Astro 210
Lecture 41
May 4, 2011

Announcements

- Final Exam: **Monday May 9, 1:30–4:30 pm**
  info online
- **ICES** course evaluation available online
  please fill it out–I *do* read & use results

Last time: the dynamic universe

- galaxy motion: $v = Hd$ Hubble's law
  Q: what's v*?* d*?* H*?*
- *Q: interpretations?*
- analogies: `www: balloon`, `www: raisin bread`
- possible cosmic fates *plot* a *vs* t
  - ▷ gravity $>$ inertia, recollapse: "big crunch"
  - ▷ gravity $<$ inertia, expand forever: "big chill"
  - ▷ gravity $=$ inertia, $H \to 0$ as $t \to \infty$ (still big chill)

Final iClicker Poll: Your Preferred Cosmic Fate

We will see: data now seem to foretell actual cosmic fate
But! final answer not known with 100% certainty

So: regardless of data, if you have to pick one of these
Which cosmic fate do you prefer?

A expand forever: Big Chill, $H > 0$ as $t \to \infty$

B expand forever: Big Chill, $H \to 0$ as $t \to \infty$

C recollapse: Big Crunch

Expansion and Gravity

Galaxies have mass $\rightarrow$ gravitate
$\Rightarrow$ gravity changes motion from free-body coasting
$\Rightarrow$ expansion rate must change with time
Since gravity attractive, expect *deceleration*
$\rightarrow$ just like upgoing pop fly

...BUT...

Current data:

Universe is *accelerating* !?!?

What does this mean?
need repulsive force to overcome gravity
only important on cosmo scales
$\rightarrow$ **dark energy**

A huge surprise!

A huge mystery!

What is dark energy? Will it change with time?

Perhaps related to very high energy processes (quantum gravity)?

Perhaps related to goings-on in very early Universe?

What little we do know:

if dark energy takes simplest form ("cosmological constant")

then dark energy force between particles (galaxies) is $F_{\mathrm{DE}} \propto r$

Q: what does this imply for fate of U.?

Dark Energy and a Dark Future

dark energy force $F_{\mathsf{DE}} \propto r$
$\rightarrow$ force *increases* as particles move apart
$\rightarrow$ more repulsion as galaxies recede
so acceleration only increases with time!
$\rightarrow$ U. fate is to expand forever!

if dark energy acts as we think (a big if!)
we are fated to a "Big Chill"

Taking the Temperature of the Universe

What does it mean to live in expanding universe?

today: Universe has very low density
$\rho_0 = 10^{-26}$ kg/m^3
in past: everything closer together $\rightarrow$ density higher

very early U. also very dense:
- particles interact/collide
- matter "thermalized" $\rightarrow$ U should have *temperature*

Q: How can we measure T of universe?
Q: Where should we look to measure T?
Q: How should T vary from place to place (at any one time)?

Cosmic Temperature Measured

if Universe was thermalized, has T, then

- should contain blackbody radiation
- this radiation should be everywhere (homogeneous, isotropic)

prediction made in early 1950's, forgotten(!) until 1965

Measure T from spectrum `www: Penzias & Wilson`
radiation everywhere
cosmic microwave background radiation (CMB)

universe spectrum is very accurate blackbody
`www: CMB spectrum, errors` $\times$ 100

$$\boxed{T = 2.728 \pm 0.004 \text{ K}}$$

Q: what does this discovery prove?

cosmic blackbody shows
U once thermalized $\rightarrow$ once very dense
$\Rightarrow$ needed hot dense phase: evidence for big bang!

- if had microwave eyes, sky very bright
  in radiation from big bang

- 10% of "snow" on TV
  is radiation from big bang

Big Bang Nucleosynthesis

Theory

atomic nuclei made of protons p and neutrons n

bound together by nuclear force

at high temperature $\rightarrow$ early times

U so hot, collisions so violent, that nuclei "ionized" into n, p

then U cools until $n, p \rightarrow$ nuclei

$t = 1$sec - 3 min: $kT = 10^{10}$ K to 10^{6} K

nuclei "ionized" (n & p only) $\rightarrow$ "neutral" (combined in nuclei)

24% helium

traces of D, ^{3}He, ^{7}Li

76% "leftover" protons (^{1}H)

Observation

measure He in universe:

$\rightarrow$ 24%

matches theory!

theory & obs. agree!

$\rightarrow$ big bang theory works well back to $t = 1s$!

The Cosmic History of Matter: Big Bang to Now

1. Big bang nuke: light elements

2. Universe cools, matter clumps
stars, Galaxies born

3. stars:
all heavy elements

Solar system, and *you*: products of
• big bang (H, He, Li)
• low mass stars (example: C from red Giants)
• high mass stars (example: O, Fe from supernovae)

a cosmic symphony; we are results

another perspective:
cosmologists M. Python
"The Galaxy Song" from The Meaning of Life *(1983)*

The Very Early Universe

before big bang nuke:

• $T > 10^{10}$ degrees

• very high-energy collisions:

study with particle accelerators

▷ Fermilab, Batavia IL (Chicago suburb–go visit!)

▷ Large Hardonic Collider (LHC), Geneva Switzerland to visit)

`www: Fermilab`

`www: tunnel`

`www: LHC`

`www: collision`

Inner Space and Outer Space

1. Fermilab and LHC are *microscopes*
   probing nature on the smallest scales

2. Fermilab and LHA are also *telescopes*
probing conditions of
universe at $kT = 1$ TeV $= 10^{12}$ eV
$\rightarrow t = 10^{-12}$sec

2. Early Universe:
$\rightarrow$ "poor man's accelerator"
exotic particles created
perhaps these are dark matter?
weakly interacting massive particles: WIMPs

deep connections between
the very small and
the very large

Remaining Questions

To name a few:

- what is the dark energy?
- how will the dark energy influence the fate of the Universe?
- what is the dark matter?
- how did galaxies form?
- when did the first stars form? the first black holes?
  what are their observable "fossils" today?
- what happened at $t = 0$ (singularity)?

THANK YOU