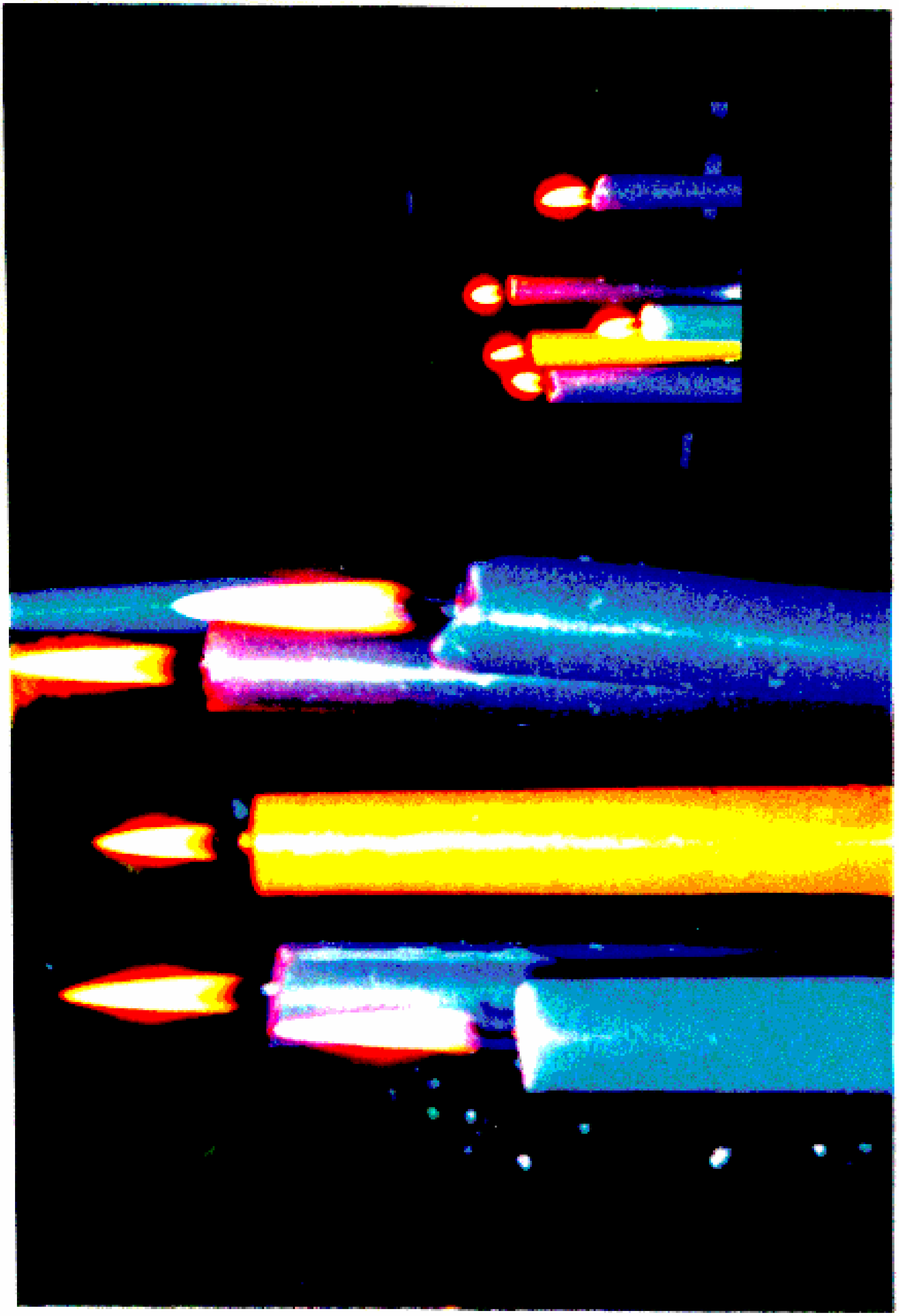
A Study of 42 Type Ia Supernovae and a Resulting Measurement of Ω_M and Ω_Λ

Talk by GERSON GOLDHABER for the

SUPERNOVA COSMOLOGY PROJECT[1]

Telescopes for Photometry: CTIO 4-m, ESO 3.6-m, INT 2.5-m, WHT 4.2-m and HST
Telescopes for Spectroscopy:
Keck I and II 10-m and ESO 3.6-m

[1]G. Aldering, A. Barth, B.J. Boyle, P.G. Castro, W.J. Couch, S. Deustua, S. Fabbro, R.S. Ellis, A.V. Filippenko, A. Fruchter, G. Goldhaber, A. Goobar, D.E. Groom, I.M. Hook, M. Irwin, A.G. Kim, M.Y. Kim, R.A. Knop, J.C. Lee, T. Matheson, R.G. McMahon, H.J.M. Newberg, C. Lidman, P. Nugent, N.J. Nunes, R. Pain, N. Panagia, C.R. Pennypacker, S. Perlmutter, P. Ruiz-Lapuente, B. Schaefer and N. Walton.



How Come Type Ia Supernovae are Standard Candles?

$M \simeq M_\odot$

- A star "burns" hydrogen and helium (nuclear fusion) to carbon and oxygen. This balances the gravitational force (pressure).

- When all the hydrogen and helium is used up, after a few billion years, gravity collapses the star – crushes the atoms – to a white dwarf of carbon and oxygen nuclei and free electrons. GRAVITY COMPENSATED BY PRESSURE OF DEGENERATE ELECT. GAS

- "A White Dwarf:" About the mass of our Sun, and about the size of our Earth.

- Often occurs with a companion star and mass transfers to the White Dwarf.

- When the mass reaches a critical value – about 1.4 times the mass of our Sun – the White Dwarf collapses and starts "burning" carbon and oxygen mainly to Nickel. This happens in a few seconds and is the SUPERNOVA EXPLOSION (Type Ia). CHANDRASEKHAR LIMIT.
  $0.6\ M_\odot$ OF ^{56}Ni.

- Since all these Supernovae start at the same mass, 1.4 M⊙, they turn out to be of about the same brightness – standard candles.

$^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$

$T_{1/2}({}^{56}Ni) = 6.0$ days

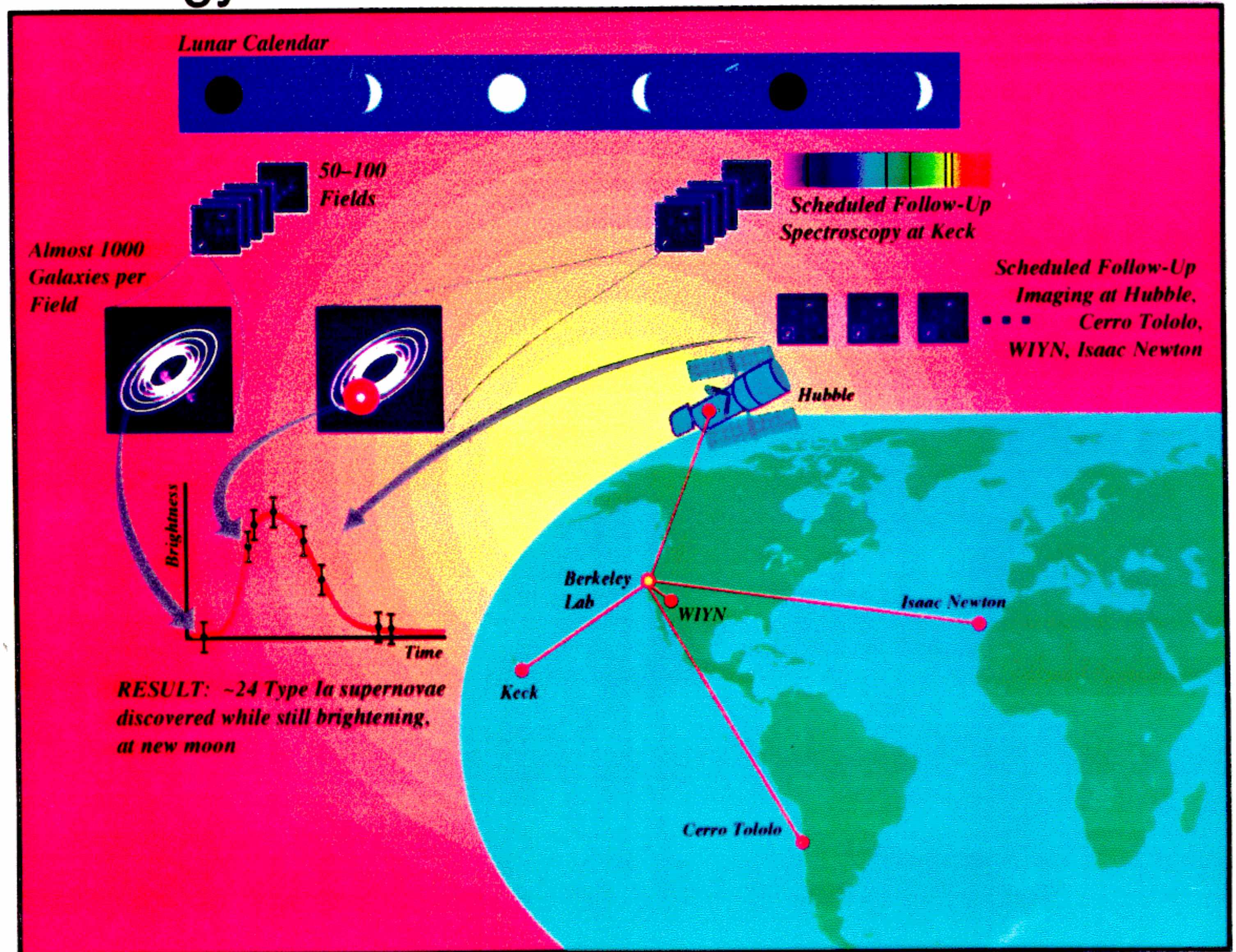
$T_{1/2}({}^{56}Co) = 77$ days

EJECTA EMMITTED at 0.3-1% of c.

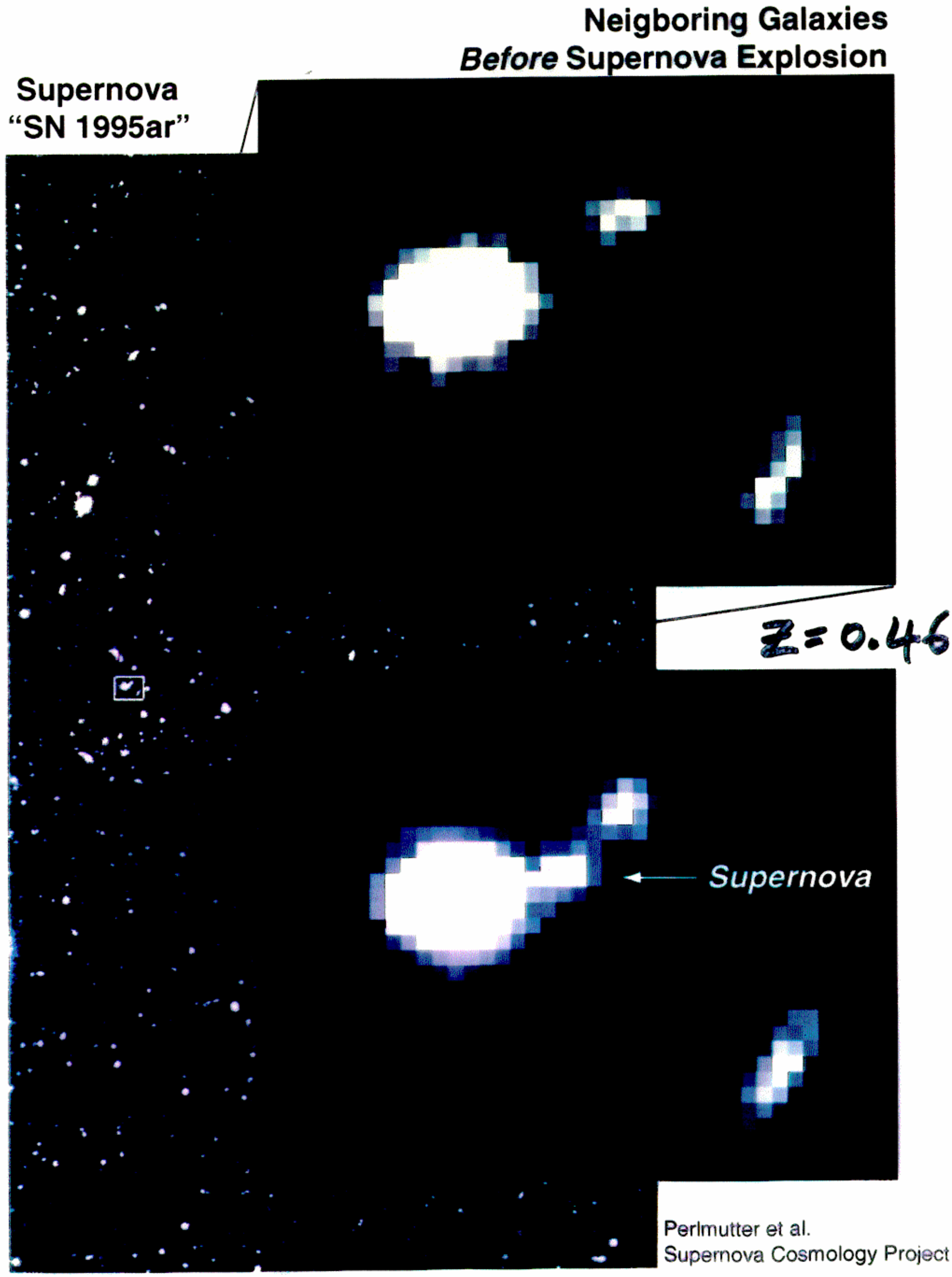
LBL Photographic Services
XBD 9505-
LAWRENCE BERKELEY LABORATORY

Strategy

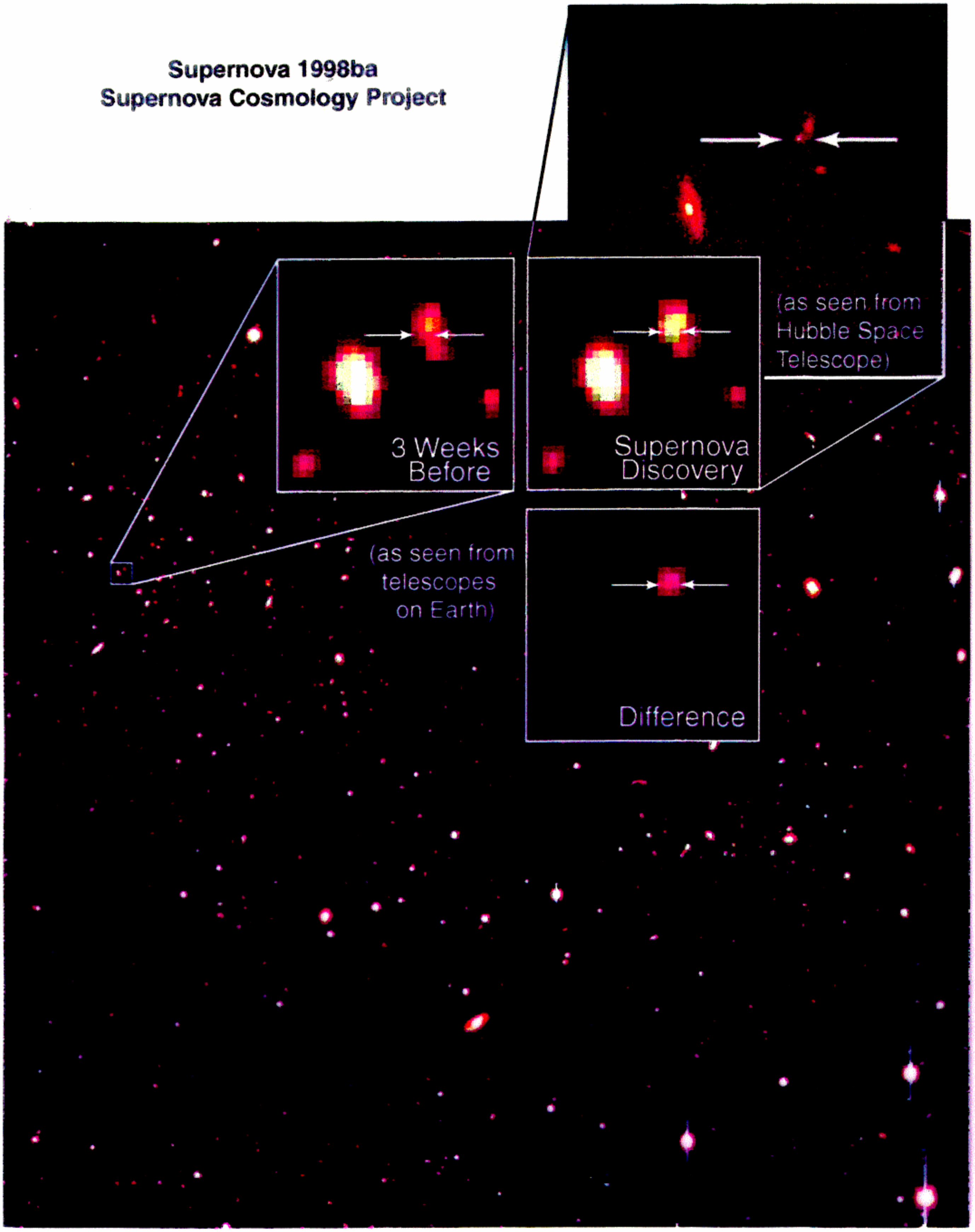
Supernova Cosmology Project



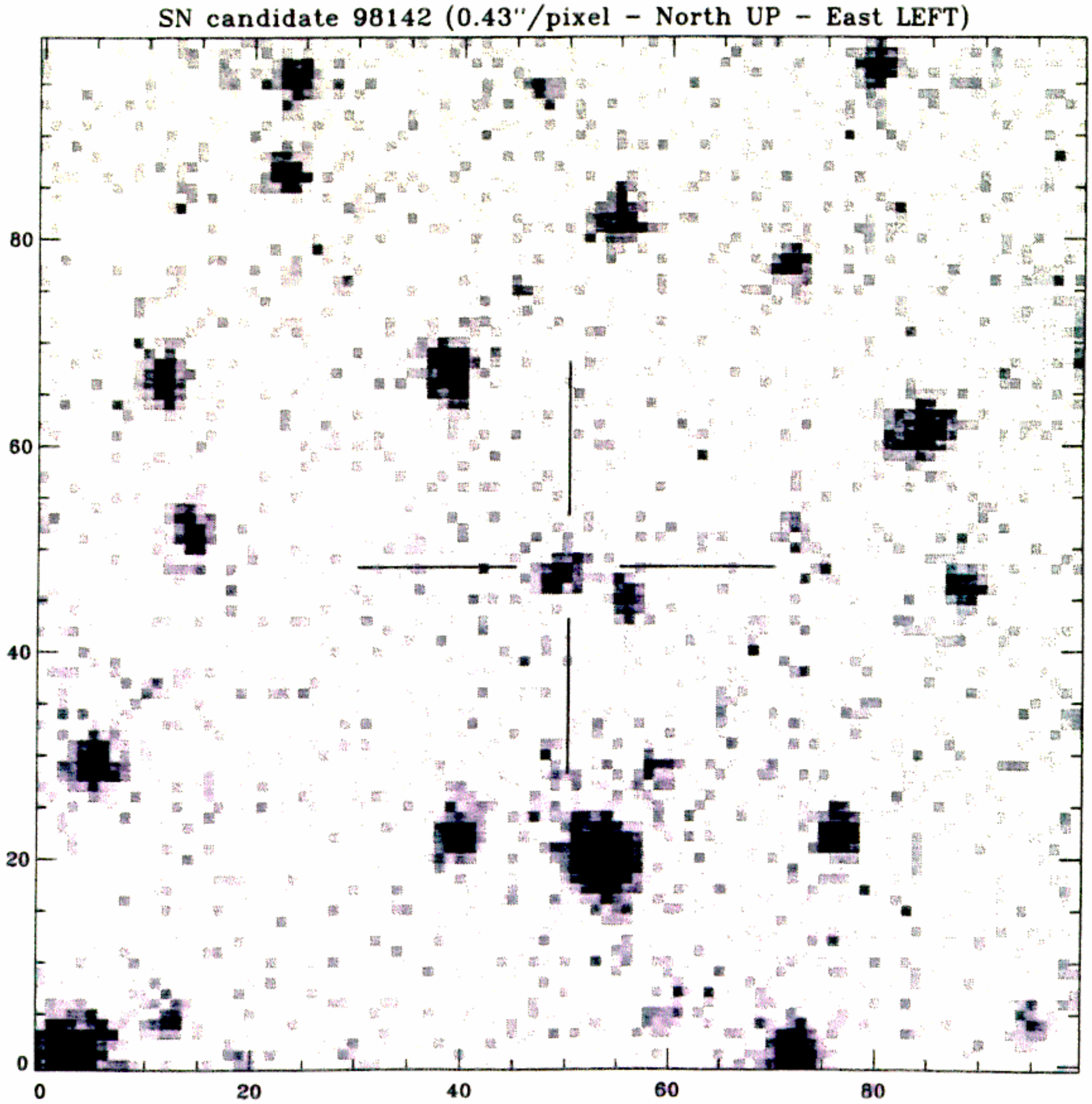
Perlmutter, *et al.*, in *Thermonuclear Supernovae*, NATO ASI, v. 486 (1997)


Neigboring Galaxies
Before Supernova Explosion
Supernova
"SN 1995ar"
Z= 0.46
Supernova
Perlmutter et al.
Supernova Cosmology Project

Supernova 1998ba
Supernova Cosmology Project



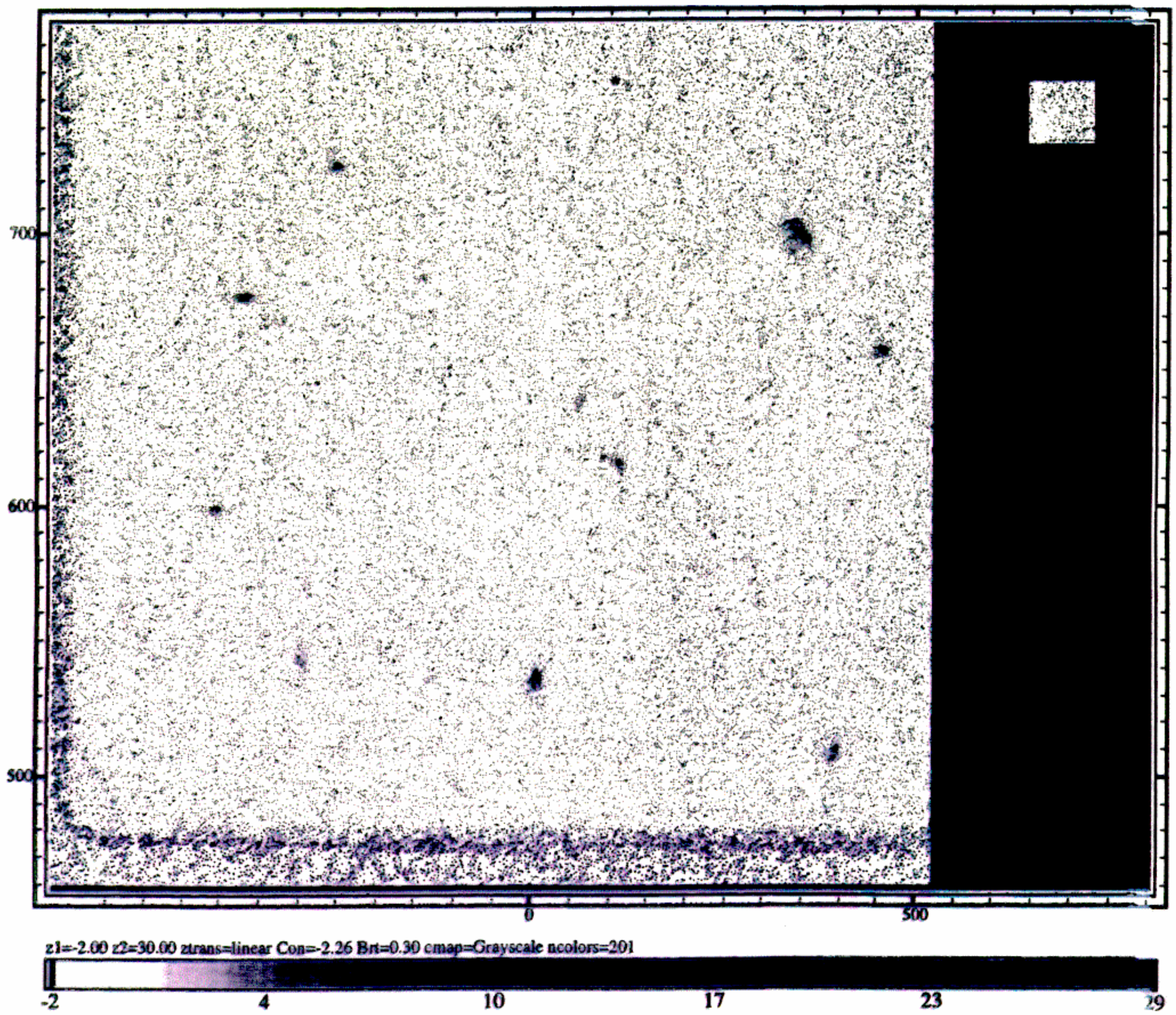
CERRO/TOLOLO
4 m TELESCOPE



Sat Mar 28 14:29:55 1998

HUBBLE SPACE TELESCOPE
2.5m

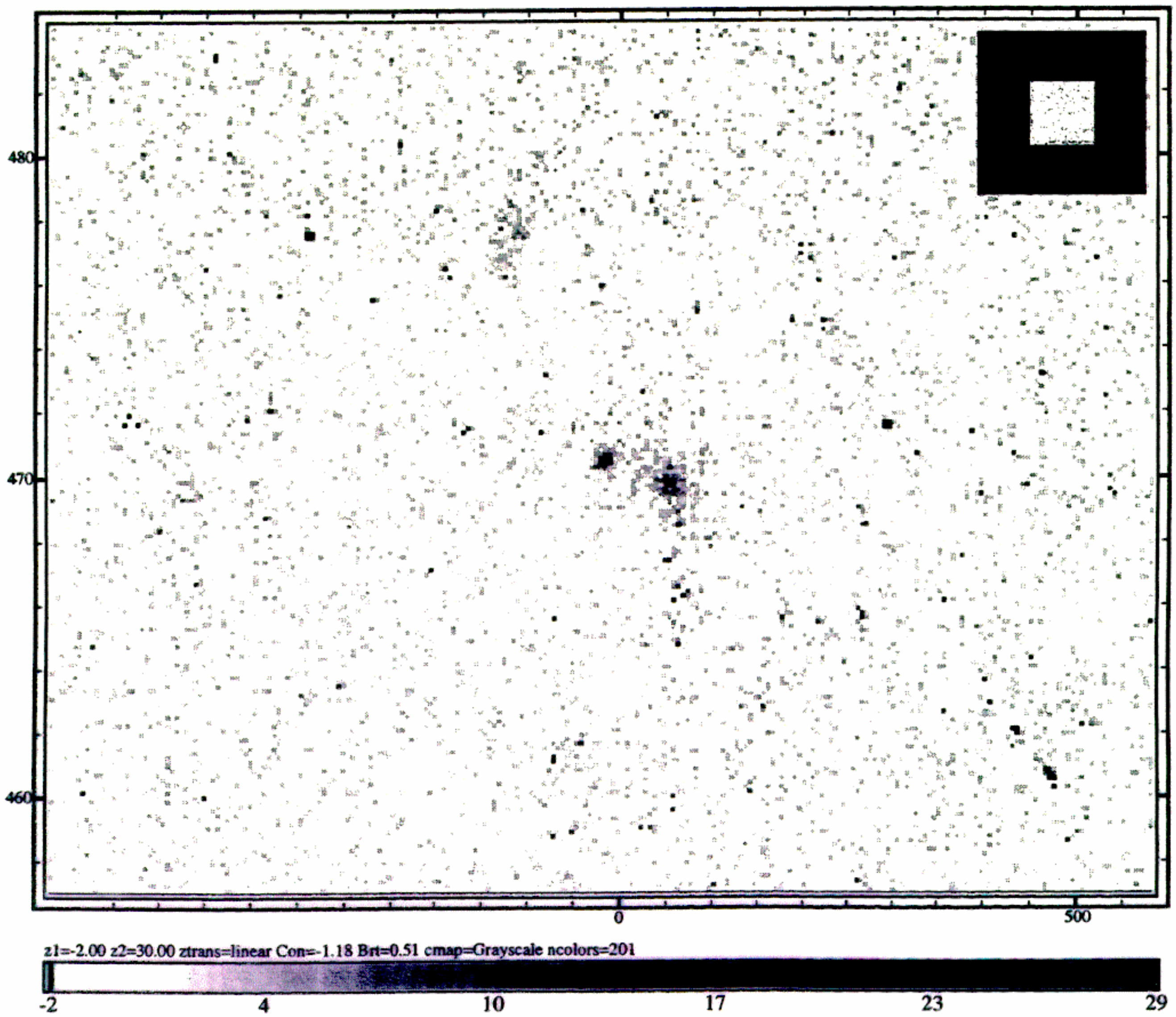
sn98142.980418.I.hhh - SN98142.980418.I[1/4]



NOAO/IRAF nidering@mamalan.lbl.gov Mon May 4 11:47:49 1998

HST WFPC

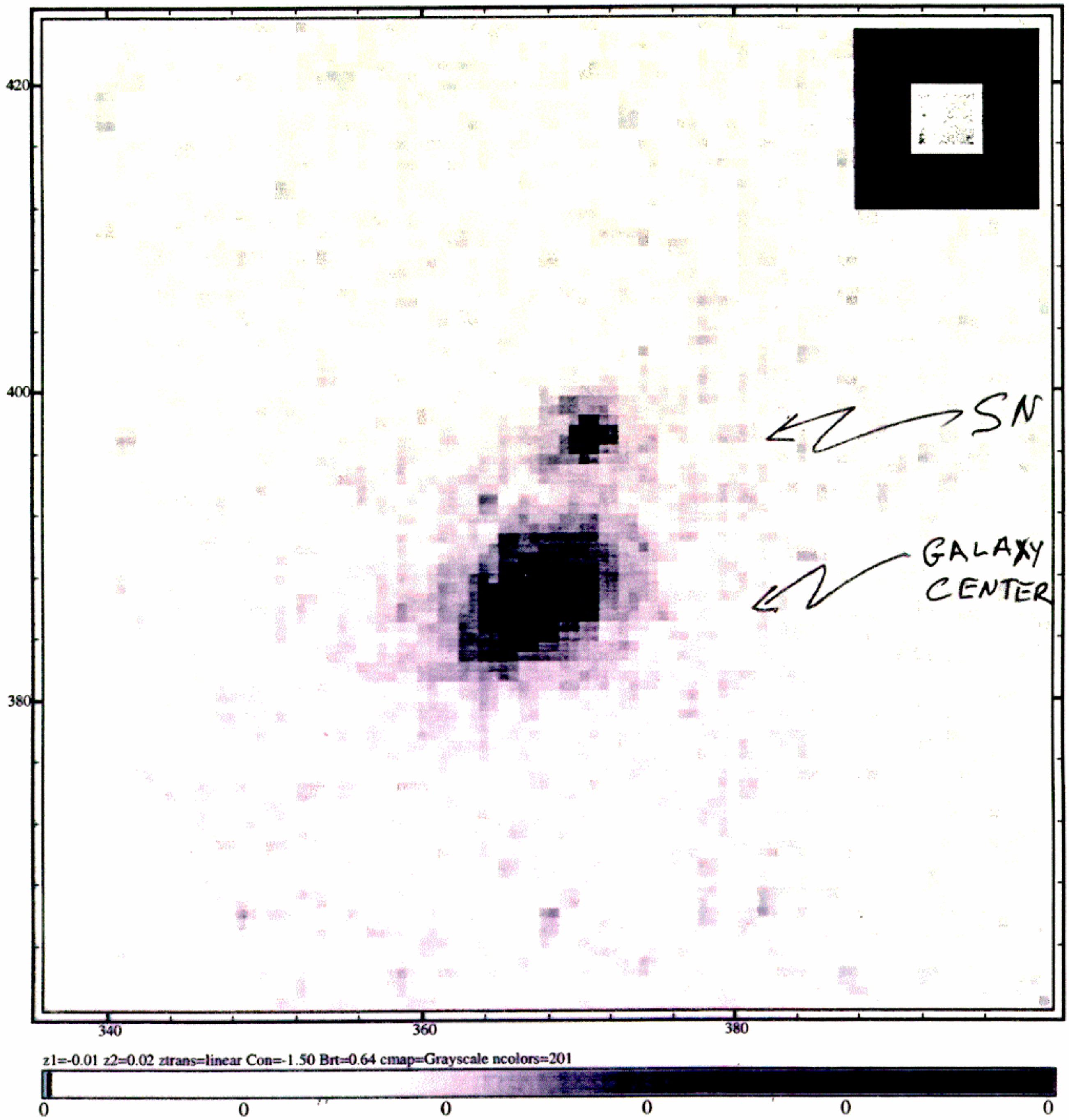
sn98142.980418.I.hhh - SN98142.980418.I[1/4]



NOAO/IRAF aldering@mamalan.lbl.gov Mon May 4 11:47:08 1998

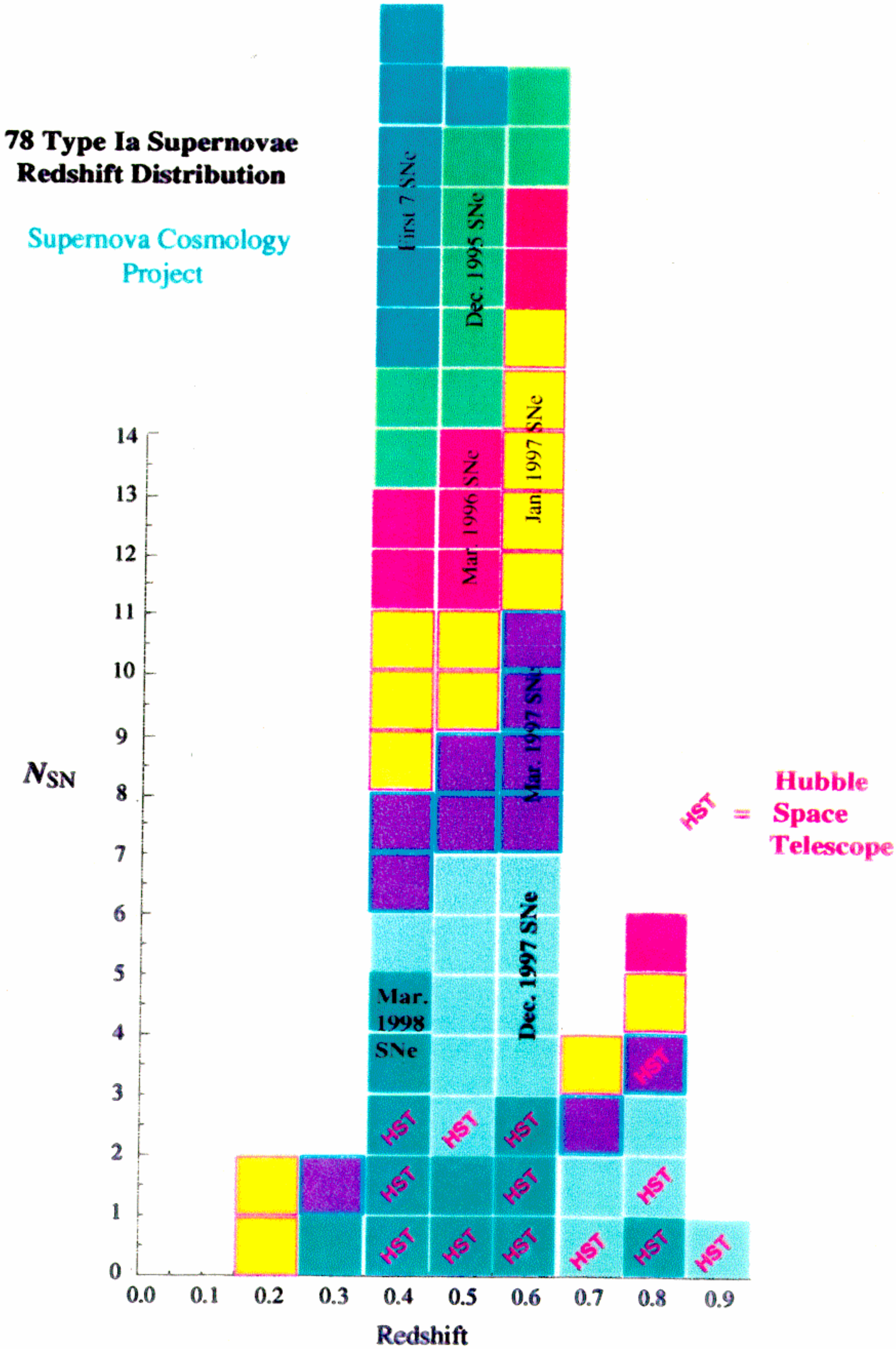
Z = 0.74 HUBBLE SPACE TELESCOPE
NICMOS $\lambda = 0.8 - 1.2\ \mu$

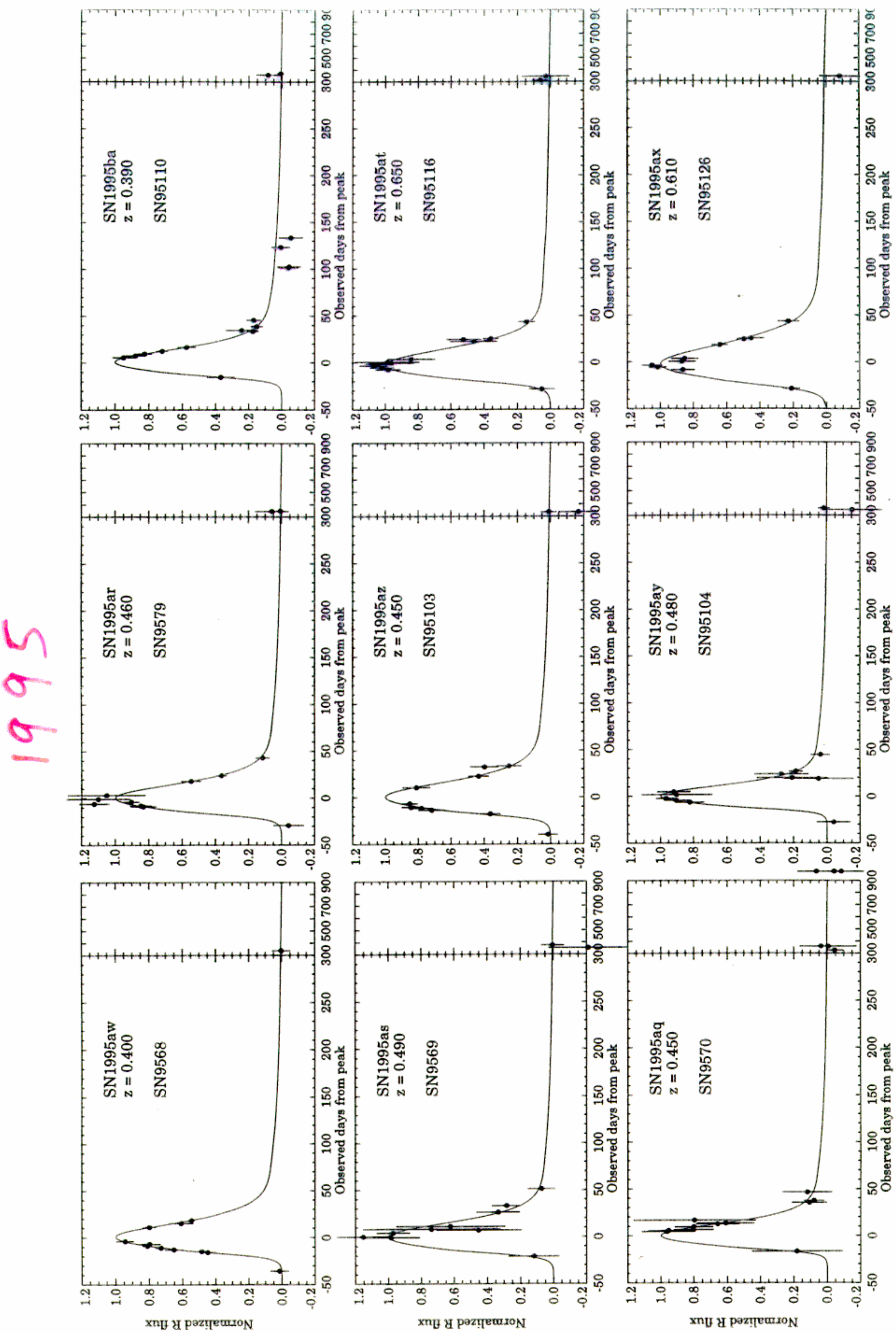
sn98142.fits -



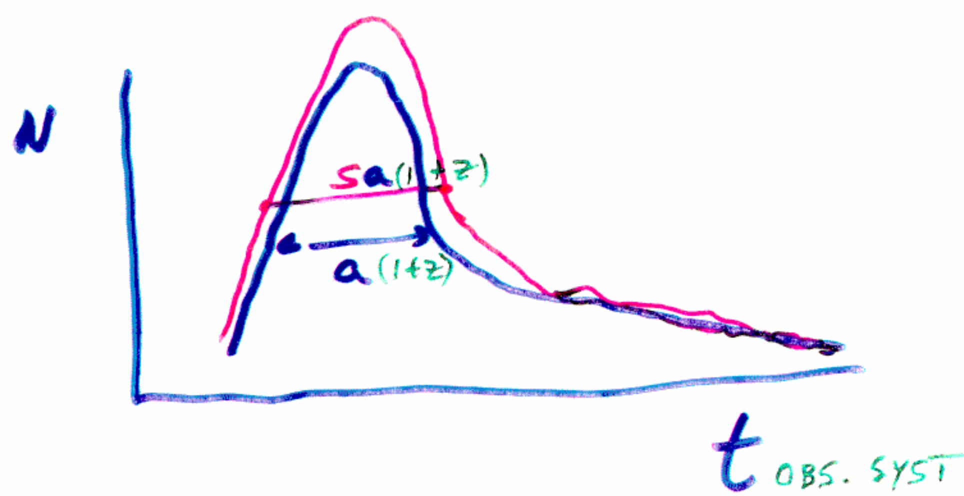
NOAO/IRAF aldering@mamalan.lbl.gov Thu Jul 23 17:52:27 1998

G. Goldhaber, SSI 1998




1995
SN1995aw
z = 0.400
SN9568
SN1995ar
z = 0.460
SN9579
SN1995ba
z = 0.390
SN95110
SN1995as
z = 0.490
SN9569
SN1995az
z = 0.450
SN95103
SN1995at
z = 0.650
SN95116
SN1995aq
z = 0.450
SN9570
SN1995ay
z = 0.480
SN95104
SN1995ax
z = 0.610
SN95126
Normalized R flux
Observed days from peak

EMPIRICAL RESULT:
WIDER <-> BRIGHTER



$$m_B^{corr} = m_B - \alpha(s-1)$$

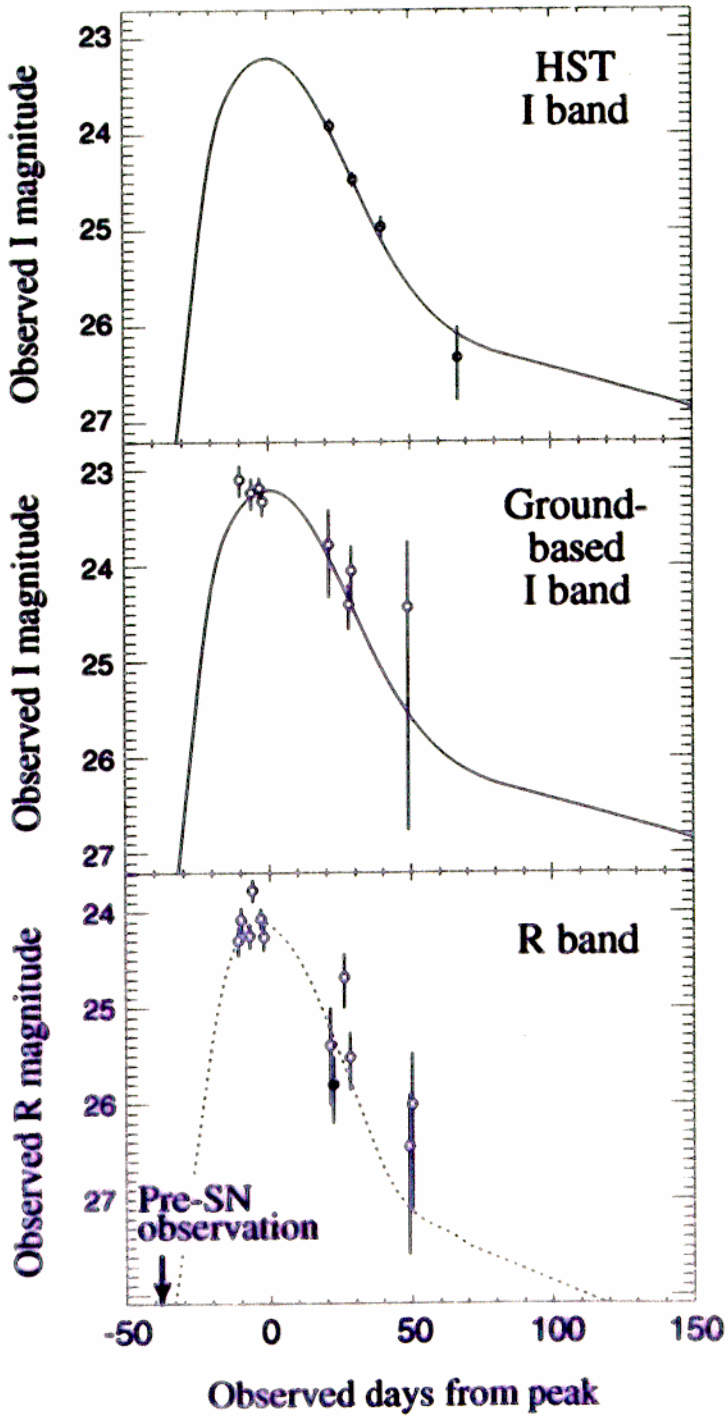
$$\alpha \simeq -1$$

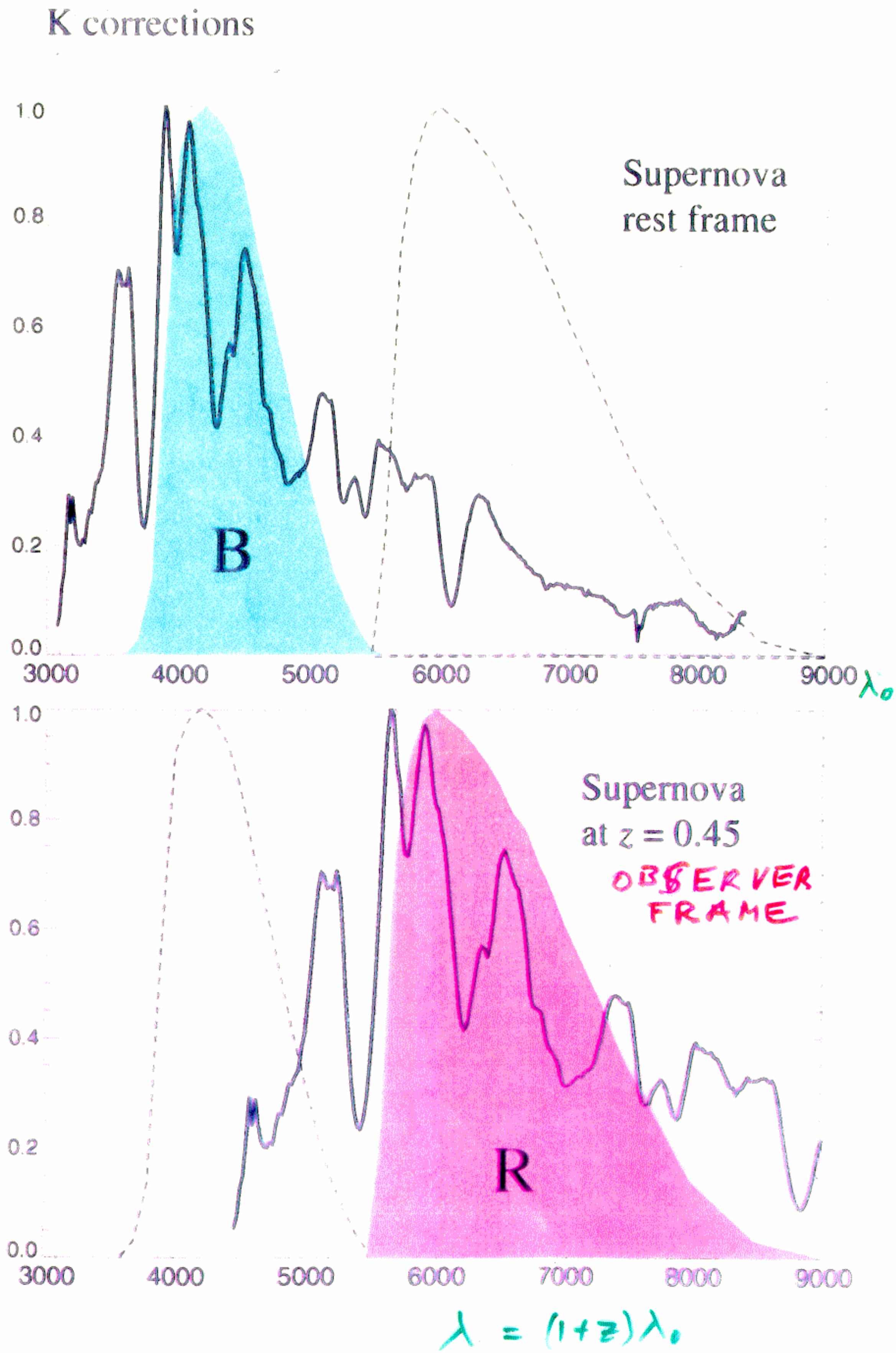
G. Goldhaber, SSI 1998

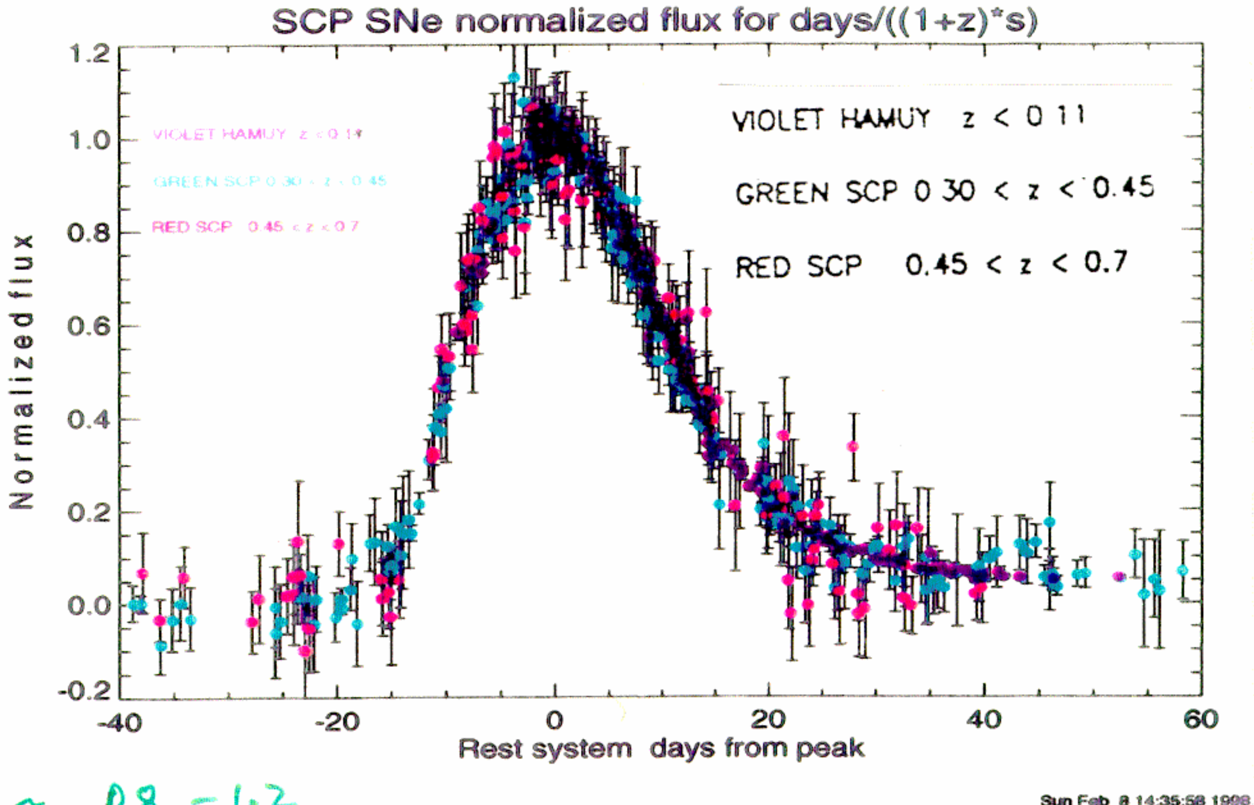
SN 1997ap at $z = 0.83$

~ 7 Billion Light years

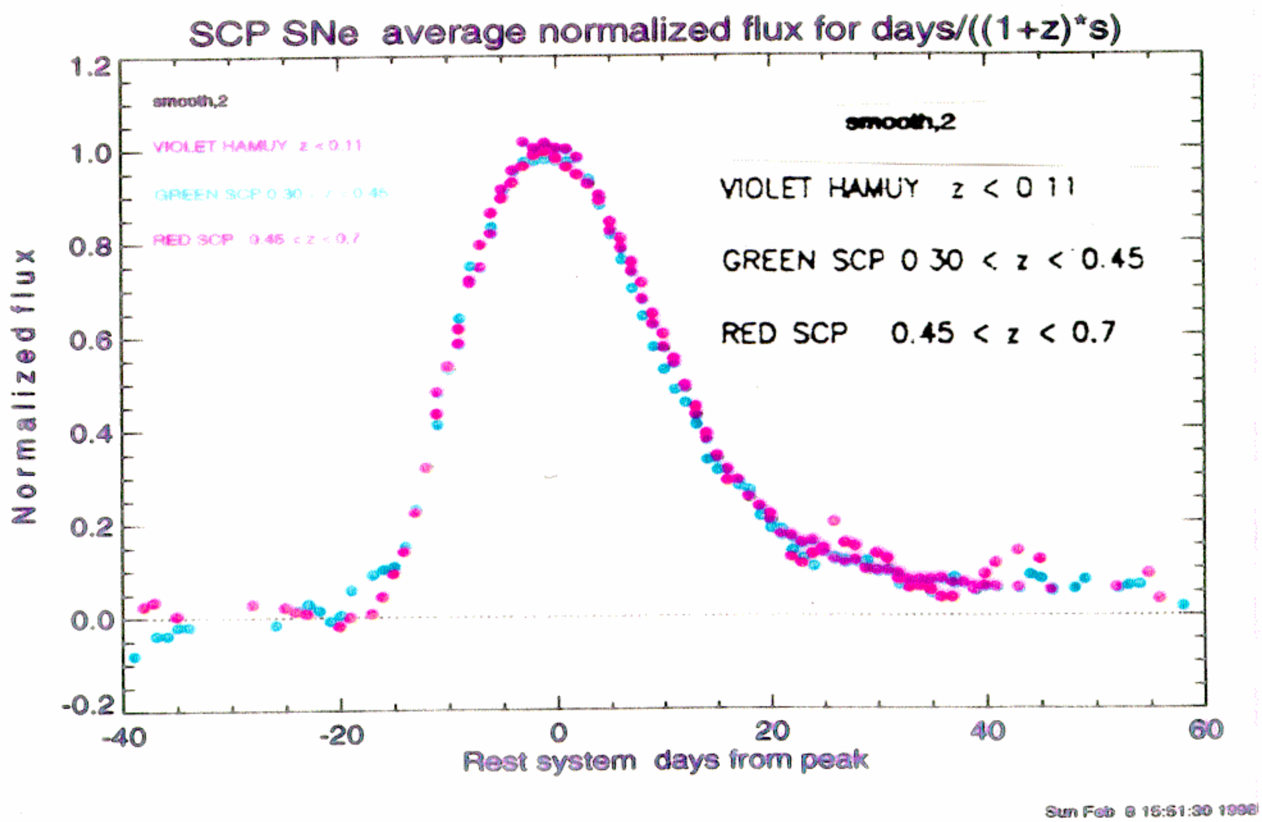
Perlmutter, *et al.*
Nature (1998)

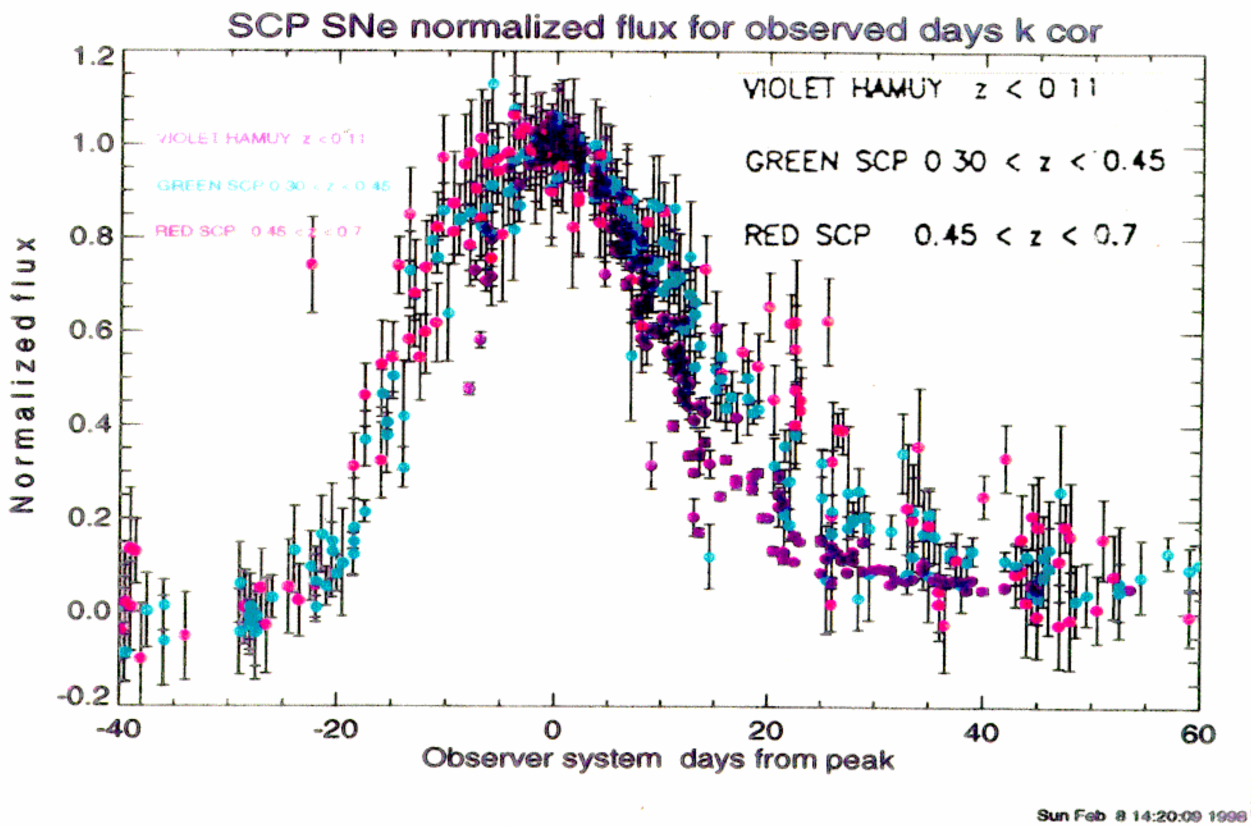


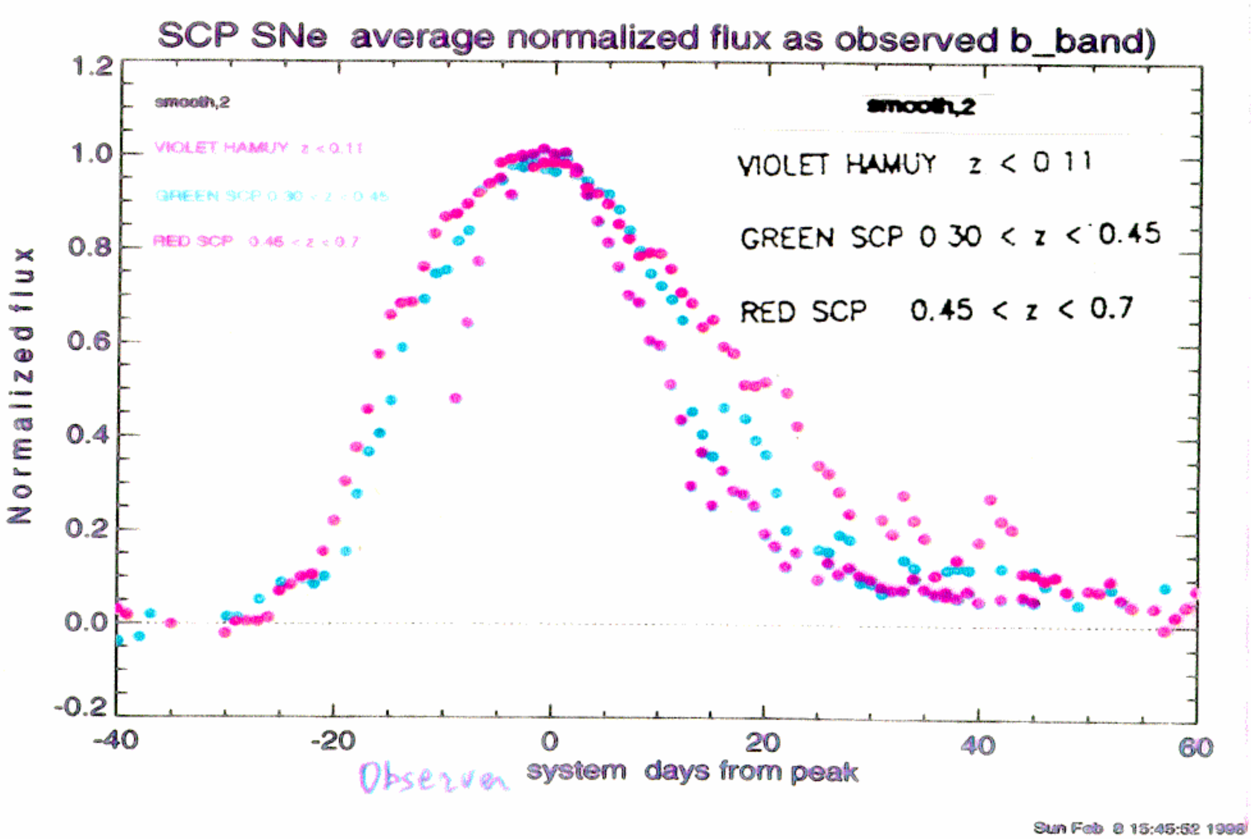

K corrections
1.0
0.8
0.6
0.4
0.2
0.0
3000
4000
5000
6000
7000
8000
9000
λ_0
Supernova
rest frame
B
Supernova
at z = 0.45
OBSERVER
FRAME
R
$\lambda = (1+z)\lambda_0$

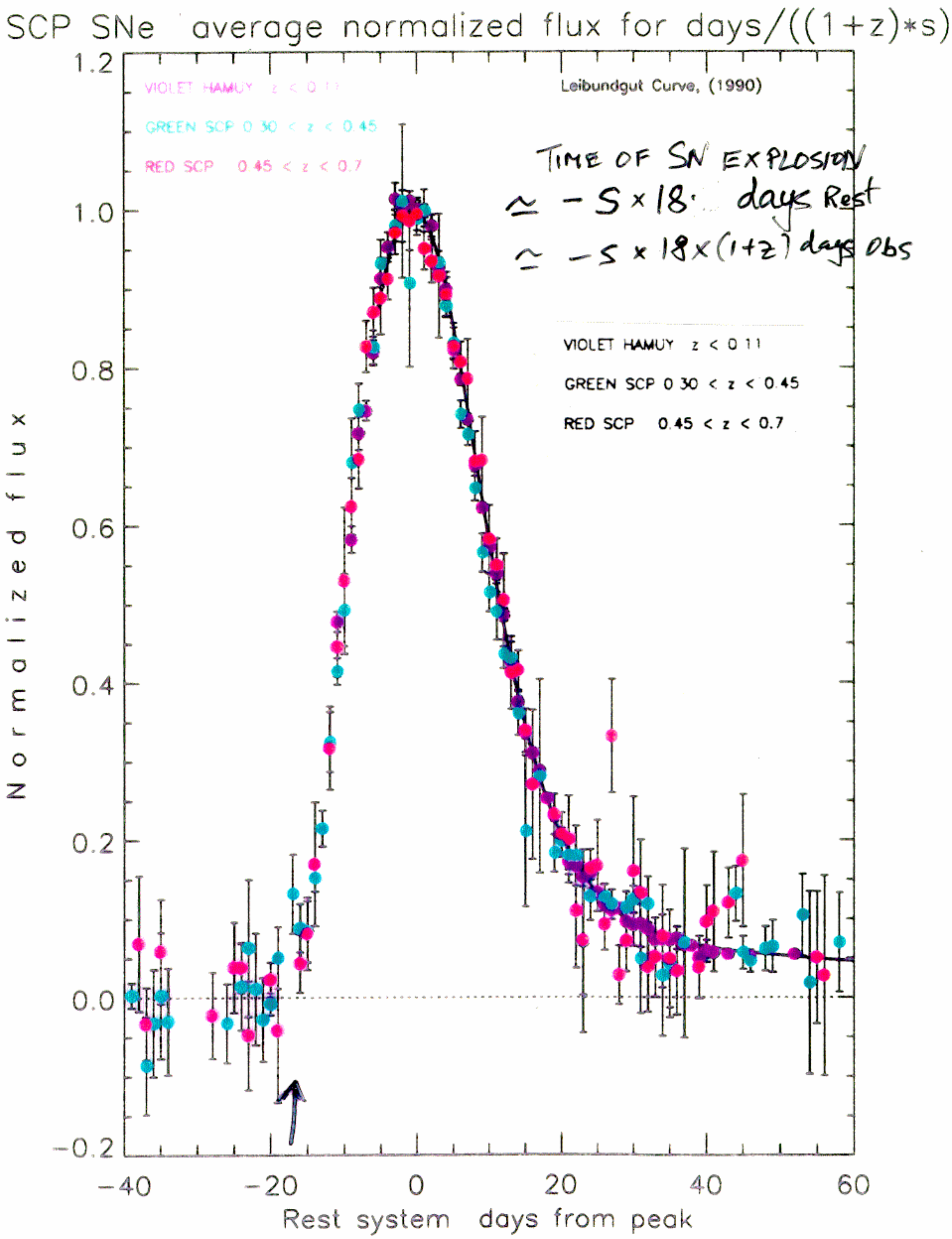


$S \simeq 0.8 - 1.2$
with a few outliers

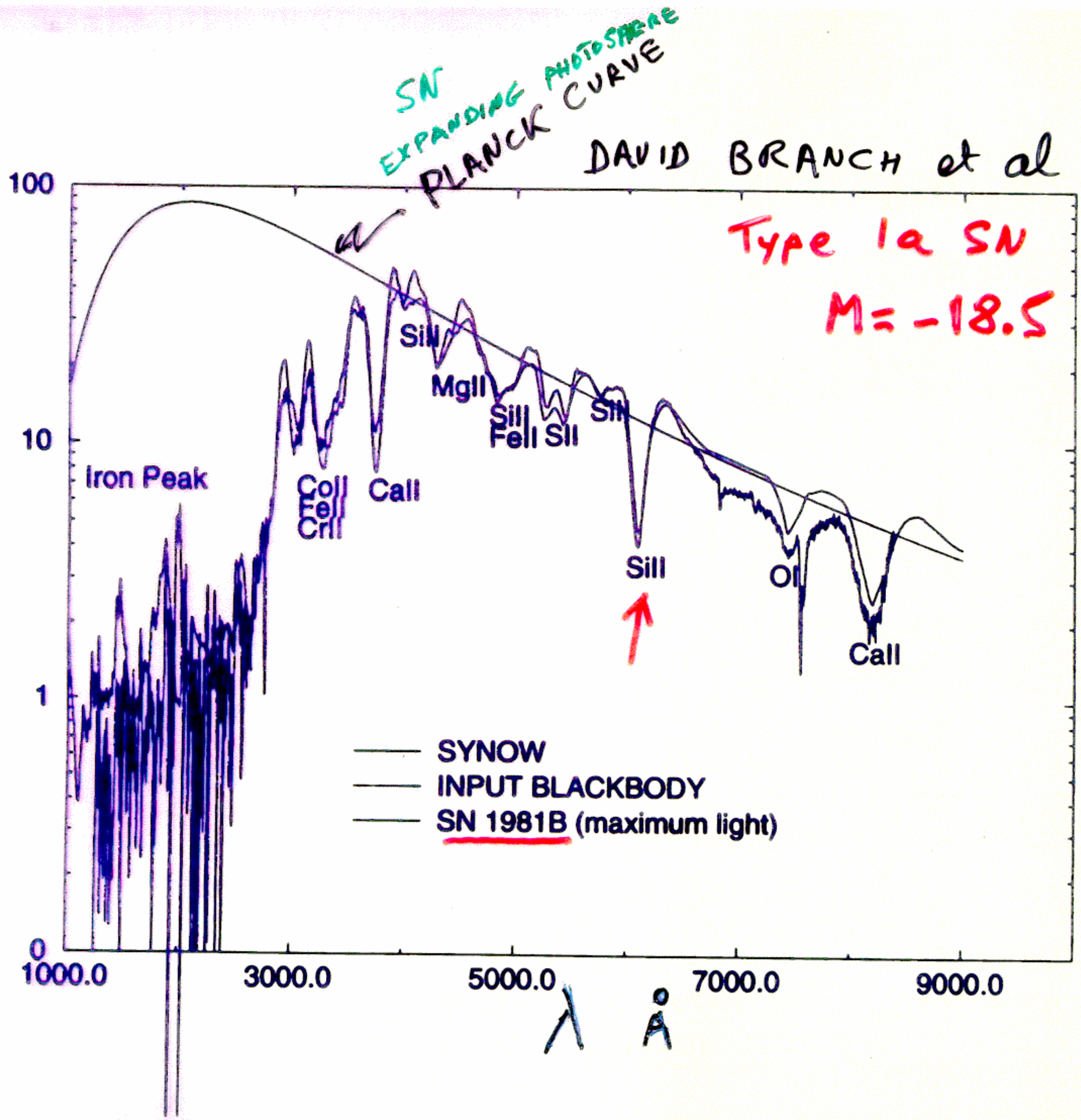



SCP SNe normalized flux for observed days k cor
VIOLET HAMUY z < 0.11
GREEN SCP 0.30 < z < 0.45
RED SCP 0.45 < z < 0.7
Normalized flux
Observer system days from peak
-40
-20
0
20
40
60
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
Sun Feb 8 14:20:09 1998


SCP SNe average normalized flux as observed b_band)
smooth,2
VIOLET HAMUY z < 0.11
GREEN SCP 0.30 < z < 0.45
RED SCP 0.45 < z < 0.7
Normalized flux
Observer system days from peak
-40
-20
0
20
40
60
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
Sun Feb 8 15:45:52 1998



Sun Feb 15 15:19:08 1998


SN
EXPANDING PHOTOSPHERE
PLANCK CURVE
DAVID BRANCH et al
Type Ia SN
M= -18.5
100
10
1
0
1000.0
3000.0
5000.0
7000.0
9000.0
λ Å
Iron Peak
CoII
FeII
CrII
CaII
SiII
MgII
SiII
FeII SII
SiII
SiII
OI
CaII
SYNOW
INPUT BLACKBODY
SN 1981B (maximum light)

P. NUGENT

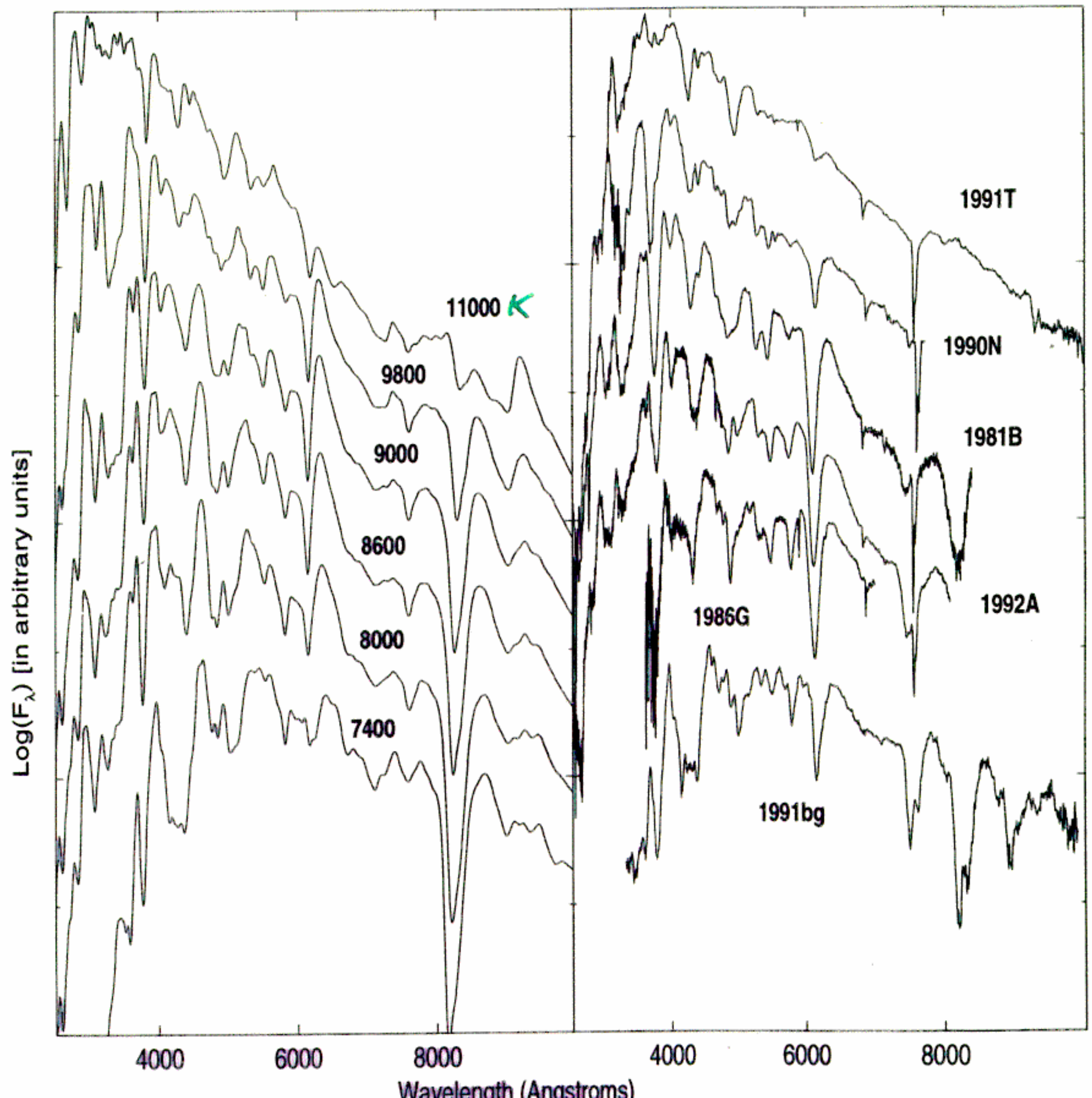
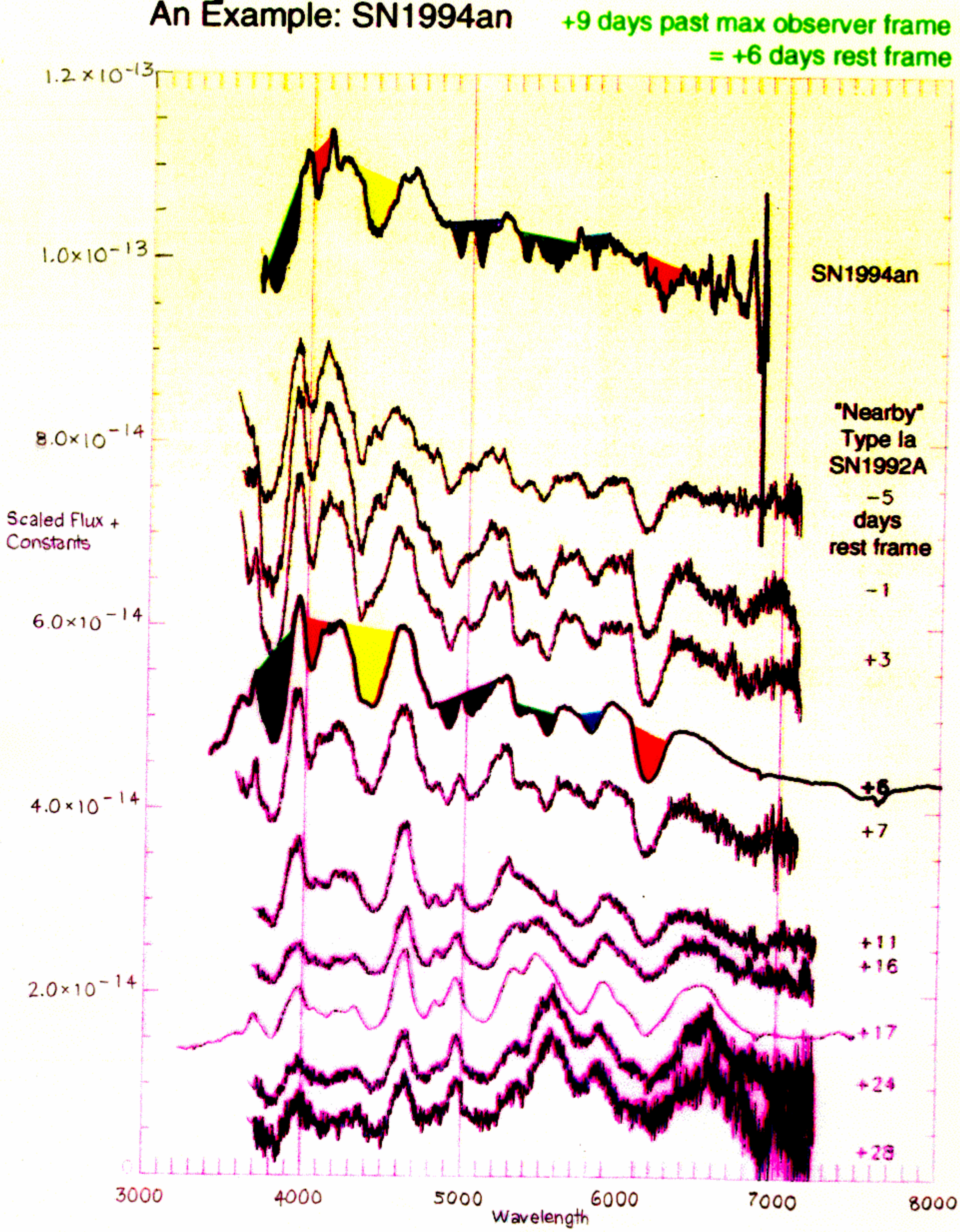


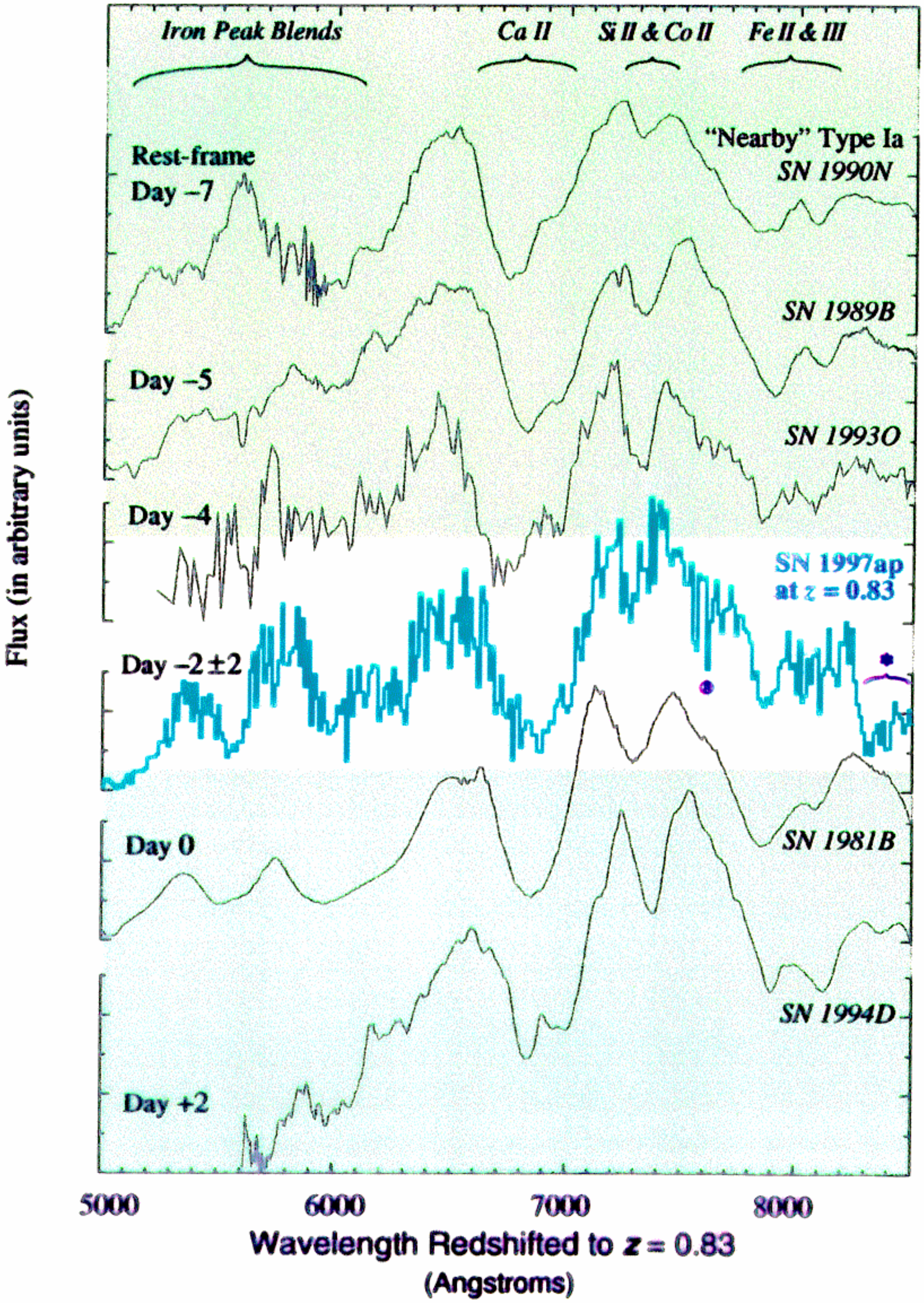
Fig. 1.— A plot of the synthetic (left) and observed (right) spectral sequences. Note the evolution in each graph of the following spectral features: Ca II at 3800 and 8200 Å, Ti II at 4200 Å and Si II at 5800 and 6150 Å.

Spectra


An Example: SN1994an
+9 days past max observer frame
= +6 days rest frame
1.2×10⁻¹³
1.0×10⁻¹³
8.0×10⁻¹⁴
6.0×10⁻¹⁴
4.0×10⁻¹⁴
2.0×10⁻¹⁴
0
Scaled Flux + Constants
SN1994an
"Nearby" Type Ia SN1992A
−5 days rest frame
−1
+3
+6
+7
+11
+16
+17
+24
+28
3000
4000
5000
6000
7000
8000
Wavelength

Supernova 1997ap
at $z = 0.83$

Perlmutter, *et al.*, Nature (1998)



−4 days (before) max observer frame
= −2 days rest frame

$\Omega = \Omega_M$ FOR A $\Lambda = 0$ UNIVERSE

$$m_B = 5 \log D_L + M_B + 25$$

$$m_B = m_R - \Delta m_{RB} - A_R - \Delta m_{cor}(s)$$

Δm_{RB} IS A "K-CORRECTION"

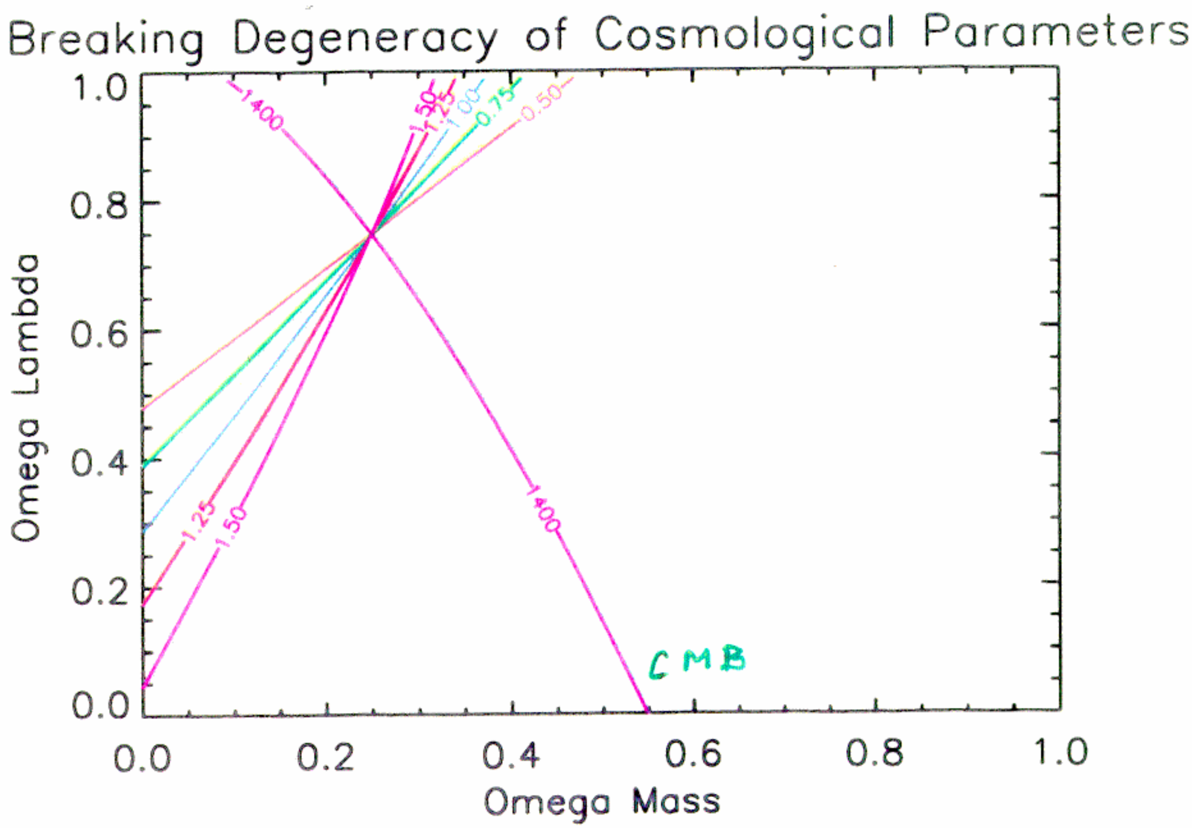
D_L IS LUMINOSITY DISTANCE

$$D_L = \frac{4c}{H_o \Omega^2} \left[1 - \Omega/2 + \Omega z/2 + (\Omega/2 - 1)(\Omega z + 1)^{1/2}\right].$$

EXPERIMENTAL INPUT:

- $M_B = -19.47 + 5 \log \frac{H_0}{65}$ ABSOLUTE B MAGNITUDE
  FROM "NEARBY" SNe
- Z FROM Red SHIFT MEASUREMENT OF SNe AT KECK 10m TELESCOPES IN HAWAII
  $$Z = \frac{\lambda - \lambda_0}{\lambda_0}$$
- m_R FROM Fit TO LIGHT CURVE
  APPARENT R MAGNITUDE.

FLAT UNIVERSE $\Omega_M + \Omega_\Lambda = 1$



GOOBAR & PERLMUTTER

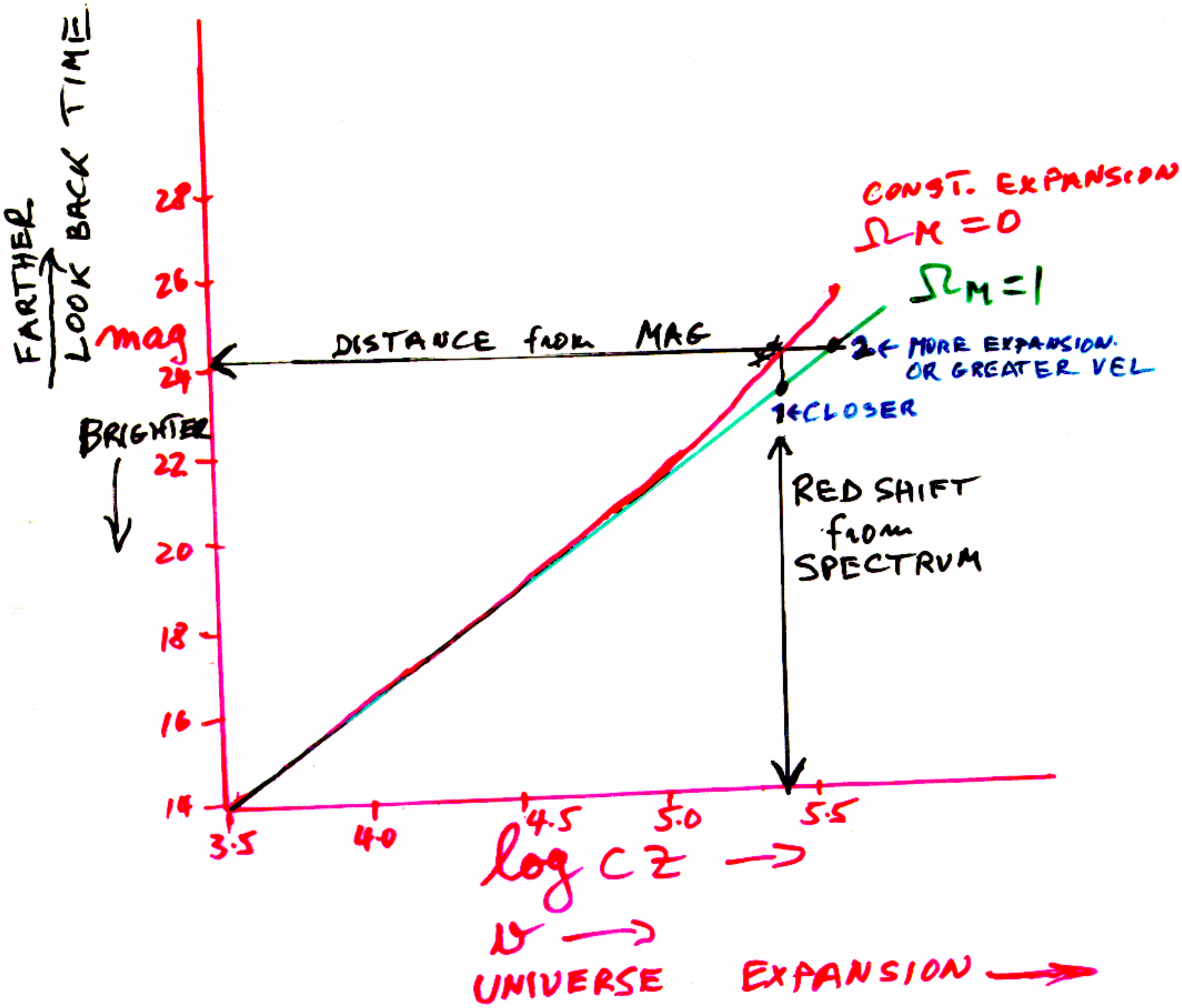
$$\Omega_{TOT} = \Omega_M + \Omega_\Lambda$$

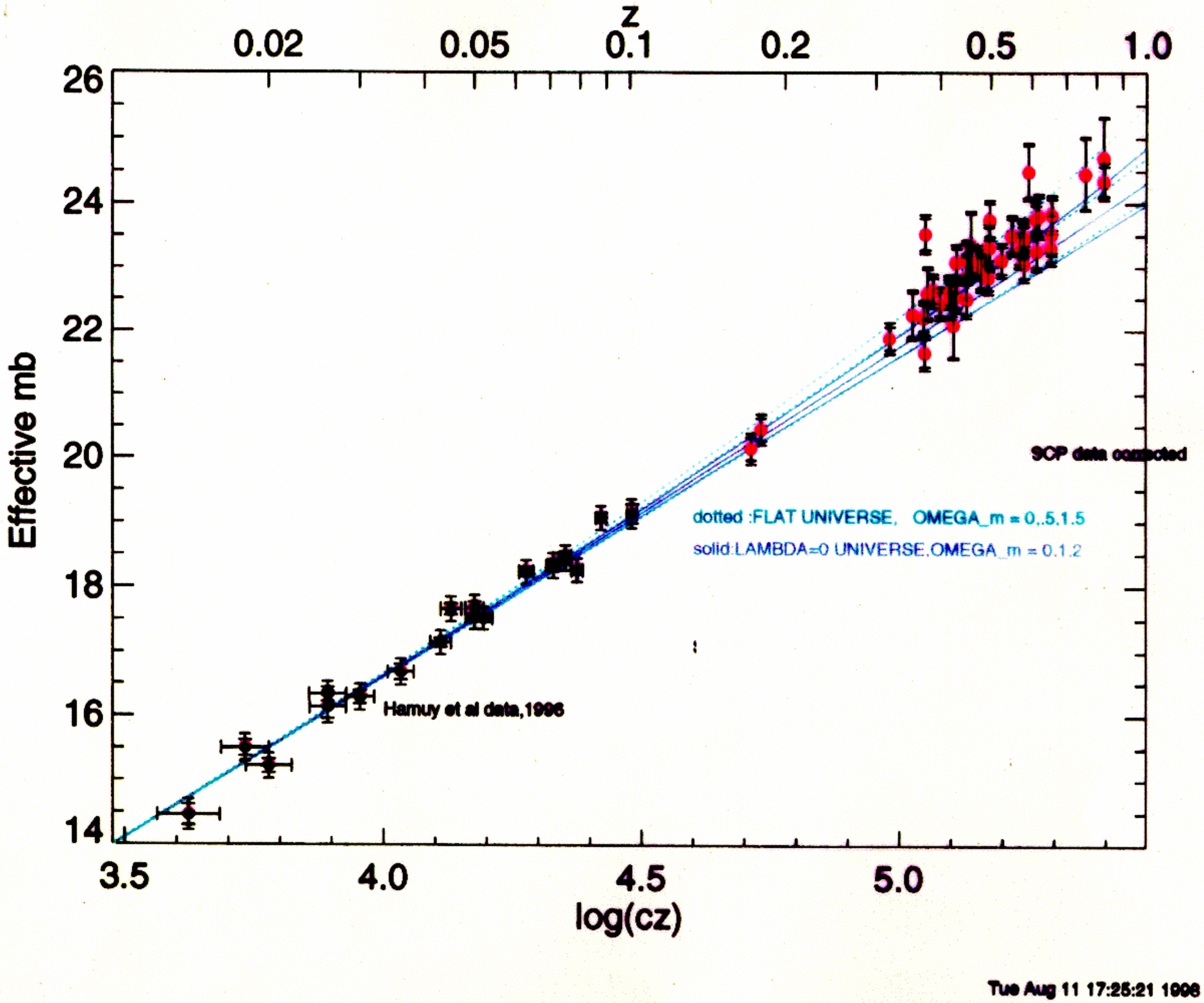
Goobar & Perlmutter (1995):

$$d_L(z;\Omega_M,\Omega_\Lambda,H_0) = \frac{c(1+z)}{H_0\sqrt{|\kappa|}} \quad \mathcal{S}\left(\sqrt{|\kappa|}\int_0^z \left[(1+z')^2(1+\Omega_M z') - z'(2+z')\Omega_\Lambda\right]^{-\frac{1}{2}} dz'\right),$$

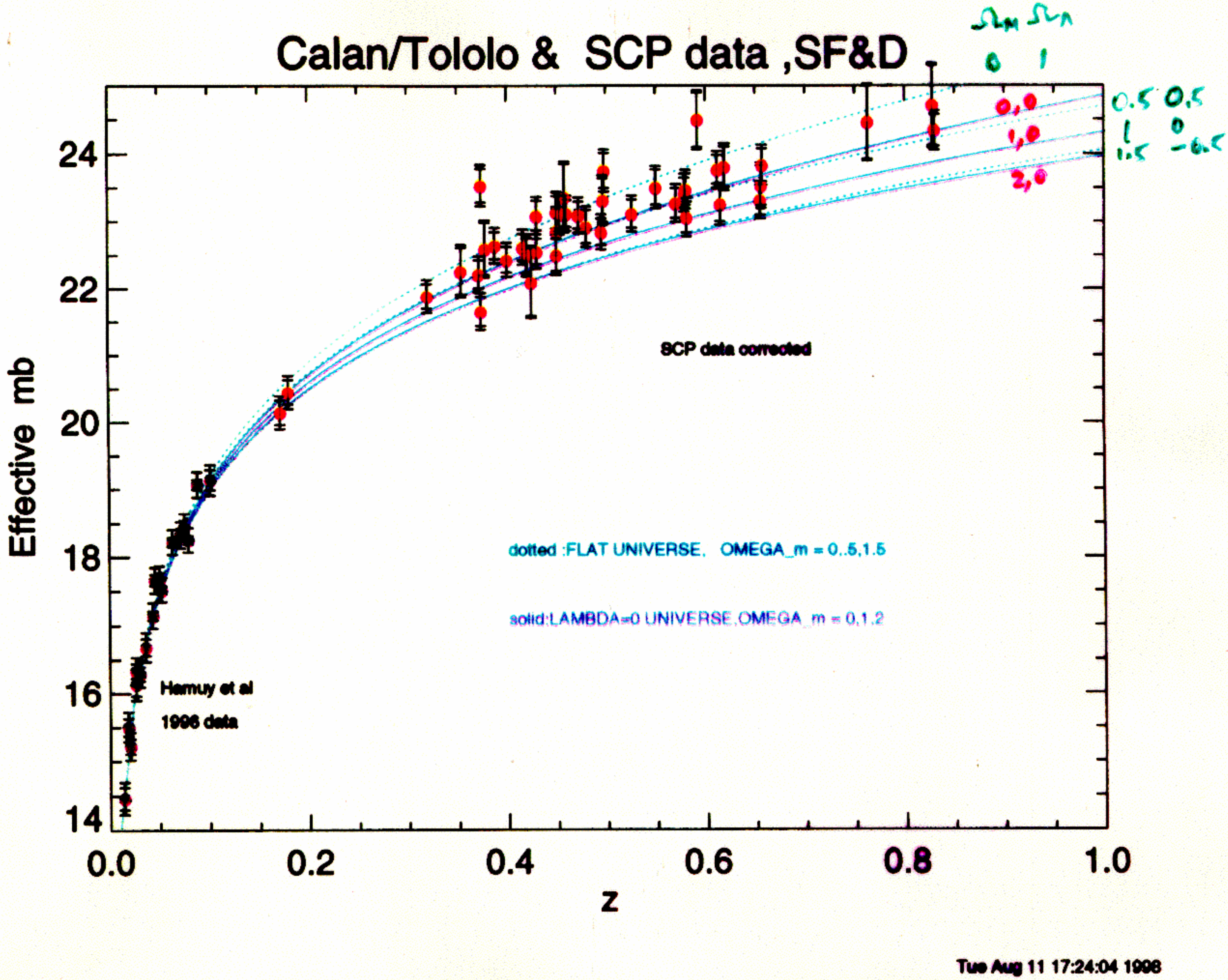
where, for $\Omega_M + \Omega_\Lambda > 1$, $\mathcal{S}(x)$ is defined as $\sin(x)$ and $\kappa = 1 - \Omega_M - \Omega_\Lambda$; for $\Omega_M + \Omega_\Lambda < 1$, $\mathcal{S}(x) = \sinh(x)$ and κ as above; and for $\Omega_M + \Omega_\Lambda = 1$, $\mathcal{S}(x) = x$ and $\kappa = 1$

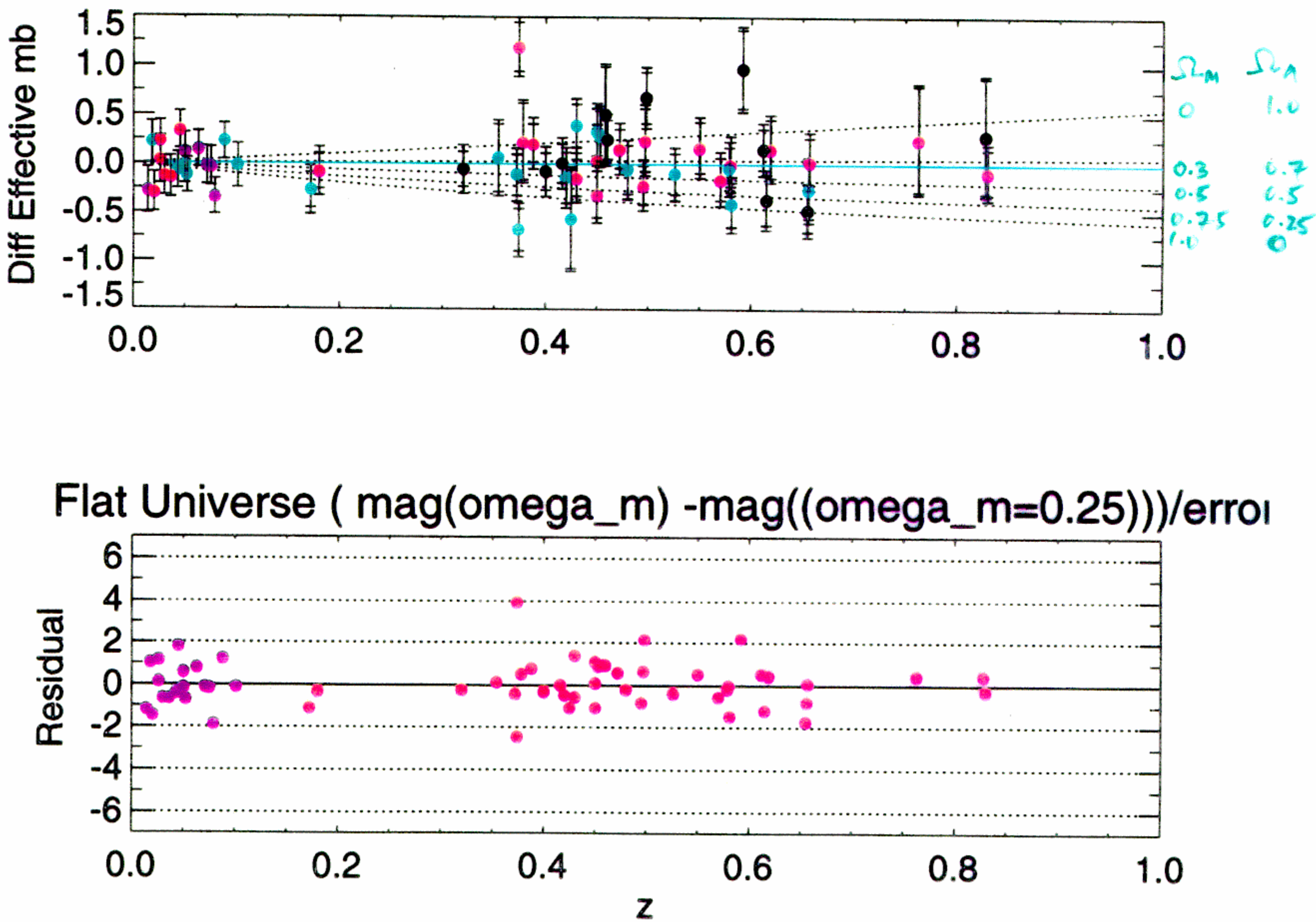
Λ = 0 UNIVERSE

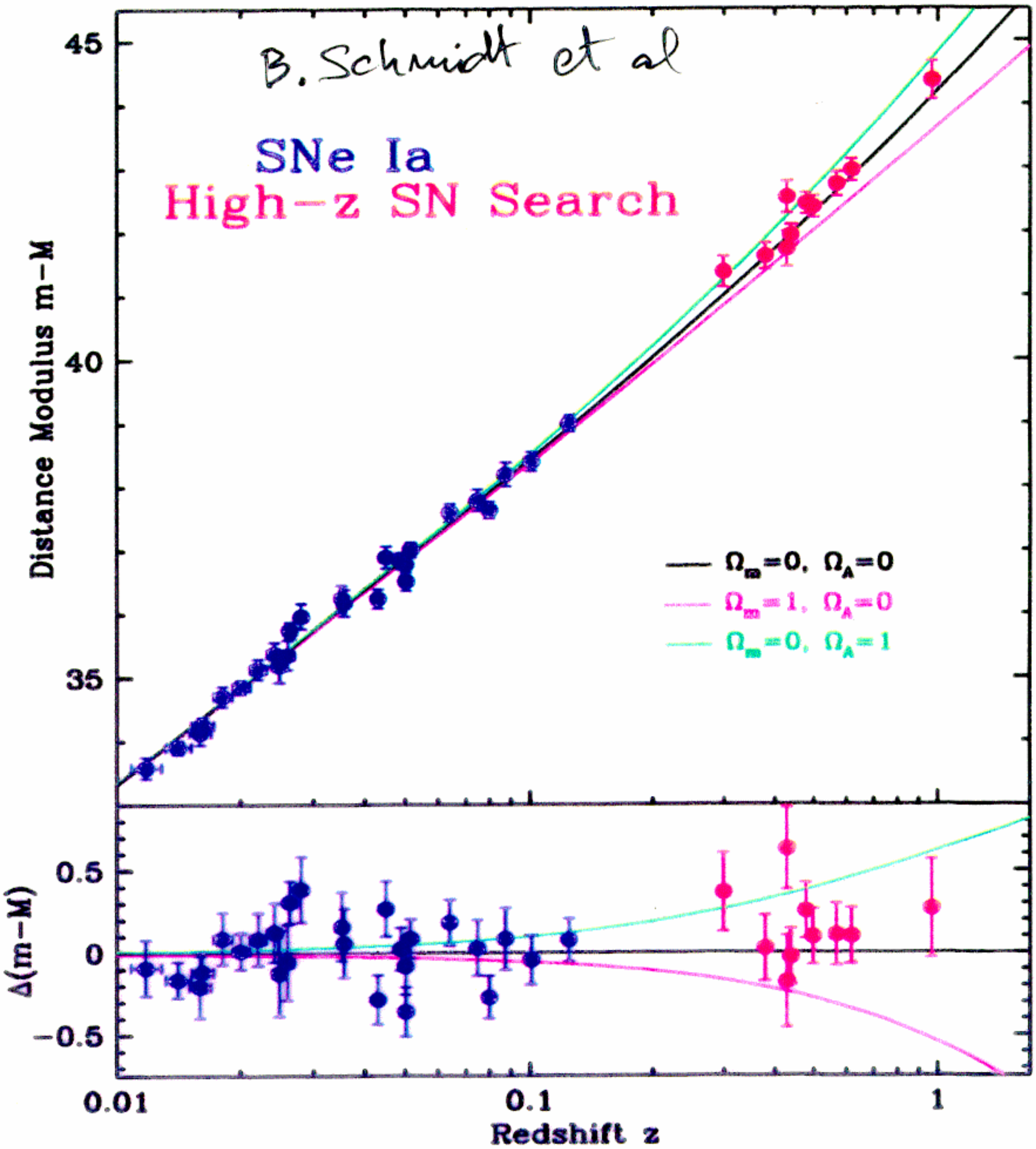

FARTHER
LOOK BACK TIME
mag
BRIGHTER
28
26
24
22
20
18
16
14
DISTANCE from MAG
CONST. EXPANSION
ΩM = 0
ΩM = 1
2 ← MORE EXPANSION.
OR GREATER VEL
1 ← CLOSER
RED SHIFT
from
SPECTRUM
3.5
4.0
4.5
5.0
5.5
log cz →
v →
UNIVERSE EXPANSION →

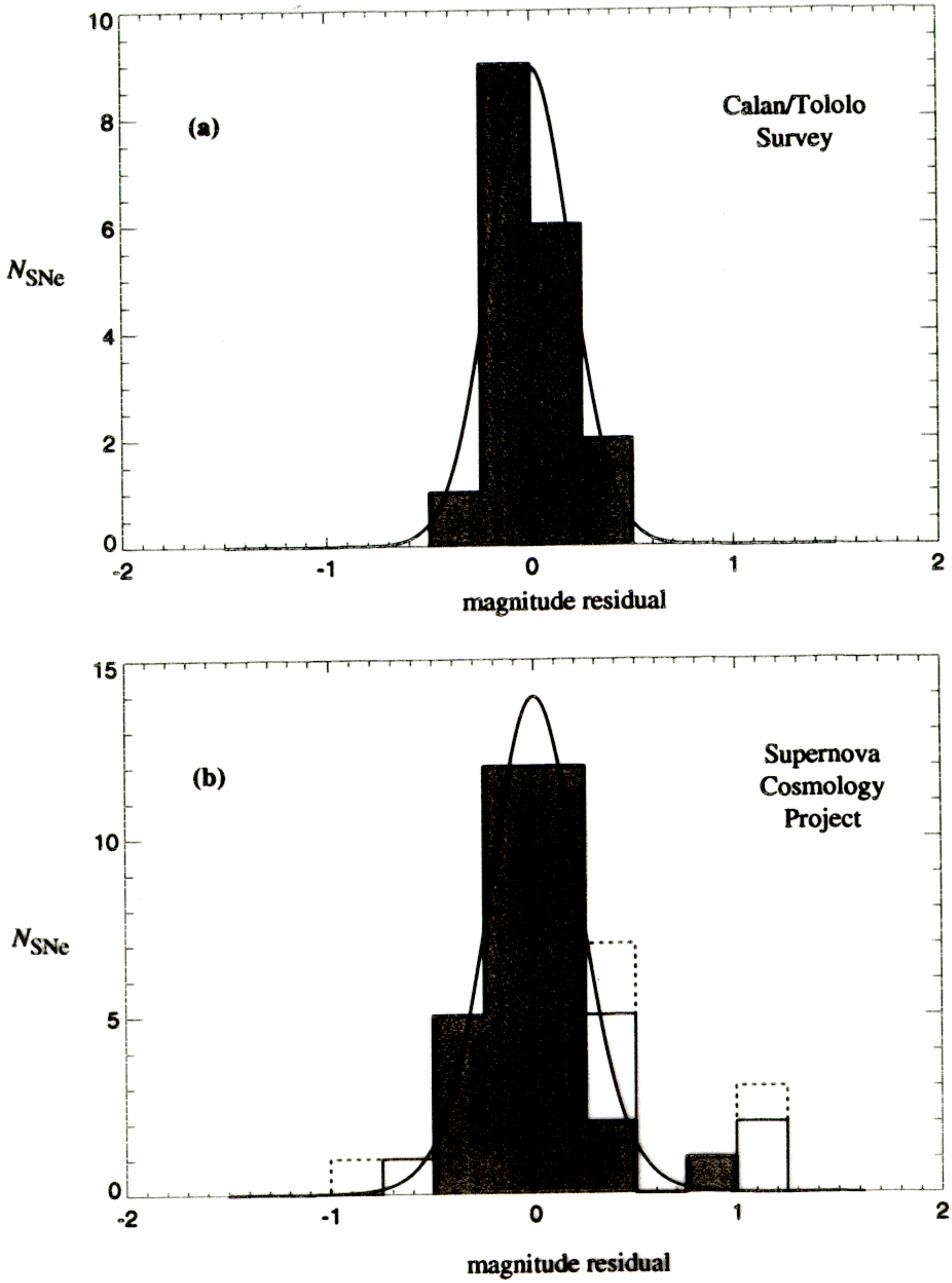

z
0.02
0.05
0.1
0.2
0.5
1.0
26
24
22
20
18
16
14
Effective mb
3.5
4.0
4.5
5.0
log(cz)
Hamuy et al data,1996
SCP data corrected
dotted :FLAT UNIVERSE, OMEGA_m = 0,.5,1.5
solid:LAMBDA=0 UNIVERSE,OMEGA_m = 0,1,2
Tue Aug 11 17:25:21 1998

Calan/Tololo & SCP data ,SF&D

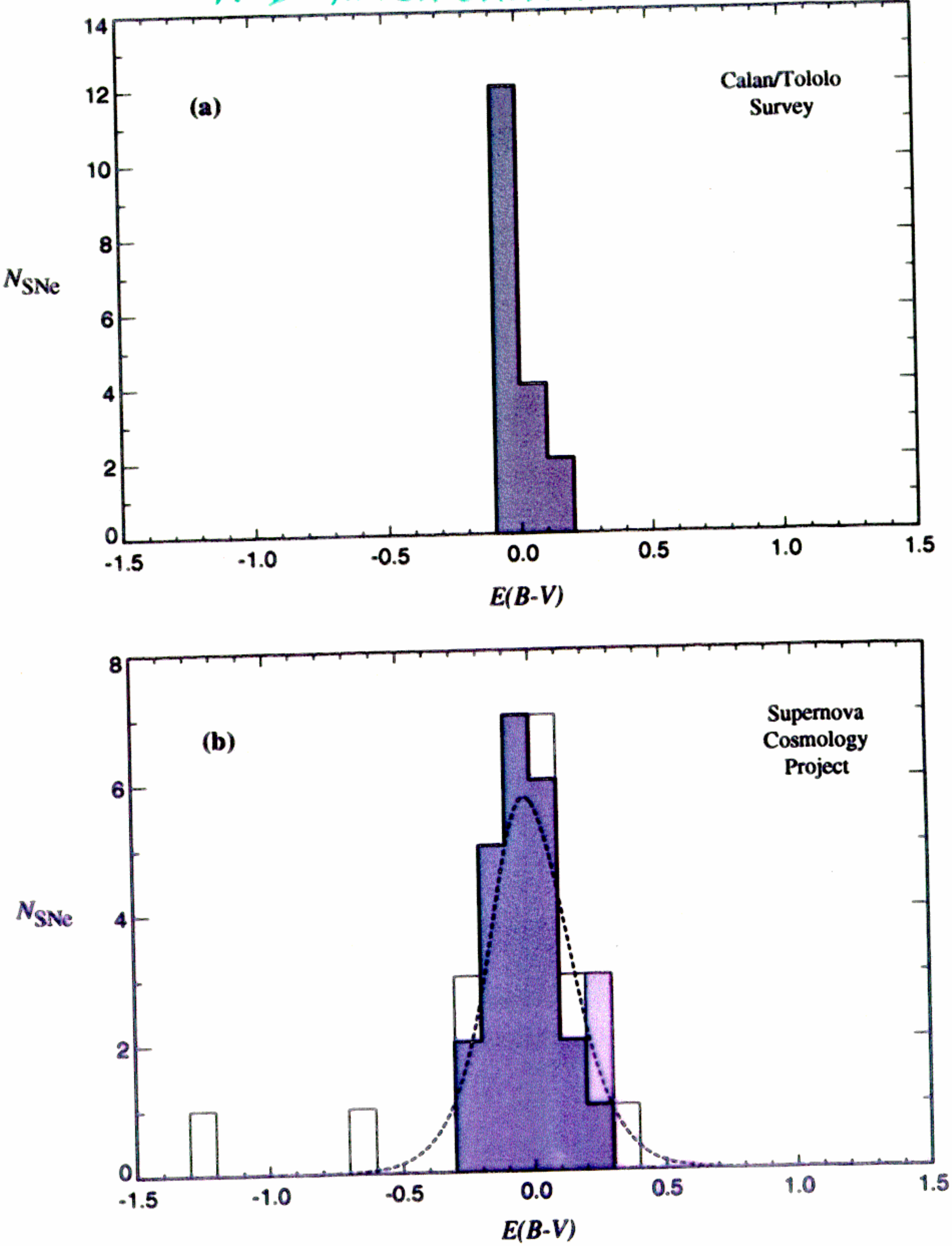


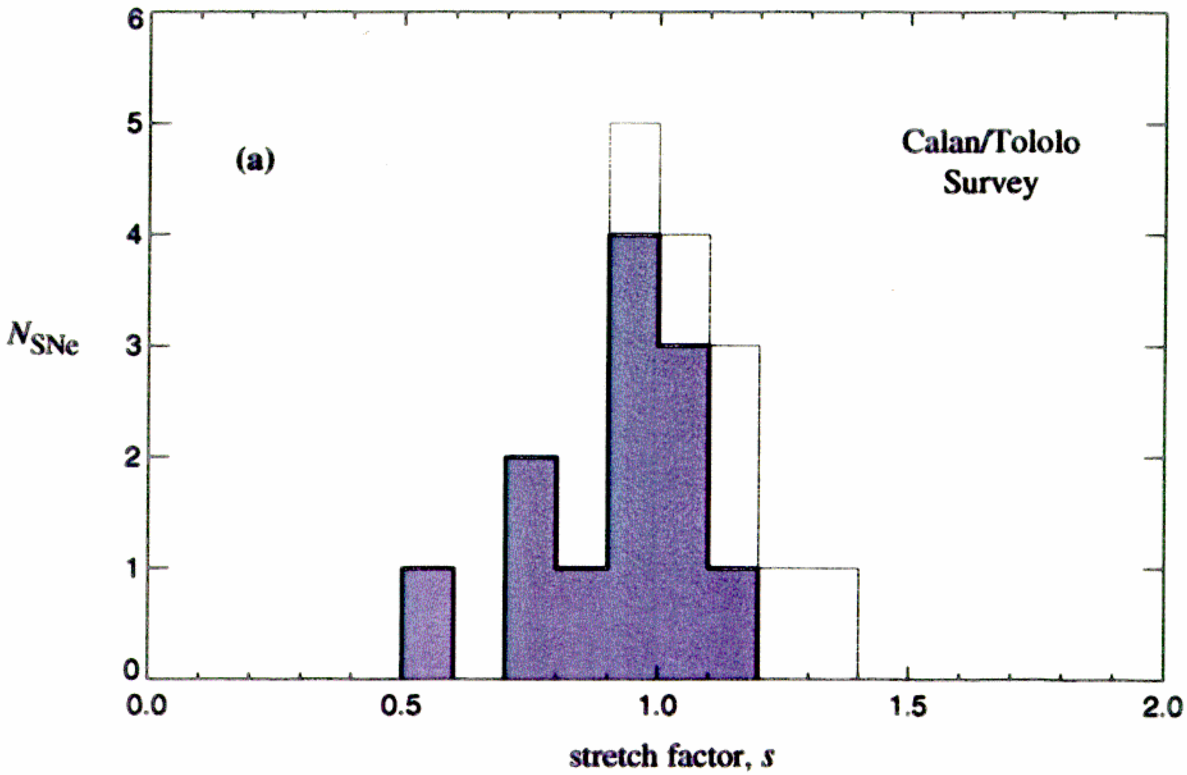

Diff Effective mb
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
0.0
0.2
0.4
0.6
0.8
1.0
Ω_M Ω_Λ
0 1.0
0.3 0.7
0.5 0.5
0.75 0.25
1.0 0
Flat Universe (mag(omega_m) -mag((omega_m=0.25)))/erroı
Residual
6
4
2
0
-2
-4
-6
z

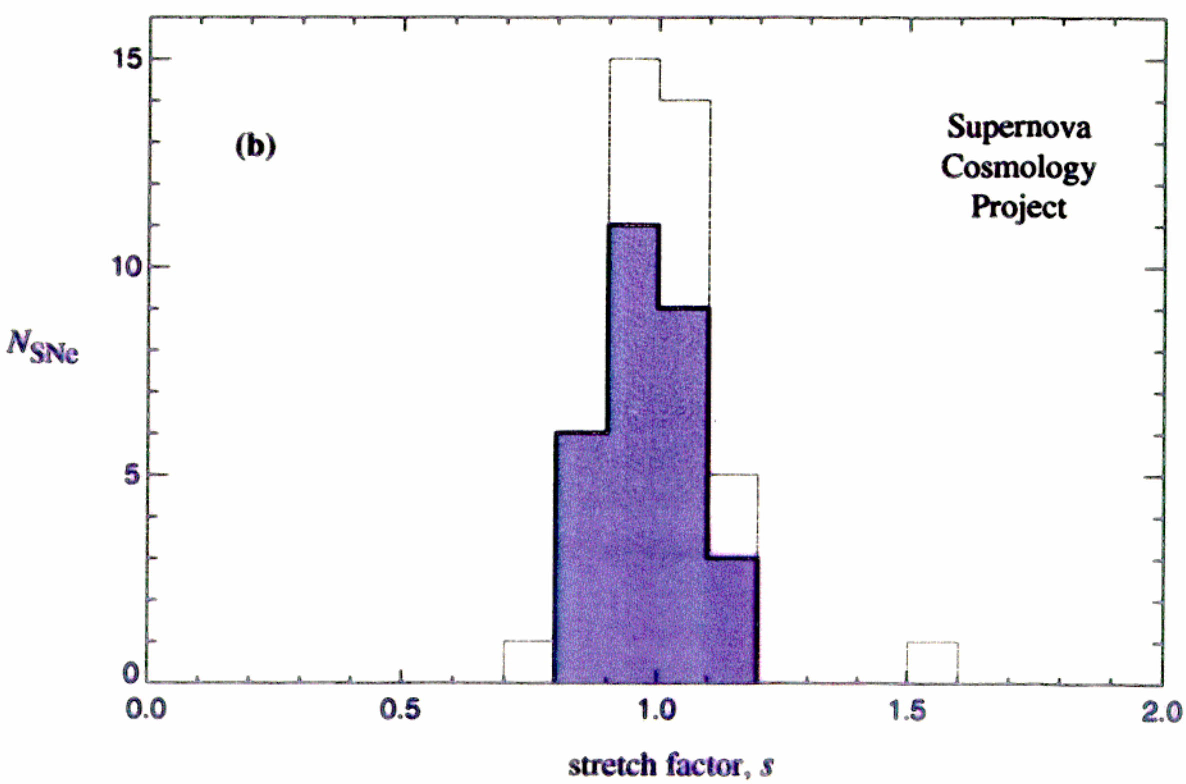

B. Schmidt et al
SNe Ia
High-z SN Search
Distance Modulus m−M
45
40
35
Ω_m=0, Ω_Λ=0
Ω_m=1, Ω_Λ=0
Ω_m=0, Ω_Λ=1
Δ(m−M)
0.5
0
−0.5
0.01
0.1
1
Redshift z

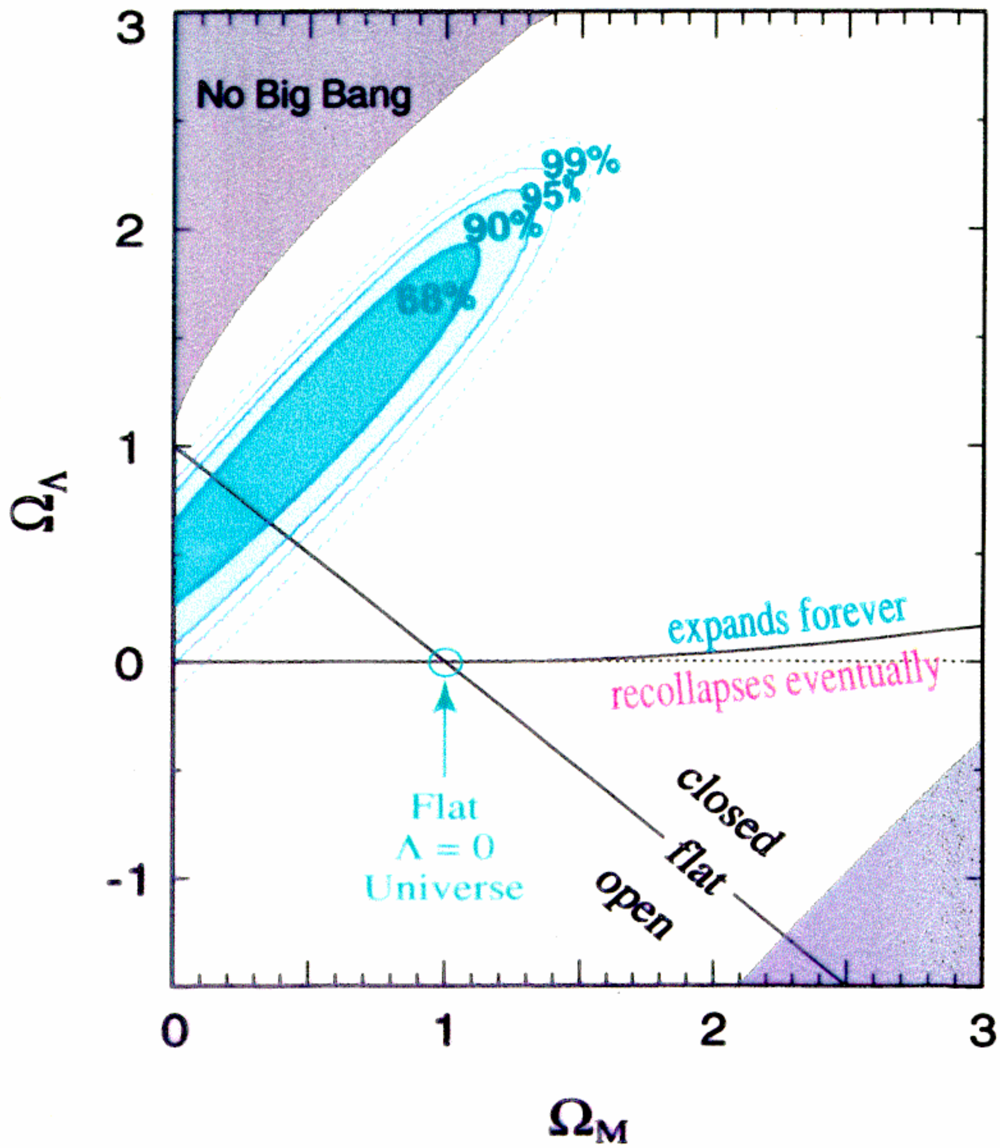

(a)
Calan/Tololo
Survey
N_{SNe}
magnitude residual
(b)
Supernova
Cosmology
Project
N_{SNe}
magnitude residual

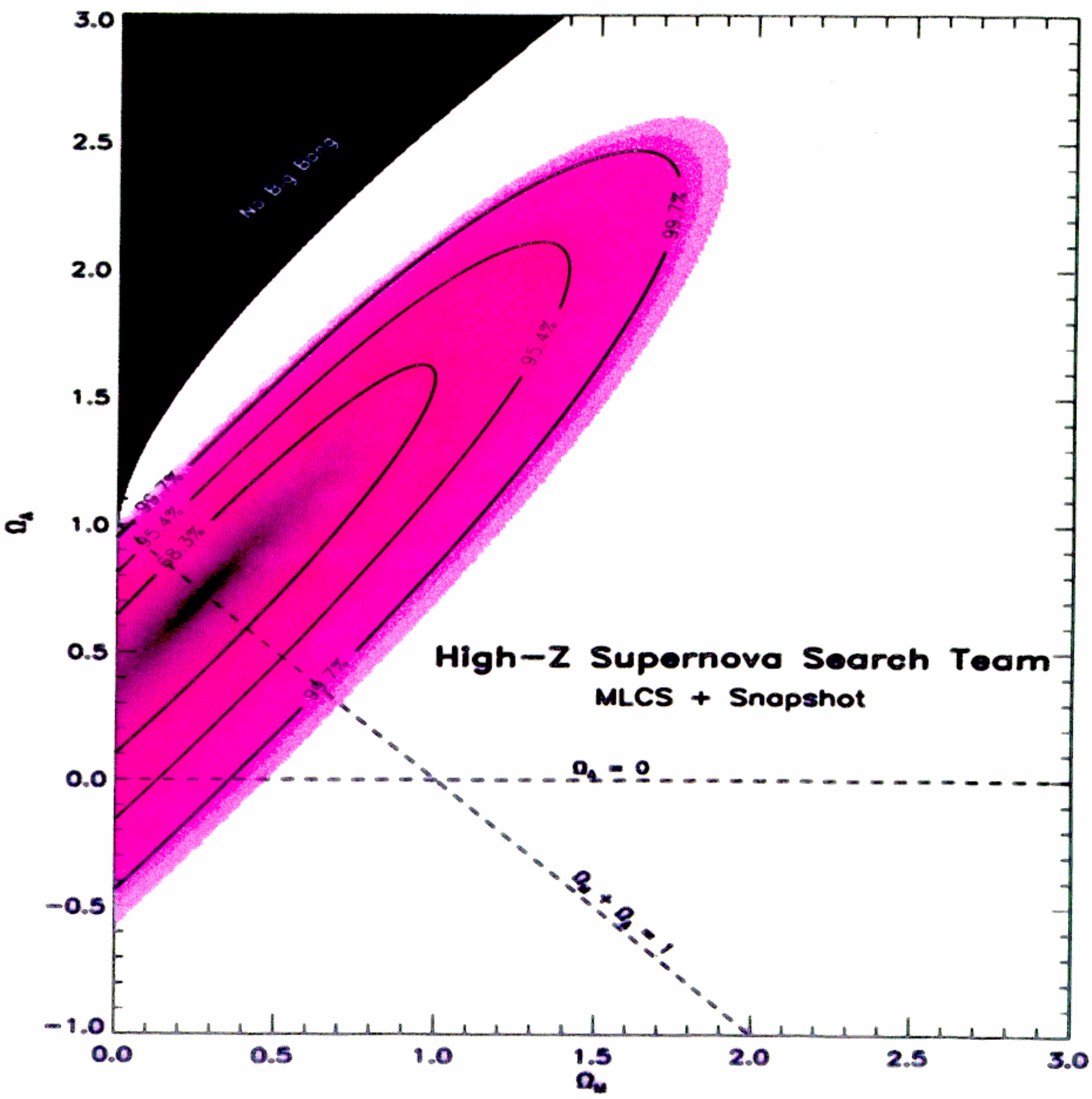
EXCESS COLOR DUE TO HOST GALAXY AND INTER GALACTIC ABSOPTION

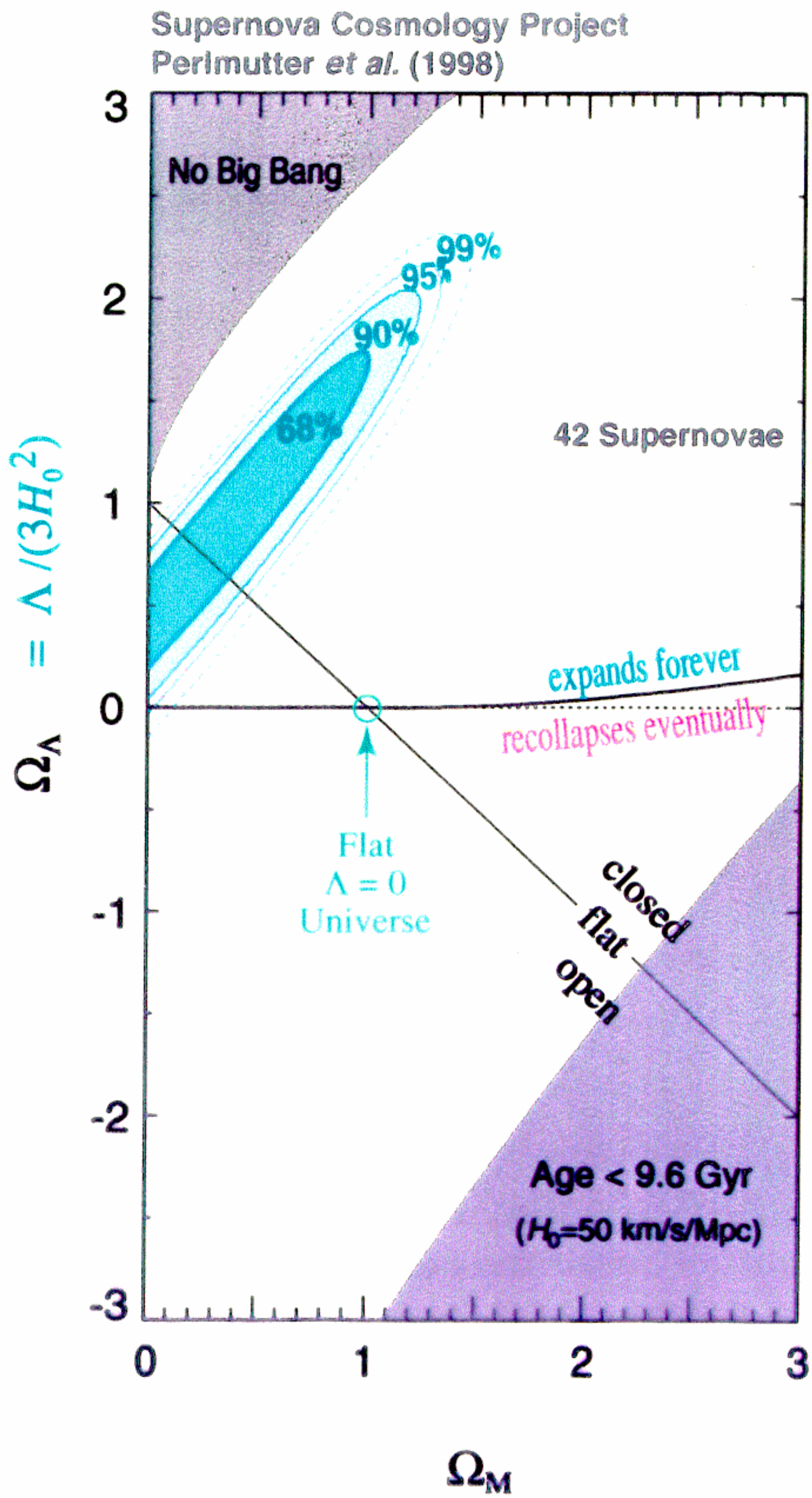


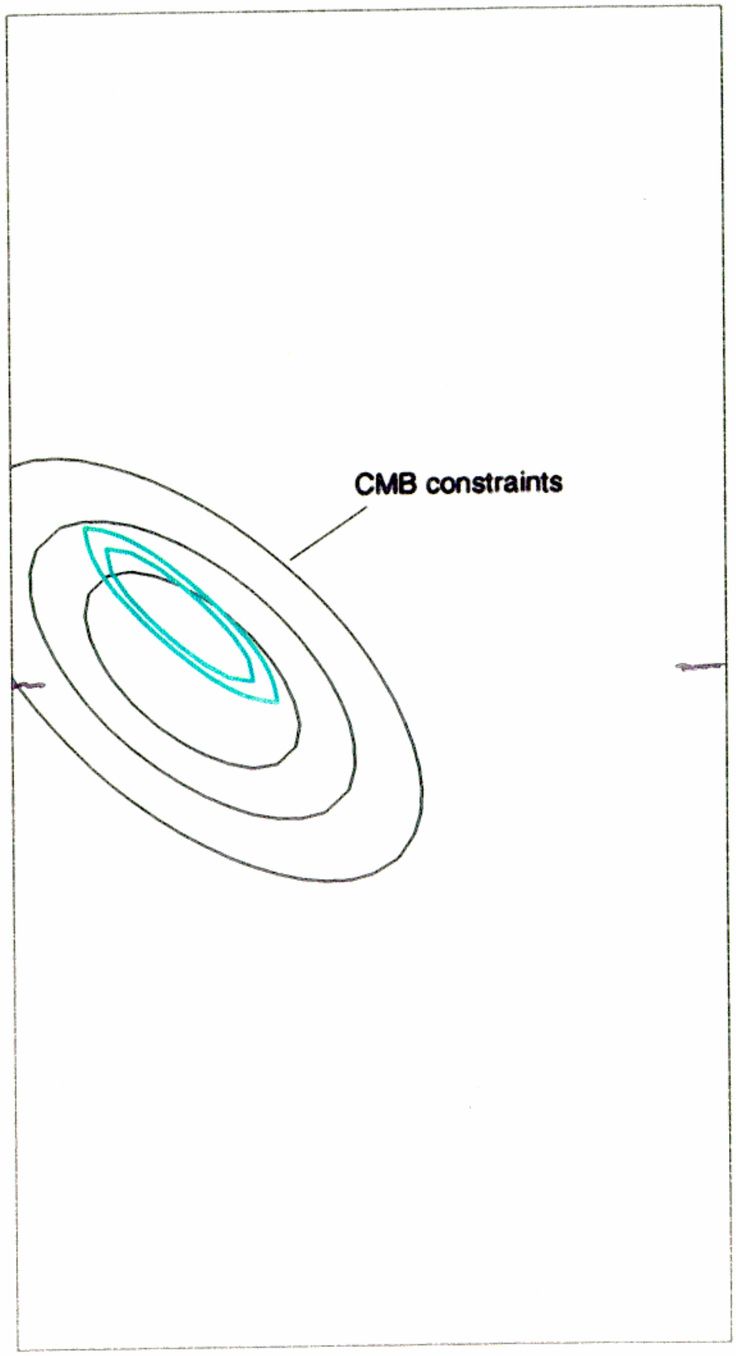

(a)
Calan/Tololo Survey
N_{SNe}
0
1
2
3
4
5
6
0.0
0.5
1.0
1.5
2.0
stretch factor, s


(b)
Supernova Cosmology Project
N_{SNe}
0
5
10
15
0.0
0.5
1.0
1.5
2.0
stretch factor, s


No Big Bang
99%
95%
90%
68%
expands forever
recollapses eventually
closed
flat
open
Flat
Λ = 0
Universe
Ω_Λ
Ω_M
3
2
1
0
-1
0
1
2
3

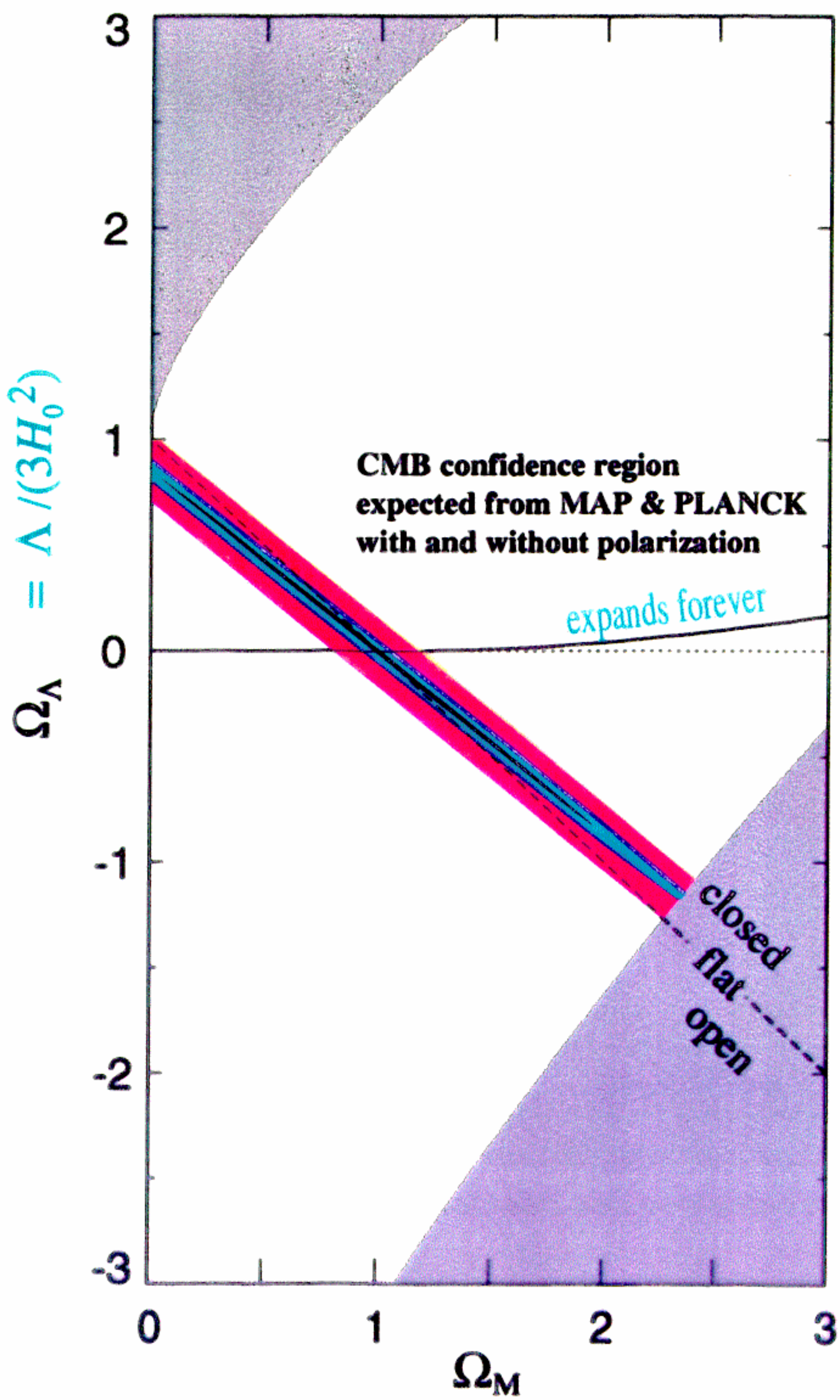

No Big Bang
99.7%
95.4%
68.3%
High−Z Supernova Search Team
MLCS + Snapshot
$\Omega_\Lambda = 0$
$\Omega_M + \Omega_\Lambda = 1$
Ω_Λ
Ω_M
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0

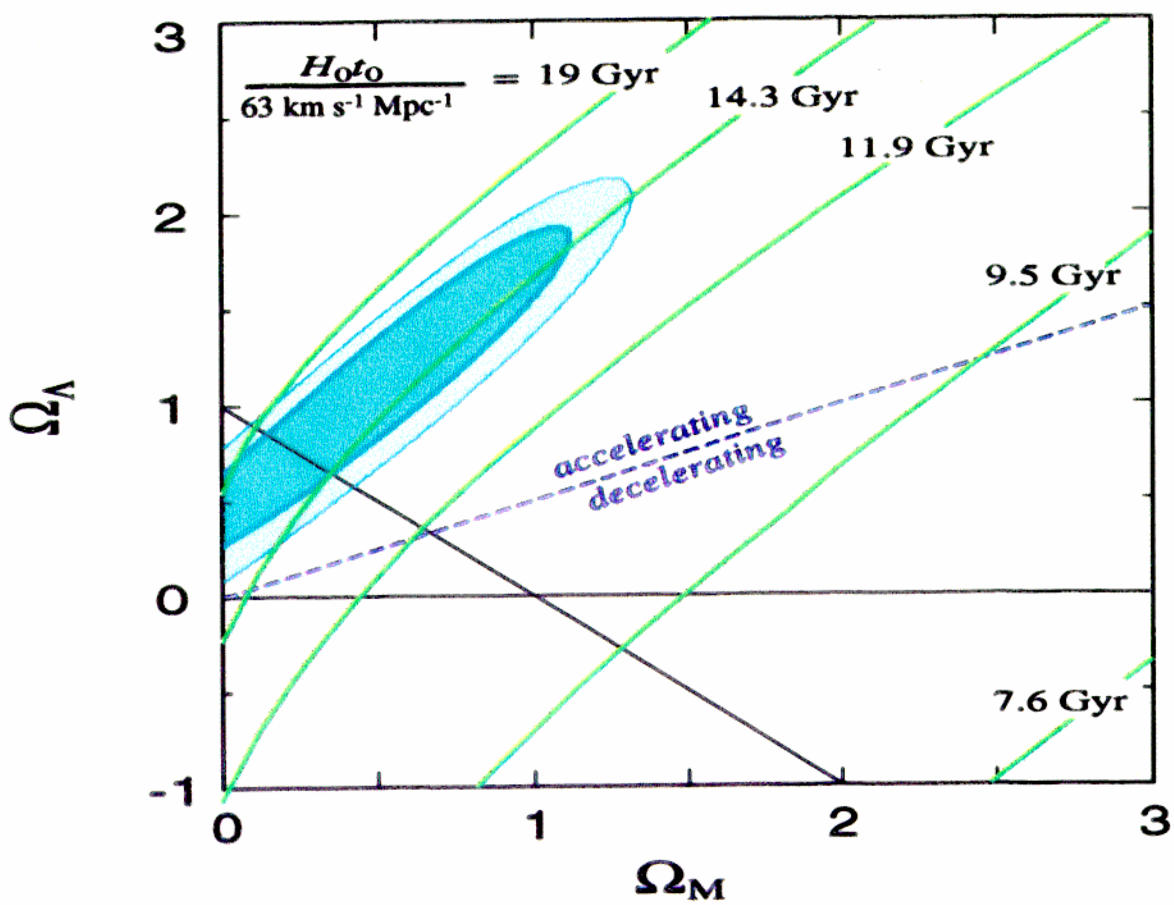

Supernova Cosmology Project
Perlmutter et al. (1998)
No Big Bang
99%
95%
90%
68%
42 Supernovae
expands forever
recollapses eventually
Flat
Λ = 0
Universe
closed
flat
open
Age < 9.6 Gyr
(H_0=50 km/s/Mpc)
$\Omega_\Lambda = \Lambda/(3H_0^2)$
Ω_M
3
2
1
0
-1
-2
-3
0
1
2
3



ESTIMATES FROM CMB DATA

Tegmark, Eisenstein, & Hu (1998)




$\frac{H_0 t_0}{63 \text{ km s}^{-1} \text{ Mpc}^{-1}}$ = 19 Gyr
14.3 Gyr
11.9 Gyr
9.5 Gyr
7.6 Gyr
accelerating
decelerating
Ω_Λ
Ω_M
3
2
1
0
-1
0
1
2
3

Recent results on Ω_M and Ω_Λ

- The Supernova Cosmology Project
  S. Perlmutter et al.

  $P(\Lambda > 0) > 98\%$

  $\Omega_M(\Omega_T = 1) = 0.30^{+0.08}_{-0.09}(\text{stat})^{+0.05}_{-0.03}(\text{syst})$

$$1.3\Omega_M - \Omega_\Lambda \simeq -0.4$$

- The High-z Supernova Search Team
  B. Schmidt et al.

$$\Omega_M(\Lambda = 0) = -0.35 \pm 0.18$$

$$\Omega_M(\Omega_T = 1) = 0.24 \pm 0.1$$

- $\Omega_M = 1, \Lambda = 0$ strongly excluded
- $\Omega_\Lambda > 0$ at $\sim 98\% C.L.$
- The Universe will expand forever
- $q_0 < 0$, expansion currently accelerating
  $(q_0^{flat} = -0.55 \pm 0.15)$

WHEN DID THE MATTER DOMINATED UNIVERSE TURN TO Λ DOMINATED?

$$(1+z)^3 \Omega_M = \Omega_\Lambda$$

$$z = 0.33$$

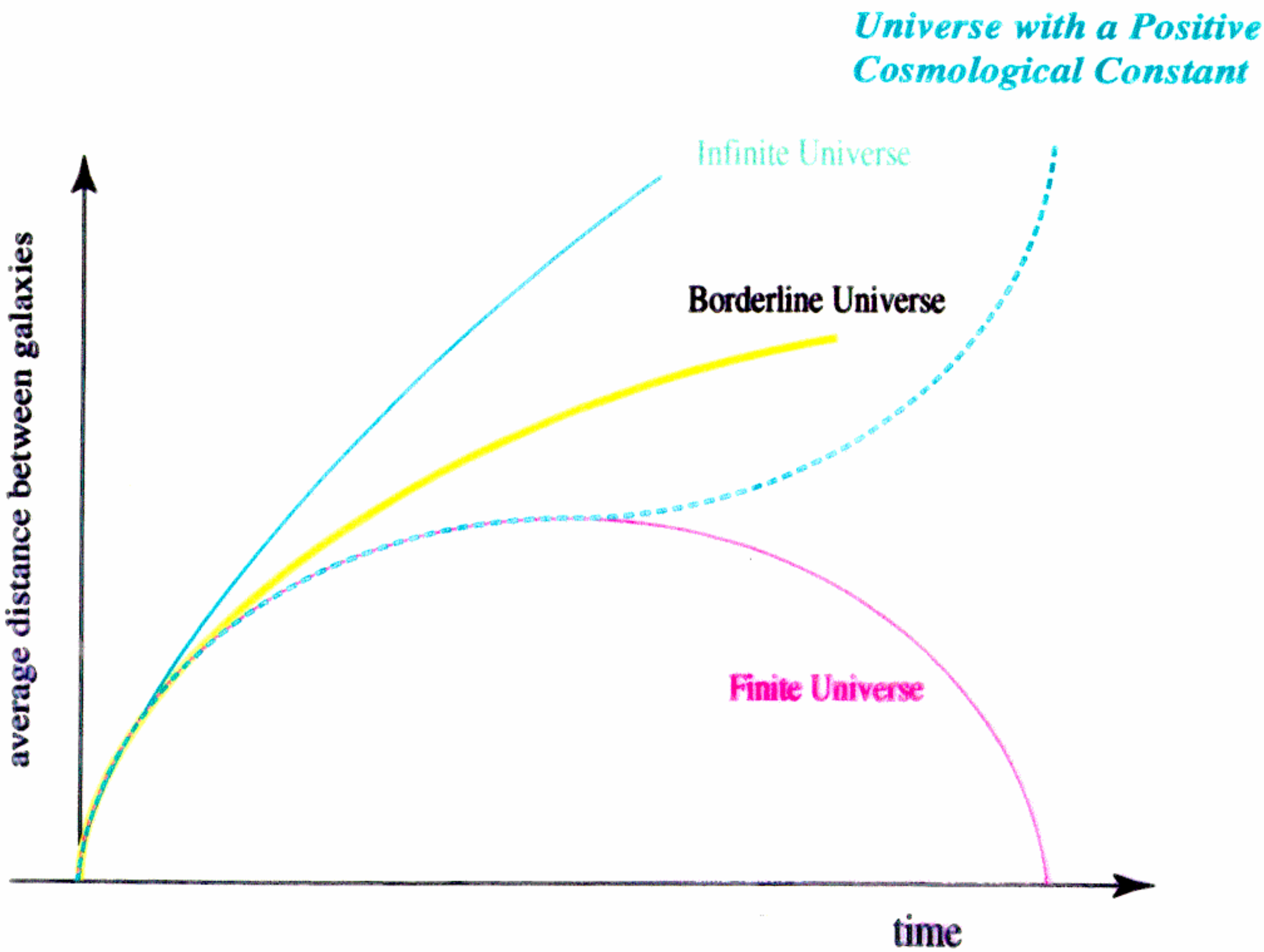
WHEN DID DECELERATION TURN TO ACCELERATION OF THE UNIVERSE?

$$q = \frac{\Omega_M}{2} - \Omega_\Lambda$$

$$(1+z)^3 \frac{\Omega_M}{2} = \Omega_\Lambda$$

$$z = 0.67$$

BOTH OCCURED DURING THE PERIODS OUR SNe WERE EXPLODING!



Universe with a Positive Cosmological Constant
Infinite Universe
Borderline Universe
Finite Universe
average distance between galaxies
time

FIRE AND ICE

By Robert Frost

Some say the world will end in fire,
Some say in ice.
From what I've tasted of desire
I hold with those who favor fire.
But if it had to perish twice,
I think I know enough of hate
To say that for destruction ice
Is also great
And would suffice.