Astro 406
Lecture 36
Nov. 20, 2013

Announcements:

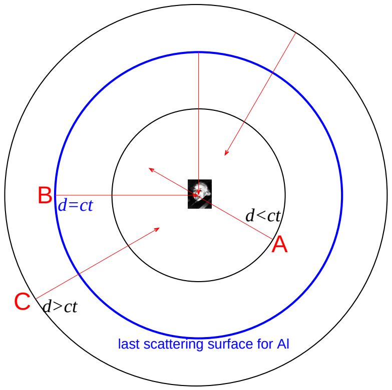
- **PS 11 due Friday** penultimate problem set!
  typo in eq. (4): T_{K} factor should read T_{K}^{4}
- Office Hours: today 1–2pm or by appt
  TA Office Hours: tomorrow 1–2 pm

Last time: the CMB, recombination, and last scattering

Q: where does a CMB photon "point back to"?

Q: when did CMB photons start their trip?

Universe today transparent to CMB photons
→ they pass through neutral hydrogen today
point back to *last scattering surface*



in early Universe: photons scattered off *free electrons*

- scattering stopped at *recombination*: $e + p \to \mathrm{H}$
- cosmic transition from *ionized → neutral*
  also the transition from *opaque → transparent*

thus: CMB is "baby picture" of the Universe at recombination
when $t \approx 400,000$ yrs

iClicker Poll: CMB Isotropy

the CMB is a picture of the Universe at $t = 400,000$ yr
$\to$ CMB is a map of cosmic T at last scattering surface

How isotropic is the CMB temperature on the sky?

A perfectly isotropic:
T precisely the same in all directions

B only sorta isotropic:
T fluctuations at $\sim 10\%$ level

C very isotropic:
T fluctuations at $\sim 0.1\%$ level

D fantastically isotropic:
T fluctuations at $\sim 0.001\%$ level

Q: what would anisotropies tell us?

CMB Isotropy

cosmo principle: U. homog, isotropic

if exact, CMB T exactly same in all directions

`www: CMB monopole, dipole, multipoles`

observe: CMB T **very** uniform!

→ U. very isotropic!

turn up contrast:

- "dipole": hotter on one side of sky, cooler on other

max diff $\Delta T = \pm 3.4 \times 10^{-3}$ K

→ $\Delta T/T \sim 10^{-3}$

interpretation:

Q: what do you think?

Dipole specifies an *axis*
really a redshift in one direction,
blueshift in another

★ dipole due to our motion w.r.t. cosmic frame
the Sun's "peculiar velocity" $v = 370$ km/s
Q: what would contribute to this peculiar velocity?

Q: what if you see fluctuations after *removing dipole?*

subtract dipole, then: *tiny fluctuations remain*

`www: COBE, WMAP, Planck`

occur at all angular scales

typical $\Delta T \sim 2 \times 10^{-5}$ K

$\Delta T/T \sim 10^{-5}$: tiny!

...but not perfectly isotropic

Q: what does this mean?

→ not perfectly homogeneous!

$\rho_{\text{rec}} \simeq \rho_{\text{matter}} \propto a^{-3} \propto T^3$

$$\frac{\Delta\rho}{\rho} = 3\frac{\Delta T}{T} \tag{1}$$

tiny density fluctuations at rec → “seeds” of galaxies, clusters, superclusters, you, me today!

Early Universe Cosmology Scorecard

Recall strategy:

- inventory universe today
- extrapolate back to early epochs
- apply known physics
- identify observable consequences ("fossils") that persist today
- measure fossils → learn about early U!

First attempt–the "atomic age"

Inventory:
hydrogen gas and blackbody radiation in expanding U

Physics predictions:
atomic physics: expect transition at $T \sim$ eV

$\Rightarrow$ recombination: ionized $\rightarrow$ neutral

matter+radiation physics: photon-electron scattering

$\Rightarrow$ loss of free e^-: opaque $\rightarrow$ transparent

Scorecard Continued

Observable consequence:
"liberated" photons persist → observable

The Test: look for thermal radiation
- CMB detected! thermal, nearly isotropic
- bonus–fluctuations → cosmo parameters, "seeds" for structure

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

Q: next stop?

The Early Universe and Particle Physics

CMB today:

$$E_{\rm peak,0} = hc/\lambda_{\rm peak,0} \sim 10^{-3}\ \mathrm{eV} \tag{2}$$

But $E_{\rm peak}(z) = (1+z)E_{\rm peak,0}$
high-z → high-E
e.g.: when $E(z) > m_e c^2$
→ $e^{\pm}$ pairs created
⇒ particle content of U changes
Early U ↔ particle physics

goes both ways: need particles to understand early U
but also can turn problem around – by understanding early U,
can learn something about fundamental physics
"The Universe is the poor man's accelerator."
– Cosmologist Yakov Zel'dovich

Nuclear Stability and Forces

Prelude: Cosmo/Particle Slang

baryon: a neutrons n, or a protons p,

...or anything made of them

i.e., all nuclei → 99.9% of all atomic mas

$\Rightarrow$ all "ordinary" matter (including neutron stars) is "baryonic"

will give more complete, quark-based definition soon

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

Q: ingredients?

Naively, expect it to fly apart

Q: why?

Q: why doesn't it?

Q: what does this imply about baryons?

The Nuclear Force and Nuclear Structure

In nucleus:
Electromagnetic repulsion between protons (like charges)
but stable: repulsion overcome by attractive force
nuclear force = **strong force** between p, n (baryons)

How strong?
nuclei: size $r \sim few \times 10^{-15}$ m = few fermi
(1 fermi = 10^{-15} m = "femtometer")
EM repulsion: 2 p at $r = 1$ fermi

$$V_{\mathrm{EM}} = \left[\frac{1}{4\pi\epsilon_0}\right]\frac{e^2}{r} = 1.4 \times 10^6 \mathrm{eV} = 1.4 \text{ MeV} \tag{3}$$

$\sim$ million times atomic binding!
nuke forces must be *stronger* than this!

Nuclei in a Nutshell

nuclei are quantum objects governed by strong force
i.e., like “juiced” atoms, with stronger force

- still energy levels: ground, excited states
- stronger force → larger binding energy $BE \sim few$ MeV
- still unbound if given energy $> BE$

Nuclear force + quantum levels → binding
weakest binding: deuterium $d = \boxed{\text{np}}$, $BE = 2.2$ MeV
strongest light nucleus (below carbon):

^{4}He $= \boxed{\text{2n+2p}}$ = “α particle, $BE = 26$ MeV

^{4}He so tightly bound, *no stable nuclei at mass 5, 8*
“would rather be alphas!”

mass 5 decays → $\alpha + n$ or p
mass 8 decays → 2α

The Cosmic Nuclear Age

in early Universe, strong/nuclear force important

Q: to zeroth order, when is epoch?

Q: what what universe like then? environment, particles?

Q: what transition(s) expected?

Q: what physical effects important? cosmo? microphysical?

Q: how quantify transition epoch?

Q: what fossils might be left over?

Q: how could we observe them?

Primordial Nucleosynthesis

Big bang nucleosynthesis (BBN): production of lightest elements
H, He, Li in the early Universe

extrapolate expanding U w/ matter, radiation
back to $t \sim 1$ sec → Universe is giant nuke reactor!

1950's: George Gamow
since early U. very dense
Q: what is densest object not a black hole?
→ all neutrons
expand: $n \rightarrow p + e^- + \bar{\nu}_e$ decay
$n + p \rightarrow$ *all elements made in first cosmic seconds!*
`www:` $\alpha\beta\gamma$ `paper`

Q: what flaw(s) in argument?

Enrico Fermi:

- big bang can't make all elements
- no stable nuclei with $n+p=5,8$ particles
- mass "gaps" stop flow

C. Hayashi:

- weak interactions (neutrinos) important
- initial baryon state *not* just neutrons!
- *Q: why? what is effect of energetic neutrinos?*

Note:

when $kT \sim$ MeV $\sim$ nuke binding

Q: are baryons (n, p) relativistic or not?

BBN: Theory

want to predict element “cooking”

Recipe:

follow weak, nuclear reactions
in expanding, cooling U.

$\boxed{\text{The Oven}}$: radiation dominated universe
$a^2 \propto t$, but since $T \propto 1/a$
$t \propto 1/T^2$

$$t = \left(\frac{1\ \text{MeV}}{kT}\right)^2\ 1\ \text{s} \tag{4}$$

so $kT = 1$ MeV $\rightarrow T \simeq 10^{10}$ K at $t \simeq 1$ s
Q: what is central temperature of Sun?
$kT \gg$ atom biding energy → U. ionized

$\boxed{\text{Ingredients}}$:

radiation: $kT < m_e c^2 = 0.5\ \text{MeV}, m_\nu c^2$

Q: so what does this mean? what is radiation?

$\rightarrow \gamma, e^{\pm}, \nu\bar{\nu}$ (3 species) relativistic

CMB now gamma rays!

matter: $kT \ll m_p c^2, m_n c^2 \simeq 1000\ \text{MeV}$

n, p non-rel; assume DM is too

also: since nuclear binding $\sim$ MeV, nuclei "ionized" too

$\rightarrow n, p$ only, no complex nuclei

key parameter: $n_{\text{baryon}}/n_\gamma \equiv \eta$

don't know yet, will solve for it

preview: $\eta \sim 10^{-9}$

$\Rightarrow$ billions of photons for every baryon!