Astro 350
Lecture 36
April 20, 2022

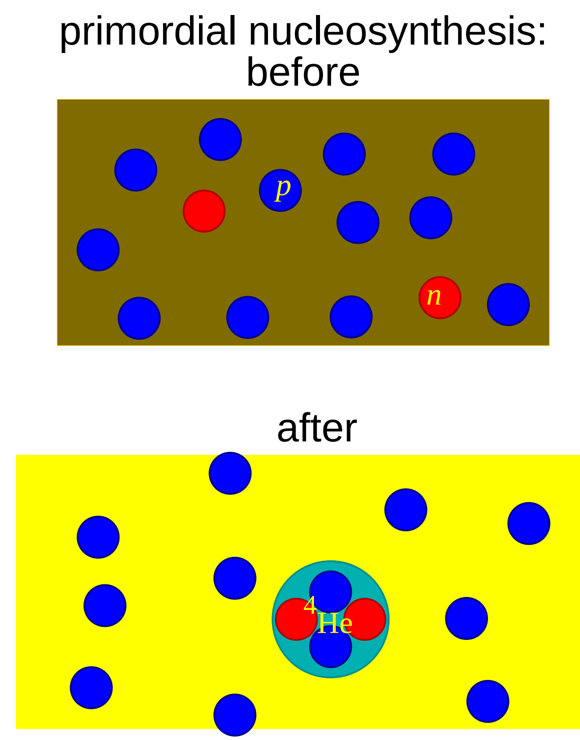
Announcements:

- **Final Discussion due today** Big Bang vs Steady State
- **Final Homework due Friday**
- **Student Presentations: next Mon Apr 25 to Mon May 2**
  information on Canvas
  sign up for a talk time using Canvas Calendar

Last time: cosmic microwave background success
a picture of the Universe when atoms first formed
allows measurement of cosmic geometry: Euclidean!
Big bang working well back to $t = 400,000$ yrs

Heartened by this success, we push back earlier!

Primordial Nucleosynthesis



Primordial nucleosynthesis,
a.k.a. Big bang nucleosynthesis (BBN):
production of lightest elements H, He, Li
in the early U.

transition from "ionized" free n and p
to "neutral" bound nuclei, largely ^{4}He

Initial conditions: $t < 1$ sec, $T < 10^{10}$ degrees

- **radiation**: sea of high-energy photons and neutrinos
- **matter** only n, p, and e
- dark matter and dark energy present but unimportant

Primordial Nucleosynthesis: Element Production

as the universe expands and cools,
n and p collisions weaker than $d = \boxed{np}$ binding
$\rightarrow$ at last d can survive: $n + p \rightarrow d$
then can combine d with n, p, and d to make heavier things
`www: reaction network`

flow $\rightarrow$ most stable (tightest binding) = $\boxed{^4\text{He}}$
essentially all $n \rightarrow {}^4\text{He}$
BBN result: 25% of baryons in He, leftover $p \rightarrow$ H (75%)
small traces of unburnt D, ^{3}He, ^{7}Li:
amounts depend strongly on density of nuclei ("*baryons*")
`www: Schramm plot`

Nothing heavier than lithium made–why?

Nuclear Freeze

nothing heavier than Li:

- no stable nuclei with masses $5, 8$
  $\Rightarrow$ don't make anything from $p + {}^4$He or ^{4}He $+ {}^4$He

- cooling universe $\rightarrow$ weaker collisions
  but combining nuclei with large charge
  requires large energy to overcome electrical repulsion

result: nuclear reactions shut down after lithium production
...and not even much of that!
"freezeout of strong interactions"

BBN Predictions: Executive Summary

Q: what are main predictions? qualitatively, quantitatively?

Q: where, when do they apply?

Q: what predictions "robust"/unavoidable?

Q: what would be involved in testing the predictions?

Q: what would it mean if BBN predictions confirmed? if not?

Q: what assumptions went into the calculation? ("Standard BBN")

Q: i.e., regarding dark matter? dark energy? neutrinos? additional element ary particles?

BBN: Observations

to test BBN: measure primordial abundances

look around the room–not 75% H, 25% He.
Q: is this a problem? Why not?

matter in solar system: mostly in Sun–mostly H, then He
but: still have heavy elements
Q: is this a problem? Why not?

Q: so how test BBN? What is the key practical issue?
Q: when in cosmic history do we expect
the first "complications"?

BBN: Observations–Idealized

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The past isn't dead.  It isn't even past.
  -- Cosmologist William Faulkner
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BBN theory: after the first three minutes
the universe filled homogeneously with
H, He, and a little Li
$\rightarrow$ these remain to this day as "fossils"
of nuclear reactions in the early universe
$\rightarrow$ evidence from the early U is all around us!

Assessing BBN: Theory vs Observations

BBN Theory:

- always get about 25% helium, 75% hydrogen

→ amounts are nearly *independent* of amount (density) of baryons in the Universe

- but the trace amounts of deuterium and lithium (and ^{3}He) *do* depend strongly on baryon density ρ_{B}

So: can measure amount of deuterium
and this *tells us* the density of baryons
→ that is, deuterium "measures" the amount of ordinary matter in the Universe!

Big-Bang Nucleosynthesis: Implications

cosmic abundances of light elements depends on
cosmic density of neutron and protons ("baryons")
i.e., density of all "ordinary" matter

Deuterium (and helium) tell us that $\Omega_{\rm B} = \rho_{\rm B}/\rho_{\rm crit}$ in range

$$0.040 \lesssim \Omega_{\rm B} \lesssim 0.050 \tag{1}$$

$\rightarrow$ baryon density is 4% to 5% of critical density

recap: extrapolated big bang to $t = 1$ s, predicted lite elts
kinda amazing: not only qualitative agreement ("lotsa helium")
but even detailed quantitative agreement with observations!
Cosmo bragging rights: BBN is earliest probe!

Q: What does this tell us?

BBN: Implications

Qualitatively

extrapolated big bang to $t = 1$ s

predicted lite elts $\rightarrow$ agreement with observations

big bang working well back to 1 sec!

Quantitatively

observed lite elements select baryon density

$\Rightarrow 0.040 \lesssim \Omega_{\mathrm{B}} \lesssim 0.050$

1. $\Omega_{\mathrm{B}} \ll 1$: baryons don't close the U.

2. $\Omega_{\mathrm{lum}} \sim 0.007 \ll \Omega_{\mathrm{B}}$

baryonic dark matter hot (10^{6-7} K) intergalactic gas?

3. $\Omega_{\text{matter}} \approx 0.3 \gg \Omega_{\text{B}}$:

non-baryonic dark matter

confirms: **most dark matter** is **not**
made of atoms of any kind in any arrangement!
$\rightarrow$ must be exotic form of matter!

known matter = anything on the periodic table
is a tiny fraction of the makeup of the cosmos!

4. Note: Big bang nuke theory assumed early Universe
was filled with a sea of **neutrinos**

- needed to set the initial amounts of n and p
- huge numbers! about as abundant as CMB photons!

$\rightarrow$ these neutrinos should be leftover today!
Q: why is this a big deal?

Neutrinos as Dark Matter

Neutrinos have mass and interact weakly
if they are everywhere: *neutrinos could be the dark matter*

And using big bang nuke we can predict precisely
the amount (number) of neutrinos today

but what counts is the gravity from neutrinos, set by
their *mass density* today
$\rightarrow$ need to know masses of neutrinos!
...which we don't know!

But: we know enough! Experiments show
• neutrinos do have mass
• each neutrino's mass is less than $0.000001 m_e$
this gives $\Omega_\nu \leq 0.01 \approx \Omega_{\text{luminous}} \ll \Omega_{\text{matter}}$
Q: and so?

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 particles from big bang
} diffuse matter: exotic particles

List is getting short!

Early Universe Cosmology Scorecard

Recall strategy:

- inventory universe today
- extrapolate back to early epochs
- apply known laws of nature to expanding, cooling U
- identify observable consequences (“fossils”) persisting today
- measure fossils $\rightarrow$ learn about early U!

Cosmo Report Card

Epoch	Recombination	Big Bang Nuke
cosmic time t	$\sim 400,000$ yr	$\sim$ 1 sec–3 min
micro-processes	nuclei+e $\rightarrow$ atoms	p+n $\rightarrow$ nuclei
predicted fossils	thermal radiation	baryons $\rightarrow$ H, He, Li
observed?	Yes! $\rightarrow$ CMB	Yes! $\rightarrow$ primordial abundances
grade	A	A

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 $E_{\text{kin}} > m_{\text{electron}}c^2$
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; LHC: $p + p$ collisions

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

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

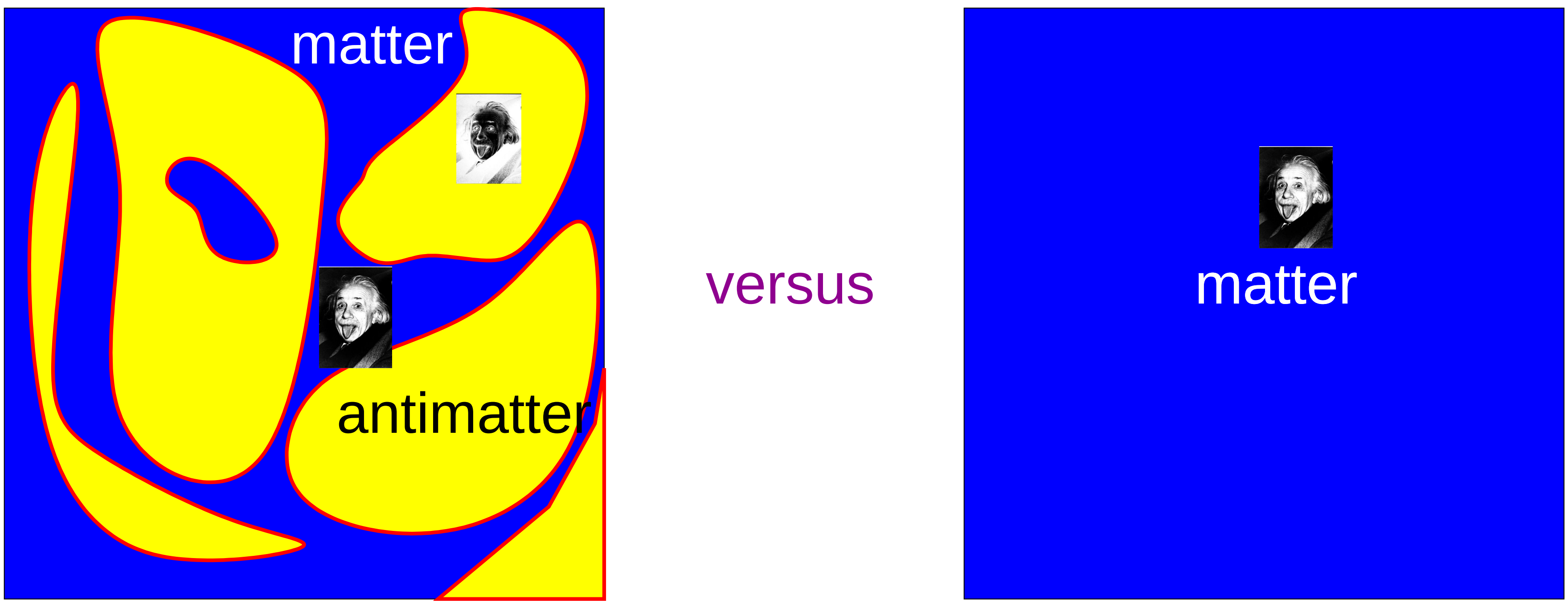
$\rightarrow$ antimatter should have been created abundantly!

Major question: where is it?

in other words–particle physics + cosmology forces choice:

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

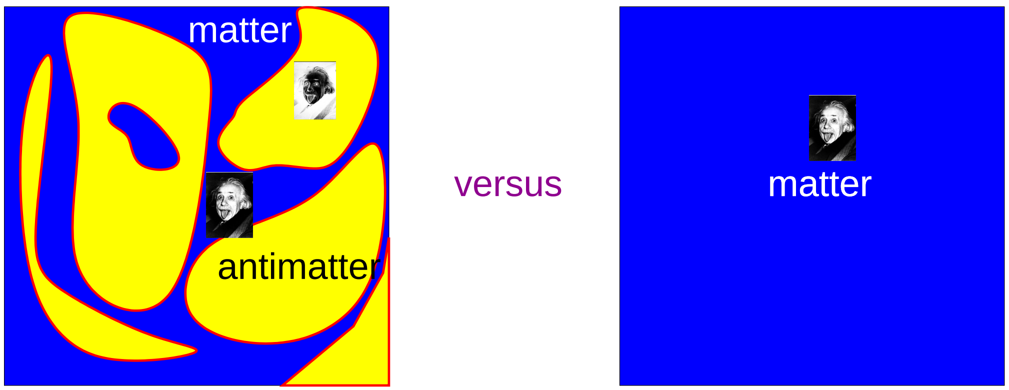
▷ is the universe made of “domains” of matter and antimatter ...and if so, why?



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!

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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

$$\frac{n_q - n_{\bar{q}}}{n_q + n_{\bar{q}}} \sim \frac{n_B}{n_\gamma} \sim 6 \times 10^{-10} \tag{2}$$

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!

Director's Cut Extras

BBN: Observations–Hard Reality

BBN theory: universal composition after ~ 3 minutes
observations: abundances in real astro systems, billons of yrs later

the first non-BBN nucleosynthetic processing:
$\rightarrow$ when first stars turn on
`www: circle of life`

problem: stars change lite elt abundances $\rightarrow$ "pollution"

the solution:
Q: how to address this problem?
Q: if can measure abundances in a system, can you unambiguously tell that stars have done some polluting?
Q: how to tell observationally which systems least polluted?

stars also make heavy elements

stellar cycling: $\boxed{\text{metals} \leftrightarrow \text{time}}$

$\rightarrow$ measure lite elts and **metals**

low metallicity $\rightarrow$ more primitive

at 0 metals $\rightarrow$ primordial

Helium-4

He atoms: tightly bound atoms, hard to excite electrons
$\rightarrow$ need relatively high energies to make observable lines
$\rightarrow$ need hot environment with strong collisions
$\rightarrow$ superheated gas in environment of massive, hot stars

need hot, metal poor gas:
$\rightarrow$ metal-poor, dwarf irregular galaxies
`www: I Zw 18`
Transp: *He emission lines*

$Y = \rho(^4\text{He})/\rho_{\text{baryon}}$ and $Z = \rho(\text{metals})/\rho_{\text{baryon}}$
$\Rightarrow$ correlated
What correlation do you expect?

Transp: Y *vs* Z
Q: significance of features?

Helium-4 Data: Trends and Implications

Data best fit by

$$Y = Y(Z) \simeq Y_0 + \frac{\Delta Y}{\Delta Z} Z \tag{3}$$

slope $\Delta Y/\Delta Z$: stellar nuke
(avg stellar "helium per metal" output)
intercept $Y_0 = Y_p$: cosmology (primordial He!)

combining all data: infer primordial abundance

$$Y_p = 0.249 \pm 0.009 \tag{4}$$

i.e., observe 24.9% of ordinary (baryon) mass to be in ^{4}He