

CMB Temperature Measurements **(title mandated to me by Jacques Dumarchez)**

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Prediction of Cosmic Background Radiation

- The cosmic microwave background was predicted in 1948 by George Gamow, Ralph Alpher, and Robert Herman.
- Alpher and Herman were able to estimate the temperature of the cosmic microwave background to be 5 K,



Ryle versus Hoyle by Barbara Gamow, George Gamow's wife:

"Your years of toil,"
Said Ryle to Hoyle,
"Are wasted years, believe me.
The steady state
Is out of date.
Unless my eyes deceive me,
My telescope
Has dashed your hope;
Your tenets are refuted.
Let me be terse:
Our universe
Grows daily more diluted!"
Said Hoyle, "You quote
Lemaître, I note,
And Gamow. Well, forget them!
That errant gang
And their Big Bang—
Why aid them and abet them?
You see, my friend,

It has no end
And there was no beginning,
As Bondi, Gold,
And I will hold
Until our hair is thinning!"
"Not so!" cried Ryle
With rising bile
And straining at the tether;
"Far galaxies
Are, as one sees,
More tightly packed together!"
"You make me boil!"
Exploded Hoyle,
His statement rearranging;
"New matter's born
Each night and morn.
The picture is unchanging!"
"Come off it, Hoyle!
I aim to foil
You yet" (The fun commences)

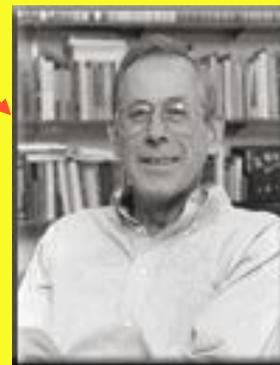
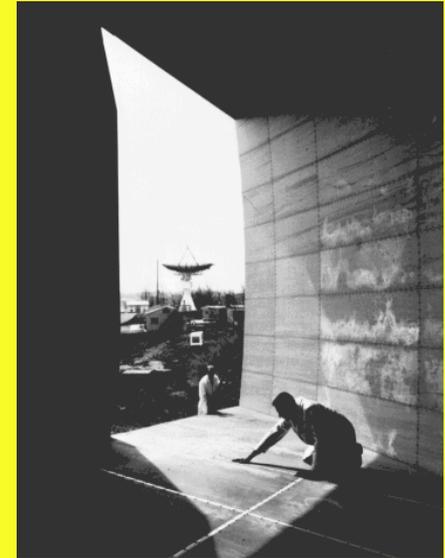
Relic Radiation from THE BIG BANG

1965 Penzias & Wilson discover isotropic emission at $\lambda=7.35$ cm. If a blackbody, $T=3\pm 0.5$ K. Penzias talks on the phone to Bernie Burke, who heard from Ken Turner about a talk by P.J.E. Peebles (Princeton) who had predicted the universe would be filled with a 5 K radiation.

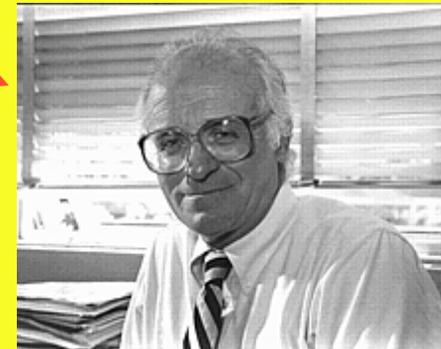
Discovery of the Cosmic Background Radiation (CBR).



Arno Penzias & Robert Wilson
Nobel Prize (1978)



Jim Peebles



Bernie Burke

Papers Relating to Discovery of CMB

A.A. Penzias & R.W. Wilson *A Measurement of Excess Antenna Temperature at 4080 Mc/s* The Astrophysical Journal, 142 (1965) p. 419–421

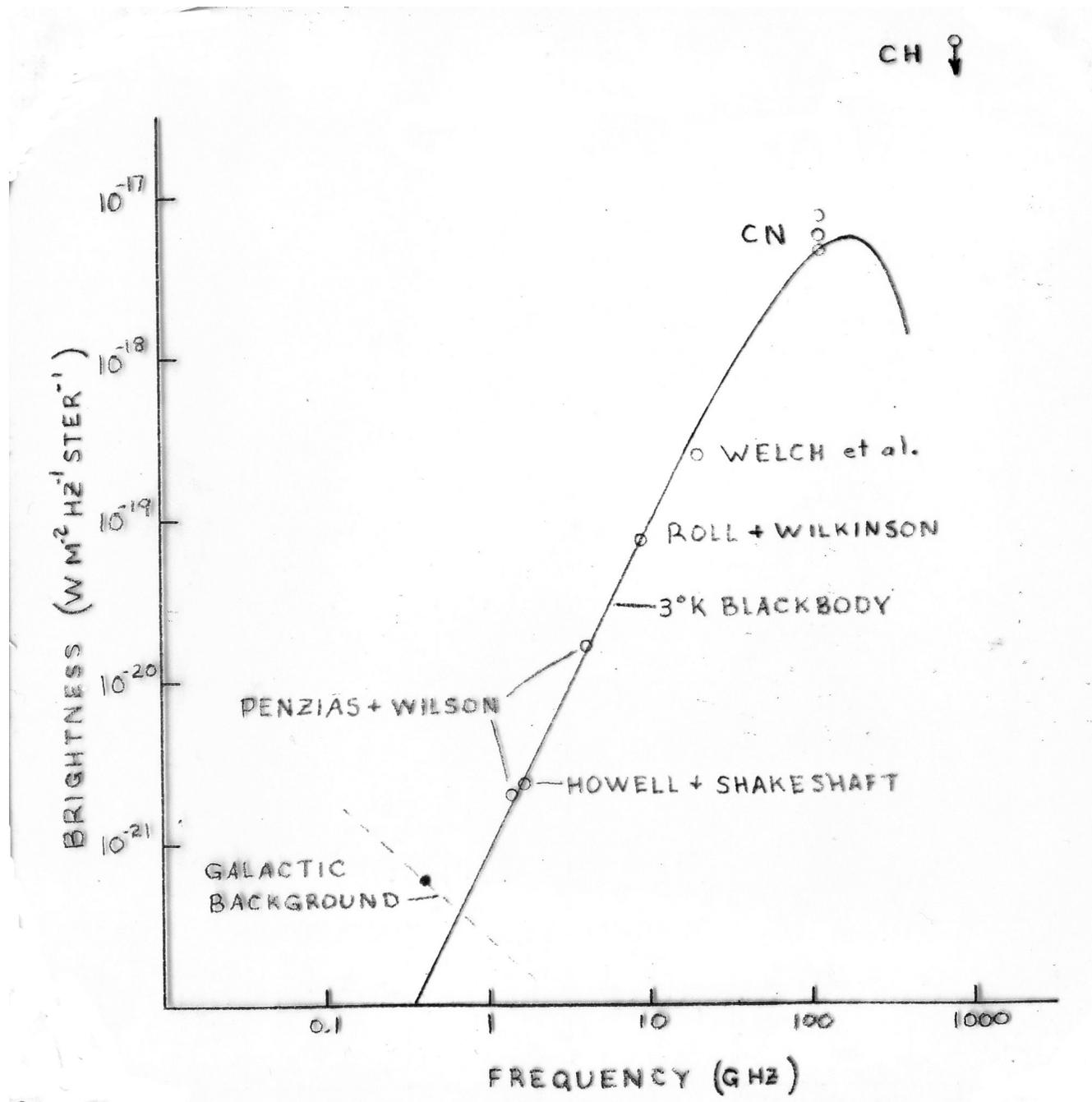
R. Dicke, P.J.E Peebles, P.G. Roll, D.T. Wilkinson *Cosmic Black-Body Radiation* The Astrophysical Journal, 142 (1965) p. 414–419

P.J.E. Peebles *The Black-Body Radiation Content of the Universe and the Formation of Galaxies* The Astrophysical Journal, 142 (1965) p. 1317

Confirmation

- **The first confirmation came quickly from an unexpected source. From 1939 to 1943 Dunham, Adams and McKellar had measured the rotational excitation of CN molecules in diffuse interstellar clouds from their absorption of star light. Herzberg wrote in his standard book on the interstellar medium.**
 - “From the intensity ratio of the lines a rotational temperature of 2.3 degrees K follows, which of course has only a very restricted meaning.”
- **The excitation of CN molecules was remembered by 3 separate groups.**
 - Burnie Burke told George Field about the measurements. George had written a paper while an assistant professor at Princeton ...
 - Pat Thaddeus asked Nick Wolfe about tests for radiation and Nick remembered the CN.
 - Iosif Shklovsky remembered the CN.
- **By the end of the year Wilkinson and Roll had made a measurement at 3-cm wavelength which agreed with P-W.**
- **Ed Ohm at Bell Labs carefully measured all of the components of the satellite receiver that he built for the 20 foot horn-reflector and found an excess 3.1K, previously – published in BLTJ**
- **John Findlay: previously set up the absolute calibration horn at NRAO, found an excess of about 2.5K; Cassiopeia A flux density at 820 MHz**
- **1955 – Émile Le Roux of the Nançay Radio Observatory, in a sky survey at $\lambda = 33$ cm, reported a near-isotropic background radiation of 3 +/- 2K**

Measurements of the CMBR at a Year since Discovery



1965: Discovery of the CMB awarded Nobel 1978



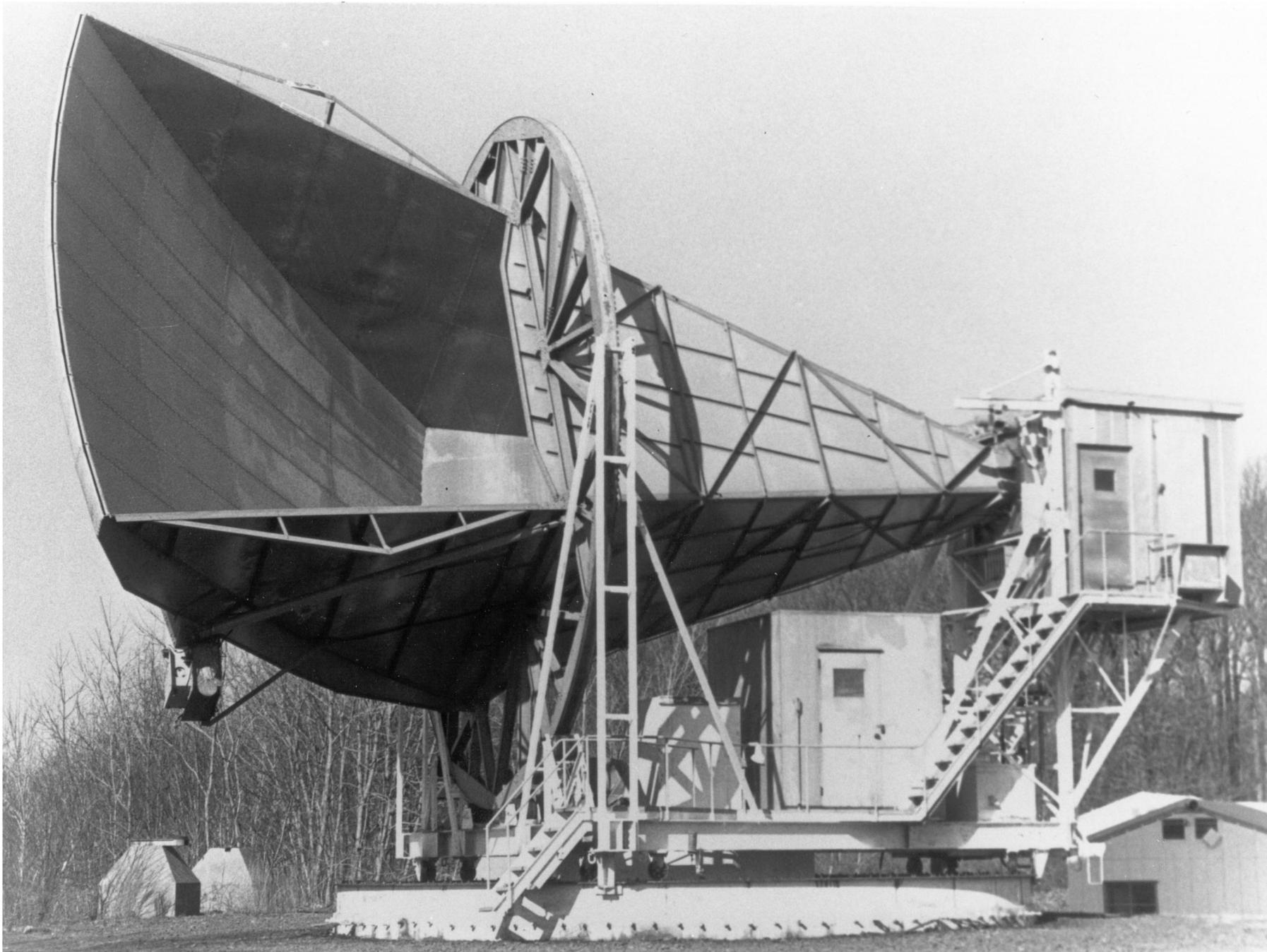
1978 Nobel Prize

“A Measurement of Excess Antenna Temperature at 4080 Mc/s”
Penzias & Wilson, *Astrophysical Journal*, vol. 142, p.419-421, 1965

National Monument 1989



The 20-foot (6-m) Horn Reflector



Penzias & Wilson / Bell Labs Receiver at Deutsches Museum





Strip Chart Recorder

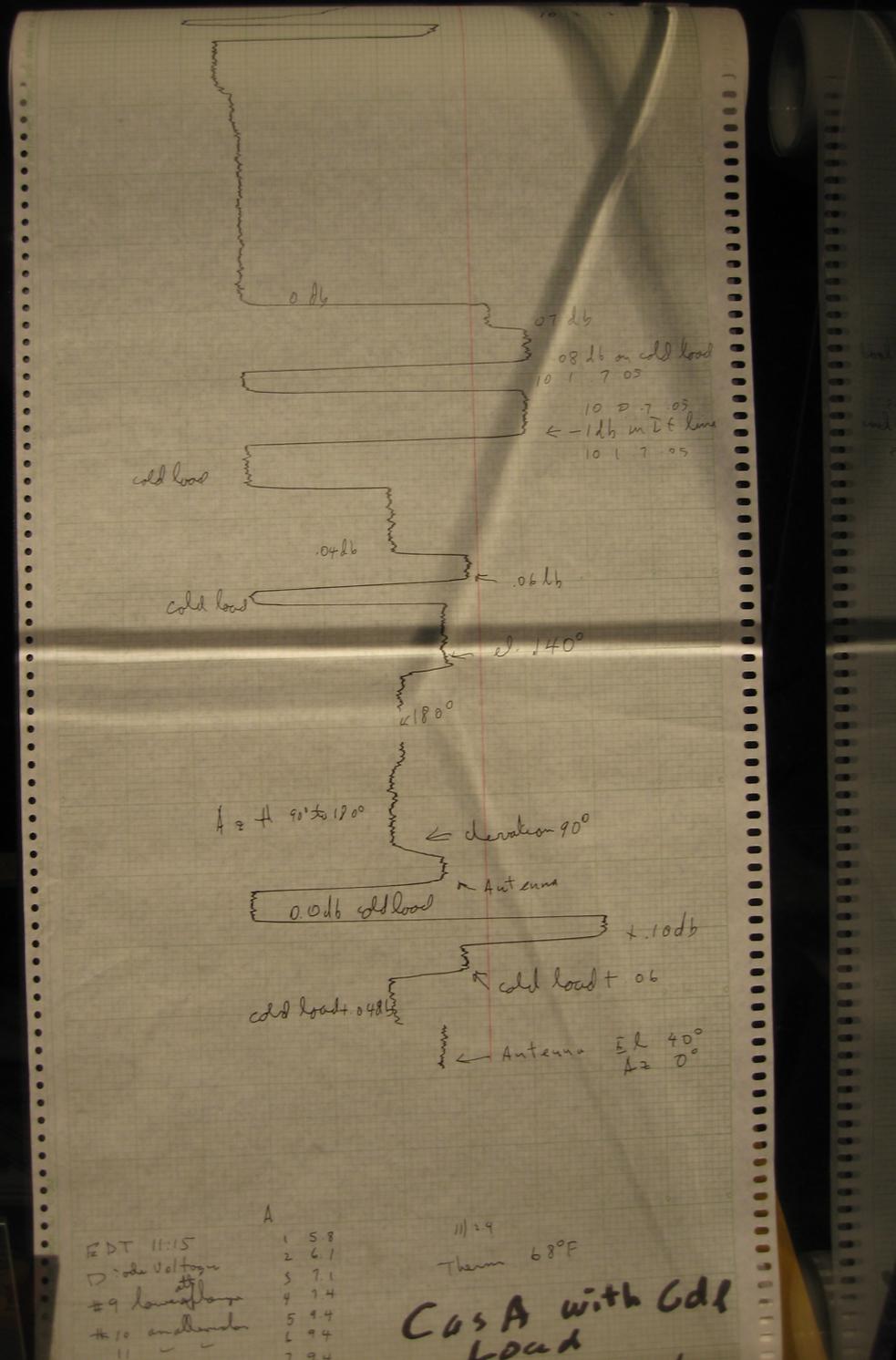
Penzance and Wilson used a strip chart recorder like this one to record the periplasmic state being picked up by their radio antenna. The strip chart is a copy of their original recording. It shows the spikes of radio noise that attended the presence of the cosmic background radiation ("cosmic temperature") compared to a laboratory source ("cold lead").

Reproduction of a Penzance and Wilson recording.
Courtesy of the University of Cambridge.

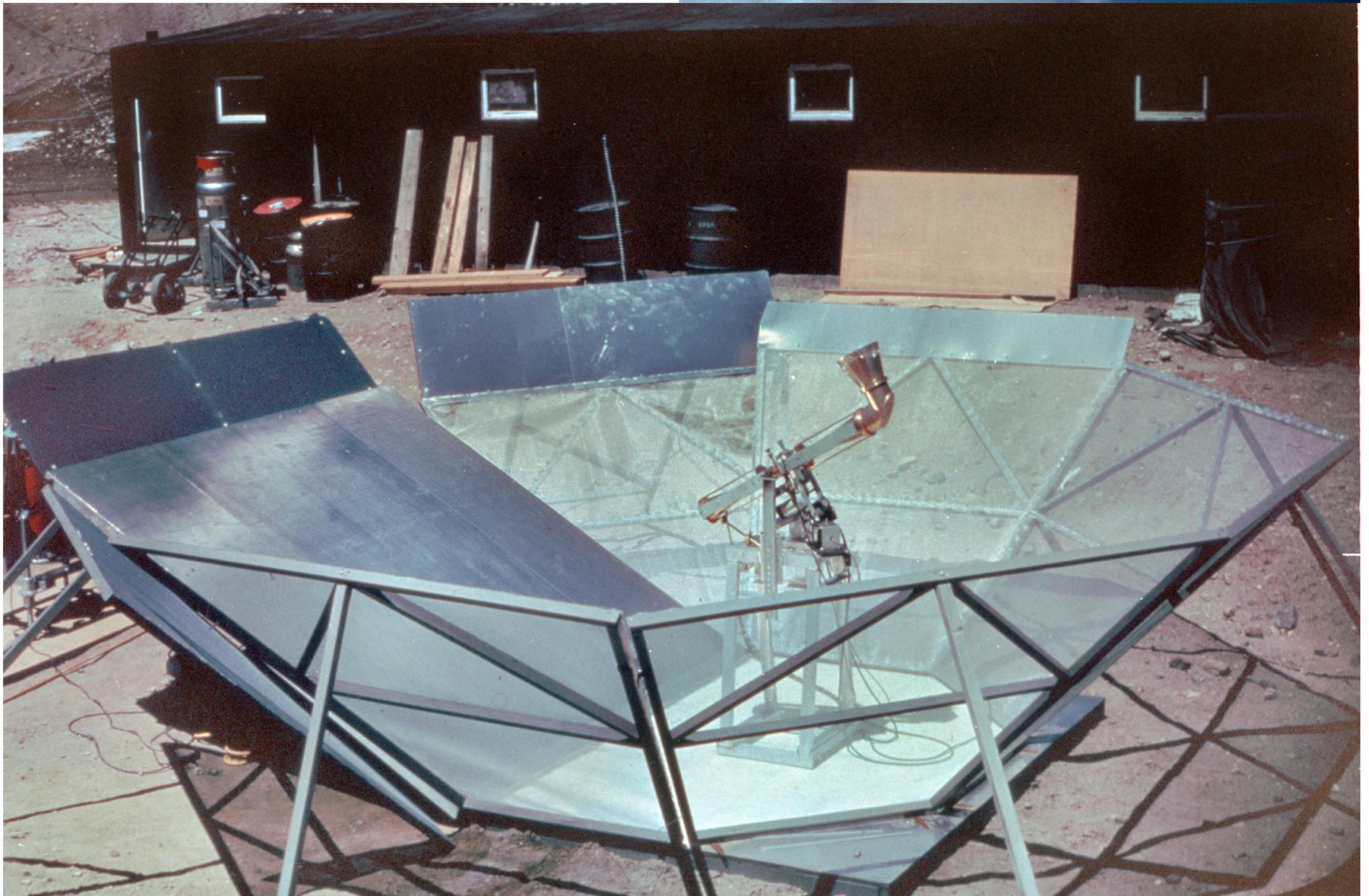
Big Bang

Original strip chart from Penzias and Wilson

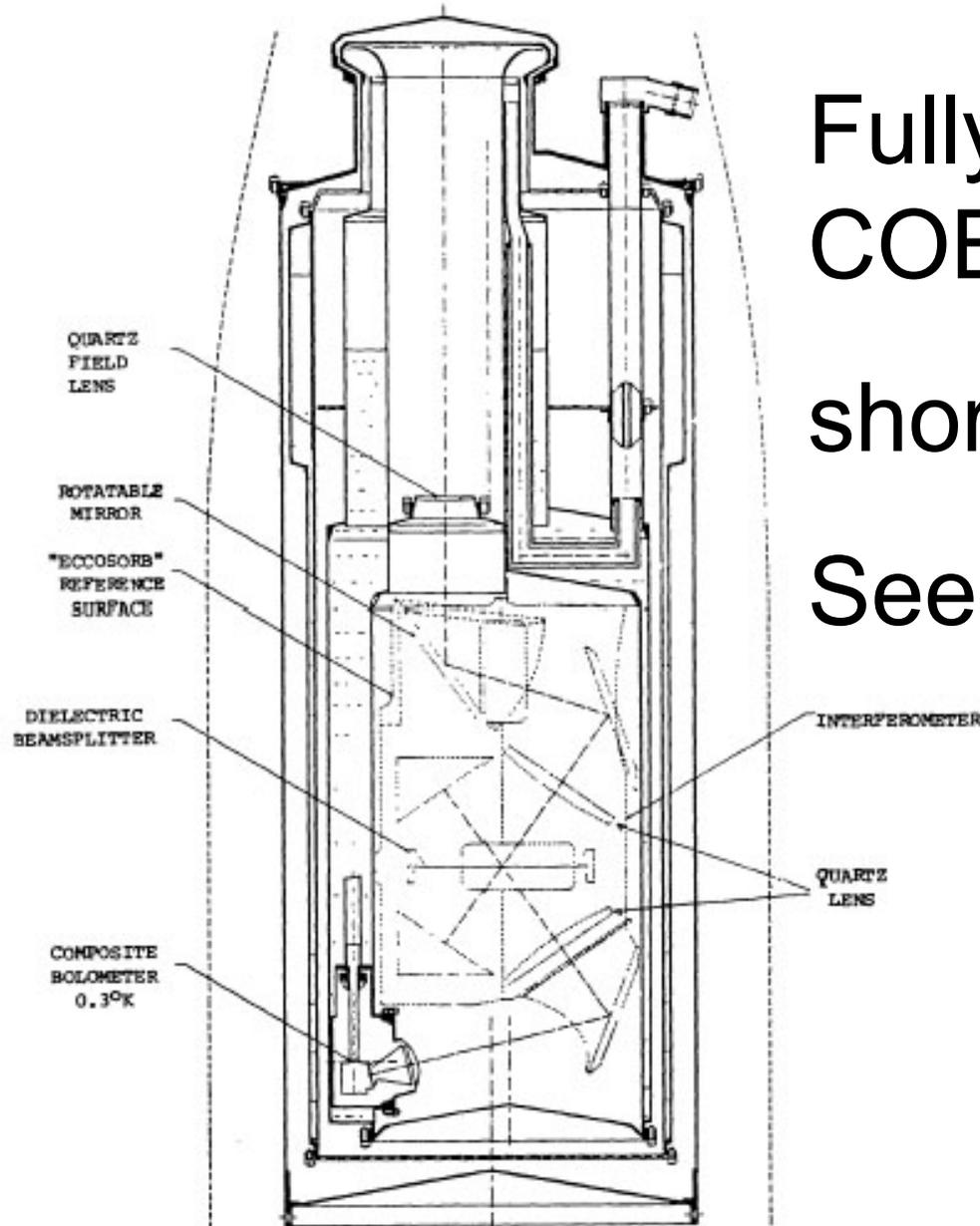
(This is how we used to take data. Big step to have ruled background to help quantify.)



Dave Wilkinson's



COBRA: Rocket borne interferometer of Gush, (later with Halpern et al)

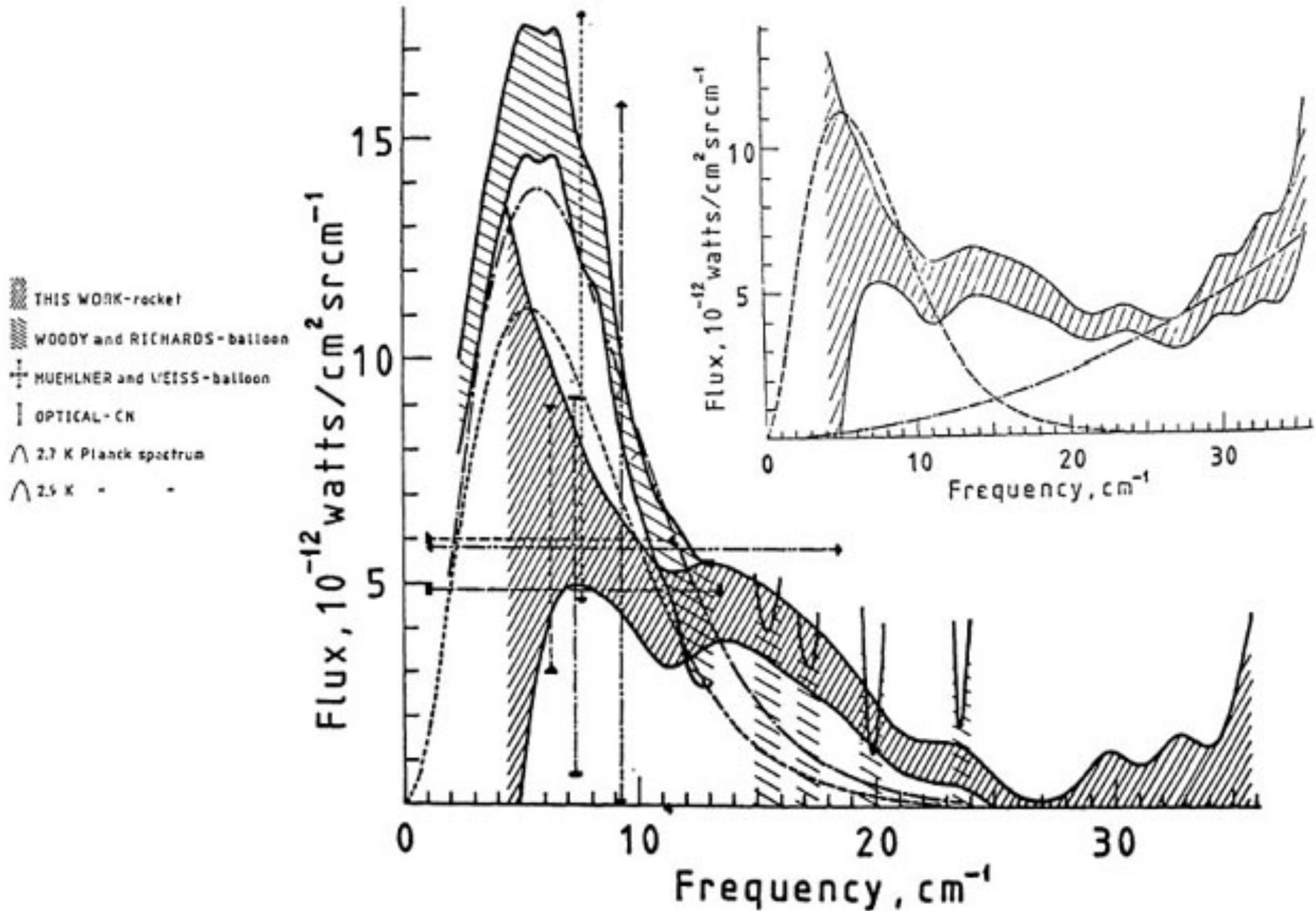


Fully successfully flight for
COBRA experiment

shortly after FIRAS results

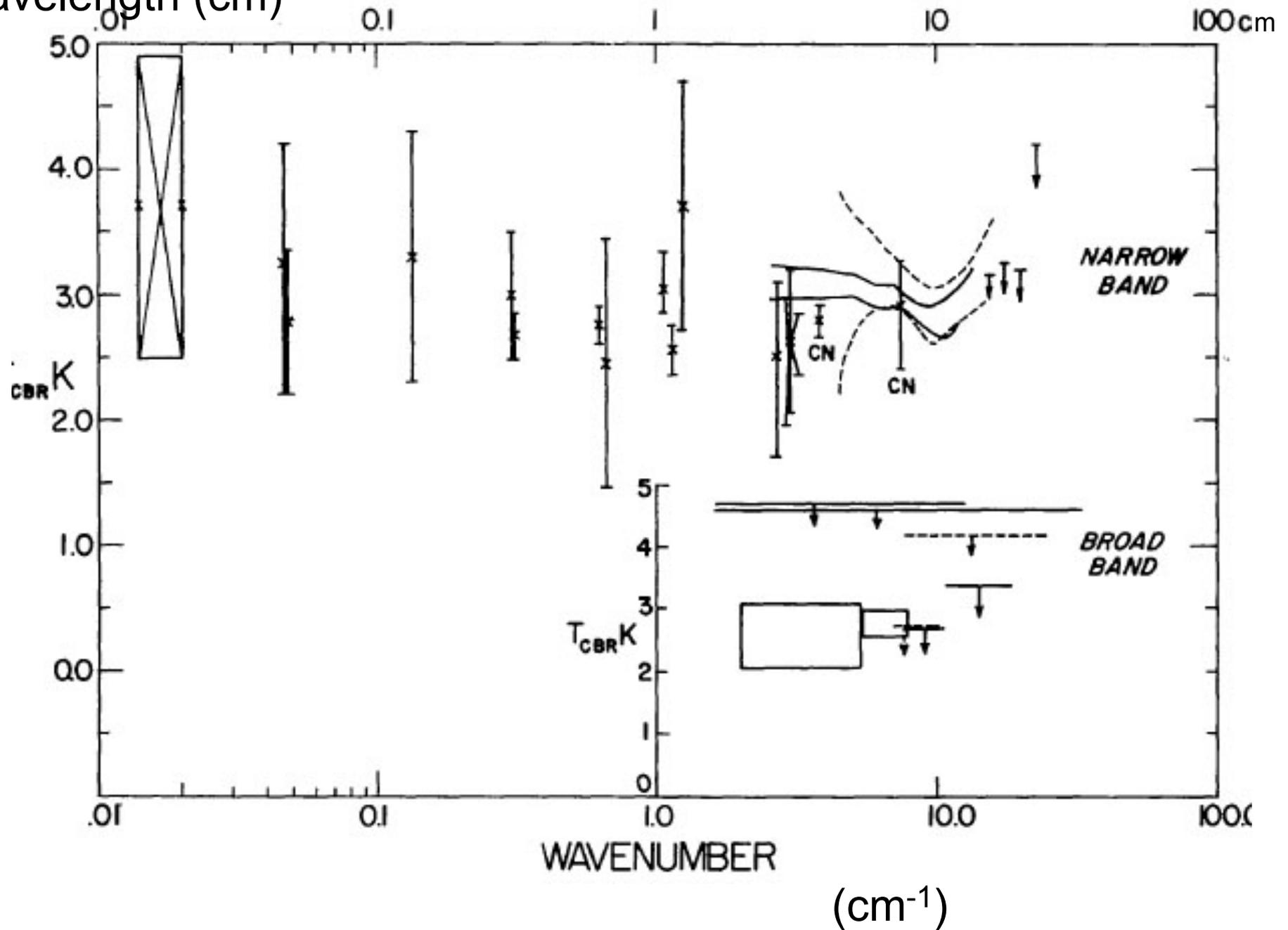
See in later plots

High Frequency Spectrum Observations



Early Spectrum Observation Summary

Wavelength (cm)



Spectrum : My Italian/American Posse at White Mtn.



Heavy Manual Operations

George Smoot, Scott Friedman, Alan Benner

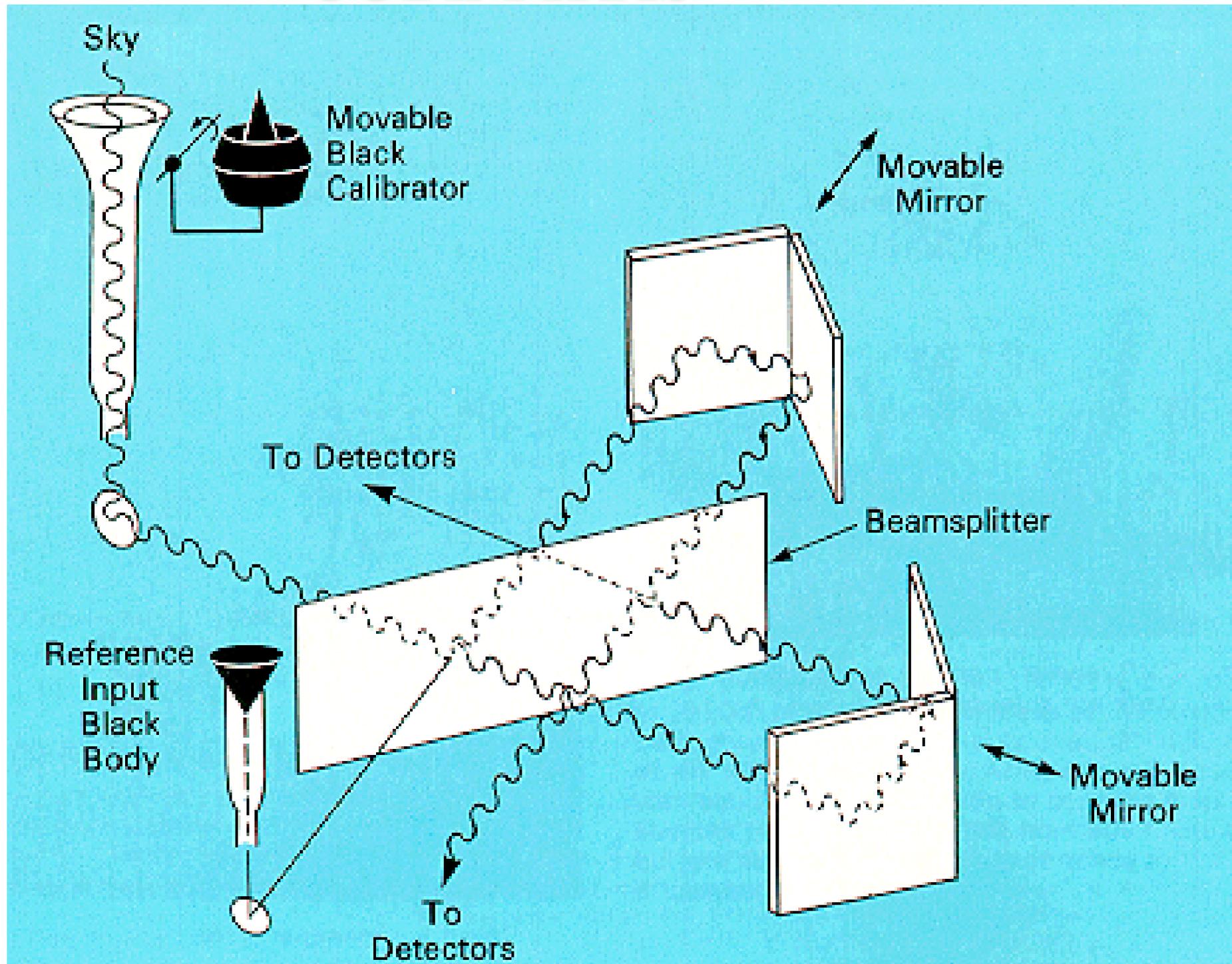




South Pole Steve Levin John Gibson Bill Vinje Giovanni de Amici Marc Bensadoun Michele Limon George Smoot Marco Bersanelli



COBE FIRAS

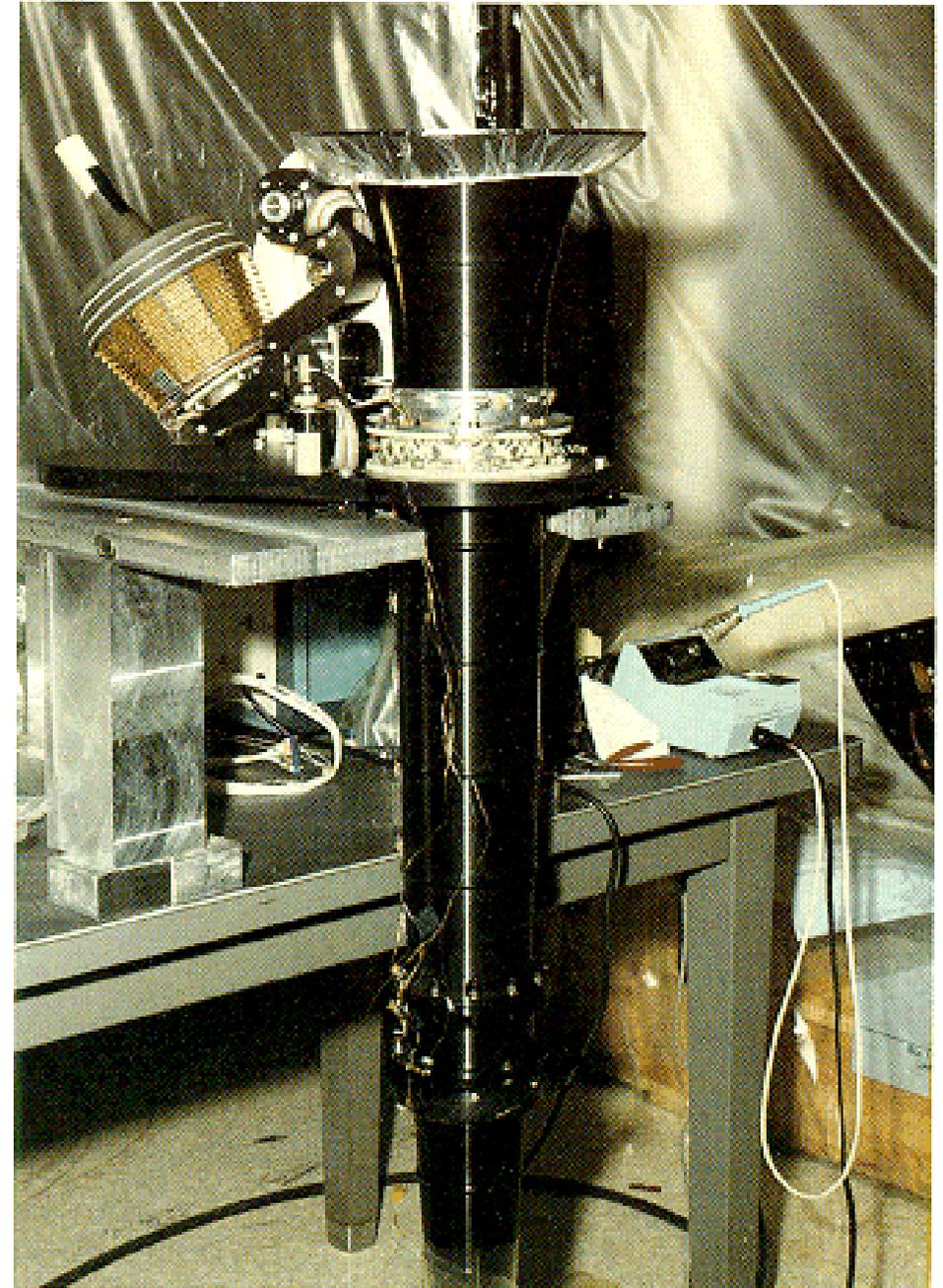
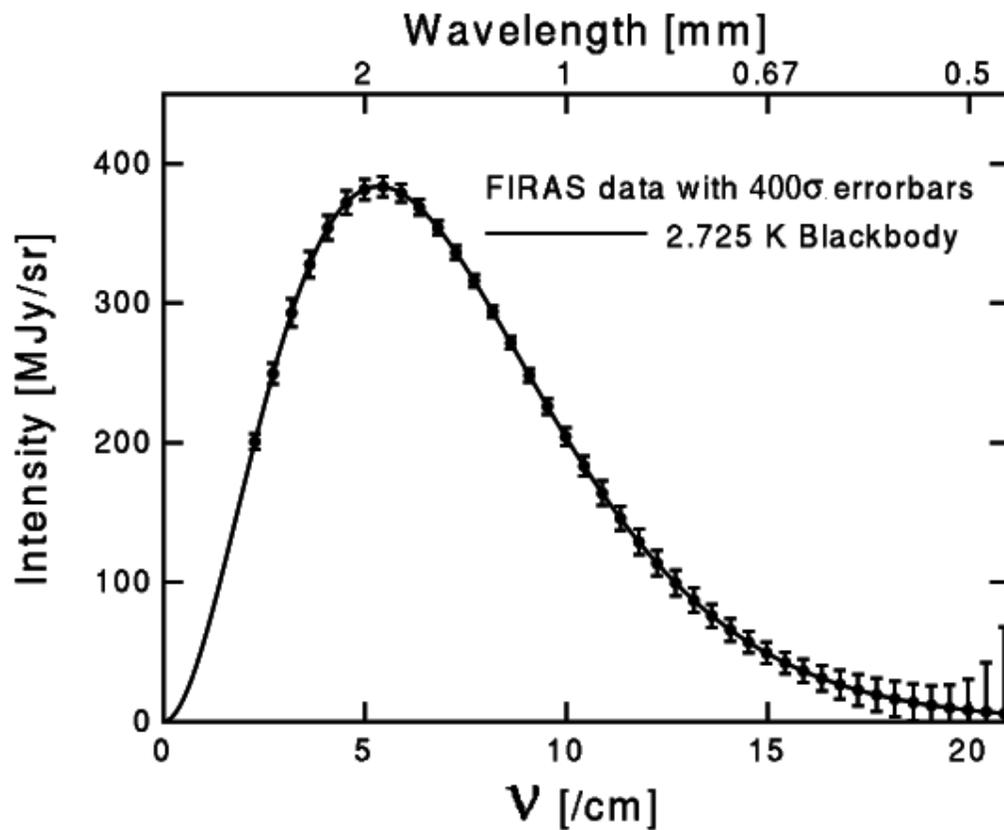


FIRAS Horn & Ext. Calibrator

COBE Spectrum of the Universe

-first 7 minutes of data

-Jan 1990 AAS meeting

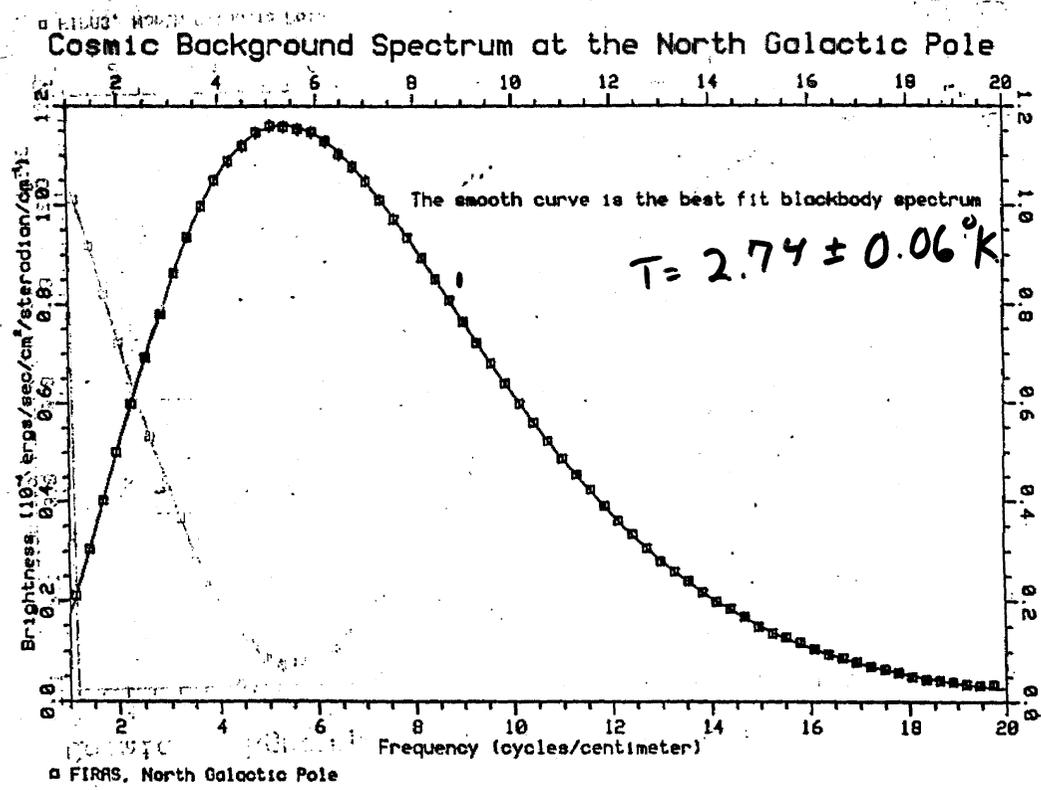


Horn antenna with movable calibrator. Protective plastic covers will be removed.

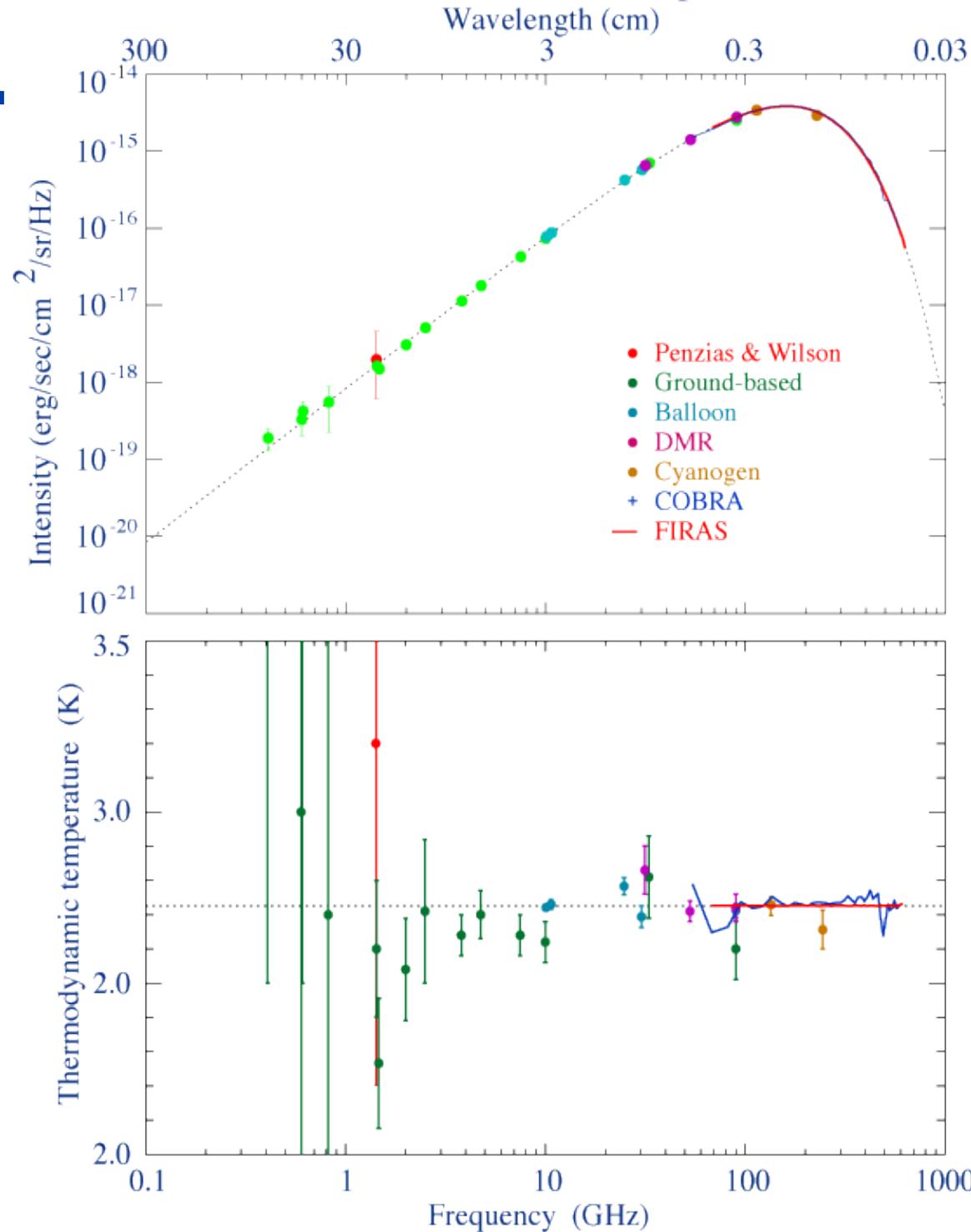
*COBE Spectrum of the Universe - first 7 minutes of data
(FAXed copy of version presented at American
Astronomical Society meeting - Jan. 1990)*

TO: MIKE SITKO

COBE/FIRAS Jan 1990 AAS meeting



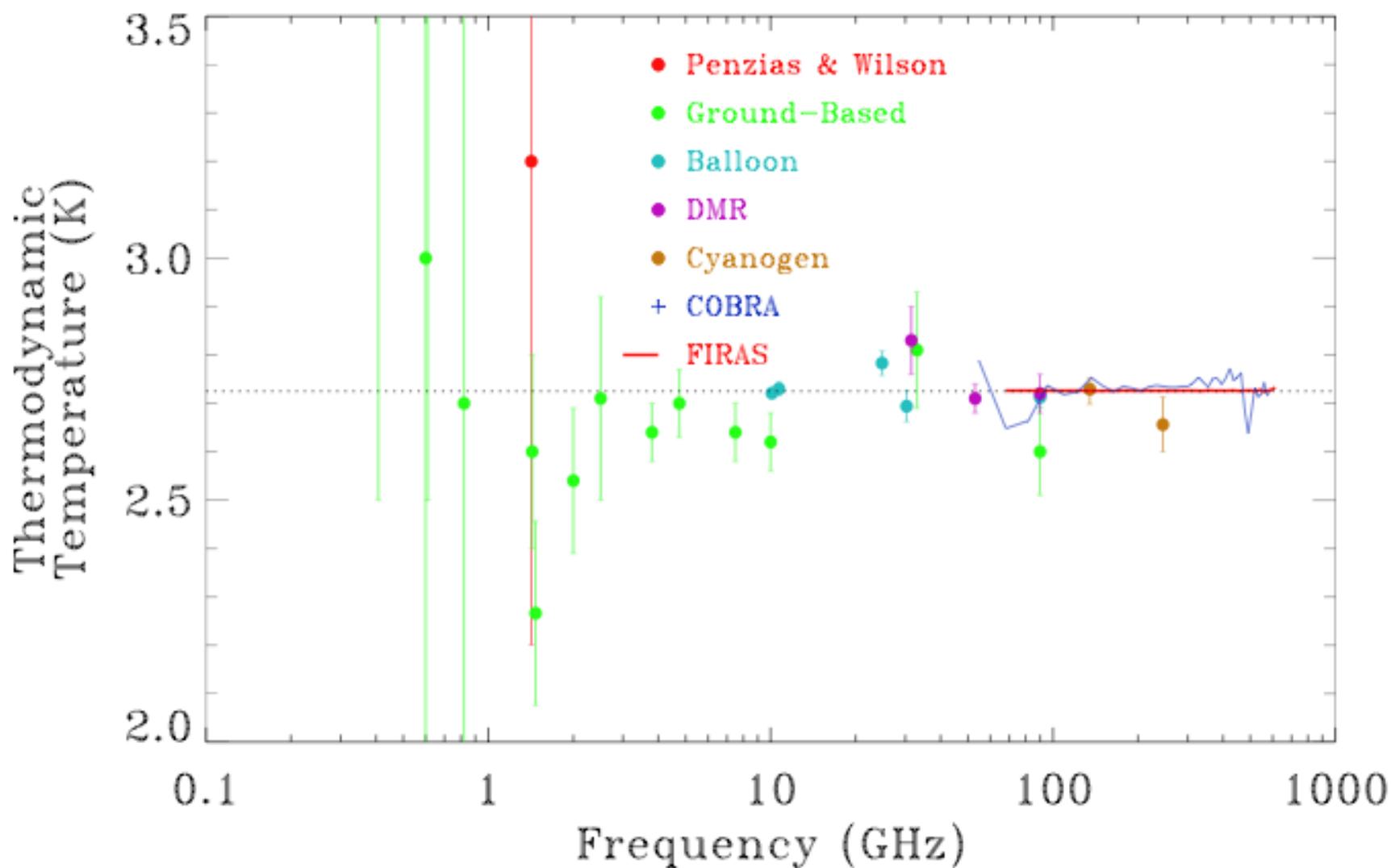
Measurements of CMB Spectrum



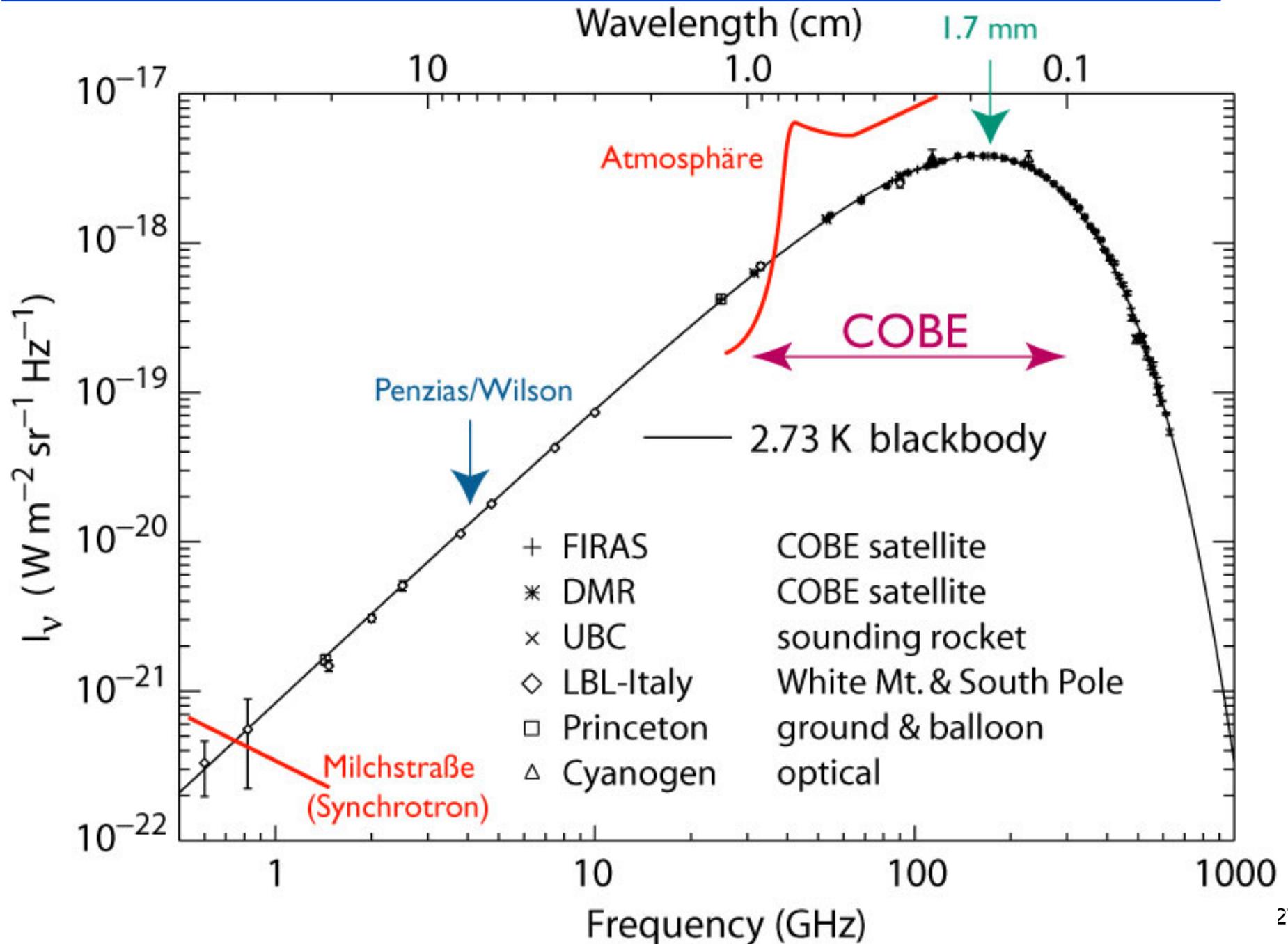
Selected Measurements of CMB Spectrum

Wavelength (cm)

300 30 3 0.3 0.03

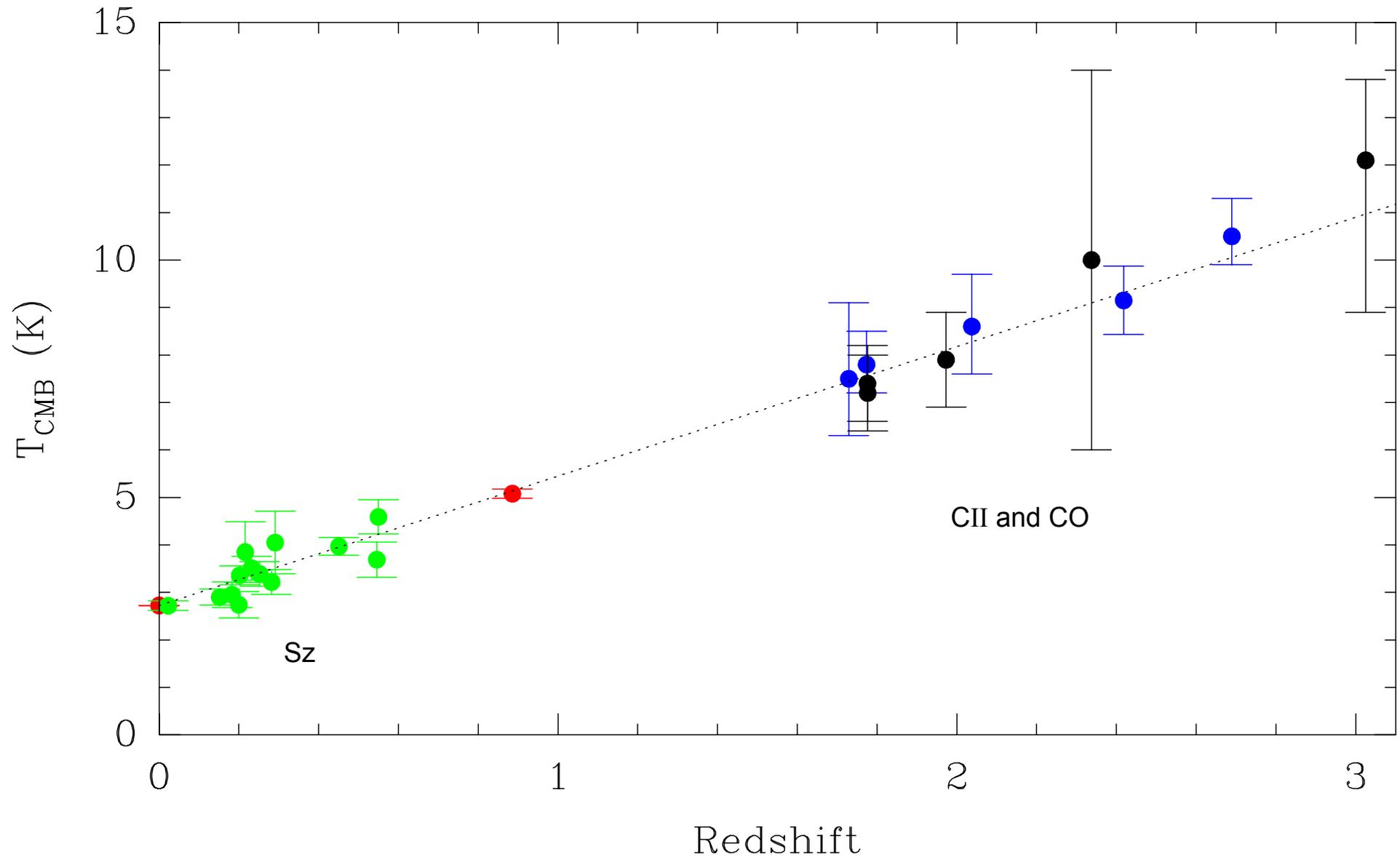


CMB Spectrum as of 1994



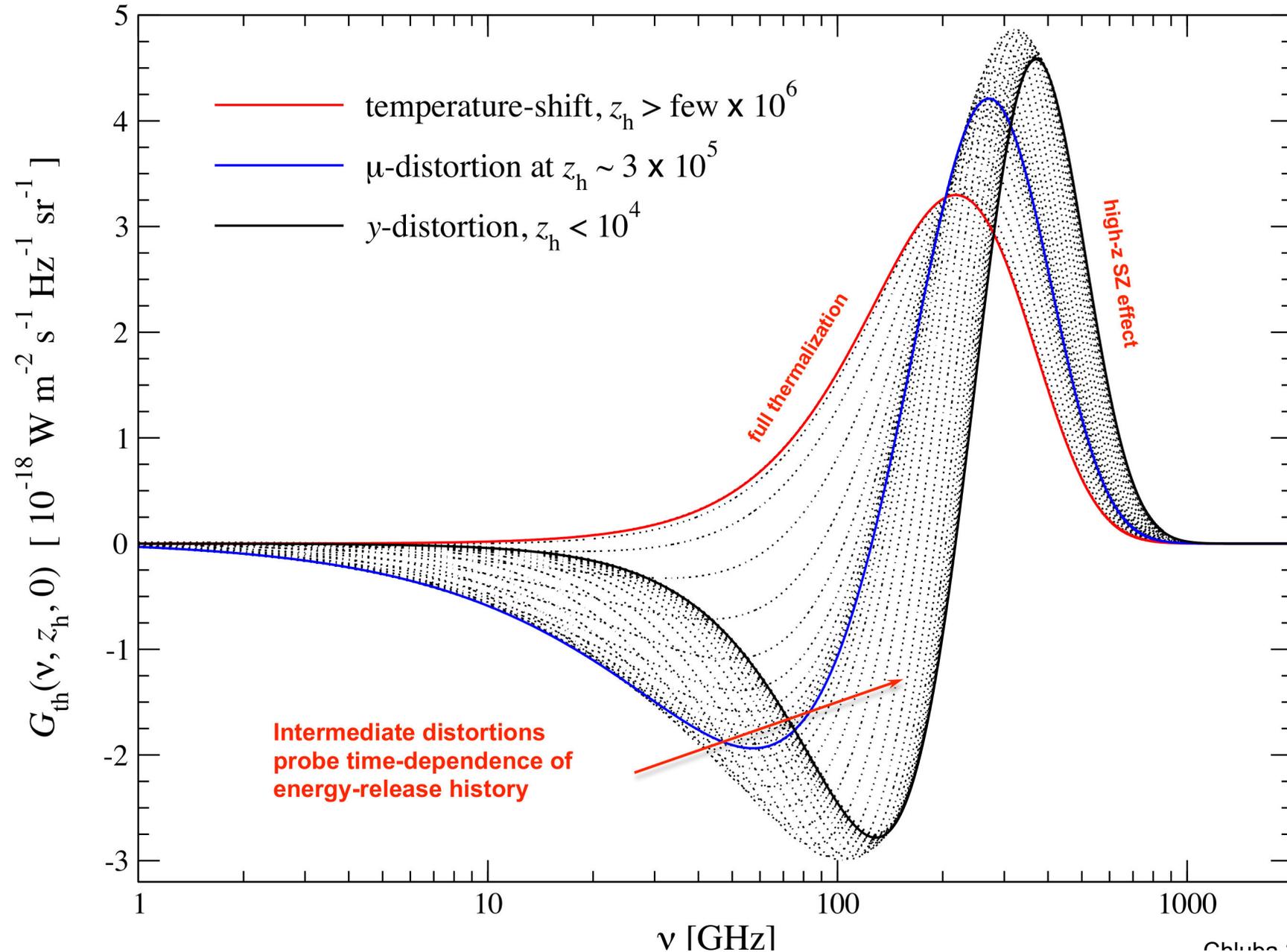
CMB Temperature vs Redshift

dotted line shows expected trend



CMB Spectral Distortions from Energy Injections

Intensity signal for different heating redshifts



Physical mechanisms that lead to spectral distortions

Standard sources
of distortions

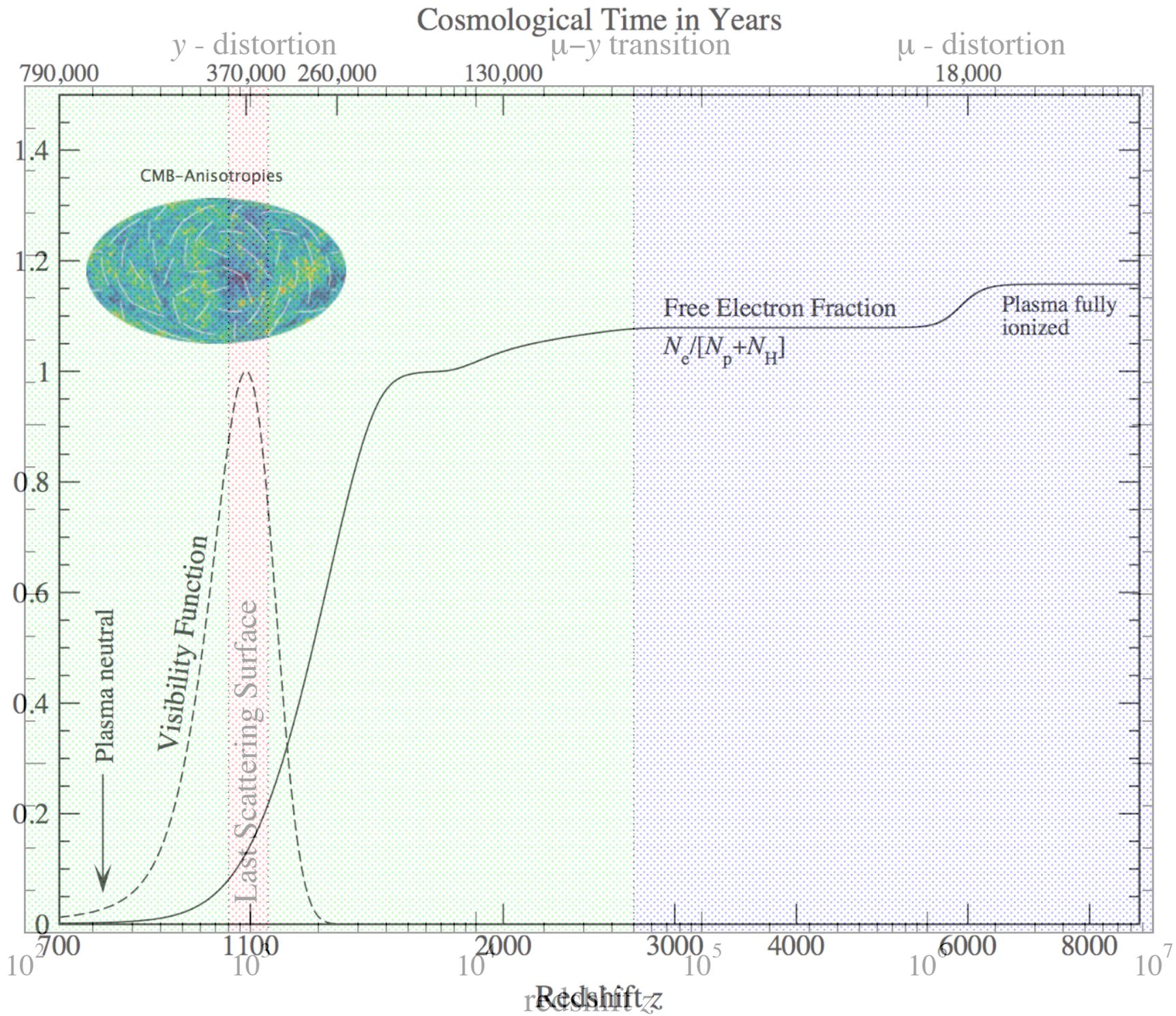
- **Cooling by adiabatically expanding ordinary matter**
(JC, 2005; JC & Sunyaev 2011; Khatri, Sunyaev & JC, 2011)
 - **Heating by decaying or *annihilating* relic particles**
(Kawasaki et al., 1987; Hu & Silk, 1993; McDonald et al., 2001; JC, 2005; JC & Sunyaev, 2011; JC, 2013; JC & Jeong, 2013)
 - **Evaporation of primordial black holes & superconducting strings**
(Carr et al. 2010; Ostriker & Thompson, 1987; Tashiro et al. 2012; Pani & Loeb, 2013)
 - **Dissipation of primordial acoustic modes & magnetic fields**
(Sunyaev & Zeldovich, 1970; Daly 1991; Hu et al. 1994; JC & Sunyaev, 2011; JC et al. 2012 - Jedamzik et al. 2000; Kunze & Komatsu, 2013)
 - **Cosmological recombination radiation**
(Zeldovich et al., 1968; Peebles, 1968; Dubrovich, 1977; Rubino-Martin et al., 2006; JC & Sunyaev, 2006; Sunyaev & JC, 2009)
-
- **Signatures due to first supernovae and their remnants**
(Oh, Cooray & Kamionkowski, 2003)
 - **Shock waves arising due to large-scale structure formation**
(Sunyaev & Zeldovich, 1972; Cen & Ostriker, 1999)
 - **SZ-effect from clusters; effects of reionization**
(Refregier et al., 2003; Zhang et al. 2004; Trac et al. 2008)
 - **more exotic processes**
(Lochan et al. 2012; Bull & Kamionkowski, 2013; Brax et al., 2013; Tashiro et al. 2013)

pre-recombination epoch

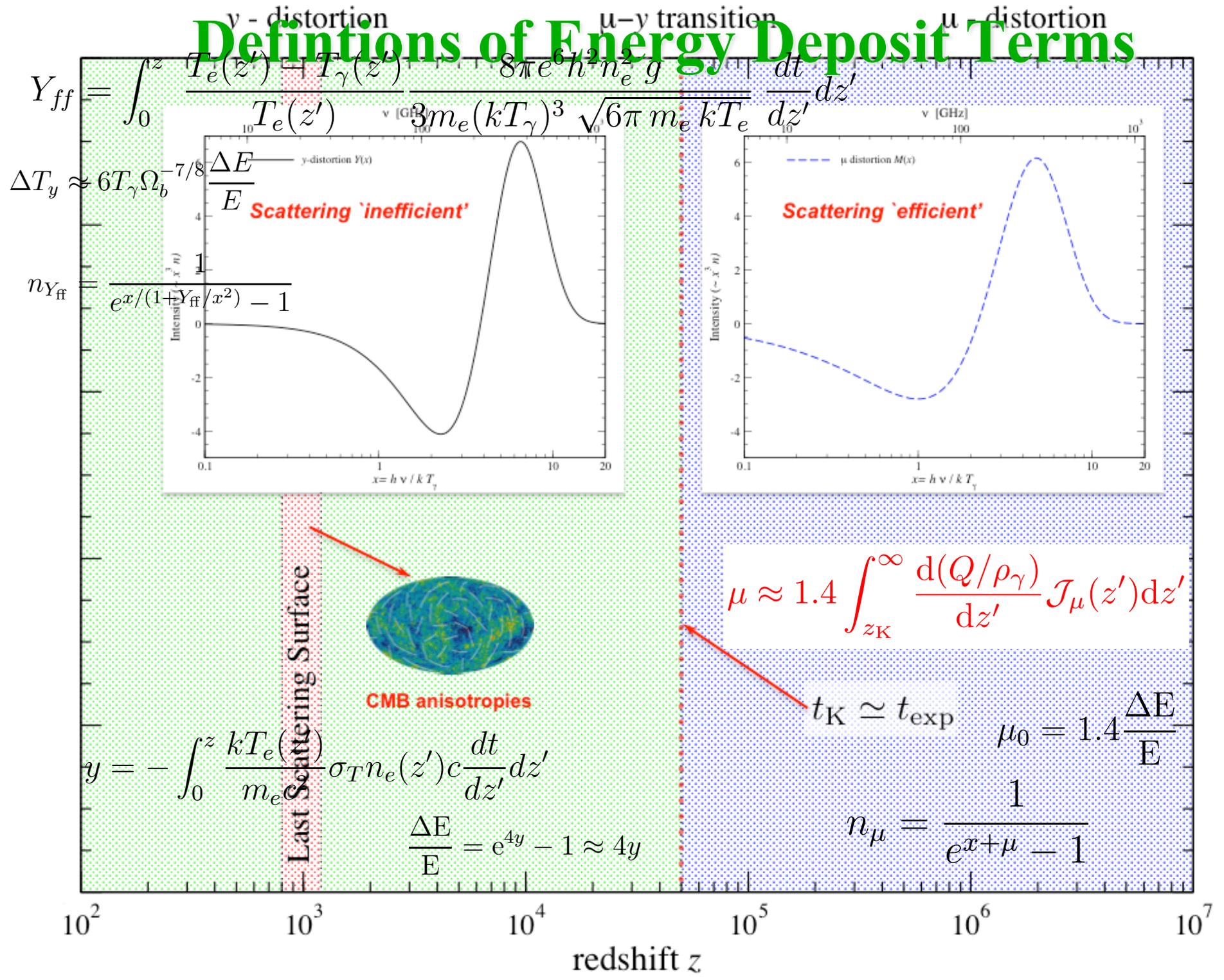
„high“ redshifts

„low“ redshifts

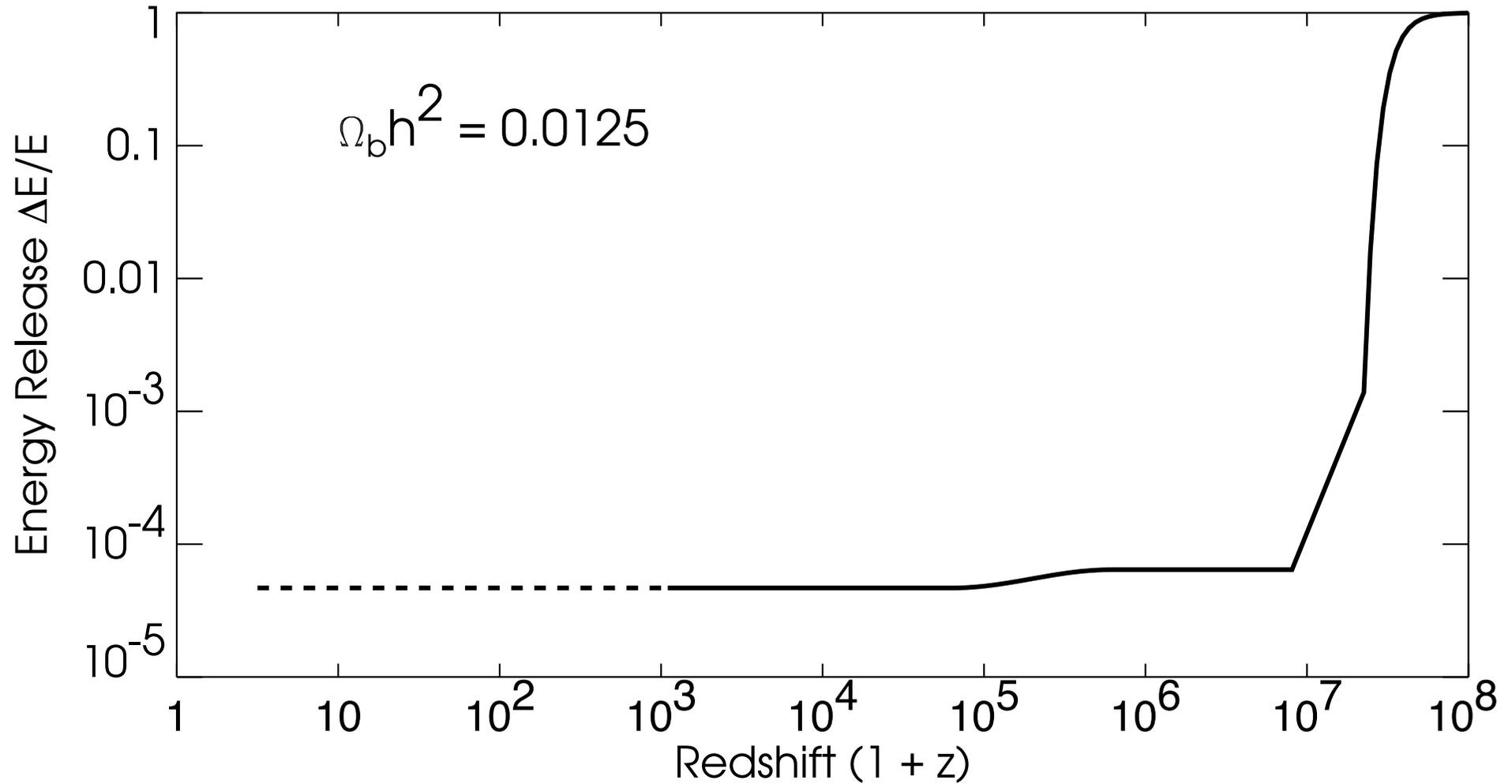
post-recombination



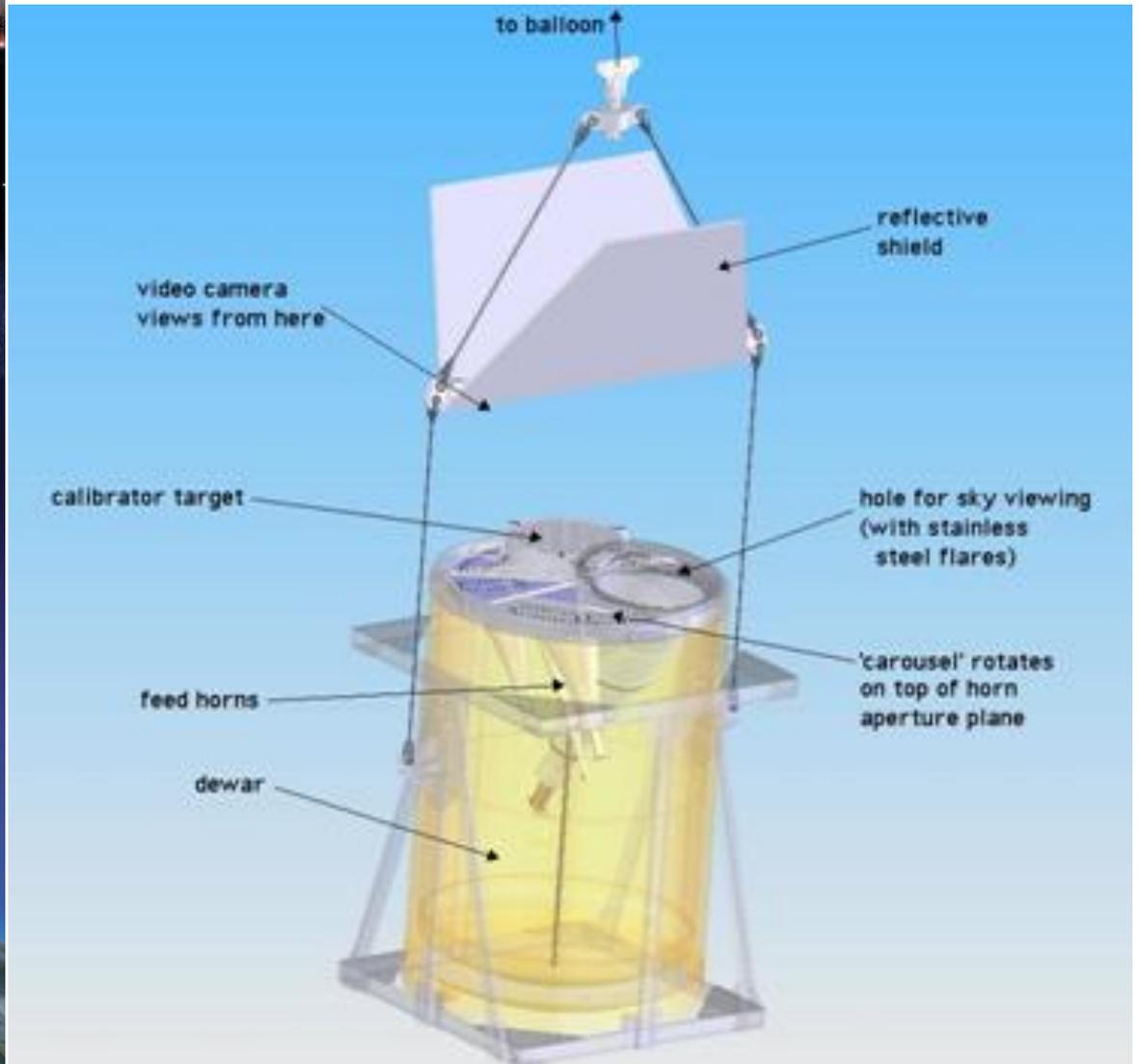
Definitions of Energy Deposit Terms



Limits on Energy Release vs Redshift



Absolute Radiometer for Cosmology, Astrophysics, and Diffuse Emission (ARCADE)

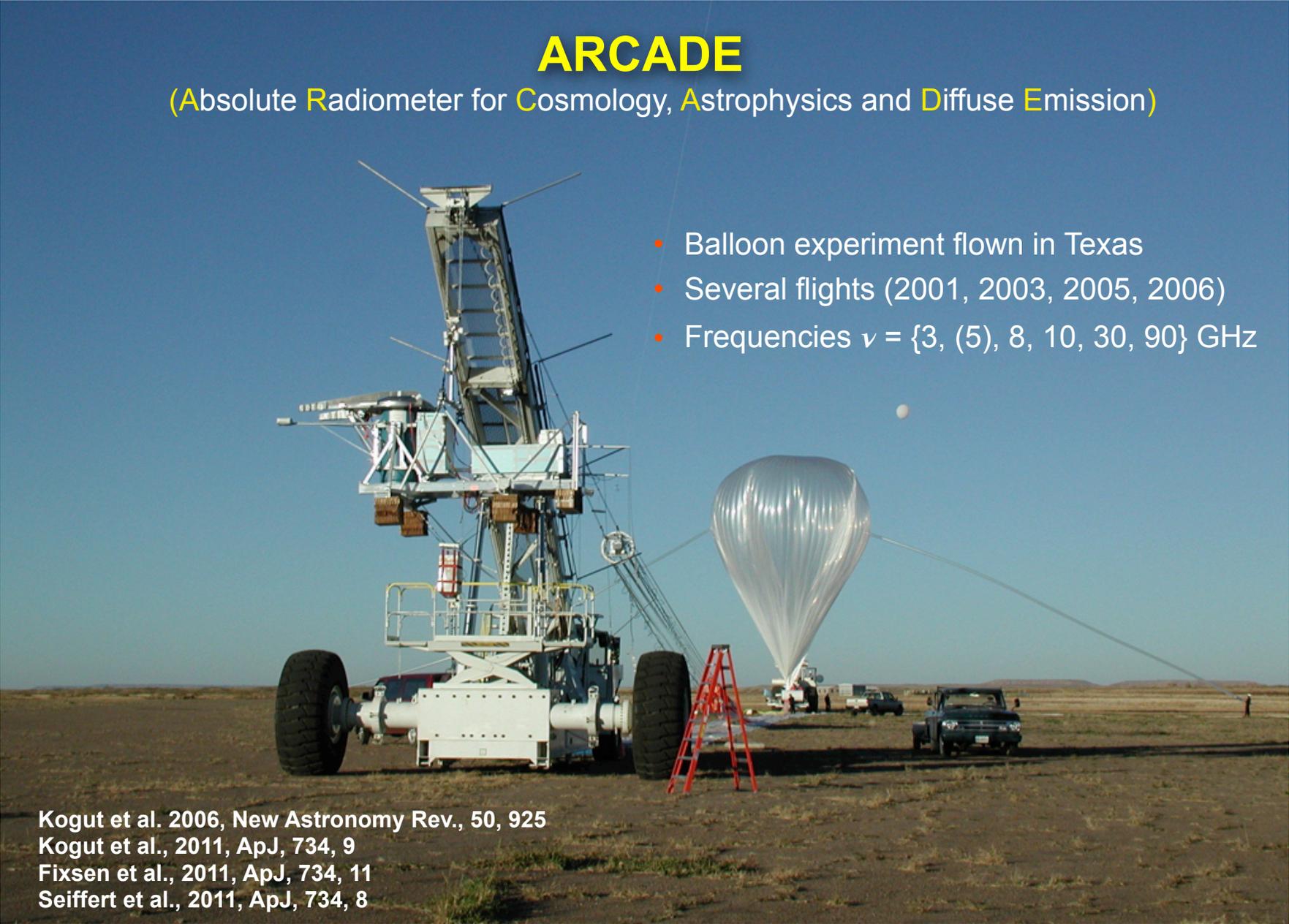


ARCADE

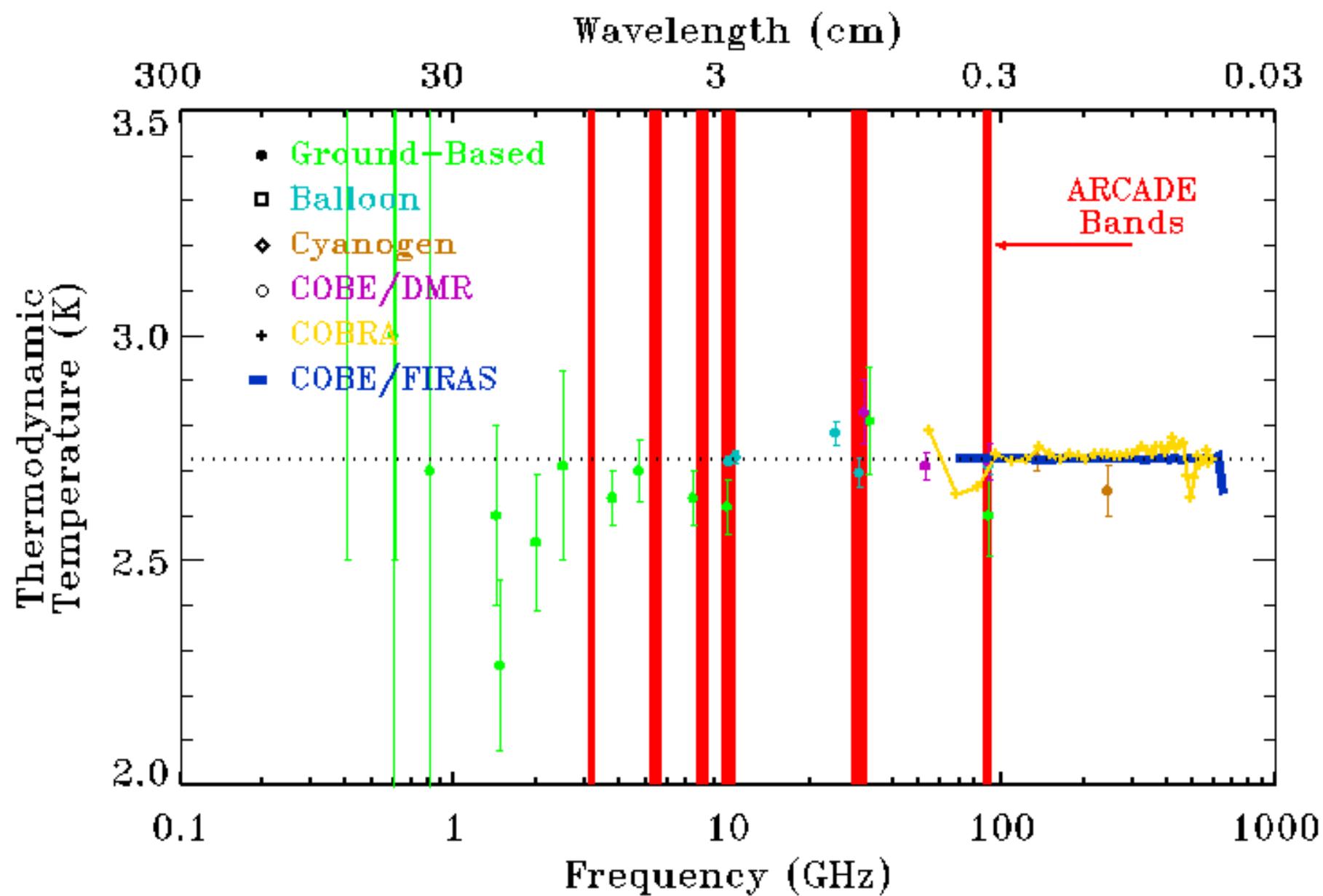
ARCADE

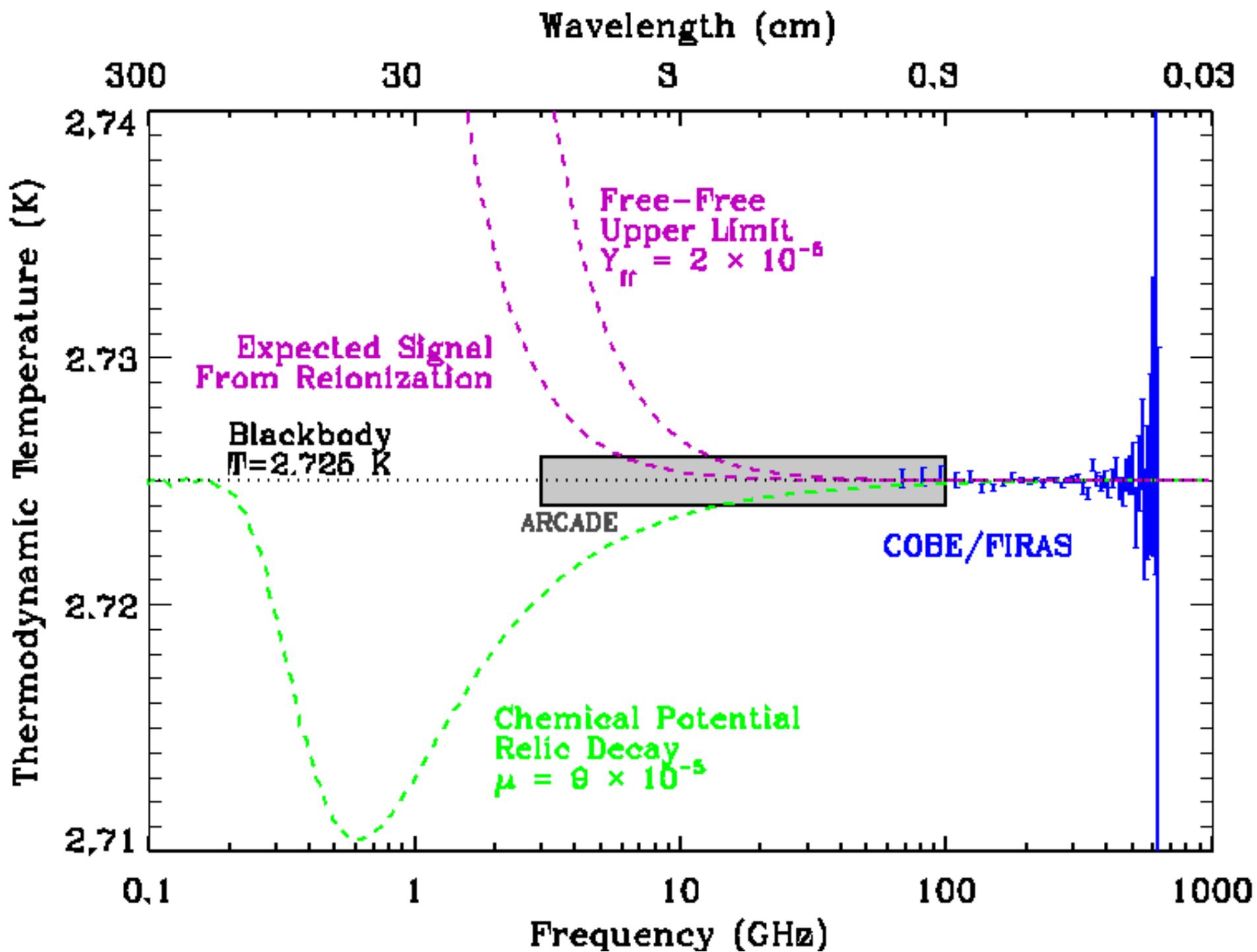
(Absolute Radiometer for Cosmology, Astrophysics and Diffuse Emission)

- Balloon experiment flown in Texas
- Several flights (2001, 2003, 2005, 2006)
- Frequencies $\nu = \{3, (5), 8, 10, 30, 90\}$ GHz

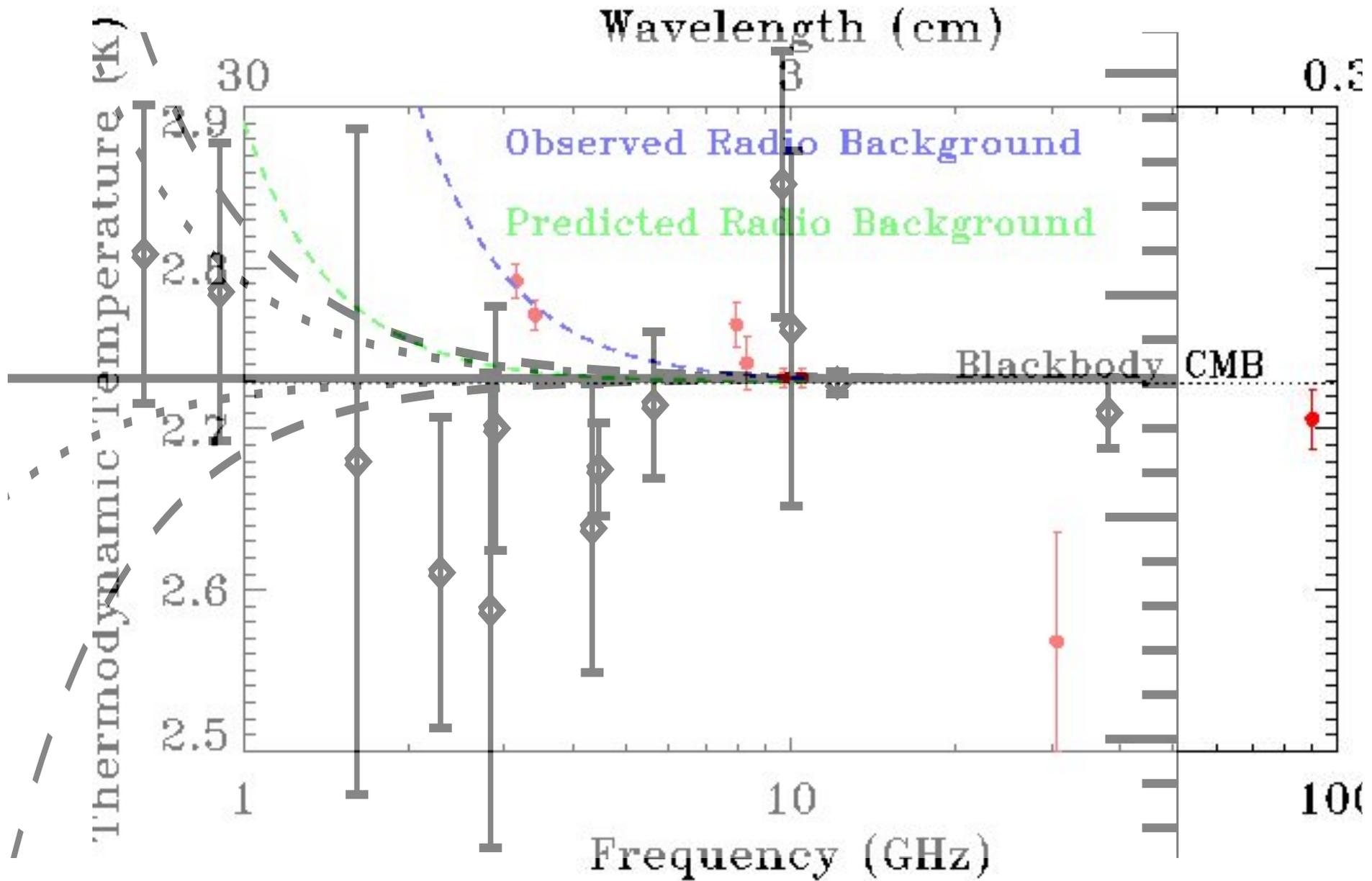
A photograph showing the ARCADE balloon experiment setup in a flat, open field. A large, white, multi-lobed balloon is being inflated by a large, white, multi-wheeled trailer. A red ladder is positioned next to the trailer. In the background, a dark pickup truck and other vehicles are visible. The sky is clear and blue, with a small white object (possibly a moon or star) visible in the upper right. The ground is dry and brownish.

Kogut et al. 2006, *New Astronomy Rev.*, 50, 925
Kogut et al., 2011, *ApJ*, 734, 9
Fixsen et al., 2011, *ApJ*, 734, 11
Seiffert et al., 2011, *ApJ*, 734, 8



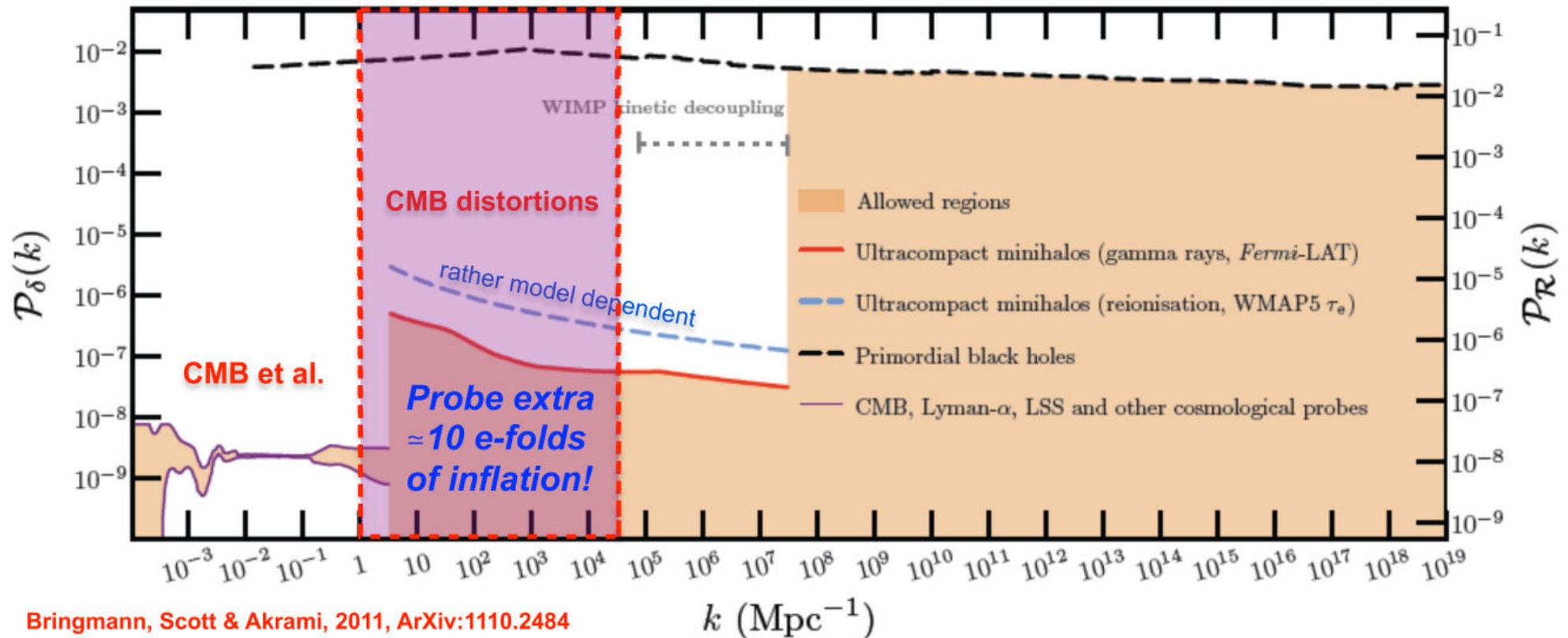


Arcade Results vs anticipated



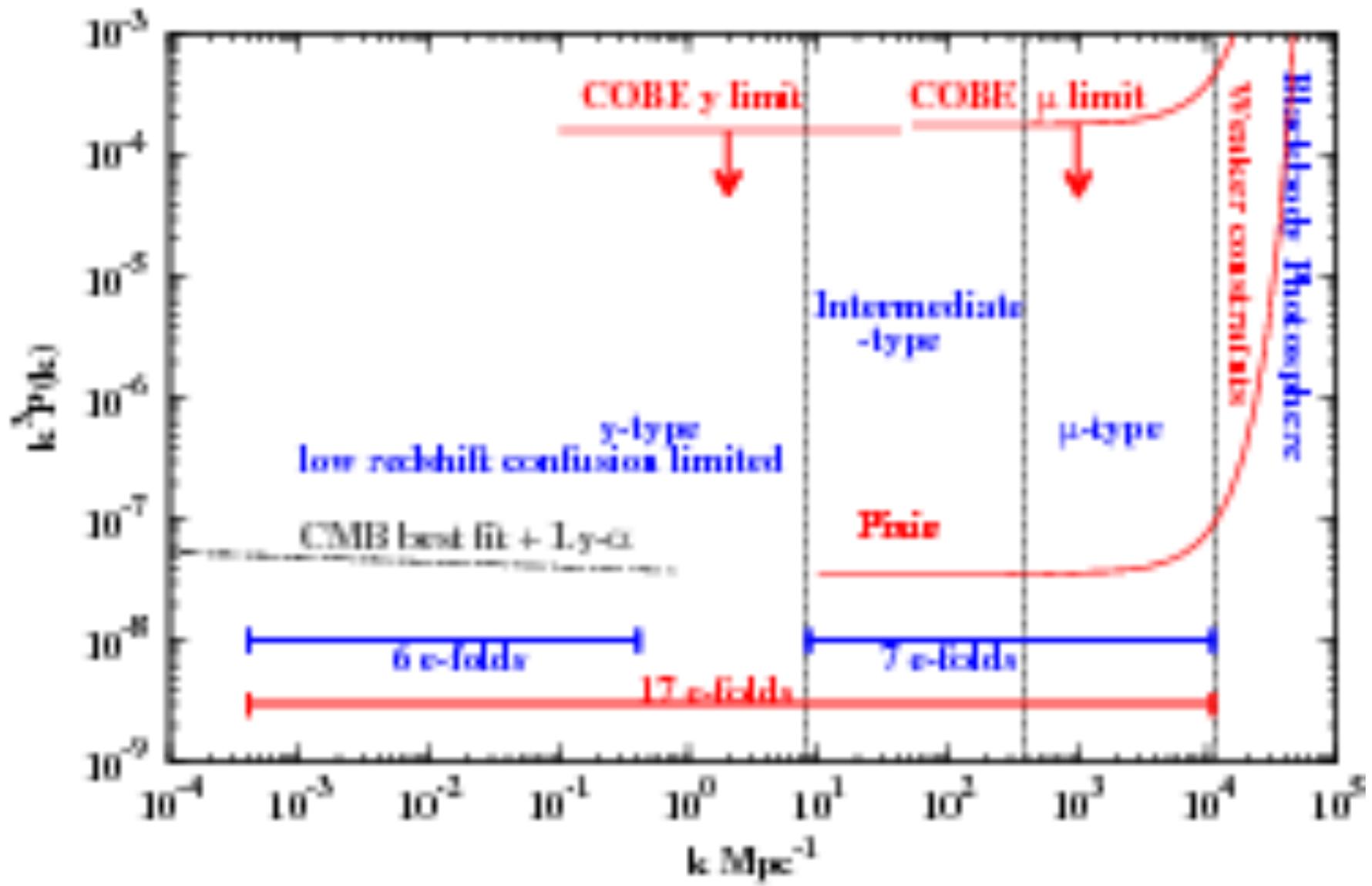
Future CMB Spectral Measurements ?

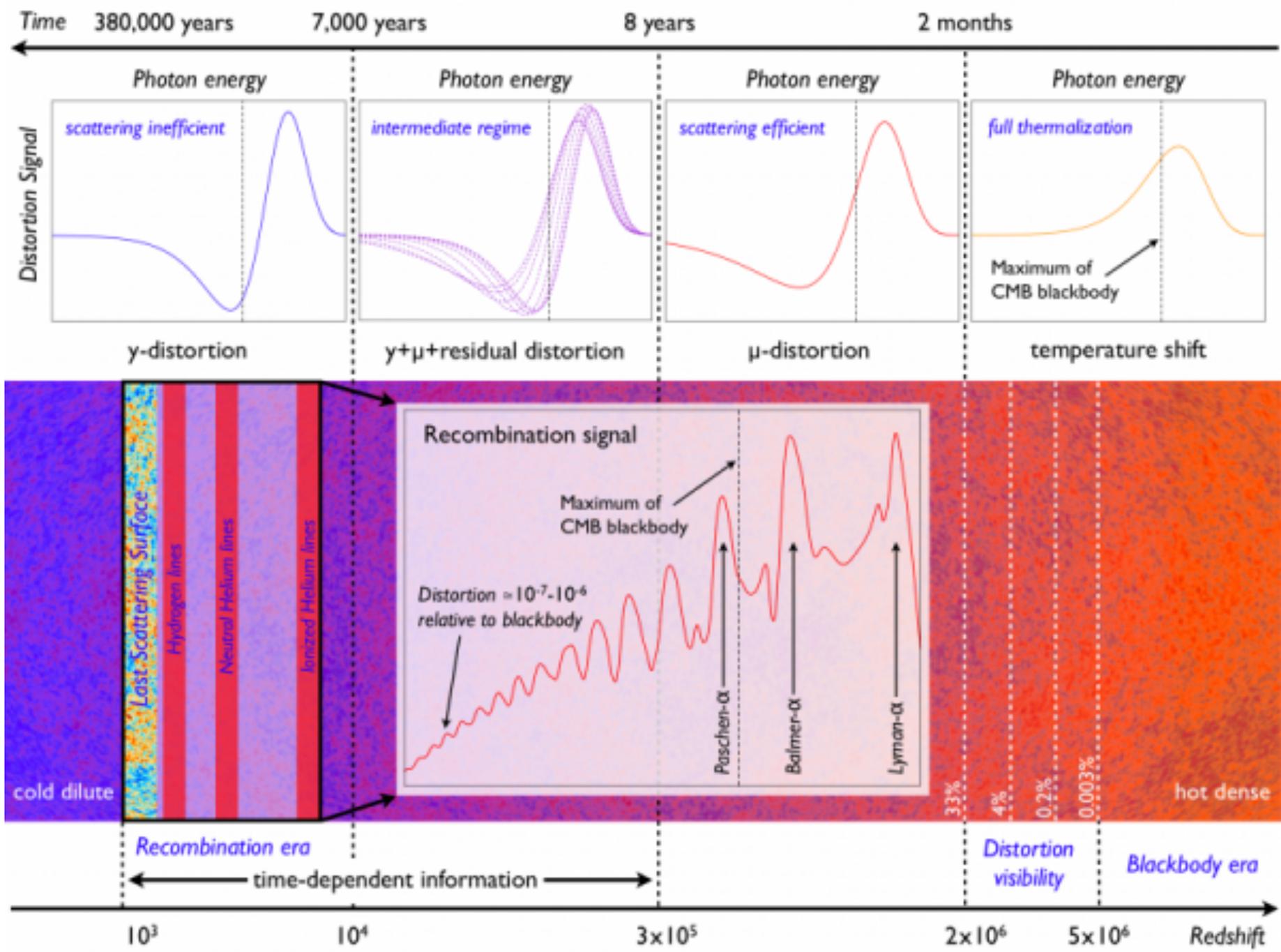
- A lot of attention has been focused lately on the possibility to measure the H and He lines from recombination (I bet they are there, who doesn't?)
- And on adding information on the fluct.spectrum



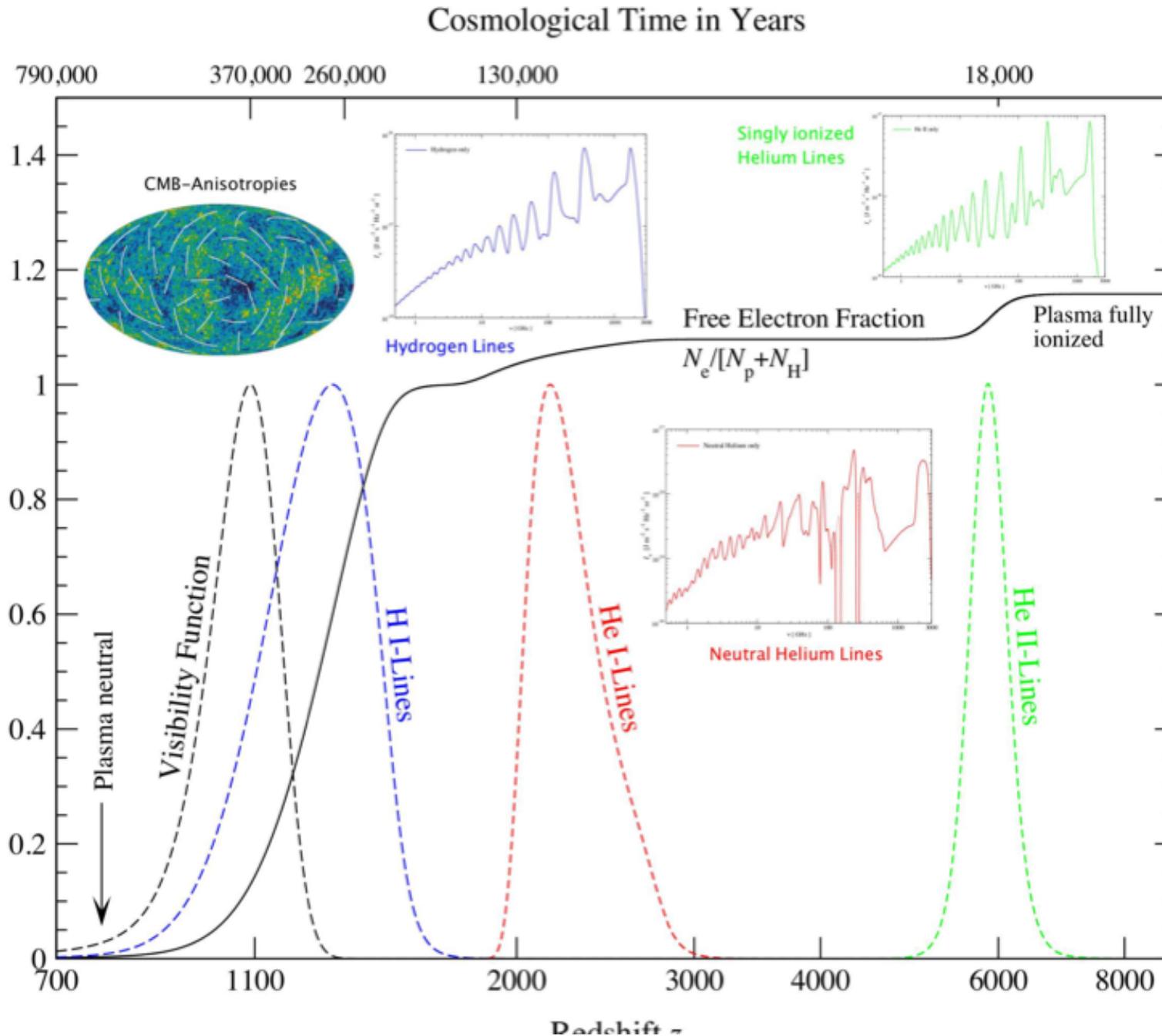
Bringmann, Scott & Akrami, 2011, ArXiv:1110.2484

Jens Chluba, Rashid Sunyaev "Free-bound emission from cosmological hydrogen recombination » A&A, 458, L29 (2006) Jose Alberto Rubiño-Martín, Jens Chluba and Rashid Sunyaev "Lines in the cosmic microwave background spectrum from the epoch of cosmological hydrogen recombination » Mon. Not. R. Astron. Soc., 371, 1939 (2006)

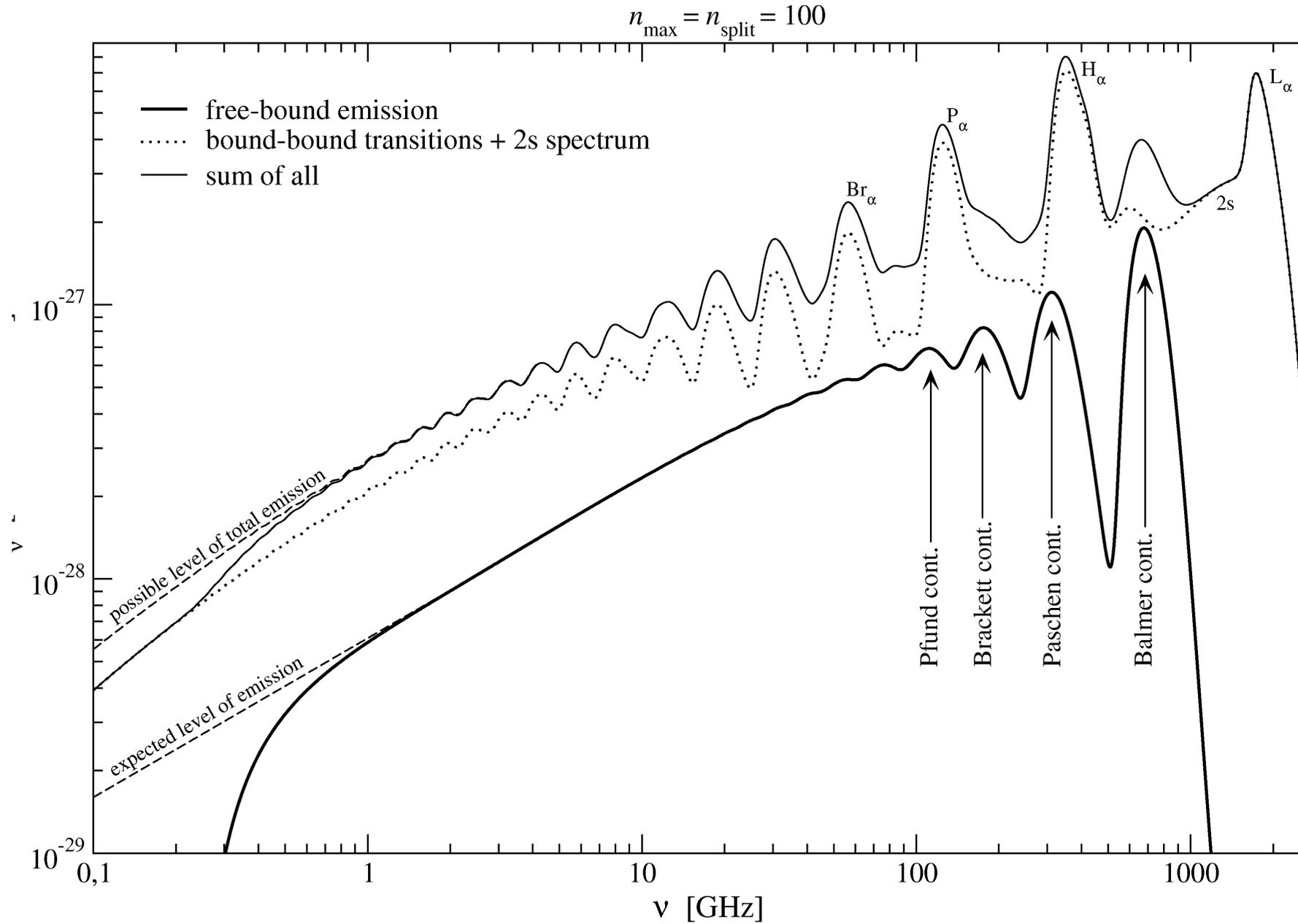




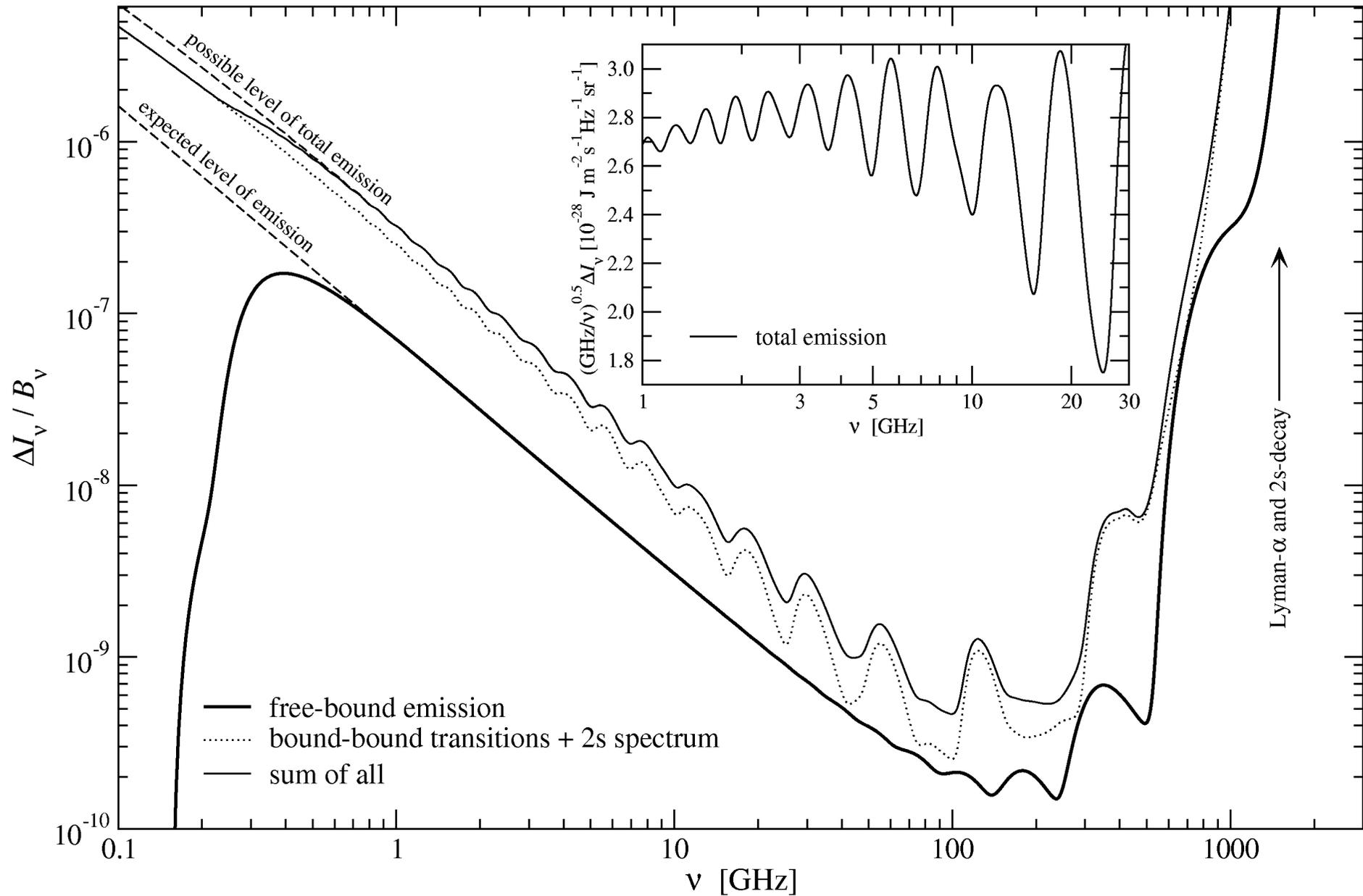
The primordial hydrogen and helium recombination lines epochs



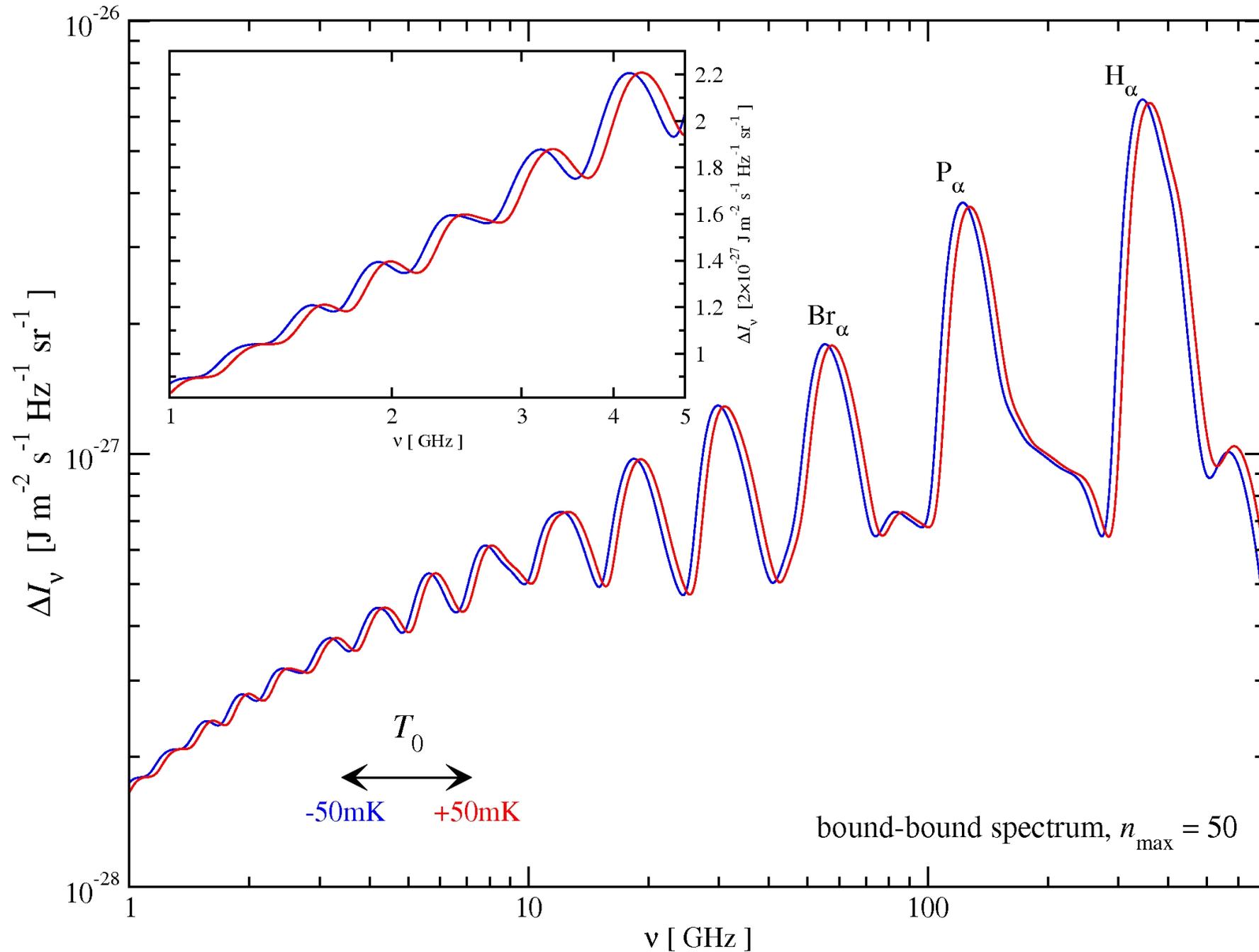
Spectral Line Distortions at Reionization



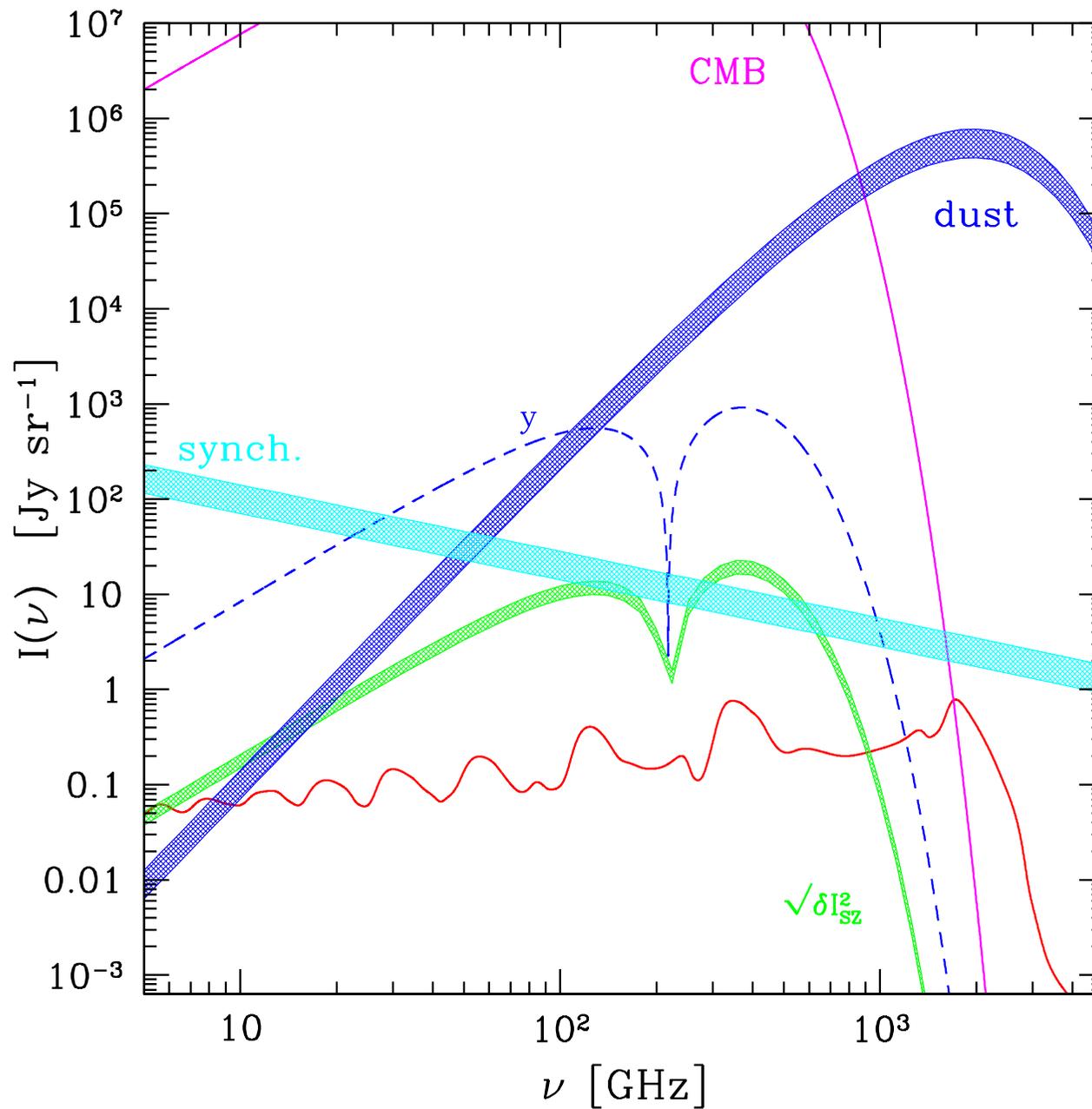
CMB spectral distortion due to hydrogen recombination



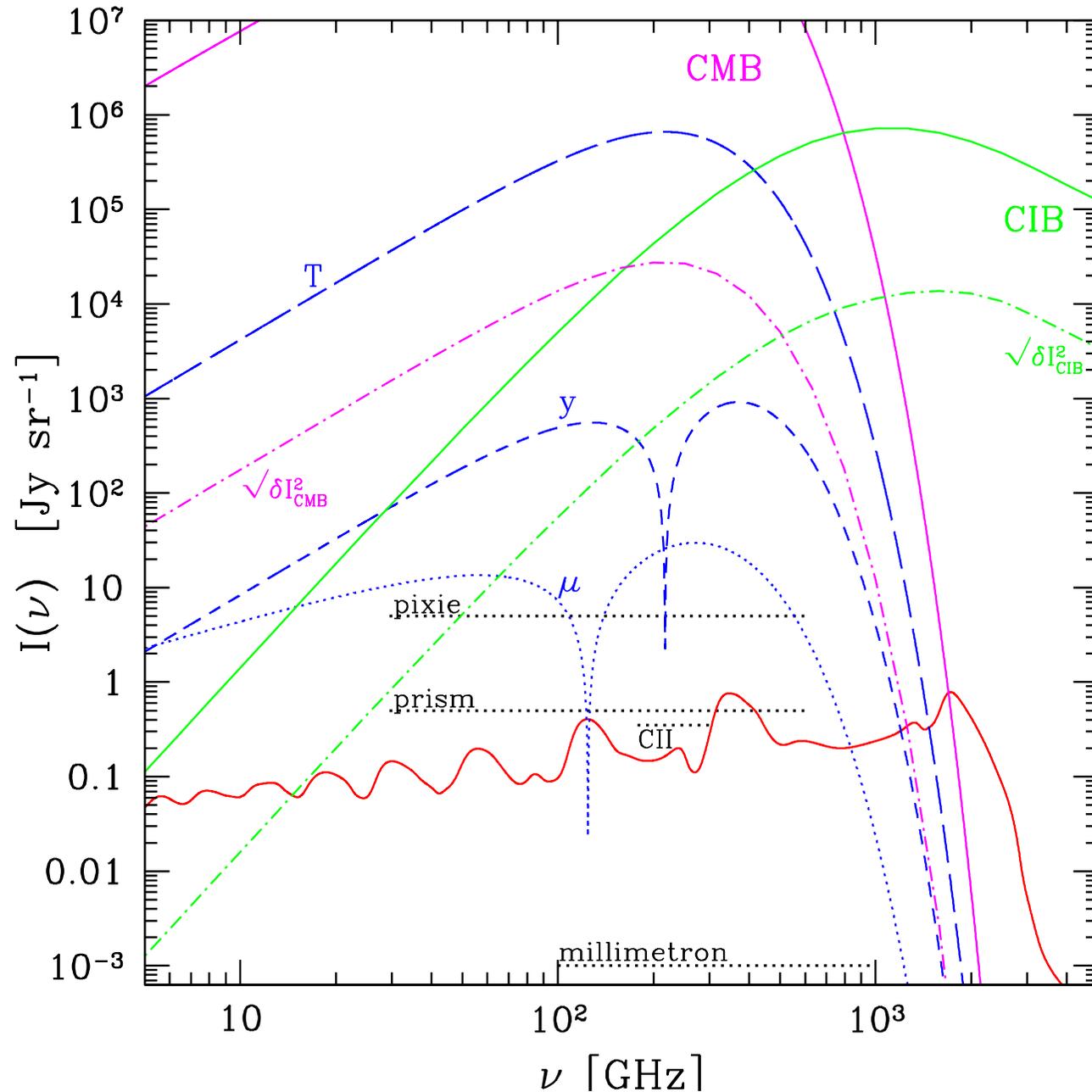
Details including bound-bound transitions



Foregrounds for CMB Spectral Distortion Measurements



Sample Signals and Sensitivities; 2 proposed experiments: Pixie & PRISM



Discussions

- **There is some science potential left in observations of CMB spectral distortions; Planck Spectrum conf.**
- **However, the science case is lacking substance. It is irresponsible and sloppy to suggest spending hundreds of millions and a thousand man years without first making a very strong scientific case.**
- **For example: for CMB polarization there are very good analyses with Fischer matrices of how the cosmological parameters would improve (x2), how lensing and B-mode affected, and what might be possible to learn from detecting B-mode polarization**
- **The science case for CMB spectral measurements is very weak and far from being serious analyses
Saying no CMB spectrum measurements in 20 years means great science potential is like saying no**