Astro 406
Lecture 32
Nov. 11, 2013

Announcements:

- **PS 10 due Friday**
- ASTR 401: make appointment to meet

Last time: the fate of the universe

a cosmic competition

Q: What effects compete?

Q: How is competition quantified?

Q: What measurements needed to determine result?

Q: What is the answer? Implications?

the fate of the Universe is the outcome
of a competition between *gravity* and *inertia*

gravity: matter and radiation slow expansion
quantified via mass-energy density $\rho = \varepsilon_{\rm tot}/c^2$
inertia: absent gravity, galaxies keep constant velocity
quantified via expansion rate H
or critical density $\rho_{\rm crit} = 3H^2/8\pi G$

cosmic geometry and fate boil down to
gravity/inertia comparison $\Omega = \rho/\rho_{\rm crit}$

CMB and clusters tell us:
- $\Omega_{\rm matter,0} \approx 0.30$ (including DM!)

but the CMB also finds a flat (Euclidean) universe
- $\Omega_0 = 1.0005 \pm 0.0033$

so we are forced to infer that today → $\Omega_{\rm other} = 0.70$?!?

Friedmann Revisited

we have seen that the Universe is *flat*
i.e., the three-dimensional space obeys *Euclidean geometry*

note that this allows us to simplify the Friedmann eq.
because our Universe has $\kappa = 0$:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho \tag{1}$$

- no pesky curvature term
- obviously $\rho > 0$ (look around), so $H > 0$ always
  cosmic expansion will never stop
  we are fated to a *big chill* ...or worse. More later.

Q: so what can we say about the stuff making up $\Omega_{\text{other}} \approx 0.70$*?*

The Cure for Ignorance is Data!

21st century cosmology tell us:
70% of cosmic mass-energy today is in an unknown form
not matter–including dark matter!
not radiation–including neutrinos!

Spoiler alert: we do not know what this unknown stuff is.
In instructors opinion: we don't even have good ideas
sure, we have ideas, but not good, compelling ideas

What *do* we know?
• must be *dark* (or we would have seen it already)
• has to gravitate: must have *mass-energy*
...but not be matter (i.e., can't be dark matter), nor radiation
$\Rightarrow$ **dark energy**

Q: another possibility?

Einstein Overthrown?

Why did we conclude that today the U is mostly dark energy?
$\rightarrow$ because Friedmann's equations to do cosmology
$\rightarrow$ and these are based on *General Relativity*

But what if the data are hinting that GR is wrong?
It is well tested in the Solar System
but hard to *independently* test beyond

alternative approach to dark energy is
alternative or *modified gravity*
that replaces Einstein's gravity

- must look different from GR on cosmological scales and cause acceleration
- but must look the same as GR on Solar System scales so that planetary motion is still okay

When faced with ignorance: *get more data!*

Dark Energy and Cosmic Expansion

measure properties of dark energy
e.g., how does dark energy change as the Universe expands?

good news: simplified Friedmann shows the way

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho = \frac{8\pi G}{3}(\rho_{\rm matter} + \rho_{\rm rad} + \rho_{\rm DE}) \qquad (2)$$

measuring expansion history $H(t)$
– or equivalently $H(z)$
will tell us how $\rho_{\rm DE}$ evolves!

Cosmic Expansion History

we want to probe dark energy via expansion history $H(t)$
i.e., measure expansion rate at different cosmic epochs

how to do this?

rough sketch of basic idea (right in sprit, but oversimplified):
use Hubble relation $v = cz \approx H\ D$

- find objects observable at wide range of times, and for each:
  1. measure redshift z
  2. measure distance $D(z)$
- infer expansion rate

$$H(z) = \frac{cz}{D(z)} \tag{3}$$

- read off expansion history by seeing change with z

Q: what's the hardest part of this procedure?

Supernovae and Cosmodynamics

goal: measure expansion at different z
$\rightarrow$ see how H evolved $\rightarrow$ probe ρ

key tool: **standard candle**
that is: an object of *known* luminosity L

procedure:
- find candle (and be sure it standard!) $\rightarrow$ know L
- measure flux F
- solve for "luminosity distance"

$$D_{\rm lum} = \sqrt{\frac{F}{4\pi L}} \tag{4}$$

need objects which:
- have fixed L indep of z, environment
- can see at high z $\rightarrow$ high L

$\rightarrow$ **supernova explosions**

Supernova Zoology: A Tale of Two Types

Massive star explosions $\rightarrow$ *SN: Type II*
bright, but: L varies w/ mass, metallicity
$\Rightarrow$ diversity is interesting but *bad for standard candle*

SN Type Ia:
`www: SN Ia images, UIUC simulations`
white dwarf explodes due to binary companion
accretion or merger?
WD $\rightarrow$ ^{56}Ni (radioactive) $\rightarrow$ ^{56}Fe
decay sets $L(t)$ $\rightarrow$ *standard candle!*

`www: SN 1994D` low-z
`www: SN subtraction image` medium-z
`www: HDF subtraction image` high-z

SN Ia and Expansion History

SN Measurements:

- SN redshift z
- SN flux F_{max} at max brightness

$\Rightarrow$ luminosity distance $D_{\text{lum}}(z) = \sqrt{L_{\text{max}}/4\pi F_{\text{max}}}$

to confuse the non-cosmologists:
SN-based $D(z)$ expressed in terms of
tblue*distance modulus*

$$\mu = m - M = -\frac{5}{2}\left[\log_{10}\frac{F(D)}{F(10\ \text{pc})}\right] = 5\log_{10}\frac{D(z)}{10\ \text{pc}} \qquad (5)$$

larger $\mu \to$ larger $D(z)$

www: SNIa results

find: as z increases, $D(z)$ *larger*
than expectations for $\Omega_{\text{matter}} = 1$ universe

...and even larger than expectations
for an empty universe $\Omega_{\text{matter}} = 0$
that is curvature-dominated

iClicker Poll: SNIa Implications

SNIa results show: $D(z)$ larger than in $\Omega_{\text{matter}} = 1$ universe

What does this say about expansion history?

A $H(z)$ was smaller than expected from matter
$\rightarrow \Omega_{\text{other}}(z)$ changes less rapidly than $\Omega_{\text{matter}}(z)$

B $H(z)$ was smaller than expected from matter
$\rightarrow \Omega_{\text{other}}(z)$ changes more rapidly than $\Omega_{\text{matter}}(z)$

C $H(z)$ was larger than expected from matter
$\rightarrow \Omega_{\text{other}}$ changes less rapidly with z

D $H(z)$ was larger than expected from matter
$\rightarrow \Omega_{\text{other}}(z)$ changes more rapidly than $\Omega_{\text{matter}}(z)$

SN Ia and Expansion History

What does this tell us?

- roughly: SN data traces expansion history $H(z) = cz/D(z)$
  so: can look for *changes* in expansion rate $H = \dot{a}/a$
  and: since $dH/dt = \ddot{a}/a - H^2$

$\Rightarrow$ SN data measures cosmic *deceleration/acceleration*

high-z supernovae are cosmic accelerometers!

Cosmic Acceleration–Predictions

expectations:

$$\frac{\ddot{a}}{a} = -\frac{4\pi}{3} G \left(\rho + 3P/c^2\right) \tag{6}$$

- ought to find $\ddot{a} < 0$
- gravity slows expansion $\Rightarrow$ expect cosmic **deceleration**

deceleration: expansion faster in past

$\rightarrow$ $H(z)$ decreases towards $z = 0$

$\rightarrow$ should find $H(z) > H(0)$

SN Ia: *Acceleration!*

SN data:
$H(z)$ **increases** towards $z = 0$
$\ddot{a} > 0$!
accelerating expansion!

`www: SN Ia data`

Q: what does this mean in the pop fly analogy?

Accelerating Universe: Pop Fly Analogy

Pop fly: ball thrown up in the air
ordinary baseballs: made of matter, feel Earth's gravity
$\rightarrow$ moves ever slower on the way up
$\rightarrow$ decelerated

but the *Universe* does the opposite!
a pop fly acting like the Universe
would get *faster* as it gets higher!
and so would launch itself to space!?!

Q: what does acceleration require in Friedmann equation?

An Accelerating Universe: Implications

SN Ia: $\ddot{a} > 0$

Friedmann:

$$\frac{\ddot{a}}{a} = -\frac{4\pi}{3}G\left(\rho + 3\frac{P}{c^2}\right) \tag{7}$$

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

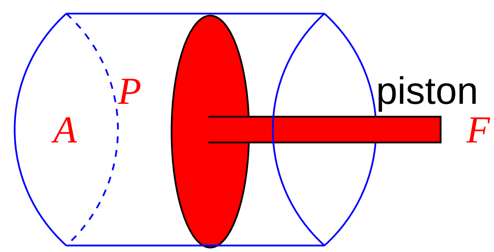
$\Rightarrow P < -\rho c^2/3$ negative pressure!?!

Physical "interpretation":

recall: $F = \int P dA$

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

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



Cosmic Acceleration: Simplest Solution

revive Einstein "**cosmological constant**"
introduce *new constant of nature* Λ

with Λ, Friedmann becomes:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3}G\rho - \frac{kc^2}{R_0^2 a^2} + \frac{\Lambda c^2}{3} \quad (8)$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi}{3}G\left(\rho + 3\frac{P}{c^2}\right) + \frac{\Lambda c^2}{3} \quad (9)$$

notice the nice features:
- with Λ, H changes more slowly than without
- Λ term positive in acceleration equation
  $\rightarrow$ naturally leads to acceleration

we can choose to encode Λ by an effective density and pressure:

$$\left(\frac{\dot{a}}{a}\right)^2 = = \frac{8\pi}{3}G\rho_{\rm tot} - \frac{kc^2}{R_0^2 a^2} \quad (10)$$

$$\frac{\ddot{a}}{a} = = -\frac{4\pi}{3}G\left(\rho_{\rm tot} + 3\frac{P_{\rm tot}}{c^2}\right) \quad (11)$$

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" `www: SN cosmo results`

SN Ia: $\Omega_\Lambda \simeq 0.7$, $\Omega_{\rm m} \simeq 0.3$

$\rightarrow$ independent evidence for $\Omega_{\rm not\,matter} \simeq 0.7$!