Astro 350
Lecture 34
April 15, 2022

Announcements:

- **final Discussion due Wednesday** 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

Q: why cosmic? microwave? background?

Q: what cosmological information does it give us?

Relativity and Cosmology: The Curvature of Space

Recall Friedmann "energy" equation

$$(\text{expansion rate})^2 = H^2 = \frac{8\pi}{3}G\rho - \frac{K}{a^2} \quad (1)$$

Newton: K corresponds to $-$(total energy)

Einstein General Relativity:

K measures the *curvature of space!*

(if nonzero: $K = \pm c^2/R^2_{\text{curv}}$)

- $K > 0 \rightarrow$ positive curvature
- $K < 0 \rightarrow$ negative curvature

$K = 0 \rightarrow$ no curvature ("flat")

Q: what does it mean for space to be curved? Geometry!

Geometry of the Universe

⋆ $K > 0$ positive curvature, roughly: "like a sphere"
parallel lines eventually meet!
triangle angles sum $> 180°$;
volume finite ("closed" universe)

⋆ $K < 0$ negative curvature, roughly: "like a saddle"
parallel lines eventually diverge!
triangle angle sum $< 180°$;
volume $= \infty$

⋆ $K = 0$ no curvature: "flat," geometry Euclidean
parallel lines keep same distance
triangle angle sum $= 180°$;
volume $= \infty$

Einstein: **geometry is experimental question** *Q: how anwer?*

The CMB and Cosmic Geometry

the CMB is a cosmic goldmine!
example: geometry

CMB and cosmic triangles

- CMB fluctuations have all sizes
  but largest on scale $d_{\text{horizon}} \approx ct_{\text{recom}}$
- fluctuations of this size $\rightarrow$ *isosceles triangle*

NASA WMAP (2003):
can measure angular size θ of fluctuations
see if triangle has angle sum 180° or not

`www: WMAP diagram`

iClicker Poll

vote your conscience!

WMAP 2003: measured geometry of Universe

Which did they find?

A positive curvature: "spherical"

B no curvature: "flat" = Euclidean

C negative curvature: "hyperbolic"

The Geometry of the Universe

WMAP 2003: no measurable evidence for curvature!
either positive or negative!

Best fit to data: **geometry Euclidean = flat!**
volume infinite!

more technically:
curvature, "radius" $> 100 \times$ size of observable U
(flat $\Leftrightarrow$ curvature radius $= \infty$)

also note:
from Friedmann: if $K = 0$, then $\rho = \rho_{\text{crit}}$ now and always!
this is how CMB tells us $\Omega = 1$ today

These results cry out for explanation!

Early Universe Cosmology Scorecard

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

First attempt–the “atomic age”

Inventory:
hydrogen gas and blackbody radiation in expanding U

Predictions:
atoms: expect transition when particle energies $\approx$ atomic binding
$\Rightarrow$ recombination: ionized $\rightarrow$ neutral
matter+radiation: photon-electron scattering
$\Rightarrow$ loss of free e^-: opaque $\rightarrow$ transparent

Observable consequence: *fossils of the cosmic atomic age*
"liberated" photons persist $\rightarrow$ observable today

The Test: look for thermal radiation

- CMB detected! thermal, nearly isotropic
- bonus–fluctuations $\rightarrow$ cosmo parameters, "seeds" for structure

Bottom line:
extrapolated back to redshift $z \sim 1000$!
$t \sim 400,000$ yr $\sim 0.00003 t_0$! 99.997% of the time to big bang
big bang working extremely well!
gives confidence to push back farther!

Q: next stop?
Hint: pre-recombination, U ionized $\rightarrow$ atoms ripped apart
Q: as collisions more energetic, what's next to be smashed?

After recombination (e.g., now)

- nuclei and electrons bound together as atoms

Before recombination ($t < 400,000$ yrs)

- nuclei and electrons unbound, free $\rightarrow$ at recombination: atoms first born!

What breaks next?

- electrons: no known substructure
  i.e., not "made of pieces" but truly indivisible!
- nuclei: definitely made of pieces!
  protons and neutrons!

So expect another transition *before* recombination
"ionized" protons and neutron $\rightarrow p, n$ bound in nuclei
at transition: nuclei first born!
big bang nucleosynthesis

Prelude to Nucleosynthesis

consider an atomic nucleus, e.g., ^{4}He$= \boxed{2p + 2n}$

Naively, expect it to fly apart

Q: why?

Q: why doesn't it?

Q: what does this imply about things made of n, p = baryons*?*

The Nuclear Force and Nuclear Structure

In nucleus:
Electrical repulsion between protons (like charges)
but stable: repulsion overcome by attractive force
nuclear force between p, n ("baryons")

How strong?
nuclei: size $r_{\text{nucleus}} \sim few \times 10^{-15}$ m $\approx 10^{-5} \text{r}_{\text{atom}}$
2 p electric repulsion at $r = 10^{-15}$ m

$$E_{\text{electromagnetic}} = \left[\frac{1}{4\pi\epsilon_0}\right] \frac{e^2}{r} = 1.4 \times 10^6 \text{eV} = 1.4 \text{ MeV} \qquad (2)$$

$\sim$ million times atomic binding!

The Nuclear Force and Nuclear Structure

In nucleus:
Electrical repulsion between protons (like charges)
but stable: repulsion overcome by attractive force
nuclear force between p, n

nuclei are quantum objects governed by nuclear force
i.e., like "juiced" atoms, with stronger force

- still energy levels: ground, excited states
- stronger force $\rightarrow$ much much larger binding energy BE
  i.e., "sticking strength" $=$ energy input to rip apart
- still unbound if given energy $> BE$

The Ties that Bind

Nuclear force + quantum levels
$\rightarrow$ determines binding of each nucleus
`www: chart of nuclides`

weakest binding: deuterium $d =$ n+p

strongest binding in a light nucleus (below carbon):
^{4}He = 2n+2p
^{4}He = α "alpha particle" tighly bound = *very stable*
consequently, *no stable nuclei at mass 5, 8*
"would rather be alphas!"
mass 5 decays $\rightarrow \alpha + n$ or p
mass 8 decays $\rightarrow 2\alpha$

Cosmic Lingo: Fancy Name for Ordinary

neutrons and protons are not elementary
$\to$ both made of 3 quarks
other 3-quark particles exist, but are unstable
$\to$ decay to n or p

any particle made of 3 quarks: **baryon**
`www: lists of known baryons`

in practice: under most conditions, baryons $=$ n or p
or things made of n and p: atoms, people, stars, galaxies

so: to cosmologists
baryons $=$ "made of atoms" "ordinary" matter $\neq$ dark matter

Primordial Nucleosynthesis

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

extrapolate expanding U, containing matter, radiation
back to $t \sim 1$ sec $\rightarrow$ U is giant nuke reactor!

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

Q: at high (but not ultrahigh) T, what are cosmic ingredients?

Primordial Nucleosynthesis Initial Conditions

time $t < 1$ sec, temperature $T > 10^{10}$ K = 10 billion degrees

radiation

- "CMB" photons now gamma rays!
- also a sea of cosmic neutrinos!

radiation density huge!

$\rightarrow \rho_{\text{radiation}} \gg \rho_{\text{matter}}$ opposite of situation today
"radiation-dominated era"

matter

- ordinary (known) matter: only n, p, and e
  collisions too violent for complex nuclei
  and certainly much too violent for atoms
- dark matter: must be around, but weakly interacting

dark energy

must also be around, but if Λ-like, unimportant

iClicker Poll: Cosmic Fusion

primordial nuke: transition from free n, p
to bound nuclei, through a series (chain) of reactions

Starting from p and n only, which nucleus is made first?

A deuterium: $d = \boxed{np}$

B helium-3: $^3\text{He} = \boxed{npp}$

C helium-4: $^4\text{He} = \boxed{nnpp}$

D lithium-7: $^7\text{Li} = \boxed{3p, 4n}$

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 $p + {}^4\text{He}$ or ${}^4\text{He} + {}^4\text{He}$

- 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
→ these remain to this day as "fossils"
of nuclear reactions in the early universe
→ evidence from the early U is all around us!

BBN: Observations–Hard Reality

BBN theory: universal composition after ~ 3 minutes, $z \sim 10^9$
observations: abundances in real astro systems, redshifts $z \sim few$

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

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!

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

$$0.040 \lesssim \Omega_{\rm B} \lesssim 0.050 \tag{3}$$

$\rightarrow$ 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!

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

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

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

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

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

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

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!

Director's Cut Extras

Helium-4

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

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

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

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

Helium-4 Data: Trends and Implications

Data best fit by

$$Y = Y(Z) \simeq Y_0 + \frac{\Delta Y}{\Delta Z} Z \quad (4)$$

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

$$Y_p = 0.249 \pm 0.009 \quad (5)$$

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