Observations of the CMB & Constraints on Cosmological Parameters

Bruce Partridge, Haverford College
bpartrid@haverford.edu

Lecture 1. The Spectrum of the CMB and What it Tells Us

Lecture 2. Large Angular Scale CMB Anisotropies

Lecture 3. Smaller Scale, Primary & Secondary Anisotropies

Lecture 4. The Future: Planck, Ground-based Observations and Polarization

Canary Islands Winter School

1. The Spectrum of the CMB and What It Tells Us

Bruce Partridge

Outline

Discovery and Interpretation
Early Results
Experimental Problems Facing Absolute Measurements
Possible Departures from Planck Spectrum
COBE (and Other) Measurements
Limits on Departures from Planck Spectrum

Canary Islands Winter School

- Accidental discovery by Penzias and Wilson in 1964.
  - “Measurements of the effective zenith noise temperature…have yielded a value about 3.5 K higher than expected. This excess temperature is…isotropic, unpolarized and free from seasonal variations.” *Ap. J.*, 1965
- Interpreted as “Cosmic Blackbody Radiation” by Dicke, Peebles, Roll and Wilkinson.Radiation left in Universe from an earlier high density, high temperature ($T > 10^{10}$ K), ionized phase: the *Hot Big Bang*.
- Two tests of this interpretation.

  Spectrum should be *blackbody* (Planck).

  Radiation should be *isotropic*.

Why Blackbody?

Thermal equilibrium established early.

- Thermal bremsstrahlung and radiative Compton effects (needed to generate photons).
- Thermal equilibrium *established* by $z \sim 2 \times 10^6$.
- Can in principle start with arbitrary spectrum and end with blackbody.

Thermal spectrum *maintained* in subsequent adiabatic expansion.

Expansion affects only temperature.

$$T(t) = T_0(z(t) + 1)$$

Equilibria

Kinetic equilibrium established by (any) scattering process with $t_{sc} < t_{exp} \sim 1/H$.

In kinetic equilibrium, μ is a “chemical potential.”

$$\eta = \left[\exp\left(\frac{h\nu}{kT} + \mu\right) - 1\right]^{-1}$$

(dashed line)

True *thermal* equilibrium requires creation/destruction of photons (Kompaneets, 1957).

- e.g., Bremsstrahlung, with cross-section $\sigma \propto \lambda^{2,}$ fills in spectrum at large λ

Depth and center frequency of dip

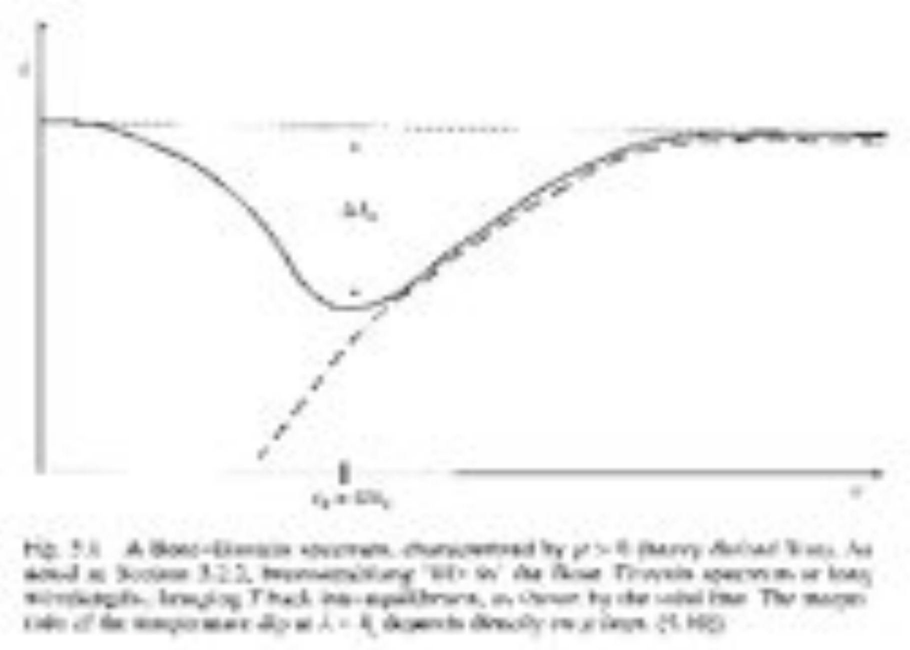
depend on μ.

m→ 0 by $z_{th} \sim 2 \times 10^{6\backslash}$

m (e.g., Burigana, 1991).

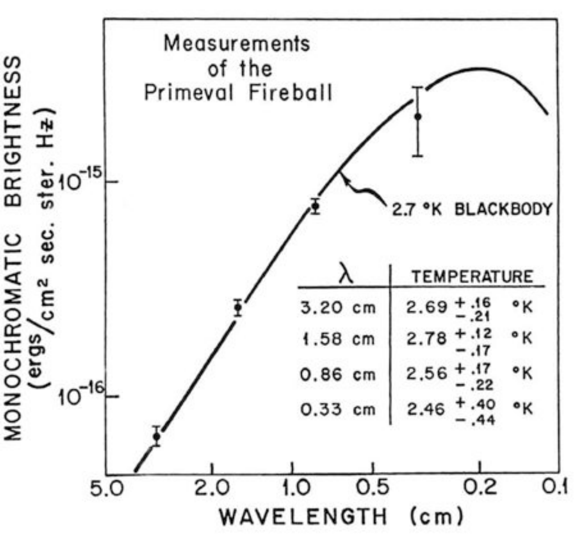
Hence $z_{th} >> z_{LS} \approx 1100$,

the epoch of Last Scattering.

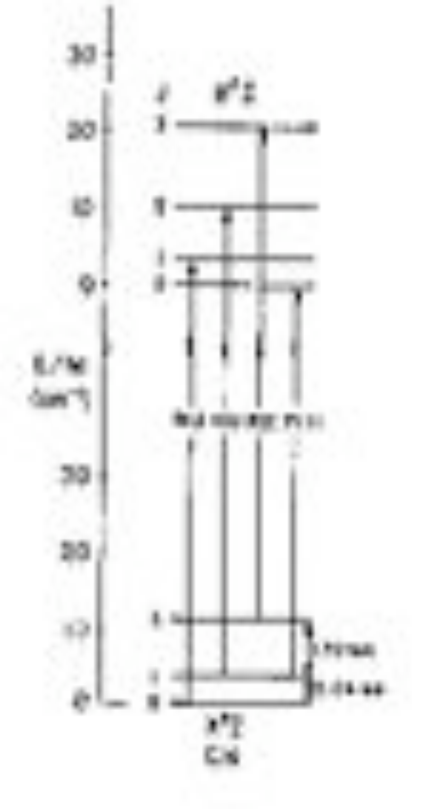


Is Spectrum Blackbody?

Early ground-based, multi-frequency observations (Stokes, Partridge and Wilkinson, 1967; Wilkinson,



λ	TEMPERATURE
3.20 cm	$2.69^{+.16}_{-.21}$ °K
1.58 cm	$2.78^{+.12}_{-.17}$ °K
0.86 cm	$2.56^{+.17}_{-.22}$ °K
0.33 cm	$2.46^{+.40}_{-.44}$ °K



Evidence from CN at $\lambda = 2.6\ mm$.

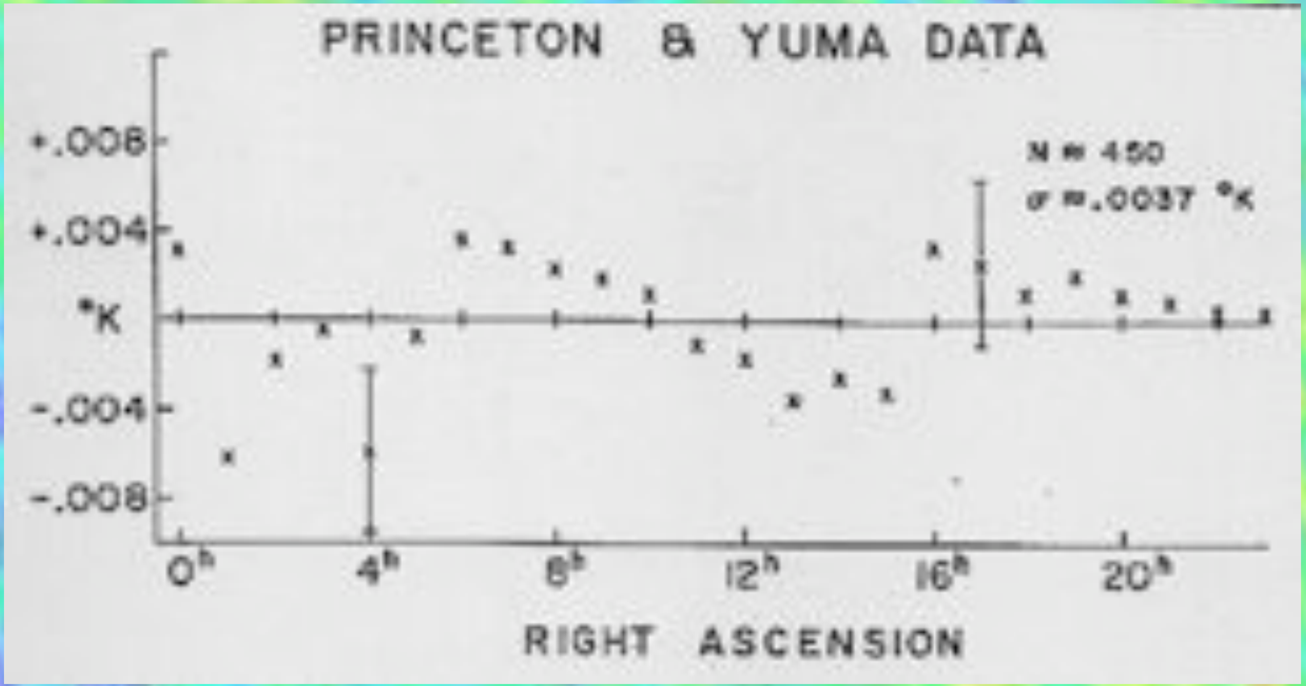
$T = 2.78 \pm 0.10\ K$ (Thaddeus, 1972)

- T independent of $\lambda \Leftrightarrow$ Blackbody Spectrum

By early 1970's, all agreed with $T_0 \approx 2.75$ K.

Is the CMB Isotropic?

- Scan around $\delta = -8°$ constant to ~ ±0.2% on large scale (Partridge and Willkinson, 1967).



- No evidence of anisotropies 1% or small scales either (Conklin and Bracewell, 1967; Epstein, 1967).

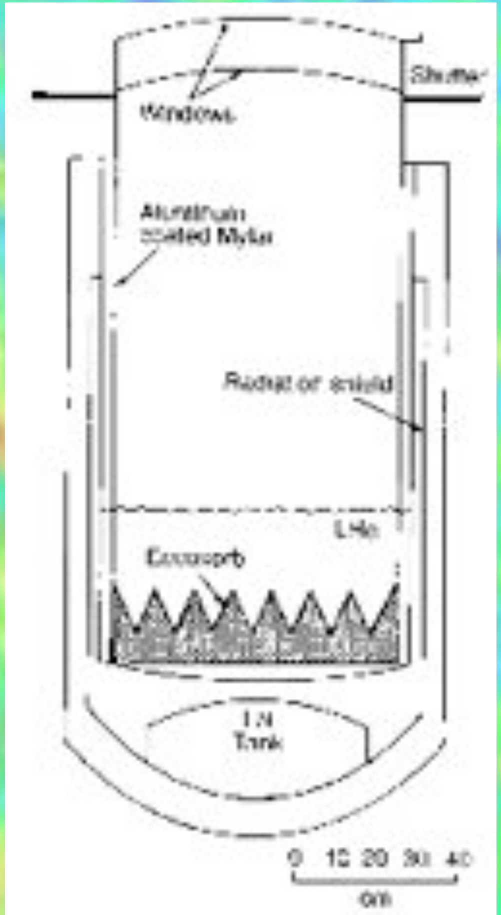
- **Both tests *passed* by ~1968.**

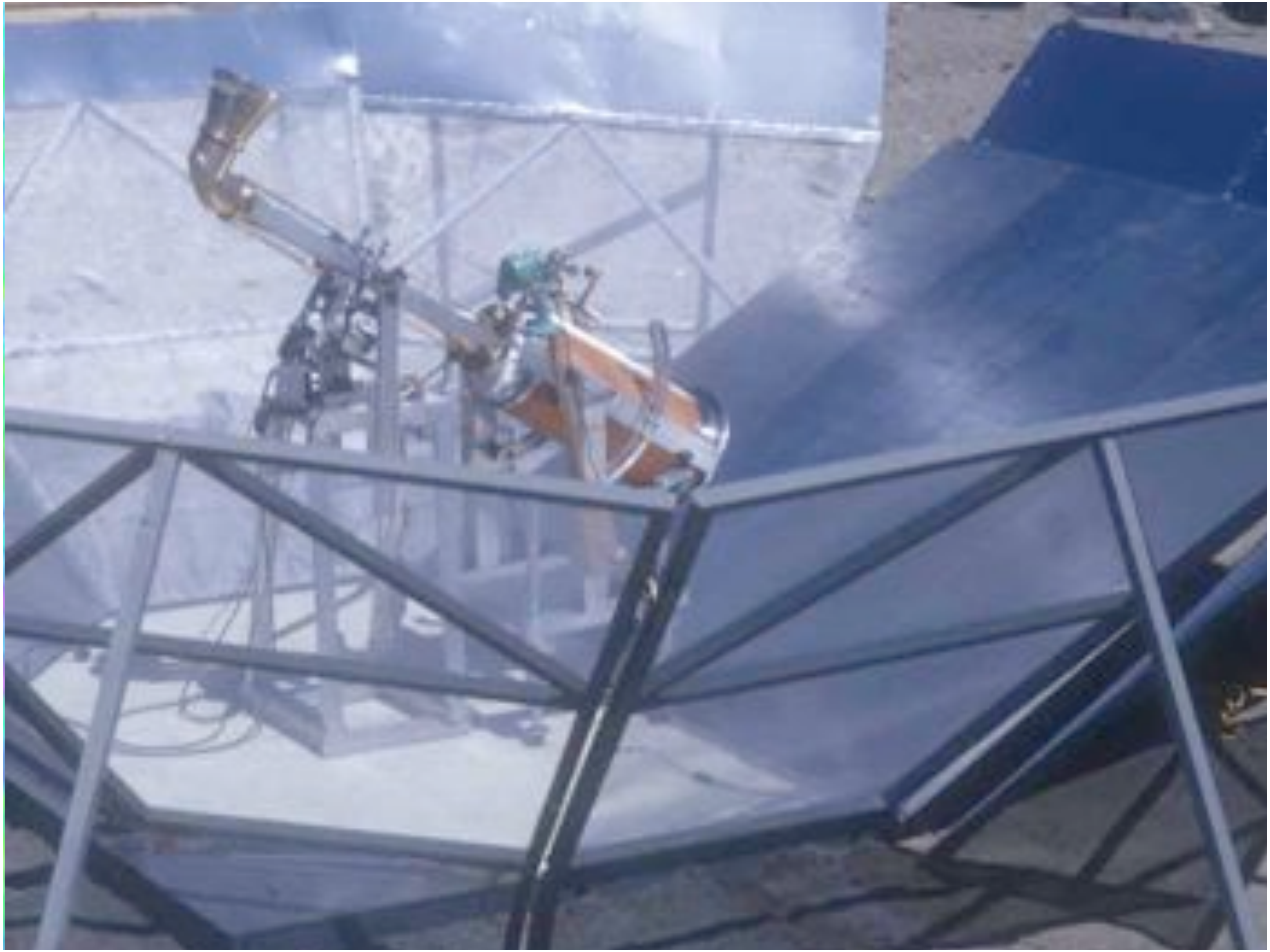
Observational Issues

For an absolute measurement of T_0 at a given λ, need

- Absolute calibration
  - perfect emitter
  - at known, low *T*
  - *"cold load."* -------------------->

- Control or measurement of foregrounds



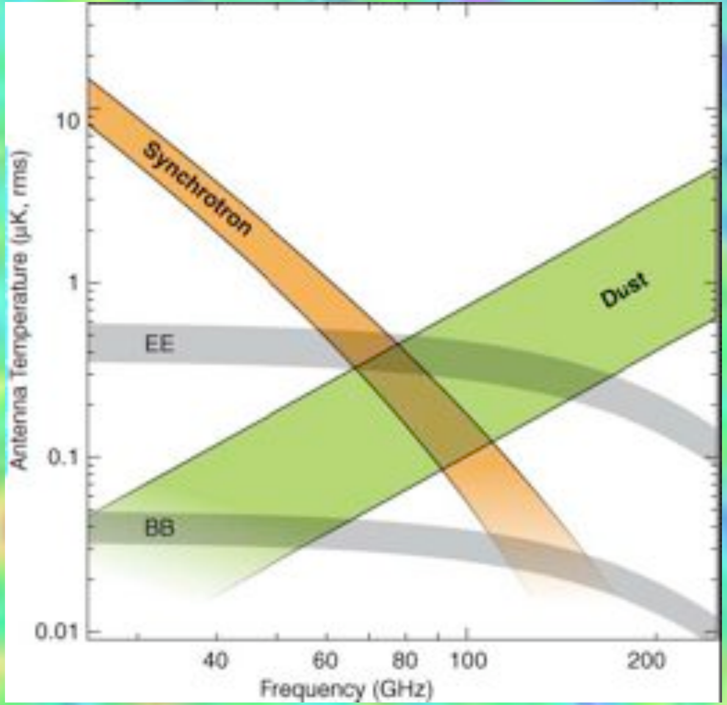


Foregrounds

Foregrounds

- Galaxy:
  - synch. spectrum
    $S \propto \nu^{- -0.7}$
  - dust, $S \propto \nu^2$
  - anomalous dust

  (all discussed in detail by Rod Davies)



- Atmosphere

Atmosphere:

Lines of O_2 and H_20; avoid by choosing proper *wavelength*

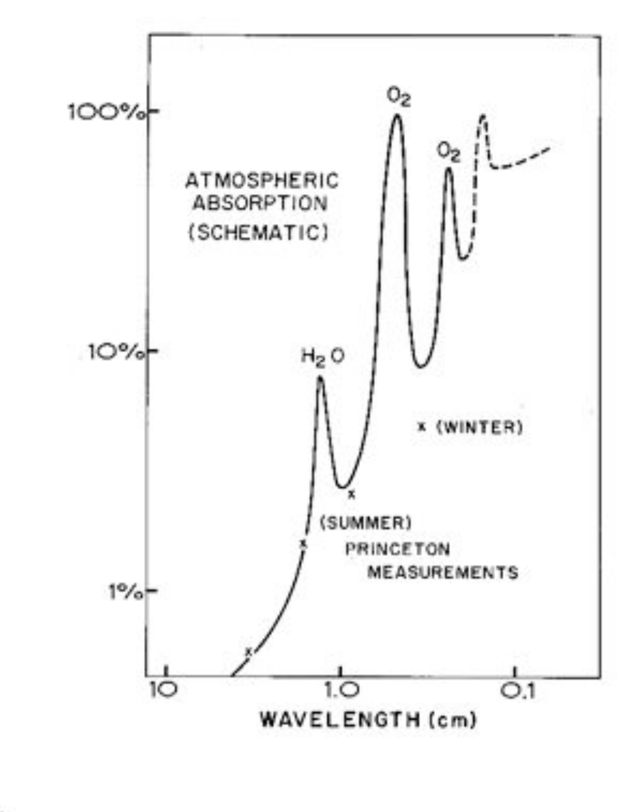
Nevertheless, at sea level

$T_{atm} > 3$ K at $\lambda < 3$ cm,

and $T_{atm} = 2$ K at $\lambda = 3$ mm

at best sites

Hence work at high altitude
and scan in zenith angle.



Additional Experimental Problems

Instrumental systematics

  - Emission from wall of cold load
  - Side- and back-lobe pickup.

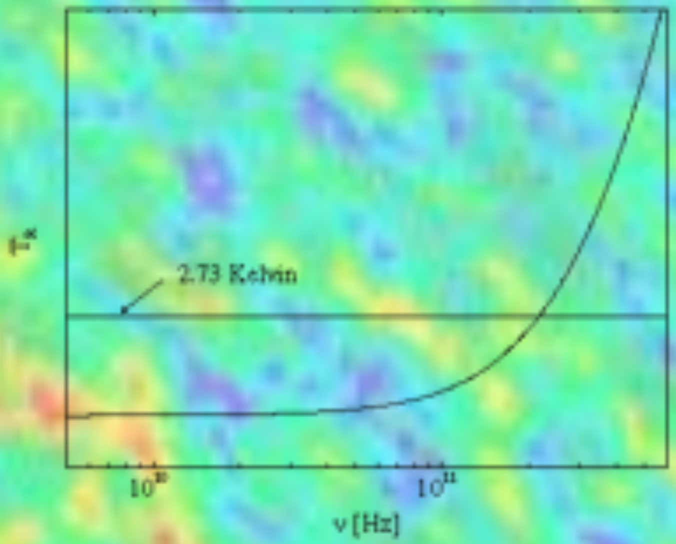
Many foreground and instrumental problems mitigated in space.

Residual problem: Galactic emission.

  - Makes accurate measurements at long λ (>10 *cm*) very hard.

Possible Departures from Planck Law

- Need consider only $z < 2 \times 10^6$.
- Scattering (photon energy changed, not photon number): Sunyaev-Zel'dovich Effect (SZE; Sunyaev and Zel'dovich, 1969 and 1980).
  - Inverse Compton scattering of "cold" CMB photons off hot e$^-$
  - Uniform distribution of plasma affects overall spectrum.



  - Measured by y parameter,

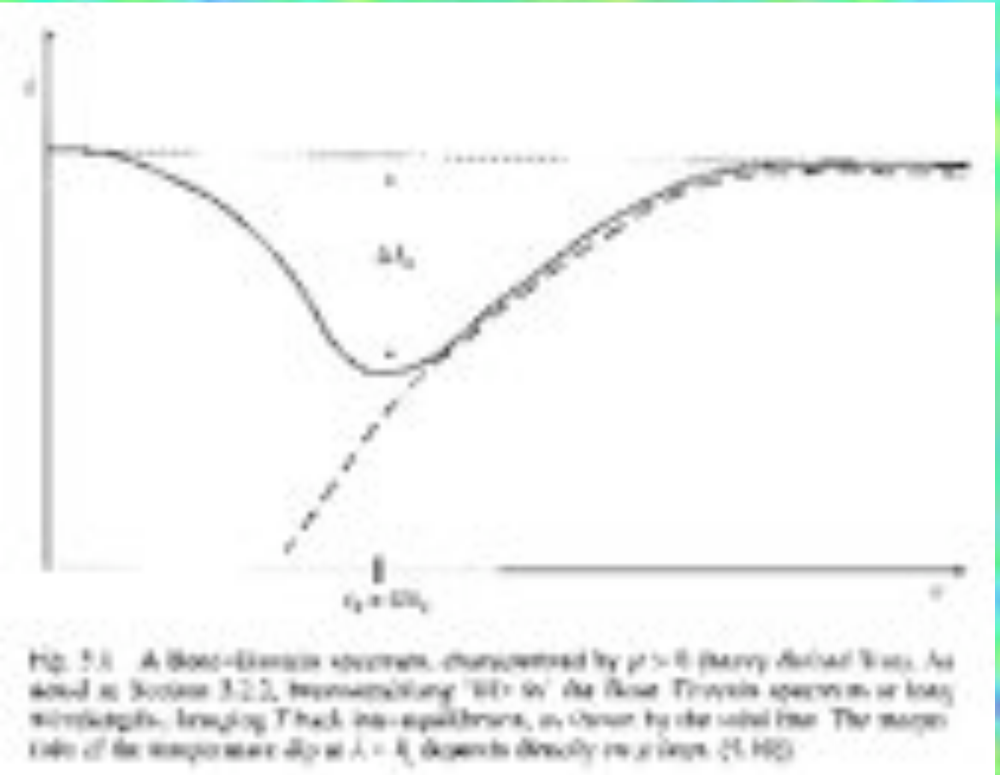
$$y = \int \frac{kT_e n_e \sigma_T}{m_e c^2} d\ell$$

where T_e, n_e and m_e are the temp. number density and mass of the electrons.

  - Effective after z ~ 10^5
  - *Localized* collections of plasma (e.g., hot gas in clusters) produce localized distortions (see Rephaeli, 1995, for review; to be discusssed by Matthias Bartelmann next week).

μ-Distortion

Energy input after thermalization (z = 2 x 10^6) to z ~ 10^5



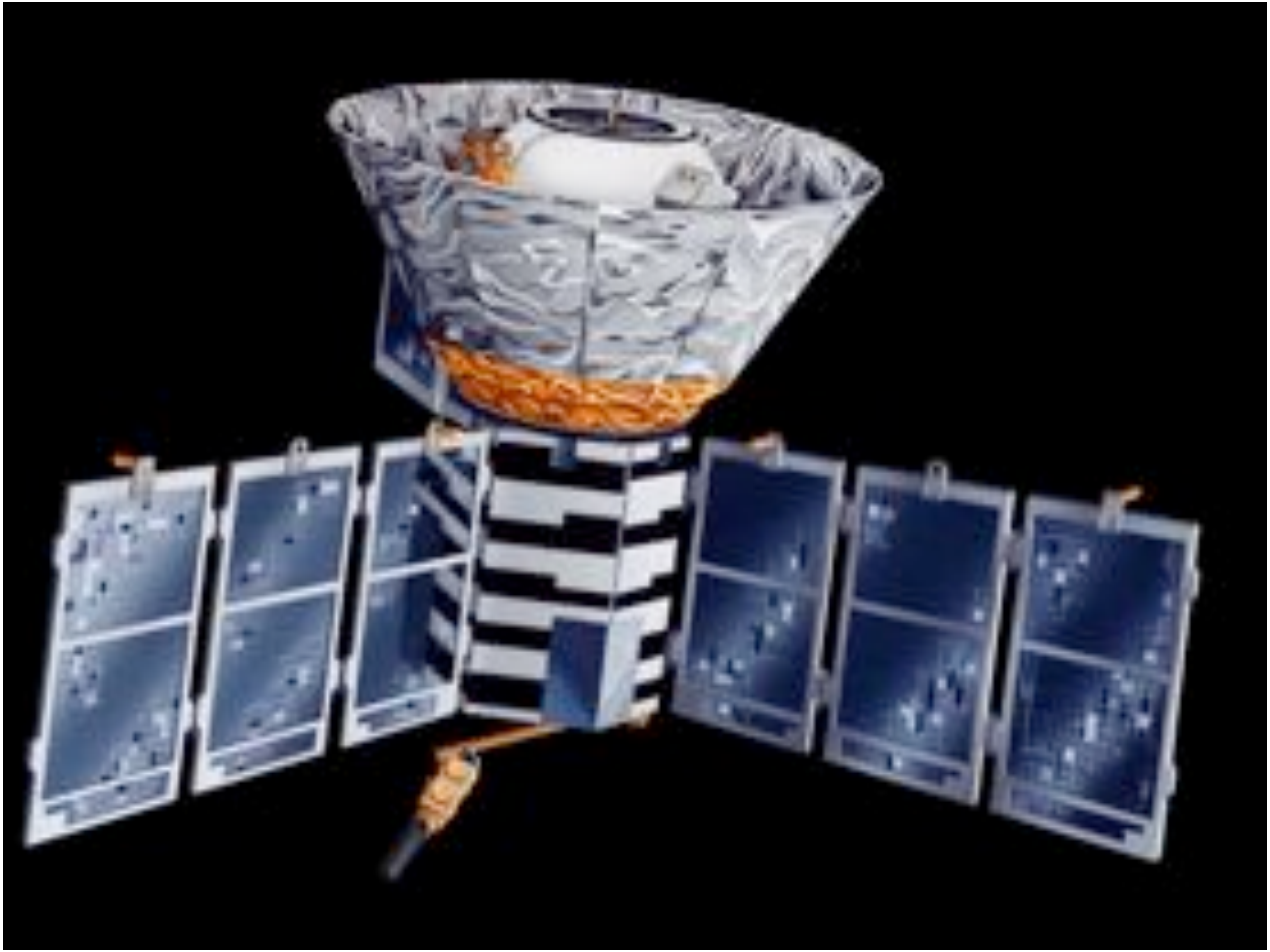
Some possible sources:

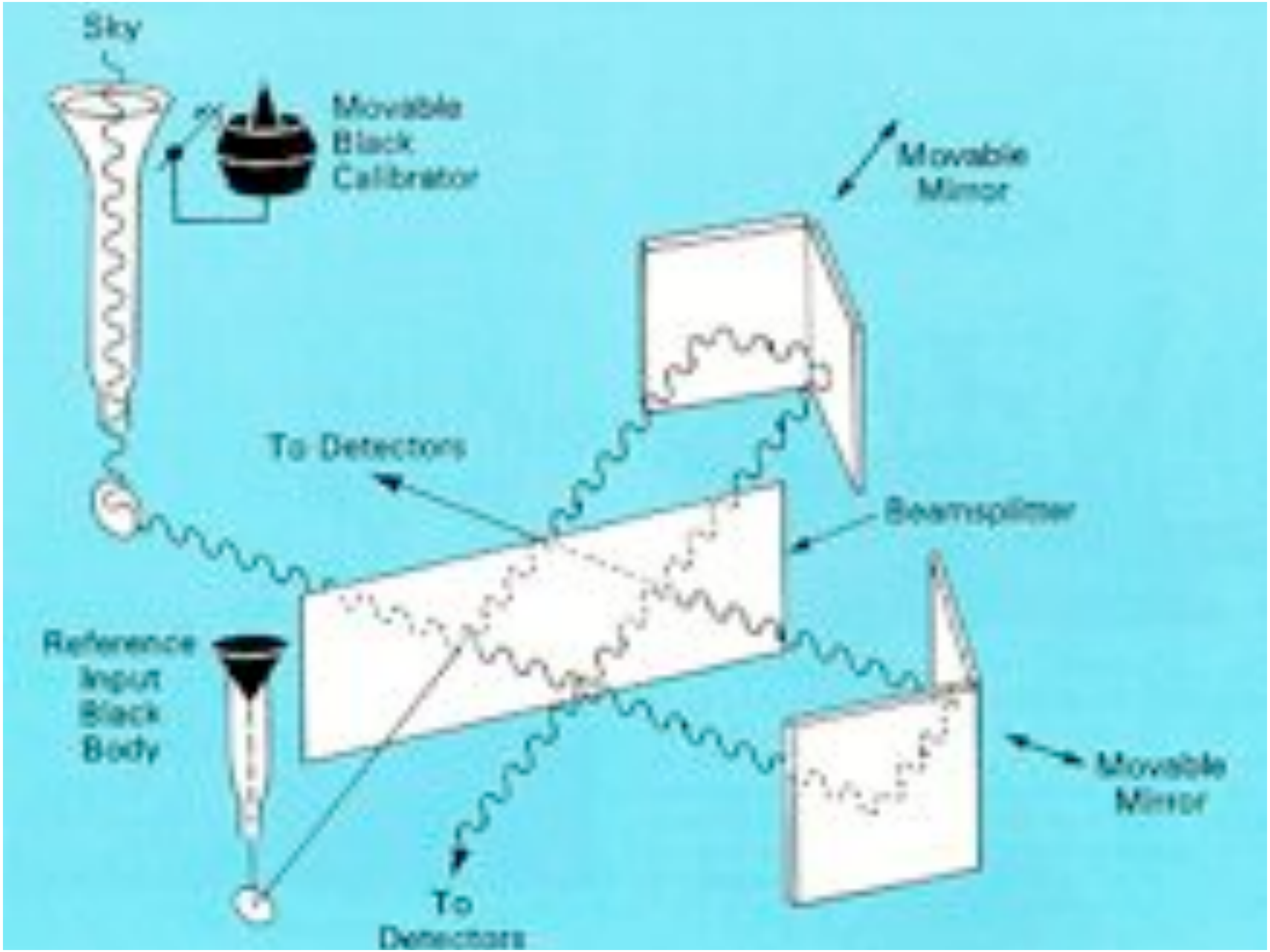
- decay of particles
- dissipation of turbulence
- decay of mini-Black Holes…

COBE

COsmic Background Explorer

- Launched 1989.
- FIRAS ("absolute spectrometer").
  - Michelson interferometer, $\lambda \approx$ 0.05-0.5 *cm*
  - allowed null measurement
  - key role of cold loads, internal and external.
- $T_0 = 2.725 \pm 0.001K$ (Fixsen & Mather,2002).
- Very similar results from rocket observation (Gush *et al.*, 1990




Sky
Movable Black Calibrator
Movable Mirror
To Detectors
Beamsplitter
Reference Input Black Body
Movable Mirror
To Detectors

Longer Wavelength Measurements

Efforts to determine spectrum at $\lambda > 1$ *cm*.

- Can be done from ground.
- Galactic emission main source of uncertainty.
  - Radio source emission plays a role

Staggs *et al.* (1996): at 3 cm, $T_0 = 2.730 \pm .014$ K

ARCADE project: at ~4 cm, $T_0 = 2.84 \pm .014$

Best results at longer wavelengths from TRIS (Gervasi *et al.*, submitted):

- at 50 cm, $T_0 = 2.685 \pm .038$ ($\pm .066$)
- At 36 cm, $T_0 = 2.772 \pm .012$ ($\pm .4$)
- At 12 cm, $T_0 = 2.516 \pm .107$ ($\pm .28$)

(numbers in parentheses include systematic error)

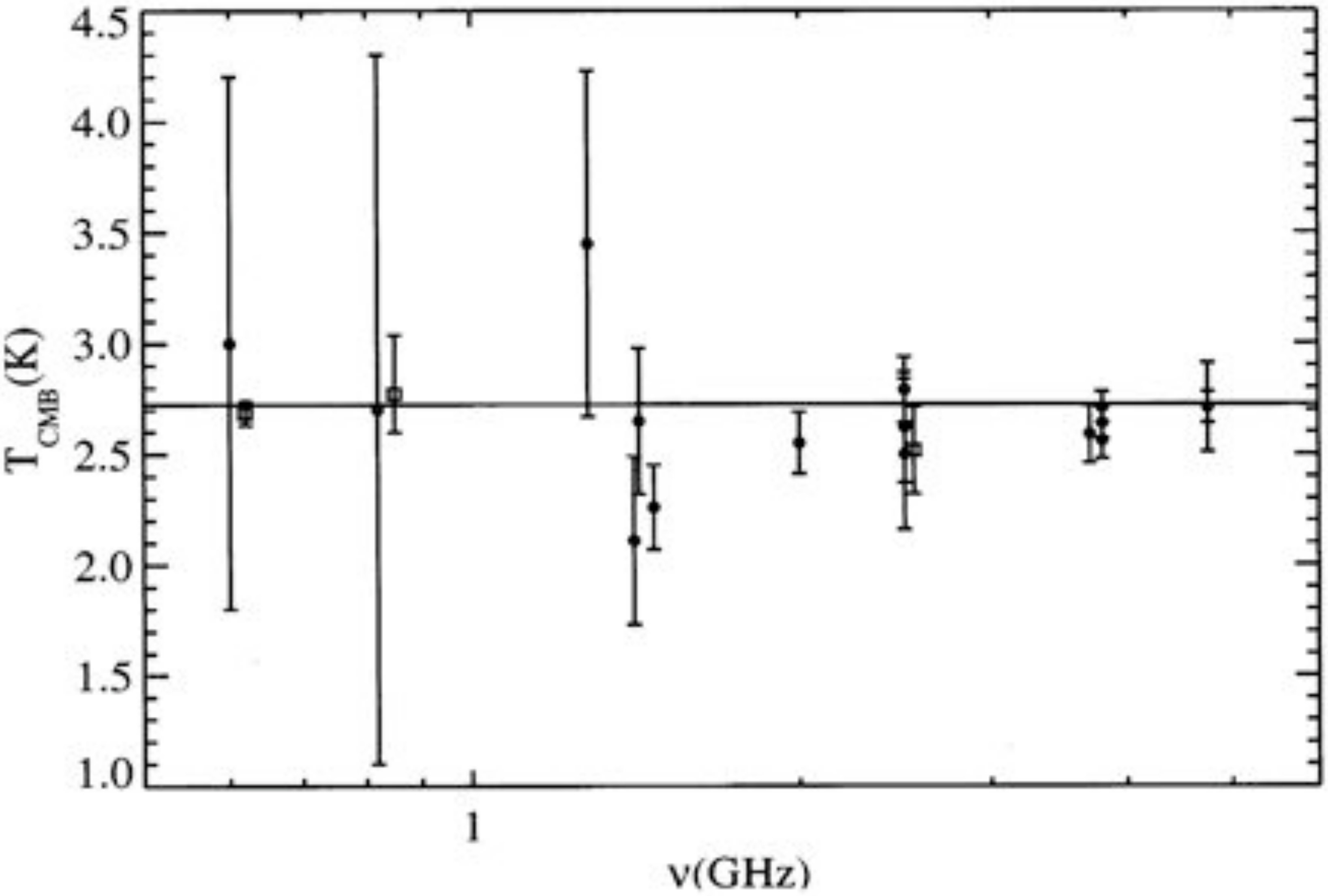


Fig. 2.— Plot of the CMB thermodynamic temperature at low frequencies. The experimental points are listed in table 1 (top side only). For easier comparison with previous measurements (solid circles), TRIS data points (open squares) have been slightly shifted in frequency. The CMB temperature obtained by FIRAS is also plotted (solid line).

Constraints on Distortions

Best limit on *y*-distortion from COBE: $y < 1.5 \times 10^{-5}$ (Fixsen, et al, 1996)

- And TRIS: $-5 \times 10^{-6} < y < 3.5 \times 10^{-6}$ (Gervsi *et al.*, 2007

Consequences:

- Energy released after epoch corresponding to $z \sim 10^5$ is $\Delta u/u_0 = 4y$ or $<$ 1.8×10^{-5}, where u_0 is CMB energy density (Wright, 1994).
- Limit on diffuse, ionized IGM at $T \sim 10^6$ K and $z << 10^3$ is $\Omega_{HII} << .01$.

To limit μ-distortion, need long-wavelength measurements

from COBE and TRIS, $\mu < 7 \times 10^{-5}$ (Fixsen *et al*., 1996; Gervasi *et al*., 2007)

Some consequences:

- Energy release at $10^5 < z < 2 \times 10^6$ is $\Delta u/u_0 \sim 0.7\mu$ or $< 5 \times 10^{-5}$.

(for more details, see Chap. 5 of *3K*)

Inverse Compton after $z = 1000$ discussed in lecture 3.