Astro 596/496 NPA
Lecture 2
January 16, 2019

Announcements:

- Pick up: Syllabus
- Preflight 1:
  posted soon on Compass
  due Fri. Jan 25 before class

Last time: overview

Now: the Great Work begins!

Program Notes: ASTR 596/496 NPA Bugs/Features

- notes online–but come to class!
  some people find it convenient to print 4 pages/sheet

- class $\in$ diverse backgrounds: ask questions!

- Socratic questions

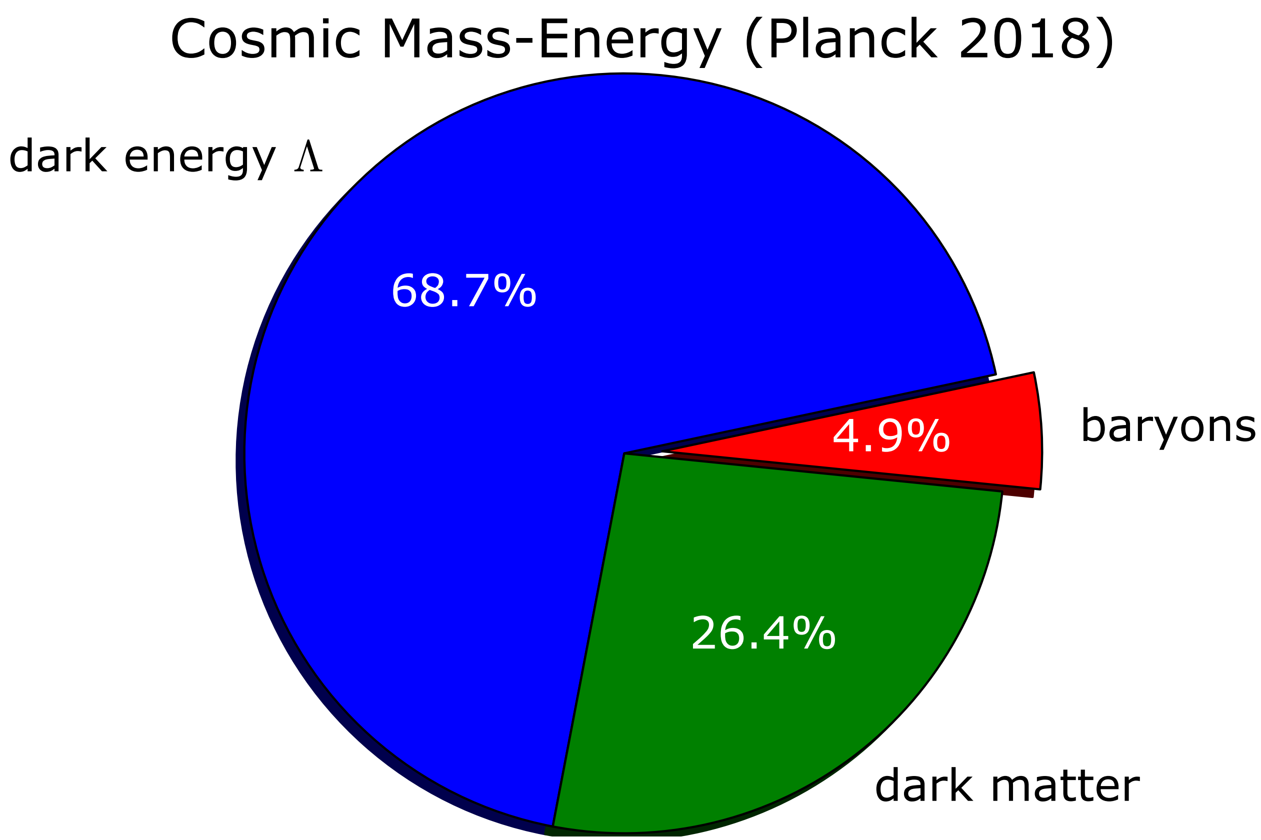
- typos/sign errors
  Dirac story
  please report errors in lectures and problem sets

Slices of the Cosmic Pie

We want to use physics to understand the nature and history of cosmic matter

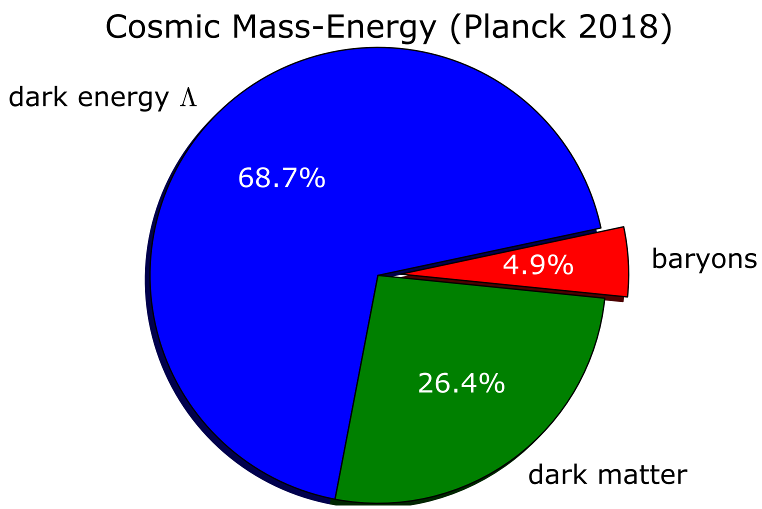
To place in context:
(looking ahead to results we haven't derived)
Q: what are the main components of the universe today?
Q: which is the dominant component, and by how much?

The Contents of the Present Universe



Q: what questions does this raise?

Cosmic Ingredients: Mysteries



- What is dark energy? how does it interact?
- What is dark matter? how does it interact?
- Are the dark components related to each other? to baryons?
- What form do the baryons take?
- What sets the abundances?
- How have these evolved with time?

Observables for Nuclear and Particle Astrophysics

To be a science: must have empirical evidence
$\longrightarrow$ need observable data to reveal/test cosmic matter history

Seek **messengers/observables** which:
- probe nature of cosmic constituents
- reveal history of cosmic matter

$\star$ *indicate nuke/particle interactions have taken place.*

Q: What are some?
(no peeking at notes)

Q: Compare observables list to cosmic pie chart. Comments?

Observables for Nuclear and Particle Astrophysics

Observable	Example
direct matter detection	terrestrial labs, cosmic rays
neutrinos	solar, supernova neutrinos
high-energy photons	X-rays, γ-rays
gravitational waves	BH-BH, NS-NS merger waves
abundances: elemental & isotopic	Sun, Galactic stars
dark matter	direct detect, annihilation product
dark energy	cosmic acceleration

Note: the dominant cosmic components today
are the *hardest* to track observationally!

will look at all observables
but central to both nuclear and particle astrophysics:
the baryonic universe

Baryons: Praise Them or Bury Them?

practical definition ("close enough for astro work"):

baryon = protons, neutrons, or any combination thereof

$\rightarrow$ all nuclei $\rightarrow$ all atoms in any form $\rightarrow$ **'ordinary' matter**

...more formal definition to come...

baryons are modest fraction of cosmic matter today
and even smaller fraction of total cosmic mass-energy

and (at least some) baryons are not exotic
with (fairly) well-understood physics

Q: so why would a particle astrophysicist study cosmic baryons?

In Defense of Baryons

⋆ because we know much about baryonic physics
  ▷ both micro (particle, nuclear, atomic)
  ▷ and macro (hydrodynamics, condensed matter)
  baryons show how particle properties are manifest
  in cosmo/astro context
  ⇒ good training for dark matter, dark energy

⋆ lessons:
  ▷ detailed picture of how baryonic microphysics determines
    cosmic properties and shapes cosmic events
  ▷ baryons respond to dark sector at least via gravity
    infer influences of dark matter and dark energy
  ▷ see how unexpected and complex phenomena emerge

⋆ **we are baryons!**
  baryonic history is our history!

Nuclei: Orders of Magnitude

Nuclear Properties: Orders of Magnitude

atomic nuclei are made of **nucleons**:
neutrons n and *protons* p

Q: what roughly is the nucleon size? how do we know?

Q: what roughly are the nucleon masses? how do we know?

Meet the Nucleons

nucleon radius similar for both n and p:

$$r_0 \sim 10^{-15} \text{ m} = 1 \text{ femtometer} = 1 \text{ fm} = 1 \text{ fermi} \quad (1)$$

measure via scattering with e, and between nucleons

masses: measure via H atom mass, neutron scattering

nucleon	mass	spin	charge
proton	$m_p c^2 = 938$ MeV	$S_p = 1/2$	$Q_p = \|Q_e\| = e$
neutron	$m_n c^2 = m_p c^2 + 1.3$ MeV	$S_n = 1/2$	$Q_n = 0$

note $m_n \approx m_p$: *nucleons have nearly the same mass*

$\Delta m / \langle m \rangle \sim 10^{-3}$

Complex Nuclei

complex nuclei are bound systems of > 1 nucleon:
N neutrons and Z protons

Q: nuclear baryon number? nuclear charge?

Q: rough estimate of nuclear mass?

Q: rough nuclear size if closely packed?

Building Nuclei

N neutrons and Z protons has

- **baryon number** = total nucleon number $\equiv A = N + Z$
- **electric charge** = **atomic number** = Z

since nucleons have similar masses, naively expect
mass $M \sim N m_n + Z m_p \approx (N + Z) m_u = A m_u$
with m_u a mean nucleon mass unit
and A also called **mass number**

nuclear **size**: if close-packed spheres
then for nucleus with mass number A expect:
total volume $V_A \approx A V_1$, so $r_A^3 \approx A r_0^3$, and

$$r_A \sim A^{1/3} r_0 \tag{2}$$

Q: implications of existence of nuclear bound states?
Q: implications of mega-nuclei being rare?

Nuclear Binding Implies a Nuclear Force

most nuclei contain $Z > 1$ protons nearly touching!
huge Coulomb repulsion!

total potential energy roughly

$$E_{\mathrm{C}} \sim \frac{Z^2 e^2}{r} \sim 1.4\ \mathrm{MeV}\ Z^2 \left(\frac{1\ \mathrm{fm}}{r}\right) \tag{3}$$

if this is unopposed, nuclei would fly apart!

thus: existence of nuclei demands a stabilizing force
the **nuclear interaction / nuclear force**

- attractive at short distances
- stronger than Coulomb force at short distances
- with $\sim$ MeV scale strength
- weakens at long distances or all nuclei would merge to one!

Nuclear Notation and Charting

notation: $\boxed{{}^{A}_{N}\mathrm{X}^{Z}}$

shorthand: chemical symbol X $\Rightarrow Z$, then can get $N = A - Z$

e.g., ${}^{3}_{1}\mathrm{He}^{2} \rightarrow {}^{3}\mathrm{He}$

"nuclide" $=$ a particular (Z, N) combination
strictly, and a particular energy state of that combo

Diagram: **Chart or Table of Nuclides**

analog of Periodic Table of Elements

plot nuclei in (N, Z) array

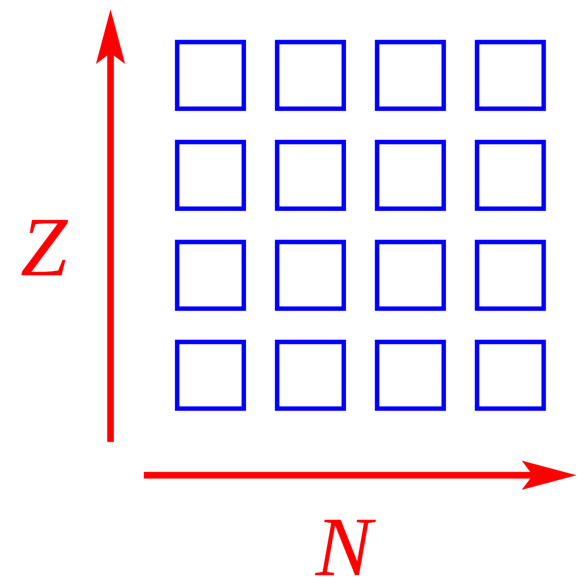
isobar: fixed A (e.g., ${}^{7}\mathrm{Li}$ and ${}^{7}\mathrm{Be}$)

isotope: fixed Z (e.g., ${}^{6}\mathrm{Li}$ and ${}^{7}\mathrm{Li}$)

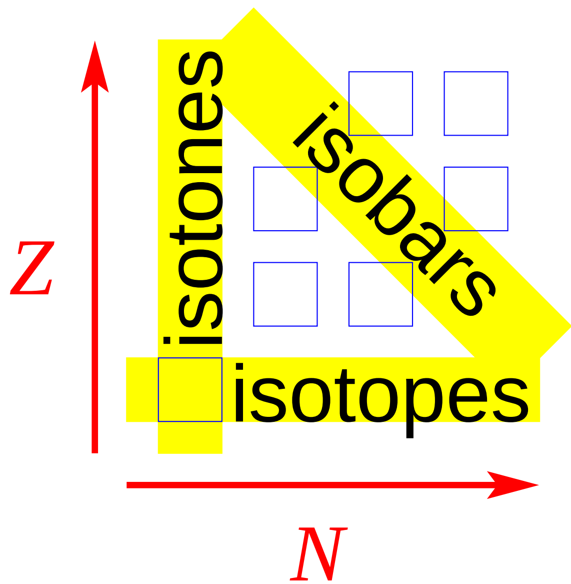
isotone: fixed N (e.g., ${}^{14}\mathrm{N}$ and ${}^{15}\mathrm{O}$)

Q: any Simpsons fans?

Q: isobar/tope/tone patterns on nuclide chart?



Meet the Chart of the Nuclides



now look at data for all known nuclei
color coded by stability/lifetime

`www: Chart of the Nuclides`

Q: what patterns do you notice?

Nuclei: Diversity and Regularity

first glance at chart of nuclides reveals **diversity!**

- huge numbers of known nuclei:
  many more than elements on Periodic Table
- generally many isotopes of each element Z
- generally many isotones for each N
- generally many isobars for each A

but also **patterns** emerge!

- at small A: stable nuclei have $N \approx Z$
  roughly equal neutrons and protons
- at large A: stable nuclei have $N > Z$
  stability requires extra neutrons
- but most known nuclei are unstable!
- *"valley of stability"* surrounded by peaks of instability
- lifetimes generally shorter the farther from valley

We will soon understand these trends!