Origin of the Universe

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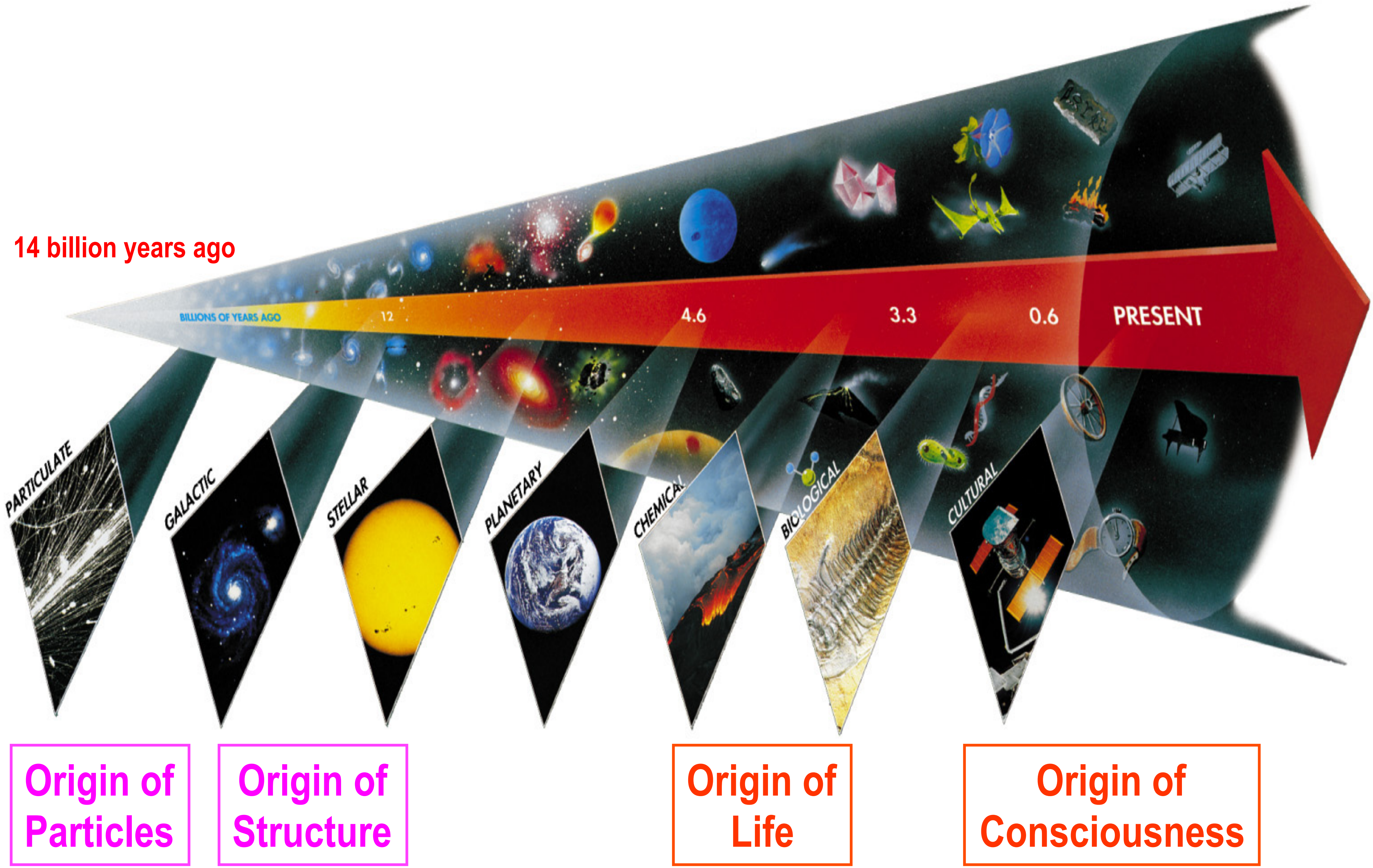
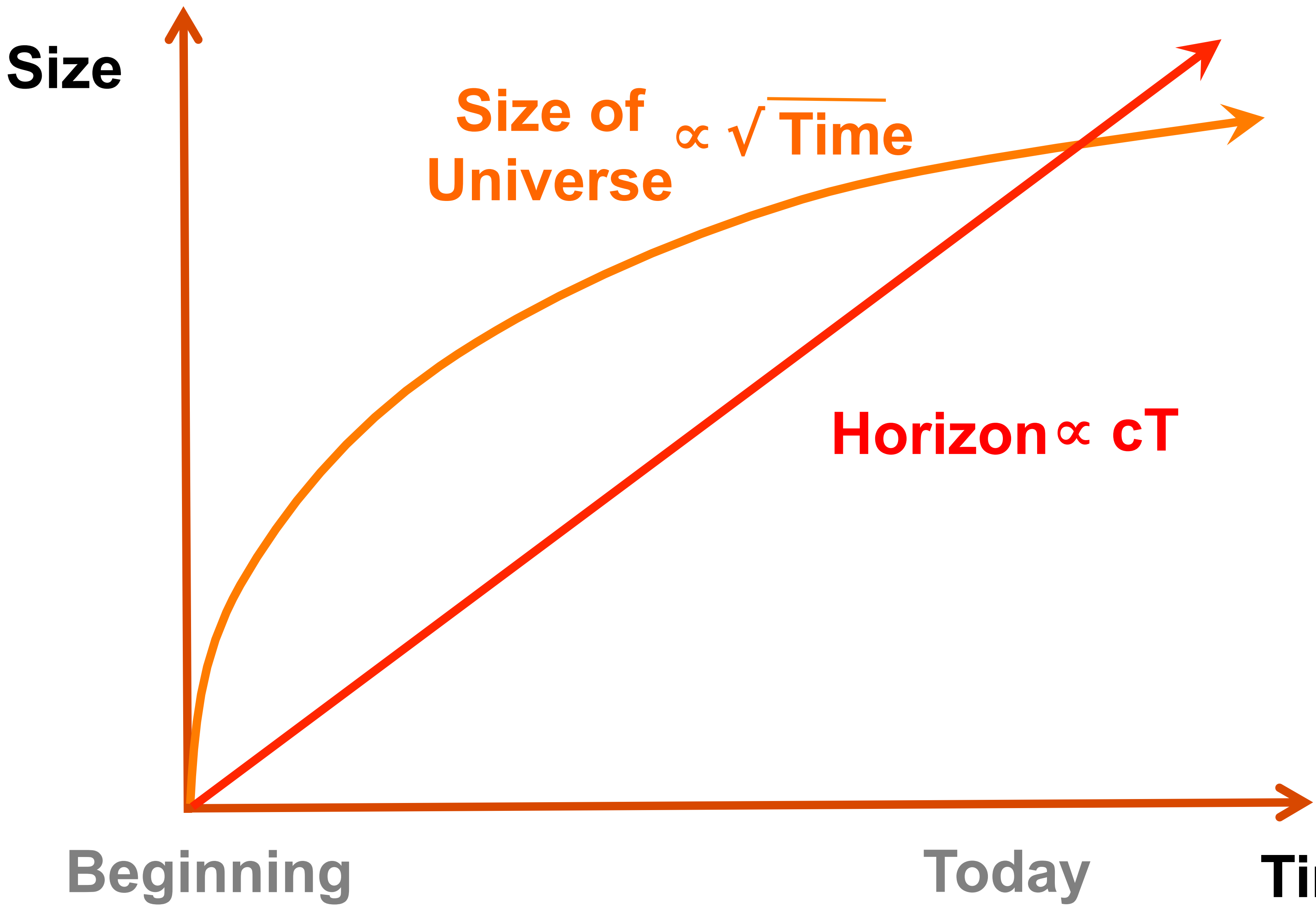
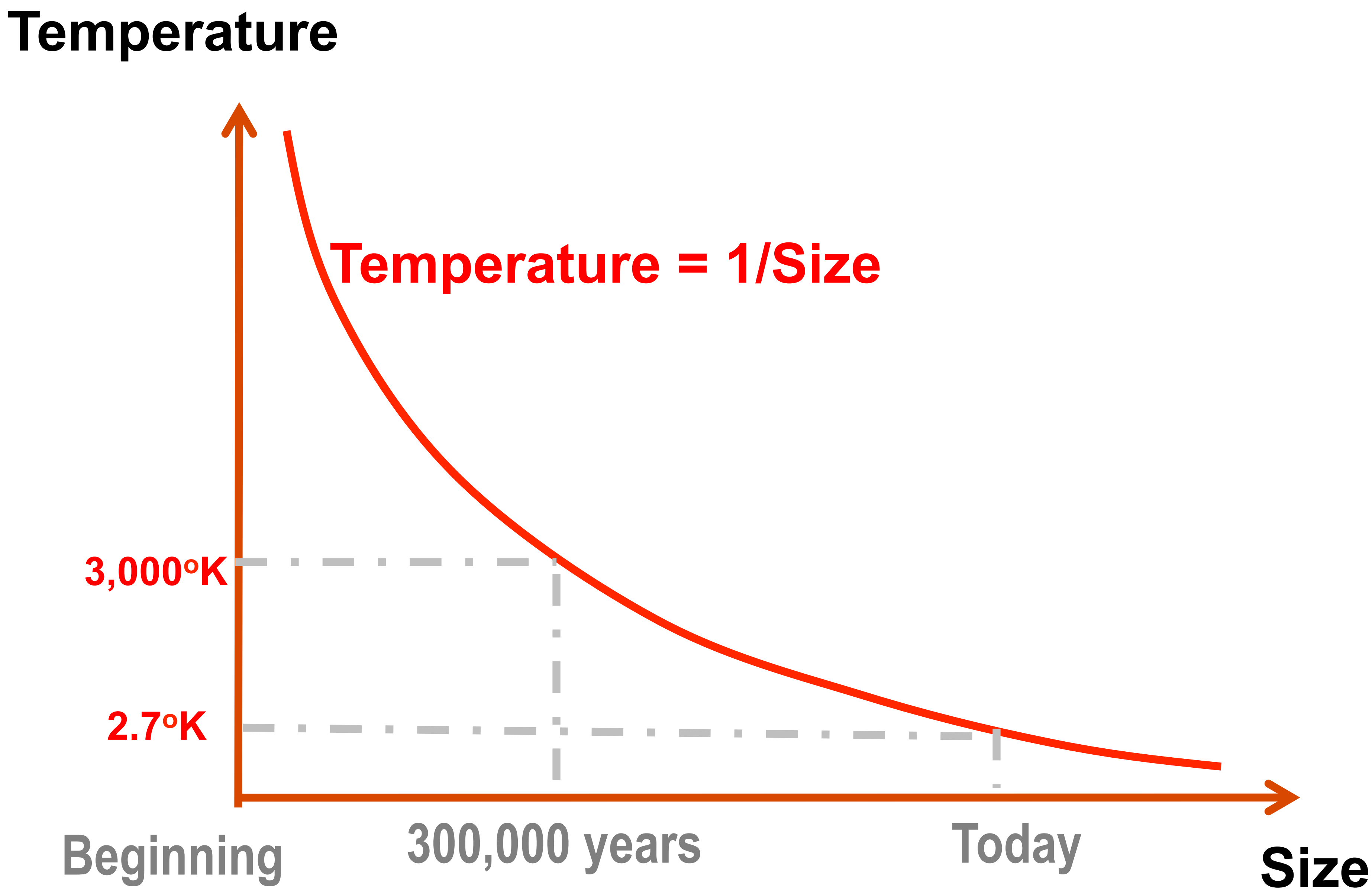
Seven Phases of Cosmic Evolution



Expansion of Universe

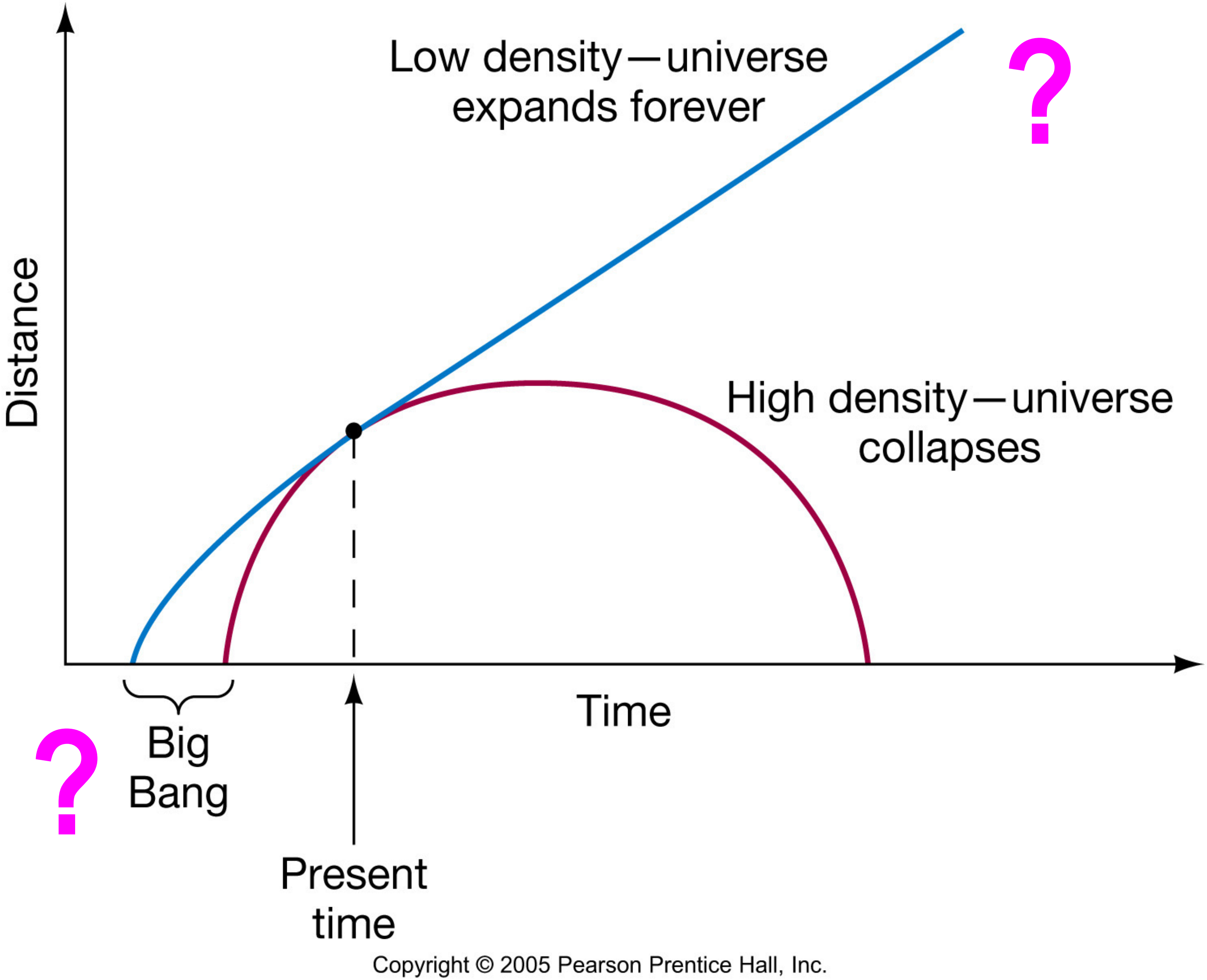


Temperature of Universe



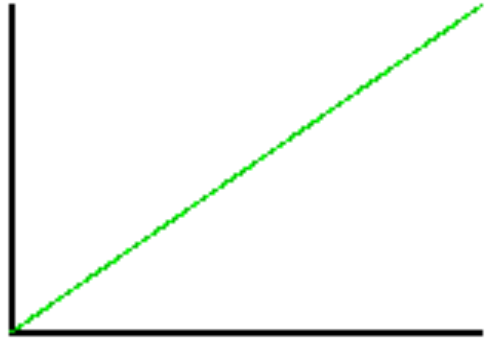
Cosmology

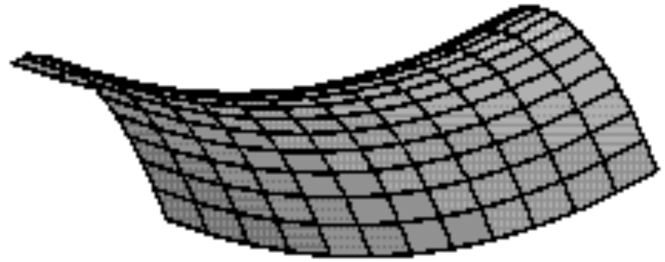
The Fate of the Cosmos



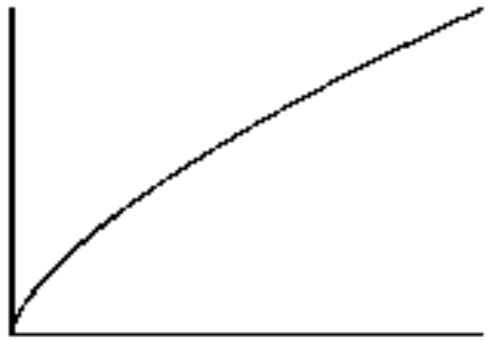
Geometry of the Universe

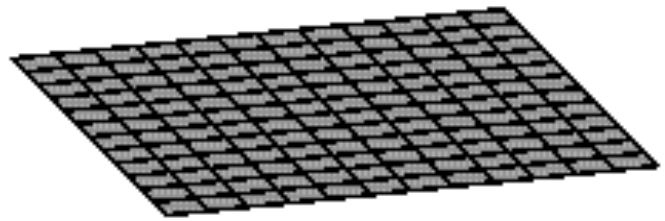
Open $\Omega<1$



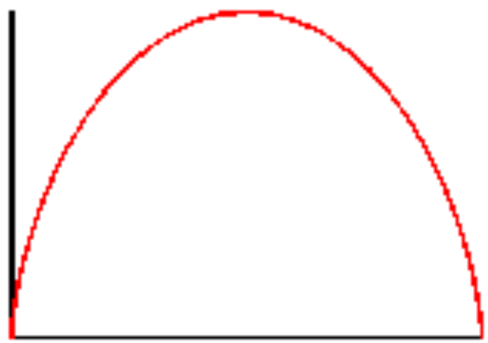


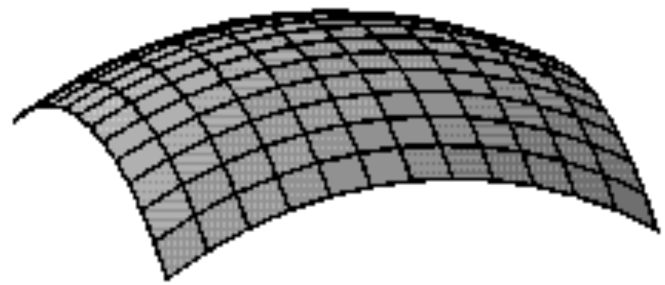
Flat $\Omega=1$

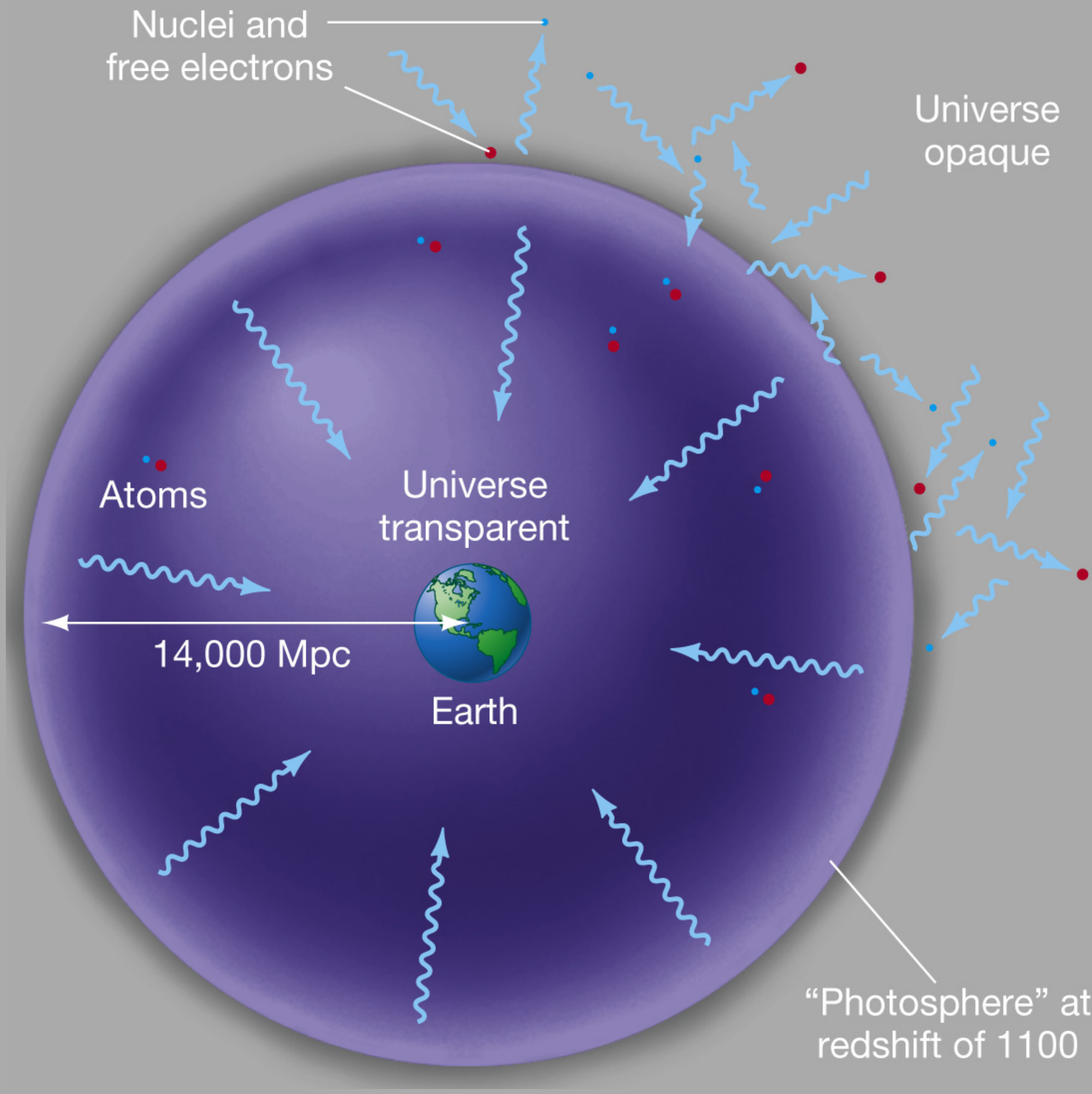




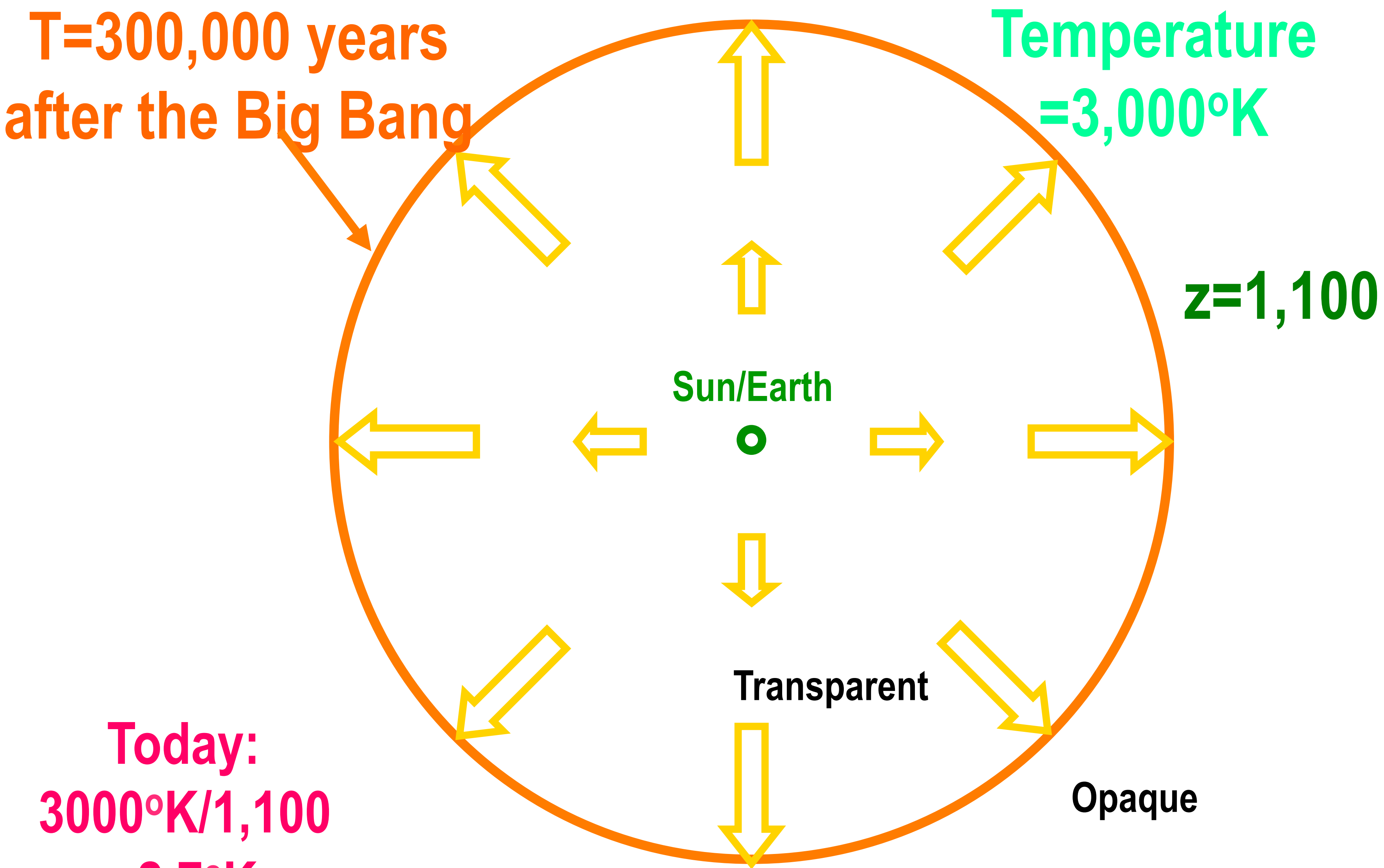
Closed $\Omega>1$






Nuclei and free electrons
Universe opaque
Atoms
Universe transparent
14,000 Mpc
Earth
“Photosphere” at redshift of 1100

Cosmic Microwave Background
(Discovered in 1964)



Time = 300,000 years , Temp.= 3000 ºK

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

⇩

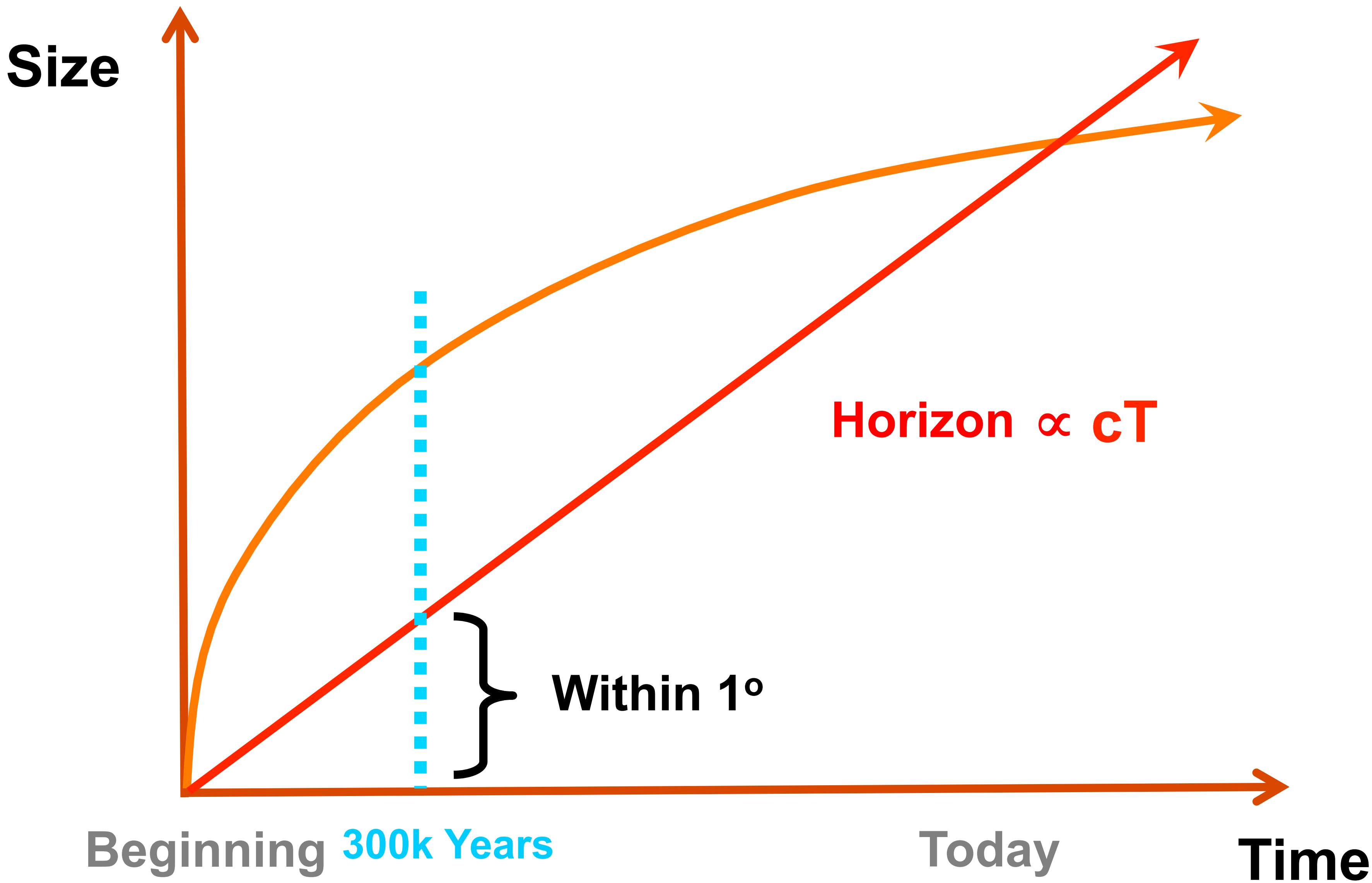
Cosmic Microwave Background (CMB)

Two Fundamental Problem of Big Bang Cosmology

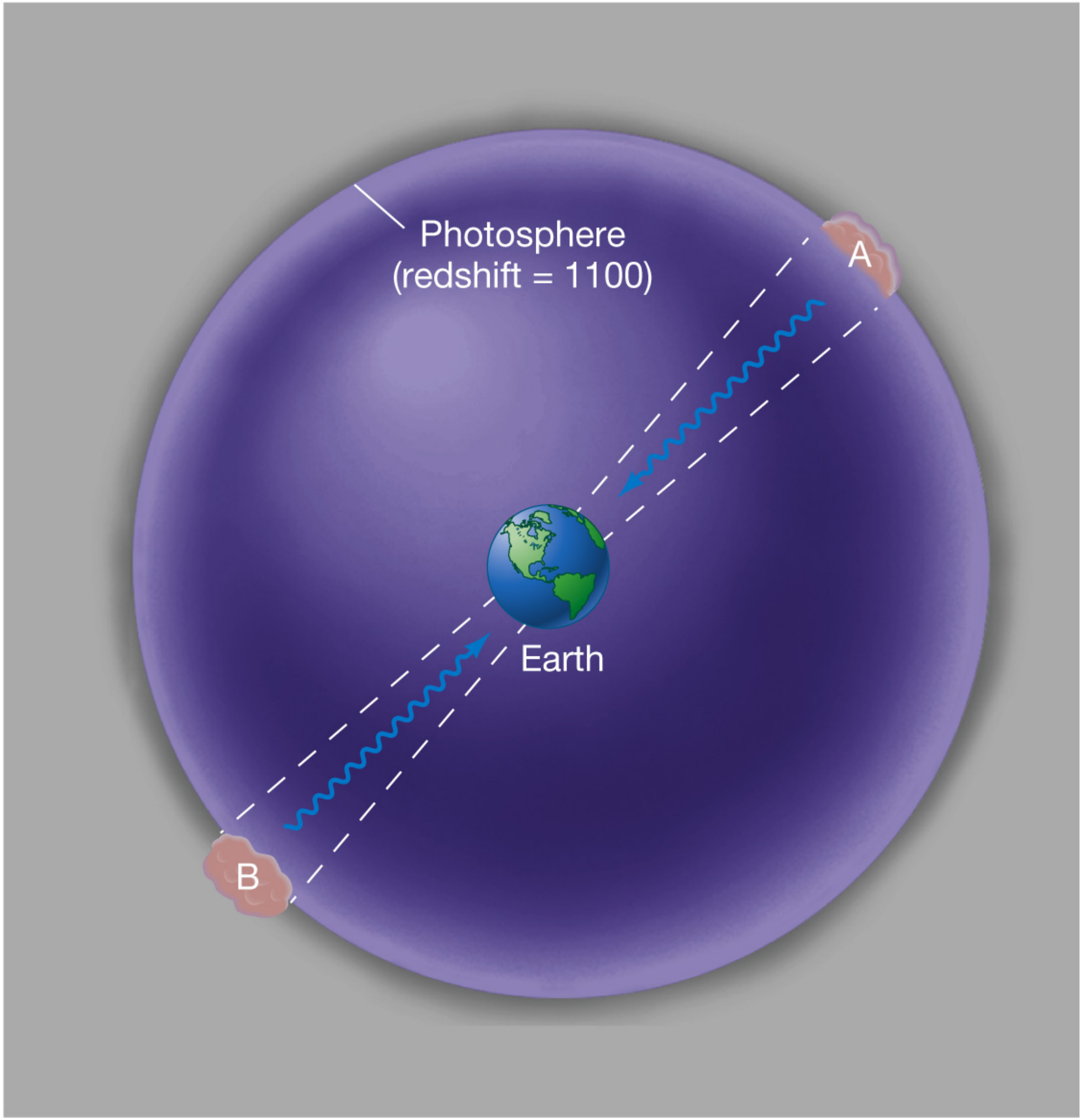
- **Horizon Problem**
  - At early Universe, Size >> Horizon.
  - Why is CMB so uniform in every direction?

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

Expansion of Universe

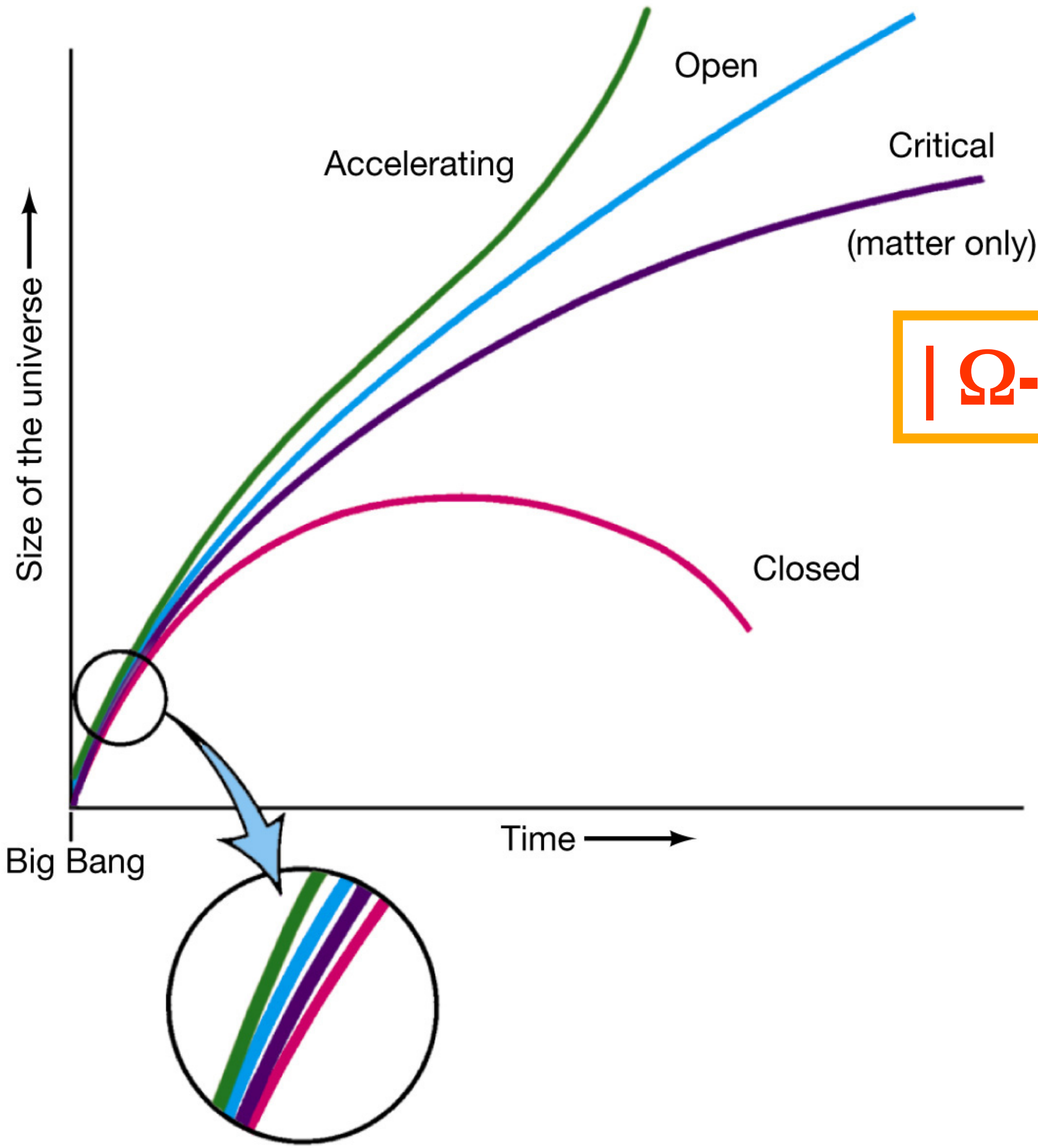


Horizon Problem



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.

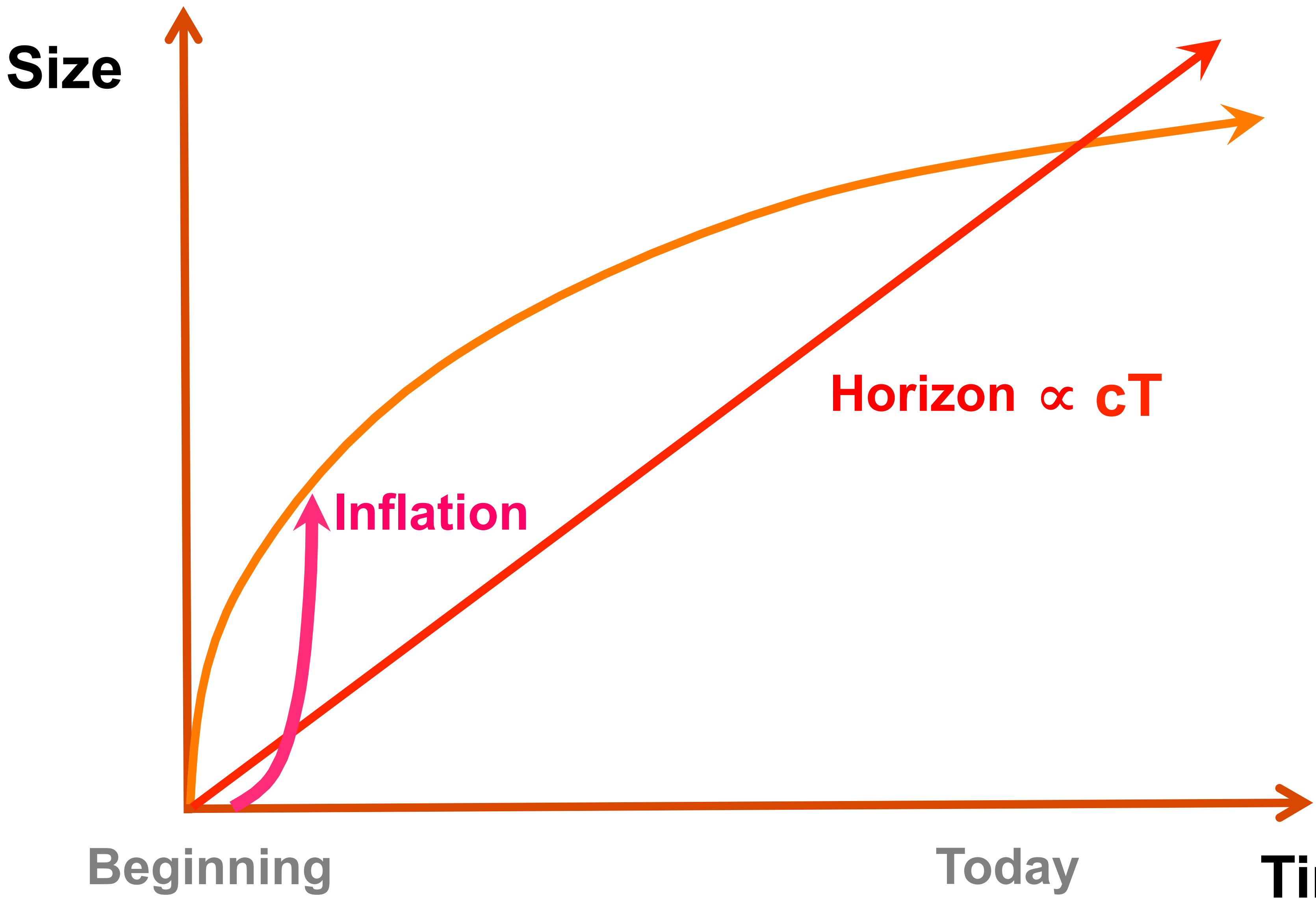
Flatness Problem



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

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}.

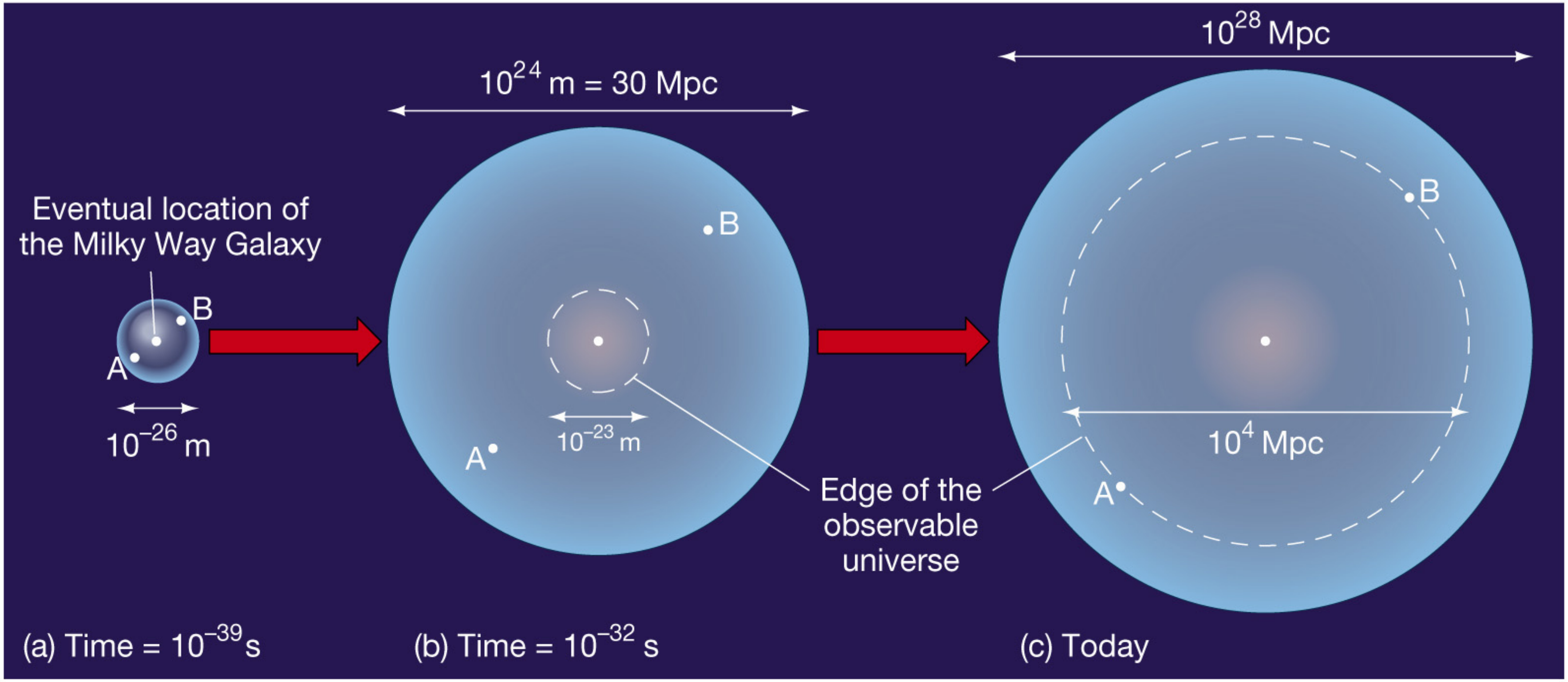
Inflation in Early Universe



The Inflationary Universe

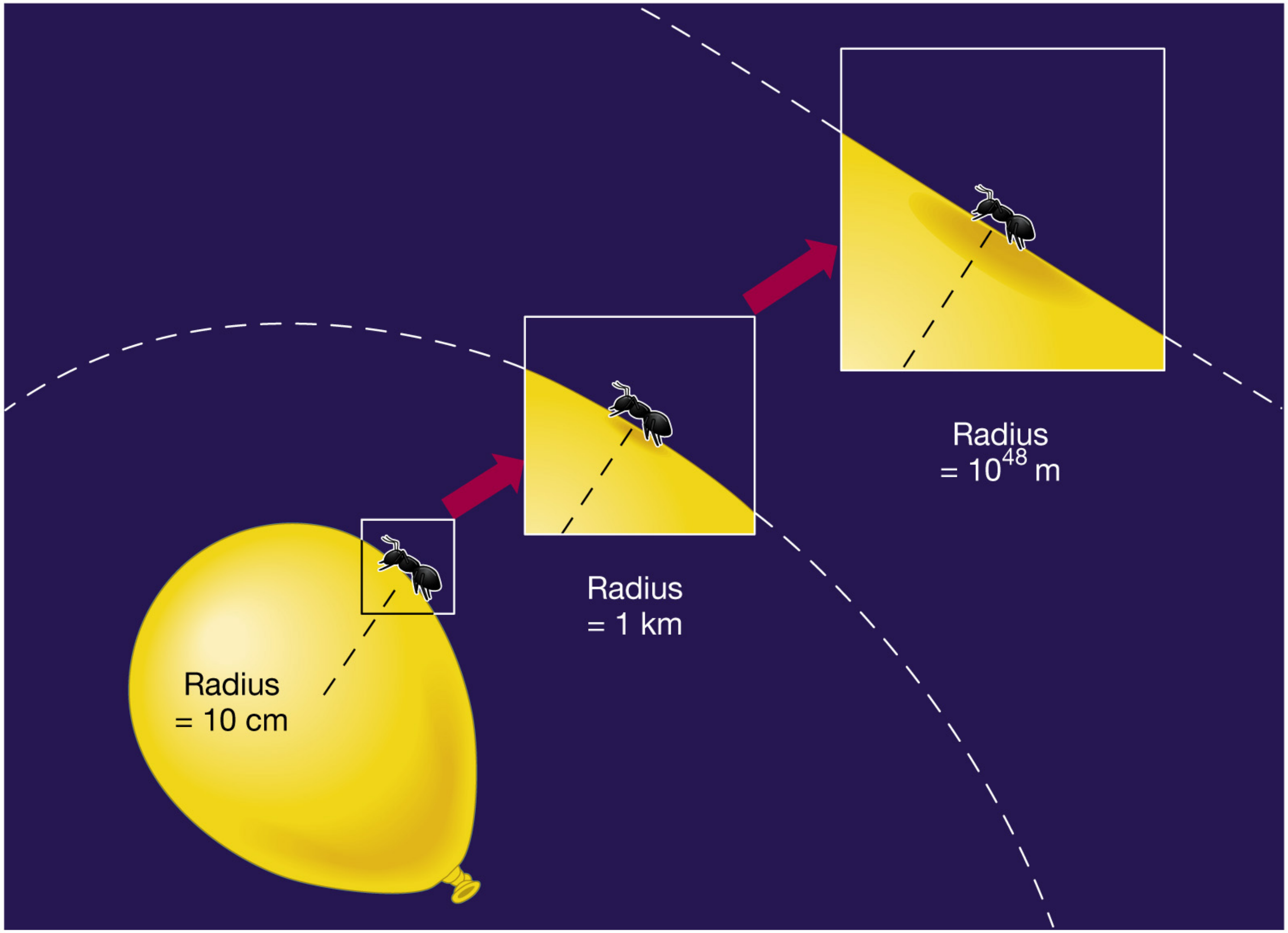
Inflation, if correct, would solve both the **horizon** and the **flatness** problems.

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

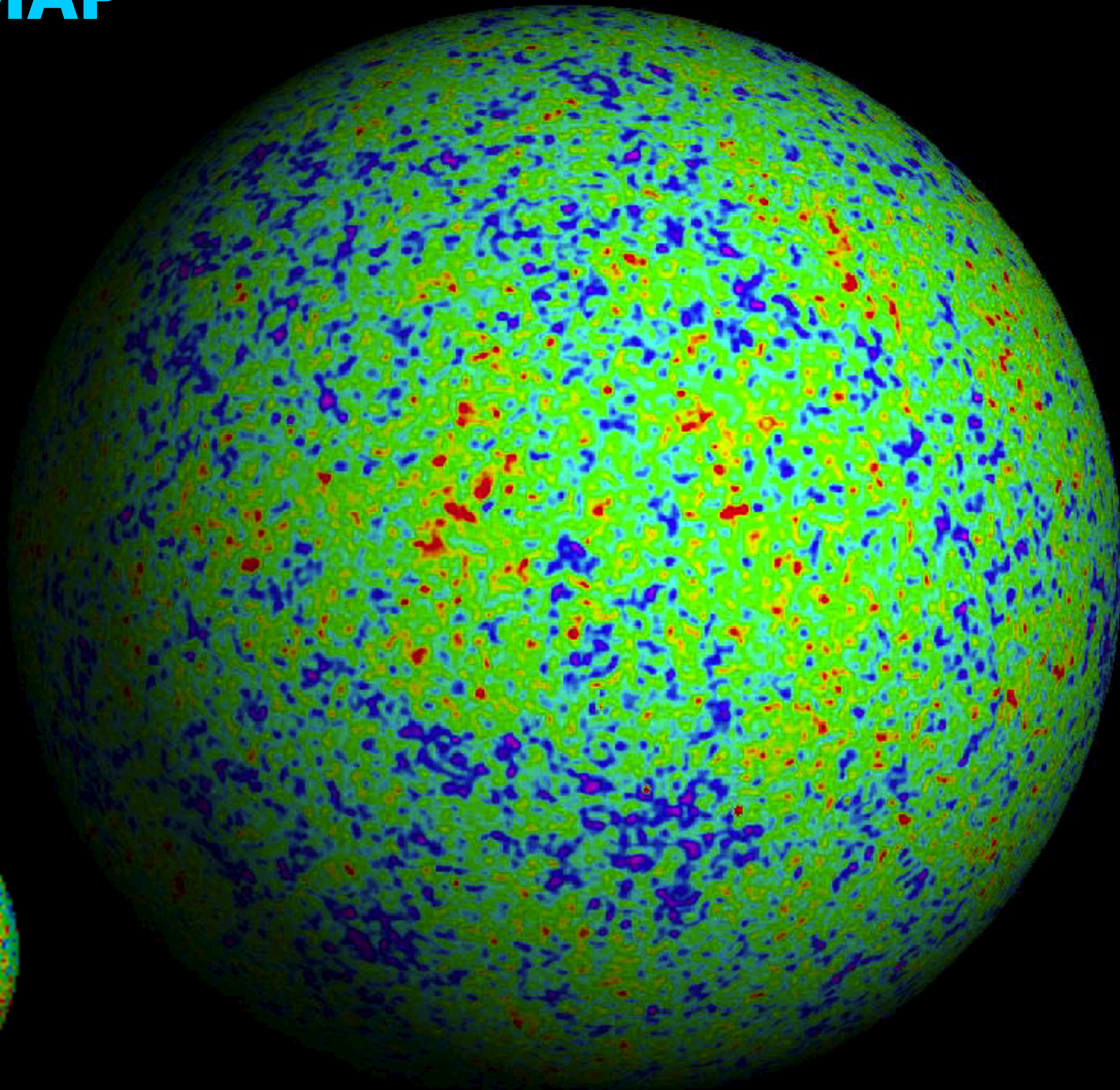


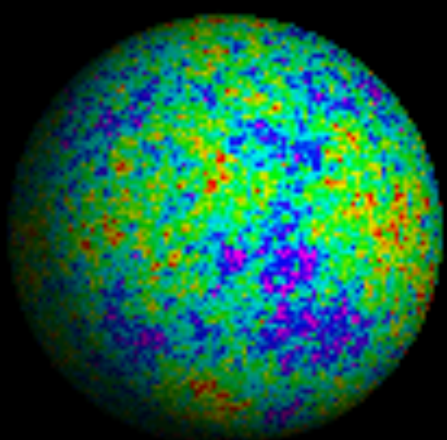
The Inflationary Universe

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:



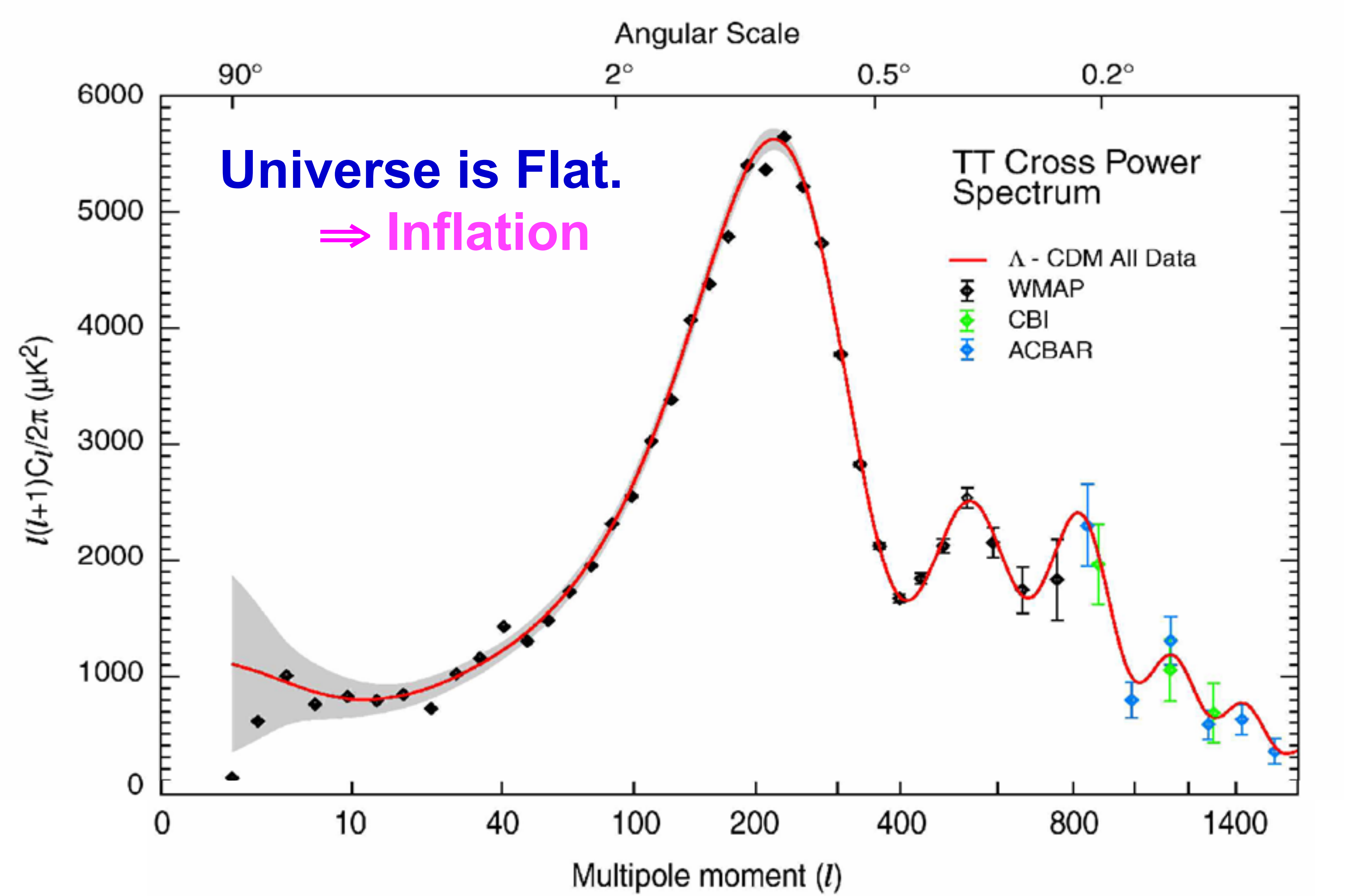
WMAP





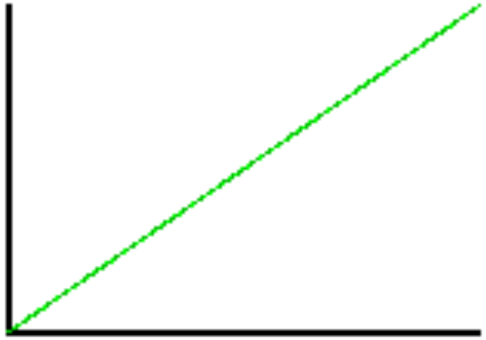
.P map from Tegmark, de Oliveira-Costa & Hamilton, astro-ph/0302496

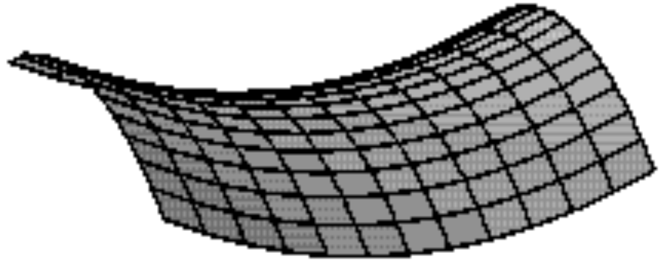
WMAP Power Spectrum



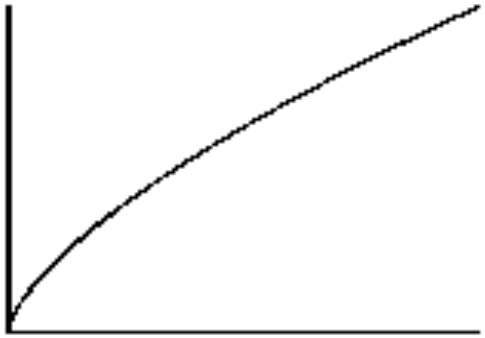
Geometry of the Universe

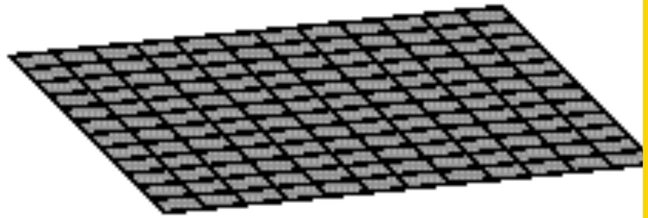
Open **Ω<1**



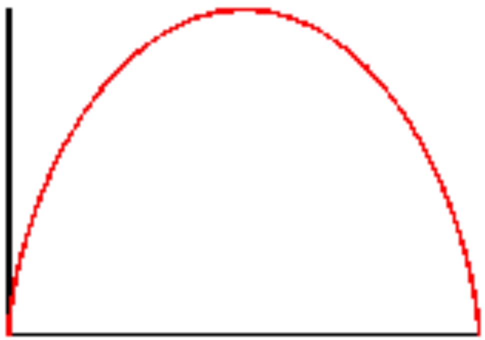


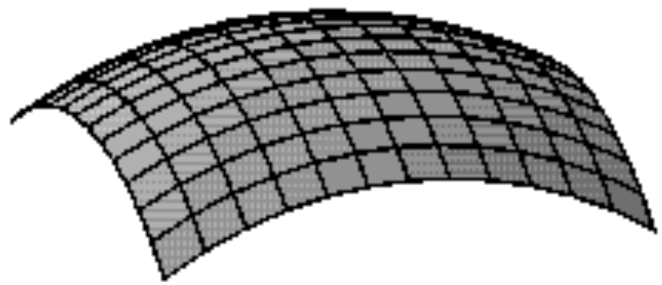
Flat **Ω=1**



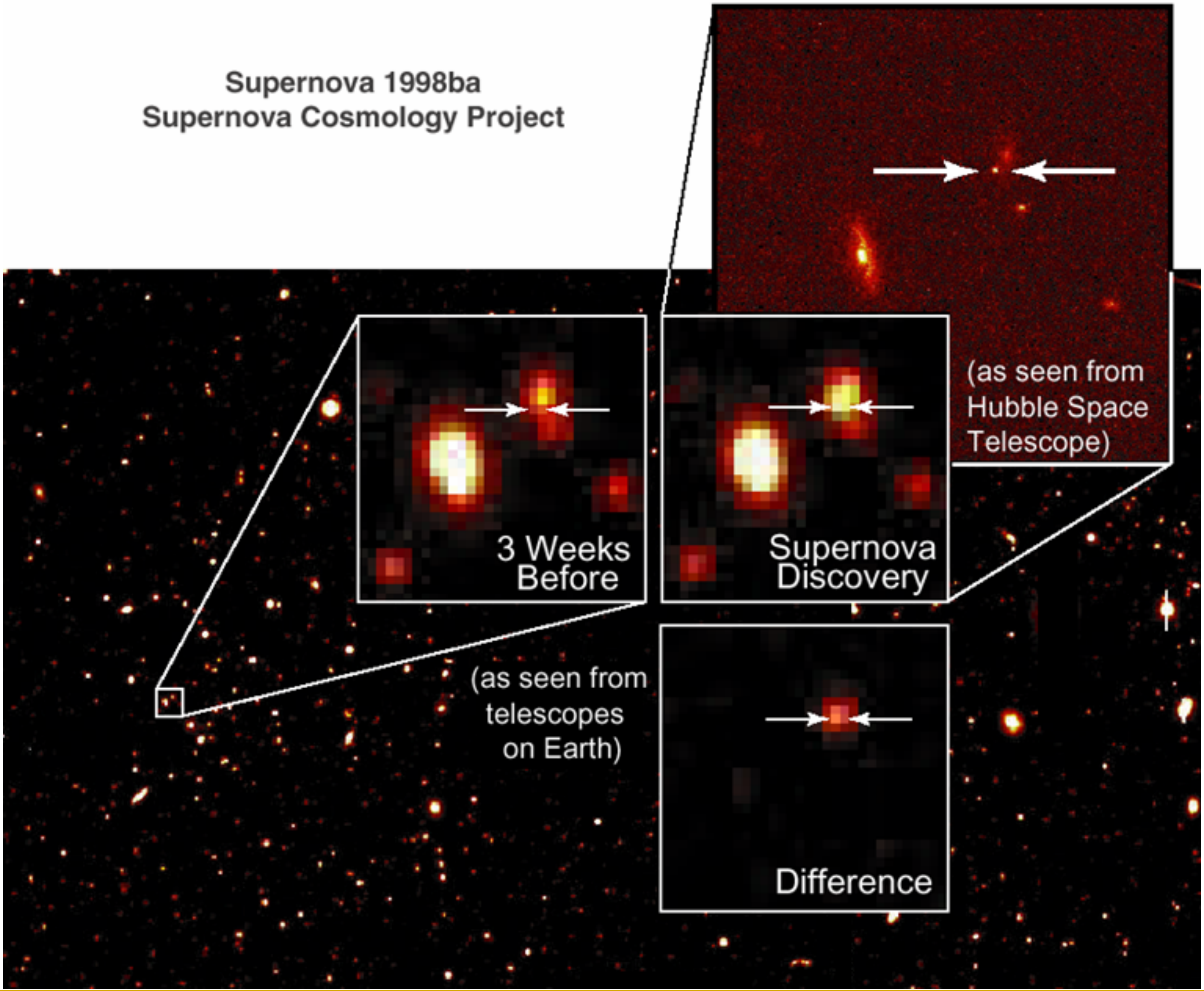


Closed **Ω>1**

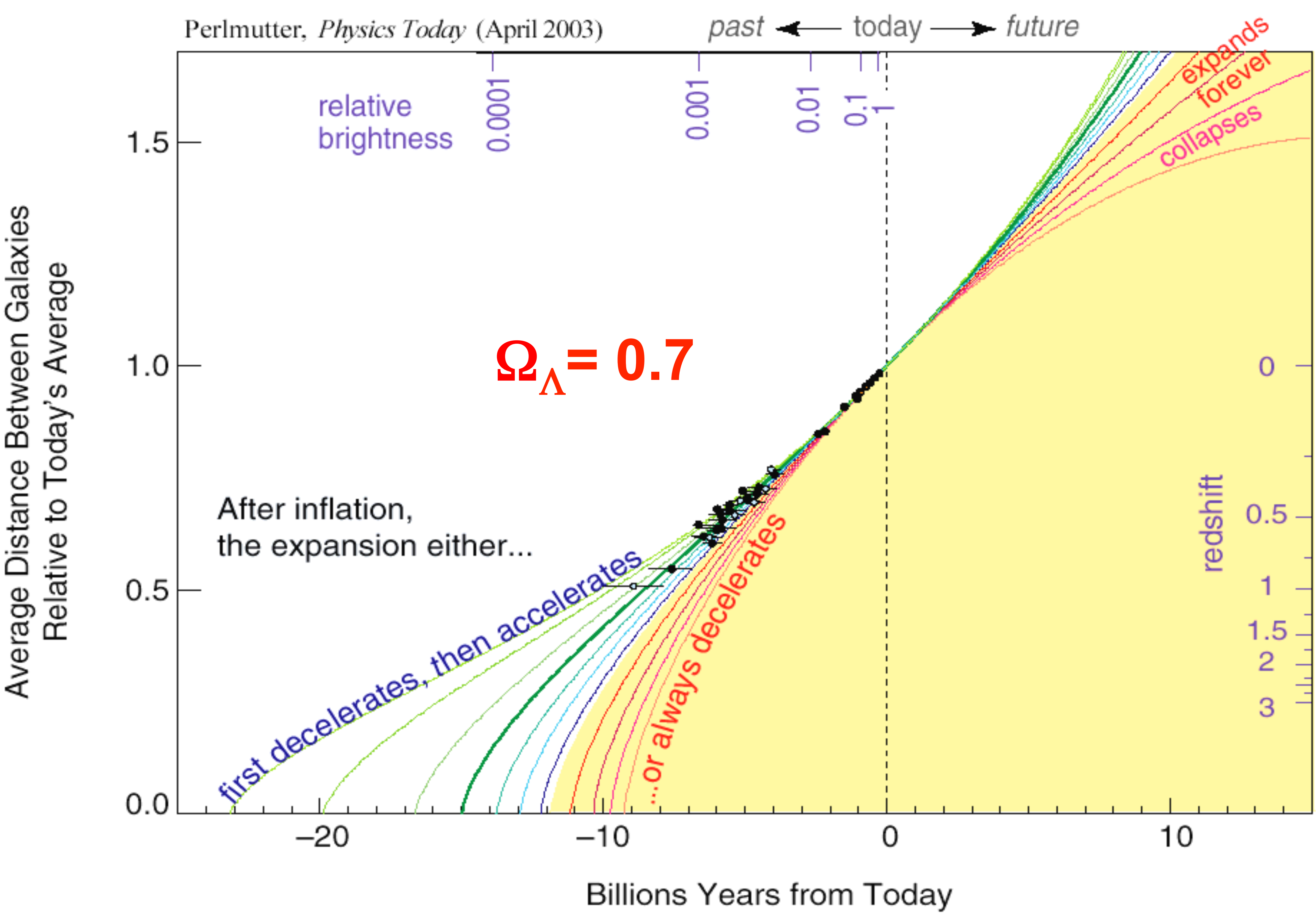




Supernova as a Standard Candle



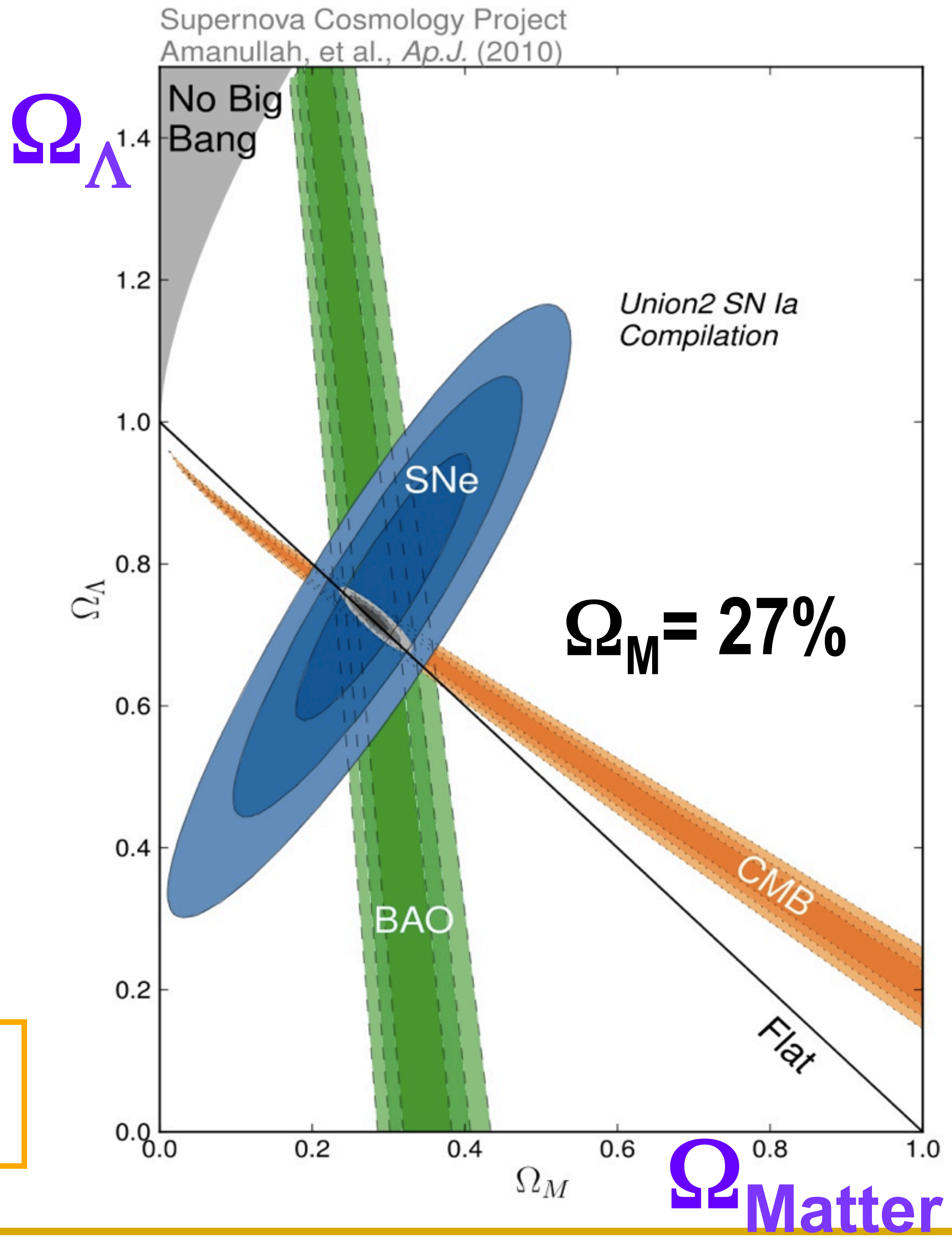
The Accelerating Universe （1998）



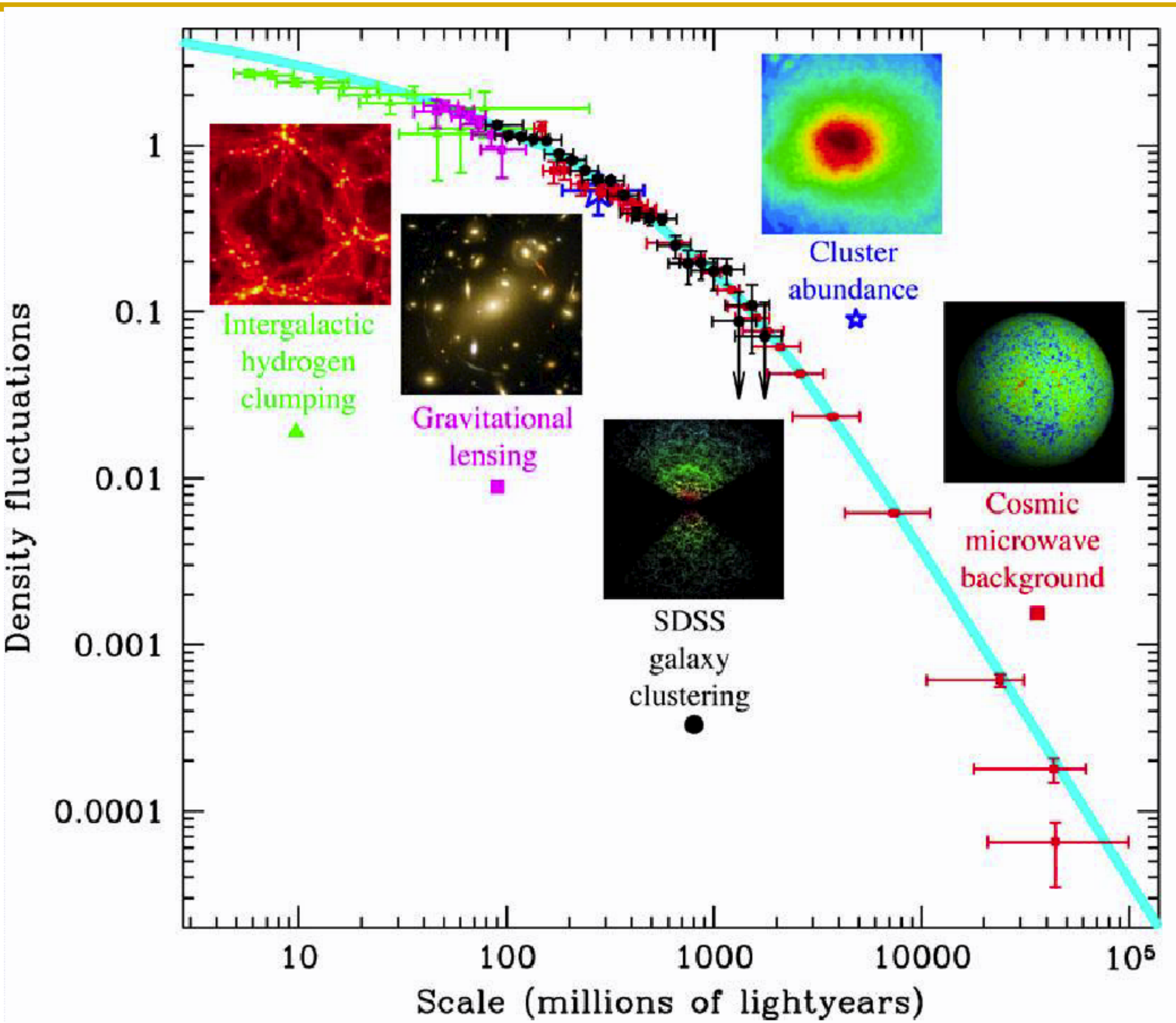
Density of Our Universe

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

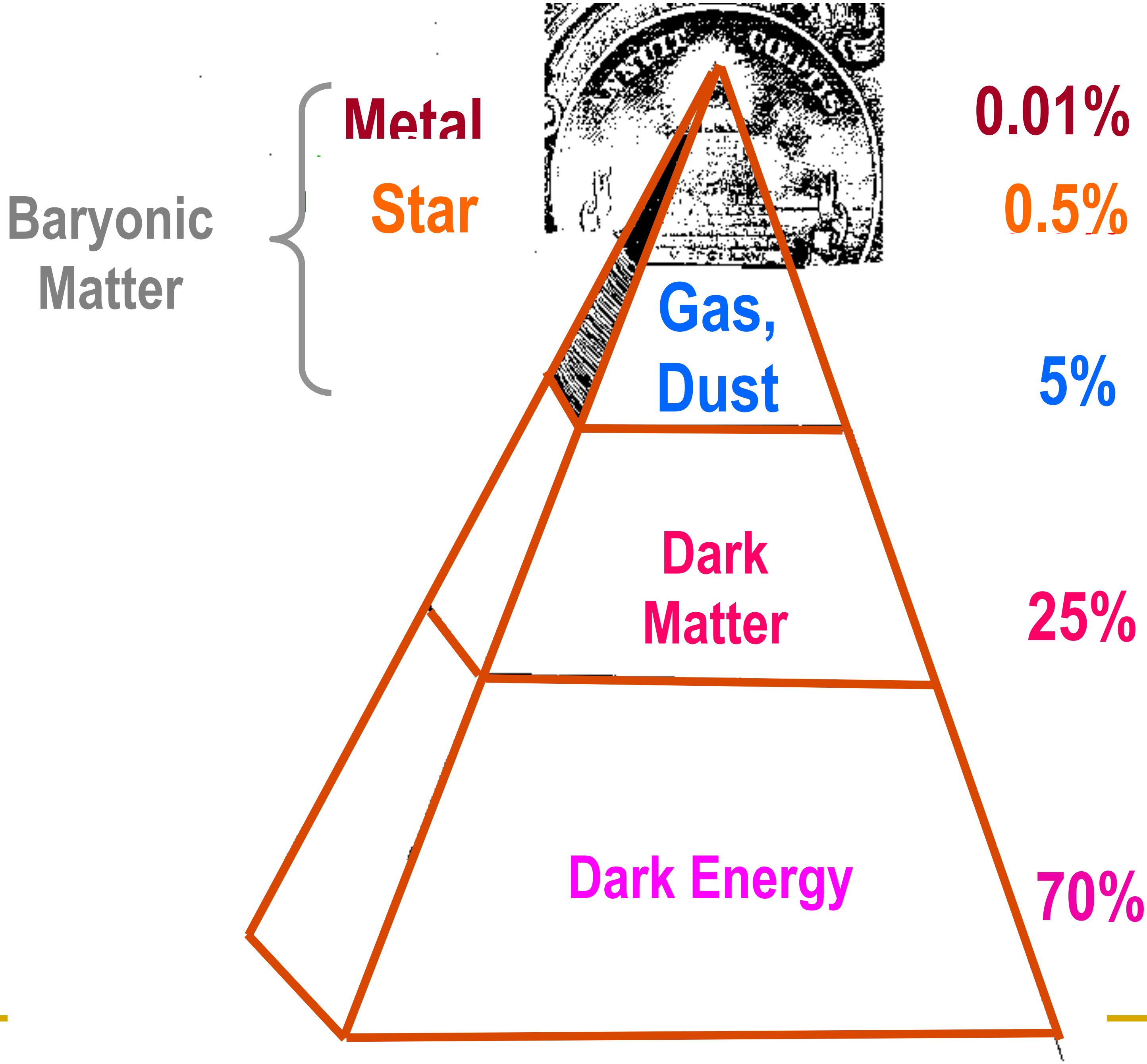
Ω_{Matter} and Ω_Λ are two of "Just Six Numbers"



Density Fluctuations



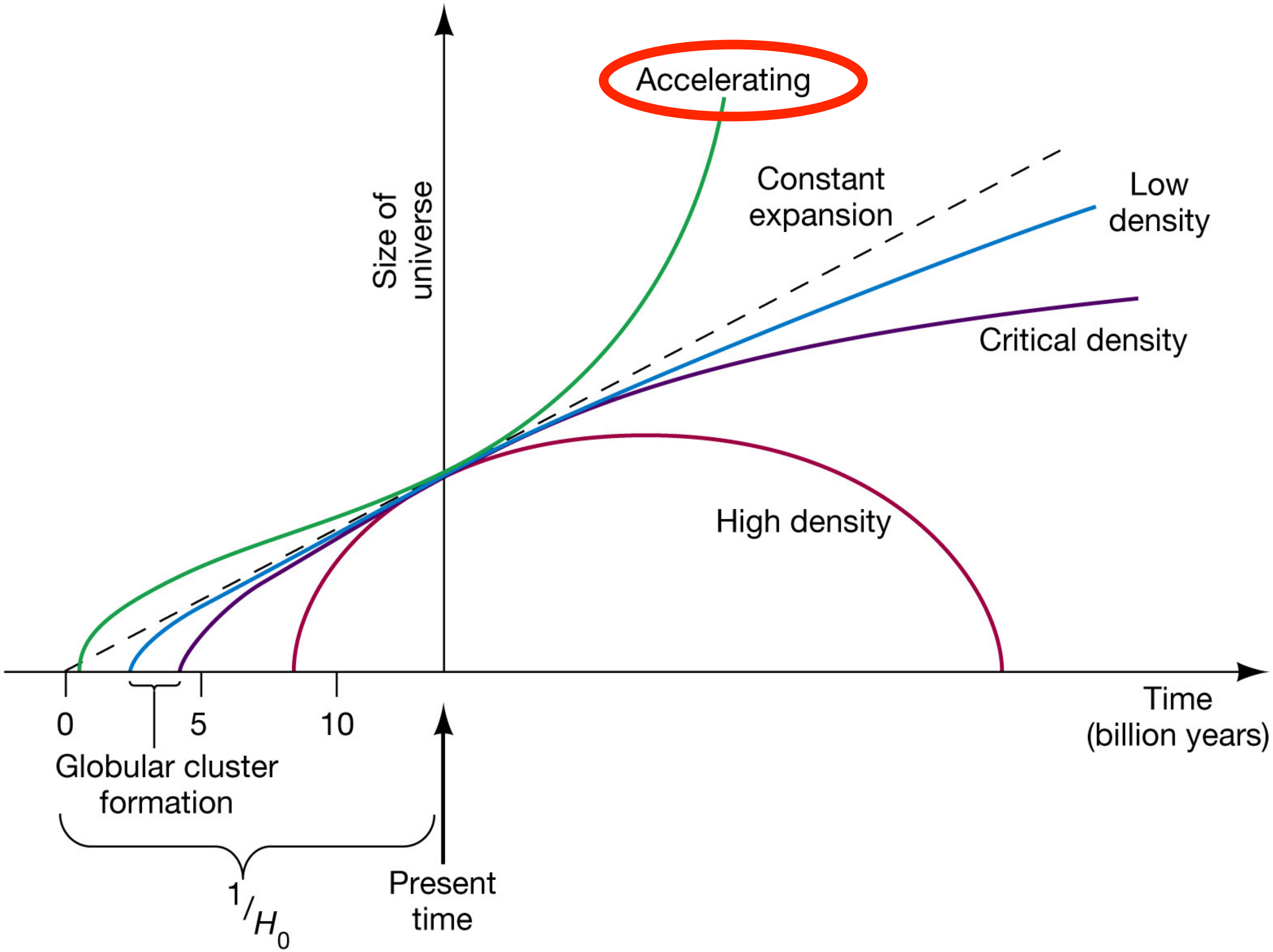
Cosmic Pyramid



Dark Energy and Cosmology

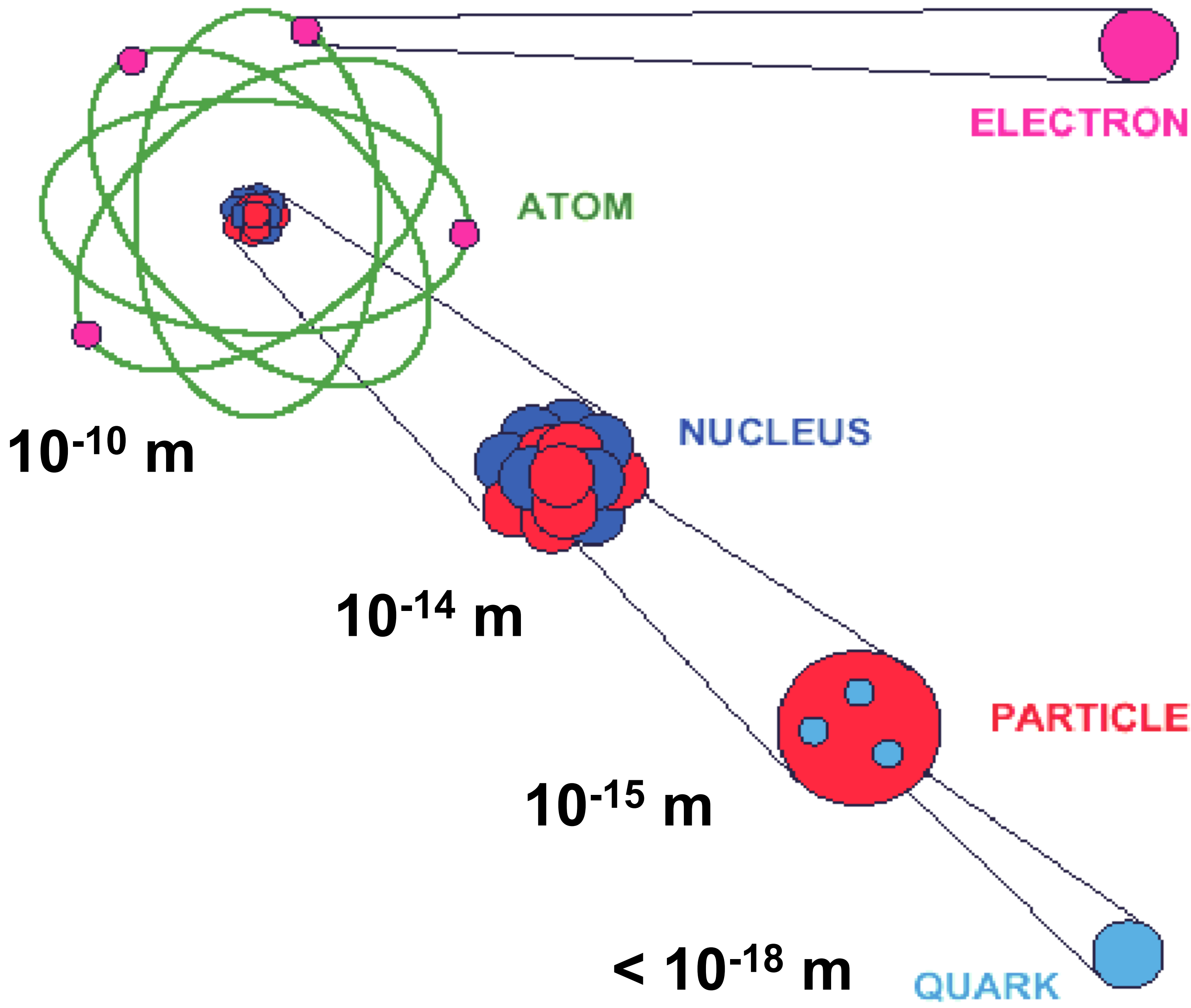
This graph now includes the accelerating universe.

Given what we now know, the age of the universe works out to be 13.7 billion years.



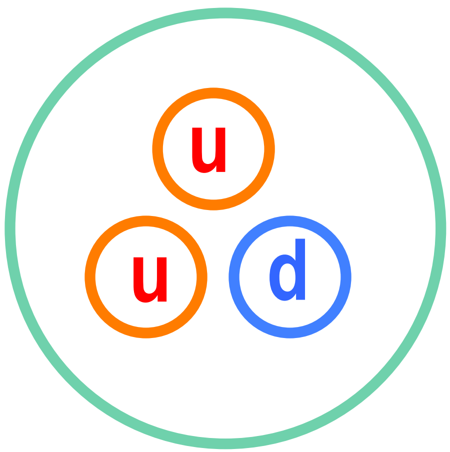
Particle Physics

Elementary Particles (~1970)



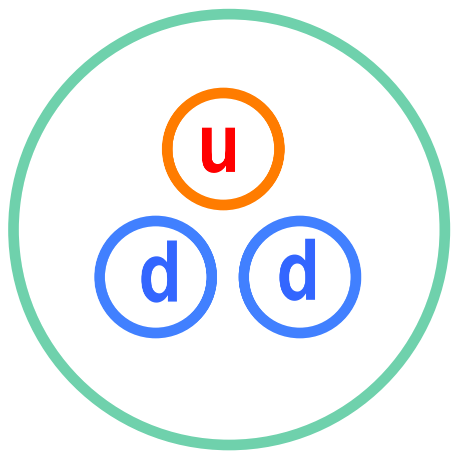
Quark Model

Proton



$+\,2/3 + 2/3 - 1/3 = 1$

Neutron

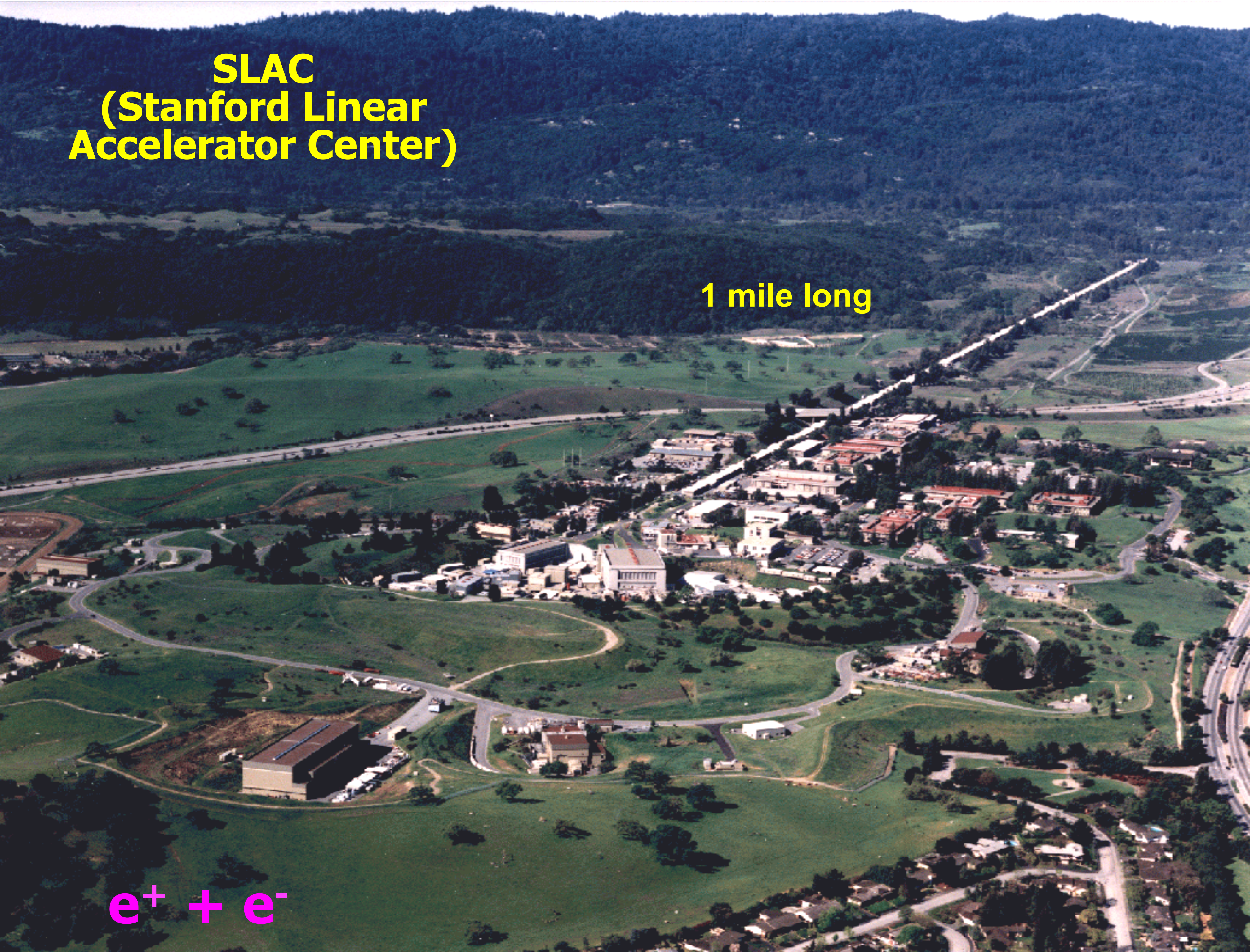


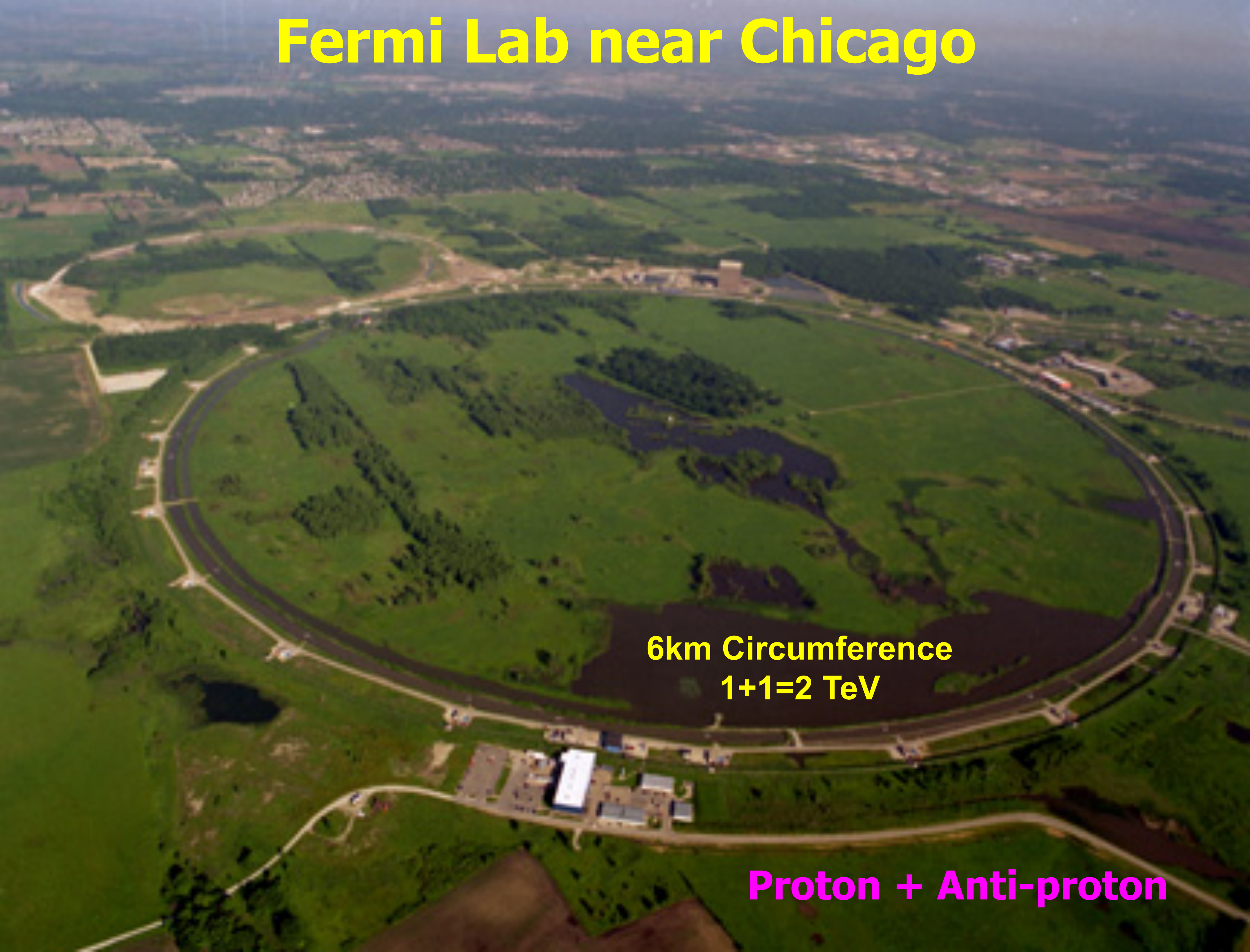
$+\,2/3 - 1/3 - 1/3 = 0$

Fermions

- **1973**
  - Elementary particles : "Fermions"

	Particle	Anti-Particle
Quarks	$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} \\ s \end{pmatrix}$	$\begin{pmatrix} \bar{u} \\ \bar{d} \end{pmatrix} \begin{pmatrix} \\ \bar{s} \end{pmatrix}$
Leptons	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}$	$\begin{pmatrix} \bar{\nu}_e \\ e^+ \end{pmatrix} \begin{pmatrix} \bar{\nu}_\mu \\ \mu^+ \end{pmatrix}$


SLAC
(Stanford Linear
Accelerator Center)
1 mile long
$e^+ + e^-$


Fermi Lab near Chicago
6km Circumference
1+1=2 TeV
Proton + Anti-proton

Discovery of more quarks

- **1974 – 1994**
  - More quarks and leptons were discovered.

- 1974 Ting (BNL) & Richter (SLAC) $J/\Psi = c\bar{c}$
- 1975 Perl (SLAC) τ-lepton
- 1978 Lederman (FNAL) $\Upsilon = b\bar{b}$
- 1994 CDF/D0 Group (FNAL) t (top quark)

All discovered at US National Labs (Many Nobels!)

Elementary Particles

Fermion Boson

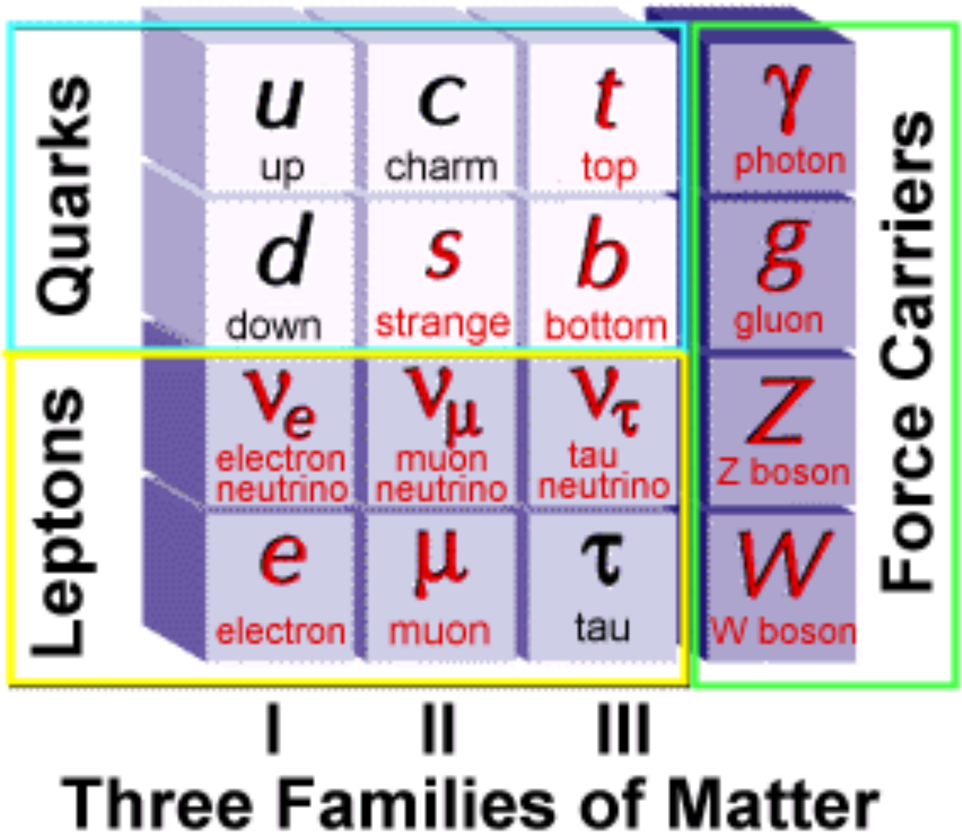
Charge

+2/3

-1/3

0

-1



Charge

0

0

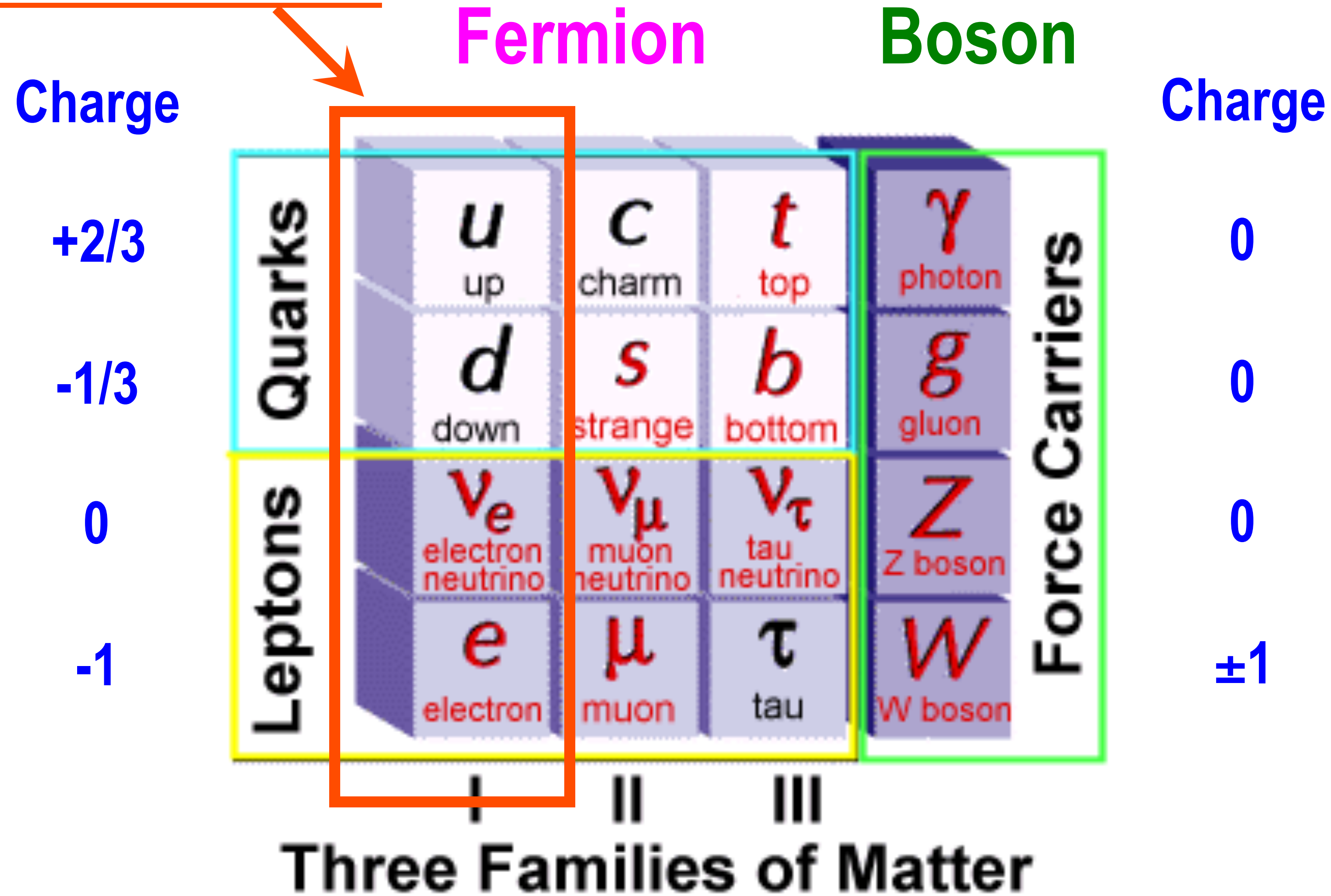
0

±1

+ Anti-particles

Elementary Particles

Today’s Universe

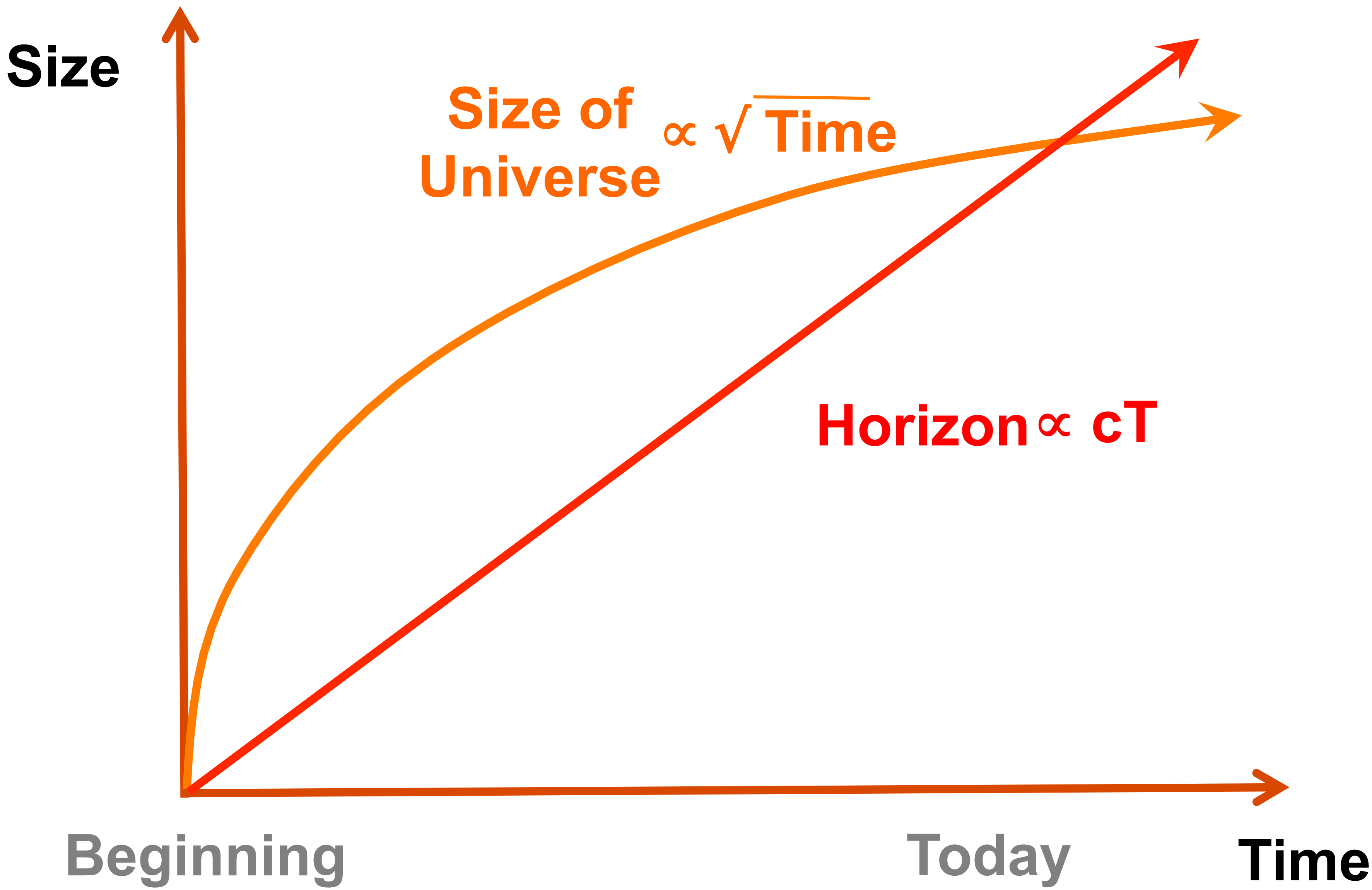


Now Time = 14B yrs, Temp.= 2.7 ºK (3×10^{-4} eV)

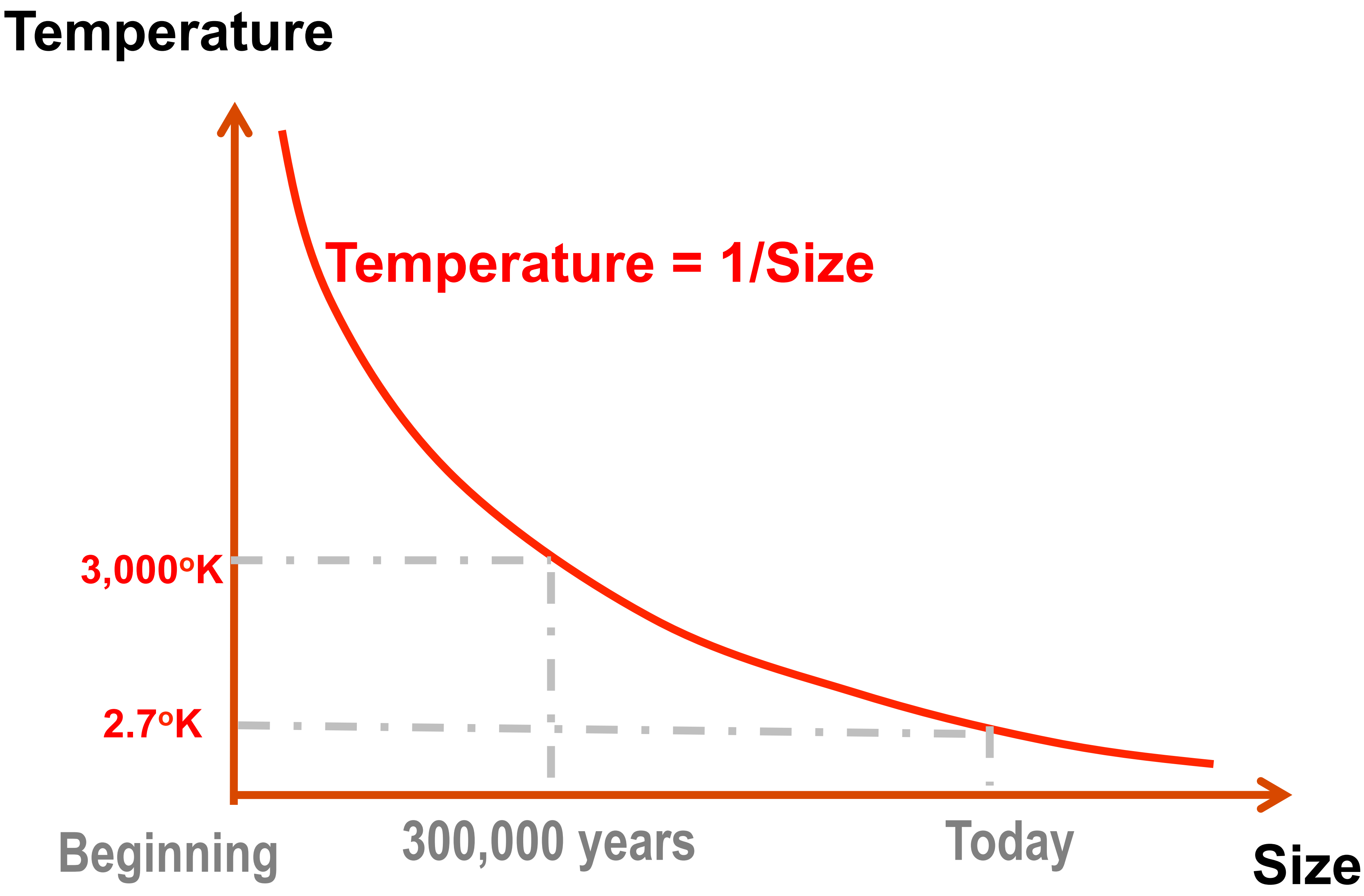
		Ratio (in numbers)
Fermions:		
▪ Lepton:	ν_e	~1
	e^-	$\sim4\times10^{-10}$
▪ Baryon:	p	$\sim4\times10^{-10}$
	n	$\sim1\times10^{-10}$
Bosons:		
▪ Photon:	γ	1

- No anti-particles
- # Photon : # Baryon = 1 : $\sim4\times10^{-10}$
- # p = # e^-

Expansion of Universe



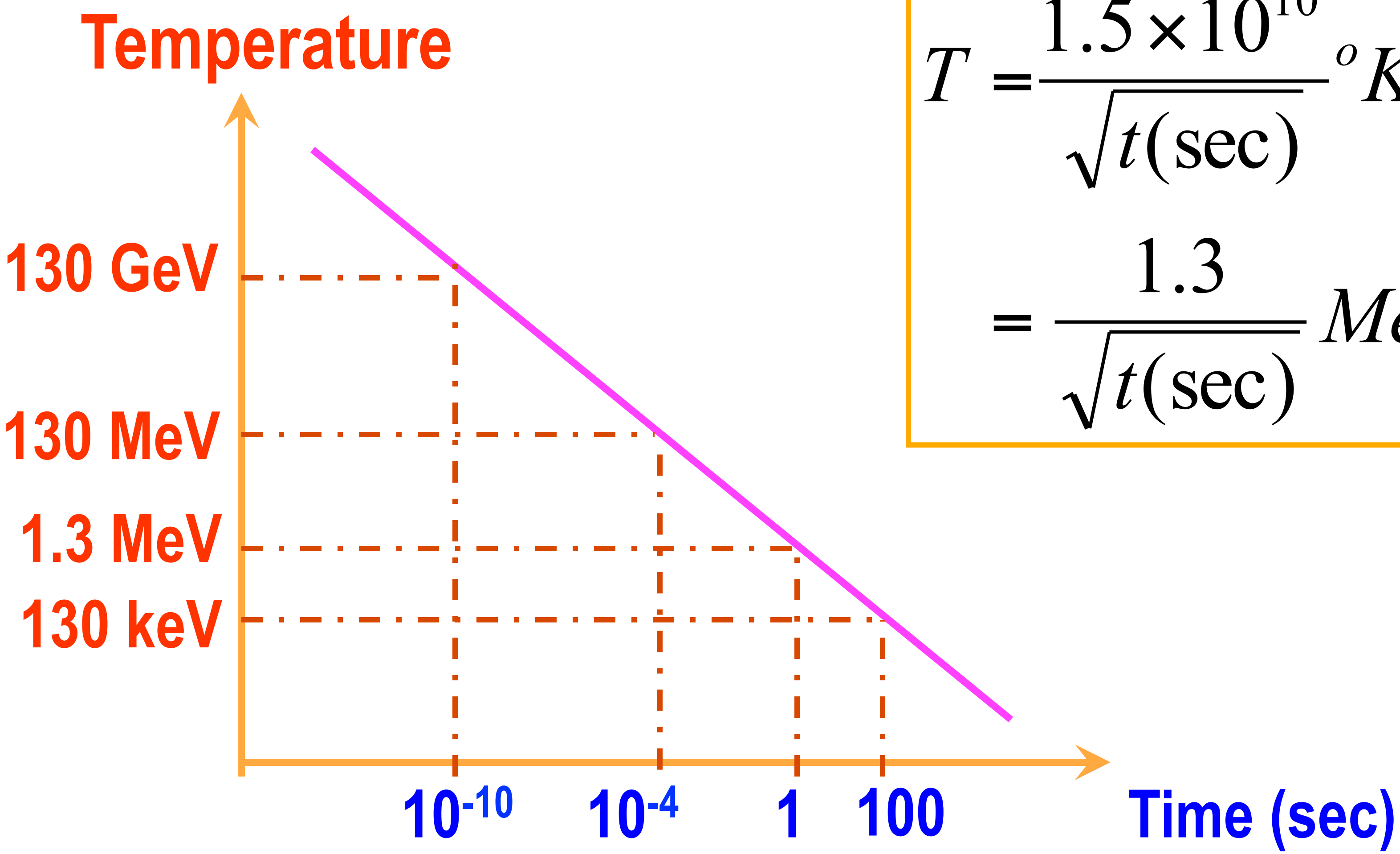
Temperature of Universe



Relation between Temperature and Time

T: Temperature
t : time

$$T = \frac{1.5 \times 10^{10}}{\sqrt{t(\sec)}} \, {}^{o}K$$
$$= \frac{1.3}{\sqrt{t(\sec)}} MeV$$



Thermal Equilibrium

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

$$E > 2\,mc^2$$

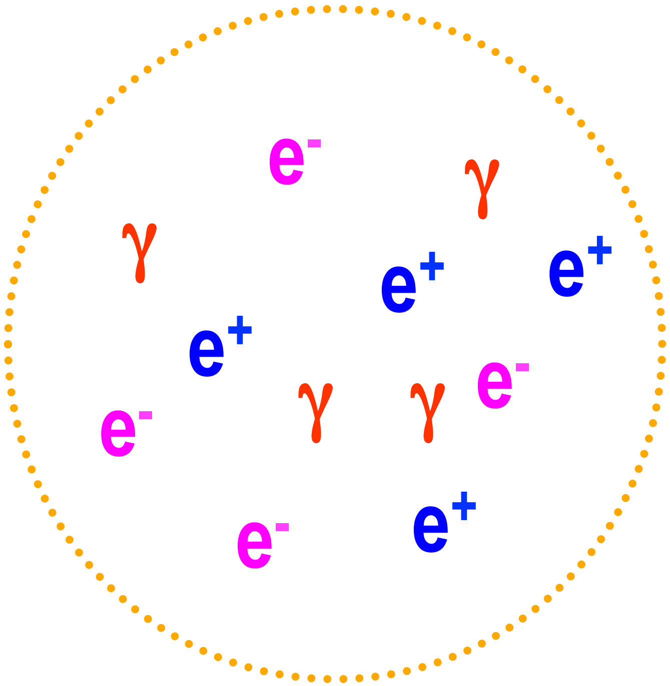
Photon ↔ Particle + Anti-particle

Example:

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

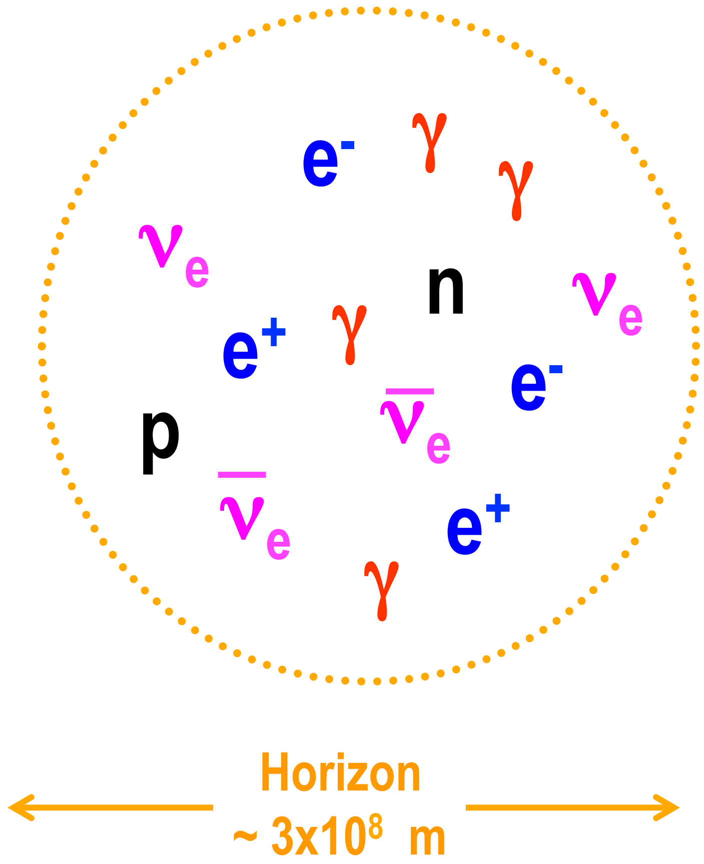
if E > 1.022 MeV

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



Time = 1 sec, Temp.= 10^{10} °K (1.3 MeV)

- **Fermions:** — **Ratio**
  - Lepton:
    - ν_e — 1
    - e^- — 1
    - $\bar{\nu}_e$ — 1
    - e^+ — 1
  - Baryon:
    - p — $\sim 4\times10^{-10}$
    - n — $\sim 1\times10^{-10}$
- **Bosons:**
  - Photon: γ — 1



Time = 10^{-4} sec, Temp.= 10^{12} °K (~100 MeV)

- **Thermal Equilibrium of Protons and Neutrons**
  - $n \leftrightarrow p + e^- + \bar{\nu}_e$
  - $n + e^+ \leftrightarrow p + \bar{\nu}_e$
  - $n + \nu_e \leftrightarrow p + e^-$

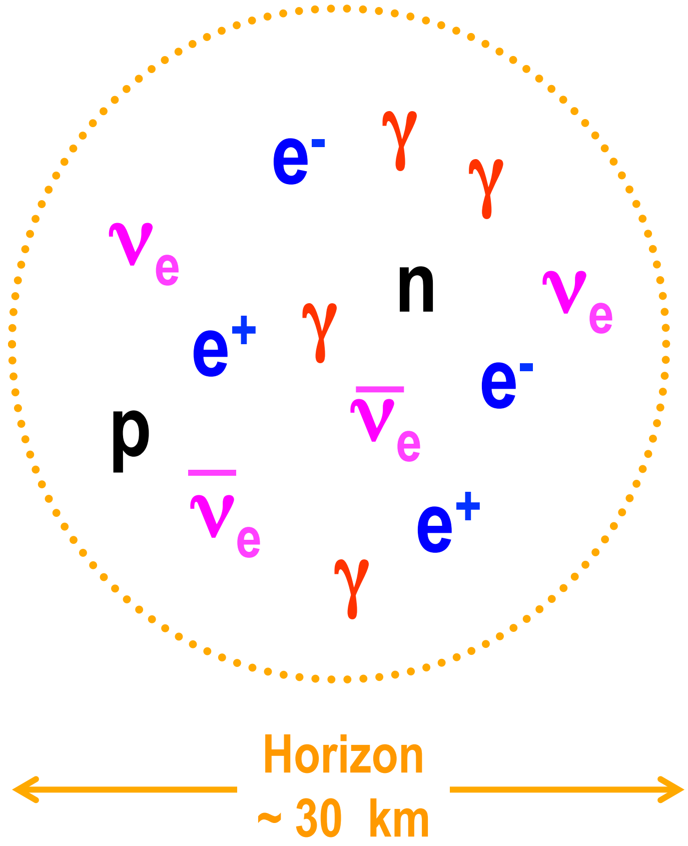
- **Lepton Dominant Era**

- **Fermions:**

		Ratio
Lepton:	ν_e	1
	e^-	1
	$\bar{\nu}_e$	1
	e^+	1
Baryon:	p	$\sim 2\times10^{-10}$
	n	$\sim 2\times10^{-10}$

- **Bosons:**

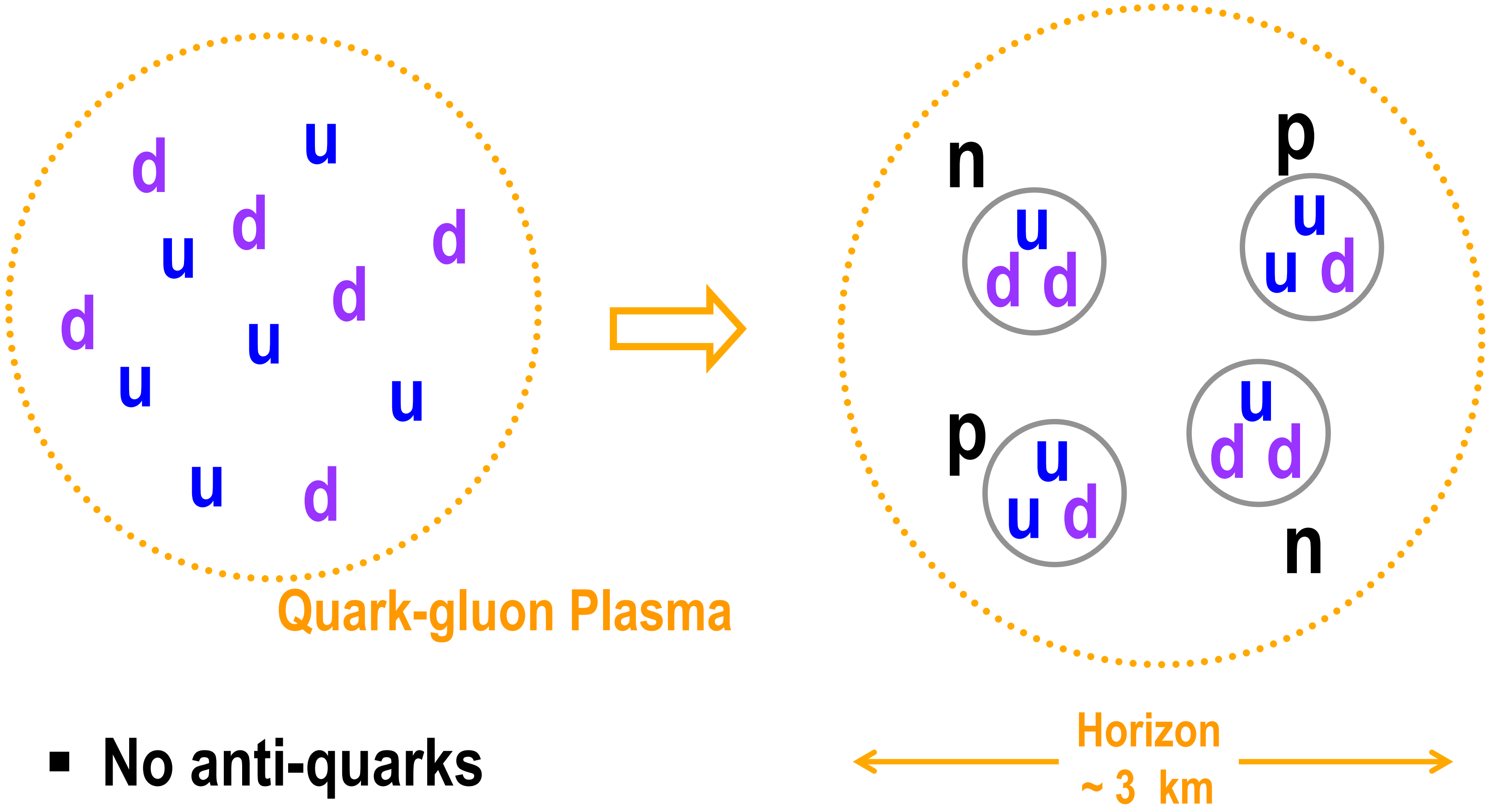
Photon:	γ	1



Time = 10^{-5} sec, Temp.= 3×10^{12} °K (300 MeV)

➢ Quark → Hadron Phase Transition

- u-quarks and d-quarks are bound together to form protons and neutrons.

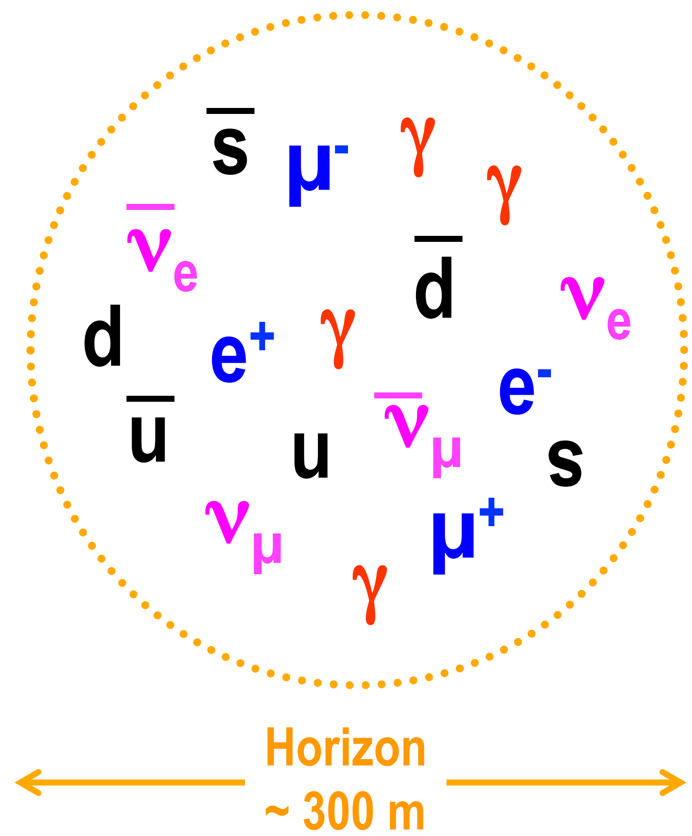


- No anti-quarks

Time = 10^{-6} sec, Temp.= 10^{13} °K (~1 GeV)

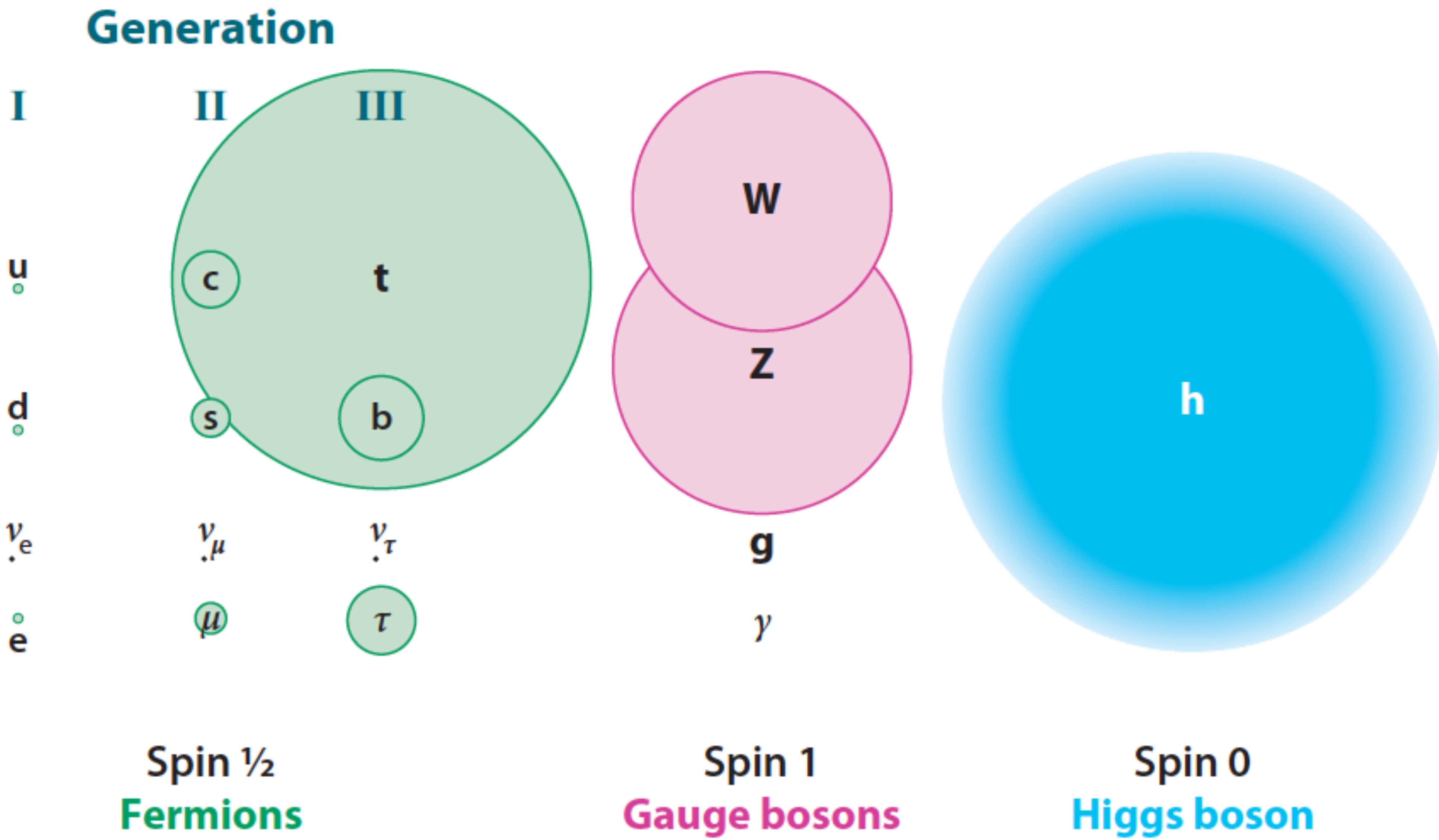
➢ Thermal Equilibrium of Photons, Leptons and Quarks

- Photon ↔ Lepton + Anti-lepton
  - $\gamma \leftrightarrow e^- + e^+$
  - $\gamma \leftrightarrow \mu^- + \mu^+$
  - $\gamma \leftrightarrow \nu + \nu$
- Photon ↔ Quark+ Anti-quark
  - $\gamma \leftrightarrow u + \bar{u}$
  - $\gamma \leftrightarrow d + \bar{d}$
  - $\gamma \leftrightarrow s + \bar{s}$



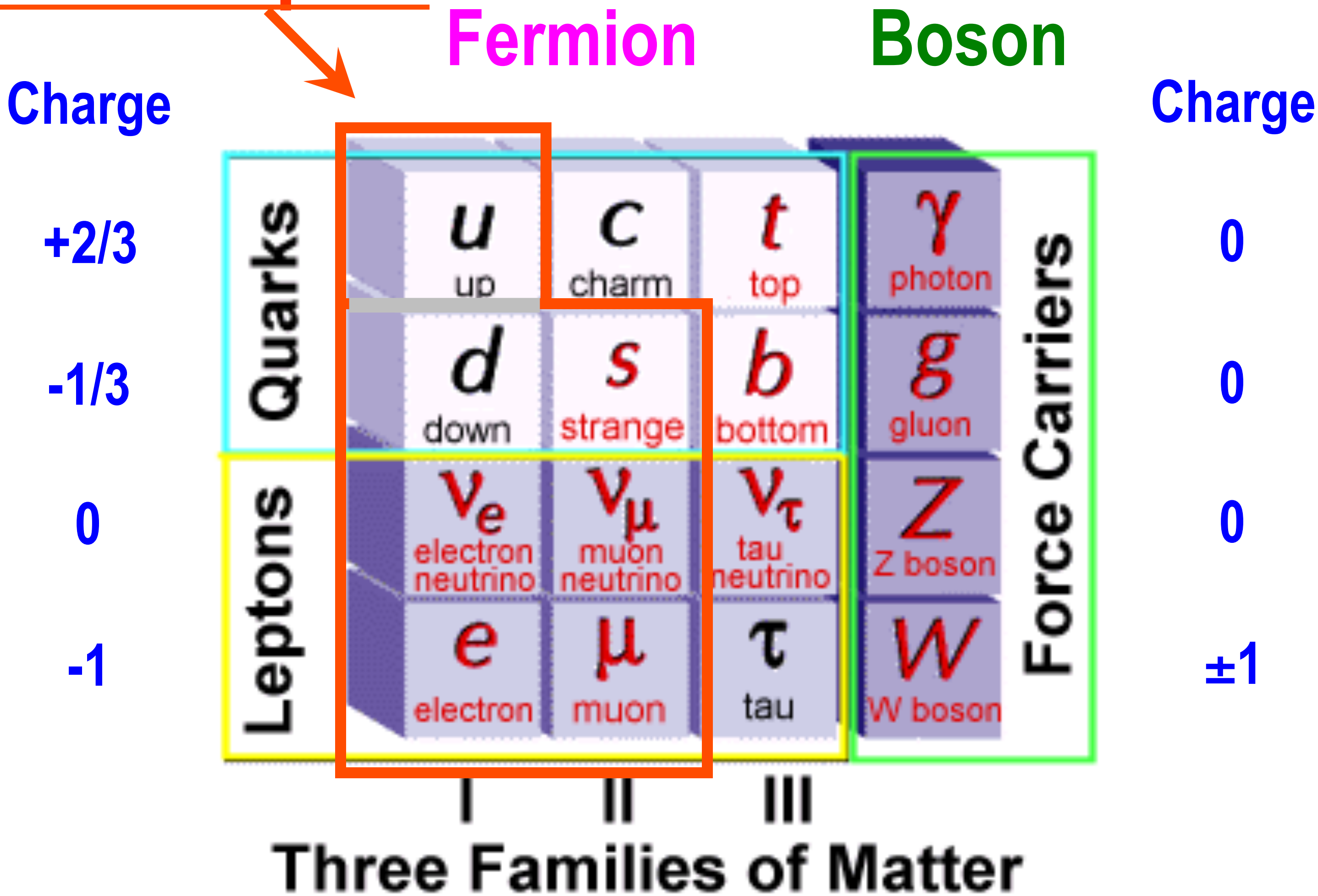
- #photon ~ #lepton ~ #quark

Mass of Particles



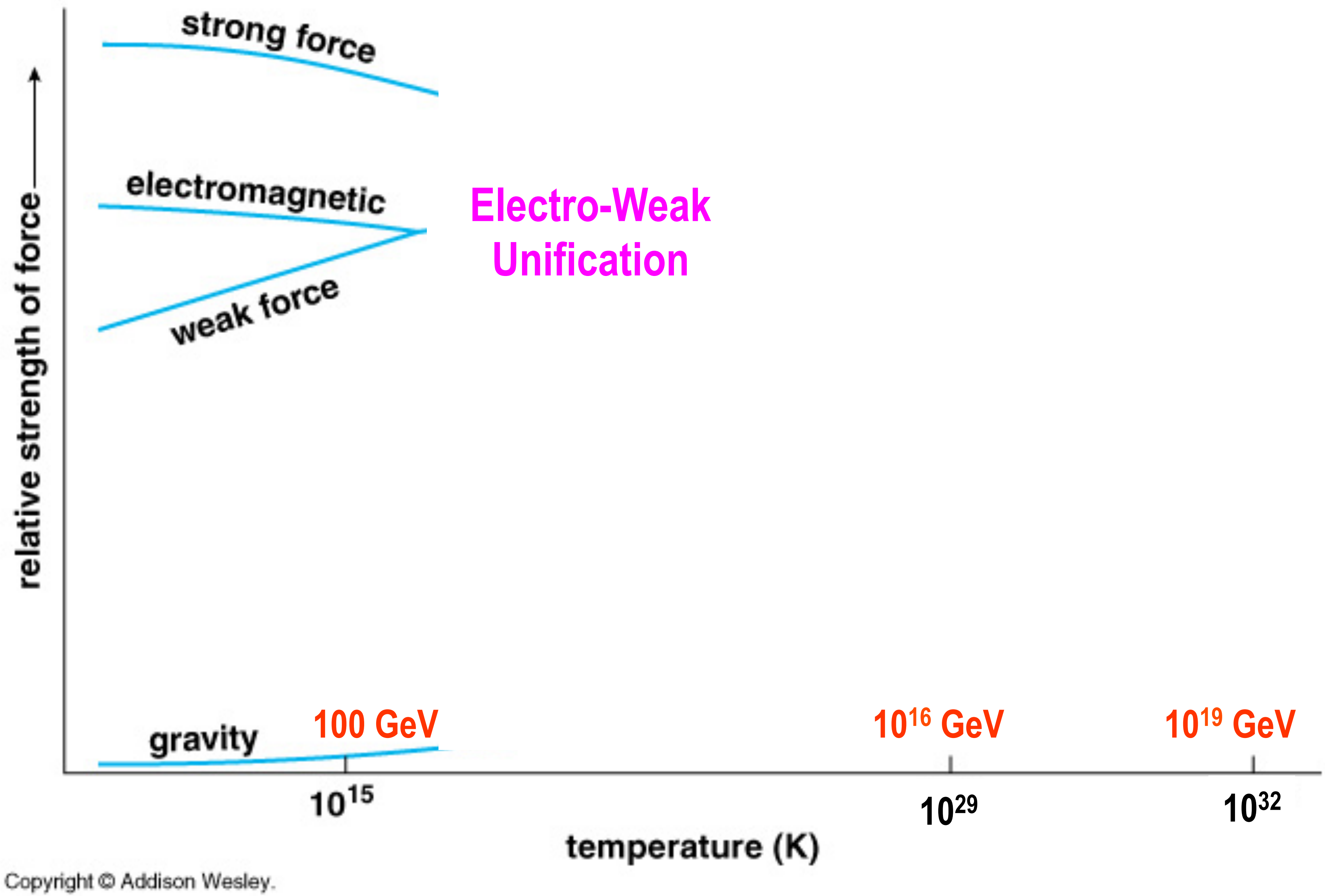
Elementary Particles

Universe at t = 1 μsec



+ Anti-particles

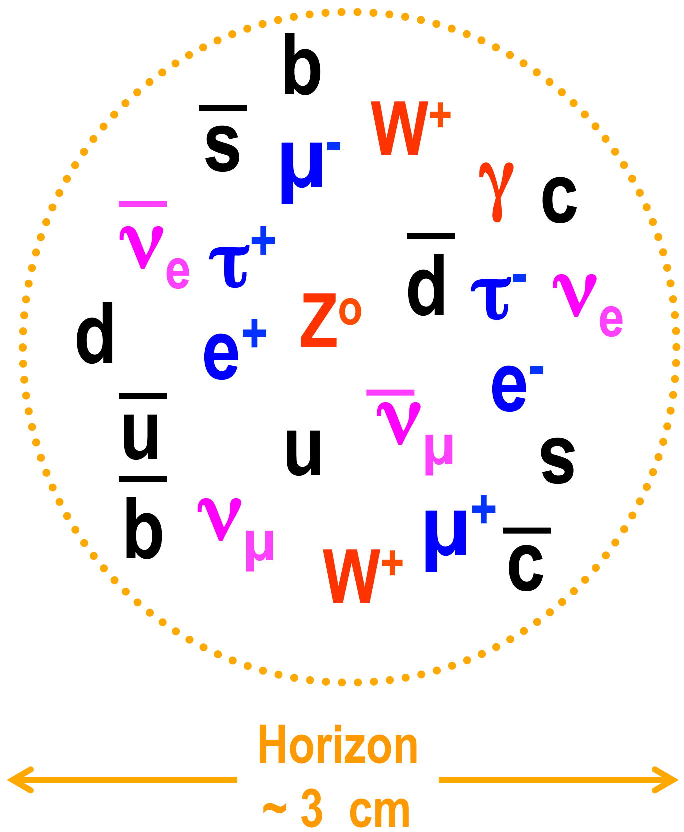
Unification of Forces



Time = 10^{-10} sec, Temp.= 10^{15} °K (~100 GeV)

➢ Electro-weak Unification

- Electro-Magnetic force = Weak force
- The highest energy we can study by the accelerators



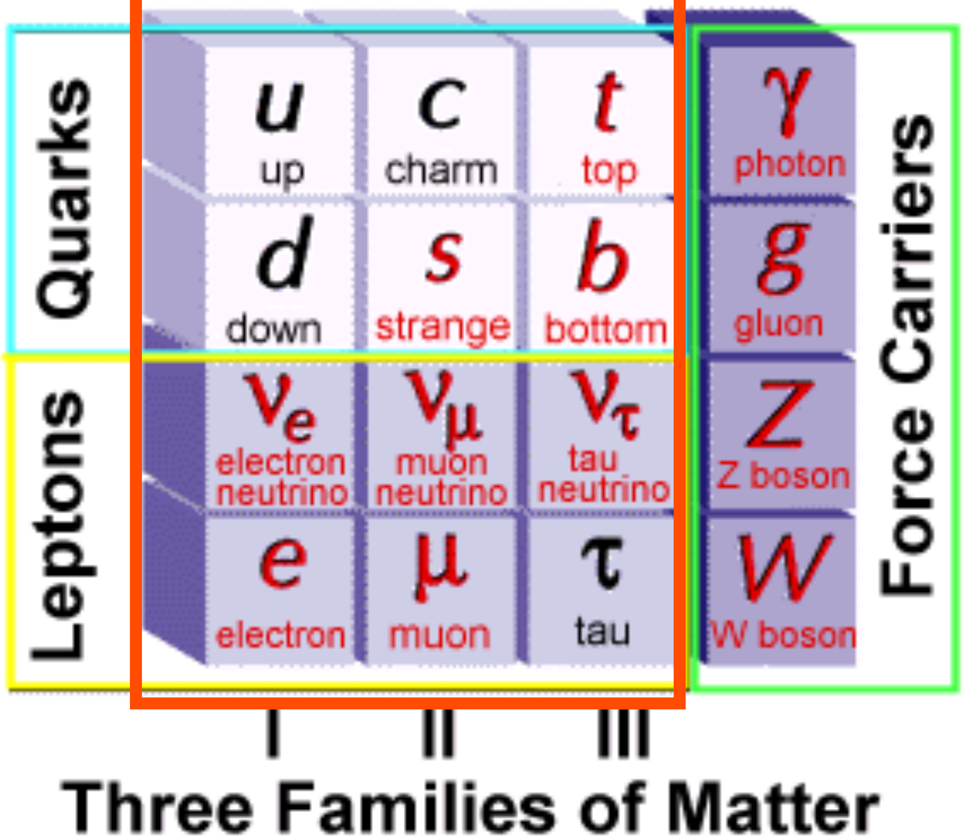
Elementary Particles

Universe at = 0.1 nsec

Fermion

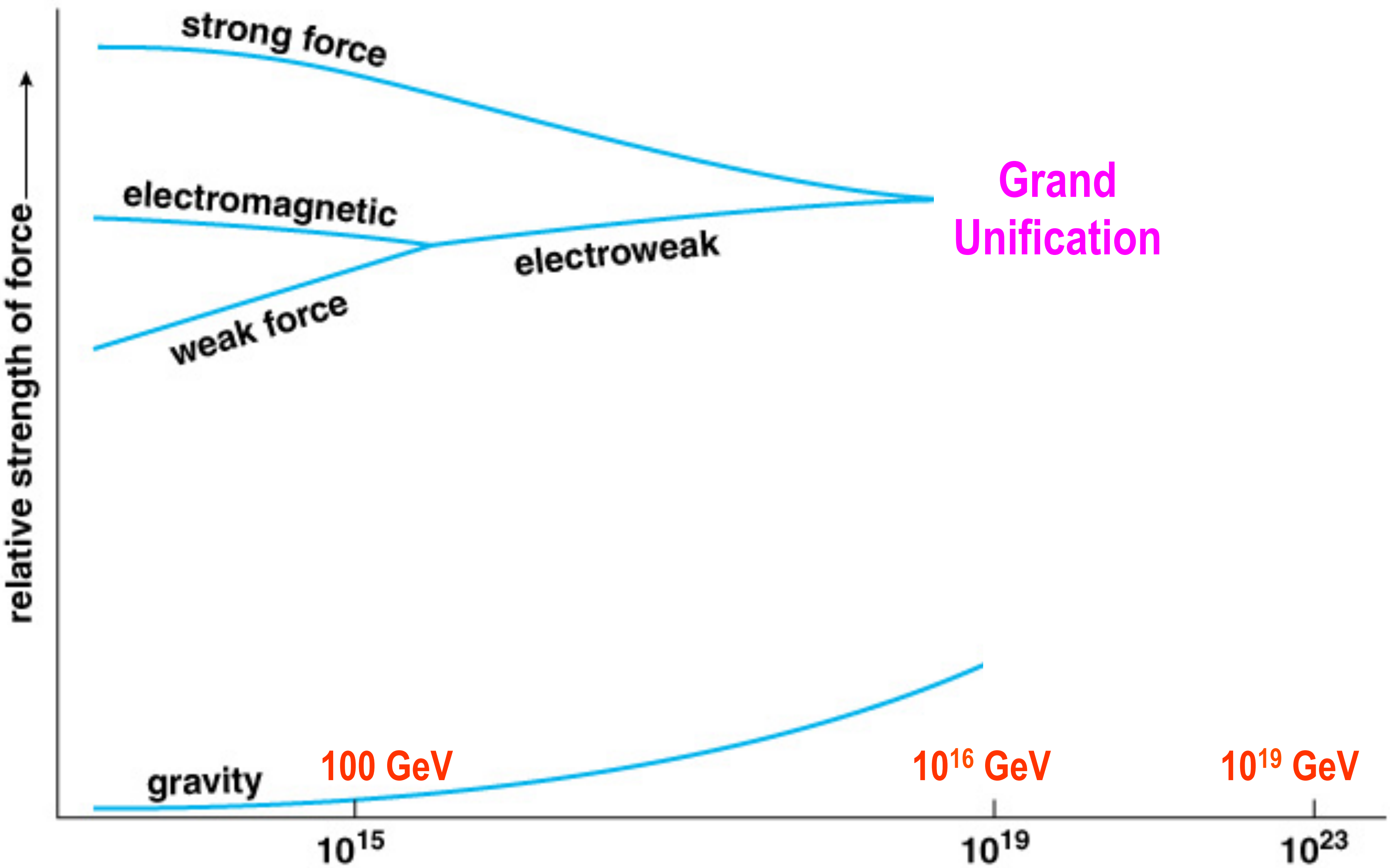
Boson

Charge		Charge
+2/3		0
-1/3		0
0		0
-1		±1



+ Anti-particles

Unification of Forces



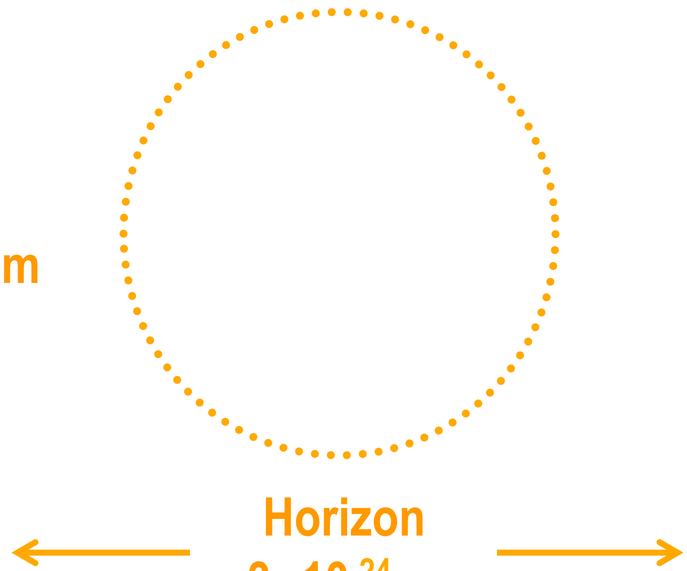
Time = 10^{-34} sec, Temp.= 10^{29} °K (~10^{16} GeV)

Grand Unification

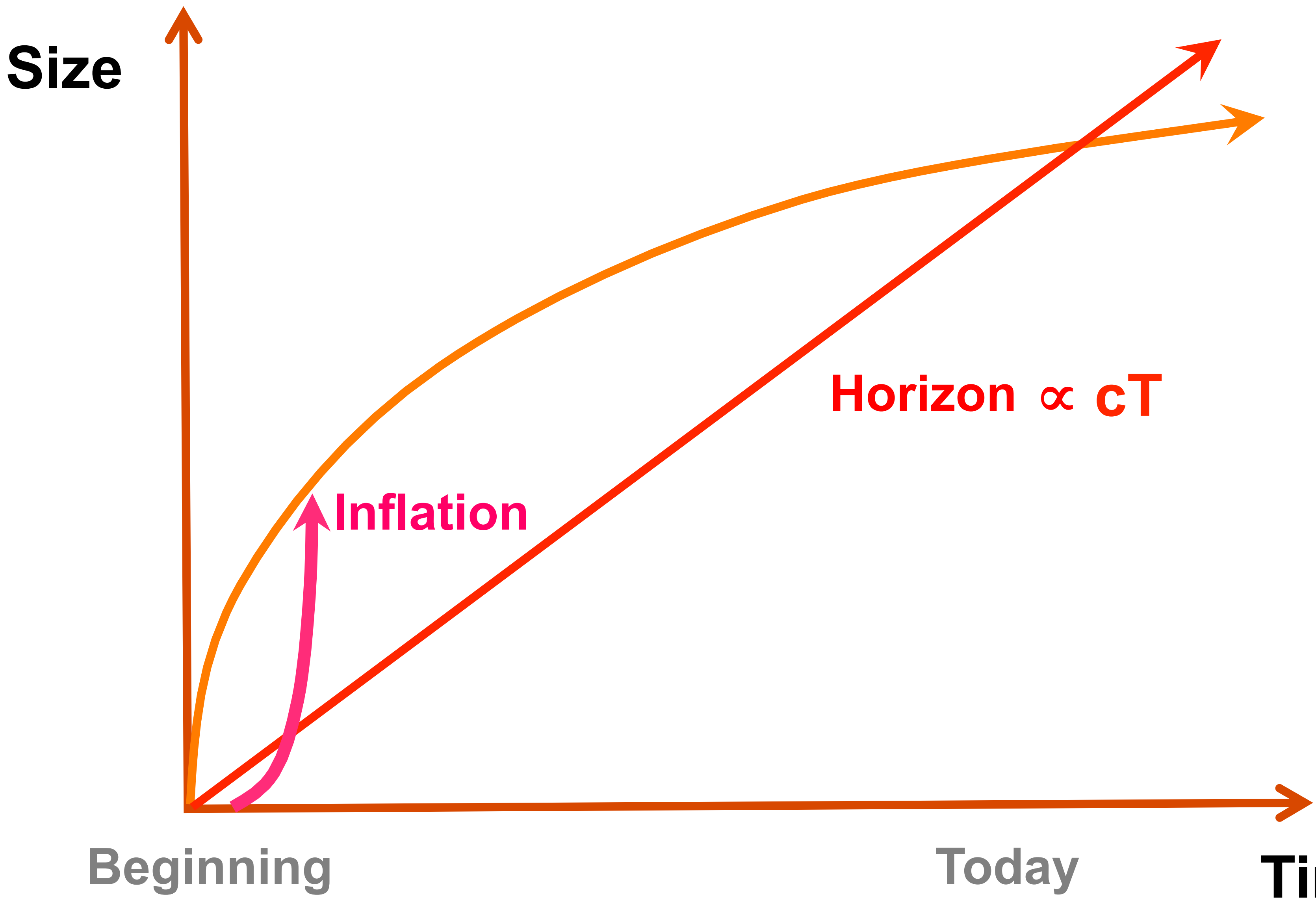
- Strong-Force = Electro-Magnetic force = Weak force
- Quark = Leptons

- Everything (except gravity) is unified.

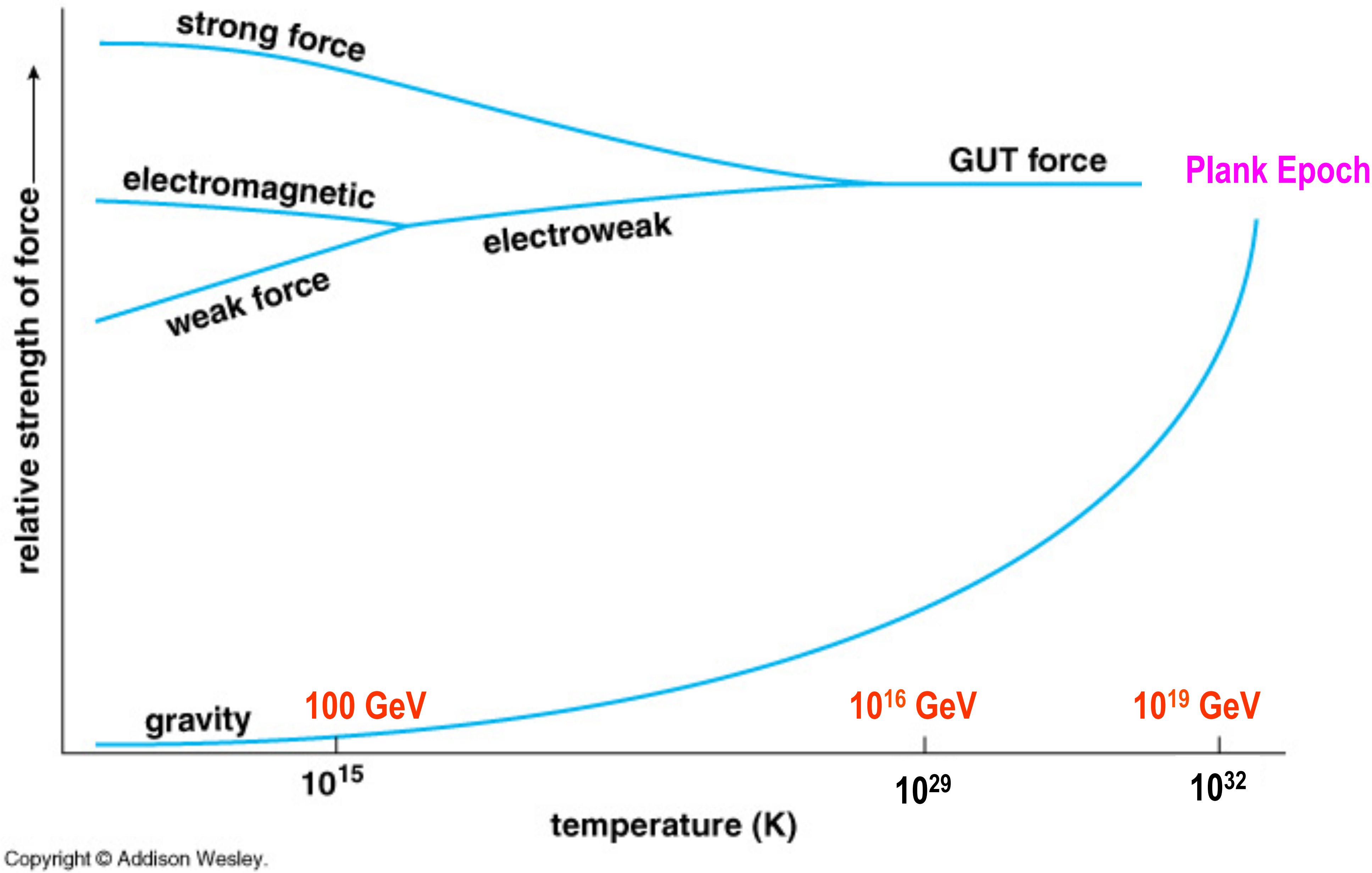
- Inflation might happen?



Inflation in Early Universe



Unification of Forces



Time = 10^{-44} sec, Temp.= 10^{32} °K (~10^{19} GeV)

- **Planck Epoch**

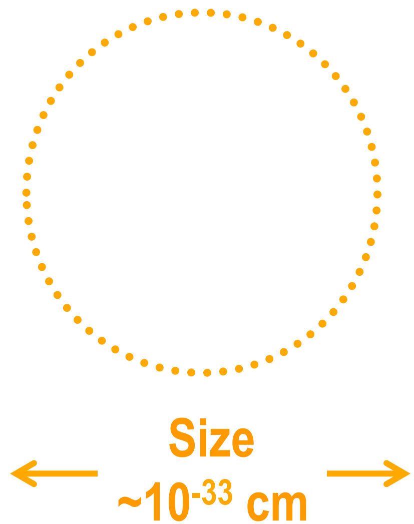
  - Gravitational Effect (Curvature of the space)

    ||

  - Quantum Mechanical effect

  - We can not define space-time any more at earlier stage.

< Plank Scale>



Physicists' View of Early Universe

Fiat lux

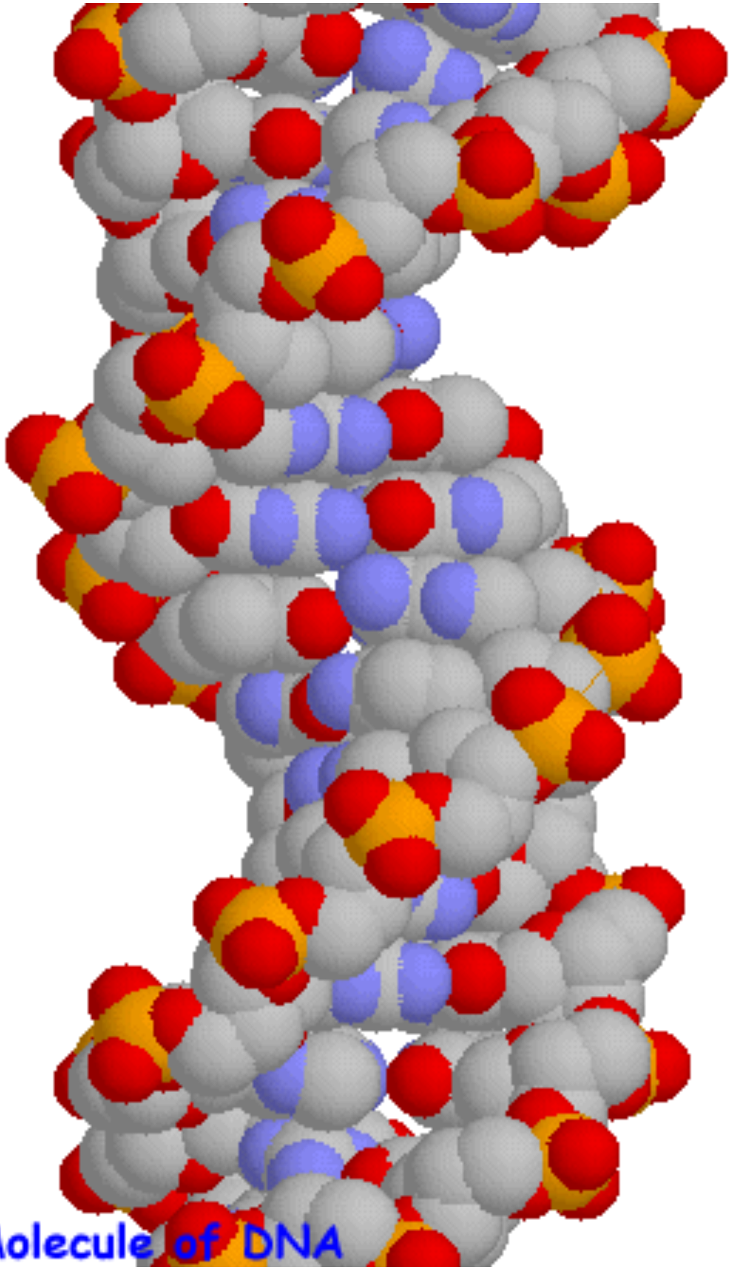
Let there be light

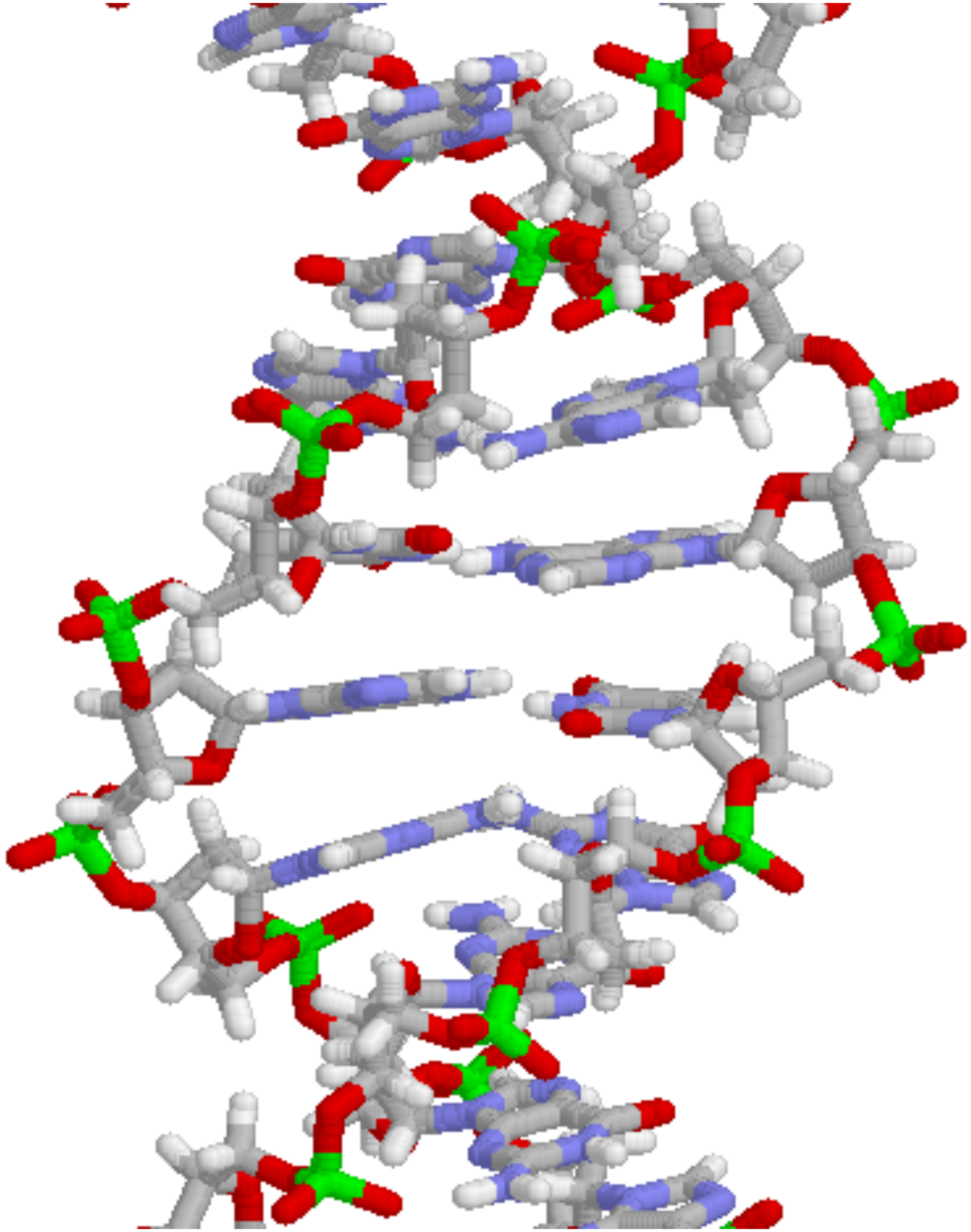
Physicists' View of Early Universe

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

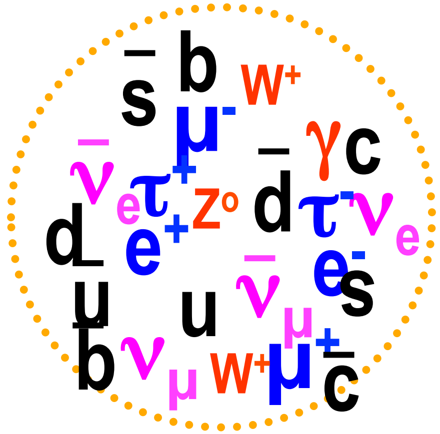
13

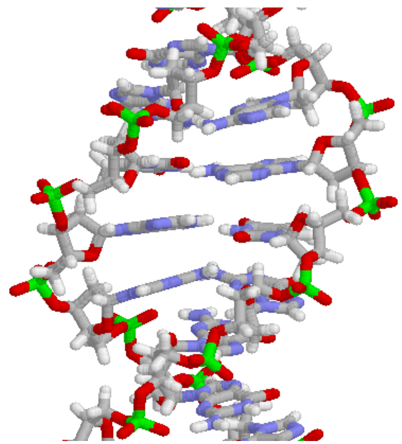
14

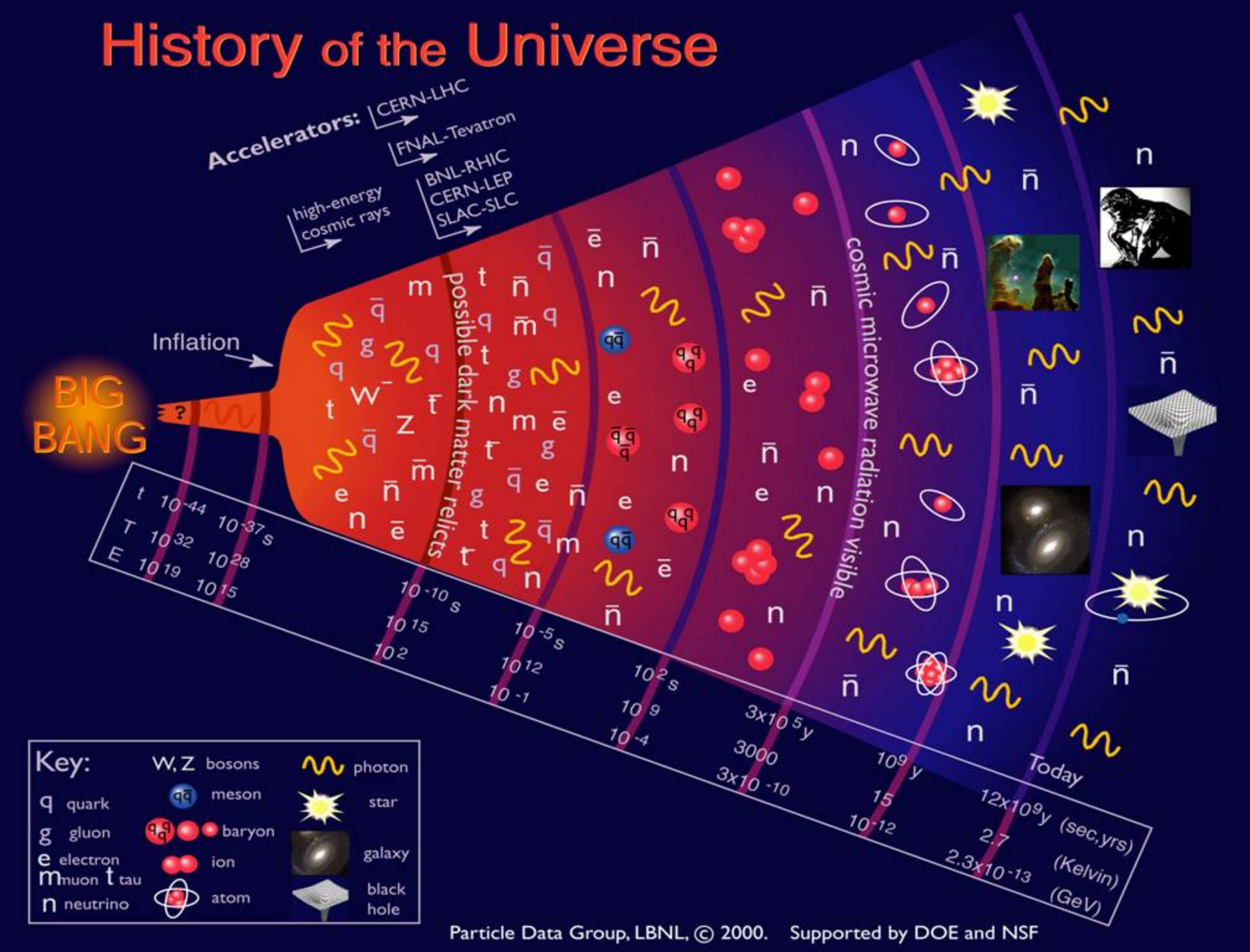
Simple

Symmetry Break Down

Complex







History of the Universe
Acceleratoirs:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
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.**

3	Space		*Flattened*
1	Time		
6	3	Strong Force	*Compacitified*
	2	Weak	
	1	Electro-Magnetic	

Early Universe & Unsolved Problems