Astro 350
Lecture 30
Nov. 9, 2012

Announcements:

- **Homework 8** due now
- **Discussion 9** due next Wednesday
- **Homework 9** due at start of class next Friday

Last time: finished our cosmic future
now: back to the past

The Cosmic Past

So far: used data on present expanding universe
to infer something about the future universe

Now turn back to past
Q: why might this be informative?
Q: how could this help us test cosmology?

*Q: how do you expect the U to have been different
   in the recent past?*
Q: what about the more distant past?

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Can use Einstein and Friedmann to predict
nature of past universe
then can observe it, directly or indirectly
$\rightarrow$ will test (and learn more about) cosmology
In the past, Galaxies closer together: $a(t) < 1$
U. was **denser**, also **hotter**

Recent past: still galaxies, but more cramped
Distant past: stars, galaxies had to form
  before then: hot "soup" of cosmic ingredients

Infer that the Universe began in a
hot, **dense** early state:
$\rightarrow$ **Big Bang!**

The Big Bang

Note: some differences in how "big bang" term used
- some cosmologists: big bang is a *process*
  U expansion from a hot dense early state
  in that sense some would say still ongoing
- others: big bang is an *event*
  instant of cosmic time $t = 0$, when scale factor $a = 0$

Q: densities, temperature at $t = 0$?
Q: implications?

Note: Cosmology is global...
Transp: *Big Bang in French Q: what's wrong with this picture?*

Q: where did the big bang occur?

A Puzzling Measurement

Spring 1965:

- Rev. Martin Luther King Jr leads march 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 $\lambda_{\text{max}} \approx 1$ 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 radiation

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

CMB temperature: present measurement

$$T_0 = 2.725 \pm 0.001 \text{ K} \tag{1}$$

note 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:
  $\rho_{\mathrm{crit}} \approx 10 m_{\mathrm{hydrogen}}/$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 $\rightarrow$ ions$=e+$nuclei $\rightarrow n+p \rightarrow$ quarks $\rightarrow$???

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?