Astro 210
Lecture 41
May 2, 2018

Announcements:

- **Final Exam: May 7, 8:00 am - 11:00 am**
  info on Moodle
  HW and Exam solutions posted
  Hint: HE2 Q1a worth a look
- Office Hours: today, TA tomorrow
- **Solar Observing: alternative exercise posted**
  for those unable to attend in person
  due Friday at 5pm
- **ICES Online still available**
  I do read and use your comments!
  pay it forward to future ASTR 210 generations

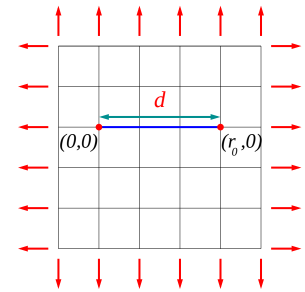
Thus Far: the Large Scale Structure of the Universe

Q: what's the Cosmological Principle?
Q: why is it very restrictive on allowable universes?

Q: what is Hubble's Law? What's a variable, what's a constant?
Q: possible interpretations?

Expansion Rate

Consider two observers (e.g., galaxies) at time t
separated by distance $d(t) = a(t) r_0$
with r_0 the distance today at time t_0, when $a(t_0) = 1$



what is velocity of one point as measured by the other?

$$
\begin{aligned}
v(t) &= \frac{\partial}{\partial t} d = \frac{\partial}{\partial t}(ar) = \dot{a} r && (1) \\
&= \frac{\dot{a}}{a}\, ar = \frac{\dot{a}}{a}\, d \equiv H\ d && (2)
\end{aligned}
$$

where "overdot" is time derivative: $\dot{a} = da/dt$

so expansion gives $v = Hd$, with $H = \dot{a}/a$

★ Hubble's law!

★ we see $H = H(t)$ measures expansion rate
and need not be constant! → "Hubble Parameter"
H_0 is present value, can (& does!) change with time

Expanding Universe: The Past

In the past, Galaxies closer together: $a(t) < 1$
U. was **denser**, also *hotter*

When universe began: $a \to 0$ as $t \to 0$
extreme conditions!
  hot
  dense
state: $\Rightarrow$ $\boxed{\text{big bang}}$

expanded, cooled to present state

Where did the Big Bang Happen?

Q: Already know enough–where?

Where Was the Big Bang?

Cosmological Principle: Universe is homogeneous & isotropic

demands: no special points!

⋆ **big bang has no center!**

⋆ **big bang happened everywhere**

Age of the Universe

Simple-minded estimate: imagine

- each galaxy launched with some initial speed $v = v_{\rm init}$
  some launched faster, some slower
- each keeps constant speed over age of universe t_0

distance traveled: $d = vt_0$

but today $v = H_0 d$, so

$$d = vt_0 = H_0 d t_0 \tag{3}$$

and so

$$H_0 t_0 = 1 \tag{4}$$

estimate "**expansion age**" $t_0 \approx 1/H_0 = 14$ billion years

Q: how does this compare to age of solar system?

Q: why is this estimate too simple?

Solar system age: 4.6 billion years
$\longrightarrow$ Sun & Earth alive for last 1/3 of age of Universe

note: estimate too simple!

- galaxies feel each other's gravity, do not "coast"
- expansion rate changes with time

using best estimate of expansion history H,
best estimate of expansion age is $t_0 = 13.7$ billion years
$\longrightarrow$ close to our simple estimate!

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*Q: given that U expanding today
what are possible fates in future?*

The Fate of the Universe

The story until $\sim$8 years ago
expansion and fate of universe is competition:
outward inertia of expansion vs *inward gravity*
...just like *pop fly* (ball hit upward)

currently: U expanding
like ball (pop fly) launched upward

future possibilities:

- gravity $>$ inertia: *recollapse*
  like $v_{\rm esc} > v$–ball falls back
- gravity $<$ inertia: *expand forever*
  like $v_{\rm esc} < v$–ball (rocket!?) leaves earth!

∞

- gravity $=$ inertia: *expand forever but $H \to 0$ at $t \to \infty$*
  like $v_{\rm esc} = v$–ball escapes but $v \to 0$ at $t \to \infty$

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

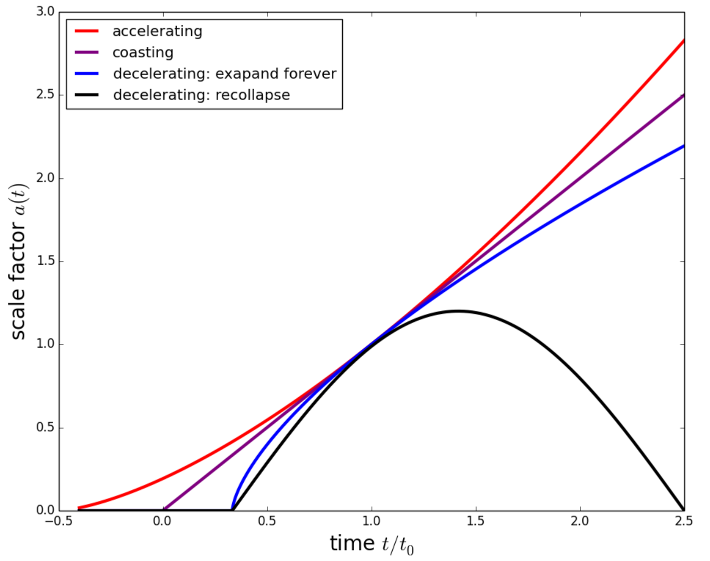
Final iClicker Poll: Cosmic Acceleration/Deceleration

How should the cosmic expansion *rate* change w/ time?

A *increase*: U. accelerates, $d^2a/dt^2 > 0$

B *decrease*: U. decelerates, $d^2a/dt^2 < 0$

C *constant*: U. coasts, $d^2a/dt^2 = 0$



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 large (cosmological) scales $\gg 1$ Mpc

$\rightarrow$ **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 acceleration between particles (galaxies)
is *repulsive*, with $g_{\mathrm{DE}} \propto r$

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

Dark Energy and a Dark Future

dark energy acceleration $g_{\mathrm{DE}} \propto r$
$\longrightarrow$ force *increases* as particles move apart
$\longrightarrow$ more repulsion as galaxies recede
so acceleration only increases with time!
$\longrightarrow$ 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
$\rho_0 = 10^{-26}\ \mathrm{kg/m^3}$
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 Microwave Background: Implications

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

$t =$ 1sec - 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)

$\boxed{\text{Observation}}$

measure He in universe:

$\longrightarrow$ 24%

matches theory!

theory & obs. agree!

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

The Cosmic History of Matter: Big Bang to Now

1. **big bang nucleosynthesis:** *light elements*

2. **Universe cools, matter clumps**
stars, Galaxies born

3. **stars:**
all heavy elements

Solar system, and *you*: products of
• big bang (hydrogen, helium, lithium)
• low mass stars (example: carbon from red giants/AGB)
• high mass stars (example: oxygen, iron from supernovae)

a cosmic symphony; we are results

The Big Picture Summarized

cosmologists M. Python
"The Galaxy Song" from The Meaning of Life *(1983)*
best viewed with subtitles on

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 Open 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)?
- will this be on the test?

THANK YOU and KEEP IN TOUCH