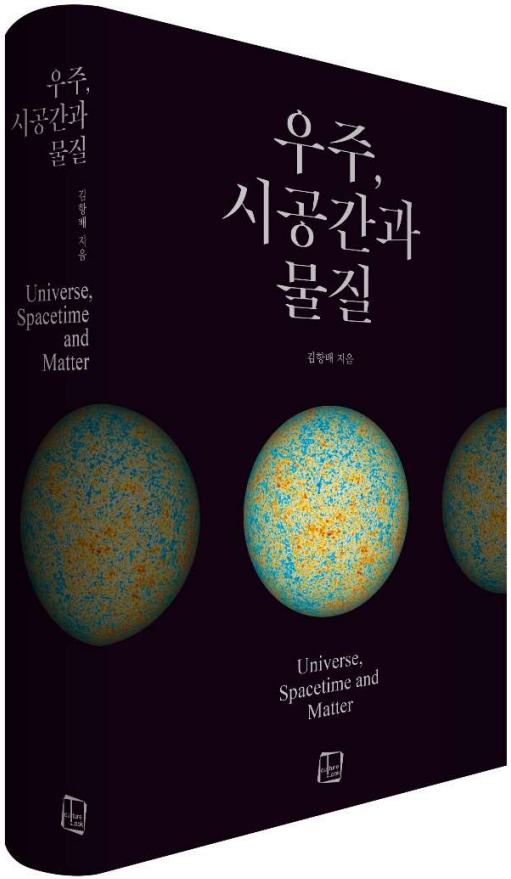
Where is Cosmology Going?

Hang Bae Kim (Hanyang University, Korea)

ICRR, 2017.05.09


우주,
시공간과
물질
김항배 지음
Universe,
Spacetime
and
Matter
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김항배 지음
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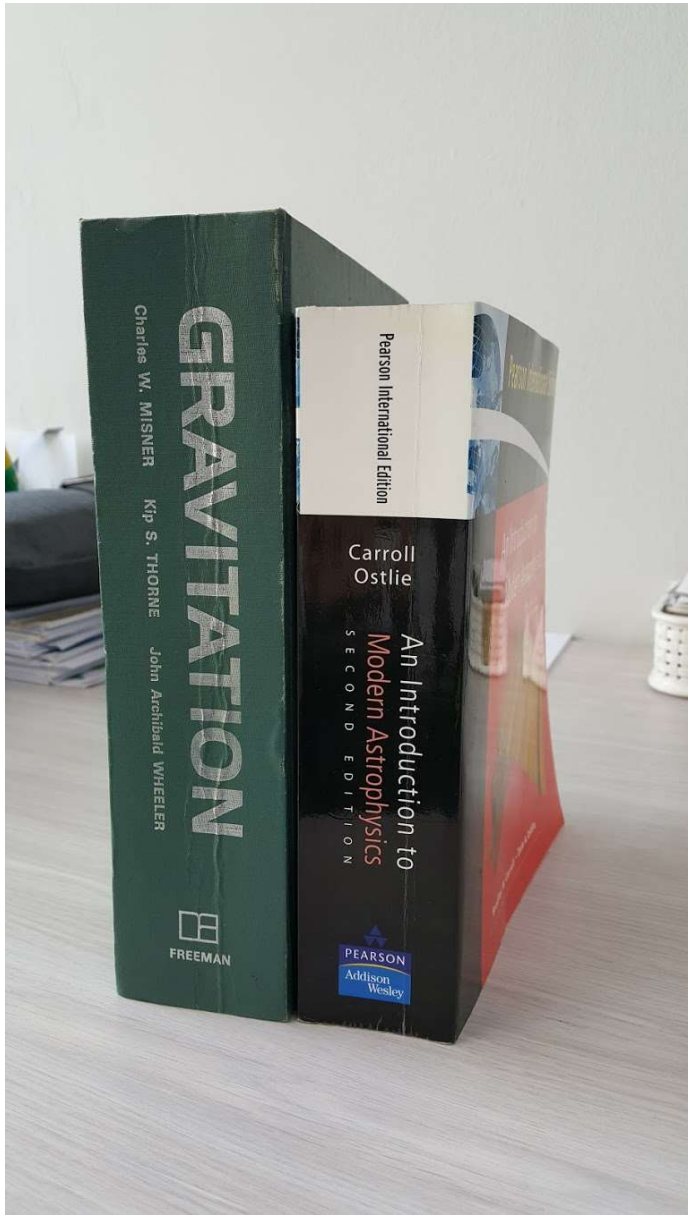
GRAVITATION
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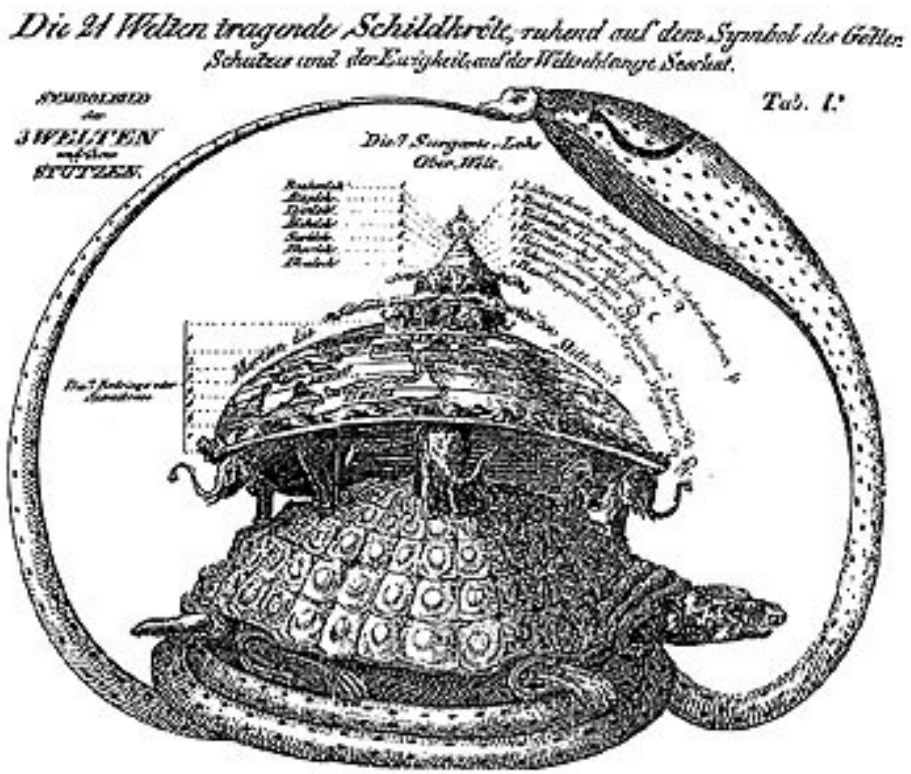
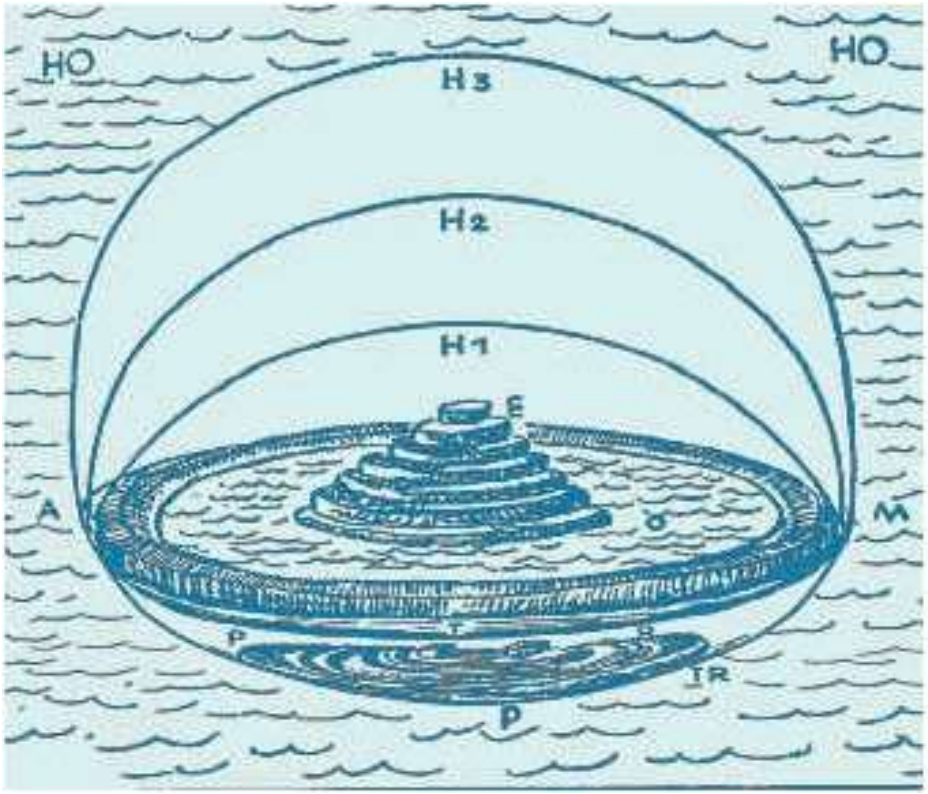
Where did cosmology come from?

Ultimate Curiosity

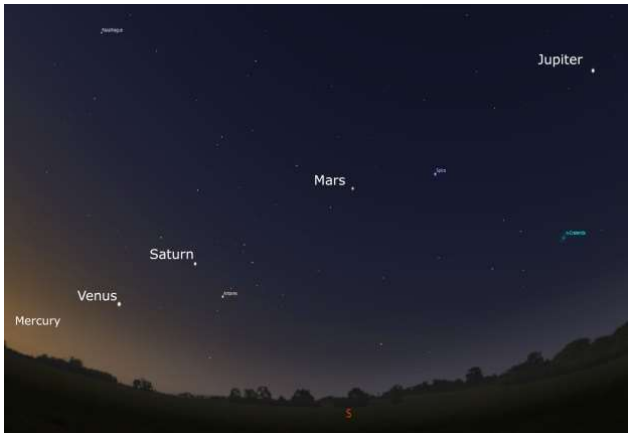


Ancient India

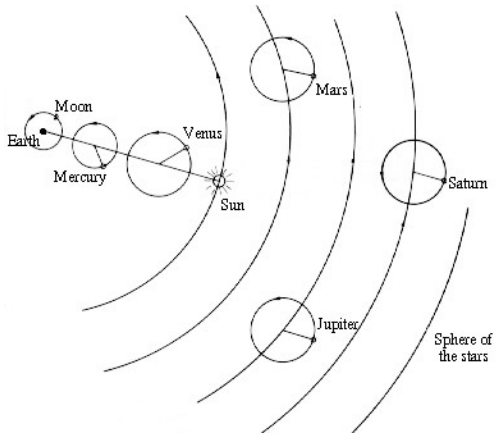


Ancient Babylonia

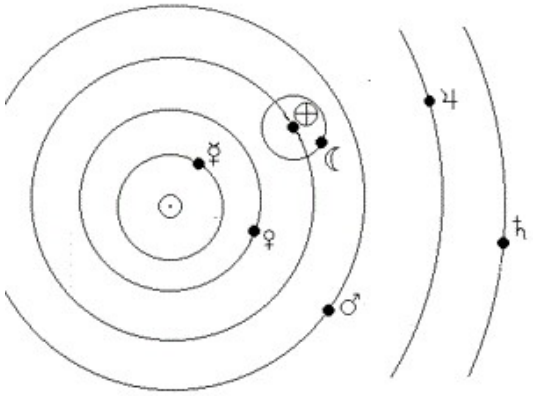
Understanding the Heaven



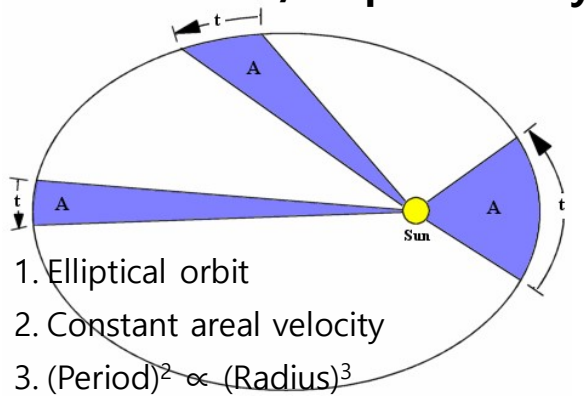
Motion of 5 planets



Geocentric vs Heliocentric



- **Tyco's observation / Kepler's analysis**



1. Elliptical orbit
2. Constant areal velocity
3. $(\text{Period})^2 \propto (\text{Radius})^3$

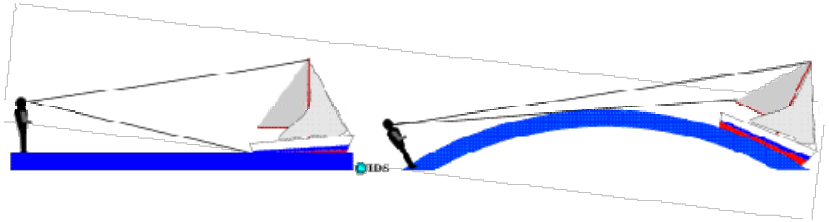
- **Newton's Law of Motion / Gravitation**
  - **Force and Motion**
  - Laws of Heaven & Earth are same.
    - Sun-Earth gravity ⇒ Revolution
    - Earth-Object gravity ⇒ Free Fall
  - **Physics began from understanding of Heaven (Motions of planets).**

How big is the Universe?

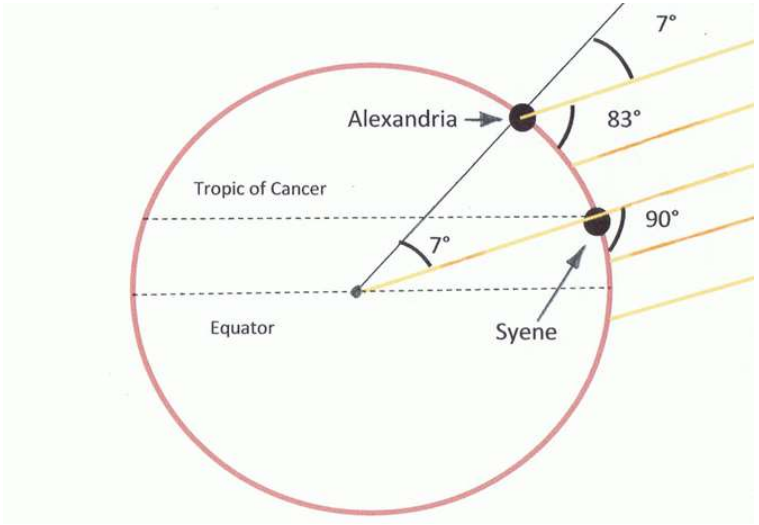
- Size of Earth
- Size of Solar system
- Distances of Stars
- Size & Shape of Galaxy
- Distances of Galaxies
- Size & Shape of Universe

Size of Earth

- Is Earth flat?
  - Limitation of apparatus
  - Influence of environments

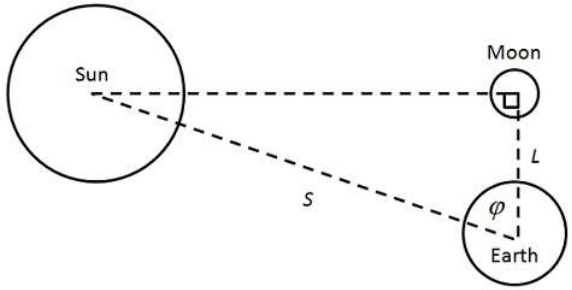


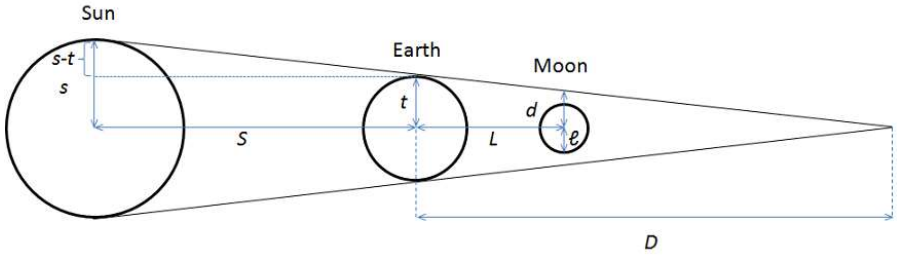
- Earth is round.
- Eratosthenes (BC 240)



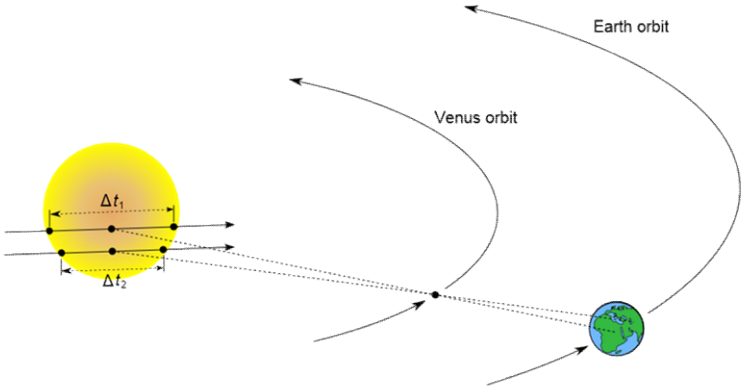
Size of Solar System

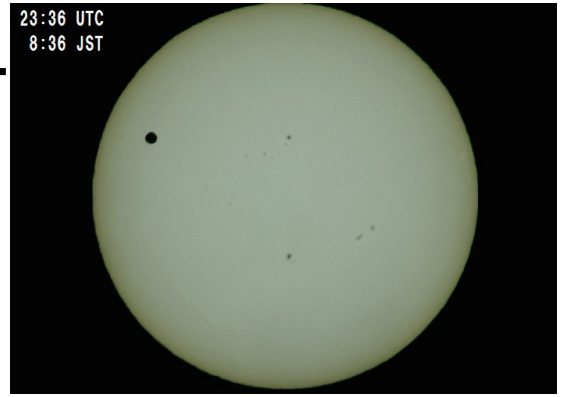
- Aristarchus of Samos (310-230BC)





- Kepler's third law gives the ratio of orbital radiuses.
- Edmond Halley's proposal (1716)

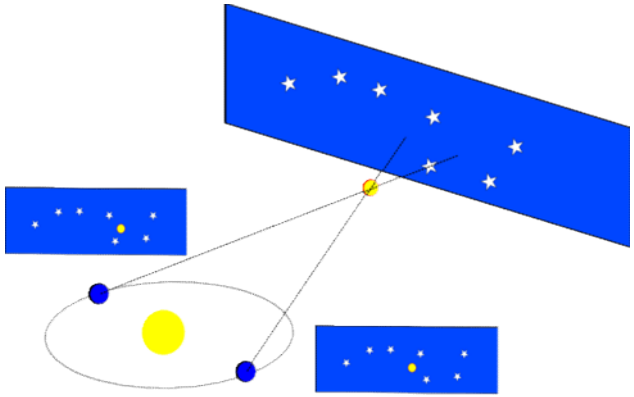




2012 transit of Venus (2012.06.05)

Distances of Stars

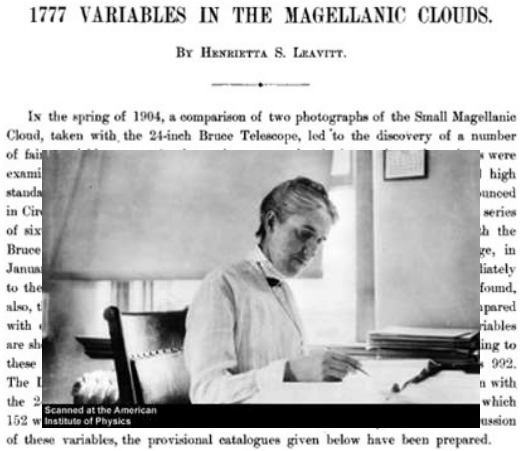
- Annual Parallax
  - Direct evidence for heliocentricism
  - Firstly measured by F. Bessel in 1838
  - Revealed that star is a distant sun
  - Measured for close stars only



$$\frac{1^\circ = 60' = 3600''}{1'' = 1 \text{ cm seen at 2 km distance}} 1^\circ$$

$$1\,\text{pc} = 3.26\,\text{ly} = 3.1 \times 10^{16}\,\text{m}$$

- Luminosity distance – **Cepheid variables**



1777 VARIABLES IN THE MAGELLANIC CLOUDS.

By Henrietta S. Leavitt.

In the spring of 1904, a comparison of two photographs of the Small Magellanic Cloud, taken with the 24-inch Bruce Telescope, led to the discovery of a number of fai... were exami... high standa... unced in Cir... series of six... h the Bruce ...ge, in Janua... liately to the ... found, also, t... pared with ... riables are sh... ing to these ... 992. The I... n with the 2... which 152 w... ussion

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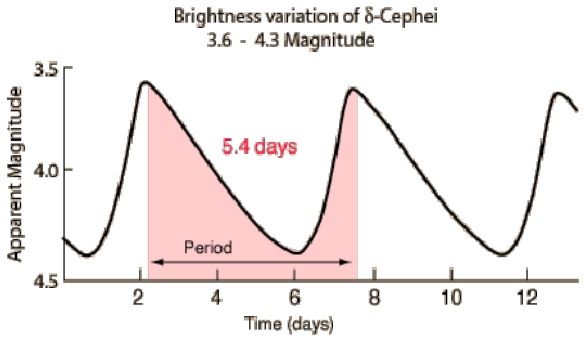
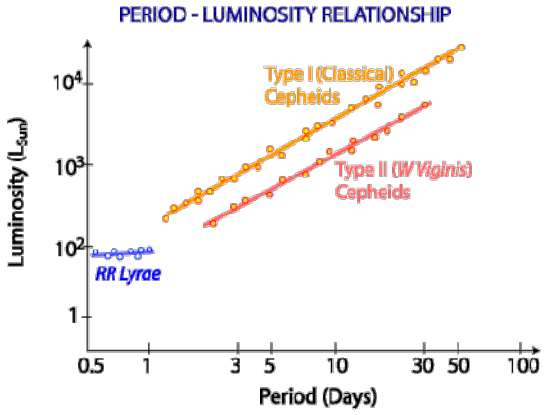
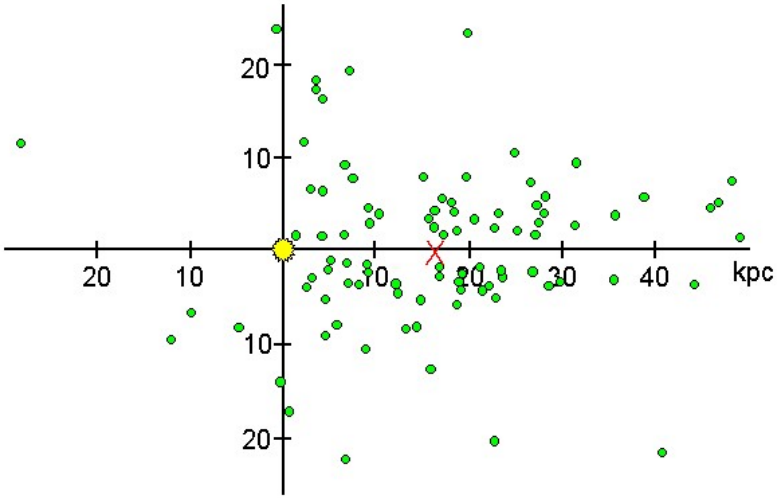
of these variables, the provisional catalogues given below have been prepared.

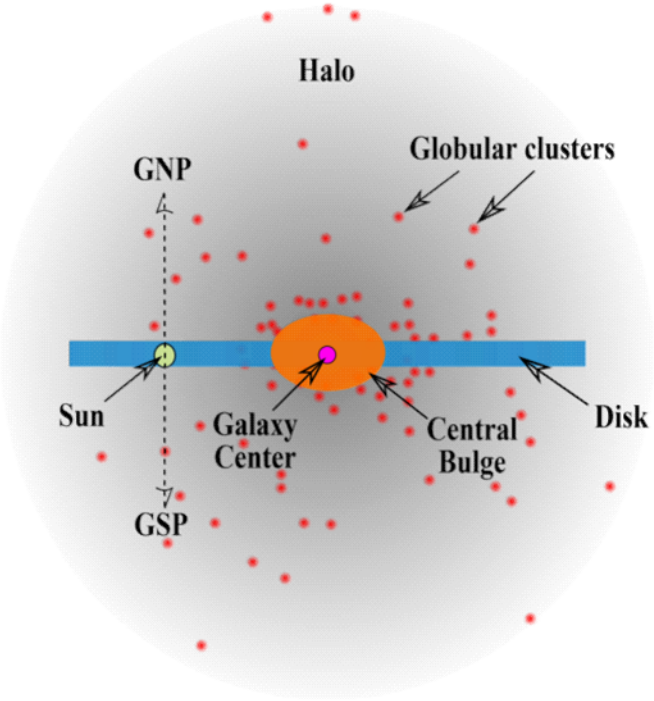




Size & Shape of Galaxy



Distribution of globular clusters of Milky Way, obtained by Harlow Shapley using Cepheid variables. Yellow circle is the position of the sun and X is the center of Milky Way.



The schematic view of Milky Way as we understand now.

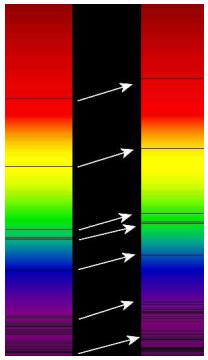
Distances of Galaxies

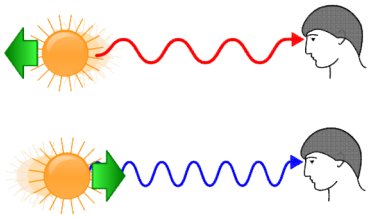
- Discovery of external galaxies
  - By Cepheid variable, Hubble found the distance of Andromeda galaxy larger than the size of our galaxy.

Edwin Hubble and Hooker(100-inch) telescope of Mount Wilson Observatory

Andromeda galaxy (M31), the nearest spiral galaxy, 2.5Mly away from us.

- Motion of external galaxies





Doppler shfit due to motion

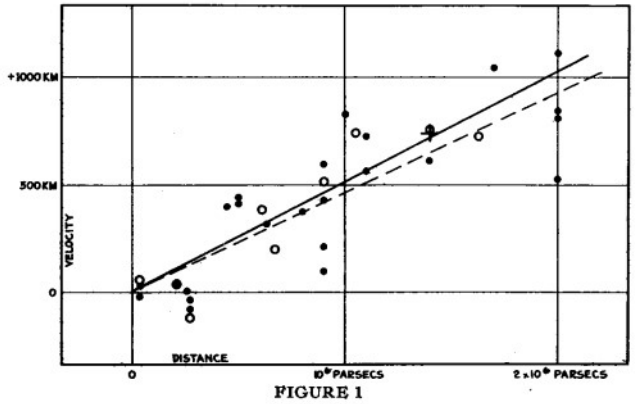


FIGURE 1

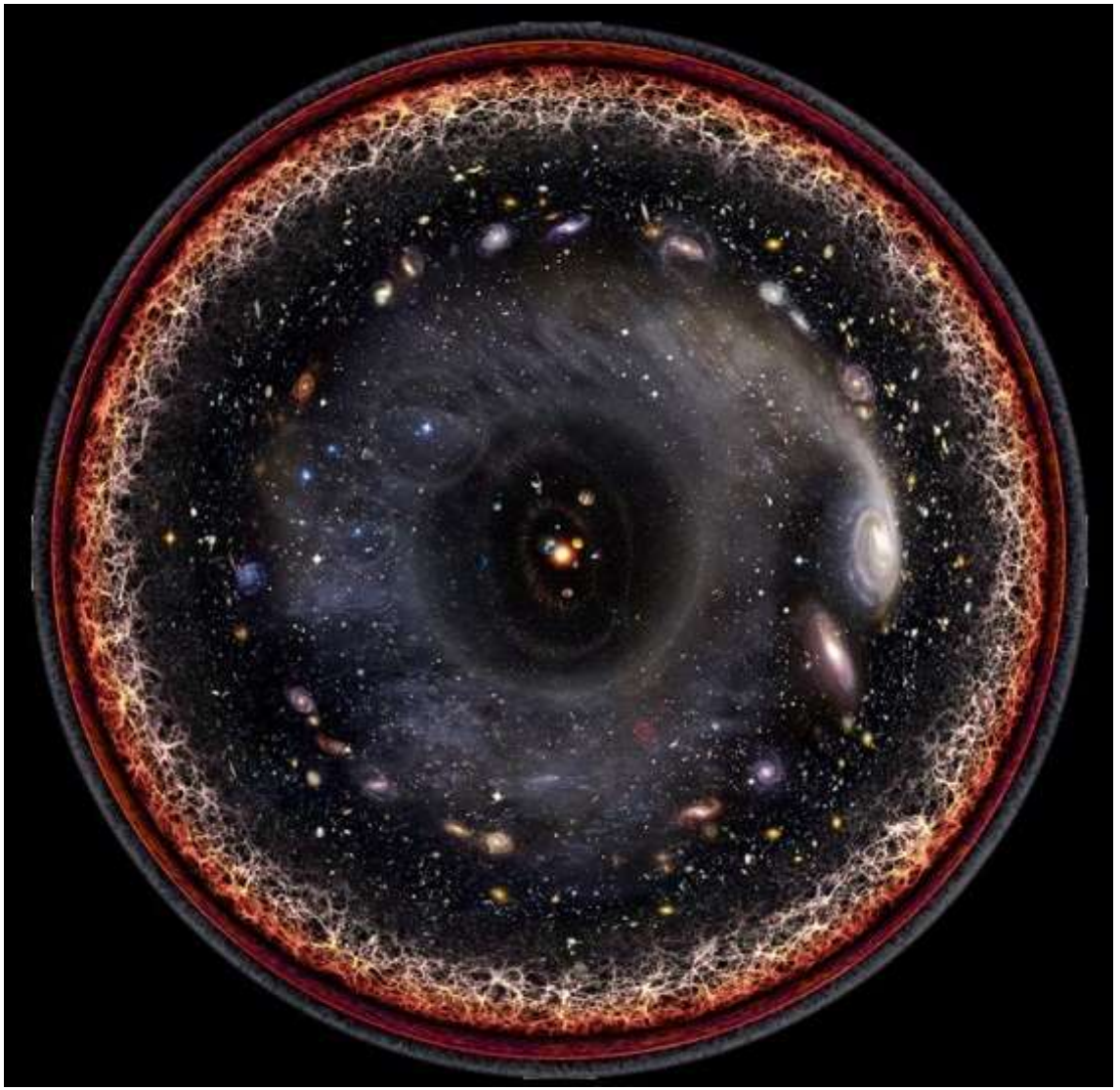
Velocity-Distance Relation among Extra-Galactic Nebulae.

- Hubble's Law
  - Recession velocity (Red shift) is proportional to distance.

$$\vec{v} = \boldsymbol{H_0}\vec{r}$$

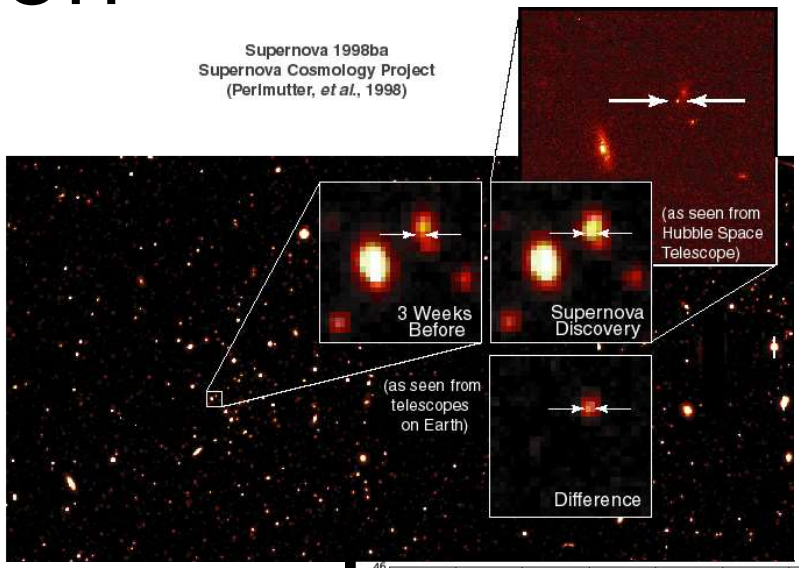
  - Interpreted as the expansion
  - Distances from red shifts

Size & Shape of Universe



Observation 1 – Expansion

- Luminosity distance – Red shift relation
  - Luminosity distance – **Standard candles**
  - Red shift – spectroscopy
- Cepheid variables
  - **H. Leavitt** (1912) – Period–Luminosity relation of Cepheid varialbles
  - **E. Hubble** (1929) – Hubble's law, Discovery of **the expansion of the universe**
- Super Novae Type Ia
  - Luminosity – Light curve calibration (1990s)
  - Discovery of **the acceleration of expansion** (1998)
  - **Dark Energy**



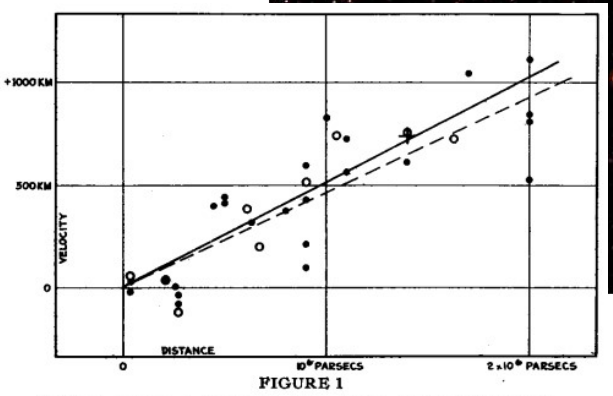
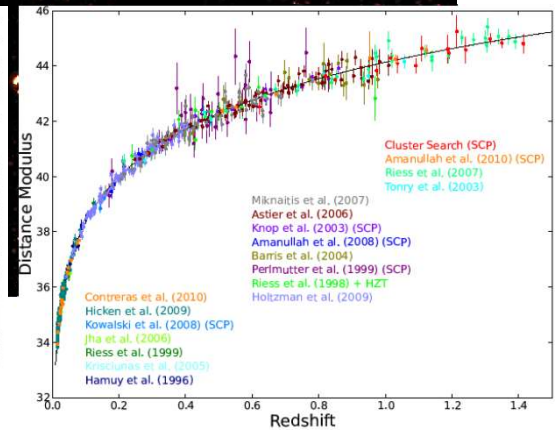
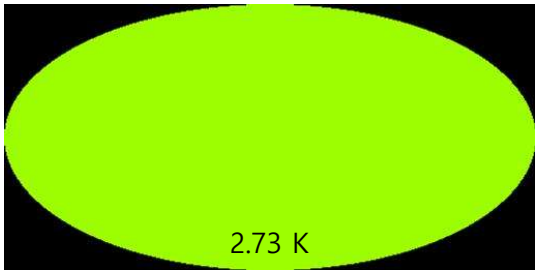
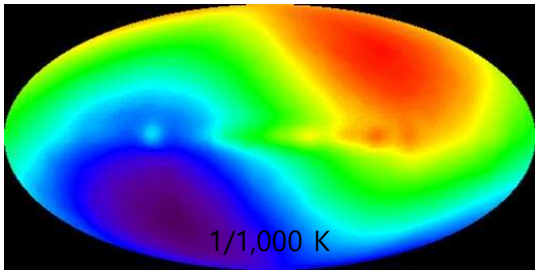


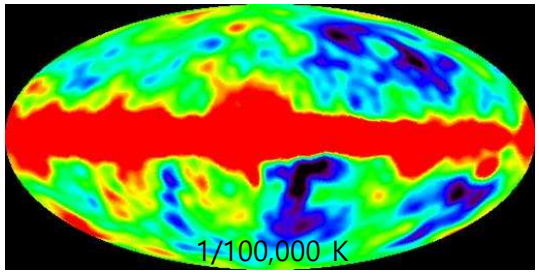
FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

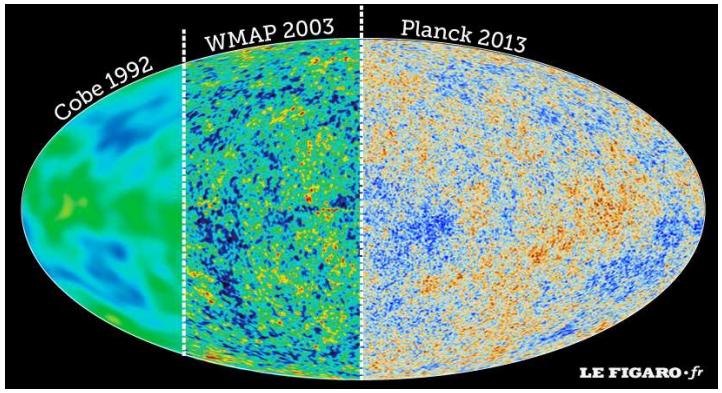


Observation 2 – Cosmic Fluctuations



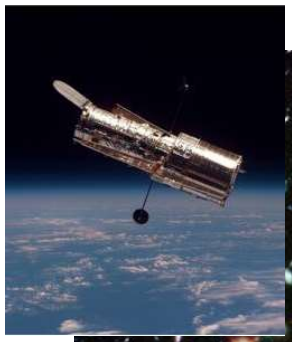


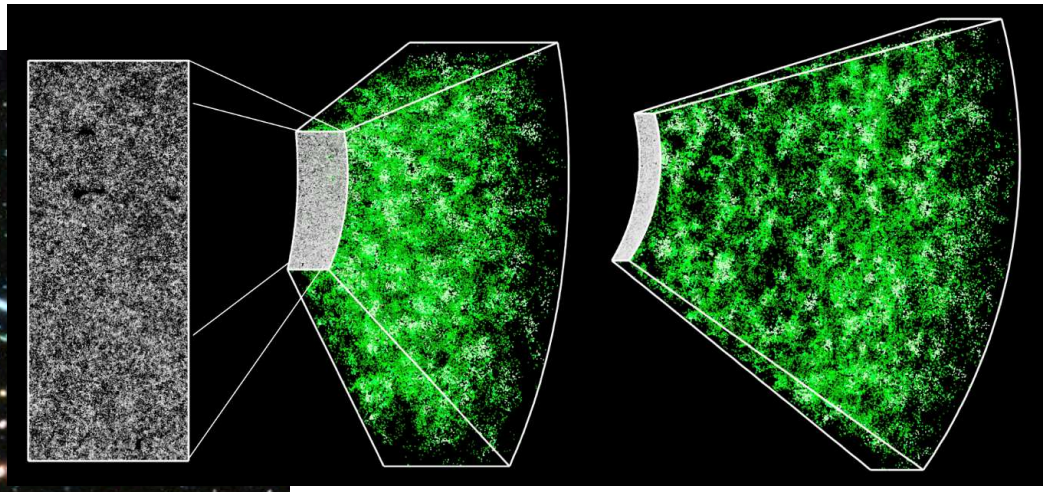




- **Observation of CMBA**
  - Density perturbations: $\delta T/T \sim 10^{-5}$
  - Matter Content: Baryon, Dark Matter, Dark Energy
  - Geometry: Flat universe
- **Cosmology became precision science !**

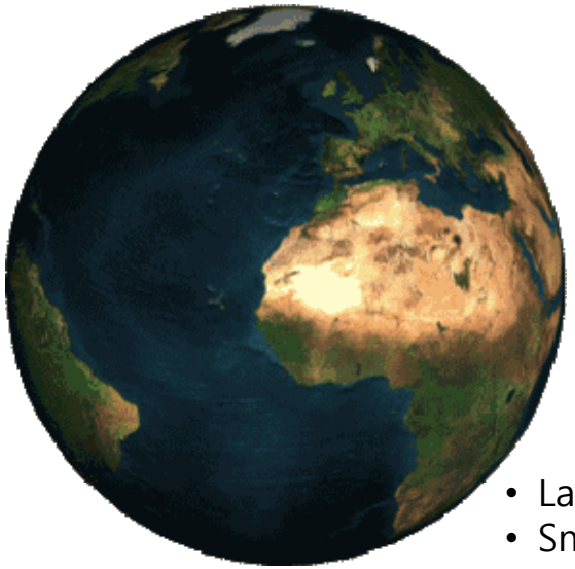
Observation 3 – Sea of Galaxies





- Galaxy surveys
  – 3D map of the universe
  - Large scales – Homogeneity
  - Small scales – Structures
  - Remnants in structures – Primordial density perturbations, Baryon acoustic oscillations

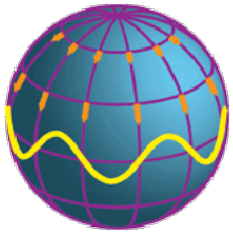
Shape of the universe?



- Large scales – Sphere
- Small scales – Surface structures
- Rotating
- Subject to the sun

- How is its size set?
- Why is it a sphere?
- Why is it rotating?
- How are surface structures formed?

- Large scales – Homogeneous & Isotropic
- Small scales – Structures
- Expanding



- How large is the universe?
- Why is it homogeneous & isotropic?
- Why is it expanding?
- How are the structures formed?

What is current understanding of the universe?

Universe – Spacetime & Matter

- Framework for understanding the universe – **Dynamics of Spacetime & Matter**

Dynamics of Spacetime

General Relativity

Einstein Equation

$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

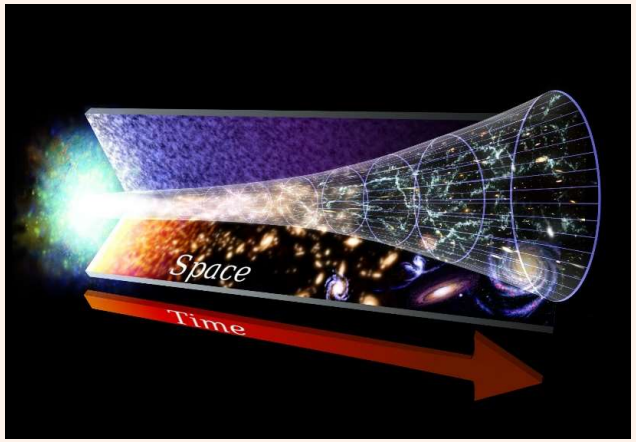
Einstein tensor
Geometry

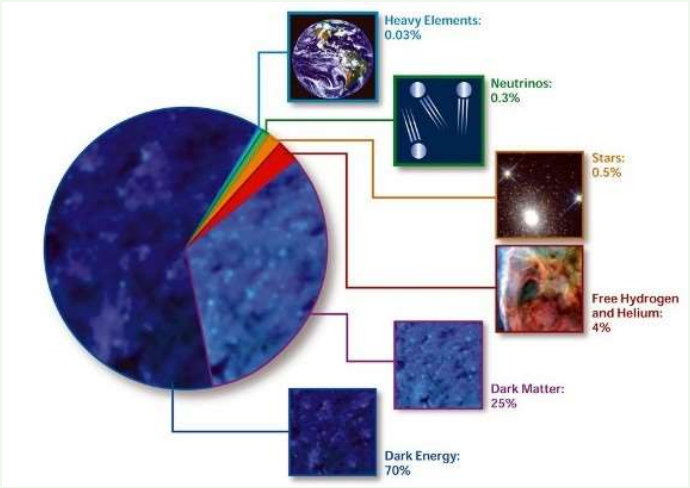
EM tensor
Matter

Dynamics of Matter

Standard Model

Boltzmann Equation



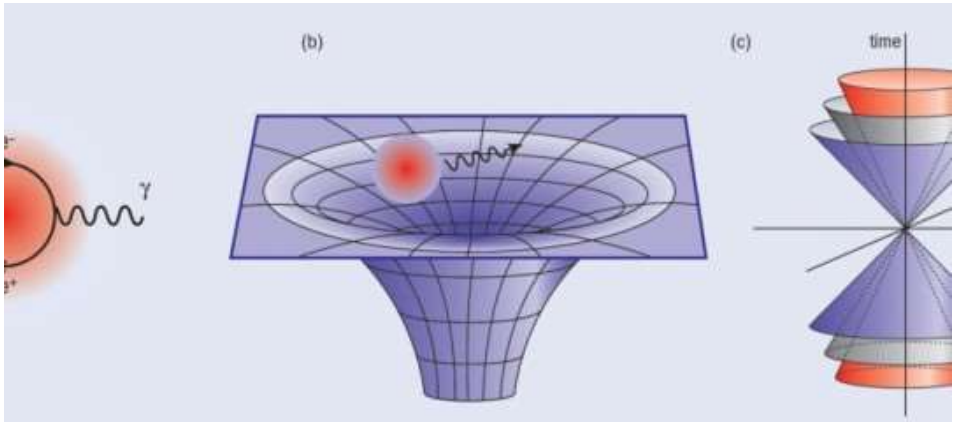


Spacetime Dynamics

- Newtonian dynamics and absolute space and time (Galilean Relativity)

- Electromagnetism and Minkowski spacetime (Special Relativity)

- Gravity and curved spacetime (General Relativity)



- **Time** & **Length** are same to all inertial observer.
- **Physical Laws** are same to all inertial observer.

- **Speed of light** is same to all inertial observer.
- **Physical Laws** are same to all inertial observer.
- Causal structure due to the speed limit
- Matter & Energy can convert into each other.

$$E = \sqrt{m^2c^2 + c^2\,|\vec{p}|^2}$$

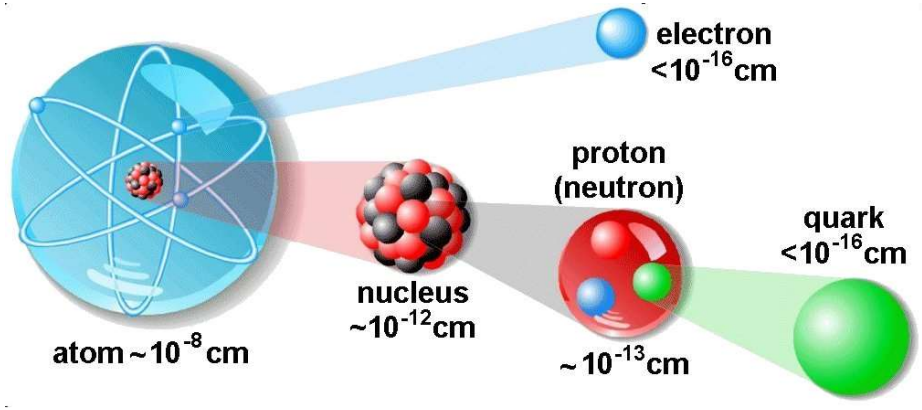
- **Time** & **Length** depends on **Gravity**.
- **Physical Laws** are same to all observer.
- Special relativity holds only locally.
- Spacetime tells matter how to move; **matter tells spacetime how to curve**.

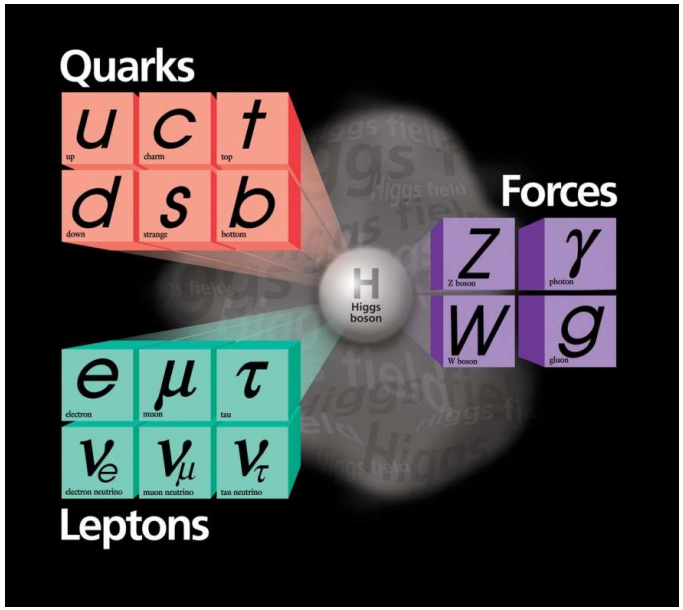
Matter Dynamics

- Quantum Mechanics – Wave-Particle duality – Uncertainty relation – Stability of matter

(Wave) $\Delta x \, \Delta k \gtrsim 1 \quad \Rightarrow \quad \Delta x \, \Delta p \gtrsim \hbar$ (Particle)

- Small world → Special relativity → Matter-Energy conversion
- Standard Model
  - Gauge symmetry
  - 3 flavors of quarks and leptons





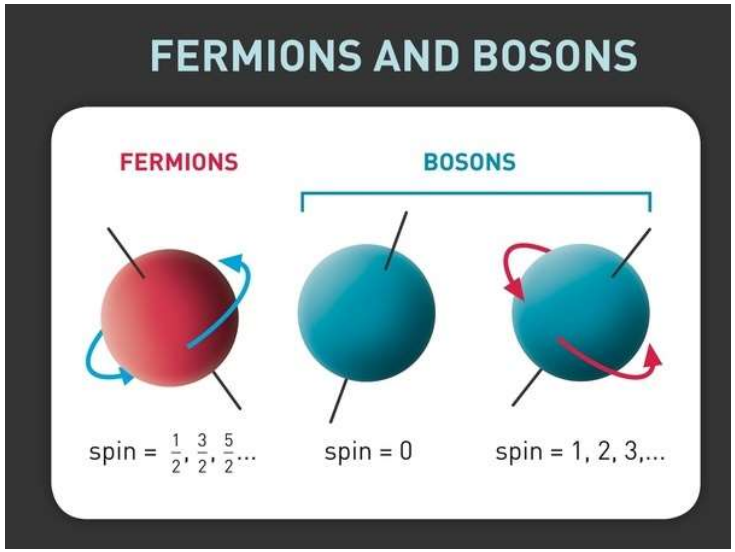
Species & States

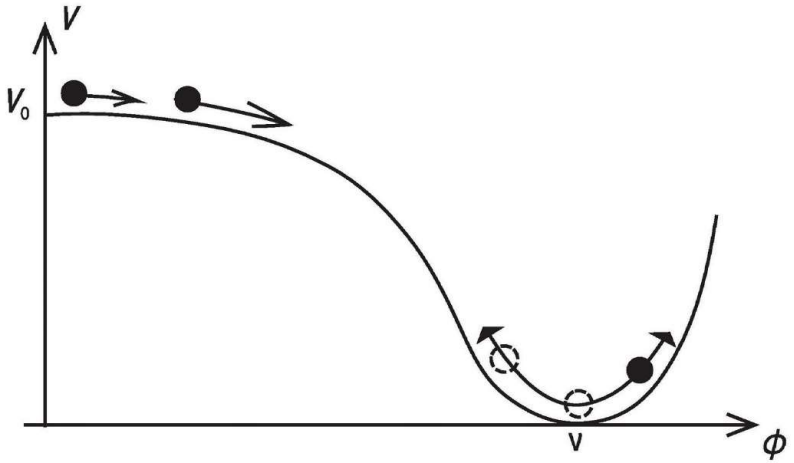
- Species
  - Fermions / (spin 1) Bosons – Matter / Forces
  - **Why are (spin 0) Scalars rarely observed**?
- States
  - Pressure as well as energy density gravitates.
  - Equation of state
- Idea Gas
- Scalar Fields

❖ **Radiation : p = $\rho/3$**

❖ **Matter : p = 0**

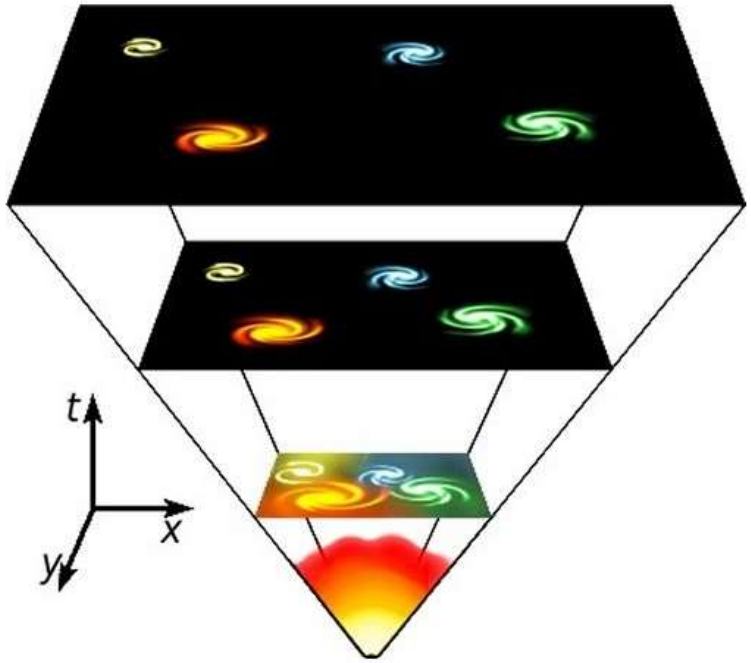
❖ **Vacuum Energy : p = $-\rho$**





Expanding Universe

▪ **What happens as the universe expands?**



▪ Universe is not eternal and immutable.

▪ **Expansion makes History.**

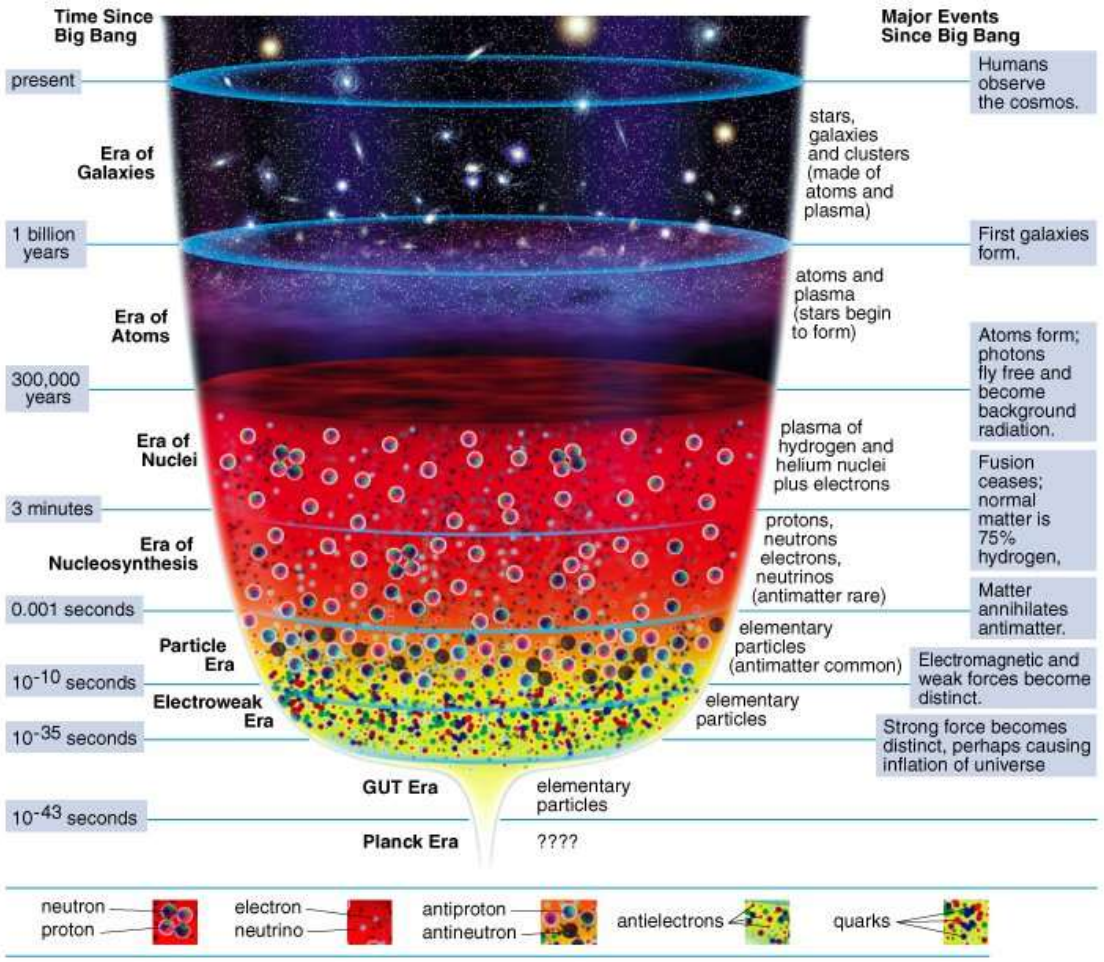
- Existence of CMB with T=2.7K
- Back in time, Temperature rises & Radiation dominates.
- **Universe began in thermal equilibrium at high temperature.**

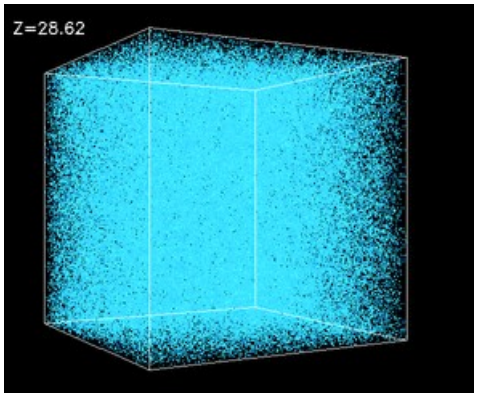
Expanding Universe **Quantum Principle**

Cosmology **The Large** ⇔ High Temp.(T) High Energy(E) ⇔ Particle Physics **The Small**

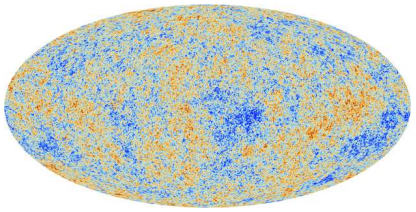
- **Understanding Early Universe (high temperature & energy) requires Particle Physics.**
- **As Universe expands and temperature goes down, some thermal equilibrium is broken and leaves remnant.**

History of Universe





Structure formation



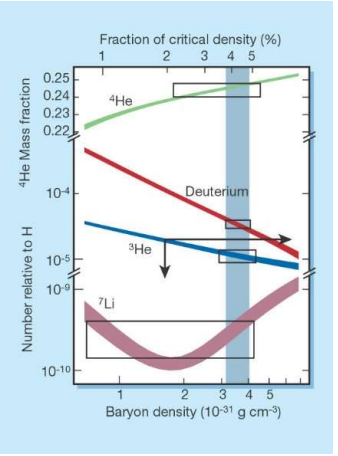
CMB decoupling

Big Bang Nucleosynthesis

Neutrino decoupling

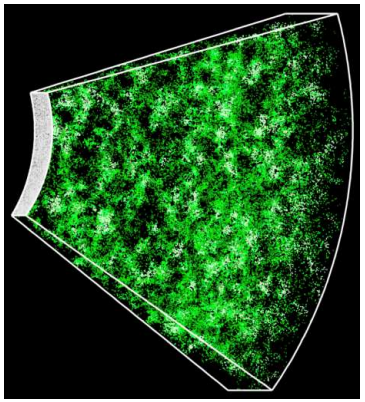
Dark Matter decoupling

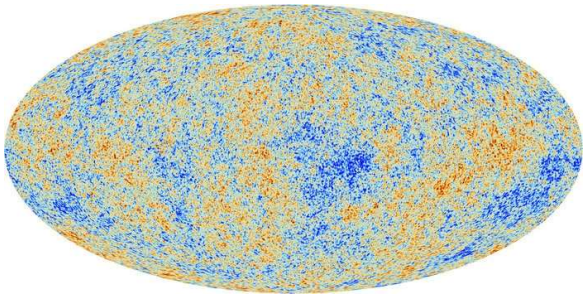
Baryogenesis



Structure Formation

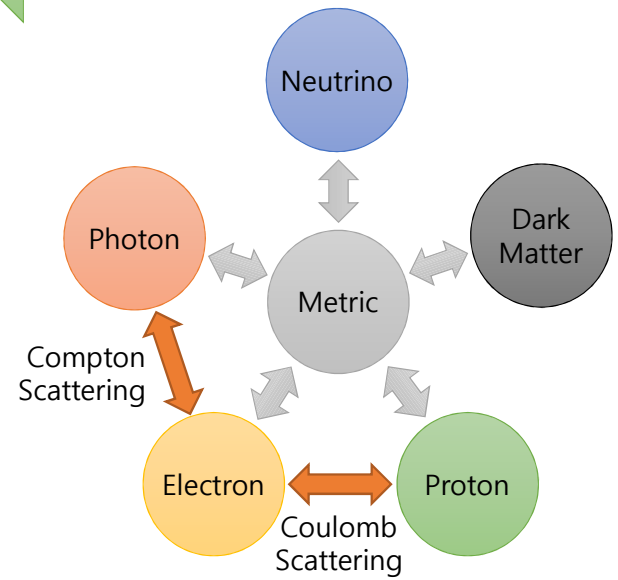
- **Current observations**
  - Galaxy Distribution
  - CMB Anisotropies



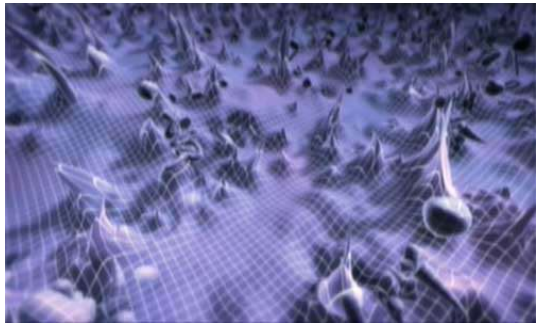


Cosmic Parameters

Expansion + Gravity

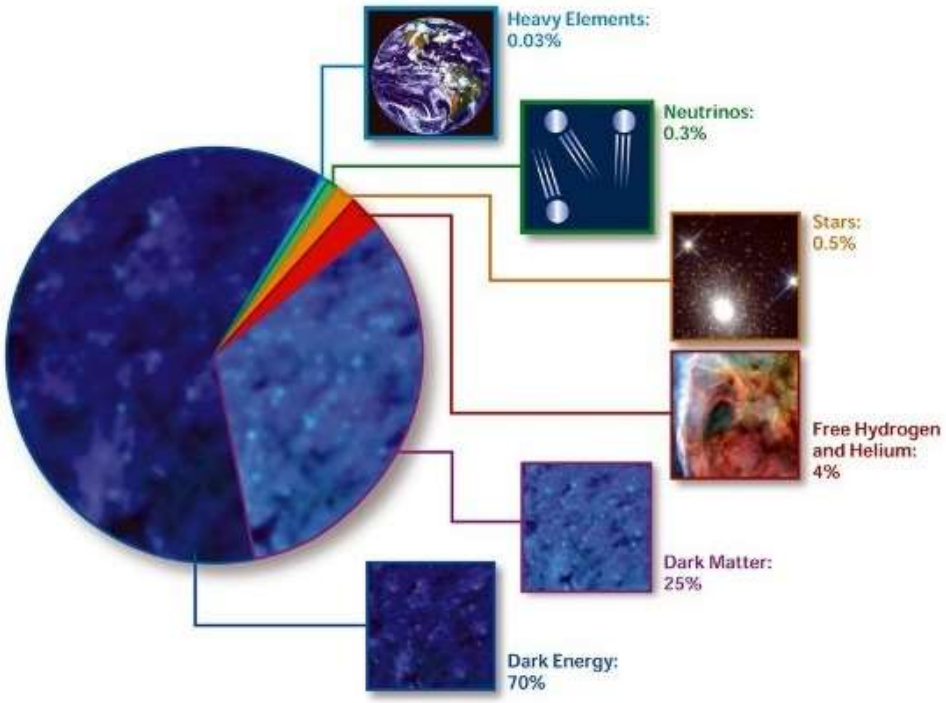


- **Initial conditions**
  - Density Perturbation ~ 10^{-5}
  - Dark Matter
  - Baryon Asymmetry

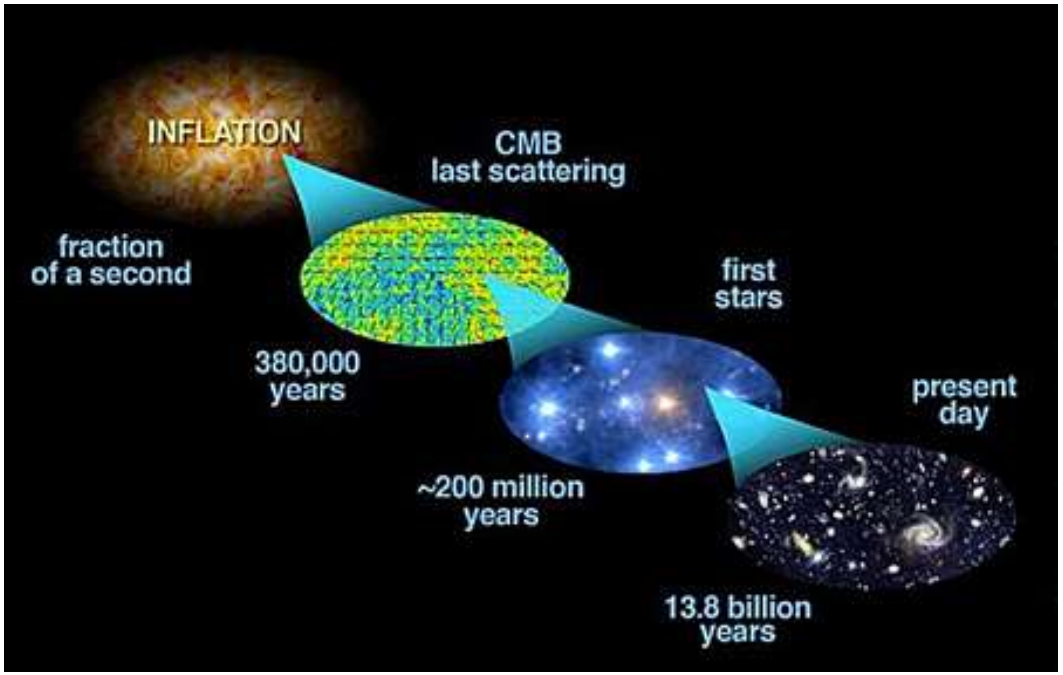


Standard Cosmology

- Matter content – **ΛCDM model**



- Initial conditions – **Inflation**
  Matter (Baryons, Dark Matter, …) & Homogeneous / Isotropic + Density Perturbation

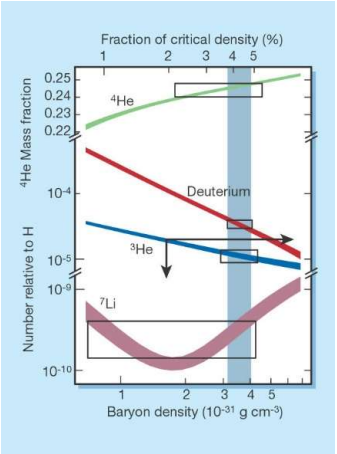


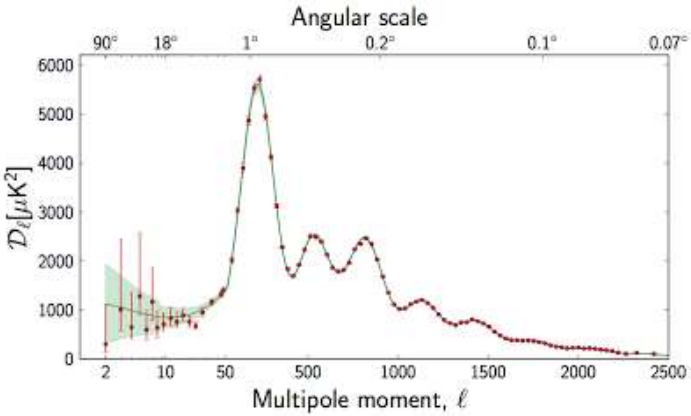
What are missing in current understanding?

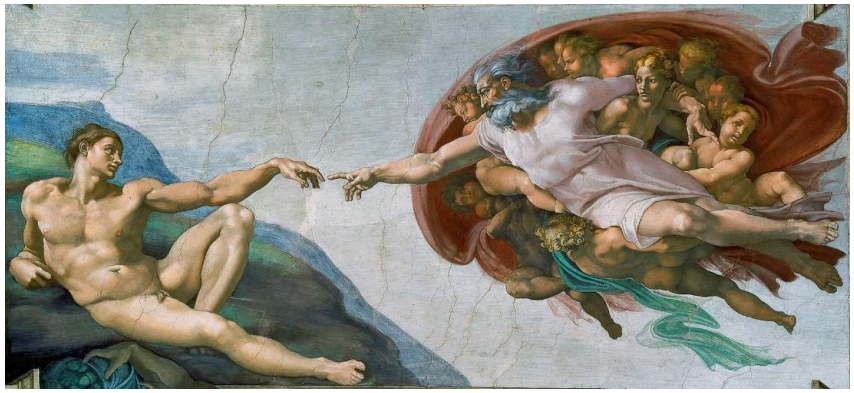
Baryons

- Baryon Asymmetry
  - Big Bang Nucleosynthesis
  - CMB Anisotropies - BAO
- 3 conditions for Baryogenesis

  B violation / C & CP violation / Out of equilibrium
- Standard Model
  - ➢ Satisfies 3 conditions, but
  - ➢ Small CP violation / Weak phase transition
  - ➢ Cannot produce the correct amount of baryons
- Beyond the standard model
  - ➢ GUT baryogenesis
  - ➢ Leptogenesis – connected with neutrino masses
  - ➢ Supersymmetry – Affleck-Dine mechanism







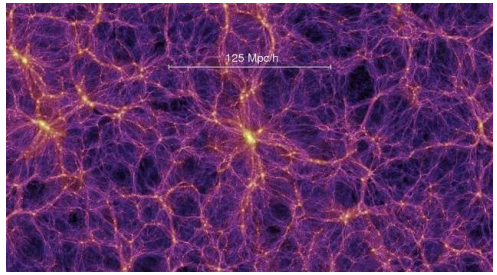
Dark Matter

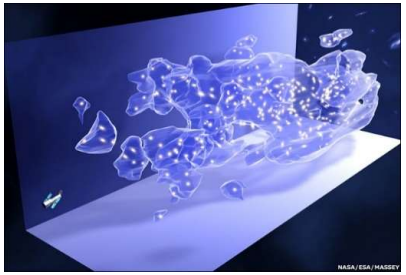
- Why Dark Matter?
  - Cosmic Structure Formation
  - Galaxy Rotation Curves
  - Gravitational Lensing
  - Galaxy Clusters

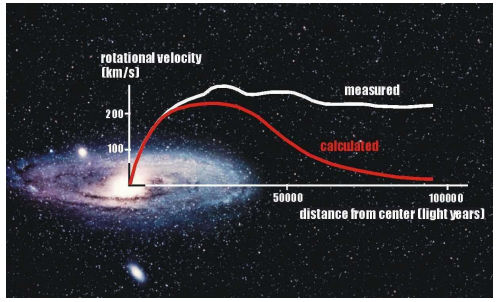
- What is Dark Matter?
  - Dark – weakly interacting with ordinary particles
  - Stable – live much longer than the universe
  - Amount – 20% of the critical density

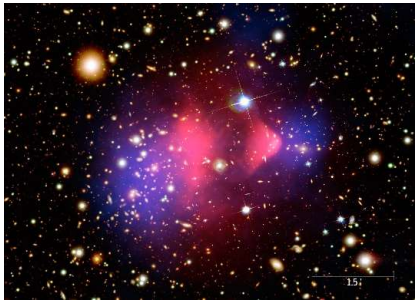
- What can be Dark Matter?
  - WIMP – weakly interacting massive particles
  - Condensates – Axions, Light scalar
  - Direct / Indirect detections

- Matter or Gravity, which is guilty?
  - MOND
  - Modified Gravity
  - Extra-dimensions





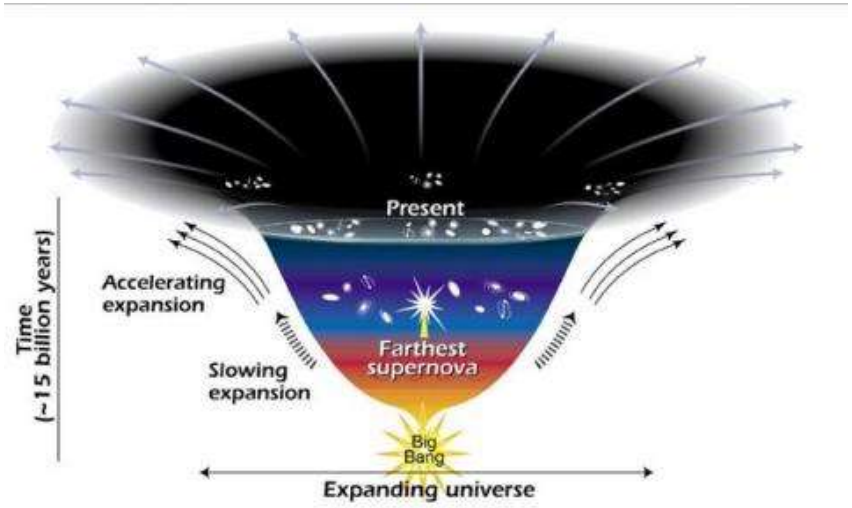




Dark Energy

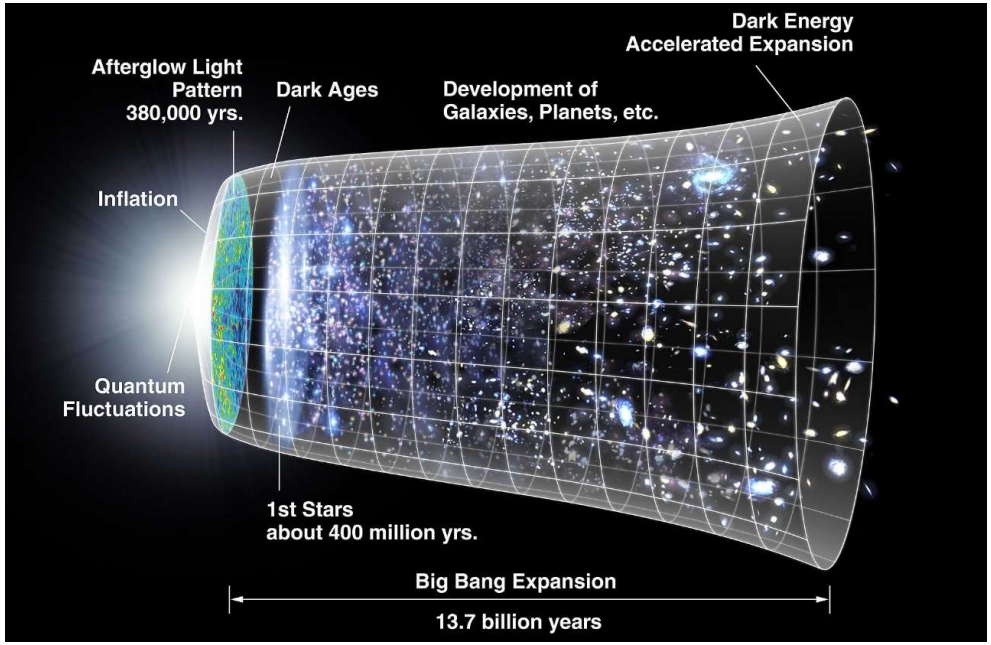
- Why Dark Energy?
  - Accelerating universe
  - Flatness
- What is Dark Energy?
  - Negative pressure
  - Stable
  - Amount – 70%
- What can be Dark Energy?
  - Vacuum Energy Density (Cosmological Constant)
  - Slowly rolling dynamical fields (Quintessence)
  - Is there any detection method other than the expansion history, direct or indirect?

- Matter or Gravity, which is guilty?
  - Local Fluctuation
  - Modified Gravity
  - Extra-Dimensions



When & How did Big Bang occur?

- **Headache of Expanding Universe**
  - Expanding Universe has the **Beginning**.
  - It approaches a **Singularity**.
- **The Beginning is very special.**
  - Homogeneous, Isotropic, Flat
  - Small density perturbation
  - Low entropy
  - Decelerating universe cannot make it by dynamical process acting causally.
- **Inflation can produce Hot Big Bang.**
  - It results in a homogeneous, isotropic, flat universe.
  - It converts **quantum fluctuations** into **density perturbations**.

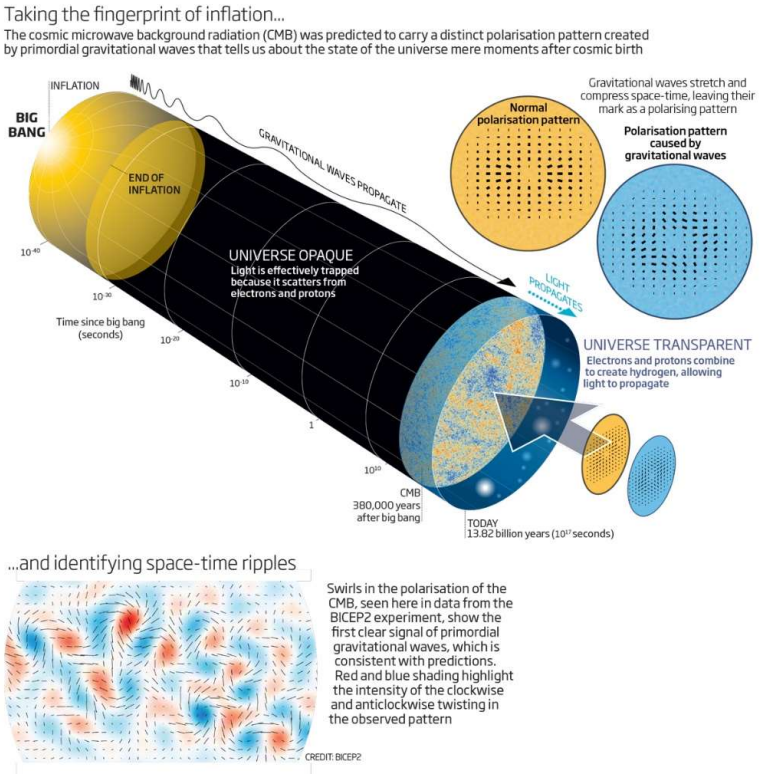


Inflation

- **Origin of Energy / Matter**
  - Where does the inflaton field come from?
  - How did inflation begin?

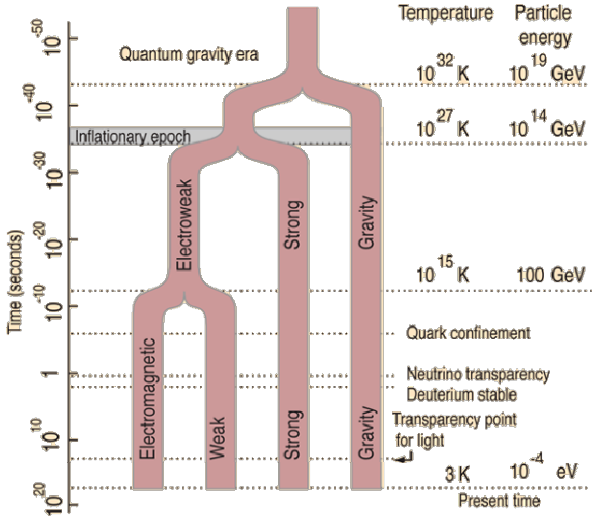
- **How to prove Inflation**
  - Homogeneity, Isotropy, Flatness
  - (nearly) Gaussian / **Scale-invariant spectrum**
  - **Gravitational wave**

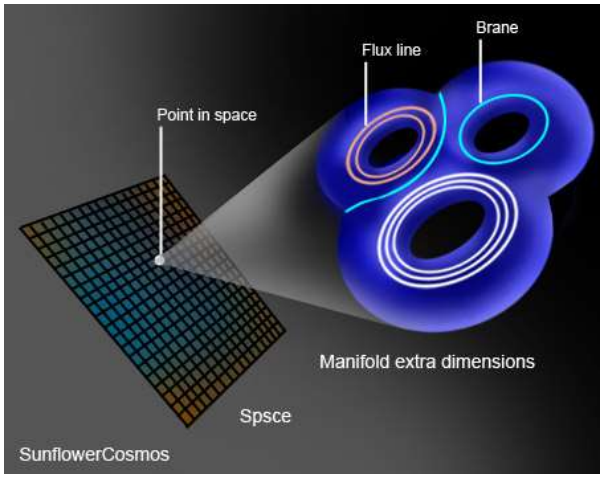
- **Side Effects of Inflation**
  - Eternal Inflation & Multiverse

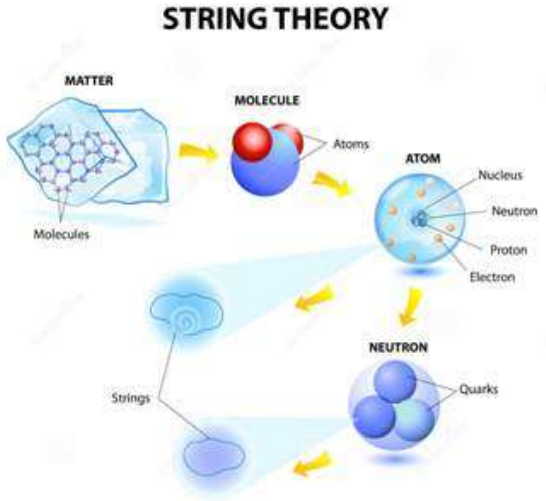


Matter Dynamics

- Grand Unified Theory – Extending the gauge symmetry groups
- Extra-dimensions – Extending the spatial dimensions
- Supersymmetry – Extending matter content by fermion-boson pairs
- String / M theory – Replacing point particles by strings or ??



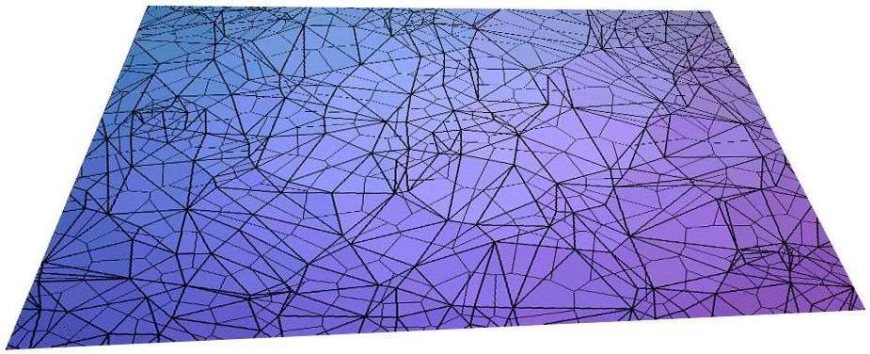




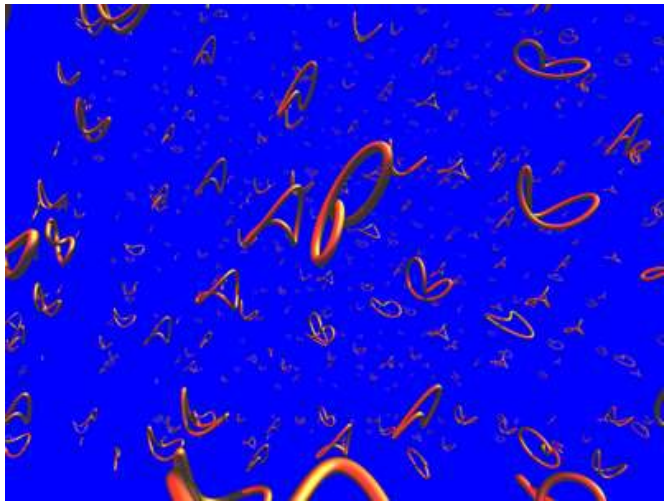
Spacetime Dynamics

- Modified Gravity
- **Gravity** and **Quantum Mechanics**
  - Inconsistent as field (point particle) theory
- Are **Time** & **Space** Continuous?
- Are **Particles** persistent?

- Loop Quantum Gravity



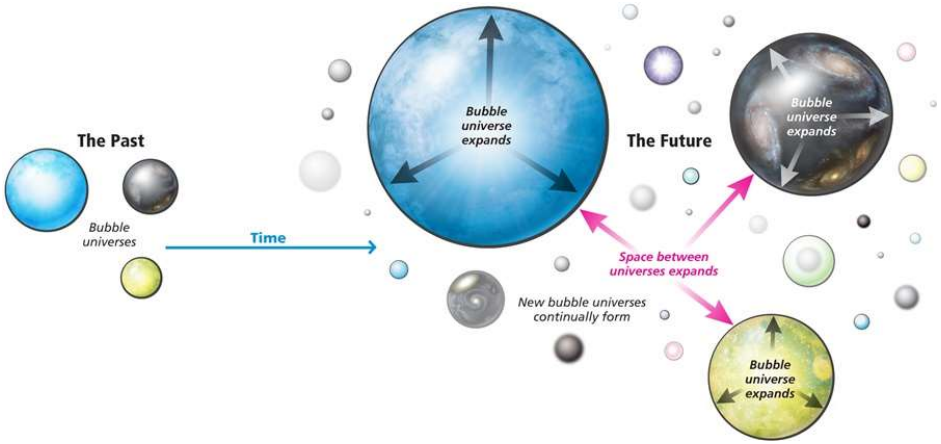
- String / M Theory



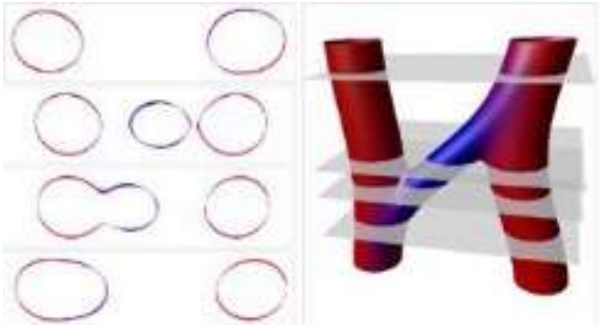
Origin of Universe

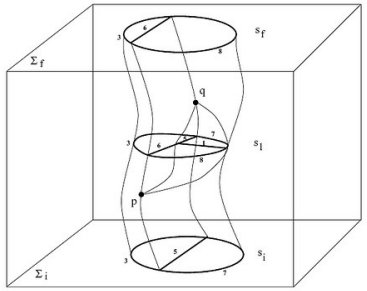
The most incomprehensible thing about the world is that it is at all comprehensible. -- Albert Einstein

- **What is the beginning of Universe?**
  - How did **Inflation** initiated?
  - **Singularity** – beyond physics
    Nature of quantum gravity, time, …
  - Are **Initial conditions** included in physical laws?



- **Eternal Inflation, Multiverse**, **Anthropic principle**
  - All possible initial states are realized in multiverse.
  - **Anthropic principle** – In multiverse, we exist in the special universe (where we can exist).

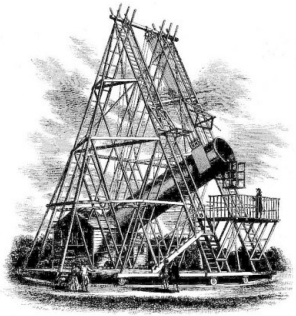




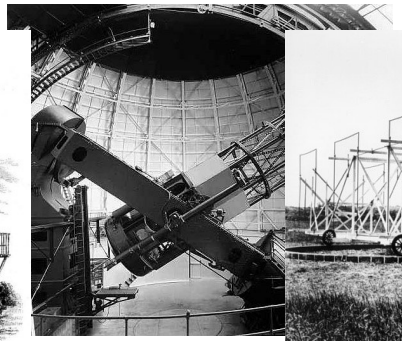
- **Quantum Gravity**
  - What happens as Δx approaches 0?
  - Is the origin of Universe **quantum fluctuation**?

Tycho's
Mural quadrant

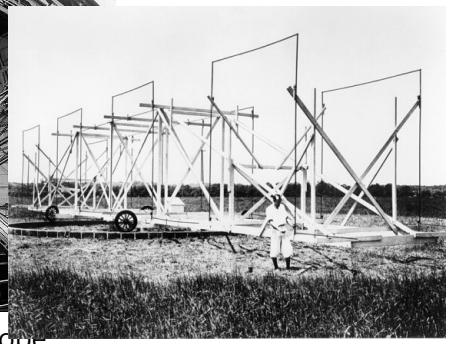
Galileo's telescope



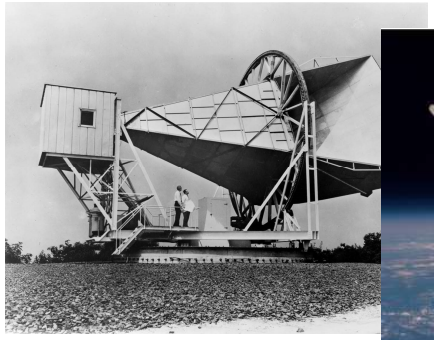
Herschel's telescope



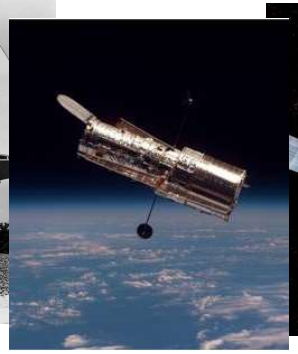
Hubble's telescope



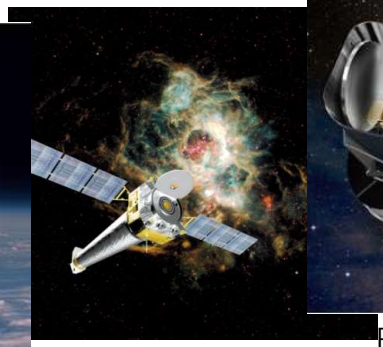
Jansky's radio antenna



Penzias & Wilson's antenna



Hubble Space Telescope



Chandra X-ray telescope

Planck satel

The fact that **we exist** is more surprising than the fact that the universe exists.