Announcements:
• PF4 due noon Friday

Last time: at last--cosmic recombination
★ \( T_{\text{rec}} \approx \frac{B_H}{40} \ll B_H \) Q: why?
★ after recomb: \( X_e \neq 0 \): some free \( e, p \) remain Q: why?

Today: spurred by successes at \( z_{\text{rec}} \sim 1500, t \sim 350,000 \text{ yr} \)
push to \( t \sim 1 \text{ sec} \)
Primordial Nucleosynthesis
Prelude to Nucleosynthesis

Q: what sets $T$ scale for element (nuclei) synthesis?

Q: what component dominates cosmic density, expansion then?

Q: what is the particle content of the universe then?

Q: what form(s) do the baryons take then? mesons?
Nucleosynthesis: Setting the Stage

★ light elements formed in nuclear reactions
relevant scale: nuclear binding energies $\sim$ MeV

★ $T \sim$ MeV at redshift $z_{\text{bbn}} = T/T_0 - 1 \sim 10^{10}$!
since $z_{\text{bbn}} \gg z_{\text{eq}}$ (matter-rad equality)
well into radiation dominated era: $\rho \approx \rho_{\text{rad}}$
www: $\Omega$ vs a plot
will see: $t(1 \text{ MeV}) \sim 1$ sec

★ particle content at BBN
relativistic species: photons, neutrinos, $e^\pm$ when $T \gtrsim m_e$
non-relativistic species: baryons, $e^-$ when $T \ll m_e$
what about dark matter? energy?
   DM presumably non-rel, weakly interacting: inert during BBN
DE: also assume not important for dynamics, microphysicals
   ...but can later relax these assumptions and test them!
Who Feels What? Particles and Forces

\[
\begin{pmatrix}
u \\ d \\ e \\ \nu_e \\
\end{pmatrix} \quad \begin{pmatrix}c \\ s \\ \mu \\ \nu_\mu \\
\end{pmatrix} \quad \begin{pmatrix}t \\ b \\ \tau \\ \nu_\tau \\
\end{pmatrix}
\]

### Quarks
- feel all fundamental forces (strong, EM, weak, gravity)
- carry conserved quantum number: **baryon number**

### Leptons
- do *not* feel strong force
- but also carry conserved quantum number: **lepton number**
- *charged* leptons: feel EM, weak, gravity
- neutrinos: only feel weak, gravity

More bragging rights:
- in BBN, *all four* fundamental forces play a crucial role!
Neutrinos: Essential Ingredient yet Barely There

antineutrinos: $\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$

since electric charge $Q(\nu) = 0$, possible that $\nu$ is own antiparticle

Q: is it?

masses: known that $m_\nu$ are nonzero (oscillations observed)
mass values not known (but for sure $\lesssim$ few $\times$ 10 eV $\ll m_e$)

Q: implications for BBN?

for quarks and charged leptons, masses increase with each family
→ same for $\nu$s??

weak interaction: qualitative characteristics

(1) “signature” is transformation of quark, lepton flavor

e.g., $n \rightarrow p + e^- + \bar{\nu}_e$ decay

really a quark change $d(ud) \rightarrow u(ud) + e^- + \bar{\nu}_e$

(2) for $E \lesssim 100$ GeV ($= M_W, M_Z$), rxn strength is weak (duh!)
e.g., $\nu_e e \rightarrow \nu_e e$ scattering $\sim 1$ MeV: $\sigma_{\nu ee} \sim 10^{-44} \text{ cm}^2 \sim 10^{-20} \sigma_T$
Nucleosynthesis: Particle Content Revisited

relativistic species:
$\gamma, \nu_i \bar{\nu}_i \ (i \in e\mu\tau), \ e^\pm \ (\text{for } T \gtrsim m_e)$

non-relativistic species:
baryons in BBN: when $T \gtrsim \text{MeV}$: $p, n$ only
when $T \leq m_e \rightarrow e$ non-rel too

★ neutrinos in BBN
Q: what sets $n_\nu, \rho_\nu, T_\nu$? how do they evolve?
Q: assumptions needed?
**BBN Initial Conditions: Ingredients of Primordial Soup**

Begin above nuke binding: \( T > 1 \text{ MeV} \)

EM reactions fast: typical rate \( \Gamma_{\text{EM}} \sim n_\gamma \sigma_T c \gg H \)

\( \Rightarrow \) baryon, photon, \( e^\pm \) pair plasma in thermal equilib:

\[ T_B = T_e = T_\gamma = T \]

weak int fast too (for now)! \( \Gamma_{\text{weak}} \sim n_\nu \sigma_{\text{weak}} c \gg H \)

all \( \nu \) species coupled to each other, and plasma

\( \rightarrow T_\nu = T_\gamma \)

What sets densities \( n_\nu, \rho_\nu \)?

not only \( T_\nu \), but also dreaded chem potential \( \mu_\nu \)

physics issue: is there a net neutrino excess: \( n_\nu \neq n_{\bar{\nu}} \)?

\( \text{c.f. net baryon excess} \rightarrow \text{exists}: n_B \neq n_{\bar{B}}, \text{but small: } n_B/n_\gamma \ll 1 \)

if net lepton number \( n_L \sim n_B \), turns out \( \mu_\nu/T \sim \eta \) negligible

we will assume \( \mu_\nu \ll T \Leftrightarrow \text{no large lepton/baryon excess} \)

if otherwise, changes story!
BBN Initial Conditions: Radiation Domination

Neutrino densities: for sure \( m_\nu \ll T \)

assume \( \mu_\nu \ll T \) → absolute \( n_\nu, \rho_\nu, P_\nu \) set by \( T_\nu \)

→ each \( \nu \) species \( i \) has \( n_{\nu i} = n_{\bar{\nu} i} \) and

\[
n_{\nu \bar{\nu}, i} \propto T^3 = \frac{3}{4} n_\gamma \quad \rho_{\nu \bar{\nu}, i} \propto T^4 = \frac{7}{8} \rho_\gamma
\]  

(2)

total relativistic energy density:

\[
\rho_{\text{rel}} = \rho_\gamma + \rho_{e \pm} + N_\nu \rho_{1\nu \bar{\nu}} \equiv g_* \frac{\pi^2}{30} T^4
\]  

(3)

where \( g_* \) counts “effective # of relativistic degrees of freedom”
at \( T \gtrsim 1 \) MeV, \( g_* = 43/4 = 10.75 \), and Friedmann:

\[
\frac{t}{\text{1 sec}} \approx \left( \frac{1 \text{ MeV}}{T} \right)^2
\]  

(4)

Q: simple way to see \( t \sim 1/T^2 \) scaling is right?

now focus on baryons Q: what sets \( n_B \) ? \( n/p \)?
BBN Initial Conditions: The Baryons

Cosmic baryon density $n_B$, and thus $\eta = n_B/n_\gamma$
not changed by reactions with $T \lesssim E_{\text{Fermilab}} \sim 1 \text{ TeV} = 10^6 \text{ MeV}$
i.e., baryon non-conservation not observed to date
▷ $n_B$ set somehow in early universe (“cosmic baryogenesis”)
▷ don’t a priori know $n_B$, treat as free parameter ($\eta$)

neutron-to-proton ratio $n/p$ can and does change at $\sim 1 \text{ MeV}$
weak int fast: $n \leftrightarrow p$ interconversion

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

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

also recall $m_n - m_p = 1.29 \text{ MeV}$: close in mass but not same!

Q: implications for $n/p$?
$n/p$ ratio “thermal”
think of as 2-state system: the “nucleon,”
• nucleon “ground state” is the proton: $E_1 = m_p c^2$
• nucleon “excited state” is the neutron: $E_2 = m_n c^2$
when in equilibrium, Boltzmann sez:

$$
\left( \frac{n}{p} \right)_{\text{equilib}} = \frac{g_n}{g_p} e^{-(E_2 - E_1)/T} = e^{-(m_n - m_p)/T}
$$

(7)

with $\Delta m = m_n - m_p = 1.293318 \pm 0.000009$ MeV

at $T \gg \Delta m$: $n/p \approx 1$

at $T \ll \Delta m$: $n/p \approx 0$

Equilibrium maintained until weak interactions freeze out
i.e., competition between weak physics, gravity physics

Q: how will weak freezeout scale compare to
nuclear binding energy scale $\sim 1$ MeV?
Weak Freezeout Temperature

Weak interactions freeze when $H = \Gamma_{\text{weak}}$, i.e.,

$$\sqrt{G_N T^2} \sim \sigma_0 m_e^{-2} T^5$$

$$\Rightarrow T_{\text{weak freeze}} \sim \frac{(G_N)^{1/6}}{(\sigma_0/m_e^2)^{1/3}} \sim 1 \text{ MeV}$$

Gravity & weak interactions conspire to give $T_f \sim m_e \sim B_{\text{nuke}}$!

For experts: note that $G_N = 1/M_{\text{Planck}}^2$, so

$$\frac{T^2}{M_{\text{Pl}}} \sim \alpha_{\text{weak}} \frac{T^5}{M_W^2}$$

$$\Rightarrow T_{\text{freeze}} \sim \left(\frac{M_W}{M_{\text{Pl}}}\right)^{1/3} M_W \sim 1 \text{ MeV}$$

Freeze at nuclear scale, but by accident!

Q: What happens to $n, p$ then? What else is going on?
Directors’ Cut Extras
Elementary Particles for the Minimalist
Antimatter

fundamental result of Relativistic QM
every particle has an antiparticle
e.g., $e^- = e^+$ positron
e.g., $\bar{p} = \text{antiproton};$ Fermilab: $p\bar{p}$ collisions

note: mass $m(\bar{x}) = m(x)$
decay lifetime $\tau(\bar{x}) = \tau(x)$
spin $S(\bar{x}) = S(x)$
electric charge $Q(\bar{x}) = -Q(x)$

sometimes particle = own antiparticle (must have charge 0)
e.g., $\bar{\gamma} = \gamma,$ but note: $\bar{n} \neq n$

**Cosmic Antimatter:** rule of thumb
$x, \bar{x}$ abundant when thermally produced: $T > m_x$
Baryons

$n$ and $p$ not fundamental particles
made of 3 pointlike particles: “quarks”
two types (“flavors”) in $n, p$: $u$ “up,” $d$ “down”
$p = uud, n = udd \rightarrow$ quark electric charge $Q_u = +2/3, Q_d = -1/3$
spin $S(u) = 1/2 = S(d)$

baryon $\equiv$ made of 3 quarks

baryon conservation:
assign “baryon number” $A(q) = +1/3, A(\bar{q}) = -1/3$
$\rightarrow A(n) = A(p) = +1$
in all known interactions: baryon number conserved:
$\sum A_{\text{init}} = \sum A_{\text{fin}}$
$\rightarrow$ guarantees stability of the proton $Q$: why?
but free $n$ unstable, decay to $p$ $Q$: why not $n$ decay in nuclei?
Periodic Table of Elementary Particles

known fundamental particles (& antipartners): 3 **families**

\[
\begin{pmatrix}
  u \\
  d \\
  e \\
  \nu_e
\end{pmatrix}
\begin{pmatrix}
  c \\
  s \\
  \mu \\
  \nu_\mu
\end{pmatrix}
\begin{pmatrix}
  \nu_e \\
  \nu_\mu
\end{pmatrix}
\begin{pmatrix}
  t \\
  b \\
  \tau \\
  \nu_\tau
\end{pmatrix}
\]

all of these are spin-1/2: **matter made of fermions!**

**Family Resemblances**

**1st family**: quarks, charged lepton (\(e\)) comprise ordinary matter

**2nd, 3rd family particles**

- same electric charges, same spins, (mostly) same interactions as corresponding 1st family cousins
- but 2nd, 3rd family quarks, charged leptons more massive and *unstable* → decay into 1st family cousins
lifetimes very short, e.g., longest is $\tau(\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu) = 2 \times 10^{-6}$ s

Q: implications for BBN epoch?
Weak $n \leftrightarrow p$ Rates

example: want rate $\Gamma_n$ per $n$ of $\nu + n \rightarrow e^- + p$ as func. of $T$

Generally,

$$\Gamma_n = n\nu\langle\sigma v\rangle \sim T^3\langle\sigma\rangle$$  \hspace{1cm} (13)

since $v_\nu \simeq c$

can show: cross section $\sigma \sim \sigma_0(E_e/m_e)^2$

where $\sigma_0 \sim 10^{-44}$ cm$^2$ very small!

so thermal avg: $\langle\sigma\rangle \sim \sigma_0(T/m_e)^2$

for experts: $\sigma \sim G_F^2T^2 \sim \alpha_{\text{weak}}T^2/M_W^4$

so $\Gamma_{\text{weak}} \sim \alpha_{\text{weak}}T^5/M_W^4$