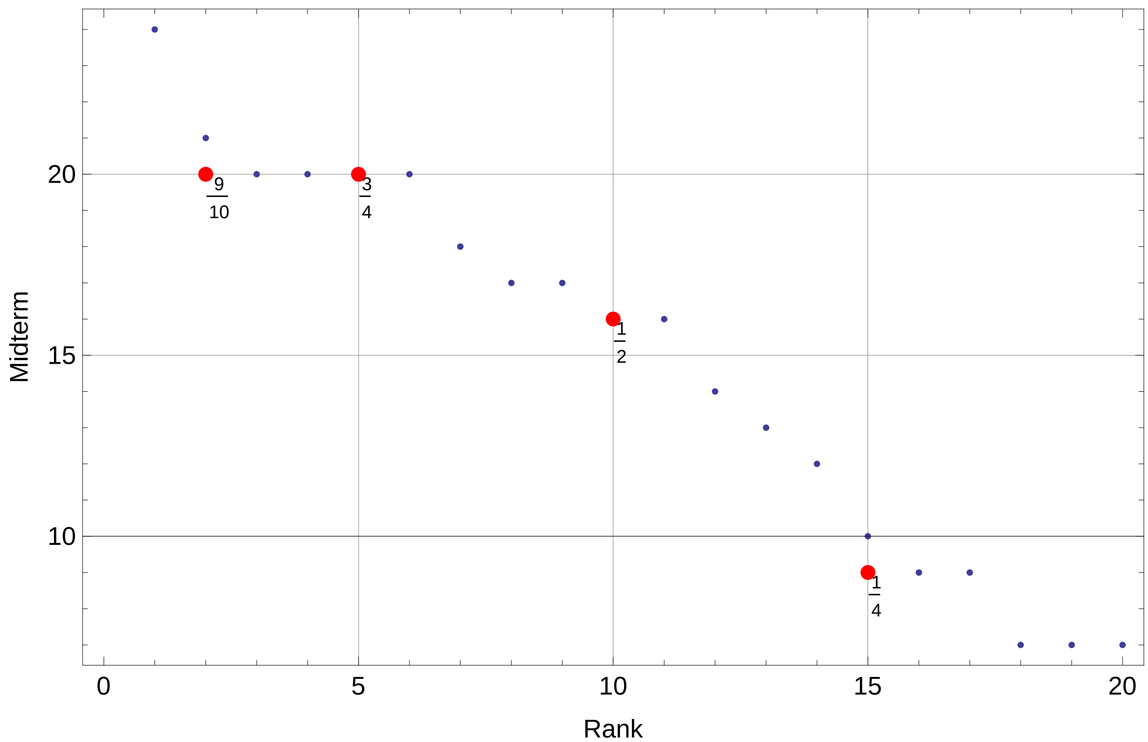
16 Feb 2012

21 Feb 2012

- Outline
  - Midterm
  - Why is the cosmic background radiation important for the history of the universe
  - Important events in the history of the universe
  - Anisotropies in the cosmic background radiation
  - WMAP satellite
  - Dipole anisotropy
  - Small-scale anisotropy
  - Sound waves

Midterm



	Mean
Q1	53%
Q2	55%
Q3	64%
Q4	46%
Midterm	53%

Why is the cosmic background radiation important for the history of the universe

Companion paper to Penzias and Wilson.
Dicke, Peebles, Roll, & Wilkinson, 1965, “Cosmic Black-body Radiation,” ApJ 142, 414.
“Could the universe have been filled with black-body radiation from this possible high-temperature state?

Black-body radiation

A wavelength characterizes black body radiation

$$\lambda = \frac{h\,c}{k\,T}.$$

Alternatively, Wien's Law. Peak of the spectrum in wavelength is

$$\lambda_{\text{peak}} = 2.9\,\text{mm}\,\frac{K}{T}$$

Temperature of the cosmic background radiation was hotter in the past

Because wavelengths expand with the universe, the wavelength of the black-body radiation increases with time and the temperature decreases.

The temperature of the radiation changes as a^{-1}.

Hotter radiation allowed different processes

Q: When a very distant gamma-ray burster sent its light out ($z = 8$), was the radiation hot enough to melt ice?

The temperature and characteristic energy in the past was very high. Processes that are not possible today were possible at one time.

Radiation dominated the mass density when the universe was younger

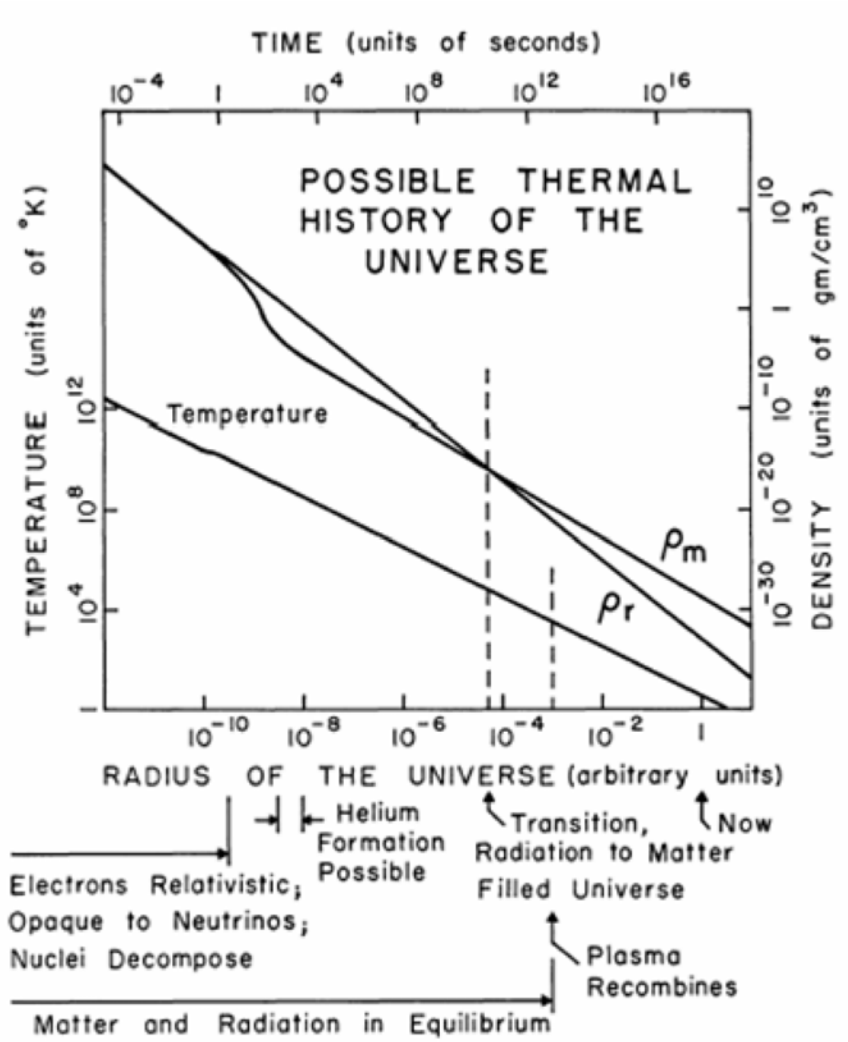
The mass-energy density changes

$$\rho_{\text{radiation}} \sim a^{-4}$$

whereas

$$\rho_{\text{pressureless matter}} \sim a^{-3}$$

a^{-4} always beats a^{-3} for small enough a. At early times, the radiation determines the expansion history of the universe.



■ Important events in the history of the universe

■ “Recombination”

Universe changes from ionized to neutral at T=3000K. $p + e^{-} \to H$

Q: What is the expansion parameter at recombination?

The ionization energy of hydrogen is 13.6eV=13.6×11600K/eV=160,000K. Why does recombination occur at such a low temperature? The density is so low that a free electron has to travel a long time to find a proton.

The cross section for scattering for free electrons is much higher than for bound electrons.

The universe was opaque before recombination.

The cosmic microwave background is a snapshot of the universe at recombination at 400 000 years.

■ **Helium forms**

The outer part of the sun is about 25% helium, 75% hydrogen, and 1% other elements by mass. How can helium be so abundant? The elements made in stars is 1% by mass.

Helium was made in the Big Bang.

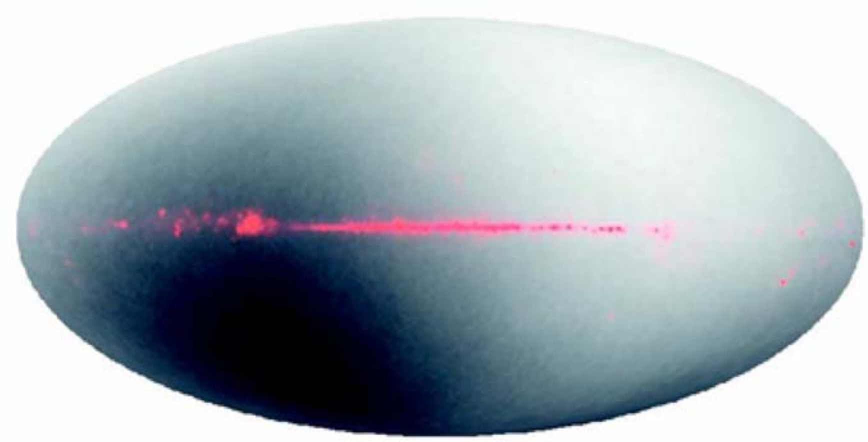
The early universe was too hot for nuclei (other than n and p) to exist.

At $a = 10^{-9}$, the universe became cool enough for deuterium to form through $n + p \to {}^2H$. Then ${}^4He$ and trace amounts of ${}^7Li$ and ${}^3He$ form.

Anisotropy of the cosmic background radiation

The universe is not completely uniform. When it was 400,000 years old, how nonuniform was it? Observing the CBR will provide an answer. One can hope to calculate how much a fluctuation grows in 400,000 years. Then one can determine the initial fluctuations.

WMAP satellite

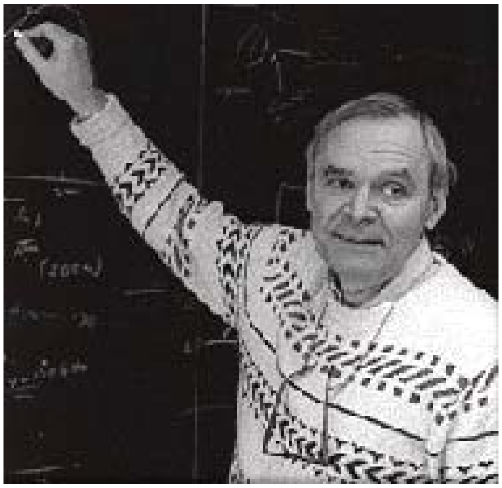


Temperature of the entire sky. Hottest spot is 3mK hotter than the average.
Pink is radiation of the Milky Way Galaxy, which has a different spectrum.

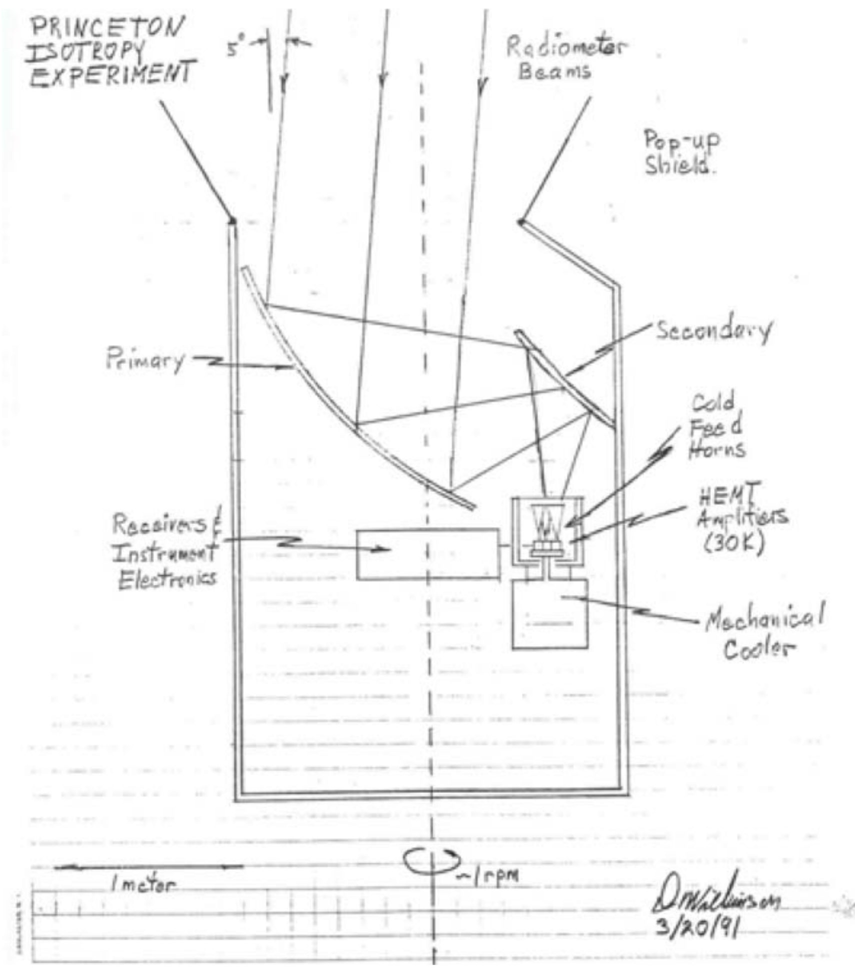
Measure spatial variations in temperature of the CBR

- Sensitivity is 35μK (a part in 100,000).
- Anything in the instrument even 0.0001K warmer is fatal.
- Symmetric design
- Record temperature difference between left & right channels. Temperature difference is small.
- Rotate entire instrument.

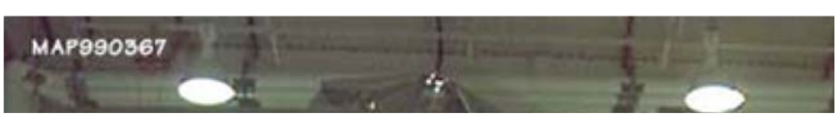
Q: What is the signature of a true signal in the sky and a signature of an instrumental problem?

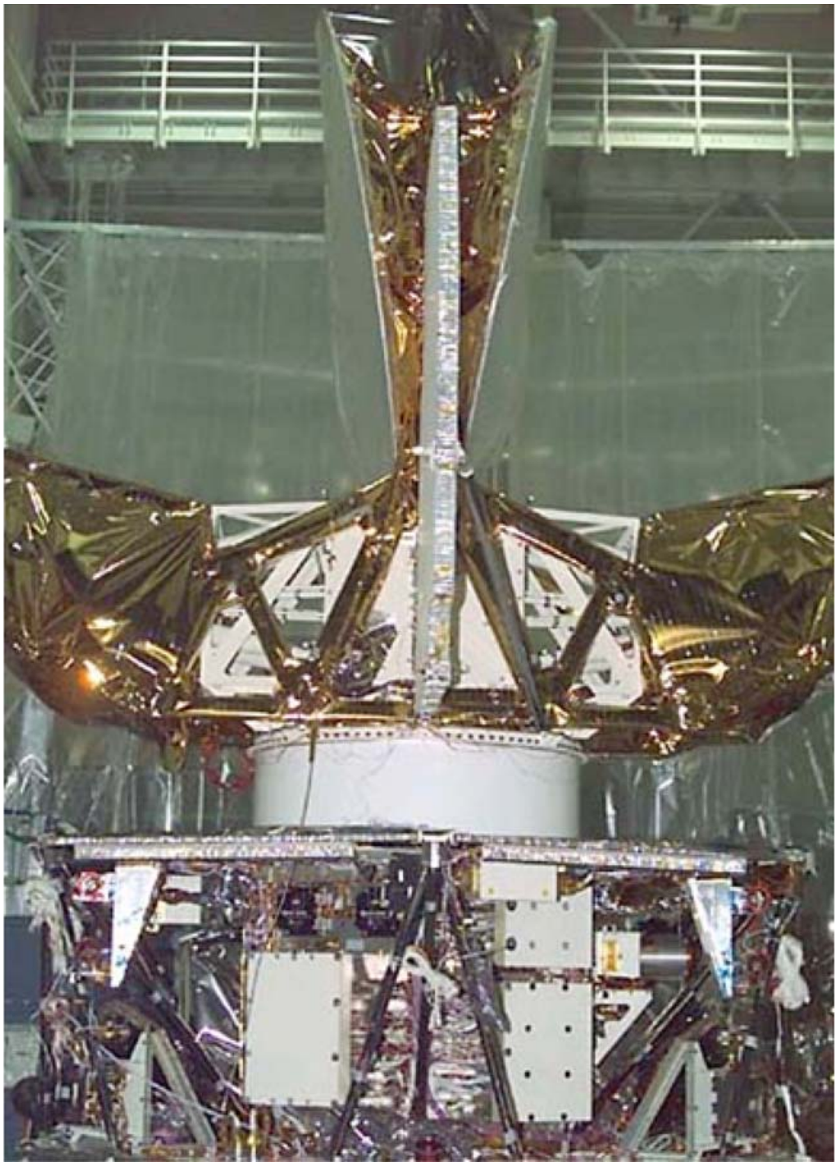


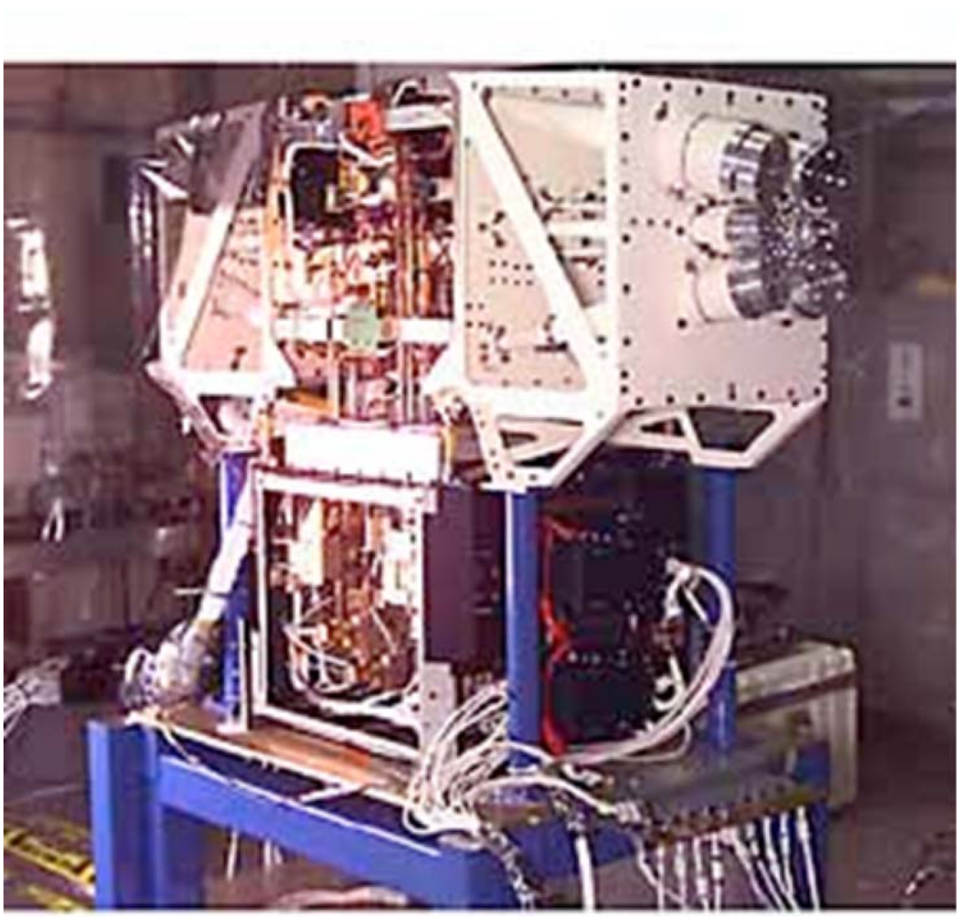
Dave Wilkinson
1935-2002, b. Hillsdale MI



Dave's notebook, (Greg Tucker)







Five wavelength bands.

Each assembly compares two regions of the sky separated by 140°.

Q: Why does each assembly compare two regions of the sky?

One assembly operates at 22 GHz, one at 30 GHz, two at 40 GHz, two at 60 GHz, and four at 90 GHz.

Q: Why is there only one assembly at 22GHz yet there are four at 90GHz?

23 Feb