ARCADE: Big, Bad, and Cold

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ARCADE

Absolute Radiometer for Cosmology, Astrophysics, and Diffuse Emission

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A New Look At The First Light

Precision Photometry at Centimeter Wavelengths

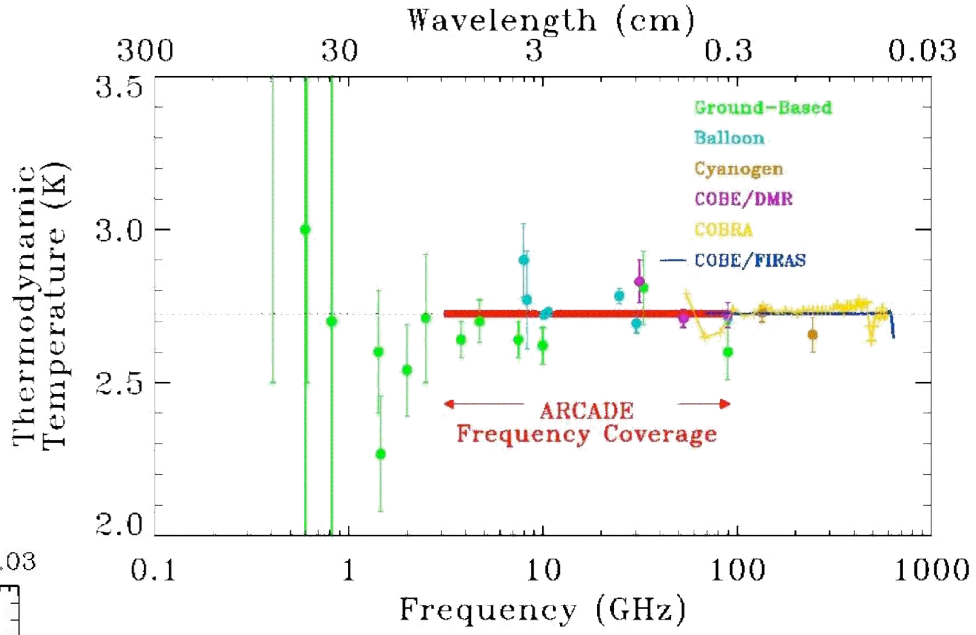
Cosmological and Astrophysical Backgrounds

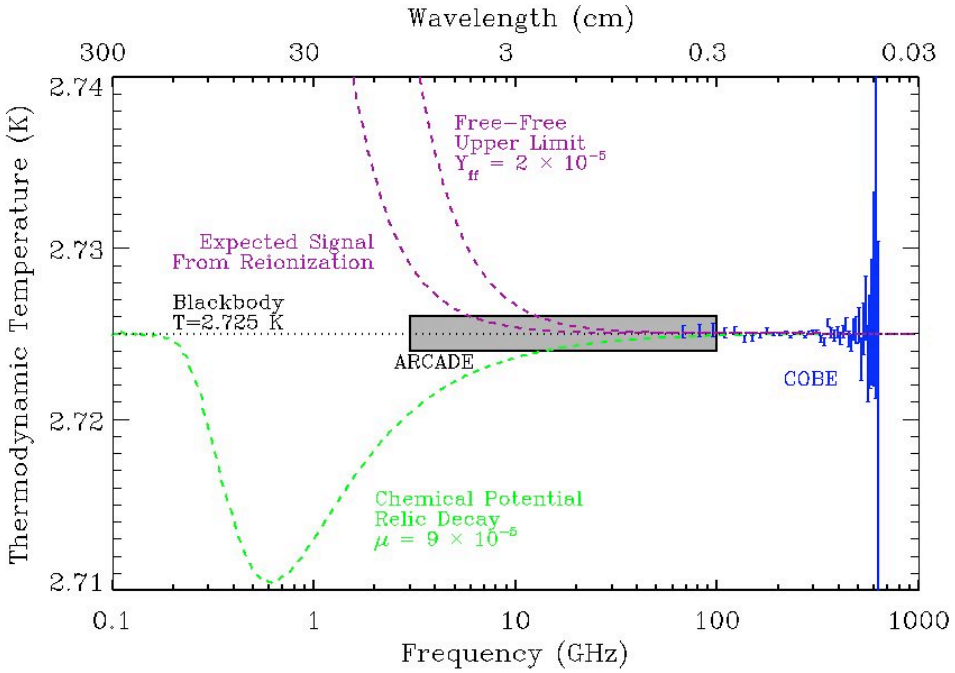
Cosmic Microwave Background at cm Wavelengths

COBE: CMB is blackbody to 50 ppm

Radio: Distortions could be 5% or more

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





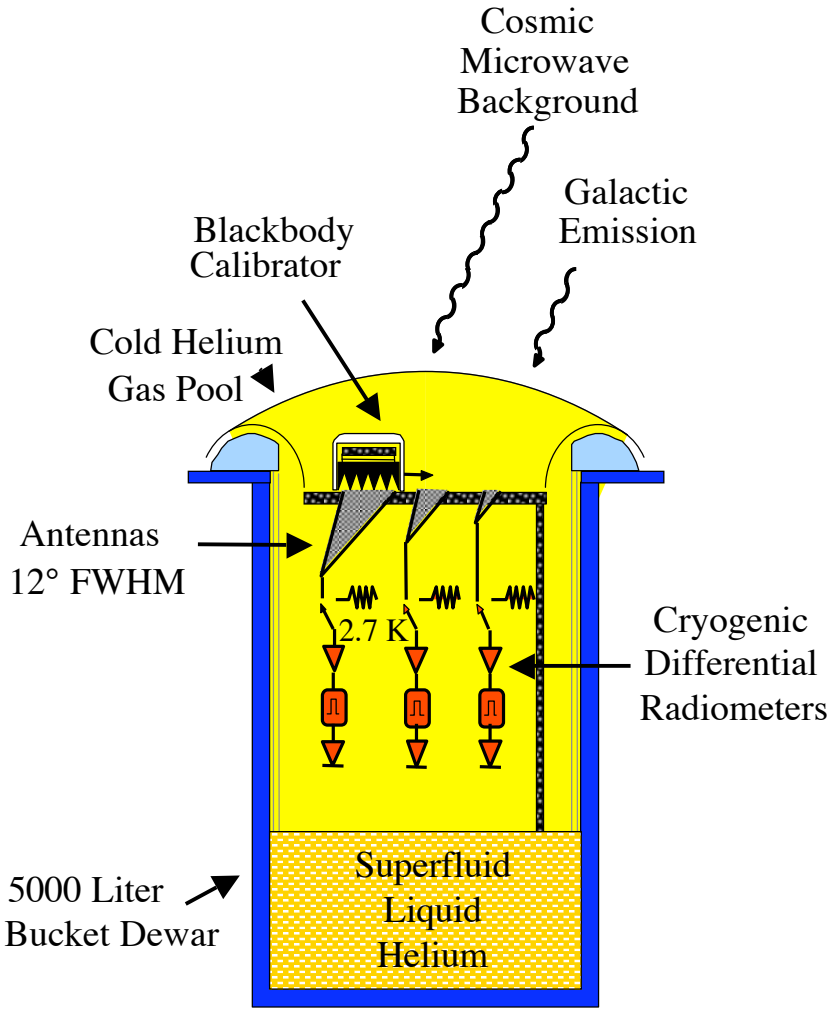
Goal: Precise measurements of sky temperature to search for distortions from blackbody spectrum

Limitations at Low Frequencies

The Atmosphere …

"Warm" Components …

Cryogenic Open-Aperture Instrument

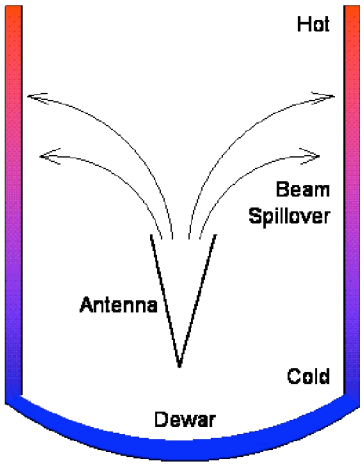


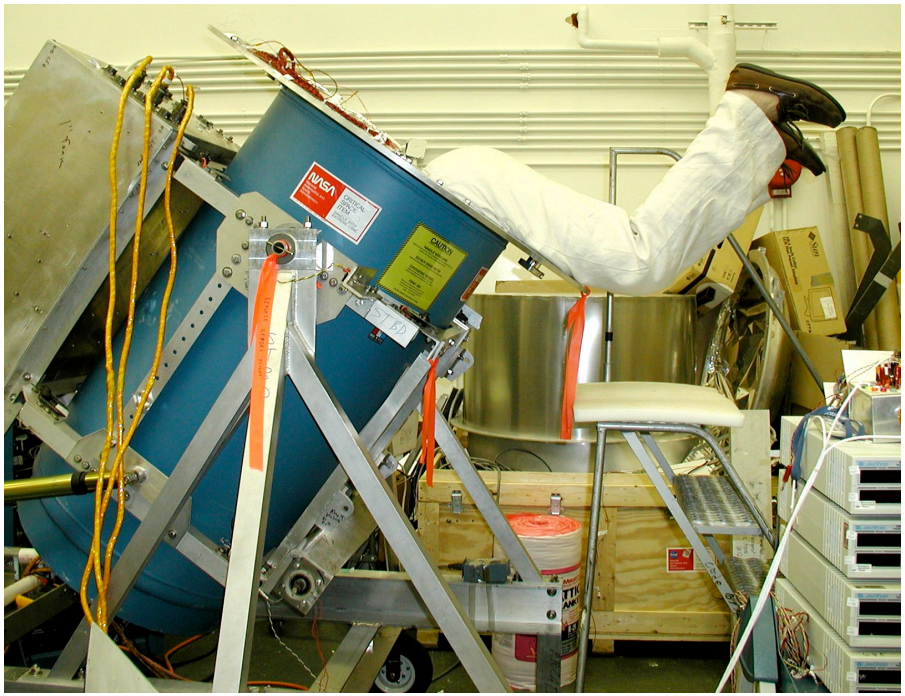
Just Get Rid of the Problem!

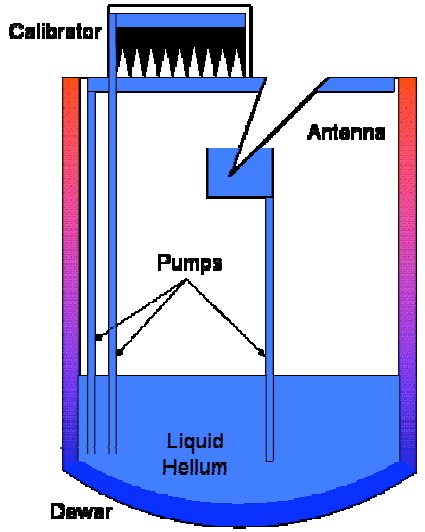
- Eliminate emission from anything warm
  - Balloon eliminates atmospheric emission
  - Entire instrument isothermal with 2.7 K CMB
  - Open aperture -- No windows!
- Double-Nulled For Your Protection
  - Adjust reference load to null antenna signal
  - Adjust calibrator to null sky signal
  - Measure small differences about null
- Calibrator: Cold and Black
  - Absorption $\varepsilon > 0.99997$ across 5 decades
  - Adjust temperature to match sky
  - Read temperature from embedded thermometers

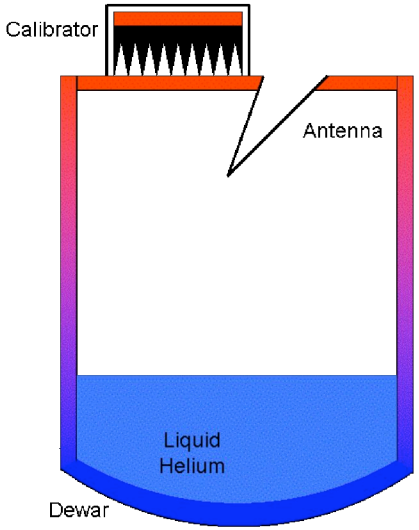
Double-Nulled, Cryogenic, and Isothermal

Stupid Dewar Tricks

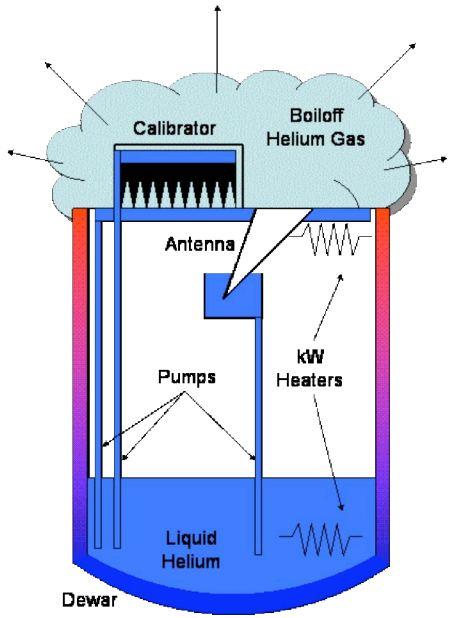




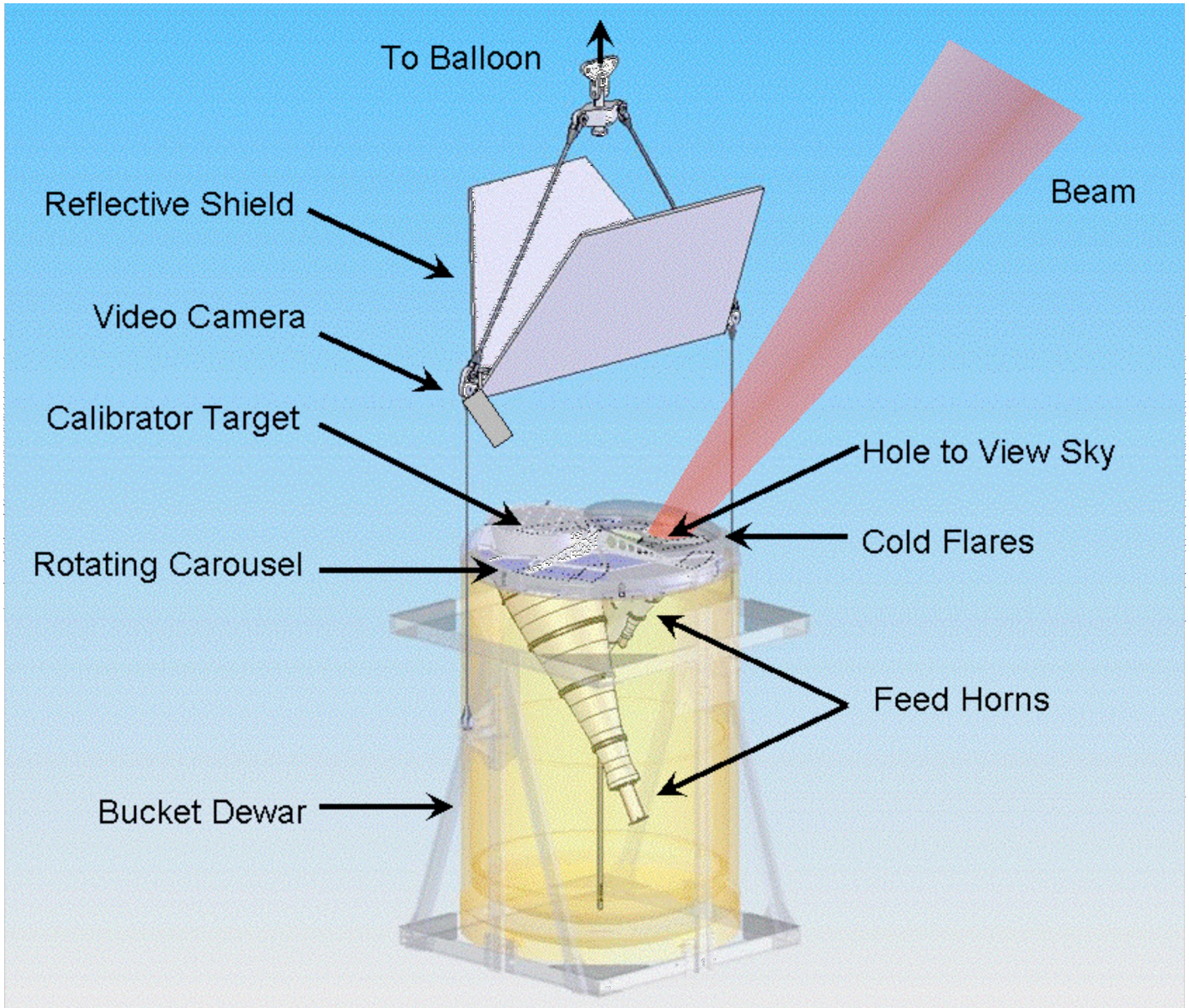




Radical thermal design puts 2.7K components outside the dewar!



Payload Schematic



Size Matters

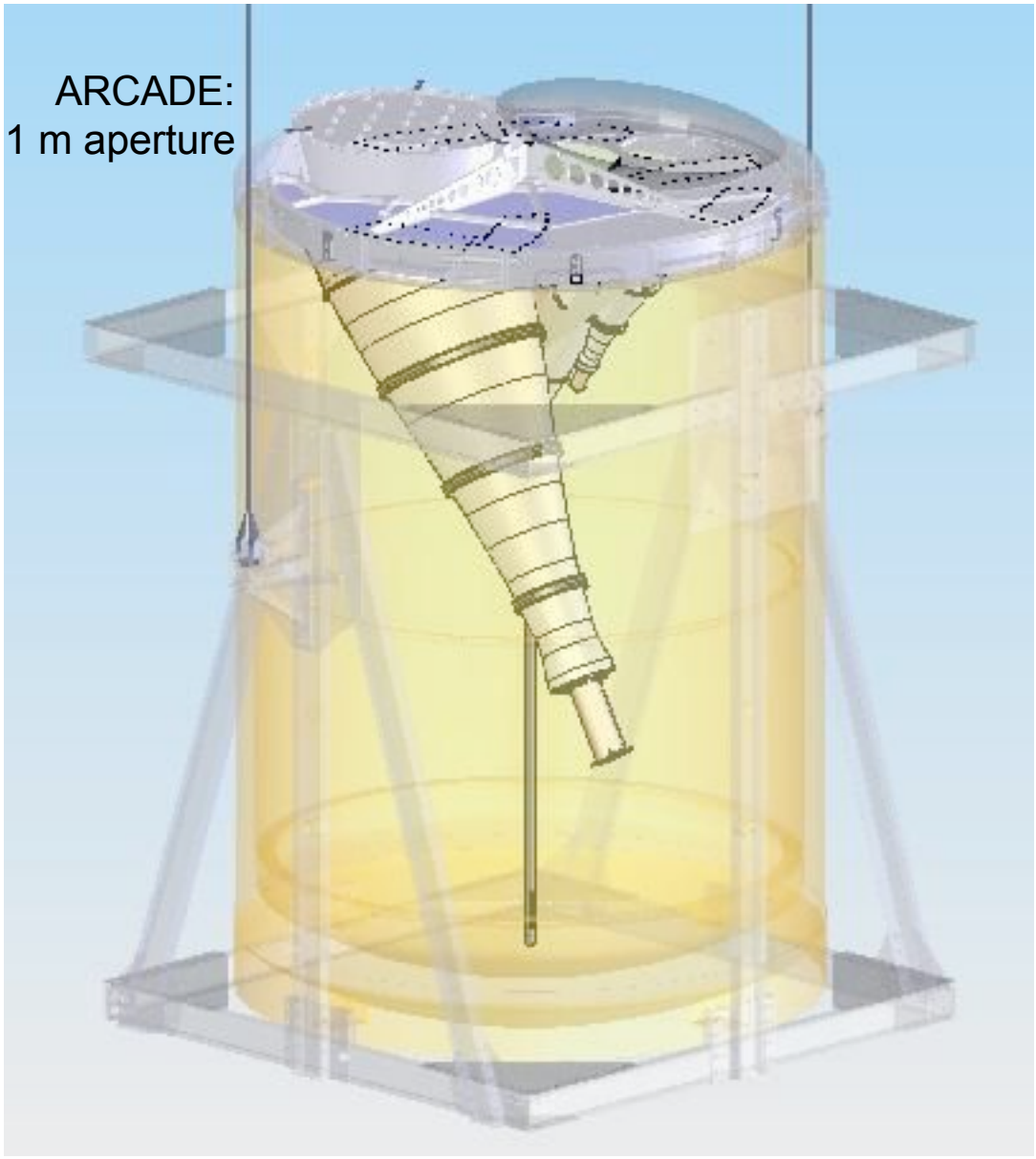
COLD

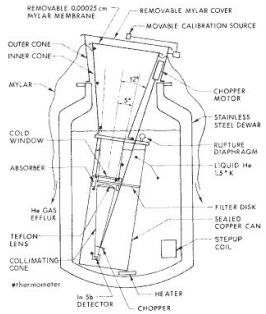
The Flying ~~Hot~~ Tub

- 1.5 m open aperture
- 1800 l LHe at launch
- 5 m^3/s boiloff gas

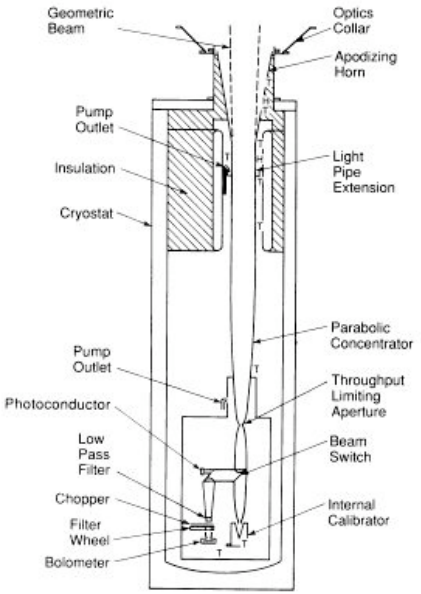
- Launch in July 2006
- Palestine, TX
- 4 hours observation at float

Open-Aperture Comparison



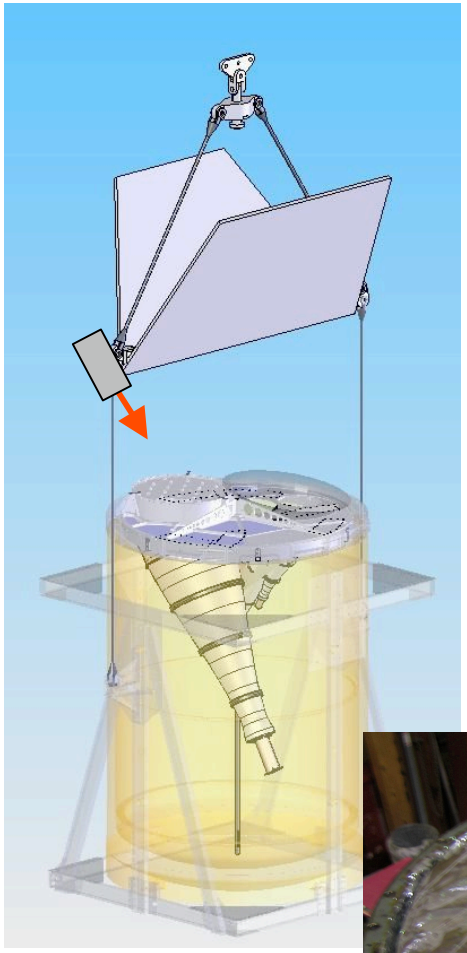


Muehlner & Weiss 1973:
15 cm aperture



Woody & Richards 1978
22 cm aperture

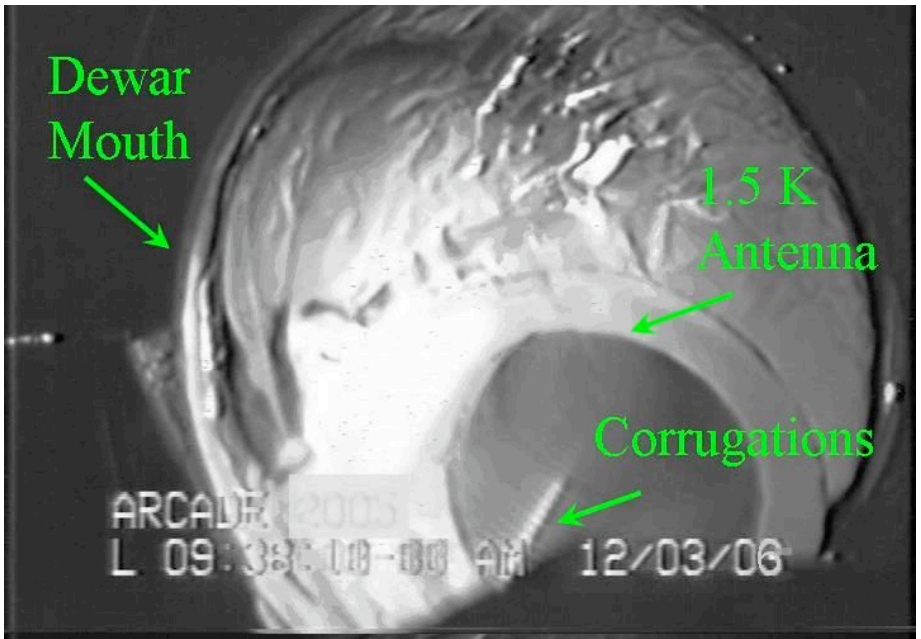
Open-Aperture Cryogenics

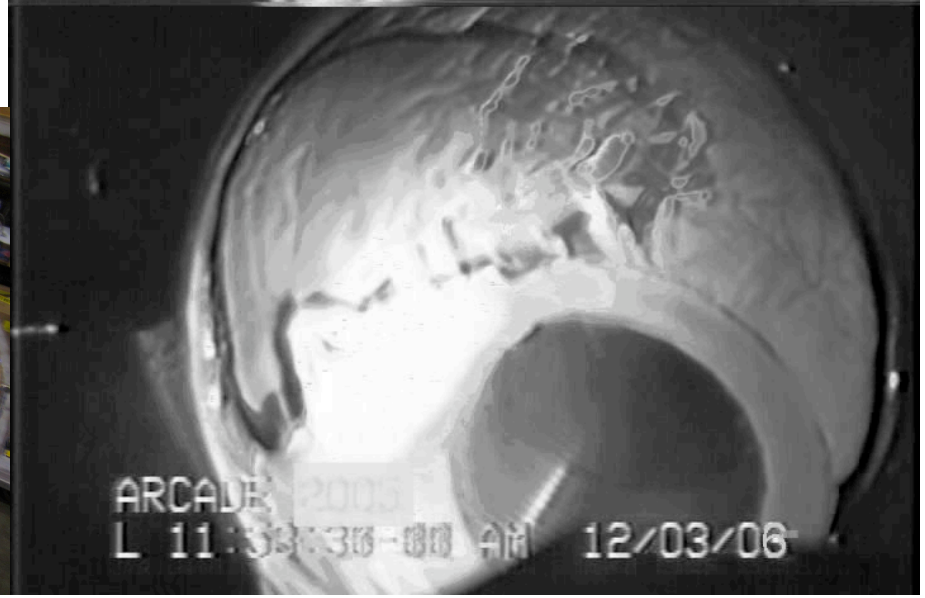


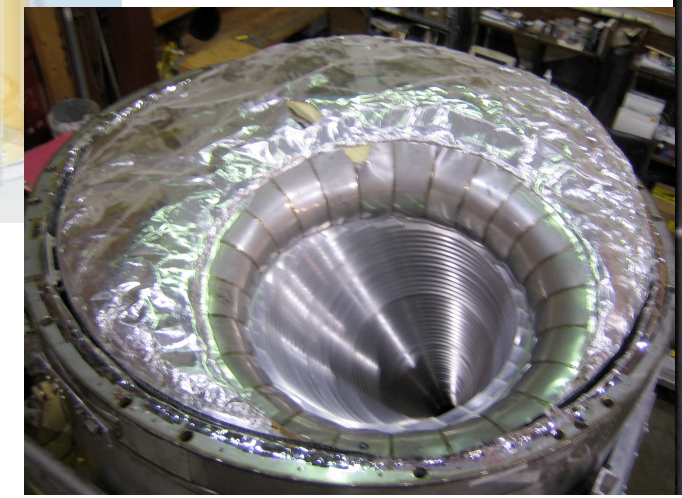
In-flight video camera looks down at dewar

Capture images of 3 GHz antenna 2 hours apart

No nitrogen condensation visible on optics

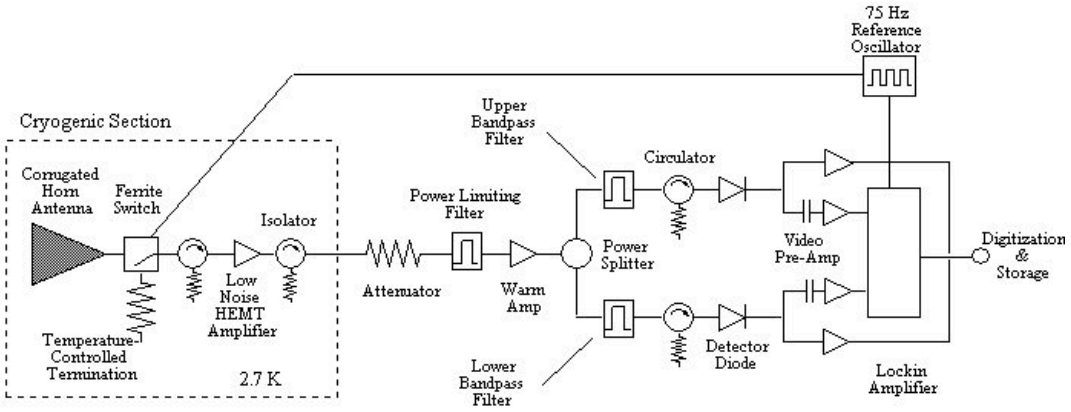






Pre-flight

Cryogenic Radiometers



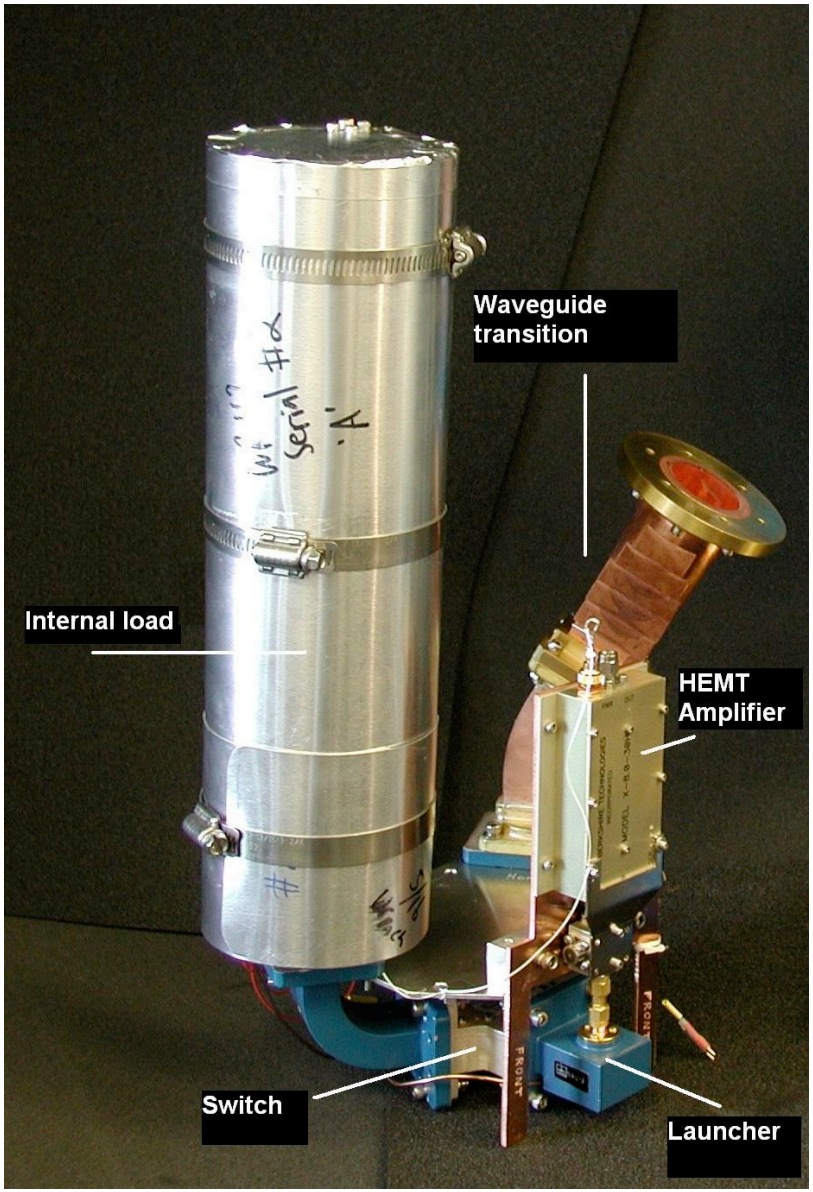
Six frequency bands: 3, ~~5~~, 8, 10, 30, 90 GHz

Chop between horn and load at 75 Hz

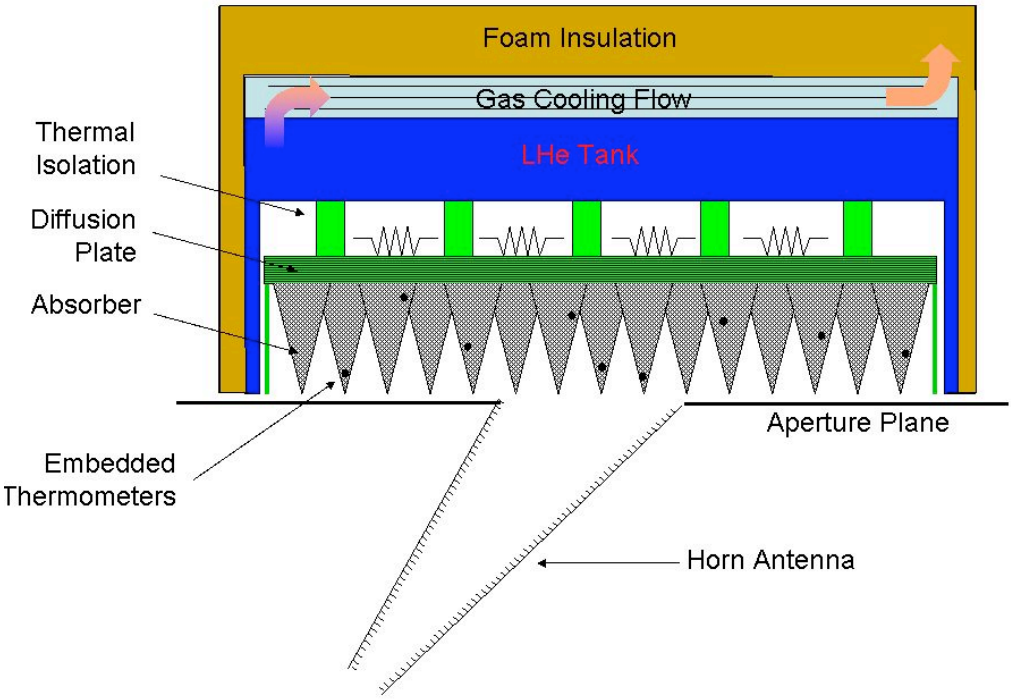
Load functions as transfer standard, but is black enough (ε>0.999) for absolute reference

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

ARCADE is a thermal experiment, not a radiometric experiment!



External Blackbody Calibrator

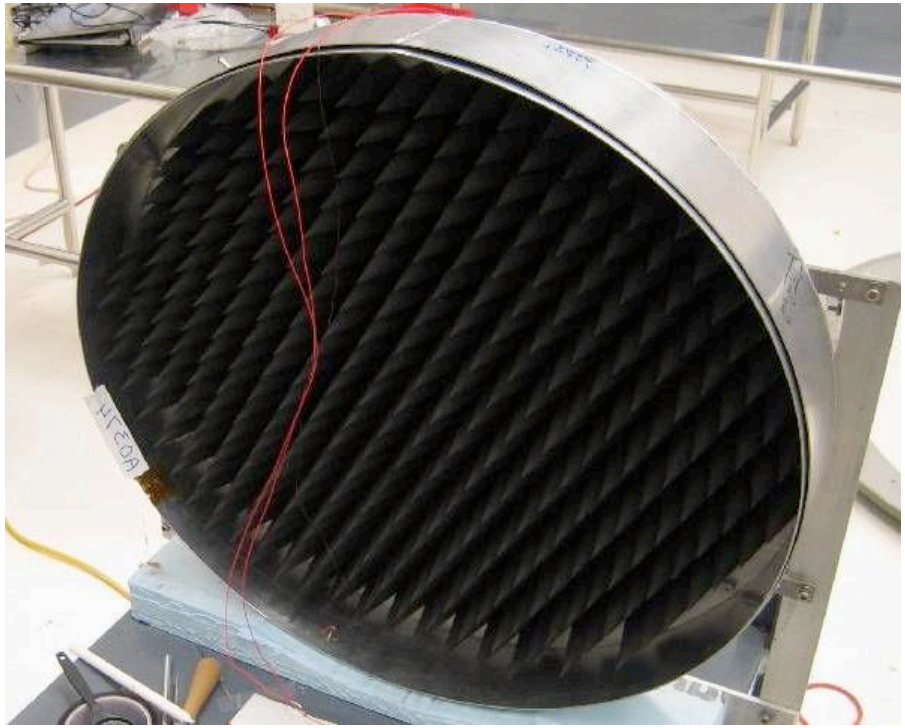


Radiometric Performance

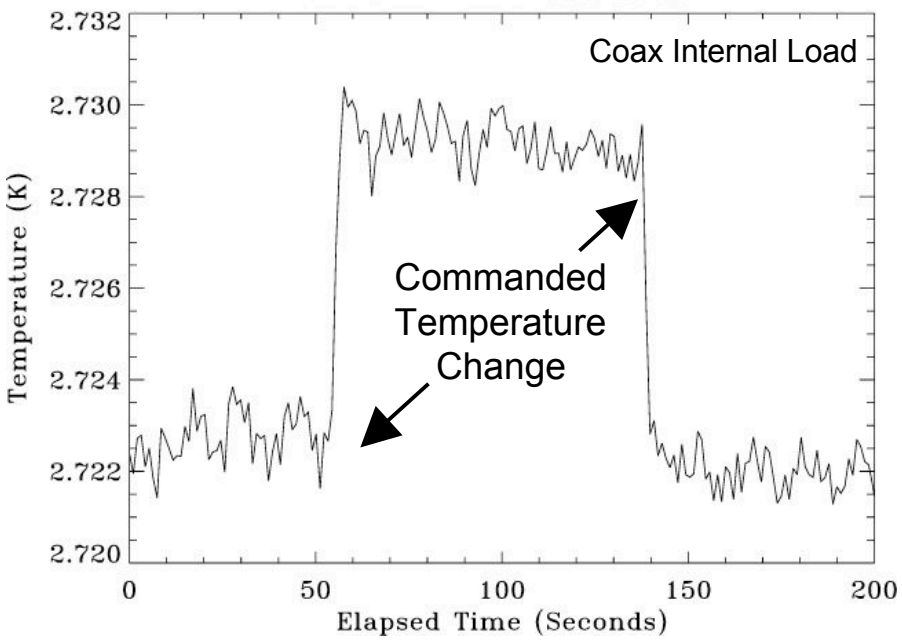
- 298 Absorbing cones
- Absorption > 0.99997 with height < λ

Thermal Performance

- LHe tank for thermal isolation
- Temperature controlled near 2.7 K
- 24 embedded thermometers
- Absolute scale verified via Λ transition

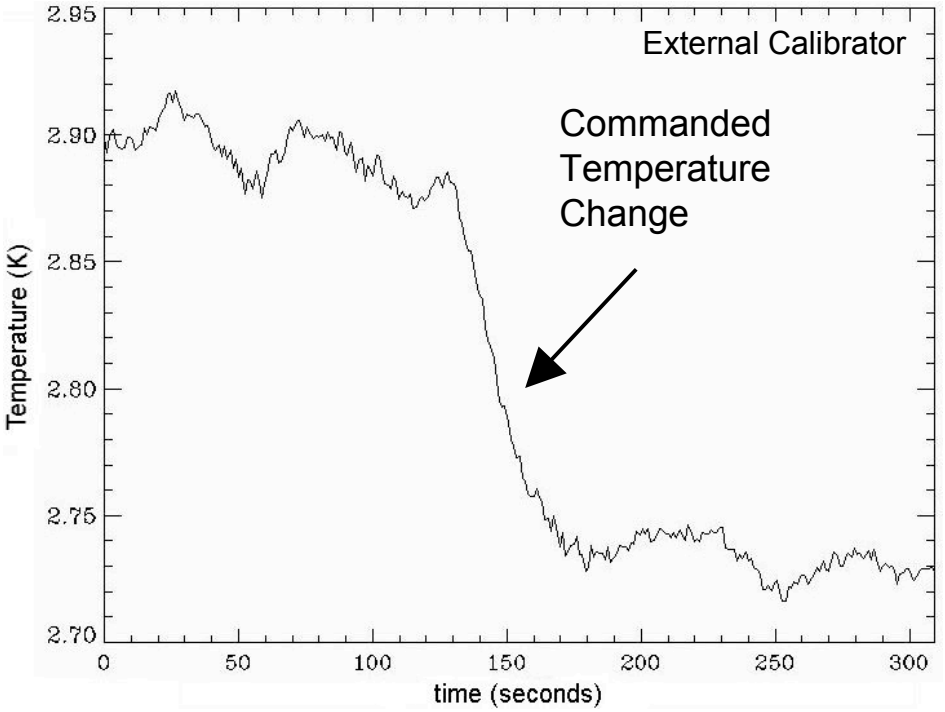


Thermal Control in Harsh Environment



All things cold and curious
Components great and small
Blown by winds so furious
We must control them all!

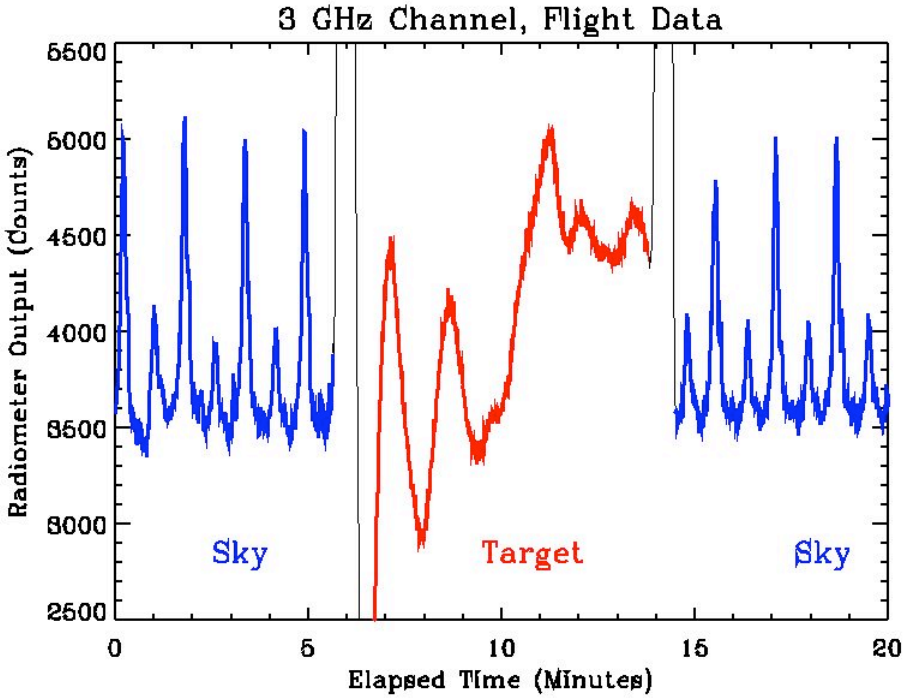
-- C.F. Alexander (sort of)



Control to mK precision

Knowledge to mK accuracy

Sky-Calibrator Comparison



Linear instrument model allows interpolation of sky temperature

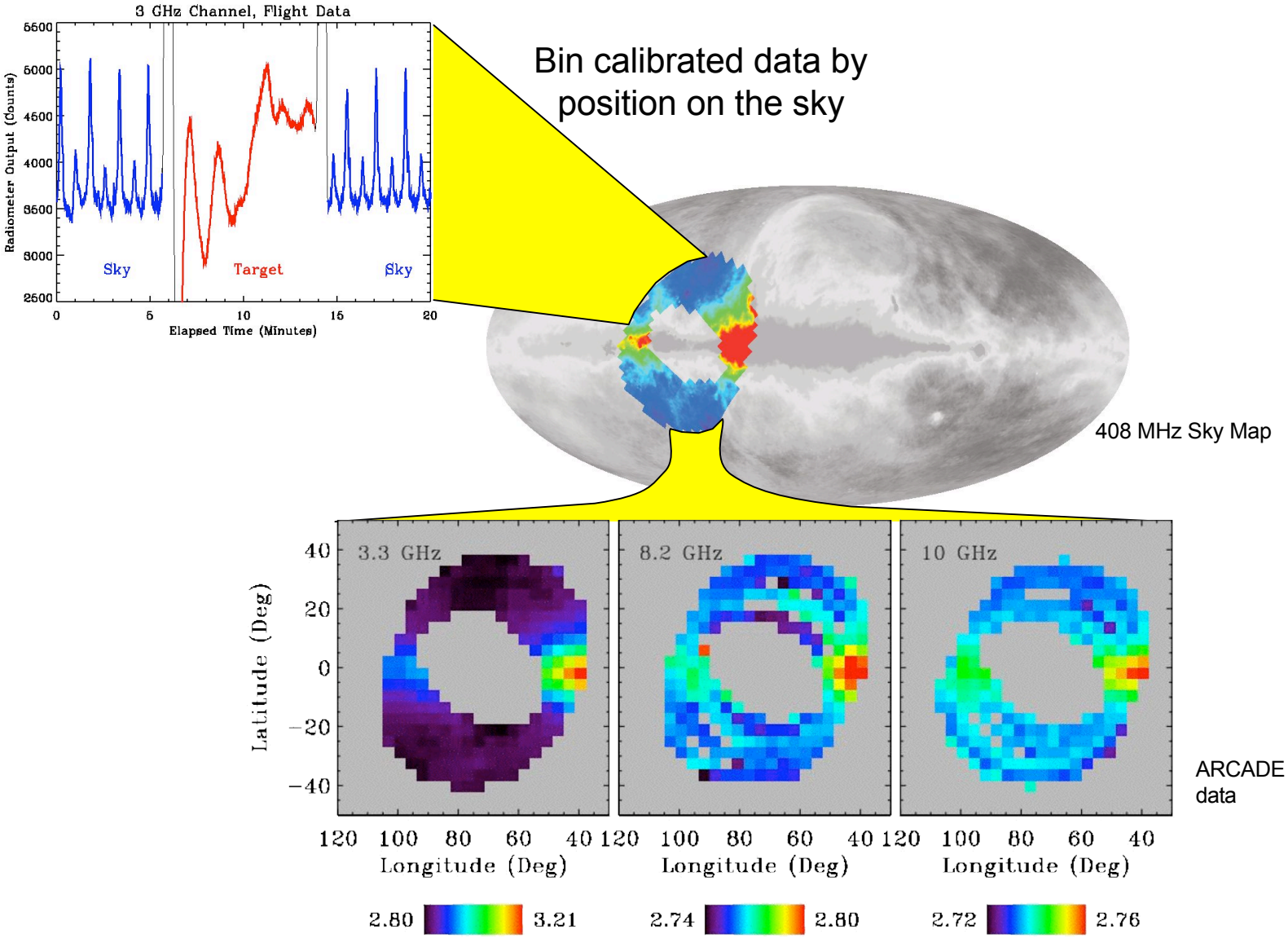
Successful thermal operations

- 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)

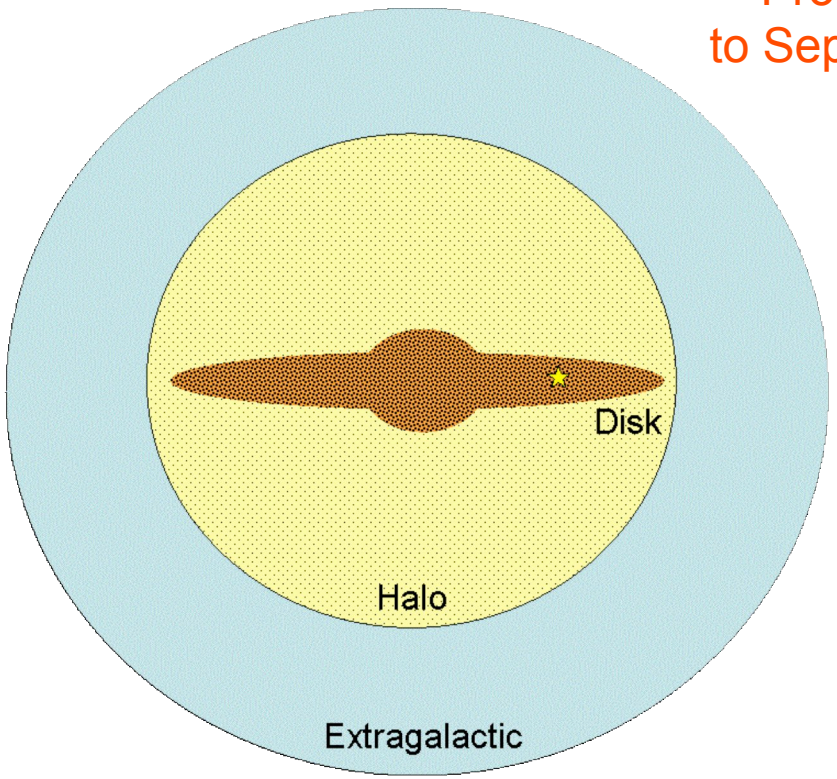
Frequency	Calibrator	Antenna	Ref Load	Amplifier
3 GHz	2731 ± 134	1486 ± 3	1987 ± 48	1439 ± 3
8 GHz	2710 ± 116	1414 ± 3	1474 ± 3	1440 ± 3
10 GHz	2728 ± 111	1470 ± 3	2840 ± 158	1403 ± 3
30 GHz	2728 ± 111	1635 ± 379	2290 ± 737	1436 ± 3
90 GHz	2724 ± 108	2775 ± 173	2970 ± 349	2961 ± 784

Binned Sky Temperatures



Subtract Galactic emission to search for extragalactic residual

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

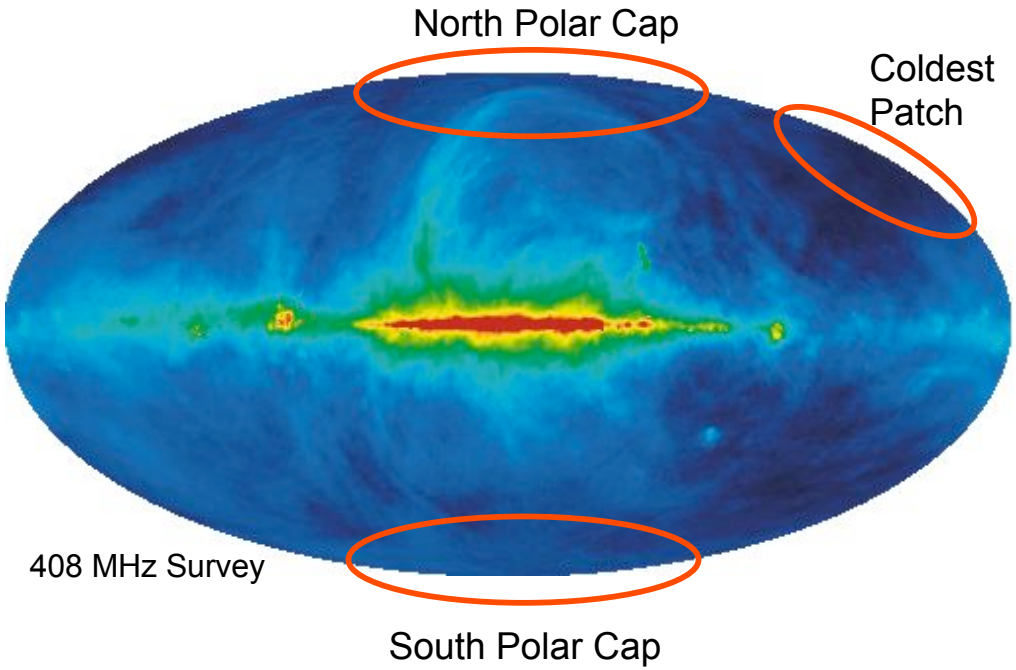
II. Line Emission

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

Look For Extra-Galactic Residual Using Multiple Lines of Sight

Galactic Emission Model

Define Total Galactic Emission in Best Regions Of The Sky



Two Independent Tests

- Plane-Parallel Model
- Radio/Atomic Line Correlation

Three Independent Lines of Sight

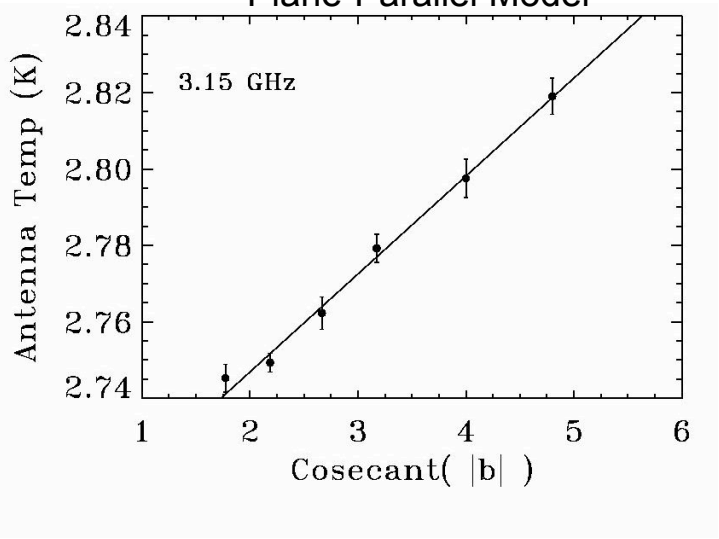
- North Polar Cap
- South Polar Cap
- Coldest Northern Patch

Five Independent Sky Surveys

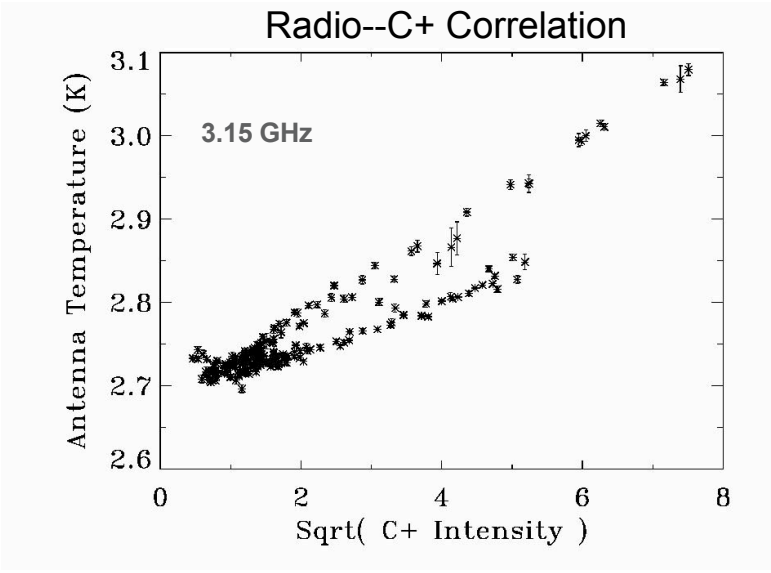
- ARCADE (3, 8, and 10 GHz)
- Surveys at 22, 45, 408, 1420 MHz

Galactic Emission at Polar Caps

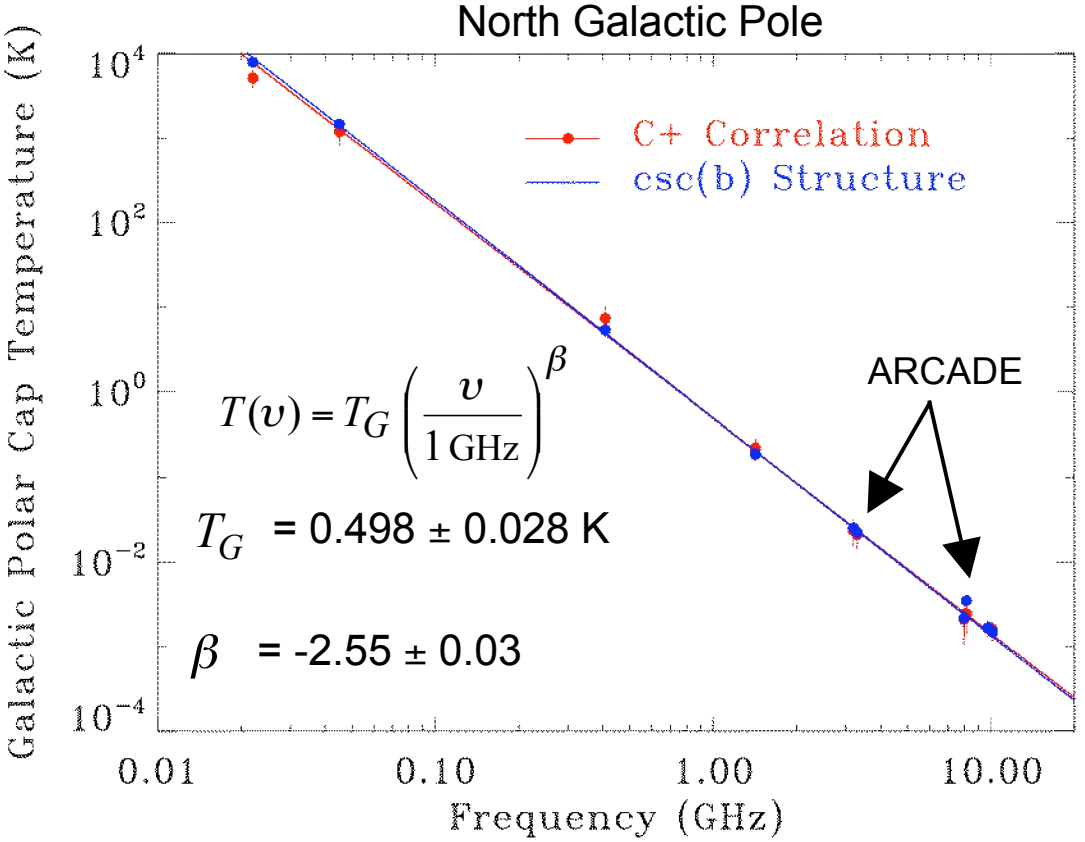
Plane-Parallel Model



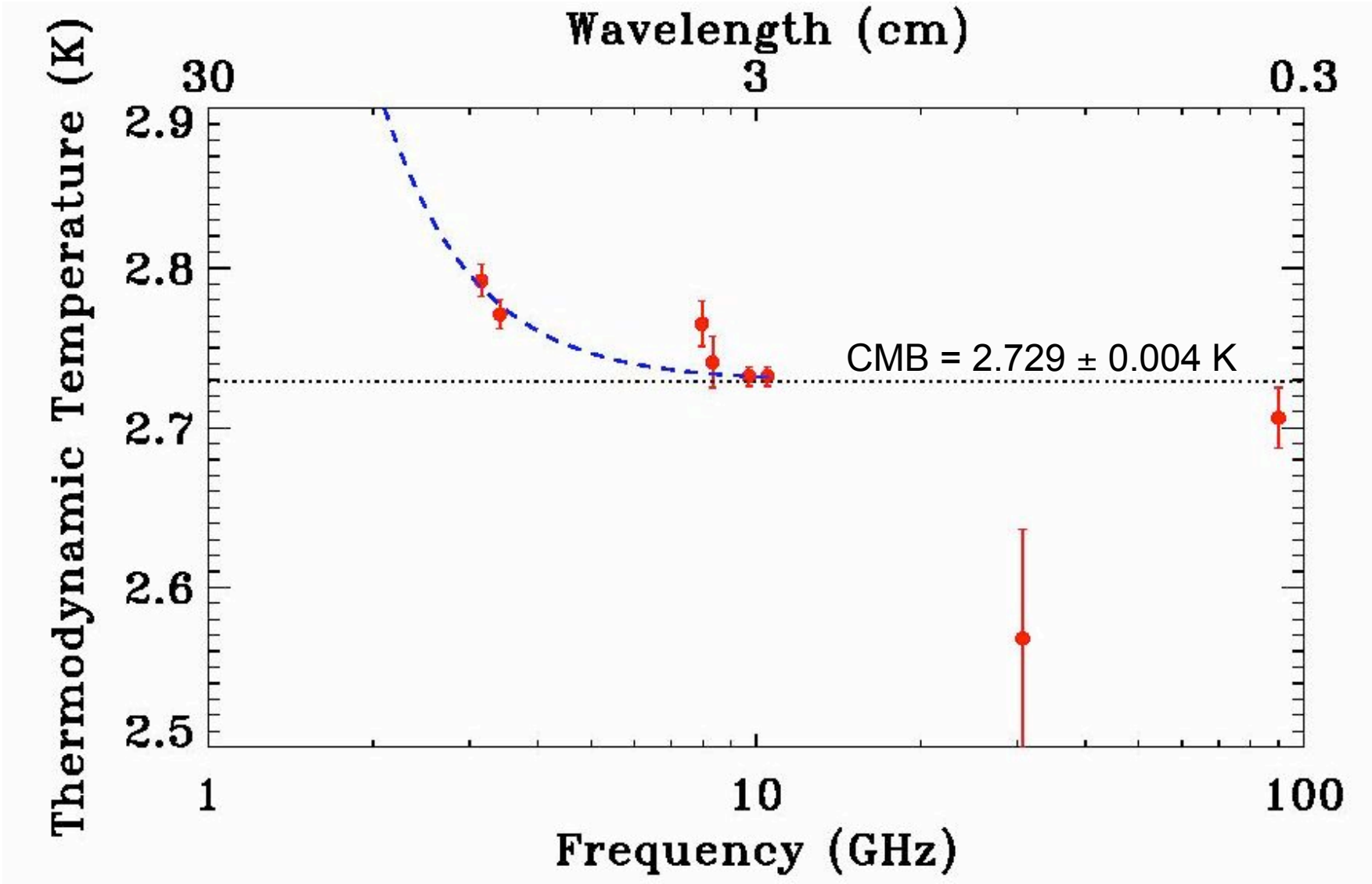
Radio--C+ Correlation



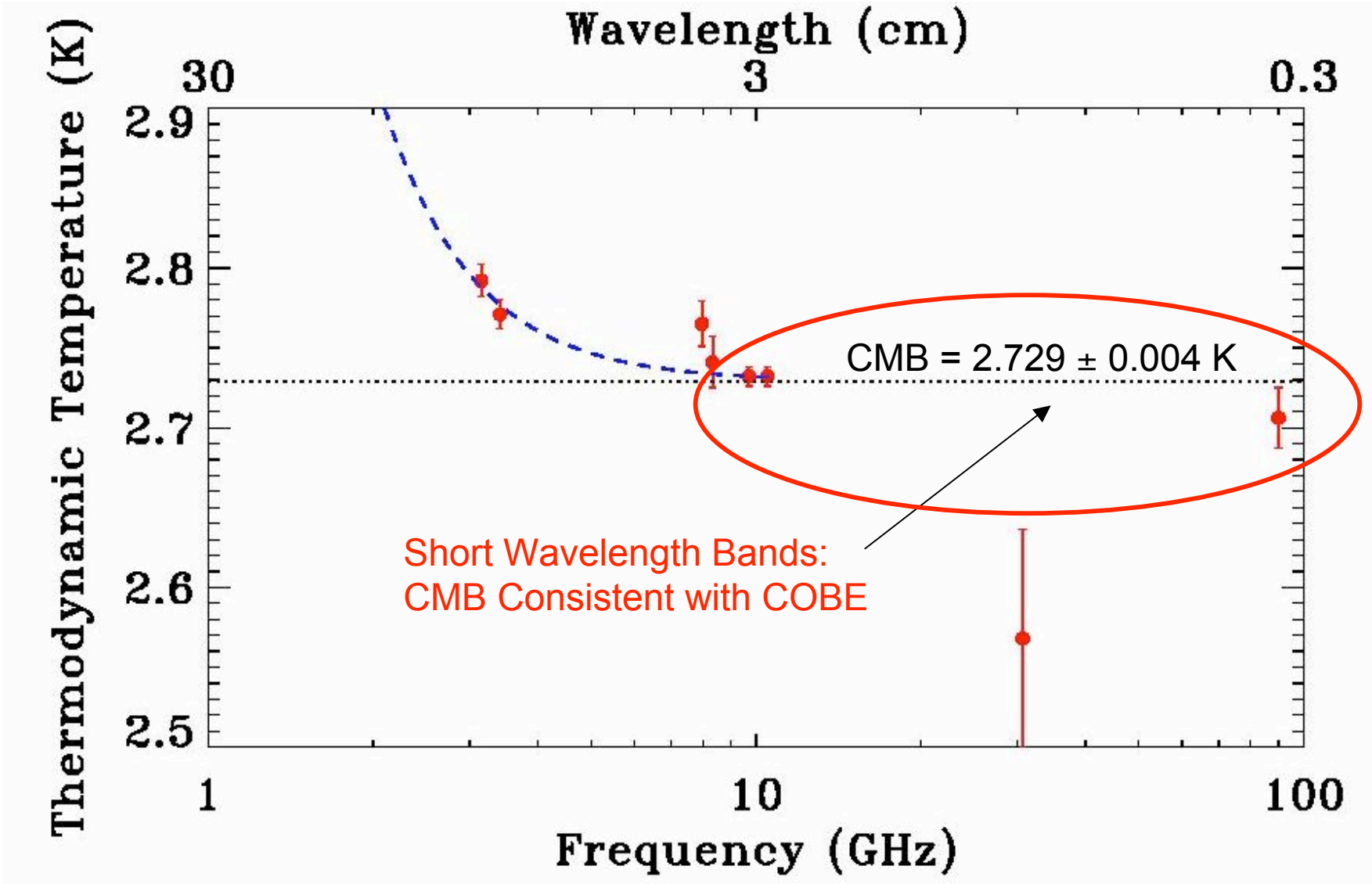
North Galactic Pole



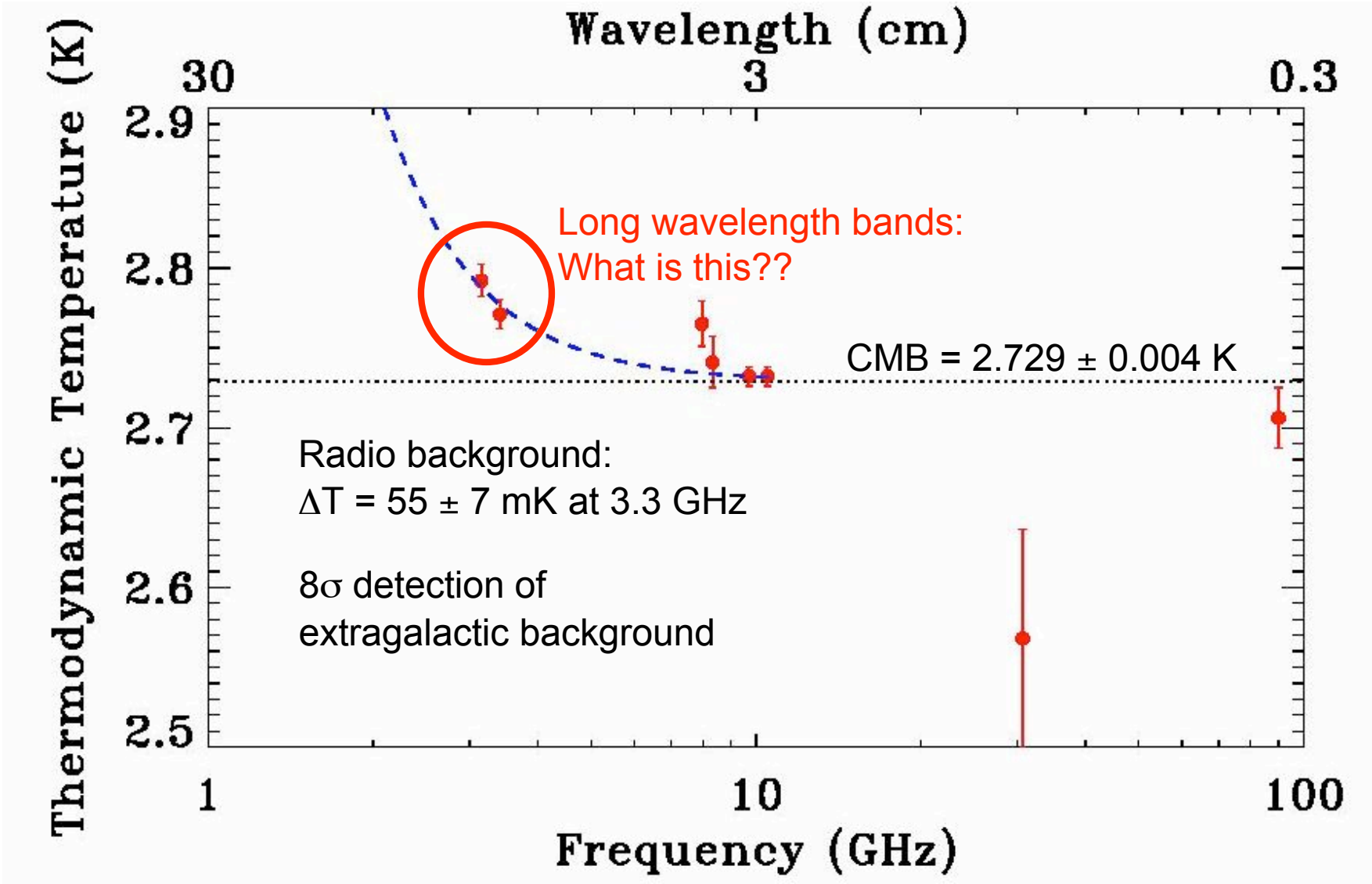
Extragalactic Sky Temperature



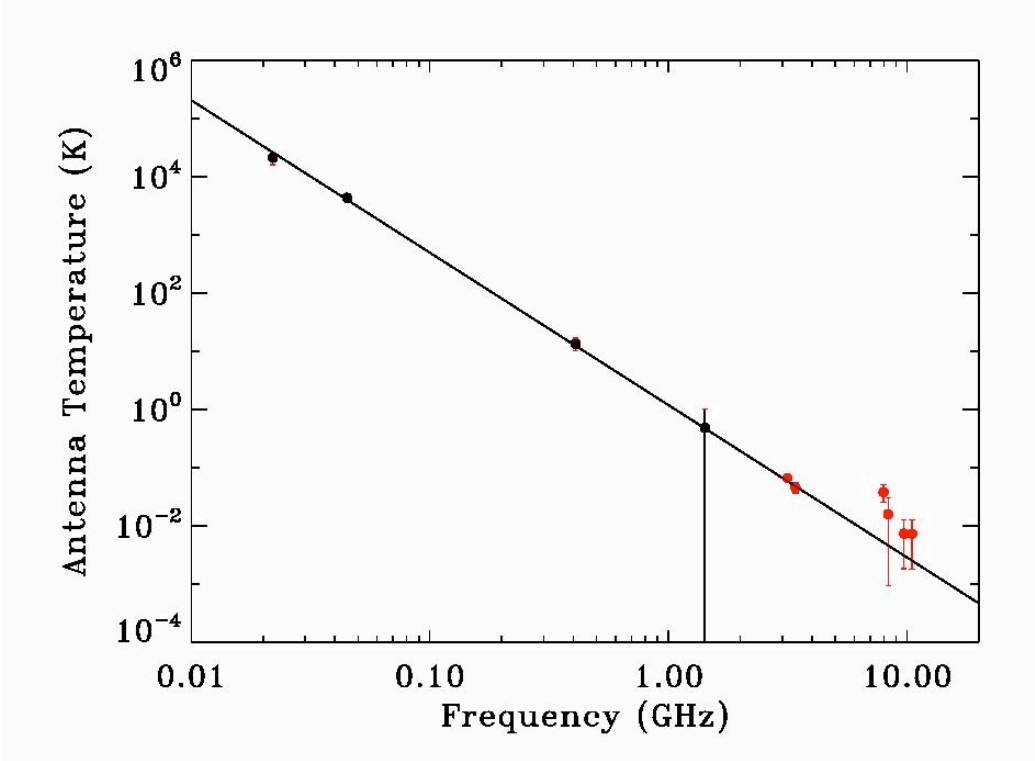
Extragalactic Sky Temperature



Extragalactic Sky Temperature



Spectral Dependence



Amplitude set by ARCADE data

Spectral index set by radio data (any or all)

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

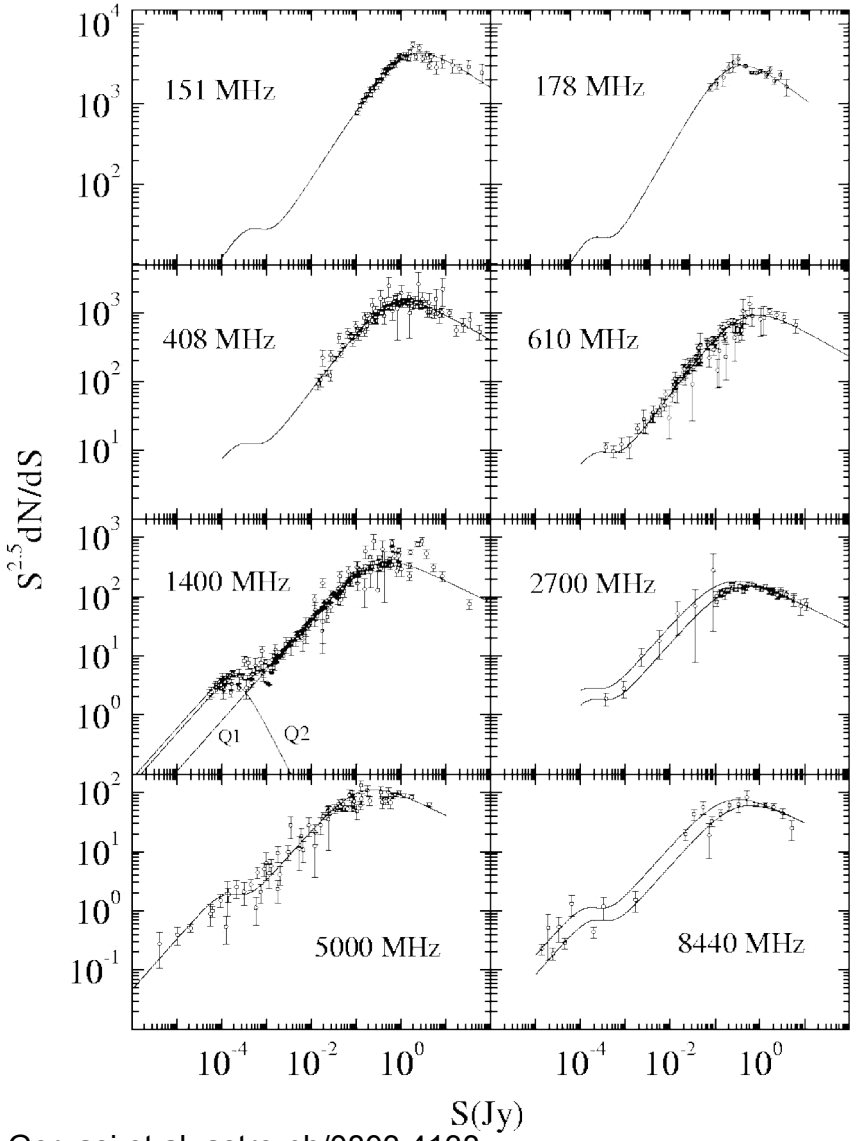
T_{CMB} = 2.729 ± 0.004 K

T_R = 1.19 ± 0.14 K

β = -2.62 ± 0.04

χ^2 = 14.5 for 10 DOF

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

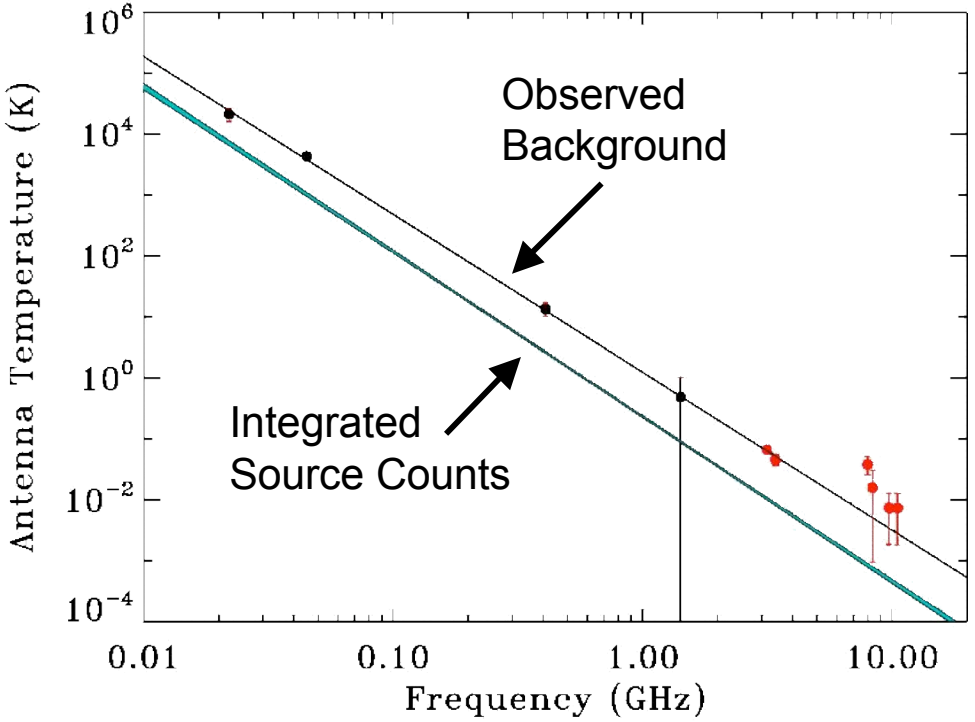
$$T_R = \frac{\lambda^2}{2\pi} \int \frac{dN}{dS} S \, dS$$

Scale observed sources to 3.3 GHz

Predicted: $T_R = 9 \pm 2$ mK

Observed: $T_R = 55 \pm 7$ mK

Wiggle Room for Radio Sources?



Detection of bright radio background

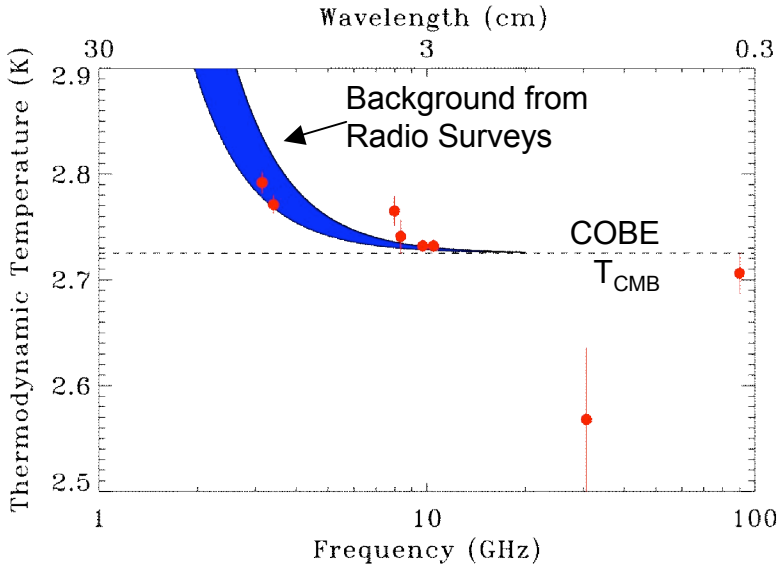
$T_R = 1.06 \pm 0.11$ K at ν=1 GHz

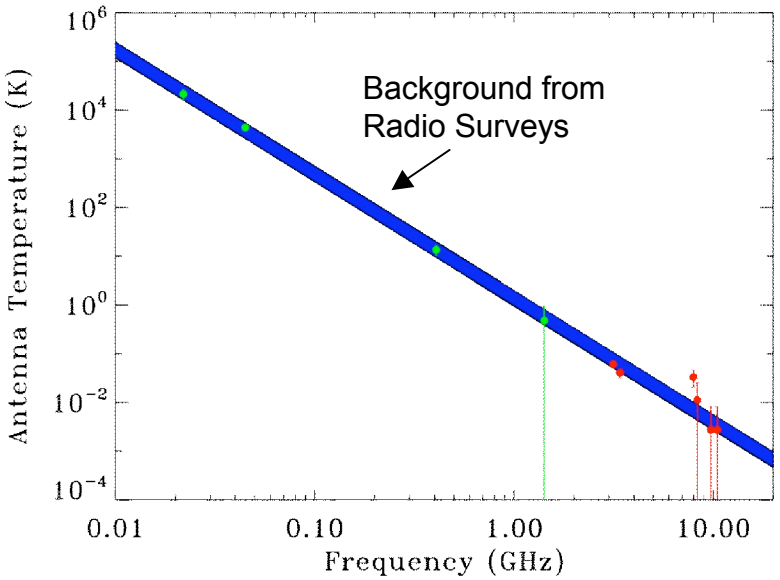
$\beta = -2.56 \pm 0.04$ (synchrotron)

6x expected point-source contribution

Modification	**Workable?**	**Notes**
Source count normalization error	No!	Requires 21σ error in dN/dS
Extended tail of source distribution	Difficult	10^6 sources amin^{-2} at 100 pJy
New source population	Maybe	1100 sources amin^{-2} at 0.75 μJy

Could ARCADE be wrong?





Compare ARCADE to COBE or radio data

- High freq: Preferentially sample cone tips
  ARCADE agrees with COBE
- Low freq: Preferentially sample cone base
  ARCADE agrees with radio surveys

Data	CMB	Background
COBE	2.725 ± 0.001	---
ARCADE	2.730 ± 0.004	1.13 ± 0.19
Radio	2.6 ± 0.6	1.5 ± 0.5

All 3 data sets in mutual agreement

Can't explain background as any single error

Could Galaxy Model Be Wrong?

		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

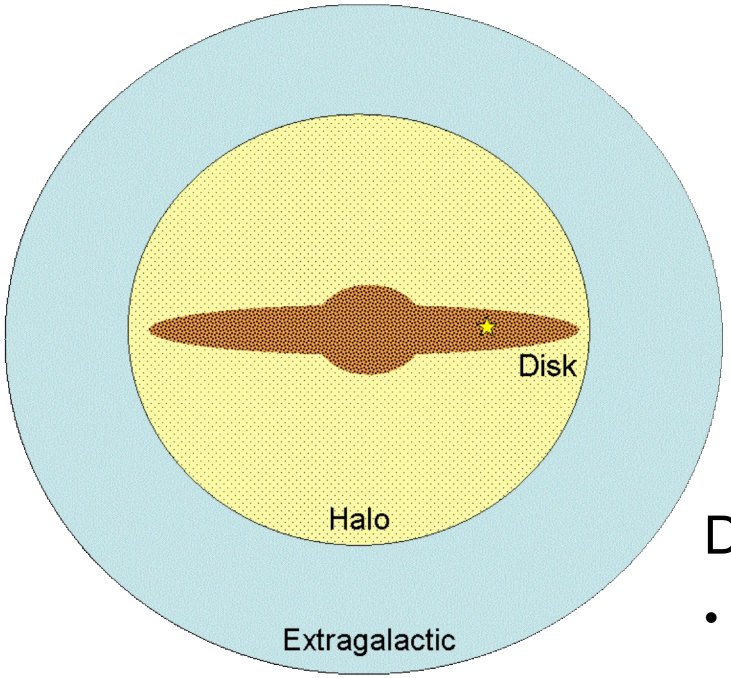
Varies by factor 2.5
from patch to patch

Mean 1.00 ± 0.04 K
χ^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

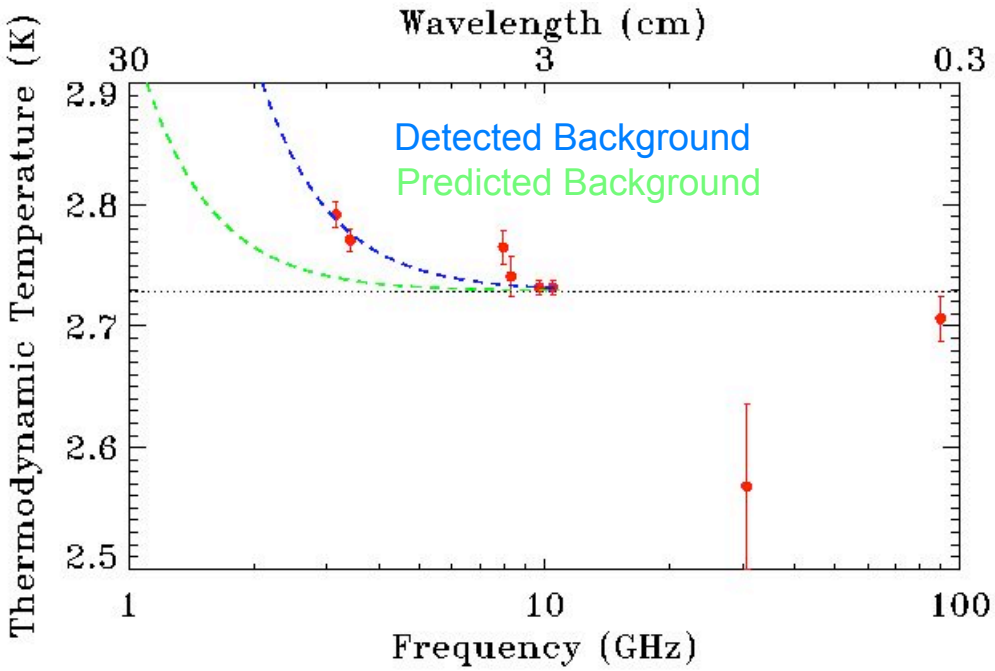
Wiggle Room For Galactic Halo?



Difficult to produce radio-bright halo

- Background is 2--3 x Galactic brightness
  - NOT a small perturbation on large Galactic signal!
- Requires halo radius large compared to disk
  - Atypical for external galaxies
  - Typically see 10--30% of disk, not 3x disk!
- No change in fit as more lines are added
  - Halo can't contain C, H, or dust (!)

ARCADE Results



ARCADE sky data with excellent calibration & control of systematics

ARCADE T_{CMB} consistent with COBE

$T_0 = 2.729 \pm 0.004$ K

Approaching COBE precision!

Improved limits to CMB distortions

$\mu < 6 \times 10^{-5}$ (95% CL)

$Y_{ff} < 8 \times 10^{-5}$ (95% CL)

Unknown origin for detected background

- New population of faint sources?
- Diffuse background?
- Cosmological origin?

Detection of bright radio background

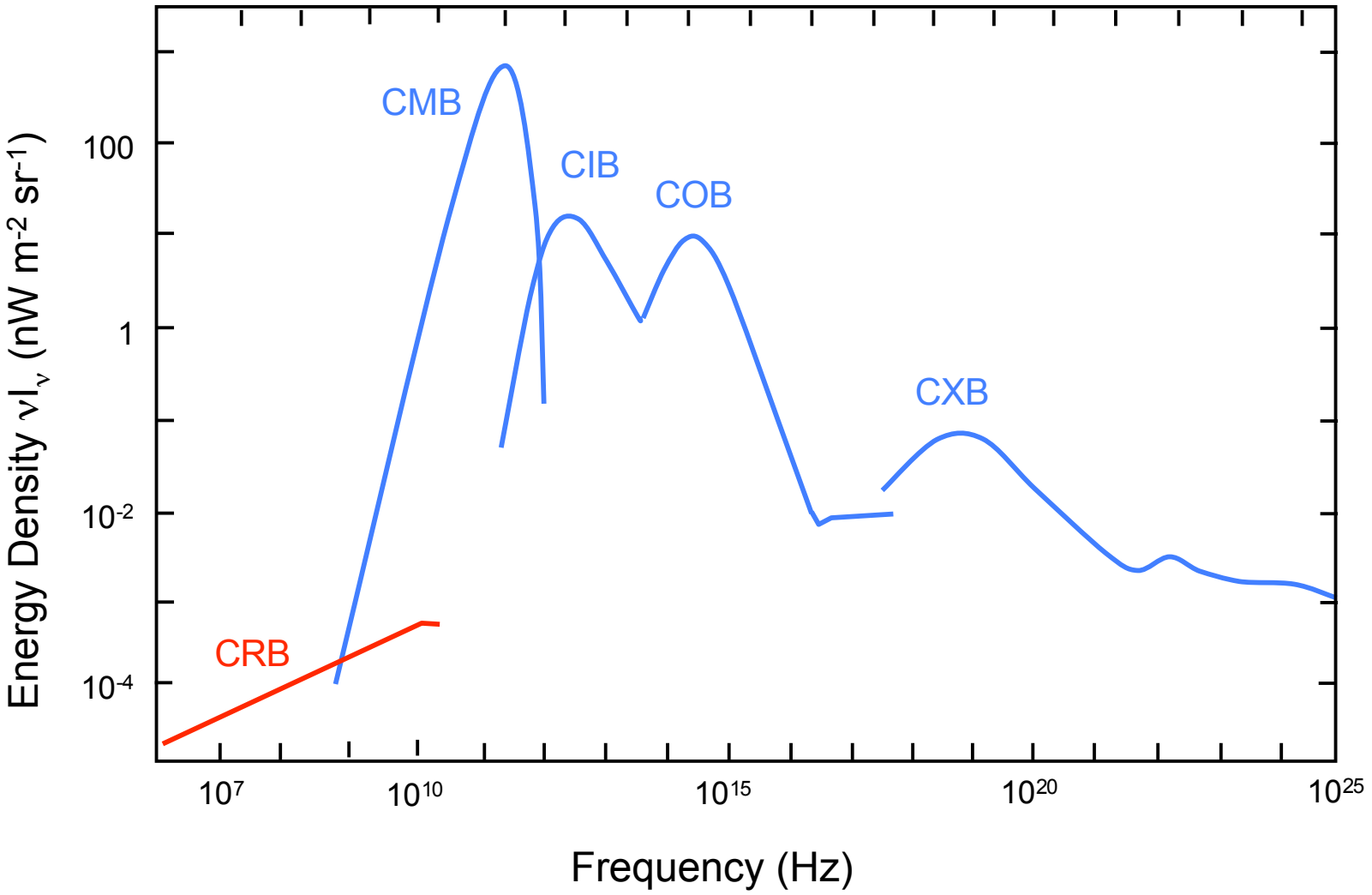
$T_R = 1.06 \pm 0.11$ K

$\beta = -2.56 \pm 0.04$

6x point-source contribution

- Amplitude: ARCADE
- Index: Radio Surveys

Cosmic Radio Background



A Look Into Al's Crystal Ball

The Advantage of Suborbital Missions

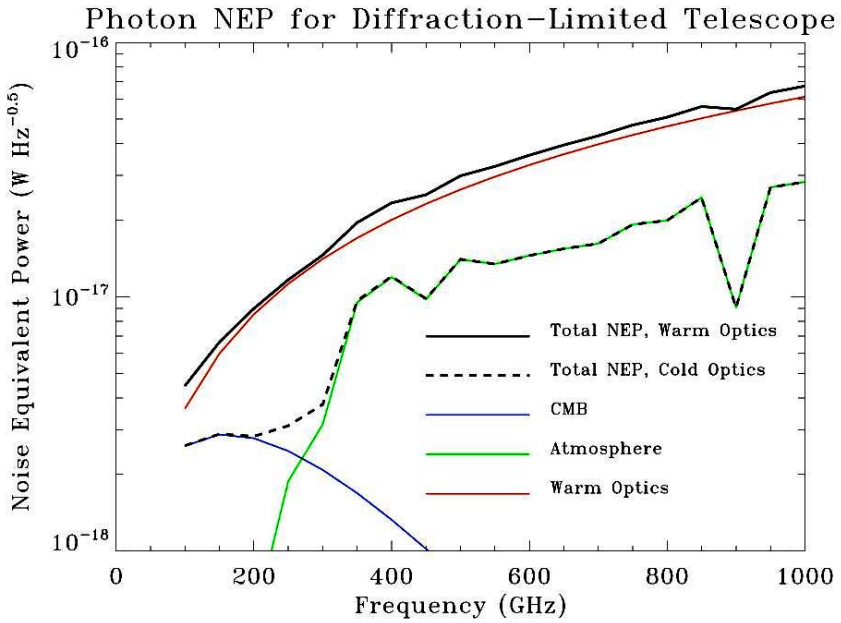
Fly payload multiple times
to develop thermal design

Sometimes you're lucky …

150 foot cliff!

… Sometimes you're not

Importance of Cold Optics



Photon noise from warm optics

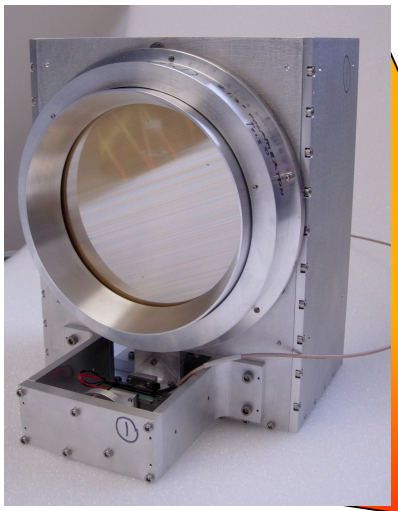
- Factor of 3 in NEP
- Factor of 10 in mapping speed

+

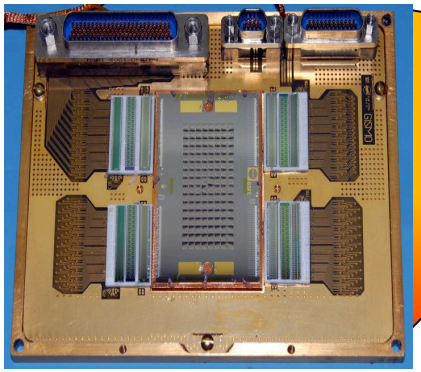
=

Near-Space Suborbital Capabilities

Primordial Inflation Polarization Explorer

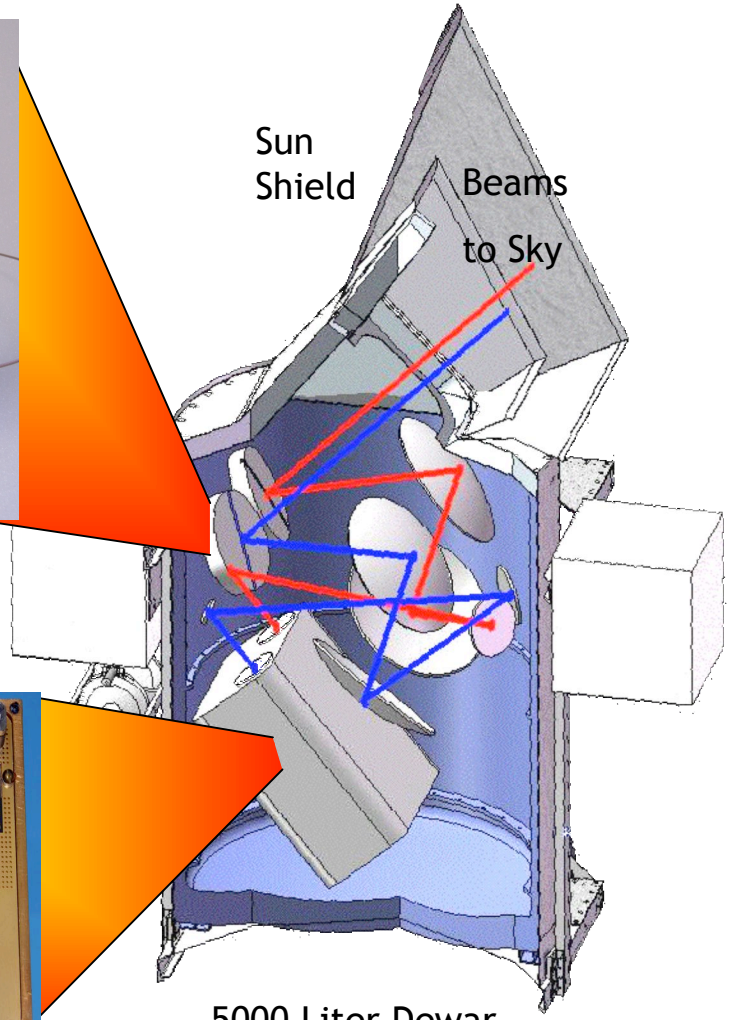


Modulator



4 Detector Arrays

Each 32x40 Bolometers



5000 Liter Dewar
(ARCADE)

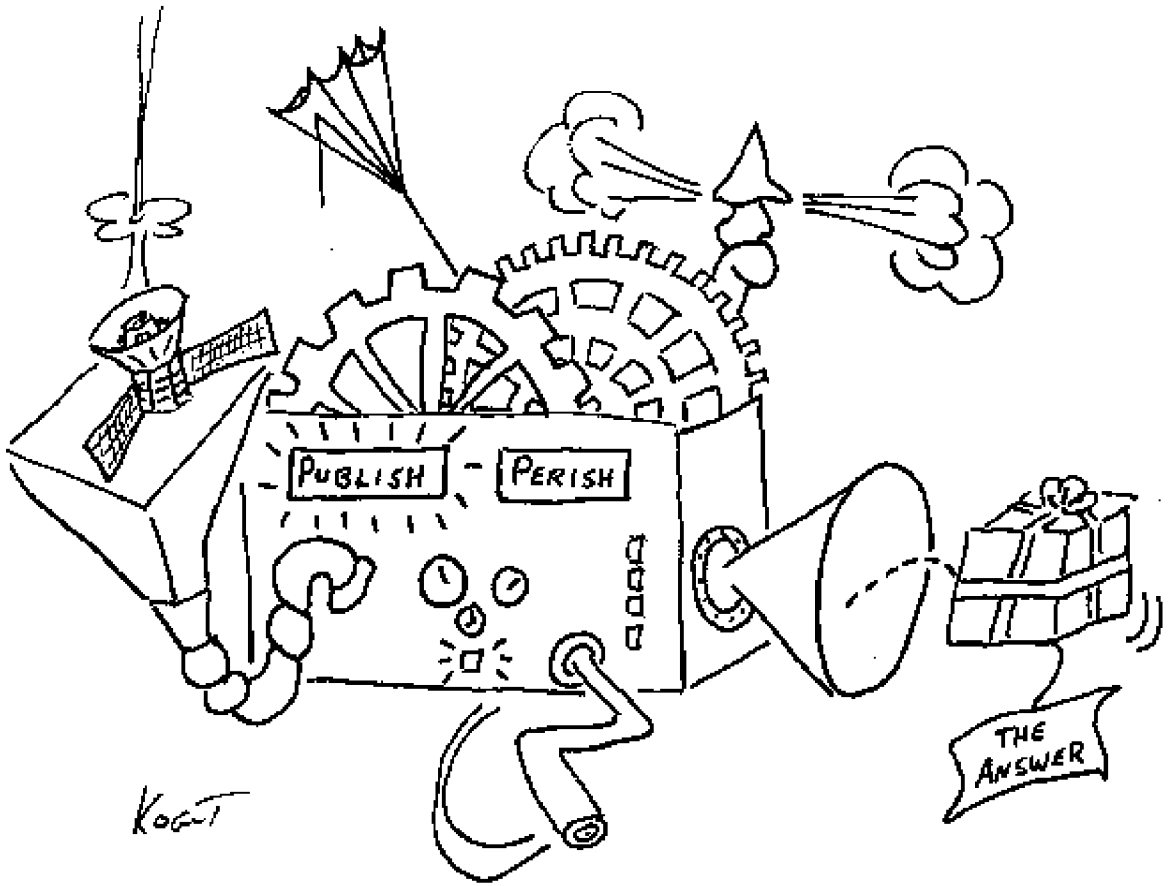
PIPER Balloon Instrument

- 5120 Detectors at 0.1 K
- 1.5 K Open-Aperture Optics
- Phase-Sensitive Modulation
- Survey sky in I, Q, U, V
- 2100, 1100, 850, 500 μm
  (CMB + dust foregrounds)

First Flight June 2012

- Sensitivity 10 nK rms to CMB polarization
- Detect signal predicted from ~all single-field inflation models

Toward a Cold Future



CMB Polarization …

The Dusty Universe …

High-R Spectroscopy …