Probing Dark Energy with Supernovae

by Sebastian Ihle

9.6.2006

Outline

- Measurement of distances
  - Supernovae Standard Candles?
  - Systematical errors
- Cosmological measurements
  - Accelerated Expansion and Alternatives
  - Newest cosmological parameters
- Supernovae Surveys

How to measure distances?

- What do we need to measure cosmological parameters?
  - Standard Candles (M=const.) would be best
  - (Relative) Distance indicators are also possible, but can introduce statistical and systematic errors

Distances in the local universe

- Assume a linear expansion ($z < 0.1$)

  Hubble law

  - $v=cz=H_0 \cdot D$
- Use the distance modulus
  - $m-M=5\log(D/10pc)-5$
- Distances of a 'standard candle' (M=const.)
  - $m=5\log(z)+M+25+5\log(c/H_0)$

Luminosity Distance

- All early papers use the series expansion

$m=5\log(z)+1.086\,(1-q_0)z+5\log(c/H_0)+M+25$

q_0 cosmic deceleration

Luminosity distance

For an expanding universe with a cosmological constant and using the Robertson-Walker metric:

$$D_L = \frac{(1+z)c}{H_0|\kappa|^{1/2}} S\left\{|\kappa|^{1/2}\int_0^z \left[\kappa(1+z')^2 + \Omega_M (1+z')^3 + \Omega_\Lambda\right]^{-1/2} dz'\right\}$$

$\Omega_M = \frac{8\pi G}{3H_0^2}\rho_M$ matter content

$\Omega_\Lambda = \frac{\Lambda c^2}{3H_0^2}$ cosmological constant

$q_0 = \frac{\Omega_M}{2} - \Omega_\Lambda$ cosmic deceleration

$\kappa = 1 - \Omega_M - \Omega_\Lambda$ curvature term

$$S(\chi) = \begin{cases} \sin(\chi) & \kappa < 0 \\ \chi & \text{for } \kappa = 0 \\ \sinh(\chi) & \kappa > 0 \end{cases}$$

(Leibundgut 2001)

The equation of state parameter ω

- General luminosity distance

$$D_L = \frac{(1+z)c}{H_0\sqrt{|\Omega_\kappa|}} S\left\{\sqrt{|\Omega_\kappa|}\int_0^z \left[\Omega_\kappa(1+z')^2 + \sum_i \Omega_i (1+z')^{3(1+\omega_i)}\right]^{-1/2} dz'\right\}$$

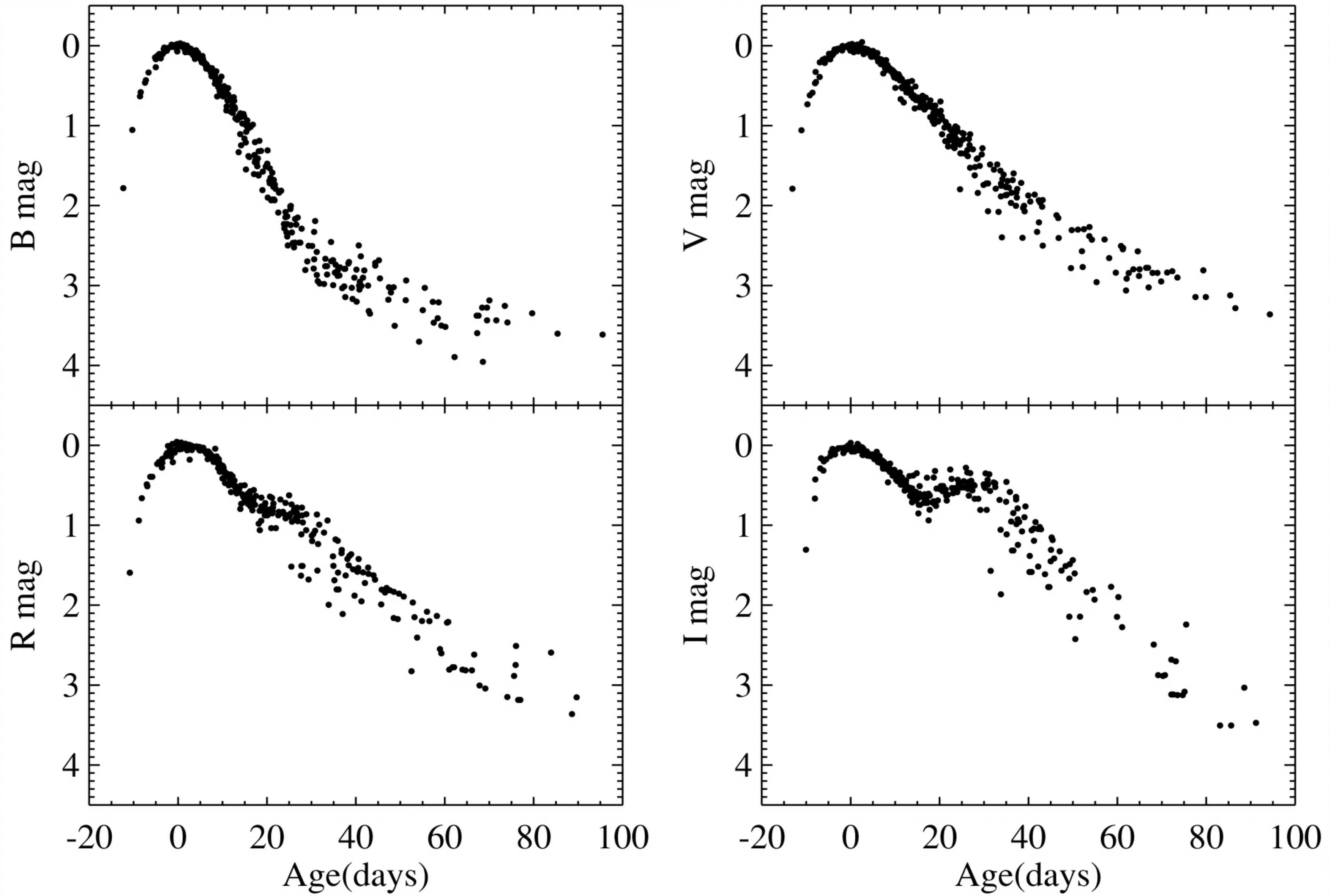
  - with $\kappa = 1 - \sum_i \Omega_i$ and $\omega_i = \frac{p_i}{\rho_i c^2}$
  - $\omega M = 0$ (matter)
  - $\omega R = ⅓$ (radiation)
  - $\omega \Lambda = -1$ (cosmological constant)

Standard Candles

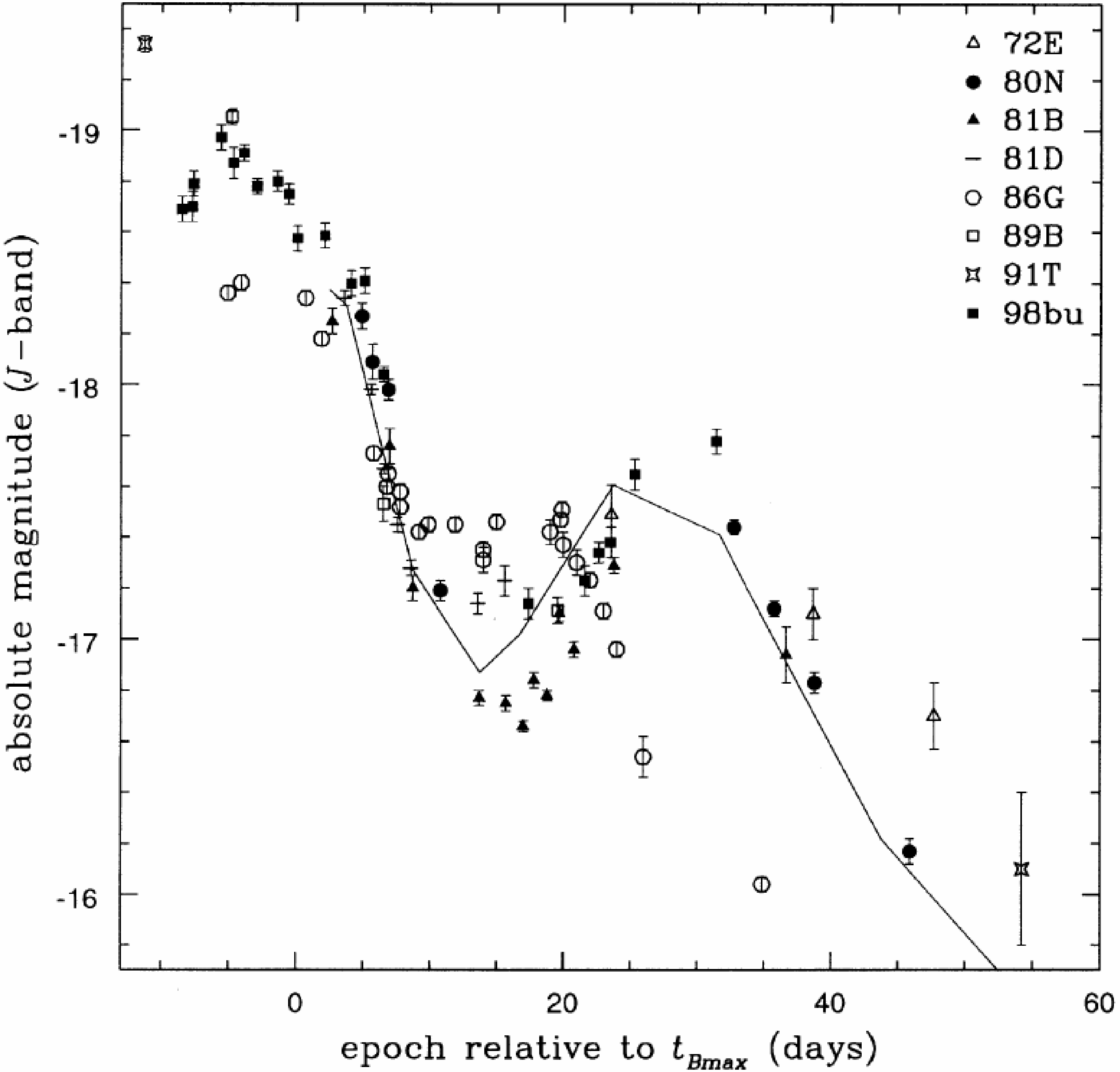
- Defined accuracy for distance measurement (~ 5% for cosmological parameters) ➔ Identical (peak) absolute luminosity
- Uniform appearance
- Readily identification
- Ideally: understanding the objects physics

SNe Ia standard candles?

- Uncorrected luminosities: scatter of ~0.2 to 0.4 mag
- Large variations in:
  - light curve shape
  - color
  - spectral evolution



(Riess et al. 1999)

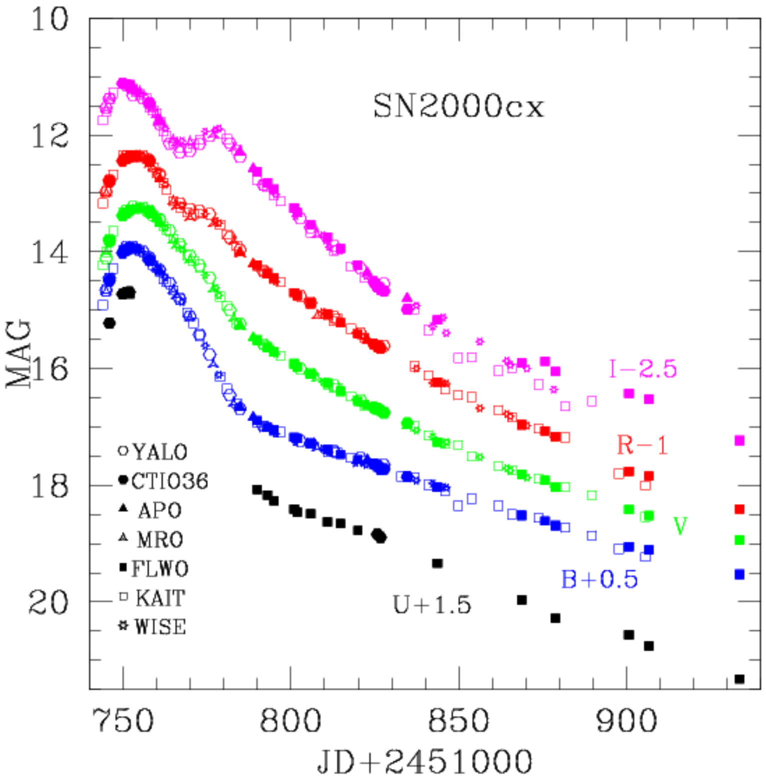


(Meikle et al. 2000)

SNe Ia standard candles?

- Uncorrected luminosities: scatter of ~0.2 to 0.4 mag
- Large variations in:
  - light curve shape
  - color
  - spectral evolution
- Outliers

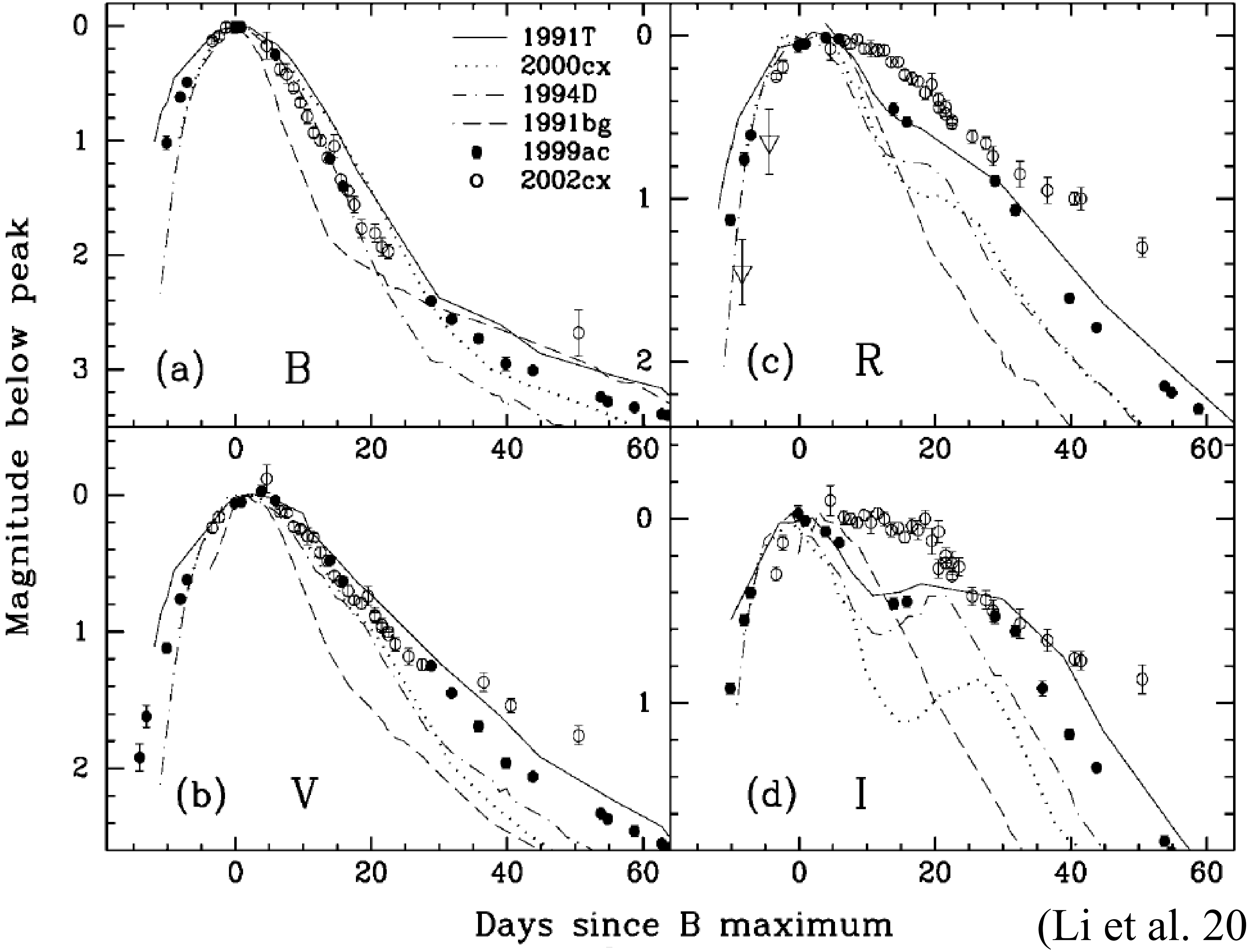
SN 2002cx



(Candia et al. 2003)

Bizarre, unique object

- extremely low expansion velocity
- photometric evolution is peculiar
- mysterious emission lines
- very different nebula phase
- inconsistent with observed spectral vs. photometric sequence and luminosity-decline rate relation


Magnitude below peak
Days since B maximum
1991T
2000cx
1994D
1991bg
1999ac
2002cx
(a) B
(b) V
(c) R
(d) I
0
1
2
3
0
20
40
60

(Li et al. 2003)

SNe Ia standard candles?

- Uncorrected luminosities: scatter of ~0.2 to 0.4 mag
- Large variations in:
  - light curve shape
  - color
  - spectral evolution
- Outliers

➔ NO standard candles

SNe Ia good distance indicators?

Steps:

- Correction of peak luminosities
- Correction for redshift (including time dilation)

SN Ia Correlations

- Luminosity vs. decline rate
  - Phillips 1993, Hamuy et al. 1996, Riess et al. 1996, 1998, Perlmutter et al. 1997, Goldhaber et al. 2001
- Luminosity vs. rise time
  - Riess et al. 1999
- Luminosity vs. color at maximum
  - Riess et al. 1996, Tripp 1998, Phillips et al. 1999
- Luminosity vs. line strengths and line widths
  - Nugent et al. 1995, Riess et al. 1998, Mazzali et al. 1998
- Luminosity vs. host galaxy morphology
  - Filippenko 1989, Hamuy et al. 1995, 1996, Schmidt et al. 1998, Branch et al. 1996

SNe Ia good distance indicators?

Steps:

- Correction of peak luminosities
- Correction for redshift (including time dilation)
- Calibration in local universe

Calibration in local universe

- Using cepheides measurements

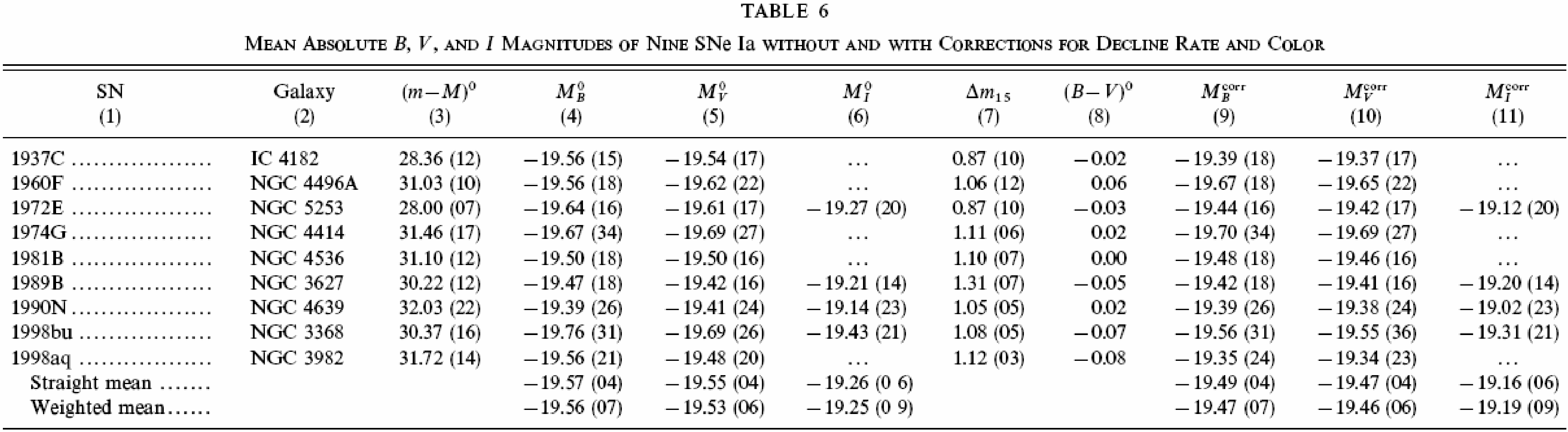


TABLE 6

MEAN ABSOLUTE *B*, *V*, AND *I* MAGNITUDES OF NINE SNe Ia WITHOUT AND WITH CORRECTIONS FOR DECLINE RATE AND COLOR

SN (1)	Galaxy (2)	$(m-M)^0$ (3)	M_B^0 (4)	M_V^0 (5)	M_I^0 (6)	Δm_{15} (7)	$(B-V)^0$ (8)	M_B^{corr} (9)	M_V^{corr} (10)	M_I^{corr} (11)
1937C	IC 4182	28.36 (12)	−19.56 (15)	−19.54 (17)	…	0.87 (10)	−0.02	−19.39 (18)	−19.37 (17)	…
1960F	NGC 4496A	31.03 (10)	−19.56 (18)	−19.62 (22)	…	1.06 (12)	0.06	−19.67 (18)	−19.65 (22)	…
1972E	NGC 5253	28.00 (07)	−19.64 (16)	−19.61 (17)	−19.27 (20)	0.87 (10)	−0.03	−19.44 (16)	−19.42 (17)	−19.12 (20)
1974G	NGC 4414	31.46 (17)	−19.67 (34)	−19.69 (27)	…	1.11 (06)	0.02	−19.70 (34)	−19.69 (27)	…
1981B	NGC 4536	31.10 (12)	−19.50 (18)	−19.50 (16)	…	1.10 (07)	0.00	−19.48 (18)	−19.46 (16)	…
1989B	NGC 3627	30.22 (12)	−19.47 (18)	−19.42 (16)	−19.21 (14)	1.31 (07)	−0.05	−19.42 (18)	−19.41 (16)	−19.20 (14)
1990N	NGC 4639	32.03 (22)	−19.39 (26)	−19.41 (24)	−19.14 (23)	1.05 (05)	0.02	−19.39 (26)	−19.38 (24)	−19.02 (23)
1998bu	NGC 3368	30.37 (16)	−19.76 (31)	−19.69 (26)	−19.43 (21)	1.08 (05)	−0.07	−19.56 (31)	−19.55 (36)	−19.31 (21)
1998aq	NGC 3982	31.72 (14)	−19.56 (21)	−19.48 (20)	…	1.12 (03)	−0.08	−19.35 (24)	−19.34 (23)	…
Straight mean			−19.57 (04)	−19.55 (04)	−19.26 (0 6)			−19.49 (04)	−19.47 (04)	−19.16 (06)
Weighted mean......			−19.56 (07)	−19.53 (06)	−19.25 (0 9)			−19.47 (07)	−19.46 (06)	−19.19 (09)

(Saha et al. 2001)

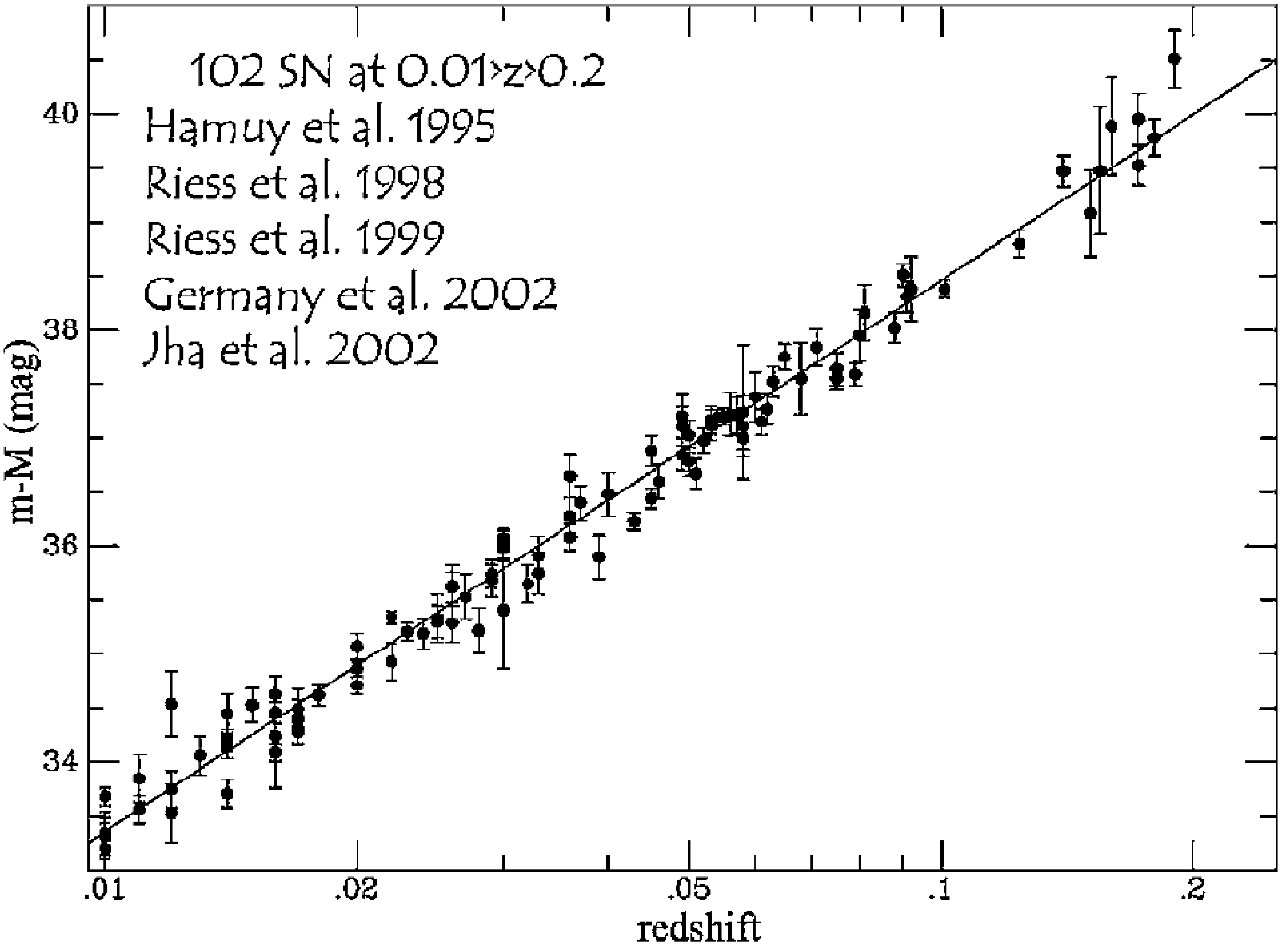
SNe Ia good distance indicators?

Steps:

- Correction of peak luminosities
- Correction for redshift (including time dilation)
- Calibration in local universe

➔YES, GOOD distance indicators!

- Hubble diagram of close SNe



(Tonry et al. 2005)

Systematical errors important

- Big samples with future instruments and surveys ➔ good statistics
- accuracy of cosmological parameters determined by systematical errors

Avoidable systematic errors

	presently	achievable
Photometric errors	0.03 mag	0.01 mag
Errors due to bandpasses	0.05 mag	0 mag
Poor light curve coverage	0.04 mag	0 mag
Host extinction	0.06 mag	0.03 mag
Totally	0.18 mag	0.04 mag

(Tonry et al. 2005)

Observation of SNe

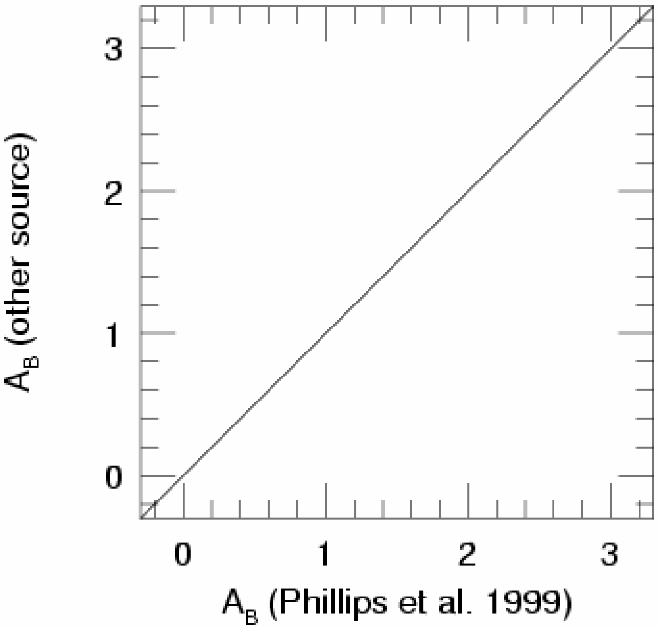
- Comparison of 2 pictures about 1 month apart, followed by spectral and photometric observations of the found SNe
  - bad light curve coverage until 2nd picture
- Continuous observation of one field over months or years
  - better photometric accuracy
  - less sensitivity to photometric systematics

Systematical errors

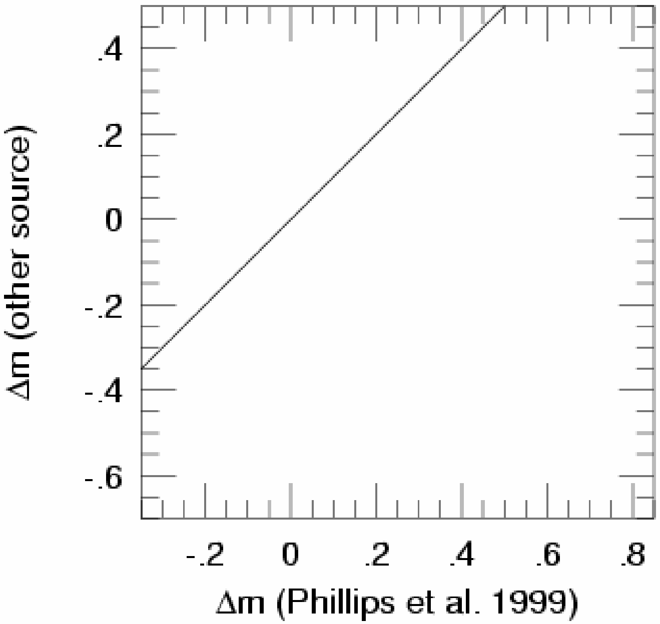
- Different calibration methods derive different peak luminosities for the same SNe in the local universe

Correction errors

Estimated absorption



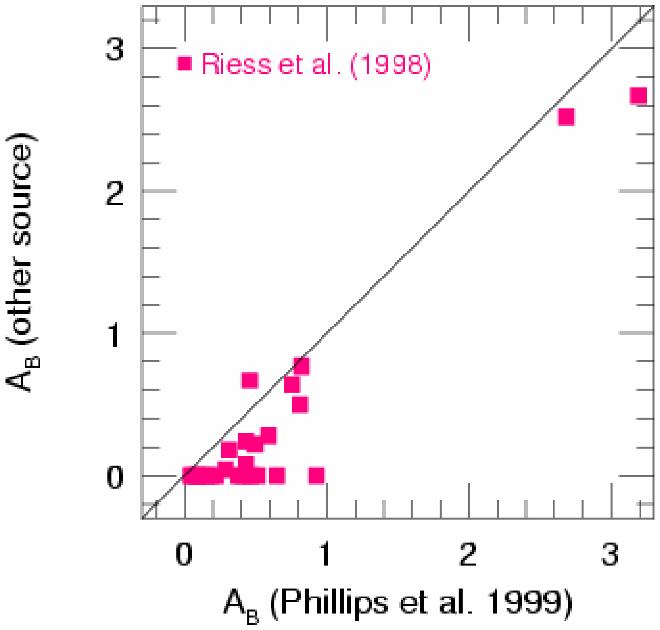
Magnitude corrections



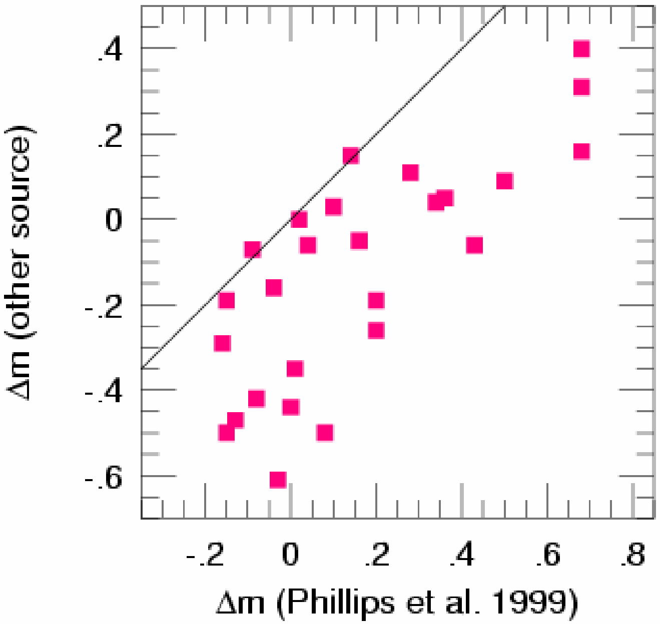
(Leibundgut 2000)

Correction errors

Estimated absorption



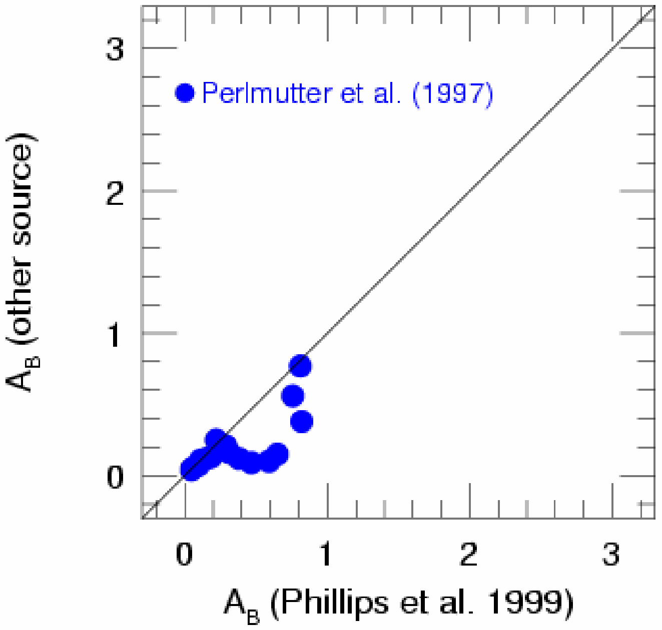
Magnitude corrections

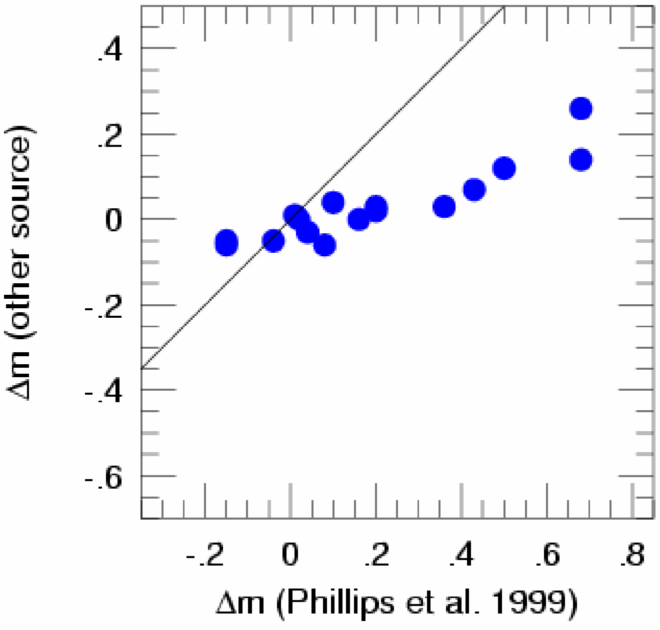


- Comparison of corrections to MLCS method
- Same SNe sample

(Leibundgut 2000)

Correction errors


Estimated absorption


Magnitude corrections

- Comparison of corrections to stretch method
- Same SNe sample

(Leibundgut 2000)

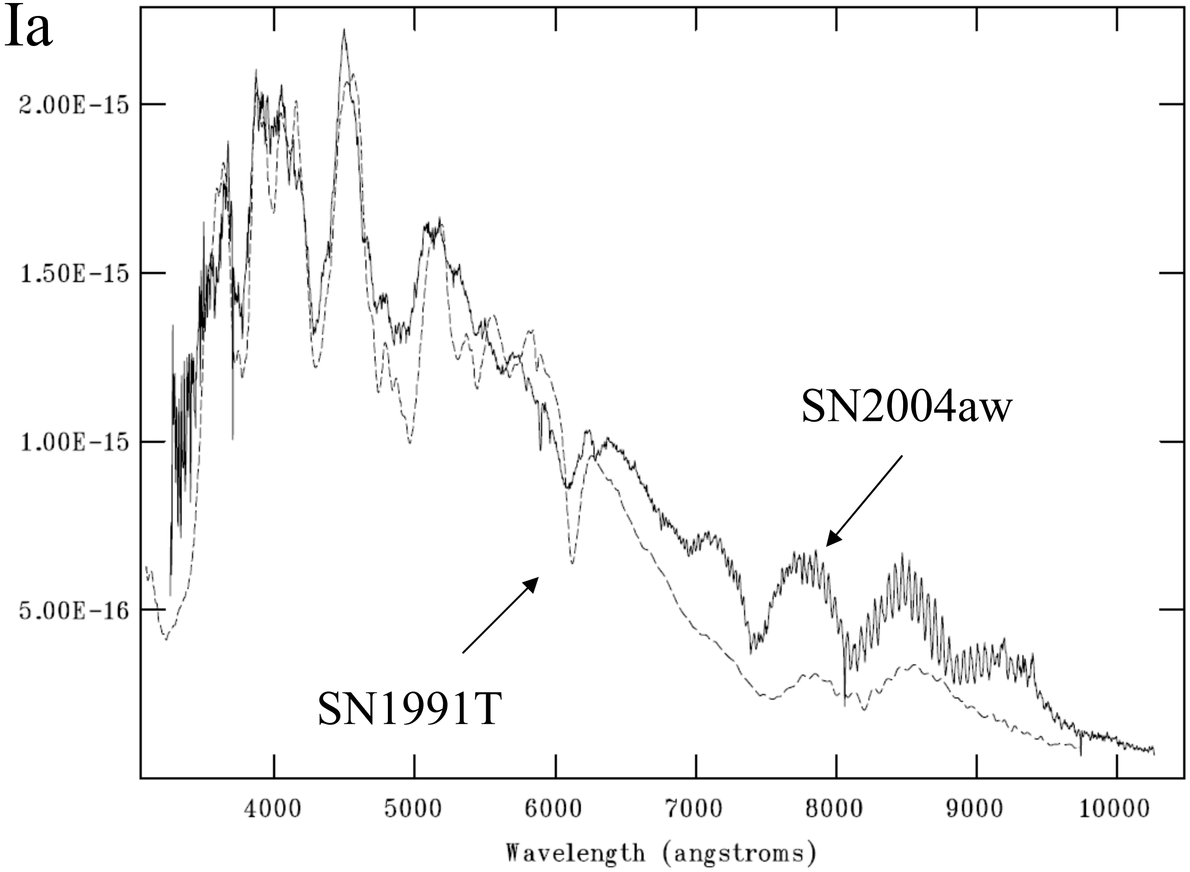
Systematical errors

- Different calibration methods derive different peak luminosities for the same SNe in the local universe
- Calibration of SNe luminosities in the local universe
- Confusion with SNe Ib/c

Confusion with SNe Ib/c

- SN2004aw around maximum
- compared to SN1991T (few days past maximum, type Ia/pec)

  ➔ classified as type Ia

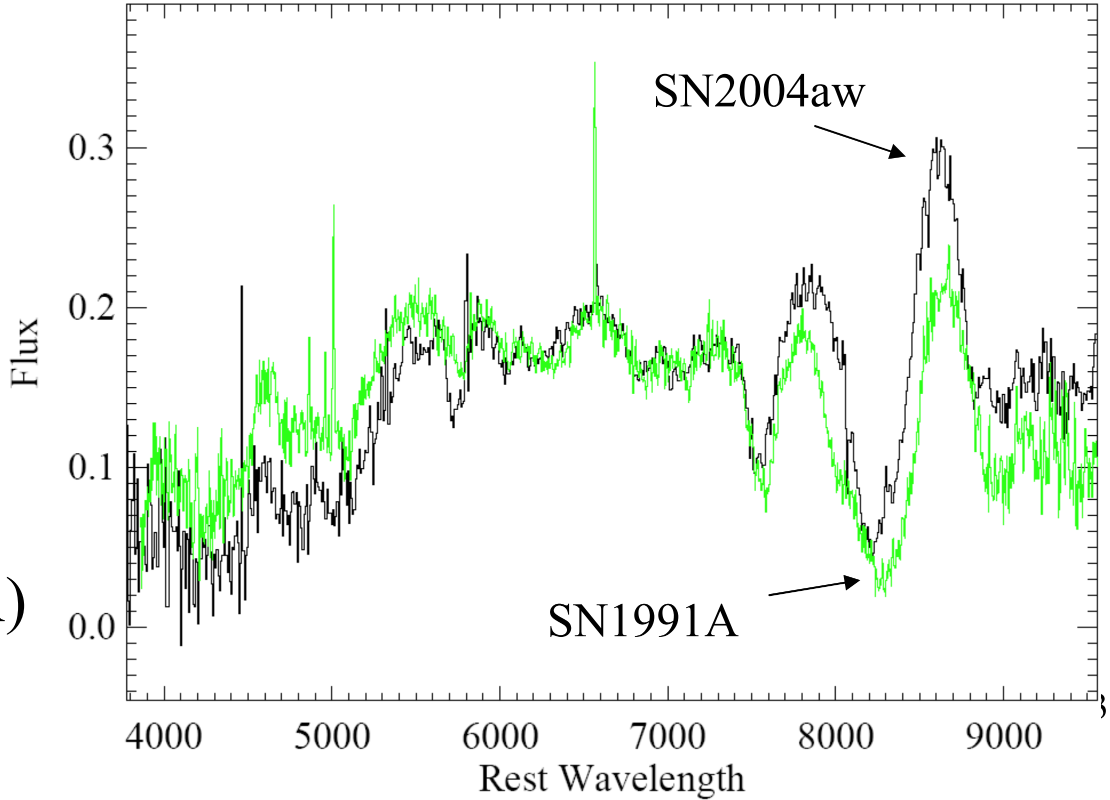


(Taubenberger, MPA)

Confusion with SNe Ib/c

- SN2004aw 30 days past maximum
- compared to SN1991A (type Ic)

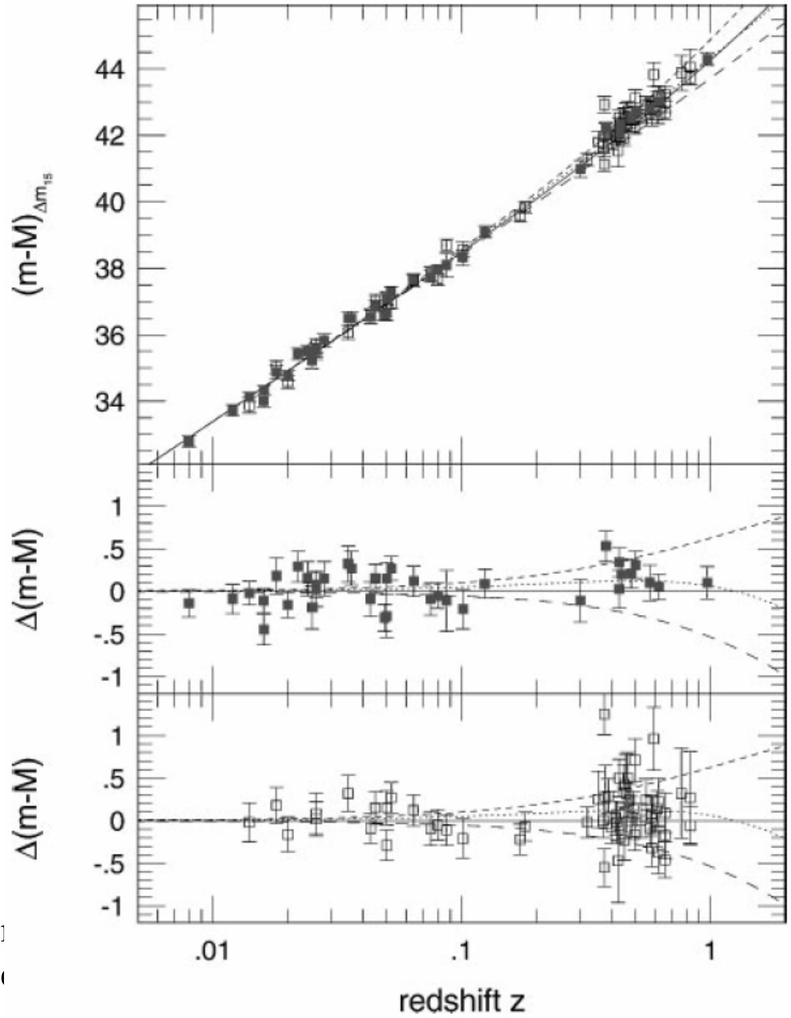
➔ SN2004aw reclassified as type Ic



(Taubenberger, MPA)

Is the expansion of the universe accelerated?

- Reported by Riess et al. 1998 and Perlmutter et al. 1999
- SNe at z ≈ 0.5 fainter:
  - 0.20±0.06 mag (Δm_{15})
  - 0.14±0.06 mag (MLCS)
  - 0.06±0.04 mag (SCP)



Alternative explanations

- Evolution of the SNe luminosity
- Absorption by dust
- Gravitational lensing
- Exotic explanations

Evolution

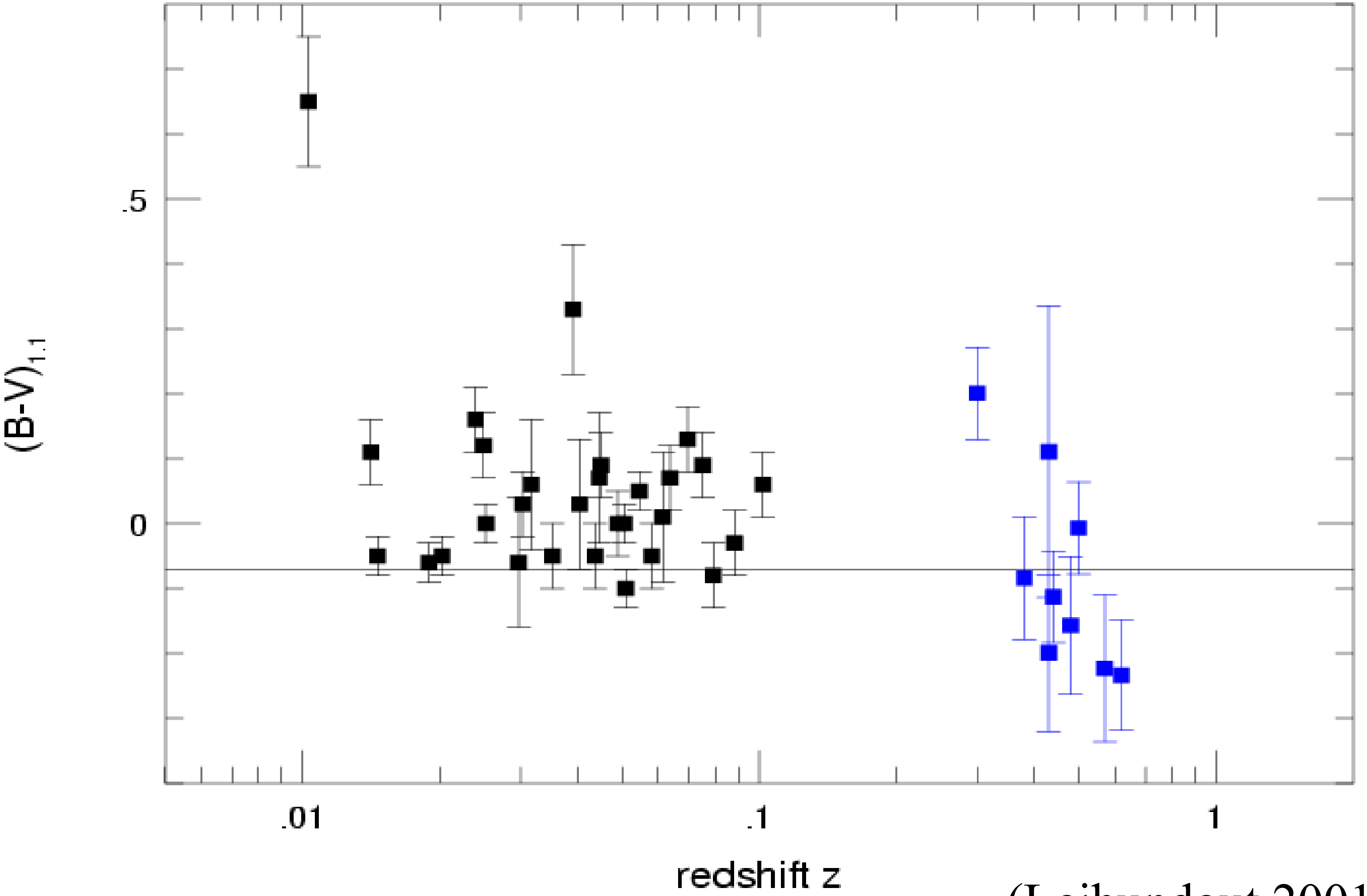
- Evolution of the SN itself by changes of
  - nuclear burning physics
  - mass of the progenitor (sub-Chandraseker shell explosions)
  - chemical composition of the progenitor
  - age of the progenitor system
  - color at peak luminosity

Evolution

- Evolution of the observed sample
  - different composition of sample ➔ different mean quantities
  - observational biases
  - decreased range of observed luminosities
- Checks:
  - better spectral observations
  - bigger samples

Dust

- Intergalactic dust
  - but: reddening not observed
    ➔ Gray dust
  - Thermalized radiation ➔ infrared background
- Chemical evolution of dust
  - $A_B \approx 0.1$-0.2 predicted
  - should be removed by reddening correction
- Checks:
  - observations with many filters



(Leibundgut 2001)

Gravitational lensing

- Any object at considerable distance will be affected by GL
- Most objects will be dimmed; few amplified
- Should increase scatter in peak luminosity
- Not measurable by SNe directly
- Depends on matter content and clumpiness

Exotic explanations

- Giving up homogeneity or isotropy out to scales of at least $z \approx 1$
- Quasi-steady state cosmology

  ➔ oscillating scale parameter
- Time-variability of physical constants

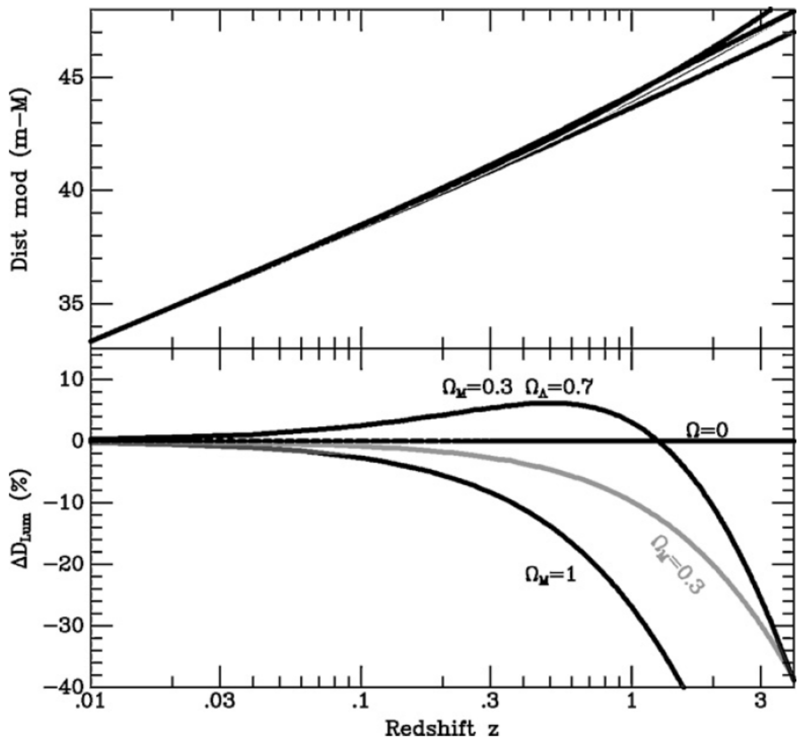
Alternatives

	Contribution to systematic errors
Evolution	0.00 mag (?)
Dust	0.02 mag
Gravitational lensing	0.03 mag ($z > 1$)

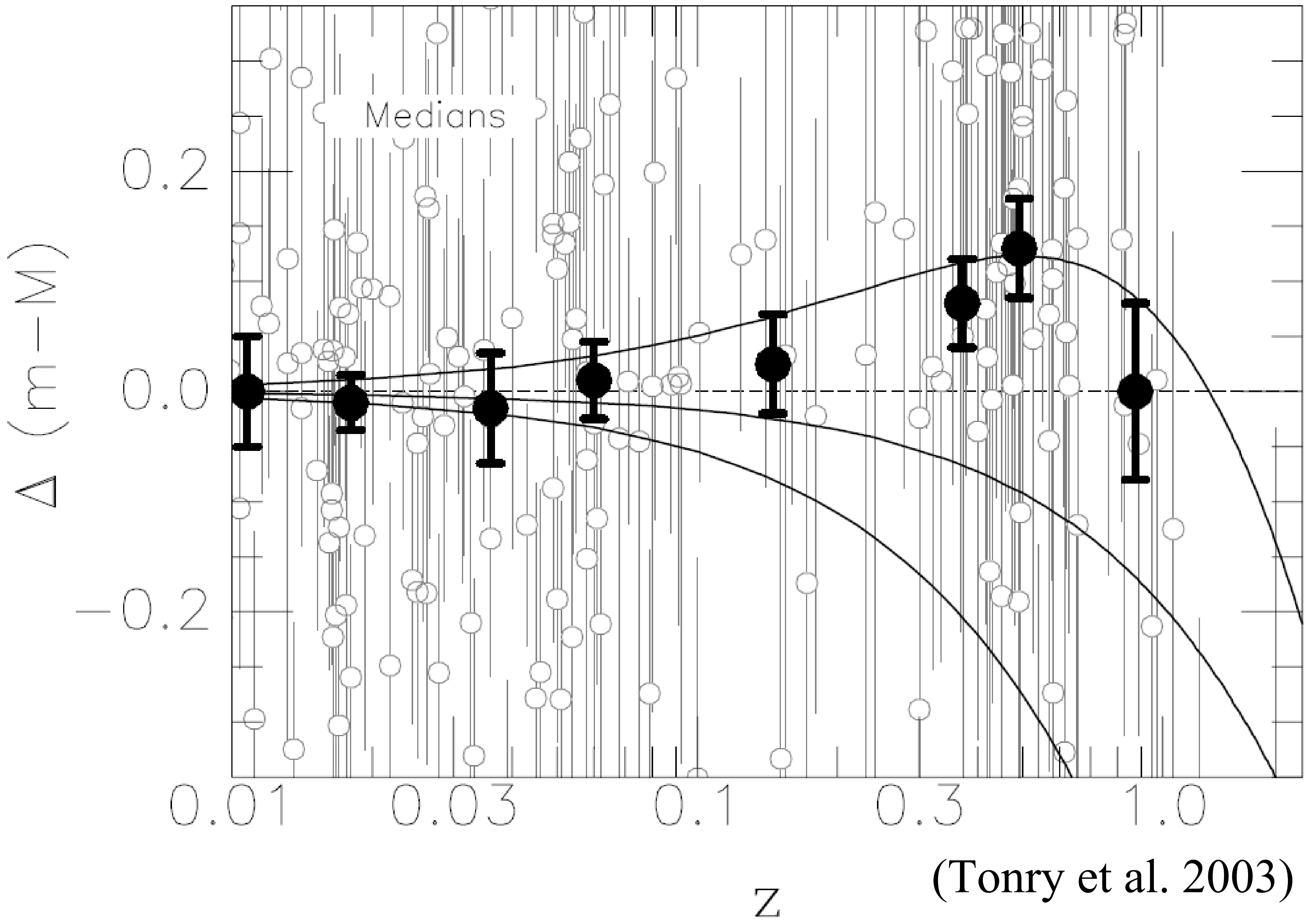
(Tonry et al. 2005)

Cosmological parameters

- Dark Energy/ accelerated expansion distinguishable from alternatives for z > 0.8
- Cosmological parameters determined by fits to models

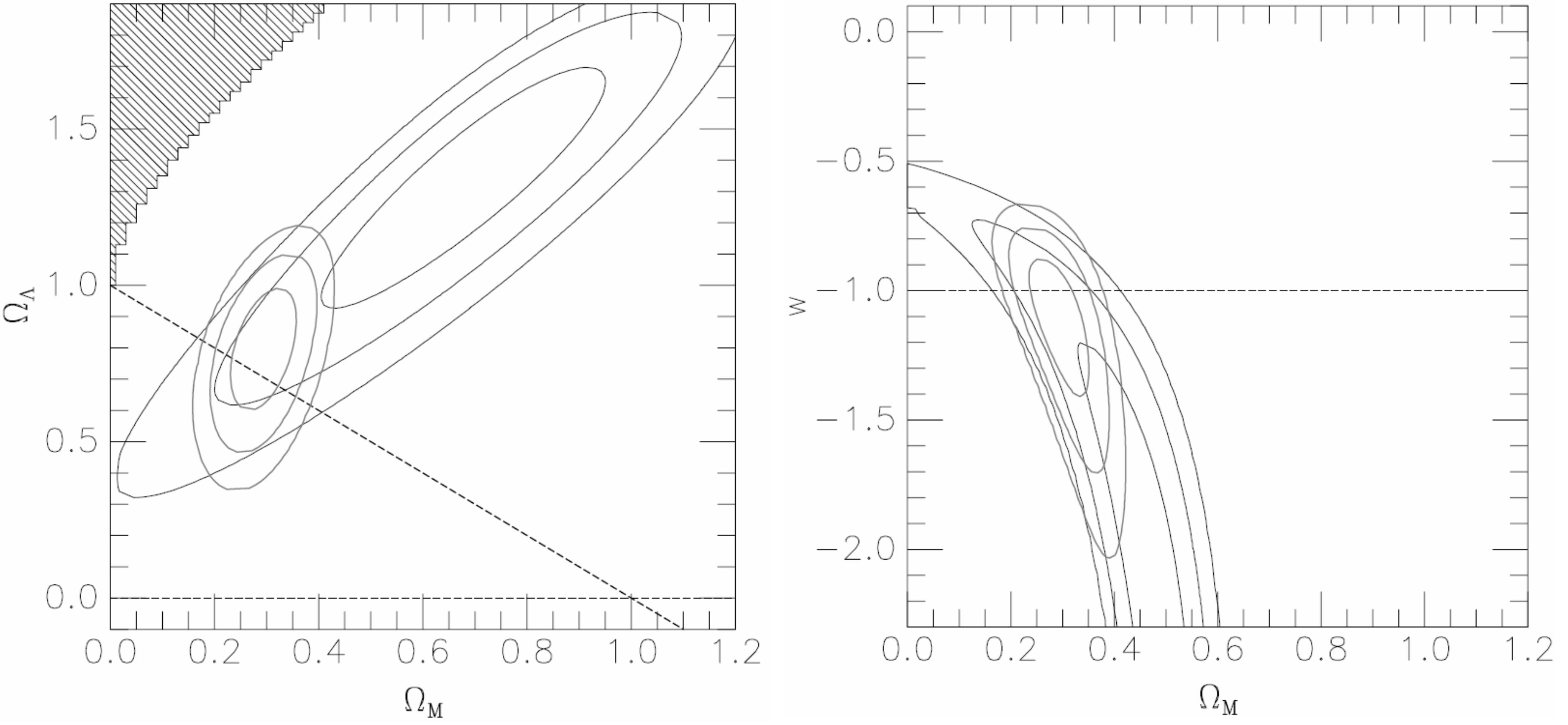


Medians of 230 SNe + binned



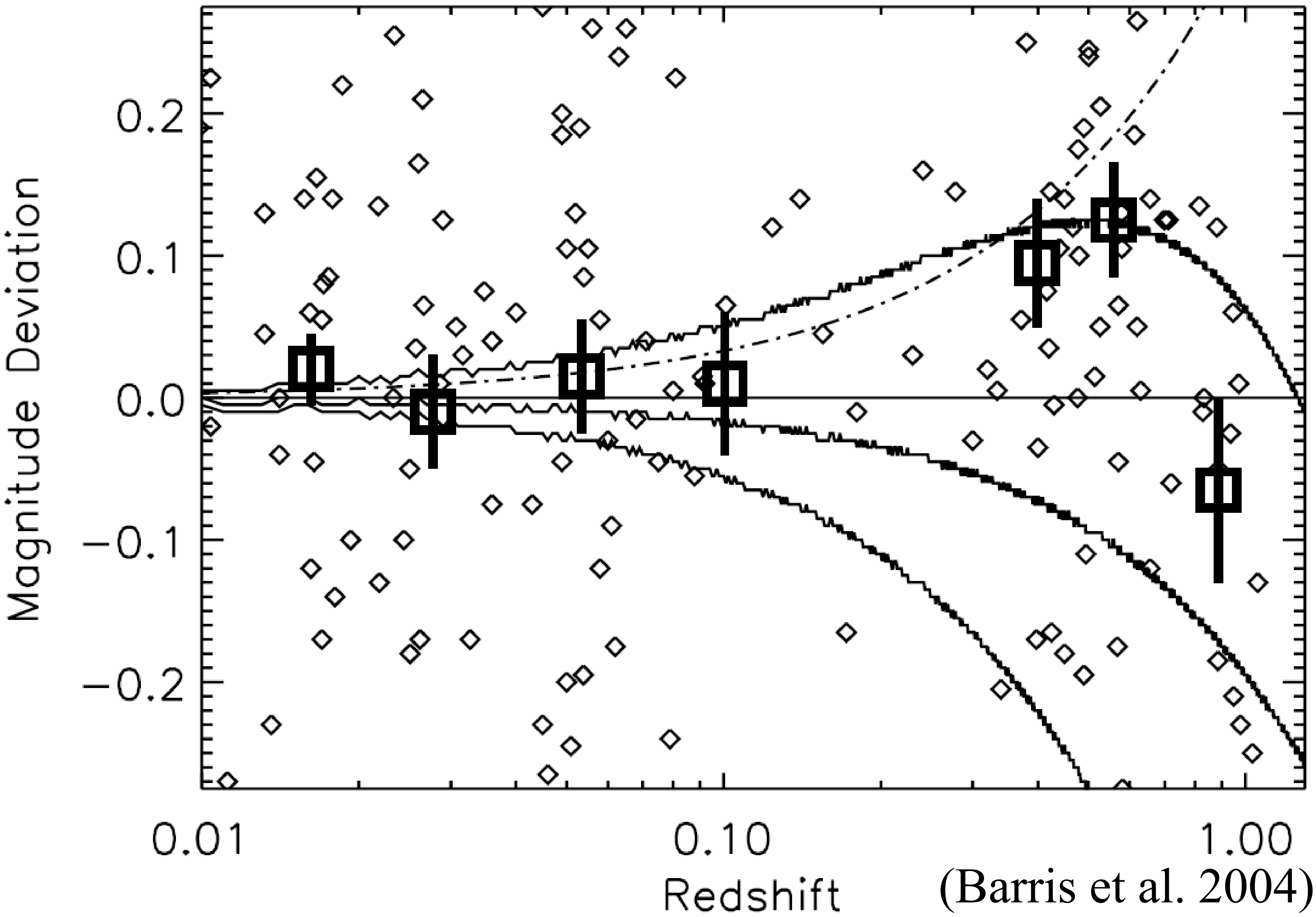
(Tonry et al. 2003)

172 SNe



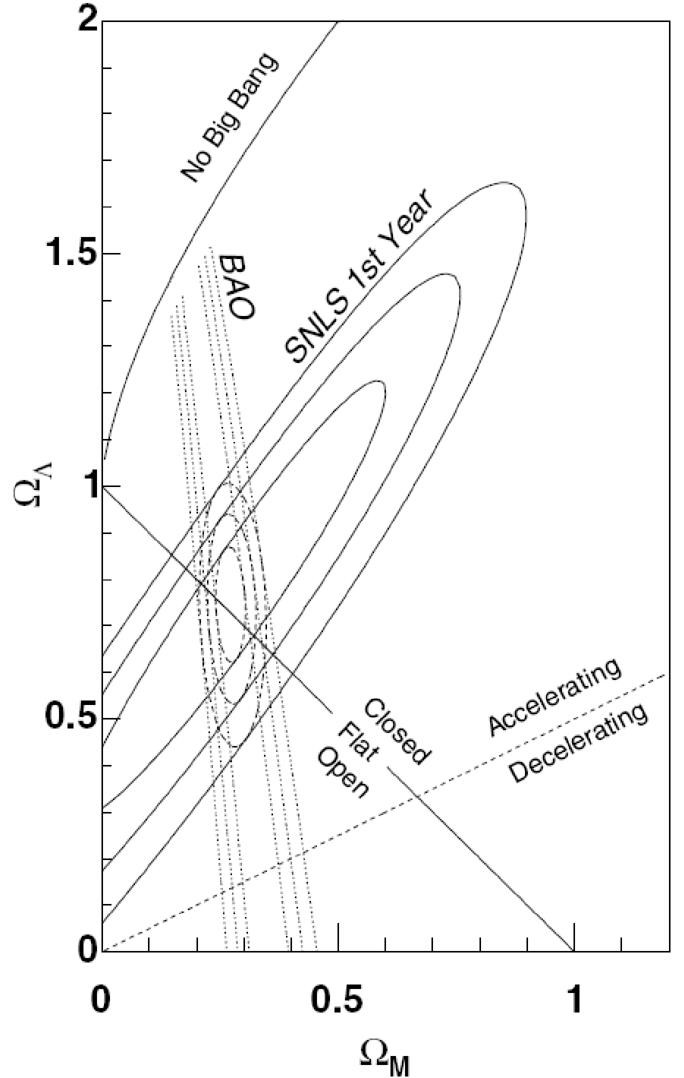
(Tonry et al. 2003)

Medians of 222 SNe + binned



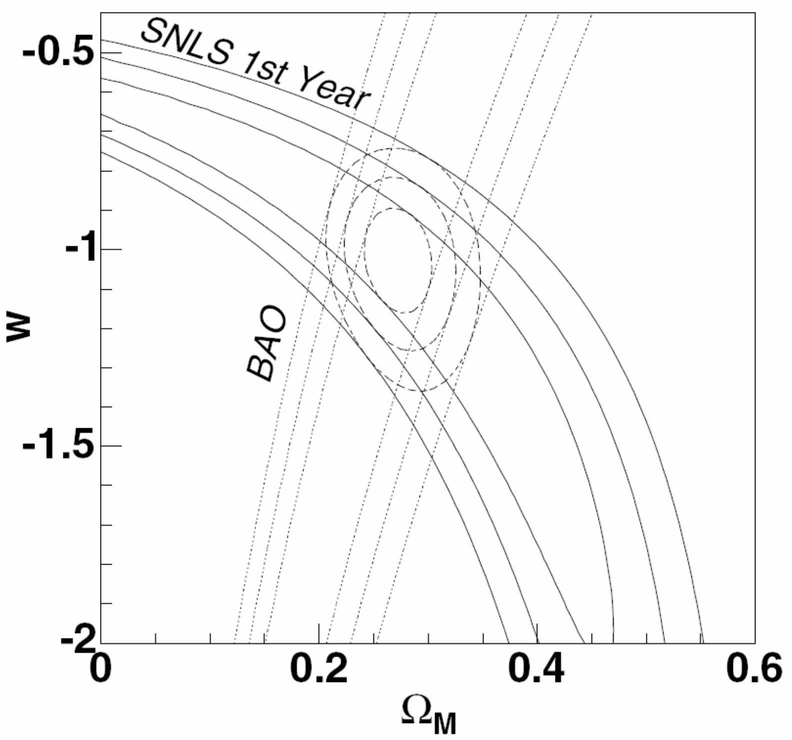
(Barris et al. 2004)

First year results of SNLS



$w = -1$

44 nearby SNe + 71 SNLS SNe



$\Omega_k = 0$

(Astier et al. 2006)

First year results of SNLS

- SNLS:

  $\Omega_M = 0.263 \pm 0.042(stat) \pm 0.032(sys)$

  (flat Λ cosmology, i.e. $w = -1$)

- SNLS + BAO SDSS:

  $\Omega_M = 0.271 \pm 0.021(stat) \pm 0.007(sys) \quad w = -1$

  $w = -1.023 \pm 0.090(stat) \pm 0.054(sys) \quad \Omega_M$ fixed

  (flat cosmology with constant equation of state)

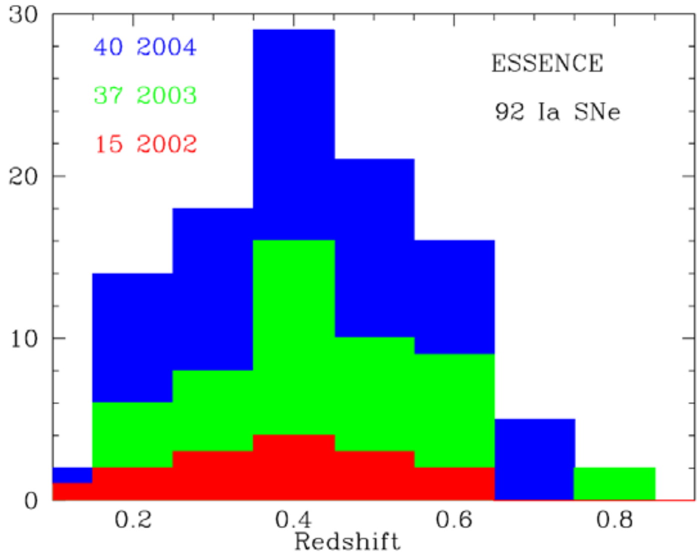
(Astier et al. 2006)

SNLS

- 5 year program (474 nights) started August 2003
- component of CFHT Legacy Survey
- spectral follow-ups with VLT, Keck, Gemini
- 4 fields
- ~ 700 SNe measurements expected
- 91 SNe Ia after one year

ESSENCE

- 5 year campaign started October 2002
- 3 month observing sessions
- 8 fields, each observed every fourth night
- ~200 SNe with $0.15 < z < 0.75$ expected
- 92 measured after 3 years
- goal: determine w to ±0.1



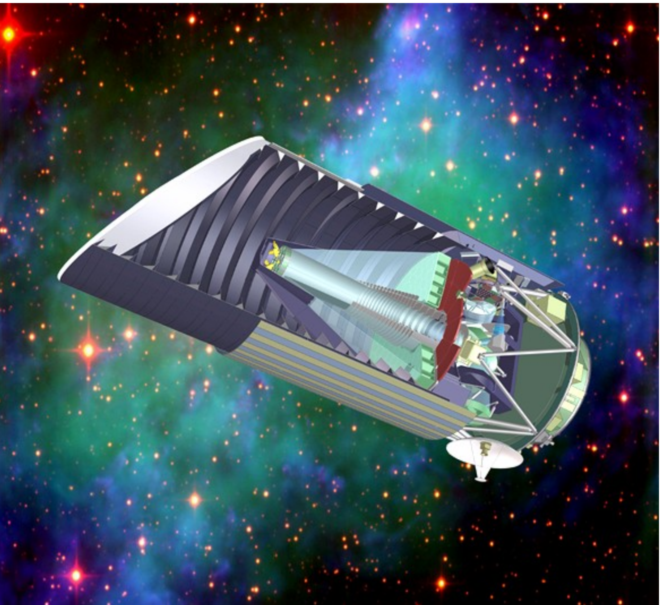
http://www.ctio.noao.edu/wproject/

SN factory

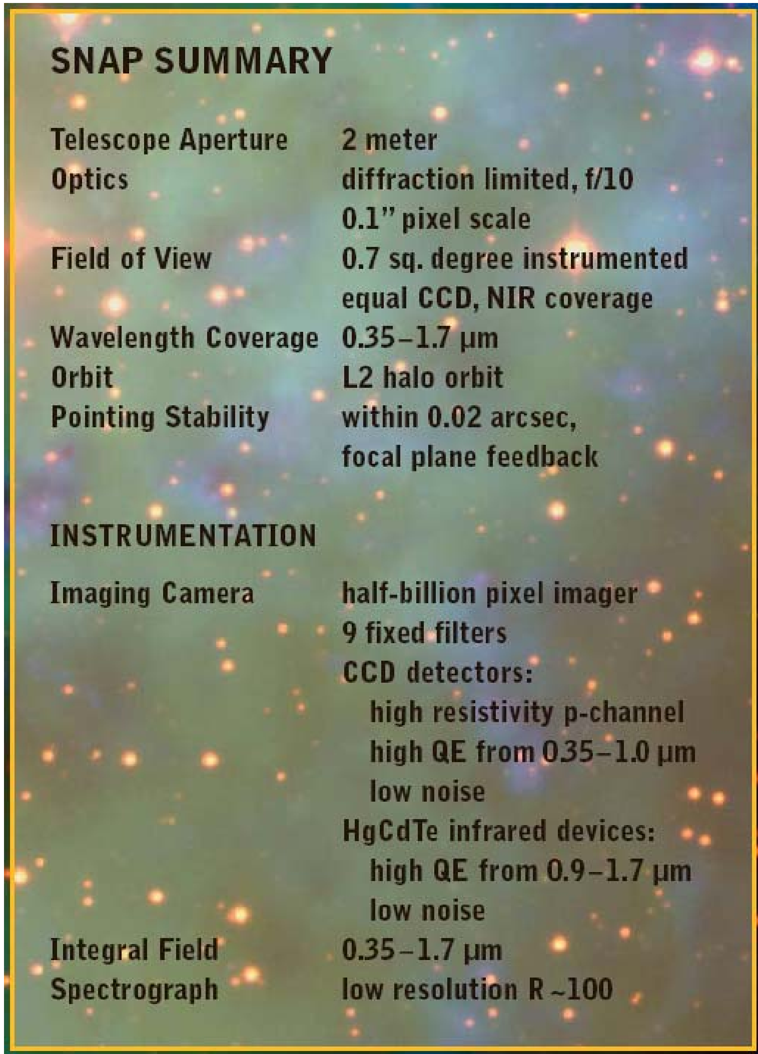
- started fall 2002
- wide-field images of NEAT
- ~300-600 SNe with $0.03 < z < 0.08$ expected
- 83 SNe found until end of 2003

SNAP – SuperNova/AccelerationProbe

- ~ 2000 SNe/year with $z < 1.7$



http://snap.lbl.gov/

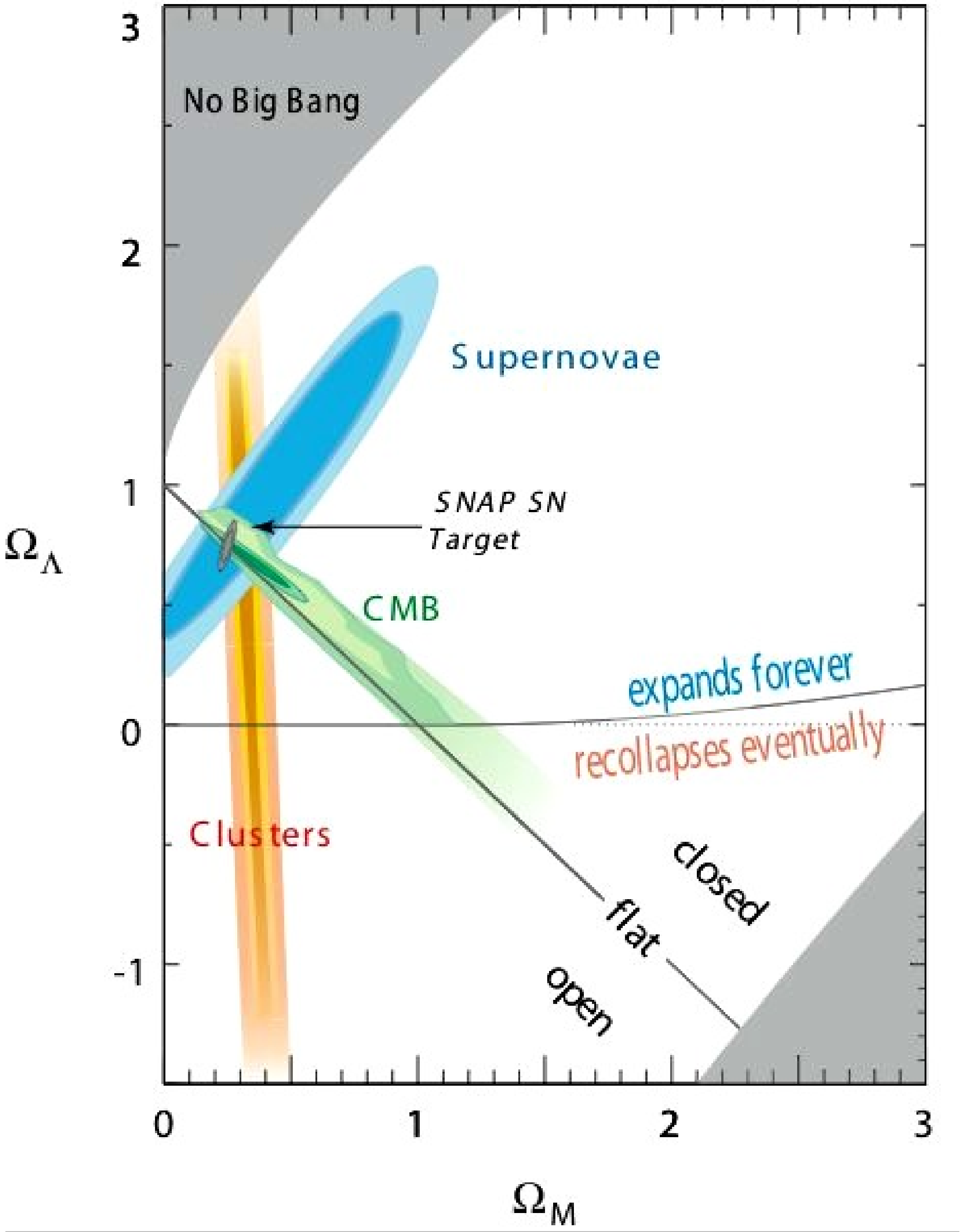


SNAP SUMMARY

Telescope Aperture	2 meter
Optics	diffraction limited, f/10 0.1" pixel scale
Field of View	0.7 sq. degree instrumented equal CCD, NIR coverage
Wavelength Coverage	0.35–1.7 µm
Orbit	L2 halo orbit
Pointing Stability	within 0.02 arcsec, focal plane feedback

INSTRUMENTATION

Imaging Camera	half-billion pixel imager 9 fixed filters CCD detectors: high resistivity p-channel high QE from 0.35–1.0 µm low noise HgCdTe infrared devices: high QE from 0.9–1.7 µm low noise
Integral Field Spectrograph	0.35–1.7 µm low resolution R ~100



http://snap.lbl.gov/

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