Physics 2D Lecture Slides
Oct 22

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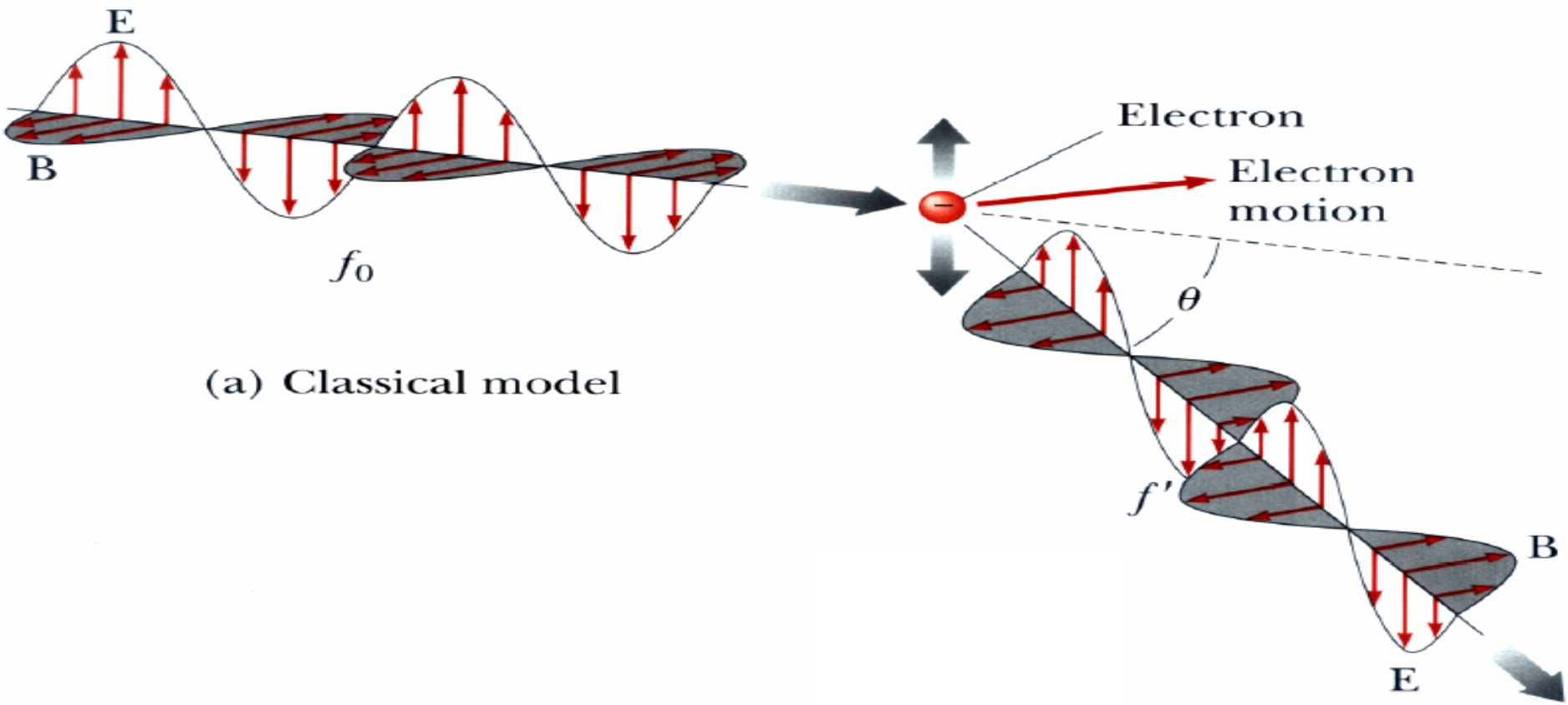
UCSD Physics

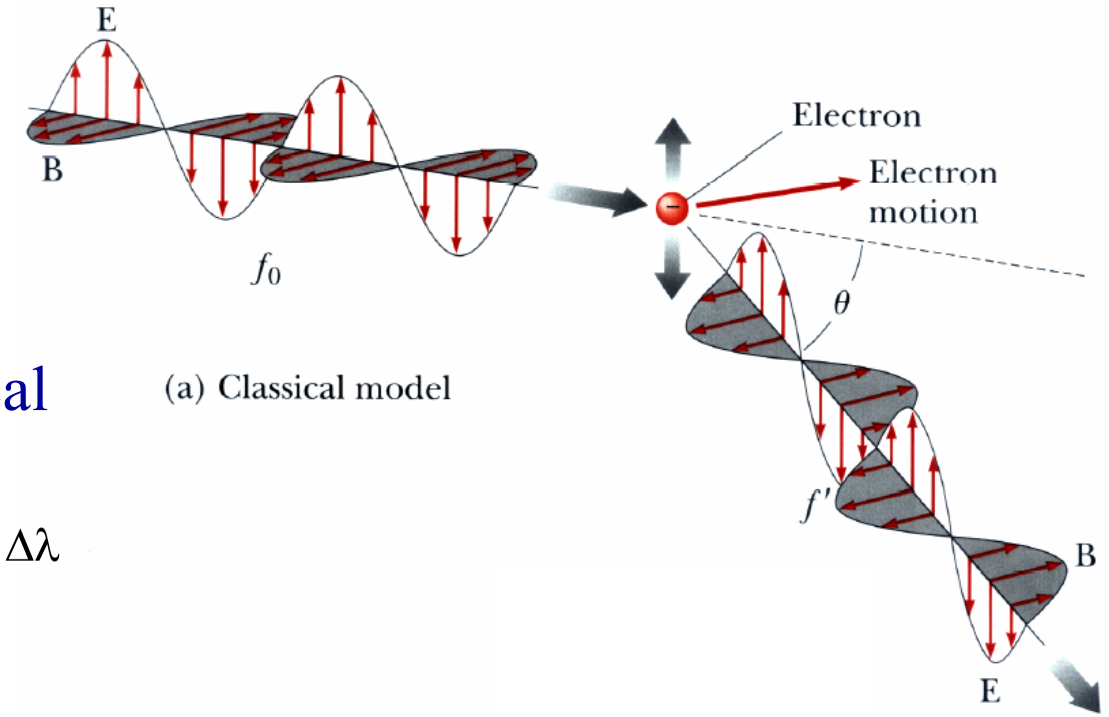
Compton Scattering : Quantum Pool !

- 1922: Arthur Compton (USA) proves that X-rays (EM Waves) have particle like properties (acts like photons)
  - Showed that classical theory failed to explain the scattering effect of
    - X rays on to free (not bound, barely bound electrons)
- Experiment : shine X ray EM waves on to a surface with "almost" free electrons
  - Watch the scattering of light off electron : measure time + wavelength of scattered X-ray



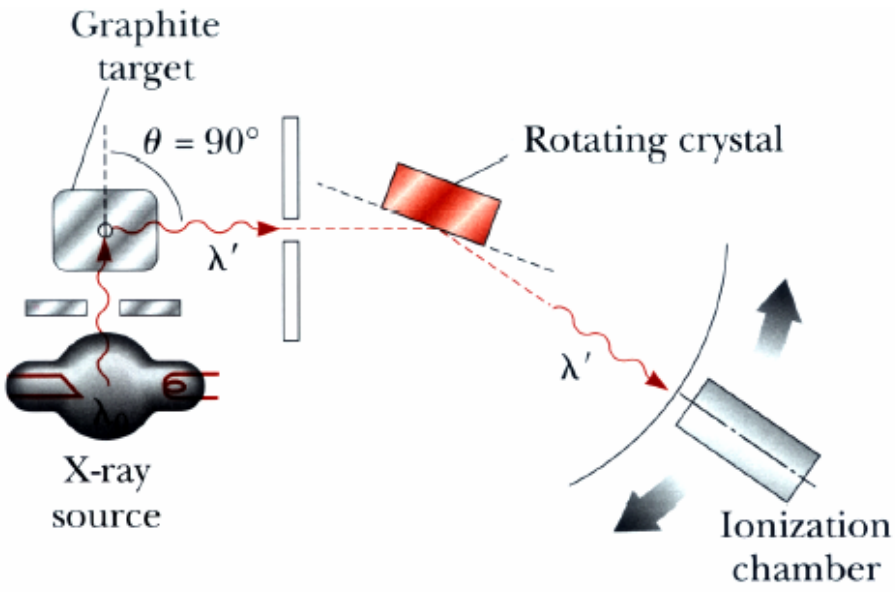
Compton Effect: what should Happen Classically?

- Plane wave [f,λ] incident on a surface with loosely bound electrons →interaction of E field of EM wave with electron: **F** = e**E**
- Electron oscillates with $f = f_{incident}$
- Eventually radiates spherical waves with $f_{radiated} = f_{incident}$
  - At all scattering angles, Δf & Δλ must be zero
- Time delay while the electron gets a "tan" : soaks in radiation



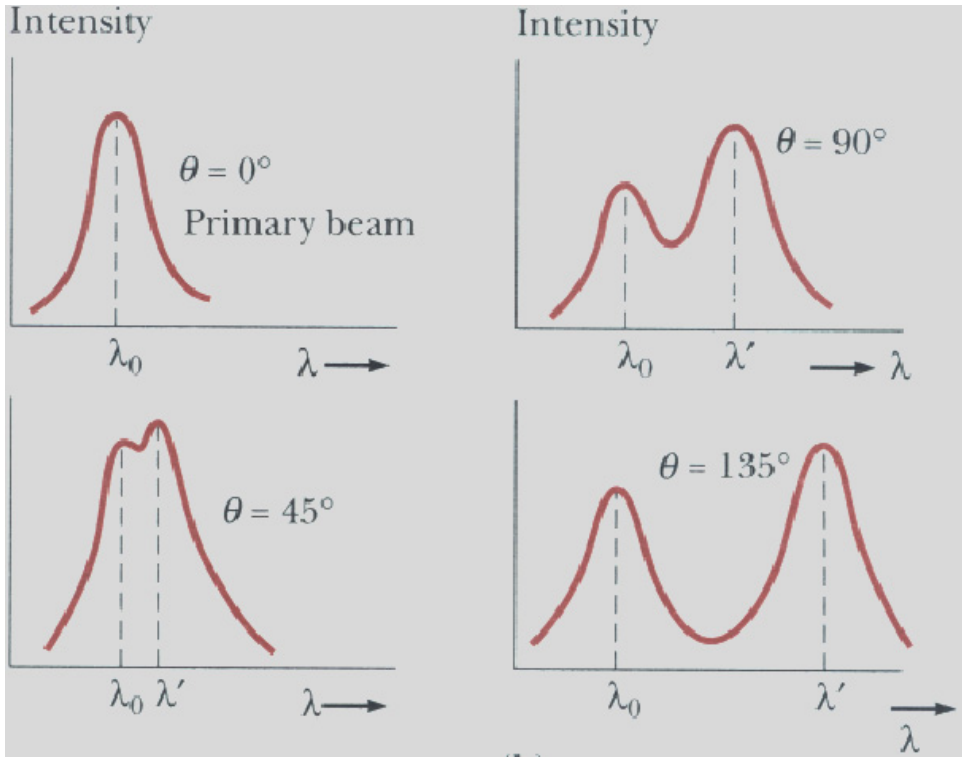
(a) Classical model

Compton Scattering : Setup & Results



$$\Delta\lambda = (\lambda' - \lambda) \propto (1 - \cos\theta)$$

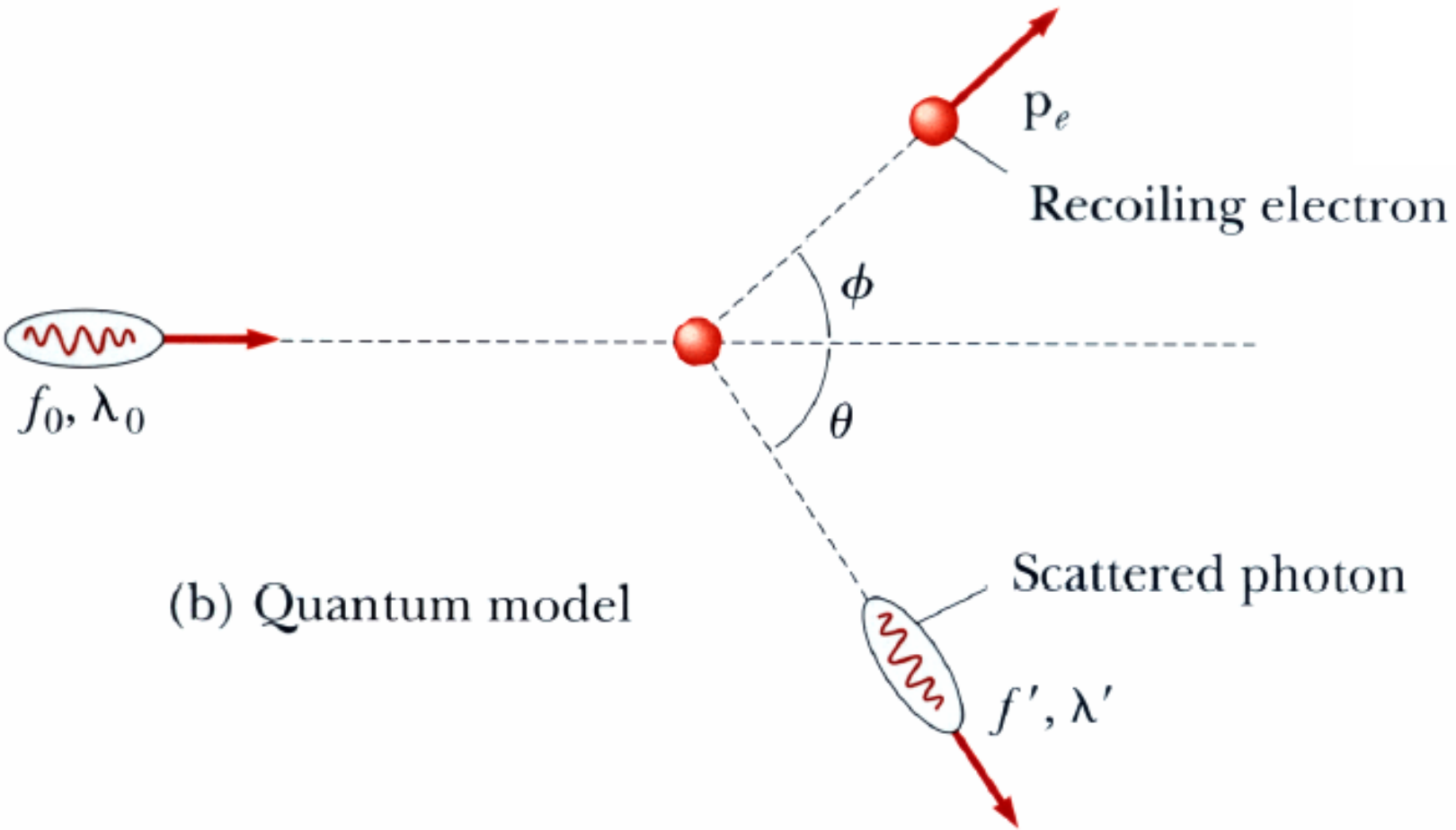
Scattered λ' larger than incident



$$\Delta\lambda = \left(\frac{h}{m_e c}\right)(1 - \cos\theta)$$

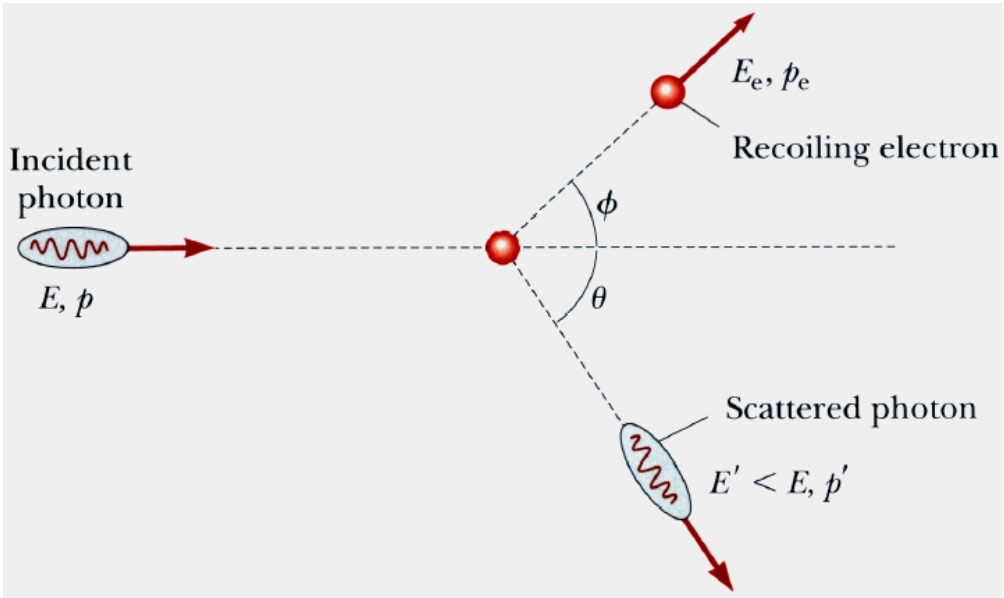
How does one explain this startling anisotropy?

Compton Effect : Quantum (Relativistic) Pool



(b) Quantum model

Compton Scattering: Quantum Picture



$p_e \cos\phi = p - p'\cos\theta$

$p_e \sin\phi = p'\sin\theta$

Square and add $\Rightarrow$

$p_e^2 = p^2 - 2pp'\cos\theta + p'^2$

Eliminate p_e & E_e using

$E_e^2 = p_e^2c^2 + m_e^2c^4$ &

$E_e = (E - E') + m_ec^2$

Energy Conservation:

$E + m_ec^2 = E' + E_e$

Momentum Conserv:

$p = p'\cos\theta + p_e\cos\phi$

$0 = p'\sin\theta - p_e\sin\phi$

Use these to eliminate electron deflection angle (not measured)

$$\left((E - E') + m_ec^2\right)^2 = \left[p^2 - 2pp'\cos\theta + p'^2\right] + (m_ec^2)^2$$

For light $p = \frac{E}{c} \Rightarrow$

$$E^2 + E'^2 - 2EE' + 2(E - E')mc^2 = \left[\frac{E^2}{c^2} - 2\frac{EE'}{c^2}\cos\theta + \frac{E'^2}{c^2}\right]c^2$$

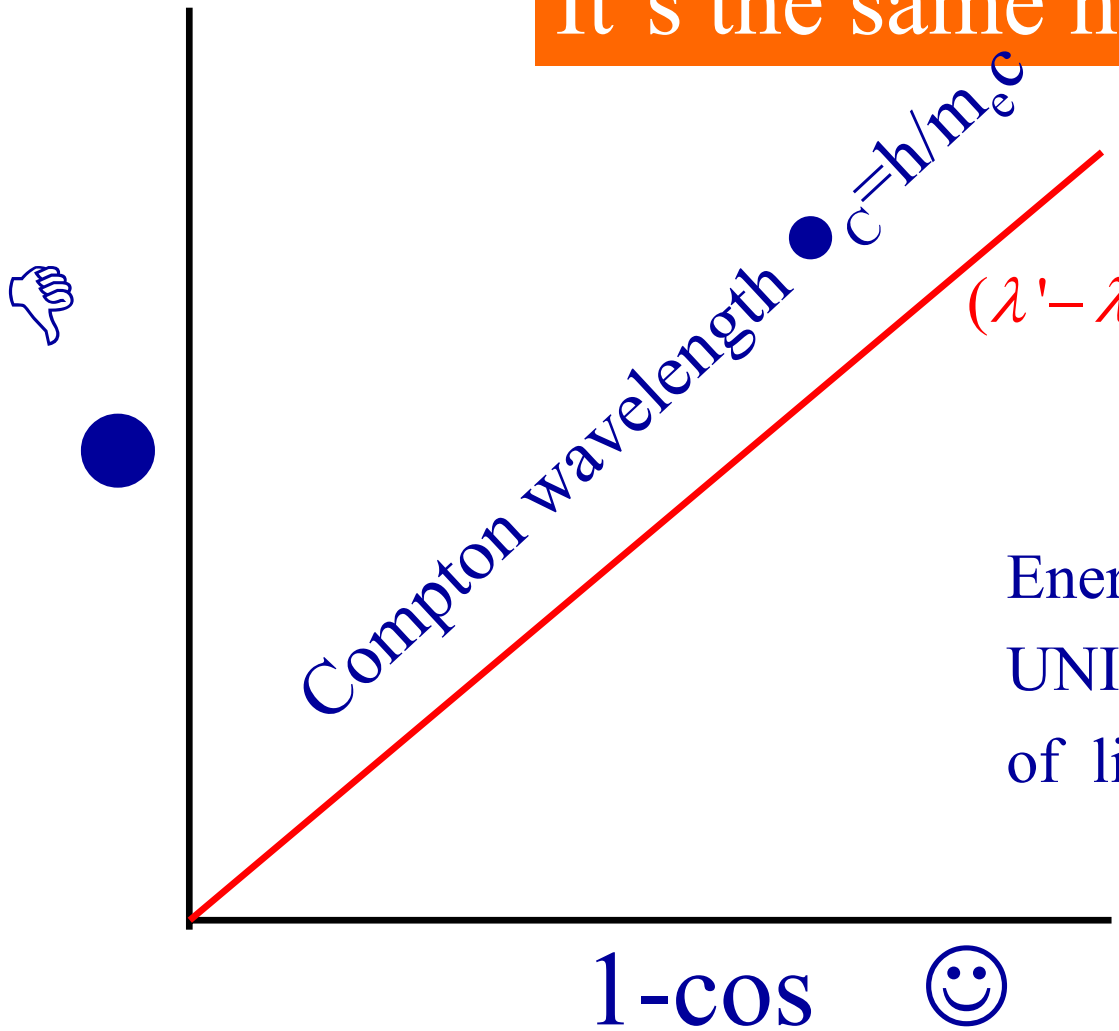
$$\Rightarrow -EE' + (E - E')mc^2 = -EE'\cos\theta$$

$$\Rightarrow \frac{E - E'}{EE'} = -\frac{1}{m_ec^2}(1 - \cos\theta) \Rightarrow (\lambda' - \lambda) = \left(\frac{h}{m_ec}\right)(1 - \cos\theta)$$

Checking for h in Compton Scattering

Plot scattered photon data, calculate slope and measure h

It's the same h !!



$$(\lambda' - \lambda) = (\frac{h}{m_e c})(1 - \cos\theta)$$

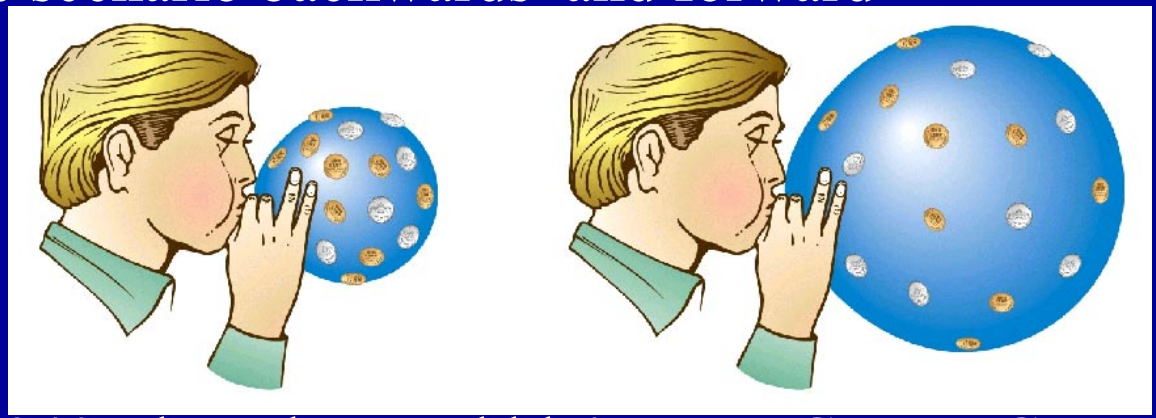
Energy Quantization is a UNIVERSAL characteristic of light (EM Waves)

Summary: Interaction of Radiation With Matter

- Photon gives up all its energy to matter → Photoelectric effect
- Photon gives up a part of its energy → Compton Scattering
- Photon converts into matter and antimatter pair
  - $\gamma \rightarrow e^+ e^-$
    - Important that all conservation laws apply
      - Conservation of energy $E=hf = (m_{e+} + m_{e-})c^2$
      - Conservation of momentum means that photon can not simply disappear into matter antimatter, need a neighborly nucleus to recoil (convince yourself)
      - Conservation of charge

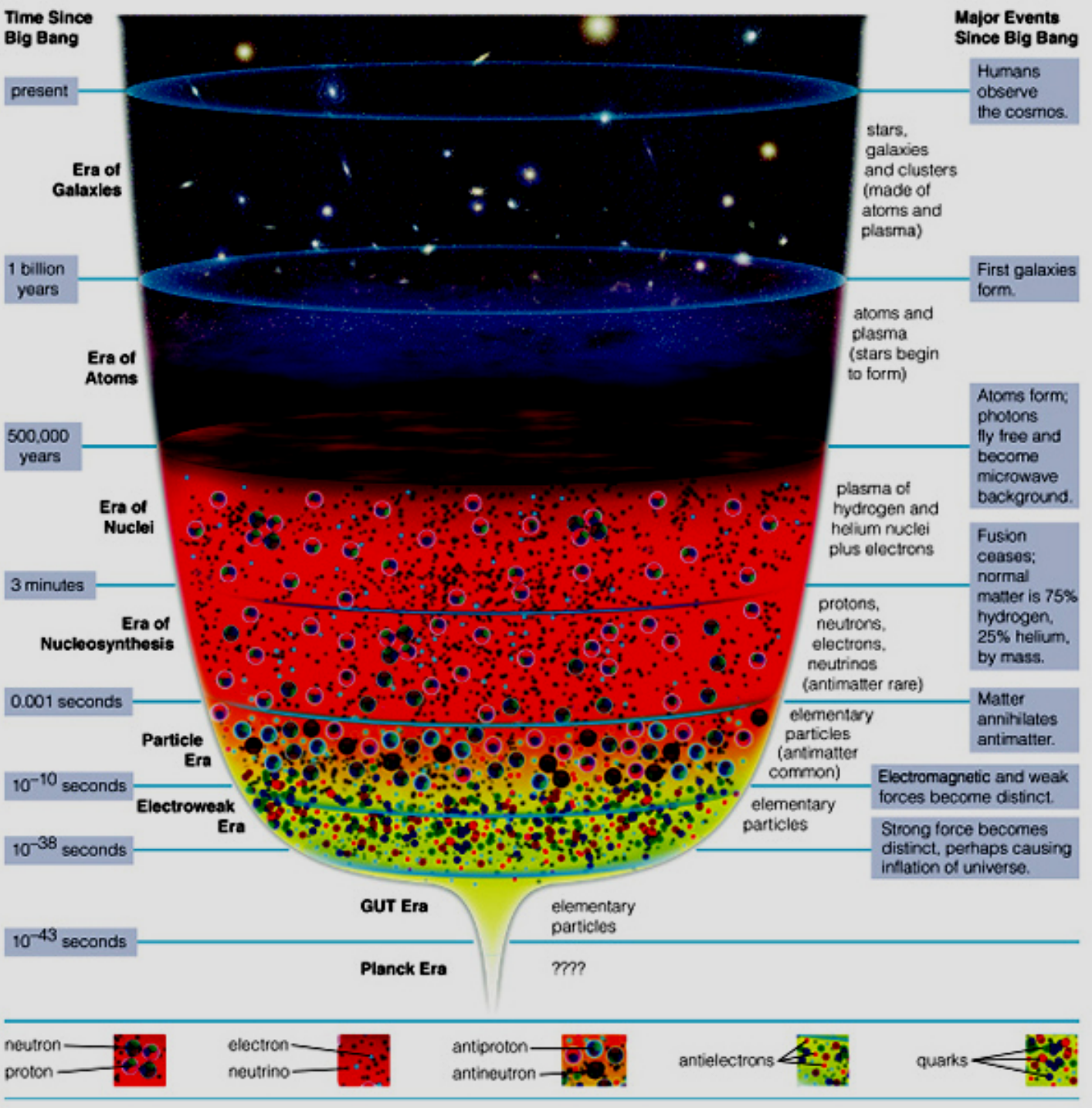
The Universe Is Expanding : Hubble's ***cosmological redshifts***

- Play the scenario backwards and forward

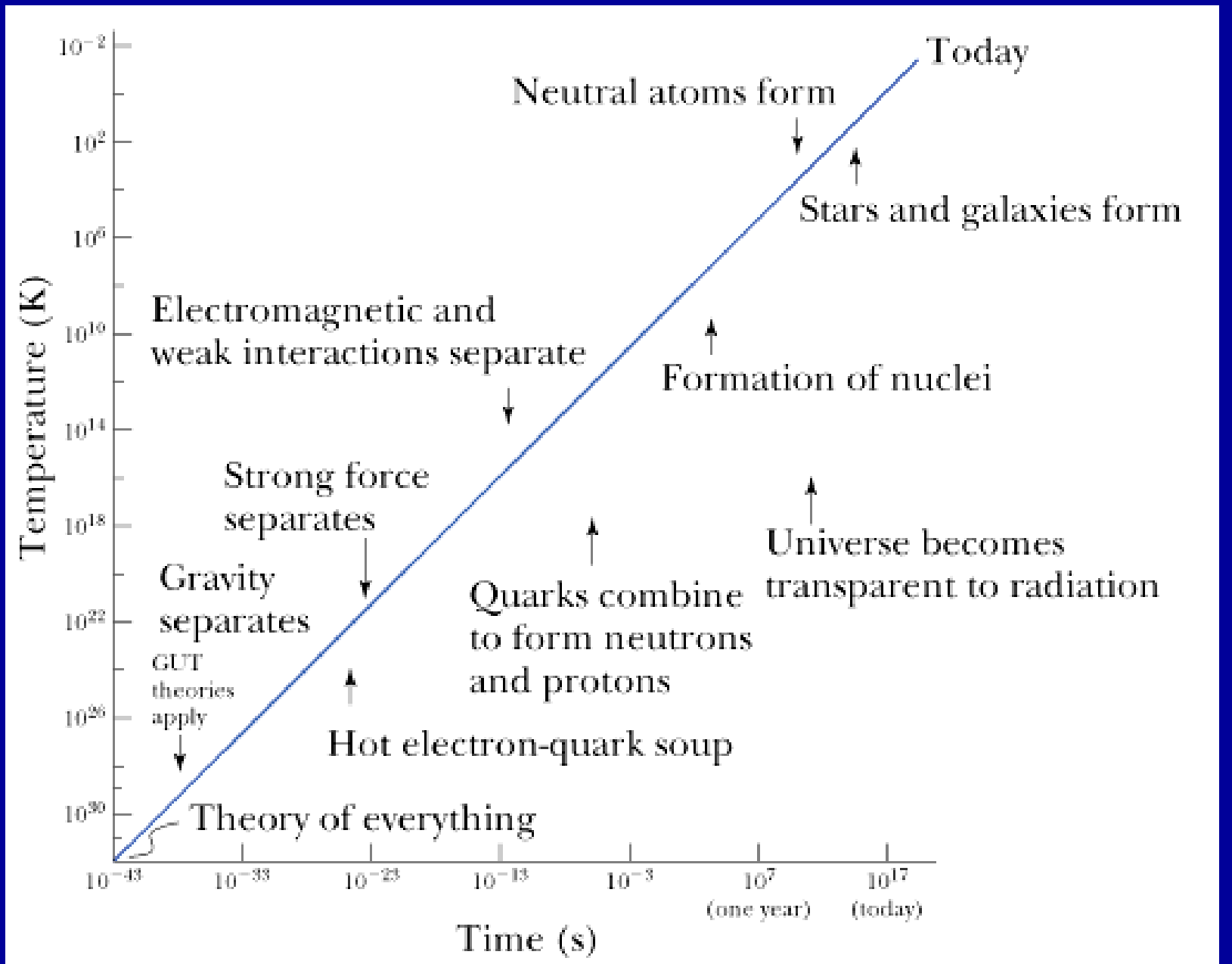


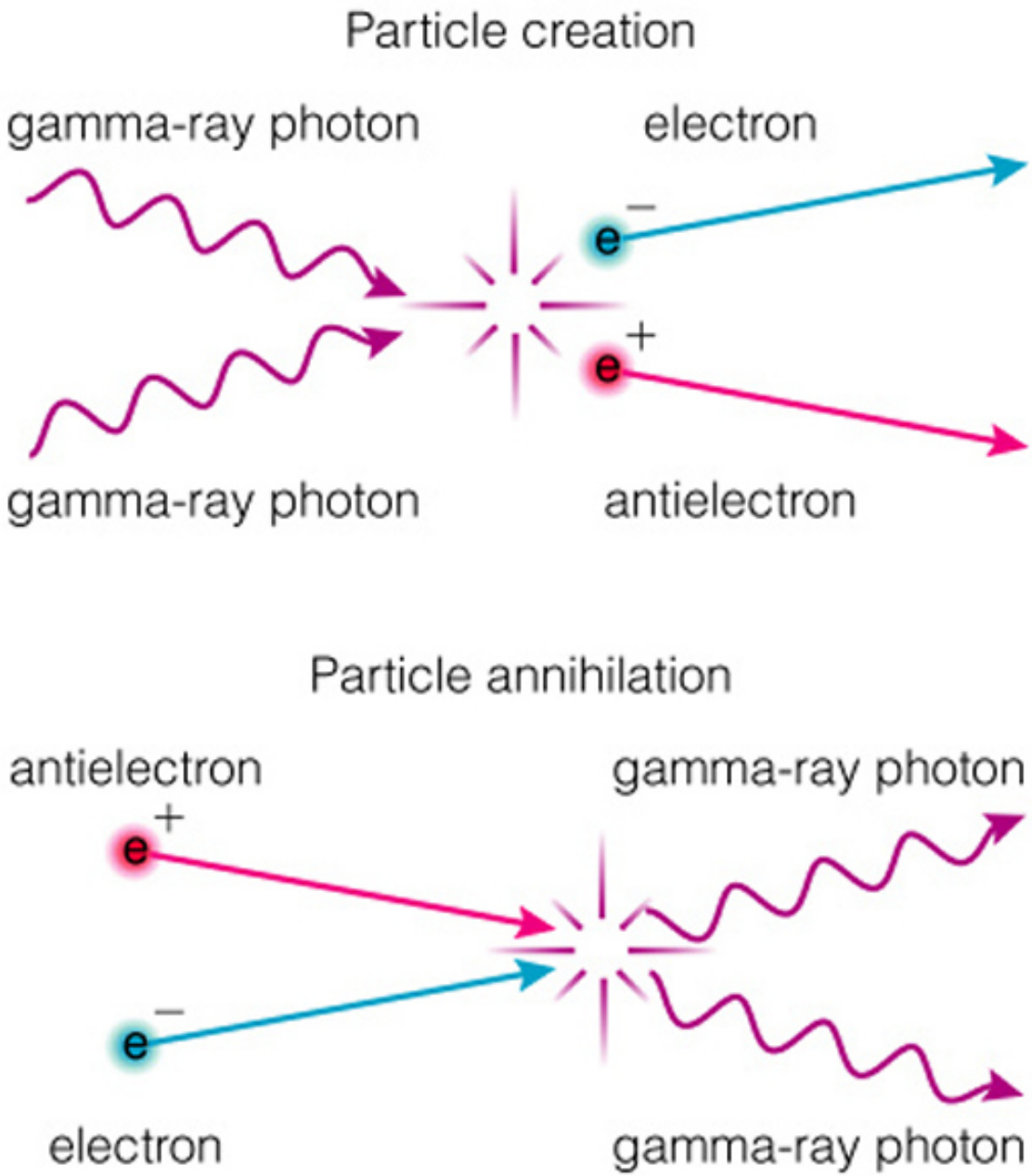
- In the 1940s, based on Hubble's Law, George Gamow proposed the universe began in a colossal explosion about 10 billion years ago
  - Based on experimental data (like we will see today) we now believe that Universe began as a singularity in spacetime
    - Where energy density and spacetime curvature were infinite
      - We don't know what exactly happened between t=0 to t=10^{-43} s
        - » The radius of the universe was about 10^{-52} cm
        - » Temperature of the Universe was about 10^{30} K
      - After that time (10^{-35} s) the Universe has expanded & is well explained by known theories of (strong, weak, EM and Gravity) interactions
        - » Temp = 10^{28} →10^{16} K, universe is a hot quark-electron soup

History Of The Universe Since Origin

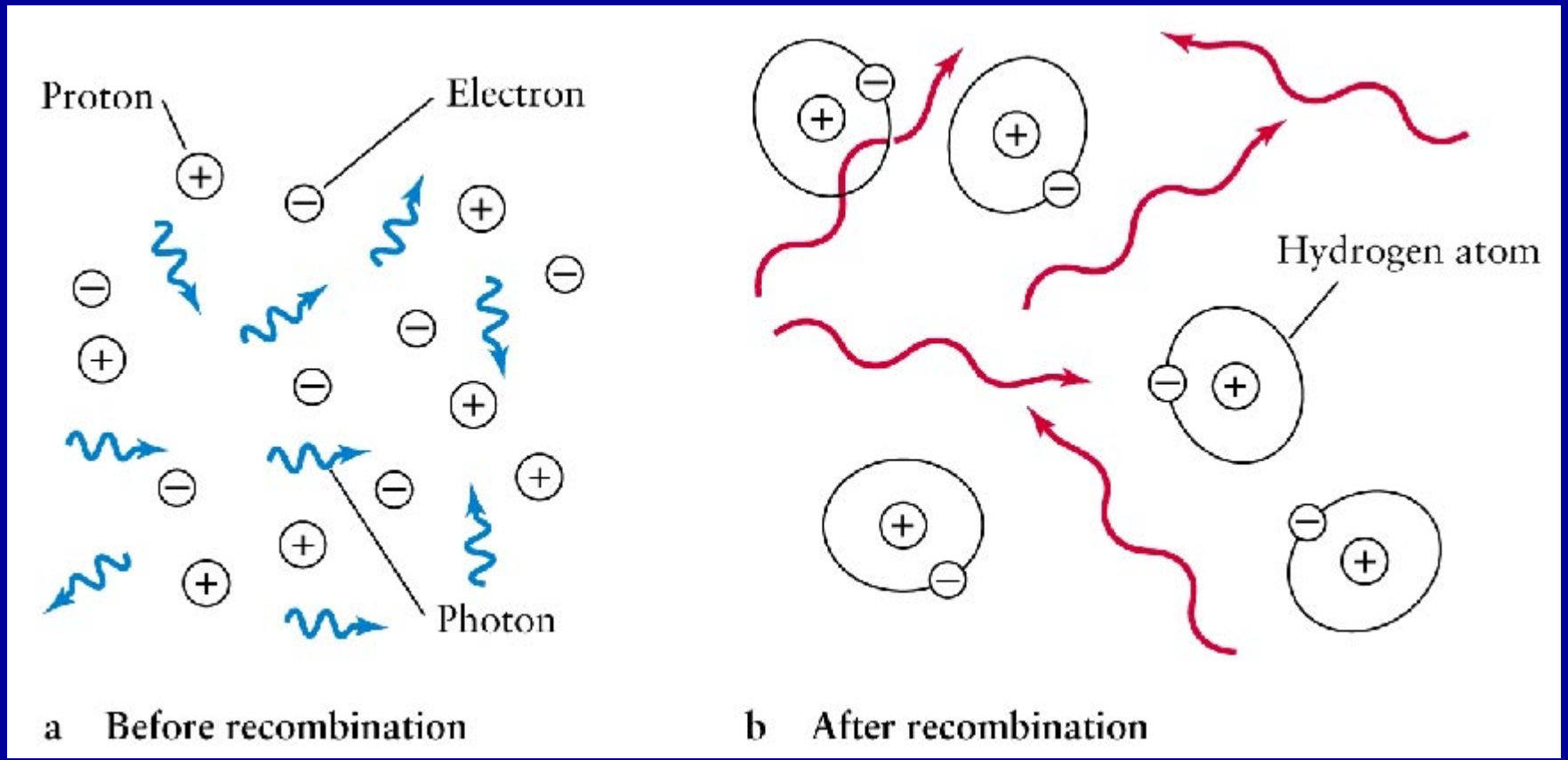


History of The Universe: Some Milestones



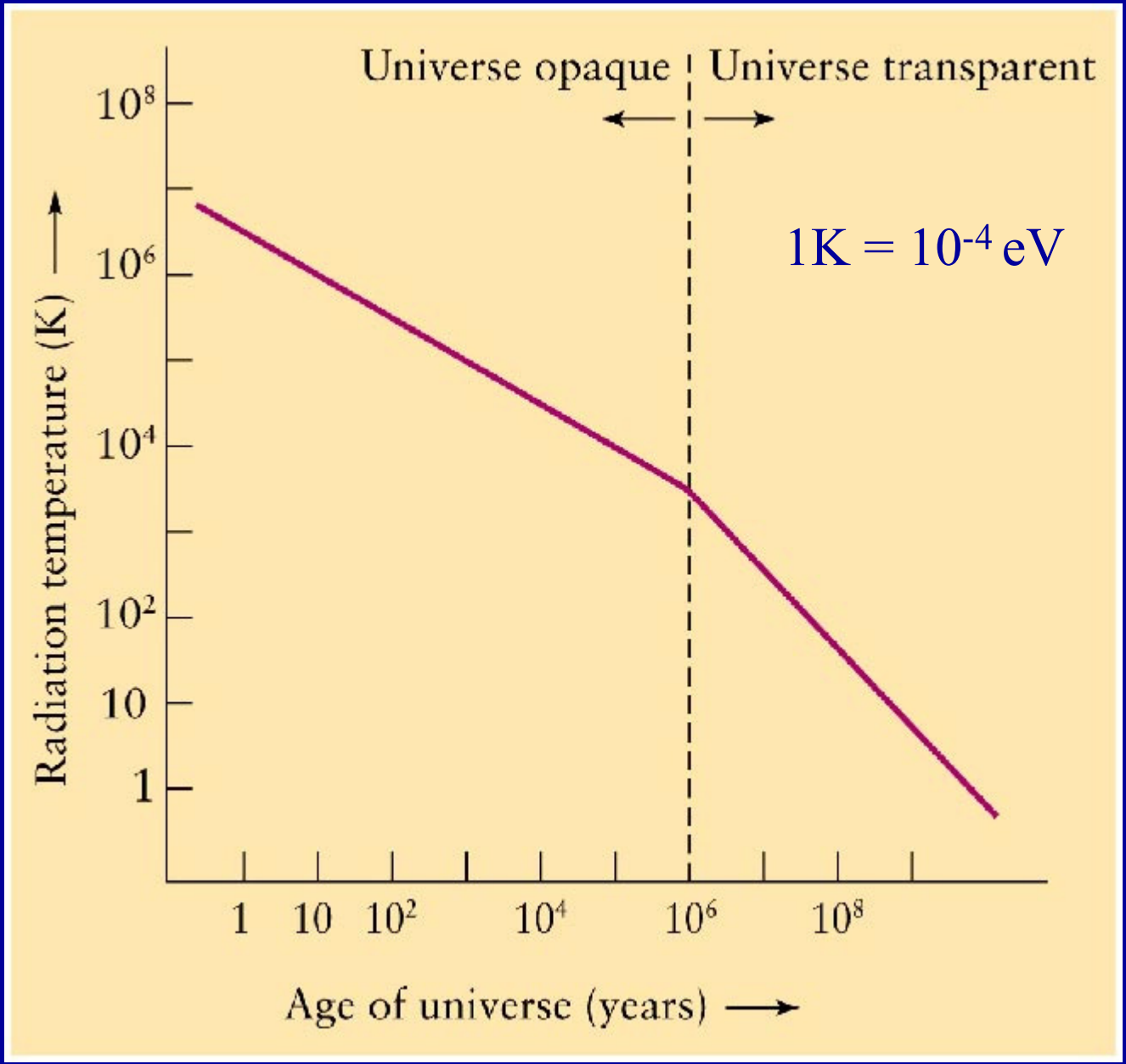

Particle creation
gamma-ray photon
electron
e
−
e
+
gamma-ray photon
antielectron
Particle annihilation
antielectron
gamma-ray photon
e
+
e
−
electron
gamma-ray photon

Universe was hot opaque plasma in first 300K years

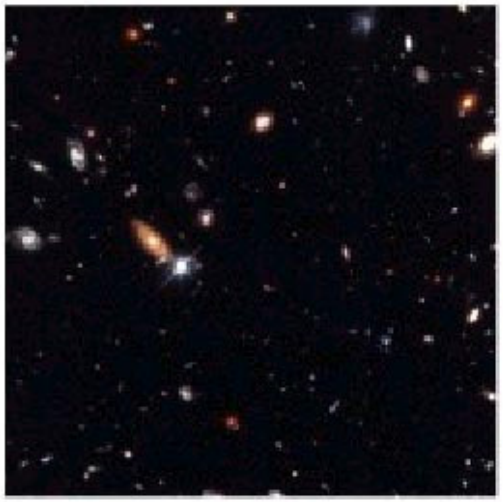


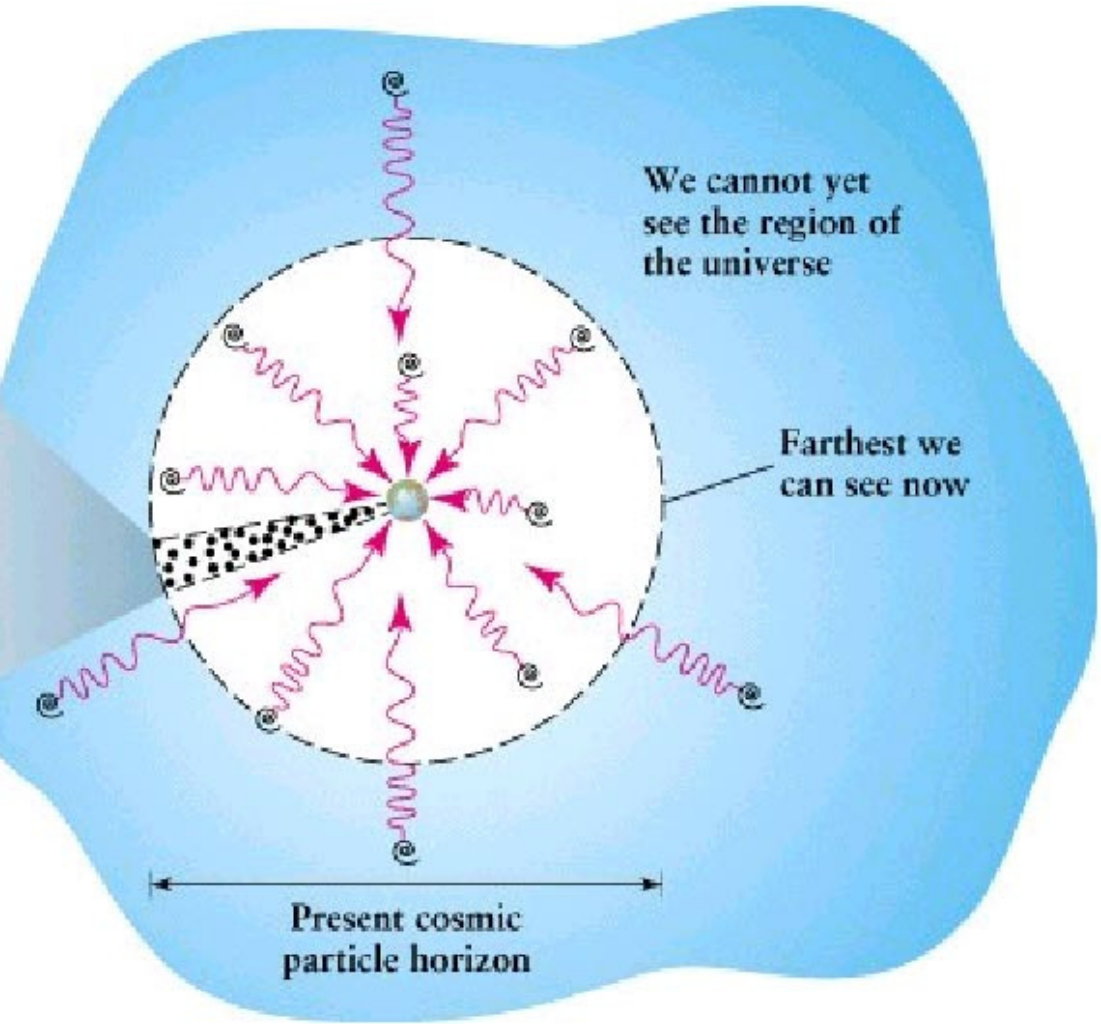
At t = 300,000 years, the universe was finally cool enough from its initial *primordial fireball* that electrons and protons could combine to form atoms (era of recombination)

Universe was hot opaque plasma in first 300K years



Farther we look into space, the farther back in time we are seeing

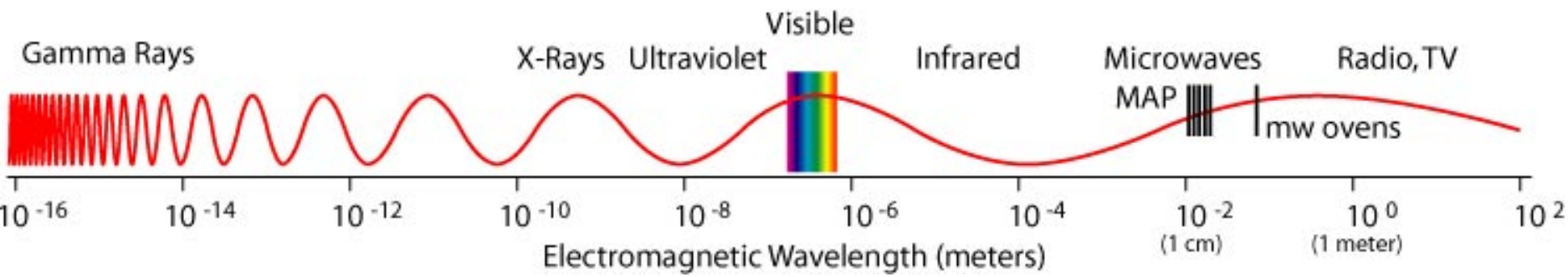


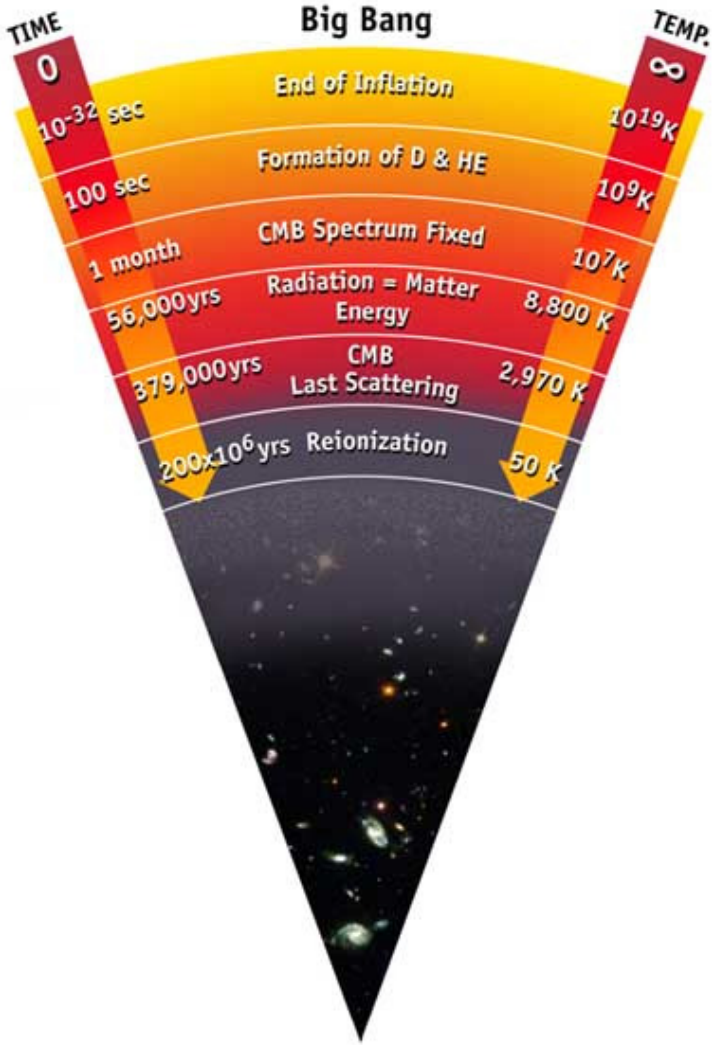


Big Bang & Cosmic Microwave Radiation

- The compact intense fireball of matter & radiation expanded, cooled, underwent series of transitions at specific temps/time
- Between 5 minutes to ≅ 100,000 years, universe consisted of plasma of H and He nuclei (and electrons) in thermal equilibrium with radiation
- Once temperature fell below E=kT = 13.6 eV (B.E. of Hydrogen)
  - Hydrogen could form and not be broken up (like when things were hotter)
  - Now matter and radiation were decoupled and Universe became transparent
- Radiation left behind (T = 3000K) could travel all over the Universe and continue to be Cosmologically red-shifted to longer and longer wavelengths
- Observer today would expect this radiation to come from all sides and to have a radiation spectrum like a blackbody at 2.7K (dominant in Microwave Frequency)
- Since then Gravity became dominant influence, density fluctuations led to formation of galaxies, stars etc

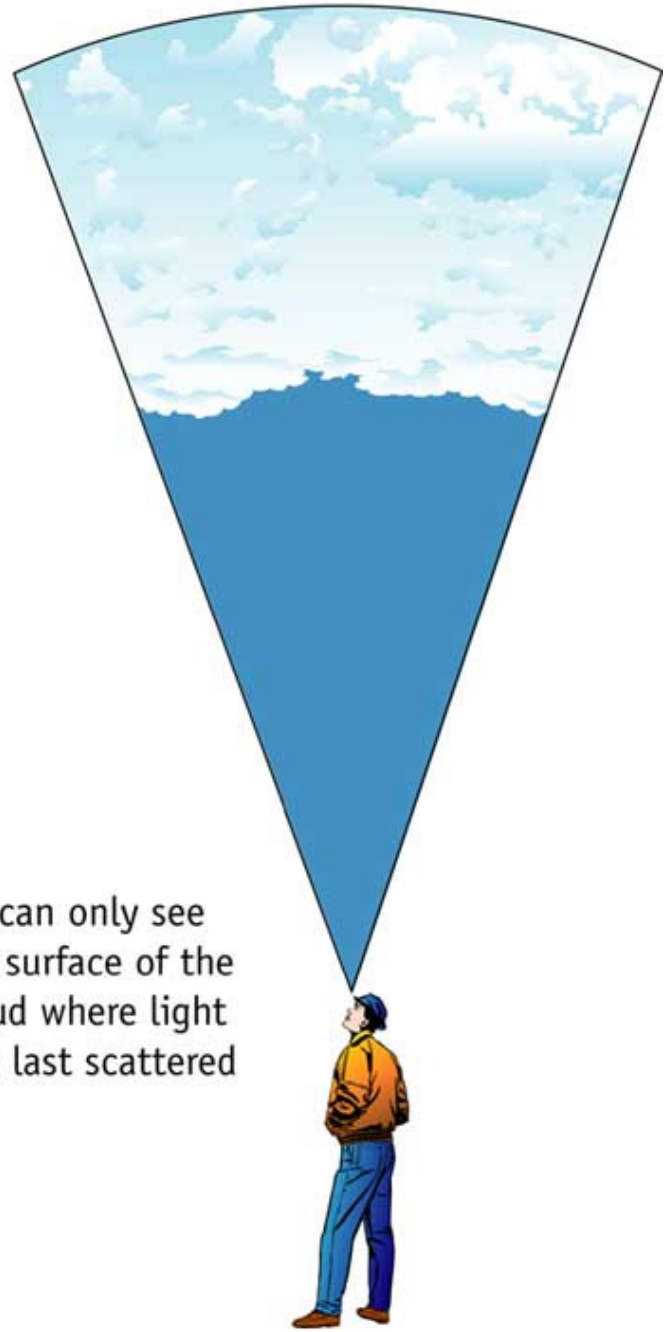
The light that is reaching us has been stretched out as the universe has stretched, so light that was once beyond gamma rays is now reaching us in the form of microwaves.



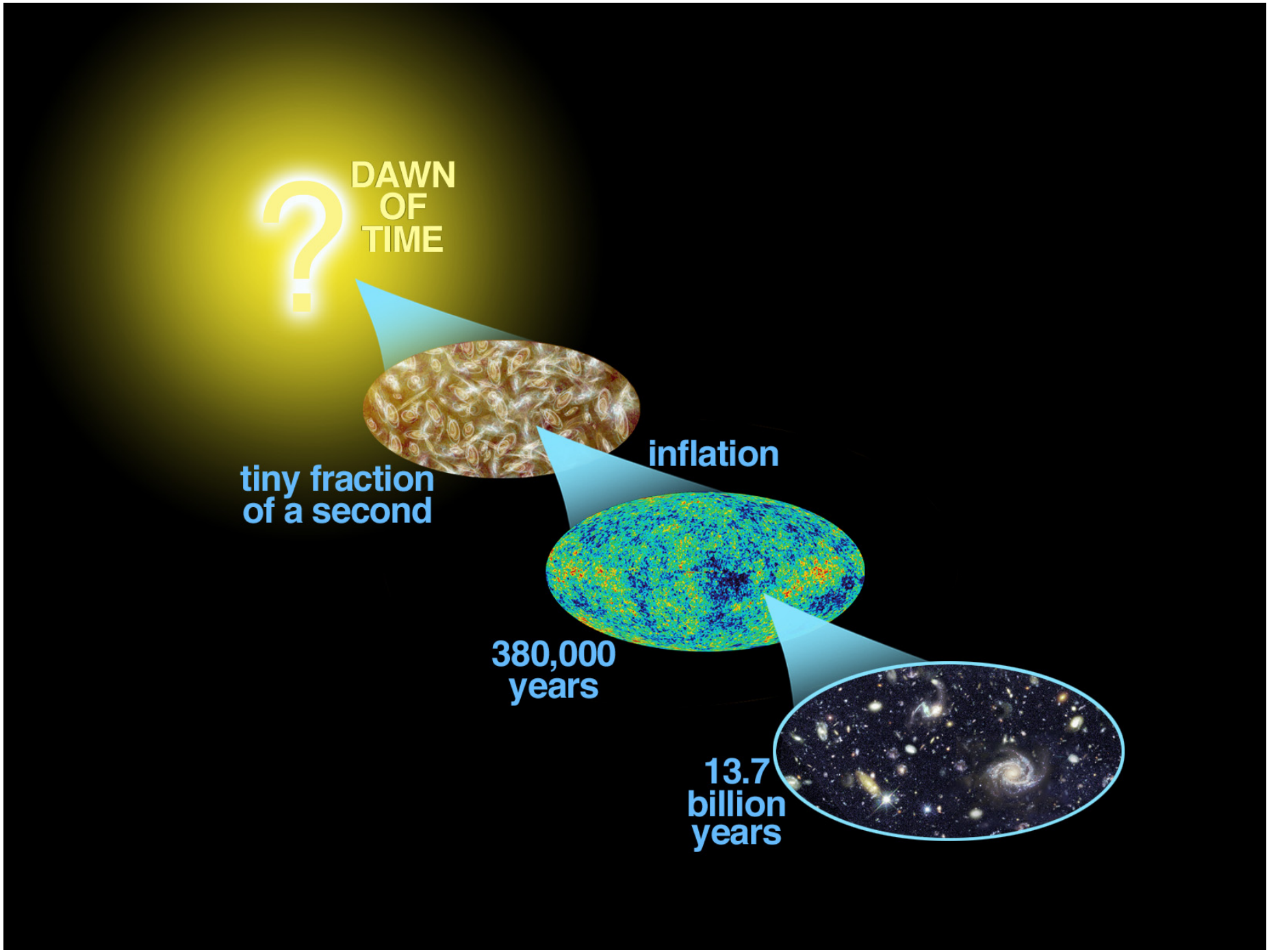


PRESENT
13.7 Billion Years after the Big Bang

The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



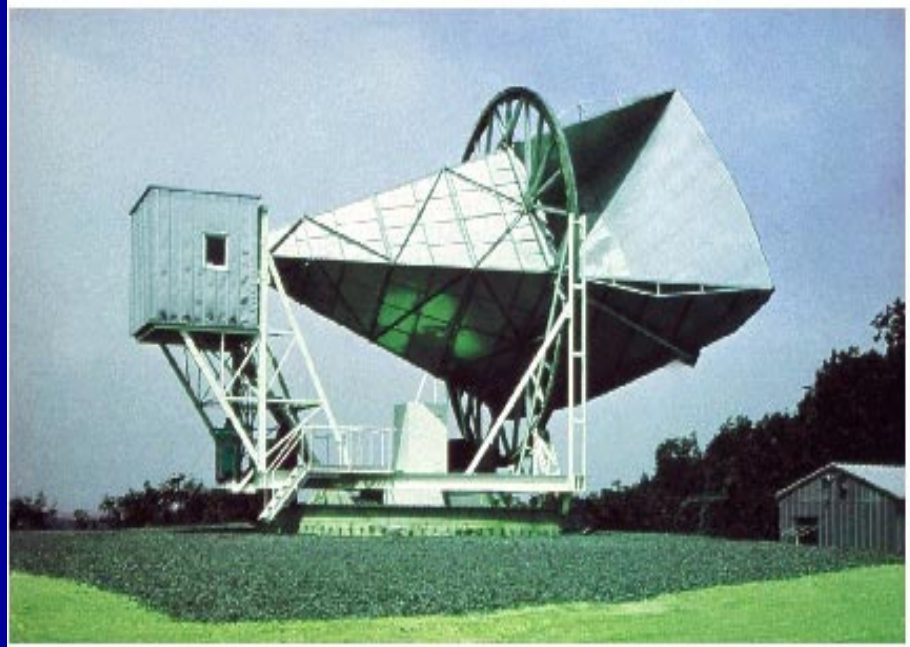
We can only see the surface of the cloud where light was last scattered


?
DAWN
OF
TIME
tiny fraction
of a second
inflation
380,000
years
13.7
billion
years

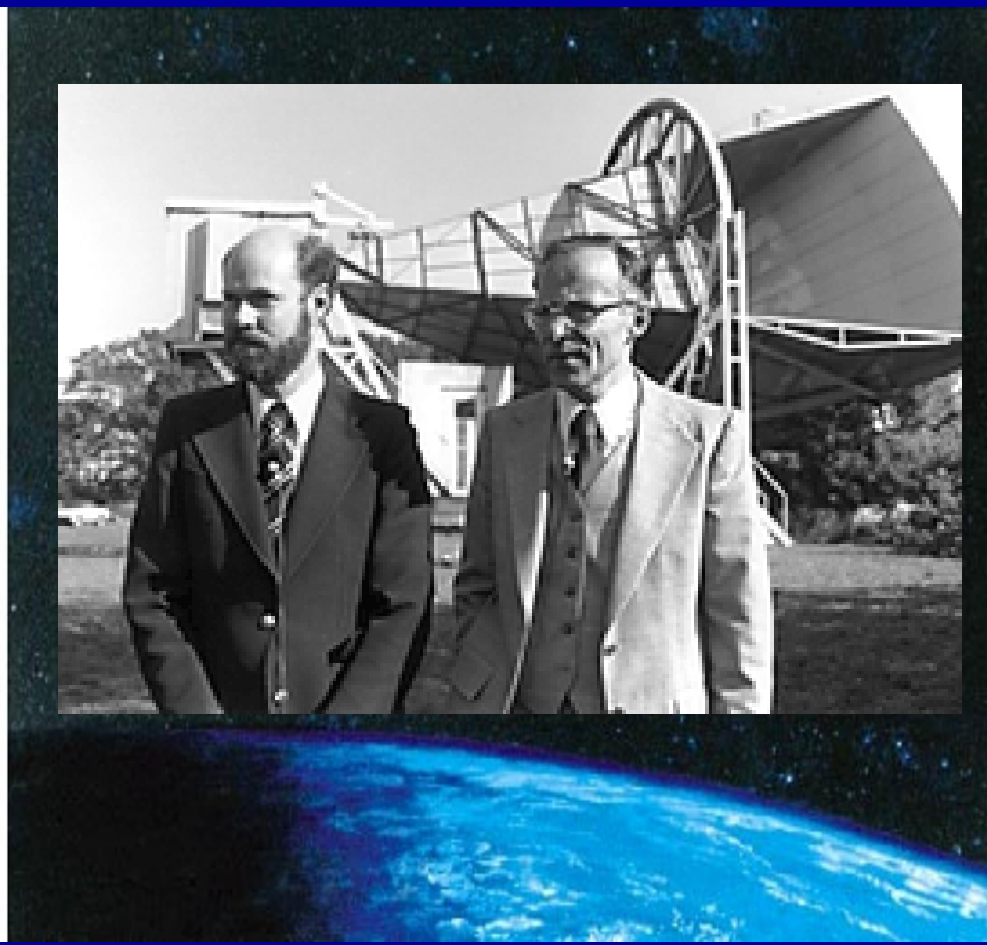
The Cosmic Microwave Radiation that fills all space is evidence of a hot Big Bang

Pure Serendipity !!

1963:Bell Lab Horn Antenna detected a Microwave signal from all parts of sky



Nobel : Penzias & Wilson



What does the Cosmic Background Radiation Sound like ?

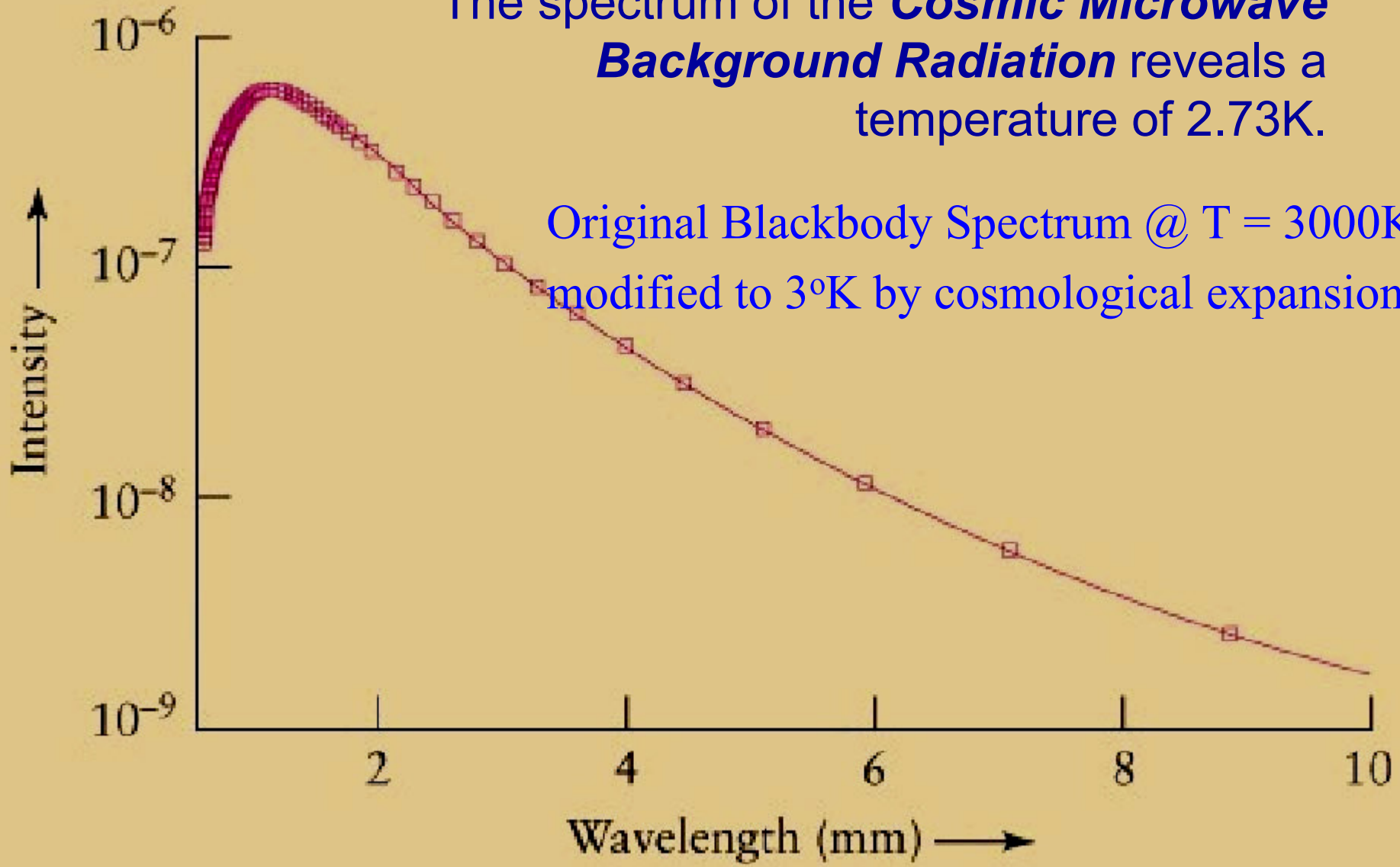
Play MP3 audio file

Cleaning up after the pigeons !

The spectrum of the ***Cosmic Microwave Background Radiation*** reveals a temperature of 2.73K.

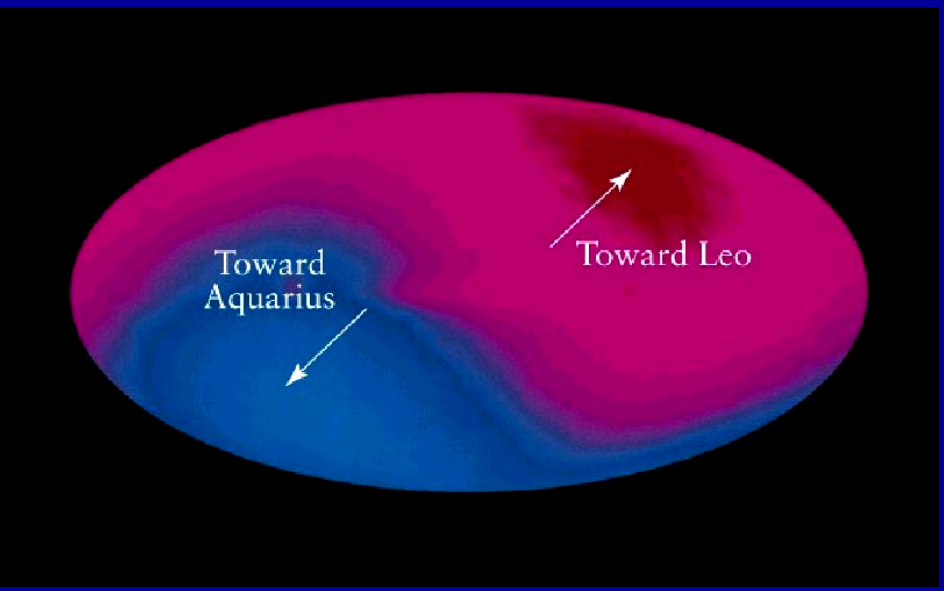
Original Blackbody Spectrum @ T = 3000K

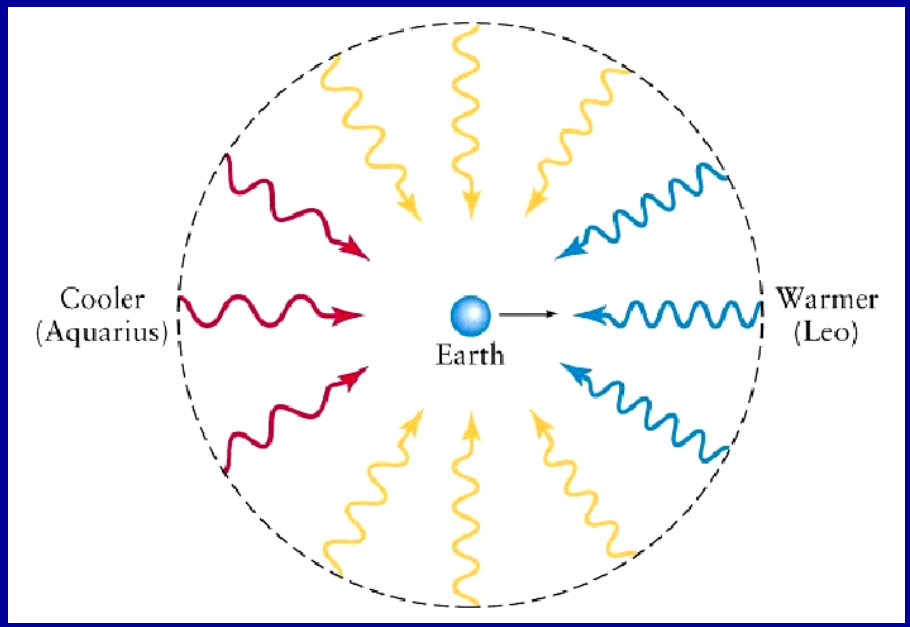
modified to 3°K by cosmological expansion



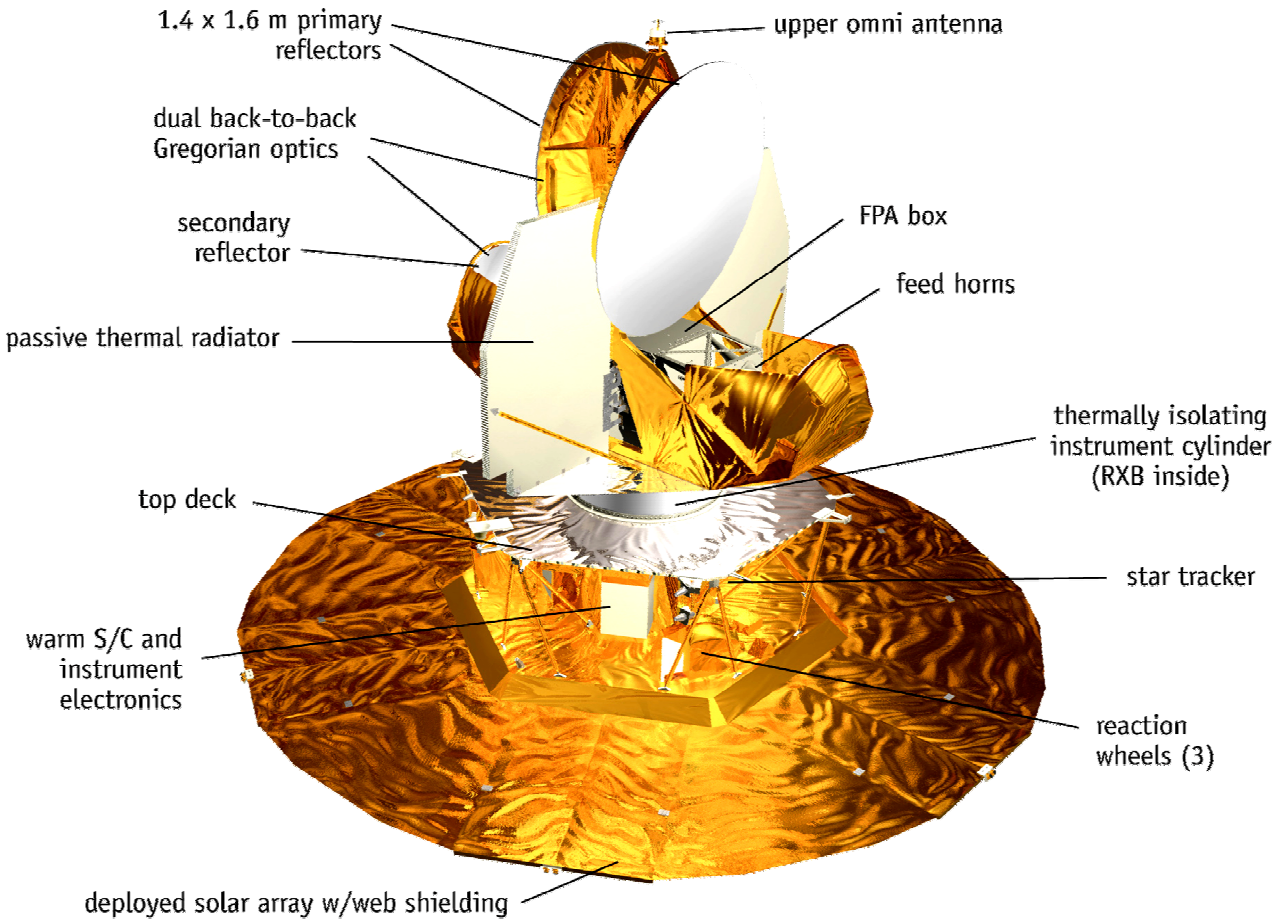
The microwave sky where variations are due to the motion of Earth through the cosmos

Doppler Effect due to Earth's motion
The Universe is at 2.726K, Variation ΔT= 0.0033K



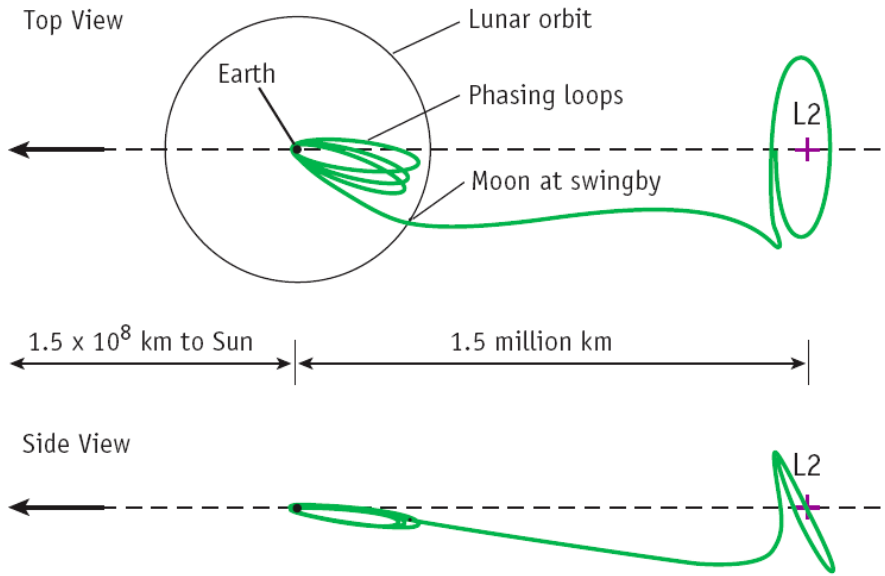


The WMAP Microwave Telescope: 2003



The WMAP instrument consists of a set of passively cooled microwave radiometers with 1.4 x 1.6 meter diameter primary reflectors to provide the desired angular resolution. Measuring the temperature of the microwave sky to an accuracy of one millionth of a degree requires careful attention to possible sources of systematic errors.

The composite/aluminum spacecraft is 150 inches (3.8 meters) high by 198 inches (5 meters) wide. WMAP weighs 1,850 pounds (840 kilograms) and is supplied with 419 Watts of power



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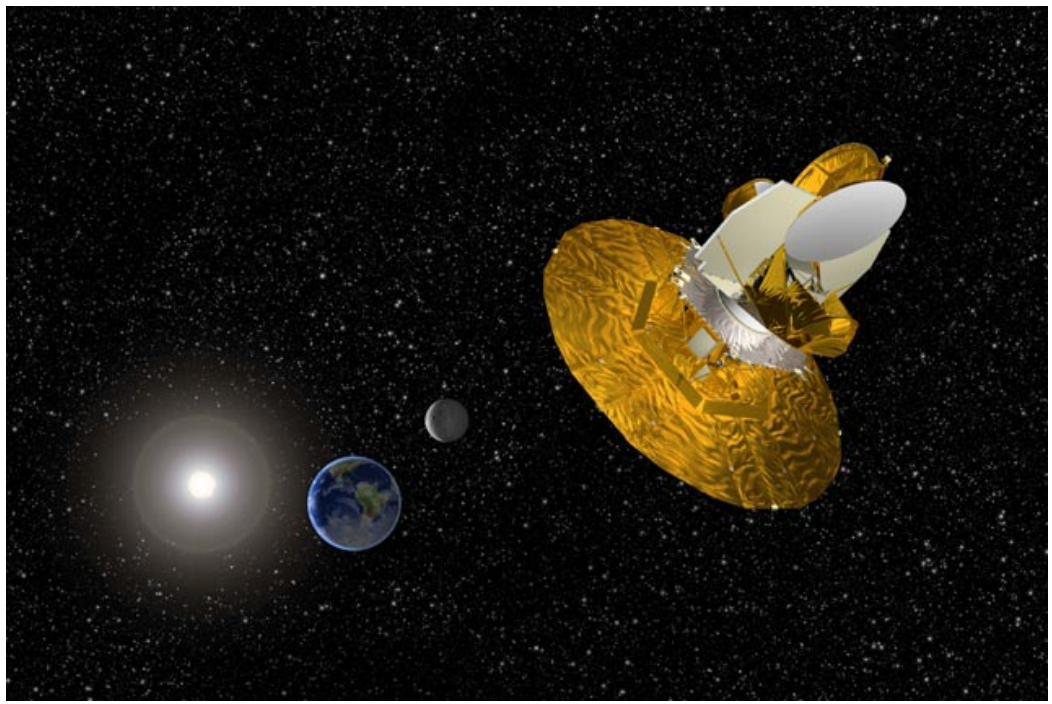
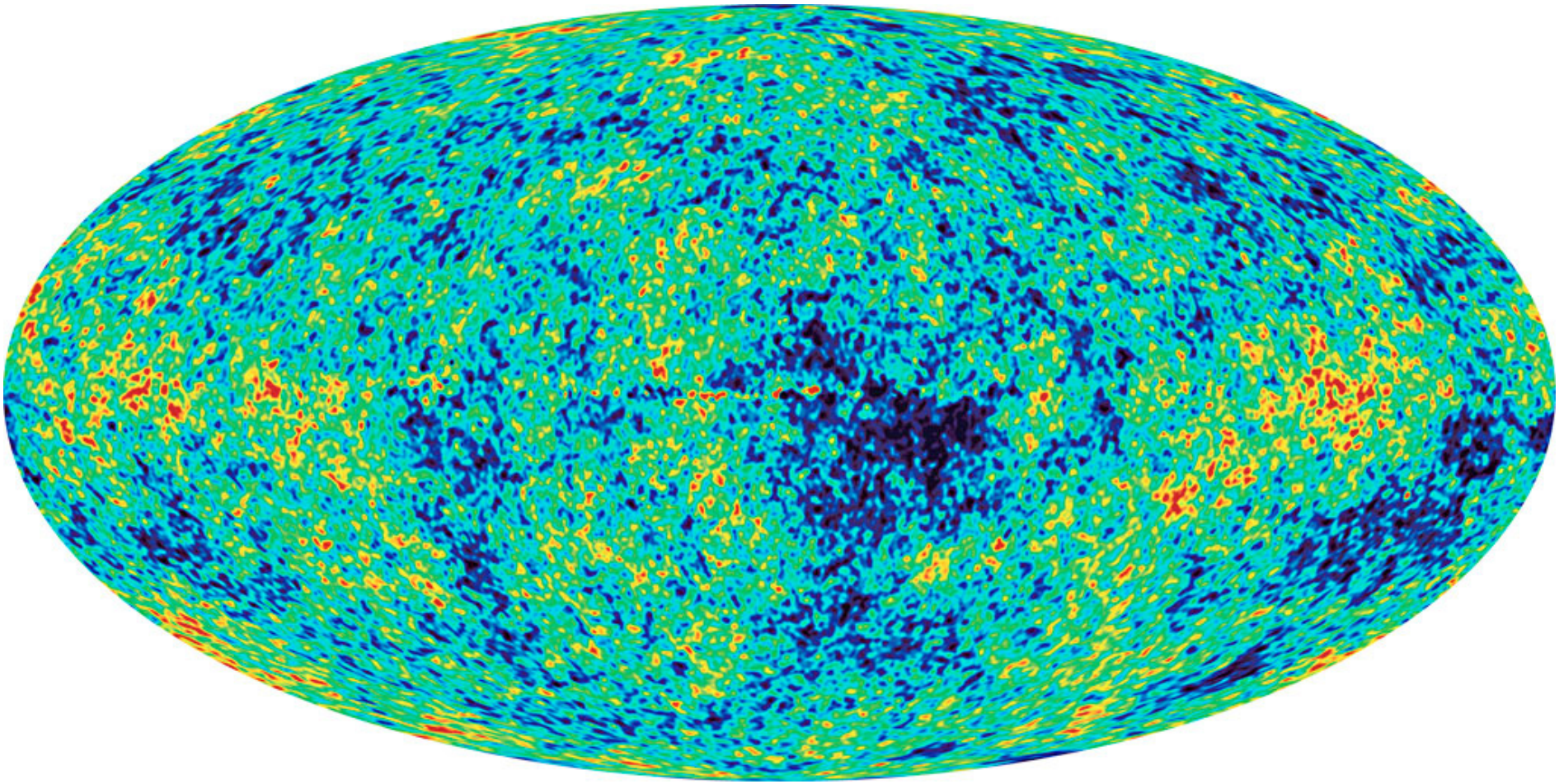
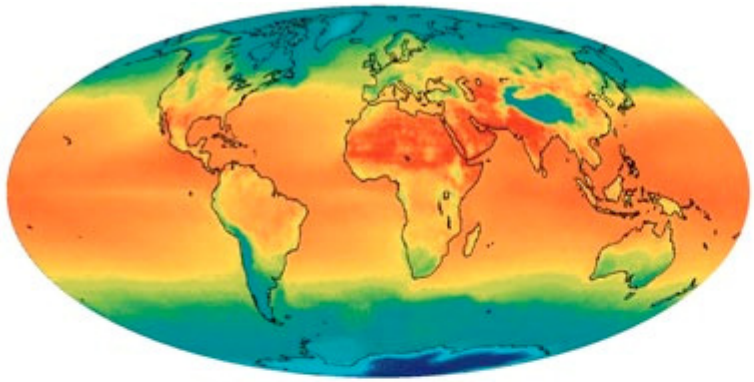


Baby picture of the Universe: 2003



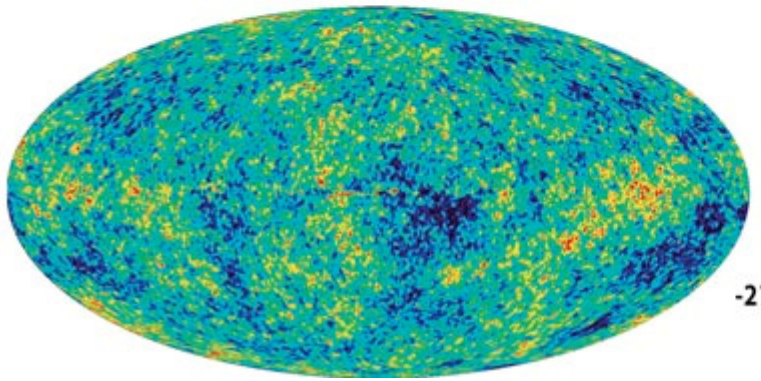
The first detailed, all-sky picture of the infant universe. The WMAP image reveals 13 billion+ year old temperature fluctuations (shown as color differences) that correspond to the seeds that grew to become the galaxies. Encoded in the patterns are the answers to many age-old questions, such as the age and geometry of the Universe

Temperature Maps



Earth
Temperatures

-63° -13° 37°
Centigrade
June 1992

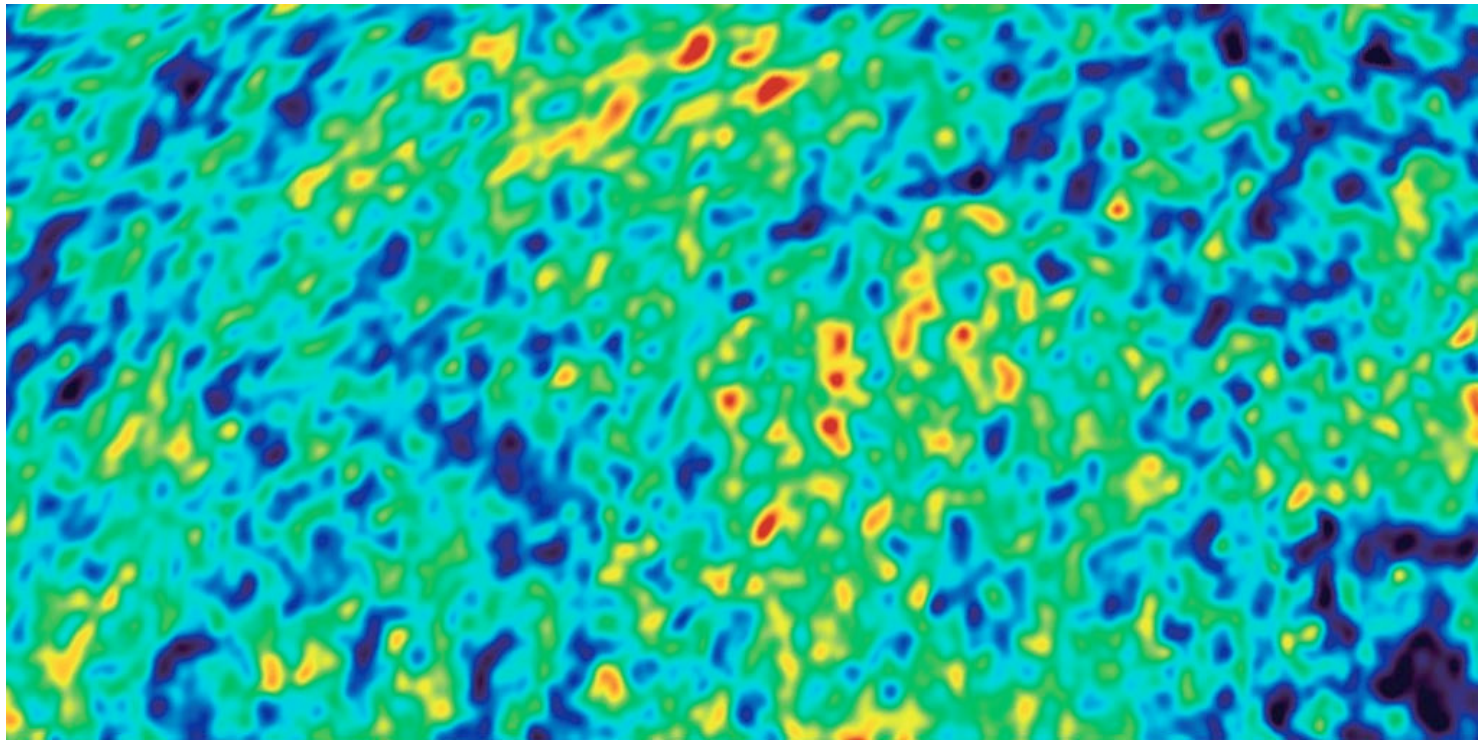


Microwave Sky
Temperatures

-270.4252° -270.4250° -270.4248°
Centigrade
380,000 Years after Big Bang

The temperature map of the Earth is a picture of data from the Earth's surface. The image captured by WMAP is from when the temperature of the universe became low enough for atoms to form, allowing light to travel great distances (to us). It is analogous to the surface of the clouds we see on an overcast day. Light travels through the clouds, but we only see the detail on the cloud's surface.

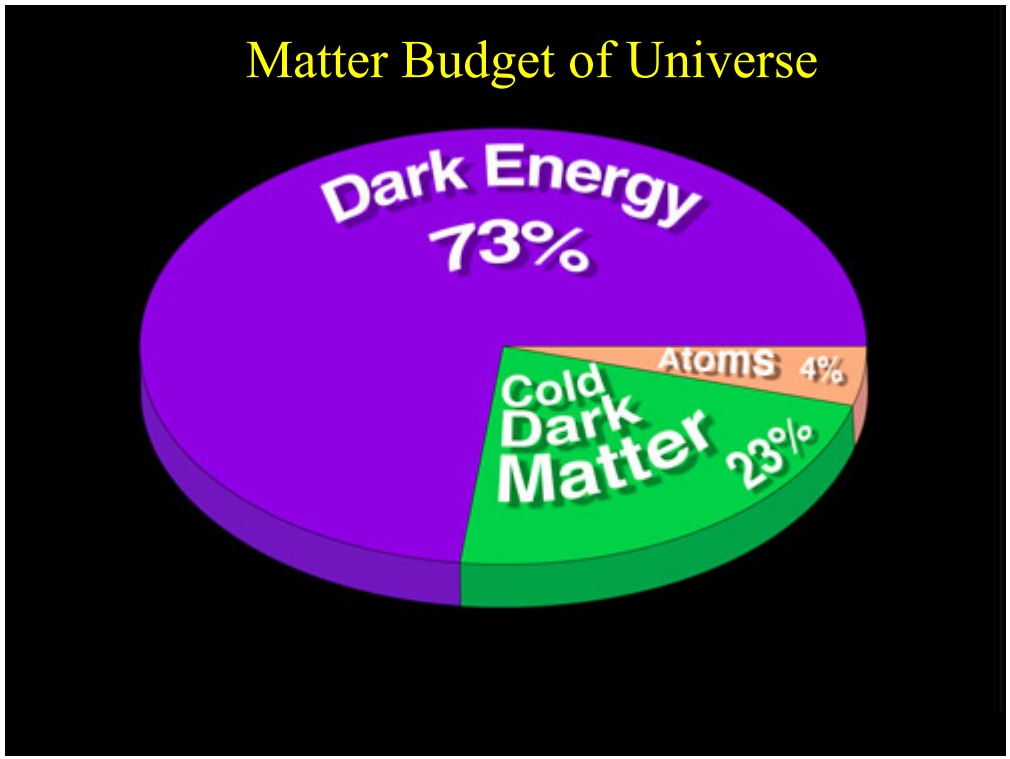
How the Universe got its spots !

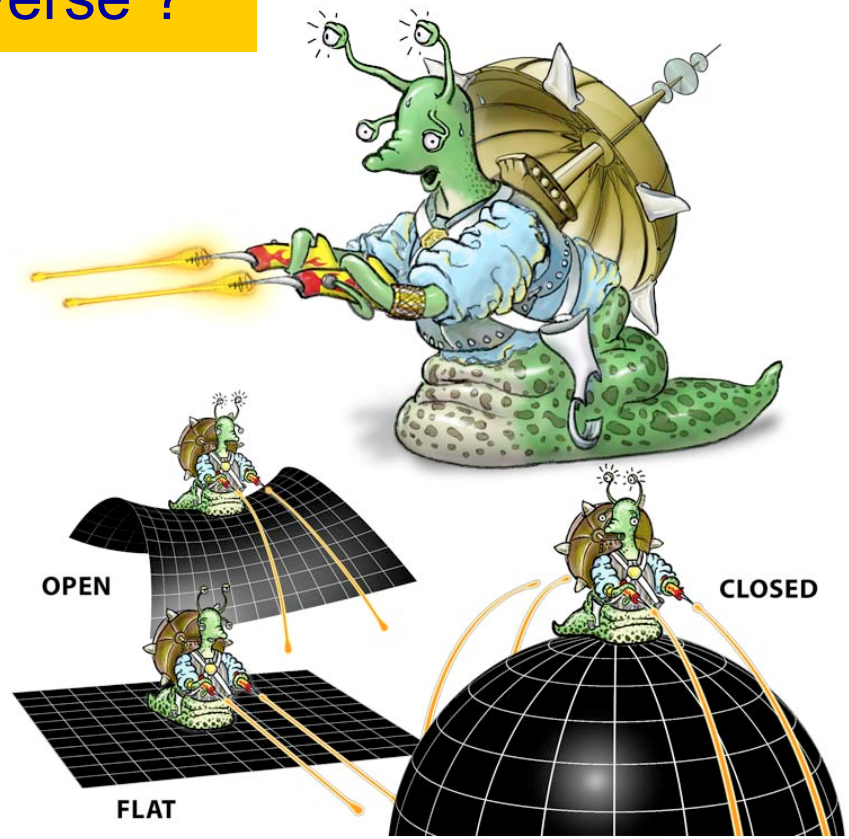


The data brings into high resolution the seeds that generated the cosmic structure we see today. These patterns are tiny temperature differences within an extraordinarily evenly dispersed microwave light bathing the Universe, which now averages a frigid 2.73 degrees above absolute zero temperature. WMAP resolves slight temperature fluctuations, which vary by only millionths of a degree.

The new data support and strengthen the Big Bang and Inflation Theories

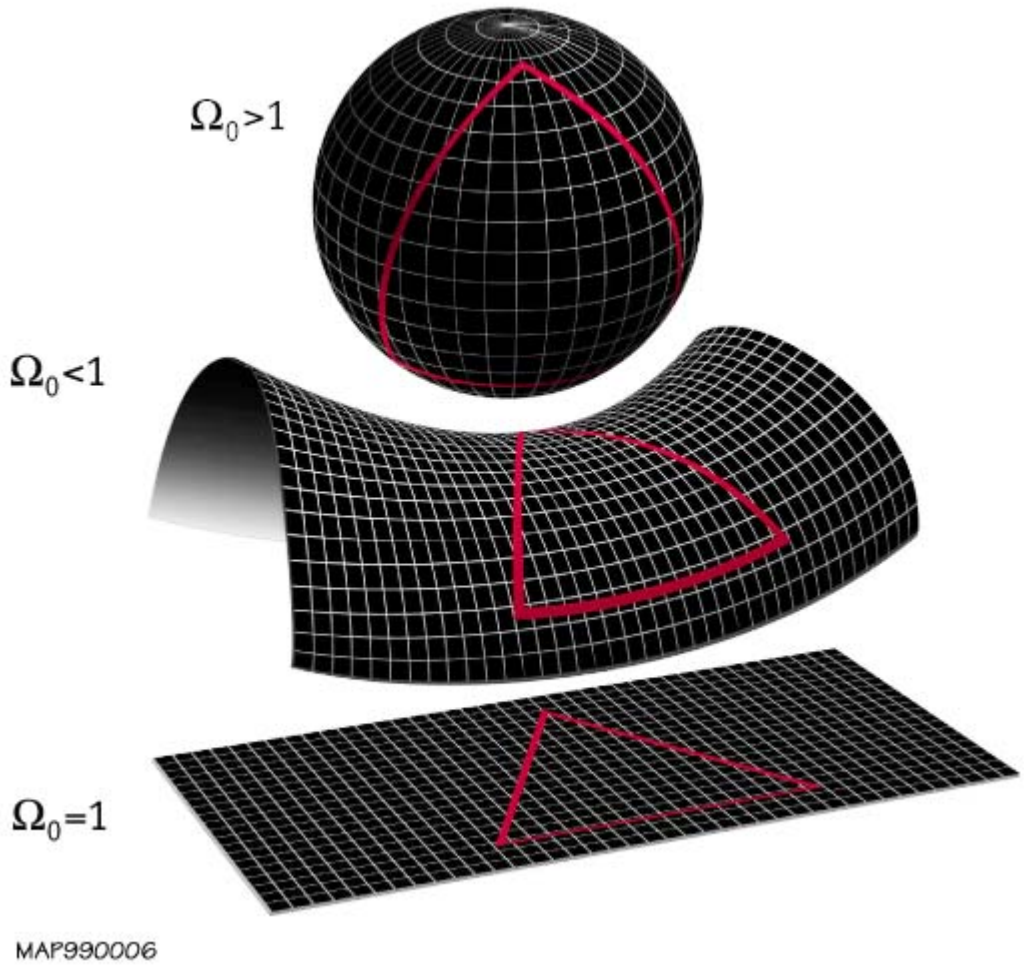
Geometry & The Fate Of The Universe ?





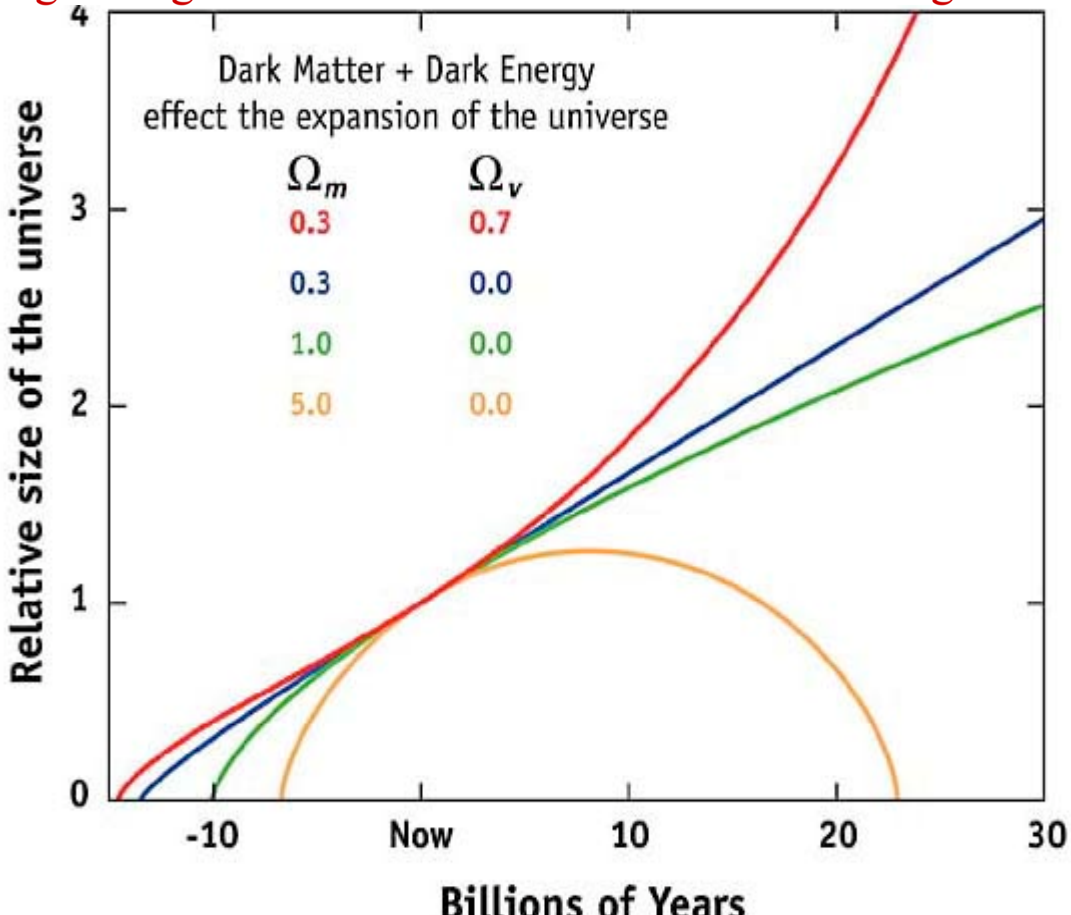
The amount of dark matter and energy in the universe plays a crucial role in determining the geometry of space. If the density of matter and energy in the universe is less than the critical density, then space is open and negatively curved like the surface of a saddle. If the density exactly equals the critical density, then space is flat like a sheet of paper. If the density is greater than critical density, then space is closed and positively curved like the surface of a sphere. In this latter case, light paths diverge and eventually converge back to a point. The Inflationary Theory, an extension of the Big Bang theory, predicts that density is very close to the critical density, producing a flat universe, like a sheet of paper.

WMAP has determined, within the limits of instrument error, that the universe is flat and will expand for ever due to the dark energy (whose nature is not understood)


$\Omega_0>1$
$\Omega_0<1$
$\Omega_0=1$
MAP990006

Possible scenarios for the expansion (or contraction) of the universe: the bottom orange curve represents a closed, high density universe which expands for several billion years, then ultimately turns around and collapses under its own weight. The green curve represents a flat, critical density universe in which the expansion rate continually slows down (the curves becomes ever more horizontal). The blue curve shows an open, low density universe whose expansion is also slowing down, but not as much as the previous two because the pull of gravity is not as strong. The top (red) curve shows a universe in which a large fraction of the matter is in a form dubbed "dark energy" which is causing the expansion of the universe to speed up (accelerate).

There is growing evidence that our universe is following the red curve



Saw what light does, Now examine matter

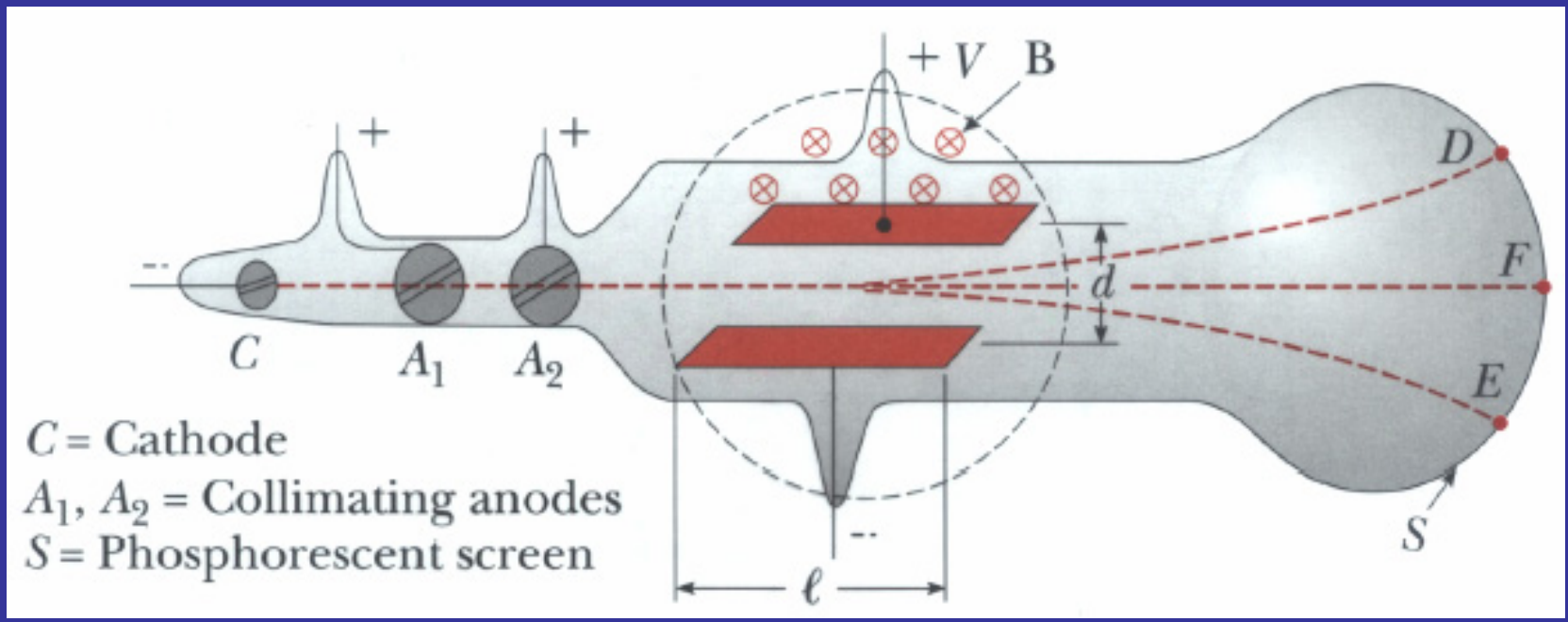
- Fundamental Characteristics of different forms of matter
  - Mass
  - Charge
    - Measurable
      - using some combination of **E** & **B**

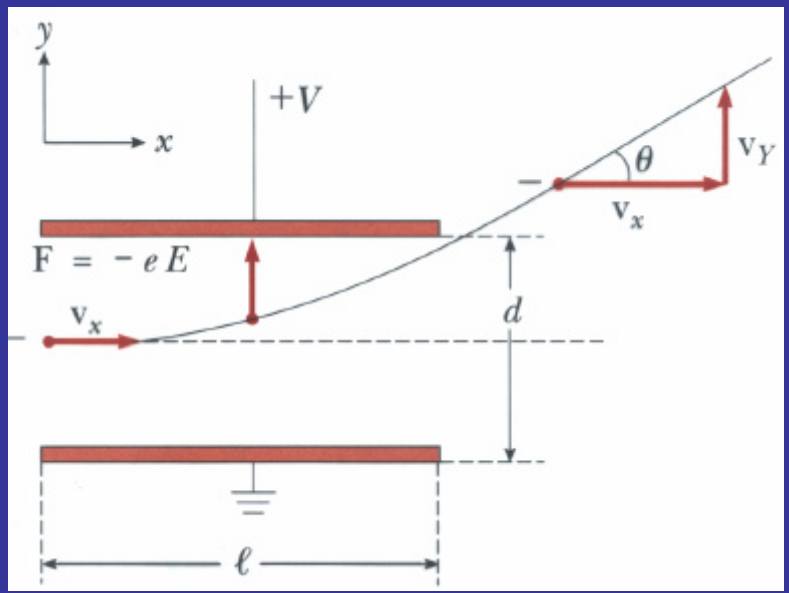
$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

      - **Or E/B and some other macroscopic force**

        e.g. Drag Force

Thomson's Determination of e/m of Electron



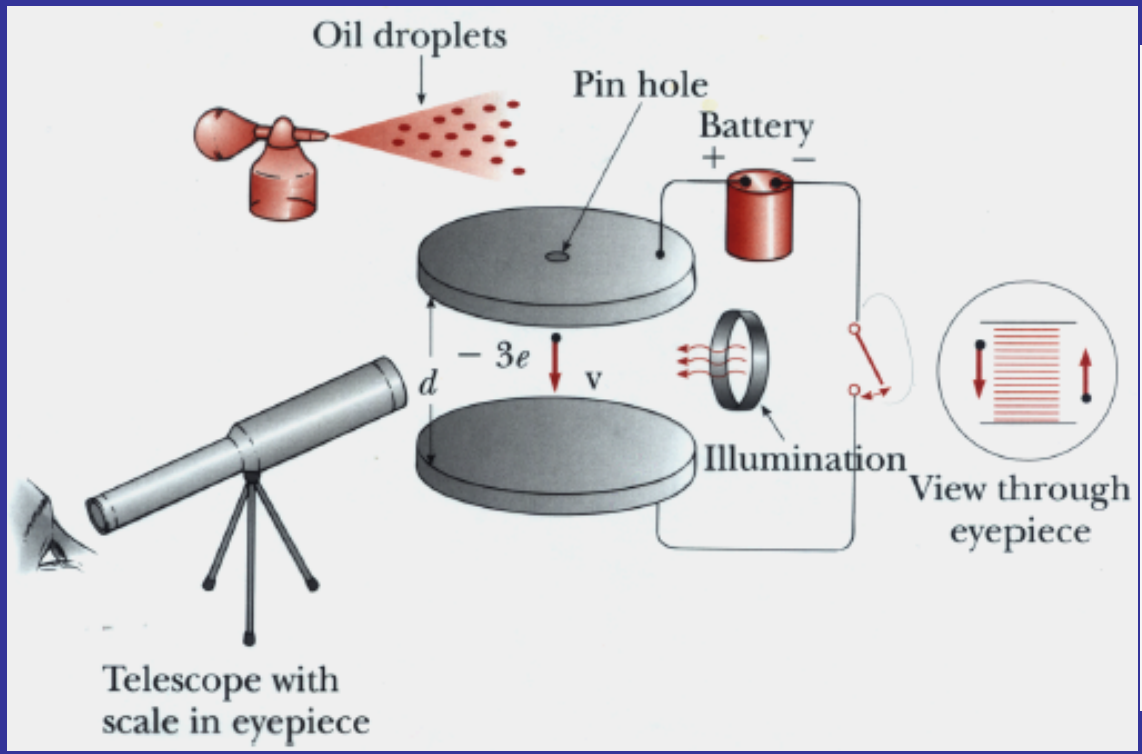


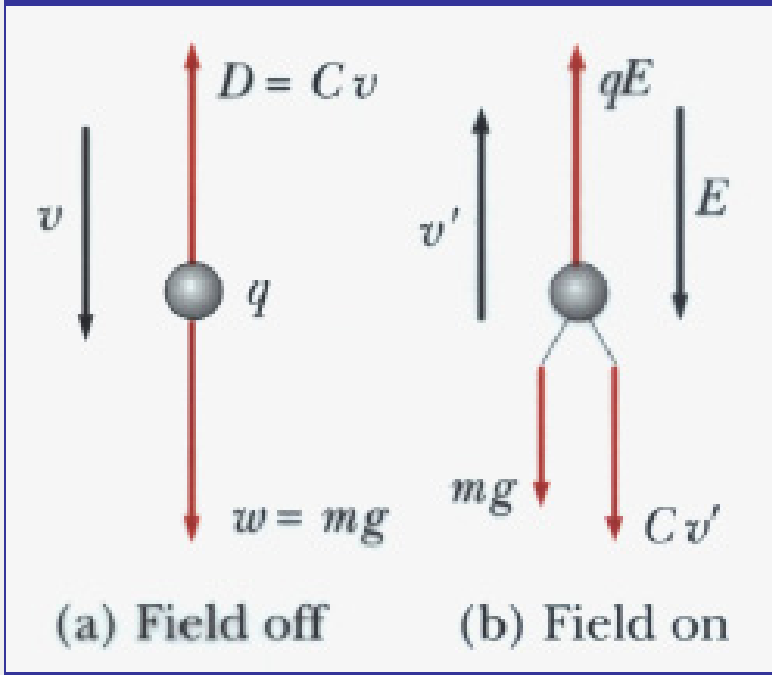
- In E Field alone, electron lands at D
- In B field alone, electron lands at E
- When E and B field adjusted to cancel

Each other's force ◊ electron lands at F

◊ e/m = 1.7588 x 10^{11} C/Kg

Millikan's Measurement of Electron Charge





Find charge on oil drop is always in integral multiple of some Q

$Q_e = 1.688 \times 10^{-19}$ Coulombs

◊ $M_e = 9.1093 \times 10^{-31}$ Kg

◊ Fundamental properties (finger print) of electron

(similarly can measure proton properties etc)