Astro 596/496 NPA
Lecture 25
March 29, 2019

Announcements:

- **Problem Set 4 due today**
- **Preflight 5 out; due next Friday**

Today: Pivot in Course

- finish early Universe; sets conditions at 3 minutes
  particles, especially baryons (light elements), dark matter
- next: stellar nucleosynthesis
  evolution of baryons over 14 Gyr
  to fill Chart of Nuclides and Solar Abundances

Want more particle and nuke physics?
Consider Physics 470, 570, or 575!

Update On Course Grades

Grading has gotten behind–*instructors fault! bad professor!*
Apologies! Will catch up soon

Gradebook on Compass: has Problem Set Points Attempted

- Why? ASTR496 students can drop on problem per set so attempted points $\neq 10$, have to track
- PS scores are points earned vs points attempted from this you can calculate how you are doing
- for ASTR596, Points Attempted $= 10$ always

Particle Dark Matter and WIMPs: Highlights

⋆ *non-baryonic dark matter* a profound outstanding question
demands particle physics beyond Standard Model

⋆ *WIMP models well-motivated, and some still viable*

⋆ *WIMP searches* very active: accelerator, direct, indirect
includes: annhilation $\psi\bar{\psi} \to \nu$ in Sun to high-energy neutrinos
annihilation $\psi\bar{\psi} \to X\bar{X}$ heating of solar system bodies

⋆ *hints of anomalies, but no unambiguous detections to date!*
motivates alternate dark matter theories and new searches
rethinking of the field – an exciting time!

Illinois active in particle dark matter experiment and theory
Profs. Filippini, Yang, Peng, Shelton, Adshead, Shapiro, BDF

Particle History in the Early Universe

BBN story began at Weak freezeout $T_{\mathrm{wf}} \sim$ 1MeV
and $t_{\mathrm{wf}} \sim 1$ sec $(1\ \mathrm{MeV}/T)^2$:

- *baryons* were n and p
- photons, neutrinos, and $e^{\pm}$ pairs relativistic and abundant

at earlier times, higher T: collisions more violent, more frequent

Going back in time:

- $T \gtrsim m_{\mu} = 106$ MeV: $\mu^{\pm}$ pairs relativistic and abundant
- $T \gtrsim m_{\pi} \sim 140$ MeV: $\pi^{\pm}, \pi^{0}$ relativistic and abundant

recall quark/gluon interactions: *Strong force*
underlying theory: quantum chromodynamics (QCD)
shows *interaction strength is energy-dependent* "asymptotic freedom"

- strongest at low energies, but weakens at high energy
- interactions weaken at energy scale $\Lambda_{\mathrm{QCD}} \sim 250$ MeV

Q: what happens in Early Universe before then?

Quark-Hadron Transition

When $T \gtrsim \Lambda_{\rm QCD} \sim 250$ MeV:

- collisions unbind quarks
- *no more bound states of baryons and mesons!*
- instead: **plasma of free quarks and gluons**
- very early universe: quark-gluon soup!

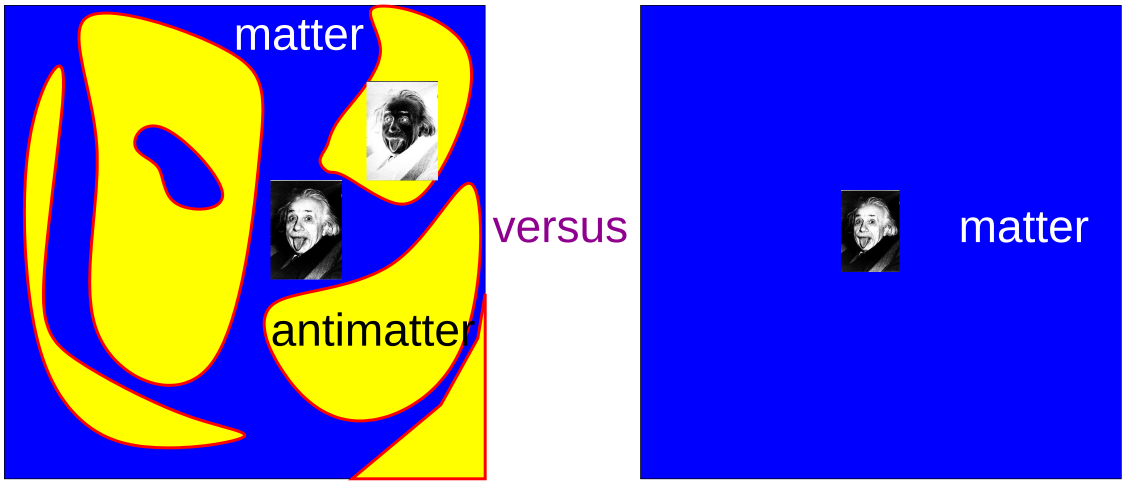
quark-gluon plasma studied in the laboratory
via **heavy ion collisions** at CERN, Brookhaven National Lab
Au + Au and Pb + Pb collisions at $\sim 0.2 - few$ TeV/nucleon
huge energy density, baryon density $\rightarrow$ quark-gluon plasma!
but short-lived, decays in huge swarm of baryons and mesons
`www: Heavy Ion Collisions`

Illinois a leader in quark-gluon research

Prof. Grosse-Perdekamp, Sickles, Makins, Reidl, El Khadra, Faulkner, Baym

Baryogenesis: Origin of Matter/Antimatter Asymmetry

Observed Matter (Baryon) Asymmetry of the Universe



As far as we are able to observe, a cosmic asymmetry exists: baryons and leptons dominate over antibaryons and antileptons

the present universe is only made of matter

Q: What is evidence for different scales? Solar Sytem, solar neighborhood, MW Galaxy, galaxy clusters, Hubble volume?

Evidence for Baryon Excess

Matter-only System	Asymmetry Evidence
Solar system	landings, solar wind, proto-$\odot$ neb
Cosmic rays	consistent with in-flight origin, e.g., $p_{\rm cr} p_{\rm ism} \to ppp\bar{p}$
MW Galaxy	cosmic rays, no annihilation γs
Galaxy clusters	no γ from galaxy-intracluster gas interface
	nor in colliding clusters
	$\Rightarrow$ all matter or all antimatter
Hubble volume	too few 1–10 MeV γ, no CMB distortion

no evidence for antimatter "domains" anywhere

Fine print:

- strictly: if animatter domains exist
  segregated from matter on scales $\gtrsim 10^{14} M_\odot$
  and probably $> d_H = 2$ Gpc
- recently: hints of anti-^{4}He reported by AMS!

Conclude: cosmic **baryon asymmetry** exists

$$\frac{n_{\mathrm{b,net}}}{n_\gamma} = \frac{n_{\mathrm{b}} - n_{\bar{\mathrm{b}}}}{n_\gamma} = \eta = 6 \times 10^{-10}$$

at $T \gtrsim \Lambda_{\mathrm{QCD}} \simeq 250$ MeV, $q\bar{q}$ pairs abundant and relativistic:
$n_q \simeq n_{\bar{q}} \sim n_\gamma$, so asymmetry was

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

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?

Q: what if we take analogy with WIMPs?

A Baryon Symmetric Universe

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

cold relic:
$\langle \sigma v \rangle_{\rm ann} \sim r_p^2 c \sim 1 \ {\rm fm}^2 \ c \sim 10^{-15} \ {\rm cm}^3 \ {\rm s}^{-1}$
$\Rightarrow T_f \sim m/40 \sim 20$ MeV
leaves relic abundance
$n_{\rm b}/n_\gamma = n_{\bar{\rm b}}/n_\gamma \sim (m/T_f) e^{-m/T_f} \simeq 10^{-18}$
$\Rightarrow$ $\boxed{\eta_{\rm sym} \sim 10^{-18} \ll \eta_{\rm obs}}$

U. 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:

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 $\Gamma > \bar{\Gamma}$

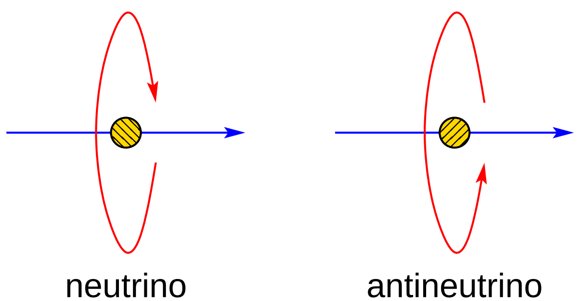
  set by particle (discrete) symmetries

Transformations

C =charge conjugation: particle $\leftrightarrow$ antiparticle

P =parity: $\vec{x} \to -\vec{x} \Rightarrow \vec{p} \to -\vec{p}$

Weak interaction: P violated, ν_e left-handed only



$P\nu_{\text{L}} = \nu_{\text{R}}$ not made via weak int

but $CP\nu_{\text{L}} = C\nu_{\text{R}} = \bar{\nu}_{\text{R}}$ OK *if CP conserved:*

$CP(a+b \to c+d) = \bar{a}+\bar{b} \to \bar{c}+\bar{d}$

i.e., identical quantum probabilities,

in particular (anti)baryon number production $\bar{\Gamma} = \Gamma$

—em generate new antibaryons as fast as baryons! aargh!

$\rightarrow$ can't have this symmetry/conservation

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`

...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 equilibrium 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

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
$\sim \Lambda_{\text{QCD}} \sim$ 250 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 (?)