Astro 350

Lecture 32

April 11, 2022

Announcements:

- **Discussion due Wednesday** − Anthropic Principle
- **Homework due Friday**
- FYI: Cosmology Colloquium in Physics: Wed 4pm, online
  Prof. Katherine Freese, U. Texas
  "The Cosmic Cocktail: Three Parts Dark Matter"

Last time: Living with Dark Energy

Today: A Census of the Cosmos

read recipe for "cosmic cocktail" − ingredient list

Gravity vs Inertia: the Battle Rages

gravity vs inertia
pop fly–cosmology analogy

Pop Fly		Universe
ball launch	$\leftrightarrow$	big bang
inertia: upward speed	$\leftrightarrow$	inertia: expanding U
gravity: speed change	$\leftrightarrow$	gravity: expansion accel/decel
present speed vs escape speed	$\leftrightarrow$	??

recall–in Newtonian gravity: escape speed

$$v_{\mathsf{esc}} = \sqrt{\frac{2GM}{r}} \tag{1}$$

Q: what's M? what's r?

Q: what is significance of v_{esc}?

Q: what is analogy in expanding universe?

Newton says:

to overcome gravity of mass M at distance r

need to move with speed $v \geq v_{\text{esc}}$

fate determined by ratio v_{esc}/v:

- if $v_{\text{esc}}/v > 1$: gravitationally bound, never leave
- if $v_{\text{esc}}/v < 1$: unbound, and $v > 0$ as $r \to \infty$
- if $v_{\text{esc}}/v = 1$: marginally unbound, $v \to 0$ as $r \to \infty$

Cosmic analogy: same ratio!

$v = Hr$ and $v_{\text{esc}}^2 = 2GM/r = 8\pi G \rho r$, so

$$\frac{v_{\text{esc}}^2}{v^2} = \frac{8\pi G \rho}{3H^2} \tag{2}$$

cosmic gravity/inertia ratio

$$\frac{v_{\text{esc}}^2}{v^2} = \frac{8\pi G\rho}{3H^2} \tag{3}$$

Convenient to define:
• cosmic **critical density** analog of pop fly launch speed!

$$\rho_{\text{crit}} = 3H^2/8\pi G \tag{4}$$

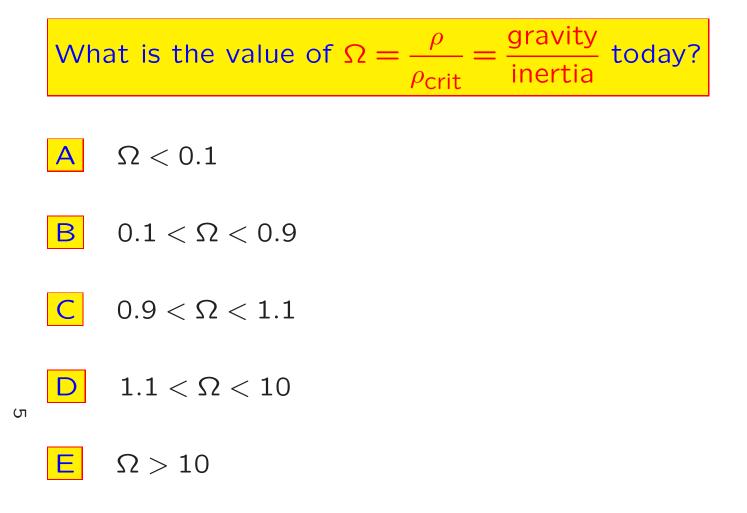• cosmic **density parameter** analog of pop fly escape/launch ratio!

$$\Omega = \frac{\rho}{\rho_{\text{crit}}} \tag{5}$$

Q: what if $\Omega > 1$? $\Omega < 1$? =1?
Q: how do we know?

iClicker Poll: Cosmic Weight and Fate

Vote your conscience!

What is the value of $\Omega = \dfrac{\rho}{\rho_{\text{crit}}} = \dfrac{\text{gravity}}{\text{inertia}}$ today?

A $\quad \Omega < 0.1$

B $\quad 0.1 < \Omega < 0.9$

C $\quad 0.9 < \Omega < 1.1$

D $\quad 1.1 < \Omega < 10$

E $\quad \Omega > 10$

Destiny and Density

Fate of U $\rightarrow$ urgent question:

What is Ω today? $\Rightarrow$ what is ρ_{total} today?

Procedure 0: *Copernican reasoning*

key idea: $\Omega = \rho/\rho_{\text{crit}} \sim \rho(t)/H^2(t)$ evolves with time

driven either to $\Omega \rightarrow 0$ or ∞ *Q: what cosmic fates are these?*

unless $\Omega = 1$, in which case stays 1 always

$\boxed{\Omega = 1 \text{ is only value that's stable over time}}$

do the experiment: look around room

$\Omega \neq 0, \infty$ which means either:

- $\Omega = 1$! i.e., density is exactly critical! ...or
- conspiracy *Q: what is nature of conspiracy?*

What is Ω?

Procedure I: weighing the universe

1. find **fair sample** of U.
2. measure total mass, volume of sample region
3. compute fair sample density ρ
4. by cosmo principle, that is ρ of U today!

Key issue: "fair sample"

Q: what counts as a fair sample?

Q: what might qualify?

Weighing the Universe

Fair samples?

• individual galaxies, including dark halo

$$\Omega_{\text{halo}} = \frac{\rho_{\text{halo}}}{\rho_{\text{crit}}} \lesssim 0.02 \ll 1 \qquad (6)$$

Q: what does this mean physically?

Q: anybody have any problems with this?

∞

Galaxy halos are not enough to "close" the universe
if that's all there is, U. expands forever!

But what if there's more dark matter (or crazier stuff)
that lies *between* the galaxies we see?
if so, we'd have *undercounted* the total density
$\rightarrow$ so try a larger sample!

- Galaxy Clusters: recall–can use grav lensing to get mass!
  and other methods too...

$$\Omega_{\text{cluster}} = 0.30 \tag{7}$$

Q: and so?

Clusters: $\Omega_{\text{cluster}} = 0.30$

but as far as we know, clusters *are* a fair sample
  (too big to "segregate" DM from normal matter)
which means, best estimate today is:

$$\Omega_{\text{matter}} = \Omega_{\text{cluster}} \approx 0.3 < 1 \tag{8}$$

not enough matter around to counter expansion
but wait, we're not done...

Procedure II Microwave background fluctuations
  (2003 result! strengthened with 2006 data!)
will get to how this works, but..

CMB very accurately measure total density

(really, very accurately measures curvature)

$$\Omega_{\text{total}} = 1.001 \pm 0.002! \tag{9}$$

i.e., within our measurement accuracy $\Omega = 1$!!

So no more calls, we have a winner:

The Universe and will expand forever!

Q: but what does $\Omega = 1$ also mean?

Wierd news:

CMB confirms cluster result:

$\rightarrow \Omega_{\text{matter}} \approx 0.30$ (including DM!)

but if $\Omega_{\text{total}} = 1.00$, then...

$\rightarrow \Omega_{\text{not matter}} = 0.70?!?$

most of the Universe not made of matter

even dark matter!

but recall: cosmic acceleration today

requires *dark energy*: simplest version is Λ

observed acceleration $\Rightarrow \Omega_{\text{DE}} = 0.7$

independent measurement, but find $\Omega_{\text{DE}} = \Omega_{\text{not matter}}$!

$\Rightarrow$ strengthens the case that these puzzles are real!

www: comic pie chart

Revolution Re-Re-Re-Re-Re-Visited

Copernican Revolution I (17th Century):
　Earth is one typical planet among many
　not center of solar system
Copernican Revolution II (earth 20th Century):
　Sun is one typical star among many
　not center of Milky Way Galaxy
Copernican Revolution III (1920's):
　Milky Way is one typical galaxy among many
　Universe much larger than previously thought
Copernican Revolution IV (20th century):
　Universe is homogeneous on large scales,
　and has no center
Copernican Revolution V (late 20th century):
　most matter in the U is weakly interacting dark matter
　we are not even made of the dominant stuff
Copernican Revolution VI (21st century):
　most of energy content of U is dark energy
　most of the U isn't made of matter at all!
… stay tuned for more?…

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?

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...

Q: "the big bang" in French?

Q: where did the big bang occur?

A Puzzling Measurement

Spring 1965:
- Rev. Martin Luther King Jr leads marches 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 $\lambda_{max} \approx 1$ 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 electromagnetic radiation

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

CMB temperature: present measurement

$$T_0 = 2.725 \pm 0.001 \text{ K} \tag{10}$$

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