

Introduction to Cosmology

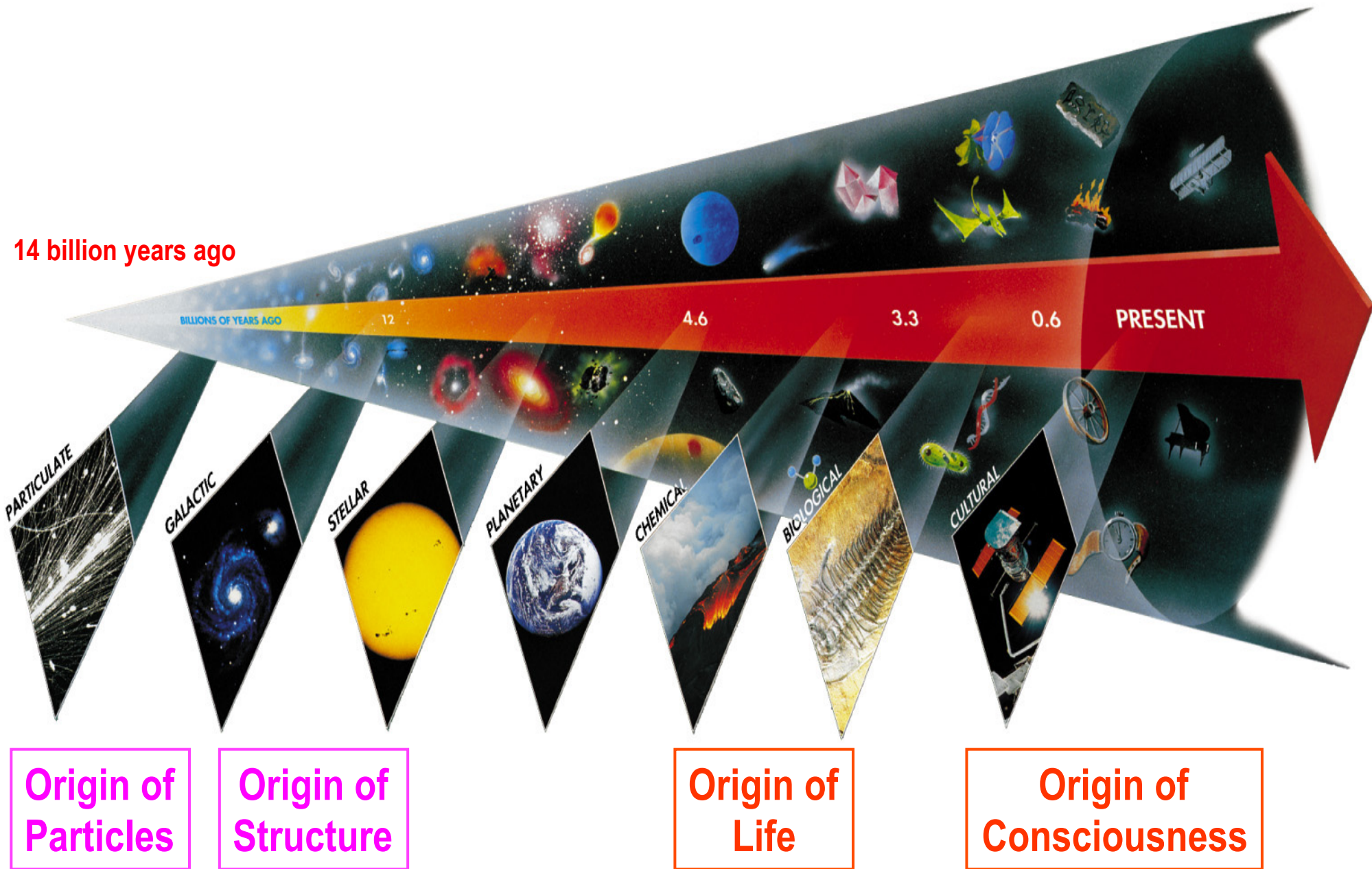
Katsushi Arisaka

*University of California, Los Angeles
Department of Physics and Astronomy*

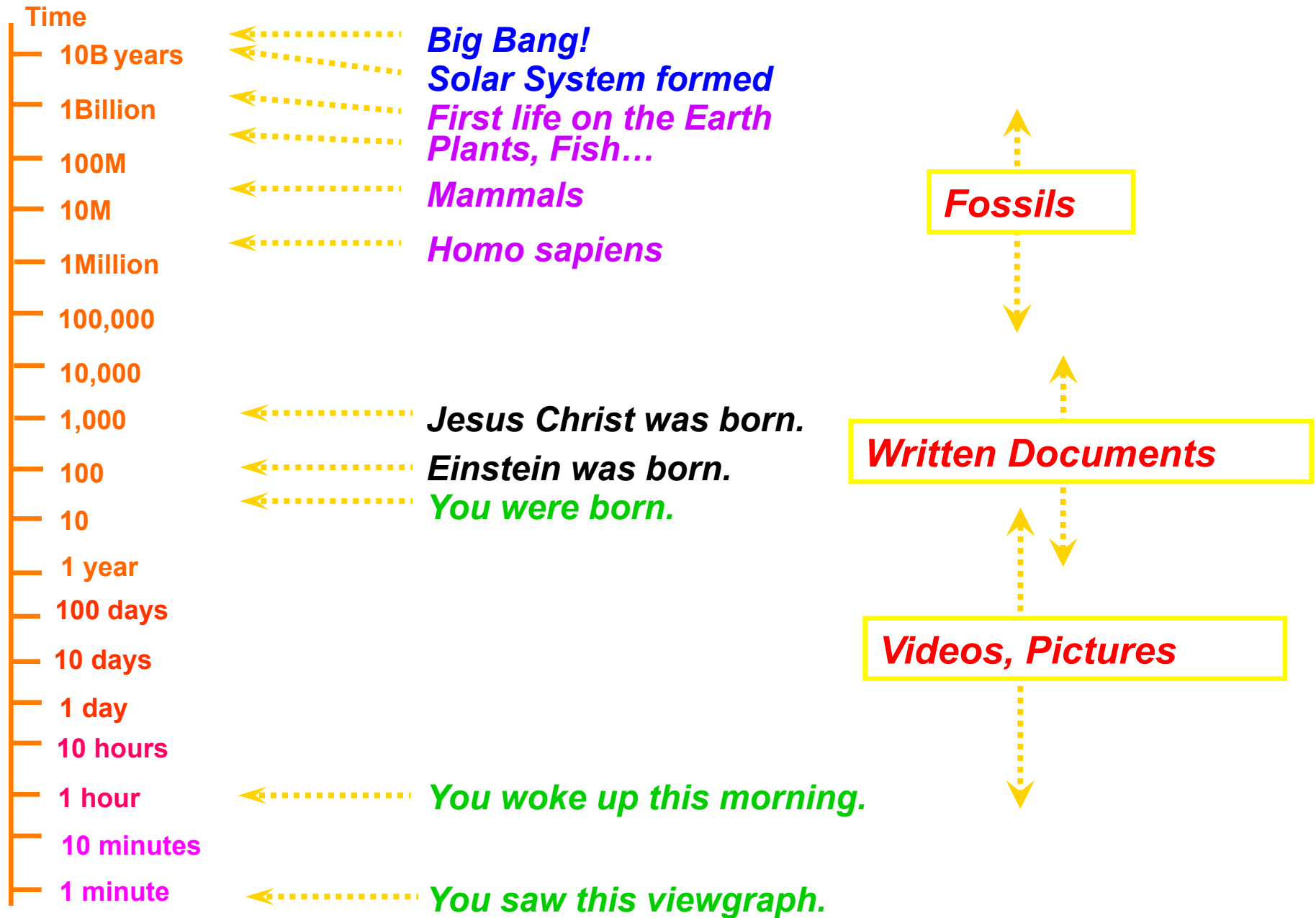
arisaka@physics.ucla.edu

Early Universe

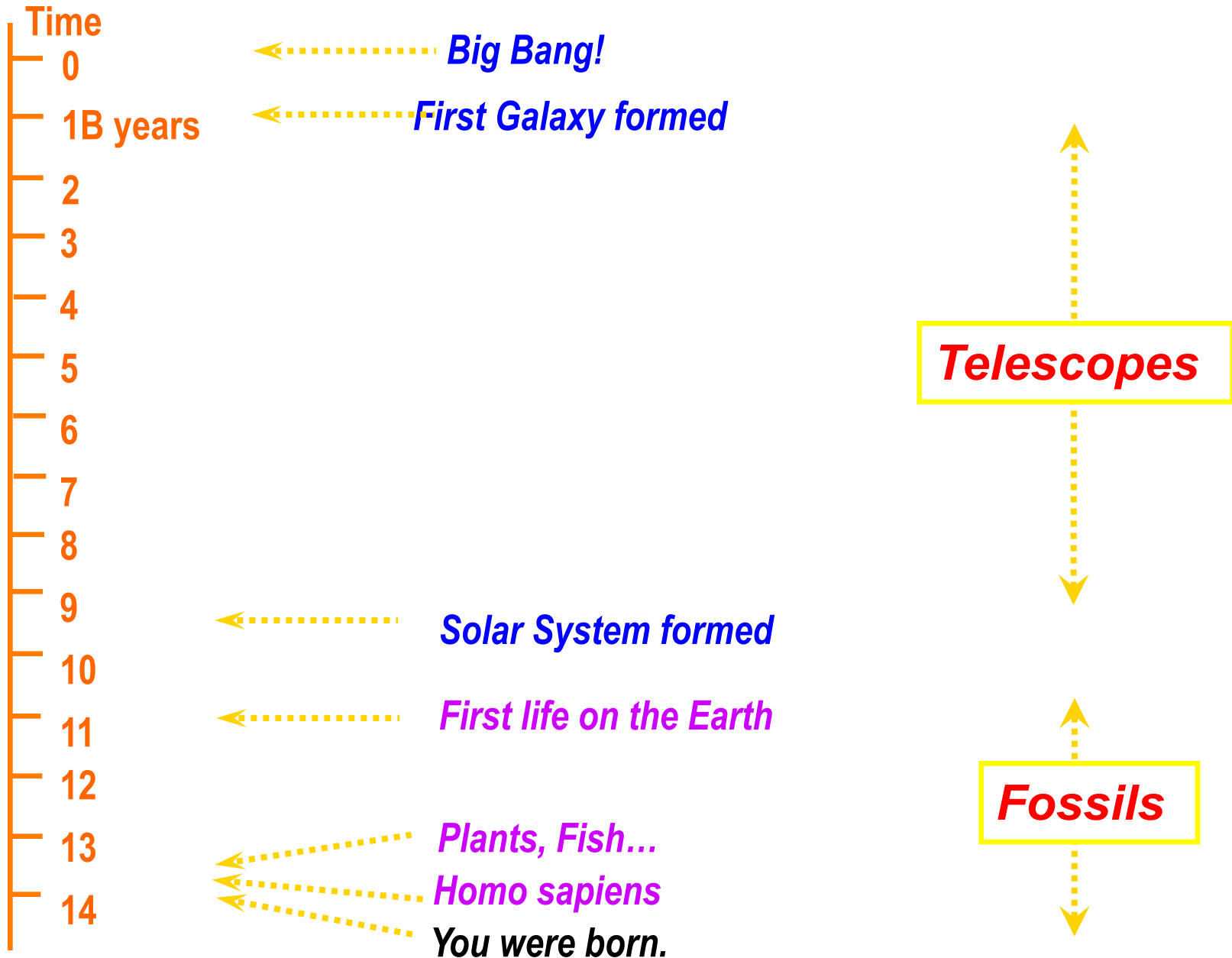
Seven Phases of Cosmic Evolution



History of Life and the Human beings



Brief History of Universe and Life





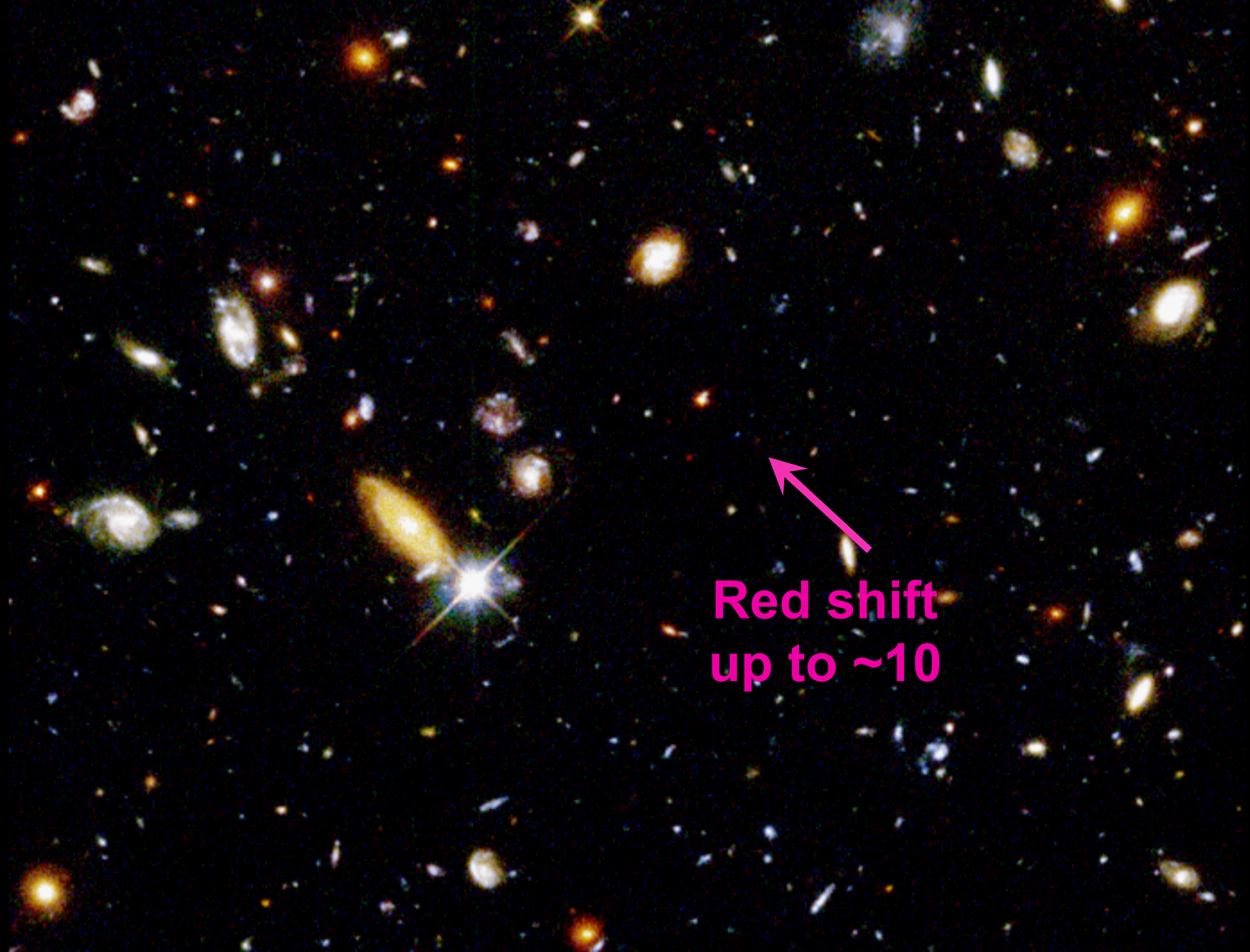
~100 Billions Stars in a Galaxy

ANDROMEDA
GALAXY.

Hubble Deep Field

The image displays a dense field of galaxies, including various types such as spirals, ellipticals, and irregular shapes, scattered across a dark background. The galaxies are concentrated in the central and lower-left regions, with some appearing as bright, distinct points of light and others as faint, diffuse structures. The overall appearance is that of a rich, multi-colored stellar population.

~100 Billion Galaxies

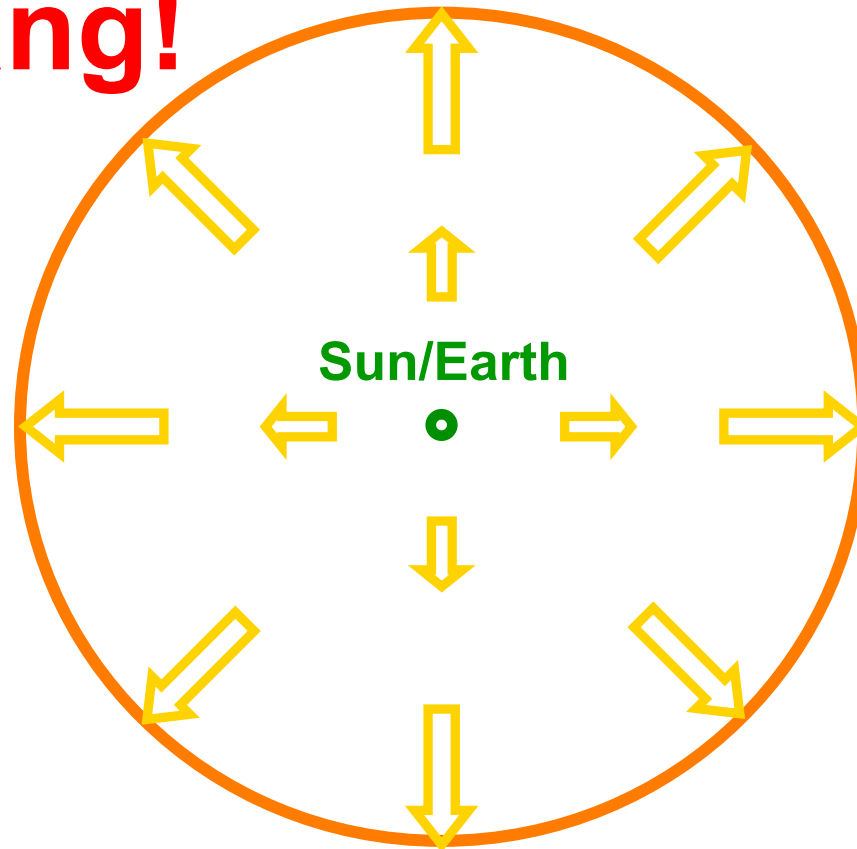


**Red shift
up to ~10**

Hubble's Law: Expansion of the Universe

Big Bang!

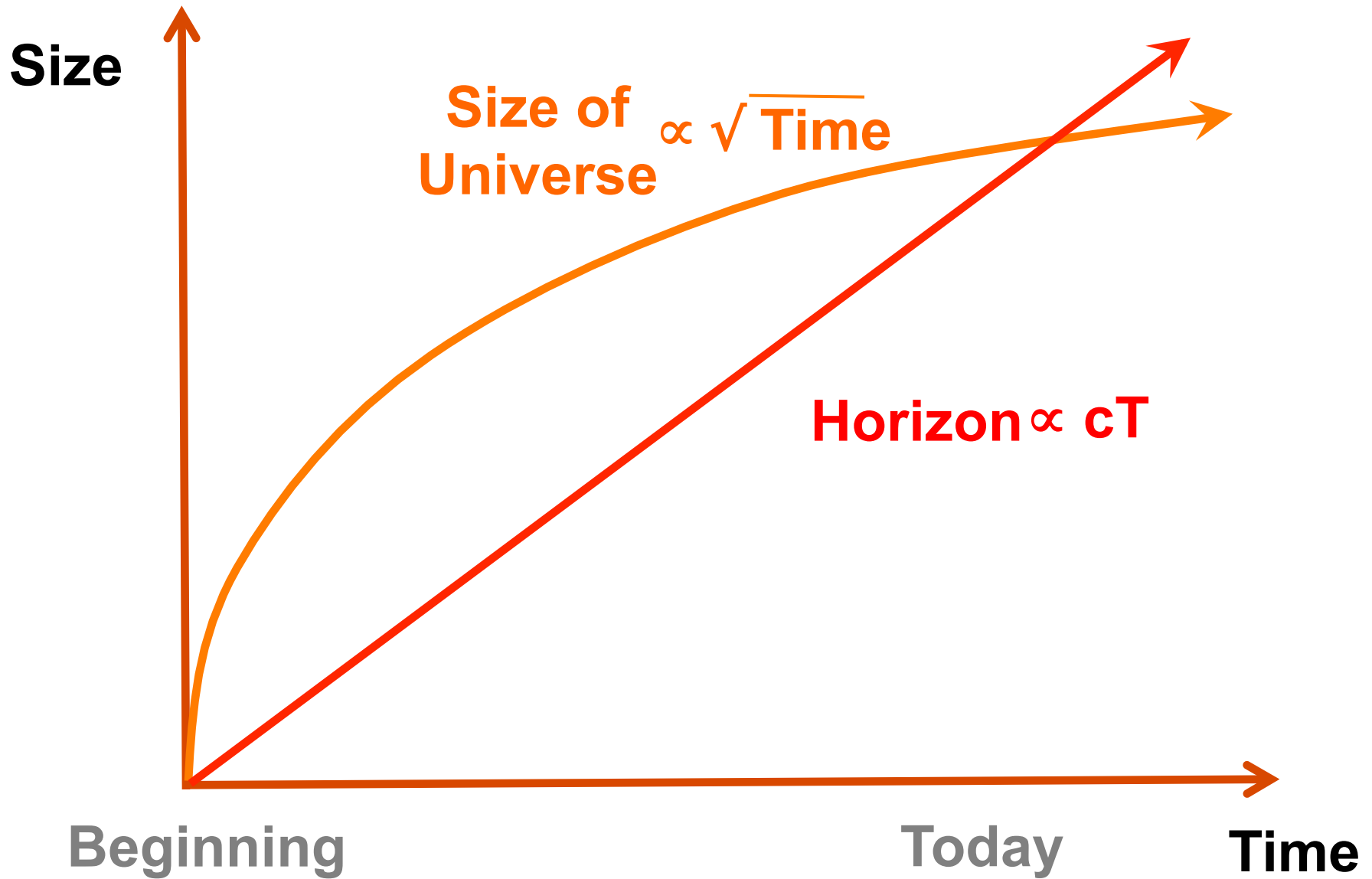
Horizon
of Universe



14 Billion
Light Years

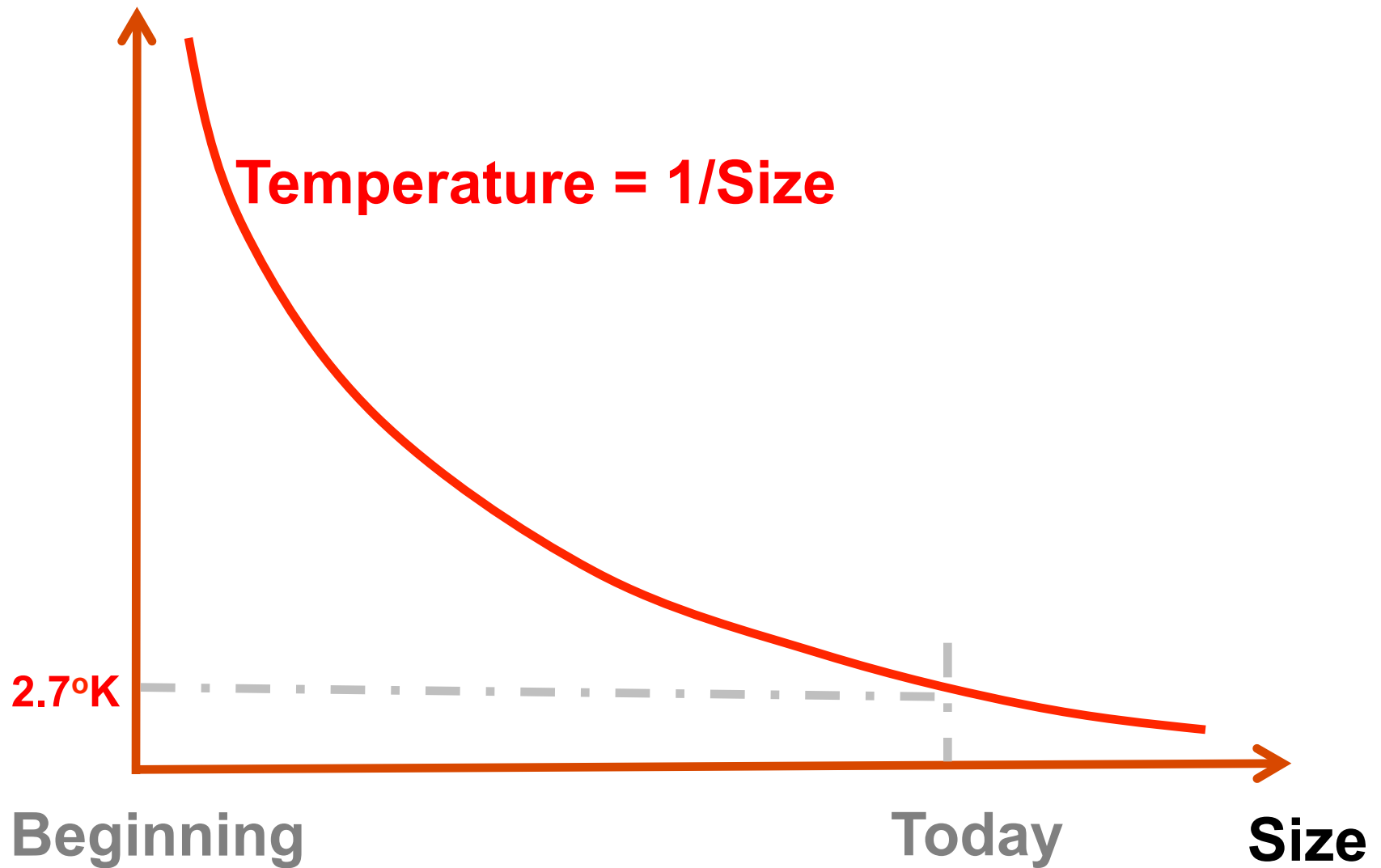
Moving Away
at Speed of Light

Expansion of Universe



Temperature of Universe

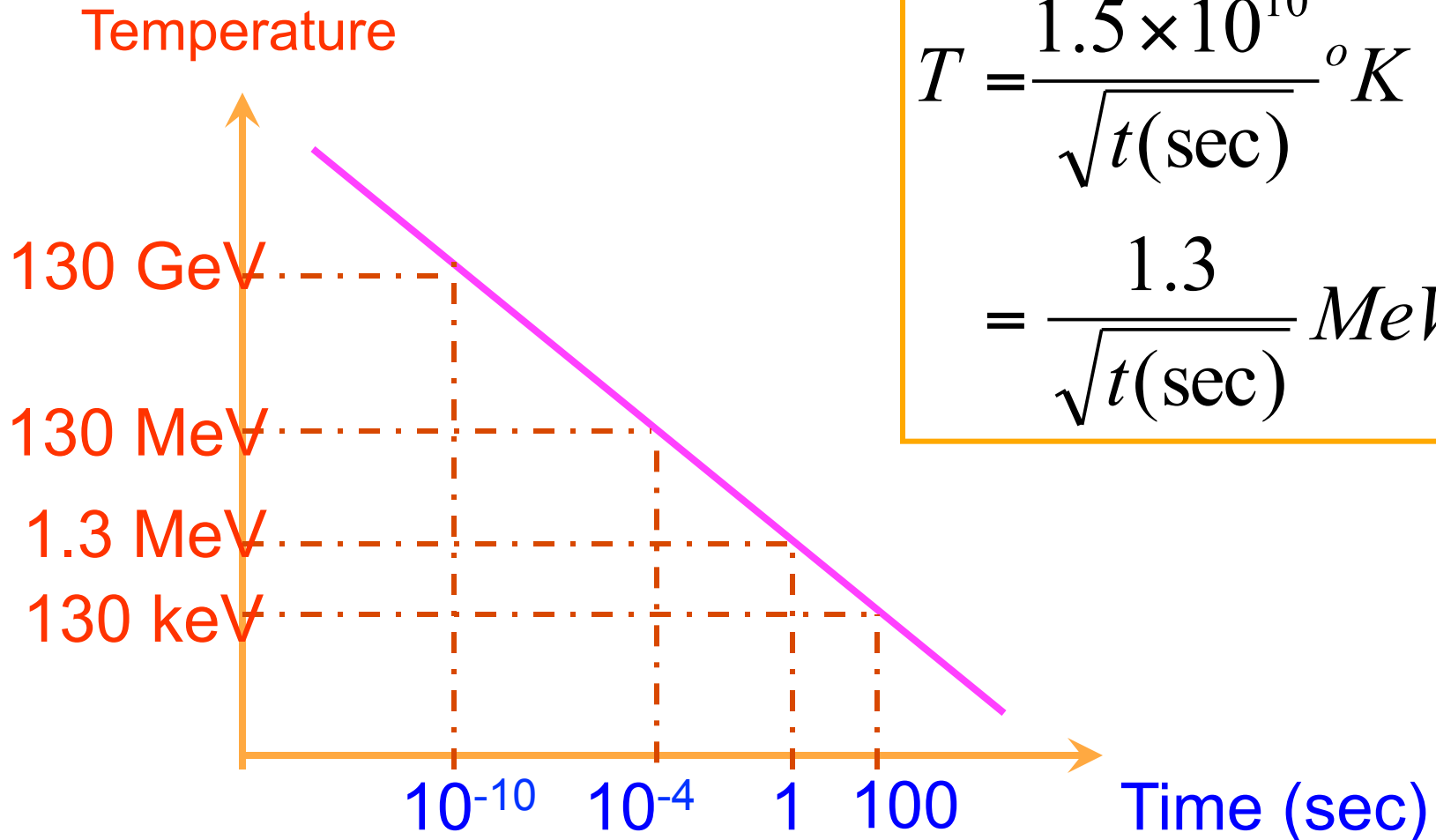
Temperature



Relation between Temperature and Time

T: Temperature

t : time



Thermal Equilibrium

- If thermal energy is greater than twice the mass of particles,

$$E > 2mc^2$$

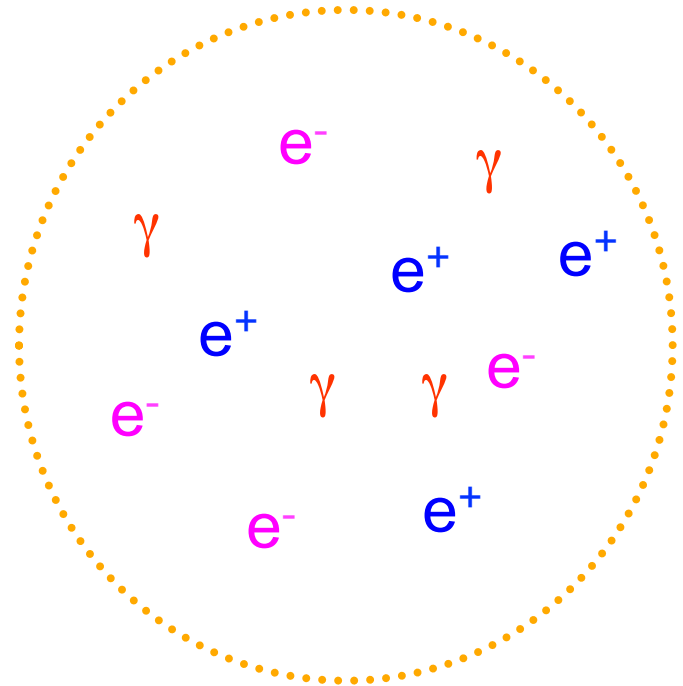
Photon \leftrightarrow Particle + Anti-particle

Example:

$$m_e = 0.511 \text{ MeV}$$

$$\text{if } E > 1.022 \text{ MeV}$$

$$\gamma \leftrightarrow e^- + e^+$$



Elementary Particles

		Fermion			Boson		
Charge						Charge	
+2/3	Quarks	<i>u</i> up	<i>c</i> charm	<i>t</i> top	γ photon	0	
		<i>d</i> down	<i>s</i> strange	<i>b</i> bottom			
-1/3	Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	<i>Z</i> Z boson	0	
0		<i>e</i> electron	μ muon	τ tau	<i>W</i> W boson	0	
-1						± 1	
		I	II	III			
		Three Families of Matter					

+ Anti-particles

Elementary Particles and Forces

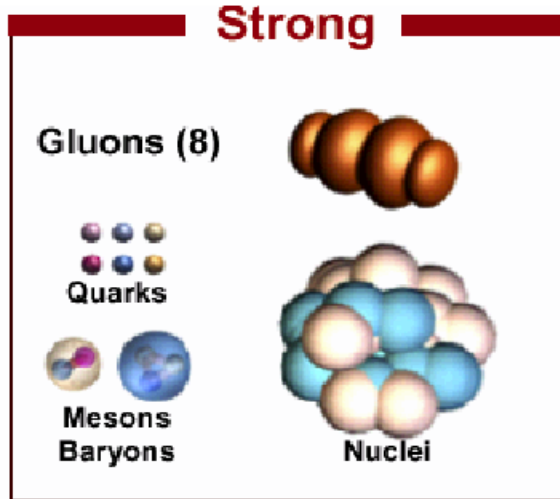
Strong

Gluons (8)

Quarks

Mesons
Baryons

Nuclei

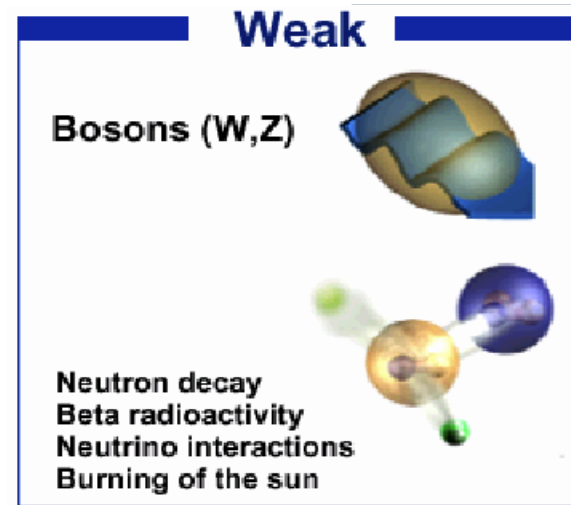
The diagram for the strong force shows various components. At the top, there are eight orange spheres representing gluons. Below them are six small spheres in two rows of three, representing quarks. Further down are two larger spheres, one with two smaller spheres inside, representing mesons and baryons. At the bottom is a large cluster of many spheres representing a nucleus.

1

Weak

Bosons (W,Z)

Neutron decay
Beta radioactivity
Neutrino interactions
Burning of the sun

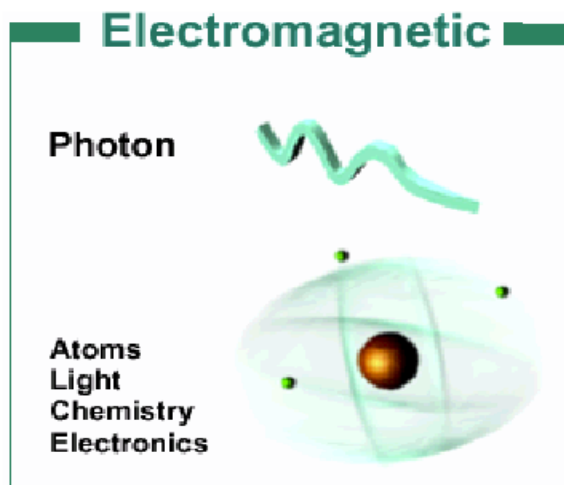
The diagram for the weak force shows two large, complex structures representing W and Z bosons. Below them is a diagram of a neutron decaying into a proton and an electron, with a neutrino also shown, illustrating beta radioactivity.

10^{-13}

Electromagnetic

Photon

Atoms
Light
Chemistry
Electronics

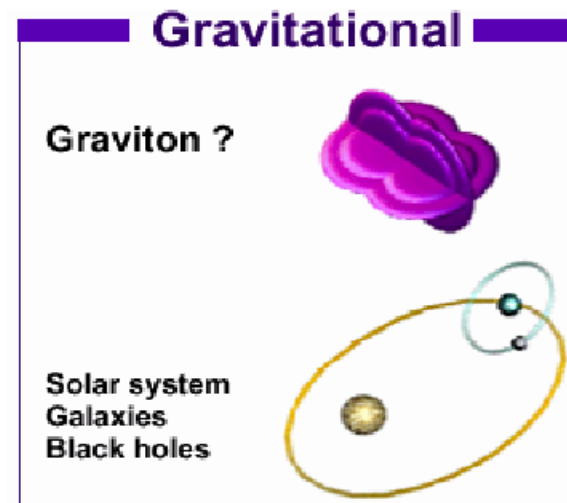
The diagram for the electromagnetic force shows a wavy green line representing a photon. Below it is a diagram of an atom with a central nucleus and several electrons orbiting it.

10^{-2}

Gravitational

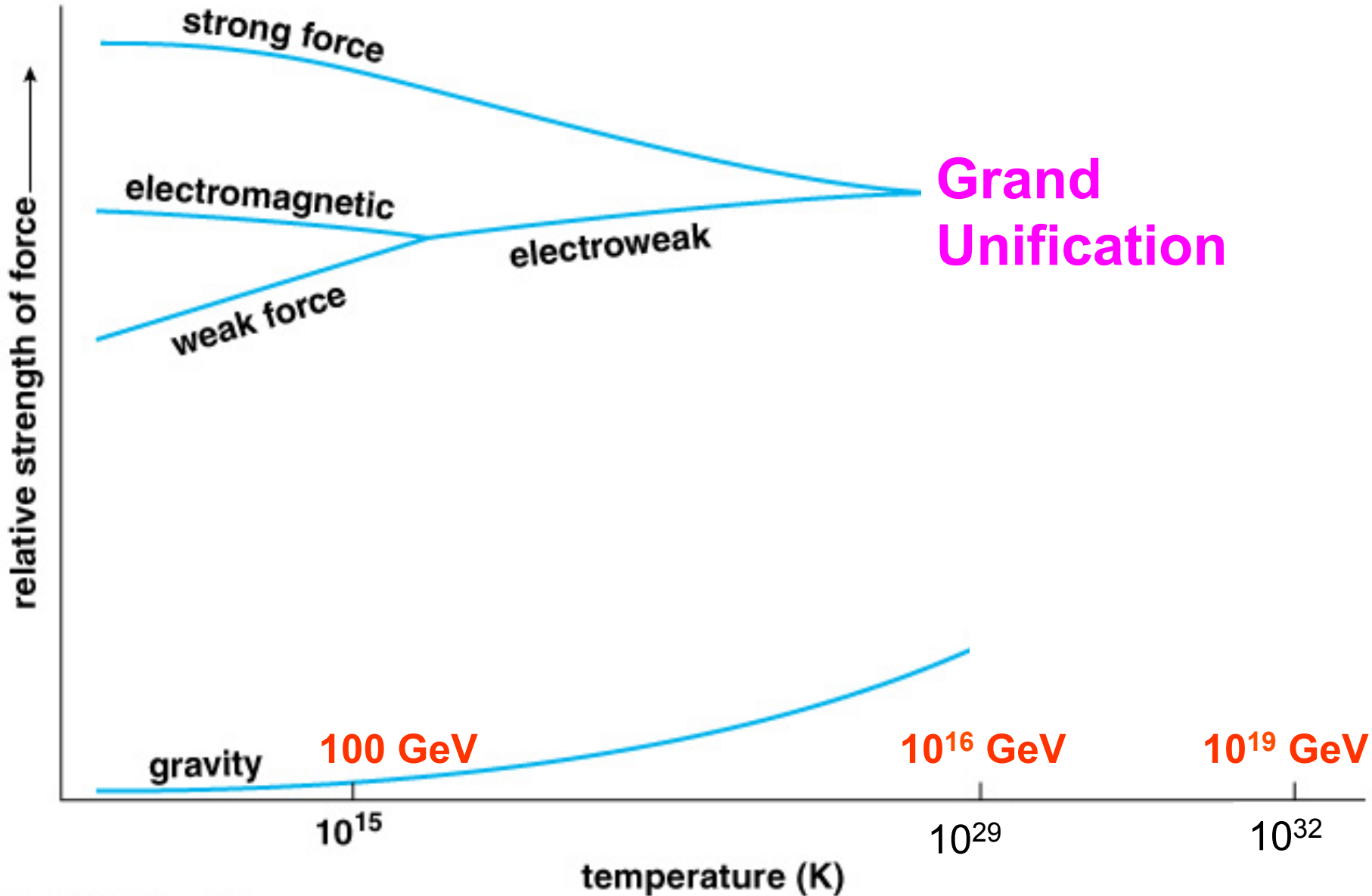
Graviton ?

Solar system
Galaxies
Black holes

The diagram for the gravitational force shows a purple, cloud-like structure representing a graviton. Below it is a diagram of a solar system with a central star and several planets orbiting it.

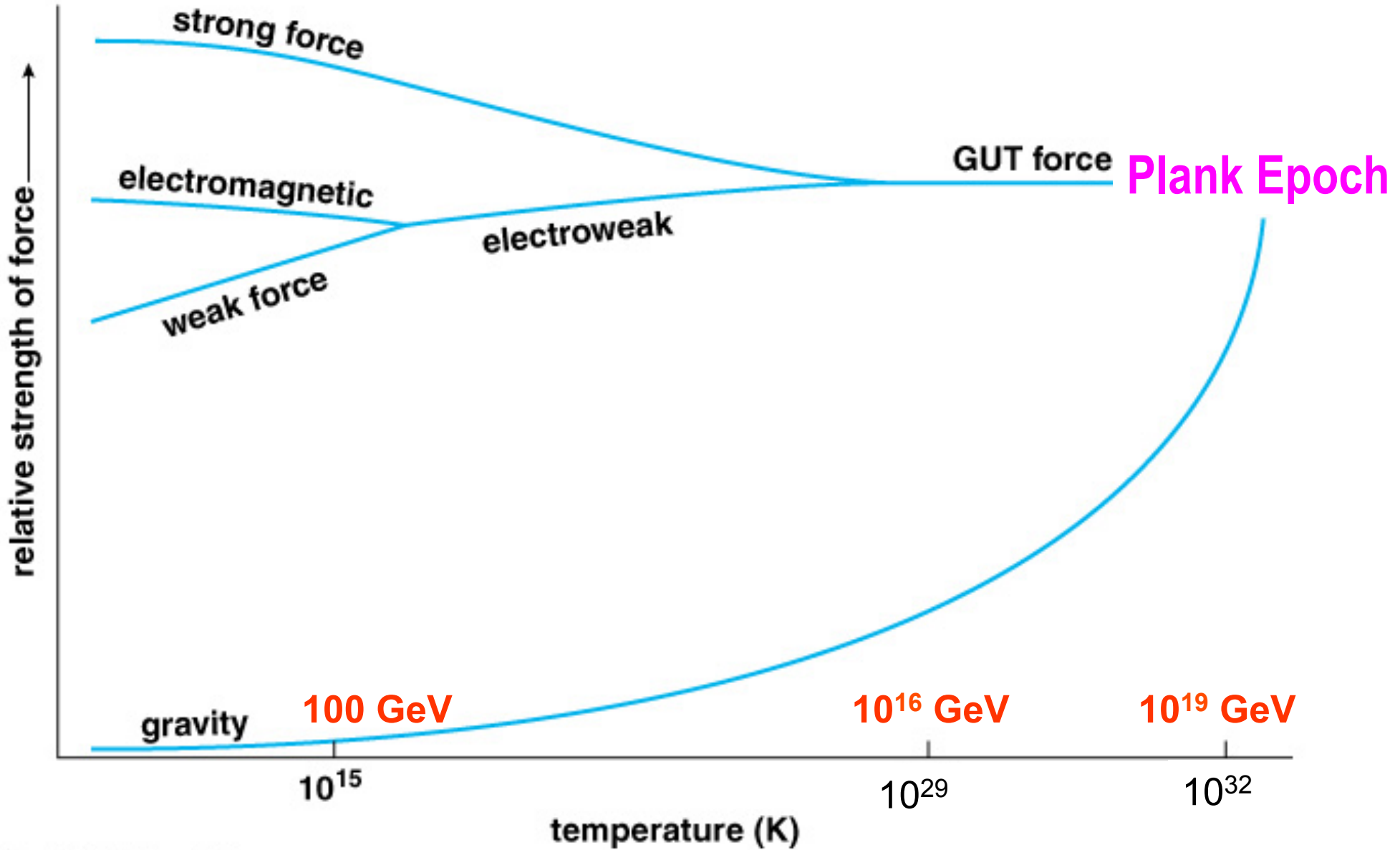
10^{-38}

Unification of Forces (1980)



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Unification of Forces (1980)



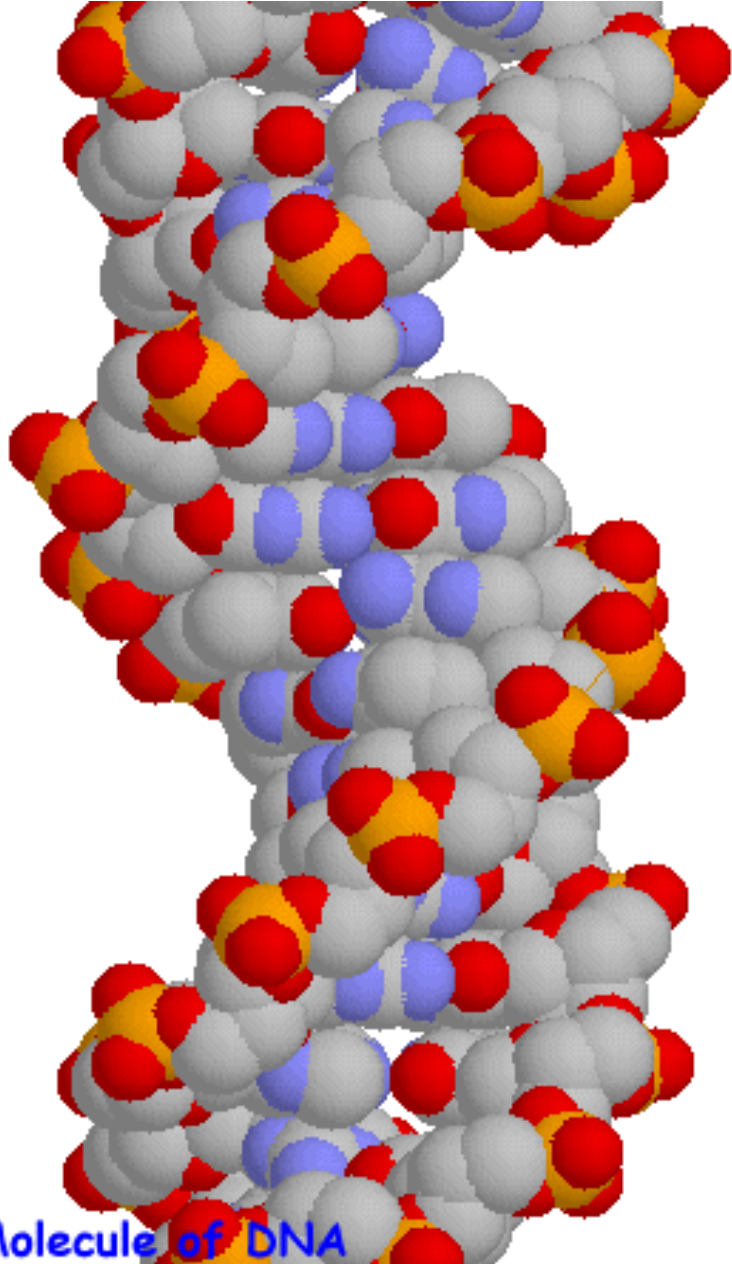
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Physicists' View of Early Universe

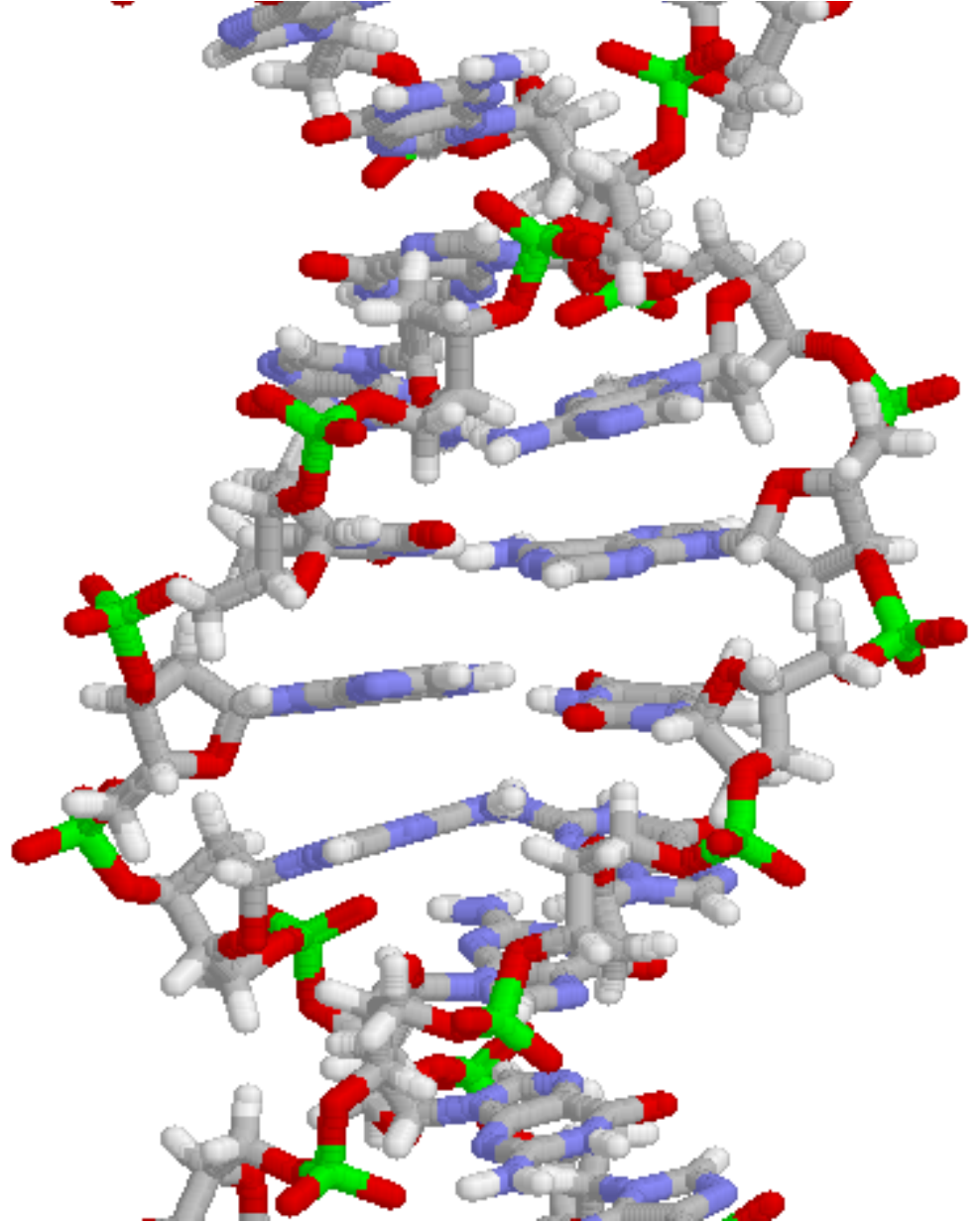
Lorentz Invariance

Local Gauge Invariance

Structure of DNA

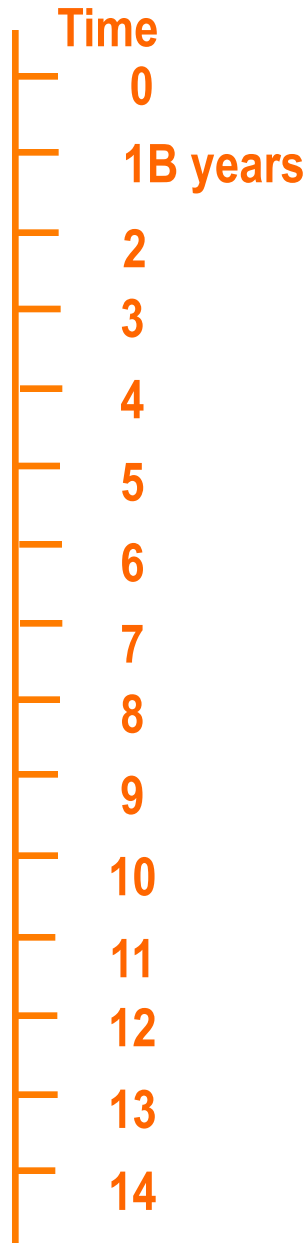


©Rothamsted Experimental Station, 1997, 1998



Molecule of DNA

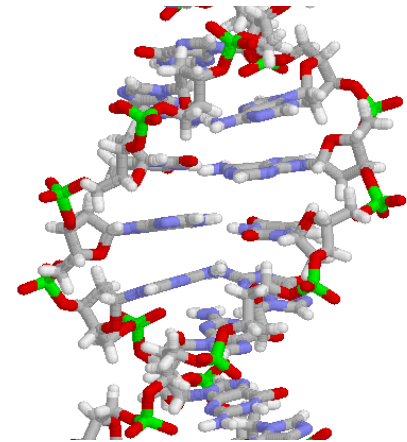
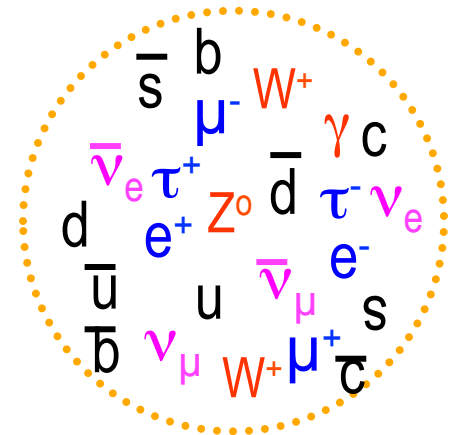
Symmetry Breaking



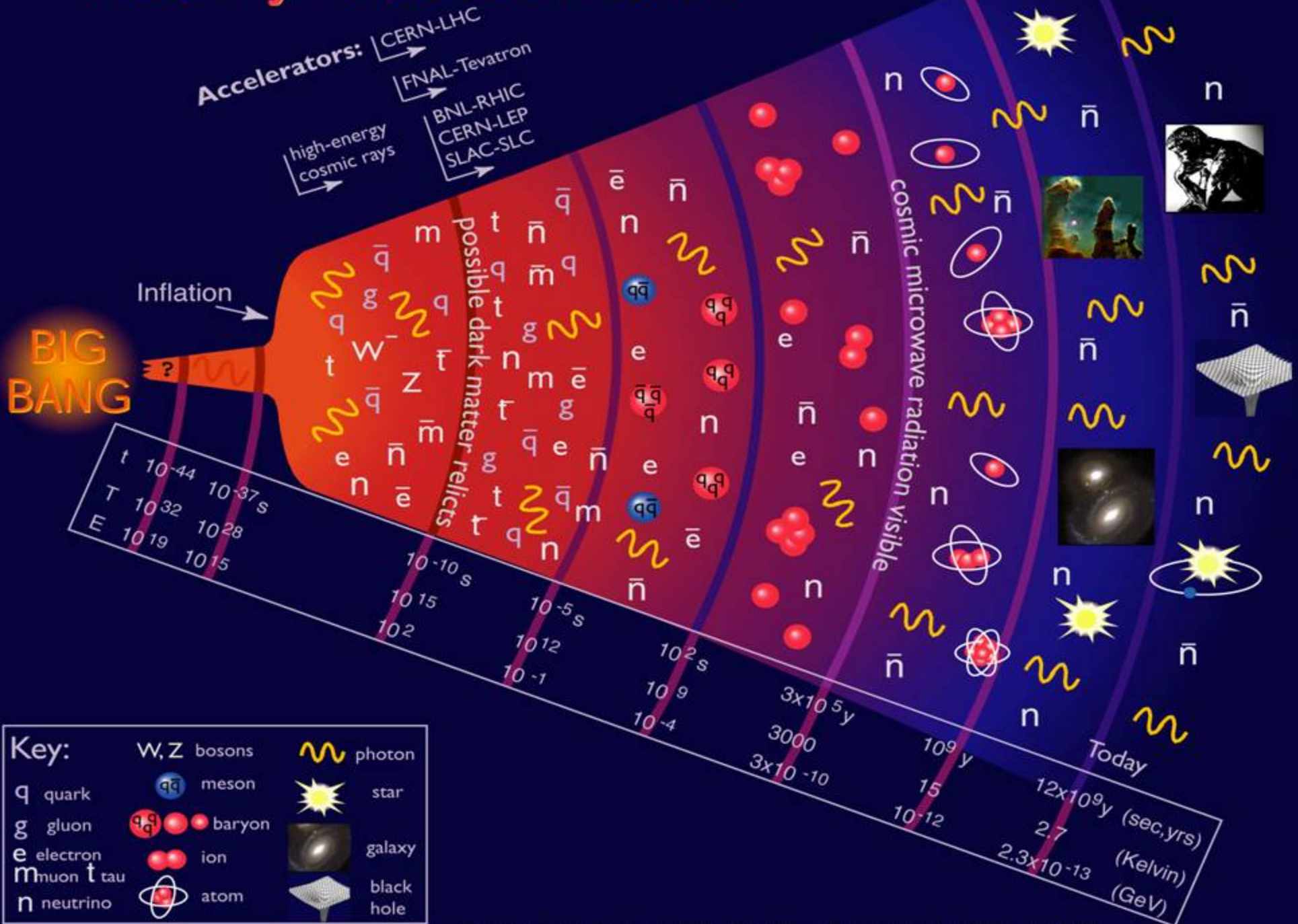
Simple

*Symmetry
Break Down*

Complex

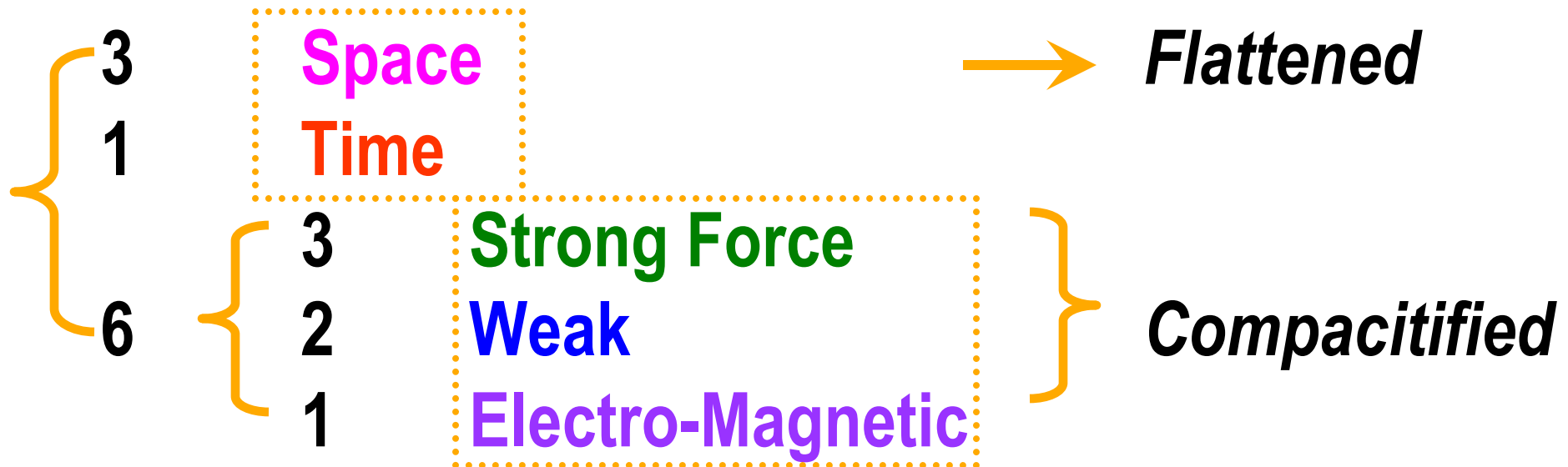


History of the Universe



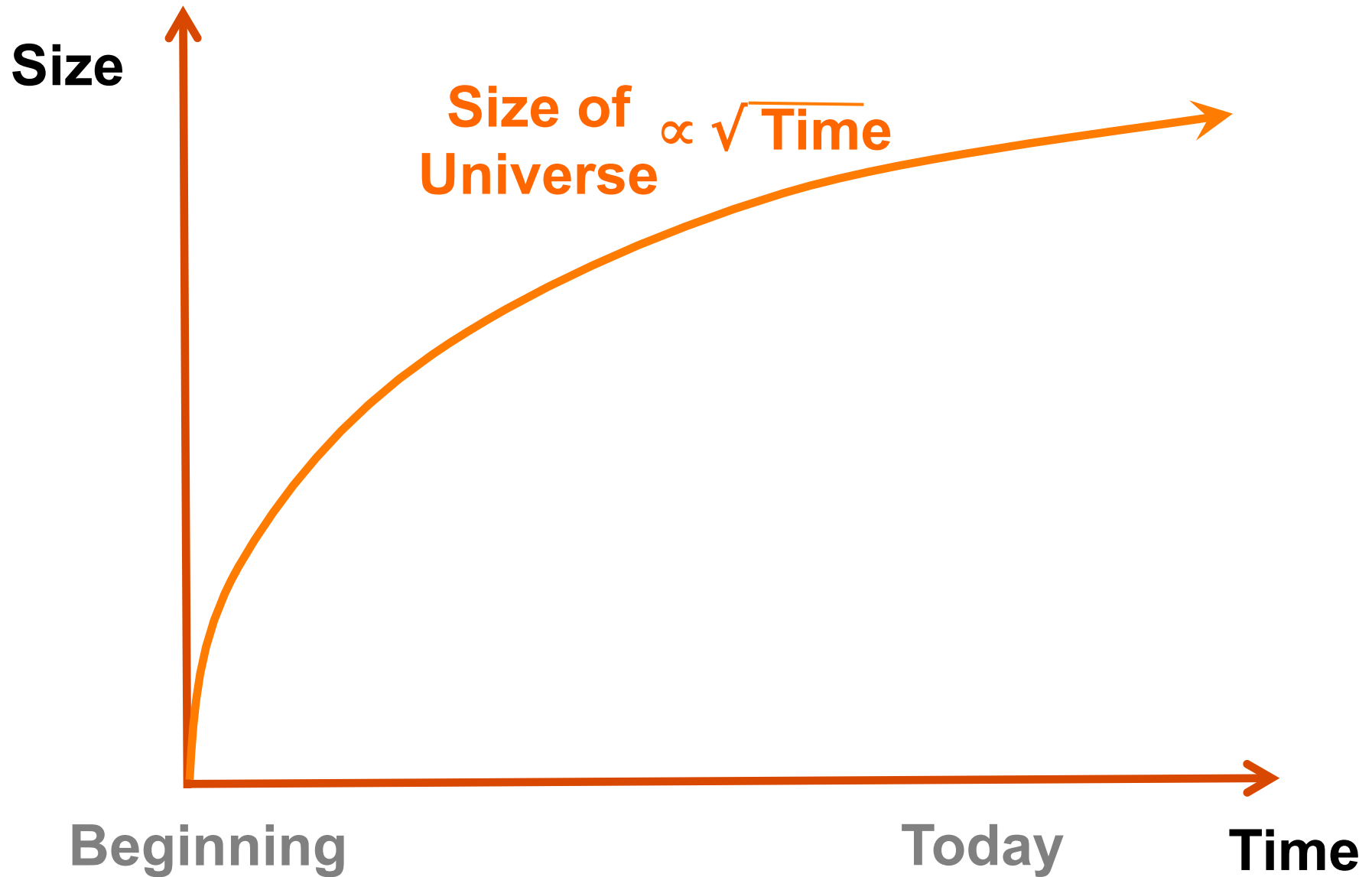
The Beginning

- Everything was the same \leftrightarrow Perfect symmetry.
 - All the particles are the same as photons.
 - All four forces are the same.
- The Universe was 10 dimension.

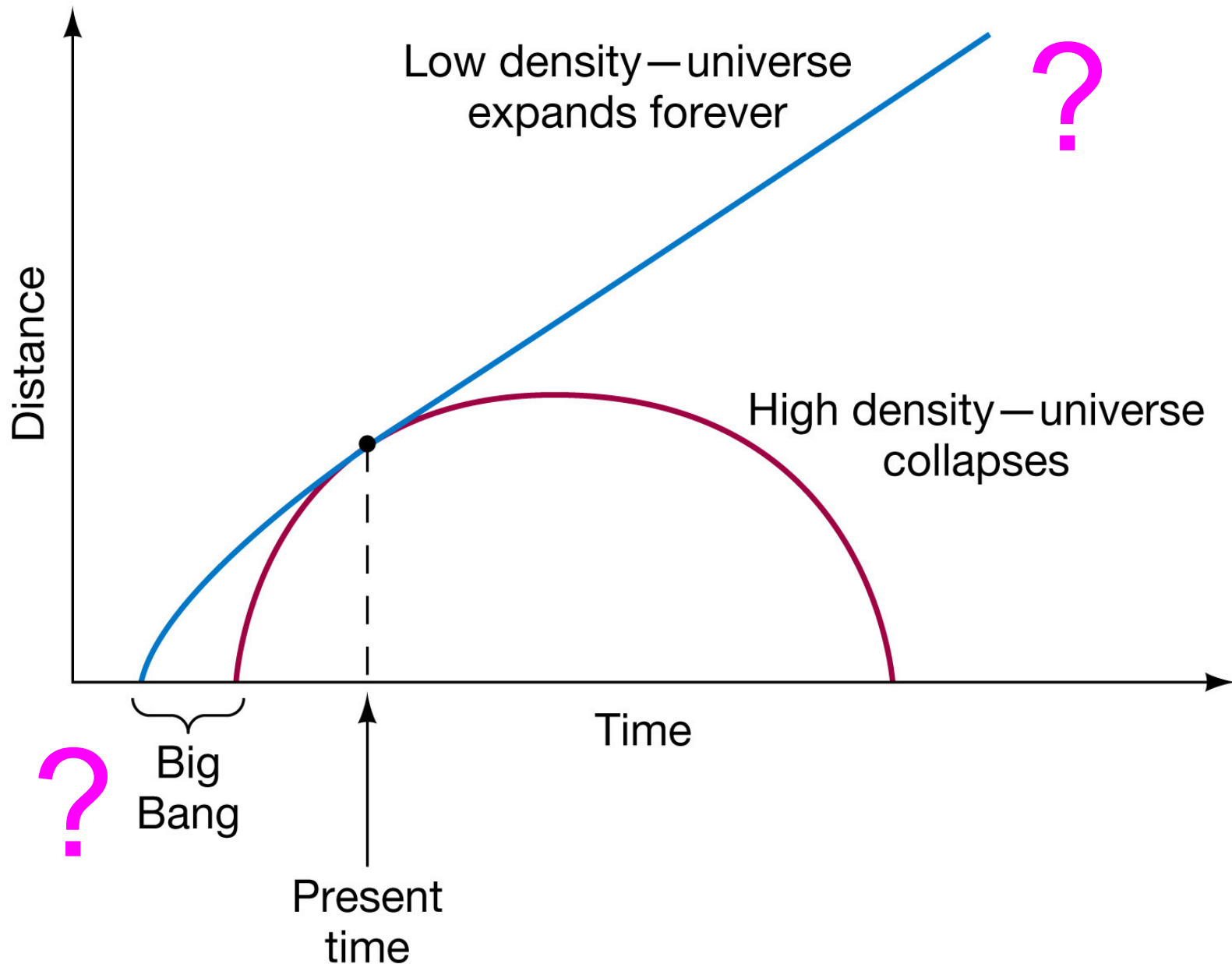


Cosmology

Expansion of Universe



The Fate of the Cosmos

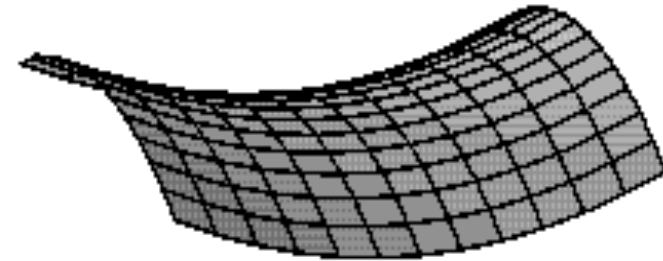
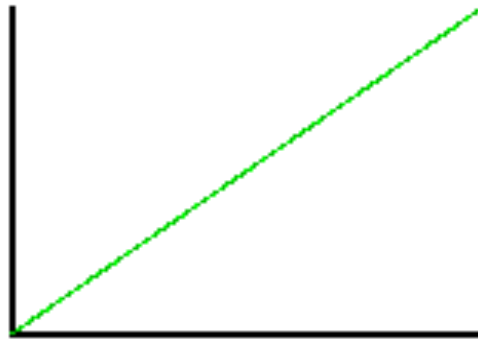


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Geometry of the Universe

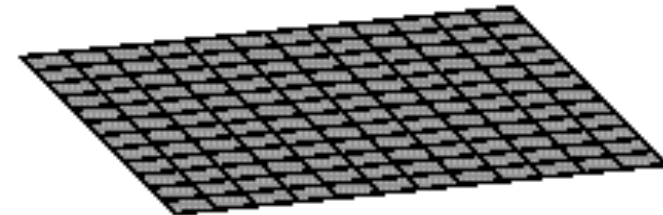
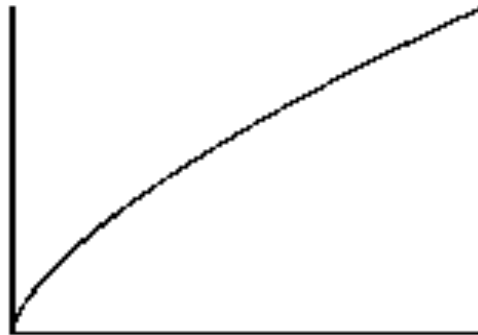
Open

$$\Omega < 1$$



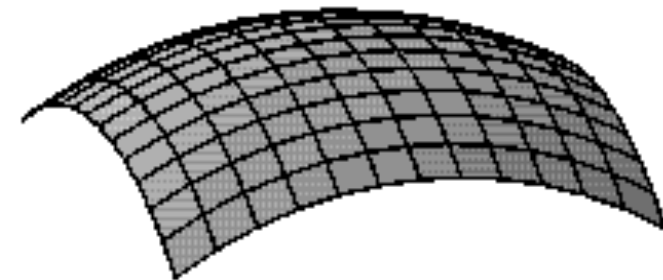
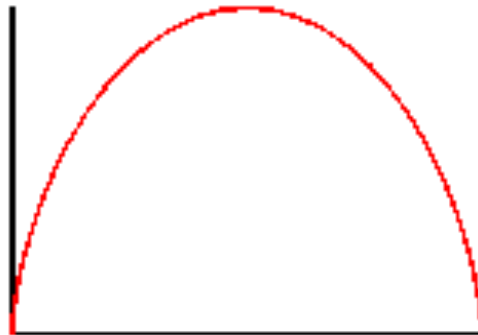
Flat

$$\Omega = 1$$



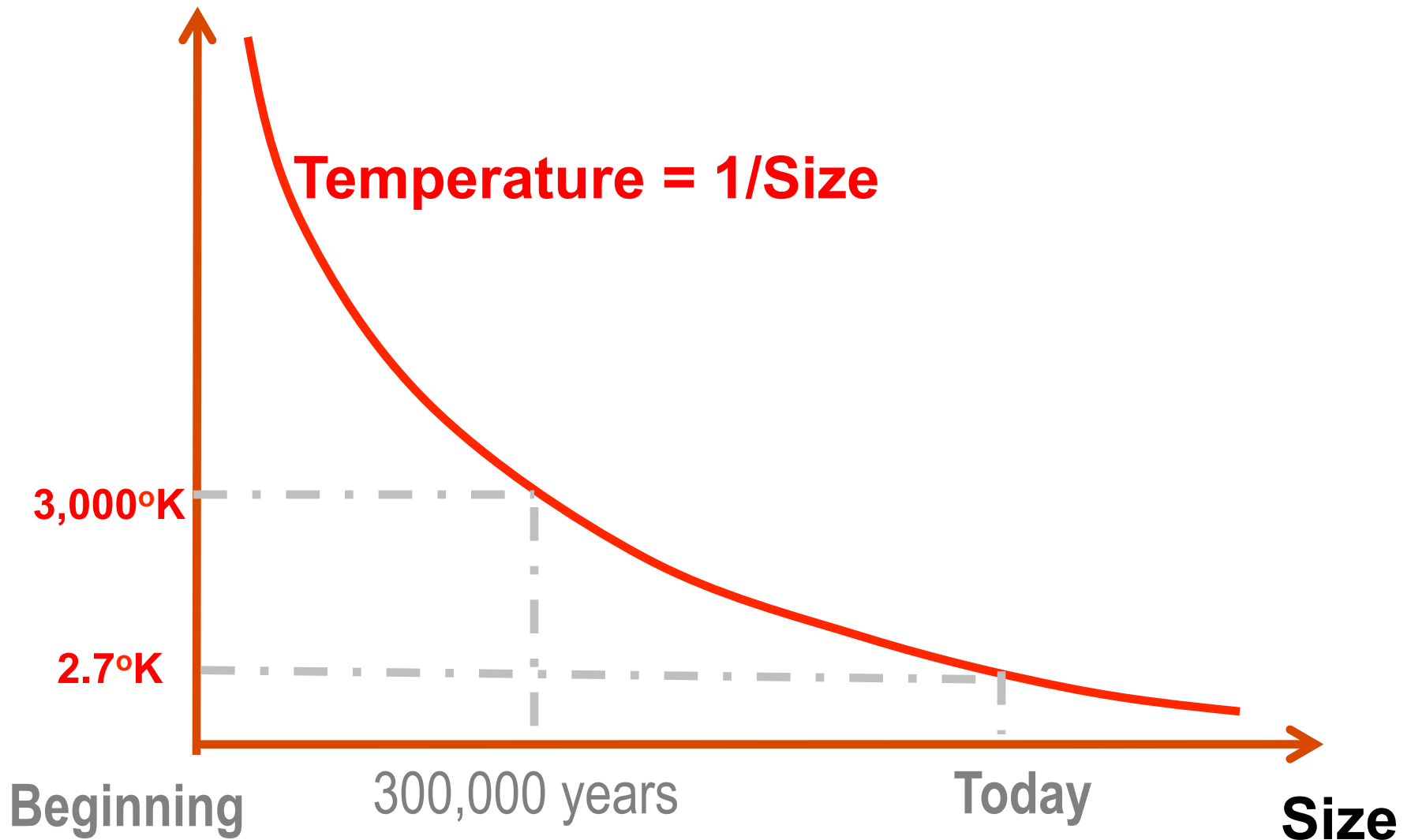
Closed

$$\Omega > 1$$



Temperature of Universe

Temperature



Time = 300,000 years , Temp.= 3000 °K

- **All the electrons were bound by Hydrogen and Helium Nuclei. → Atoms formed.**
- **The Universe became transparent. Photons were released. → Radiation decoupled.**

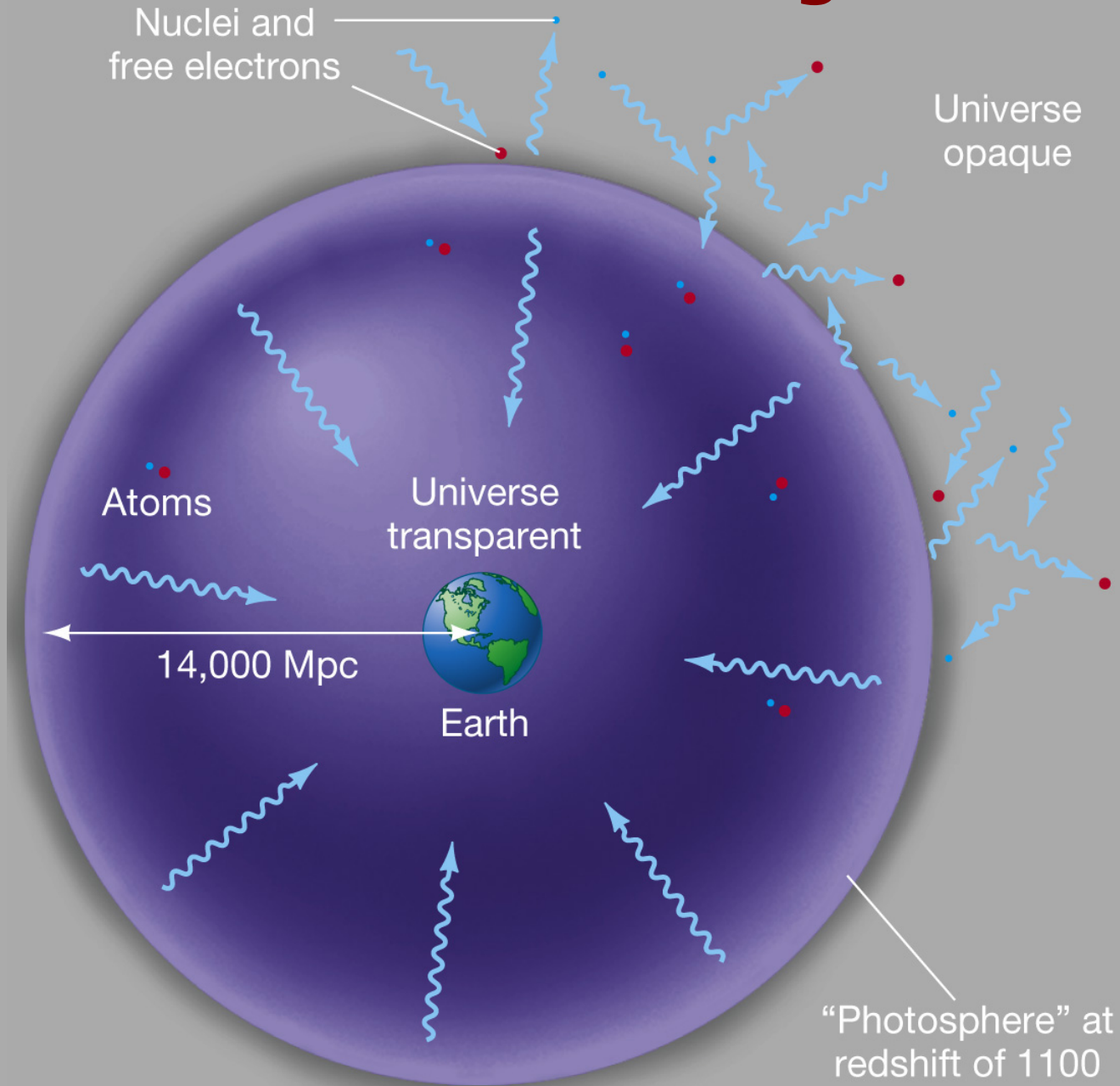


Cosmic Microwave Background (CMB)

The Sun



Cosmic Microwave Background



Cosmic Microwave Background (Discovered in 1964)

T=300,000 years
after the Big Bang

Temperature
=3,000°K

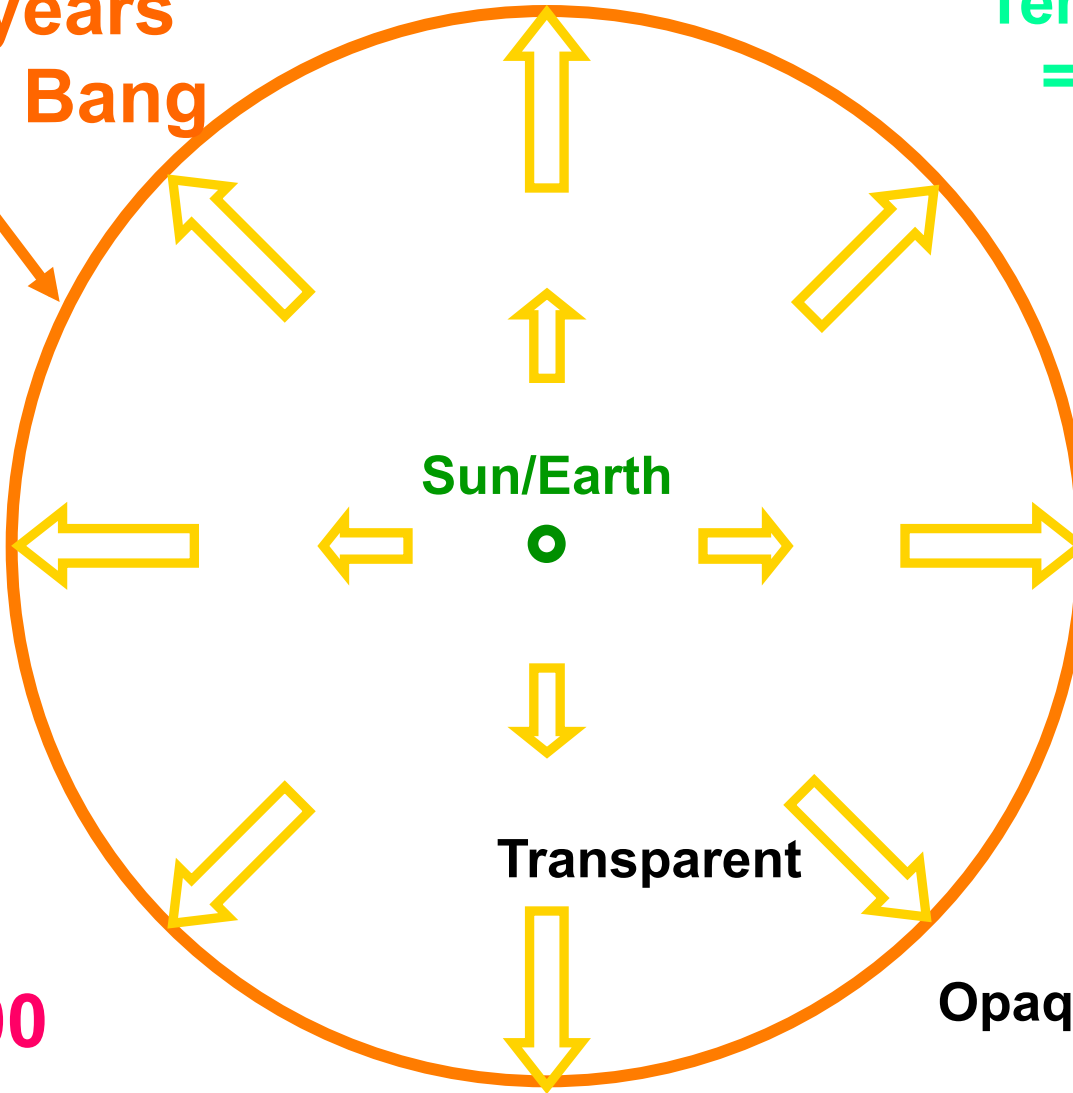
$z=1,100$

Sun/Earth

Transparent

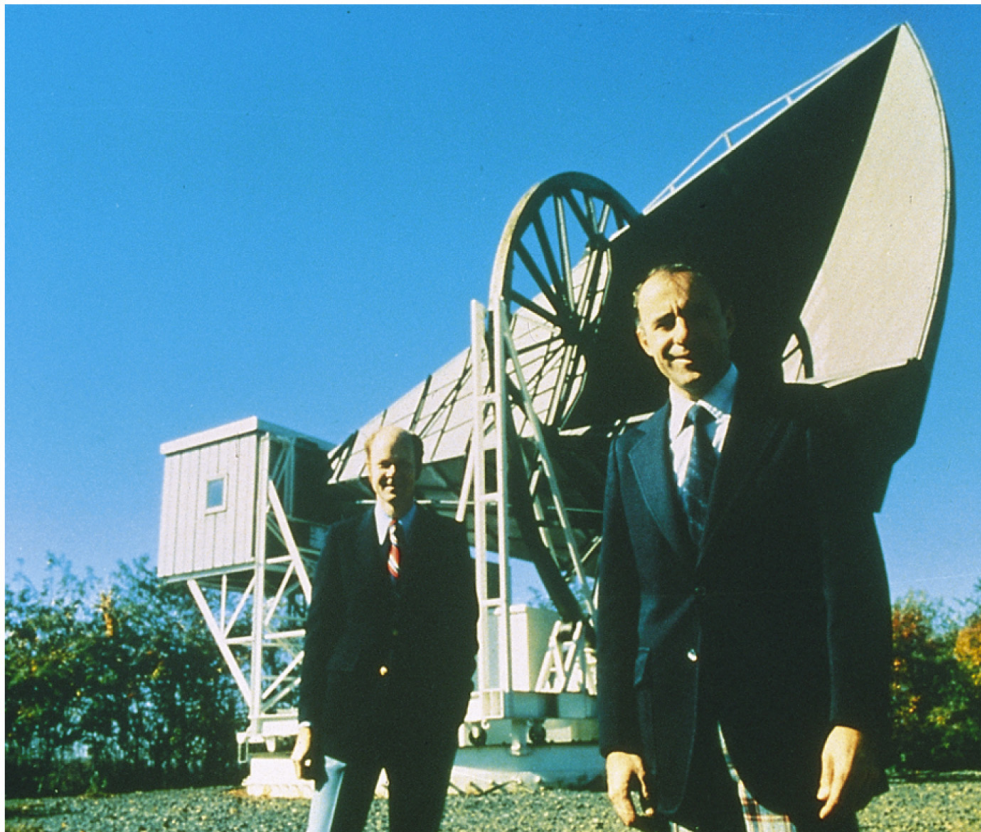
Opaque

Today:
3000°K/1,100
=2.7°K



The Cosmic Microwave Background

The cosmic microwave background was discovered fortuitously in 1964, as two researchers tried to get rid of the last bit of “noise” in their radio antenna.

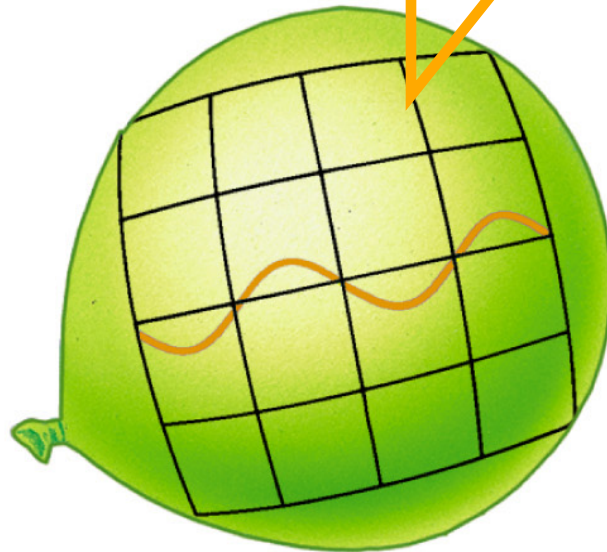
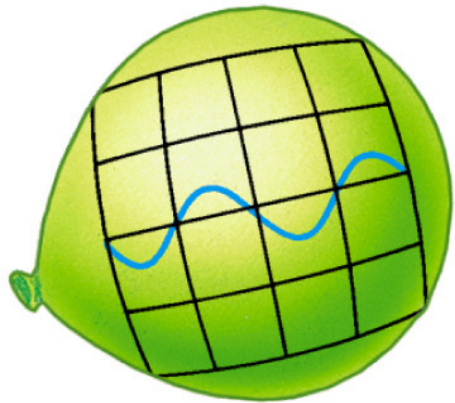


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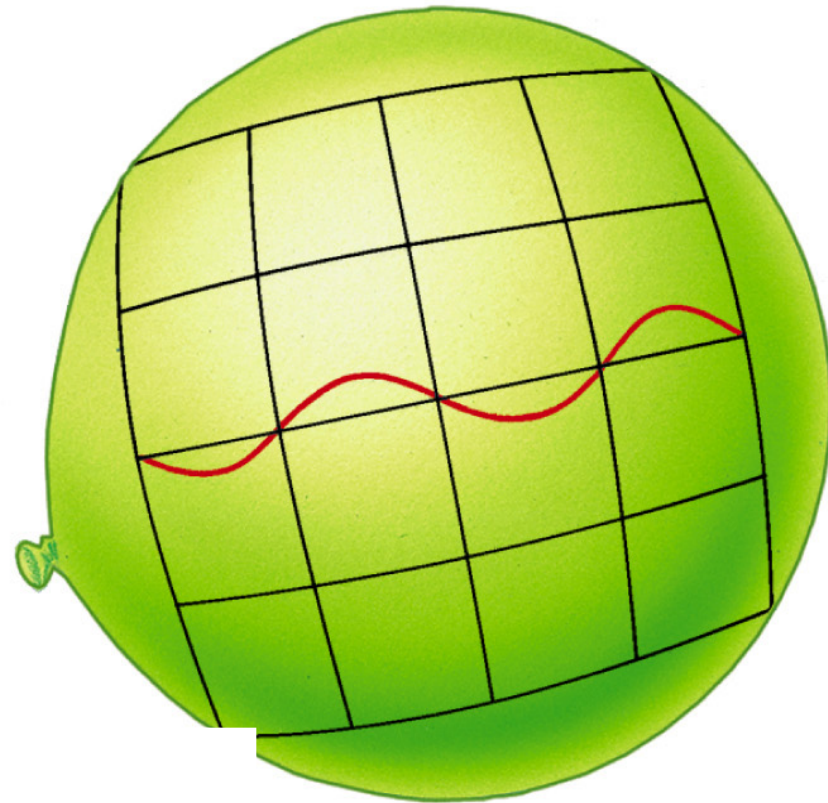
Instead they found that the “noise” came from all directions and at all times, and was always the same. They were detecting photons left over from the Big Bang.

Cosmological Redshift

$T = 300,000$ years
 3000°K

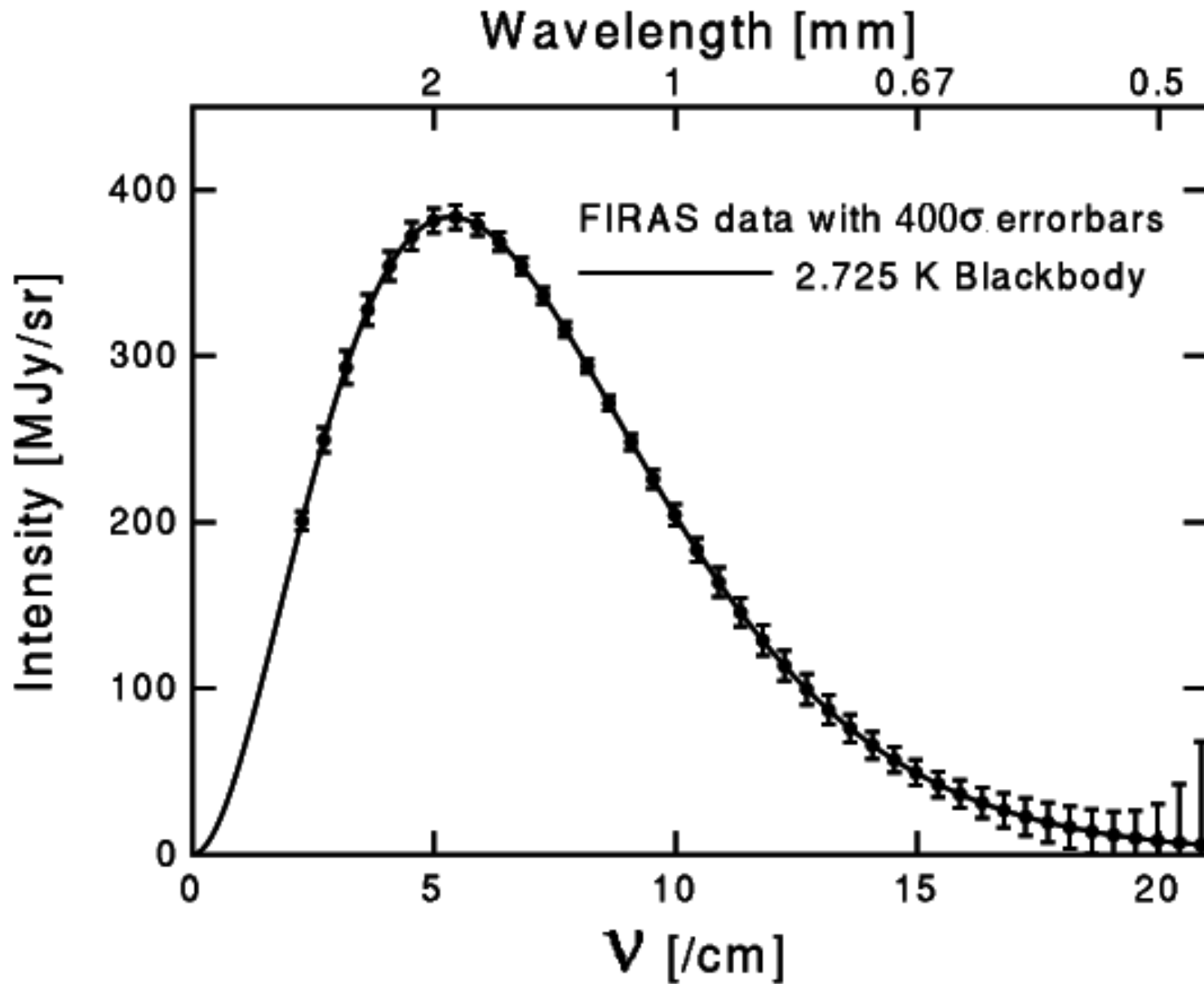


$T = 13.7$ B years (Today)
 $3000^\circ\text{K}/1,100 = 2.7^\circ\text{K}$



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The CMB Spectrum by FIRAS



Inflation

Two Fundamental Problems of Big Bang Cosmology

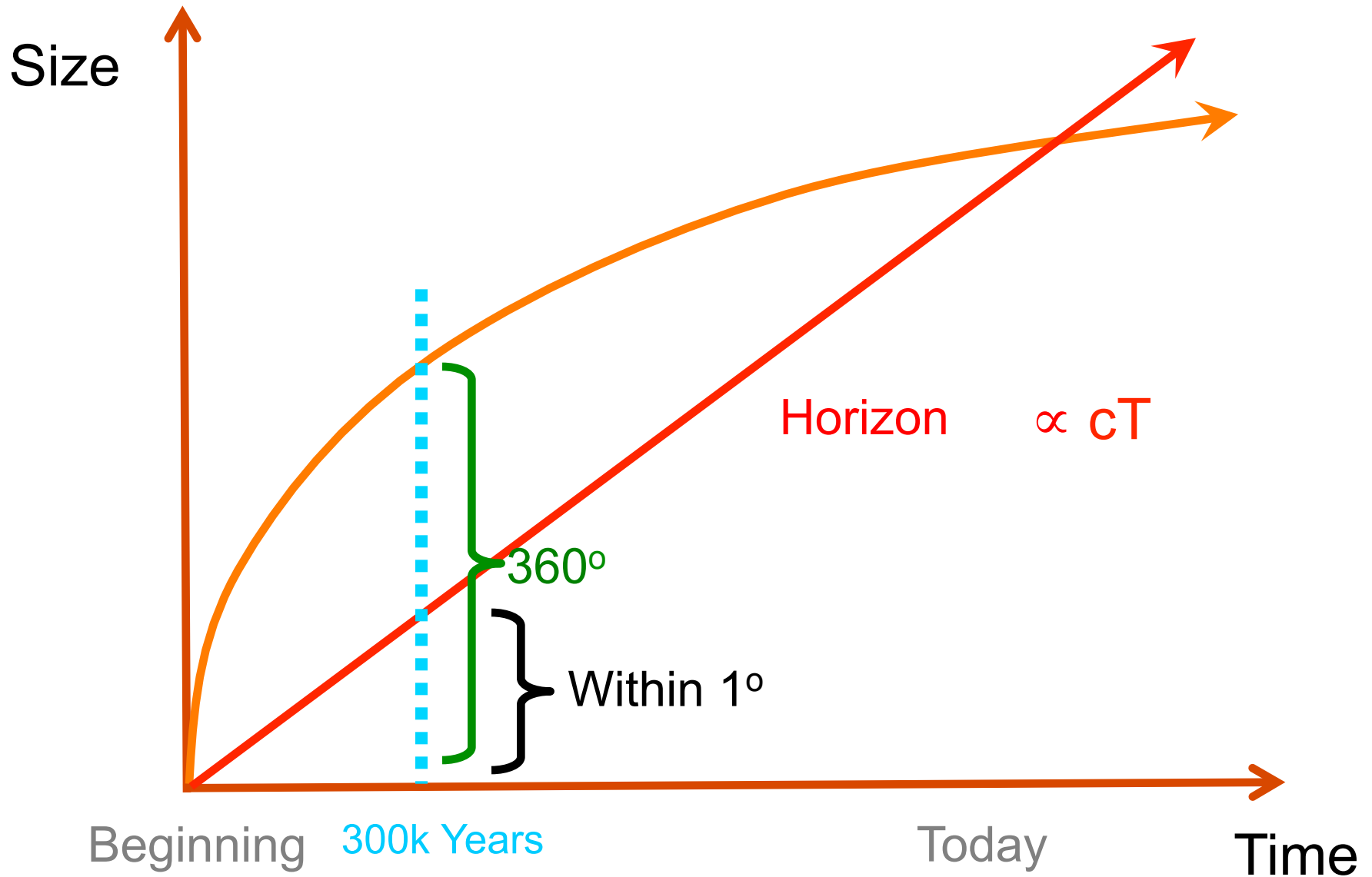
➤ Horizon Problem

- At early Universe, Size \gg Horizon.
- Why is CMB so uniform in every direction?

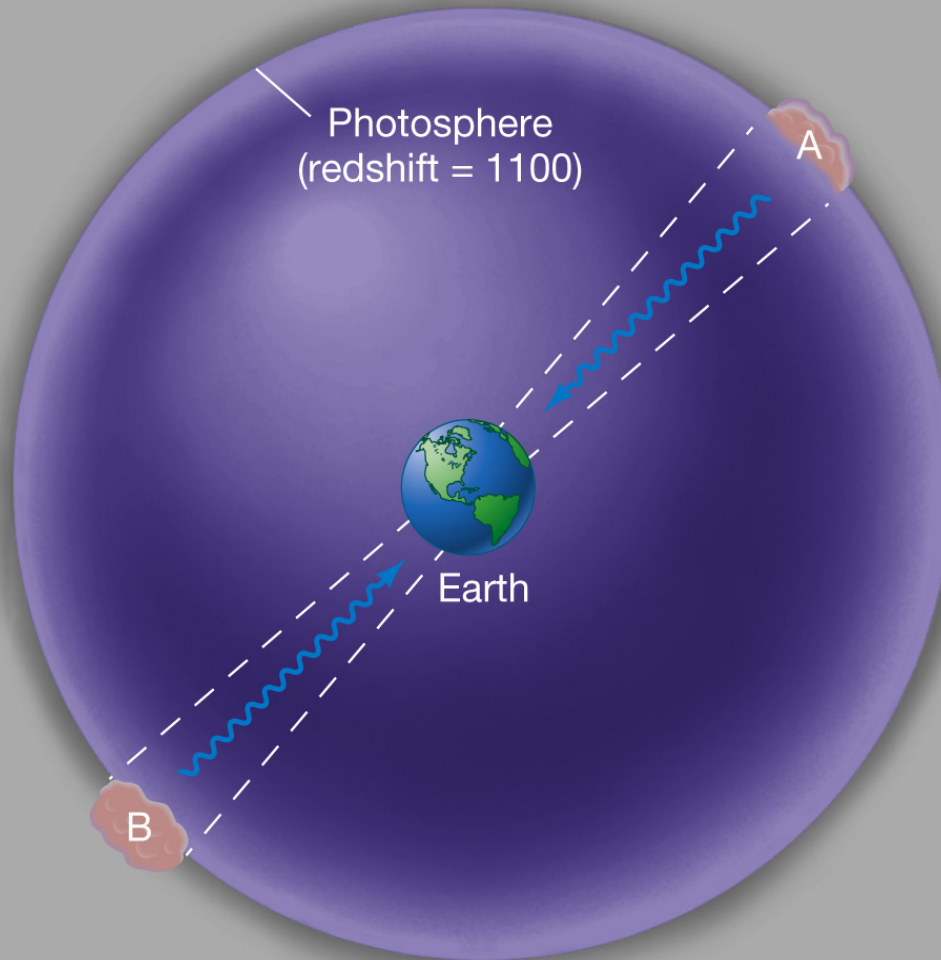
➤ Flatness Problem

- $|\Omega - 1|$ grows proportional to the size of the Universe.
- Why is Ω of today close to 1?

Expansion of Universe

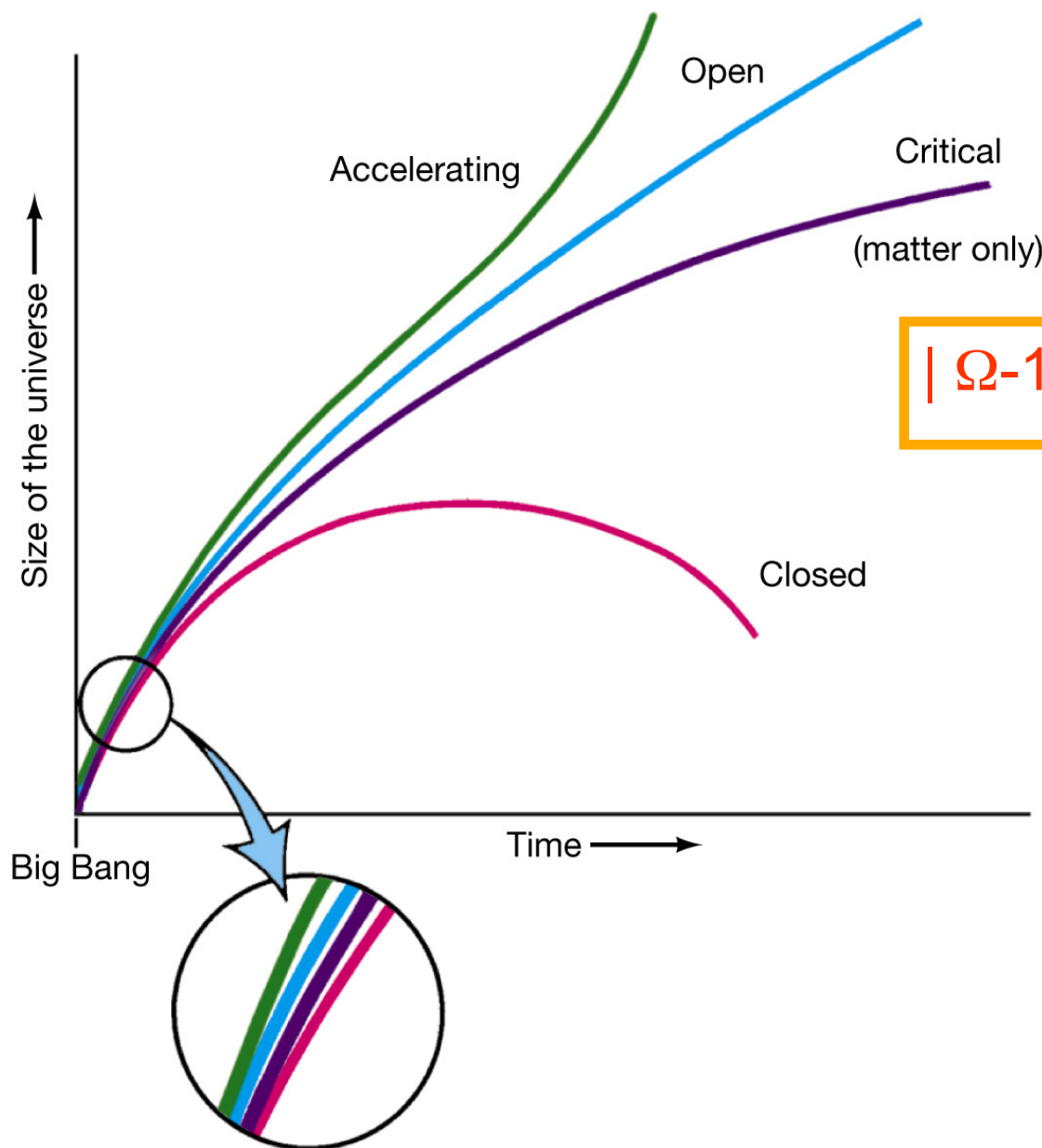


Horizon Problem



The horizon problem: When observed in diametrically opposite directions from Earth, cosmic background radiation appears the same even though there hasn't been enough time since the Big Bang for them to be in thermal contact.

Flatness Problem

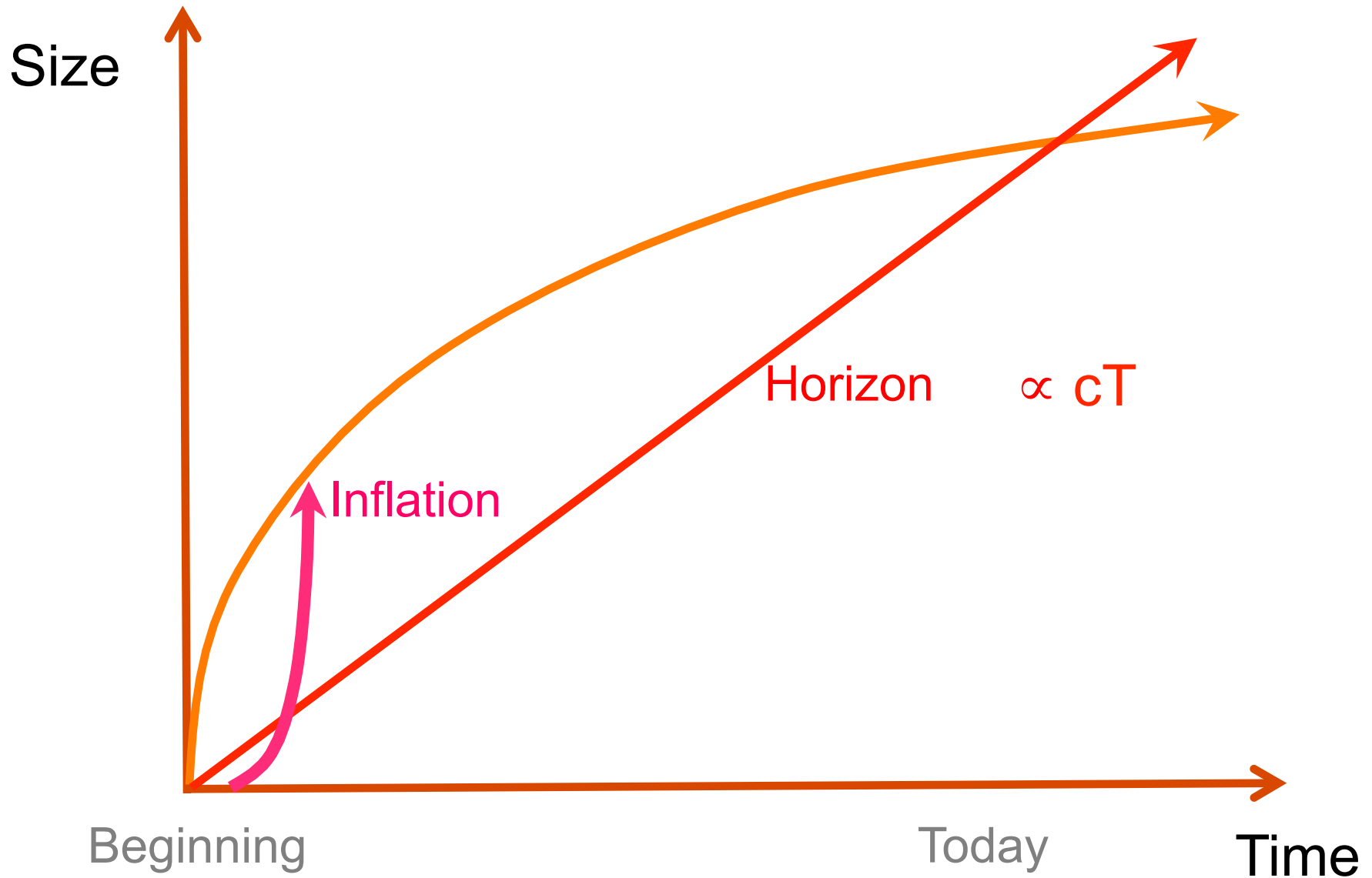


$$|\Omega - 1| \propto \text{Size of Universe}$$

The flatness problem: In order for the universe to have survived this long, its density in the early stages must have differed from the critical density by no more than 1 part in 10^{15} .

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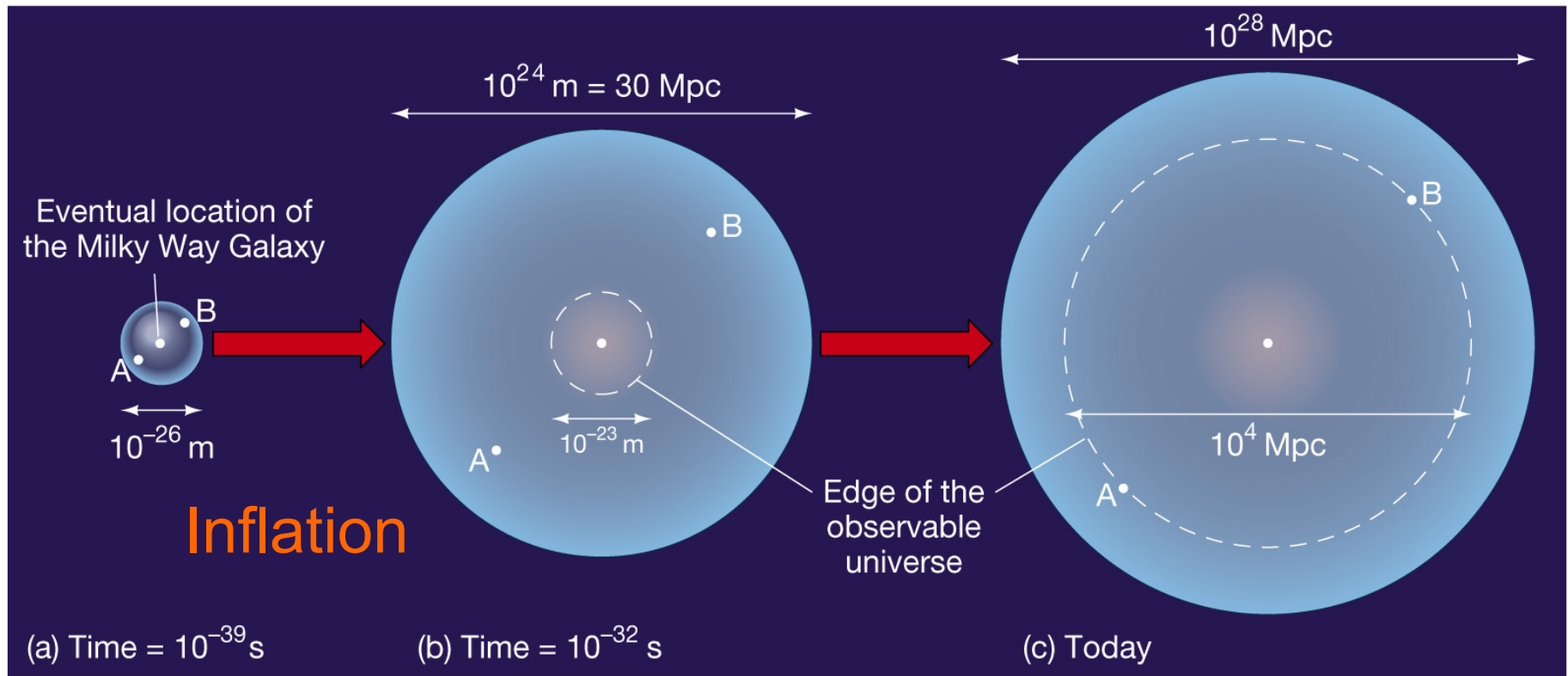
Inflation in Early Universe



The Inflationary Universe

Inflation, if correct, would solve both the horizon and the flatness problems.

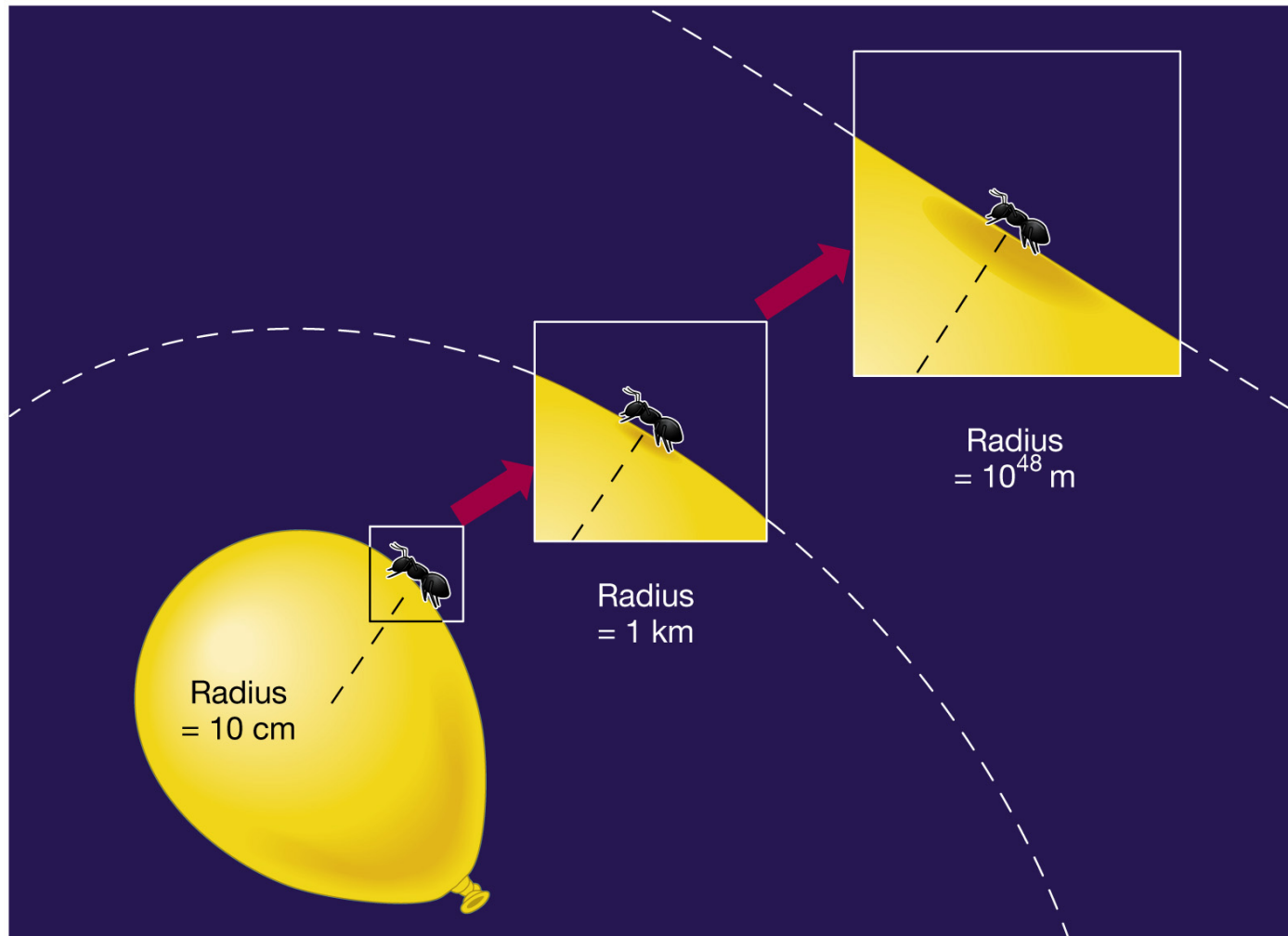
This diagram shows how the horizon problem is solved – the points diametrically opposite from Earth were in fact in contact at one time.



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The Inflationary Universe

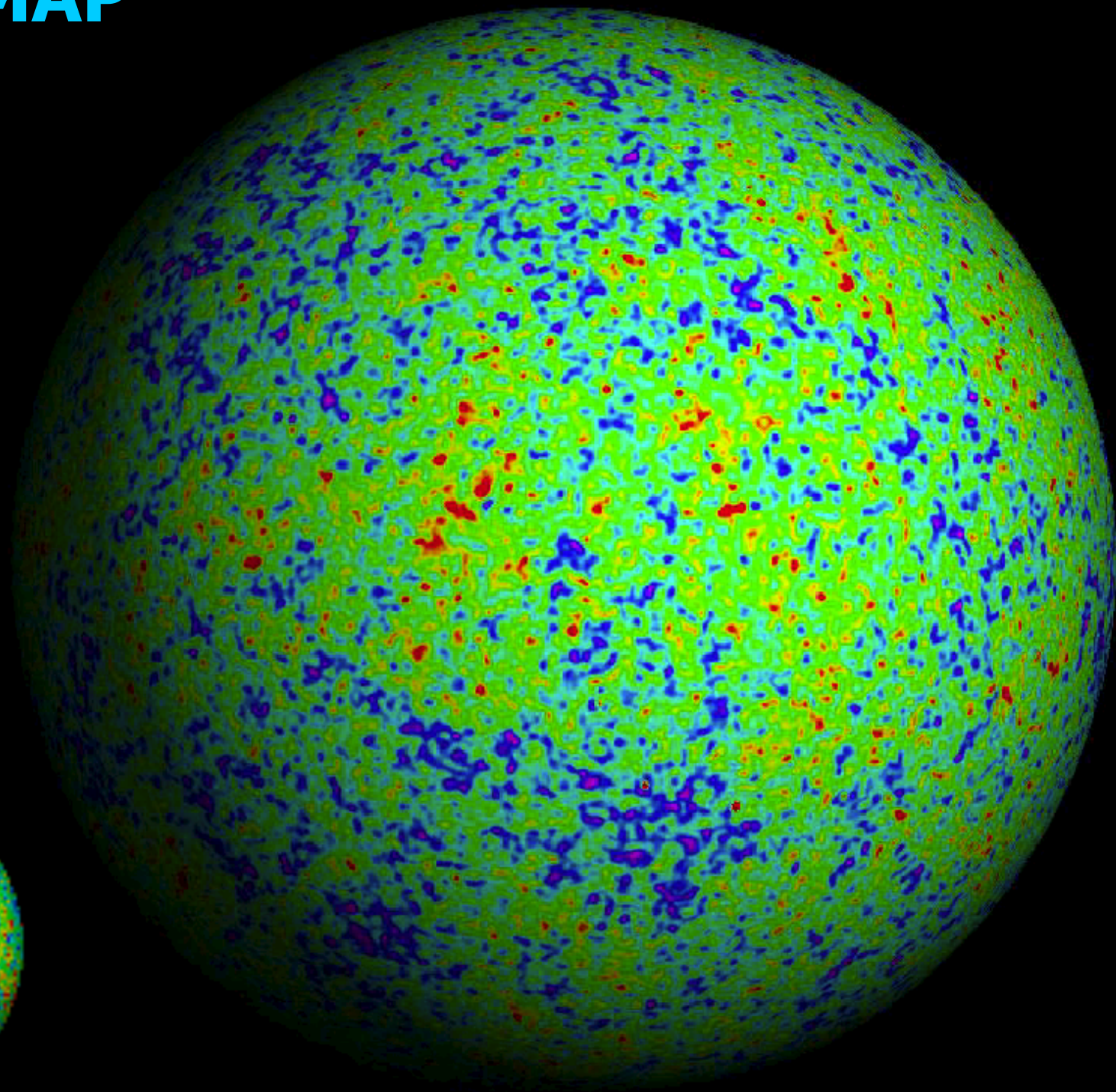
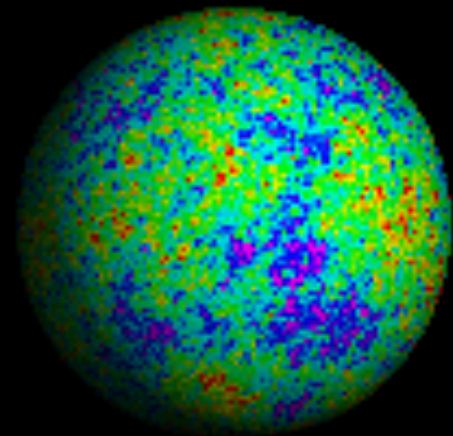
The flatness problem is solved as well – after the inflation the need to be exceedingly close to the critical density is much more easily met:



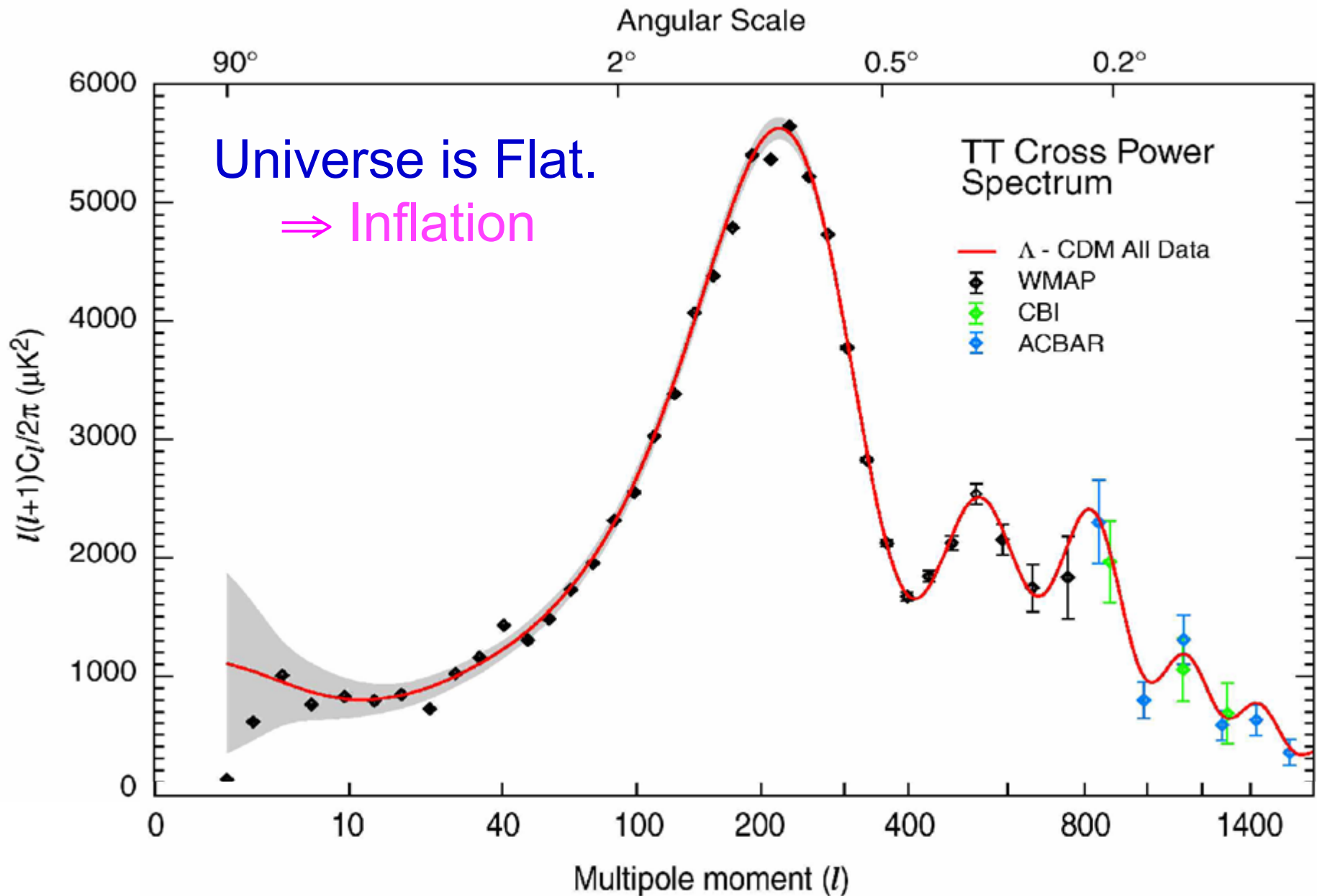
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WMAP

l-P map from Tegmark, de Oliveira-Costa & Hamilton, astro-ph/0302496



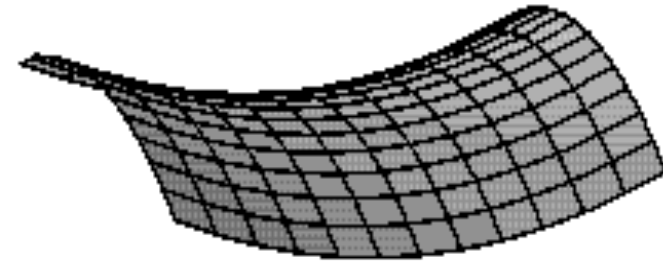
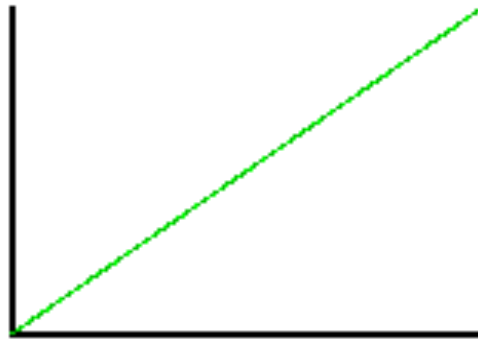
WMAP Power Spectrum



Geometry of the Universe

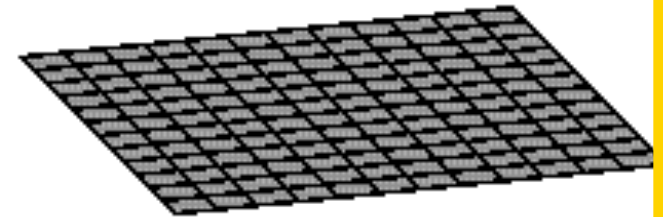
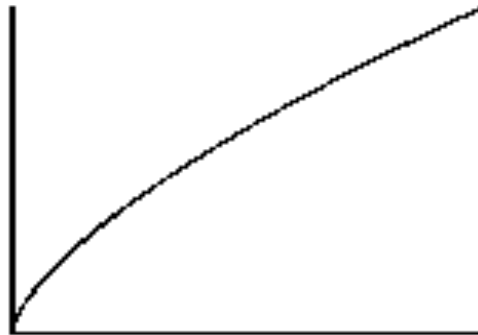
Open

$$\Omega < 1$$



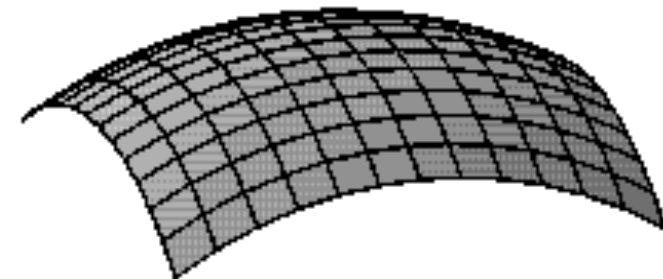
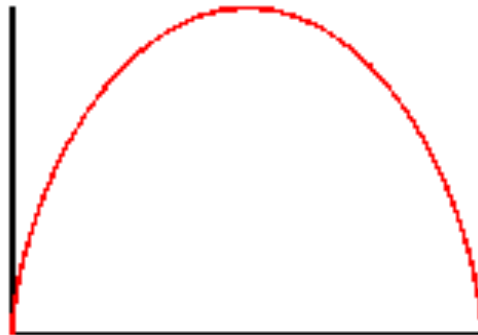
Flat

$$\Omega = 1$$



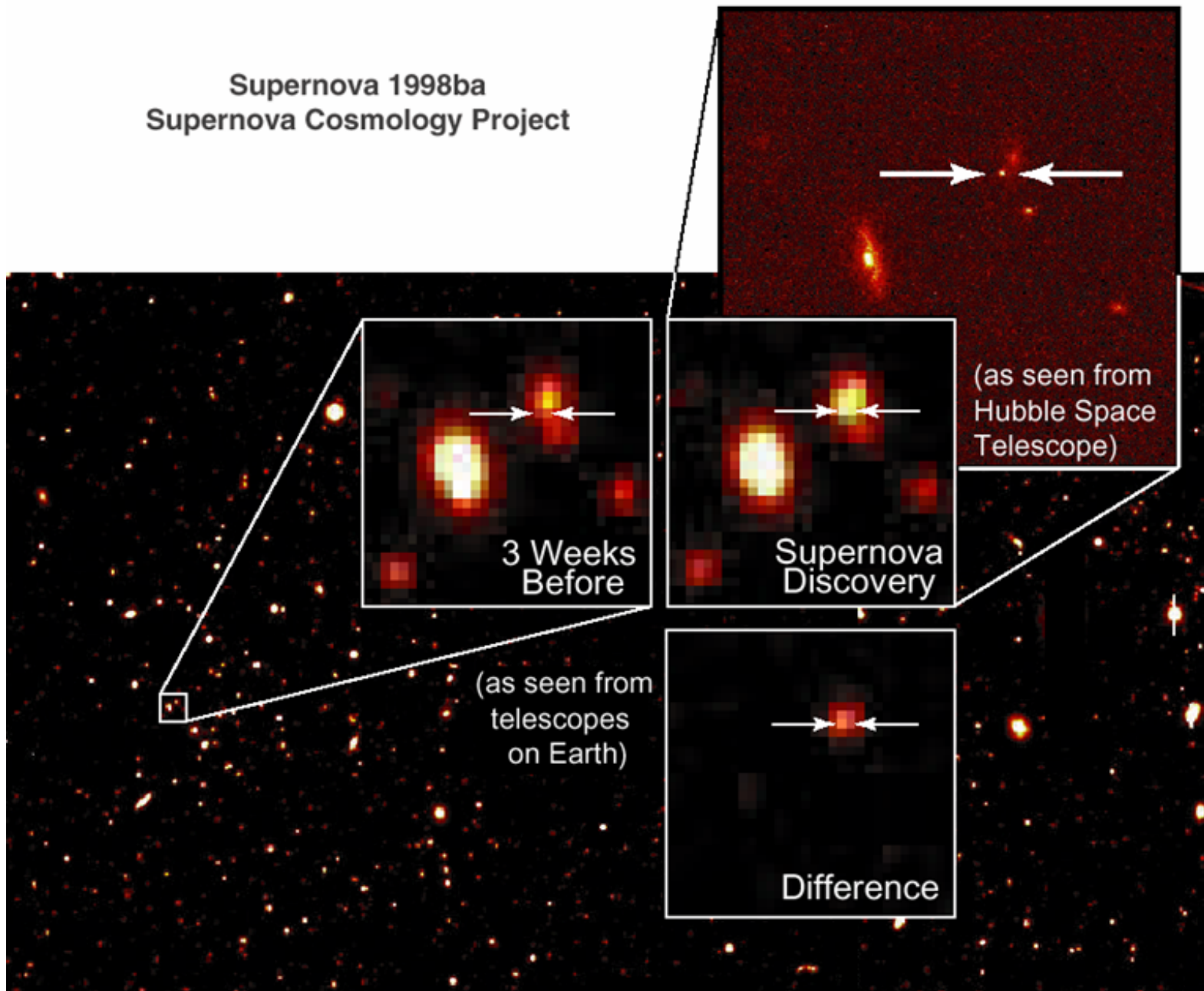
Closed

$$\Omega > 1$$



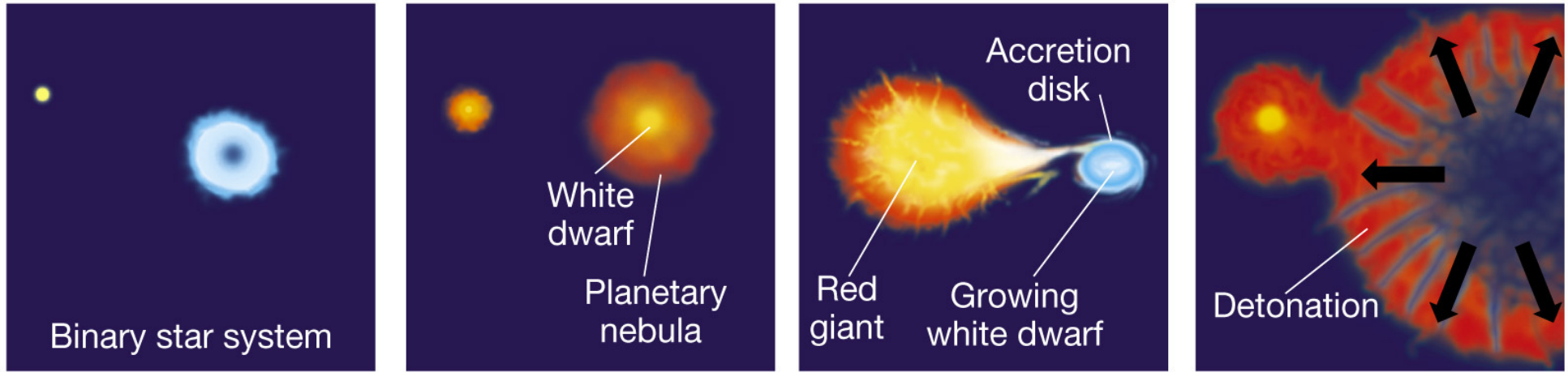
Dark Energy

Supernova as a Standard Candle



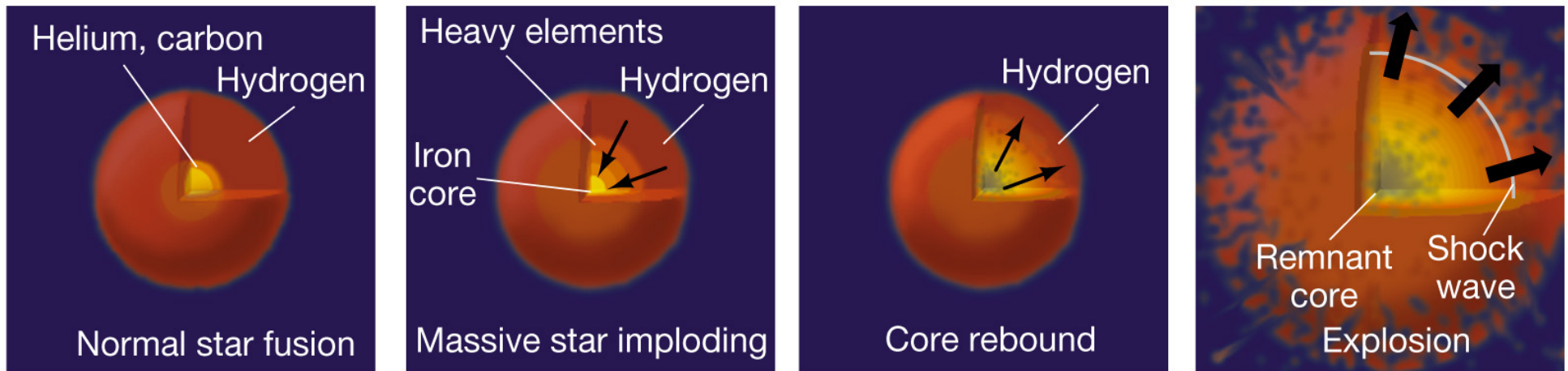
Two Types of Supernovae

(a) Type I Supernova



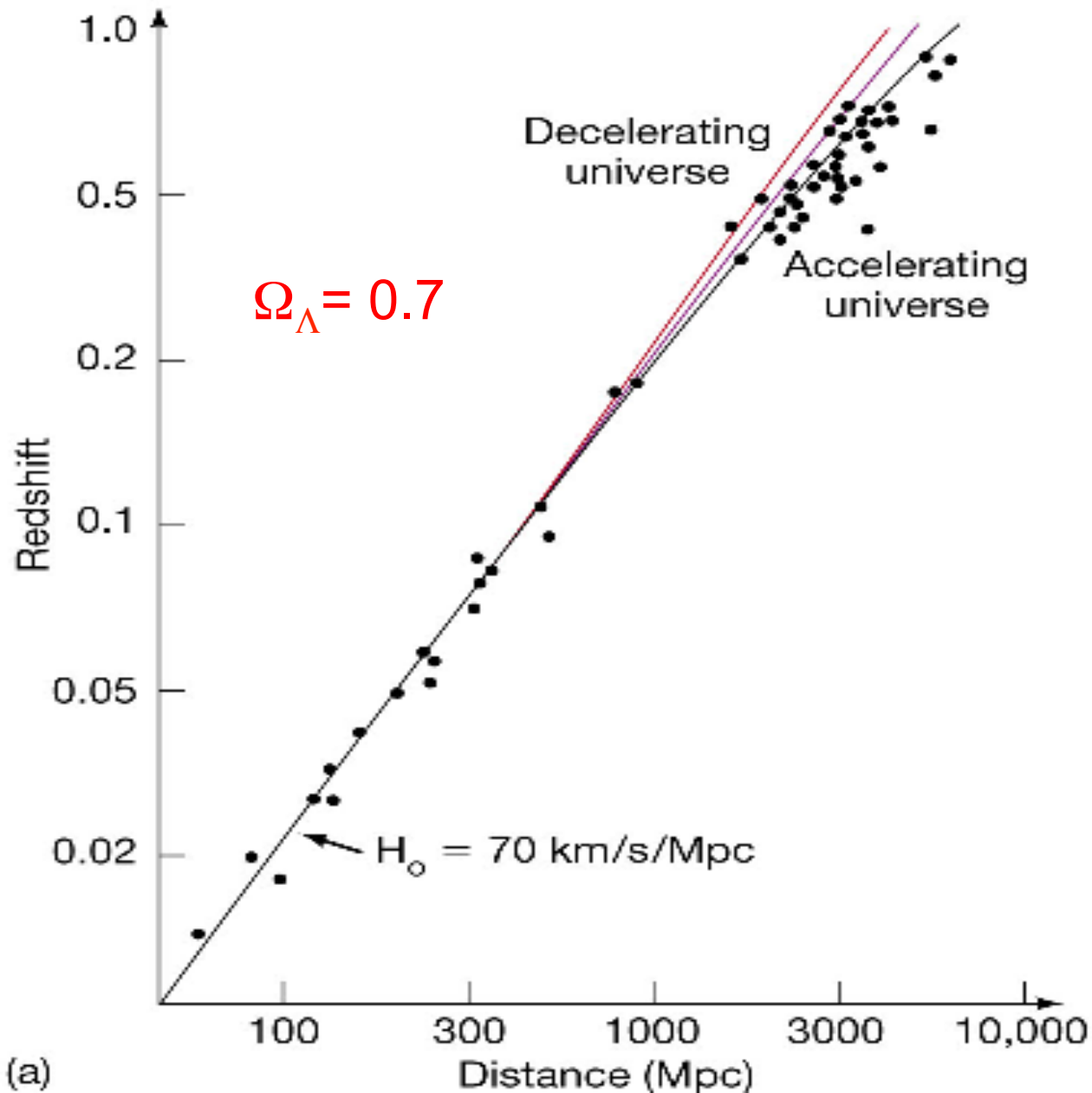
Time

(b) Type II Supernova



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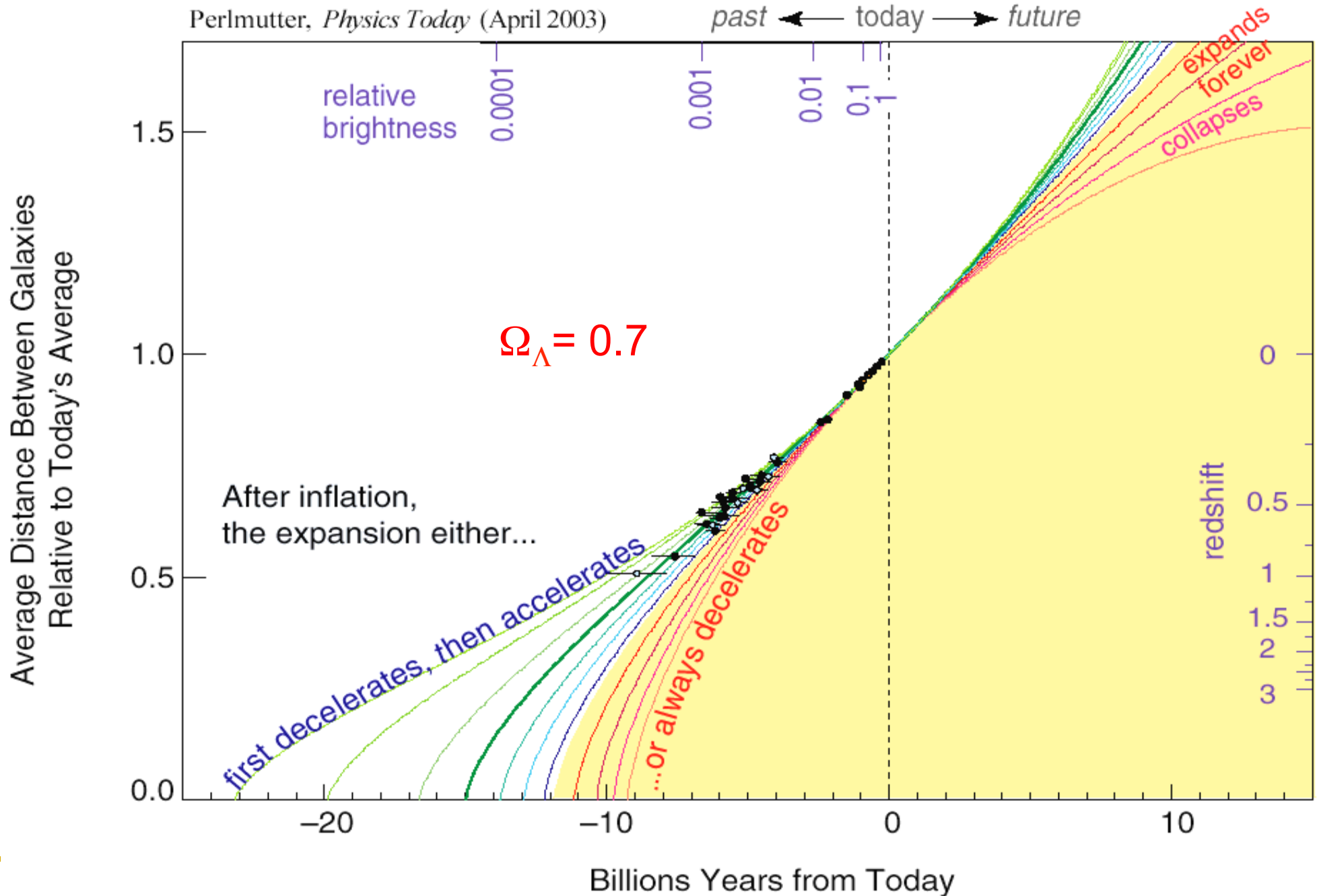
Will the Universe Expand Forever?



When we look at the data, we see that it corresponds not to a decelerating universe, but to an accelerating one.

This acceleration cannot be explained by current theories of the universe, although we do know it is not caused by either matter or radiation.

The Accelerating Universe (1998)

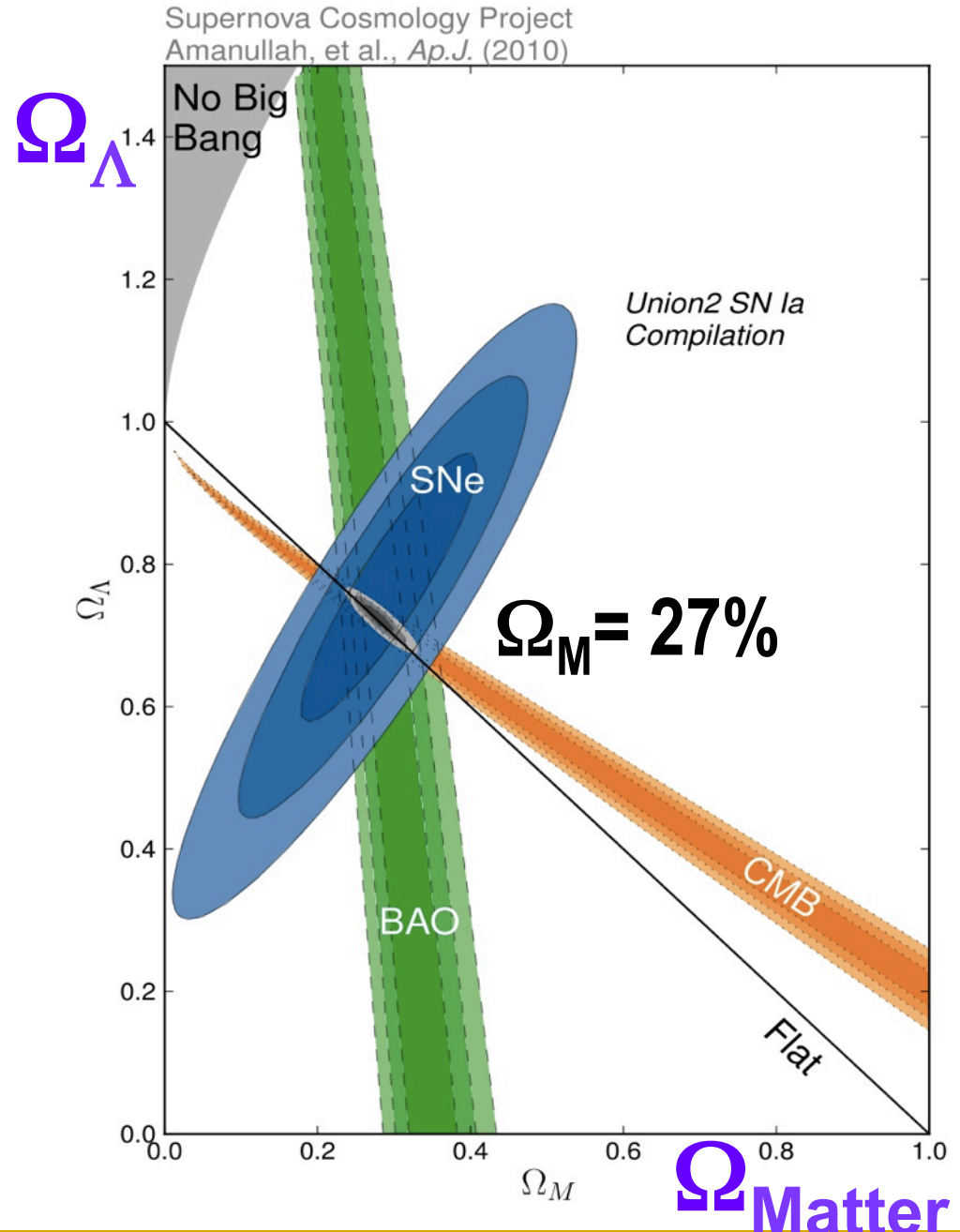


Density of Our Universe

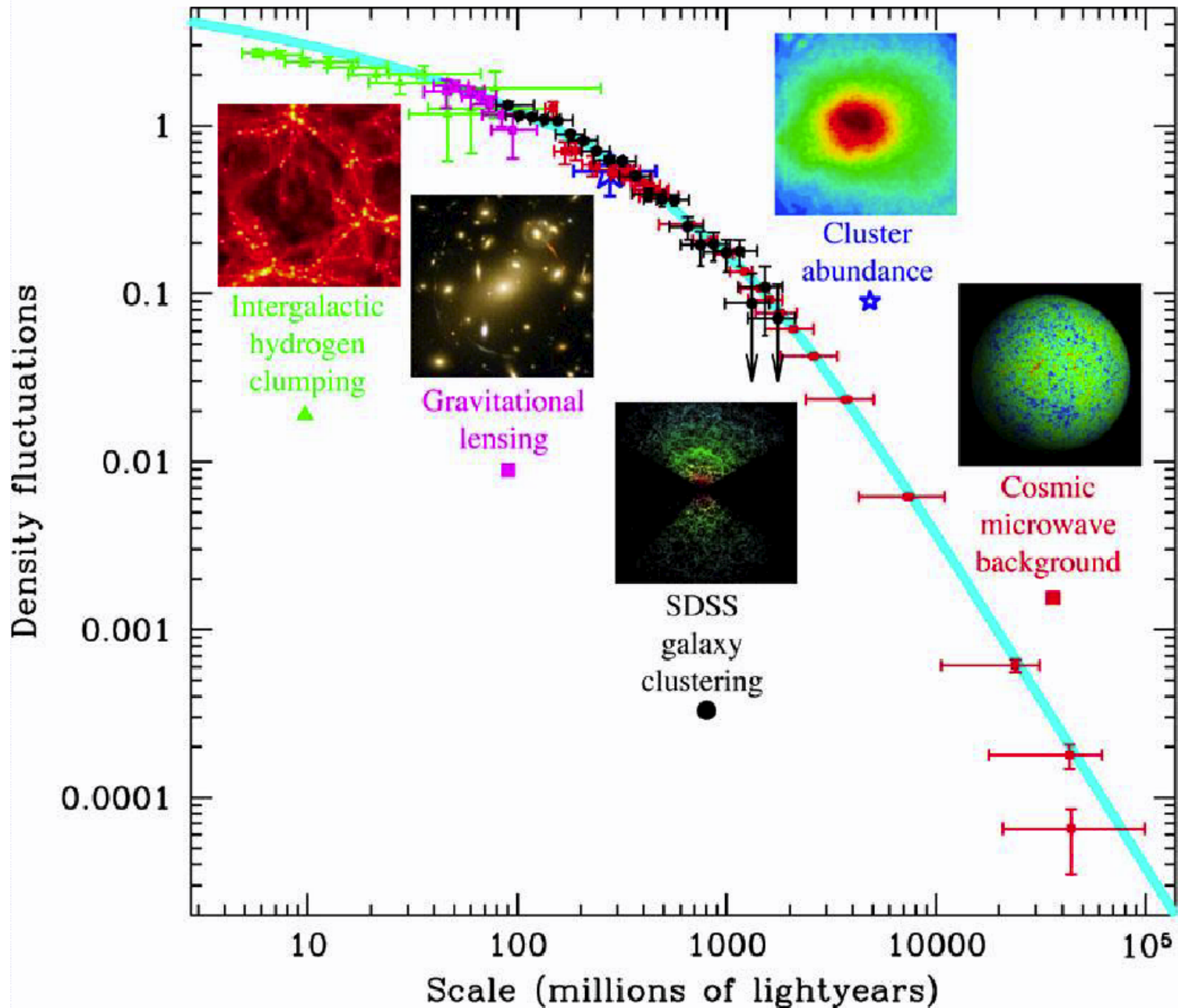
➤ $\Omega_{\text{Total}} = \Omega_{\Lambda} + \Omega_{\text{Matter}} = 1.0$

➤ Universe is Flat.
⇒ Inflation

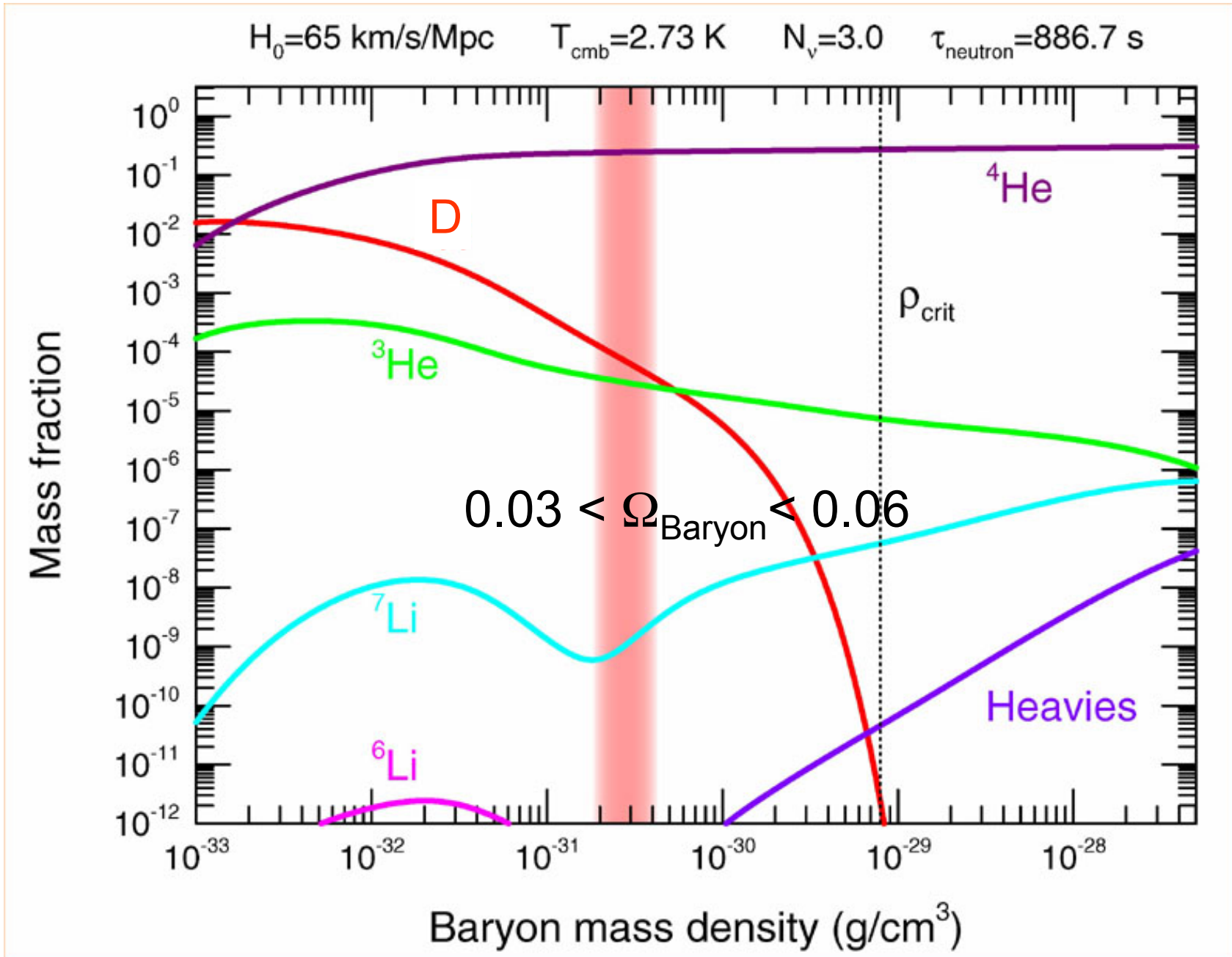
➤ 73% is Dark Energy.
⇒ Accelerating



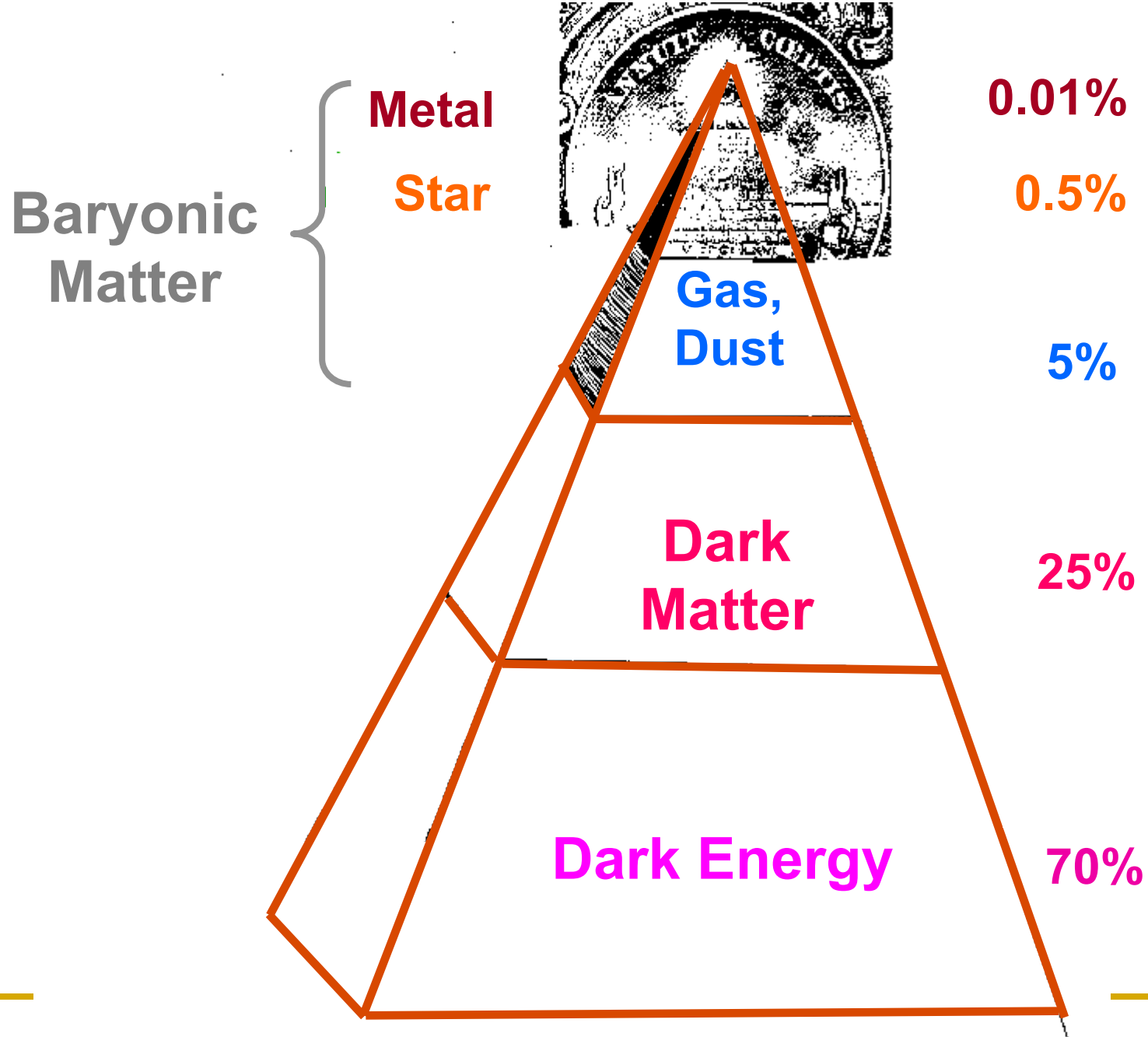
Density Fluctuations



Abundance vs. Density



Cosmic Pyramid

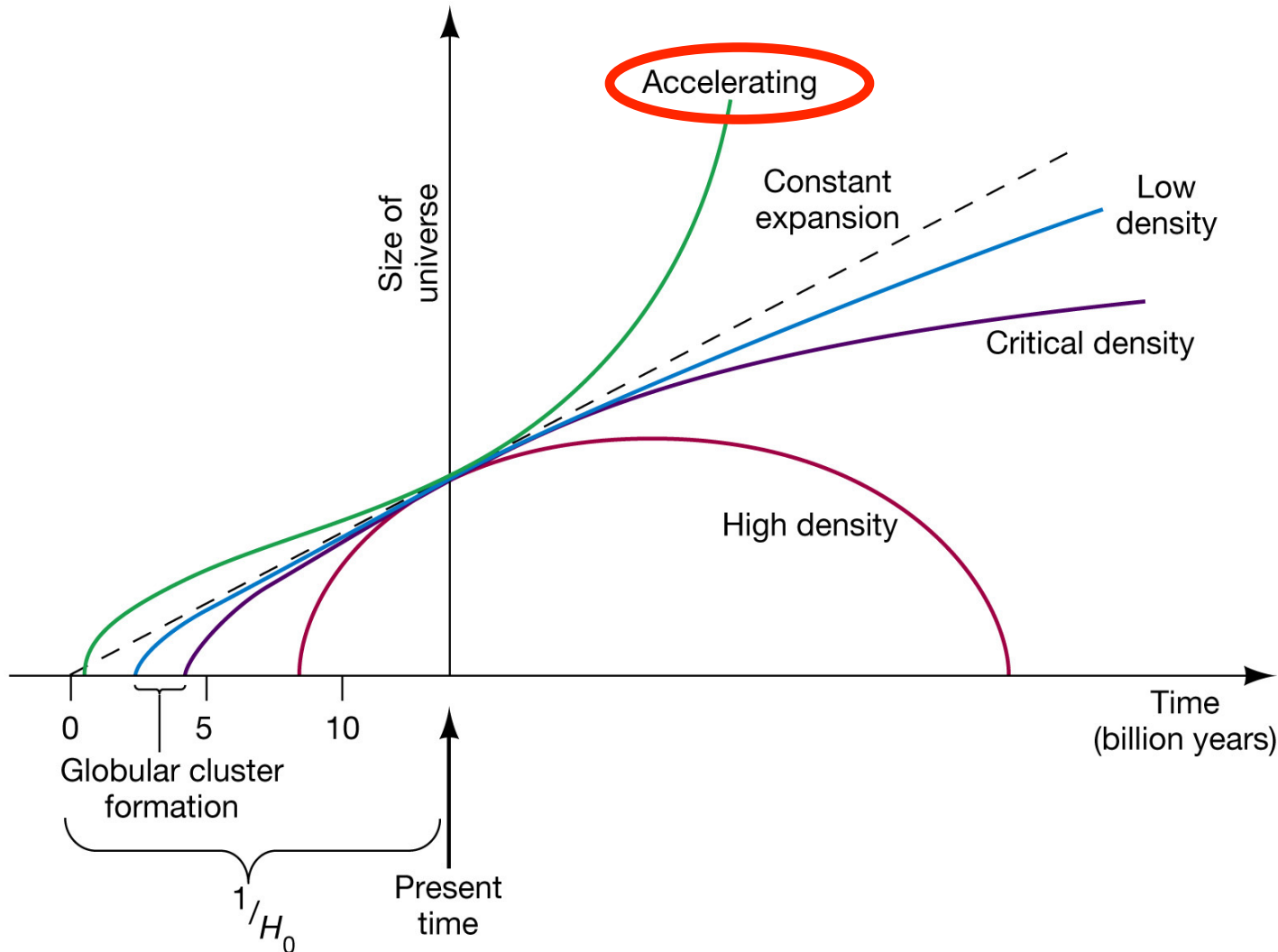


Dark Energy and Cosmology

This graph now includes the accelerating universe.

Given what we now know, the age

of the universe works out to be **13.7 billion years.**



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Dark Matter

What is Dark Matter?


➤ Must be a heavy particle

- Only weakly interacting.
- Gravitationally attracted.

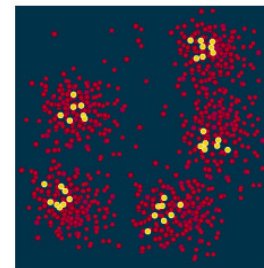
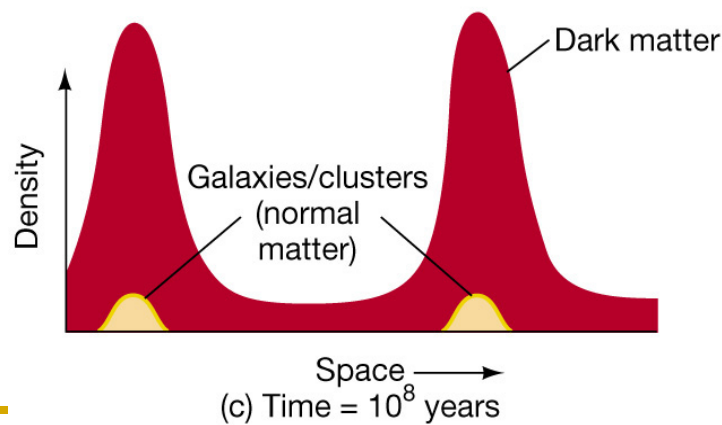
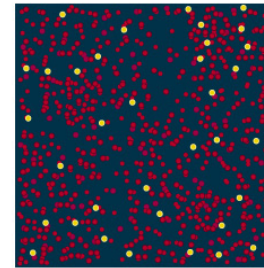
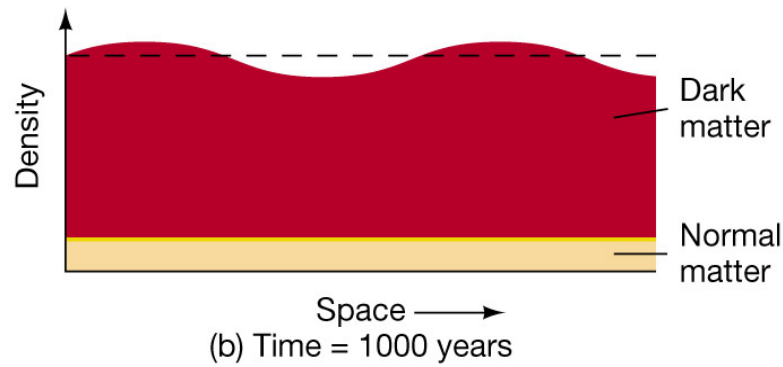
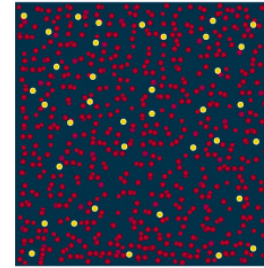
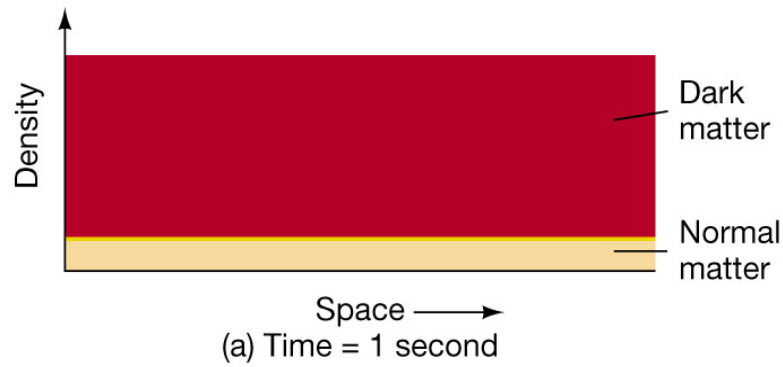
➤ Candidates

- “MACHO” (Massive Compact Halo Objects) ✗
 - → Baryonic Dark Matter
- Heavy Neutrino ✗
 - → Hot Dark Matter
- “WIMP” (Weakly Interacting Massive Particle)
 - → Cold Dark Matter

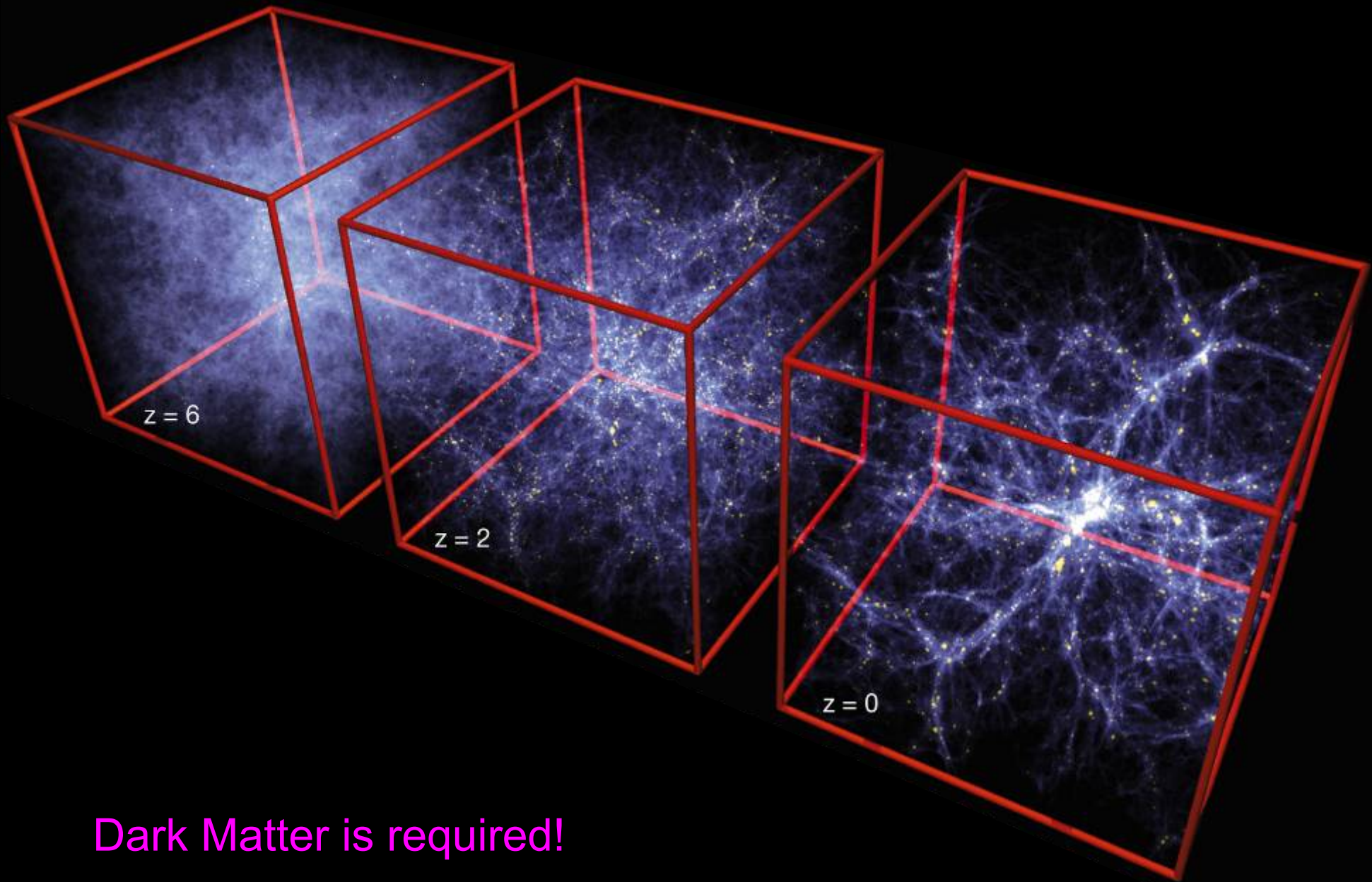
Candidate of “WIMP”

- A leading candidate of WIMP is “Neutralino”
 - Least-massive Super-Symmetric Particle.
 - Super-Symmetry is the symmetry between Fermion ↔ Boson
 - This symmetry was broken
 - at energy around 100 GeV – 1 TeV
 - at time around 10^{-10} – 10^{-11} second.
- 
- Neutralinos were decoupled.
 - Started to be attracted each other gravitationally.

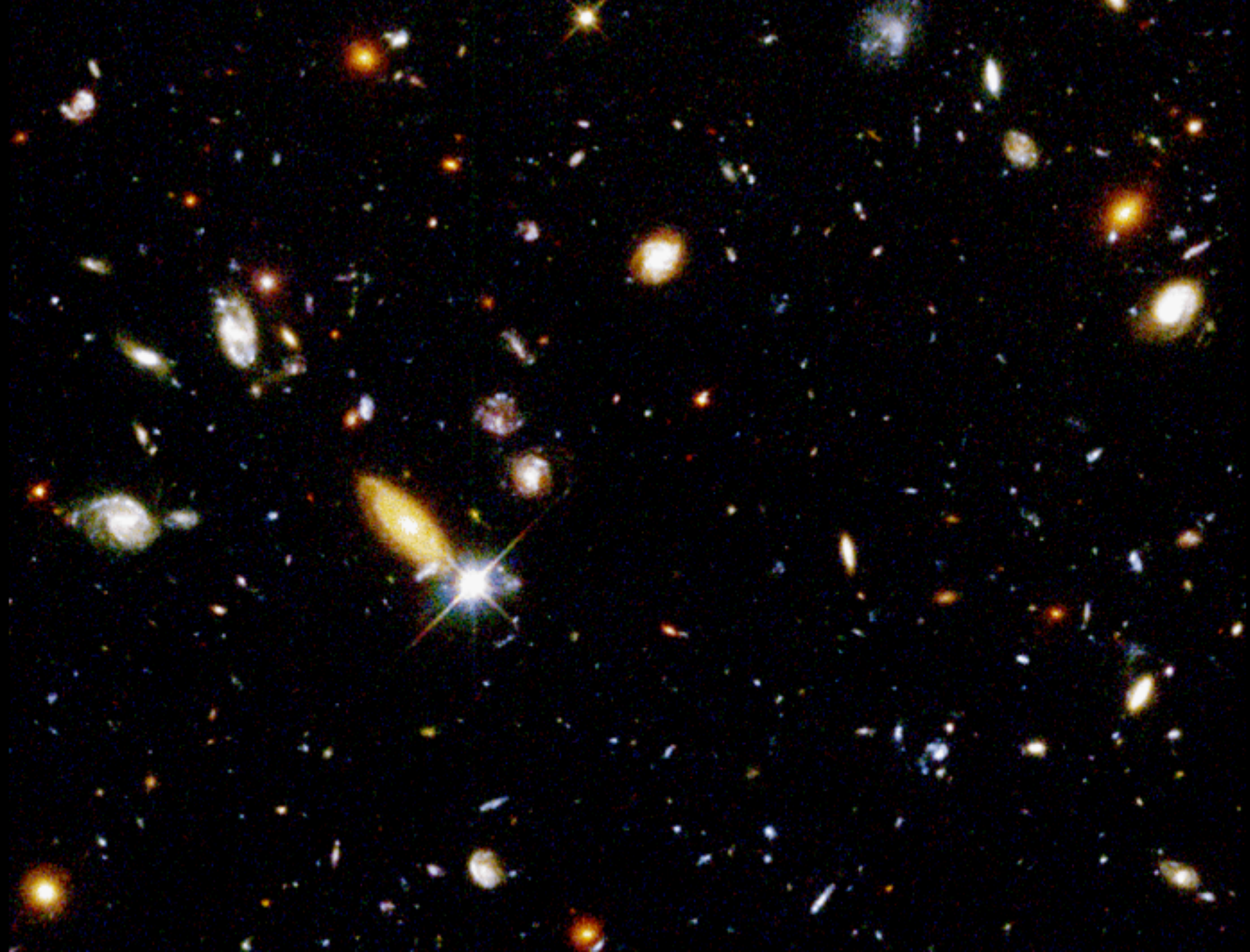
Formation of Structure by Dark Matter



Formation of Structure in the Universe



Dark Matter is required!



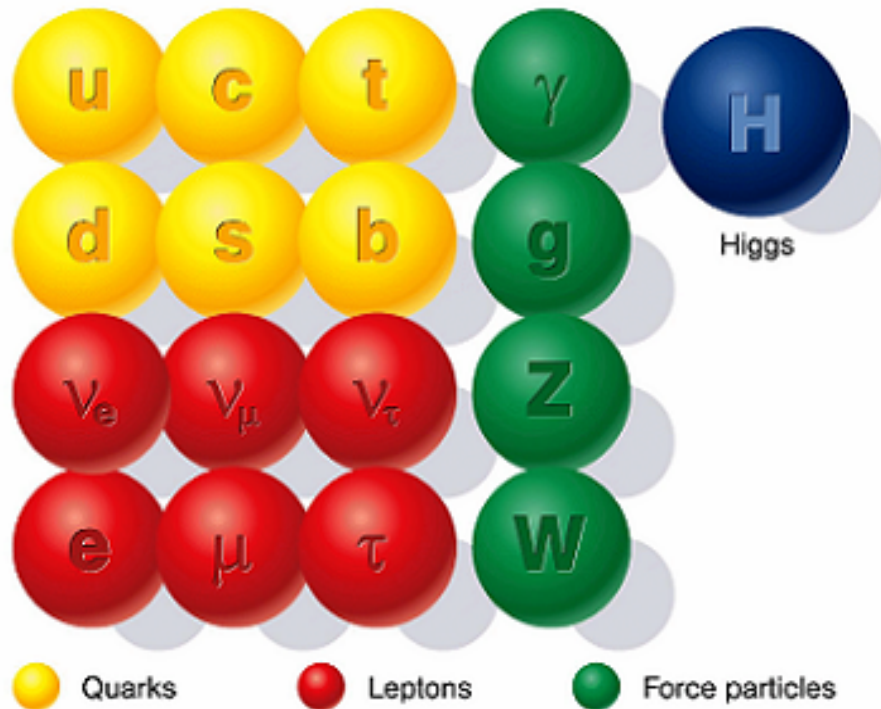


Dark Matter is required!

ANDROMEDA
GALAXY.

SUSY Particles and Neutralino

Standard particles



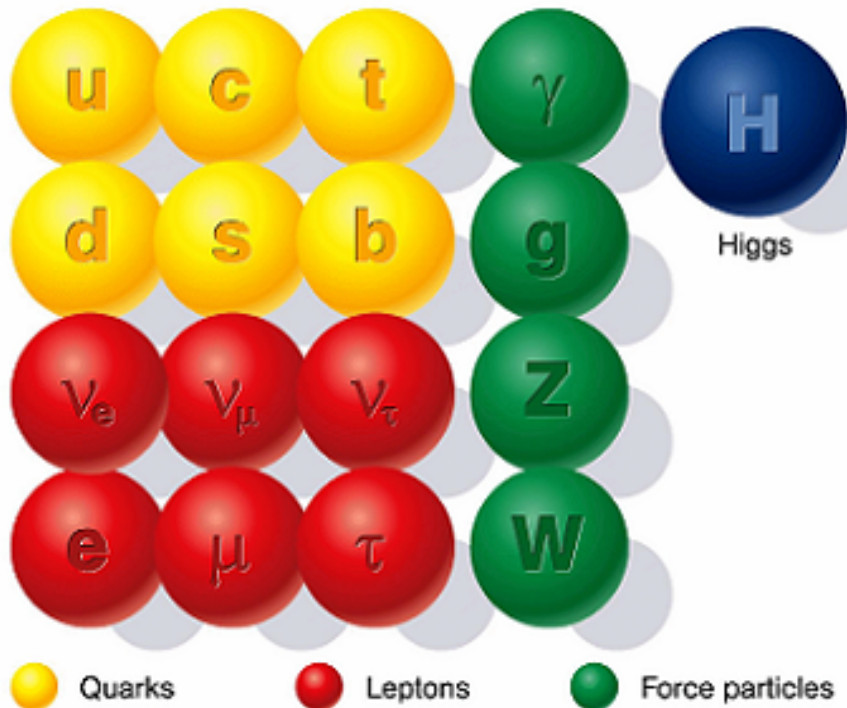
Spin 1/2 1 0

SUSY Particles and Neutralino

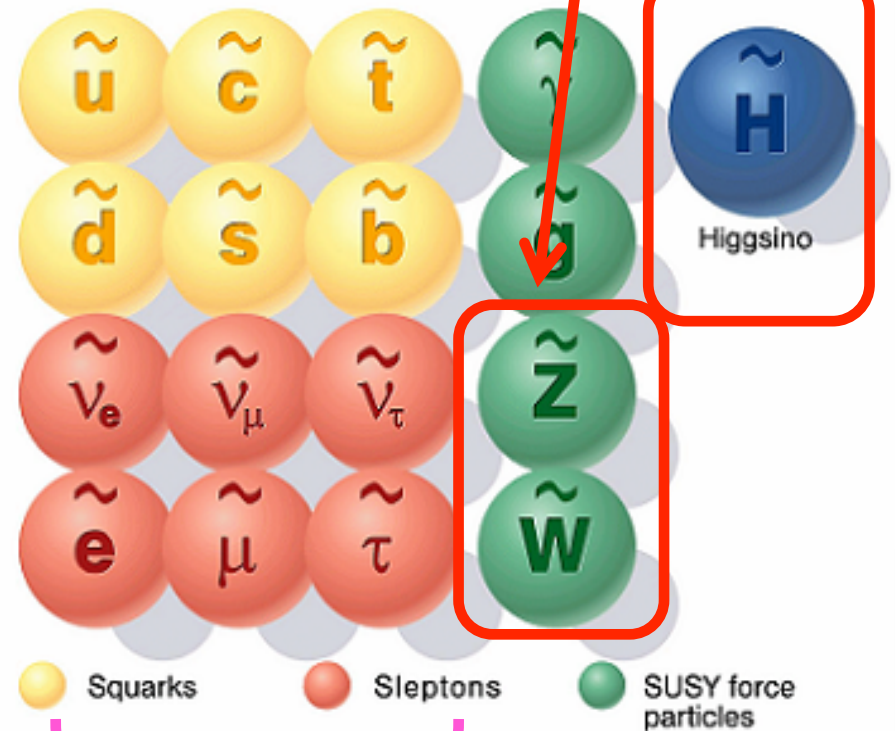
Super Symmetry

Neutralino

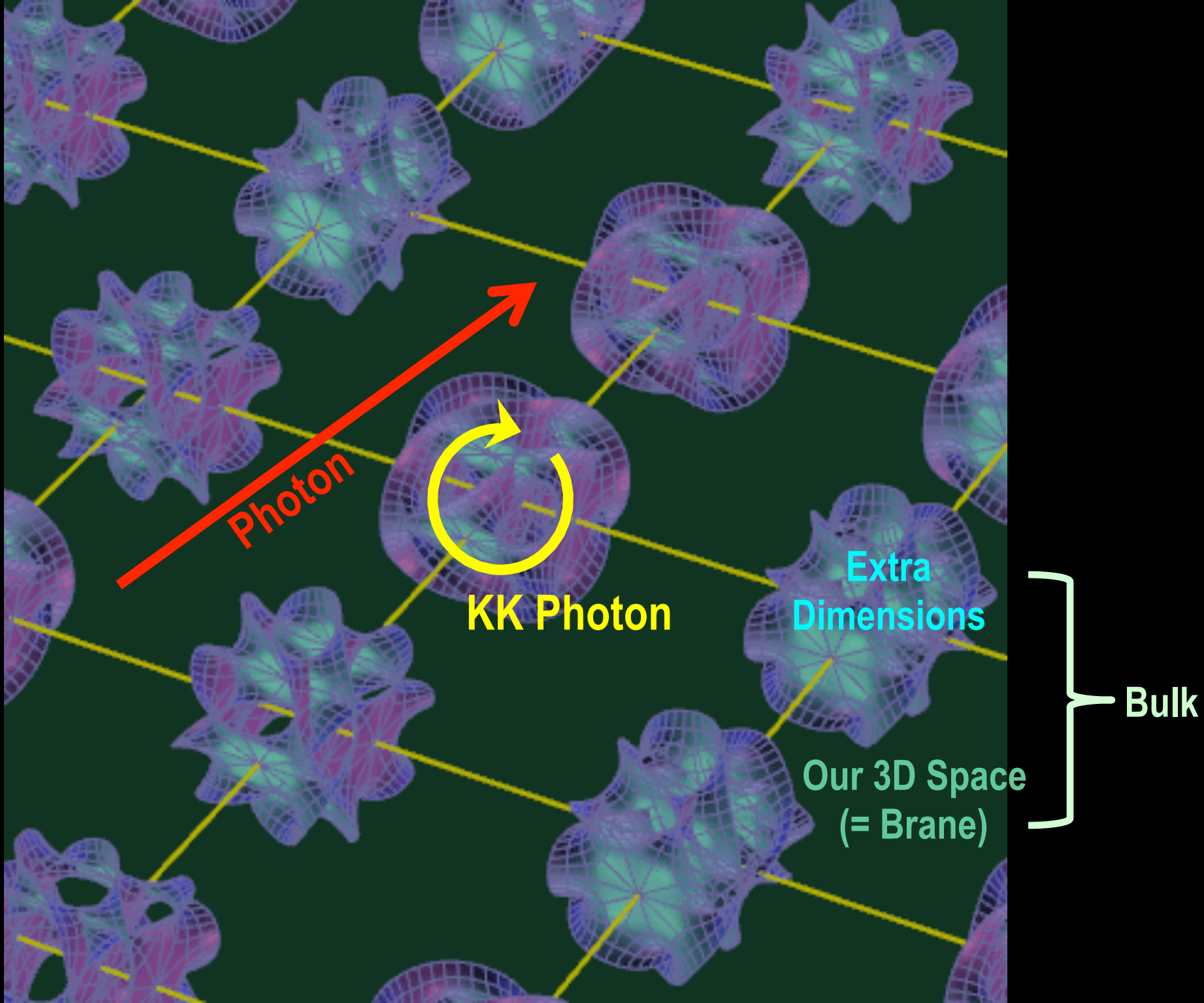
Standard particles



SUSY particles



Spin 1/2 1 0 0 1/2 1/2



Origin of Mass in Extra Dimensions

$$E = mc^2 \rightarrow m = E/c^2$$

- Mass can be generated as kinetic energy in extra dimensions.
 - Origin on mass
 - Dark matter is running in the extra dimensions
- Gravity can escape into the extra dimensions.
 - Why gravity is so small
 - Origin of dark energy

Early Universe & Unsolved Problems

