Class 12 : Supernova cosmology and the acceleration of the Universe

- This class
  - Redshift-distance relation as a probe of the cosmological model
  - Type-1A supernovae
  - Supernovae and cosmology
  - Discovery of acceleration
  - It all fits together… concordance cosmology

0 : Recap of last two classes

- Used FRW metric to examine propagation of photons. Radially propagating photons described by

$$\int_{t_e}^{t_r} \frac{c\,dt}{a} = \int_0^{r_0} \frac{dr}{\sqrt{1-kr^2}}$$

- Derived redshift/scale-factor relation

$$1+z = \frac{a(t_r)}{a(t_e)}$$

- Found that, for at least some cosmological models (e.g. matter or radiation dominated flat models), photons only travel finite proper distance since big-bang. Introduces idea of particle horizon. Example; for matter-dominated flat Universe we have

$$d_H = a_0 r_H = 3ct_0$$

- Found that, practically, there are different definitions of distances…
- Luminosity distance (i.e. that which appears in the inverse square law connecting luminosity and flux)…

$$d_L = a_0 r \times (1+z)$$

- Angular size distance (i.e. that which appears in the expressions for the angular size of an object)

$$d_A = \frac{a_0 r}{(1+z)}$$

I : Diagnostic power of redshift-distance relation

- Important point...
  - When viewing a galaxy, function r(z) depends upon cosmological model.
- Example: matter-dominated flat Universe
  - Coordinate distance is

$$a_0 r(z) = 3ct_0 \left[1 - \frac{1}{\sqrt{1+z}}\right]$$

  - Luminosity distance is

$$d_L = 3ct_0 \left[1 + z - \sqrt{1+z}\right]$$

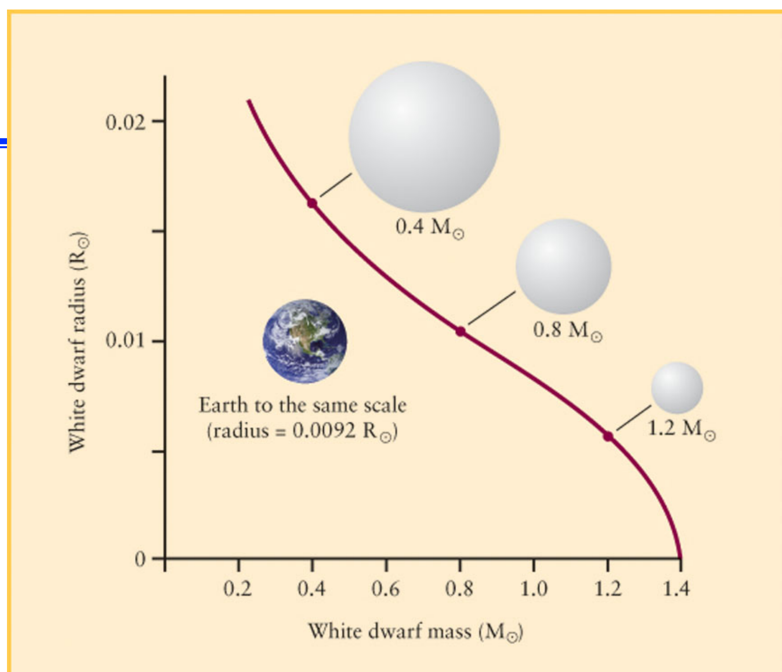
  - For small redshifts, we have

$$d_L \approx \frac{3ct_0}{2}\left[z - \frac{1}{4}z^2\right] = \frac{cz}{H_0}\left[1 - \frac{1}{4}z\right]$$

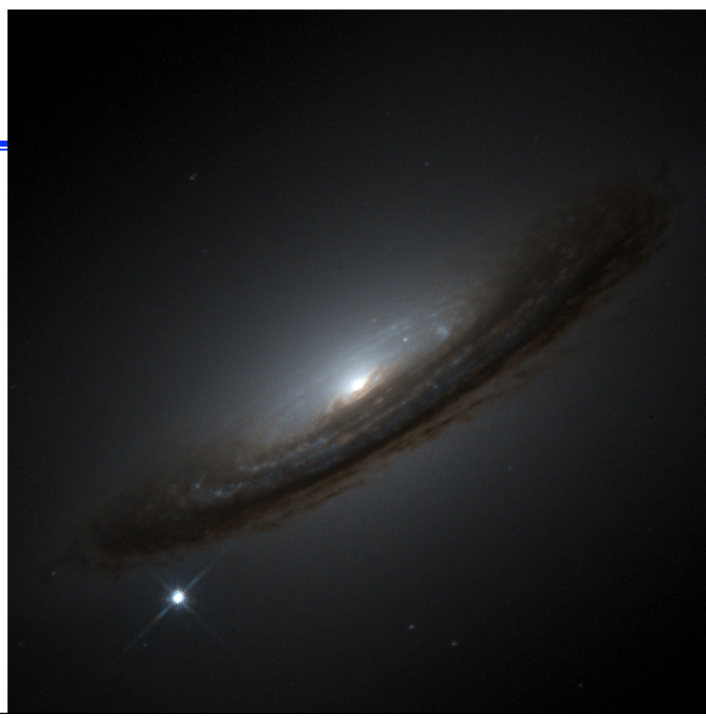
  - What have we just recovered?

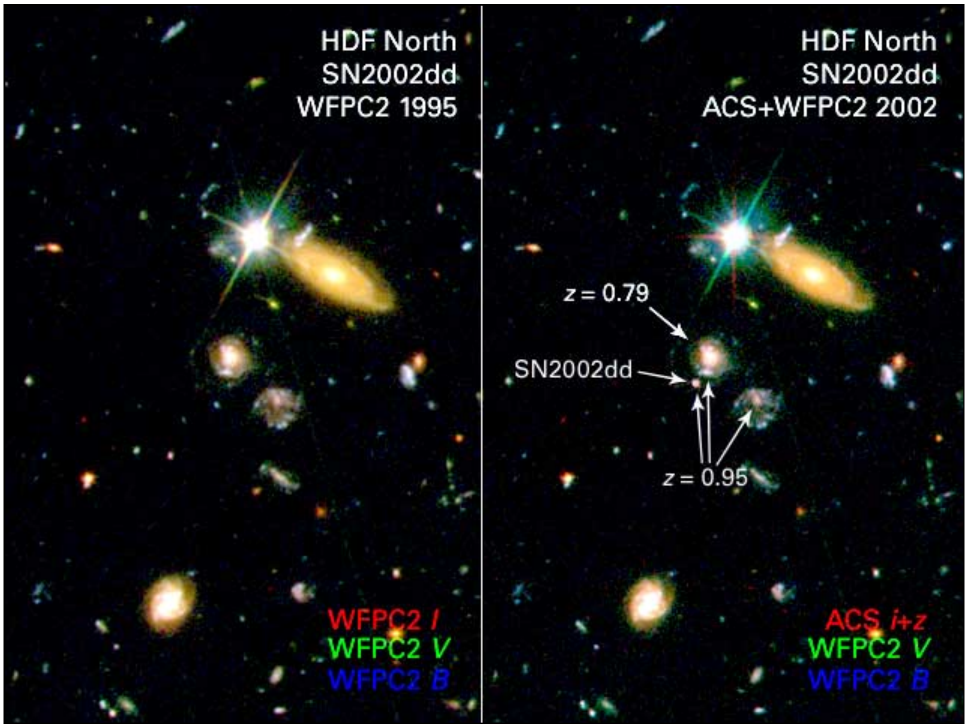
II : Type-1A Supernovae

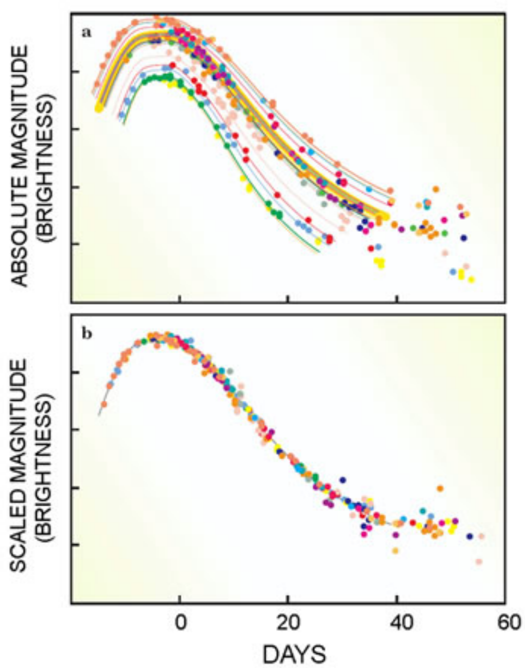
- Basic goal : to determine luminosity distance as a function of redshift out to high redshift; then compare with predictions from cosmological models
- We need to objects that are good standard candles:
  - Need to have a known luminosity
  - Need to be very luminous (so we can see them at cosmological distances)
  - Need to be easily recognized (so we don't confuse them with other things)
- Type-1A supernovae fit the bill!



- What is a Type-1A supernova?
  - SN1A's are white dwarfs that have been pushed over the Chandrasekar limit ($1.4M_{sun}$) by the accretion of material from a companion…
  - WD starts to collapse
  - Collapse induces thermonuclear incineration
- In more detail, here's a possible scenario…
  - Start off with a binary star system
  - One star comes to end of its life – forms a "white dwarf" (made of helium, or carbon/oxygen)
  - If close enough, tidal forces of the white dwarf pull matter off the other star… adds to mass of white dwarf (accretion)
  - If accretion pushes white dwarf over the **Chandrasekhar Mass Limit**, it starts to collapse
  - Rapid compression initiates **thermonuclear runaway**… burn whole mass of white dwarf to iron/nickel in few seconds
  - Liberated energy blows the star apart… **no remnant**.



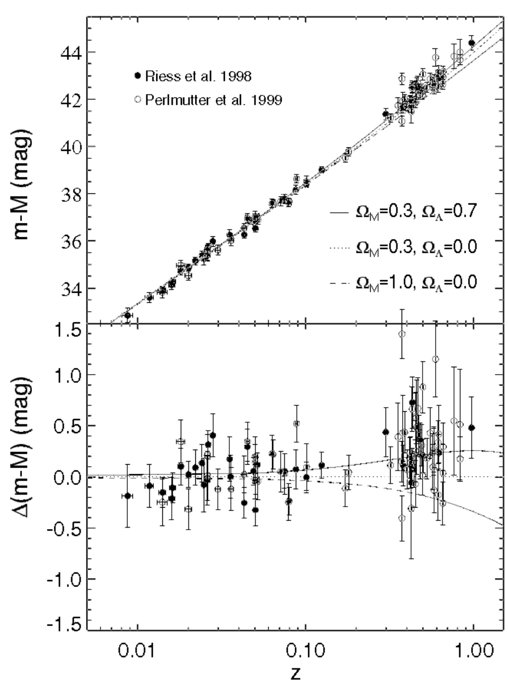




Complication *: In fact, SN1A's are not perfect standard candles… one needs to apply a "stretch correction" to correct for intrinsic differences*

III : Supernova cosmology

- The program…
  - Search for SN1a in nearby & distant galaxies
  - When you find one… measure its redshift and track its lightcurve so you can apply the stretch correction and derive its luminosity
  - Compare inferred luminosity with measured flux in order to derive its luminosity distance
  - Compare with expectations from cosmological models…
    - Nearby supernovae give us H_0
    - Distant supernovae tell us about how H changes with time



IV : Acceleration and Dark Energy

- Supernovae imply that the scale factor is accelerating!!
- Let's look at acceleration equation

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

  - Acceleration means that we must have

$$p < -\frac{1}{3}\rho c^2$$

  - Strange stuff!   Has negative pressure!
  - Indeed, it formally violates the "Strong Energy Principle"

- So we say that, in addition to matter and radiation, there is a new component/fluid, **dark energy**, with an equation of state

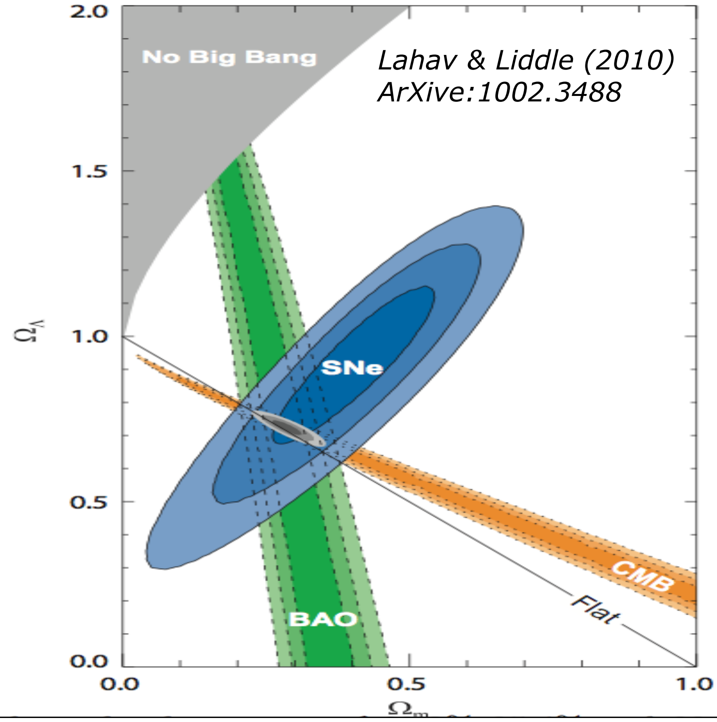
$$p = w\rho c^2 \quad \text{with} \quad w < -\frac{1}{3}$$

- There is a different way of looking at things…
- What if we change the way gravity works?
  - Einstein found that the mathematics permitted the inclusion of an additional term in the GR field equations.
  - Tracking this through gives the "Cosmological Constant" (Λ) terms in the Friedmann and acceleration equation…

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

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

  - Einstein first proposed Λ-term because he thought that the Universe was static (later called this his "greatest mistake")
  - Λ-term acts just like dark energy with $p=-\rho c^2$.
  - Λ-term also acts like a vacuum energy ρ=constant



Parameter	Symbol	Value
Hubble parameter	h	0.72 ± 0.03
Total matter density	$\Omega_{\rm m}$	$\Omega_{\rm m} h^2 = 0.133 \pm 0.006$
Baryon density	$\Omega_{\rm b}$	$\Omega_{\rm b} h^2 = 0.0227 \pm 0.0006$
Cosmological constant	Ω_Λ	$\Omega_\Lambda = 0.74 \pm 0.03$
Radiation density	$\Omega_{\rm r}$	$\Omega_{\rm r} h^2 = 2.47 \times 10^{-5}$
Neutrino density	Ω_ν	See Sec. 1.1.2
Density perturbation amplitude	$\Delta^2_{\mathcal{R}}(k = 0.002\,{\rm Mpc})$	$(2.41 \pm 0.11) \times 10^{-9}$
Density perturbation spectral index	n	$n = 0.963^{+0.014}_{-0.015}$
Tensor to scalar ratio	r	$r < 0.43$ (95% conf.)
Ionization optical depth	τ	$\tau = 0.087 \pm 0.017$
Bias parameter	b	See Sec. 1.3.4

Lahav & Liddle (2010)
ArXive:1002.3488