The First Three Minutes
Meeting 4

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February 3, 2021

Meeting 4 – The Cosmic Microwave Background

- Announcements
- Discussion of III The CMB
  - Measurement of the CMB and what is means
- Break
- Black body radiation
  - Temperature and thermal motion
  - Photons and states
  - Thermal equilibrium
  - CMB sky surveys
  - Lumpiness

Announcements

- Notes, slides, etc. on website, tinyurl.com/firstthreeminutes
- Please read Chapter IV for next week
- Questions
  - Future of the universe – does expansion stop?
  - Temperature and radiation emission
  - Transparency of the universe

From last time - Expansion

z	a	v/c	Time Since start of Universe
0.	1.	0.	13.8 Gyr
1.	0.5	0.6	4.89 Gyr
2.8	0.26	0.87	1.87 Gyr
4.4	0.19	0.93	1.1 Gyr
6.3	0.14	0.96	0.701 Gyr
10.	0.091	0.98	0.379 Gyr

Main result: Hubble law relates time, distance, and velocity, so we can use *a, z, v/c,* and time interchangably.

Pros use *z*, observable.

Chapter III – Cosmic Microwave Background Radiation

"Light from the Big Bang", released at 377,000 y when hydrogen formed

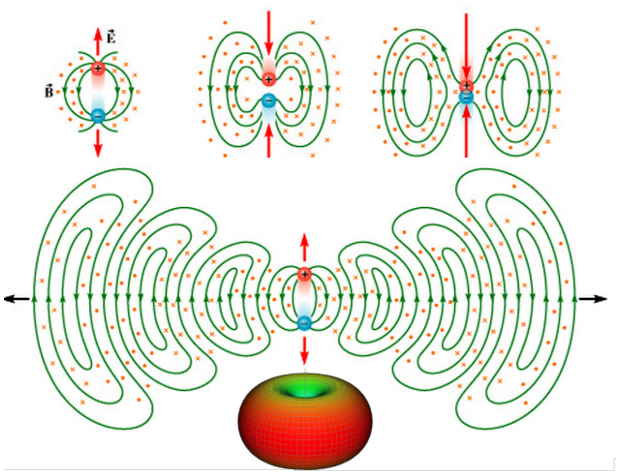
Detected in 1963, major source of information ever since.

Second major piece of evidence for Big Bang

Interaction of light and matter

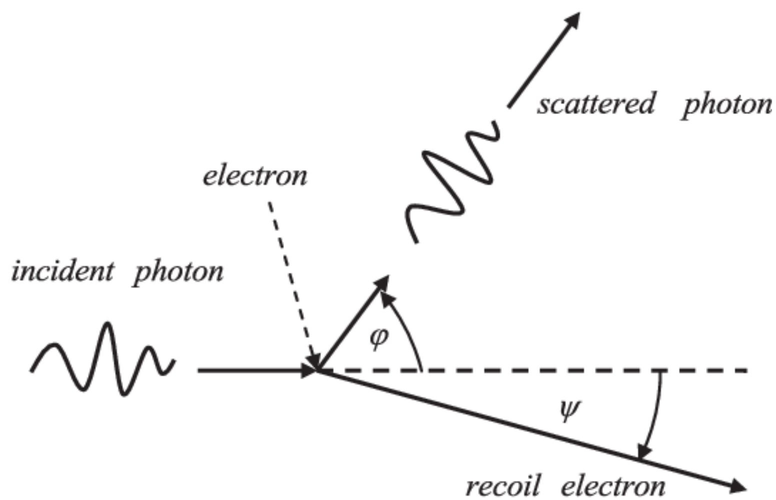
Two rules:

1. Accelerating charged particles create light (radiation)



Electromagnetic Radiation from Oscillating Dipole

2. Light bounces off or “scatters” from charged particles



Energy unit – the electron volt

- Energy of photons:

  Red: 1.65-2.01 eV

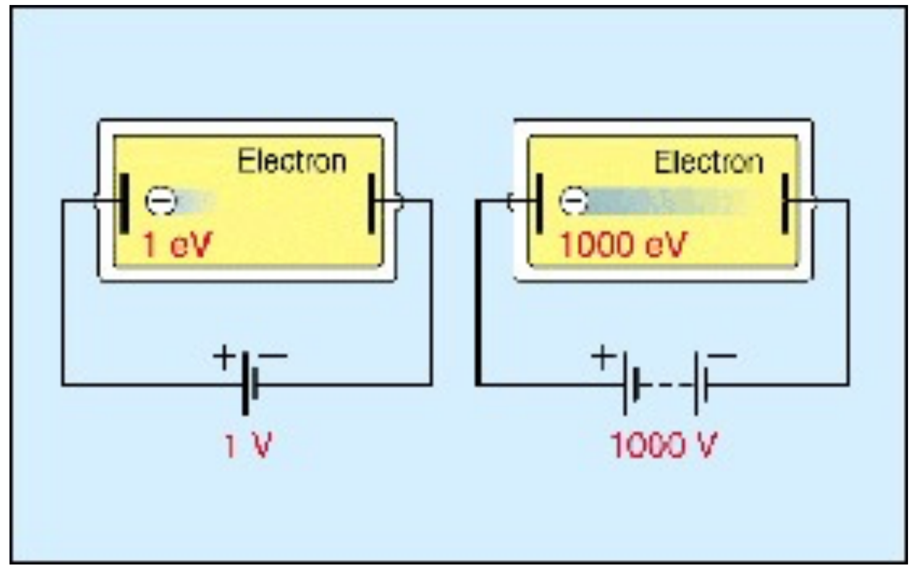
  Green: 2.21-2.49 eV

  Blue: 2.57-2.76 eV

- Masses

  proton: 938 MeV/c^2

  electron: 0.511 MeV/c^2



After nuclei form:

At t=5 min, the universe is composed of p, He, (Li), $e^{+/-}$, γ, ν

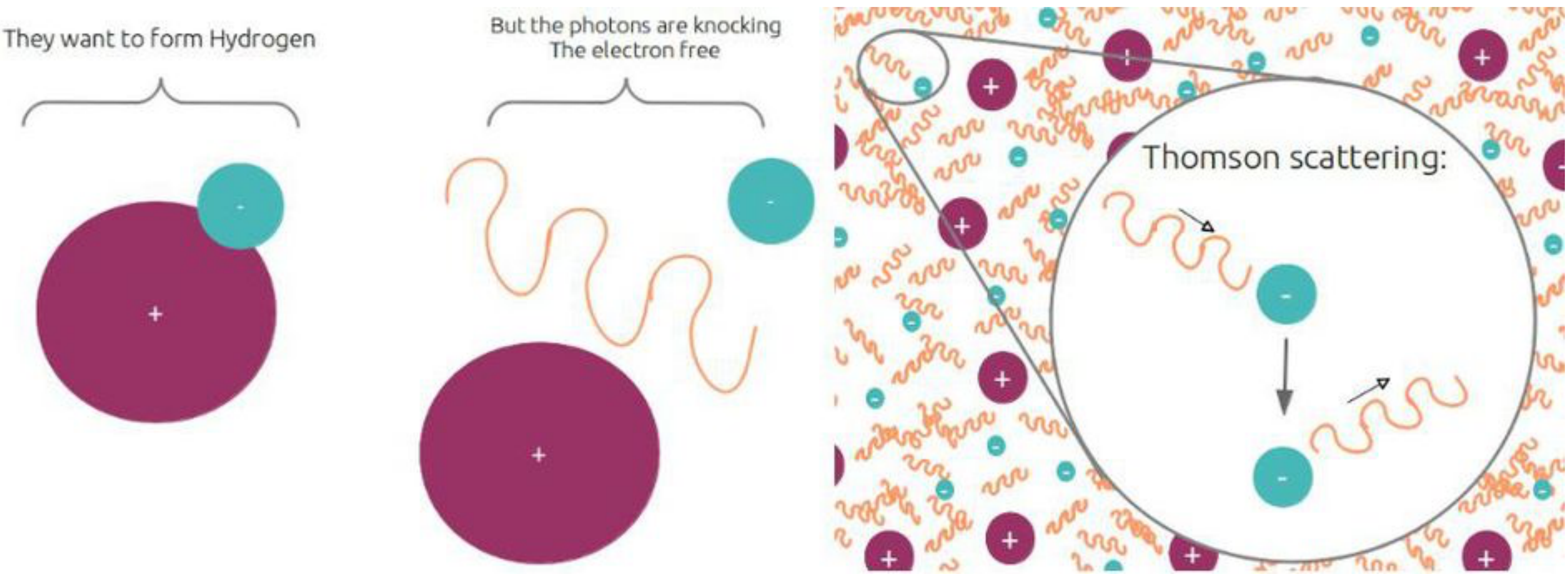
T=6 MK, average thermal energy of 54 keV

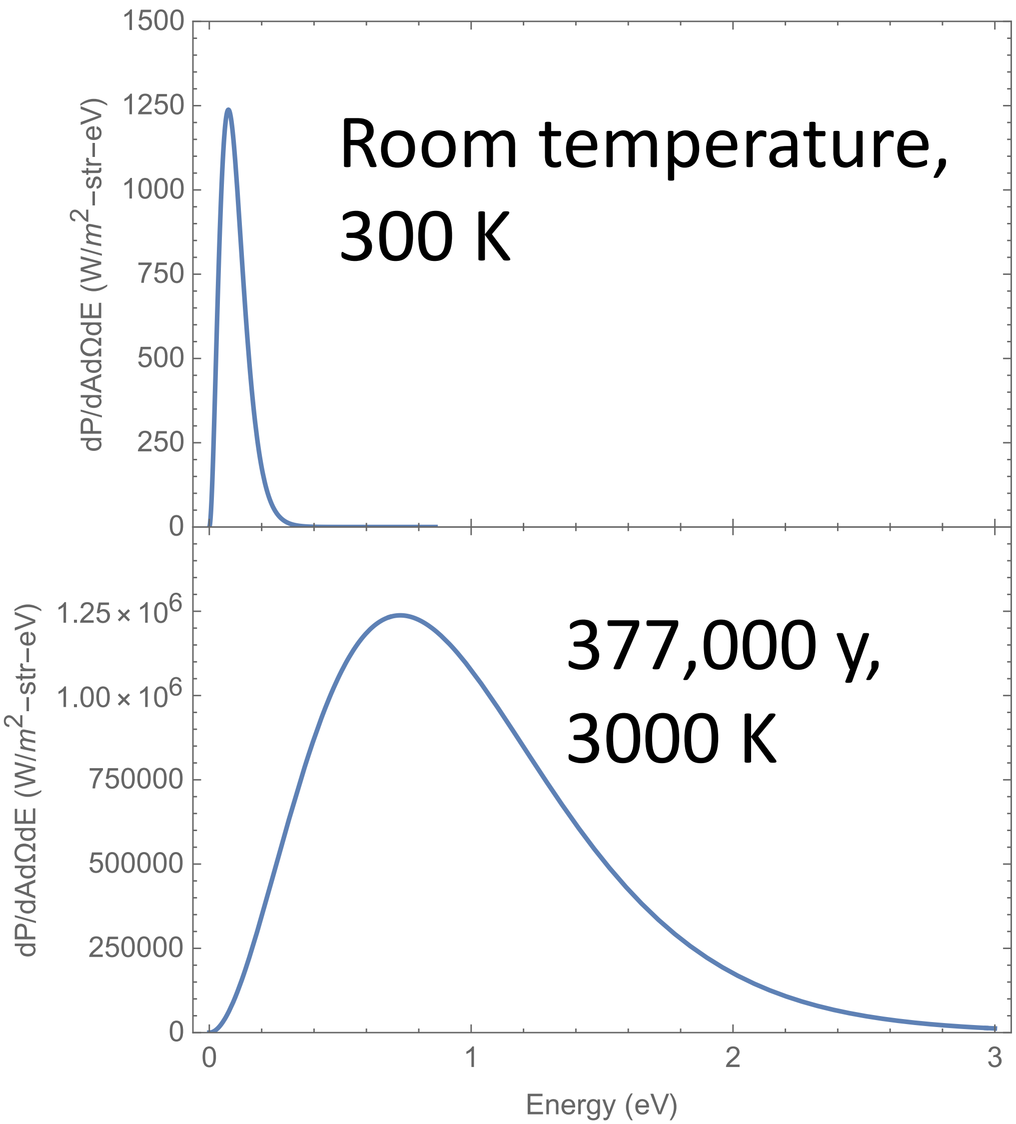
At this temperature, the electrons cannot bind to the protons to make hydrogen.

The resulting state of matter is called a plasma

CMBR (cont.)

At t=5 min, unbound electrons, positrons, and protons scattered the photons, effectively trapping them.





When confined in the plasma, the particles and photons are in thermal equilibrium (same temperature).

The photons have a characteristic spectrum called the black body spectrum.

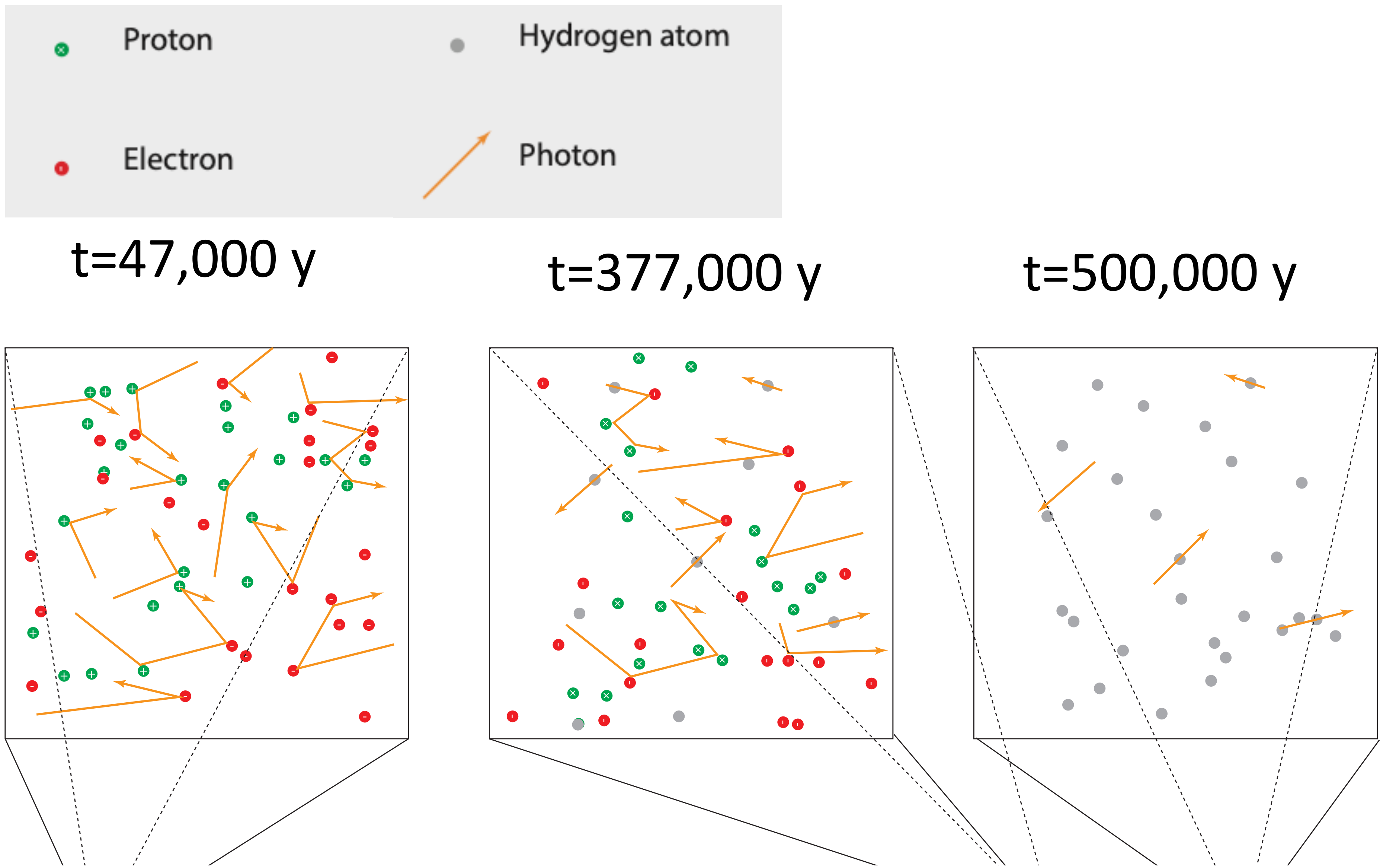
More on this later…

CMBR (cont.)

The universe expanded and cooled. The expansion stretched the photons, lowering their energy.

At 47,000 y, the temperature is 7,400 K and the energy density of the particles (p, He, e) equals the energy density of the photons.

At 377,000 y, the temperature is 2,610 K and the electrons are mostly bound to the protons and He. The universe has become electrically neutral.


Proton
Hydrogen atom
Electron
Photon
t=47,000 y
t=377,000 y
t=500,000 y

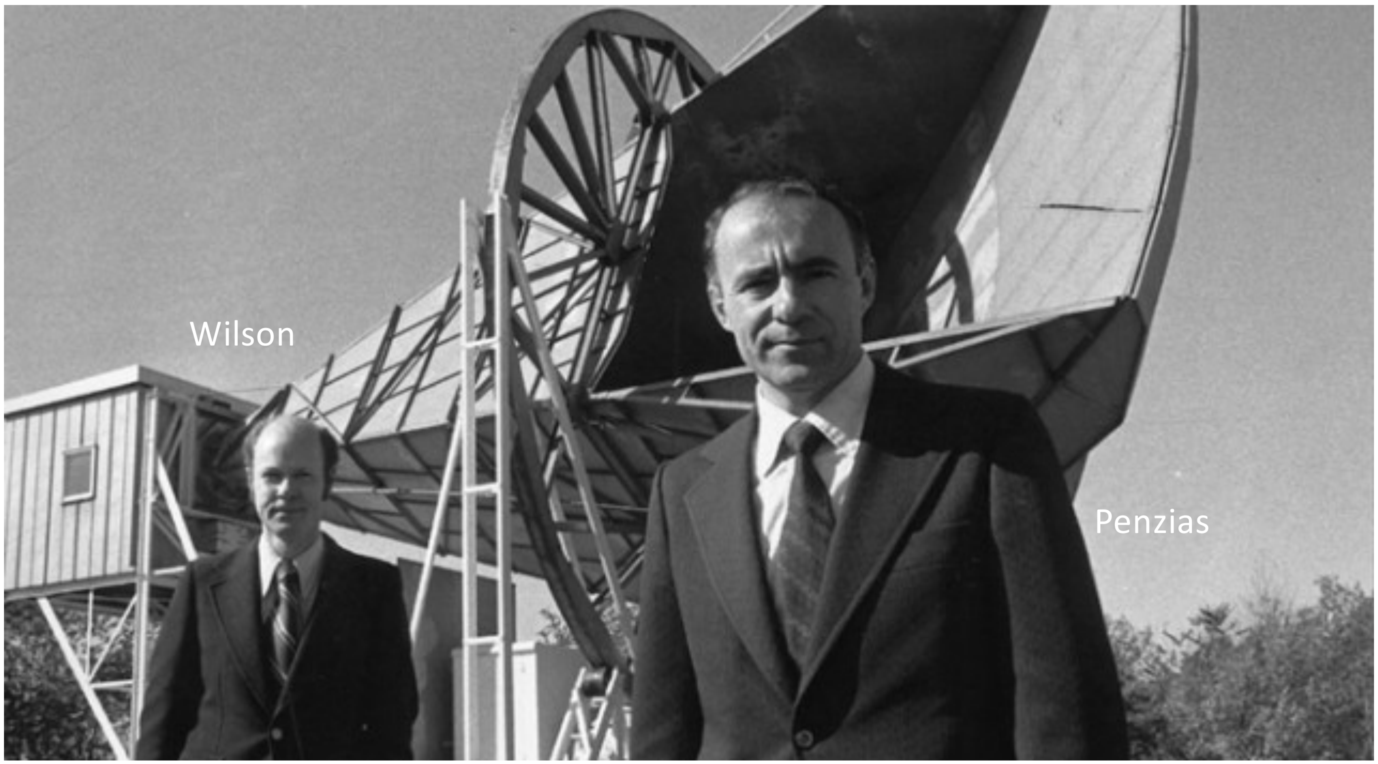
CMBR (cont.)

When neutral hydrogen formed, the photons no longer had charged particles to scatter from – they were no longer in equilibrium – they had decoupled.

The photons had a black-body spectrum with T=2,600 K.

They travelled 13.6 Gy, during which time the waves stretched by a factor of 1,100 from the expansion of the universe. The CMB now has a temperature of 2.7 K.

Observation



Penzias and Wilson, 1963 at the Holmdale antenna

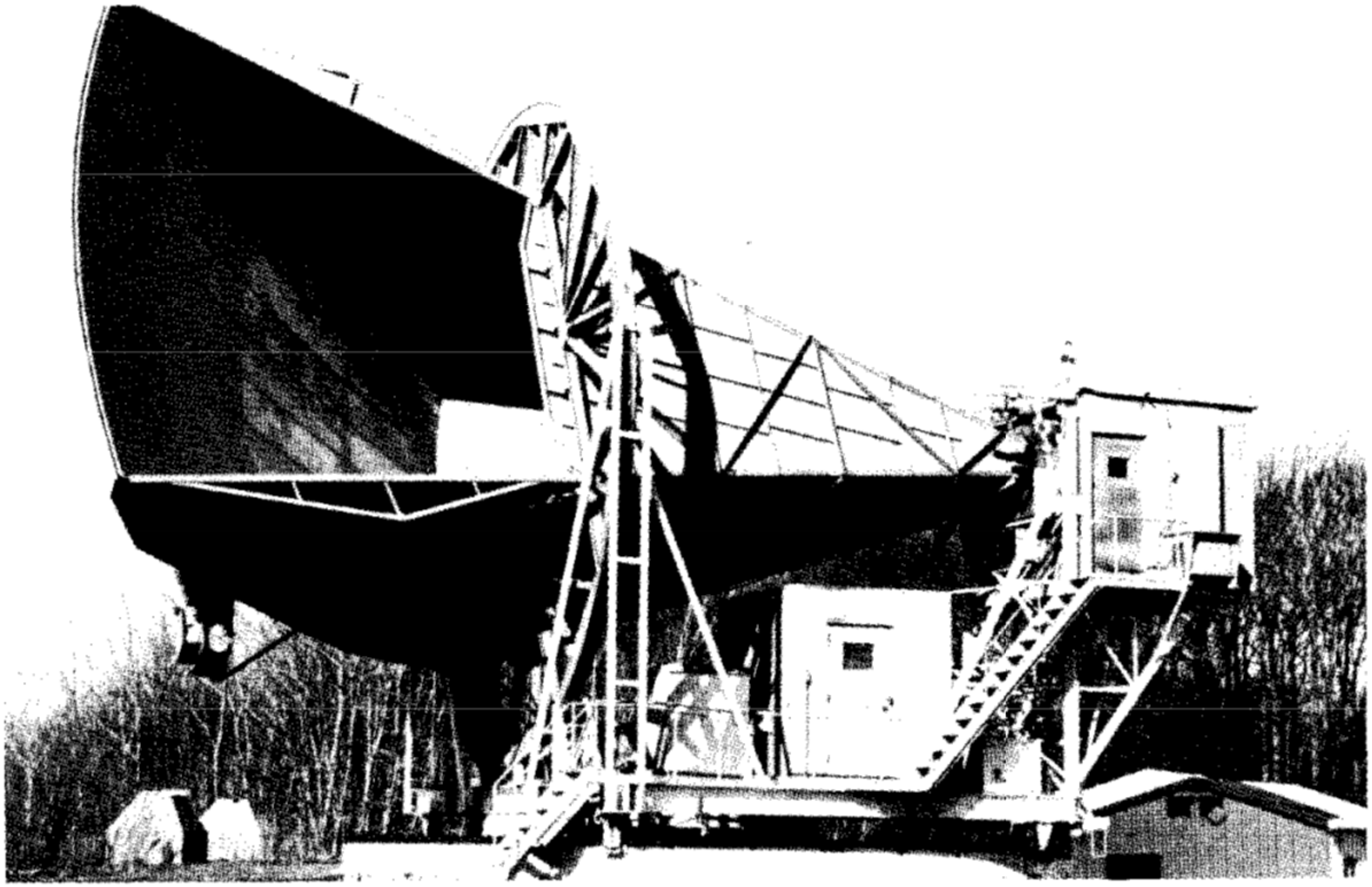
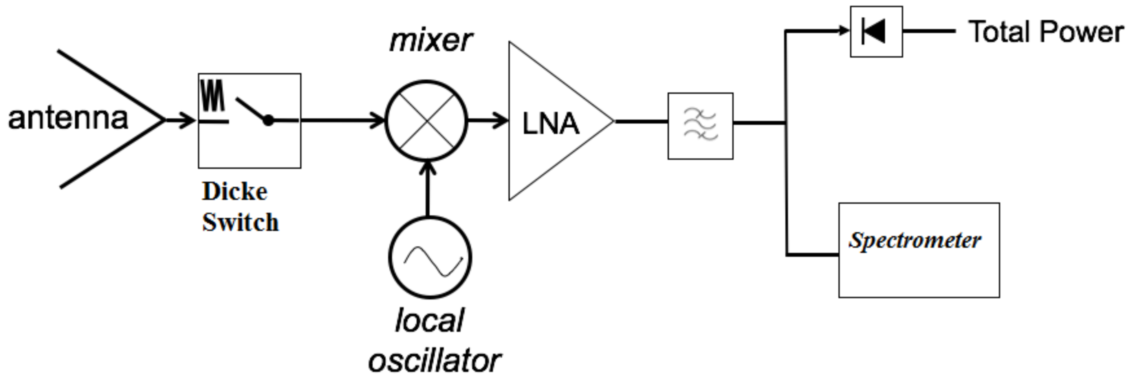


Fig. I The 20 foot horn-reflector which was used to discover the Cosmic Microwave Background Radiation.



Bob Dicke

Detects 63 zW

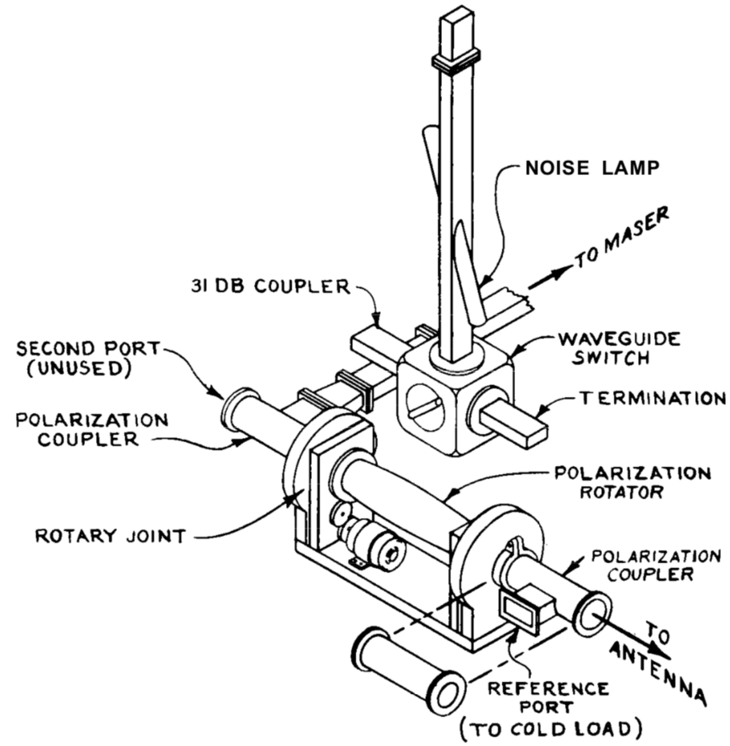


Fig. 3 The switching and calibration system of our 7.35 cm radiometer, The reference port was normally connected to the helium cooled reference source through a noise adding attenuator.

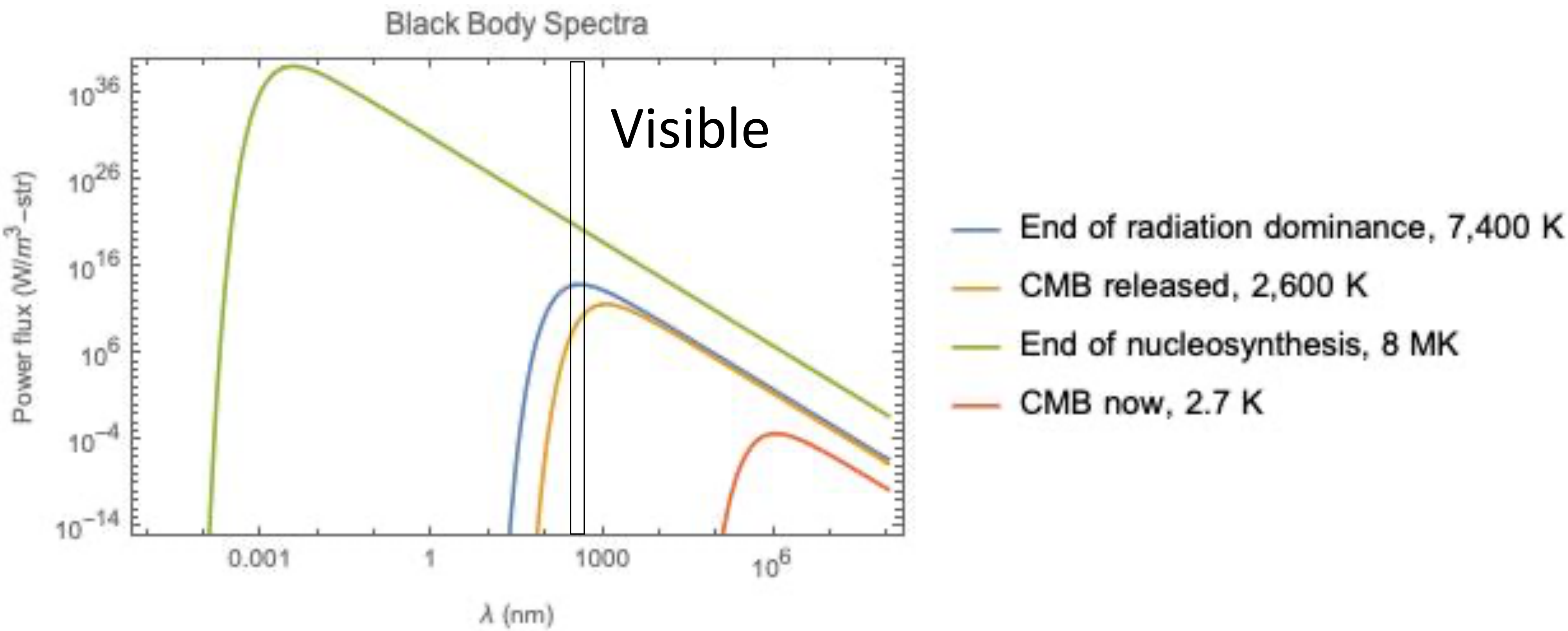
1 W=1,000,000,000,000,000,000,000 WZ

Princeton
3.2 cm

5 m Break

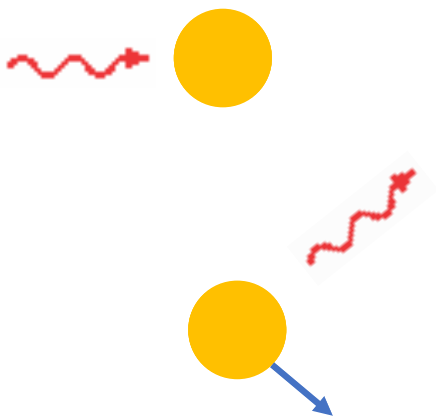
Black body spectrum

- Independent of material
- Total power output proportional to T^4

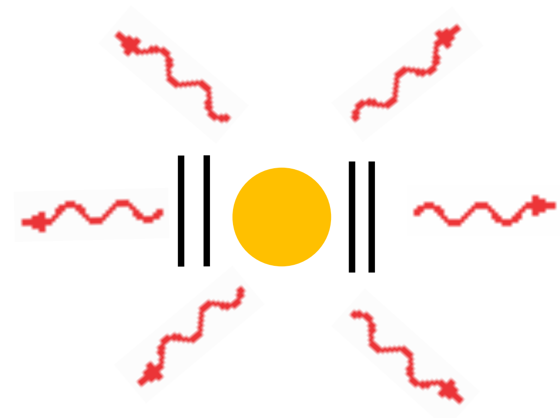


Interaction of Light with Matter

Scattering



Radiation



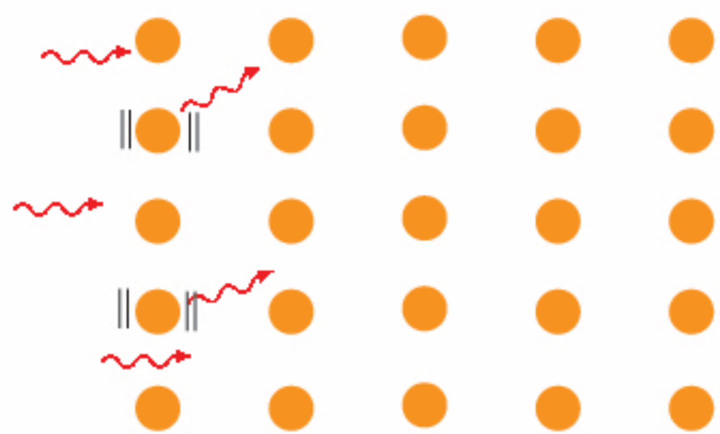
Vibration is acceleration

Lattice of atoms form a solid material – the interactions between the atoms hold them in place as if by springs

If displaced slightly and released, the atoms will oscillate back and forth and radiate.

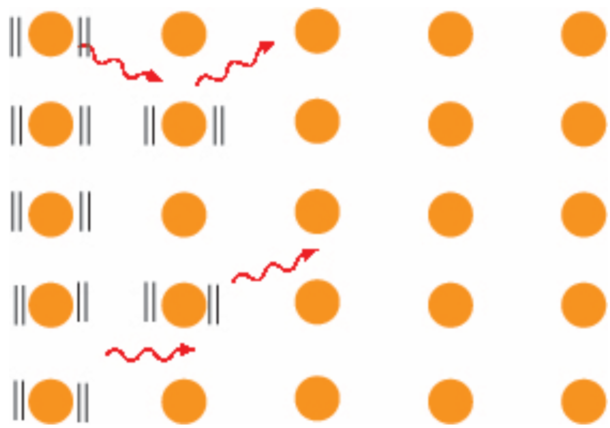
In a room, T=300 K, light of many different frequencies impinging on the lattice

Some of the atoms get hit by light, which bounces off (Thompson scattering). The atom gets pushed a little and vibrates.



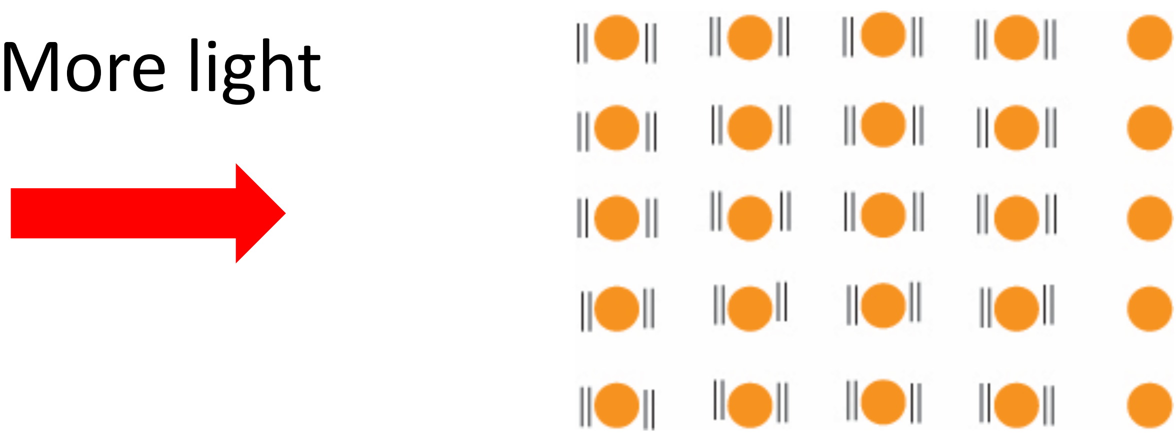
More atomics get hit and begin to vibrate. Atoms next to vibrating atoms begin to vibrate.

More light



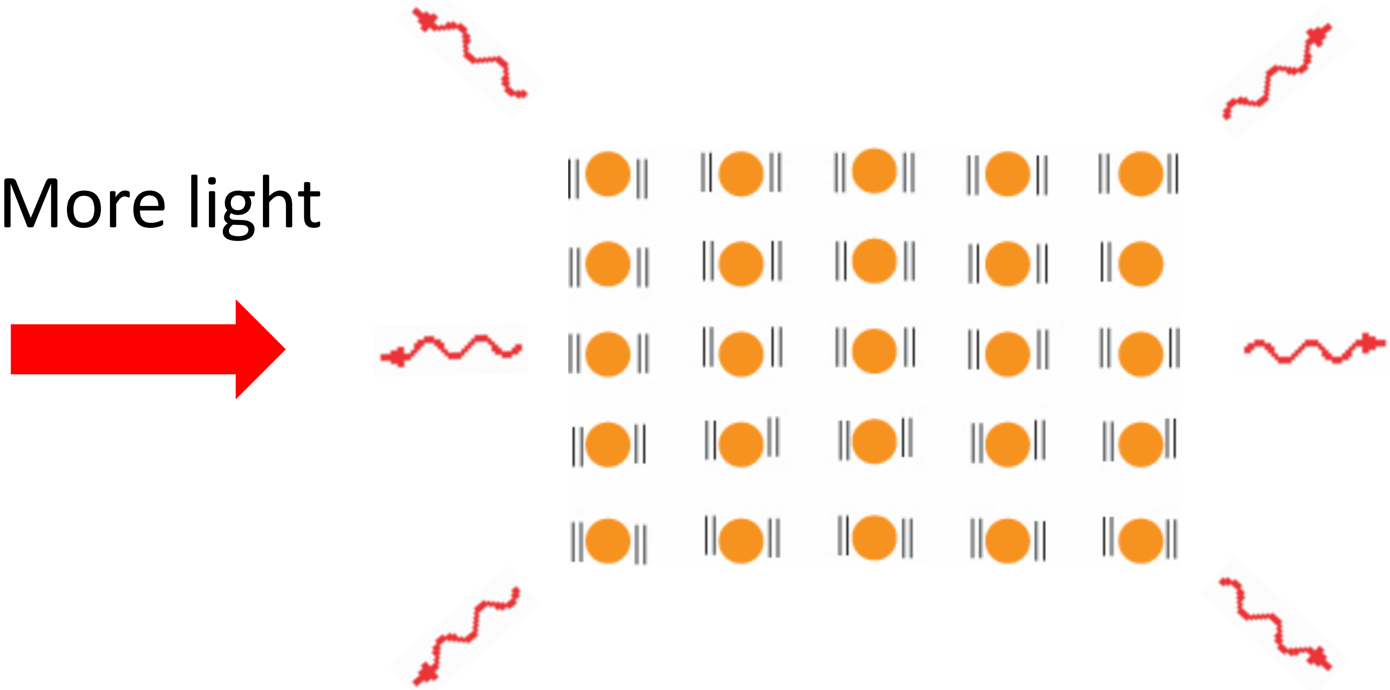
The vibrations spread throughout the material.

More light



Eventually, all the atoms are vibrating the same amount and radiating energy.

More light

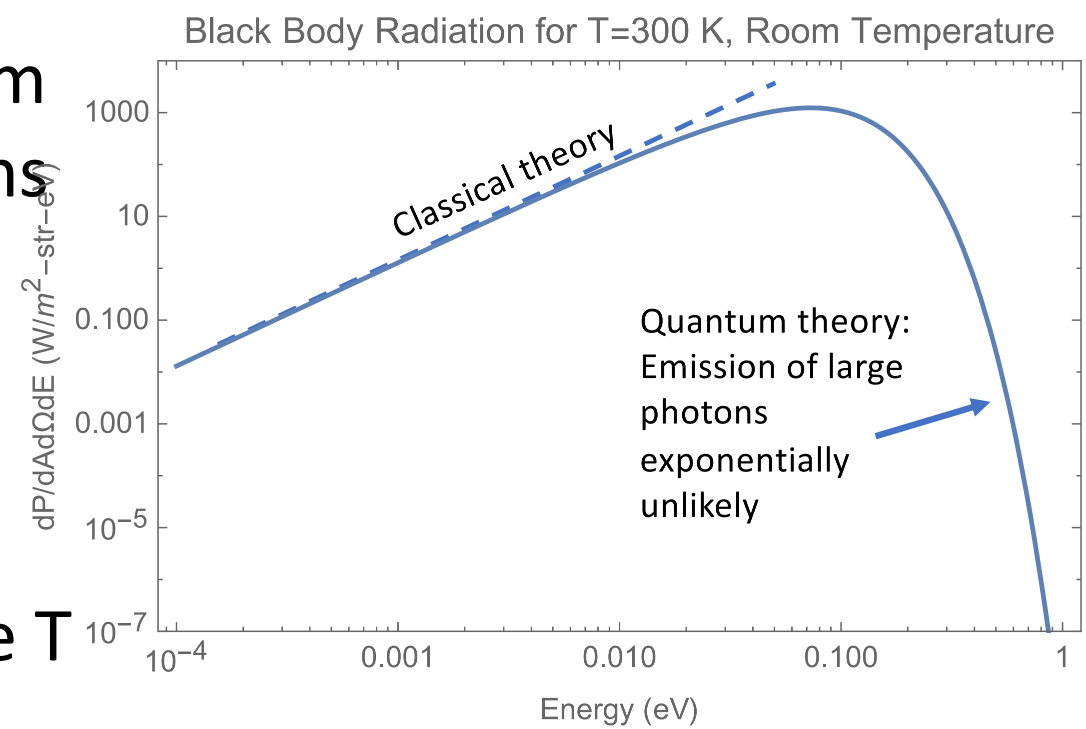


The radiated light energy equals the light energy coming in.

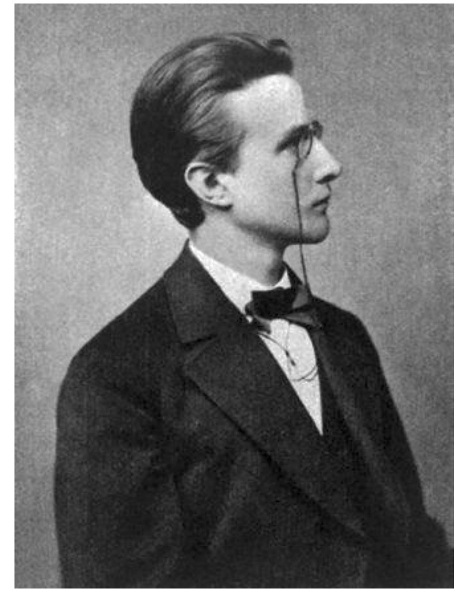
Spectrum

The radiation spectrum from a material of vibrating atoms is

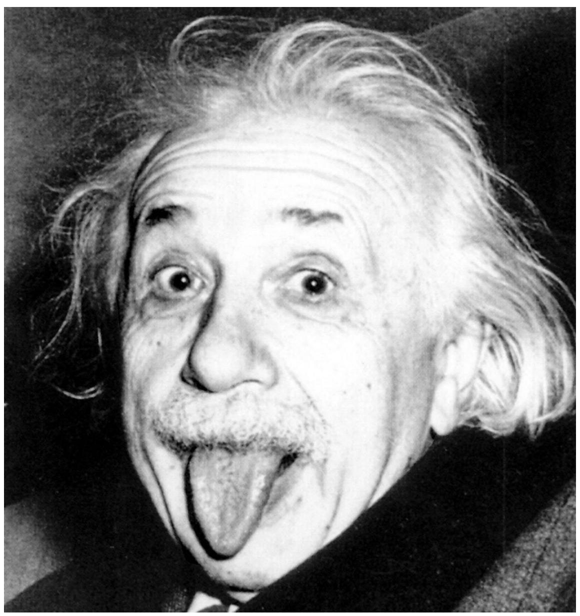
- Independent of the material
- Characterized by a single quantity, the temperature T
- Inherently quantum mechanical



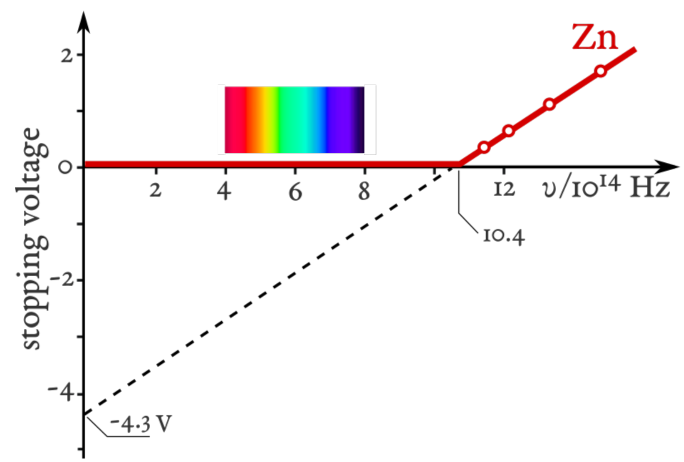
Max Planck, 1894, black body problem

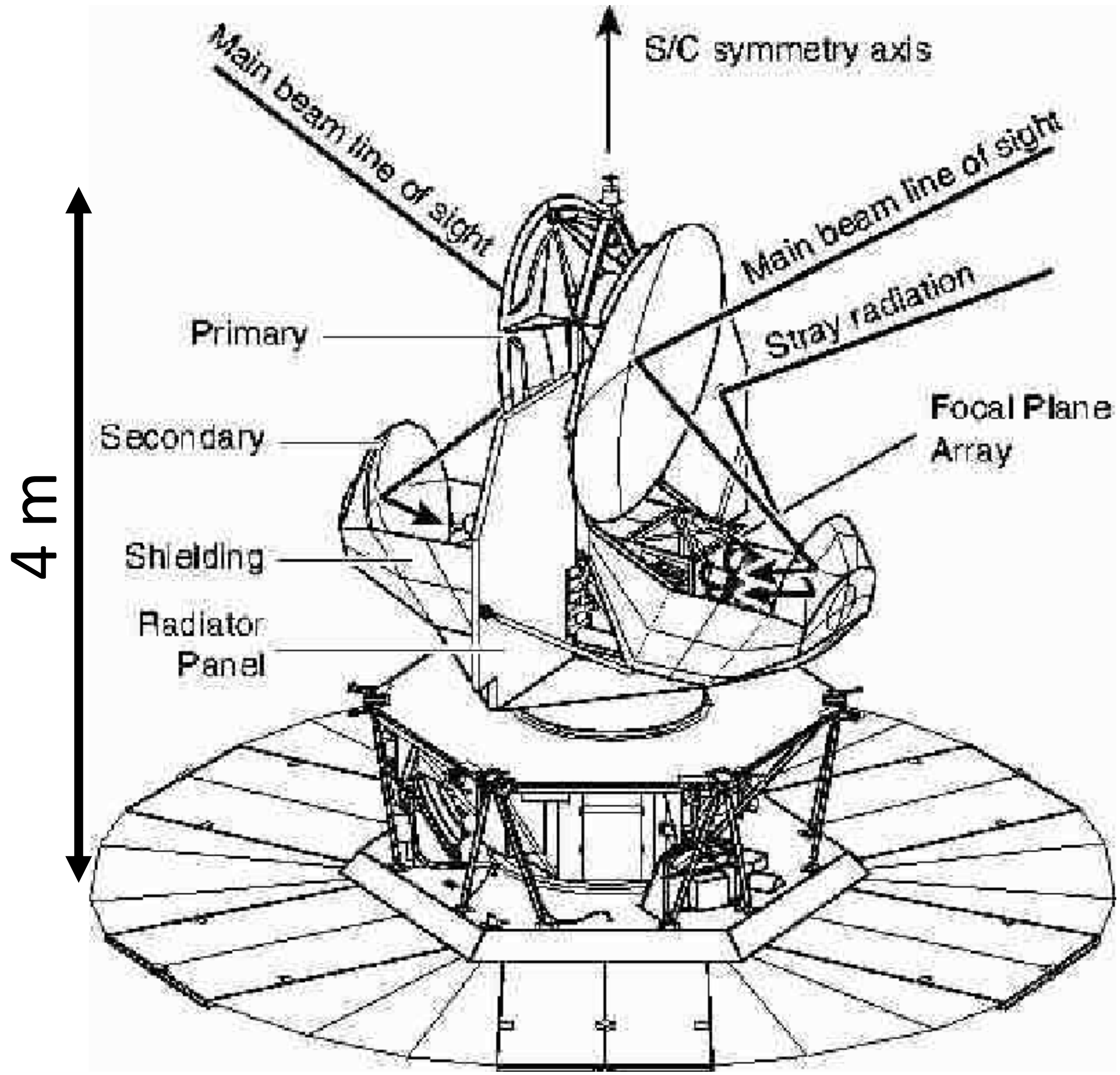


Postulate: light quantized into packets, energy is *hf*, f is frequency, *h* is a constant



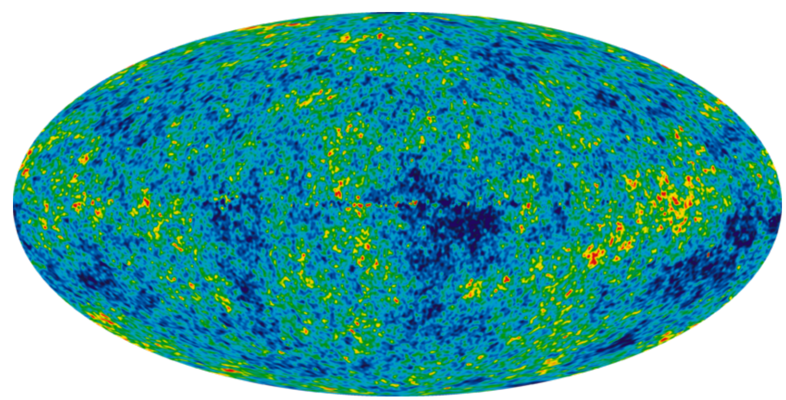
Einstein (1905) – Photo-electric effect, energy depends on frequency, not intensity



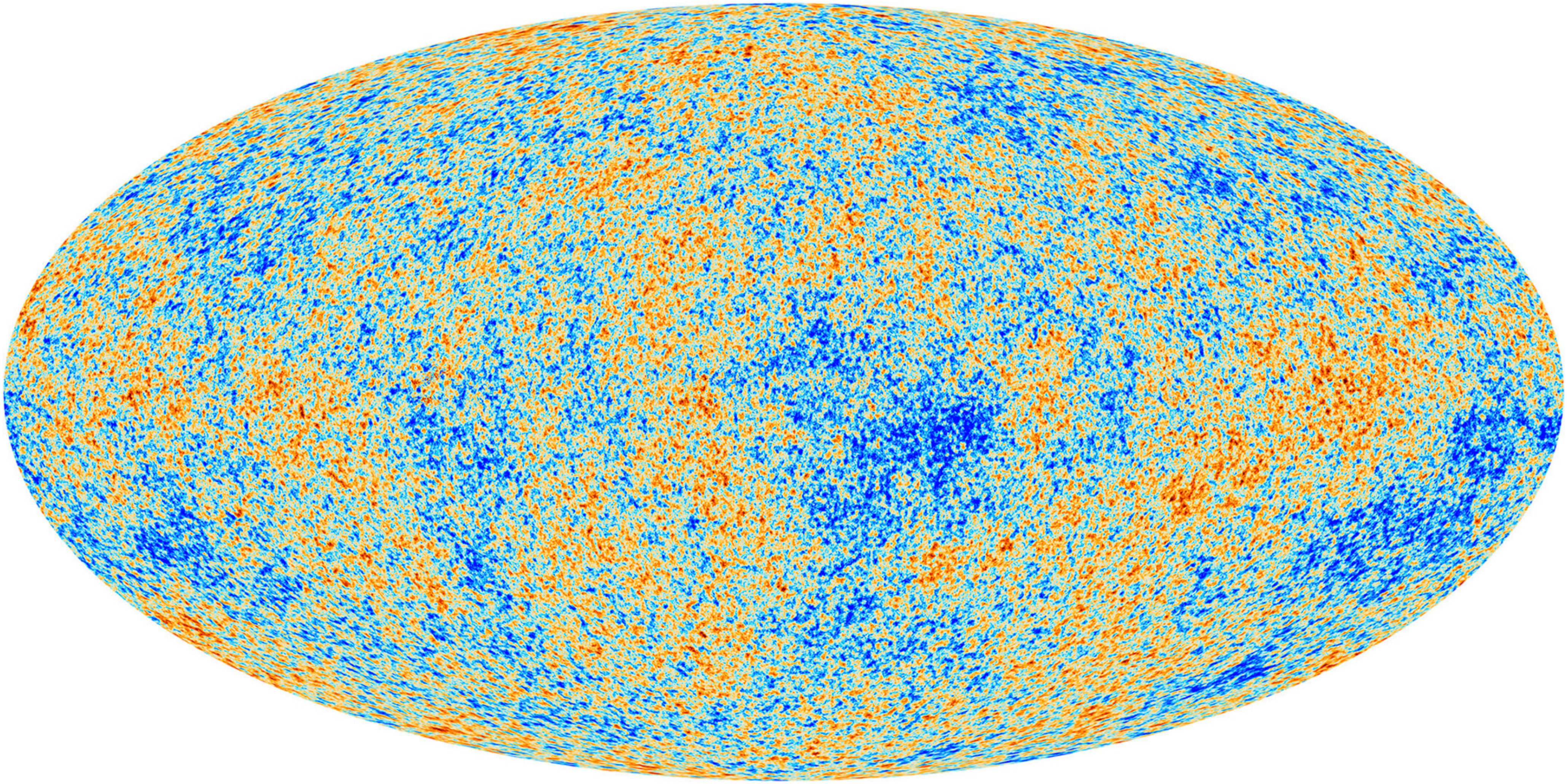


Wilkinson Microwave Anisotropy Probe (WMAP)

- Differential measurement
- Operated 2001-10



Planck Sky Map



Back on Earth

Gravitational waves in the inflaton field can cause very small (!) changes to the CMB called "B modes". This is the next big thing in CMB experiments.

Abigail Vierregg - Chicago

Keck Array at the South Pole

Next week – Recipe for a Hot Universe
How annihilation happens