Planck scale

use ħ=c=1:

$$F = -G\frac{mM}{r^2} = \frac{mM}{M_P^2\, r^2} = \frac{mM\, r_P^2}{r^2}$$

in ordinary units:

$$M_P = \sqrt{\frac{\hbar c}{G}} = 1.221\cdot 10^{19}\,\mathrm{GeV/c^2} = 2.177\cdot 10^{-8}\,\mathrm{kg}$$

$$L_P = ct_P = \sqrt{\frac{\hbar G}{c^3}} = 1.616\cdot 10^{-35}\,\mathrm{m}$$

$$t_P = 5.39\cdot 10^{-44}\,\mathrm{s}$$

History of the Universe

Time	Size	Energy/part.	Temperature	Era
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10^{10} yr	10^{10} ly	10^{-4} eV	3 K	Matter

Building Blocks of Matter

$Q=-{}^1/_3$	$Q=+{}^2/_3$	$Q=-1$	$Q=0$
ddd 5MeV	uuu 3MeV	e^- 0.5MeV	ν_e ~0
sss 120MeV	ccc 1.5GeV	μ^- 106MeV	ν_μ ~0
bbb 5GeV	ttt 170GeV	τ^- 1.78GeV	ν_τ ~0
Quarks		Leptonen	

Building Blocks of Matter and Antimatter

$Q=-^1/_3$	$Q=+^2/_3$	$Q=-1$	$Q=0$
ddd 5MeV	uuu 3MeV	e^- 0.5MeV	ν_e ~0
sss	ccc	μ^- 106MeV	ν_μ ~0
		τ^- 1.78GeV	ν_τ ~0
		Leptonen	

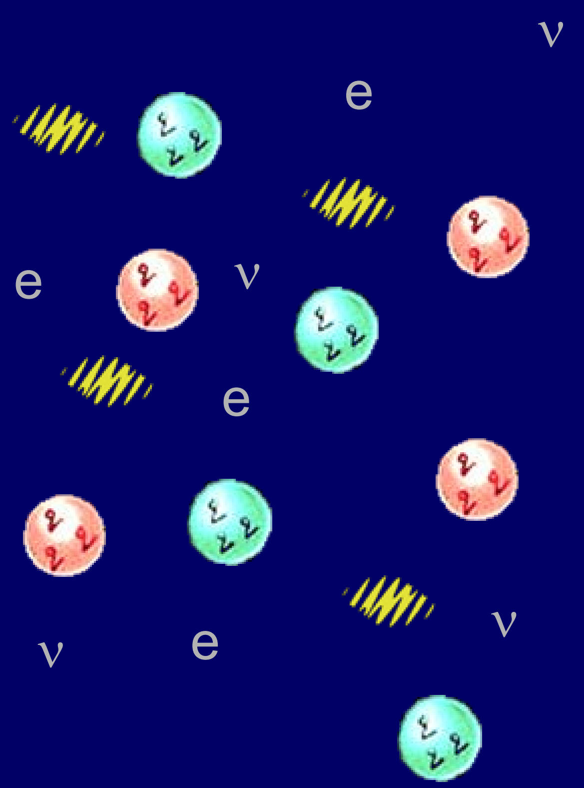
$Q=+^1/_3$	$Q=-^2/_3$	$Q=+1$	$Q=0$
anti-ddd 5MeV	anti-uuu 3MeV	e^+ 0.5MeV	anti-ν_e ~0
anti-sss 120MeV	anti-ccc 1.5GeV	μ^+ 106MeV	anti-ν_μ ~0
anti-bbb 5GeV	anti-ttt 170GeV	τ^+ 1.78GeV	anti-ν_τ ~0
Anti-Quarks		Anti-Leptonen	

24 “elements” for matter
+ 24
for antimatter

Condensation of Nucleons

1s after the Big Bang
T = 10 000 000 000 K

Quarks “condense” into Baryons
the stable ones remaining are the Nucleons
p (Proton uud) und **n** (Neutron udd)



equilibrium of

$p + e^- \leftrightarrow n + \nu$

$n + e^+ \leftrightarrow p + \nu$

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

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

$e^+ + e^- \leftrightarrow$ 2 photons

$n + \bar{n} \leftrightarrow$ 2 photons

…

$$r_n = \frac{\# n}{\# p} = e^{-\Delta mc^2 / kT} \approx \frac{1}{3}$$

History of the Universe

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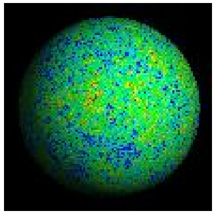
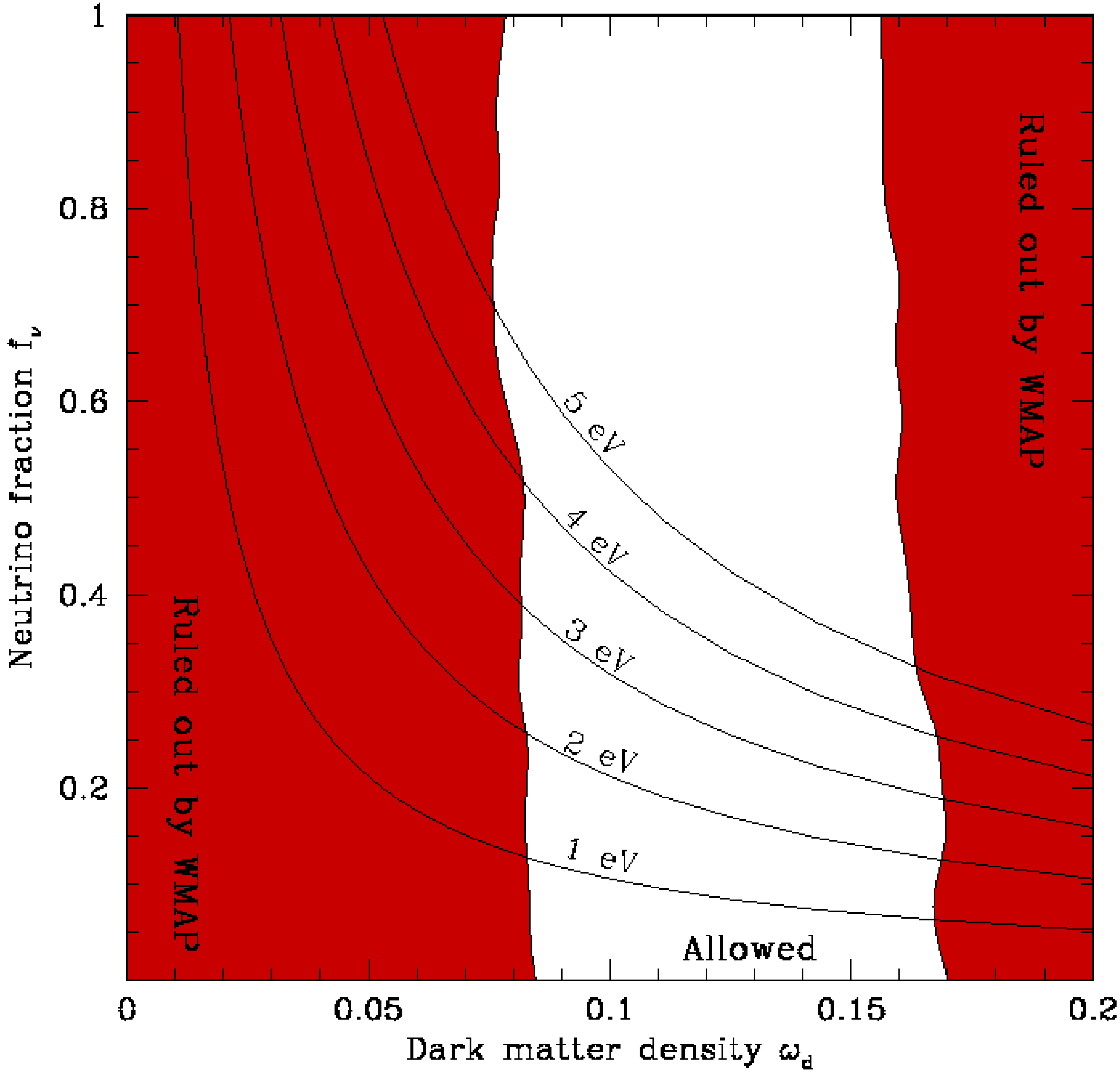
Neutrinos Decoupling

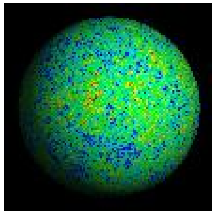
- Cooling Down
  (like Background Radiation)
- $E_{kin} \approx 0.3$ meV
- Today: ca. 110/cm^3 cold neutrinos everywhere (cf. 400/cm^3 photons from CMB)

- r_n decreasing due to n decay


CMB

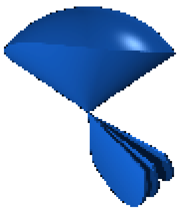
Neutrinos


1
0.8
0.6
0.4
0.2
0
0.05
0.1
0.15
0.2
Neutrino fraction f_ν
Dark matter density ω_d
Ruled out by WMAP
Ruled out by WMAP
Allowed
5 eV
4 eV
3 eV
2 eV
1 eV



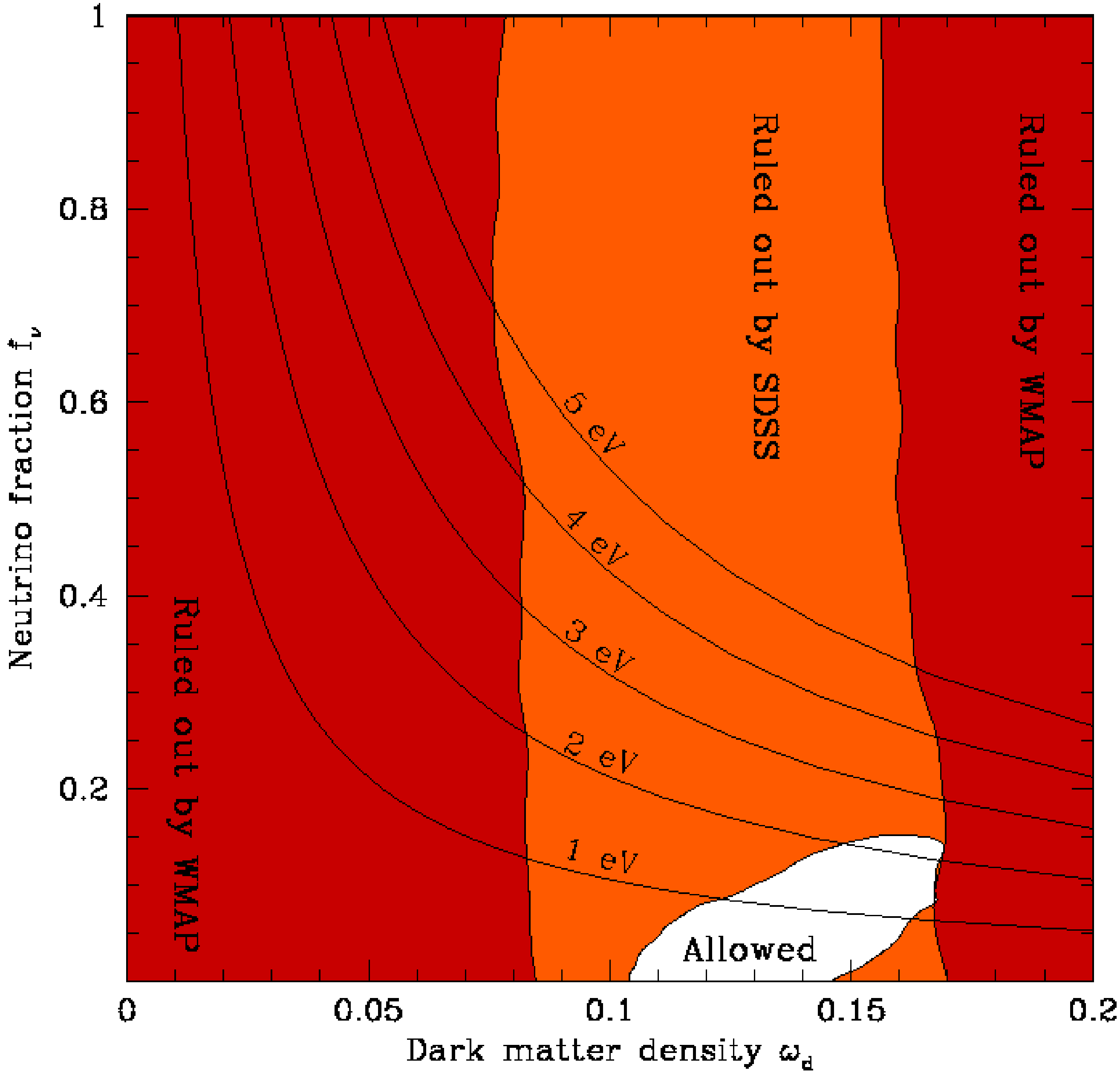
CMB

+



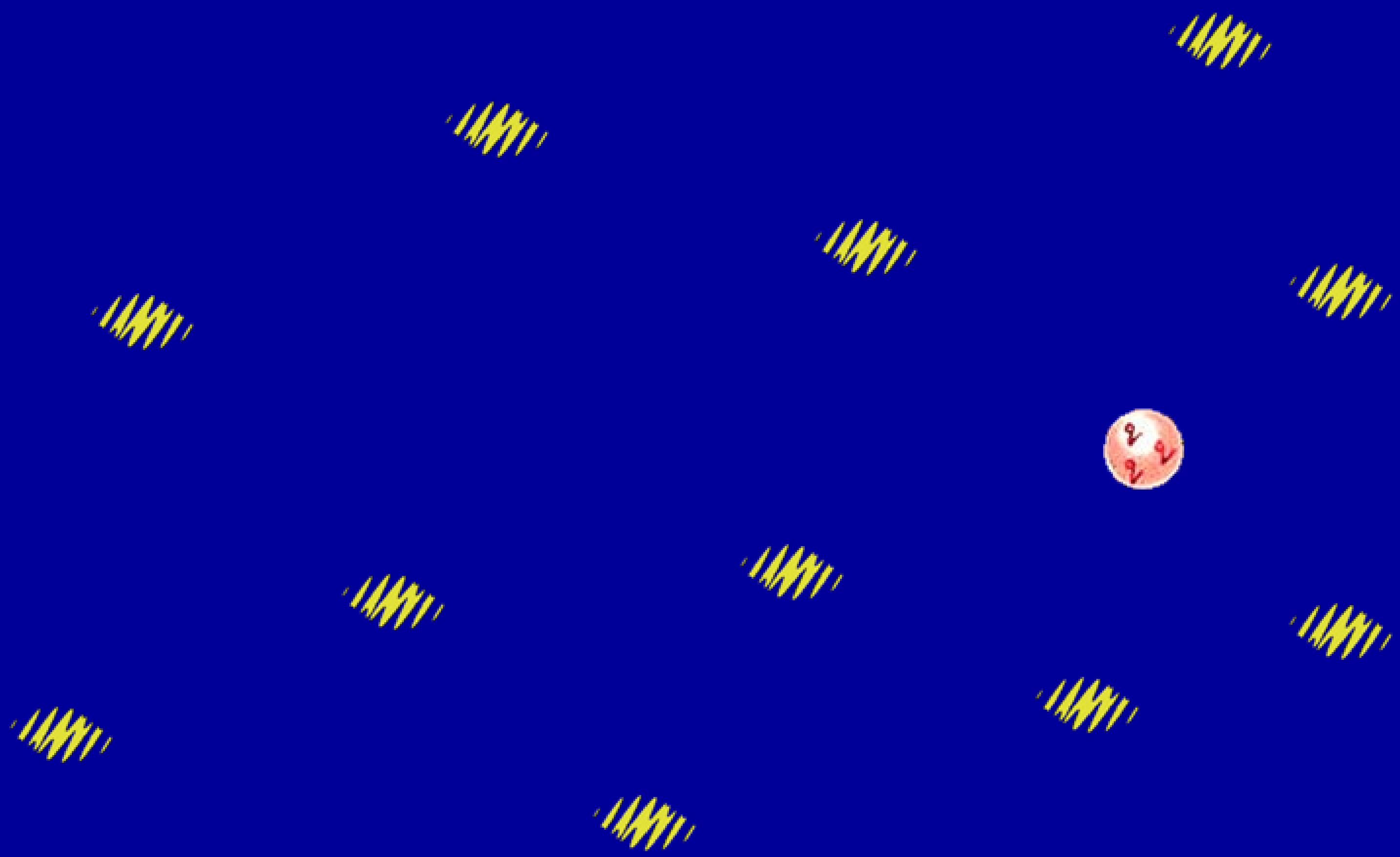
Survey

Neutrinos



Within the 1st Minute the Universe is cooled to 1 000 000 000 K

due to a tiny excess of matter over antimatter we have 6 nucleons per 10 000 000 000 photons (still now)



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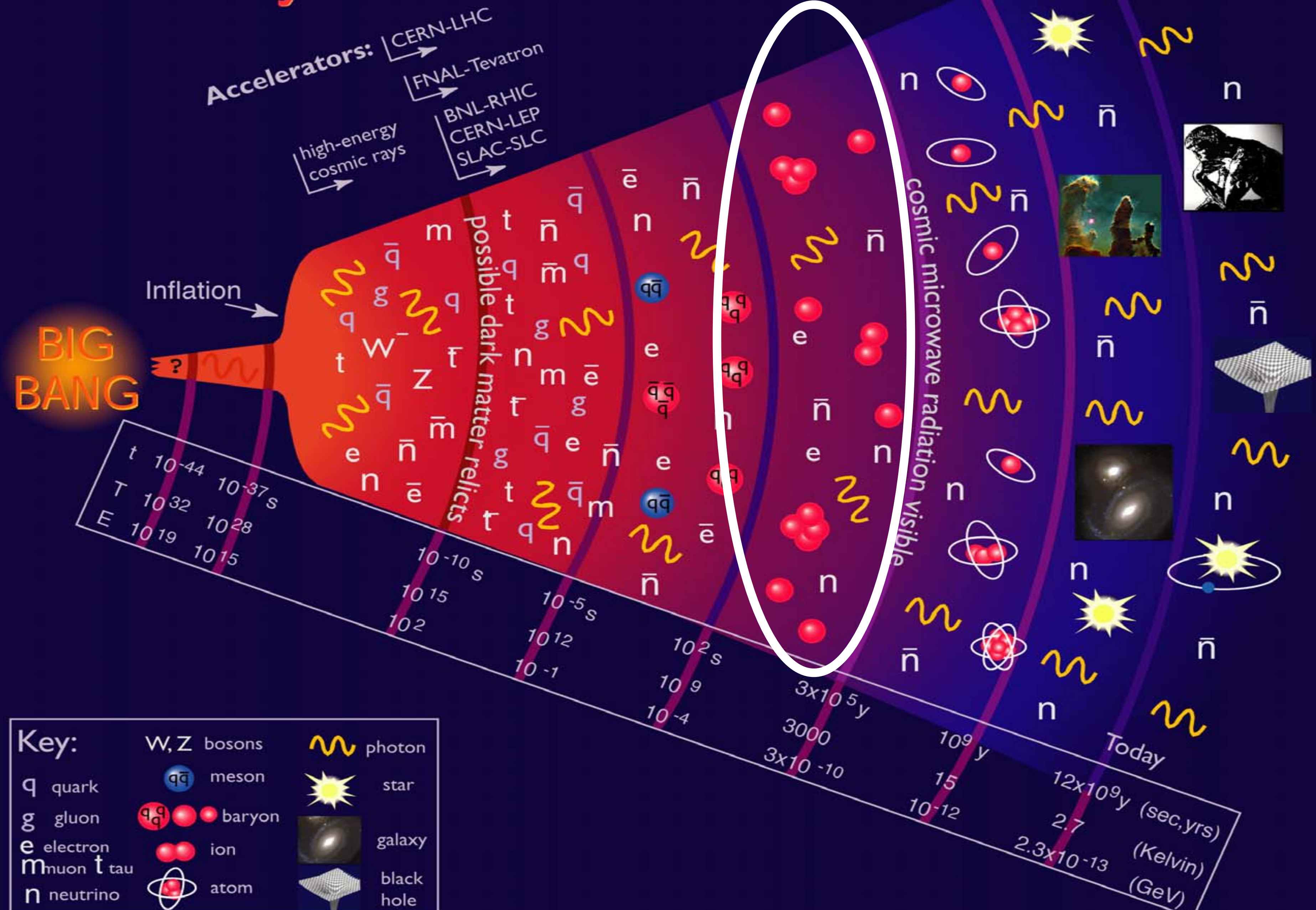
History of the Universe



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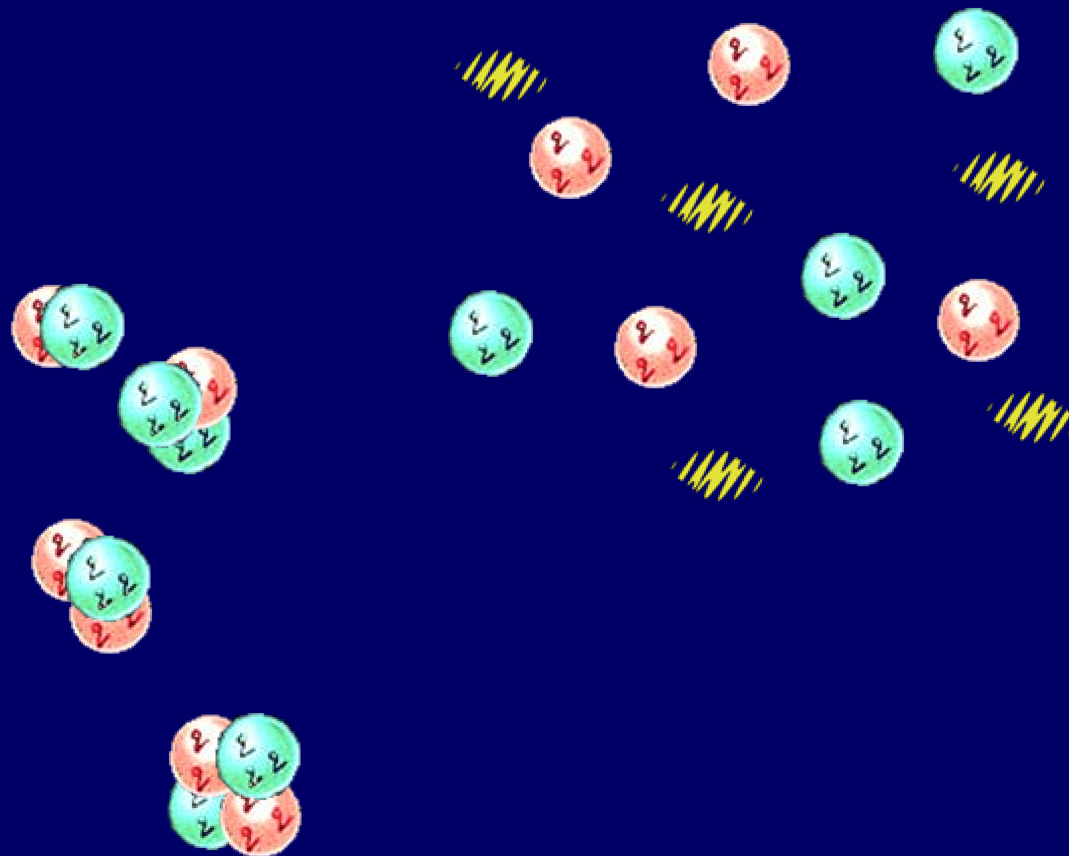
Temperature: 1 000 000 000 K

>1min after Big Bang



Reactions:

$p + n \rightarrow {}^{2}H + \text{Photon}$

${}^{2}H + n \rightarrow {}^{3}H + \text{Photon}$

${}^{3}H + p \rightarrow {}^{4}He + \text{Photon}$

${}^{2}H + p \rightarrow {}^{3}He + \text{Photon}$

${}^{3}H + p \rightarrow {}^{4}He + \text{Photon}$

${}^{3}He + n \rightarrow {}^{4}He + \text{Photon}$

${}^{2}H + {}^{2}H \rightarrow {}^{3}He + n$

${}^{2}H + {}^{2}H \rightarrow {}^{3}H + p$

${}^{2}H + {}^{3}H \rightarrow {}^{4}He + n$

${}^{2}H + {}^{3}He \rightarrow {}^{4}He + p$

${}^{2}H + {}^{2}H \rightarrow {}^{4}He + \text{Photon}$

${}^{2}H$ = Deuterium 

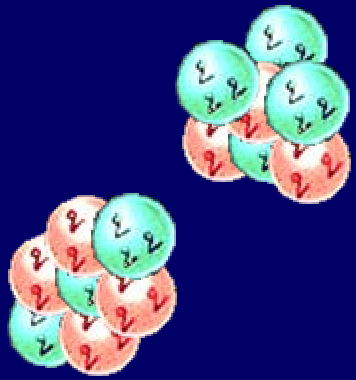
Temperature: 1 000 000 000 K

2min after Big Bang

more nuclear reactions:

$^{3}H + ^{4}He \rightarrow ^{7}Li + photon$

$^{3}He + ^{4}He \rightarrow ^{7}Be + photon$

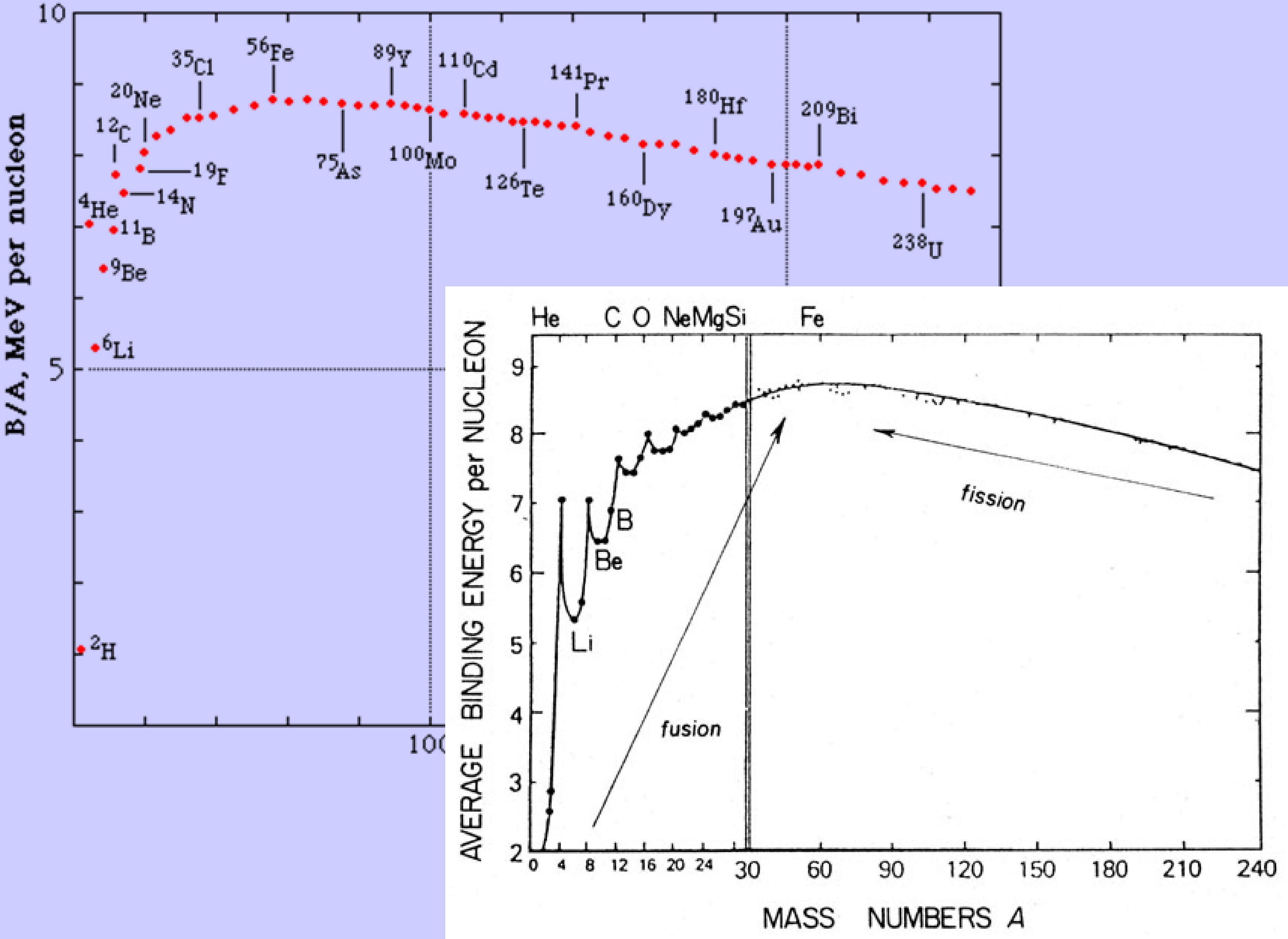


neutrons continue to decay:

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

mean lifetime is ~900 s = 15 min

Binding energy per nucleon



Nucleosynthesis of He

$2p + 2n \rightarrow 1\,{}^4\text{He}$ consuming all n that do not decay

$$\#(\text{He}) = \frac{1}{2}\#(n), \quad \#(\text{H}) = \#(p) - \#(n)$$

$$r_n := \frac{\#(n)}{\#(p)}$$

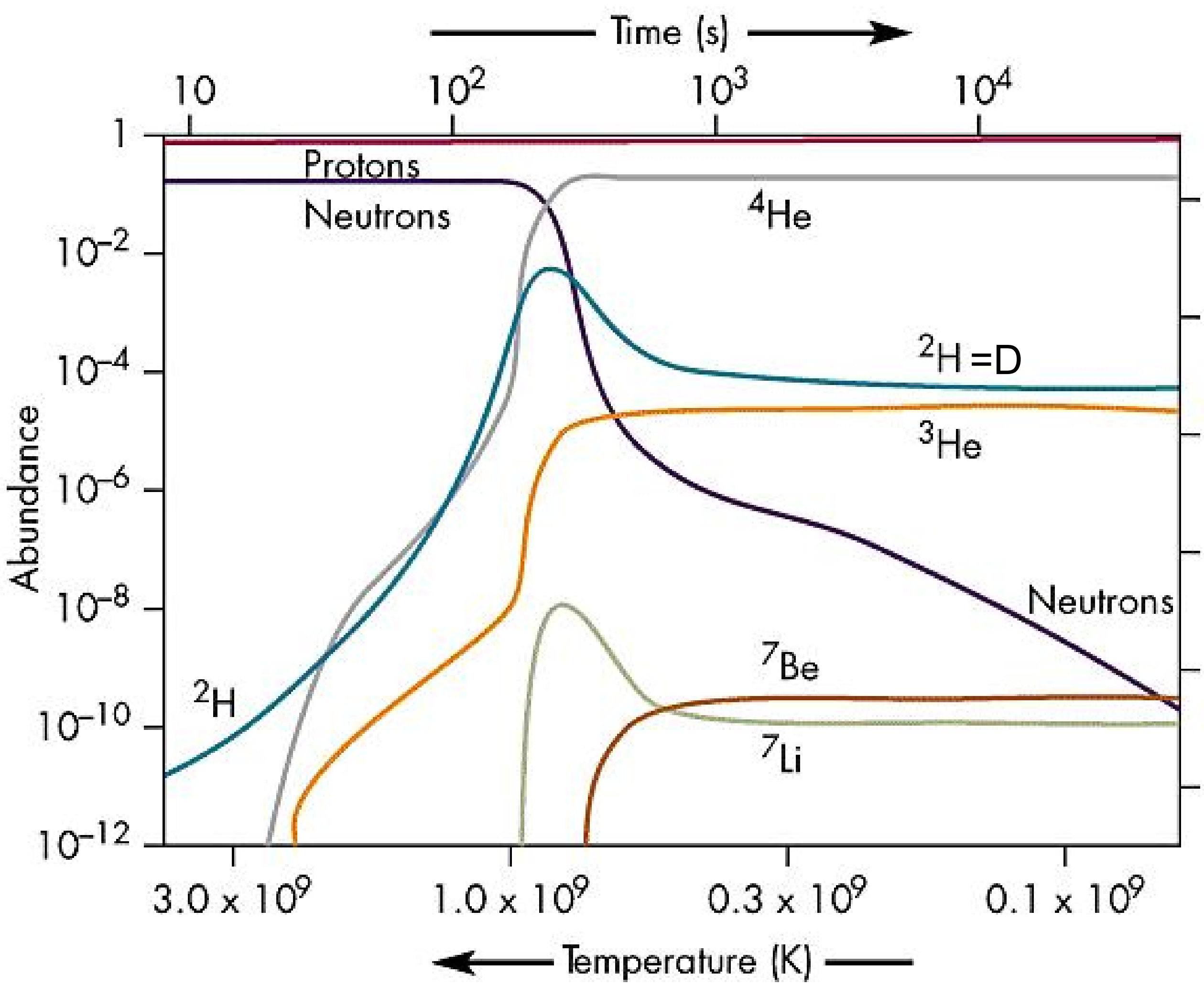
$$\frac{\#(He)}{\#(H)} = \frac{\frac{1}{2}\#(n)}{\#(p) - \#(n)} = \frac{r_n}{2(1 - r_n)}$$

r_n is determined by thermodynamics $r_n = e^{-\Delta mc^2/kT} \approx 1/3$
at T = 10 000 000 000 K
and later by n decay (half life time = 614 s) $r_n \rightarrow 0.14$

$$\frac{\#(He)}{\#(H)} = 0.08$$

$$f_{\text{He}} = \frac{4\#(He)}{4\#(He) + \#(H)} = 0.25$$

Nucleosynthesis

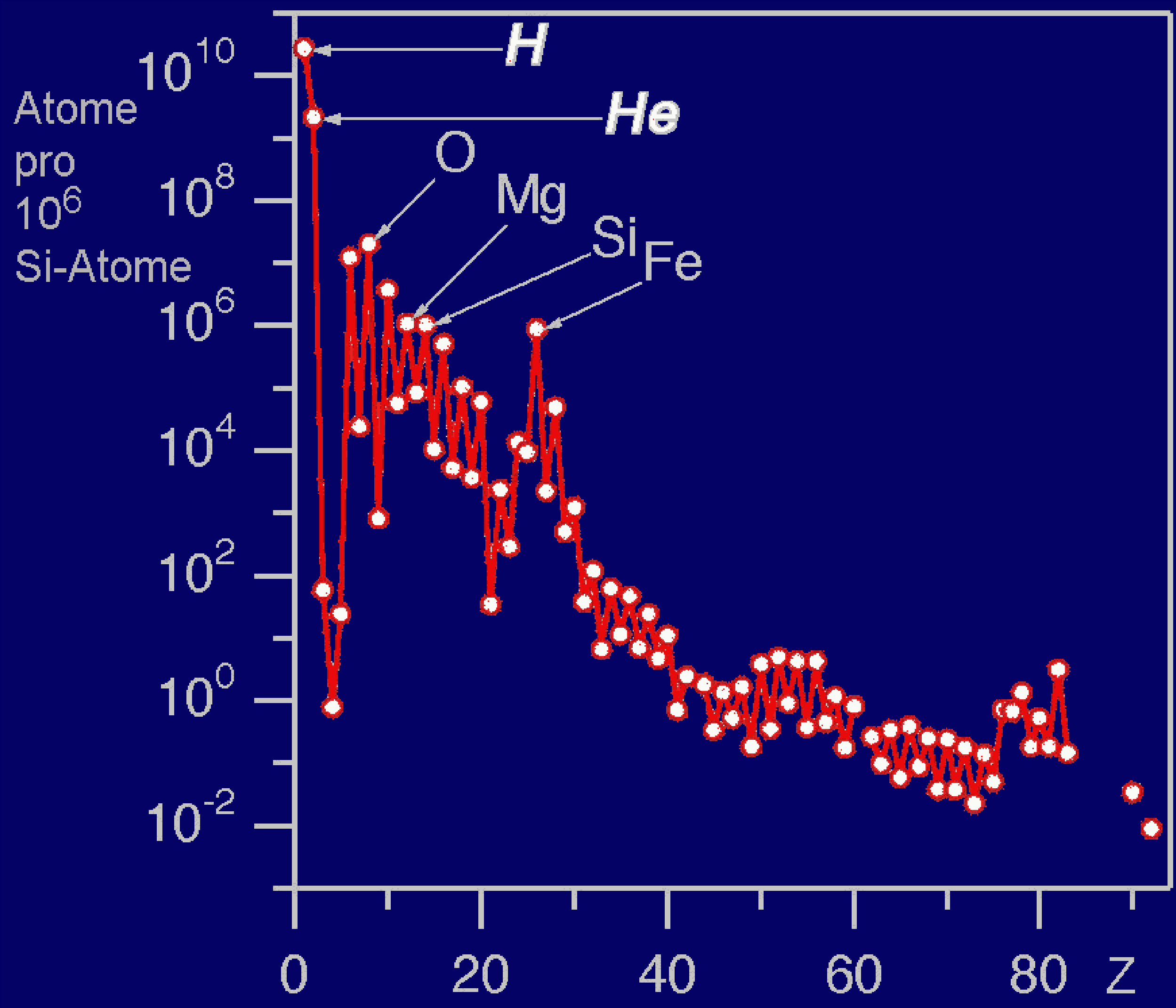


^{4}He : all
mass fraction: 24%
particle fraction: 7.4%
He : H ≈ 0.08

most stable element, production depends (almost) not on density

but production of other elements does!

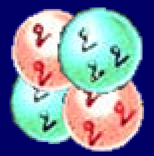
Abundance of Elements in the Universe



mostly hydrogen

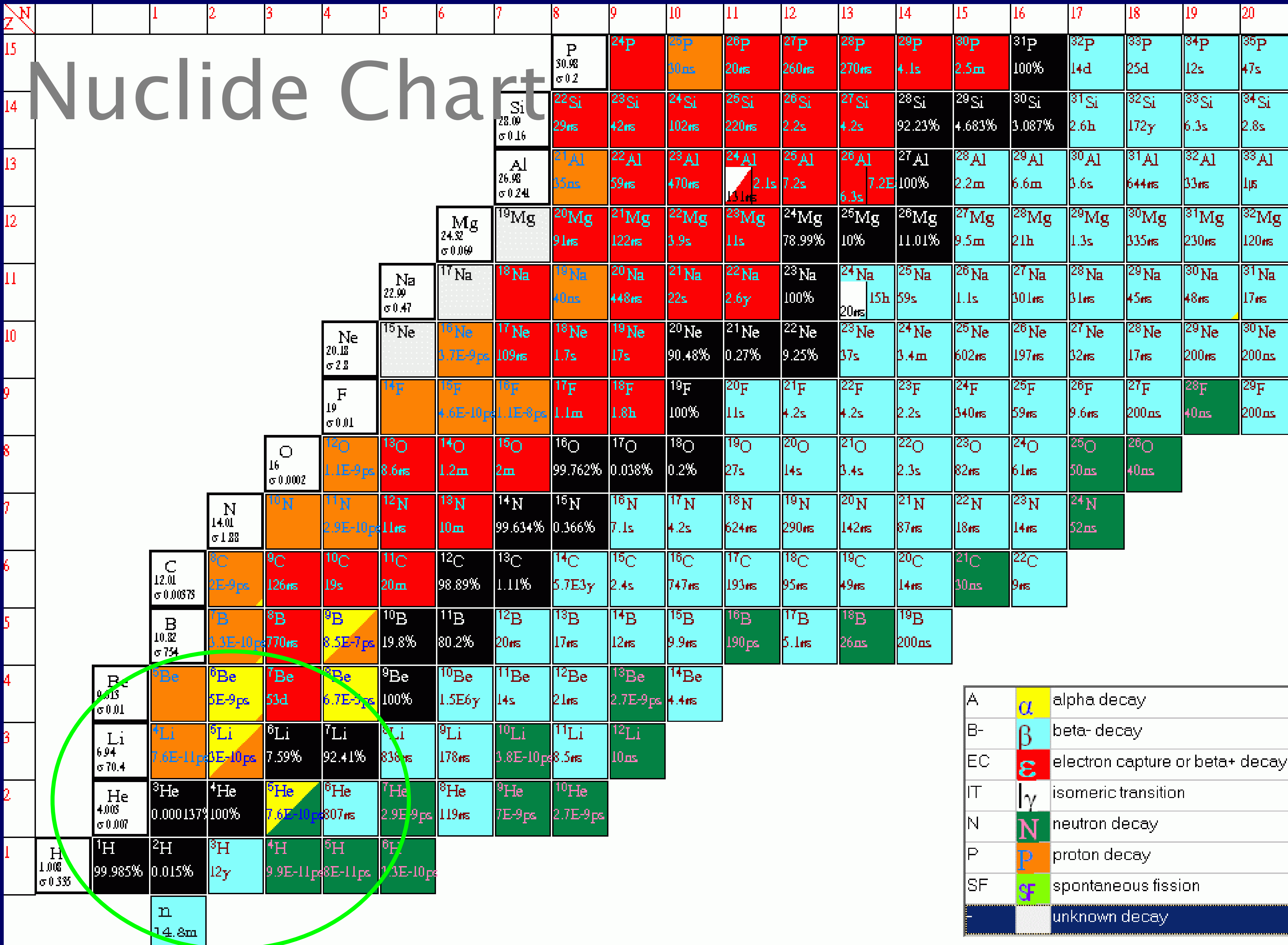
some Helium

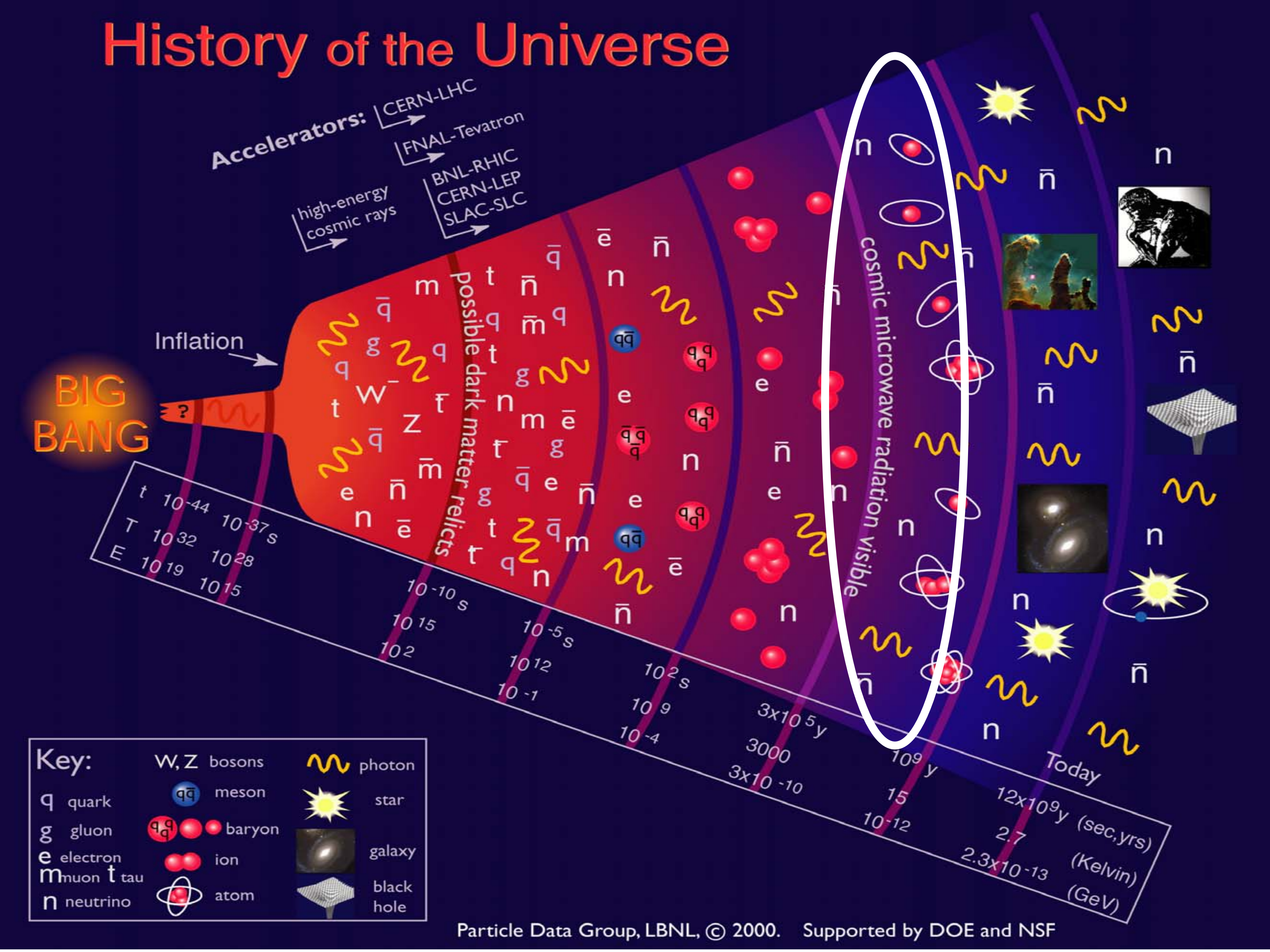
^{4}He



rest below 1%

Nuclide Chart





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 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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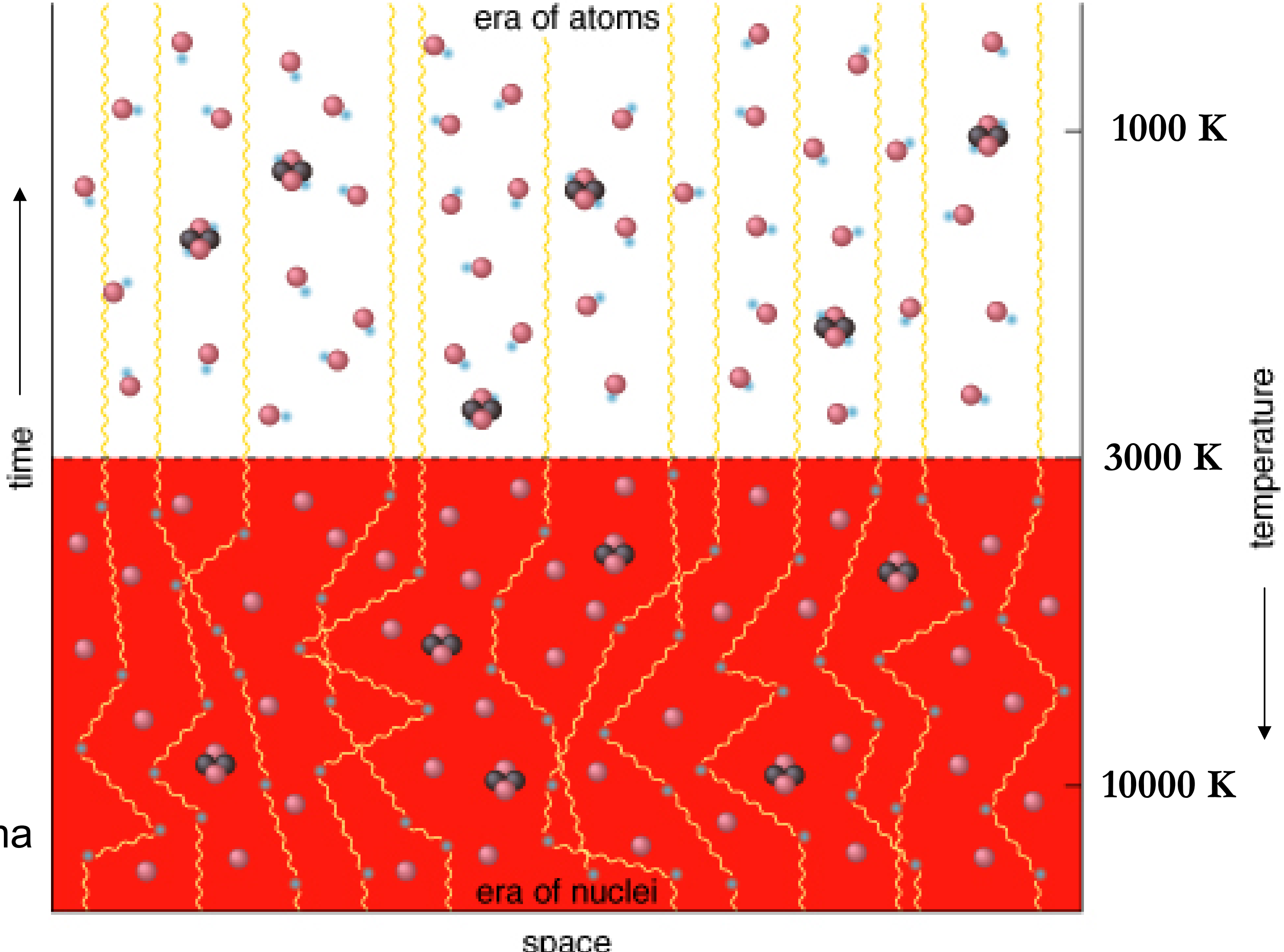
Photon/Matter-Decoupling

Age
ca.
300 000 a
10^{13} s

plasma

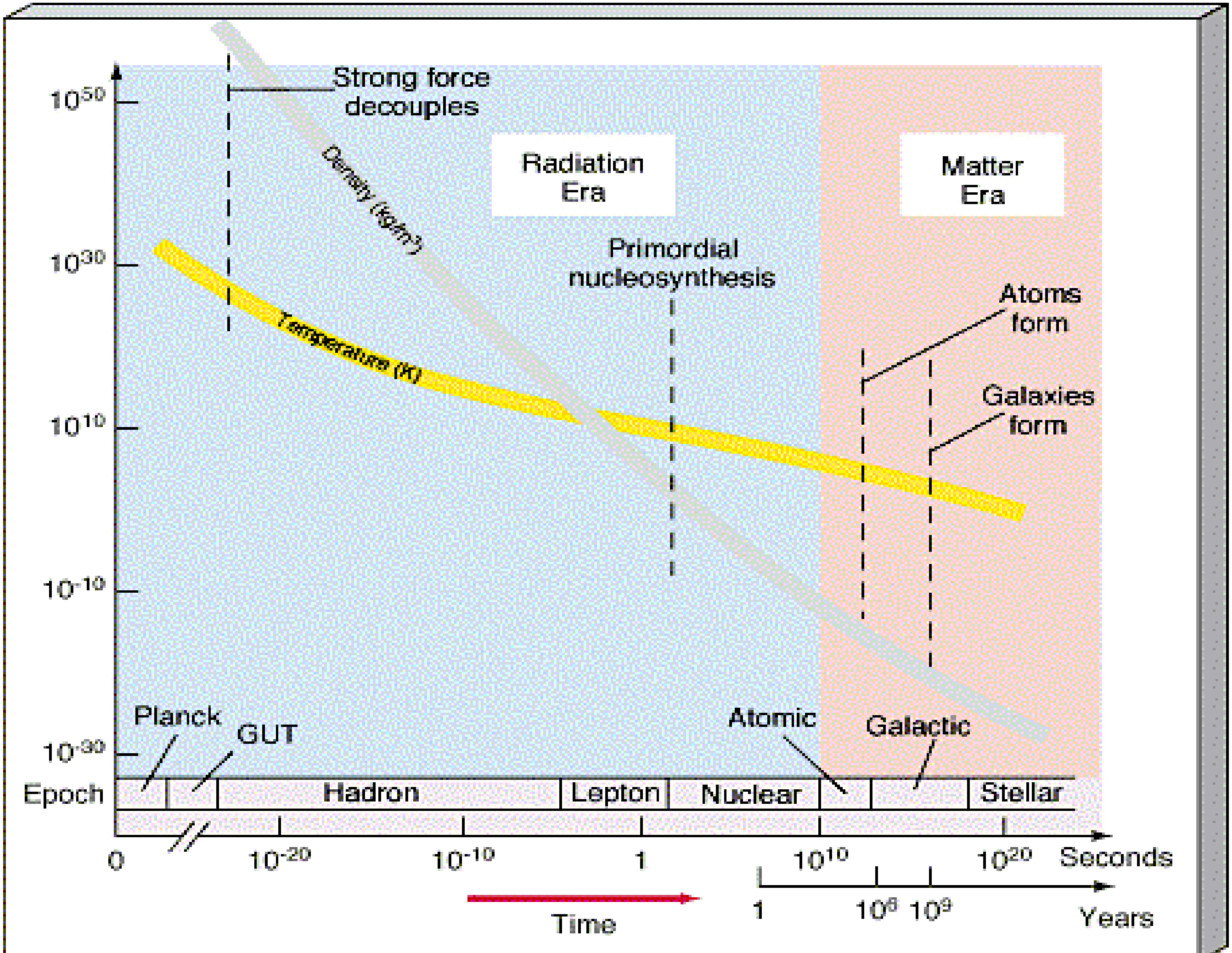


The Early Universe is not Transparent

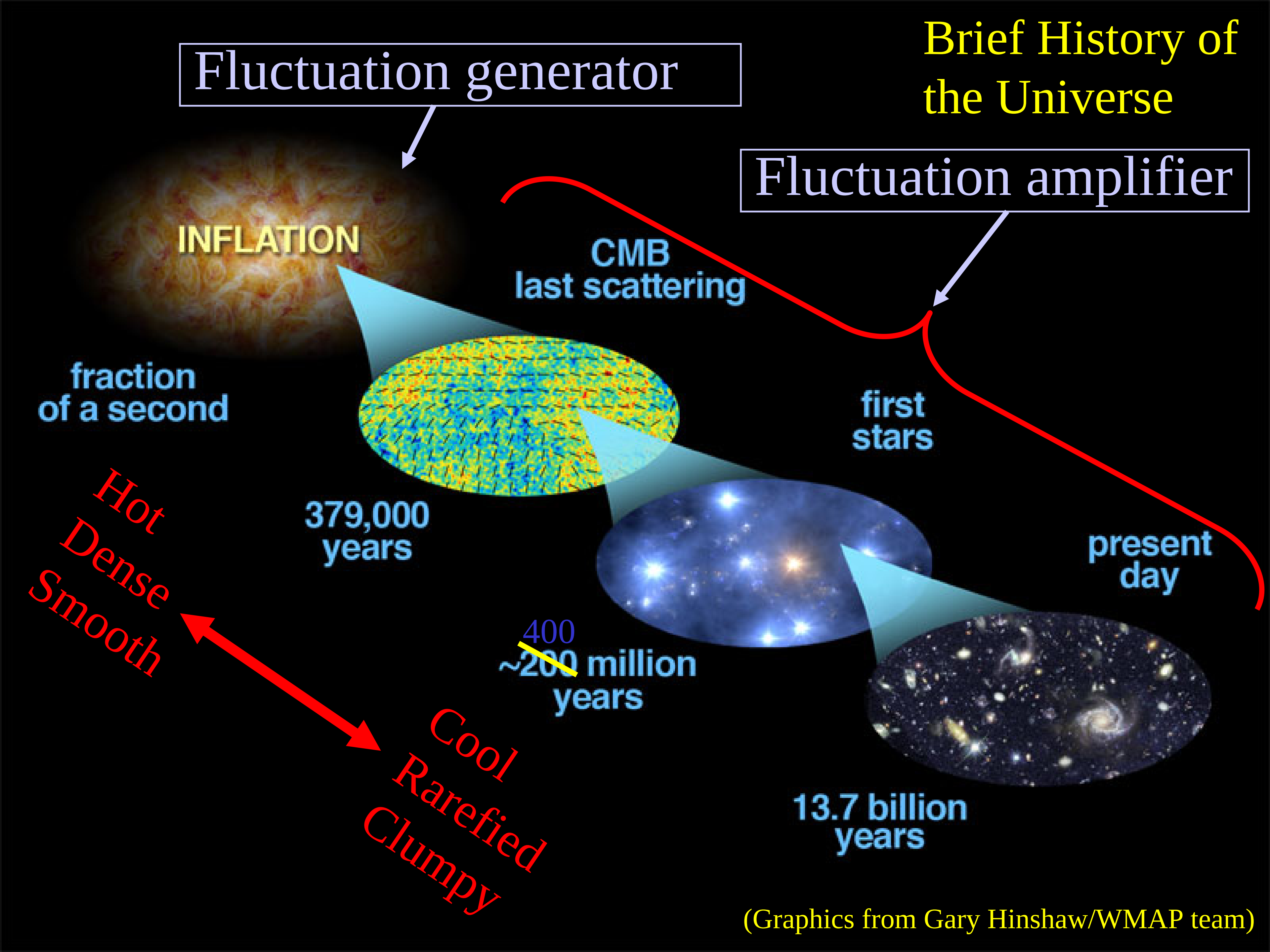
Plasma
(nuclei + electrons
 + photons)

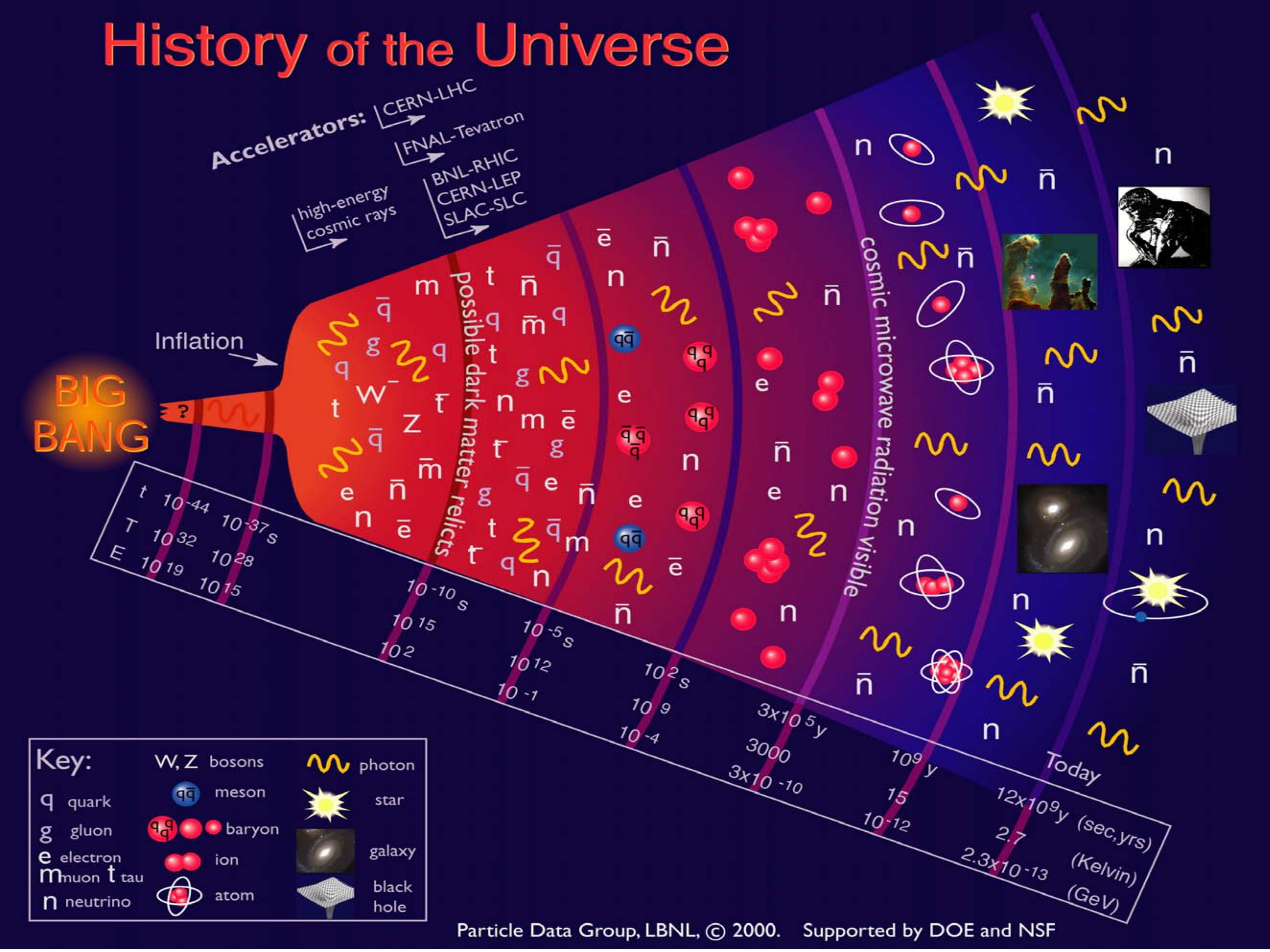
at age = 300 000 years
neutral atoms (gas)

Cosmology



Strong force decouples
Radiation Era
Matter Era
Density (kg/m³)
Primordial nucleosynthesis
Atoms form
Temperature (K)
Galaxies form
10^{50}
10^{30}
10^{10}
10^{-10}
10^{-30}
Planck
GUT
Atomic
Galactic
Epoch
Hadron
Lepton
Nuclear
Stellar
0
10^{-20}
10^{-10}
1
10^{10}
10^{20}
Seconds
1
10^{6}
10^{9}
Years
Time


Brief History of the Universe
Fluctuation generator
Fluctuation amplifier
INFLATION
fraction of a second
CMB last scattering
379,000 years
first stars
400
~200 million years
present day
13.7 billion years
Hot Dense Smooth
Cool Rarefied Clumpy
(Graphics from Gary Hinshaw/WMAP team)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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
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later…

15% of Cosmic Background Radiation
was re-scattered due to reionization
by early stars (population III)
at z = 20 or 400 million years after the Big Bang