Astro 596/496 NPA
Lecture 15
Sept. 28, 2009

Announcements:

- Preflight 3 due noon Friday

Last time: cosmic thermal history

Today: begin journey to early universe
strategy: go from known microphysics → unknown
  i.e., "run movie backwards"
  from epochs at lower $z, T \rightarrow$ higher z, T

Firs stop: the Nuclear Age

BIG BANG NUCLEOSYNTHESIS

Gateway to the Early Universe

Big Bang Nucleosynthesis: Introduction

(K-KZ Ch. 4; Kolb & Turner Ch. 4; Olive, Steigman & Walker astro-ph)

Big Bang Nucleosynthesis = BBN = Primordial nucleosynthesis

Basic idea:

follow weak, nuke reactions in expanding universe
initially: nuclei "ionized" to n, p only
when T low enough: $n, p \rightarrow$ "ground state"

To get in mood:

- What is appropriate T (E) scale for nuclear "recombination"?
- What particles alive? decayed?
- At this T, what is non-rel, rel?
- U. expansion is dominated by?
- What is role of dark matter, dark energy?

nuclear "recombination" when $T \sim$ nuke binding ~ 1 MeV

BBN epoch: for $T \sim 1$ MeV $\sim 10^{10}$ K
- scale factor $a \sim 10^{-10}$
- redshift $z \sim 10^{10} \gg z_{\rm eq} \sim 10^4$: much before matter/rad eq

$\Rightarrow$ universe is deep in *radiation-dominated era*

`www: cosmic epochs`

since $T \gtrsim 1$ MeV $> m_e$, pairs $e^\pm$ abundant & relativistic!
- "radiation" species: $\gamma, e^\pm, \nu\bar{\nu}$
- "matter" species: $m_n, m_p \gg T$: neutrons, protons non-relativistic
- dark matter, dark energy presumably present
  but we *assume* non-interacting, and unimportant
  but maybe not! can see what happens if so, and probe DM/DE!

- While nuclei "ionized," is n or p more abundant?
- When "recombine," what is "ground state"?

when only n, p: expect roughly similar abundances
but: since $m_n > m_p$, higher "cost" for neutrons
→ should have $n/p < 1$: neutrons less abundant

when T low enough, $n, p \to$ "ground state":
set by maximum available binding energy

- globally, max B/A for ^{56}Fe,
  but not enough time to reach this state
- locally, max B/A at ^{4}He
  → highest binding energy of light nuclei

so when light nuclei form, products are:

- $^{4}\text{He}=\boxed{2p2n}$: limited by the available n
- H: leftover "unpartnered" p

but incomplete nuke "burning" leaves

- traces of D, ^{3}He, ^{7}Li

key controlling parameter: baryon-to-photon ratio $\boxed{n_B/n_\gamma \equiv \eta}$
Q: individually, do n_B and n_γ depend on T? How?

photons: $n_\gamma \propto T^3$ (relativistic thermal distribution)
baryons: $n_B \propto a^{-3} \propto T^3$ (baryon # conservation)
$\Rightarrow$ baryon-to-photon ratio $\eta = n_B/n_\gamma = const$
same today as at end of BBN!

Predicted primordial abundances depend on η
$\rightarrow$ can use observations to *measure* baryon/photon ratio
 i.e., can us BBN to *find* η as *output*
but preview: will find $\eta \sim 10^{-9}$
$\rightarrow > 10^9$ thermal (CMB) photons per cosmic baryon

BBN: Pioneering Days

Gamow group: (Gamow, Alpher, Herman; 1940's)
Initial conditions:
early U → high density → all neutrons
(like neutron star)
$\alpha\beta\gamma$ paper

Hayashi (1950):
weak interactions non-negligible
weak equilibrium deutermines n/p ratio

Alpher, Follin, & Herman (1953):
first "modern" calculation of n/p ratio

Burbidge, Burbidge, Fowler & Hoyle ($\equiv$ B^{2}FH, 1957):
heavy elements made in stars (not BB)
outlined nuclear processes light elements: unknown "X-process"

BBN Initial Conditions: Radiation Domination

Neutrino densities: for sure $m_\nu \lesssim 1\text{eV} \ll T$
assume $\mu_\nu \ll T$ → absolute n_ν, ρ_ν, P_ν set by T_ν
→ each ν species i has $n_{\nu_i} = n_{\bar{\nu}_i}$ and

$$n_{\nu\bar{\nu},i} \propto T^3 = \frac{3}{4} n_\gamma \quad \rho_{\nu\bar{\nu},i} \propto T^4 = \frac{7}{8} \rho_\gamma \tag{1}$$

total relativistic energy density:

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

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

$$\frac{t}{1\ \text{sec}} \approx \left(\frac{1\ \text{MeV}}{T}\right)^2 \tag{3}$$

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 $T \lesssim E_{\text{Fermilab}} \sim 1$ TeV $= 10^6$ 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 (η)

neutron-to-proton ratio n/p *can* and *does* change at ~ 1 MeV
Q: what kind of interaction needed to change $n \leftrightarrow p$*?*
Q: what happens to n, p *if such reactions are "fast"?*
Q: what sets the scale for "fast"?

for $n \leftrightarrow p$ interchange

nucleon (quark) type must change

$\Rightarrow$ only happens in **weak** interactions

weak int fast:

$n \leftrightarrow p$ interconversion, e.g.

$$n + \nu_e \leftrightarrow p + e^- \tag{4}$$

$$p + \bar{\nu}_e \leftrightarrow n + e^+ \tag{5}$$

"Fast": rates per particle $\Gamma = n\sigma v \gg H$

or, mean life against rxn $\tau = \Gamma^{-1} \ll H^{-1} \sim t$

Note: since weak interactions fast, EM rxns also fast:

$\Rightarrow$ all particles thermal, w/ same T