Astro 350

Lecture 31

April 8, 2022

Announcements:

- **Homework due Friday**
- **Discussion due Wednesday**

cosmic acceleration and the preposterous universe

Q: what are the possible explanations for acceleration?

Q: which solution is the least radical?

Man, there's a lot of unexplained phenomenon
out there in the world.
Lot of things people say
What the heck's going on?
– Cosmologist Mojo Nixon

Cosmo-tip: acceleration is strange!

Expanding universe already a challenge to imagine
...now add acceleration on top of this!

if it doesn't bother you
you probably need to think harder about it!

Simplest solution: to cosmic acceleration
Einstein "cosmological constant" Λ (greek: Lambda)

originally invented by Big Al (1917):

- "fudge factor" in General Relativity
- invented to prevent cosmic expansion
  recall: Hubble's law published in 1929

  stock market crashing, Universe expanding

cosmo constant Λ changes Newton's gravity force law:
mass m at distance r from mass M feels force

$$F_{\text{gravity}} = -\frac{GMm}{r^2} + \frac{1}{3}\Lambda m r \qquad (1)$$

Q: what if $\Lambda = 0$ and $M = 0$? what does this mean?
Q: what do we get if $\Lambda = 0$ but $M > 0$? why the $-$ sign?
what happens to particle released from rest?
Q: what if $M = 0$ and $\Lambda > 0$?
what happens to particle released from rest?
Q: Λ invented to prevent cosmic expansion–how?

The Onset of Acceleration

recall: supernova data show that

- the universe is *accelerating* now and in "recent" past
  in blatant contradiction to expectations
- but in more distant past, universe was *decelerating*

How can we understand this?

Example: if cosmological constant Λ, then

$$\text{acceleration} = \frac{\ddot{a}}{a} = -\frac{4\pi}{3} G\rho + \frac{1}{3}\Lambda \qquad (2)$$

Q: Which term is bigger today?

Q: what about the past–what is a like at earlier times?

Q: How does matter density ρ change in the past? Λ?

Q: and so what happens in the past? what about the future?

Aside: Matter Density and Cosmic Expansion

matter density: mass per volume

for representative sample of the cosmos ("expanding box")

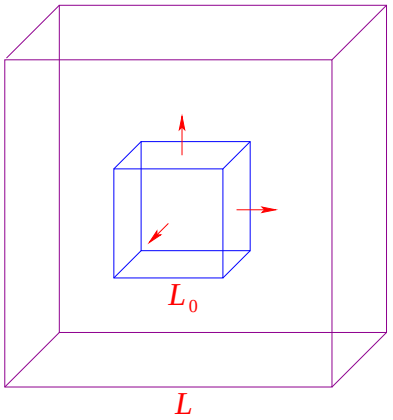
- find mass in matter $M_{\rm matter}$ and volume V
- density is $\rho_{\rm matter} = M_{\rm matter}/V$

How does this change as the Universe expands?

- mass M does not change
- volume $V \propto a^3$

thus matter density changes as

$$\rho_{\rm matter} \propto \frac{1}{V} \propto \frac{1}{a^3}$$



expansion means a increases

$\Rightarrow$ $\rho_{\rm matter}$ decreases

same mass in larger volume – more dilute!

so the past: cosmic mass density was higher!

$$\text{acceleration} = \frac{\ddot{a}}{a} = -\frac{4\pi}{3}G\rho + \frac{1}{3}\Lambda \qquad (3)$$

today:

- U accelerating, so acceleration > 0
- and thus positive Λ term $>$ negative ρ term

in the past:

- scale factor a smaller (U is expanding!)
- Λ same, but matter density $\rho = \rho_0/a^3 \propto 1/a^3$
  $\Rightarrow$ in past, density higher: ρ bigger
- at some point in past (some value of a):
  negative ρ term wins $\rightarrow$ U decelerates!
- in fact, not long ago: terms equal when $a = 1/1.3 = 0.75$!

in the future:

- ρ keeps getting smaller, but Λ same
- acceleration becomes even more positive

$\Rightarrow$ *a Λ universe will accelerate (and expand) forever! Big chill!*

Λ and the Cosmic Coincidence Problem

cosmo constant Λ – what *is* it?

- a new constant of nature (like c, G)
- can be viewed as "antigravity" source everywhere
- but also can be viewed as a "substance"
  filling all of space, at all times,
  with uniform density of energy $\rho_\Lambda = \Lambda/8\pi G$

"vacuum energy density"

curious fact: today $\rho_\Lambda \approx 2\rho_{\text{matter},0}$
but ρ_Λ never changes with U expansion
while ρ_{matter} always changes
$\Rightarrow$ so why do we live at a special time:
  almost at the moment when the two are equal?
at most cosmic times, either $\rho_{\text{matter}} \gg \rho_\Lambda$
  or $\rho_\Lambda \gg \rho_{\text{matter}}$

huge coincidence!? seems anti-Copernican! *Q: ways out?*

Dark Energy

to keep "spirit of Λ"
but avoid cosmic coincidence problem:

generalize vacuum energy idea $\Rightarrow$ **dark energy**
then: $\rho = \rho_{\text{matter}} + \rho_{\text{DE}}$

- dark energy is a new energy field ("scalar field")
  known matter and energy fields fail!
  have positive pressure and thus attractive gravity
- also has negative pressure, causes acceleration
- but dark energy density can change – and usually does!
  ρ_{DE} can decrease with expansion
  but in some models can even *increase*!

Dark Energy and Cosmic Coincidence

some dark energy models ("quintessence")
find dark energy change (evolution) is linked
to the rest of cosmic contents (matter, radiation)

evolution occurs in such a way that
always keep $\rho_{\rm DE}$ close $\rho_{\rm matter+rad}$
so this is *always* true, not just now
$\rightarrow$ alleviates cosmic coincidence
of acceleration starting "yesterday"

Dark Energy vs Cosmo Constant

technically: dark energy density $\rho_{\rm DE} \propto a^{-3(1+w)}$

with w unknown except that need $w < -1/3$ for acceleration

cosmological constant: $w = -1$ exactly, so $\rho_{\rm DE} \propto a^0 = const$

Note: cosmo constant is *special case* of dark energy

simplest possible version: unchanging always

Q: so how do we tell if we have Λ
or more general dark energy?

Q: and who cares? what's the difference?

Unmasking Dark Energy

cosmo constant is very special:
Λ and thus ρ_Λ strictly constant
never change in time or space

so if can measure cosmic expansion in past
can find the density needed to cause this
see if it changes or not

technically: measure w from $\rho_{\rm DE} \propto a^{3(1+w)}$

cosmo constant if and only if $w = -1$

Who cares?

- if Λ: why do we live at the moment
  it has revealed itself? Anthropic principle?
- if *not* Λ: what is this weird
  evolving dark energy that fills the universe?

iClicker Poll: Refine Your Bets on Cosmic Acceleration

What is causing cosmic acceleration?

A a cosmological constant Λ

B dark energy (but not special case of cosmo constant)

C modified gravity

Uh Oh.

Warning!
some dark energy models have $\rho_{\rm DE}$ *increasing* with time!
"phantom energy" models:
expansion $\rightarrow$ *larger* density of dark energy!?!

leads to scale factor growth

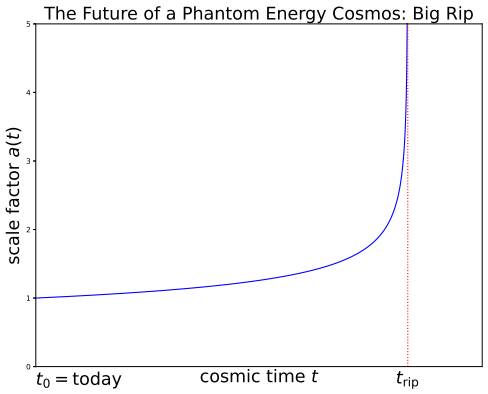
$$a_{\rm future}(t) \propto \frac{1}{t_{\rm rip} - t} \tag{4}$$

where $t_{\rm rip} > t_0$ is a fixed future time
Q: what happens when $t \rightarrow t_{\rm rip}$? why is this bad?

The Big Rip

if DE density increases with expansion
then expansion rate $H^2 \propto \rho_{\mathrm{DE}}$
accelerates more & more

$$a_{\mathrm{future}}(t) \propto \frac{1}{t_{\mathrm{rip}} - t}$$



- ▷ scale factor $a \to \infty$ at $t = t_{\mathrm{rip}}$
- ▷ in finite time, all particles move infinitely far from all other particles: **the big rip**

Cosmologists & Ghostbusters Harold Ramis & Bill Murray

Harold: It would be bad.

Bill: I'm a little fuzzy on the whole
"good/bad" thing here. What do you mean "bad"?

Harold: Try to imagine all life as you know it
stopping instantaneously and every molecule
in your body exploding at the speed of light.

www: Cosmologist Woody Allen, *Annie Hall (1977)*

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
$\rightarrow$ no current data demand something more complicated than Λ
$\rightarrow$ but other dark energy models survive
$\rightarrow$ 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

Illinois is deeply involved in these projects
• ground-based: Dark Energy Survey and Vera Rubin Telescope/LSST
• space-based: Nancy Grace Roman Telescope

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!
$\rightarrow$ 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 25 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 $\rightarrow$ need **modified gravity**

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

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

- upcoming projects to better measure "Λ,"
  or whatever dark energy is...
  or to uncover mistake! could this be our "ether?"

$\star$ either way Illinois a major player in making progress!