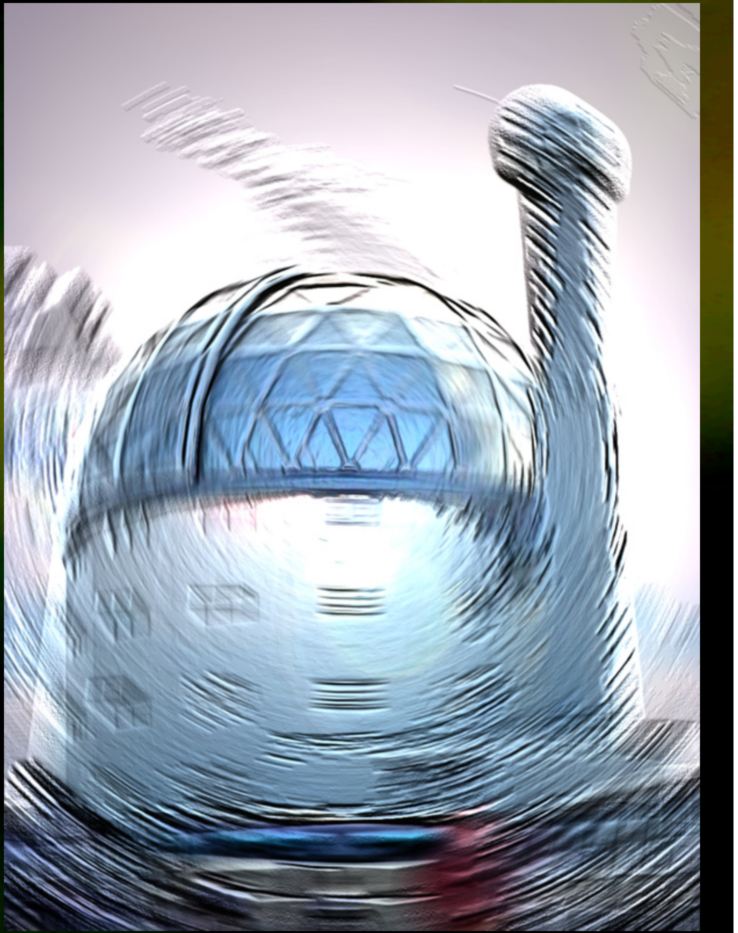
Big Bang Nucleosynthesis



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BAO

Contents

1. Why should we care about BBN?
2. What is Big Bang Nucleosynthesis (BBN)?
3. What does it tell us?

I will mainly be using astro-ph/0303073

"Nucleosynthesis without a computer", V. Mukhanov

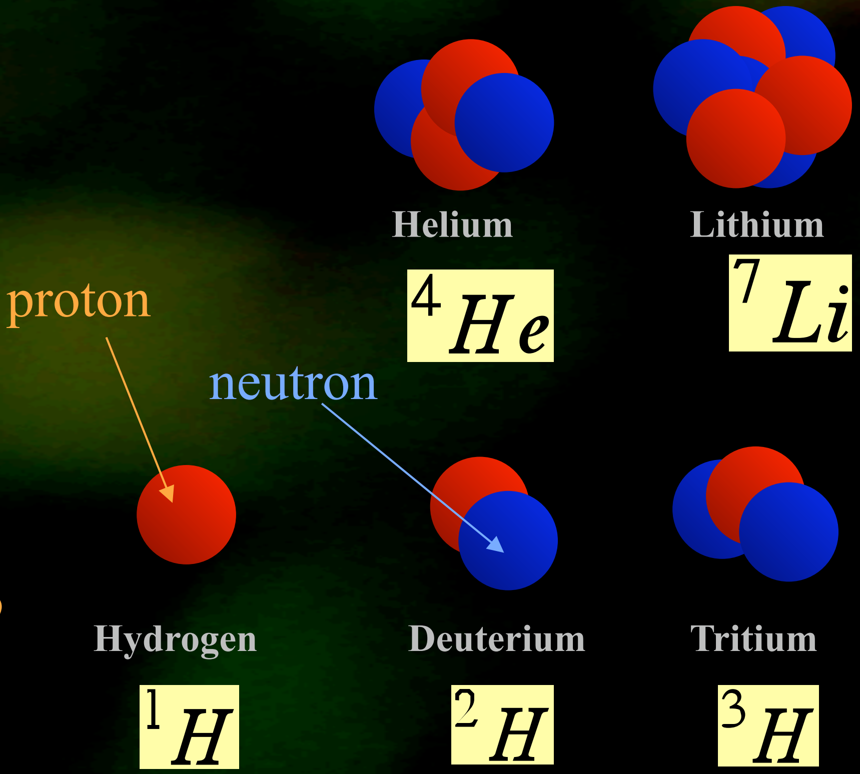
Brief thermal history of the Universe

- 10^{19} GeV – The Planck energy. Quantum gravity required.
- 10^{16} GeV – The GUT scale; inflation
- 100 GeV – Electroweak symmetry breaking
- 100 MeV – Quark-gluon plasma
- 1 MeV – BBN
- 1 eV – Formation of the CMB
- 10^{-3} eV – Cosmic acceleration, dark energy

Big Bang Nucleosynthesis

The observed abundances of light elements according to mass fraction are:

- Hydrogen 75%
- Helium 24%
- Metals ~1%



Why this distribution?

Why should we care about BBN?

It’s a great laboratory…

- BBN happens on small scales at energies below **10 MeV**, hence we should have complete control over the physics.

Unlike the very early universe at ultra-high energies or the late universe on ultra-large scales

Why should we care about BBN?

It gives great constraints on new physics

- BBN predictions are very sensitive to ambient conditions at t ~ 1 sec (T~ 1 MeV). Hence the constraints on new physics are some of the best available…

- E.g. Cosmologists knew first that there are only three generations

Initial conditions in the early universe

1.1 T >> 1MeV, t << 1s

Equilibrium is maintained between p, n via weak interactions ("beta-decay")

$$n + \nu \rightleftarrows p + e^-, \qquad n + e^+ \rightleftarrows p + \overline{\nu}.$$

(looks like a 4-fermion interaction but actually exchange of W-bosons involved):

1.2 In equilibrium the numbers of species *i* is

$$\boxed{N_i \propto (m_i T)^{3/2} \exp\left(\frac{-m_i}{T}\right)}$$

Hence the equilibrium ratio of neutrons to protons is:

$$\boxed{\frac{n}{p} \approx \exp\left(\frac{-Q}{T}\right)}$$

where $Q = m_n - m_p \sim 1.29\,\mathrm{MeV}$

Hence at high temperatures T > 1 MeV the number of neutrons ~ number of protons

$$\boxed{n \approx p}$$

While at very low temperatures

$$\boxed{n / p \rightarrow 0}$$

which is important since neutrons are crucial for making the elements!

But can we trust the equilibrium expressions?

To be in equilibrium or not?

- If the universe expands too fast chemical equilibrium cannot be maintained…
- The criterion for being in equilibrium is actually

$$\boxed{\Gamma > H}$$

$$\boxed{H \equiv \frac{\dot{a}}{a}}$$

Where Γ is the interaction/decay rate. Why?

When is weak strong?

- At what temperature do the weak interactions go out of equilibrium?

$$n + \nu \rightleftarrows p + e^-, \qquad n + e^+ \rightleftarrows p + \overline{\nu}.$$

$\Gamma_{pe—n\nu} \sim G_F^2\, T^5$ (high T) $\sim 10^{-10}/\mathrm{GeV}^4\, T^5$

$H \sim T^2 / M_{pl}$ (Why is this true?)

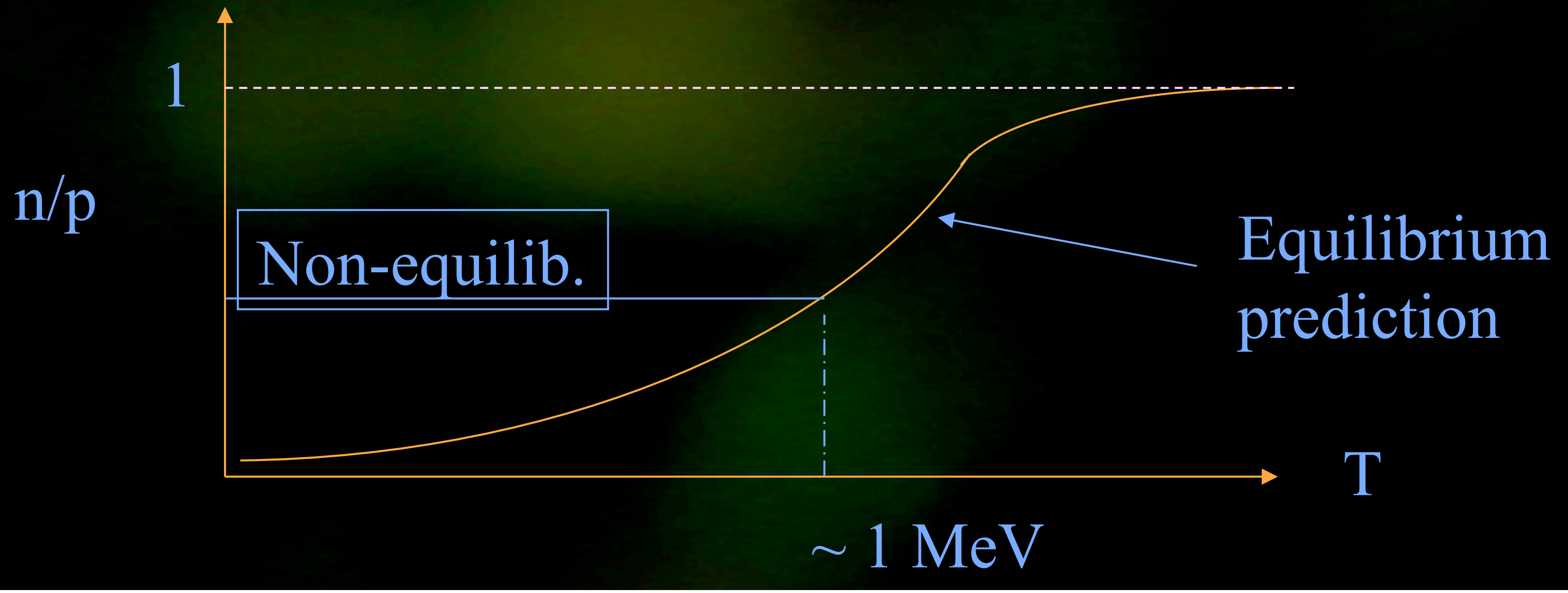
Where $M_{pl} \sim 10^{19}$ GeV

Hence the weak interactions go out of equilibrium below (why below?)

Tcrit $\sim 10^{-3}$ GeV = 1 MeV (actually 0.8 MeV)

Why do we care?

- Below this critical temperature, the equilibrium cannot be maintained and the ratio of neutrons to protons freezes out and becomes essentially constant



Why do we care? II

- Almost all neutrons available get used to make helium
- Knowing the n/p ratio accurately is crucial to making accurate predictions for the light element abundances…

The freeze-out n/p ratio

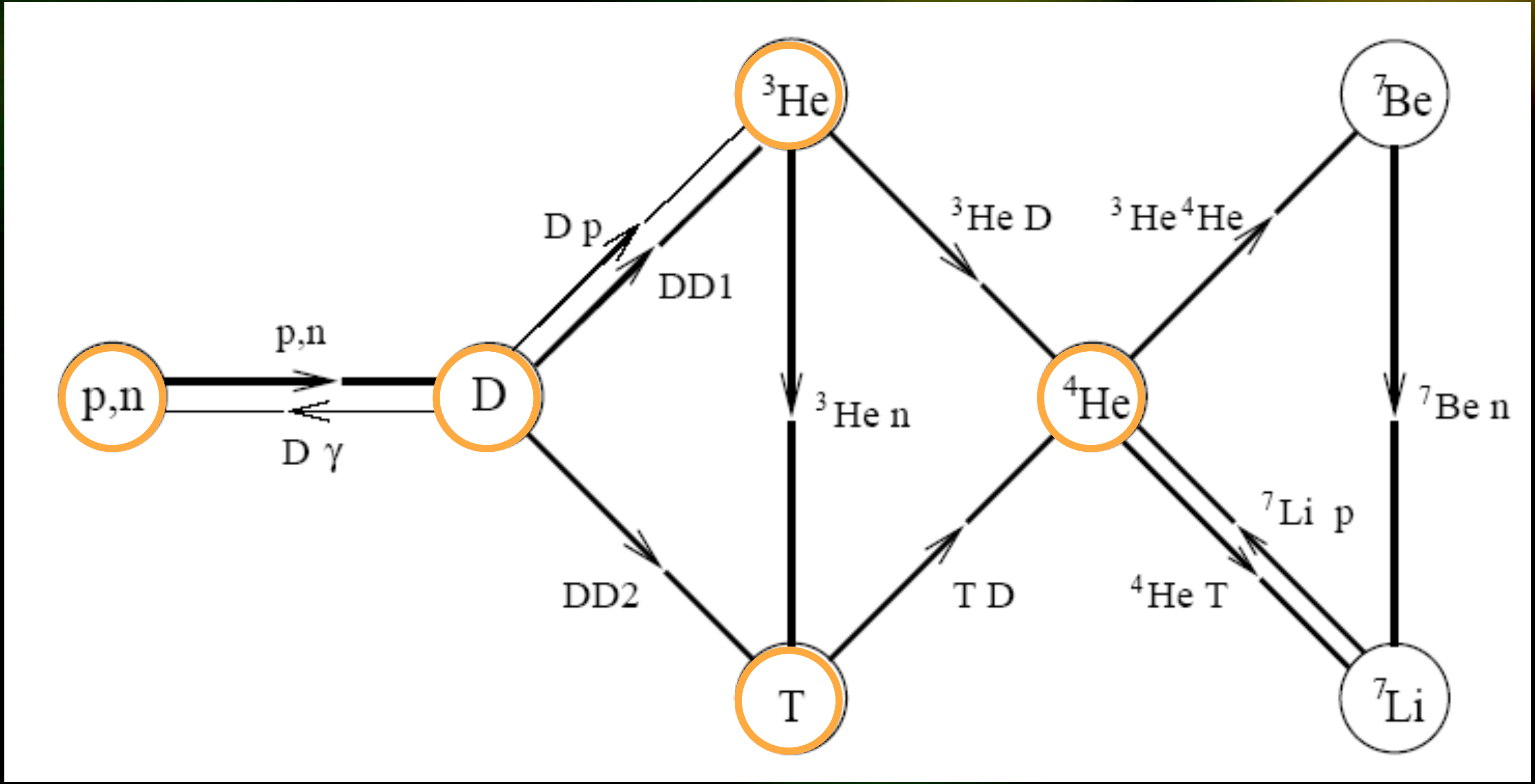
The freeze-out ratio is given by:

$$\frac{n}{p} \approx \exp\left(\frac{-Q}{T_{crit}}\right) \approx \exp(-1.29/0.8) \approx {}^{1}\!/_{5}$$

With time this decreases slightly to ~ 1/6.

Hence, at most we could form 33% of ^{4}He by mass which is significantly larger than the observed 24%. Why is there only 24% helium?

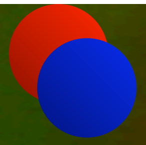
Getting to the heavy elements…



Not through….

$$2p + 2n \rightarrow ^4 He$$

Deuterium



^2H

- The process $p + n \rightleftarrows D + \gamma$

  is in equilibrium at ~ 1 MeV
- Define:

$$X_D \equiv 2n_D/n_B$$

- Then

$$\boxed{X_D \sim \eta\, X_p\, X_n \sim 10^{-12}}$$ (for T ~ 1 MeV)

Where $\eta = n_B/n_\gamma \sim 10^{-8}\,\Omega_B h^2$ is the baryon-to-photon ratio (entropy). So almost no ^{4}He can be formed at this point because there are too many energetic photons left to form any *D*!

Deuterium II

- One can show the number of photons with energies above the *D* binding energy (2.2 MeV) drops below the number of *D* nuclei at T = 0.06 MeV

- Hence we have to wait until this low temperature for significant amounts of *D* (and hence other elements) to form.

Tutorial Problem

1. Calculate the age of the universe when the temperature falls to 0.08 MeV assuming that at *1 s* the temperature was 1 MeV

1. Calculate the age of the universe when the temperature falls to 0.08 MeV

$$a \propto 1/T, a \propto t^{1/2}$$

$$\Rightarrow t_2 = t_1 \left(\frac{T_2}{T_1} \right)^2 \approx 1s \times \left(\frac{1MeV}{0.08MeV} \right)^2 \approx 156s$$

Helium 4

- At T ~ 0.08 *MeV* the universe is about 200 seconds old and light elements can be formed.
- Basically every available neutron at this time goes into ^{4}He.
- But we said that the n/p ratio is frozen at T < 0.8 MeV …so why don't we get 33% of ^{4}He by mass?

Neutron half-life

- Free neutrons decay with a half-life of

$$\tau_n = 885.7 \pm 0.8 \ sec$$

- Hence, after ~ 200s the ratio of free neutrons to protons has decreased to

$$\frac{n}{p} \approx \frac{1}{6}\exp\left(-\frac{200}{886}\right) \approx 0.125$$

- Hence we expect $X_{^4He} \approx 2(n/p) = 0.25$

which agrees very well with the observed fraction. Crucial that the age of the universe and neutron half-life are comparable!

Lithium and Beryllium

- One can show that the final predicted value of ^7Li is

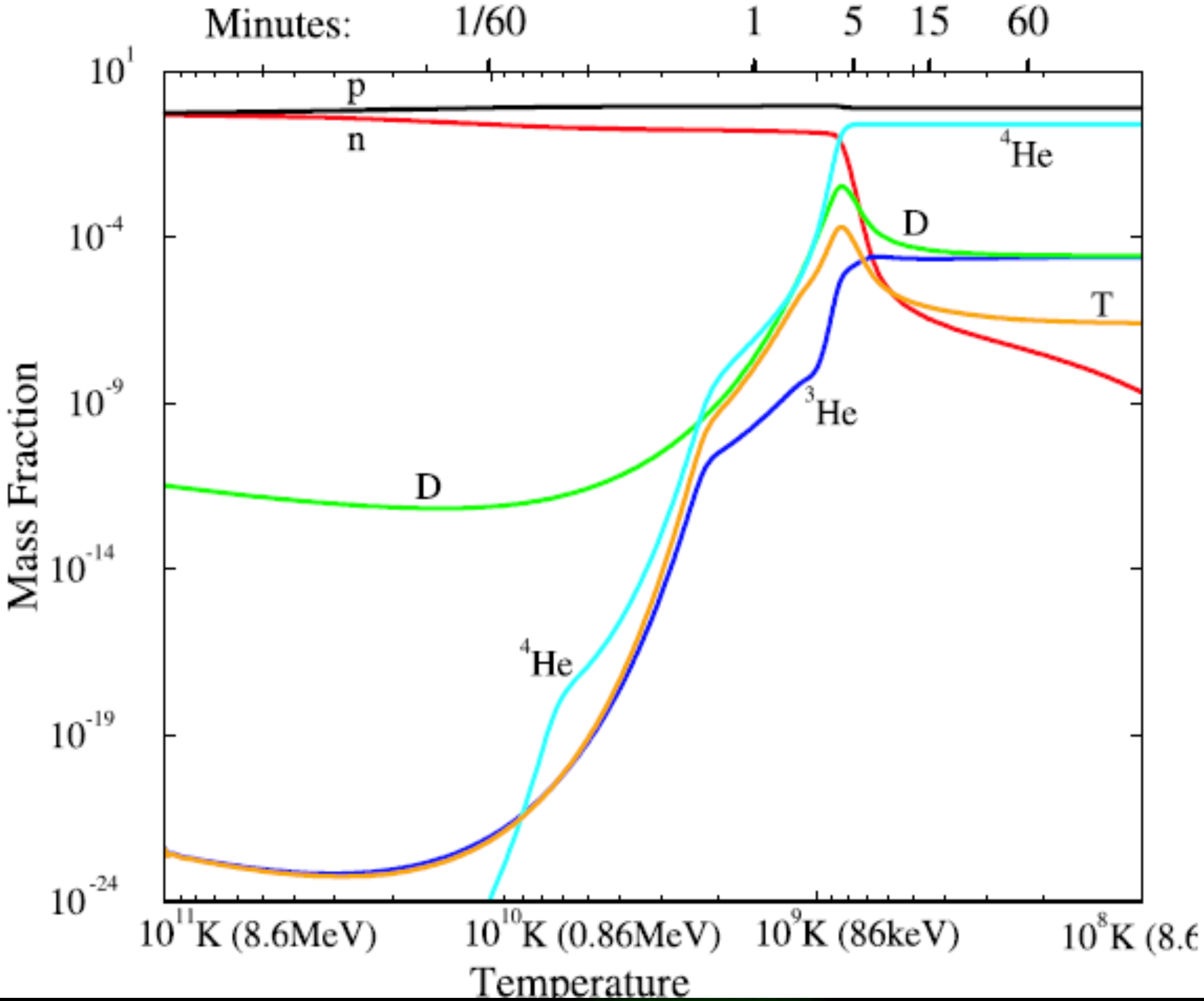
$$X_{li} \sim 10^{-9}$$

And for ^7Be

$$X^f_{^7Be} \sim O\left(1\right) 10^{-12} \frac{X^f_{^3He}}{\left(X^f_D\right)^2}$$

$X^f_D \sim 4 \times 10^{-4}$, $X^f_{^3He} \sim 0.1 X^f_D$ and correspondingly $X^f_{^7Be} \sim 2.5 \times 10^{-10}$.

Hence BBN makes precise predictions for *all* the light elements which are in good agreement with observed abundances.


Minutes:
1/60
1
5
15
60
10^{1}
10^{-4}
10^{-9}
10^{-14}
10^{-19}
10^{-24}
Mass Fraction
p
n
^{4}He
D
T
^{3}He
D
^{4}He
10^{11}K (8.6MeV)
10^{10}K (0.86MeV)
10^{9}K (86keV)
10^{8}K (8.6
Temperature

Using BBN as a test of new physics

- The abundance of light elements is very sensitive to two things:

1. The age of the universe when the temperature drops to 0.08 MeV (why?)
2. The expansion rate of the cosmos at T ~ 1MeV (why?)

Neutron decay

- If the cosmos was e.g. 10 years old at T=0.08 MeV there would be no free neutrons and hence no ^{4}He.

- This can be used to constrain *any* physics which changes the half-life of free neutrons (such as changes to the fine-structure "constant") or the age of the cosmos at T=0.08 MeV

Expansion rate sensitivity

- If the cosmos was expanding very slowly, the n/p ratio would stay in equilibrium much longer and drop towards zero before freezing since

$$\frac{n}{p} \approx \exp\left(\frac{-Q}{T}\right)$$

- Hence we can constrain any new physics which changes the expansion rate at this time…
- This puts strong limits on new types of particles, magnetic fields, dark energy etc…

The classic examples

- One can calculate the ^4He fraction allowing for an arbitrary number of generations of quarks, neutrinos etc… (call it N_ν)

$$X^f_{^4He} \simeq 0.25 + 0.012\,(N_\nu - 3) + 0.0082 \ln \eta_{10}$$

where $\eta_{10} \equiv \eta/10^{-10}$

This strongly favours $N_\nu = 3$ (later confirmed by particle physicists) and tells us about the baryon density in our universe…

The Baryon density…

- Value of Ω_B from BBN is self-consistent

  and gives $\Omega_B \sim 0.04\text{-}0.05$
- This value agrees well with the completely *independent* estimate from the CMB
- BBN is very strong support for the expansion of the cosmos and the standard Big Bang model.