Cosmology,

lect. 7

Thermal History

FRW

Thermodynamics

FRW Dynamics

$$\ddot{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)a + \frac{\Lambda}{3}a$$

$$\dot{a}^2 = \frac{8\pi G}{3}\rho a^2 - \frac{kc^2}{R_0^{\ 2}} + \frac{\Lambda}{3}a^2$$

To find solutions a(t) for the expansion history of the Universe, for a particular FRW Universe ,

one needs to know how the density ρ(t) and pressure p(t) evolve as function of a(t)

FRW equations are implicitly equivalent to a third Einstein equation, the energy equation,

$$\dot{\rho} + 3\left(\rho + \frac{p}{c^2}\right)\frac{\dot{a}}{a} = 0$$

FRW Dynamics: Adiabatic Cosmic Expansion

Important observation:
the energy equation,

$$\dot{\rho} + 3\left(\rho + \frac{p}{c^2}\right)\frac{\dot{a}}{a} = 0$$

is equivalent to stating that the change in internal energy

$$U = \rho c^2 V$$

of a specific co-expanding volume V(t) of the Universe, is due to work by pressure:

$$dU = -p\, dV$$

Friedmann-Robertson-Walker-Lemaitre expansion of the Universe is

→ Adiabatic Expansion ←

FRW Dynamics: Thermal Evolution

Adiabatic Expansion of the Universe:

- Implication for Thermal History
- Temperature Evolution of cosmic components

For a medium with adiabatic index γ:

$$TV^{\gamma-1} = cst$$

Radiation (Photons)	$\gamma = \frac{4}{3}$	$T = \frac{T_0}{a}$
Monatomic Gas (hydrogen)	$\gamma = \frac{5}{3}$	$T = \frac{T_0}{a^2}$

Radiation
&
Matter

Cosmic Radiation

The Universe is filled with thermal radiation, the photons that were created in The Big Bang and that we now observe as the Cosmic Microwave Background (CMB).

The CMB photons represent the most abundant species in the Universe, by far !

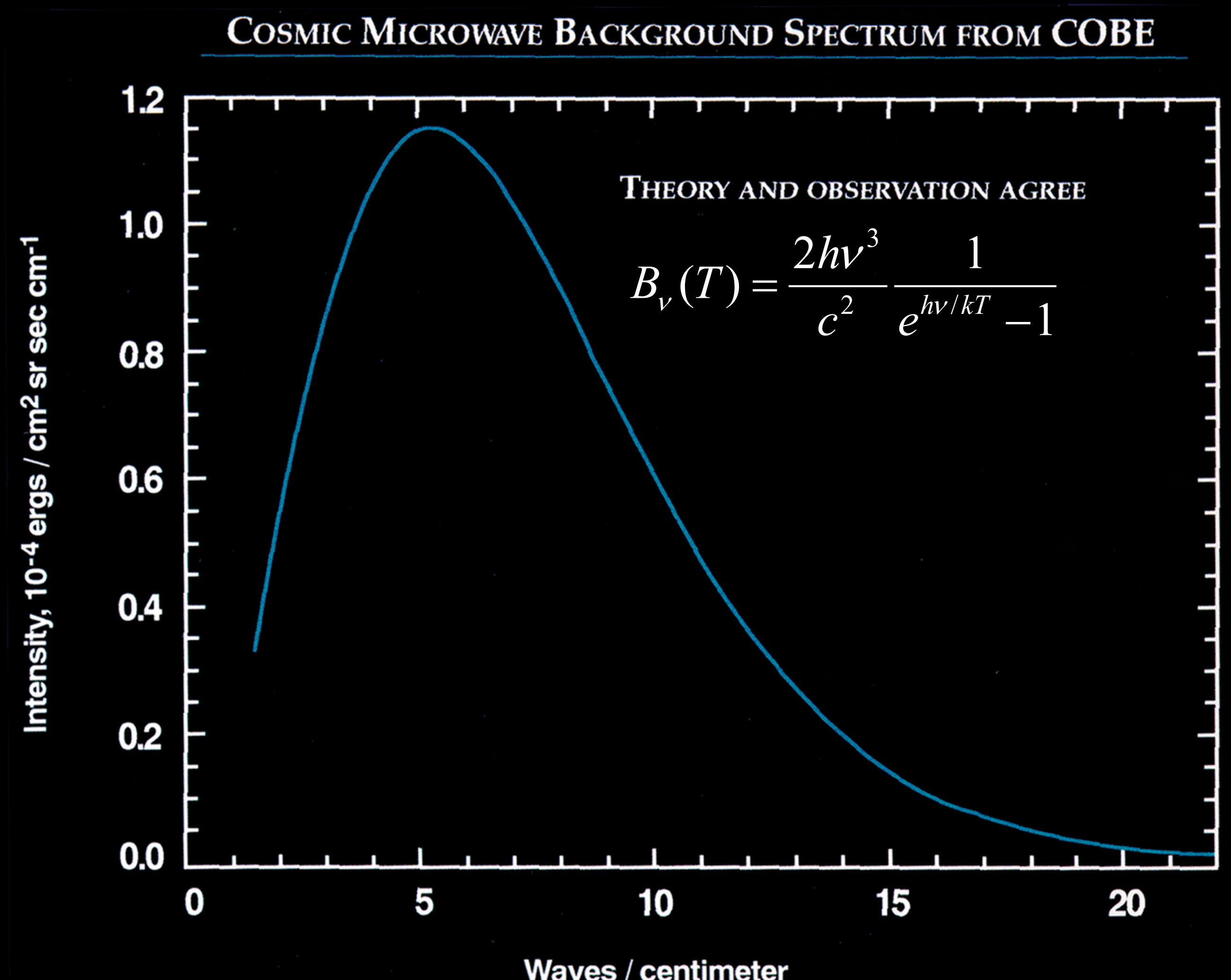
The CMB radiation field is PERFECTLY thermalized, with their energy distribution representing the most perfect blackbody spectrum we know in nature. The energy density $u_\nu(T)$ is therefore given by the Planck spectral distribution,

$$u_\nu(T) = \frac{8\pi h\nu^3}{c^3}\frac{1}{e^{h\nu/kT}-1}$$

At present, the temperature T of the cosmic radiation field is known to impressive precision,

$$T_0 = 2.725 \pm 0.001 K$$

CMB Radiation Field
Blackbody Radiation



- COBE-DIRBE:
  temperature, blackbody
- T = 2.725 K
- John Mather
  Nobelprize physics 2006
- Most accurately measured
  Black Body Spectrum
  Ever !!!!!

Cosmic Radiation

With the energy density $u_\nu(T)$ of CMB photons with energy $h\nu$ given, we know the number density $n_\nu(T)$ of such photons:

$$n_\nu(T) = \frac{u_\nu(T)}{h\nu} = \frac{8\pi\nu^2}{c^3}\frac{1}{e^{h\nu/kT}-1}$$

The total number density $n_\gamma(T)$ of photons in the Universe can be assessed by integrating the number density $n_\gamma(T)$ of photons with frequency ν over all frequencies,

$$n_\gamma(T) = \int_0^\infty n_\nu(T)d\nu =$$

$$= \int_0^\infty \frac{8\pi\nu^2}{c^3}\frac{1}{e^{h\nu/kT}-1}d\nu = 60.4\left(\frac{kT}{hc}\right)^3$$

$$T = 2.725\,K$$

⬇

$$n_\gamma(T) = 412\ cm^{-3}$$

Baryon-Photon Ratio

Having determined the number density of photons, we may compare this with the number density of baryons, $n_b(T)$. That is, we wish to know the PHOTON-BARYON ratio,

$$\eta \equiv \frac{n_\gamma}{n_B}$$

$$n_b = \frac{\rho_B}{m_p} = \frac{\Omega_B \, \rho_{crit}}{m_p}$$

The baryon number density is inferred from the baryon mass density. here, for simplicity, we have assumed that baryons (protons and neutrons) have the same mass, the proton mass $m_p \sim 1.672 \times 10^{-24}$ g. At present we therefore find

$$n_b = 1.12 \times 10^{-5} \; \Omega_b h^2 \; g \, cm^{-3}$$

⬇

$$\eta_0 = \frac{n_\gamma}{n_B} \approx 3.65 \times 10^7 \, \frac{1}{\Omega_b h^2} \; g \, cm^{-3}$$

We know that $\Omega_b \sim 0.044$ and $h \sim 0.72$:

$$\eta_0 = \frac{n_\gamma}{n_b} \approx 1.60 \times 10^9$$

Baryon-Photon Ratio

From simple thermodynamic arguments, we find that the number of photons is vastly larger than that of baryons in the Universe.

$$\eta_0 = \frac{n_\gamma}{n_b} \approx 1.60 \times 10^9$$

In this, the Universe is a unique physical system, with tremendous repercussions for the thermal history of the Universe. We may in fact easily find that the cosmic photon-baryon ratio remains constant during the expansion of the Universe,

$$n_b(t) = \frac{n_{b,0}}{a^3}$$

$$n_\gamma(t) \propto T(t)^3 \propto \frac{1}{a^3} \Rightarrow n_\gamma(t) = \frac{n_{\gamma 0}}{a^3}$$

$\Rightarrow$

$$\eta = \frac{n_\gamma(t)}{n_b(t)} = \frac{n_{\gamma,0}}{n_{b,0}} = \eta_0$$

Entropy of the Universe

The photon-baryon ratio in the Universe remains constant during the expansion of the Universe, and has the large value of

$$\eta = \frac{n_\gamma(t)}{n_b(t)} = \frac{n_{\gamma,0}}{n_{b,0}} = \eta_0 = 1.60\times10^9$$

This quantity is one of the key parameters of the Big Bang. The baryon-photon ratio quantifies the ENTROPY of the Universe, and it remains to be explained why the Universe has produced such a system of extremely large entropy !!!!!

The key to this lies in the very earliest instants of our Universe !

Cosmic Light (CMB): most abundant species

By far,

the most abundant particle species

in the Universe

$n_{\gamma}/n_{B} \sim 1.9$ billion

Hot Big Bang:

Thermal History

Adiabatic Expansion

- The Universe of Einstein, Friedmann & Lemaitre expands *adiabatically*
- Energy of the expansion of the Universe corresponds to the decrease in the energy of its constituents
- *The Universe COOLS as a result of its expansion !*

$$T(t) \propto 1/a(t)$$

Equilibrium Processes

Throughout most of the universe's history (i.e. in the early universe), various species of particles keep in (local) thermal equilibrium via interaction processes:

$$\psi_i + \psi_j \rightleftarrows \chi_i + \chi_j$$

Equilibrium as long as the interaction rate Γ_{int} in the cosmos' thermal bath, leading to N_{int} interactions in time t,

$$\Gamma_{\rm int} \quad \Rightarrow \quad N_{\rm int} = \int \Gamma_{\rm int}(t)\, dt$$

is much larger than the expansion rate of the Universe, the Hubble parameter H(t):

$$\Gamma_{\rm int} \gg H(t)$$

Reconstruction Thermal History Timeline

Strategy:

To work out the thermal history of the Universe, one has to evaluate at each cosmic time which physical processes are still in equilibrium.

Once this no longer is the case, a physically significant transition has taken place.

Dependent on whether one wants a crude impression or an accurately and detailed worked out description, one may follow two approaches:

- **Crudely:**

  Assess transitions of particles out of equilibrium, when they decouple from thermal bath. Usually, on crude argument:

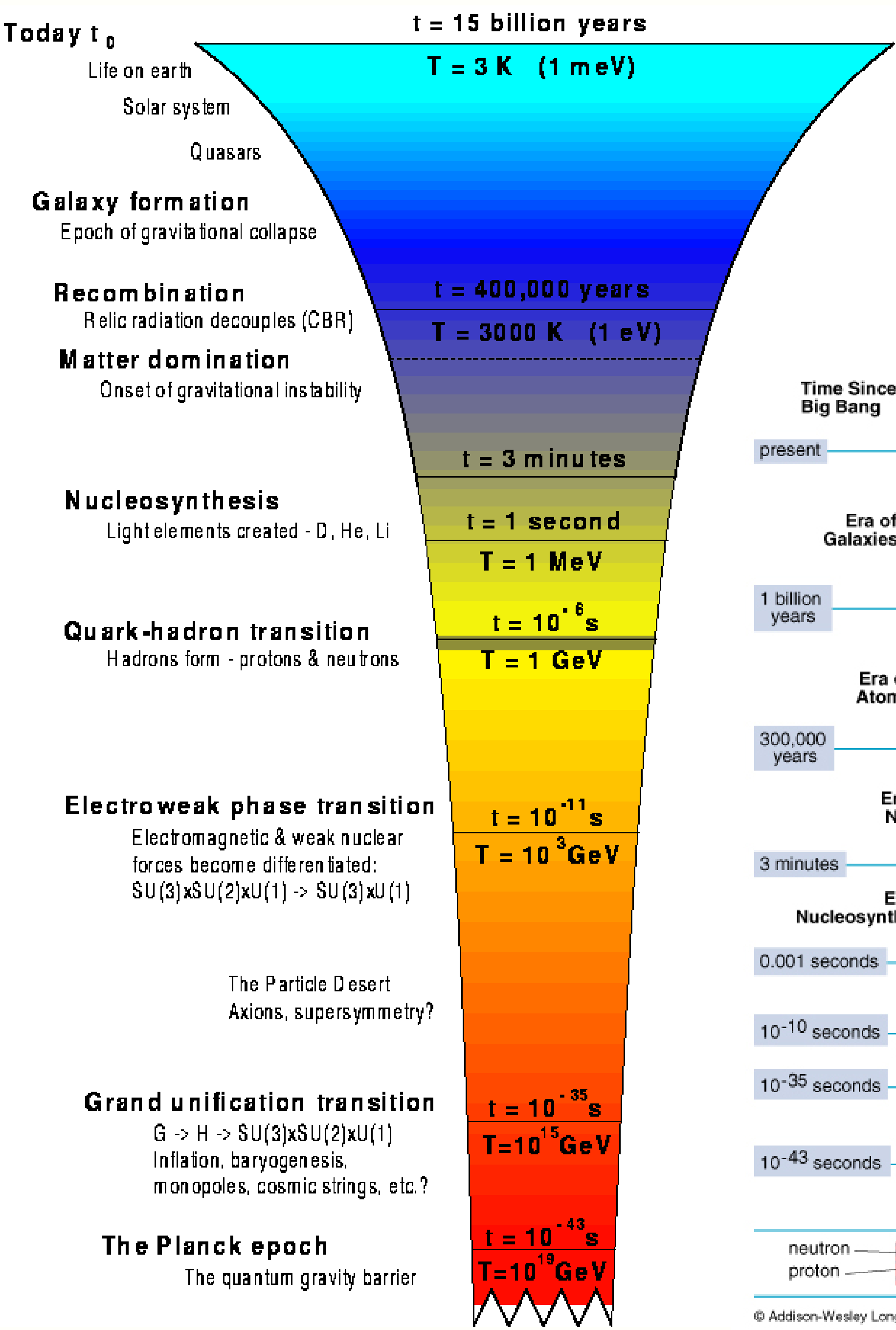
$$\Gamma_{\rm int} \gg H(t) \quad \Longrightarrow \quad \Gamma_{\rm int} < H(t)$$

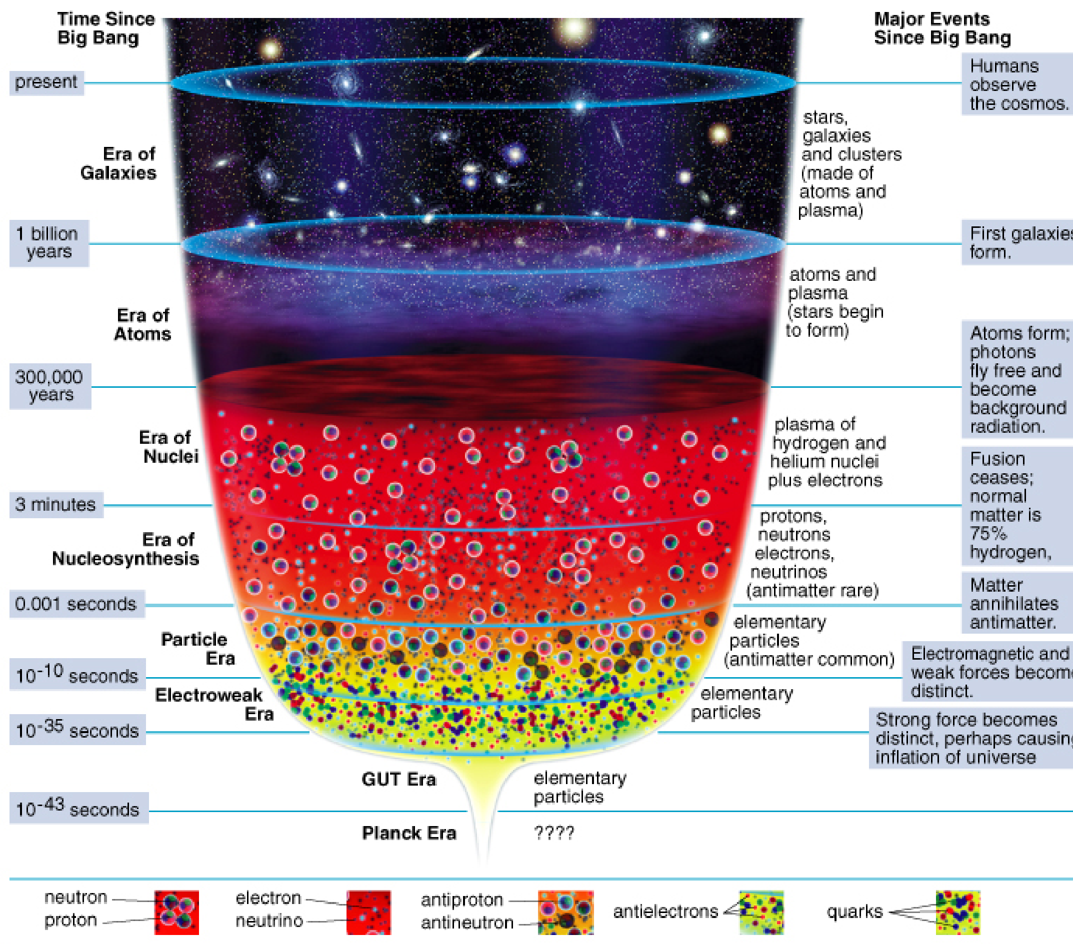
- **Strictly:**

  evolve particle distributions by integrating the Boltzmann equation

Adiabatic Expansion

reconstruction Thermal History of the Universe





Thermal History: Interactions

Particle interactions are mediated by gauge bosons:

- photons for the electromagnetic force,
- W bosons for weak interactions,
- gluons for the strong force.

The strength of the interaction is set by the coupling constant,

leading to the following dependence of the interaction rate Γ, on temperature T:

(i) mediated by massless gauge boson (photon):

$$\Gamma_{int}/H \;\sim\; \alpha^2\, m_{Pl}/T$$

α : coupling strength

m_{Pl} : Planck mass

(ii) mediated by massive gauge boson ($W^{+/-}$, Z^0)

$$\Gamma_{int}/H \;\sim\; G_x^2\, m_{Pl}\, T^3$$

G_x : coupling strength

m_{Pl} : Planck mass

Hot Big Bang
Eras

Cosmic Epochs

Planck Epoch		$t < 10^{-43}$ sec
Phase Transition Era	GUT transition electroweak transition quark-hadron transition	10^{-43} sec $< t < 10^{5}$ sec
Hadron Era		$t \sim 10^{-5}$ sec
Lepton Era	muon annihilation neutrino decoupling electron-positron annihilation primordial nucleosynthesis	10^{-5} sec $< t <$ 1 min
Radiation Era	radiation-matter equivalence recombination & decoupling	1 min $< t <$ 379,000 yrs
Post-Recombination Era	Structure & Galaxy formation Dark Ages Reionization Matter-Dark Energy transition	$t >$ 379,000 yrs

History of the Universe in Four Episodes: I

On the basis of the
1) complexity of the involved physics
2) our knowledge of the physical processes
we may broadly distinguish four cosmic episodes:

(I)

Origin universe

???

$t < 10^{-43}$ sec

fundamental physics:

- totally unknown

Planck Era

History of the Universe in Four Episodes: II

(II)

$10^{-43} < t < 10^{-3}$ sec

VERY early universe

fundamental physics:
- poorly known
- speculative

- ⍰$_{tot:}$ curvature/ flatness
- ⍰$_b$ (n_b/$n_⍰$)
- `exotic' dark matter
- primordial fluctuations

History of the Universe in Four Episodes: III

(III)

$10^{-3} < t < 10^{13}$ sec

Standard

Hot Big Bang

Fireball

fundamental microphysics:

known very well

- primordial nucleo-synthesis
- blackbody radiation: CMB

History of the Universe in Four Episodes: IV

(IV)

complex macrophysics:

-Fundamentals known

- complex interplay

$t > 10^{13}$ sec

Post (Re)Combination universe

- structure formation:

  stars,
  galaxies
  clusters
  …

Origins:

the Planck Epoch

Thermal History: Episode by Episode

Planck Epoch

$t < 10^{-43}$ sec

- In principle, temperature T should rise to infinity as we probe earlier and earlier into the universe's history:

$$T \to \infty, \quad R \downarrow 0$$

- However, at that time the energy of the particles starts to reach values where quantum gravity effects become dominant. In other words, the de Broglie wavelength of the particles become comparable to their own Schwarzschild radius.

Thermal History: Planck Epoch

Once the de Broglie wavelength is smaller than the corresponding Schwarzschild radius, the particle has essentially become a "quantum black hole":

de Broglie wavelength: $\lambda_B = \frac{2\hbar\pi}{mc}$

$\leq$

Schwarzschild radius: $\lambda_S = \frac{2Gm}{c^2}$

These two mass scales define the epoch of quantum cosmology, in which the purely deterministic metric description of gravity by the theory of relativity needs to be augmented by a theory incorporating quantum effects: quantum gravity.

Thermal History: Planck Epoch

On the basis of the expressions of the de Broglie wavelength and the Schwarzschild radius we may infer the typical mass scale, length scale and timescale for this epoch of quantum cosmology:

$$m_{Pl} \equiv \sqrt{\frac{\hbar c}{G}} \sim 10^{19}\,\mathrm{GeV} \qquad \text{Planck Mass}$$

$$l_{Pl} \equiv \sqrt{\frac{\hbar G}{c^3}} \sim 10^{-35}\,\mathrm{m} \qquad \text{Planck Length}$$

$$t_{Pl} \equiv \sqrt{\frac{\hbar G}{c^5}} \sim 10^{-43}\,\mathrm{sec} \qquad \text{Planck Time}$$

Because our physics cannot yet handle quantum black holes, i.e. because we do not have any viable theory of quantum gravity we cannot answer sensibly questions on what happened before the Planck time. In other words, we are not able to probe the ultimate cosmic singularity … some ideas of how things may have been do exist …

Statistical Equilibrium

Maxwell-Boltzmann

Non-relativistic medium

For statistical equilibrium, the Maxwell-Boltzmann distribution specifies for a temperature T, the density of particles:

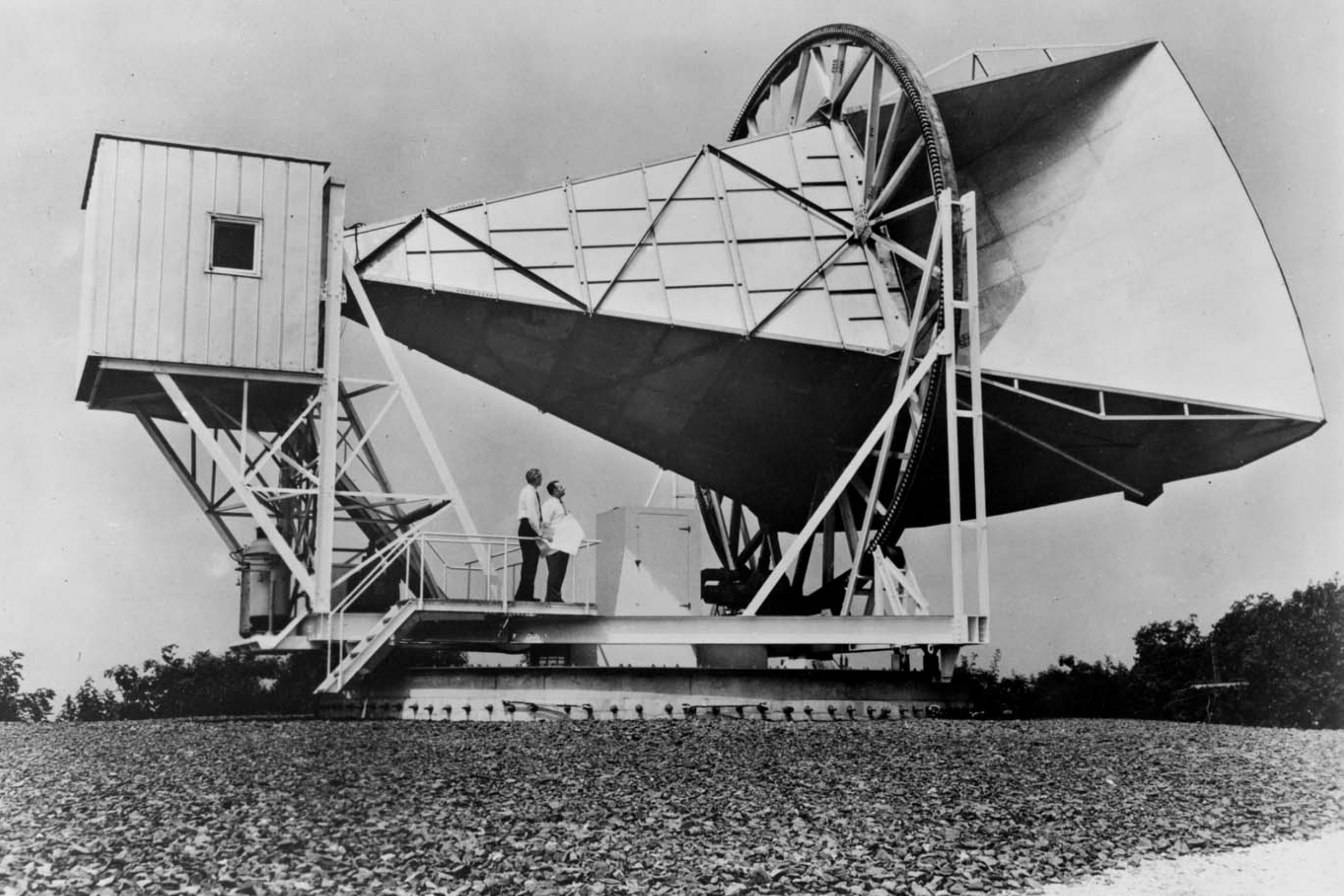
- **number density n_i**
- **particles with mass m_i**
- **statistical weight g_i**
- **chemical potential μ_i**

$$n_i = g_i \frac{\left(2\pi m_i kT\right)^{3/2}}{\left(2\pi\hbar\right)^3} \exp\left\{\frac{\mu_i - m_i c^2}{kT}\right\}$$

Echo of the Big Bang:

Recombination,
Decoupling,
Last Scattering

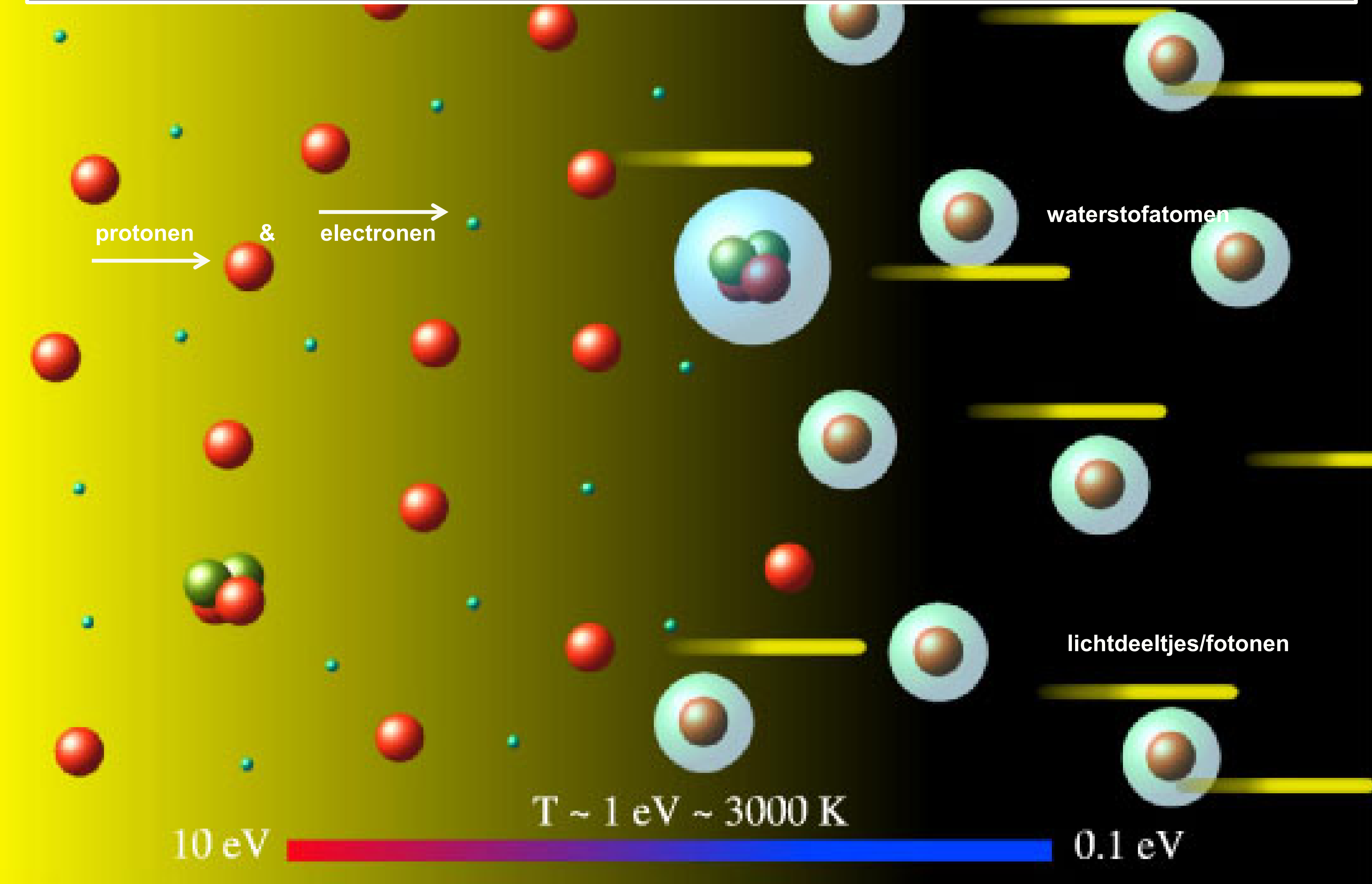
CMB Discovery: Penzias & Wilson



Cosmic Light (CMB): the facts

- Discovered serendipitously in 1965 — Penzias & Wilson, Nobelprize 1978 !!!!!
- Cosmic Licht that fills up the Universe uniformly
- Temperature: T_γ=2.725 K
- (CMB) photons most abundant particle in the Universe: $n_\gamma \sim 415\ cm^{-3}$
- Per atom in the Universe: $n_\gamma/n_B \sim 1.9 \times 10^9$
- Ultimate evidence of the Big Bang !!!!!!!!!!!!!!!!!!!!

Recombination & Decoupling



the Cosmic TV Show

Note:

far from being an exotic faraway phenomenon, realize that the CMB nowadays is counting for approximately 1% of the noise on your (camping) tv set ...

!!!! Live broadcast from the Big Bang !!!!

Courtesy: W. Hu

Recombination & Decoupling

T ~ 3000 K

z_{dec}=1089 (Δz_{dec}=195); t_{dec}=379.000 yrs

- Before the "Recombination Epoch
  Radiation and Matter are tightly coupled through Thomson scattering.

- The events surrounding "recombination" exist of THREE major (coupled, yet different) processes:

Recombination	protons & electrons combine to H atoms
Decoupling	photons & baryonic matter no longer interact
Last scattering	meaning, photons have a last kick and go ...

Recombination & Decoupling

$T \sim 3000$ K

$z_{dec}=1089$ $(\Delta z_{dec}=195)$; $t_{dec}=379.000$ yrs

- Before this time, radiation and matter are tightly coupled through Thomson scattering:

$$e^- + \gamma \rightleftharpoons e^- + \gamma$$

Because of the continuing scattering of photons, the universe is a "fog".

- A radical change of this situation occurs once the temperature starts to drop below T~3000 K. and electrons. Thermodynamically it becomes favorable to form neutral (hydrogen) atoms H (because the photons can no longer destory the atoms):

$$p + e^- \rightleftharpoons \mathrm{H}$$

- This transition is usually marked by the word "recombination", somewhat of a misnomer, as of course hydrogen atoms combine just for the first time in cosmic history. It marks a radical transition point in the universe's history.

Recombination - Saha

Recombination Process:

$$p + e^- \rightleftarrows H + \gamma$$

Statistical Equilibrium sets the density of electrons, protons and hydrogen atoms involved in the recombination process:

$$n_e = g_e \frac{\left(2\pi m_e kT\right)^{3/2}}{\left(2\pi\hbar\right)^3} \exp\left\{\frac{\mu_e - m_e c^2}{kT}\right\}$$

$$n_p = g_p \frac{\left(2\pi m_p kT\right)^{3/2}}{\left(2\pi\hbar\right)^3} \exp\left\{\frac{\mu_p - m_p c^2}{kT}\right\}$$

$$n_H = g_H \frac{\left(2\pi m_H kT\right)^{3/2}}{\left(2\pi\hbar\right)^3} \exp\left\{\frac{\mu_H - m_H c^2}{kT}\right\}$$

Recombination - Saha

Recombination Process:

$$p + e^- \rightleftarrows H + \gamma$$

Taking along that for the chemical potentials

$$\mu_p + \mu_e = \mu_H$$

we find for the relation between the number densities

$$\frac{n_H}{n_e n_p} = \frac{g_H}{g_e g_p}\left(\frac{m_H}{m_e m_p}\right)^{3/2}\left(\frac{kT}{2\pi\hbar^2}\right)^{-3/2}\exp\left\{\frac{[m_p + m_e - m_H]c^2}{kT}\right\}$$

Recombination - Saha

Recombination Process:

$$p + e^- \rightleftarrows H + \gamma$$

- mass electron small: $m_H / m_p \approx 1$
- binding energy hydrogen atom: $\left(m_e + m_p - m_H\right)c^2 = \chi = 13.6\ eV$
- weights g_i: $g_e = 2,\ \ g_p = 2,\ \ g_H = 4$

results in the Saha Equation,

$$\frac{n_H}{n_e n_p} = \left(\frac{m_e kT}{2\pi\hbar^2}\right)^{-3/2} \exp\left\{\frac{\chi}{kT}\right\}$$

which specifies the shifting ionization state as a function of shifting temperature T

Recombination - Ionization

Recombination Process:

$$p + e^{-} \rightleftarrows H + \gamma$$

Photon number density in blackbody bath temperature T:

$$n_\gamma = \frac{2.404}{\pi^2}\left(\frac{kT}{\hbar c}\right)^3 = 0.243\left(\frac{kT}{\hbar c}\right)^3$$

Ionization fraction x:

$$X = \frac{n_p}{n_p + n_H}$$

$$n_e = n_p = Xn$$

$$n = n_p + n_H \simeq n_b$$

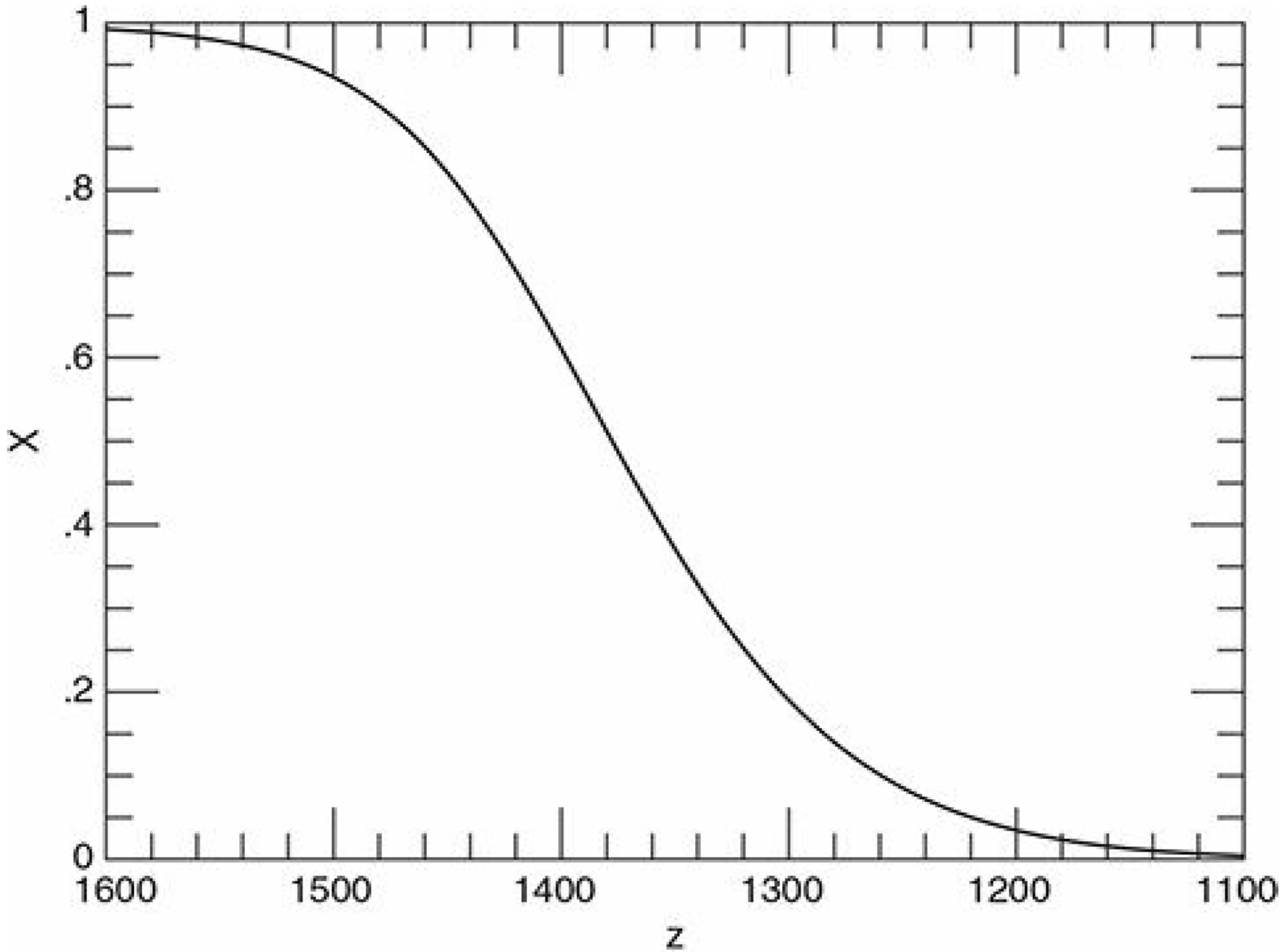
Baryon-photon ratio η:

$$\eta = \frac{n_b}{n_\gamma} = \frac{n_p}{Xn_\gamma}$$

Proton number density at T:

$$n_p = 0.243\, X\, \eta \left(\frac{kT}{\hbar c}\right)^3$$

Recombination: Ionization Evolution (Saha)



Recombination - Ionization

Recombination Process:

$$p + e^- \rightleftarrows H + \gamma$$

Relation between temperature T and ionization fraction X:

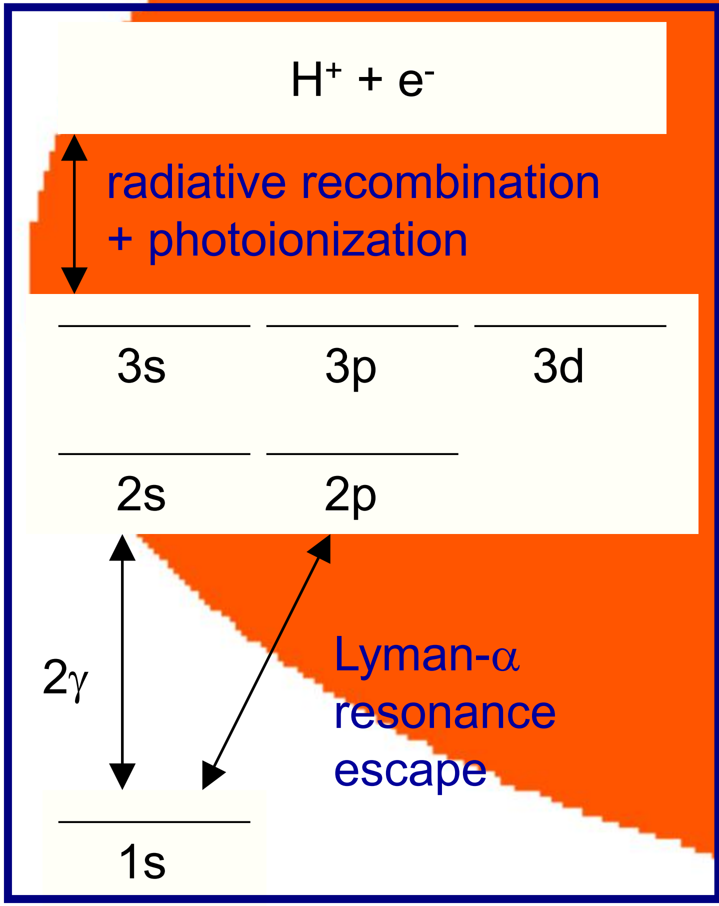
$$\frac{1-X}{X^2} = 3.84\eta \left(\frac{kT}{m_e c^2} \right)^{3/2} \exp\left\{ \frac{\chi}{kT} \right\}$$

Moment of recombination:

$$X = \frac{1}{2} \qquad kT_{rec} \approx 0.323\ eV = 3740\ K$$

Standard theory of H recombination

(Peebles 1968, Zel'dovich et al 1968)



Recombination Process
not entirely trivial:

- ground state could be reached via Lya transition (2P-1S)

DOES NOT WORK !!!!!

large abundance Lya → Ionization

- Recombination in parts:
  forbidden transition = 2-photon emission:
  2S – 1S

- Takes 8.23 s^{-1} →
  much slower than 'direct', and thus

  recombination occurs late ...
  at T ~ 3000 K

Decoupling

Decoupling:

$$\gamma + e^- \rightleftarrows \gamma + e^-$$

Thomson scattering:
Elastic scattering of photons off electrons

Cross-section: $$\sigma_e = 6.65 \times 10^{-29}\ m^2$$

Mean free path: $$\lambda = \frac{1}{n_e \sigma_e}$$

Interaction rate: $$\Gamma = \frac{c}{\lambda} = n_e \sigma_e c$$

Decoupling - Primordial Plasma

Decoupling:

$$\gamma + e^- \rightleftarrows \gamma + e^-$$

Thomson scattering:

Fully ionized plasma:

$$n_e = n_p = n_b$$

$$n_e = n_b = \frac{n_{b,0}}{a^3}$$

Interaction rate: $\Gamma = \frac{n_{b,0}\ \sigma_e c}{a^3}\ s^{-1} = \frac{4.4\times 10^{-21}}{a^3}\ s^{-1}$

$a = 10^{-5}: \quad \sim 3\ \ per\ \ week$

Decoupling - Primordial Plasma

Decoupling:

$$\gamma + e^- \rightleftarrows \gamma + e^-$$

Thomson scattering:

Fully ionized plasma:

Interaction rate - Hubble expansion rate: $\Gamma \quad > \quad H$

$$\frac{H^2}{H_0^{\,2}} = \frac{\Omega_{r,0}}{a^4} \qquad \Rightarrow \qquad H = \frac{H_0 \Omega_{r,0}^{\;1/2}}{a^2} = 2.1\times 10^{-20}\ s^{-1}$$

radiation-dominated phase

$$\Gamma = \frac{n_{b,0}\ \sigma_e c}{a^3}\ s^{-1} = \frac{4.4\times 10^{-21}}{a^3}\ s^{-1}$$

If fully ionized: decoupling at $a \approx 0.023 \quad \Rightarrow \quad z \approx 42,\ T = 120\ K$

Decoupling - Recombination

Decoupling:

$$\gamma + e^- \rightleftarrows \gamma + e^-$$

Thomson scattering:

While plasma undergoes recombination,
number density electrons n_e decreases,
substantially altering interaction rate:

$$\Gamma(z) = n_e(z)\sigma_e c = X(z)\,(1+z)^3\, n_{b,0}\,\sigma_e c$$
$$= 4.4\times10^{-21}\ s^{-1}\ X(z)(1+z)^3$$

Decoupling - Recombination

Decoupling:

$$\gamma + e^- \rightleftarrows \gamma + e^-$$

Thomson scattering:

Interaction rate vs. Hubble expansion rate:

$$\frac{H^2}{H_0{}^2} = \frac{\Omega_{m,0}}{a^3} = \Omega_{m,0}(1+z)^3 \Rightarrow \quad H(z) = 2.1\times 10^{-18}\,(1+z)^{3/2}\,s^{-1}$$

Decoupling when $\Gamma < H$

$$1 + z_{dec} = \frac{43.0}{X(z_{dec})^{2/3}}$$

Saha equation value X(z):

$$z_{dec} \approx 1130$$

Last Scattering

Thomson scattering:

$$\gamma + e^- \rightleftarrows \gamma + e^-$$

Probability scattering in time interval dt:

$$dP = \Gamma(t)\ dt$$

Expected number of scatterings since time t when CMB photon seen at t0,

$$\tau(t) = \int_t^{t_0} \Gamma(t)\, dt$$

This is *Optical Depth !*

Last Scattering

Thomson scattering:

$$\gamma + e^- \rightleftarrows \gamma + e^-$$

Last Scattering Epoch:

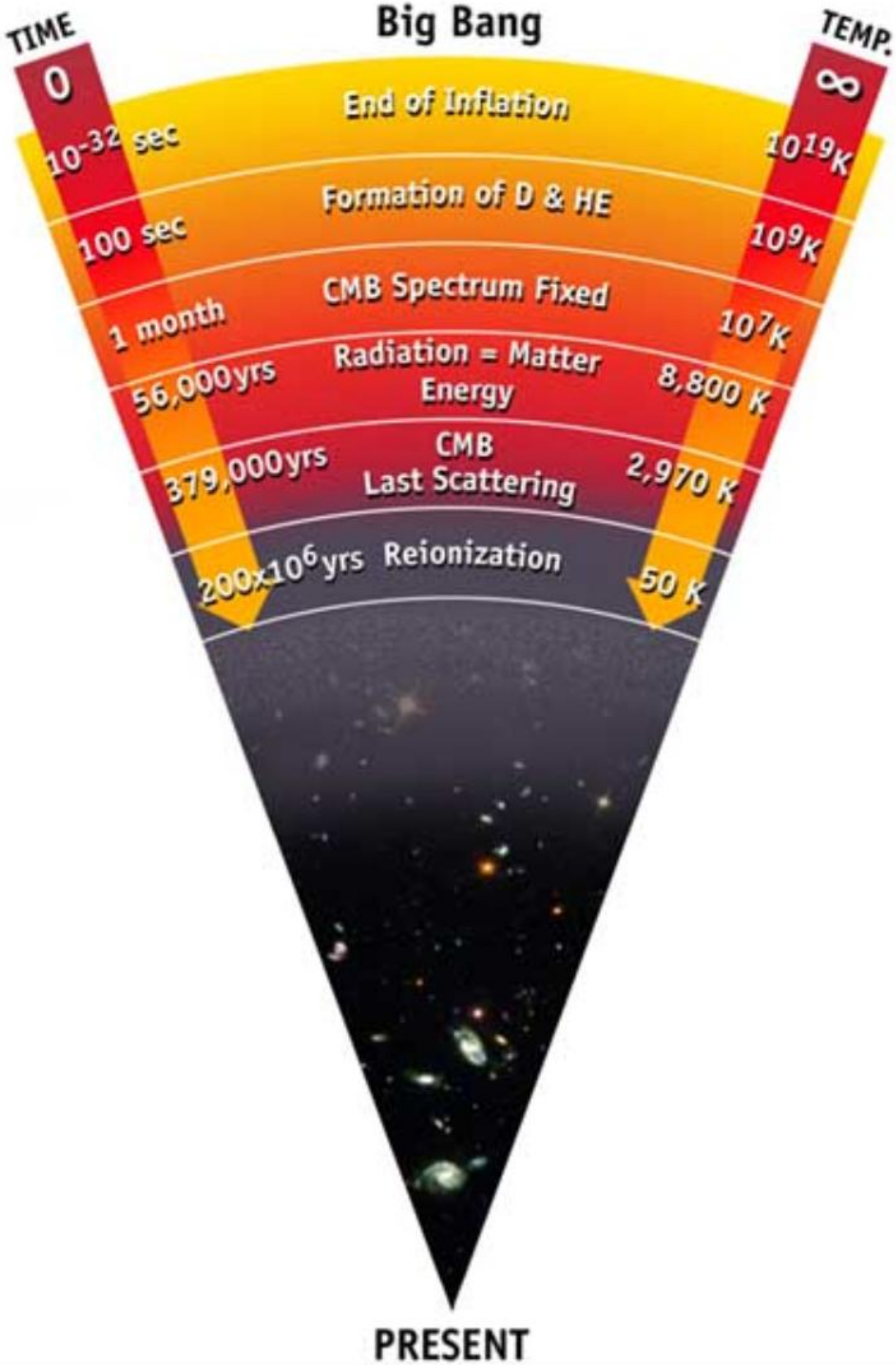
time t for which

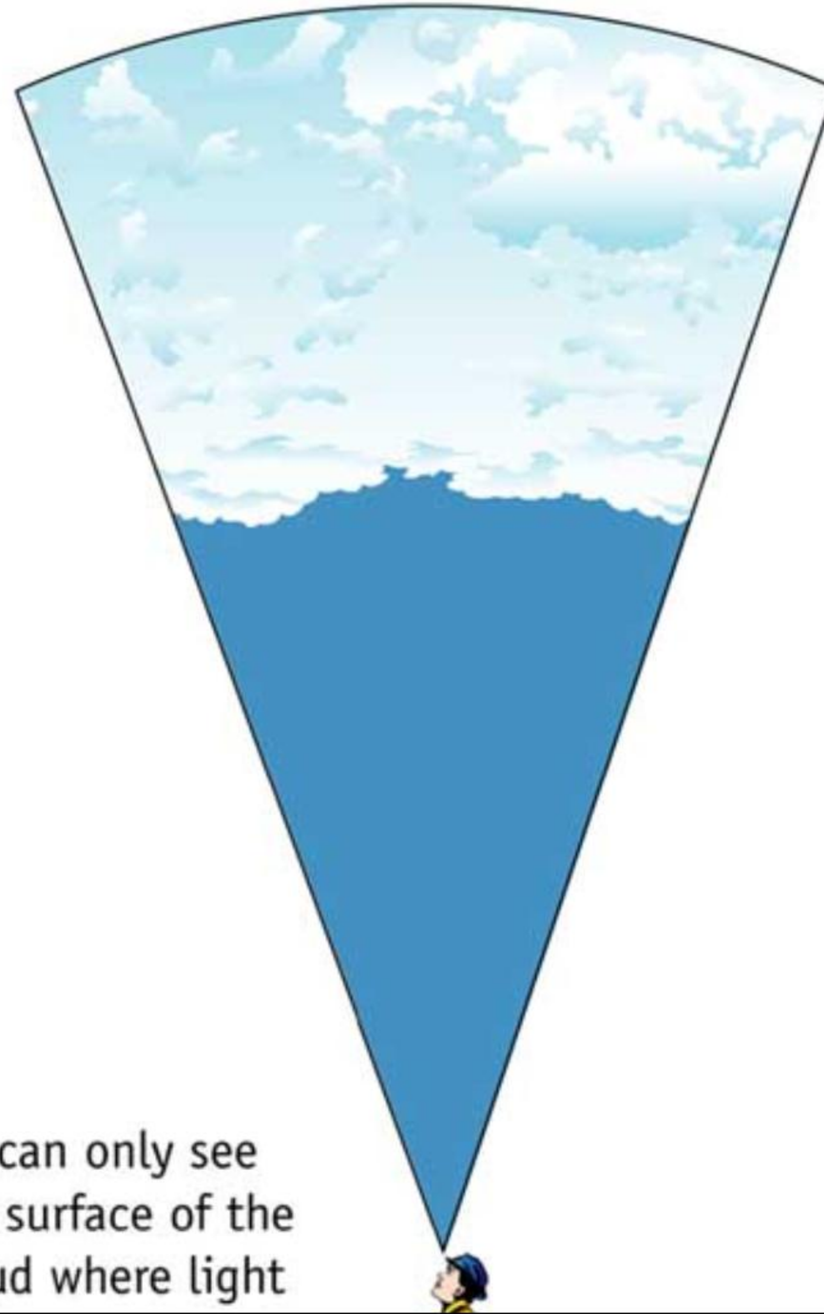
$$\tau(t) = \int_t^{t_0} \Gamma(t)\, dt = 1$$

Last scattering epoch:

$$\tau(a) = \int_a^1 \Gamma(a) \frac{da}{\dot{a}} = \int_a^1 \frac{\Gamma(a)}{H(a)} \frac{da}{a} \quad \Rightarrow \quad \tau(z) = \int_0^z \frac{\Gamma(z)}{H(z)} \frac{dz}{1+z} = 0.0035 \int_0^z X(z)(1+z)^{1/2} dz$$

$$z_{ls} \approx z_{dec} \approx 1100$$





We can only see
the surface of the
cloud where light

Recombination & Decoupling

- In summary, the recombination transition and the related decoupling of matter and radiation defines one of the most crucial events in cosmology. In a rather sudden transition, the universe changes from

Before z_{dec}, $z>z_{dec}$

- universe fully ionized
- photons incessantly scattered
- pressure dominated by radiation:

$$p = \frac{1}{3} a T^4$$

After z_{dec}, $z<z_{dec}$

- universe practically neutral
- photons propagate freely
- pressure only by baryons:

$$p = n k T$$

- (photon pressure negligible)

Origin CMB Photons

Important Issues:

- When were the CMB photons produced ?
- How did they become a blackbody/thermal radiation field
- At which time were they scattered for the last time (in other words, what are we looking at ?)

Origin CMB Photons

$T < 10^9$ K

$t \sim 1$ min, $z \sim 10^9$

Origin CMB photons:

- most were produced when electrons & positrons annihilated each other

$$e^+ + e^- \rightleftharpoons 2\gamma$$

- (a few perhaps even at reheating phase inflation)

CMB thermalization

- At the onset certainly not thermally distributed energies
- Photons keep on being scattered back and forth until z ~ 1089, the epoch of recombination.
- Thermal equilibrium (blackbody spectrum) of photons reached within 2 months after their creation

Blackbody Spectrum produced through three scattering processes

- Compton scattering
- Free-free scattering
- Double Compton scattering

CMB Thermalization

- Thermalization through three scattering processes
  - Compton scattering — + dominant energy redistribution
  - Free-free scattering — + creates new photons to
  - Double Compton scattering — adjust spectrum to Planck

- While Compton scattering manages to redistribute the energy of the photons, it cannot adjust the number of photons. Free-free scattering and Double Compton scattering manage to do so ...

- But ...

  only before $z < 10^5$, after that the interaction times too long ....

CMB Thermalization

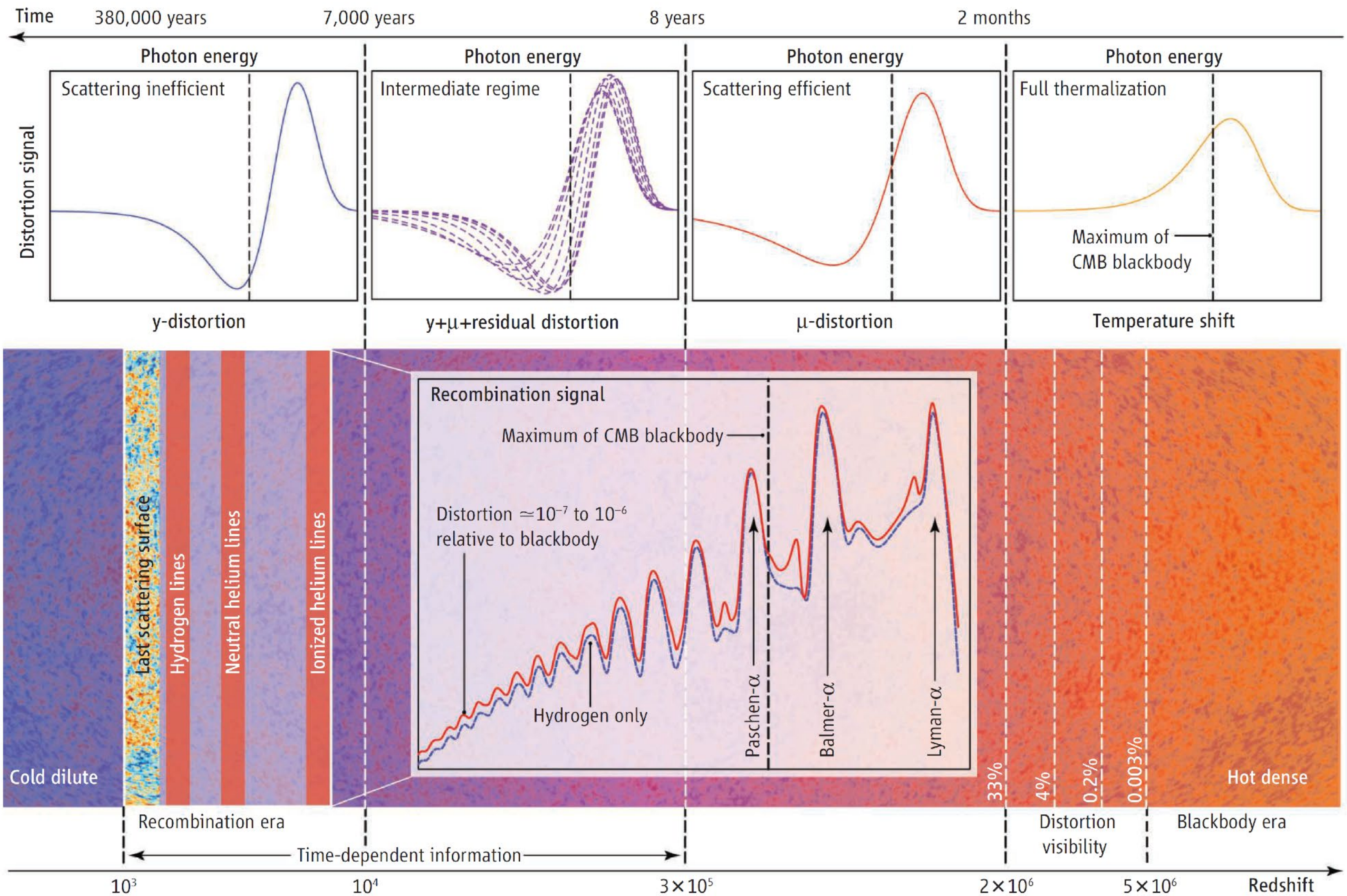
- Following this thermalization, a perfect blackbody photon spectrum has emerged:

$$I_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$

- This is the ULTIMATE proof of the HOT BIG BANG

- Note: after $z \sim 10^5$ till recombination, the interaction between electrons and photons exclusively by Thomson Scattering

CMB hermalization



Chluba & Silk 2015

First Three Minutes:

Big Bang Nucleosynthesis

Photon Energy   Early Universe

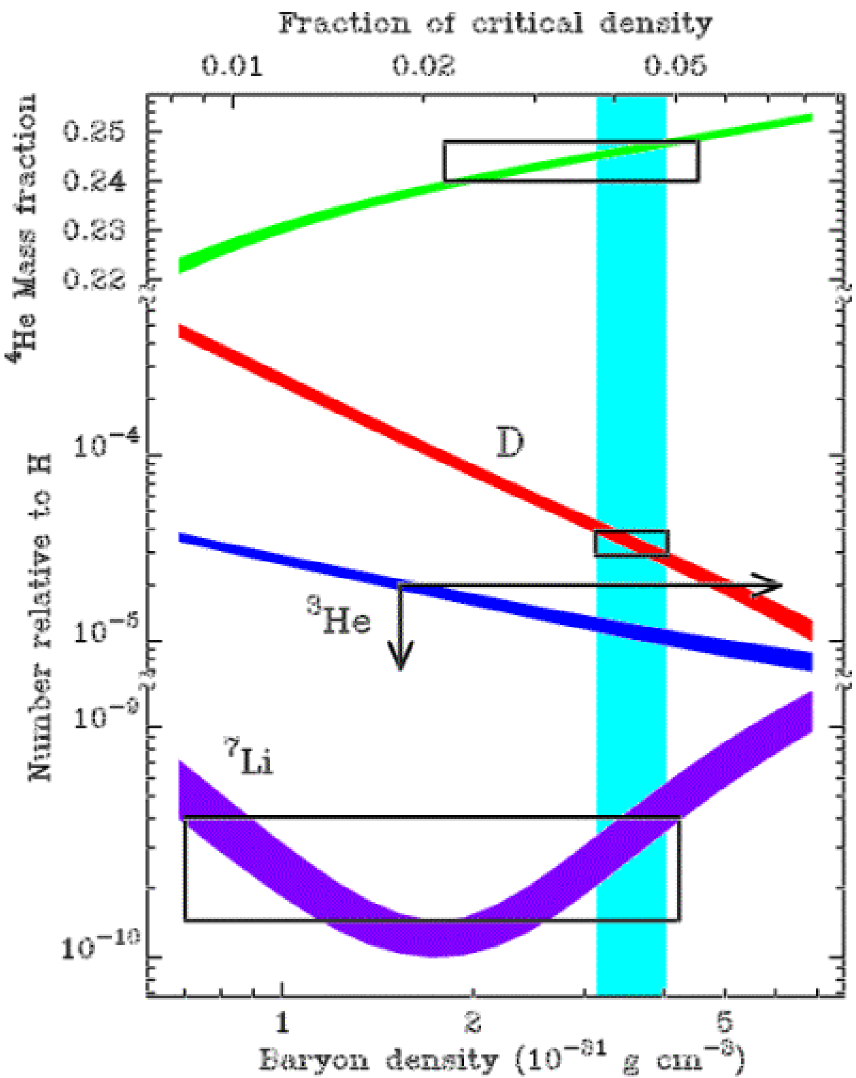
Radiation-dominated phase:

$$T(t) \approx 10^{10}\ K \left(\frac{t}{1\ \text{sec}} \right)^{-1/2}$$

$$kT \approx 1\ \ MeV \left(\frac{t}{1\ \text{sec}} \right)^{-1/2}$$

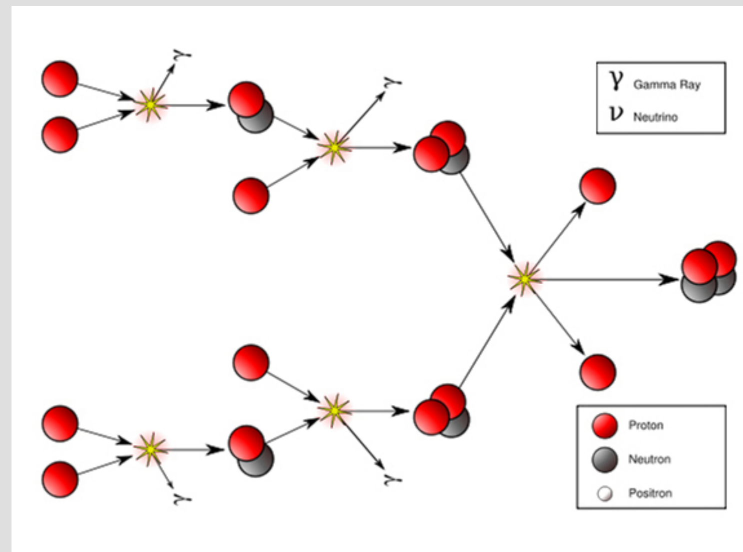
Big Bang Nucleosynthesis

p/n ~1/7: 1 min na BB



Mass Fraction Light Elements

24%	^{4}He	nuclei
traces	D, ^{3}He, ^{7}Li	nuclei
75%	H	nuclei (protons)



Between 1-200 seconds after Big Bang, temperature dropped to 10^9 K:

Fusion protons & neutrons into light atomic nuclei

Neutron-Proton – before Neutrino Decoupling

Before Neutrino Decoupling:

equilibrium between protons & neutrons through 2 weak interactions:P

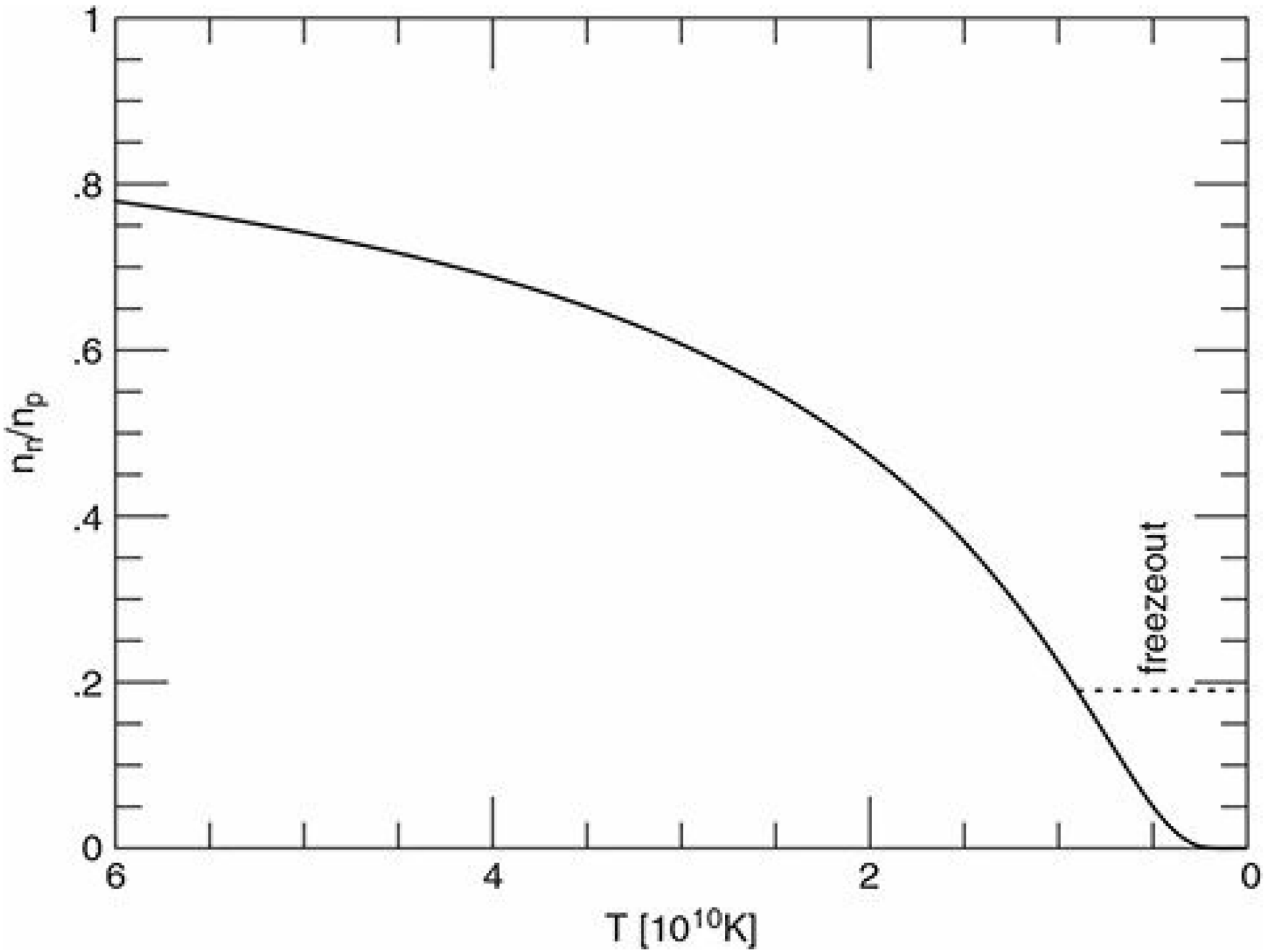
$$n+\nu_e \rightleftarrows p + e^-$$

$$n+e^+ \rightleftarrows p + \overline{\nu}_e$$

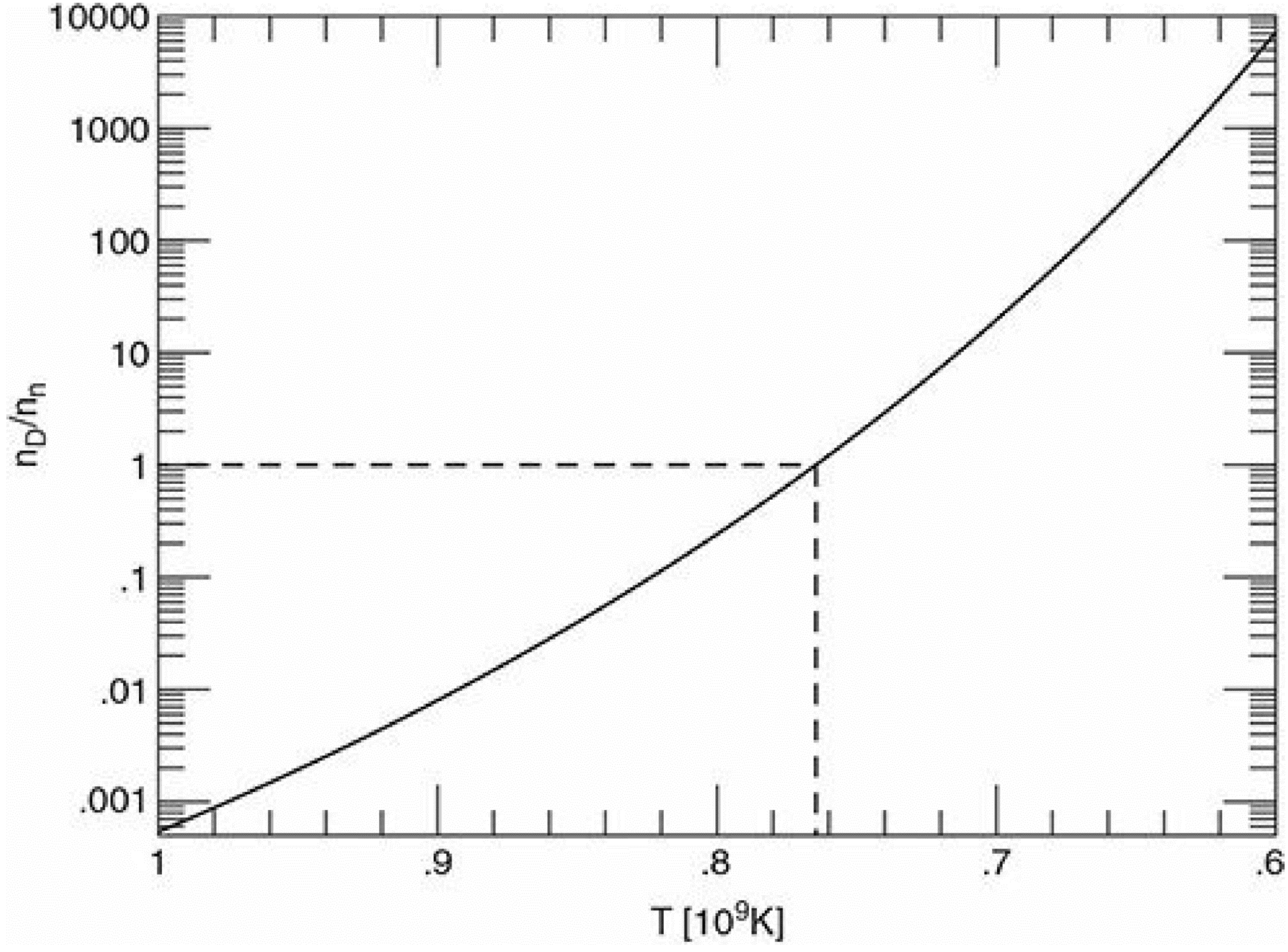
we find for the relation between the number densities

$$\frac{n_n}{n_p}=\left(\frac{m_n}{m_p}\right)^{3/2} \exp\left\{\frac{[m_n - m_p]c^2}{kT}\right\}$$

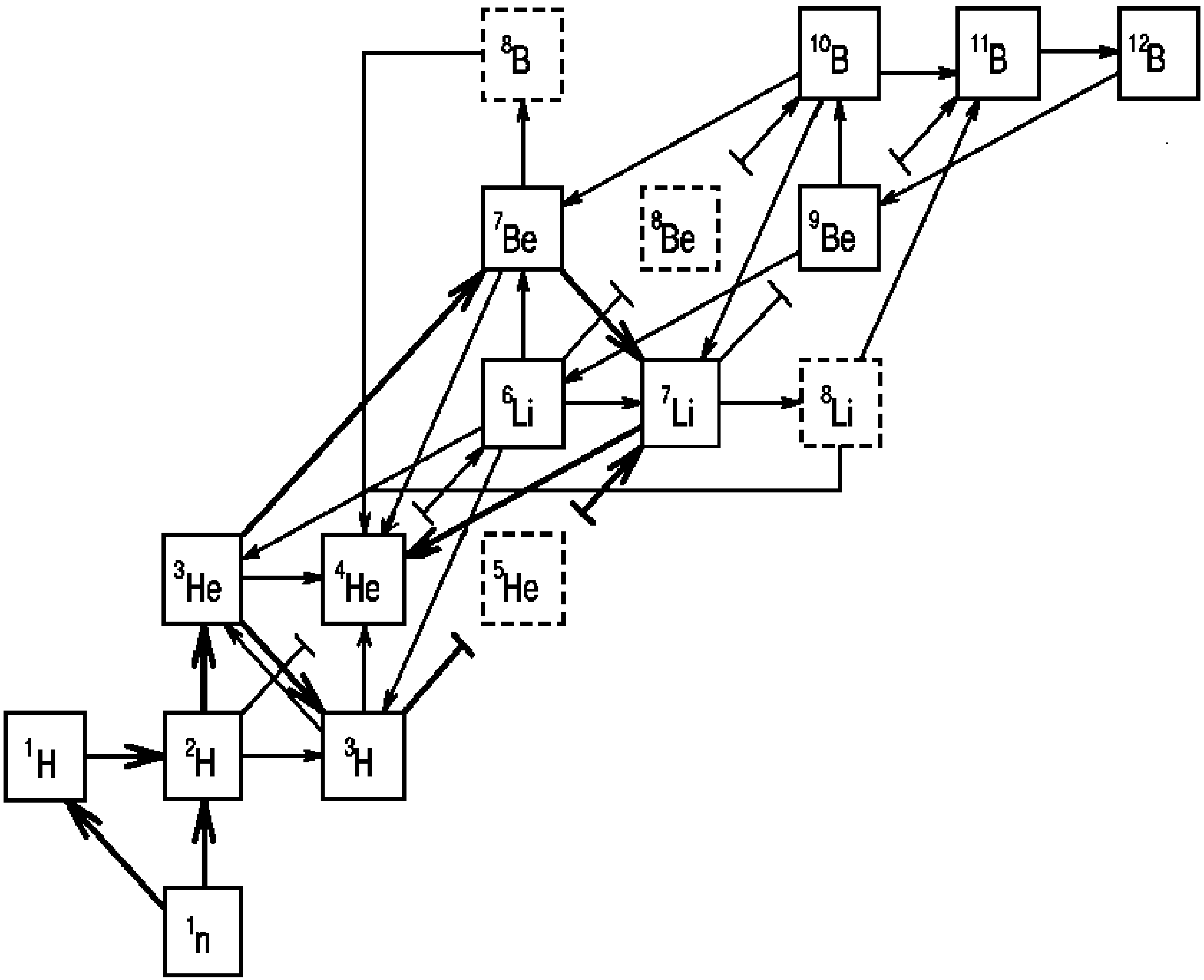
Neutron-Proton - Saha



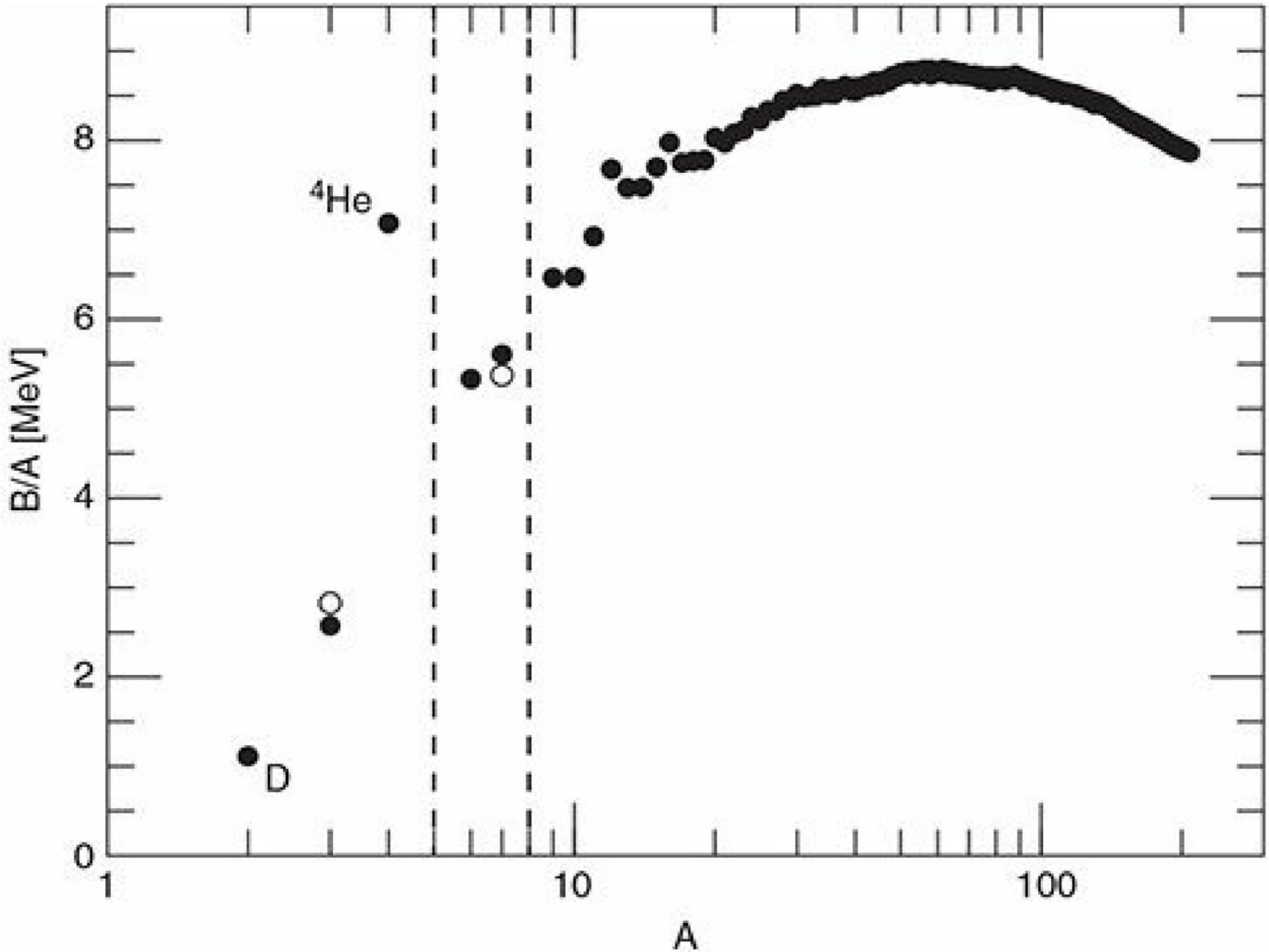
Deuterium-Neutron - Saha

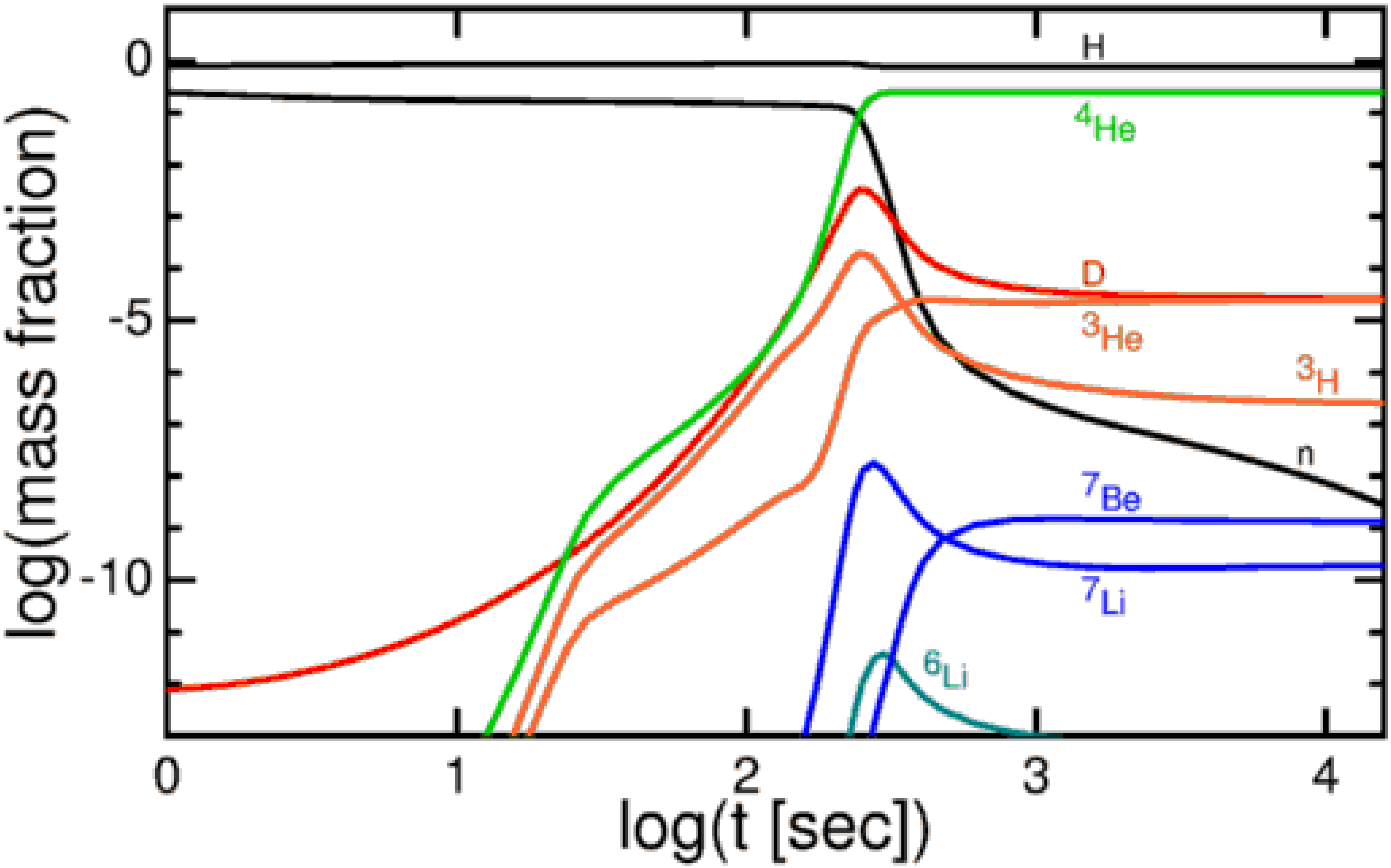


Big Bang Reaction Network

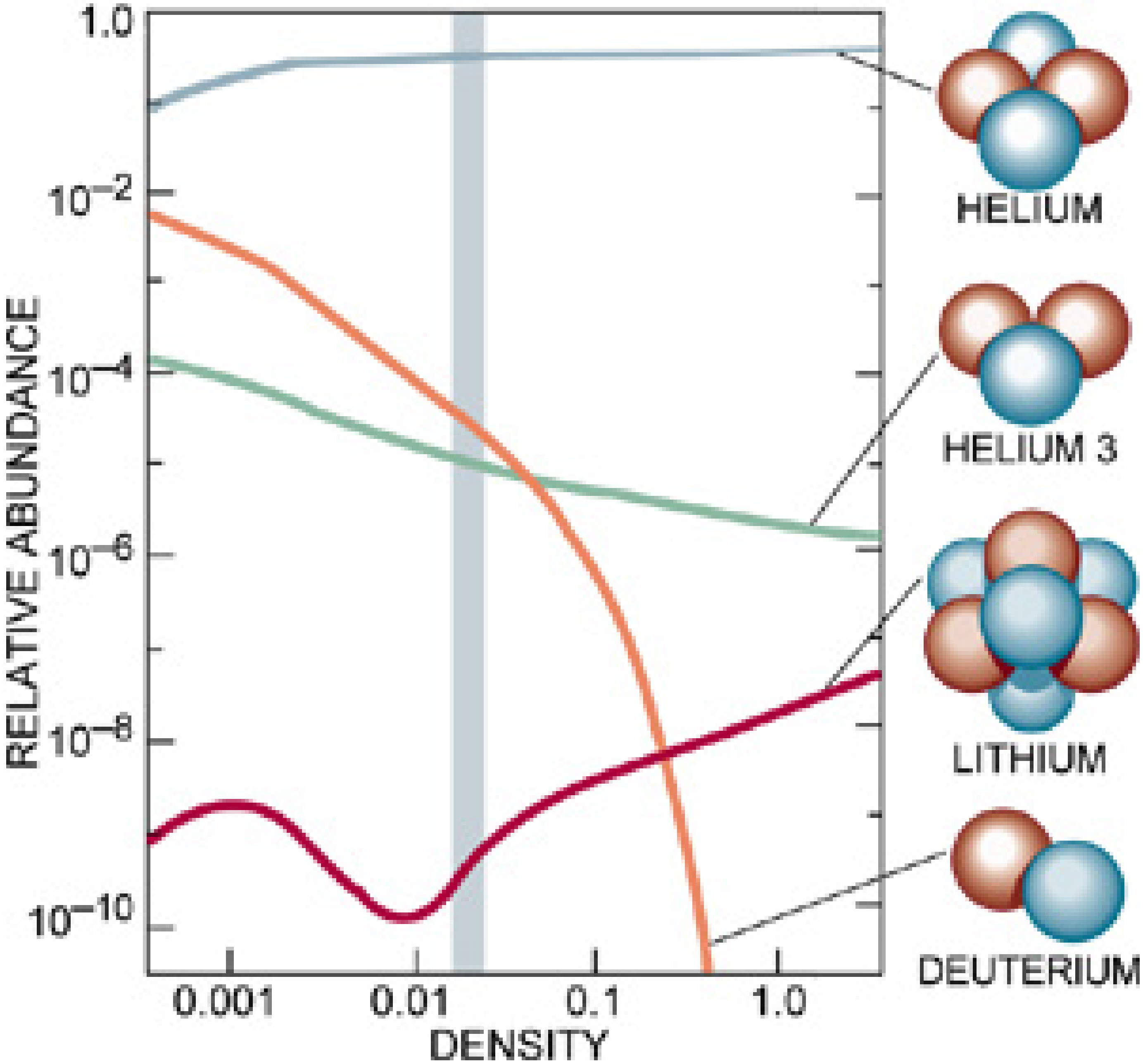


Nucleus Binding Energies





H
4He
D
3He
3H
n
7Be
7Li
6Li
0
-5
-10
0
1
2
3
4
log(mass fraction)
log(t [sec])


1.0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
RELATIVE ABUNDANCE
0.001
0.01
0.1
1.0
DENSITY
HELIUM
HELIUM 3
LITHIUM
DEUTERIUM

Helium Abundance – Neutrino's