Astro 350
Lecture 31
Nov. 12, 2012

Announcements:
- **Discussion 9** due Wednesday
- **Homework 9** due at start of class Friday

Last time: Penzias & Wilson accidentally discover CMB but have no idea what it is!
Q: how is the CMB cosmic? microwave? background? radiation?
Q: What are observed CMB properties?
Q: What is it "trying to tell us" ?

CMB discovered accidentally in 1965 `www: 2-page paper`

- microwaves = radio photons
- apparent brightness = flux is **isotropic**
  $\rightarrow$ same glow across the skky
- spectrum is **blackbody** = thermal

Fun CMB Trivia

- your TV set “sees” the CMB!

$\rightarrow$ cosmic signal is about 10% of ‘snow” in “empty” channel

Lessons:

- *Universe filled with EM radiation (light)*
- *Universe has temperature*

Raises new questions:

- How did the Universe get a temperature?
- When was this radiation created?
- Gasses cool when they expand–how hot was the early Universe?

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 $\rightarrow$ neutrons, protons, e $\rightarrow$ nuclei,e=plasma $\rightarrow$ atoms

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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?*

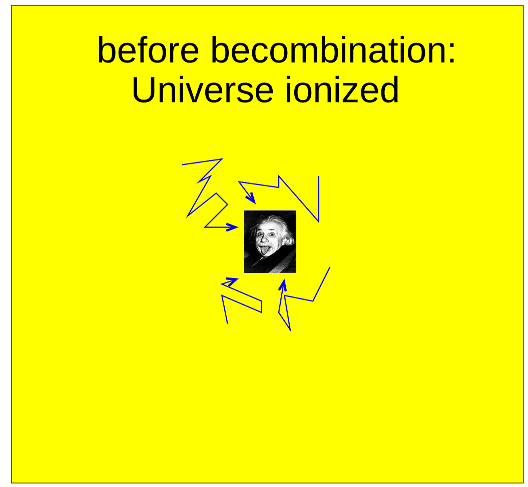
CMB: Photon Paths?

before recombination:

photons constantly scattered

can't travel far: "cosmic fog"

we see: only nearby sources



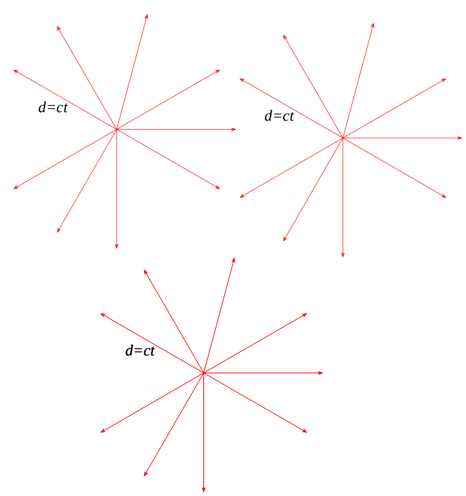
after recombination:

photons no longer scattered

travel freely: "the fog lifts"

at time t after:

travel distance $d = ct$

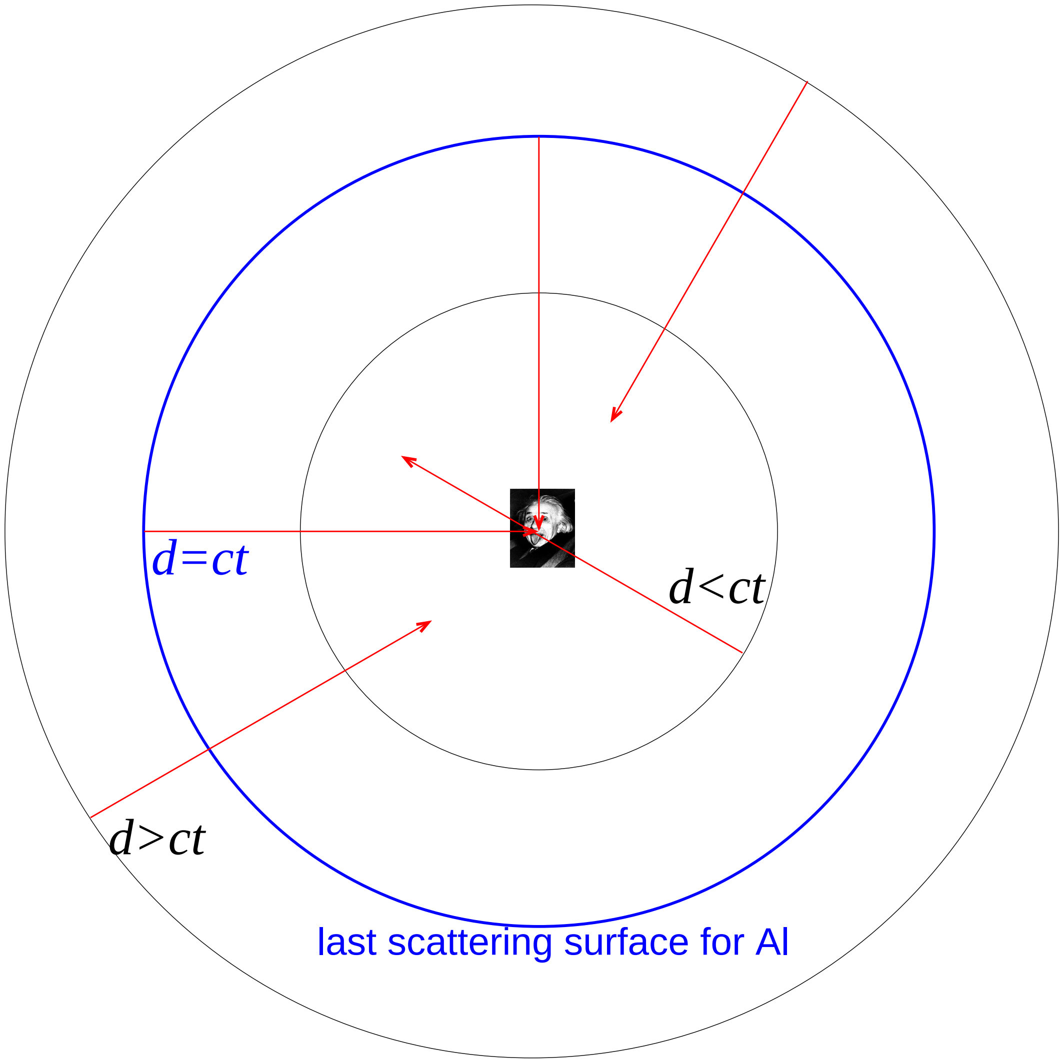


Q: which photons seen at t (where/when emitted)?

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 $d_{\mathrm{ls}} = ct$

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 $t_{\mathrm{rec}} \sim 400,000$ yr: ancient!
- came from $d_{\mathrm{ls}} \approx d_{\mathrm{horizon}} \sim ct_0 \sim$ "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

$$(\Delta T)_{\rm avg} = (T_{\rm obs} - T_{\rm avg}) \approx 0.00001 T_{\rm avg} \quad (1)$$

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`