Astro 350

Lecture 37

April 22, 2022

Announcements:

- **Final Homework due today!**
- **Student Presentations: next Mon Apr 25 to Mon May 2**
  information on Canvas
  sign up for a talk time using Canvas Calendar

Last time:

the birth of the lightest elements in big-bang nucleosynthesis

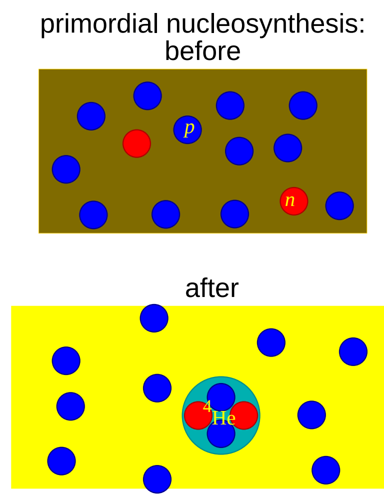
Q: what happens? leftover "fossils?"

Q: how does theory compare with observation? implications?

Big-Bang Nucleosynthesis Summary

Universe from 1 second to 3 minutes:
giant nuclear reactor
neutrons and protons $\rightarrow$ hydrogen, helium, traces of lithium

- mostly ordinary H and ^{4}He
- traces of deuterium and ^{3}He

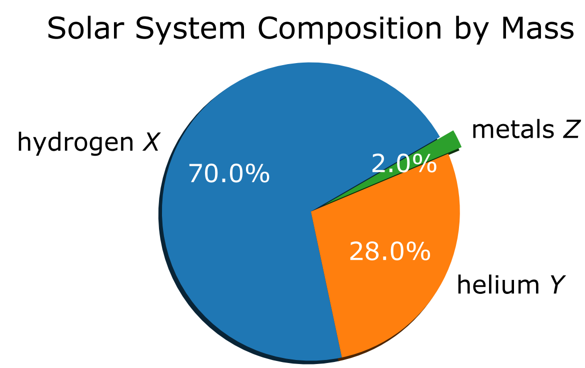


detailed predictions agree with observations!

Origin of the Elements

primordial H and He are most of “ordinary” (baryonic) matter
heavier elements (“metals”) made mostly in stars
heaviest elements also from neutron star mergers
`www: astronomer's periodic table`

Lessons:
⋆ most *atoms* in the Universe
are *primordial* H and He
⋆ the diversity of *elements* in the Universe
is mostly due to *stars*



Big Bang Nuke: Implications

big bang working well back to 1 sec!

observed lite elements select baryon density
$\Rightarrow 0.040 \lesssim \Omega_{\rm B} \lesssim 0.050$

1. $\Omega_{\rm B} \ll 1$: most of the cosmos isn't atoms

2. $\Omega_{\rm lum} \sim 0.007 \ll \Omega_{\rm B}$: most atoms unseen
baryonic dark matter

3. $\Omega_{\rm matter} \approx 0.3 \gg \Omega_{\rm B}$: most dark matter isn't atoms
non-baryonic dark matter

4. cosmic neutrinos abundant, but with ν mass data:
$\Omega_{\rm matter} \gg \Omega_{\nu}$: most dark matter isn't neutrinos

The Very Early Universe

CMB success $\Rightarrow$ understand Univ at $t \sim 400,000$ yr
$z \sim 1100$ and $T \sim 3000$ K

BBN success $\Rightarrow$ understand Universe at $t \sim 1$ s
$z \sim 10^{10}$ and $T \sim 10$ billion K

success gives confidence:
boldly extrapolate to $t \ll 1$ s
and $T \gg 1$ MeV

Q: what are conditions like?

Very Early Universe: Microscopic Conditions

at times $t \ll 1$ sec Universe was extremely **hot** and **dense**

hot: particles collided with extremely high energy
dense: particles collided very frequently

consider an early time with temperature so high that:
particles collide with kinetic energies $E_{\text{kin}} > m_{\text{electron}} c^2$

Q: what can happen?
Q: how can we recreate those conditions today?
Q: what if temperature even higher?

Early Universe: Particle Production

high temperature $\rightarrow$ high particle kinetic energies

if collision between particles with kinetic energies $E_{\rm kin} > m_{\rm electron} c^2$
there is enough energy to *create a new electron!*
because $E = mc^2$: mass and energy can be converted to each other!

we see this all the time the the laboratory
accelerate protons or electrons to high energies and collide them
many new particle created! `www: CERN LHC events`

implications:
the hot, dense Early Universe was a soup of particles!
some stable, some unstable
the stable ones remain today
and so *the Early Universe was a giant particle accelerator!*
particle properties control the nature of the earliest times!

Antimatter

Fundamental result of Special Relativity + Quantum Physics
every particle has an antiparticle
e.g., $\overline{e^-} = e^+$ positron
e.g., $\bar{p} =$ antiproton
Fermilab: $p + \bar{p}$ collisions

mass: same for particle an antiparticle $m(\bar{x}) = m(x) \geq 0$
electric charge: opposite $Q(\bar{x}) = -Q(x)$
combine $x + \bar{x} \rightarrow$ energy $\rightarrow$ other particles: annihilation
energy release: $E = m_x c^2 + m_{\bar{x}} c^2 = 2 m_x c^2$

in hot early Universe: when $E_{\text{avg,particle}} > 2 m_e c^2$
∞ particle collisions violent enough to create $e^+ e^-$ pairs
early universe full of matter and antimatter

Cosmic Matter vs Antimatter

so far: assumed that universe only had normal matter

But we know:

- antimatter exists
- the U went through a hot big bang

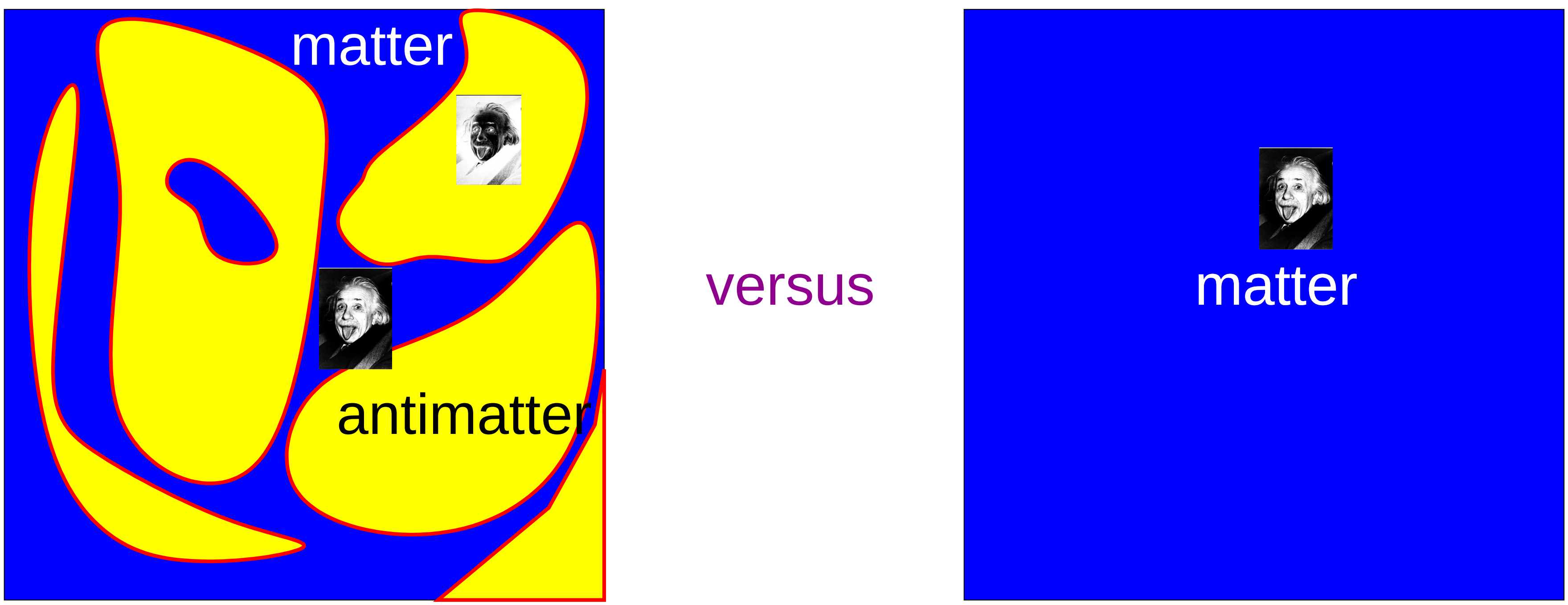
$\rightarrow$ antimatter should have been created abundantly!

Major question: where is it?

in other words–particle physics + cosmology forces choice:

▷ is the universe only matter–and if so, why?

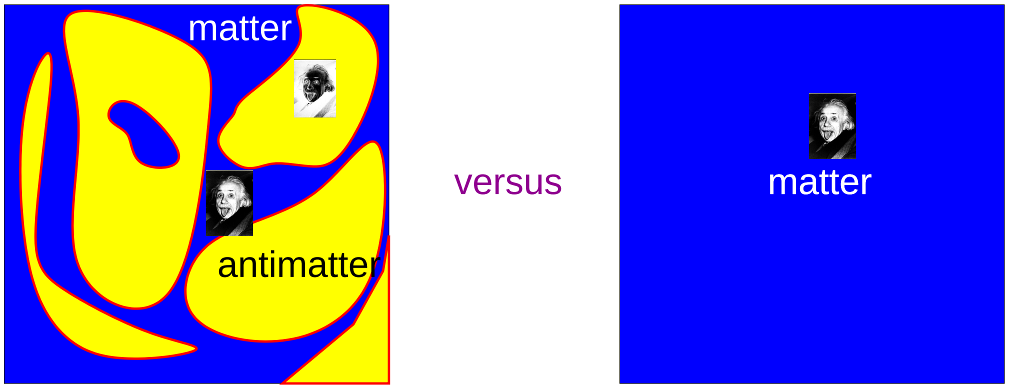
▷ is the universe made of "domains" of matter and antimatter ...and if so, why?



iClicker Poll: Antimatter

Vote your conscience!

What is the matter/antimatter layout of our Universe?



A *equal* amount of regions with matter or with antimatter
on average, matter/antimatter symmetric and "democratic"

B *entirely matter*, *no* regions of antimatter
"bias" against antimatter

Antimatter in Our Universe

A democratic universe:
Imagine U made of domains of matter (protons & electrons) and antimatter (antiprotons and positrons)
Q: what would life be like in the anti-regions? How would it differ from life here?

Searching for antimatter:
what **observable evidence** tells us:

- *Are there antimatter domains in this room?*
- *...on the Earth?*
- *Is the Moon matter or antimatter?*
- *...the Sun?*
- *...other solar system bodies?*
- *Is the local solar neighborhood matter or antimatter?*
- *Are there domains in our Galaxy?*
- *Are galaxy clusters matter/antimatter combinations?*
- *What about the observable universe?*

Observed Matter (Baryon) Asymmetry of the Universe

cosmic asymmetry: matter dominates over antimatter

Matter-only System	Evidence
Solar system	landings, meteors/comets, solar wind, proto-$\odot$ n
Cosmic rays	direct detection
MW Galaxy	cosmic rays, no annihilation γs
Galaxy clusters	no γ from galaxy-intracluster gas interface
	$\Rightarrow$ all matter or all antimatter
Hubble volume	too few 1–10 MeV γ, no CMB distortion

if antimatter domains, exit they must segregated from matter
on mass scales $\gtrsim 10^{14} M_{\odot}$
and probably length $> d_H = c/H \sim 3$ Gpc

Conclude: the universe is made of matter only!

The Matter Excess–How Much?

More particle physics:
baryons n, p not elementary–made of quarks!
in fact: baryon=3 quark system
$p = uud$, $n = udd$, $u, d =$ "up, down" quarks

Early universe was quark/antiquark soup
where quarks slightly outnumbered antiquarks

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

for every 6 billion $\bar{q}$, there were 6 billion + 1 q
excess tiny –but crucial!

annihilation $\rightarrow$ baryons today
Q: what about the photons?
where are they now?

annihilation photons are CMB today!

$\rightarrow$ tiny baryon-to-photon ratio a result of
tiny matter/antimatter asymmetry in early U!

Particle Physics Today: Success and Its Discontents

Current theory of elementary particles:
"the Standard Model of Particle Physics"

all known particles explained in terms of

- matter particles in "families" of quarks and "leptons" (e, ν and cousins)
- interacting with four fundamental forces: gravity, electromagnetism, and the nuke and weak forces
- with forces "carried" by another set of particles i.e., photons and cousins

The Standard Model: Report Card

How does this stack up against experiment?

extremely (annoyingly!) successful theory $\Rightarrow$ *no* known disagreement with experiment!

- all expected particles discovered after Higgs found July 2012

  ...more on Higgs soon...

- all measured particle properties behave as expected
  e.g., e^- magnetic moment $(g-2)$ measurement
  agrees with theory to 1 part in 10^{10}!

- But: Standard Model only tested in lab
  to LHC energies $E = 8\,\mathrm{TeV} = 8 \times 10^{12}\,\mathrm{eV} = 8000\mathrm{m_p c^2}$
  roughly the kinetic energy of a housefly...but all in one particle

- And: Standard Model begs the questions:
  why the patterns of particles we see?
  why four forces are they unified (like E&M are)?
  where does mass come from?
  why is matter one class of particles (fermions)
  and force carriers another (bosons)?

Standard Model a "victim of its own success"
carries the seeds of its destruction/supplanting

To address these questions: *new particle theories proposed*
that go beyond the Standard Model
to give possible answers to these questions

as a by-product, new theories *postulate/invent new particles*:

- almost always high-mass ($m \gtrsim 1$ TeV $= 1000\ m_{\rm proton}$)
- almost always weakly interacting
  (at "low" energies = Fermilab/CERN)
- note: invented to fix particle problems,
  not with cosmology in mind (no ulterior motive!)

Today: new particles hard to make
But in early U: created everywhere!
Q: possible fossils today? what conditions needed?

The Heavenly Accelerator and Dark Matter

If exotic massive particles exist
$\rightarrow$ created in early universe

If stable: remain today
$\rightarrow$ natural candidates for **dark matter**
bonus: naturally weakly interacting

"just what the doctor ordered"
Weakly Interacting Massive Particles: WIMPs!
key point: not invented for cosmology
but for particle physics reasons

So: if particle theorists are right:
can't *avoid* a U filled with crazy WIMPs

iClicker Poll: WIMP Status

Many cosmologists (including your instructor) believe dark matter = weakly interacting massive particles: WIMPs

Vote your conscience!

Right now do we have any real evidence for WIMP particles?

A No–and there never will be because weakly interacting particles are impossible to detect.

B No, but it is possible to detect WIMPs, so maybe they don't exist.

C Maybe!? There are conflicting claims and hints of WIMPs

D Yes! WIMPs have been discovered!

Direct Detection of WIMPs

Difficult! ...but not impossible

weakly interacting $\rightarrow$ experiments similar to ν detection
- go underground
- expect small count rate ($\lesssim$ few events/month)

`www: WIMP experiments`

WIMP-nucleus collisions: nucleus recoils with ~ 1 keV
measure recoil energy: cryogenic detectors

strategy: look for annual variations
$\vec{v}_{\rm WIMP} = \vec{v}_\odot + \vec{v}_{\rm Earth,orbit}$
$\rightarrow$ velocity has time change due to earth orbit
$\rightarrow$ modulation in 1-year period, amplitude $v_{\rm Earth} \sim 10\% v_\odot$

Direct WIMP Search Results

1998: Italian experiment (DAMA) claims evidence!

by now: claim evidence is strong

- very controversial result!
- most competing groups don't see signal
- could be different WIMP interactions for different nuclei
- ...or could be false alarm

How to resolve dispute? Better experiments

- will be coming online
- either will find WIMPs, or rule out favorite theories
- stay tuned!

Indirect WIMP Searches

In early Universe: WIMPs expected to be created in pairs
energy $\rightarrow$ WIMP + anti-WIMP
actually, in many theories anti-WIMP = WIMP: their own antiparticle!

today: if WIMPs and anti-WIMPs meet
they annihilate, and produce Standard Model particles
that is, particles we *can* detect

Q: where are annihilations most likely to occur?
Q: how might we find evidence that this has happened?

WIMP Annihilation Signatures

WIMP annihilations most likely where WIMPs most abundant
so that they can most easily collide
$\rightarrow$ regions of highest WIMP concentration
$\rightarrow$ regions of highest dark matter density
$\rightarrow$ *centers of galaxies*

So: look for WIMP annihilation products at centers of galaxies!
$\rightarrow$ high-energy particles

2012: *Fermi* gamma-ray space telescope
claimed to see unexplained gamma-ray signal!
- coming from our Galactic center
- at energy 130 GeV $\approx 150 m_p c^2$

Controversial claim! Possibly an instrumental problem!
not clear what is going on! stay tuned

Lineup of Dark Matter Suspects

~~hot gas~~
~~cold gas~~
} ~~diffuse ordinary matter: gas~~

~~black holes~~
~~neutron stars~~
~~white dwarfs~~
~~brown dwarfs~~
~~planets: "Jupiters"~~
} ~~clumpy ordinary matter:~~ compact objects = dead and failed stars

~~neutrinos~~
relic particle from early U
} diffuse matter: exotic particles

relic particles like WIMPs are only candidates left!

Will either be detected soon, or back to drawing board

$\rightarrow$ *these are exciting times for dark matter!*