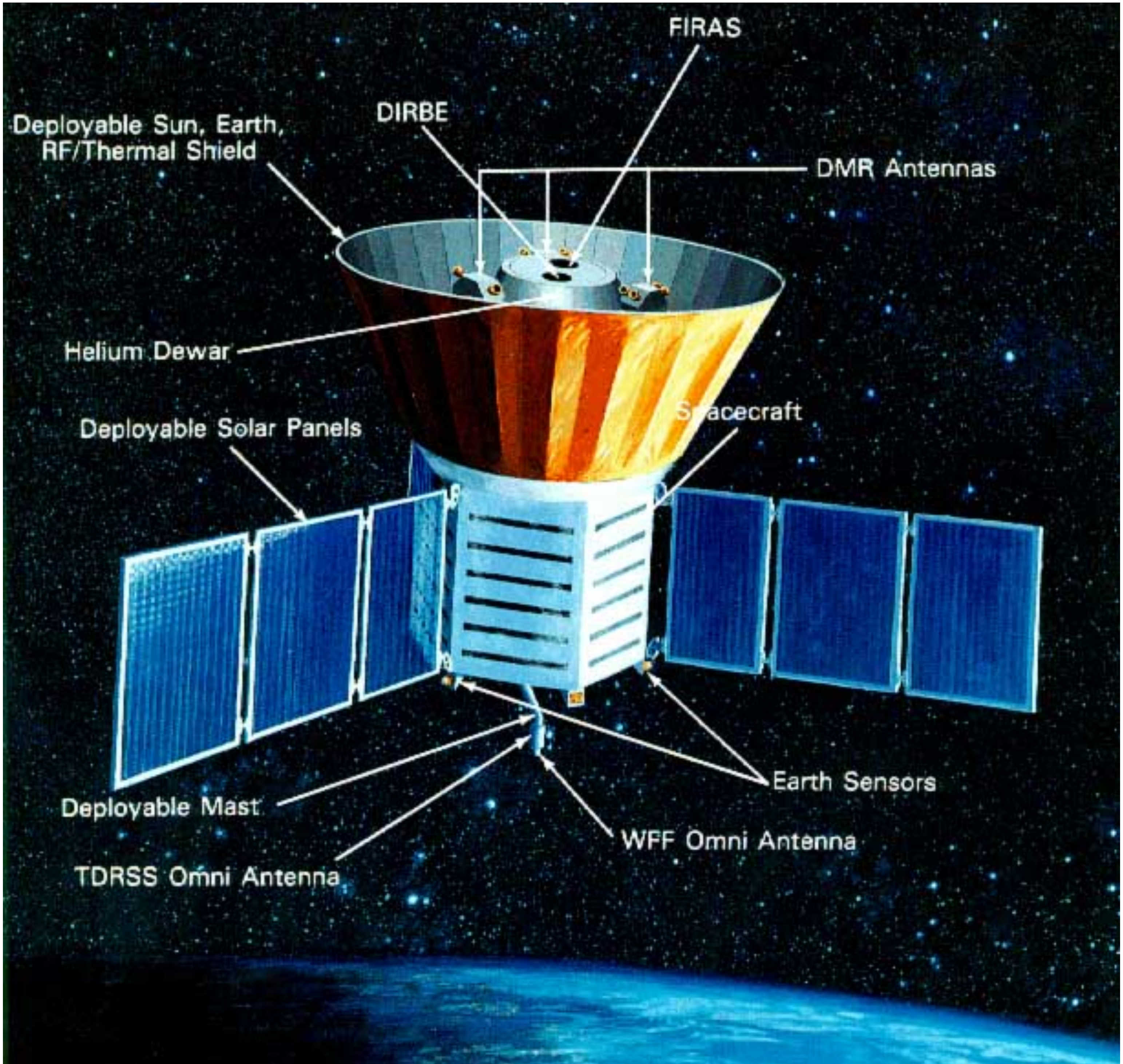
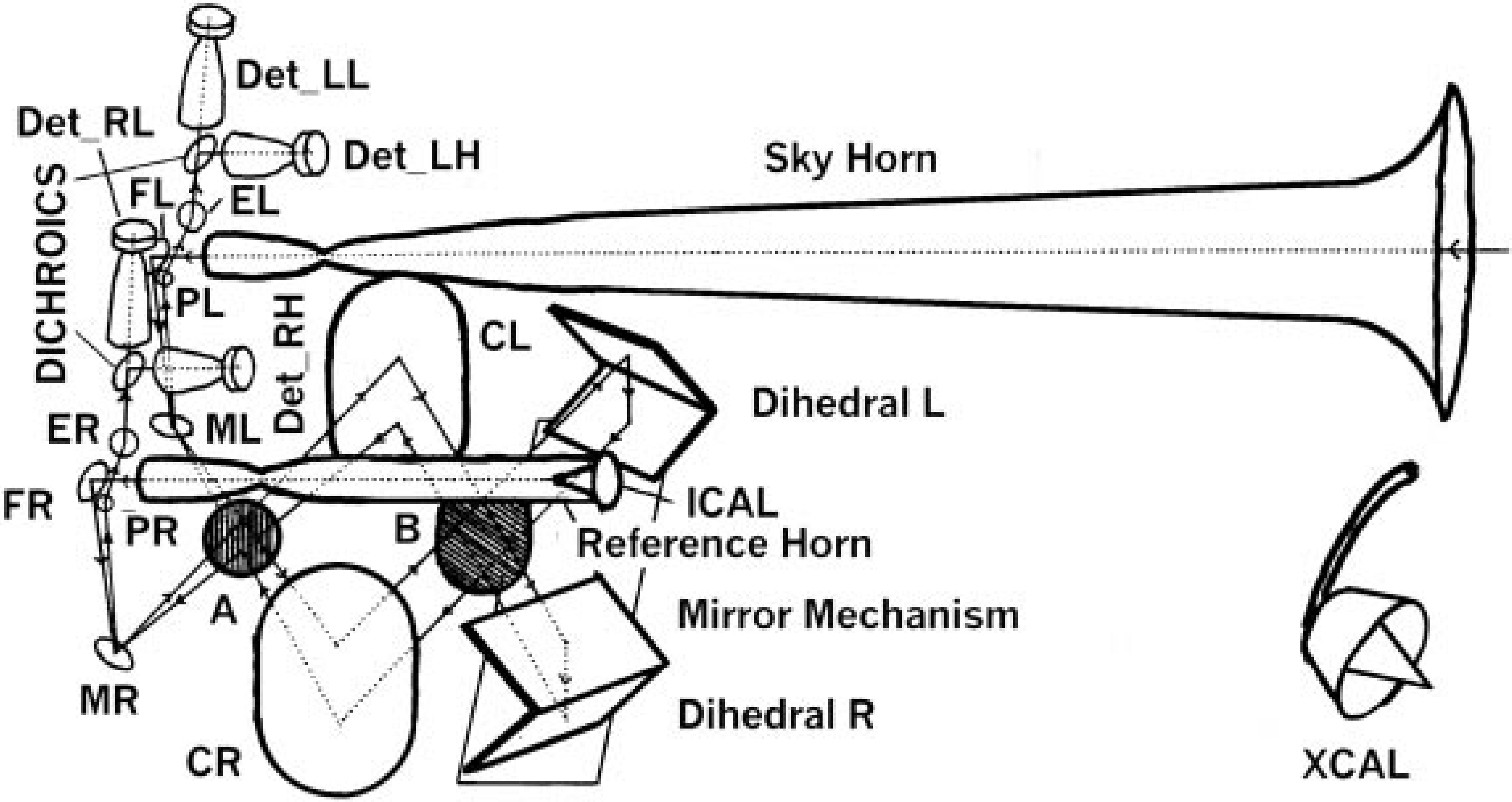
What have we learned from FIRAS

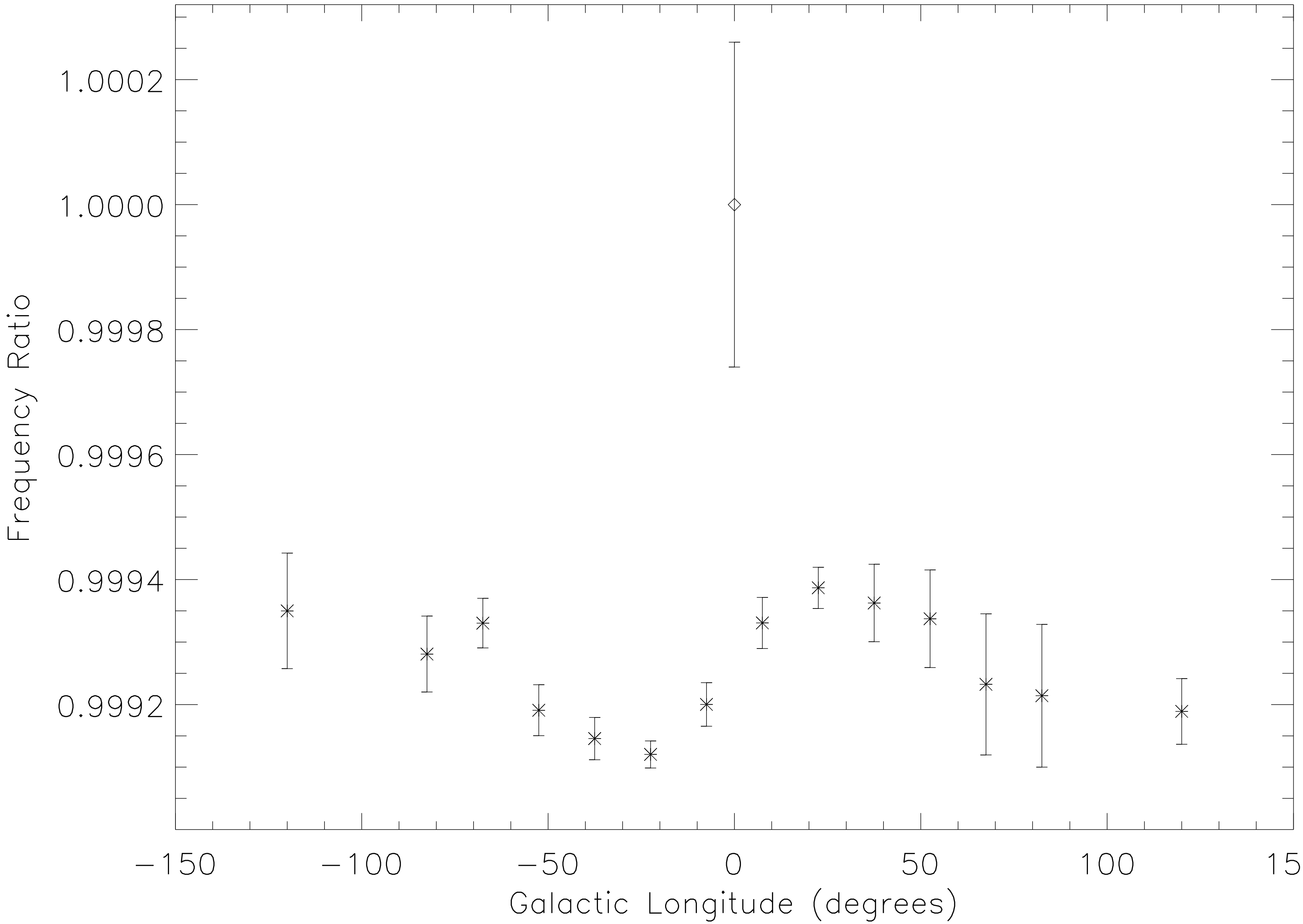


Design of FIRAS



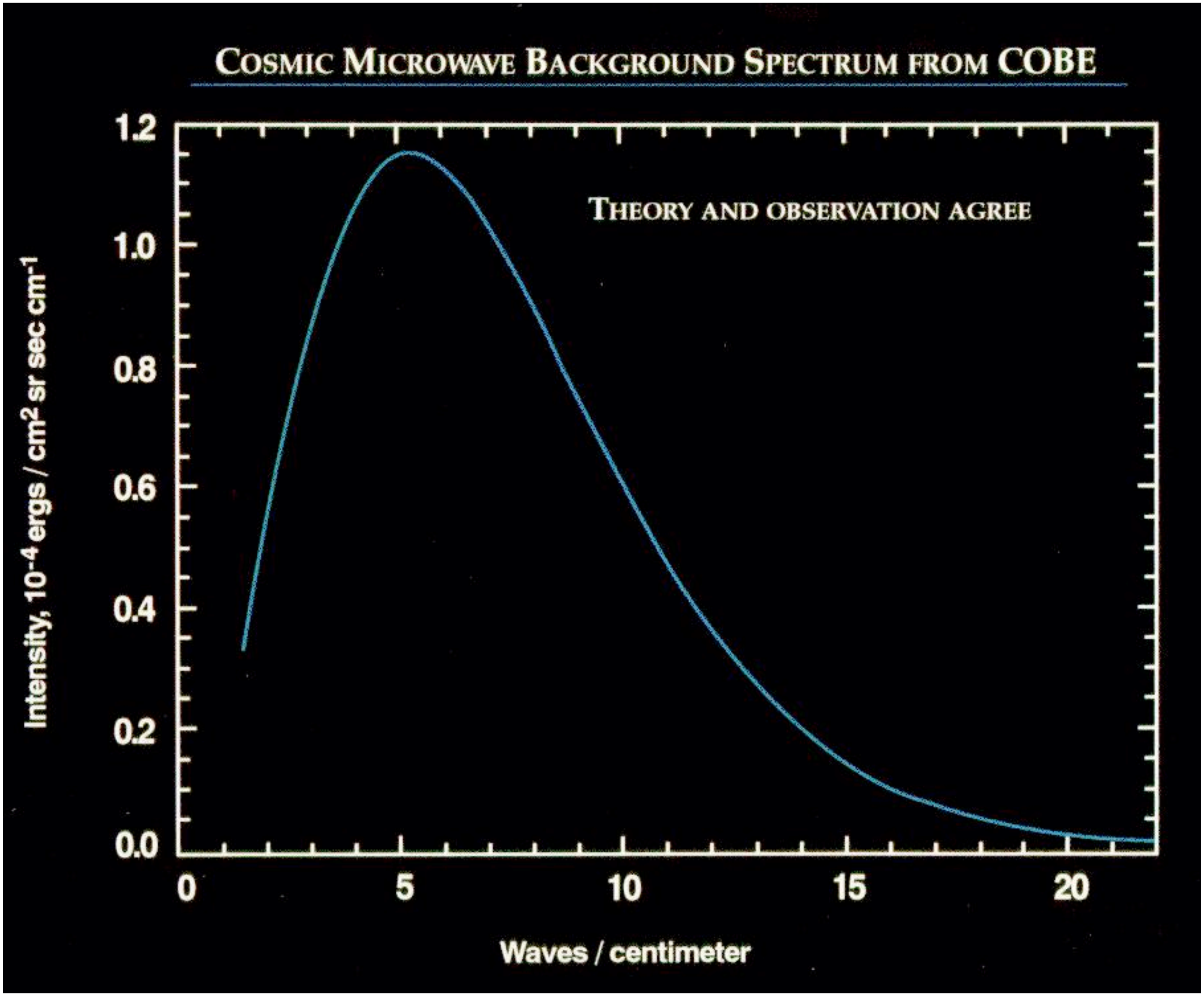
Mather etal SPIE 2019:168 1993

Calibration of FIRAS



Fixsen etal ApJ 420:457 1994

Spectrum good to 50 ppm



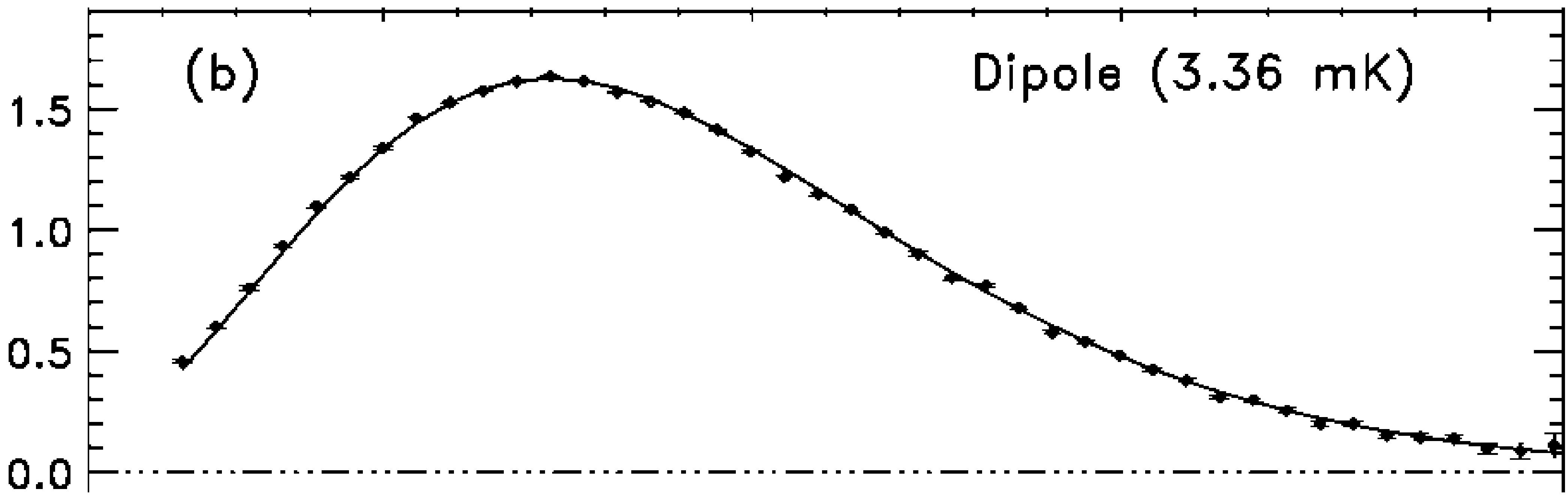
Fixsen etal ApJ 473:576 1996

Temperature is 2.72548 +/- .00057

BECAUSE spectrum “is” a black body it can be described with a single number:

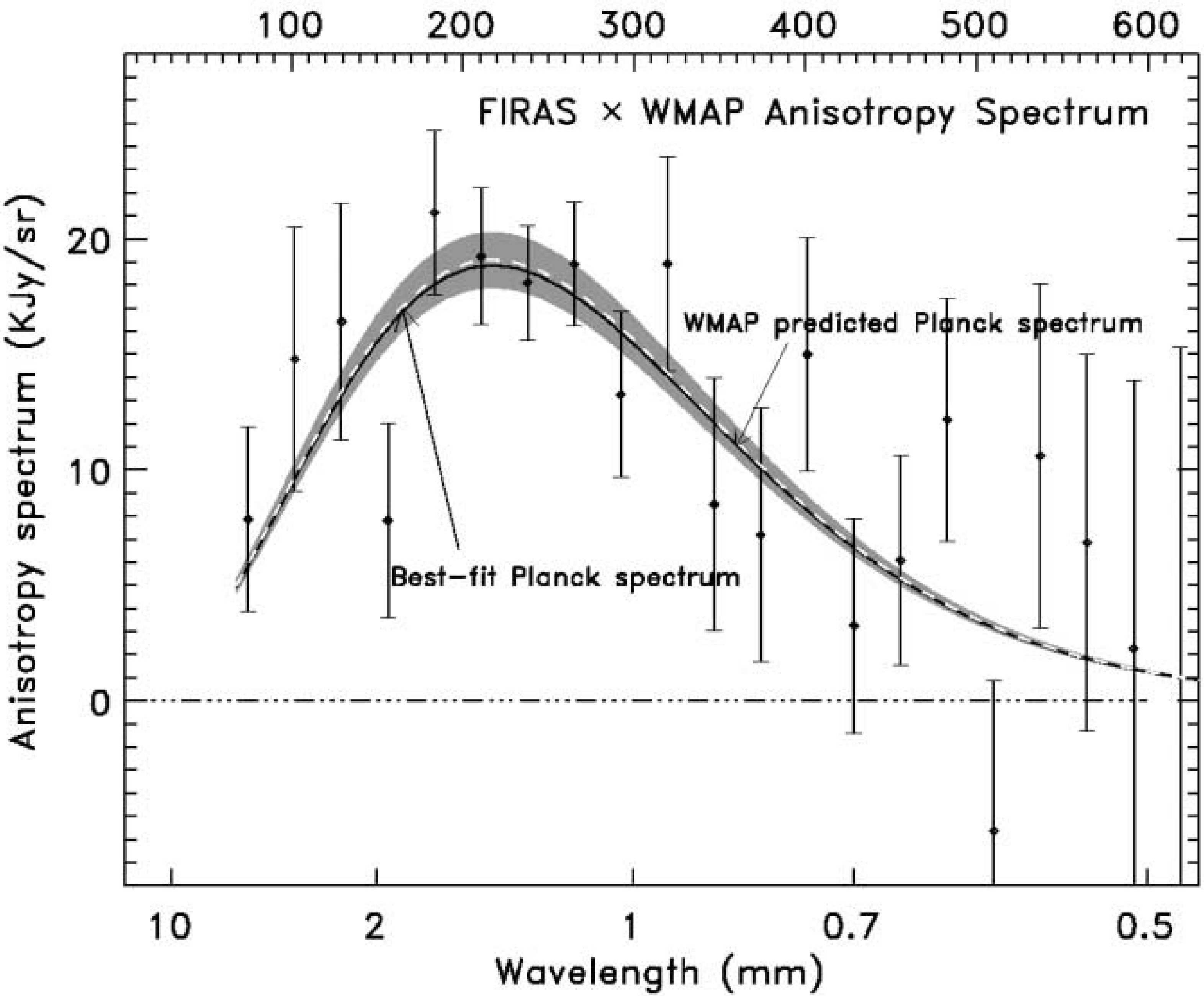
The Temperature

Spectrum of dipole is dP/dT



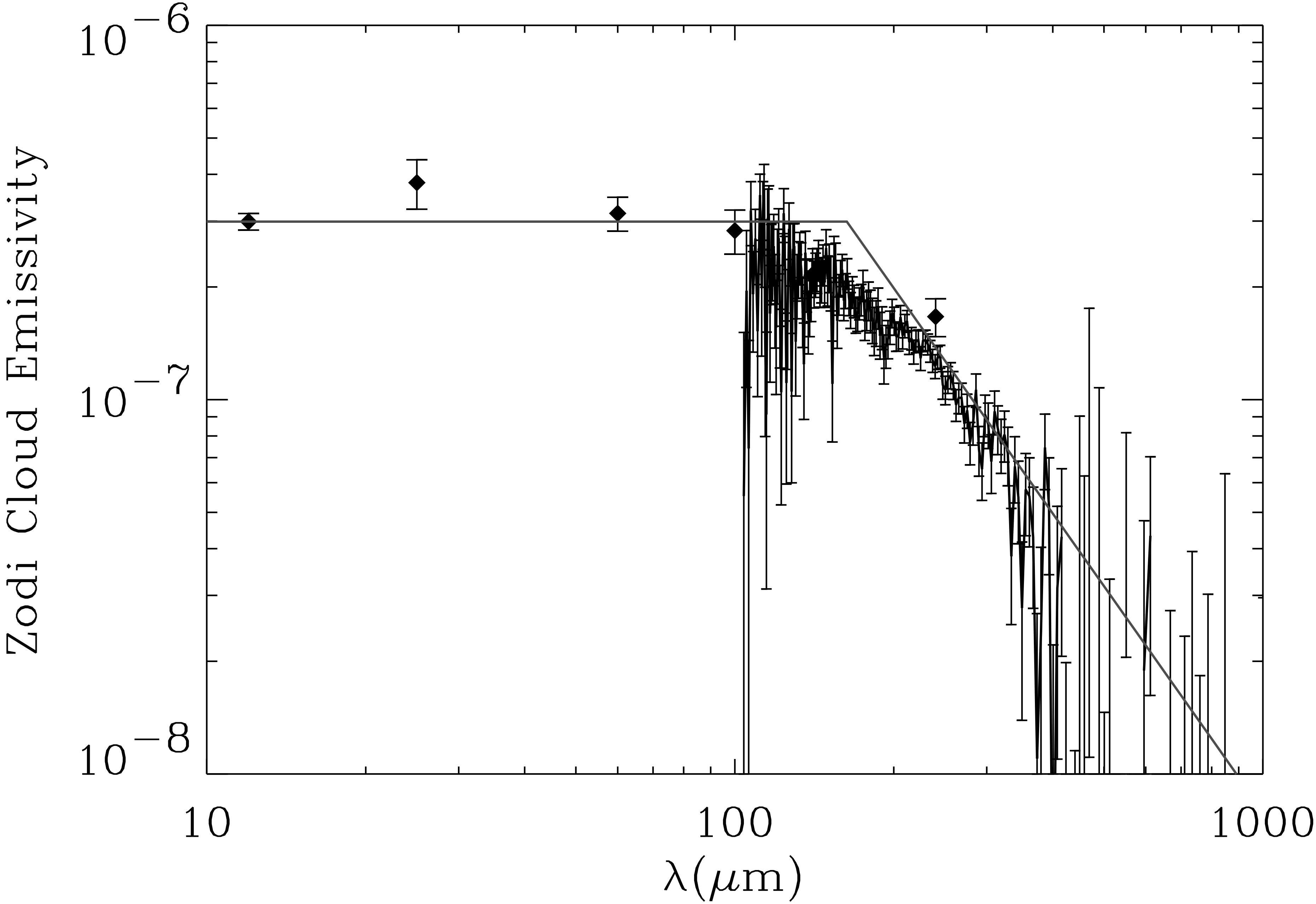
Fixsen etal ApJ 473:576 1996

Spectrum of anisotropy is dP/dT



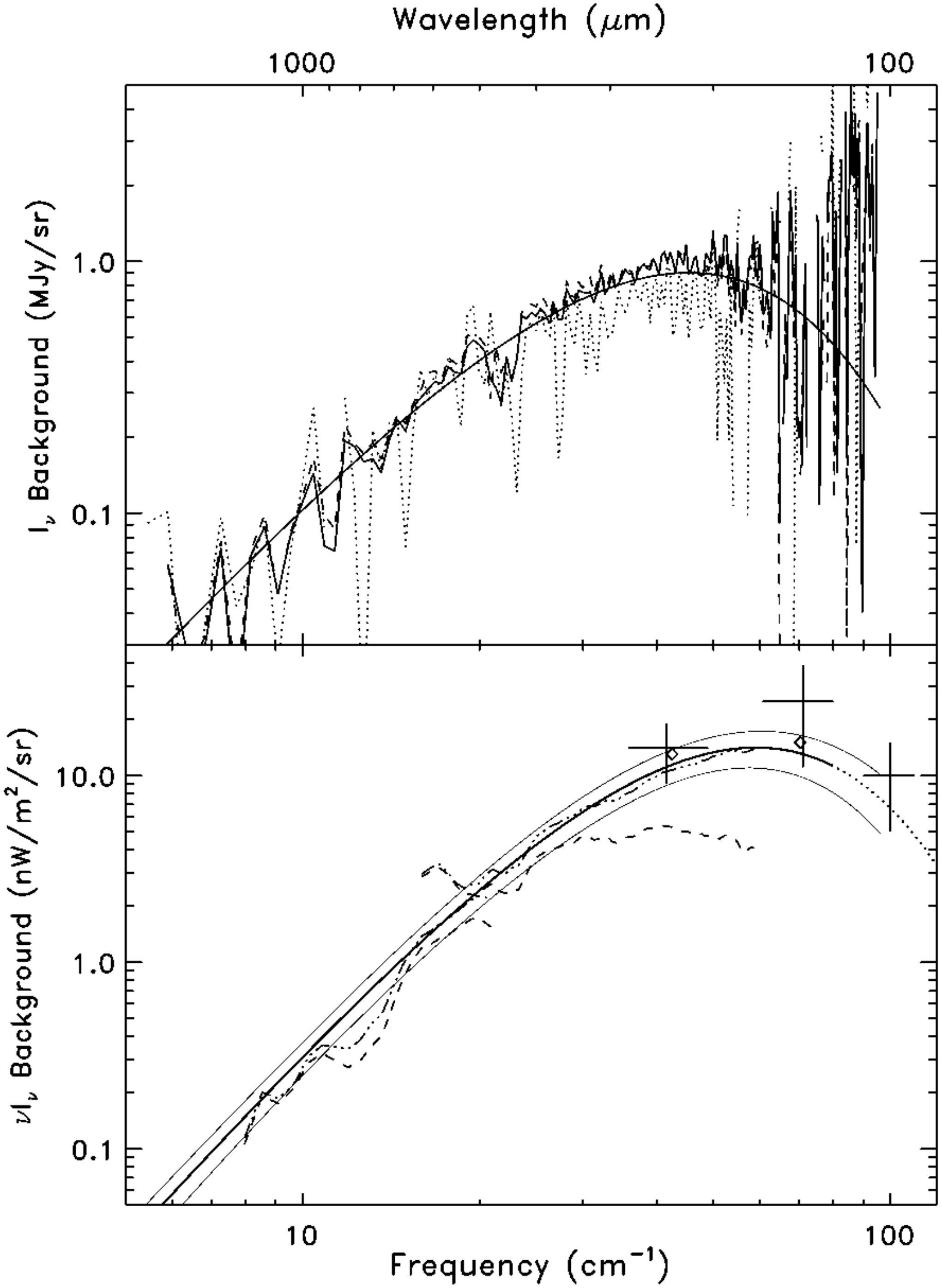
Fixsen ApJ 594L:67 2003

Spectrum of Zodiacal Light



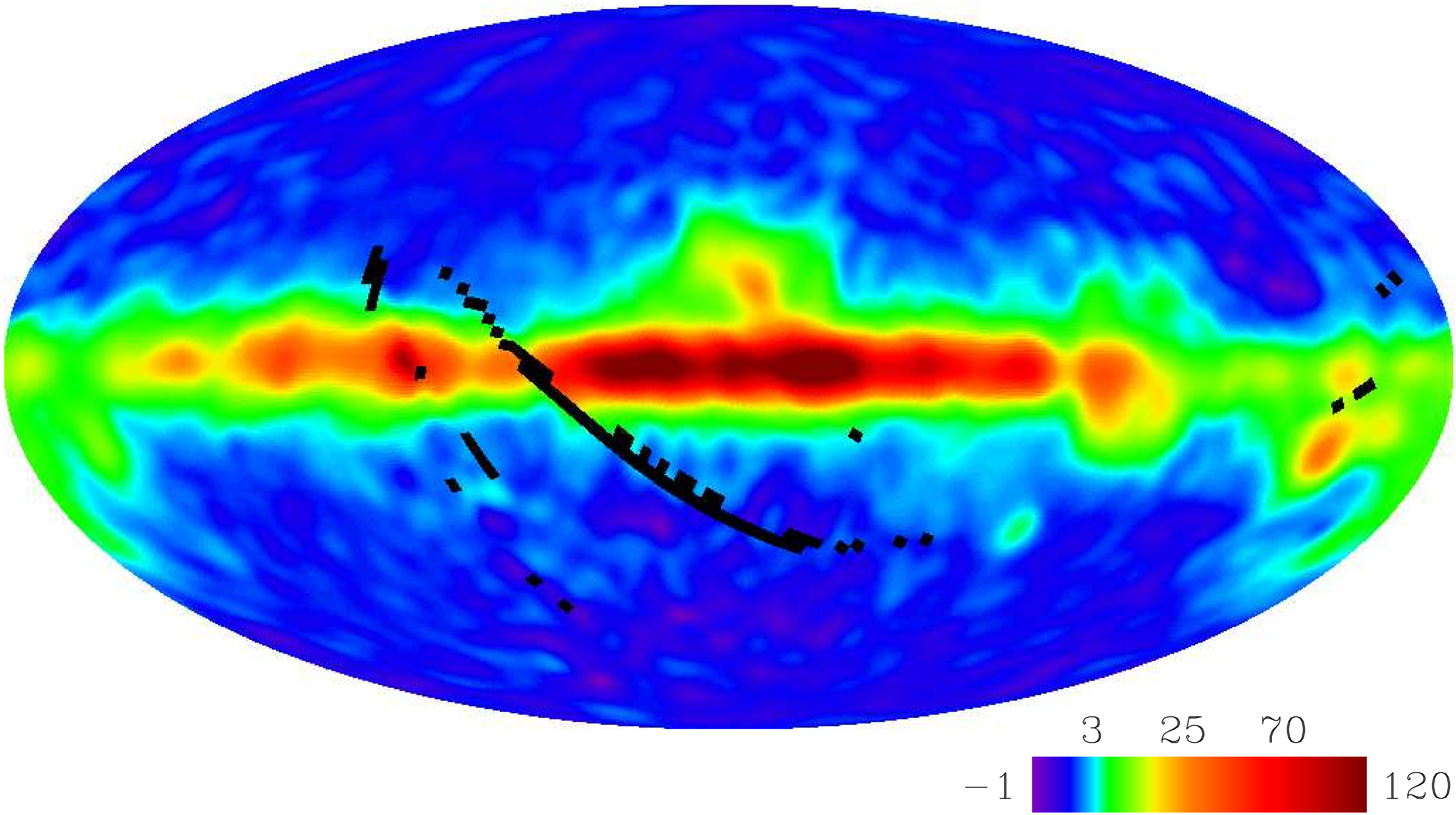
Fixsen & Dwek ApJ 578:1009 2002

Spectrum of CIB



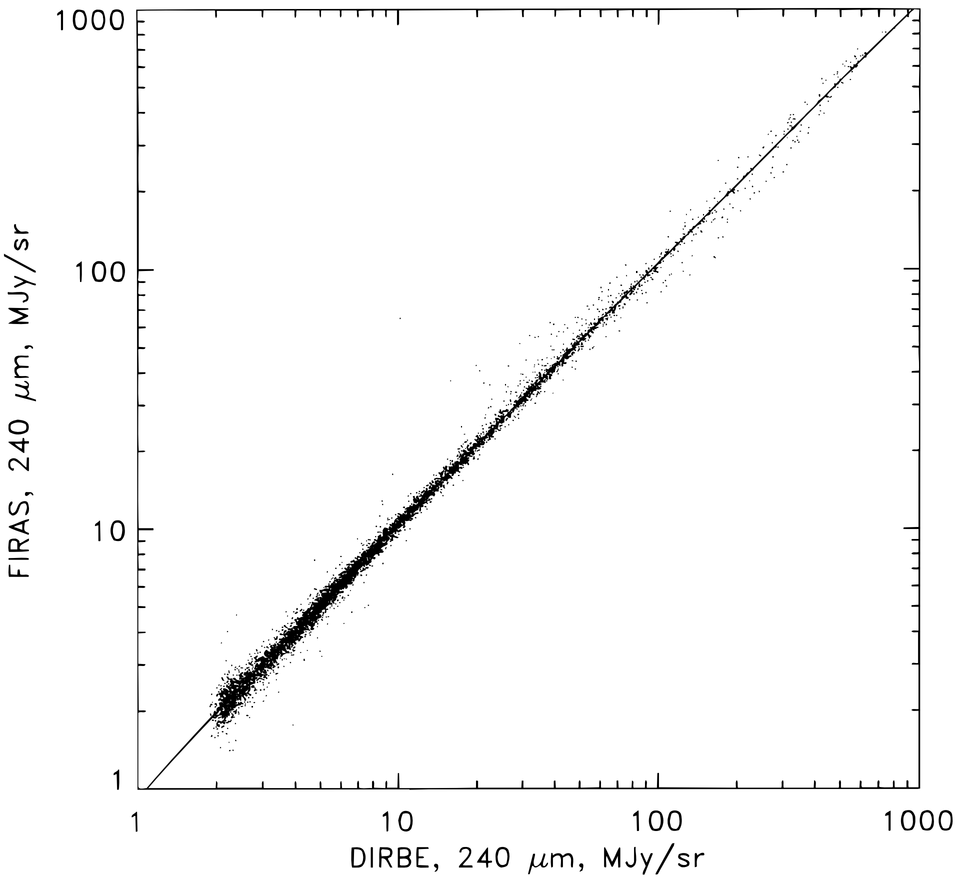
Fixsen etal ApJ 508:123 1998

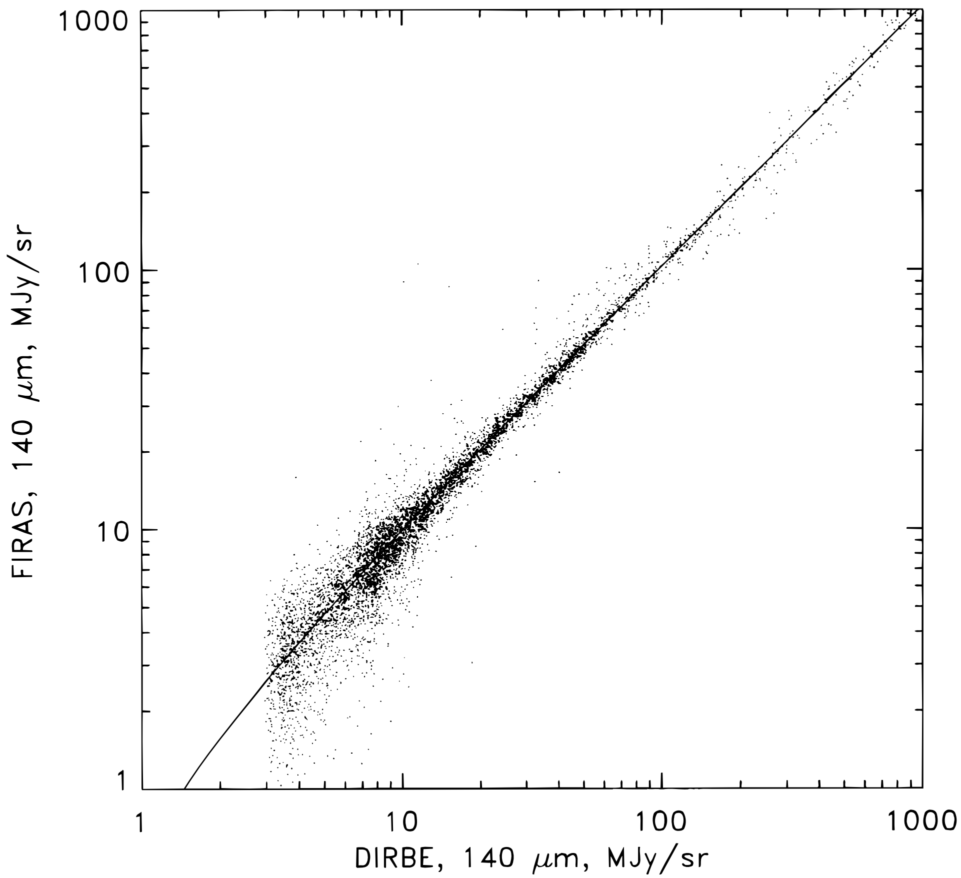
Full sky map of Major Galactic Lines



Fixsen, Bennet & Mather ApJ 526:20 1999

Calibration check of DIRBE





Fixsen etal ApJ 490:482 1997

Good Ideas

- ✧Fourier Transform Spectrometer (FTS)
  - Direct measurement of Spectrum Difference
- ✧Constant Frequency Sampling
  - Stationary Noise
- ✧External Calibrator
  - Needs to be Blacker for improved Measurement
  - Look at it More
- ✧Winston Concentrator
  - Needs to be Square to Maintain Polarization
  - Hard to get less than 5 deg Tophat Beam
- ✧Large Detector
  - Bigger is Better
  - Make it a Mesh to minimize Cosmic Rays

Not so Good Ideas

- ✧Rarely looked at external calibrator
  - Limit is how well we see the Calibrator not Sky
- ✧Lots of modes of operation
  - Most of useful data from SS
- ✧Sampling in only One direction
  - Limits phase separation between Det & Inst
- ✧Averaging data before deglitching
  - Reduces signal to find CR
  - Increases amount of data contaminated
- ✧Bad Detectors (RL, LH)
  - RL is worth ~15% or LL; LH is worth 5% of RH
- ✧Internal Calibrator
  - 94% Black: Metal cup??
- ✧Vibrating Mirror

Improvements?

- ✧Larger Etendu
- ✧Colder Detectors (Reduce noise)
- ✧Good Detectors (All 4)
- ✧Instrument to match CMB (2.725 K)
- ✧Take Data in BOTH directions
- ✧Use Telescope to fed FTS instead of Horn
- ✧Always look at Calibrator
- ✧Symmetrize Instrument
- ✧Record all Data

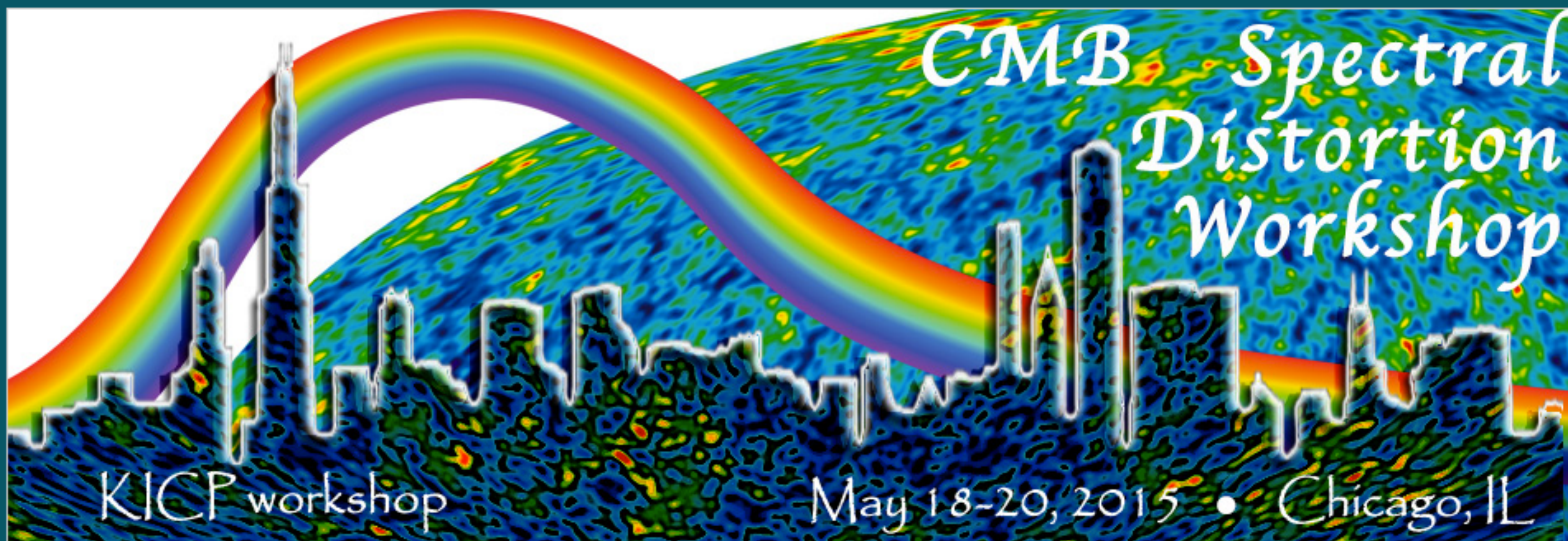
FIRAS was a Great experiment
Let’s do it again
This time with ***feelin’***

Kicp-workshops.uchicago.edu/CMB_Distortion

KICP Hub: CMB Polarizatio... | Workshop: CMB Distortion

https://kicp-workshops.uchicago.edu/CMB_Distortion/

Most Visited | (13634 unread) -... | BETTII Document...

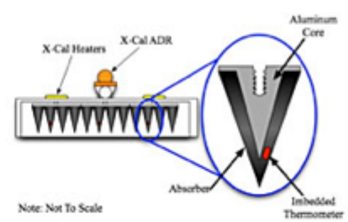


OVERVIEW | REGISTRATION APPLICATION | PARTICIPANTS | PROGRAM | PRESENTATIONS | LOGISTICS

Overview

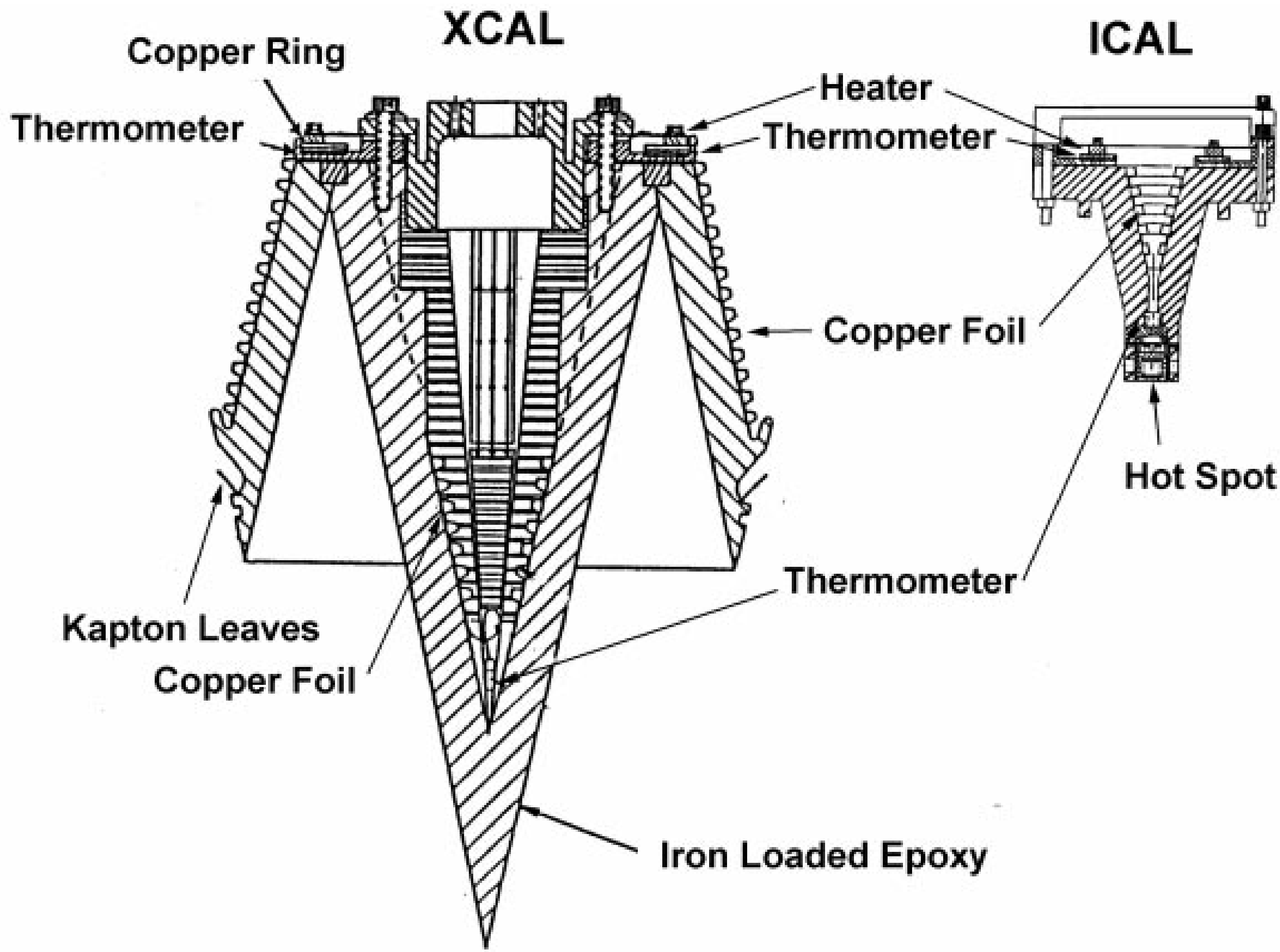
PURPOSE

The Kavli Institute for Cosmological Physics (KICP) at the University of Chicago is hosting a workshop on CMB spectral distortions.



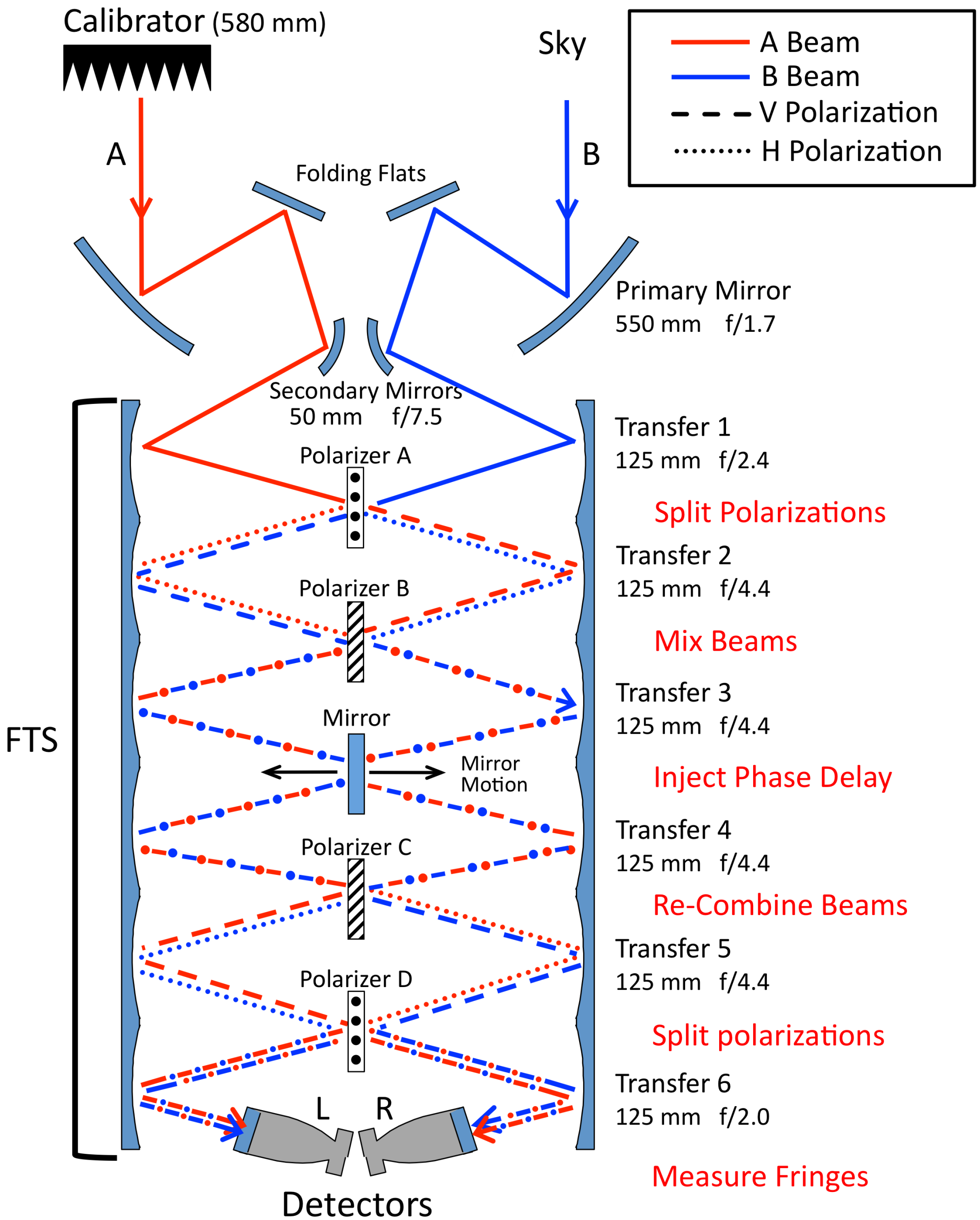
The frequency spectrum of the Cosmic Microwave Background has been shown to be a blackbody to a precision of 50 parts per million. However, at higher sensitivity the CMB is expected to show distortions from the blackbody shape. These distortions contain the signatures of energy-

Calibrator Design



Mather etal ApJ 512:511 1999

PIXIE Nulling Polarimeter



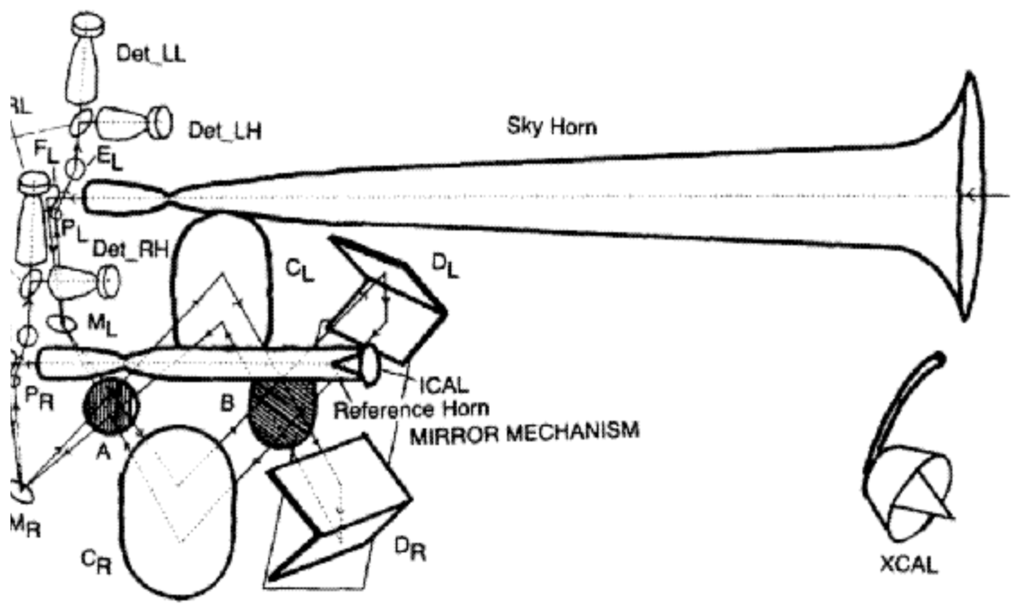
AC Readout
Nulling Polarimeter: Zero = Zero

$$P_{Lx} = \frac{1}{2}\int\left(E_{Ay}^2 + E_{Bx}^2\right) + \left(E_{Bx}^2 - E_{Ay}^2\right)\cos(z\nu/c)\, d\nu$$

$$P_{Ly} = \frac{1}{2}\int\left(E_{Ax}^2 + E_{By}^2\right) + \left(E_{By}^2 - E_{Ax}^2\right)\cos(z\nu/c)\, d\nu$$

$$P_{Rx} = \frac{1}{2}\int\left(E_{Ax}^2 + E_{By}^2\right) + \left(E_{Ax}^2 - E_{By}^2\right)\cos(z\nu/c)\, d\nu$$

$$P_{Ry} = \frac{1}{2}\int\left(E_{Ay}^2 + E_{Bx}^2\right) + \left(E_{Ay}^2 - E_{Bx}^2\right)\cos(z\nu/c)\, d\nu$$



Fourier Transform

$$P_{Lx} = \frac{1}{2}\int \left(E_{Ay}^2 + E_{Bx}^2\right) + \left(E_{Bx}^2 - E_{Ay}^2\right)\cos(z\nu/c)\, d\nu$$

$$P_{Lx}(\omega) = g_{Lx}(\omega)\left(S_{Bx}(\nu) - S_{Ay}(\nu)\right), \qquad \omega = \nu * u/c$$

$$P_{Ly}(\omega) = g_{Ly}(\omega)\left(S_{By}(\nu) - S_{Ax}(\nu)\right)$$

$$P_{Rx}(\omega) = g_{Rx}(\omega)\left(S_{Ax}(\nu) - S_{By}(\nu)\right)$$

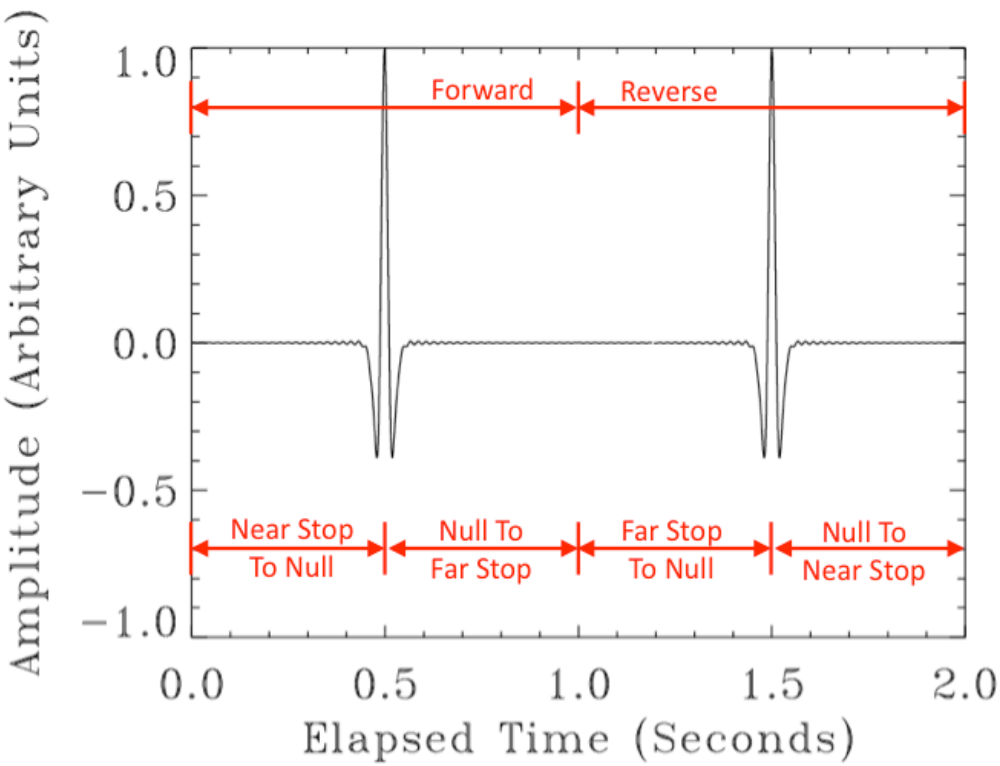
$$P_{Ry}(\omega) = g_{Ry}(\omega)\left(S_{Ay}(\nu) - S_{Bx}(\nu)\right)$$

Resolution set by maximum excursion,

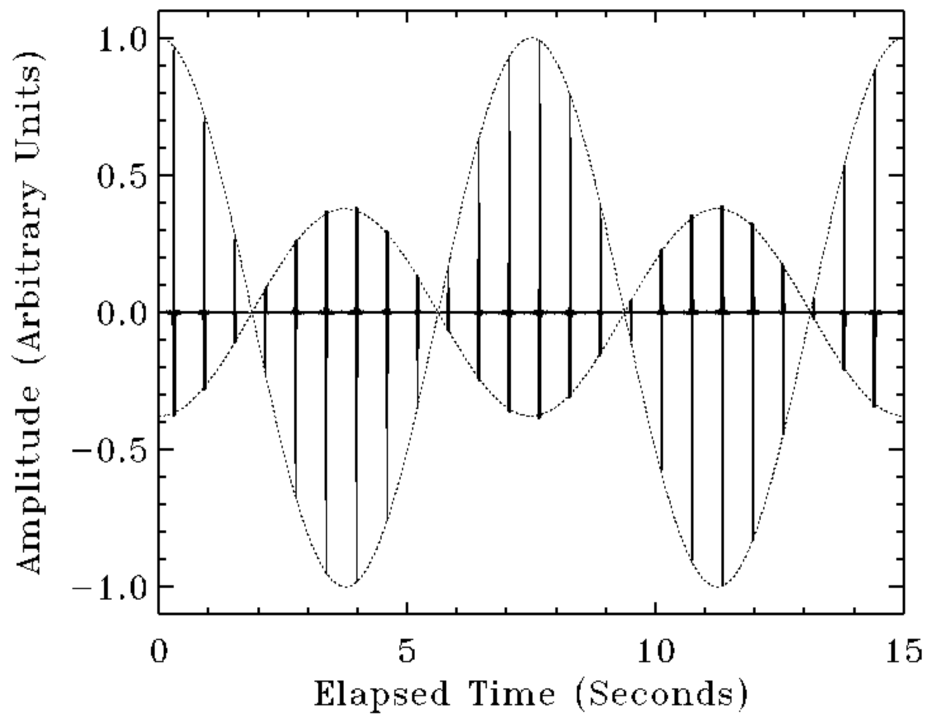
highest frequency set by sample spacing

Systematic Error Control

Multiple Instrumental Symmetries



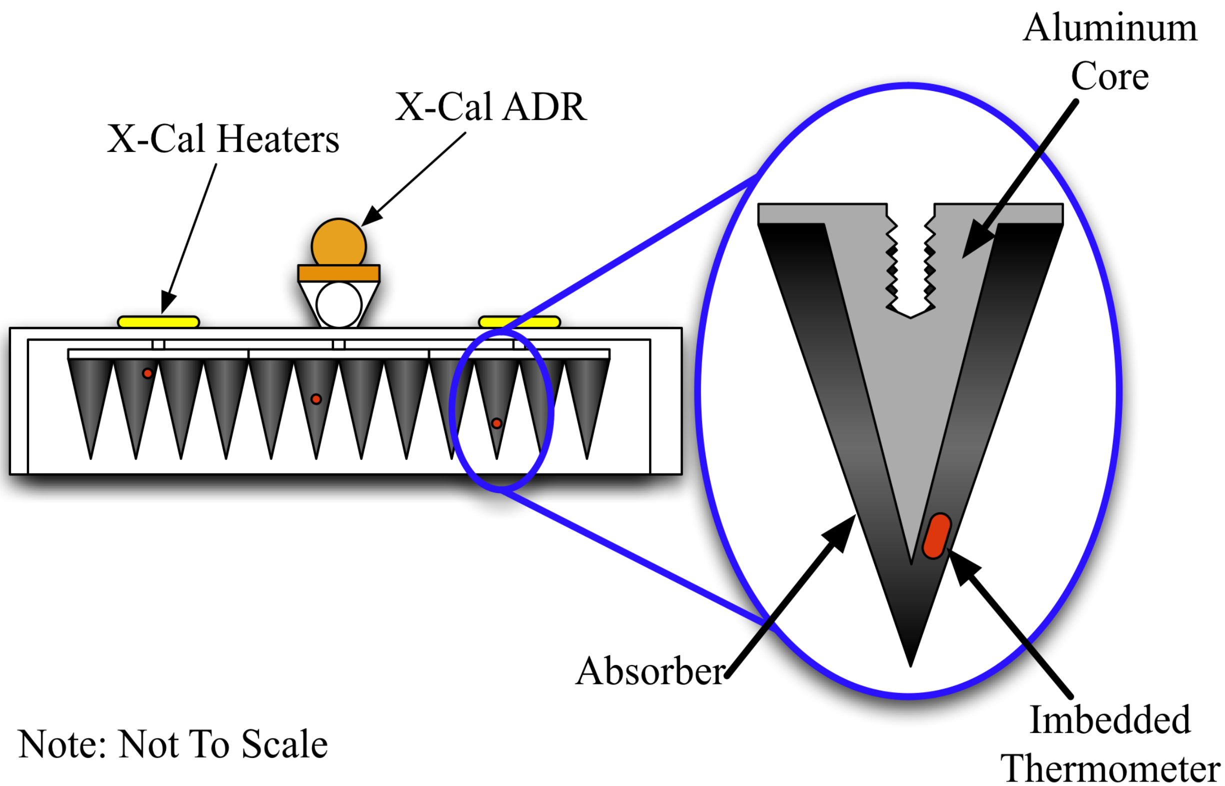
Same information 4x per stroke with different time/space symmetries



Spacecraft spin imposes amplitude modulation of entire fringe pattern

Multiple Redundant Symmetries Allow Clean Instrument Signature

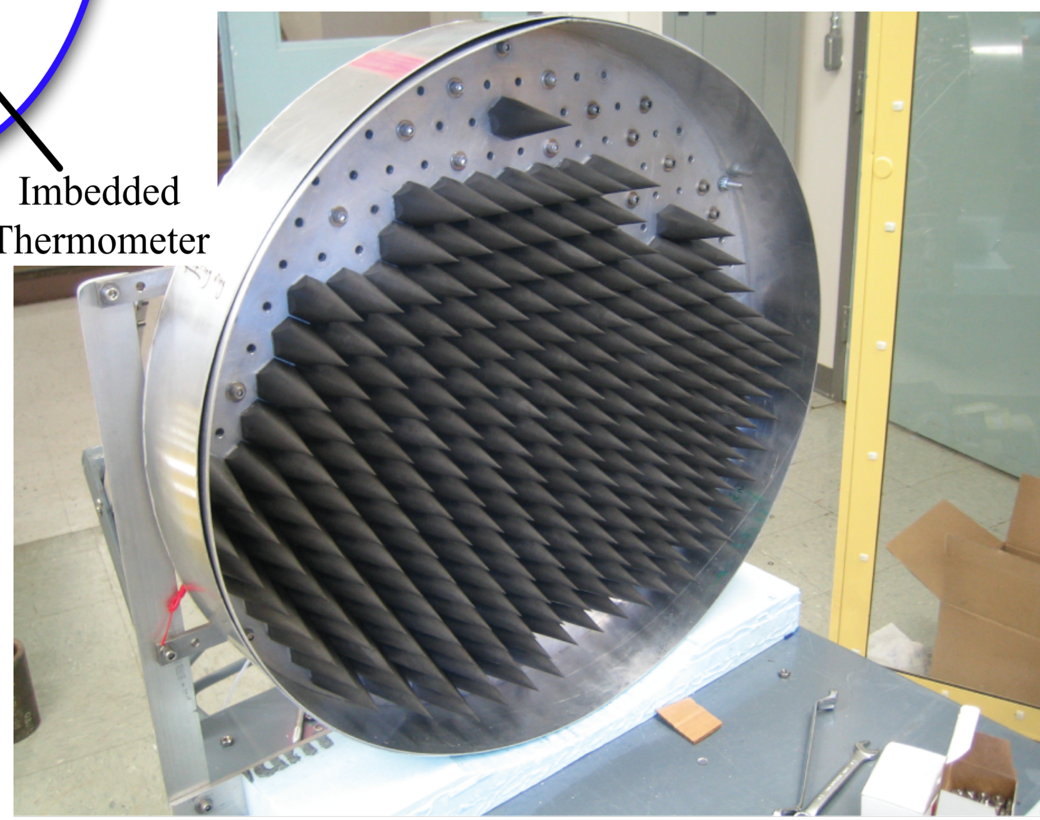
Blackbody Calibrator



3 Positions Left Right Out
40 thermometers to measure gradients

Based on successful ARCADE calibrator

Note: Not To Scale



XCal Requirements		
Parameter	**Requirement**	**Performance**
Blackness (30 to 300 GHz)	< -60 dB	-65 dB
Blackness (> 300 GHz)	< -20 dB	-50 dB
Temperature Range (Body)	2.6 -3.5 K	2.6 -3.5K
Temperature Range (Single Cone)	2.6 -20 K	2.6 -20 K
Temperature Gradient	< 3 μK	< 1 μK

PIXIE Fourier Transform

Phase delay L sets channel width

$\Delta\nu = c/L$

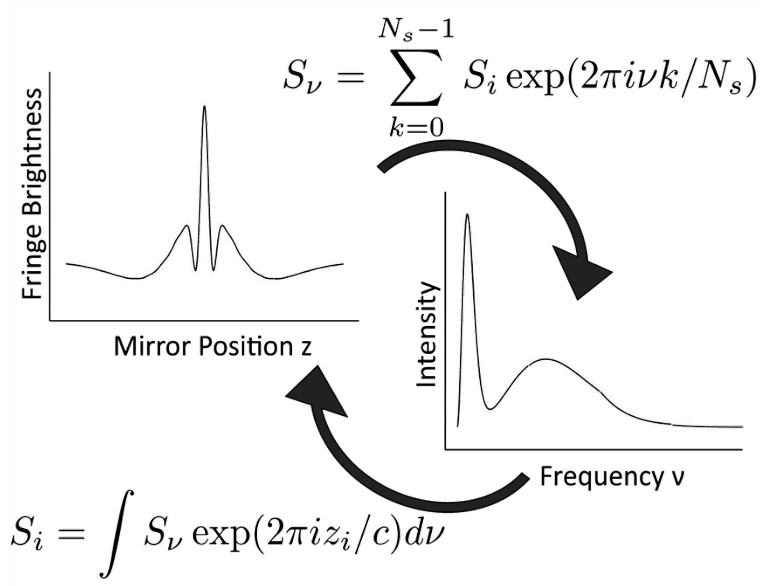
Number of samples sets frequency range

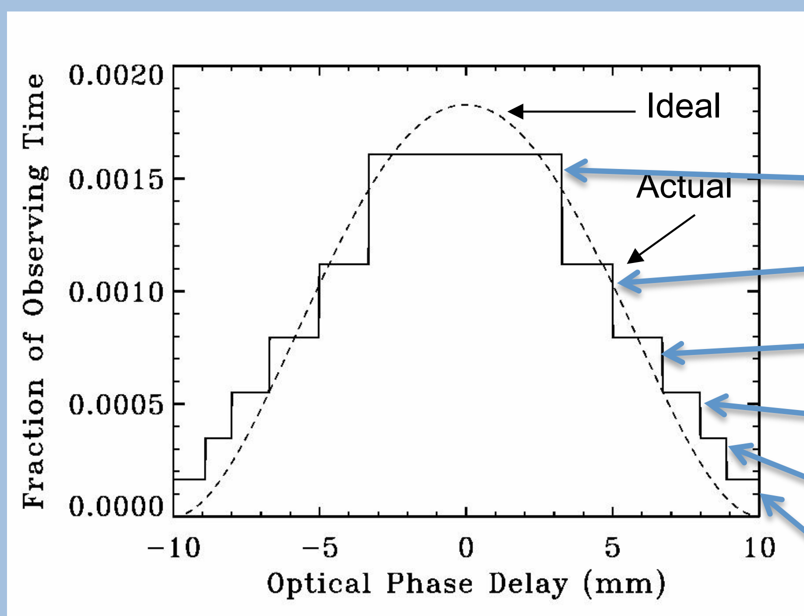
N_chan = N_samp / 2

PIXIE: ~400 usable channels

$\Delta\nu$ = 15 GHz

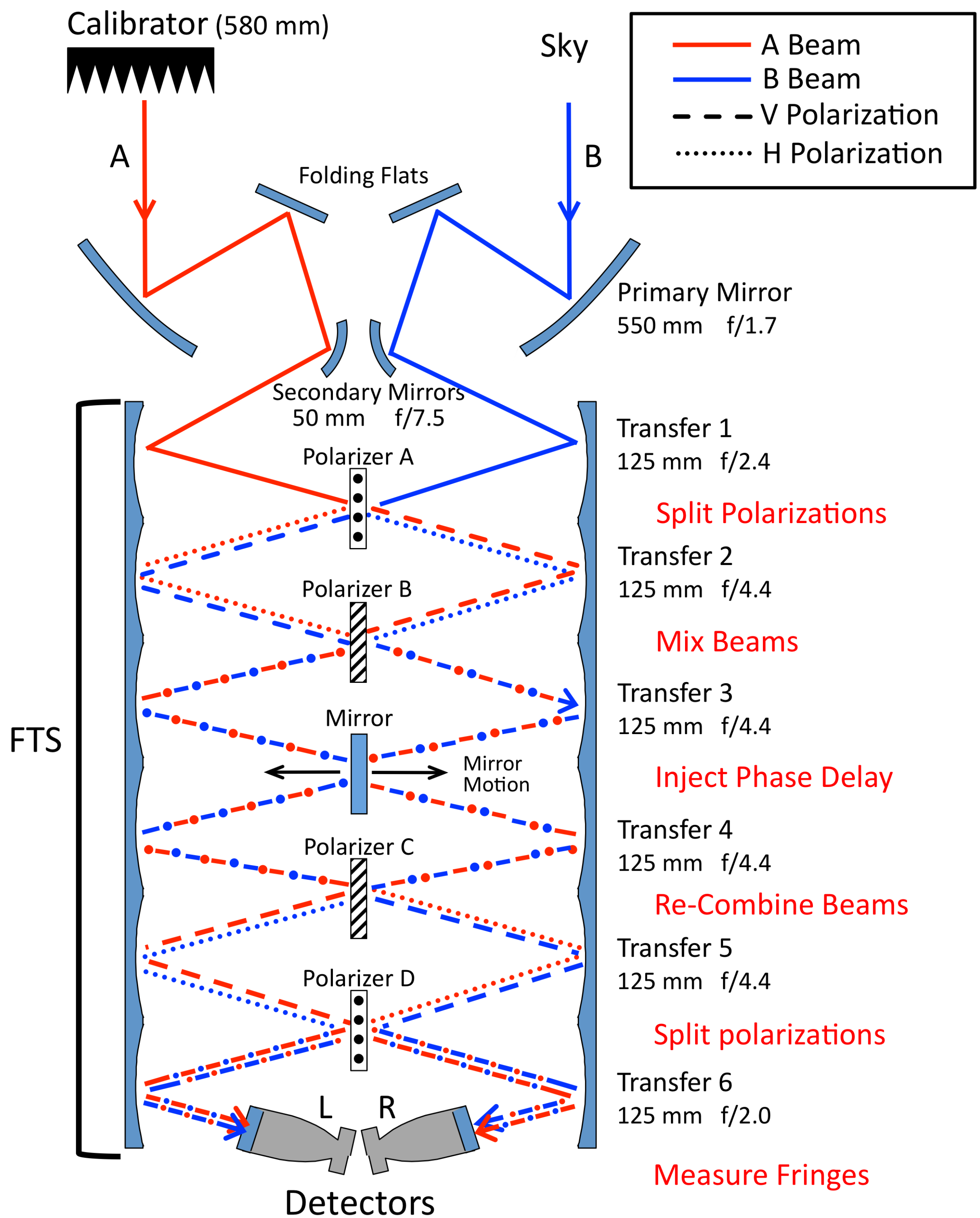
30 GHz to 6 THz (1 cm to 50 μm)





Optical Delay	Physical Stroke	Samples per Stroke	Strokes per Spin
±3.3 mm	±0.9 mm	341	24
±5.0 mm	±1.3 mm	512	16
±6.7 mm	±1.7 mm	683	12
±8.0 mm	±2.1 mm	819	10
±8.9 mm	±2.3 mm	910	9
±10 mm	±2.5 mm	1024	8

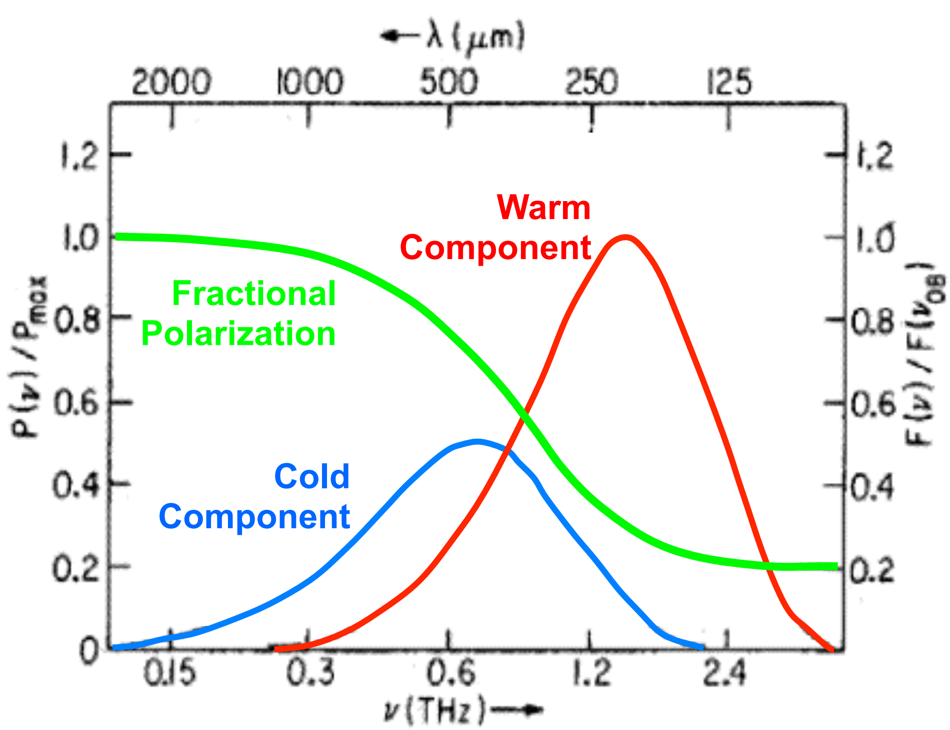
Vary stroke length to apodize Fourier transform


Calibrator (580 mm)
Sky
A Beam
B Beam
V Polarization
H Polarization
A
B
Folding Flats
Primary Mirror
550 mm f/1.7
Secondary Mirrors
50 mm f/7.5
Transfer 1
125 mm f/2.4
Polarizer A
Split Polarizations
Transfer 2
125 mm f/4.4
Polarizer B
Mix Beams
Transfer 3
125 mm f/4.4
Mirror
Mirror Motion
Inject Phase Delay
FTS
Transfer 4
125 mm f/4.4
Polarizer C
Re-Combine Beams
Transfer 5
125 mm f/4.4
Polarizer D
Split polarizations
Transfer 6
125 mm f/2.0
L
R
Measure Fringes
Detectors

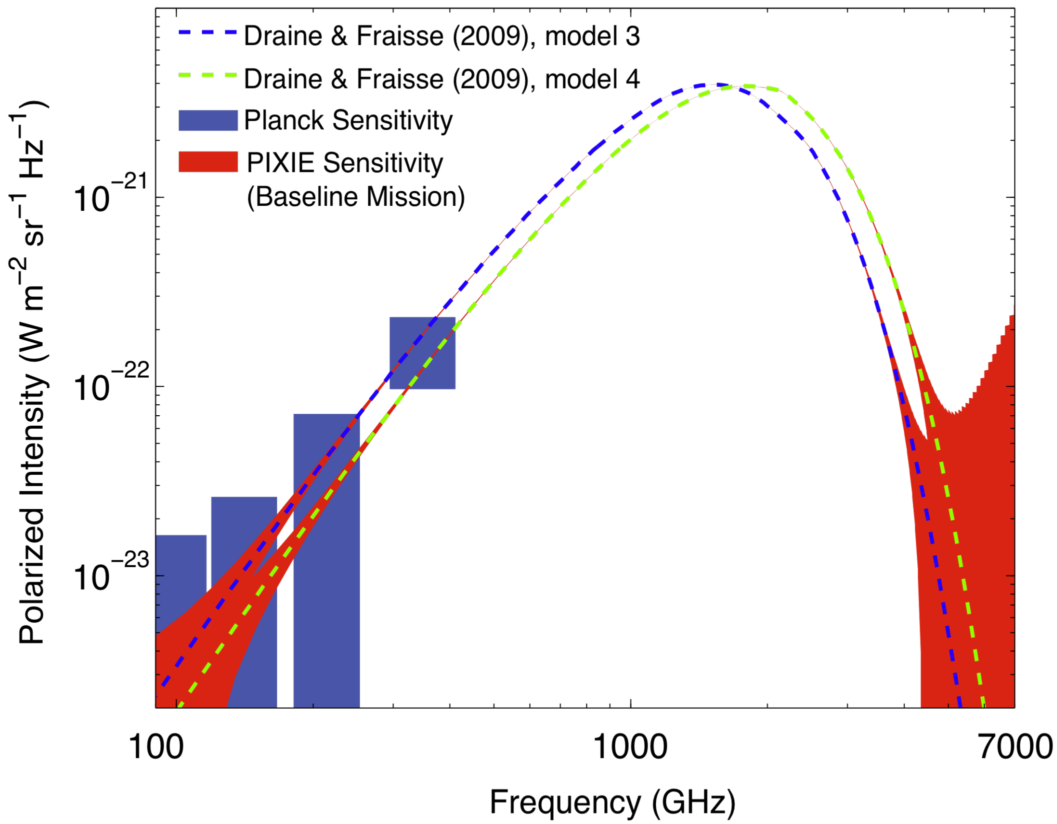
Foreground Science

Polarization depends on composition
- Silicate: Colder, More polarized
- Carbonaceous: Warmer, Less polarized

Sensitive probe of dust composition



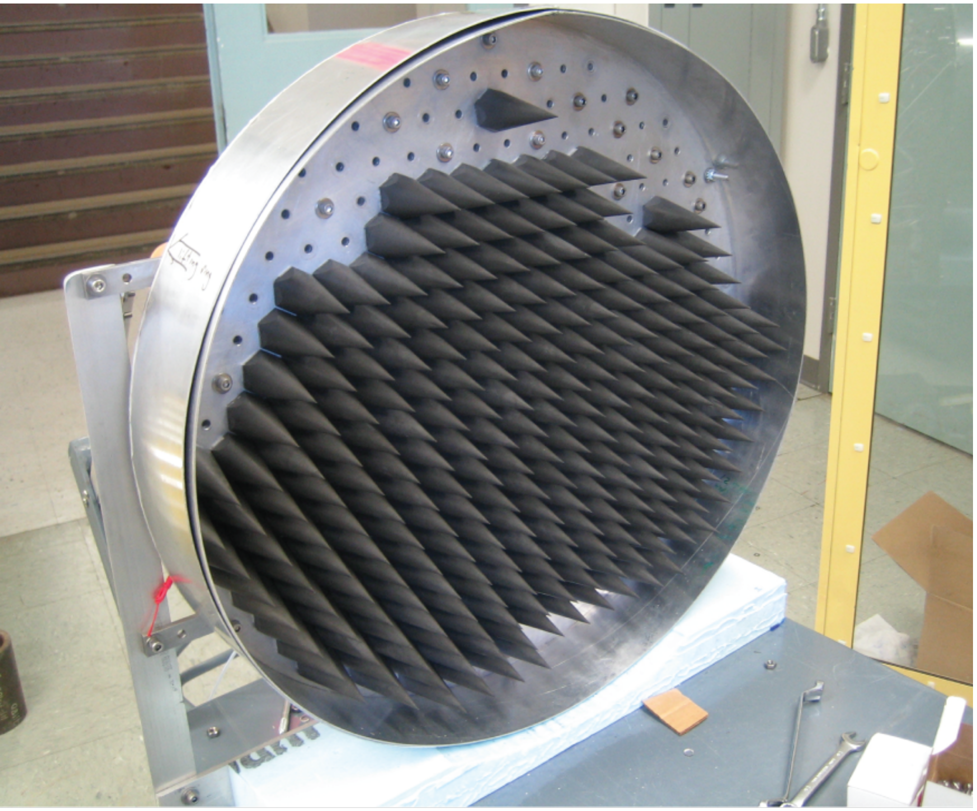
Hildebrand & Kirby 2004



PIXIE data from 30 GHz to 6 THz
- Temperature(s)
- Fractional polarization
- Chemical composition

Constrain dust properties for each line of sight

Secondary Science: Inflation

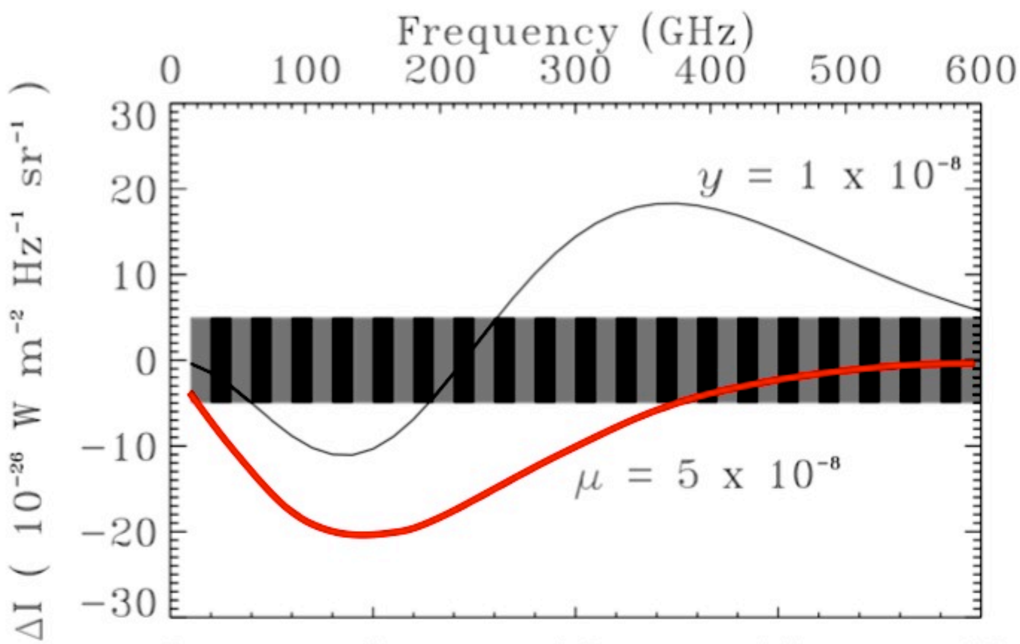


Blackbody calibrator: Spectral distortions

Chemical potential $\mu = 1.4 \frac{\Delta E}{E}$

Energy release at $10^6 < z < 10^8$

PIXIE limit $\mu < 10^{-8}$

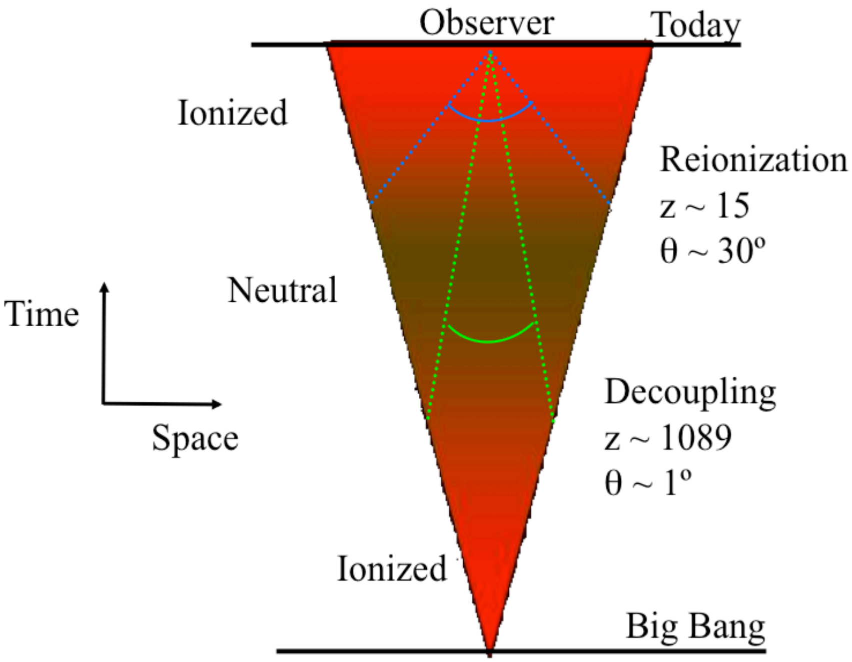


Silk damping of primordial perturbations

- Scalar index n_s and running dln n_s/dln k
- Physical scale ~1 kpc ($1M_\odot$)

Daly 1991
Hu, Scott, & Silk 1994
Khatri, Sunyaev, & Chluba 2011

Secondary Science: Reionization

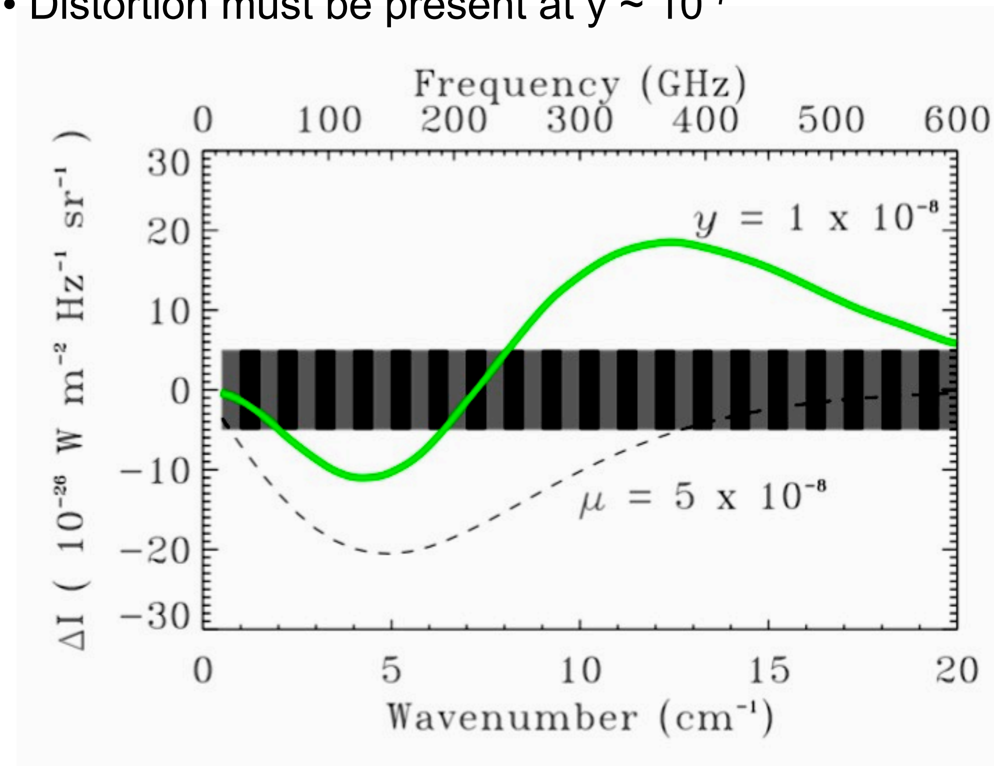


Polarization: Optical depth ~ Electron density n(z)

Angular scale ←→ Horizon at redshift z

Spectrum: y distortion ~ Electron pressure $\int nkT_e$

- PIXIE limit $y < 5 \times 10^{-9}$
- Distortion must be present at $y \sim 10^{-7}$



Same scattering for both signals:

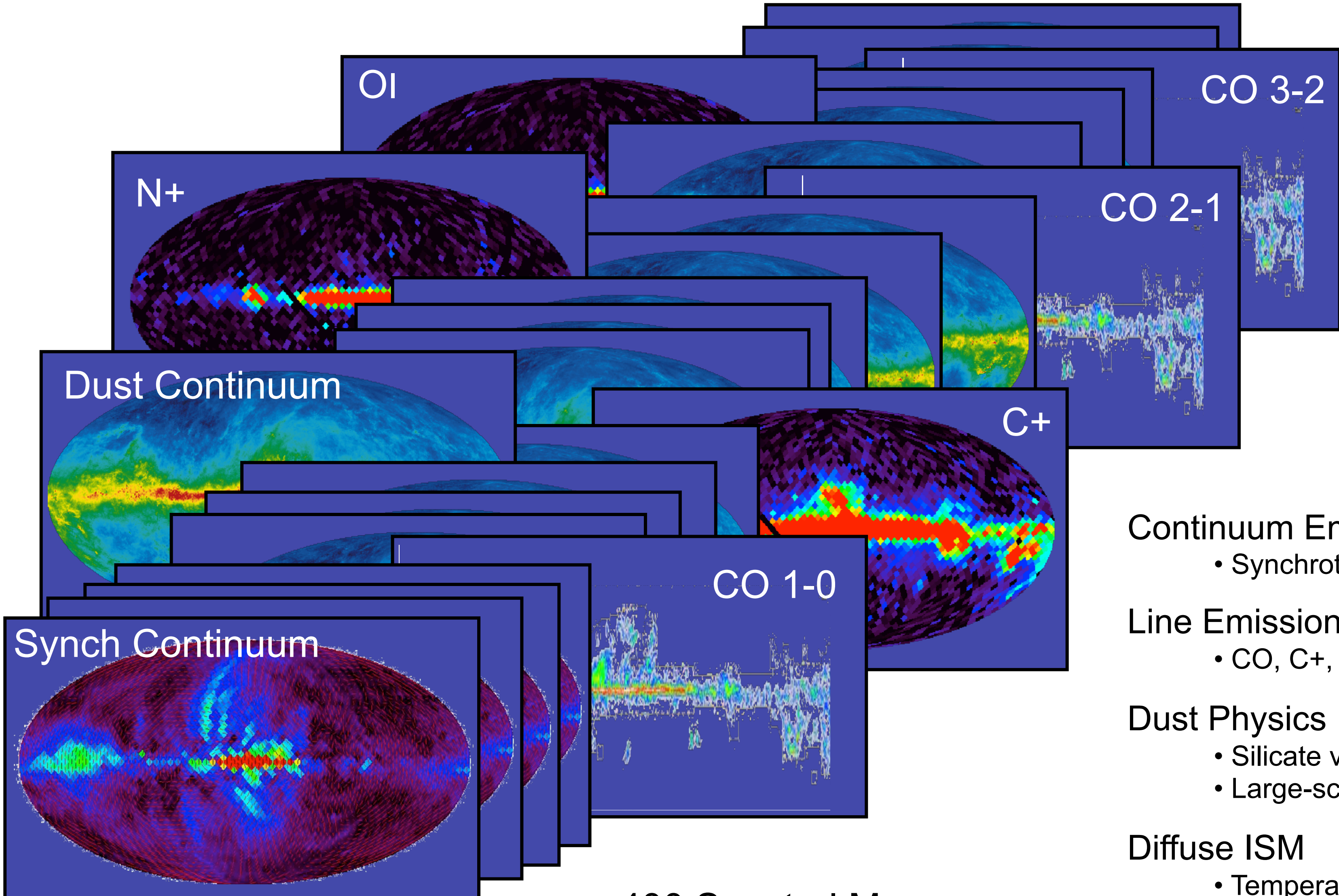
Combine to get n(z) and T_e

- T_e probes ionizing spectrum
- Distinguish Pop III, Pop II, AGN

Determine nature of first luminous objects

Hu & Holder 2003

Secondary Science: Interstellar Medium



400 Spectral Maps
Stokes I, Q, U
$\Delta\nu$ = 15 GHz

Extremely Rich Data Set!

Continuum Emission
- Synchrotron, Dust

Line Emission
- CO, C+, N+, O, …

Dust Physics
- Silicate vs carbonaceous dust
- Large-scale magnetic field

Diffuse ISM
- Temperature, Density
- Energy Balance
- Metalicity

The FIRAS Experience

Results

Temperature to 2.72548 +/-57

Fixsen ApJ 707:916 (2009)

Black Body (+/- 50 PPM)

Fixsen etal ApJ 473:567 (1996)

Dipole Spectrum (+/- 1%)

Fixsen etal ApJ 473:567 (1996)

CIB Spectrum (+/- 30%)

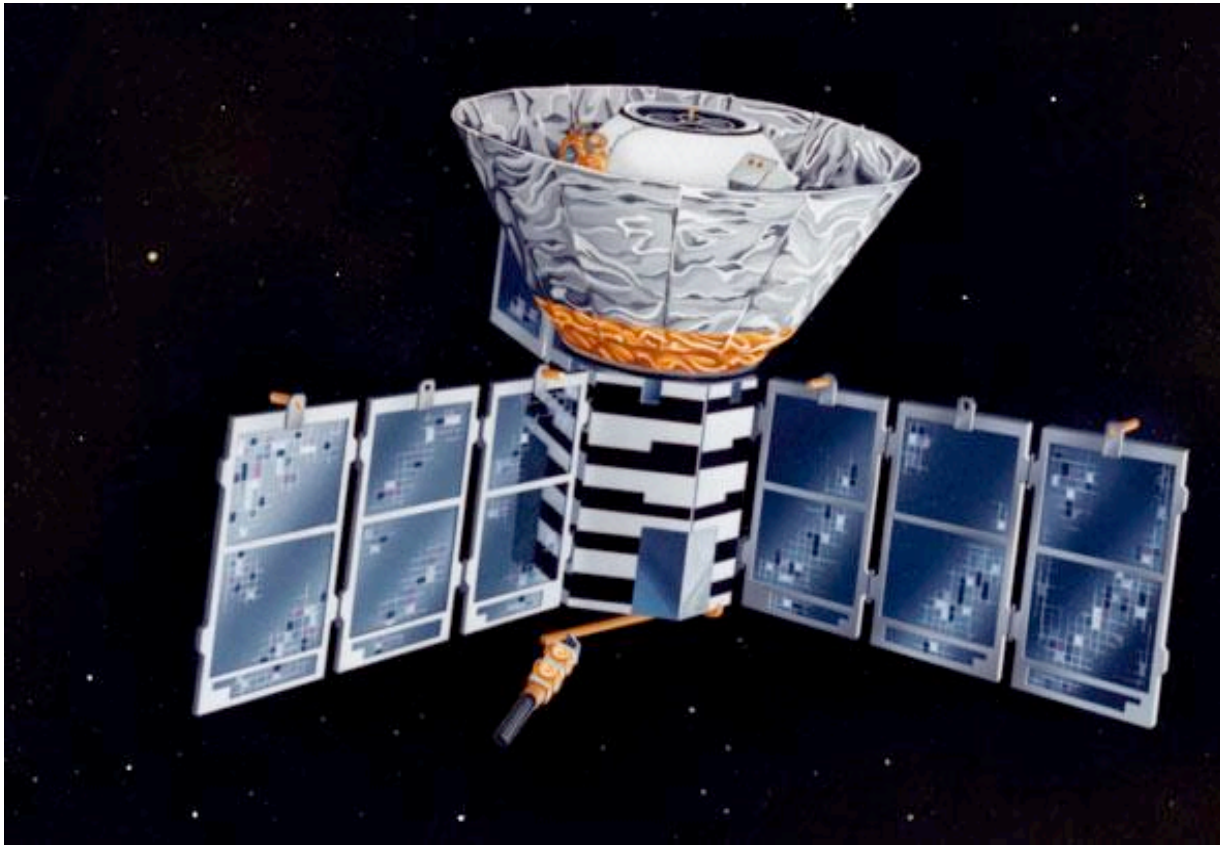
Fixsen etal ApJ 508:123 (1998)

CMB Anisotropy

Fixsen etal ApJ 486:623 (1997)

Spectrum of CMB Anisotropy

Fixsen ApJ 594:L67 (2003)

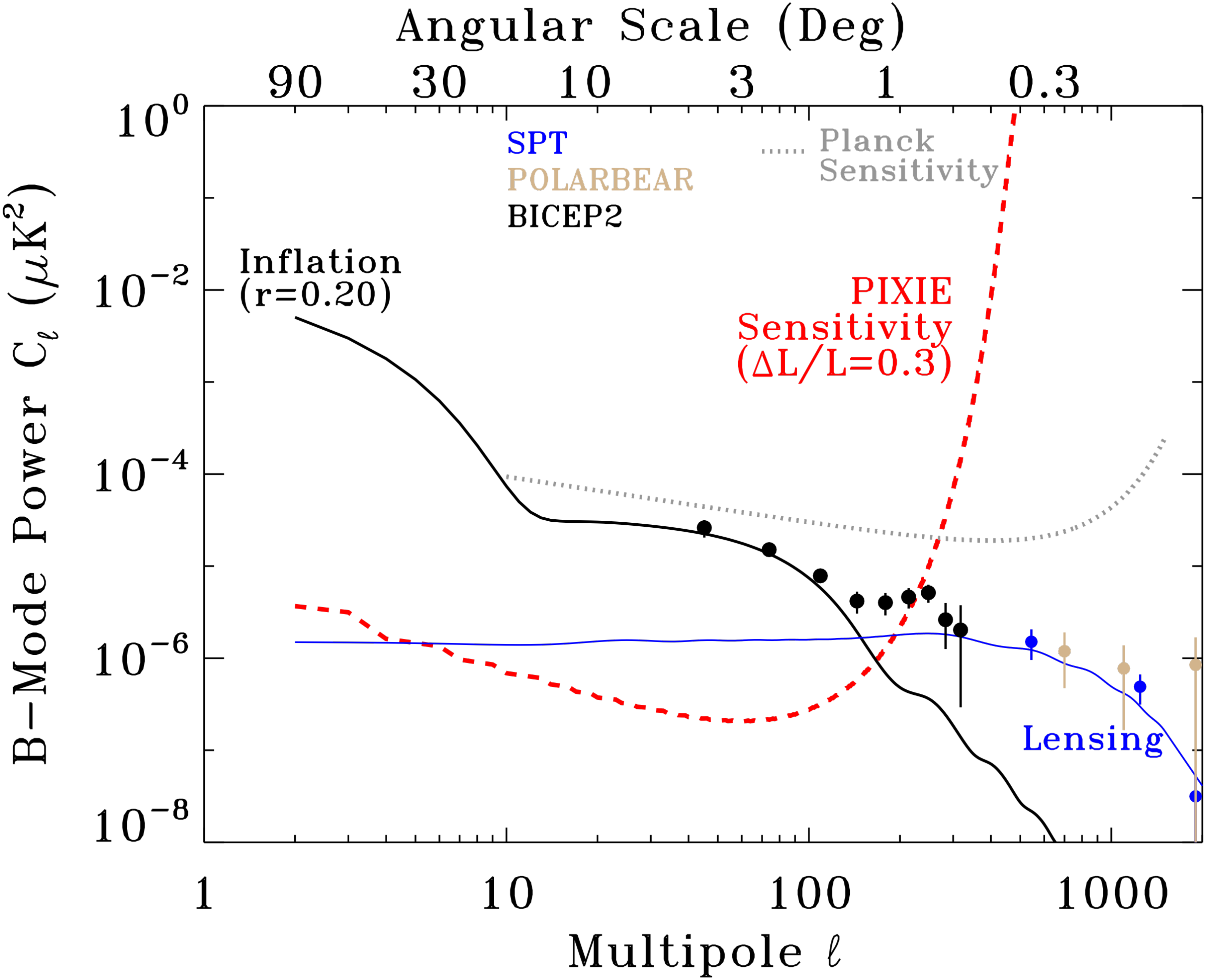


The Instrument

- Fourier Transform Spectrometer
- Cold External Calibrator
- Internal Nulling
- 1.4 K detector

Limitations

- 1.4 K detector (one good)
- Particle hits
- Averaged before fitting
- Limited Calibration Data
- Limited Thermometry



Angular Scale (Deg)
90
30
10
3
1
0.3
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
B−Mode Power C_ℓ (μK^2)
SPT
POLARBEAR
BICEP2
Planck
Sensitivity
Inflation
(r=0.20)
PIXIE
Sensitivity
(ΔL/L=0.3)
Lensing
1
10
100
1000
Multipole ℓ