Distances and acceleration

Cosmology WS22/23

Luminosity distance…

$$f = \frac{L}{4\pi r^2(z)(1+z)^2}$$

$$d_L = r(z)(1+z)$$

$$ds^2 = dt^2 - a^2(t)[\frac{dr^2}{1+\Omega_{k0}H_0^2 r^2} + r^2 d\Omega^2]$$

$$d_L(z) = \frac{1+z}{H_0\sqrt{\Omega_{k0}}} \sinh(H_0\sqrt{\Omega_{k0}}\int \frac{dz}{H(z)})$$

$$H(z) = H_0(\Omega_{m0}a^{-3} + \Omega_\Lambda + \Omega_{k0}a^{-2})^{1/2}$$

…and magnitudes

$$f = \frac{L}{4\pi d_L^2}$$

Apparent magnitude

$$m = -2.5 \log f + c_1$$

Absolute magnitude

$$M = -2.5 \log L + c_2$$

$$m = M + 25 + 5 \log d_L(Mpc)$$

Mapping the expansion rate

$$f = \frac{L}{4\pi d_L^2}$$

$$d_L \sim \int \frac{dz}{E(z; \Omega_{i,0}, w_i)}$$

Flux ---> distance ---> cosmology

Distance indicators: parallax

1836
Friedrich Bessel

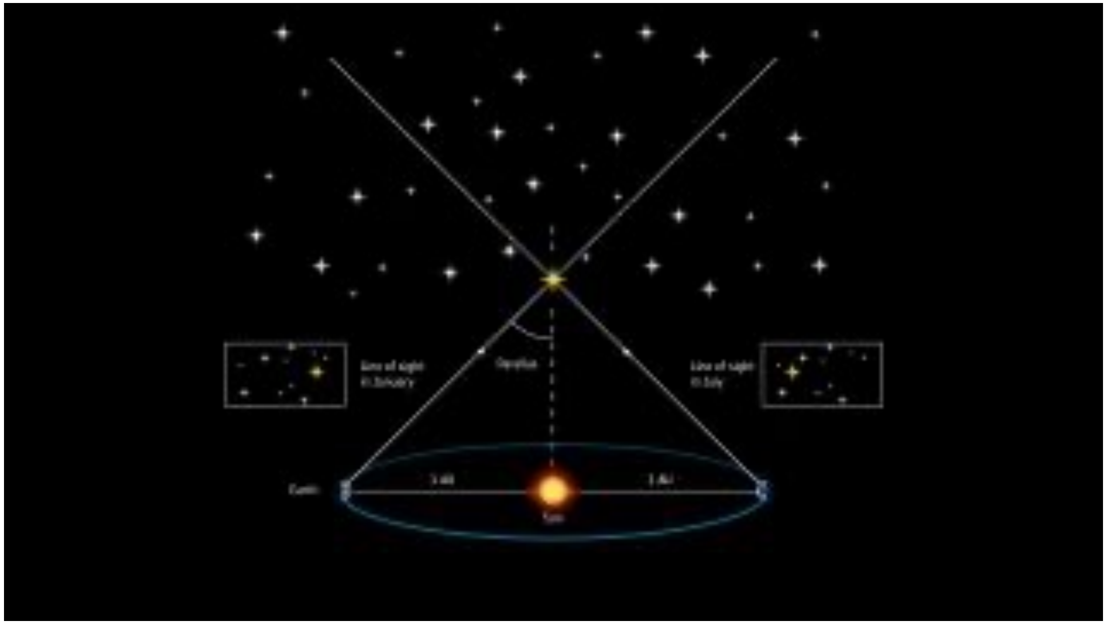


Image credit: ESA

$$d = \frac{1\text{pc}}{\theta[\text{arcsec}]}$$

$1\text{pc} = 2.3 \cdot 10^{13} km$

GAIA satellite $10^{-5} arcsec$ ---> 50-100kpc

Distance indicators: parallax

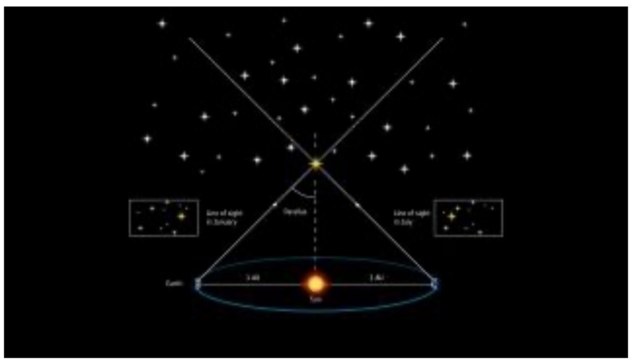
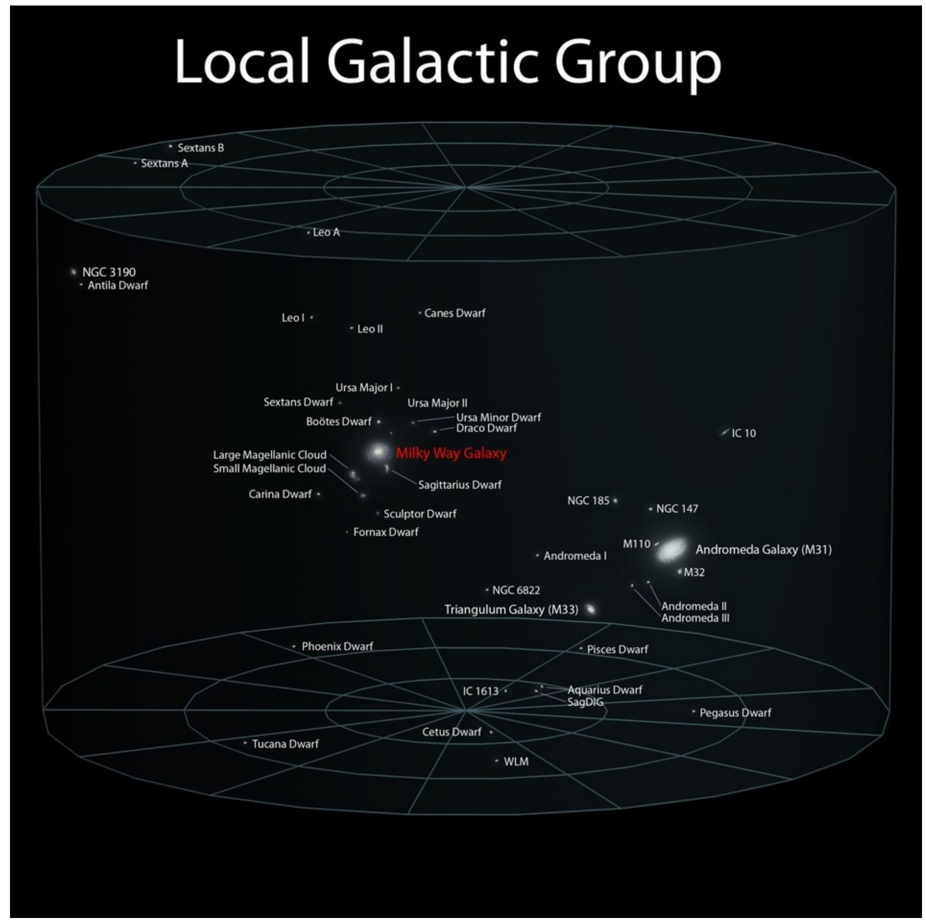


Image credit: ESA

GAIA satellite $10^{-5} arcsec$

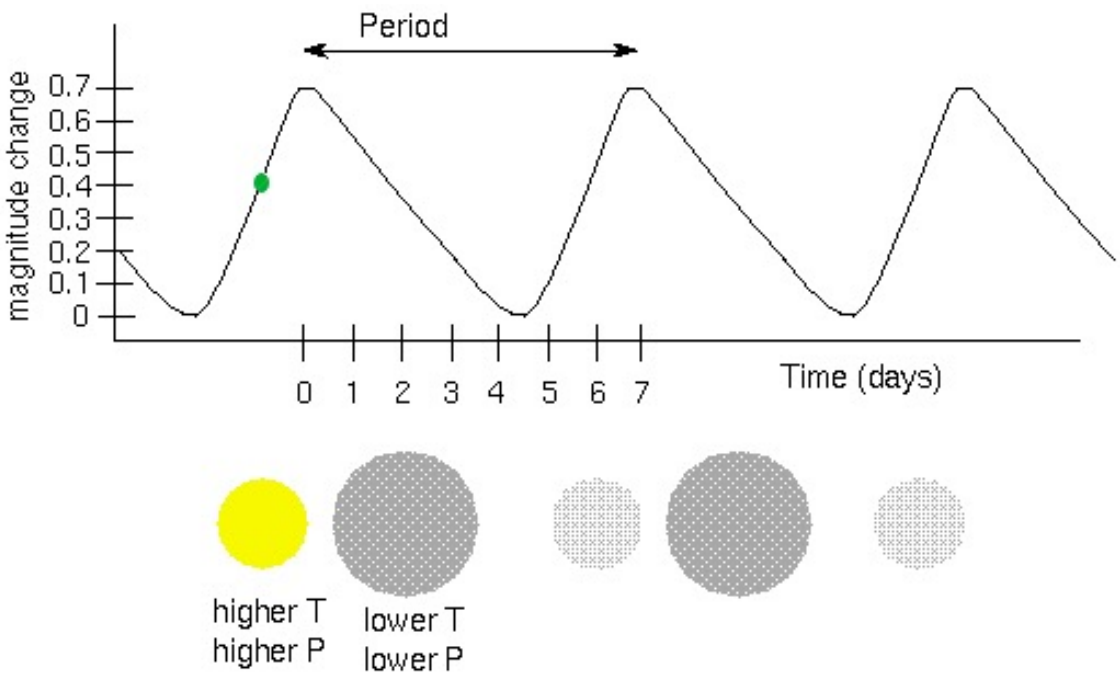
---> 50-100kpc



Credit: By Azcolvin429, via Wikimedia Commons

1Mpc

Distance indicators: Cepheids



Cepheid variables: outward pressure (P) and inward gravity compression are out of sync, so star changes size and temperature: it **pulsates**. *RR-Lyrae* variables are smaller and have pulsation periods of less than 24 hours. Also, their light curve looks different from the Cepheid light curve.

Henrietta Leavitt
1910's

$L \sim P^{1.3}$

Variability phase lasts for some thousand years

Distance indicators: Cepheids

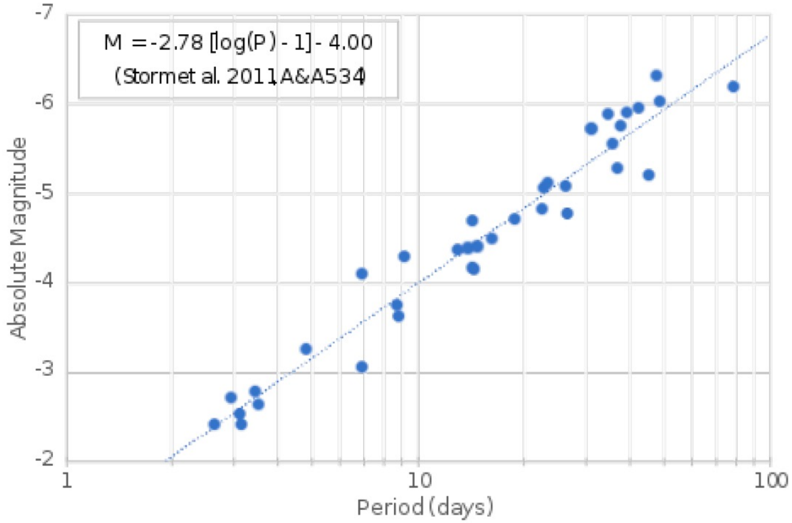


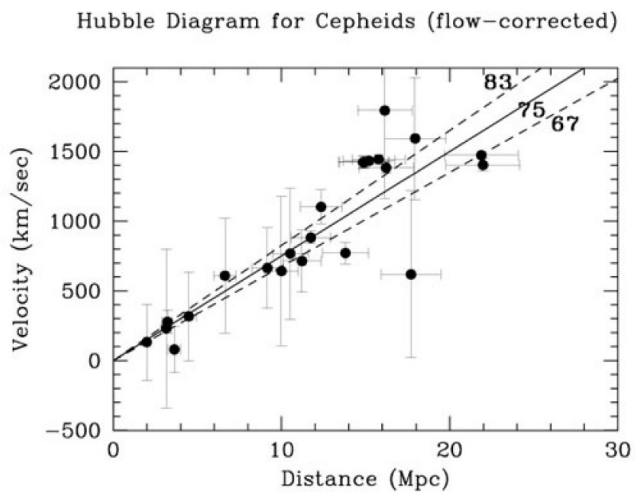
Figure 5.2.1: Period-Luminosity relation for Magellanic Cloud Cepheid variable stars; data from Storm et al. 2011, A&A, 534. (Wikicommons, author: Dbenford)

Period-luminosity-color relation

$$M_V = 3.32(V - I) - 3.93 \log P - 2.92,$$

Sandage et al. 2008

Distance indicators: Cepheids



Distances up to 30-50 Mpc

Figure 5.2.2: Hubble constant from the Cepheid method (Freedman et al., Ap. J., Volume 553, Issue 1, pp. 47-72, 2001. © *AAS. Reproduced with permission*).

Distance indicators: planetary nebulae

Late phase
of red giants

Distance indicators: planetary nebulae

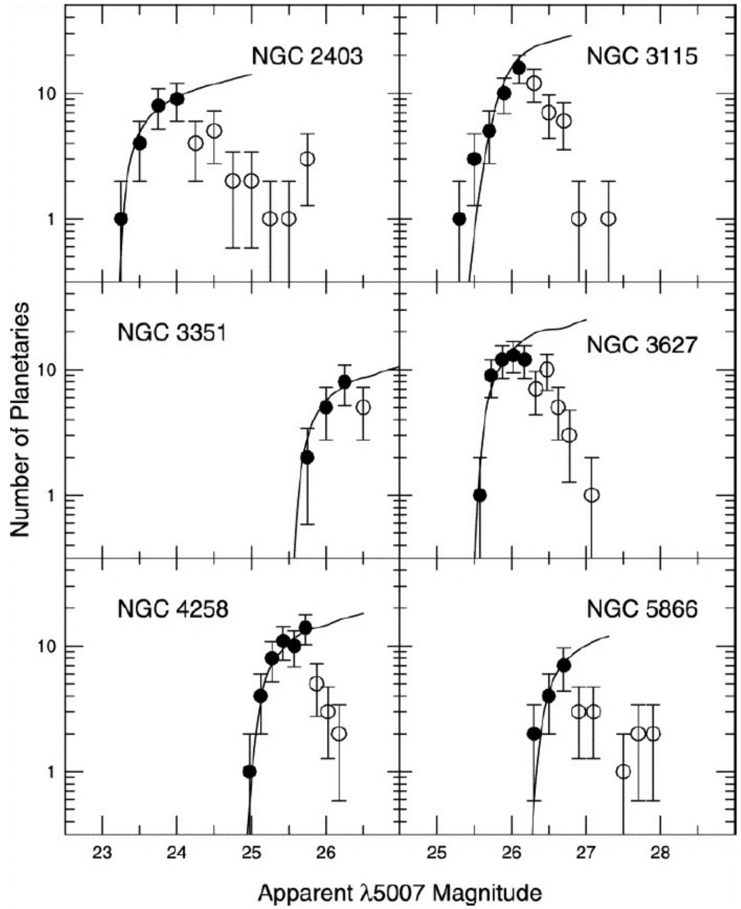
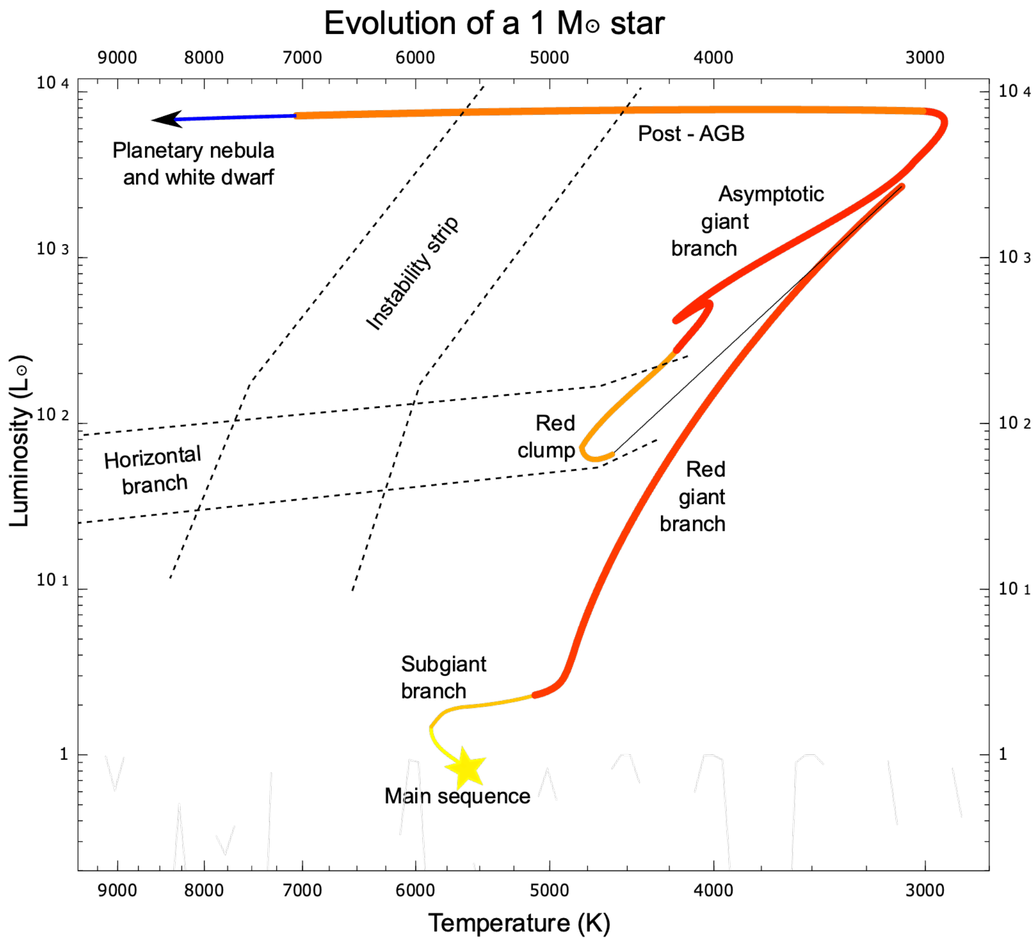
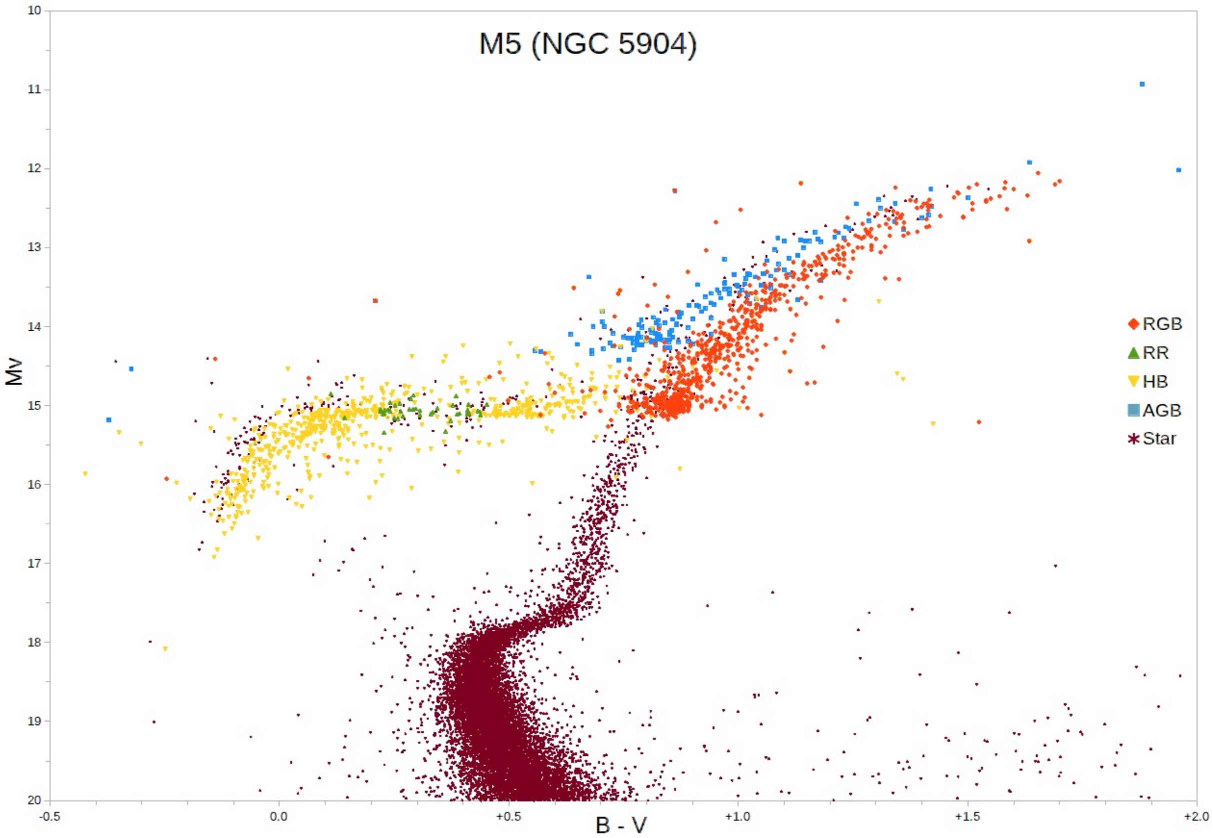


Figure 5.3.1: Luminosity functions of planetary nebulae in a sample of galaxies. Notice the sharp cut-off at high luminosity. (From Ciardullo et al. 2002, astro-ph/0206177, Astrophys.J. 577 (2002) 31-50. © *AAS. Reproduced with permission.*)

Distance indicators: Tip of Red Giant Branch



Distance indicators: Tip of Red Giant Branch



Distance indicators: Tully-Fisher

Spiral galaxies

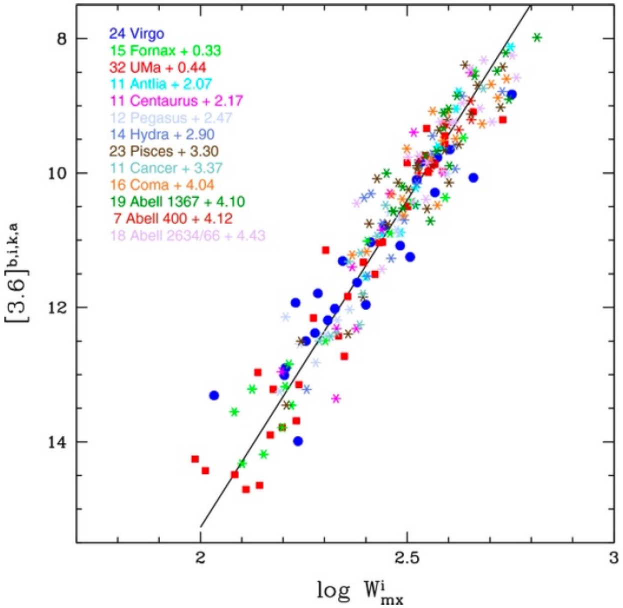


Figure 5.5.2: Tully-Fisher relation in the IR band around 3.6μm (Sorce et al., 2013ApJ...765...94S, © *AAS. Reproduced with permission*) for galaxies up to roughly 200 Mpc.

Virial theorem

$$\langle v^2 \rangle = \langle \Phi \rangle = \frac{GM}{R_{vir}}$$

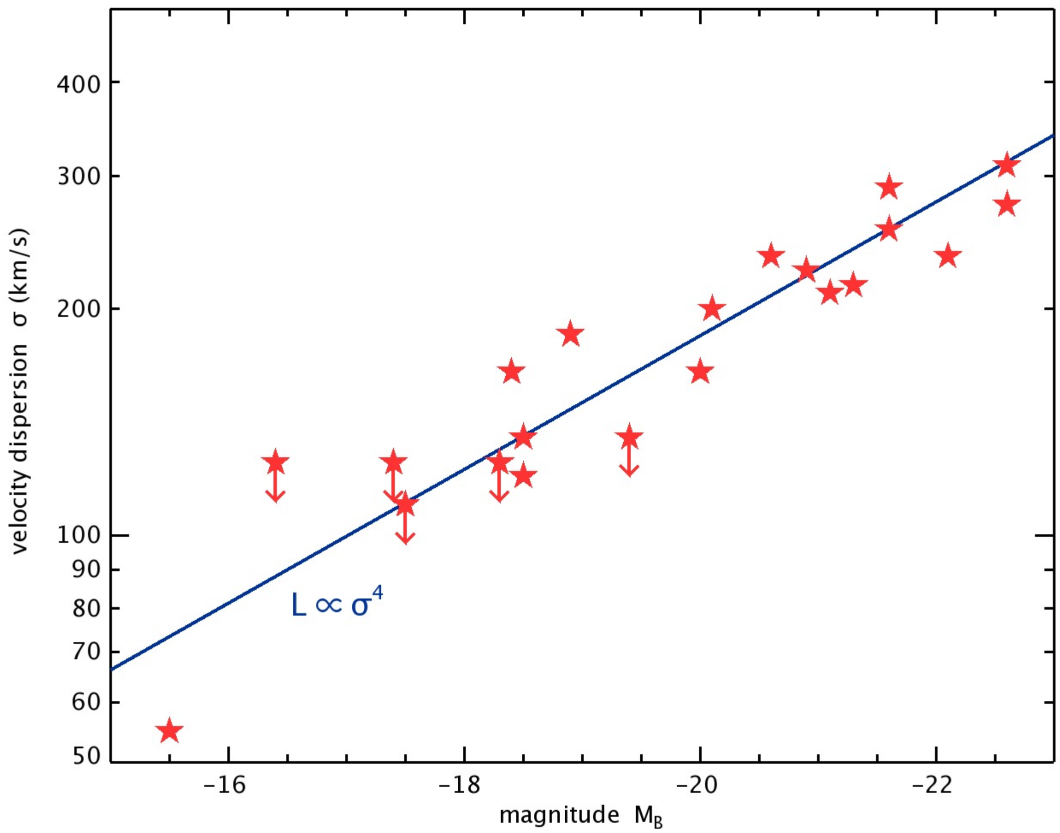
$$M \sim L \sim R^2$$

$$L \sim \sigma_{rot}^{\alpha}$$

$$\alpha \approx 3.5 - 4$$

Distance indicators: Faber-Jackson

Elliptical galaxies



Virial theorem

$$\langle v^2 \rangle = \langle \Phi \rangle = \frac{GM}{R_{vir}}$$

$$L \approx \sigma^{\gamma}$$

$$\gamma \approx 3 - 4$$

For less massive galaxies

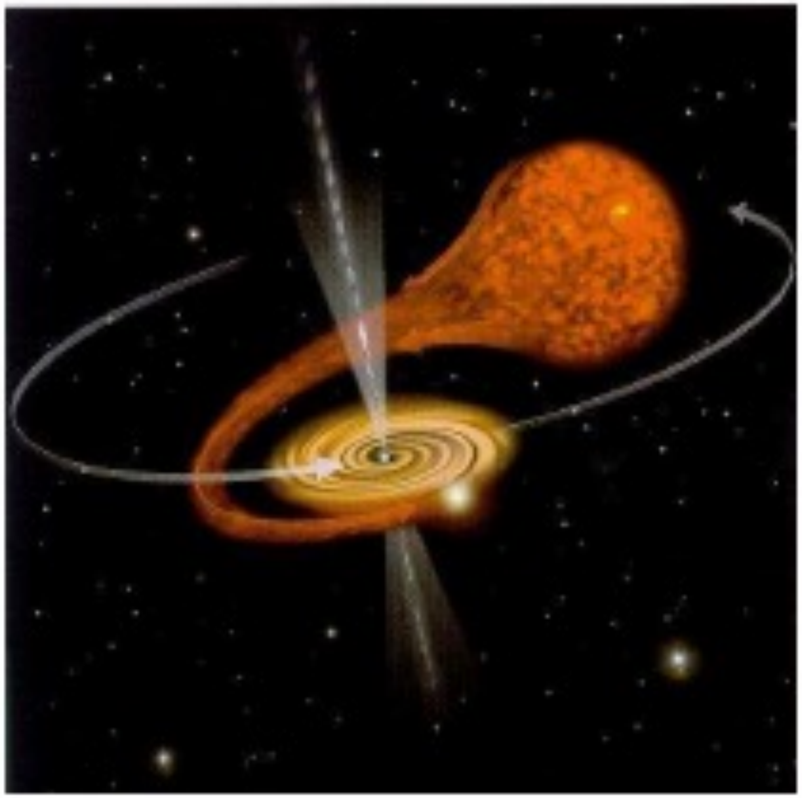
Lighthouses in the dark

$$d^2 = \frac{L}{4\pi f}$$

Supernovae Ia

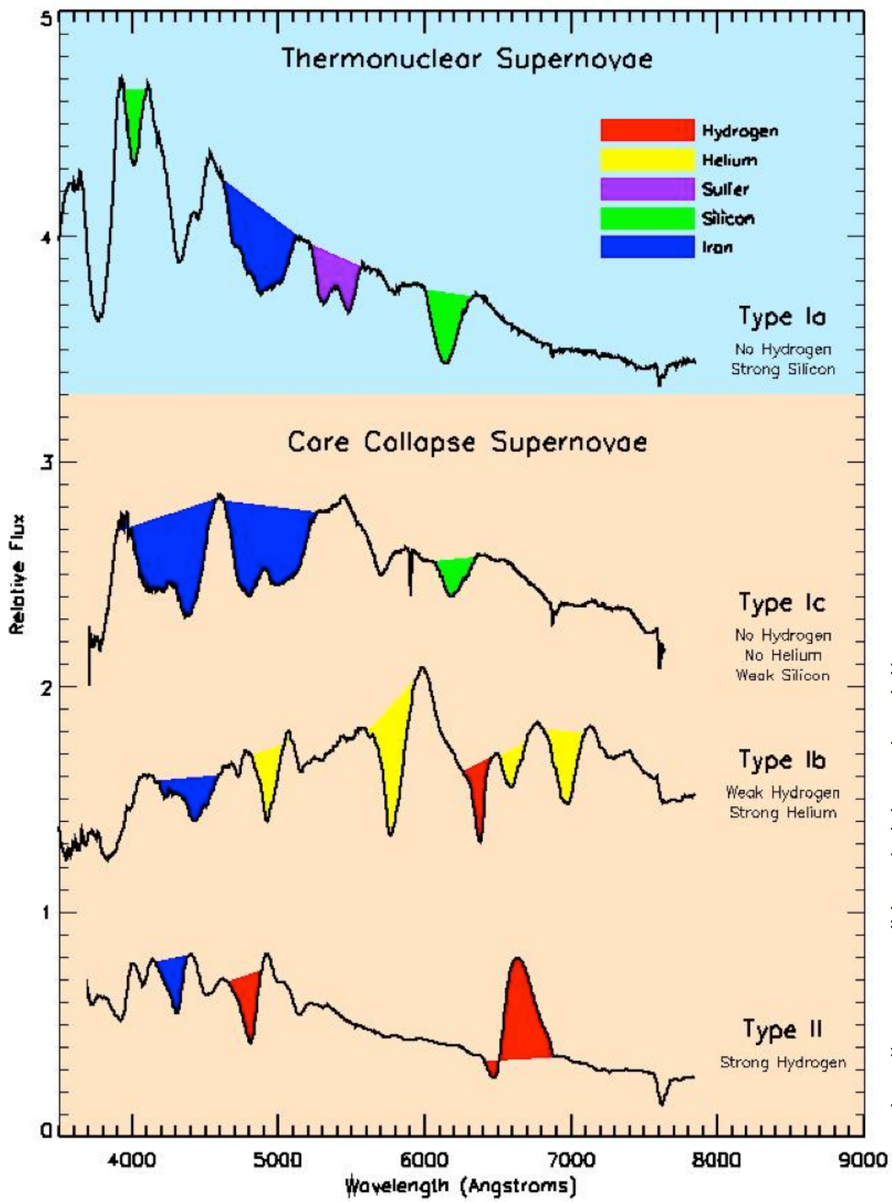
$$m - M = 5\log d_L + 25$$

Komori Unsplash

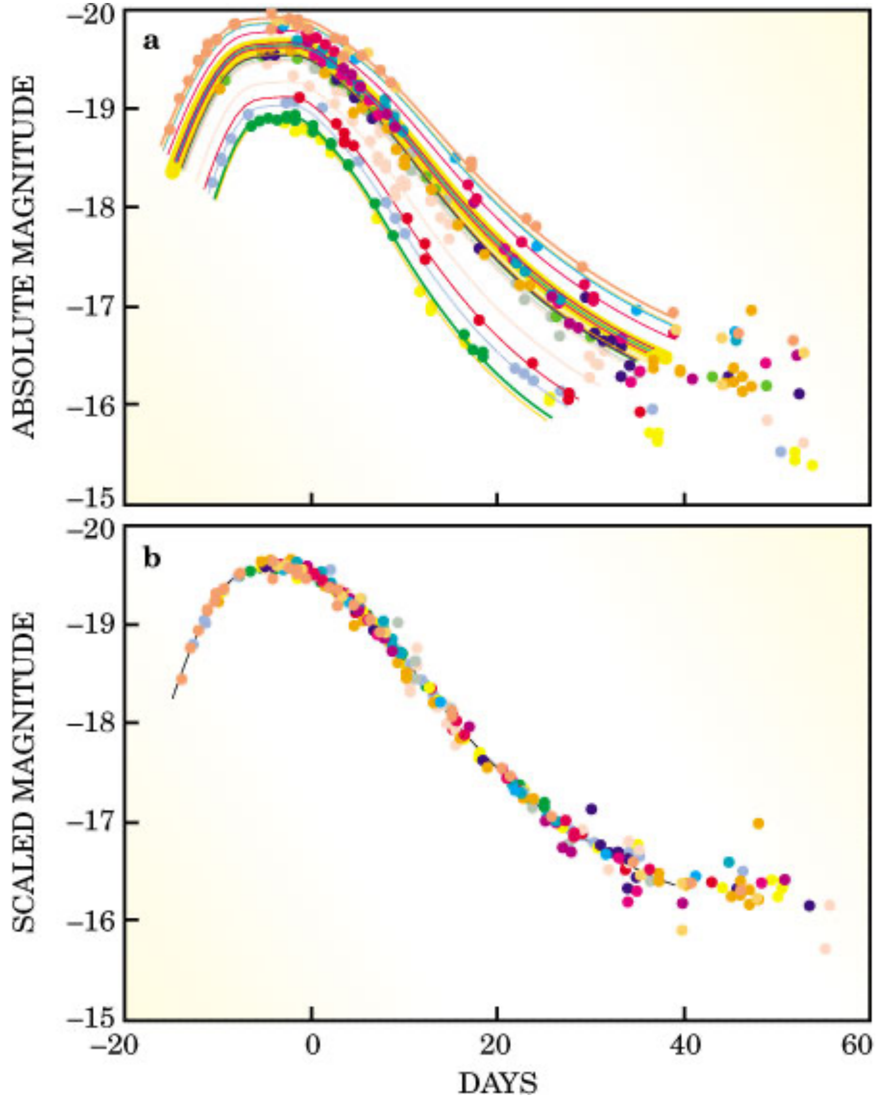


- This hypothesis can be tested and calibrated through a local sample whose distance we know by other means.

Types of supernovae



http://supernova.lbl.gov/~dnkasen/tutorial/

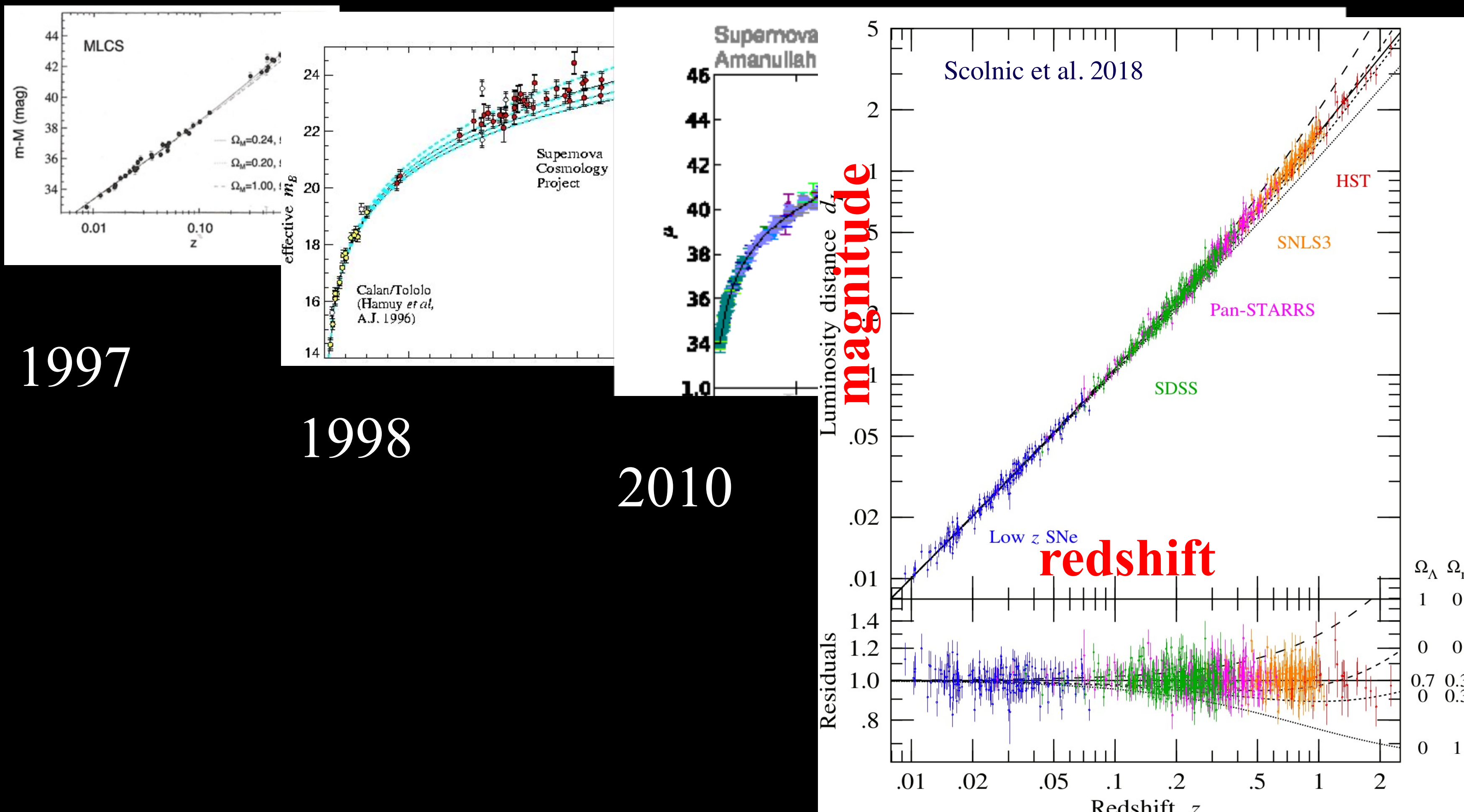


Phillips, Hamuy, et al. 1993, 1995

- Then, we compare $m_{obs}(z)$ with

$$m_{theor}(z) = M + 25 + 5 \log d(z; \Omega_M, \Omega_\Lambda, ..)$$

Hubble diagram



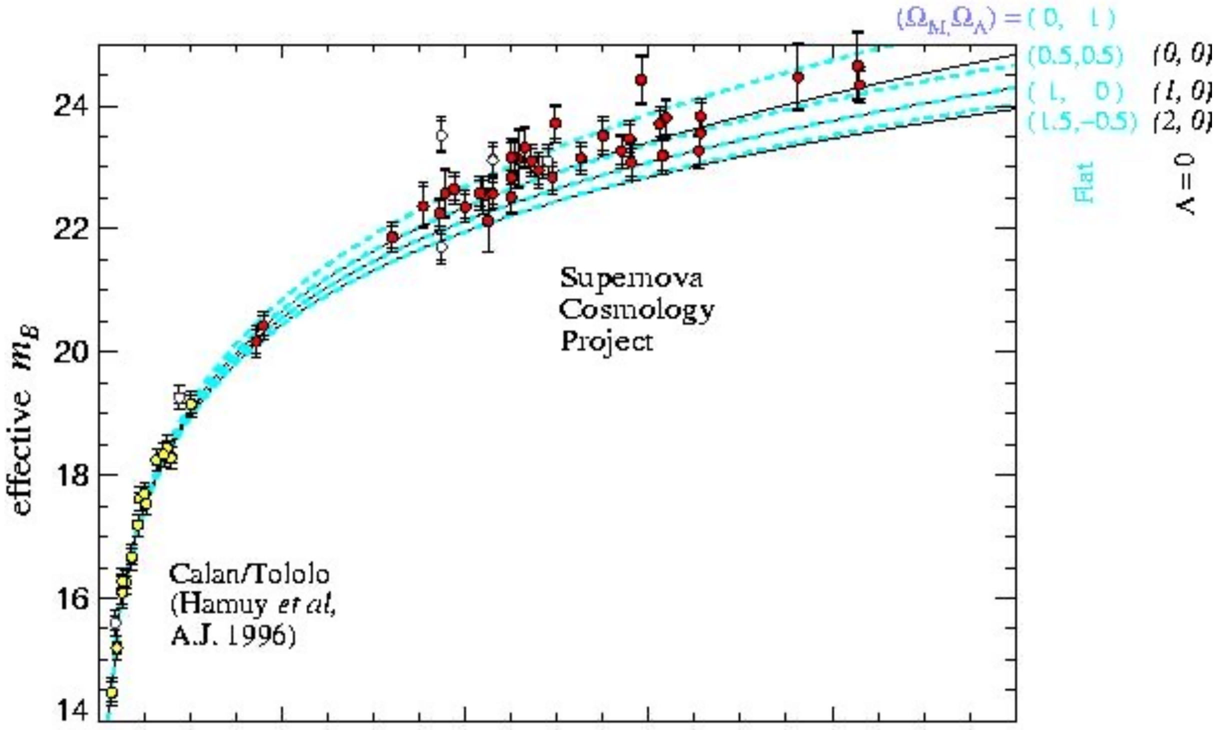
1997

1998

2010

2018

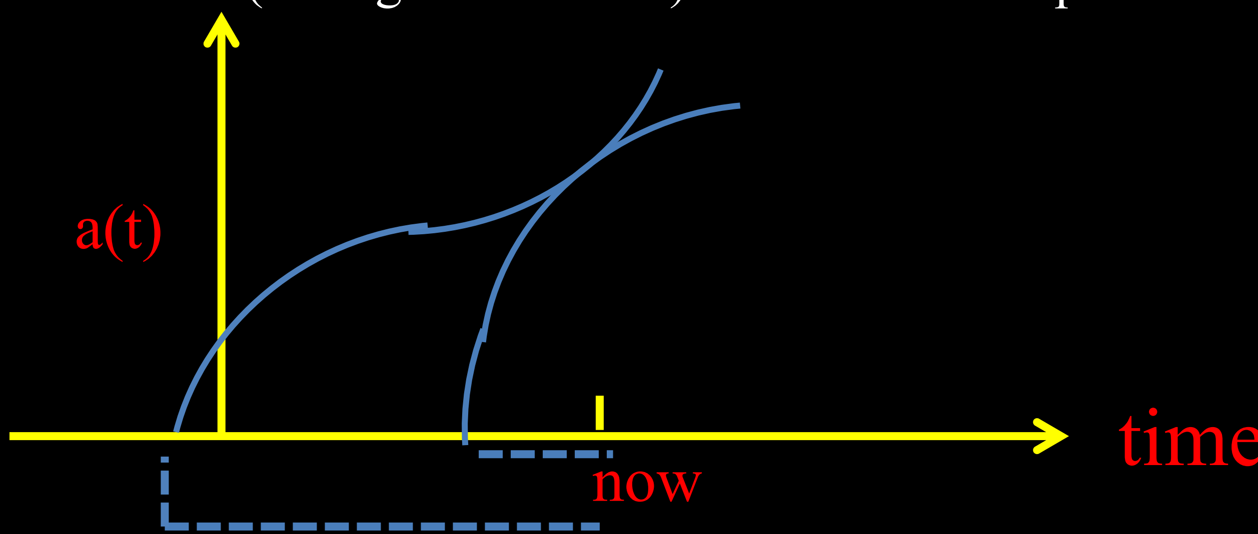
SNIa are dimmer than expected!



Basic property 1

Local Hubble law $r(z) = \frac{z}{H_0}$ ⟶ $r(z) = \int \frac{dz}{H(z)}$ Global Hubble law

If H(z) in the past is smaller (i.e. acceleration), then r(z) is larger: larger distances (for a given redshift) make dimmer supernovae



LambdaCDM

$$H^2 = H_0^2[\Omega_{m,0}(1+z)^3 + \Omega_{\Lambda,0} + (1-\Omega_{m,0}-\Omega_{\Lambda,0})(1+z)^2]$$

Only two parameters!

$$d_L \sim \int \frac{dz}{E(z;\Omega_{i,0},w_i)}$$

$$d_L(z;\Omega_{m,0},\Omega_{\Lambda,0}) \sim \int \frac{dz}{[\Omega_{m,0}(1+z)^3 + \Omega_{\Lambda,0} + (1-\Omega_{m,0}-\Omega_{\Lambda,0})(1+z)^2]^{1/2}}$$

Statistics in three steps

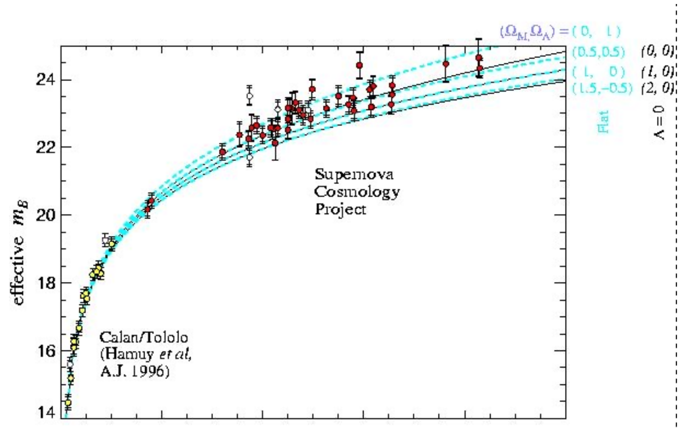
1: take a model

$$H^2 = H_0^2 E^2(z; params)$$

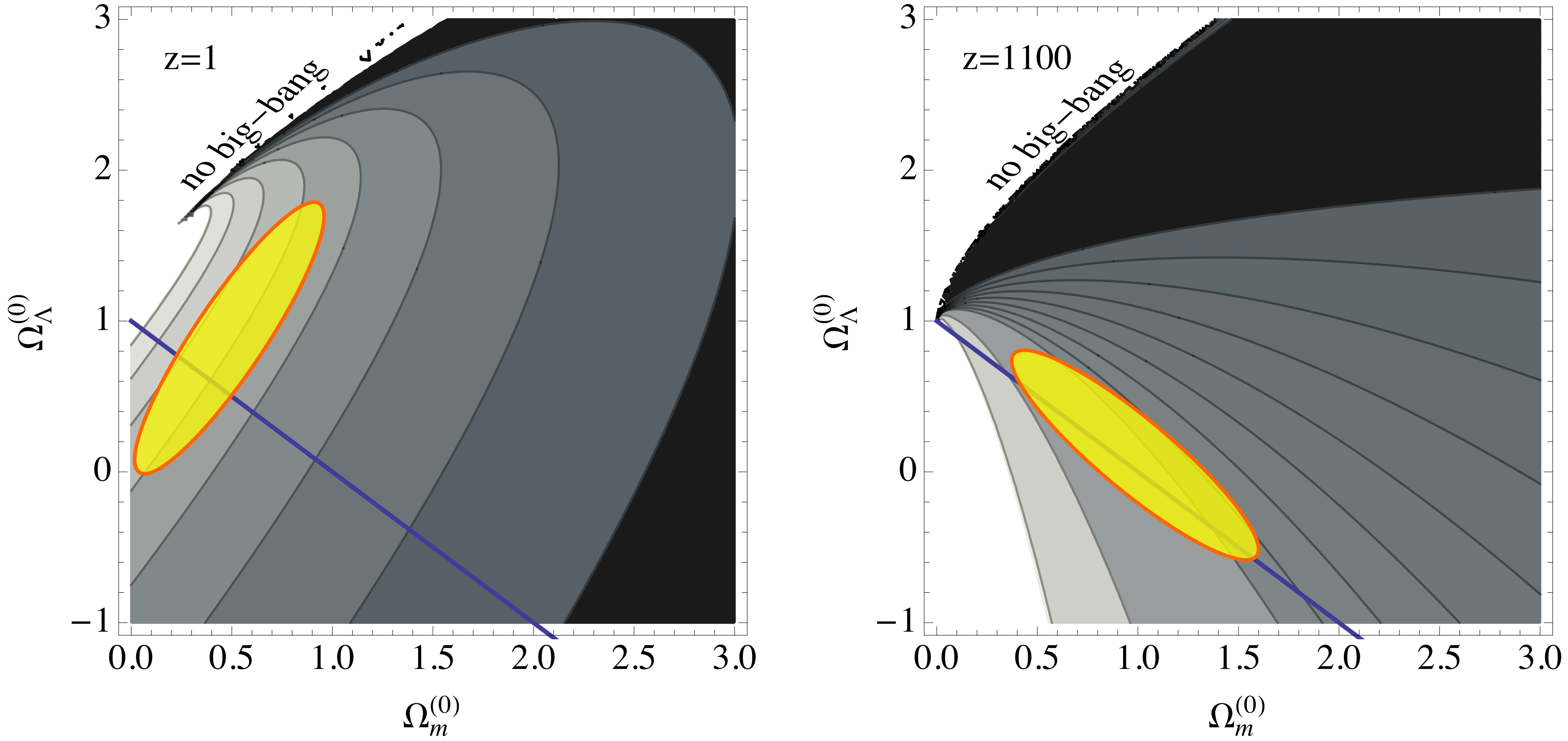
2: find the distance

$$d_L(z; params) \sim \int \frac{dz}{E(z)}$$

3: vary the parameters and minimize the chi-squared with data

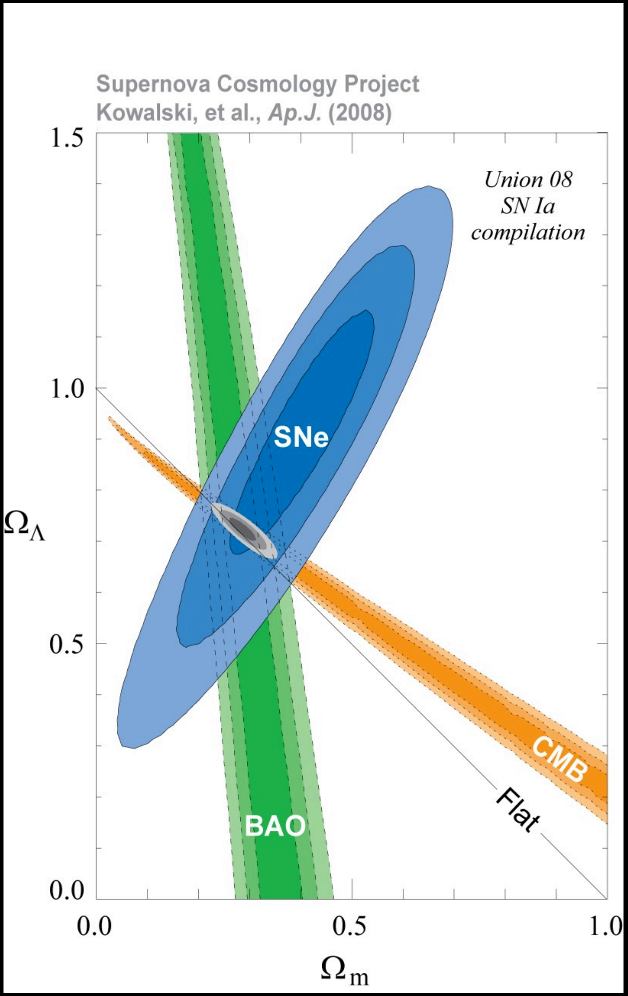


Basic property 2

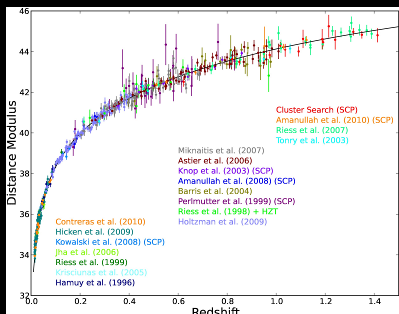


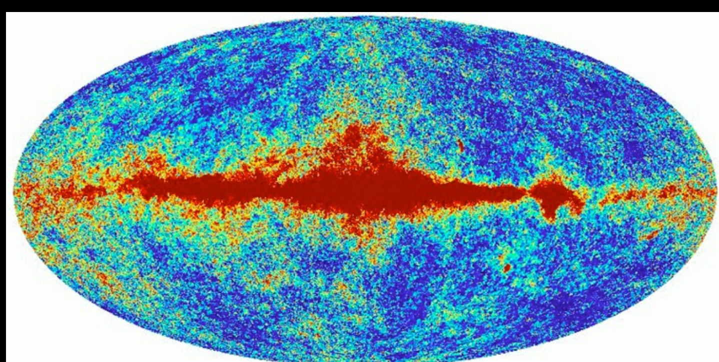
Curves of constant luminosity distance

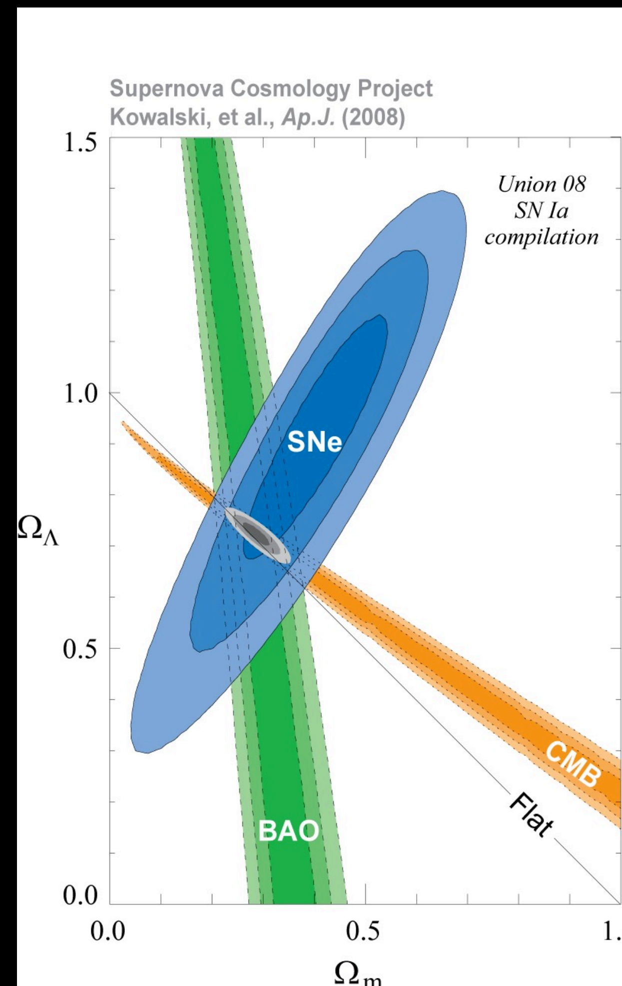
Properties of Dark Energy



Properties of Dark Energy







Constant EoS

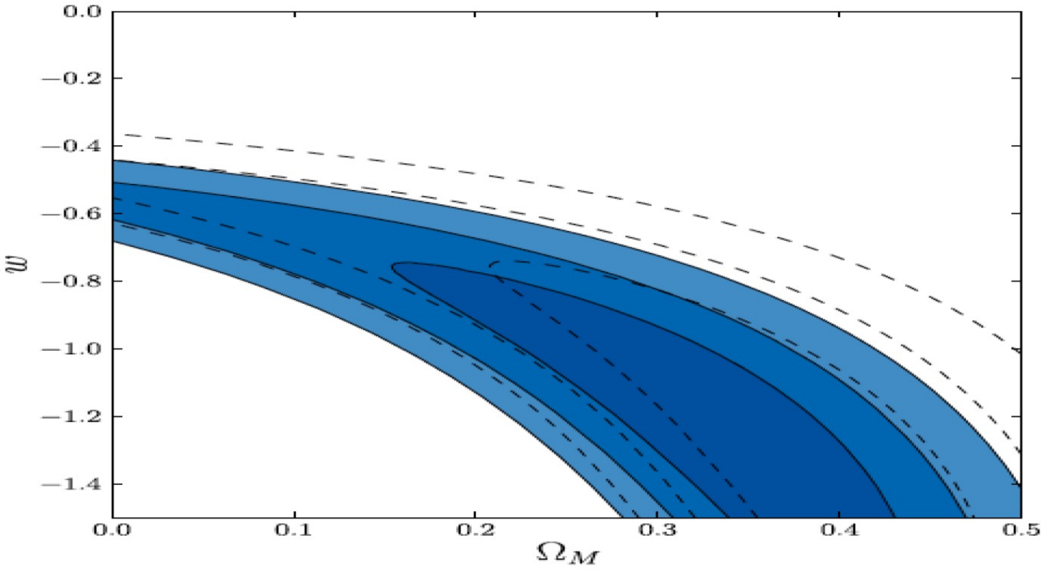


Figure 6.1.3: 68.3 %, 95.4 % and 99.7 % confidence level contours on $(\Omega_m^{(0)}, w_{\rm DE})$ from the SN Ia observations (denoted as Ω_M and w in the figure) compiled in Amanullah et al. 2010ApJ...716..712A *(© AAS. Reproduced with permission).*