Supernova Cosmology:
The Quest for Precise Luminosity Distances

Wolfgang Hillebrandt
MPI für Astrophysik
Garching

Forschungszentrum Karlsruhe,
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In collaboration with ….

Fritz Röpke,

Bruno Leibundgut,

& the RTN/ESC

Distances in the local universe

- Assume a linear expansion ("Hubble law")

$$v=cz=H_0 \cdot D$$

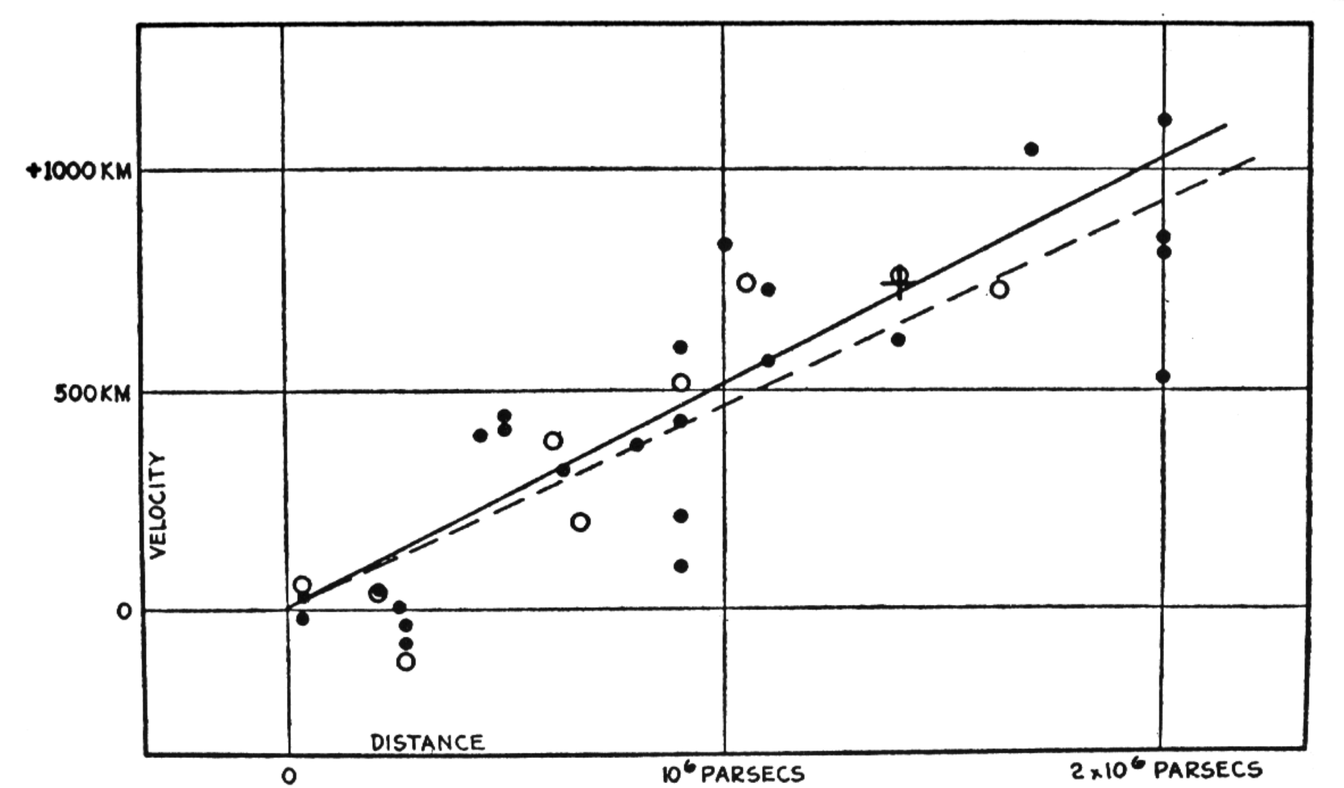
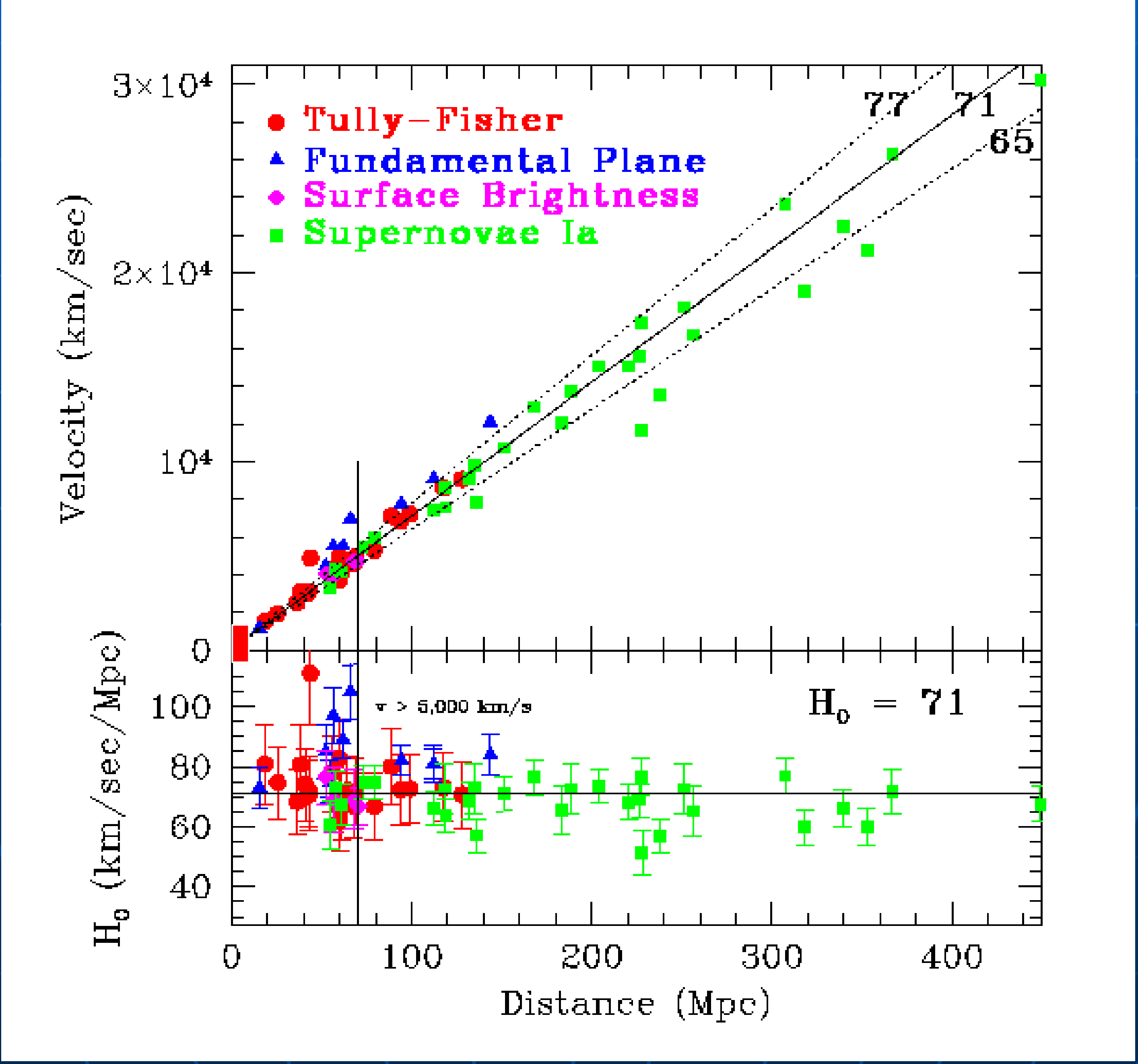
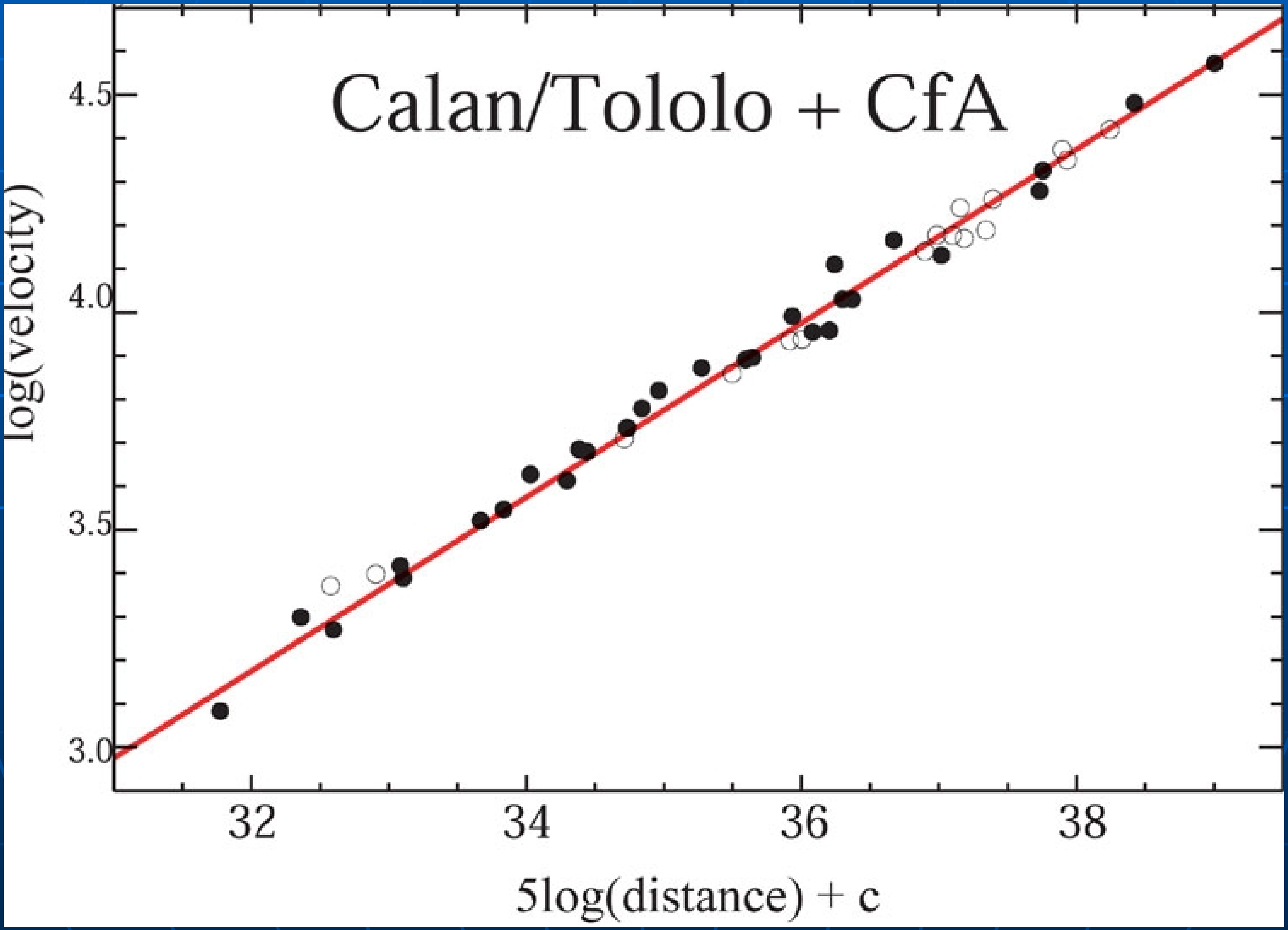


FIG. 9. *The Formulation of the Velocity-Distance Relation.*

A “modern” Hubble diagram



Universal expansion
(as measured by type Ia supernovae)



Distances in the local universe

- Assume a linear expansion (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.)
  $m = 5\log(z) + b$
  $b = M + 25 + 5\log(c) - 5\log(H_0)$

The Hubble constant

- Sets the absolute scale of cosmology
  - (“replaces these annoying *h*’s in all the theorists talks” ; B. Leibundgut)
- Measure redshifts and distances in the nearby universe
  - Supernovae can do this in two ways:
    - Expanding photosphere method of core-collapse SNe
    - accurate (relative) distances from SN Ia

Expanding Photosphere Method

- Baade (1926), Schmidt et al. (1993), Eastman et al. (1996), Hamuy et al. (2001)

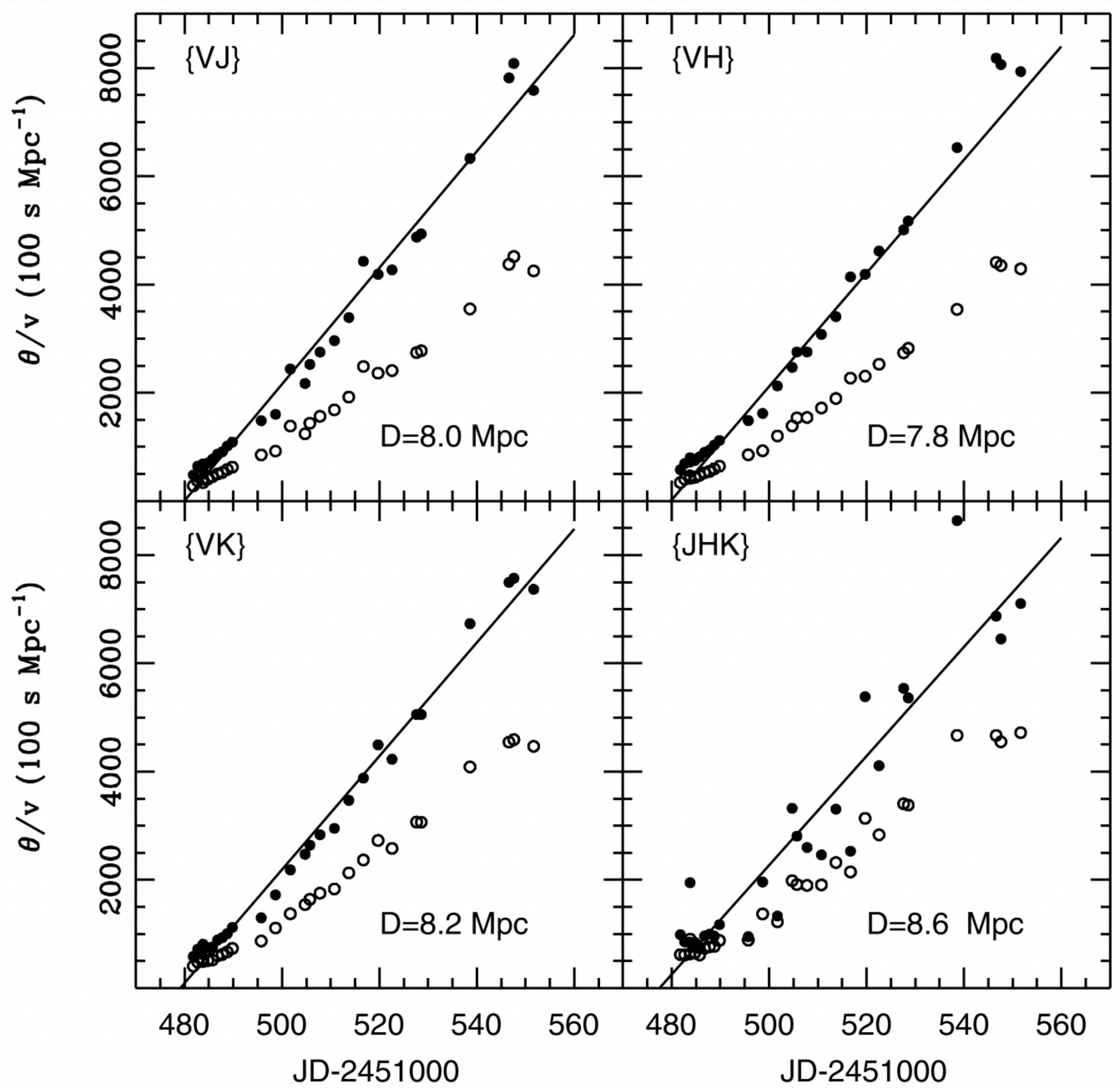
- Assume homologous expansion: $R(t)=R_0+v(t-t_0)$

- Photometric angular diameter

$$\Theta = \frac{R}{D} = \sqrt{\frac{f_\lambda}{\zeta_\lambda^2 \pi B_\lambda(T) 10^{-0.4A(\lambda)}}}$$

Distances from EPM

(SN 1999em, Hamuy et al. 2001)



$$\frac{\Theta_i}{v_i} \approx \frac{t_i - t_0}{D}$$

Slope gives the distance

Intercept the size of the progenitor and/or time of explosion

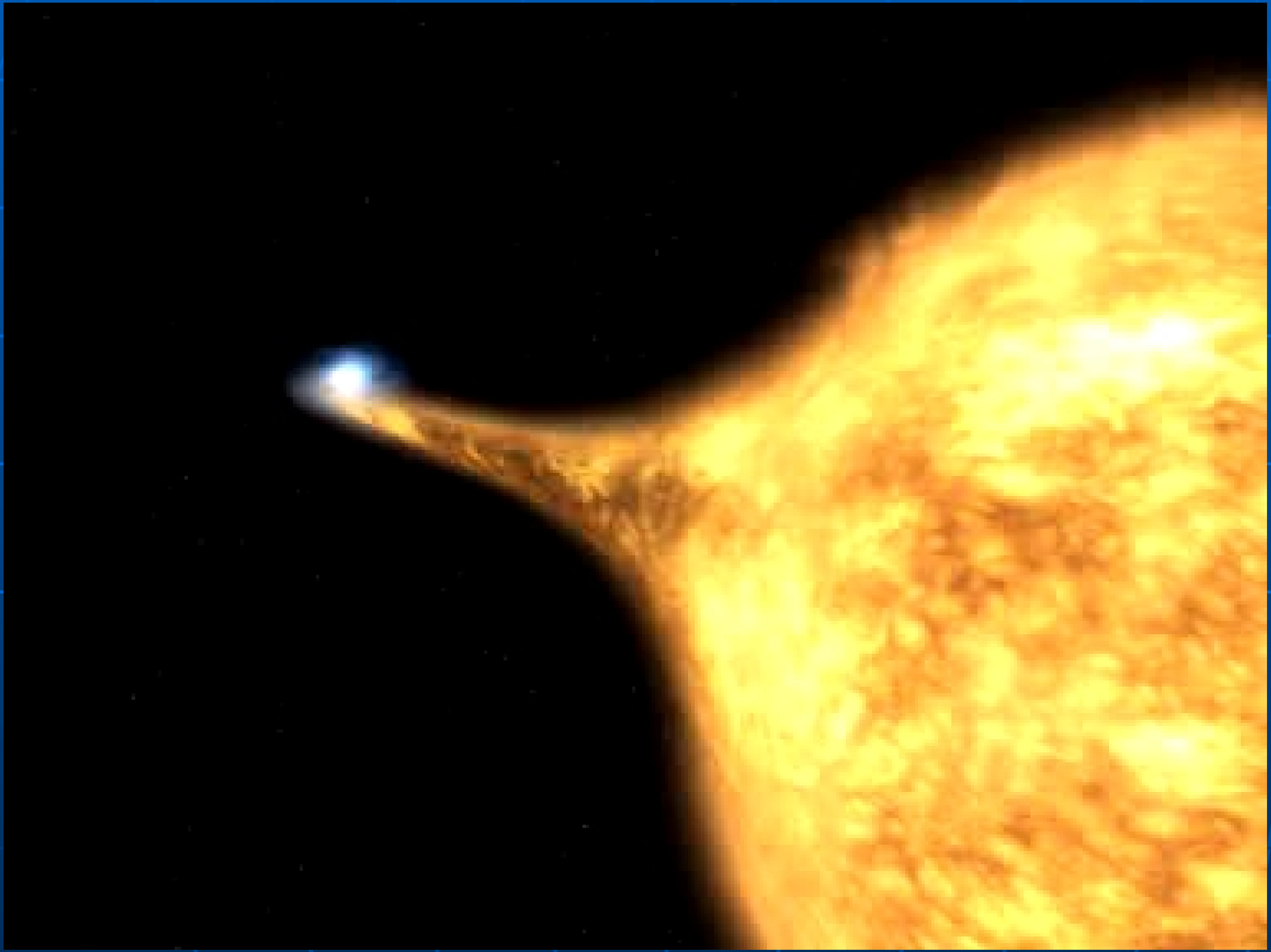
Distances from EPM

- Note that this distance measurement is completely independent of any other astronomical object!
  - no distance ladder
- Assumption:
  - massive envelope that creates a photosphere
  - spherical symmetry
    - not true for many core collapse supernovae
  - correction factors for deviation from black body spectrum
    - model dependent

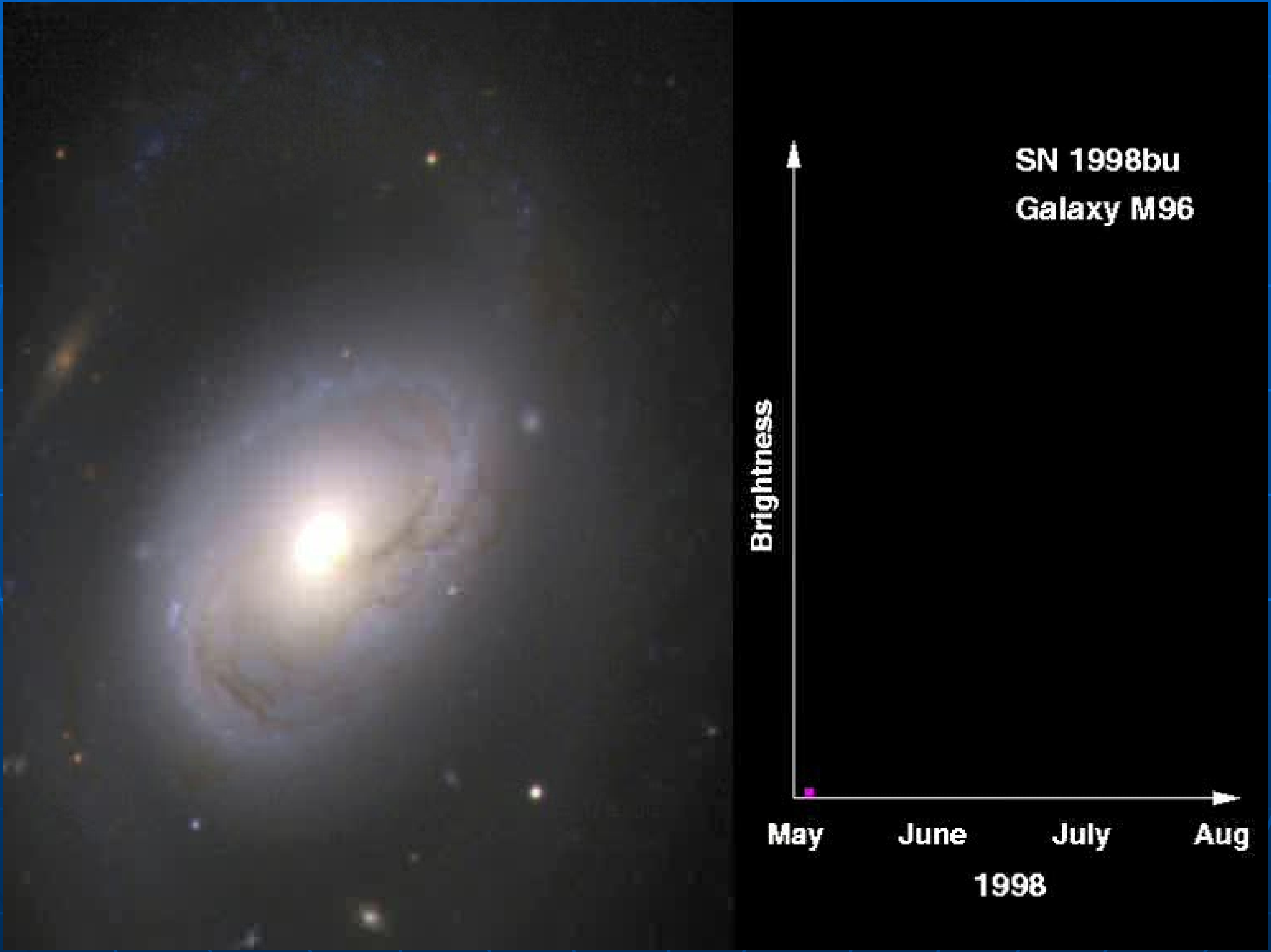
EPM so far

- Limitations
  - needs large and extensive data sets
  - difficulties to get into the Hubble flow
  - distances only to galaxies with supernovae
    - difficult to build large sample
- Promise
  - completely independent distance measurements
    - checks on the Cepheid distance scale

The "standard model" of a SN Ia



- White dwarf in a binary system
- Growing to M_{Chan} by mass transfer



SN 1998bu
Galaxy M96
Brightness
May
June
July
Aug
1998

Distances with Type Ia Supernovae

- Use the Hubble diagram (*m-M vs.* log *z*)
  - $m\text{-}M = 5\log(z) + 25 + 5\log(c) - 5\log(H_0)$
- Note that the slope is given here.

- Hubble constant can be derived when the absolute luminosity *M* is known
  - $\log H_0 = \log(z) + 5 + \log(c) - 0.2(m\text{-}M)$

Absolute Magnitudes of SNe Ia

SN	Galaxy	m-M	M_B	M_V	M_I
1937C	IC 4182	28.36 (12)	-19.56 (15)	-19.54 (17)	-
1960F	NGC 4496A	31.03 (10)	-19.56 (18)	-19.62 (22)	-
1972E	NGC 5253	28.00 (07)	-19.64 (16)	-19.61 (17)	-19.27 (20)
1974G	NGC 4414	31.46 (17)	-19.67 (34)	-19.69 (27)	-
1981B	NGC 4536	31.10 (12)	-19.50 (18)	-19.50 (16)	-
1989B	NGC 3627	30.22 (12)	-19.47 (18)	-19.42 (16)	-19.21 (14)
1990N	NGC 4639	32.03 (22)	-19.39 (26)	-19.41 (24)	-19.14 (23)
1998bu	NGC 3368	30.37 (16)	-19.76 (31)	-19.69 (26)	-19.43 (21)
1998aq	NGC 3982	31.72 (14)	-19.56 (21)	-19.48 (20)	-
Straight mean			-19.57 (04)	-19.55 (04)	-19.26 (0 6)

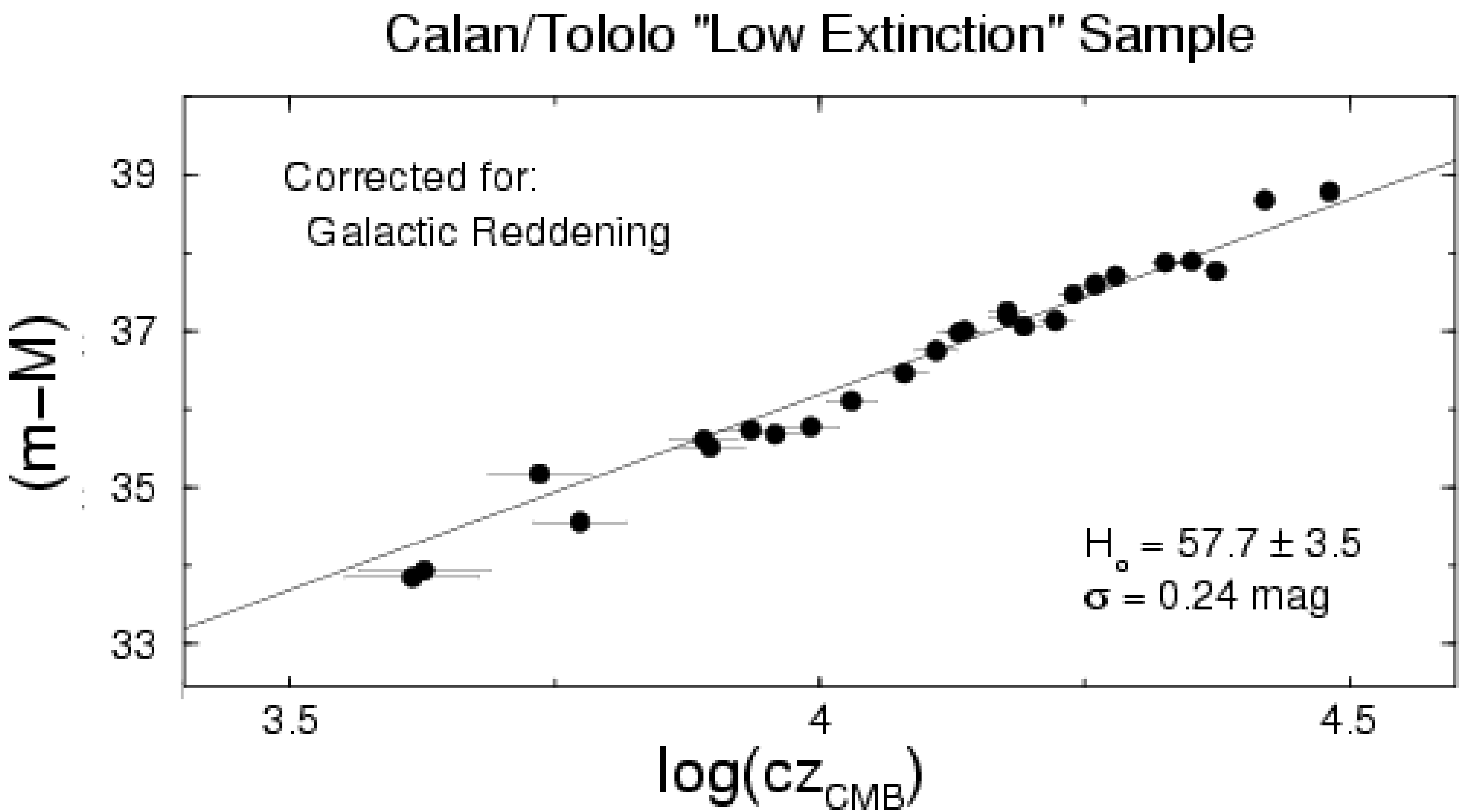
(Saha et al. 1999)

Testing the SNe Ia as distance indicators

- Hubble diagram of SNe Ia in the local, linear expansion, Hubble flow
- Calibration through “primary” distance indicators
- Theoretical models

Nearby SNe Ia

Phillips et al. (1999)



Light curve shape – luminosity

- Δm_{15} relation

  Phillips (1993), Hamuy et al. (1996), Phillips et al. (1999)

- MLCS

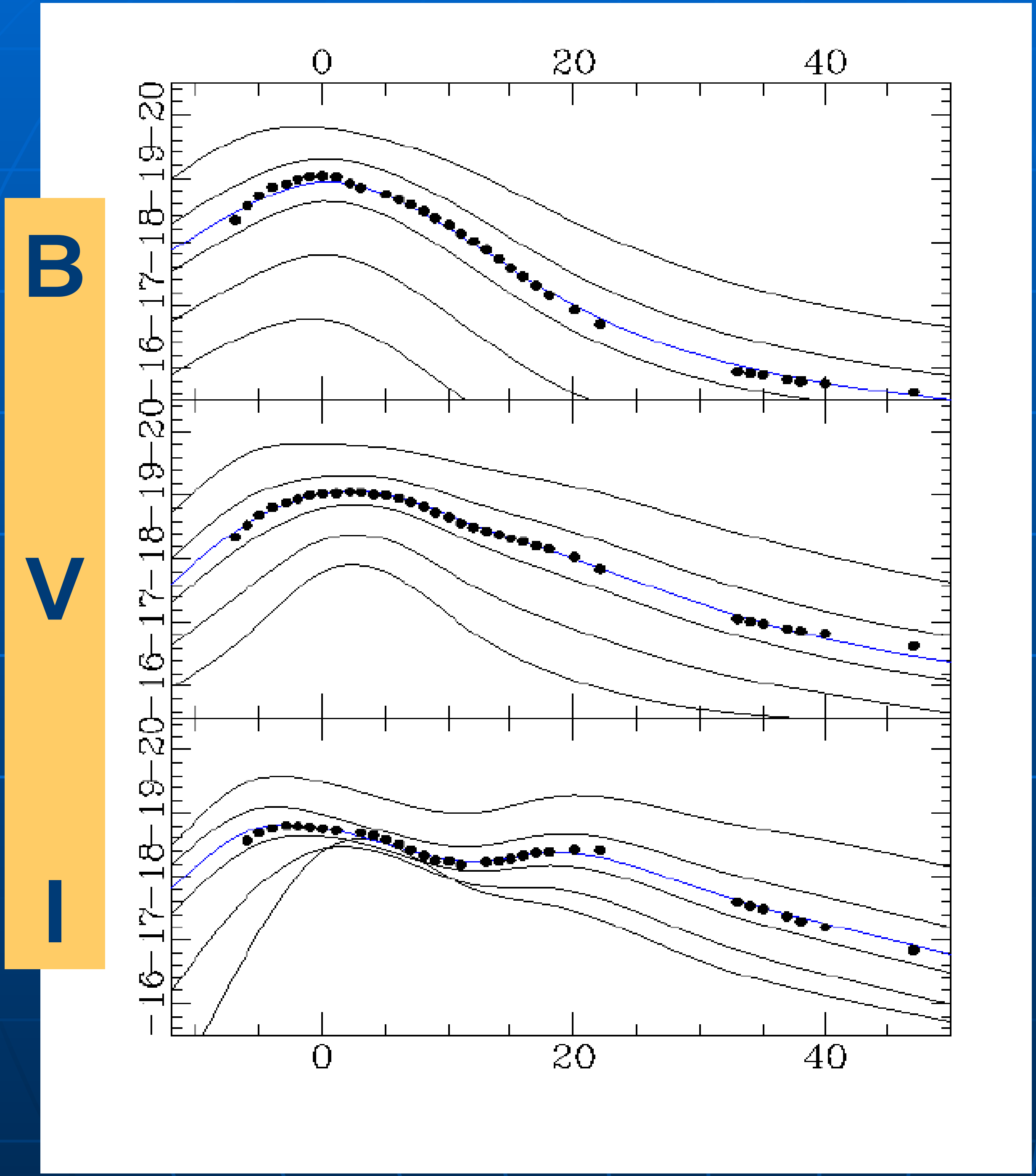
  Riess et al. (1996, 1998), Jha et al. (2003)

- "stretch"

  Perlmutter et al. (1997, 1999), Goldhaber et al. (2001)

- MAGIC

  Wang et al. (2003)

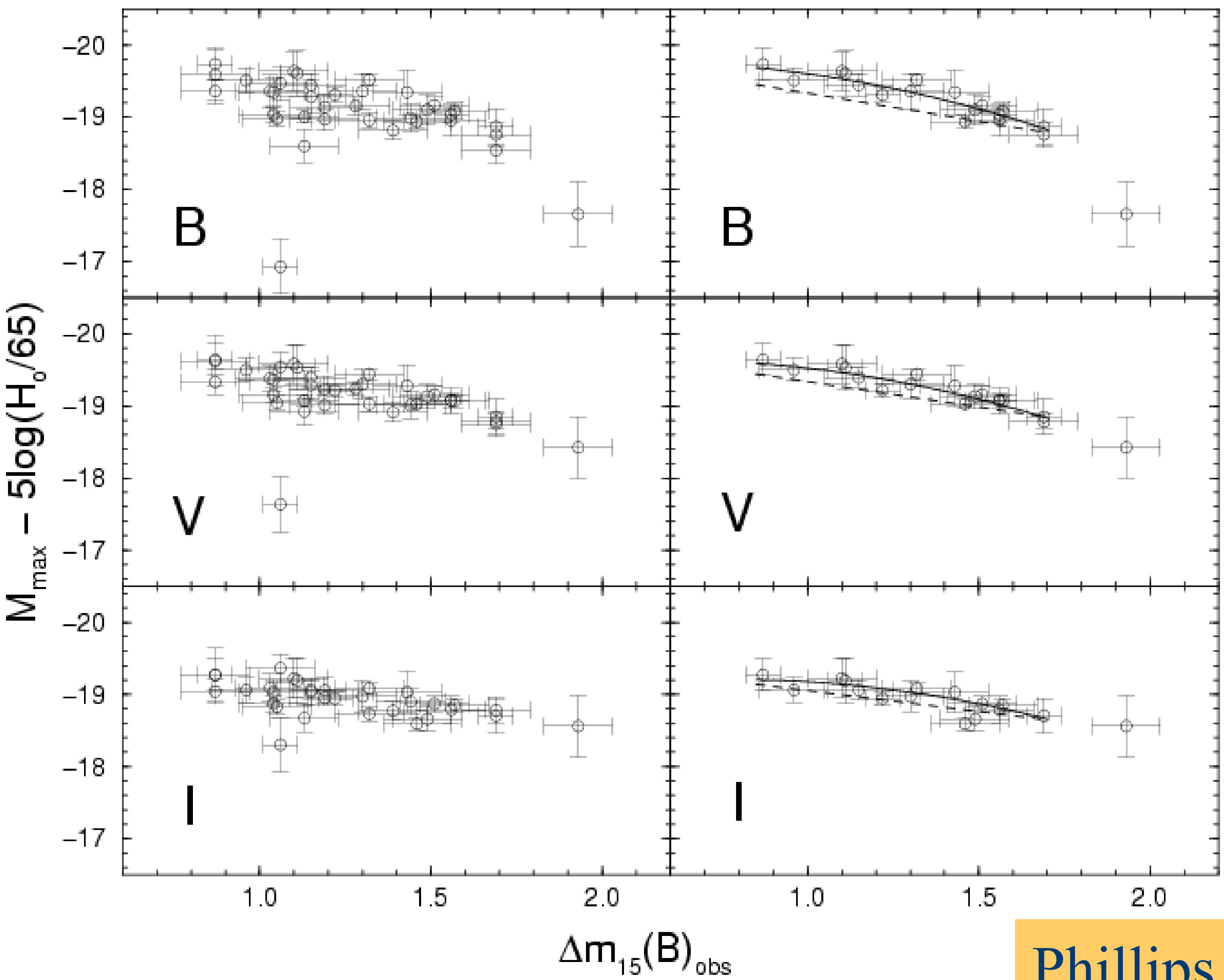


The SN Ia luminosity can be normalised:

Bright = slow
Dim = fast

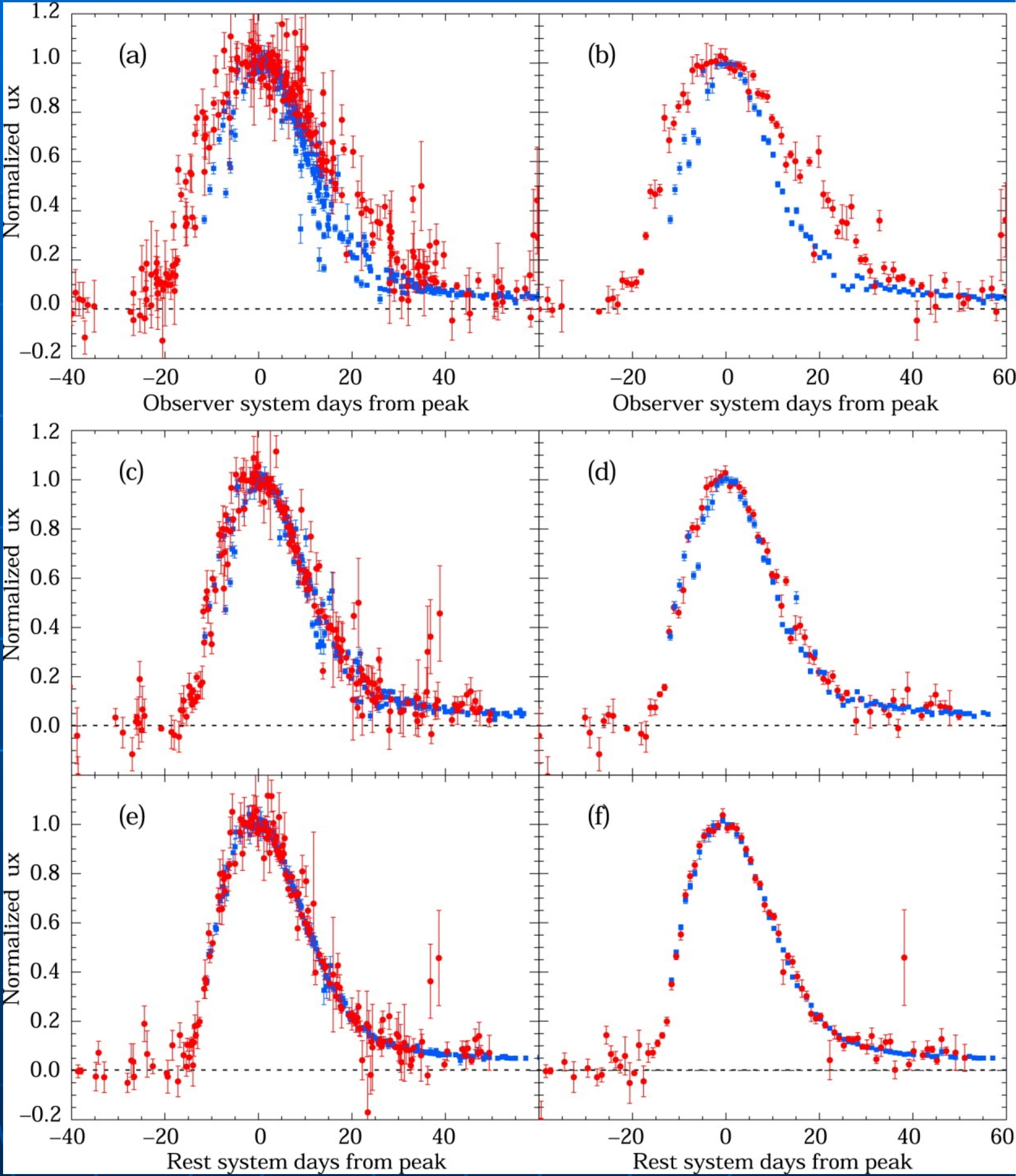
(Riess et al. 1996)

Correlations



Phillips et al. 1999

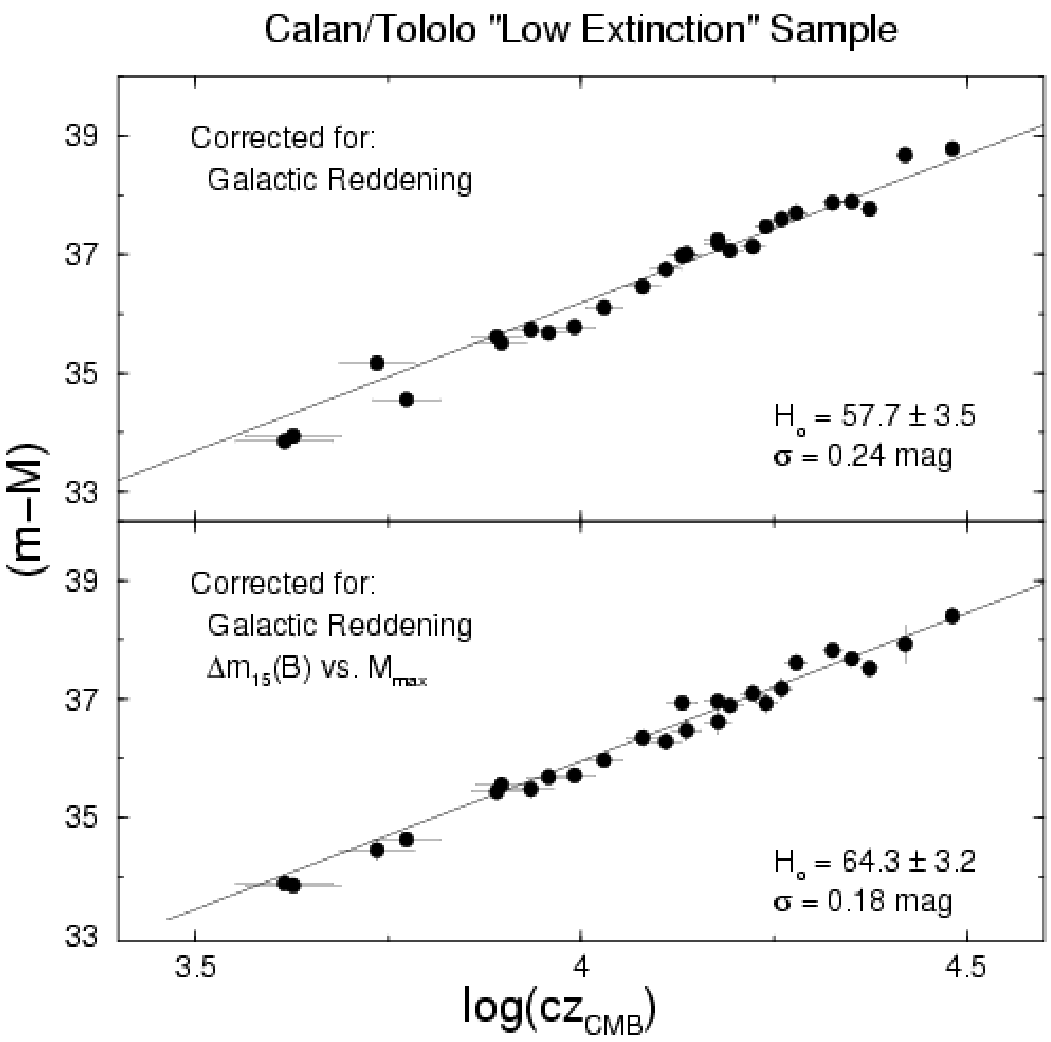
The principles of light-curve calibrations



(Goldhaber et al. 2001)

Normalisation of the peak luminosity

Phillips et al. 1999



- Using the luminosity-decline rate relation one can normalise the peak luminosity of SNe Ia

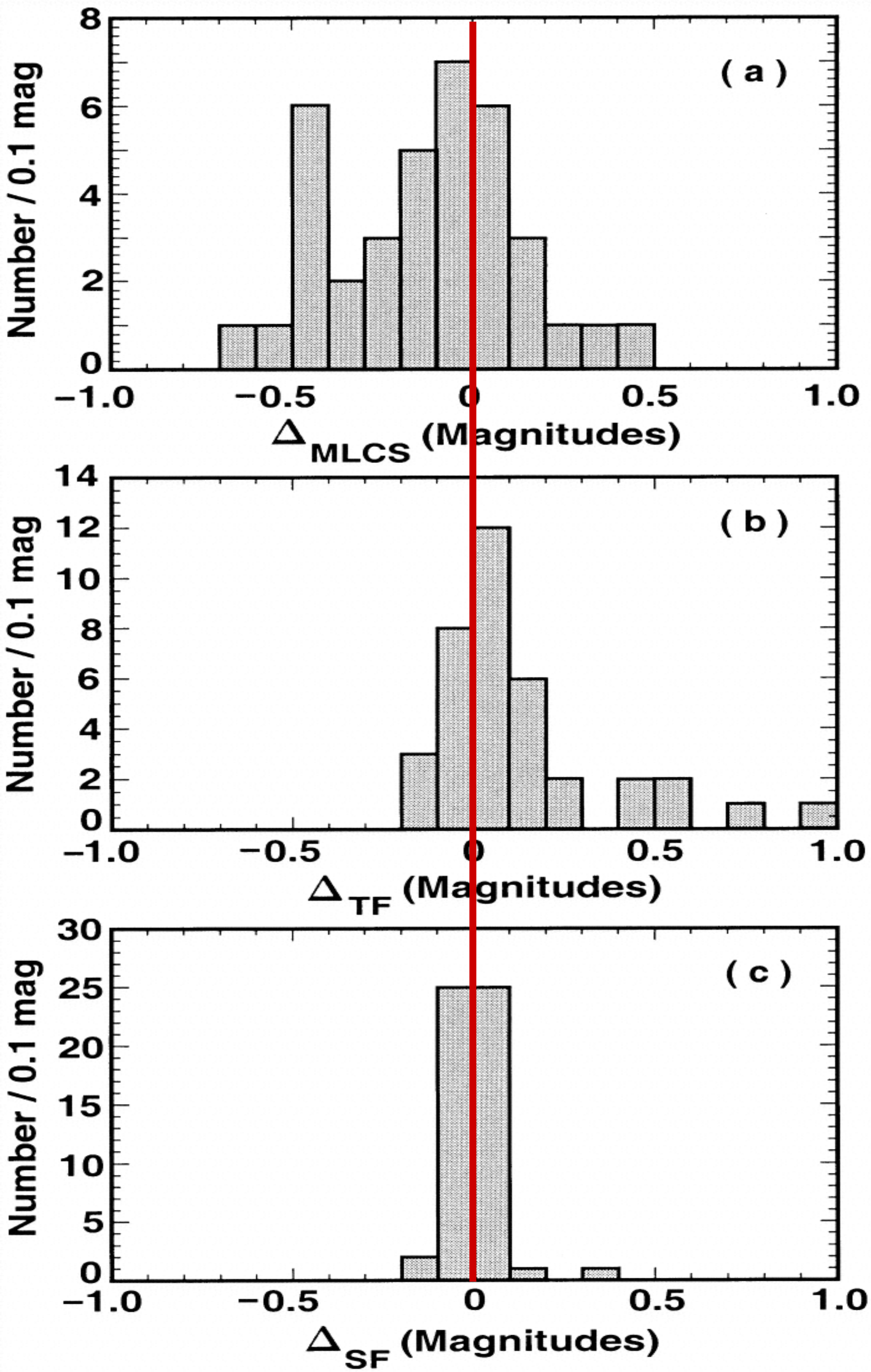
→

Reduces the scatter!

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

SN Ia Correlations



Riess et al. 1998

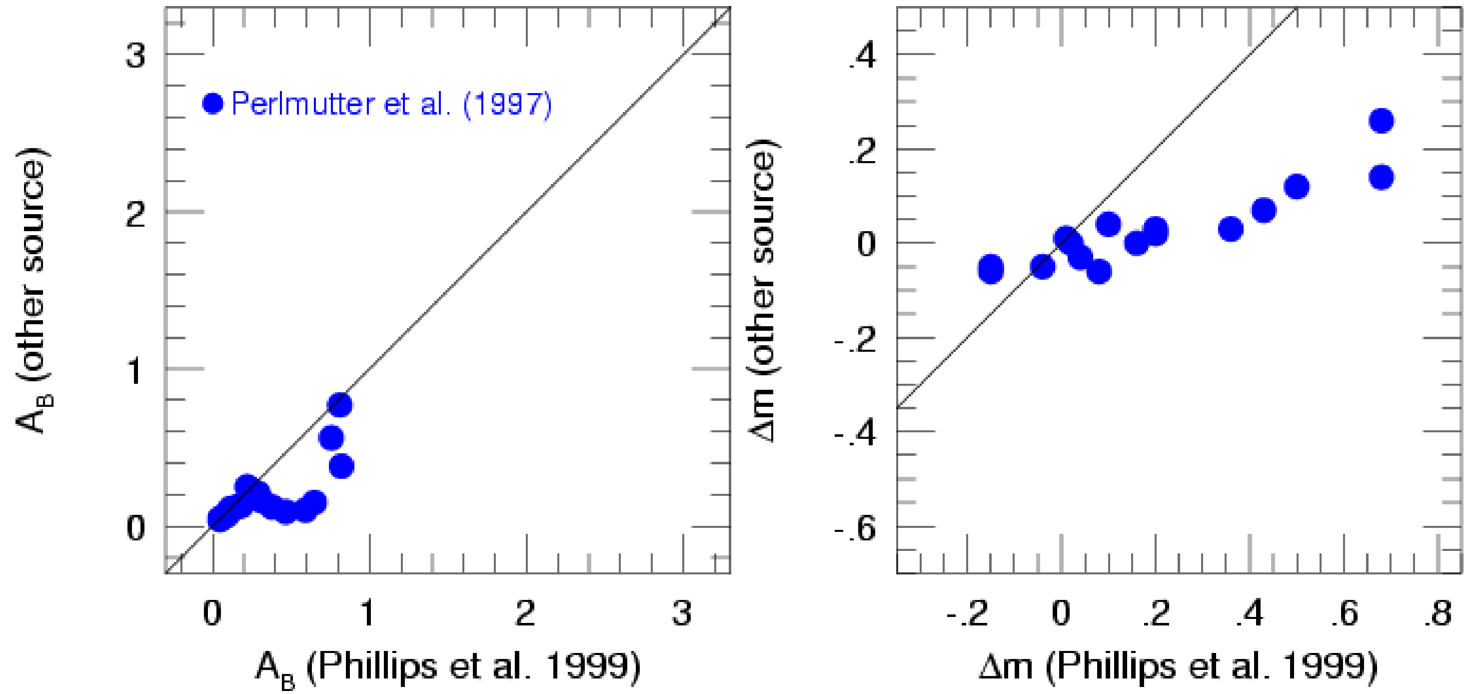
Phillips et al. 1999

Perlmutter et al. 1997

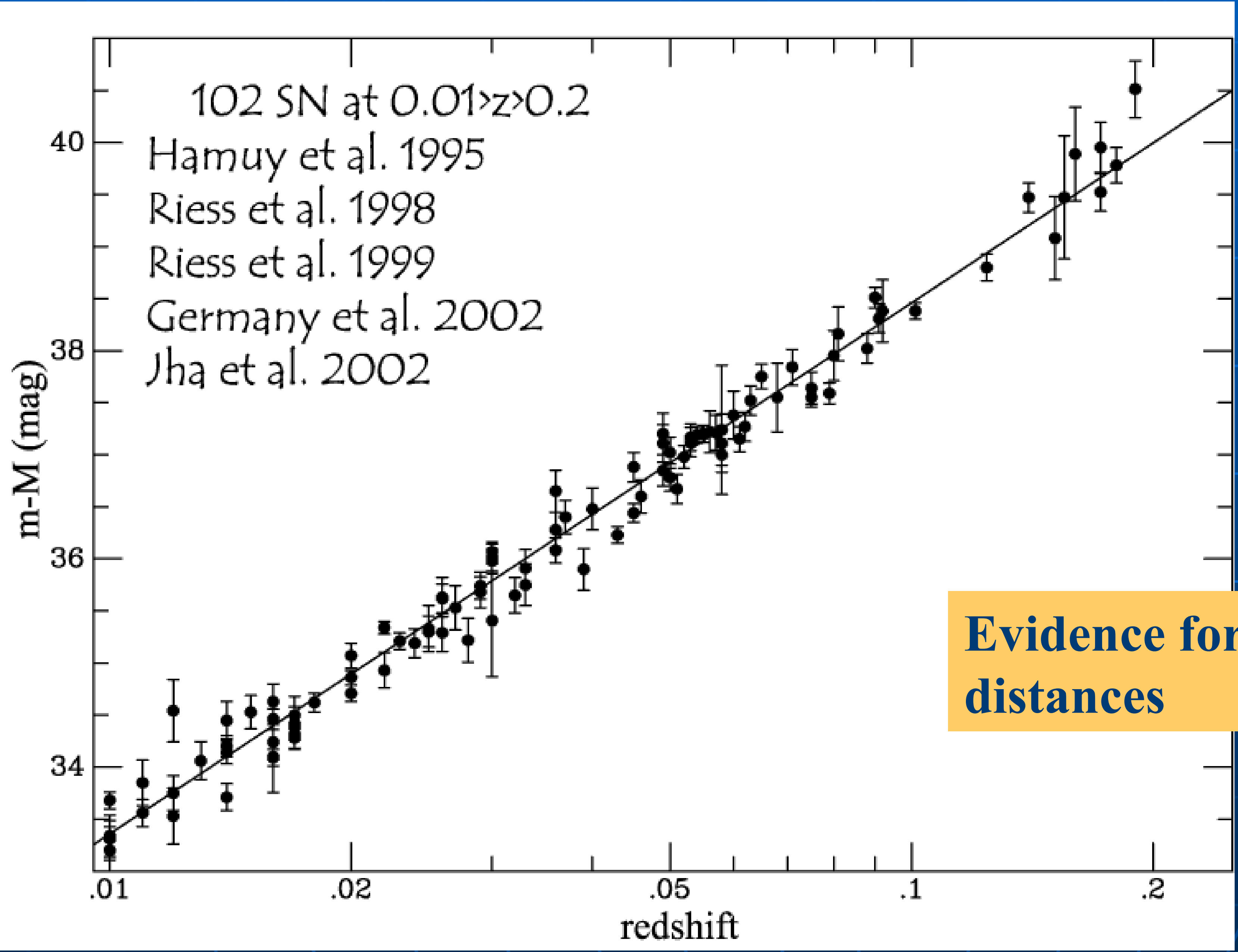
(Drell et al. 2000)

SN Ia Correlations

Leibundgut 2000



The nearby SN Ia sample

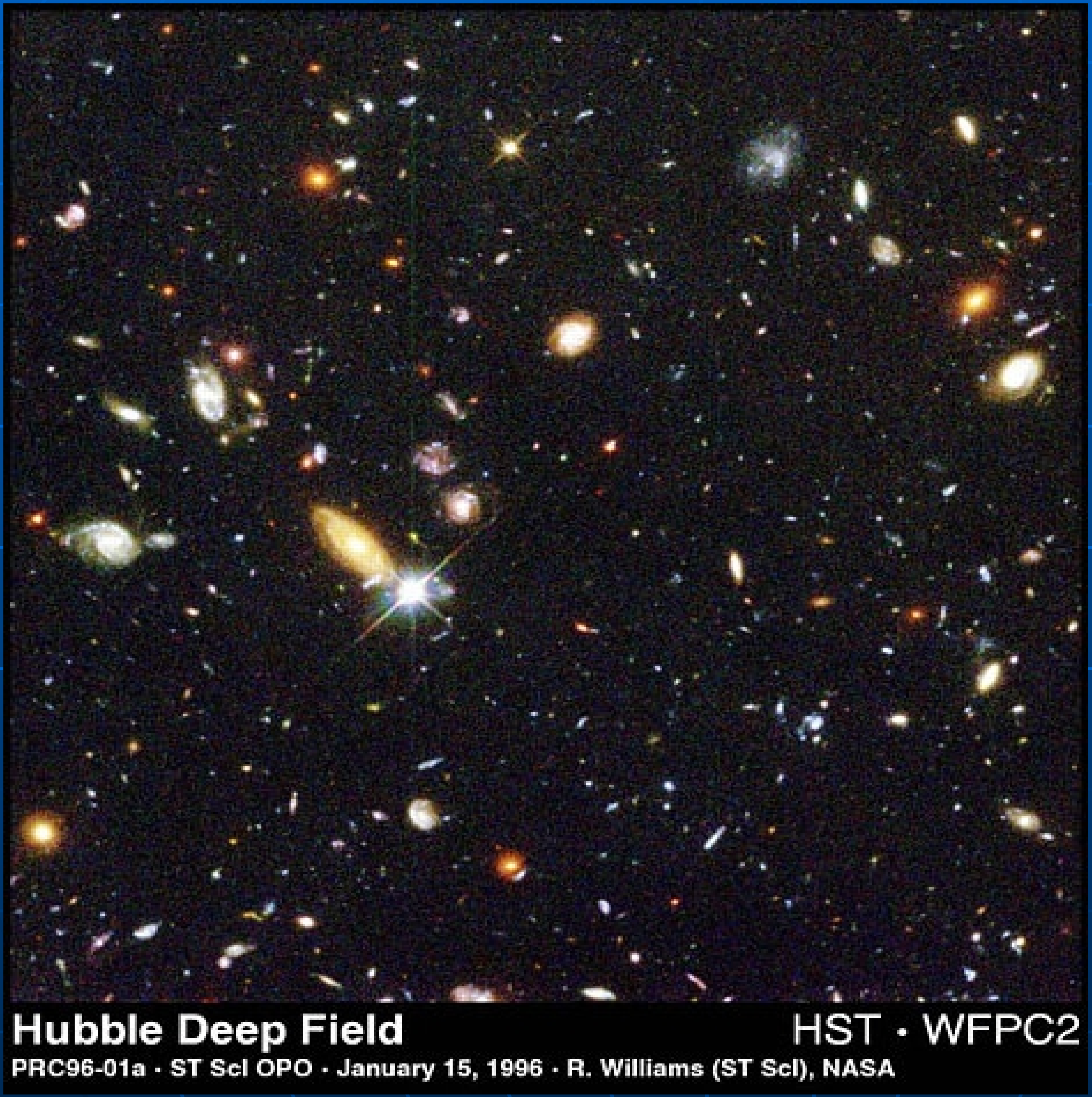


Evidence for good distances

Hubble constant from SNe Ia

- Extremely good (relative) distance indicators
  - distance accuracy around 10%
- Uncertainty in H_0 mostly from the LMC and the Cepheid P-L relation

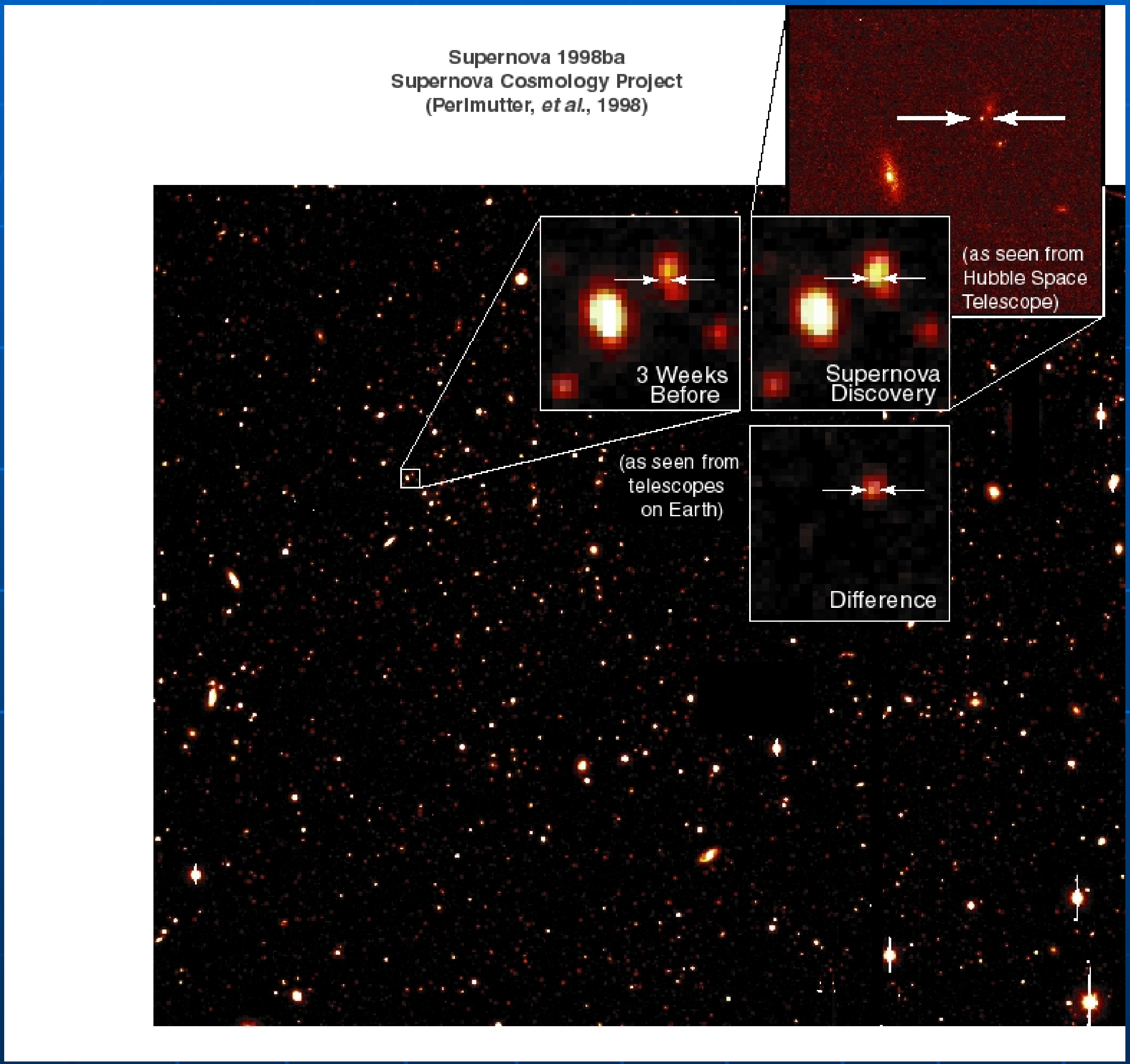
Very distant supernovae



Supernovae are very rare, ~ 1 SN per 100 years and galaxy.

→

One has to observe very many galaxies!

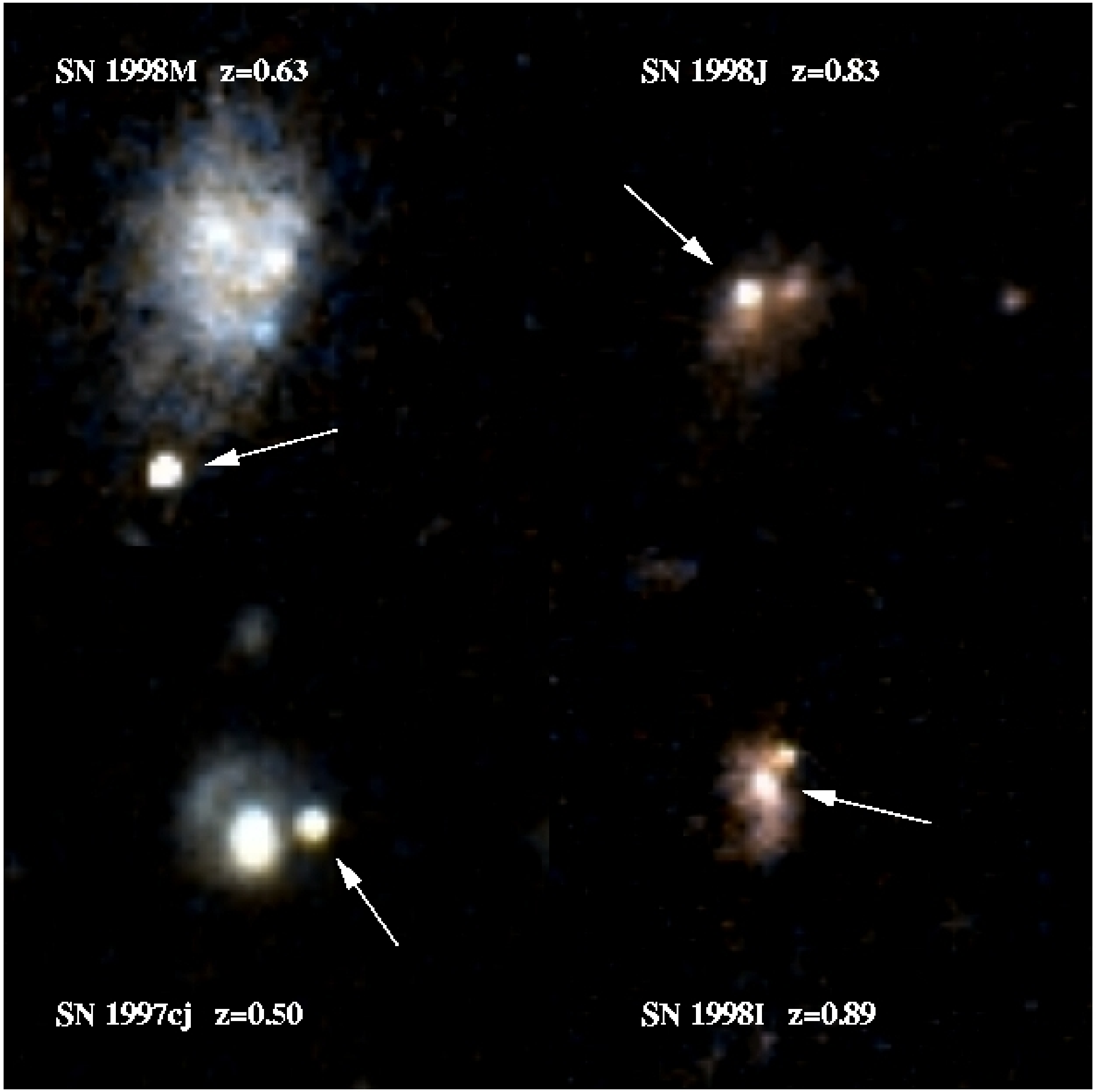


Search strategy:

1. Repeated scanning of a certain field.

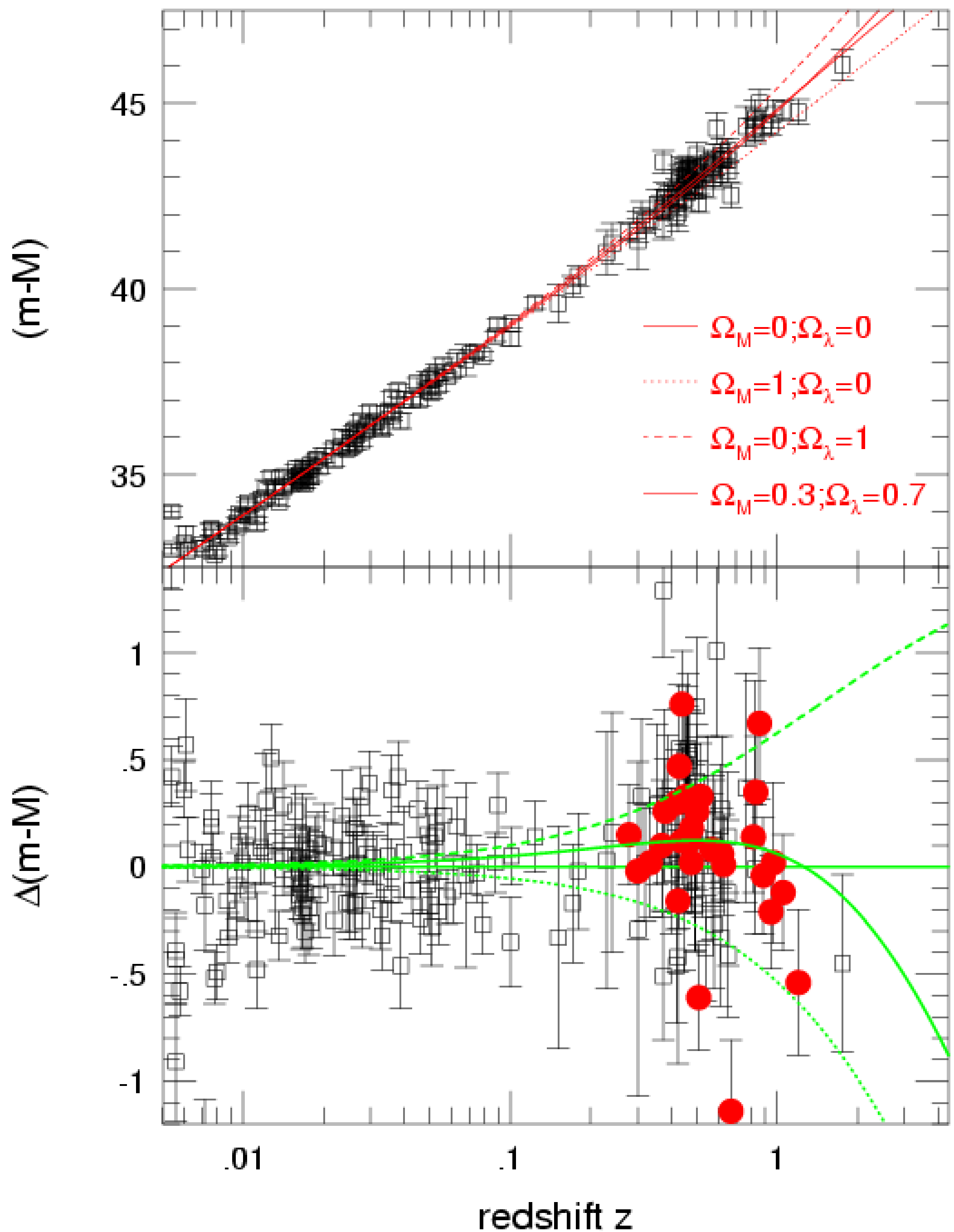
2. Electronic readout of the data.

3. Follow-up observations, e.g., HST, VLT, …



Supernovae are routinely detected at redshifts Z > 0.1:

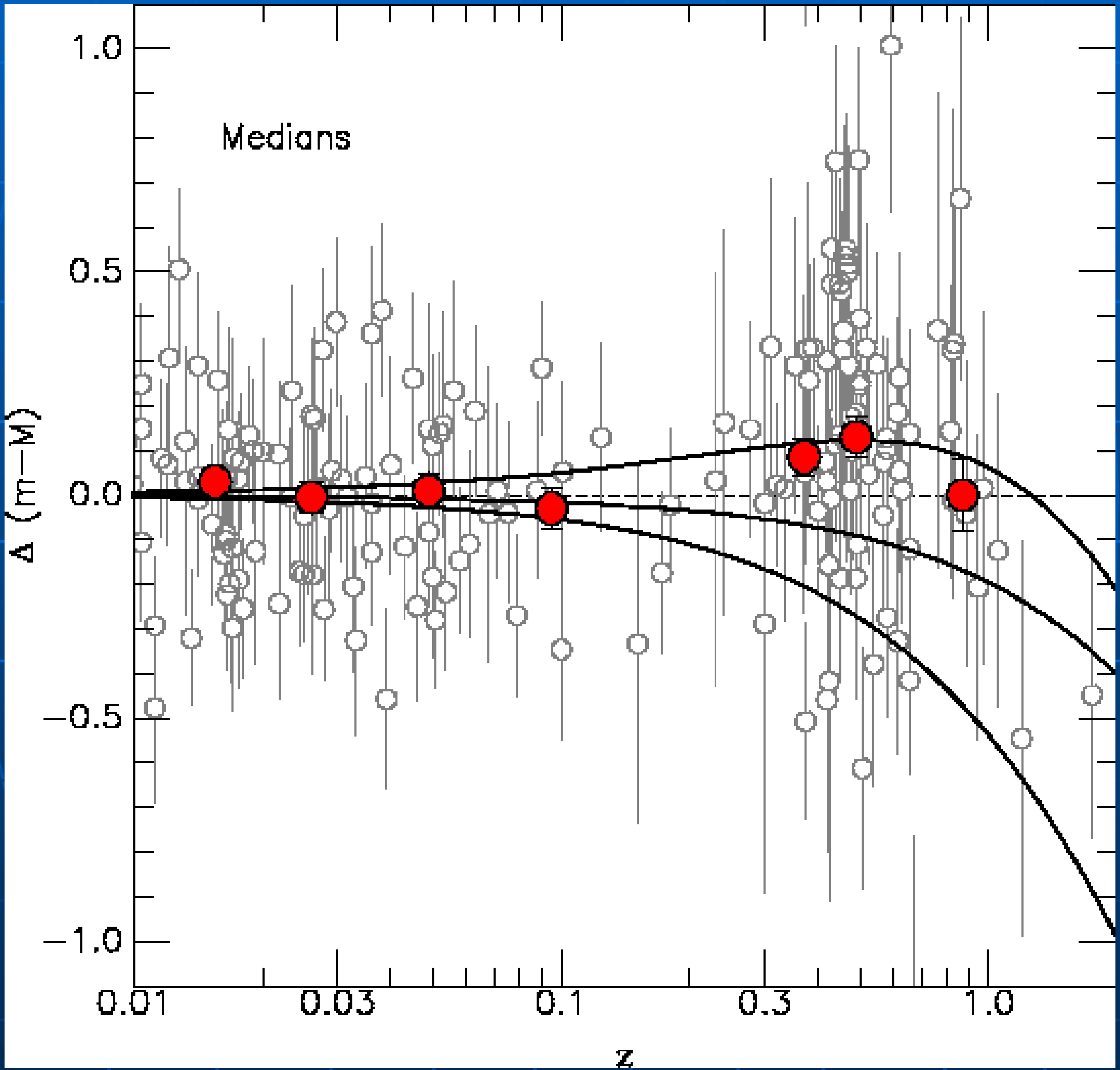
- What is the intrinsic scatter in luminosities?
- Are they different from the local sample?
- Do we understand the differences?



Supernovae at high redshifts

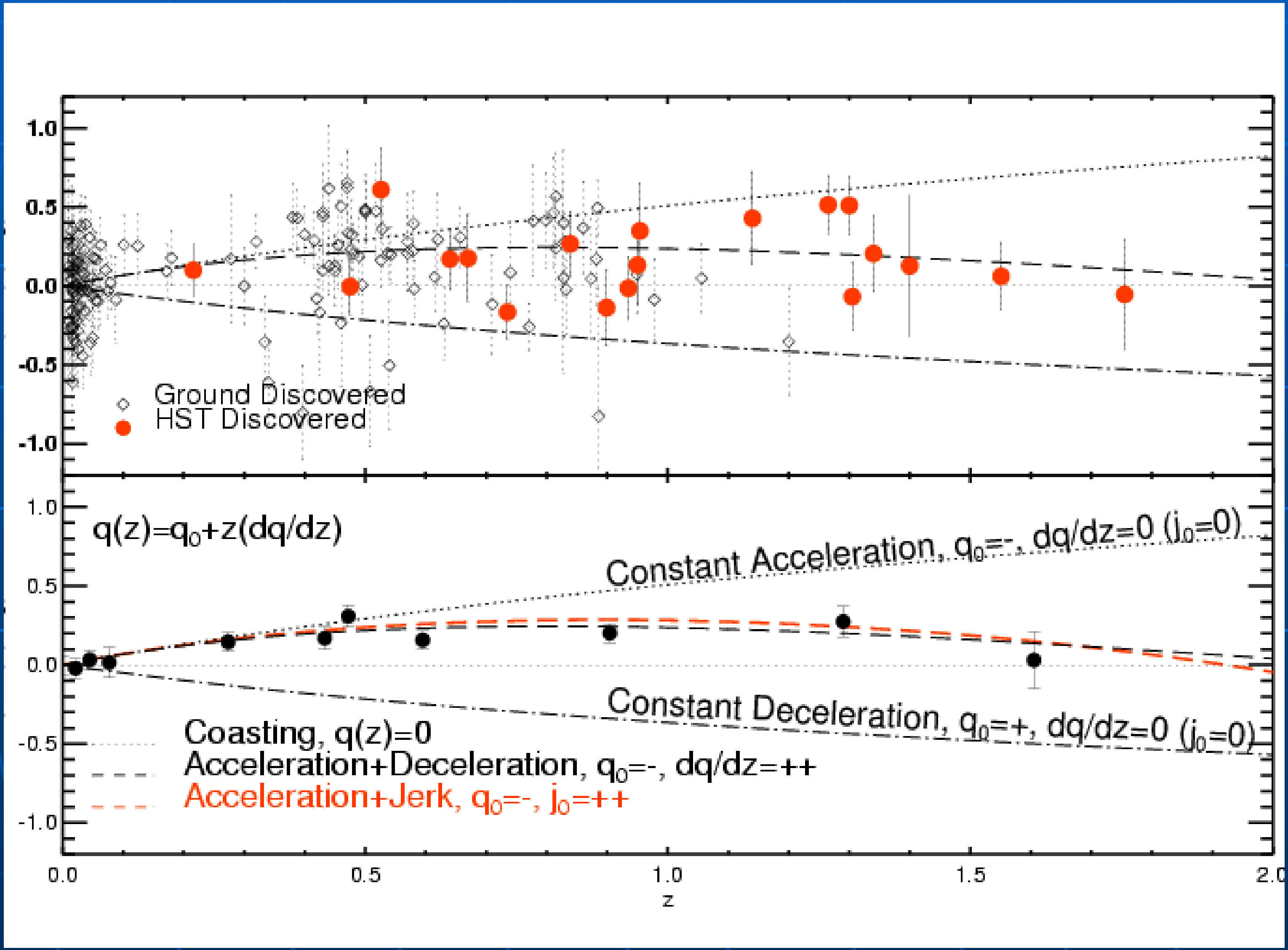
Tonry et al. 2003

209 SNe Ia and medians

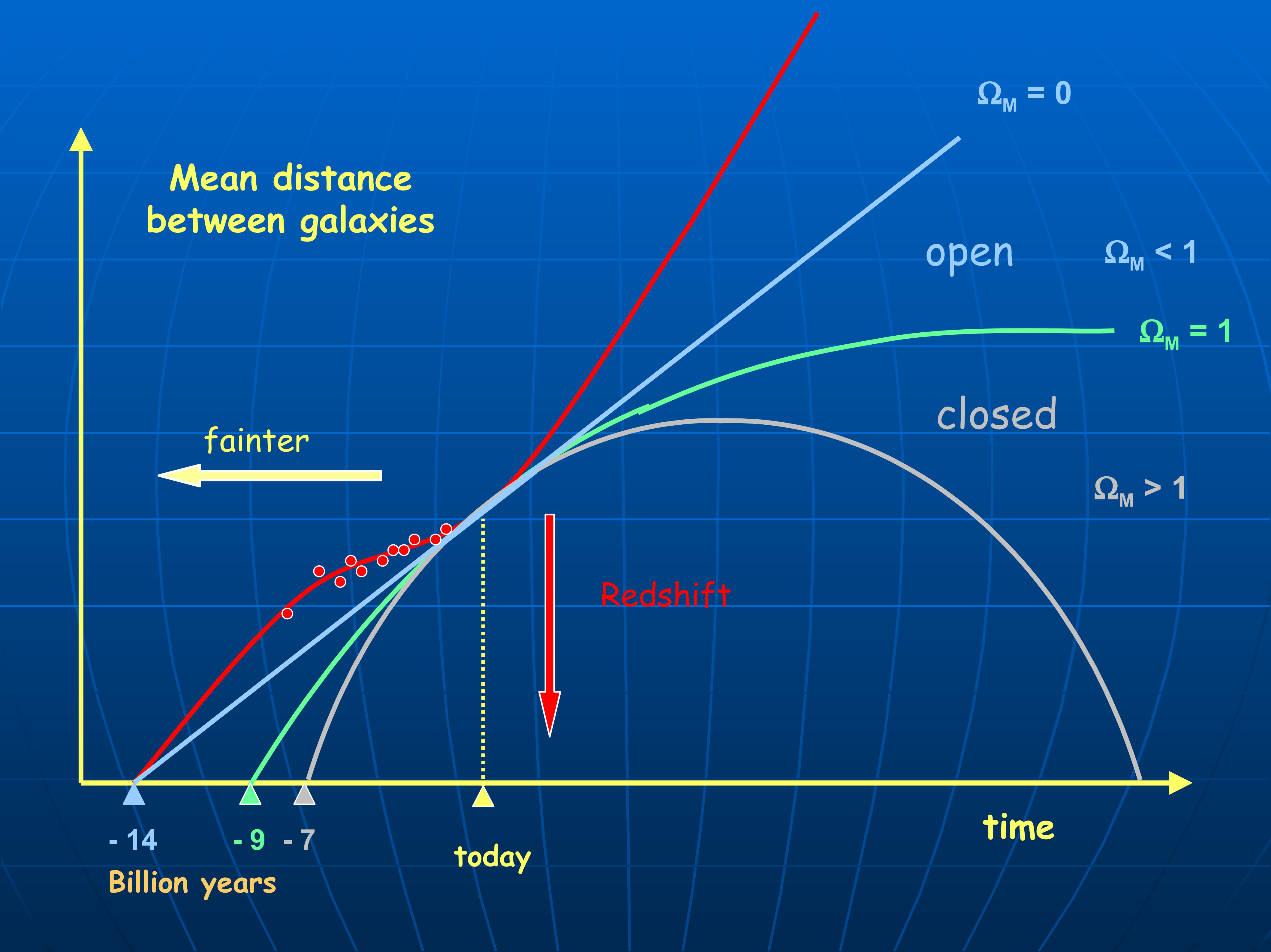


Tonry et al. 2003

Very high redshift SNe Ia



Riess et al. 2004



Mean distance between galaxies
Ω_M = 0
open
Ω_M < 1
Ω_M = 1
closed
Ω_M > 1
fainter
Redshift
time
- 14
- 9
- 7
today
Billion years

General luminosity distance

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

- with $\Omega_k = 1 - \sum_i \Omega_i$ and $w_i = \frac{p_i}{\rho_i c^2}$

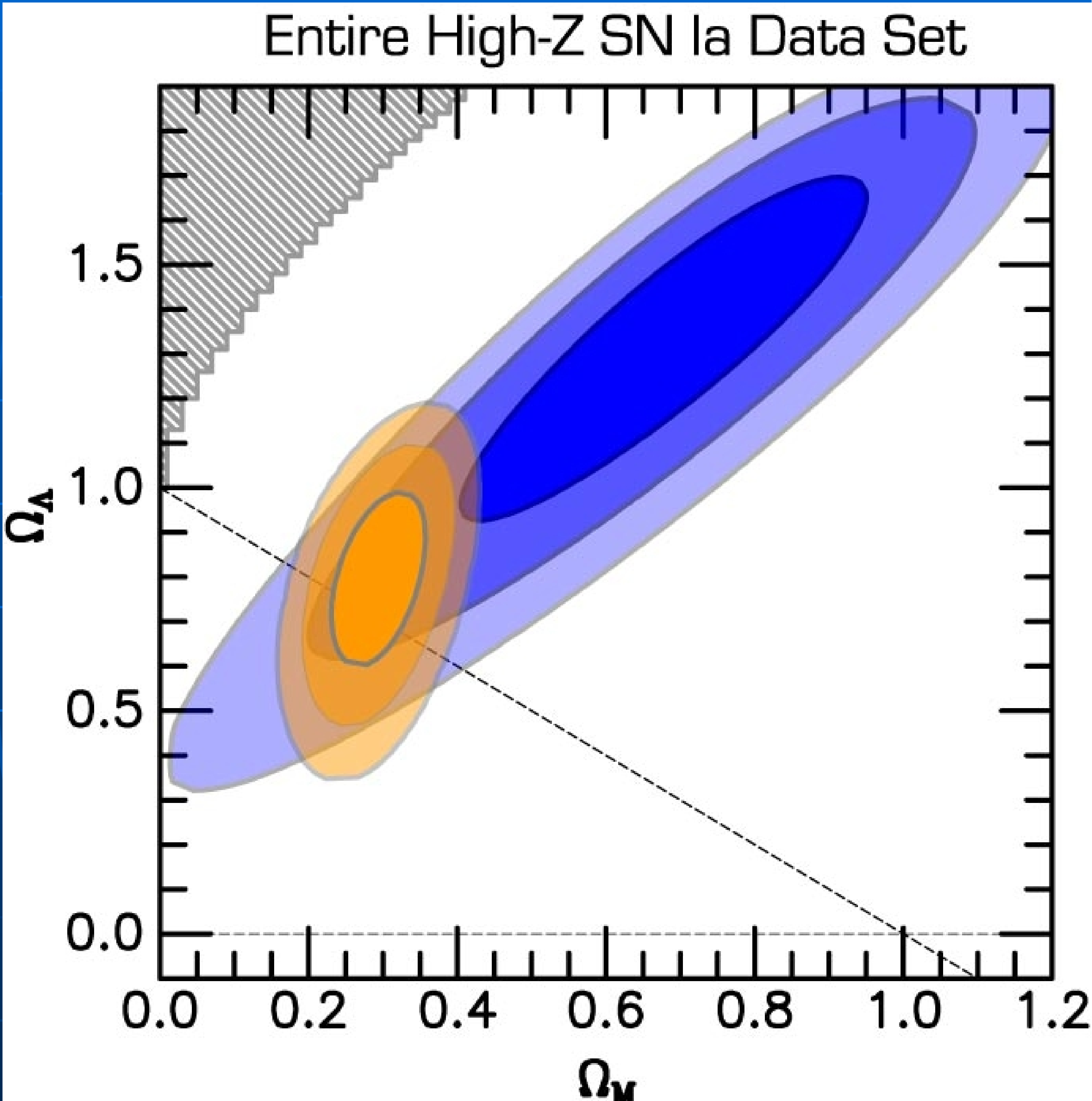
$w_M = 0$ (matter)

$w_R = 1/3$ (radiation)

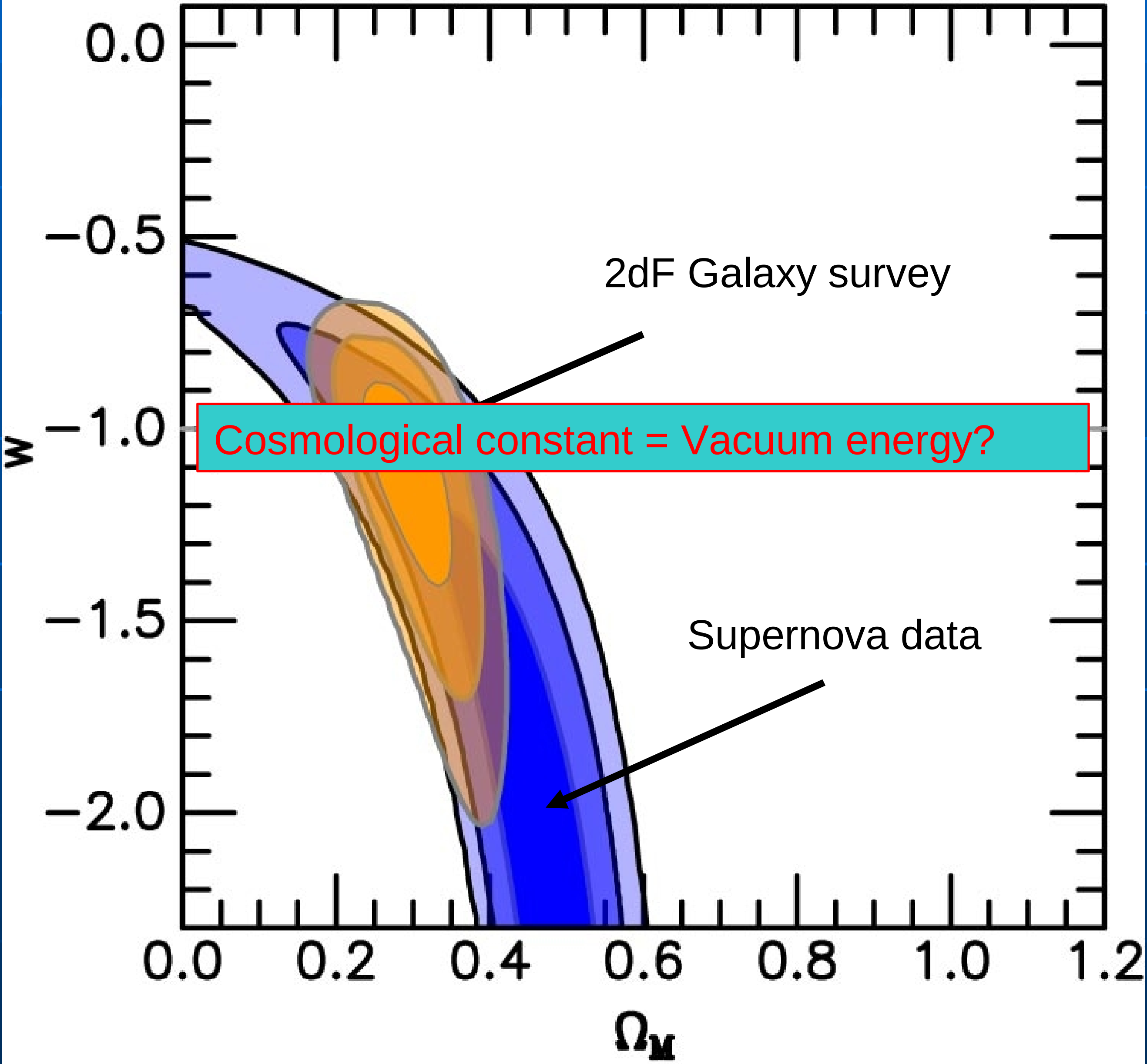
$w_\Lambda = -1$ (cosmological constant)

2dF:
Ω_M=0.2±0.03

KP:
h = 0.72 ± 0.08



Cosmology and Typ Ia supernovae



The "equation of state" of the Universe:

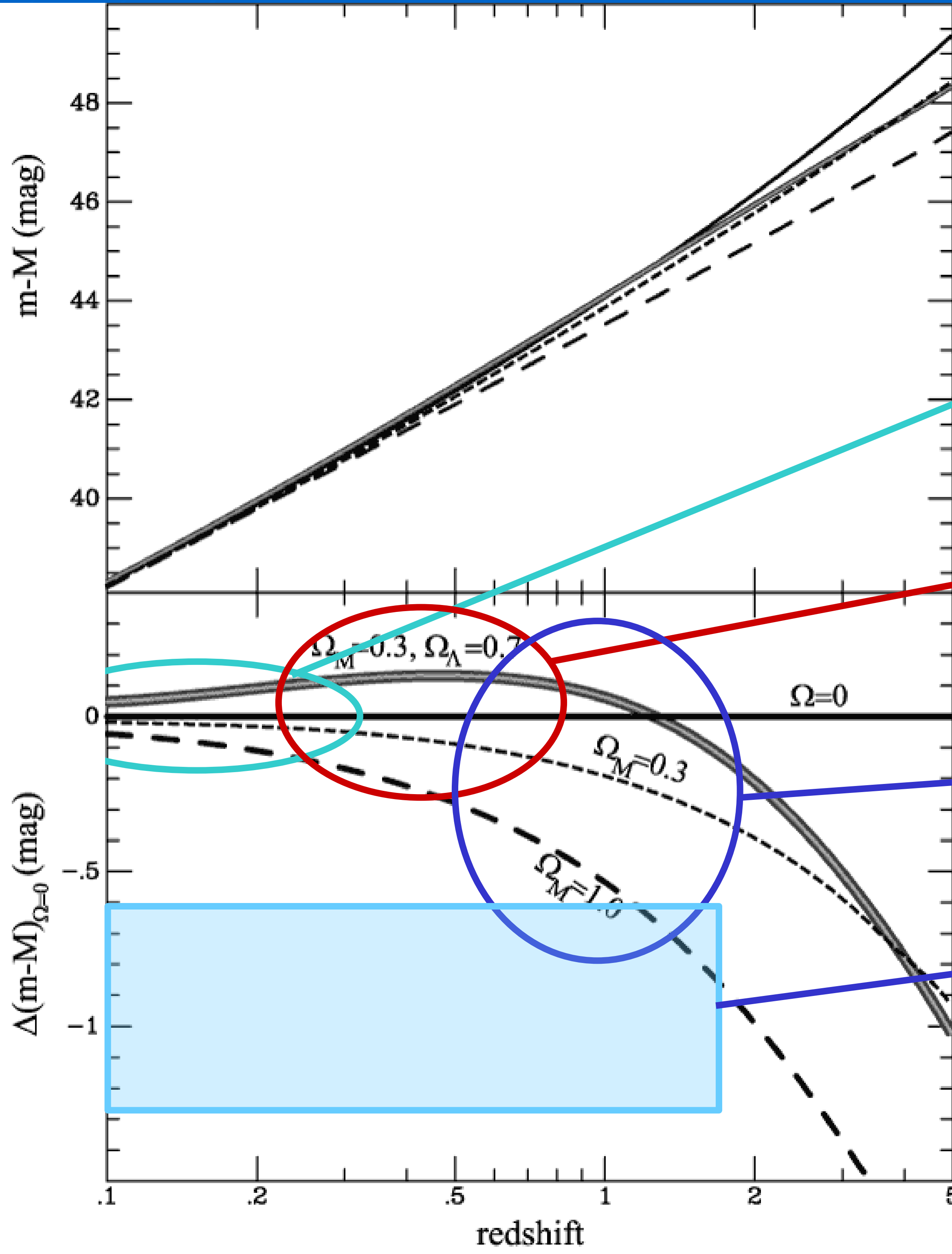
$p = w\rho$

$\ddot{a} \sim (\rho + 3p)$

$w < -1/3$:

Acceleration!

SN Projects

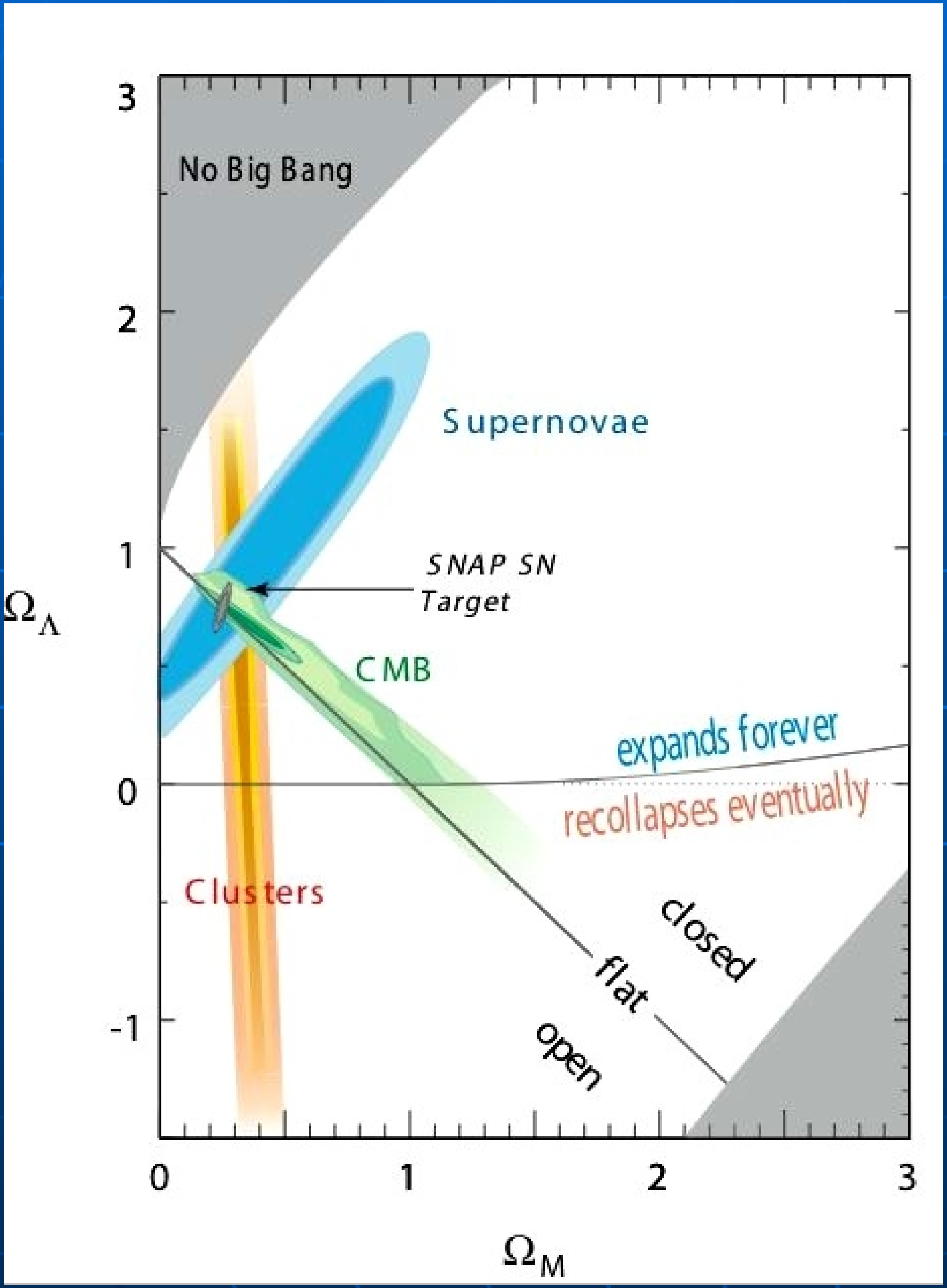


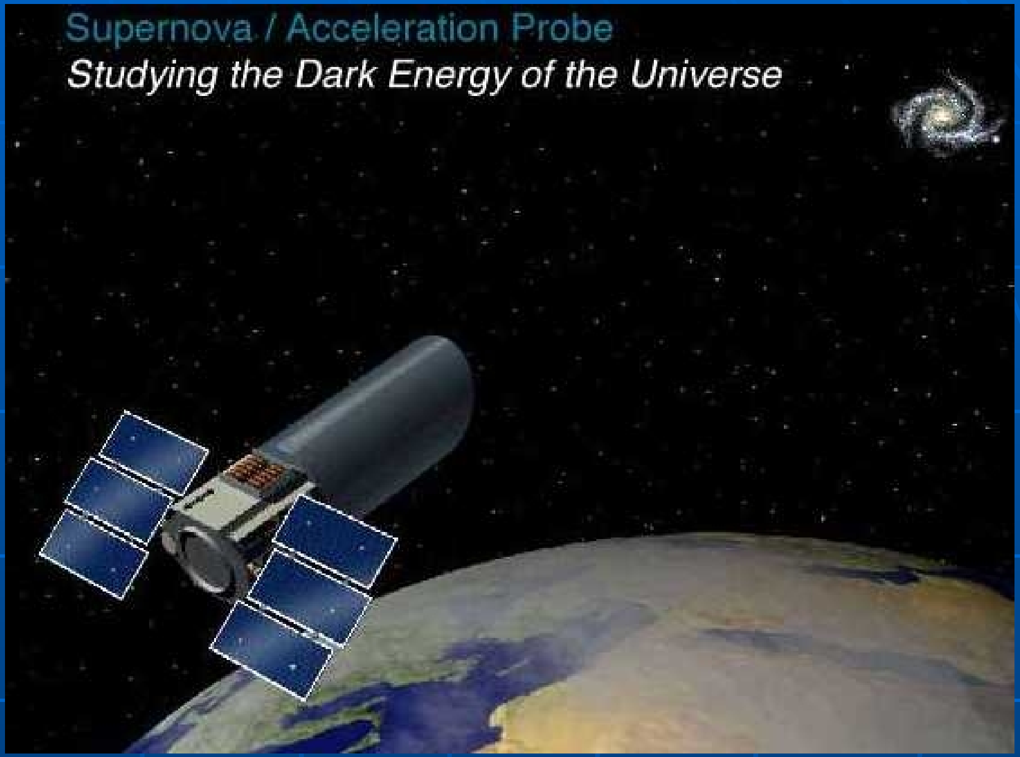
SN Factory
Carnegie SN Projekt

ESSENCE
CFHT Legacy Survey

High-z SN Search
(GOODS)

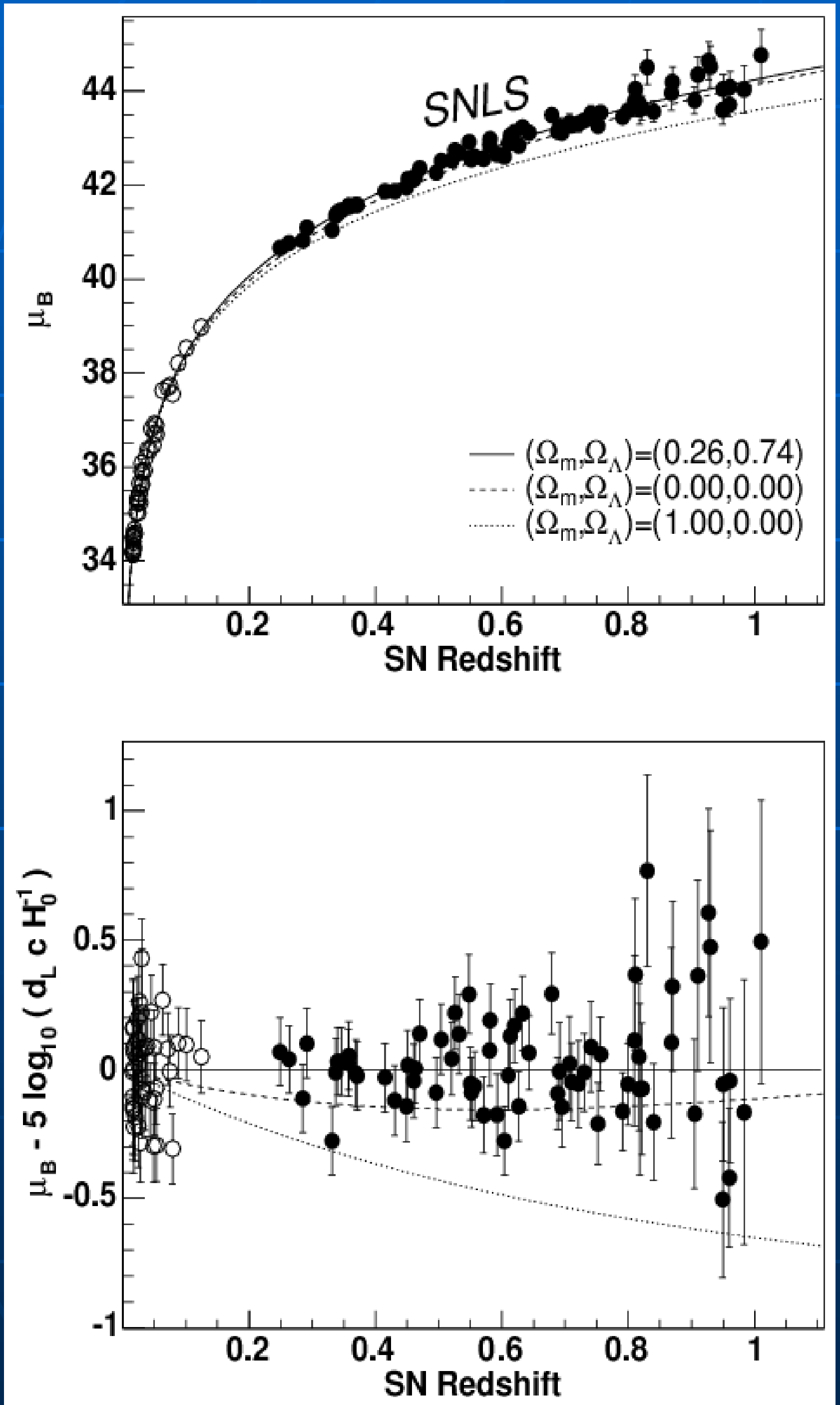
SNAP
(Supernova
acceleration
Probe)





SNAP:
"Supernova/Acceleration Probe"

SNLS's first year Hubble diagram



Final sample :

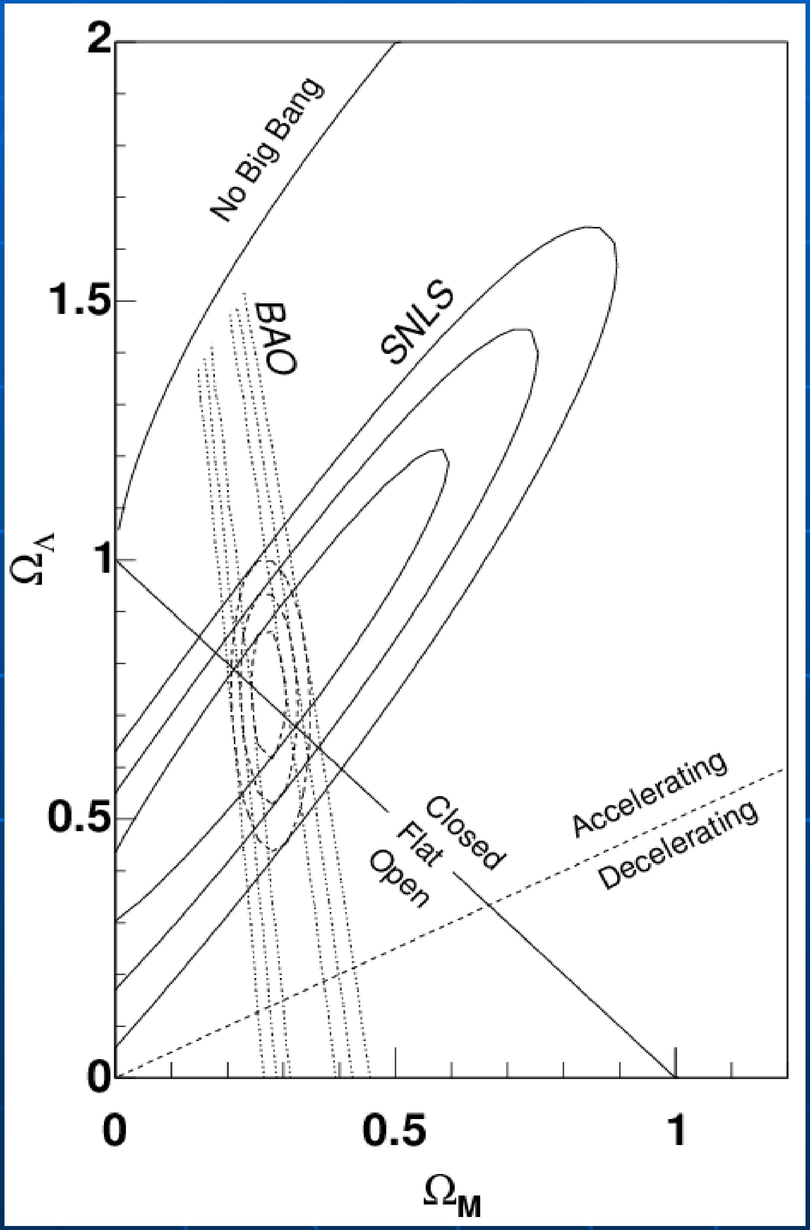
45 nearby SNe from literature

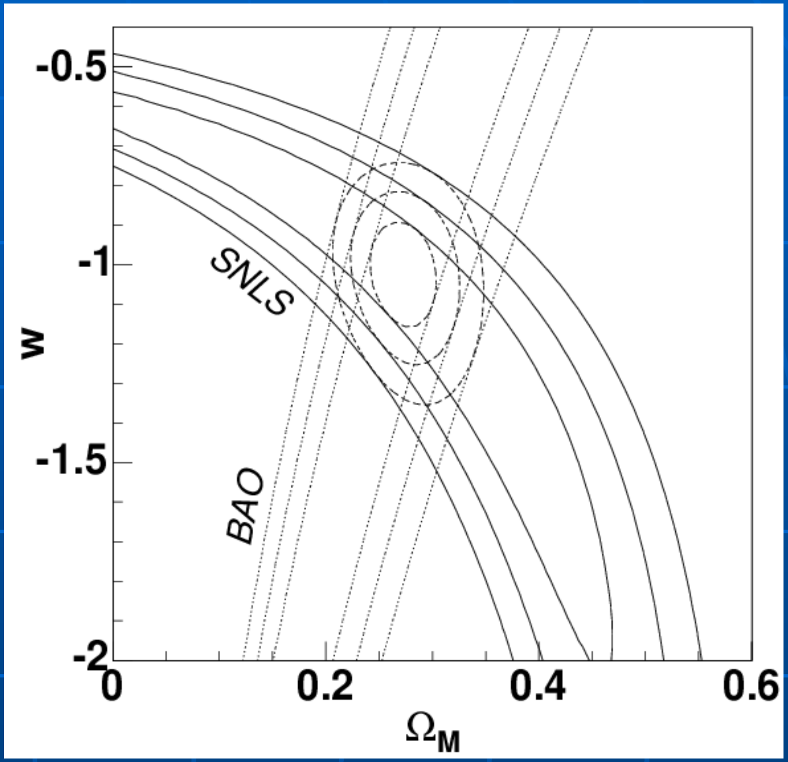
+71 SNLS SNe

Intrinsic scatter: (0.13 ± 0.02) mag

(Astier et al., 2006)

SNLS's Cosmological parameters





<u>Solid contours :</u> SNLS
<u>Dotted contours :</u> Baryon acoustic oscillations (BAO) (SDSS, Eisenstein et al., 2005)
(68.3, 95.5 and 99.7% CL)

(Astier et al., 2006)

SNLS 1st year results on Cosmology

For a flat ΛCDM cosmology :

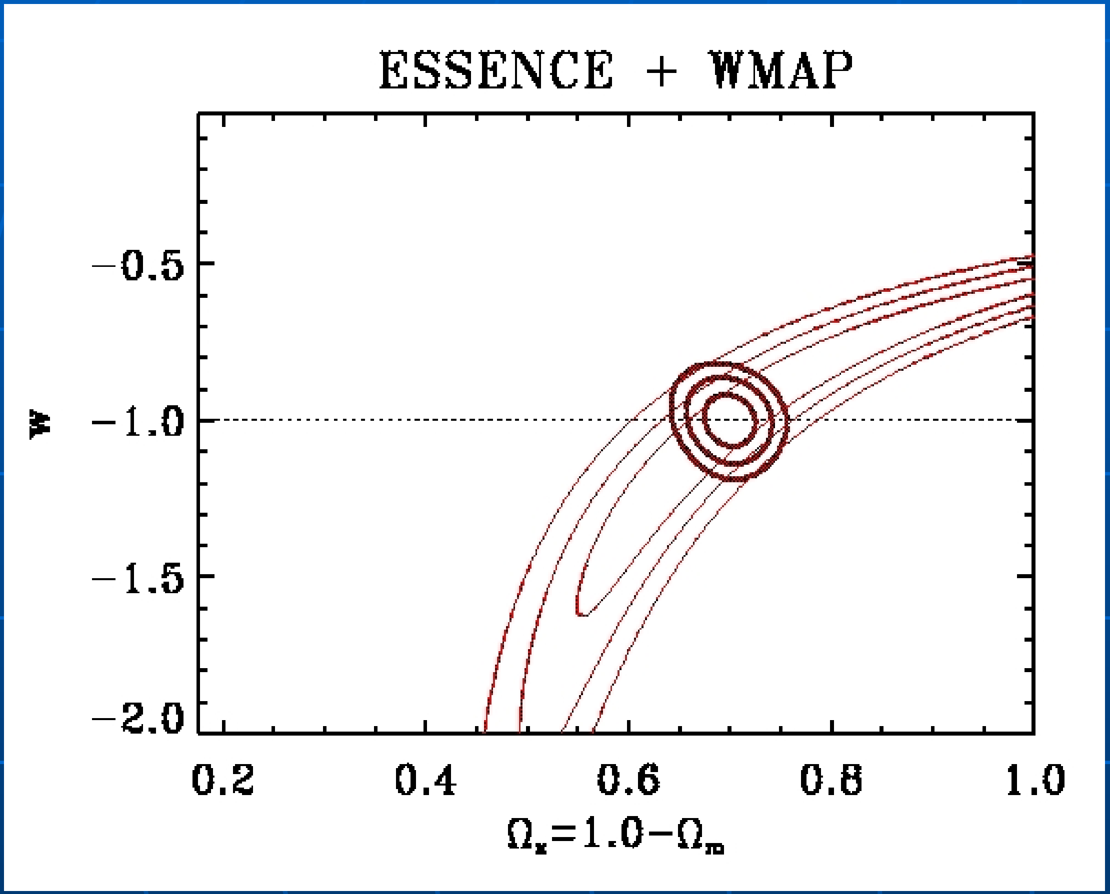
$$\Omega_M = 0.264 \pm 0.042\ (stat) \pm 0.032\ (sys)$$

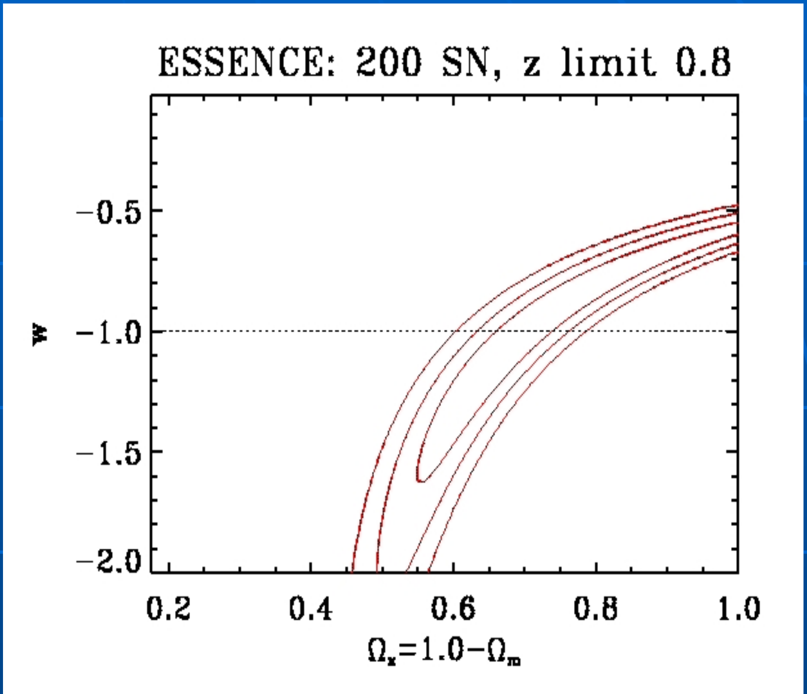
Combined with BAO (Eisenstein, 2005) :

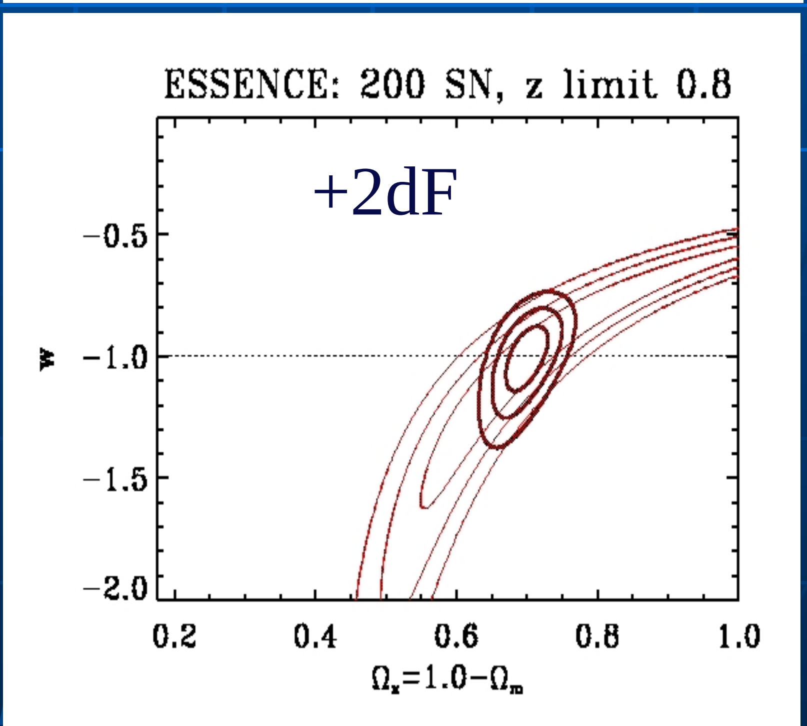
$$\Omega_M = 0.271 \pm 0.021\ (stat) \pm 0.007\ (sys)$$
$$w = -1.02 \pm 0.09\ (stat) \pm 0.054\ (sys)$$

(Astier et al., 2006)

ESSENCE: Anticipated Cosmology Limits





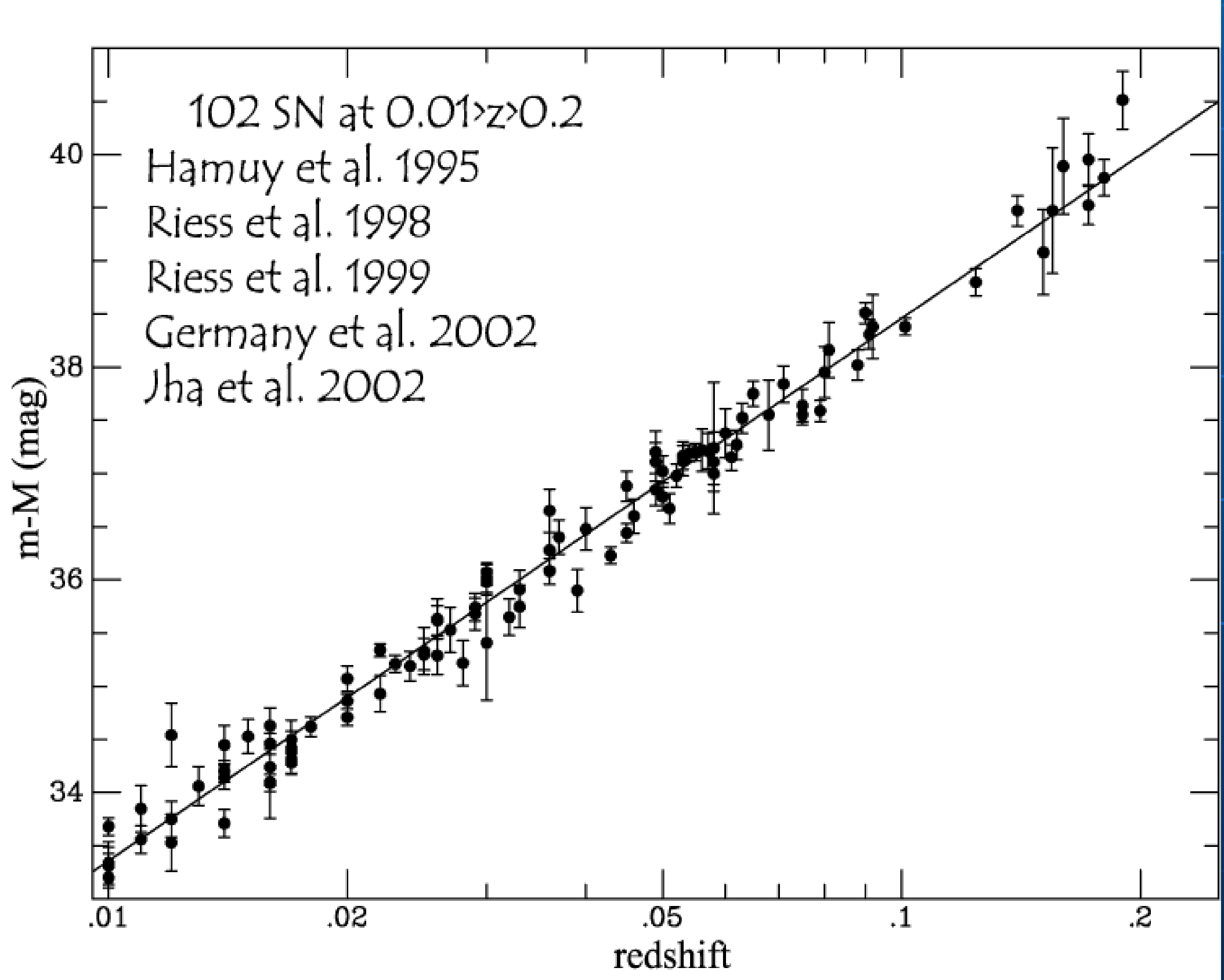


(Tonry & Miknaitis 2004)

What can still be wrong???

- Systematic errors?
- Pollution of high-Z samples?

Systematics: Nearby supernovae?



Hubble diagram:

Scatter in (m – M):

≈ 0.15 mag

(≈ 0.13 mag, SNLS)

Required for w:

≈ 0.02 mag !

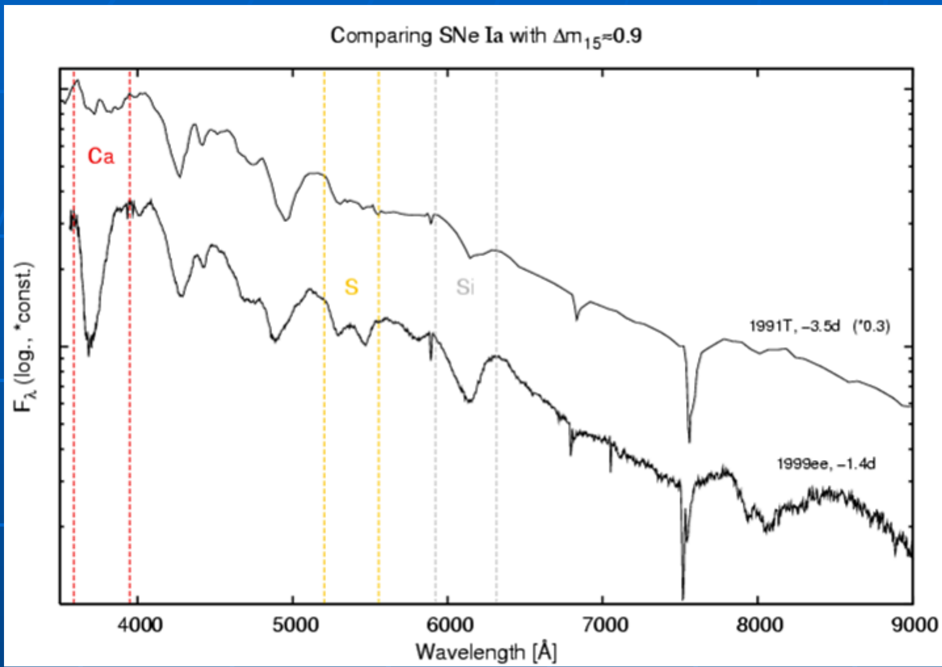
Statistics?

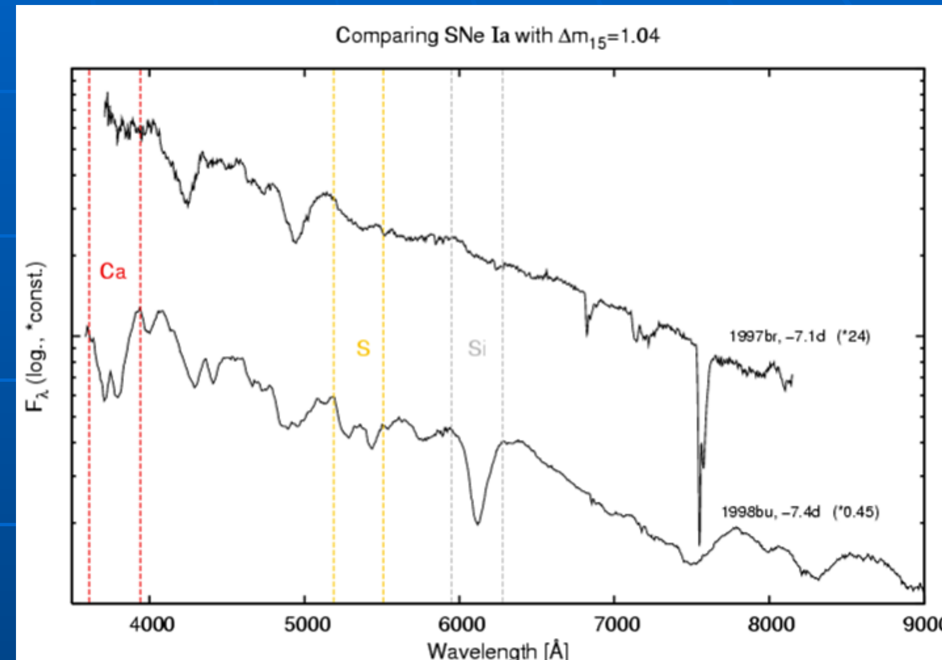
Systematics?

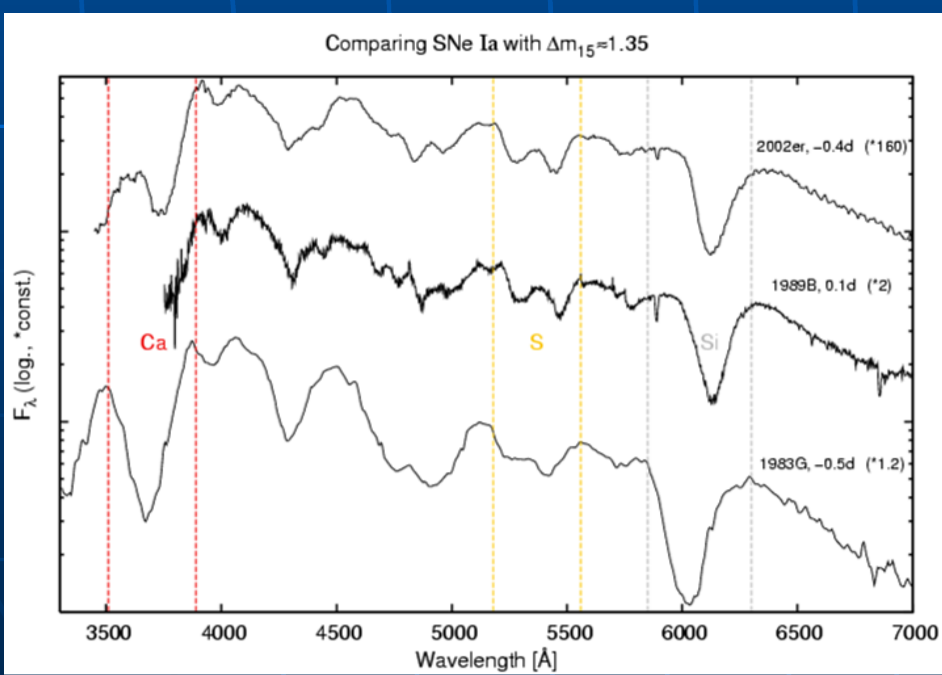
(Tonry et al. 2003)

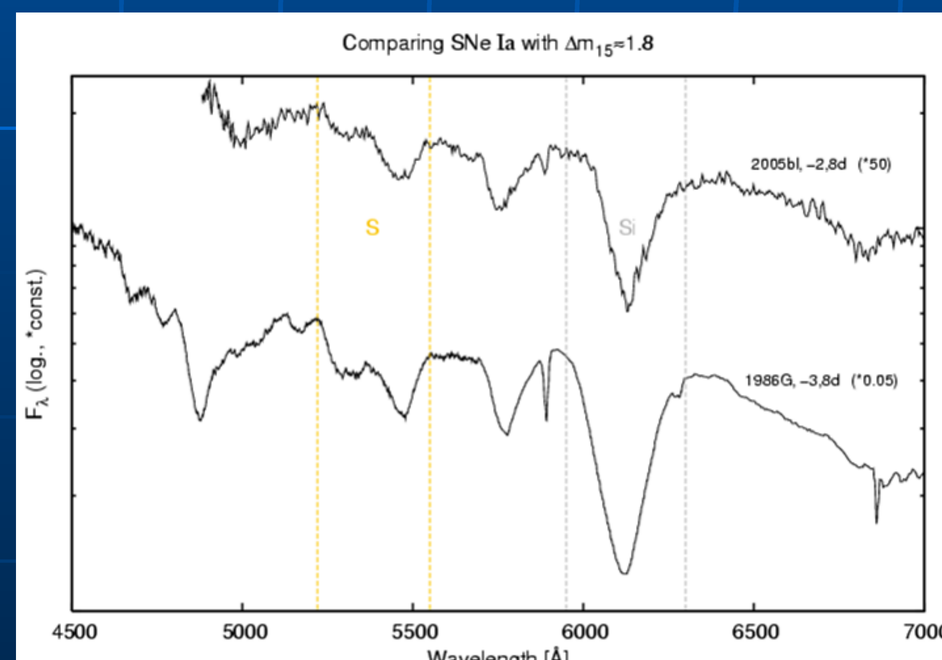
Are they different?

(Early spectra; court. Stephan Hachinger)



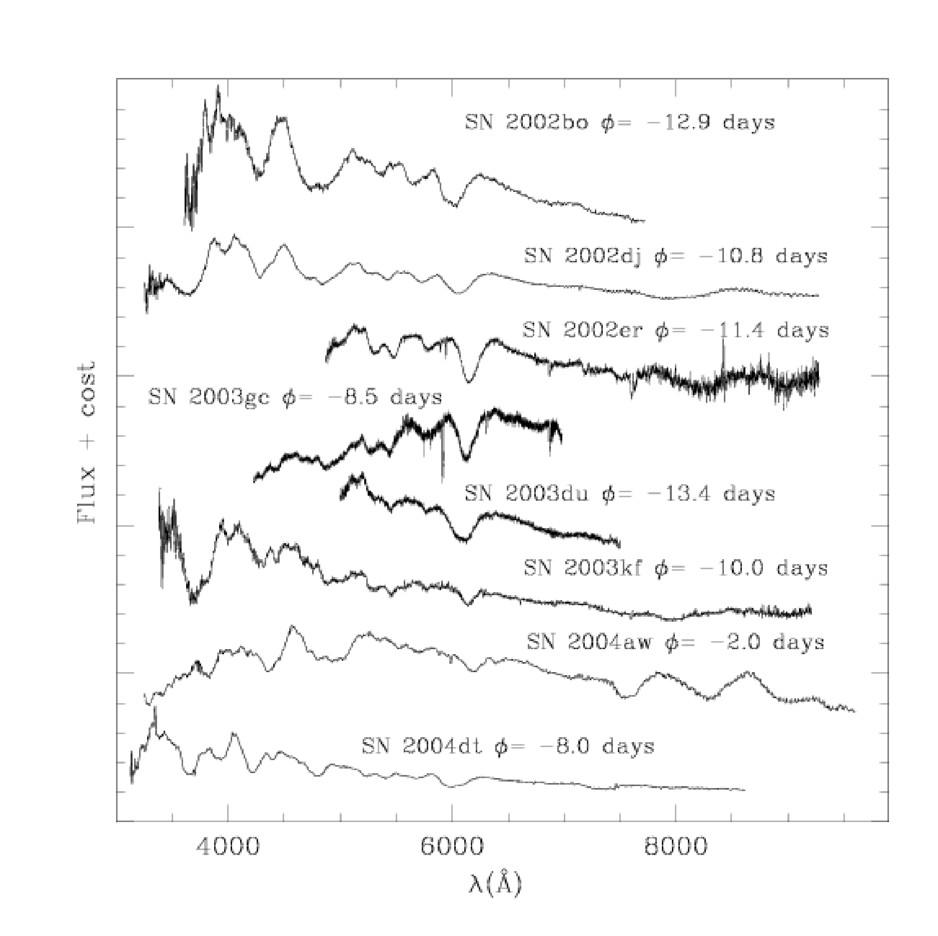


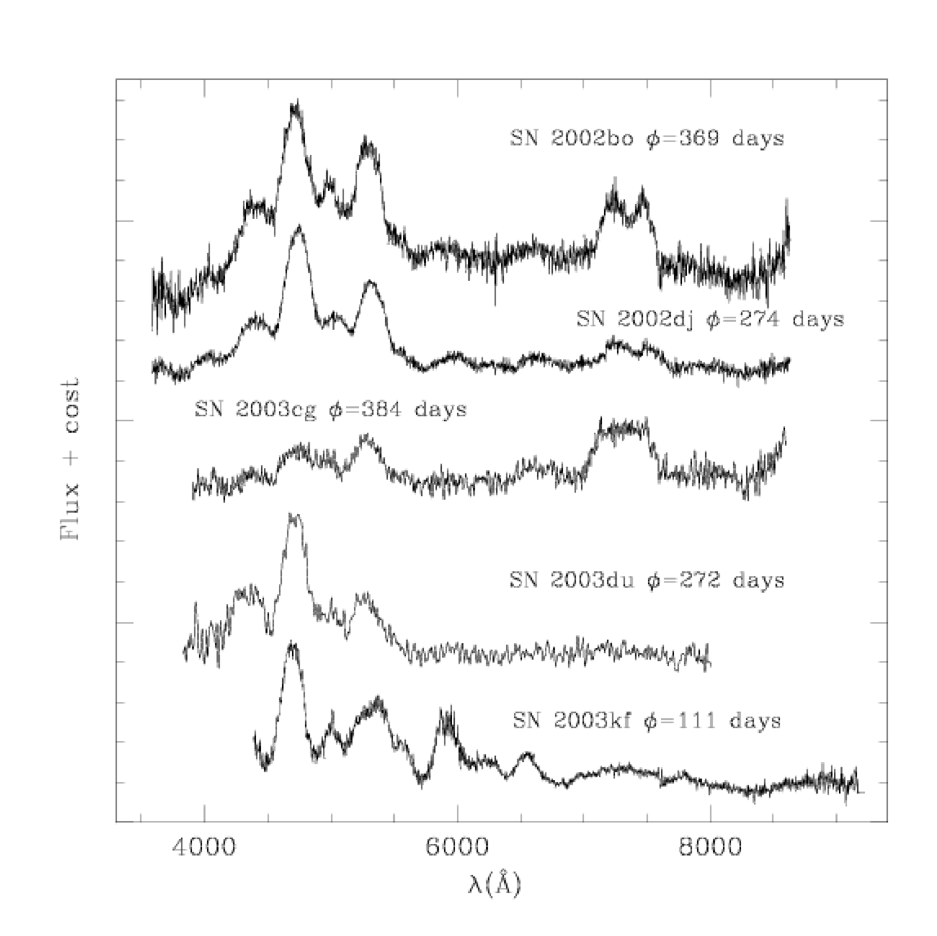




Are they different?

(RTN/ESC data)



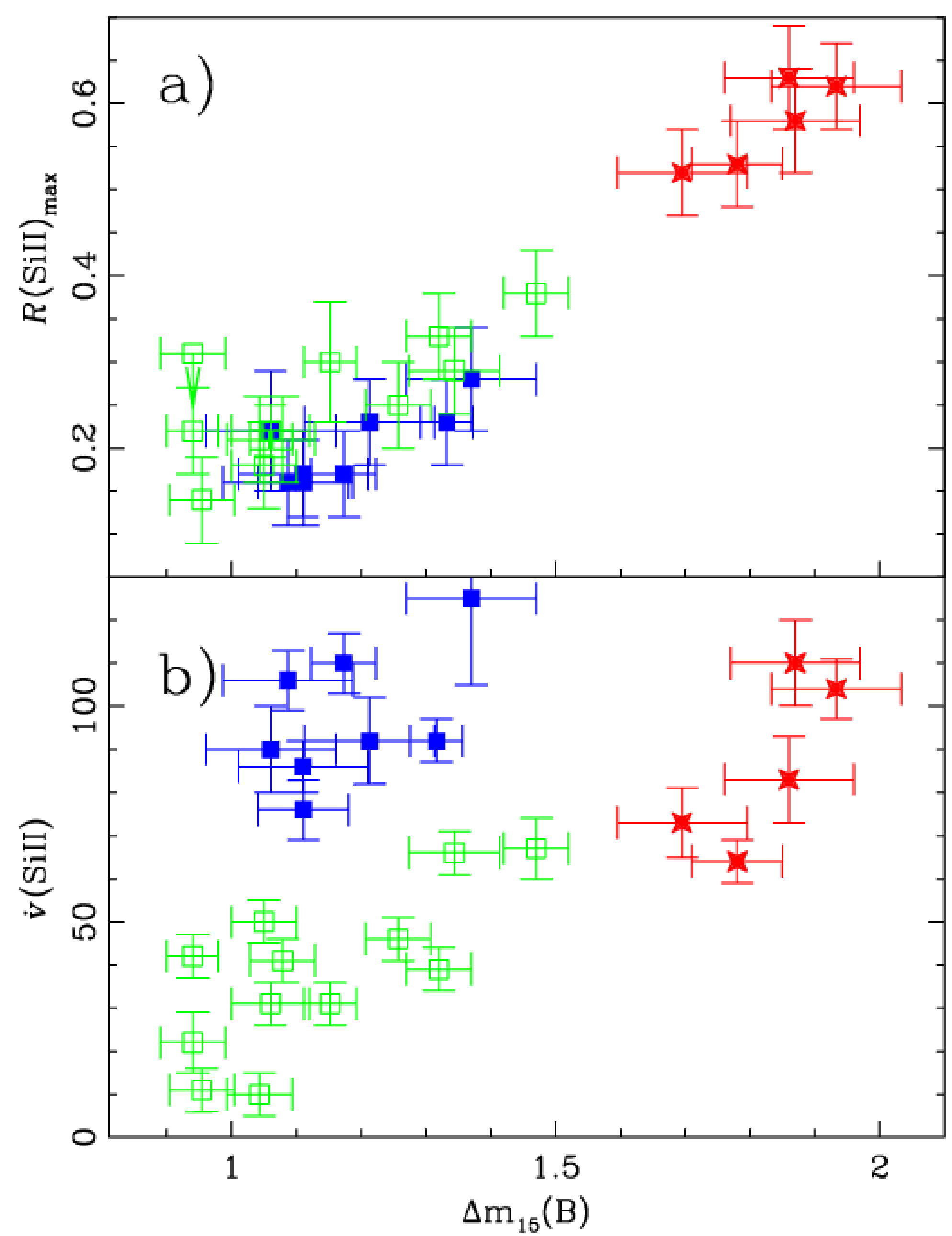


Early and late spectra

of "normal" SN Ia (exception: SN 2004aw!)

Expansion velocities?

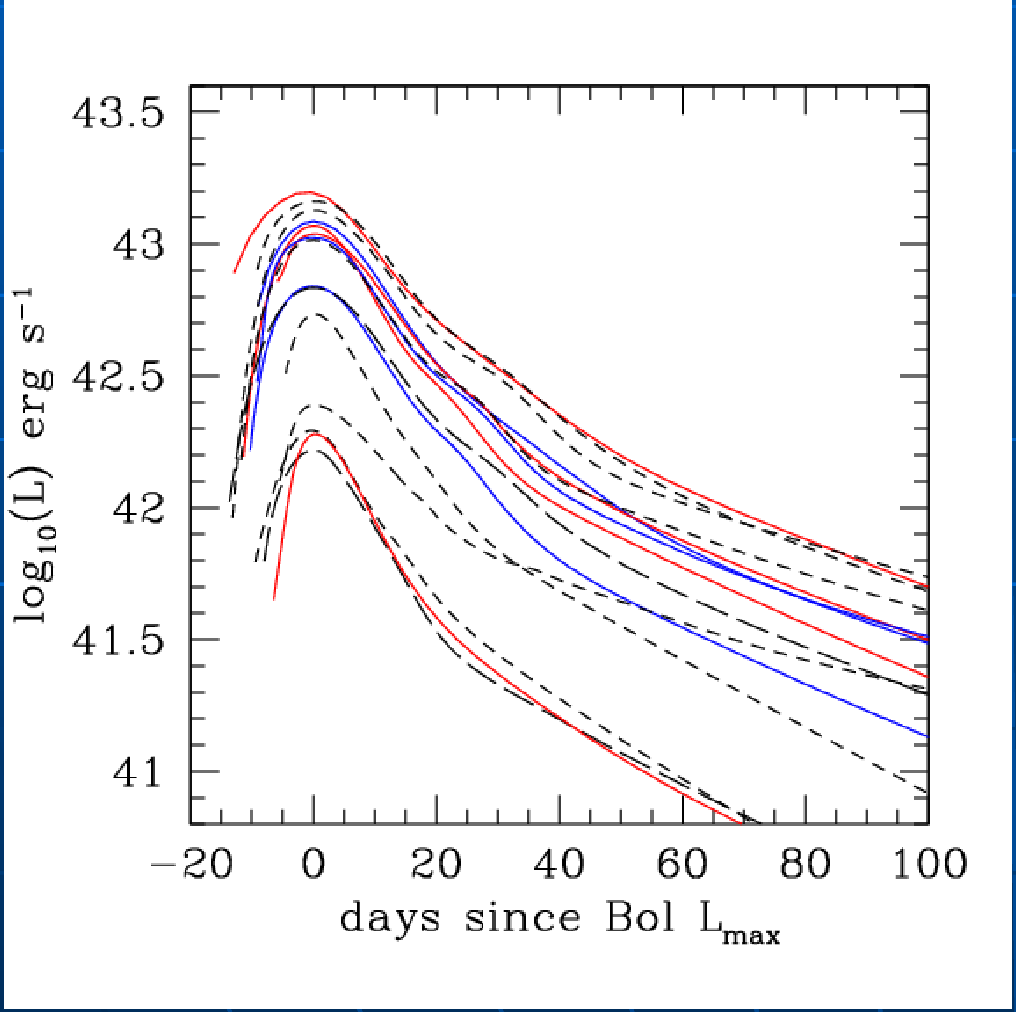
(mostly RTN/ESC data)

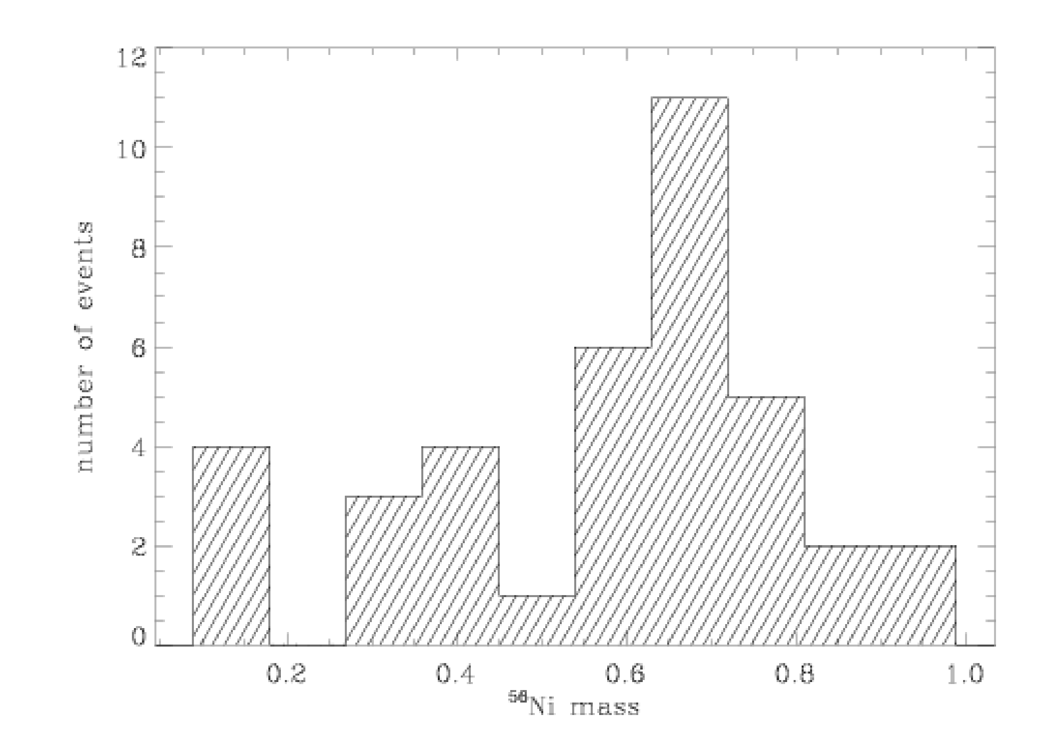


(Benetti et al. 2004, 2005)

Bolometric LC's and Ni-masses?

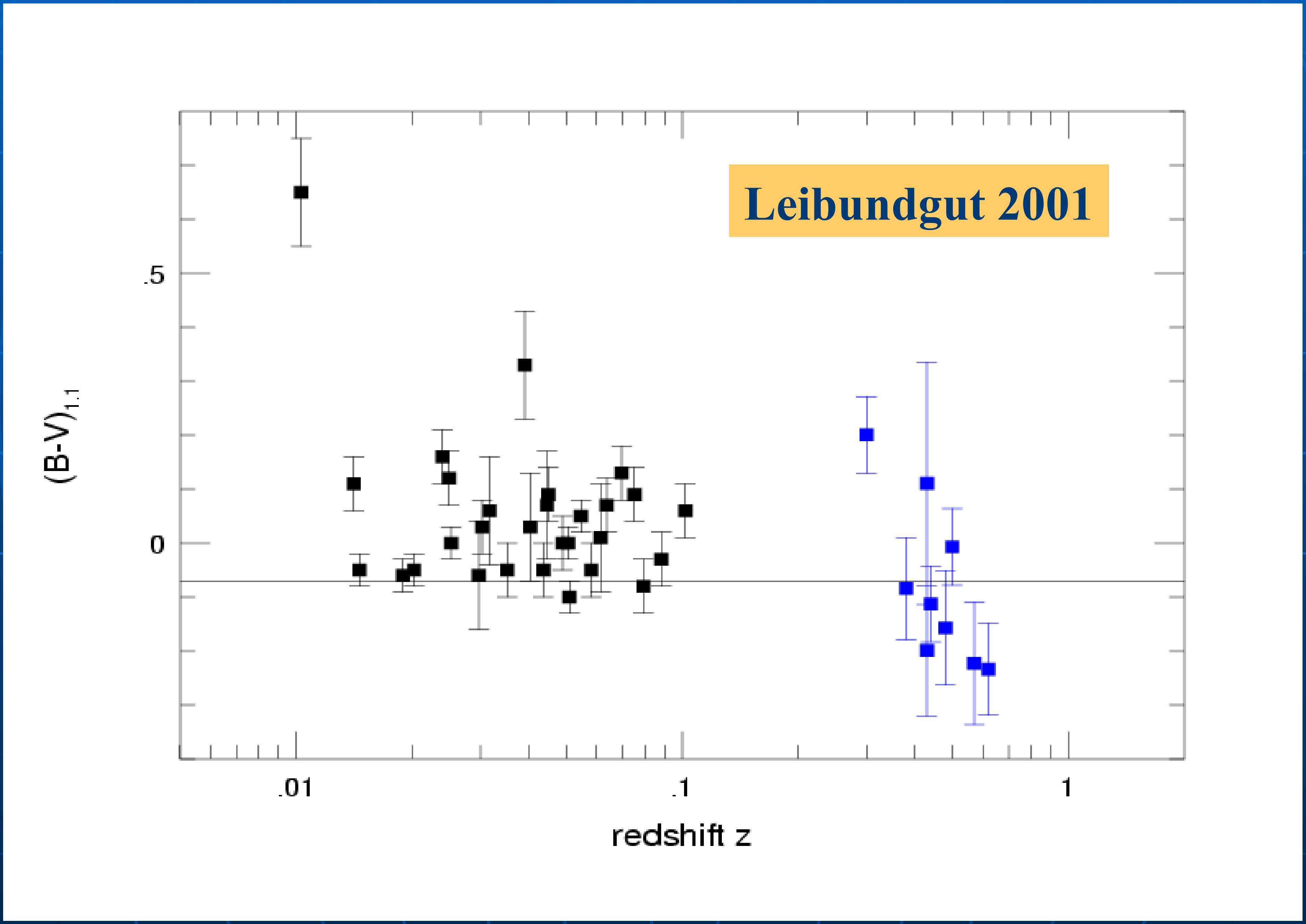
(mostly RTN/ESC data)





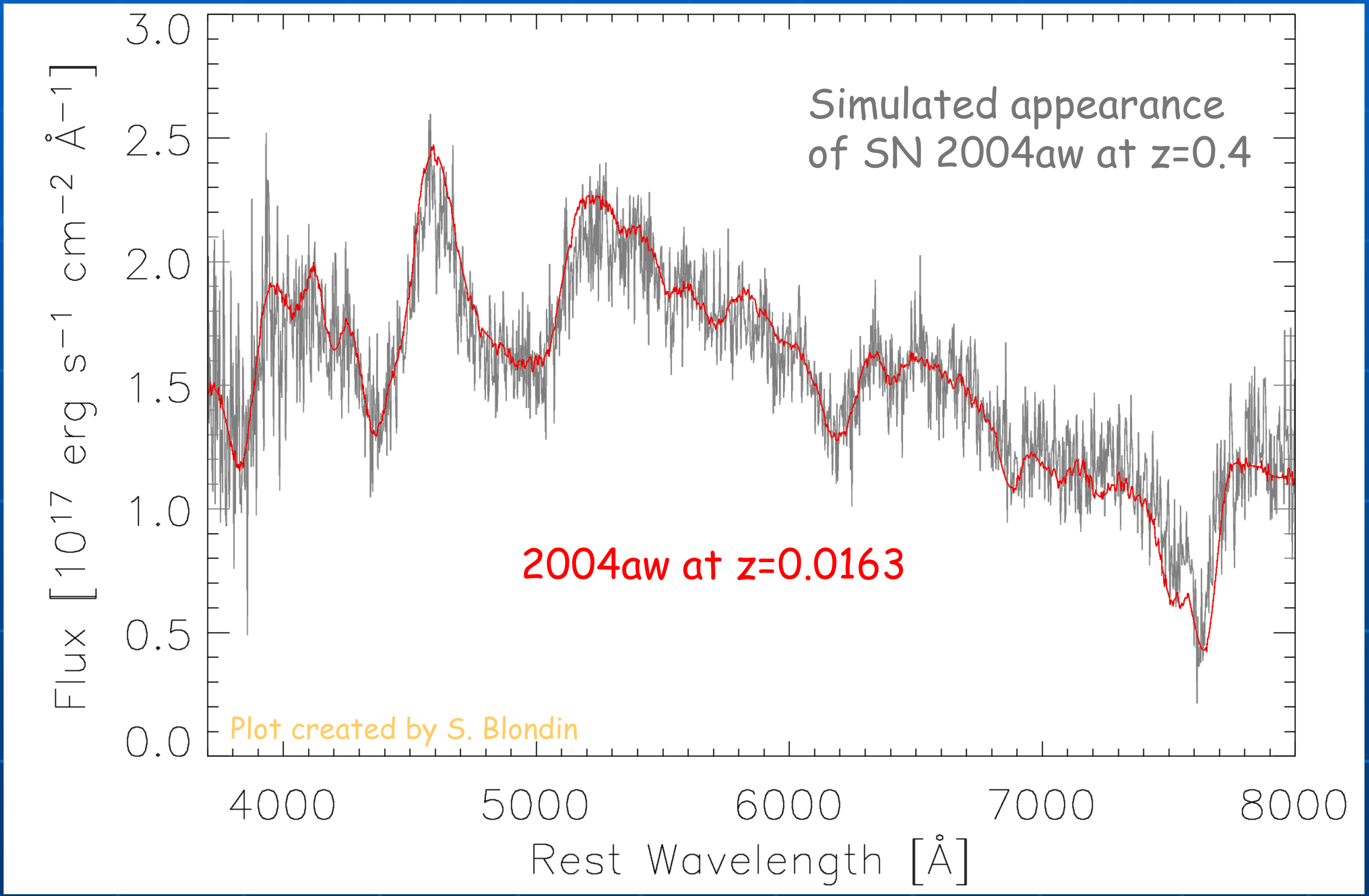
(Court. M. Stritzinger)

Is evolution a problem?



Absorption distributions?

High-z sample contamination ?



+1.5 days spectrum

(S. Taubenberger)

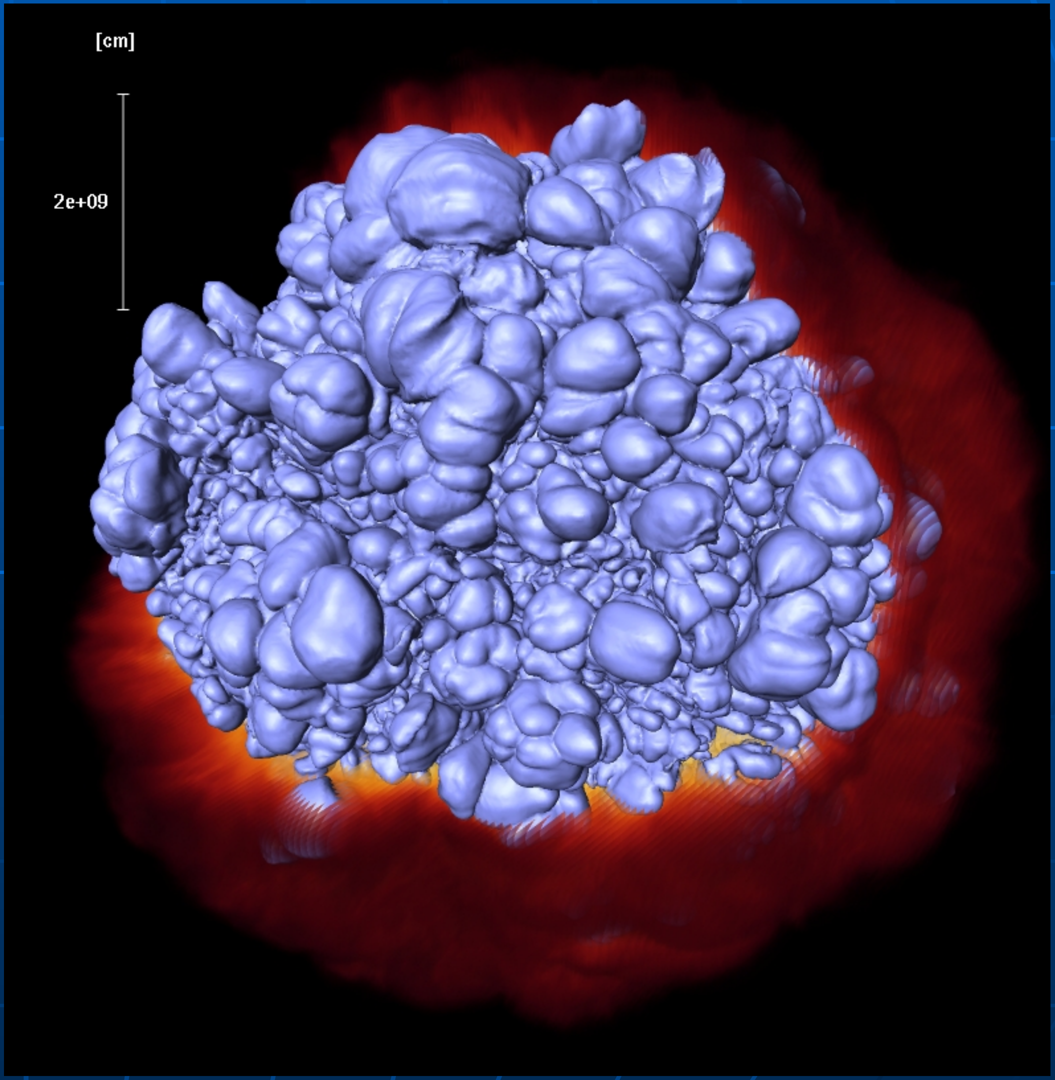
Result of a classification code of S. Blondin (for the z = 0.4 case):

- best match: 1991T (Ia pec) @ +17.4d
  second best: 1992A (Ia) @ +9.0d
  third best: 1995D (Ia) @ +8.1d

Can theory help to reduce the systematic uncertainties?

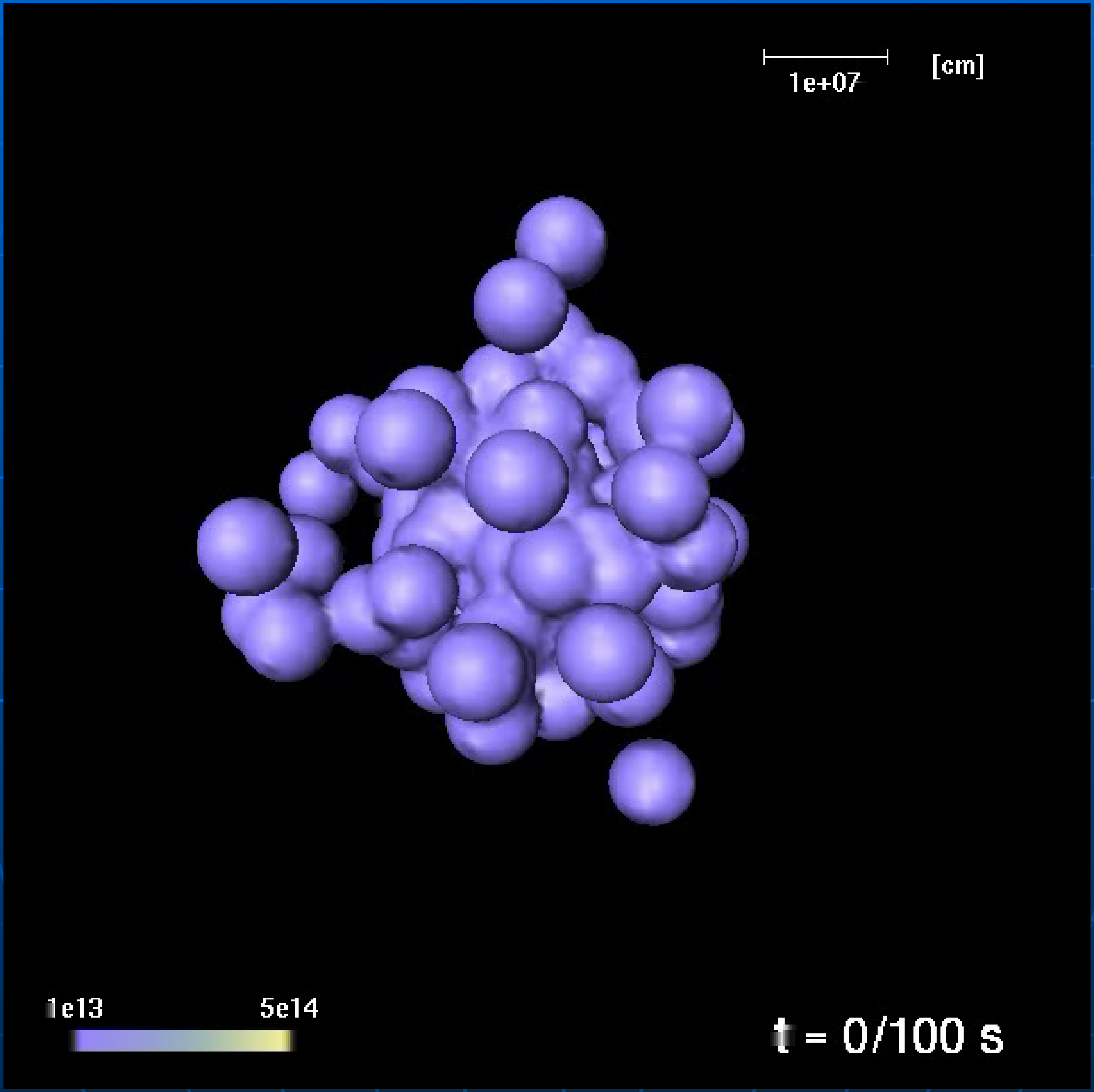
The best model todate:

- "4π"
- 1024^3 grid
- initial resolution near the center ≈ 800m
- moving grid
- local & dynamical sgs-model



Preliminary results look very good!

(Röpke et al., in preparation)


1e+07
[cm]
1e13
5e14
t = 0/100 s

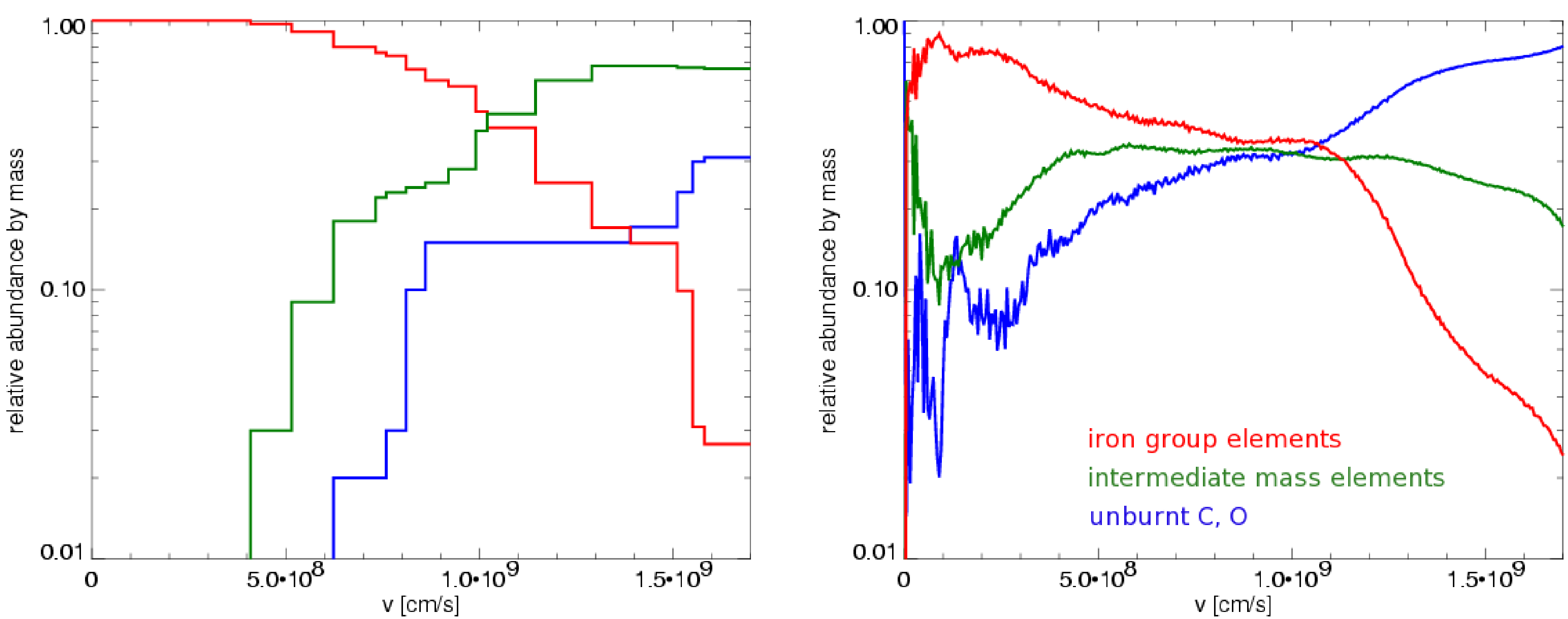
Some preliminary results:

- $E_{kin} = 8.1 \cdot 10^{50}$ erg
- Iron-group nuclei (mostly ^{56}Ni): 0.61 M_{sun}
- Intermediate-mass nuclei: 0.43 M_{sun}
- Unburnt C+O: 0.37 M_{sun} (less than 0.08 M_{sun} at v<8000km/s !)
- Vmax ≈ 17.000 km/s

Note: This is a pure deflagration model!

Röpke et al. (2005)

Abundance tomography

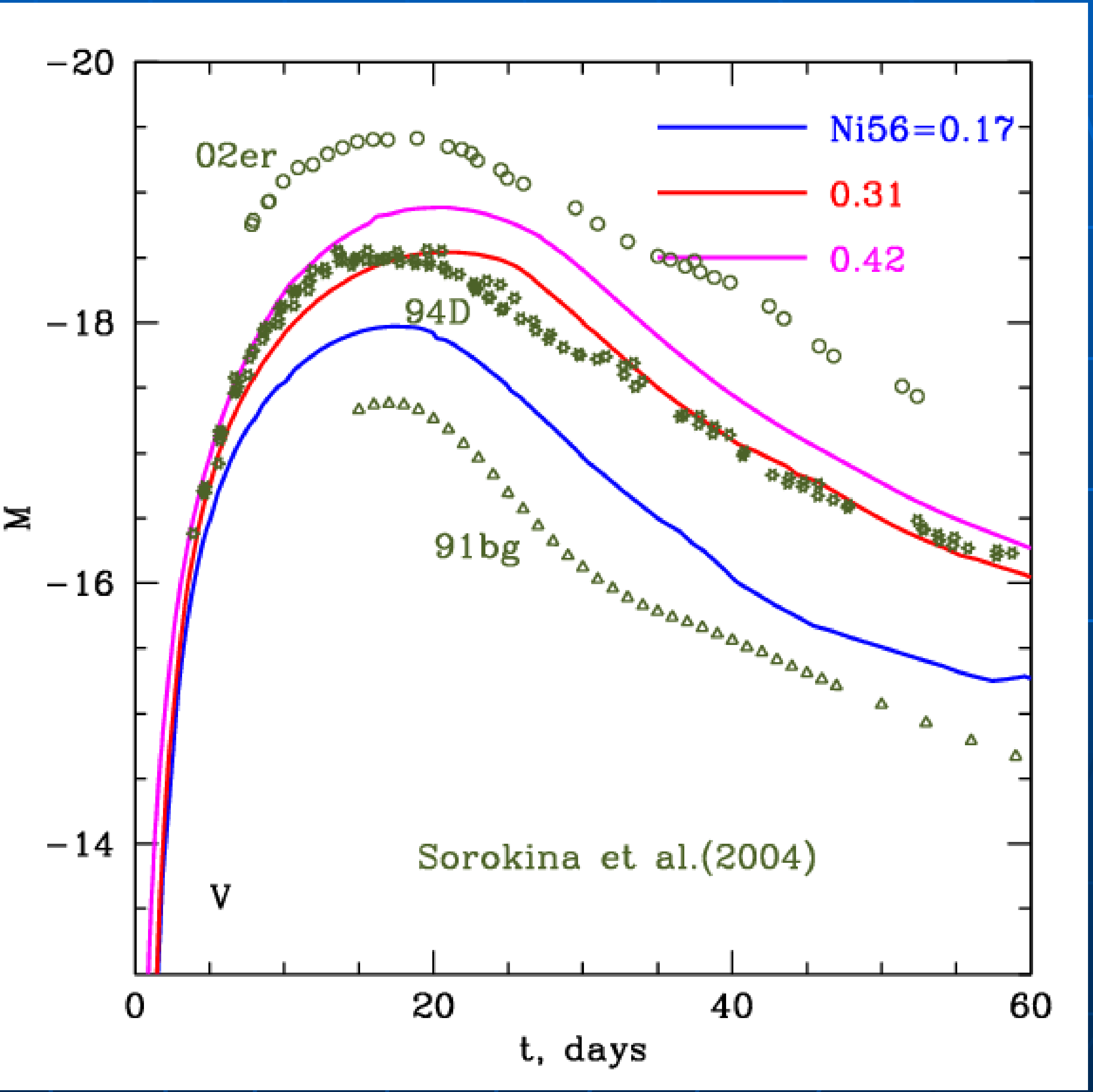


A couple of results and predictions

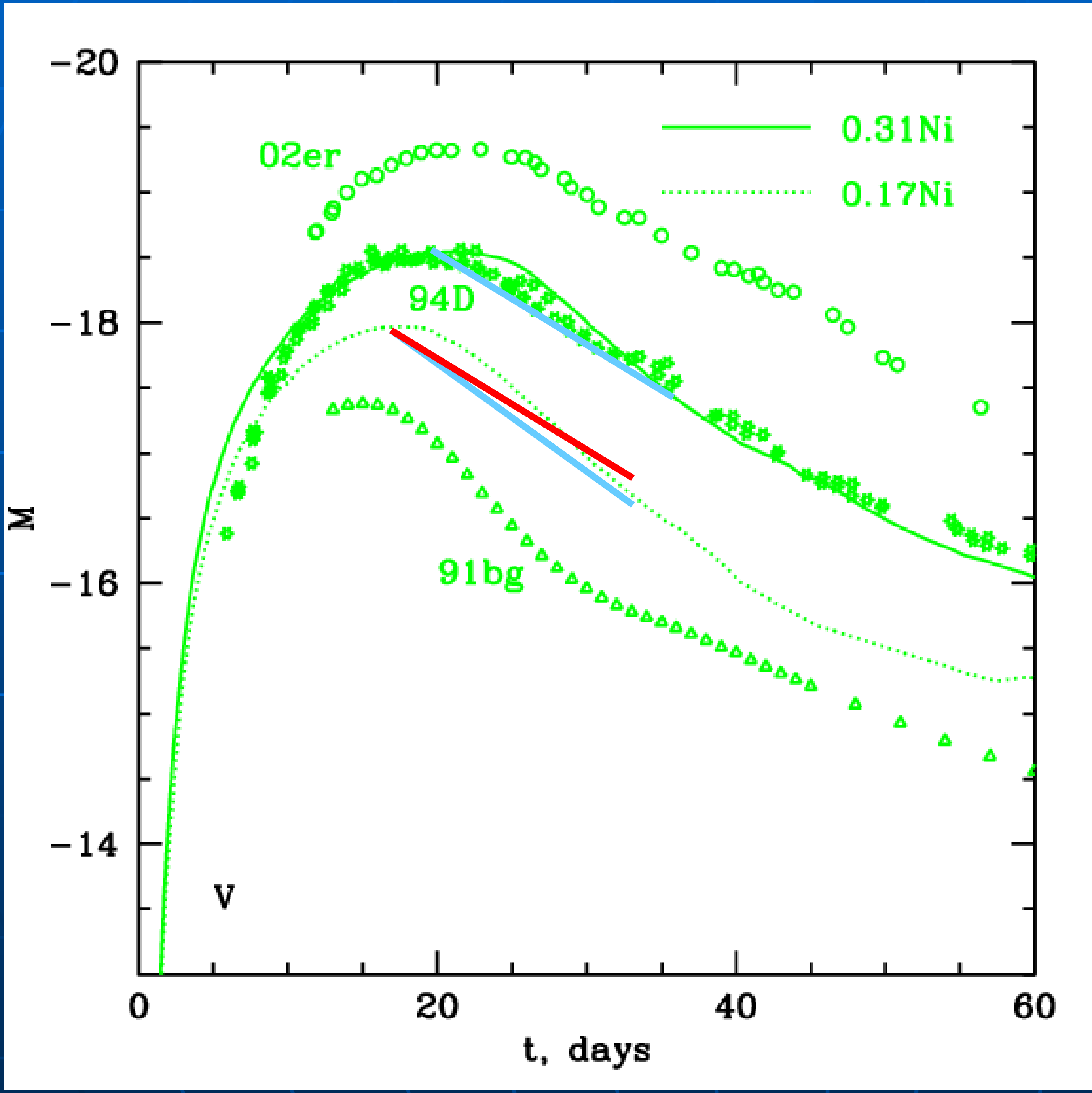
(mostly based on models with lower resolution)

1. Light curves

(Sorokina et al. 2004, 2005)



V-band LC's



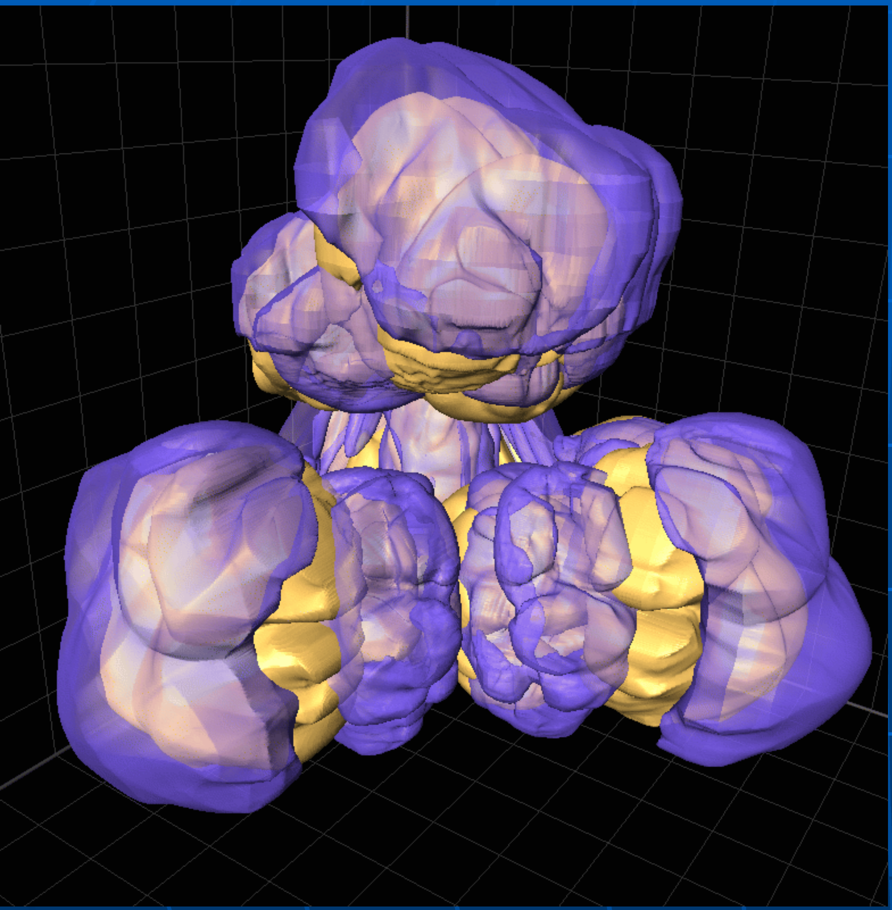
Prediction from theory :

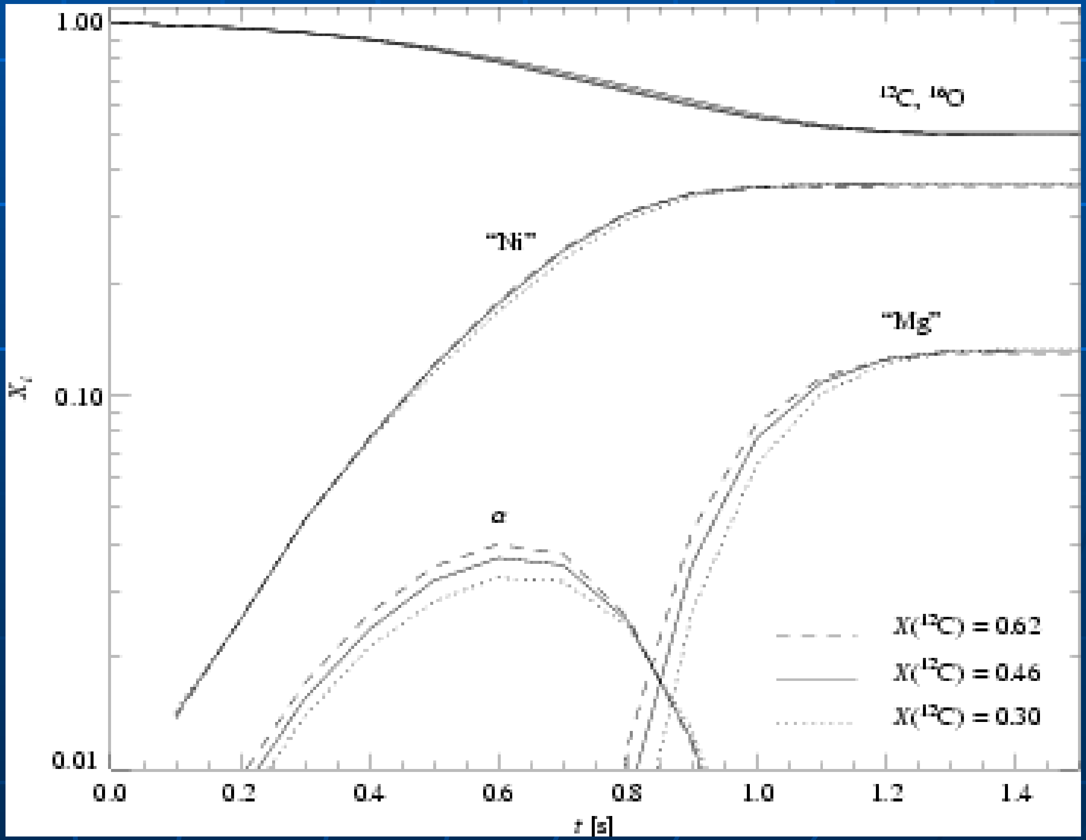
Light-curve shape/ luminosity correlation?

2. C-to-O ratio

(Röpke & Hillebrandt 2004)

$X(^{12}C)$	E_{nuc} (10^{50} erg)	M(Ni) ($M_\odot$)	M_α^{max} ($M_\odot$)
0.30	8.85	0.5178	0.0458
0.46	9.46	0.5165	0.0518
0.62	9.97	0.5104	0.0564



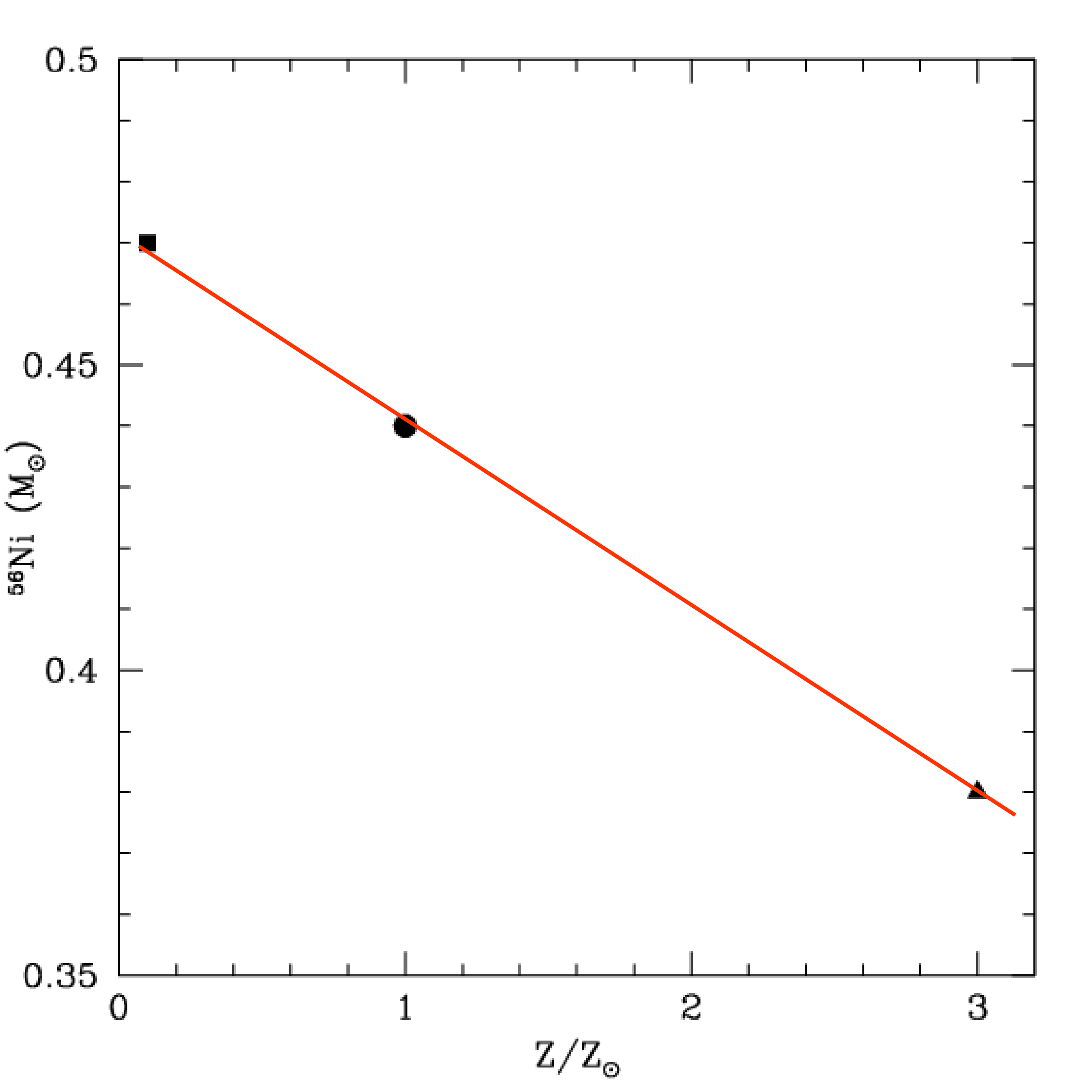


Ni-mass (luminosity) independent of initial C/O!

3. Metallicity dependence

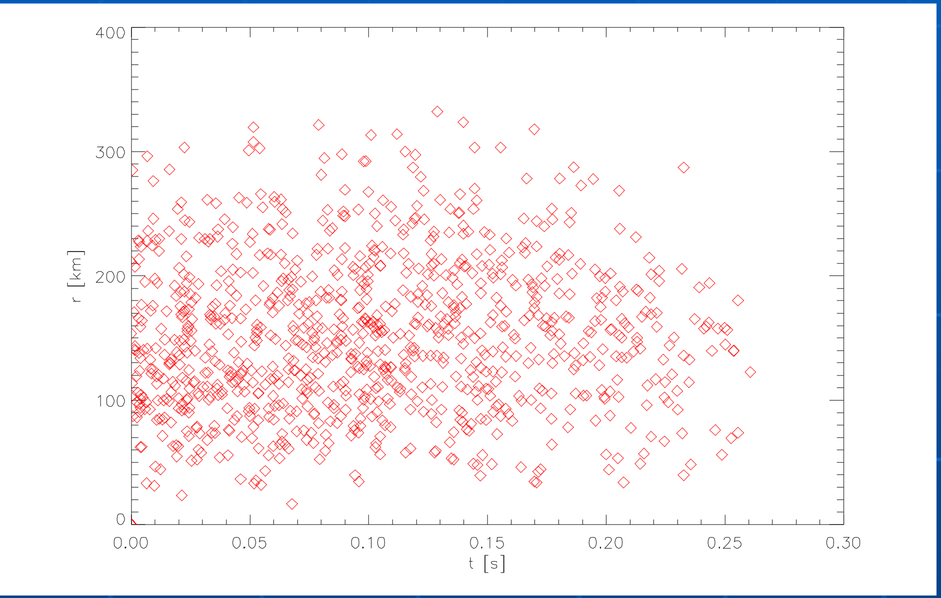
(Travaglio et al. 2005)

(Model “b30_3d”)

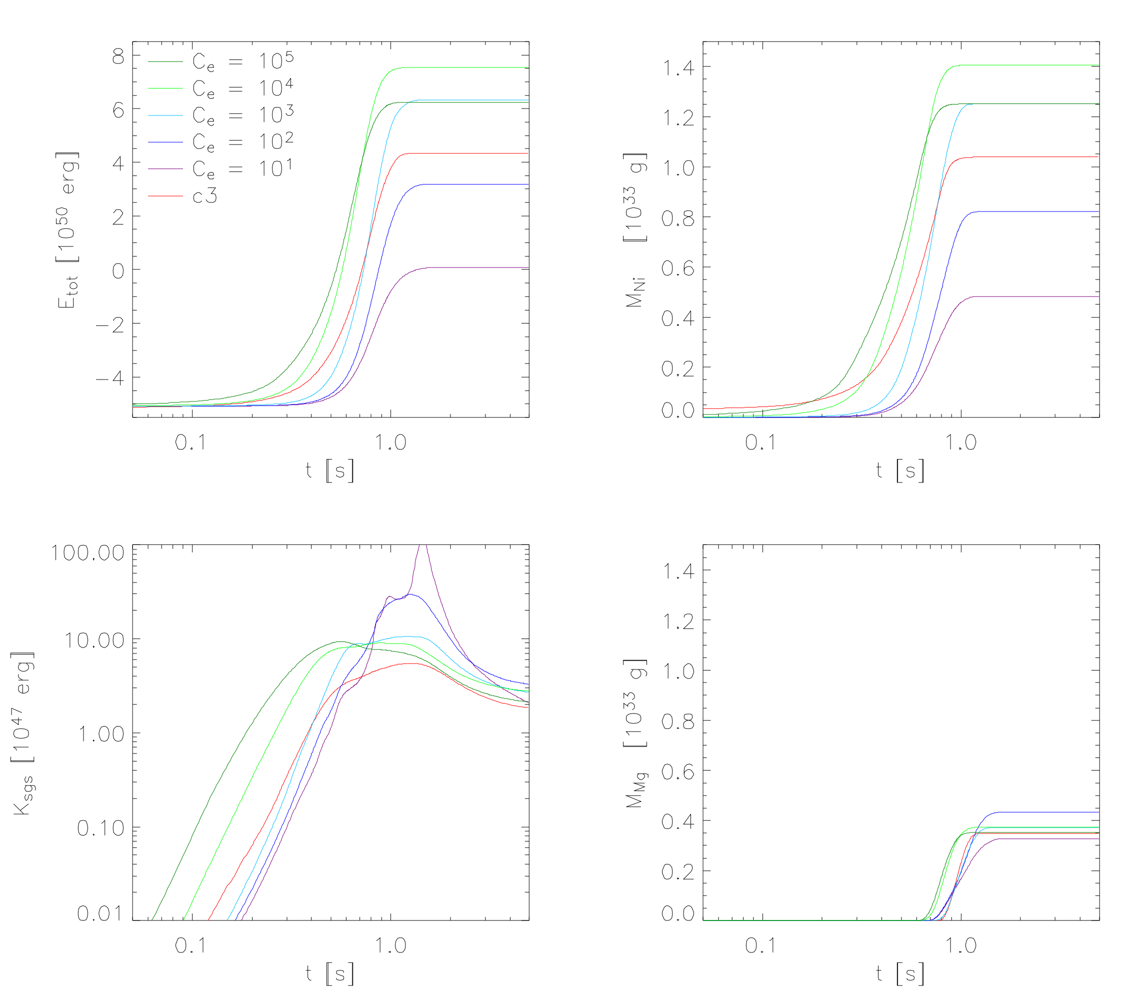


Weak metallicity dependence (in agreement with Timmes et al. 2003)

4. Ignition conditions: Reason for the diversity?



"Stochastic ignition"



Schmidt & Niemeyer. (2005)

Summary and Conclusions

- Type II supernovae are good distance indicatores out to a few Mpc.
- They measure absolute distances without any calibration!
- Type Ia supernovae are very good distance indicators in the local Universe .
- They allow to measure relative distances very accurately (after calibration).
- They provide the best distance indicators for cosmological distances if systematic errors can be controlled.

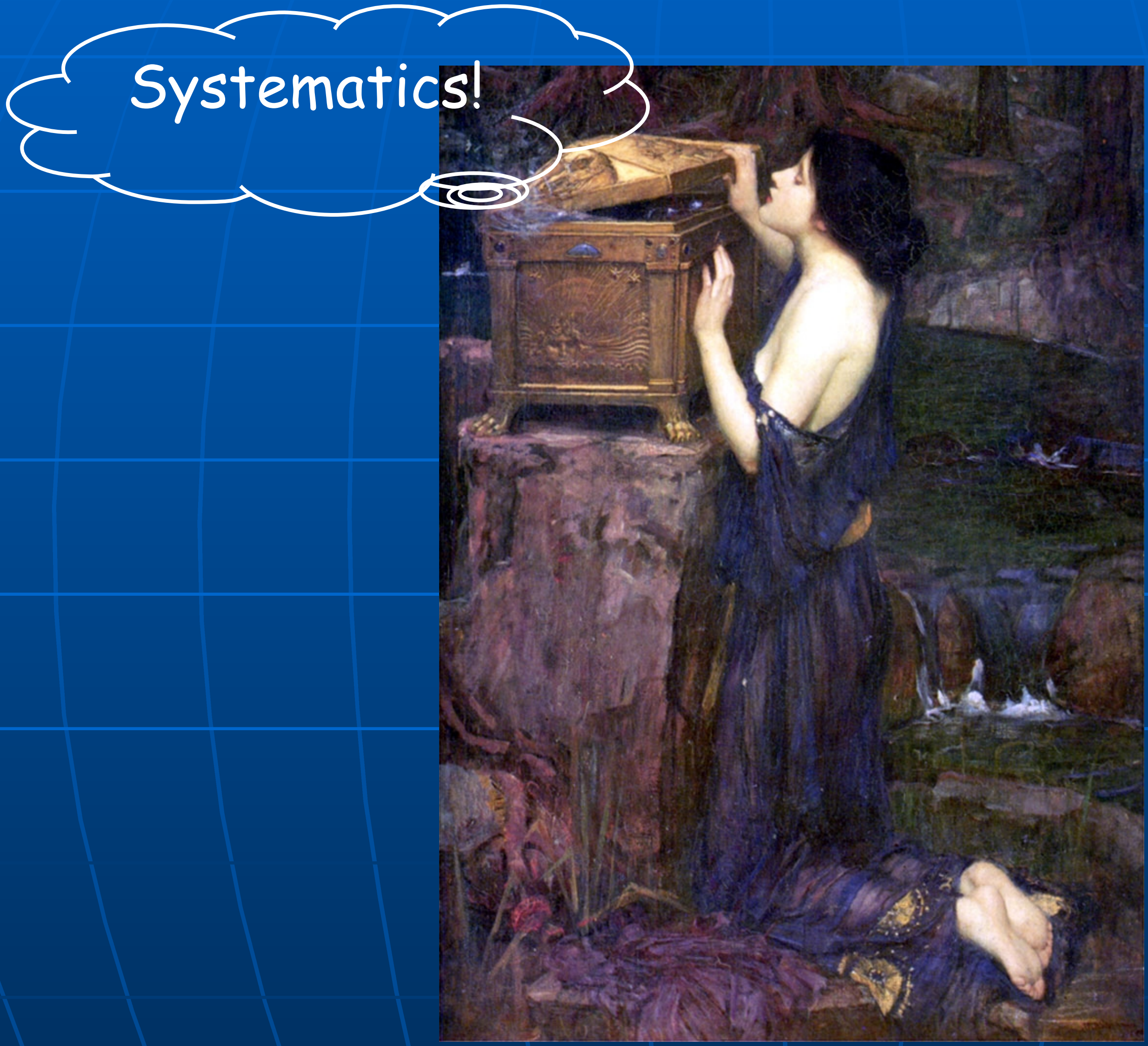
Summary and conclusions (cont.)

- "Parameter-free" thermonuclear models of type Ia supernovae, based on Chandrasekhar-mass C+O white dwarfs explode with about the right energy.
- They allow to predict light curves and spectra, depending on physical parameters!
- They can explain (most of ?) the observed properties well.
- The diversity may be due to randomness in the ignition conditions , (C/O), and metallicity (or other physical parameters, e.g., rotation).

Summary and conclusions (cont.)

- But: there are potential sources of systematic errors!
- *Can they be controlled by more observations and better models?*

But, as far as Cosmology is concerned:



Hope is left in Pandora's box!