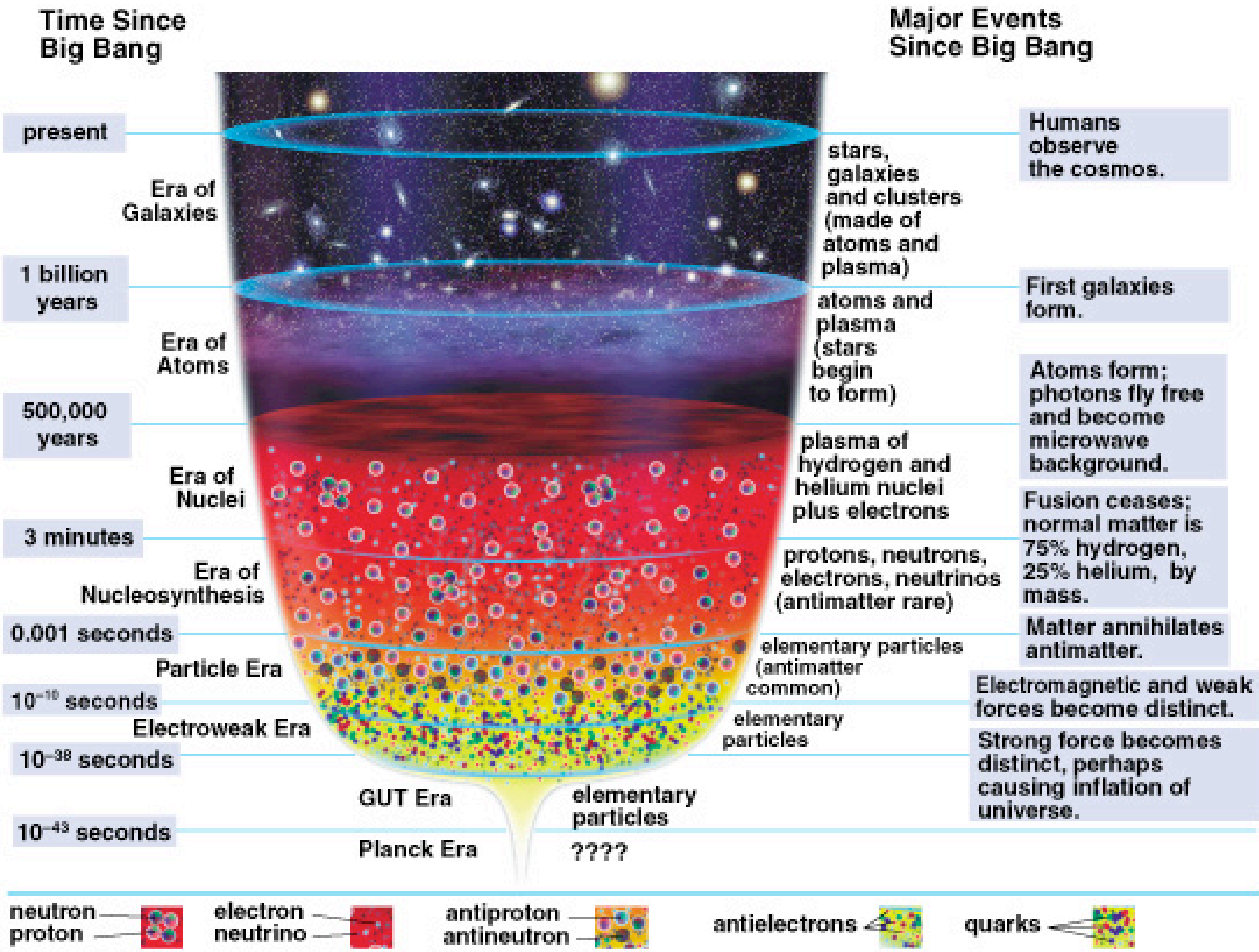
Brief History of Time



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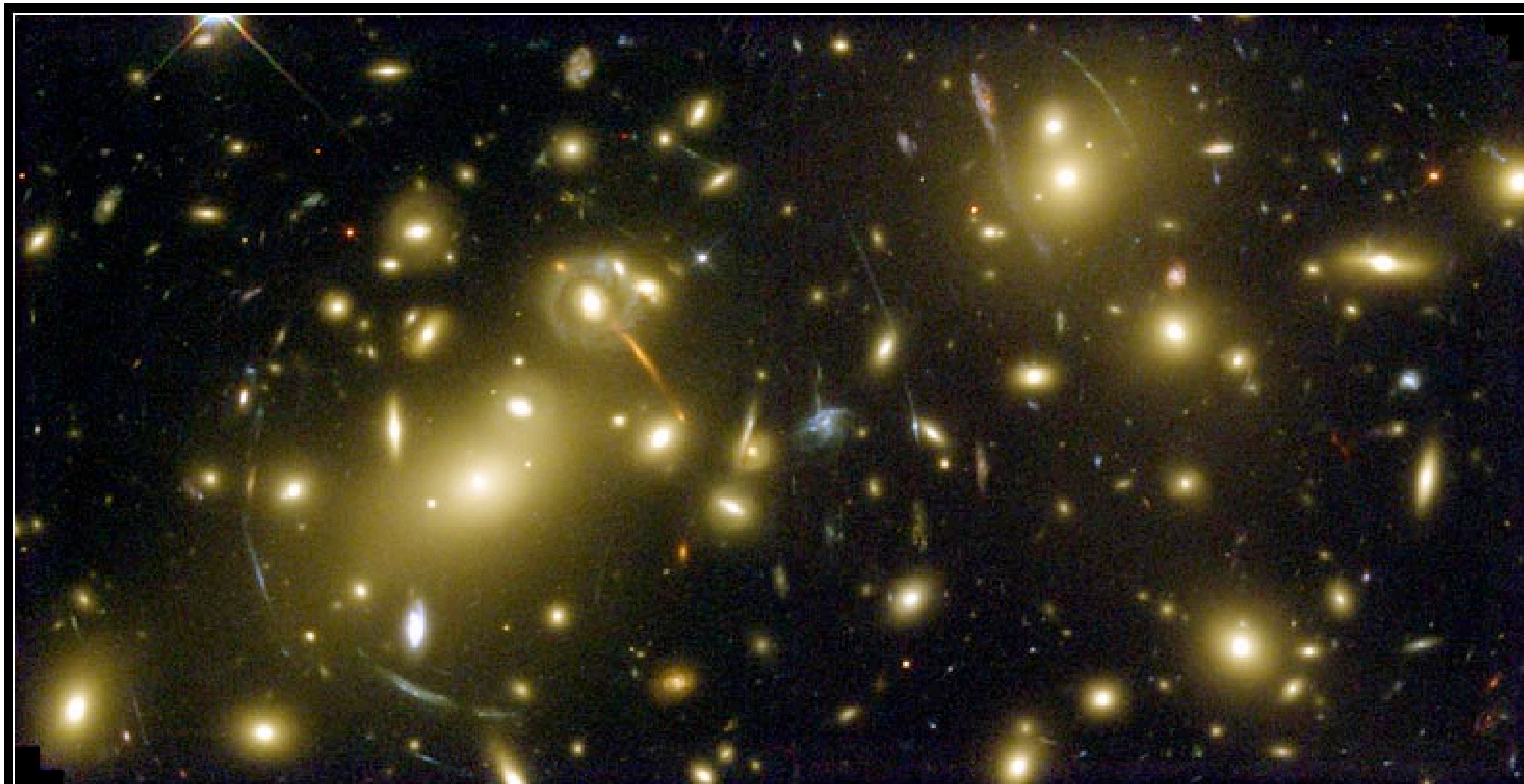
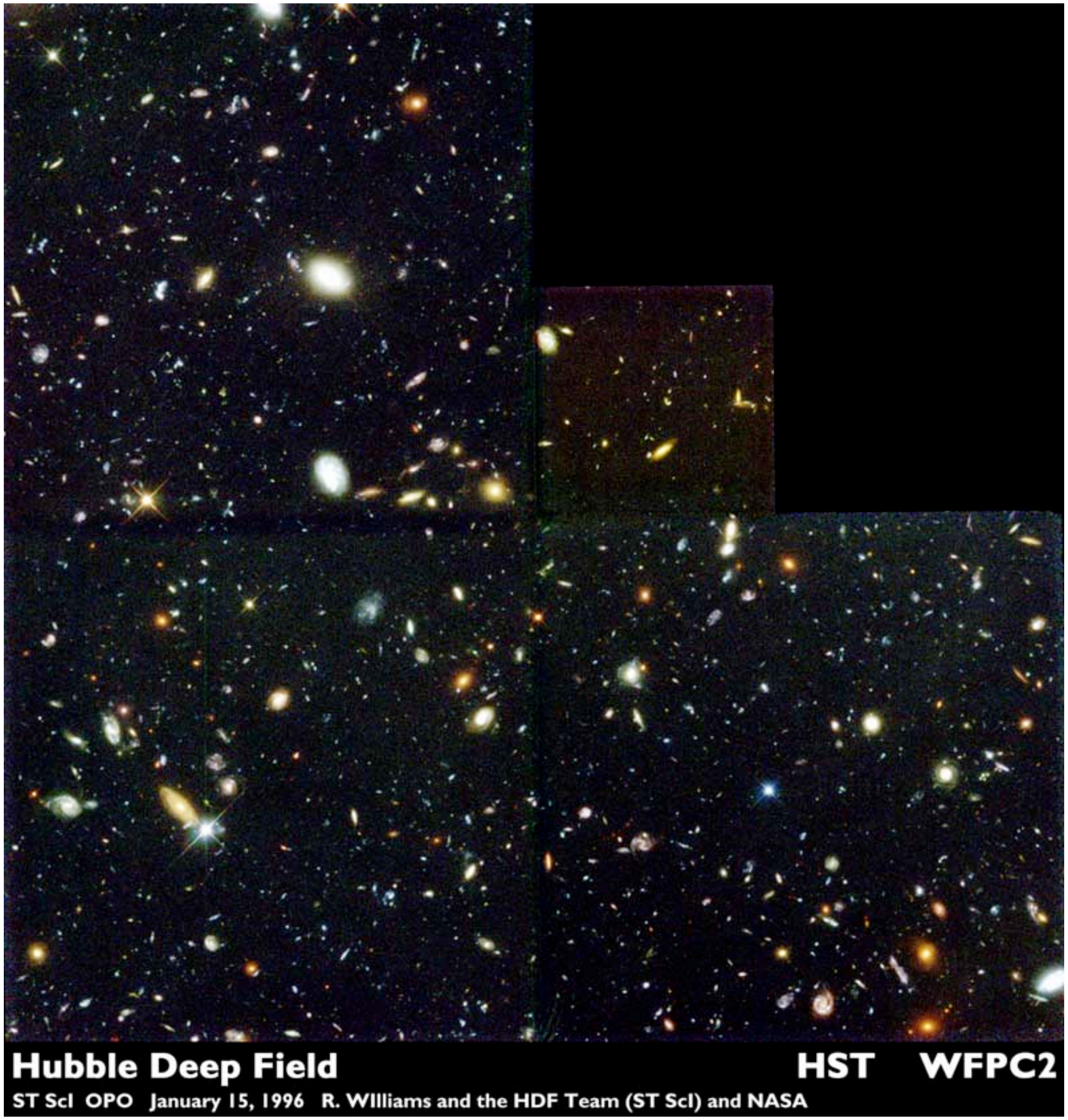
Today ("Recent"…)

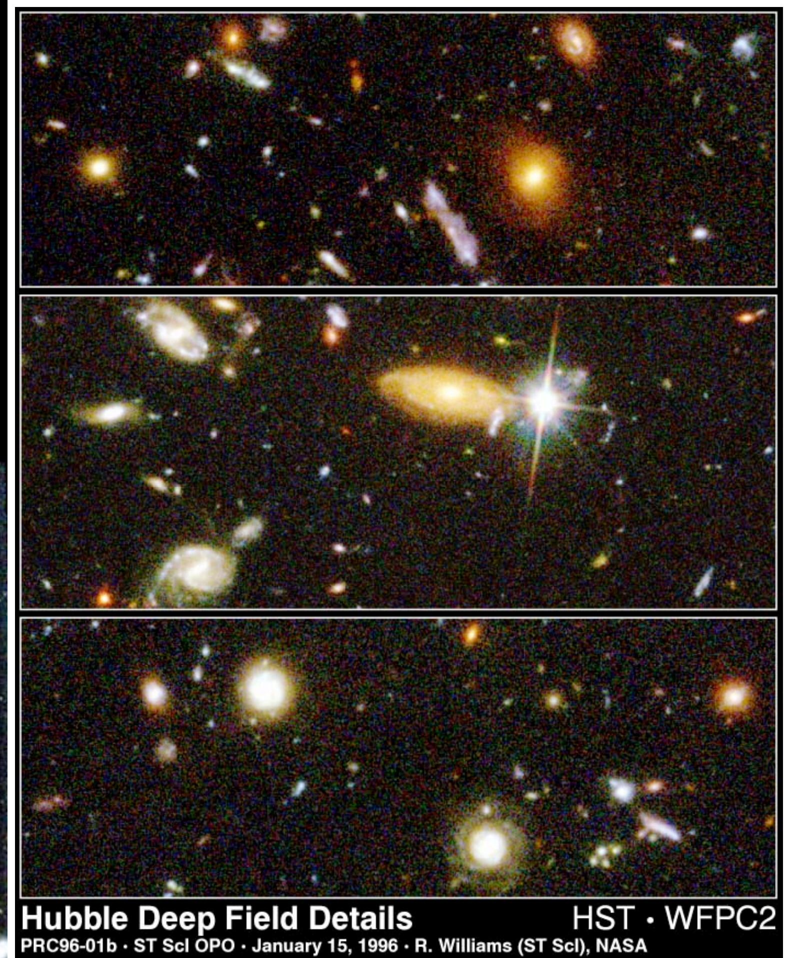
Z ~ 0



Galaxy Cluster Abell 2218 HST • WFPC2
NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08

Distant Past: Hubble Deep Field Z ~ few



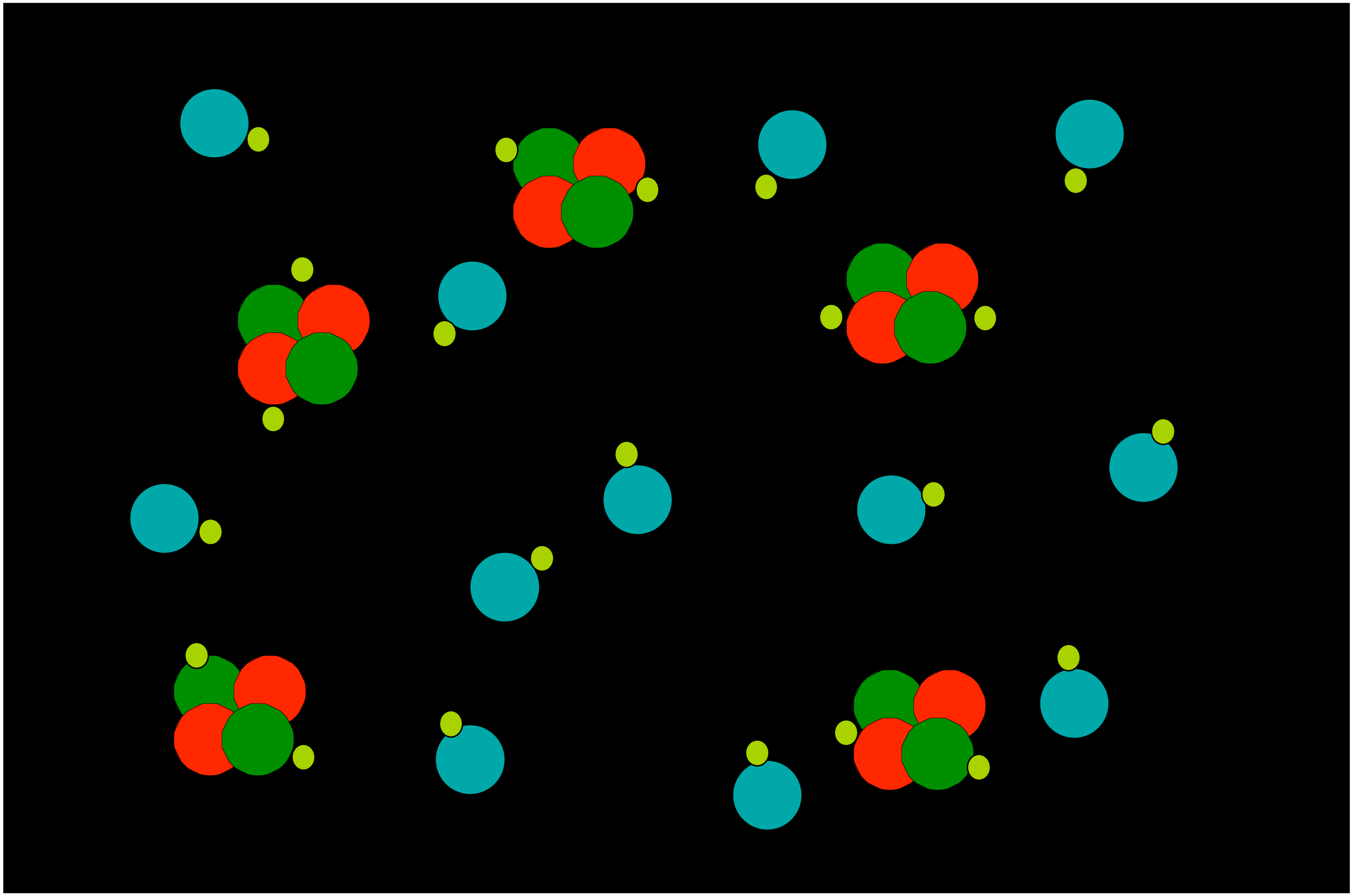


Z > 20±10

Dark Ages…

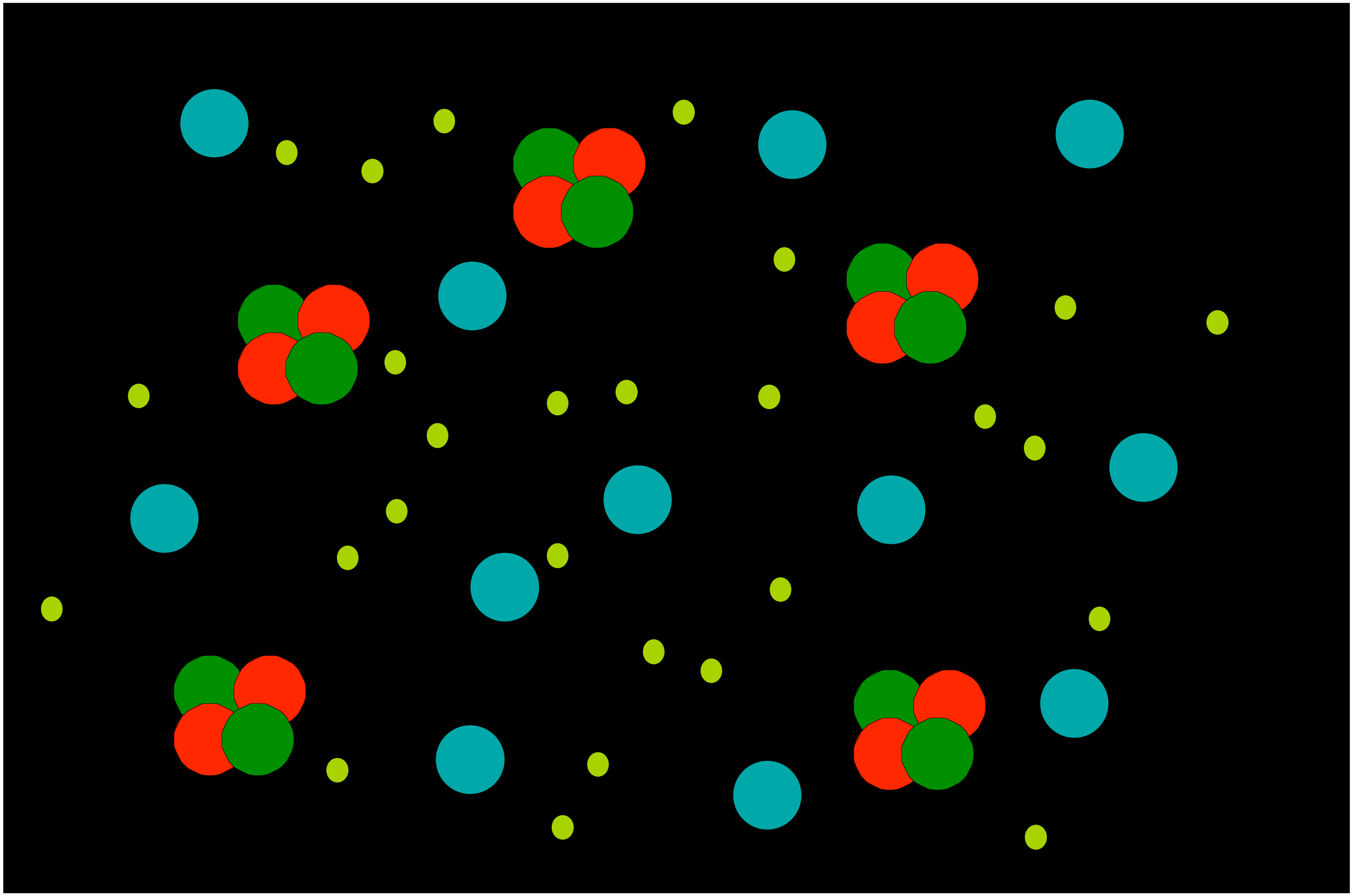
After Recombination

$Z < 1100$

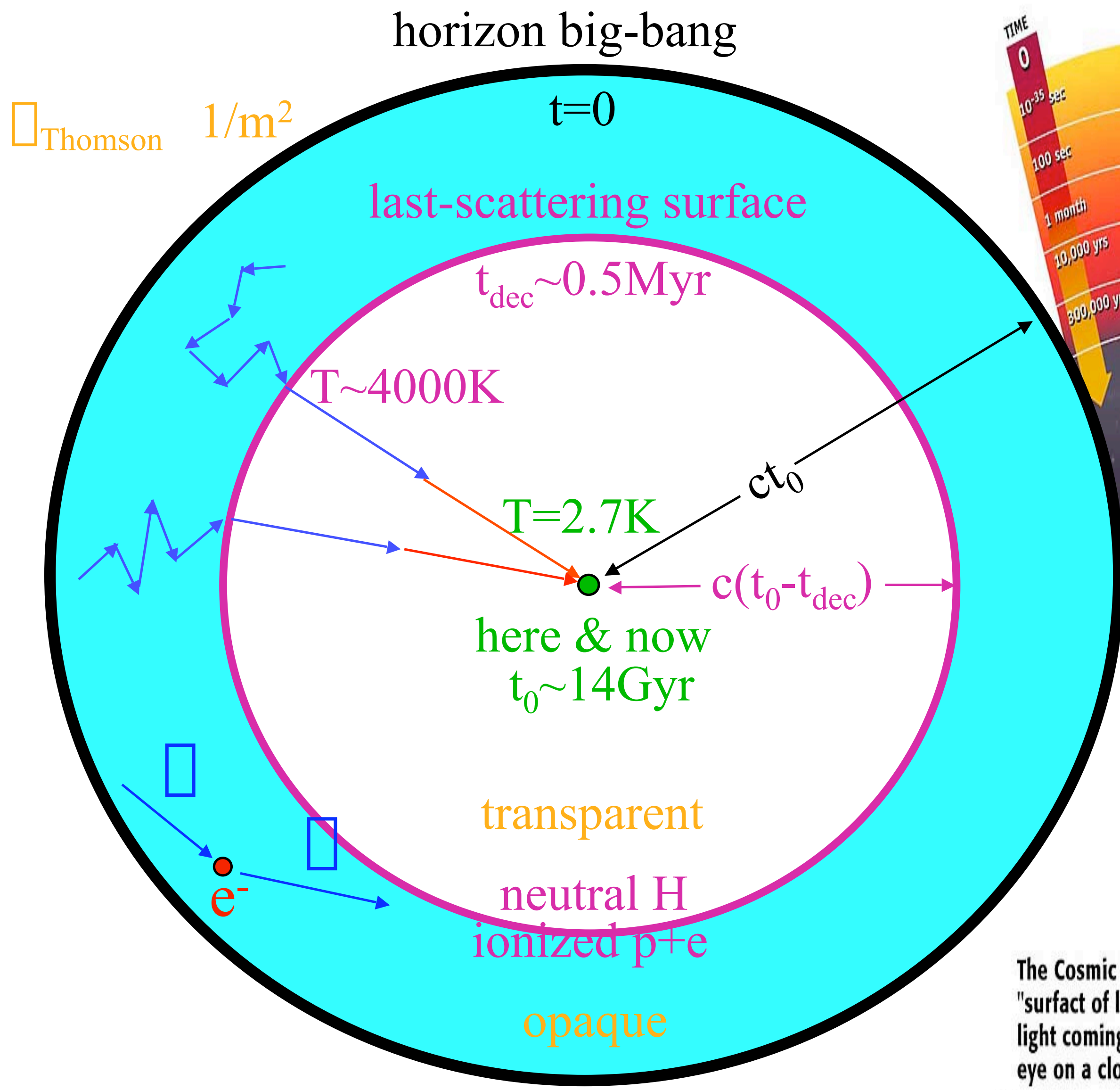


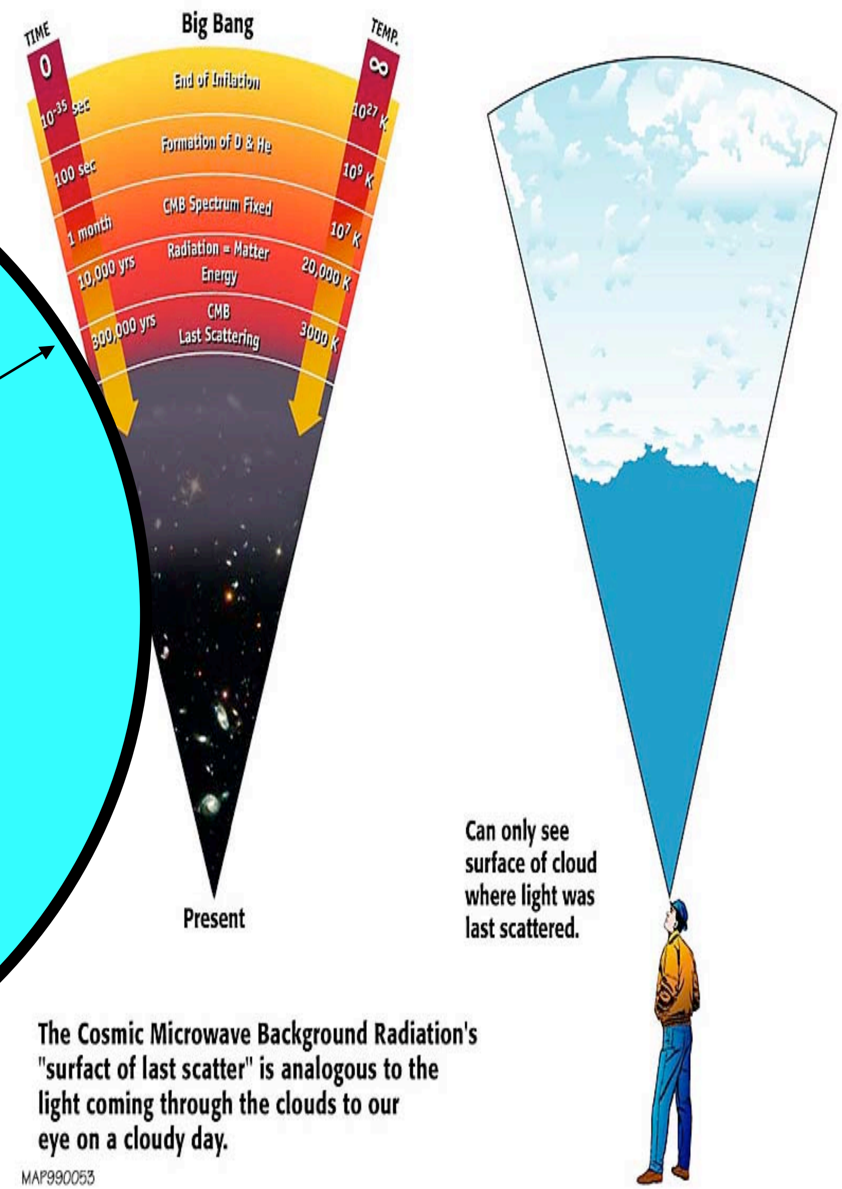
Before Recombination

$Z > 1100$



Cosmic Microwave Background





Thermal History

p+e $\rightarrow$ H   B=13.6 eV

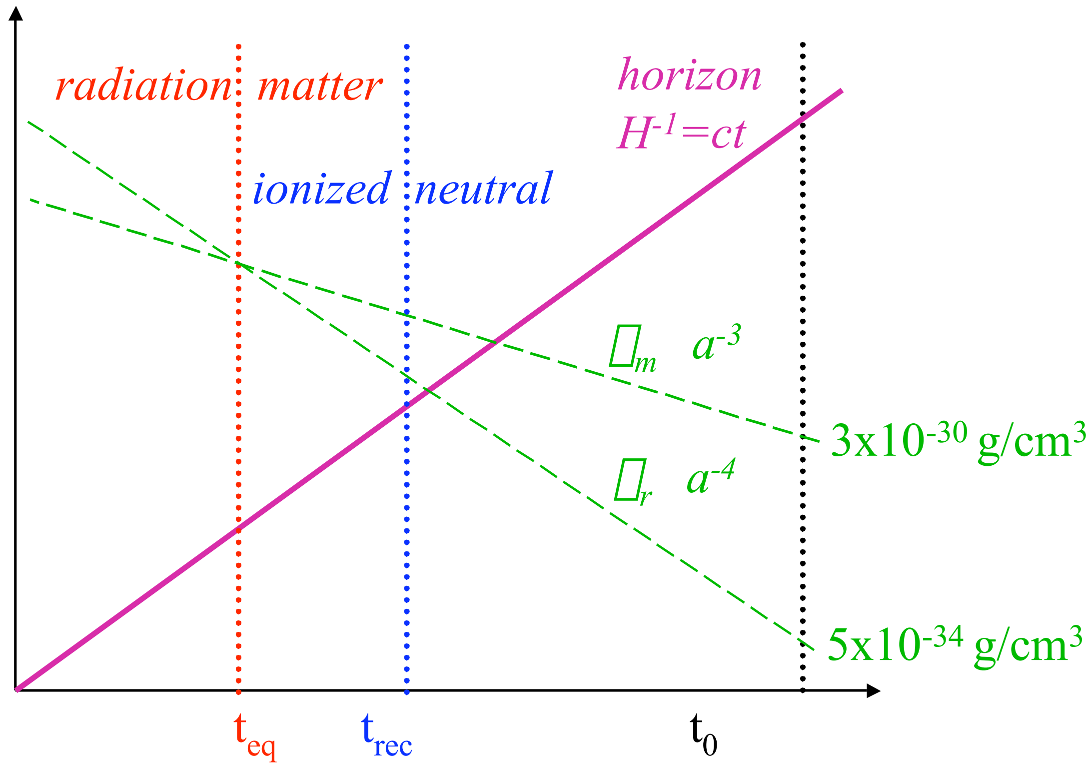
scale r

Saha equation:

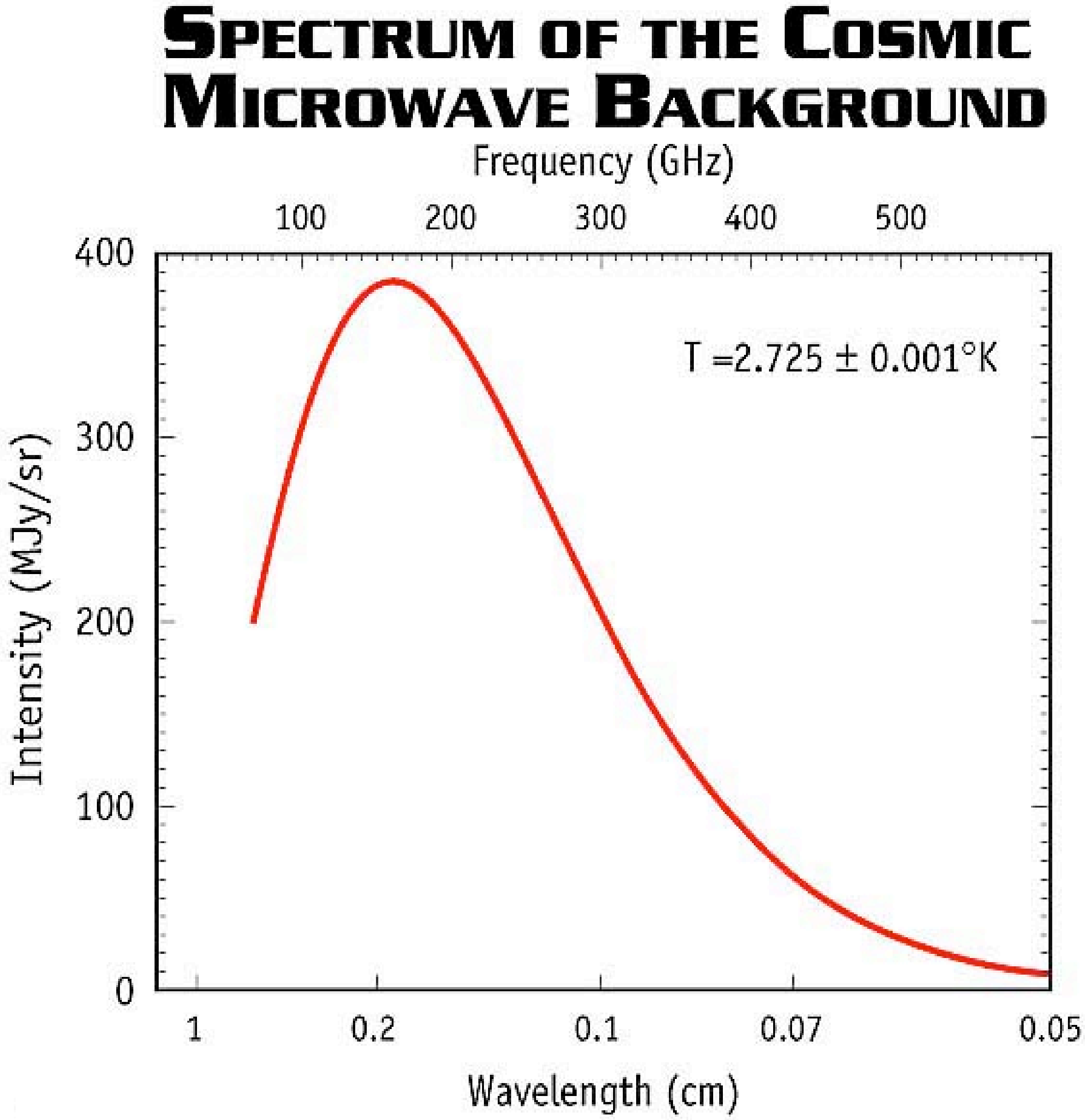
$$\frac{\mathbf{x}^2}{1+\mathbf{x}^2} = \frac{(2\pi m_e k\mathbf{T})^{3/2}}{h^3 \mathbf{n}} e^{-B/k\mathbf{T}}$$

$$\mathbf{x} = \frac{n_e}{n} \quad \mathbf{T} \propto a^{-1} \quad \mathbf{n} \propto a^{-3}$$

x=1/2 at T_{rec}~ 4000 K



t~	10^4y	$5\text{x}10^5$y	$1.5\text{x}10^{10}$y
1+z~	10^4	10^3	1
T~		4000K	2.7K



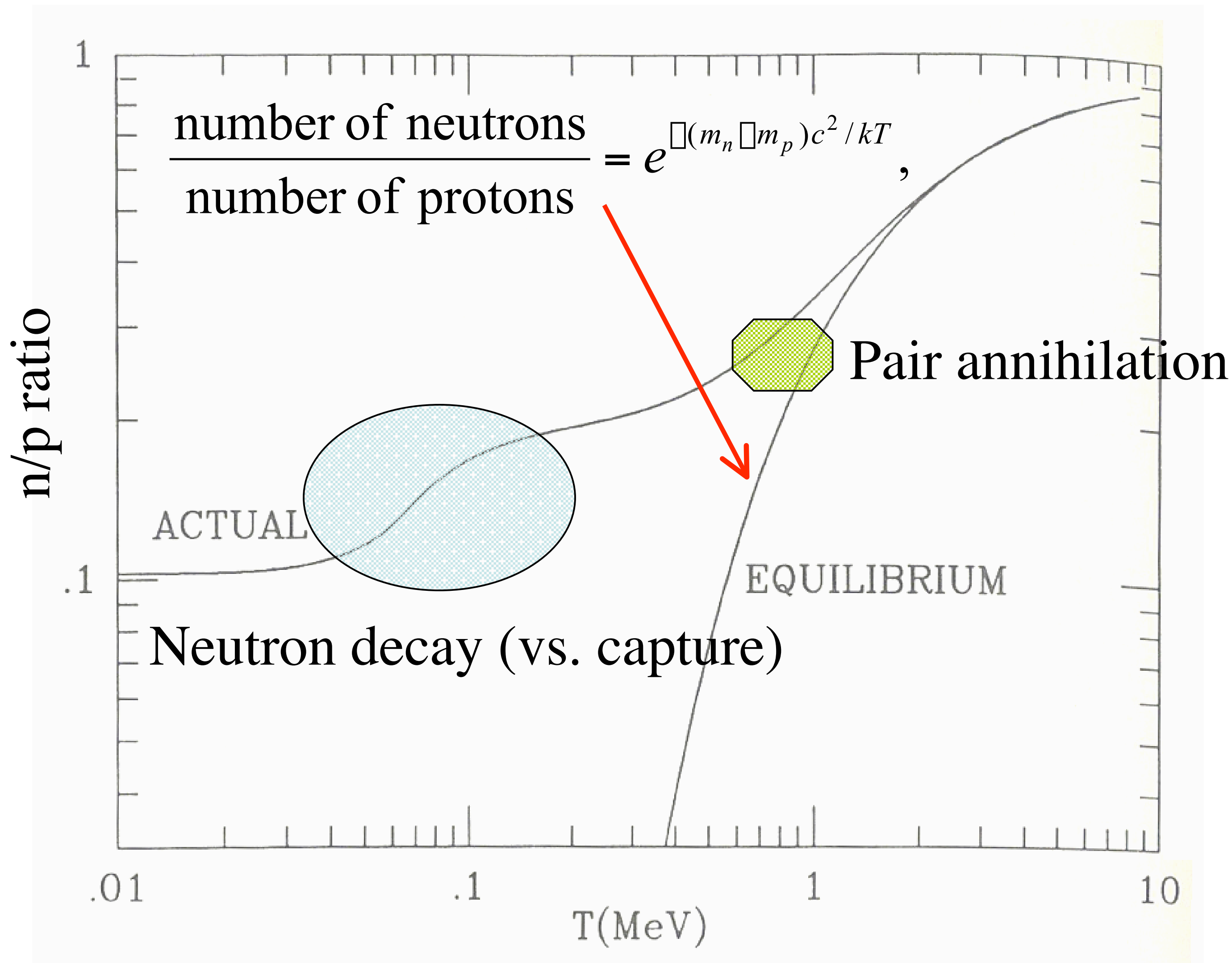
COBE 1992

Plank black-body spectrum

$$I(\nu)d\nu = \frac{2h}{c^2}\frac{\nu^3 d\nu}{e^{h\nu/kT} - 1}$$

I=energy flux per unit area, solid angle, and frequency interval

BBNS (Big-Bang Nucleosynthesis)



Big Bang Nucleosynthesis

$m_n > m_p \Rightarrow n + \nu \rightarrow p + e^-$
only 12.5% n left after decaying to $p \rightarrow$ 75% H + 25% He (in mass)

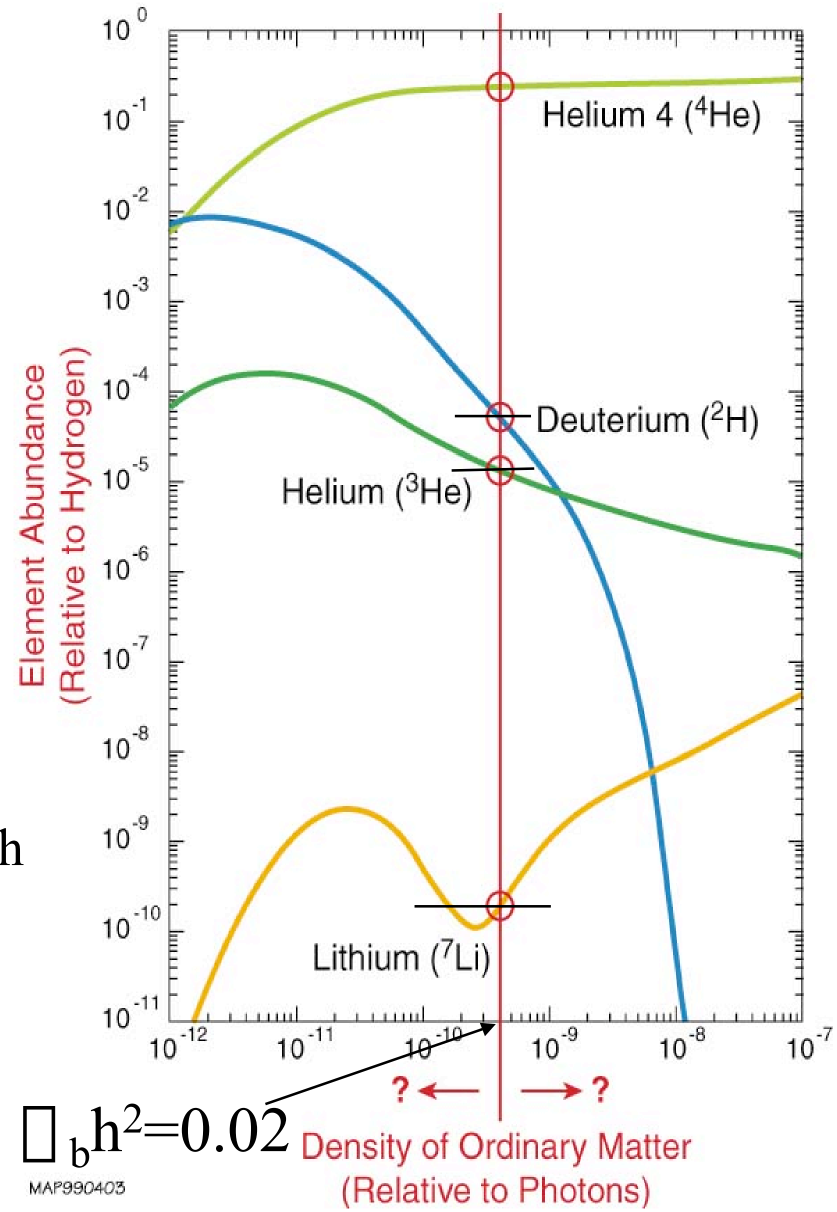
At T~10^9K deuterium becomes stable and nucleosynthesis starts:

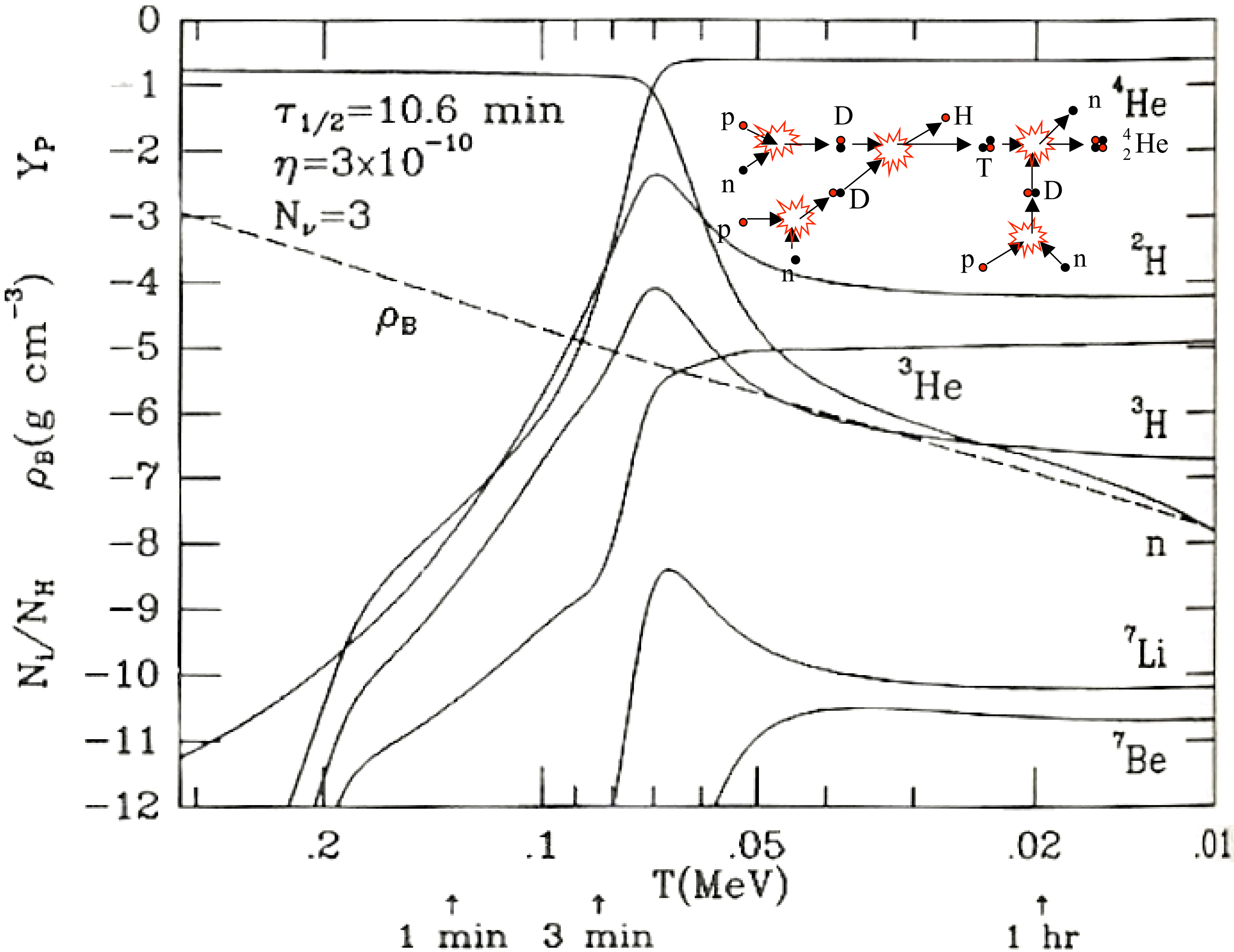
$$p + n \rightarrow d(pn) + \gamma$$

$$d \xrightarrow{p} {}^3He(ppn) \xrightarrow{n} {}^4He$$

A minute later p becomes too cold to penetrate the Coulomb barrier by p in d and process stops. Rate $\propto n_p^2 \Rightarrow$ abundances of d and ^3He decrease with Ω_b

$\Omega_b = 0.04 \pm 0.01$





$\tau_{1/2}$=10.6 min
η=3x10^{-10}
N_ν=3
ρ_B
Y_P
ρ_B(g cm^{-3})
N_i/N_H
^{4}He
^{2}H
^{3}He
^{3}H
n
^{7}Li
^{7}Be
p
n
D
H
T
$^4_2$He
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
.2
.1
.05
.02
.01
T(MeV)
1 min
3 min
1 hr

Higher Temperatures:

- Depends on “Standard Model”
- Phase Transitions
- Inflation?

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

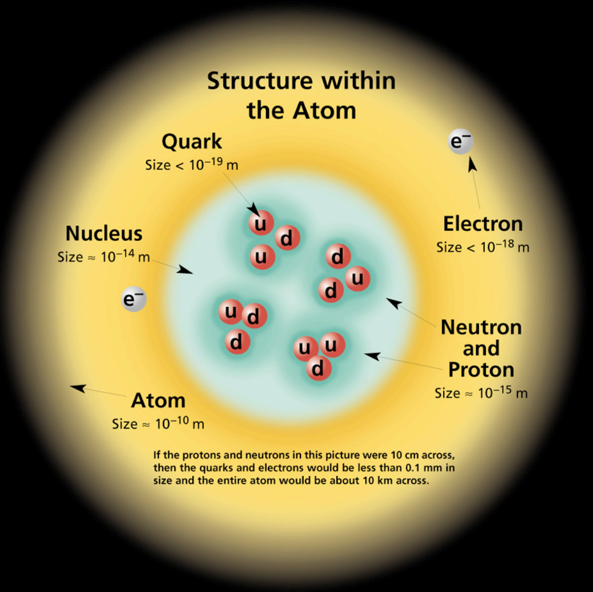
Leptons spin = 1/2		
Flavor	**Mass GeV/c^2**	**Electric charge**
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2		
Flavor	**Approx. Mass GeV/c^2**	**Electric charge**
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	**Mass GeV/c^2**	**Electric charge**
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	**Mass GeV/c^2**	**Electric charge**
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
Strength relative to electromag for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$
Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$
Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

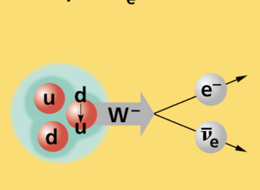
Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

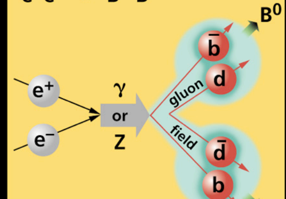
These diagrams are an artist's conception of physical processes. They are *not* exact and have *no* meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

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



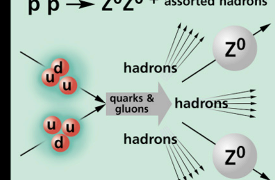
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \rightarrow B^0\, \bar{B}^0$



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

$p\,p \rightarrow Z^0Z^0$ + assorted hadrons



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

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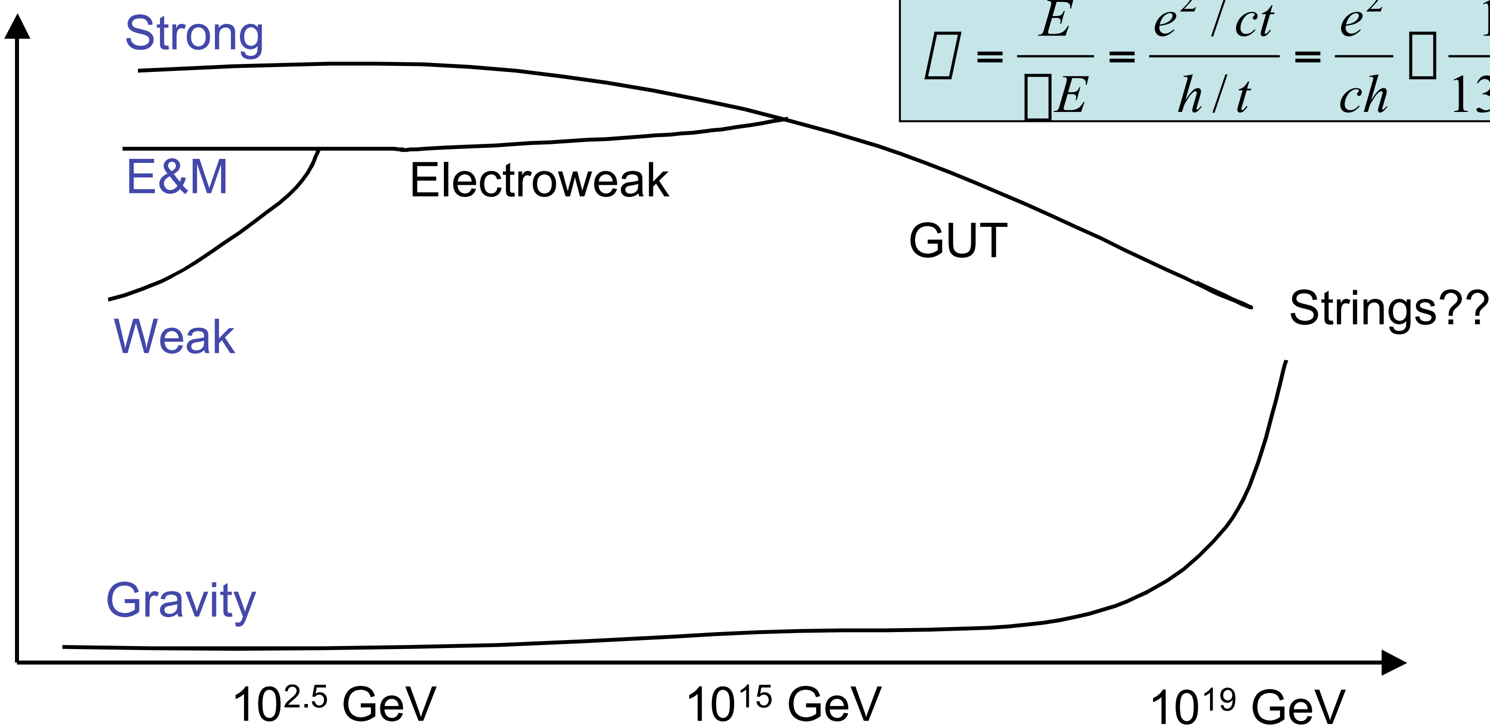
Unification of Forces at High *T*

e.g., strength of E&M interaction:

$$\Delta E \approx h/t$$

$$\alpha = \frac{E}{\Delta E} = \frac{e^2/ct}{h/t} = \frac{e^2}{ch} \approx \frac{1}{137}$$



Phase Transitions

- When a symmetry is broken

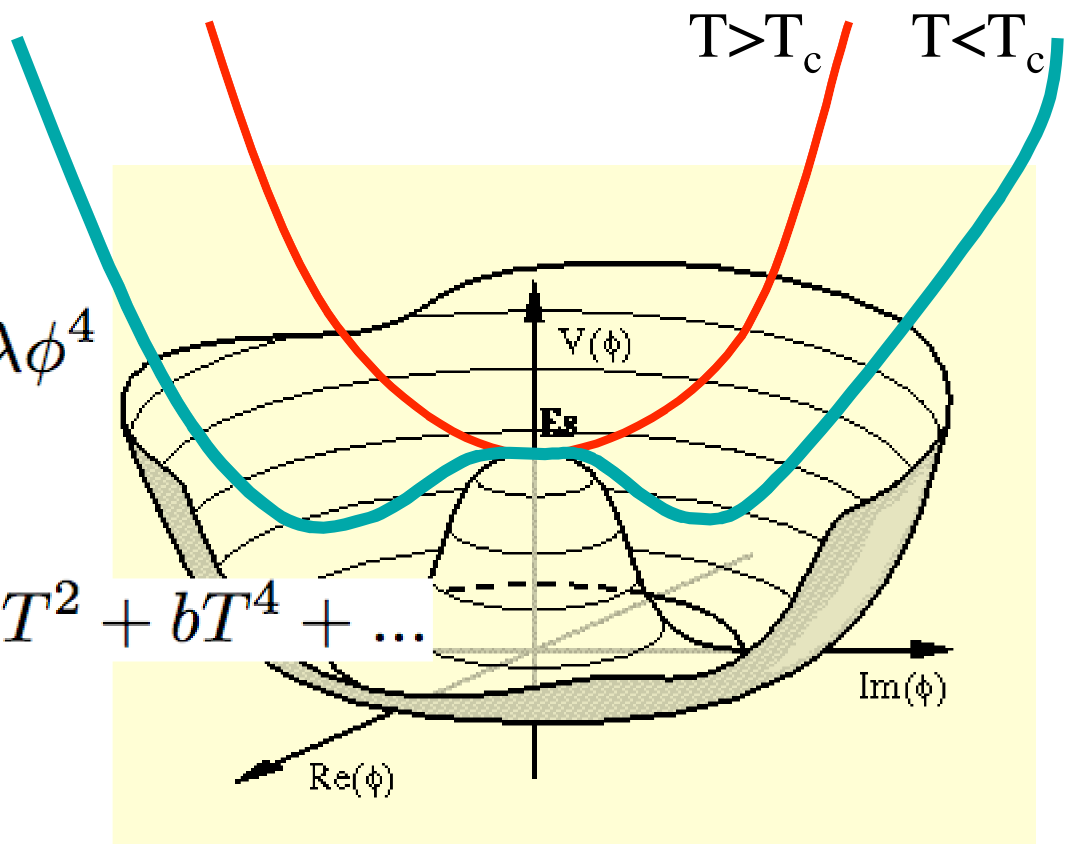
$$\mathcal{L} = \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - V(\phi)$$

$$V(\phi) = -\frac{1}{2}m^2\phi^2 + \frac{1}{4}\lambda\phi^4$$

At finite T:

$$V(\phi, T) = V(T) + a\phi^2 T^2 + bT^4 + \dots$$

$$a \approx \frac{\lambda}{48}$$



Planck Scale

quantum fluctuations gravity horizon

$$\Delta E \cdot t \approx h \qquad E \approx mc^2 \approx \frac{Gm^2}{l} \qquad l \approx ct$$

$$m_P = \left(\frac{hc}{G}\right)^{1/2} \approx 2.5 \times 10^{-5}\, g$$

$$E_P = \left(\frac{hc^5}{G}\right)^{1/2} \approx 1.2 \times 10^{19}\, GeV$$

$$t_P = \left(\frac{hG}{c^5}\right)^{1/2} \approx 10^{-43}\, s$$

$$l_P = \left(\frac{Gh}{c^3}\right)^{1/2} \approx 1.7 \times 10^{-33}\, cm$$

$$T_P \approx 6 \times 10^{30}\, K$$

$$\frac{a_P}{a_0} \approx \left(\frac{t_P}{t_0}\right)^{1/2} \approx 5 \times 10^{-31}$$

$$\rho_P \approx 1.2 \times 10^{93}\, g / cm^3$$