Cosmology

Master NPAC

Lesson 4 :
Universe Thermodynamics : Thermal History
Primordial Nucleosynthesis

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4.1

Thermal History
An Overview

Eras : radiation, matter, « vacuum »

- Radiation dominated

$$\varepsilon_r(t) = \varepsilon_{r,0} a(t)^{-4}$$

$$a(t) \propto t^{1/2} \qquad \varepsilon(t) \propto a^{-4} \propto t^{-2}$$

- Matter dominated

$$\varepsilon_m(t) = \varepsilon_{m,0} a(t)^{-3}$$

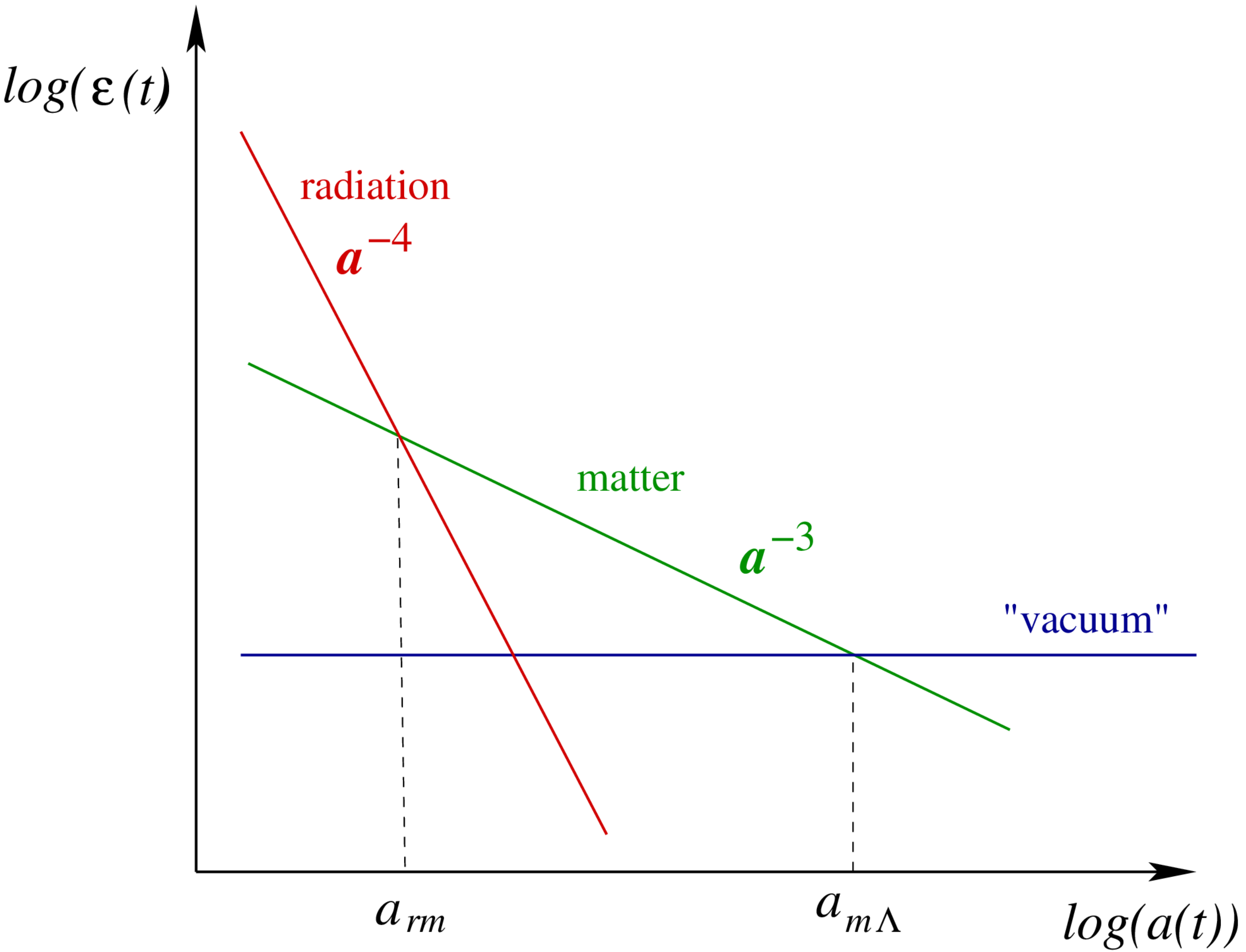
$$a(t) \propto t^{2/3} \qquad \varepsilon(t) \propto a^{-3} \propto t^{-2}$$

- « vacuum » dominated Λ

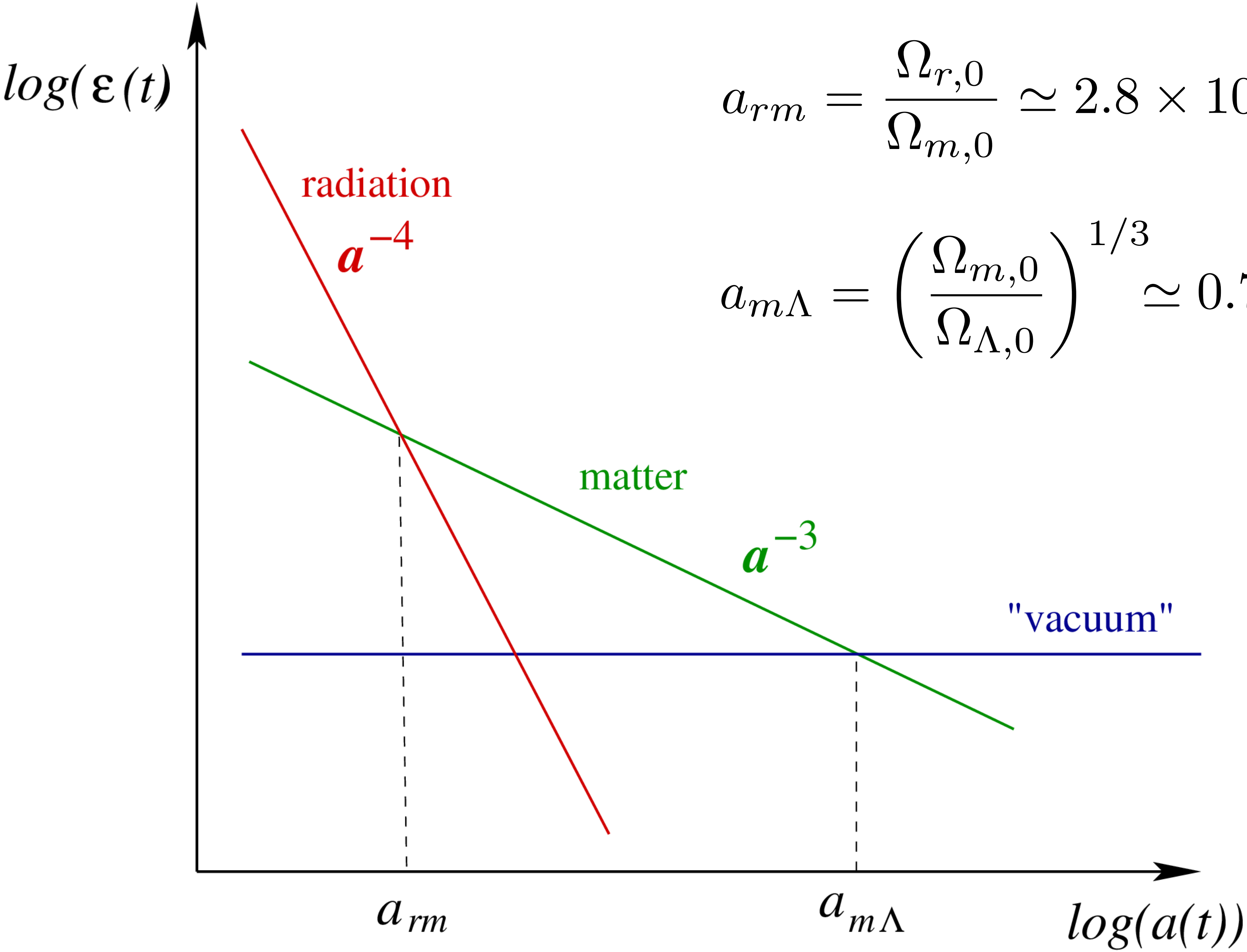
$$\varepsilon_\Lambda(t) = \varepsilon_{\Lambda,0} = \mathrm{cste} \quad H(t) = H_0 = \mathrm{cste}$$

$$a(t) \propto e^{H_0 t}$$

Eras : radiation, matter, « vacuum »



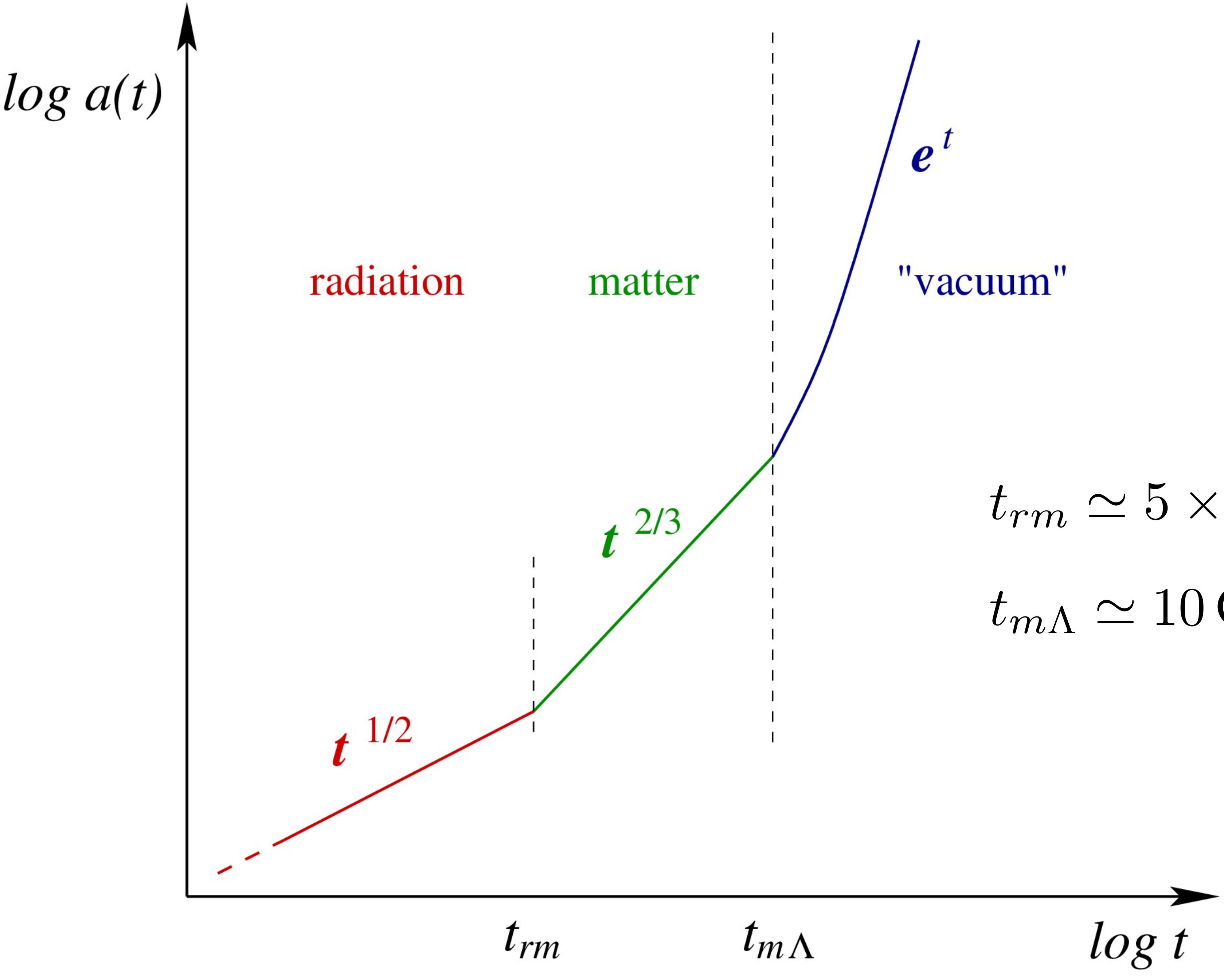
Eras : radiation, matter, « vacuum »



$$a_{rm} = \frac{\Omega_{r,0}}{\Omega_{m,0}} \simeq 2.8 \times 10^{-4}$$

$$a_{m\Lambda} = \left(\frac{\Omega_{m,0}}{\Omega_{\Lambda,0}} \right)^{1/3} \simeq 0.75$$

Eras : radiation, matter, « vacuum »



$$t_{rm} \simeq 5 \times 10^4 \, \mathrm{yr}$$

$$t_{m\Lambda} \simeq 10 \, \mathrm{Gyr}$$

The Universe expands...

$$H^2(t) = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2}\varepsilon - \frac{kc^2}{R_0^2 a^2}$$

$$\frac{H^2(t)}{H_0^2} = \Omega_{r,0}a^{-4} + \Omega_{m,0}a^{-3} + \Omega_{\Lambda,0} + \cdots + (1-\Omega_0)a^{-2}$$

Entropy is being conserved $TdS = dE + p\,dV = 0$

any heat flow would defined a prefered direction → isotropy

The Universe expands ***adiabatically****, like a fluid in equilibrium*

Radiation $a(t) \propto t^{1/2}$ $\varepsilon(t) \propto a^{-4} \propto t^{-2}$ $T \propto a^{-1} \propto t^{-1/2}$

The Universe ***cools down*** *while expanding...*

→ ***hotter*** *and* ***denser*** *in the past...*

Cosmic Microwave Background (CMB)

A. A. Penzias & R. W. Wilson (1965)

Black Body spectrum (microwave)

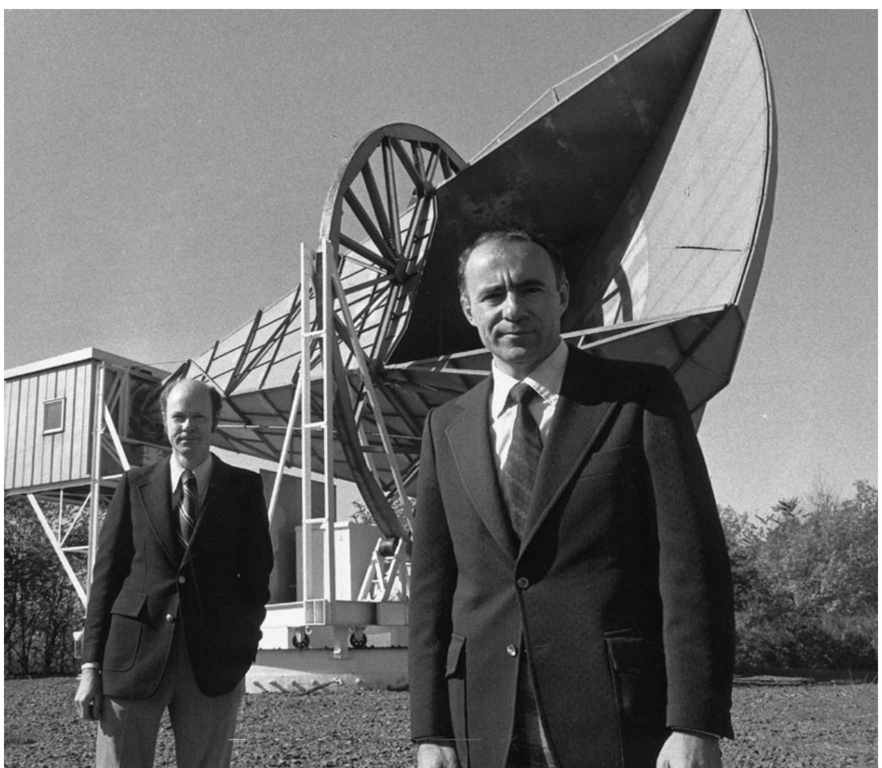
T ~ 2.73 K   (BB spectrum up to 10^{-5})

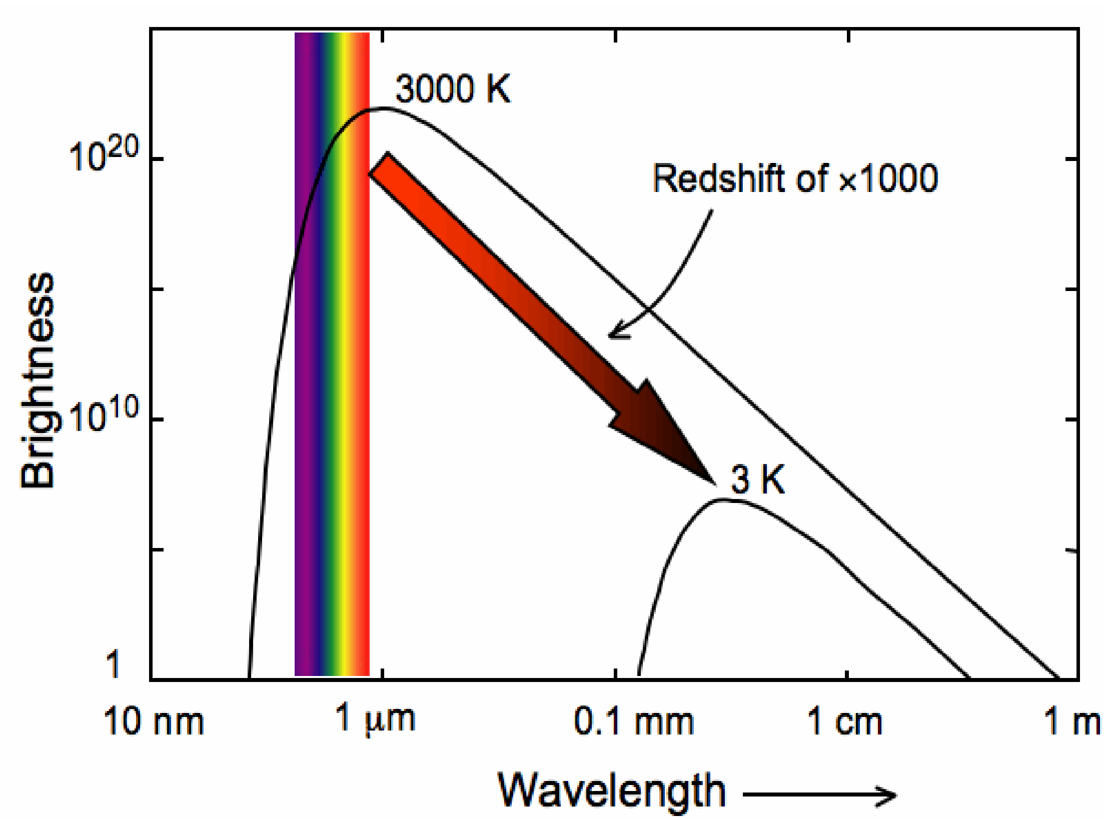
Predicted by the « hot Big Bang » model

Hot Universe in the Past

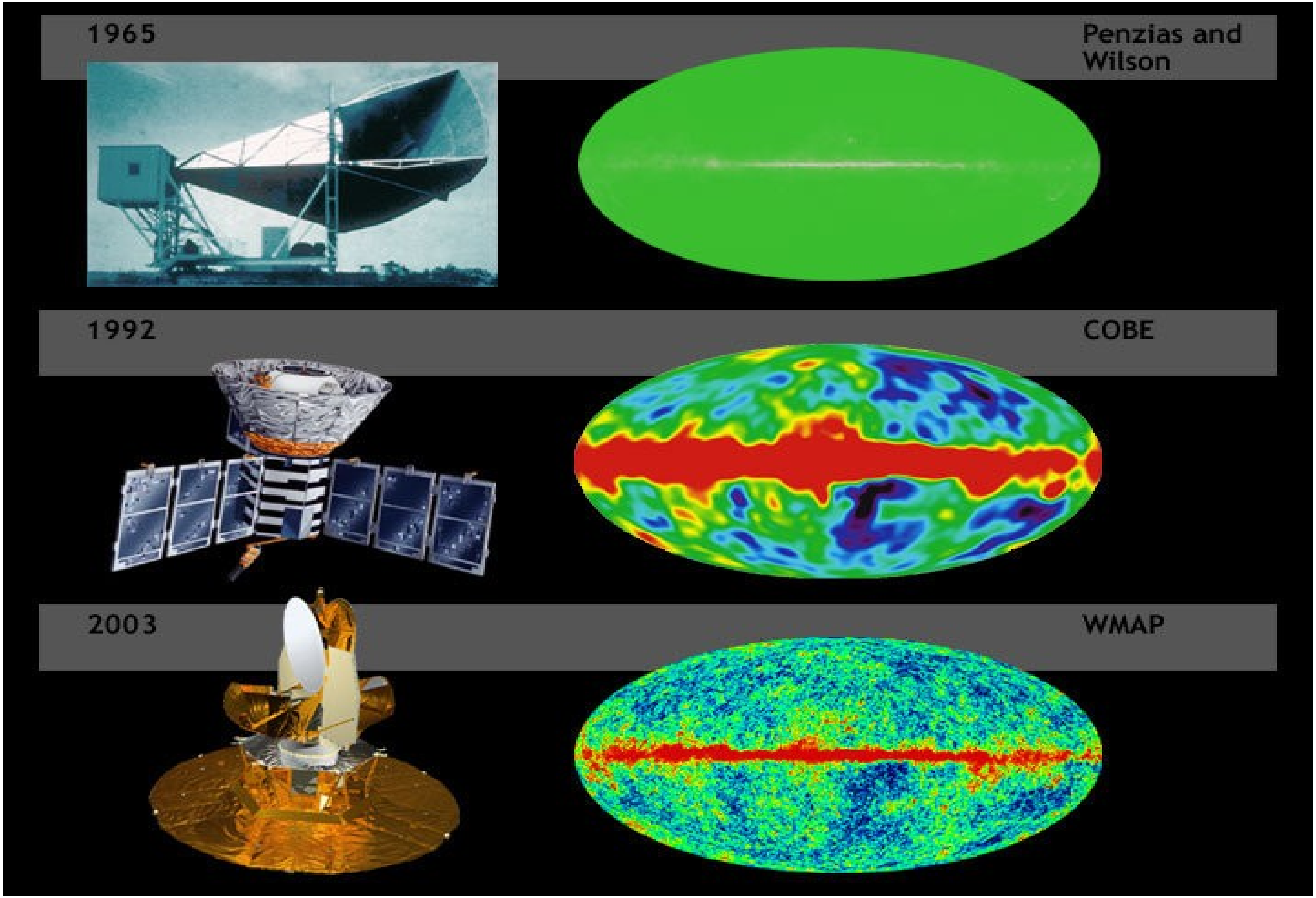
Black body spectrum emitted at the time of last ionizations (decoupling of photons and matter)

T ~ 2.73 K implies a redshift of ~1100





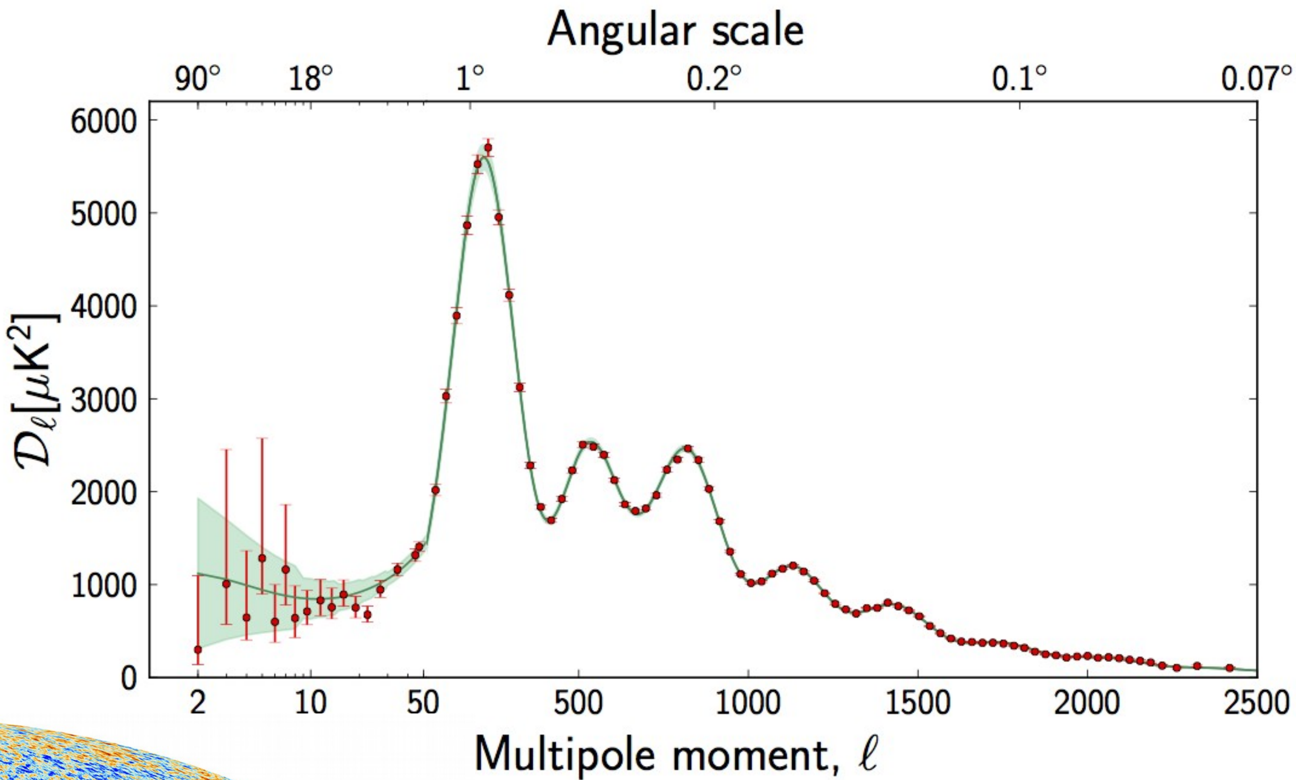
Cosmic Microwave Background (CMB)

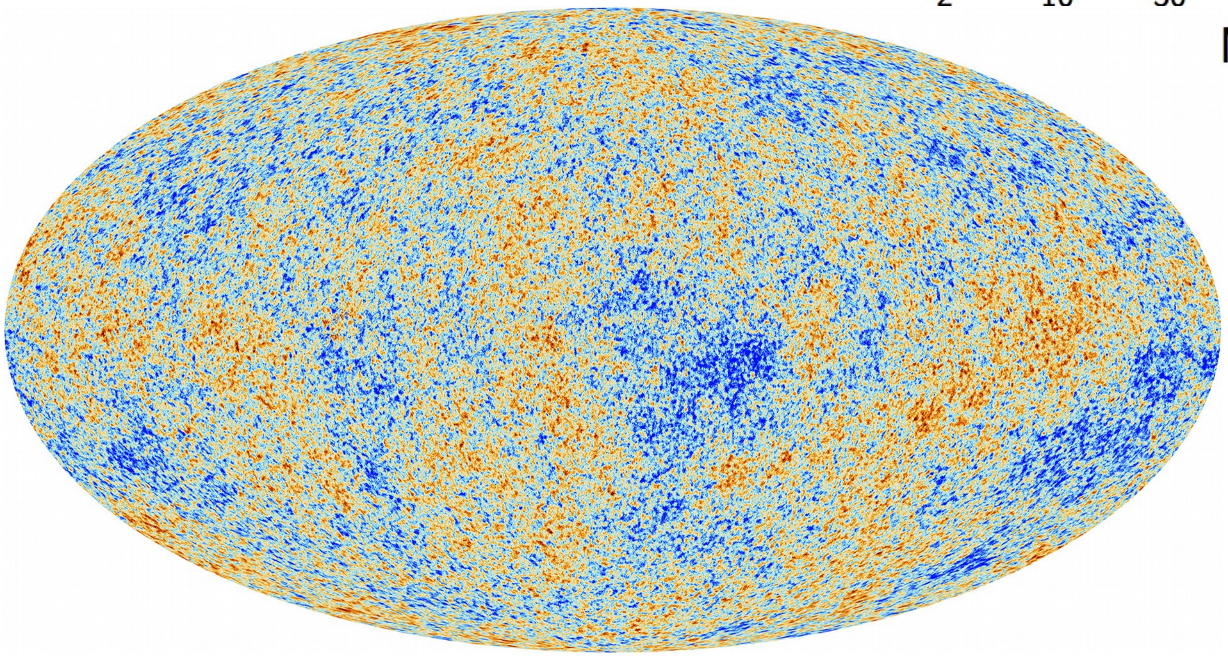


Cosmic Microwave Background (CMB)

Anisotropies reveal densities fluctuations at the time of emission of the CMB

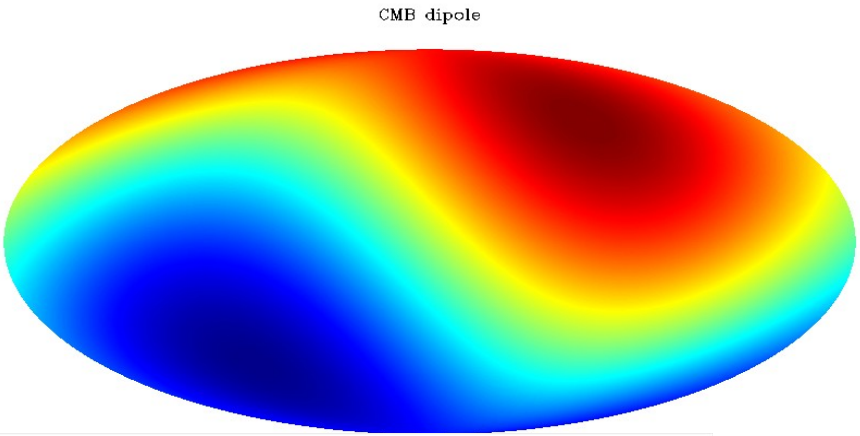
z~1100
Age ~ 370 000 y

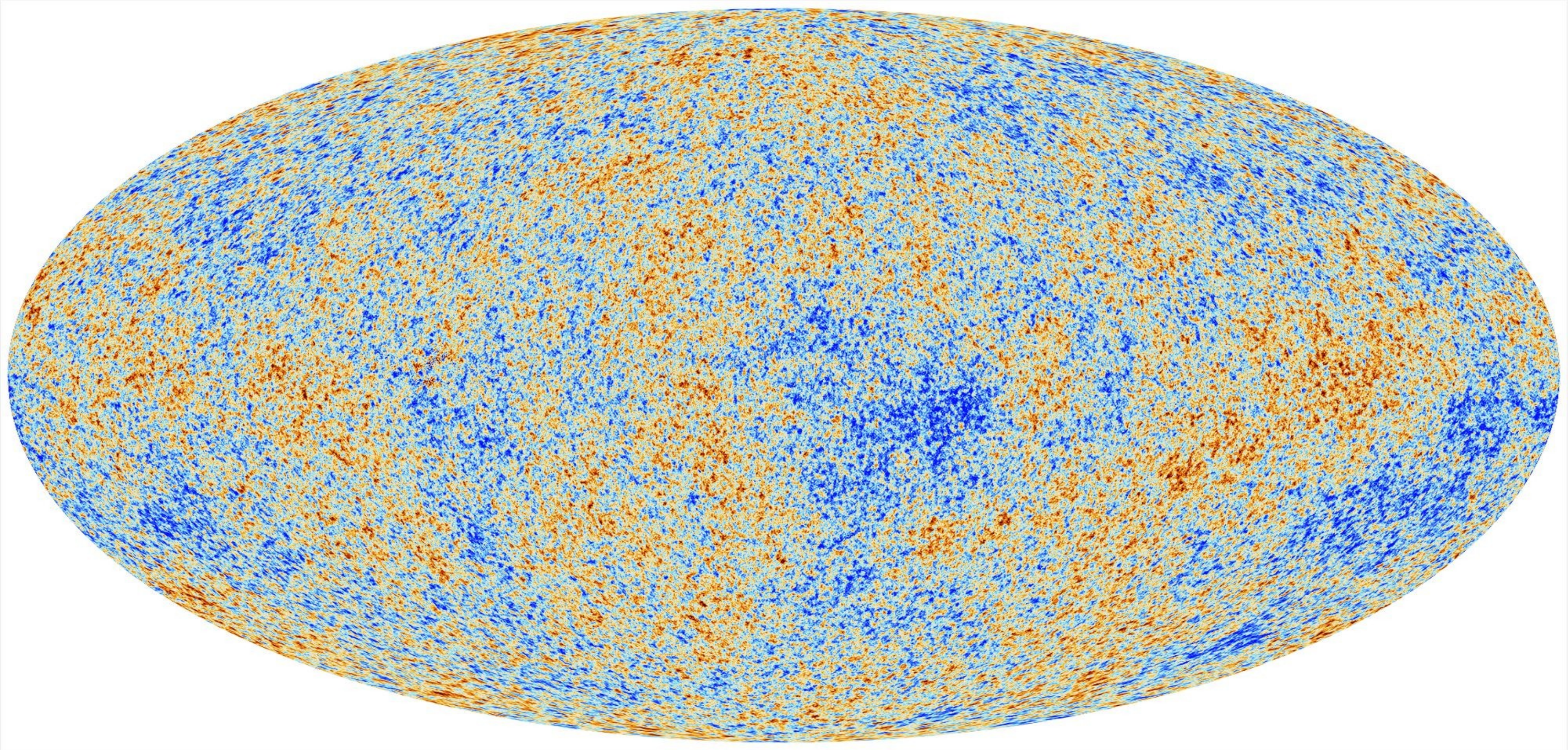




Planck
2009-2012

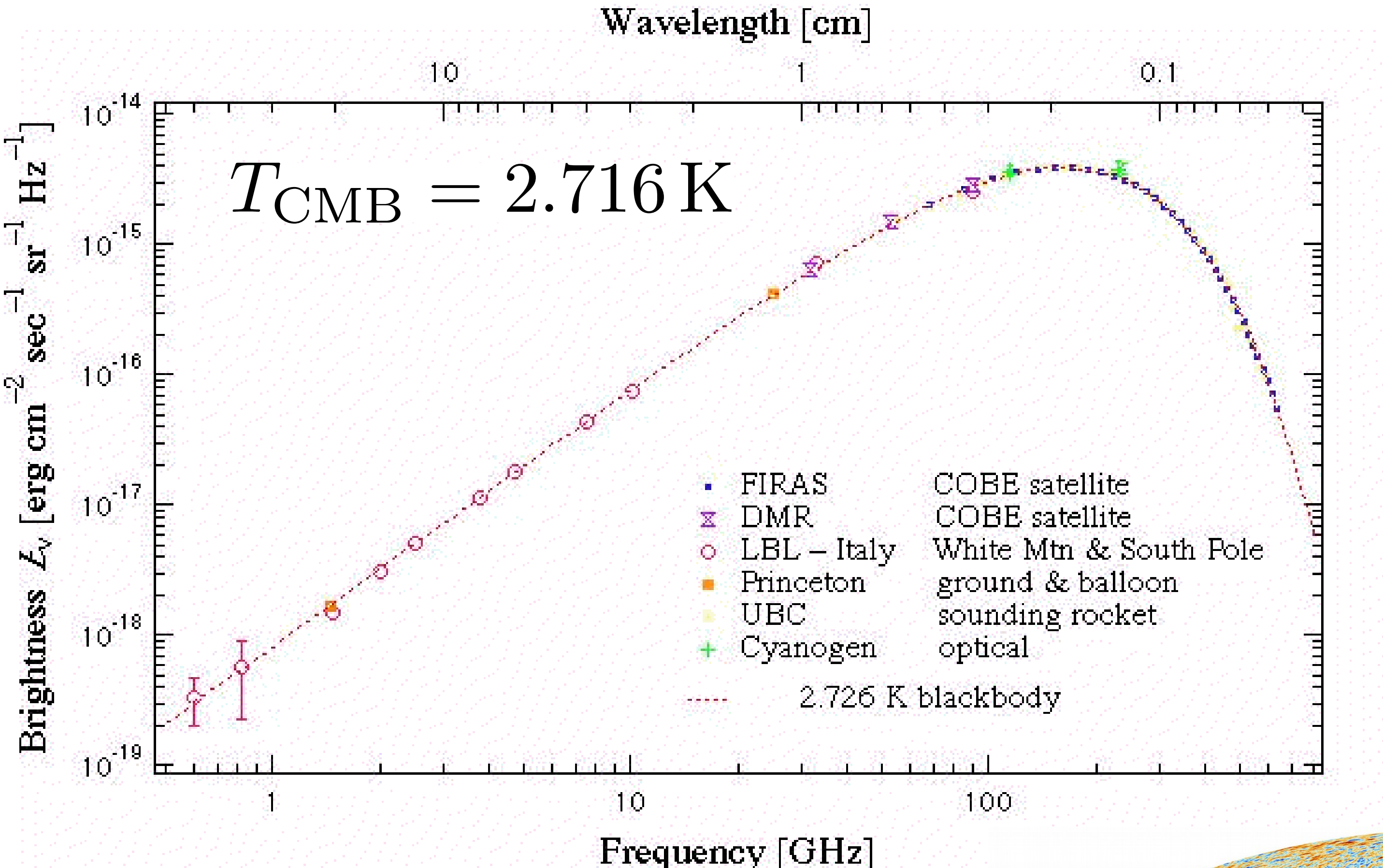
CMB
nearly perfect black body spectrum





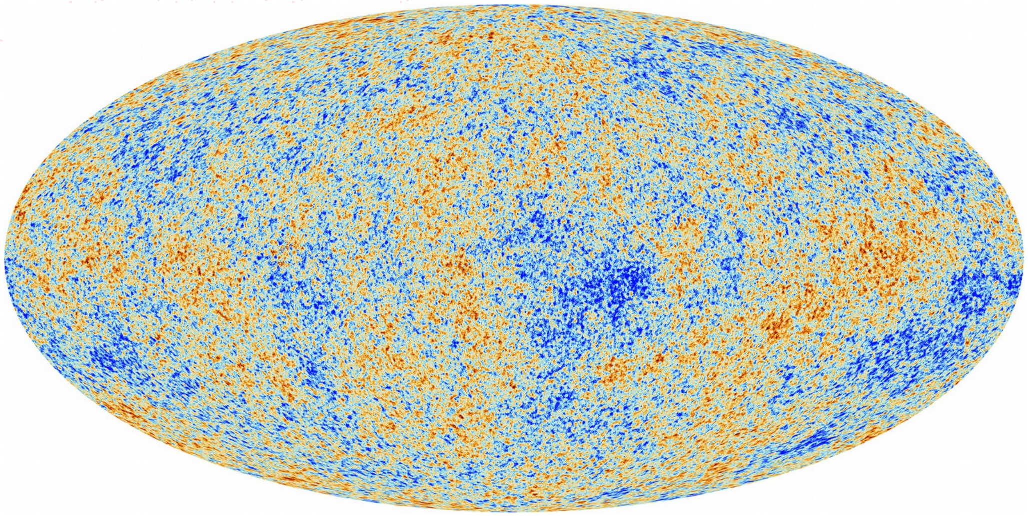
Anisotropies at the level of 10^{-5} (once dipole is removed)

Hot Big Bang theory : CMB



$$I(\nu, T) \propto \frac{\nu^3}{e^{h\nu/kT} - 1}\, d\nu$$

$$T \propto a^{-1} = 1 + z$$



Hot Big Bang theory : CMB

- Cosmic microwave background (CMB)
  - black body (BB) spectrum at 2.7 K

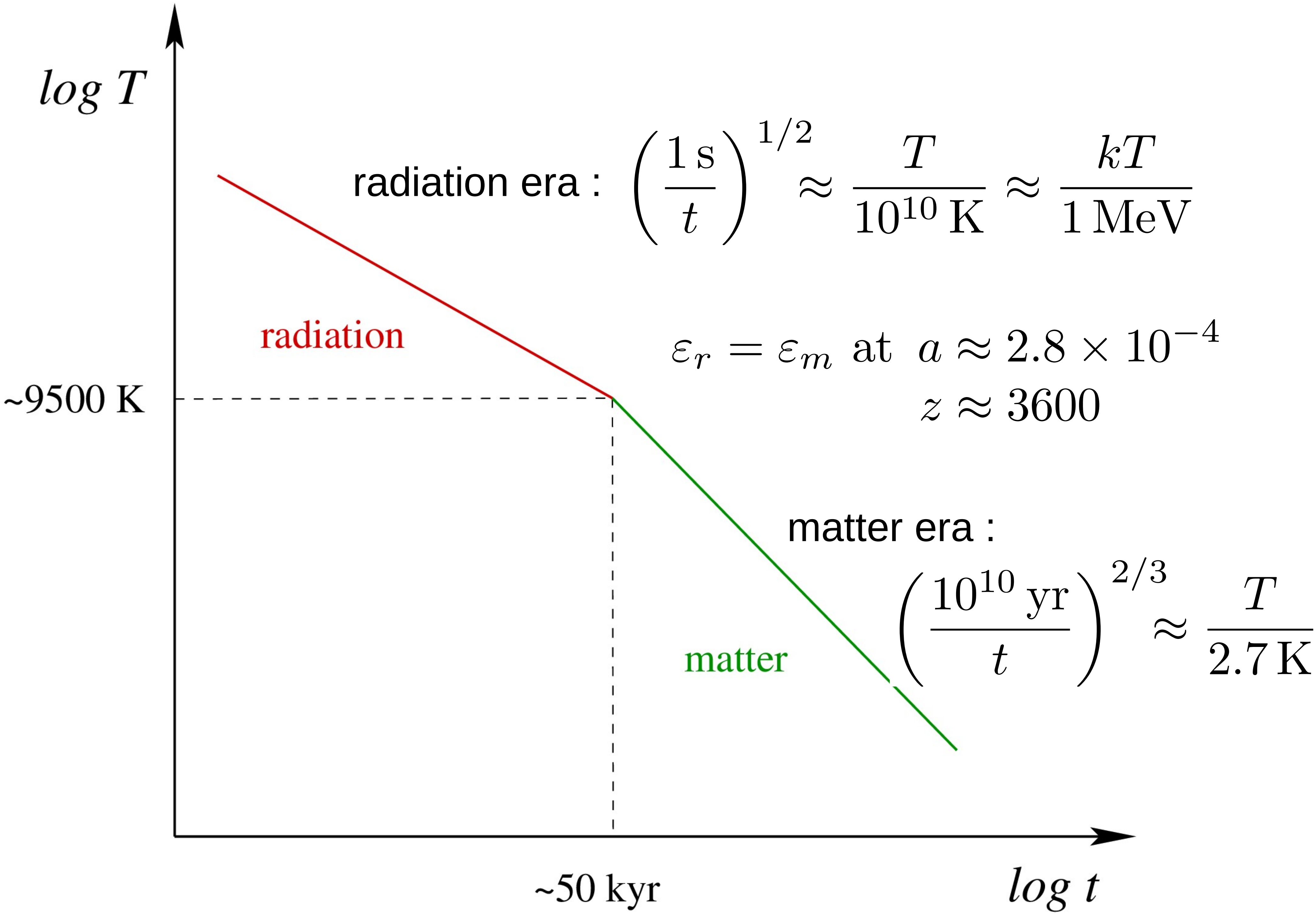
  → recombination of H^+ and e^- around *T*~3000 K

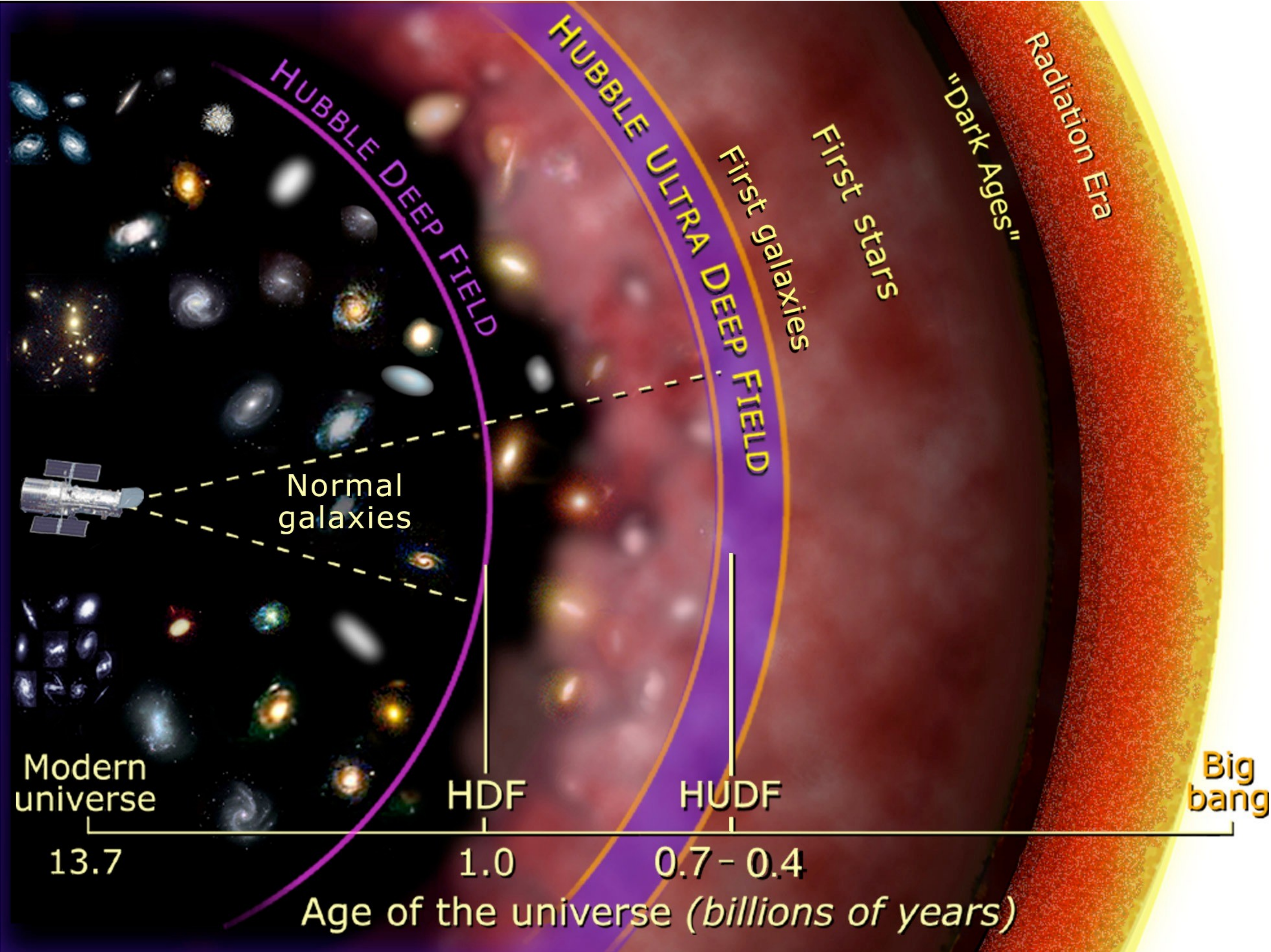
- redshifted by the expansion $\frac{\nu_{\mathrm{emit}}}{\nu_{\mathrm{obs}}} = \frac{\lambda_{\mathrm{obs}}}{\lambda_{\mathrm{emit}}} = 1 + z = \frac{1}{a_{\mathrm{emit}}}$
  - BB spectrum redshifted is still a BB spectrum !

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

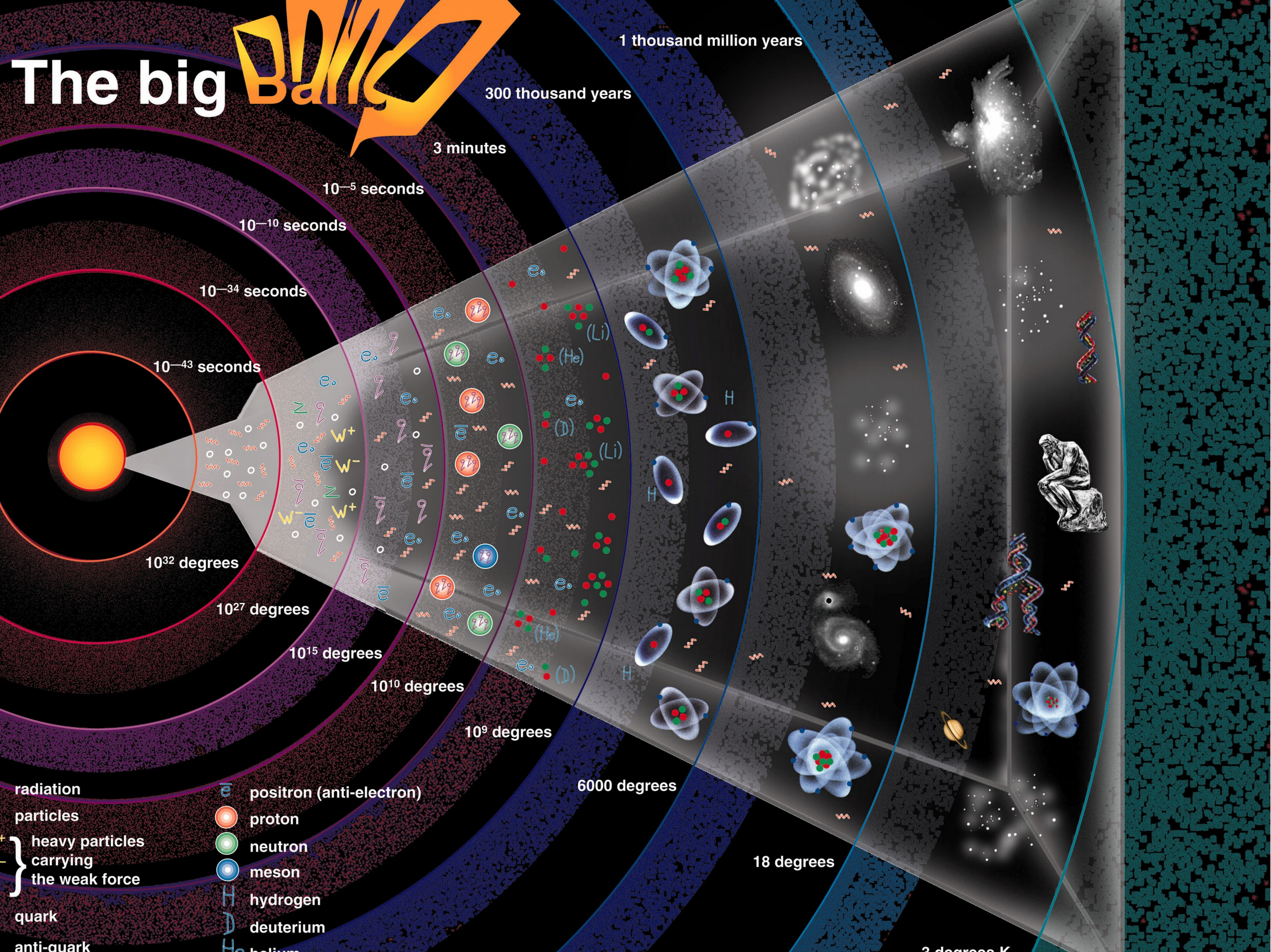
$$z_{\mathrm{CMB}} \approx 1100 \qquad T_{\mathrm{CMB},0} = \frac{T_{\mathrm{CMB}}}{1+z}$$

Universe : cooling history



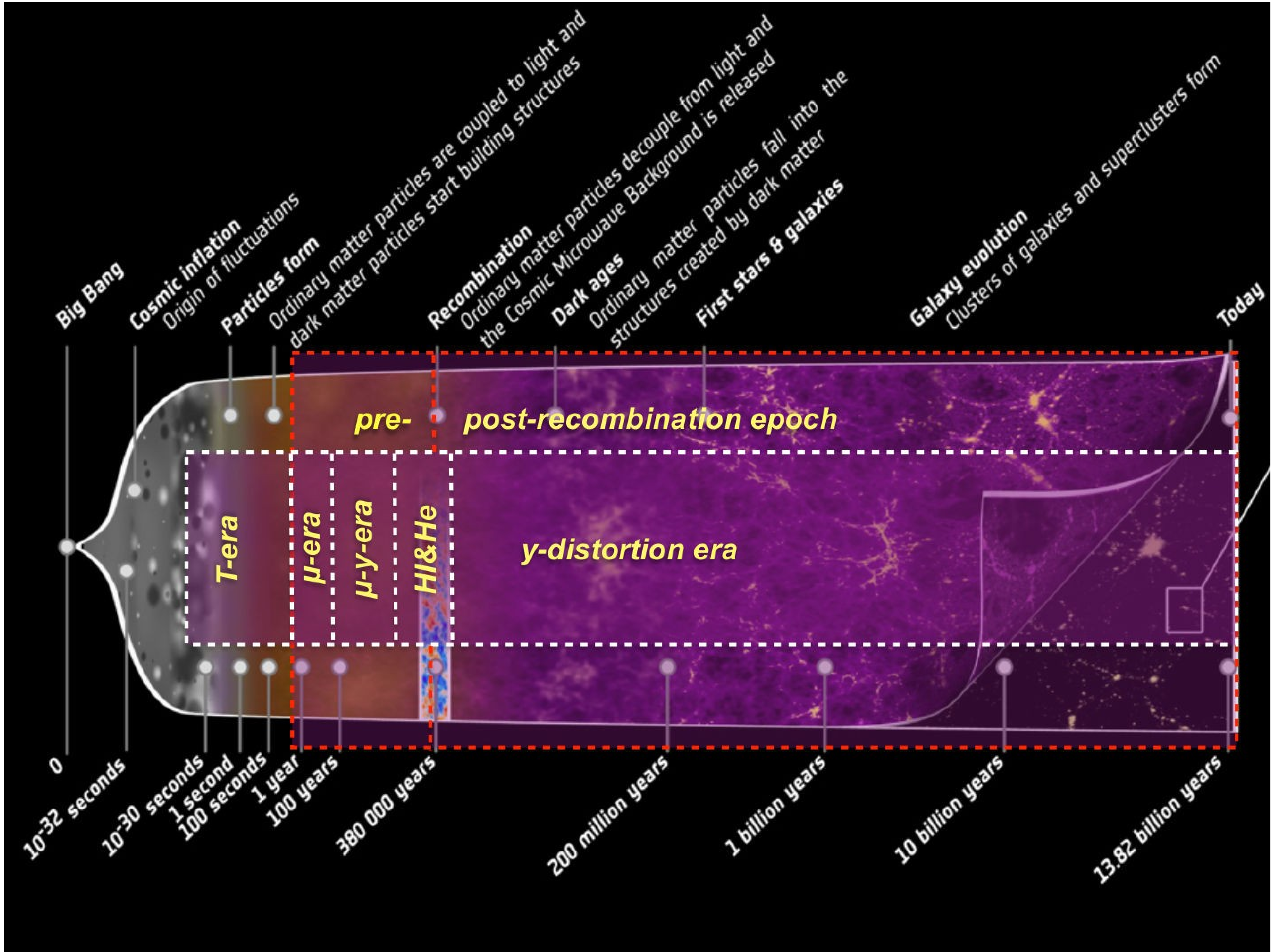


HUBBLE DEEP FIELD
HUBBLE ULTRA DEEP FIELD
First galaxies
First stars
"Dark Ages"
Radiation Era
Normal galaxies
Modern universe
HDF
HUDF
Big bang
13.7
1.0
0.7 – 0.4
Age of the universe (billions of years)


The big Bang
1 thousand million years
300 thousand years
3 minutes
10^{-5} seconds
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 degrees
18 degrees
W^+
W^-
Z
(Li)
(He)
(D)
H
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium

Universe : cooling history

Event	T	kT	z	t
Quantum gravity	10^{32} K	10^{19} GeV	10^{32}	10^{-43} s
Grand unification	10^{28} K	10^{15} GeV	10^{28}	10^{-36} s
E-W unification	$10^{15.5}$ K	250 GeV	10^{15}	10^{-12} s
Nucleon pairs	10^{13} K	1 GeV	10^{13}	10^{-7} s
Neutrino decoupl.	10^{10} K	~1 MeV	10^{10}	1 s
Nucleosynthesis		10-0.1 MeV		10^{-1} – 10^{3} s
Pairs e+ e-	$10^{9.7}$ K	0.5 MeV	$10^{9.5}$	4 s
$\varepsilon_r = \varepsilon_m$	9500 K	0.8 eV	3600	50 kyr
Recombination	3000 K	3 eV	1100	380 kyr
Reionization			11 – 4	0.4 – 0.1 Myr
First Galaxies	16 K	10^{-3} eV	5	1 Gyr
$\varepsilon_m = \varepsilon_\Lambda$		3 10^{-4} eV	0.3	10 Gyr
Now	2.7 K	2 10^{-4} eV	0	13.5 Gyr



Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
pre-
post-recombination epoch
T-era
μ-era
μ-y-era
HI&He
y-distortion era
0
10^{-32} seconds
10^{-30} seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

Planck scales : mass, time, length, ...

- Fundamental constants :

$$\hbar = h/2\pi = 1.055 \times 10^{-34}\,\mathrm{J\cdot s} = 6.579 \times 10^{-15}\,\mathrm{eV\cdot s}$$

$$G = 6.674 \times 10^{-11}\,\mathrm{kg}^{-1}\cdot\mathrm{m}^3\cdot\mathrm{s}^{-2}$$

$$c = 299\,792\,458\,\mathrm{m}\cdot s^{-1}$$

- « Natural » units : $\hbar^\alpha c^\beta G^\gamma$
  - Planck length $\ell_{\mathrm{Pl}} = \sqrt{\dfrac{\hbar G}{c^3}} = 1.616 \times 10^{-35}\,\mathrm{m}$
  - Planck time $t_{\mathrm{Pl}} = \ell_{\mathrm{Pl}}/c = 5.391 \times 10^{-44}\,\mathrm{s}$
  - Planck mass $m_{\mathrm{Pl}} = \sqrt{\dfrac{\hbar c}{G}} = 2.177 \times 10^{-8}\,\mathrm{kg}$

    Max particle mass
  - Planck temperature $T_{\mathrm{Pl}} = \dfrac{m_{\mathrm{Pl}} c^2}{k_{\mathrm{B}}} \simeq 1.417 \times 10^{32}\,\mathrm{K}$

    Quantum gravity

Equilibrium distributions

Studying the hot universe plasma...

Thermal equilibrium in the early universe

- Hypotheses :
  - ~ Ideal gas – interactions are **negligible**
  - **Thermal equilibrium** (tiny fraction of collision occurs)

- Equilibrium between radiation (dominating) $\leftrightarrow$ matter

$$\gamma + \gamma \Longleftrightarrow A + \bar{A} \qquad\qquad \Gamma$$

  - As long as $\dfrac{1}{\Gamma} \ll \dfrac{1}{H}$ *i.e.* $\Gamma \gg H$

- Particles stay in **thermal equilibrium with the photons**...

… Until they **stop interacting** when $\Gamma \ll H$

… then they **decouple** (*freeze*)

Thermal equilibrium : distributions

- Density of states in 6D phase space

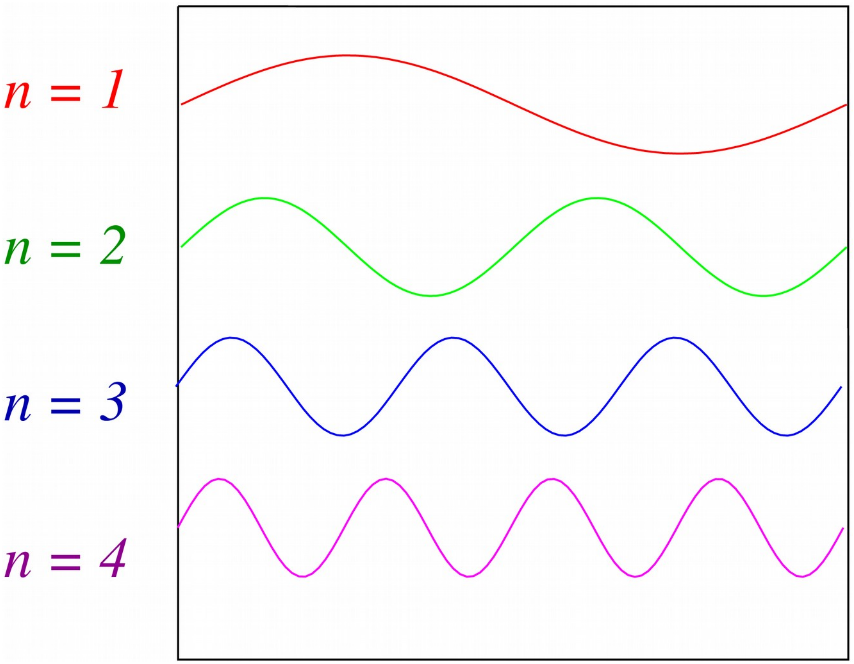
$$\lambda = L/n$$

$$k = \frac{2\pi}{\lambda} = n\Delta k \quad \Delta k = 2\pi/L$$

$$\frac{dn}{d^3\mathbf{k}\, d^3\mathbf{x}} = \frac{g}{L^3\, \Delta k^3} = \frac{g}{(2\pi)^3}$$

$$d^3\mathbf{k} = 4\pi k^2\, dk \qquad p = \hbar k$$

Waves in a box of size L



- Particle density *(g : degrees of freedom)*

$$n = \frac{dn}{d^3\mathbf{x}} = \int \frac{g\, f(k)}{(2\pi)^3}\, d^3\mathbf{k} = \frac{g}{(2\pi)^3} \int_0^{+\infty} f(p)\, 4\pi p^2\, dp$$

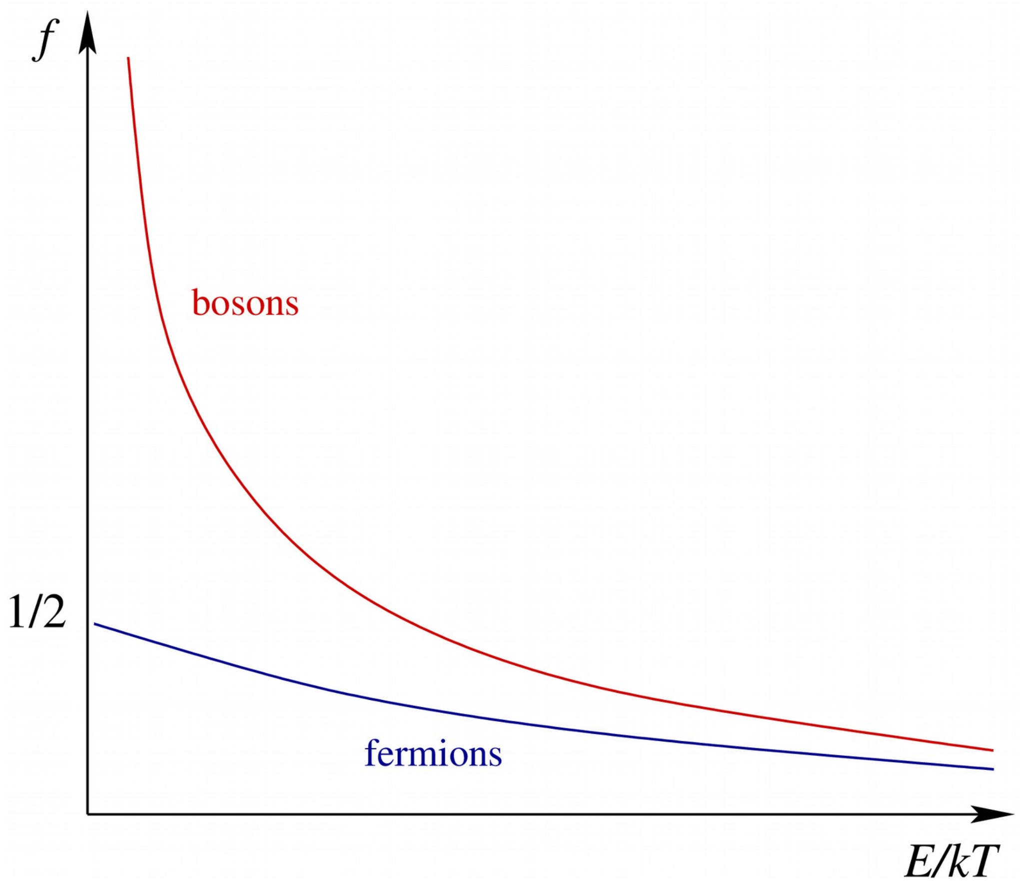
Thermal equilibrium : distributions

- Occupation density

$$f(\mathbf{p}) = \frac{1}{e^{(E-\mu)/k_B t} \pm 1}$$

$$\begin{array}{ll} + & \text{fermions} \\ - & \text{bosons} \end{array}$$

$$E = \sqrt{m^2c^4 + p^2c^2}$$



$$f(\mathbf{p}) = \frac{1}{e^{E/k_B T} \pm 1}$$

$$\begin{array}{ll} \mu = 0 & \text{photons} \\ \mu \approx 0 & \text{symetry particle/antiparticle} \end{array}$$

Thermal equilibrium : distributions

- Number density $$n = \frac{g}{(2\pi\hbar)^3} \int_0^{+\infty} f(\mathbf{p})\, 4\pi p^2 \, \mathrm{d}p$$
- Energy density $$\varepsilon = \frac{g}{(2\pi\hbar)^3} \int_0^{+\infty} E(\mathbf{p})\, f(\mathbf{p})\, 4\pi p^2 \, \mathrm{d}p$$
- Pressure $$P = \frac{g}{(2\pi\hbar)^3} \int_0^{+\infty} \frac{p^2}{3E(\mathbf{p})}\, f(\mathbf{p})\, 4\pi p^2 \, \mathrm{d}p$$
- Entropy $$S(T) = \frac{E + PV}{T} \qquad s = \frac{S}{V} = \frac{\varepsilon + P}{T}$$
  - Entropy is conserved

$$dS = 0 \qquad sa^3 = \mathrm{cste}$$

Relativistic / non relativistic particles

Non relativistic matter
Cold matter

$$m > 0 \qquad p \ll mc$$

$$E = \gamma mc^2 \approx mc^2$$

$$\varepsilon_m \approx Nmc^2 a^3 \propto a^{-3}$$

Radiation, relativistic particles
Hot matter

$m = 0$ or $m > 0$ $\qquad p \gg mc$

$$E = h\nu = hc/\lambda \propto a^{-1}$$

$$\varepsilon_r = Nh\nu a^{-3} \propto a^{-4}$$

Relativistic limit

$$k_B T \gg mc^2 \qquad E \approx pc$$

- Number density

$$n = \frac{g}{(2\pi\hbar)^3} \int_0^{+\infty} \frac{4\pi p^2 \, dp}{e^{pc/kT} \pm 1} = \frac{4\pi g}{(2\pi\hbar)^3} \left(\frac{k_B T}{c}\right)^3 \int_0^{+\infty} \frac{y^2 \, dy}{e^y \pm 1}$$

Energy density

$$\varepsilon = \frac{g}{(2\pi\hbar)^3} \int_0^{+\infty} \frac{4\pi p^3 c \, dp}{e^{pc/kT} \pm 1} = \frac{4\pi g}{(2\pi\hbar)^3} \frac{(k_B T)^4}{c^3} \int_0^{+\infty} \frac{y^3 \, dy}{e^y \pm 1}$$

Useful Integrals and formulas...

For bosons $$I_n = \int_0^{+\infty} \frac{y^n\, dy}{e^y - 1} = \Gamma(n+1)\zeta(n+1)$$

For fermions $$J_n = \int_0^{+\infty} \frac{y^n\, dy}{e^y + 1} = \left(1 - \frac{1}{2^n}\right)\Gamma(n+1)\zeta(n+1)$$

Gamma function

$$\Gamma(n+1) = n!$$

Riemann zeta function

$$\zeta(2) = \frac{\pi^2}{6} \qquad \zeta(3) \simeq 1.202 \qquad \zeta(4) = \frac{\pi^4}{90}$$

Relativistic limit

- Number density

$$n = \frac{\zeta(3)}{\pi^2} \frac{1}{(\hbar c)^3} g (k_B T)^3 \times \begin{cases} 3/4 & \text{fermions} \\ 1 & \text{bosons} \end{cases} \qquad n \propto g T^3$$

- Energy density

$$\varepsilon = \frac{\pi^2}{30} g \frac{(k_B T)^4}{(\hbar c)^3} \times \begin{cases} 7/8 & \text{fermions} \\ 1 & \text{bosons} \end{cases} \qquad \varepsilon \propto g T^4$$

- Pressure $P = \dfrac{\varepsilon}{3}$ $\qquad w = 1/3$

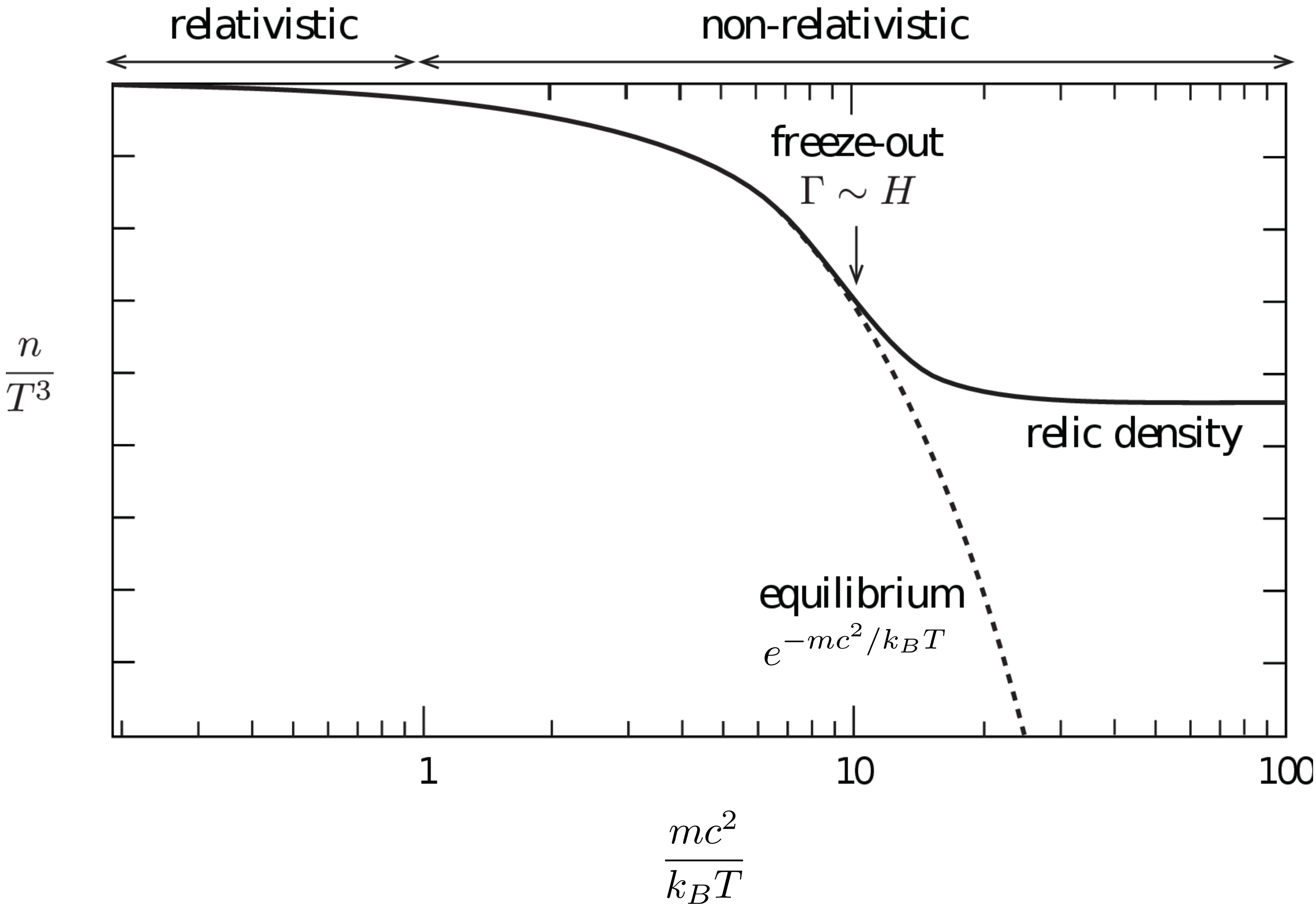
- Entropy $s = \dfrac{\varepsilon + P}{T} = \dfrac{4}{3}\dfrac{\varepsilon}{T} = 3.602\, k_B\, n \times \begin{cases} 7/6 & \text{fermions} \\ 1 & \text{bosons} \end{cases}$

$$s \propto g T^3 \qquad s \propto n$$

Relativistic and non relativistic limits

	$kT \gg mc^2$		$kT \ll mc^2$
	Bosons	Fermions	Non relativistic gas
n	$\frac{\zeta(3)}{\pi^2} g_B \frac{(k_B T)^3}{(\hbar c)^3}$	$\frac{3}{4}\frac{\zeta(3)}{\pi^2} g_B \frac{(k_B T)^3}{(\hbar c)^3}$	$g\left(\frac{m k_B T}{2\pi\hbar^2}\right)^{3/2} e^{\frac{-mc^2}{k_B T}}$
ε	$\frac{\pi^2}{30} g_B \frac{(k_B T)^4}{(\hbar c)^3}$	$\frac{7}{8}\frac{\pi^2}{30} g_F \frac{(k_B T)^4}{(\hbar c)^3}$	$n\left(mc^2 + \frac{3}{2} k_B T\right)$
P	$\frac{\varepsilon}{3}$	$\frac{\varepsilon}{3}$	$n k_B T$
s	$\frac{4}{3}\frac{\varepsilon}{T}$	$\frac{4}{3}\frac{\varepsilon}{T}$	$\frac{n}{T}\left(mc^2 + \frac{5}{2} k_B T\right)$

Number density of non relativistic particles exponentially suppressed, until they decouple from thermal bath...



Number density of non relativistic particle exponentially suppressed, until they decouple from thermal bath...

Total energy density

$$\varepsilon(T) = \varepsilon_{\text{rel.}} + \varepsilon_{\text{n.r.}} = \varepsilon_{\text{rel.}}^{\text{th.}} + \varepsilon_{\text{n.r.}}^{\text{th.}} + \varepsilon_{\text{rel.}}^{\text{dec.}} + \varepsilon_{\text{n.r.}}^{\text{dec.}}$$

$$\varepsilon_{\text{rel.}} = \sum_{B,i} g_{B,i} \frac{\pi^2}{30} \frac{(k_B T_i)^4}{(\hbar c)^3} + \frac{7}{8} \sum_{F,i} g_{F,i} \frac{\pi^2}{30} \frac{(k_B T_j)^4}{(\hbar c)^3}$$

$$\varepsilon_{\text{rel.}} = g_* \frac{\pi^2}{30} \frac{k_B^4}{\hbar^3 c^3} T^4$$

Where $g_*(T) = \sum_{B,i} g_{B,i} \left(\frac{T_i}{T}\right)^4 + \frac{7}{8} \sum_{F,j} g_{F,j} \left(\frac{T_j}{T}\right)^4$

For particles still at equilibrium with the photons (« th »), $T_i = T_j = T$

$$g_*^{\text{th}}(T) = \sum_{B,i} g_{B,i} + \frac{7}{8} \sum_{F,j} g_{F,j}$$

Once a particle population is non relativistic, it is removed from g_*

Entropy

$$s_{\rm rel.} = \sum_{B,i} g_{B,i} \frac{2\pi^2}{45} \frac{k_B^4 T_i^3}{(\hbar c)^3} + \frac{7}{8} \sum_{F,i} g_{F,i} \frac{2\pi^2}{45} \frac{k_B^4 T_j^3}{(\hbar c)^3}$$

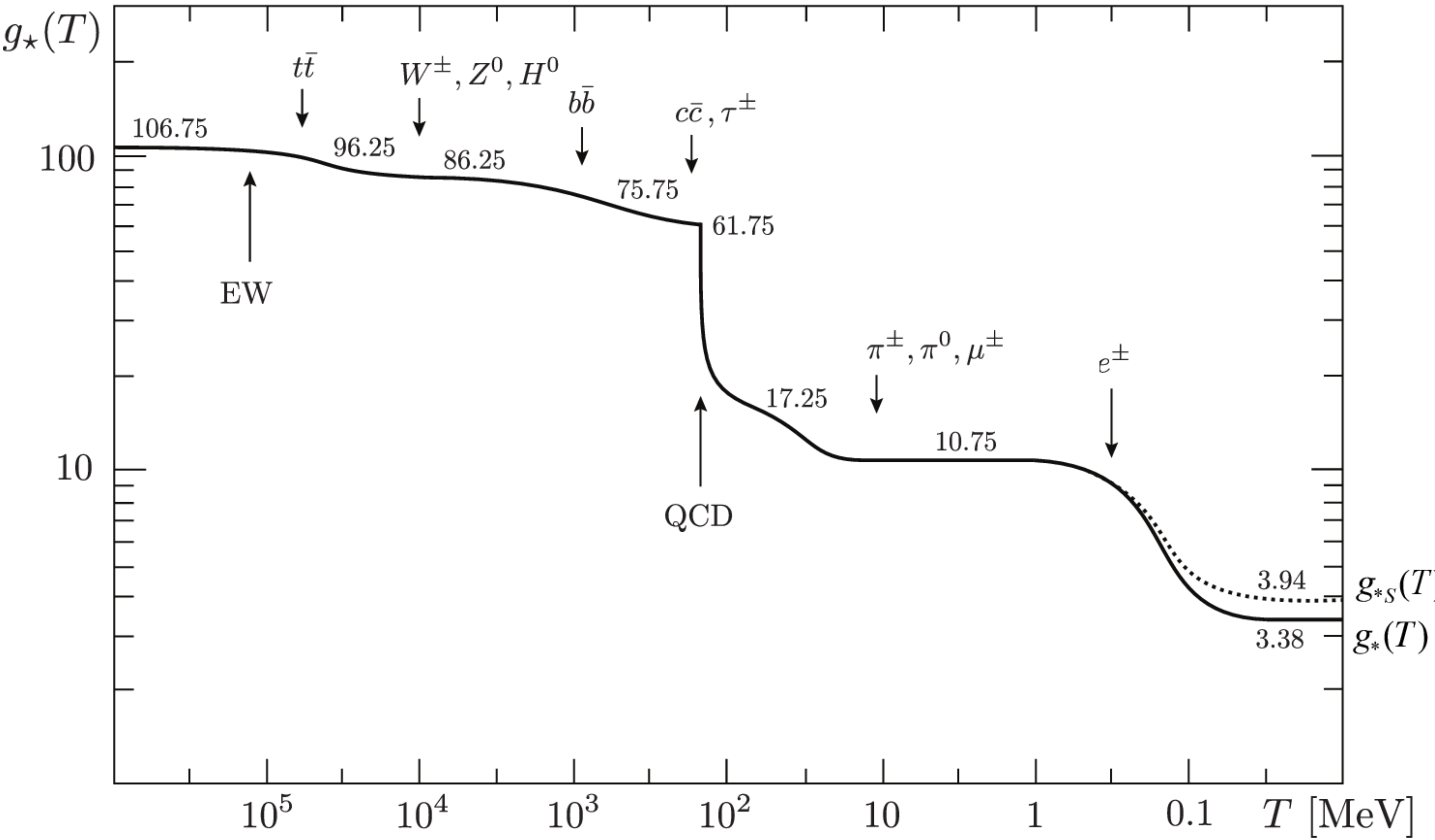
$$s_{\rm rel.} = \frac{2\pi^2}{45} \frac{k_B^4}{(\hbar c)^3} g_{*,s} T^3$$

Where $$g_{*,s}(T) = \sum_{B,i} g_{B,i} \left(\frac{T_i}{T}\right)^3 + \frac{7}{8} \sum_{F,j} g_{F,j} \left(\frac{T_j}{T}\right)^3 \neq g_*(T)$$

For particles still at equilibrium with the photons (« th »), $T_i = T_j = T$

$$g_{*,s}^{\rm th}(T) = \sum_{B,i} g_{B,i} + \frac{7}{8} \sum_{F,j} g_{F,j} = g_*^{\rm th}(T)$$

When a particle species decouples, its entropy is transfered to the heat bath… and $g_{*,s}$ *drops.* *Total entropy is conserved.*



$g_\star(T)$
100
10
106.75
$t\bar{t}$
$W^\pm, Z^0, H^0$
96.25
86.25
$b\bar{b}$
75.75
$c\bar{c}, \tau^\pm$
61.75
EW
$\pi^\pm, \pi^0, \mu^\pm$
17.25
$e^\pm$
10.75
QCD
3.94
$g_{*S}(T)$
3.38
$g_*(T)$
10^5
10^4
10^3
10^2
10
1
0.1
T [MeV]

$g_*, \;\; g_{*,s}$

When $k_B T \gg 175\,\mathrm{GeV}$

All SM particles are relativistic :

Fermions :

$$g_F = 12 \times 6 + 6 \times 2 + 3 \times 2 = 90$$

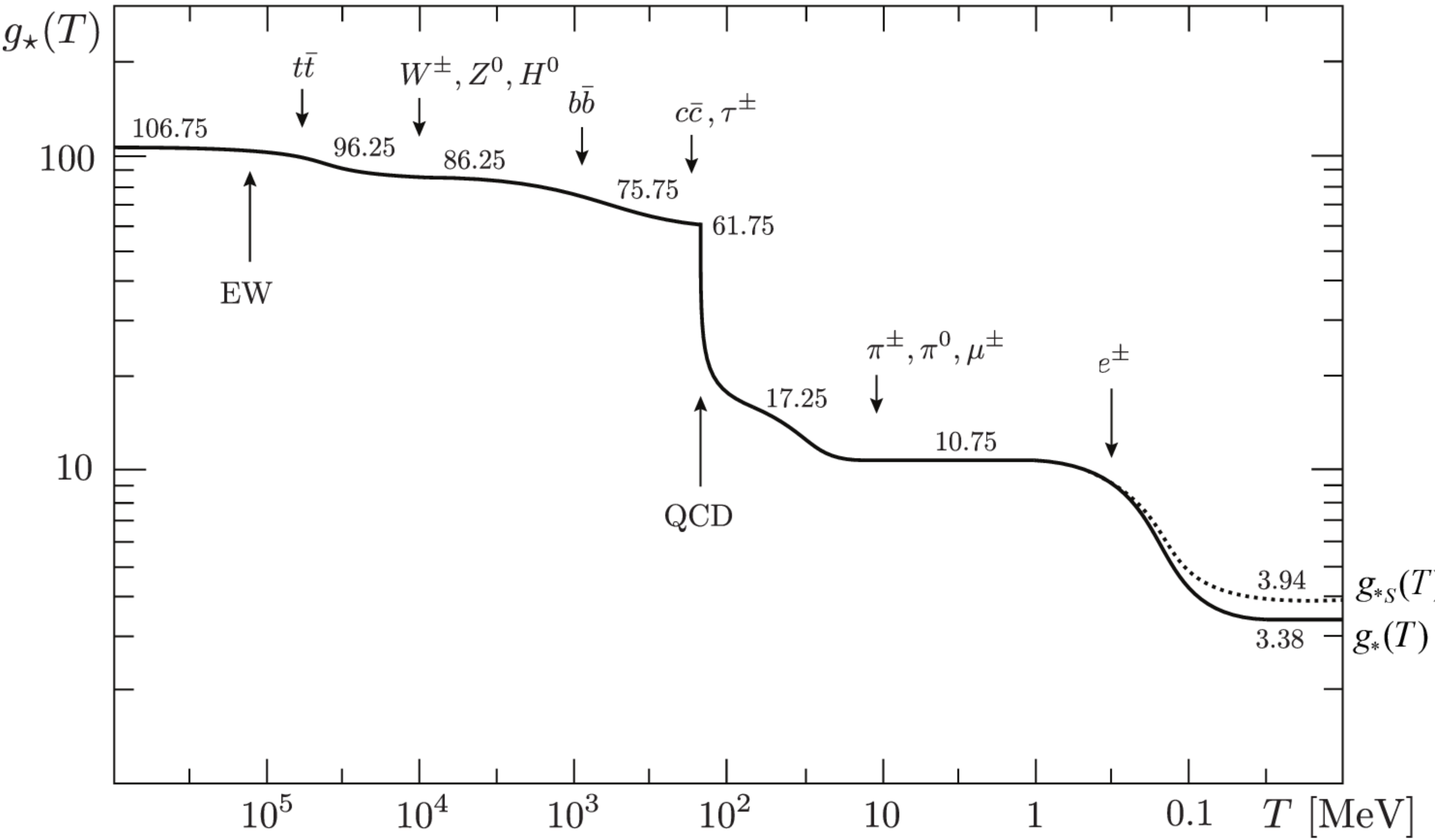
Bosons :

$$g_B = 8 \times 3 + 2 + 3 \times 3 + 1 = 28$$

$$g_* = g_{*,s} = 28 + \frac{7}{8} \times 90$$

$$g_* = g_{*,s} = 106.75$$

type		mass	spin	g
quarks	$t, \bar{t}$	173 GeV	$\frac{1}{2}$	$2 \cdot 2 \cdot 3 = 12$
	$b, \bar{b}$	4 GeV		
	$c, \bar{c}$	1 GeV		
	$s, \bar{s}$	100 MeV		
	$d, \bar{s}$	5 MeV		
	$u, \bar{u}$	2 MeV		
gluons	g_i	0	1	$8 \cdot 2 = 16$
leptons	$\tau^\pm$	1777 MeV	$\frac{1}{2}$	$2 \cdot 2 = 4$
	$\mu^\pm$	106 MeV		
	$e^\pm$	511 keV		
	$\nu_\tau, \bar{\nu}_\tau$	< 0.6 eV	$\frac{1}{2}$	$2 \cdot 1 = 2$
	$\nu_\mu, \bar{\nu}_\mu$	< 0.6 eV		
	$\nu_e, \bar{\nu}_e$	< 0.6 eV		
gauge bosons	W^+	80 GeV	1	3
	W^-	80 GeV		
	Z^0	91 GeV		
	γ	0		2
Higgs boson	H^0	125 GeV	0	1



$g_\star(T)$
100
10
106.75
$t\bar{t}$
$W^\pm, Z^0, H^0$
96.25
86.25
$b\bar{b}$
75.75
$c\bar{c}, \tau^\pm$
61.75
EW
QCD
17.25
$\pi^\pm, \pi^0, \mu^\pm$
10.75
$e^\pm$
3.94
$g_{*S}(T)$
3.38
$g_*(T)$
10^5
10^4
10^3
10^2
10
1
0.1
T [MeV]

Decoupled species

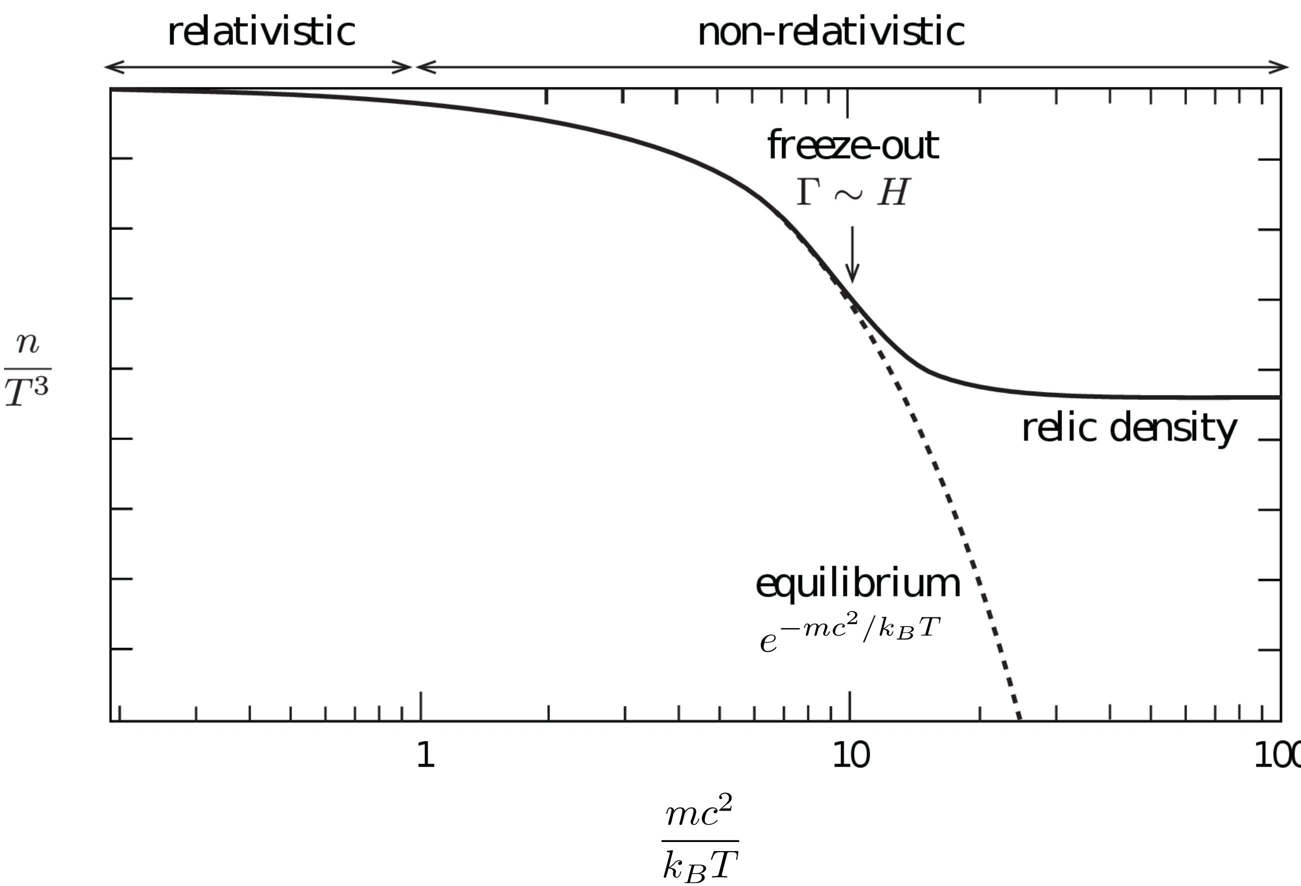
- Before decoupling → **phase space distribution** (prev.)
- Decoupling when $\Gamma \approx H$
- After decoupling : **relic density** (*frozen*)
  - Relativistic species (neutrinos, …) :

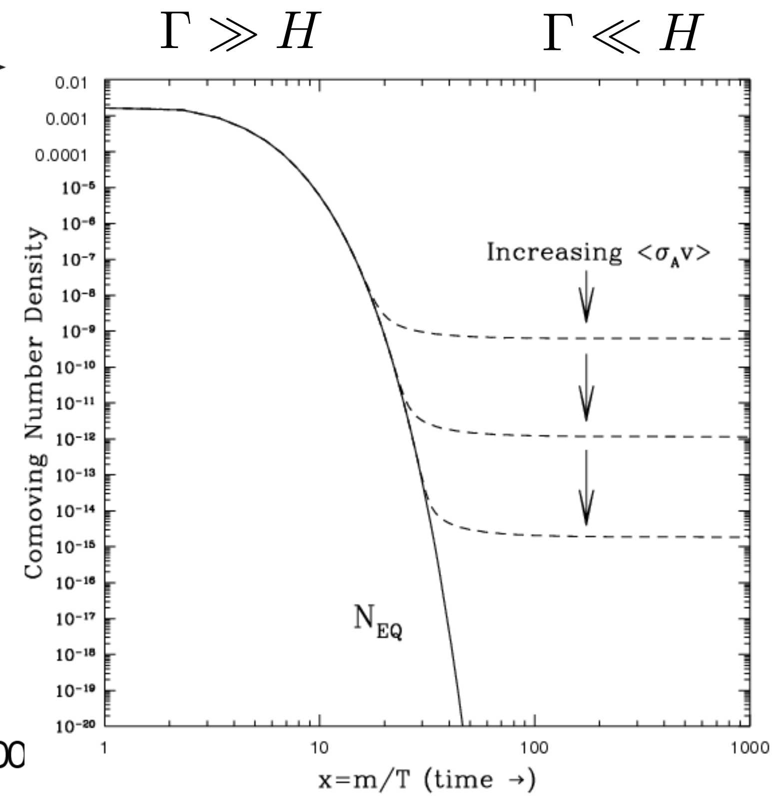
$$f(p) = \frac{1}{e^{E/k_B T_{\rm eff}} \pm 1} \qquad T_{\rm eff} = T_{\rm dec.} \frac{a_{\rm dec.}}{a(t)} \propto a^{-1}$$

  - Non relativistic species :

particles per unit of comobile volume conserved
particles dilute…

$$n \propto a^{-3} \qquad T_{\rm eff} = T_{\rm dec.} \left(\frac{a_{\rm dec.}}{a(t)}\right)^2 \propto a^{-2}$$





The remaining amount (relic density) depends on the desintegration cross-section.

Neutrino decoupling

Equilibrium with heat bath :

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

$$\frac{\Gamma_\nu}{H} \approx 5.4 \frac{G_F^2}{M_{\rm Pl}} T^3$$

Happens when $\Gamma_\nu \approx H$

i.e. $k_B T_\nu^{\rm dec.} \approx 0.8\,{\rm MeV}$

Freeze the neutron / proton ratio

$$\frac{n_n(T)}{n_p(T)} = e^{-(m_n - m_p)c^2/k_B T}$$

$$\frac{n_n}{n_p} \approx 0.34$$

Entropy conservation : $T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma$

Annihilation pairs e+ e-

It occurs around $k_B T \approx mc^2 = 0.511\,\mathrm{MeV}$

At time $\frac{t}{1\,\mathrm{s}} \approx \left(\frac{1\,\mathrm{MeV}}{k_B T}\right)^2 \approx \left(\frac{1}{0.511\,\mathrm{MeV}}\right)^2 \approx 4 \qquad t \approx 4\,\mathrm{s}$

Entropy conserved : $s(a_1)a_1^3 = s(a_2)a_2^3$

Before (1) : $\gamma, e^+, e^-, \nu, \bar{\nu}$ (neutrinos already decoupled)

After (2) : γ (relic e-, neutrinos already decoupled)

$$g_{*,s}(a_1)T_1^3 a_1^3 = g_{*,s}(a_2)T_2^3 a_2^3 \qquad T_2 = \left(\frac{11}{4}\right)^{1/3} T_1 \frac{a_1}{a_2}$$

$$T_2 = T_\gamma(a_2) \quad T_1 \frac{a_1}{a_2} = T_\nu(a_2) \quad T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \quad T_\nu \approx 1.95\,\mathrm{K}$$

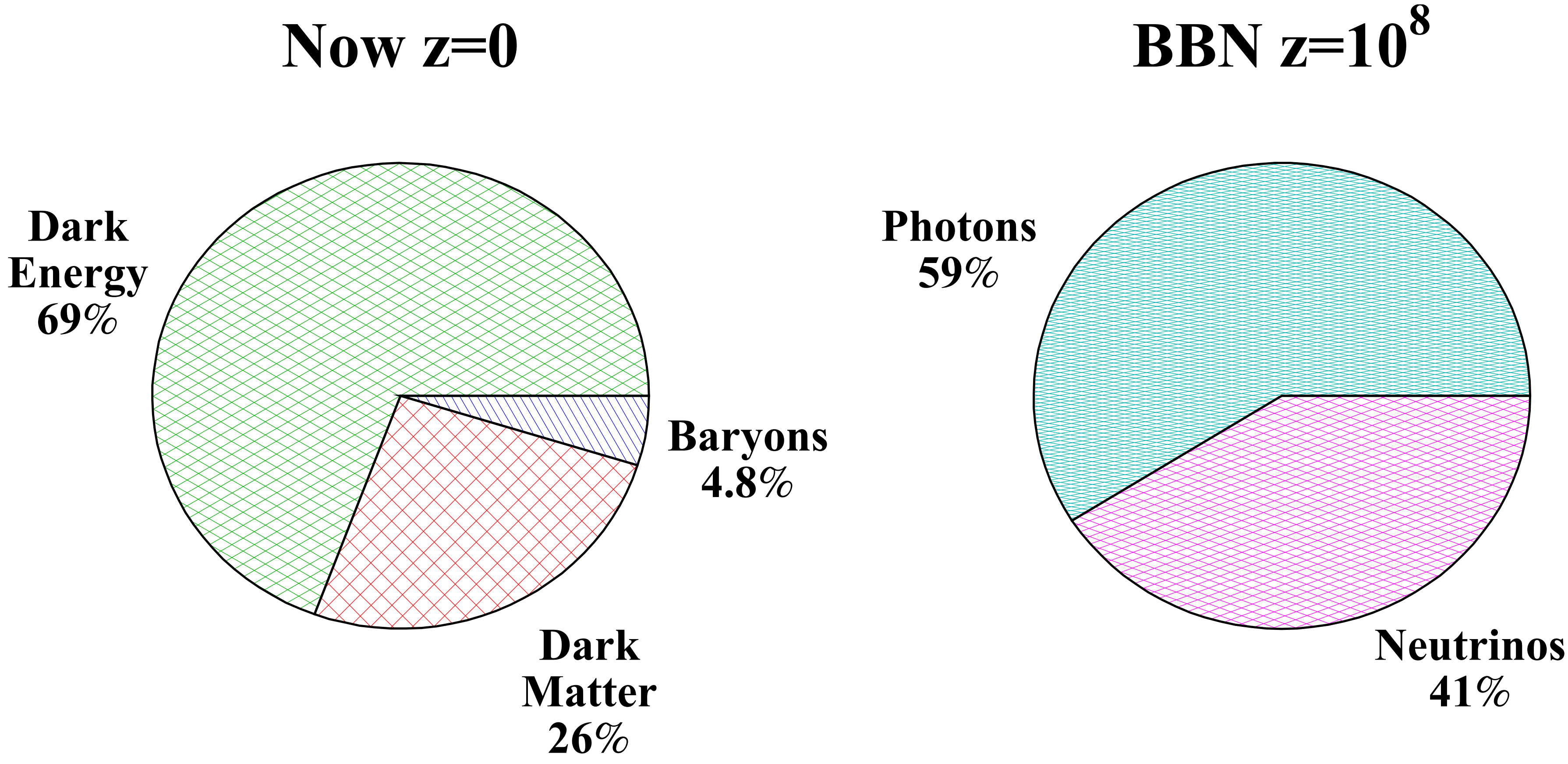
4.3

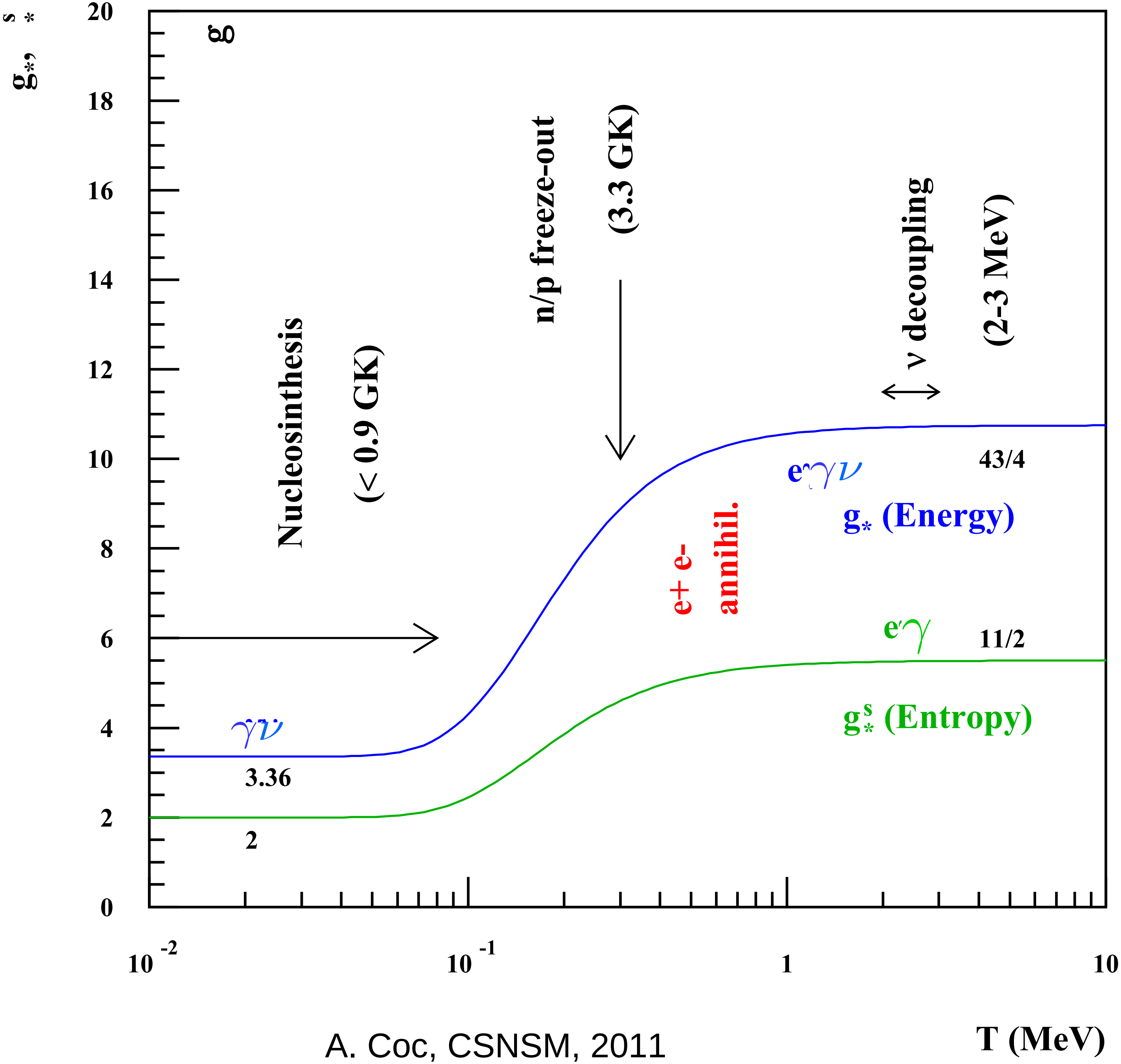
Primordial nucleosynthesis

How the first nuclei appeared...

Big Bang nucleosynthesis

Era dominated by radiation





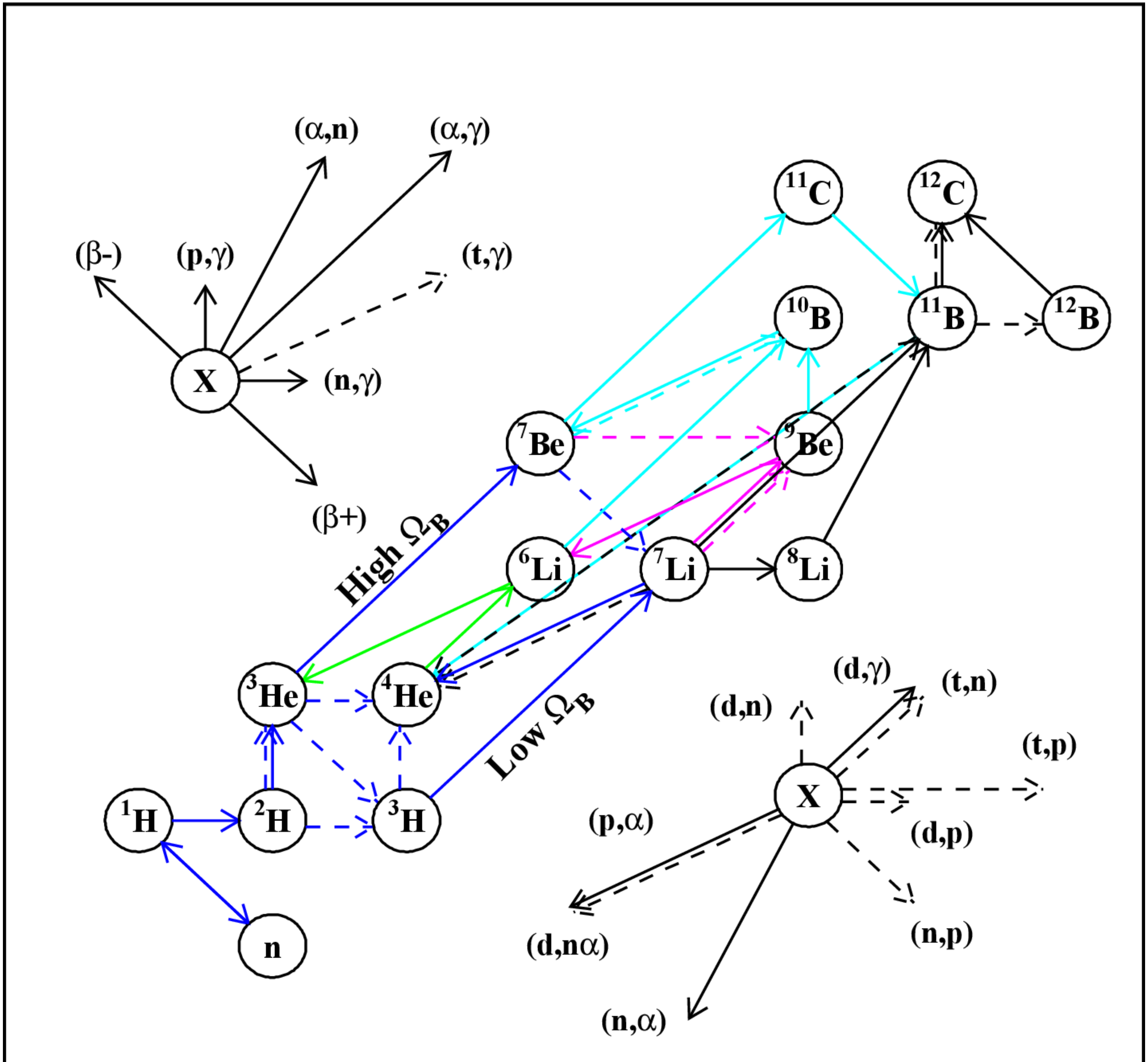
A. Coc, CSNSM, 2011

Big Bang nucleosynthesis

- Critical parameter : density of baryons

$$\Omega_{b,0} = \varepsilon_{b,0}/\varepsilon_{c,0} \qquad n_b \approx \frac{\Omega_{b,0}\varepsilon_{c,0}}{m_p} \qquad \eta = \frac{n_b}{n_\gamma} \simeq 6 \times 10^{-10}$$

Time < 1 s	$p + e^- \longleftrightarrow n + \nu_e$ $n + e^+ \longleftrightarrow p + \bar{\nu}_e$	Neutron/proton freeze-out
1 – 100 s	$n \longrightarrow p + e^- + \bar{\nu}_e$	Neutrons decay $\tau \approx 880\,\mathrm{s}$
100 – 200 s	$p + n \longleftrightarrow \mathrm{D} + \gamma$	Deuterium formed Allows neutrons to survive
200 – 1000 s	$^3\mathrm{H},\ ^3\mathrm{He},\ ^4\mathrm{He}; \ldots$	Deuterium burned to produce next elements


(α,n)
(α,γ)
(β-)
(p,γ)
(t,γ)
X
(n,γ)
(β+)
^{11}C
^{12}C
^{10}B
^{11}B
^{12}B
^{7}Be
^{9}Be
High Ω_B
^{6}Li
^{7}Li
^{8}Li
^{3}He
^{4}He
Low Ω_B
^{1}H
^{2}H
^{3}H
n
(d,γ)
(t,n)
(d,n)
(t,p)
X
(p,α)
(d,p)
(d,nα)
(n,p)
(n,α)

$$\mathrm{D} + n \longrightarrow {}^3_1\mathrm{H} + \gamma$$

$${}^3_1\mathrm{H} + p \longrightarrow {}^4_2\mathrm{He} + \gamma$$

$$\mathrm{D} + p \longrightarrow {}^3_2\mathrm{He} + \gamma$$

$${}^3_2\mathrm{He} + n \longrightarrow {}^4_2\mathrm{He} + \gamma$$

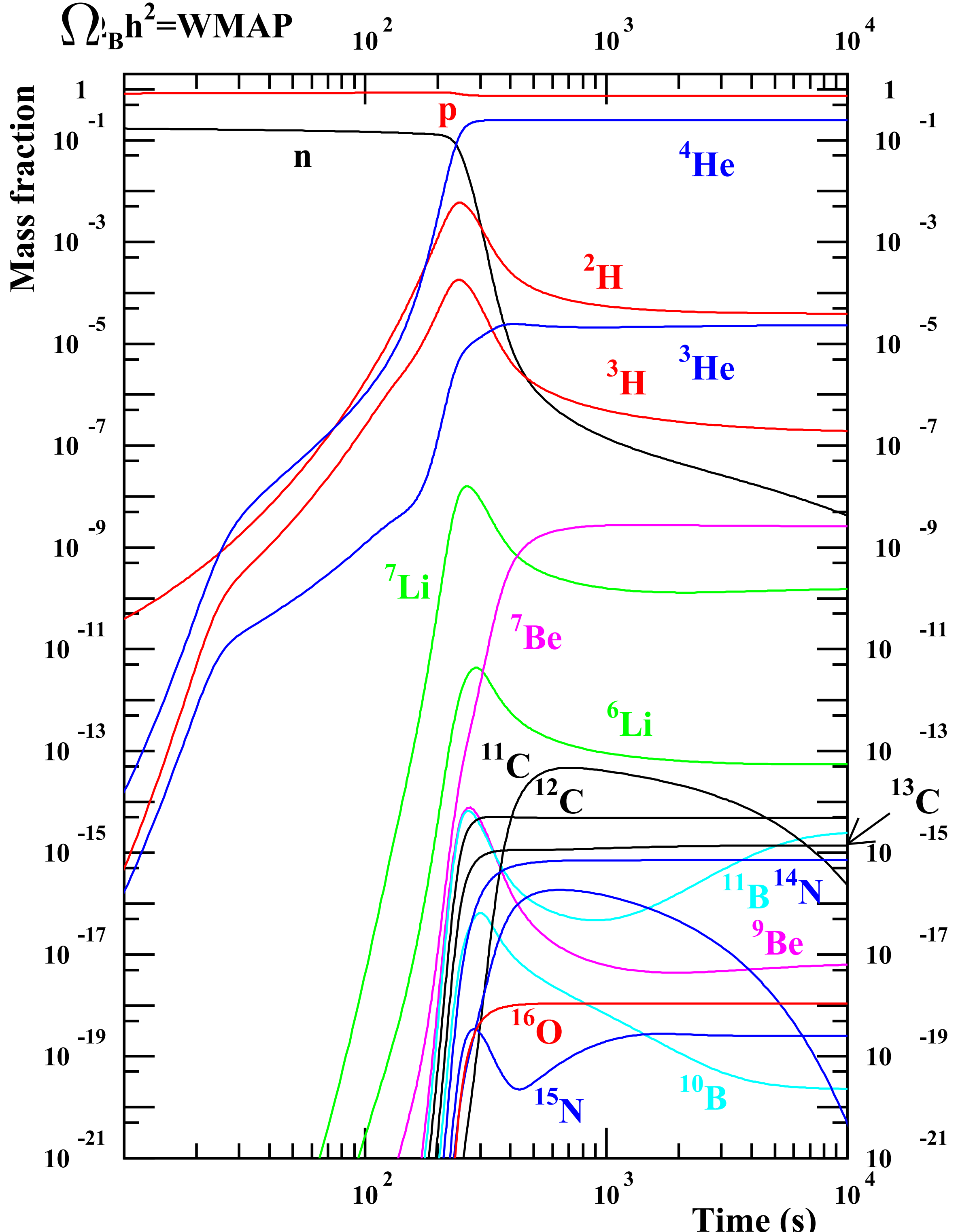
$$\mathrm{D} + \mathrm{D} \longrightarrow {}^3_2\mathrm{He} + n$$

$$\mathrm{D} + \mathrm{D} \longrightarrow {}^3_1\mathrm{H} + p$$

$${}^3_1\mathrm{H} + \mathrm{D} \longrightarrow {}^4_2\mathrm{He} + n$$

Etc...

$$Y_P({}^4_2\mathrm{He}) \approx 0.25$$



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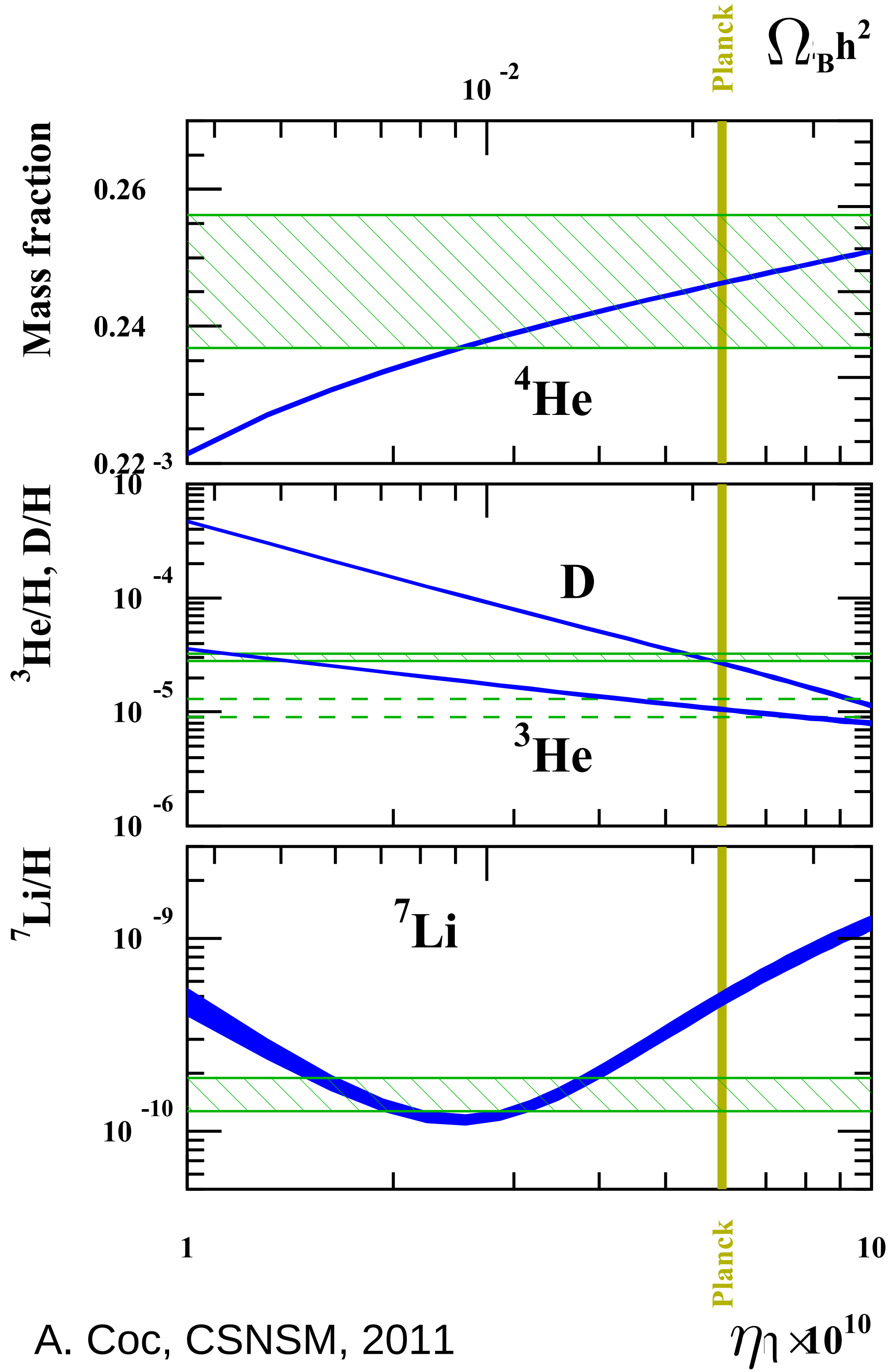
$$\eta = \frac{n_b}{n_\gamma} \simeq 6 \times 10^{-10}$$

$$\Omega_{b,0} = \varepsilon_{b,0}/\varepsilon_{c,0}$$



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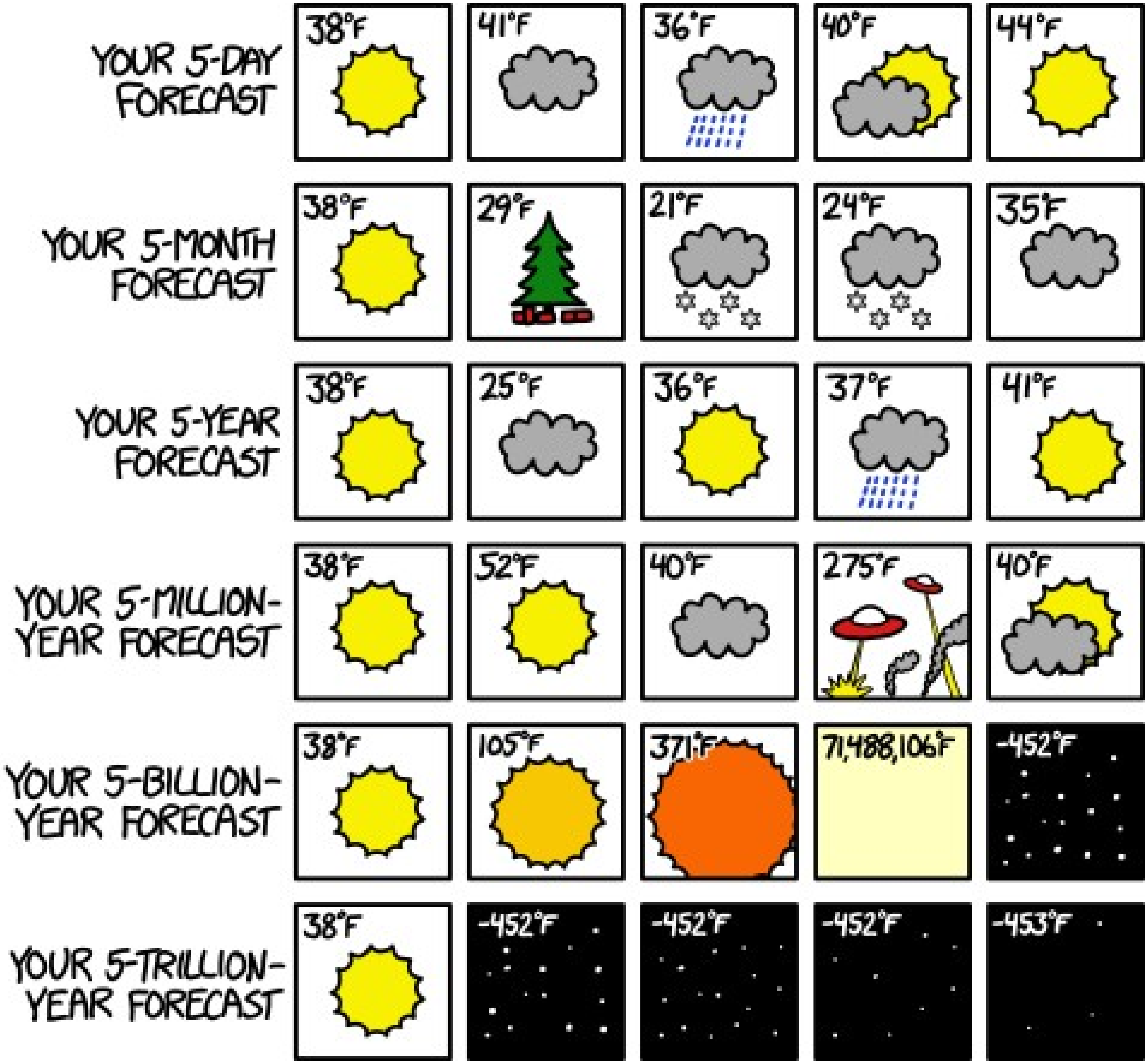

http://xkcd.com/1606/