Astro 596/496 NPA

Lecture 9

Sept. 14, 2009

Announcements:

- Preflight 2 posted, due next Friday, noon
- Astronomy Colloquium tomorrow, here, 4pm:
  William Hanlon, on Ultra-High-Energy Cosmic Rays
  $E_{\mathrm{UHECR}} > 10^{19}$ eV ~ 1 Joule!
  $\rightarrow$ highest-energy particles observed!

Today:

- finish particle physics
- begin cosmology

Fundamental Interactions and Forces

at quantum level, matter (fermions) interacts by boson exchange

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

boson mass $\leftrightarrow$ *interaction range*
exchange timescale: $\Delta E \, \Delta t \sim m_{\rm boson} c^2 \tau_{\rm exch} \lesssim \hbar$
$\Rightarrow$ range $r \lesssim c\tau_{\rm exch} \sim \hbar / m_{\rm boson} c$ (*Compton wavelength*)

- **EM**: photon $m_\gamma = 0 \rightarrow$ infinite range
  $V_{\rm EM}(r) \sim 1/r$, so $V \neq 0$ for $r < \infty$
- **Gravity**: also $V_{\rm Grav} \sim 1/r \rightarrow$ massless graviton(??)
- **Weak** interaction: massive bosons
  $W^\pm, Z^0$, $M \gg m_p \rightarrow$ finite range

- **Strong** interaction: felt by quarks

key: $V_{\text{strong}}(r) \sim a/r + kr$

as $r \to \infty$, $V \to \infty$!

"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

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

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

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

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

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

Clearing the Palette: Fermilab Tour Headcount

www: Fermitour info

COSMOLOGY

Physical Cosmology

Modest goals:
scientific understanding of the

- origin
- evolution
- contents
- structure
- future

of the Universe

we will see:

⋆ known particle & nuke physics plays decisive role

⋆ open questions in cosmology probably (?) linked to open questions in particle physics

Cosmography Units: Astronomical Distances

Charity begins at home: *Astronomical Unit* (AU)

- average Earth-Sun distance, known very precisely
- $r(\text{Earth} - \odot) \equiv 1\ \text{AU} = 1.49597870660 \times 10^{13}\ \text{cm}$

parsec

- derives from trigonometric parallax measures of stars
- star with parallactic angle p lies at distance

$$r(p) = \frac{1\ \text{AU}}{\tan p} \approx \frac{1\ \text{AU}}{p} \tag{1}$$

for $p = 1$ arcsec $= 4.8 \times 10^{-6}$ rad, distance is

$$r(1\ \text{arcsec}) \equiv 1\ \text{parsec} \equiv 1\ \text{pc} = 3.0857 \times 10^{18}\ \text{cm} \approx 3\ \text{lyr} \tag{2}$$

Q: pc, kpc, Mpc, Gpc *characteristic scales for what?*

Typical Lengthscales: Cosmic Hierarchy

- ⋆ typical star-star separation in galaxies ~ 1 pc

- ⋆ typical (visible) galaxy size $\sim$ 1kpc $= 10^3$ pc

- ⋆ (present-day) typical galaxy-galaxy separation ~ 1 Mpc $= 10^6$ pc

- ⋆ (present-day) observable universe ~ 1 Gpc $= 10^9$ pc

Q: Why is this a "hierarchy"?

Observational Cosmology: Zeroth-Order Picture

Cosmic Matter Distribution

observable cosmo "building blocks" − galaxies
$\approx$ all stars in galaxies

`www: Galaxy Survey: 2dFGRS`
Q: what do you notice?
Q: e.g., distribution on small, large scales?
Q: distribution in different directions?

The Universe to Zeroth Order: Cosmological Principle

Observations teach us that
- at any given cosmic time ("epoch")
- to "zeroth order":

the Universe is both

1. **homogeneous** average properties same at all points

2 **isotropic** looks same in all directions

"Cosmological Principle"

the universe is homogeneous & isotropic

first guessed(!) by A. Einstein (1917)
- no special points! no center, no edge!
- "principle of mediocrity"? "ultimate democracy?"

Q: do you need both?

Q: e.g., how can you be isotropic but not homogeneous?

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Example: Cosmo principle and galaxy properties

Q: if cosmo principle true, how should it be reflected in observations of galaxies at any given time?

Q: what does cosmo principle say about how galaxy properties evolve with time?

Cosmo principle and galaxy properties:
at any given time:

- **average** density of galaxies same everywhere

- *distribution* of galaxy *properties* same everywhere
  range of types
  range of colors
  range of luminosity L, mass M, ...
  ratios of normal/dark matter

These are very restrictive constraints!

- time evolution:
  must maintain large-scale homogeneity and isotropy
  but otherwise, **by itself** cosmo principle allows any changes!

Cosmo Principle hugely powerful & the "cosmologist's friend"
very strongly constrains possible cosmologies
$\longrightarrow$ large-scale spatial behavior maximally simple

Director’s Cut Extras

Relativistic Kinematics

Special relativity:

given two events separated by $dX = (dt, dx, dy, dz)$

interval $ds^2 = c^2dt^2 - dx^2 - dy^2 - dz^2$ is

invariant: same value for all observers

massless particles (e.g., γ): $ds^2 = 0$

Lorentz transform (boost):

if know $X^\mu = (ct, \vec{x})$ one observer, what is it for another (X')?

$X' = [\gamma(ct - \beta x), \gamma(x - \beta ct), y, z]$

where $\beta = v/c$, $\gamma = 1/\sqrt{1 - v^2/c^2}$

formally similar to spatial rotations

$\rightarrow$ coordinates "mix" in linear combo

but Lorentz mixes space and time

Objects which transform this way: 4-vectors

$\Rightarrow$ energy-momentum: $P = (E_{\text{tot}}, c\vec{p})$ is 4-vec

conservation $\rightarrow \sum P_i = \sum P_f$ (same frame)

$\rightarrow \sum E_i = \sum E_f$ and $\sum \vec{p}_i = \sum \vec{p}_f$

include rest mass energy!

note: $P_i^2 = P_f^2$ invariant for any i, f frames

where $P_1 \cdot P_2 = E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2$

particle at rest: $P = (mc^2, 0)$

boost with vel $\vec{v}$:

$P' = (\gamma mc^2, \gamma\vec{\beta}mc^2)$

$\Rightarrow$ $E = \gamma mc^2$, and $\vec{p} = \gamma m\vec{\beta}c = \gamma m\vec{v}$

note: invariant $P^2 = E^2 - \vec{p}^2 = m^2 = const$ OK

$\vec{v}/c = c\vec{p}/E$ (when E includes rest mass)

kinetic energy: $T = E - mc^2 = (\gamma - 1)mc^2$

Massless particles:

$m^2 = 0 = E^2 - (cp)^2 \Rightarrow E = cp$

Natural Units

Fundamental dimensionful constants set natural scales
natural to use these as *standards*
- simplifies notation
- very common in particle, nuclear, cosmo literature

fundamental speed limit set by c
- so write all speeds as fraction of this

$\longrightarrow$ effectively set $c = 1$
i.e., all v in terms of c
$E^2 - p^2 = m^2$, $v = p/E$

sometimes also use fundamental angular momentum $\hbar$:
effectively set $\hbar = 1$

helpful conversion: $\hbar c \simeq 200$ MeV fm
e.g., Compton wavelength
$r_c = 1/m = \hbar/mc = \hbar c/mc^2 = 200\ \mathrm{fm}/m_{\mathrm{MeV}}$

The Plague of "Little h"

Back in the old days ($\gtrsim$ 10 yr ago): H_0 poorly measured
$H_0(\mathrm{old\,data}) \sim 50 - 100 \ \mathrm{km\,s^{-1}\,Mpc^{-1}}$
Worse still: many cosmo results sensitive to H_0
$\rightarrow$ how to show effect of uncertainties?

Parameterized Uncertainty:
introduce "little h" via

$$H_0 \equiv 100 \ h \ \ \mathrm{km\,s^{-1}\,Mpc^{-1}} \tag{3}$$

i.e., $h = H_0/100 \ \mathrm{km\,s^{-1}\,Mpc^{-1}}$
- back in the day: $h = 0.5 - 1$
- but now $h = 0.73 \pm 0.03$

The H_0 nightmare is over, but the literature
is full of fossil little-h
$\rightarrow$ whenever you see it, think $h = 0.73 \approx 1/\sqrt{2}$