Astro 350

Lecture 29

Nov. 2, 2011

Announcements:

- Discussion Question 8 due today
- HW 8 due Friday

Office hours: Instructor – today after class

TA: tomorrow 2-3 pm

Hints for Q2: in *static* U, $a(t) = \text{constant} = 1$ always!

and $\rho = \text{constant}$ always and everywhere

Last time:

- matter-only universe: $a(t) \propto t^{2/3}$

  Q: what is the final fate of such a universe?

  how do you tell?

  matter-only prediction: cosmic age $t_0 = \frac{2}{3}\frac{1}{H_0} = 9.2$ billion yr

  typo fixed from last ime

  but oldest stars have age > 12 billion years

Q: and so?

fate of Universe: what happens in distant future
mathematically, far future: $t \to \infty$

matter-only: $a \propto t^{2/3}$
so as $t \to \infty$, then $a \to \infty$
distances between objects grow infinitely large!
universe expands forever!

matter-only prediction: $t = 9.2$ billion years
actual data: $t > 12$ billion years
$\Rightarrow$ contradiction!

We do not live in the "what you see is what you get"
matter-only universe!

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:

$\star$ can measure *change* in expansion rate
$\Rightarrow$ can measure cosmic deceleration/acceleration

Acceleration vs Deceleration

consider to objects today, say two galaxies
presently at some distance r_0, say 100 Mpc

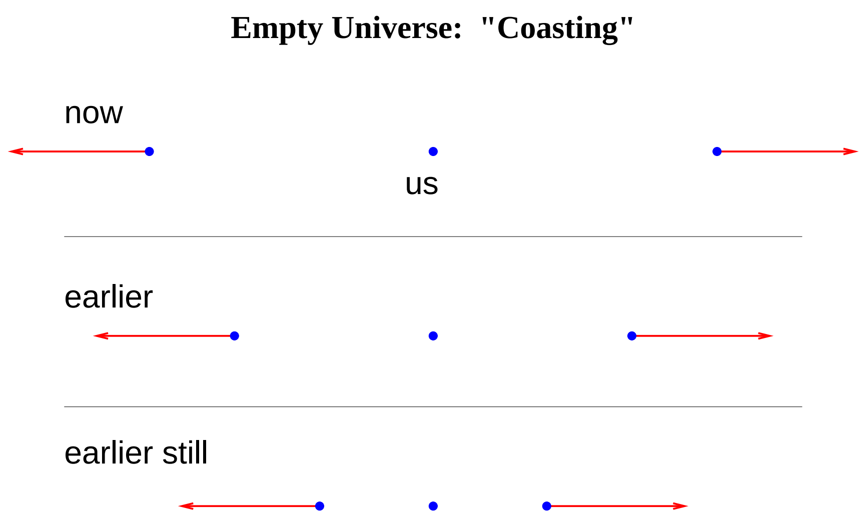
right now moving apart at some speed given by $v_0 = H_0 r_0$
due to cosmic expansion

imagine times the past, when closer together
Q: if "turn off" gravity (really, remove all matter), what are speeds at earlier times?
Q: now turn on (ordinary, attractive) gravity: what are speeds at earlier times?
Q: but now follow supernova results–what are speeds at earlier times?

Q: what could explain these results?

Matter-Free “Empty” Universe

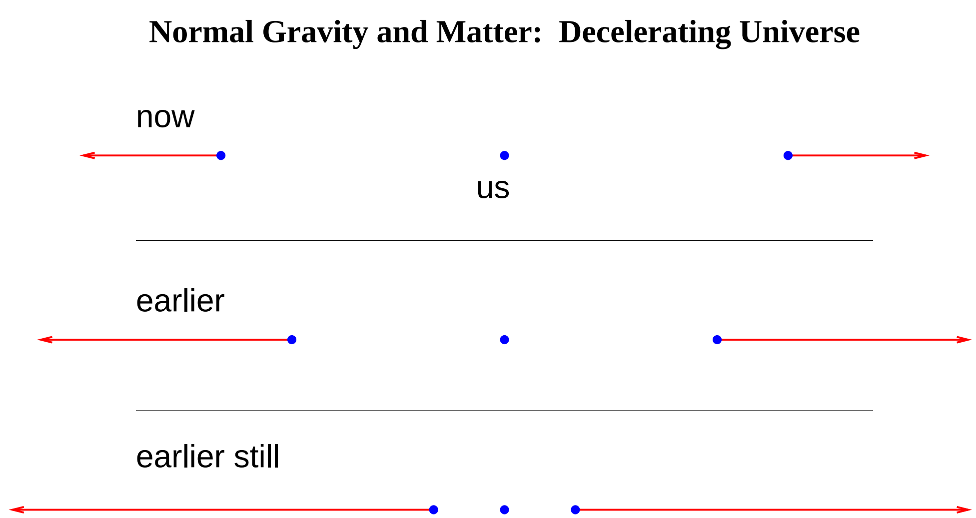
No matter $\rightarrow$ no attraction between galaxies
$\rightarrow$ nothing to change galaxy speeds
$\rightarrow$ galaxies “coast” keeping constant velocity
$\Rightarrow$ same speeds in past



expansion rate:
neither accelerated **nor** decelerated

Ordinary Gravity and Matter

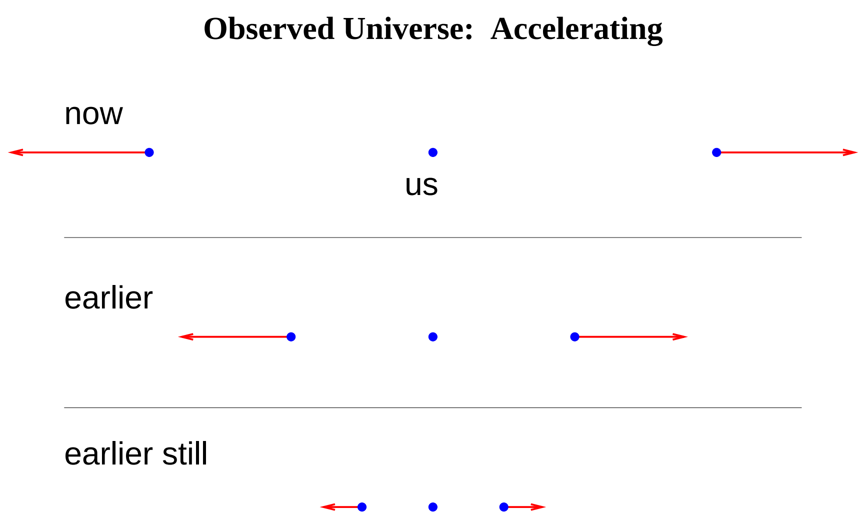
The real universe has galaxies with mass $\rightarrow$ attract each other
$\rightarrow$ inward gravity slows expansion
$\rightarrow$ speeds constantly *decreasing*, galaxies *decelerating*
$\Rightarrow$ to achieve observed speed today, had to be *faster* in past!



expansion rate: **decelerated**

Observed Universe

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



∞ expansion rate: **accelerated!**

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**
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 bizzare 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: Einstein "cosmological constant" Λ

originally invented by Big Al (1917):
"fudge factor" in General Relativity

changes 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?*

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: 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 detail: 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 $P_\Lambda = -\rho_\Lambda c^2$

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!

Λ and its Discontents

Recall that expansion accelerated only "recently"
seems we live in a special time – right when acceleration begins
Why Λ only important right now?

Try another approach: look for more general solutions
acceleration does requires new strange cosmic ingredient
but not required to be cosmo constant

Acceleration $\rightarrow$ U Contains Negative Pressure Substance
but: can prove that matter of any kind
  and radiation of any kind must have $P \geq 0$
$\Rightarrow$ only known substance that has $P < 0$ is
  new kinds of energy fields ("scalar fields")

generically–negative pressure substances: **dark energy**
- Λ simplest, does not evolve with time or z
- generally, dark energy *does* evolve:
  can be larger or smaller in past

In particular: some dark energy models (“quintessence”)
give DE evolution that always keeps
$\rho_{\rm DE}$ close to $\rho_{\rm matter}$
so not unusual that the two are close today+

Warning!
some dark energy models have $\rho_{\rm DE}$ increasing with time!
i.e., expansion $\rightarrow$ *larger* density of dark energy!?!
leads to scale factor growth

$$a_{\rm future}(t) \propto \frac{1}{t_{\rm rip} - t} \tag{5}$$

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