

Astro215hf  
CMB Experiments, Surveys and  
Analysis  
Lecture 1

Clem Pryke

Feb 9 2016

# Modern cosmology in a nutshell:



Edwin Hubble

1) The universe is expanding.  
(Hubble, 1920s)

2) It was once hot and dense, like the inside of the Sun.

(Alpher, Gamow, Herman, 1940s)

3) You can still see the glow!  
*The Cosmic Microwave Background*  
(Penzias & Wilson, 1964)



Bob Wilson & Arno Penzias  
1978 Nobel Prize

⇒ acceptance of the “HOT BIG BANG”

# Hubble and the expanding Universe

- In the 1920's discovery that Universe is expanding

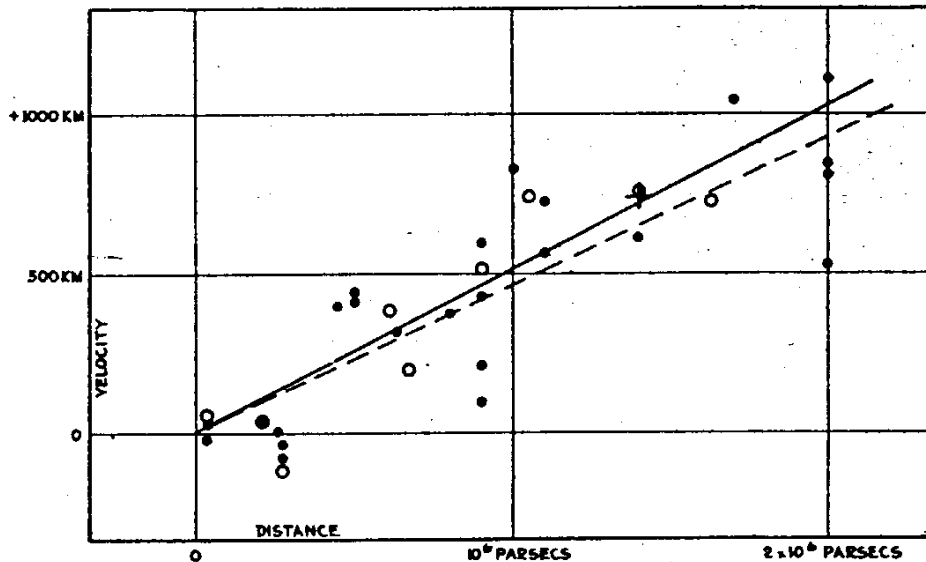
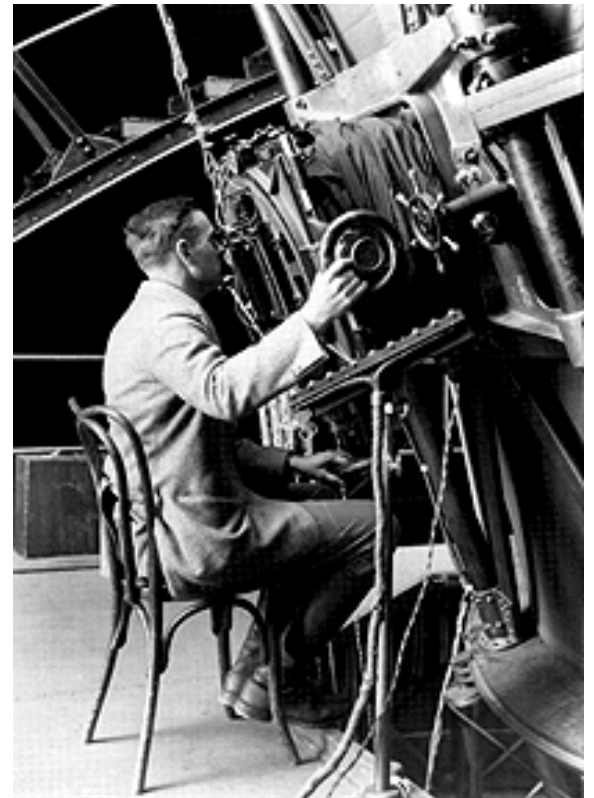


FIGURE 1



# Birth of Big Bang Nucleosynthesis

- In late 1940's Gamow, Alpher and Hermann were developing theories of element formation by neutron capture in first few minutes after big bang
- Implicit that thermal photon field present...



# BB Radiation in expanding universe

- The Planck function specifies not just the distribution, but also the absolute number density of photons in a thermal radiation field
- The energy density in  $\text{J m}^{-3} \text{ Hz}^{-1}$  is

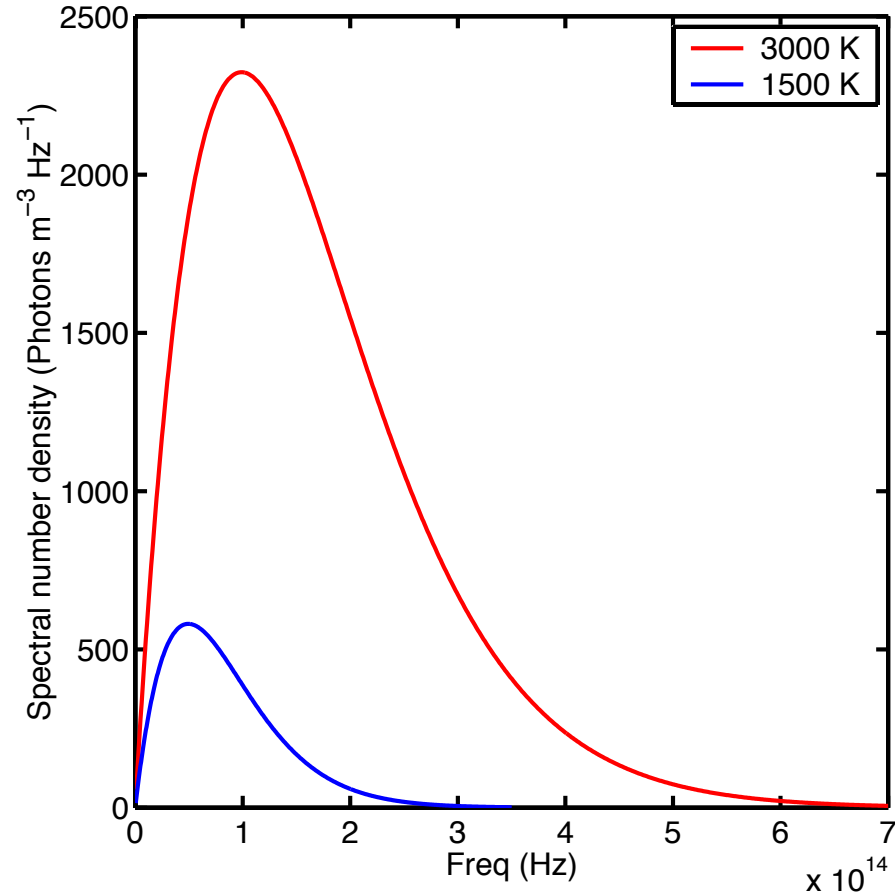
$$I(\nu) = \frac{8\pi h\nu^3}{c^3} \frac{1}{e^{h\nu/kT} - 1}$$

- Dividing by the energy per photon  $E = h\nu$  the photon number density in ptcles.  $\text{m}^{-3} \text{ Hz}^{-1}$  is

$$I(\nu) = \frac{8\pi\nu^2}{c^3} \frac{1}{e^{h\nu/kT} - 1}$$

# BB Radiation in expanding universe

- Stretch space by factor 2:
  - Each photon goes to  $\nu/2$
  - Each bin in Hz now has twice as many...
  - ...but diluted into 8x the space
- Net effect of this is the same as T goes to  $T/2$
- If it was anything other than  $\nu^2$  the photon field would not remain thermal

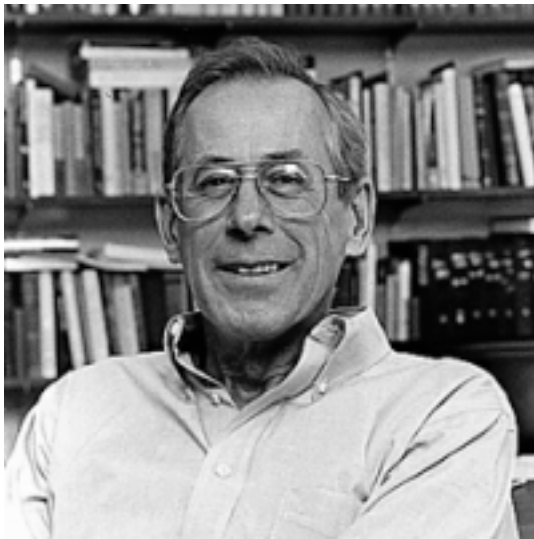


# Conference at Princeton last summer:

## cosmic microwave background

2015 june | 10 - 12 | princeton university

@50



- Jim Peebles gave a talk
- Emphasized that this was first pointed out by Tolman in 1934

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Beltsville, New Jersey, at 4080 Mc/s have yielded a value about 1.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and

free from seasonal variations (July, 1964-April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter in this issue.

The total antenna temperature measured at the zenith is 6.7° K, of which 2.5° K is due to atmospheric absorption. The calculated contribution due to ohmic losses in the antenna and back-lobe response is 0.9° K.

The radiometer used in this investigation has been described elsewhere (Penzias and Wilson 1965). It employs a traveling-wave mixer, a low-loss (1027-db) coupler, and a signal helium-cooled reference termination (Penzias 1965). Measurements were made by switching manually between the antenna input and the reference termination. The antenna, reference termination, and radiometer were well matched so that a round-trip return loss of more than 55 db existed throughout the measurement; thus errors in the measurement of the effective temperature due to impedance mismatches can be neglected. The estimated error in the measured value of the total antenna temperature is 0.3° K and comes largely from uncertainty in the absolute calibration of the reference termination.

The contribution to the antenna temperature due to atmospheric absorption was obtained by recording the variation in antenna temperature with elevation angle and employing the secant law. The result,  $2.5 \pm 0.2^\circ \text{K}$ , is in good agreement with published values (Hogg 1959; Heitram, Hogg, Ohm, and Lovell 1959; Ohm 1961).

The contribution to the antenna temperature from ohmic losses is computed to be  $0.8^\circ \pm 0.4^\circ \text{K}$ . In this calculation we have divided the antenna into three parts: (1) two non-uniform tapes approximately 1 m in total length which transform between the 11-inch round output waveguide and the 6-inch-square antenna throat opening; (2) a double-choke rotary joint located between these two tapers; (3) the antenna itself. Care was taken to clean and align joints between these parts so that they would not significantly increase the loss in the structure. Appropriate tests were made for leakage and loss in the rotary joint with negative results.

The possibility of losses in the antenna horns due to imperfections in its seams was eliminated by means of a taping test. Taping all the seams in the section near the throat and most of the others with aluminum tape caused no observable change in antenna temperature.

The back-lobe response to ground radiation is taken to be less than 0.2° K for two reasons: (1) Measurements of the response of the antenna to a small transmitter located on the ground in its vicinity indicate that the average back-lobe level is more than 30-db below isotropic response. The horn-reflector antenna was pointed to the zenith for these measurements, and complete rotations in azimuth were made with the transmitter in each of ten locations using horizontal and vertical transmitted polarization from each position. (2) Measurements on smaller horn-reflector antennas at these laboratories, using pulsed measuring sets on flat antenna apertures, have consistently shown a back-lobe level of 30 db below isotropic response. Our larger antenna would be expected to have an even lower back-lobe level.

From a combination of the above, we compute the remaining unaccounted-for antenna temperature to be  $3.5^\circ \pm 1.0^\circ \text{K}$  at 4080 Mc/s. In connection with this result it should be noted that DeGraess et al. (1959) and Ohm (1961) give total system temperatures at 5650 Mc/s and 2390 Mc/s, respectively. From these it is possible to infer upper limits to the background temperatures at these frequencies. These limits are, in both cases, of the same general magnitude as our value.

We are grateful to R. H. Dicke and his associates for helpful discussions of their results prior to publication. We also wish to acknowledge with thanks the useful comments and advice of A. B. Crawford, D. C. Hogg, and E. A. Ohm in connection with the problems associated with this measurement.

Note added in proof.—The highest frequency at which the background temperature of the sky had been measured previously was 404 Mc/s (Pauliny-Toth and Shkashnik 1962), where a minimum temperature of 10° K was observed. Combining this value with our result, we find that the average spectrum of the background radiation over this frequency range can be no steeper than  $kT$ . This clearly eliminates the possibility that the radiation we observe is due to radio sources of types known to exist, since in this event, the spectrum would have to be very much steeper.

A. A. Penzias  
R. W. Wilson

May 13, 1965

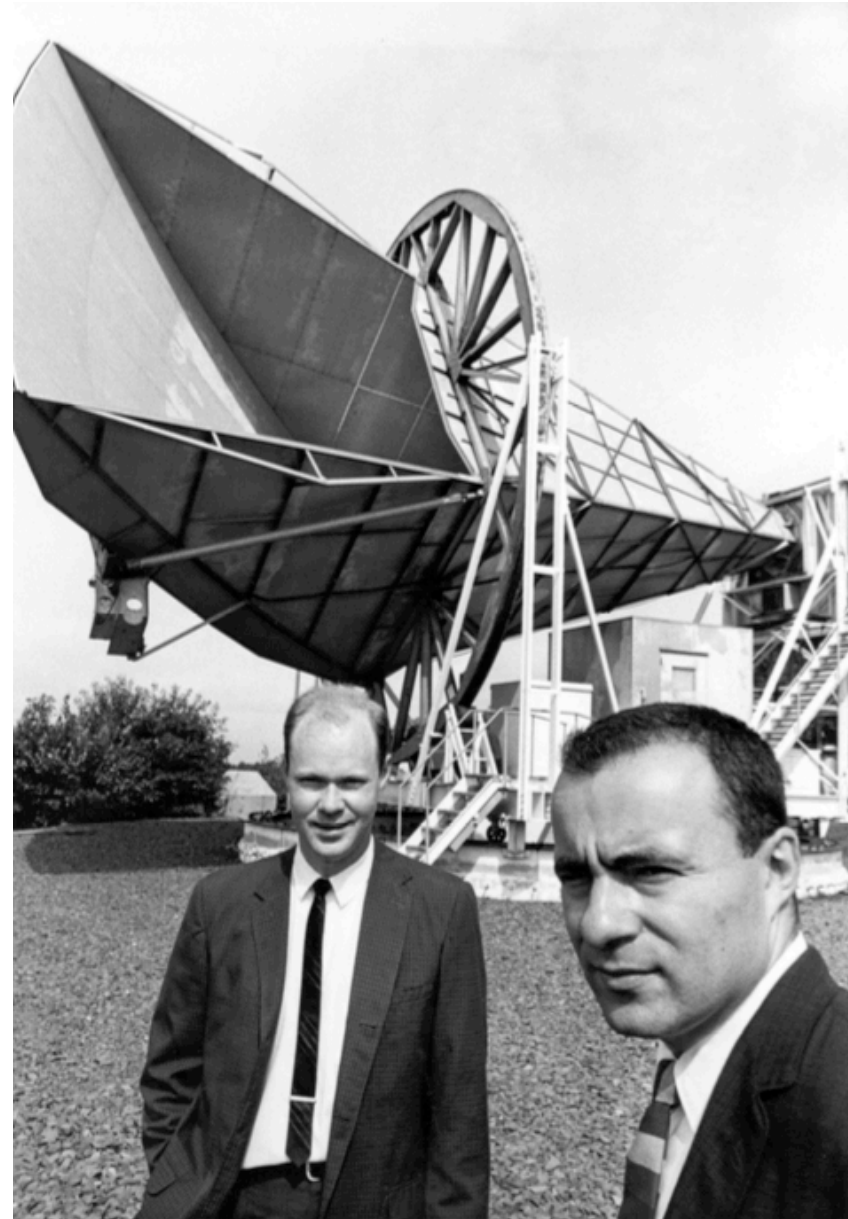
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CRAWFORD HILL, BELTSVILLE, NEW JERSEY

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# Penzias and Wilson 1965

- Fresh radio astronomy PhD's
- Found excess isotropic signal
- Turned out to be CMB!
- Paper is a letter



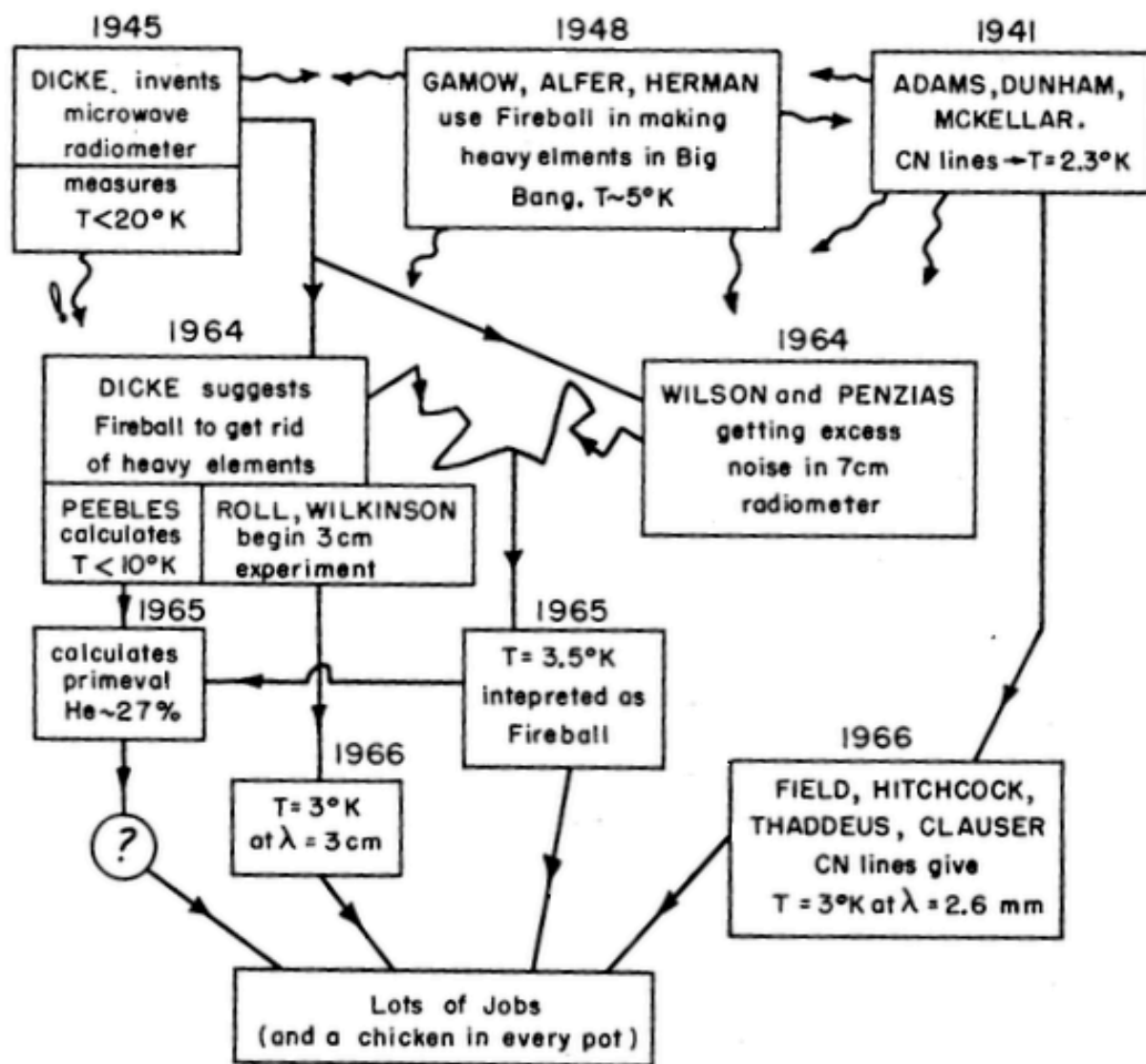


# Finding the CMB

CMB@50

June 2015

PJE Peebles



The negative for this figure is marked December 1966.