Supernova Cosmology

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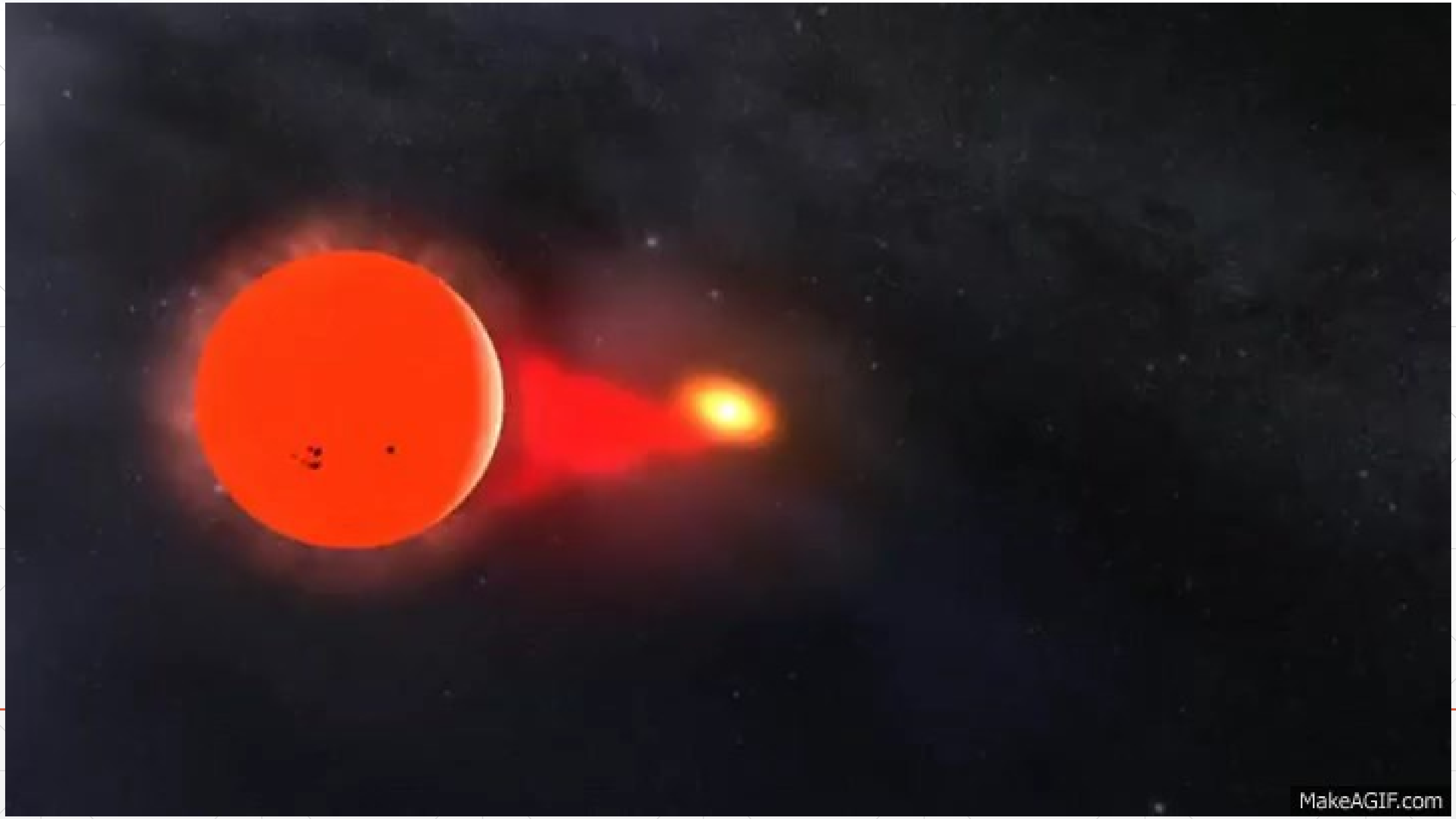
MACSS School, May 2017.


explosions in the sky

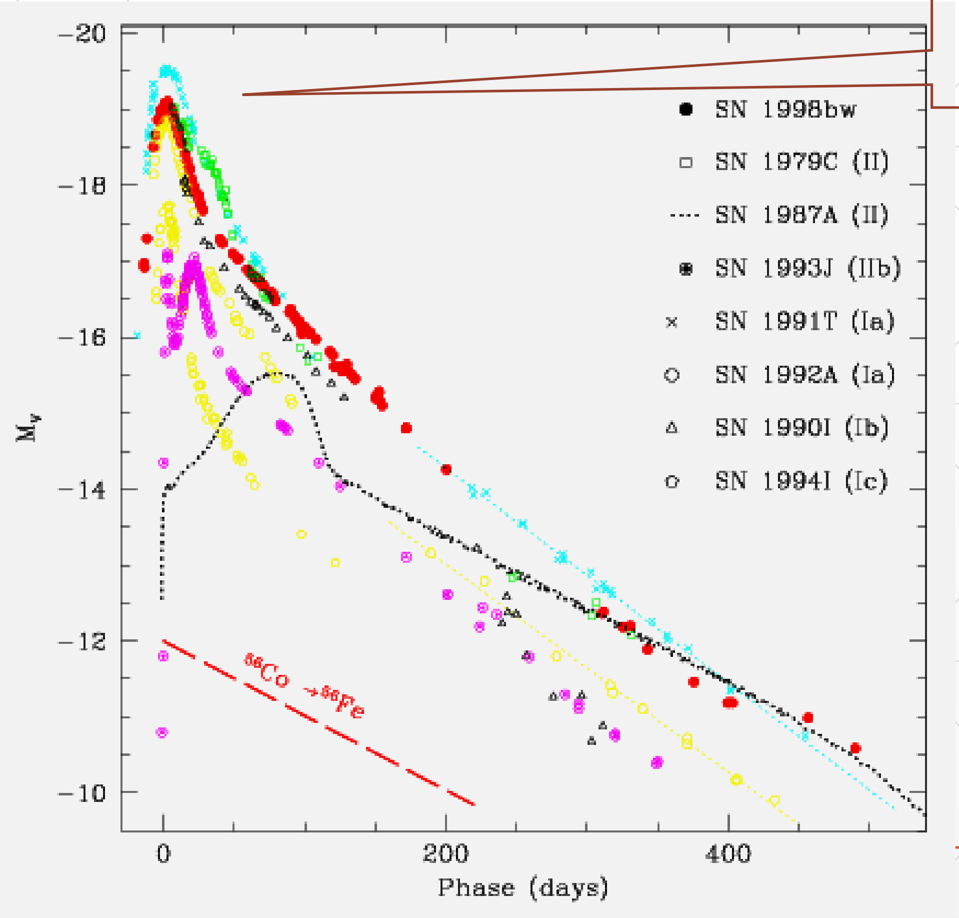

MakeAGIF.com

Explosions in the Sky

- Type Ia Supernovae are produced in the explosion of a White Dwarf: a star constituted by protons and electrons sustained by degenerate pressure.
- If our WD has a less compact companion nearby (A red giant or an even smaller WD) it will accrete its outer layers increasing its mass
- The star becomes unstable upon reaching the Chandrasekhar Mass Limit at $1.4\ M_{\odot}$
- The gravitational instability triggers an explosion.

THE SUPERNOVA EXPLOSION

Highest peak luminosity $L \approx 10^6 L_\odot$



^{56}Ni exploding near Chandrasekhar limit

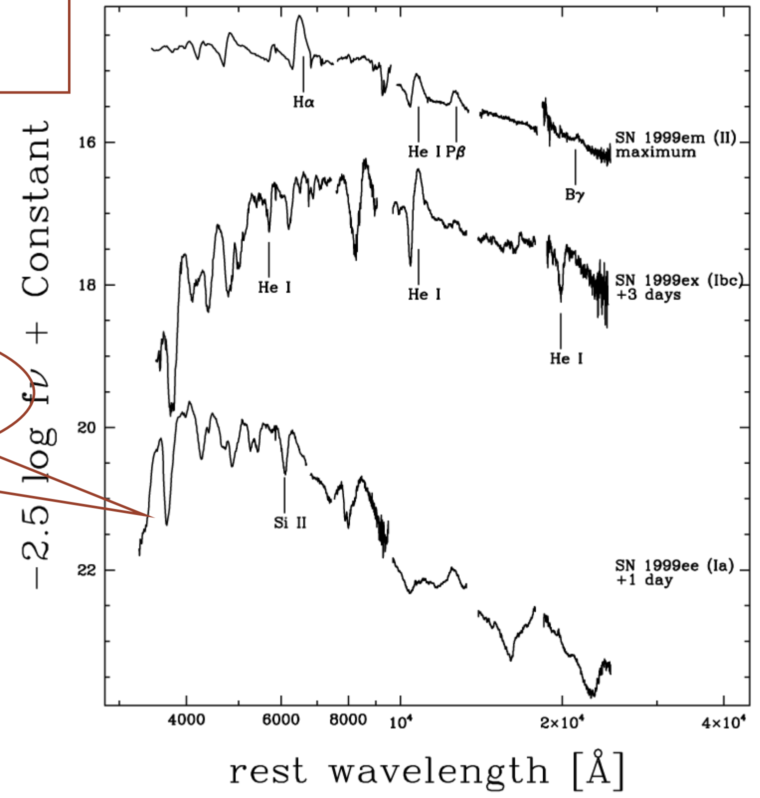
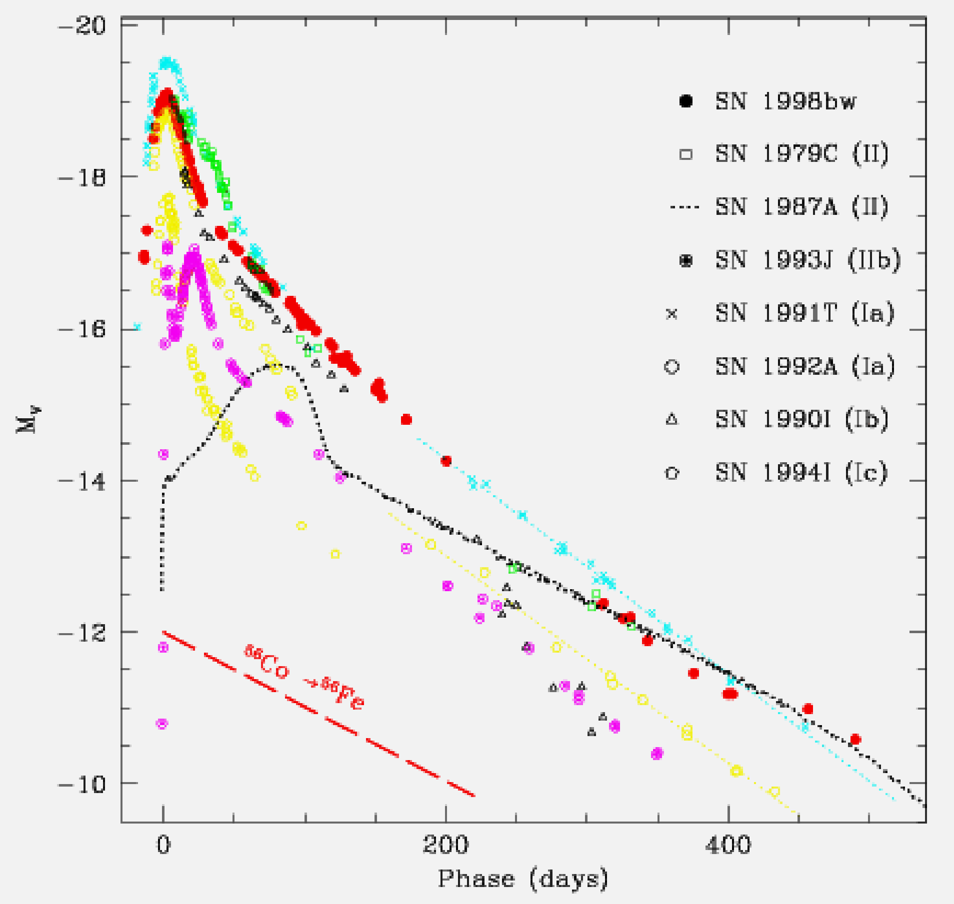


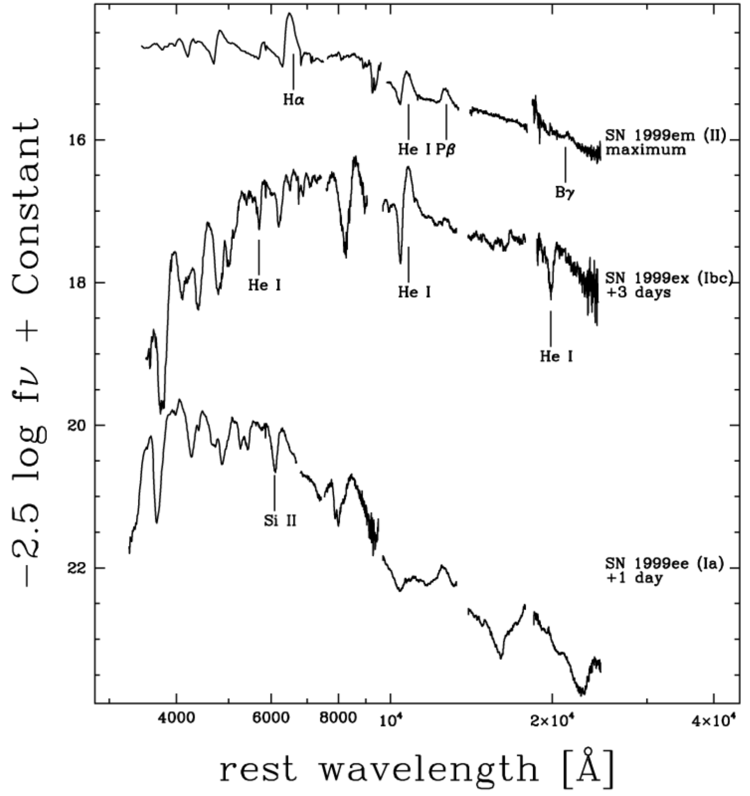
Fig. 13.— Combined optical and IR maximum-light spectra of the Type II SN 1999em, the Type Ib/c SN 1999ex, and the Type Ia SN 1999ee.



- Brightest SNe
- Characteristic heavy element synthetization

$$^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$$

- Homogeneity in both spectra and lightcurves
- But…



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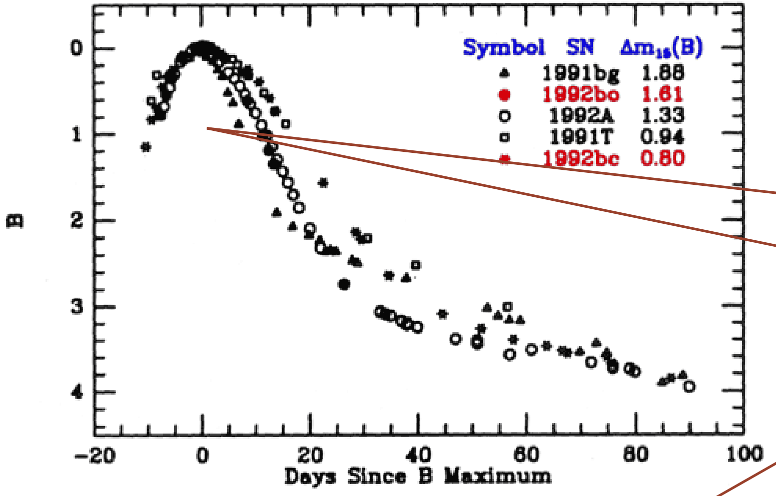
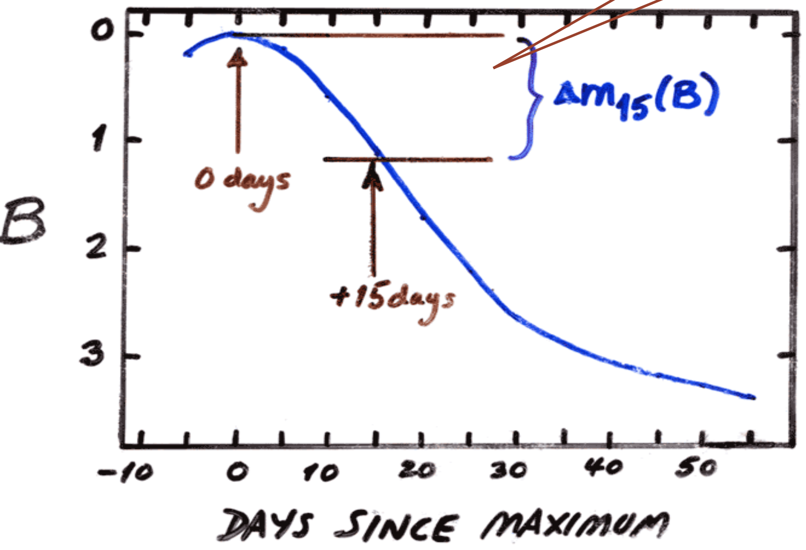


But Standard Candle luminosity is dependent on a light-curve evolution parameter Δm



$$M_{\max}(B) = -21.726 + 2.698\Delta m_{15}(B)$$

Philips '93: "measuring the total amount in magnitudes that the light curve decays from its peak brightness during some specified period following maximum light"

Absolute magnitude

- Δm will modify the absolute magnitude $M = -19.6$ (?) at the peak of luminosity: the total luminosity measured at 10 Mpc. The observed flux is proportional to the apparent magnitude m

$$m = -2.5 \log_{10} F + \text{const.}$$

$$Flux = \frac{emmited\ power}{unit\ area} = \frac{source\ luminosity}{area\ of\ sphere} = \frac{L}{4\pi d_l^2}$$

$$\boxed{\mu \equiv M - m = 5\log_{10}\left(\frac{d_\ell}{10\ pc.}\right)}$$

- With luminosity distance computed from the Cosmological model.

Both pieces of μ dependent on predetermined H_0 (Cepheids)

A ΛCDM Distance calculation

- Luminosity distance computed from the FLRW metric and the Friedmann equation

$$H^2 = \frac{8\pi G}{3}\left[\rho(t) + \frac{\rho_{cr}-\rho_0}{a(t)^2} + \frac{\Lambda}{8\pi G}\right], \quad \text{with} \qquad \rho_{cr} = \frac{3}{8\pi G} H_0^2$$

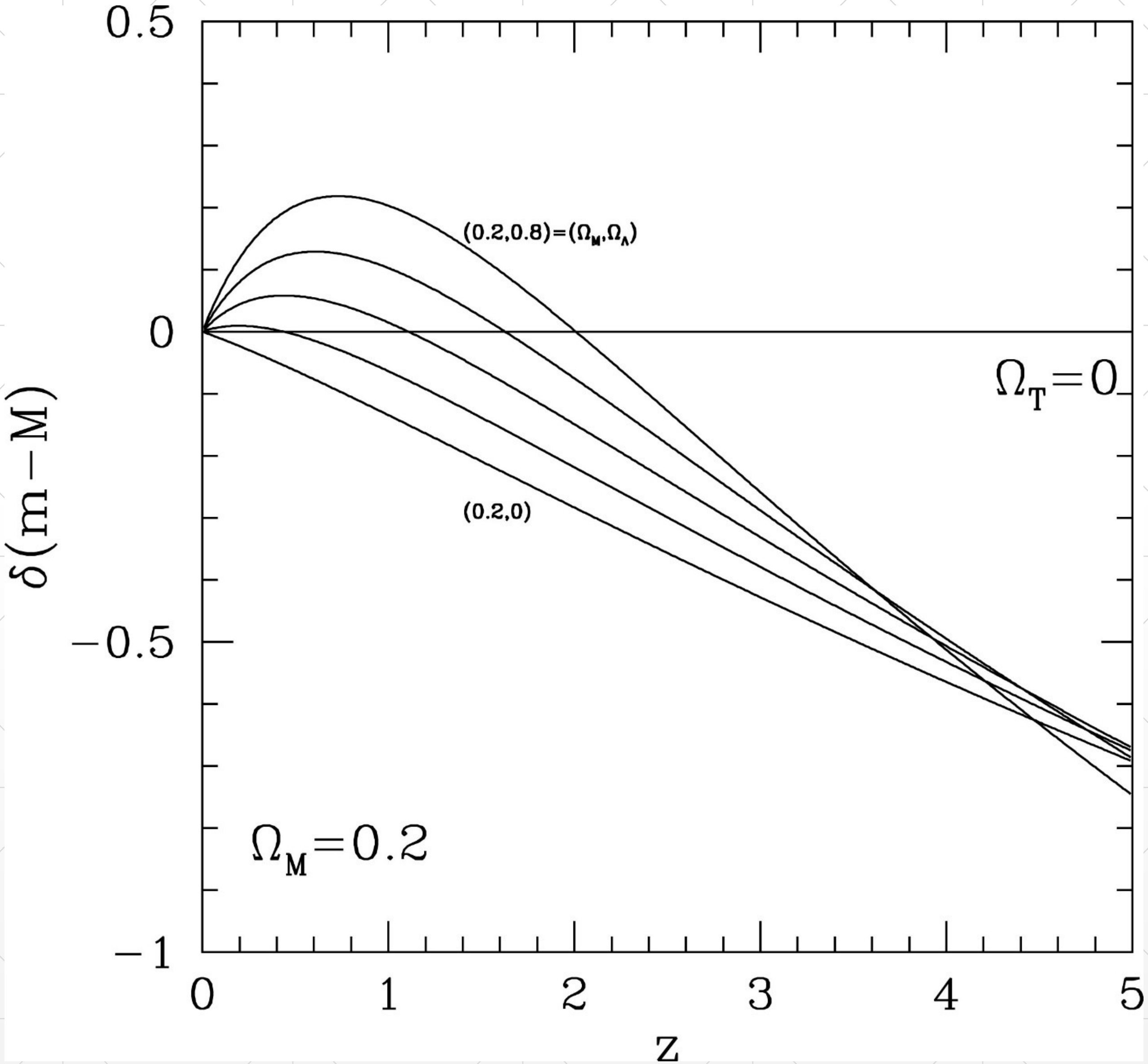
- In a flat universe with cosmological constant Λ, the density parameter $\Omega_\Lambda = \frac{\Lambda}{3H_0^2}$ dictates the luminosity distance as

$$d_l = (1+z)c\, H_0^{-1} \int_{a(z)}^{0} \frac{da}{\left[\Omega_\Lambda + \frac{1-\Omega_\Lambda}{a^3}\right]^{1/2}}$$

- The magnitude relation compares theory and observations

Absolute magnitude vs. distance

- Hubble diagram of Sne $(M\ vs.\ v_0)$ show scatter due to peculiar motions, extinction in the parent galaxy and absolute magnitude scatter.
- It is inferred that the intrinsic scatter in absolute magnitude is less than $\sigma_B = 0.2$ mag.



Other Nuiasence (parameters)

- Hubble diagram of Sne $(M\ vs.\ v_0)$ show scatter due to peculiar motions, extinction in the parent galaxy and absolute magnitude scatter.
- The dipole moment of the CMB may impact on the data of samples of SNe which assume an isotropic, homogeneous background.
- The observed difference in peak luminosities are correlated to observed differences in the shape of their lightcurves. The brighter the maximum, the slower is the decline on brightness after the maximum.

$$\mu_i \equiv M - m_i = 5\log_{10}\left(\frac{d_\ell(z_i)}{10\ pc.}\right) + \alpha X_{1,i} - \beta C_i$$

Sne Ia prospects

- What cosmology?
- Is physics involved understood?

"Dark Energy", Ed. P. Ruiz-Lapuente, CUP, 2009.

offer the as yet unproven possibility of delivering constraints on growth though the change in the amplitude of the power spectrum. The time-dependence of the matter density perturbations, $\delta\rho/\rho$ obeys the equation

$$\ddot{\delta} + 2H\dot{\delta} = 4\pi G\rho_m\delta. \tag{1.9}$$

COSMOLOGY

Dark is the new black

Richard Massey *Nature* **461**, 740-741 (8 October 2009)

Rival experimental methods to determine the Universe's expansion are contending to become the fashionable face of cosmology. Fresh theoretical calculations make one of them the hot tip for next season.

Earth. However, the accelerating expansion of the Universe means that distant supernovae have already receded farther from us and

parameterized only to a certain precision, and

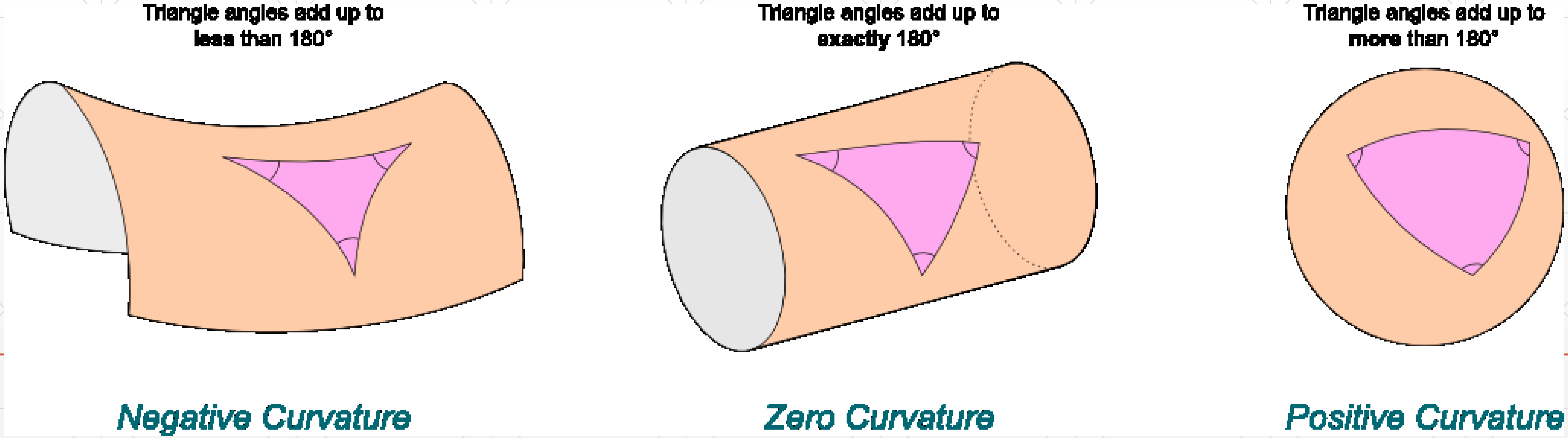
740

COSMOLOGY

FLRW Metric

$$ds^2 = -dt^2 + a(t)^2\left[\frac{dr^2}{1-kr^2} + r^2\left(d\theta^2 + \sin(\theta)^2 d\phi^2\right)\right]$$

$$k = \begin{cases} +1 & \textit{Closed Universe} \\ 0 & \textit{Flat Universe} \\ -1 & \textit{Open Universe} \end{cases}$$



FLRW Metric

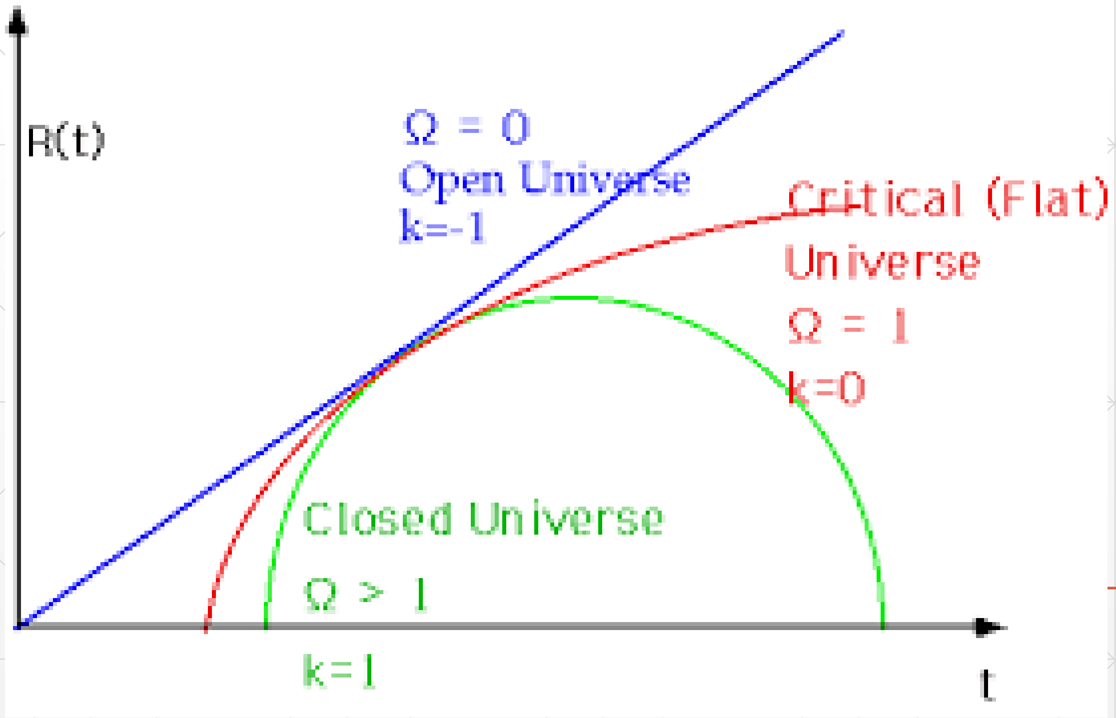
$$ds^2 = -dt^2 + a(t)^2 \left[d\chi^2 + f_k(\chi)^2 (d\Omega)\right]$$

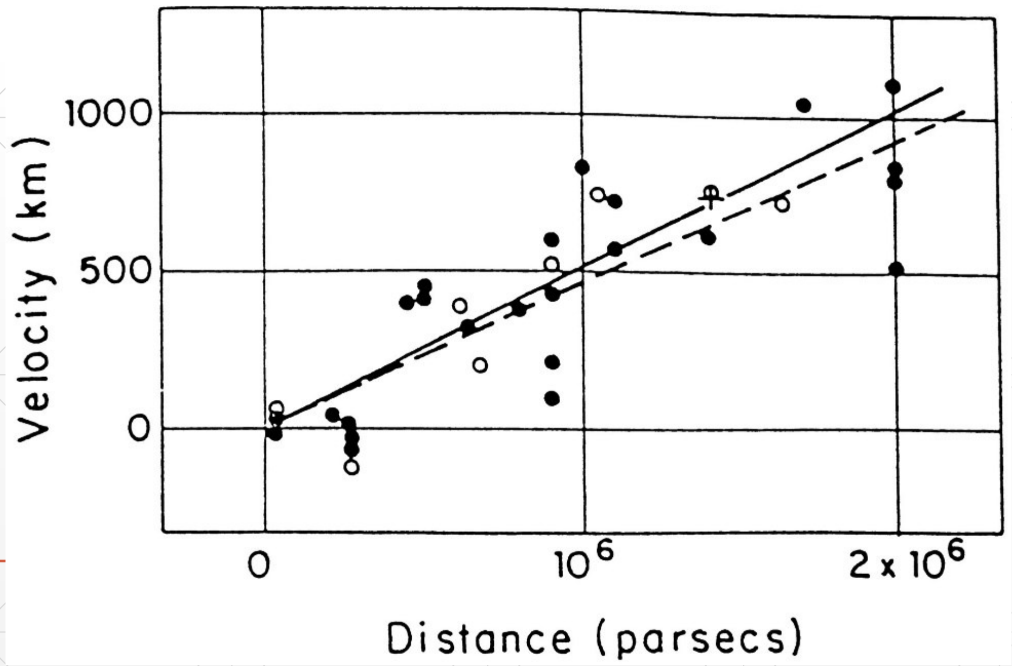
E. Hubble, 1929

$$\boxed{H \equiv \frac{1}{a}\frac{d}{dt}a = \frac{\dot{a}}{a}}$$

$$\underline{v} = H\underline{R}(t, \underline{r})$$

Expansion History





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HST, 2009

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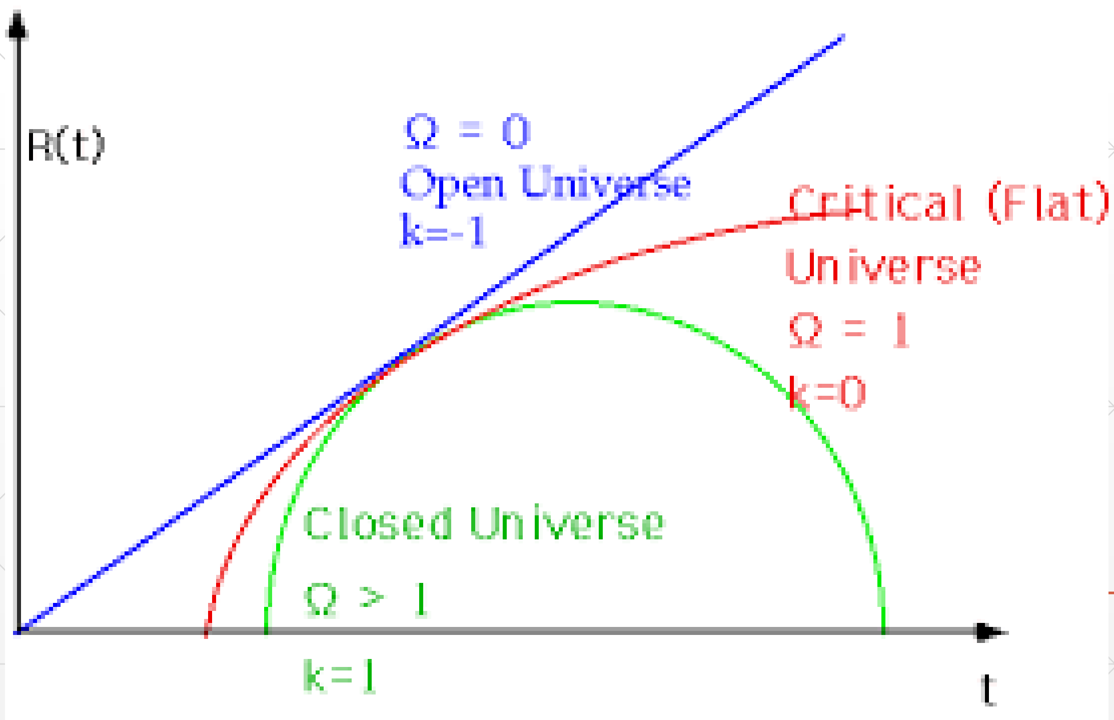
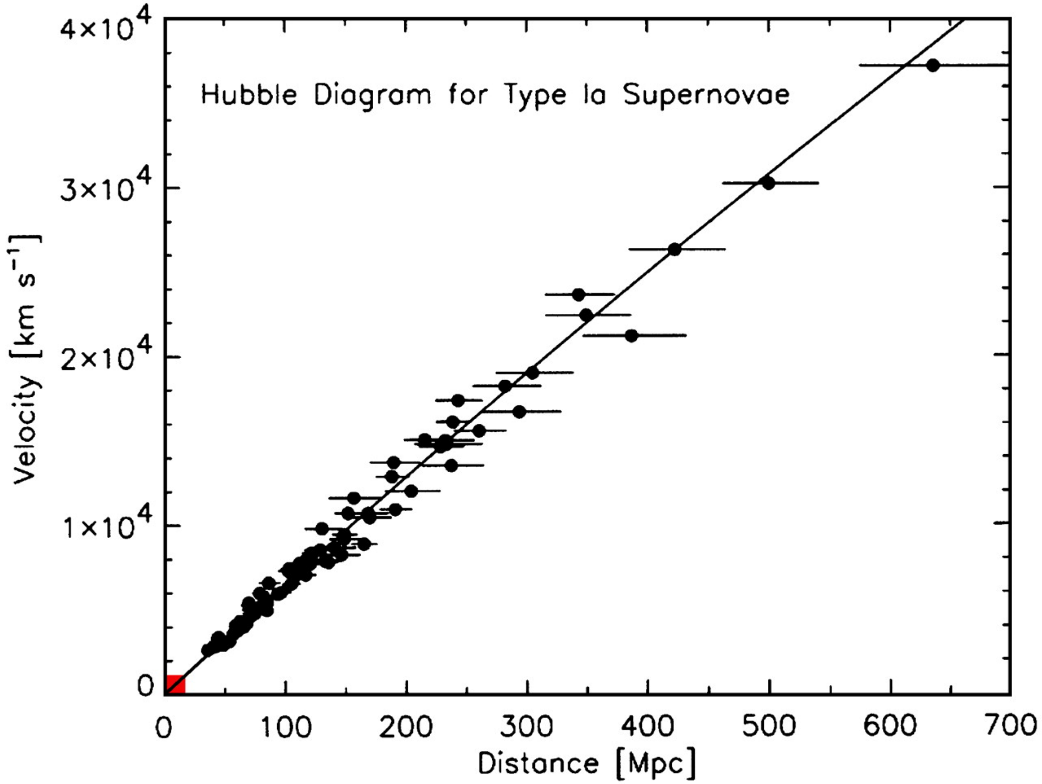


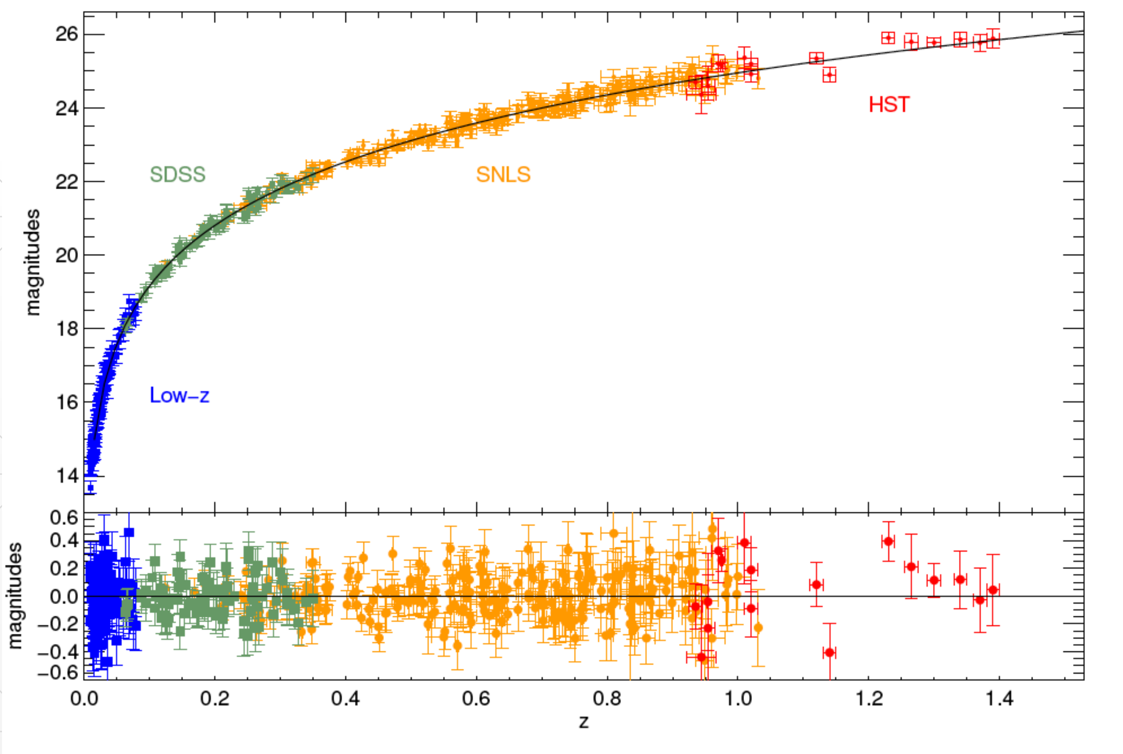


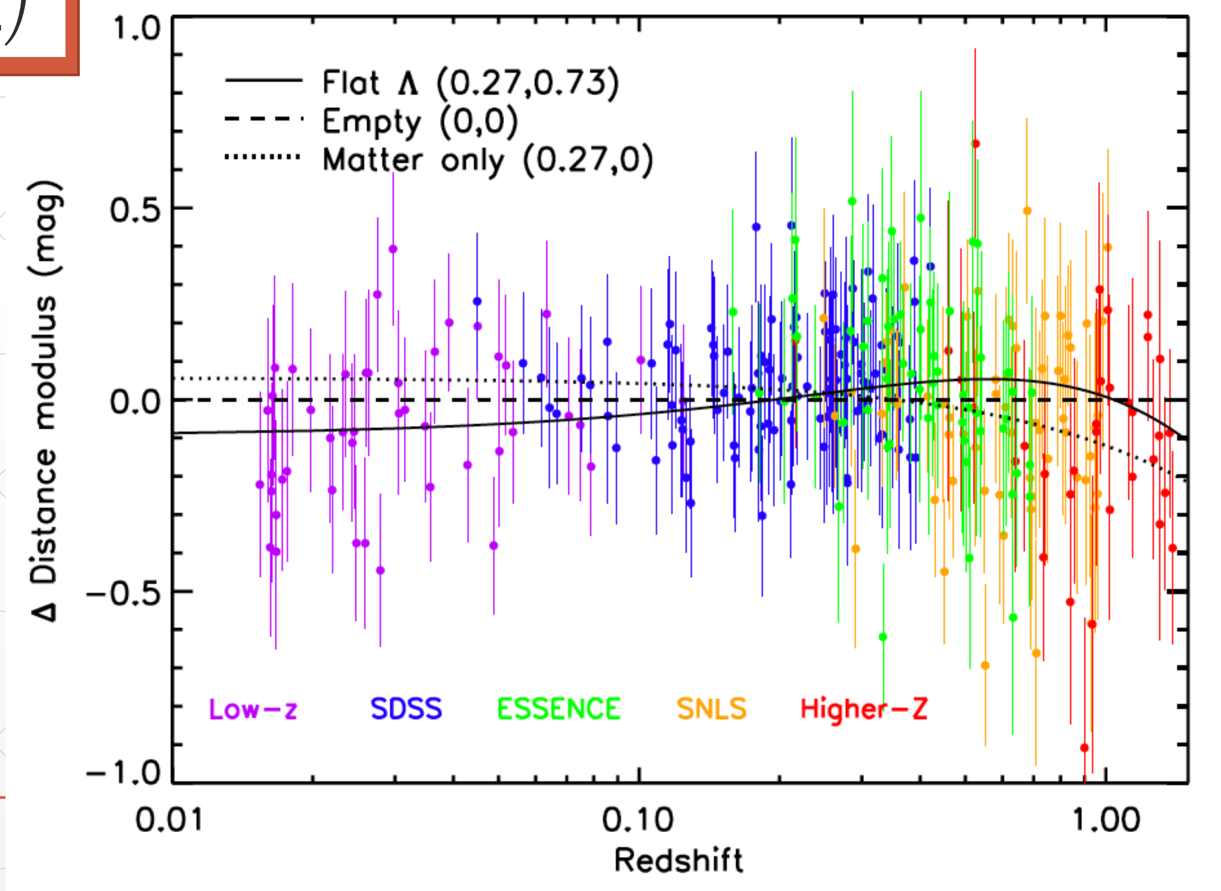
FLRW Metric

$$ds^2 = -dt^2 + a(t)^2 \left[d\chi^2 + f_k(\chi)^2 (d\Omega)\right] \quad f_k(\chi) = \begin{cases} \sin\chi & k = +1 \\ \chi & k = 0 \\ \sinh\chi & k = -1 \end{cases}$$

Expansion history

$$\boxed{\mu \equiv M - m = 5\log_{10}\left(\frac{d_\ell}{10\ pc.}\right)}$$





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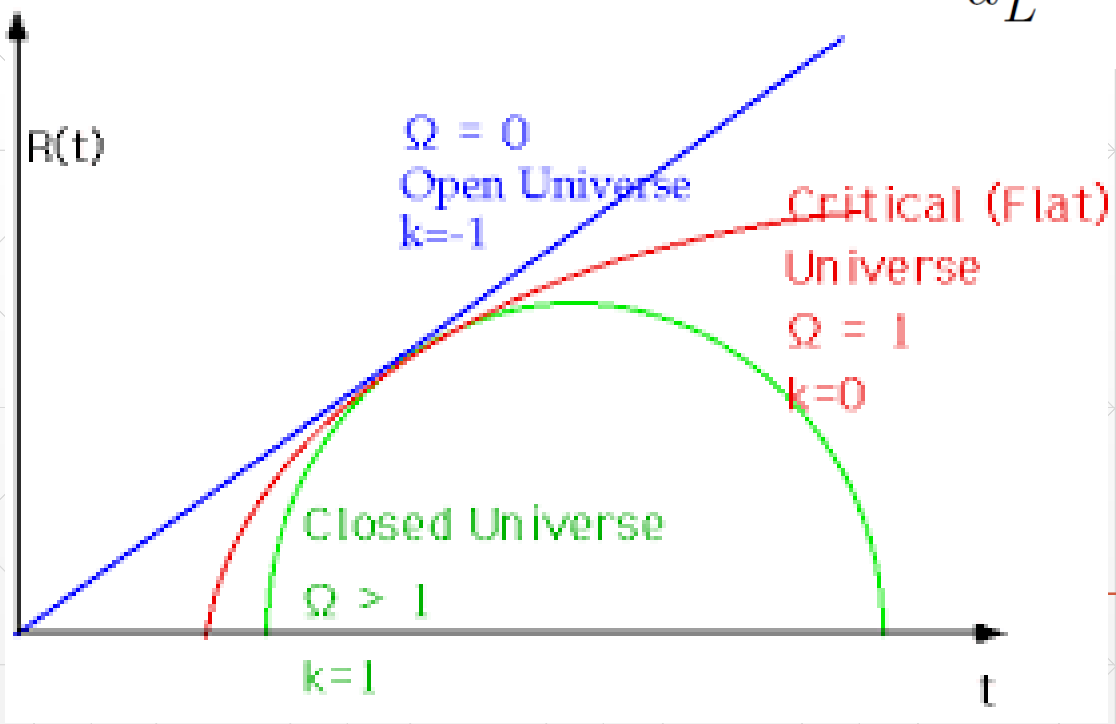
Luminosity Distance

$$d_L^2 = \frac{L_{\rm em}}{4\pi\mathcal{F}} = (a_0 f_k(\chi))^2\frac{L_{\rm em}}{L_{\rm obs}} = (a_0 f_k(\chi)(1+z))^2$$



$$\boxed{d_L = (a_0 f_k(\chi)(1+z))}$$

Comoving Distance

$$\boxed{\chi = d_c = \frac{c}{H_0}\int_0^z \frac{dz}{H(z)/H_0}}$$

Hubble Equation

$$H^2 = \frac{8\pi G}{3}(\rho_{\rm rad} + \rho_{\rm m} + \rho_{\rm DE}) - \frac{c^2}{a^2}K$$

- Define Density parameters

$$\Omega_{\rm DE} = \frac{8\pi G \rho_{\rm DE}}{H_0^2}$$

- Comoving distance integrates:

$$\frac{H^2}{H_0^2} = \left[\Omega^0_{\rm rad}(1+z)^4 + \Omega^0_{\rm m}(1+z)^3 + \Omega_{\rm DE}(z) + \Omega^0_k\,(1+z)^2\right]$$

MODEL DEPENDENT

Dark Energy Parameters

$$\Omega_{\rm DE} = \frac{8\pi G\rho_{\rm DE}}{H_0^2}$$

- D.E. as a fluid $P_{\rm DE} = \omega_{\rm DE}\rho_{\rm DE}$

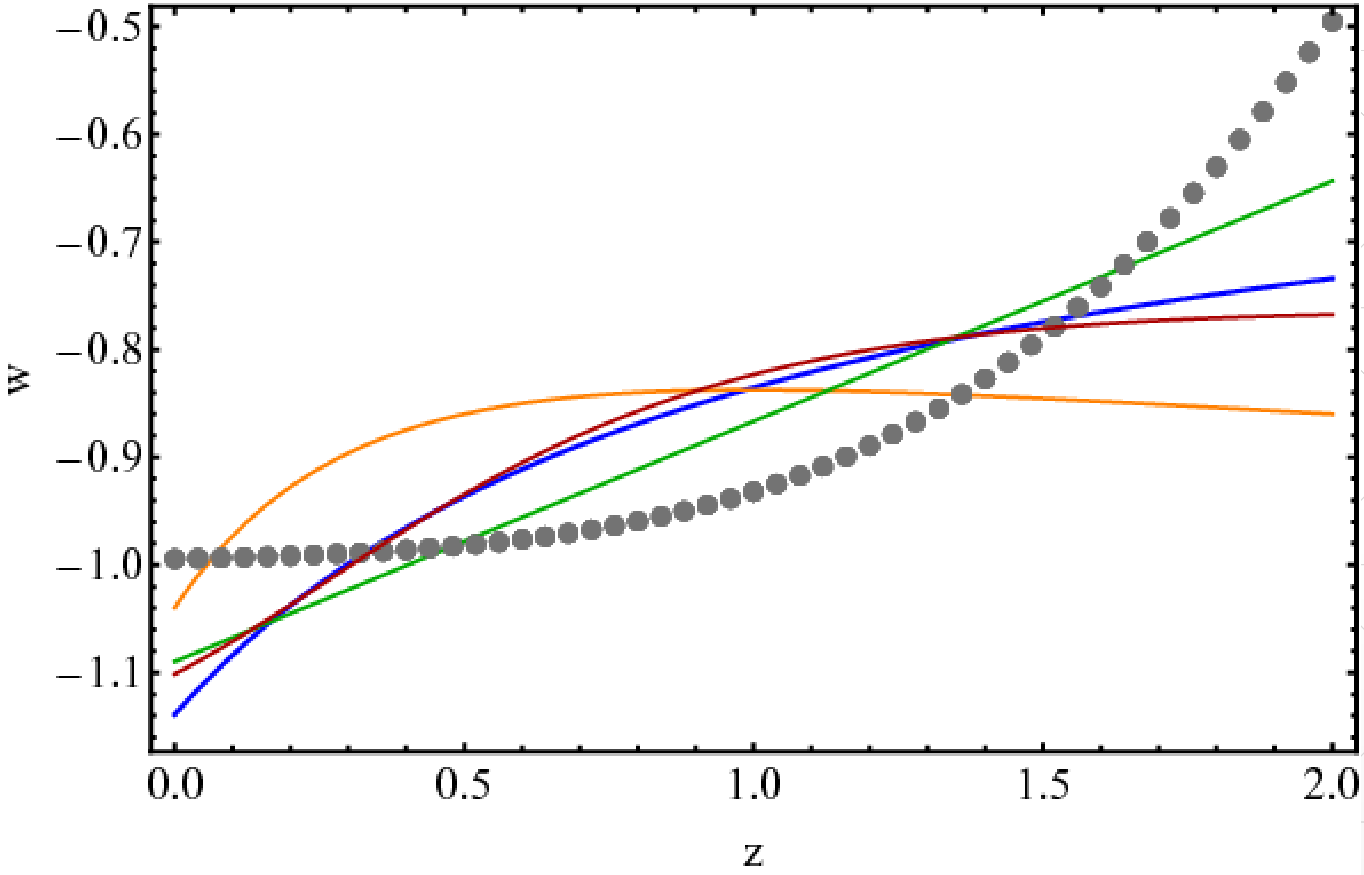
$$\rho_{\rm DE}(z) = \rho_{\rm DE}^0 \exp\left[\int_0^z \frac{3(1+\omega_{\rm DE})}{1+\tilde{z}} d\,\tilde{z}\right]$$

- Several realizations from particular models of $\omega_{\rm DE}$
- Linear model $\boxed{\omega(z) = \omega_0 + \left(\frac{d\omega}{dz}\right)_{z=0}}$
- Chevalier-Polarski-Linder (CPL) $\boxed{\omega(z) = \omega_0 + \left(\frac{z}{1+z}\right)\omega_1}$
- Barboza-Alcaniz BA $\boxed{\omega(z) = \omega_0 + \left(\frac{z(1+z)}{1+z^2}\right)\omega_1}$

Dark Energy Parameters

- Linear model
- Chevalier-Polarski-Linder (CPL)
- Barboza-Alcaniz (BA)
- Jassal-Bagna-Padmanabhan

$$\omega(z) = \omega_0 + \frac{z}{(1+z)^2}\omega_1$$



Pantazis et al. 2016

THIS COURSE (part 1)

μ vs. distance

- Employ (download) the Union 2.1 sample of Sne ($\mu\ vs.\ d_l$ for 580 Type Ia SNe) and the associated Covariance Matrix

html://supernova.lbl.gov/union

- Compute the Log-Likelyhood
$$\mathcal{L}(D|\Theta_i) = exp\left[-\left(\mu^i_{obs} - \mu(\Theta_i)\right) C^{-1}_{ik} \left(\mu^k_{obs} - \mu(\Theta_k)\right)/2\right]$$
- Compute the Log-Like (χ^2 test) for $\mu(z_i, \Omega_\Lambda)$
- Plot the Log-Like for the single parameter Ω_Λ
- Derive the confidence region for the Ω_Λ parameter in a flat ΛCDM cosmology.
- Plot the confidence region for the Ω_Λ parameter