

SUPERNOVAE
PhD Course 2013, SISSA

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V. Type Ia Supernovae and Cosmology

Type Ia SNe as distance indicators

Type Ia SNe: ‘standard candles’

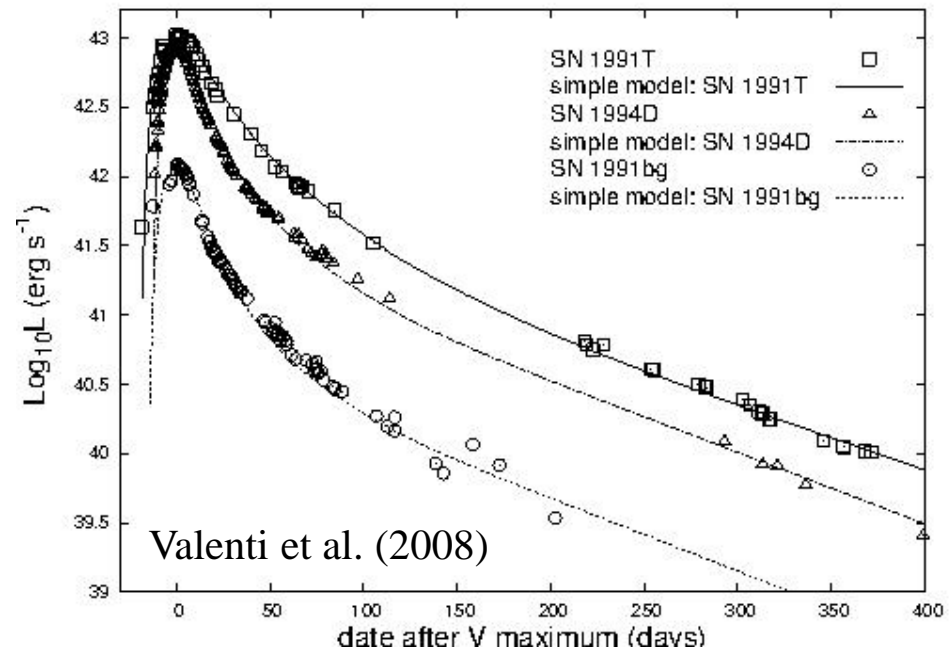
It has long been recognized that Type Ia SNe could be very useful distance indicators (e.g. Branch & Tammann 1992; Branch 1998) because they have:

- *exceedingly high luminosity: $L=1.0e43$ erg/s (B band magnitude=-19)*
- *small dispersion among their peak absolute L (<0.3 mag)*
- *homogeneous spectral properties, if compared at similar phases (Riess et al. 1997)*

80% of them are homogeneous (Branch et al. 1993)

But also heterogeneity (Suntzeff 1996):

- SN 1991T
 - no Si II or Ca II absorption lines in the pre-maximum spectrum
 - light curve broader and more luminous than average
- SN 1991bg
 - subluminous and intrinsically red
 - peculiar absorption (Ti II)
 - no secondary maximum in I band
 - slow expansion velocity

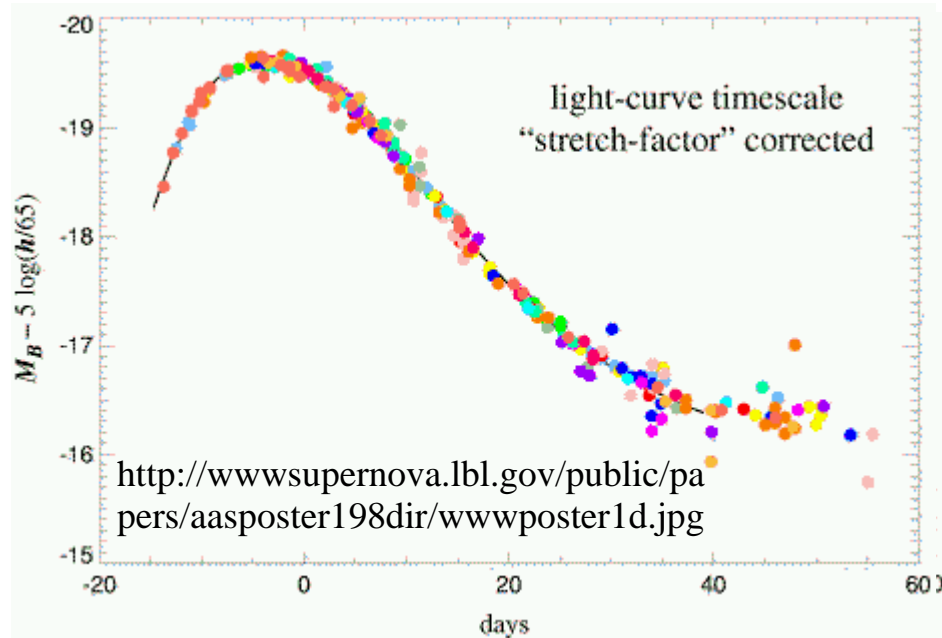


Calibrating Type Ia SNe

Correlation between light curve shape and luminosity at maximum (Phillips 1993; Hamuy et al. 1995, 1996)

- intrinsically bright SNe Ia decline more slowly than dim ones (correlation stronger in *B* band)
- *Dm15* measures the total drop from *B*-band maximum at $t = 15$ days after maximum (*B* magnitudes)
- **Phillips calibration relation** (Phillips 1993):

$$M_{max} = -21.726 \pm 0.498 + (2.698 \pm 0.359) Dm15$$



Other parameterizations of the correlation:

- 'stretch' factor, that multiplies the lightcurve timescale (Perlmutter et al. 1997; Goldhaber et al. 2001)
- multi-color light curve shape (MLCS) method (Riess et al. 1996)

Type Ia SNe: Cosmological use

Hubble diagram: low-z

$$m_{max} - M_{max} = 5 \log D_L - 5$$

$$D_L = cz/H_0 \quad z \ll 1$$

$$m_{max} - M_{max} = -5 - 5 \log H_0 + 5 \log cz$$

After correcting M_{max} with calibration relations, the correlation is significantly improved.

Top: objects are assumed to be *standard candles*

→ $\sigma = 0.42 \text{ mag}$, $H_0 = 58 \pm 8 \text{ km/s/Mpc}$

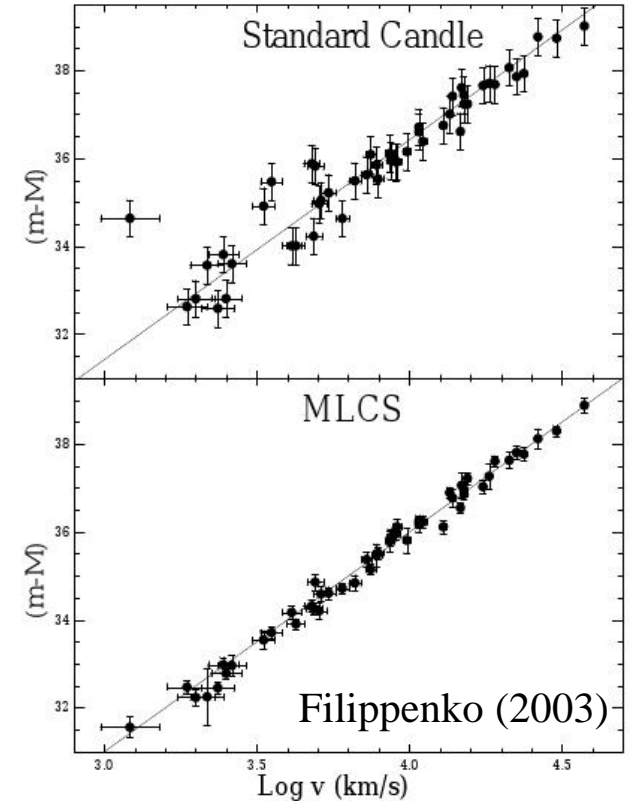
Bottom: same objects, after correcting M_{max}

→ $\sigma = 0.15 \text{ mag}$, $H_0 = 65 \pm 2 \text{ km/s/Mpc}$

$$D_L = \frac{c(1+z)}{H_0 \sqrt{|\Omega_k|}} \text{sinn} \quad \text{Luminosity distance}$$

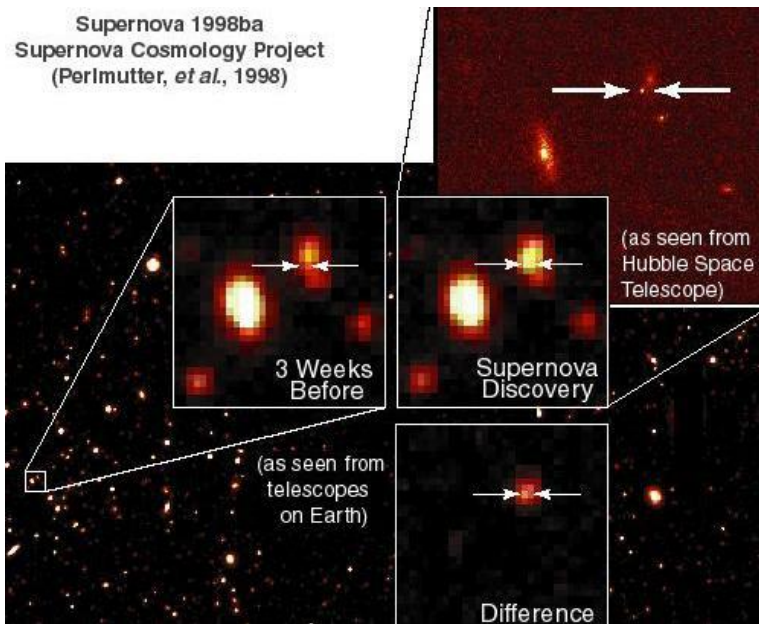
$$\times \left\{ \sqrt{|\Omega_k|} \int_0^z \left[\sum_i \Omega_i (1+z')^{3(1+\alpha_i)} + \Omega_k (1+z')^2 \right]^{-1/2} dz' \right\}, \quad (1)$$

$$\text{sinn}(x) = \begin{cases} \sinh(x), & \text{if } \Omega_k > 0; \\ x, & \text{if } \Omega_k = 0; \\ \sin(x), & \text{if } \Omega_k < 0, \end{cases} \quad (2)$$



Extending the Hubble diagram to higher redshifts, it is possible to probe additional cosmological parameters

Searches for Type Ia SNe at high- z



Searching high- z Type Ia SNe

- Pairs of first-epoch images (for removal of cosmic rays and asteroids)
- Followed by second-epoch images 3–4 weeks later
- Subtracting them, new SN candidates are identified
- Spectra obtained as soon as possible after discovery to check type and determine z
- Intensive photometric follow-up in filters that match the redshifted B and V bands
- Correction for intrinsic cosmological stretch ($1+z$)

'Supernova Cosmology Project' (SCP) led by Saul Perlmutter

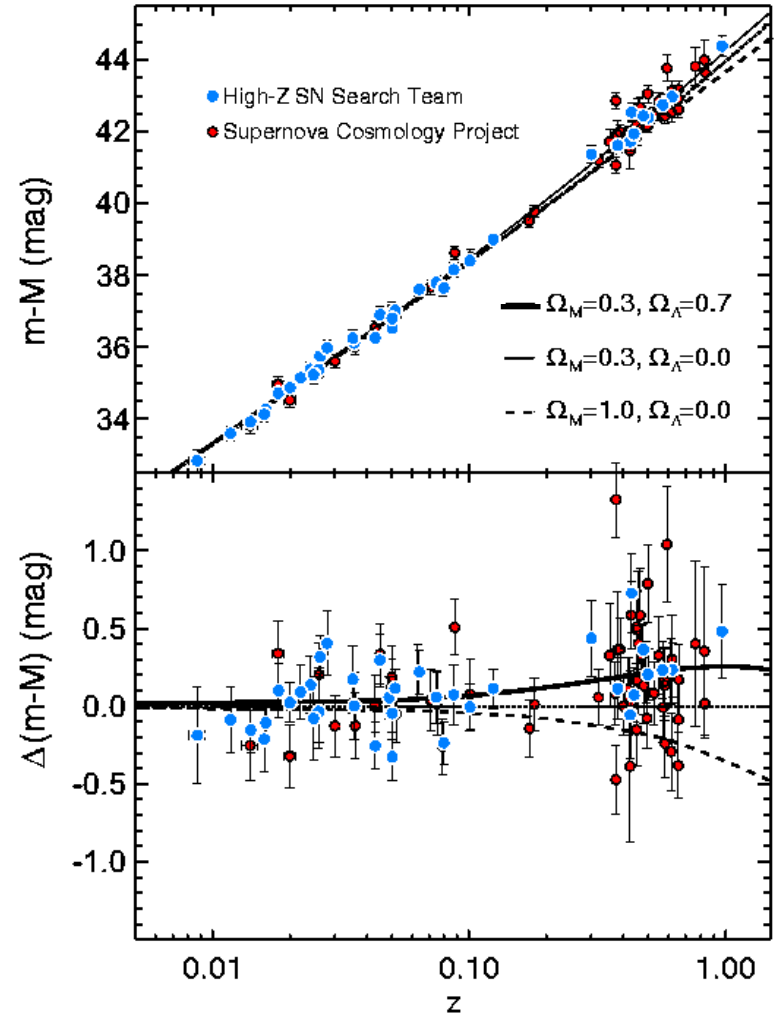
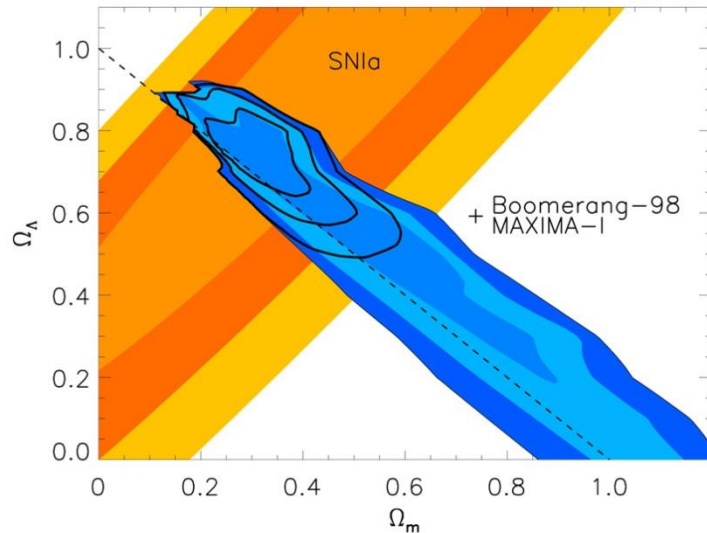
'High-Z Supernova Search Time' (HZT) led by Brian Schmidt and Adam Riess.

Hubble diagram: high-z

First evidence of a low ω_m Universe and of $\omega_\Lambda > 0$ (Perlmutter et al. 1998; Filippenko and Riess 1998)

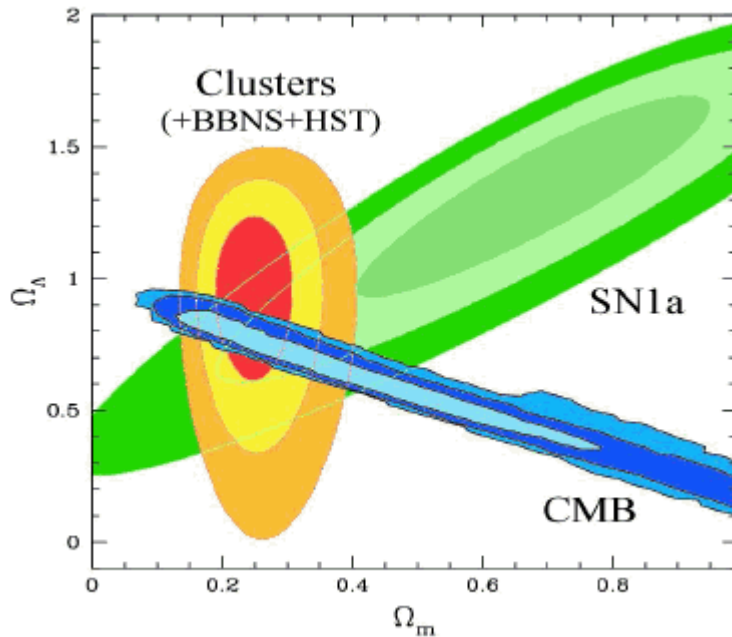
Constraints from SNe and angular scale of the the CMB (Riess et al. 1998; Perlmutter et al. 1999)

- 1) $\omega_m + \omega_\Lambda = 0.94 \pm 0.26$
- 2) $\omega_\Lambda > 0$



Filippenko (2003)

Putting all together



http://hera.ph1.unikoeln.de/~heintzma/k5/b3/Cosmic_Acc.gif

Studies of clusters of galaxies (e.g. Bahcall et al. 1999) show that $\omega_m \approx 0.3$

Two-Degree Field Galaxy Redshift Survey (2dFGRS; Peacock et al. 2001; Percival et al. 2001; Efsthathiou et al. 2002), combined with CMB maps, is inconsistent with a universe dominated by dark matter

Wilkinson Microwave Anisotropy Probe (WMAP), together with the 2dFGRS constraints, confirmed and refined the concordance cosmology (Spergel et al. 2003):

$$\Omega_m = 0.27$$

$$\Omega_\Lambda = 0.73$$

$$\Omega_b = 0.044$$

$$H_0 = 71 \pm 4 \text{ km/s/Mpc}$$

$$t_0 = 13.7 \text{ Gyrs}$$

For updated values from the 7 years WMAP observations see Larson et al. (2011)

... and now results from the Planck mission!

Type Ia SNe: Systematic effects

Evolution, extinction by dust, systematic errors

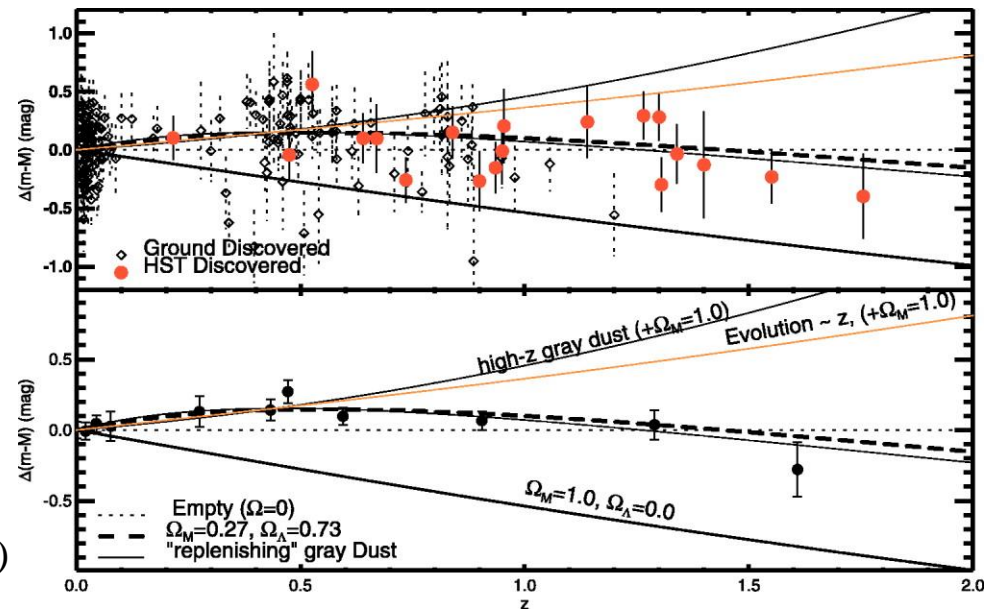
High- z SNe are dimmer than expected in an empty Universe. Possible systematics:

- Evolution of peak luminosity of SNe Ia with z
- *Intergalactic grey dust extinction could dim SNe without causing significant reddening*

Current calibrations of Type Ia SNe include corrections for host galaxy properties and SN colors (spectral shape)

Various tests performed with SNe segregated according to their light curve and host galaxy properties (e.g. Sullivan et al. 2012) \rightarrow errors of this type contribute at the 2% level

Systematic uncertainties dominated by photometric (flux) calibration



Riess et al. (2004)

Dark Energy Equation of State

The most recent searches: Dark Energy EOS

Supernova Legacy Survey three year sample (SNLS3): 472 SNe Ia

Sample sufficiently large to constrain the dark energy parameters to a cosmologically interesting accuracy (D_L depends on $w=\alpha$)

SNLS3 data + WMAP7 power spectrum + Sloan Digital Sky Survey luminous red galaxy angular power spectrum + Hubble constant from SHOES

Results are consistent with a flat Universe, with
 $w = p/\rho c^2 = -1.069 +^{0.091}_{-0.092}$
and no evolution (Sullivan et al. 2011)

<http://www.nature.com/ncomms/journal/v2/n6/images/ncomms1344-f2.jpg>

