Cosmology

13.7 Gyrs of Big Bang History

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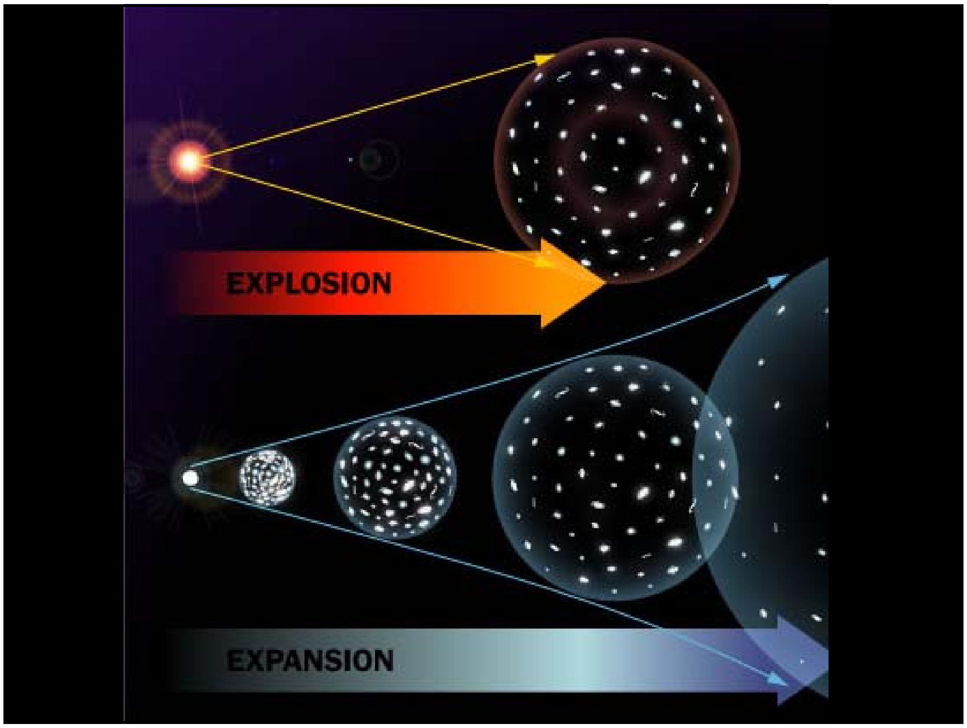

EXPLOSION
EXPANSION

Cosmology

Science of the Universe

Essential & Existential Questions Occupying Humanity since Dawn of Civilization

- Where does the World come from ?
- What is the World made of ?
- How did the World begin ?
- When did the World begin ?
- Did it begin at all ?
- How "big" is the World ? (finite, infinite ...)
- What is the role of humans in the cosmos ?
- What is the fate of the Universe ?

Cosmic Time: Origin and Fate ?

- Does the Universe have an origin ?
  If so, how old is it ?
  Or, … did it always exist, infinitely old …
- What is the fate of the Universe ?
  … will it always be there, or is there an end ?

What Propels the Universe ?

- Laws of Nature Universal: - over space
  - in time
- Fundamental Forces/Laws of Nature
- Dominant Force ?
  Gravity, the "weakest force", rules the Cosmos

Energy:
Content of the Universe

- What are the components of the Universe ?
- How does each influence the evolution of the Universe ?

  … and …
- How is each influenced by the evolution of the Universe ?

A unique time …

- The past century, since 1915, marks a special epoch
- For the first time in human history, we are able to address the great questions of Cosmology …
- scientifically …

Cosmology

Modern Questions ...

What is the Universe ?

- **Space & Time…**
- **Energy**

Space & Time ?

- Geometry ? - Rigid & Flat
  - Dynamic & Curved
- Extent ? - Open: spatially ∞
  - Closed: spatially finite
- Topology ? - Simple Euclidian
  - Complex Connectivity

What do you mean, Cosmic Time ?

- GR: time locally determined
- What about universal time ?
  Weyl's Theorem

Cosmology

Questions not yet answerable…

Cosmological Riddles

- Is our Universe unique, or are there many other Universes (multiverse) … ?
- What made the Universe originate ?

Cosmological Riddles

- Why are the physical laws as they are ?
  Do they need to be ?

- How many dimensions does the Universe have?
  More than 1timelike + 3 spacelike ?

Cosmological Riddles

- … and …

- Are our brains sufficiently equipped to
  understand and answer
  the ultimate questions … ?

Cosmology

Observing our Universe

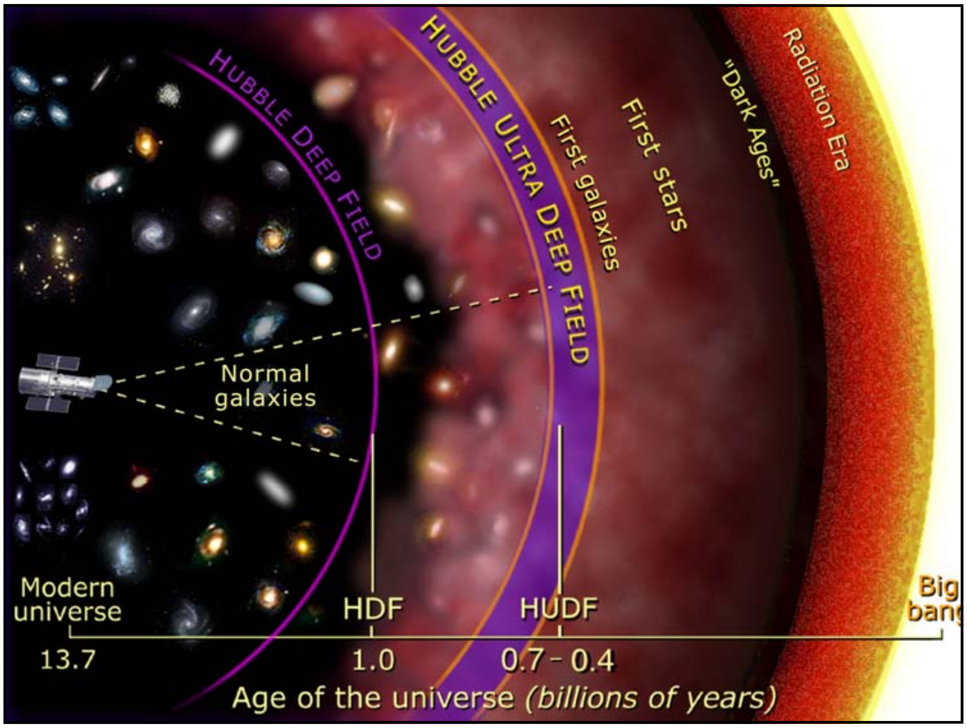
Cosmology: exploring Space & Time

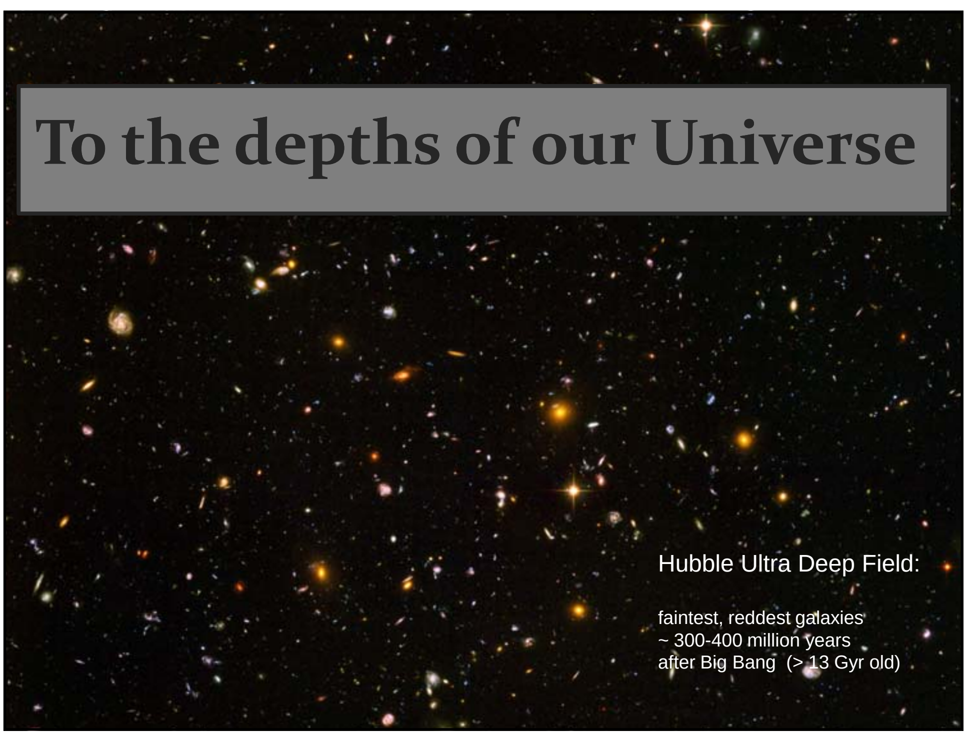
Cosmology is a unique science:

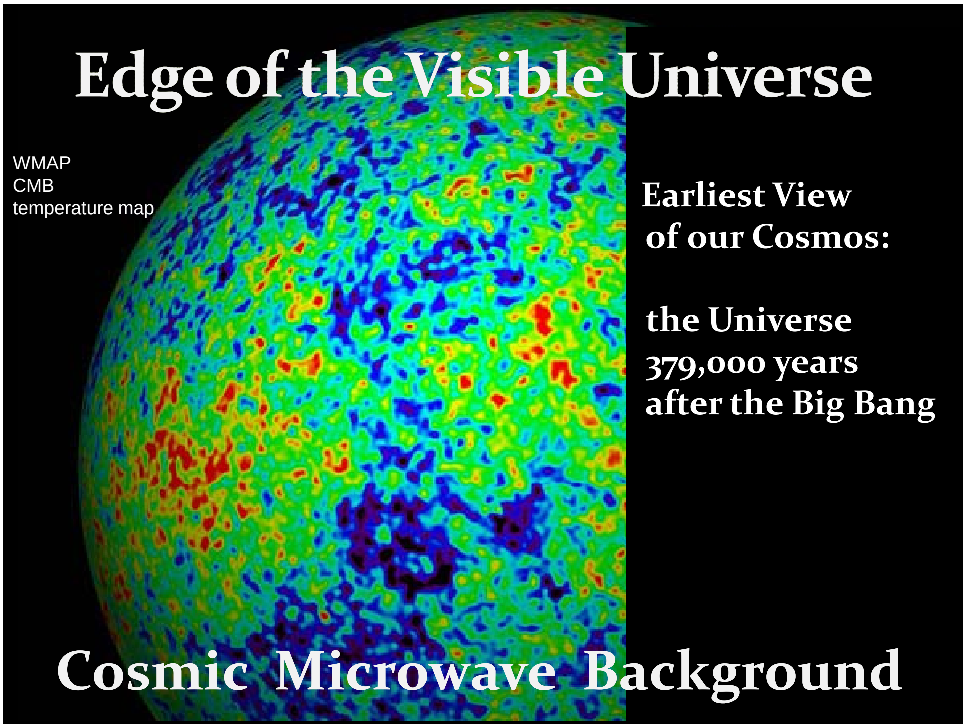
not only it looks out to the deepest realms and
largest scales of our Universe

on cosmological scales,
the finite velocity of light becomes a critical factor …

thus, it also looks back in time, to the earliest moments,
and thus is the ultimate archaeological science


Hubble Deep Field
Hubble Ultra Deep Field
First galaxies
First stars
"Dark Ages"
Radiation Era
Normal galaxies
Modern universe
HDF
HUDF
Big
13.7
1.0
0.7 – 0.4
Age of the universe (billions of years)


To the depths of our Universe
Hubble Ultra Deep Field:
faintest, reddest galaxies
~ 300-400 million years
after Big Bang (> 13 Gyr old)



the Universe:

a Unique Astrophysical Object

- There is only one (visible) Universe ...
- Finite velocity of light, c:

  ... a look in depth = a look back in time ...
- c & implications for space-time:

  observational cosmology limited to only
  a minor thin "shell" of all of spacetime ...

Hot Big Bang

Key Observations

Big Bang Evidence

- **Olber's paradox:**
  the night sky is dark
  → finite age Universe (13.7 Gyr)

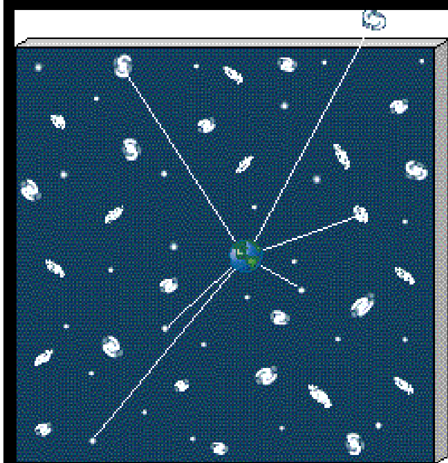
- **Hubble Expansion**
  uniform expansion, with
  expansion velocity ~ distance: v = H r

- **Explanation Helium Abundance 24%:**
  light chemical elements formed (H, He, Li, …)
  after ~3 minutes …

- **The Cosmic Microwave Background Radiation:**
  the 2.725K radiation blanket, remnant left over
  hot ionized plasma → neutral universe
  (379,000 years after Big Bang)

- **Distant, deep Universe indeed looks different …**

1. Olber's Paradox



In an infinitely large, old and unchanging Universe each line of sight would hit a star:

→

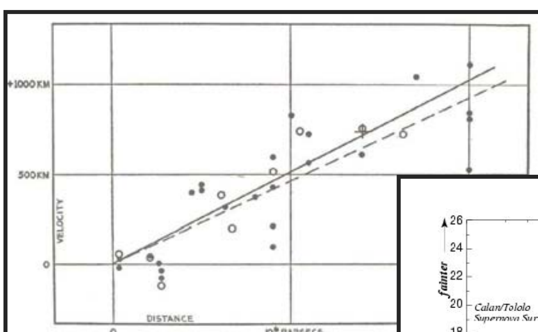
Sky would be as bright as surface of star:

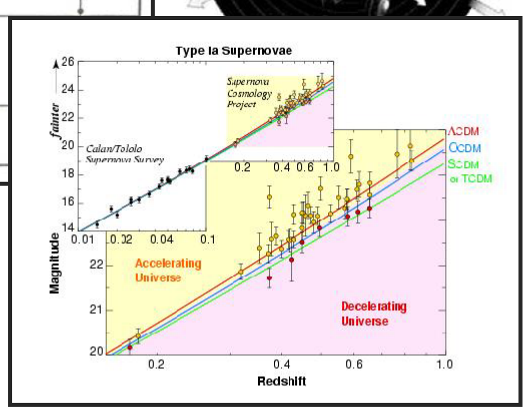
Night sky as bright as Solar Surface, yet the night sky is dark

→

finite age of Universe (13.7 Gyr)

2. Hubble Expansion

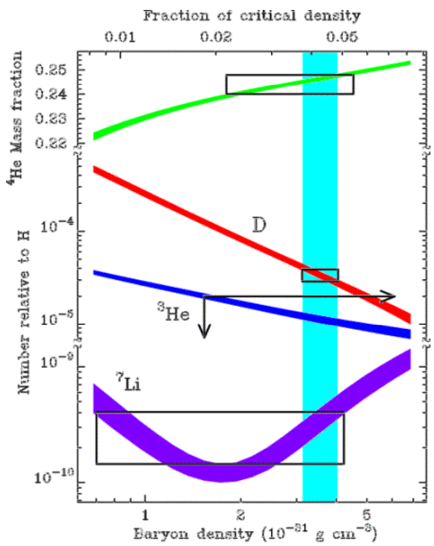




Hubble Diagram: ↑

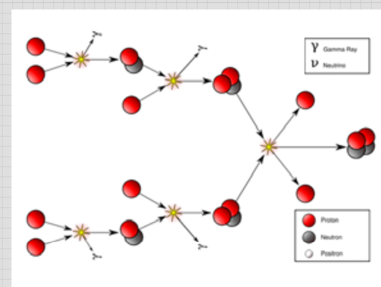
- Hubble 1929: Universe expands !!!!
- Supernova Projects (1998) Cosmic Expansion is accelerating →

3. Light Element Abundance



Mass Fraction Light Elements

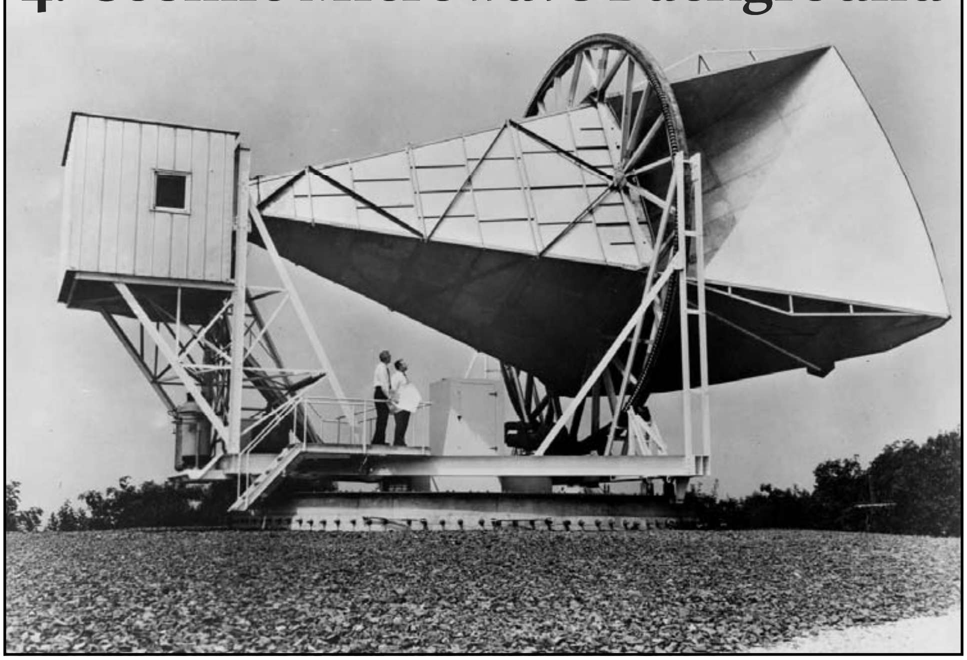
24% ^{4}He nuclei
traces D, ^{3}He, ^{7}Li nuclei
75% H nuclei (protons)



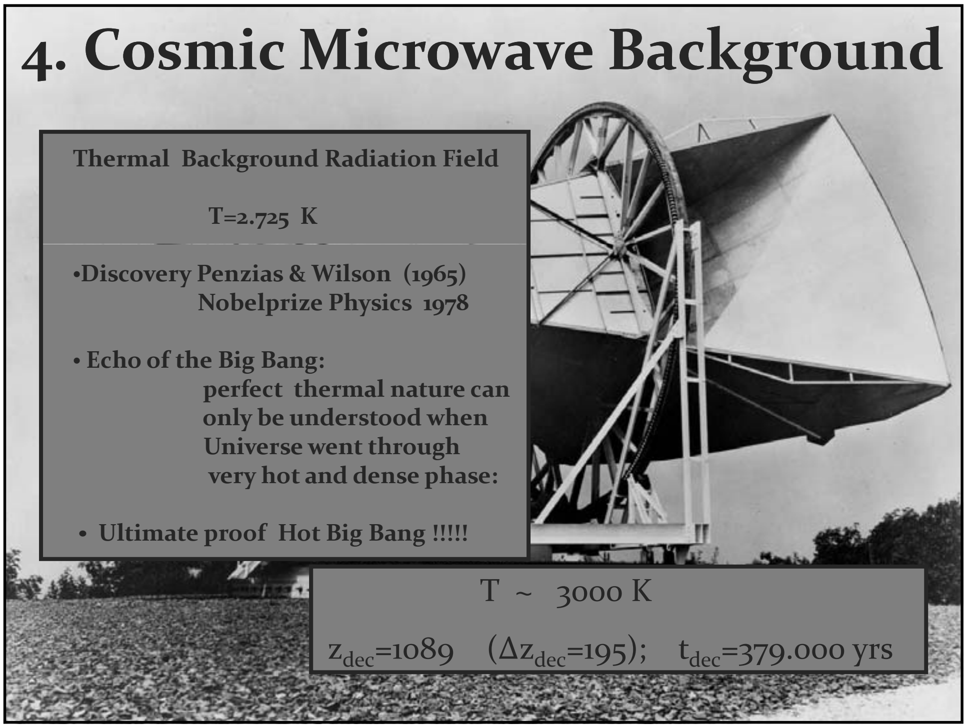
Between 1-200 seconds after Big Bang, temperature dropped to 10^9 K:

Fusion protons & neutrons into light atomic nuclei

4. Cosmic Microwave Background



4. Cosmic Microwave Background



Thermal Background Radiation Field

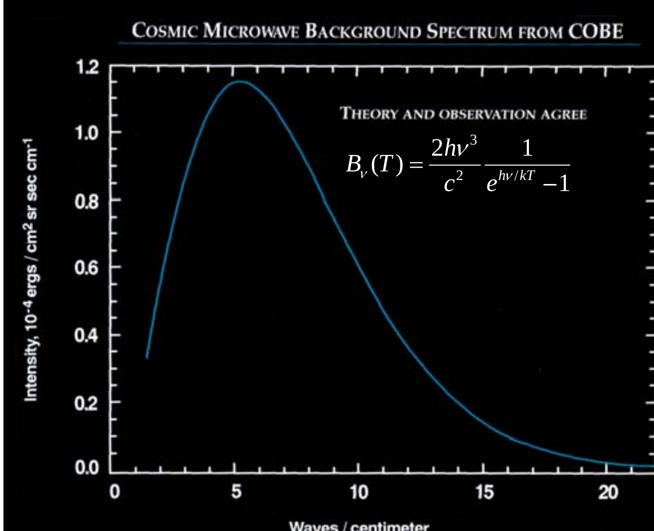
T=2.725 K

- Discovery Penzias & Wilson (1965)
  Nobelprize Physics 1978
- Echo of the Big Bang:
  perfect thermal nature can only be understood when Universe went through very hot and dense phase:
- Ultimate proof Hot Big Bang !!!!!

T ~ 3000 K

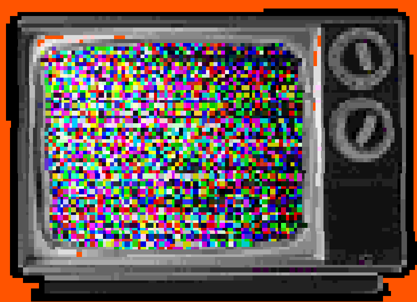
z_{dec}=1089 (Δz_{dec}=195); t_{dec}=379.000 yrs

CMB Radiation Field
Blackbody Radiation



- COBE-DIRBE: temperature, blackbody
- T = 2.725 K
- John Mather
  Nobelprize physics 2006
- Most accurately measured Black Body Spectrum Ever !!!!!

CMB Photons

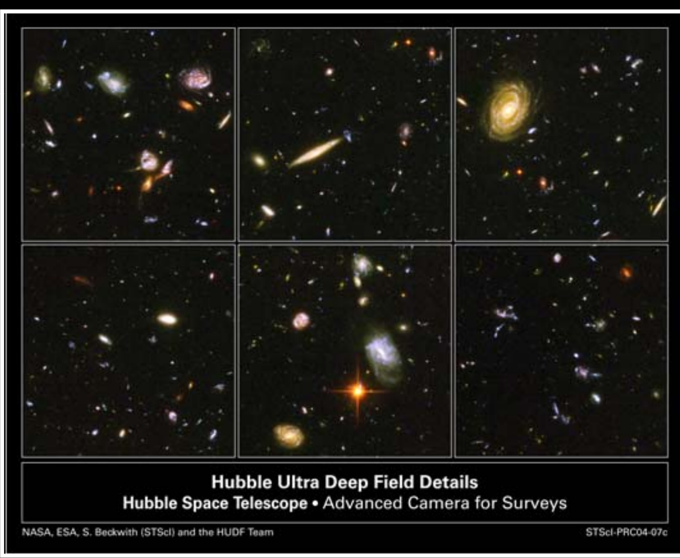


Note:

far from being an exotic faraway phenomenon, realize that the CMB nowadays is counting for approximately 1% of the noise on your tv set …

Courtesy: W. Hu

5. Changing Universe

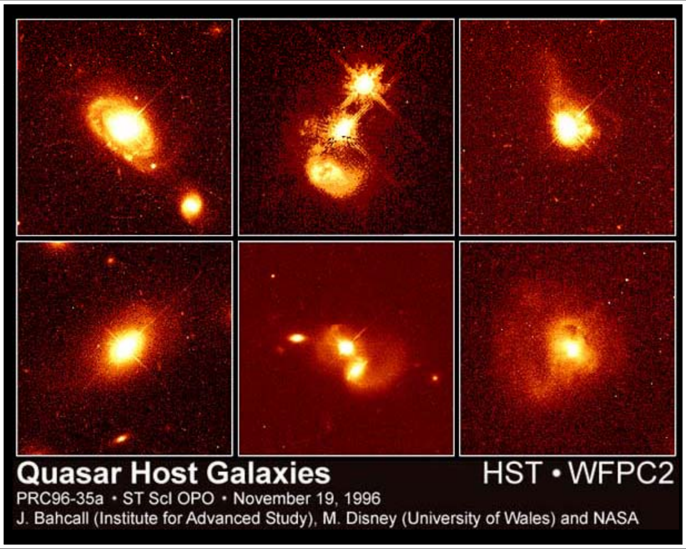


The appearance of the Universe does change when looking deeper into the Universe:

Depth=Time

Galaxies in Hubble Ultra Deep Field

5. Changing Universe



The appearance of the Universe does change when looking deeper into the Universe:

Depth=Time

→

Quasars

(very high z)

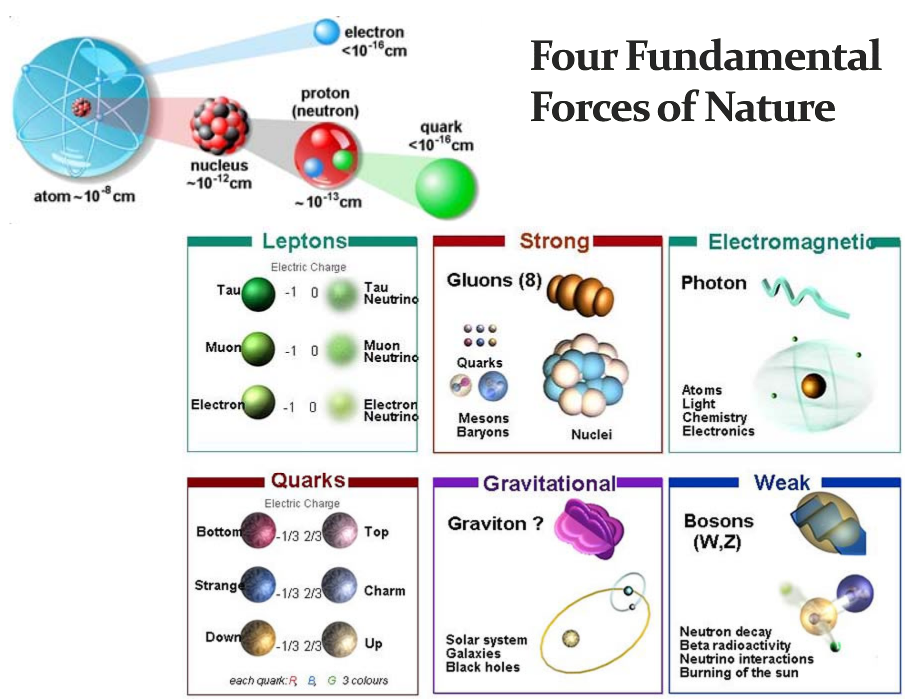
Gravity:

Ruler of the Universe

Four Fundamental Forces of Nature

- **Strong Nuclear Force**
  Responsible for holding particles together inside the nucleus.
  The nuclear strong force carrier particle is called the gluon.
  The nuclear strong interaction has a range of 10^{-15} m (diameter of a proton).
- **Electromagnetic Force**
  Responsible for electric and magnetic interactions, and determines structure of atoms and molecules.
  The electromagnetic force carrier particle is the photon (quantum of light)
  The electromagnetic interaction range is infinite.
- **Weak Force**
  Responsible for (beta) radioactivity.
  The weak force carrier particles are called weak gauge bosons (Z, W^+, W^-).
  The nuclear weak interaction has a range of 10^{-17} m (1% of proton diameter).
- **Gravity**
  Responsible for the attraction between masses. Although the gravitational force carrier
  The hypothetical (carrier) particle is the graviton.
  The gravitational interaction range is infinite.
  By far the weakest force of nature.

Four Fundamental Forces of Nature

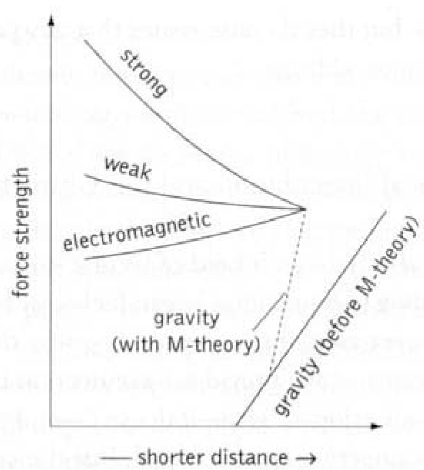


Interaction	Current Theory	Mediators	Relative Strength[1]	Long-Distance Behavior	Range(m)
Strong	Quantum chromodynamics (QCD)	gluons	10^{38}	1 (see discussion below)	10^{-15}
Electromagnetic	Quantum electrodynamics (QED)	photons	10^{36}	$\frac{1}{r^2}$	infinite
Weak	Electroweak Theory	W and Z bosons	10^{25}	$\frac{e^{-m_{W,Z}r}}{r}$	10^{-18}
Gravitation	General Relativity (GR)	gravitons	1	$\frac{1}{r^2}$	infinite

The weakest force, by far, rules the Universe …

Gravity has dominated its evolution, and determines its fate …

Grand Unified Theories (GUT)



Grand Unified Theories

* describe how
  - Strong
  - Weak
  - Electromagnetic

  Forces are manifestations of the same underlying GUT force …

* This implies the strength of the forces to diverge from their uniform GUT strength

* Interesting to see whether gravity at some very early instant unifies with these forces ???

Newton's Static Universe

The Unchanging Universe

- In two thousand years of astronomy,
  no one ever guessed that the universe might be expanding.

- To ancient Greek astronomers and philosophers,
  the universe was seen as the embodiment of perfection,
  the heavens were truly heavenly:
  – unchanging, permanent, and geometrically perfect.

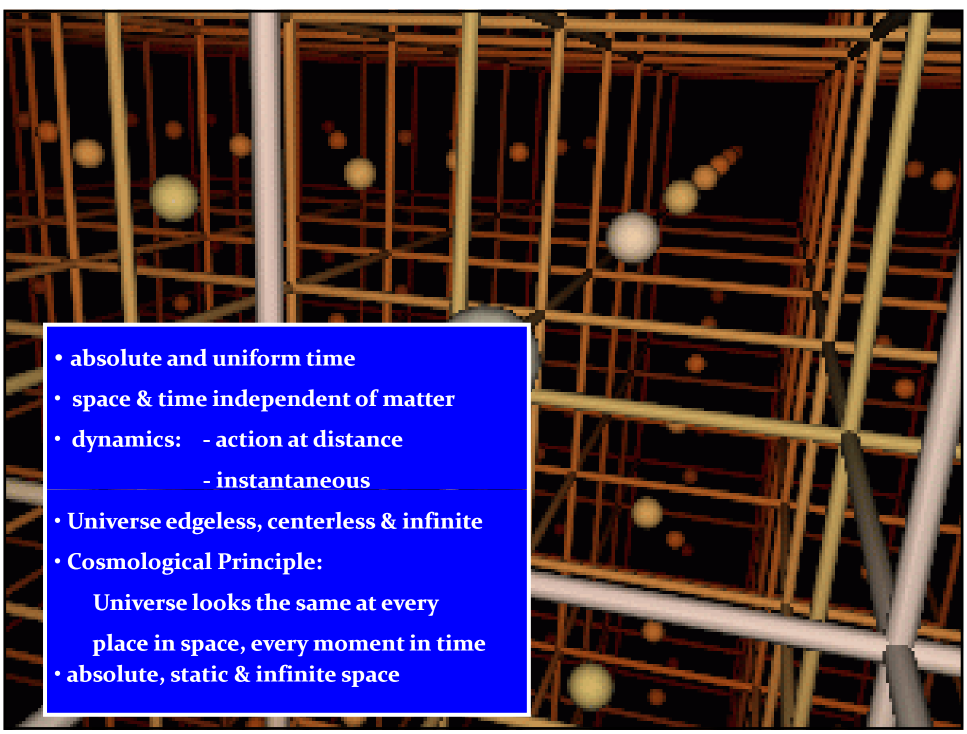
- In the early 1600s, Isaac Newton developed his law of gravity,
  showing that motion in the heavens obeyed the same laws
  as motion on Earth.

Newton's Universe

- However, Newton ran into trouble when he tried to apply his theory of gravity to the entire universe.
- Since gravity is always attractive, his law predicted that all the matter in the universe should eventually clump into one big ball.
- Newton knew this was not the case, and assumed that the universe had to be static
- So he conjectured that:

the Creator placed the stars such that they were

``at immense distances from one another.”



Einstein's

Dynamic & Geometric Universe

Einstein's Universe

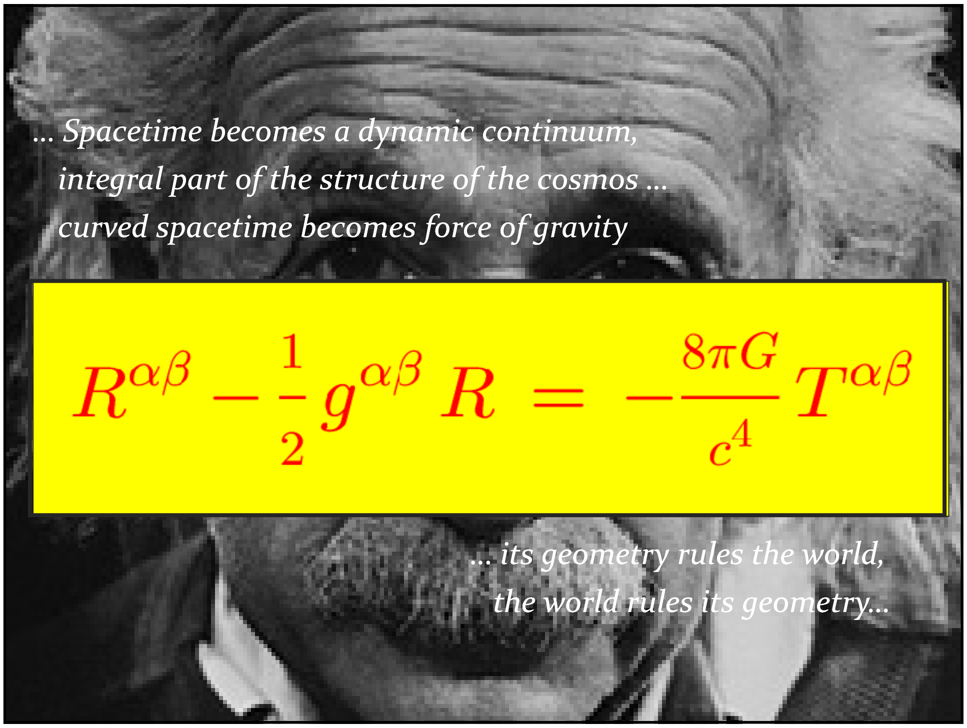
In 1915,
Albert Einstein completed his General Theory of Relativity.

- General Relativity is a "metric theory":
  gravity is a manifestation of the geometry, curvature, of space-time.

- Revolutionized our thinking about the nature of space & time:
  - no longer Newton's static and rigid background,
  - a dynamic medium, intimately coupled to the universe's content of matter and energy.

- All phrased into perhaps the most beautiful and impressive scientific equation known to humankind, a triumph of human genius,

Einstein Field Equations



Albert Einstein

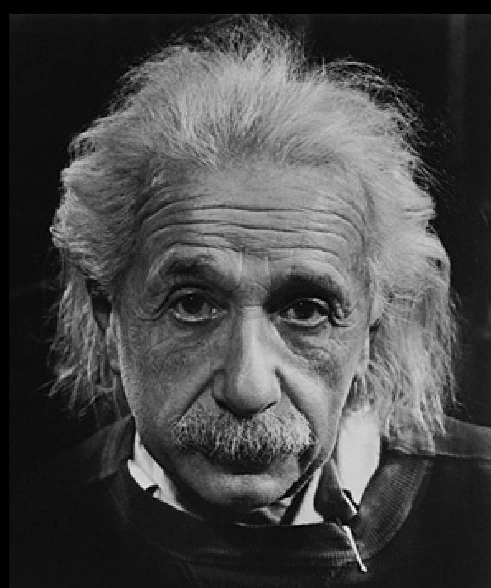
Albert Einstein
(1879-1955; Ulm-Princeton)

father of
General Relativity (1915),

opening the way towards
Physical Cosmology

The supreme task of the physicist is to arrive at those universal elementary laws from which the cosmos can be built up by pure deduction.

(Albert Einstein, 1954)



General Relativity

A crucial aspect of any particular configuration is the geometry of spacetime: because Einstein's General Relativity is a metric theory, knowledge of the geometry is essential.

Einstein Field Equations are notoriously complex, essentially 10 equations. Solving them for general situations is almost impossible.

However, there are some special circumstances that do allow a full solution. The simplest one is also the one that describes our Universe. It is encapsulated in the

Cosmological Principle

On the basis of this principle, we can constrain the geometry of the Universe and hence find its dynamical evolution.

Cosmological Principle: the Universe Simple & Smooth

"God is an infinite sphere whose centre is everywhere and its circumference nowhere"
Empedocles, 5th cent BC

Cosmological Principle:

Describes the symmetries in global appearance of the Universe:

- Homogeneous → The Universe is the same everywhere:
  - physical quantities (density, T,p,...)
- Isotropic → The Universe looks the same in every direction
- Universality → Physical Laws same everywhere
- Uniformly Expanding → The Universe "grows" with same rate in
  - every direction
  - at every location

"all places in the Universe are alike"
Einstein, 1931

Geometry of the Universe

Fundamental Tenet

of (Non-Euclidian = Riemannian) Geometry

There exist no more than THREE uniform spaces:

1) Euclidian (flat) Geometry — Euclides
2) Hyperbolic Geometry — Gauß, Lobachevski, Bolyai
3) Spherical Geometry — Riemann

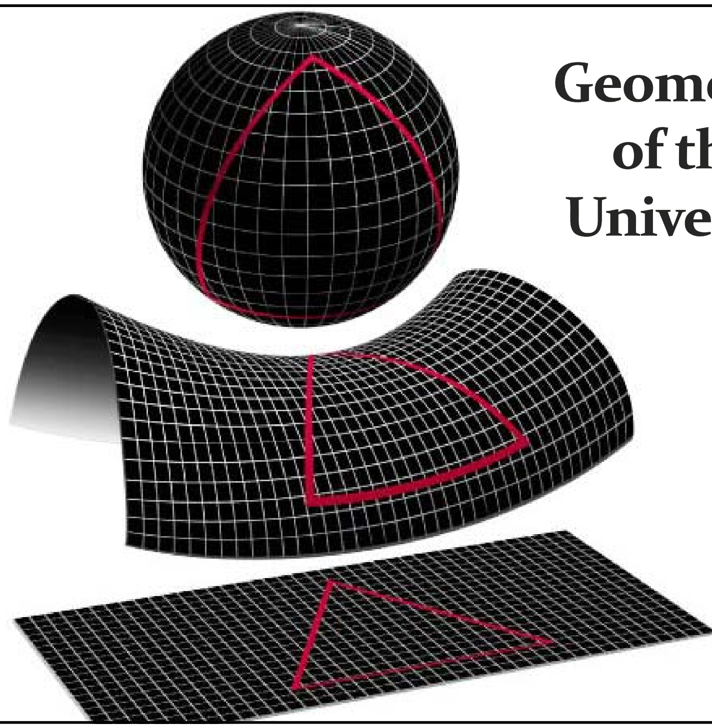
uniform=
homogeneous & isotropic
(cosmological principle)

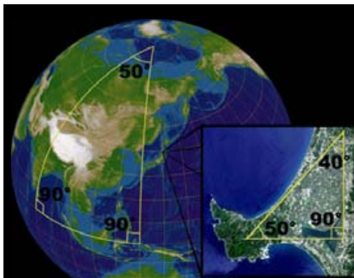
Geometry of the Universe

Positive Curvature
$k = +1$

Negative Curvature
$k = -1$

Flat
$k = 0$





Uniform Spaces:

Geometric Characteristics

	Parallel Lines	Triangular Angles $\alpha+\beta+\gamma$	Circumference Circle $x \equiv \frac{S}{2r}$	Curvature k	Extent	Boundary
Flat Space	parallels: 1 never intersects	π	π	0	open: infinite	unbounded
Spherical Space	parallels: ∞ along great circles, all intersect	$> \pi$	$< \pi$	$1/R^2$ > 0	closed: finite	unbounded
Hyperbolic Space	parallels: ∞ diverge & never intersect	$< \pi$	$> \pi$	$-1/R^2$ < 0	open: infinite	unbounded

Robertson-Walker Metric

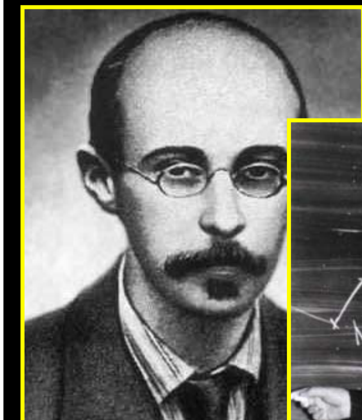
Distances in a uniformly curved spacetime is specified in terms of the Robertson-Walker metric. The spacetime distance of a point at coordinate (r,θ,ϕ) is:

$$ds^2 = c^2 dt^2 - a(t)^2 \left\{ dr^2 + R_c^{\;2} S_k^{\;2}\left(\frac{r}{R_c}\right)\left[d\theta^2 + \sin^2\theta\, d\phi^2\right]\right\}$$

where the function $S_k(r/R_c)$ specifies the effect of curvature on the distances between points in spacetime

$$S_k\left(\frac{r}{R_c}\right) = \begin{cases} \sin\left(\frac{r}{R_c}\right) & k=+1 \\ \frac{r}{R_c} & k=0 \\ \sinh\left(\frac{r}{R_c}\right) & k=-1 \end{cases}$$

Friedmann & Lemaitre



Alexander Friedmann (1888 -1925)
George Lemaitre (1894-1966)

They discovered (independently) theoretically the expansion of the Universe as a solution to the Theory of General Relativity.

... and derived the equations that describe the expansion and evolution of the universe,

the foundation for all of modern Cosmology:

Friedmann-Lemaitre Equation

Expanding Universe

- Einstein, de Sitter, Friedmann and Lemaitre all realized that in General Relativity, there cannot be a stable and static Universe:
- The Universe either expands, or it contracts ...

- Expansion Universe encapsulated in a

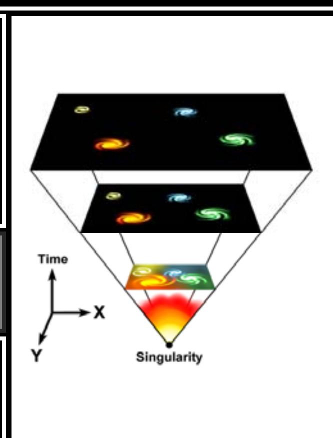
GLOBAL expansion factor a(t)

- All distances/dimensions of objects uniformly increase by a(t):

at time t, the distance between two objects i and j has increased to

$$\vec{r}_i - \vec{r}_j = a(t)\left(\vec{r}_{i,0} - \vec{r}_{j,0}\right)$$

- Note: by definition we chose $a(t_o)=1$, i.e. the present-day expansion factor



Friedmann-Robertson-Walker-Lemaitre Universe

Because of General Relativity, the evolution of the Universe is determined by four factors:

- density $\rho(t)$
- pressure $p(t)$
- curvature kc^2 / R_0^2 — $k = 0, +1, -1$; R_0: present curvature radius
- cosmological constant Λ

• Density & Pressure: - in relativity, energy & momentum need to be seen as one physical quantity (four-vector)
- pressure = momentum flux

• Curvature: - gravity is a manifestation of geometry spacetime

• Cosmological Constant: - free parameter in General Relativity
- Einstein's "biggest blunder"
- mysteriously, since 1998 we know it dominates the Universe

Friedmann-Robertson-Walker-Lemaitre Universe

$$\ddot{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)a + \frac{\Lambda}{3}a$$

$$\dot{a}^2 = \frac{8\pi G}{3}\rho a^2 - \frac{kc^2}{R_0^2} + \frac{\Lambda}{3}a^2$$

Friedmann-Robertson-Walker-Lemaitre Universe

$$\ddot{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)a + \frac{\Lambda}{3}a$$

density

pressure

cosmological constant

curvature term

$$\dot{a}^2 = \frac{8\pi G}{3}\rho a^2 - \frac{kc^2}{R_0^2} + \frac{\Lambda}{3}a^2$$

Friedmann-Robertson-Walker-Lemaitre Universe

Relativistic Cosmology

$$\ddot{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)a + \frac{\Lambda}{3}a$$

$$\dot{a}^2 = \frac{8\pi G}{3}\rho a^2 - \frac{kc^2}{R_0^2} + \frac{\Lambda}{3}a^2$$

Newtonian Cosmology

$$\ddot{a} = -\frac{4\pi G}{3}\rho a$$

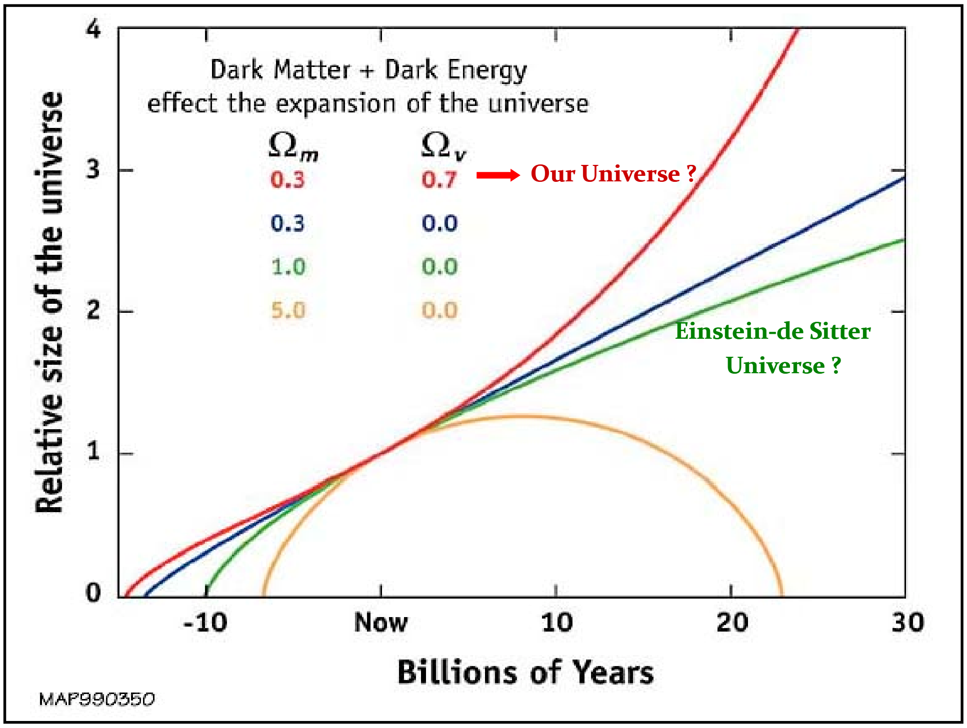
$$\dot{a}^2 = \frac{8\pi G}{3}\rho a^2 + E$$

$-kc^2 / R_0^2$ Curvature

Λ Cosmological Constant

p Pressure

E Energy



Evolution & Fate
Friedmann-Robertson-Walker-Lemaitre Universe

Fully determined by three factors:

- energy content of the Universe
  (density & pressure)
- geometry of the Universe
  (curvature term)
- cosmological constant