Cosmology with Supernovae

Bruno Leibundgut

European Southern Observatory

Outline

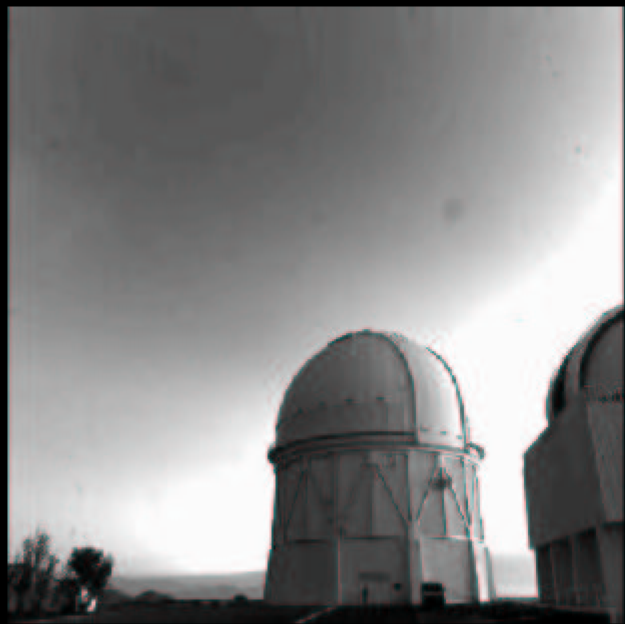
Supernova types

- core-collapse supernovae
- thermonuclear supernovae

Cosmology with supernovae

- Hubble constant, H_0 ➔ lecture I
- mapping of the cosmological expansion history, H(z) ➔ lecture II

Supernova observing



Supernovae

Supernovae

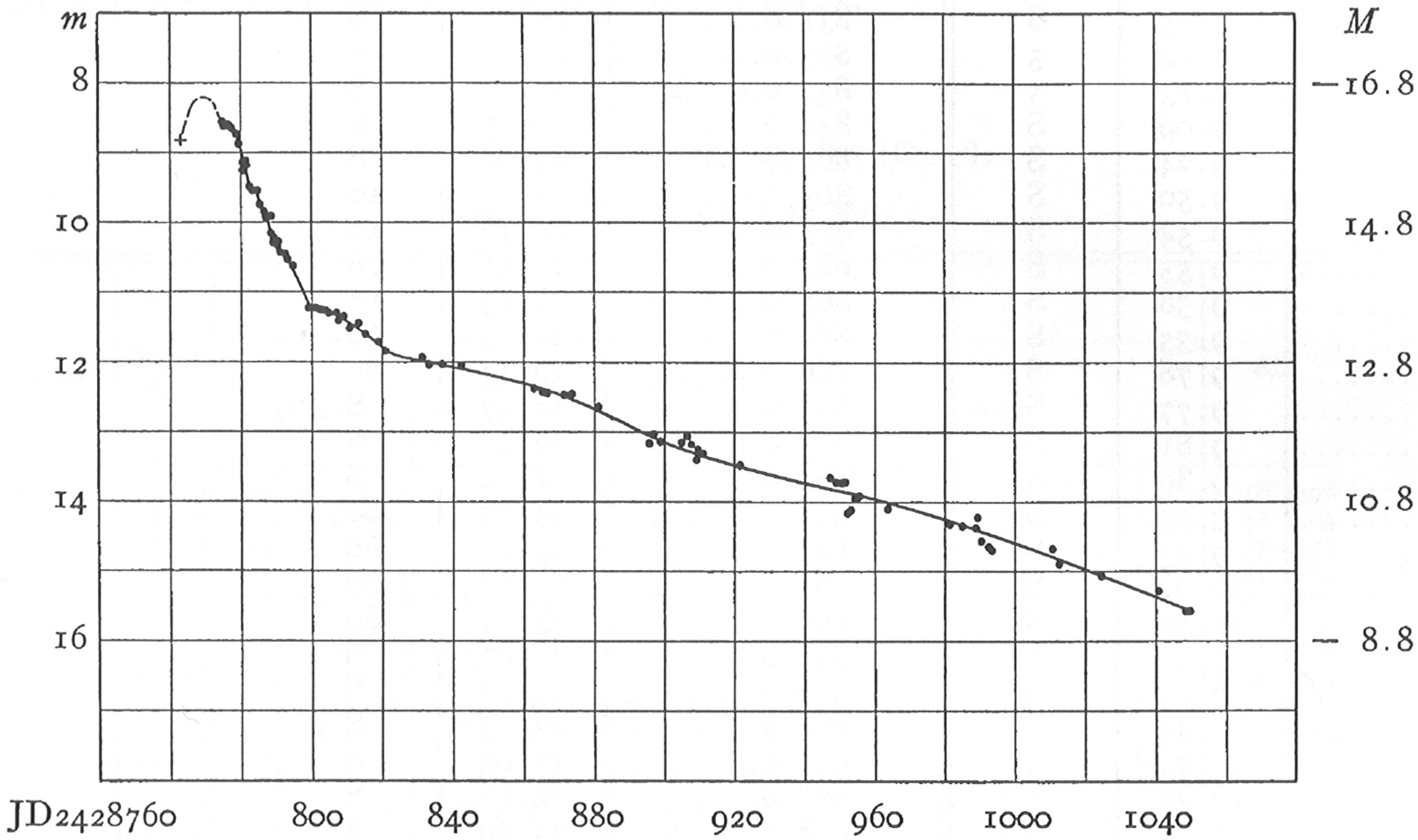
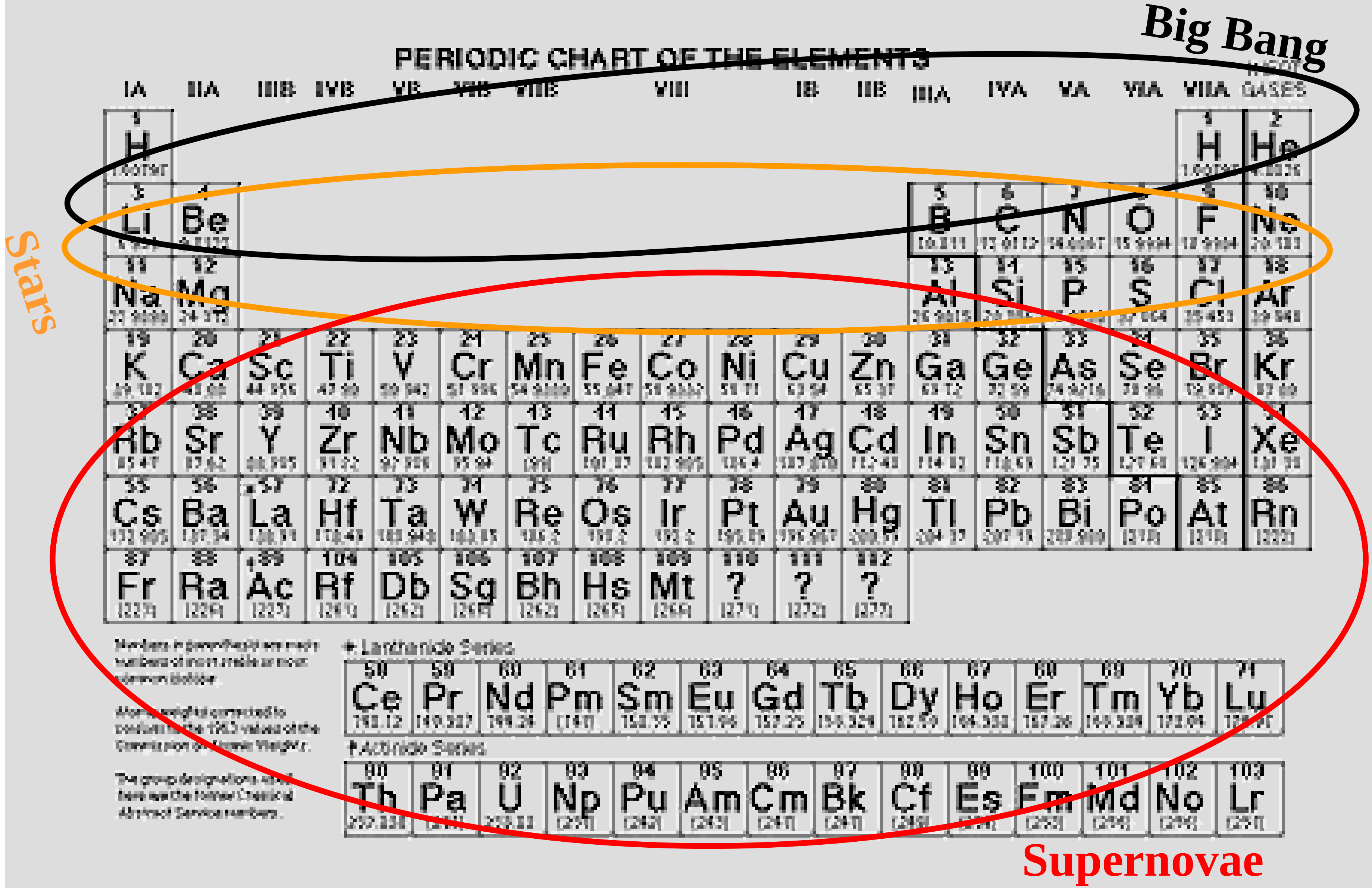


FIG. 1.—Photographic light-curve of supernova in IC 4182

Supernovae



Supernovae

Extremely bright stellar explosions

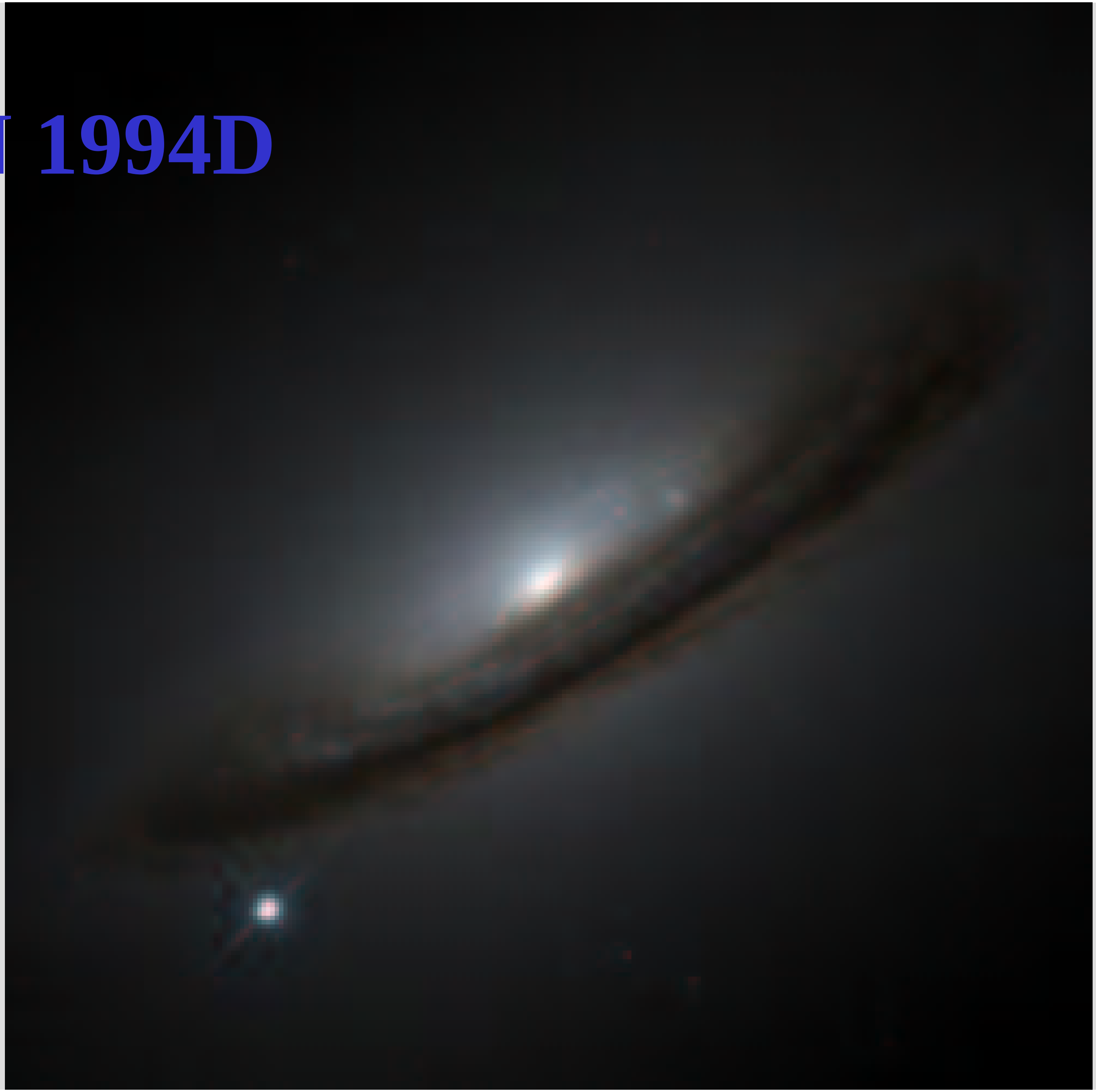
Important for the production of the heavy elements

Best distance indicators in the universe

The only reliable way of determining extragalactic distances is through supernova investigations.

F. Zwicky

SN 1994D



Supernova classification

Based on spectroscopy

core collapse
in massive stars

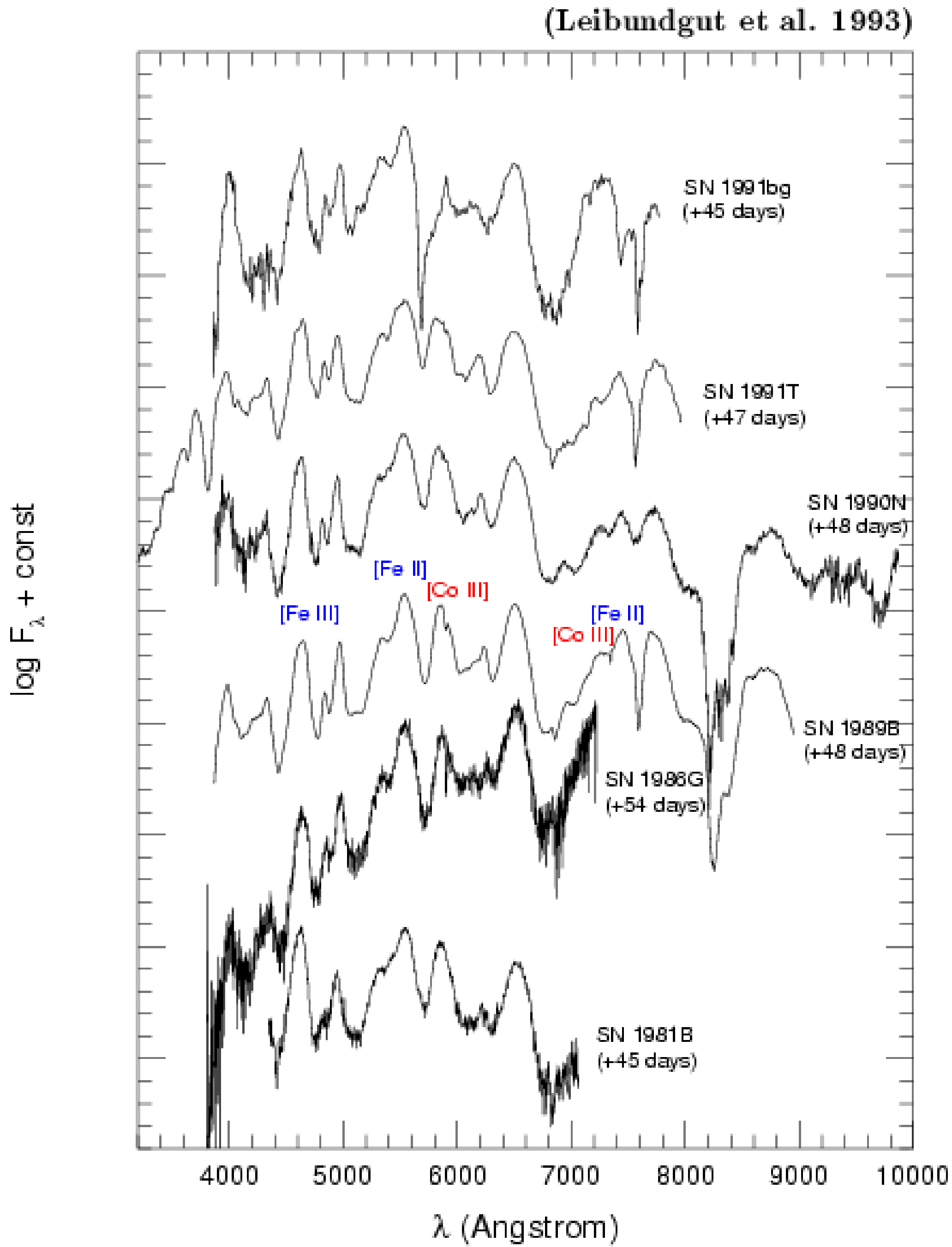
SN II (H)
SN Ib/c (no H/He)
Hypernovae/GRBs

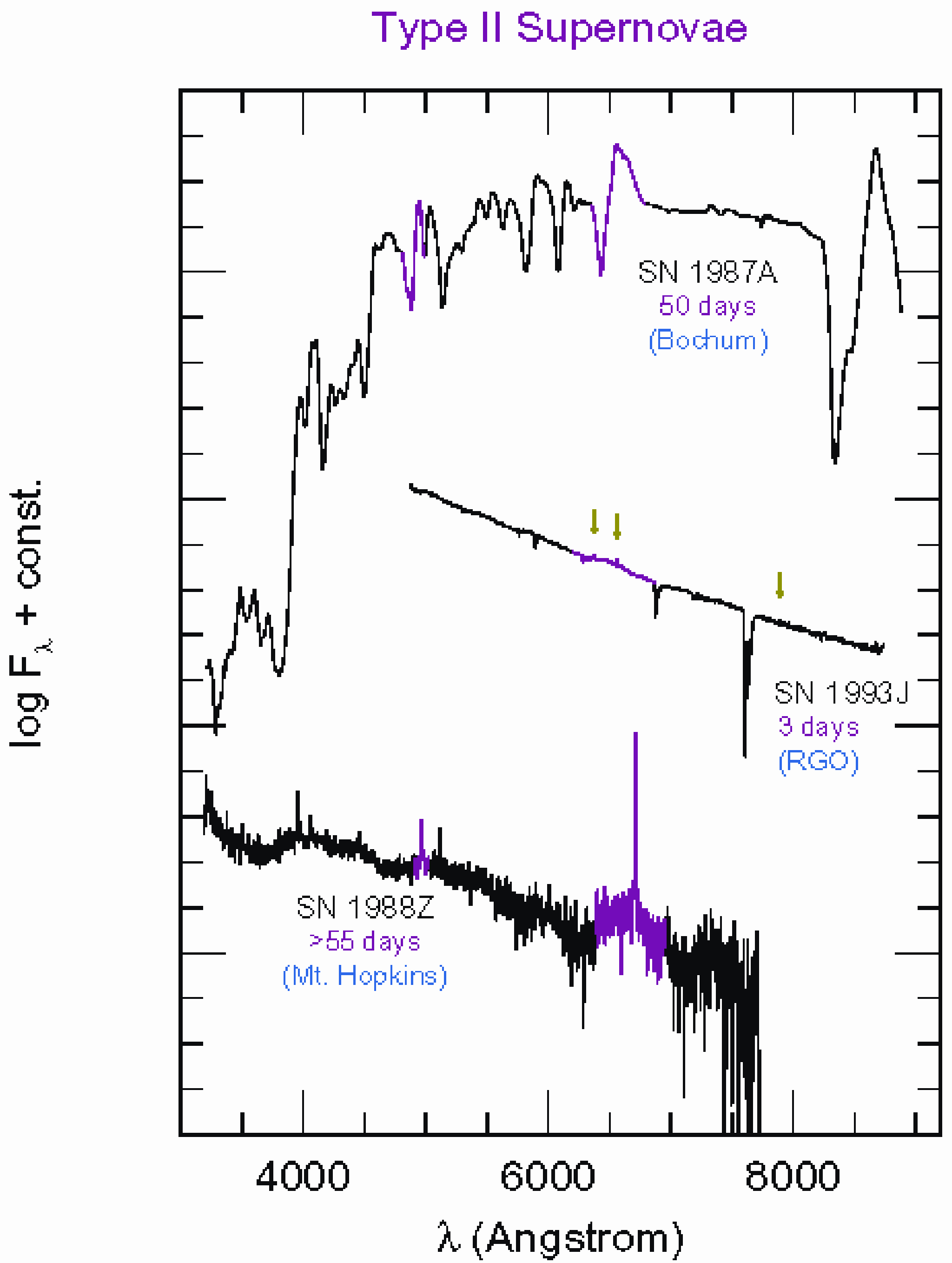
SN Ia (no H)

thermonuclear
explosions

Supernova Spectroscopy

Type Ia





Supernova Spectroscopy

Type II

Supernova types

thermonuclear SNe

- from low-mass stars ($<8M_\odot$)
- highly evolved stars (white dwarfs)
- explosive C and O burning
- binary systems required
- complete disruption

core-collapse SNe

- high mass stars ($>8M_\odot$)
- large envelopes (still burning)
- burning due to compression
- single stars (binaries for SNe Ib/c)
- neutron star

Shaping supernova emission

Light curves as signatures of the energy release in supernovae

- energy sources
- photon escape
- modulations
- external effects

Colours

Luminosity

Energy sources

shock

- breakout
- kinetic energy

cooling

- due to expansion of the ejecta

radioactivity

- nucleosynthesis

recombination

- of the shock-ionised material

Importance of light curves

explosion mechanisms

energy sources

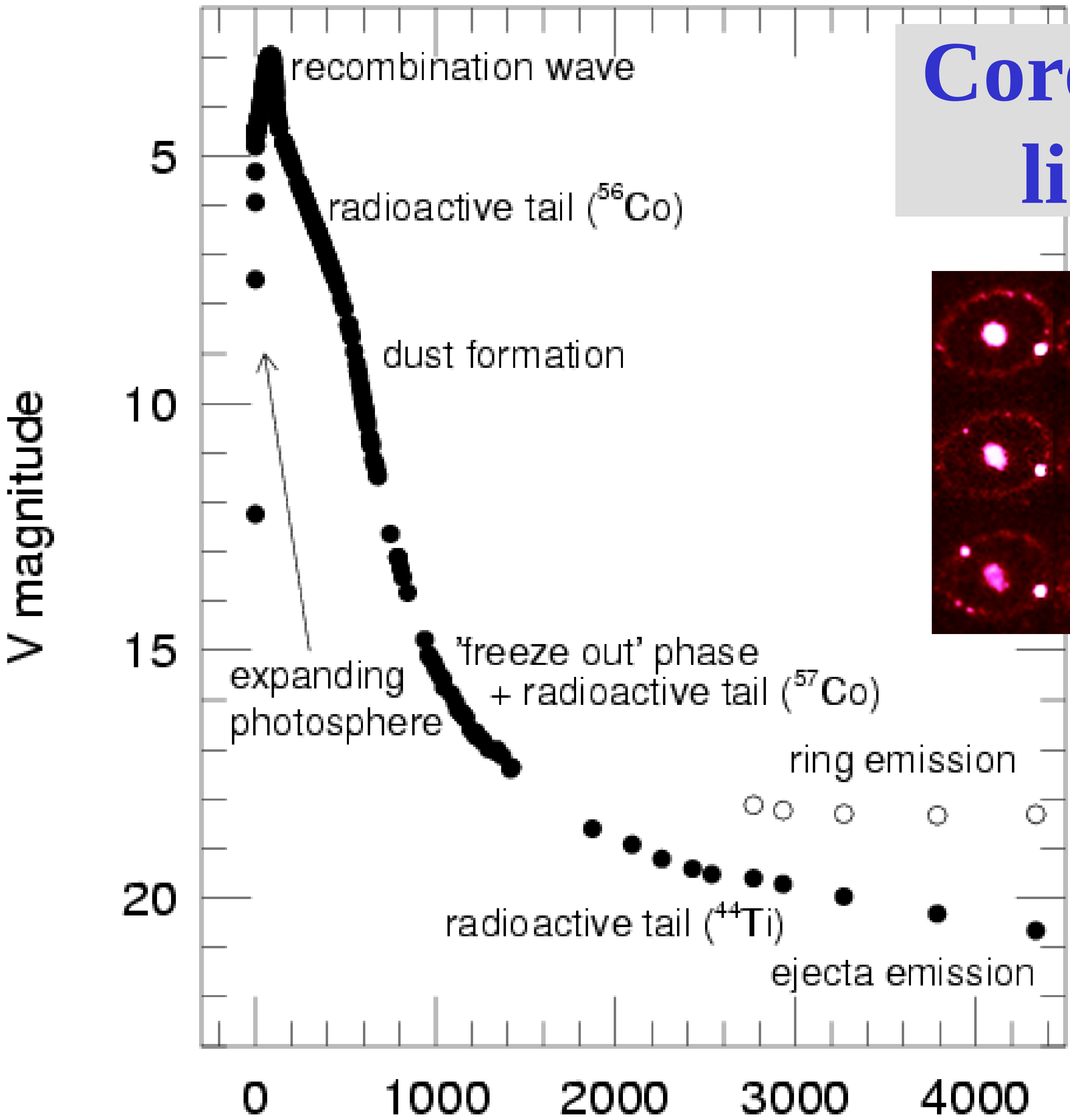
environmental effects

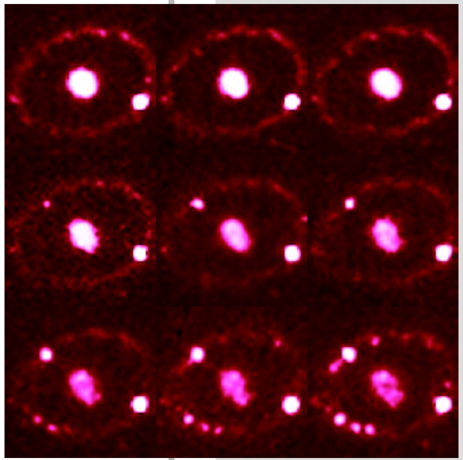
progenitor systems

remnants

distance determinations and cosmology

Core collapse light curve



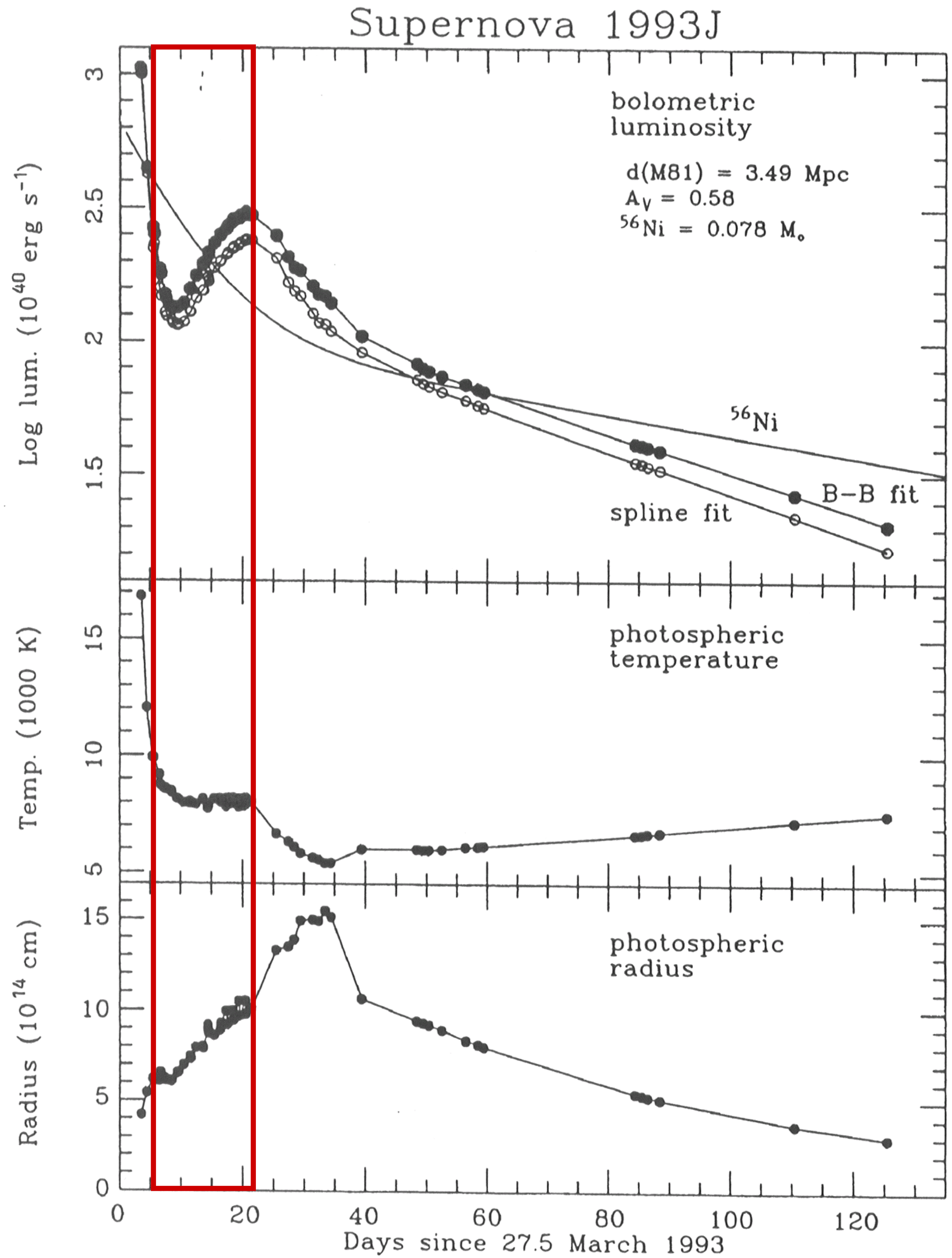


Suntzeff (2003)

Expansion

Brightness increa

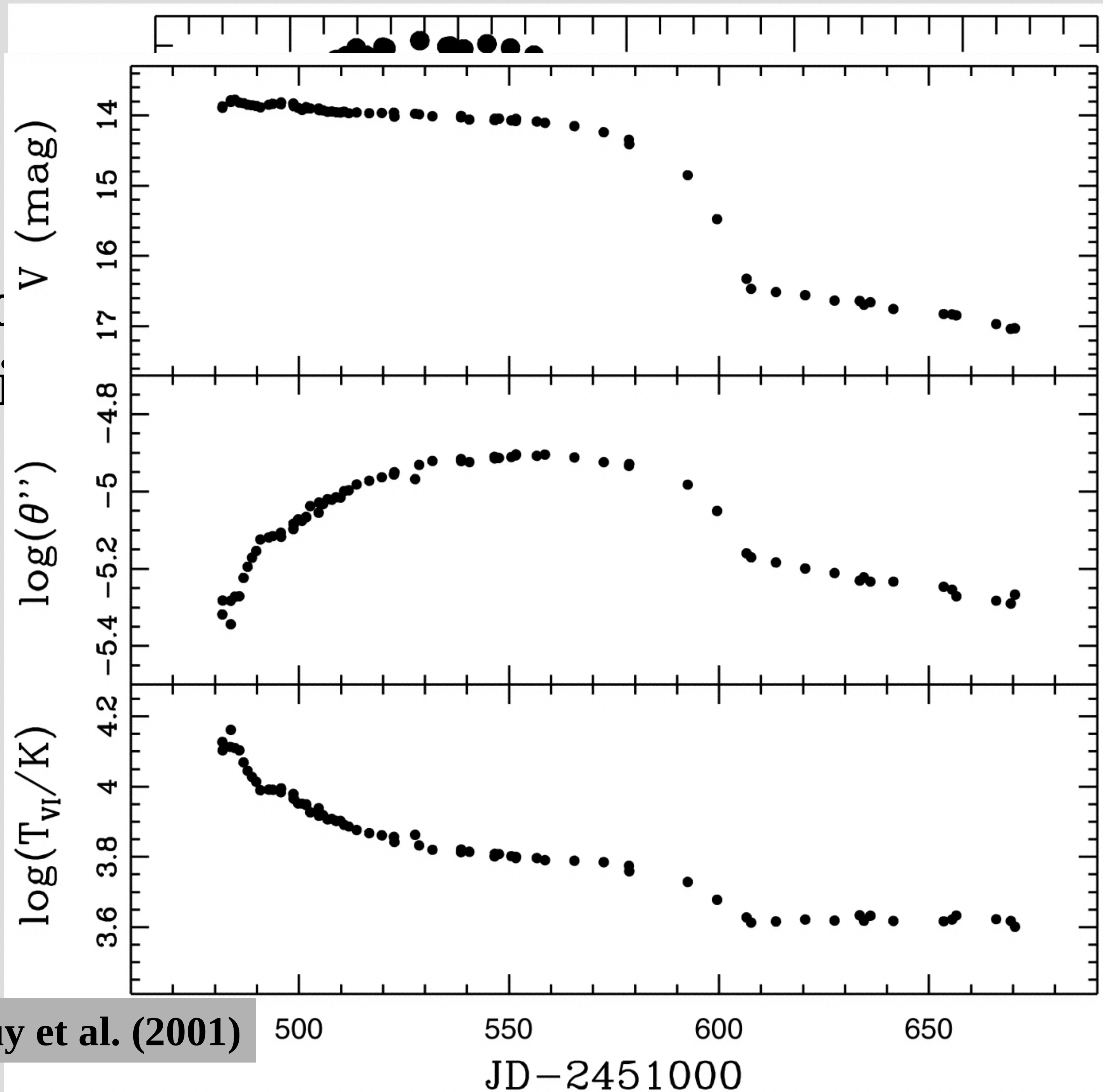
- **increased surfa**
- **slow temperatu**



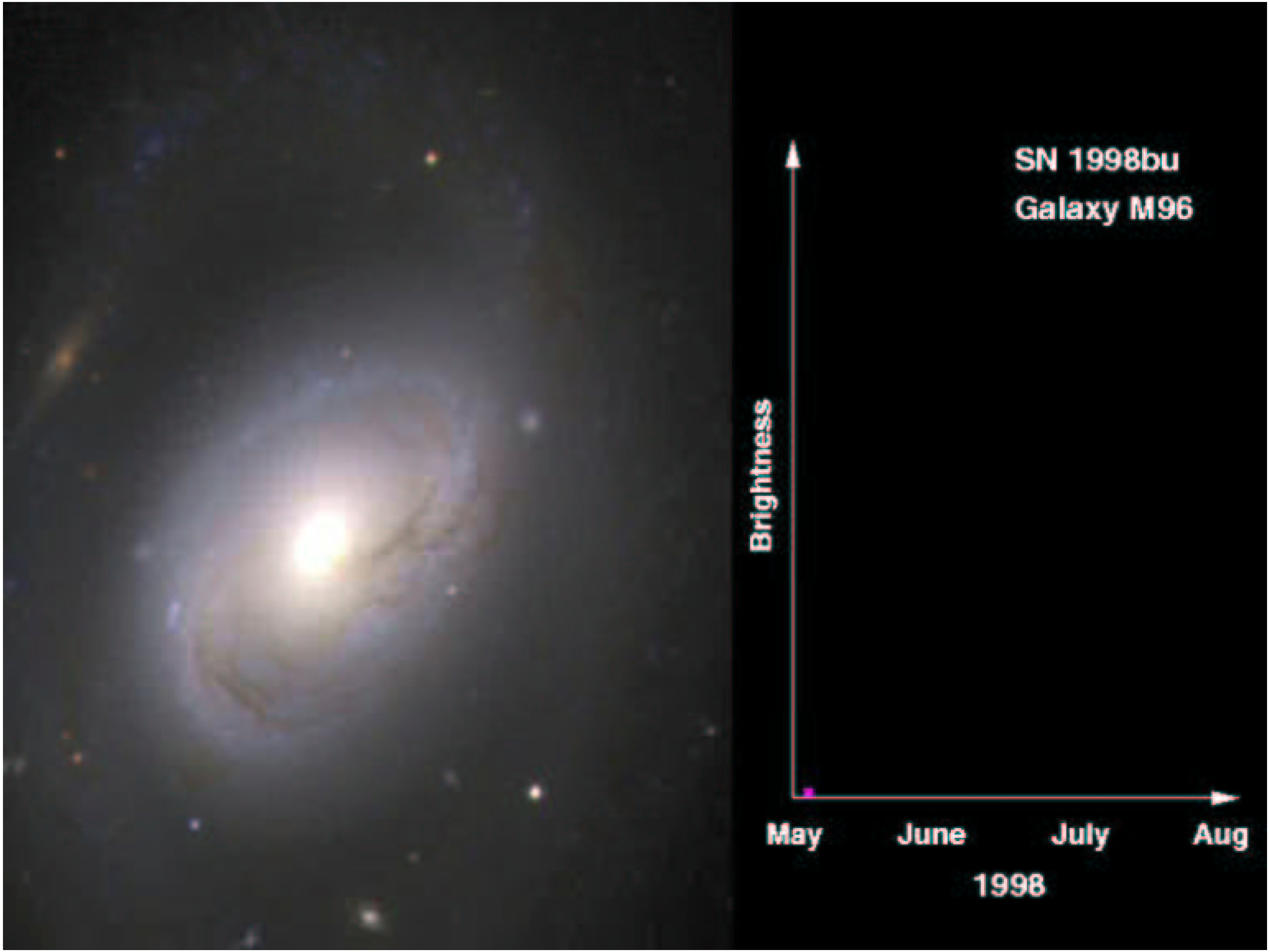
Balance c

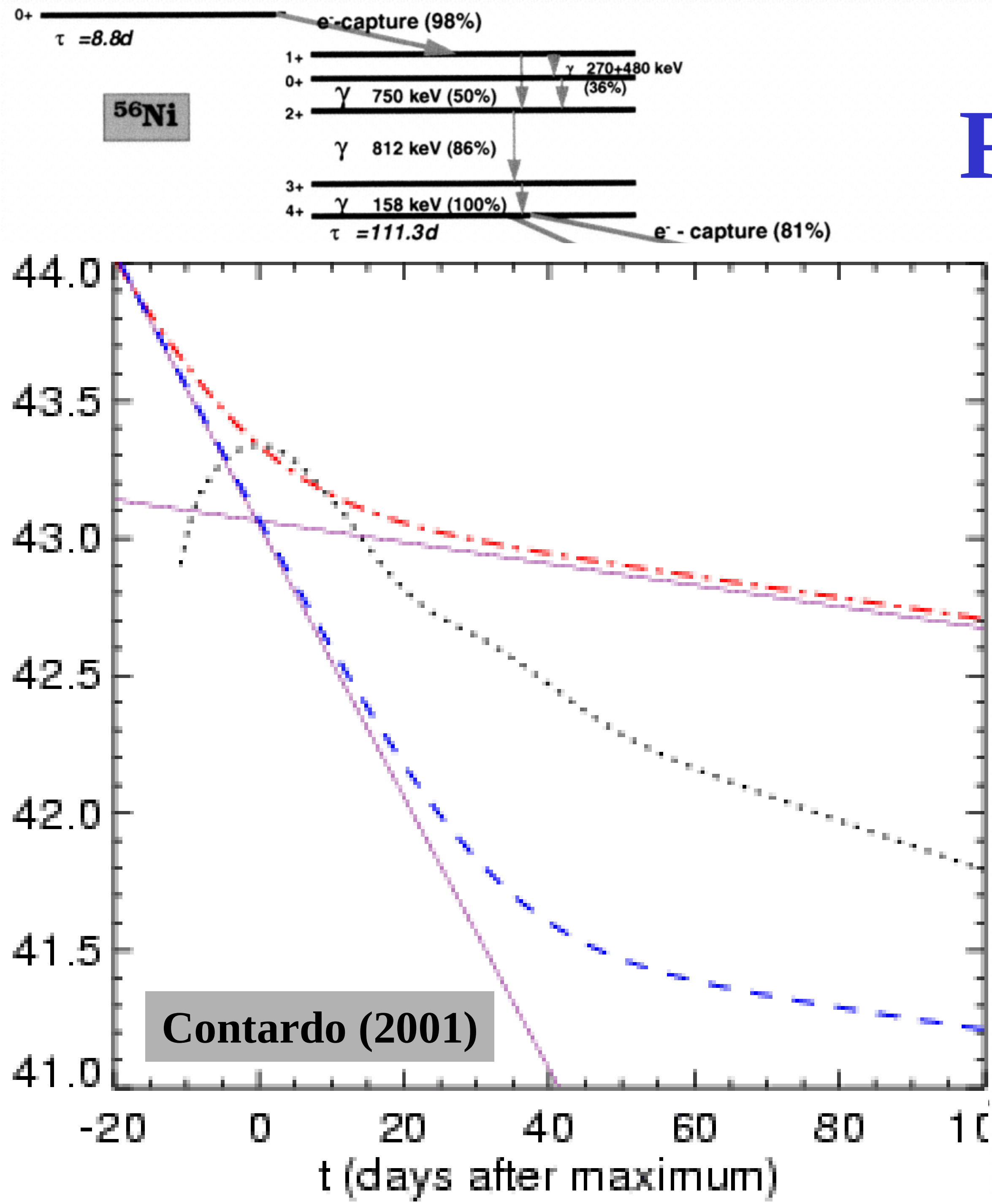
expansi

- **leads**



Hamuy et al. (2001)


SN 1998bu
Galaxy M96
Brightness
May
June
July
Aug
1998

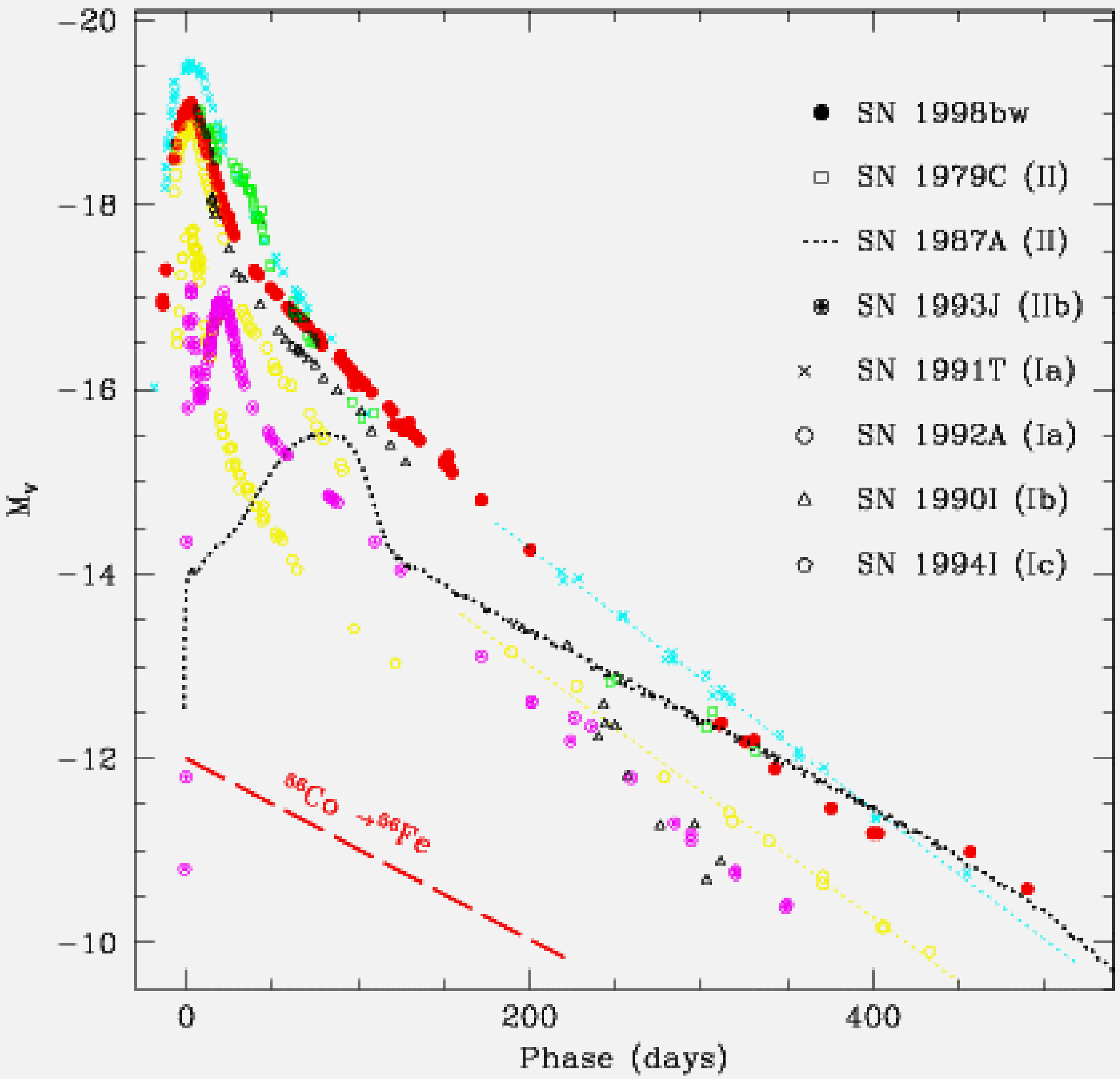


Radioactivity

Isotopes of Ni and other elements

- conversion of γ-rays and positrons into heat and optical photons

The variety of SN light curves



Patat et al. (2001)

Distances in the local universe

Assume a linear expansion

Hubble law

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

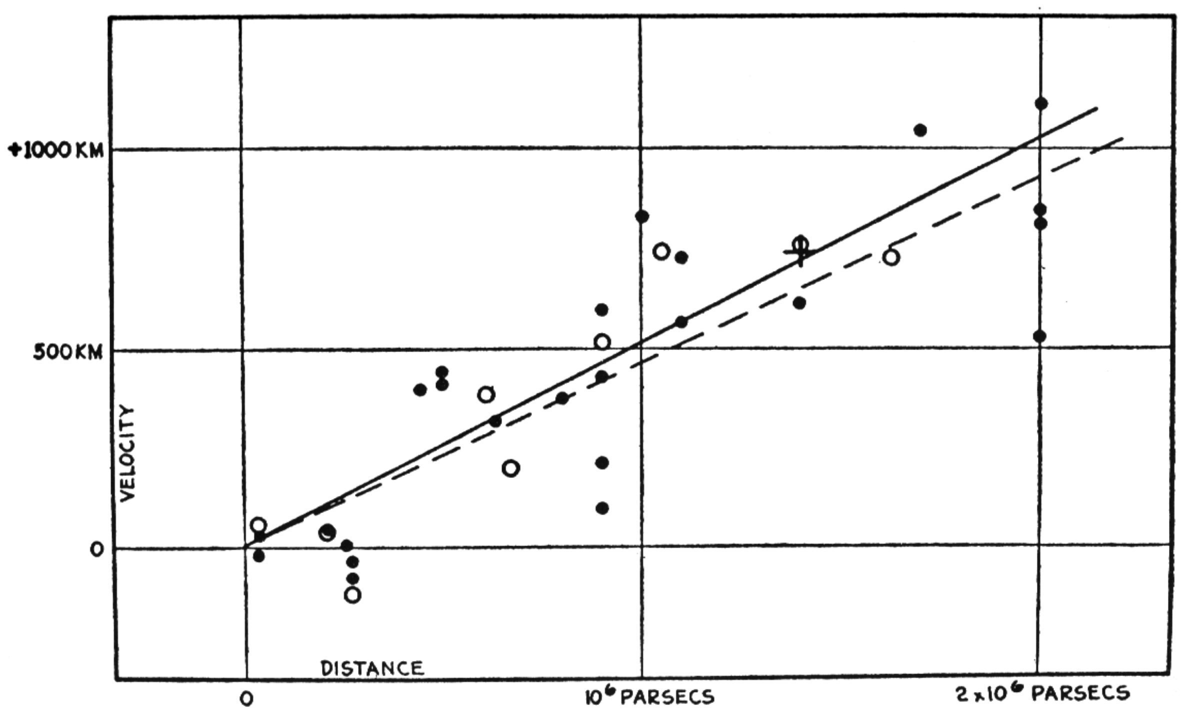
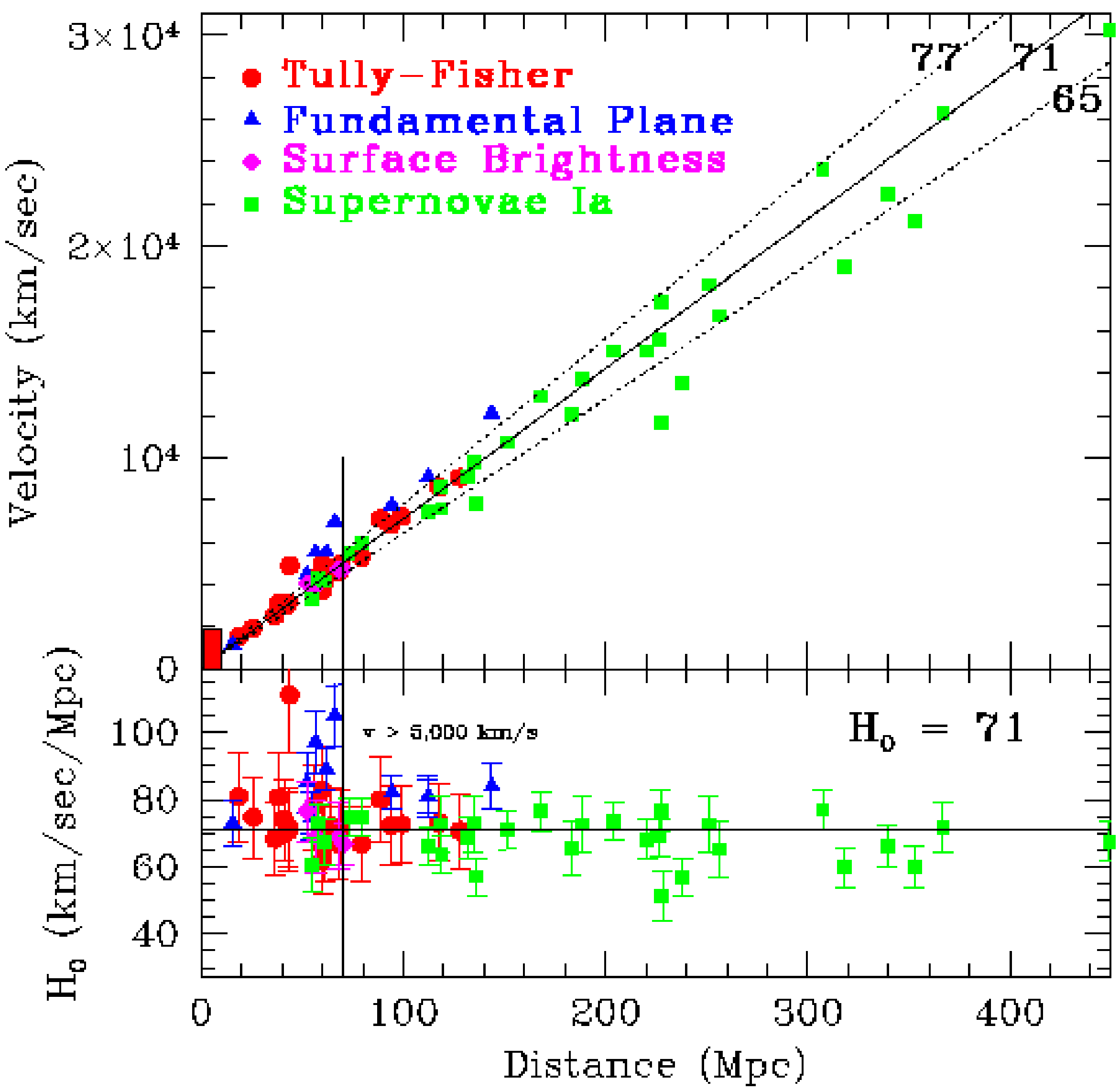
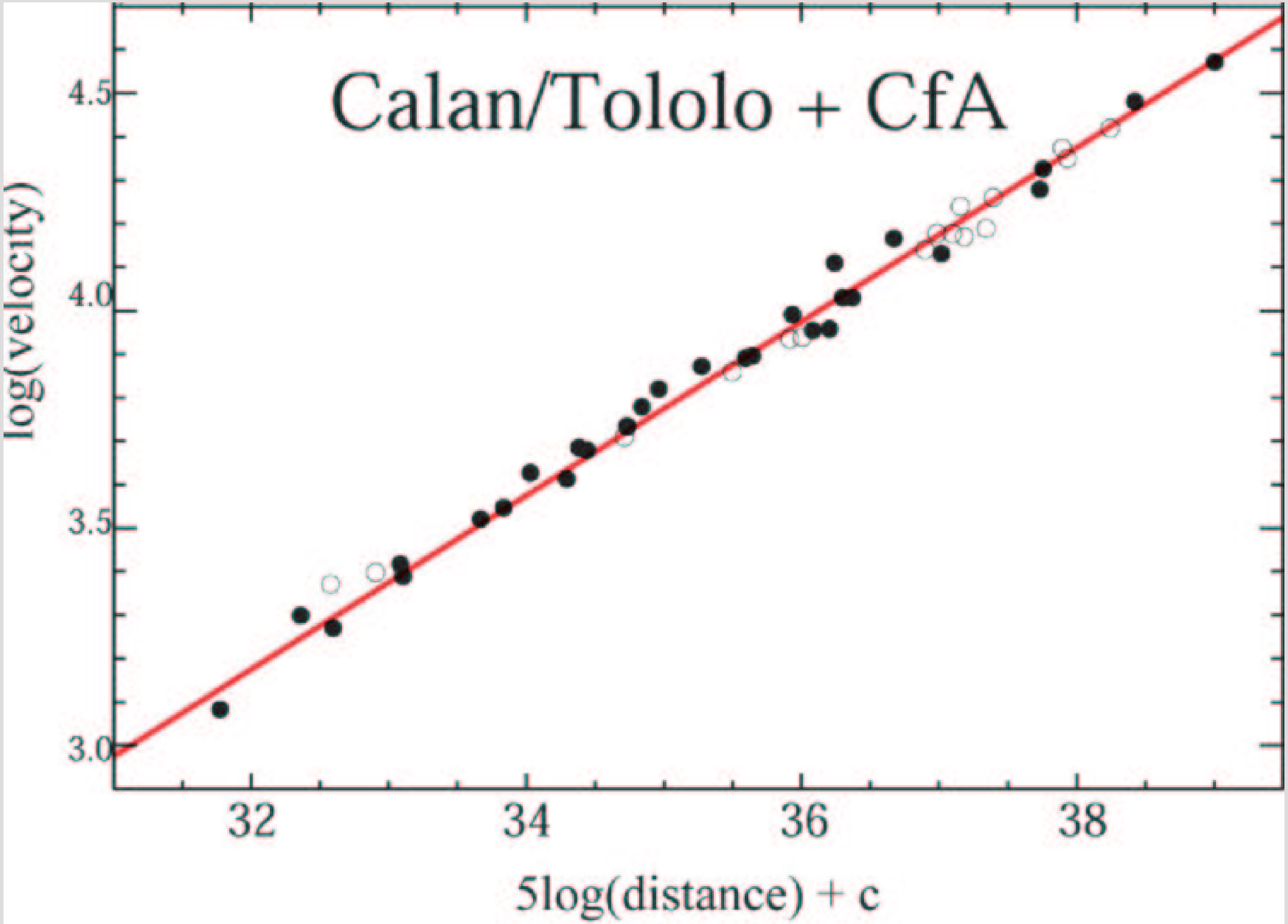


FIG. 9. *The Formulation of the Velocity-Distance Relation.*

A modern Hubble diagram



Universal expansion



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**

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 (1942)

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

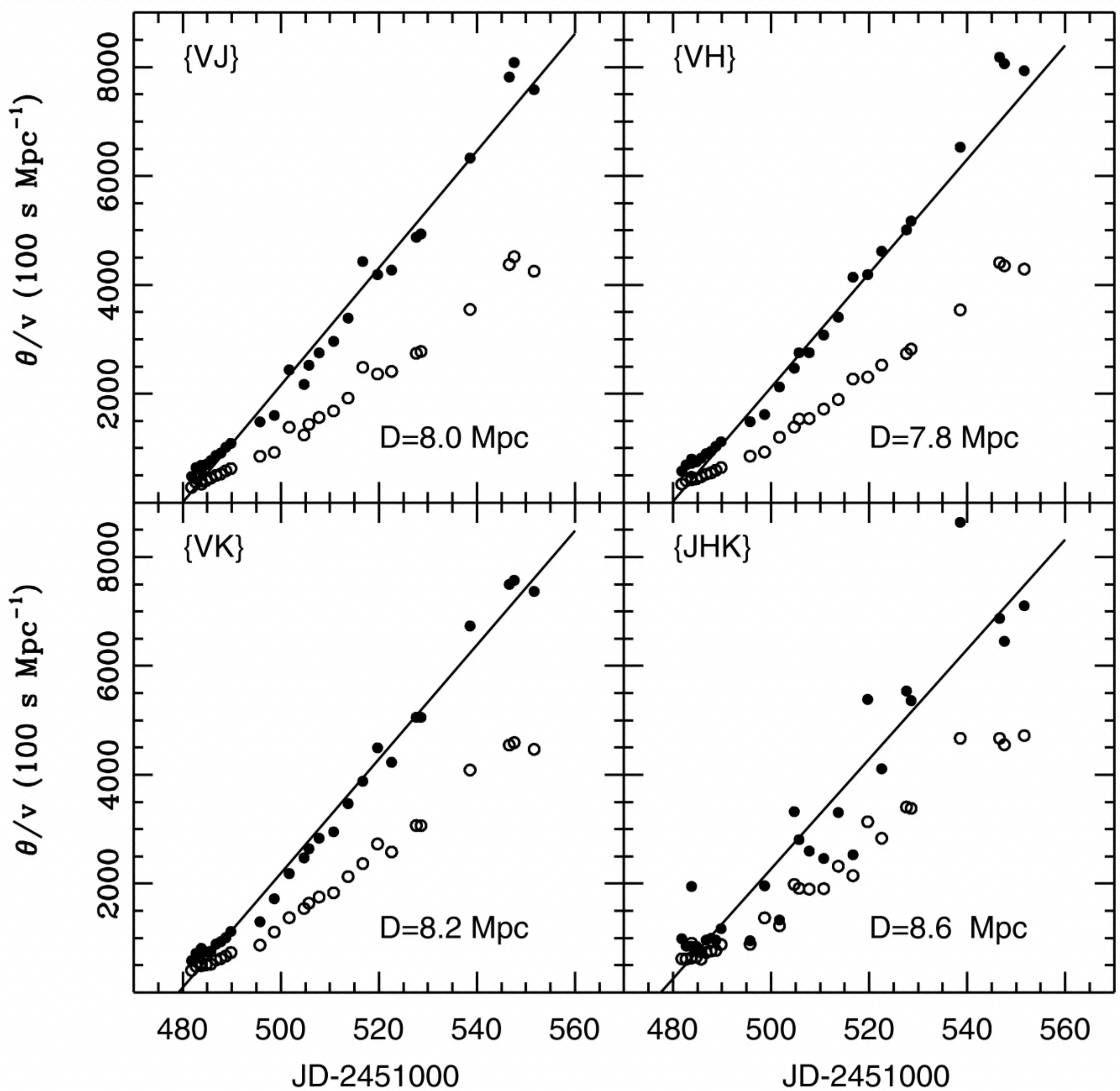
Assume homologous expansion

$$R(t)=R_0+v(t-t_0)$$

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



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

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

Distances with Type Ia Supernovae

Use the Hubble diagram (*m-M vs.* log *z*)

$$m\text{-}M=5\log(z)+25+5\log(c)-5\log(H_0)$$

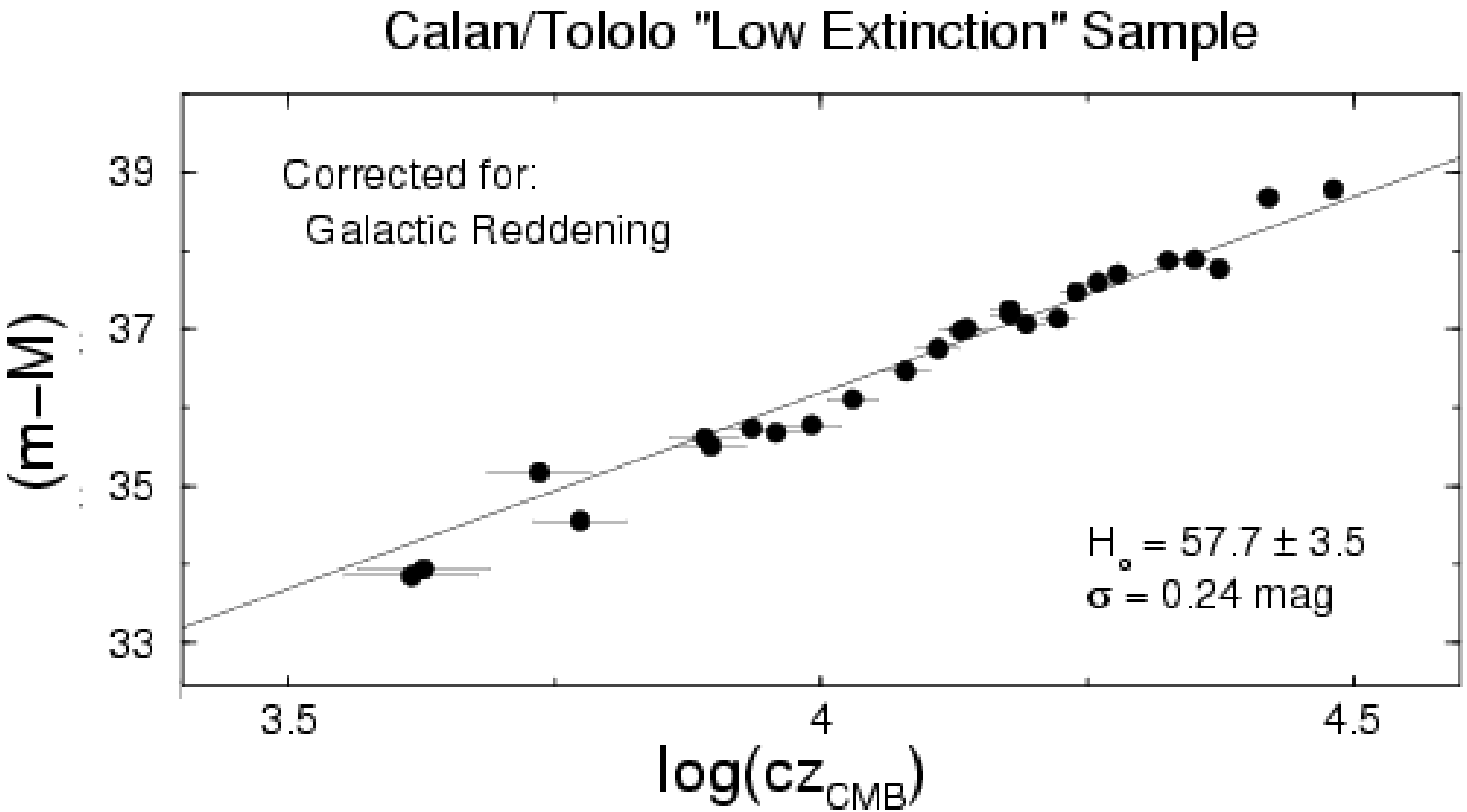
Note that the slope is given here.

Hubble constant can be derived when the absolute luminosity *M* is known

$$\log H_0=\log(z)+5+\log(c)-0.2(m\text{-}M)$$

Nearby SNe Ia

Phillips et al. (1999)



Hubble constant from SNe Ia

Calibrate the absolute luminosity

- **through Cepheids**
  - ‘classical distance ladder’
    - depends on the accuracy of the previous rungs on the ladder
    - LMC distance, P-L(-C) relation, metalicities
  - HST program (Sandage, Tammann)
  - HST Key Programme (Freedman, Kennicutt, Mould)
- **through models**
  - extremely difficult

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

Absolute Magnitudes of SNe Ia

SN	Galaxy	m-M	M_B	M_V	M_I	Δm_{15}
1937C	IC 4182	28.36 (12)	-19.56 (15)	-19.54 (17)	-	0.87 (10)
1960F	NGC 4496A	31.03 (10)	-19.56 (18)	-19.62 (22)	-	1.06 (12)
1972E	NGC 5253	28.00 (07)	-19.64 (16)	-19.61 (17)	-19.27 (20)	0.87 (10)
1974G	NGC 4414	31.46 (17)	-19.67 (34)	-19.69 (27)	-	1.11 (06)
1981B	NGC 4536	31.10 (12)	-19.50 (18)	-19.50 (16)	-	1.10 (07)
1989B	NGC 3627	30.22 (12)	-19.47 (18)	-19.42 (16)	-19.21 (14)	1.31 (07)
1990N	NGC 4639	32.03 (22)	-19.39 (26)	-19.41 (24)	-19.14 (23)	1.05 (05)
1998bu	NGC 3368	30.37 (16)	-19.76 (31)	-19.69 (26)	-19.43 (21)	1.08 (05)
1998aq	NGC 3982	31.72 (14)	-19.56 (21)	-19.48 (20)	-	1.12 (03)
Straight mean			-19.57 (04)	-19.55 (04)	-19.26 (0 6)	
Weighted mean			-19.56 (07)	-19.53 (06)	-19.25 (0 9)	

Saha et al. 1999

Light curve shape – luminosity

Δm_{15} relation

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

MLCS

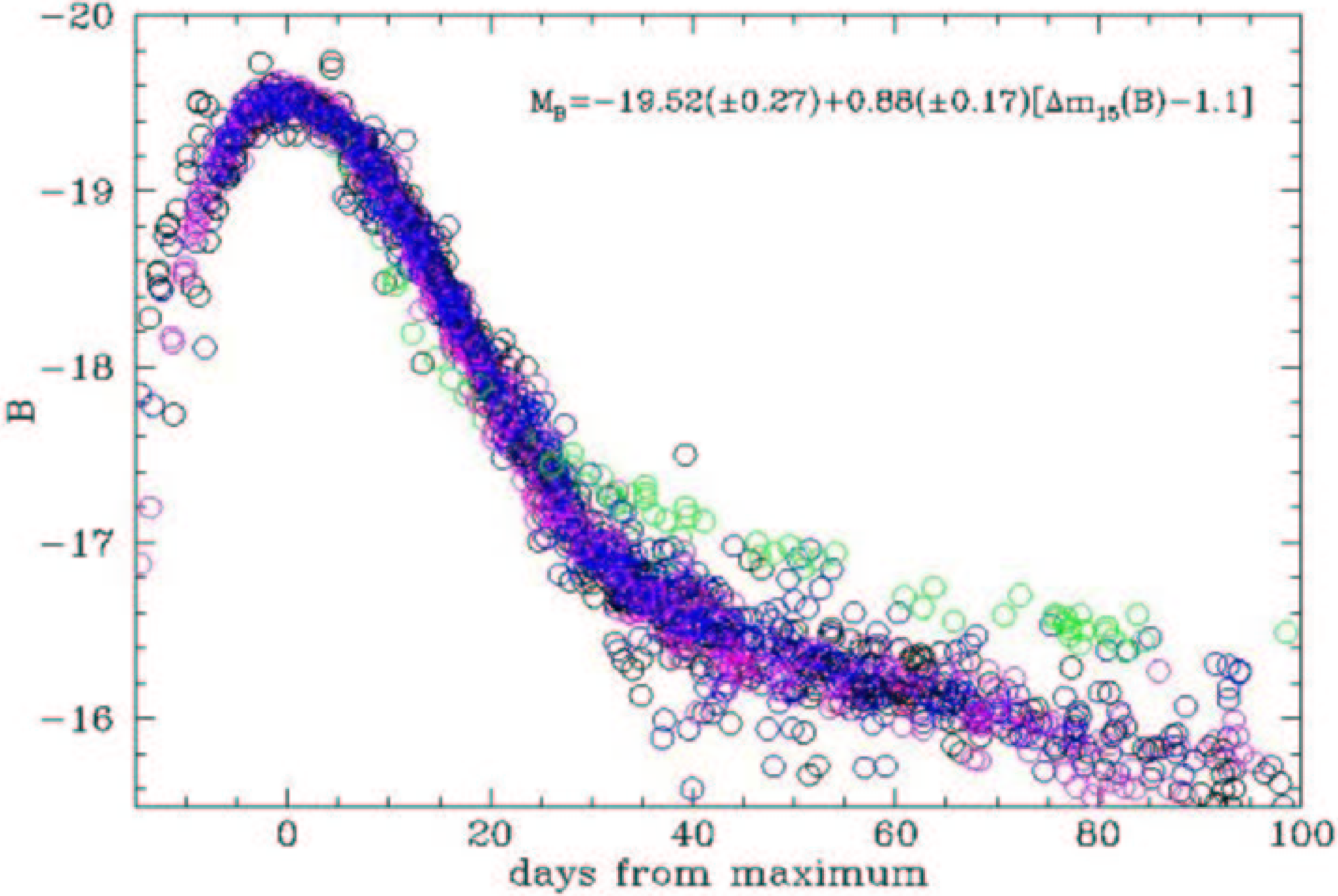
Riess et al. (1996, 1998), Jha et al. (2003)

stretch

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

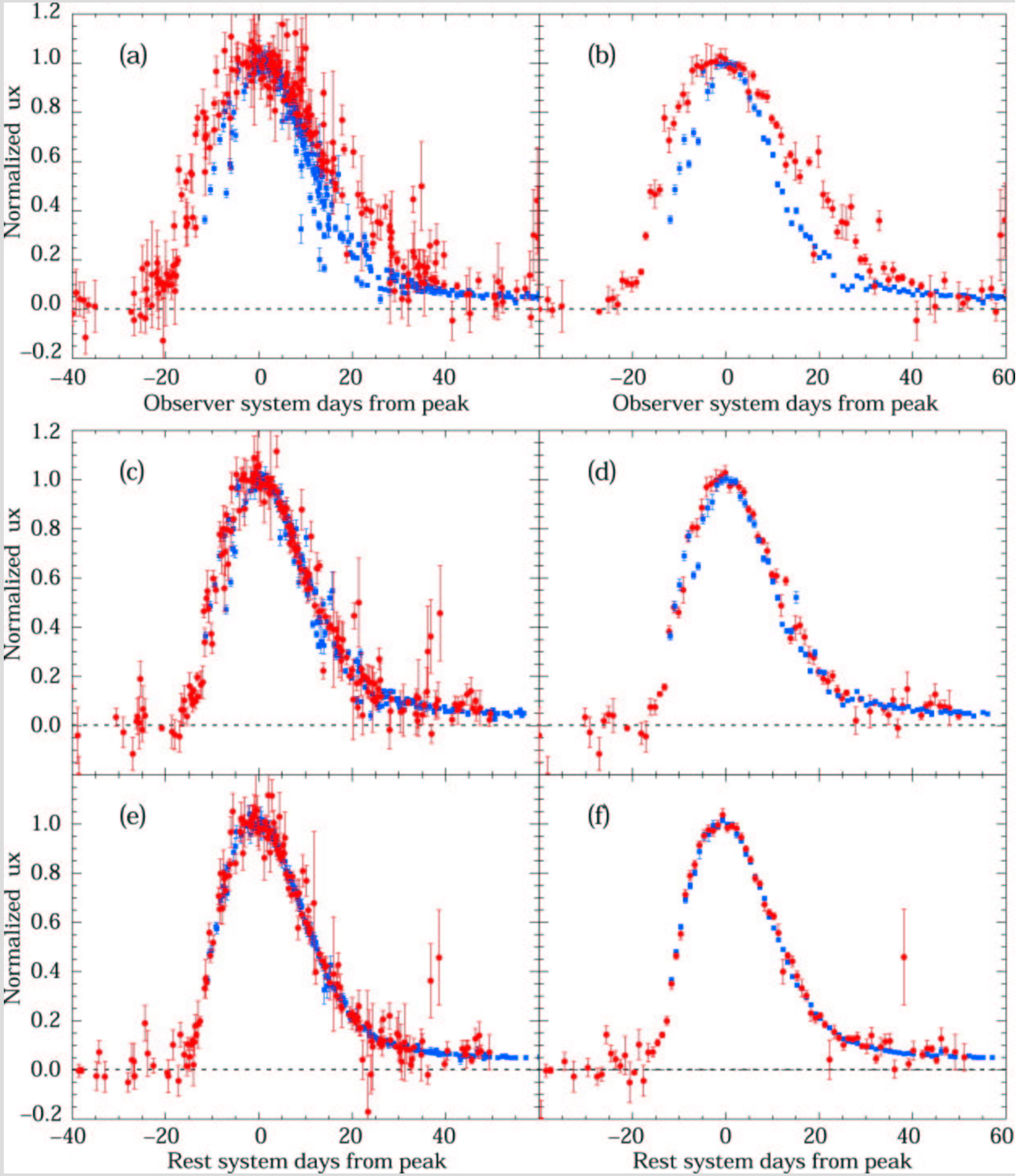
MAGIC

Wang et al. (2003)

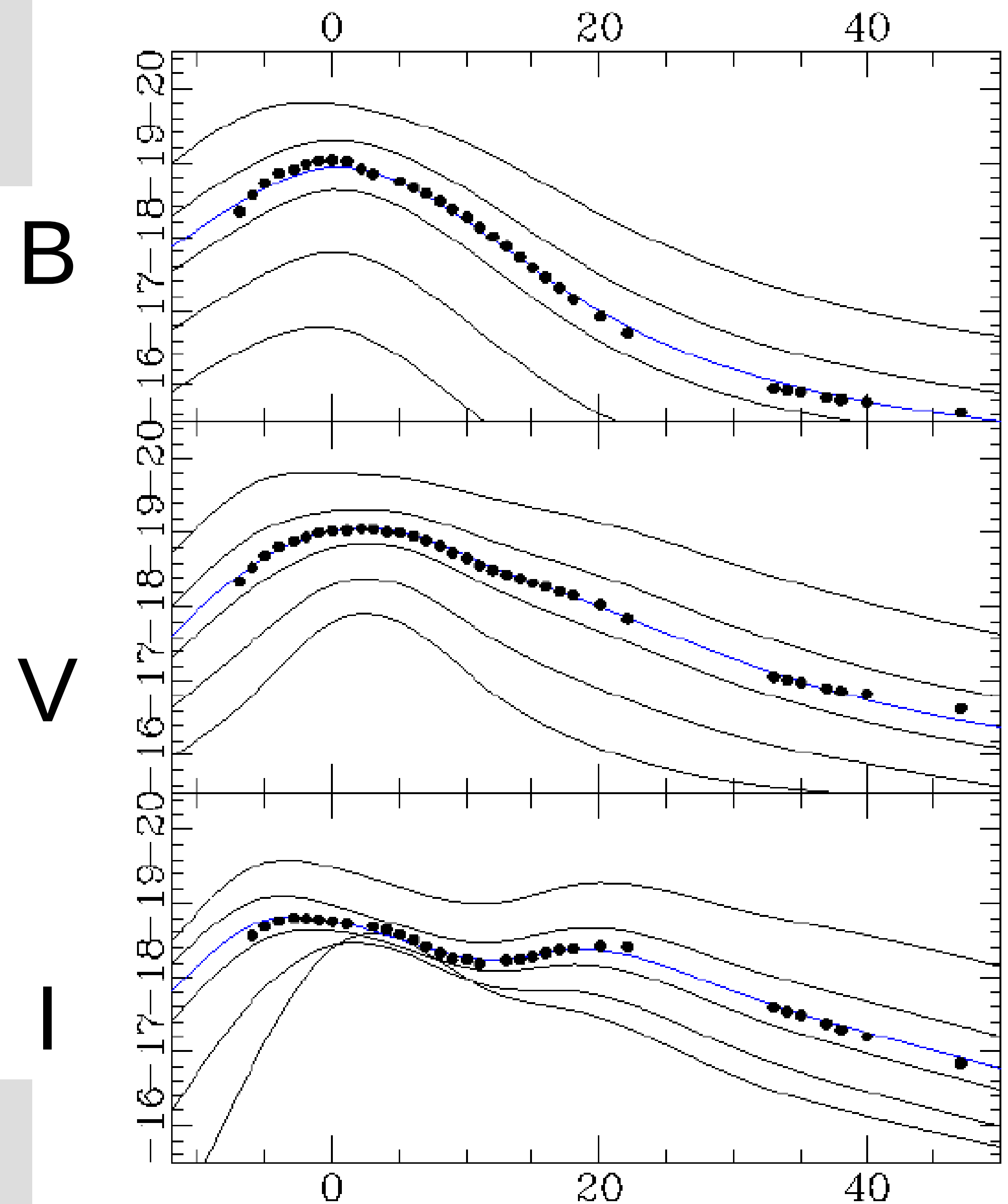


Altavilla, Thesis

The magic of the light curve shapes



Goldhaber et al. 2001

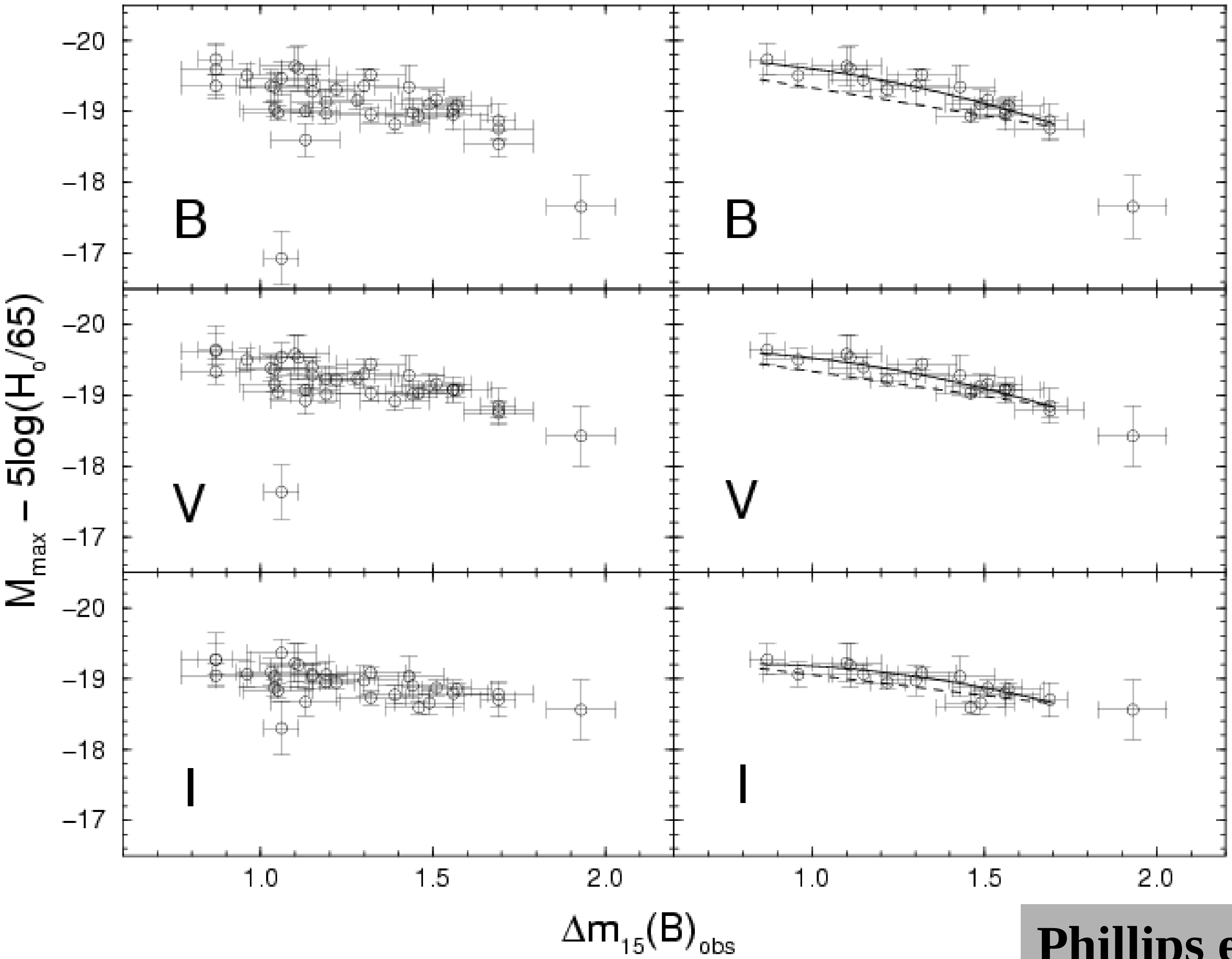


The SN Ia luminosity can be normalised

Bright = slow
Dim = fast

Riess et al. 1996

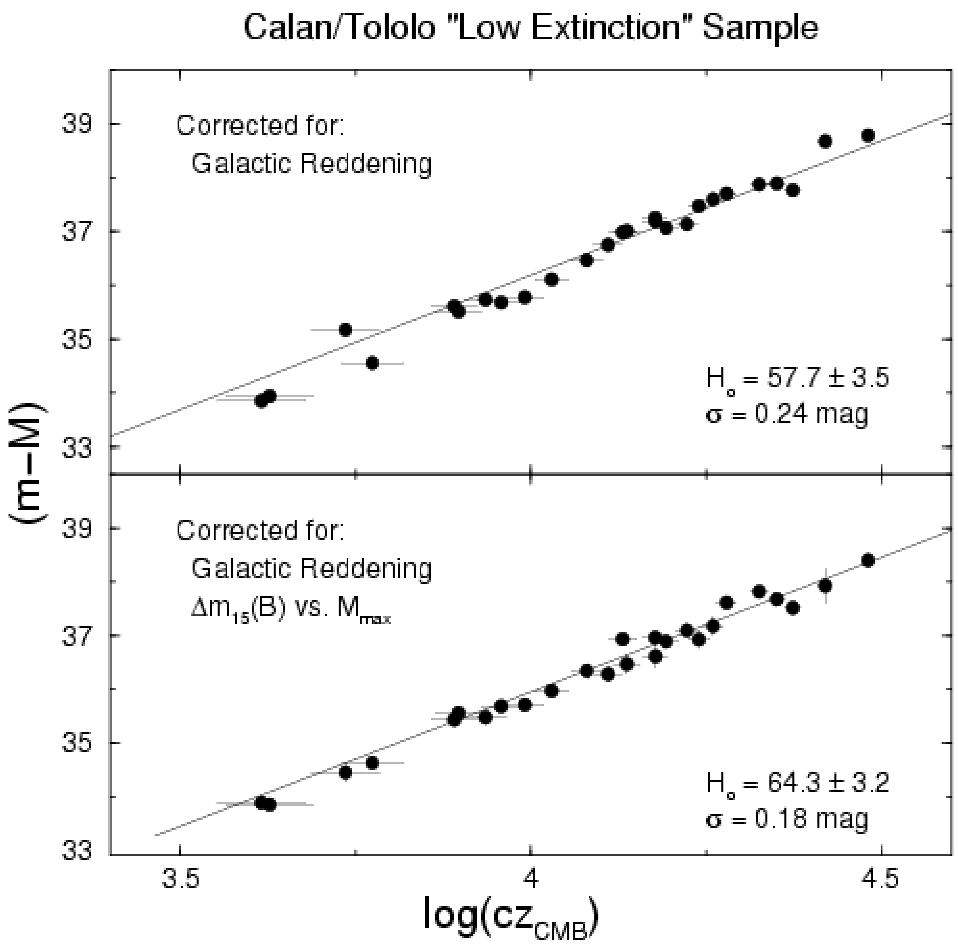
Correlations



Phillips et al. 1999

Normalisation of the peak luminosity

Phillips et al. 1999



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

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

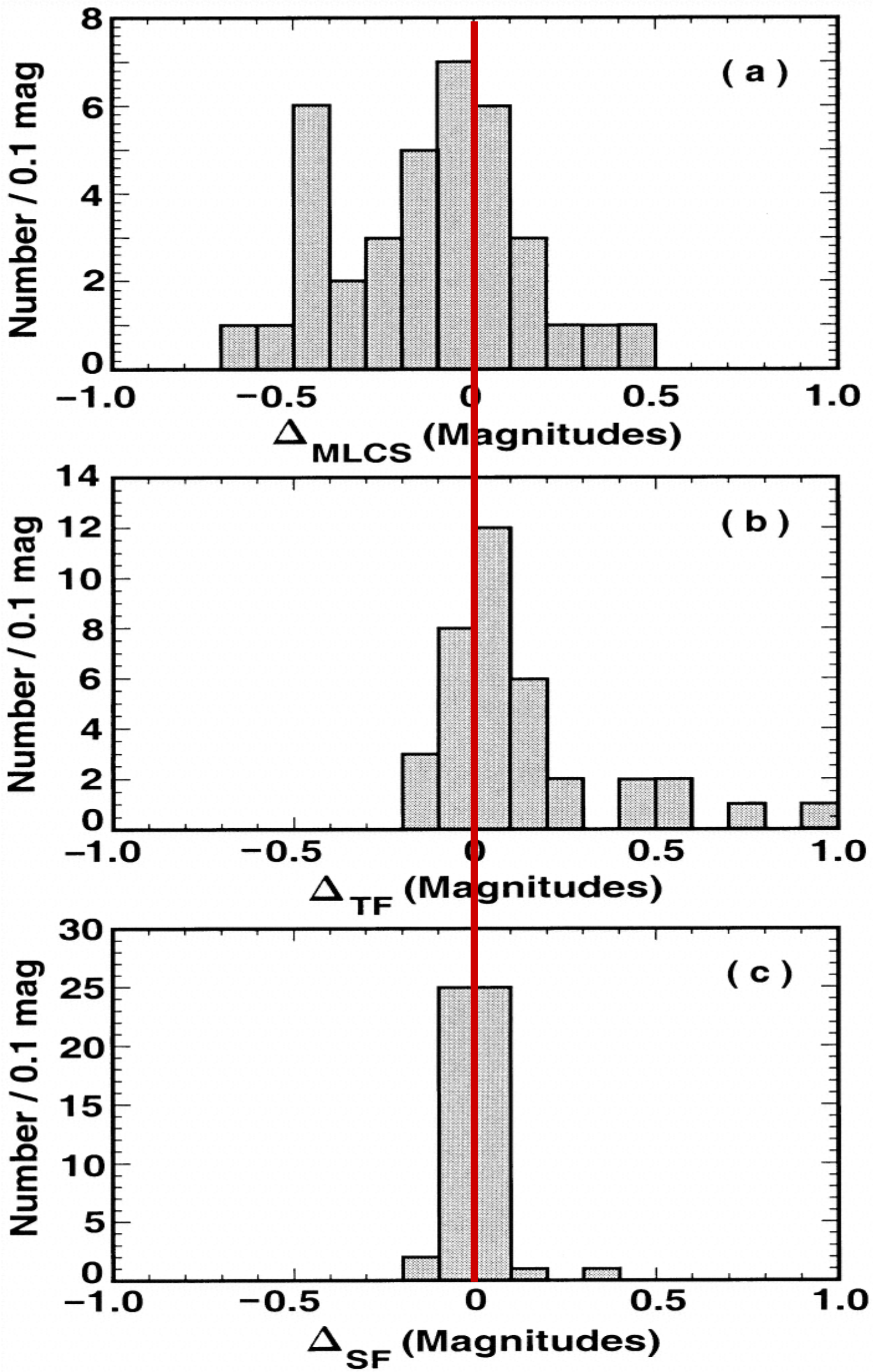
Luminosity vs. line strengths and line widths

- 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

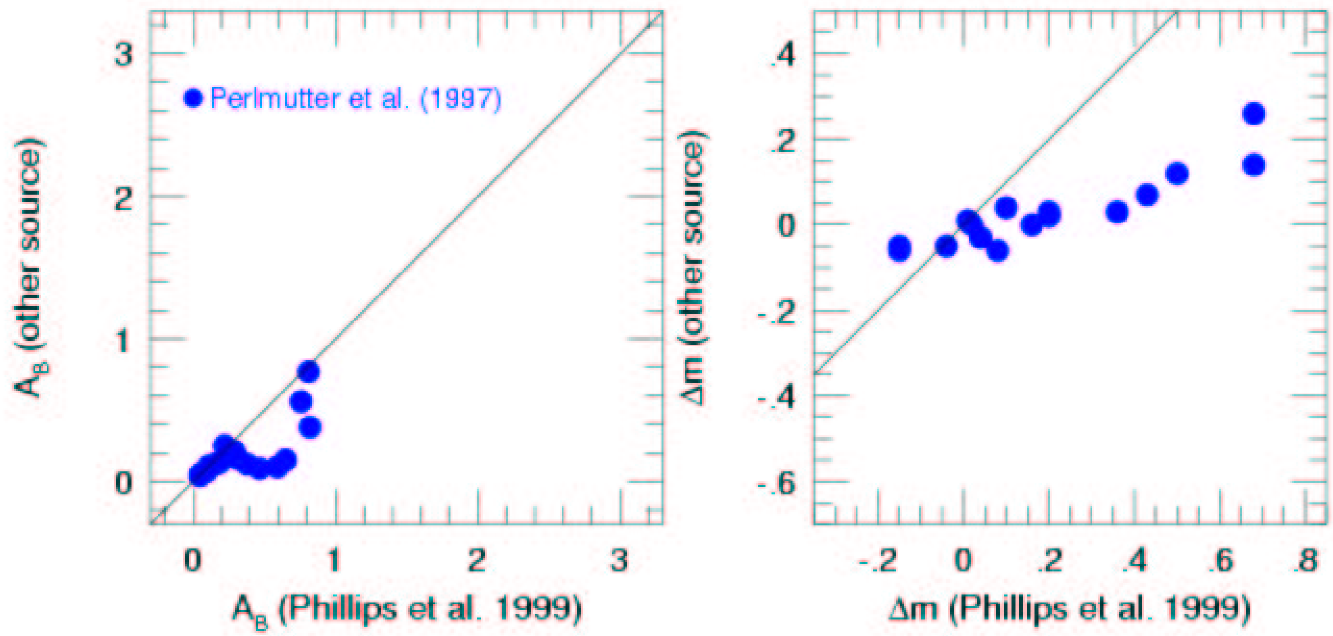
Phillips et al. 1999

Perlmutter et al. 1997

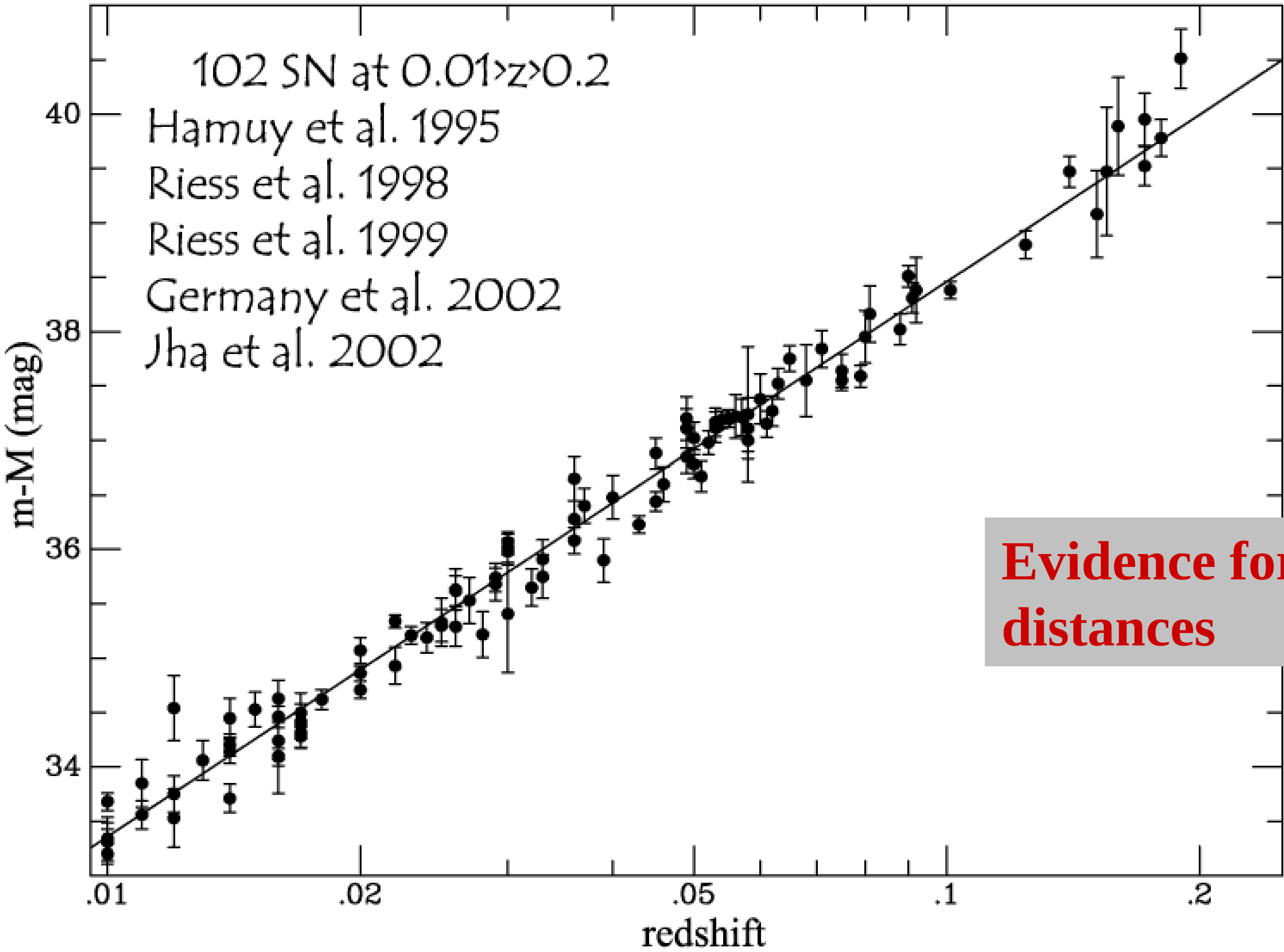
Drell et al. 2000

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 on the LMC and the Cepheid P-L relation