

Astro 350
Lecture 33
Nov. 11, 2011

Announcements:

- HW 9 due now
- HW10 available, due next Friday
- Discussion Question 10 posted, due next Wednesday

Last time: Penzias & Wilson accidentally discover CMB
but have no idea what it is!

Q: What are observed CMB properties?

cosmic microwave background radiation:

- ↳ ● Universe filled with EM radiation (light)
- Universe has temperature

inner space/outer space connection

Give me an atom, and I will construct the universe.

– Cosmologist (Full-Time!) George Gamow

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?*

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

ω *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 → 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:

→ lab experiments on electron behavior set cosmic history!

Implications...

early universe uniformly filled with photons

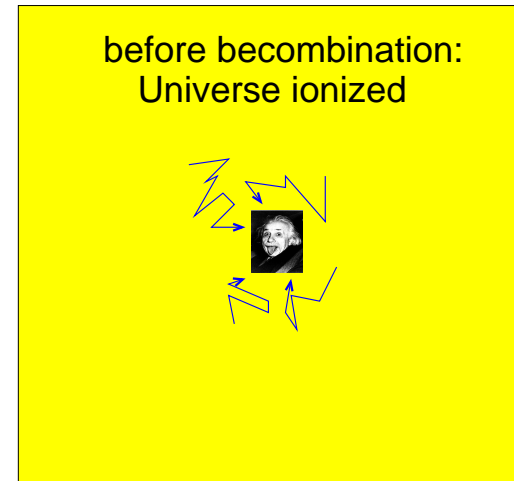
*Q: what are photon paths **before** recombination?*

*Q: what are photon paths **after** recombination?*

CMB: Photon Paths?

before recombination:

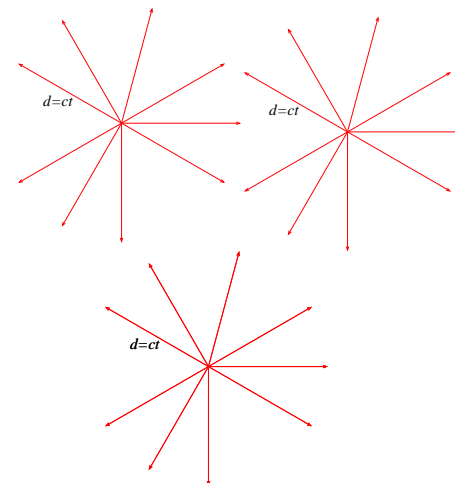
photons constantly scattered
can't travel far: "cosmic fog"
we see: only nearby sources



after recombination:

photons no longer scattered
travel freely: "the fog lifts"
at time t after:

○ travel distance $d = ct$

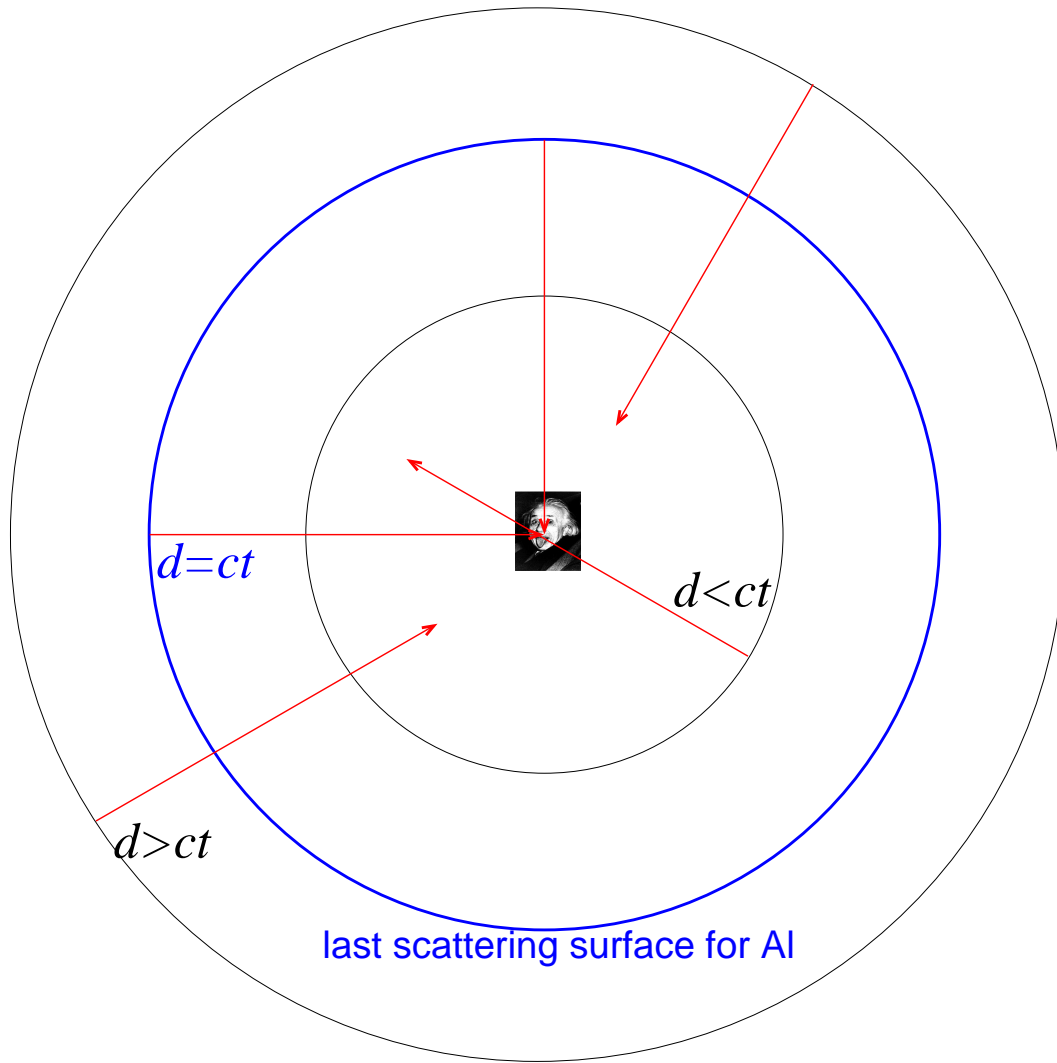


Q: which photons seen at t (where/when emitted)?

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!**
- γ s last scattered at $t_{\text{rec}} \sim 400,000$ yr: ancient!
- came from $d_{\text{ls}} \approx d_{\text{horizon}} \sim ct_0 \sim$ “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!

→ 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?

hint: what really observed is **spectrum**:

λ_{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” $v = 370 \text{ km/s} = 0.83 \text{ million mph!}$

Q: what would contribute to this peculiar velocity?

subtract dipole, then: more fluctuations

occur at all angular scales

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

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

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

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