Astro 596/496 PC
Lecture 13
Feb. 17, 2010

Announcements:

- PS2 due Friday in class
  TA office hours Thursday 2–3pm, or by appt

Last time: finished cosmo muscle building
▷ passed Olympic trials
▷ onward to Vancouver!

ASTR 596/496 PC thus far: classical cosmology observations, Newtonian & Relativistic theory

Beginning now: 21st Century Cosmology

Cosmic Acceleration & Dark Energy

Cosmic Conundrum: Observations vs Good Taste

1990's Cosmology:

▷ theory (Dicke coincidence, inflation), good taste,
and some observational hints on large scales
$\rightarrow \Omega_0 = 1$

▷ observation (e.g., galaxy halos, clusters) $\rightarrow \Omega_m \sim 0.3$

Q: possible reasons for discrepancy?

Q: observational tests?

Probing Cosmic Expansion as Far as the Eye Can See

Friedmann: cosmic *contents* control cosmic *dynamics*
$\rightarrow$ cosmic ingredients encoded in *history* of cosmic expansion

Strategy: **measure** $H(z)$ over large range in z

- Friedmann: $H = H(z; \Omega_0) \rightarrow$ data over large z range determine Ω_0
- alternatively, Friedmann accel:

$$H^2 = -2\frac{\ddot{a}}{a} - 8\pi GP - \frac{\kappa c^2}{R^2 a^2}$$

$H(z)$ sensitive to acceleration, pressure, curvature

▷ *Q: what observables trace $H(z)$? what needed for large z range?*

Supernovae as Standard Candles

long "baseline" in $z \to$ **bright** sources
supernova explosions–can outshine a galaxy
at peak, $L_{\mathrm{SN}} \sim 10^{10} L_{\odot}$
`www: SN 1994D`

Procedure:

- identify SNe to use as standard candles
- measure flux F for events over wide range in z
- find $d_L(z) = \sqrt{L_{\mathrm{SN}}/4\pi F} \sim (1+z) \int_0^z dz/H(z)$
- infer $H(z) \to$ cosmic dynamics, parameters

First step:
all SN not created equal!
Q: what are basic SN classes? how distinct physically?

Supernova Zoology 101

▷ **Type II* (Core-Collapse) Supernovae**

massive star $\gtrsim 8 - 10 M_{\odot}$ gravitational collapse
optical (baryonic) explosion: $E_{\text{vis}} \sim 10^{51}$ erg
but most energy released in neutrinos: $E_{\nu} \sim 3 \times 10^{53}$ erg
neutron star/black hole remnant

*Types Ib and Ic events also due to core-collapse

▷ **Type Ia (Thermonuclear) Supernovae**

binary system: white dwarf and companion
WD accretes $\rightarrow$ pushed over Chandrasehkar limit
i.e., drive $M_{\text{WD}} > 1.4 M_{\odot}$ $\rightarrow$ gravitationally unstable
thermonuclear detonation $E_{\text{exp}} \sim 10^{51}$ erg

Q: pros and cons of each Type for cosmology?

Supernova Cosmology: The Good, the Bad, and the Ugly

Type II Supernovae

Pro

- Understand basic physics:
  most E_{SN} in neutrinos
  saw 1987A neutrinos
  confirmed basic picture

Con

- Don't understand optical explosion:
- $E_{\mathrm{vis}} \sim 1\% E_{\mathrm{SN}}$ tough!
  models often don't explode!
- core collapse: range of masses, E_{SN}

$\Rightarrow$ diverse range of L $\Rightarrow$ candle not std

occur in $\star$-form regions $\rightarrow$ obscured

Type Ia Supernovae

Pro

- Chandra limit $\sim$ fixed mass
  $+$ nuke binding $\sim$ fixed
  $\approx$ fixed E release
  $\Rightarrow$ fixed $L(t)$: std candle!
- low-z SN Ia nearly identical $L(t)$
- outside $\star$-form: less(?) osbscured

Con

- Don't understand basic
  scenario: who is companion?
  giant? another WD?
  astrophysical "black box"
- low-z Ia *not* identical $L(t)$

Type Ia Supernovae: "Standardizable" Candles

Type Ia events: best candidates on balance (for now)

- empirically (low-z) closest to std candles
- typically ~ 1 mag brighter than SN II $\rightarrow$ can probe higher z
- ...but check for systematics!

Type Ia light curves (low-z): *E Pluribus Unum*

light curve $L(t)$ same basic shape–rise, fall

... but spread in timescale ($\sim$ FWHM) & peak L

... but these are tightly *correlated*!

$\rightarrow L(t)$ spread can be empirically fit with 1 parameter

$\Rightarrow$ *scaled* light curves $\approx$ identical! `www: light curves`

$\Rightarrow$ "**standardized**" candles!

Supernova Cosmology Campaigns

Automated searches:

▷ digital sky scans $\sim$ 3–4 weeks apart

▷ subtraction $\rightarrow$ SN Ia, max light

▷ followup to get spectra as dims

`www: SN images, spectra`

⋆ Supernova Cosmology Project
starting with SN 1992bi:

- $\sim$ 100 SN Ia
- $0.15 < z < 1.2$

⋆ High-z Supernova Search
Starting with SN 1995K:

- $\sim$ 50 SNe
- $0.3 < z < 1.2$

⋆ Hubble Space Telescope

fewer but very high-z events

Riess et al (2004):

- 16 SN Ia
- $0.6 < z < 1.6$; highest-z sample

Riess et al (2007), GOODS survey with ACS:

- 13 new SN Ia
- $0.5 < z < 1.4$

Combine low-z + high-z data, then:

1. do cosmology
2. worry

Luminosity Distance and Acceleration

for a flat universe

$$d_L(z) = (1+z)\int_0^z \frac{dz'}{H(z')}$$

so $d_L(z) \sim \langle 1/H(z) \rangle$ traces expansion rate history

strategy:

- measure d_L over large z range
- infer change in $\langle 1/H \rangle$

Q: What does this give us?

Q: What are basic trends?

Change in $1/H \rightarrow$ change in H:
$\Rightarrow$ acceleration vs deceleration

in fact, can show d_L (and d_A!) sensitive to
acceleration parameter

$$q \equiv -\frac{\ddot{a}/a}{(\dot{a}/a)^2} \tag{1}$$

Q: why conventional $-$ sign?

present value: q_0
but in general q can evolve

For the Experts...

Can show

$$d_L(z) = (1+z)\frac{c}{H_0}\int_0^z \frac{dz'}{1+z'} e^{-\int_0^{z}{}' q(u)\, d\ln(1+u)}$$

- cosmological details only enter via q
- uses only RW, not Friedmann: result indep of GR!

Compare different "universes" – i.e., models with different $q(z)$

$$\frac{d_L(z)_{\text{universe 1}}}{d_L(z)_{\text{universe 2}}} = \frac{\int_0^z \frac{dz'}{1+z'} e^{-\int_0^{z'} q(u)_{\text{universe 1}}\, d\ln(1+u)}}{\int_0^z \frac{dz'}{1+z'} e^{-\int_0^{z'} q(u)_{\text{universe 2}}\, d\ln(1+u)}}$$

Compare two possible universes

- non-accelerating: $q = 0$
- decelerating: $q > 0$

Q: which has bigger d_L at fixed z and fixed H_0?

Q: what if positive acceleration*?* `www:` d_L `plots`

SN Ia Survey Predictions

Luminosity distance: $d_L(z) = (1+z) r_{\text{com}}(z)$

- $r_{\text{com}} \stackrel{\text{flat}}{=} \int dt/a(t) = \int dz/H(z)$: closest in decelerating U
  $\Rightarrow d_L^{\text{decel}} < d_L^{\text{non-accel}} < d_L^{\text{accel}}$
- candle brightness: $F_{\text{decel}} > F_{\text{non-accel}} > F_{\text{accel}}$

but since gravity is attractive, should slow expansion...

▷ deceleration: $q > 0$

faster H in past $\rightarrow$ smaller $1/H$

$\rightarrow$ predict $d_L(\text{obs}) < d_L(\text{non}-\text{accel})$

$\rightarrow$ predict $F_{\text{obs}} > F_{\text{non-accel}}$:

expect std candles *brighter* than in $q = 0$

SN Ia Survey Observations

`www:  SNIa survey data`

Exactly the *opposite* of predictions!

⋆ std candles **faint!**

in mags, $m_{\rm obs} > m_{\rm non-accel}$

flux $F_{\rm obs} < F_{\rm non-accel}$

⋆ $d_L(\text{obs}) > d_L(\text{non} - \text{accel})$

Q: possible explanations?

...(at least 3 distinct classes)

Q: pros and cons?

Q: how to observationally test?

Faint SN Ia: Whodunit?

⋆ **Blame the Observations**

i.e., m(obs) $\neq$ m(std candle)

e.g., different rotation rates could affect explosion *Q: why? how?*

possible explanation for stretch factor, or scatter around it?

maybe: SN Ia peak L evolution with cosmic t?

intervening dust $\rightarrow$ non-cosmo dimming

but: no evidence for SN Ia envt dependence

at $z > 1$, $F_{\rm obs} \rightarrow F_{\rm non-accel}$: not obscuration

⋆ **Blame Einstein**

observations correct, but

expectations based on gravity theory = GR

maybe: **GR incorrect/incomplete**

$\dot{a}(t)$ and $\ddot{a}(t)$ don't follow Friedmann

$\Rightarrow$ SN Ia point beyond GR! Quantum Gravity?

but: GR successful in "local" precision tests

on Earth, in SS, in binary pulsar

⋆ **Blame the Universe**

observations correct, and GR correct as well, so

infer existence of **new cosmic contents** which drive acceleration

e.g., acceleration points to an accelerant!

maybe: Friedmann OK, but missing terms

i.e., beyond matter (including DM!) and radiation

new source(s) of ρ, P

but: Who ordered that!?! What is the physics?