Astro 596/496 NPA
Lecture 24
Oct. 19, 2009

Announcements:
- Problem Set 4 due in class Friday

Last time: cosmic matter asymmetry
Q: what's the evidence for a matter (baryon) asymmetry?
Q: what quantifies the baryon/antibaryon excess?

cosmic baryon asymmetry exists

$Y_B = n_B/s \simeq n_B/7n_\gamma = \eta/7 \sim 10^{-10}$

at $T \gtrsim \Lambda_{\mathrm{QCD}} \simeq 200$ MeV, $q\bar{q}$ pairs abundant,

$n_q \simeq n_{\bar{q}} \sim n_\gamma$, so asymm was

$$\frac{n_q - n_{\bar{q}}}{n_q + n_{\bar{q}}} \sim \frac{n_B}{n_\gamma} \sim 6 \times 10^{-10} \tag{1}$$

for every 1,000,000,000 antiquarks

there were 1,000,000,001 quarks

a tiny but crucial excess!

but on theoretical grounds, expect particle creation in pairs

so how did this happen?

A Baryon Symmetric Universe

If start baryon symmetric ($n_B = n_{\bar{B}}$)
what is relic abundance?
$\Rightarrow$ apply freezeout technology

assume nucleons are a **symmetric cold relic**
predict relic abundance after $N\bar{N}$ annihilation freezeout:
$\langle \sigma v \rangle_{\mathrm{ann}} \sim r_p^2 c \sim 1 \ \mathrm{fm}^2 \ c \sim 10^{-15} \ \mathrm{cm}^3 \ \mathrm{s}^{-1}$
$\Rightarrow T_f \sim m/40 \sim 20$ MeV
$Y_{B,\infty} \sim (m/T_f) e^{-m/T_f} \simeq 10^{-19}$
$\Rightarrow$ if U baryon symmetric, predict $\boxed{\eta_{\mathrm{sym}} \sim 10^{-18} \ll \eta_{\mathrm{obs}}}$

Universe must have been baryon **asymmetric**
how did this arise?

Baryogenesis Ingredients: A. Sakharov (1967)

Assume: initially, $n_B = n_{\bar{B}}$
then Universe generated asymmetry (i.e., asymm is *dynamical*)

Requirements:

$\boxed{1.}$ Baryon number non-conservation
not yet observed: e.g., $\tau_p > 10^{33}$ yr (!)
but theoretically expected (GUT theories)

but: B violation *necessary* but not *sufficient*

consider B-violating rxns

Rxn	B change	Rate
$a + b \rightarrow c + d$	ΔB	Γ
$\bar{a} + \bar{b} \rightarrow \bar{c} + \bar{d}$	$-\Delta B$	$\bar{\Gamma}$

net baryon production rate: $\Gamma_{\rm net} = \Delta B(\Gamma - \bar{\Gamma})$
Q: which means we need what?

we need: $\Gamma_{\text{net}} = \Delta B(\Gamma - \bar{\Gamma}) > 0$

- baryon non-conservation gives $\Delta B \neq 0$
- but *also* need $\Gamma > \bar{\Gamma}$
  set by particle (discrete) symmetries

Transformations
C =charge conjugation: particle ↔ antiparticle
P =parity: space inversion $\vec{x} \rightarrow -\vec{x} \Rightarrow \vec{p} \rightarrow -\vec{p}$
Weak interation: P *maximally* violated:
ν_e measured as *left-handed only*
`www:  Lee, Yang, Wu`

$P\nu_{\text{L}} = \nu_{\text{R}}$ not made via weak int
but $CP\nu_{\text{L}} = C\nu_{\text{R}} = \bar{\nu}_{\text{R}}$ OK

neutrino helicity sketch

if CP conserved:

$CP(a+b\rightarrow c+d) = \bar{a}+\bar{b}\rightarrow\bar{c}+\bar{d}$
i.e., identical quantum probabilities,
in particular (anti)baryon number production $\bar{\Gamma} = \Gamma$
generate new antibaryons as fast as baryons! aargh!
→ can't have this symmetry/conservation

$\boxed{2.}$ CP (and C) Violation

1964: CP violation show for $K^0, \bar{K}^0$ decays
www: Fitch & Cronin Nobel prize
current precision limits: KTeV Fermilab
2001: " " " " $B^0, \bar{B}^0$ decays ($B = \bar{b}d$)
www: BaBar, Belle
www: B^0 vs $\bar{B}^0$ decay asymmetries: matter/antimatter difference!

...but *still* not guaranteed B excess!

3. Departure from thermal equilibrium

basic idea: in thermodynamic equilib., reaction details irrelevant

$\mu_B = \mu_{\bar{B}} = 0$ since B violated, and so

$$f_b(p) = \frac{1}{e^{E_b/T}+1} \quad f_{\bar{b}} = \frac{1}{e^{E_{\bar{b}}/T}+1} \tag{2}$$

but $E_b(p) = \sqrt{p^2 + m_b^2} = E_{\bar{b}}(p)$ since $m_b = m_{\bar{b}}$
so therm eq. $\Rightarrow f_b = f_{\bar{b}} \Rightarrow n_b = n_{\bar{b}}$

But we know the U leaves eq. sometimes – *freezeouts!*

Baryogenesis models have been constructed
with GUT particle theories
can get $\eta \sim 10^{-10}$: encouraging!
$\Rightarrow$ need more particle physics data to test

Other unfinished business:
Fortune Cookie

Early Universe: Some Highlights

Energy/Temperature T	Event
$\sim m_\mu \sim$ 100 MeV	$\mu^+\mu^-$ abundant
$\sim m_\pi \sim$ 140 MeV	π abundant
$\sim \Lambda_{\rm QCD} \sim$ 200 MeV	quark-hadron transition: baryons + mesons $\leftrightarrow$ "plasma" of unbound quarks + gluons
$\sim few \times M_W, M_Z \sim$ 300 GeV	Electroweak transition: EM + weak forces unified
$\sim 10^{15}$ GeV (?)	Grand Unified Theory (GUT) transition: strong + electroweak forces unified Inflation (accelerated expansion, $\Omega \to 1$) after Inflation: Baryogenesis matter vs antimatter excess created
$\sim 10^{19}$ GeV	Planck epoch: quantum gravity; all forces unified (?)

Interlude

Cosmologist W. Allen

Annie Hall (1977)

STELLAR EVOLUTION AND NUCLEOSYNTHESIS

Stellar Evolution and Nucleosynthesis

Overview

Star structure, evolution, nuke
all determined by:
- mass
- composition
- (binarity)

theory:
inputs: M, composition determine
output: structure and evolution; history of
L, T_{eff}, τ, nucleosynthesis

recall:
stellar lifetimes $\tau(M)$ very strongly *inverse* with mass
Q: implications for stellar populations and nucleosynthesis?

Stellar Lifetimes and Nucleosynthesis Roles

mass M	lifetime $\tau(M)$	fate
$\lesssim 0.9 M_\odot$	$\gtrsim t_0$	"never" die
1 to $\sim 10 M_\odot$	10 Gyr to 30 Myr	red giant $\rightarrow$ AGB $\rightarrow$ white dwarf + PN
$\gtrsim 10 M_\odot$	$\lesssim$ 30 Myr	supernova

- low-mass stars just "accumulate"
  $\Rightarrow$ "sinks" for baryons and nucleosynthesis products
- high-mass stars rapidly die:
  $\rightarrow$ first sources of post-big bang elements
  $\rightarrow$ many supernova "generations" till today
- different nucleosynthesis roles for different masses