Frontiers in Astrophysics

Particle Astrophysics:

BBN

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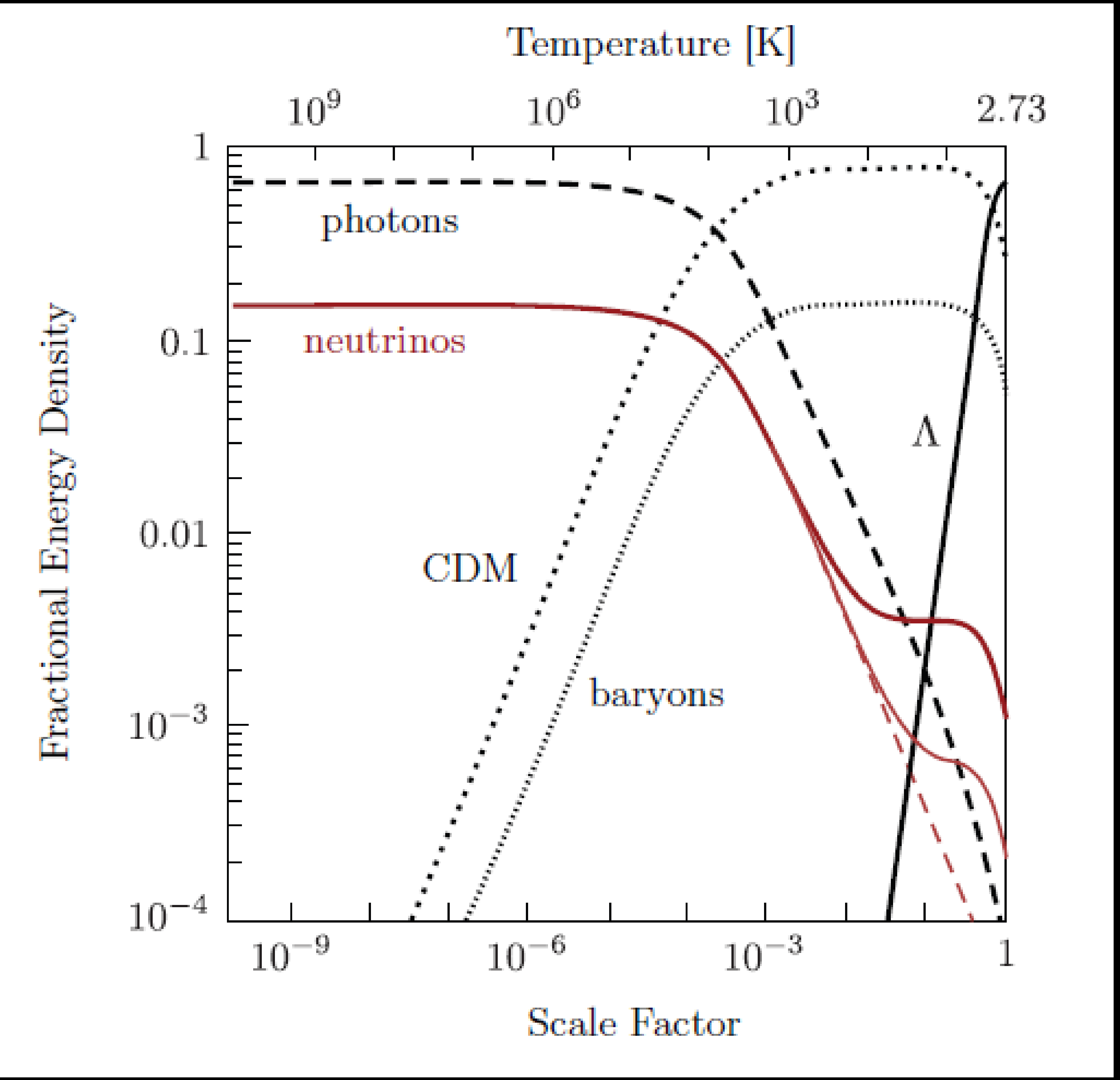
Timeline of Particle Cosmology

Event	time t	redshift z	temperature T
Inflation	10^{-34} s (?)	–	–
Baryogenesis	?	?	?
EW phase transition	20 ps	10^{15}	100 GeV
QCD phase transition	20 μs	10^{12}	150 MeV
Dark matter freeze-out	?	?	?
Neutrino decoupling	1 s	6×10^{9}	1 MeV
Electron-positron annihilation	6 s	2×10^{9}	500 keV
Big Bang nucleosynthesis	3 min	4×10^{8}	100 keV
Matter-radiation equality	60 kyr	3400	0.75 eV
Recombination	260–380 kyr	1100–1400	0.26–0.33 eV
Photon decoupling	380 kyr	1000–1200	0.23–0.28 eV
Reionization	100–400 Myr	11–30	2.6–7.0 meV
Dark energy-matter equality	9 Gyr	0.4	0.33 meV
Present	13.8 Gyr	0	0.24 meV



D. Baumann, *TASI Lectures on Primordial Cosmology*, arXiv:1807.03098.

Radiation Domination

$$n = \frac{g}{2\pi^2}\int_0^\infty f(p)\, p^2\, \mathrm{d}p \qquad f(p) = \frac{1}{e^{(E-\mu)/T} \pm 1}$$

$$\rho = \frac{g}{2\pi^2}\int_0^\infty f(p)\, E(p)\, p^2\, \mathrm{d}p \qquad E(p) = \sqrt{p^2 + m^2}$$

Non-relativistic:

$$E \approx m + 3/2T$$

$$n = g\left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T}$$

$$\rho = nm$$

Relativistic:

$$n = \begin{cases} \frac{1.202..}{\pi^2}\, g\, T^3 & \text{Bosons} \\ \frac{3}{4}\frac{1.202..}{\pi^2}\, g\, T^3 & \text{Fermions} \end{cases}$$

$$\rho = \begin{cases} \frac{\pi^2}{30}\, g\, T^4 & \text{Bosons} \\ \frac{7}{8}\frac{\pi^2}{30}\, g\, T^4 & \text{Fermions} \end{cases}$$

Effective (energetic/entropic) relativistic degrees of freedom

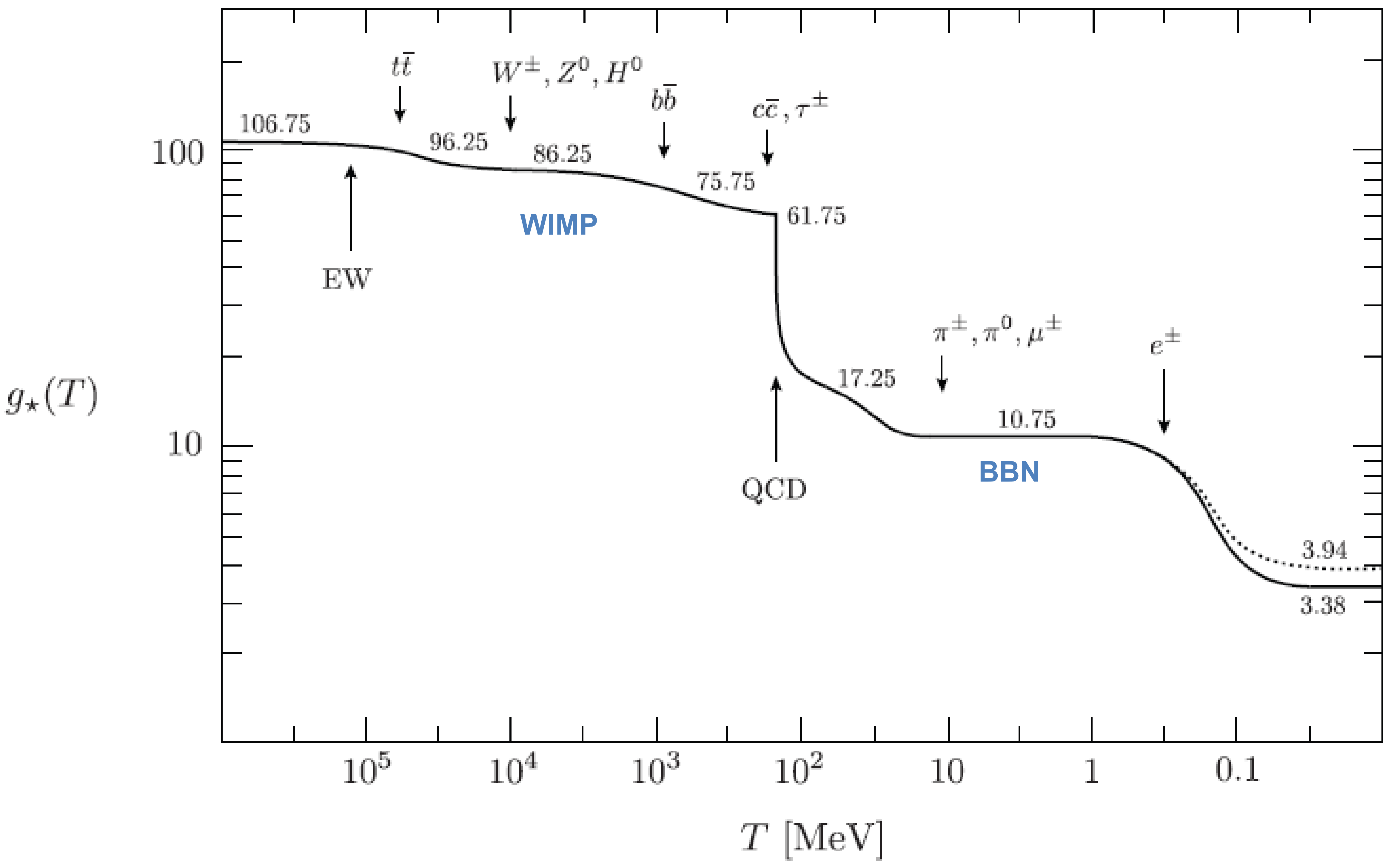


Figure 3.4: *Evolution of relativistic degrees of freedom $g_\star(T)$ assuming the Standard Model particle content. The dotted line stands for the number of effective degrees of freedom in entropy $g_{\star S}(T)$.*

$$\rho_r = \sum_i \rho_i = \frac{\pi^2}{30} g_\star(T) T^4$$

$$g_\star^{dec}(T) = \sum_{i=b} g_i \left(\frac{T_i}{T}\right)^4 + \frac{7}{8} \sum_{i=f} g_i \left(\frac{T_i}{T}\right)^4$$

$g_b = 28$	photons (2), $W^\pm$ and Z^0 $(3 \cdot 3)$, gluons $(8 \cdot 2)$, and Higgs (1)
$g_f = 90$	quarks $(6 \cdot 12)$, charged leptons $(3 \cdot 4)$, and neutrinos $(3 \cdot 2)$

$$g_\star = g_b + \frac{7}{8} g_f = 106.75 \, .$$

Aside: Entropy scales differently. We won't need this:

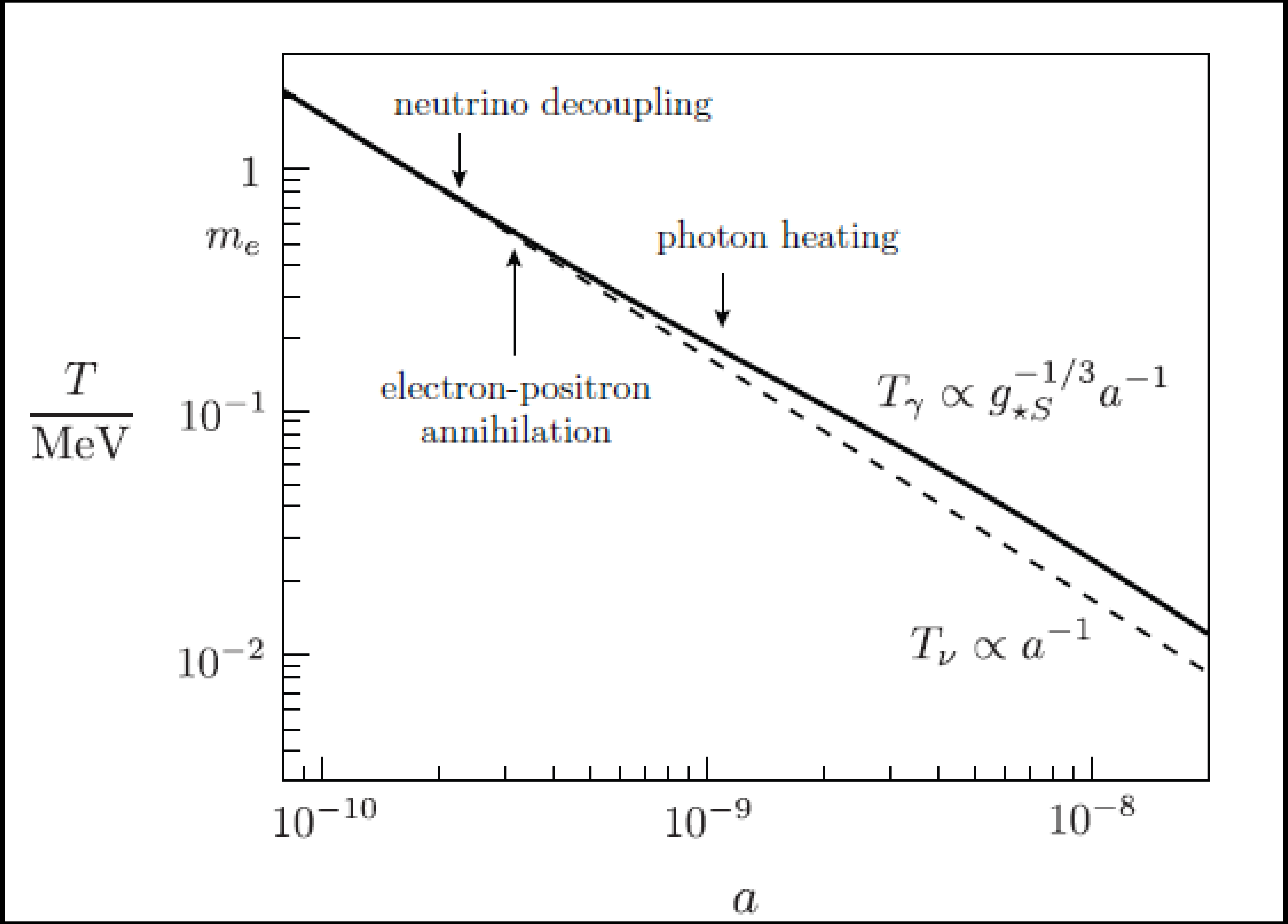
$$s = \sum_i \frac{\rho_i + P_i}{T_i} \equiv \frac{2\pi^2}{45} g_{\star S}(T) T^3 \, ,$$

$$g_{\star S}^{dec}(T) \equiv \sum_{i=b} g_i \left(\frac{T_i}{T}\right)^3 + \frac{7}{8} \sum_{i=f} g_i \left(\frac{T_i}{T}\right)^3 \neq g_\star^{dec}(T) \, .$$

D. Baumann, *TASI Lectures on Primordial Cosmology*, arXiv:1807.03098.

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

Neutrino Decoupling: Photon Heating



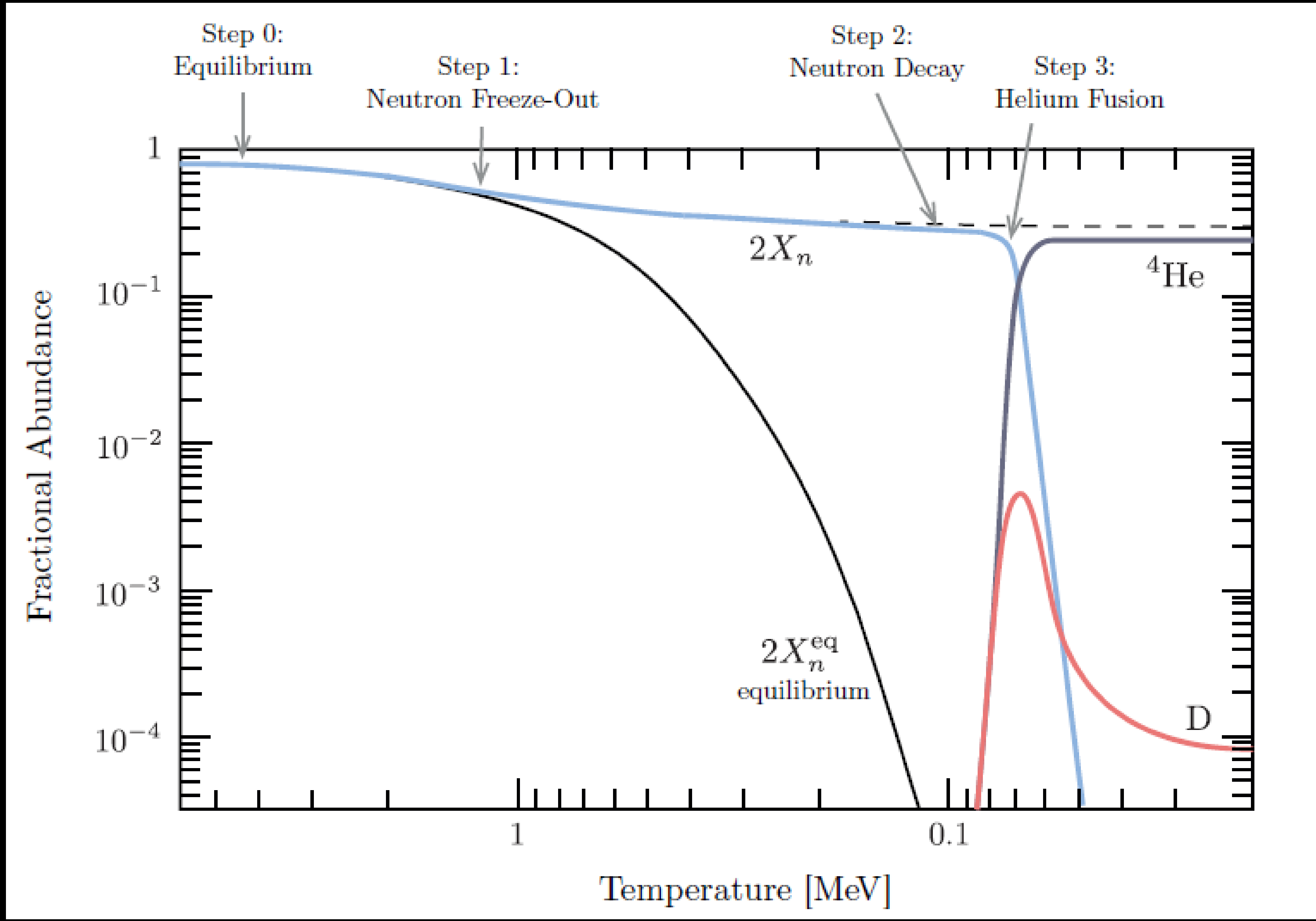
$$\nu_e + \bar{\nu}_e \;\leftrightarrow\; e^+ + e^- \,,$$
$$e^- + \bar{\nu}_e \;\leftrightarrow\; e^- + \bar{\nu}_e \,.$$

$$\frac{\Gamma}{H} \sim \left(\frac{T}{1\,\mathrm{MeV}}\right)^3 .$$

$$e^+ + e^- \;\leftrightarrow\; \gamma + \gamma \,.$$

D. Baumann, *TASI Lectures on Primordial Cosmology*, arXiv:1807.03098.

Proton/Neutron Freezeout: BBN Begins



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

Neutrons continue to decay (proton stable):

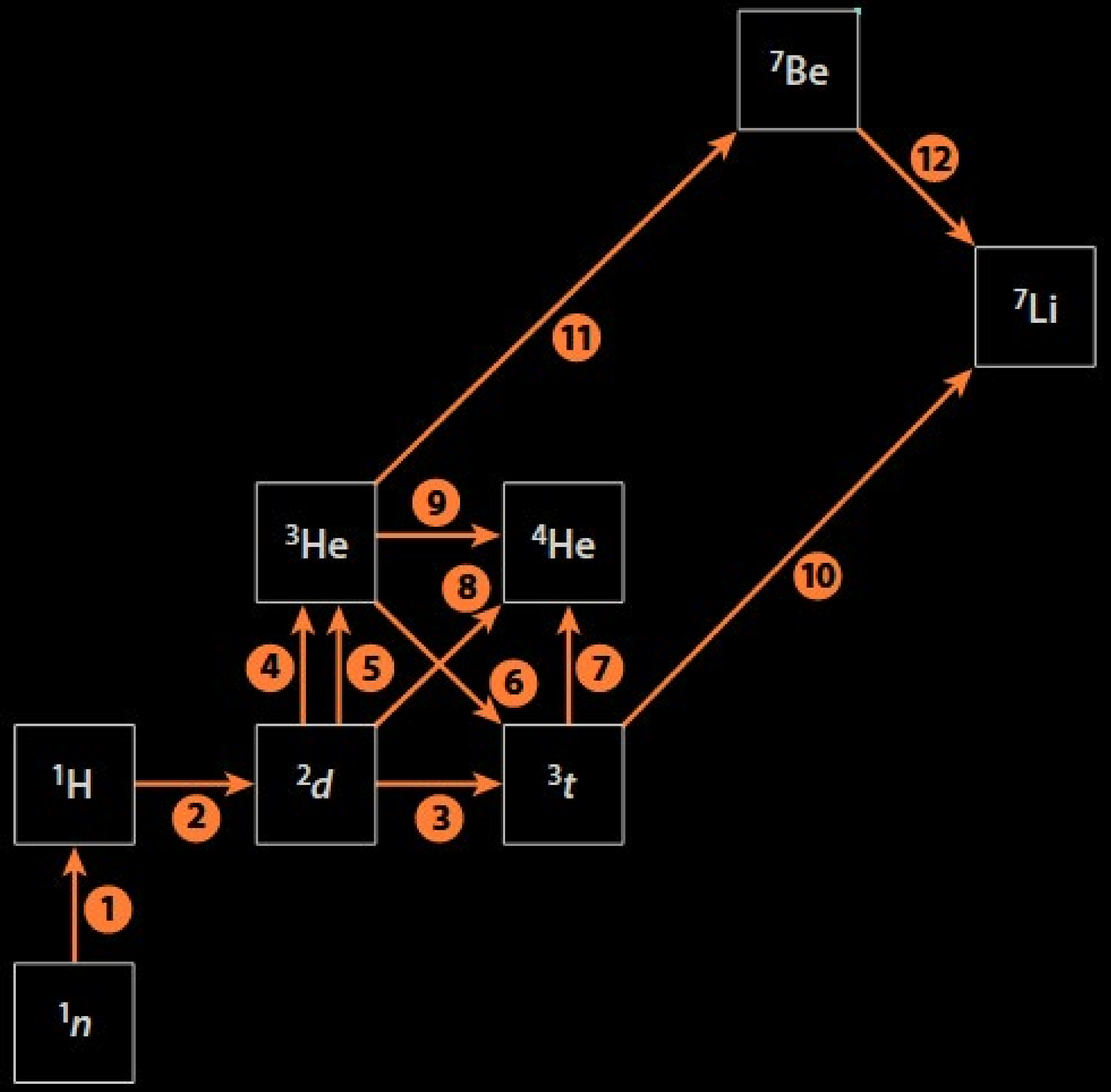
$$n \leftrightarrow p^+ + e^- + \bar{\nu}$$

When cool enough for deuterium (p+n) to survive: neurons funnelled into D

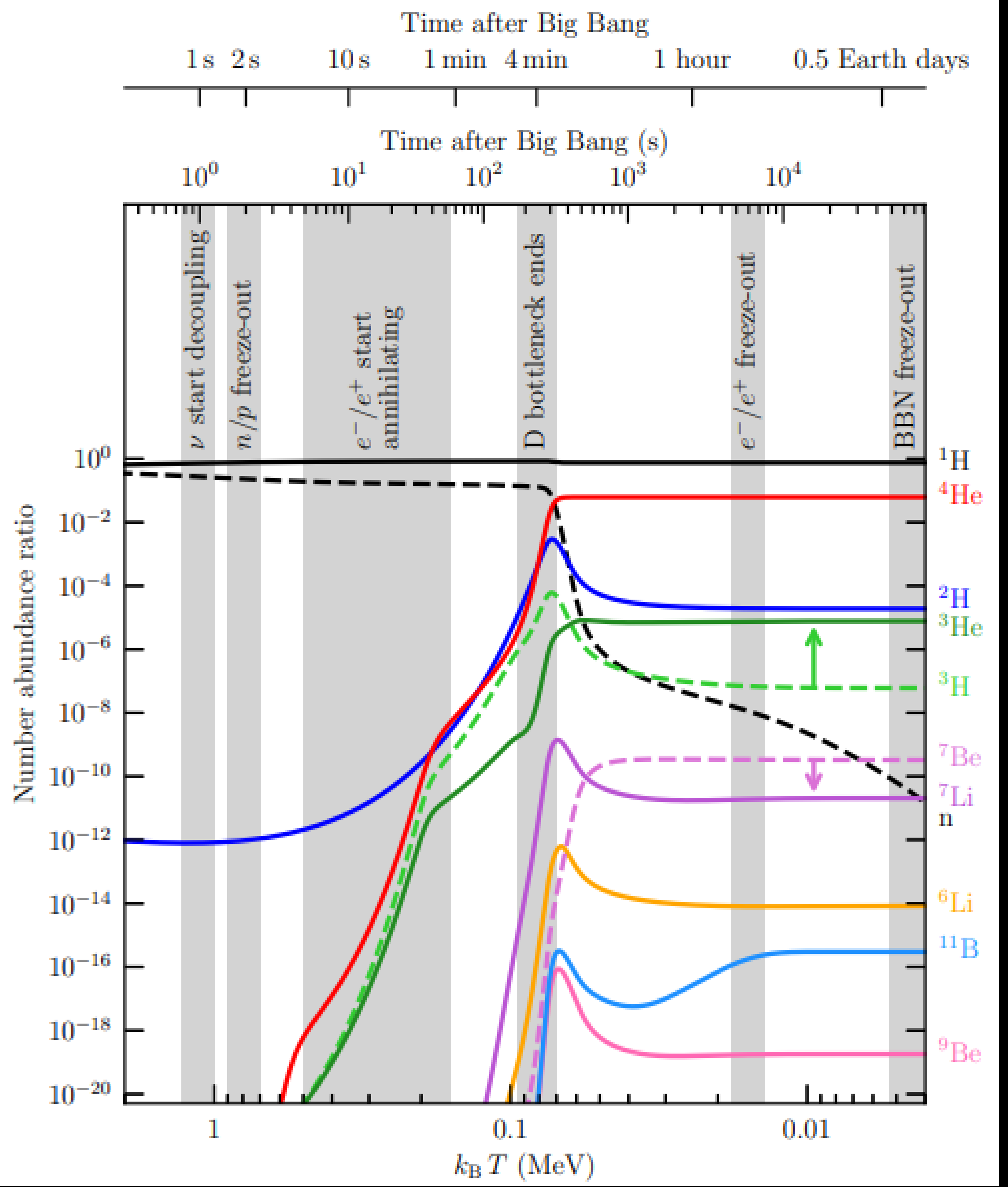
$$n + p^+ \leftrightarrow \mathrm{D} + \gamma\ .$$

D. Baumann, *TASI Lectures on Primordial Cosmology*, arXiv:1807.03098.

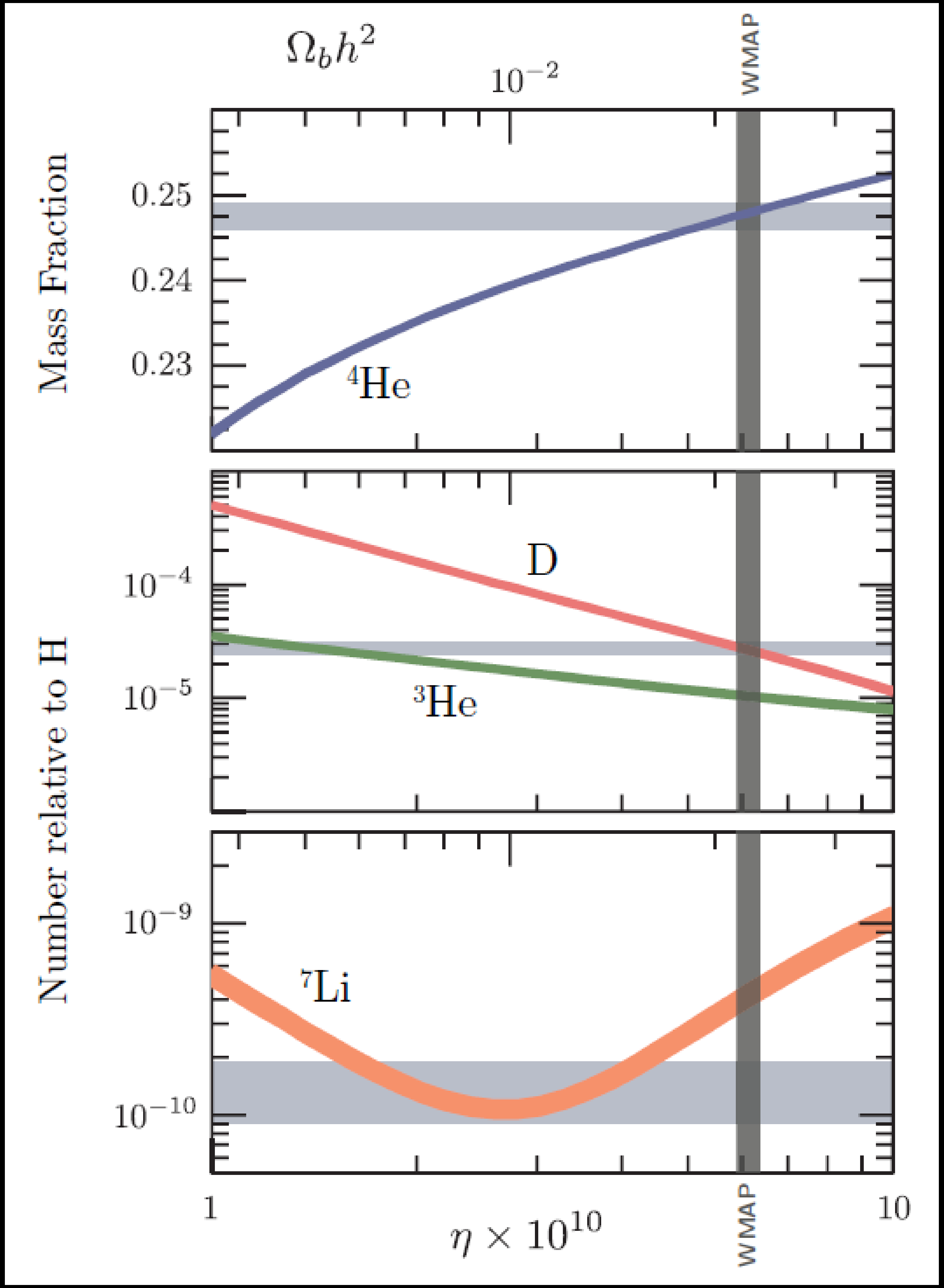
BBN continues:



1. $n \to pe\nu$
2. $n(p,\gamma)d$
3. $d(d,p)t$
4. $d(p,\gamma)^3He$
5. $d(d,n)^3He$
6. $^3He(n,p)t$
7. $t(d,n)^4He$
8. $d(d,\gamma)^4He$
9. $^3He(d,p)^4He$
10. $t(\alpha,\gamma)^7Li$
11. $^4He(\alpha,\gamma)^7Be$
12. $^7Be(n,p)^7Li$



B. D. Fields, *The Primordial Lithium Problem*,
Annual Review of Nuclear and Particle Science **61**, 47 (2011) [arXiv:1203.3551].



- Ratios of light elements very sensitive to baryon density
- Excellent agreement between prediction and observation
- Nails down baryon-photon ratio independent from CMB

- Issue: Li problem – disagrees by factor of 3
- However, both theory + observations harder

R. Cooke, *Big Bang Nucleosynthesis*, arXiv:2409.06015.

Neutron lifetime