Astro 350
Lecture 33
April 13, 2022

Announcements:

- **Discussion due Wednesday** – Anthropic Principle
- **Homework due Friday**
- FYI: Cosmology Colloquium in Physics: Wed 4pm, online
  Prof. Katherine Freese, U. Texas
  "The Cosmic Cocktail: Three Parts Dark Matter"

ASTR350:
Black Holes – check!
The End of the Universe – check!
The Big Bang the rest of the course

Q: where was the big bang?

A Puzzling Measurement

Spring 1965:

- Rev. Martin Luther King Jr leads marches on Selma AL
- Beatles play Shea Stadium
- first successful launch of unmanned Saturn I rocket
  nine Apollo Saturn V rockets went to the Moon 1968–1972
- astronomers Arno Penzias & Robert Wilson

were using radio telescope to study interstellar gas clouds

`www: Penzias and Wilson at Bell Labs`

made careful measurements, noticed that
when pointing radio telescope ("horn") away from clouds
signal readout dropped, but did *not* go to zero
no matter where pointing "off source"

Q: what are possible explanations?

What is all this noise?

Bell Labs radio telescope reads out nonzero signal even when pointed away from any sources

Possibilities:

Problem with telescope?

- instrumental noise?
  Penzias & Wilson carefully checked system
  characterized noise–too small to explain signal
- contamination/damage to antenna?
  scraped off pigeon droppings

Result: after careful checking
Penzias & Wilson could not explain away signal
$\rightarrow$ forced to conclude: **Signal is real!**

Penzias & Wilson reported their result
in 2-page scientific paper **`www: their paper`**
devoted to showing how they checked antenna noise
and which made not attempt to interpret signal

mysterious radio signal found to be :

- isotropic (as far as they could measure) *Q: meaning?*
- unchanging with seasons *Q: which implies what?*

Q: what other properties of signal would be useful to measure?

Mysterious Radio Signal

mystery signal does not change with seasons
$\rightarrow$ not related to Earth, or solar system
$\rightarrow$ comes from our Galaxy or beyond

in fact: all other know sources of radiation
observed to lie *in front* of this mystery signal

- signal comes from great distance: **cosmic**
- signal is **background** to all else

signal found in radio: electromagnetic radiation
$\rightarrow$ essential to measure *spectrum*
quickly done, found to have blackbody form! *Q: what's that?*
peak around $\lambda_{\rm max} \approx 1$ cm: **microwave**
which corresponds to temperature $T \approx 3$ K *Q: hot or cold?*

Q: what does this all mean?

Cosmic Microwave Background Radiation

mystery signal: cosmic microwave background radiation = **CMB**
Universe today filled with electromagnetic radiation

- **isotropic** – had to be! confirms cosmological principle!
- **blackbody** = thermal = has temperature

CMB temperature: present measurement

$$T_0 = 2.725 \pm 0.001 \text{ K} \quad (1)$$

note the high precision!
cosmic temperature known to within better than 0.05%!

spectrum: blackbody `www: CMB spectrum (FIRAS)`
purely thermal (so far): `www: CMB spectrum residuals`

CMB: enormously important cosmological clue and goldmine!
need to figure out what it means

The Early Universe

For the rest of the course: look back to the past
try to develop (and test!) understanding of what happened

Strategy: run the movie backwards

Inputs:
- known (or suspected) present contents of U
- known (or suspected) laws of nature

Output:
- "pre" dictions about the past behavior
- and consequences that are observable today

Q: present cosmic contents?
Q: how would each act in early U?

Looking Back

Cosmic Inventory: Universe today composed of

- radiation: blackbody, $T \sim 3$ K
- normal matter: mostly H and He
- dark matter: weakly interacting *Q: why?*
- dark energy: constant density (?)

Run movie backwards: in the past

▷ T higher

▷ radiation, matter hotter, denser

▷ dark energy unimportant (?)

normal matter: well studied in the lab!
known properties for different ρ, T
$\rightarrow$ use known physics to deduce
history of matter and radiation!

Temperature and Atoms

Universe has temperature! cold today, hotter in past

For a gas of atoms, as temperature goes *up*

What is affect on average atom?

A hotter = higher average speed, higher average energy

B hotter = lower average speeds, higher average energy

C hotter = higher average speed, lower average energy

D hotter = lower average speed, lower average energy

The History of Atoms

Today:

- normal matter* (i.e., made of atoms) is mostly gas
  mostly ($\sim 70\%$) hydrogen, with $\sim 28\%$ helium, 2% "metals"
- cosmic temperature $T \approx 3$ K
- cosmic average density very low:
  $\rho_{\text{crit}} \approx 10 m_{\text{hydrogen}}$/cubic meter

Q: how do atoms behave in these conditions?
Q: in past, higher T & ρ–what transition expected?
Q: what sets transition temperature?

*Tech lingo: "made of atoms (really, protons & neutrons)" = "baryonic"

The Atomic Age

laboratory atomic physics:
in atoms, electrons attracted, bound ("stuck") to nuclei
• takes energy input to rip apart, unbind
• well-defined "binding energy" needed to tear apart

So: in gas with particle energy $<$ atomic binding energy
i.e., $kT < E_{\text{bind,atoms}} \sim 1$ eV ($T \lesssim 10,000$ K)
$\Rightarrow$ electrons bound to nuclei: atoms!
i.e., electrically neutral gas particles

but if particle energy $>$ atomic binding energy
i.e., $kT > 1$ eV, $T > 10,000$ K
atoms ripped apart $\rightarrow$ gas of free e^-, nuclei
ionized "plasma" of charged particles
`www: laboratory hydrogen plasma`
more familiar plasma examples: flames, neon lights

Matter and Temperature: Haiku Version

As matter gets *hotter*
collisions *more violent*
ground to smaller bits

Cold   Hot

atoms $\to$ ions=e+nuclei $\to$ $n + p$ $\to$ quarks $\to$???

So the history of atoms in cosmos is:

- early Universe ($T > 10,000$ K) ionized
  no atoms could survive–torn apart
- but as cooled, became neutral
  atoms were stable, *had* to form
- so *must* have been a time of transition: key moment!
  the epoch of (re)combination
  plasma "condensation" $\rightarrow$ birth of atoms!

Procedure:

- follow physics of expanding, cooling H gas
  in bath of thermal radiation *Q: what is λ/color?*
- through ionized $\rightarrow$ neutral transition
- then ask ourselves: what observable traces ("fossils")
  would this leave behind? ("cosmic archæology")

Q: guesses?

inner space/outer space connection

Give me an atom, and I will construct the universe.
– Cosmologist (Full-Time!) George Gamow

Recall behavior of *cooling matter*:

Hot Cold
quarks → neutrons, protons, e → nuclei,e=plasma → atoms

Spoiler alert: this is the history of the Unvierse!

The atomic era
now radiation chilly $T \approx 3$ K; but hotter in past! $T \propto 1/a = 1 + z$
Q: hydrogen gas at low T? at high T?
Q: cosmic transition in gas? effect on radiation?

Thermal Radiation in the Early Universe

Recall: light $\leftrightarrow$ heat connection
namely: "glow" of object at T = blackbody radiation
peak emission (color): $T \propto 1/\lambda_{\text{peak}}$
but recall: photons have $E_\gamma \propto 1/\lambda$, so $T \propto E_\gamma$ (check!)

What color was the cosmic thermal glow?
When Universe $T \sim few 1000$ K, similar to $T_{\text{surface},\odot}$
$\rightarrow$ peak emission is visible to eye!
$\rightarrow$ you could have seen cosmic radiation
(but better wear the asbestos suit...)

Key issue:

- how do the thermal photons interact with the hydrogen?

In particular:

- how does light respond to a neutral vs ionized gas?

iClicker Poll: Light Through a Flame

Demo: pass projector light thru flame

How will the flame region look on screen?

A darker

B brighter

C same as rest of screen

Q: implications for cosmic recombination?

Early Universe

early U hotter, denser

- particle motions ever more energetic: $E_{\text{particle}} \propto T$
- more crowded $\rightarrow$ particle collisions more frequent, violent

Ordinary matter today:

cold U, hydrogen at 3K is neutral gas

but early enough: H ionized $\rightarrow$ free $p + e$ plasma

$\rightarrow$ at some time, had to be transition ionized $\rightarrow$ neutral

Cosmic radiation today:

doesn't interact with neutral H (only absorbed at special λ)

but when ionized: free e scatter photons efficiency

Demo: light through bigger flame than last time

Light Scattering in Gas vs Plasma

Neutral gas is (mostly) transparent
  e.g., look around the room – can see opposite side
  because neutral air molecules are (essentially)
  transparent to visible light

...but..

Ionized gas (plasma) is opaque
  e.g., can't see thru flame, neon light

Why?

▷ neutral atoms only absorb at characteristic λ ("lines")
  otherwise "ignore" light

▷ in plasma, free electrons abundant
  very strongly scatter light $\rightarrow$ photon path "scrambled"
  cannot see through electron "fog"

Implications for cosmology:

- cooling early universe undergoes transition from ionized to neutral
- and so also undergoes transition from opaque to transparent

Notice the inner space/outer space interplay:
$\rightarrow$ lab experiments on electron behavior set cosmic history!

Implications...
early universe uniformly filled with photons
Q: what are photon paths before *recombination?*
Q: what are photon paths after *recombination?*

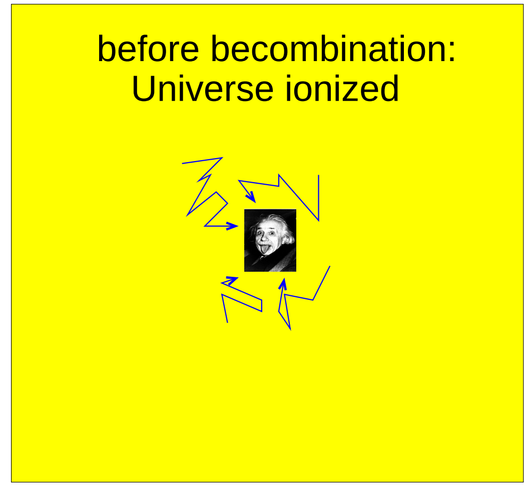
CMB: Photon Paths?

before recombination:

photons constantly scattered

can't travel far: "cosmic fog"

we see: only nearby sources



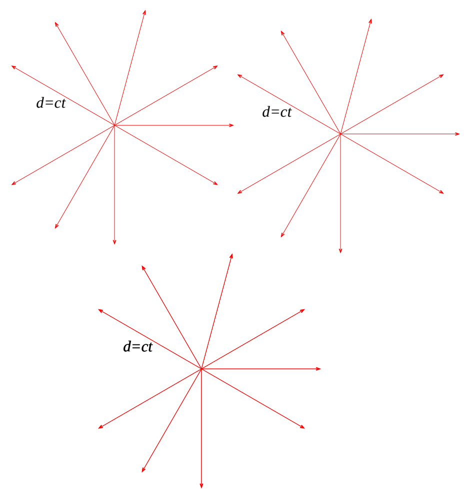
after recombination:

photons no longer scattered

travel freely: "the fog lifts"

at time t after:

travel distance $d = ct$

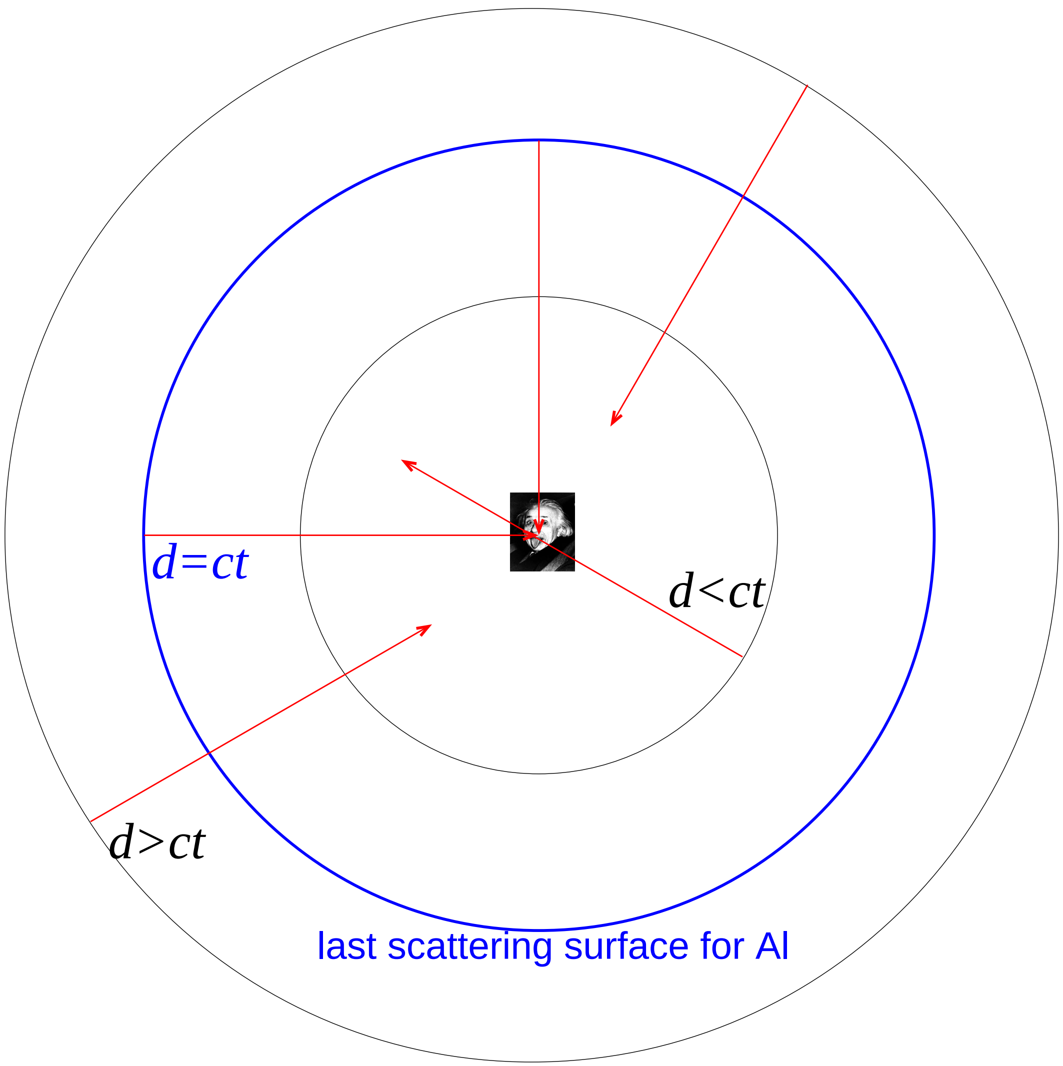


Q: which photons seen at t (where/when emitted)?

Q: what happened to the photons that were here at t_{recomb}?

*Q: who can see "our" photons now,
and where are these observers?*

Last Scattering Surface



at t, see sources at $d_{\text{ls}} = ct$

surface of last scattering

"edge of observable universe"

iClicker Poll: The End of the CMB?

Will there be a time when we *cannot* see any more CMB photons?

A yes

B no

C maybe, depends on future expansion history

can *always* see CMB photons
last scattering surface distance $d = ct$
advances outward as universe ages!
redshifts as the universe expands

Thus:

- CMB =*snapshot* of U at recomb.!
  baby picture of the Universe!
- γs last scattered at $t_{\rm rec} \sim 400,000$ yr: ancient!
- came from $d_{\rm ls} \approx d_{\rm horizon} \sim ct_0 \sim$ "cosmic (particle) horizon"
  i.e., the edge of the observable universe!
  "as far as the eye can see"

CMB Temperature Mapping: Predictions

cosmo principle: U. homog, isotropic
Q: if exact, what is CMB T pattern on sky?

but U. not homogeneous on small scales
what if density fluctuations on small scales:
Q: what happens to a photon coming from an overdensity?
Q: an underdensity?
Q: how would these effects appear on the CMB T pattern?

`www: CMB temperature maps`

CMB Temperature Mapping: Observations

observe: CMB T **very** uniform!
$\rightarrow$ 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
$\rightarrow \Delta T / T \sim 10^{-3}$
interpretation:
Q: what do you think?
hint: what really observed is **spectrum**:
$\lambda_{\rm peak}$ slightly smaller on one side of sky, slightly larger in the other side

CMB dipole:
due to our motion w.r.t. cosmic rest frame
"peculiar vel" $v = 370$ km/s $= 0.83$ million mph!
Q: what would contribute to this peculiar velocity?

subtract dipole, then: more fluctuations
occur at all angular scales
typical $\Delta T \sim 2 \times 10^{-5}$ K
$\Delta T/T \sim 10^{-5}$: tiny!
discovery 1991 `www: COBE`
precision measurements 2003-today `www: WMAP`

CMB not perfectly isotropic!
Q: what does this tell about Early Universe?

CMB Temperature Fluctuations ("Anisotropies")

CMB temperature differences in different directions

$$(\Delta T)_{\mathrm{avg}} = (T_{\mathrm{obs}} - T_{\mathrm{avg}}) \approx 0.00001 T_{\mathrm{avg}} \quad (2)$$

i.e., differences are in 5th decimal place!
very tiny effect, a huge technology challenge to measure

Small fluctuations are big deal!
what causes T differences? differences in density!
so measuring $\Delta T \rightarrow$ cosmic density fluctuations existed

tiny density fluctuations at rec $\rightarrow$ "seeds" of
galaxies, clusters, superclusters, you, me today!
`www: 2006 Nobel Prize in Physics`