Introduction to Cosmology

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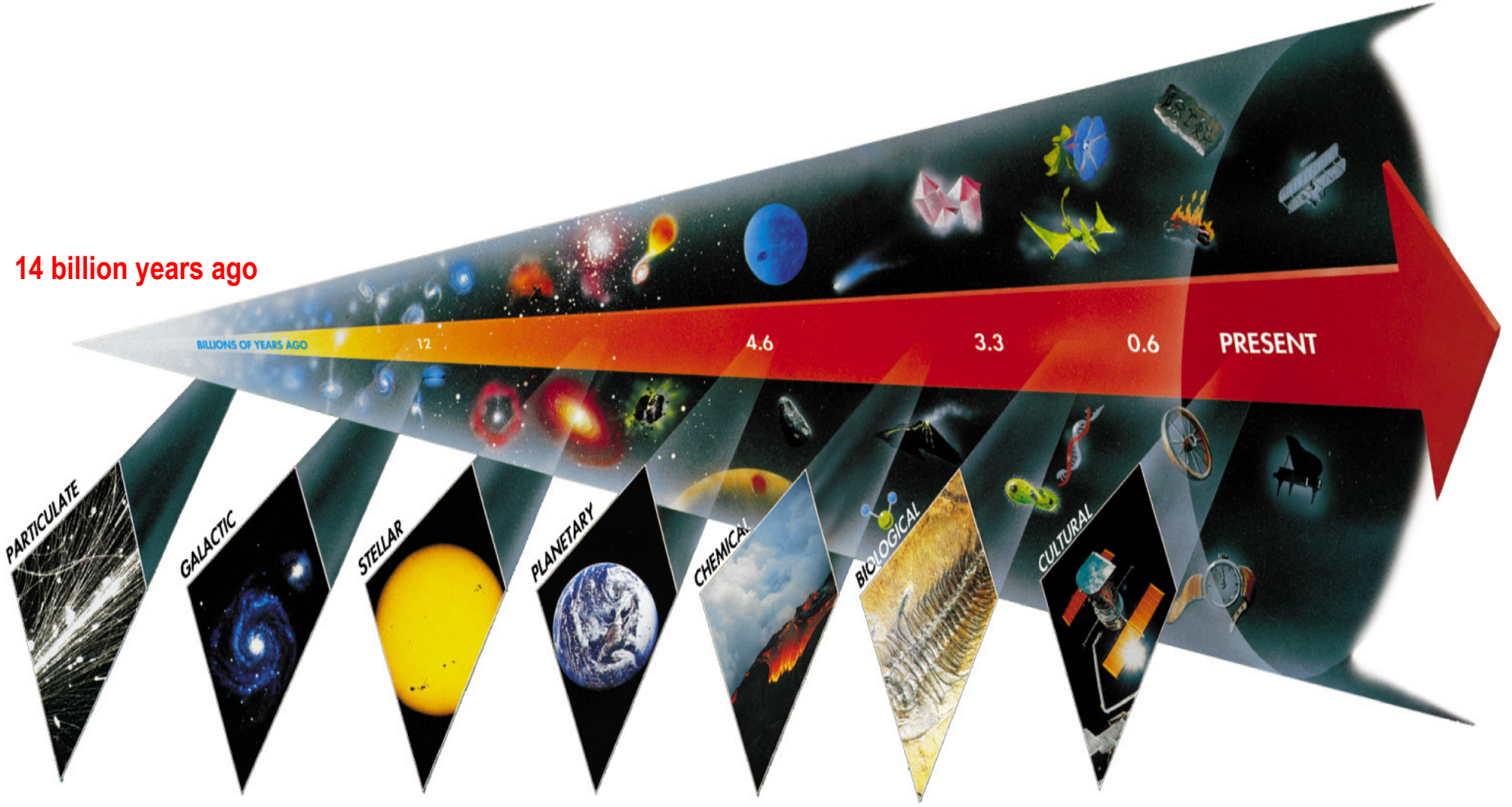
Early Univese

Seven Phases of Cosmic Evolution



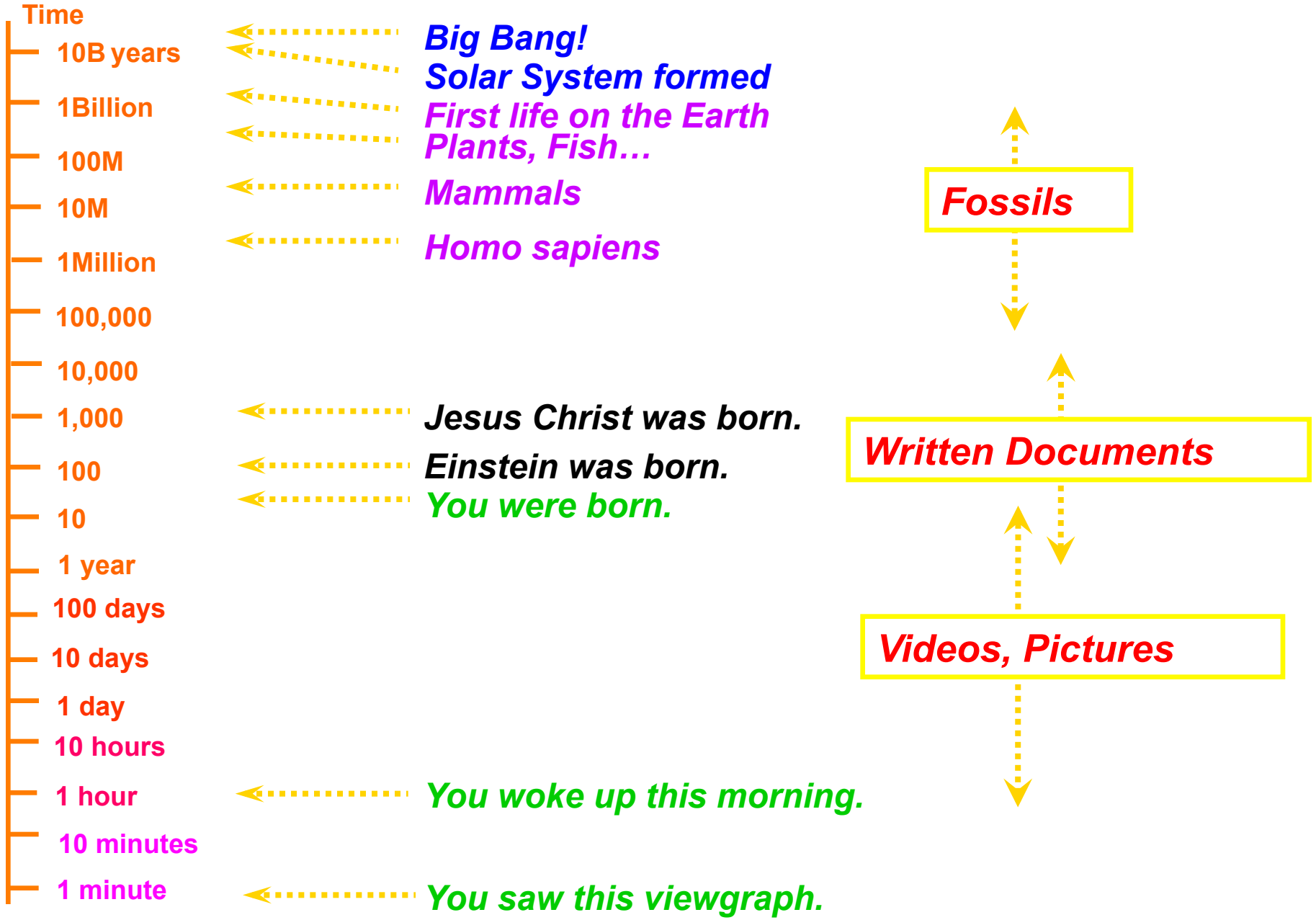
Origin of Particles

Origin of Structure

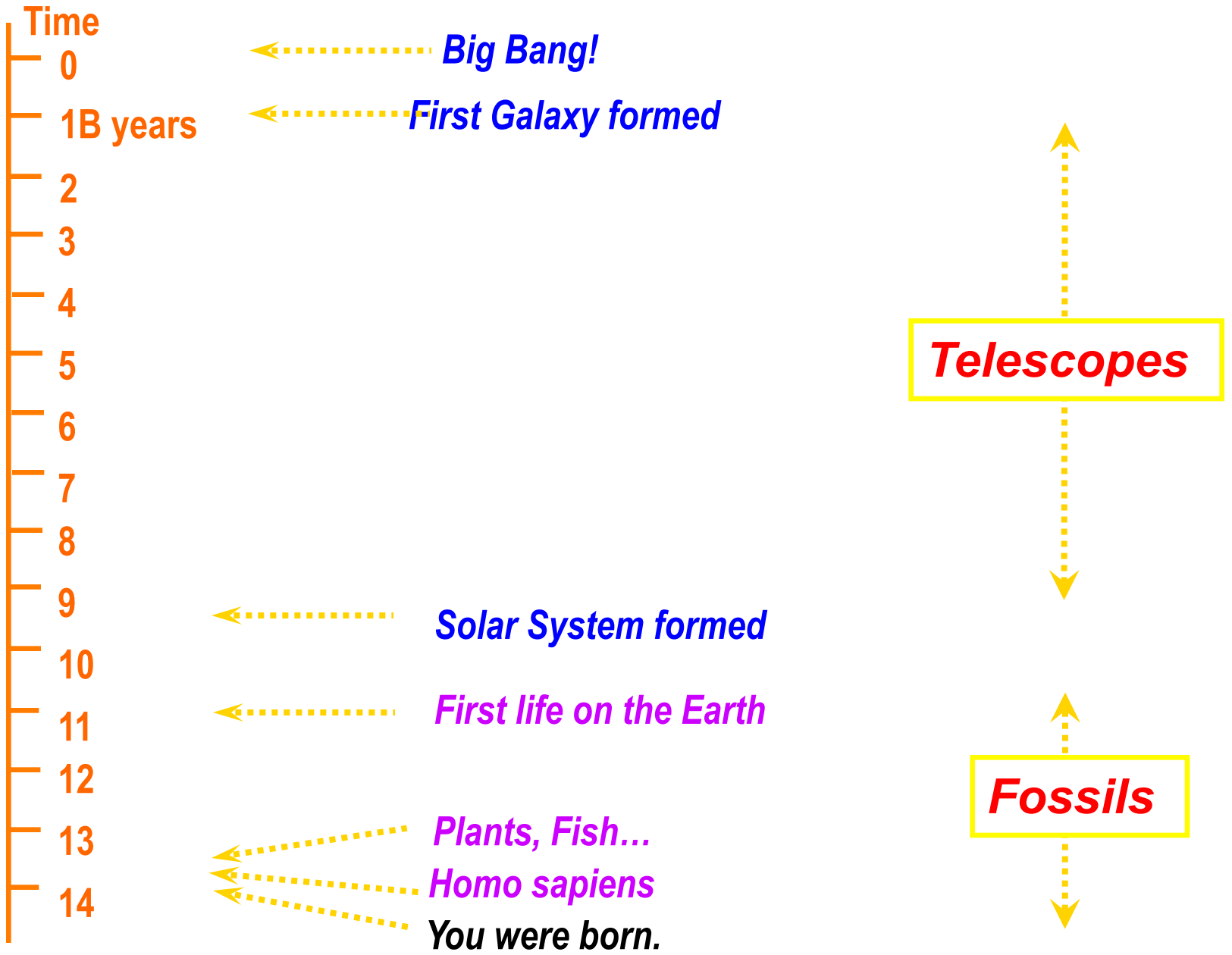
Origin of Life

Origin of Consciousness

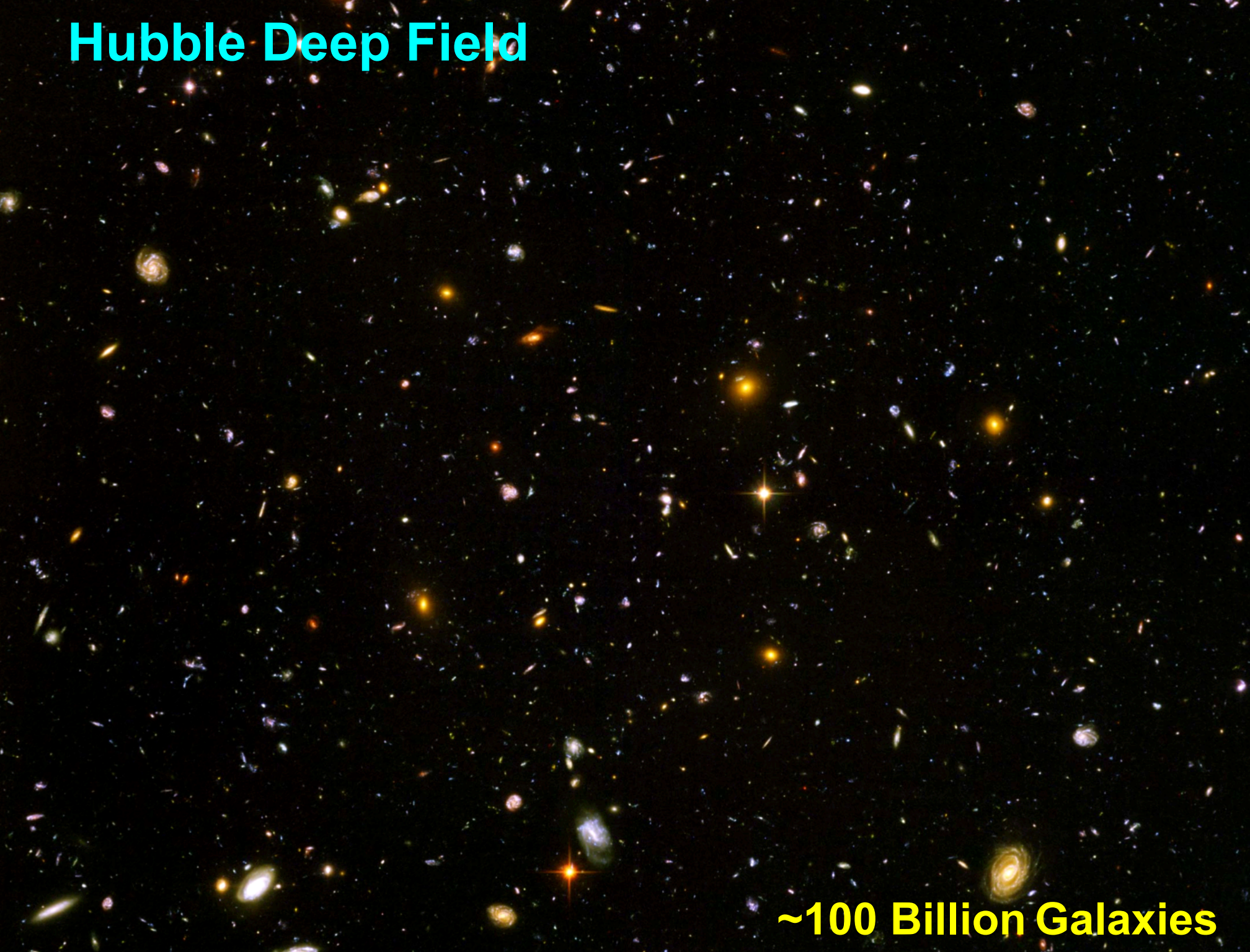
History of Life and the Human beings

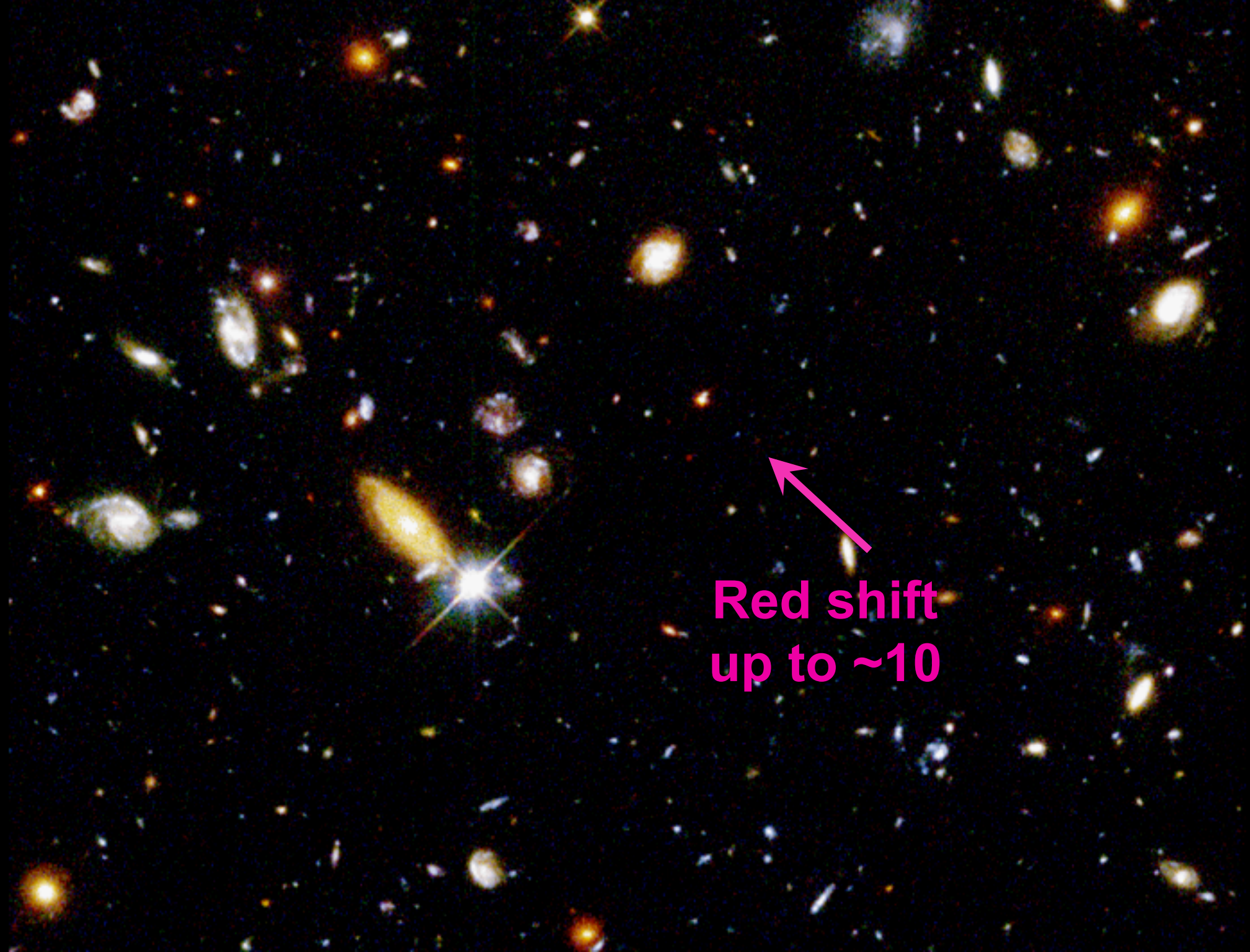


Brief History of Universe and Life



~100 Billions Stars in a Galaxy

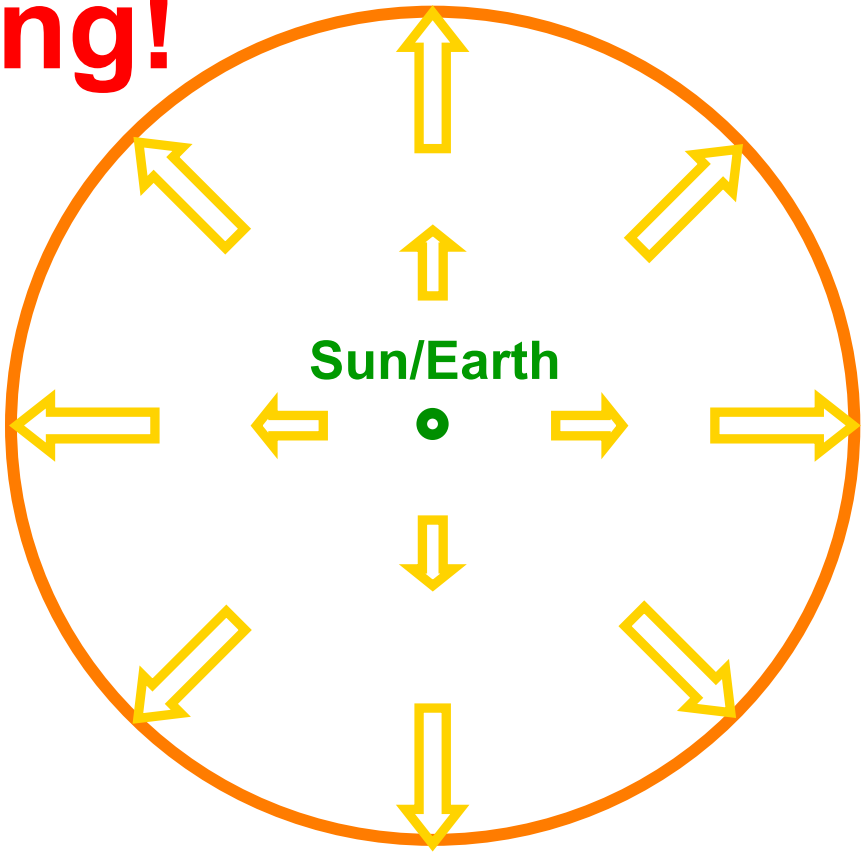

Hubble Deep Field
~100 Billion Galaxies


Red shift
up to ~10

Hubble's Law: Expansion of the Universe

Big Bang!

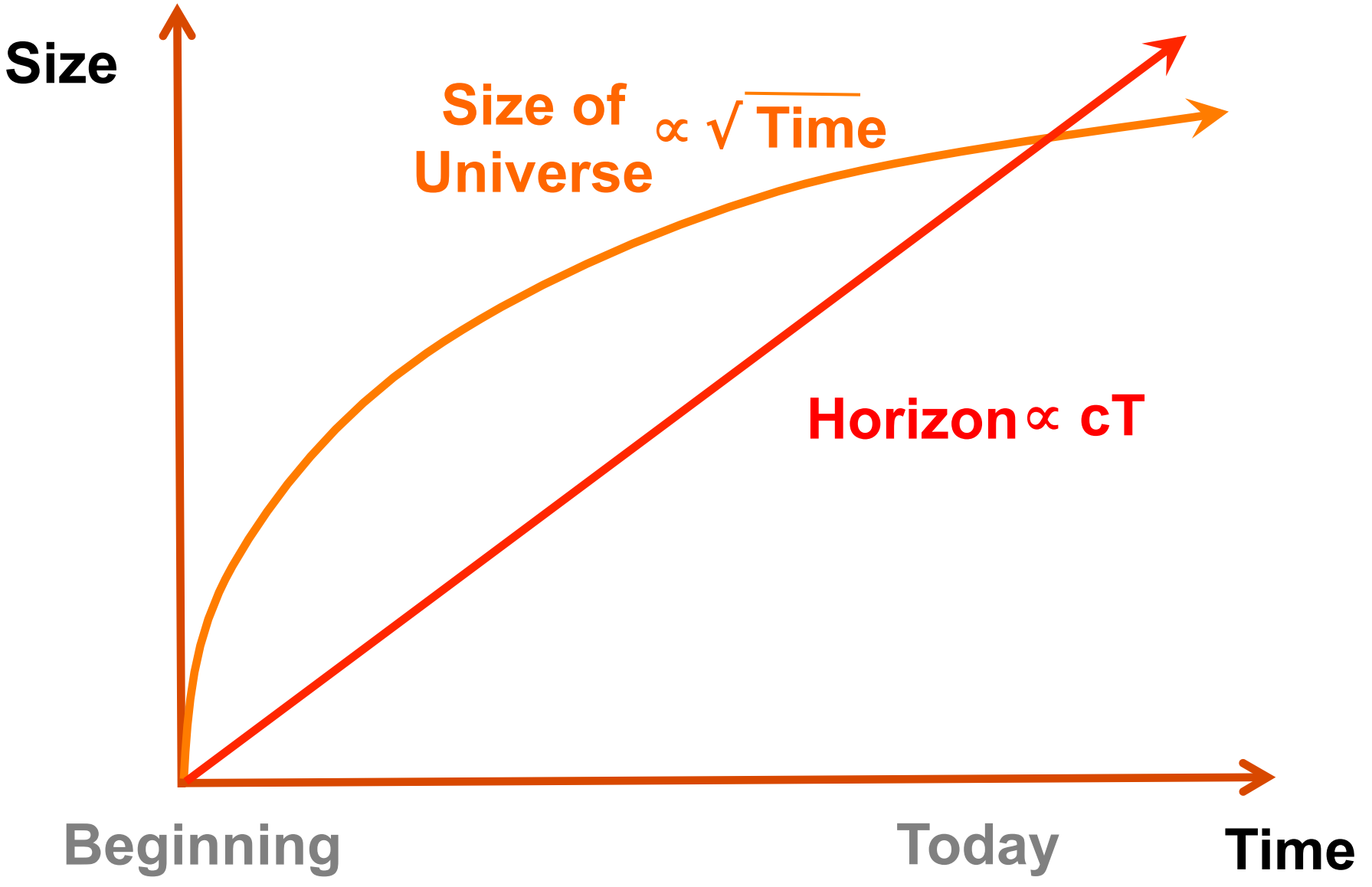
Horizon of Universe



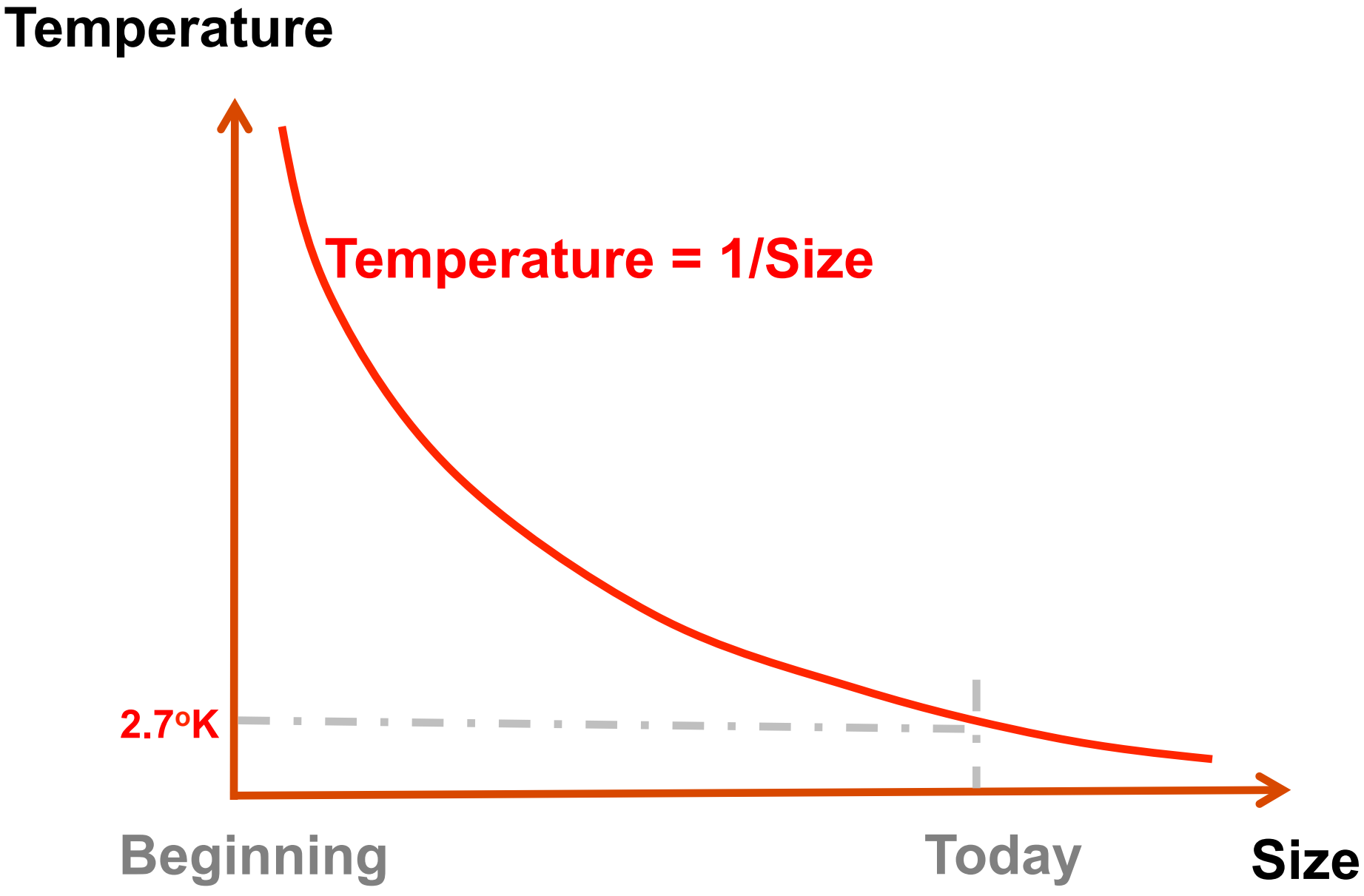
14 Billon Light Years

Moving Away at Speed of Light

Expansion of Universe



Temperature of Universe



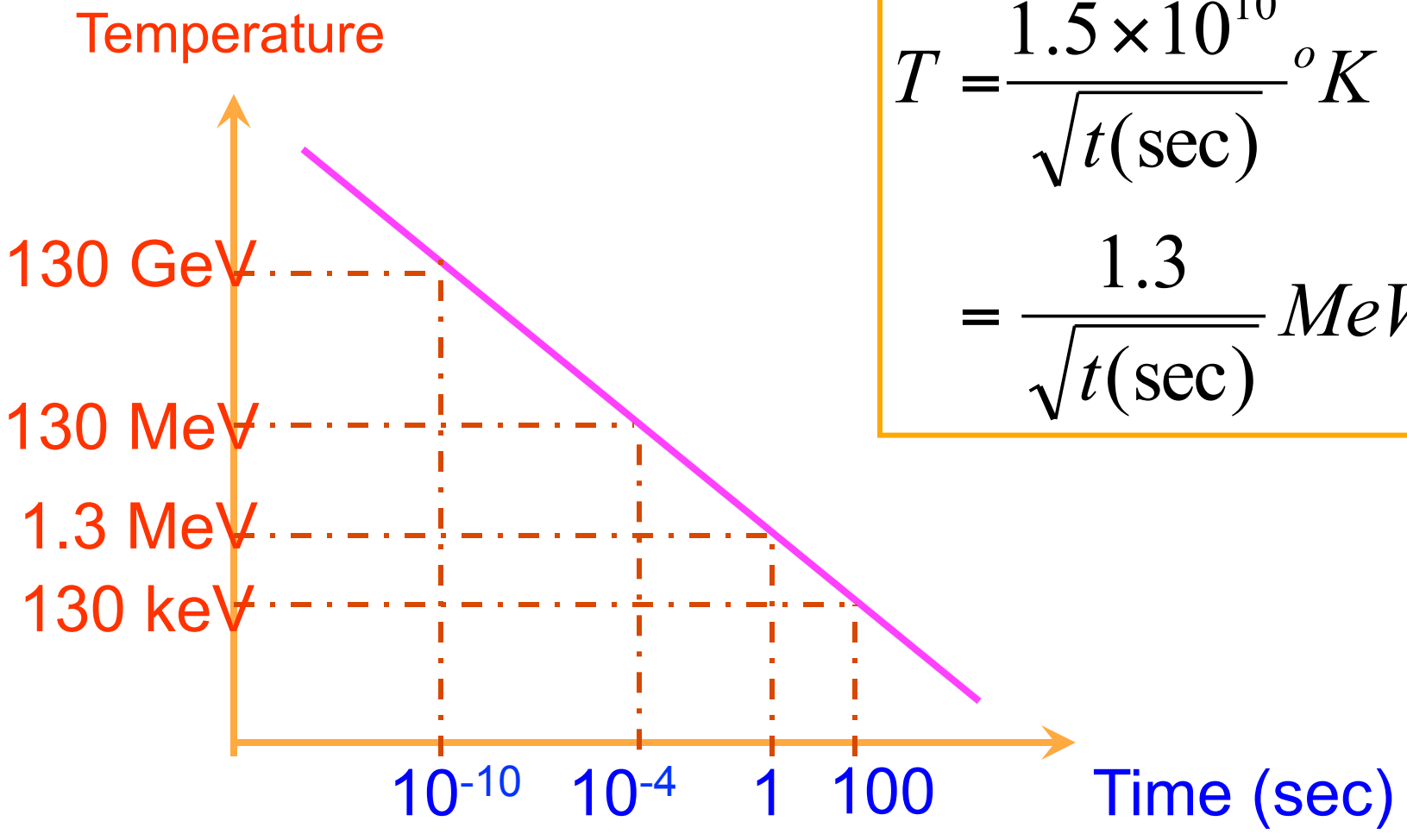
Relation between Temperature and Time

T: Temperature

t : time

$$T = \frac{1.5 \times 10^{10}}{\sqrt{t(\text{sec})}}\, {}^{o}K$$

$$= \frac{1.3}{\sqrt{t(\text{sec})}}\, MeV$$



Thermal Equilibrium

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

$$E > 2mc^2$$

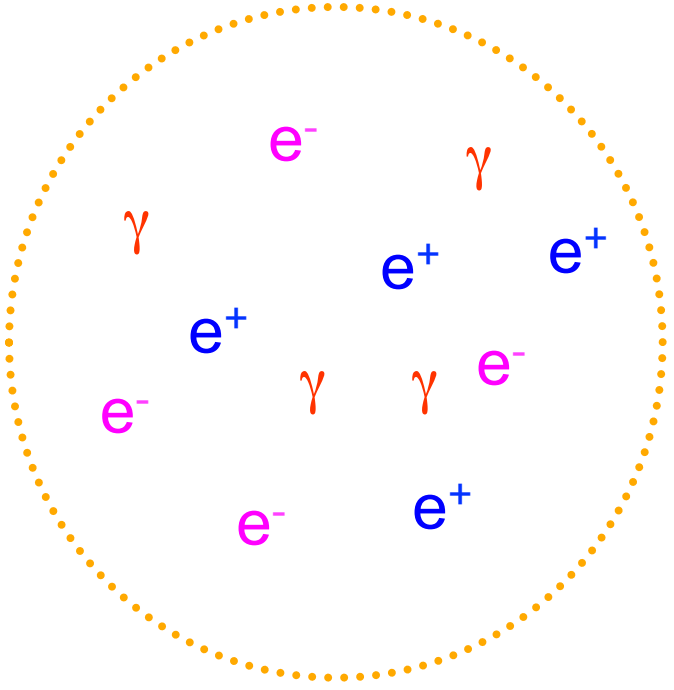
Photon ↔ Particle + Anti-particle

Example:

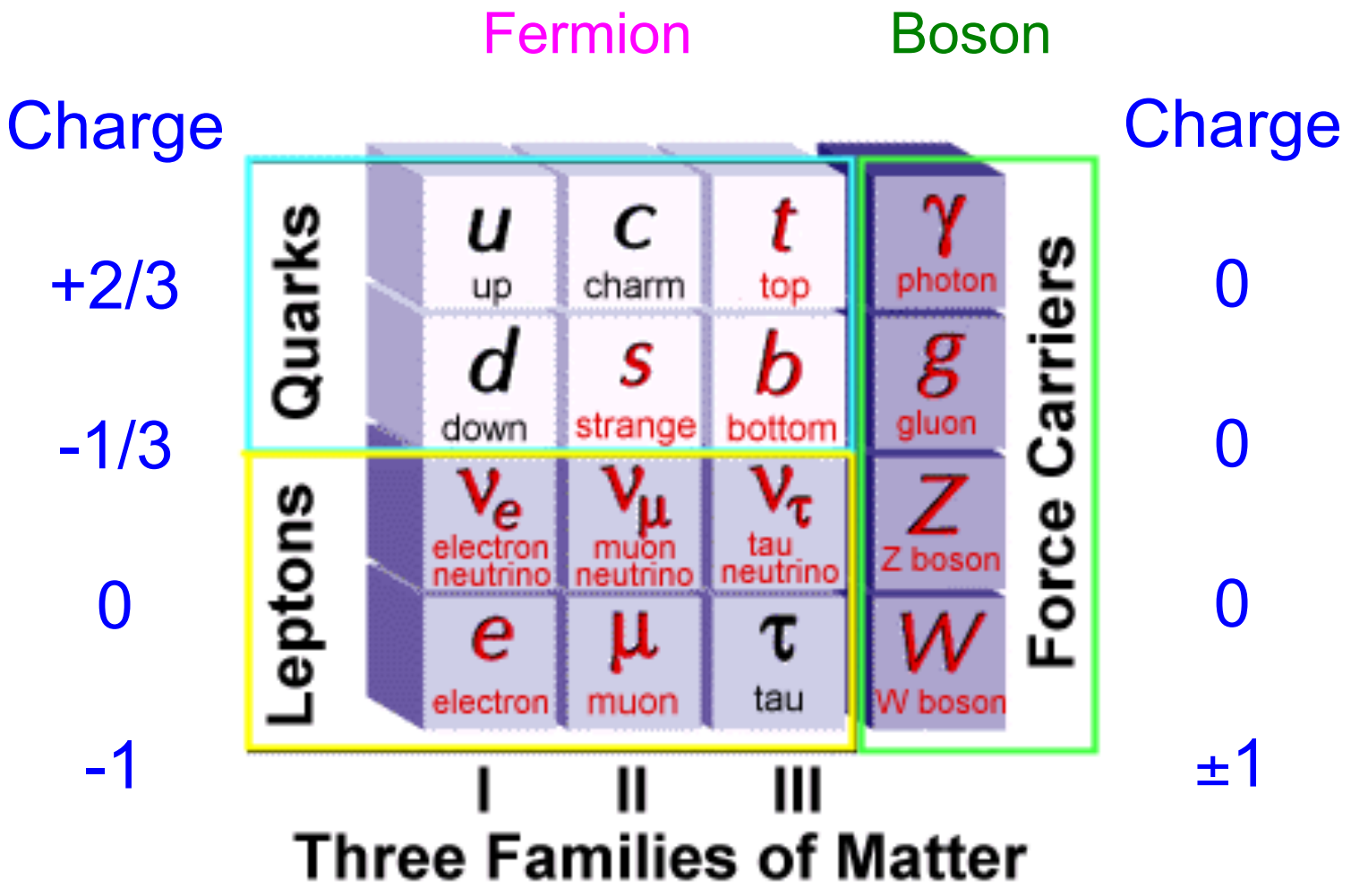
$m_e = 0.511$ MeV

if $E > 1.022$ MeV

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

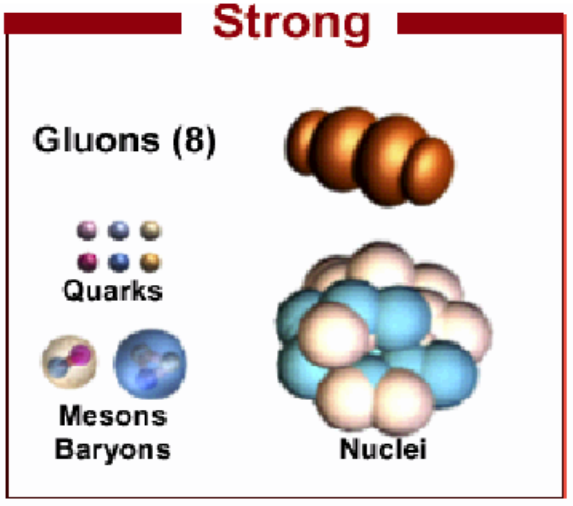


Elementary Particles



+ Anti-particles

Elementary Particles and Forces



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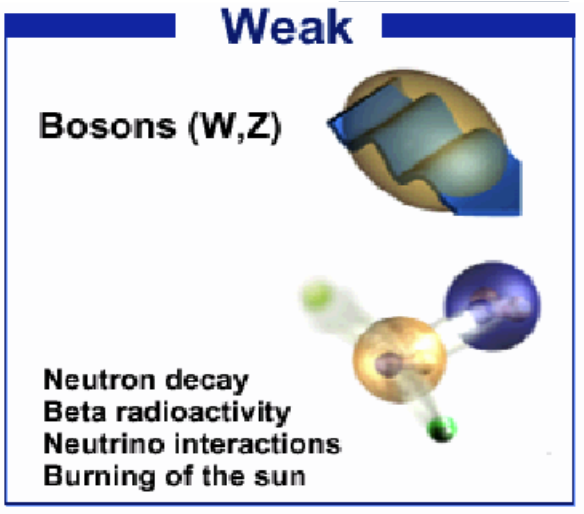
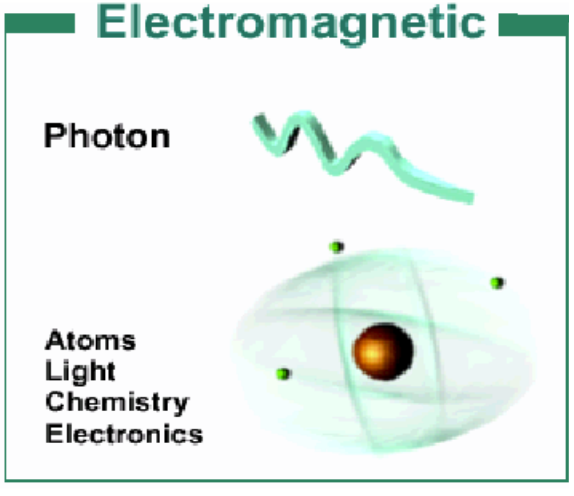
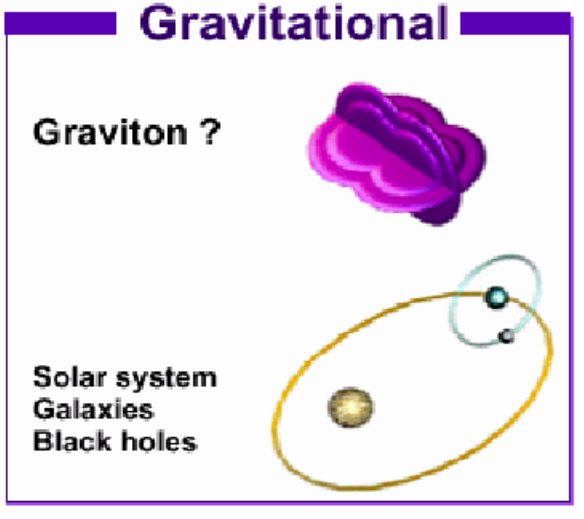


10^{-13}

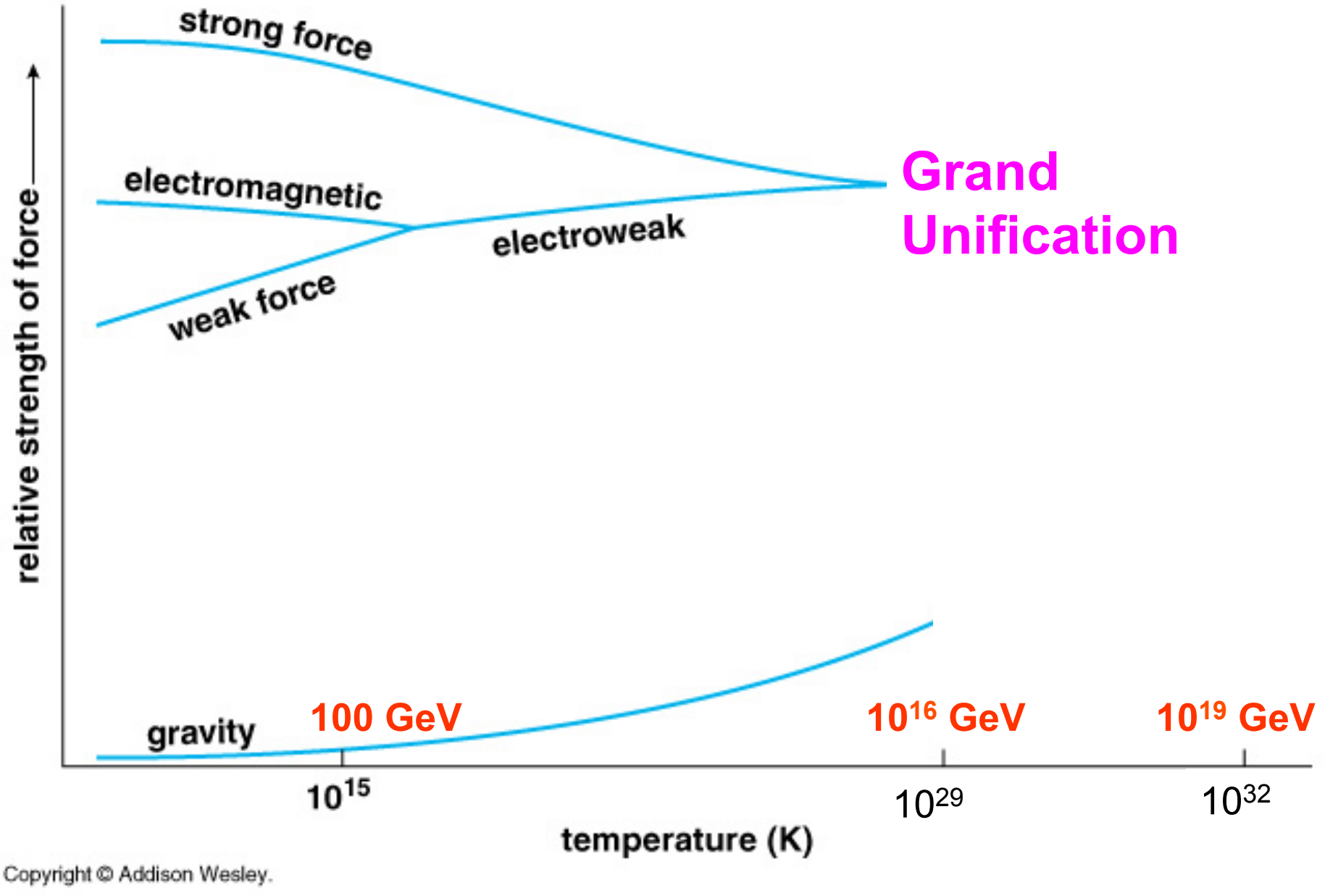
10^{-2}



10^{-38}



Unification of Forces (1980)



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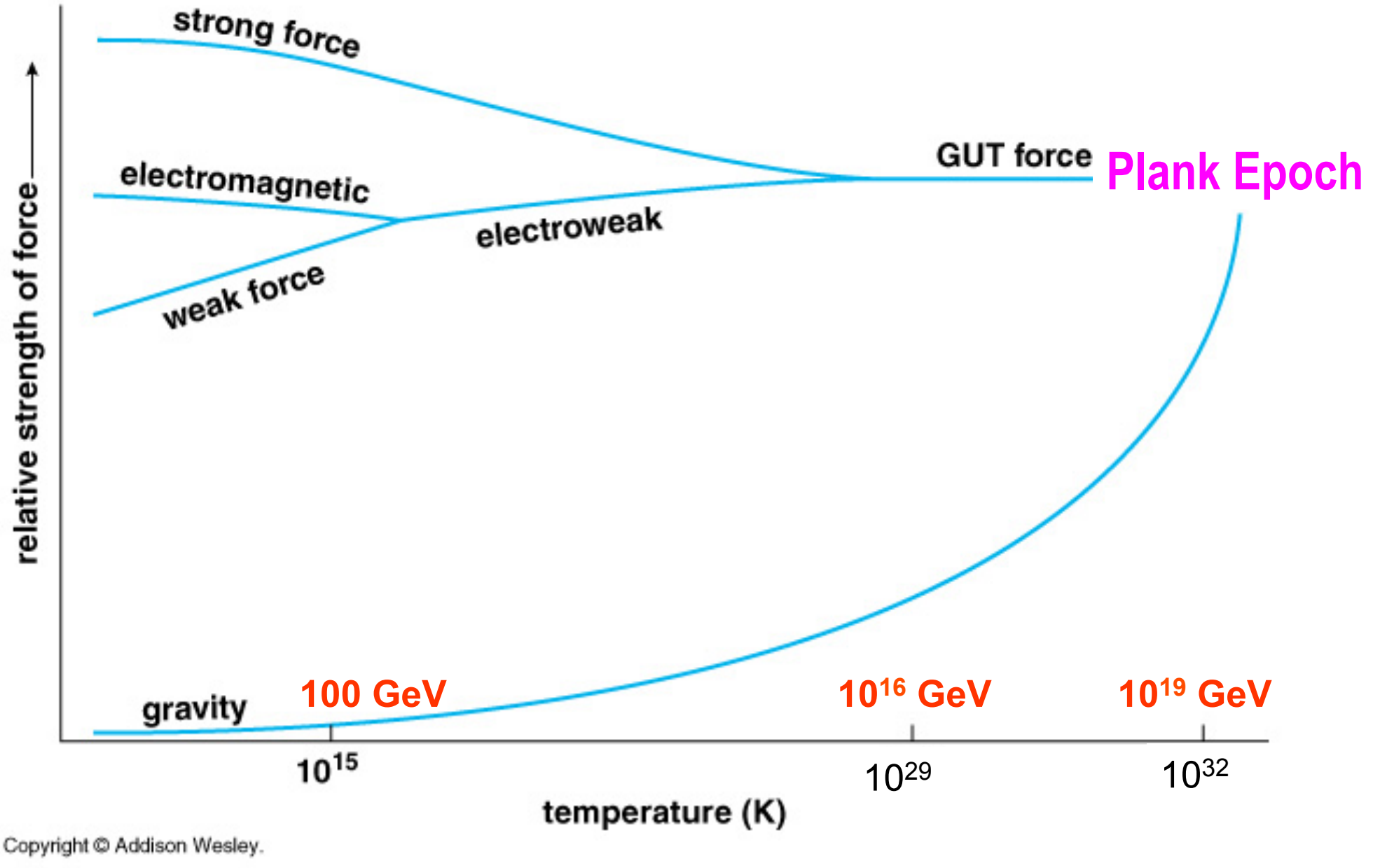


Physicists' View of Early Universe

Fiat lux

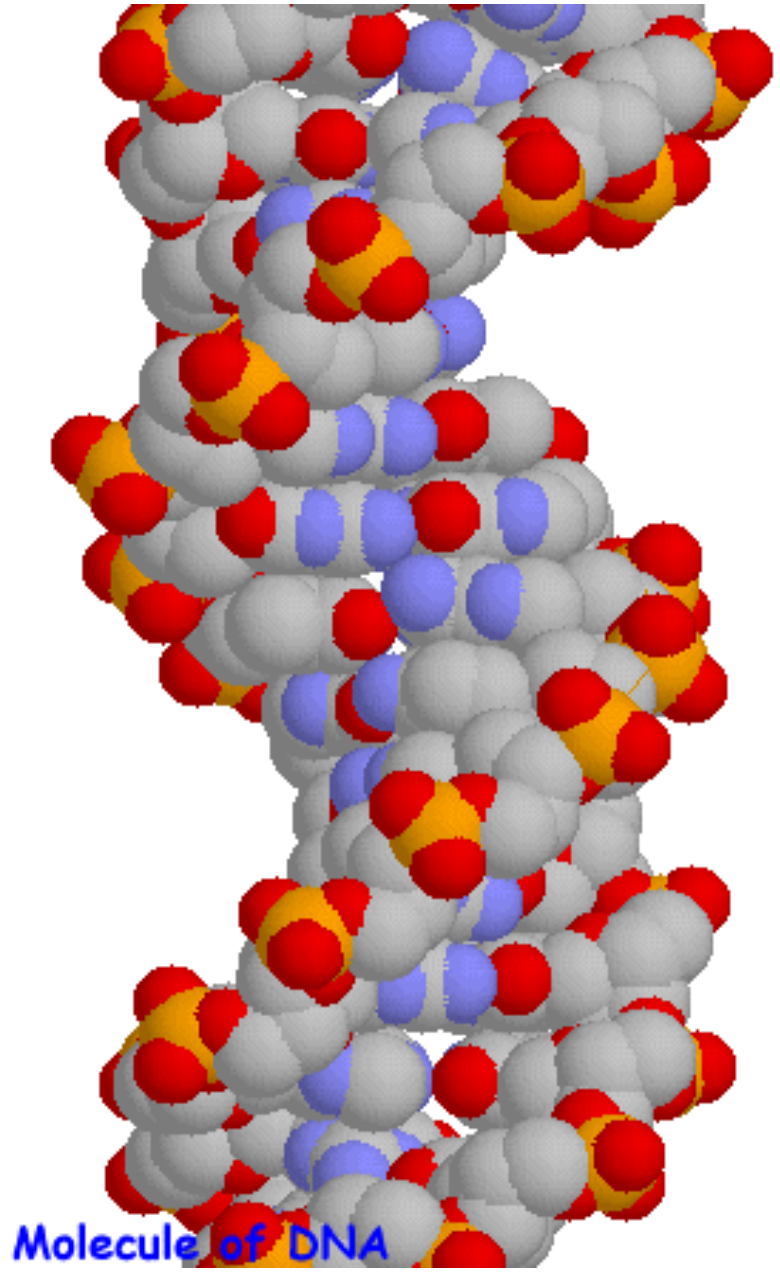
Let there be light

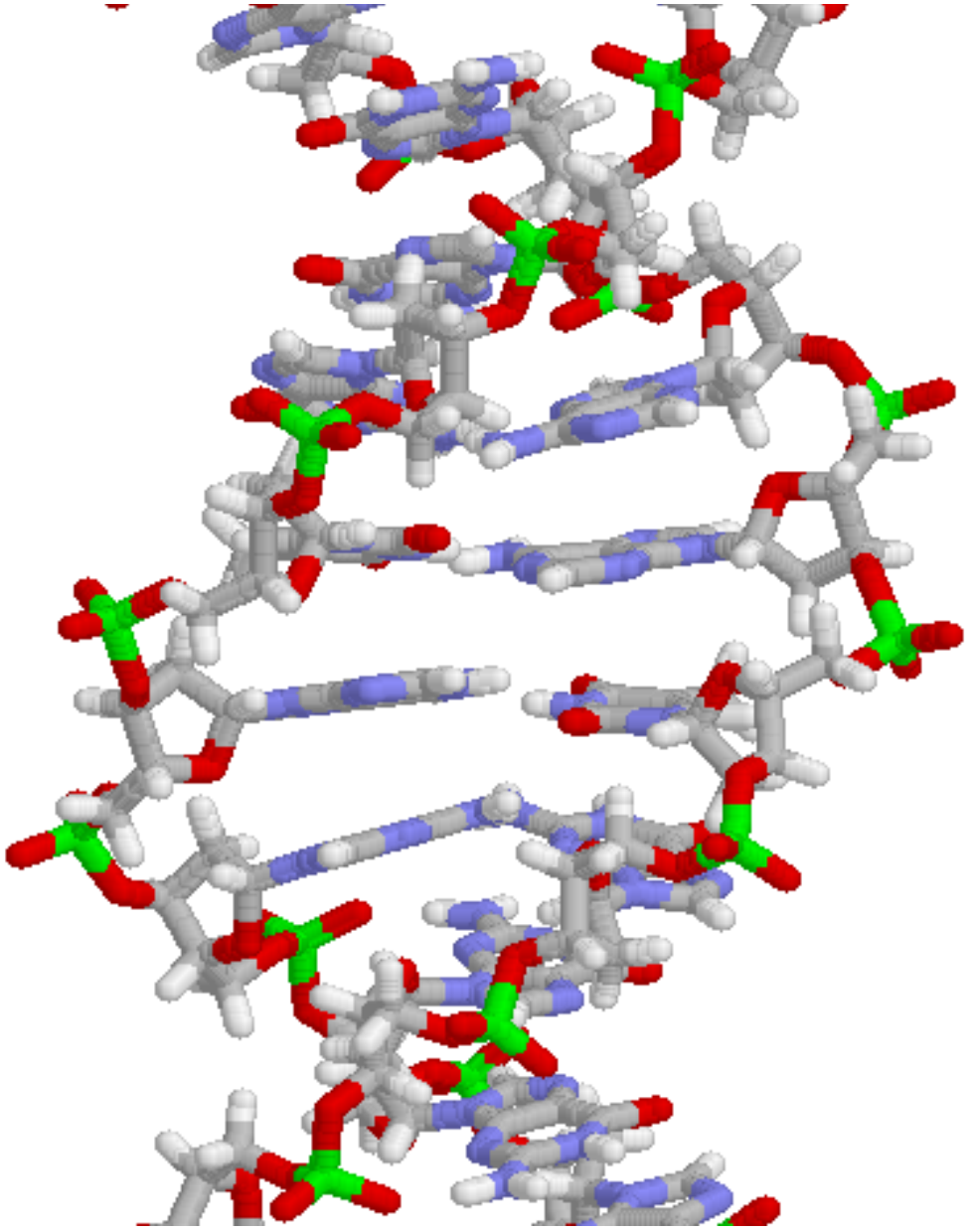
Physicists' View of Early Universe

Lorentz Invariance

Local Gauge Invariance

Structure of DNA





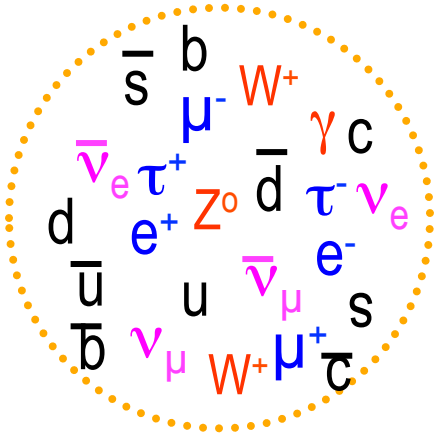
Symmetry Breaking

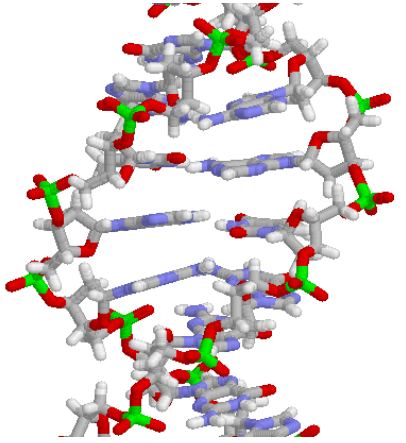
Time
0
1B years
2
3
4
5
6
7
8
9
10
11
12
13
14

Simple

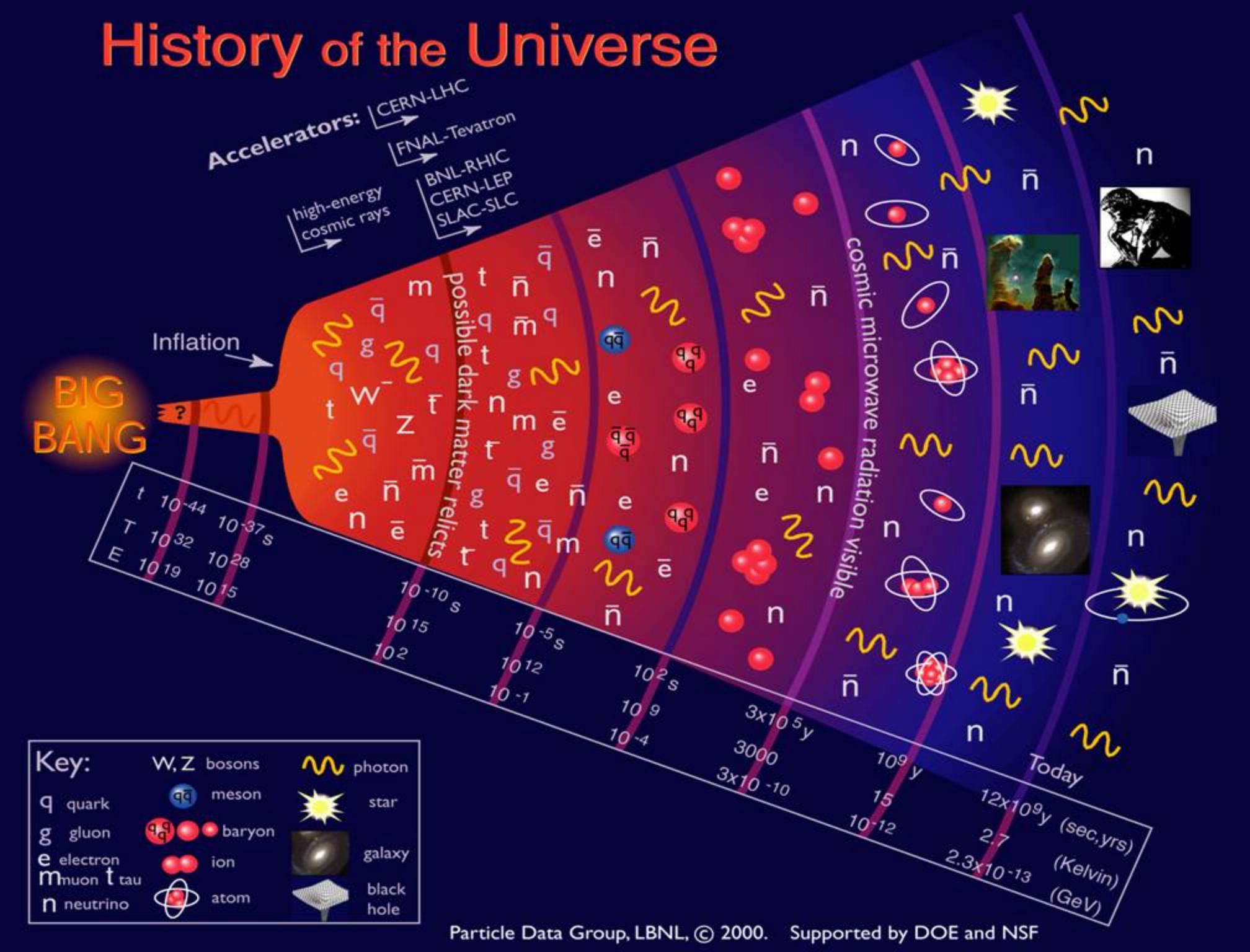
Symmetry Break Down

Complex





History of the Universe



Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

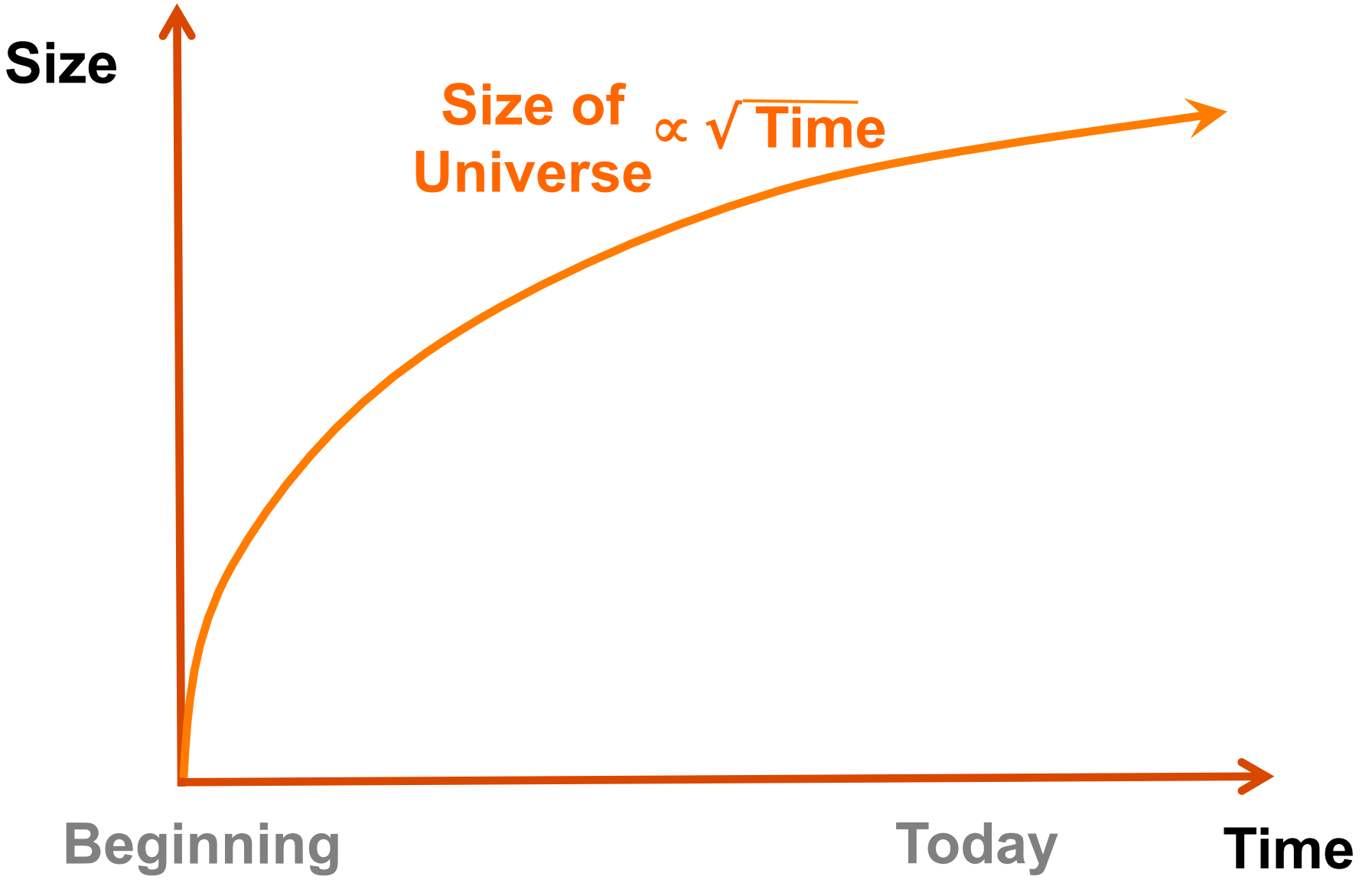
The Beginning

- **Everything was the same ↔ Perfect symmetry.**
  - All the particles are the same as photons.
  - All four forces are the same.

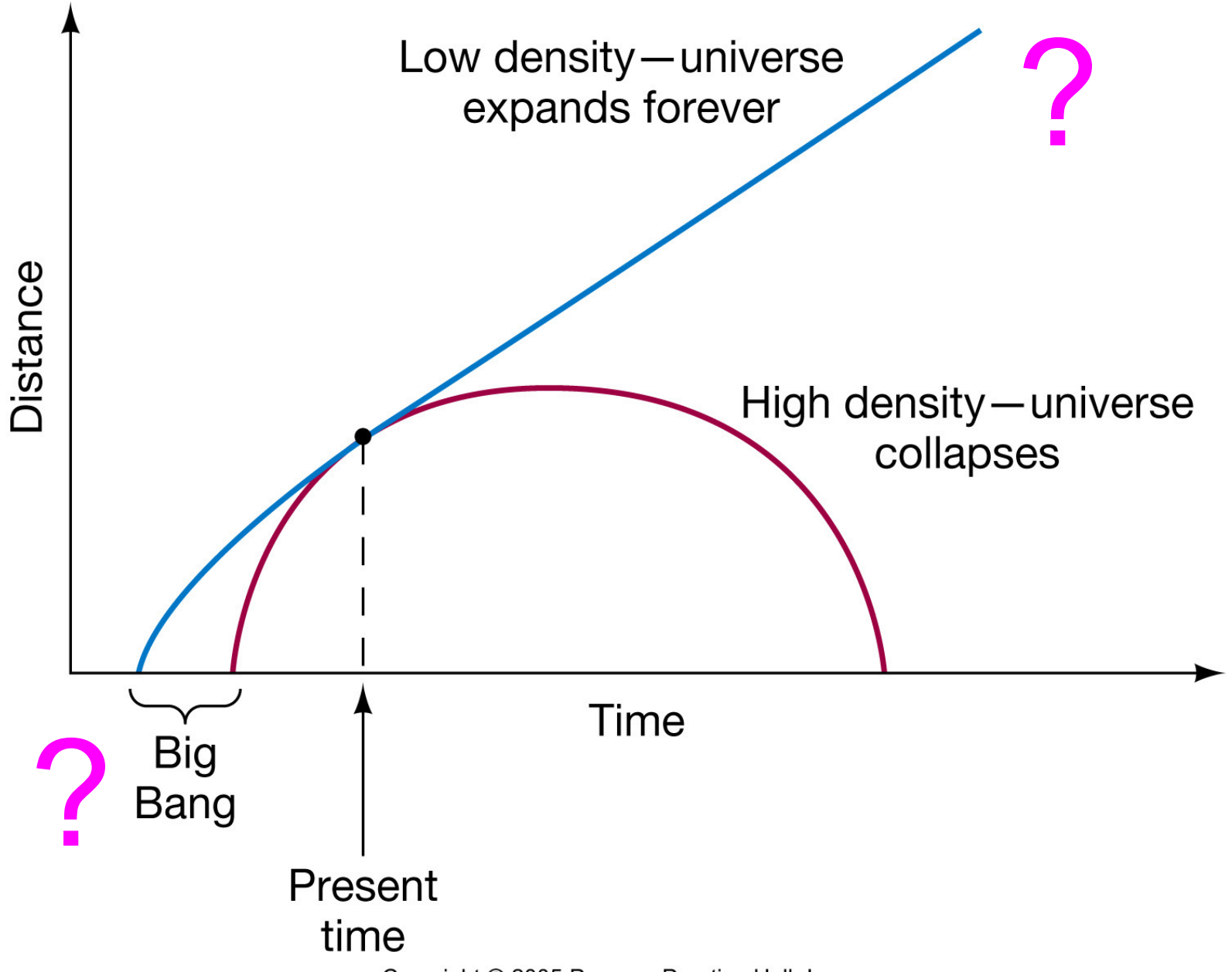
- **The Universe was 10 dimension.**

Cosmology

Expansion of Universe

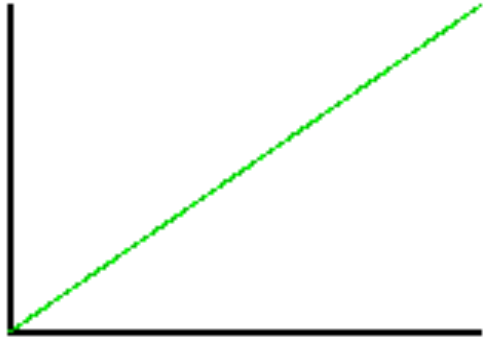


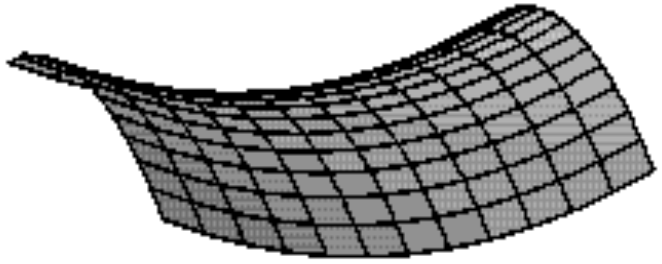
The Fate of the Cosmos



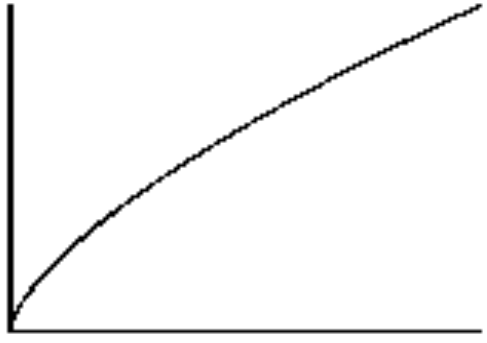
Geometry of the Universe

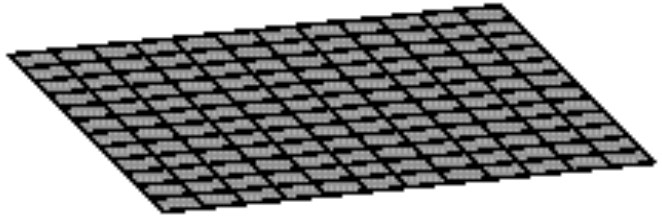
Open $\Omega<1$



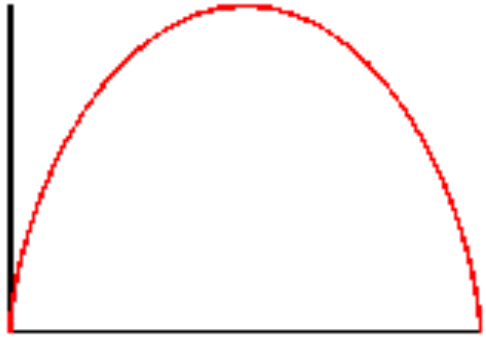


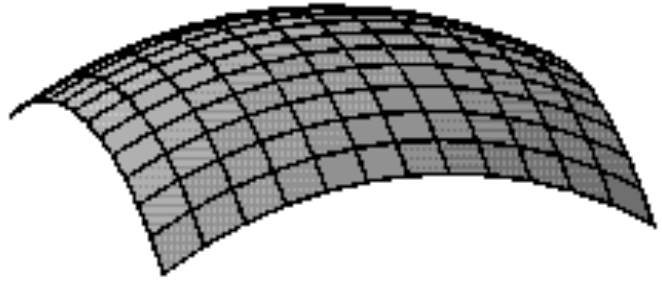
Flat $\Omega=1$



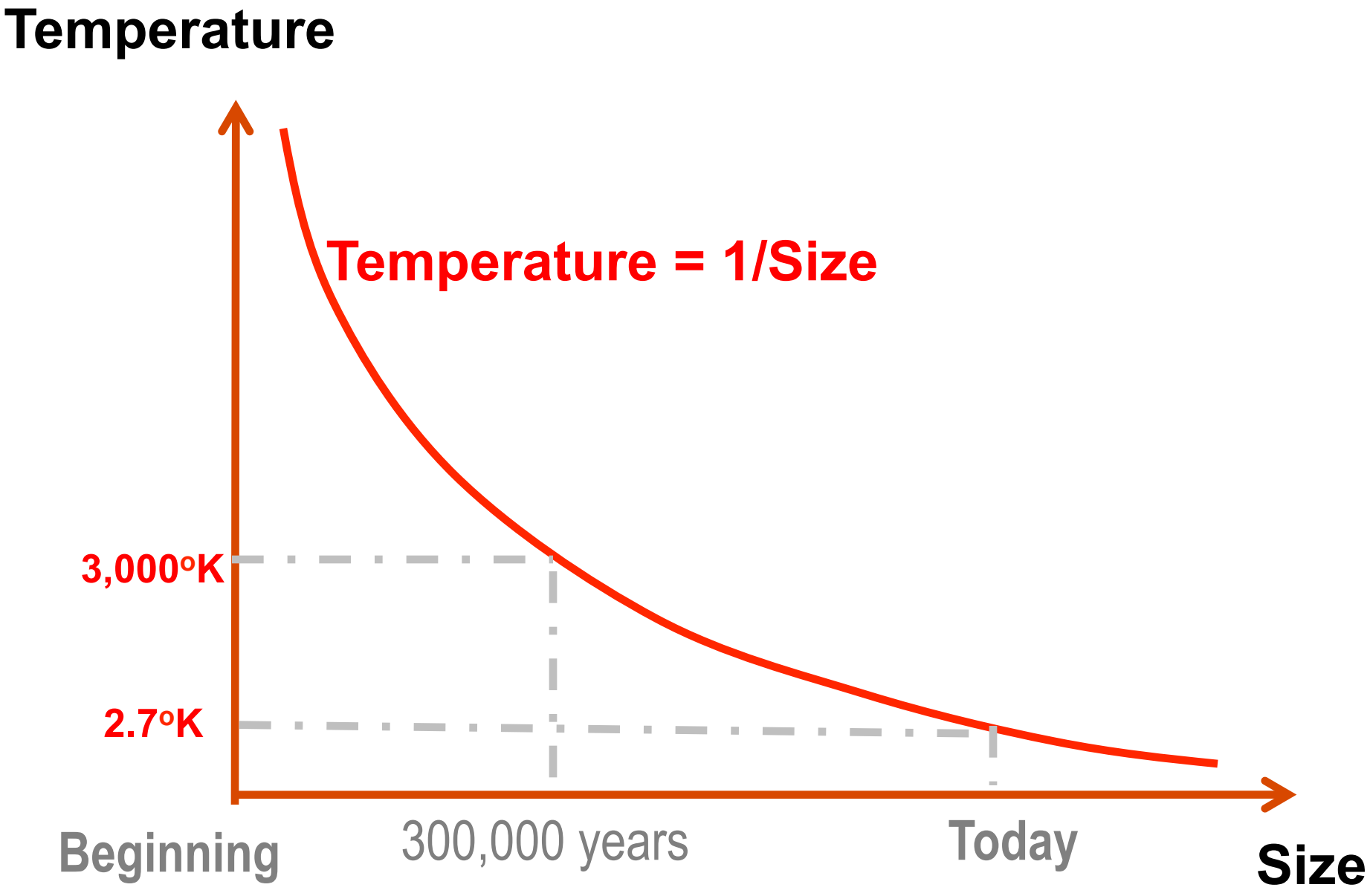


Closed $\Omega>1$





Temperature of Universe



Time = 300,000 years , Temp.= 3000 ^{o}K

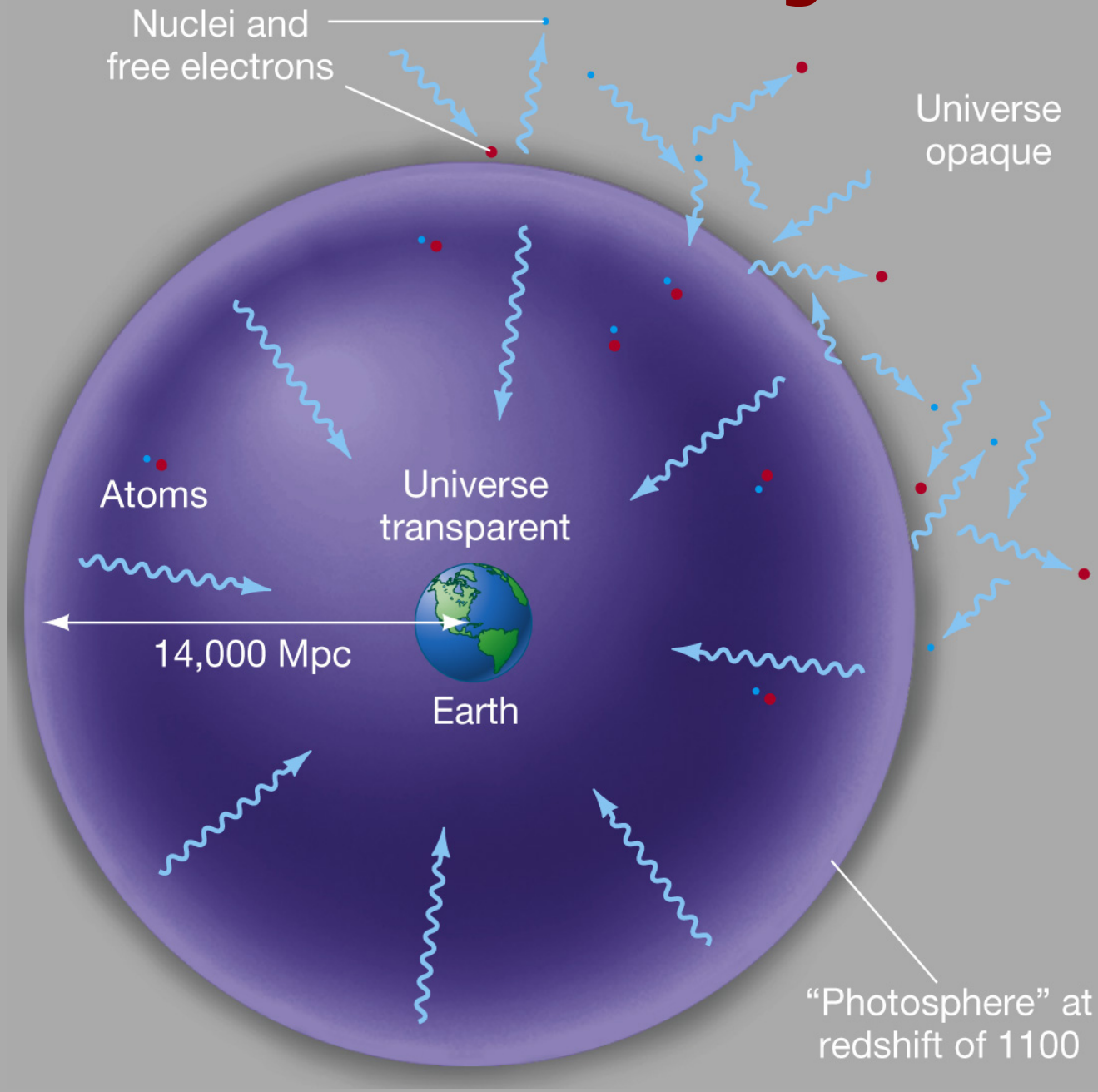
- All the electrons were bound by Hydrogen and Helium Nuclei. → Atoms formed.
- The Universe became transparent. Photons were released. → Radiation decoupled.

⇩

Cosmic Microwave Background (CMB)

The Sun

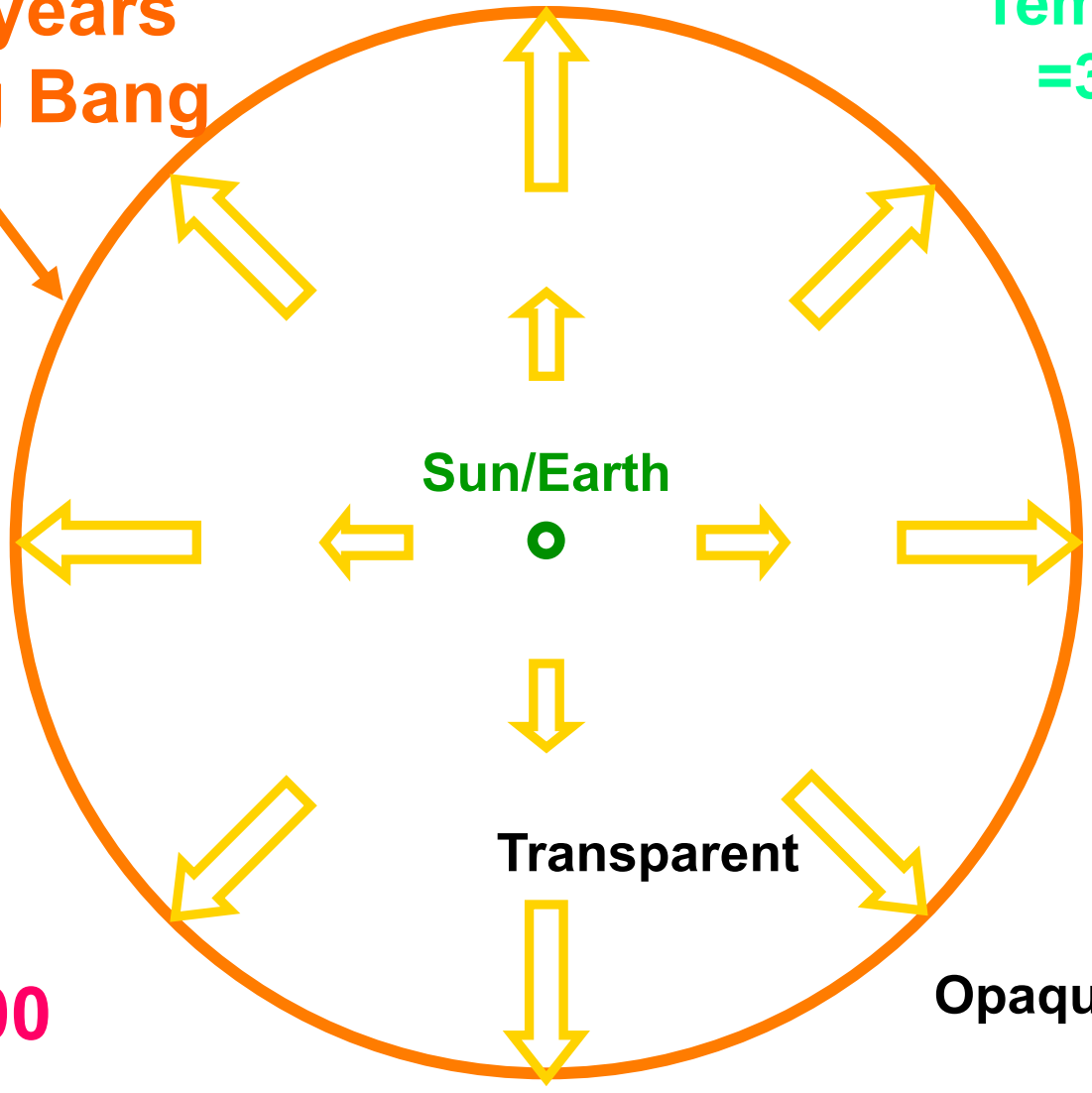
Cosmic Microwave Background



Cosmic Microwave Background
(Discovered in 1964)

T=300,000 years after the Big Bang

Temperature =3,000°K

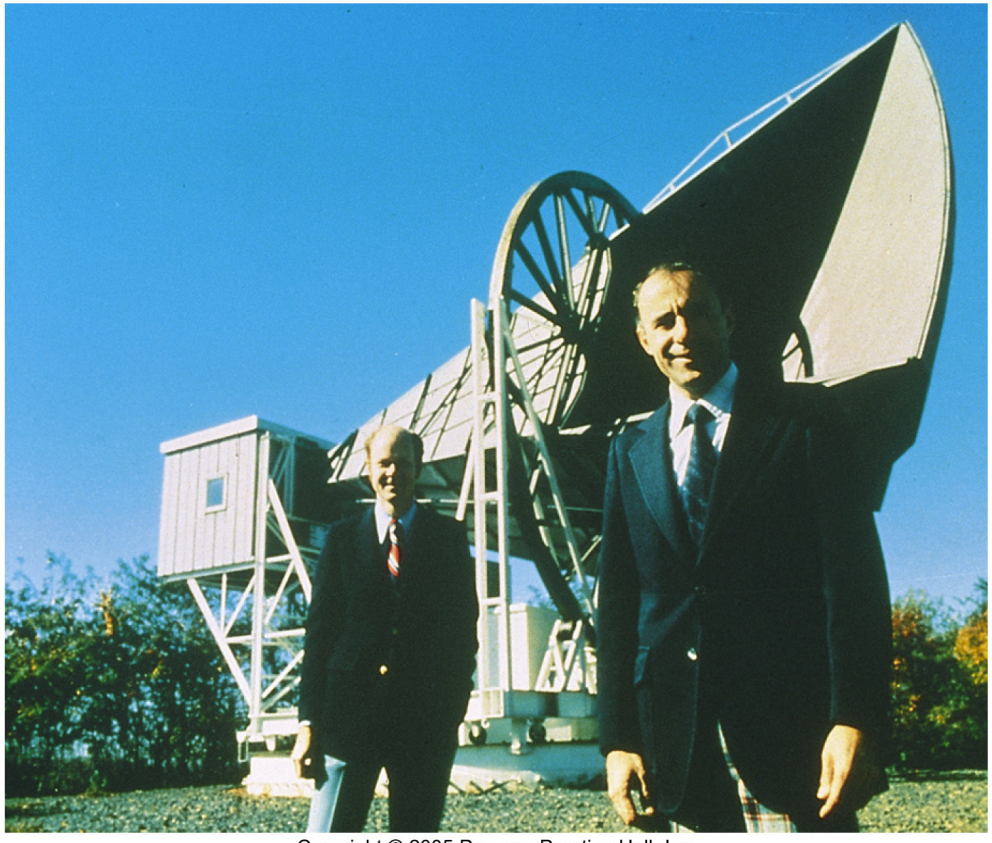


z=1,100

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.

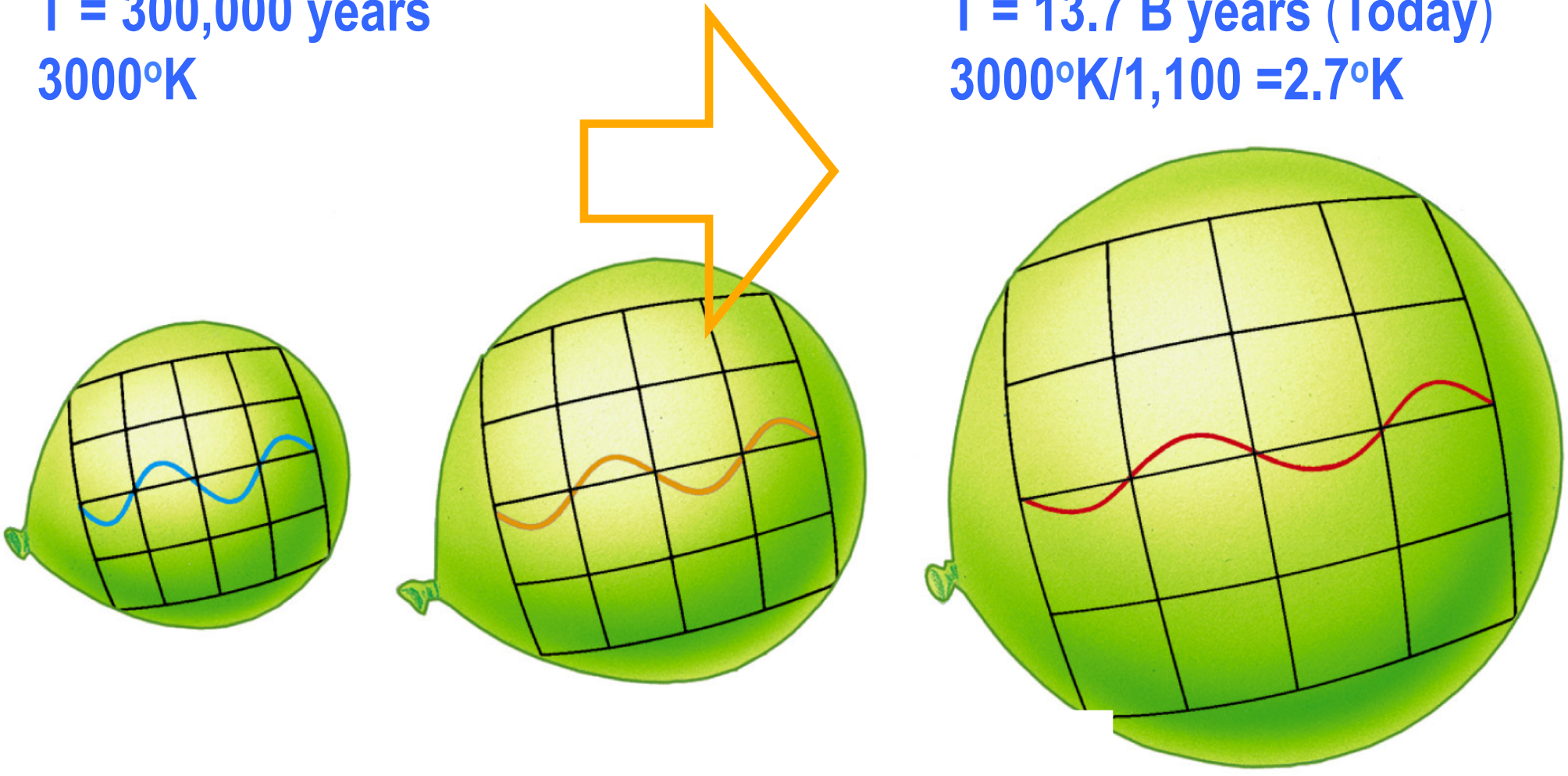


Instead they found that the "noise" came from all directions and at all times, and was always the same. They were detecting photons left over from the Big Bang.

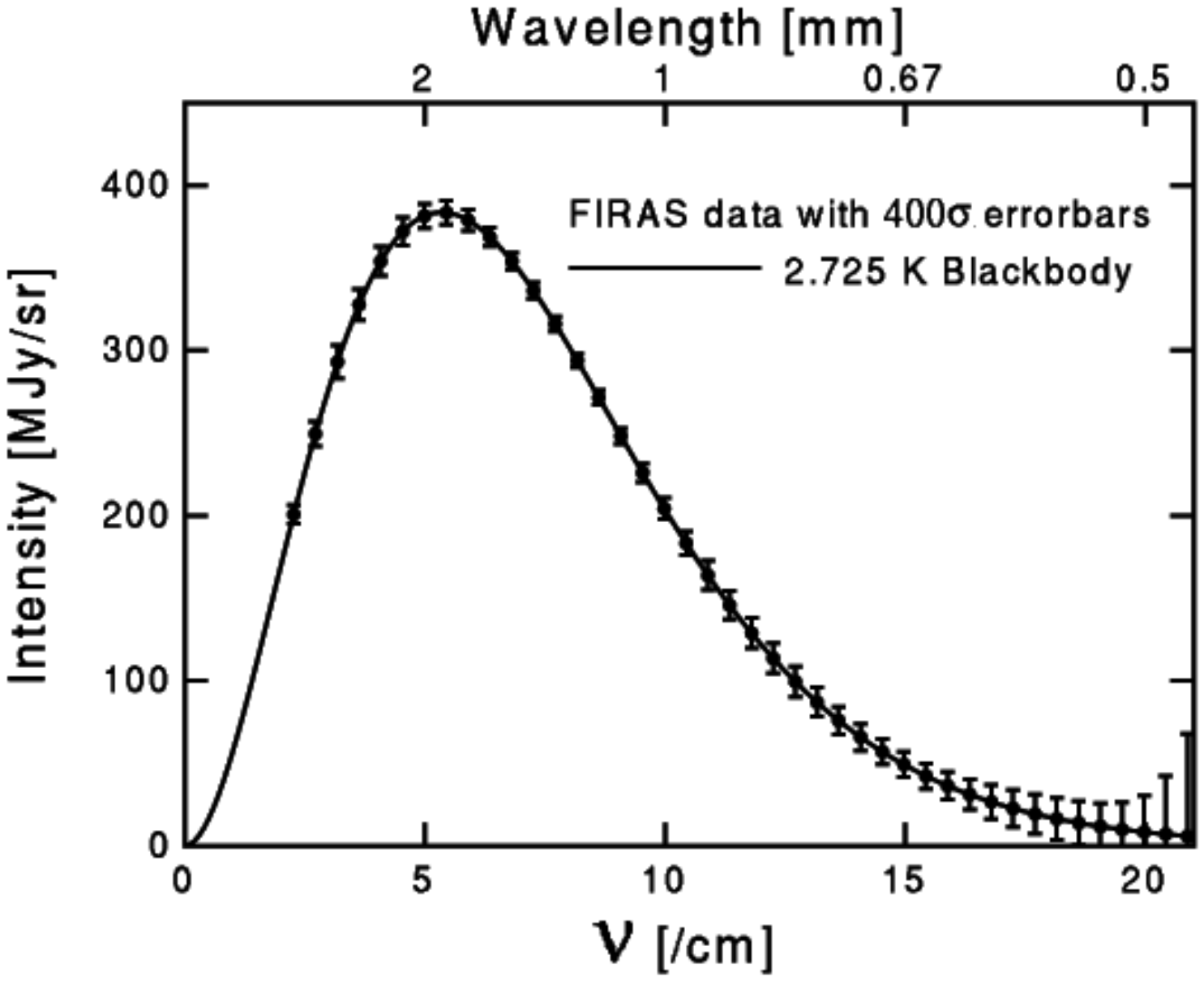
Cosmological Redshift

T = 300,000 years
3000°K

T = 13.7 B years (Today)
3000°K/1,100 =2.7°K



The CMB Spectrum by FIRAS

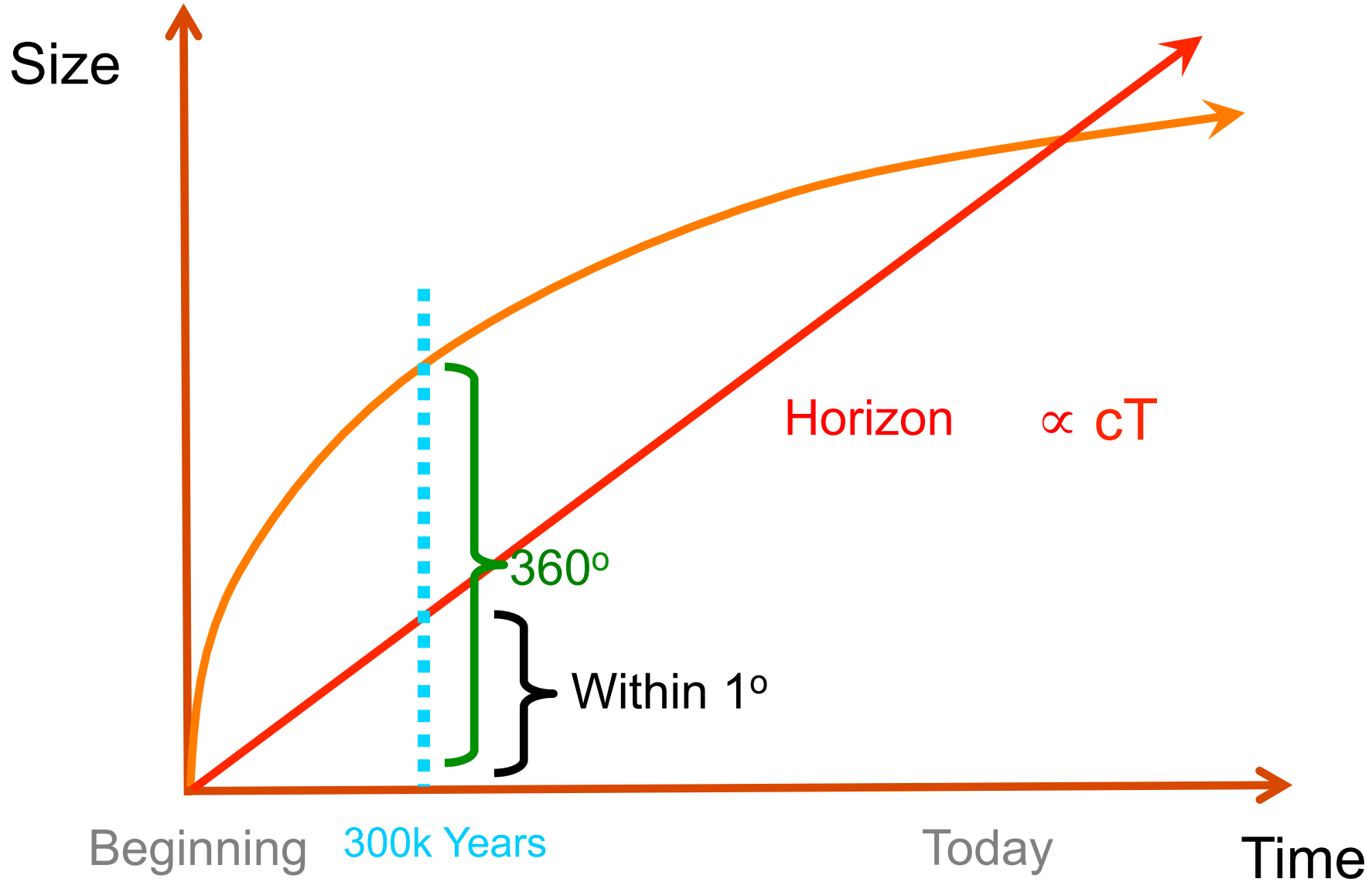


Inflation

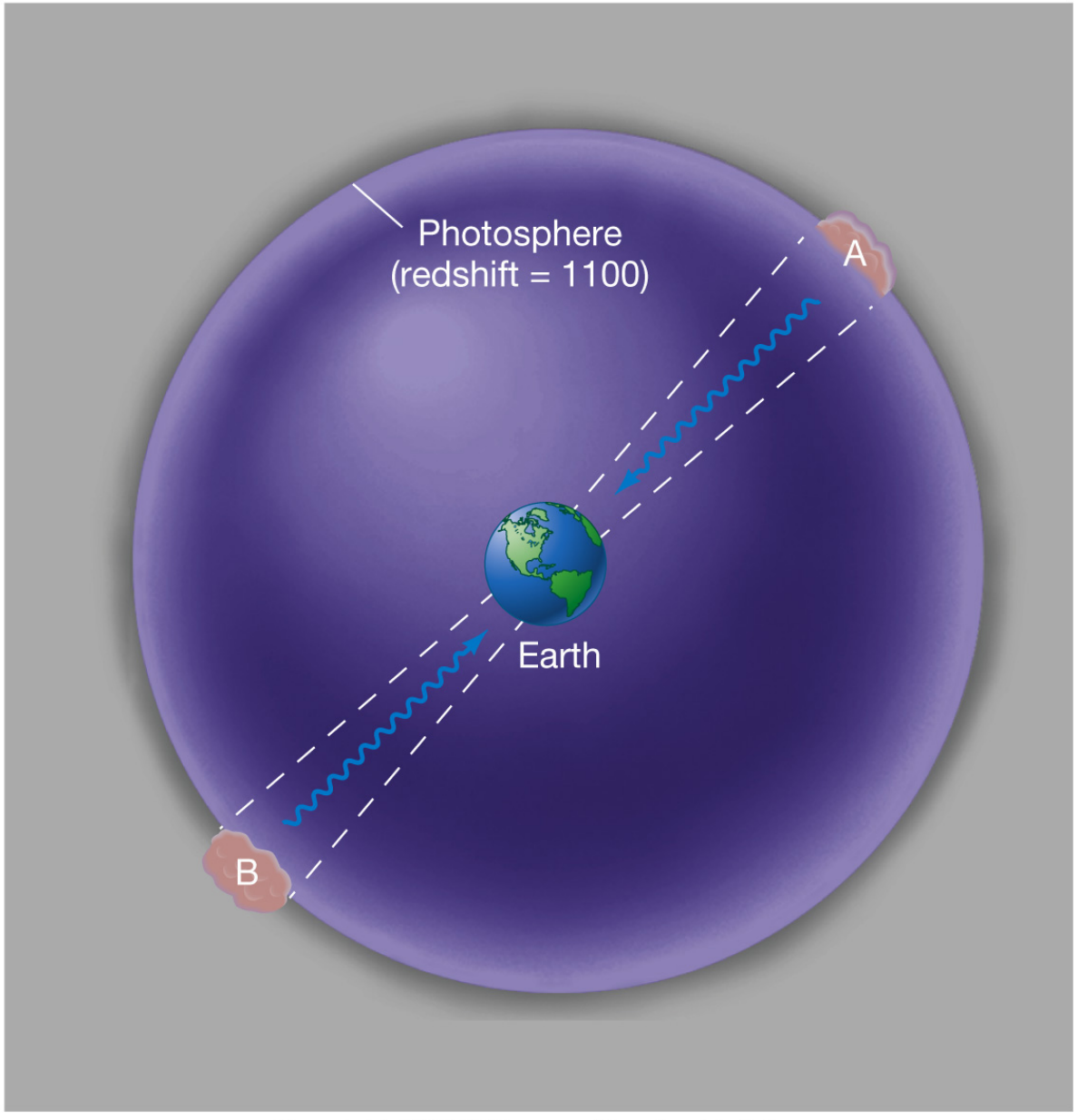
Two Fundamental Problem of Big Bang Cosmology

- **Horizon Problem**
  - At early Universe, Size >> 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

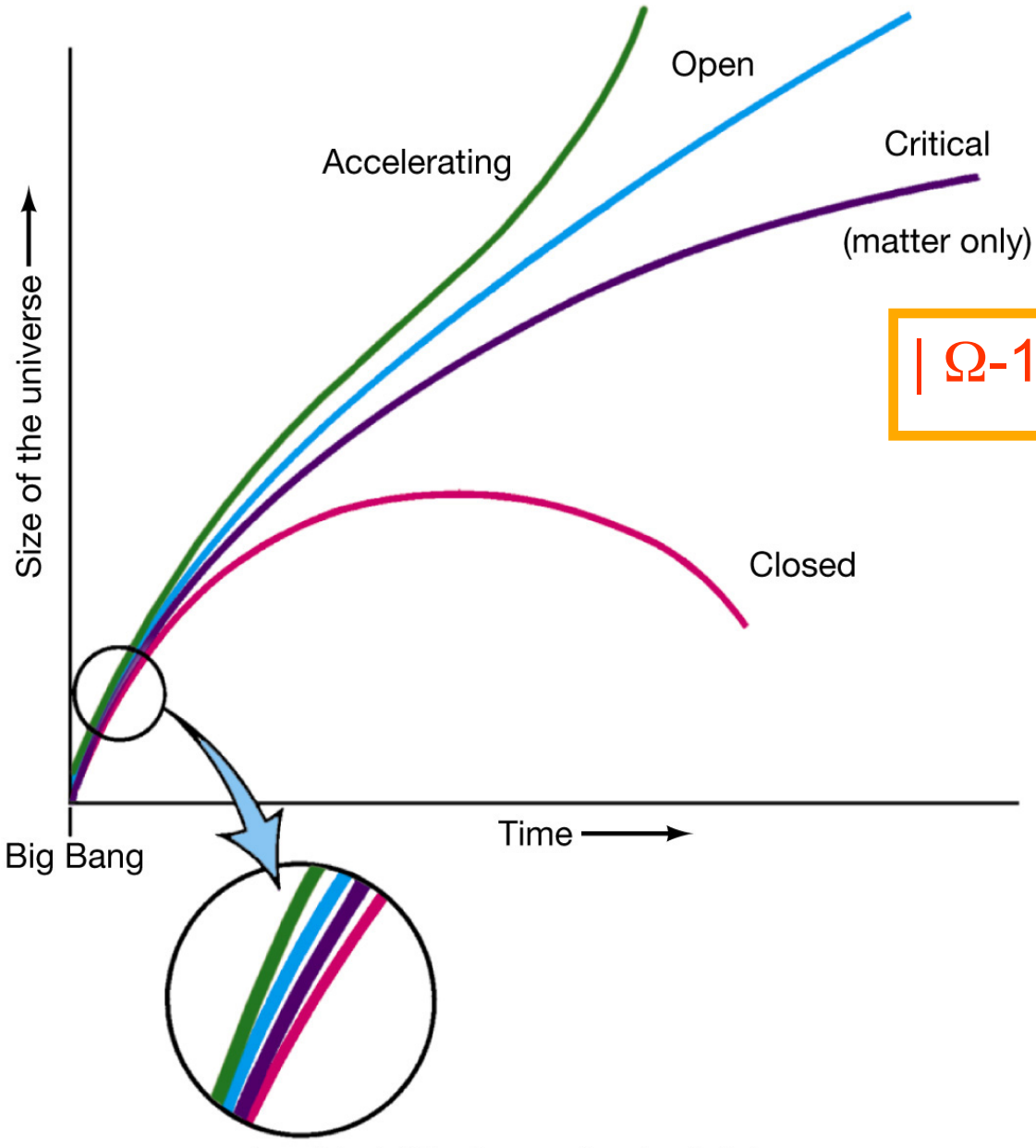


Horizon Problem



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.

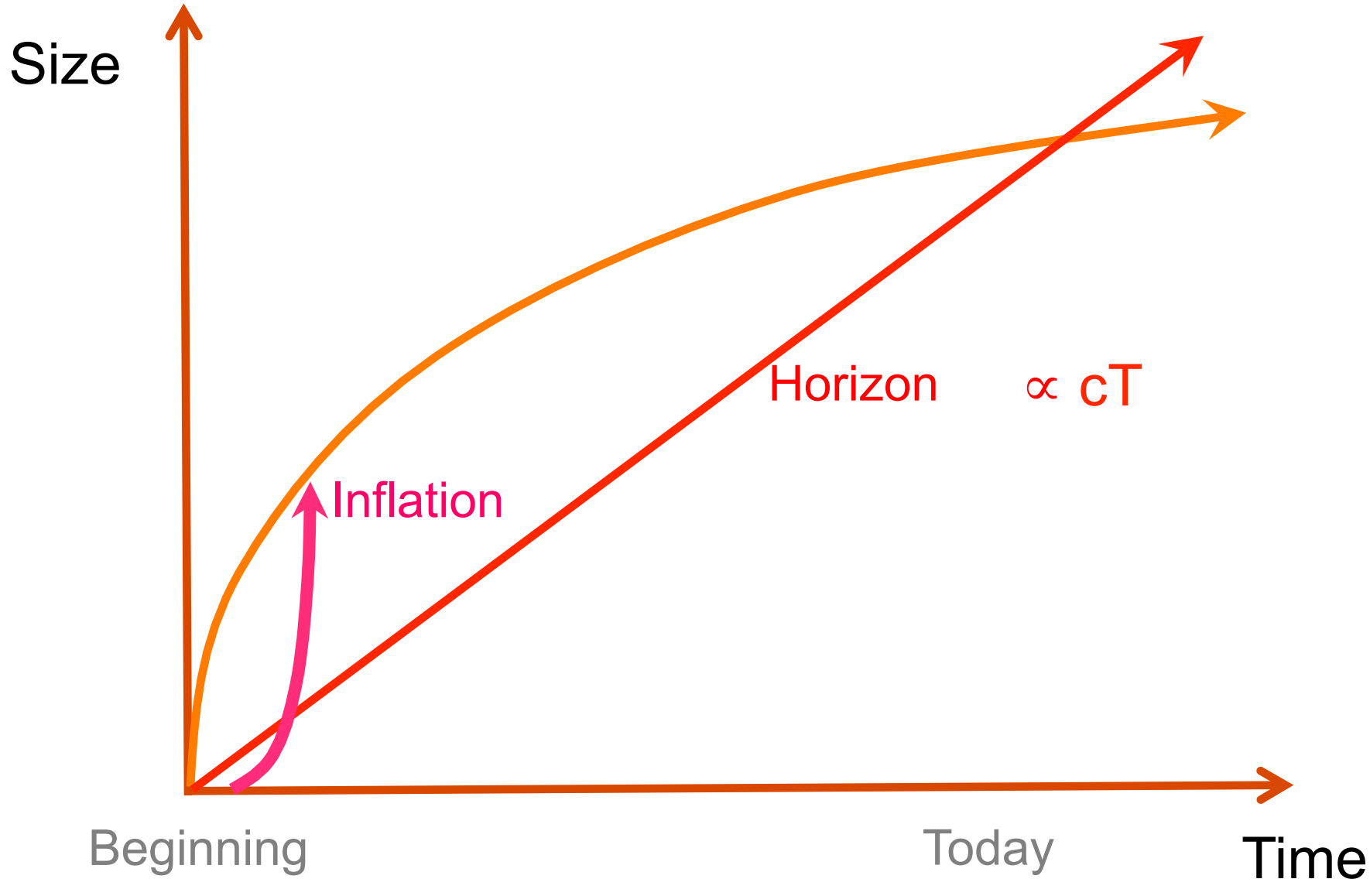
Flatness Problem



$|\Omega - 1| \propto$ 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}.

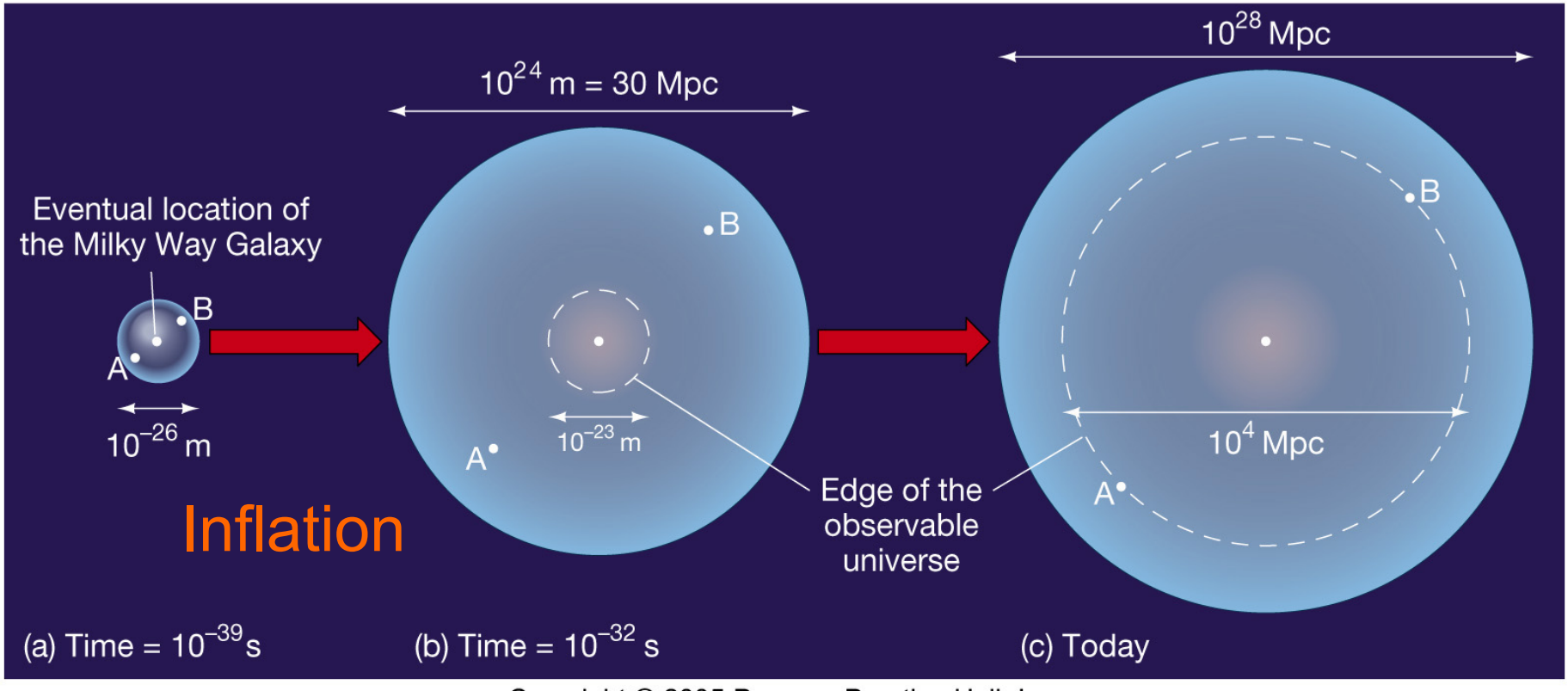
Inflation in Early Universe



The Inflationary Universe

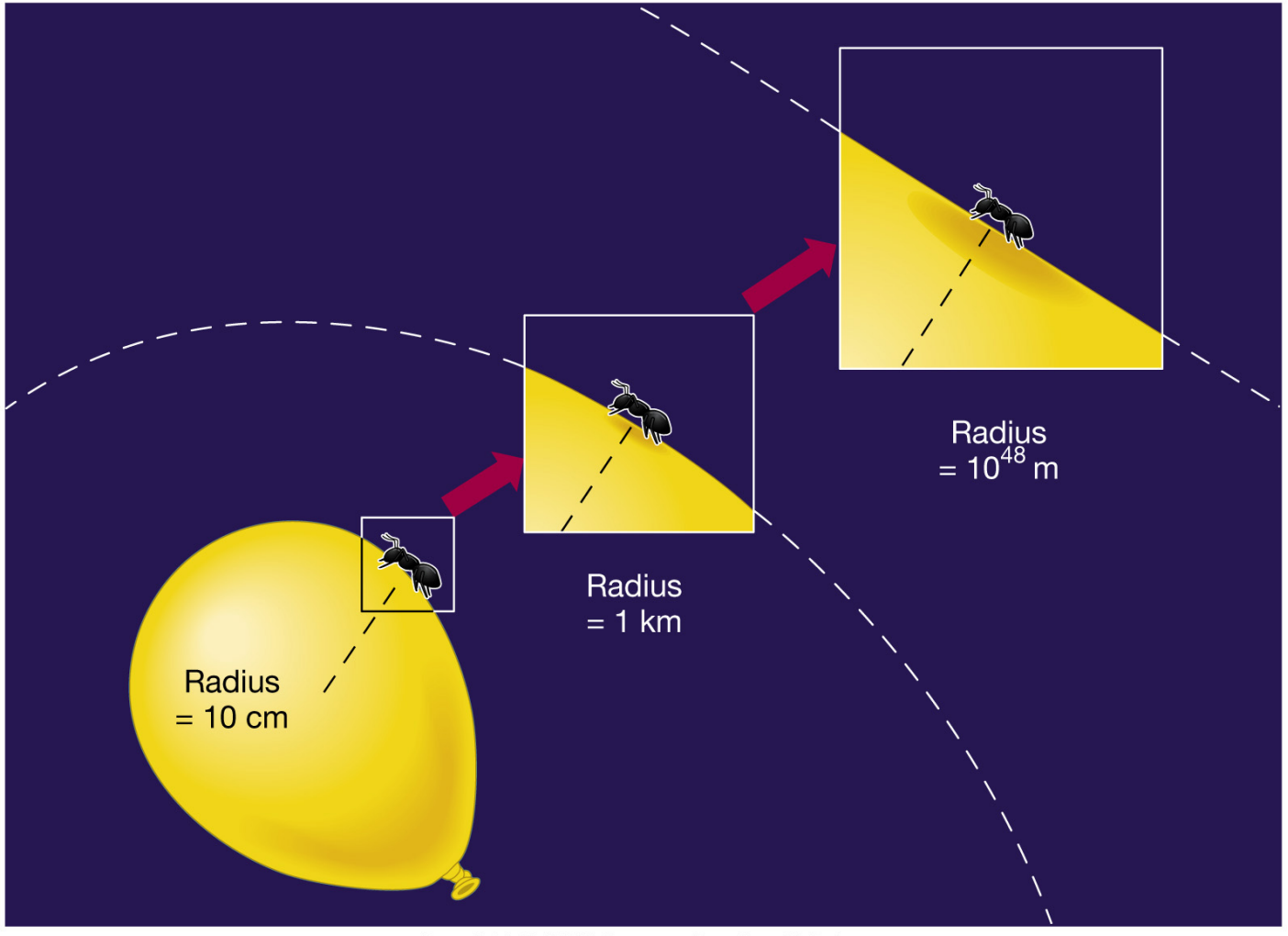
Inflation, if correct, would solve both the horizon and the flatness problems.

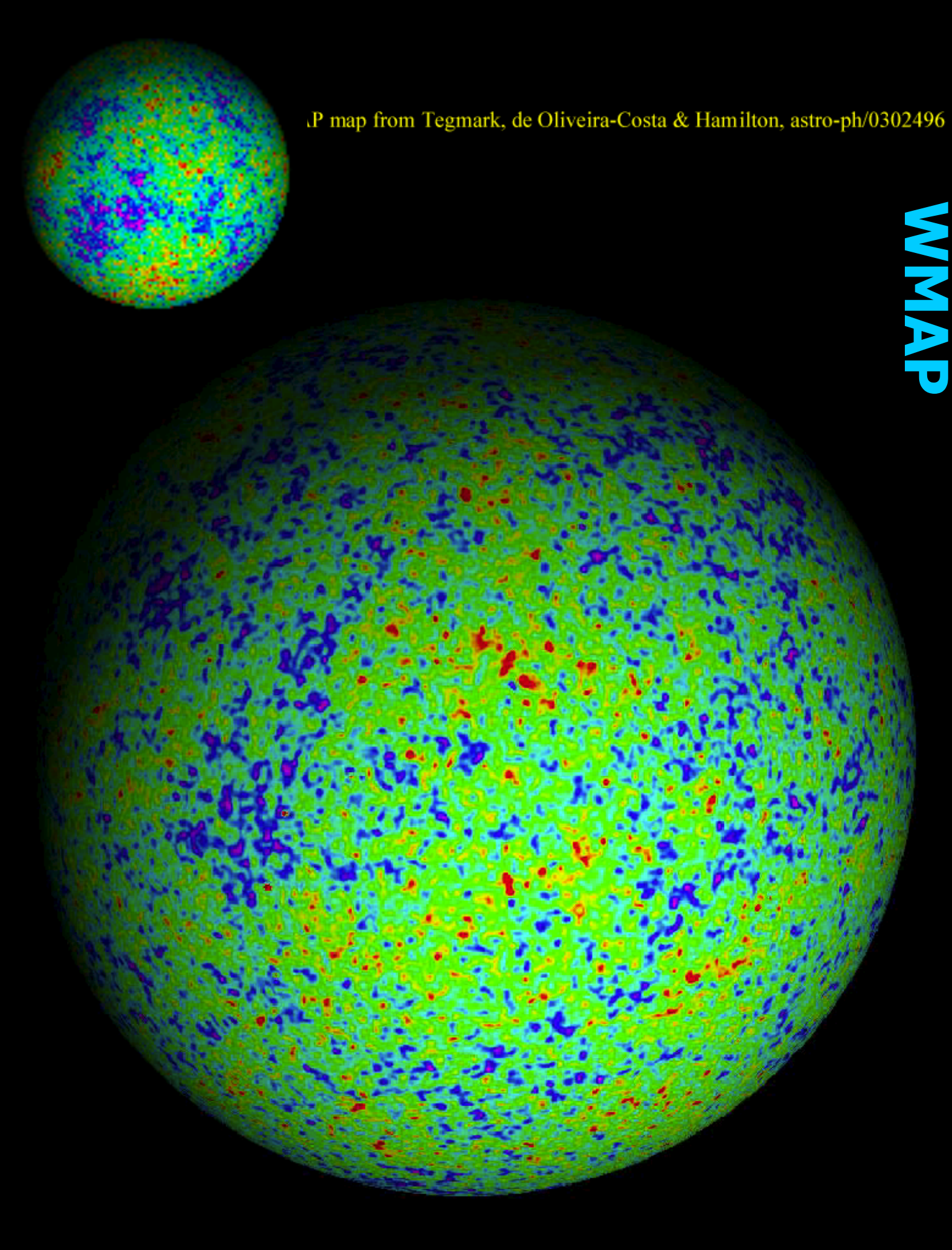
This diagram shows how the horizon problem is solved – the points diametrically opposite from Earth were in fact in contact at one time.



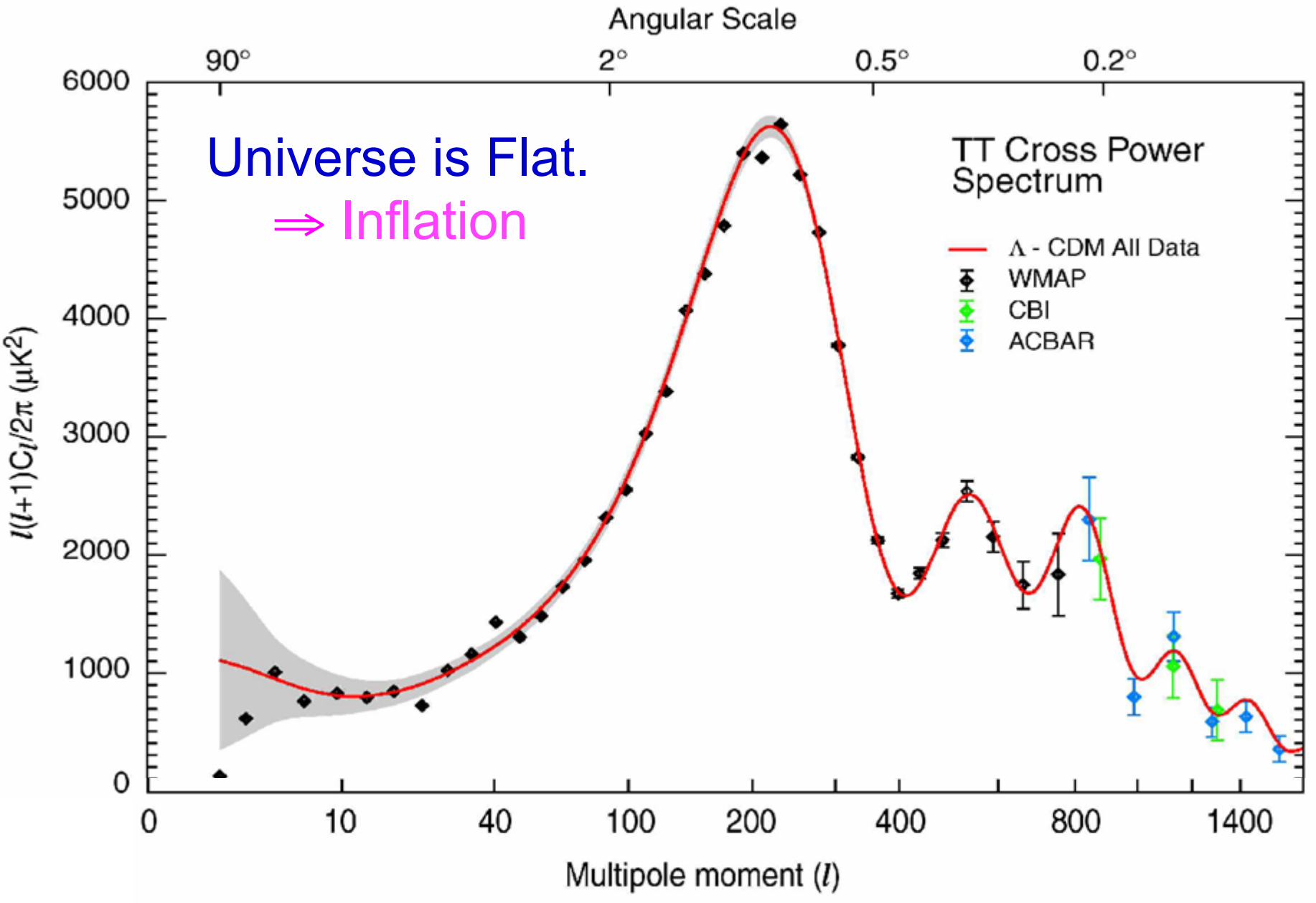
The Inflationary Universe

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:



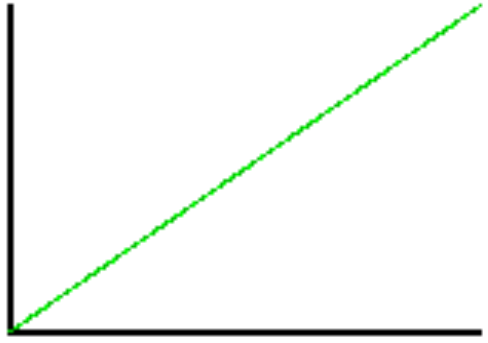

.P map from Tegmark, de Oliveira-Costa & Hamilton, astro-ph/0302496
WMAP

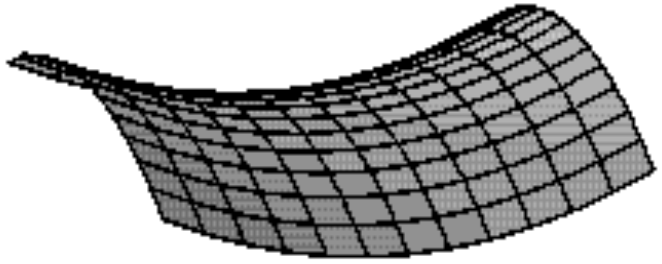
WMAP Power Spectrum



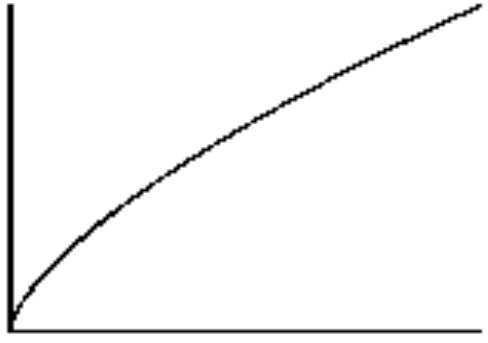
Geometry of the Universe

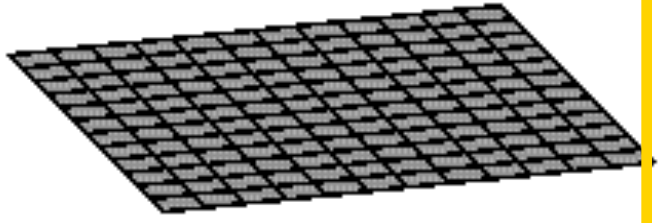
Open $\Omega<1$



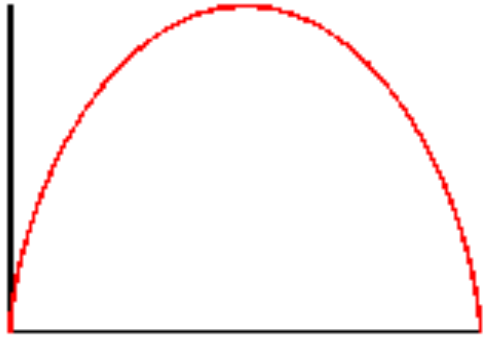


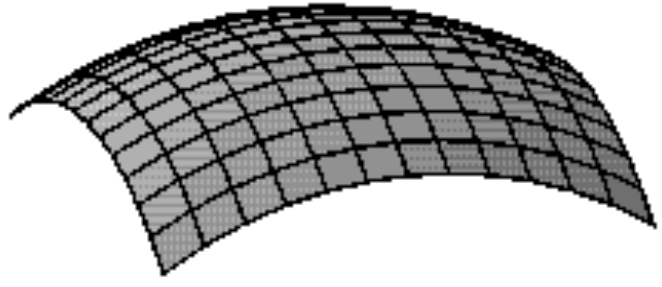
Flat $\Omega=1$





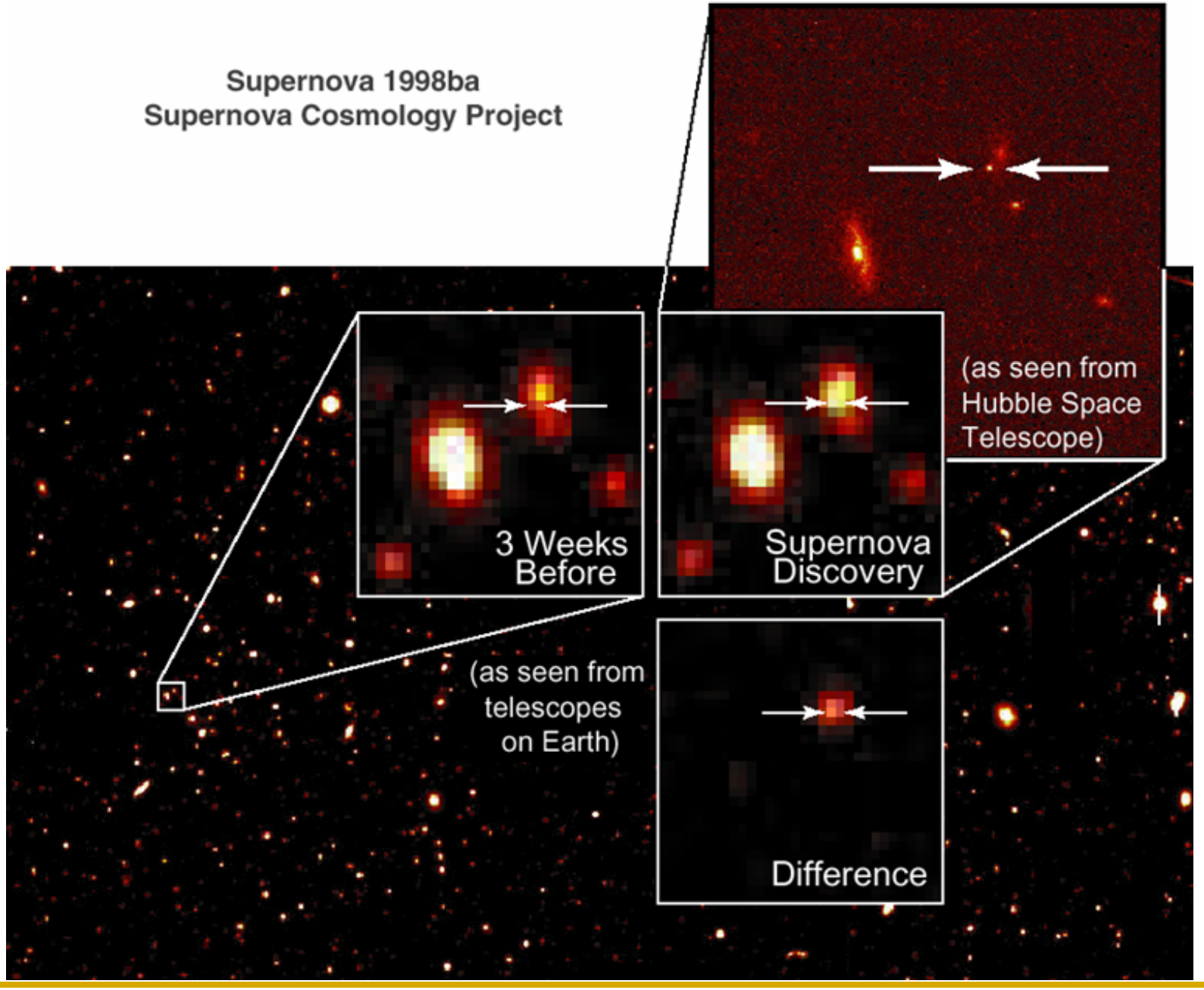
Closed $\Omega>1$



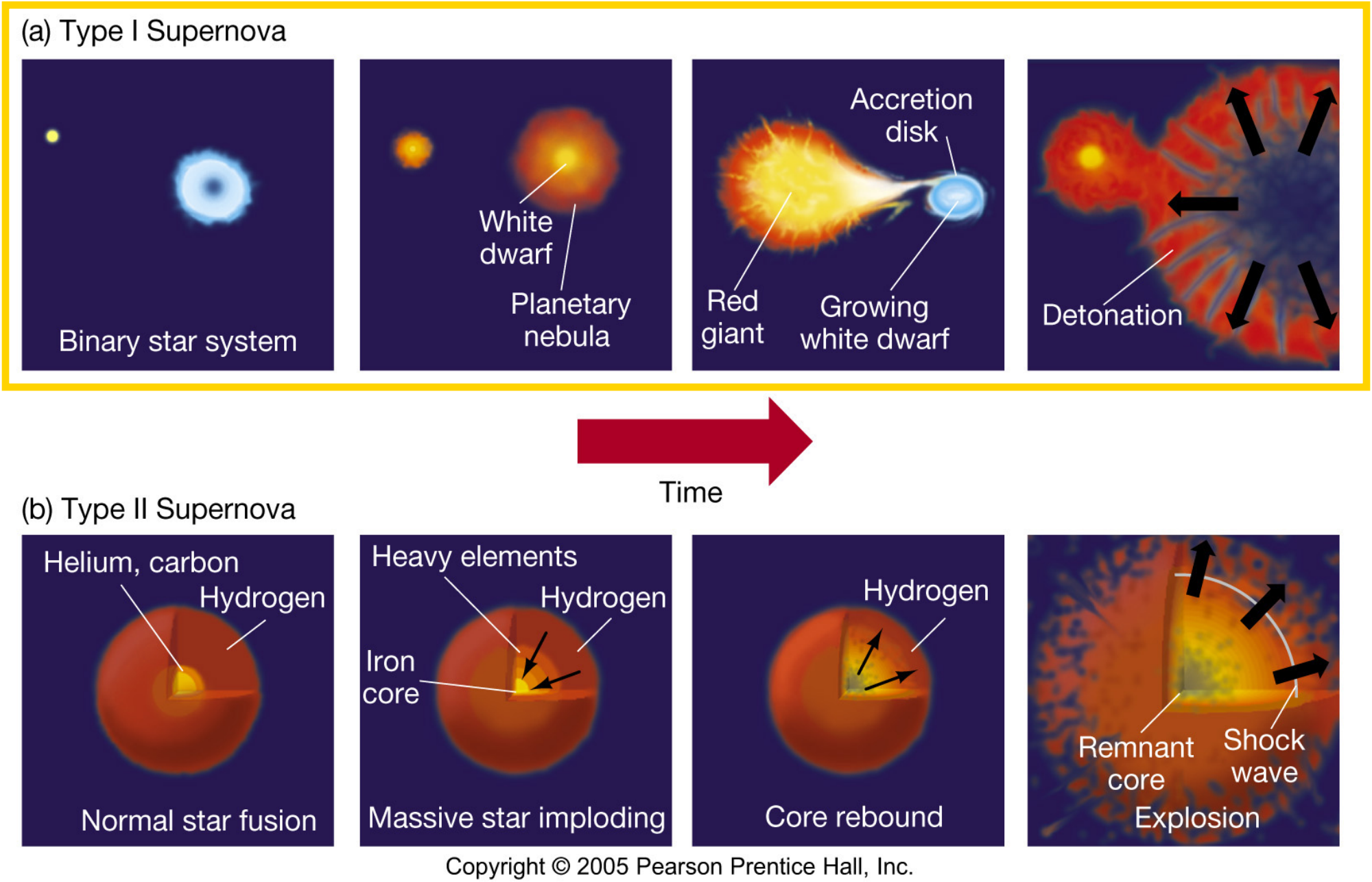


Dark Energy

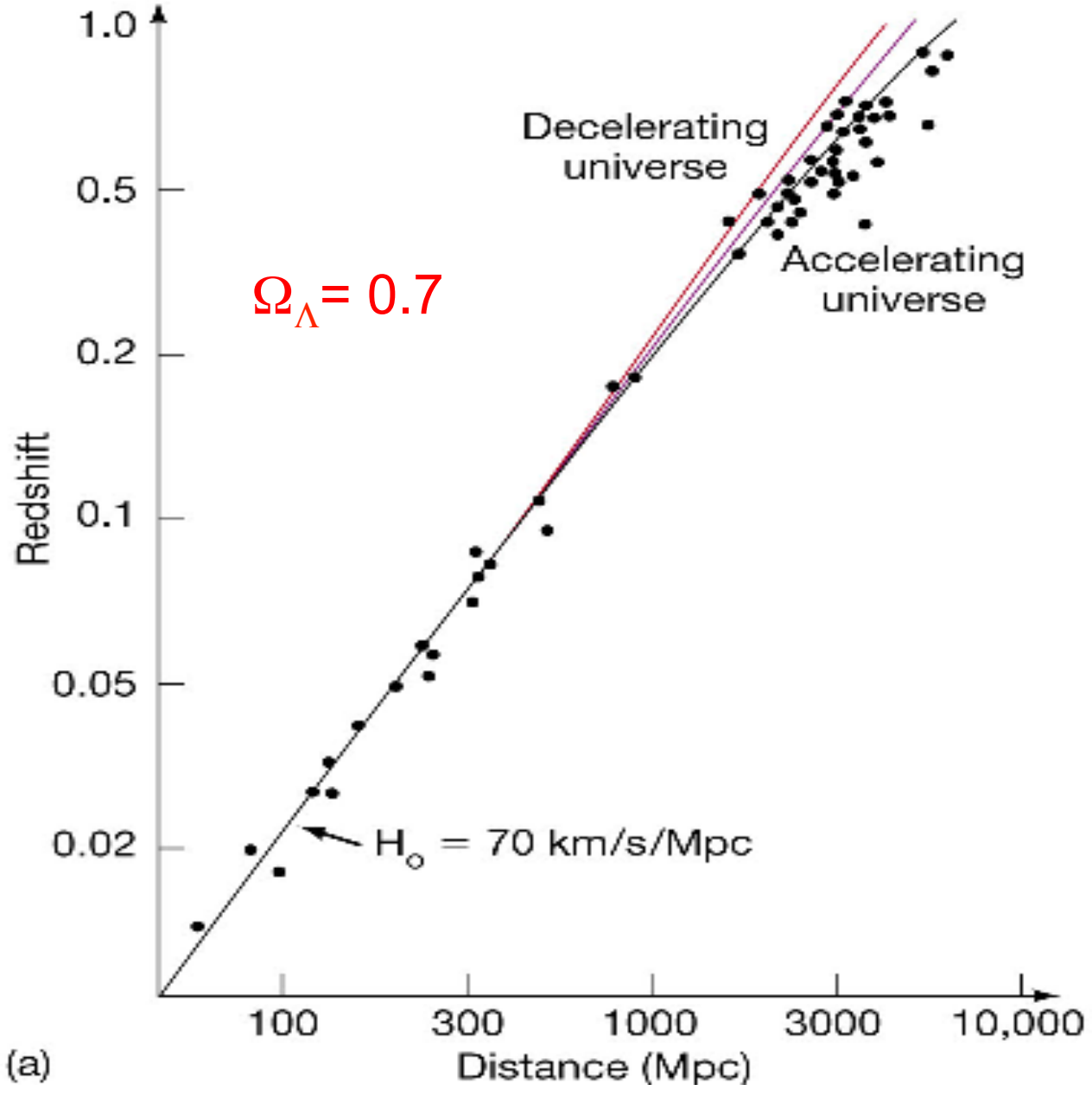
Supernova as a Standard Candle



Two Types of Supernovae



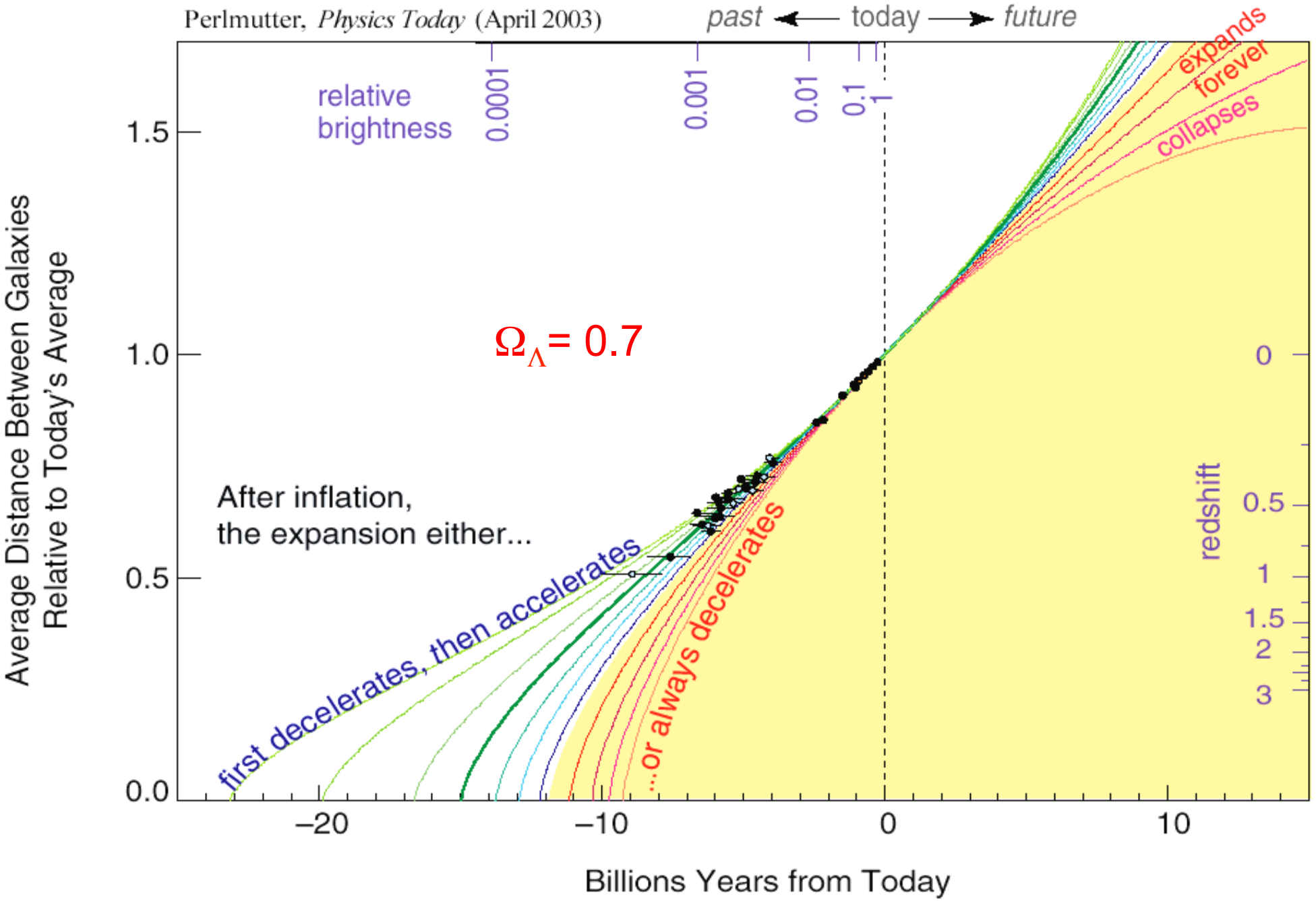
Will the Universe Expand Forever?



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

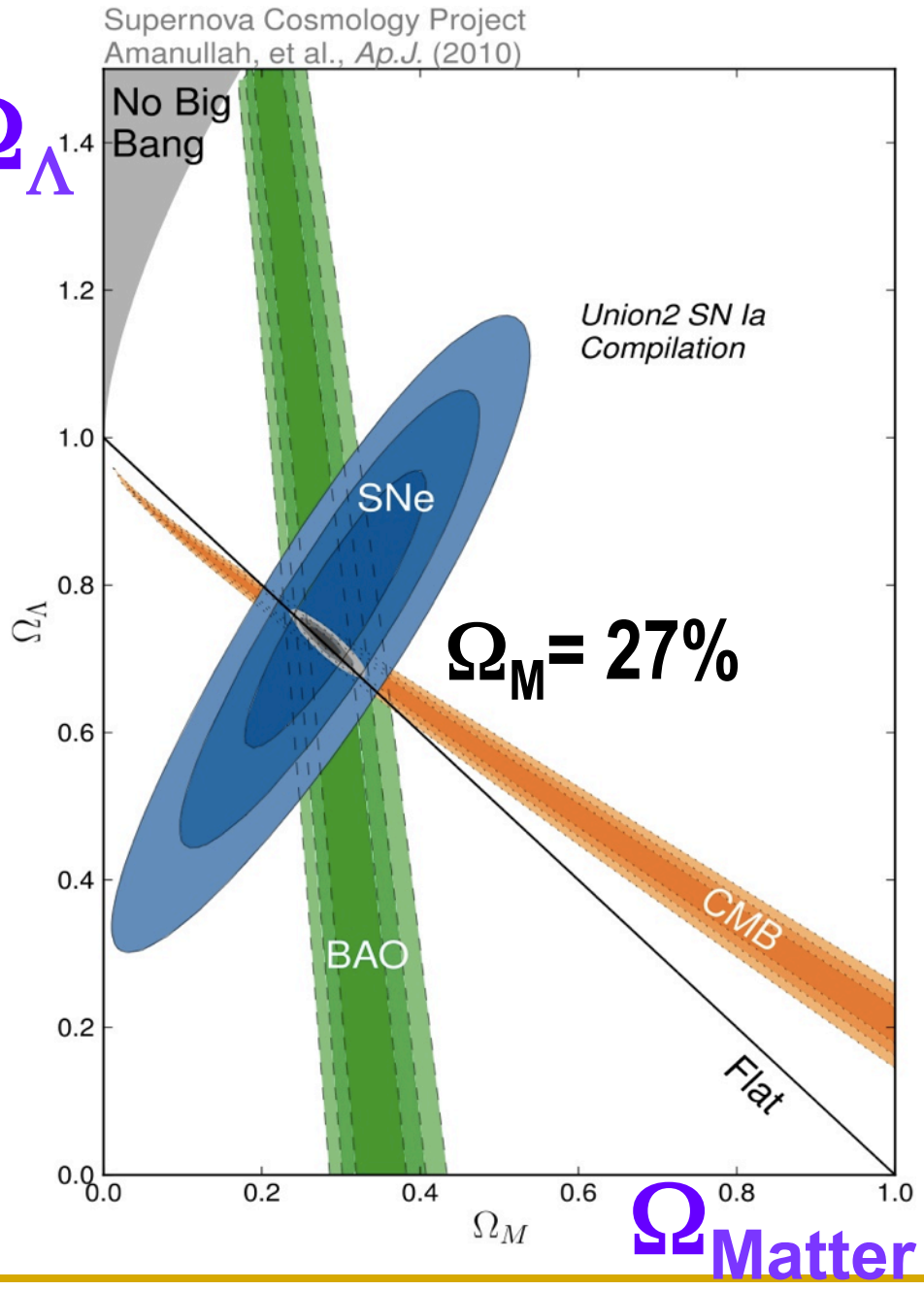
This acceleration cannot be explained by current theories of the universe, although we do know it is not caused by either matter or radiation.

The Accelerating Universe (1998)

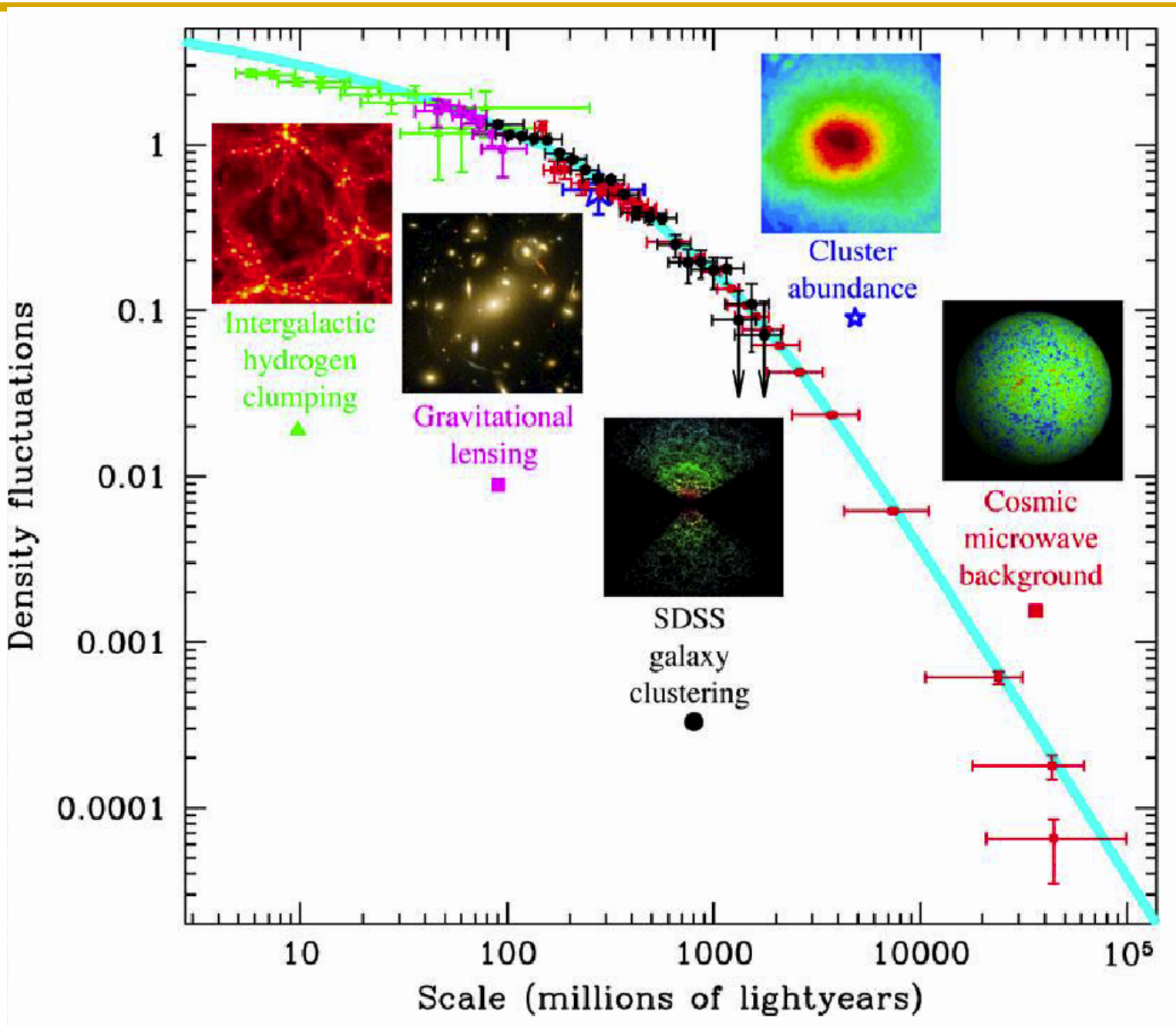


Density of Our Universe

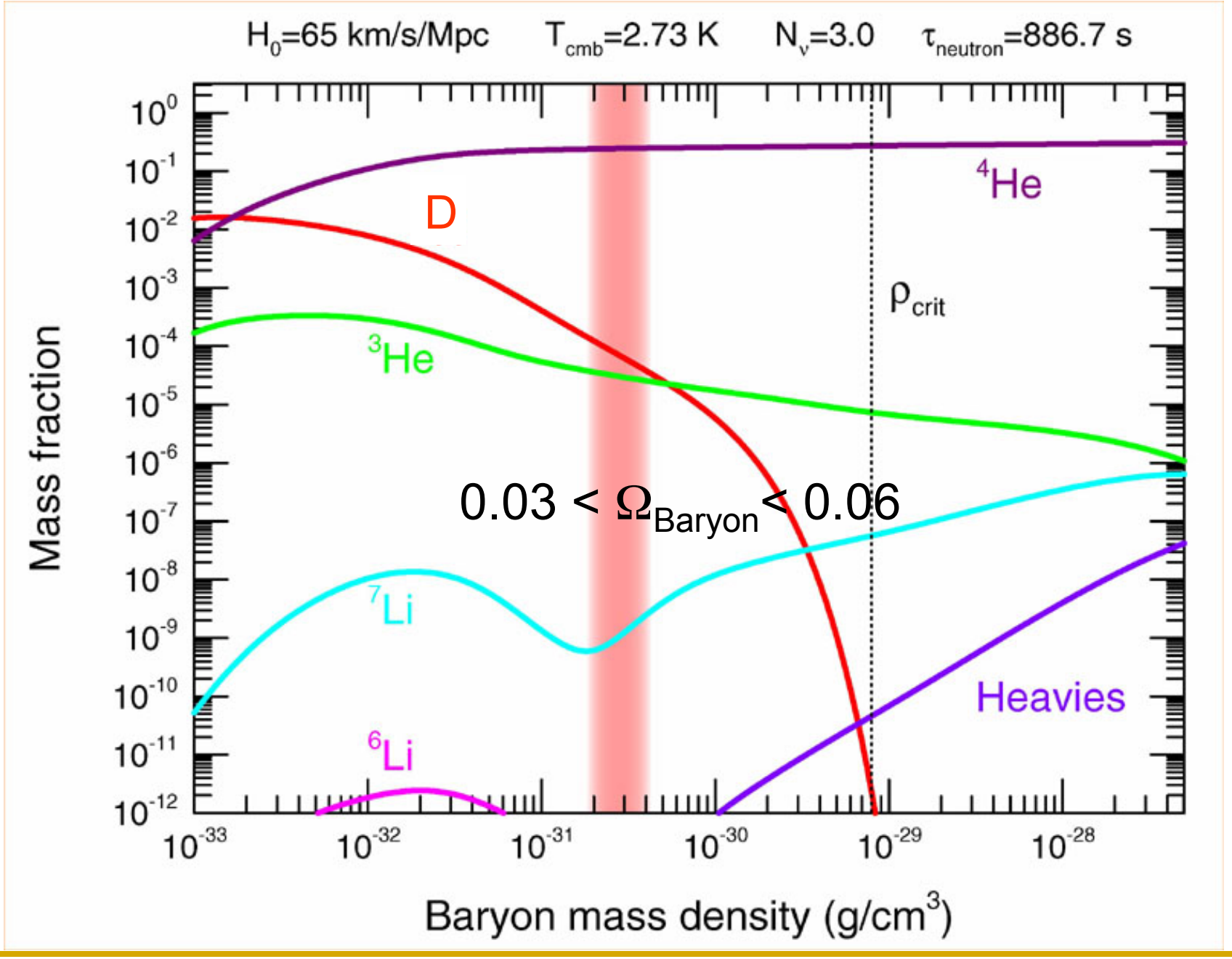
- $\Omega_{Total}=\Omega_{\Lambda}+\Omega_{Matter}=1.0$
- Universe is Flat.
  - ⇒ Inflation
- 73% is Dark Energy.
  - ⇒ Accelerating



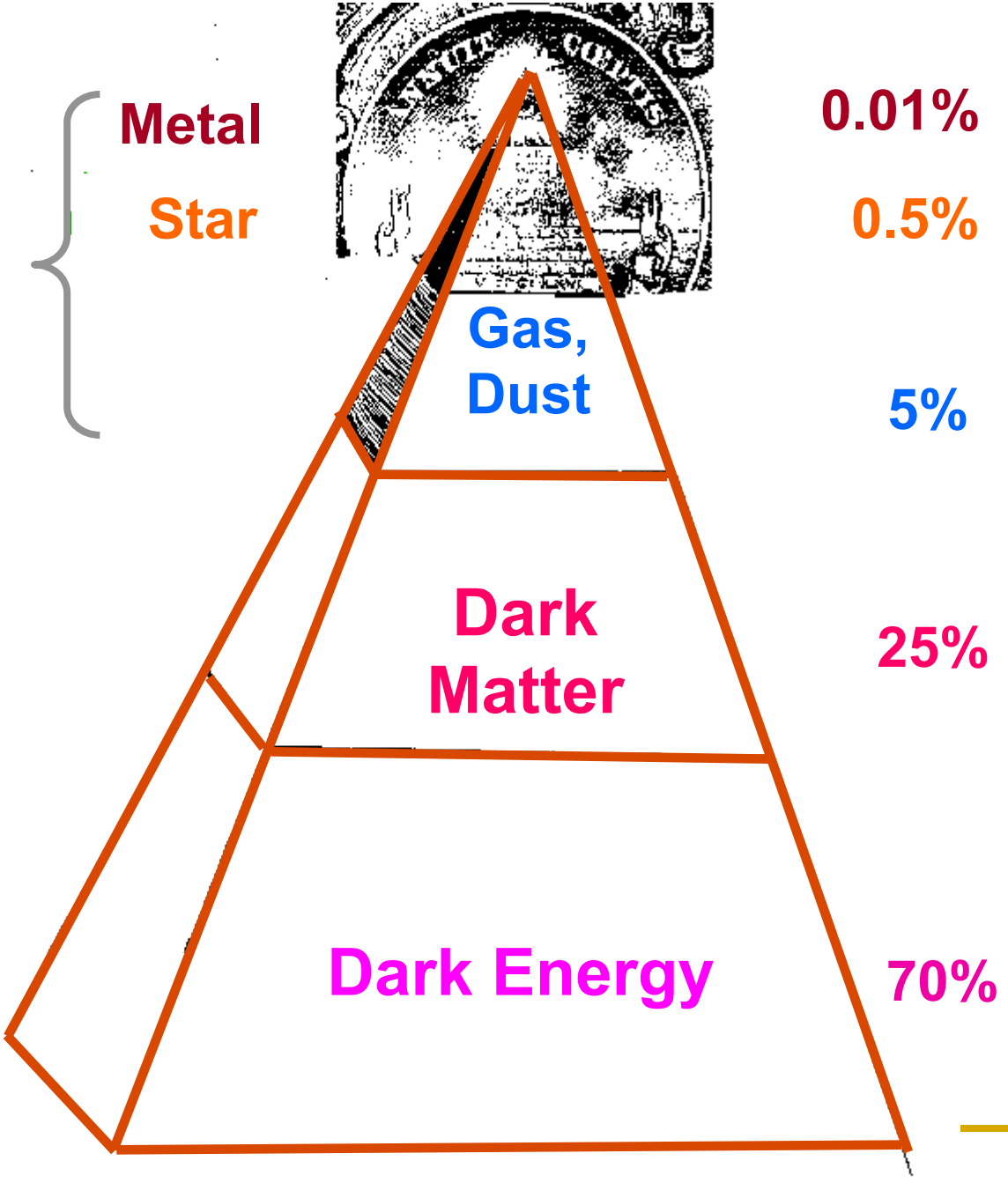
Density Fluctuations



Abundance vs. Density



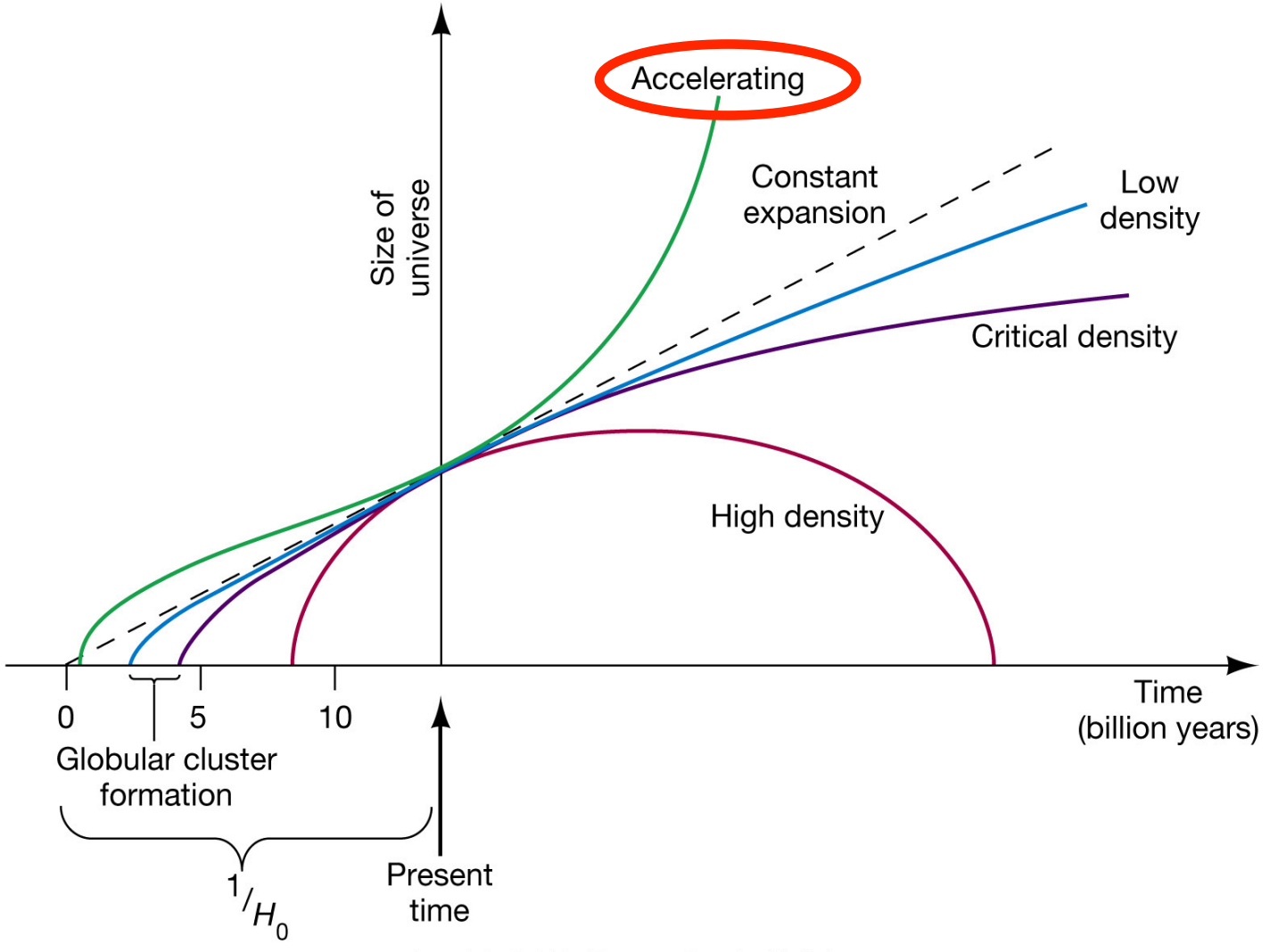
Cosmic Pyramid



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.



Dark Matter

What is Dark Matter?

- **Must be a heavy particle**
  - Only weakly interacting.
  - Gravitationally attracted.

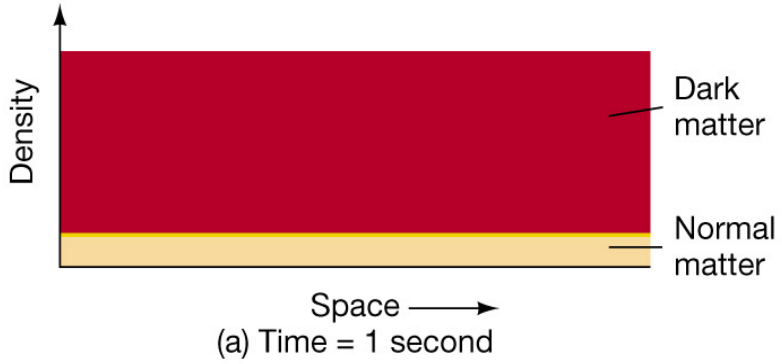
- **Candidates**
  - "MACHO" (Massive Compact Halo Objects) X
    - →Baryonic Dark Matter
  - Heavy Neutrino X
    - →Hot Dark Matter
  - "WIMP" (Weakly Interacting Massive Particle"
    - →Cold Dark Matter

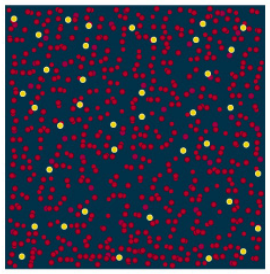
Candidate of "WIMP"

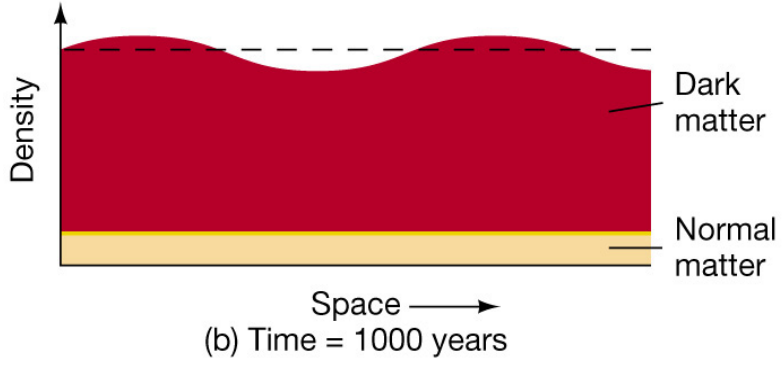
- A leading candidate of WIMP is "Neutralino"
  - Least-massive Super-Symmetric Particle.
- Super-Symmetry is the symmetry between Fermion ↔ Boson
- This symmetry was broken
  - at energy around 100 GeV – 1 TeV
  - at time around 10^{-10} – 10^{-11} second.

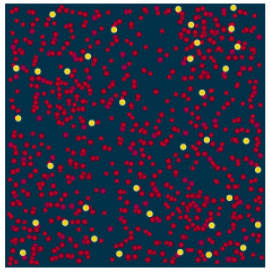
- Neutralinos were decoupled.
- Started to be attracted each other gravitationally.

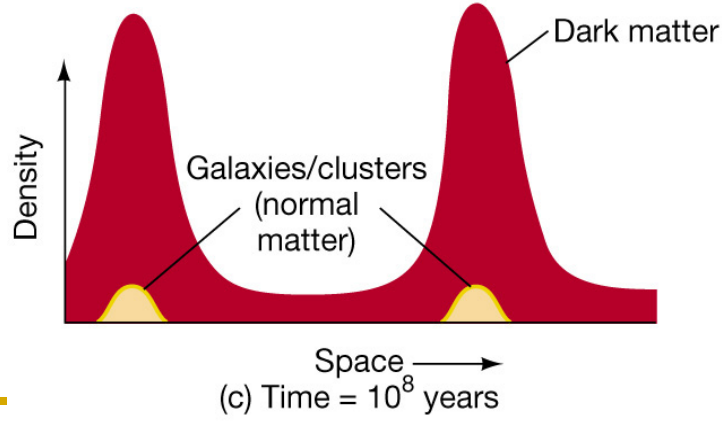
Formation of Structure by Dark Matter

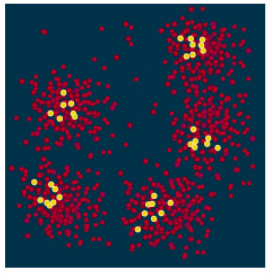




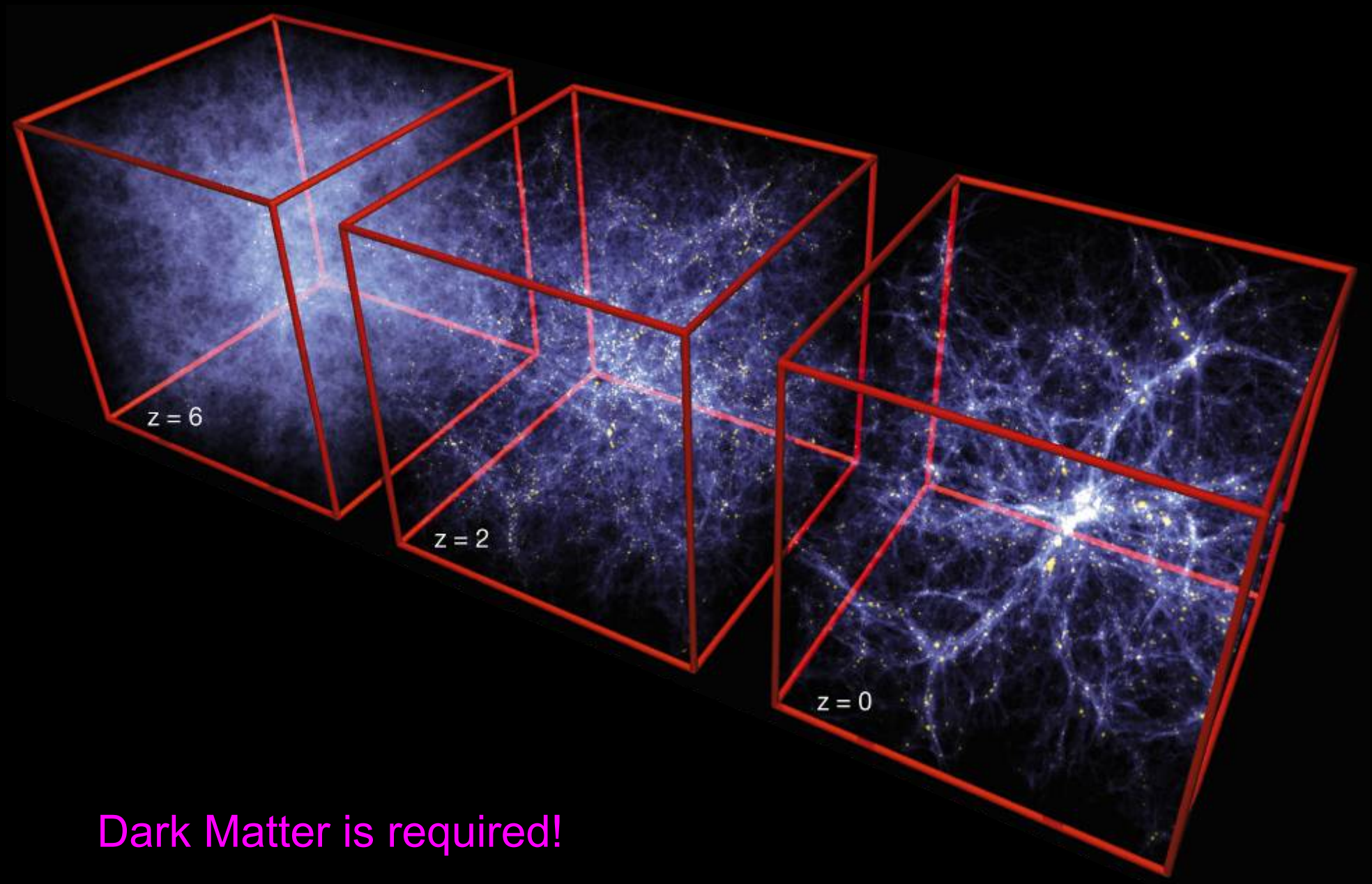








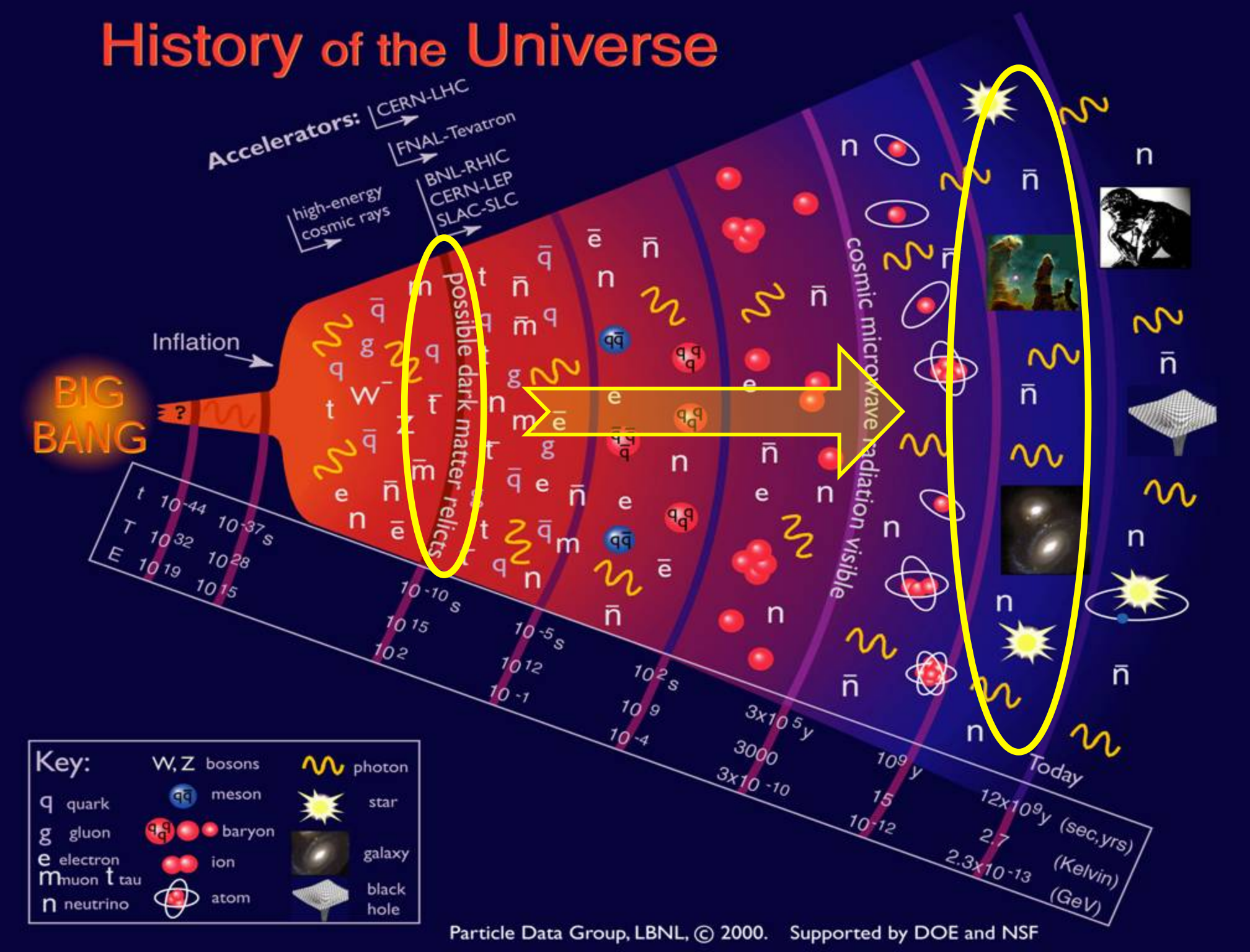
Formation of Structure in the Universe



Dark Matter is required!

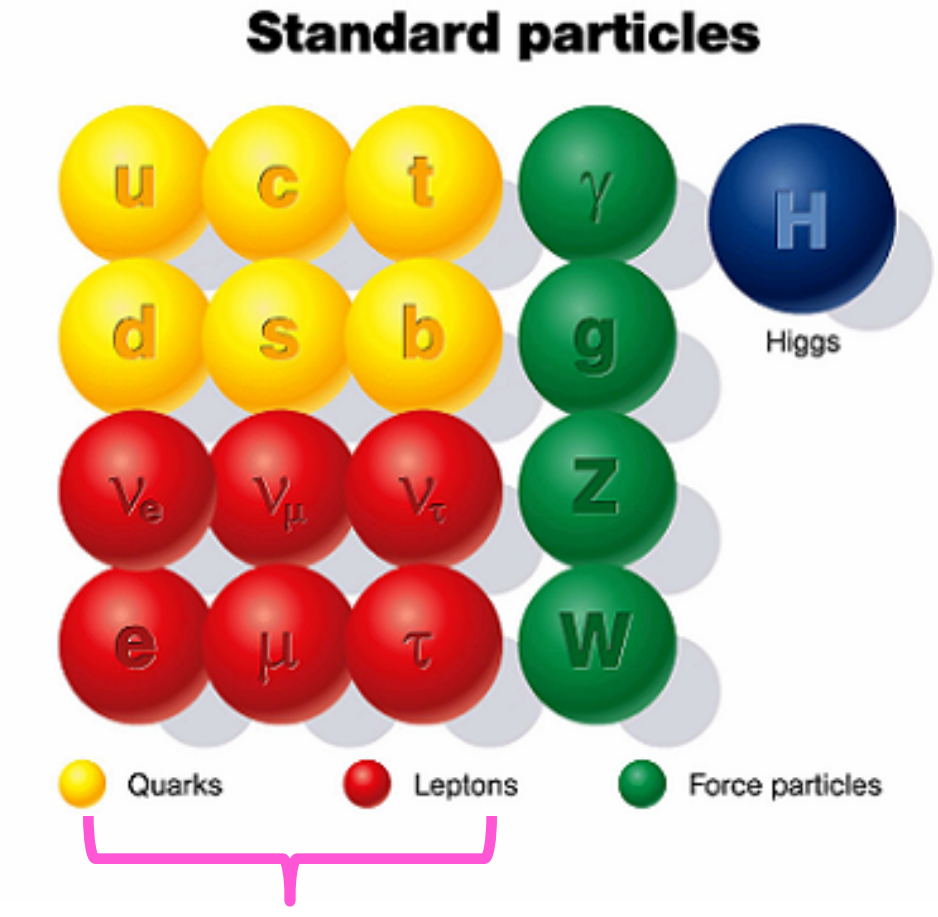

Dark Matter is required!
ANDROMEDA
GALAXY

History of the Universe

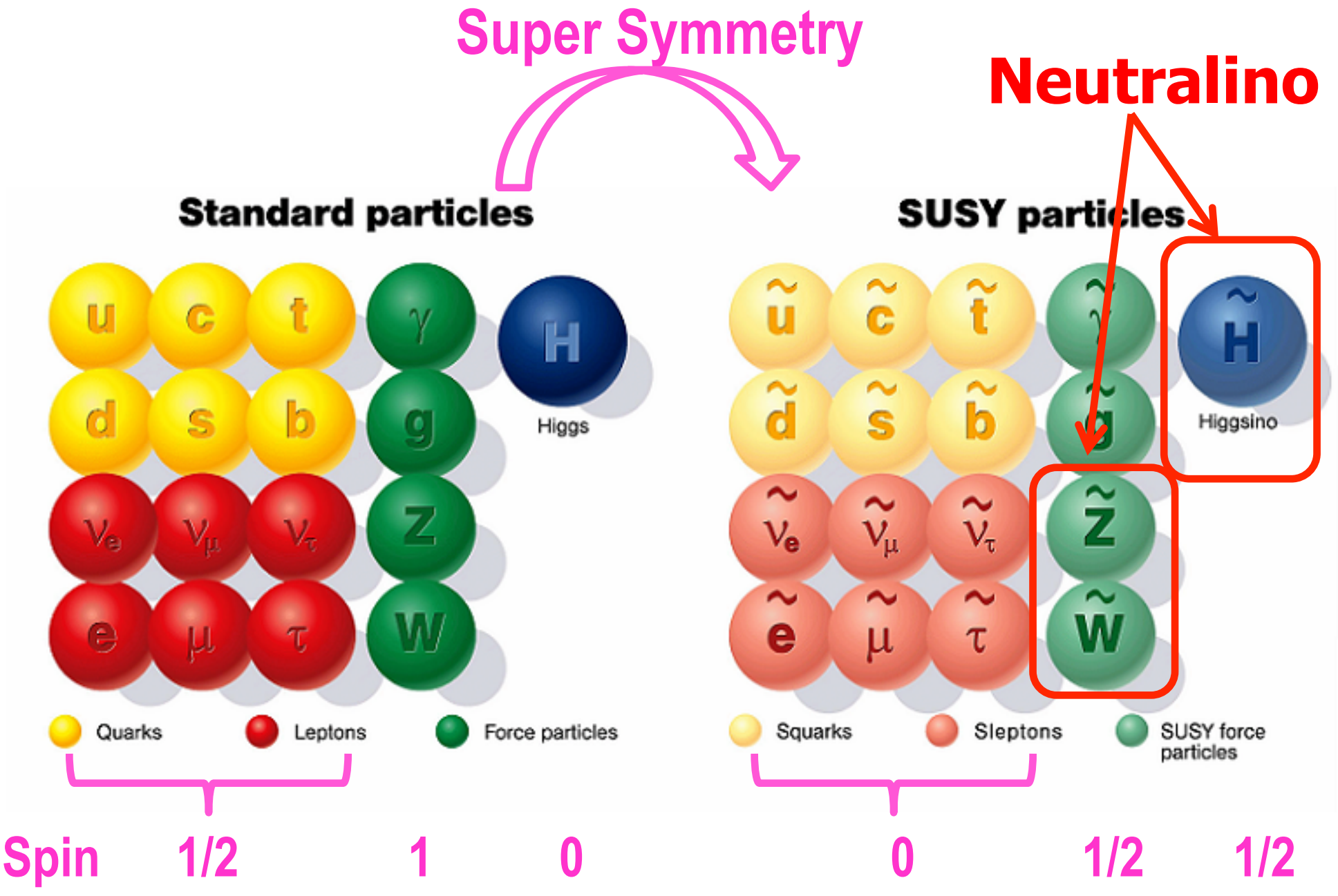


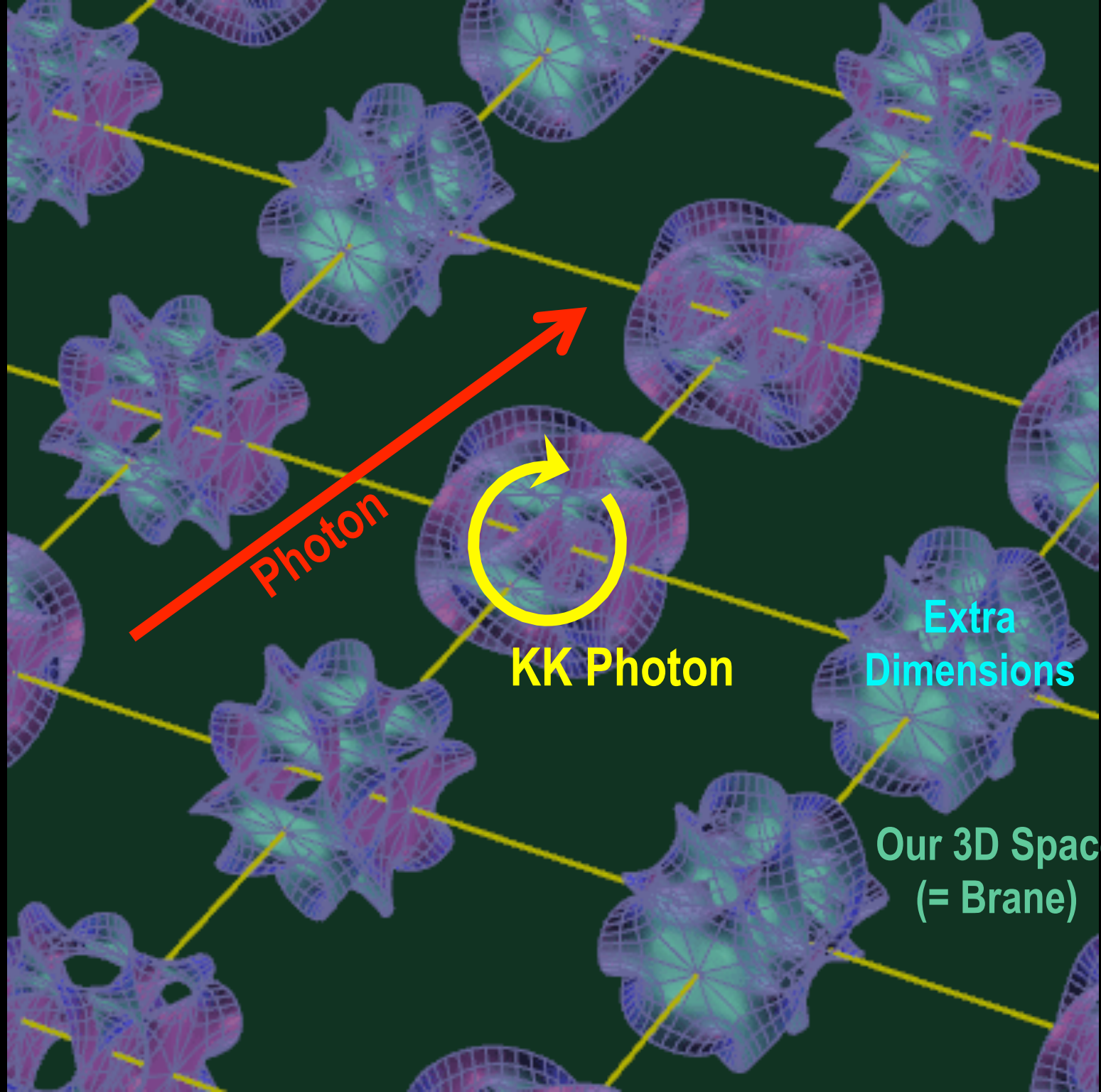
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

SUSY Particles and Neutralino



SUSY Particles and Neutralino



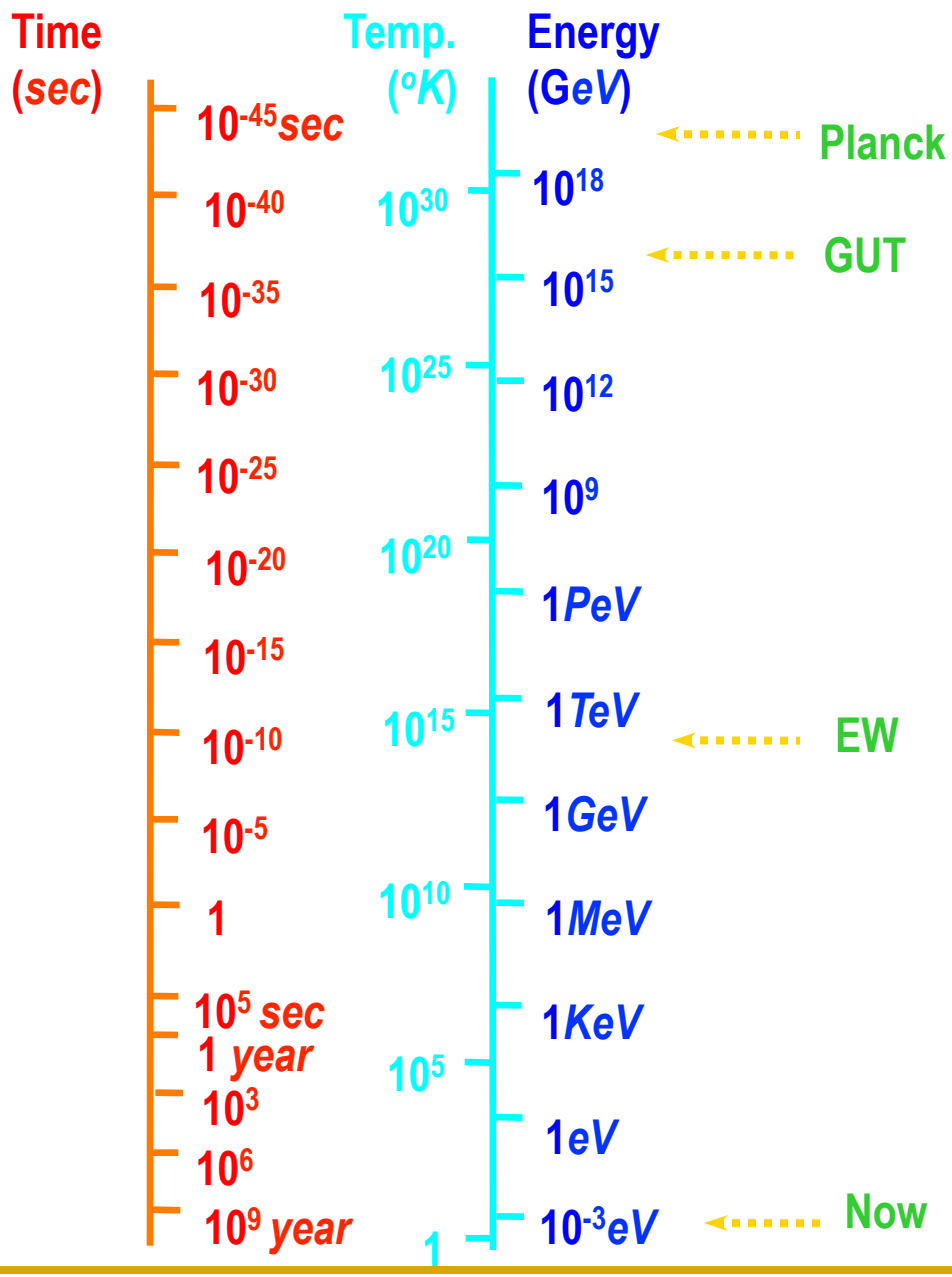

Photon
KK Photon
Extra
Dimensions
Bulk
Our 3D Space
(= Brane)

Origin of Mass in Extra Dimensions

$$E = mc^2 \rightarrow \boxed{m = E/c^2}$$

- **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



The Beginning

Plank Epoch

Grand Unification

Inflation

Dark Matter

Electro-Weak Unification

Matter-Radiation Decoupling

Dark Energy