Early Universe

Lectures at Canary Islands Winter School 2022

Outline:

1) CMB & BBN
2) Baryogenesis
3) Inflation (background)
4) Inflation (perturbations)

Literature

- Bailin, Love : Cosmology in gauge field theory and string theory
- Baumann: TASI Lecture Notes Inflation arxiv: 0907.5424

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0) Some GR & equilibrium thermodynamics

Einstein's equations: $$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu}$$

metric

matter

→ Friedmann equations:

0) Some GR & equilibrium thermodynamics

Einstein's equations: $$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu}$$

metric → (left-hand side) matter → (right-hand side)

metric

$$ds^2 = -dt^2 + a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\Omega\right)$$

matter

perfect fluid $T^\mu_\nu = \mathrm{diag}(\rho, -p, -p, -p)$

e.g. gas of relativistic particles:

$$\rho = \left(N_B + \frac{7}{8} N_F\right) \frac{\pi^2 T^4}{30}$$

$$p = (\qquad\qquad) \frac{\pi^2 T^4}{90}$$

$$s = \underbrace{(\qquad\qquad)}_{g_*} \frac{2\pi^2 T^3}{45}$$

$w = \rho/p$ equation of state parameter

→ Friedmann equations:

$$\left(\frac{\dot a}{a}\right)^2 = H^2 = \frac{1}{3}\rho - \frac{k}{a^2} \qquad (F1)$$

$$\frac{\ddot a}{a} = \dot H + H^2 = -\frac{1}{6}(\rho + 3p) \qquad (F2)$$

$$\hookrightarrow \frac{d\rho}{dt} = -3H(\rho + p)$$

$$\hookrightarrow \rho \propto a^{-3(1+w)}$$

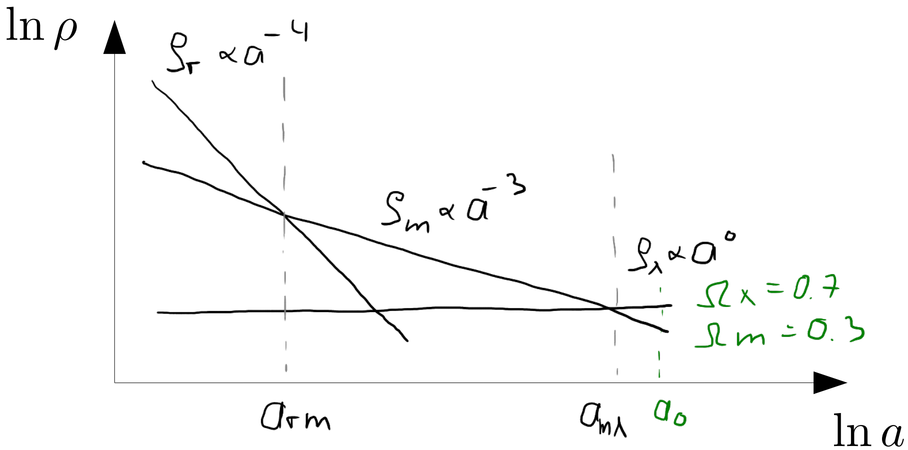
rad: $w = 1/3$
mat: $w = 0$
cc: $w = -1$

matter radiation equality

equality temperatures:

time evolution of energy densities:

matter radiation equality



equality temperatures:

$$\rho_m = \rho_r$$

$$\hookrightarrow T_{rm} = 5.68\, \Omega_m h^2\, eV$$
$$\simeq eV$$

$$\rho_m = \rho_\Lambda$$

$$\hookrightarrow T_{m\Lambda} = 3 \cdot 10^{-4}\, eV$$

time evolution of energy densities:

$$\rho_m = 3 M_P^2 H_0^2 \; \Omega_m \left(\frac{T}{T_0} \right)^3$$

$$T_0 = 2.7\,K = 2 \cdot 10^{-4}\, eV$$

$$\rho_r = \frac{\pi^2}{30} g_{*,\text{eff}}\, T^4$$

$$2 + \frac{7}{8} \cdot 6 \cdot \left(\frac{4}{11} \right)^{4/3} \simeq 3.36$$

$\uparrow$ γ $\quad$ $\uparrow$ ν

[T_γ reheating after ν-decoupling due to $e^+ e^- \to \gamma\gamma$,

$$\frac{g_*(\gamma)}{g_*(\gamma, e^\pm)} = \frac{4}{11}$$

1) CMB

degrees of freedom at T ~ eV:

're-combination' :

Propagation of sound waves

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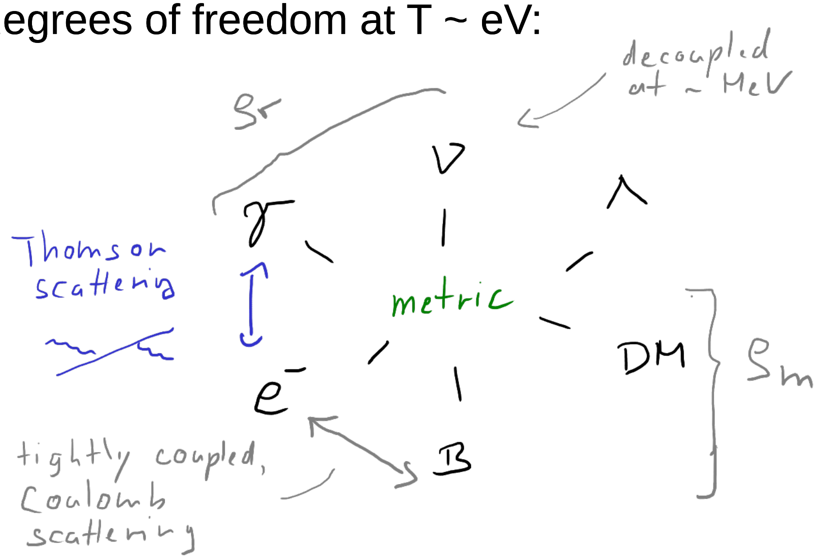

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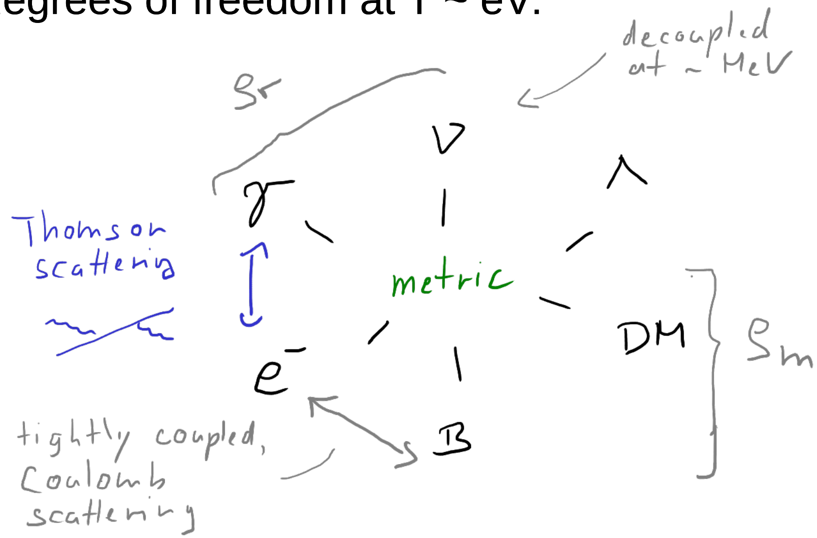

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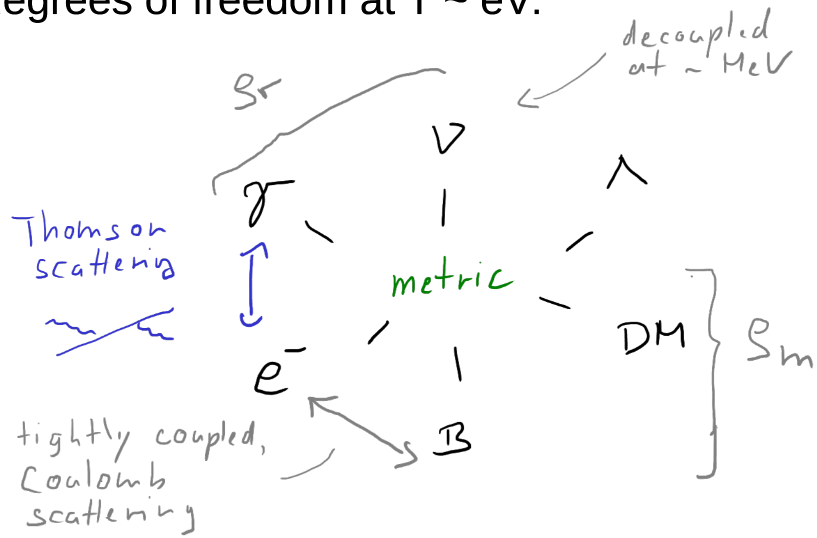

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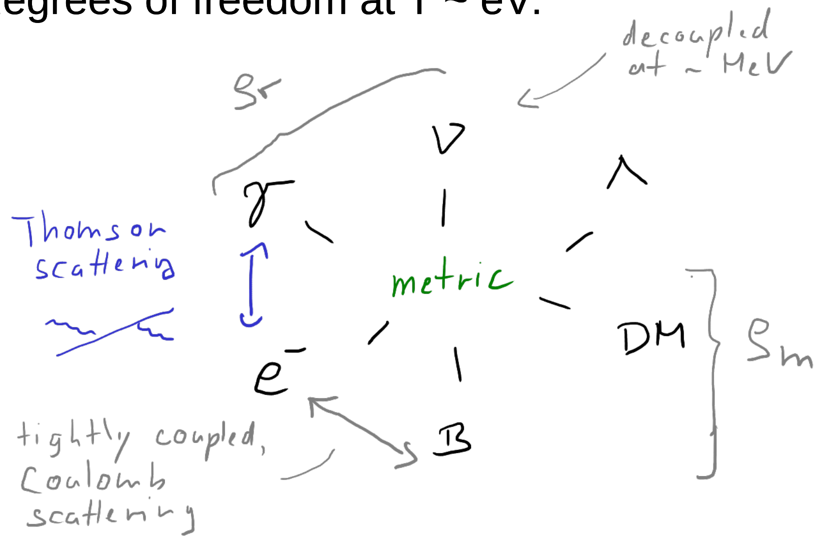

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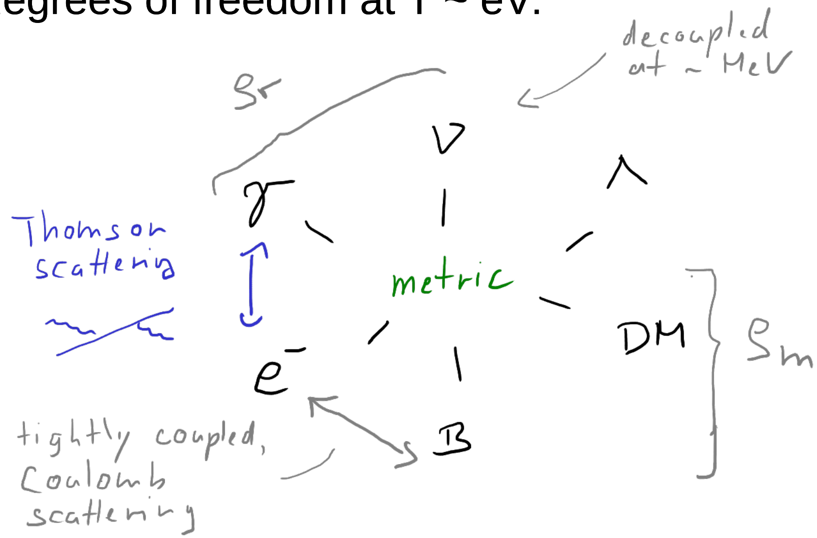

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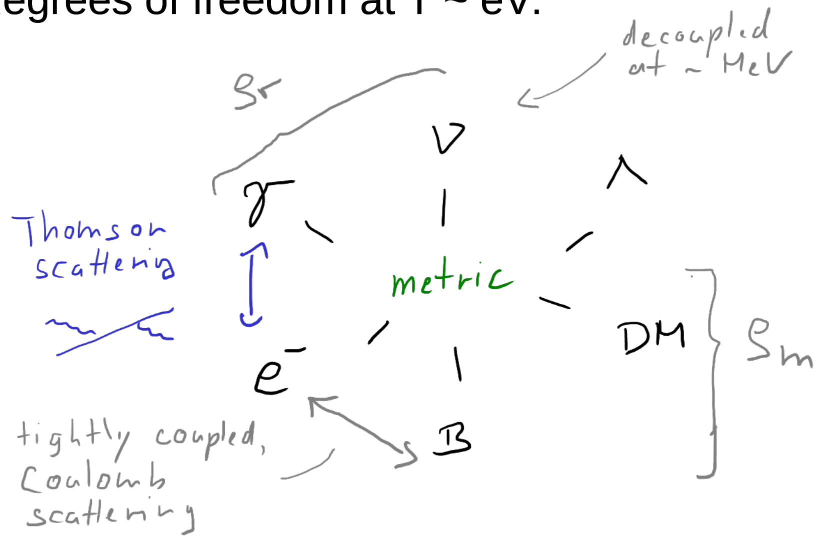

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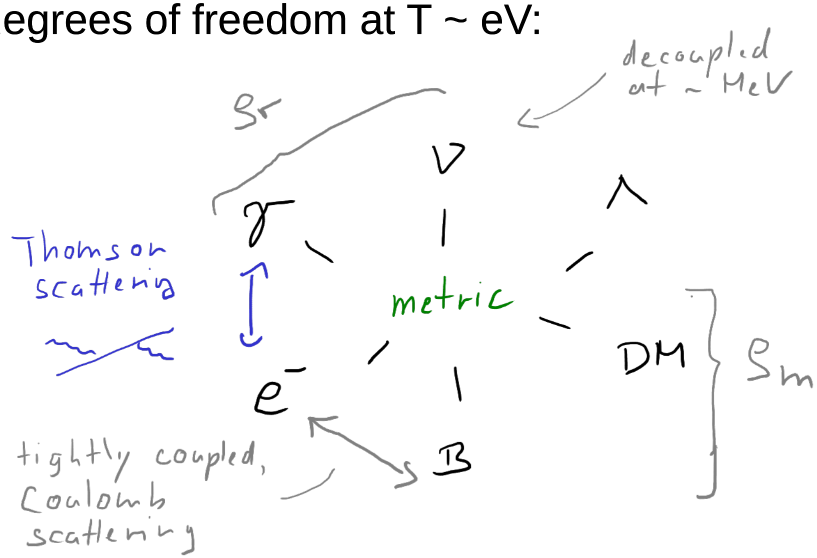

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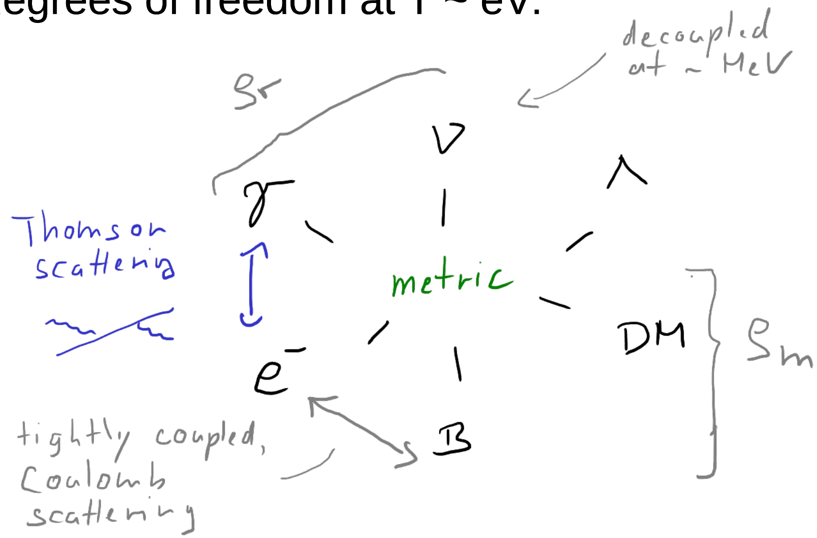

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- depends on plasma properties

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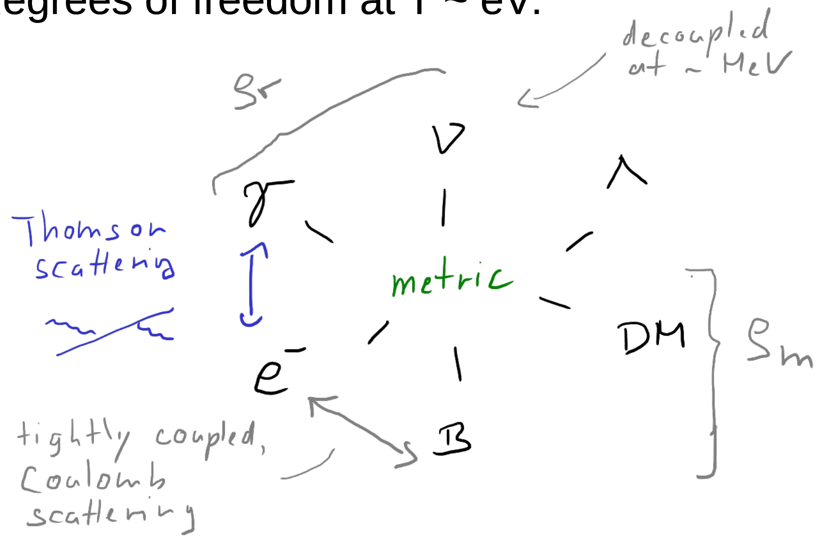

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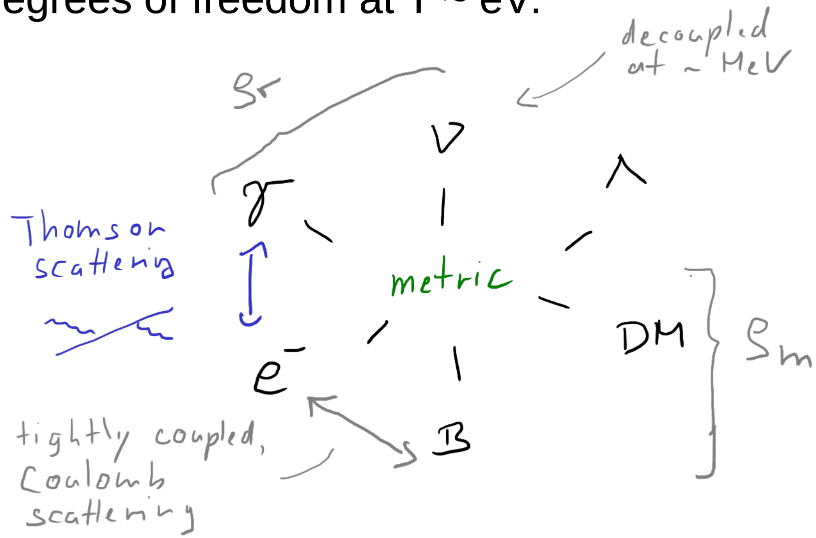

Propagation of sound waves

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$$\Omega_m, \Omega_\Lambda, \Omega_B, \Omega_r, \Omega_{\rm tot}$$

- and initial conditions (→ inflation)
- locally $\delta a_{\rm rec} \to \delta T_{\rm CMB}$

  → CMB anisotropies
  → lectures by Fabio Finelli

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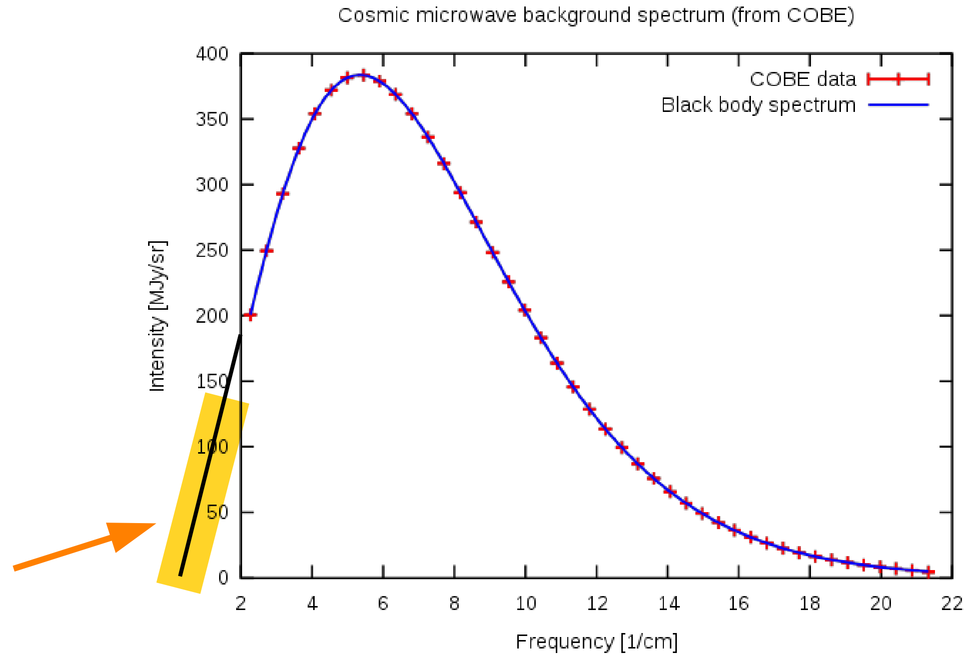
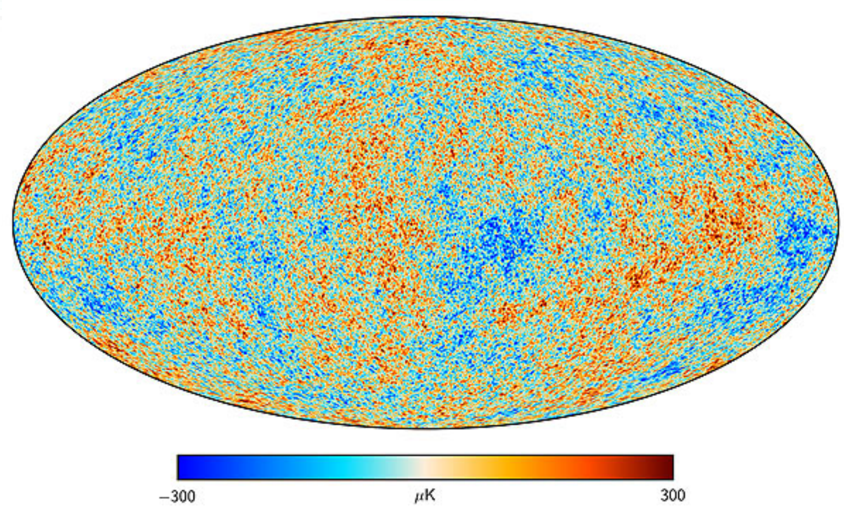
Arno Penzias, Robert Wilson 1964



COBE satellite, 1989-93

PLANCK Satellit, 2009 - 2013



2) BBN Formation of light elements

a) neutron freeze-out

b) deuterium formation

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a) neutron freeze-out

$T \gg \text{MeV}$: $n \nu_e \leftrightarrow p e^-$, ... w. rate $\lambda_{p\to n} = \lambda_{n \to p} \, e^{-\Delta m / T}$ ↑ $m_n - m_p = 1.293$ MeV

$X_n \equiv \frac{n_n}{n_n + n_p}$, $\dot{X}_n = \lambda_{p\to n}(1 - X_n) - \lambda_{n\to p} X_n$

$\dot{X}_n = 0 \to X_n^{eq} = (1 + e^{\Delta m / T})^{-1}$

luckily $\mathcal{O}(1)$!

$\left.\begin{array}{l}\lambda_{n\to p}, \lambda_{p\to n} \sim H \\ \text{at } T_{dec} \sim \text{MeV}\end{array}\right\} \to n$ decoupling $\to X_n(t_{dec}) = X_n^{eq}(t_{dec}) = \frac{1}{1 + e^{\Delta m / T_{dec}}}$

(weak force vs. gravity)

$(\simeq 0.15)$

b) deuterium formation

$n p \leftrightarrow D \gamma$ (in eq. until 10^{-3} eV)

in eq: $X_D = X_n X_p \frac{24\,\zeta(3)}{\sqrt{\pi}} \left(\frac{T}{m_p}\right)^{3/2} \eta \, e^{\Delta_D / T}$

$\Delta_D = m_p + m_n - m_D = 2.23$ MeV

↳ $\frac{X_D}{X_n X_p} \sim 1$ at $T_{BBN} \sim \frac{\Delta_D}{33} = 0.068$ MeV

↑ $\eta = \frac{n_B}{n_\gamma} \sim 10^{-10}$

$(\hat{=}\ t = 3\,\text{min})$

deuterium bottle-neck

c) light element abundances

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- $p\,D \to {}^3He\,\gamma, \ldots$; $D\,T \to {}^4He\,n, \ldots$
- no stable $A = 5$ nuclei

  $\rightarrow$ all D converted to ${}^4He$

  $\rightarrow$ $Y_p({}^4He) = 2\,X_n(t_{BBN}) = X_n(t_{dec}) \cdot e^{-t_{BBN}/\tau_n} \simeq 0.24$

neutron decay

$\tau_n \sim 15\,\text{min}$

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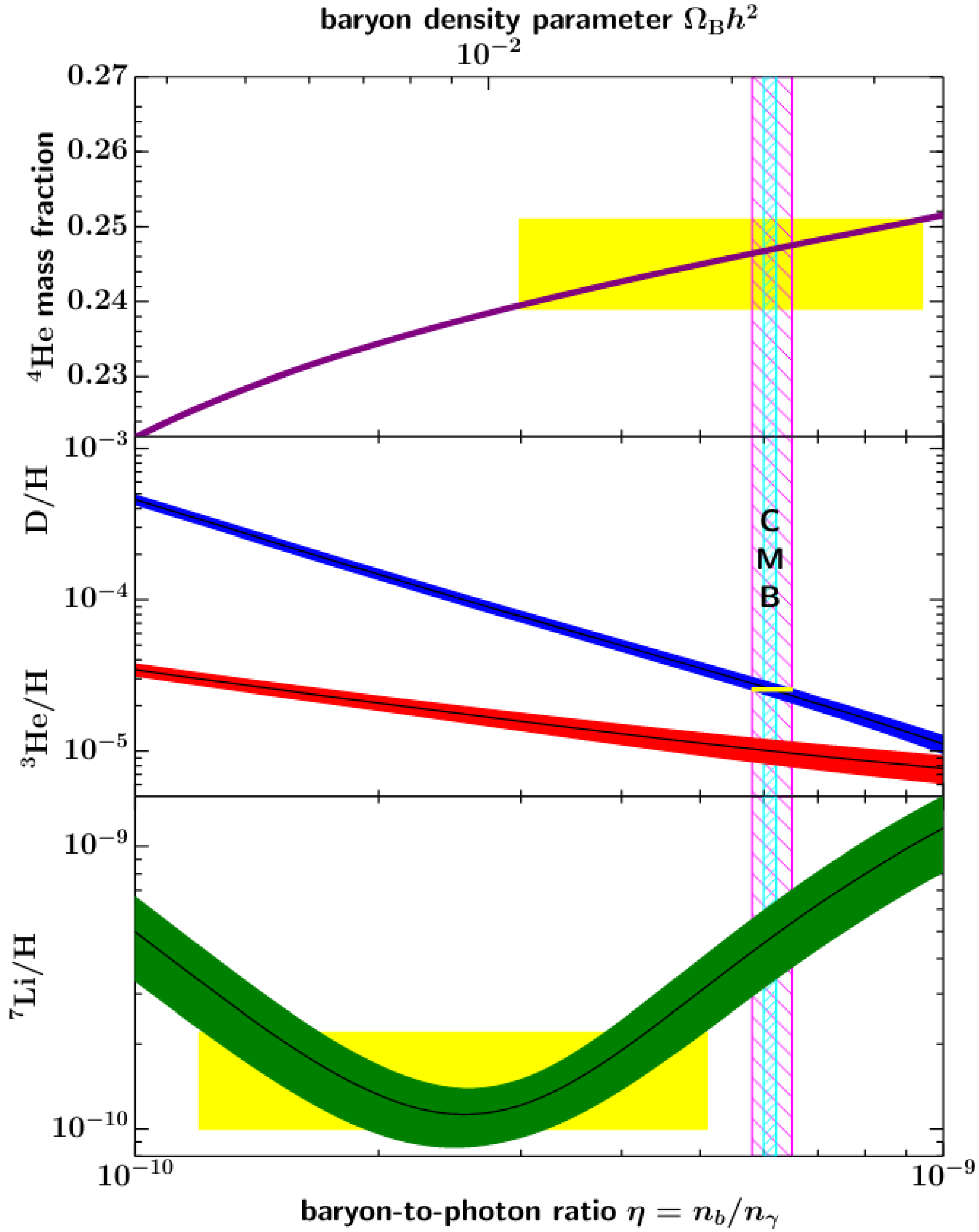
neutron decay
$\tau_n \sim 15\,min$

→ small η delays ^{4}He formation (due to D photo dissociation)

→ fraction of n is lost to n-decay

→ ^{4}He abundance as measure of baryon-to-photon ratio η
(similar for ^{3}He, D, ^{7}Li)



observed abundances

colored bands: BBN predictions

Fig. from PDG