Evolution of the Early Universe

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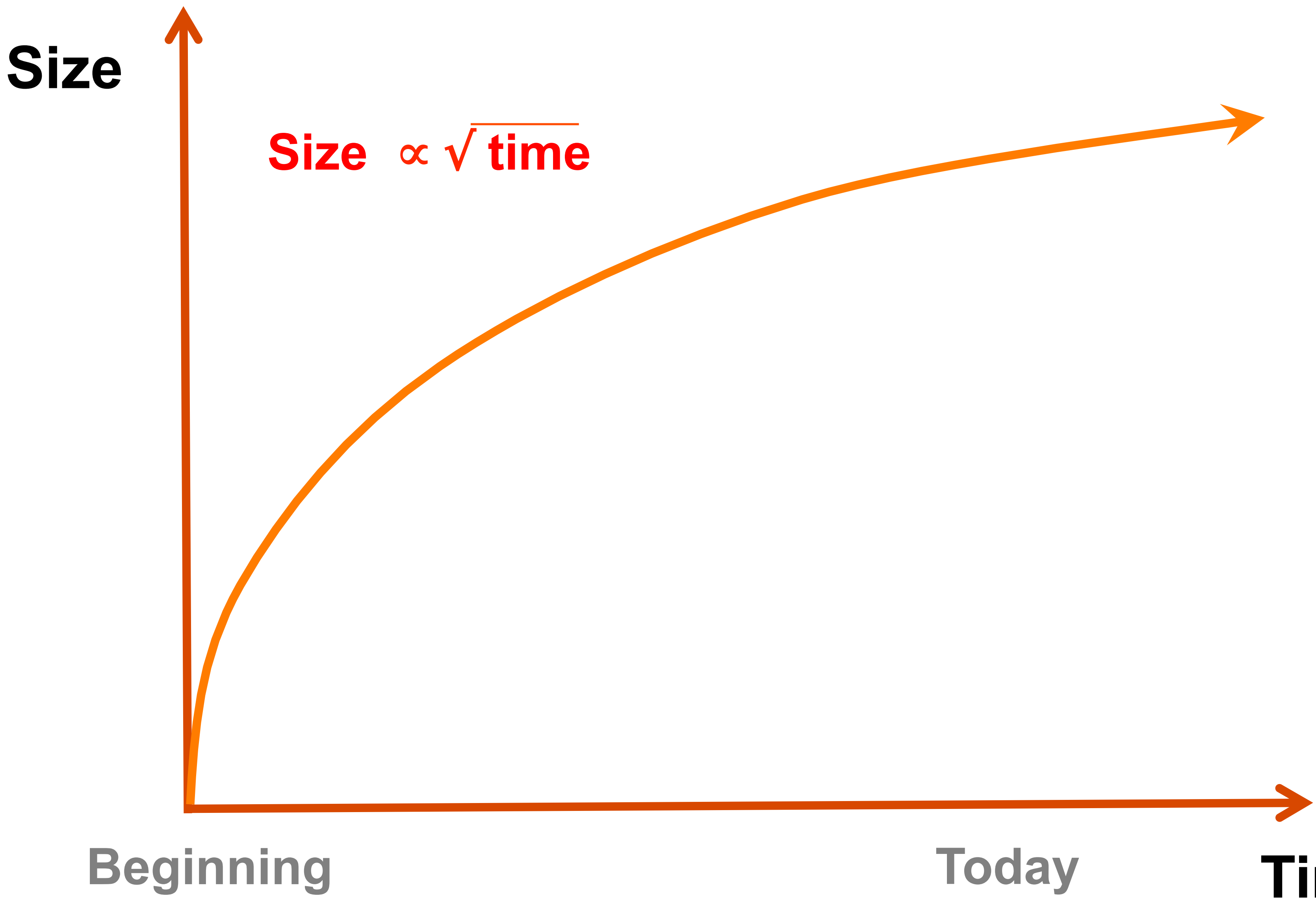
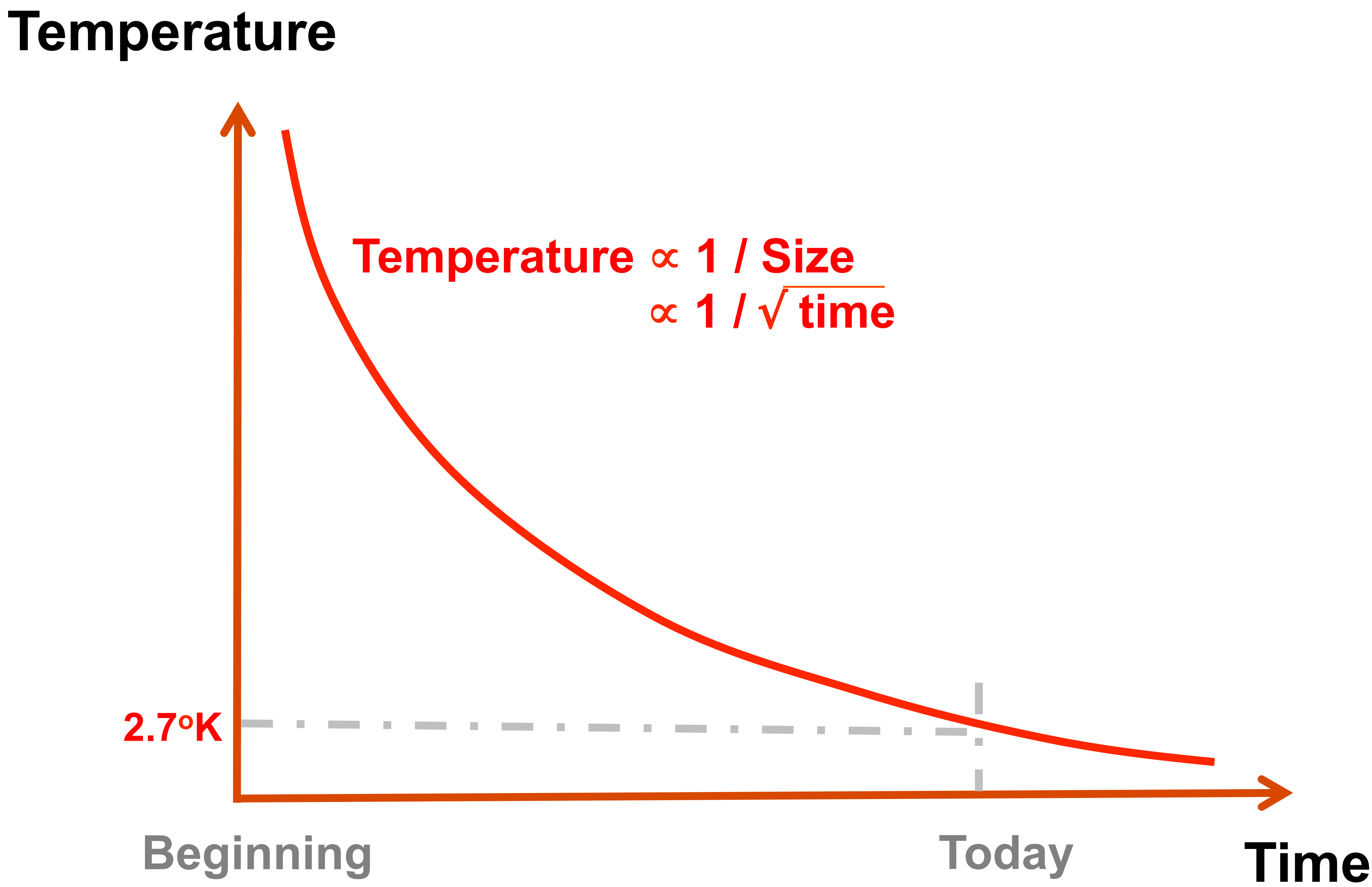
Expansion of Universe



Temperature of Universe

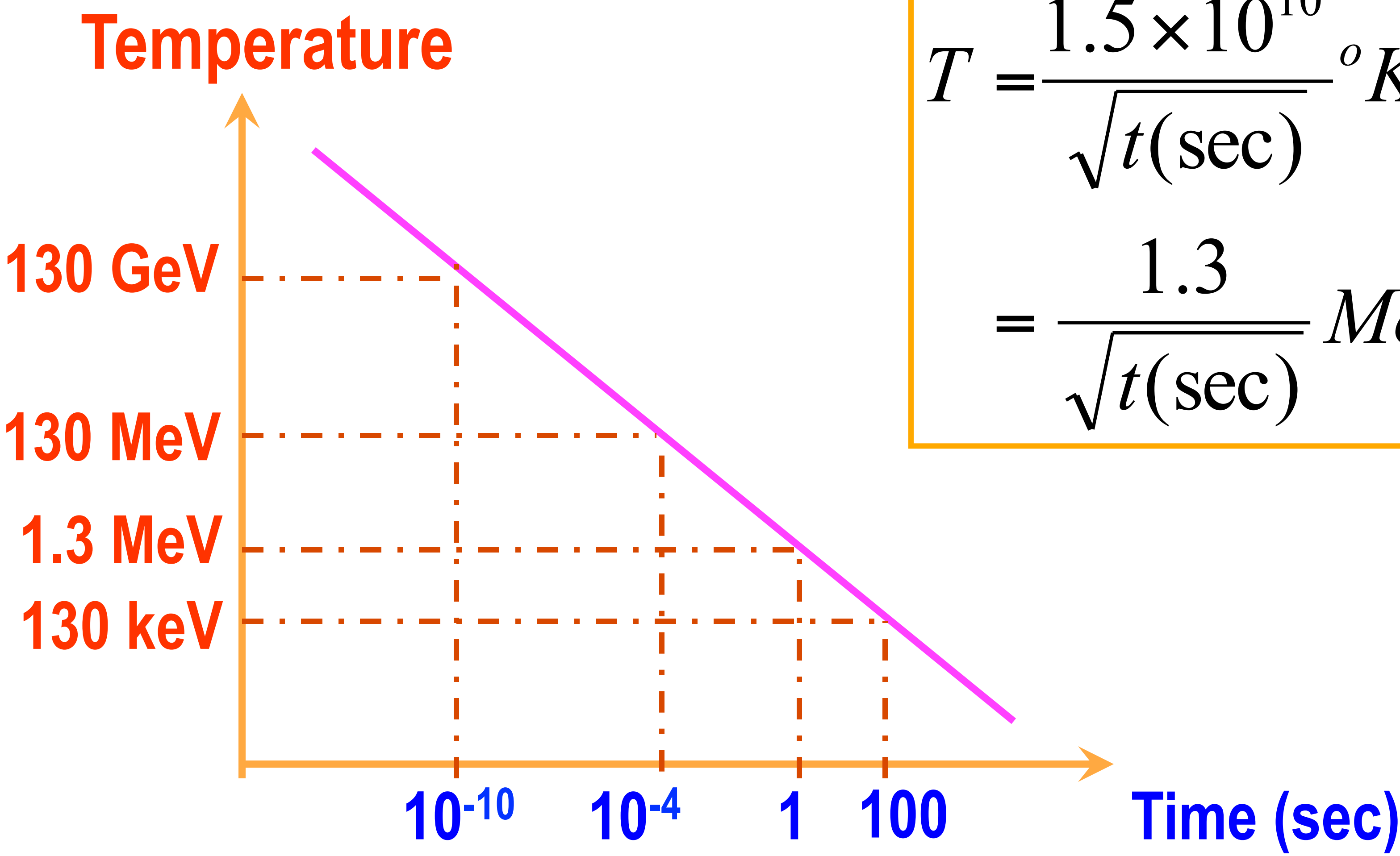


Relation between Temperature and Time

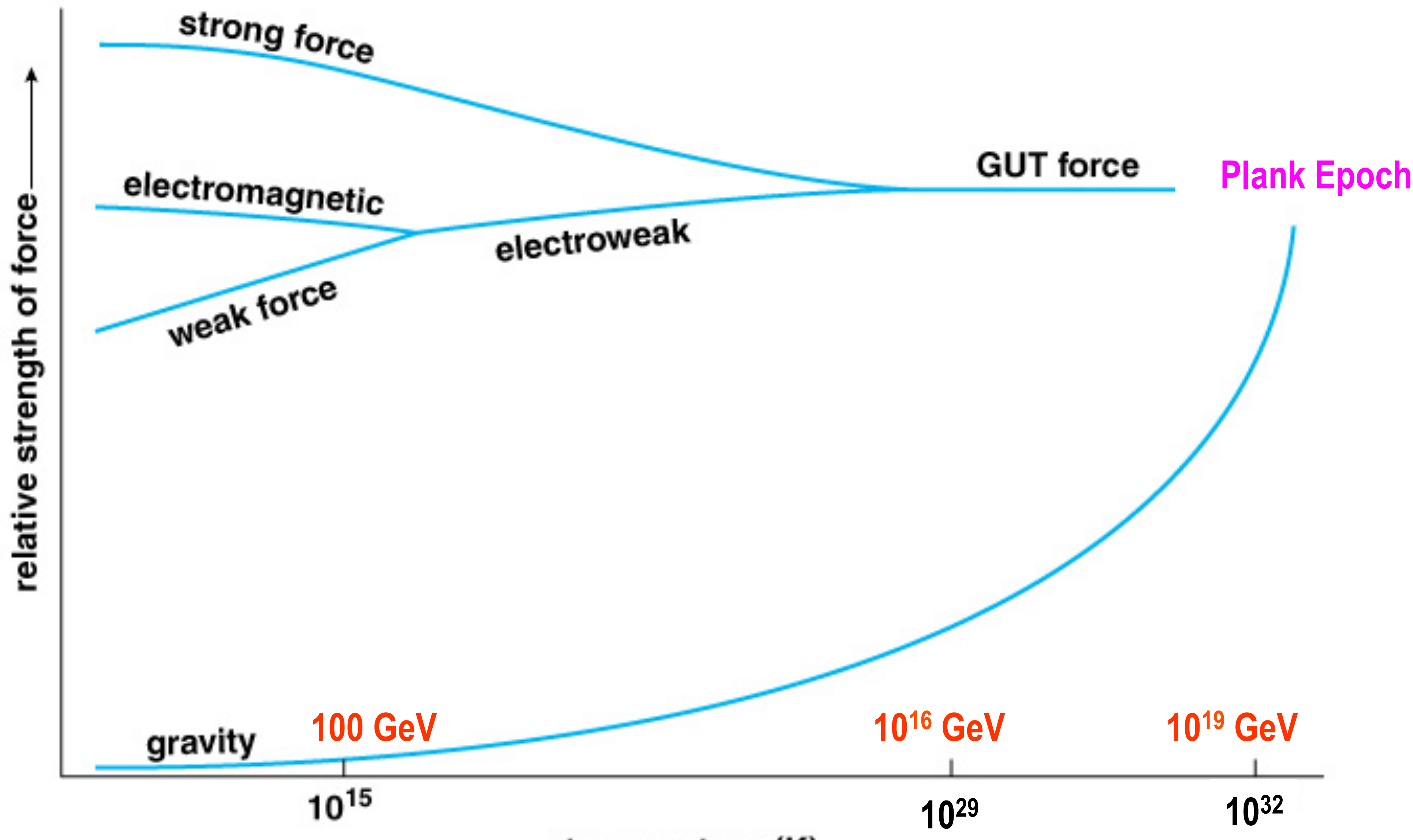
T: Temperature
t : time

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

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



Unification of Forces



Physicists' View of Early Universe

Fiat lux

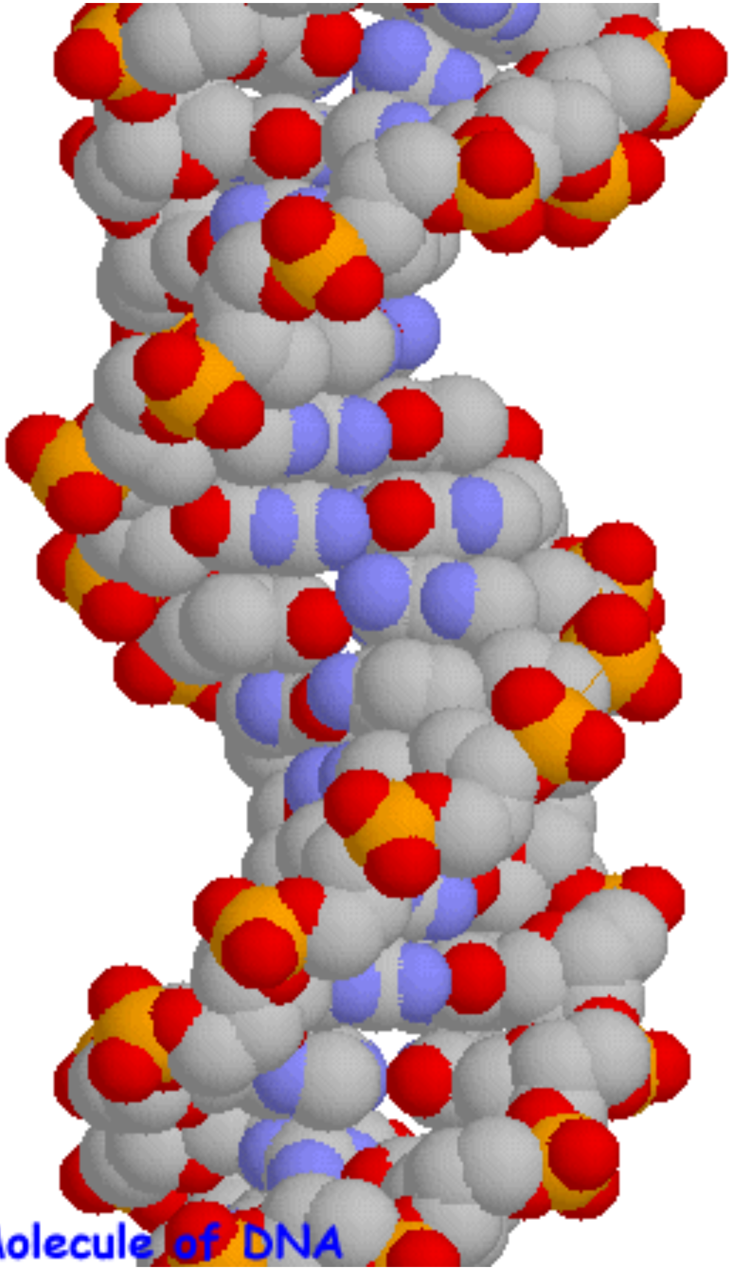
Let there be light

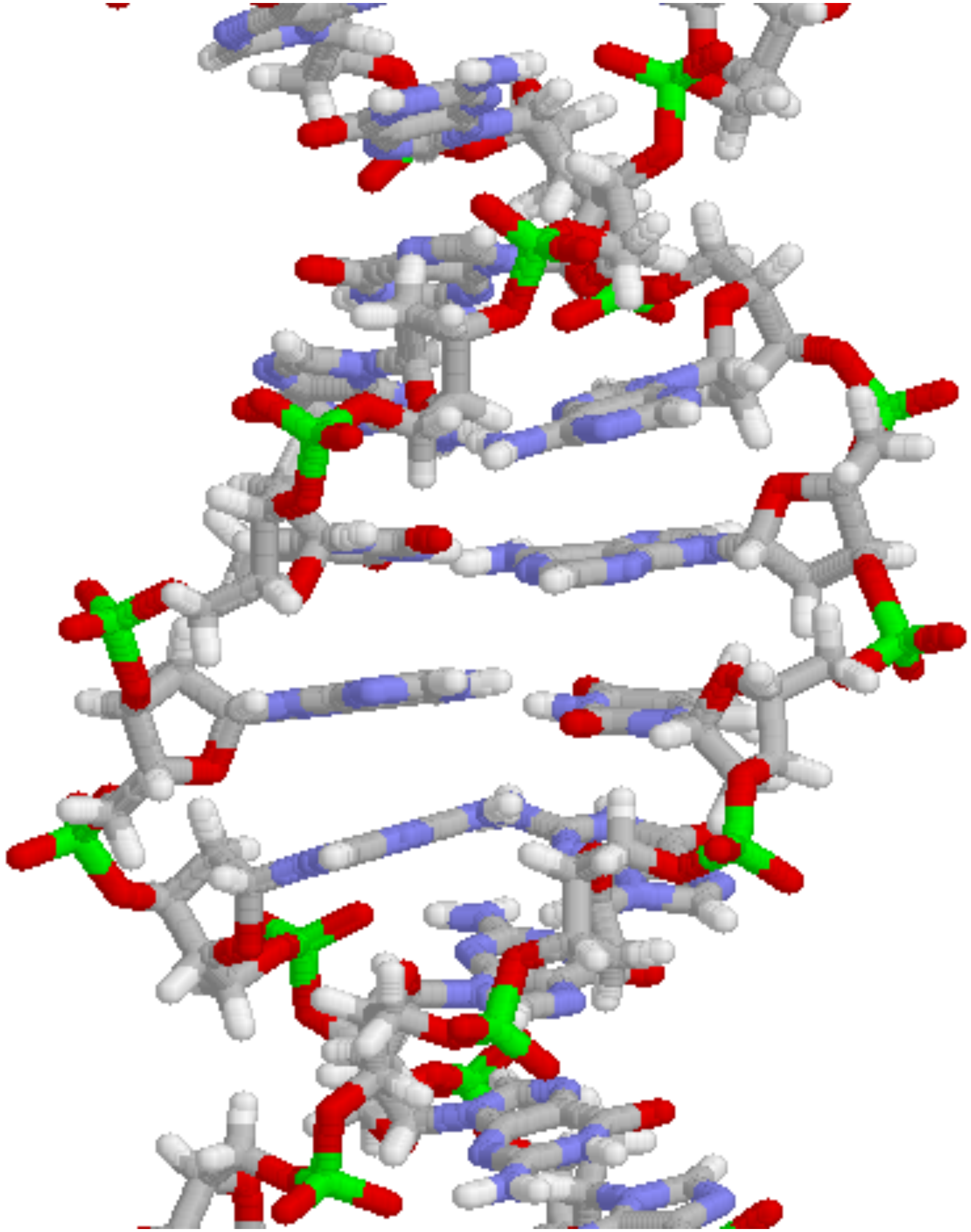
Physicists' View of Early Universe

Lorentz Invariance

Local Gauge Invariance

Structure of DNA





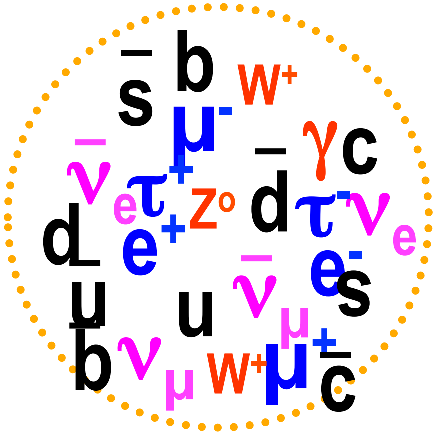
Symmetry Breaking

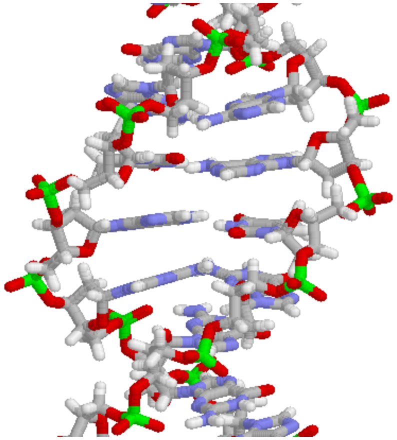
Time
0
1B years
2
3
4
5
6
7
8
9
10
11
12
13
14

Simple

Symmetry Break Down

Complex





The Beginning

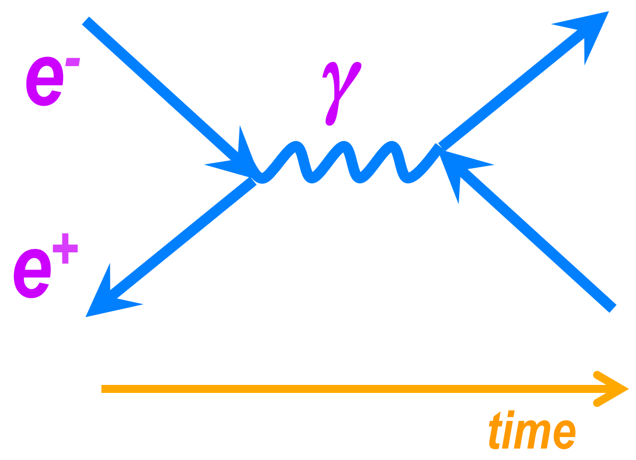
- Everything was the same ↔ Perfect symmetry.
  - All the particles are the same as photons.
  - All four forces are the same.

- The Universe was 10 dimension.

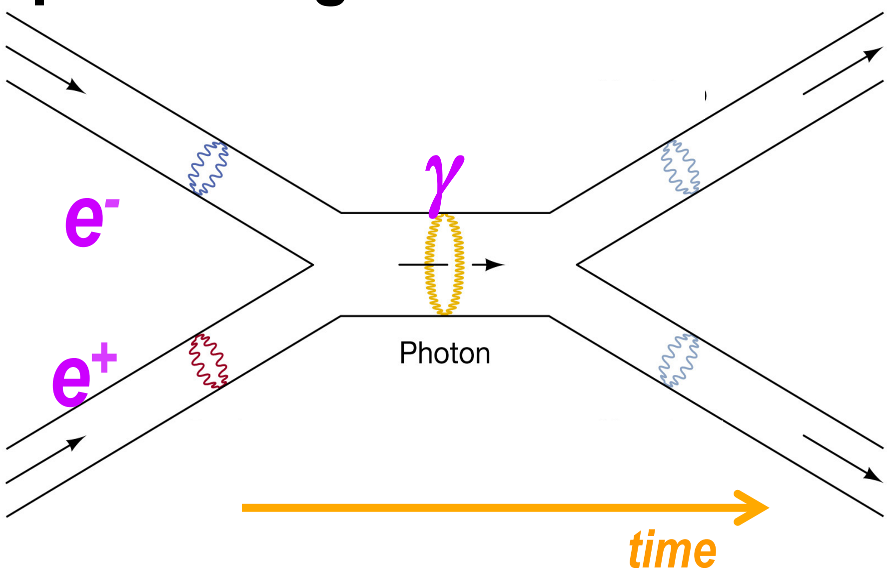
4	3	Space	→ *Flattened*
	1	Time	
6	3	Strong Force	*Compacitified*
	2	Weak	
	1	Electro-Magnetic	

Superstring?

- In the "standard model"
  - fundamental particles = point-like (No internal structure)



- In the "Superstring model"
  - Fundamental particles = loop of string (Size < Planck scale)



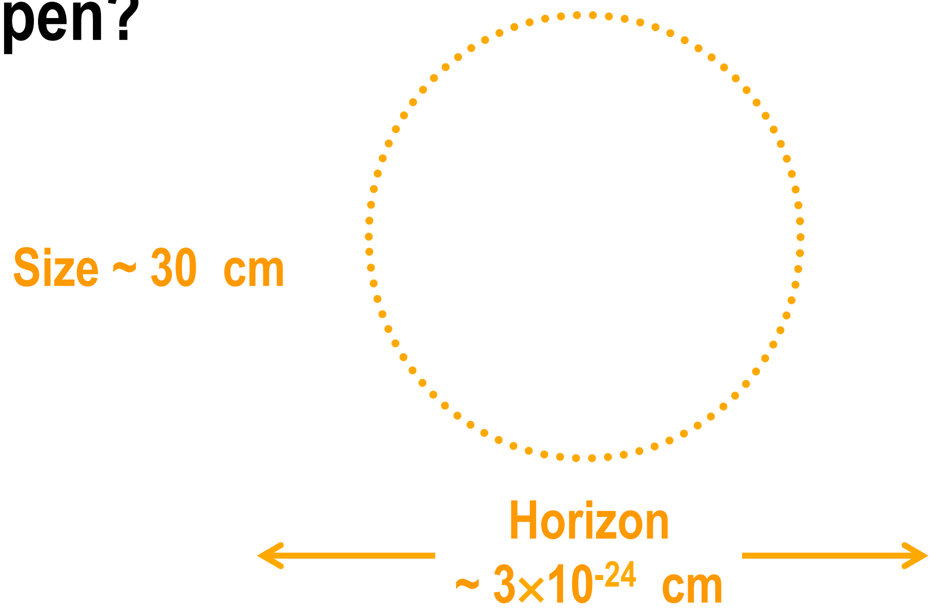
Time = 10^{-34} sec, Temp.= 10^{29} °K (~10^{16} GeV)

➢ Grand Unification

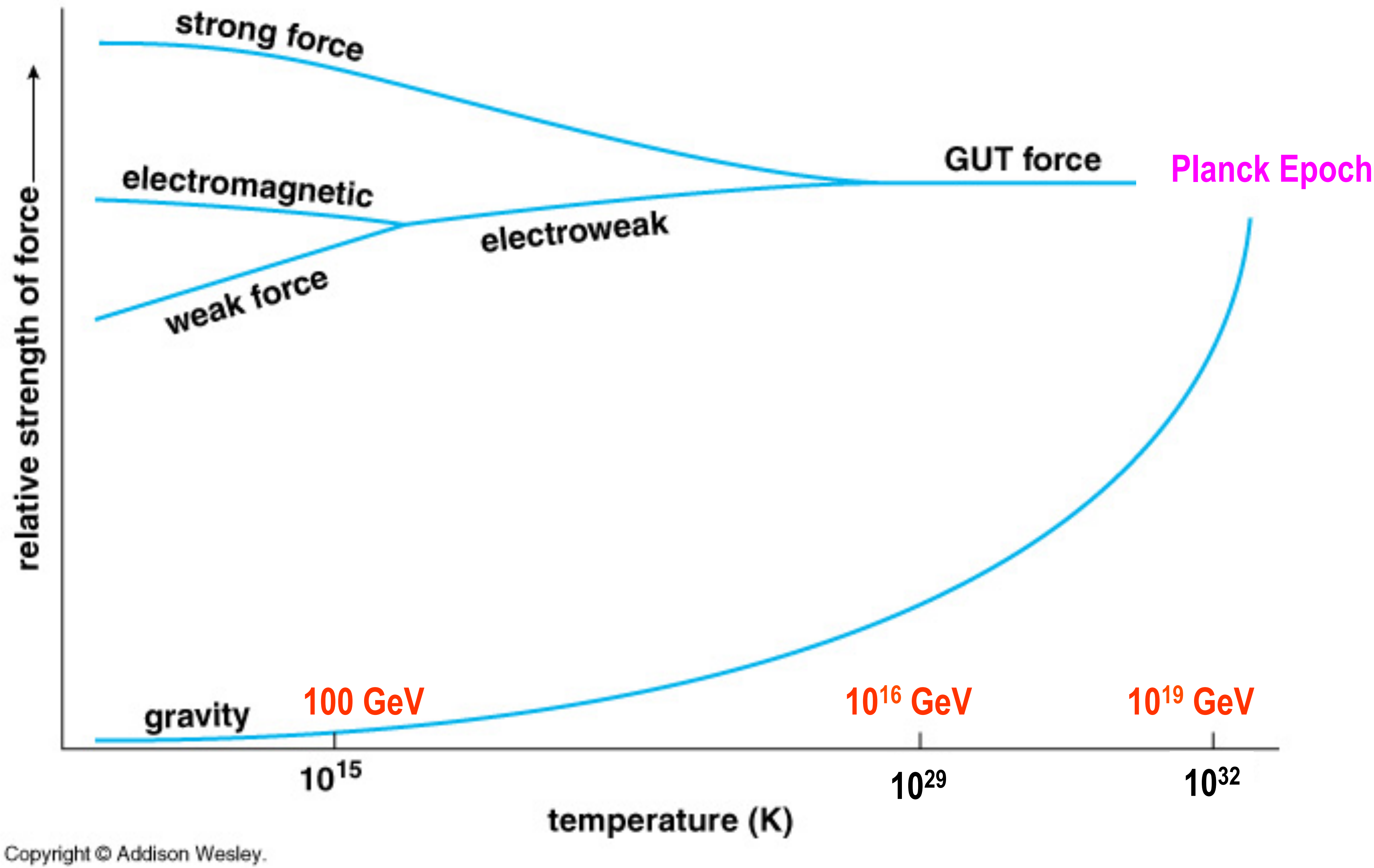
- Strong-Force = Electro-Magnetic force = Weak force
- Quark = Leptons

- Everything (except gravity) is unified.

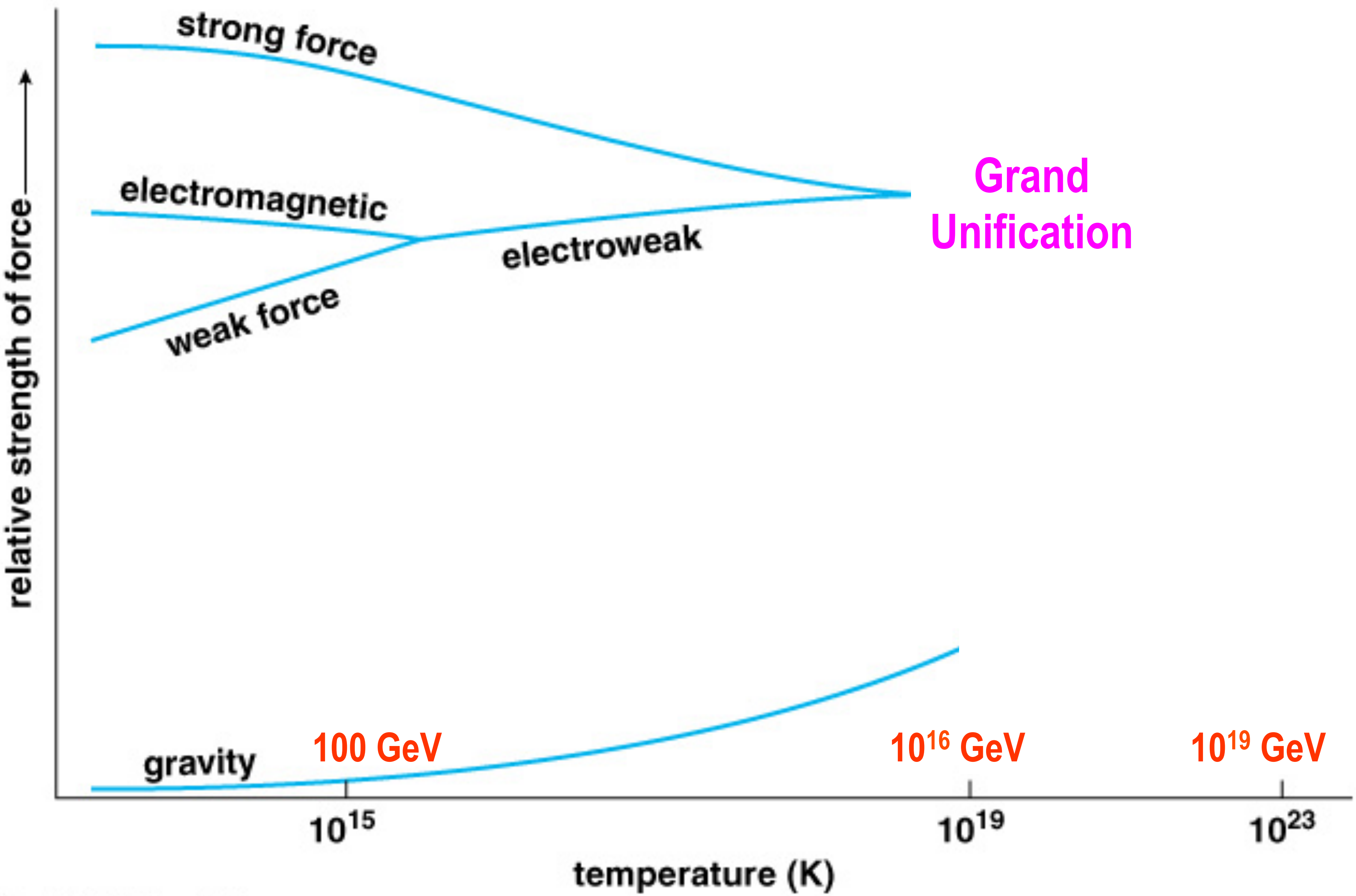
- Inflation might happen?



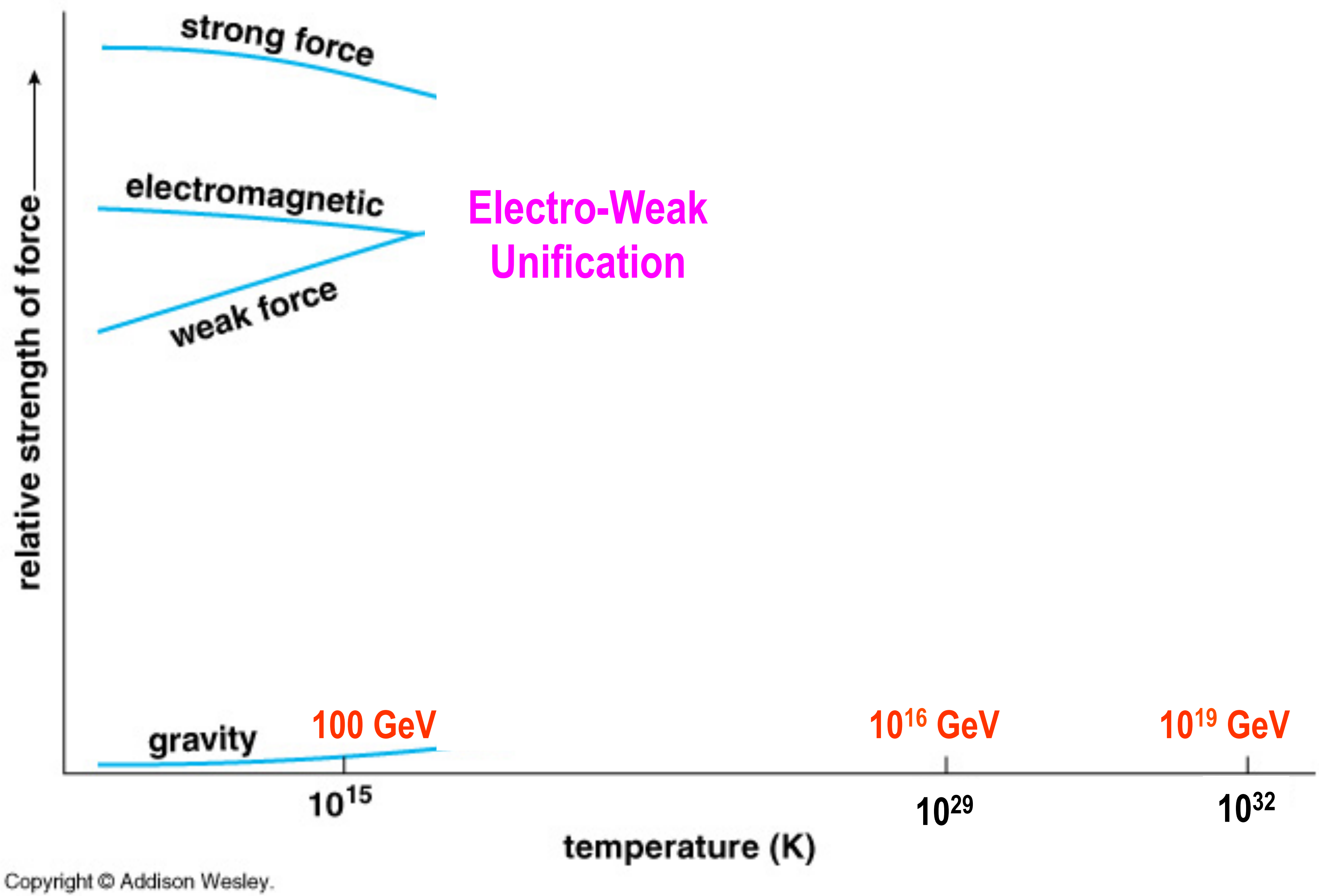
Unification of Forces



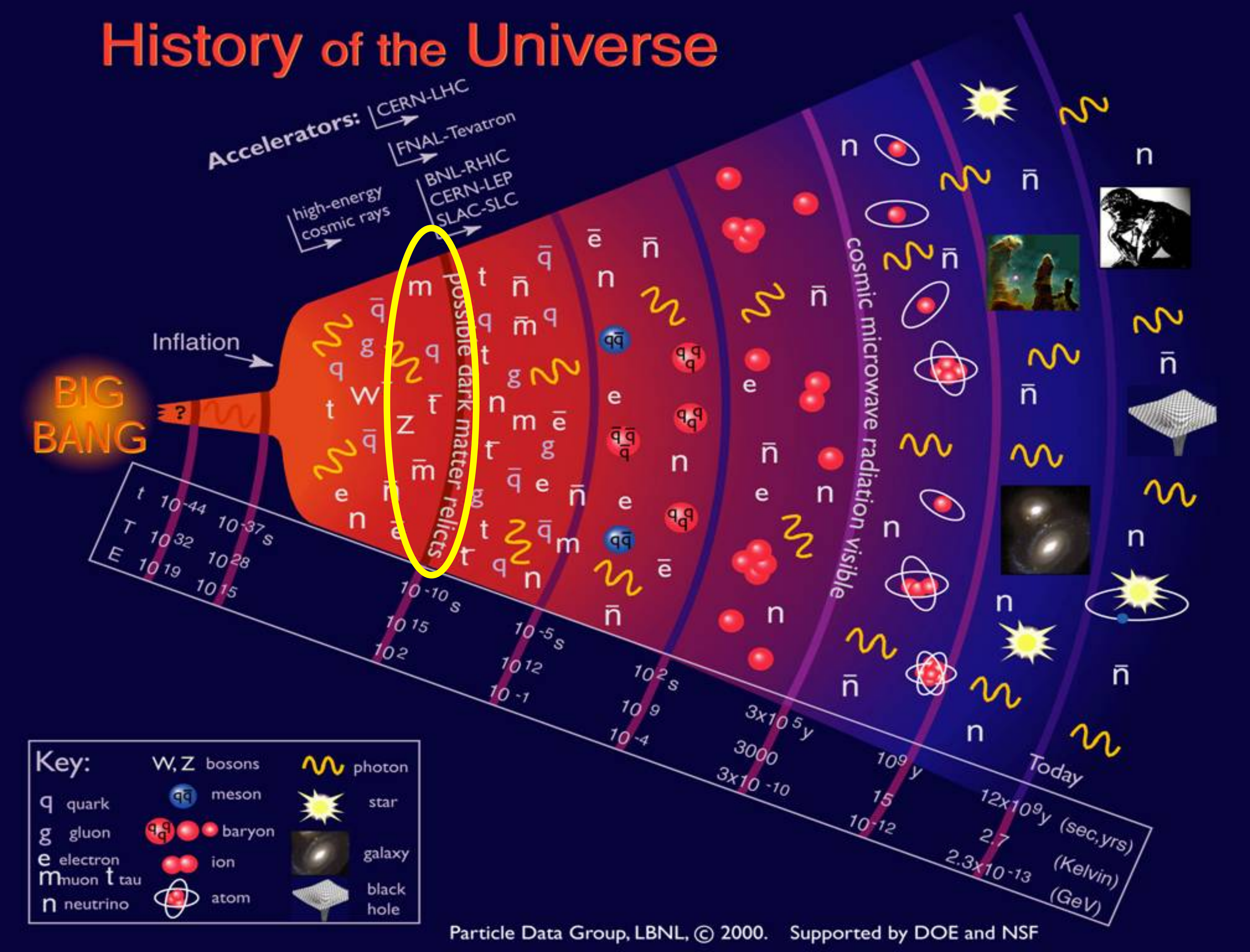
Unification of Forces



Unification of Forces



Origin of Particles and LHC



History of the Universe
Accelerators:
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 1032 1028
E 1019 1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
Today
12x109 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
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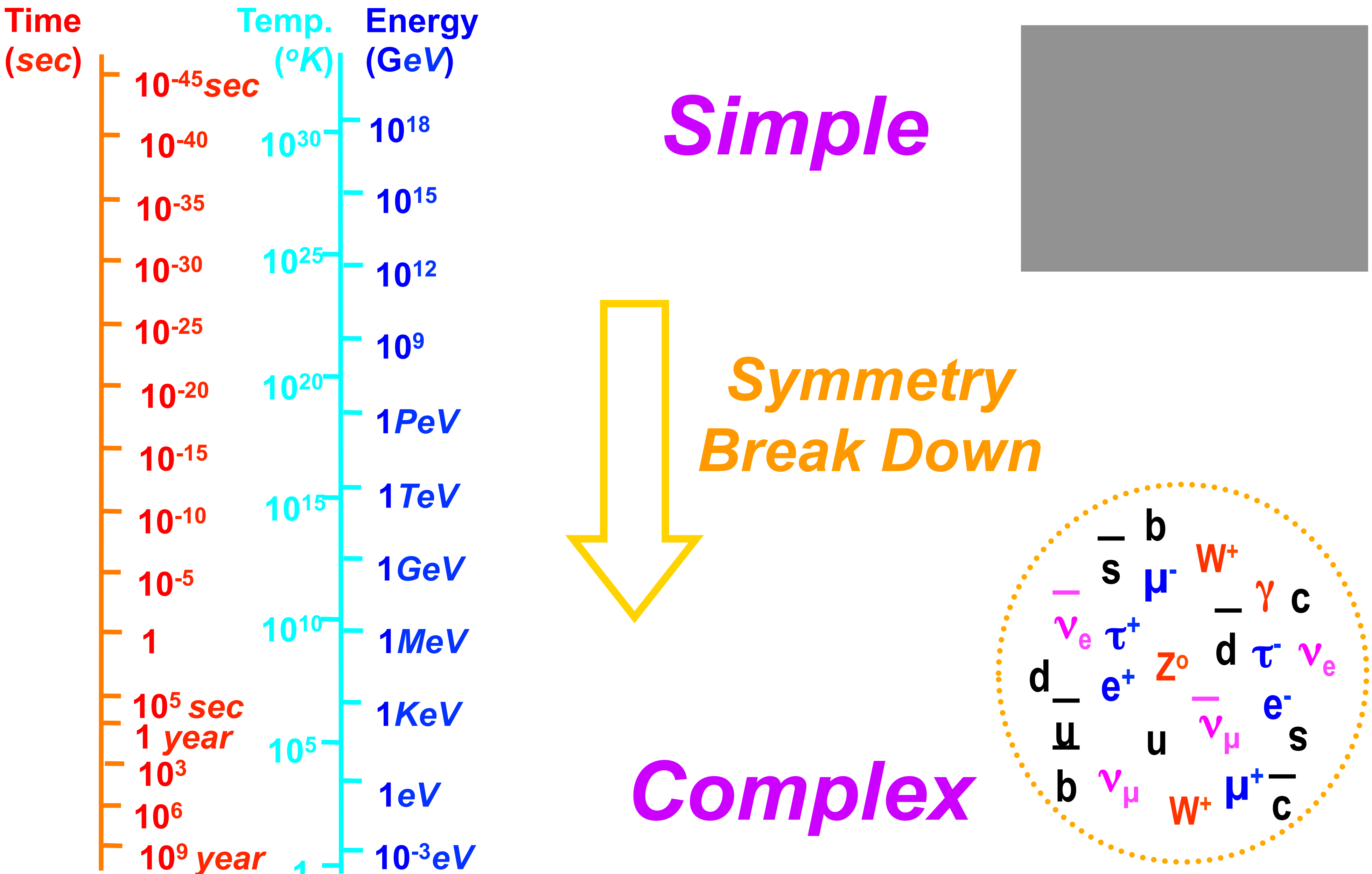
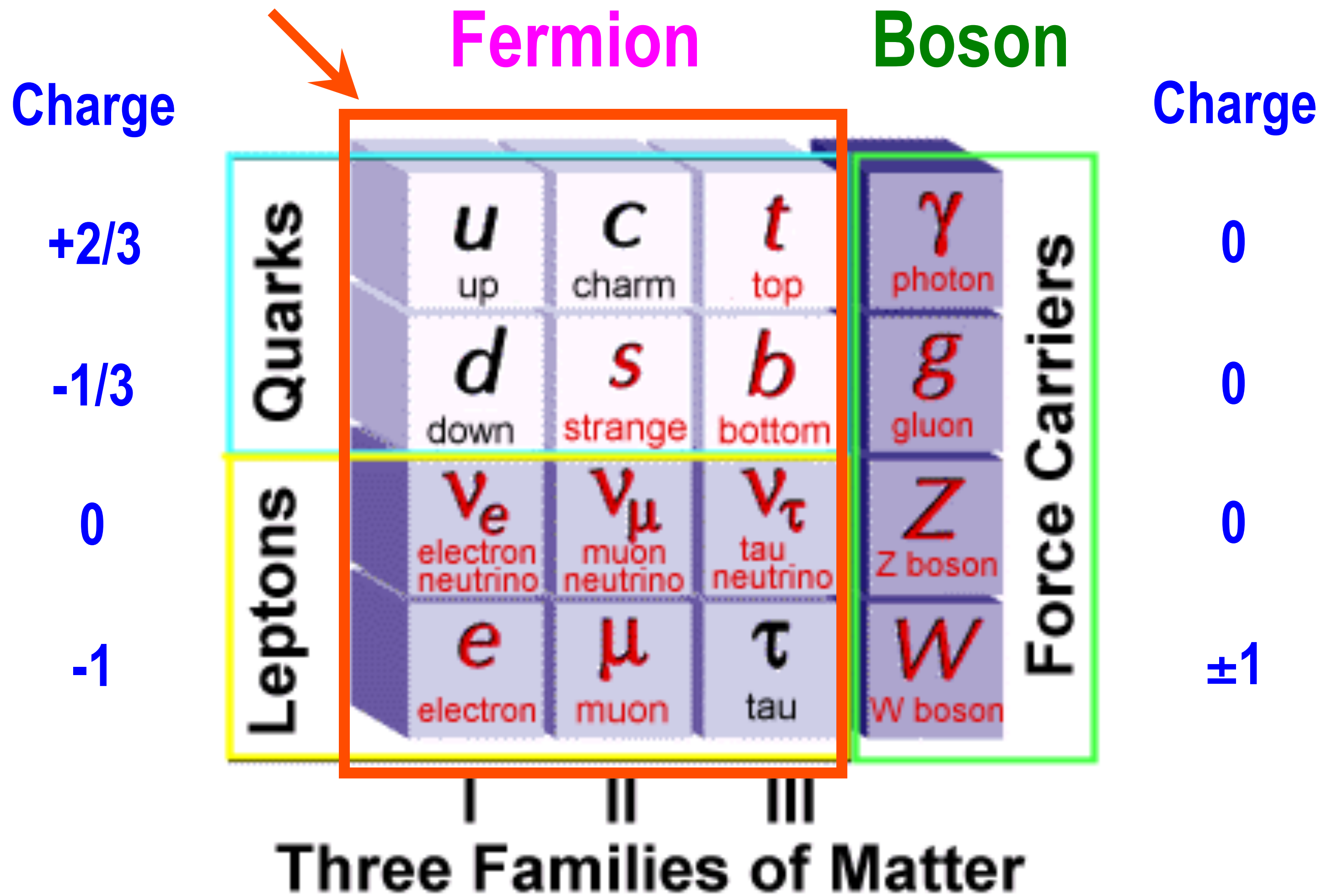
Symmetry Breaking



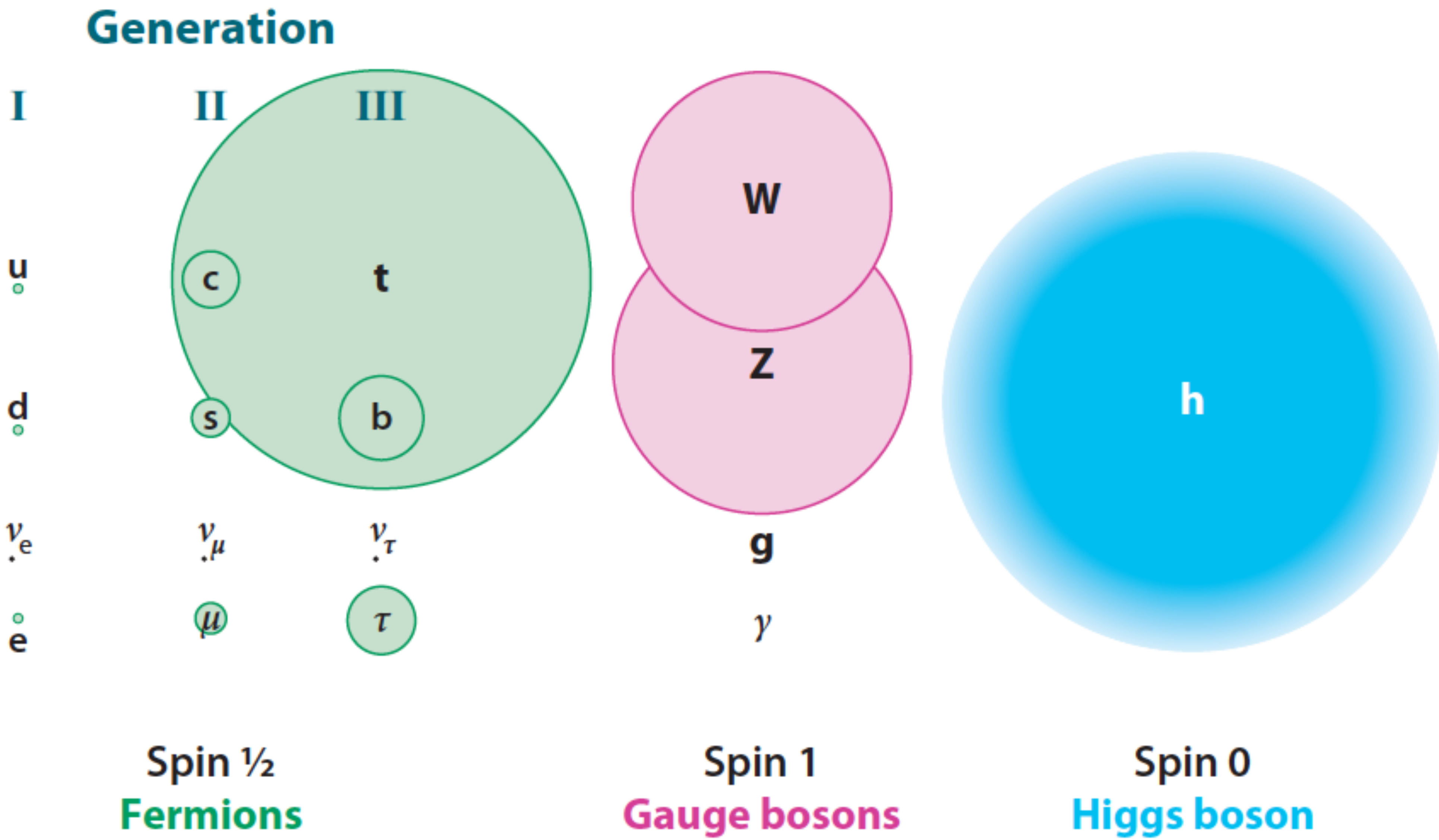
Elementary Particles

Universe at = 0.1 nsec



+ Anti-particles

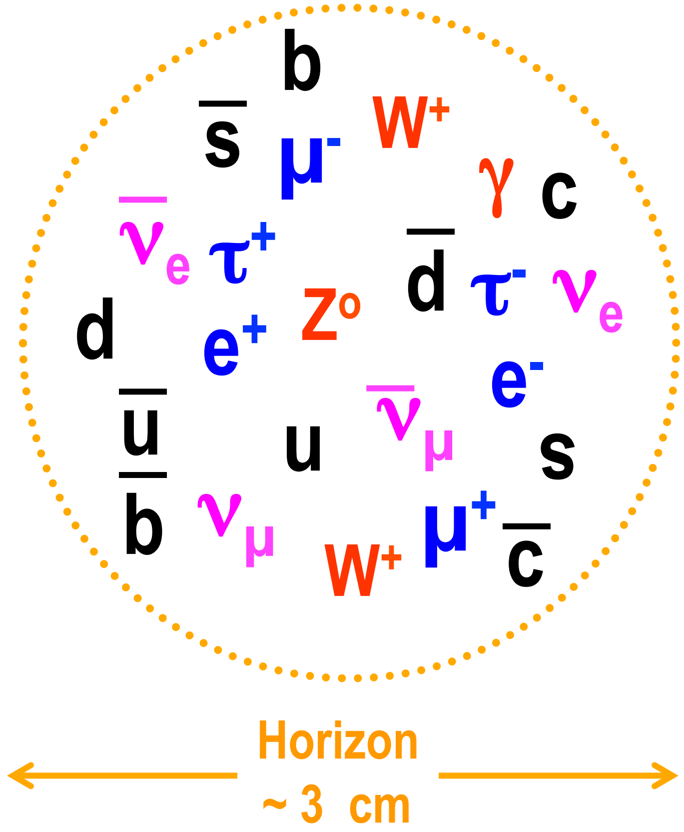
Mass of Particles (at T = 0.1 ns)



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



Mystery of the Mass (since 1970)

1) How to create mass from energy?

Energy → Mass

While maintaining the initial symmetry

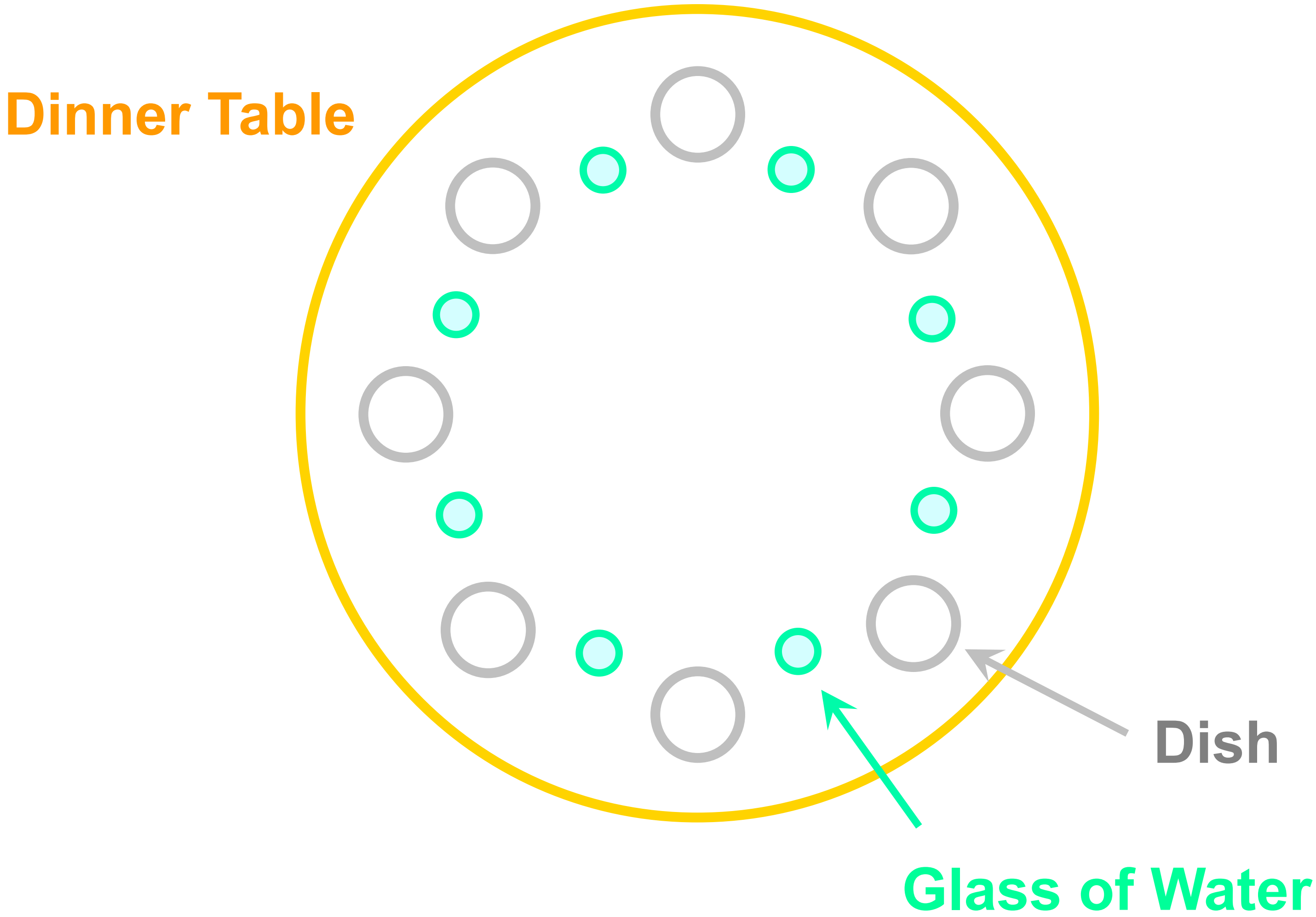
Spontaneous Symmetry Breaking

2) Particle mass << Plank Mass

MeV – GeV 10^{19} GeV

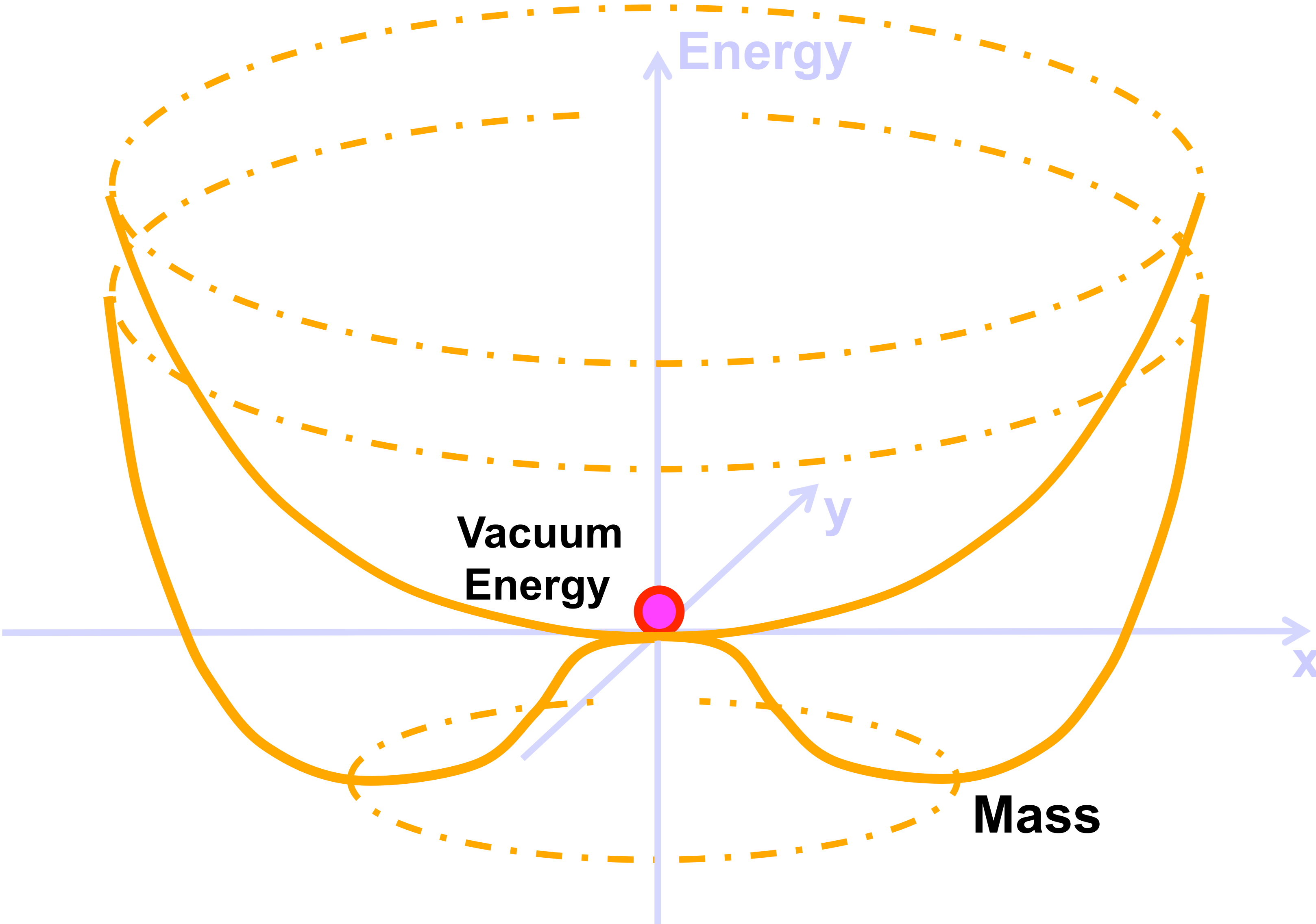
3) Why so many particles (Generations) with different masses?

Spontaneous Symmetry Breakdown at a Dinner Table

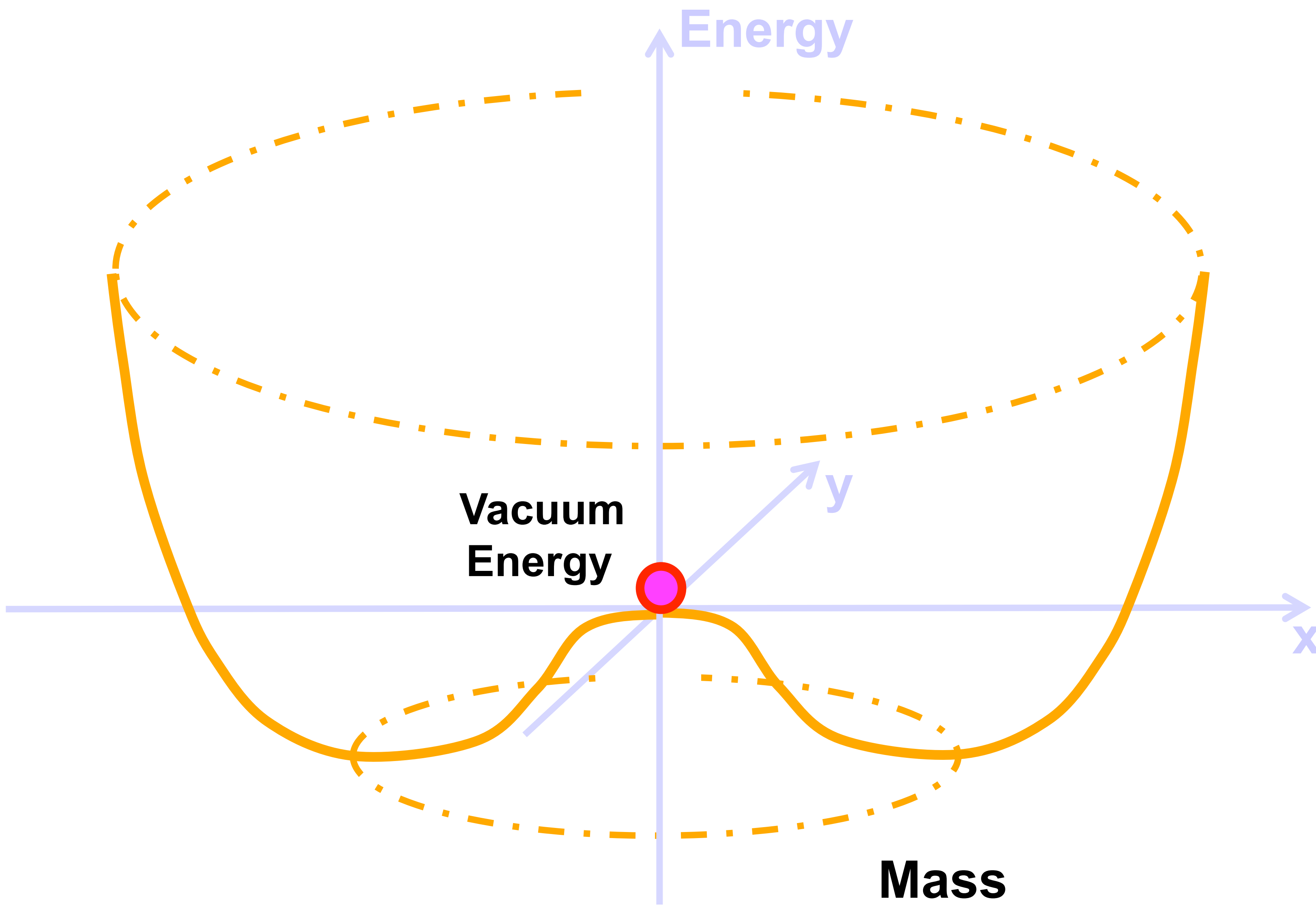


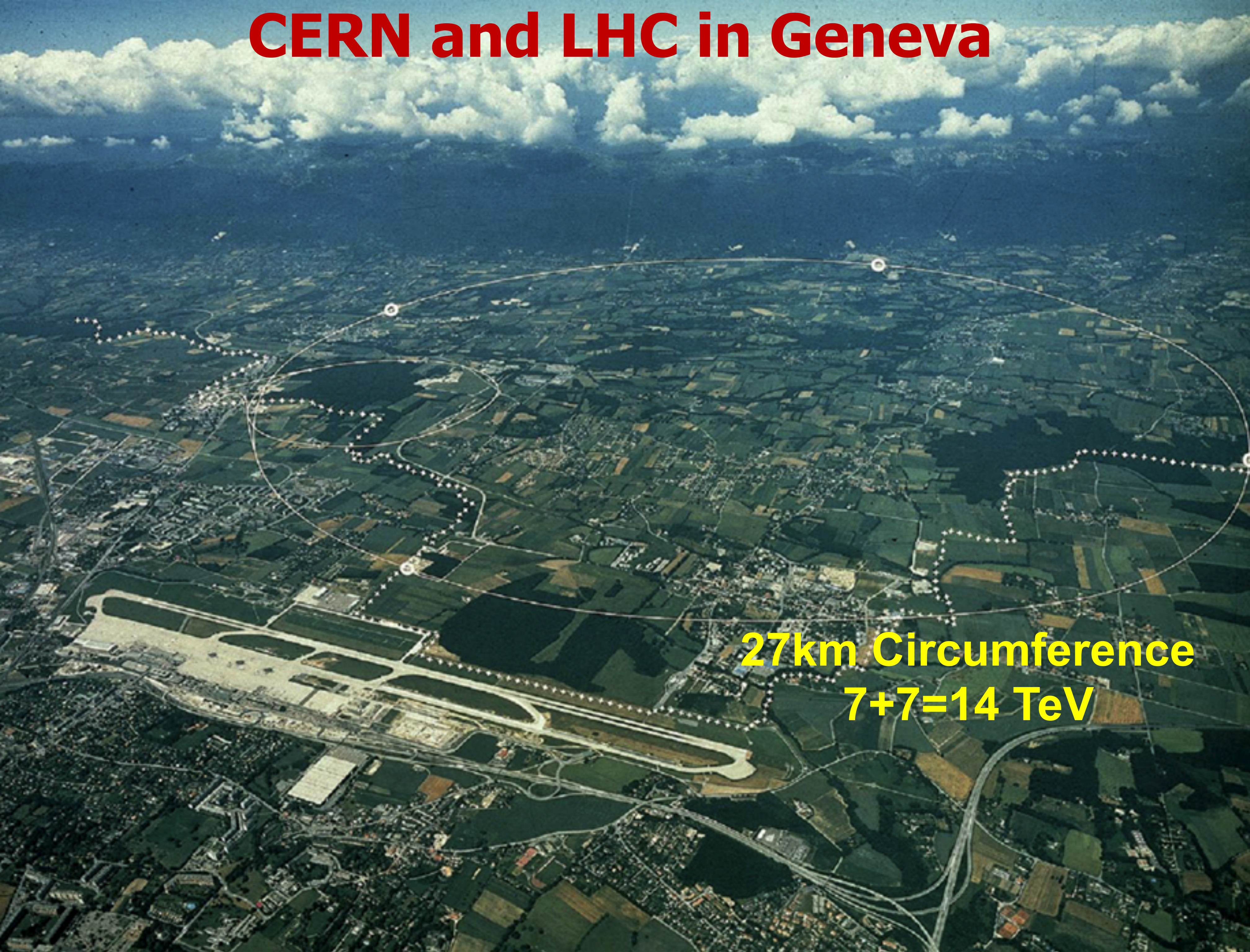
by Nambu Yoichiro

Spontaneous Symmetry Breaking
- Higgs Mechanism -



Spontaneous Symmetry Breaking
- Higgs Mechanism -




CERN and LHC in Geneva
27km Circumference
7+7=14 TeV

Los Angeles Times

Physicists are celebrating their Higgs boson 'triumph'

July 05, 2012 | Eryn Brown

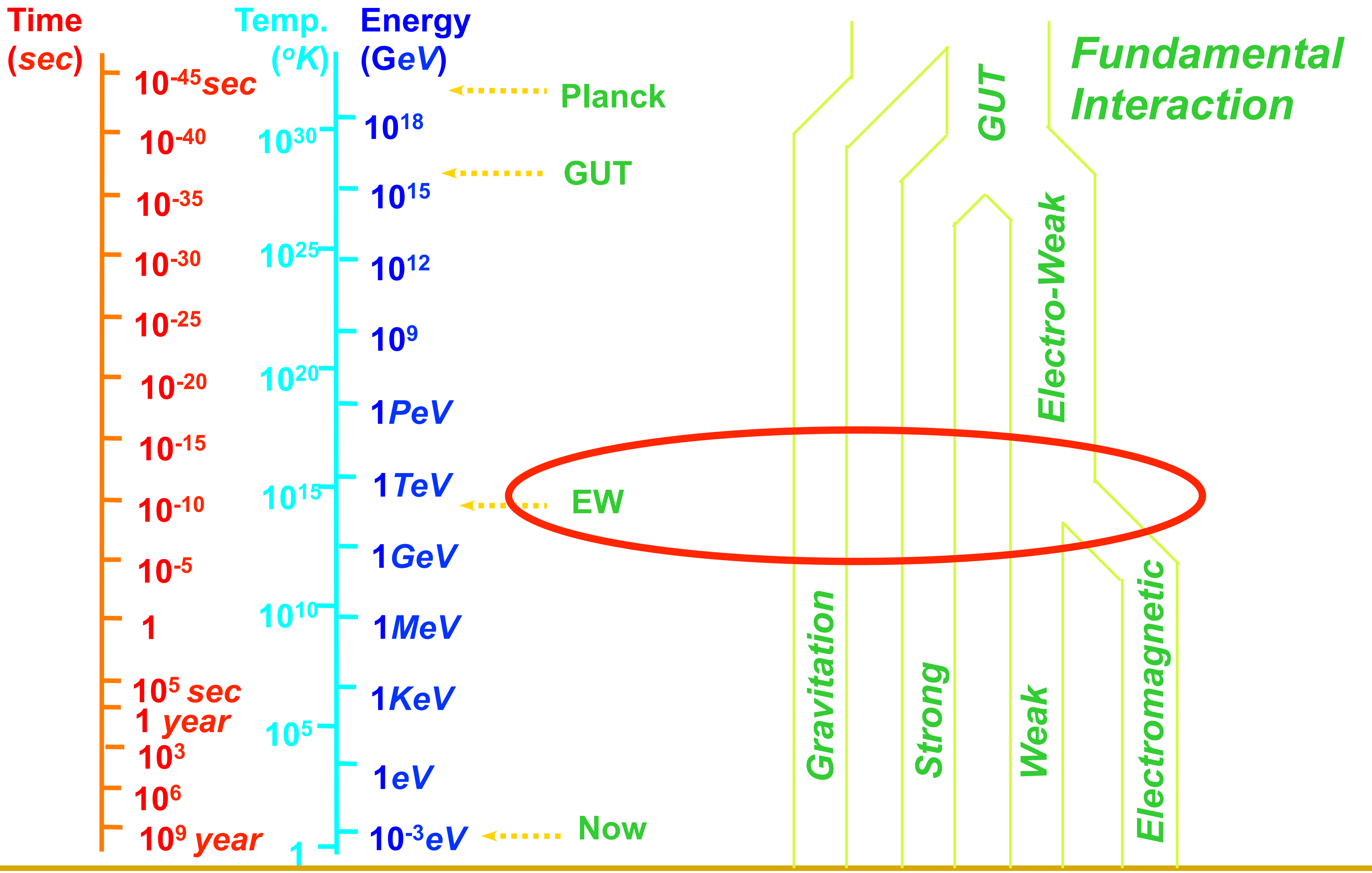
News release on July 4th at CERN

For physicists, it was a moment like landing on the moon or the discovery of DNA.

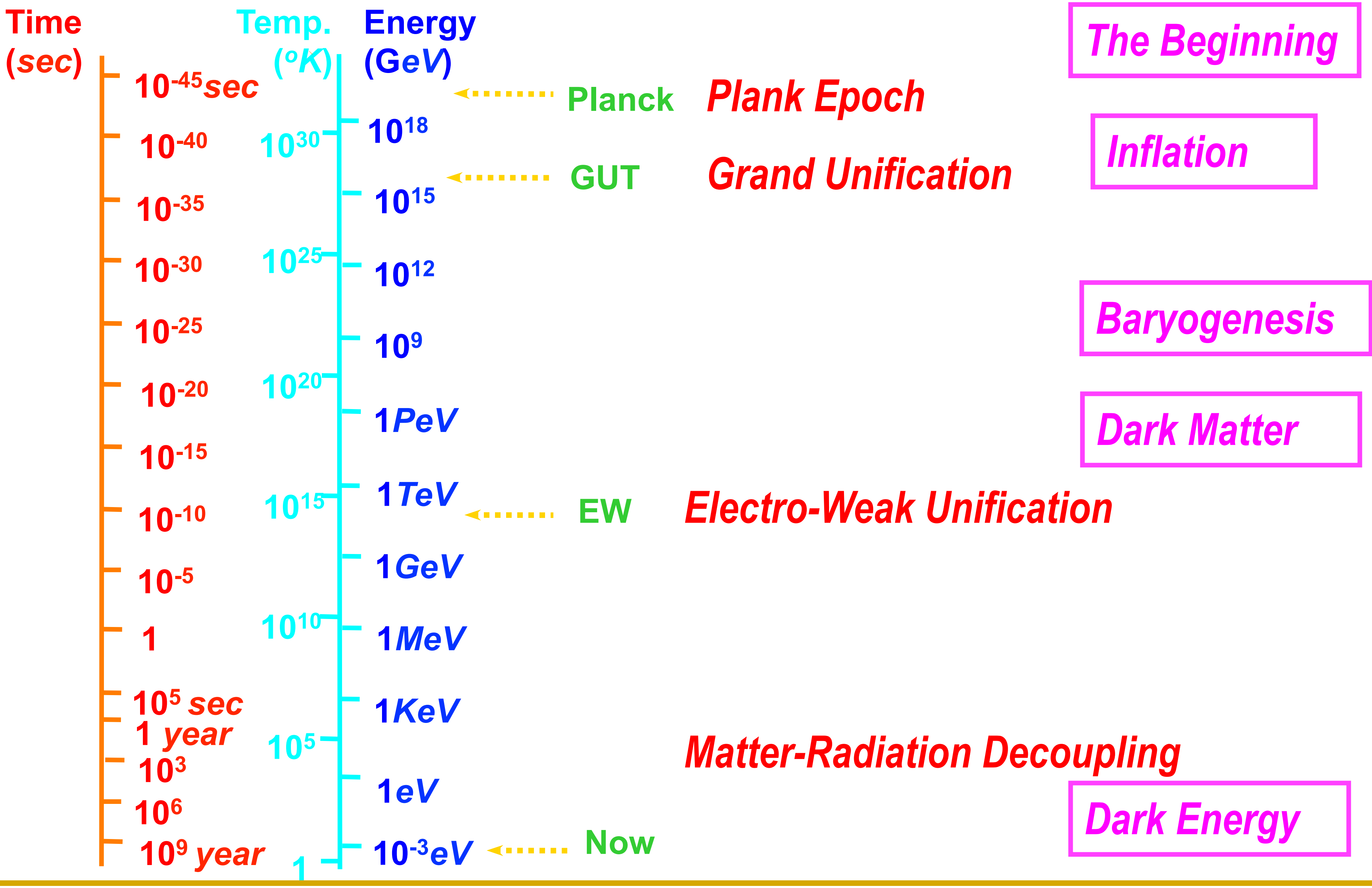
Belgian physicist Francois Englert, left, speaks with British physicist... (Fabrice Coffrini / AFP/Getty...)

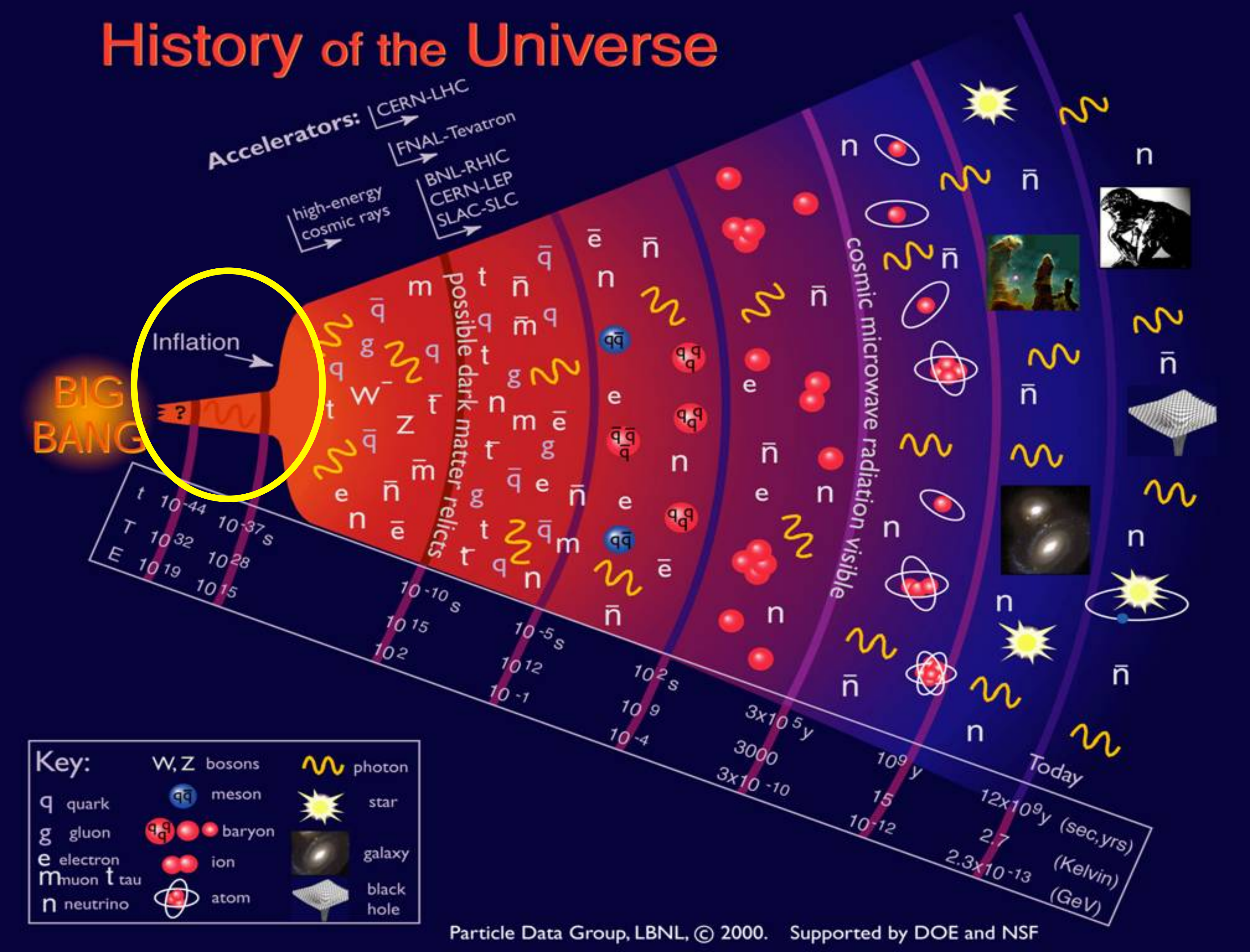
The focus was the Higgs boson, a subatomic particle that exists for a mere fraction of a second. Long theorized but never glimpsed, the so-called God particle is thought to be key to understanding the existence of all mass in the universe. The revelation Wednesday that it -- or some version of it -- had almost certainly been detected amid more than hundreds of trillions of high-speed collisions in a 17-mile track near Geneva prompted a group of normally reserved scientists to erupt with joy.

Unification of Fundamental Forces



Early Universe & Unsolved Problems





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BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^{-44} 10^{-37}s 10^{-10}s 10^{-5}s 10^{2}s $3x10^{5}$y 10^{9}y Today $12x10^{9}$y (sec,yrs)
T 10^{32} 10^{28} 10^{15} 10^{12} 10^{9} 3000 15 2.7 (Kelvin)
E 10^{19} 10^{15} 10^{2} 10^{-1} 10^{-4} $3x10^{-10}$ 10^{-12} $2.3x10^{-13}$ (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
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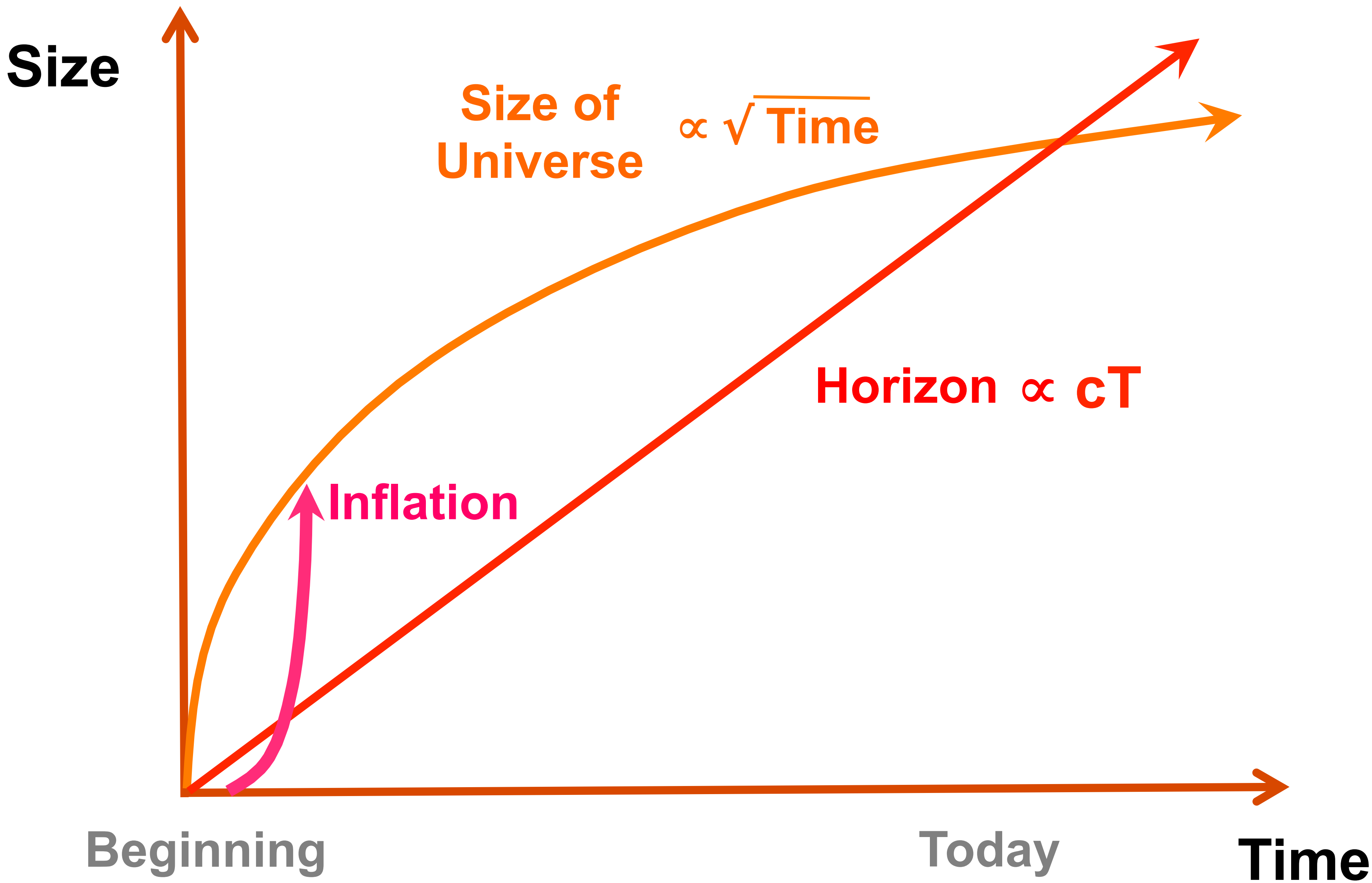
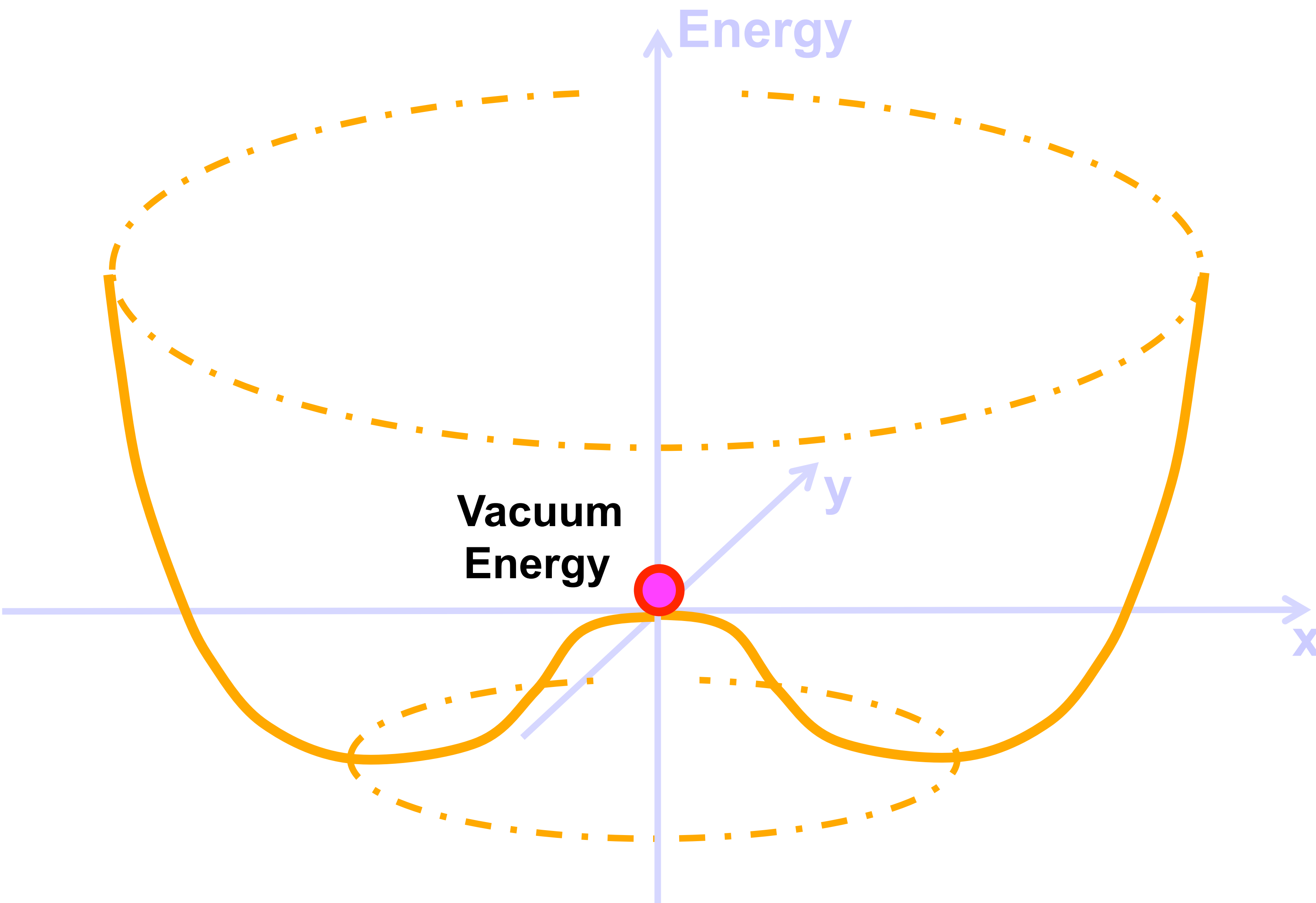
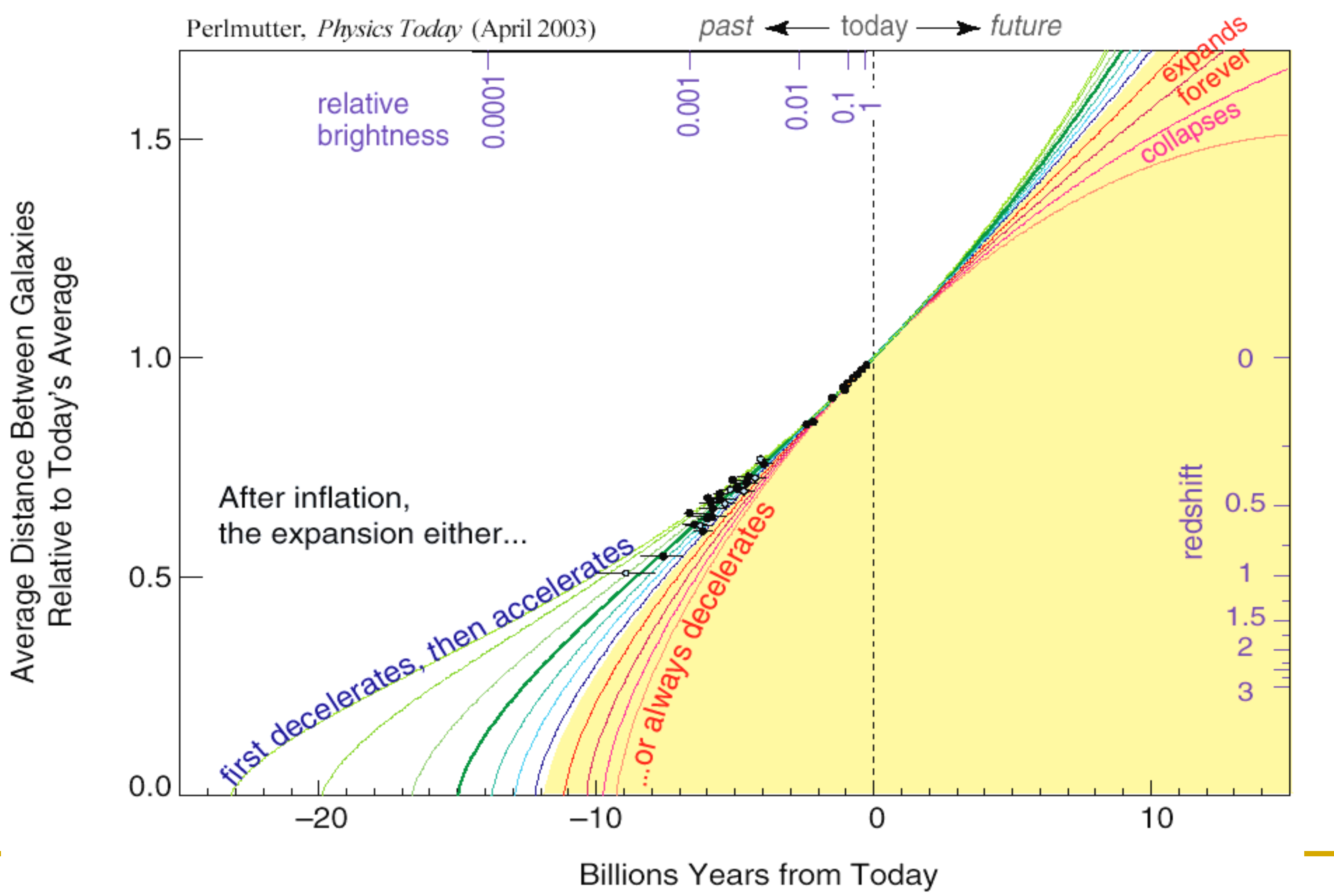
Inflation in Early Universe



Origin of Inflation

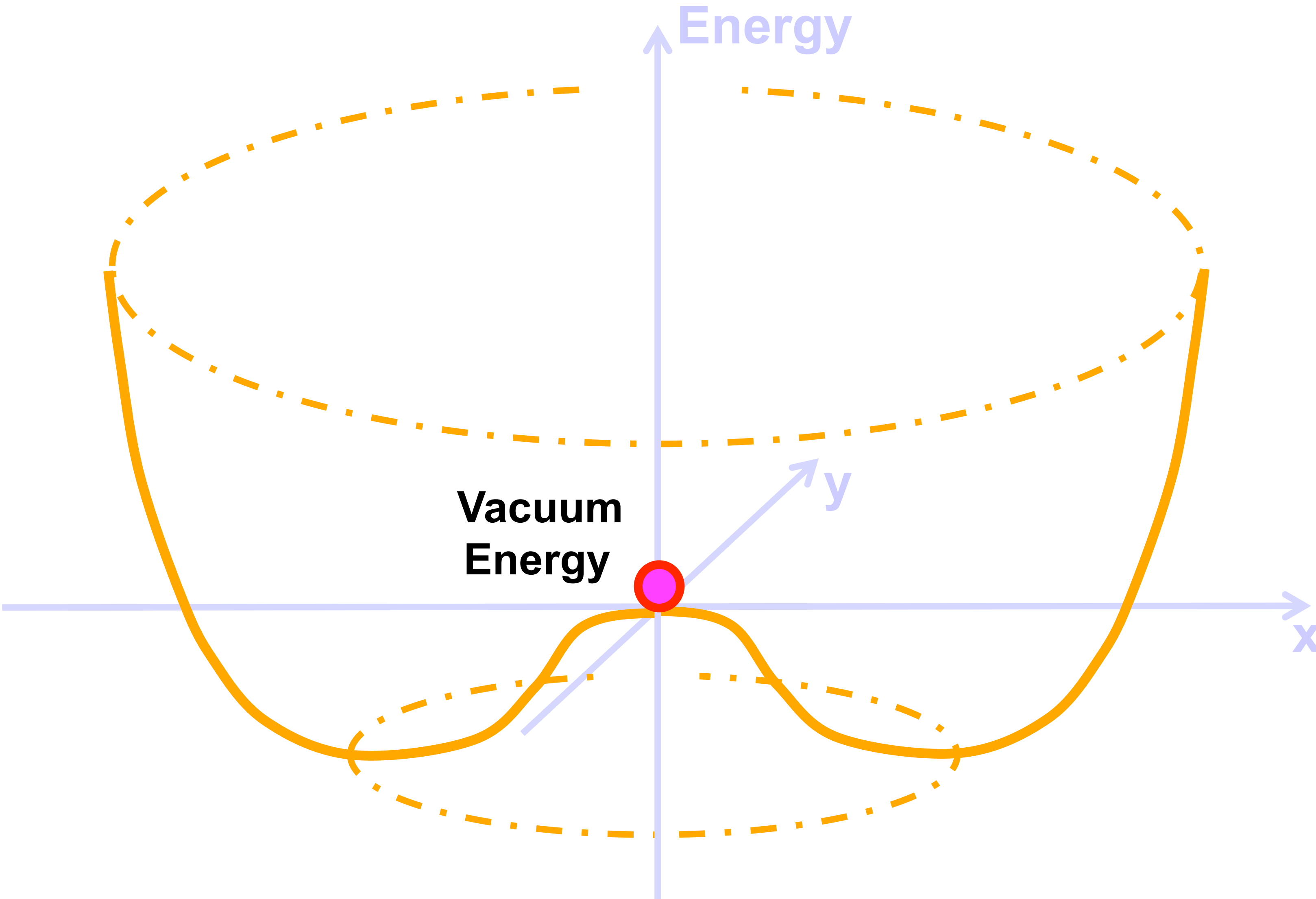


The Accelerating Universe



Origin of Dark Energy

Same as Inflation



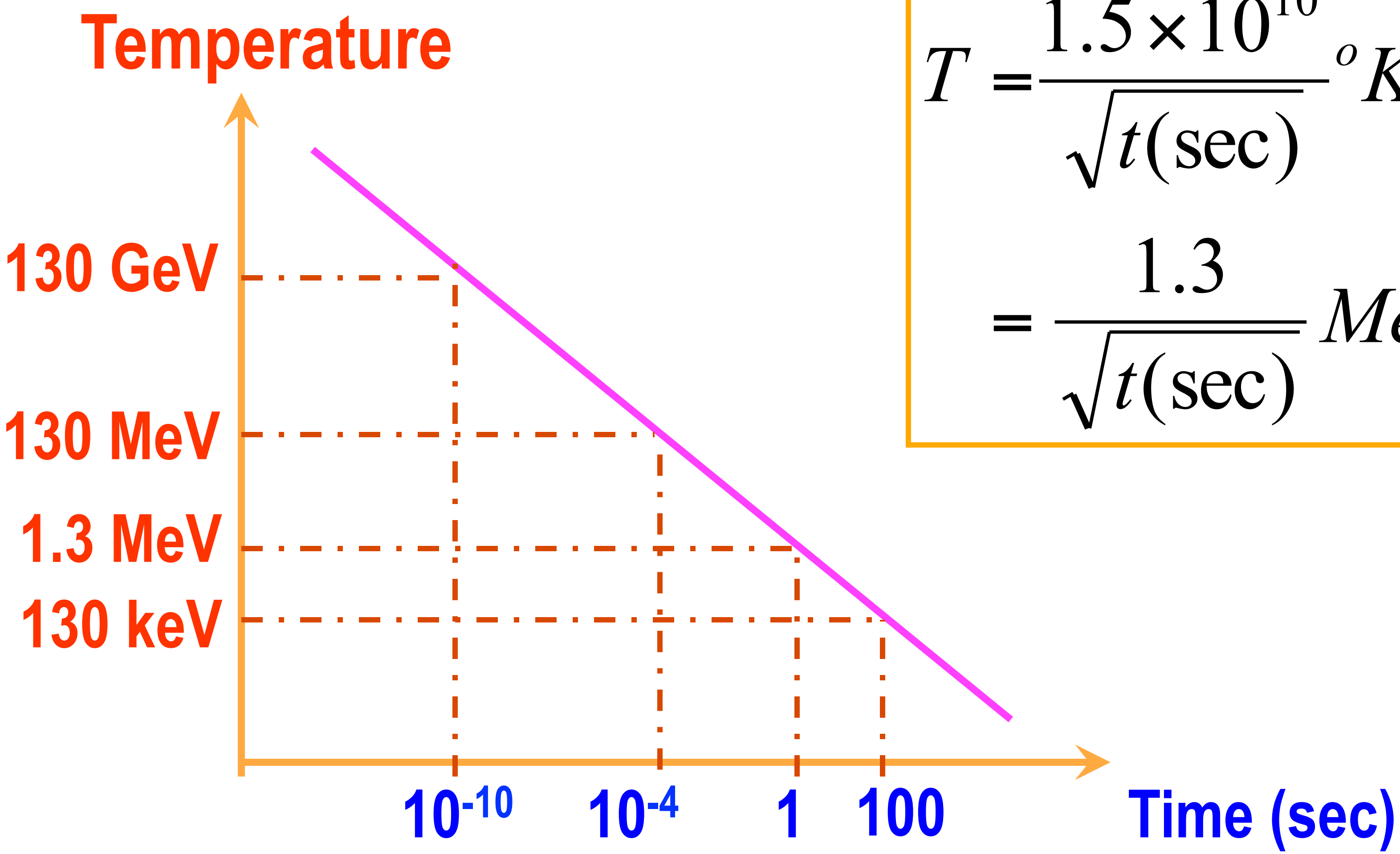
The First One Second

Relation between Temperature and Time

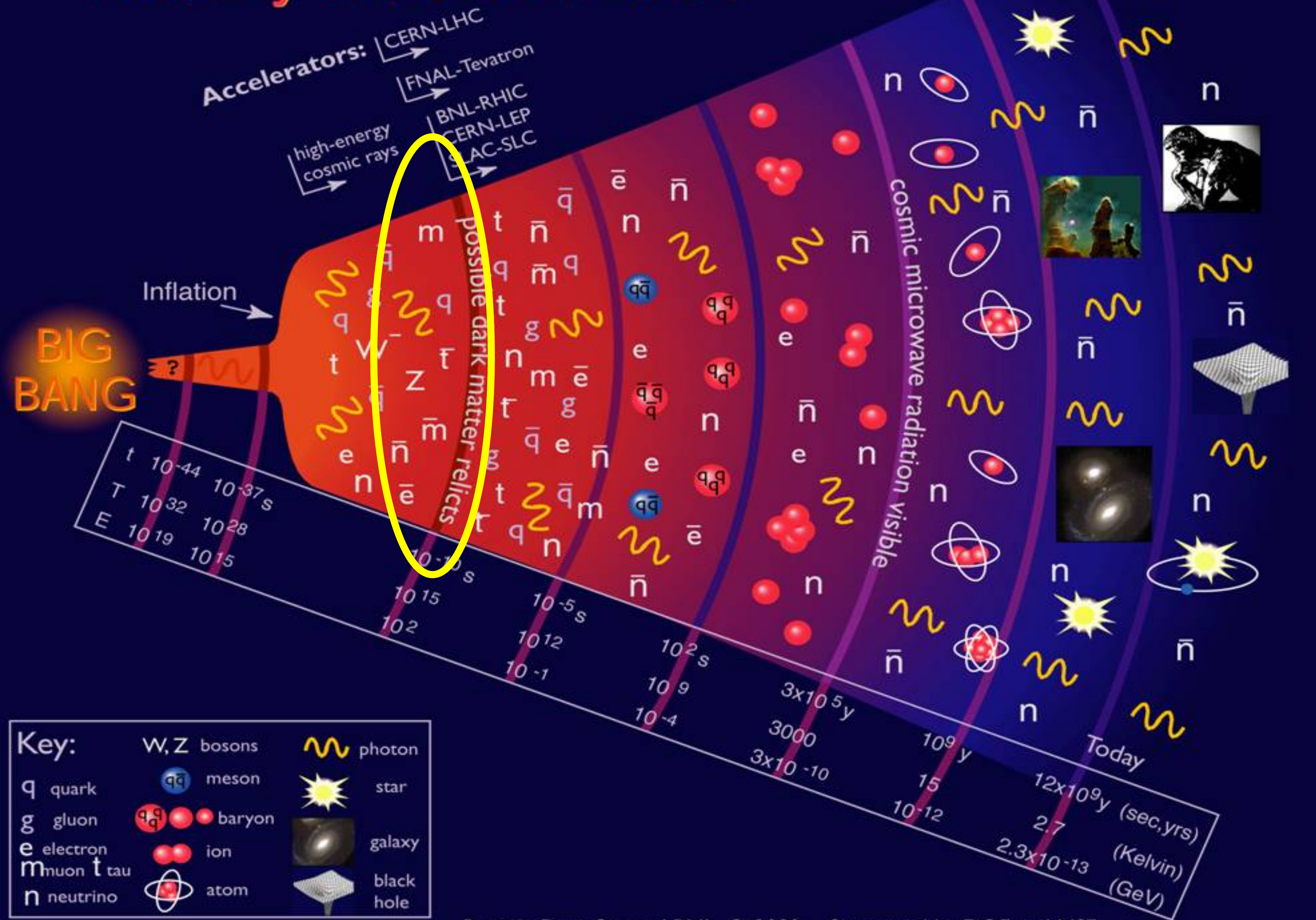
T: Temperature
t : time

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

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



History of the Universe



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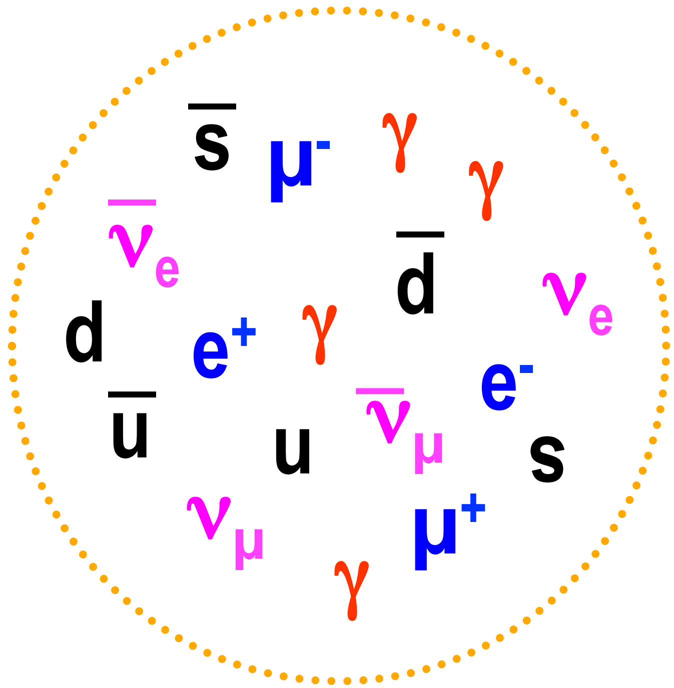
Time = 10^{-6} sec, Temp.= 10^{13} °K (~1 GeV)

➢ Thermal Equilibrium of Photons, Leptons and Quarks

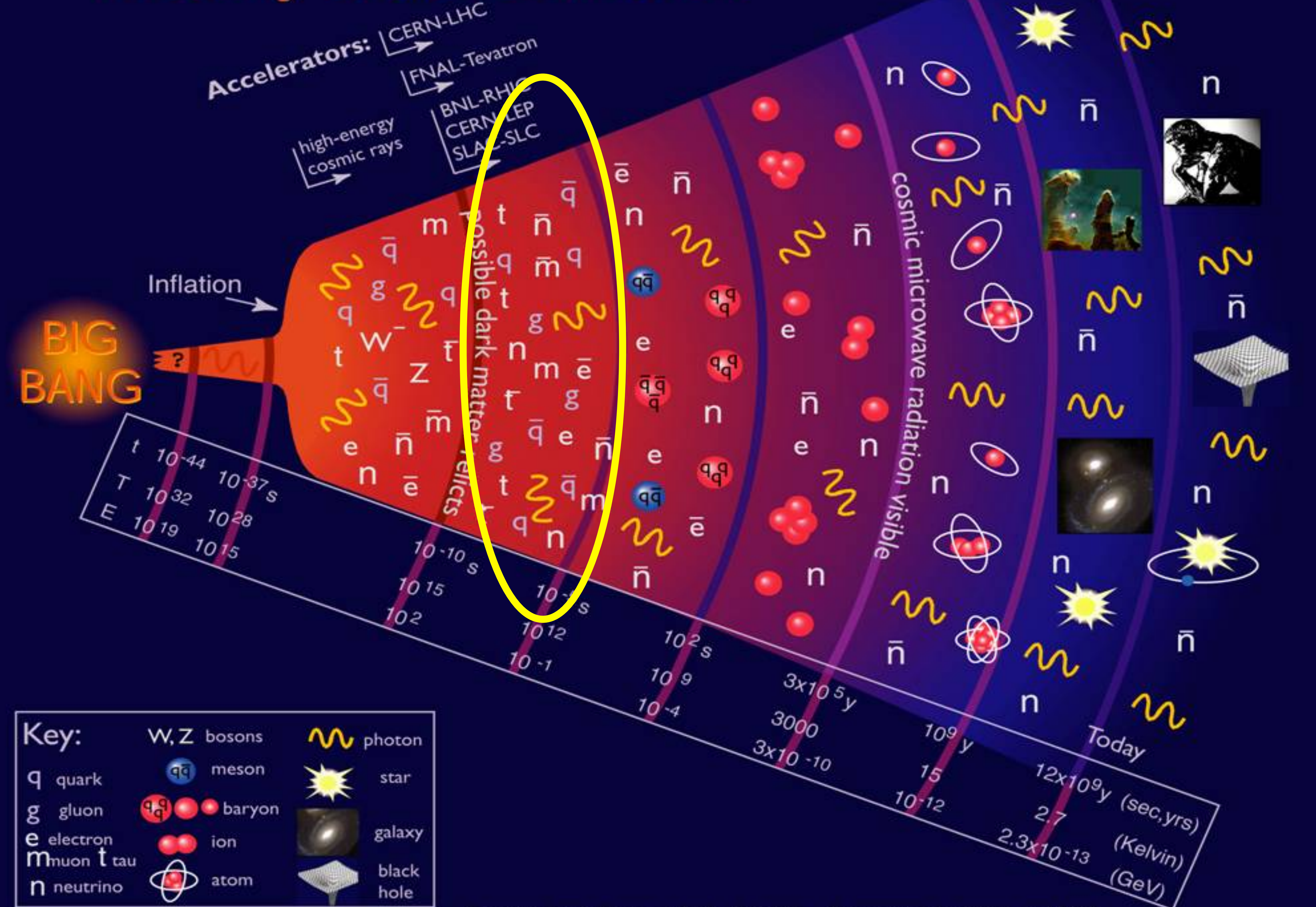
- Photon ↔ Lepton + Anti-lepton
  - $\gamma \leftrightarrow e^- + e^+$
  - $\gamma \leftrightarrow \mu^- + \mu^+$
  - $\gamma \leftrightarrow \nu + \nu$
- Photon ↔ Quark+ Anti-quark
  - $\gamma \leftrightarrow u + \bar{u}$
  - $\gamma \leftrightarrow d + \bar{d}$
  - $\gamma \leftrightarrow s + \bar{s}$



- #photon ~ #lepton ~ #quark
- #particle ~ #anti-particle

Horizon
~ 300 m

History of the Universe



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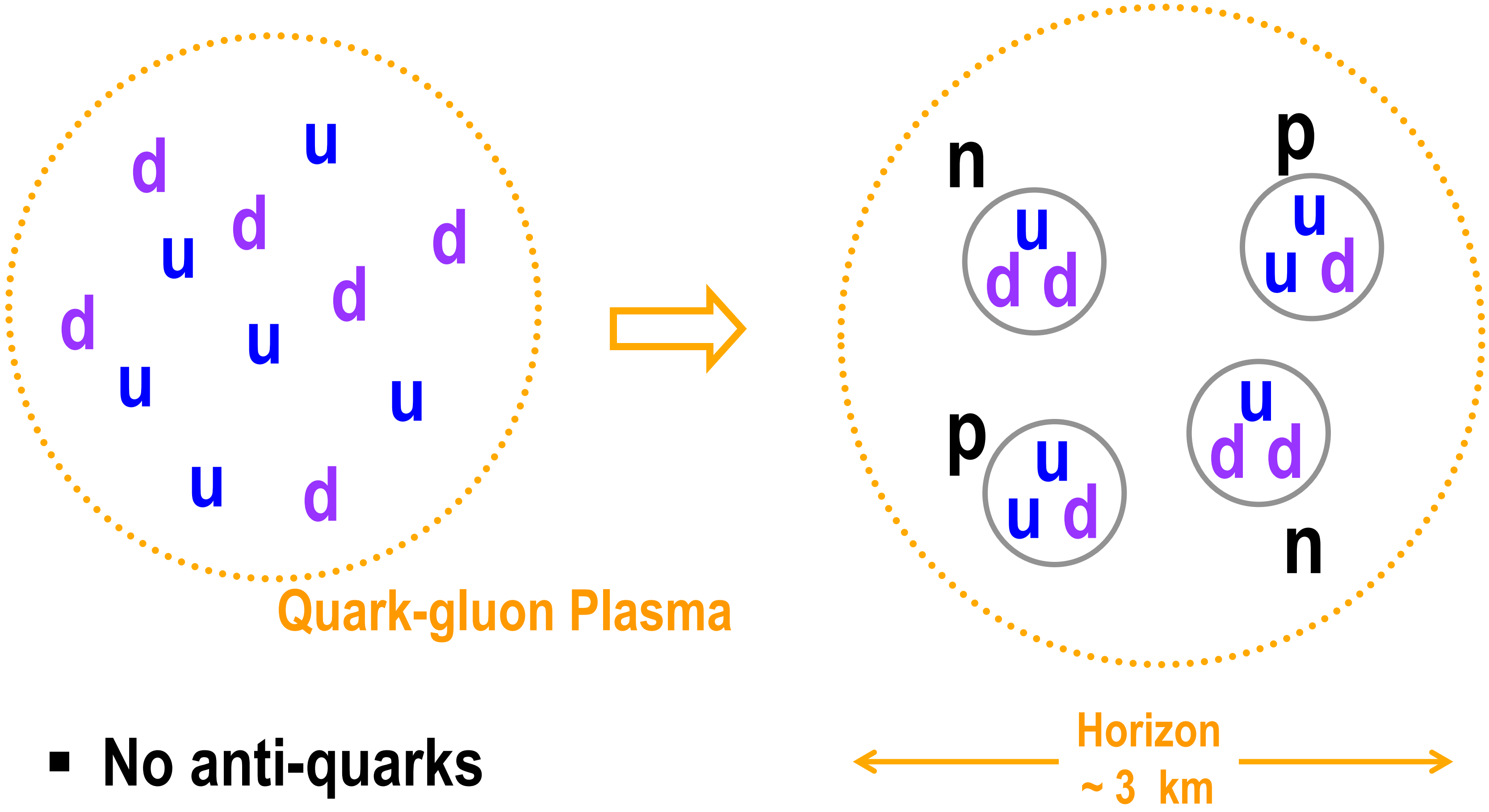
Time = 10^{-5} sec, Temp.= 3×10^{12} °K (300 MeV)

➢ Quark → Hadron Phase Transition

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



- No anti-quarks

Baryogenesis

- Why did anti-particle disappear?

  #Photon : #Baryon : #Anti Baryon

  $= 1 : \sim 4 \times 10^{-10} : 0$

- Sakharov's three conditions:
  - Baryon number violation
  - Out of equilibrium
  - CP Violation

⇩

- No clear clue yet

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

➢ Thermal Equilibrium of Protons and Neutrons

- $n \leftrightarrow p + e^- + \bar{\nu}_e$
- $n + e^+ \leftrightarrow p + \bar{\nu}_e$
- $n + \nu_e \leftrightarrow p + e^-$

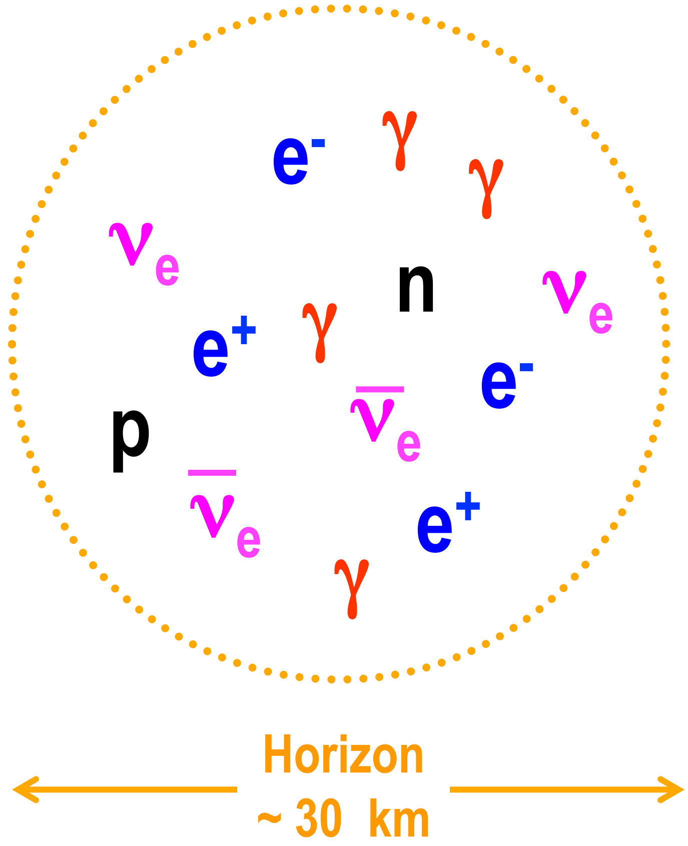
➢ Lepton Dominant Era

➢ 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



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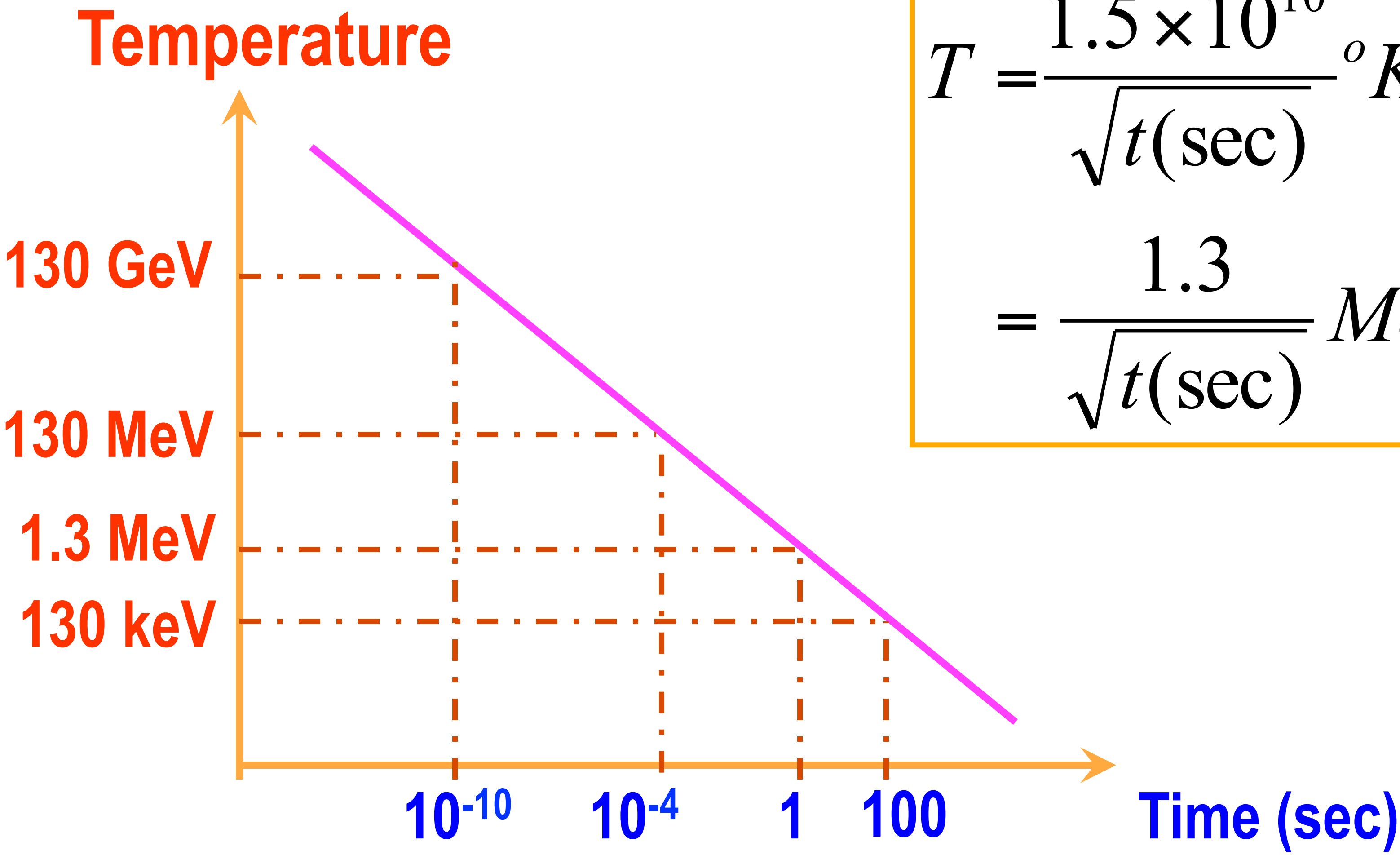


Thermal Equilibrium

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

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

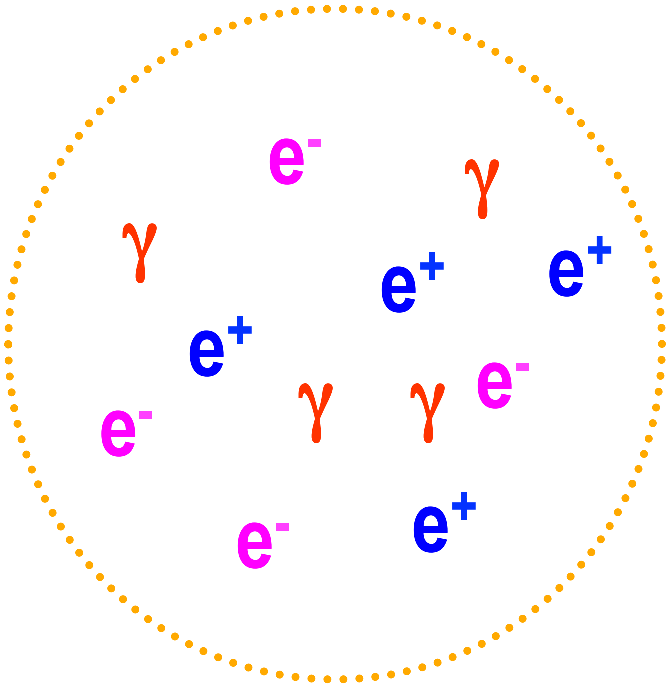
Photon ↔ Particle + Anti-particle

Example:

$m_e = 0.511$ MeV

if $E > 1.022$ MeV

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



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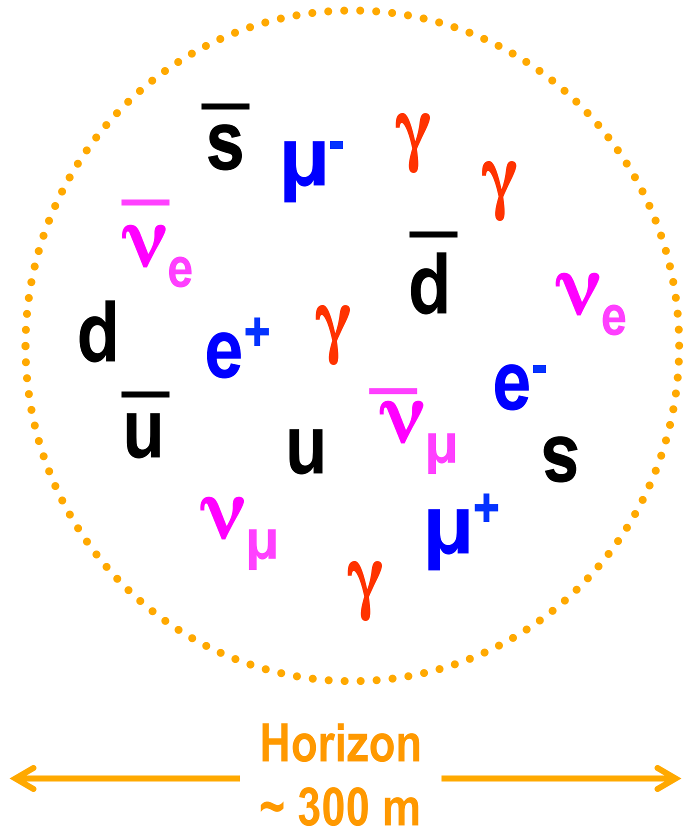


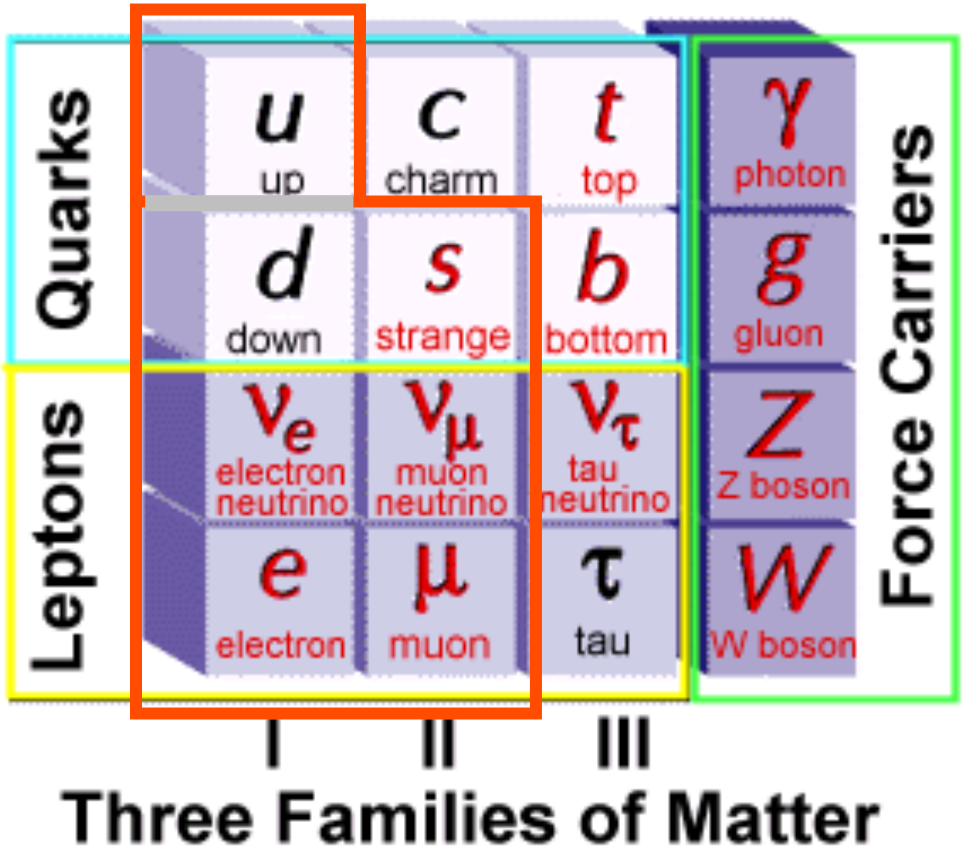
- #photon ~ #lepton ~ #quark

Elementary Particles

Universe at t = 1 μsec

Fermion Boson

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

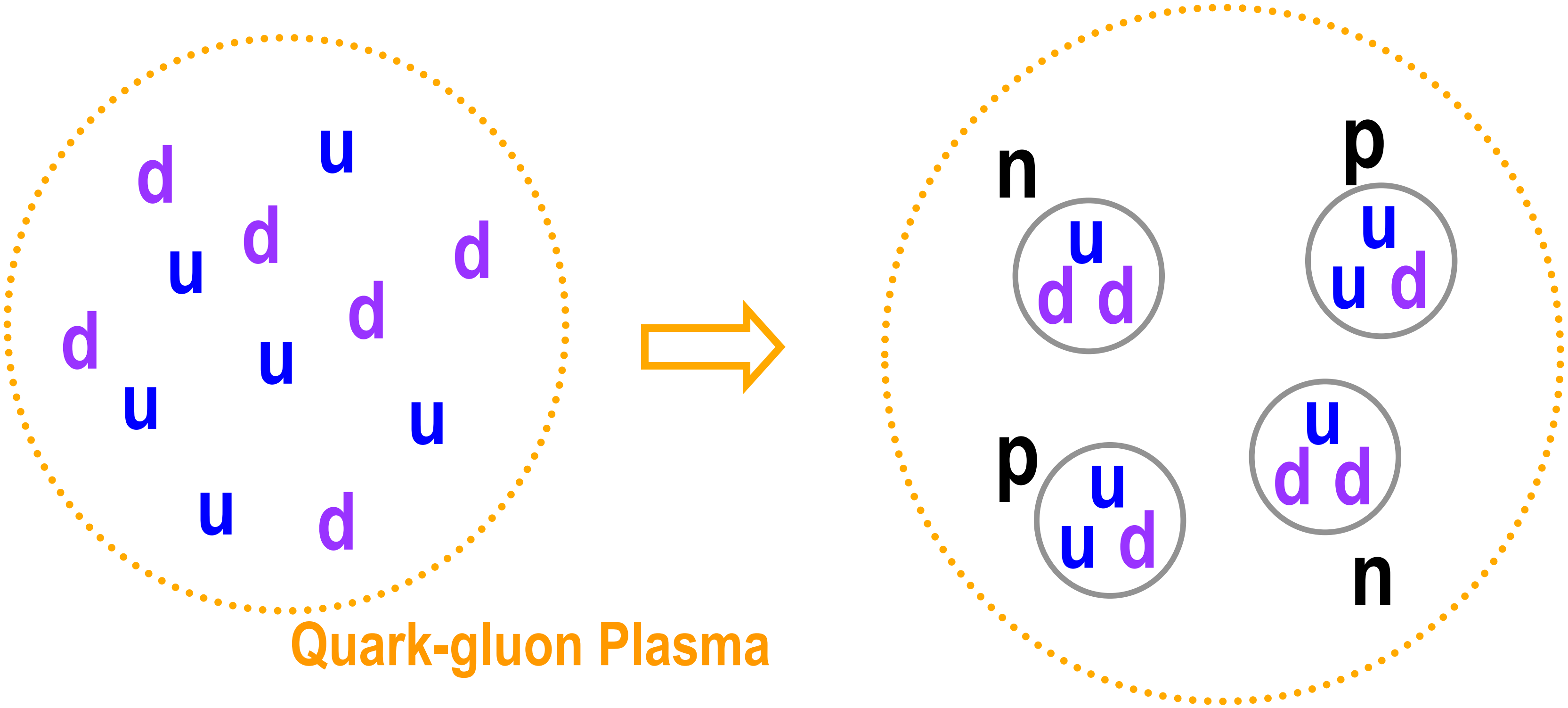


+ Anti-particles

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

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

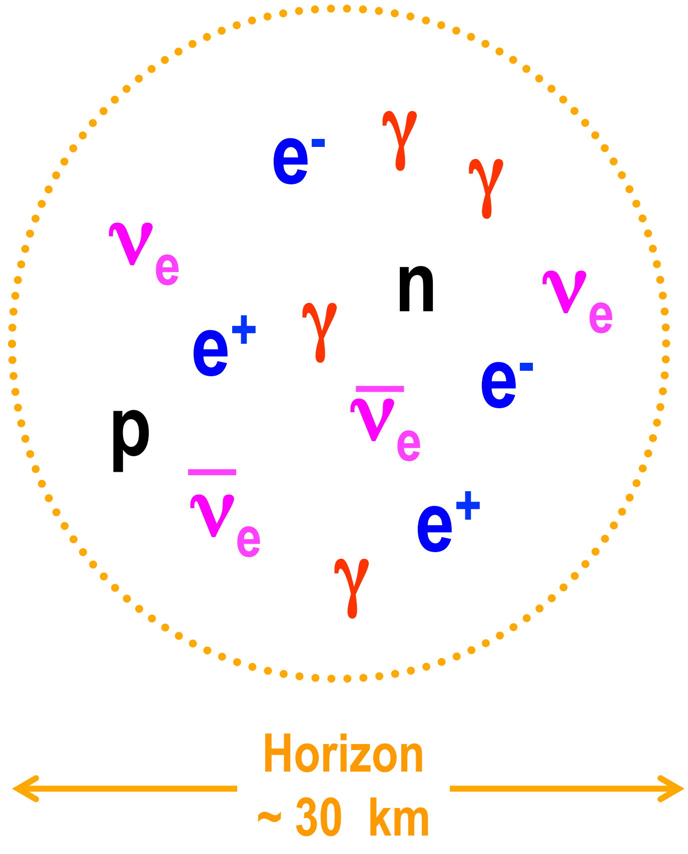
- **Lepton Dominant Era**

- **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:**

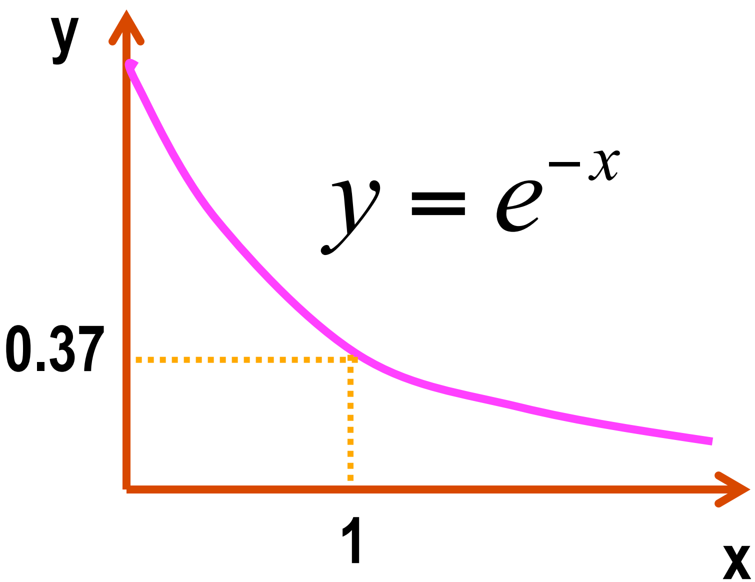
Photon:	γ	1



Neutron/Proton Ratio

- At T << 1 GeV, $m_n > m_p$, therefore #n < #p
  - $n \rightarrow p + e^- + \bar{\nu}_e$
  - $n + e^+ \rightarrow p + \bar{\nu}_e$
  - $n + \nu_e \rightarrow p + e^-$

$$\frac{\#n}{\#p} = Exp\left(-\frac{m_n - m_p}{T}\right) = Exp\left(-\frac{1.3MeV}{T}\right)$$



Time	T	#n/#p
10^{-4} sec	130 MeV	0.99
0.01 sec	13 MeV	0.9
1sec	1.3 MeV	0.3

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

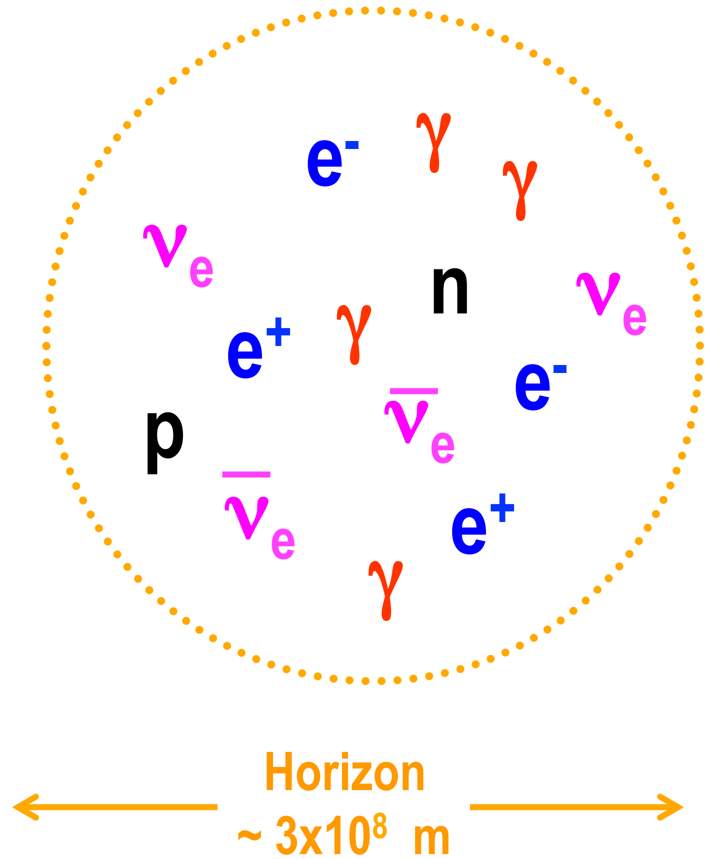
- **Fermions:** — **Ratio**
  - Lepton:

	Ratio
ν_e	1
e^-	1
$\bar{\nu}_e$	1
e^+	1

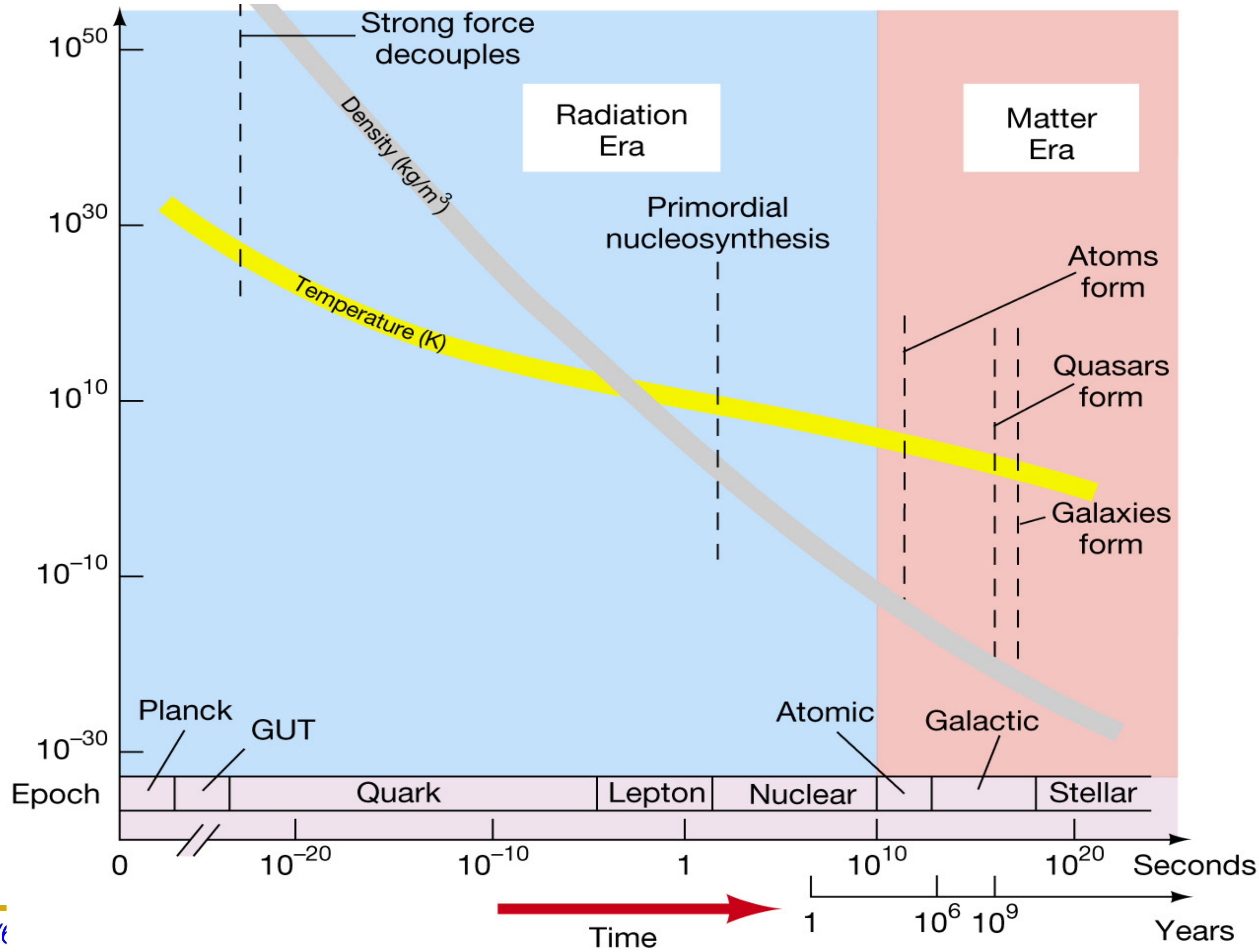
  - Baryon:

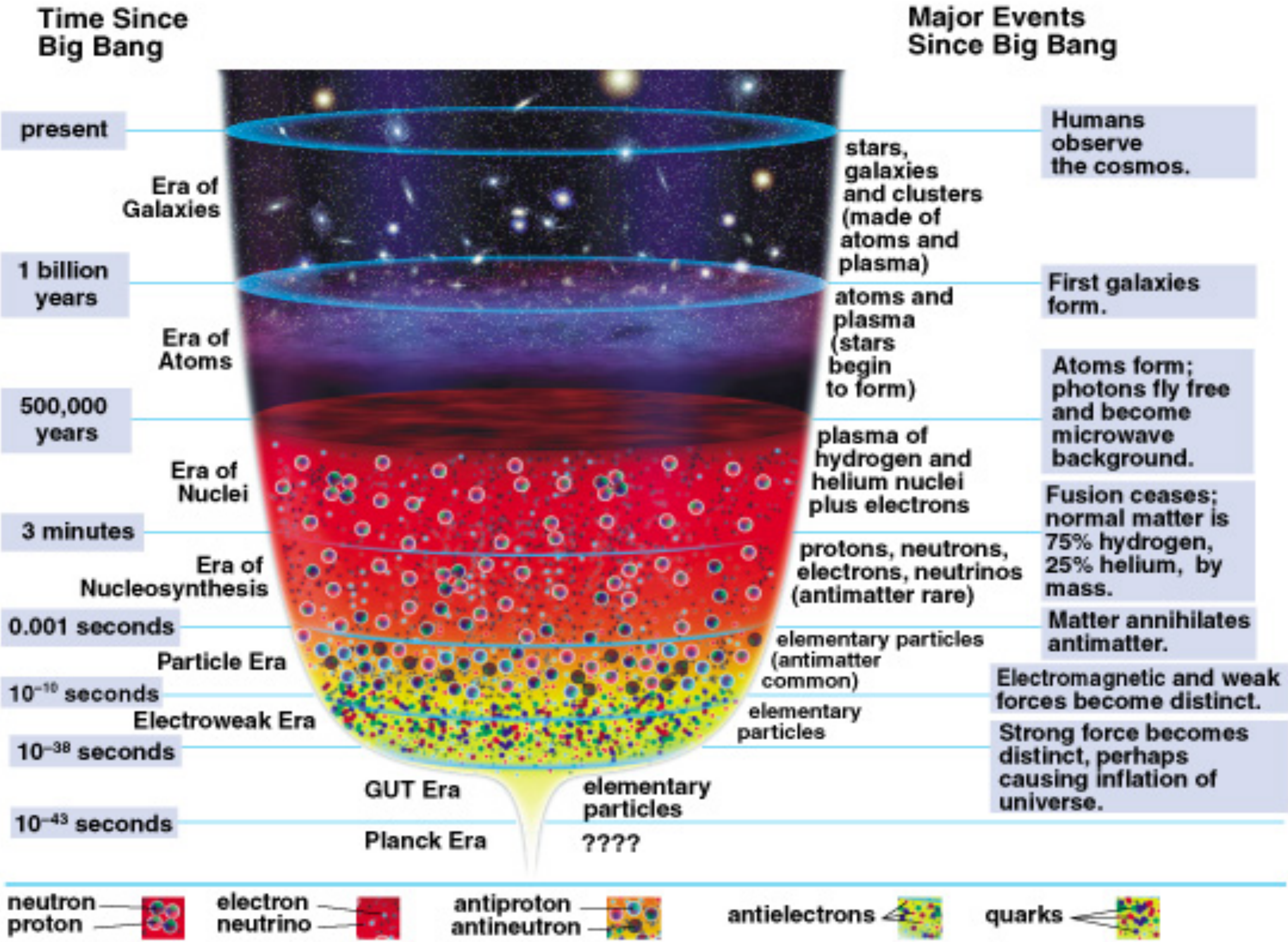
	Ratio
p	$\sim 4\times10^{-10}$
n	$\sim 1\times10^{-10}$

- **Bosons:**
  - Photon: γ — 1



The Evolution of the Universe





Time Since Big Bang
Major Events Since Big Bang
present
Humans observe the cosmos.
stars, galaxies and clusters (made of atoms and plasma)
Era of Galaxies
1 billion years
First galaxies form.
atoms and plasma (stars begin to form)
Era of Atoms
500,000 years
Atoms form; photons fly free and become microwave background.
plasma of hydrogen and helium nuclei plus electrons
Era of Nuclei
3 minutes
Fusion ceases; normal matter is 75% hydrogen, 25% helium, by mass.
protons, neutrons, electrons, neutrinos (antimatter rare)
Era of Nucleosynthesis
0.001 seconds
Matter annihilates antimatter.
elementary particles (antimatter common)
Particle Era
10^{-10} seconds
Electromagnetic and weak forces become distinct.
elementary particles
Electroweak Era
10^{-38} seconds
Strong force becomes distinct, perhaps causing inflation of universe.
GUT Era
elementary particles
10^{-43} seconds
Planck Era
????
neutron
proton
electron
neutrino
antiproton
antineutron
antielectrons
quarks

The First Three Minutes

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

- The expansion of the Universe is so fast that neutrons have no more chance to interact with leptons (e^+ or ν_e).
- The only process is

$$n \rightarrow p + e^- + \bar{\nu}_e$$

- Life time = 15 minutes (900 seconds)

⇩

- Neutrons slowly decay for the next 100 seconds.

$$\#n / \#p \rightarrow \sim 0.13$$

Time ~ 100 sec, Temp.= 10^9 °K (130 keV)

- Essentially the same particles as today.
- **Fermions:** — **Ratio (in numbers)**
  - Lepton: ν_e ~1; e^- ~4×10^{-10}
  - Baryon: p ~4×10^{-10}; n ~0.5×10^{-10}
- **Bosons:**
  - Photon: γ 1

		Ratio (in numbers)
Lepton	ν_e	~1
	e^-	~4×10^{-10}
Baryon	p	~4×10^{-10}
	n	~0.5×10^{-10}
Photon	γ	1

- No anti-particles
- # Photon : # Baryon = 1 : ~4×10^{-10}
- # p = # e^-

Time = 3 minutes, Temp.= ~10^9 °K (~100 keV)

- Neutrons are captured by protons.

$$\left\{ \begin{array}{l} n + p \rightarrow D + \gamma \\ D + D \rightarrow {}^3He + n \\ {}^3He + D \rightarrow {}^4He + p \end{array} \right.$$

D = (pn)
^{3}He = (ppn)
^{4}He = (ppnn)

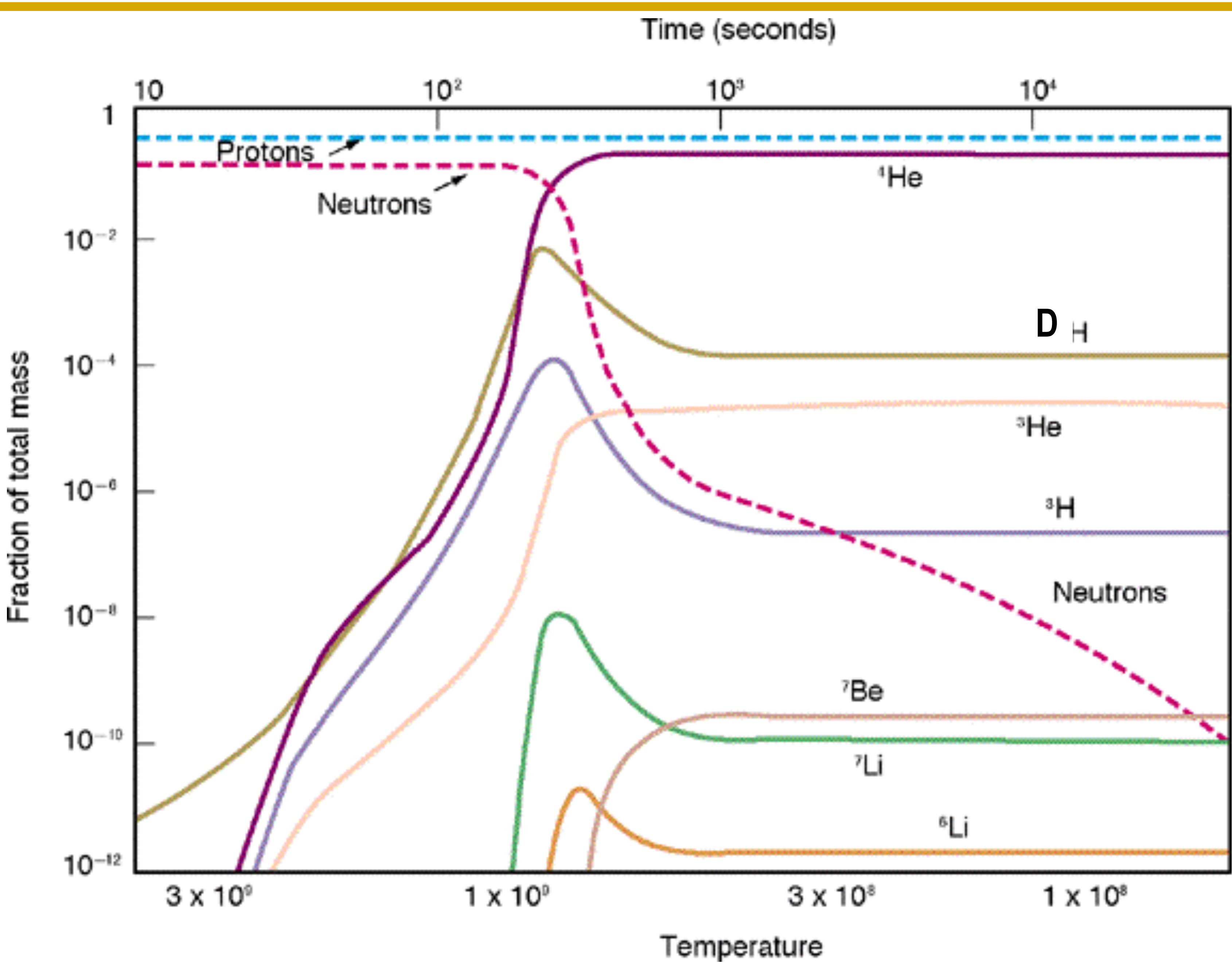
- Finally ^{4}He is made!

- But no other heavier elements.
  - Expansion of the Universe was too fast for other nuclear fusions!

H : ^{4}He = 75% : 25 %

by weight

Abundance vs. Time



Baryon/Photon Ratio

- Amount of ^{4}He depends on the amount of photon at that time.

  More Photons → D breaks to n + p
  → n decays to p
  → less ^{4}He

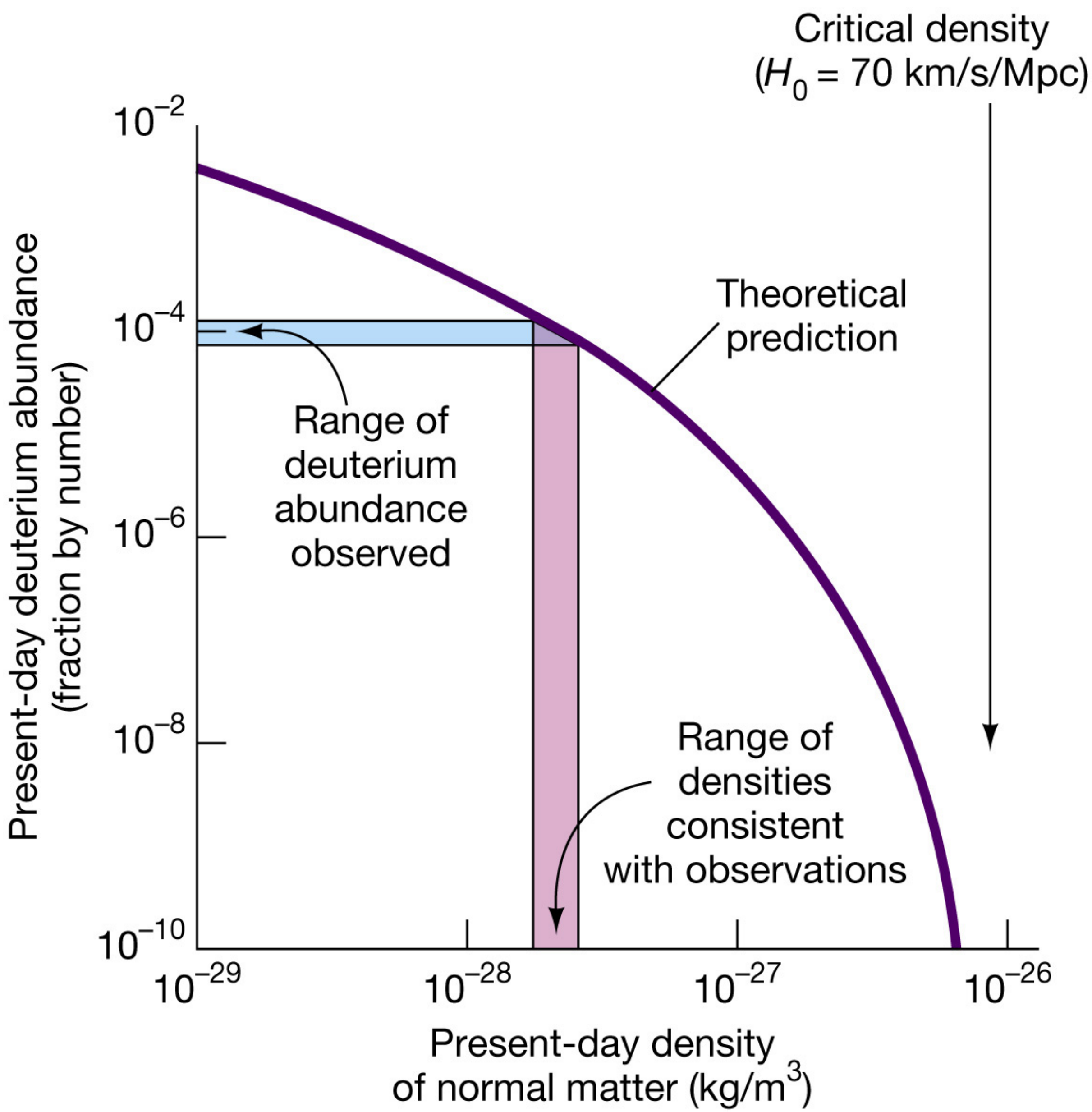
- From the amount of ^{4}He and D, we can estimate

$$\eta = \frac{\# Baryon}{\# Photon} = (3-4)\times 10^{-10}$$

- We know that #photon = 420 /cm^3

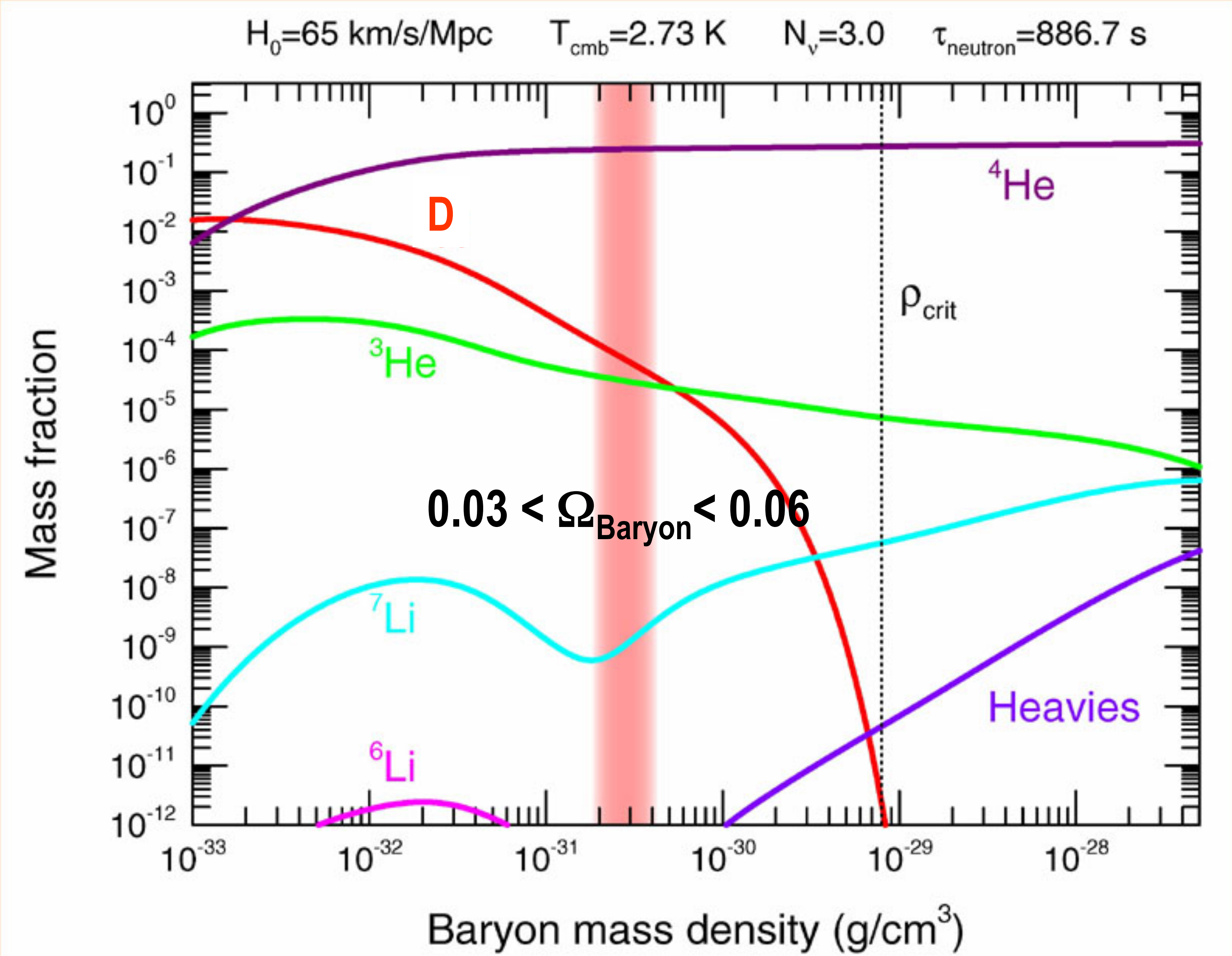
$$0.03 < \Omega_{Baryon} < 0.06$$

The Formation of Nuclei and Atoms



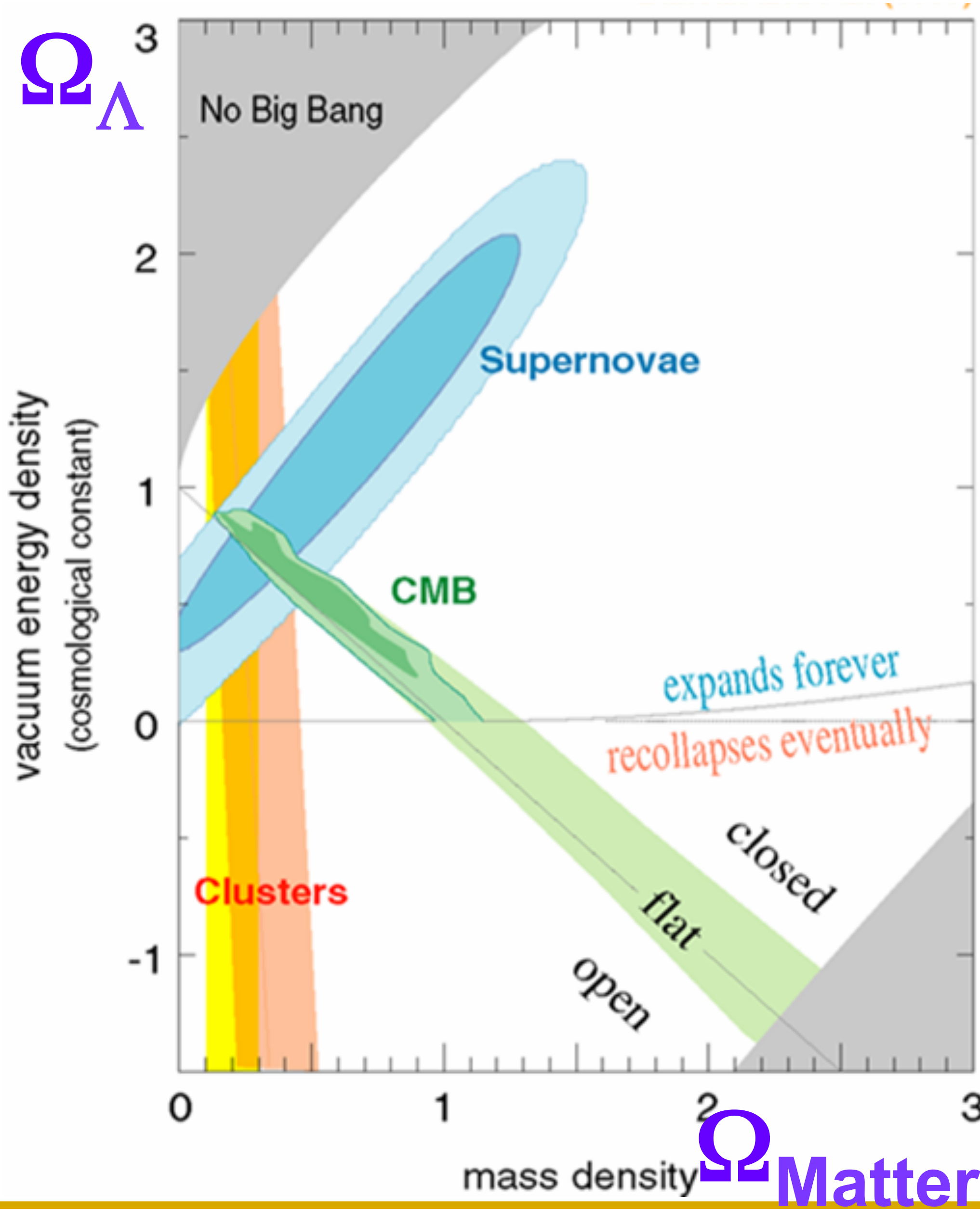
As with galaxy measurements, the total matter density determined by deuterium abundance shows that the matter density is only a few percent of the critical density.

Abundance vs. Density



Density of Our Universe

- $\Omega_{Total} = \Omega_{\Lambda} + \Omega_{Matter}$
  $= 1.0$
- Universe is Flat.
  ⇒ Inflation
- 70% is Dark Energy.
  ⇒ Accelerating



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^{3}He = (ppn)

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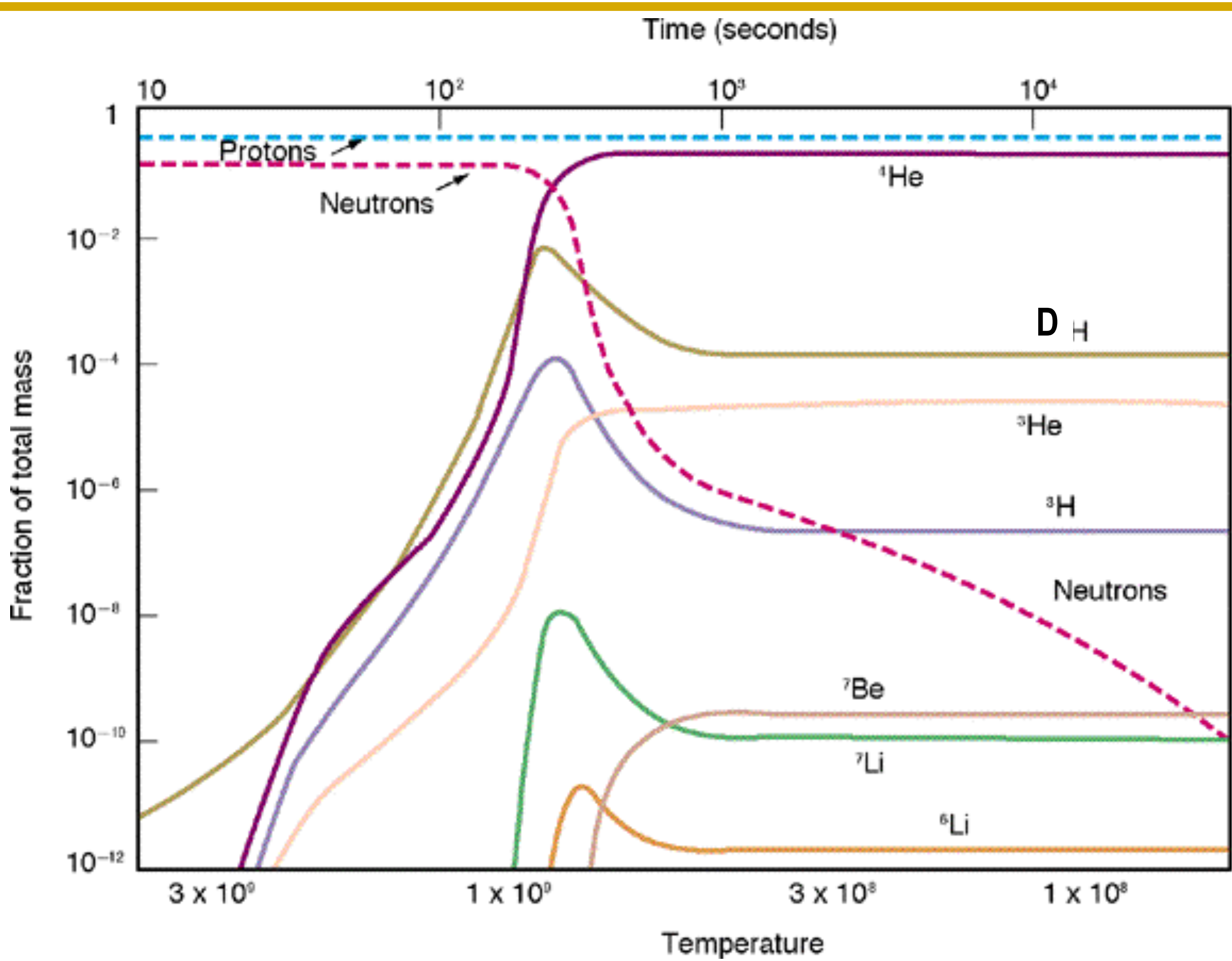

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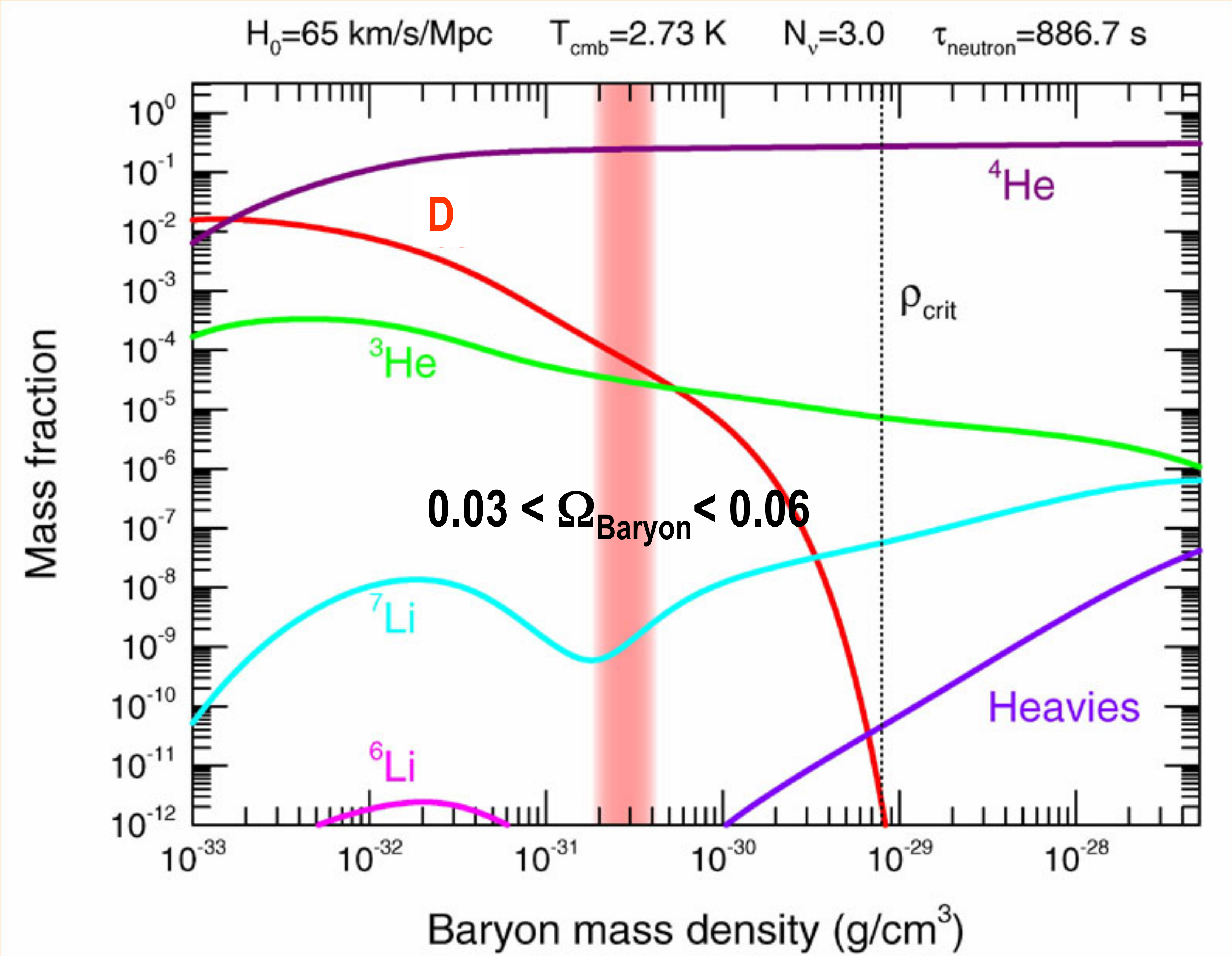
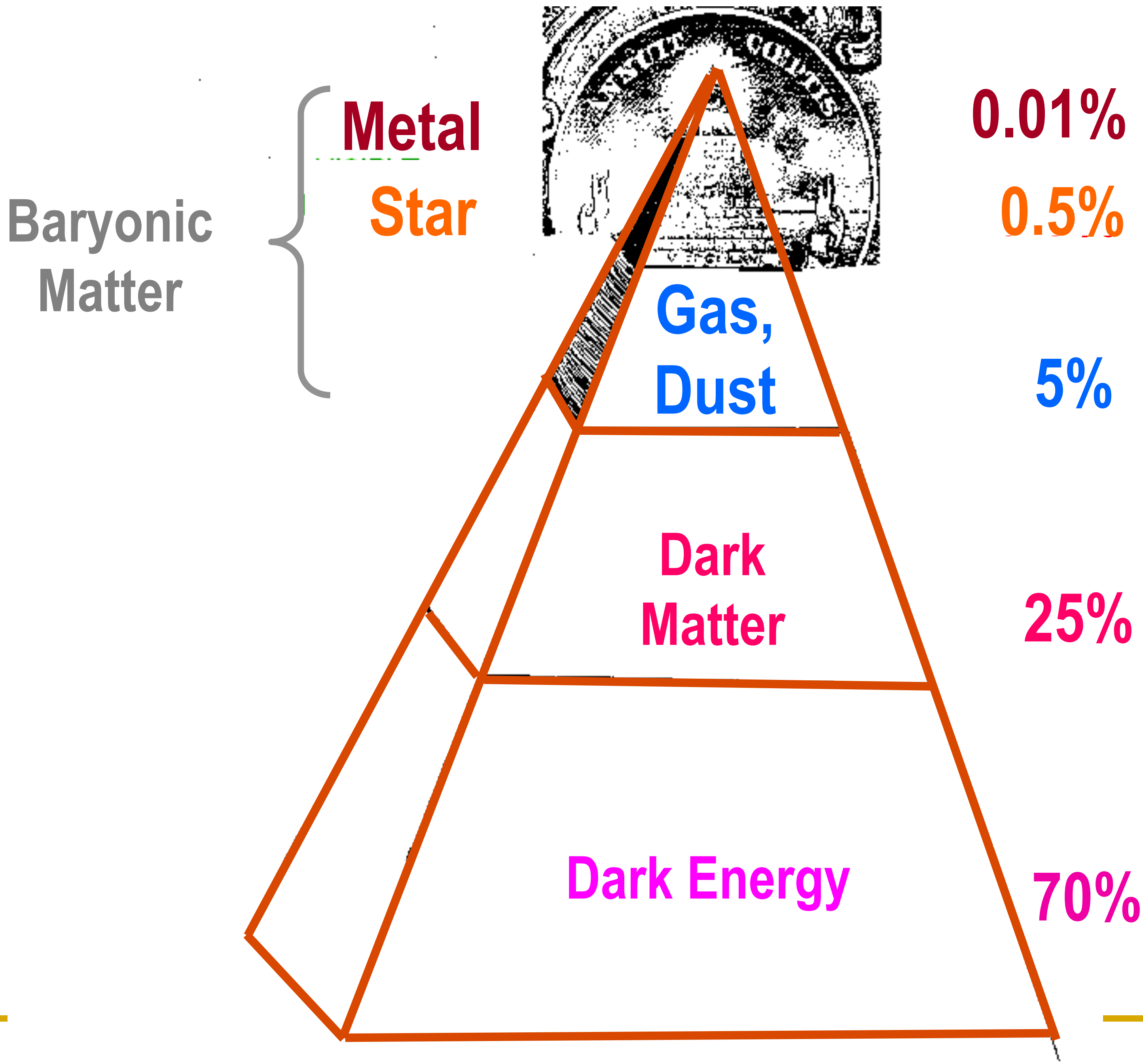
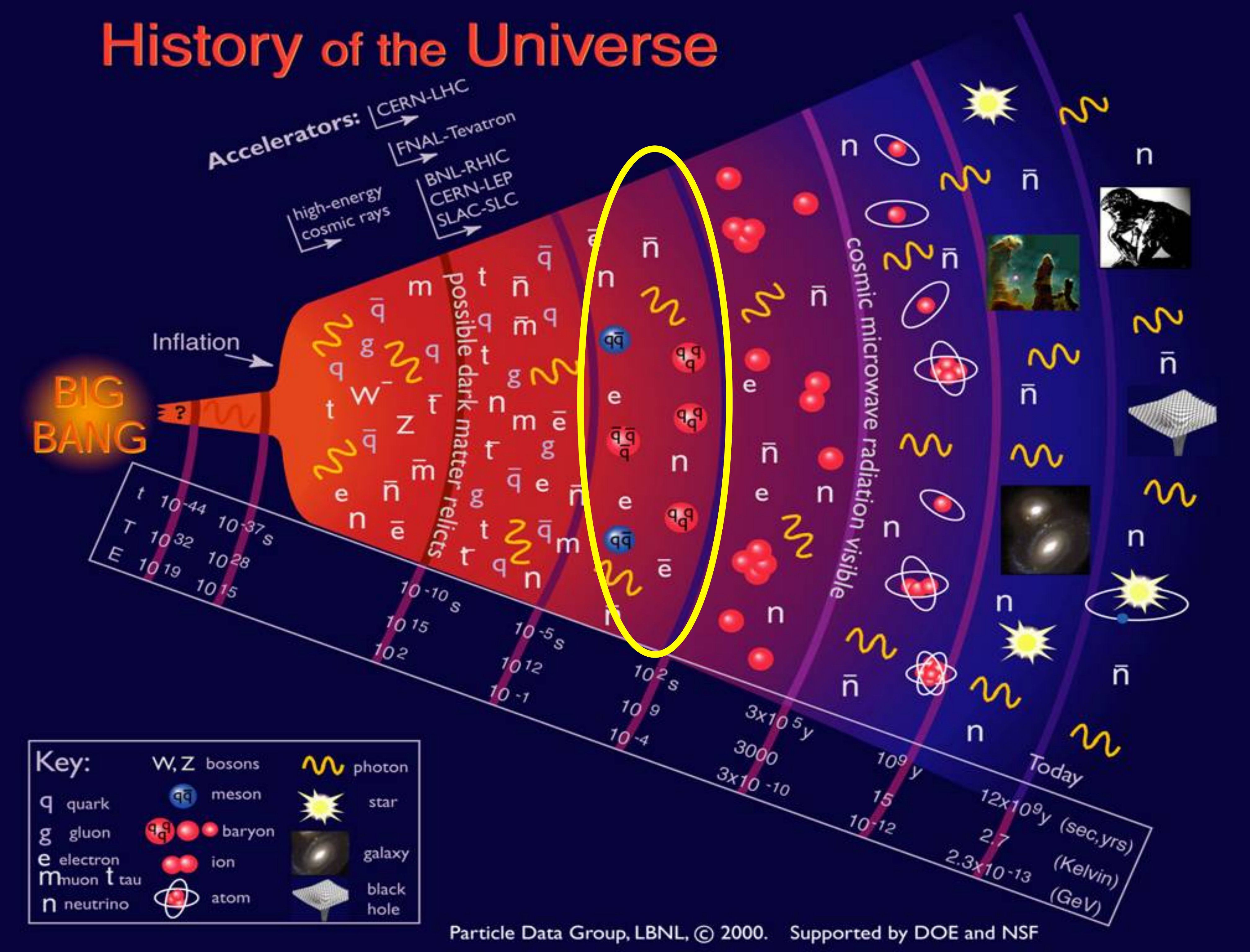


Cosmic Pyramid



Evolution of the Universe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n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

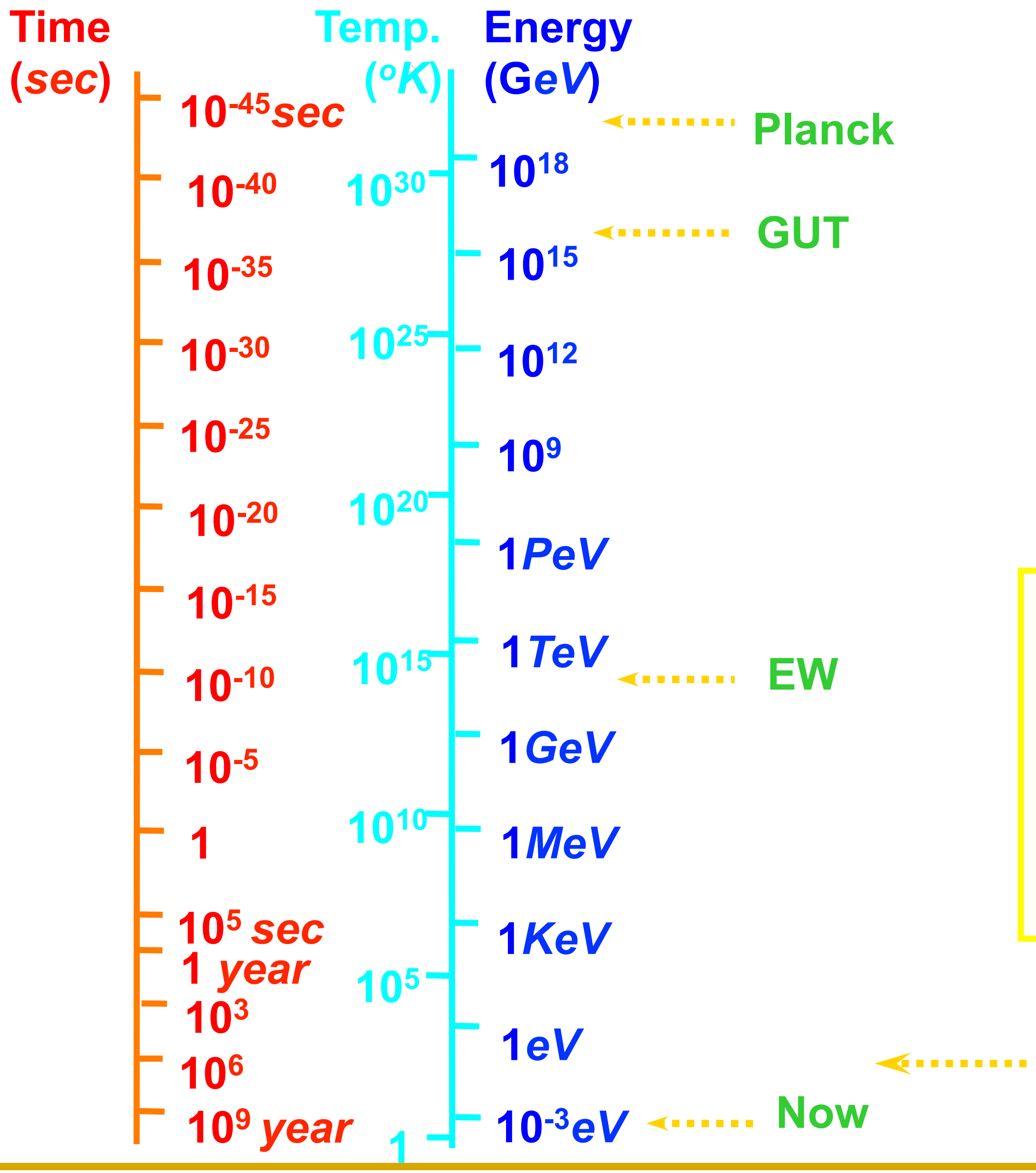
Time = 300,000 years , Temp.= 3000 ºK

- 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)

Cosmic Microwave Background (CMB)
Matter-Radiation Decoupling



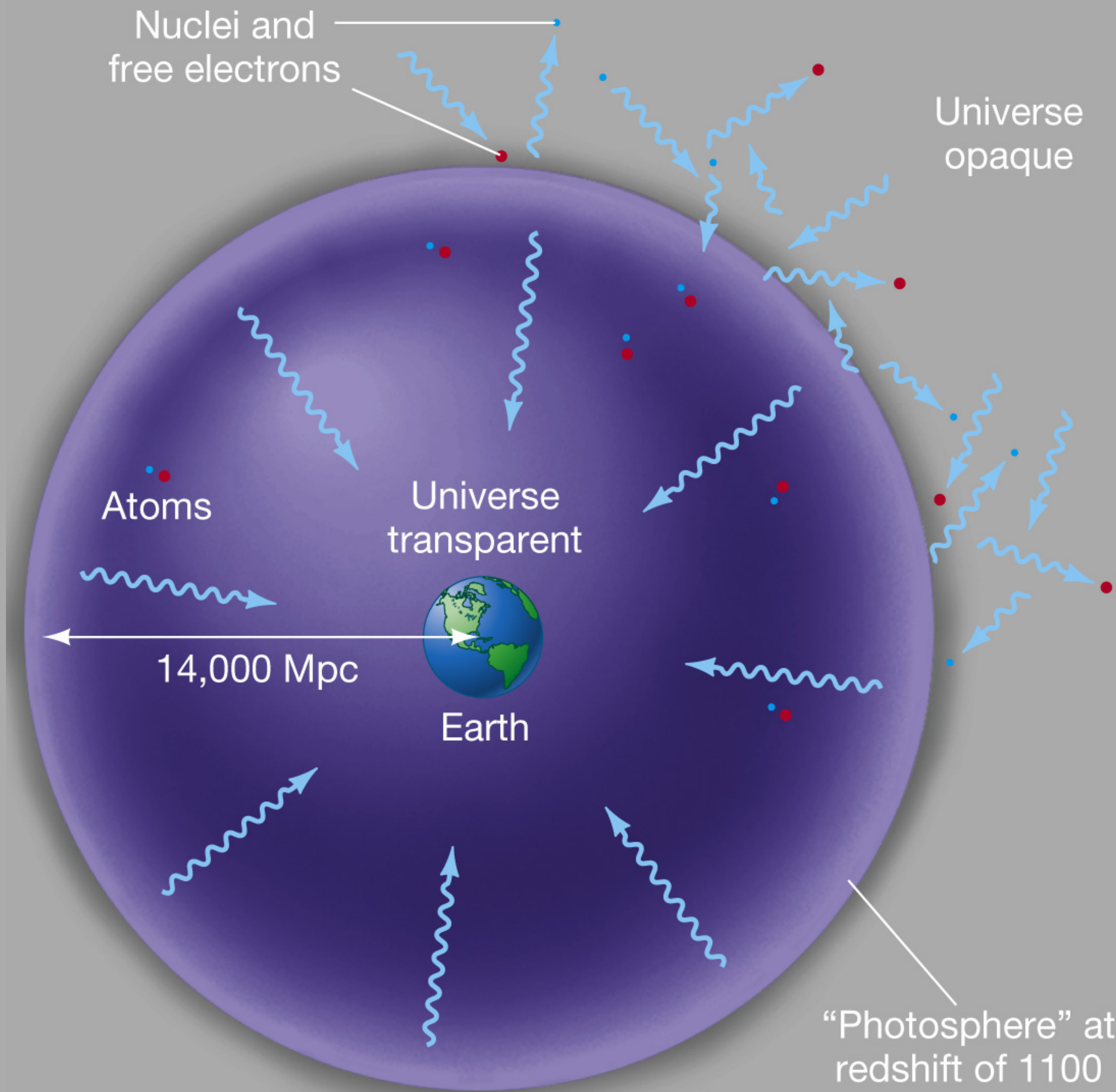
Time = 300,000 *years*

Temperature = 3,000 *°K*

Energy = 0.3 *eV*

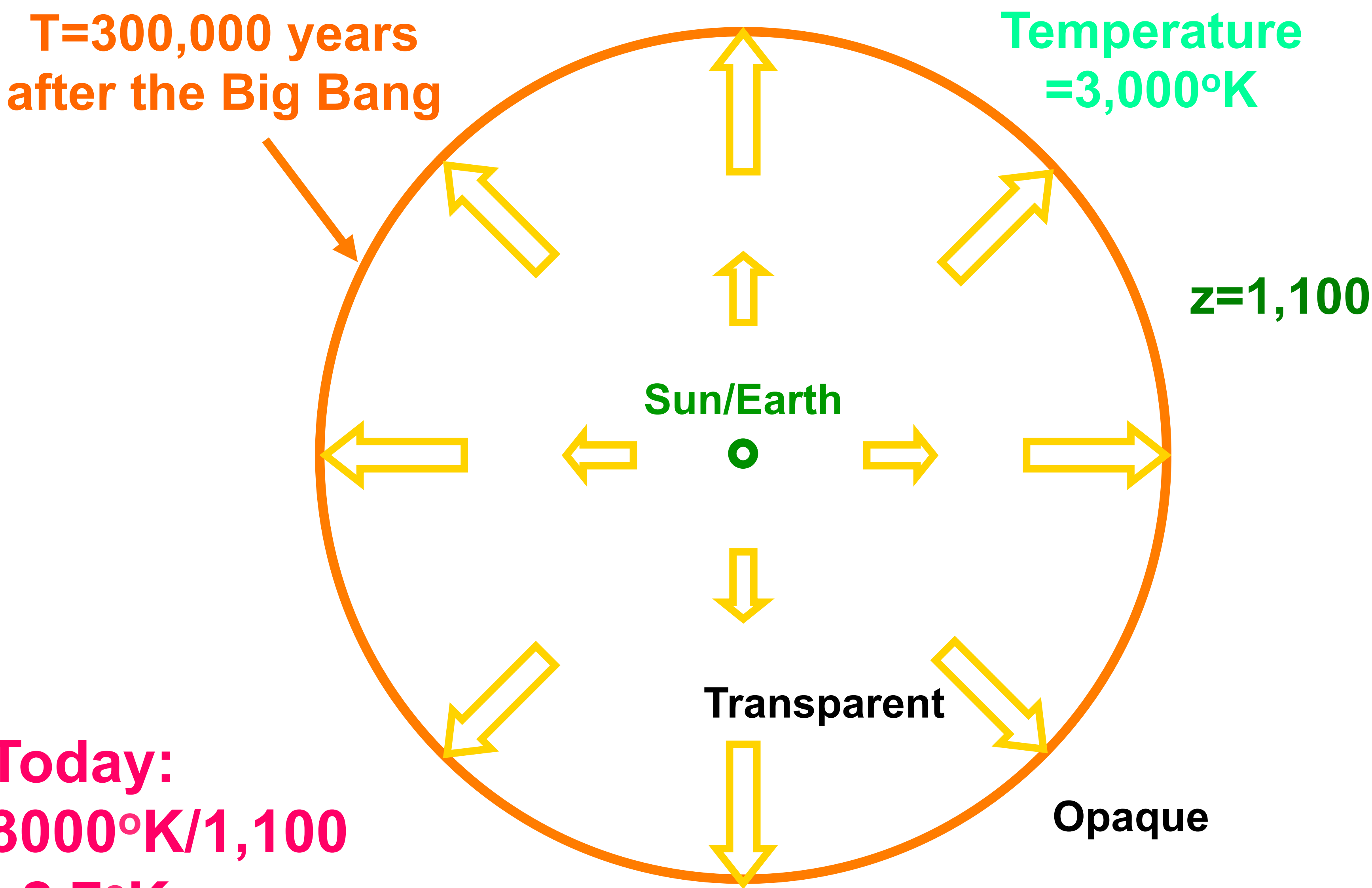
Z = 1,100

Matter-Radiation Decoupling $\Rightarrow$ ***CMB***



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

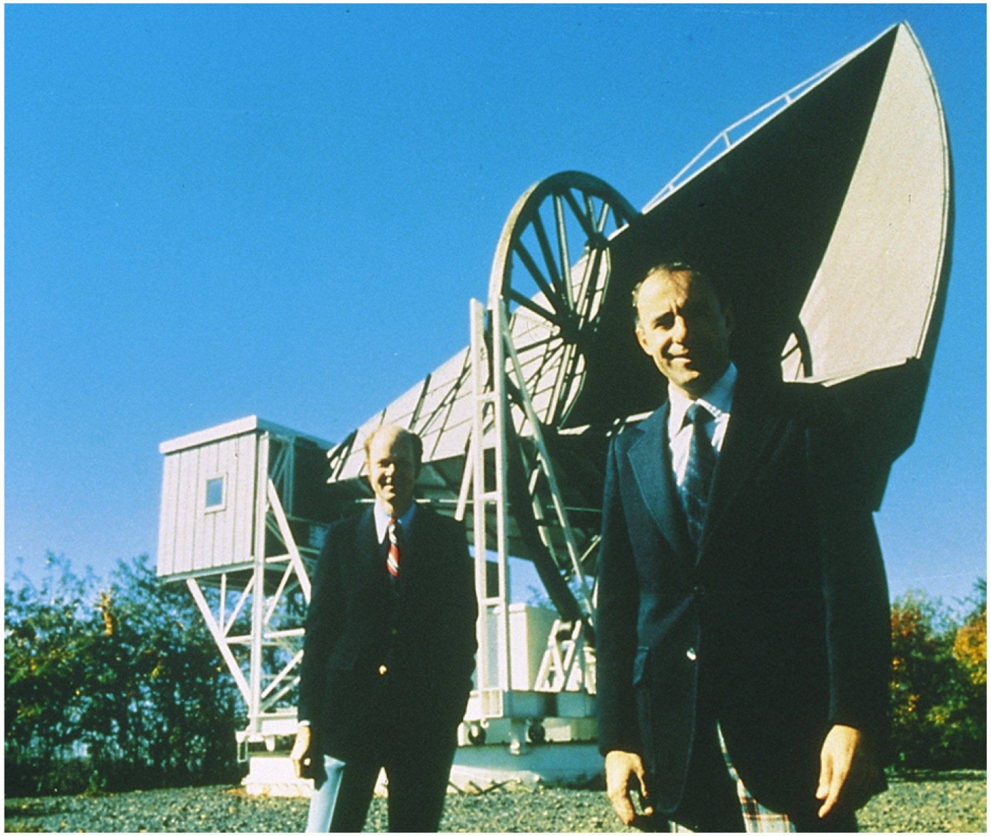
Cosmic Microwave Background
(Discovered in 1964)



Today:
3000ºK/1,100
=2.7ºK

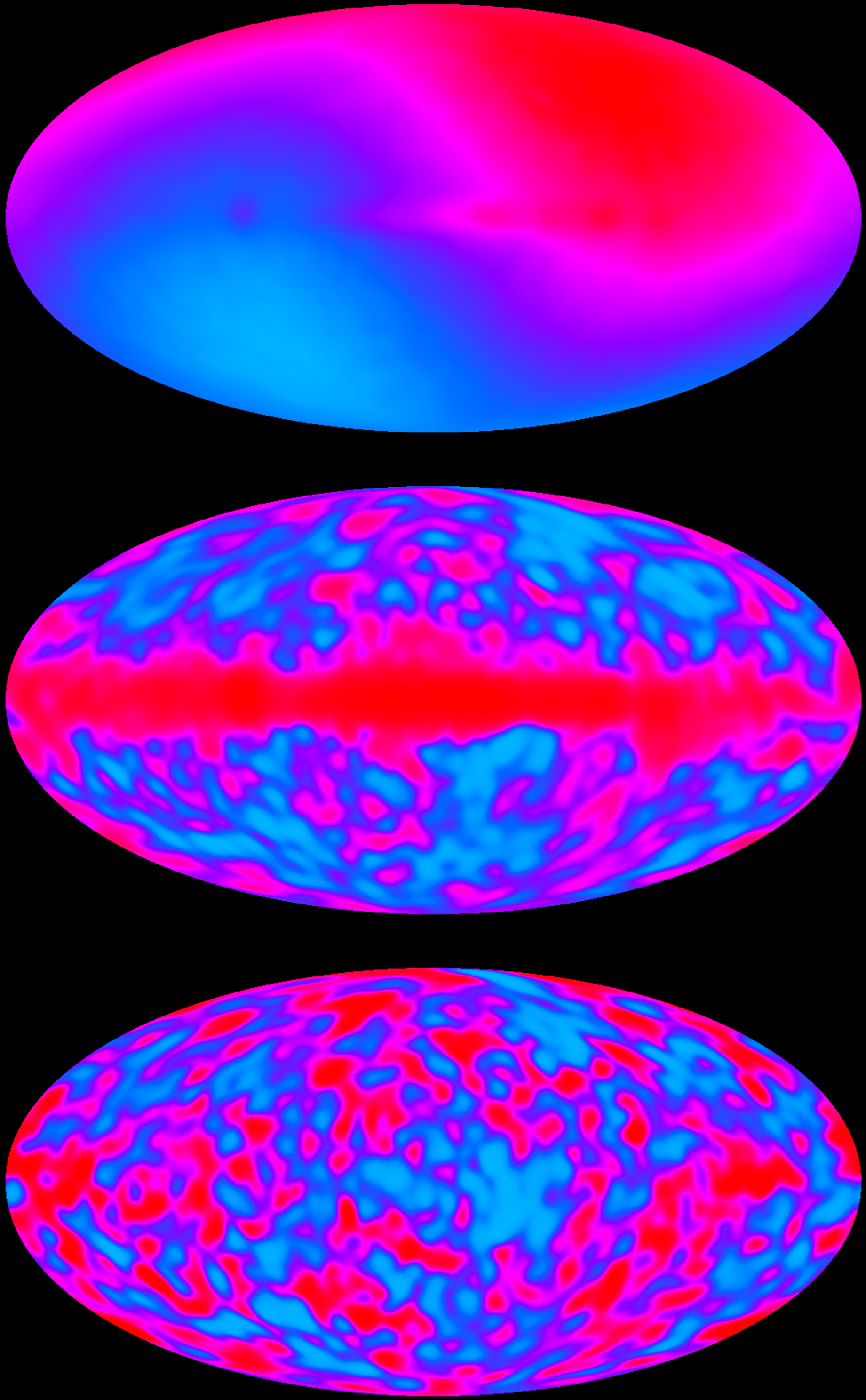
The Cosmic Microwave Background

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.



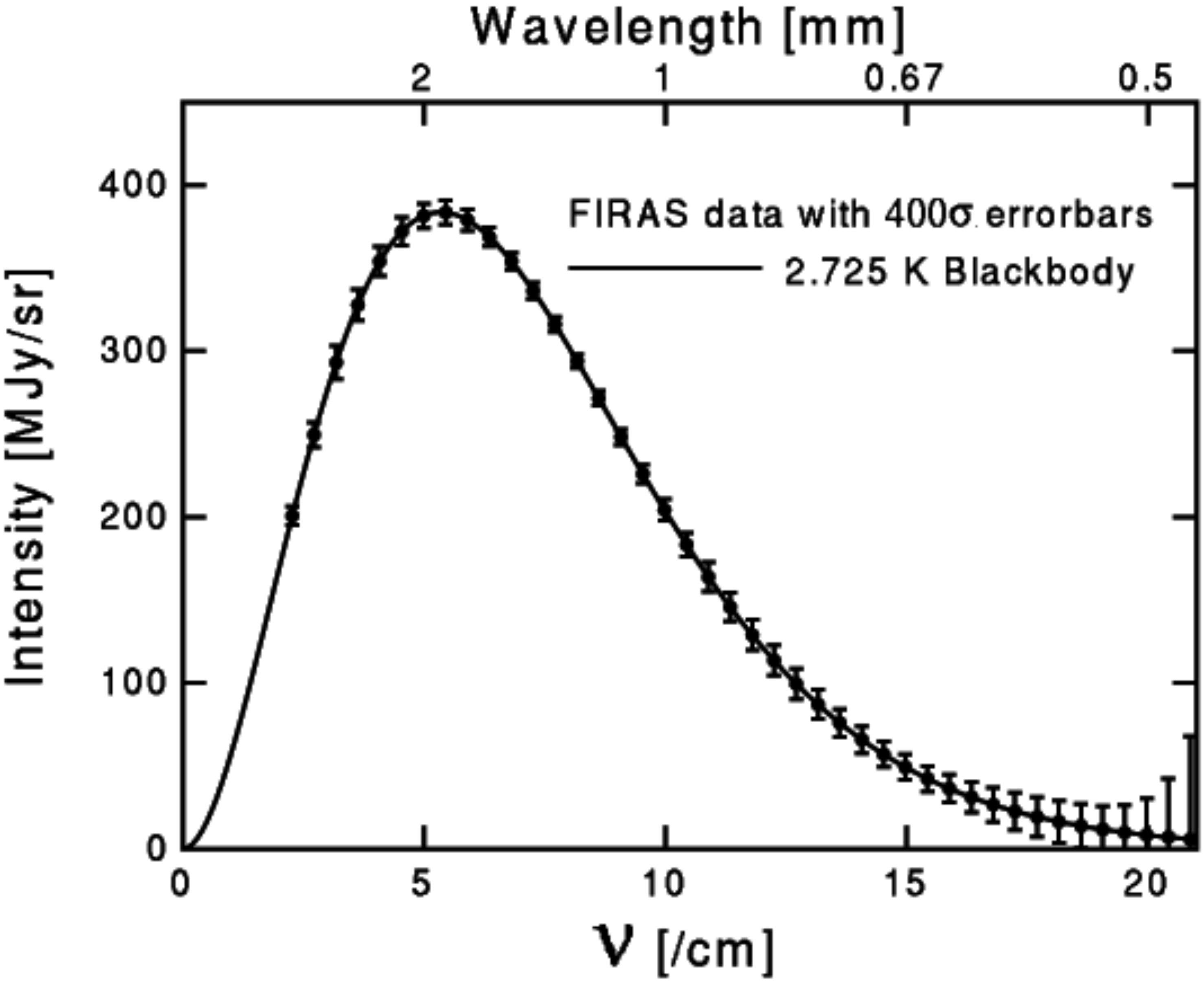
Instead they found that the "noise" came from all directions and at all times, and was always the same. They were detecting **photons** left over from the **Big Bang**.

COBE Results

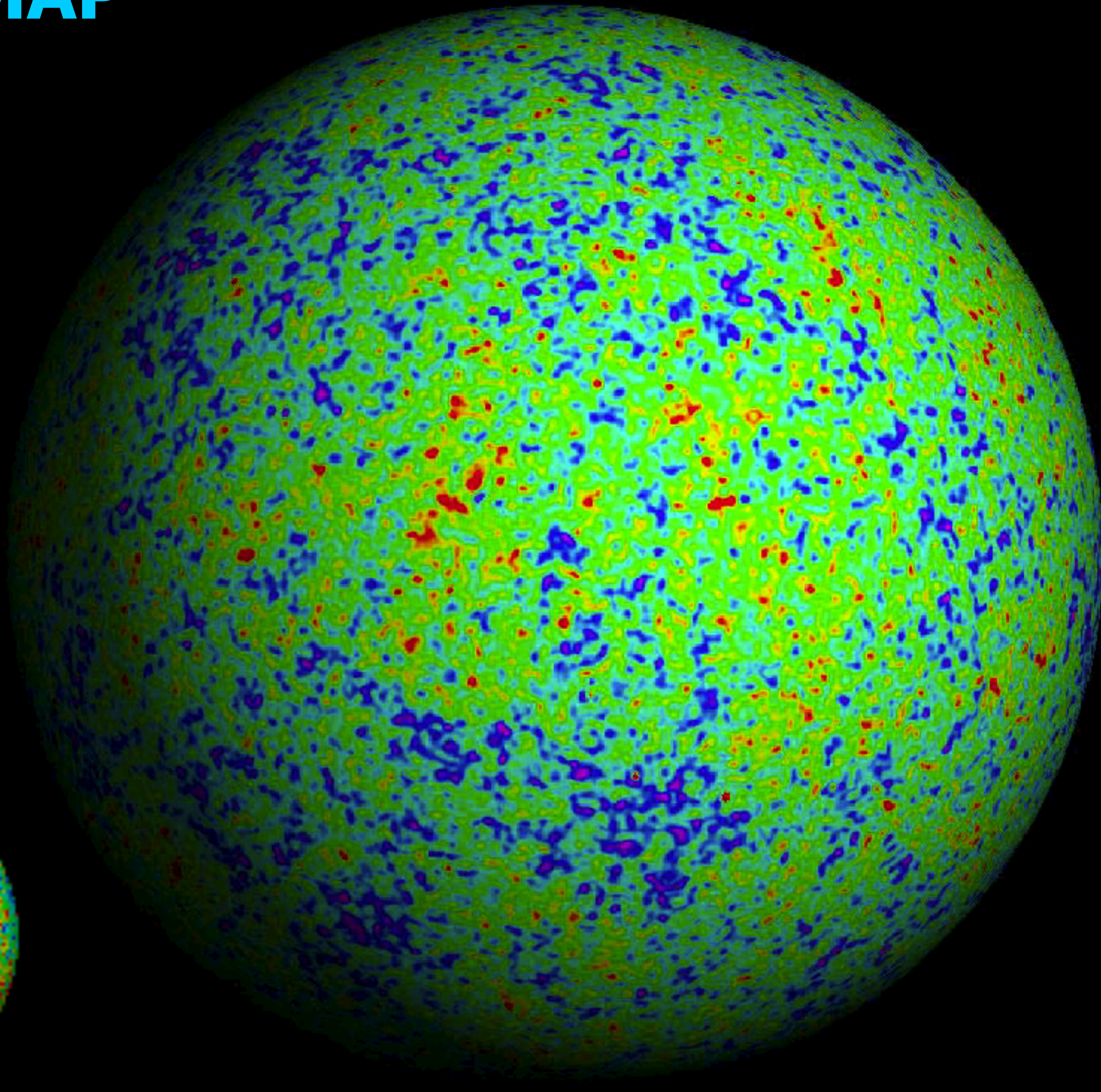


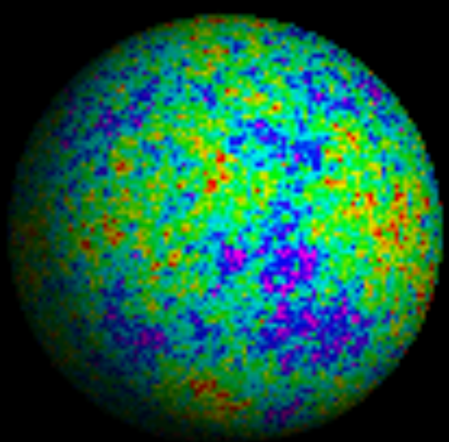
launched November 18, 1989

The CMB Spectrum by FIRAS



WMAP



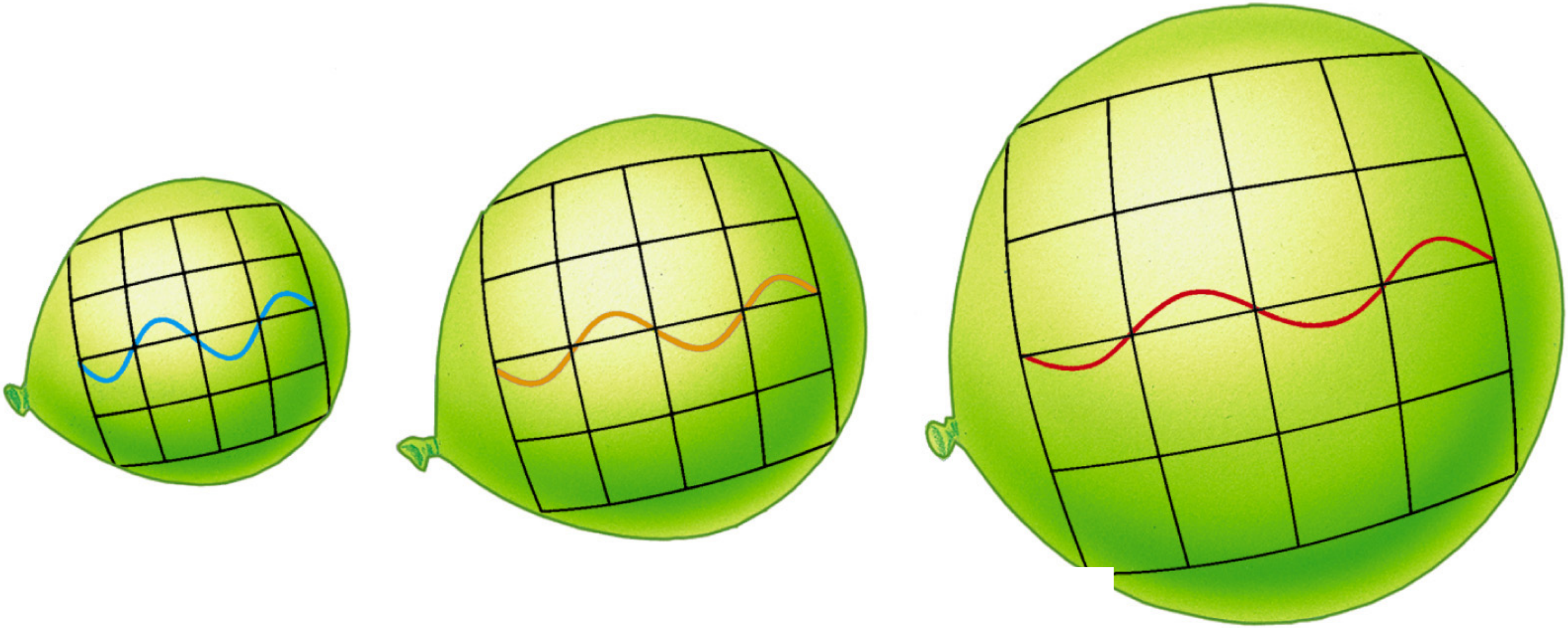


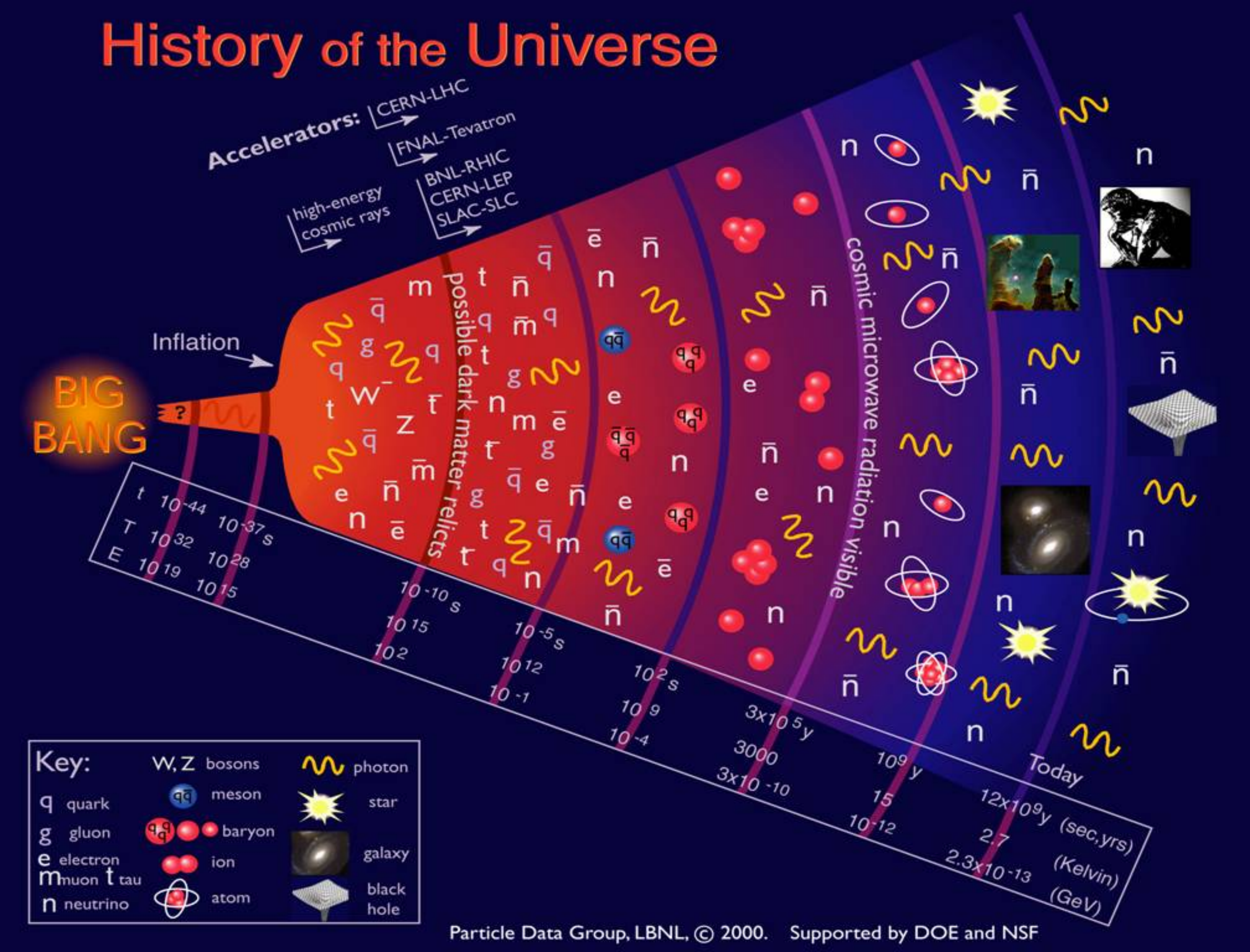
.P map from Tegmark, de Oliveira-Costa & Hamilton, astro-ph/0302496

Cosmological Redshift

T = 300,000 years
3000°K

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

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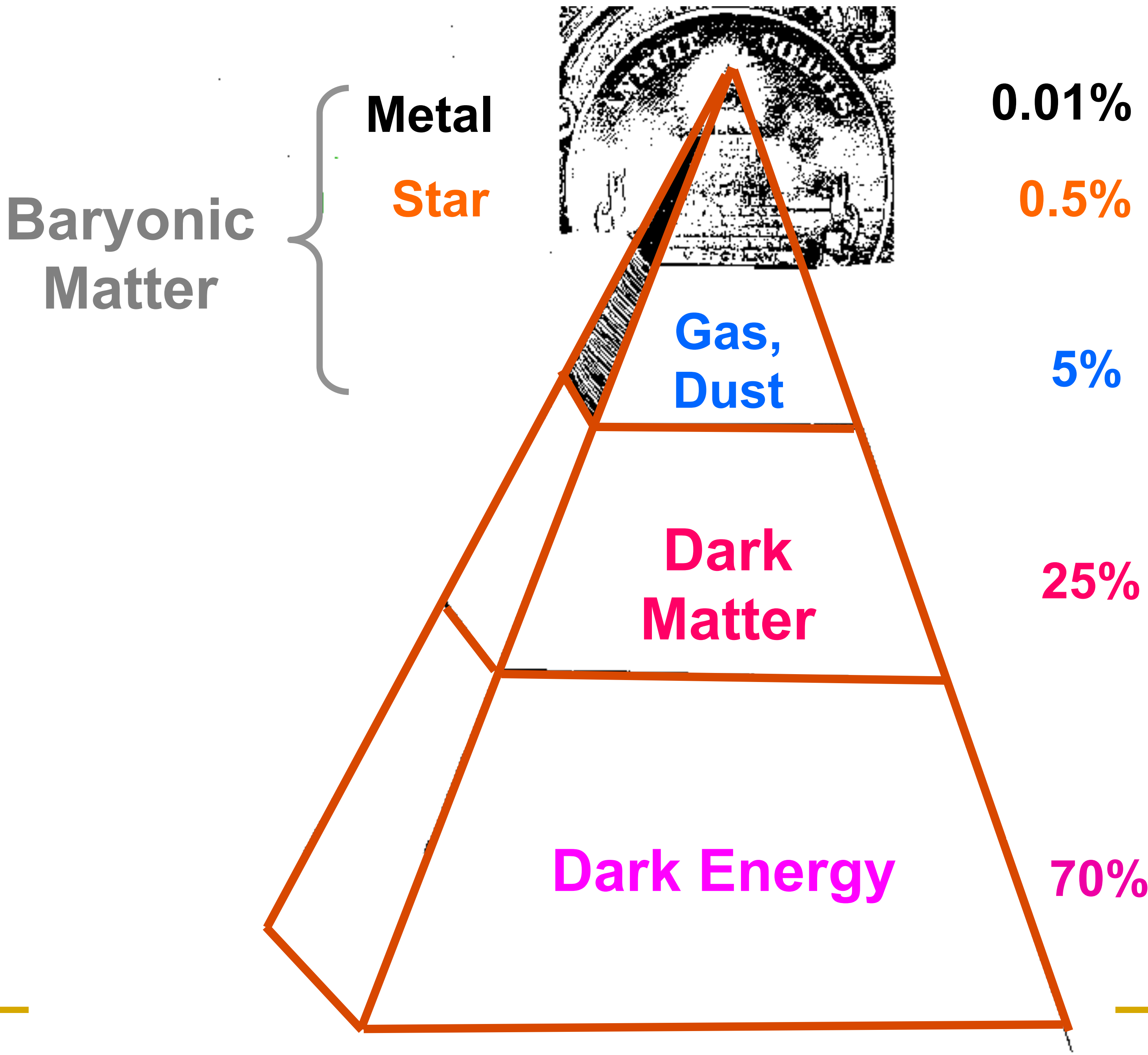
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Structure Formation of the Universe

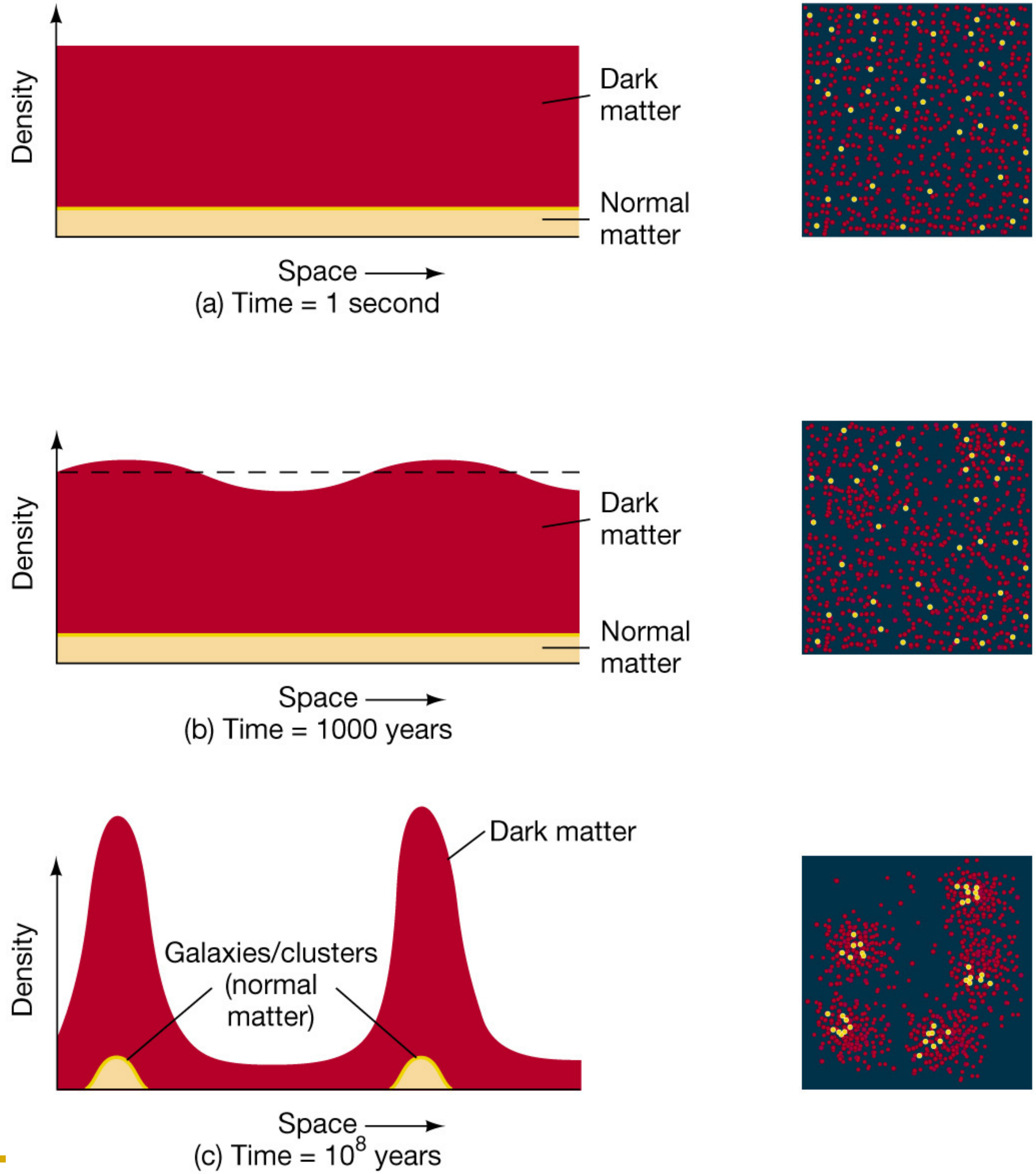
Time = 1B yrs, Temp.= 10 °K

- **Galaxies formed.**
  - **Size ~ 16% of today**
  - **The furthest place we can observe by telescopes.**
  - **At least Quasers (~ Active Galacic Nuclei) were already formed.**

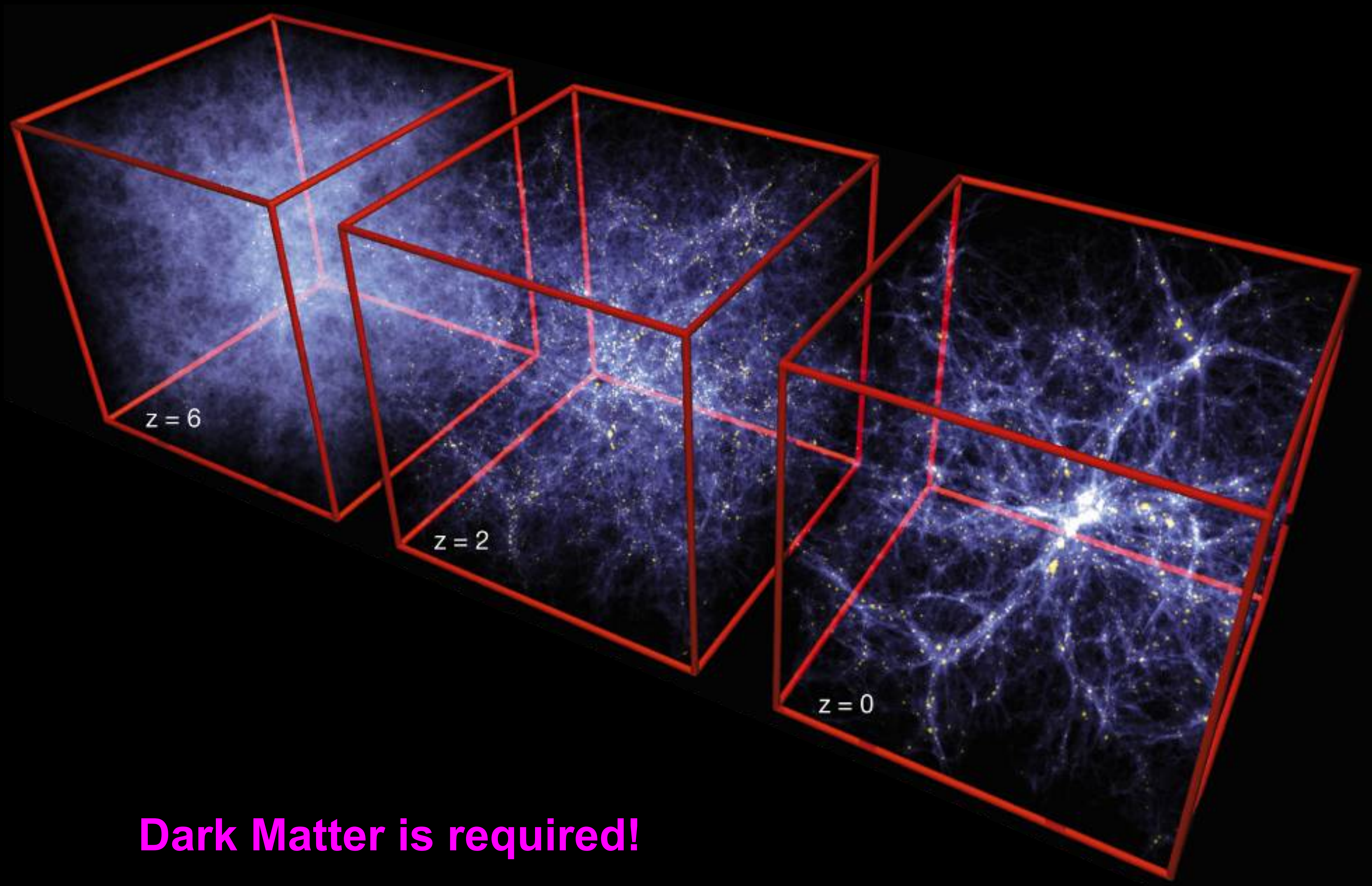
Cosmic Pyramid



Formation of Structure by Dark Matter

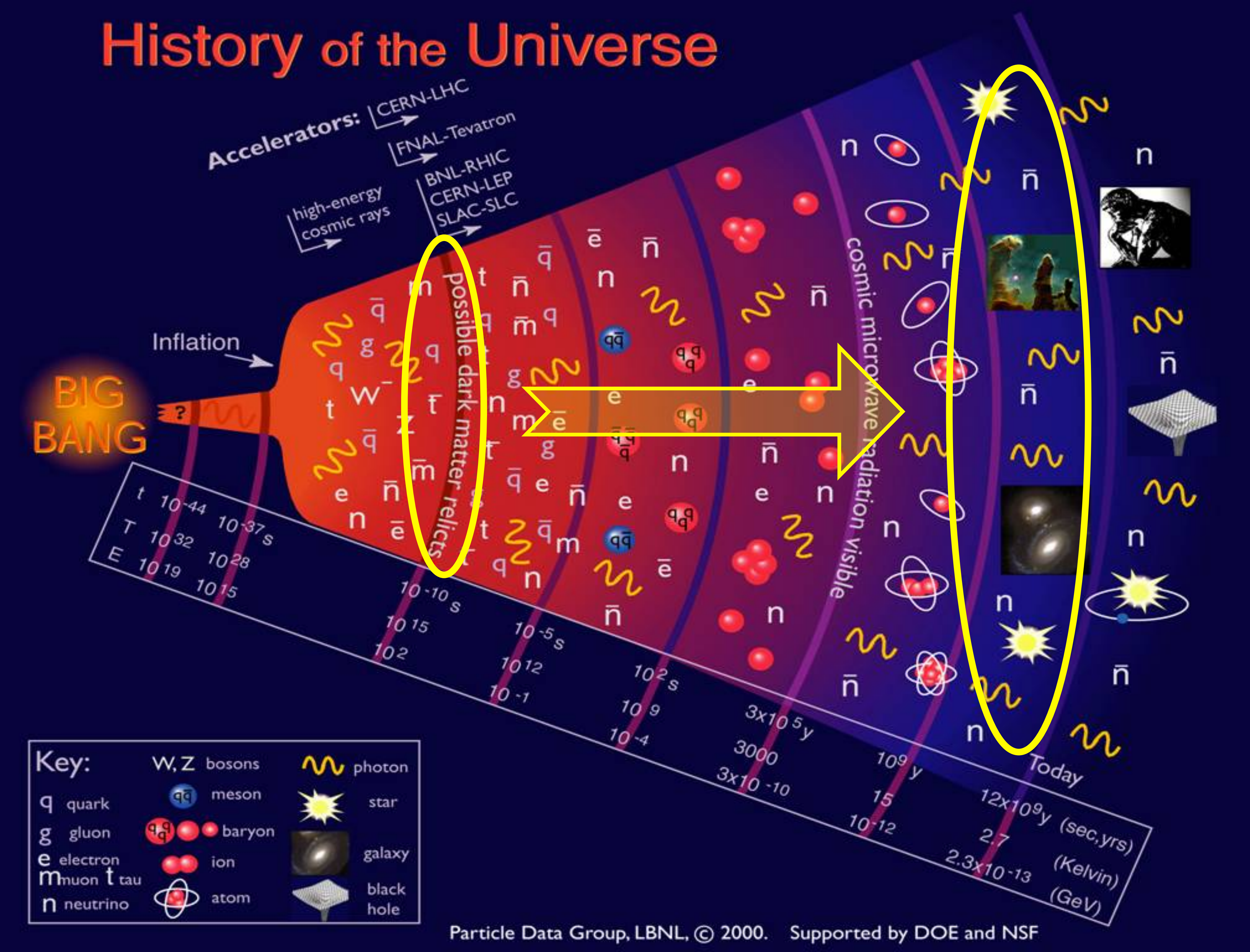


Formation of Structure in the Universe



Dark Matter is required!


Dark Matter is required!
ANDROMEDA
GALAXY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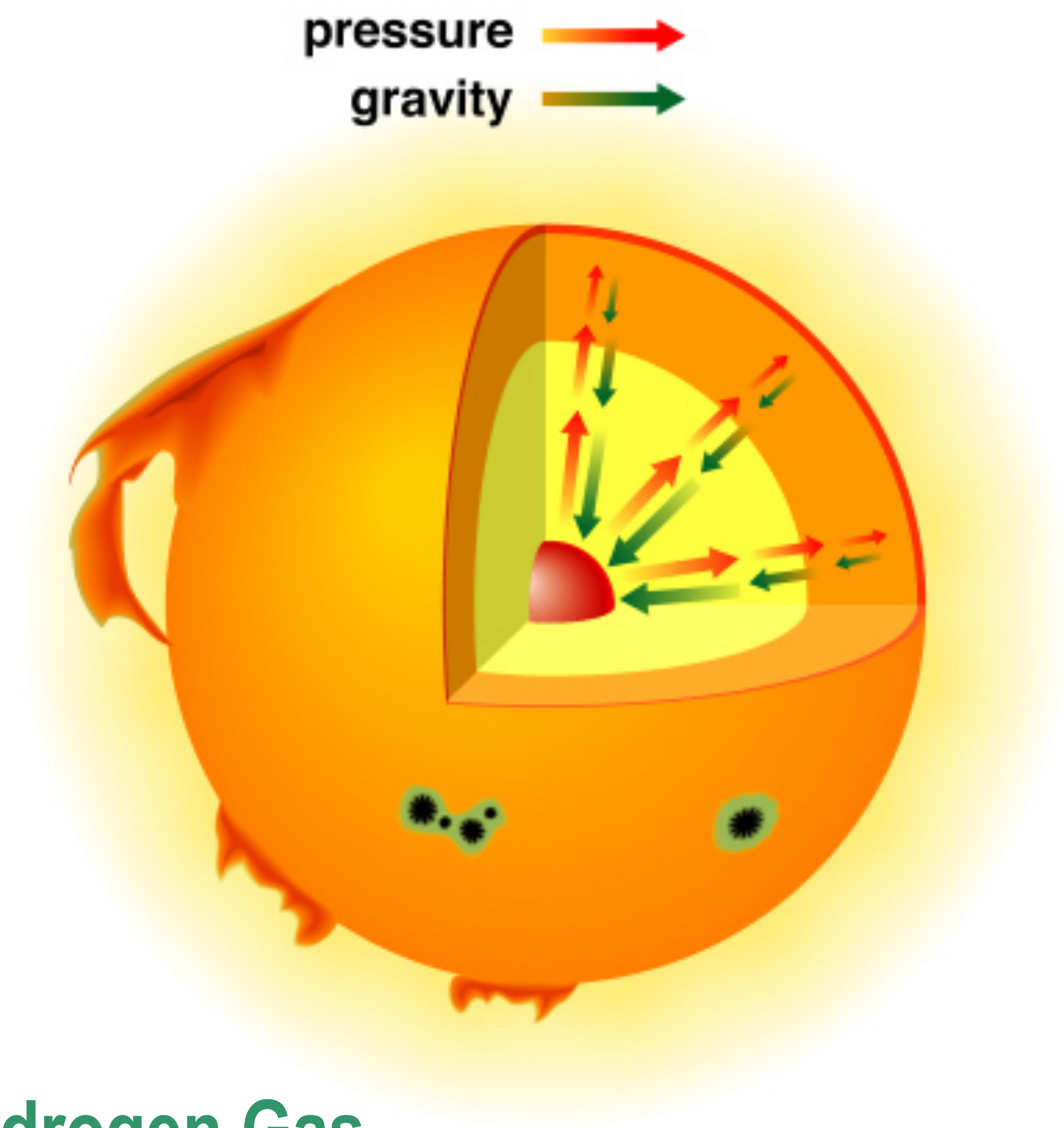
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

The Solar Interior

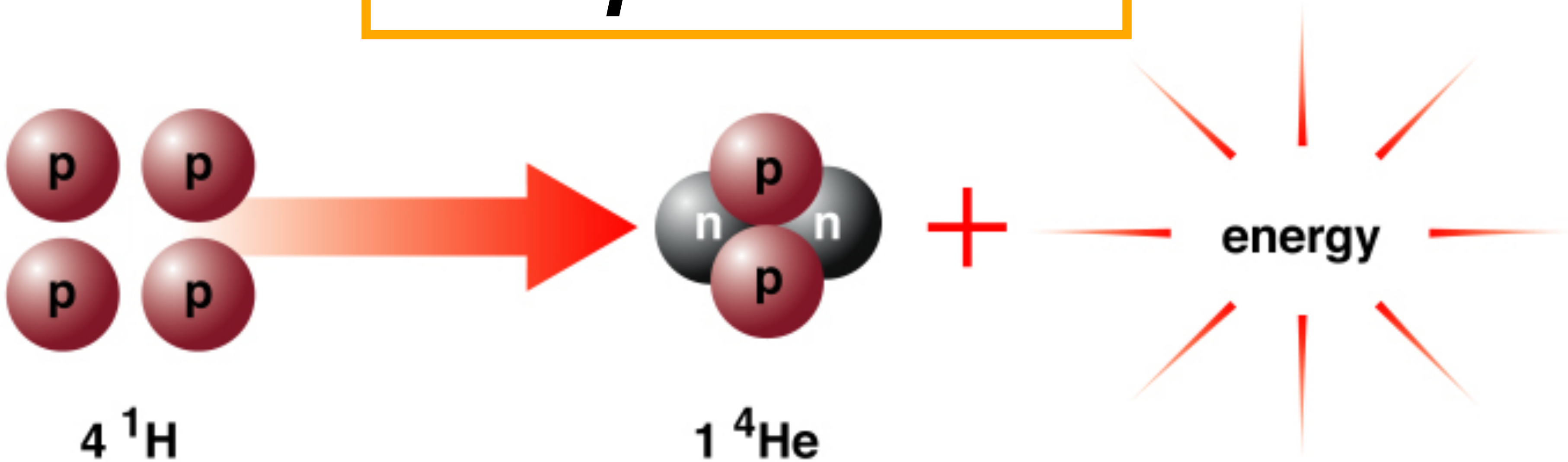


Hydrogen Gas

Solar Energy

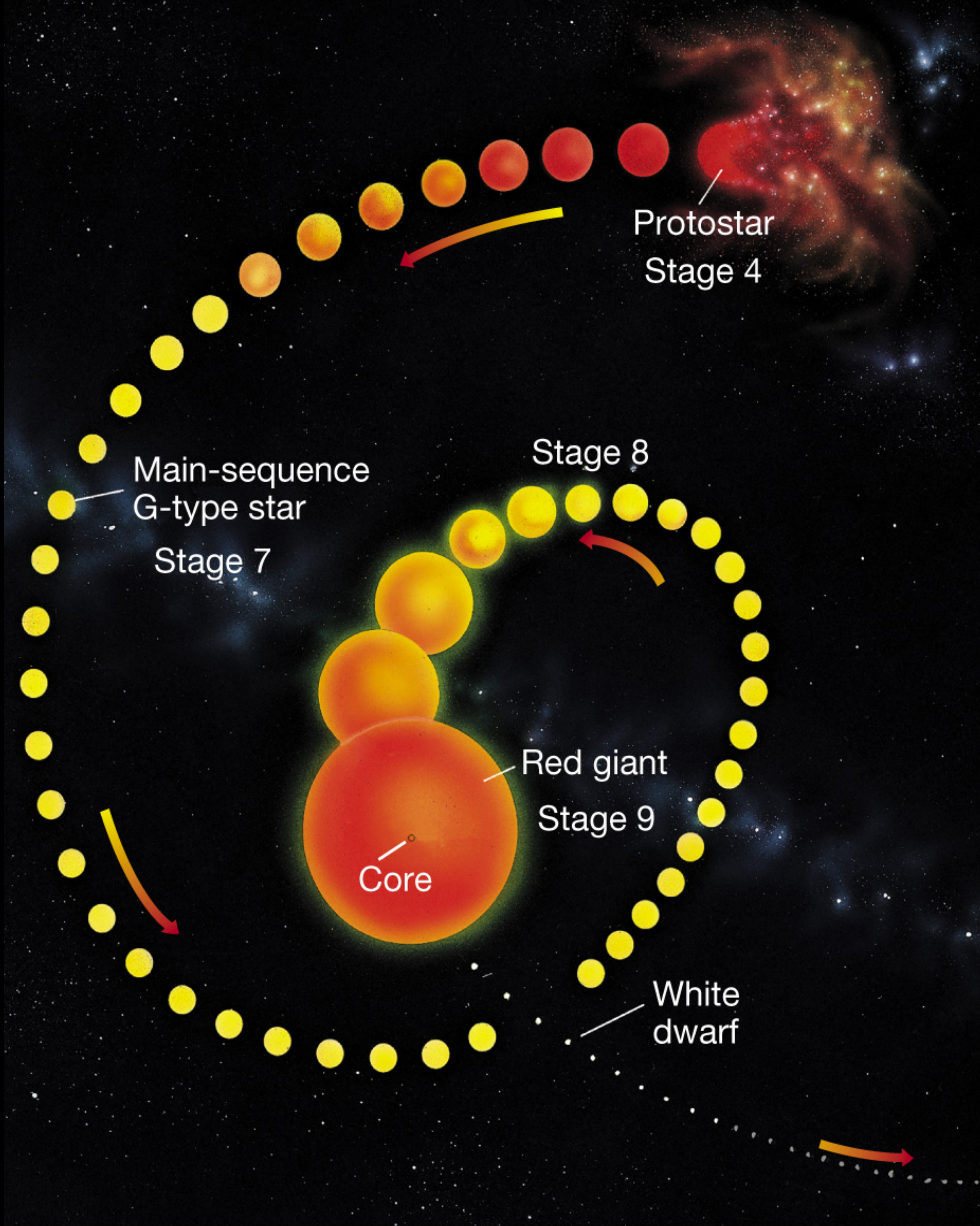
$$E = mC^2$$

$$m_{4p} > m_{He}$$

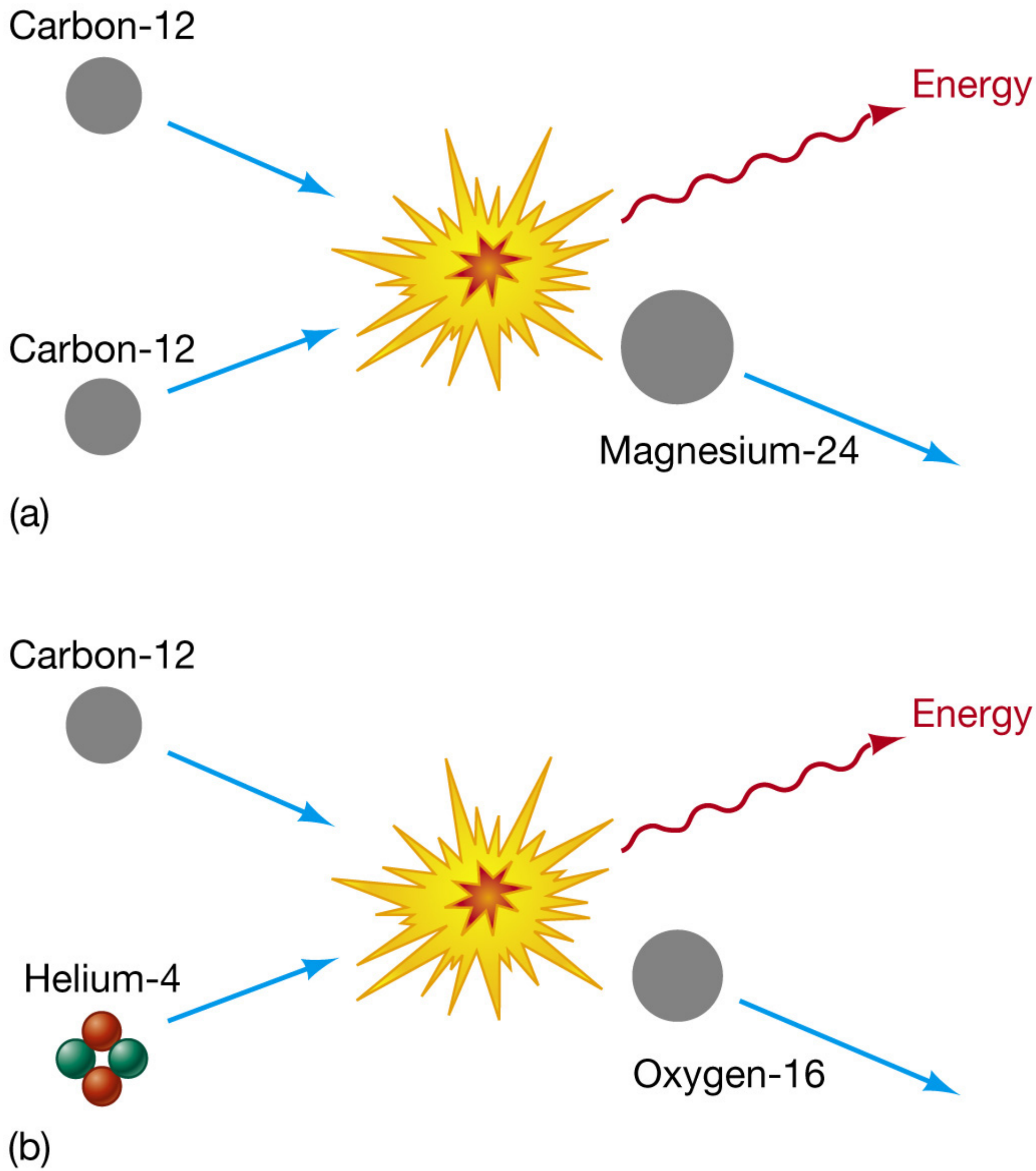


4 ^{1}H 1 ^{4}He

ε = = 0.007


Protostar
Stage 4
Main-sequence
G-type star
Stage 7
Stage 8
Red giant
Stage 9
Core
White
dwarf

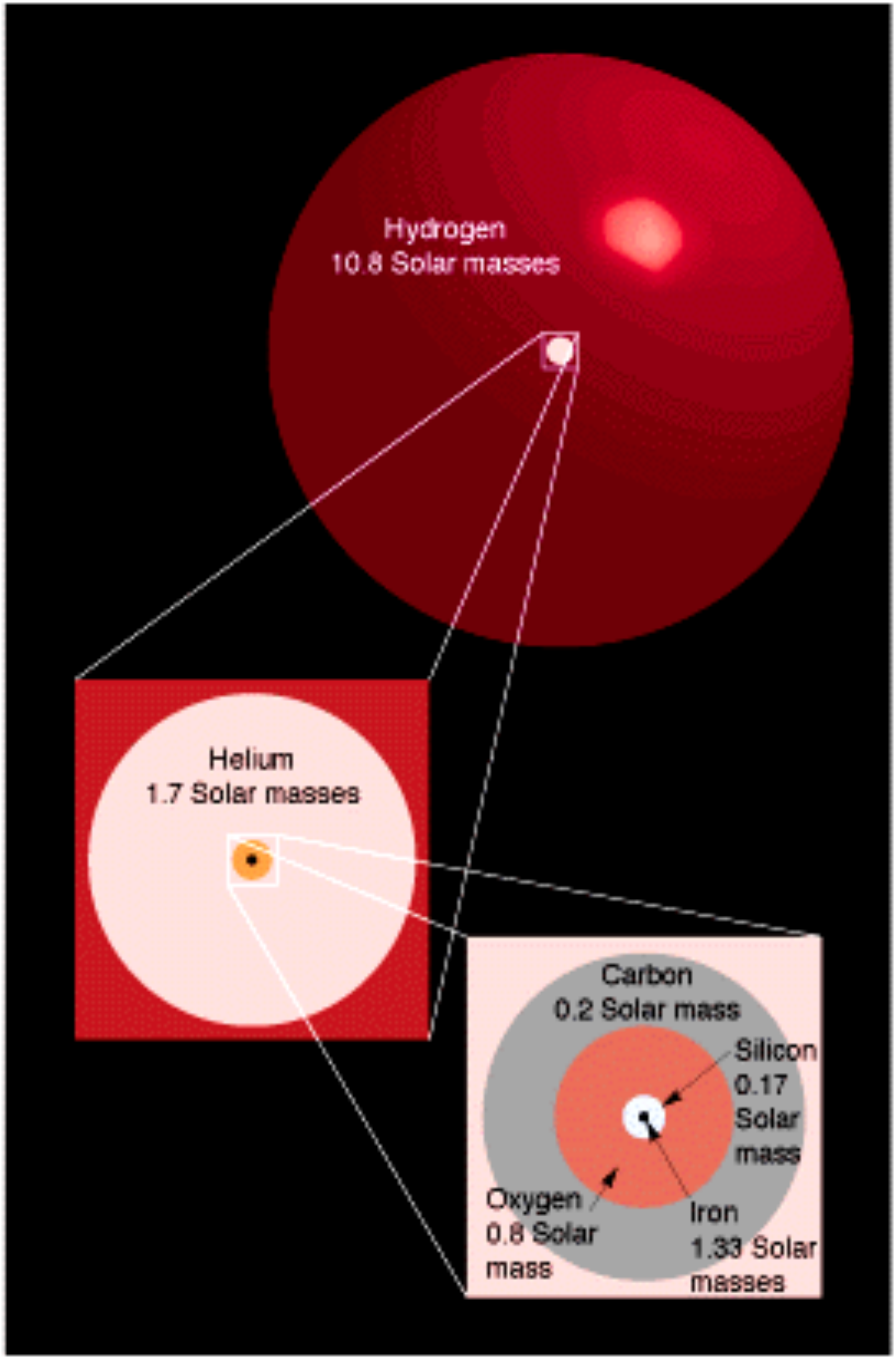
The Formation of the Elements



Nuclear Burning in High Mass Stars

(times for a 20 M_o star)

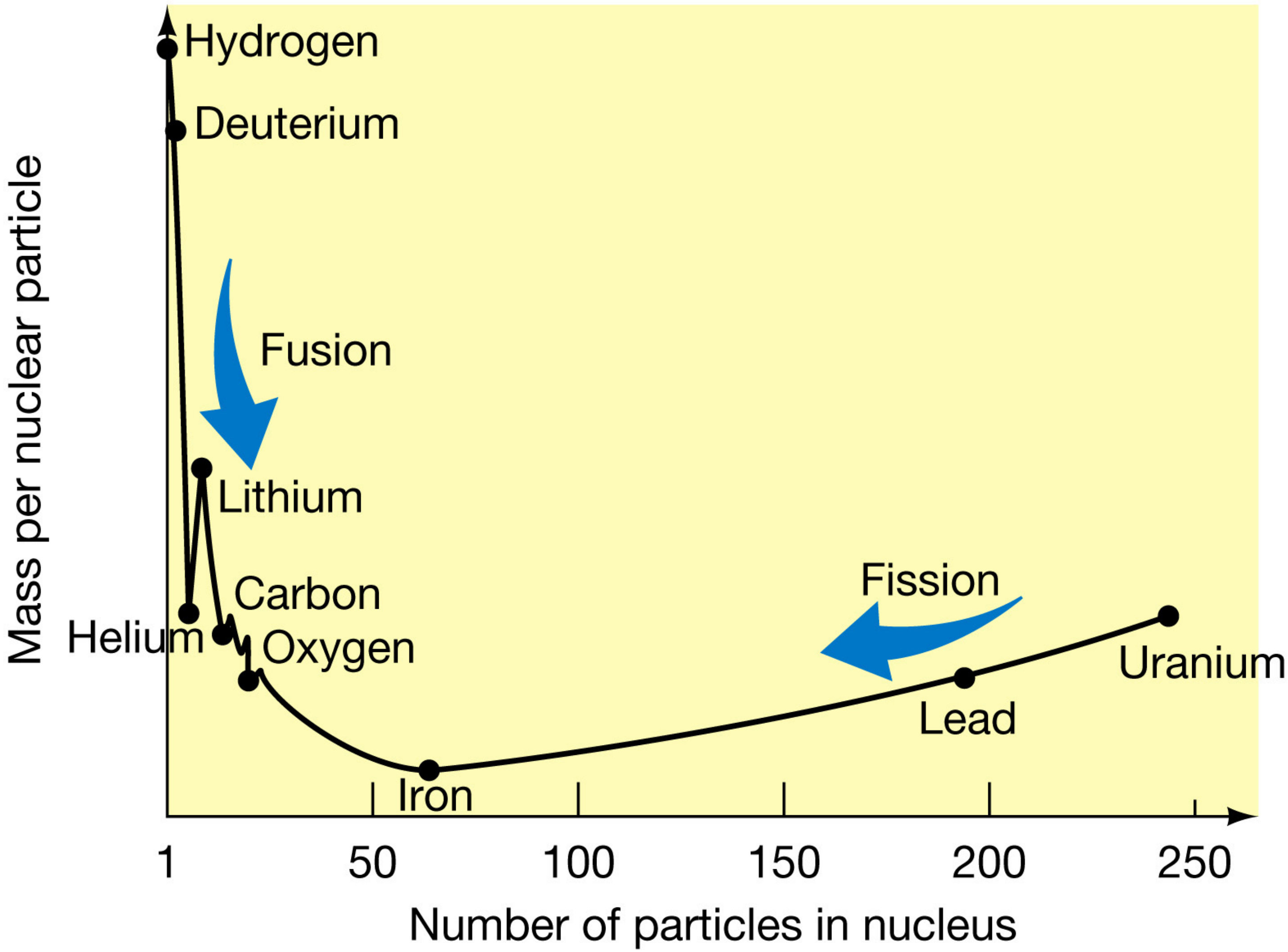
Hydrogen	*10^7 yr*
Helium	*10^6 yr*
Carbon	*10^3 yr*
Oxygen	*1 yr*
Neon	
Magnesium	
Silicon	*1 week*
Iron	*< 1 day*



The End of a High-Mass Star

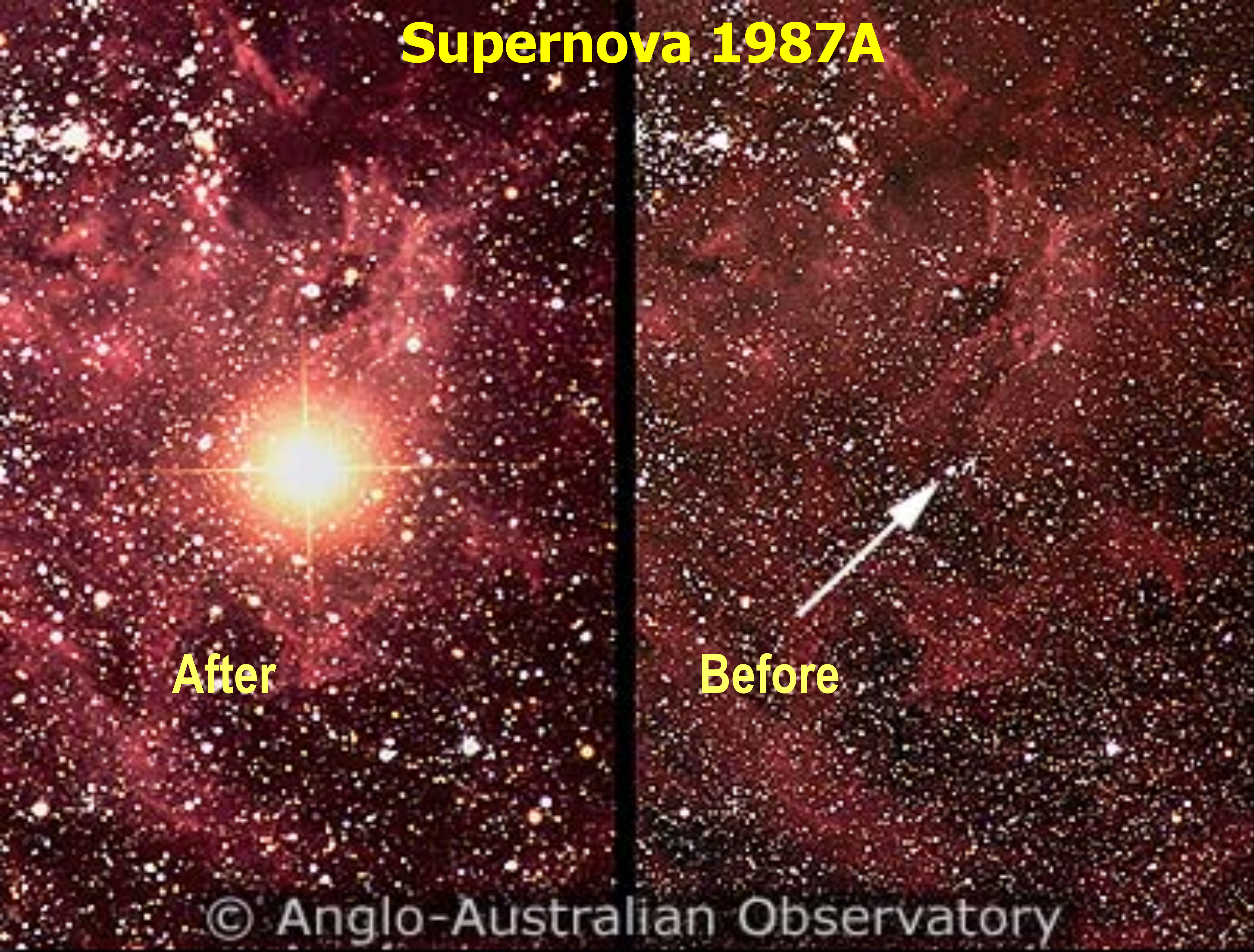
This graph shows the relative **stability** of nuclei. On the left, nuclei gain energy through **fusion**; on the right they gain it through **fission**.

Iron is the crossing point; when the core has fused to iron, no more fusion can take place.



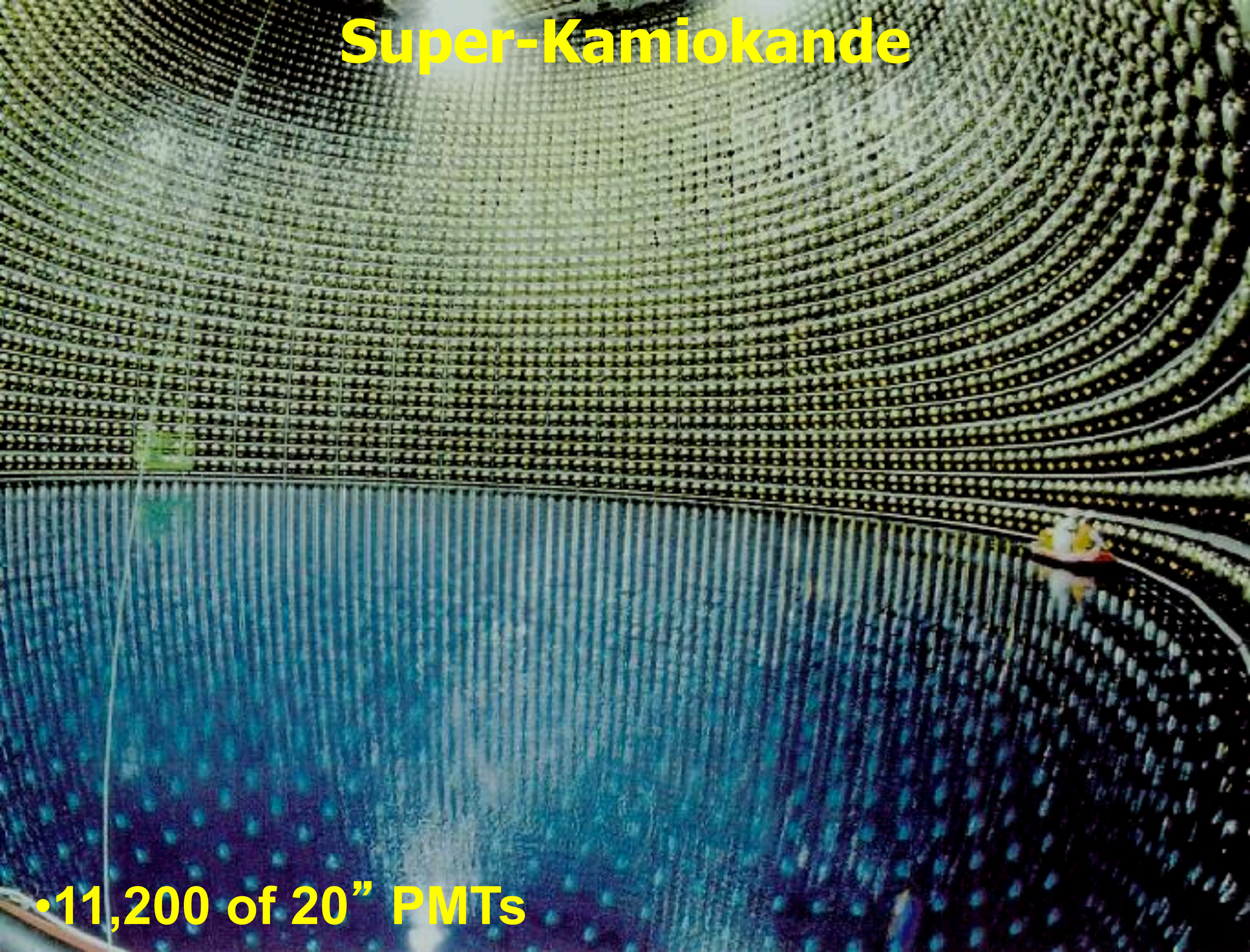
Power of Super Novae

- Within a few hours
  - one billion times solar luminosity
- Within a few months
  - ~ same as the Sun's total energy during 10 billion years of life
- Not only that, > 99.99 % of energy is released by neutrino within ~ 10 seconds.
  - First observed in 1987 by Kamiokande experiment in Japan.



Supernova 1987A
After
Before
© Anglo-Australian Observatory

Super-Kamiokande



- 11,200 of 20" PMTs

Nobel Prize in 2002

The Nobel Prize in Physics 2002

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"

Raymond Davis Jr.

Masatoshi Koshiba

Riccardo Giacconi

End Results of Stars

Initial Mass	End Results		
< 8 M ☺	White Dwarf		< 1.4 M ☺
8 – 20 M ☺	Type II Supernova	Neutron Star	1.4 – 3 M ☺
> 20 M ☺		Black Hole	> 3 M ☺

Pauli's Exclusion Principle

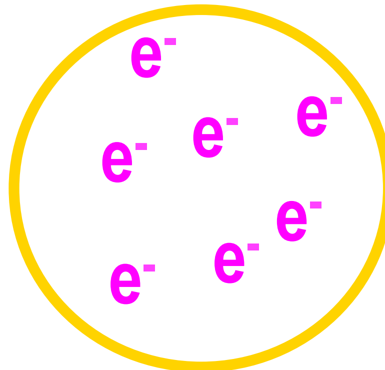
- **Fermi Statistics:**
  - According to quantum mechanics, each state is occupied by one particle (Fermion). Another particle can not stay in the same state.

⇩

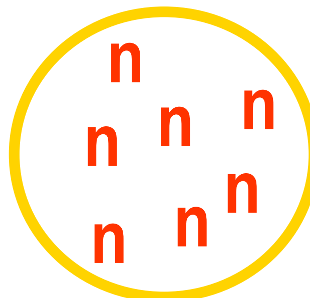
- **Degenerate matter:**
  - All possible states are occupied.

Degenerate Matter

- **White Dwarf (< 1.4 M☺)**
  - Carbon Core
  - Electrons are tightly packed



- **Neutron Star (1.4 M☺ – 3 M☺)**
  - Neutrons are tightly packed



- **Black Hole (> 3 M☺)**
  - Gravity wins

Origin of Elements

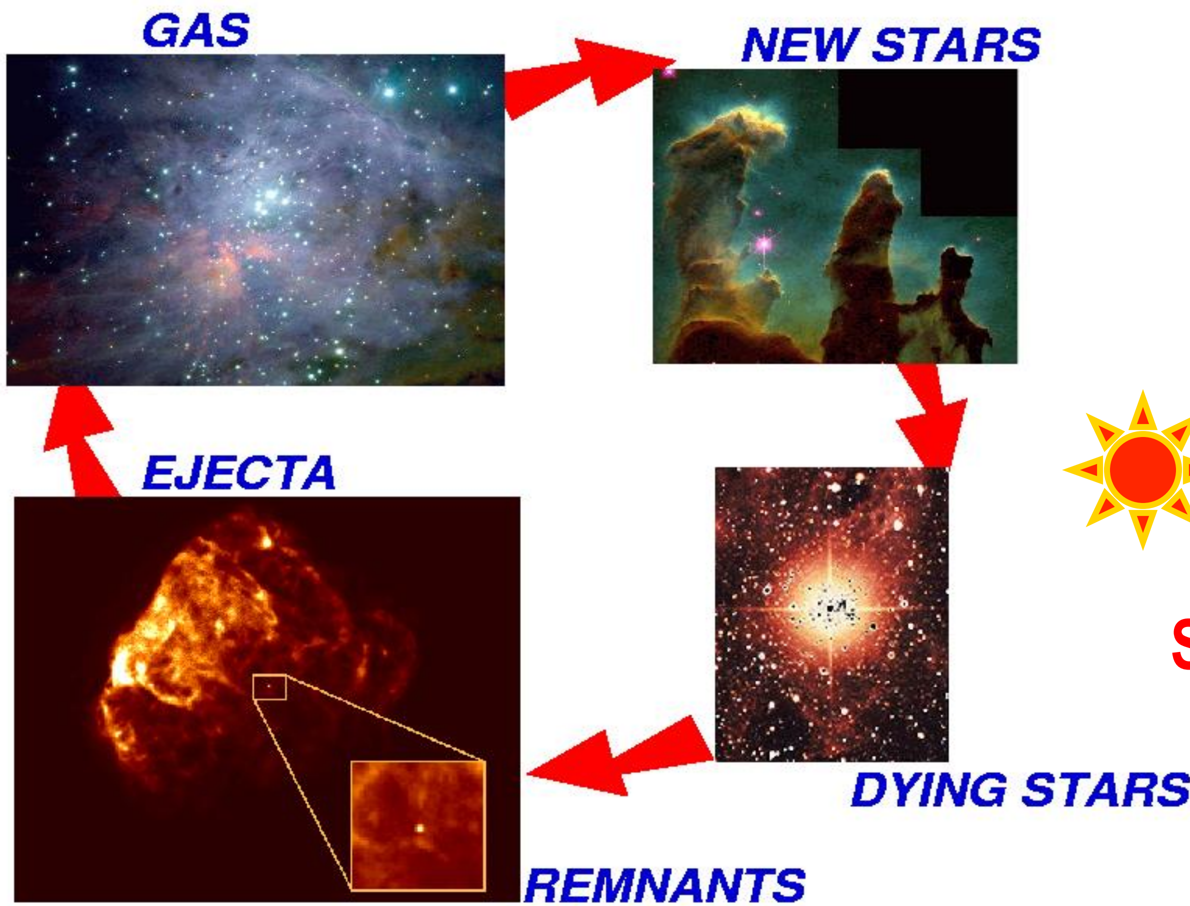
- **Hydrogen, Helium**
  - From "Big Bang"
- **Carbon – Oxygen – Iron**
  - From "Nuclear fusion" at massive stars (> 8 M_{sun})
- **Heavier than Iron (Cu, Au, Pt, Pb…)**
  - From "Supernovae"

Origin of Life

We are made from "stardust"

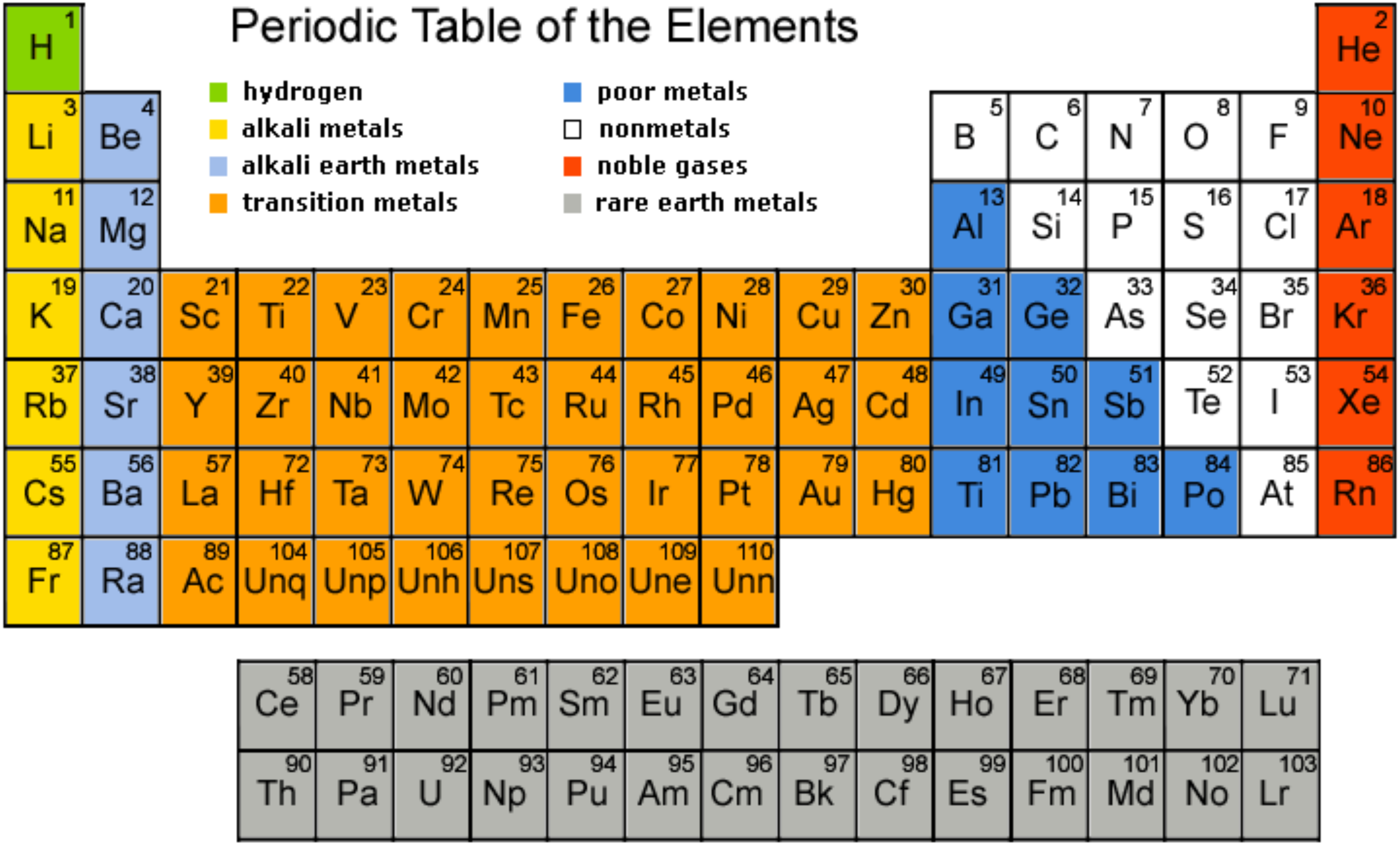
Star's Life Cycle

Big Bang! (14 B years ago)

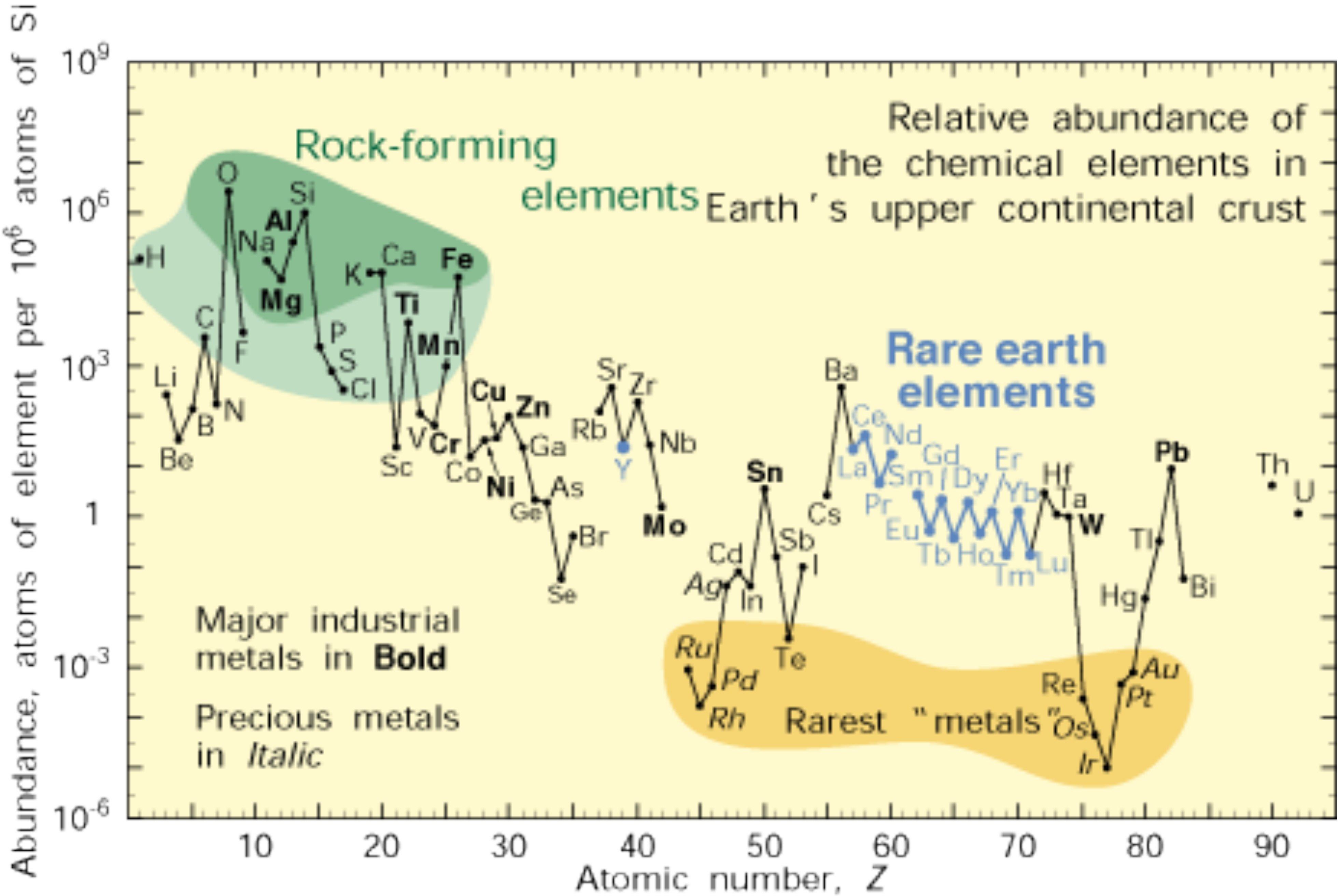


Sun (4.6 B years ago)

Periodic Table of Elements



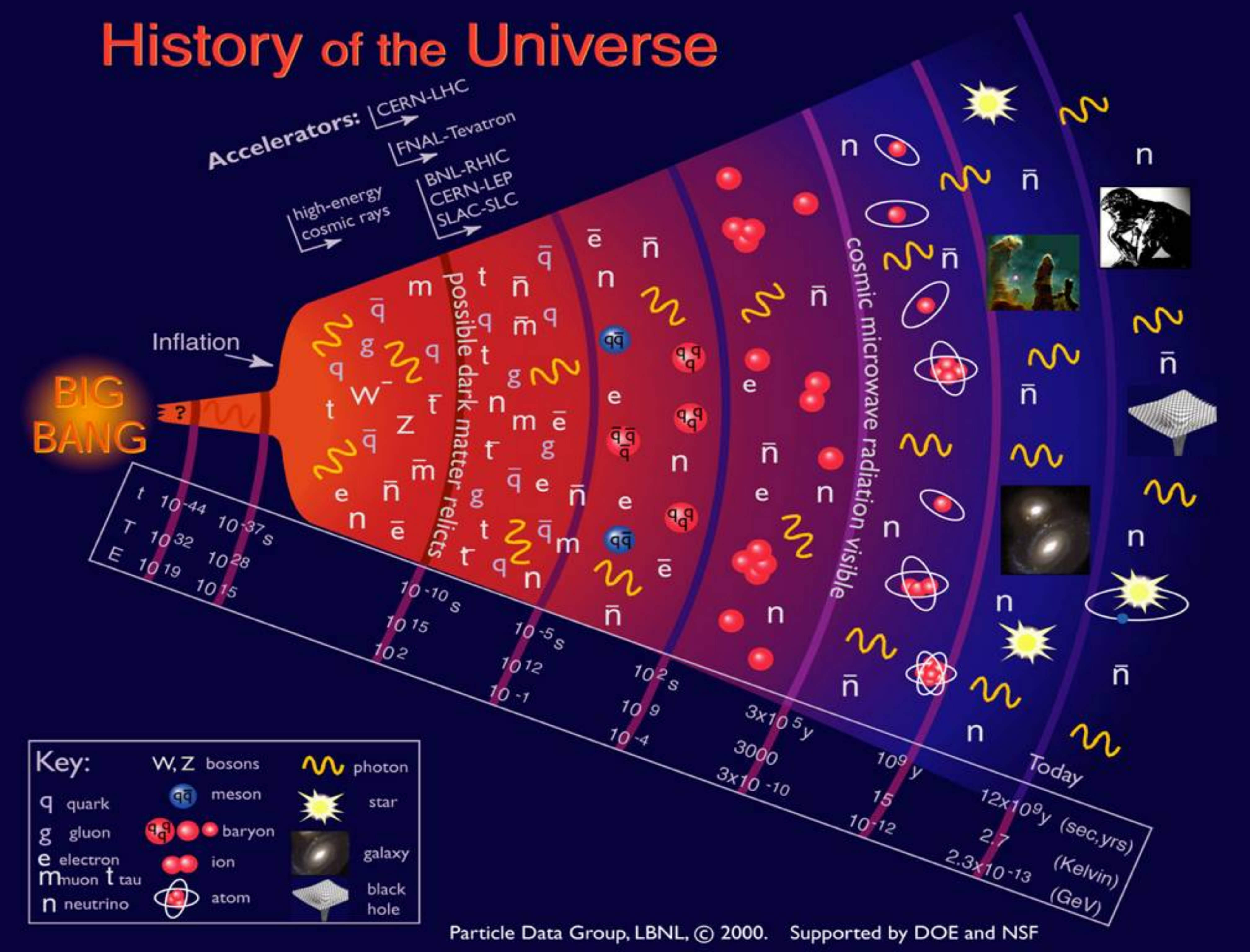
Abundance of Elements



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

		Ratio (in numbers)
Fermions:		
▪ Lepton:	ν_e	~1
	e^-	$\sim4\times10^{-10}$
▪ Baryon:	p	$\sim4\times10^{-10}$
	n	$\sim0.5\times10^{-10}$
Bosons:		
▪ Photon:	γ	1

- No anti-particles
- # Photon : # Baryon = 1 : $\sim4\times10^{-10}$
- # p = # e^-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3000
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10 9 y
15
10 -12
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12x10 9 y (sec,yrs)
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Key:
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g gluon
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n neutrino
W, Z bosons
meson
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ion
atom
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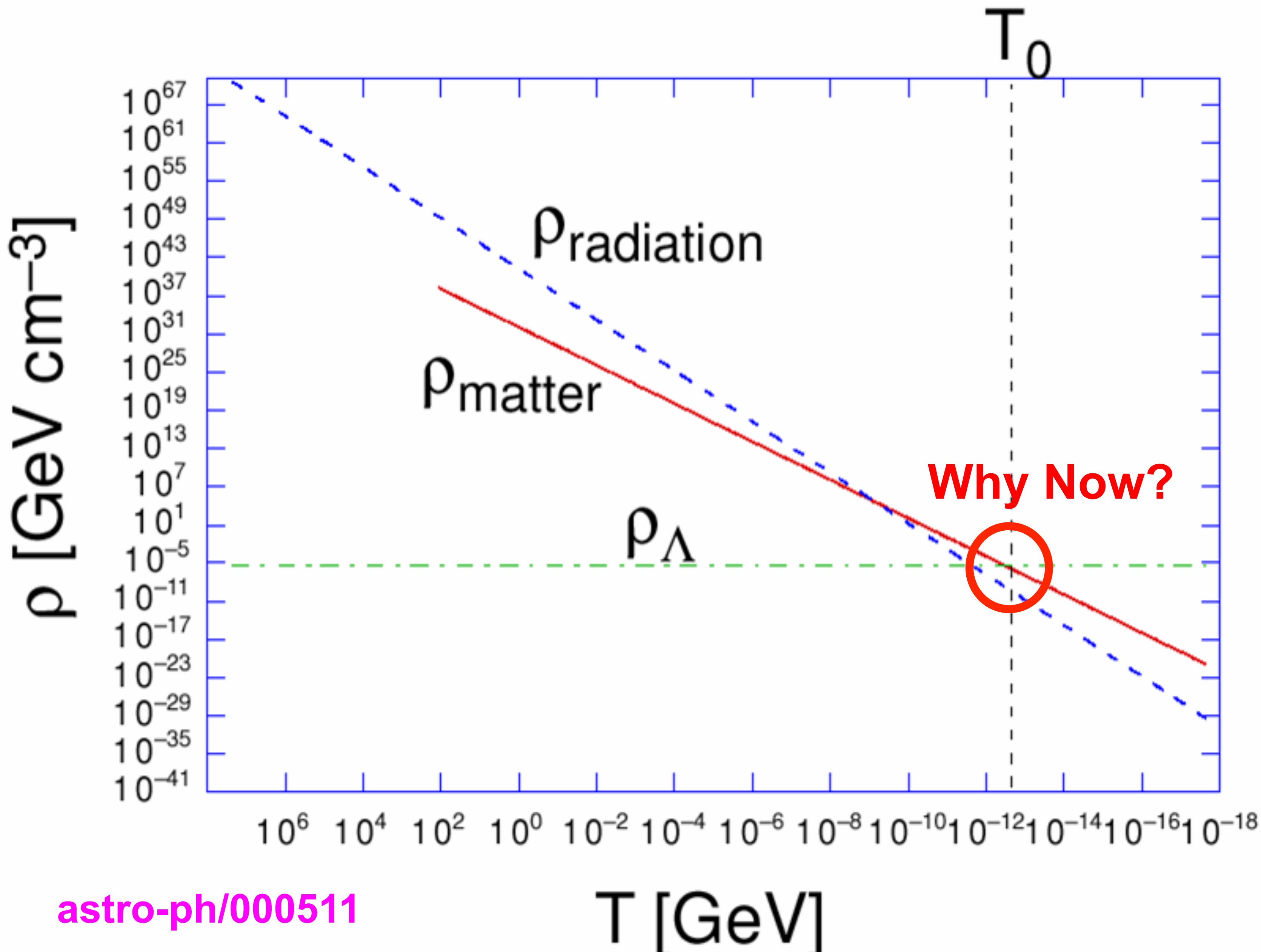
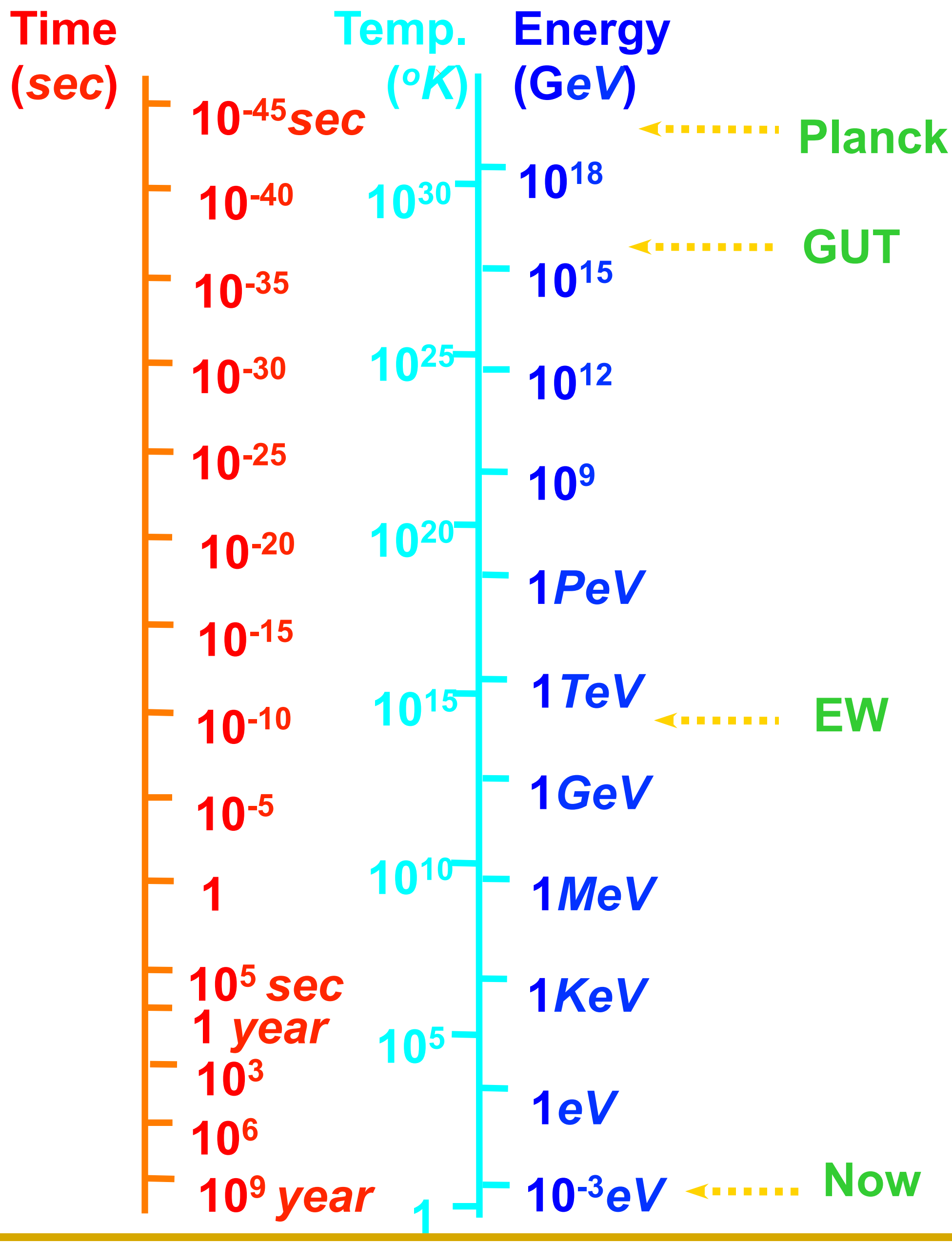
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Cosmic Triple Coincidence



astro-ph/000511

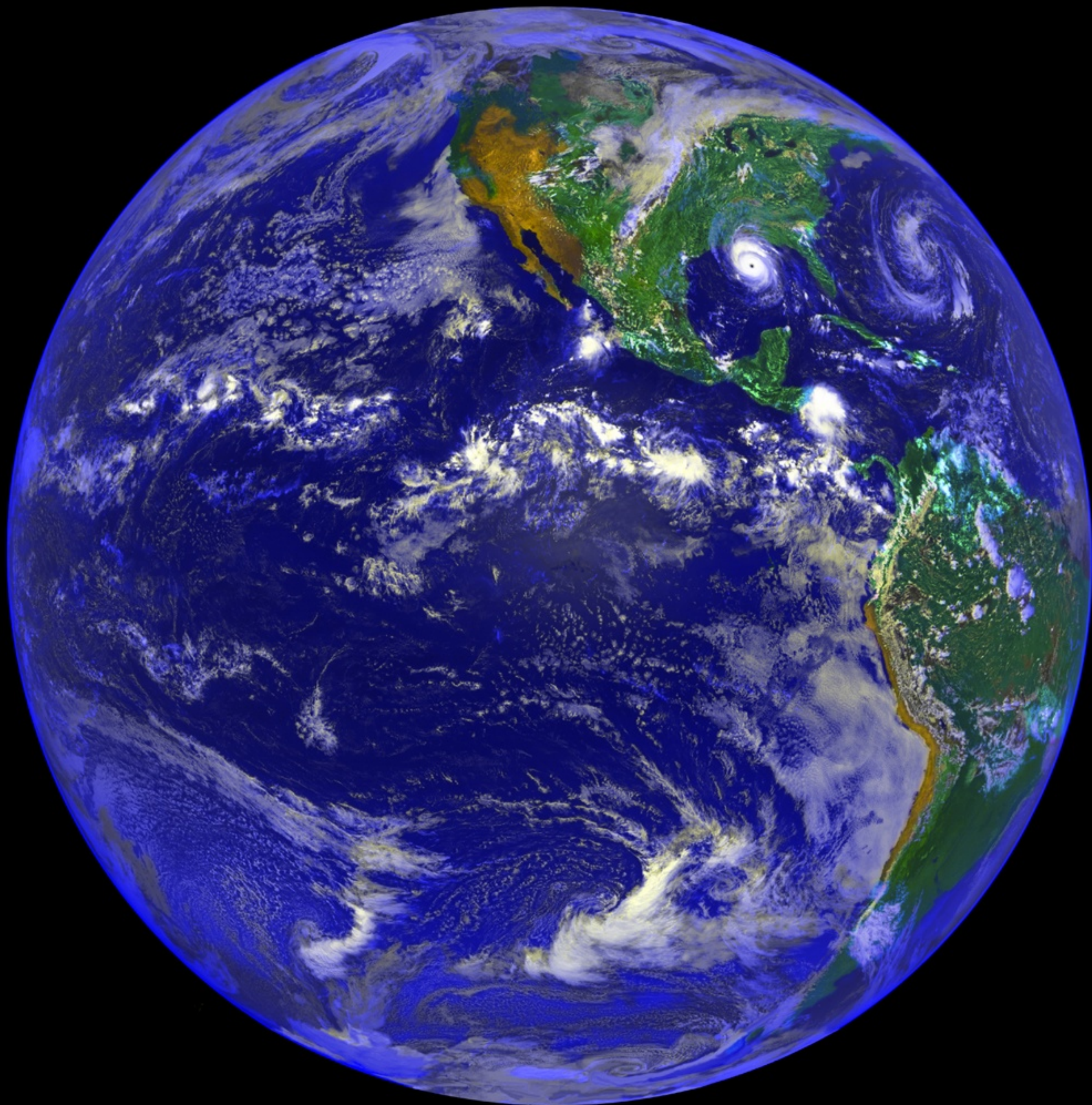
Cosmic Coincidence



$$\alpha_{Gravity} \approx \alpha_{Strong} \approx \alpha_{EM} \approx \alpha_{Weak}$$

$$\frac{E_{EW}}{E_{Planck}} \approx \frac{E_{Now}}{E_{EW}} \approx 10^{-15}$$

$$\Omega_{Rad} \approx \Omega_{\nu} \approx \Omega_{CDM} \approx \Omega_{B} \approx \Omega_{\Lambda}$$



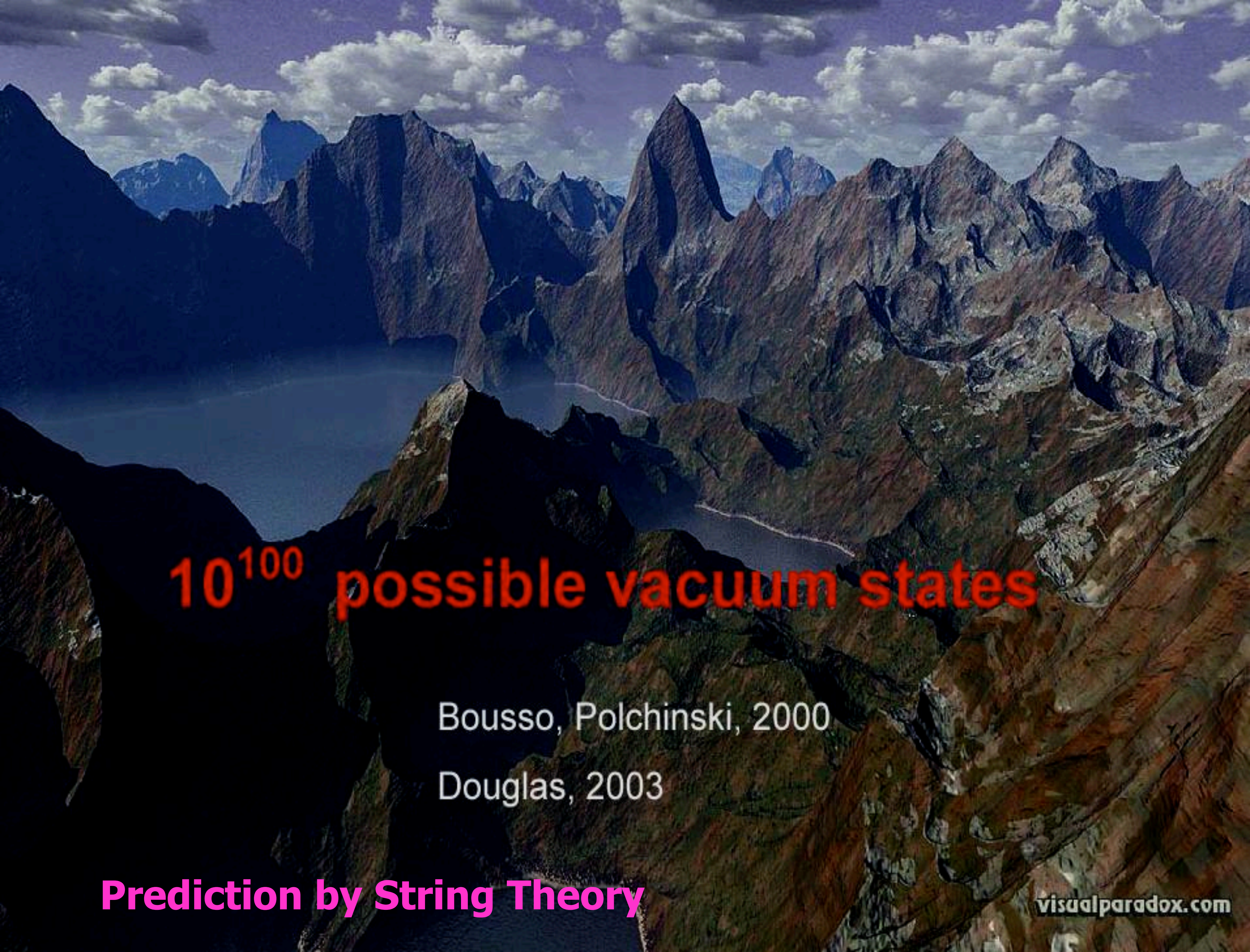
Why are we here?

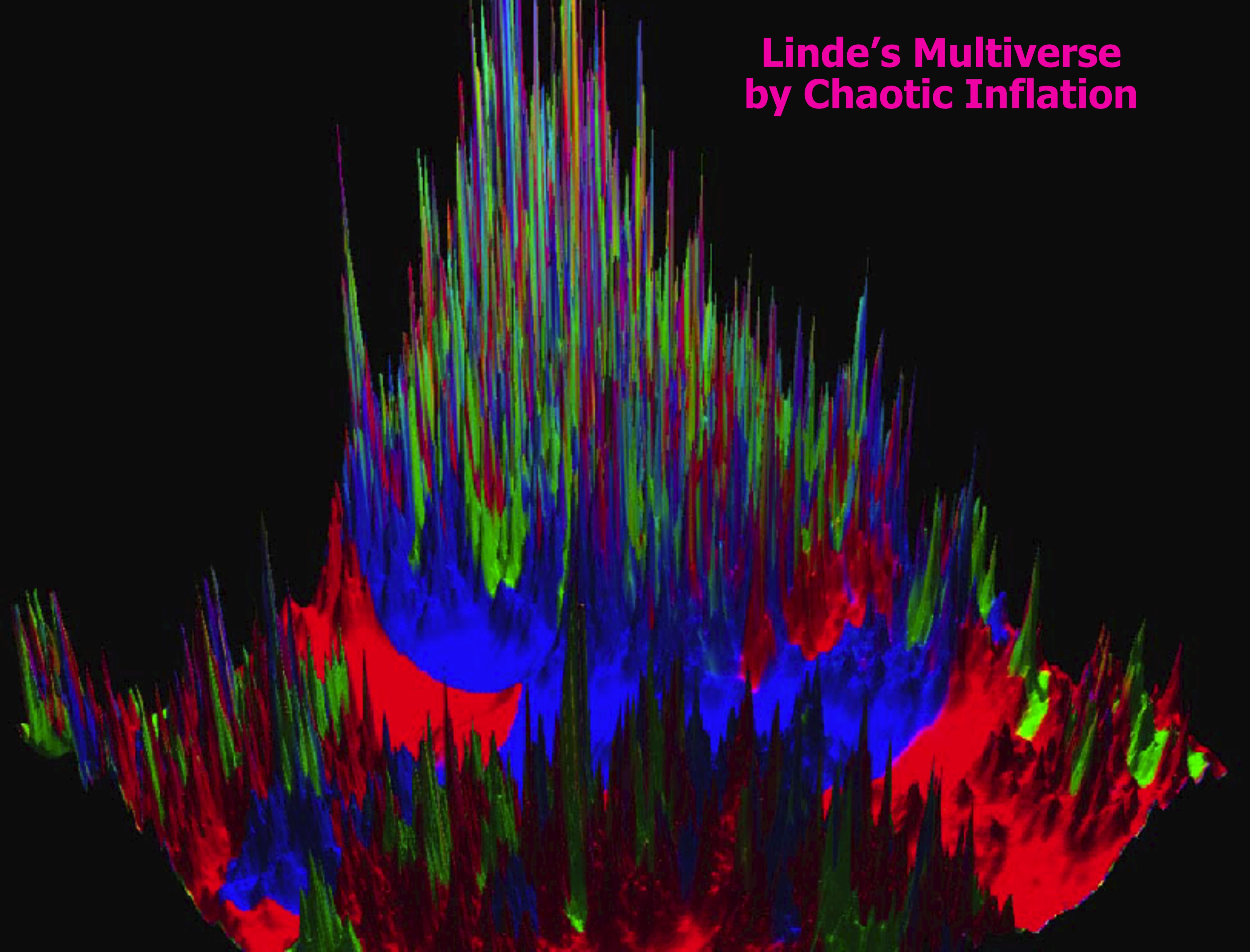
Anthropic Principle

- Observations of the physical universe must be compatible with the conscious life that observes it.

- It explains why the universe has the age and the fundamental physical constants necessary to accommodate conscious life.

Are there more than one Universe?


10^{100} possible vacuum states
Bousso, Polchinski, 2000
Douglas, 2003
Prediction by String Theory
visualparadox.com


Linde's Multiverse
by Chaotic Inflation


There may be ~100 Billion Universes.