Mystery of the Universe

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22/08/2023@IIT Madras

$c = \hbar = 1, \quad M_G = 1/\sqrt{8\pi G} \sim 2.4 \times 10^{18}\mathrm{GeV}.$

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  How to probe the history of the Universe ?
- **Big-Bang cosmology**

  What is the standard model of early Universe ?
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Introduction

Mystery of Human-being & Universe

Museum of fine arts

「 Where Do We Come From ? What Are We ?
Where Are We Going ? 」(Paul Gauguin, 1897)

We, human-being, have asked this kind of questions since the era of myth.

Common questions

- **What is the history of the Universe ?**
- **What is the edge of the Universe ?**
- **What is the main content of the Universe ?**
- **What is the future of the Universe ?**
- **…**

How to probe the history of the Universe ?

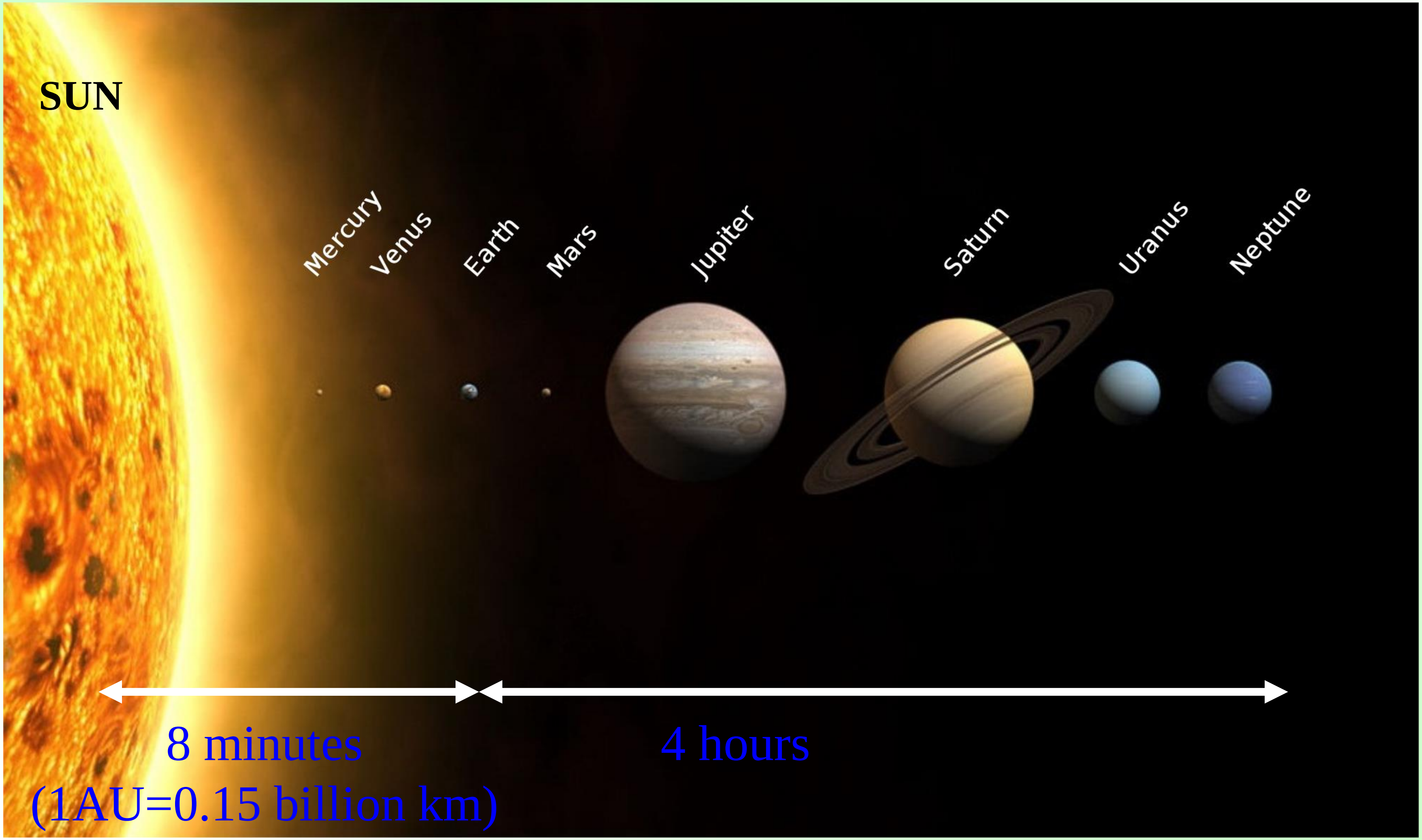
Speed of light is "finite" !!

Even speed of light, which can transmit the information fastest, is finite.

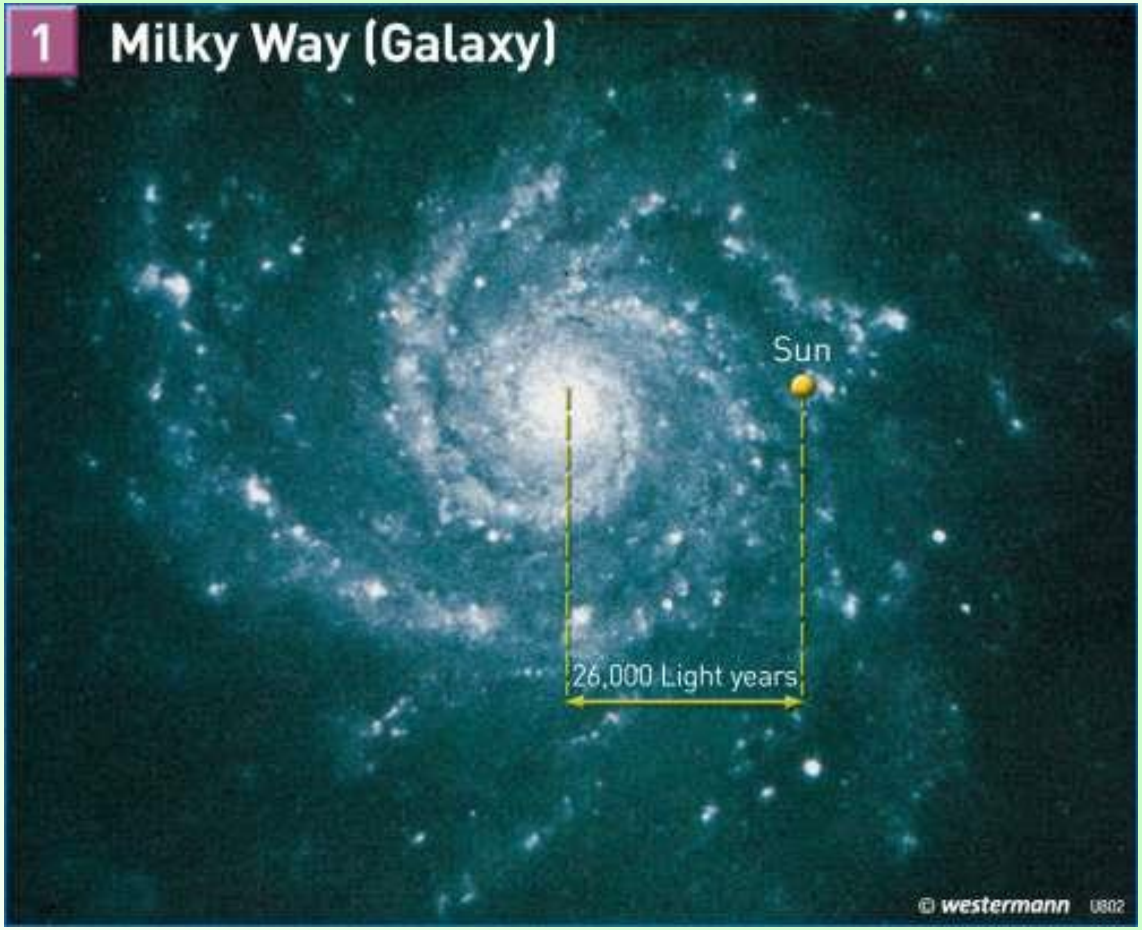
For example,
sunlight we observe was emitted from Sun 8 minutes ago.

That is, observing distant Universe is equivalent to observing past Universe.

Solar system



Our galaxy (Milky way galaxy)

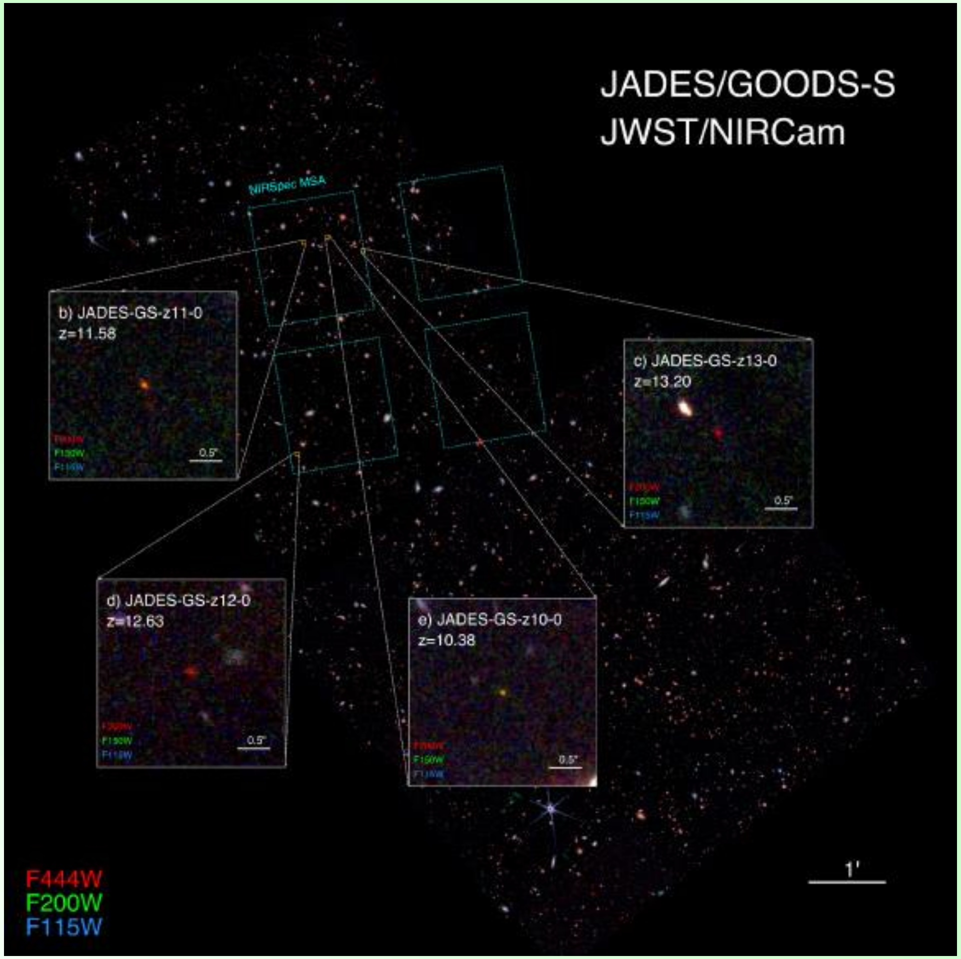


100,000 light years

Neighborhood galaxy
(Andromeda galaxy M31)

2.5M light years from Earth

The (observed) most distant galaxy (JADES-GS-z13-0)



JWST

13.47 G light years from Earth (z =13.20)

How distant (past) Universe can we observe through photons ?

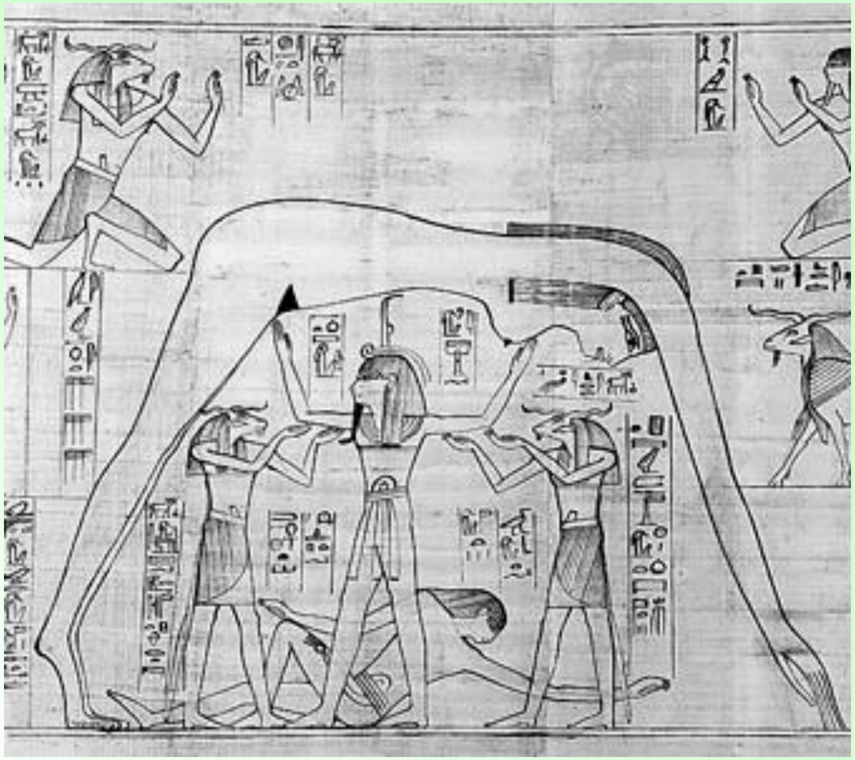
Is it possible to probe the real onset of the Universe through photons ?

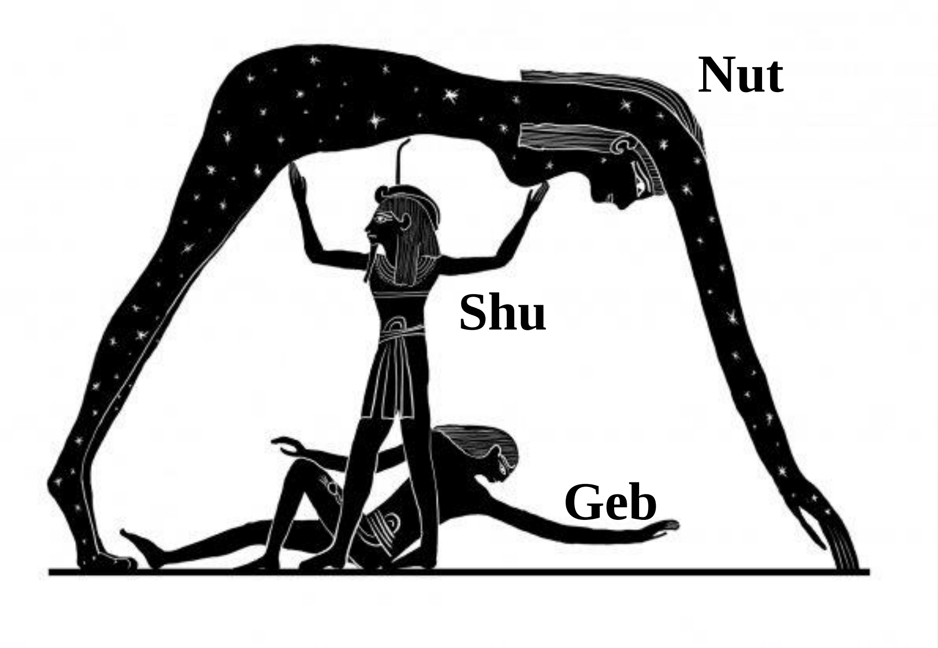
↑

In order to address this question, we need to know in which state the early Universe was.

Evolution ??? of the Universe

The ancient Egyptian cosmos





The British Museum

The ancient Egyptian view of the cosmos：

The sky goddess Nut, supported by the air god Shu, arches over the earth god Geb.

Newton's mechanics & gravity

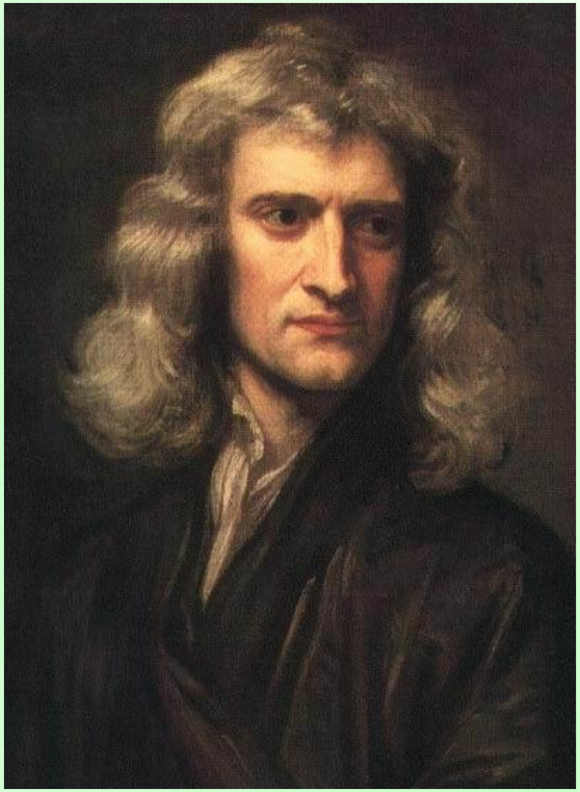
A popular story:

When Newton was sitting under an apple tree, an apple fell on his head, and he suddenly thought of the Universal Law of Gravitation.

↓

The same law on earth can explain the motion of planets in the sky (Kepler's law).

But, the Universe (space) is invariant and is never supposed to change.



painted by Godfrey Kneller 1689

General relativity (1915)

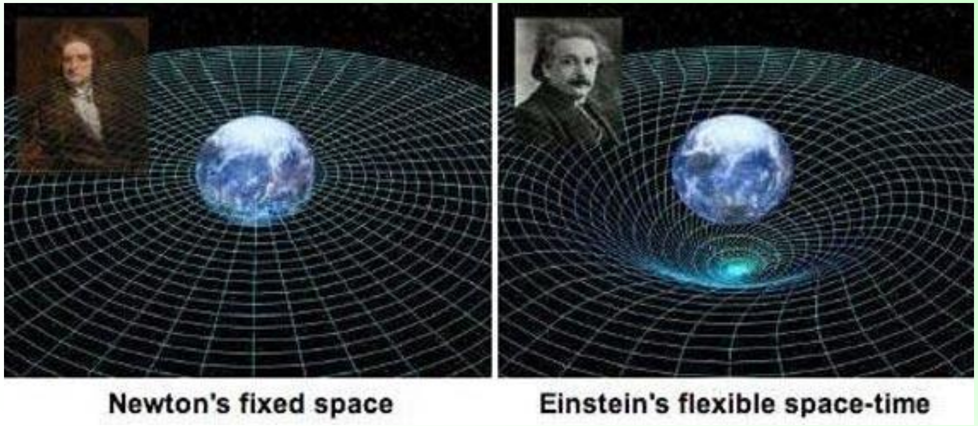
Einstein's general relativity connects spacetime to its matter content, which enables us to discuss the dynamics of spacetime, for the first time.

Einstein equation

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

spacetime ⟺ matter

http://karapaia.livedoor.biz/archives/52004824.html

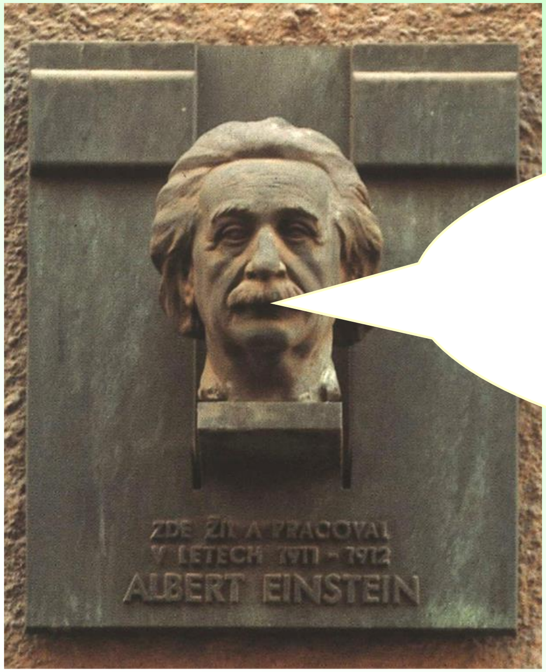


Young Albert Einstein in Munich. 1893.

Evolution of the Universe ???

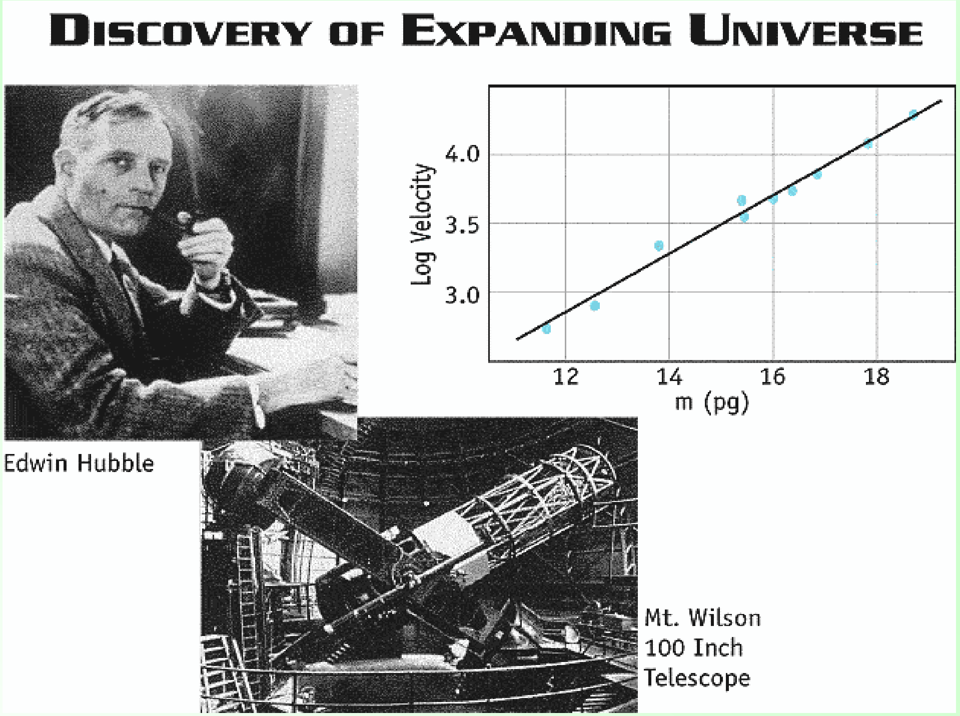
No beginning, no end, eternal
(steady state Universe)

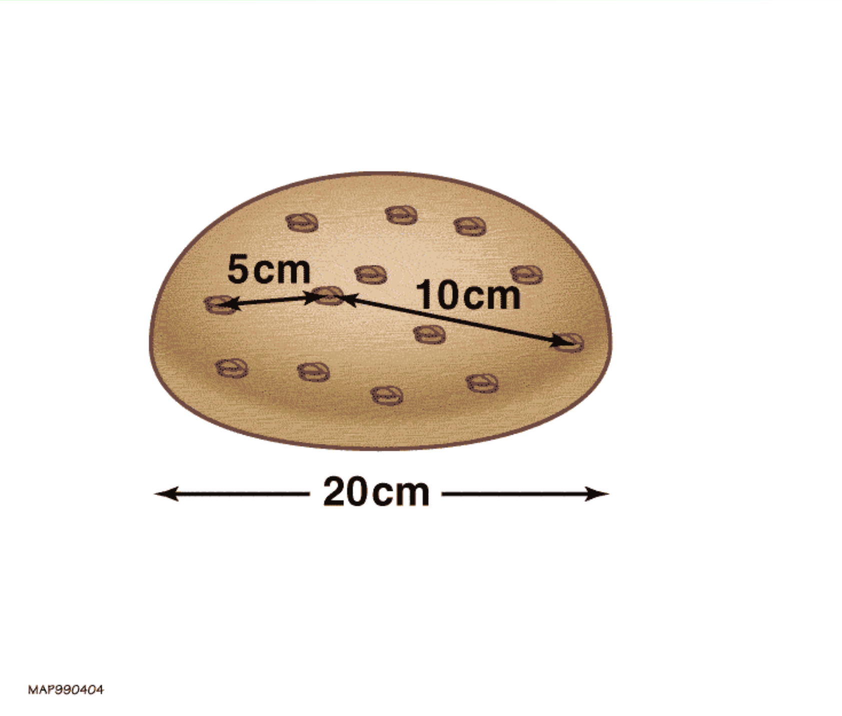
Believed for a long time.



Nonsense !!
The Universe never changes.

Discovery of cosmic expansion (1929)





http://map.gsfc.nasa.gov/

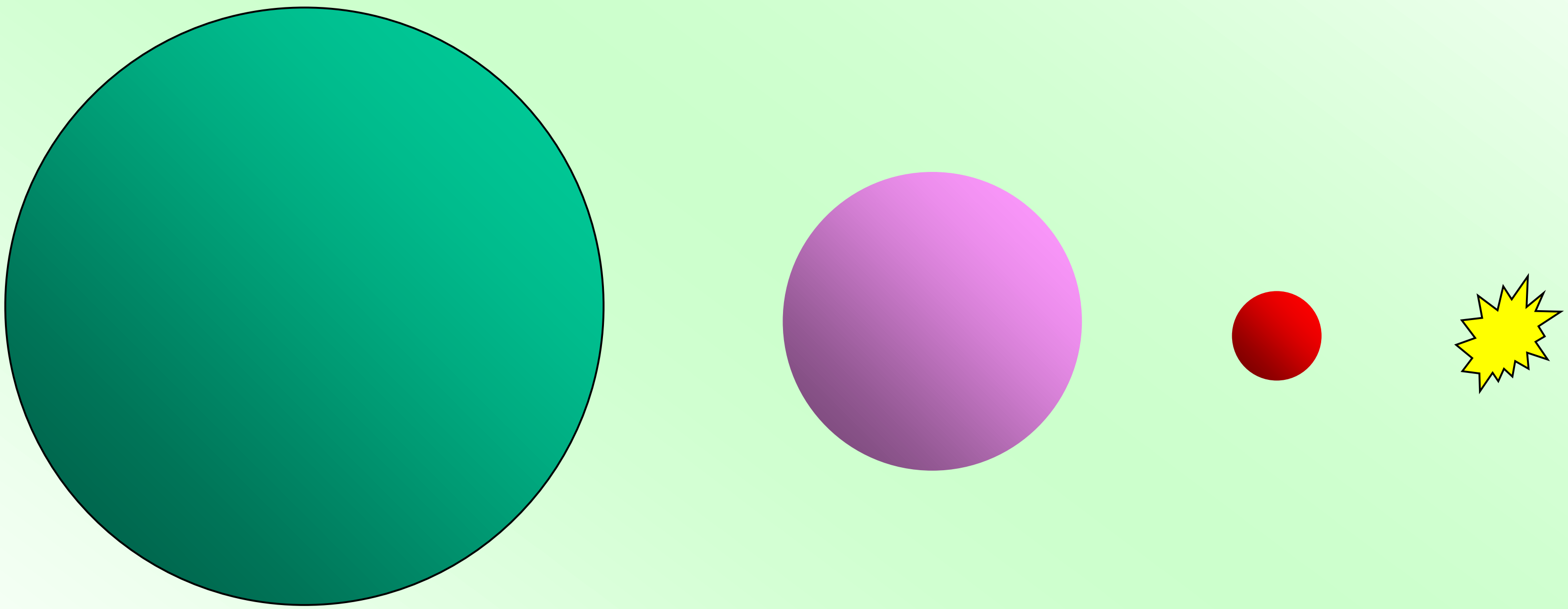
Hubble–Lemaître law :

The farther the galaxies are, the faster they recede.

Evidence of cosmic expansion

(The Universe is not eternal but has a beginning !!)

Early Universe was so small

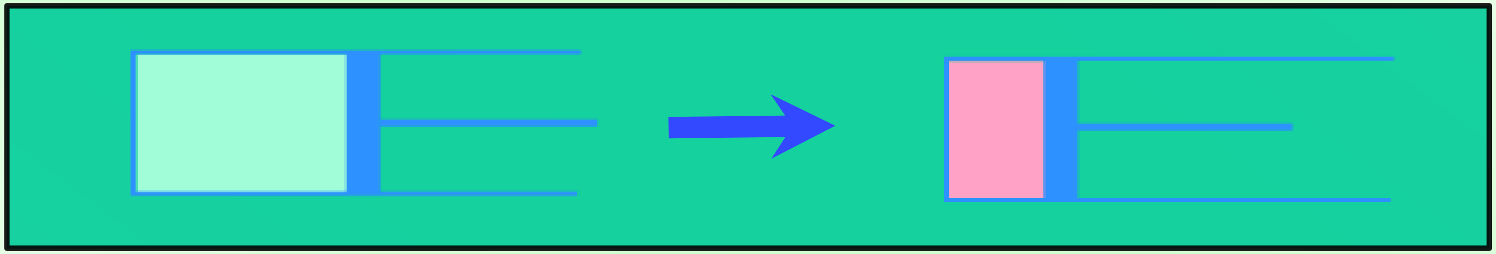


present past

Big-bang cosmology

Hot Universe

Cosmic expansion → **The past Universe was so small**



Compression raises temperature and pressure

The past Universe was small, hot, and dense.

Everything was resolved into pieces !!

Resolved Universe

Any compound and structure like star and galaxy was completely broken into atoms.

In the far past, even atom was decomposed.

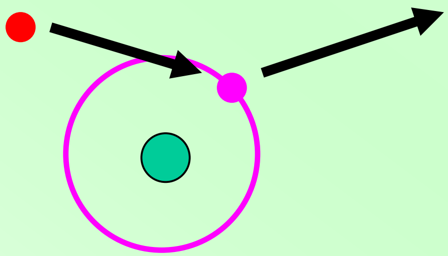
Hydrogen atom

photon

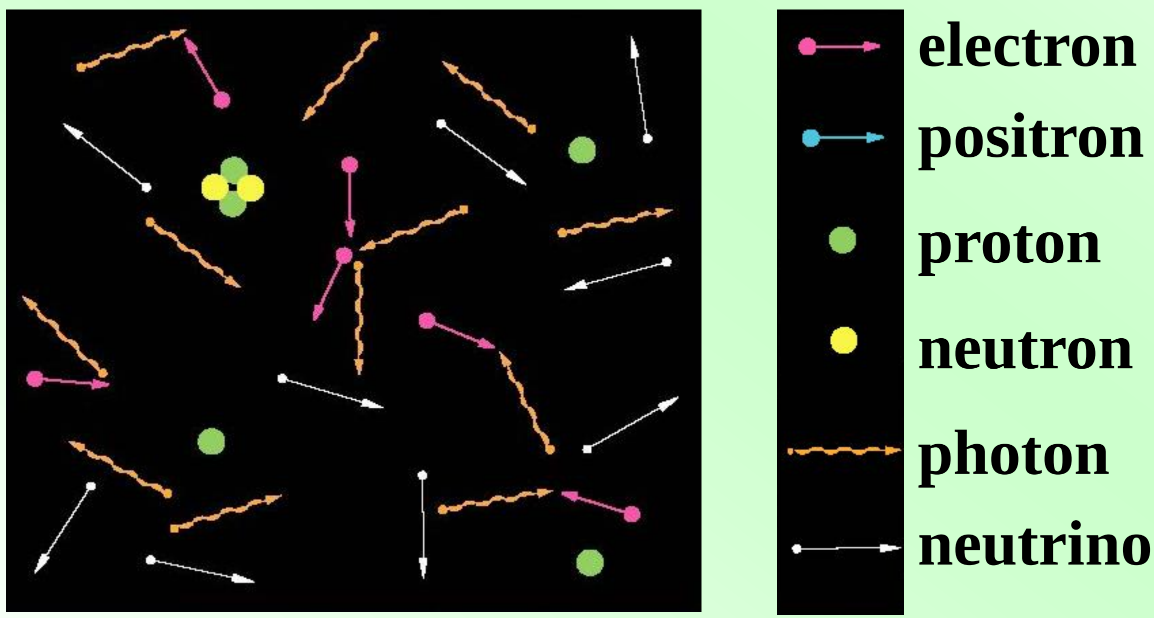
Electron is scattered by overcoming the Coulomb force.

Atom is ionized.

Disturbed photons !!



Photons cannot travel freely by disturbing free electrons.



Photons & electrons are in thermal equilibrium.

The past Universe we can observe through photons is limited.

We cannot observe the Universe before this epoch (through photons).

Temperature is around 3,000 Kelvin.
13.8 billion years ago（Age is around 380 K year old.）

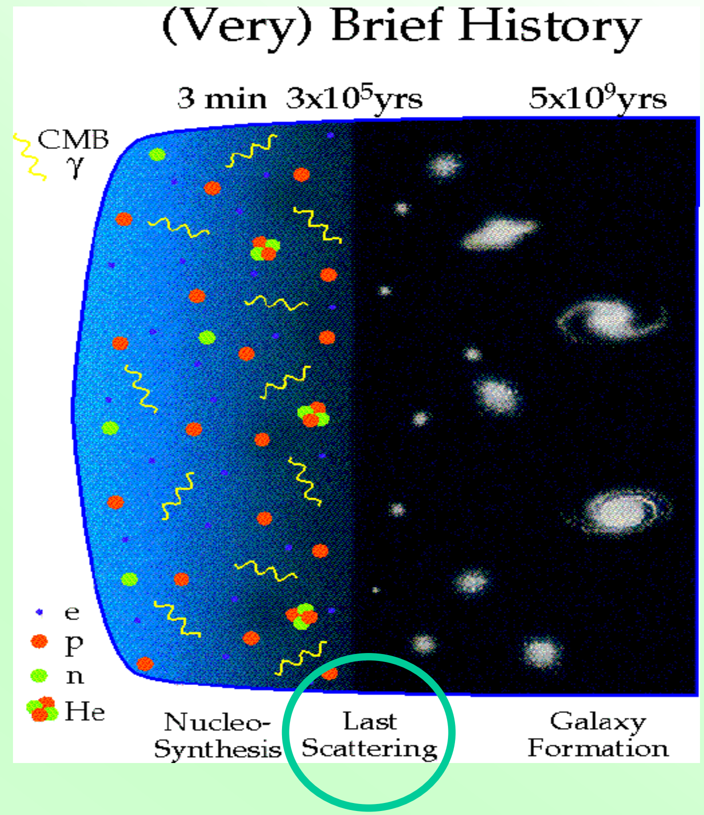
This is the view, with which we see the Universe from the present to the past.

On the other hand, if we imagine the Universe forward in time, what happened ?

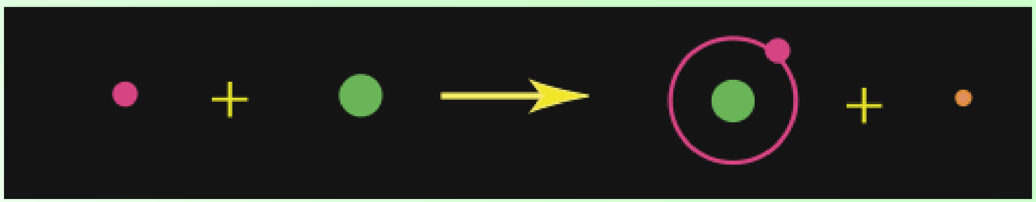
Recombination of electron

At T ~ 3000K (t ~ 3.8 x 10^5 years)

http://background.uchicago.edu/



electron + proton ➔ hydrogen + photon



Photons can freely travel without being hindered by electrons.

We can observe such photons as cosmic microwave background radiation (CMBR).

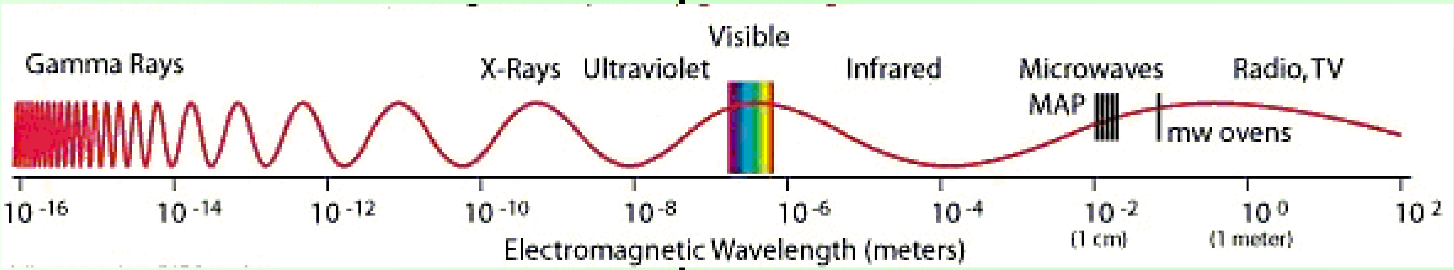
(This is the direct evidence that the Universe was hot in the past.)

Cosmic microwave background radiation

CMBR ： remnants of hot Universe

High T (short wavelength)

Extension of wavelength by cosmic expansion

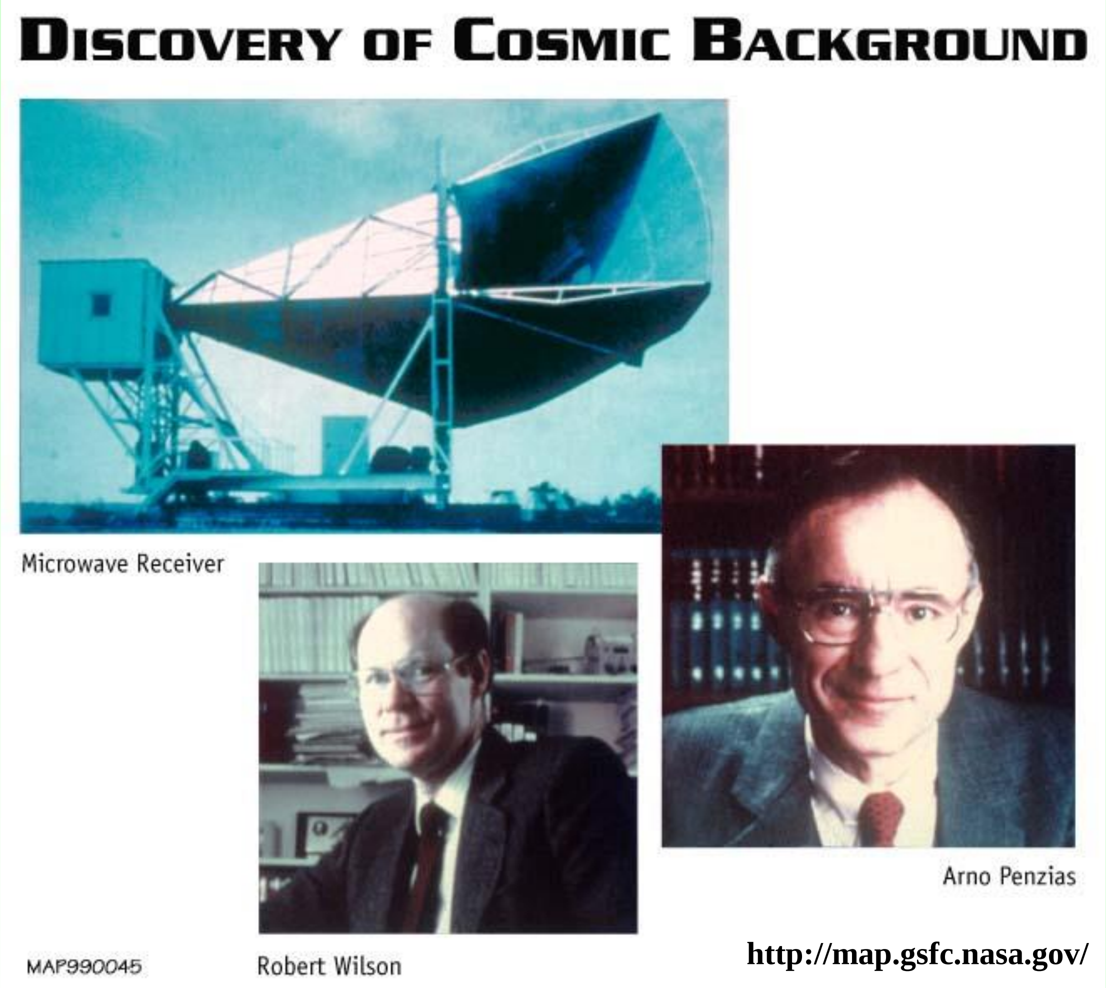


http://map.gsfc.nasa.gov/

Low T (long wavelength)

The Universe is now filled with such photons.

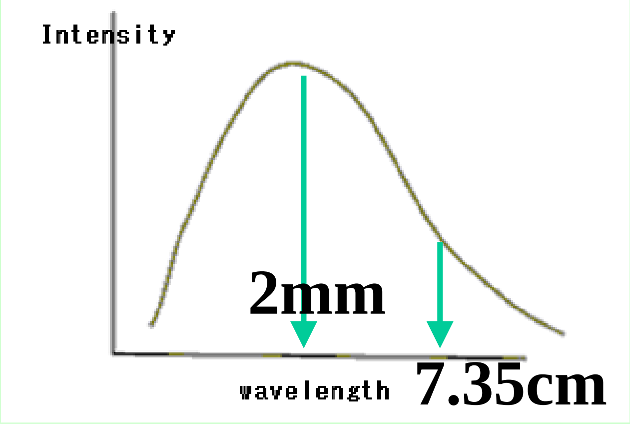
Discovery of cosmic microwave background radiation (CMBR)



3K

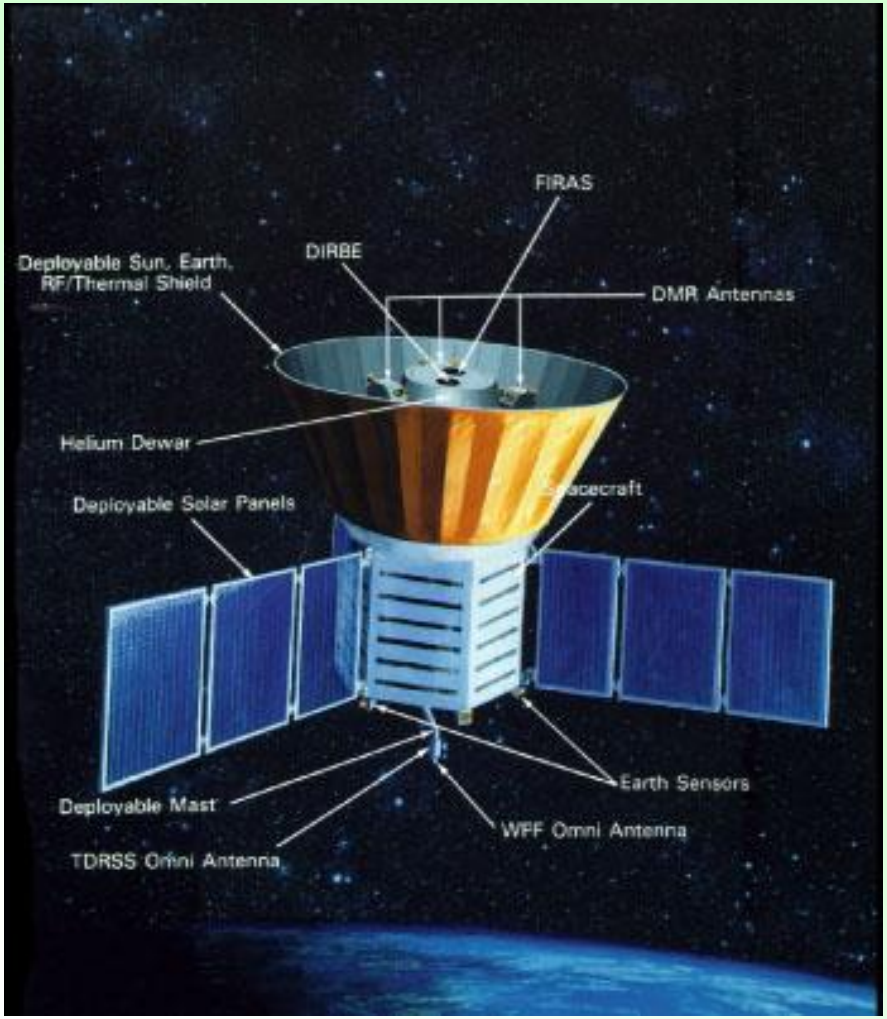
(centigrade temperature -270)

awarded the Nobel Prize for Physics in 1978



Discovered by Penzias & Wilson in 1964.

COBE (COsmic Background Explorer)



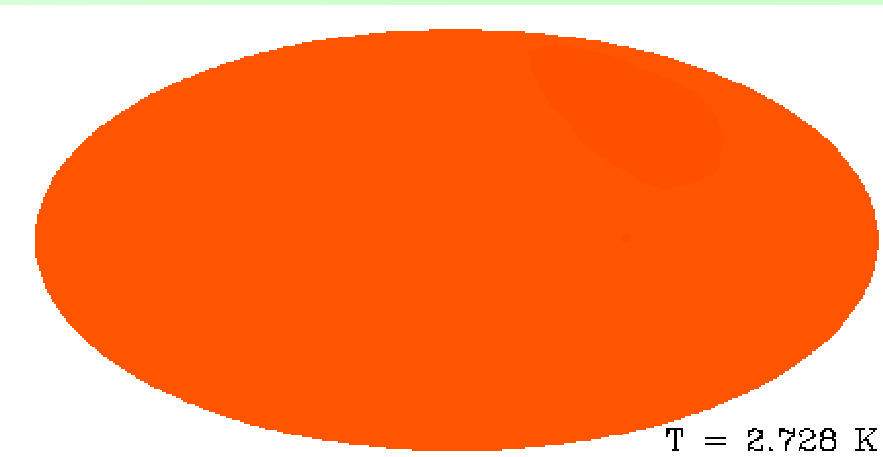
Launched by NASA in 1989

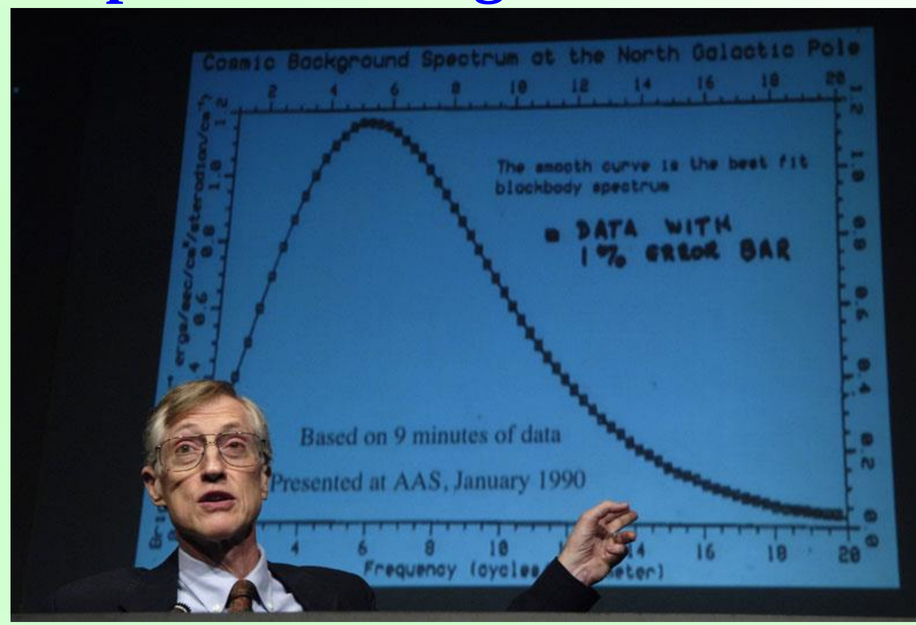
Awarded the Nobel Prize for Physics in 2006 !!

Almost perfect blackbody

Our Universe was hot !!

Planck distribution with
peak wavelength ~ 2mm





John C. Mather was awarded the Nobel Prize for Physics in 2006 !!

Almost perfect black body with 2.7K

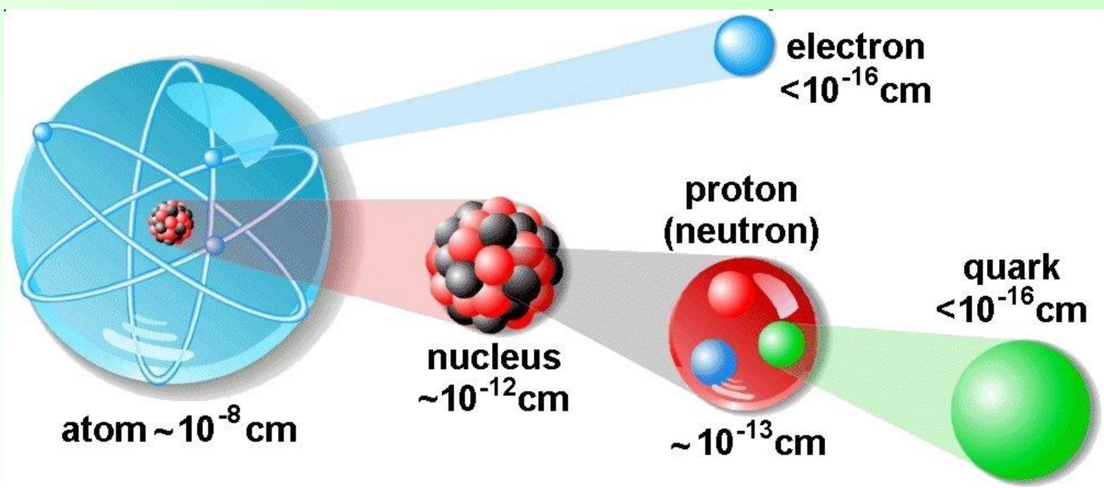
Further past ???

In the further past, even nucleus is decomposed into proton and neutron.

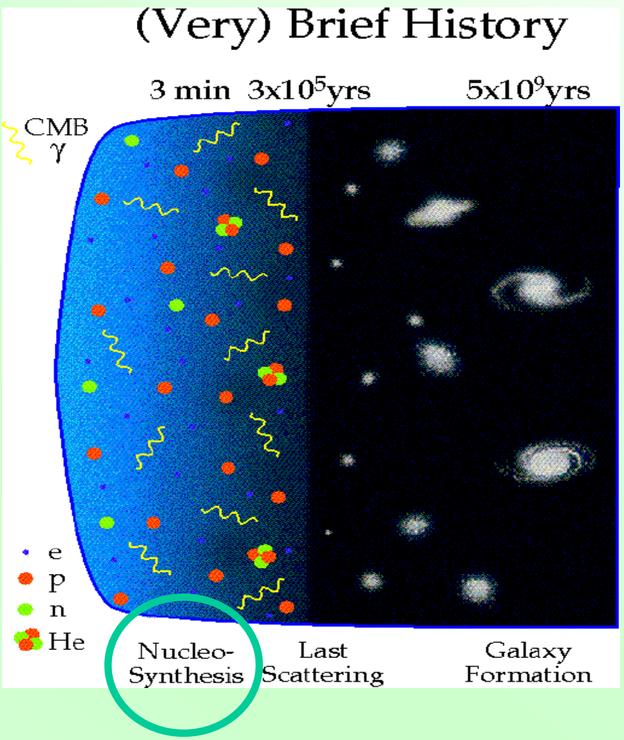
http://background.uchicago.edu/

3000K (30K year)
atom is ionized

0.3G K (3 minutes)
nucleus is decomposed



https://www.quora.com/What-size-are-the-particles-of-an-atom-in-relation-to-its-size



Atom (nucleus) did not exist from the beginning and was produced from protons and neutrons (quarks) later.

Nucleosynthesis in the early Universe

While the temperature drops from 10G K to 0.3G K,

2(proton) + 2(neutron) ⟶ Helium

Almost all of the neutrons in the Universe are absorbed into Helium 4.

Consistent with observation !!

At the same time, small amounts deutrium, Helium 3, & Litium 7 are produced.

Heavier elements are synthesized in stars.

Big Bang Nucleosynthesis (BBN)

- Light elements were synthesized in the early Universe (t = 1 - 100 sec).
  (Heavy elements are synthesized in the star and SN)
- Almost all neutrons are incorporated into ^{4}He.

How to estimate the abundance of ^{4}He ?

(i) β equilibrium between p & n :

$$n \leftrightarrow p + e^- + \overline{\nu}_e, \quad n + \nu_e \leftrightarrow p + e^-, \quad n + e^+ \leftrightarrow p + \overline{\nu}_e.$$

$$(n/p) = \exp\left(-Q_{np}/T\right), \quad Q_{np} \equiv (m_n - m_p)c^2 = 1.29 \text{ MeV}.$$

(ii) β equilibrium freezes out when the expansion rate dominates.

$$\Gamma_\beta \simeq G_F^2 T^5 = H \simeq T^2/M_G^2 \implies T_f \simeq 1/\left(G_F^2 M_G\right)^{1/3} \simeq 1 \text{ MeV} \implies (n/p) \simeq 1/6.$$

(iii) Nucleosynthesis starts from D : p+n ➔ D+γ, B_D =2.22 MeV.

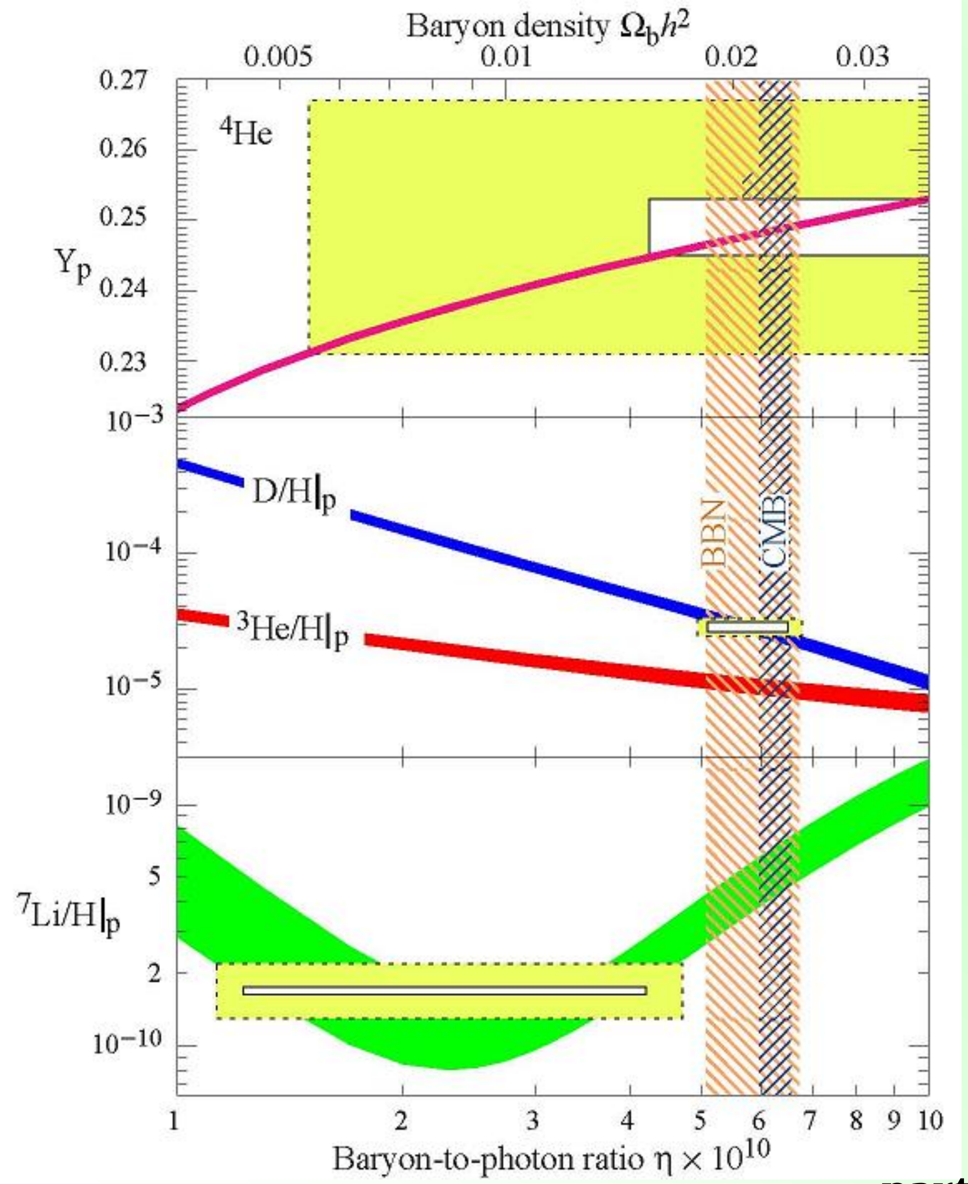
$$(D/n) \simeq 7.2\eta\,(T/m_n)^{3/2} \exp\left(B_D/T\right) \implies T_D \sim 0.07 \text{ Mev} \implies (n/p) \simeq 1/7.$$

$$\left(\eta = n_b/n_\gamma \simeq 6 \times 10^{-10}\right)$$

(Decay of n with τ_n = 890 s)

$$Y \equiv \frac{\text{total mass of } ^4\text{He}}{\text{total masses of p \& n}} = \frac{\frac{n_n}{2} \times 4m_p}{n_p m_p + n_n m_n} \simeq \frac{2\frac{n_n}{n_p}}{1 + \frac{n_n}{n_p}} \simeq 0.25.$$

Consistency between theory and observation



The abundance of baryon (nucleons) can be estimated by BBN.

$$\Omega_b \simeq 0.05$$

$$(\Omega = \rho/\rho_c)$$

$$\rho_c \sim 3H_0^2/(8\pi G)$$
$$\sim 10^{-29}\mathrm{g/cm^3}$$

particle data group

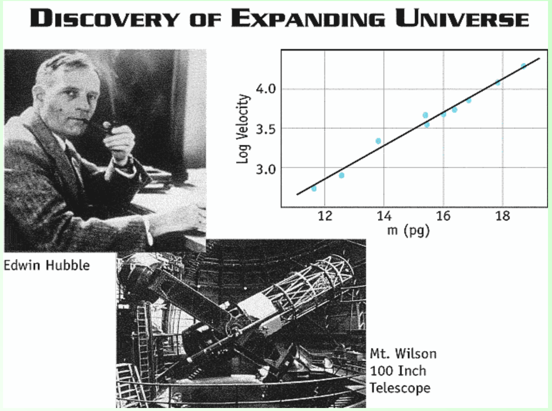
Big Bang cosmology

Gamow

The Universe "starts" from a hot and dense state called Big Bang, and then cools down according to the expansion.

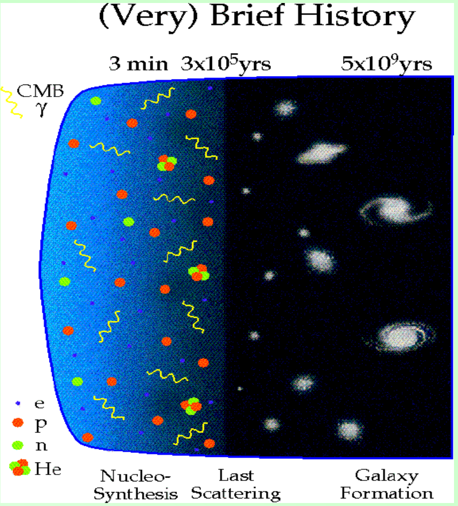
Observational supports for Big bang cosmology

● Hubble expansion



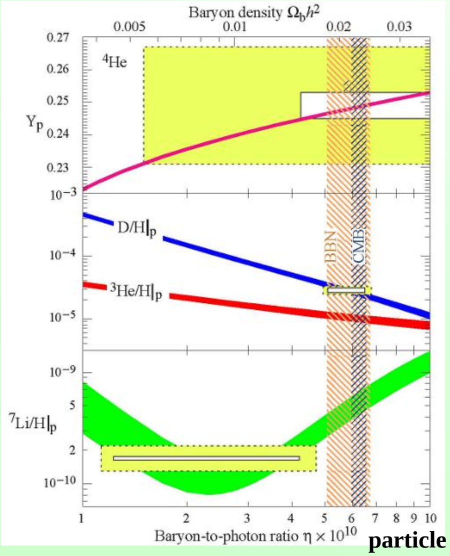
http://map.gsfc.nasa.gov/

● CMBR



http://background.uchicago.edu/

● Big Bang Nucleosynthesis



particle data group

The Universe expands like the balloon.

$$a(t) \propto t^{1/2} \quad \textbf{RD}$$
$$a(t) \propto t^{2/3} \quad \textbf{MD}$$

We can observe lights emitted 13.7 billion years ago.

Black body with almost the same temperature irrespective of the directions

Almost all neutrons are incorporated into ^{4}He.

$$\Omega_b \simeq 0.05$$

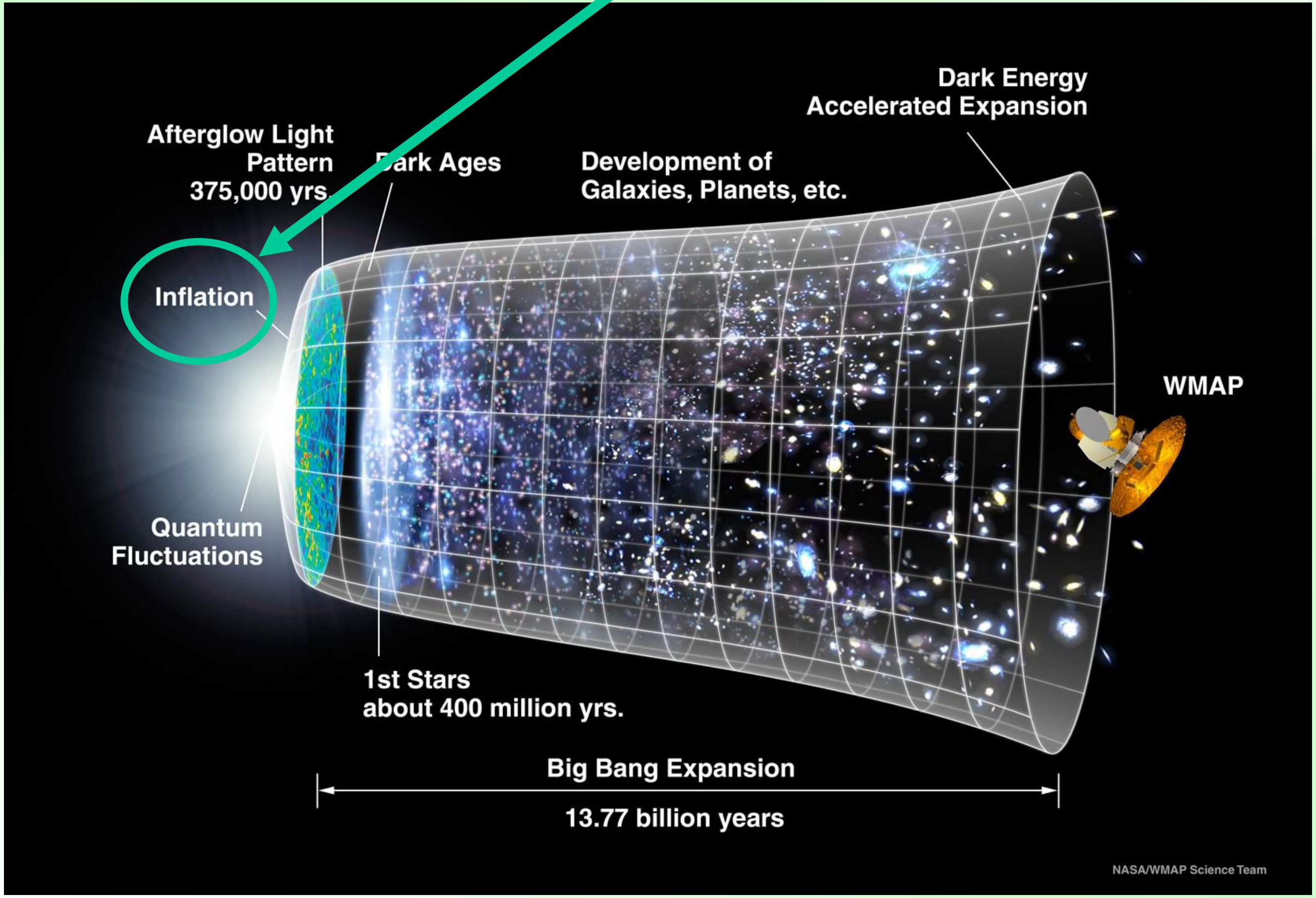
$$\Omega = \rho/\rho_c$$
$$\rho_c \sim 10^{-29} \mathrm{g/cm^3}$$

What is the true onset of the Universe ?

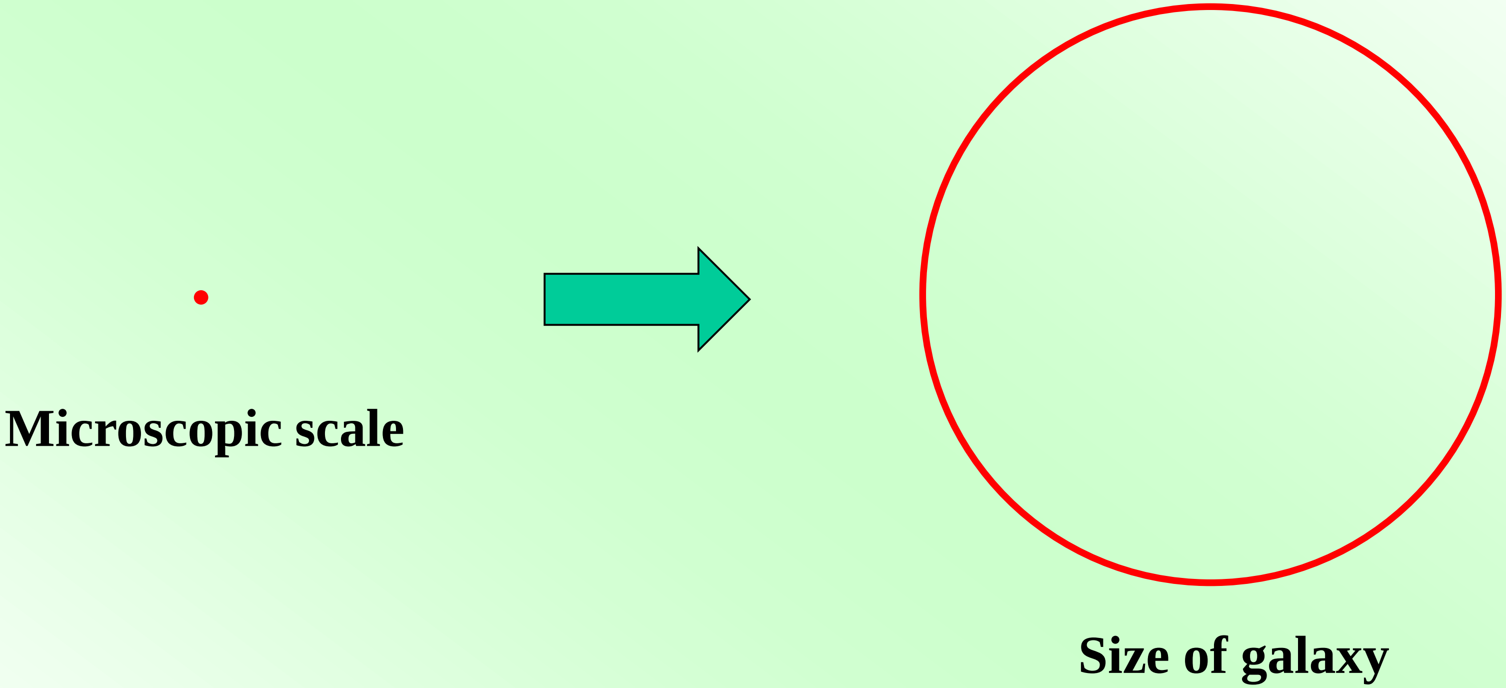
- We can observe the past Universe until 13.8 billion years (Age is around 38 K year old) through photons.
- At that time, the Universe was so tiny and hot.
  It was filled with photons, electrons, nucleons etc.
- How to probe the far past Universe ?
  What happened before the hot Universe ?
  (Did Big-Bang happen ?)

Inflationary Universe

(Rapid expansion called inflation is supposed to have happened before Hot Universe)



Inflationary expansion



10^{26} expansion during 10^{-37} second

The expansion of the Universe is faster than light.

Inflation is caused by "unusual" energy

The expansion rate of the Universe is determined not by energy but by energy density of the Universe from general relativity.

$$\frac{1}{2}m\dot{a}^2 - \frac{GmM}{a} = 0 \quad \Longleftrightarrow \quad H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho. \quad \left(M = \frac{4\pi a^3}{3}\rho\right)$$

$$\rho = E/V \propto a^{-3}, \quad E = Mc^2.$$

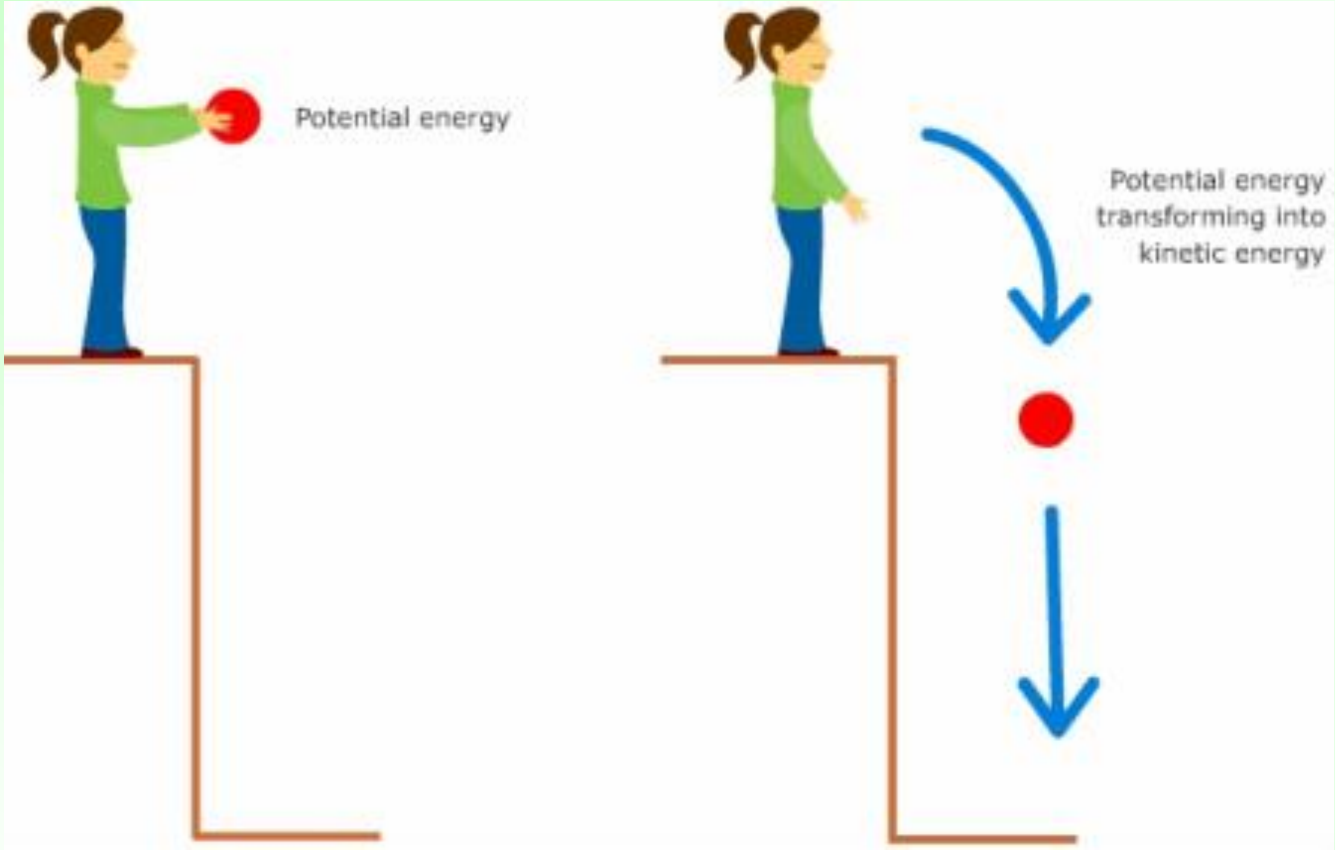
(a: the size of the Universe)

For usual matter, the energy density decreases as the Universe expands because the volume increases.

In order to keep inflation (almost constant expansion rate) long, the energy density of the Universe must be almost constant even though the Universe expands rapidly !!

Is there such an energy ?

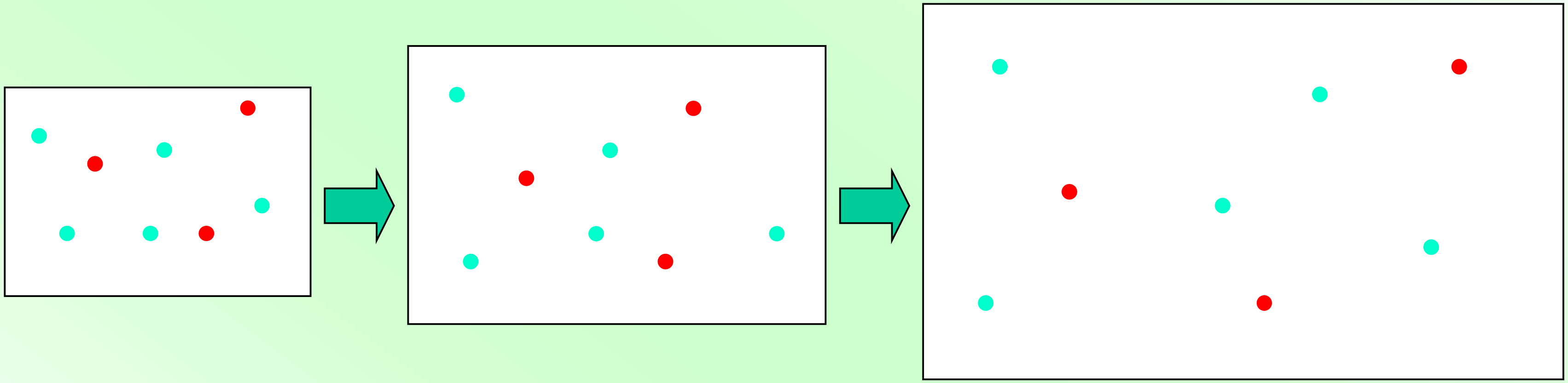
Position (potential) energy density = energy determined by "state"



http://physchemreview.weebly.com/motion--forces.html

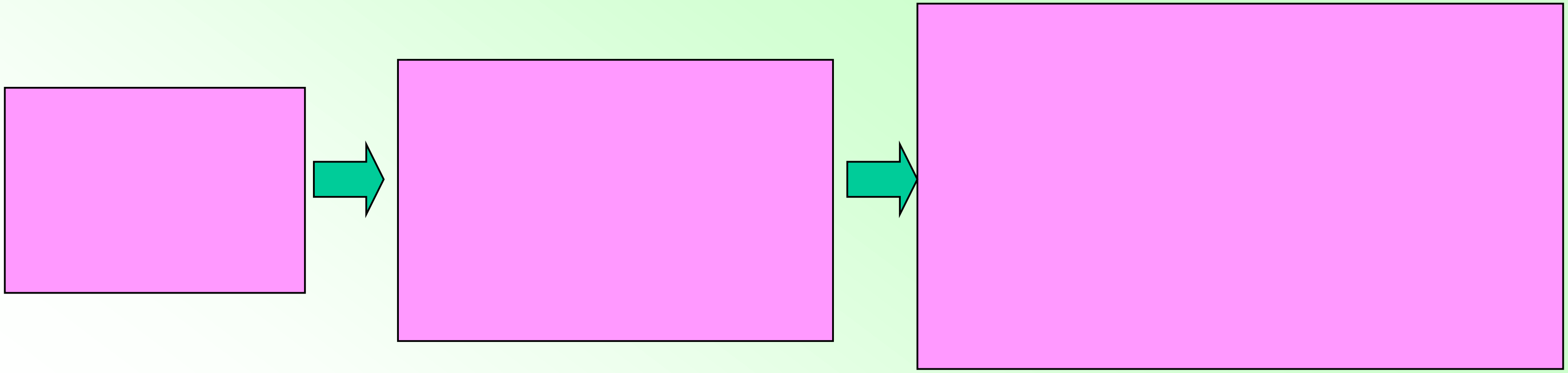
Position (potential) energy density does not decrease as the Universe expands.

Energy density of standard matter decreases as the Universe expands.



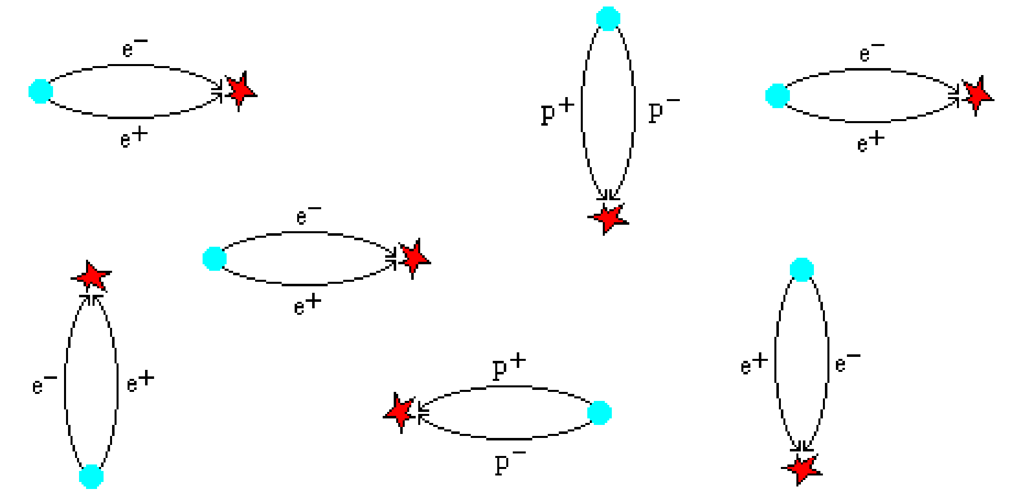
(credit: J.Yokoyama)

Position(potential) energy density is determined by a state so that it does not necessarily decrease as long as the state does not change.



Vacuum

- **Classically, vacuum is just an empty state.**
- **Quantum mechanically, vacuum is a state, in which no real particle exists but a pair of virtual particle and anti-particle is created due to uncertainty principle.**



http://abyss.uoregon.edu/~js/ast123/lectures/lec17.html

Vacuum can have its energy density, which causes inflation.

Quantum field theory

Quantum mechanics :

uncertainty principle

$$\Delta q \cdot \Delta p \gtrsim \hbar/2$$

Special relativity :

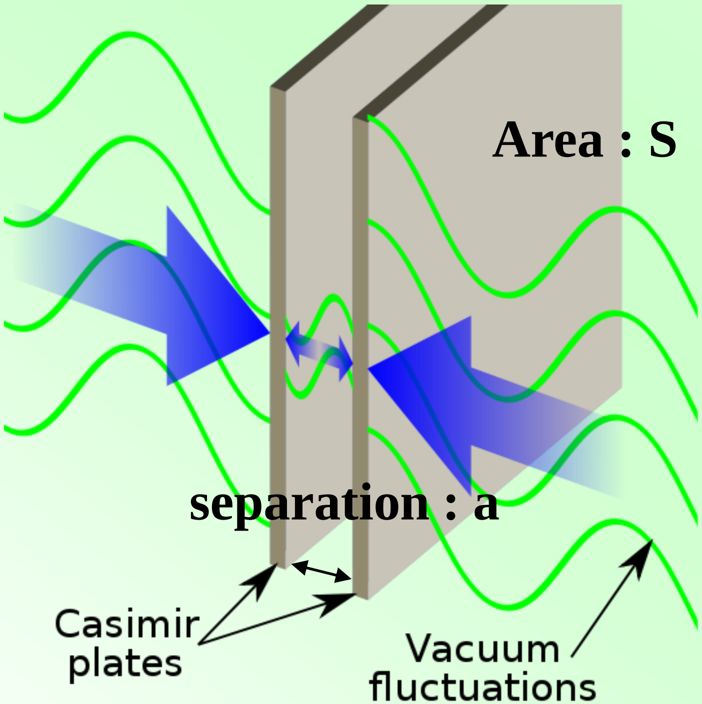
mass-energy equivalence

$$E = mc^2$$

Quantum field theory :

Virtual particles are continuously created even in a vacuum state, in which no real particle exists. Then, vacuum fluctuates and has energy, which is confirmed as Casimir effects.

Casimir effects



https://en.wikipedia.org/wiki/Casimir_effect

Energy for electromagnetic (or scalar) field :

$$E_{\boldsymbol{k}} = \hbar\omega_{\boldsymbol{k}}\left(n_{\boldsymbol{k}} + \frac{1}{2}\right)$$

Vacuum energy

Without boundary (plate),
any mode is allowed.

$$E_0 = \int d^3\boldsymbol{k}\frac{1}{2}\hbar\omega_{\boldsymbol{k}}$$

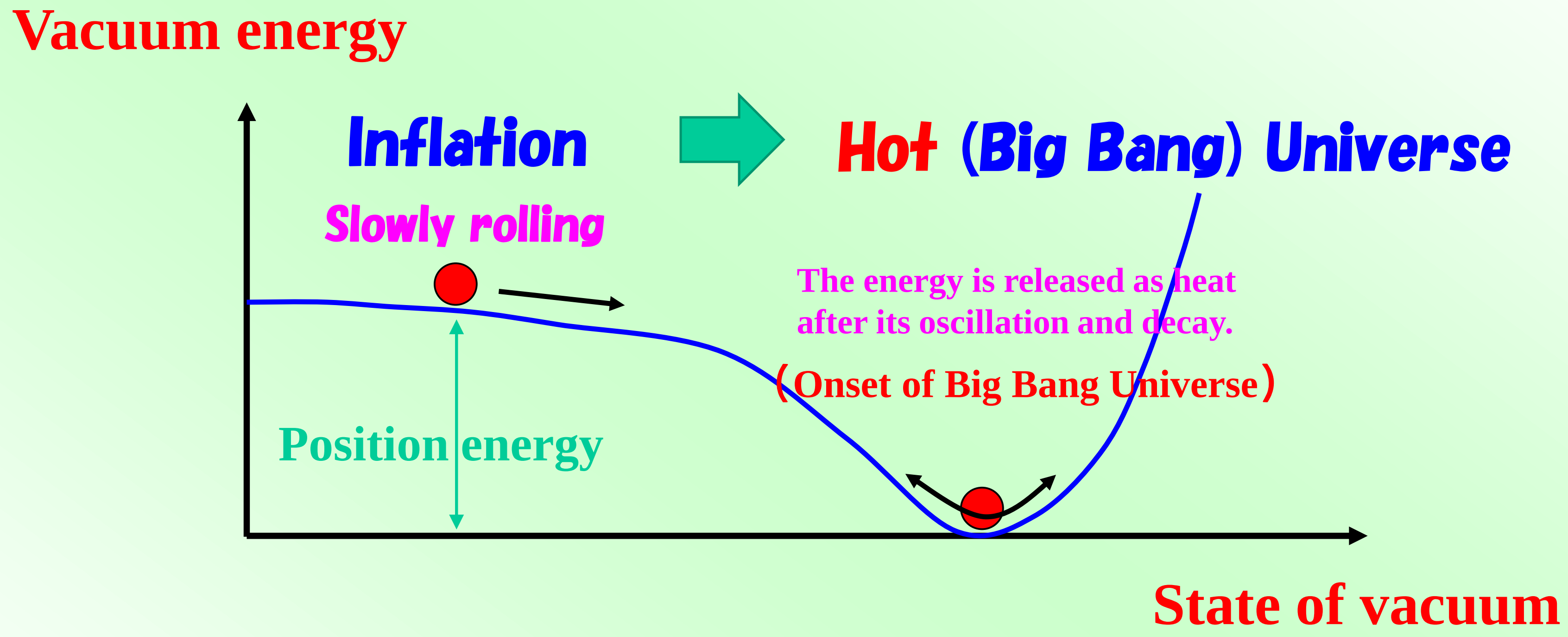
With boundary (plate),
only some modes are allowed.

$$E_0 = \sum_{\boldsymbol{k}}\frac{1}{2}\hbar\omega_{\boldsymbol{k}}$$

$$E(a) = \int d^3\boldsymbol{k}\frac{1}{2}\hbar\omega_{\boldsymbol{k}} - \sum_{\boldsymbol{k}}\frac{1}{2}\hbar\omega_{\boldsymbol{k}}$$

$$\frac{1}{S}F(a) = \frac{1}{S}\frac{\partial E(a)}{\partial a} = \frac{\pi^2}{240}\frac{\hbar c}{a^4}$$

From Inflation to Big Bang

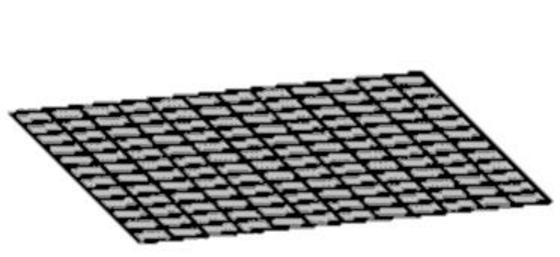


Vacuum energy(position energy) causes inflation.
After its oscillation and decay, energy is released as heat.
This epoch is the onset of hot (Big Bang) Universe.

Predictions of inflation

Generic predictions of inflation

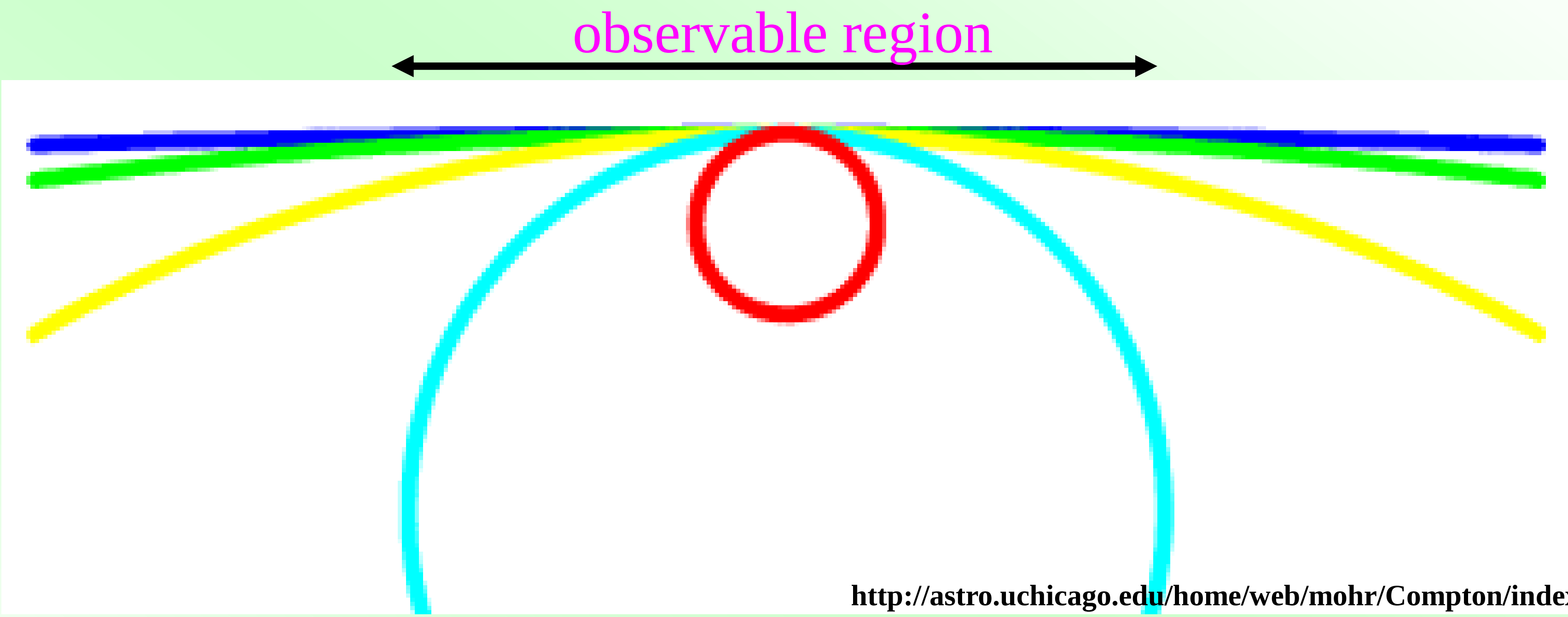
- Spatially flat universe



- Generate primordial density fluctuations, which source stars and galaxies.

- (Generate primordial gravitational waves)

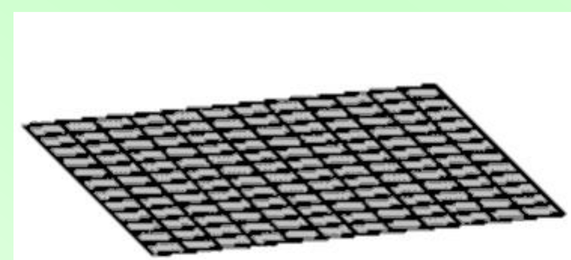
Inflation makes our Universe spatially flat



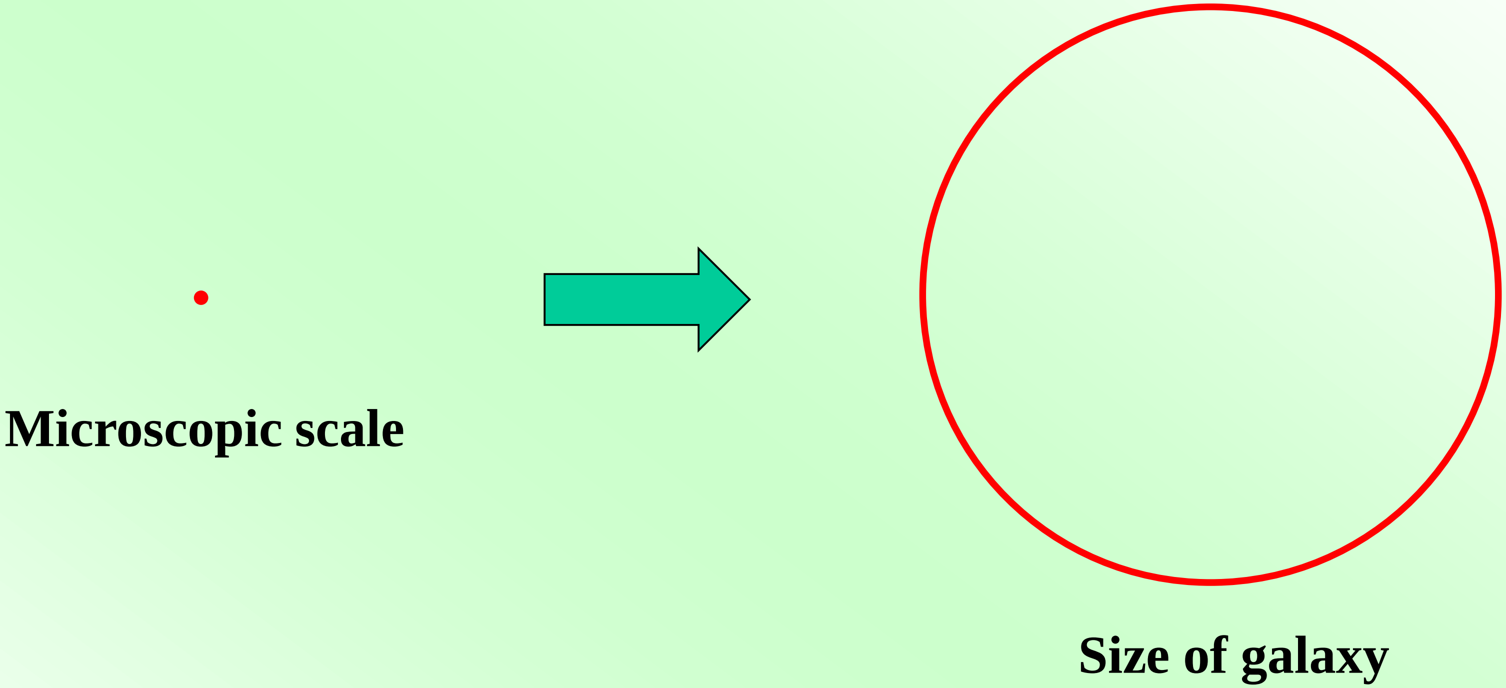
http://astro.uchicago.edu/home/web/mohr/Compton/index.html

The Universe becomes effectively flat due to rapid expansion

Predict spatially flat Universe



Inflationary expansion



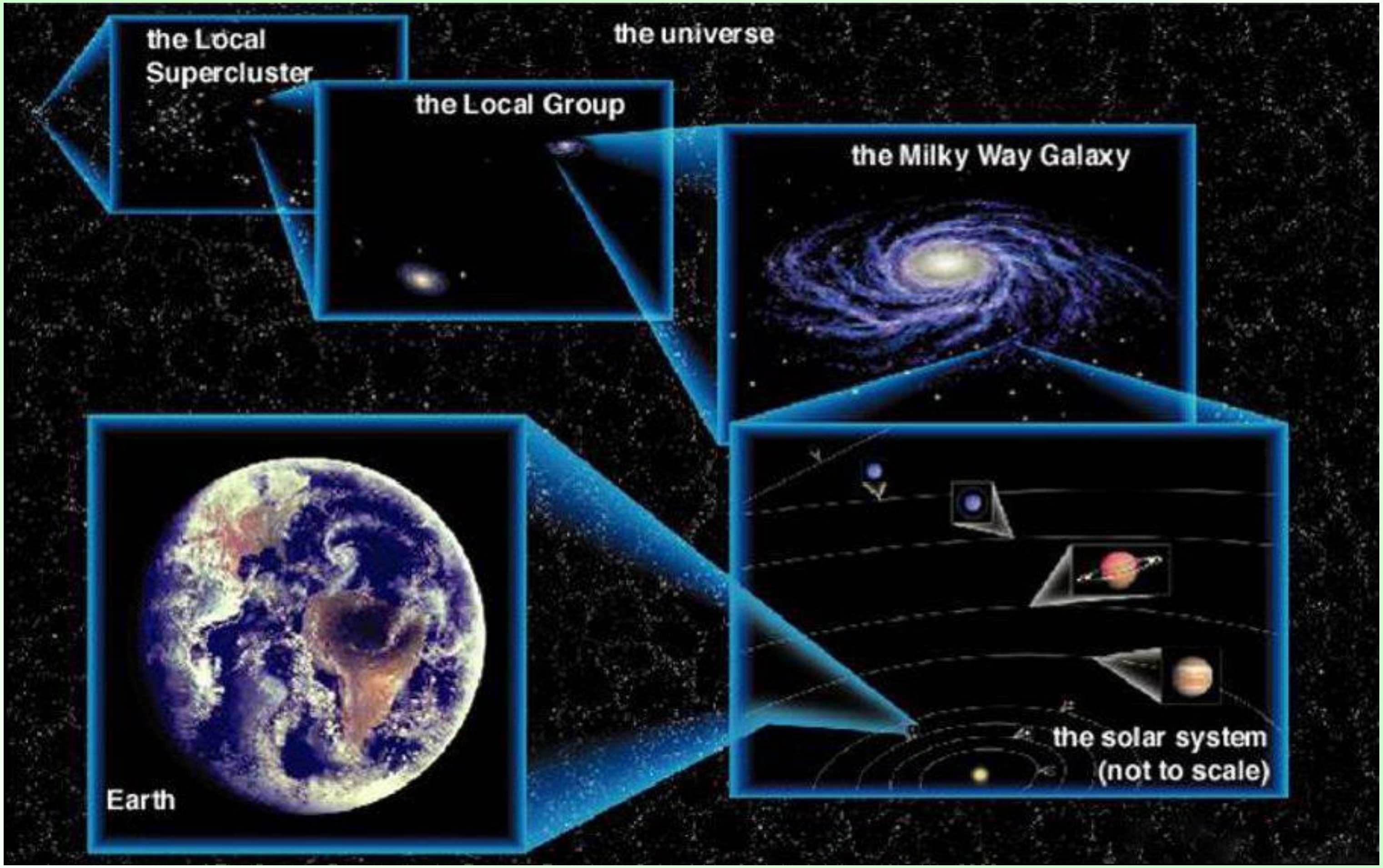
10^{26} expansion during 10^{-37} second

Any structure before inflation is effectively erased.

Needs primordial fluctuations to source stars and galaxies.

Structure of the Universe

Our Universe has fruitful structure

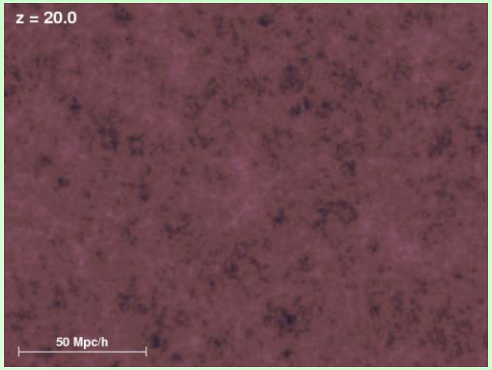


http://images.slideplayer.com/5/1508294/slides/slide_3.jpg
The Cosmic Perspective, Bennett et al.

Why and how was this kind of structure formed ?

Formation of structure

- The structures of the Universe such as stars and galaxies are formed from the primordial density fluctuations, which grow due to the instabilities of gravity.



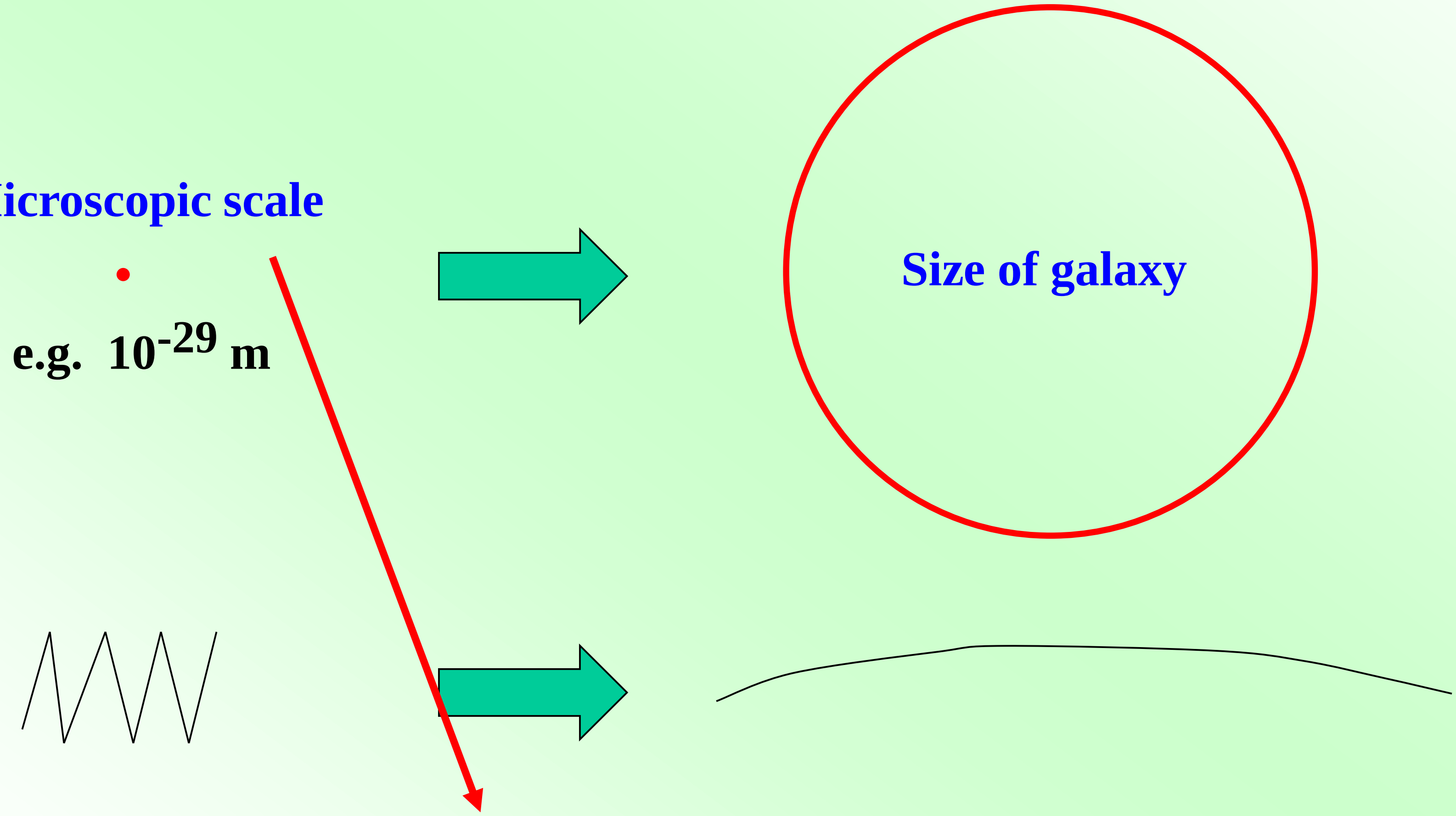
http://wwwmpa.mpa-garching.mpg.de/galform/data_vis/index.shtml#viewthreed

- How do you confirm the presence of such primordial density fluctuations ?

Generation of primordial perturbations

(Keys: vacuum, uncertainty principle)

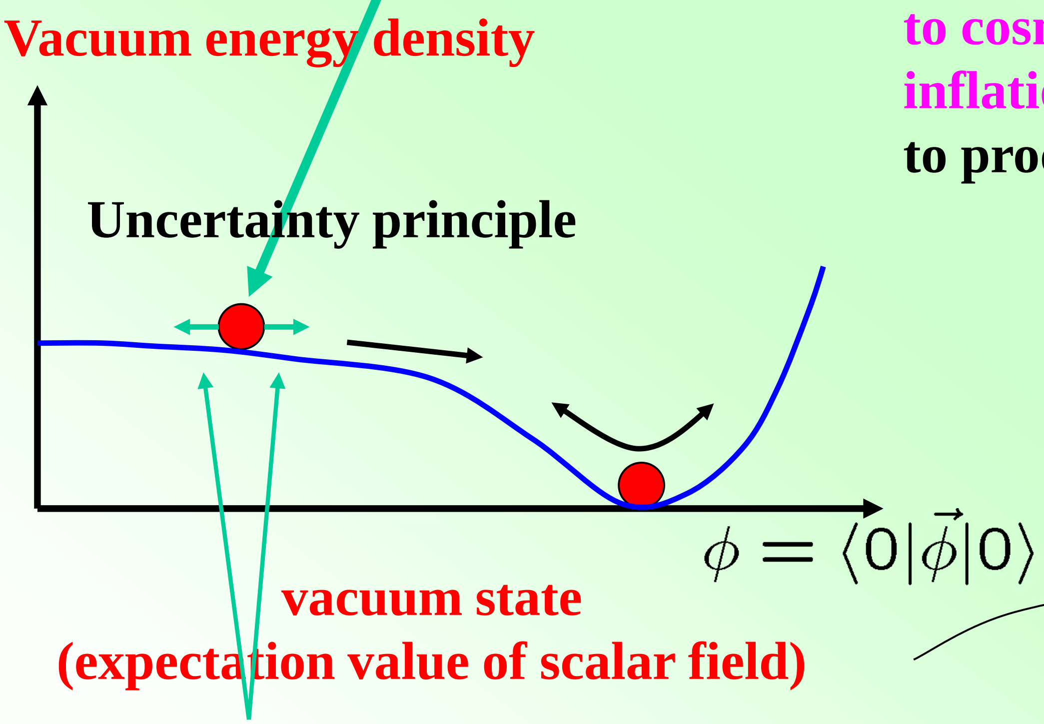
Inflation connects small scales to large scales.



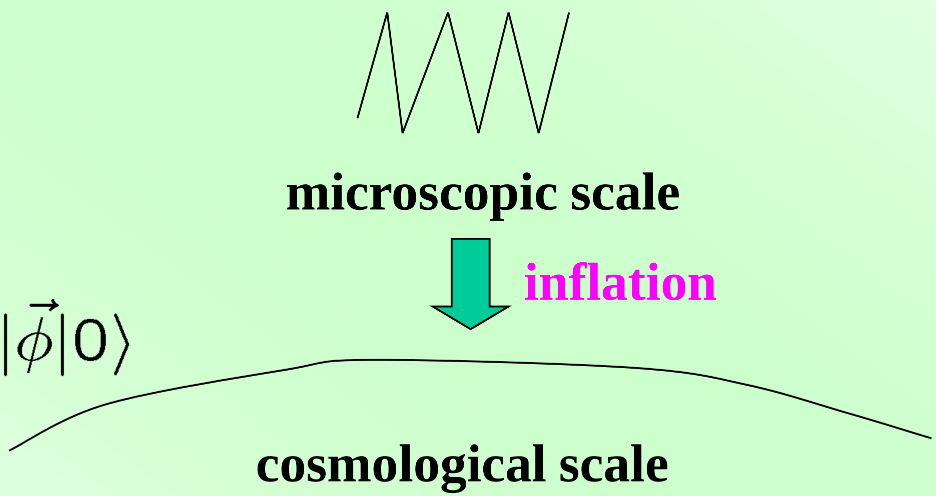
During inflation, quantum effects are very important.

Primordial density fluctuations

The position, φ, fluctuates quantum mechanically.

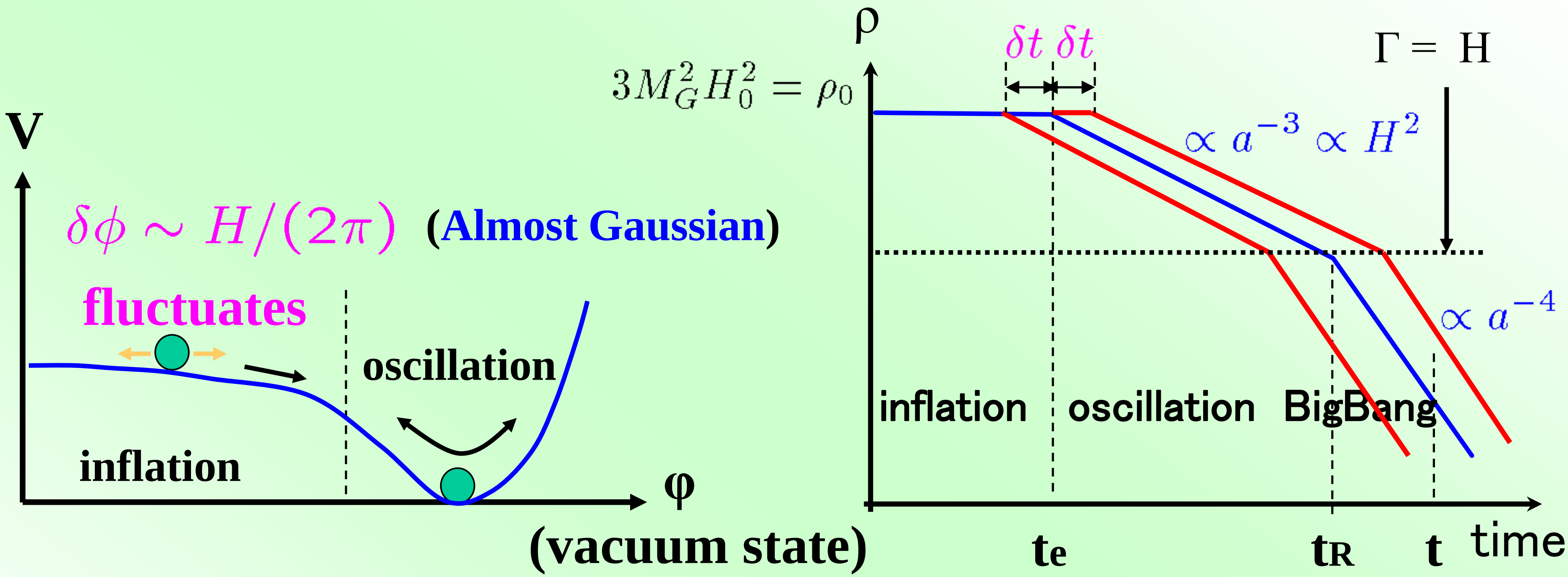


These quantum fluctuations are stretched to cosmological scales thanks to inflationary expansion, and become seeds to produce stars and galaxies.



How are these fluctuations transformed into density fluctuations ?

Primordial density fluctuations II



$$\delta\rho/\rho\Big|_{t_k} \sim \delta t/t \sim (\delta\phi/\dot{\phi})/H^{-1} \sim H^2/\dot{\phi}\Big|_{t_k^*}$$

Density fluctuation

$$\delta t(\boldsymbol{x}, t) = \frac{\delta\phi(\boldsymbol{x}, t)}{\dot{\phi}_{\rm cl}}$$

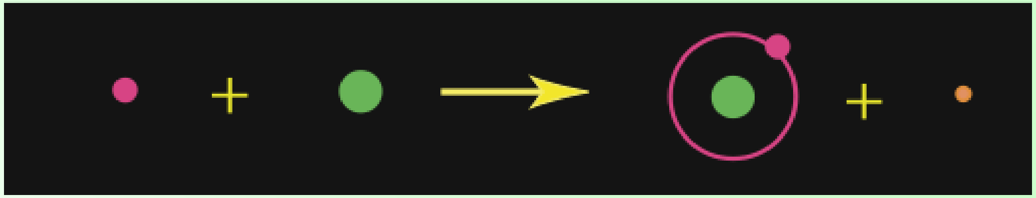
Almost scale invariant fluctuations are predicted.

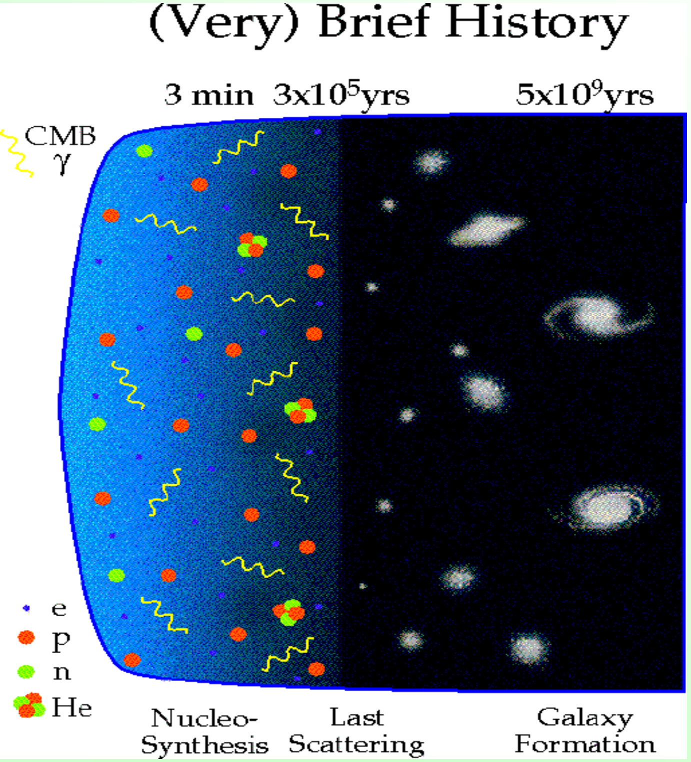
These primordial fluctuations generate cosmic microwave background anisotropies.

Recombination of electron

At T ~ 3000K (t ~ 3.8 x 10^5 years)

electron + proton ➔ hydrogen + photon





Photons can freely travel without being hindered by electrons.

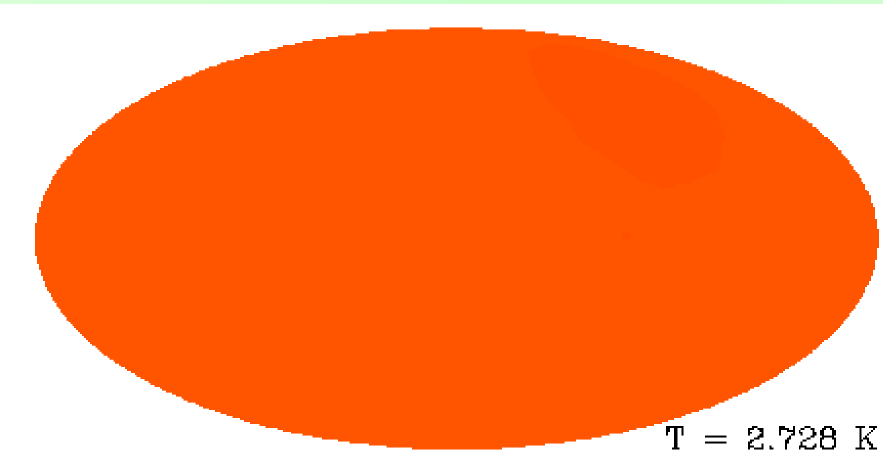
➔ We can observe such photons as cosmic microwave background radiation (CMBR).

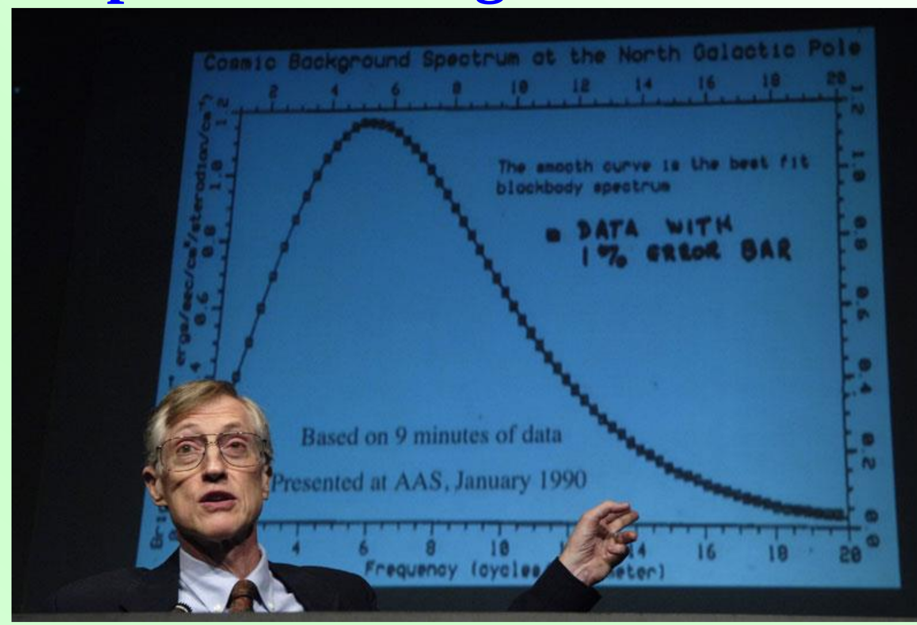
(This is the direct evidence that the Universe was hot in the past.)

Almost perfect blackbody

Our Universe was hot !!

Planck distribution with peak wavelength ~ 2mm

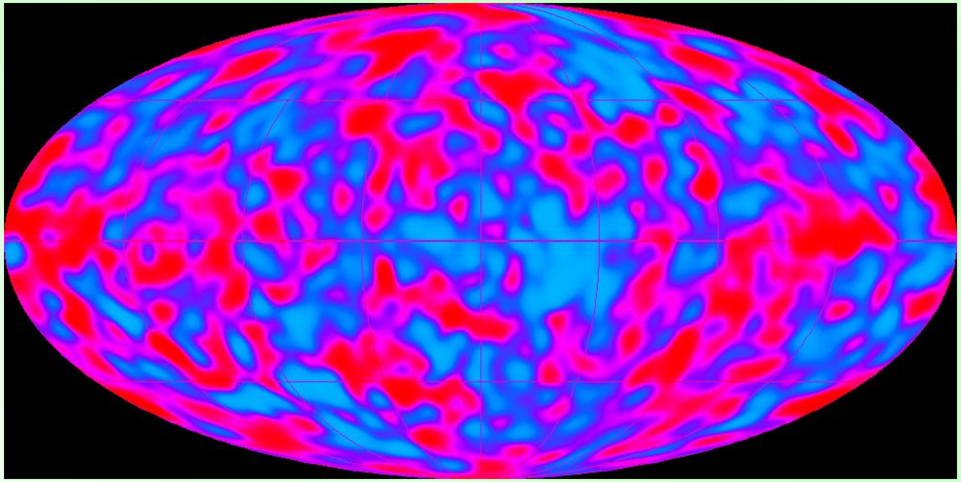


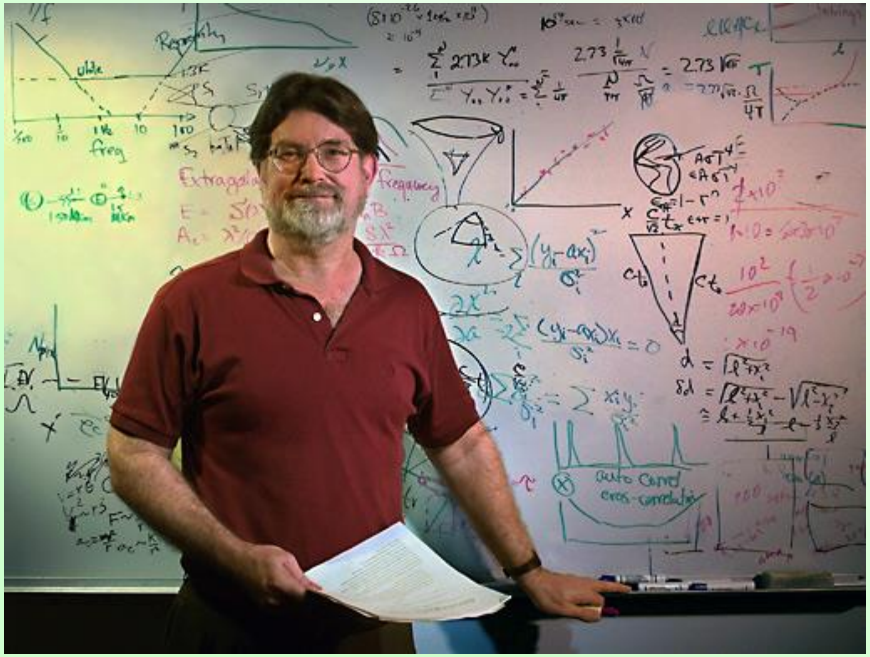


John C. Mather was awarded the Nobel Prize for Physics in 2006 !!

Almost perfect black body with 2.7K

Anisotropy of CMBR





Fluctuation with 10^{-5} order

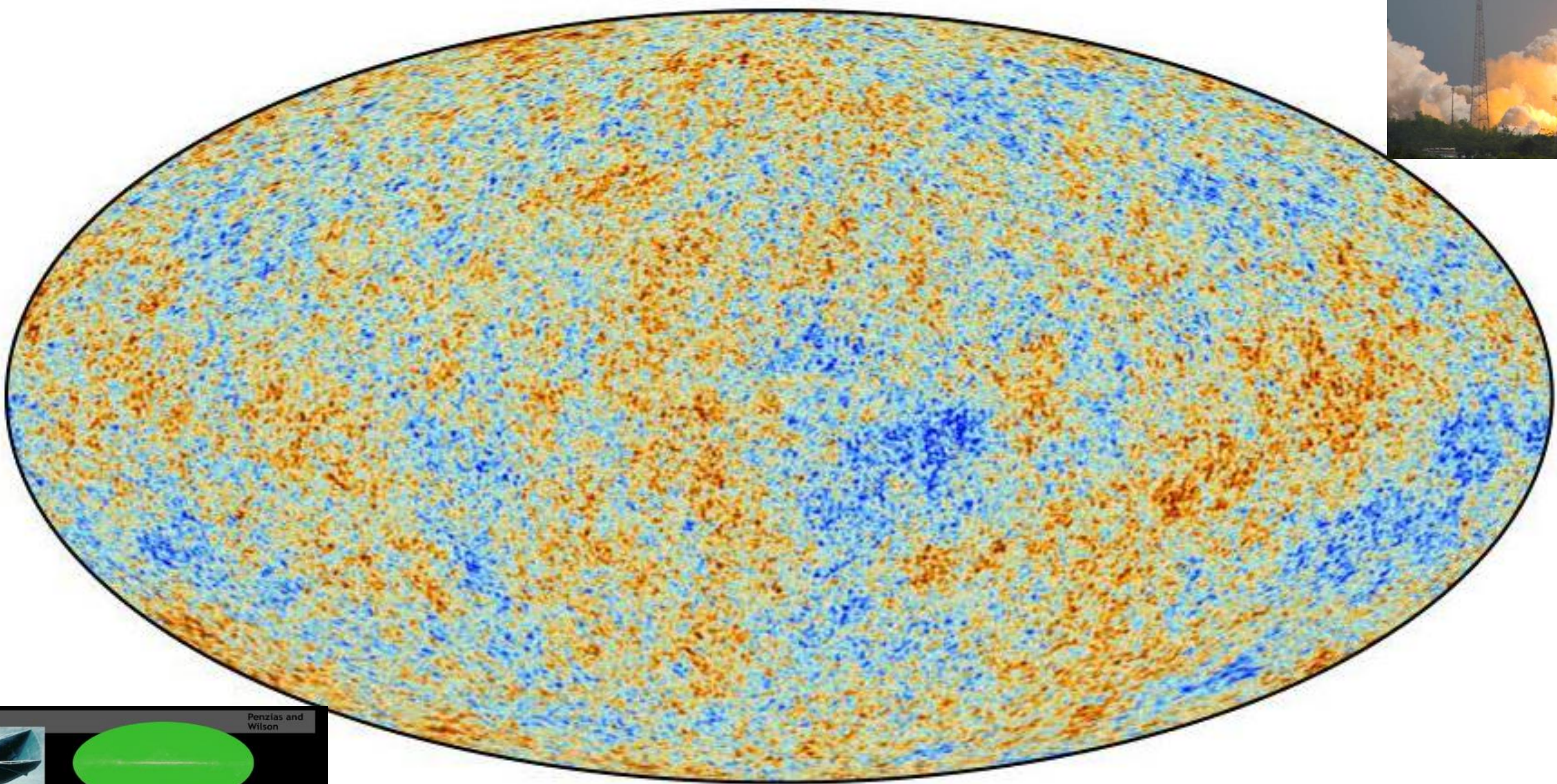
George F. Smoot was awarded the Nobel Prize for Physics in 2006 !!

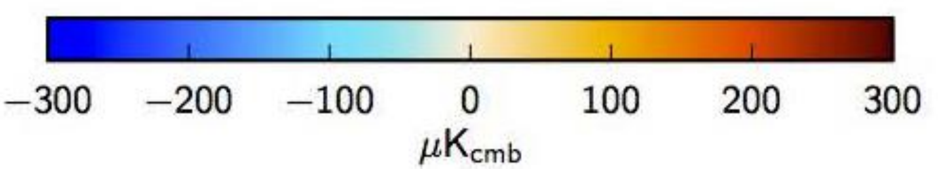
Anisotropies of CMBR are generated from primordial fluctuations. Stars and galaxies are formed from these small seeds of fluctuations.

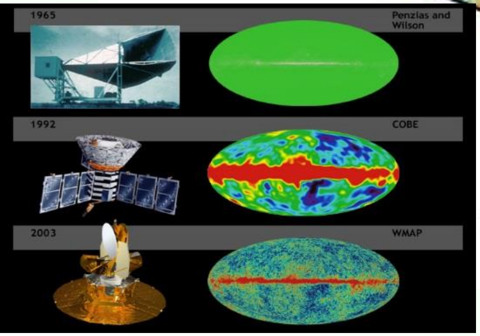
CMB MAP by PLANCK

Temperature anisotropy

Planck Collaboration: The *Planck* mission





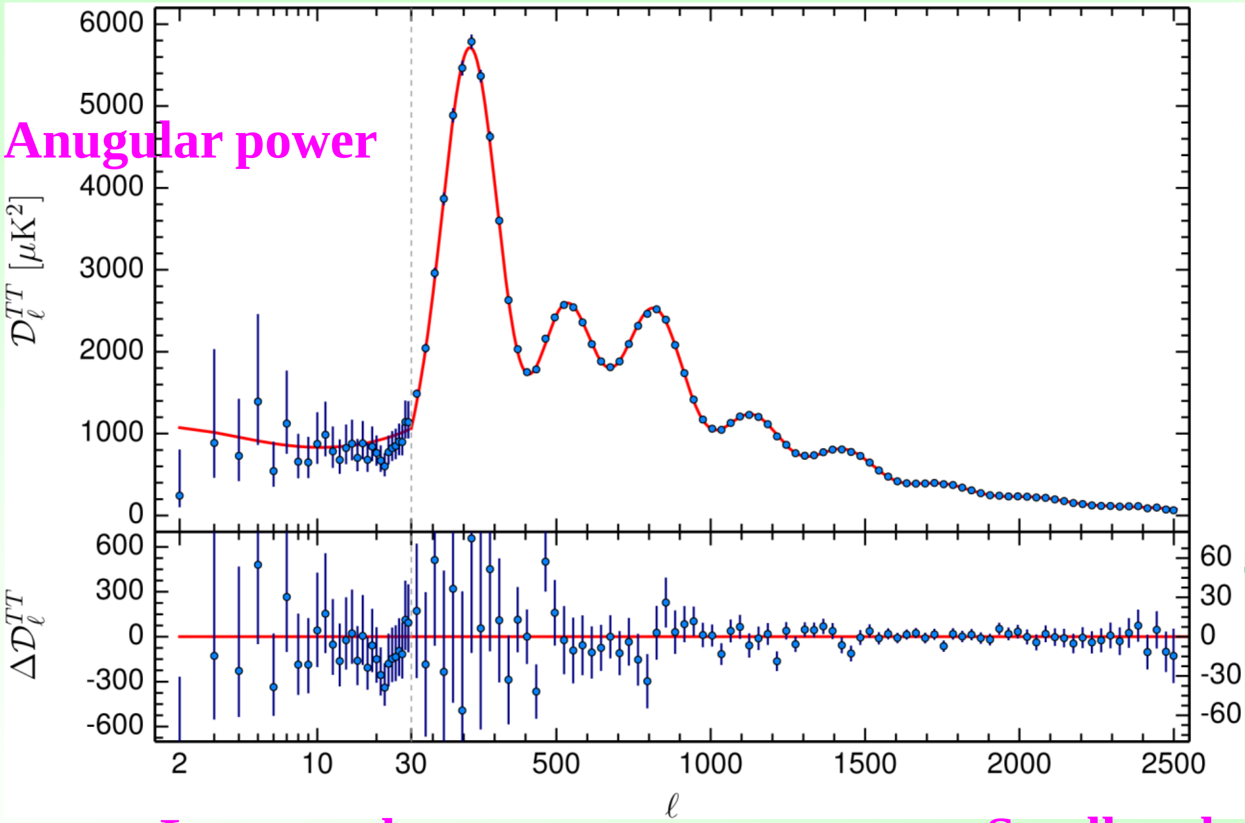


http://map.gsfc.nasa.gov/

Planck 2015 results. I
1502.01582

(Angular) powerspectrum of temperature fluctuations observed by PLANCK

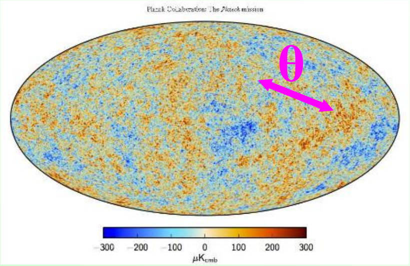
http://www.cosmos.esa.int/web/planck/picture-gallery



Anugular power

Large scale

Small scale



Angle θ~ 180° / l

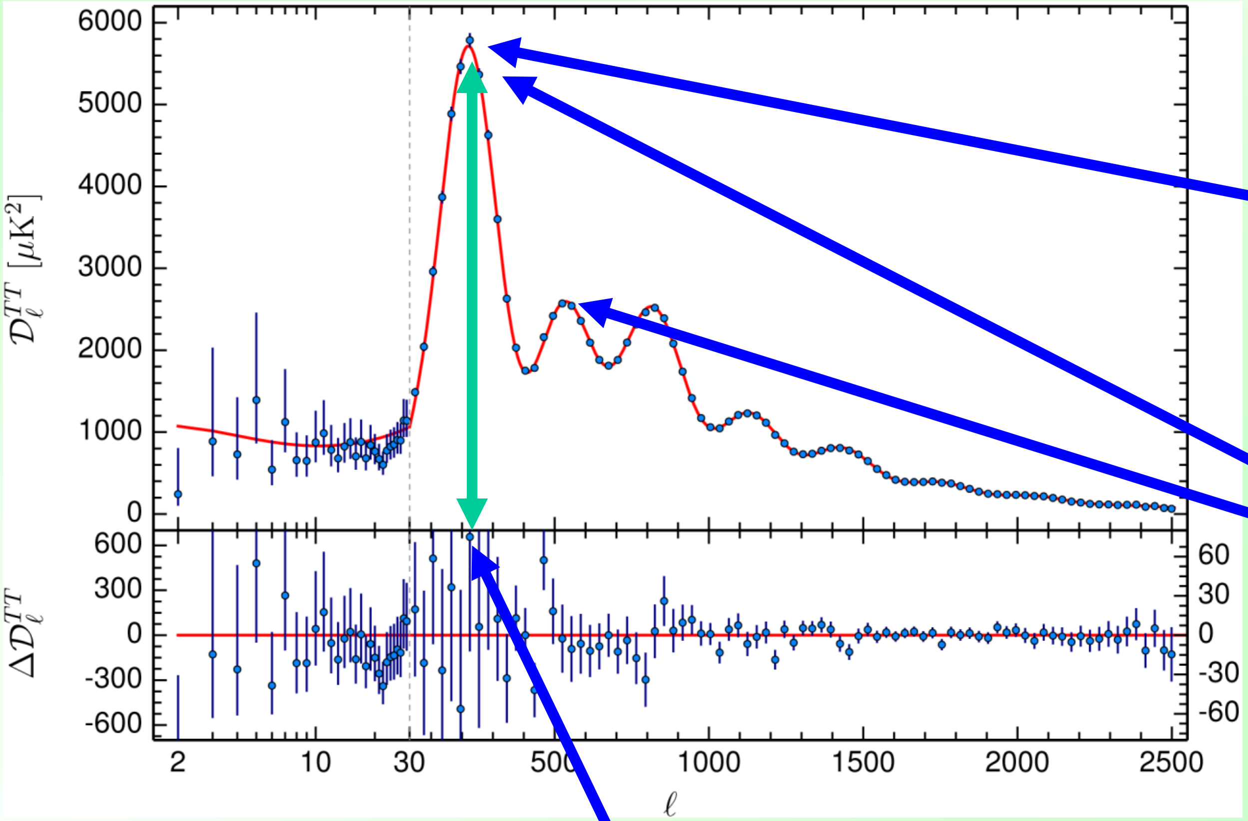
Red line : prediction by inflation

Blue points : observation by PLANCK

→ well consistent

$$\frac{\delta T}{T}(\theta, \varphi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta, \varphi), \quad \langle a_{l_1 m_1} a^*_{l_2 m_2} \rangle = C_{l_1} \delta_{l_1 l_2} \delta_{m_1 m_2}.$$

Parameter dependence



http://www.cosmos.esa.int/web/planck/picture-gallery

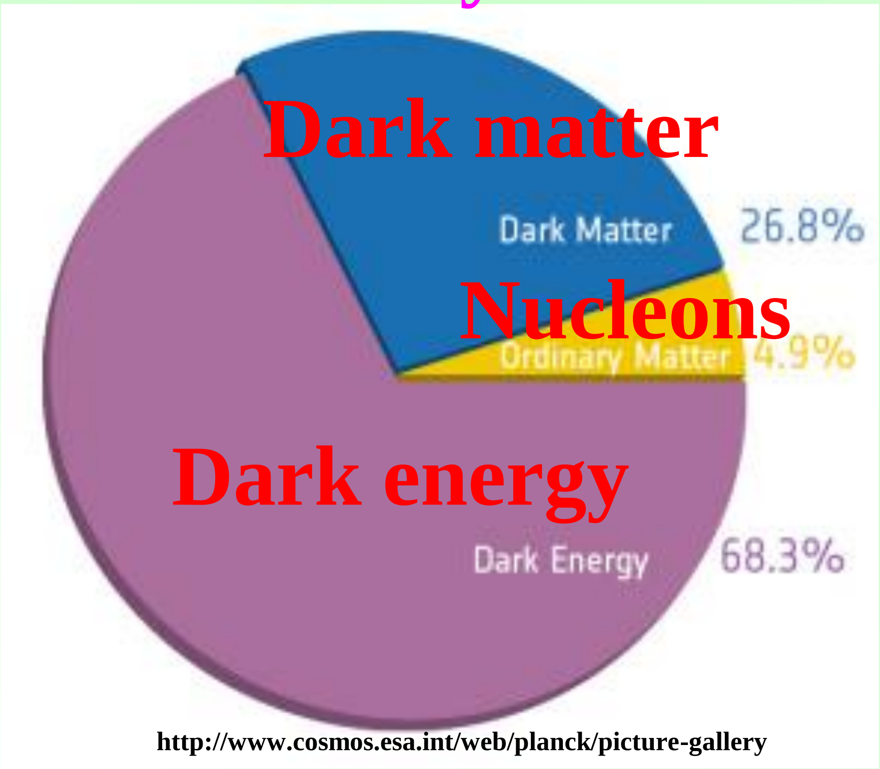
Abundance of dark matter

Abundance of nucleons

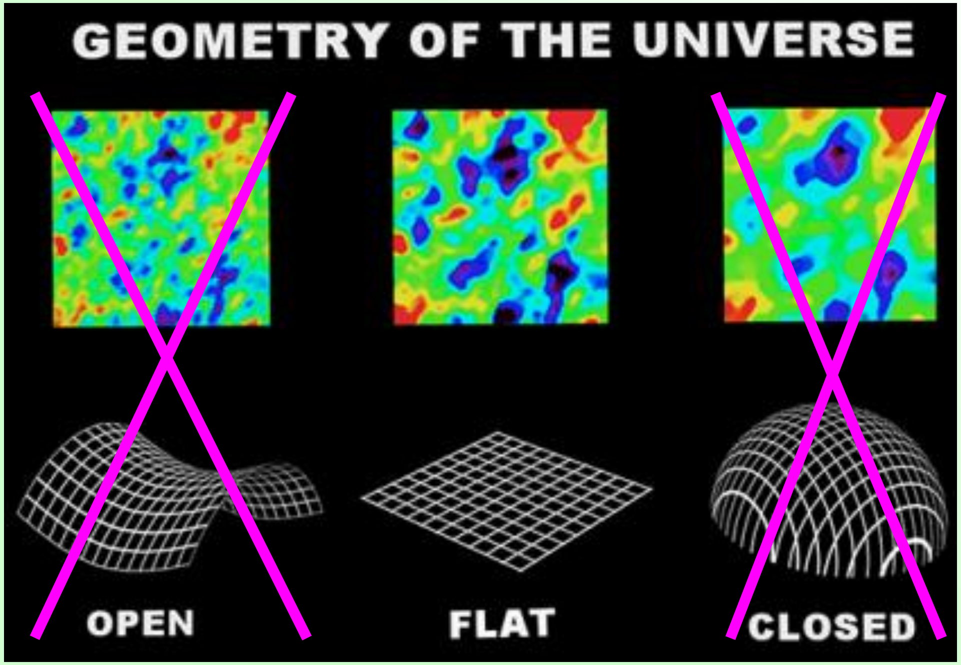
Total energy density ←→ Geometry of our Universe

Present state of our Universe

13.8 billion years old



http://phys.org/news/2014-09-geometry-universe.html



As predicted by inflation

We do not know the identification of more than 95% of content.

We do not know when inflation happened & which field caused inflation.

Summary

- **If we look back to the past of the Universe, it was in a hot and dense state called Big-Bang.**
- **Such a Big-Bang theory was strongly supported by observations such as (1) Hubble's expansion law, (2) cosmic microwave background, (3) light elements synthesis .**
- **However, it has several drawbacks, which were solved by inflation theory, in which the Universe rapidly expanded before Big-Bang (hot Universe).**
- **Our Universe has fruitful structure, which is formed from primordial perturbations through gravitational instabilities. Such primordial perturbations are generated as quantum fluctuations during inflation.**
- **The inflation theory is strongly supported by CMB observations.**

Unfortunately, nobody knows when inflation happened, what happened before inflation, and what is true beginning of the Universe.

We know the amount of matter contents of the Universe.
But, nobody knows
what they
(dark matter, dark energy) are.