Astro 596/496 NPA
Lecture 22
March 11, 2019

Announcements:

- **Respite: no class meetings this Wed & Fri**
- **Nothing due this Friday!**

Last time: BBN concordance and implications

- CMB + BBN agreement on cosmic baryon content
- ...but lurking lithium problem
- FLRW cosmology working back to $t \sim 1$ sec, $z \sim 10^{10}$
- baryonic dark matter
- non-baryonic dark matter

Particle Dark Matter

BBN and Particle Dark Matter

BBN motivates dark matter theory & searches two ways:

Quantitative. $\Omega_B \ll \Omega_{\rm m}$: must have non-baryonic dark matter
...and lots of it!

Qualitative. BBN success at $t \sim 1$ s $\rightarrow$ early U as physics lab

"The universe is the poor man's particle accelerator"
– Ya. Zel'dovich

Big implications for–and motivations from–particle physics

Q: what can we say about DM properties generally?

Q: what can we say if DM is in particle form?
lifetime, mass, interactions, quantum #s?

Q: what known particles are candidates for non-baryonic DM?

Q: does particle theory offer dark matter candidates?

Elementary Particle Physics and Dark Matter

Dark matter

dark: no/feeble EM, strong interactions

matter: behaves as nonrelativistic material $\rightarrow \rho \propto a^{-3}$, $P \ll \rho c^2$

before inventing new particles

first see if we have any particles "ready to go"

Fundamental Particles

high-energy experiments reveal: "everyday" stable species but also *a zoo of unstable particles*

Puzzle:

- huge numbers of unstable particles found that interact with nucleons
- *hadrons* = i.e,. feel strong nuclear force
- `www: Particle Data Group` hadrons

Puzzle:

- e mag moment is $\mu_e \simeq 2e\hbar/m_e c$

$\mu_p = 2.79\ e\hbar/m_p c$,

$\mu_n = -1.91\ e\hbar/m_n c$

Q: what could be going on?

key experiment: $e - N$ scattering – show nucleons not pointlike!
instead: nucleon made of 3 pointlike particles

Quarks

n and p *not* fundamental particles, but "composite"
bound states of 3 pointlike quarks
name due to Gell-Mann: from J. Joyce's *Finnegan's Wake*)

two types ("flavors") in N: u "up," d "down"
$p = uud$, $n = udd$ $\rightarrow$ quark electric charge $Q_u = +2/3$, $Q_d = -1/3$
$\Rightarrow$fundamental charge really is $e/3$
spin $S(u) = 1/2 = S(d)$

hadron particle "spectroscopy" understandable with quarks

Hadrons: Systems of Quarks

hadron = made of quarks

= strongly interacting

baryon = bound $\boxed{qqq}$ triple

proton $p = \boxed{uud}$, neutron $n = \boxed{udd}$

also numerous unstable baryons, e.g.,

$\Delta^{++} = \boxed{uuu}$, $\Delta^{-} = \boxed{ddd}$

`www: PDG baryon listings`

meson = bound $\boxed{q\bar{q}}$ pair (which decays)

e.g., "pion" $\pi^+ = u\bar{d}$, $\pi^- = \overline{\pi^+} = \bar{u}d$

$\pi^0 = 1/\sqrt{2}(u\bar{u} - d\bar{d})$

$m(\pi^\pm) = 140$ MeV, $m(\pi^0) = 135$ MeV

decay: $\pi^0 \to \gamma\gamma$, $\tau(\pi^0) = 8.4 \times 10^{-17}$ s

`www: PDG meson listings`

Particle Families

Group normal matter constituents as "*family*"

$$\begin{pmatrix} q_{+2/3} \\ q_{-1/3} \\ \ell_{-1} \\ \ell_0 \end{pmatrix} = \begin{pmatrix} u \\ d \\ e \\ \nu_e \end{pmatrix} \qquad (1)$$

High-Energy expts show:
other quarks, leptons exist!
e.g., strange quark s: $Q(s) = -1/3$
$\rightarrow$ strange baryons $\Lambda = uds$, mesons $K^- = s\bar{u}$
e.g., mu-lepton (muon) μ:
$m(\mu) = 105.7$ MeV $\simeq 200 m_e$; I. Rabi: "Who ordered that?"
`www: PDG lepton listings`

3 family "generations" known
new particles decay to "first family" particles
e.g., $\Lambda \rightarrow p + \pi^-$

Periodic Table of Elementary Particles

known fundamental particles: 3 families

$$\begin{pmatrix} u \\ d \\ e \\ \nu_e \end{pmatrix} \begin{pmatrix} c \\ s \\ \mu \\ \nu_\mu \end{pmatrix} \begin{matrix} \text{charm quark} \\ \\ \\ \\ \end{matrix} \quad \begin{pmatrix} t \\ b \\ \tau \\ \nu_\tau \end{pmatrix} \begin{matrix} \text{top quark} \\ \text{bottom quark} \\ \text{tau lepton} \\ \\ \end{matrix} \tag{2}$$

+antiparticles

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

for quarks and charged leptons, masses increase with each family

same for νs??

Generalized Conservation Laws

Conservation laws: as before, but now

baryon number: includes quarks: $B_q = 1/3$
e.g., $B(\Lambda) = 1$, $B(q\bar{q}) = 0$
$\rightarrow$ "meson number" not conserved

lepton number:
separately conserved for each family
e, μ, and τ lepton number each conserved
e.g., $\mu^- \rightarrow e^- + \gamma$: $\otimes$! L_μ, L_e non-cons
instead $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$ OK

Whenever see a reaction:
first task is to ensure conservation laws obeyed

Fundamental Interactions: Overview

Interaction	Field Quantum	Mass $m_{\text{boson}}c^2$ (GeV)	Range (cm)	Relative Strength	Typical Cross section at 1 GeV (cm^2)
Strong	Gluon	0	$\sim 10^{-13}$	~ 1	$\sim 10^{-26}$
Weak	$W^{\pm}, Z^0$	82, 91	$\sim 10^{-16}$	$\sim 10^{-5}$	$\sim 10^{-40}$
Electromagnetic	photon	0	∞	$\alpha = 1/137$	$\sim 10^{-29}$
Gravitation	graviton(?)	0	∞	$\sim 10^{-38}$	N/A

Fundamental Interactions and Forces

at quantum level:

matter made of fermions

forces between fermions transmitted by boson exchange

e.g., Coulomb scattering: $e\mu \rightarrow e\mu$ exchange photon

boson mass $\leftrightarrow$ *force range*

exchange timescale $\Delta E \, \Delta t \sim m_{\mathrm{boson}} c^2 \, \Delta t \lesssim \hbar$

$\Rightarrow$ range $r \lesssim c \, \Delta t \sim \hbar / m_{\mathrm{boson}} c$

boson Compton wavelength

EM: photon $m_\gamma = 0 \rightarrow$ infinite range. $V_{\mathrm{Coul}} \sim 1/r$

Gravity: also $V \sim 1/r \rightarrow$ massless graviton(?)

Weak: massive bosons $W^\pm, Z^0 \rightarrow$ finite range Strong: gluons massless, but interaction $V_{\mathrm{strong}}(r) \sim a/r + kr$

Q: what's weird about this? implications?

Quark Confinement

gluon interactions between quarks (and each other!)

$$V_{\text{strong}}(r) \sim \frac{a}{r} + kr \tag{3}$$

linear term: as $r \to \infty$, $V \to \infty$!

but once interaction energy $V > m_q c^2$, can make more quarks

$q \quad \bar{q} \to q\bar{q} + q\bar{q}$

quark confinement: no free quarks found!

always bound into baryons (qqq) mesons ($q\bar{q}$)

(note: nuclear force $\simeq \pi$ exchange

range $r_{\text{nuke}} \sim \hbar/m_\pi c \sim 1$ fm)

Particle Interactions: Who feels what?

all particles subject to gravity, and

neutrinos "feel" only weak interaction

charged leptons feel only weak and EM

quarks feel all forces

Note: β decay really quark transformation

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

$udd \rightarrow uud + e^- + \bar{\nu}_e$

$\Rightarrow d \rightarrow u + e^- + \bar{\nu}_e$

The Standard Model of Particle Physics: Twitter Version

- **3 matter families** of quarks and leptons

- massless neutrinos

- *fundamental interactions/forces: exchange of field quanta*
  structure set by internal *symmetry*
  ▷ strong: quanta are gluons
  ▷ electromagnetic: photon γ
  ▷ weak: W^+,W^-,Z^0
  ▷ and gravity (graviton?)

- **Higgs field:** scalar field, couples to all particles
  coupling strength $\rightarrow$ particle mass
  Higgs field quanta: spin-0 **Higgs boson**
  mass $m(H^0) = 125.18 \pm 0.16$ GeV largest known
  unstable: decays to everything! e.g., $H^0 \rightarrow b\bar{b}$

Non-Baryonic Dark Matter: Standard Model Candidates

Q: what Standard Model particles could *be non-baryonic dark matter?*

Q: hint–what Standard particles are stable?

Q: what is needed to tell if Standard Model particles are DM?

Standard Model Non-Baryonic Dark Matter

non-baryonic dark matter:

- *not baryons: quarks are out*
- *matter:* non-relativistic: photons are out
- *stable: Higgs, $W^{\pm}$, Z^0 out*

Leaves leptons

Charged leptons: e, μ, τ

only e stable, charge neutrality $n_e = n_Z$, $m_e \ll m_\mathrm{u}$

$\rightarrow \rho_e \ll \rho_B$

neutral leptons: neutrinos! ν_e, ν_μ, ν_τ

- not baryons!
- stable!
- weakly interacting
- families: get "three for price of one!"

excellent non-baryonic dark matter candidate!

...and the only Standard Model non-baryonic DM candidate!

Neutrino Dark Matter

neutrinos are a guaranteed component of non-baryonic dark matter!

even better: *we know the cosmic neutrino number density!*
recall: neutrinos freeze out at BBN, with $T_\nu = (4/11)^{1/3} T_\gamma$
so per $\nu\bar{\nu}$ neutrino species: $n(\nu\bar{\nu}) = (4/11) n_\gamma$
but: what is ρ_ν, Ω_ν? depends on neutrino masses

★ Laboratory studies of β decay
e.g., precision measurement of e^- energy in $^3\text{H} \to {^3\text{He}} + e^- + \bar{\nu}_e$
place limits on ν_e mass *Q: how?*
current PDG limit: $\boxed{m(\nu_e) < 2 \text{ eV}}$

★ We shall see: *solar* and *atmospheric* νs
will ultimately show *all* 3 species have $\boxed{m(\nu) \lesssim few \text{ eV}}$

But you will show (PS 4): neutrino density parameter is

$$\Omega_\nu \simeq \frac{\sum_i m(\nu_i)}{45 \text{ eV}} \tag{4}$$

Q: implications for dark matter?

Q: implications for particle physics?

Dark Matter Requires New Physics

no viable particle dark matter candidates
in Standard Model of particle physics

non-baryonic DM **demands** *physics beyond the Standard Model*

Hugely important and exciting for particle physics!

Unlike dark energy: particle physics *does* offer solutions!
particle candidates available "off the shelf"
invented for particle physics motivations independent from DM!

- lightest supersymmetric particle
- axion
- strangelets...

(Almost) all of these are formed as *cold relics*