Astro 350
Lecture 31
Nov. 7, 2011

Announcements:

- HW 9 available, due Friday
- Discussion Question 9 due Wednesday
- Hour Exam: grading continues!

Last time: dark energy

Today: cosmic inventory and cosmic fate

Gravity vs Inertia: the Battle Rages

gravity vs inertia
pop fly–cosmology analogy

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

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

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 $\Omega = \frac{\rho}{\rho_{\rm crit}} = \frac{\rm gravity}{\rm inertia}$ today?

A $\Omega < 0.1$

B $0.1 < \Omega < 0.9$

C $0.9 < \Omega < 1.1$

D $1.1 < \Omega < 10$

E $\Omega > 10$

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

$\Omega = 1$ 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 prinicple, 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

$$\Omega_{\rm halo} \lesssim 0.02 \ll 1 \tag{6}$$

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...

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

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! strenthened with 2006 data!)
will get to how this works, but..

Good news

CMB very accurately measure total density
(really, very accurately measures curvature)

$$\boxed{\Omega_{\text{total}} = 1.02 \pm 0.02!} \tag{9}$$

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 measurment, 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-Visisted

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 III (late 20th century):
most matter in the U is weakly interacting dark matter
we are not even made of the dominant stuff

Copernican Revolution IV (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**

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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?