Introducing Cosmology

講師資訊

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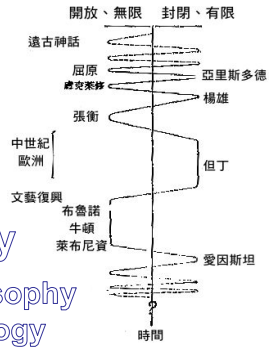
What is the Universe?

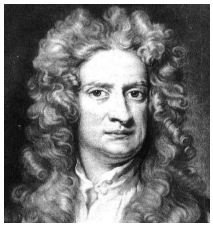
- When?
- How?
- Size?
- Shape?
- What?
- Where?

Cosmology

- Why? Philosophy
- Who? Theology



First Qualitative Cosmology: Newton-Bentley Exchange



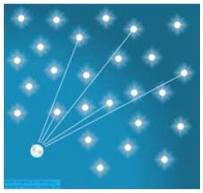
1643－1727

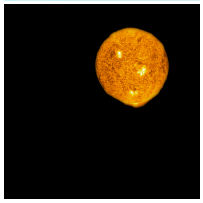
1662–1742

Newton's Static Universe

- Universe is static and composed of an infinite number of stars that are scattered randomly throughout an infinite space.
- Universe is infinitely old and will exist forever without any major changes.
- Time and Space are steady and independent of one another and any objects in existence within them.

Olbers's Paradox





Why is the sky dark at night?
(Kepler, 1610. Olbers, 1823)

If the universe is infinite, then every line of sight should end on the surface of a star at some point.

⇒ The night sky should be as bright as the surface of stars!

Solution to Olbers's Paradox:

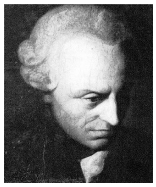
Allan Poe(1848, Eureka), Kelvin(1901)

If the universe had a beginning, then we can only see light from galaxies that has had time to travel to us since the beginning of the universe.

⇒ The **visible** universe is **finite**!

About the Edge of the Universe: Newton-Leibniz-Kant Debate

1646 – 1716



1724 – 1804

- ☐ edged, finite
- ☐ no edge, infinite
- ☐ finite, edged
- ☐ infinite, no edge

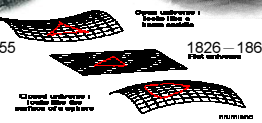
1. Stable system
2. No center
3. Infinite(Euclide space)

→ insoluble

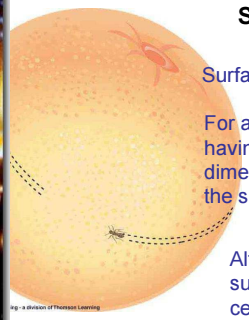
Curved Space: Gauss and Riemann

1777 – 1855

1826 – 1866 (1854)



Finite, but without Edge?



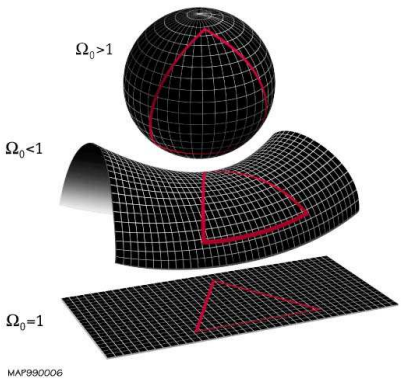
2-dimensional analogy
Surface of a sphere

Surface is finite, but has no edge.

For a creature living on the sphere, having no sense of the third dimension, there's no center (on the sphere!): All points are equal.

Alternative: Any point on the surface can be defined as the center of a coordinate system.

Curvature: the shape of Universe

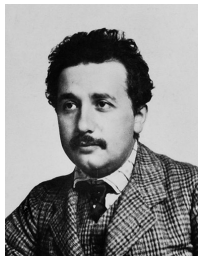


The New Physics

- Special Relativity, 1905
- General Relativity, 1915

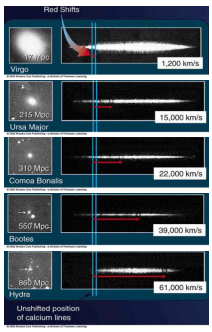
$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- Solutions in General Relativity
  - Schwarzchild, 1916
  - Einstein, 1917
    - ➢ cosmological constant
  - Friedmann & Lemaître, 1922, 1931
  - Einstein & de Sitter, 1932



1879 – 1955

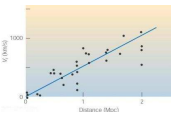
Hubble's Law



1889–1953

Vesto Slipher

1875–1969



Henrietta Leavitt

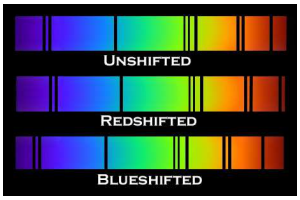
1868–1921

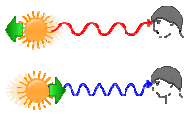
Distant galaxies are receding from us with a speed proportional to distance. $v = H_0 D$ (1929)

Doppler Effect and Redshift

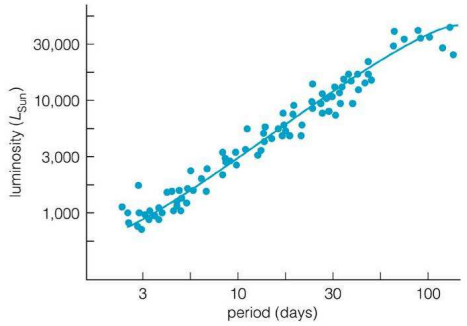
$$z \equiv \frac{\Delta\lambda}{\lambda} = \frac{\lambda - \lambda_0}{\lambda_0} \approx \frac{v}{c}$$

- Doppler effect
- Cosmological redshift
- Gravitational redshift





Period-Luminosity Relation of Cepheid



Density parameter Ω, Curvature and destiny of Universe

$$v = H_0 R$$

$$v_e = \sqrt{\frac{2GM}{R}}$$

$$M = \frac{4\pi}{3} R^3 \rho_0$$

$$\Rightarrow \rho_c = \frac{3H_0^{\,2}}{8\pi G}$$

$if\ v > v_e \Rightarrow \rho_c > \rho_0$ **...A**

$if\ v < v_e \Rightarrow \rho_c < \rho_0$ **...B**

$if\ v = v_e \Rightarrow \rho_c = \rho_0$ **...C**

$\Omega = \rho_0 / \rho_c$

$\rho_c \fallingdotseq 9\times10^{-27}$ kg/m^3

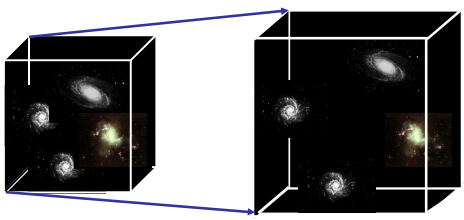
A. negative curvature
open, infinite
expand forever

B. positive curvature
closed, finite
expand to shrink

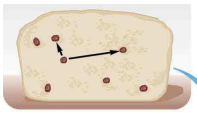
C. flat universe
open, infinite
expand forever

The Expanding Universe

- On large scales, galaxies are moving apart, with velocity proportional to distance.
- It's not galaxies moving through space.
- Space is expanding, carrying the galaxies along!
- The galaxies themselves are not expanding!

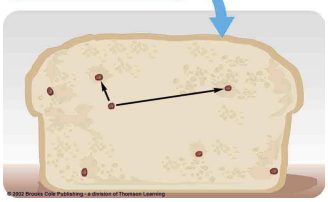


Expanding Space



Analogy:

A loaf of raisin bread where the dough is rising and expanding, taking the raisins with it.



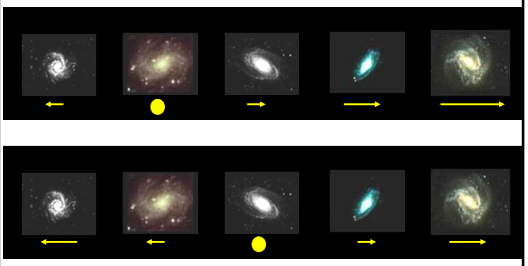
Misconception:

What is the Universe expanding into?

Where is north of the North Pole?

The Expanding Universe

This does not mean that we are at the center of the universe!



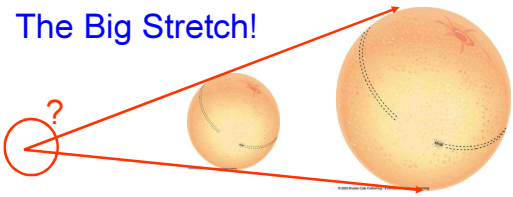
You have the same impression from any other galaxy as well.

The Necessity of a Big Bang

If galaxies are moving away from each other with a speed proportional to distance, there must have been a beginning, when everything was concentrated in one single point:

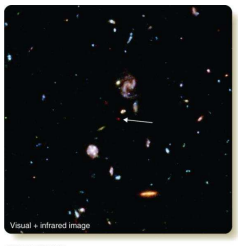
The Big Bang!

The Big Stretch!



The Age of the Universe

Knowing the current rate of expansion of the universe, we can estimate the time it took for galaxies to move as far apart as they are today:



time = distance / velocity

$v = H_0 D$

H_0=67.80±0.77 Mpc/km/s
(Planck, 2013)

$t \approx d/v = 1/H \sim 13.8$ billion years

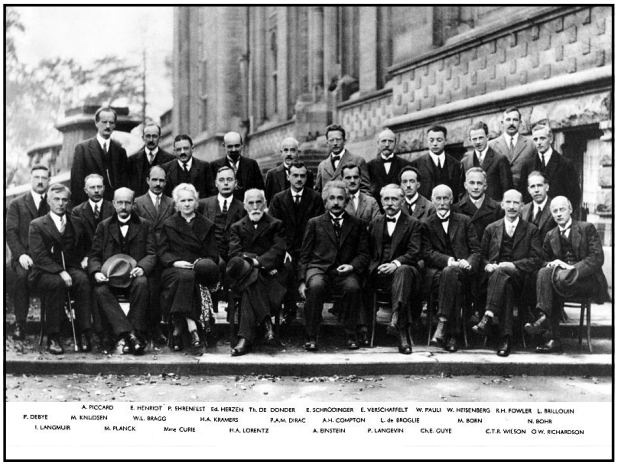
Hubble time

It's a estimated age!

Lemaître and Primeval Atom

1894-1966

- Derived Hubble's law, but not linear relation, 1927
- Published "Hypothesis of the Primeval Atom" in Nature,128 1931Natur.128..704L
- Propose the expansion of the Universe was accelerating, 1931

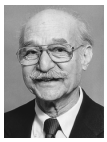


$\alpha\ \beta\ \gamma$ & Cosmic Background Radiation

George Gamow
1904—1968

Ralph Alpher
1921—2007

Hans Bethe
1906-2005



Robert Herman
1914—1997

- Advocate and developer of Lemaître's Big Bang
- Modeling the creation of elements, 1942
- Hot Big Bang & CBR~50K , 1946
- Dicke and Peebles: Helium abundance → hot early Universe → blackbody radiation field, 1946
- Alpher and Herman: CBR~5K, 1948

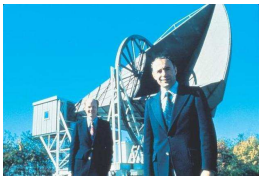
Cosmic Background Radiation

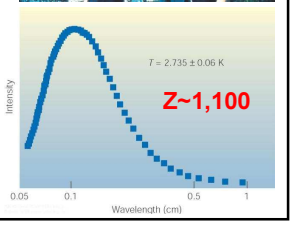
The radiation from the very early universe should still be detectable

Wilson (1936-) & Penzias (1933-)

discovered blackbody radiation with T = 2.73 K ($dE_\lambda/d\lambda$=1.063 mm, 160 GHz, Microwave)

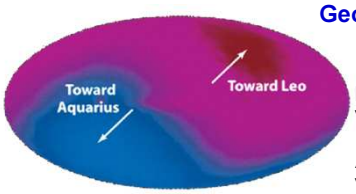
be awarded the Nobel Prize for Physics in 1978





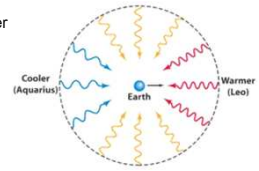
CMB: Modern Ether Drift Experiments

George Smoot
1945-

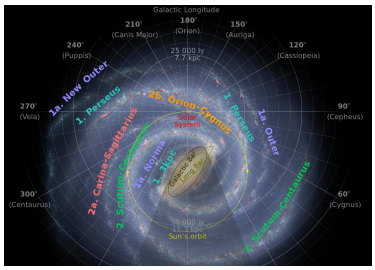


l=245°±15°
b=54°±10°
V=390±60 km/s
(1977)
ΔT=0.00337K
V=371 km/s

DMR
Differential Microwave Radiometer

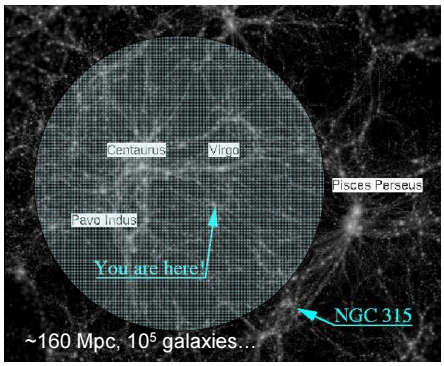


Galactic Particular Velocity



- Earth's Rotation: 0~0.465 km/sec
- Earth orbits around the Sun: 29.786 km/sec
- Sun orbits around the Galaxy: 250 km/sec
- CMB value: ~620 km/sec

Earth's new address: Solar System, Milky Way, Laniakea



CMB: Modern Ether Drift Experiments

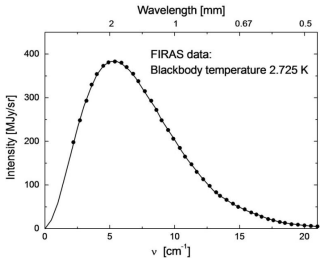
Vera Rubin
1928-

- Started to develop an interest in astronomy since 10.
- BA at Vassar College, enroll at Princeton but be denied.
- "galaxies might be rotating around unknown centers, rather than simply moving outwards, as suggested by the Big Bang theory" (Master at Cornell U, 1951).
- "galaxies clumped together, rather than being randomly distributed" (Georgetown U. PhD, 1954).
- Galaxy rotation problem: Dark Matter (1970-1980).

COBE look at the CMB

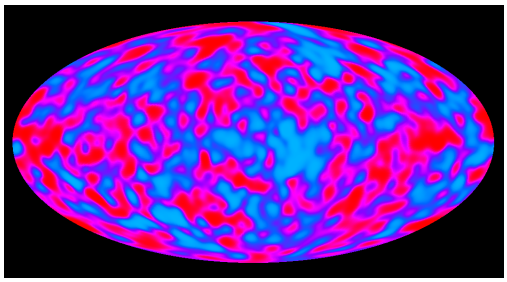
COsmic **B**ackground **E**xplorer (November 18, 1989)

Principal Investigators
George Smoot, John Mather



FIRAS
Far Infrared Absolute Spectrophotometer

Cosmology's Holy Grail



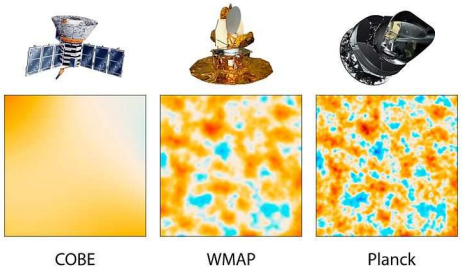
COBE detected **anisotropies** at the level 100 μK of the CMB. The density fluctuations are believed to have produced structure formation.

The Nobel Prize in Physics 2006

"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation".

John C. Mather
NASA Goddard Space Flight Center, Greenbelt, MD, USA,
George F. Smoot
University of California, Berkeley, CA, USA

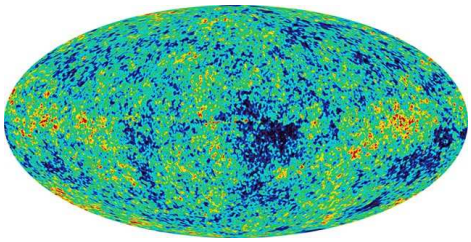
COBE,WMAP, Planck Comparison



Ever-increasing resolution of our maps of the cosmic microwave background radiation from COBE launched in 1989 to WMAP in 2001 (30x better resolution than COBE) to Planck in 2009 (2.5x better than WMAP)

Cosmology with the Cosmic Microwave Background

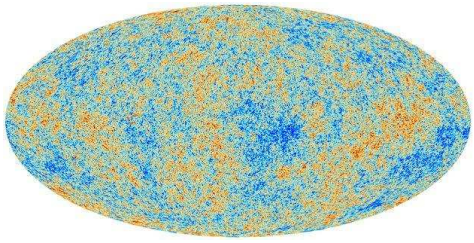
If the universe were perfectly homogeneous on all scales at the time of recombination (z = 1100), then the CMB should be perfectly isotropic over the sky.



Instead, it shows small-scale fluctuations:

Planck Reveals an Almost Perfect Universe

The image is based on the initial 15.5 months of data from Planck and is the mission's first all-sky picture of the oldest light in our Universe



Cosmic microwave background seen by Planck

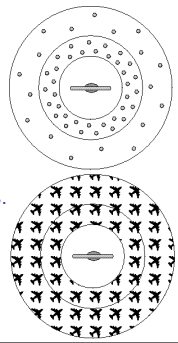
The Cosmological Principle

Considering the largest scales in the universe, we make the following fundamental assumptions:

Homogeneity
the local universe has the same physical properties throughout the universe.

Isotropy
the local universe looks the same in any direction that one observes.

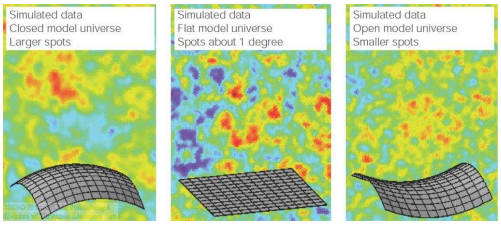
Universality
the laws of physics are the same everywhere in the universe.



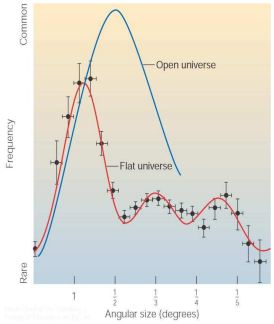
Fluctuations in the Cosmic Microwave Background

The angular size of the CMB fluctuations allows us to probe the geometry of space-time!

CMB fluctuations have a characteristic size of 1 degree.



Analysis of the Cosmic Background Fluctuations

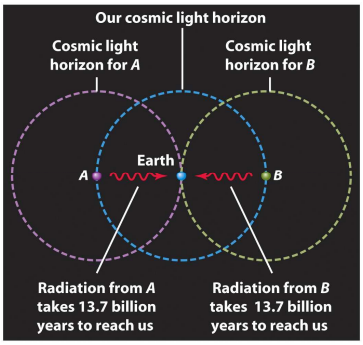


Analyze frequency of occurrence of fluctuations on a particular angular scale

→ Universe has a flat geometry

go

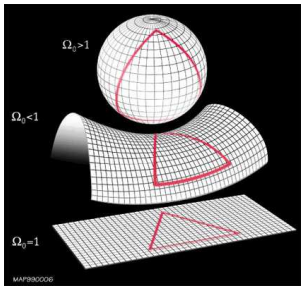
The Isotropy (Horizon) Problem



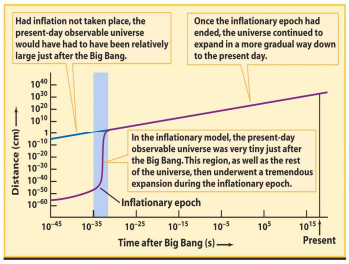
The Flatness Problem

Ω very close to 1, $|\Omega-1|<0.01$ currently,

10^{-62} at the Planck era.



Inflationary theory

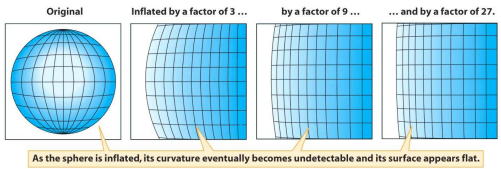


10^{-36} ~ 10^{-32} second, expand 10^{20} ~ 10^{30}

Alan Guth

1947~, 1979

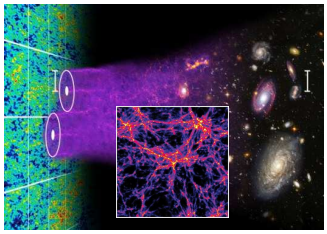
Inflation explains why the universe is nearly flat and the 2.725 K microwave background is almost perfectly isotropic



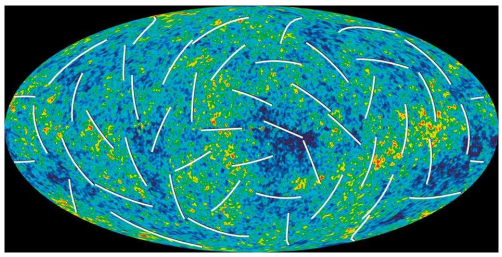
Baryon Acoustic Oscillations

quantum fluctuation during inflation → higher density of plasma → radiation pressure from the photons resists the gravitational compression → sound waves propagate in the universe, last to recombination era. (~37,6000 years) → large scale structures formed from density fluctuations.

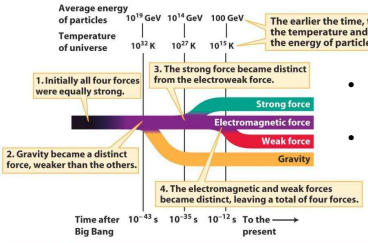
- size of Universe ~ 27.6 Mpc at that time
- major oscillation angular angle~ 1°
- **oscillation ~ 150 Mpc at present**



Evidence of Inflation: Polarization of CMB



The Fundamental Force of Nature

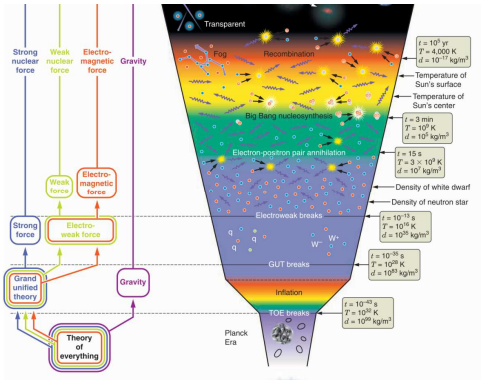


- Grand unified theories (GUTs)
- 4-forces were equivalent just after the Big Bang.

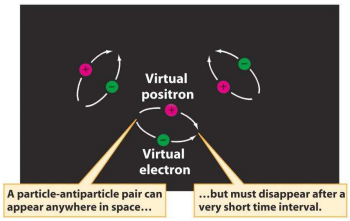
table 29-1 The Four Forces

Force	Relative strength	Particles exchanged	Particles on which the force can act	Range	Example
Strong	1	gluons	quarks	10^{-15} m	holding protons, neutrons, and nuclei together
Electromagnetic	1/137	photons	charged particles	infinite	holding atoms together
Weak	10^{-4}	intermediate vector bosons	quarks, electrons, neutrinos	10^{-16} m	radioactive decay
Gravitational	6×10^{-39}	gravitons	everything	infinite	holding the solar system together

Evolution of the Universe



Quantum Mechanics and Heisenberg's Uncertainty Principle



$$\Delta E \times \Delta t = \frac{h}{2\pi} \qquad \Delta m \times \Delta t = \frac{h}{2\pi c^2}$$

ΔE = uncertainty in energy

Δt = time interval over which energy is measured

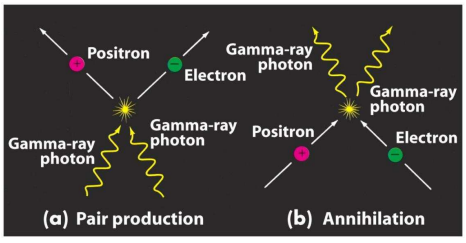
h = Planck's constant = 6.625×10^{-34} J s

$$\Delta t = \frac{1}{\Delta m} \frac{h}{2\pi c^2} = \cdot$$

$$= 6.43 \times 10^{-22} \text{ s}$$

$$\Delta E = \Delta m \times c^2$$

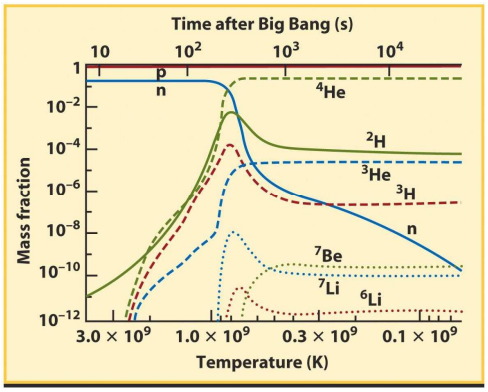
Matter and Antimatter, Pair Production and Annihilated

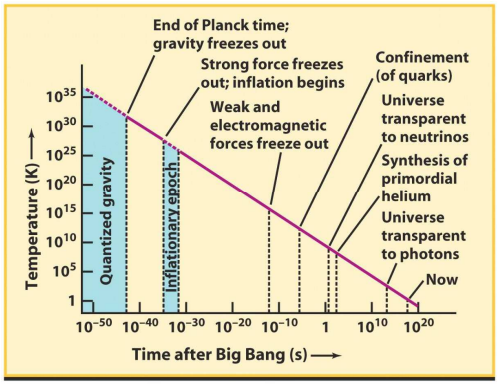


- A virtual pair can become a real particle-antiparticle pair when high-energy photons collide
- In this process, called pair production, the photons disappear, and their energy is replaced by the mass of the particle-antiparticle pair
- In the process of annihilation, a colliding particle-antiparticle pair disappears and high energy photons appear

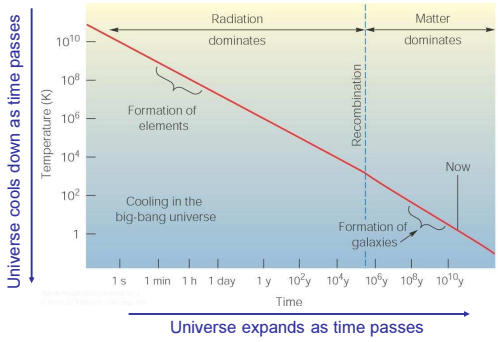
The Early History of the Universe

- $t=10^{-6}$ s, $T=10^{13}$K, E= 1GeV. After Quark confinement period: proton and neutron appear.
- t=1s, $T=6\times10^{9}$K, electron and positron appear. Gamma-ray background radiation
- Primordial Fireball ~380,000 yrs
- Asymmetry between matter and anti-matter: 10^{9}+1:1
- $n \rightarrow p + e^{-} + \bar{\nu}$ half-life ~10.5 mins
- deuterium bottleneck (unstable)
- After 3 mins, photon didn't break deuterium
- p : n~ 6 : 1, n + deuterium → helium
- After 15 mins, nucleosynthesis stop
- Only H: He~9:1, little Li, Be

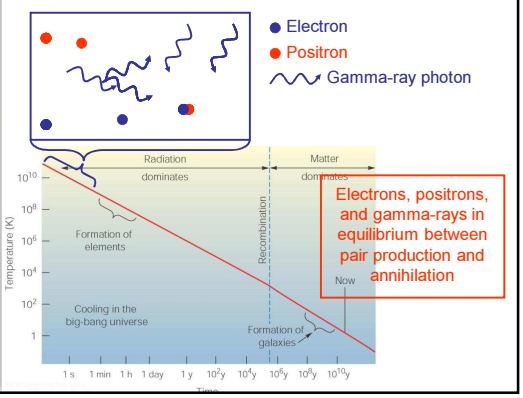




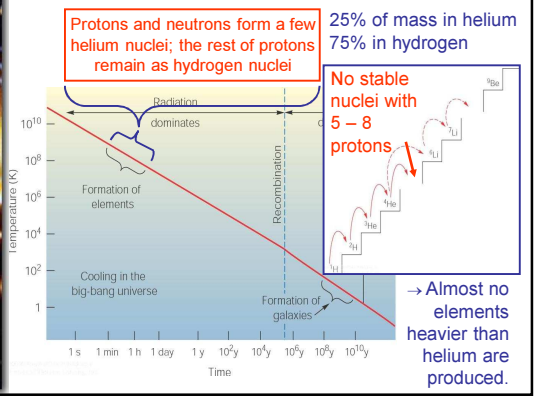
The History of the Universe



The Early History of the Universe



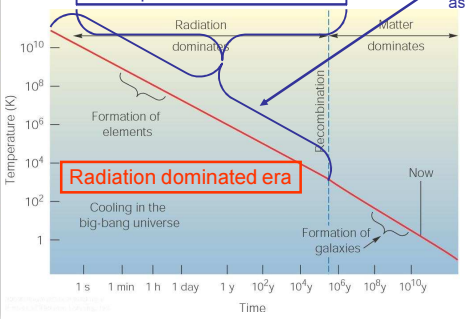
The Early History of the Universe



The Early History of the Universe

Photons are incessantly scattered by free electrons; photons are in equilibrium with matter

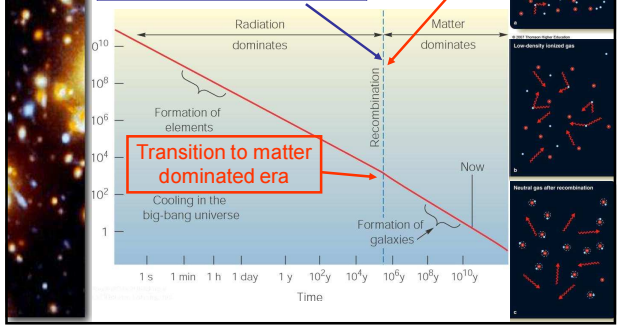
Photons have a blackbody spectrum at the same temperature as matter.



Recombination

Protons and electrons recombine to form atoms => universe becomes transparent for photons

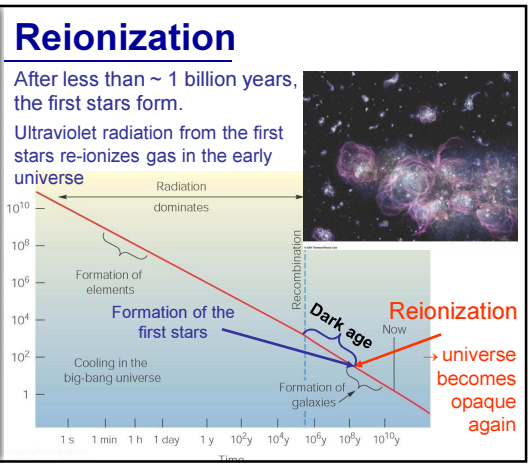
z ≈1100
T ≈ 3000 K



Reionization

After less than ~ 1 billion years, the first stars form.

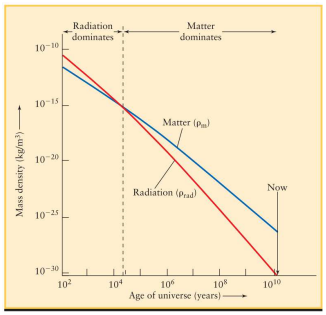
Ultraviolet radiation from the first stars re-ionizes gas in the early universe



→ universe becomes opaque again

Radiation and Matter in the Universe

The total energy of the universe consists of both radiation and matter.



$$\rho_{rad} = \frac{4\sigma T^4}{c^3}$$

For the present-day

$\rho_{rad} = 4.6 \times 10^{-31}$ kg/m³

$\rho_m = 2.4 \times 10^{-27}$ kg/m³

luminous 4.2×10^{-28} kg/m³

After Big Bang 24,000 years, universe from

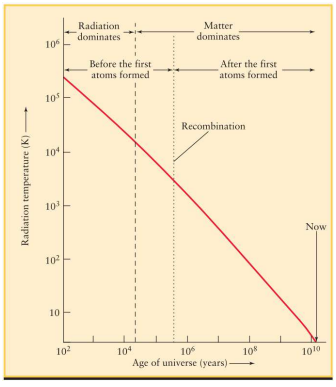
Radiation-dominated

⇩

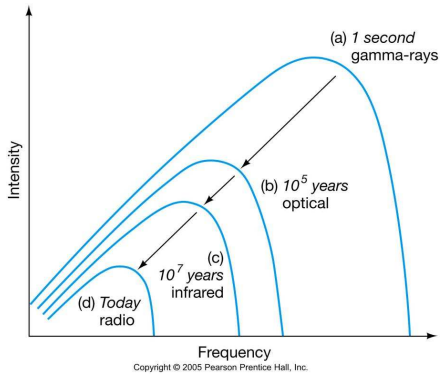
Matter-dominated

Z=5,200

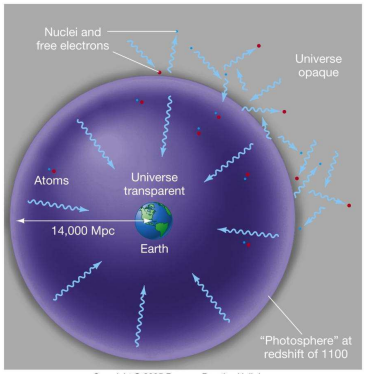
Evolution of Radiation Temperature



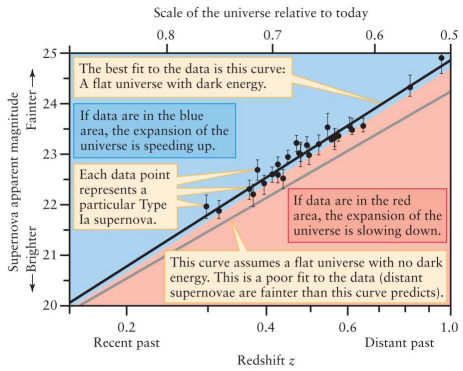
The History of CBR



Origin of the CBR: Scattering Surface

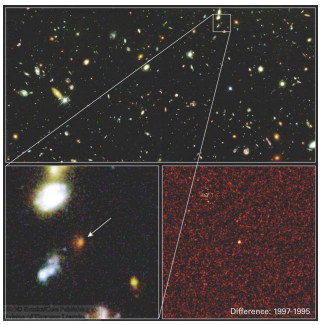


The Accelerating Universe



Confirmation of the Acceleration

Observation of the high-red-shift (z = 1.7) SN Ia SN1997ff seems to confirm the acceleration of the universe.



The Nobel Prize in Physics 2011

"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"

Photo: Ariel Zambelich, Copyright © Nobel Media AB

Saul Perlmutter

Photo: Belinda Pratten, Australian National University

Brian P. Schmidt

Photo: Homewood Photography

Adam G. Riess

The Cosmological Constant

- Cosmic acceleration can be explained with the "Cosmological Constant", Λ (upper-case lambda)
- Λ is a free parameter in Einstein's fundamental equation of general relativity; previously believed to be 0.
- Energy corresponding to Λ can account for the missing mass/energy ($E = mc^2$) needed to produce a flat space-time.

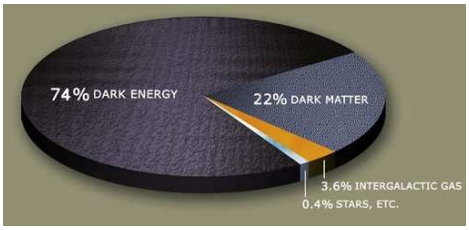
→ "**Dark Energy**"

Cosmological Parameters from 2013 Planck results

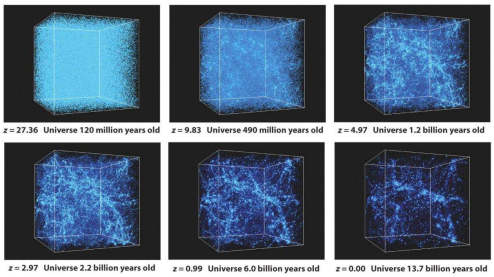
Age of the universe (Ga)	Hubble's constant ($^{km}/_{Mpc \cdot s}$)	Physical baryon density	Physical cold dark matter density
13.819	67.11	0.022068	0.12029

Dark energy density	Density fluctuations at $8h^{-1}$Mpc	Scalar spectral index	Reionization optical depth
0.6825	0.8344	0.9624	0.0925

Estimated distribution of Matter and Energy in the Universe

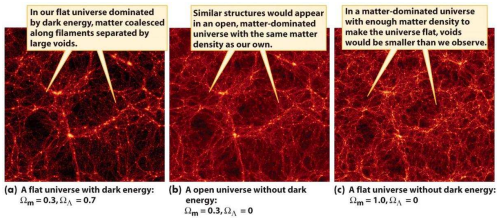


Simulation of the Formation of Large-scale Structures

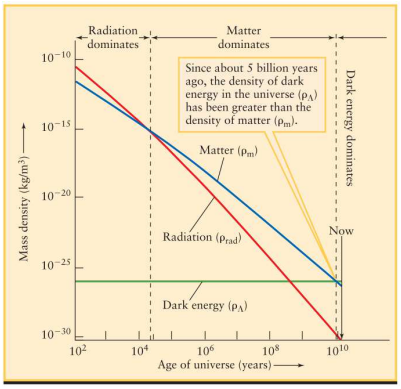


Structures in the Universe

Models based on dark energy and cold dark matter give good agreement with details of the large-scale structure



Evolution of Density, Revisited



Thank you for your attention

Q & A