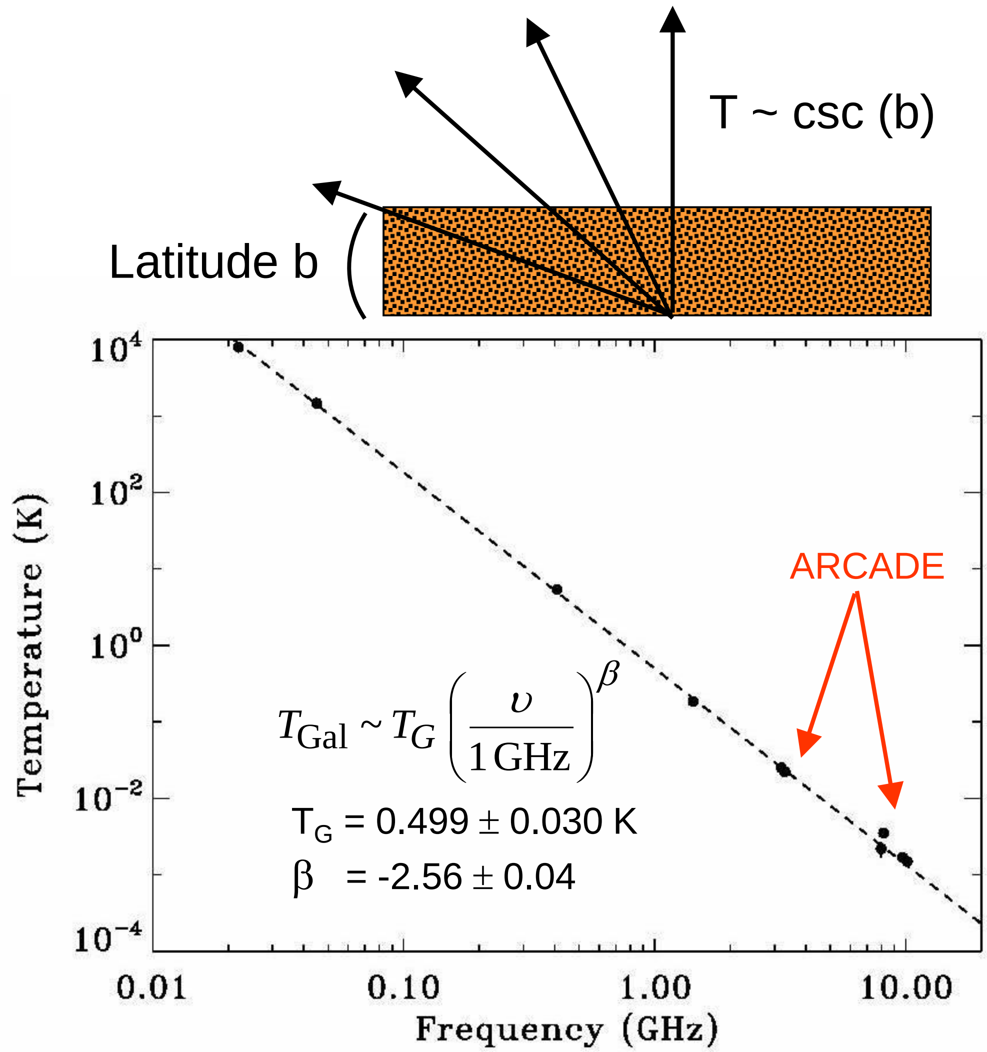
- Clean tracer of Galactic structure
- Compare radio to line emission

Look For Extra-Galactic Residual Using Multiple Lines of Sight

# Plane-Parallel Model

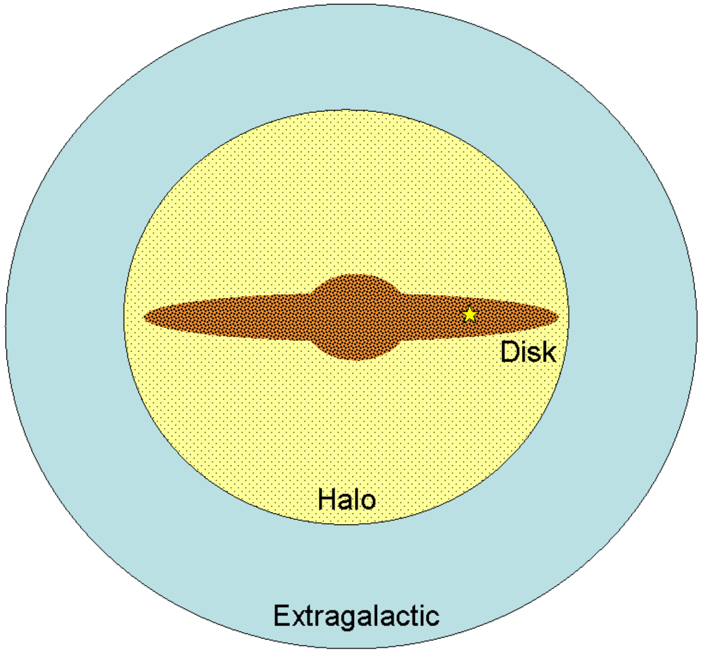
North Galactic hemisphere




Scatter from longitudinal structure dominates uncertainty in fit

# Radio/Atomic Line Correlation



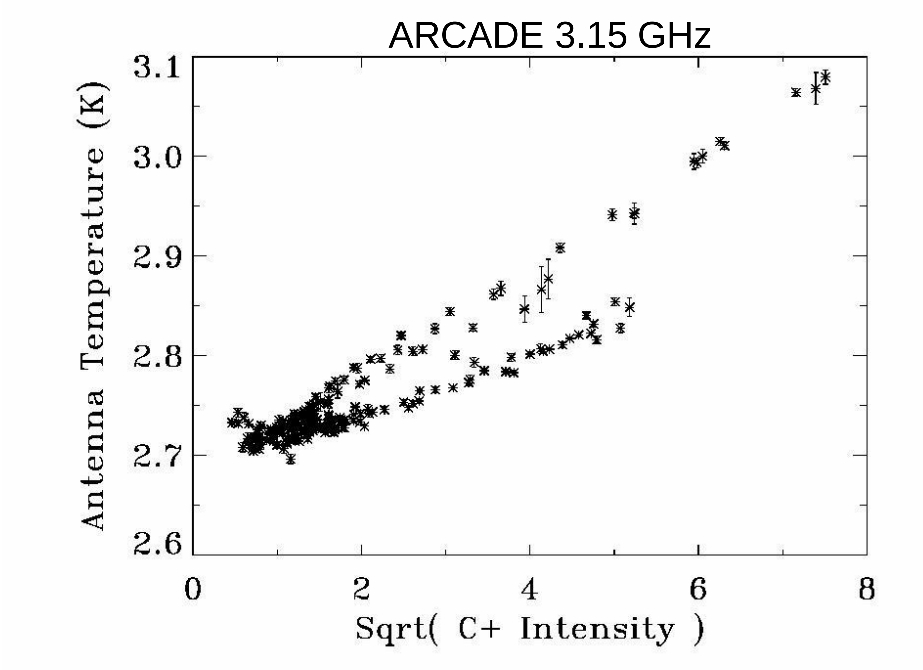

How Could We Detect Radio Halo?

Correlate radio vs line emission!

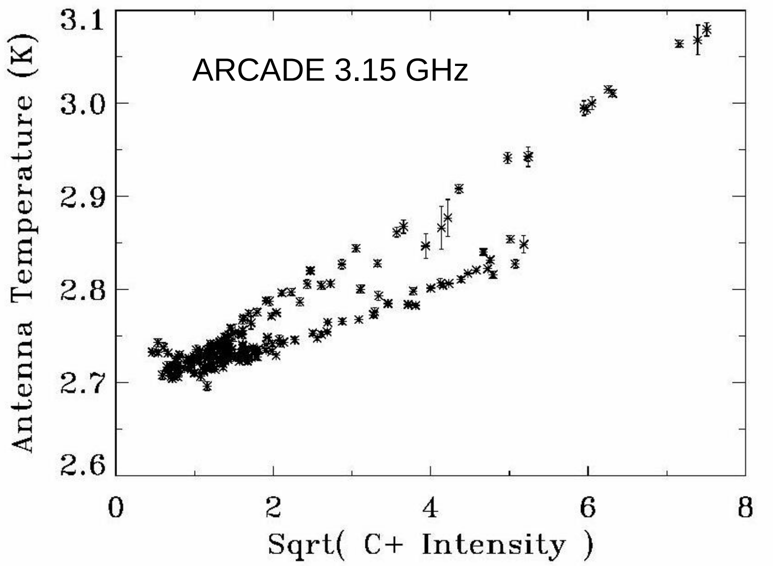
- Line emission associated with Galaxy
- Line emission has well-defined zero level
- Several full-sky surveys (H$\alpha$, 21 cm, C+)

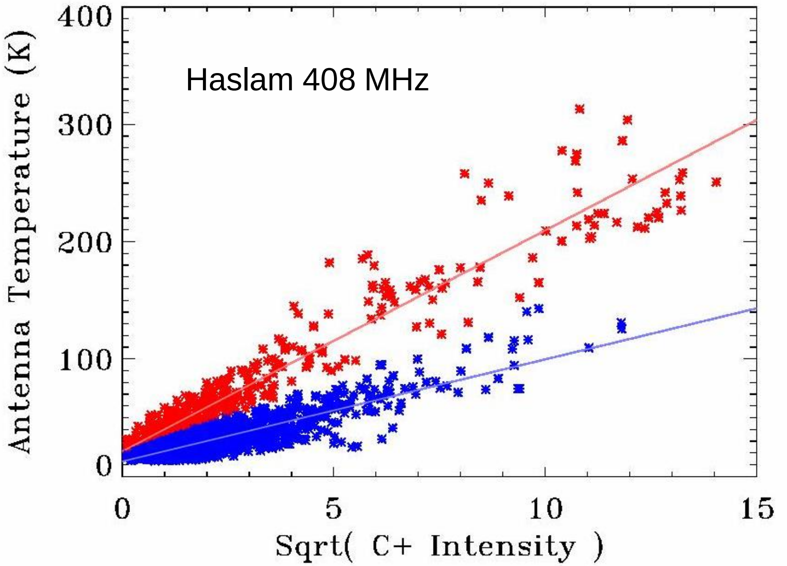
Correlate ARCADE vs C+ 158 $\mu$m line

- Well mixed in ISM
- Important cooling mechanism
- Unaffected by extinction



# Radio/C+ Correlation



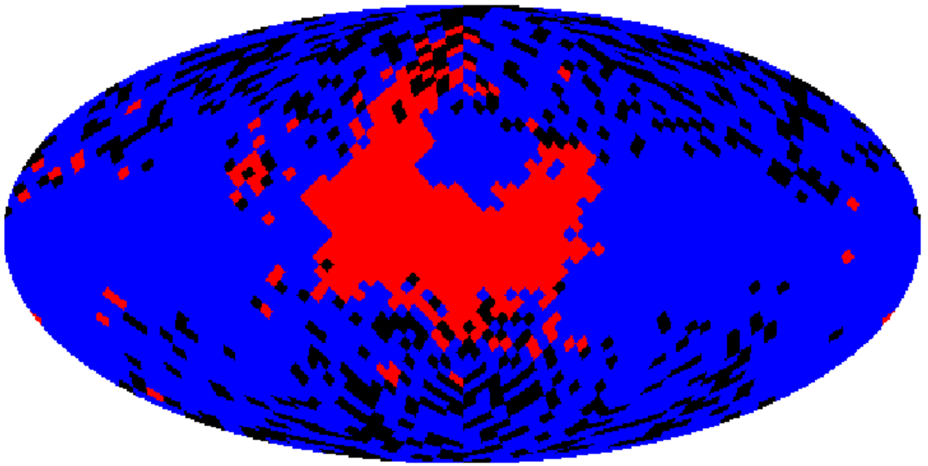

Clear correlation T ~ Sqrt( C+ )

- Radio emission ~ n and C+ ~ $n^2$
- Bifurcation suggests 2 components
- Spatial localization to synchrotron features

Radio/C+ slope

Estimated Galactic emission = $<\alpha> (I_C)^{1/2}$

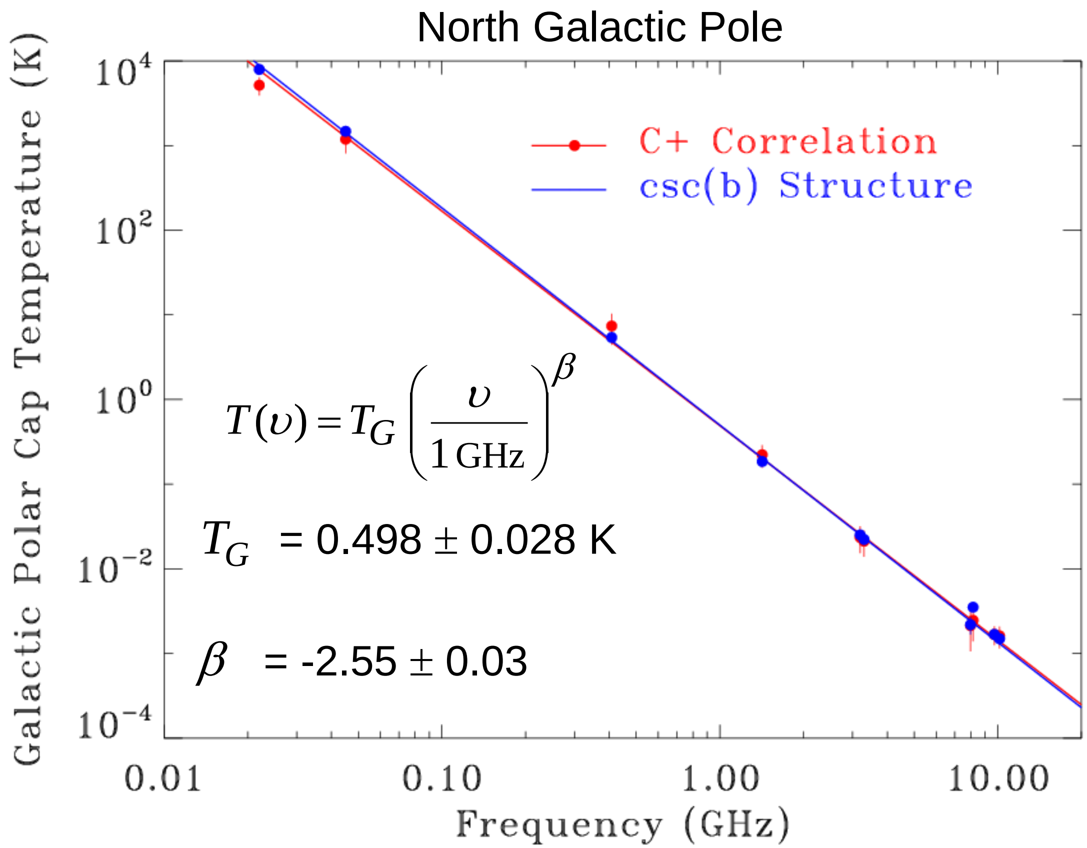
C+ Intensity in Selected Region



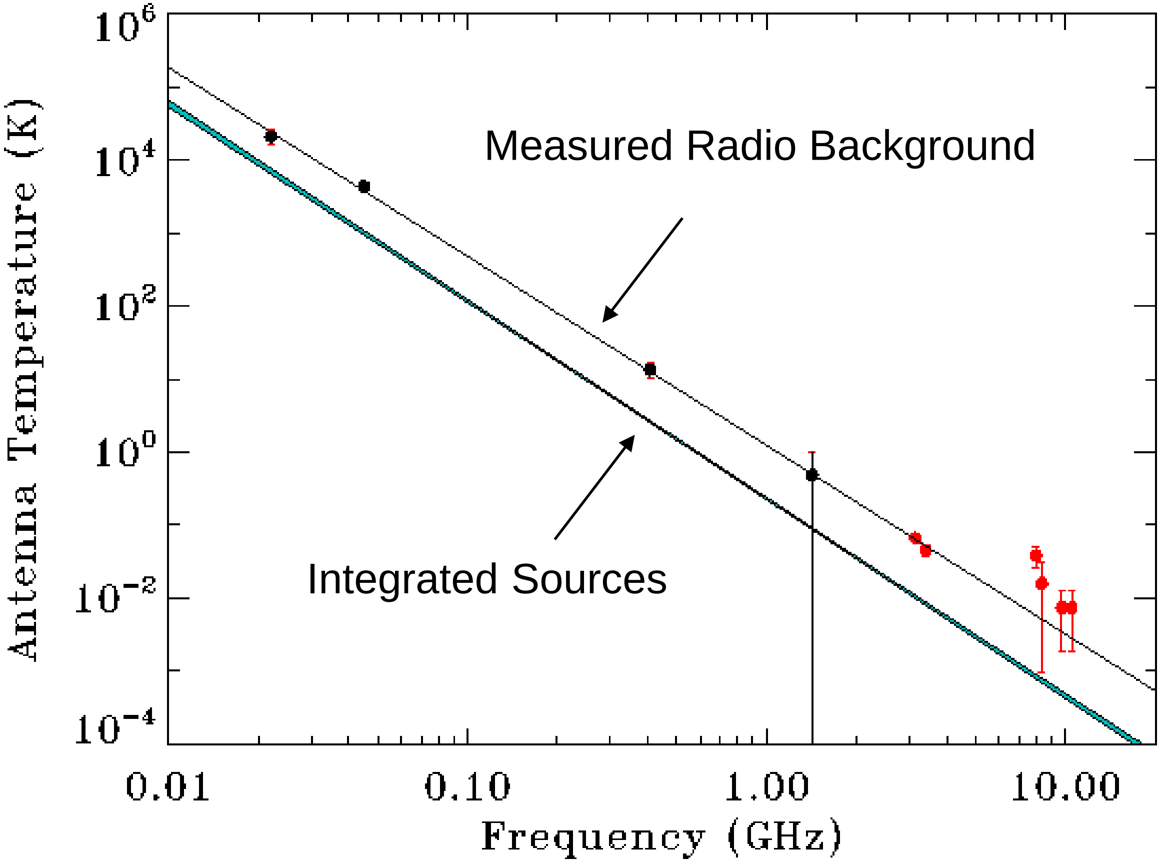
# Galactic Emission Estimate

Simple models work well
in best regions of the sky

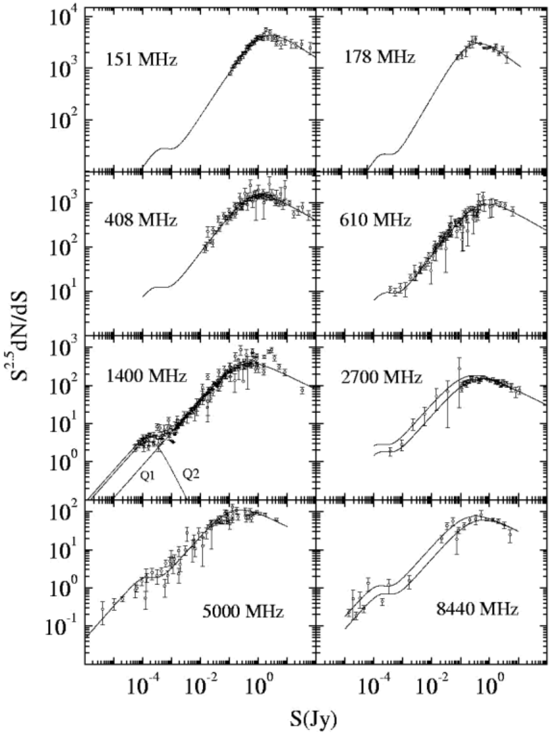
- Two methods agree
- Single power-law dependence
- Consistent with synchrotron



# Radio Background




**Measured Background 6x Brighter Than Predicted**




Gervasi et al. astro-ph/0803.4138

# Galaxy vs Background

| | | Galactic Emission | | Extra-Galactic Emission | |
|---|---|---|---|---|---|
| Model Technique | Reference Position | Amplitude (K) | Index | Amplitude (K) | Index |
| C+ | NGP | 0.49 ± 0.10 | -2.53 ± 0.07 | 0.94 ± 0.14 | -2.65 ± 0.04 |
| csc(b) | NGP | 0.50 ± 0.03 | -2.56 ± 0.04 | 0.88 ± 0.07 | -2.65 ± 0.03 |
| | | | | | |
| C+ | SGP | 0.30 ± 0.05 | -2.59 ± 0.06 | 1.13 ± 0.08 | -2.65 ± 0.02 |
| csc(b) | SGP | 0.37 ± 0.03 | -2.65 ± 0.05 | 1.06 ± 0.07 | -2.65 ± 0.02 |
| | | | | | |
| C+ | Coldest | 0.19 ± 0.13 | -2.56 ± 0.12 | 0.93 ± 0.13 | -2.58 ± 0.02 |

Varies by factor 2.5
from patch to patch

Mean 1.00 ± 0.04 K
$\chi^2$ = 6.2 for 4 DOF

Galactic part agrees between methods, but varies patch to patch
Extra-galactic part agrees over both methods and all patches

# Comparisons Among Data Sets

*Fit for CMB temperature plus radio amplitude & index*

| Data Set | $T_R$ (K) | Index | $T_0$ (K) | $\chi^2$/DOF |
|---|---|---|---|---|
| **LF+ARC+COBE** | $1.17 \pm 0.12$ | $-2.597 \pm 0.035$ | $2.725 \pm 0.001$ | 17.5/11 |
| **LF+ARC** | $1.10 \pm 0.16$ | $-2.620 \pm 0.040$ | $2.732 \pm 0.005$ | 15.2/10 |
| **LF+COBE** | $1.16 \pm 0.38$ | $-2.602 \pm 0.065$ | $2.725 \pm 0.001$ | .68/2 |
| **ARC+COBE** | $1.17 \pm 0.14$ | (-2.60) | $2.725 \pm 0.001$ | 16.8/8 |
| **LF** | $1.15 \pm 0.50$ | $-2.607 \pm 0.07$ | $2.81 \pm 0.7$ | .66/1 |
| **ARC** | $1.04 \pm 0.16$ | (-2.60) | $2.732 \pm 0.004$ | 14.4/7 |

*Any combination of independent data sets gives the same answer*

# New Measurements

Control/measure offset

Gain 1% or better

Measure polarization

High frequencies: Liquid Helium load

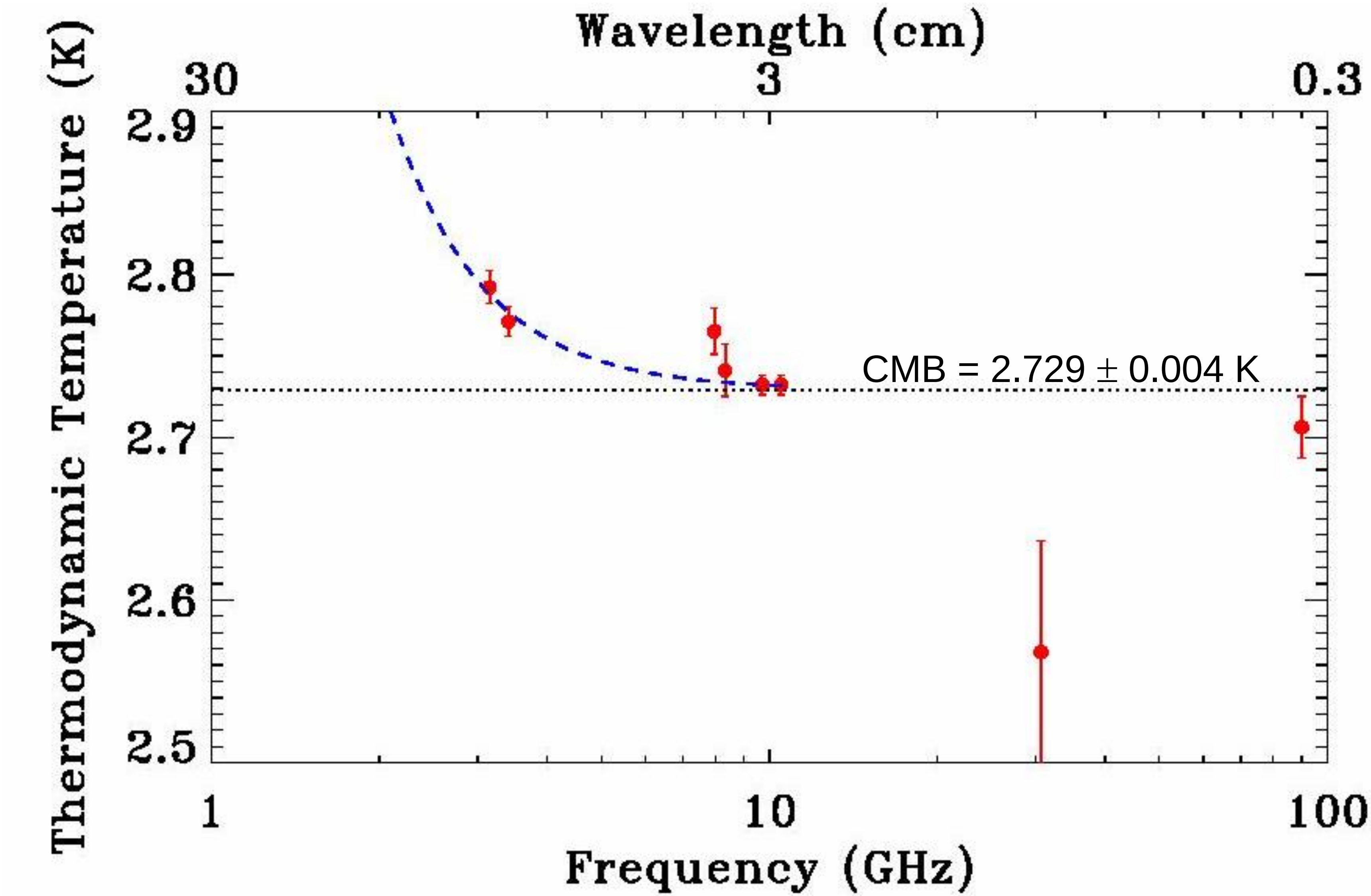
Low frequencies: Phased Array

# Potential CRB Measurements

| Frequency | Wavelength | Diameter | Back Temp | Precision | Notes |
|---|---|---|---|---|---|
| **3 GHz** | 10 cm | 2 m | 2.8 | .6 mK | ARCADE, Liq He |
| **1.3 GHz** | 23 cm | 6 m | 3.3 | 5 mK | Liquid Helium |
| **610 MHz** | 49 cm | 10 m | 6.6 | 30 mK | Liquid Helium |
| **250 MHz** | 1.2 m | 30 m | 42 | .4 K | Liquid Nitrogen |
| **110 MHz** | 2.7 m | 75 m | 334 | 3 K | Room Temp |
| **74 MHz** | 4 m | 100 m | 935 | 9 K | Astronomy Band |
| **38 MHz** | 7.9 m | 200 m | 5300 | 53 K | Astronomy Band |
| **25 MHz** | 12 m | 300 m | 16000 | 160 K | Astronomy Band |

1% Gain precision

# Extragalactic Sky Temperature



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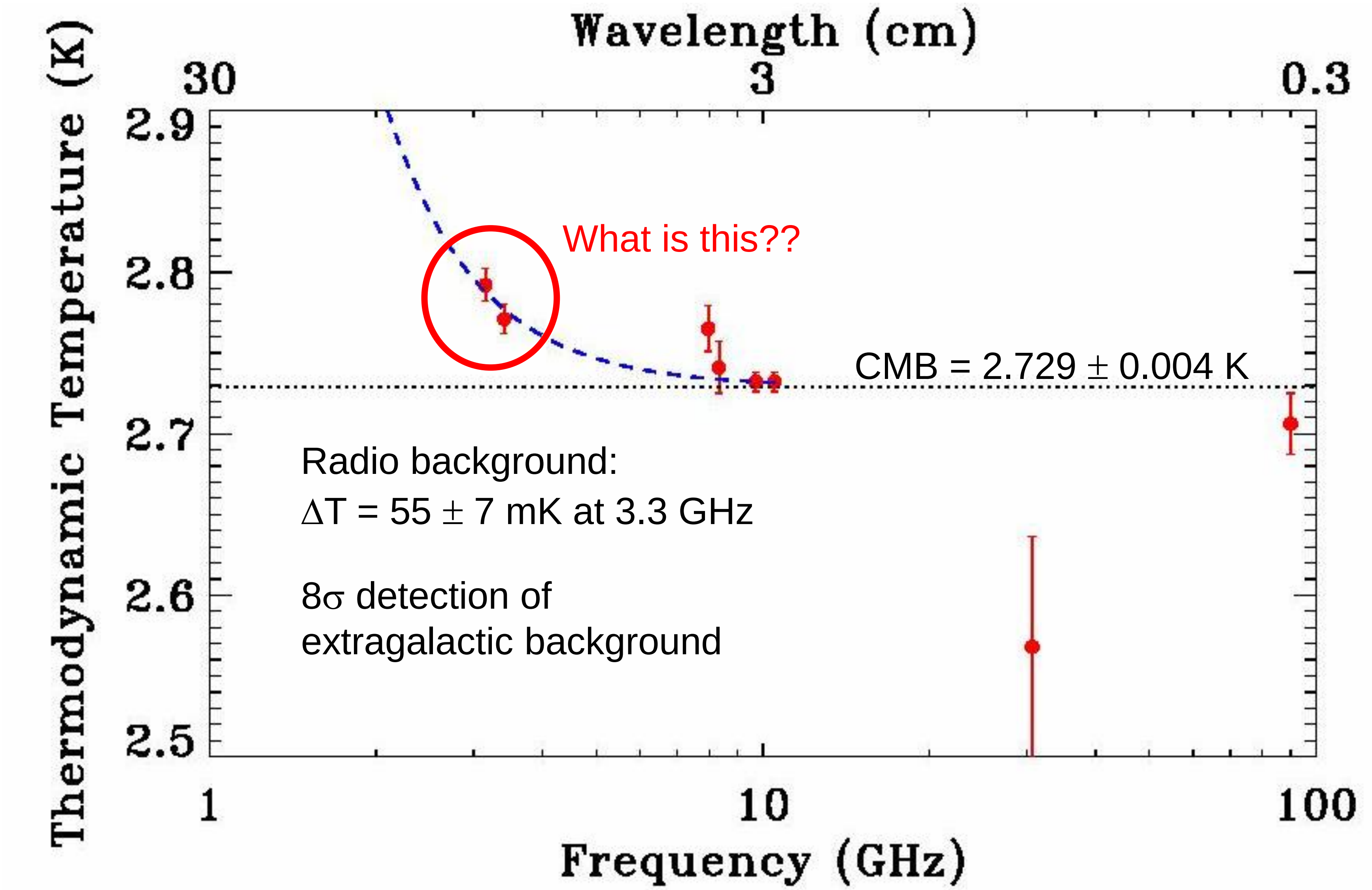
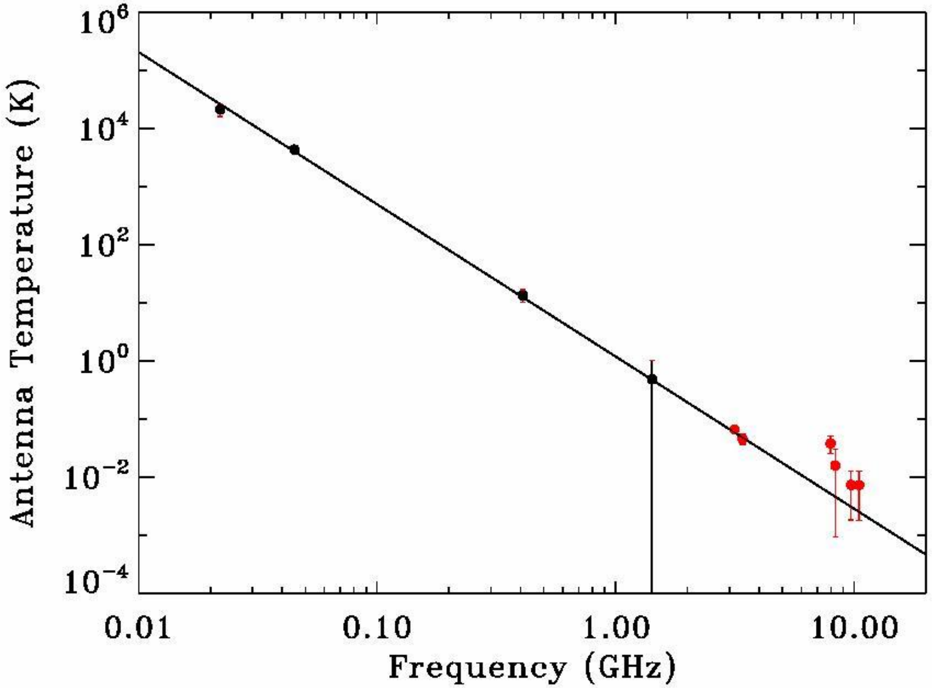


# Observed Radio Background




ARCADE by itself can not determine spectrum of background

Perform identical analysis for full-sky low-frequency radio surveys

- 22 MHz (Roger et al. 1999)
- 45 MHz (Maeda et al 1999, Alvarez et al 1997)
- 408 MHz (Haslam et al. 1981)
- 1420 MHz (Reich & Reich 1986)

Combined ARCADE + Radio data

$T_{CMB}$ = 2.732 ± 0.005 K

$T_R$ = 1.10 ± 0.16 K

$\beta$ = -2.62 ± 0.04

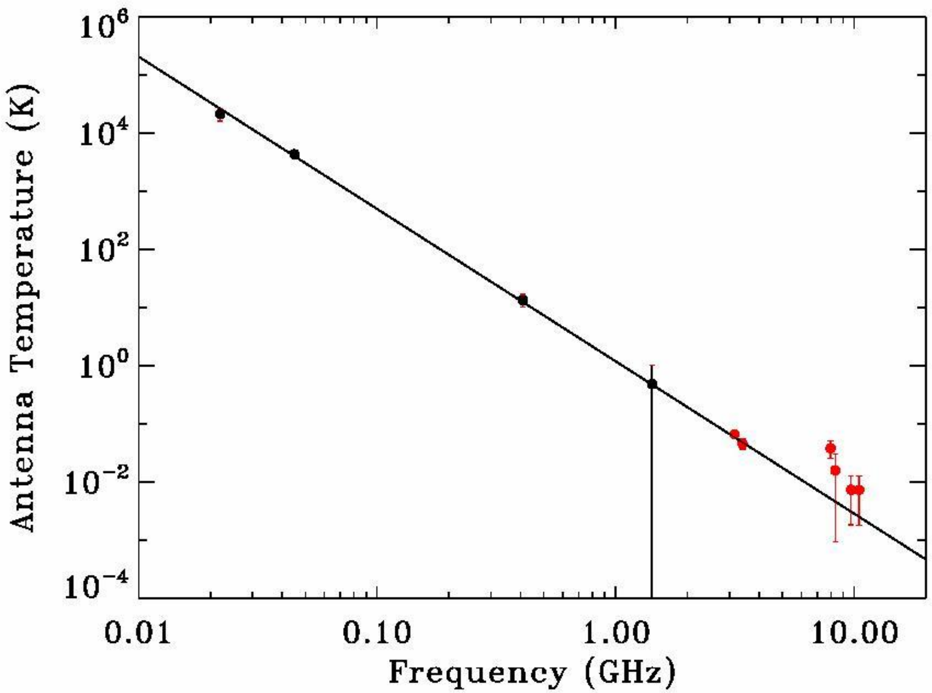
$\chi^2$ = 15.2 for 10 DOF

ARCADE $T_{CMB}$ consistent with COBE (approaching COBE precision!)

Radio amplitude set by ARCADE

Radio index set by low-freq surveys

# Observed Radio Background

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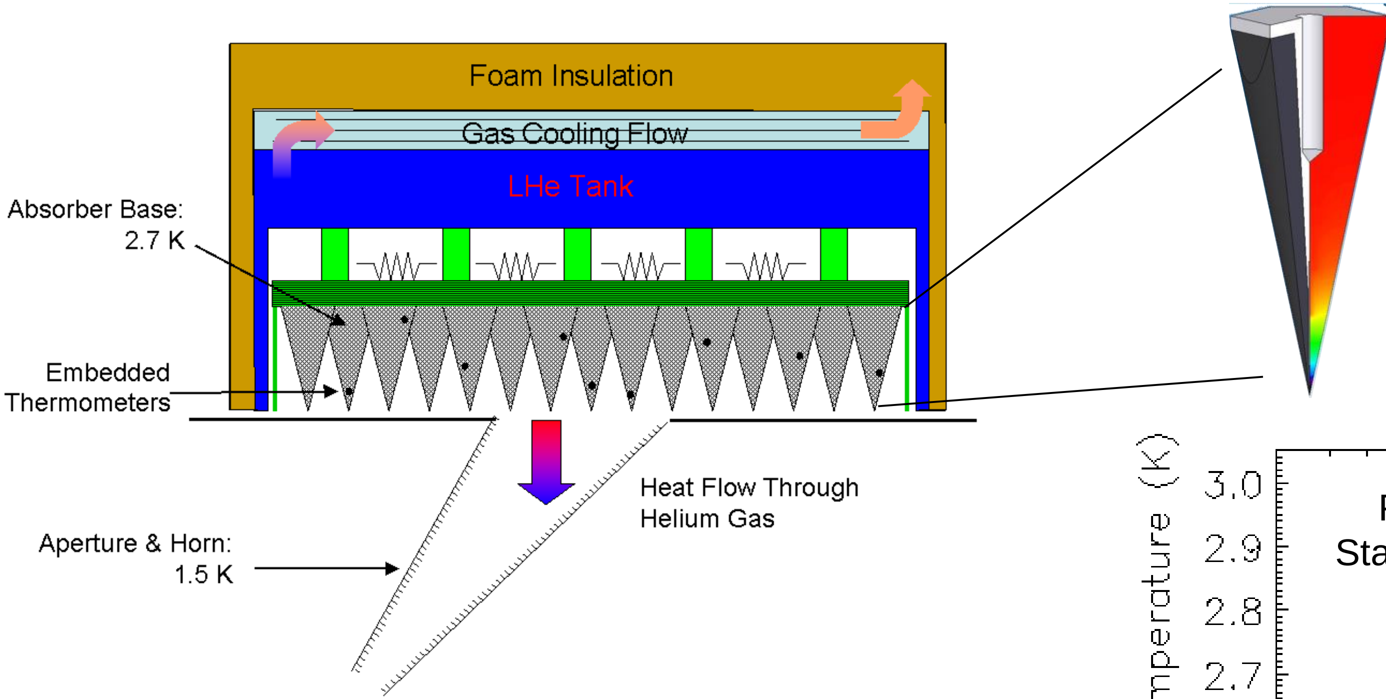
Radio amplitude set by ARCADE

Radio index set by low-freq surveys

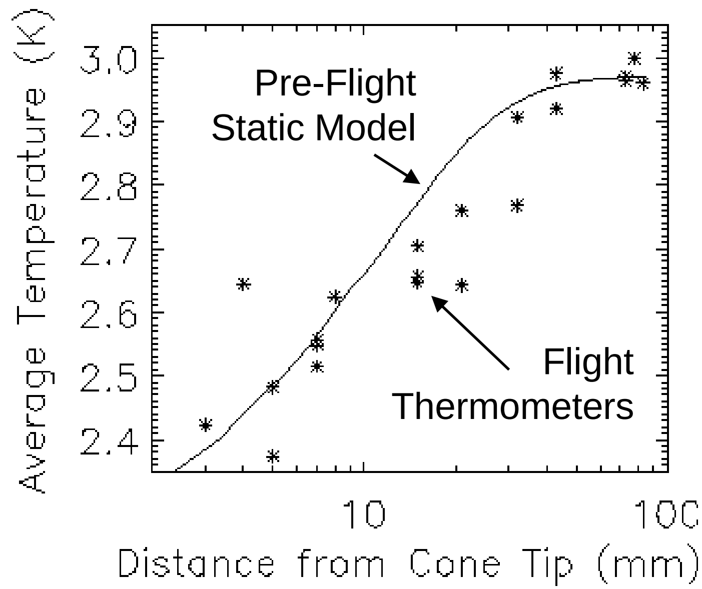
Observed spectral index inconsistent with signature from reionization ($\beta = -2.1$)

# Loopholes I: ARCADE Error?

## Thermal Gradients in External Calibrator




Model Thermal Profile
in Absorbing Cone




Thermal gradient from heat flow in absorber

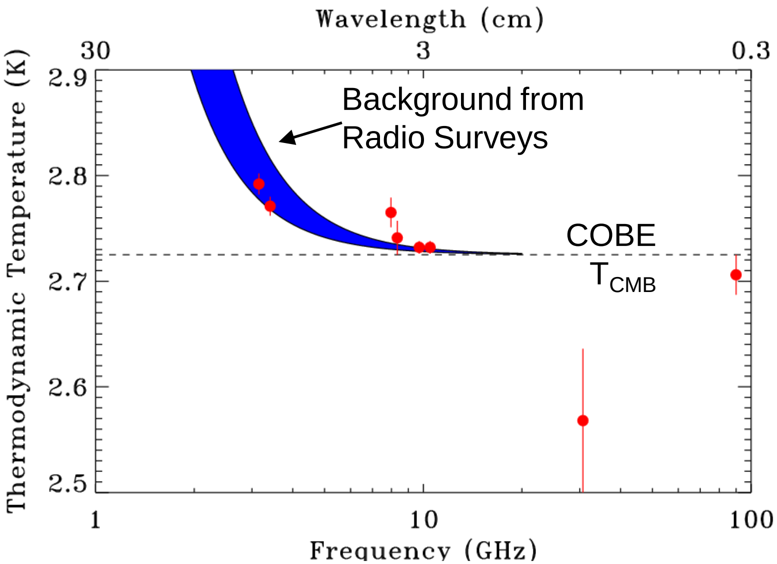
21 thermometers sample actual gradient

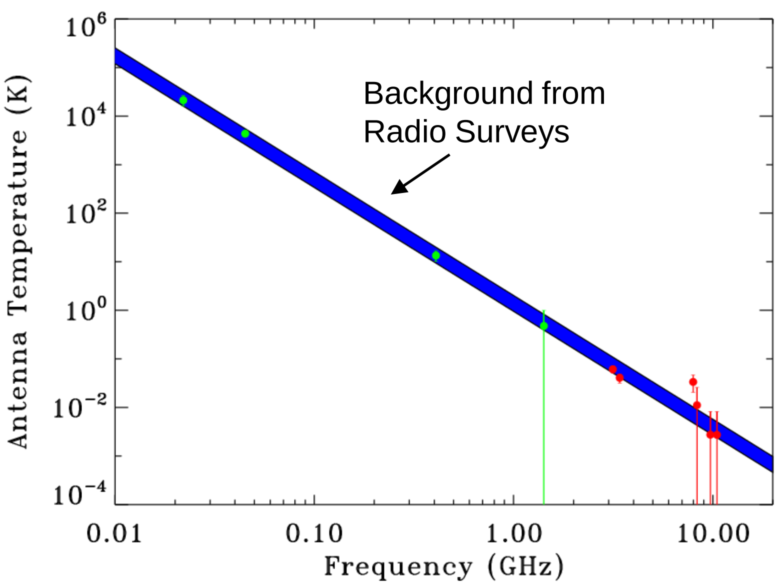
97% of absorber volume within 10 mK of base

Coupling to radiometers set by data, not model

**ARCADE is hugely over-populated with thermometers!**

# Cross-Checks Above & Below




| Data | CMB | Background |
|---|---|---|
| COBE | 2.725 ± 0.001 | --- |
| ARCADE | 2.732 ± 0.004 | 1.04 ± 0.16 |
| Radio | 2.8 ± 0.7 | 1.14 ± 0.5 |

Agreement between ARCADE and independent data sets at higher & lower frequencies rules out gradient error

- High freq: Preferentially sample cone tips
- Low freq: Sample full absorber volume

Combined ARCADE + COBE + Radio data

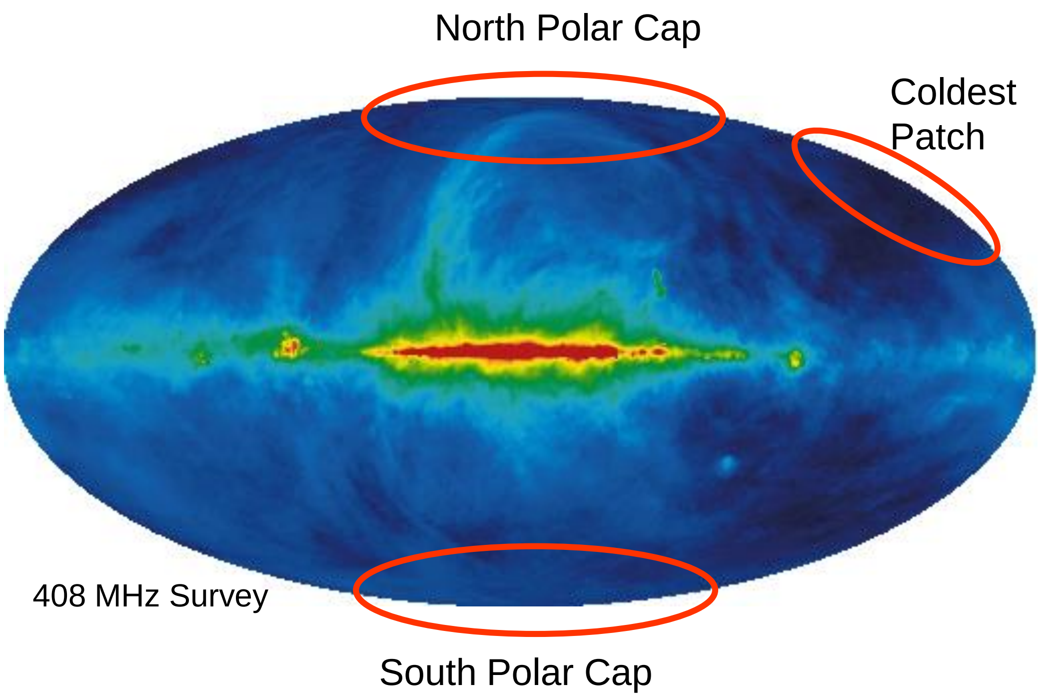
$T_{CMB}$ = 2.725 ± 0.001 K

$T_R$ = 1.17 ± 0.12 K

$\beta$ = -2.60 ± 0.04

$\chi^2$ = 17.5 for 11 DOF

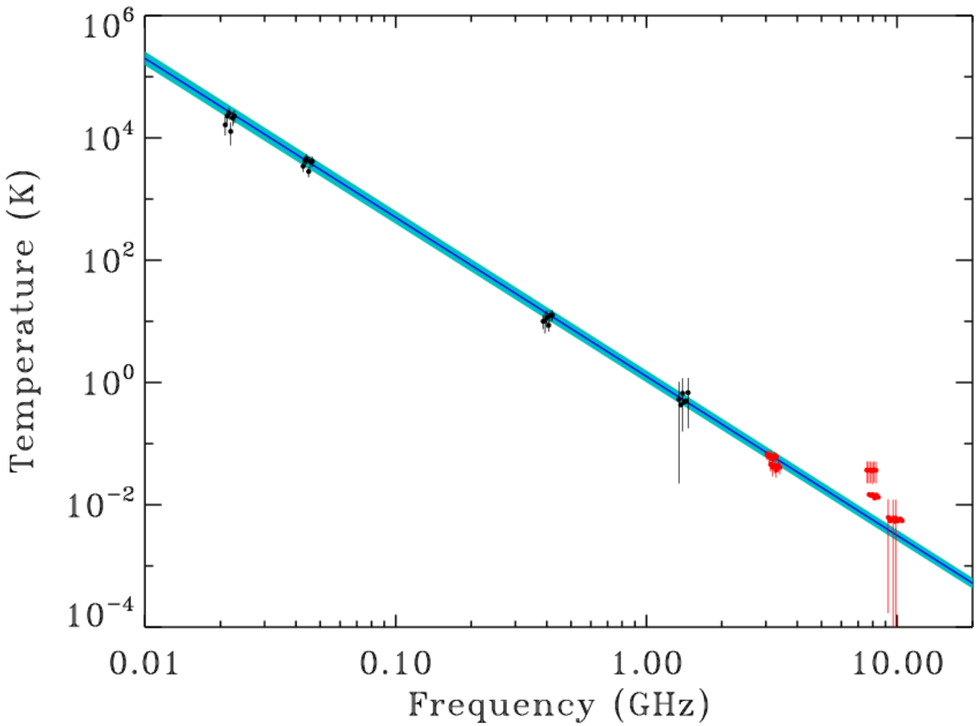
# Loopholes 2: Error in Galactic Model




Multiple cross-checks on background

- 2 independent techniques
- 3 independent reference lines of sight
- Consistent background estimate as foregrounds vary by factor of 3

# Multiple Background Estimates




60 Estimates of Radio Background

- 10 frequencies
- 3 lines of sight
- 2 Galaxy models

Highly correlated in some "directions"

Best-Fit Power-Law Model
(including covariance)

$$T(\upsilon) = T_R \left( \frac{\upsilon}{1\,\text{GHz}} \right)^{\beta}$$

Straight Fit To Sky Data

$T_R = 1.17 \pm 0.12$ K

$\beta = -2.60 \pm 0.04$

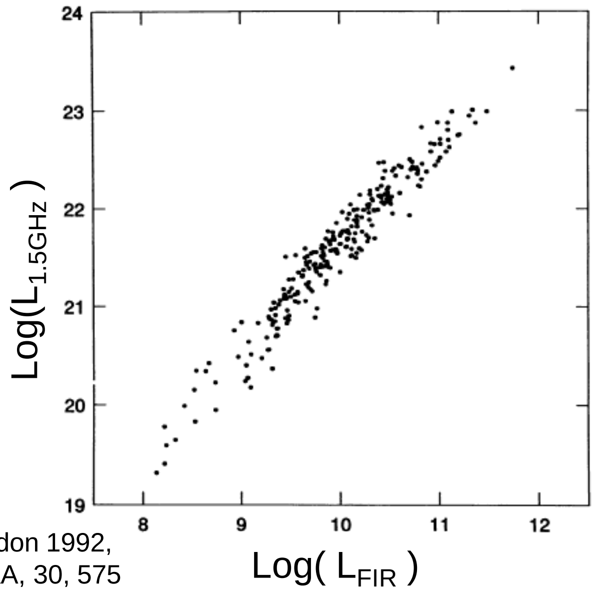
Corrected For Radio Sources

$T_R = 0.97 \pm 0.14$ K

$\beta = -2.56 \pm 0.04$

***Consistent Estimate of Radio Background***

# Hints of an Origin



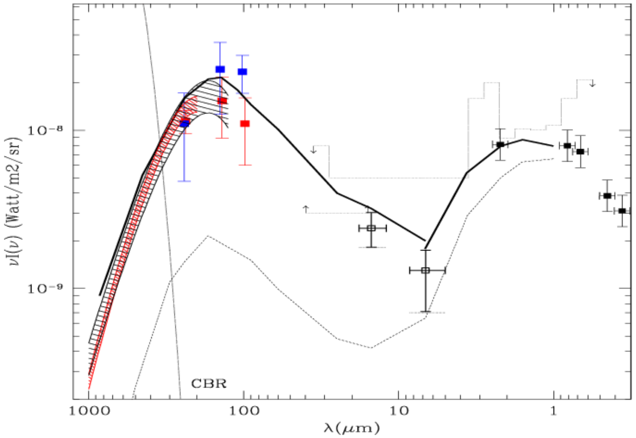

Condon 1992,
ARAA, 30, 575

Tight correlation between radio and IR emission

Predict radio background associated with observed far-IR background

- Predict $T_R$ ~ 5--10 mK at 3 GHz
- Consistent with radio source counts
- Too small to make up observed background

Dwek & Barker 2002, APJ, 575, 7



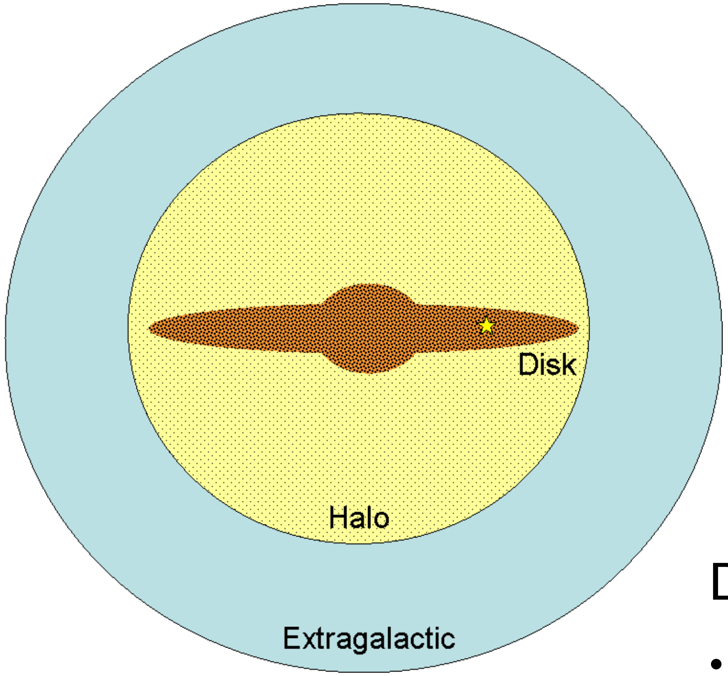

Franceschini et al 2001,
A&A, 378, 1

**Required Source Properties:**

- Bright in synchrotron
- Faint in infrared

Need mechanism to break radio/IR correlation

# Loopholes 3: Bright Galactic Halo?




Difficult to produce radio-bright halo

• Background is 2--3 x Galactic brightness

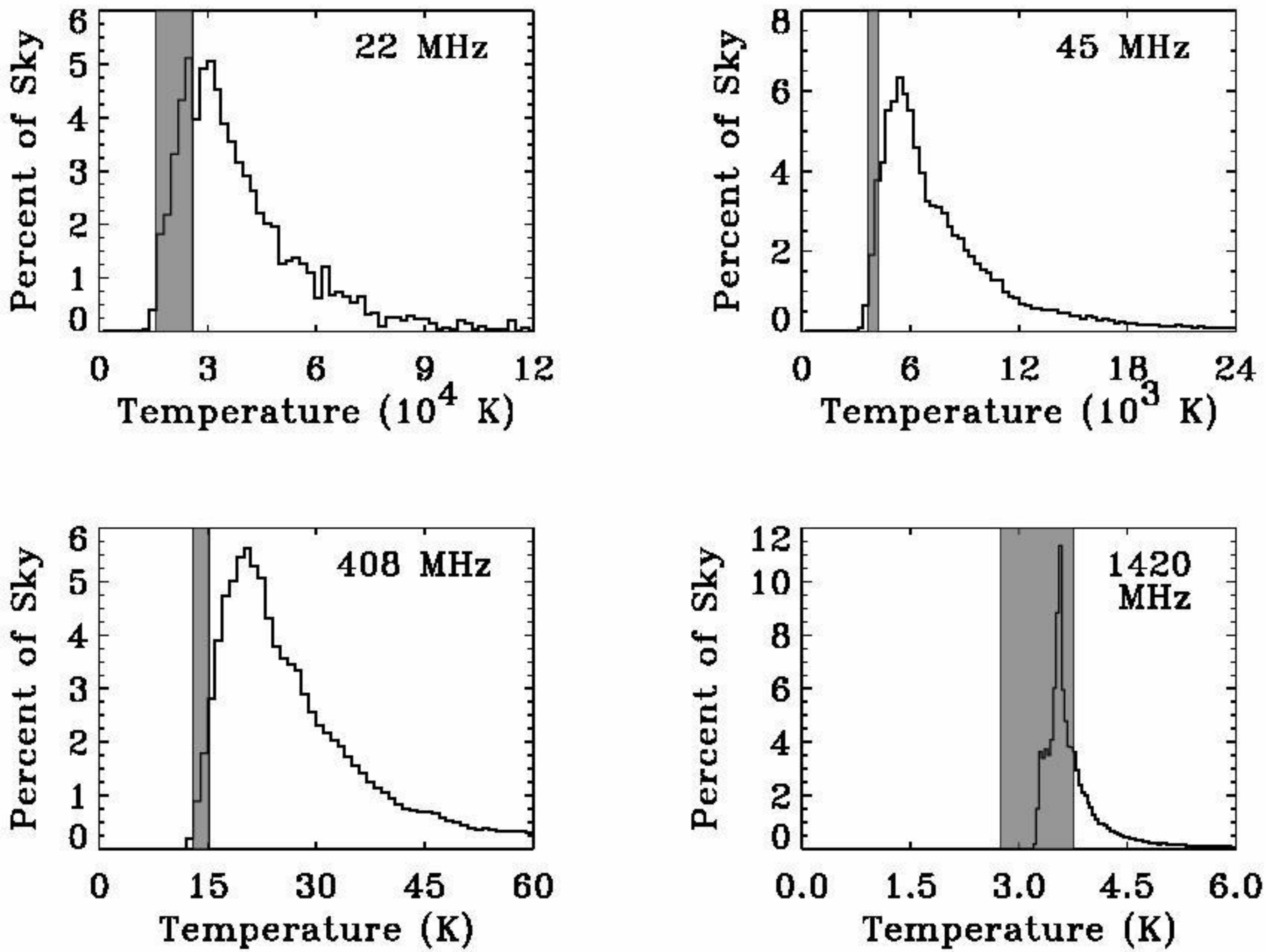
Halo radius large compared to disk

Large halo atypical for external galaxies

• No change in fit as more lines are added

Halo can't contain C, H, or dust (!)

# Background vs Noise in Radio Surveys

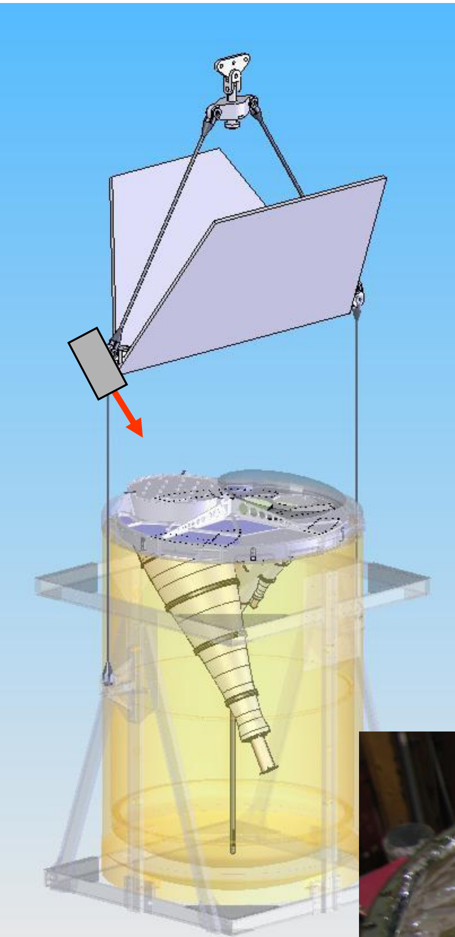


# ARCADE Uncertainties

| Source | 3L | 3H | 8L | 8H | 10L | 10H | 30L | 30H | 90L | 90H | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Thermometer Cal | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | Verify using LHe $\Lambda$ transition |
| Radiometer Cal | 6.7 | 5.7 | 4.2 | 4.4 | 4.3 | 4.2 | 153 | 75 | 35 | 20 | Calibrator Gradients |
| Statistics | 5.0 | 4.7 | 7.7 | 8.6 | 3.9 | 4.1 | 27 | 14 | 14 | 6.9 | White noise plus 1/f |
| Galaxy | 5.3 | 4.9 | 0.6 | 0.6 | 0.4 | 0.4 | 0.0 | 0.0 | 0.0 | 0.0 | |
| Instrument Emission | 3.2 | 1.7 | 11.0 | 12.7 | 0.9 | 0.7 | 1.3 | 1.4 | 5.2 | 5.1 | Spreader bar |
| Atmosphere | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.7 | 0.7 | 1.4 | 1.4 | |
| Quadrature Sum | 10.5 | 9.1 | 14.1 | 16.0 | 6.0 | 6..0 | 155 | 76 | 38 | 22 | |

Measure sky temperature to absolute precision ~ 10 mK

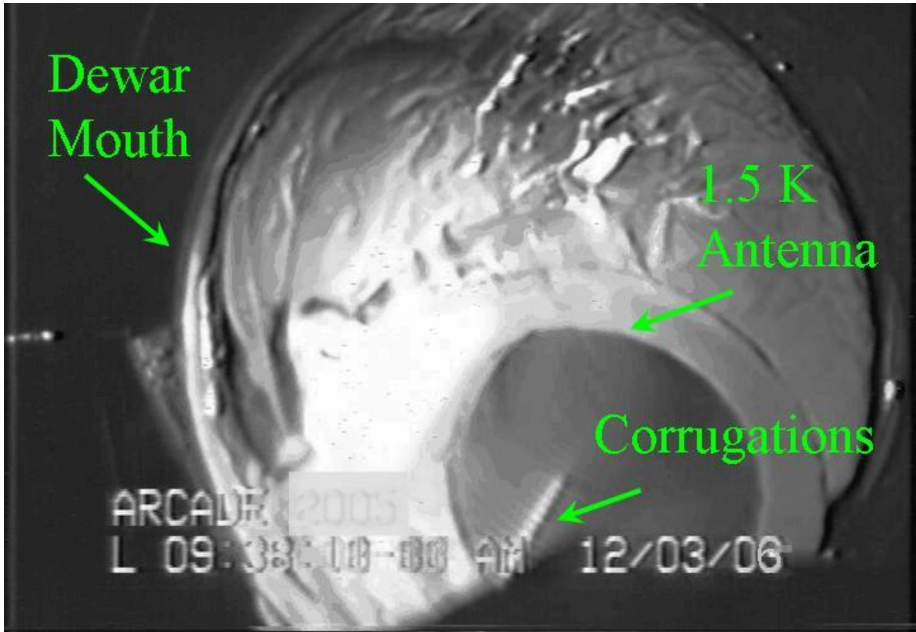
# Open-Aperture Cryogenics

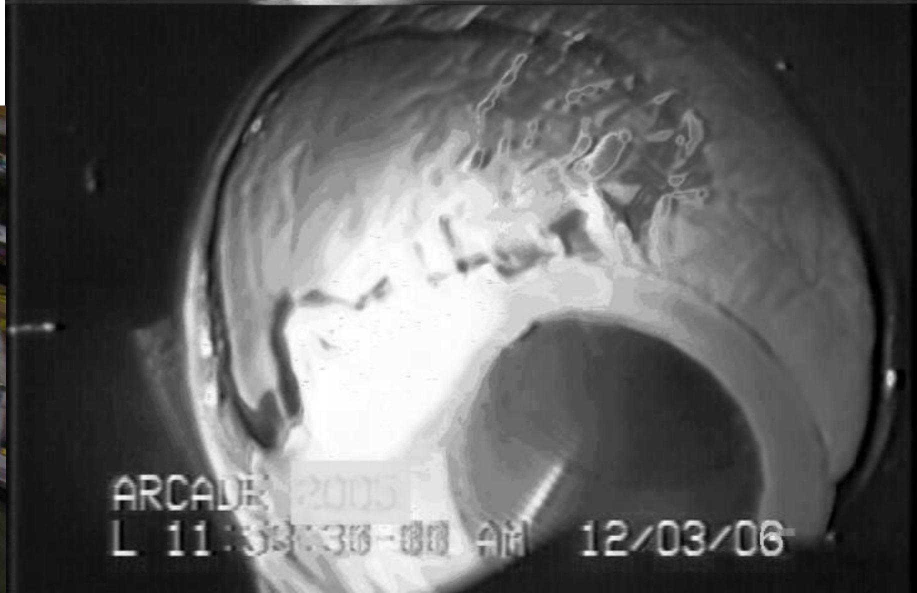


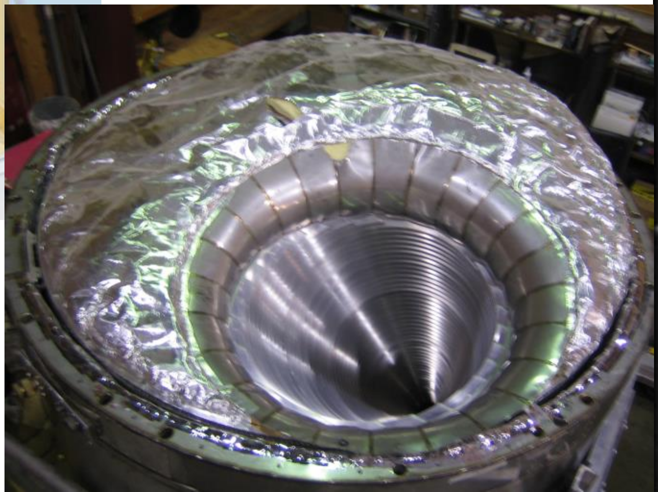
In-flight video camera looks down at dewar

Capture images of 3 GHz antenna 2 hours apart

No nitrogen condensation visible on optics

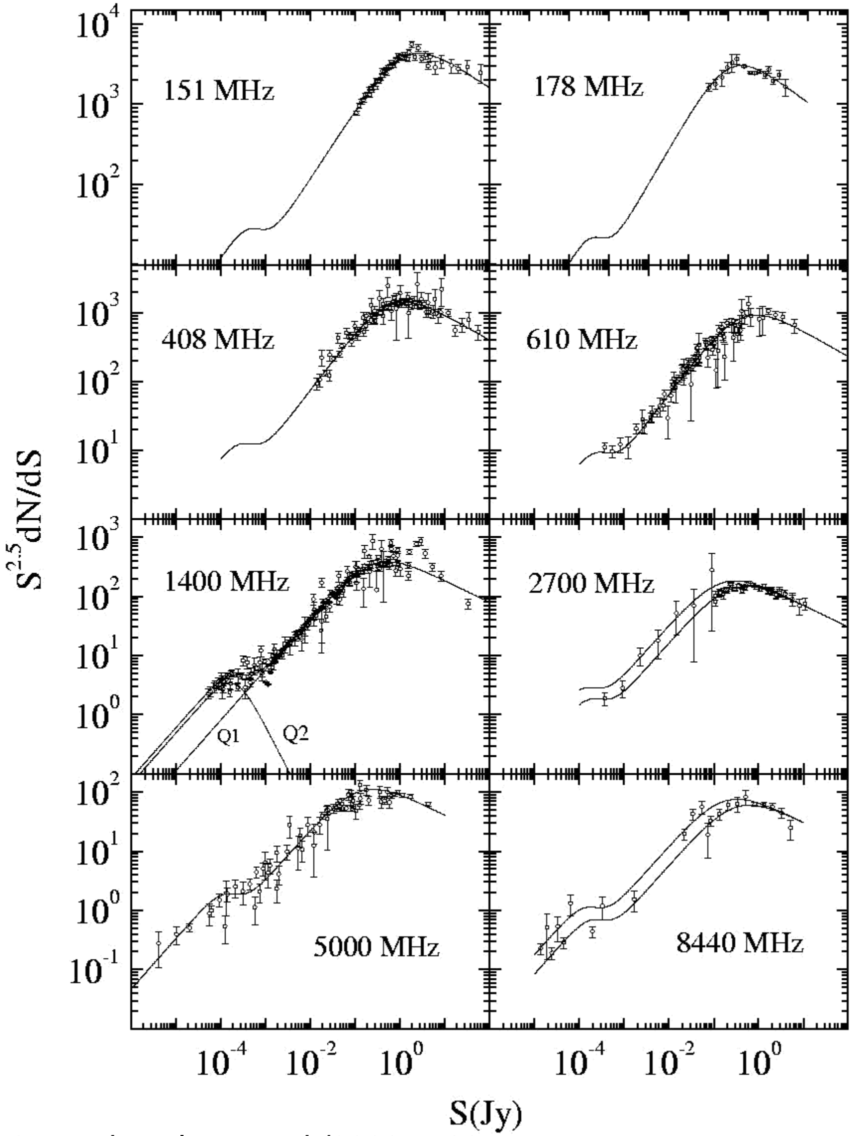


Pre-flight

# Predicted Radio Background




Gervasi et al. astro-ph/0803.4138

$$\frac{dN}{dS} = S^{-\gamma} \text{ with } \gamma = 2.11 \pm 0.13$$

Integrated Radio Background

$$T_R = \frac{\lambda^2}{2\pi} \int \frac{dN}{dS} S \, dS$$

Scale observed sources to 3.3 GHz

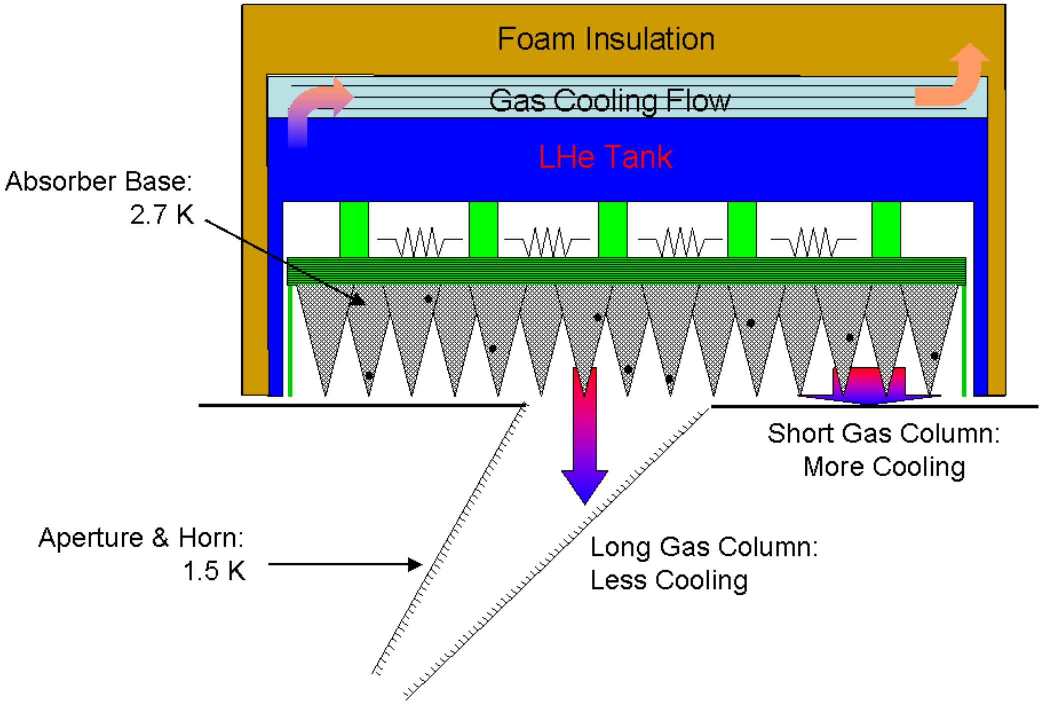
Predicted: $T_R = 9 \pm 2$ mK

Observed: $T_R = 55 \pm 7$ mK

**Observed Background is 6x brighter than expected!**

***Are There Any Loopholes?***

# Calibrator Thermal Gradients



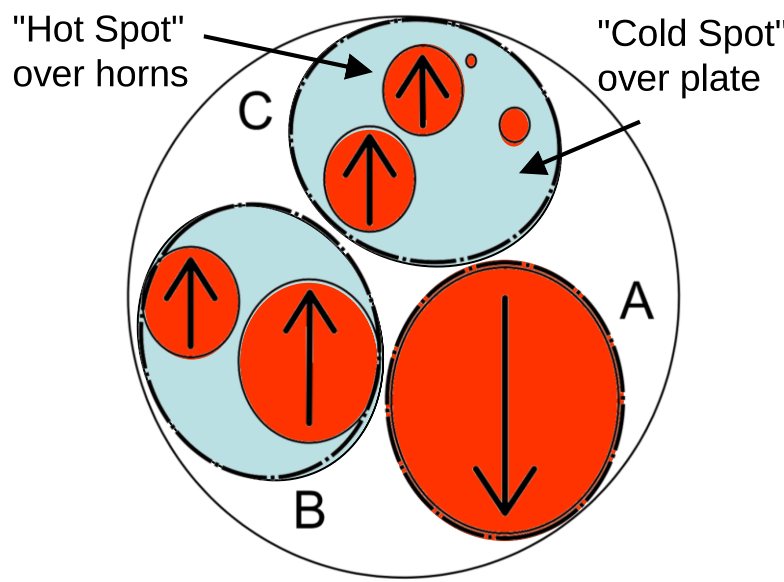

Expect gradients linked to heat flow from absorber to aperture

- 600 mK front--back
- 20 mK "footprint" of horns

Embedded thermometers measure actual in-flight gradients

$$T_A = \frac{\int T(x,y,z)P(x,y,z)}{\int P(x,y,z)}$$

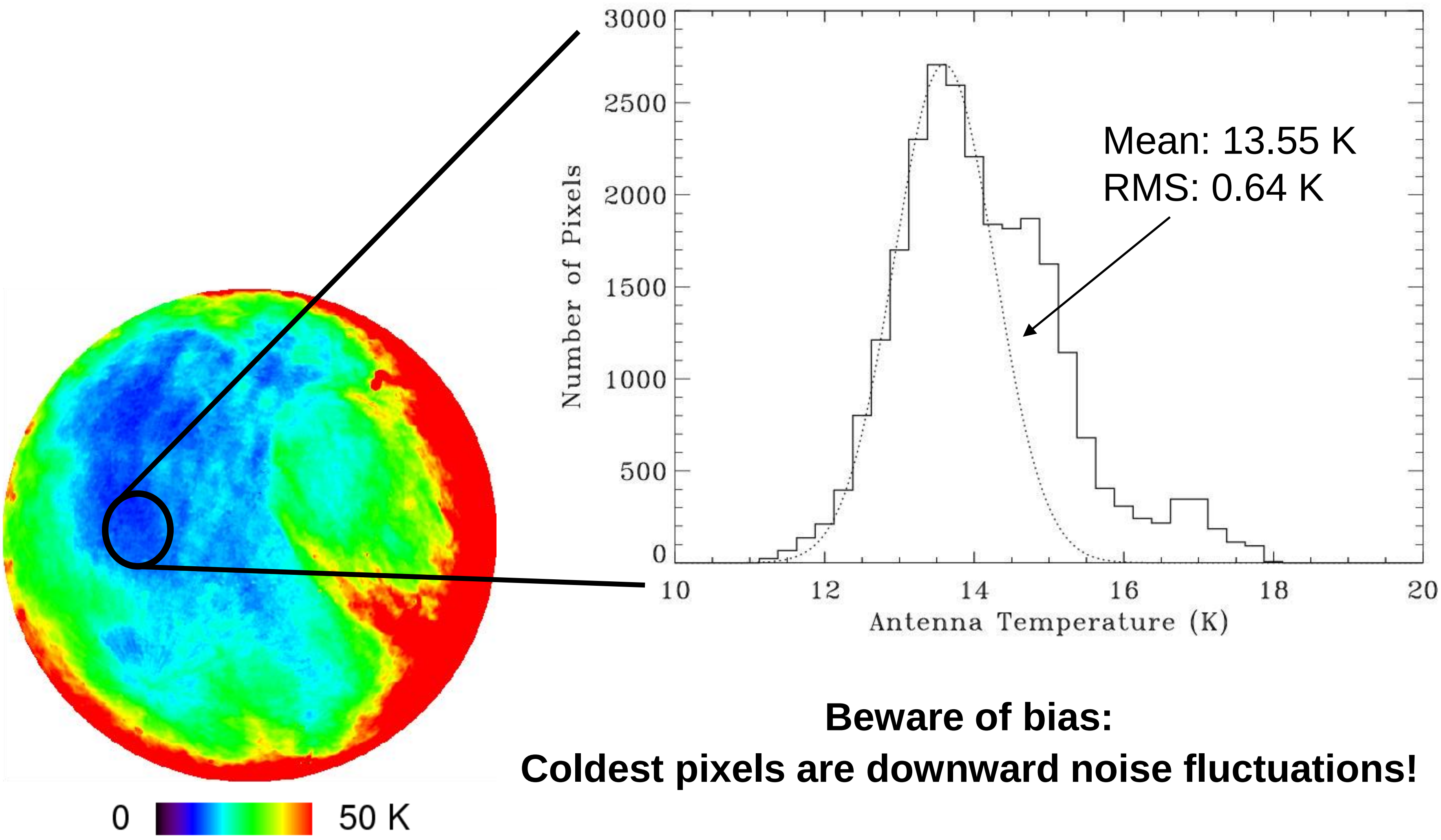
Horn "Footprint" on Calibrator




Two ways to model calibrator emission

- Correlate radiometer output vs thermometers
- Principal components of thermometer data alone

# Coldest Pixels




**Beware of bias:**
**Coldest pixels are downward noise fluctuations!**

408 MHz survey, Northern Hemisphere

# Principal Component Model

Eigenvector decomposition of thermometer readout vs time

$$V \cdot D \cdot V^T = T\,T^T$$

21 eigenvectors: $V V^T = I$

21 diagonal eigenvalues

Thermometer data: 21 rows x N samples

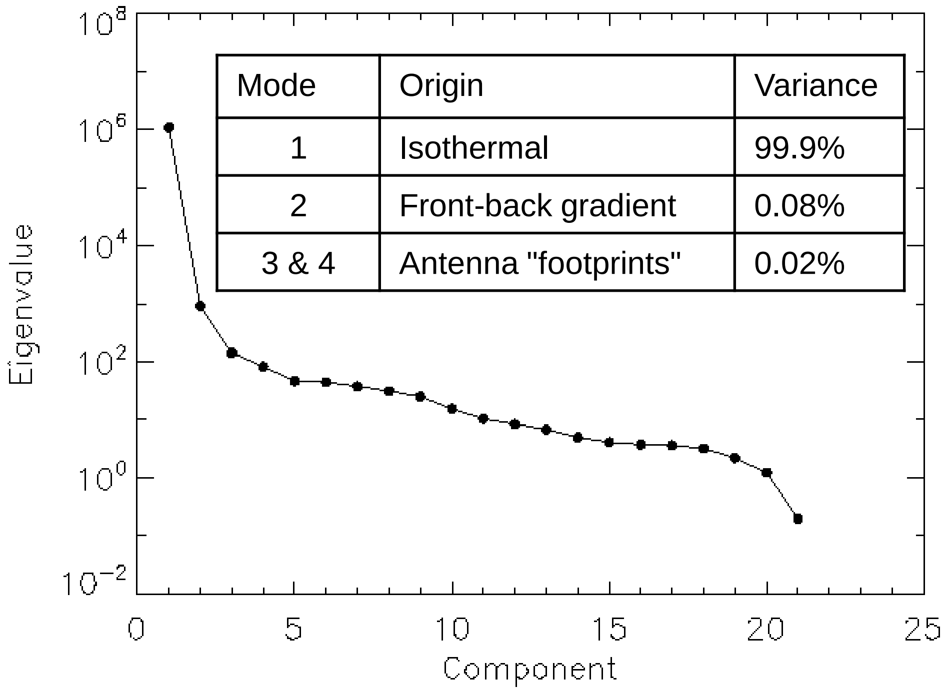
Use entire data set (even during moves) to define thermal modes

Evaluate modes only during "quiet" data for radiometer calibration

Radiometer calibration uses first 10 modes (99.996% of variance)

Using more/fewer modes, or 10 random thermometers, only changes sky results by few mK

*ARCADE calibrator is hugely over-populated with thermometers!*




| Mode | Origin | Variance |
|---|---|---|
| 1 | Isothermal | 99.9% |
| 2 | Front-back gradient | 0.08% |
| 3 & 4 | Antenna "footprints" | 0.02% |

# Radiometer Component Summary

TABLE 1
TABLE OF SELECTED RADIOMETER HARDWARE SPECIFICATIONS

| | 3 GHz | 5 GHz | 8 GHz | 10 GHz | 30 GHz | 30#[a] GHz | 90 GHz |
|---|---|---|---|---|---|---|---|
| Low Band (GHz) | 3.09-3.30 | 5.16-5.50 | 7.80-8.15 | 9.2-10.15 | 28.5-30.5 | 28.5-30.5 | 87.5-89.0 |
| High Band (GHz) | 3.30-3.52 | 5.50-5.83 | 8.15-8.50 | 10.15-10.83 | 30.5-31.5 | 30.5-31.5 | 89.0-90.5 |
| Switch Type[b] | MEMS | MEMS | Cir | Cir | Cir | Cir | Cir |
| Cold Amplifier Mfg. | Berkshire | Berkshire | Berkshire | Berkshire | Spacek | Spacek | JPL |
| Cold Amp Model # | S-3.5-30H | C-5.0-25H | X8.0-30H | X10.0-30H | 26-3WC[c] | 26-3WC[d] | 90 GHz Amps |
| Cold Amp Serial # | 105 | 106 | 108 | 101 | 5D12 | 6C21 | W82&W105[d] |
| Cold Amp Gain (dB) | 40 | 29 | 40 | 40 | 26 | 20 | 52 |
| Warm Amp 1 Gain (dB) | 35 | 33 | 33 | 30 | 46 | 22 | -7[e] |
| Attenuator (dB) | -26 | -13 | -26 | -20 | -3 | -10 | -6 |
| Warm Amp 2 Gain (dB) | 35 | 33 | 33 | 31 | - | 23 | 40 |
| Detector Power (dBm) | -21.3 | -20.6 | -28 | -24.6 | -25.9 | -42.5 | -24.6 |

[b] 30# designates the 30 GHz channel with the narrower antenna beam.
[b] Switches are either MEMS (Micro-Electro-Mechanical System) or ferrite latching waveguide circulator switches.
[c] These model numbers have the prefix "SL315-".
[d] At 90 GHz there two are cold amplifiers in series.
[e] The 90 GHz channel warm stage uses a mixer, with a 79.5 GHz local oscillator, to translate it to 8-11 GHz, and all following components operate in that frequency range.

Singal et al. 2009, ApJ (submitted)
arXiv:0901.0546

# Instrument Emission Summary

Estimates of the radiometric temperature contribution from the balloon and other components visible in the antenna beams, for channels used for science analysis in the 2006 flight. See §??. All estimates are in mK.

| Component | 3L | 3H | 8L | 8H | 10L | 10H | 30L | 30H | 90L | 90H |
|---|---|---|---|---|---|---|---|---|---|---|
| Balloon | 0.1 | 0.1 | 0.2 | 0.2 | 0.3 | 0.3 | 1.9 | 2.0 | 14.8 | 14.8 |
| Reflector shield | 1.5 | 0.9 | 4.2 | 4.5 | 0.5 | 0.5 | 0.8 | 0.8 | 0.8 | 0.7 |
| Lights[a] | 0.3 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Spreader bar | 8.5 | 4.3 | 31.4 | 36.6 | 1.7 | 1.1 | 1.3 | 1.7 | 1.3 | 1.1 |
| Upper Suspension[b] | 0.1 | 0.0 | 0.2 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Lower Suspension[b] | 0.0 | 0.0 | 0.2 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Cold Flare[c] | 0.3 | 0.3 | 0.3 | 0.5 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| Total | 10.8 | 5.8 | 36.6 | 42.2 | 2.9 | 2.3 | 4.4 | 4.8 | 17.2 | 16.9 |

[a] A bank of lights can be commanded on for when the video camera views the aperture. Data when the lights are on are not used for science analysis. This emission estimate is for the lights off.
[b] The lower suspension cables suspend the dewar from the spreader bar, while the upper suspension cabes support the spreader bar from the truck plate, which is hidden from view of the antenna beams by the reflector plate. Both are visible in Figure ??.
[c] Stainless steel flares surround the sky port.

Singal et al. 2009, ApJ (submitted)
arXiv:0901.0546

# Radiometer Performance Summary

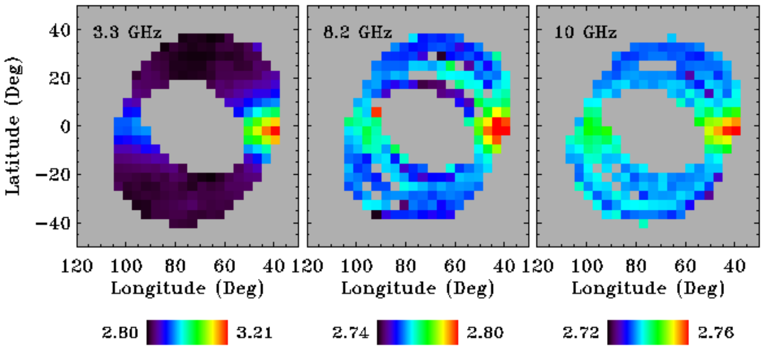
TABLE OF SELECTED MEASURED RADIOMETER PERFORMANCE SPECIFICATIONS FROM THE 2006 FLIGHT

| Channel | Cntr Frequency (GHz) | Bandwidth (MHz) | $T_{rcvr}$ [a] (K) | Offset [b] (mK) | Noise (pre-flt) [c] (mK$\sqrt{s}$) | Noise (rsduls) [d] (mK$\sqrt{s}$) | Noise (map) [e] (mK$\sqrt{s}$) |
|---|---|---|---|---|---|---|---|
| 3 GHz Lo | 3.15 | 210 | 5.5 | 180 | 7.1 | 9.3 | 11.8 |
| 3 GHz Hi | 3.41 | 220 | 6.5 | 35 | 7.1 | 7.8 | 10.1 |
| 5 GHz Lo | 5.33 | 340 | 6 | -210 | 3.2 | - | - |
| 5 GHz Hi | 5.67 | 330 | 6 | -200 | 3.5 | - | - |
| 8 GHz Lo | 7.97 | 350 | 10 | 6 | 1.4 | 5.5 | 5.5 |
| 8 GHz Hi | 8.33 | 350 | 8 | 11 | 1.4 | 6.1 | 5.2 |
| 10 GHz Lo | 9.72 | 860 | 13 | 180 | 6.8 | 3.7 | 3.0 |
| 10 GHz Hi | 10.49 | 680 | 11 | 35 | 5.3 | 3.7 | 3.0 |
| 30 GHz Lo | 29.5 | 2000 | 75 | -30 | 21.5 | 208.2 | 206.9 |
| 30 GHz Hi | 31.0 | 1000 | 72 | -15 | 14.9 | 103.3 | 103.4 |
| 30# GHz Lo | 29.5 | 2000 | 270 | x | 18 | 885.0 | 880.4 |
| 30# GHz Hi | 31.0 | 1000 | 340 | x | 14 | 418.5 | 406.1 |
| 90 GHz Lo | 88.2 | 1500 | 44 | -75 | 5.2 | 50.5 | 42.0 |
| 90 GHz Hi | 89.8 | 1500 | 38 | -95 | 5.7 | 25.3 | 27.1 |

[a] $T_{rcvr}$ is the receiver noise temperature of the amplifier, a figure of merit that is equal to the temperature that would be observed by a total power radiometer containing the amplifier and viewing a source at a temperature of absolute zero. This values presented here were measured in ground testing prior to the 2006 flight.
[b] The constant offset is the radiometer output when the internal reference load and the object being viewed are at the same temperature, multiplied here by the gain to be expressed as a temperature.
[c] This is the white noise as measured in ground testing prior to the 2006 flight.
[d] This is the white noise determined from the residuals of the data from the 2006 flight.
[e] This is the white noise as determined from the sky map variance in the 2006 flight.

Singal et al. 2009, ApJ (submitted)
arXiv:0901.0546

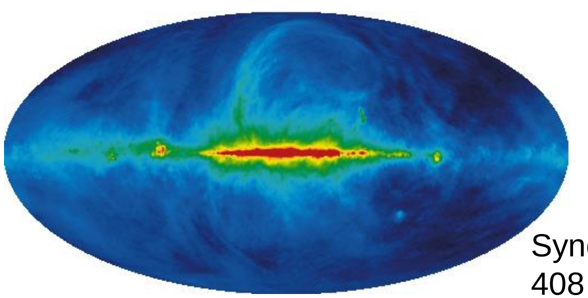
# Model for Galactic Emission



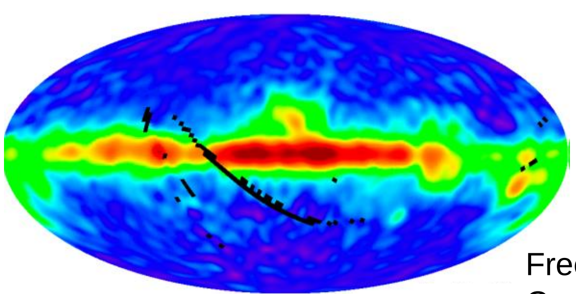

Spatial Structure: Use "Template" Model

$$T(\upsilon, p) = \sum_i \alpha_i(\upsilon)\, X_i(p)$$

Add offset $\alpha_0(\nu)$ to match emission along some reference line of sight where total Galactic emission is known.



Synchrotron Template
408 MHz survey

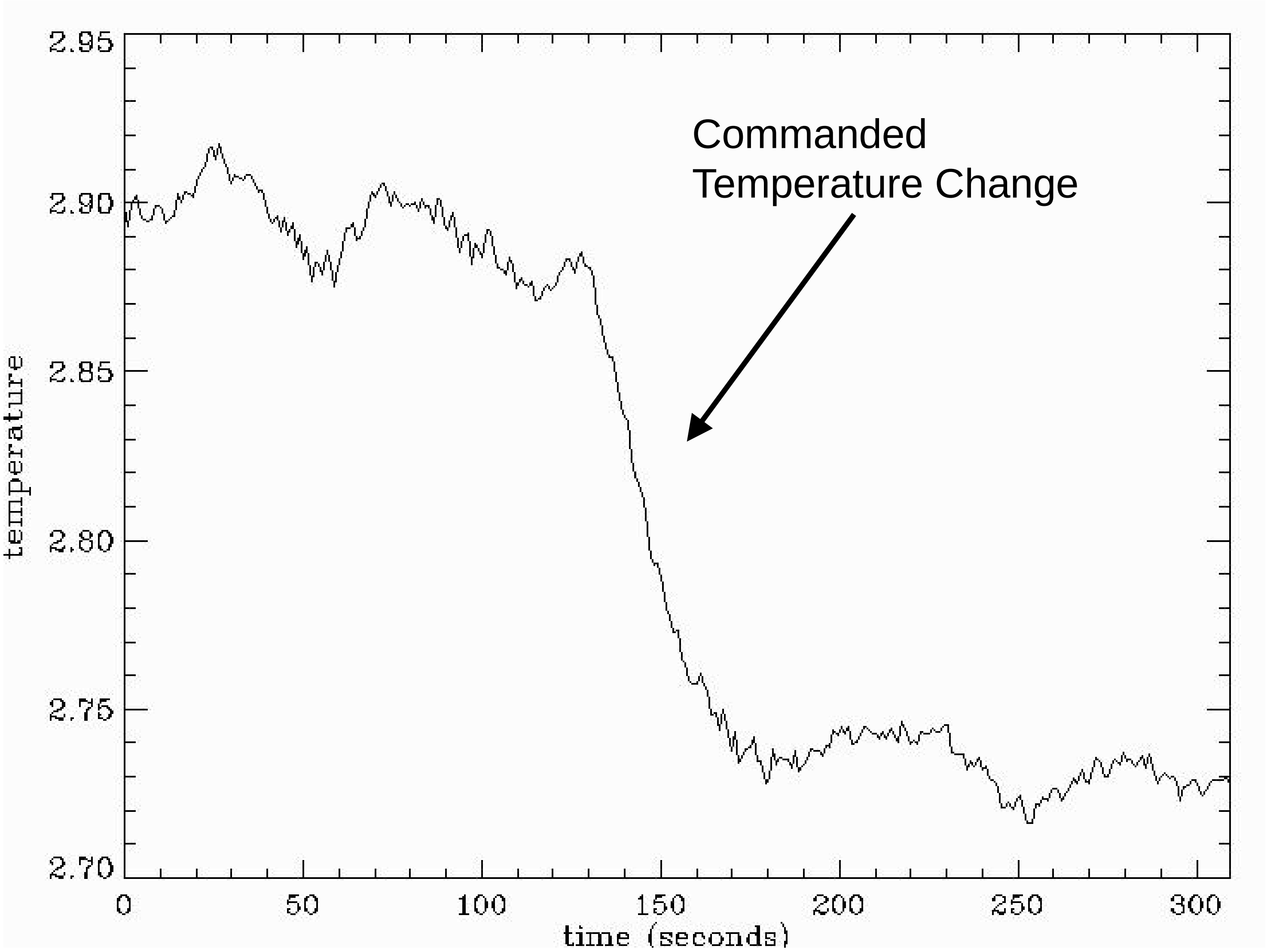


Free-Free Template
C+ 158 $\mu$m map

Best-Fit Template Coefficients

| Frequency (GHz) | $\alpha_{synch}$ mK / K | $\alpha_{ff}$ mK $nW^{-1}$ $m^2$ sr |
|---|---|---|
| 3.15 | 2.02 ± 0.05 | 3.22 ± 0.11 |
| 3.41 | 1.70 ± 0.04 | 3.06 ± 0.09 |
| 7.98 | 0.24 ± 0.02 | 0.26 ± 0.05 |
| 8.33 | 0.24 ± 0.02 | 0.28 ± 0.05 |
| 9.72 | 0.04 ± 0.01 | 0.39 ± 0.03 |
| 10.49 | 0.04 ± 0.01 | 0.37 ± 0.03 |
| Spectral Index | -2.5 ± 0.1 | -2.0 ± 0.1 |

# Calibrator Temperature Control



# CMB + Radio Background

$$T(\nu) = T_0 + A(\nu/1\,GHz)^{\beta} + \Delta T(\nu)$$

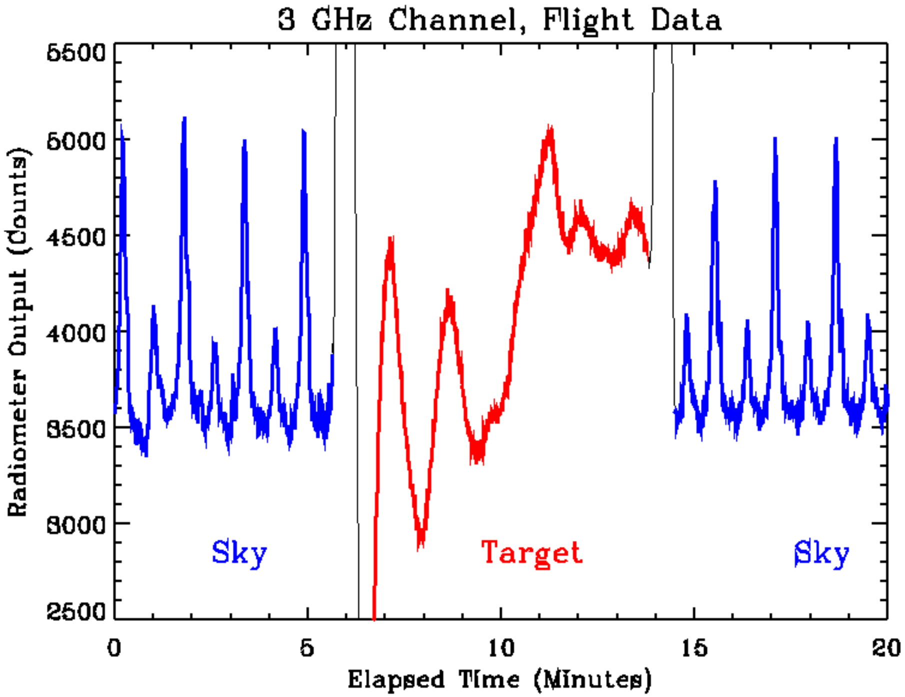
CMB baseline — Temp at 1 GHz — Power law index — CMB spectral distortions

Using ARC+LF+FIRAS

| Parameter | Power Law | Power Law + $Y_{ff}$ | $Y_{ff}$ only | Power Law + μ |
|---|---|---|---|---|
| $T_0$ | 2.725 ± 0.001 | 2.725 ± 0.001 | 2.725 ± 0.001 | 2.725 ± 0.001 |
| A | 1.06 ± 0.11 | 1.00 ± 0.37 | - | 1.05 ± 0.11 |
| β | -2.56 ± 0.04 | -2.58 ± 0.11 | - | -2.56 ± 0.05 |
| FF amplitude | - | 0.04 ± 0.24 | 0.54 ± 0.07 | - |
| μ amplitude | - | - | - | (0.73 ± 0.33) e-5 |
| DOF | 53 | 52 | 54 | 52 |
| $\chi^2$ | 70.0 | 60.8 | 107.1 | 60.8 |
| reduced $\chi^2$ | 1.15 | 1.17 | 1.98 | 1.17 |

Fits prefer no CMB spectral distortions. New robust 2σ upper limits:
$\mu < 5.8 \times 10^{-5}$, $|Y_{ff}| < 5.8 \times 10^{-5}$

# Sky-Calibrator Comparison




Successful thermal operations

- Calibrator brackets sky temp
- Instrument nulled to < 0.1 K
- 8 sky/calibrator comparisons per band
- Stable "transfer standard"

Component Temp and RMS Variation (mK)

| Frequency | Calibrator | Antenna | Ref Load | Amplifier |
|---|---|---|---|---|
| 3 GHz | 2731 ± 134 | 1486 ± 3 | 1987 ± 48 | 1439 ± 3 |
| 8 GHz | 2710 ± 116 | 1414 ± 3 | 1474 ± 3 | 1440 ± 3 |
| 10 GHz | 2728 ± 111 | 1470 ± 3 | 2840 ± 158 | 1403 ± 3 |
| 30 GHz | 2728 ± 111 | 1635 ± 379 | 2290 ± 737 | 1436 ± 3 |
| 90 GHz | 2724 ± 108 | 2775 ± 173 | 2970 ± 349 | 2961 ± 784 |

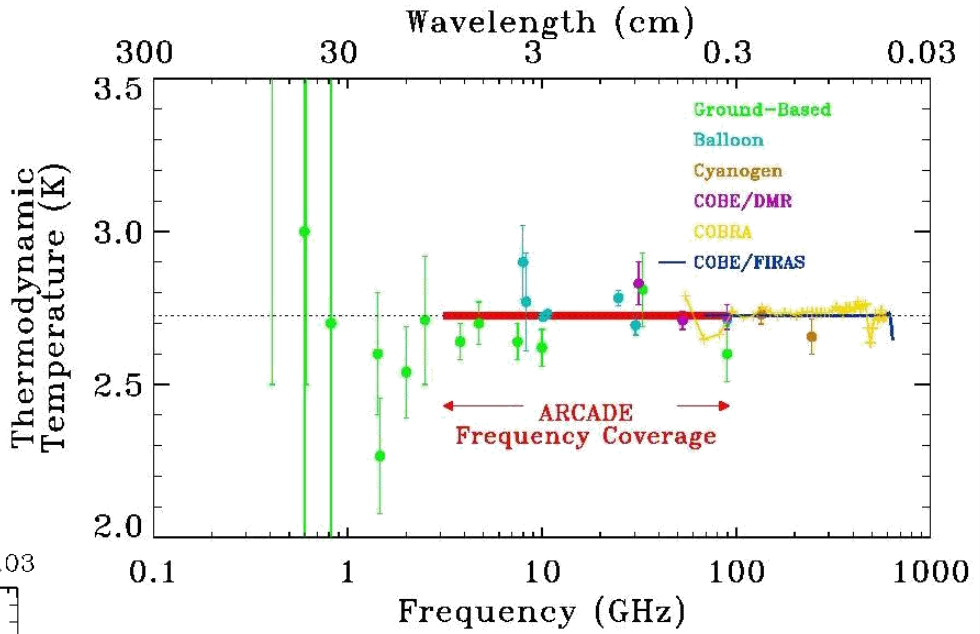
*Linear instrument model allows interpolation of sky temperature*

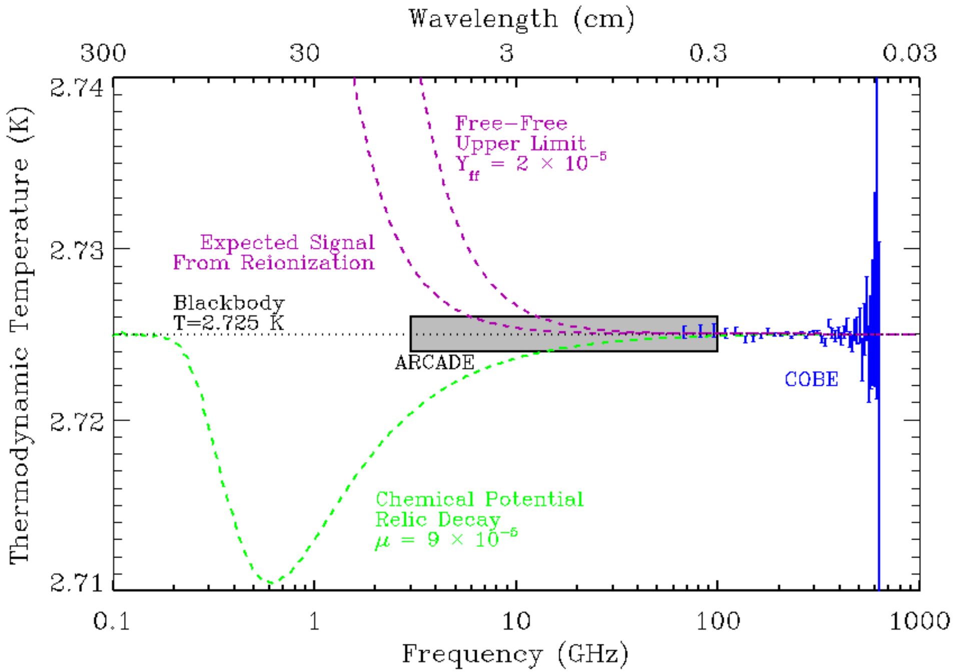
# Cosmic Microwave Background at cm Wavelengths

COBE: CMB is blackbody to 50 ppm

Radio: Distortions could be 5% or more

- Reionization
- Dark matter annihilation/decay
- Other/Unknown




*Goal: Precise measurements of sky temperature to search for distortions from blackbody spectrum*


NSBF