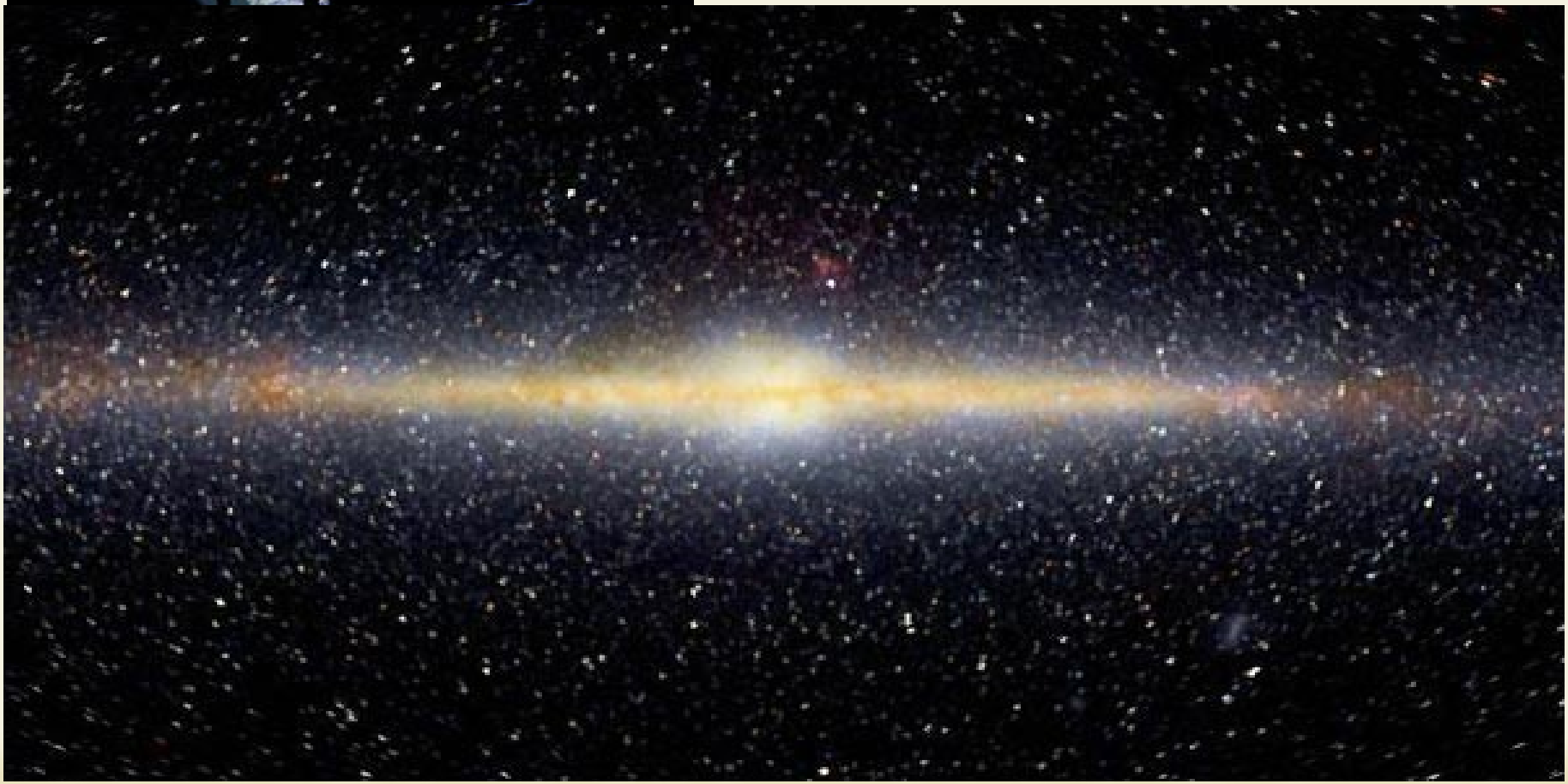
Window to the Dark Side of the Universe

Dr. Russell Herman
Physics and Physical Oceanography, UNCW

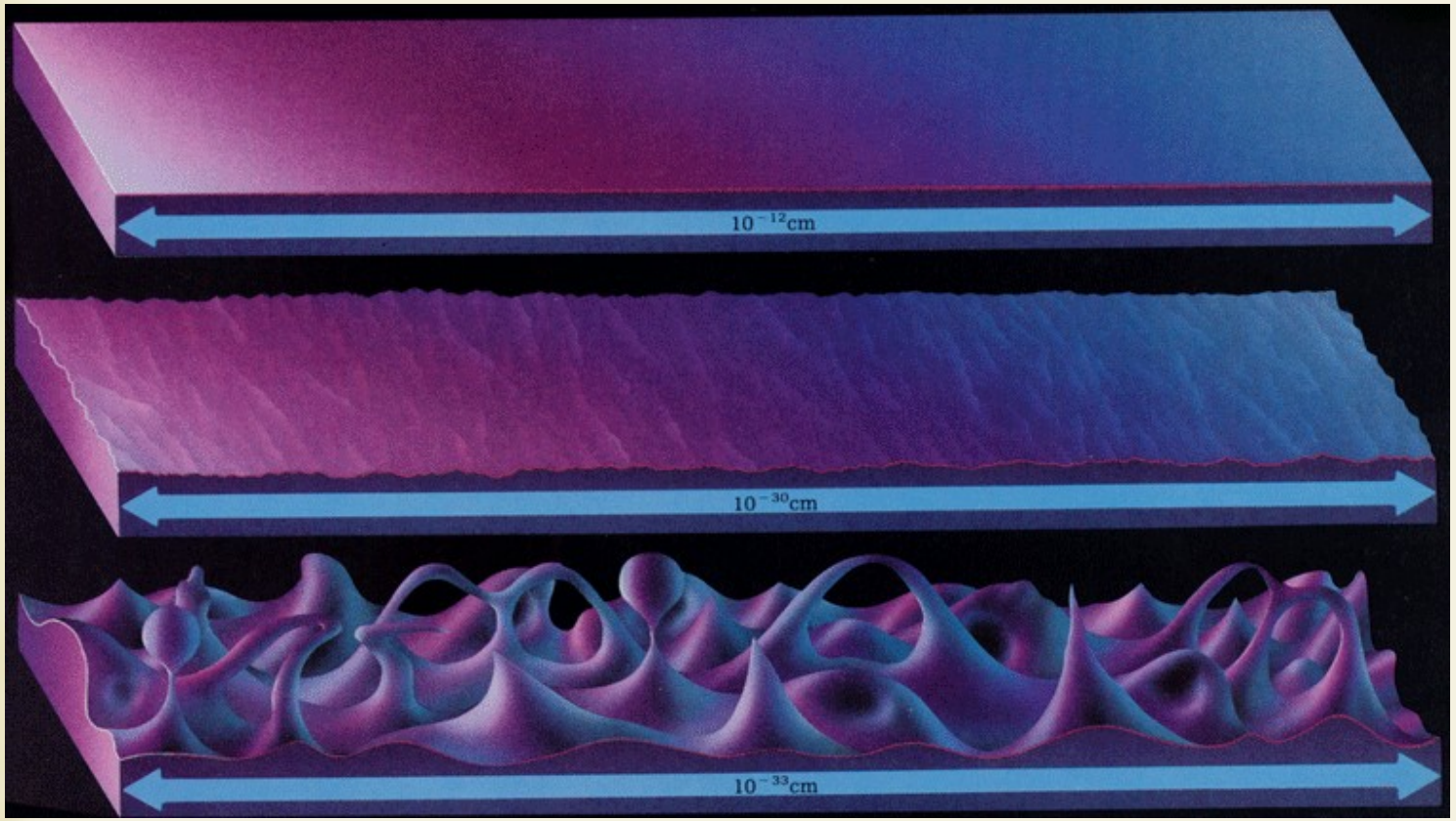
for
Osher Lifelong Learning Institute
March 1, 2012



http://www.dimijianimages.com/More-p20-Madagascar-p7/night-sky-from-Madagascar-gallery.htm

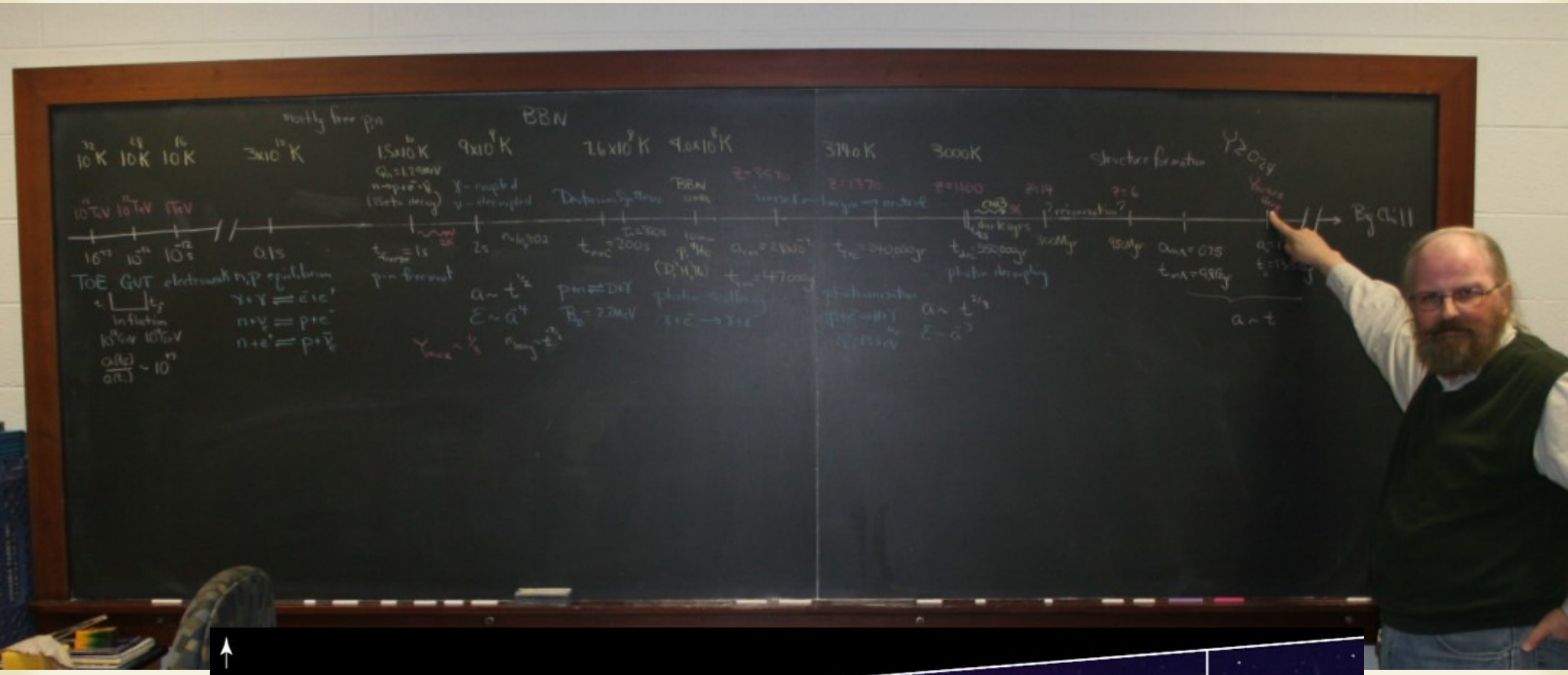
About 13,750,000,000 yrs ago

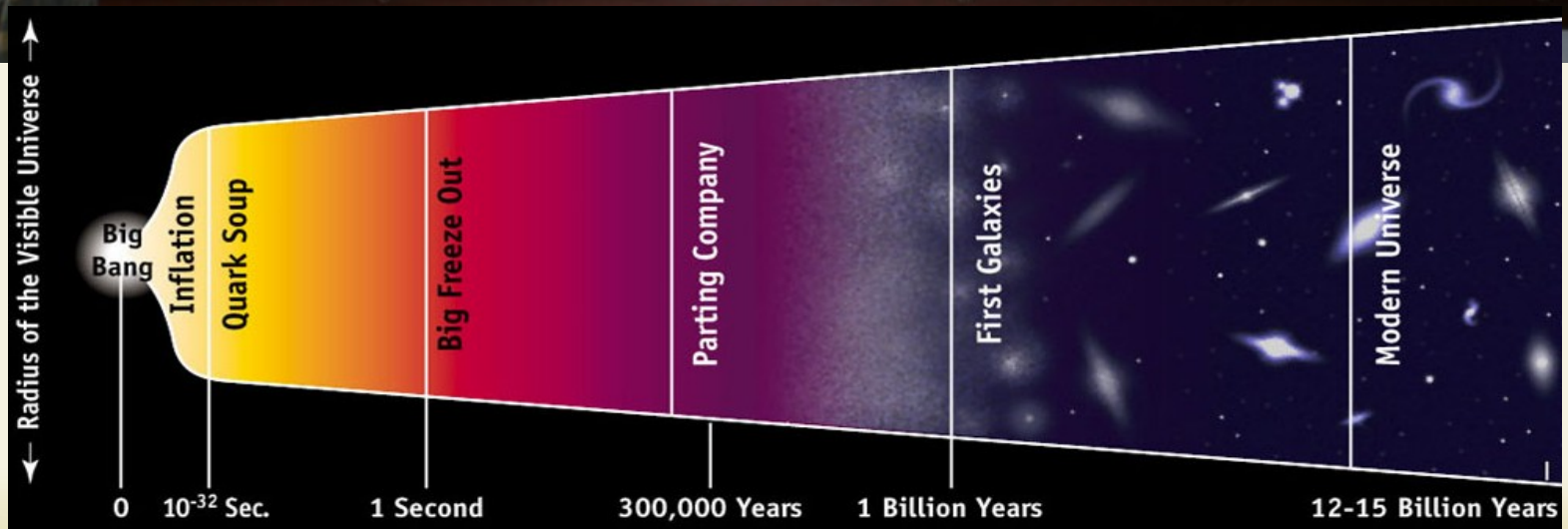
(plus or minus 110,000,000 yrs and a day or two)



http://www.zamandayolculuk.com/cetinbal/HTMLdosya1/QuantumFoam.htm

History of the Universe



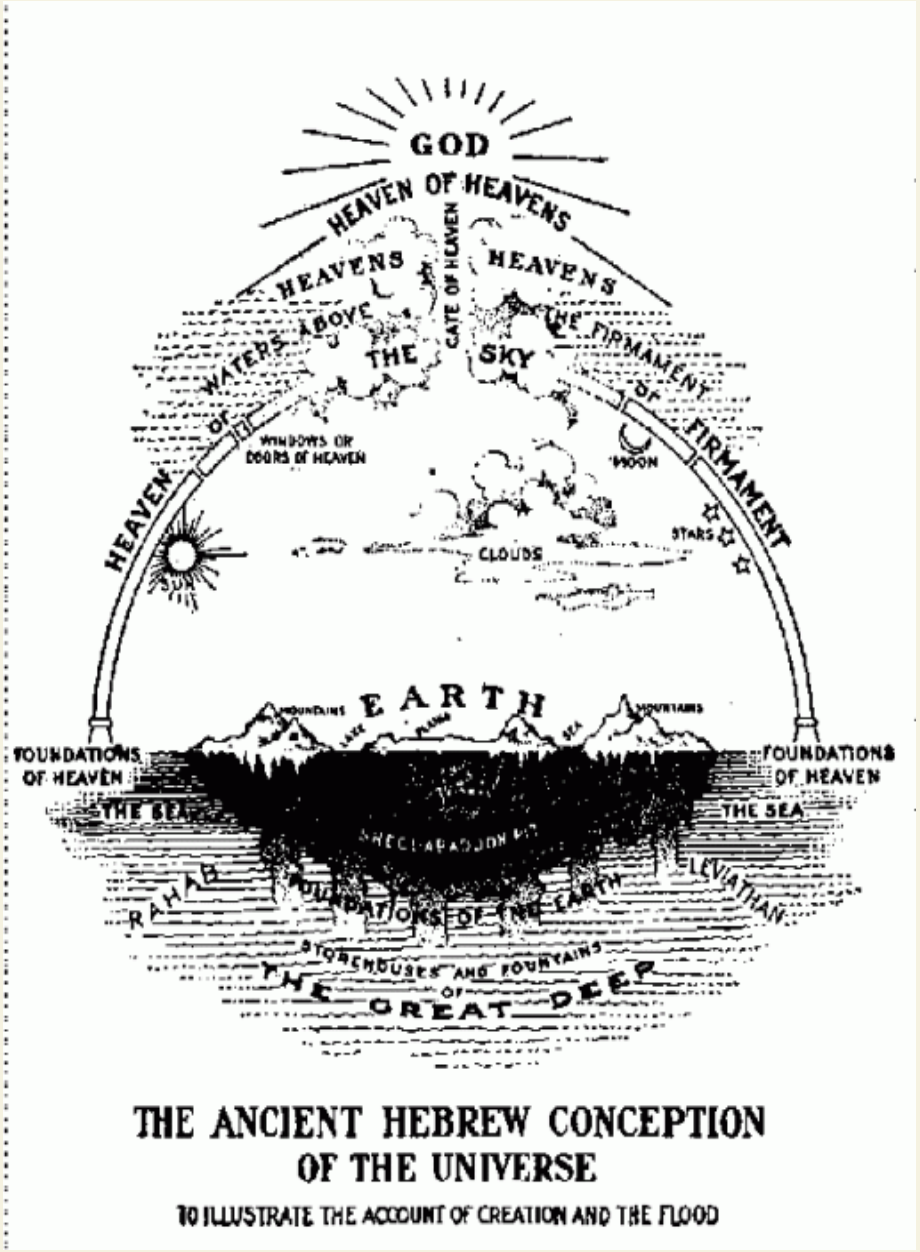


Known Universe

- Homogeneous and Isotropic
- Expanding, Spatially Flat

- Age - 13.75 billion years old
- Size - > 93 billion lights years across
- Density - 9.9×10^{-30} gm/cubic centimeter.
- Temperature – 2.725 K +/- 0.00001 K

- Appears to consist of
  - 73% dark energy,
  - 23% dark matter
  - 4% ordinary matter.



THE ANCIENT HEBREW CONCEPTION OF THE UNIVERSE

TO ILLUSTRATE THE ACCOUNT OF CREATION AND THE FLOOD

Early Models

In the beginning ...

http://www.spaceandmotion.com/cosmology-history-astronomy-universe-space.htm

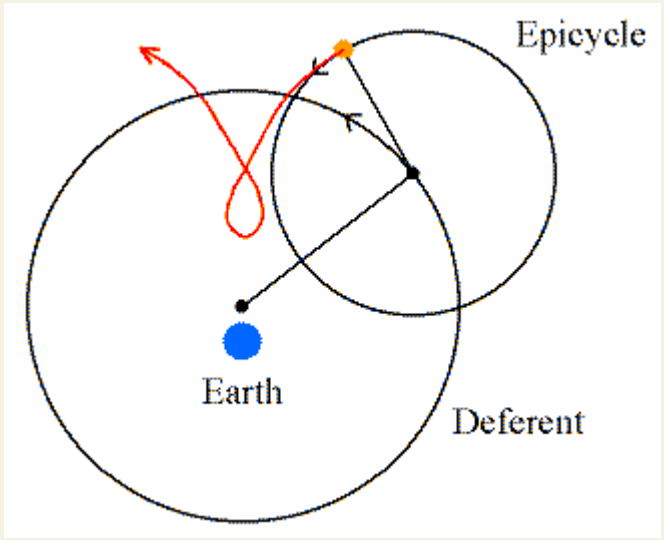
- **Thales of Miletus (624 BC – 546 BC)**
- **Pythagoras (585-497 BC)**
  Harmony of the Spheres
- **Socrates (469-399 BC)**
- **Democritus (460-370 BC)**
- **Plato (427-347 BC)**
- **Aristotle (384-322 BC)**
- **Archimedes (287-212 BC)**

Earth is fixed and immovable,
stars fixed in sky, *planets = wanderers*

- **Hipparchus (190-120 BC) - seasonal inconsistencies**

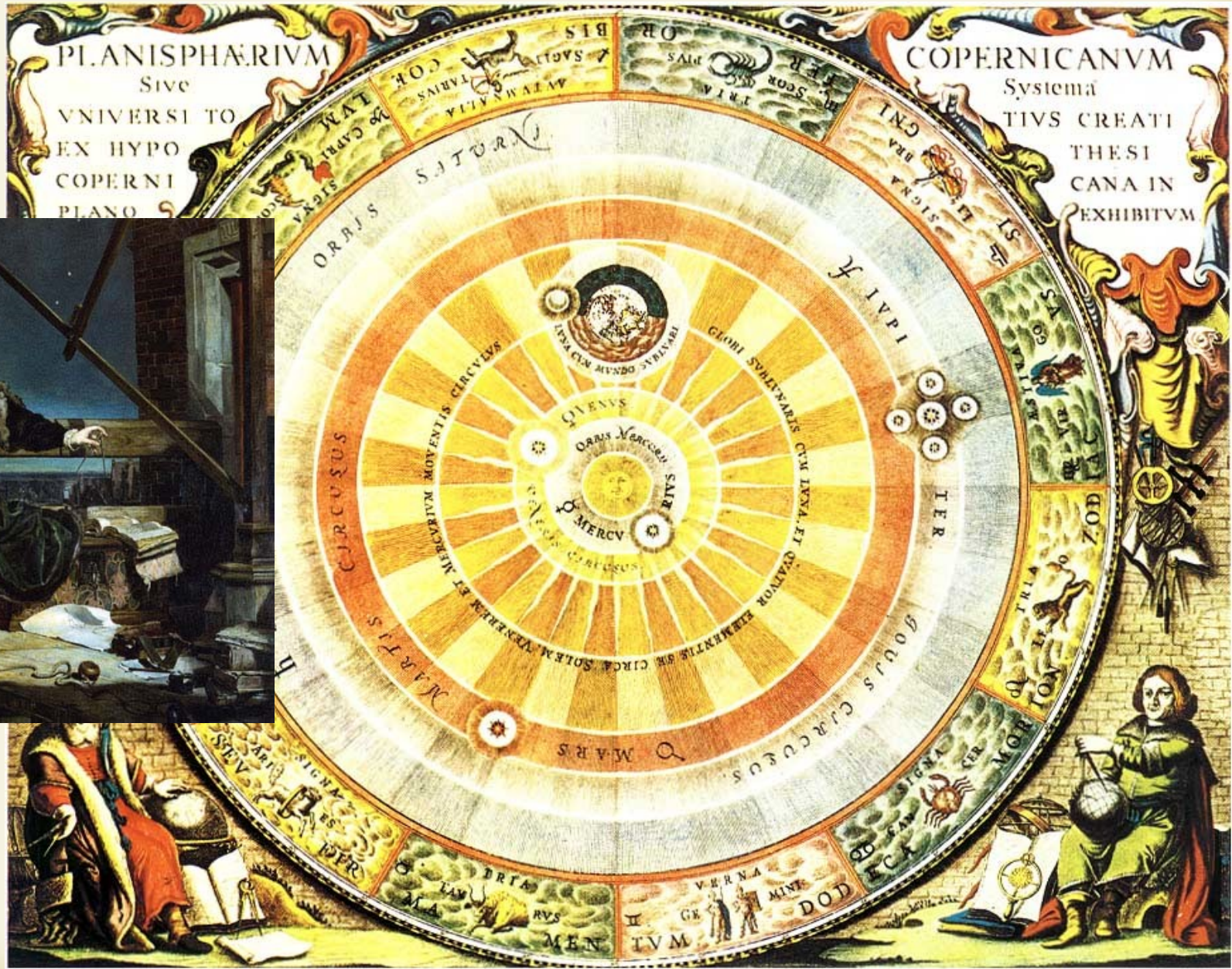
Geocentric System Ptolemy (85-165)

http://www.sacred-texts.com/eso/sta/sta03.htm

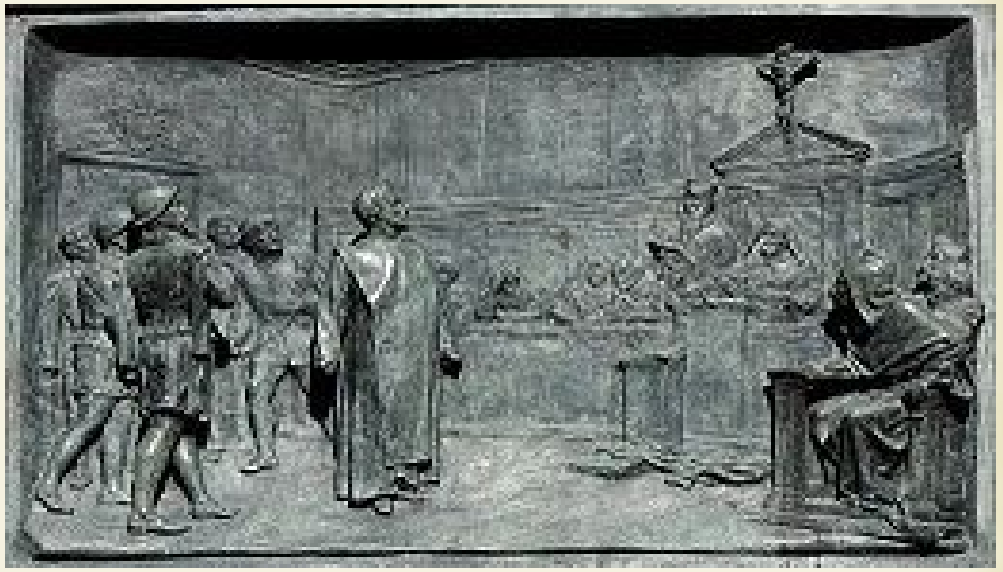


http://www.daviddarling.info/images/epicycle.gif

Heliocentric System
Copernicus (1473-1543)



Giordano Bruno (1548-1600)



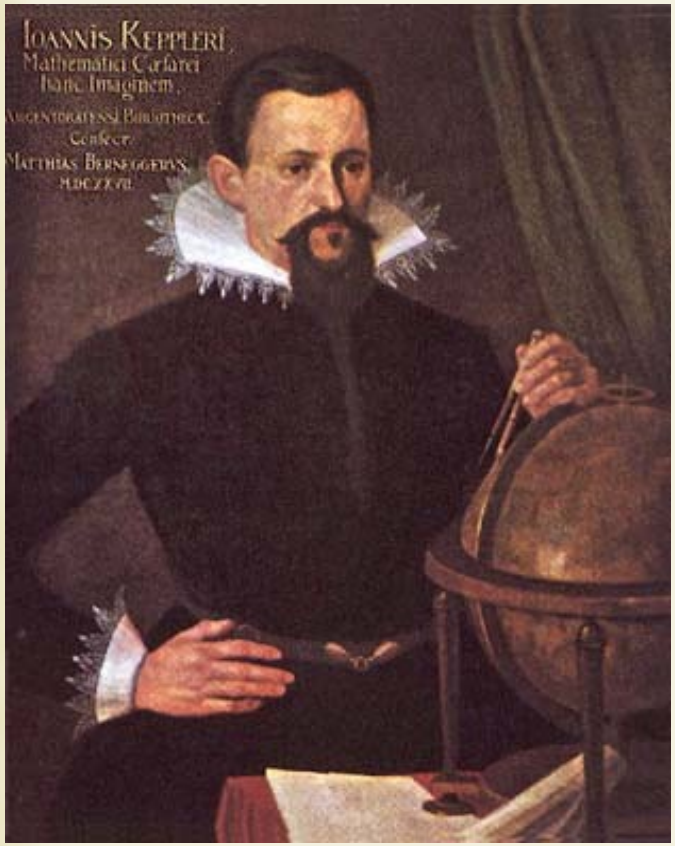
- Heretic
  - Supported Copernicus
- View of Universe
  - Infinite, homogeneous, isotropic
  - Stars like our sun – with planets
  - Infinite number of inhabited worlds
- Burned at stake

The Rise of Classical Physics (1500-1900)

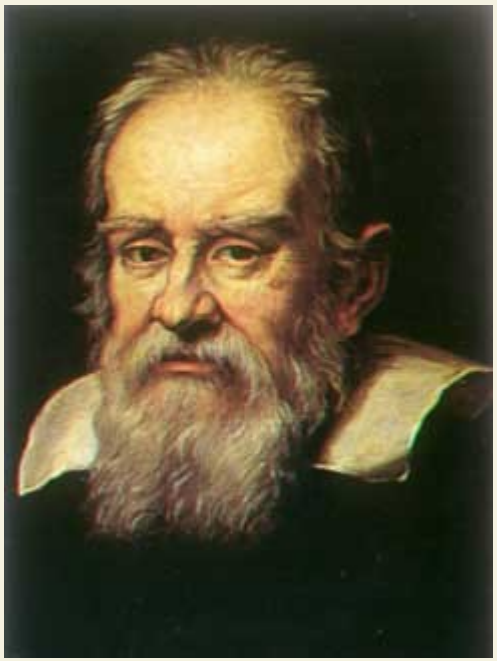
Scientific Deduction

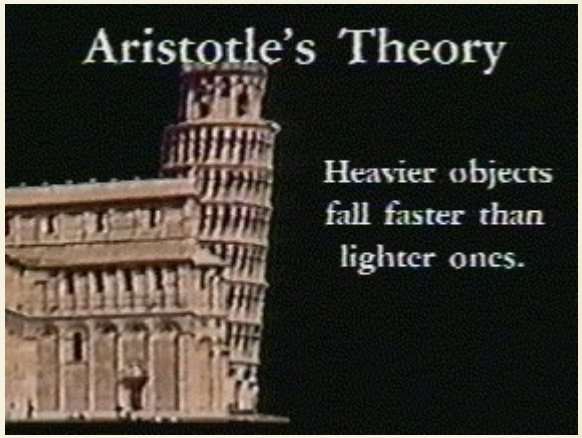
Tycho Brahe
(1546-1601)

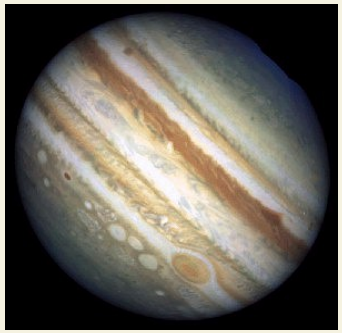
Johannes Kepler
(1571-1630)

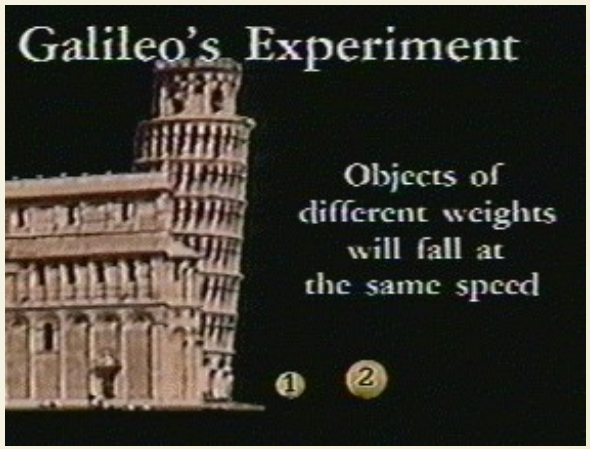


Galileo Galilei
(1564-1642)









The Clockwork Universe

Sir Isaac Newton (1642-1727)

- **Principia (1689)**

  ***Philosophiae Naturalis Principia Mathematica (Mathematical Principles of Natural Philosophy)* (1687)**

Laws of Motion

Law of Gravitation

Kepler's Laws Explained

Calculus (with Leibniz)

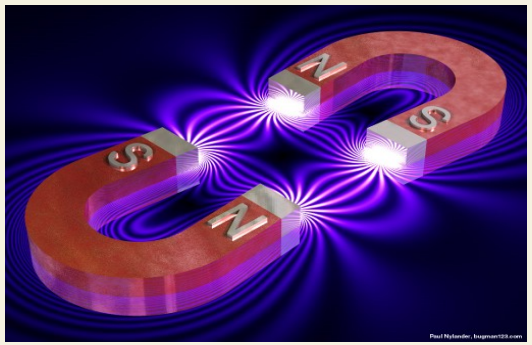
Unification

... the force responsible for bodies falling on the Earth is the same as that causing the moon to follow its orbit.

http://upload.wikimedia.org/wikipedia/commons/thumb/b/b2/Isaac_Newton.jpeg/481px-Isaac_Newton.jpeg

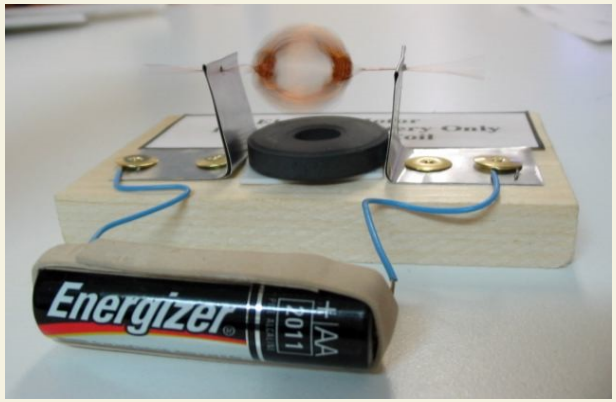
Electricity and Magnetism

- **Magnetism**
  - **Lode stones**
  - **Compasses**
- **William Gilbert (1544-1603)**
- **Thomas Browne (1605-1682)**
- **Benjamin Franklin (1706-1790)**
- **Luigi Galvani (1737-1798)**
- **Alessandro Volta (1745-1827)**



Electromagnetism

- **André-Marie Ampère, (1775 - 1836)**
- **Hans Oersted (1777-1851)**
  current deflects compass needles
- **Georg Simon Ohm (1789-1854)**
- **Joseph Henry (1797-1878)**
  electromagnetic induction, first motor, telegraph
- **Michael Faraday (1791-1867)**
  electrolysis, motors, induction coils, ...



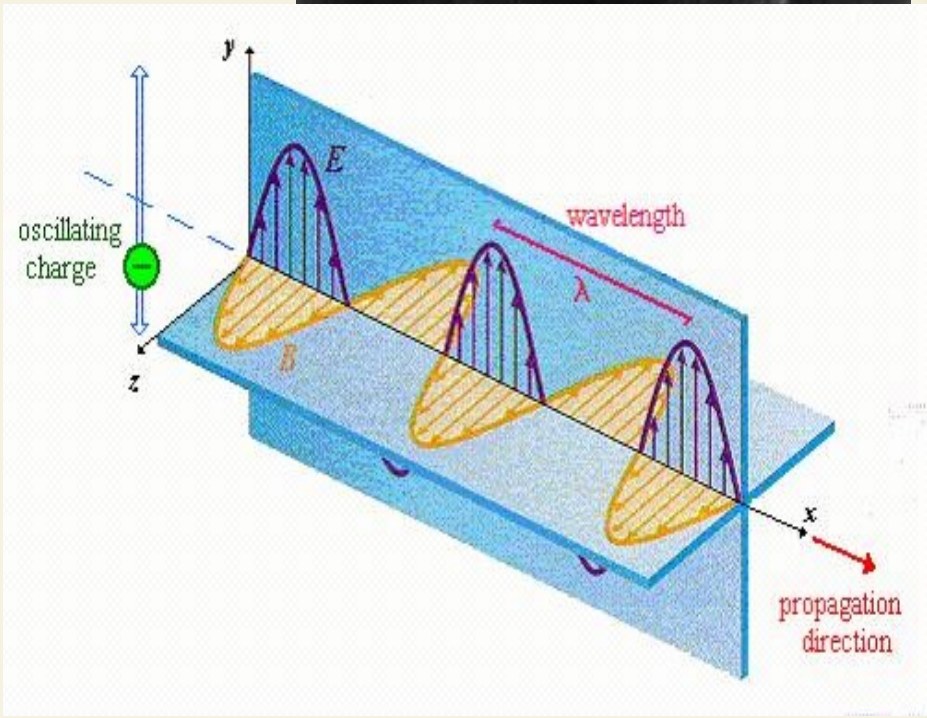
http://hilaroad.com/camp/projects/magnet.html

Electromagnetic Waves

- **James Clerk Maxwell (1831-1879)**
  - **Theory of electromagnetism.**
  - **Predicted the electromagnetic waves.**
  - **Electromagnetic waves travel at**

    c = 299,792,458 m/s = 186,000 mi/s
- **Heinrich Hertz (1857-1894)**
  - **sent the first radio waves (1888)**

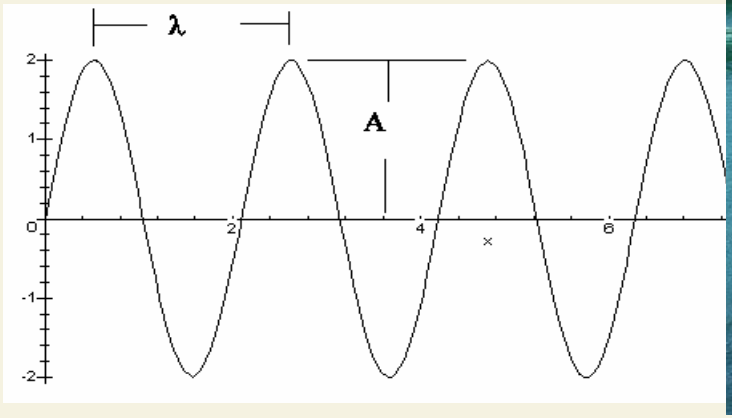
    What is the medium?
    Luminiferous Aether
- **Michelson-Morley (1887)**
  - **could not detect it.**



Waves

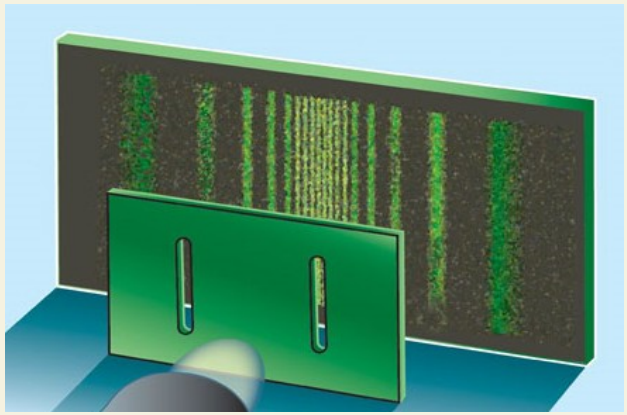
Characteristics

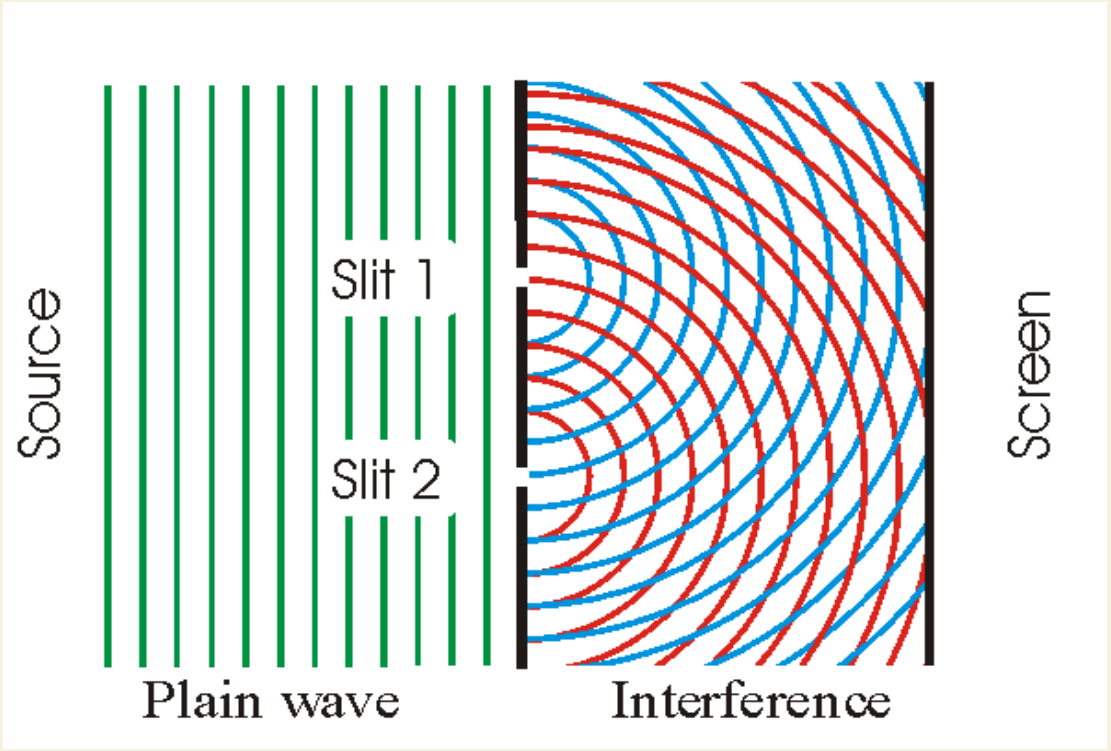
- Wavelength
- Frequency
- Wavespeed



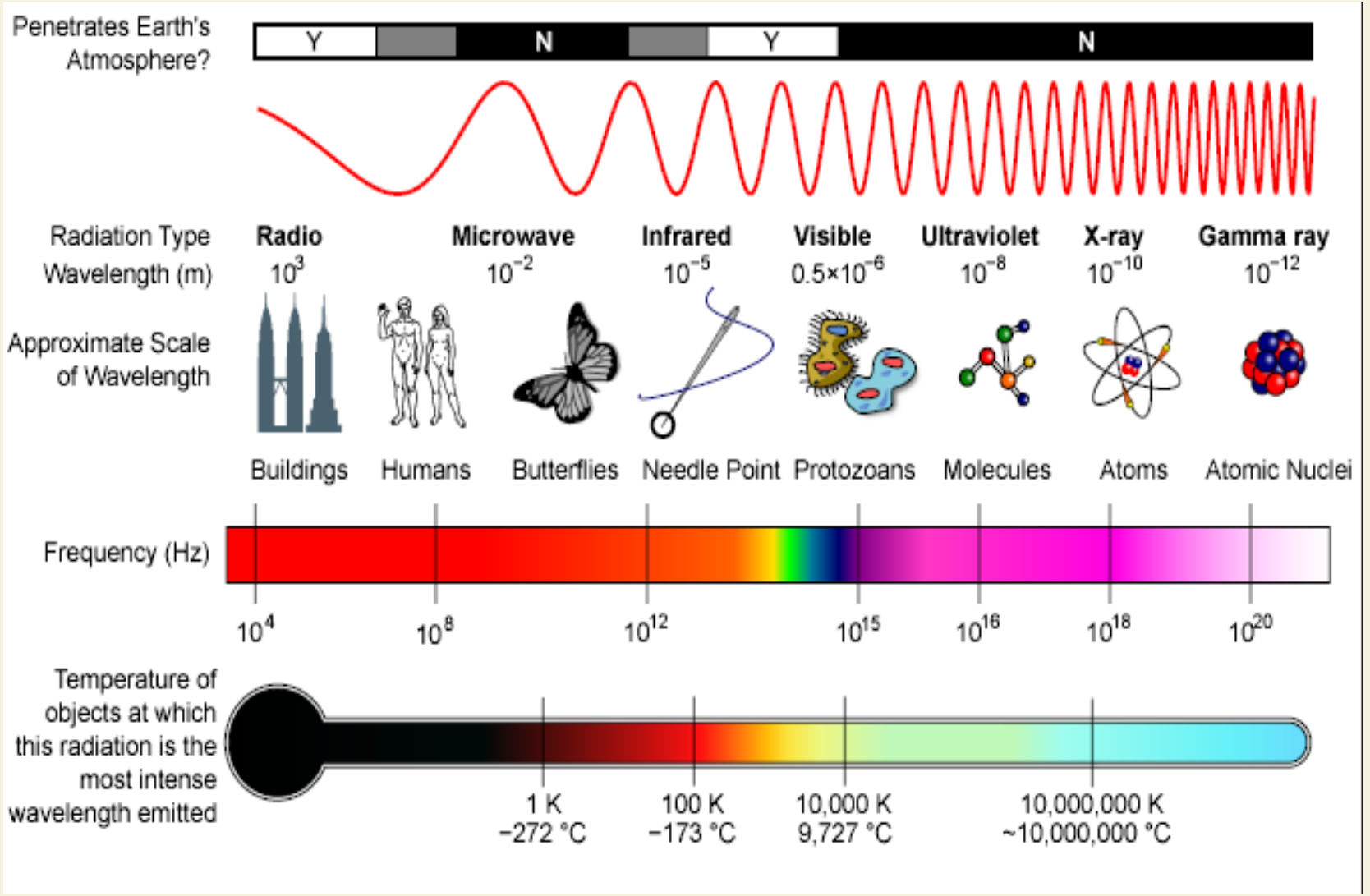
Behavior

- Superposition
- Interference
- Diffraction





EM Spectrum



http://en.wikipedia.org/wiki/Electromagnetic_spectrum

Spectroscopy

Ionized gas gives off radiation

~**Johann Balmer 1885**

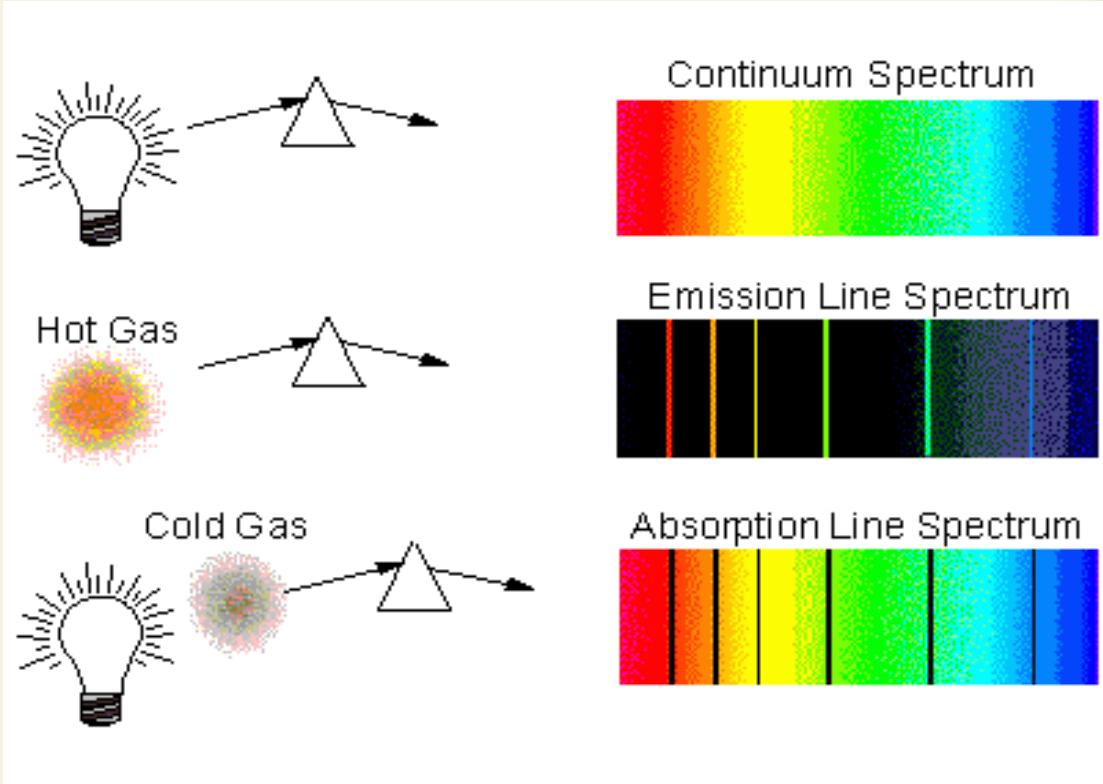
Spectral Lines: Hydrogen
410, 434, 486, 656 nm

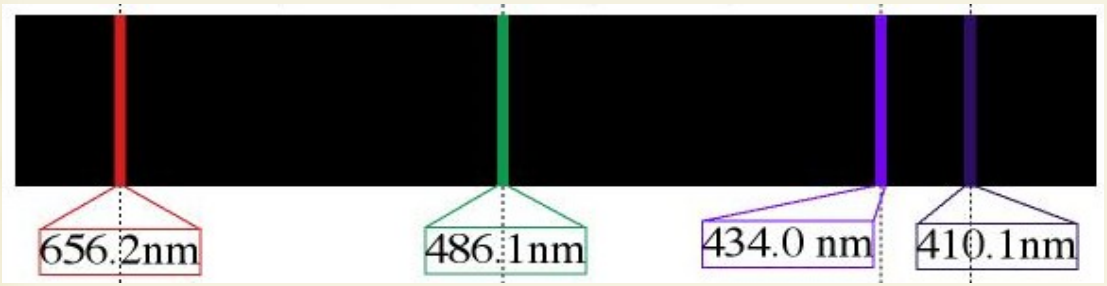
Empirical Formula:

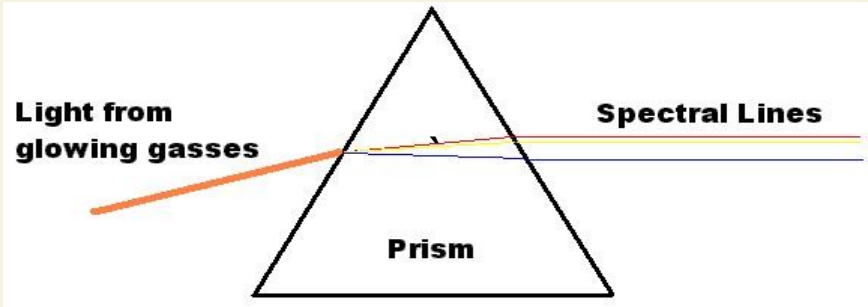
$$\lambda = R\,(1/4 - 1/n^2)$$

Predicted 5th-7th lines

~**Lyman and Paschen Series**







Laws of Thermodynamics

- **James Joule (1818-1889)**
  Mechanical Equivalent of Heat
- **Engines: Watt, Carnot, Kelvin, Clausius, Carnot**
- **Entropy and the Arrow of Time**
- **Laws of Thermodynamics**

1. Adding heat energy or doing work on a body increases internal energy.
2. A body will not spontaneously get hotter.

- **Joseph Stefan (1835-1893)** and **Ludwig Boltzmann (1844-1906)**

  Heated bodies Radiate - Stefan-Boltzmann Law
  Radiation from blackbody proportional to T^4.

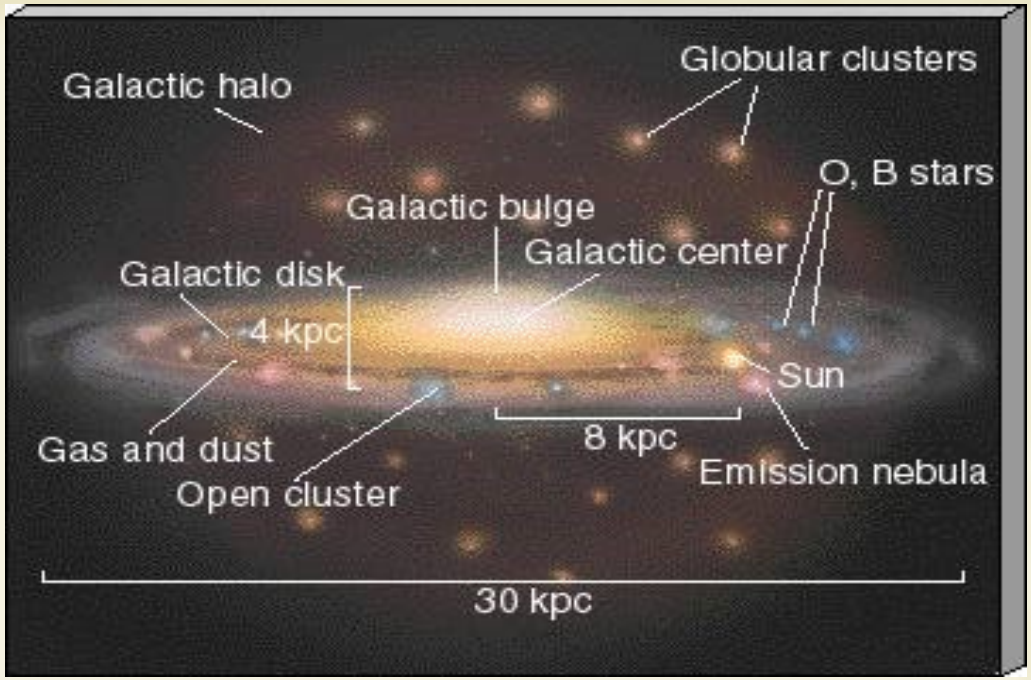
- **Maxwell-Boltzmann Statistical Mechanics – Bah Humbug!**

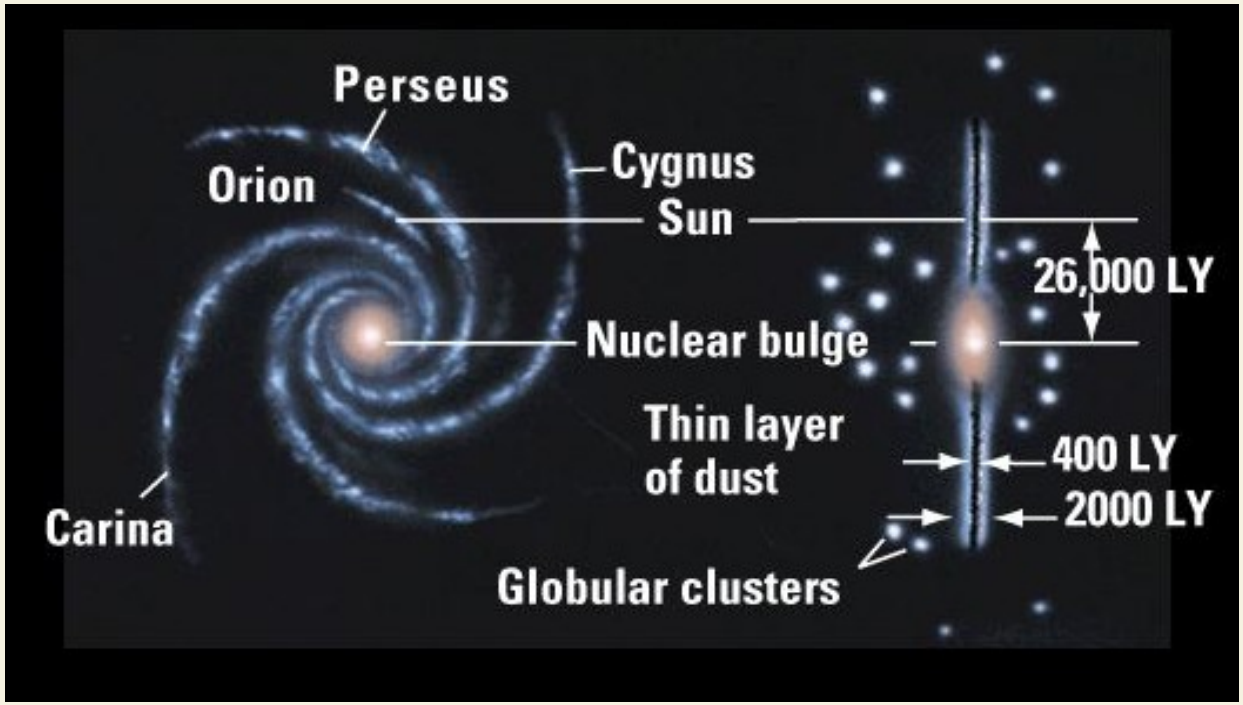
Reaching for the Stars

The Milky Way

- ~$4x10^{11}$ stars
- ~$>6x10^{11}$ sun mass
- ~$M_{ave} = 0.3$ sun

How do we know?



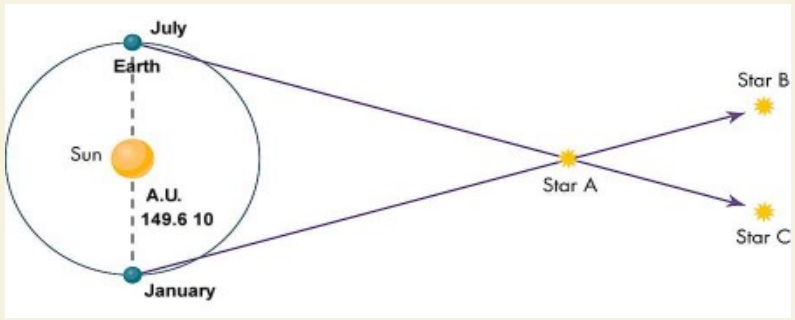


http://zebu.uoregon.edu/~imamura/123/lecture-2/lecture-2.html

Distances & the Milky Way Galaxy

- **Frederick William Herschel (1738-1822)**
  - Built telescopes, discovered Uranus
  - Measured stellar distances
  - Stars distributed in a pancake shape – Milky Way
  - 1000 siriometers x 100 siriometers
  - Asteroids, infrared radiation ...

- **Friedrich Wilhelm Bessel (1784-1846)** – 28 years
  - Established stellar distances using parallax

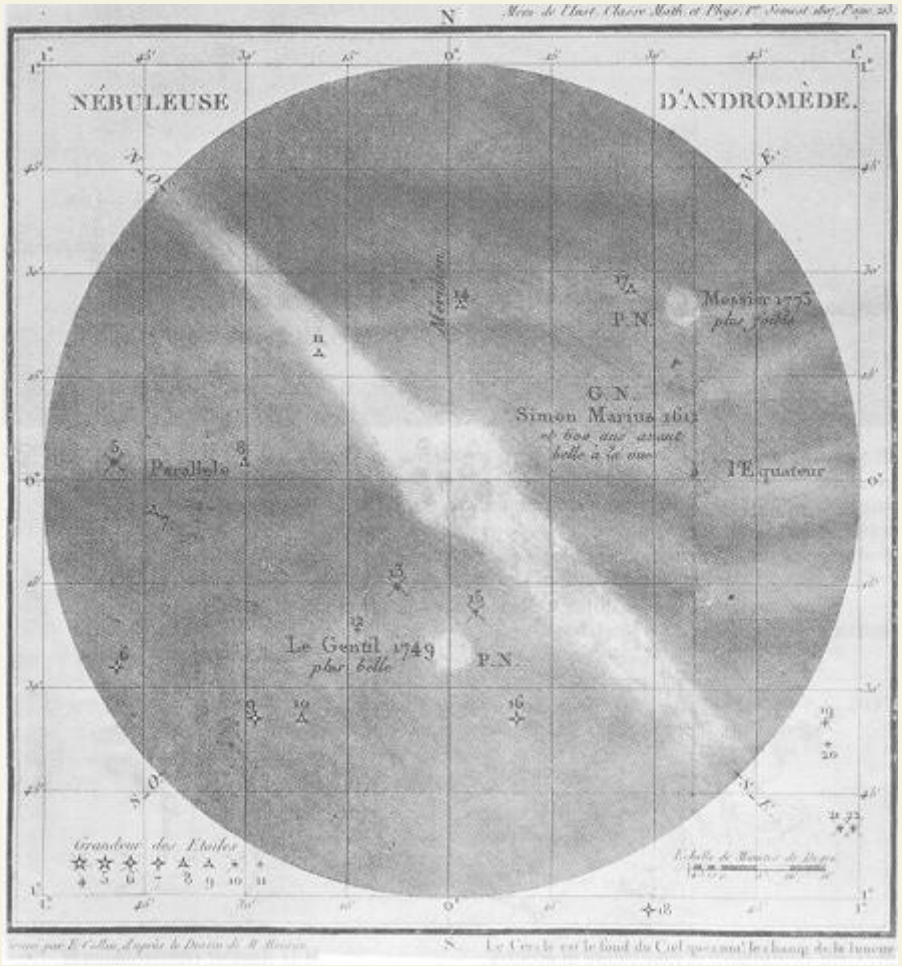


The Search for Nebulae

- **Charles Messier** (1730-1817)
  - Catalog of 103
    - Crab Nebulae M1
    - Andromeda N. M31

Are they in Milky Way or beyond?

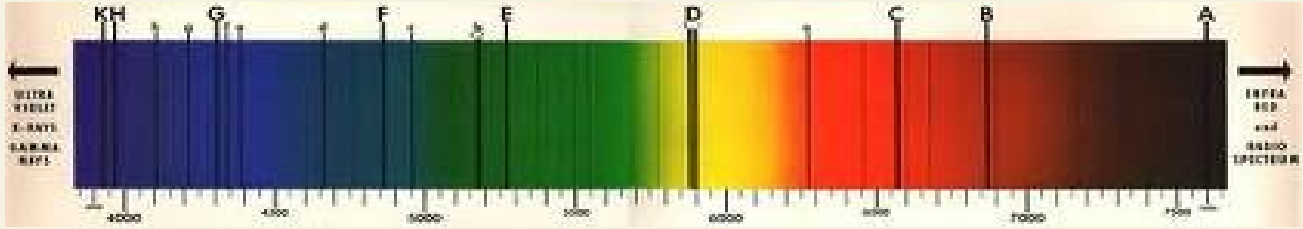
- **William/Caroline Hershel**
  - Cataloged 2500 nebulae
  - Sited a star in some
    – perhaps solar system birth
  - Therefore, in Milky Way
- **Immanuel Kant** (1724-1804)
  - Believed nebulae (island universes) were beyond Milky Way



Messier Catalog http://www.seds.org/MESSIER/data2.html

Stellar Spectra

- Joseph Fraunhofer (1787-1826)
  - Dark lines in Sun's spectrum



- Christian Doppler (1803-1853)
  - Moving objects – shift in wavelength
- Vesto Slipher (1875-1969)
  - Discovered red shift in spiral nebulae
- Henrietta Leavitt (1868-1921)
  - Cepheid variables, better distances

“The Great Debate” Shapley-Curtis Debate - 1920

Are distant nebulae relatively small and within our galaxy, or are they large, independent galaxies?

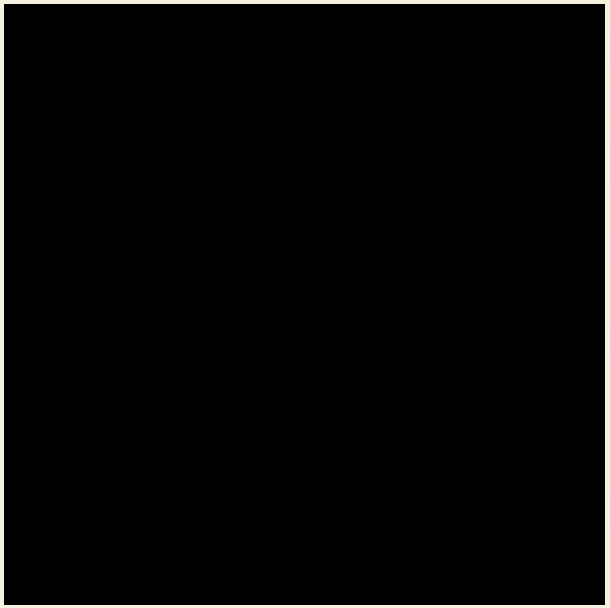
http://en.wikipedia.org/wiki/Image:Andromeda_galaxy.jpg

- Harlow Shapley (1885-1972)
  - Nebulae part of galaxy
  - Sun in outer regions of galaxy
- Herbert Doust Curtis (1872-1942)
  - Nebulae outside galaxy
  - Sun at center
- Walter Baade (1893-1960) – Milky Way is typical galaxy!

Before leaving the skies ....

Why is the night sky dark?

Olber's Paradox - 1823



http://en.wikipedia.org/wiki/Olbers'_paradox

Assumptions:

- Universe is infinite.
- Stars are uniformly distributed in all directions.
- Universe was and always will be around.

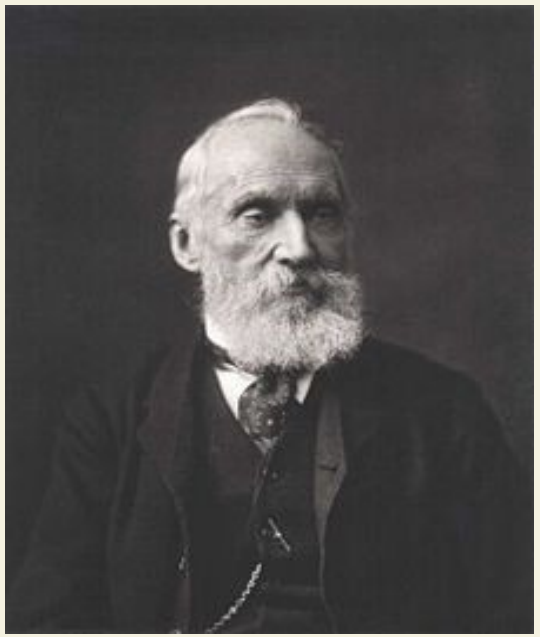
Consequence:

- Every line of sight would cross a star, and the night sky should be lit up in all directions!

This is Not Your Father's Physics
1900's

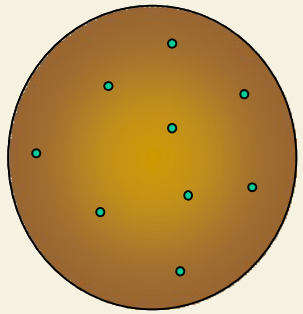
Physics Revolutions

William Thomson, (1824 – 1907)
1st Baron Kelvin (**Lord Kelvin**)

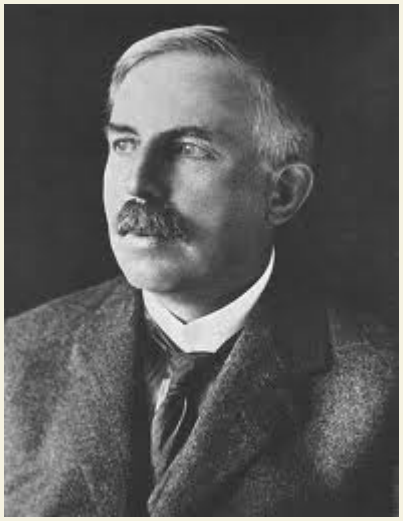


"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement." - 1900

1895 **Wilhelm Röntgen** discovers X-rays.
1898 **Marie and Pierre Curie** separate radioactive elements.
1898 **Joseph Thomson** measures electron,
- "plum-pudding" model of the atom
- a slightly positive sphere with small, raisin-like negative electrons.



Radioactivity and the Atom



1897 - J.J. Thomson discovers the electron.

1898 - Marie and Pierre Curie discover first radioactive elements: radium and polonium.

1899 - Ernest Rutherford - radiation = alpha and beta rays.

1900 - Pierre Curie observes gamma rays.

1911 - Ernest Rutherford discovers the atomic nucleus

1913 - Niels Bohr introduces the first atom model, mini solar system.

1913 - Hans Geiger invents Geiger counter for measuring radioactivity.

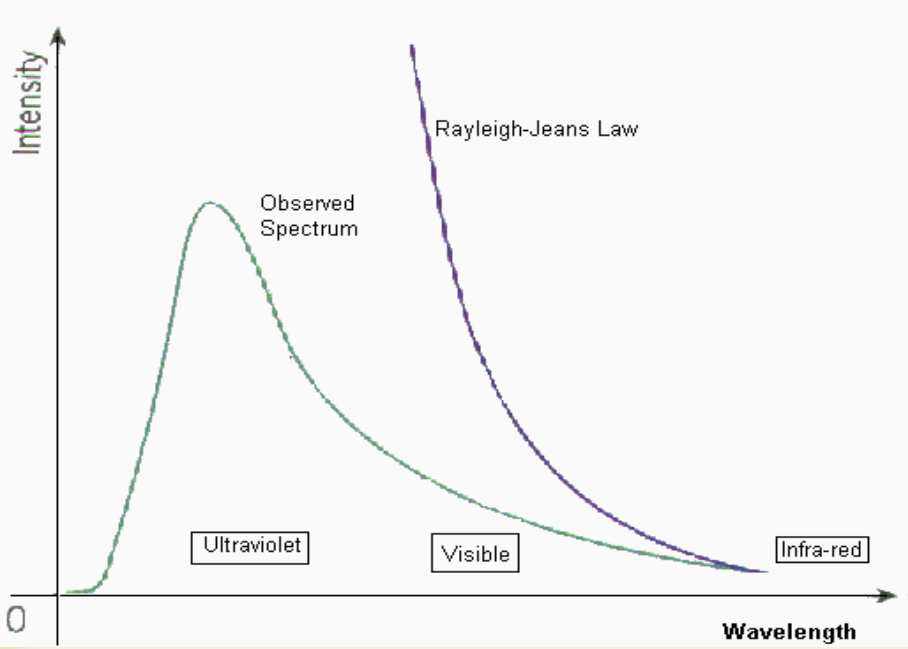
1920 - Ernest Rutherford discovered and named the proton.

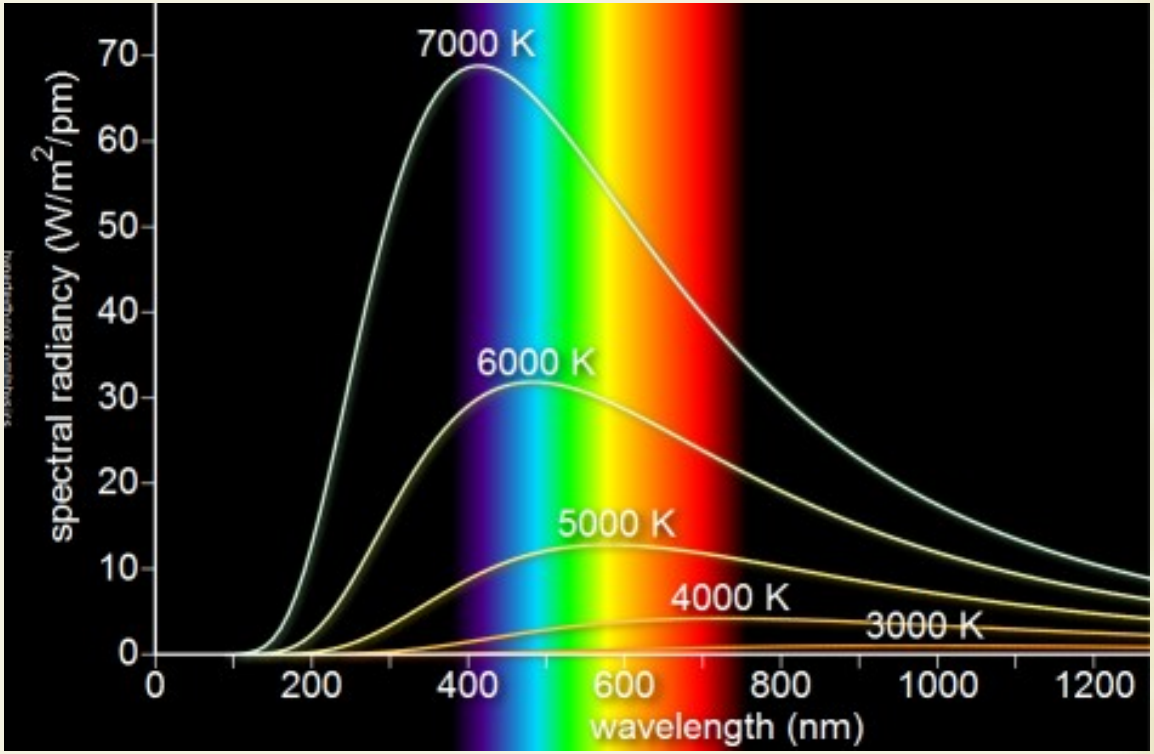
1932 - James Chadwick discovers the neutron. Won Nobel Prize in 1935.

Blackbody Spectrum

Blackbody - a theoretical object that absorbs 100% of the radiation that hits it.

Wien's Law (1896)
Rayleigh - Jeans Law (1900)





Ultraviolet Catastrophe "... when you turn on your toaster, you are instantly fried by a massive gamma ray burst, since your little blackbody toaster should emit infinite energy at the shortest wavelengths."

Quantum Theory

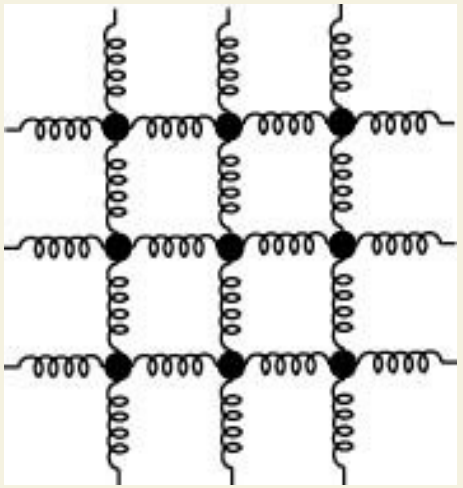
Max Planck
(Karl Ernst Ludwig Marx Planck 1858-1947)

oscillators can only vibrate at discrete frequencies:

$$E_n = n(hf),\ n = 1,2,3\ ....$$

Thus, the energy difference

$$\Delta E = hf,$$



where Planck's constant is given by

$$h = 6.63 \times 10^{-34}\ Js$$

Albert Einstein(1879-1955)

Einstein's 1905 Papers

- March – Photoelectric Effect
- May – Brownian Motion
- June – Theory of Relativity
- September – $E = mc^2$

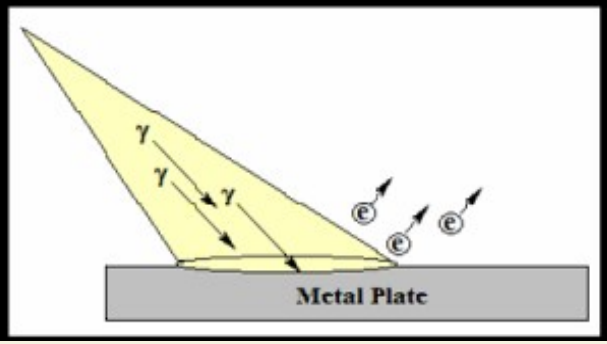
These papers lead to revolutions in physics that defined physics research for the entire century:

- Confirming molecular theory.
- Questioning how we view space and time.
- Unifying electromagnetic theory with mechanics.
- Introducing wave-particle duality.

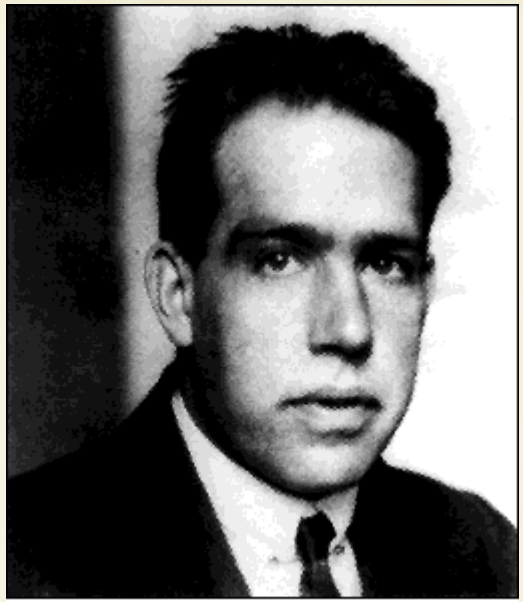
Photoelectric Effect

Light can cause currents

- Electrons can be ejected from irradiated metal plates.
- Light can be act like either particles (quanta) or waves.
- Extended Planck's ideas of energy quantization.
- Lead to explanation of electromagnetic spectra,
- Lead to the development of lasers, transistors and other applications.



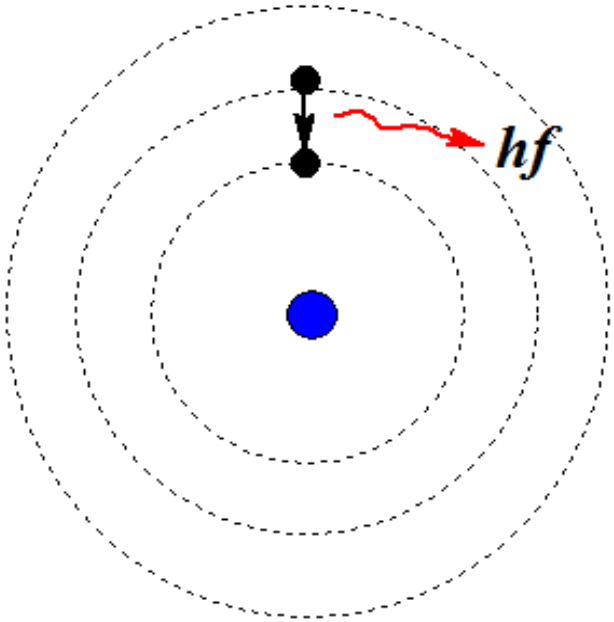
Bohr's Atom - 1913

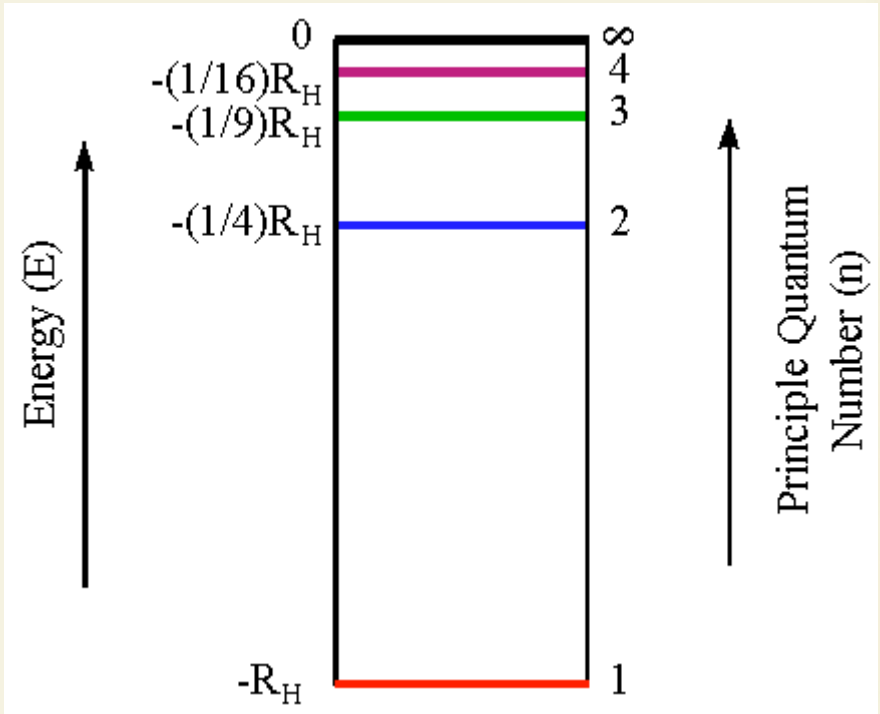

Neils Bohr

Niels Bohr (1885-1962)

Electrons move in specific orbits.
Accelerating electrons radiate at specific energies.

$$E_n = R_H(1/m^2 - 1/n^2)$$





Early Quantum Mechanics

1900 - Planck Explains Blackbody Radiation

1905 - Einstein - the Photoelectric Effect, Photons

1913 - The Bohr Model for Hydrogen

1916 - Confirmation of photon, Millikan

1923 - Compton Effect – X-Ray Scattering

1924 – de Broglie - Particles Behave Like Waves

1925 - Matrix Mechanics - Heisenberg

1926 - Derivation of Planck's Law – Dirac

1926 - Wave Mechanics - Schrödinger

1927 - The Uncertainty Principle - Heisenberg

1927 - Davisson-Germer Verified de Broglie's idea

1928 - Relativistic Quantum Mechanics - Dirac

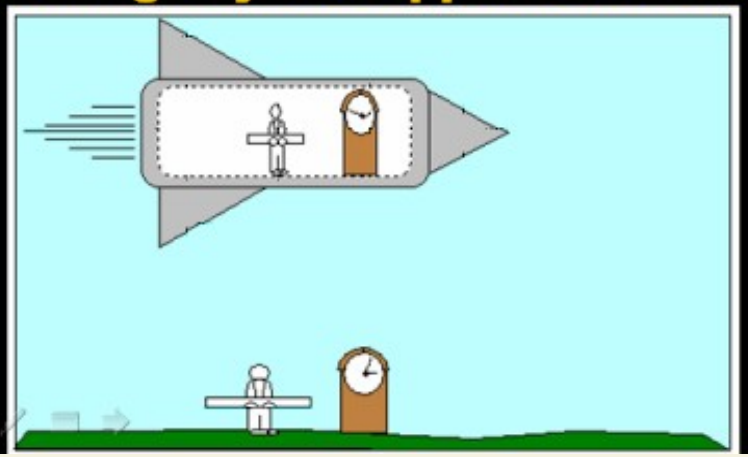
Special Relativity - 1905

Theory of Relativity

Physics looks the same to all observers moving at a constant velocity

The speed of light in a vacuum is the same for all observers

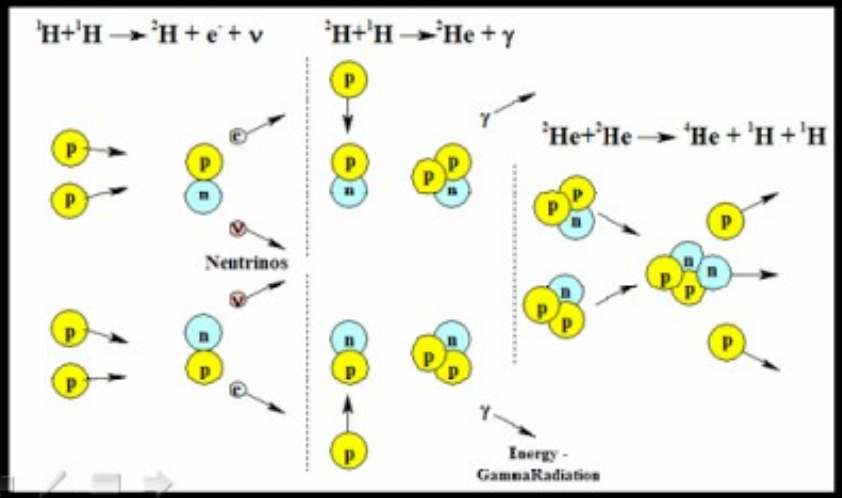
- **There is no absolute time or position**
- **Moving clocks tick slower.**
- **Moving objects appear shorter.**



$E = mc^2$

Mass and Energy are different aspects of the same thing

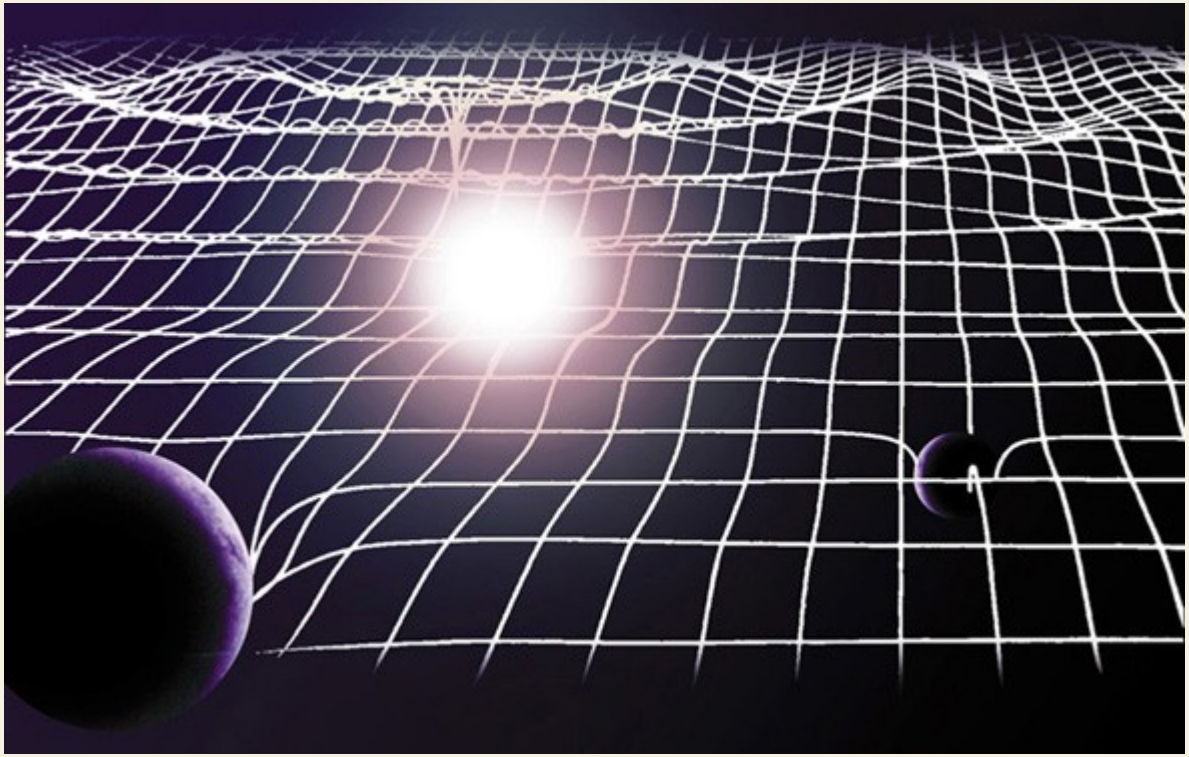
- **A consequence of special relativity**
- **Small bits of matter lead to large energy releases**
- **Lead to the atomic bomb**
- **Hydrogen Fusion in Sun:**



Paradigm Shifts

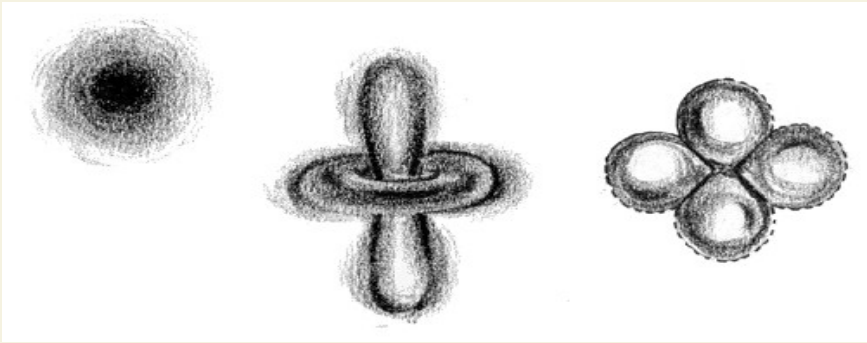
Relativity

Space and Time not absolute, not Euclidean

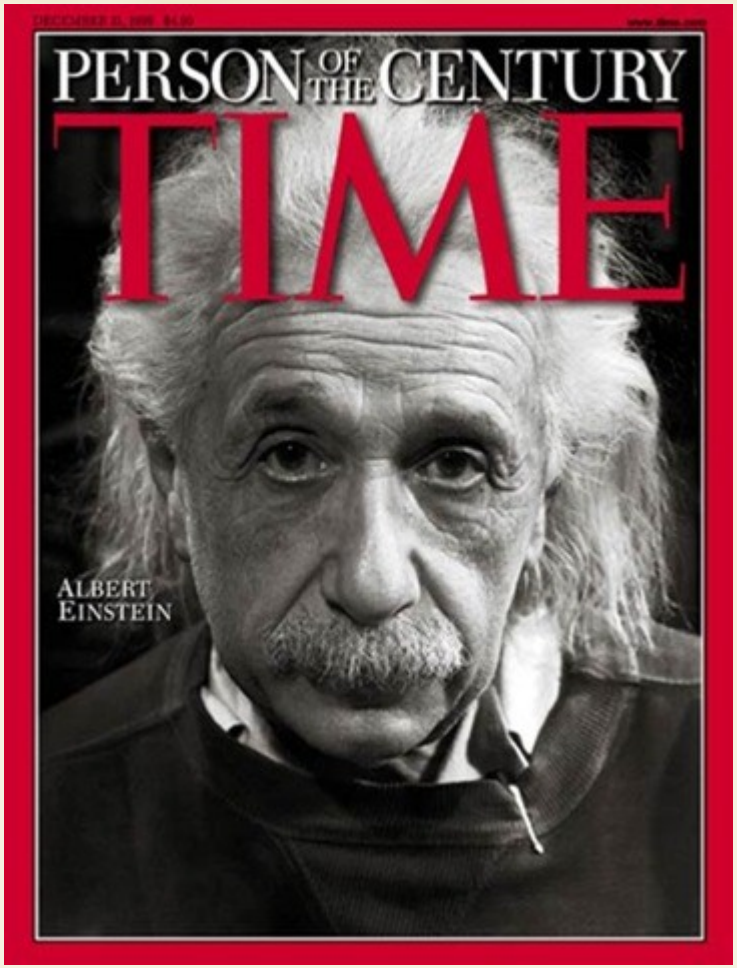


Quantum Mechanics

Loss of Determinism



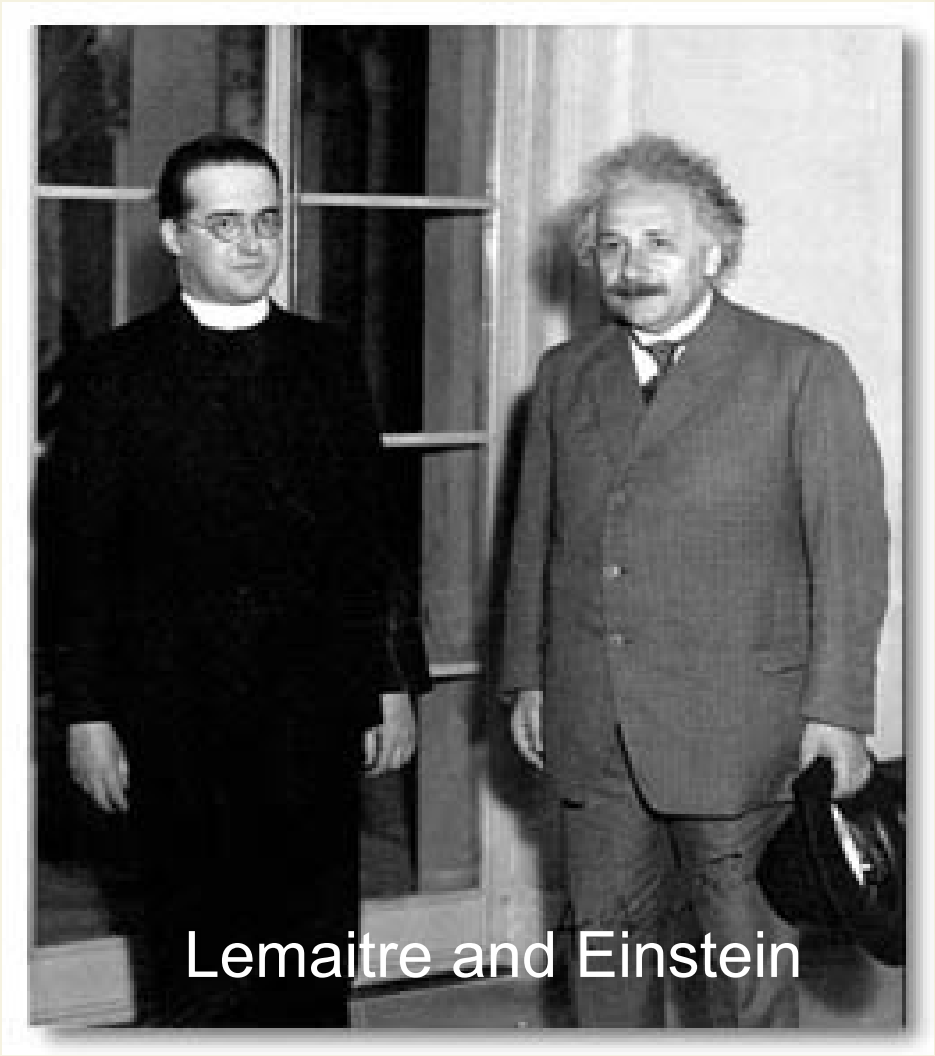
http://www.zamandayolculuk.com/cetinbal/AE/Deformation.jpg



The Birth of Cosmology

Pre-Modern Cosmology

- 1915 General Relativity
- 1916 Schwarschild
- 1917 Einstein Model
- 1922 Friedman
- 1927 Lemaitre
- 1929 Hubble
- 1932 Einstein-de Sitter
- 1948 Gamow - CMB
- 1950 Hoyle – Steady State
- 1965 Penzias and Wilson - CMB


Lemaitre and Einstein

http://www.catholiceducation.org/articles/science/sc0022.html

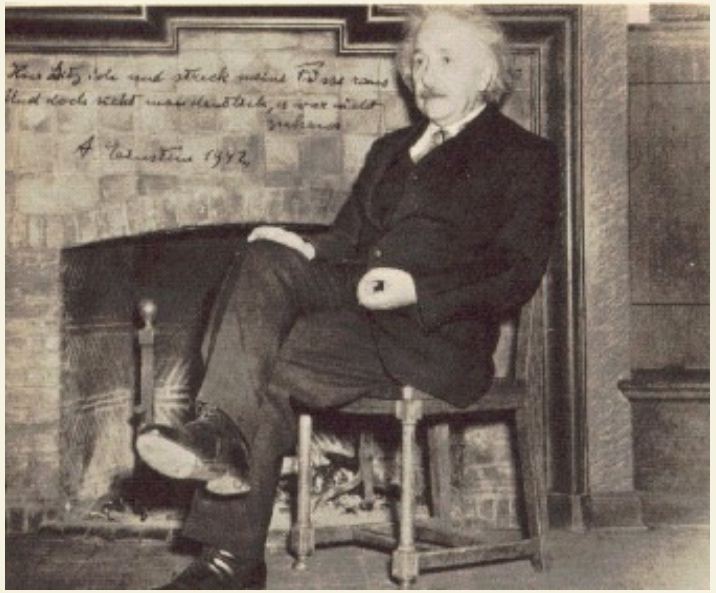
General Relativity

- **Einstein - 1915**

  Newton's gravitational attraction replaced

  Curvature of spacetime tells bodies how to move

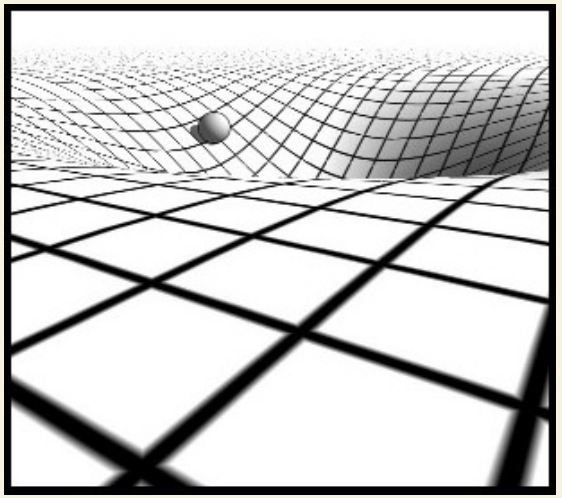
  Bodies tell spacetime how to curve



- **Karl Schwarzschild (1873-1916)**

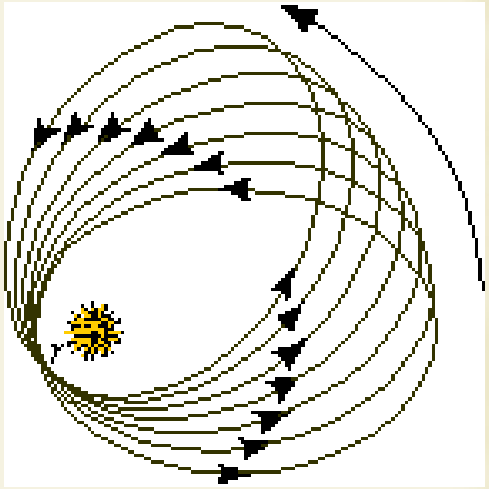
  Papers on spherical solution sent from WWI front

  Einstein presented Feb 24, 1916



Testing of General Relativity

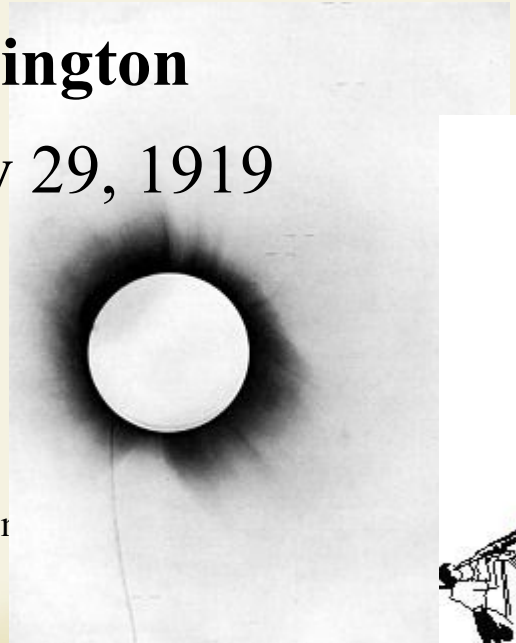
New Theories need to derive known results & predict new results

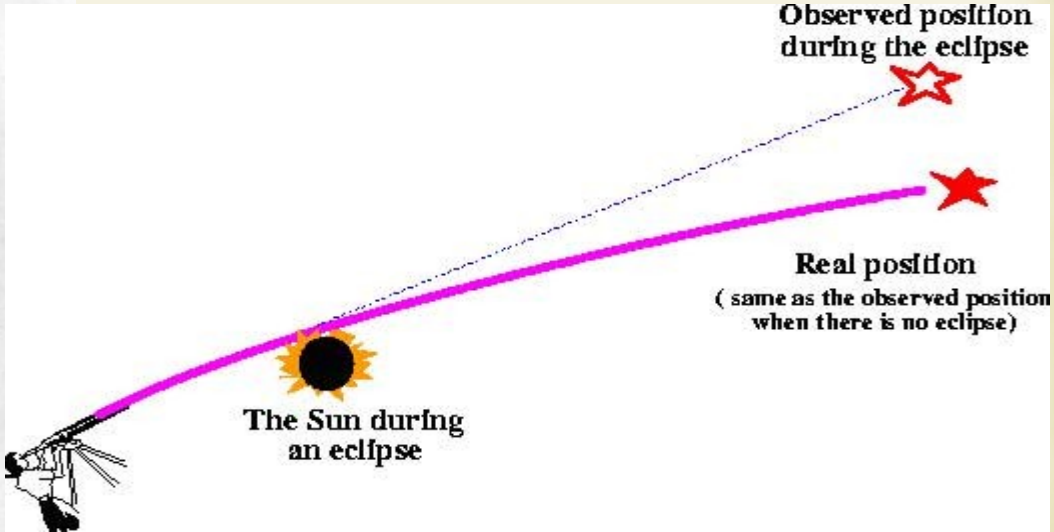


- **Mercury's Orbit Precession**
  - 1858 Urbain Le Verrier – 531/574 arcsec/century
  - Nov 18, 1915 Einstein – GR gives 574!
- **Bending of Light**
  - **Erwin Freundlich – 1912**
    - Crimea – Aug 21, 1914
  - **Sir Arthur Eddington**
    - Brazil – May 29, 1919


LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.





1917- Cosmological Considerations

Cosmological Considerations of the General Theory of Relativity, Einstein

Cosmological Principle

The universe is the same everywhere

Homogeneous

The universe looks the same from every point

Isotropic

The universe looks the same in every direction

Einstein's Model – Not Static!

All bodies attract leading to collapse – unstable universe!

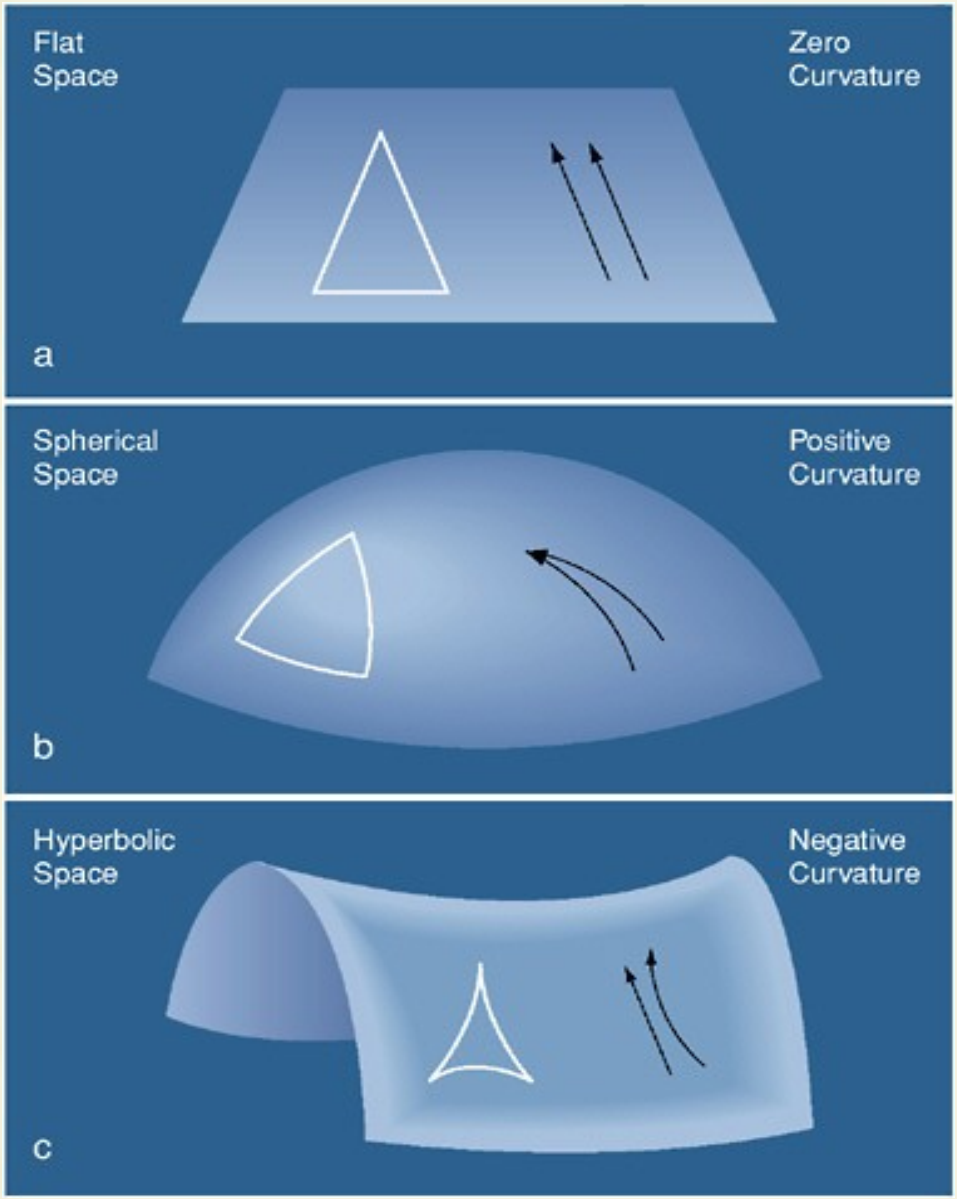
Fudge Factor - "his greatest blunder"

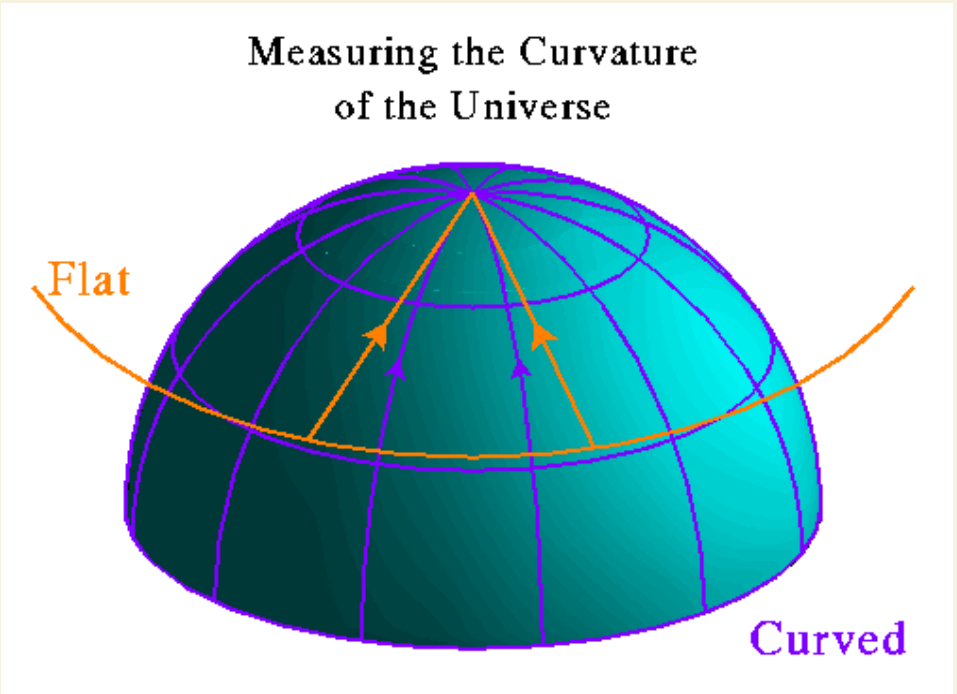
Einstein adds **cosmological constant**, **Λ**

Provides a repulsion of masses

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

Curved Space



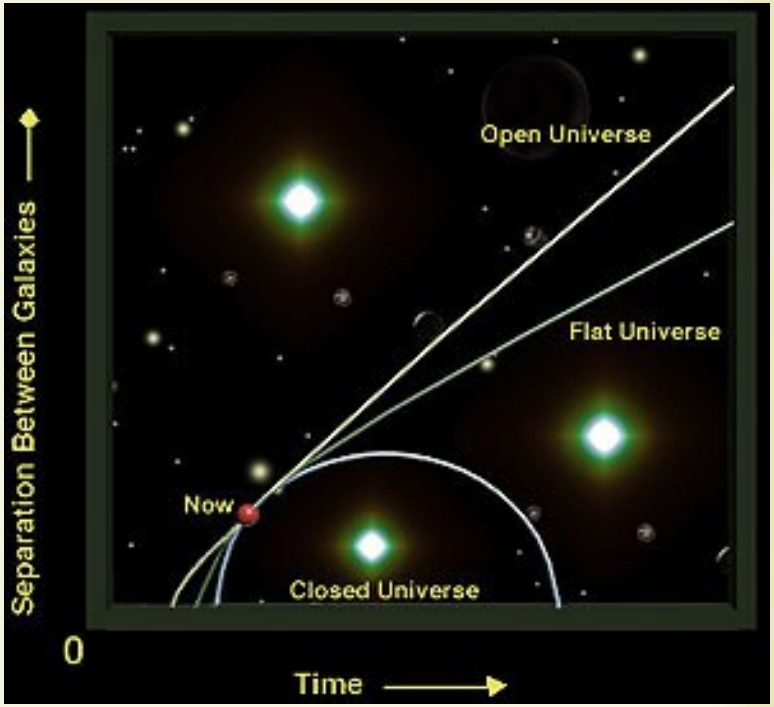


Cosmology Theories

- **Aleksandr Friedmann (1888-1925) - 1922**

  - Gave universe an initial kick
  - Initial density scenarios
    - Low density – forever expands
    - High density – re-contracts
    - Critical density – slows without halting

$$d\tau^2 = dt^2 - a^2(t)\left\{\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\varphi^2\right\},$$



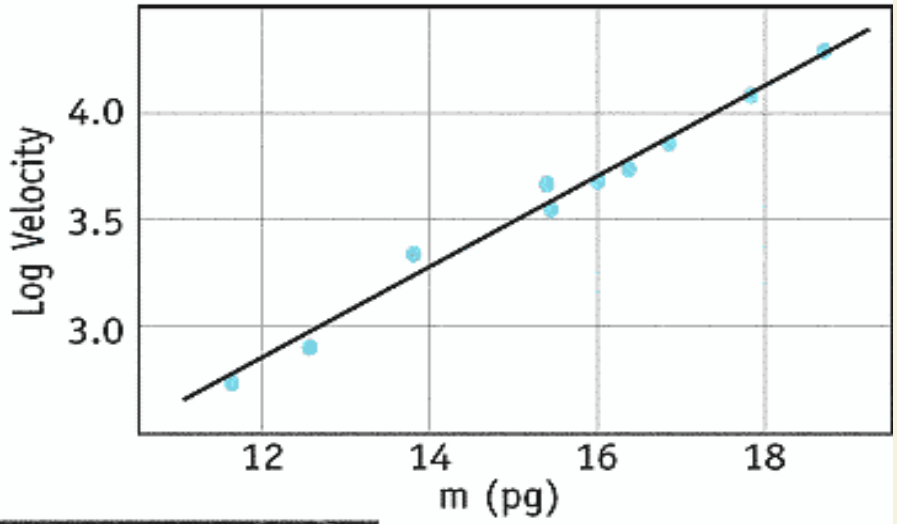
- **George Lemaitre (1894-1966) - 1927**

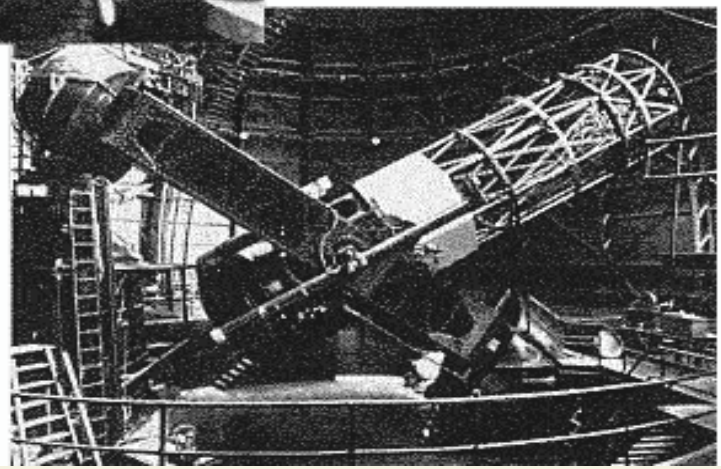
  - Physicist and Priest, worked with Eddington
  - Rederived Friedmann's work
  - Consequence - traced back in time to moment of creation
  - Proposed cosmic rays came from early universe

Edwin Powell Hubble (1889-1953)

Discovery of Expanding Universe

Edwin Hubble





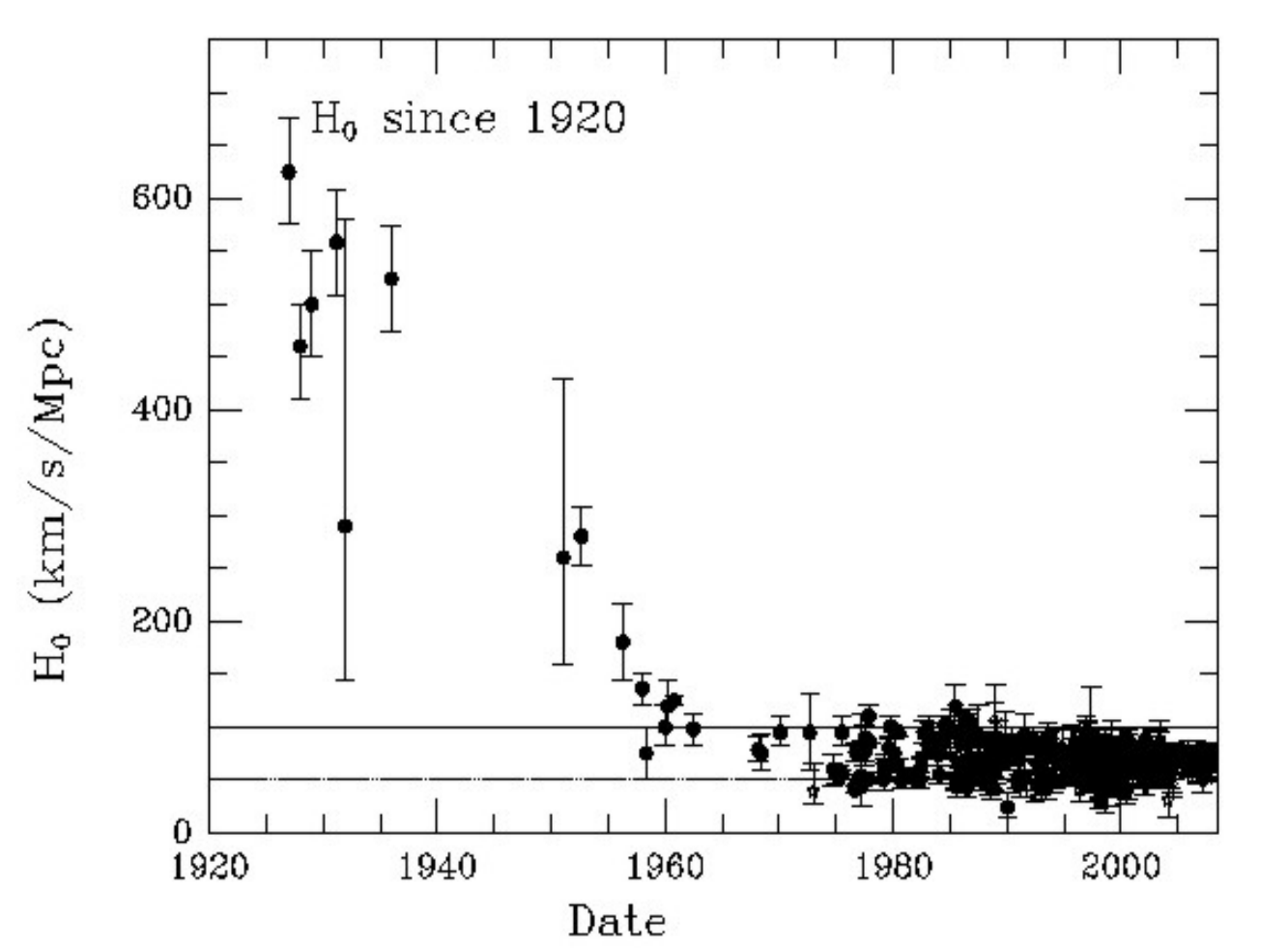
Mt. Wilson
100 Inch
Telescope

http://map.gsfc.nasa.gov/media/ContentMedia/990044b.gif

Expanding Spacetime

H0 and the Age of the Universe

- **Age** = $1/H_0$ = 1/500 km/s/Mpc = 2 billion yrs
- **BUT** – 1930 - Geologists, "Earth 3 billion yrs old!"



http://cfa-www.harvard.edu/~huchra/hubble/

Age of Universe

Current Value H_0: 72 +/- 8 km/s/Mpc

1 Mpc = 3.086×10^{22} m

1 km/s/Mpc = 3.24×10^{-20} 1/s

$1/H_0 = 4.286 \times 10^{17}$ s

= **13.6 Gyr**

WMAP – 13.7 +/- 0.13 Gyr

If flat and matter dominated – $2/(3H_0)$ – 9 Gyr

Big Bang vs Steady State Models

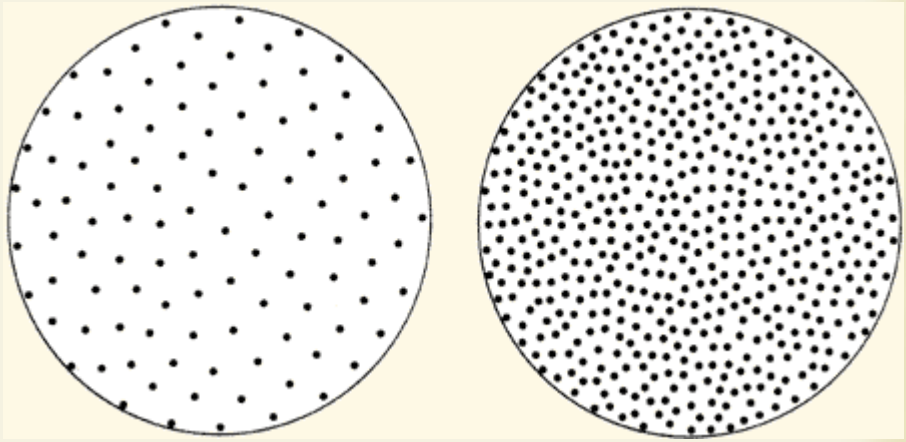
Gamow, Alpher, Herman - 1948

Expansion and cooling of universe
Initial state - infinite density and temperature.
"Ylem" = protons, neutrons, and electrons in an ocean of radiation.
Computer calculation of nuclear processes
Gave off radiation => the universe is now 5K

Hoyle, Bondi, Gold - 1950

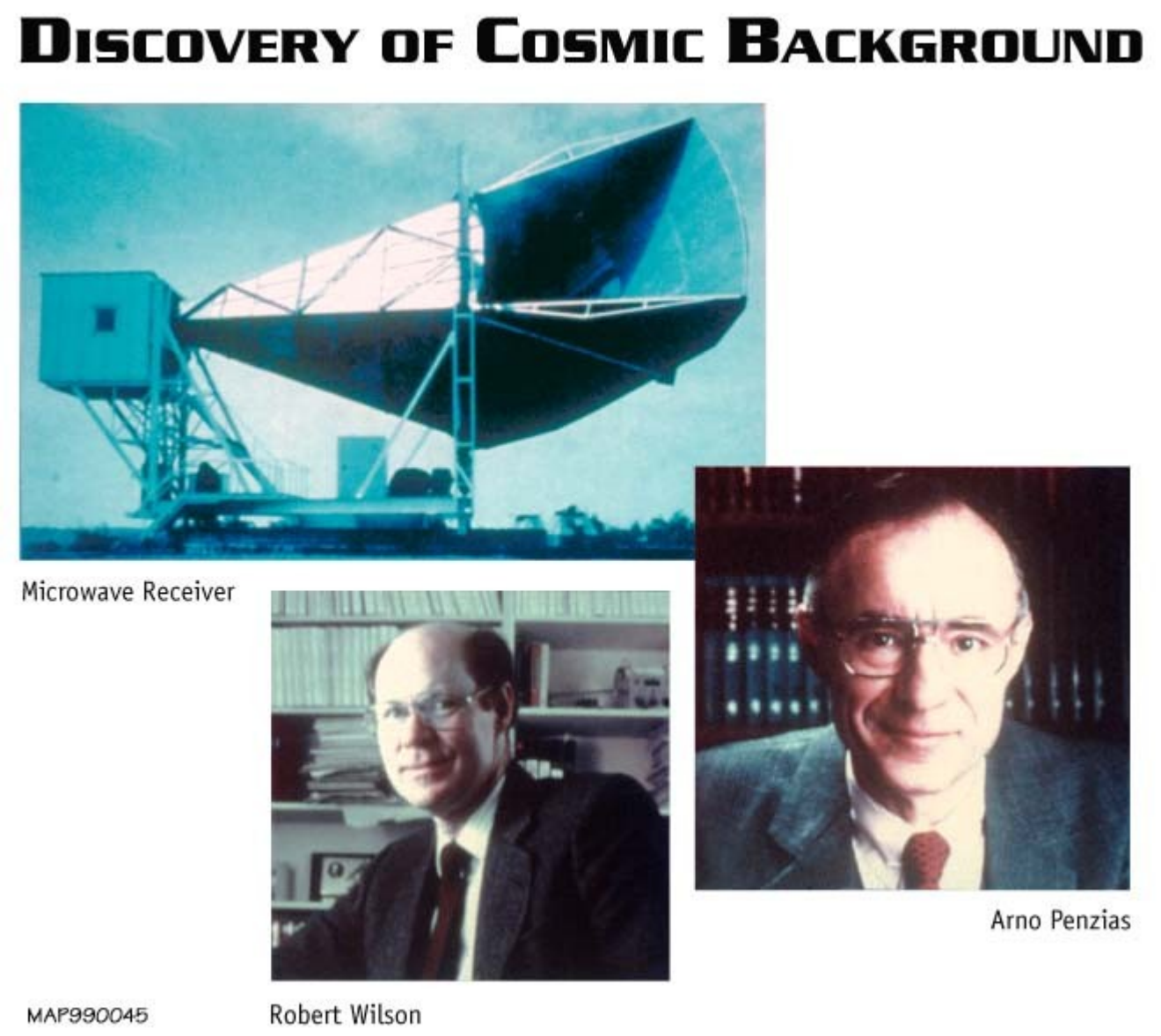
In a steady state universe the density would remain constant.

1 – Age of Universe
2 - The rate of expansion of the universe.
Big Bang - rate would slow
Steady State-rate would remain constant.



http://www.aip.org/history/cosmology/ideas/bigbang.htm

Arno Penzias and Robert Wilson - 1965



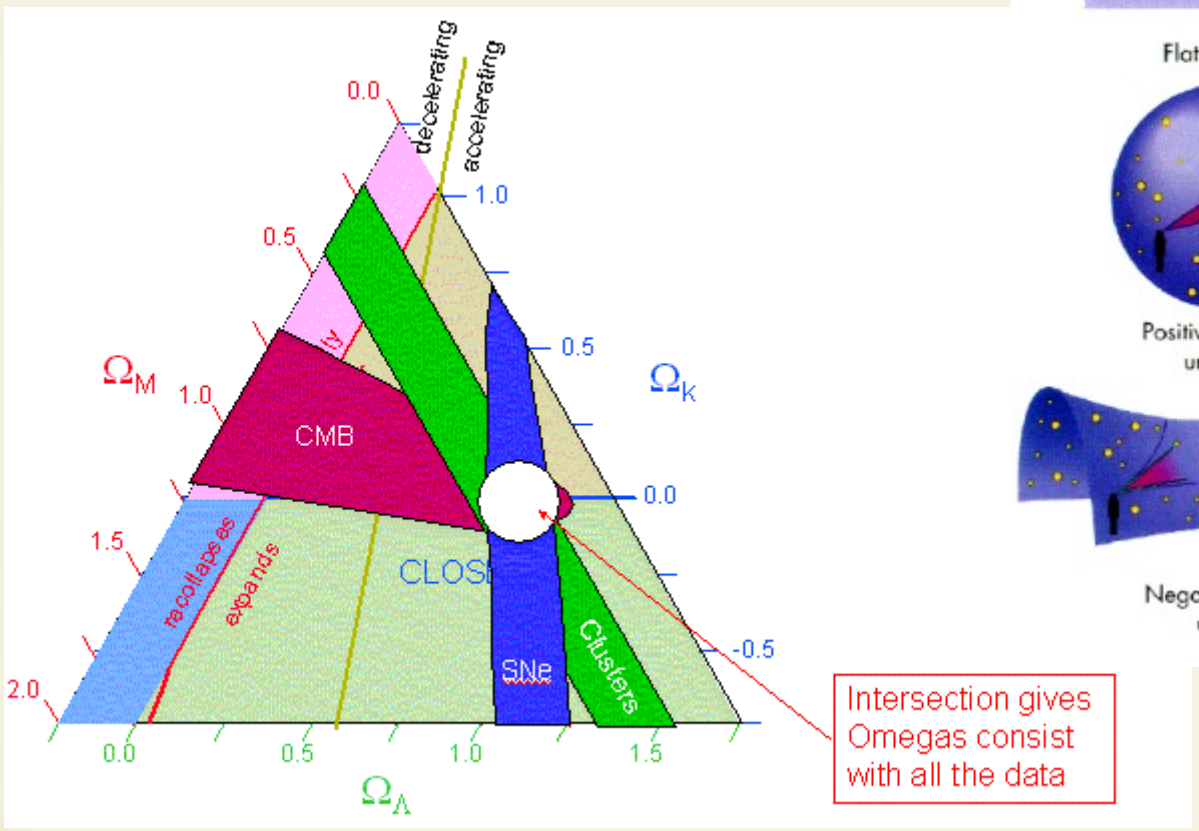
http://www.jca.umbc.edu/~george/images/cosmology/penzias_wilson_pic.jpg

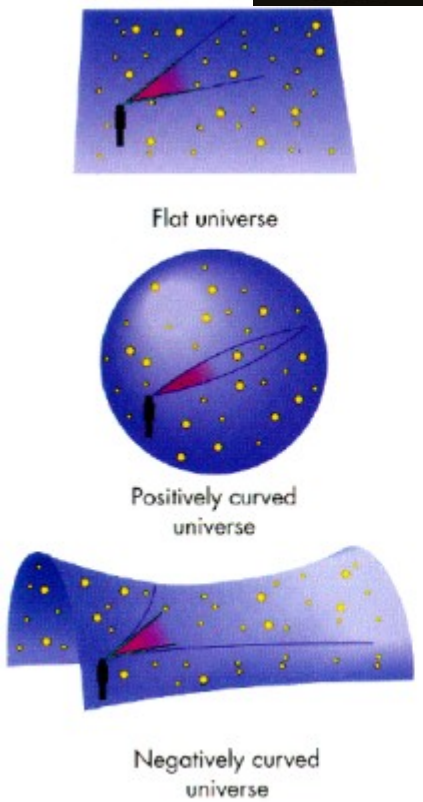
Nature of Expansion

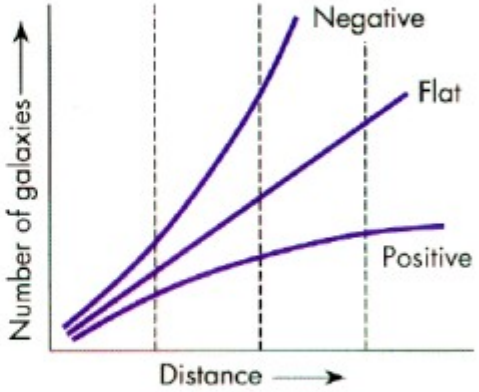
- What drives expansion?
- Is it constant, increasing, decreasing?
- What is the geometry?

$$H^2 + \frac{\kappa}{a^2} = \frac{8\pi G}{3}\rho(a)$$

expansion rate | curvature of space | energy density

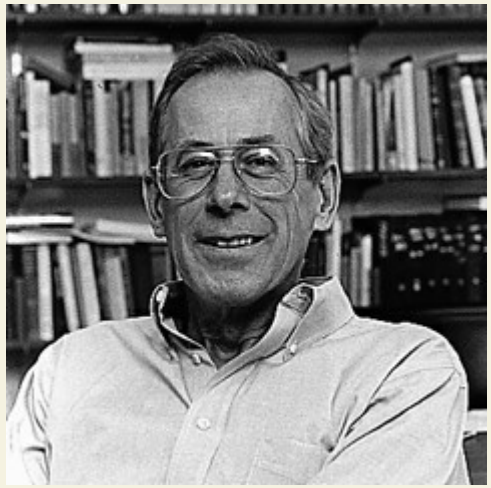




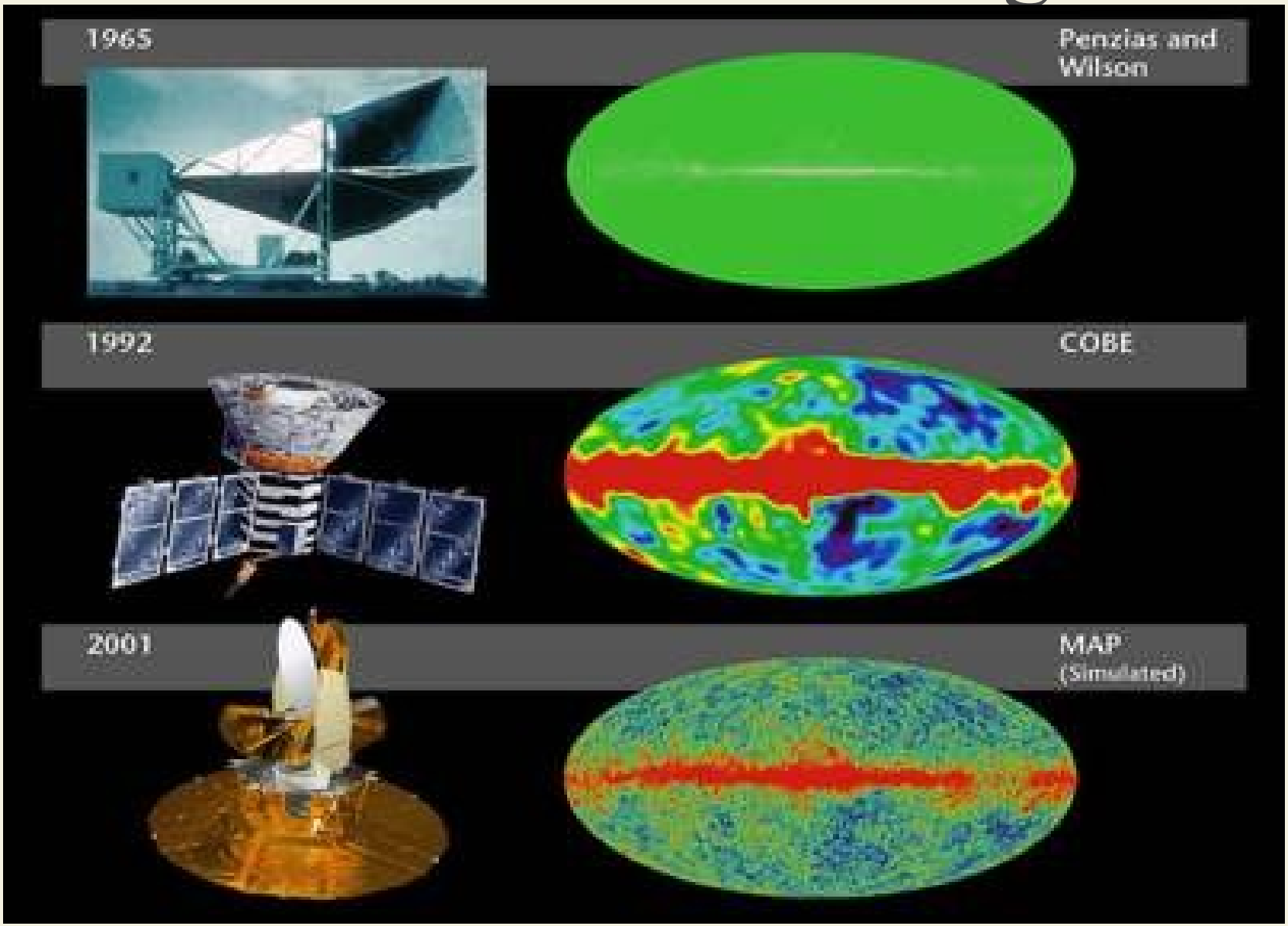


Formation of Galaxies and Clusters

- James Peebles
- CMB Photons came from opaque wall
- Abundances of He, Deuterium depend on present density of baryons
- Formation of Structure
  - After decoupling of photons from baryons
  - Gravitational collapse starts 300,000 yrs
  - After inflationary period
- Seek fluctuations in CMB

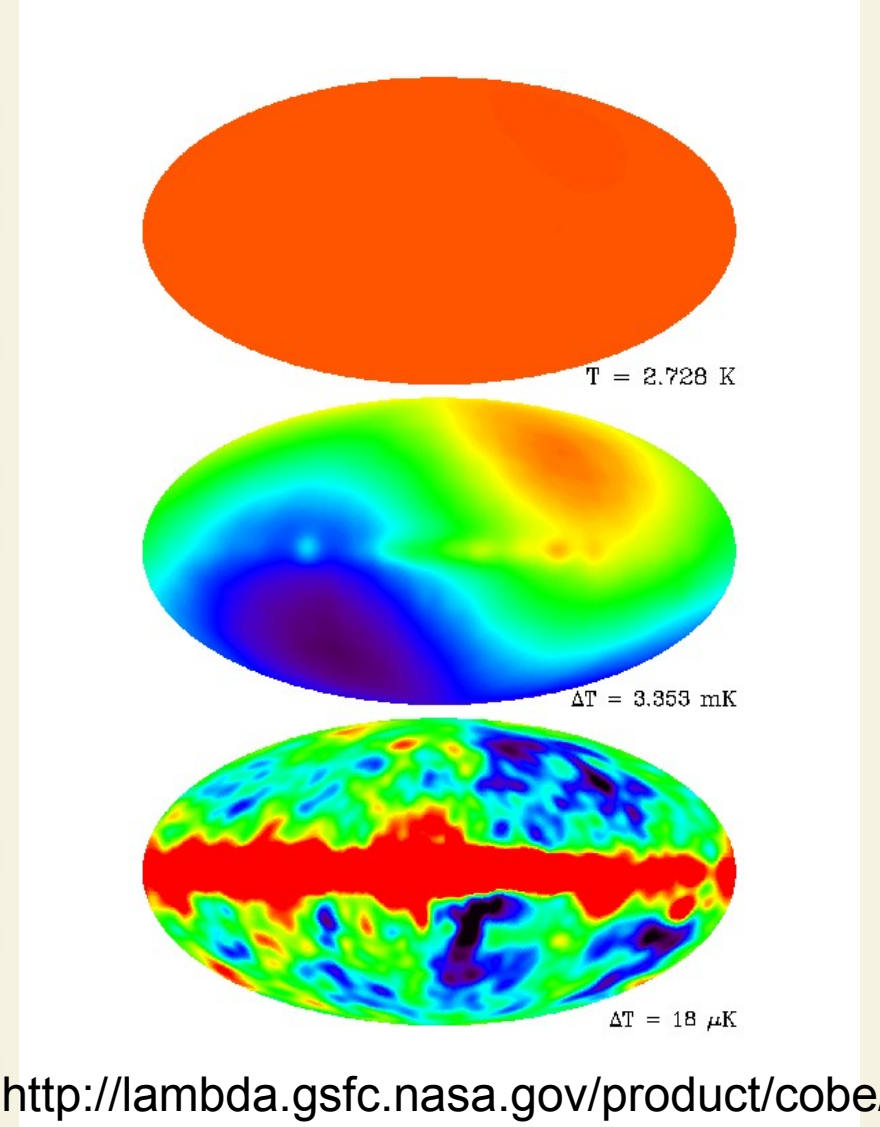


Cosmic Microwave Background

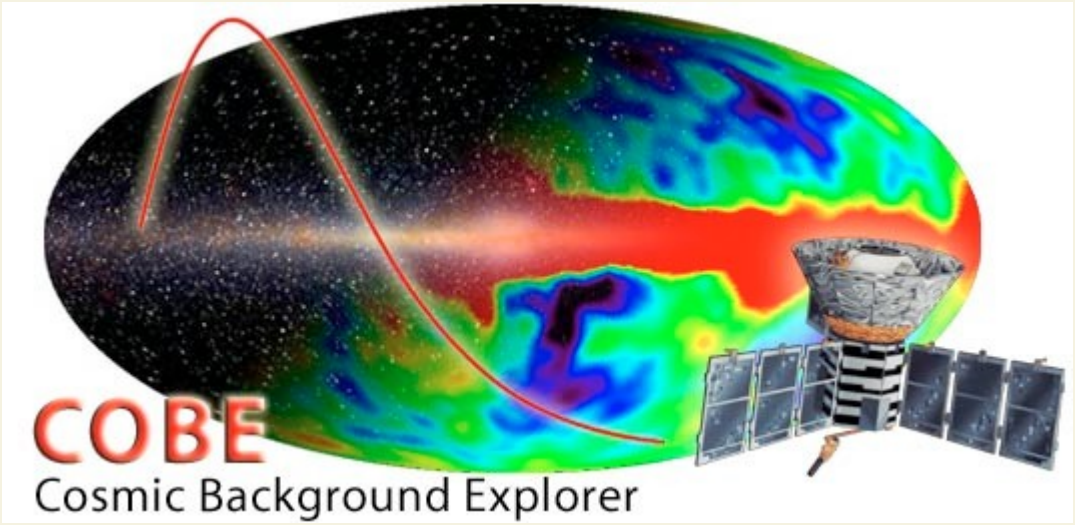


http://www.space.com/scienceastronomy/map_mission_basics_030211.html

COBE - 1991



http://lambda.gsfc.nasa.gov/product/cobe/



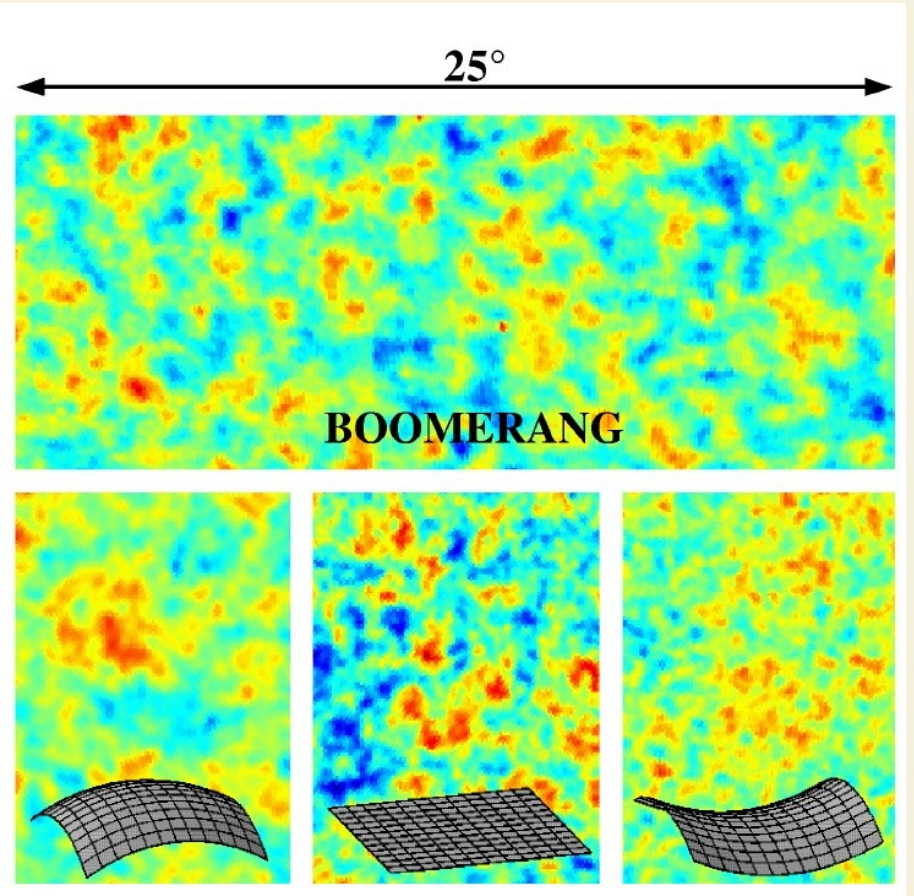
- Detected fluctuations (anisotopies)
- 2006 Nobel
  John Mather and George Smoot

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

BOOMERanG

Balloon Observations Of Millimetric Extragalactic Radiation and Geophysics

- ~2000 – Universe is flat!
- ~30% Matter (5% Baryonic)

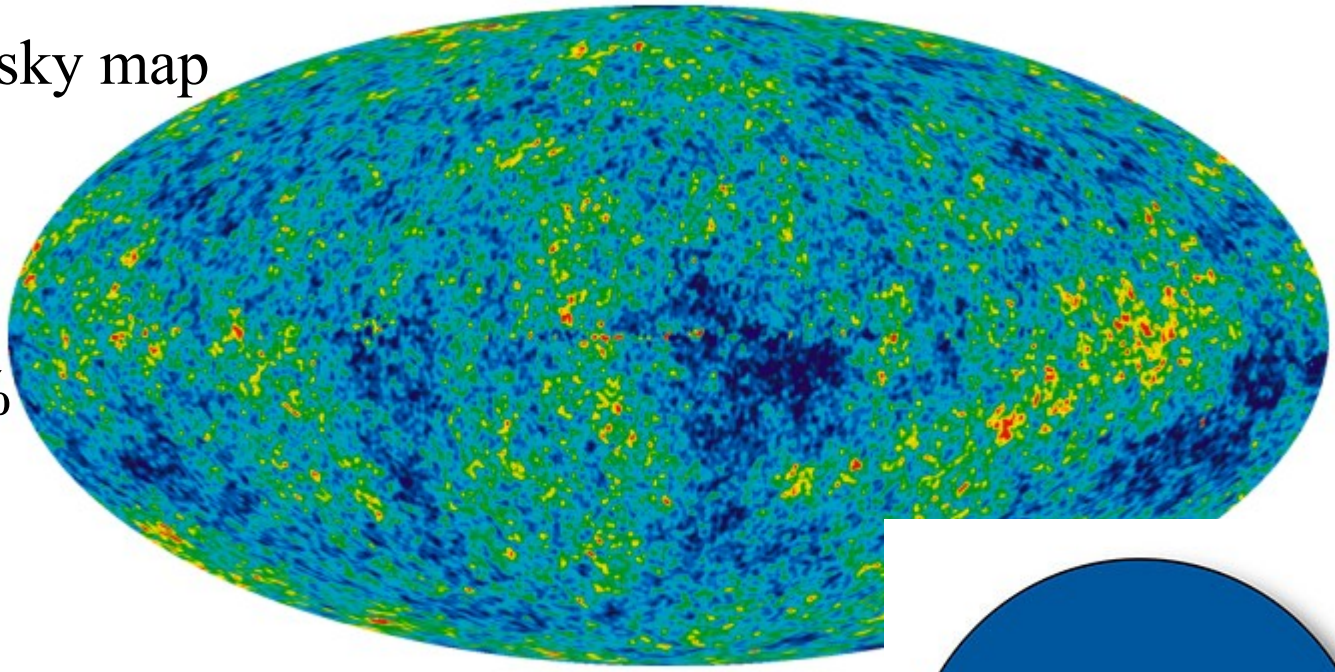


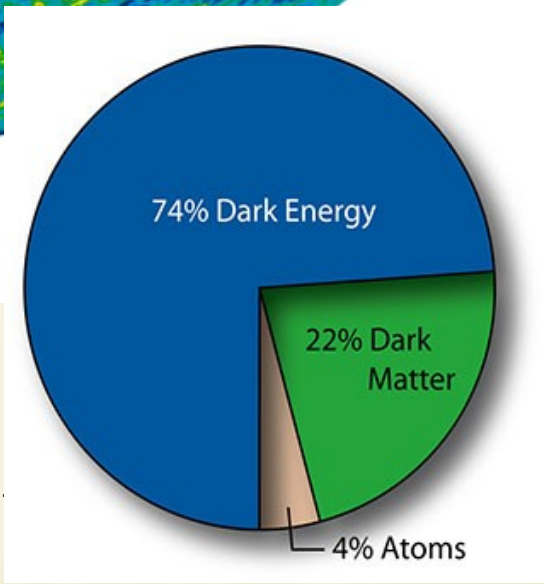
http://science.nasa.gov/science-news/science-at-nasa/2000/ast27apr_1/

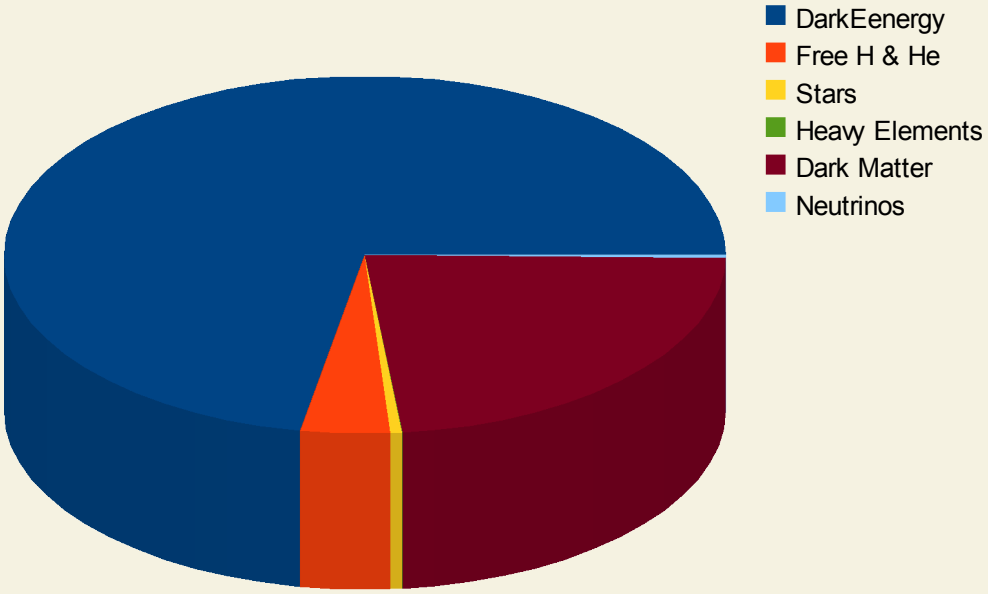
WMAP – launched 2001

Wilkinson Microwave Anisotropy Probe

- 7 yrs of data
- Fine resolution full sky map
- Age 13.73 +/- 1%
- Flat within 1%
- Ordinary atom 4.6%
- Dark Matter 23.3%
- Dark Energy 73.1%



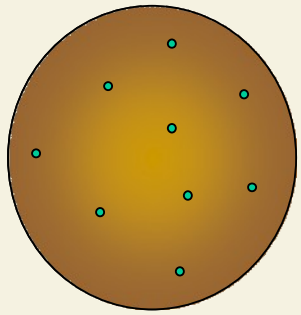


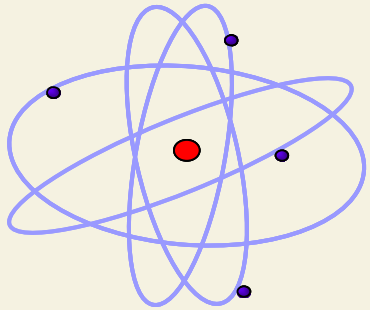


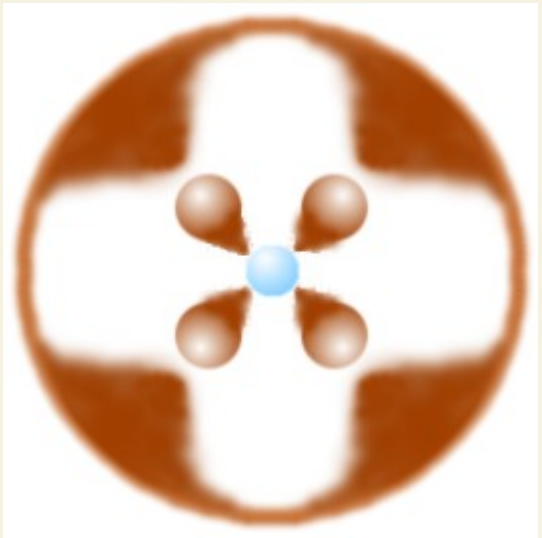
Building Blocks – Particle Physics

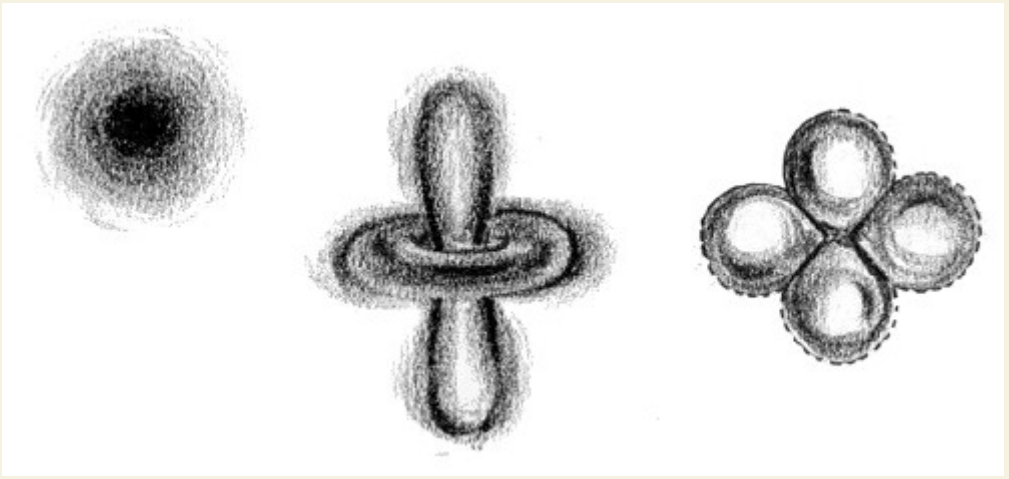
What is the Universe Made Of?

- Atoms -
- Electrons
- Nucleus - Nucleons
- Antiparticles
- And ... quarks?





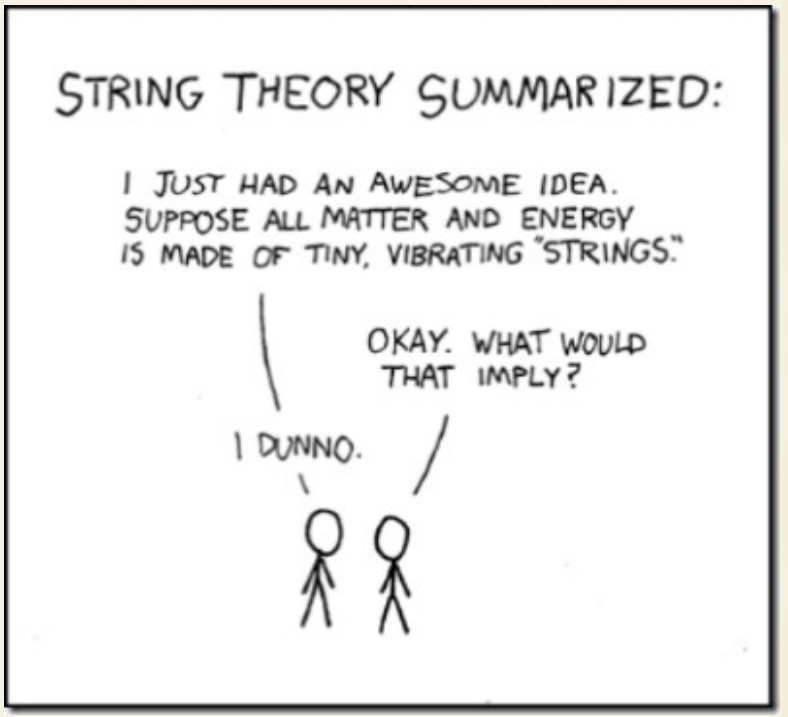


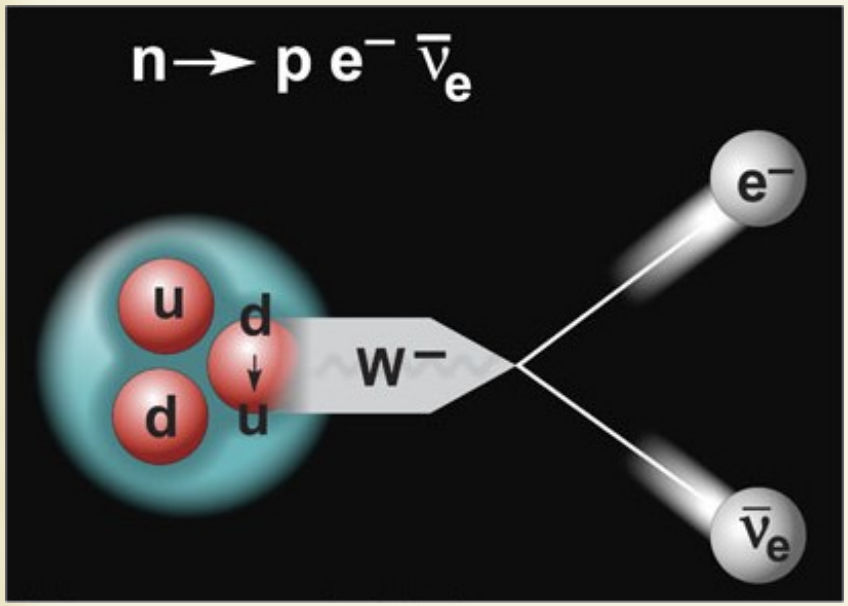


http://www.parentcompany.com/creation_explanation/cx6a.htm

What Holds it Together?

- Gravitational Force
- Electromagnetic Force
- Strong Force
- Weak Force





Unification of Forces –

Electricity/Magnetism = EM

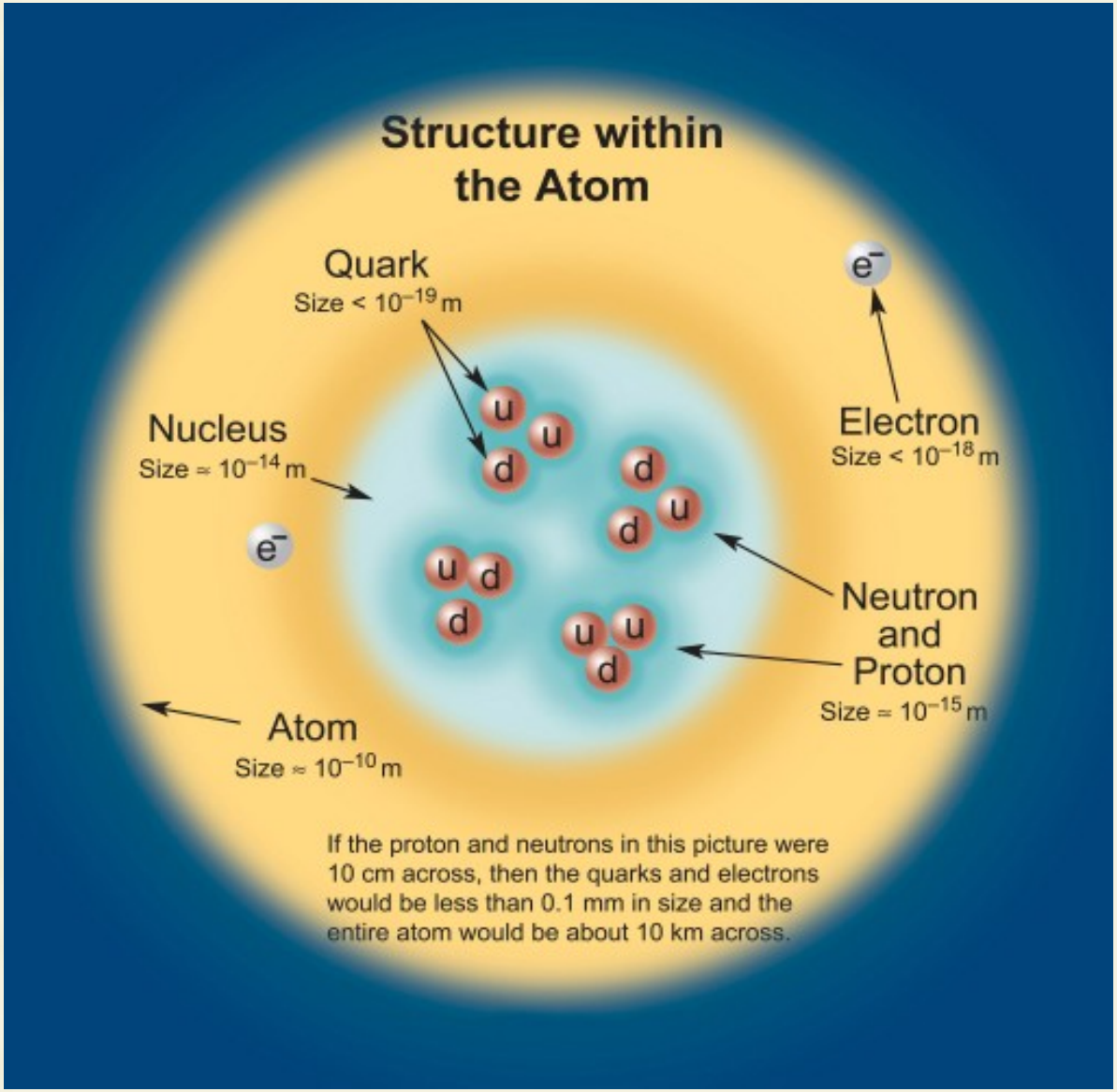
Quantum and EM = QED

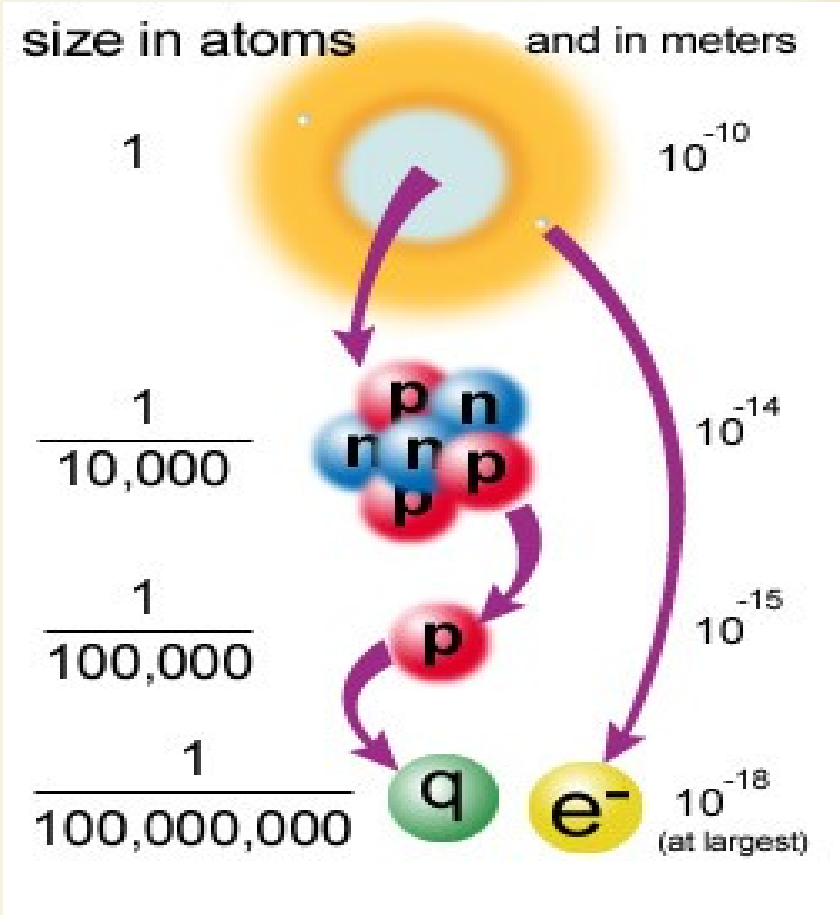
QED and Weak = Electroweak

Quantum & Strong = QCD

QCD & Electroweak = **Standard Model**

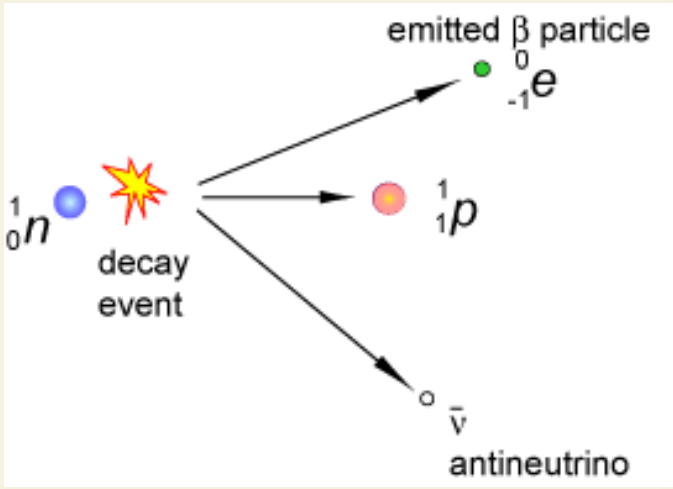
The Standard Model





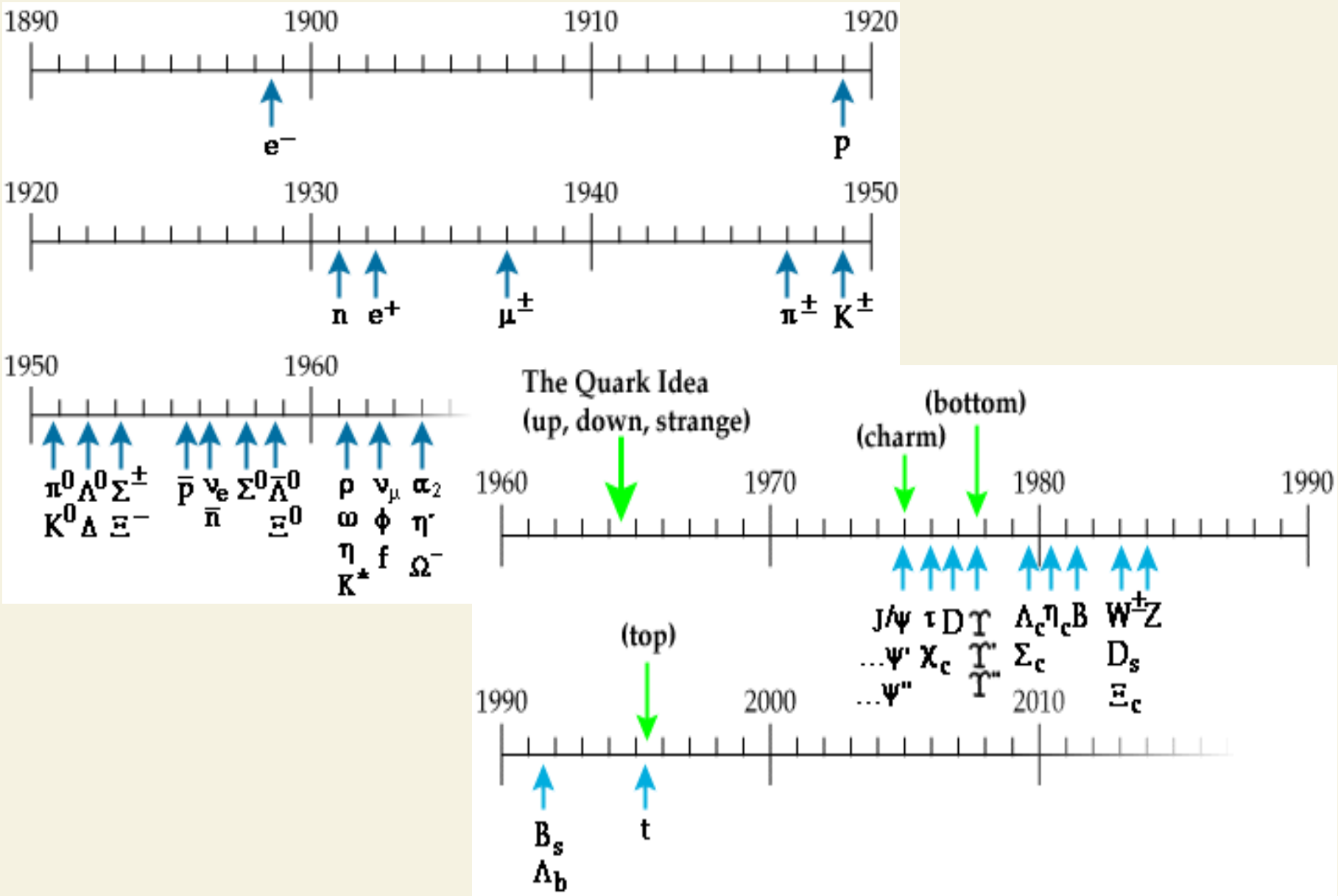
Particle Discoveries

1930 **Wolfgang Pauli** "**neutrino**"
1931 **Paul Dirac** **positrons/antiparticles**
1931 **James Chadwick** **neutron**.
1933-34 **Enrico Fermi** - theory of beta decay
1933-34 **Hideki Yukawa** "**pions**" between protons and neutrons.
1937 **Muon** is discovered in cosmic rays.
1946-47 "**lepton**" is introduced
1947 Pion found in cosmic rays.
1949 Discovery of K^+ via its decay.
1950 The neutral pion is discovered.
1951 lambda^0 and the K^0.
1952 **delta** particle: (delta^{++}, delta$^+$, delta^0, and delta$^-$.)
1953 The beginning of a "**particle explosion**"
1953-57 **internal structure** for protons and neutrons



1957 **Julian Schwinger** **unification of weak and electromagnetic interactions**.
1957-59 **Julian Schwinger**, **Sidney Bludman**, and **Sheldon Glashow**,
weak interactions are mediated W^+ and W^-
1962 Experiments verify two distinct types of **neutrinos** (electron and muon neutrinos).

The Particle Explosion



http://www.particleadventure.org/other/history

Timeline -Quarks

1964 **Murray Gell-Mann** and **George Zweig** tentatively put forth **quarks**.
mesons and baryons are composites of three quarks or antiquarks:
up, down, strange

1964 Leptons suggest fourth quark, **charm** - **Sheldon Glashow** and **James Bjorken**

1965 **O.W. Greenberg**, **M.Y. Han**, and **Yoichiro Nambu** introduce **color charge**.

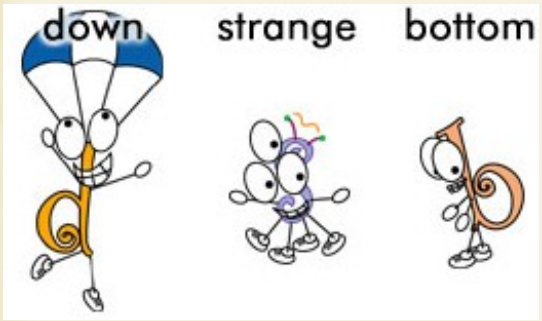
1967 **Steven Weinberg** and **Abdus Salam**
Unified electromagnetic and weak interactions, predict Higgs Boson
Theory needs neutral, weakly interacting boson that mediates weak interaction

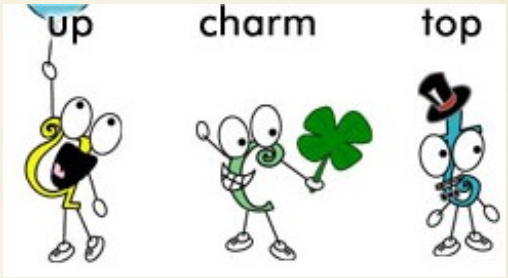
1968-69 Stanford Linear Accelerator - electrons are scattered off protons,
Electrons appeared to be bouncing off small hard cores inside proton.
James Bjorken and **Richard Feynman** analyzed as particles inside proton

1970 **Sheldon Glashow, John Iliopoulos,** and **Luciano Maiani**
recognize the importance of a fourth type of quark in **Standard Model**.

1973 **Donald Perkins**, re-analyzes old CERN data,finds indications of $\mathbf{Z^0}$ exchange.

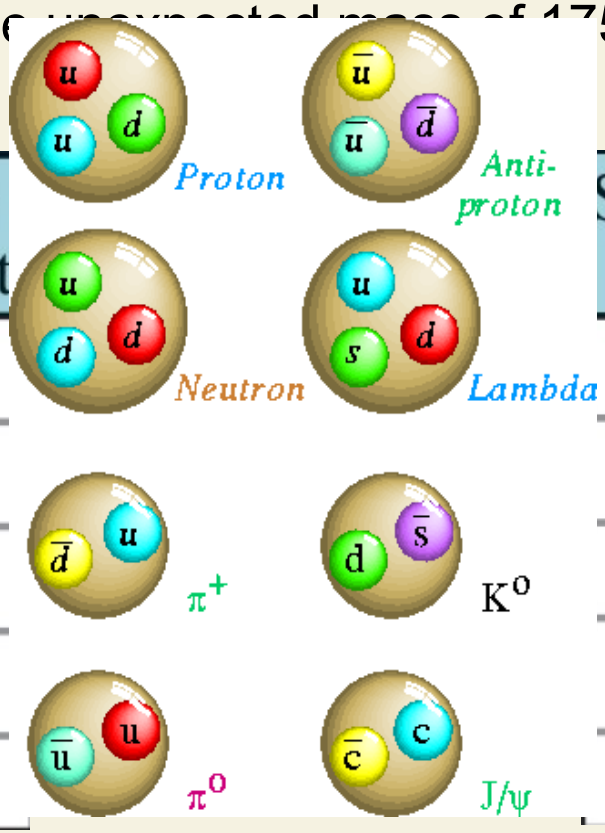
1973 A quantum field theory of strong interaction - **quantum chromodynamics (QCD)**.





Timeline - Standard Model

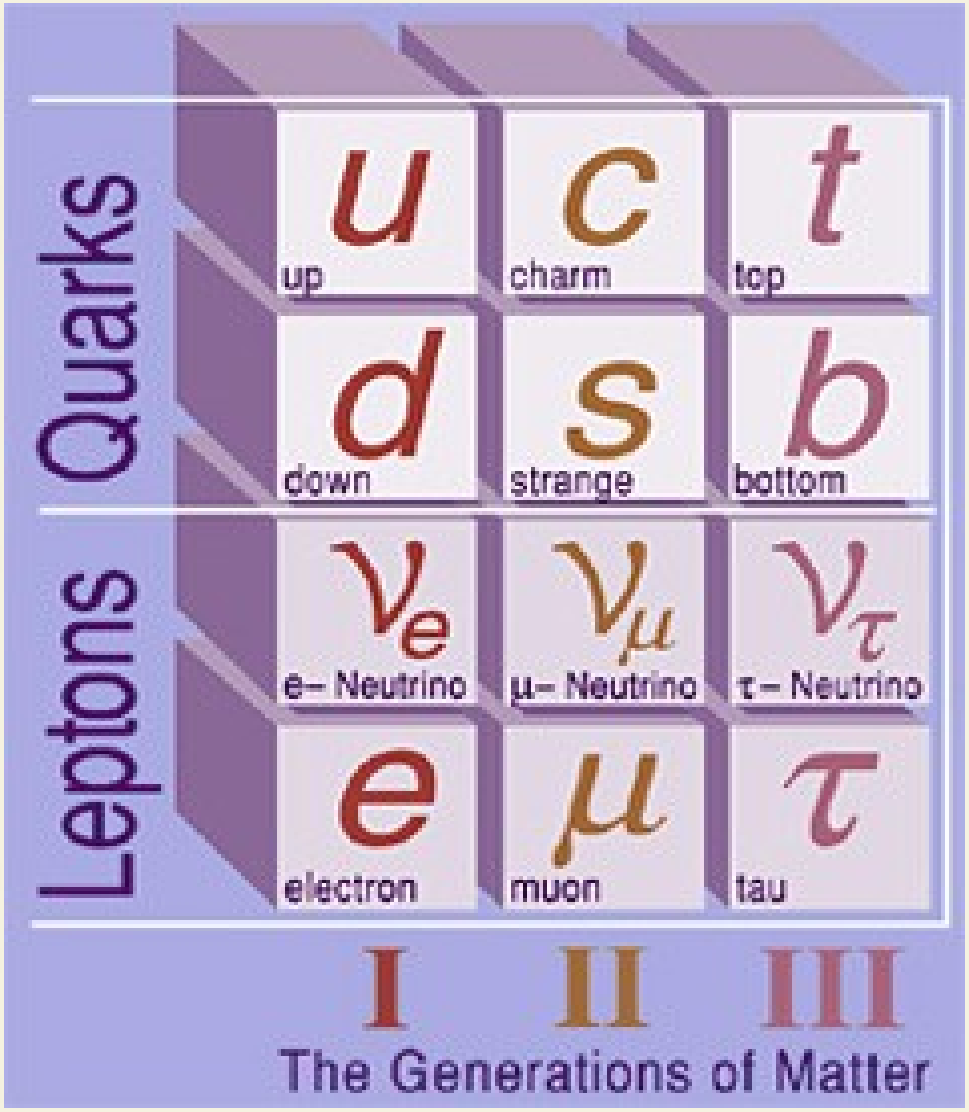
1974 **Burton Richter** and **Samuel Ting**, - "**J/psi**" particle, a charm-anticharm meson.
1976 **Gerson Goldhaber** and **Francois Pierre** find the **D^0** meson (anti-up and charm).
1976 The **tau** lepton is discovered by **Martin Perl** and collaborators at SLAC.
1977 **Leon Lederman** and his collaborators at Fermilab discover the **bottom** quark.
1978 **Charles Prescott** and **Richard Taylor** observe a **Z^0** mediated weak interaction
1983 Find **$W^{\pm}$** and **Z^0** intermediate bosons using the CERN synchrotron
using p and anti-p techniques of **Carlo Rubbia** and **Simon Van der Meer**
1995 The **top** quark found at the unexpected mass of 175 GeV



Symbol	Name	Quark content
p	proton	uud
$\bar{p}$	antiproton	$\bar{u}\bar{u}\bar{d}$
n	neutron	udd
Λ	lambda	uds
Ω^-	omega	sss

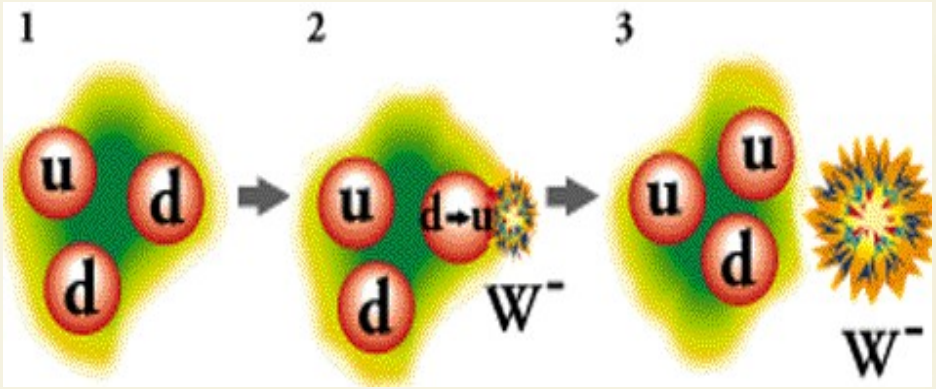
Symbol	Name	Quark content
π^+	pion	$u\bar{d}$
K^-	kaon	$s\bar{u}$
ρ^+	rho	$u\bar{d}$
B^0	B-zero	$d\bar{b}$
η_c	eta-c	$c\bar{c}$

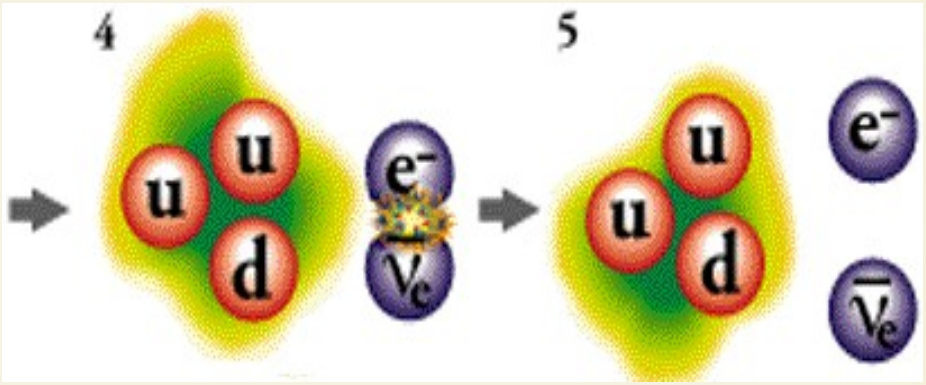
Quarks and Leptons



Neutron - udd
Proton - uud

$n \Rightarrow p + e^- + \underline{\nu}_e$

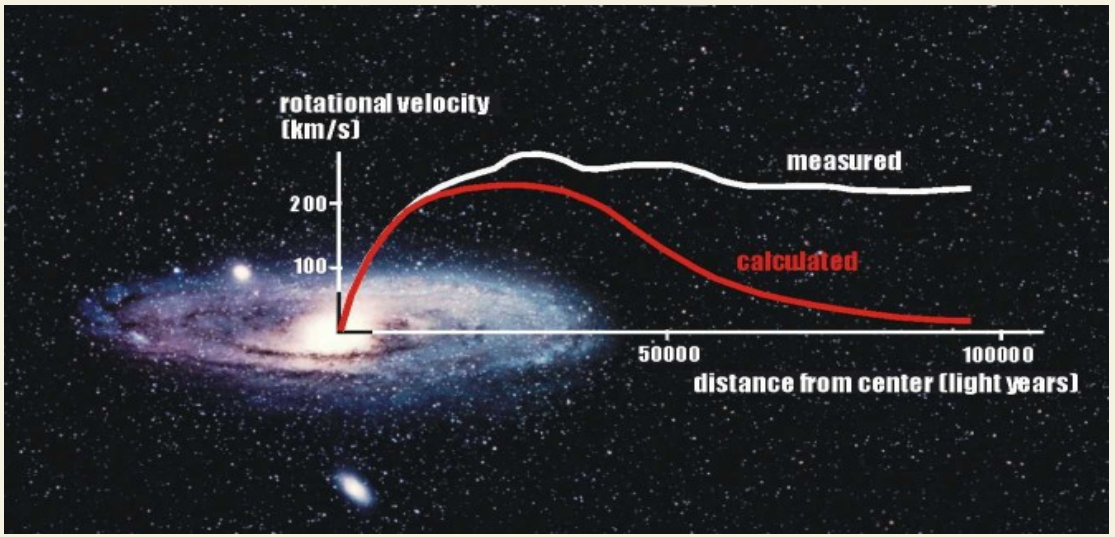




The New Cosmology

Galaxies

- Stars mostly at center
- Circling center
- Orbital speed greater at center
- Speed vs distance decreases



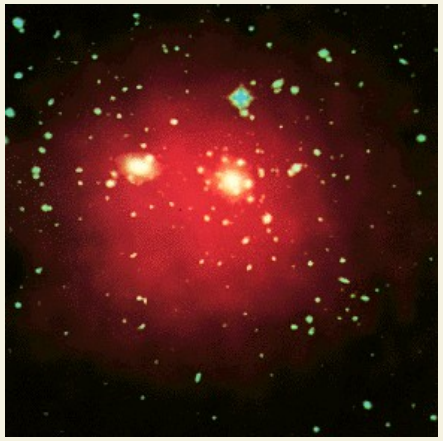
Dark Matter

- Fritz Zwicky, 1933
  - Coma Cluster – galaxies moving too fast!
  - Mass 100x too little
  - Must be *dark matter*
- Vera Rubin & Kent Ford, 1970 M31
  Dark Halos
- Galaxies embedded in spherical cloud of DM
- Hot vs Cold DM
- Candidates – Neutrinos, WIMPs, supersymmetric particles ...

Coma Cluster

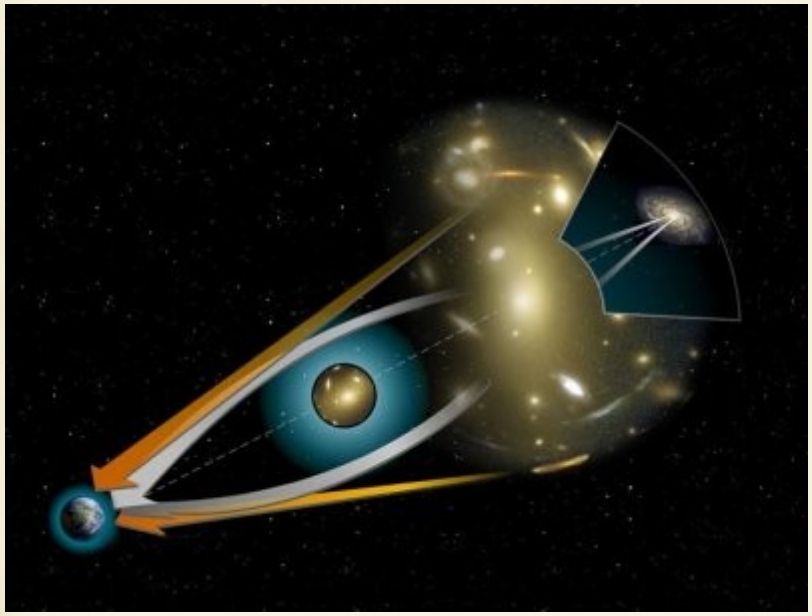
Galaxy Cluster Abell 1689
Hubble Space Telescope • Advanced Camera for Surveys

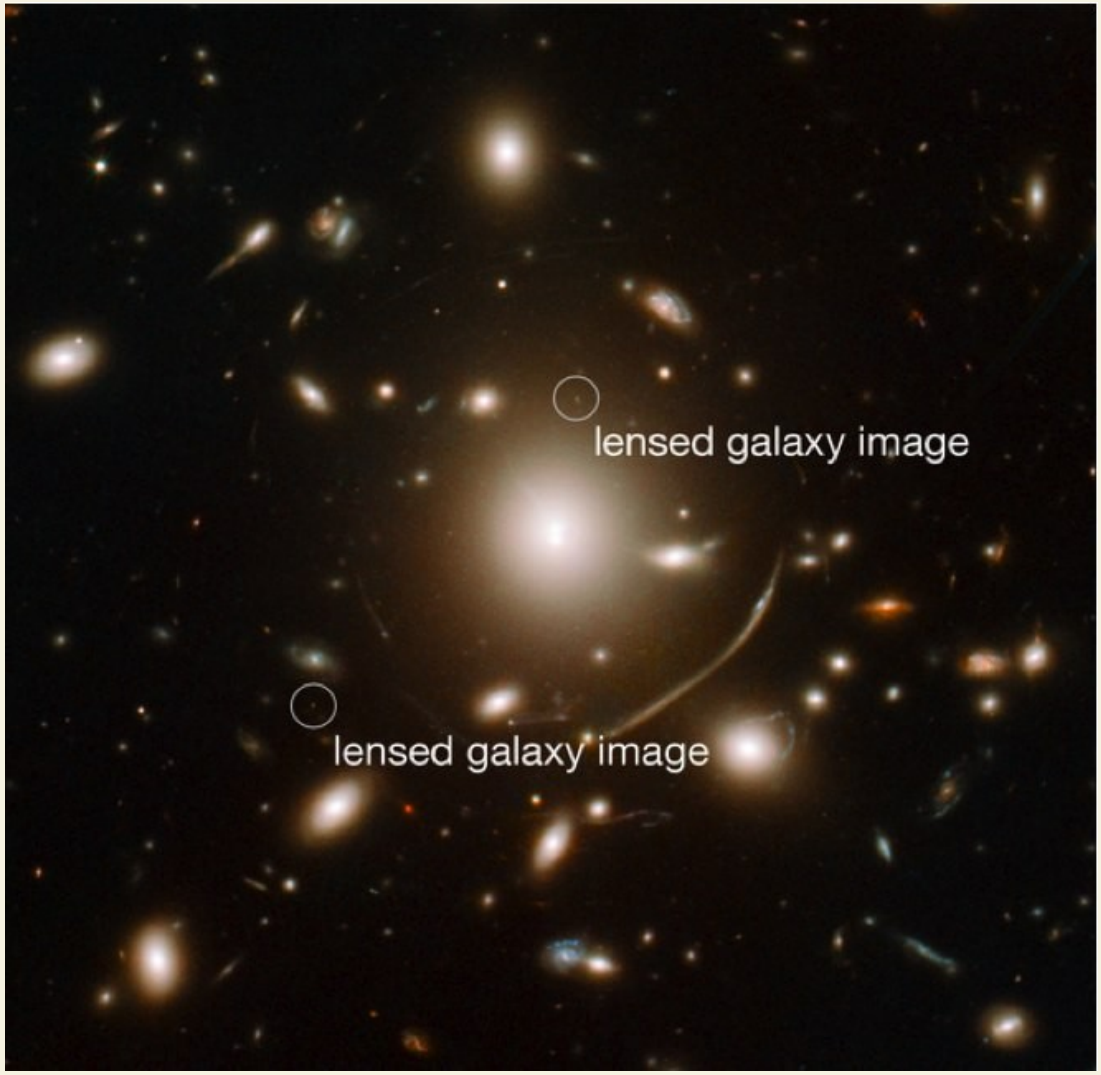
NASA, N. Benitez (JHU), T. Broadhurst (The Hebrew University), H. Ford (JHU), M. Clampin(STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA
STScI-PRC03-01a



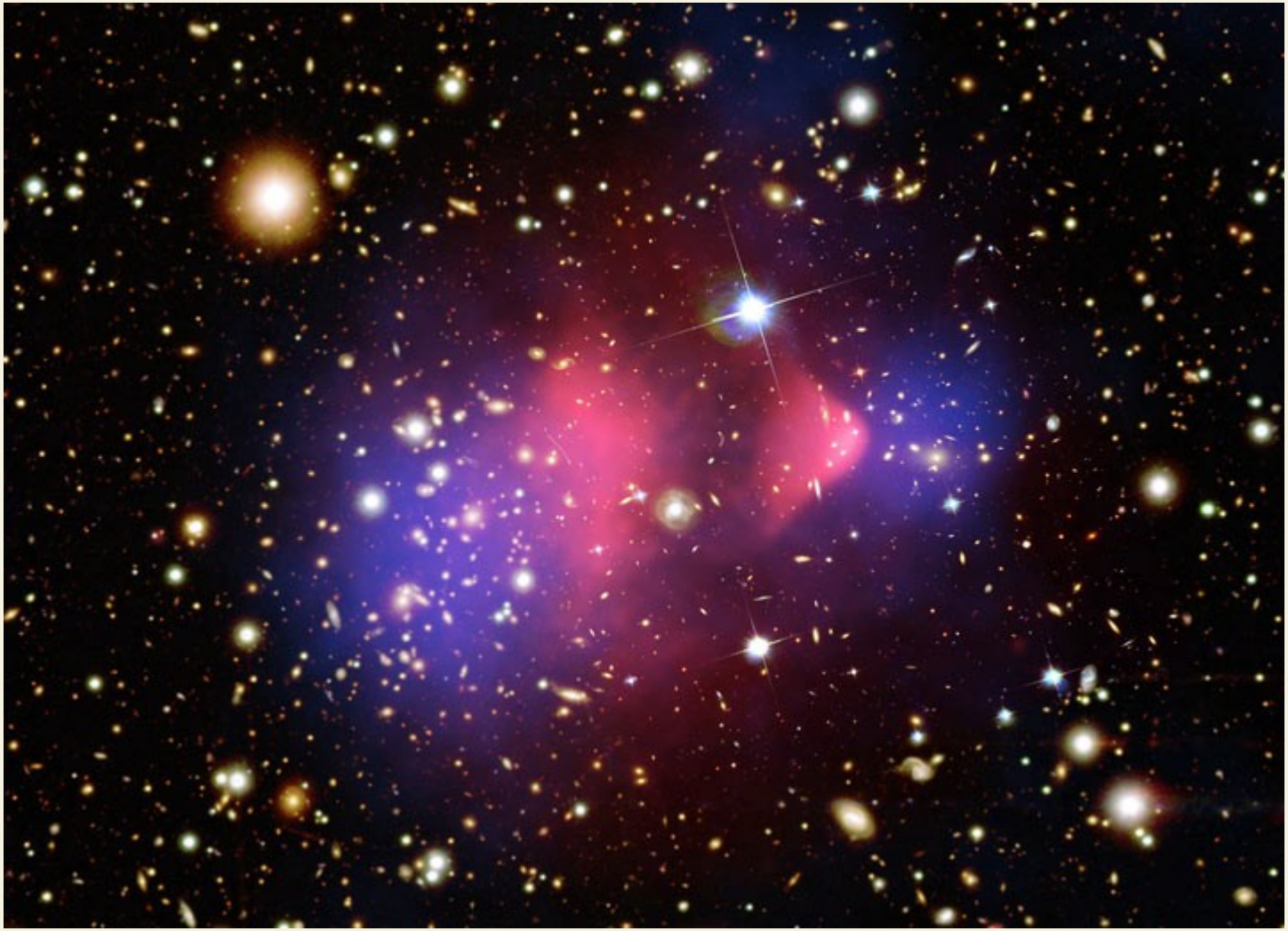
- How do we see dark matter?

Gravitational Lensing



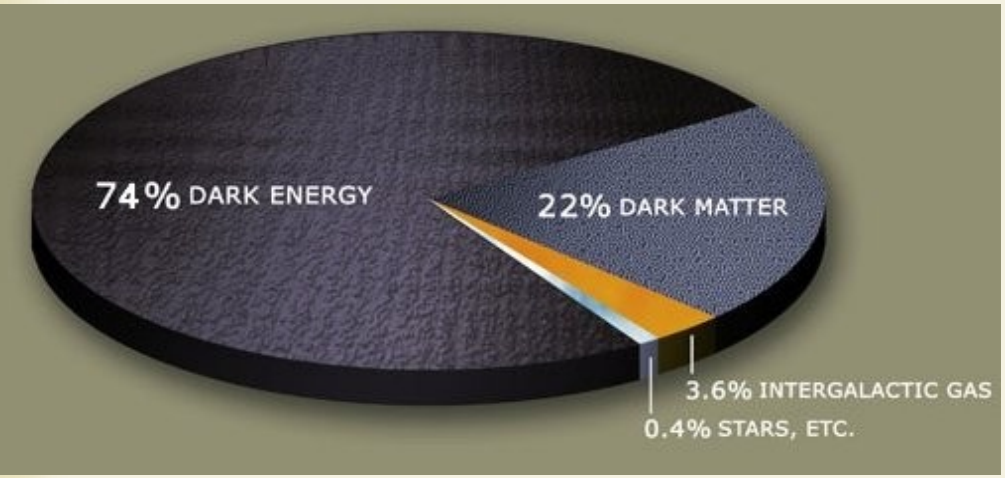


Colliding Galaxies

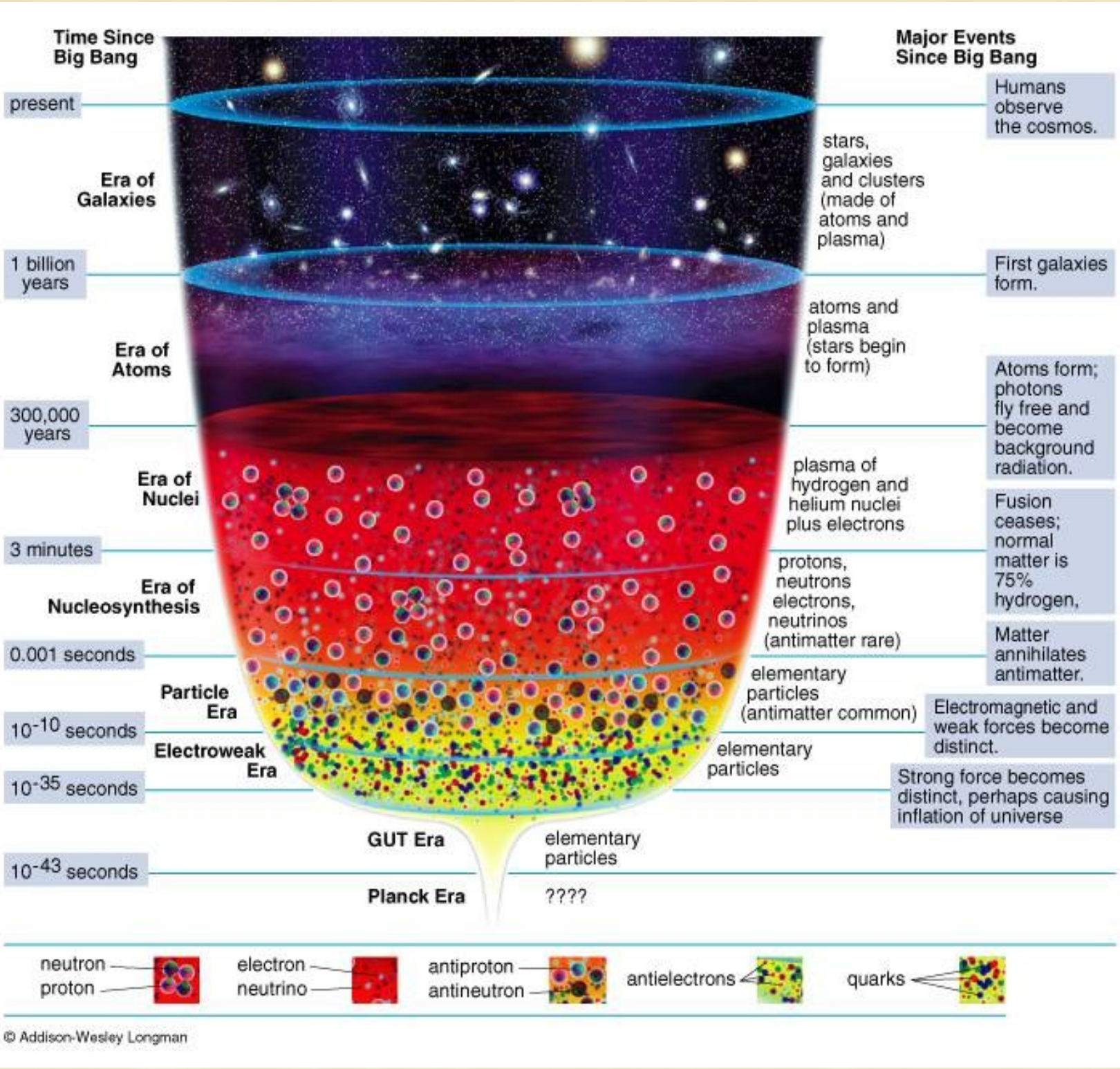


The Energy of Empty Space – Dark energy

- Saul Perlmutter, Adam Riess, Brian Schmidt
- 1998 – Expansion is accelerating!



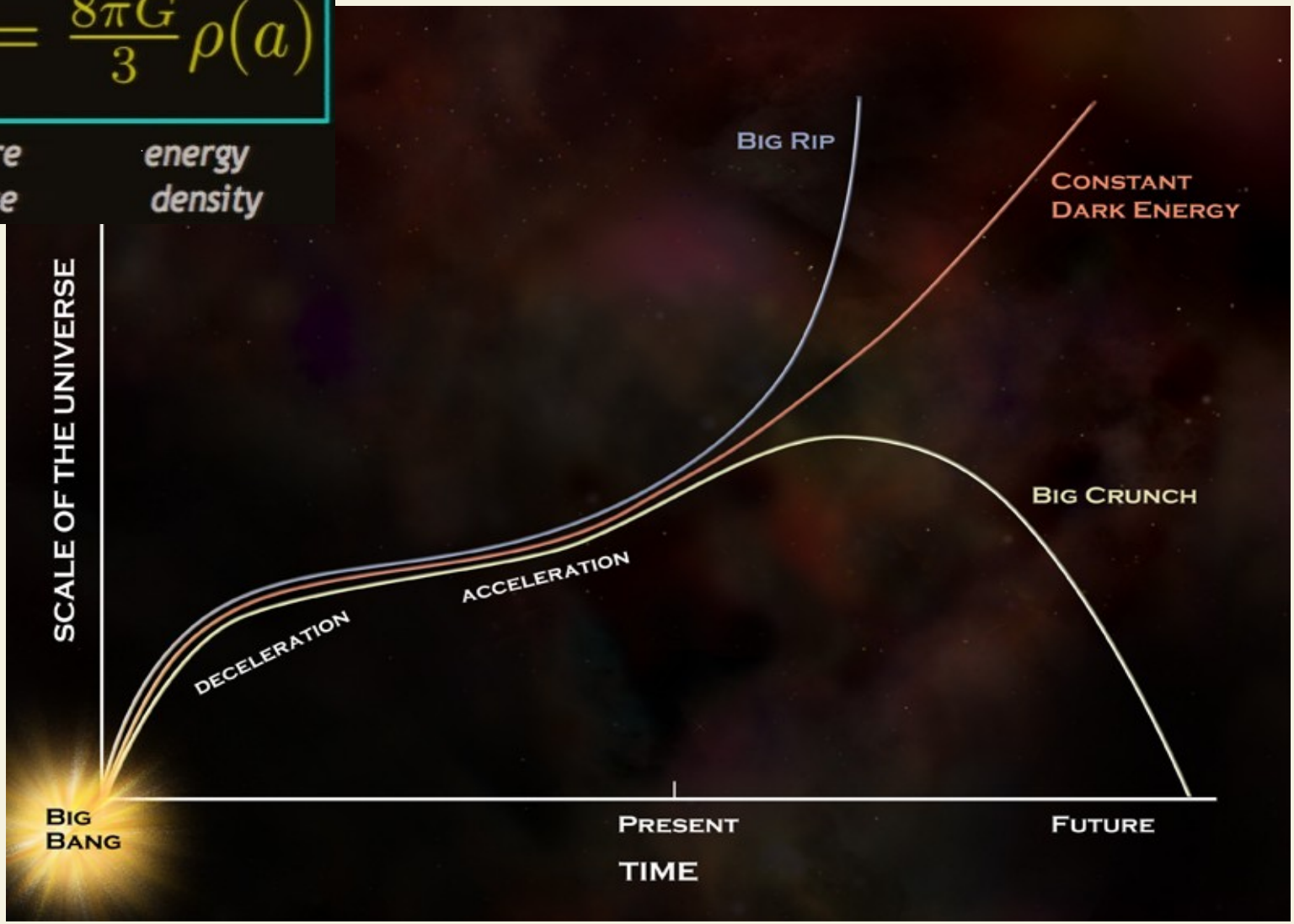
In 1998, published observations of Type Ia supernovae ("one-A") by the High-z Supernova Search Team followed in 1999 by the Supernova Cosmology Project suggested that the expansion of the universe is accelerating. This work was awarded by the Nobel Prize in Physics in 2011.



The Future of the Universe?

$$H^2 + \frac{\kappa}{a^2} = \frac{8\pi G}{3}\rho(a)$$

expansion rate | curvature of space | energy density



More Mysteries

LHC
Higgs Particle
String Theory
Multiverses
????

Universe Accelerating?

The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

Why No Antimatter?

Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

Dark Matter?

Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?

Origin of Mass?

In the Standard Model, for fundamental particles to have masses, there must exist a particle called the Higgs boson. Will it be discovered soon? Is supersymmetry theory correct in predicting more than one type of Higgs?

We know more, but miles to go before we sleep!

"There is a theory which states that if ever anyone discovers exactly what the Universe is for and why it is here, it will instantly disappear and be replaced by something even more bizarre and inexplicable."

"There is another theory which states that this has already happened.",

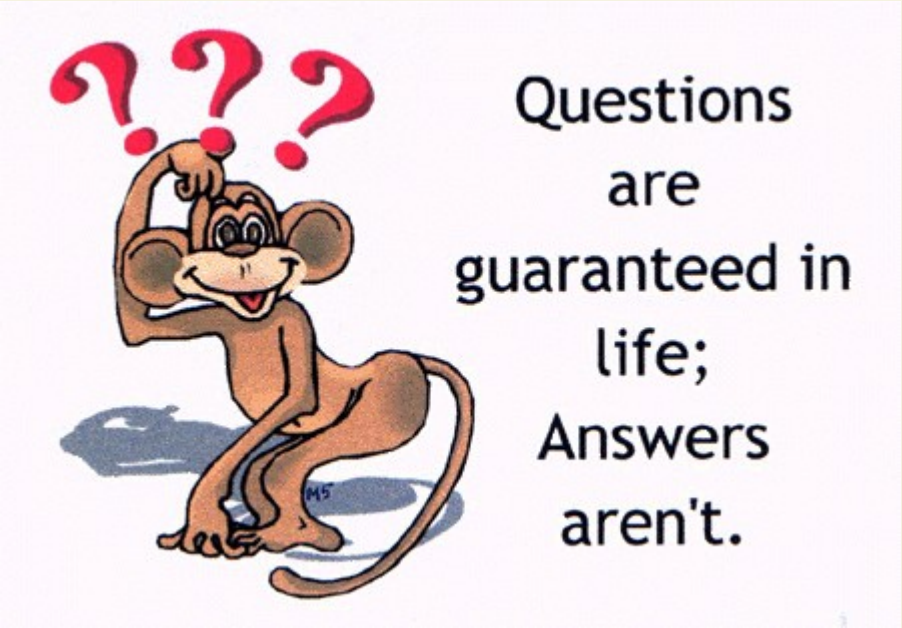
Restaurant at the End of the Universe, Douglas Adams

Further Reading

The First Three Minutes, S. Weinberg
The 4% Universe, R. Panek
A Universe from Nothing, L. Krauss
The Day We Found the Universe, Marcia Bartusiak
How the Universe Got its Spots, Janna Levin
Endless Universe: Beyond the Big Bang, P. J. Steinhardt and N. Turok
Big Bang: The Origin of the Universe (P.S.), S. Singh
Dark Side of the Universe: Dark Matter, Dark Energy, and the Fate of the Cosmos, I. Nicolson
The Elegant Universe or The Fabric of the Cosmos, B. Greene
Parallel Worlds: A Journey Through Creation, Higher Dimensions, and the Future of the Cosmos, M. Kaku

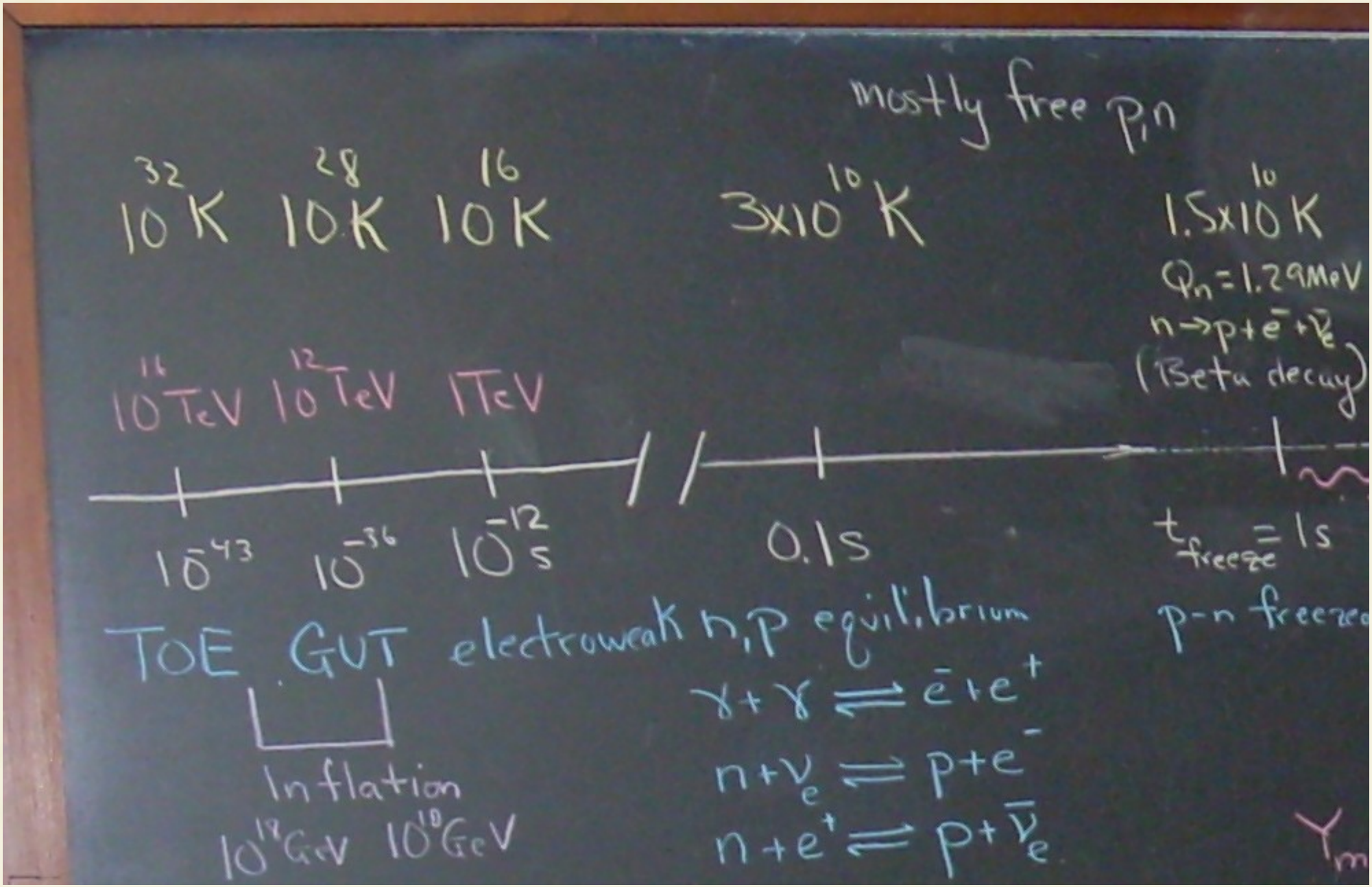
A Brief History of Time, S. Hawking
A Briefer History of Time, S. Hawking and L. Mlodinow

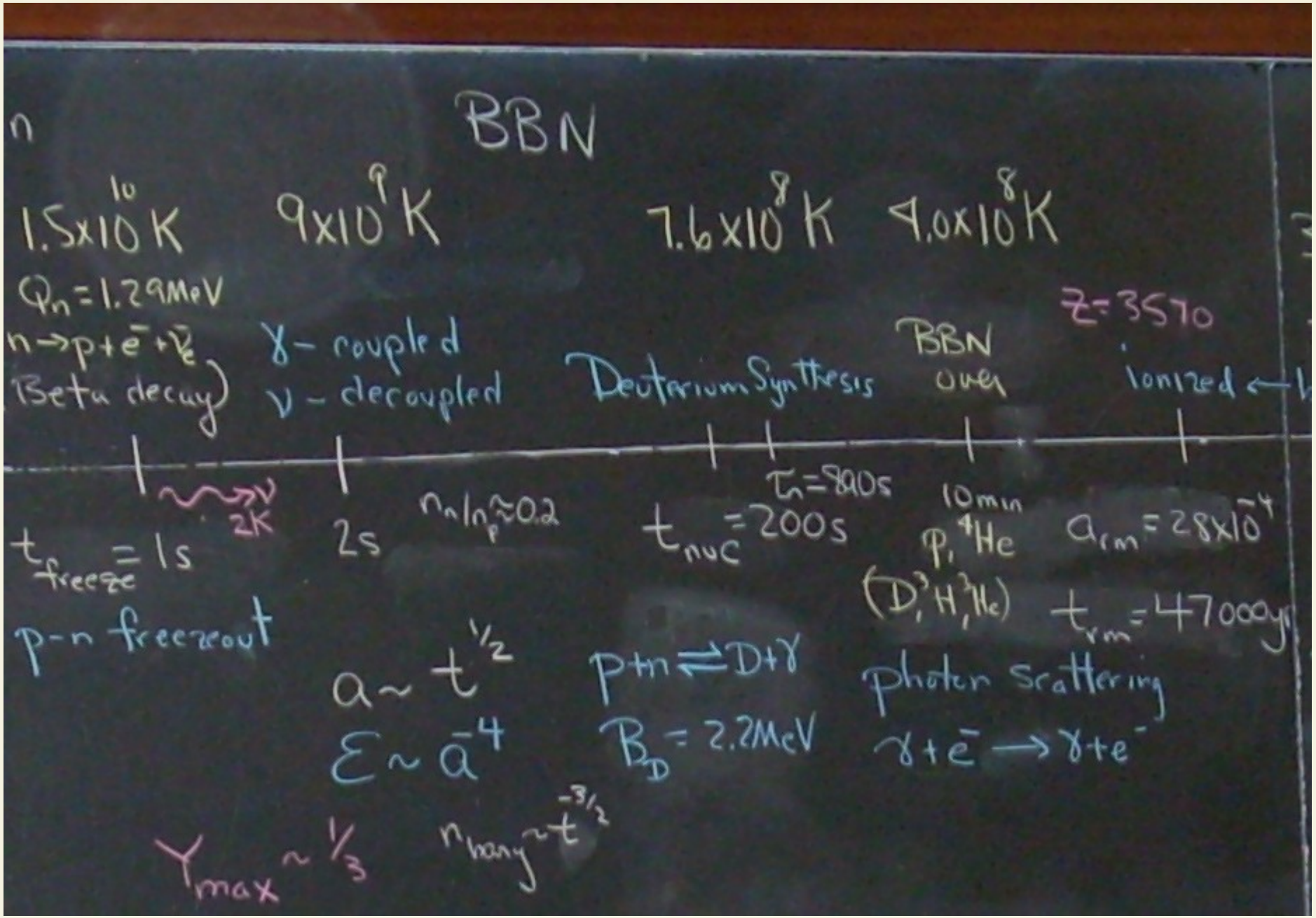
What Don't We Know?

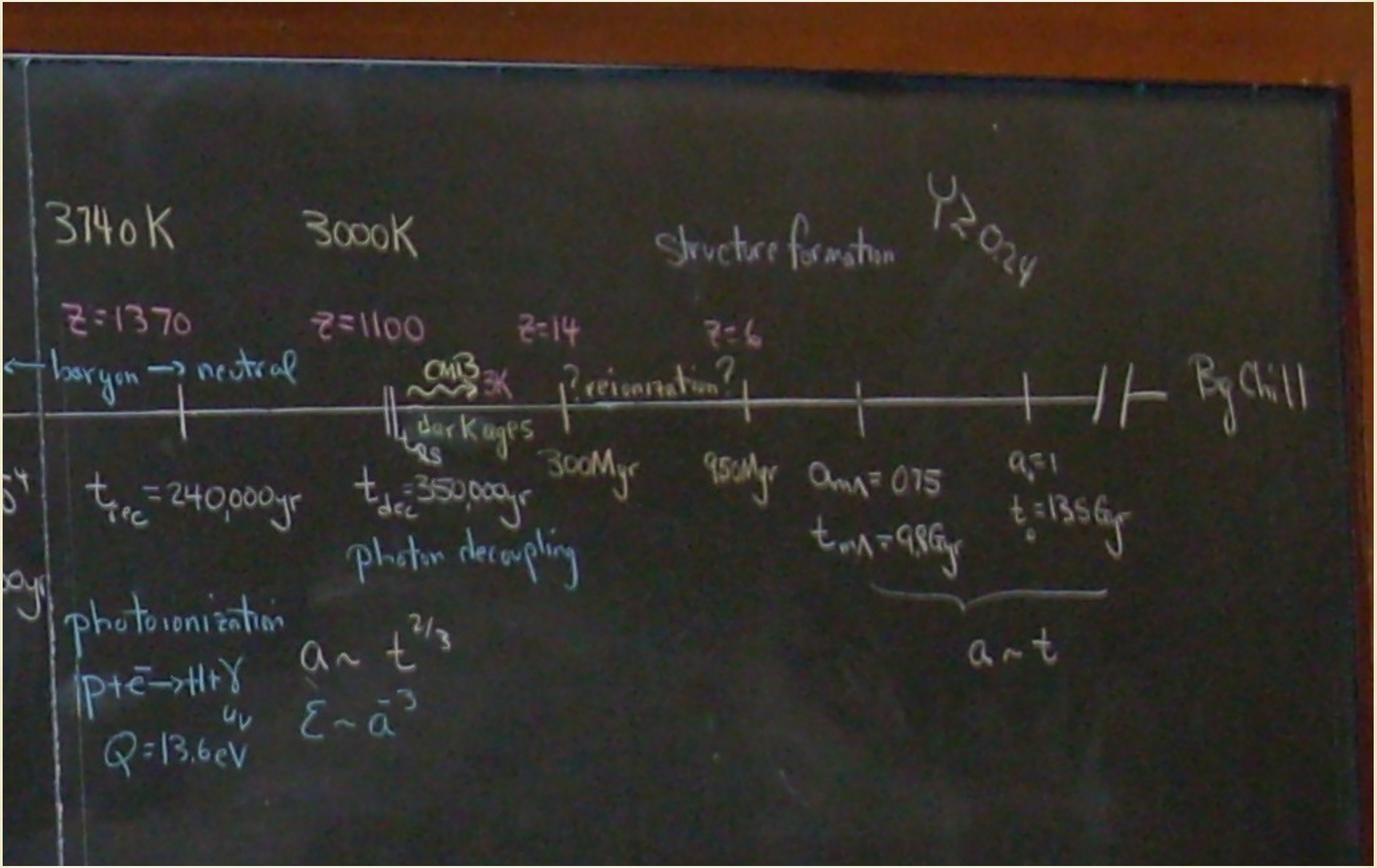


More information:
http://people.uncw.edu/hermanr/

Back Matter – Blow up of timeline


mostly free p,n
10^{32} K
10^{28} K
10^{16} K
3×10^{10} K
1.5×10^{10} K
$Q_n = 1.29$ MeV
$n \to p + e^- + \bar{\nu}_e$
(Beta decay)
10^{16} TeV
10^{12} TeV
1 TeV
10^{-43}
10^{-36}
10^{-12} s
0.1 s
$t_{freeze} = 1$ s
TOE
GUT
electroweak
Inflation
10^{19} GeV
10^{10} GeV
n,p equilibrium
$\gamma + \gamma \rightleftharpoons e^- + e^+$
$n + \nu_e \rightleftharpoons p + e^-$
$n + e^+ \rightleftharpoons p + \bar{\nu}_e$
p-n freeze
Y_m


n
BBN
1.5×10^{10} K
9×10^{9} K
7.6×10^{8} K
9.0×10^{8} K
$Q_n = 1.29$ MeV
$n \to p + e^- + \bar{\nu}_e$
(Beta decay)
γ - coupled
ν - decoupled
Deuterium Synthesis
BBN over
z = 3570
Ionized
$\tau_n = 880$s
10 min
2K
$t_{freeze} = 1$s
2s
$n_n/n_p \approx 0.2$
$t_{nuc} = 200$s
$p, {}^4He$
$(D, {}^3H, {}^3He)$
$a_{rm} = 2.8\times10^{-4}$
$t_{rm} = 47000$y
p-n freezeout
$a \sim t^{1/2}$
$p + n \rightleftharpoons D + \gamma$
Photon Scattering
$\mathcal{E} \sim a^{-4}$
$B_D = 2.2$MeV
$\gamma + e^- \longrightarrow \gamma + e^-$
$Y_{max} \sim 1/3$
$n_{baryon} \sim t^{-3/2}$


3740 K
3000K
structure formation
Y ≥ 0.24
z = 1370
z = 1100
z = 14
z = 6
baryon → neutral
CMB 3K
? reionization ?
dark ages
By Chill
t_rec = 240,000 yr
t_dec = 350,000 yr
300 Myr
950 Myr
Ω_mΛ = 0.75
t_mΛ = 9.8 Gyr
a_0 = 1
t_0 = 13.5 Gyr
photon decoupling
photoionization
p + e⁻ → H + γ
uv
Q = 13.6 eV
a ~ t^{2/3}
ε ~ a^{-3}
a ~ t