Astro 350
Lecture 30
April 6, 2022

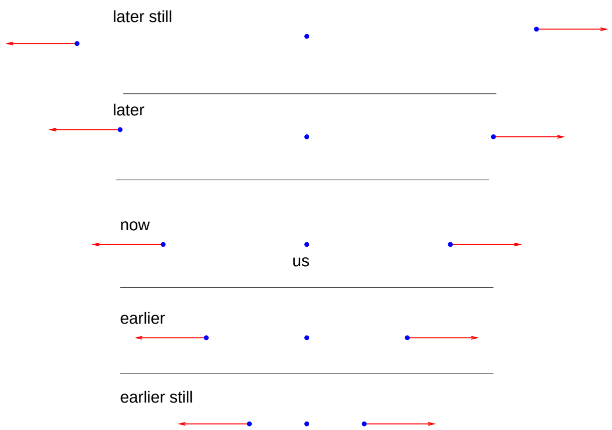
Announcements:

- **Discussion due today**
- **Homework due Friday**
- This week only: office hours by appointment (not after class)

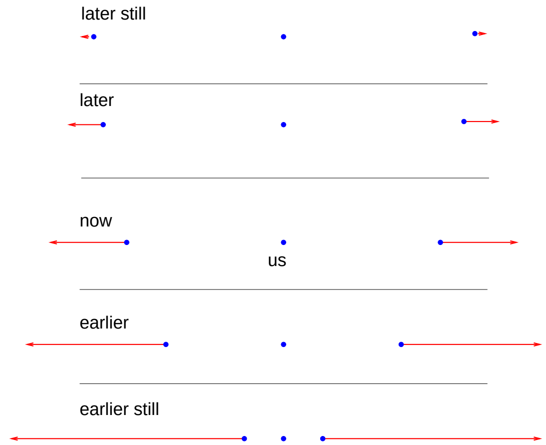
Last time:

- effect of matter in the universe
  $\rightarrow$ weight is fate! density is destiny! *Q: why?*
- measuring the *changes* in expansion rate
  Q: expected result in "empty" U? U with matter?
  Q: actual observed result?

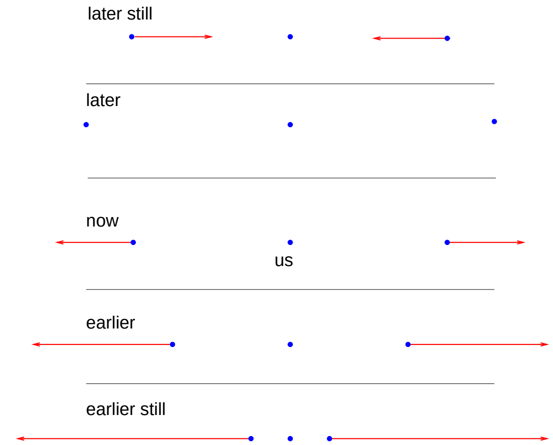
Empty Universe: "Coasting"



Low−matter−density universe: future



High−matter−density universe: future



also last time:
cosmic expansion history and cosmic acceleration

key ideas:

- at any time t, everywhere $v(t) = H(t)\ r(t)$

- when looking at galaxies far, far away
  seeing light emitted a long time ago

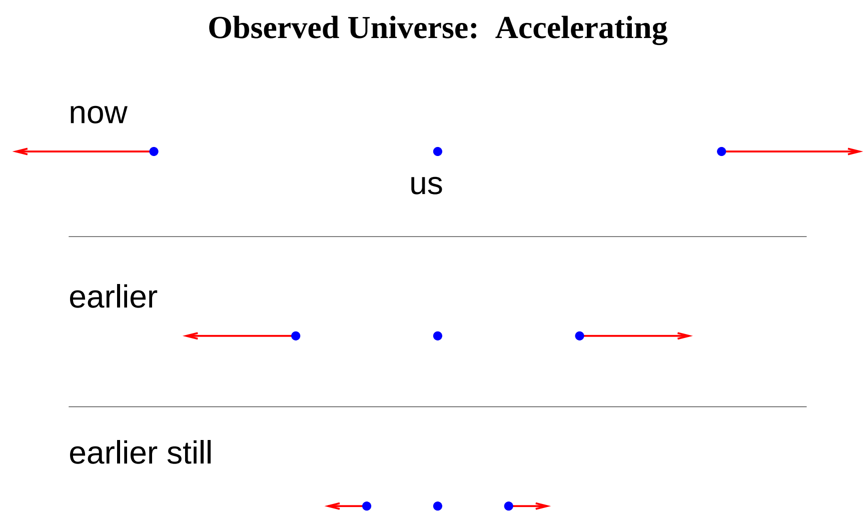
- so if measure v (from redshift) and r (from std candle)
  then can find $H(t) = v(t)/r(t)$ = expansion at past time t!

- even better: can find $H(t)$ for many times t *Q: how?*

Bottom line:
⋆ can measure *change* in expansion rate
⇒ can measure cosmic deceleration/acceleration

Distant Supernovae: The Verdict

Our actual observed universe: galaxies *slower* in past!



SN data: $H(z)$ **smaller** in the past (high z and small t)
$\Rightarrow H(z)$ **increases** with time!
$\Rightarrow \ddot{a} > 0$!

expansion rate: **accelerated!**
Q: what would this mean in the pop fly analogy?

An Accelerating Universe: Implications

Recall: expected deceleration because ordinary matter
(even dark matter!) has gravitational attraction
matter-filled universe should have *slowing* expansion
→ if matter is all there is, U should decelerate

But: found acceleration – exact opposite of intuition
→ something present which has gravitational repulsion!
→ Universe seems to contain something having "antigravity" !?!
...and huge amounts of such stuff!
enough of it to overwhelm the attraction of ordinary matter!

In more detail: SN Ia: $\ddot{a} > 0$, but Friedmann sez

$$\text{change in expansion rate} = \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + 3\frac{P}{c^2}\right)$$

observation say Universe is accelerating: $\ddot{a} > 0$

this requires $\rho + 3P/c^2 < 0$

but $\rho > 0$: mass/energy are positive

so we must have: $P < -3\rho c^2$

the cosmos is filled with substance with large negative pressure!?!

Physical "interpretation":

Pressure is force per area

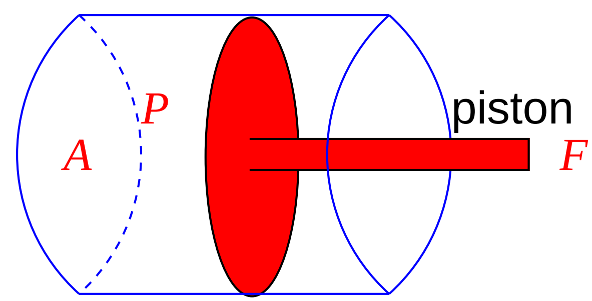
so $F =$ pressure $\times$ area

$P > 0$: outward force (e.g., ideal gas)

expansion reduces pressure

$P < 0$: inward force (e.g., elastic)

expansion increases pressure



Cosmic Expansion History: the Full Story

in fact, observations show that cosmic expansion
had *two* phases

⋆ *today and in the recent past*
expansion is **accelerating**
opposite of prediction from matter + General Relativity

⋆ *in the more distant past*
at redshifts $z > 0.3$, times before $t < 10$ billion years
that is, more than about 3 billion years ago
expansion was **decelerating**
$\leadsto$ agrees with prediction from matter + General Relativity!

Cosmic Acceleration: Who Ordered That?!

ordinary matter and ordinary gravity: **attractive**
gravity acts to draw galaxies together,
$\Rightarrow$ slows outward expansion
should give cosmic **deceleration**

but we observe cosmic **acceleration**!
two known options:

1. Universe contains something bizarre that
pushes objects apart!
in fact, this repulsion has to be so strong
that it overcomes gravity attraction from matter!

2. *Q: what's the other option?*

Einstein Overthrown?

cosmic acceleration seen when looking at the Universe
over vast distances

result is surprising because our gravity theory
= Einstein's General Relativity
predicts gravity makes matter attractive

but note: while GR very well tested on Earth
and in Solar System
not tested on cosmic lengthscales

perhaps acceleration tells us:
General Relativity is incomplete/wrong
$\rightarrow$ if so, need new gravity theory!
Q: requirements for such a theory

Improving on Einstein?

if new gravity theory:
still have to explain *all* data

so: any new theory has to

- give same answers as GR
  on Earth, solar system scales
- and keep other successful GR features:
  redshifting, lensing, time dilation
- yet also give different *answers on cosmic scales*

iClicker Poll: The Reason for Cosmic Acceleration

Vote your conscience!

Of these two basic explanations for cosmic acceleration
Which do you think is right?

A General Relativity *correct*, but the Universe contains something bizarre that makes it accelerate

B General Relativity *incorrect*, and the Universe only contains matter

Explaining Cosmic Acceleration

Cosmologists are working hard on *both* avenues

- a new cosmic "accelerant": "dark energy"
- alternatives to General Relativity: "modified gravity"

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

originally invented by Einstein (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

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

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?

In cosmological context, Λ changes acceleration to

$$\frac{\ddot{a}}{a} = -\frac{4\pi}{3} G\rho + \frac{1}{3}\Lambda \tag{2}$$

can "fine-tune" Λ to prevent expansion/collapse by
exactly compensating for normal gravity
and make the universe not accelerate or decelerate

Q: how? what fine tuning needed?

Einstein did this

but: after Hubble sees expansion in 1929,
Al allegedly sez Λ his "greatest blunder"

Q: what if Λ exist but not fine tuned?

However: if Λ *not* fine-tuned
can "overcompensate" for gravity attraction
$\rightarrow$ lead to acceleration!
so: in wake of SNIa results, Λ rebirth!

$\rightarrow$ even Al's blunders turn into gold!

in math language: Λ alters Friedmann:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3}G\rho - \frac{K}{a^2} + \frac{\Lambda c^2}{3} = \frac{8\pi}{3}G\rho_{\rm tot} - \frac{K}{a^2} \quad (3)$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi}{3}G\left(\rho + 3\frac{P}{c^2}\right) + \frac{\Lambda c^2}{3} = -\frac{4\pi}{3}G\left(\rho_{\rm tot} + 3\frac{P_{\rm tot}}{c^2}\right) \quad (4)$$

where $\rho_{\rm tot}$ includes $\rho_\Lambda = \Lambda c^2/8\pi G$ "vacuum energy density"
$P_{\rm tot}$ includes $P_\Lambda = -\rho_\Lambda c^2$: "vacuum pressure"

In other words:

- $\Lambda \neq 0$ gives energy content to empty space!
  ("vacuum energy")
- and vacuum energy has negative pressure!

$\Rightarrow$ fills the bill for acceleration!

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

$$\text{acceleration} = \frac{\ddot{a}}{a} = -\frac{4\pi}{3}G\rho + \frac{1}{3}\Lambda \tag{5}$$

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?

$$\text{acceleration} = \frac{\ddot{a}}{a} = -\frac{4\pi}{3}G\rho + \frac{1}{3}\Lambda \tag{6}$$

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!*

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 $\rho_\Lambda \approx 2\rho_{\mathrm{matter},0}$
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 $\rho_{\mathrm{matter}} \gg \rho_\Lambda$
or $\rho_\Lambda \gg \rho_{\mathrm{matter}}$

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**

- previously unknown energy field ("scalar field")
  known matter and energy fields fail!
  have positive pressure and thus attractive gravity
- also has negative pressure, causes acceleration
- but now density can change – and usually does!
  ρ_{DE} can drop 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?