

Cosmology with Supernovae

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Outline

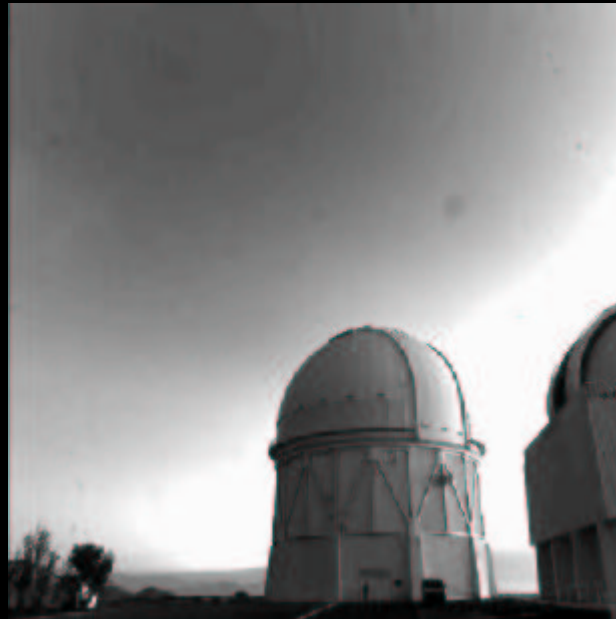
Supernova types

- **core-collapse supernovae**
- **thermonuclear supernovae**

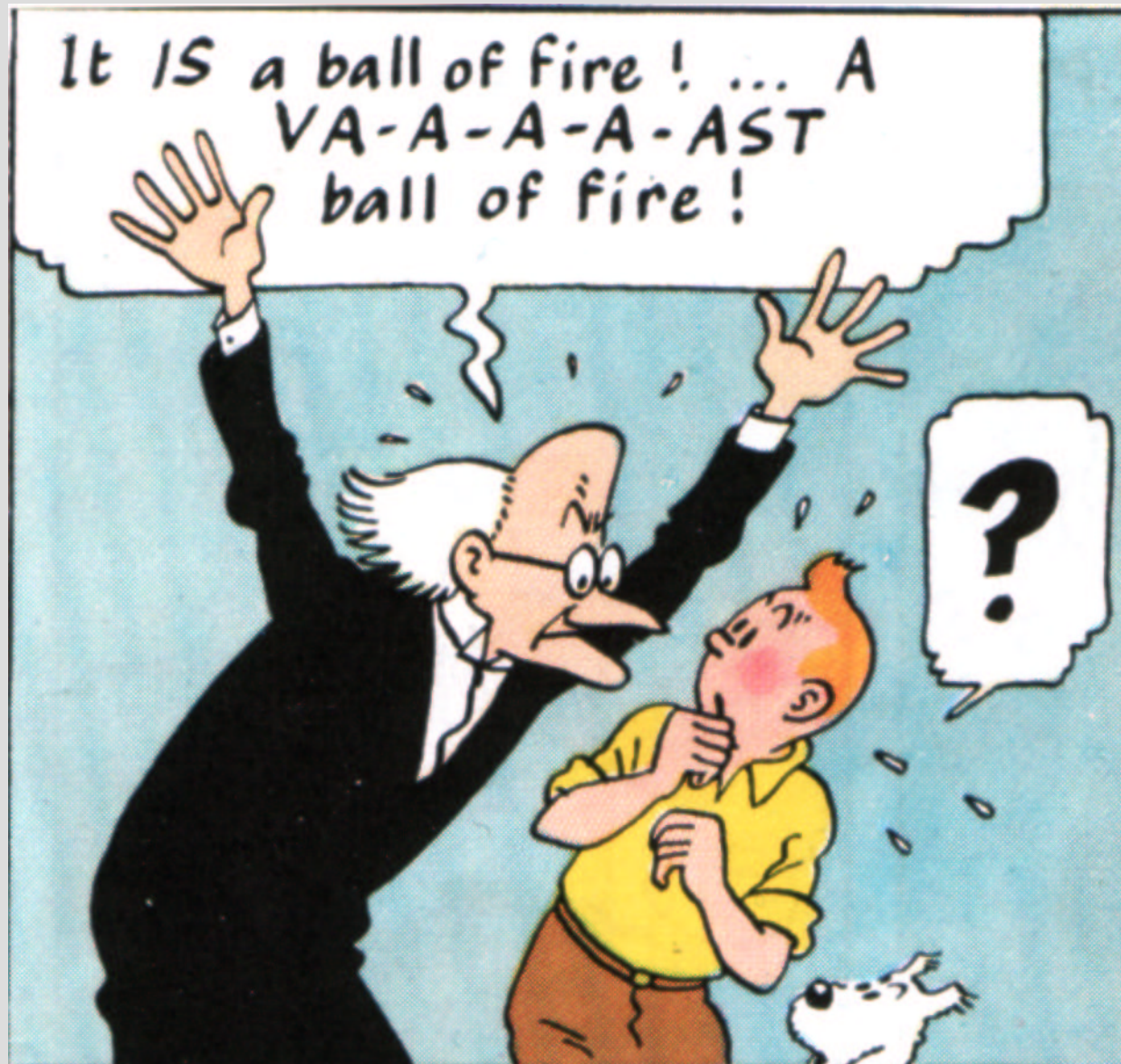
Cosmology with supernovae

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

Supernova observing



Supernovae



Supernovae

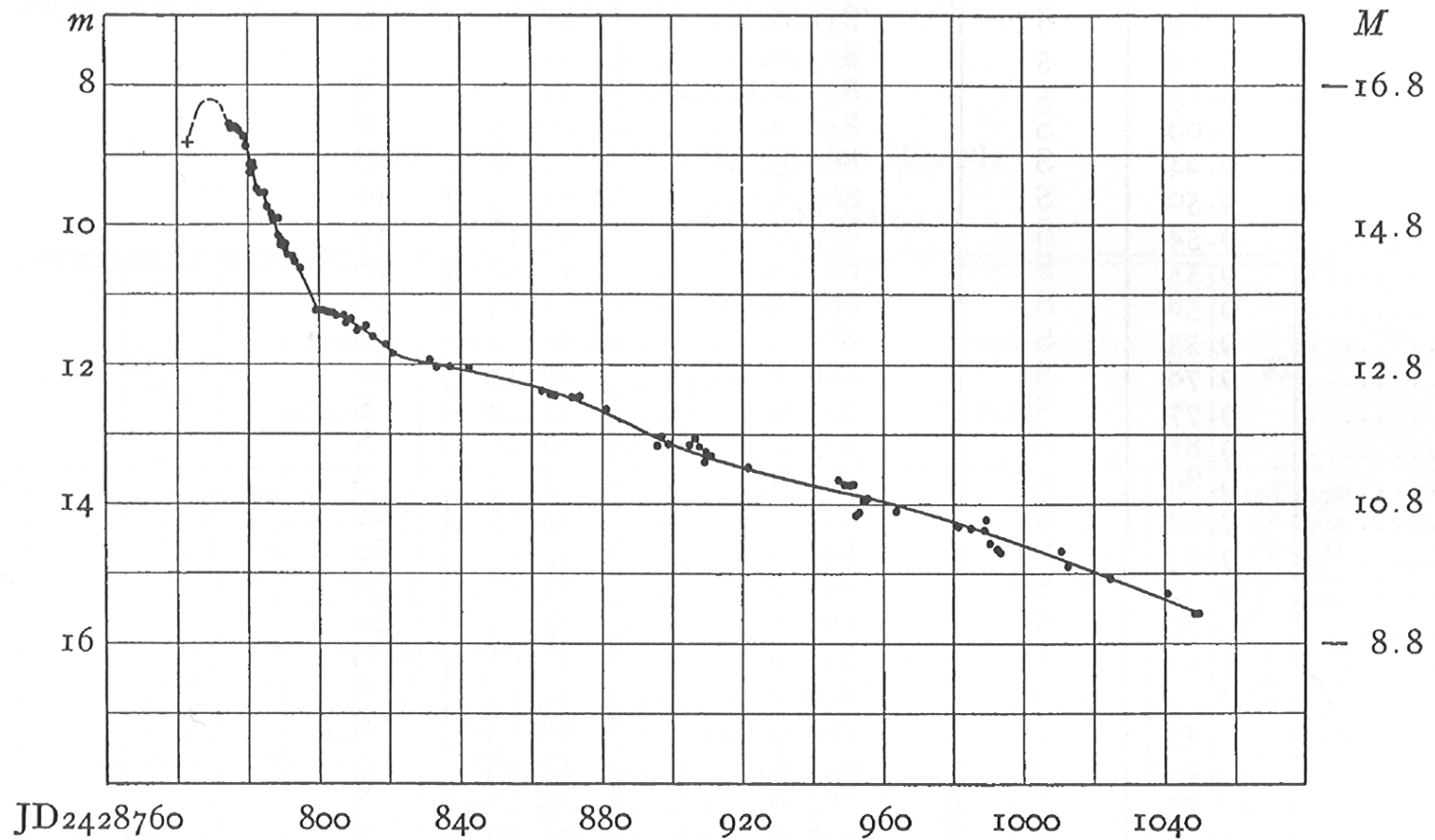


FIG. 1.—Photographic light-curve of supernova in IC 4182

Supernovae

Big Bang

Stars

PERIODIC CHART OF THE ELEMENTS

IA	IIA	IIIB	IVB	VB	VIB	VII	VIII	IX	X	XI	XII	IIIA	IVA	VA	VIA	VIIA	VIIIA	GASES					
1 H 1.00794																	1 H 1.00794	2 He 4.00260					
3 Li 6.941	4 Be 9.0122																	5 B 10.811	6 C 12.0112	7 N 14.0067	8 O 15.9994	9 F 18.9984	10 Ne 20.183
11 Na 22.9897	12 Mg 24.305																	13 Al 26.9815	14 Si 28.0855	15 P 30.9738	16 S 32.065	17 Cl 35.453	18 Ar 39.948
19 K 39.0983	20 Ca 40.078	21 Sc 44.9559	22 Ti 47.88	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.847	27 Co 58.9332	28 Ni 58.71	29 Cu 63.546	30 Zn 65.38	31 Ga 69.723	32 Ge 72.63	33 As 74.9216	34 Se 78.96	35 Br 79.904	36 Kr 83.80						
37 Rb 85.47	38 Sr 87.62	39 Y 88.905	40 Zr 91.224	41 Nb 92.906	42 Mo 95.94	43 Tc 98	44 Ru 101.07	45 Rh 102.905	46 Pd 106.4	47 Ag 107.868	48 Cd 112.411	49 In 114.818	50 Sn 118.71	51 Sb 121.757	52 Te 127.6	53 I 126.905	54 Xe 131.29						
55 Cs 132.905	56 Ba 137.33	57 La 138.905	72 Hf 178.49	73 Ta 180.948	74 W 183.85	75 Re 186.207	76 Os 190.23	77 Ir 192.225	78 Pt 195.084	79 Au 196.967	80 Hg 200.59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po 209	85 At 210	86 Rn 222						
87 Fr 223	88 Ra 226	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 ?	111 ?	112 ?												

Numbers in parentheses are atomic numbers of isotopes or most common isotopes.

Most weights are corrected to carbon-12. The 1963 values of the Commission on Atomic Weights.

The group designations at the top are the former Chemical Abstract Service numbers.

Lanthanide Series

58 Ce 140.12	59 Pr 140.907	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.925	66 Dy 162.50	67 Ho 164.930	68 Er 167.26	69 Tm 168.930	70 Yb 173.054	71 Lu 174.967
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Actinide Series

90 Th 232.038	91 Pa (231)	92 U 238.029	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (260)
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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)

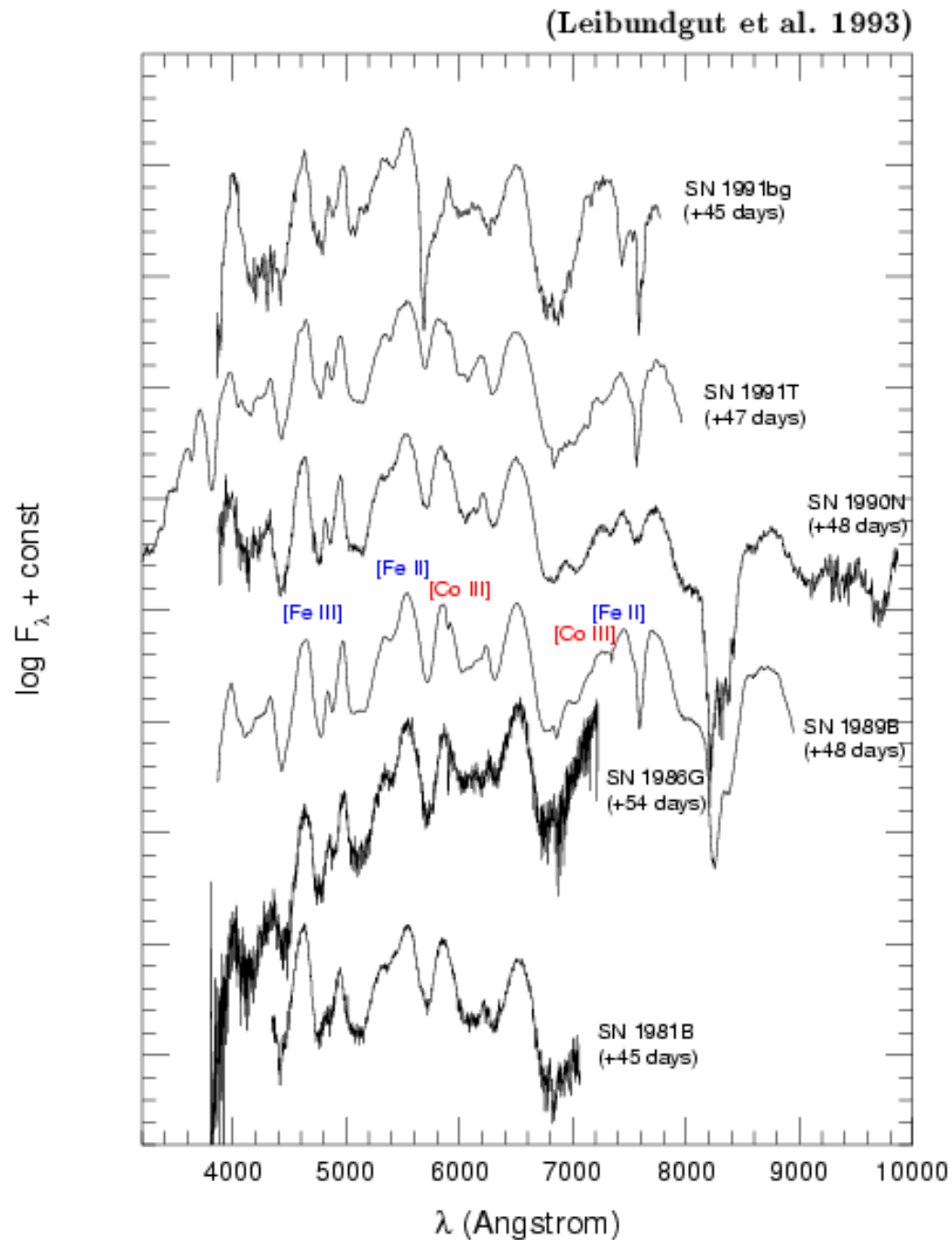
Hypernovae/GRBs

SN Ia (no H)

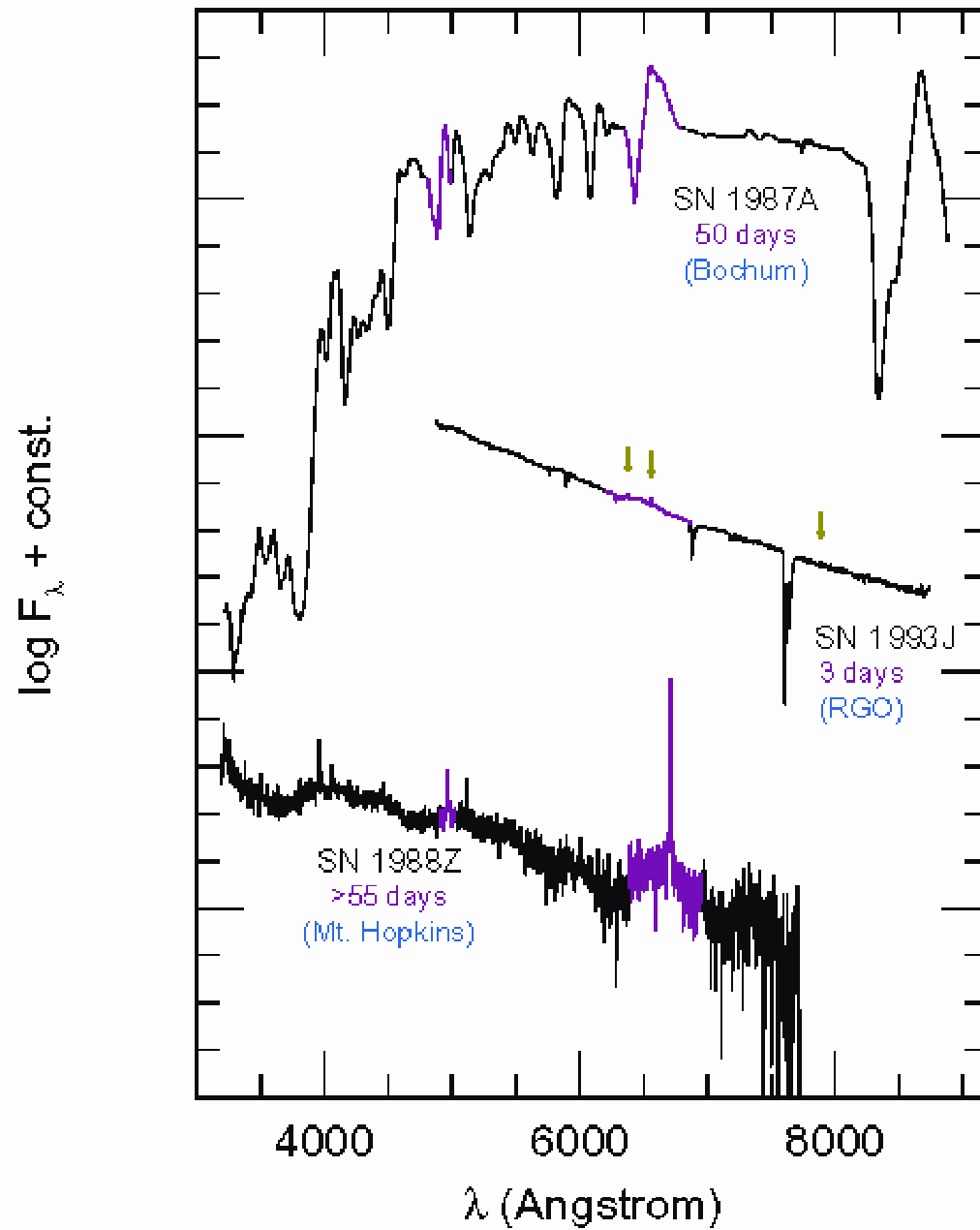
**thermonuclear
explosions**

Supernova Spectroscopy

Type Ia



Type II Supernovae



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

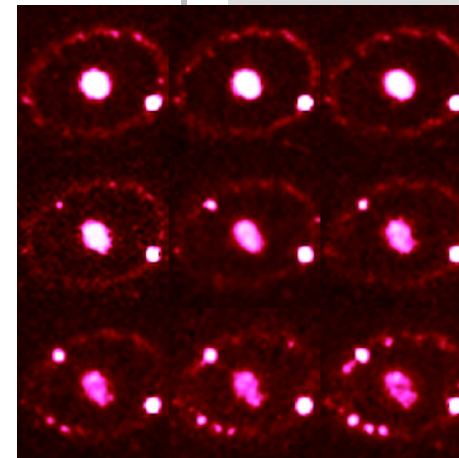
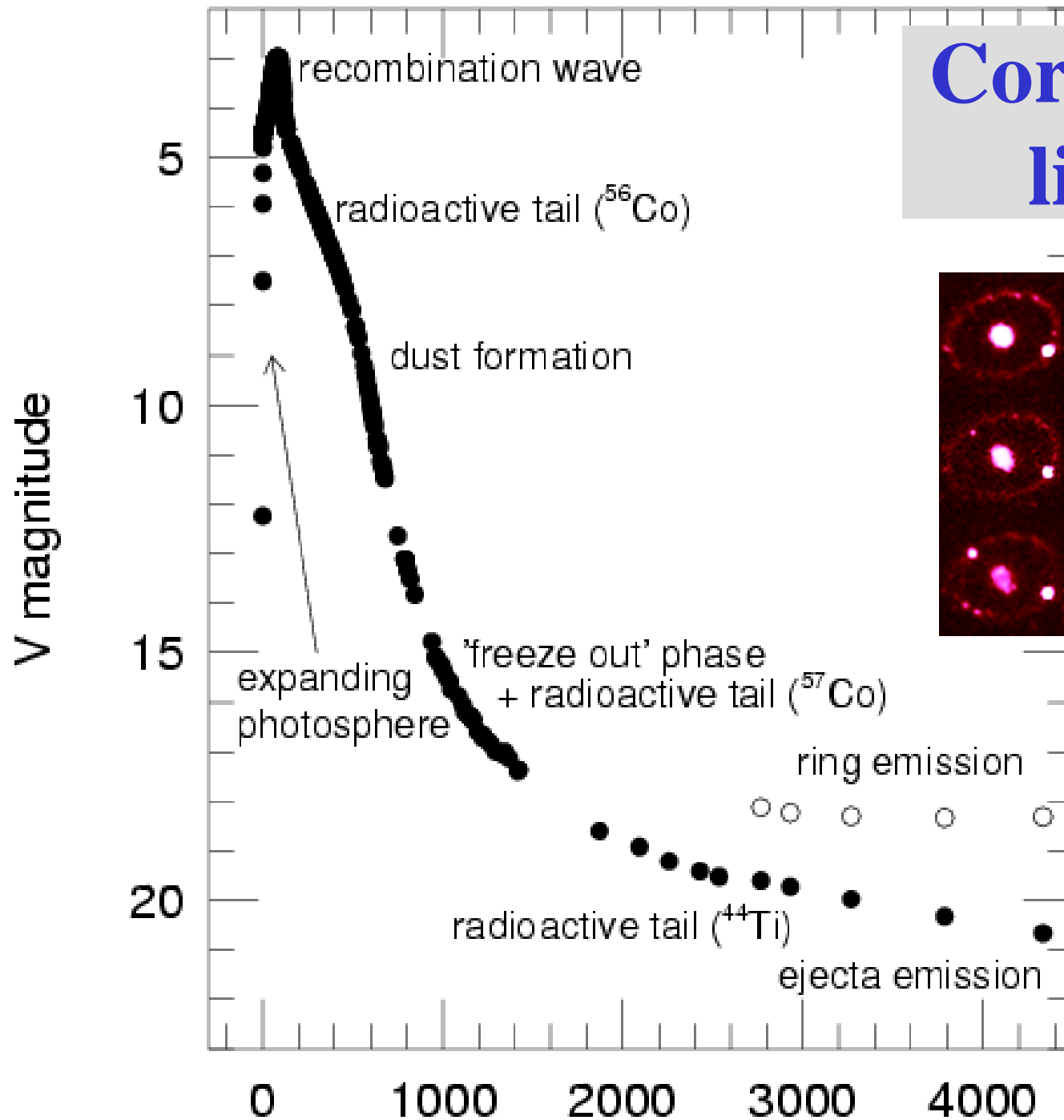
environmental effects

progenitor systems

remnants

distance determinations and cosmology

Core collapse light curve

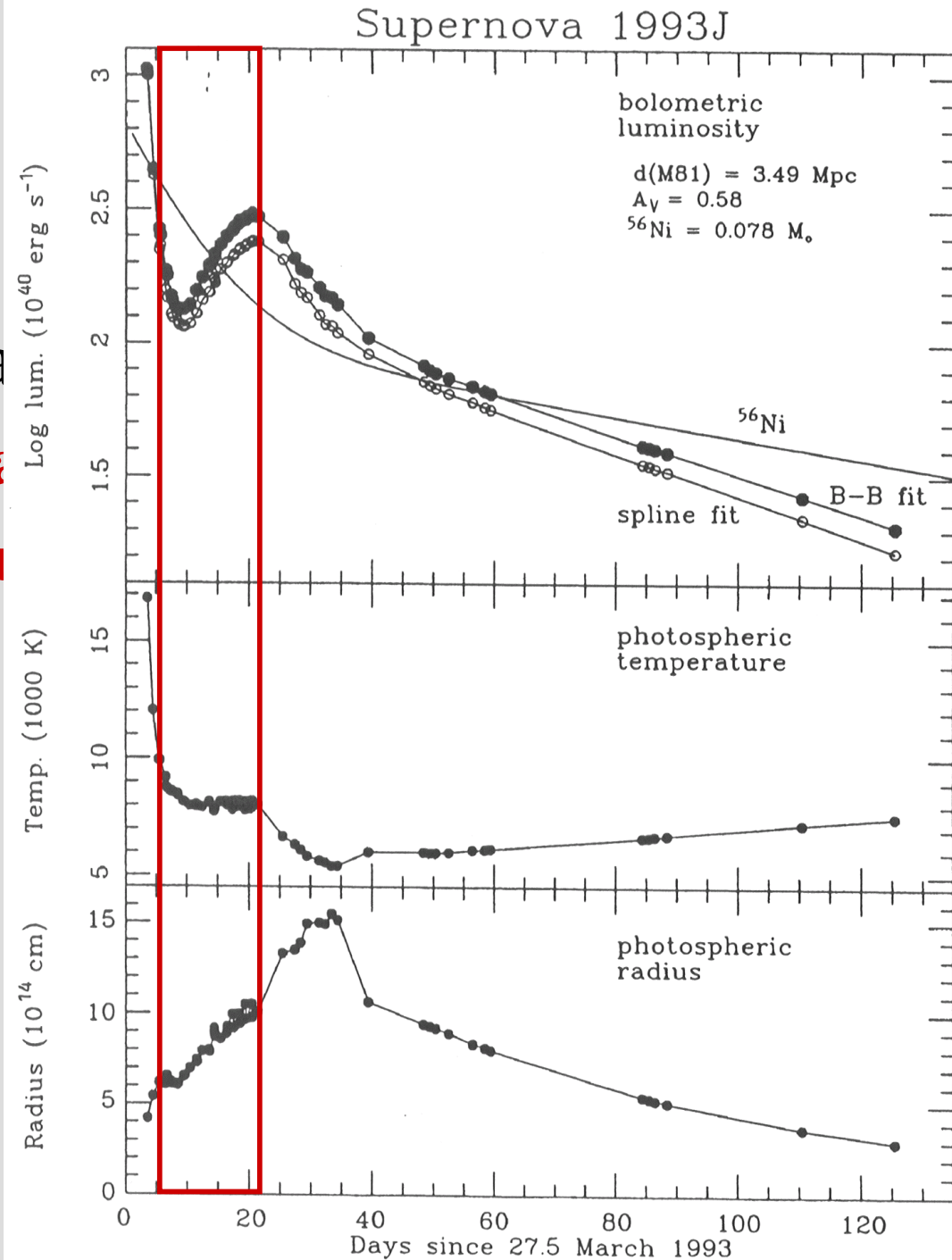


Suntzeff (2003)

Expansion

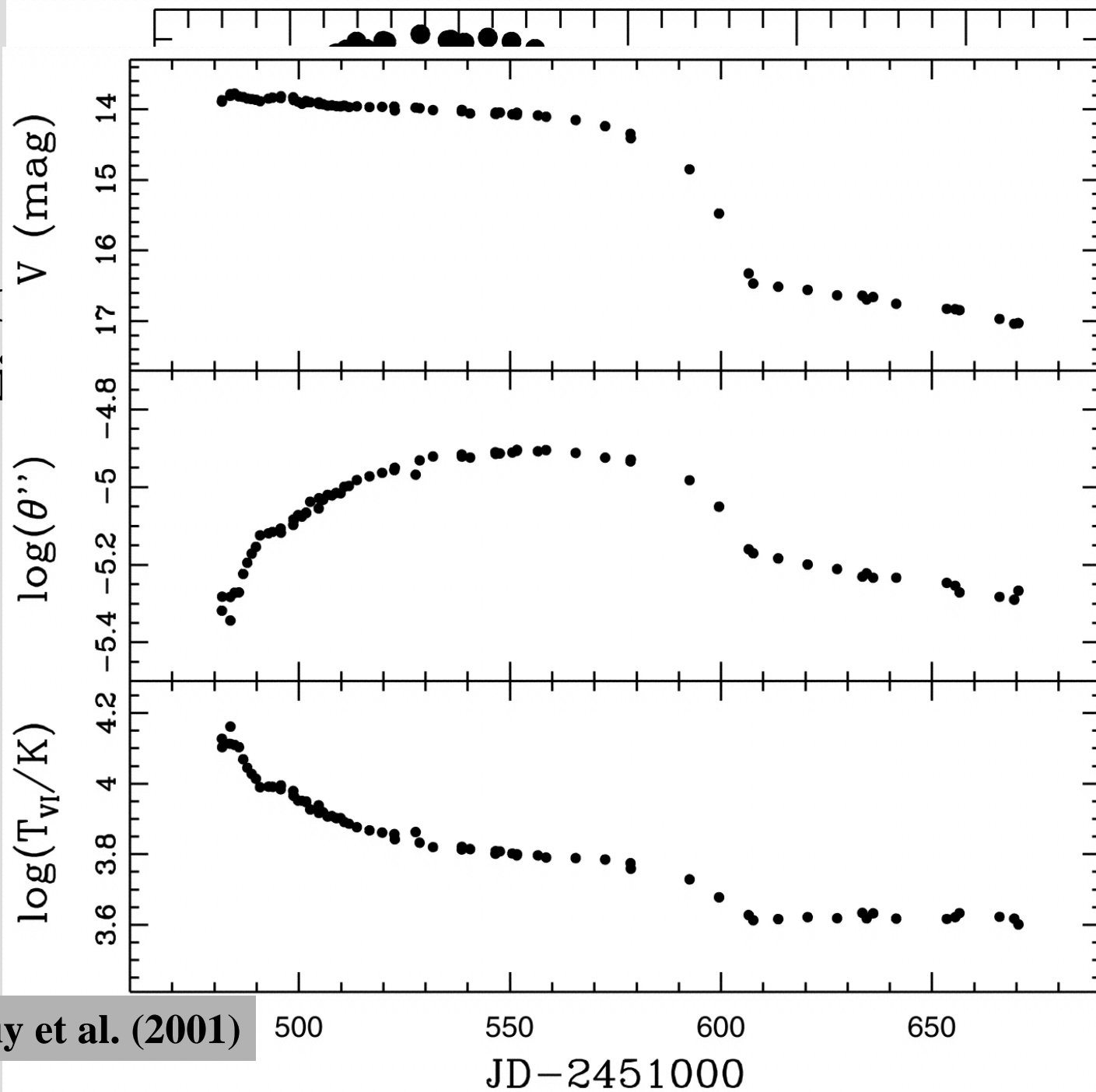
Brightness increase

- increased surface area
- slow temperature decrease

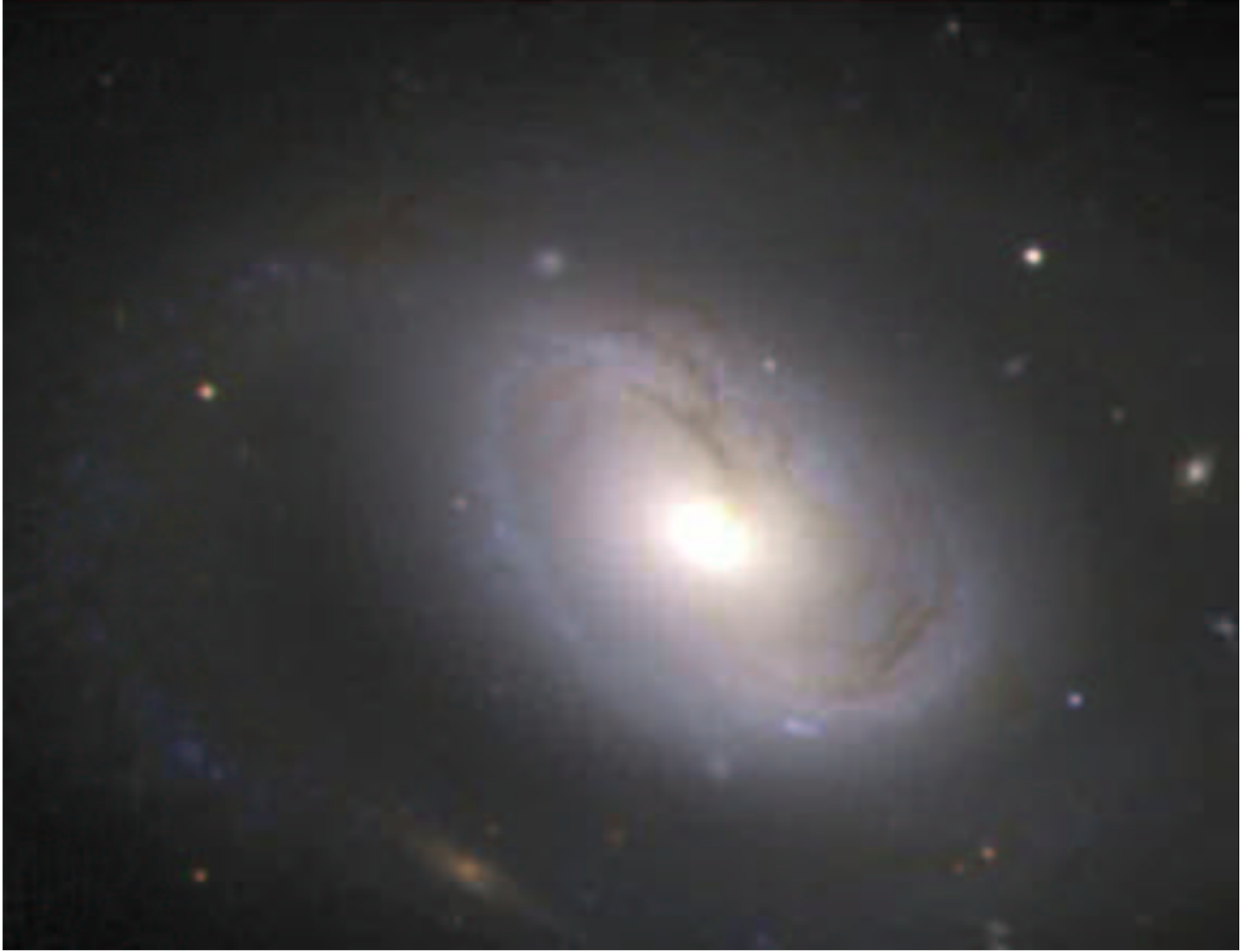
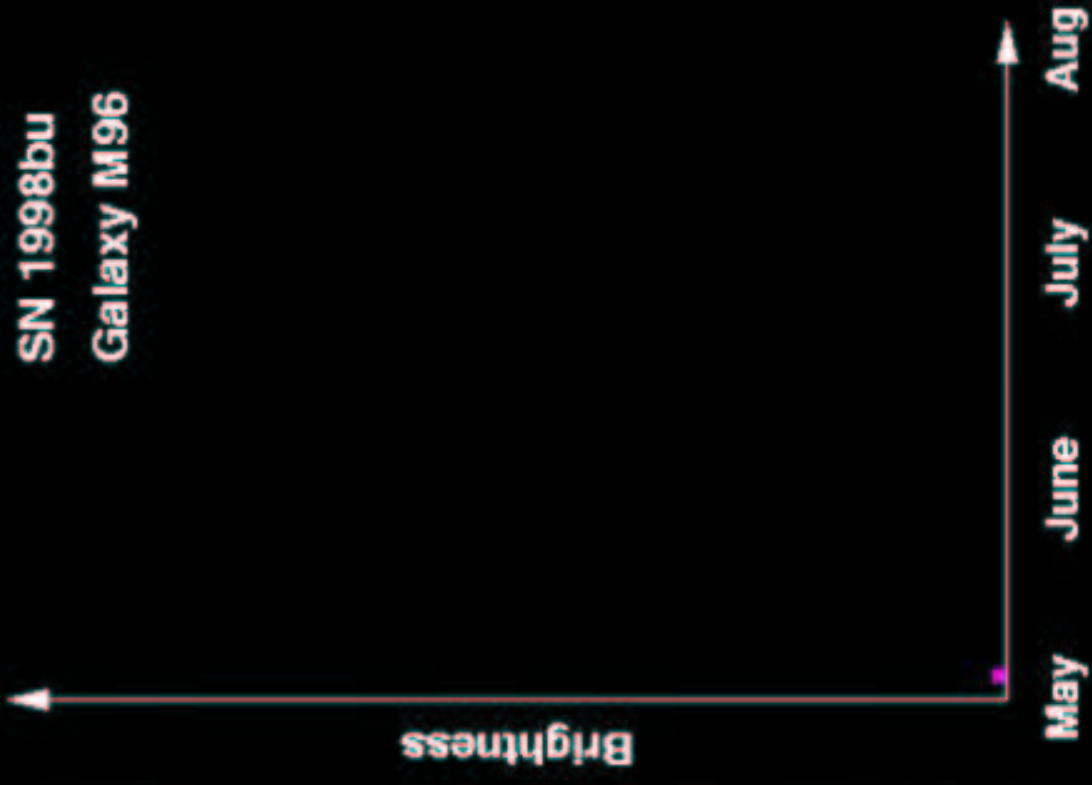


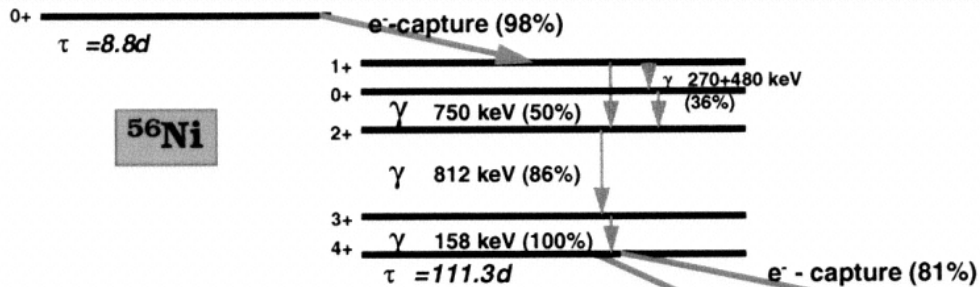
Balance of expansion

- leads



SN 1998bu
Galaxy M96

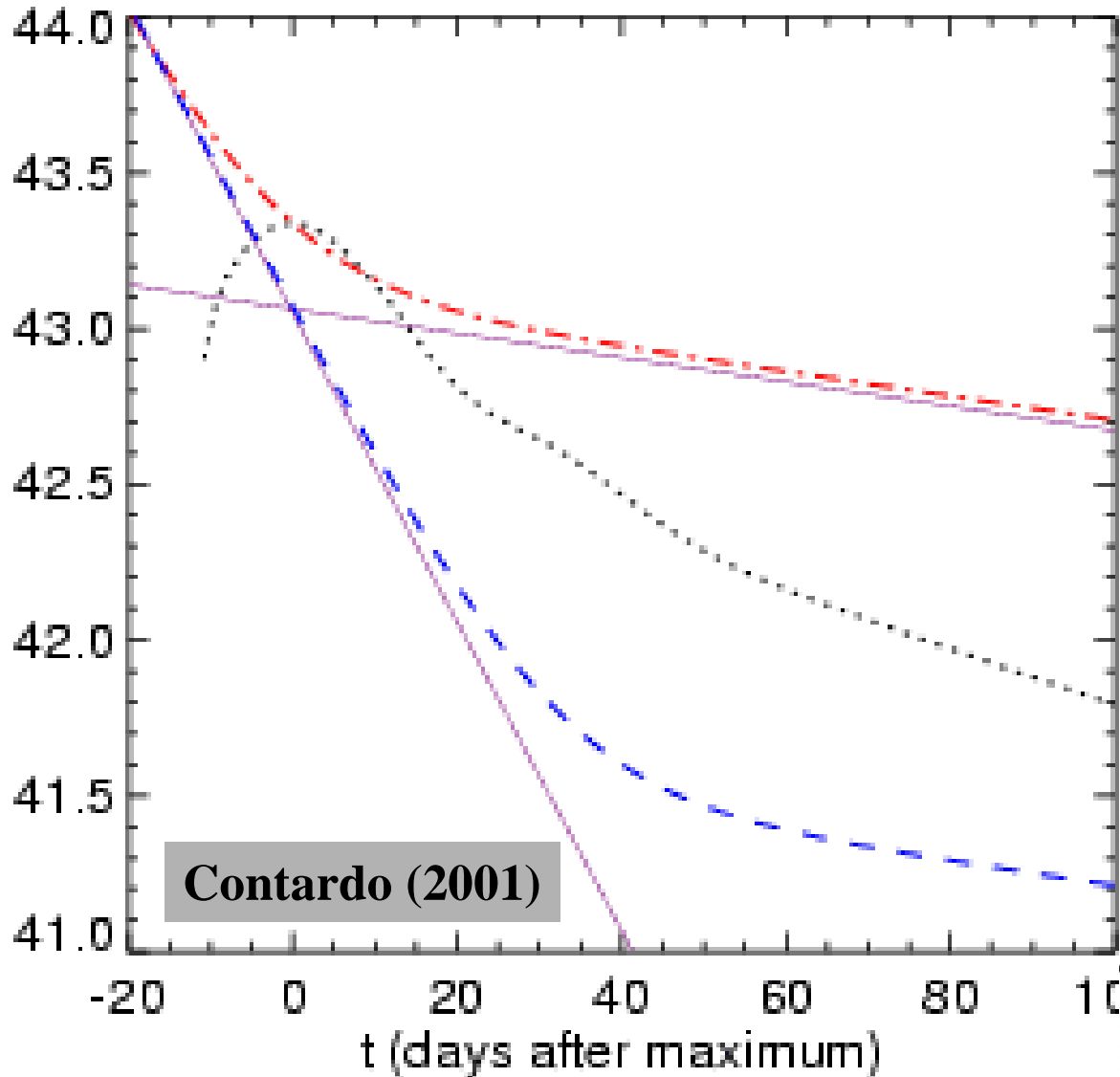




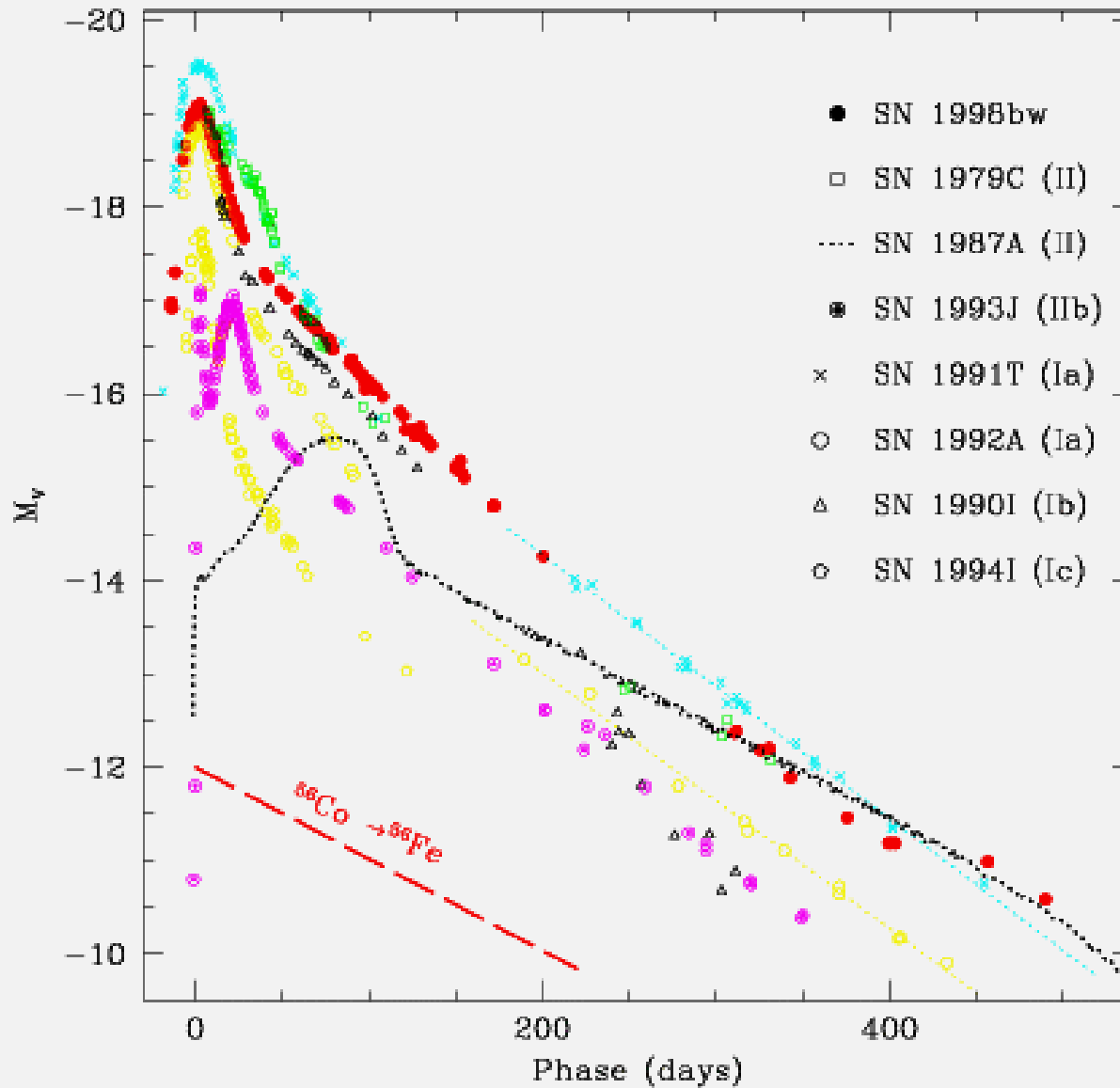
Radioactivity

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

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

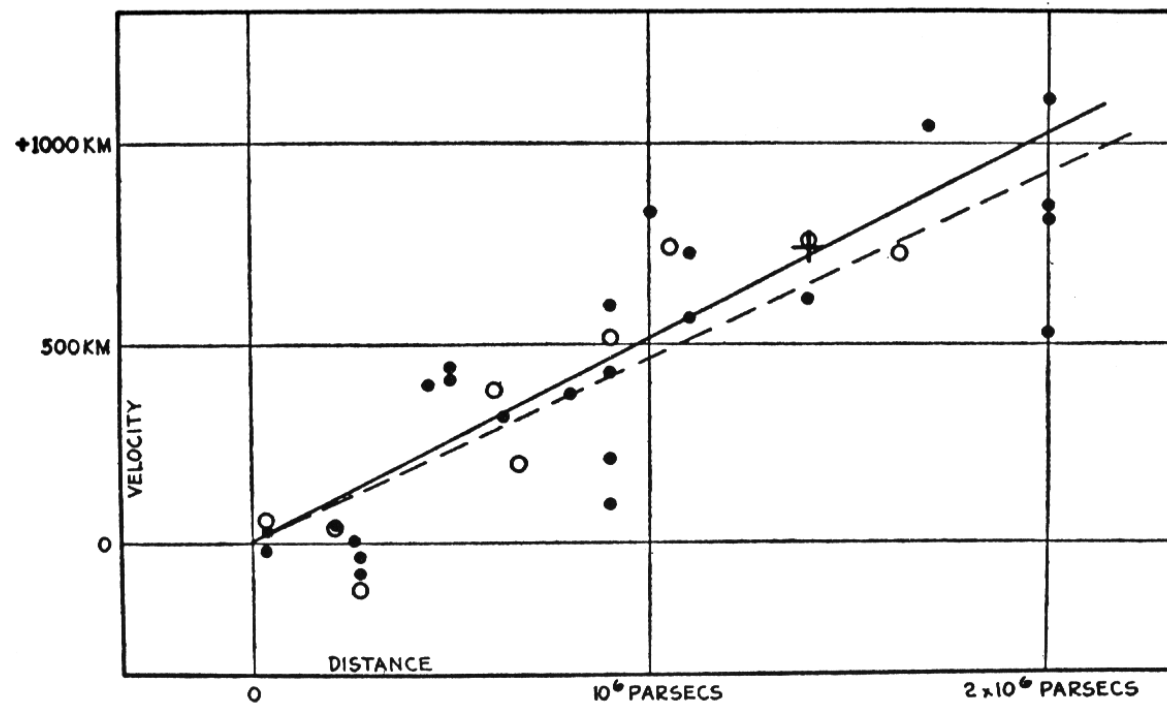
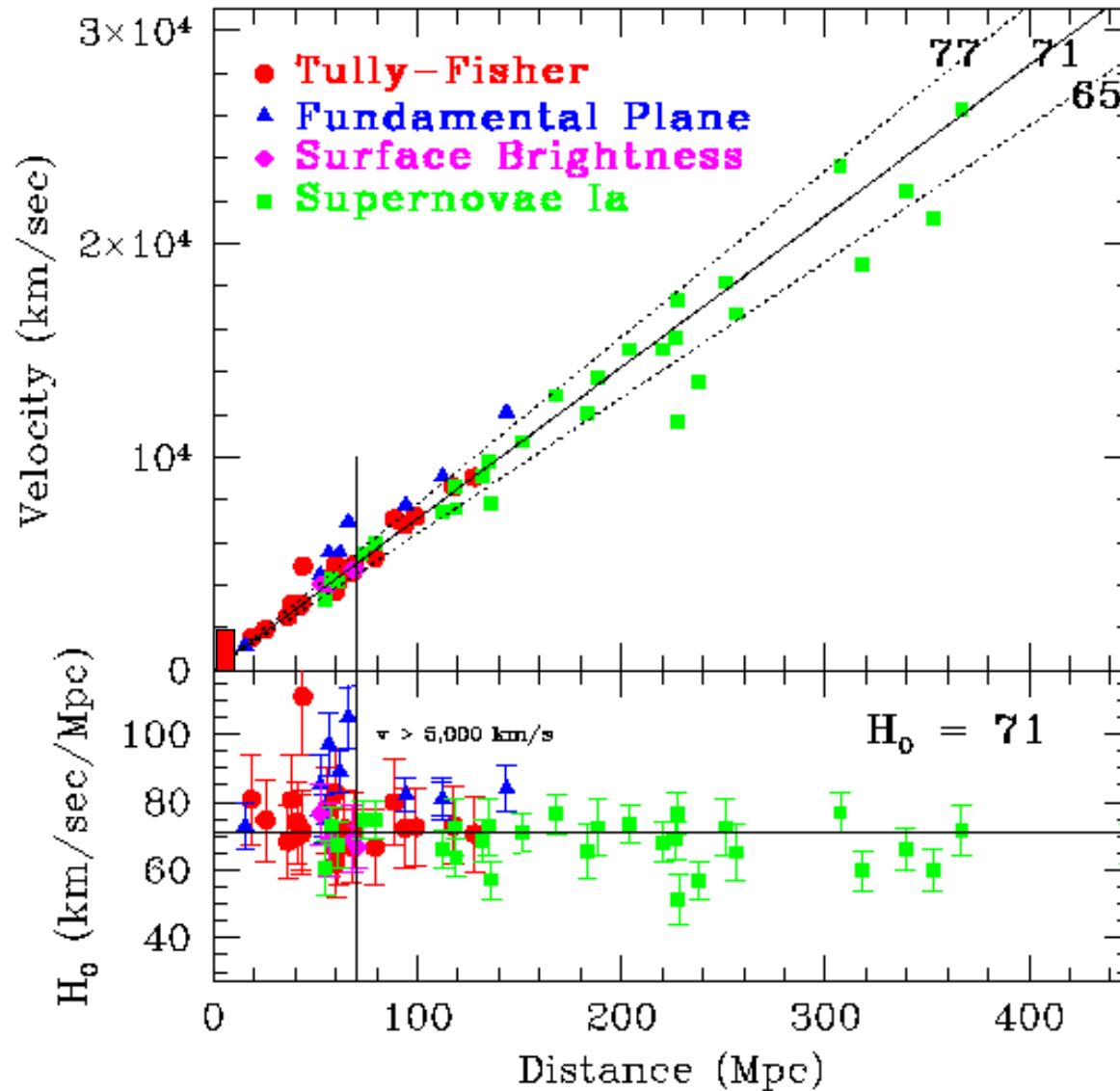
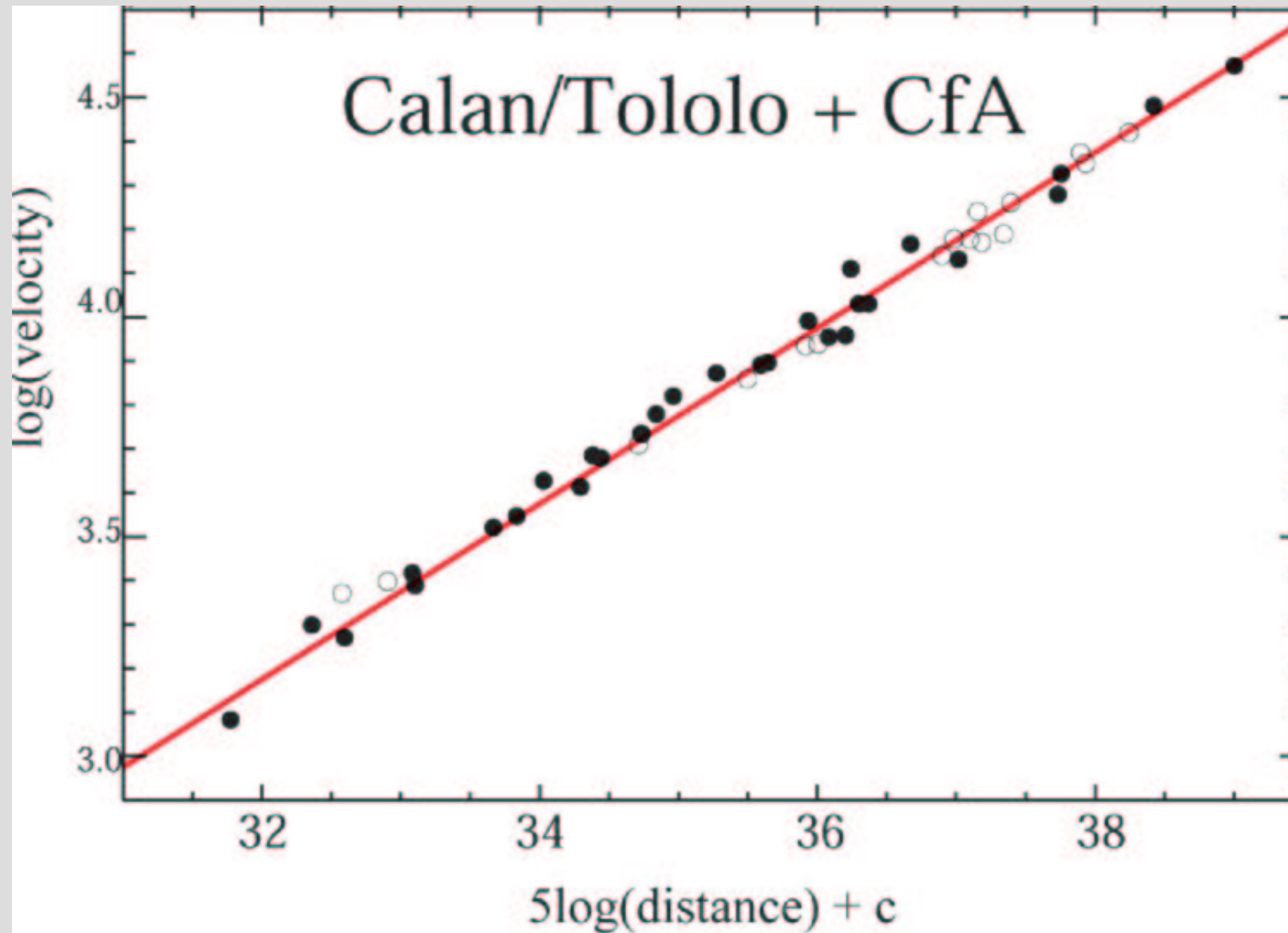


FIG. 9. *The Formulation of the Velocity-Distance Relation.*

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)

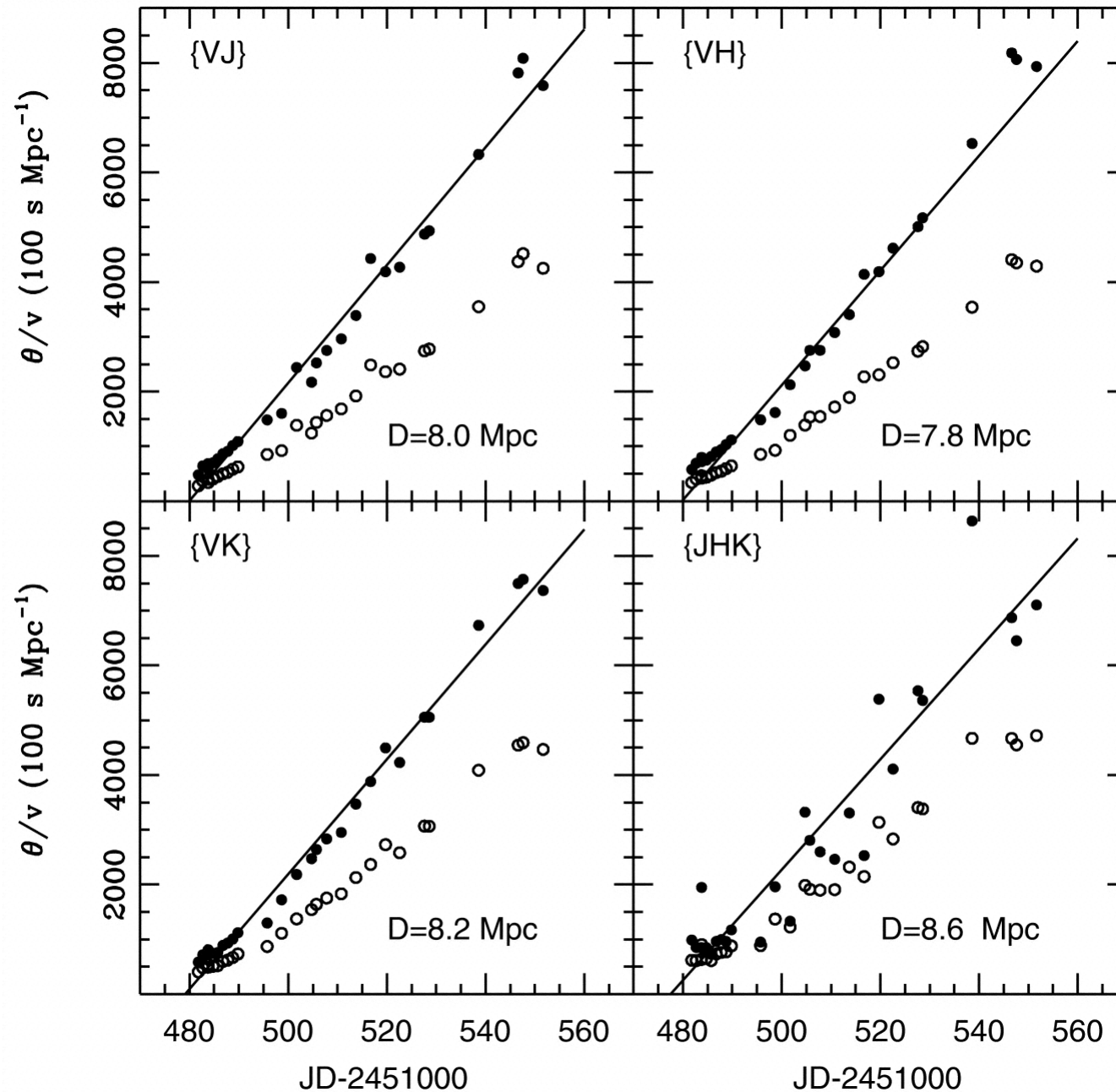
Assume homologous expansion

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

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. $\log z$)

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

Note that the slope is given here.

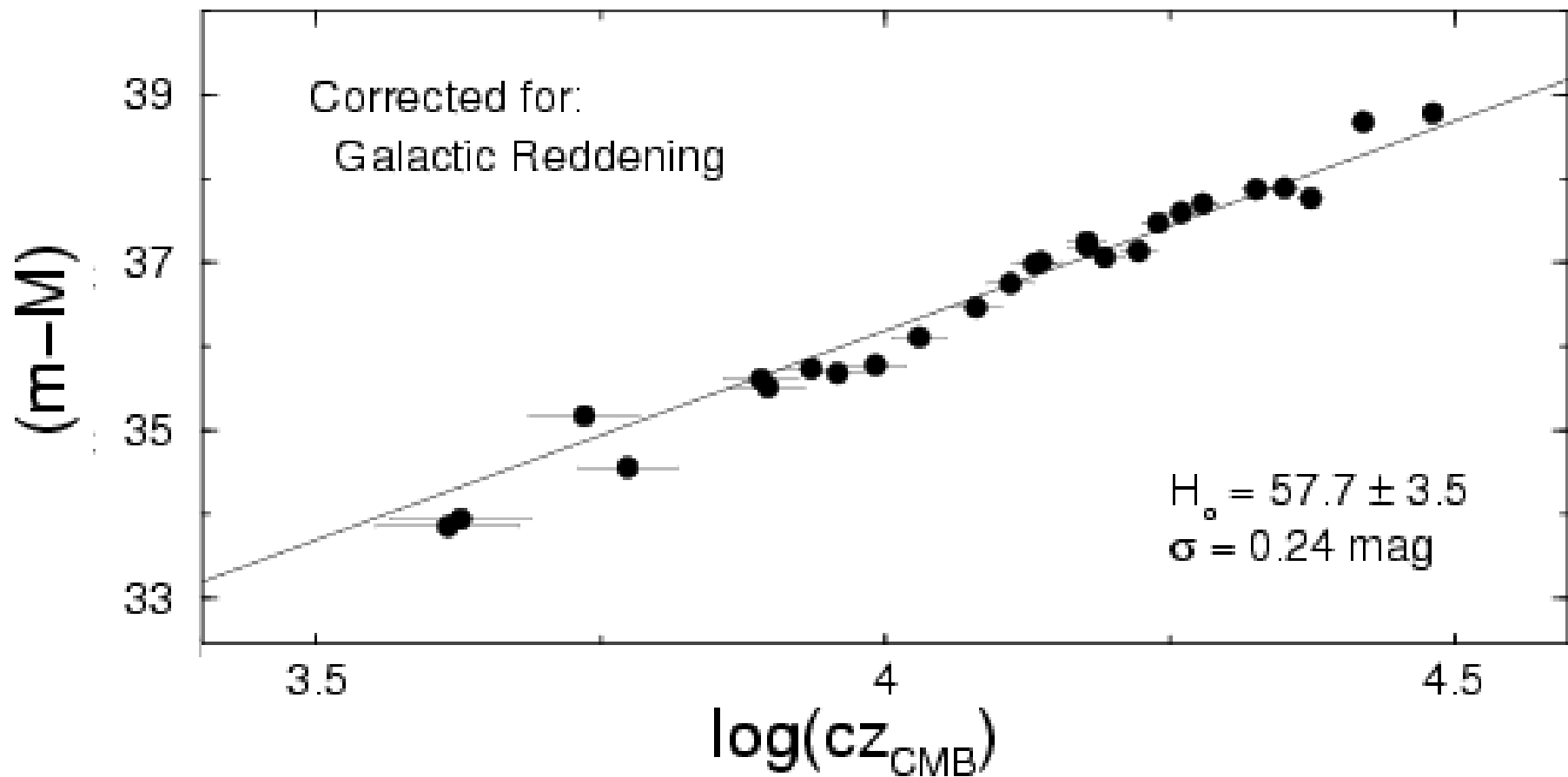
Hubble constant can be derived when the absolute luminosity M is known

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

Nearby SNe Ia

Phillips et al. (1999)

Calan/Tololo "Low Extinction" Sample



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, metallicities
- 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 4496	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

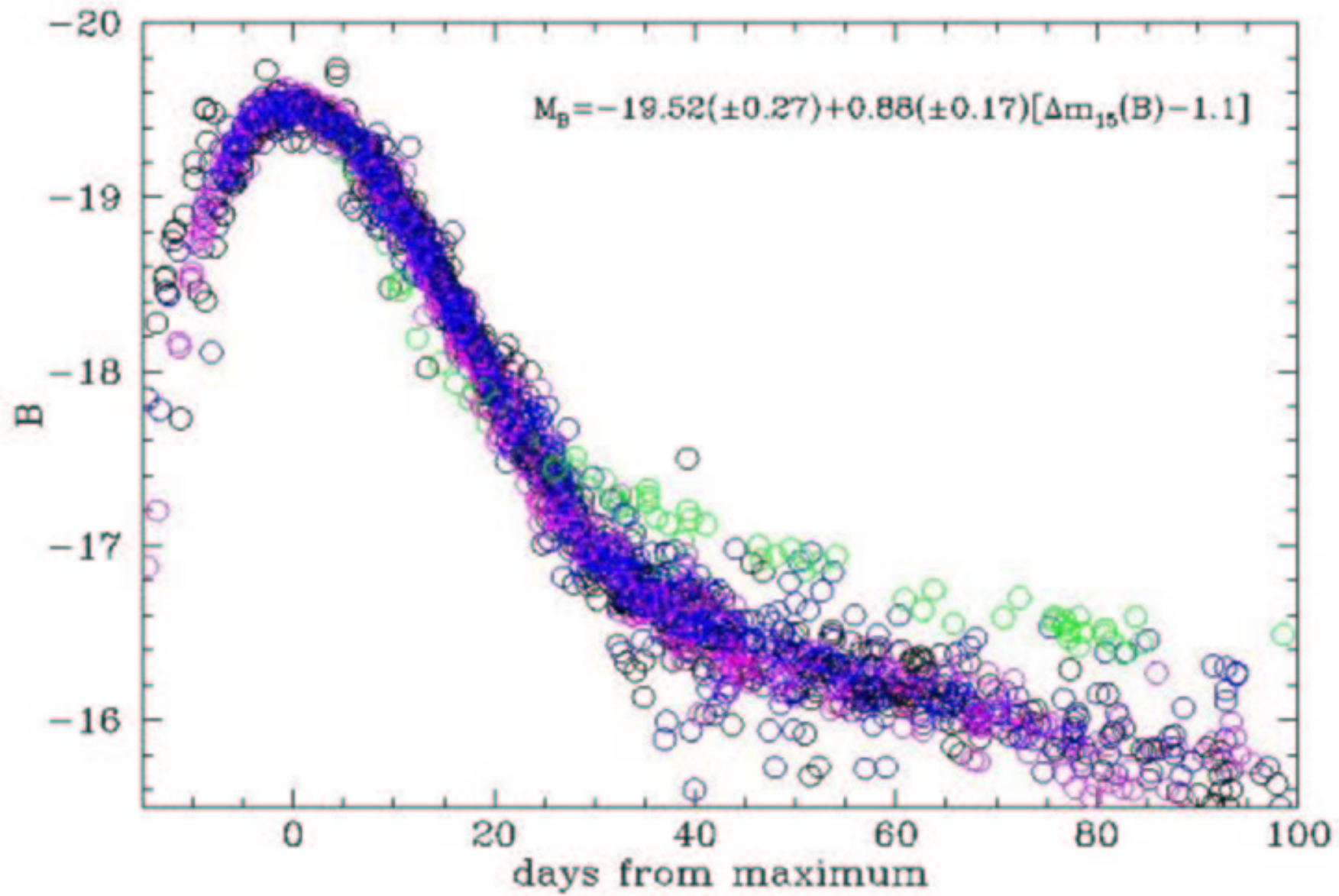
Riess et al. (1996, 1998), Jha et al. (2003)

stretch

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

MAGIC

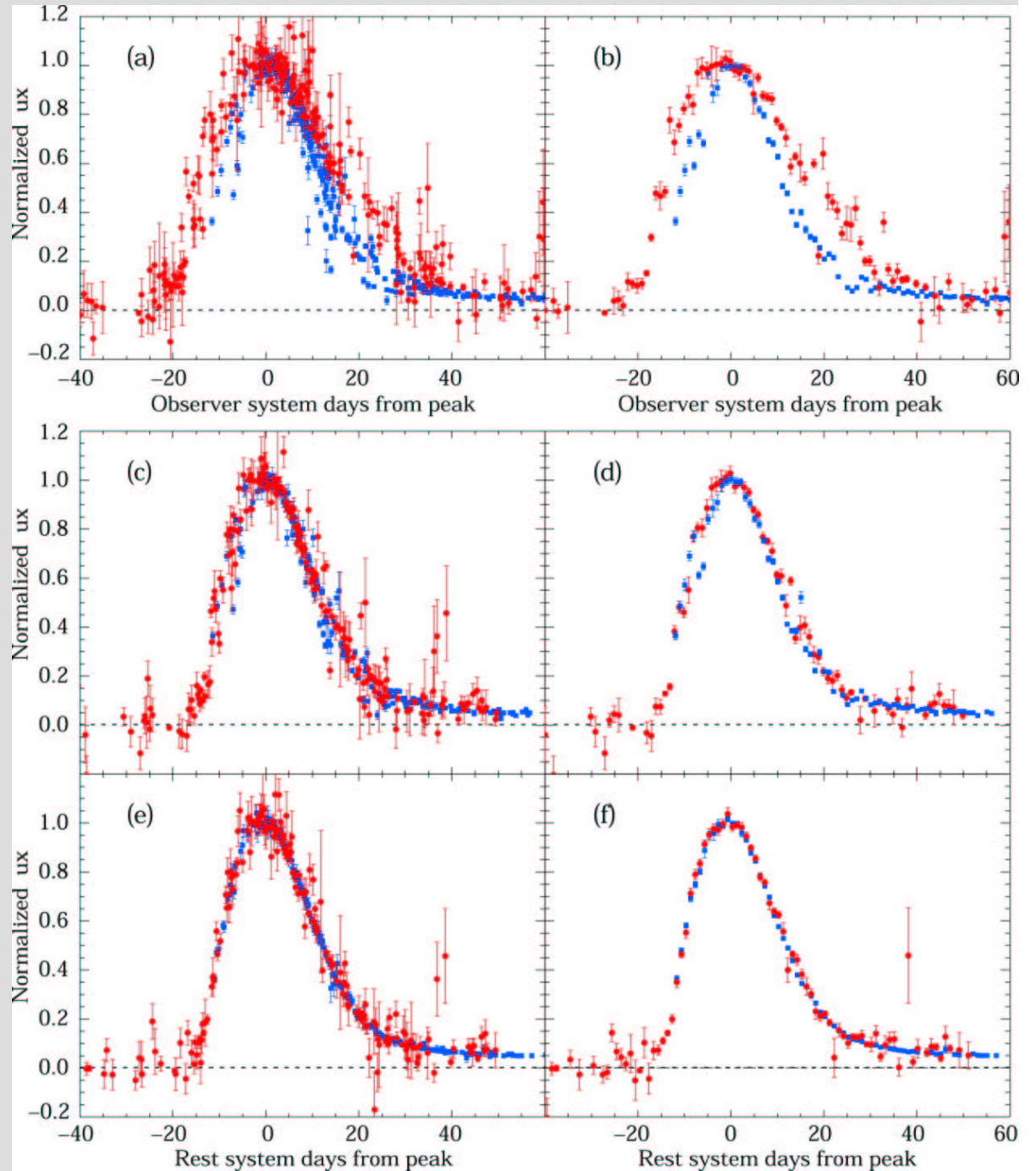
Wang et al. (2003)



Altavilla, Thesis

The magic of the light curve shapes

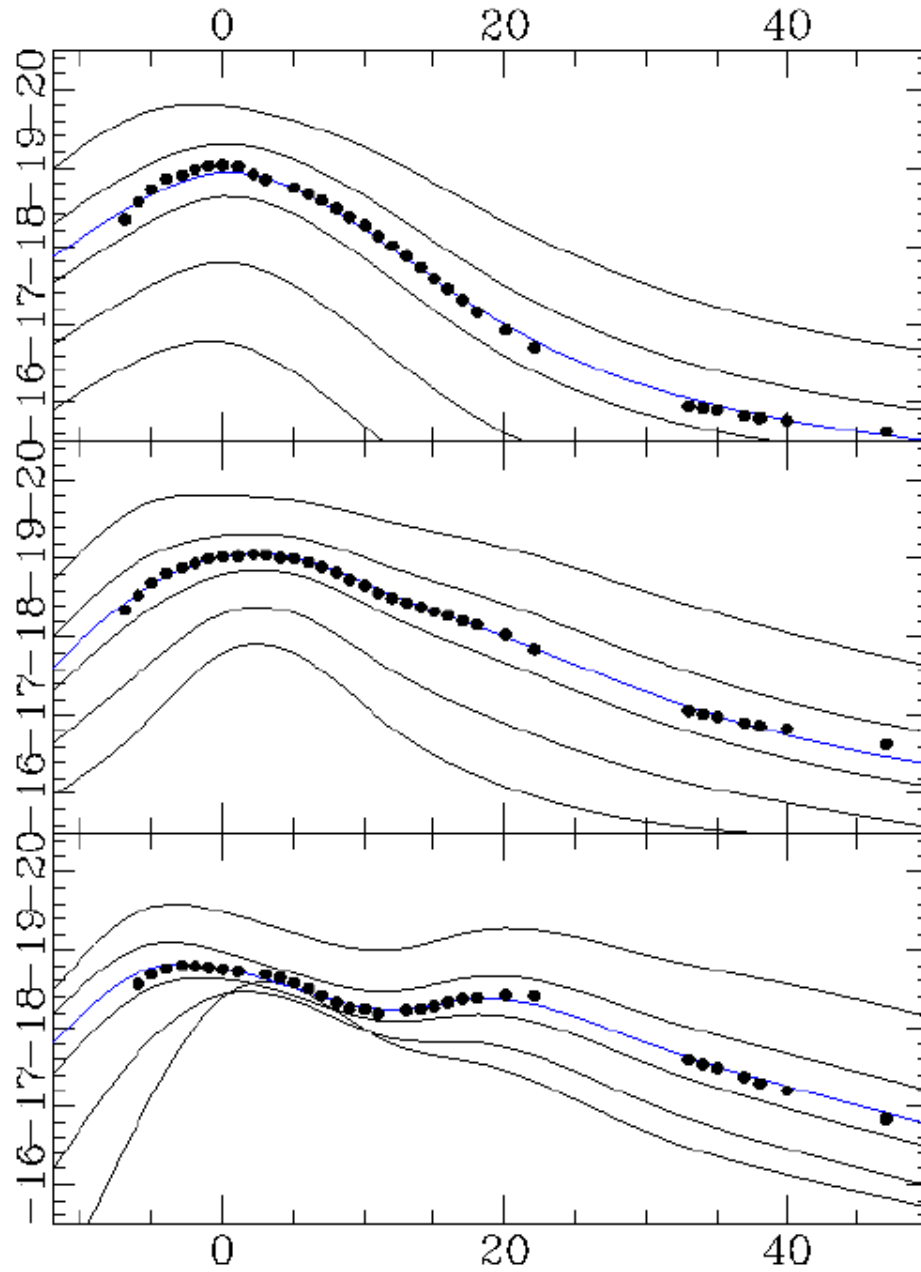
Goldhaber et al. 2001



B

V

I



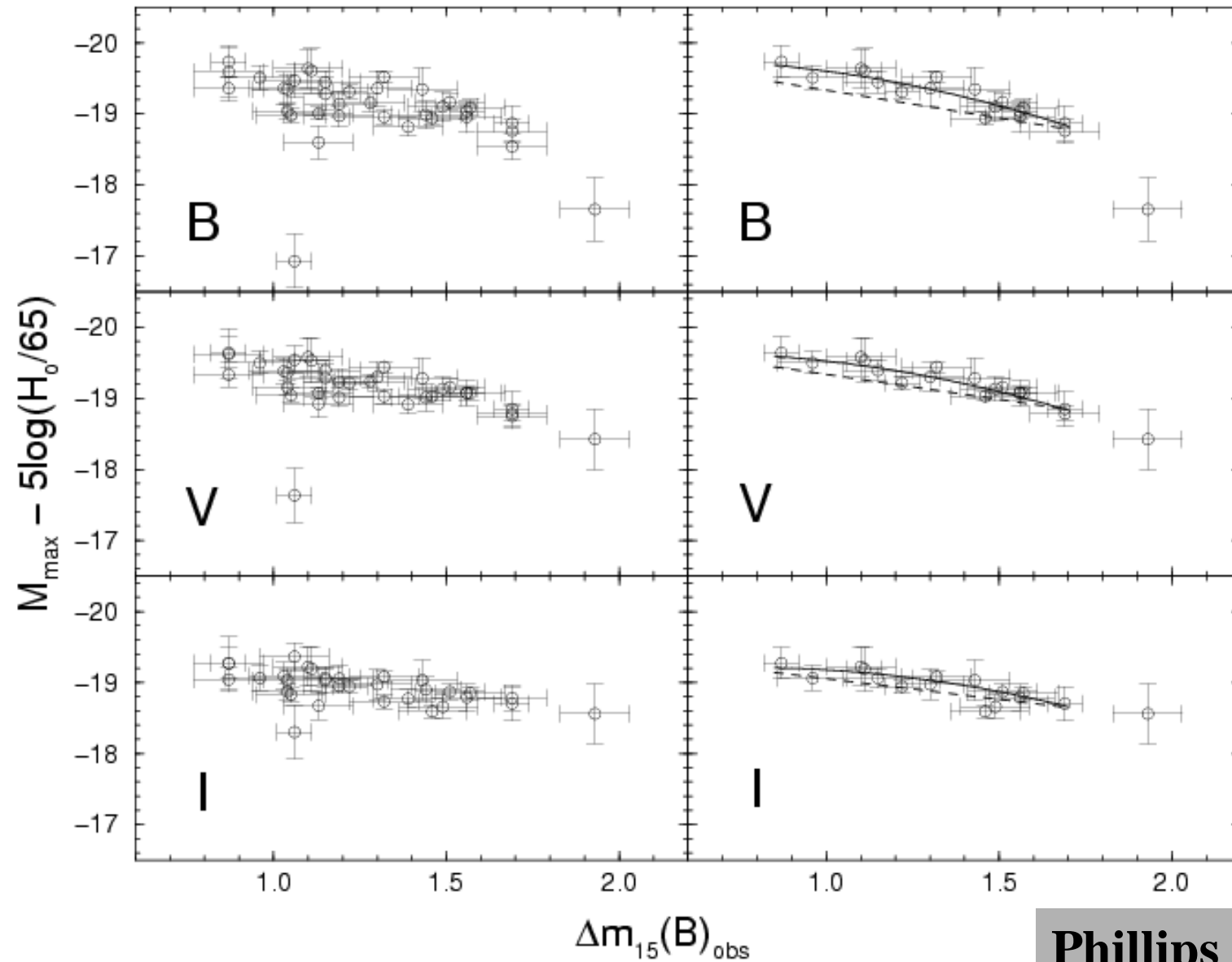
The SN Ia luminosity
can be normalised

Bright = slow

Dim = fast

Riess et al. 1996

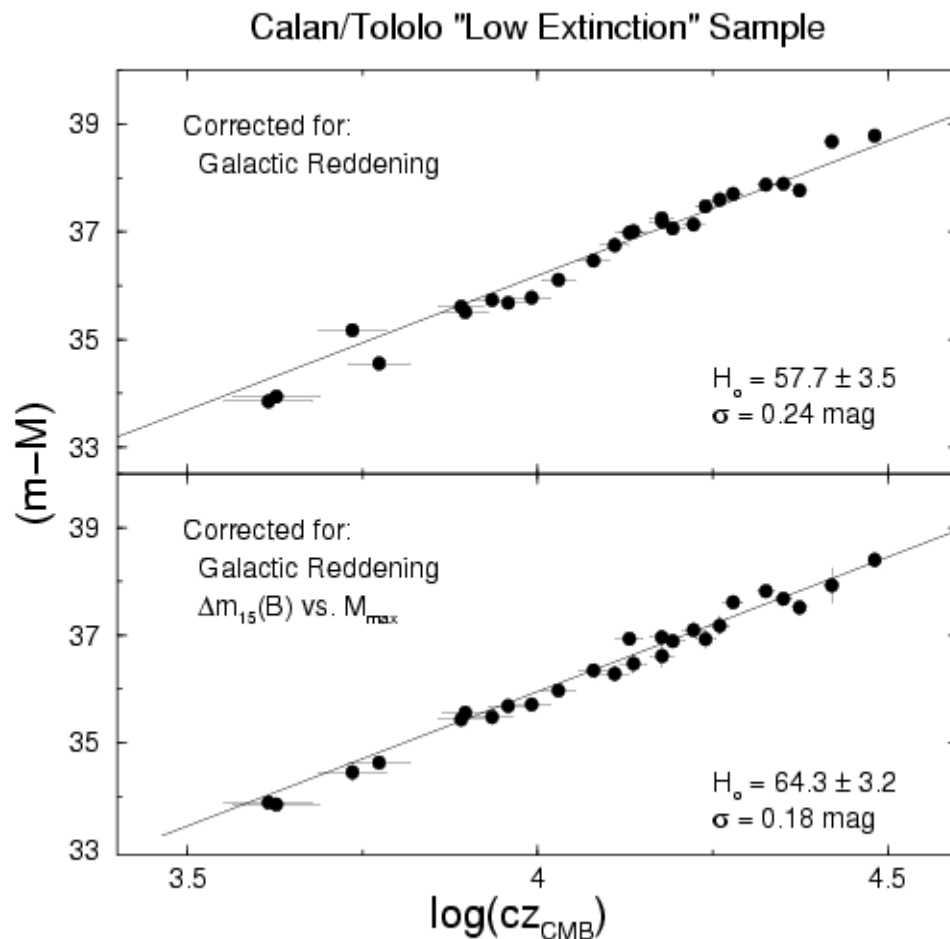
Correlations



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

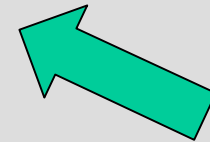
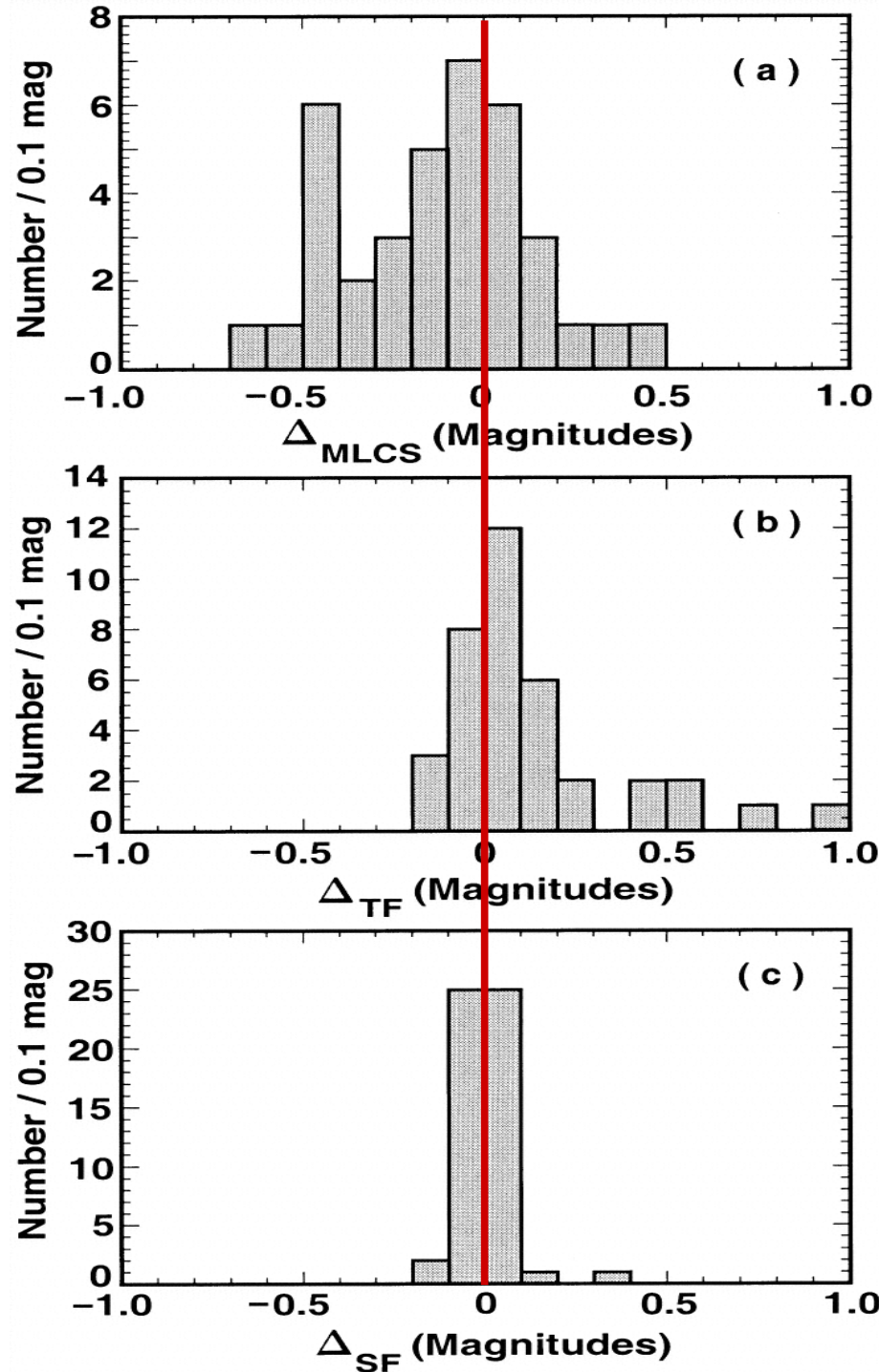
Luminosity vs. line strengths and line widths

- Nugent et al. 1995, Riess et al. 1998, Mazzali et al. 1998

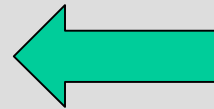
Luminosity vs. host galaxy morphology

- Filippenko 1989, Hamuy et al. 1995, 1996, Schmidt et al. 1998, Branch et al. 1996

SN Ia Correlations

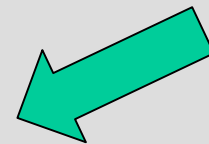


Riess et al. 1998



Phillips et al. 1999

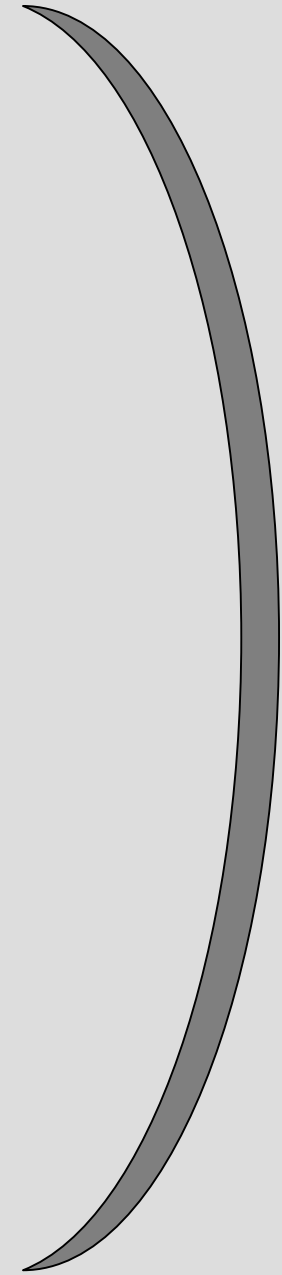
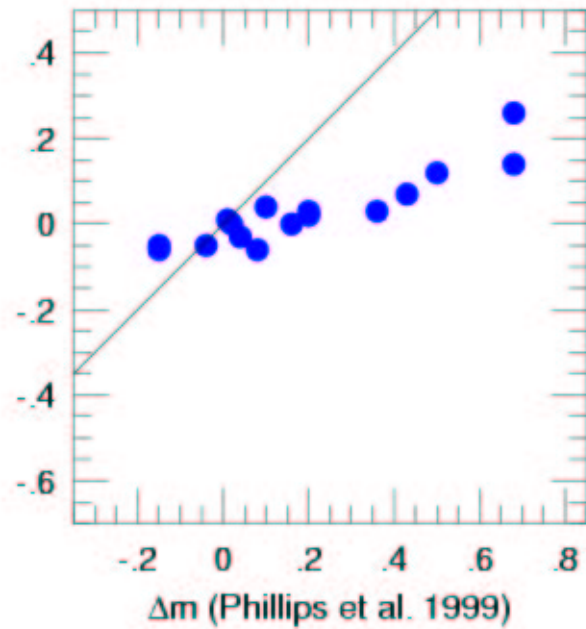
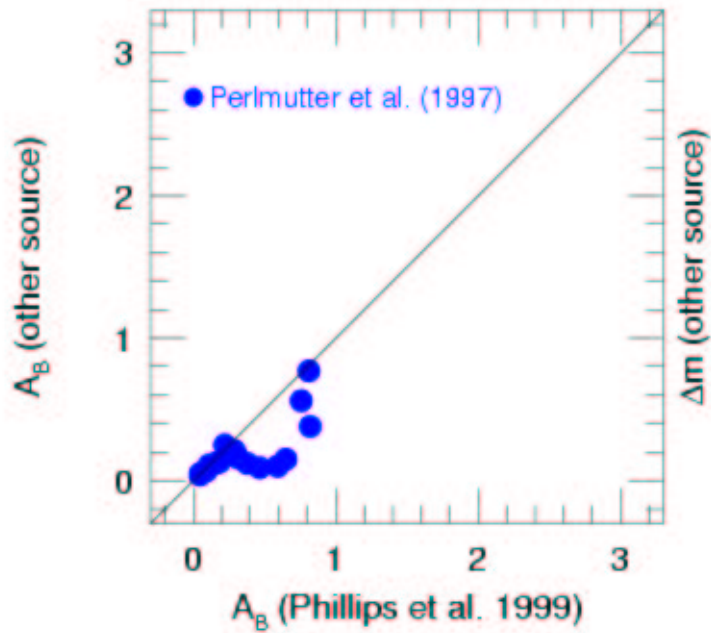
Perlmutter et al. 1997



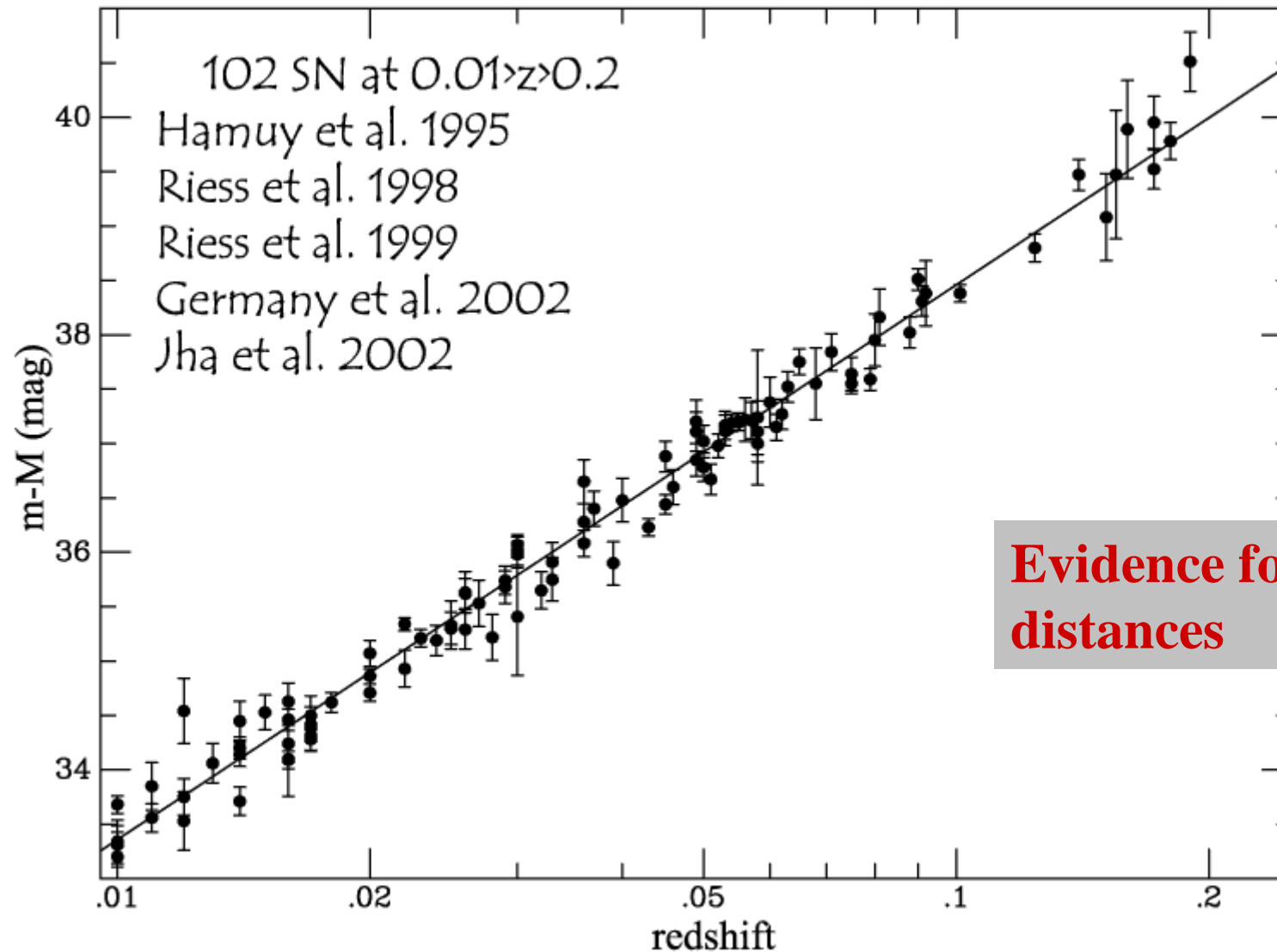
Drell et al. 2000

SN Ia Correlations

Leibundgut 2000



The nearby SN Ia sample



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