

Astro 350  
Lecture 29  
Nov. 7, 2012

Announcements:

- **Discussion 8** due today
  - **Homework 8** due at start of class Friday
  - **Discussion 9** out today, due next Wednesday
- Office Hours: instructor–today 1pm, or by appt  
TA: tomorrow 9:30-10:30 am

Last time: living with cosmic acceleration

- cosmological constant  $\Lambda$   
*Q: what's that? who invented it? what does it do?*
- dark energy  
*Q: what's that? relation to cosmo constant?*

cosmological constant  $\Lambda$

- “fudge factor” Einstein stuck into General Relativity equations
- invented to keep Universe static: cosmic anti-gravity
- adds repulsive acceleration  $\Lambda r/3$  to ordinary gravity

*Q: why don't we notice this antigravity in Solar System?*

- $\Lambda$  can also be interpreted as  
“energy of empty space” = “vacuum energy”  
constant density  $\rho_\Lambda = \Lambda/4\pi G$  and pressure  $P_\Lambda = -\rho_\Lambda$
- today:  $\rho_{\Lambda} \approx 3\rho_{\text{matter}}$  cosmic coincidence?

dark energy: generalization of vacuum energy

- density  $\rho_{\text{DE}}$  can change over time  
special case: no change—then  $\rho_{\text{DE}} = \text{constant} = \rho_\Lambda$
- can change to keep  $\rho_{\Lambda}$  and  $\rho_{\text{matter}}$  similar always  
→ then not a coincidence to see this today
- in some models,  $\rho_{\text{DE}}$  increases with time  
...which is bad. *Q: why?*

*Cosmologist David Letterman reacts*

From the Wahoo Gazette, July 23, 2003

Dave was enjoying a nice read of the New York Times after Tuesday's show when he came upon an article [on page 19] which claims the universe is splitting in two. Some "dark energy" is wrenching the universe apart.

Dave says "If the world and the universe is actually splitting apart like the New York Times says, then **why is it on page 19?** Shouldn't it be on Page 1?" For the rest of the program, everything seems minor and inconsequential considering that the universe is being pulled apart by a mysterious dark energy.

## Living with Dark Energy

Current Data:

acceleration demands dark energy of some kind

cosmo constant is simplest version, but also works well

→ no current data demand something more complicated than  $\Lambda$

→ but other dark energy models survive

→ big rip not required or strongly favored, but also  
can't be ruled out by current data!

Why don't we know what's causing acceleration?

to measure cosmic acceleration is hard!

- have to measure *changes* in expansion rate
- and so have to carefully measure and compare expansion across great distances and times

to test dark energy vs modified gravity is hard!

- need to identify different predictions
  - both designed to give acceleration (*large-scale* Universe)
  - but differ in development of *small-scale* lumpiness over time
- i.e., how galaxies & clusters form and grow over time

Q: so what is needed to solve this puzzle?

# Solving the Mystery of Acceleration: Observations

to understand *why* the Universe is accelerating  
we need very precise measurements of *how* the U has accelerated  
over as much of cosmic time as possible  
→ this requires many standard candles out to large distances  
→ need large telescopes scanning for supernovae  
over large regions of sky for a long time

to compare dark energy/mod gravity predictions for galaxy growth  
we need very precise measurements of *how* cosmic structure  
has arisen and changed over time  
→ requires measuring galaxies and lensing out to great distances  
→ need large scopes mapping galaxies and measuring their shapes

these requirements set goals for this decade's new telescopes:

- ● ground-based: Dark Energy Survey and LSST (Illinois!)
- space-based: Euclid (ESA)

## Solving the Mystery of Acceleration: Theory

cosmic acceleration was a major surprise  
no great theoretical ideas were “lying around”  
still remains a huge challenge for theoretical cosmologists!  
→ no really compelling (to me, anyway) ideas available  
that relate dark energy to everything else we know  
about the very large and the very small

contrast to dark matter: we will see that  
there are too many good ideas of what it might be!

cosmic acceleration remains an open theoretical problem  
many bold (=crazy-sounding) ideas:

- ~ e.g., our 3+1 dimensional U is a “brane” in  
larger 11-dimensional “bulk”

Cosmologist Jim Peebles, *The Large Scale Structure of the Universe* (1980)

end of the final paragraph (on a different topic, but still apt):

... we must still bear in mind [cosmologist Hermann] Bondi's caution that "there are probably few features of theoretical cosmology that could not be completely upset and rendered useless by new observational discoveries." For the present subject we might add, "or by a good new idea."



## Cosmic Acceleration: Outlook

for 15 years, evidence has become ever stronger:  
the expansion of the universe is accelerating

either: this means we don't understand gravity on large scales  
and General Relativity is wrong → need **modified gravity**

or: most of universe dominated by a force/substance  
we don't at all understand! → need **dark energy**

major cosmological puzzle! one of biggest questions in all of  
science!

- upcoming projects to better measure “ $\Lambda$ ,”  
or whatever dark energy is...

◦ or to uncover mistake! could this be our “ether?”

★ either way Illinois a major player in making progress!

# Gravity vs Inertia: the Battle Rages

*gravity vs inertia*  
*pop fly–cosmology analogy*

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

recall—in Newtonian gravity: escape speed

$$v_{\text{esc}} = \sqrt{\frac{2GM}{r}} \quad (1)$$

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

Q: *what is significance of  $v_{\text{esc}}$ ?*

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  $v_{\text{esc}}/v$ :

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

Cosmic analogy: same ratio!

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

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

cosmic gravity/inertia ratio

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

Convenient to define:

- cosmic **critical density** analog of pop fly launch speed!

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

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

$$\Omega = \frac{\rho}{\rho_{\text{crit}}} \quad (5)$$

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  $\Omega = \frac{\rho}{\rho_{\text{crit}}} = \frac{\text{gravity}}{\text{inertia}}$  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  $\Omega$  today?  $\Rightarrow$  what is  $\rho_{\text{total}}$  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  $\infty$  *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 $\Omega$ ?

**Procedure I:** weighing the universe

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

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

*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

→ so try a larger sample!

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

$$\Omega_{\text{cluster}} = 0.30 \quad (7)$$

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:

$$\Omega_{\text{matter}} = \Omega_{\text{cluster}} \approx 0.3 < 1 \quad (8)$$

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..

## Good news

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

$$\Omega_{\text{total}} = 1.02 \pm 0.02! \quad (9)$$

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:

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

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

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

**most** of the Universe **not** made of matter  
even dark matter!

but recall: cosmic acceleration today

requires *dark energy*: simplest version is  $\Lambda$

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!

# 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?...