The Status of the Cosmological Parameters: Supernovae, Dark Energy, and the Accelerating Universe

Lepton Photon 99
Stanford University, August 1999

Saul Perlmutter
Supernova Cosmology Project
Lawrence Berkeley National Laboratory
Center for Particle Astrophysics, U.C. Berkeley

at LBNL:

Gerson Goldhaber
Greg Aldering
Don Groom
Carl Pennypacker
Alex Kim
Peter Nugent
Rob Knop
Susana Deustua
Matthew Kim
Reynald Pain (France)
Ariel Goobar (Sweden)
Isobel Hook (Germany)
Sebastien Fabbro (France)

Cambridge:
Richard Ellis
Richard McMahon
Mike Irwin

UCB:
Alex Filippenko

ESO:
Chris Lidman

Fermilab:
Heidi Newberg

Yale:
Brad Schaefer

+ others

http://supernova.LBL.gov

Ap.J. ⟶ **astro-ph/9812133**

High-Z Supernova Search Team

Brian Schmidt
(MSSSO)

Adam Riess, Alex Filippenko
(UCB)

Nick Suntzeff, Mark Phillips,
Bob Schommer, Alejandro Clocchiatti
(CTIO)

Bob Kirshner, Peter Garnavich,
Pete Challis, Saurabh Jha
(CfA)

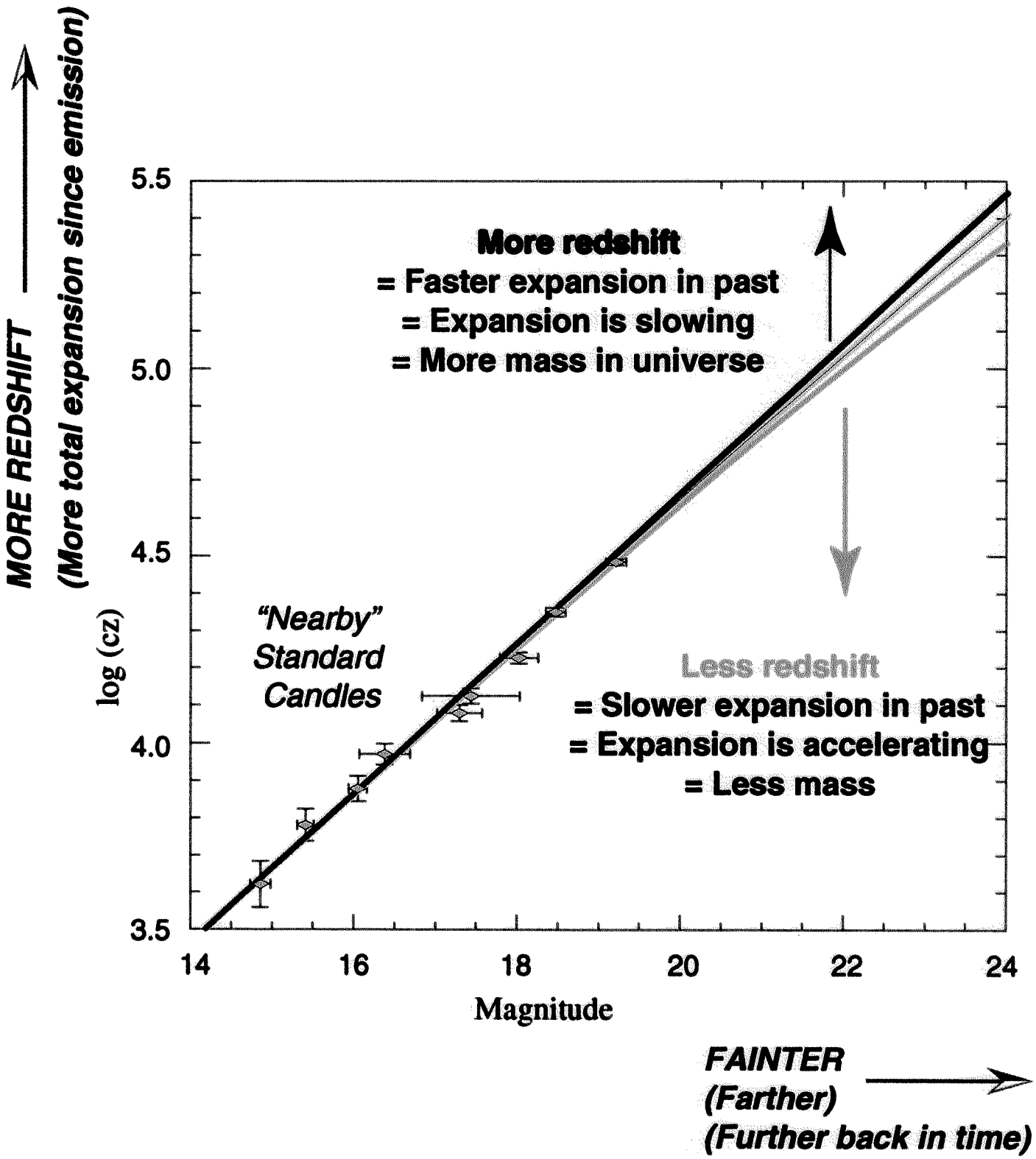
Craig Hogan, Chris Stubbs
David Reiss, Al Dierks
(UW)

Bruno Leibundgut, Jason Spyromilio (ESO)

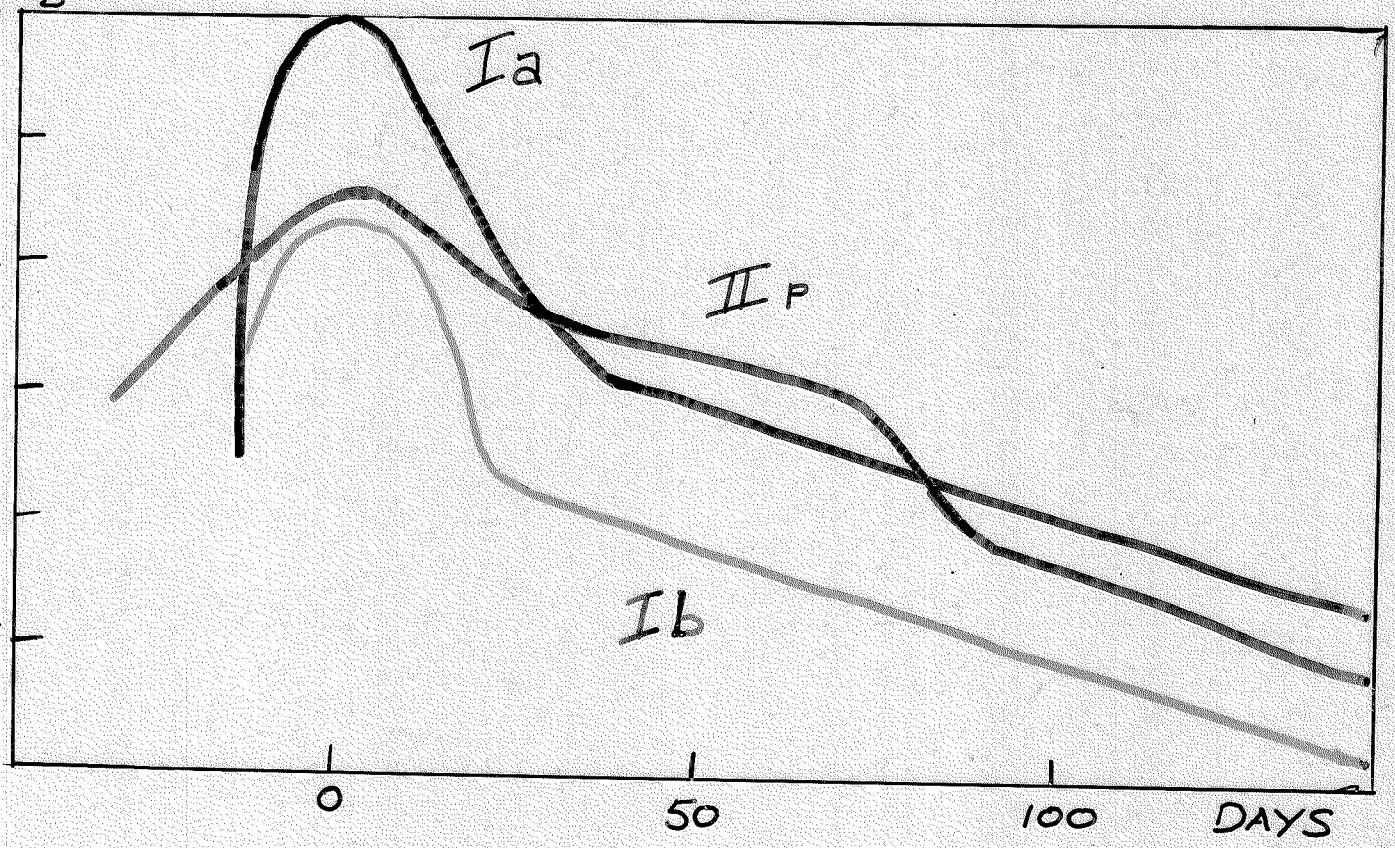
Chris Smith
(UM)

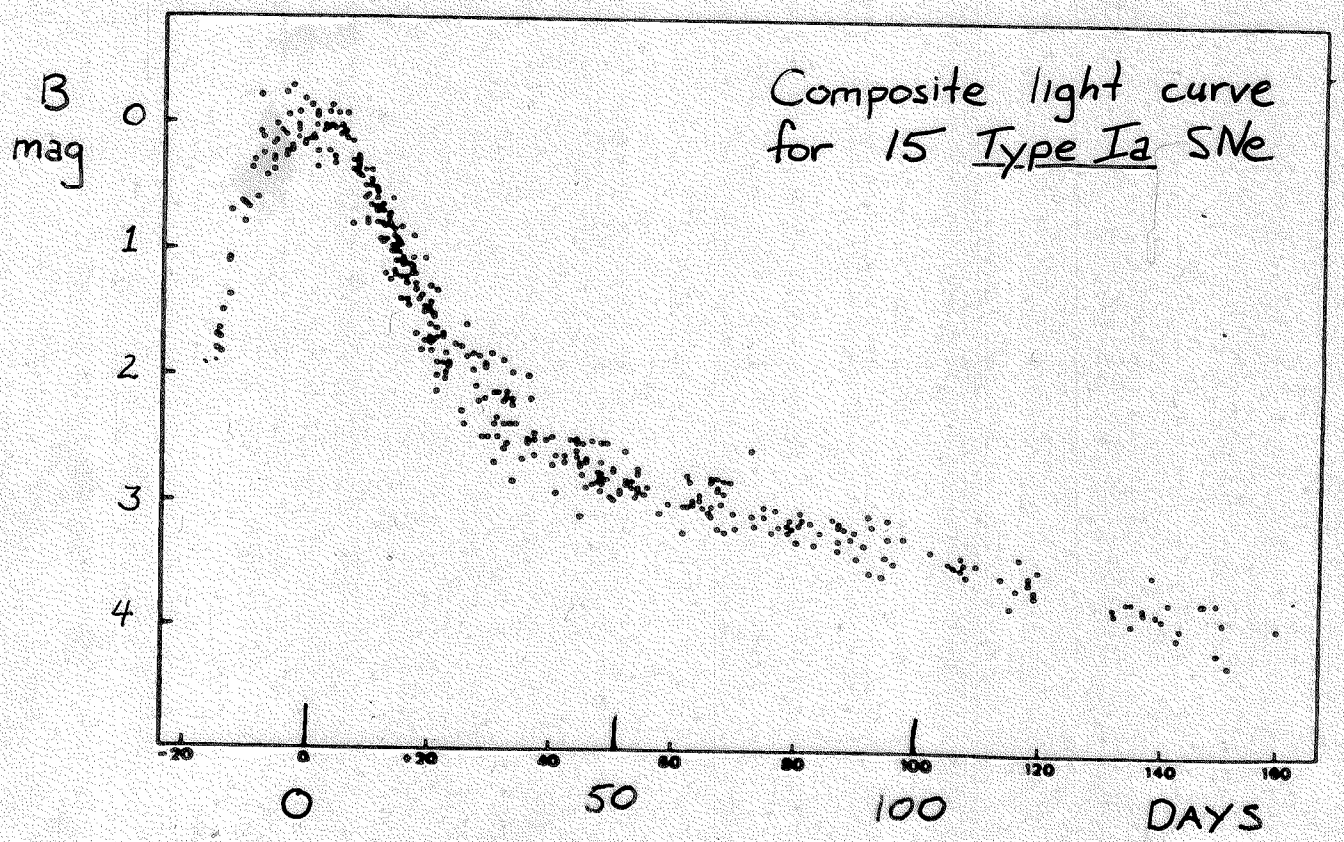
John Tonry
(UH)

Ron Gilliand
(STScI)


MORE REDSHIFT
(More total expansion since emission)
5.5
5.0
4.5
4.0
3.5
log (cz)
More redshift
= Faster expansion in past
= Expansion is slowing
= More mass in universe
"Nearby"
Standard
Candles
Less redshift
= Slower expansion in past
= Expansion is accelerating
= Less mass
14
16
18
20
22
24
Magnitude
FAINTER
(Farther)
(Further back in time)

SUPERNOVA LIGHT CURVES





Baade (1938)	Supernovae @ max as a Standard Candle for cosmological measurements
Tammann (1979, 1984) Colgate (1979)	Type I SNe to measure deceleration parameter, q_0 (with HST!)
Nørgaard-Nielsen et al. (1989)	Intensive search for high-redshift SNe finds one in two years, of Type Ia (several weeks past max)

PROBLEMS

with SNe Ia as tool for cosmology

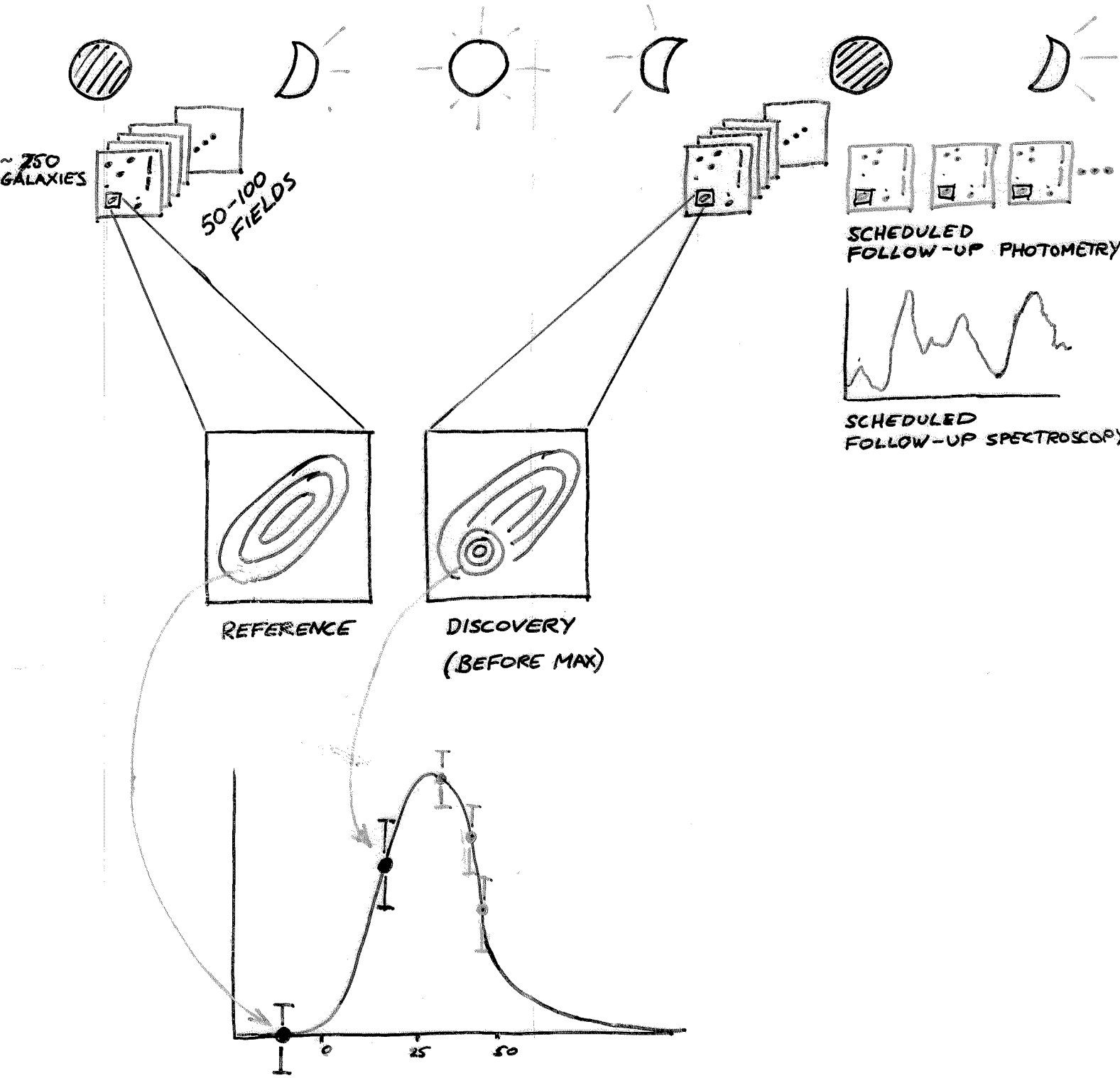
Rare ~1 / 500 years / galaxy

Random can't schedule telescope time or plan discoveries at new moon

Fast difficult to catch before maximum light

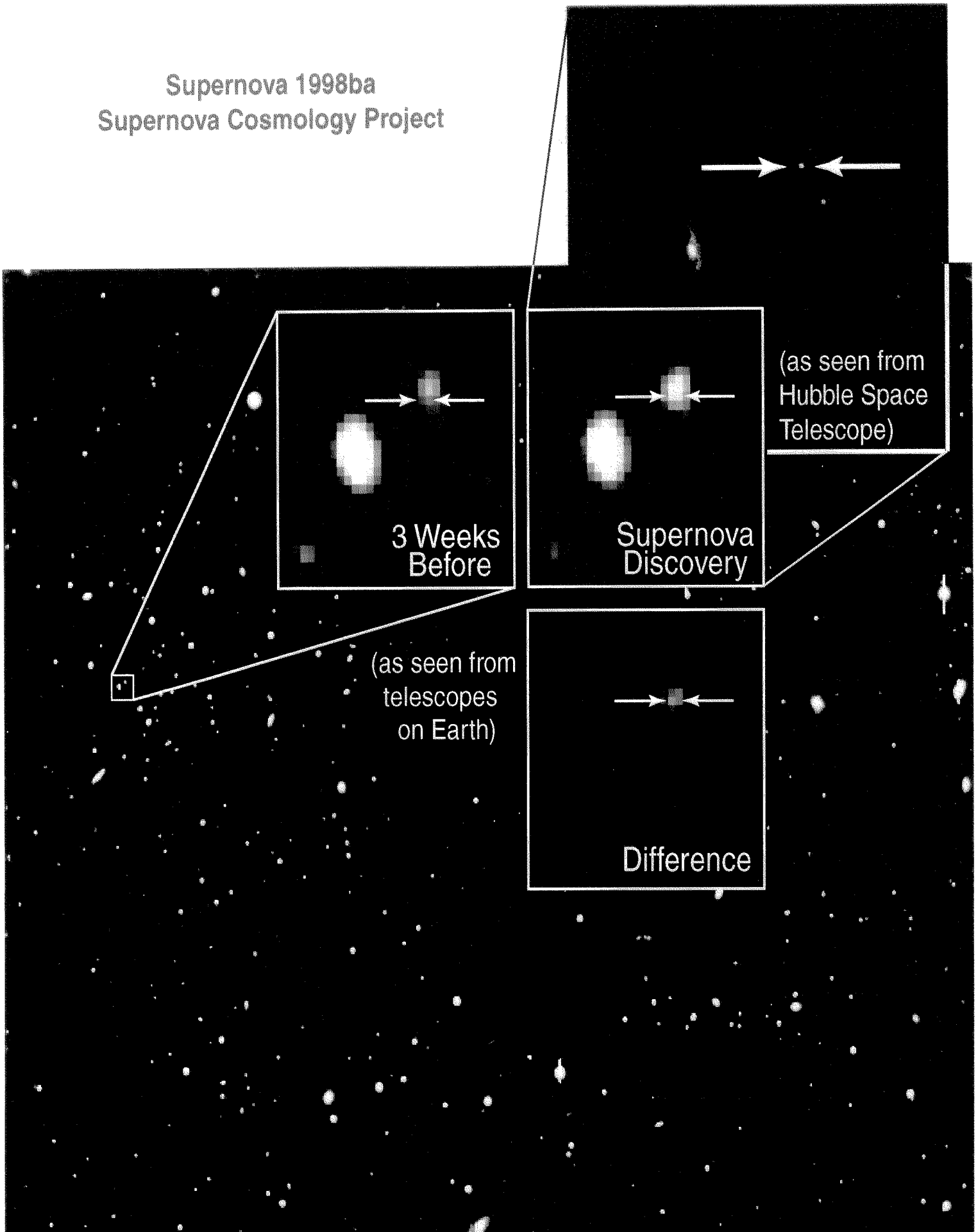
STRATEGY

PERLMUTTER ET AL. (1995)



RESULT: ~~4-8~~ 12-20 SNe Ia DISCOVERED

BEFORE MAXIMUM, AT NEW MOON ⇒ FOLLOW-UP


Supernova 1998ba
Supernova Cosmology Project
(as seen from Hubble Space Telescope)
3 Weeks Before
Supernova Discovery
(as seen from telescopes on Earth)
Difference

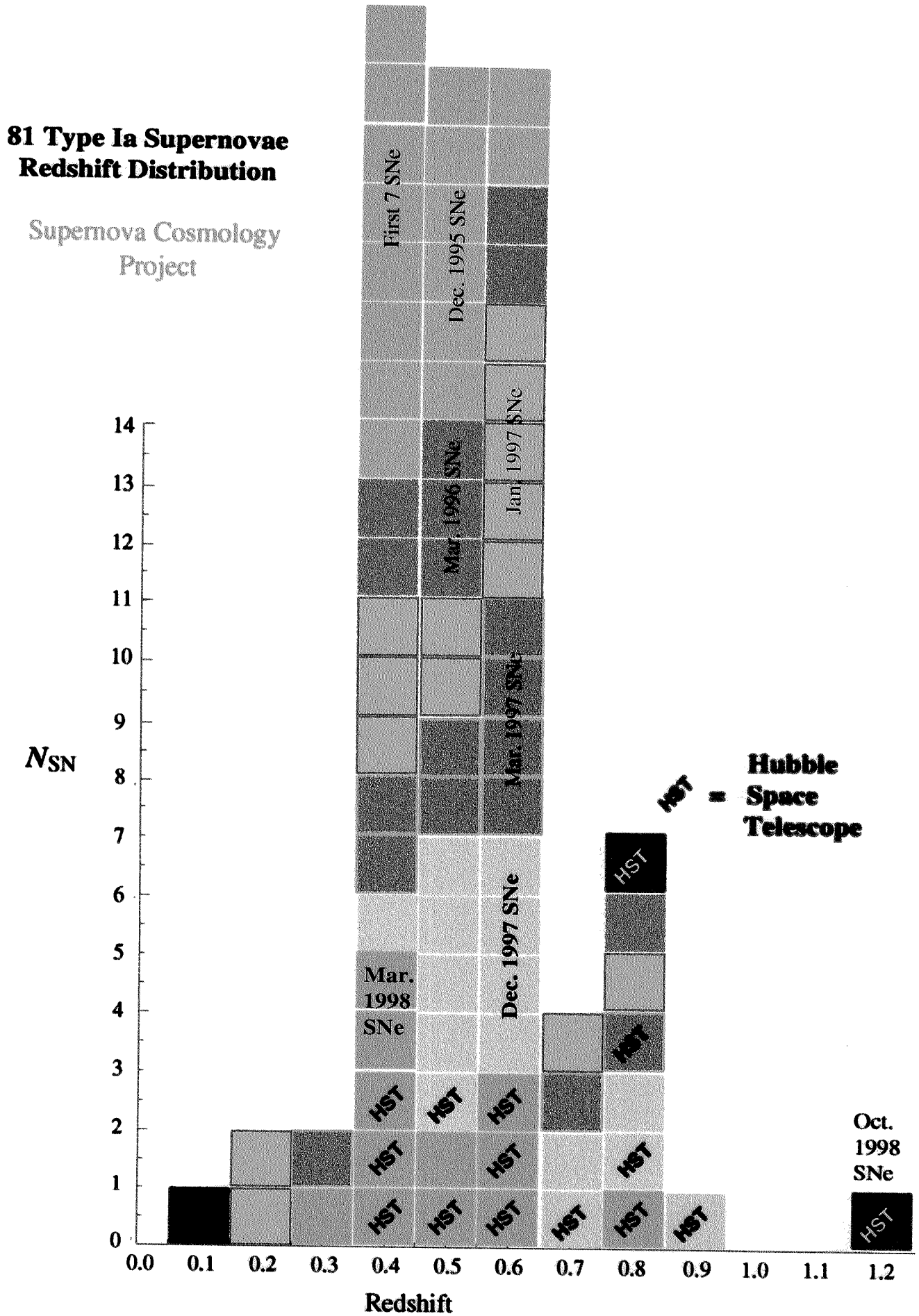
Central Bureau for Astronomical Telegrams
INTERNATIONAL ASTRONOMICAL UNION
Postal Address: Central Bureau for Astronomical Telegrams
Smithsonian Astrophysical Observatory, Cambridge, MA 02138, U.S.A.
IAUSUBS@CFA.HARVARD.EDU or FAX 617-495-7231 (subscriptions)
BMARSDEN@CFA.HARVARD.EDU or DGREEN@CFA.HARVARD.EDU (science)
Phone 617-495-7244/7440/7444 (for emergency use only)

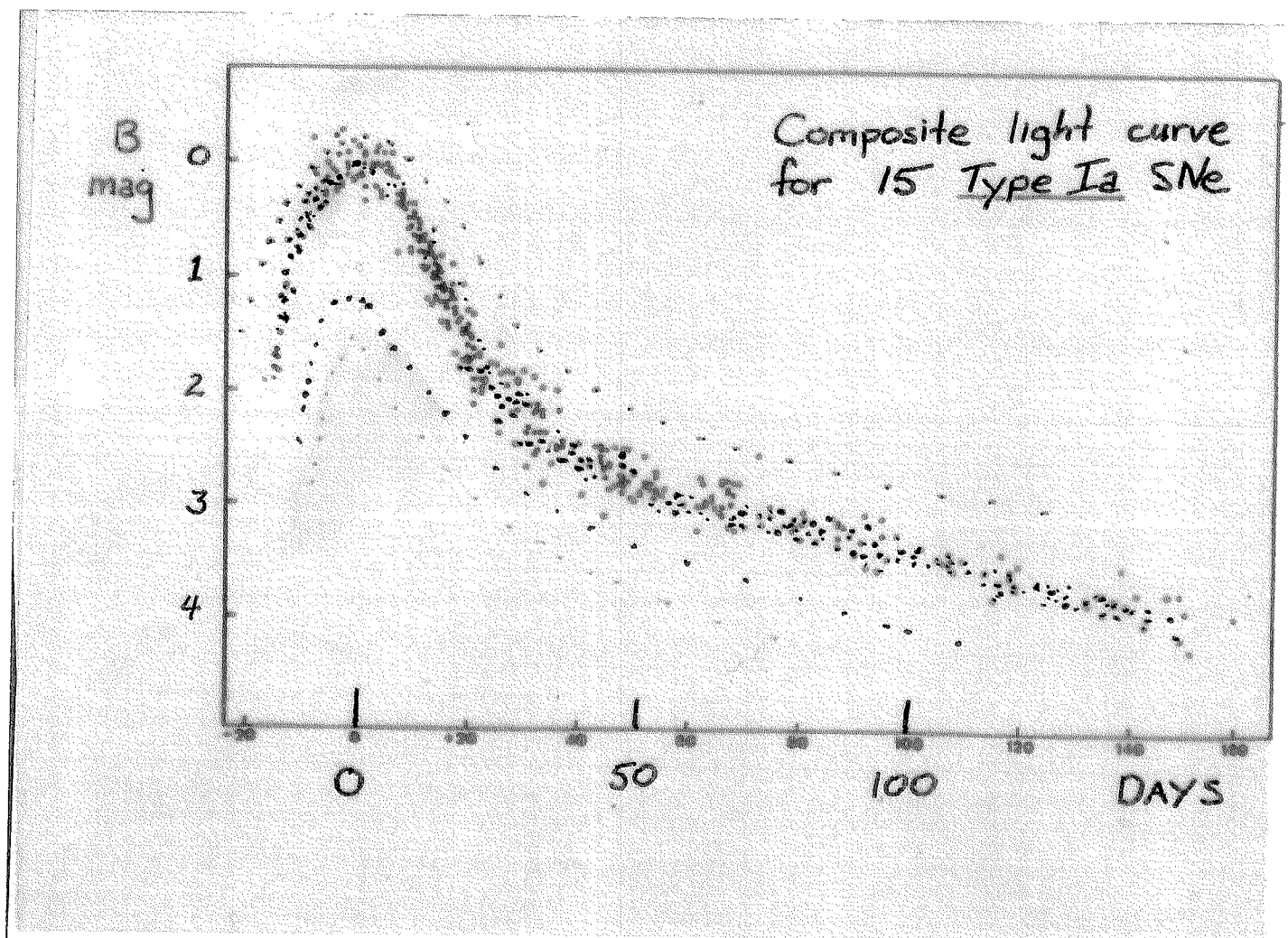
SUPERNOVAE

The Supernova Cosmology Project [S. Perlmutter, S. Deustua, G. Goldhaber, D. Groom, I. Hook, A. Kim, M. Kim, J. Lee, J. Melbourne, C. Pennypacker, and I. Small, Lawrence Berkeley Lab. and the Center for Particle Astrophysics; A. Goobar, Univ. of Stockholm; R. Pain, CNRS, Paris; R. Ellis and R. McMahon, Inst. of Astronomy, Cambridge; and B. Boyle, P. Bunclark, D. Carter, and M. Irwin, Royal Greenwich Obs.; with A. V. Filippenko and A. Barth (Univ. of California, Berkeley) at the Keck telescope; W. Couch (Univ. of N.S.W.) and M. Dopita and J. Mould (Mt. Stromlo and Siding Spring Obs.) at the Siding Spring 2.3-m telescope; H. Newberg (Fermi National Accelerator Lab.) and D. York (Univ. of Chicago) at the ARC telescope] report eleven supernovae found with the Cerro Tololo (CTIO) 4-m telescope in their 1995 High Redshift Supernova Search:

SN	1995 UT	R.A. (2000)	Decl.	R	Offset
1995aq	Nov. 19	0 29 04.26	+ 7 51 20.0	22.4	0".6 W, 1".4 S
1995ar	Nov. 19	1 01 20.41	+ 4 18 33.8	23.1	2".9 W, 0".5 S
1995as	Nov. 19	1 01 35.30	+ 4 26 14.8	23.3	0".7 W, 0".7 N
1995at	Nov. 20	1 04 50.94	+ 4 33 53.0	22.7	0".3 W, 0".4 S
1995au	Oct. 29	1 18 32.60	+ 7 54 03.5	20.7	1".4 E, 3".3 N
1995av	Nov. 20	2 01 36.75	+ 3 38 55.2	20.1	0".2 W, 0".0 N
1995aw	Nov. 19	2 24 55.54	+ 0 53 07.5	22.5	0".2 W, 0".2 S
1995ax	Nov. 19	2 26 25.80	+ 0 48 44.2	22.6	0".3 W, 0".2 S
1995ay	Nov. 20	3 01 07.52	+ 0 21 19.4	22.7	0".9 W, 1".4 S
1995az	Nov. 20	4 40 33.59	- 5 30 03.6	24.0	1".6 W, 1".7 N
1995ba	Nov. 20	8 19 06.46	+ 7 43 21.2	22.6	0".1 E, 0".2 N

The spectra (Keck, Nov. 26-28) are consistent with type-I supernovae (except SN 1995av, a probable type II) at the redshift of the host galaxy: z = 0.45, 0.46, 0.49 (preliminary type-I identification), 0.65, 0.16, 0.30, 0.4 (supernova redshift only), 0.61, 0.48, 0.45, 0.39. Photometry obtained on Nov. 21-23 at CTIO (A. Walker) and Nov. 23-27 at WIYN (D. Harmer, D. Willmarth) indicates that SNe 1995ar, 1995at, 1995av, 1995aw, 1995ay, and 1995az are now before or at maximum, while the others are slightly past maximum. The previous observations not showing the supernovae (to limiting mag about 24) were on Oct. 29-30 at the CTIO 4-m (except SN 1995au, on 1994 Sept. 29 at the Kitt Peak 4-m telescope). Continuing R, I, and B photometry is important. Contact saul@LBL.gov for finding charts.

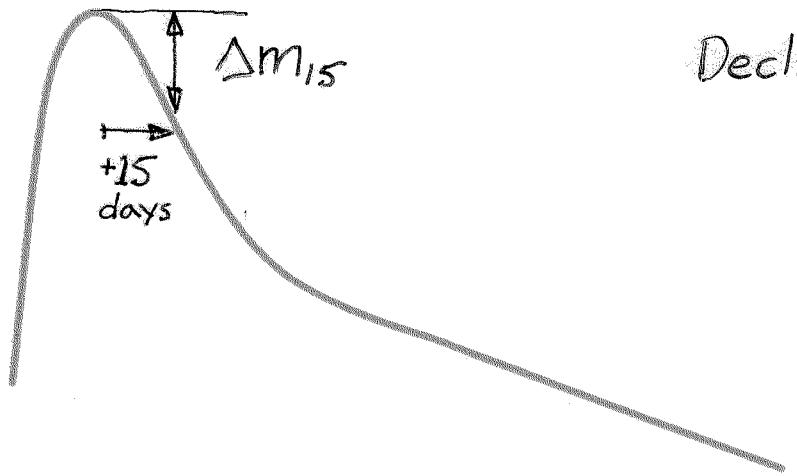

81 Type Ia Supernovae
Redshift Distribution
Supernova Cosmology
Project
First 7 SNe
Dec. 1995 SNe
Jan. 1997 SNe
Mar. 1996 SNe
Mar. 1997 SNe
Dec. 1997 SNe
Mar.
1998
SNe
HST
HST = Hubble
Space
Telescope
Oct.
1998
SNe
N_{SN}
Redshift
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2


Composite light curve
for 15 Type Ia SNe
B
mag
0
1
2
3
4
0
50
100
DAYS

Light-curve Width-Luminosity Relation

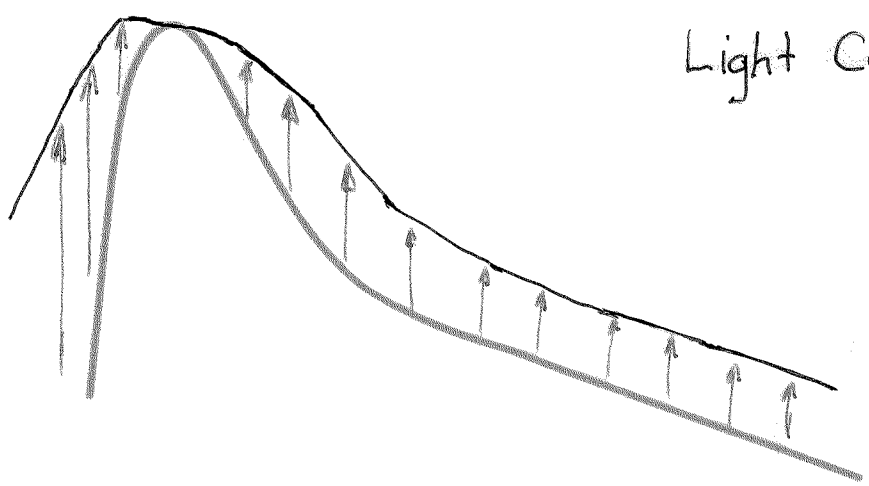
CHARACTERIZED BY:

Phillips:
(1993–)



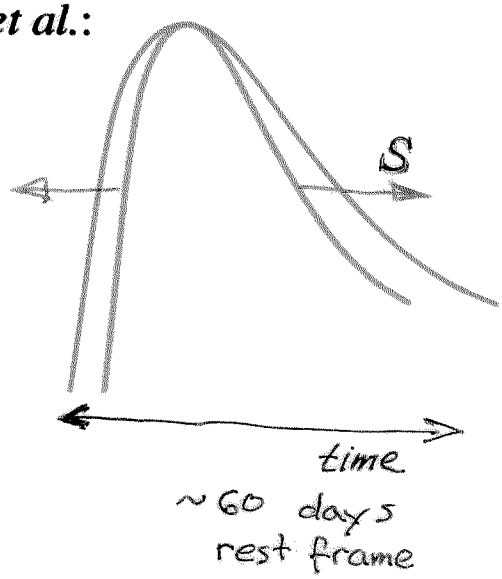
Decline Rate

Riess, Press, & Kirshner:
(1995–)



Light Curve Shape (LCS)

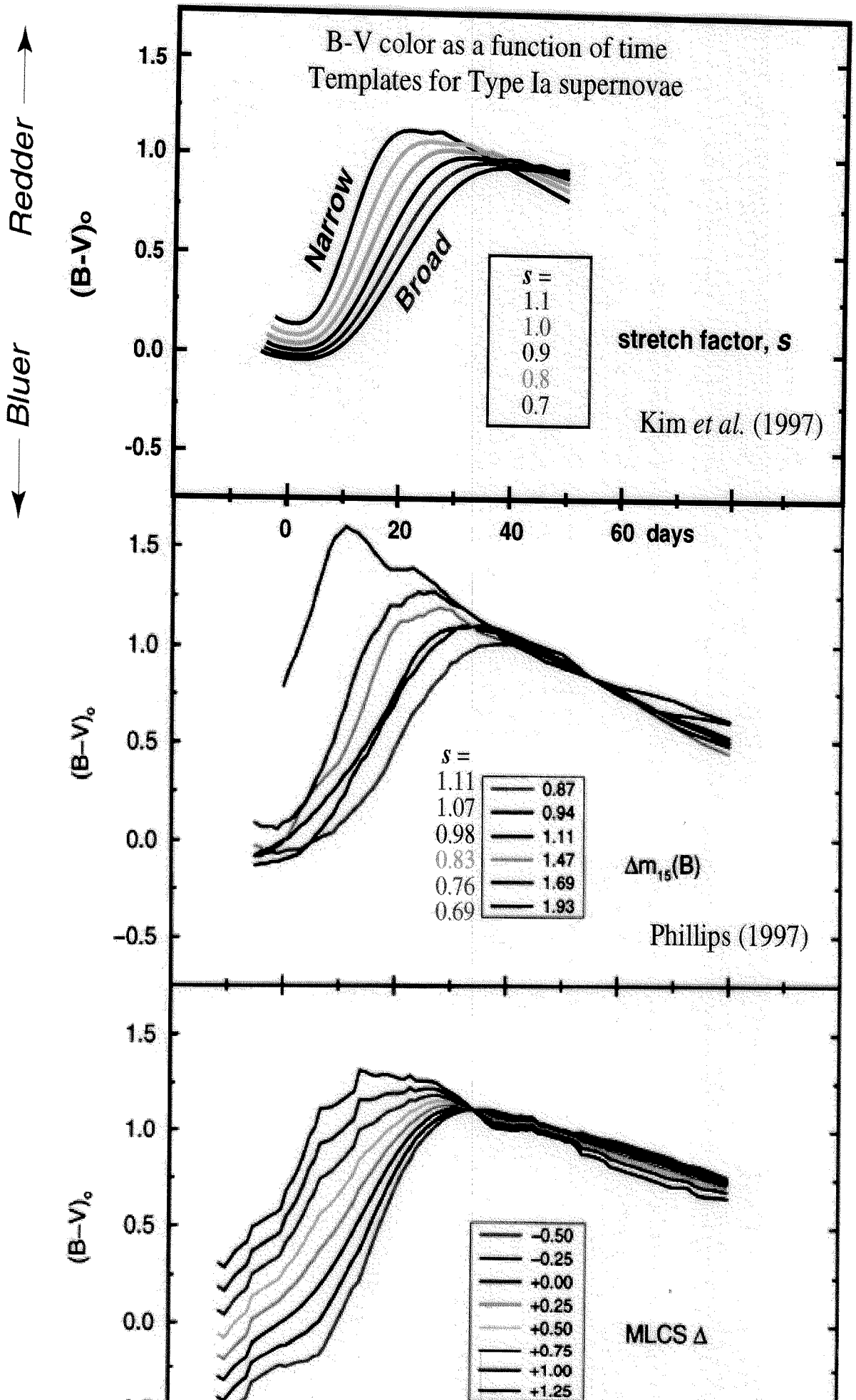
Perlmutter *et al.*:
(1996–)

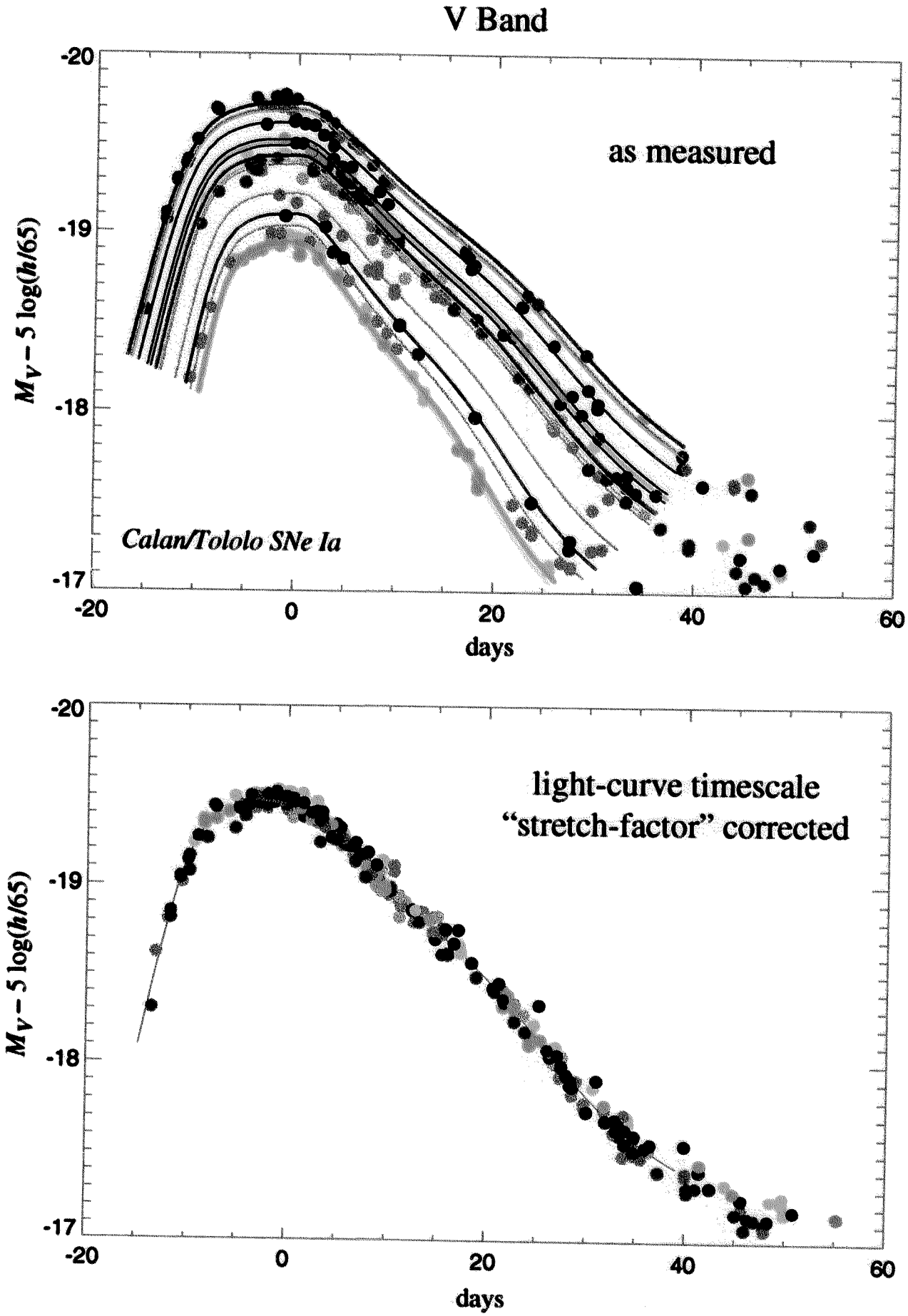


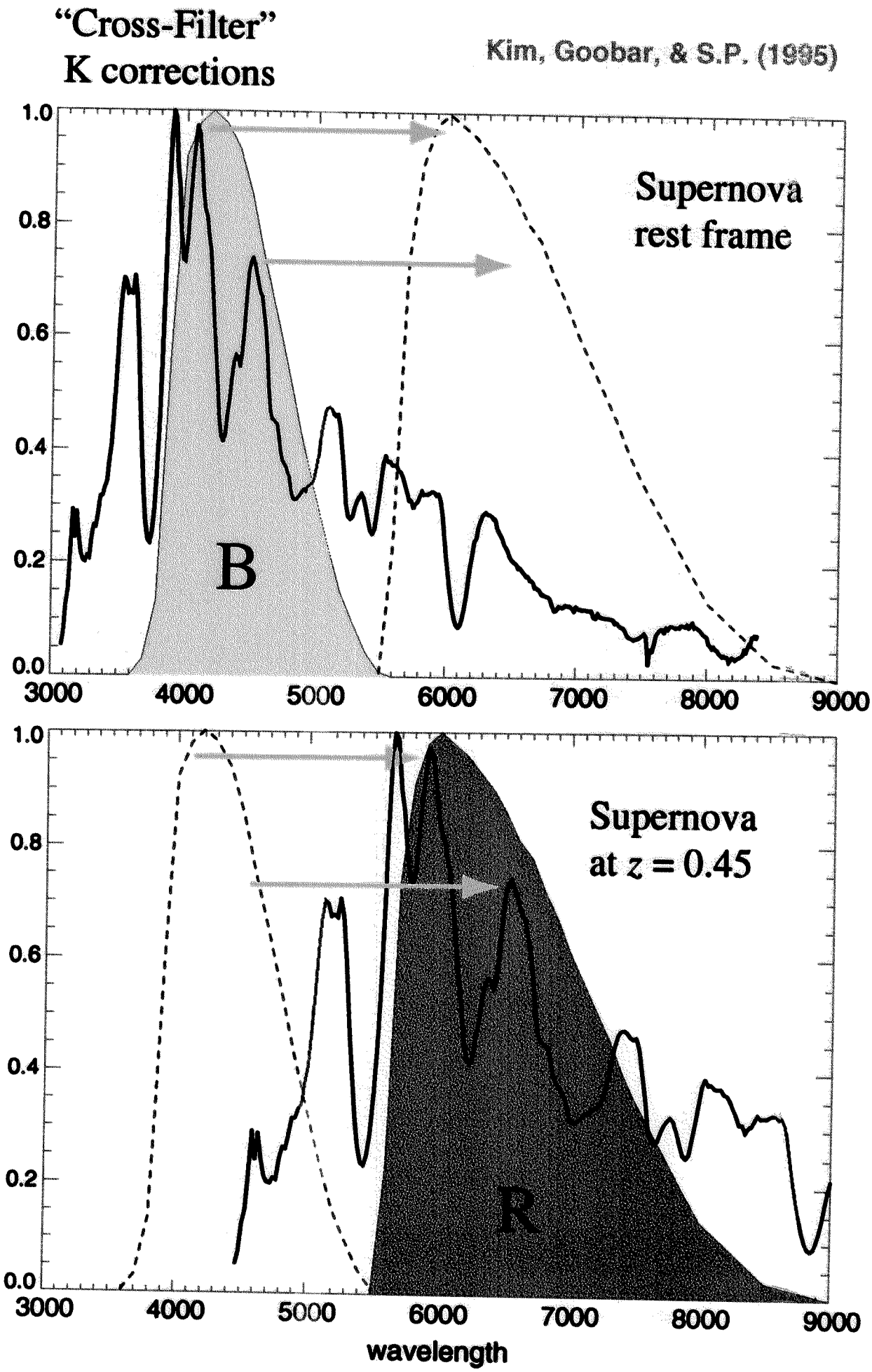
Timescale "stretch factor"

$S > 1$: Broader / Slower
lightcurves are Brighter

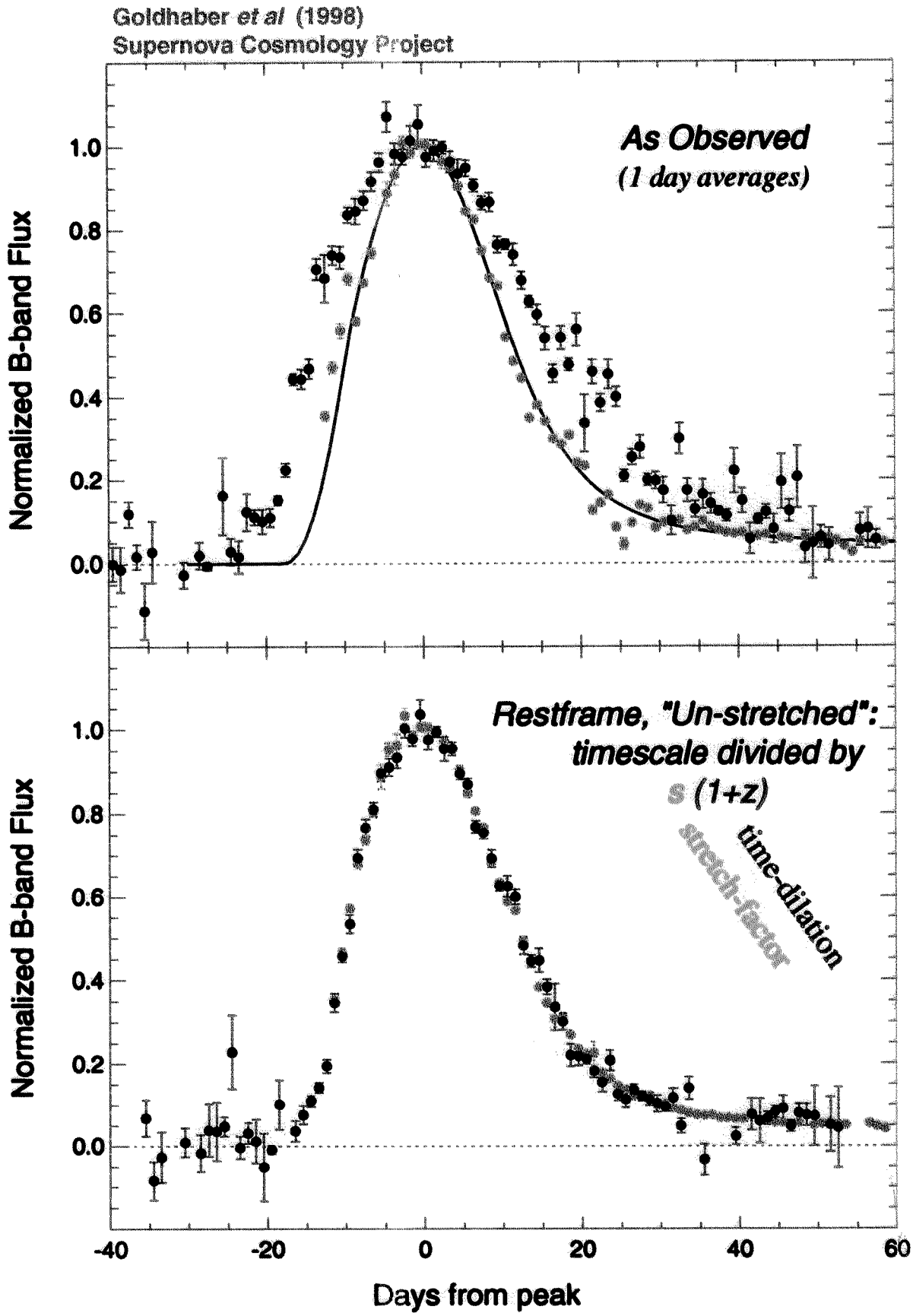
$S < 1$: Narrower / Faster
light curves are Fainter

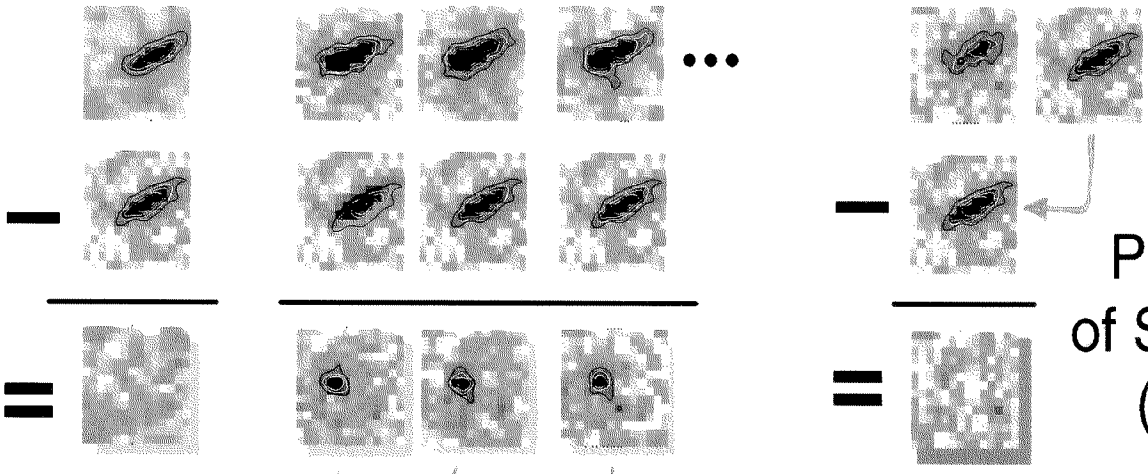

B-V color as a function of time
Templates for Type Ia supernovae
Redder
Bluer
(B-V)o
Narrow
Broad
s =
1.1
1.0
0.9
0.8
0.7
stretch factor, s
Kim et al. (1997)
0
20
40
60 days
s =
1.11
1.07
0.98
0.83
0.76
0.69
0.87
0.94
1.11
1.47
1.69
1.93
Δm15(B)
Phillips (1997)
−0.50
−0.25
+0.00
+0.25
+0.50
+0.75
+1.00
+1.25
MLCS Δ


V Band
as measured
Calan/Tololo SNe Ia
$M_V - 5\log(h/65)$
days
-20
-19
-18
-17
0
20
40
60
light-curve timescale
"stretch-factor" corrected

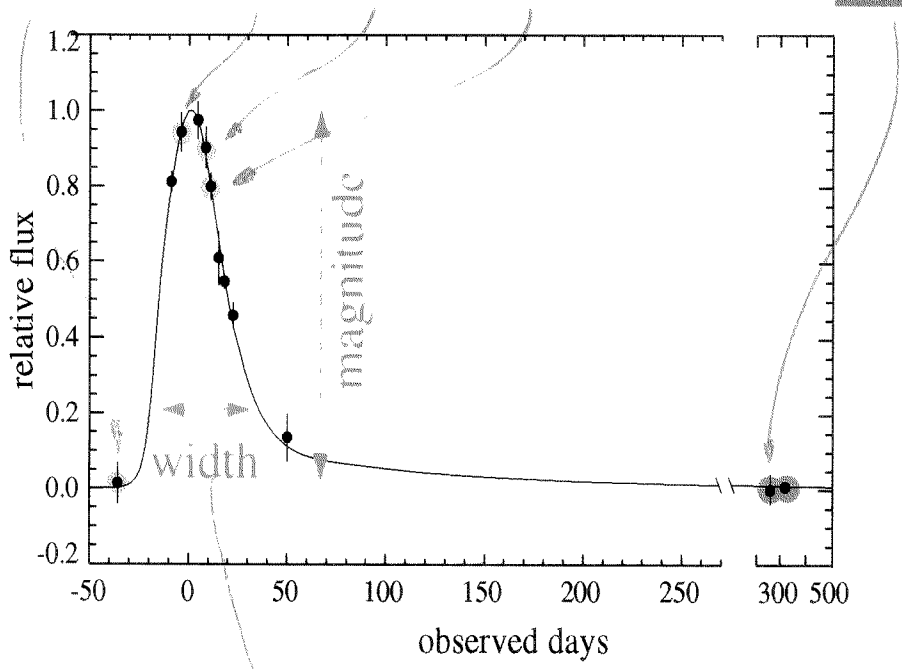

"Cross-Filter"
K corrections
Kim, Goobar, & S.P. (1995)
Supernova
rest frame
B
Supernova
at z = 0.45
R
1.0
0.8
0.6
0.4
0.2
0.0
3000
4000
5000
6000
7000
8000
9000
wavelength

• 18 Low Redshift SNe: Calan/Tololo Supernova Survey
• 35 High Redshift SNe: Supernova Cosmology Project

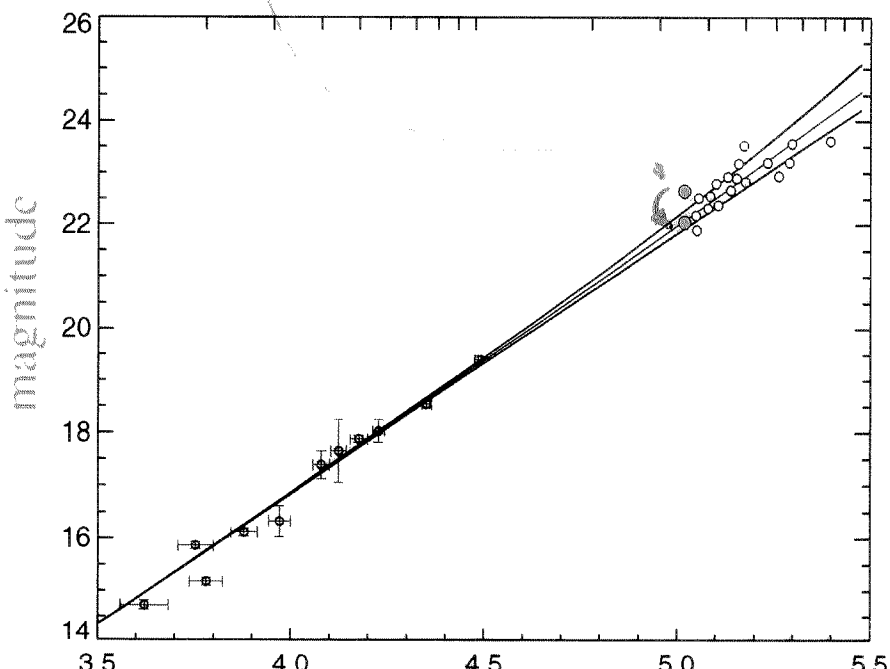




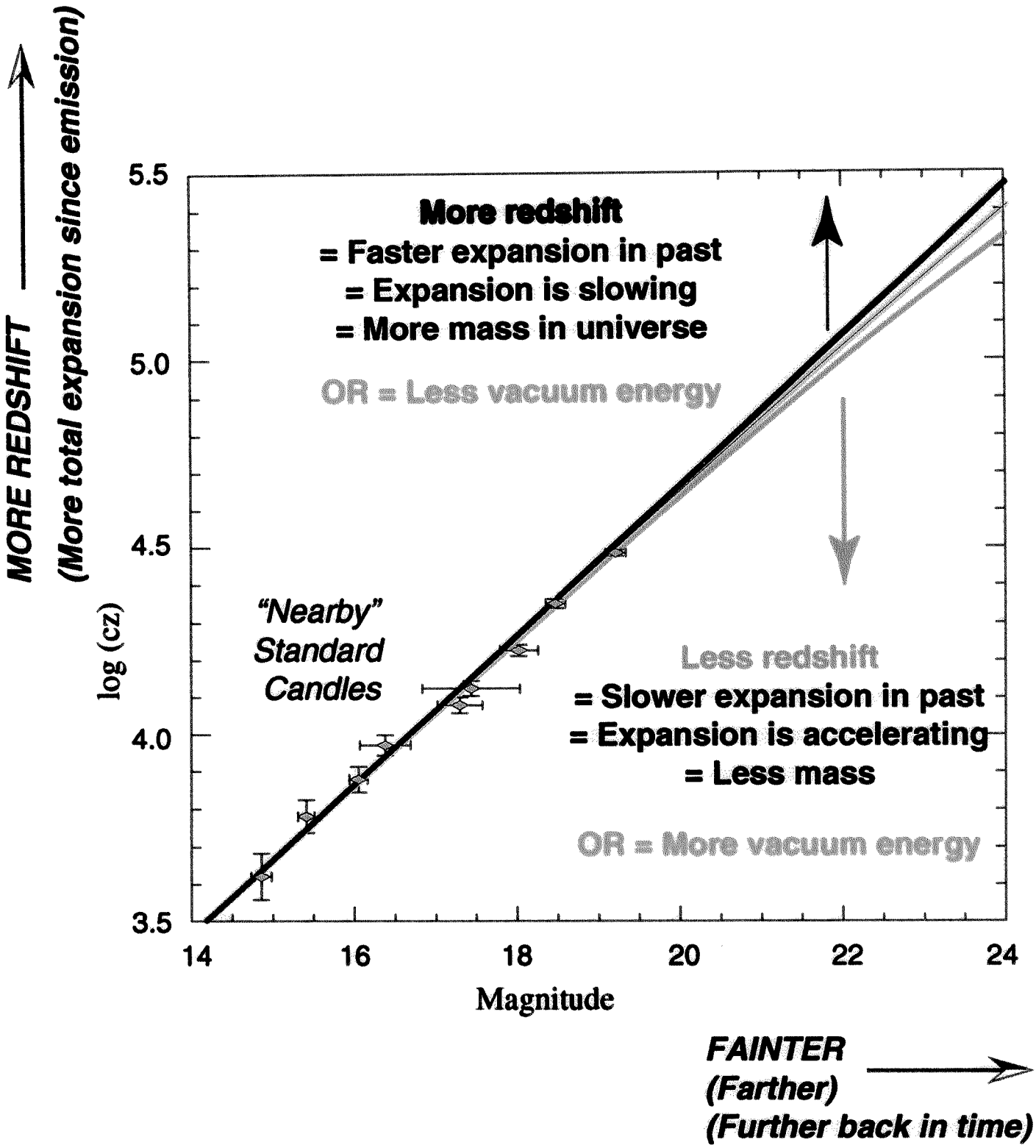
1.
Photometry
of SN – galaxy
(2 colors)



2.
Fit to
low-*z* SN
light curves
(*K*-corrected)



3.
Fit
cosmology
(Ω, Λ) on
Hubble diagram


MORE REDSHIFT
(More total expansion since emission)
5.5
5.0
4.5
4.0
3.5
log (cz)
More redshift
= Faster expansion in past
= Expansion is slowing
= More mass in universe
OR = Less vacuum energy
"Nearby"
Standard
Candles
Less redshift
= Slower expansion in past
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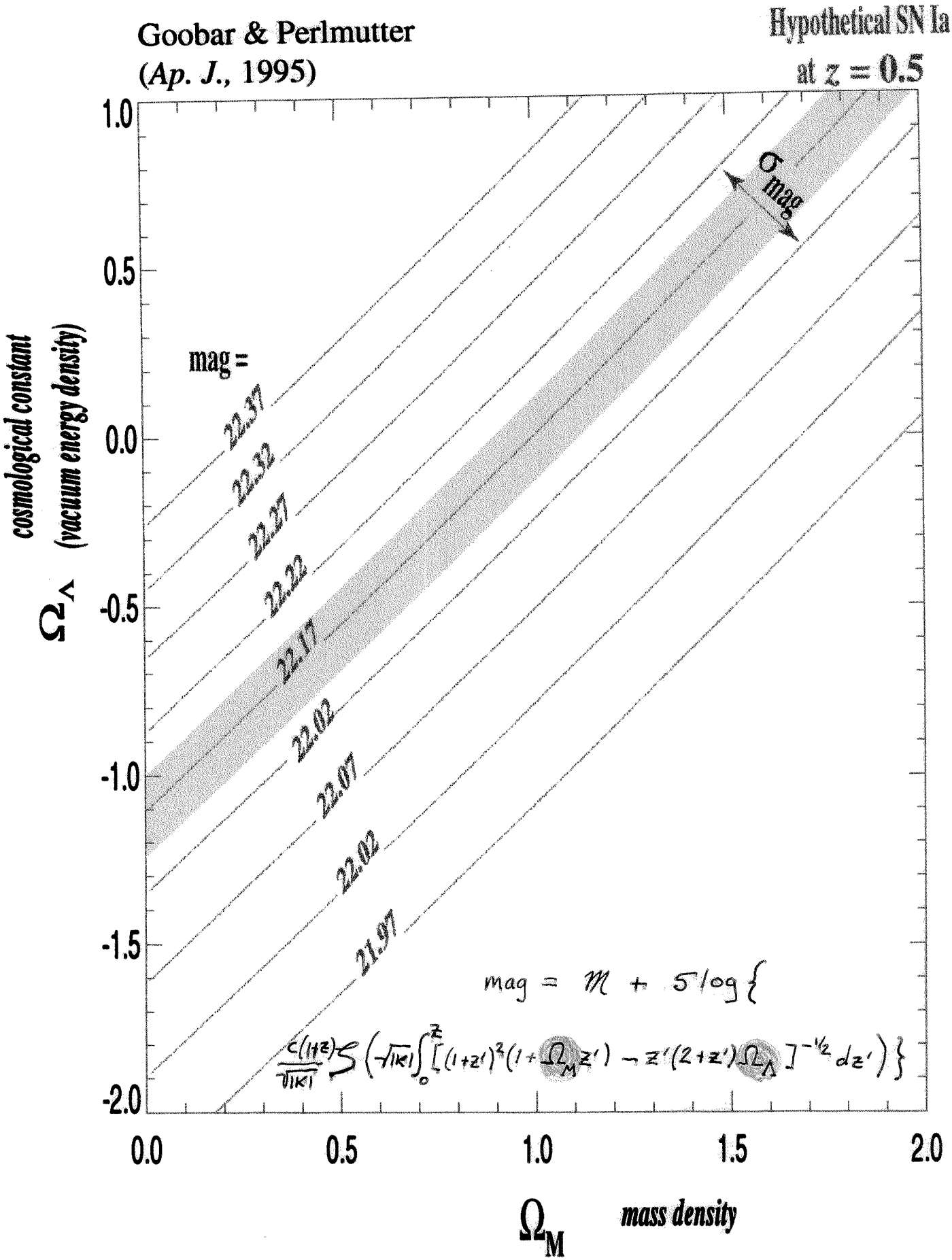
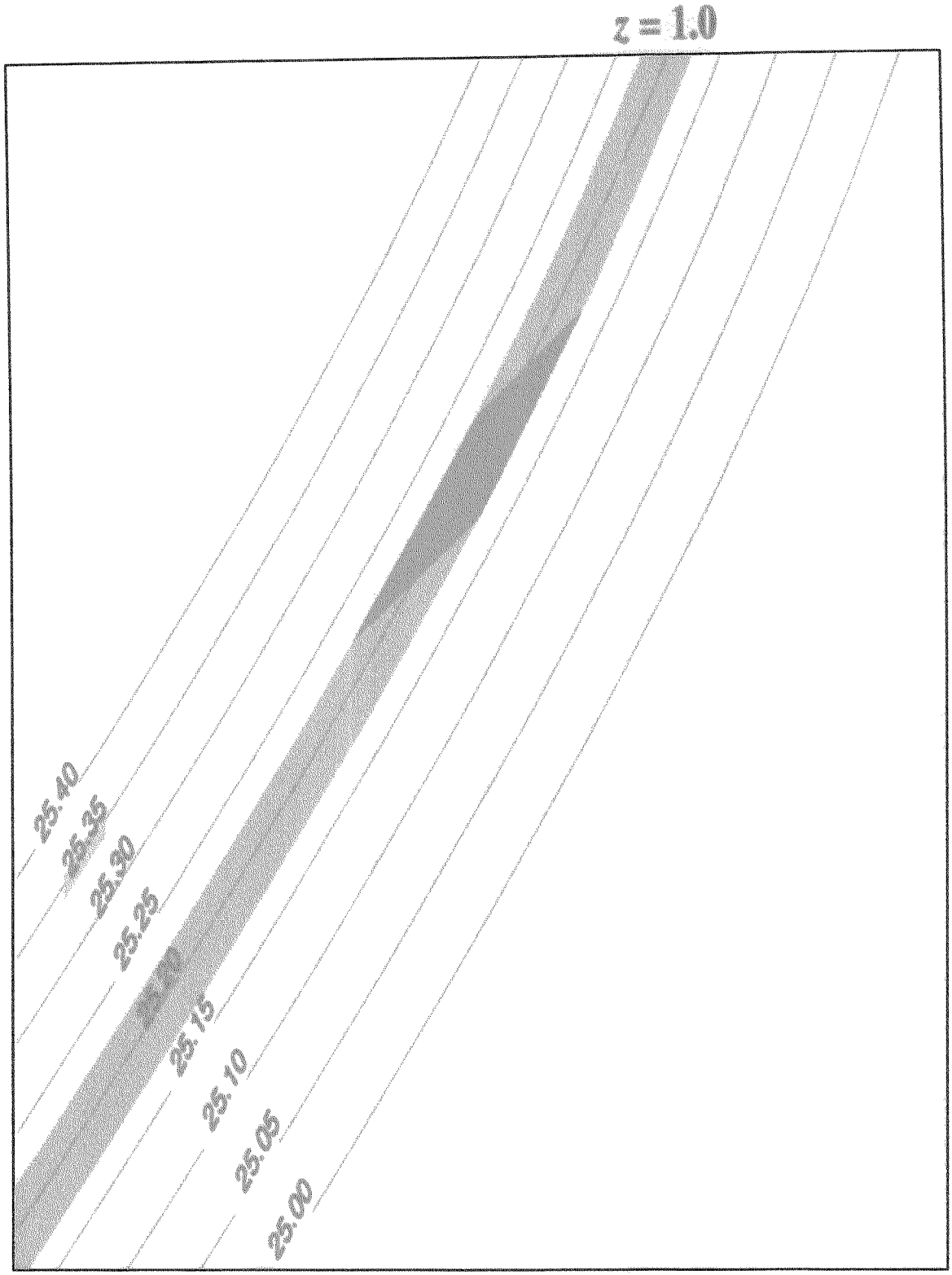
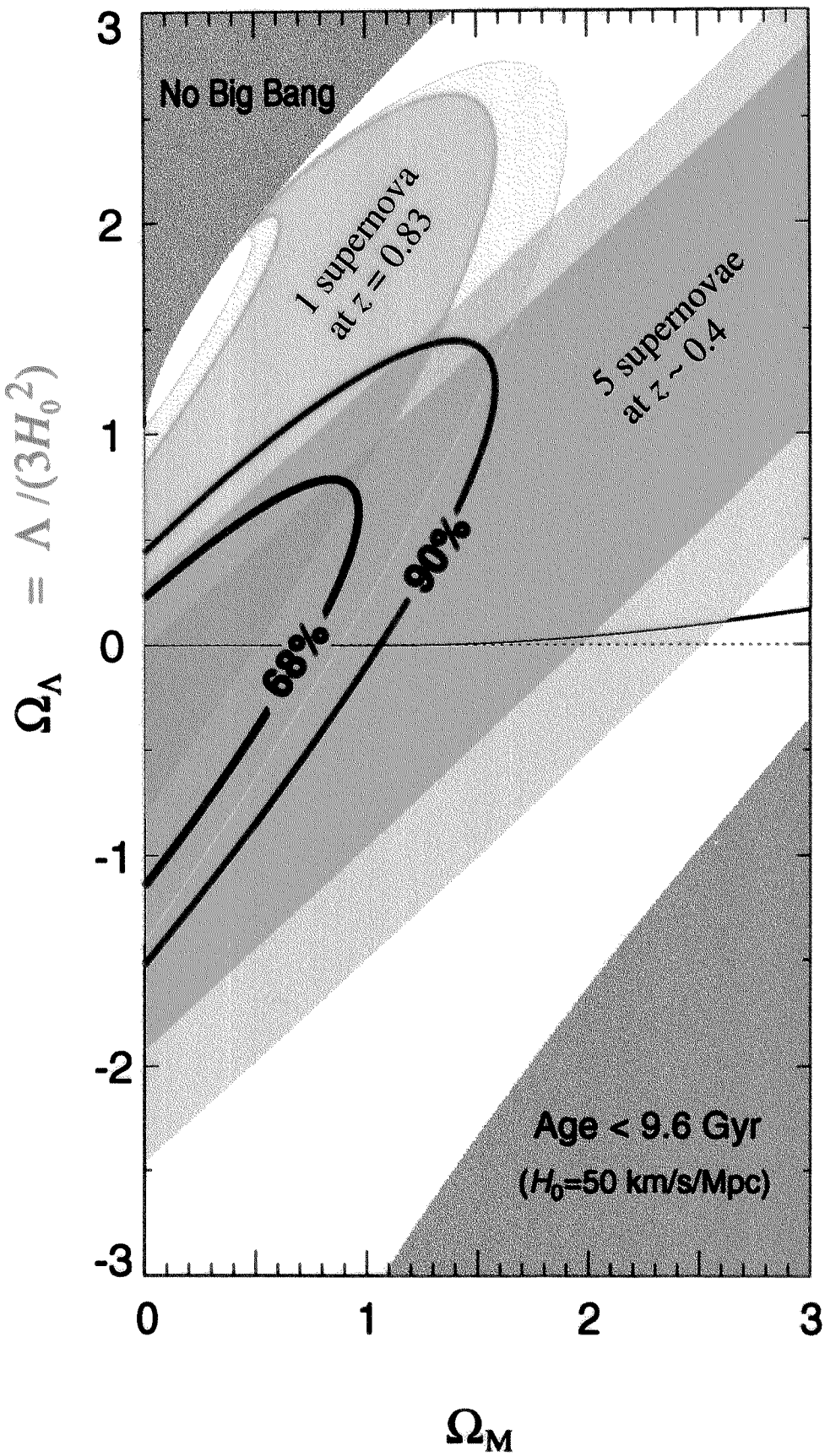
14
16
18
20
22
24
Magnitude
FAINTER
(Farther)
(Further back in time)


Goobar & Perlmutter
(Ap. J., 1995)
Hypothetical SN Ia
at z = 0.5
mag =
22.37
22.32
22.27
22.22
22.17
22.02
22.07
22.02
21.97
σ mag
mag = M + 5 log {
c(1+z)/√|k| S (√|k| ∫₀^z [(1+z')²(1+Ω_M z') − z'(2+z')Ω_Λ]^{−1/2} dz') }
cosmological constant
(vacuum energy density)
Ω_Λ
mass density
Ω_M
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0.0
0.5
1.0
1.5
2.0

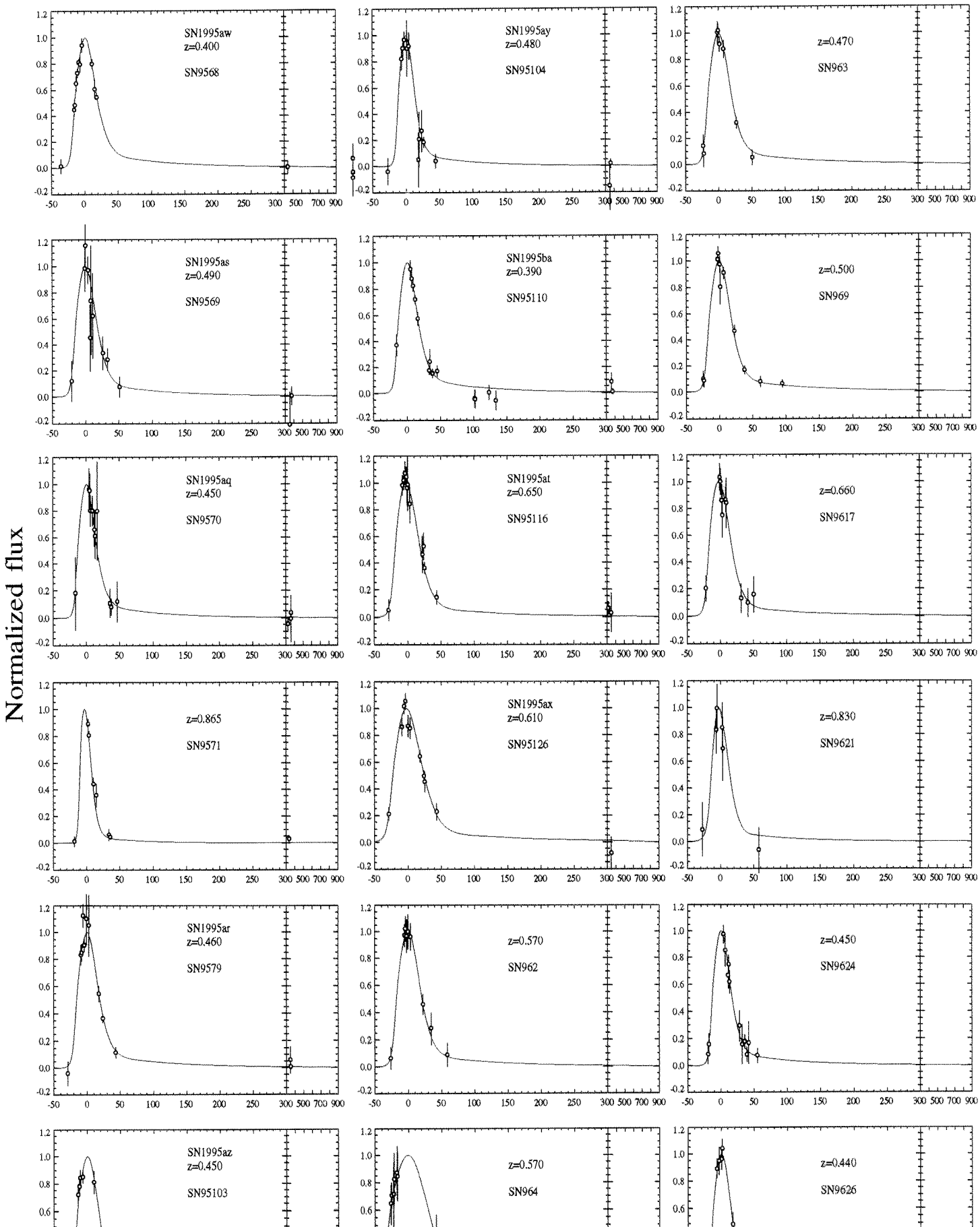

z = 1.0
25.40
25.35
25.30
25.25
25.20
25.15
25.10
25.05
25.00

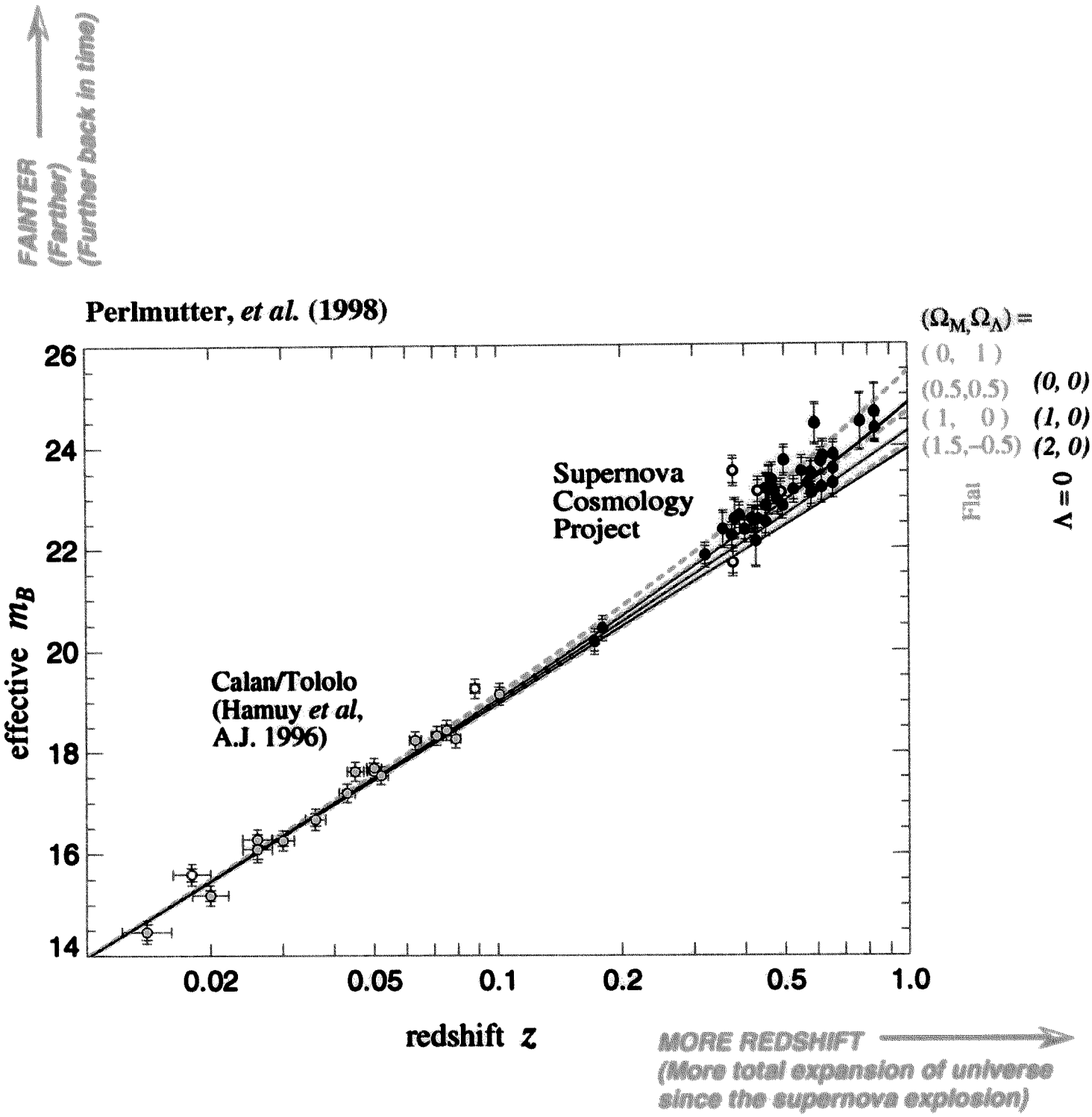
Perlmutter, *et al.*, Nature (1998)



Fall '95 & Spring '96 SNe in R & I bands

(R shown)

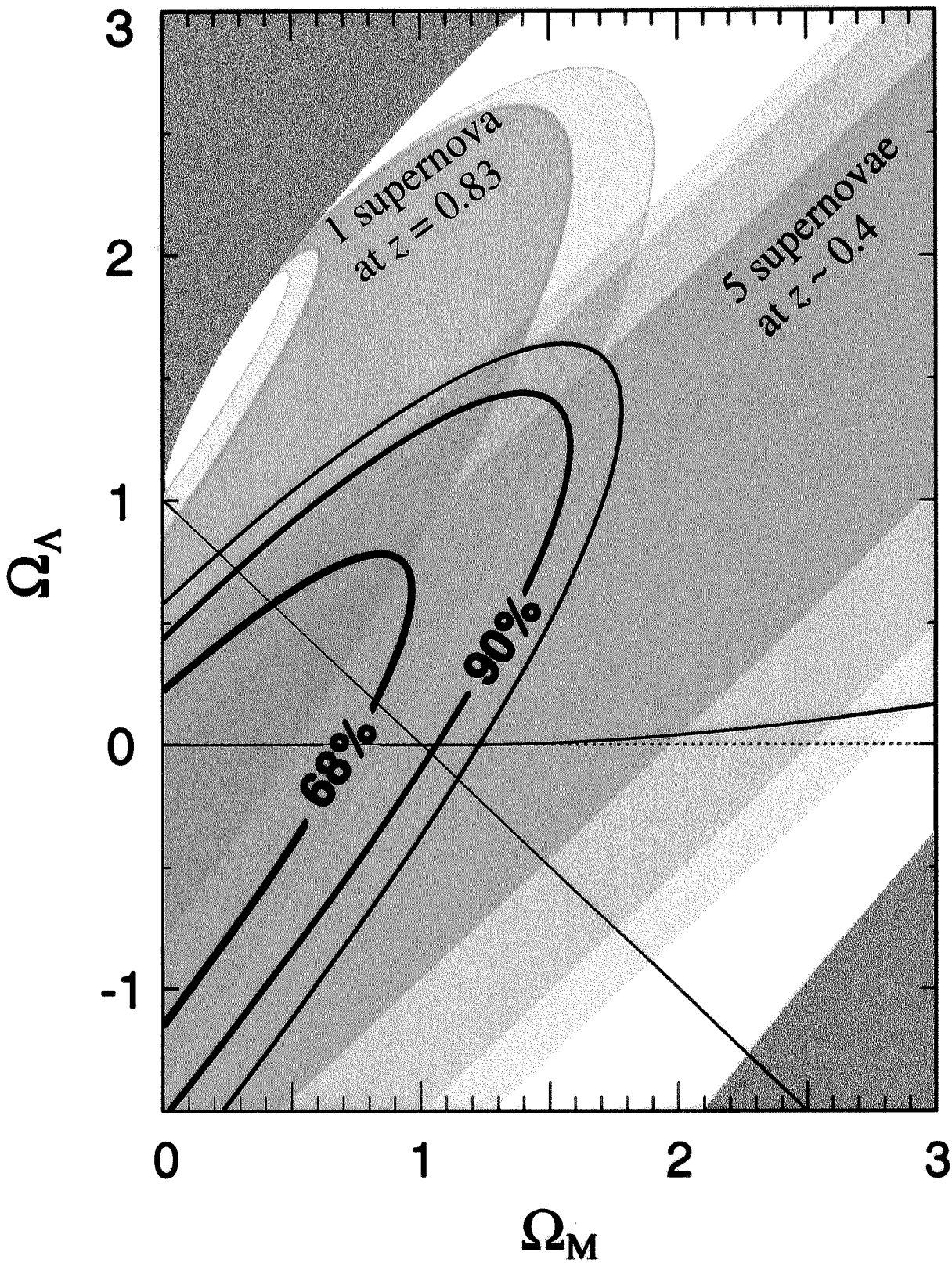




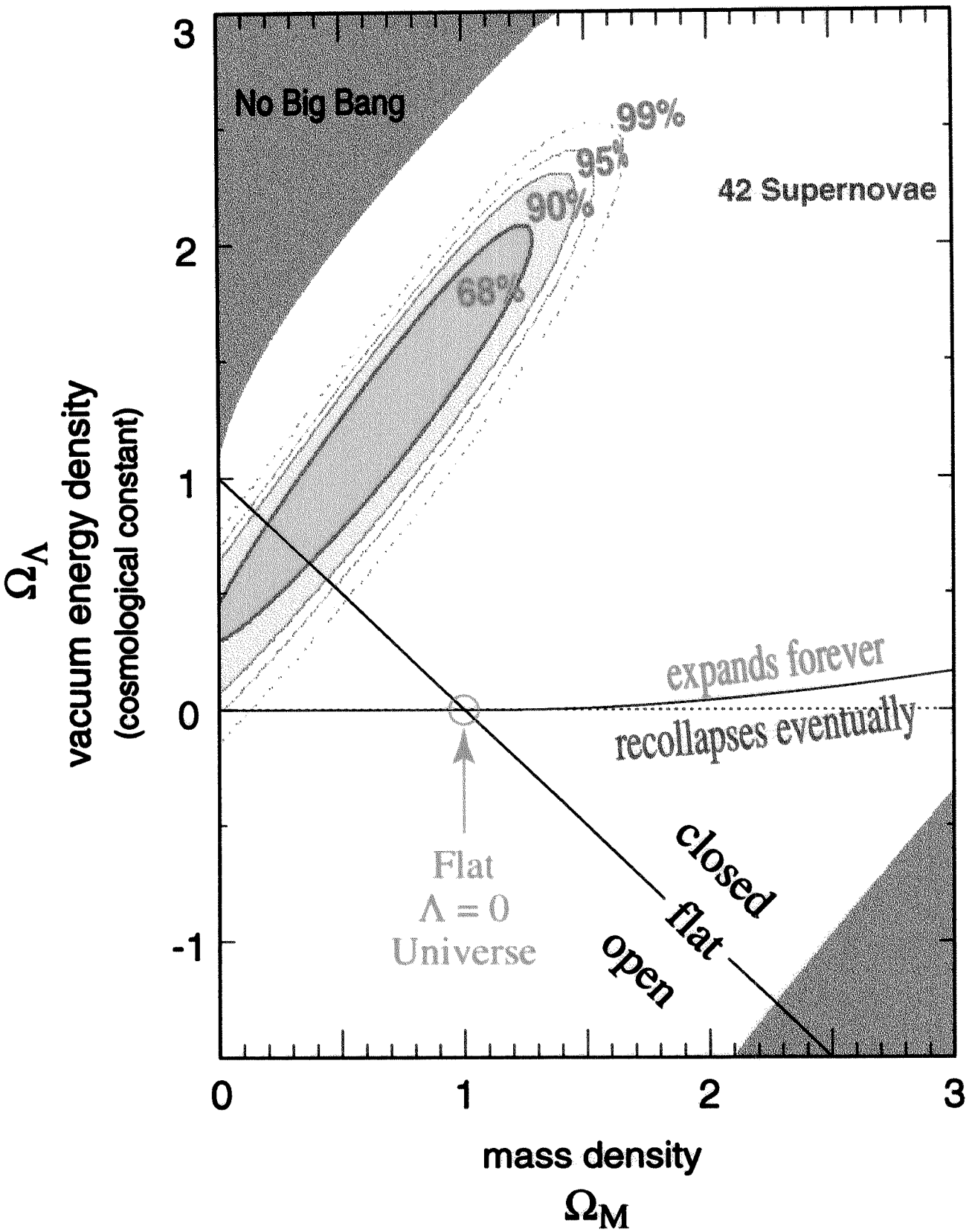
In flat universe: $\Omega_M = 0.28$ [± 0.085 statistical] [± 0.05 systematic]

Prob. of fit to $\Lambda = 0$ universe: 1%

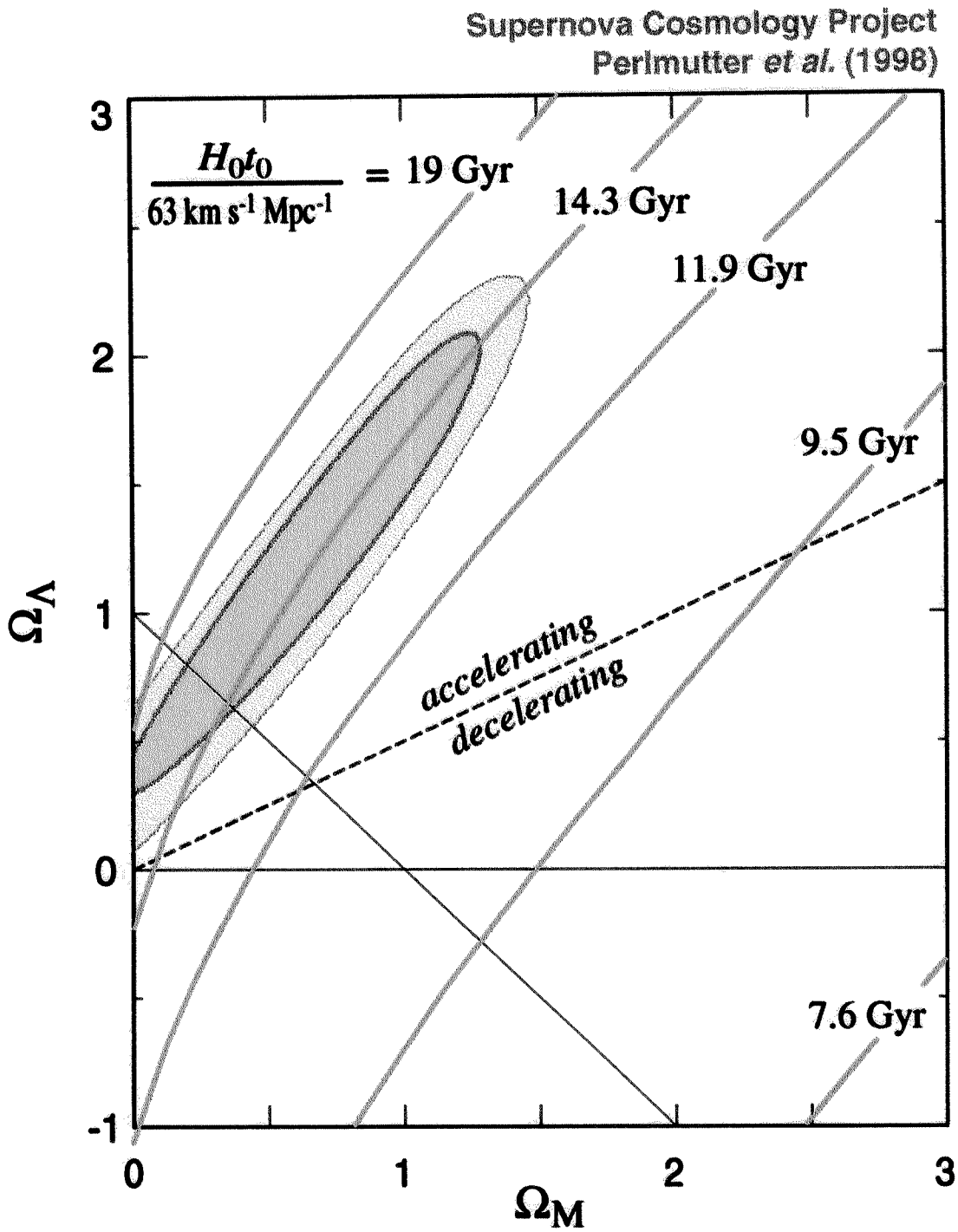
Perlmutter, *et al.*, Nature (1998)



Supernova Cosmology Project
Perlmutter *et al.* (1998)



Ap.J.
astro-ph/9812133

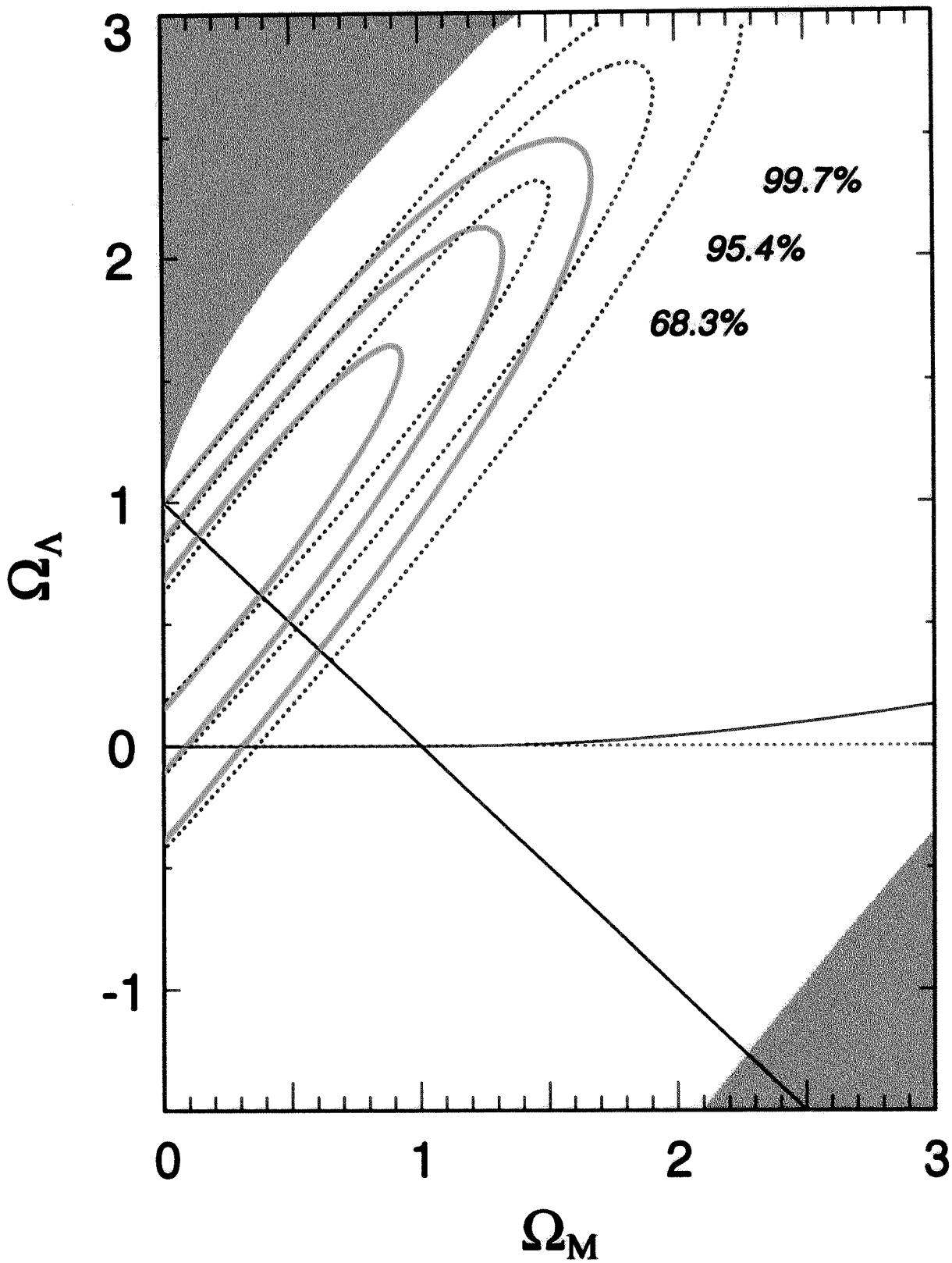


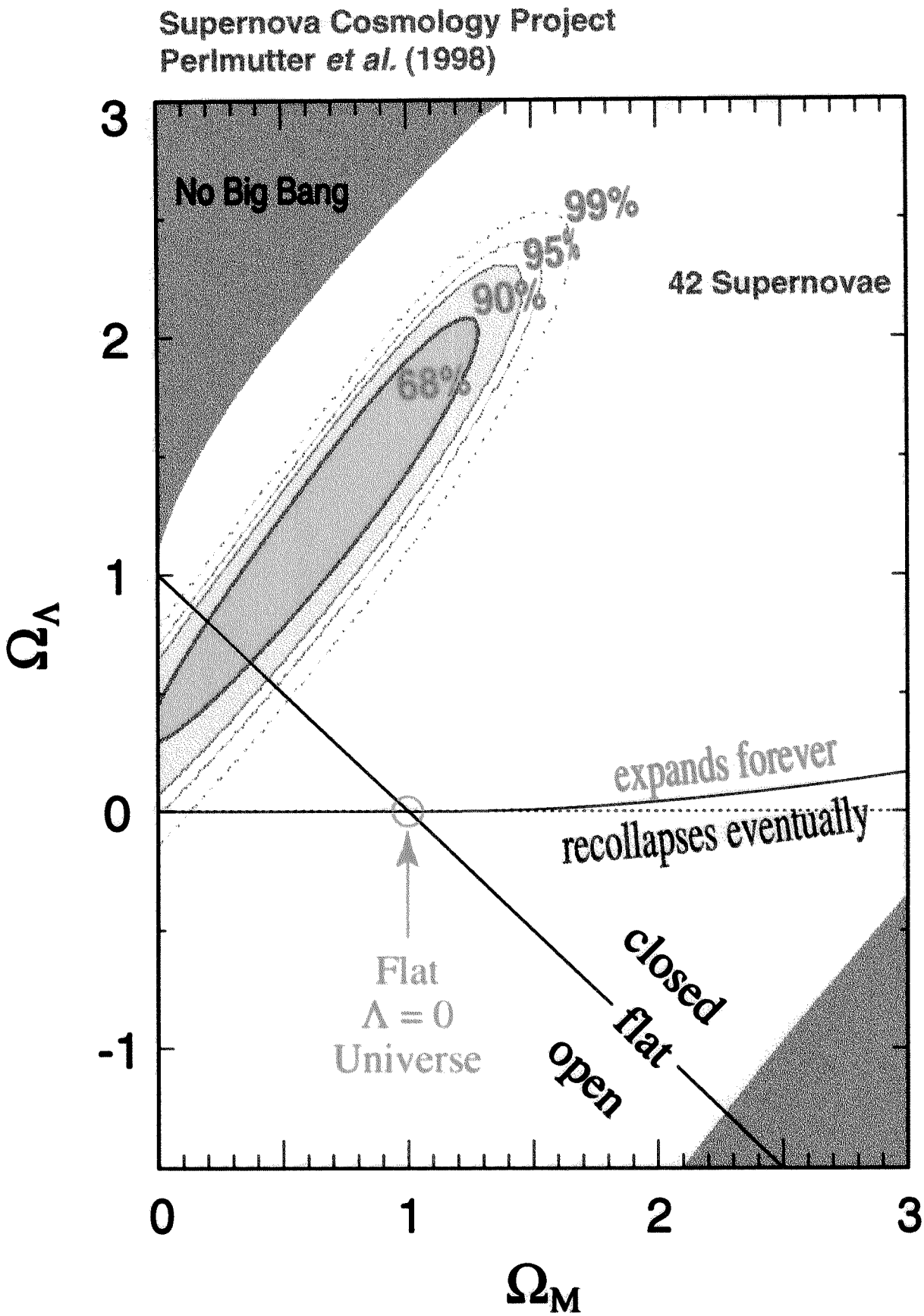
Best fit age of universe: $t_o = 14.5 \pm 1\ (0.63/h)$ Gyr

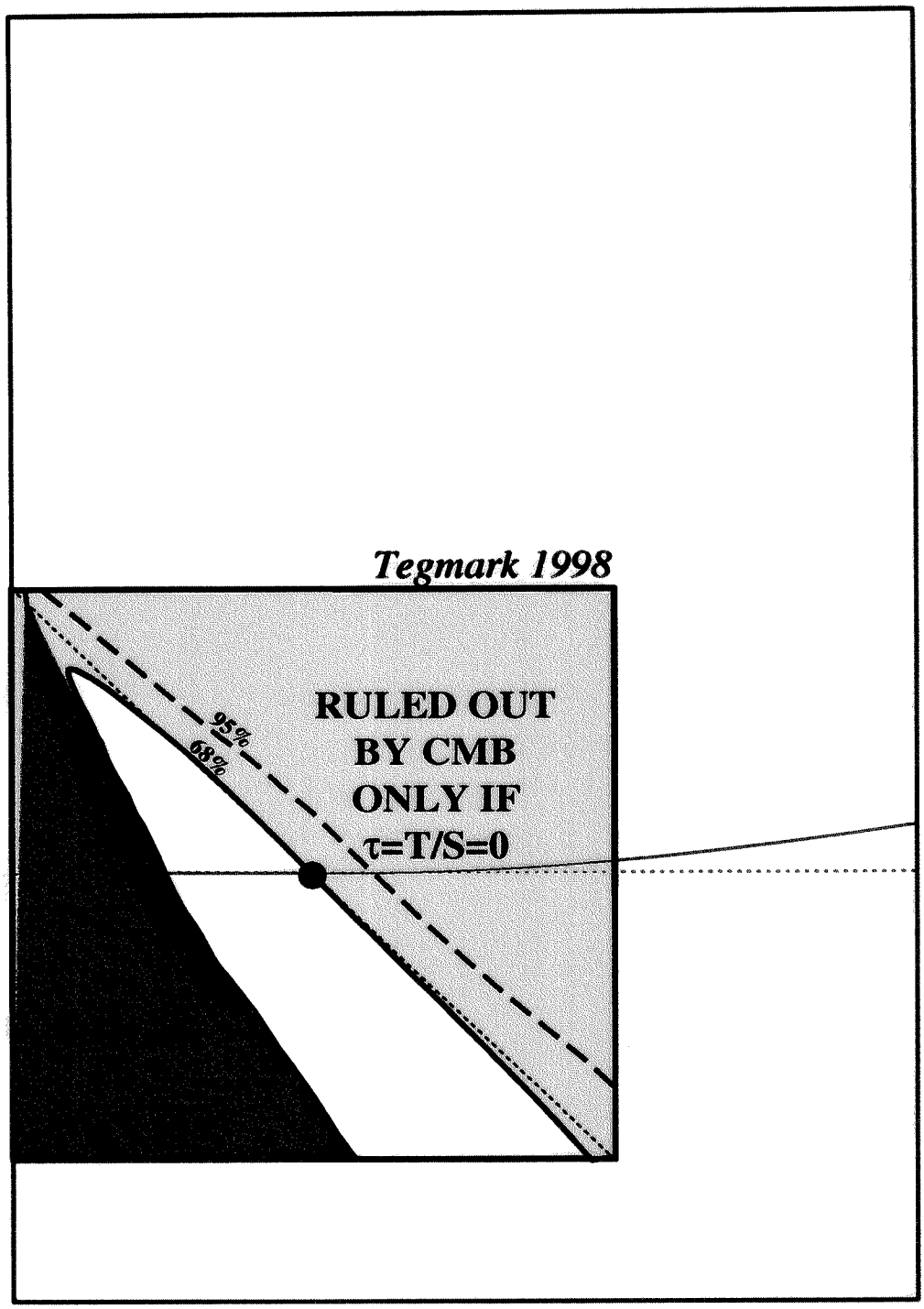
Best fit in flat universe: $t_o = 14.9 \pm 1\ (0.63/h)$ Gyr

14 Supernovae from High-z Supernova Search Team
+2 Supernovae from Supernova Cosmology Project

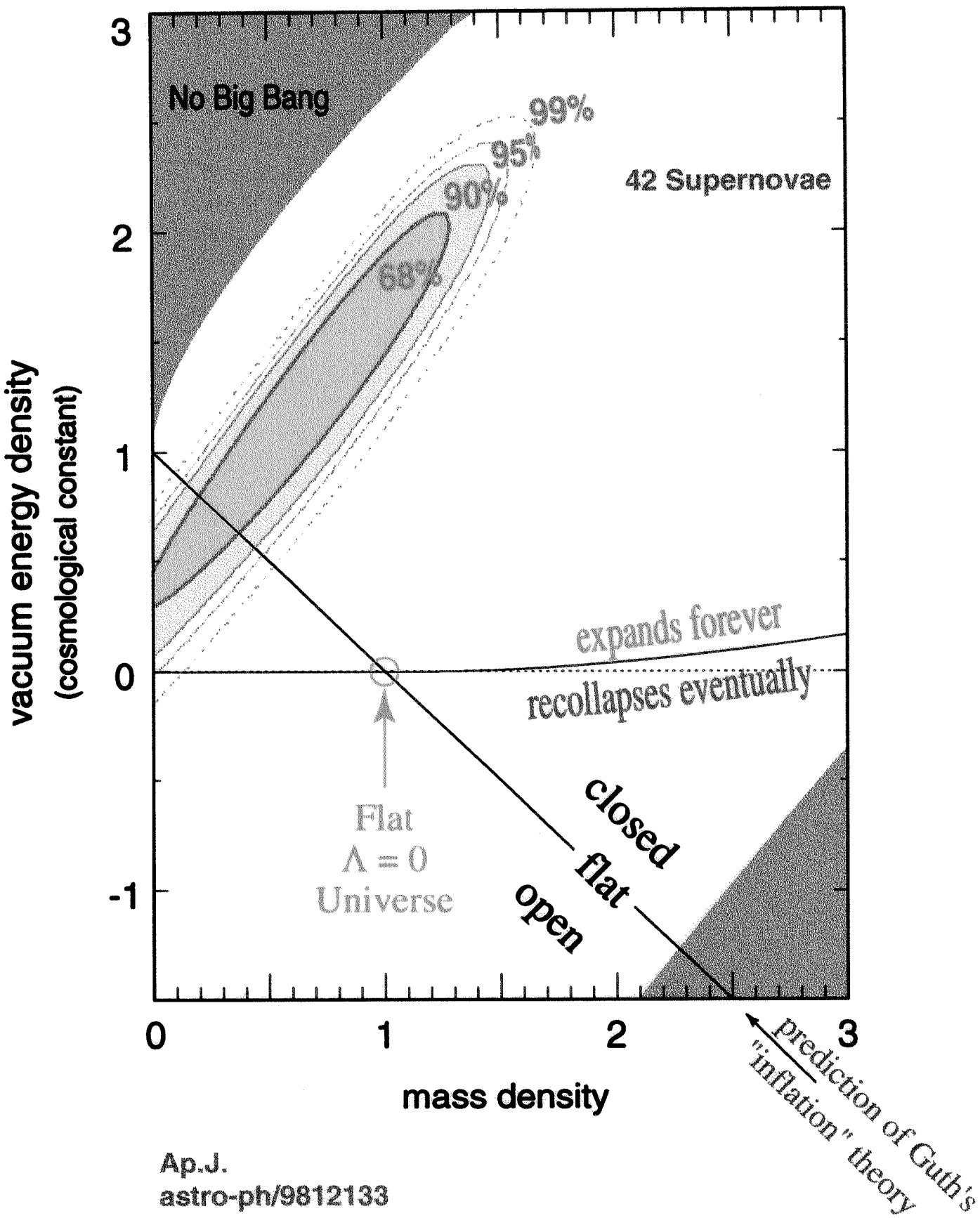
Reiss *et al.* (1998)




Supernova Cosmology Project
Perlmutter et al. (1998)
No Big Bang
99%
95%
90%
68%
42 Supernovae
expands forever
recollapses eventually
closed
flat
open
Flat
Λ = 0
Universe
3
2
1
0
-1
0
1
2
3
Ω_Λ
Ω_M


Tegmark 1998
RULED OUT
BY CMB
ONLY IF
τ=T/S=0
95%
68%

Supernova Cosmology Project
Perlmutter *et al.* (1998)

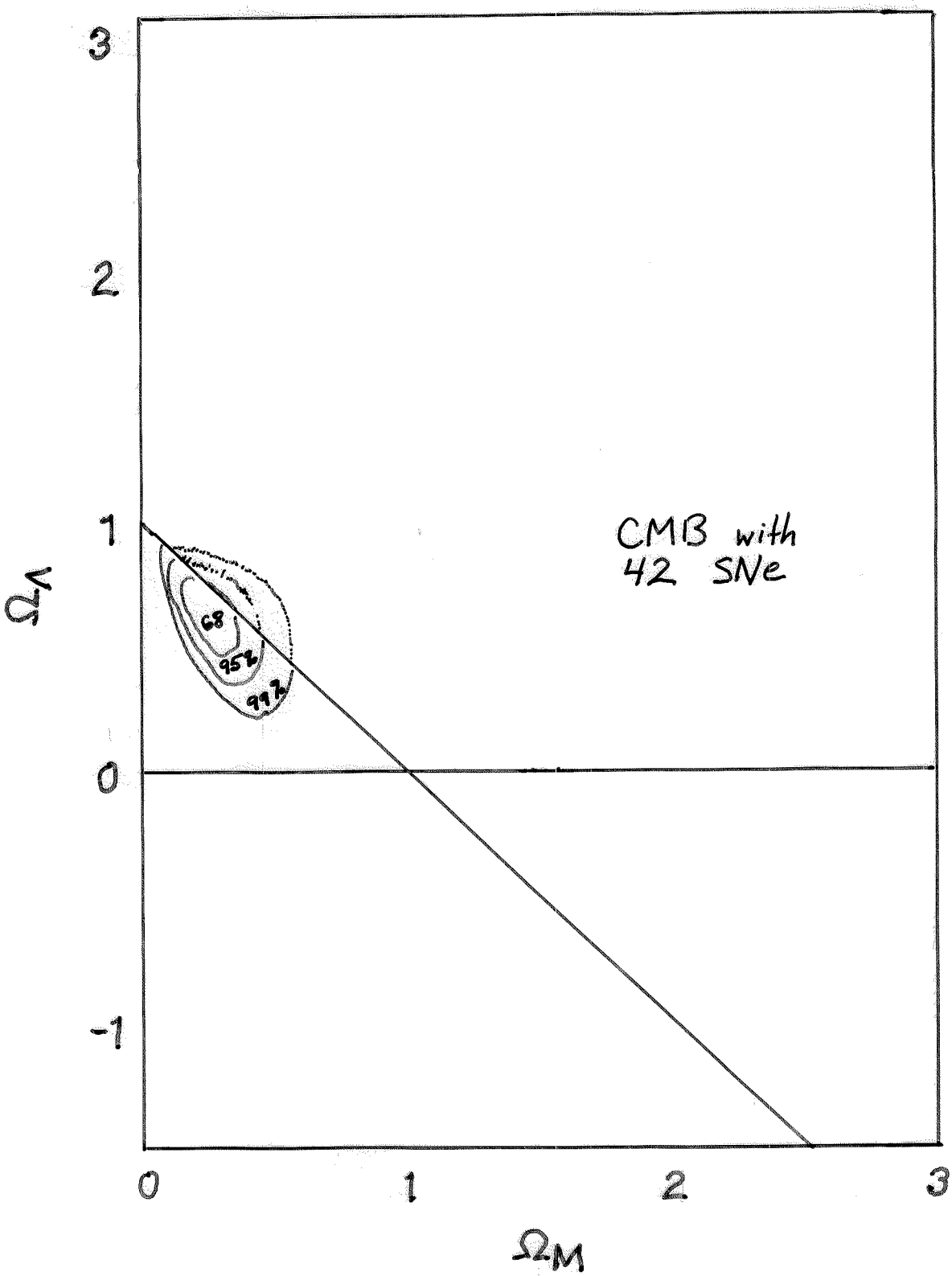


Ap.J.
astro-ph/9812133

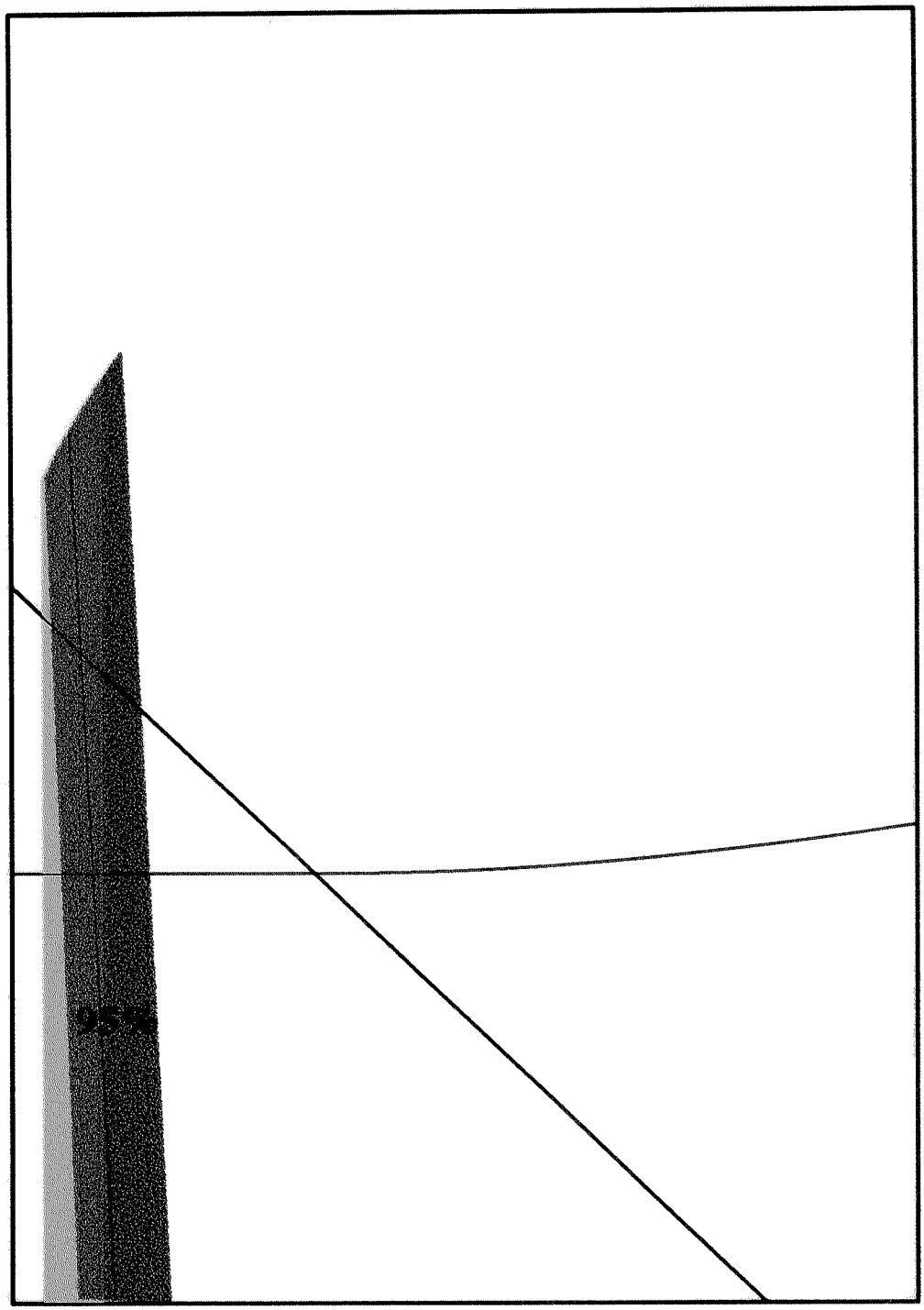
[cf. Garnavich et al (1998)
astro-ph/9806396]

astro-ph/9812226

Efstathiou et al. (1998)



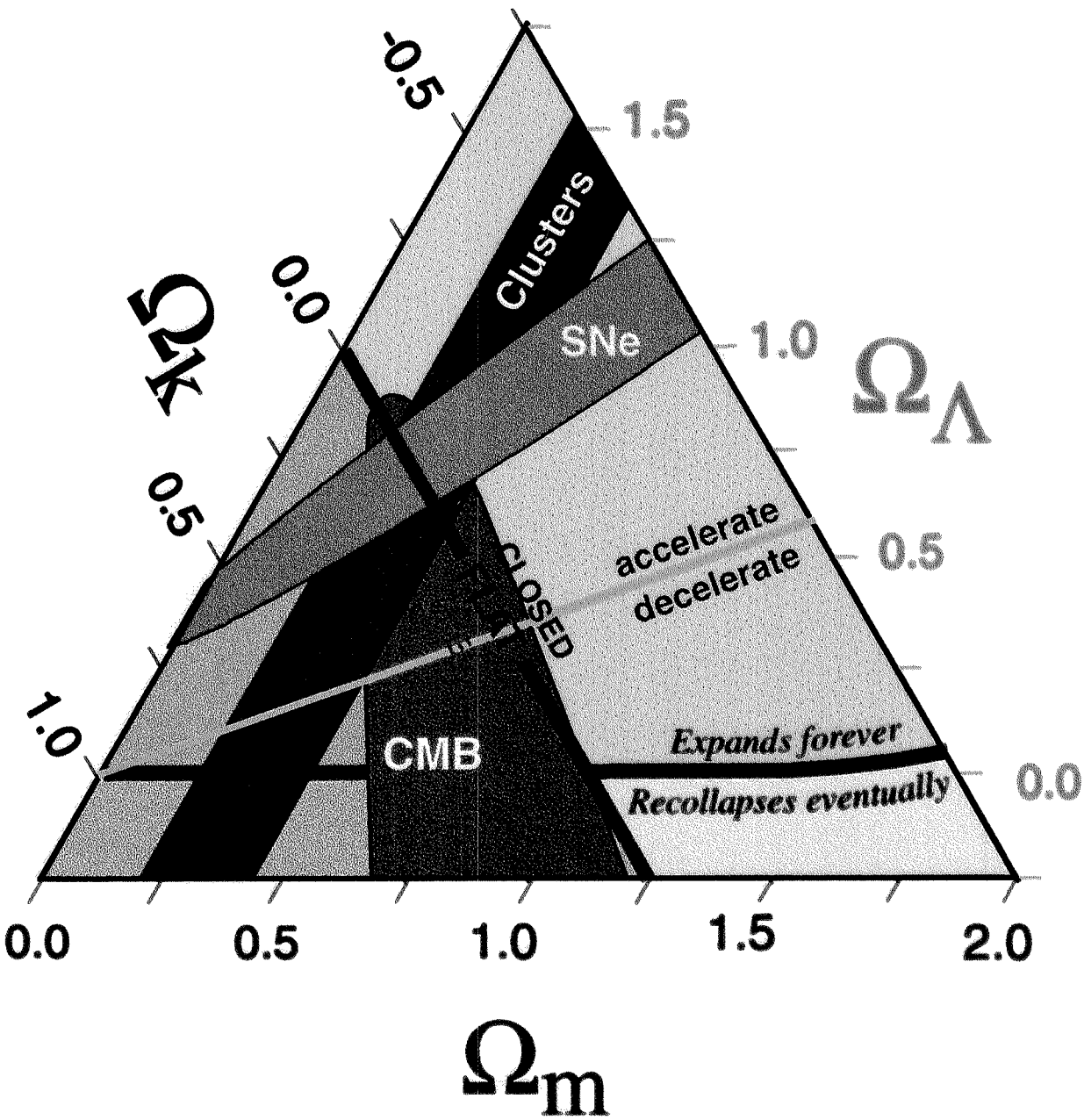
Bahcall & Fan 98a, 98b



Cluster Evolution

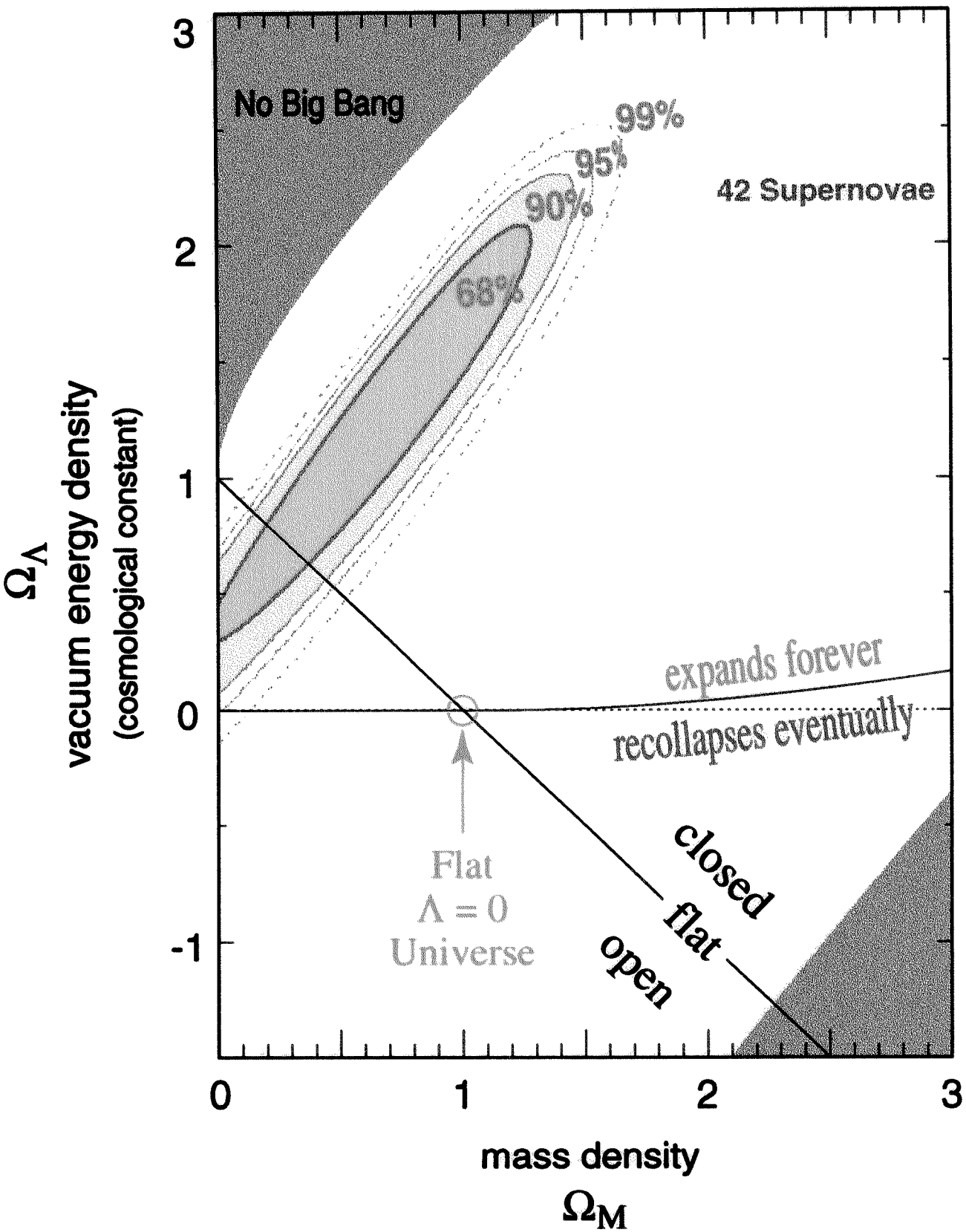
Cluster Dynamics

The "Cosmic Triangle"

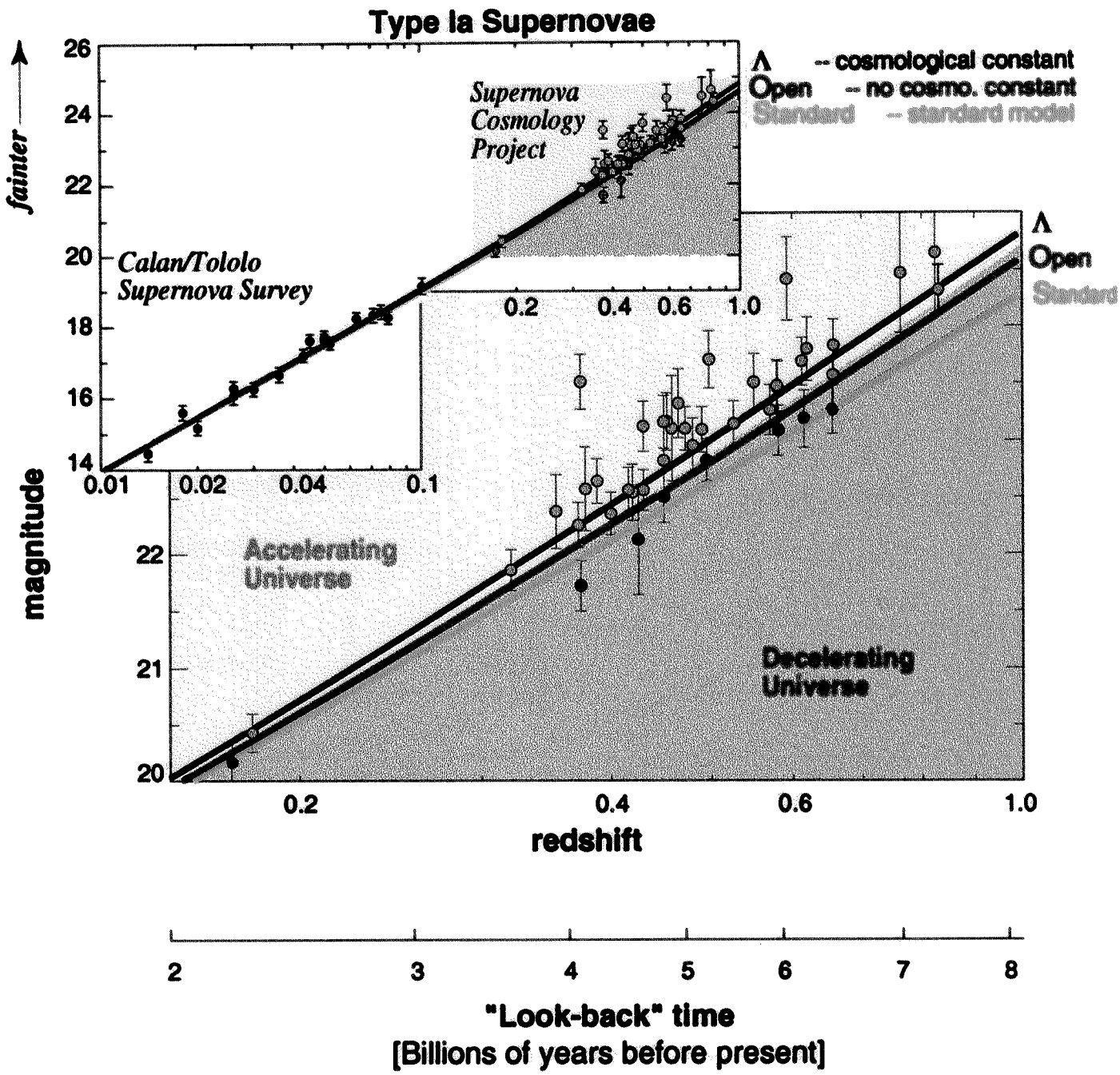


Bahcall, Ostriker, Perlmutter, & Steinhardt
***Science* (1999)**

Supernova Cosmology Project
Perlmutter *et al.* (1998)



Ap.J.
astro-ph/9812133


Type Ia Supernovae
Λ -- cosmological constant
Open -- no cosmo. constant
Standard -- standard model
fainter
magnitude
Supernova Cosmology Project
Calan/Tololo Supernova Survey
Accelerating Universe
Decelerating Universe
redshift
"Look-back" time
[Billions of years before present]

Systematic Error Checks

- Malmquist bias

⇒ • Extinction in SN-host galaxy or our Galaxy.

Evolution of dust ?

⇒ • Evolution of SNe Ia

Shift in $\left\{ \begin{array}{l} \text{metalicity} \\ \text{progenitors} \end{array} \right\}$? Calibratable?

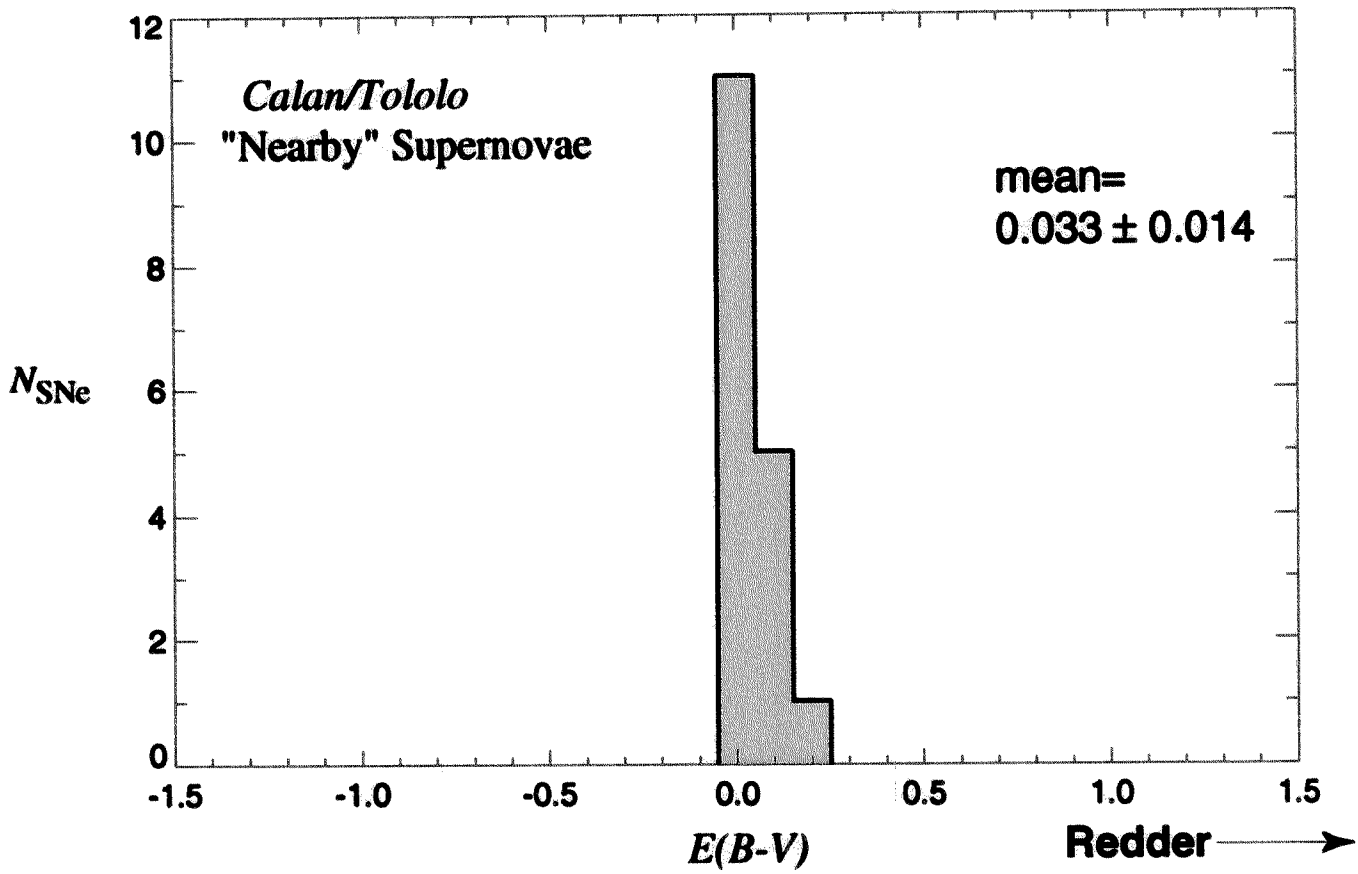
- Local Hubble bubble

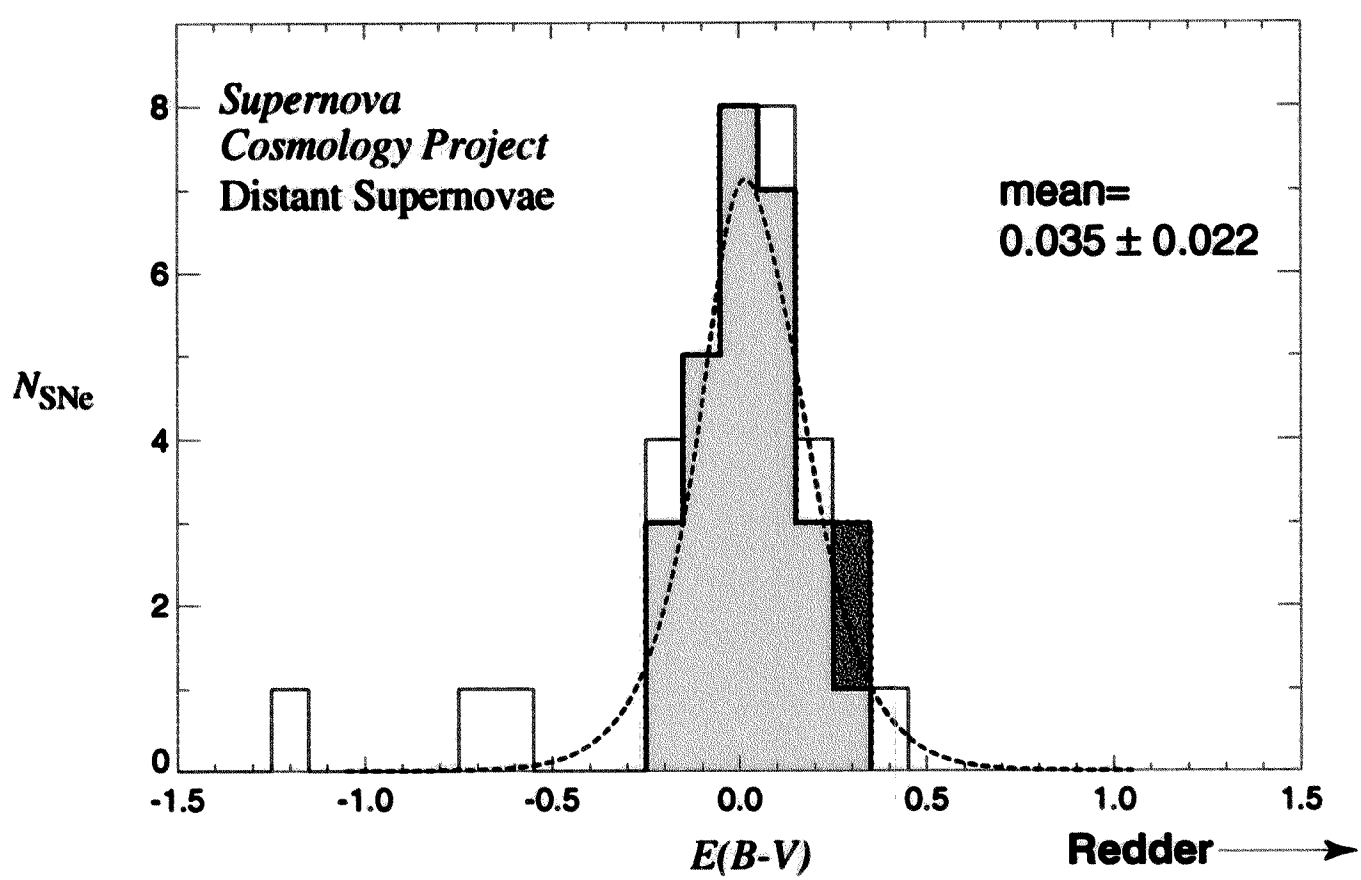
Kim et al (ApJ 1996)
Riess et al (1997)

- Gravitational Lensing

Frieman (Comments Ap 1996)
Wambsgans et al (1996)
Kantowski et al (1994)
Holz & Wald (1998)

Color-Excess Distributions

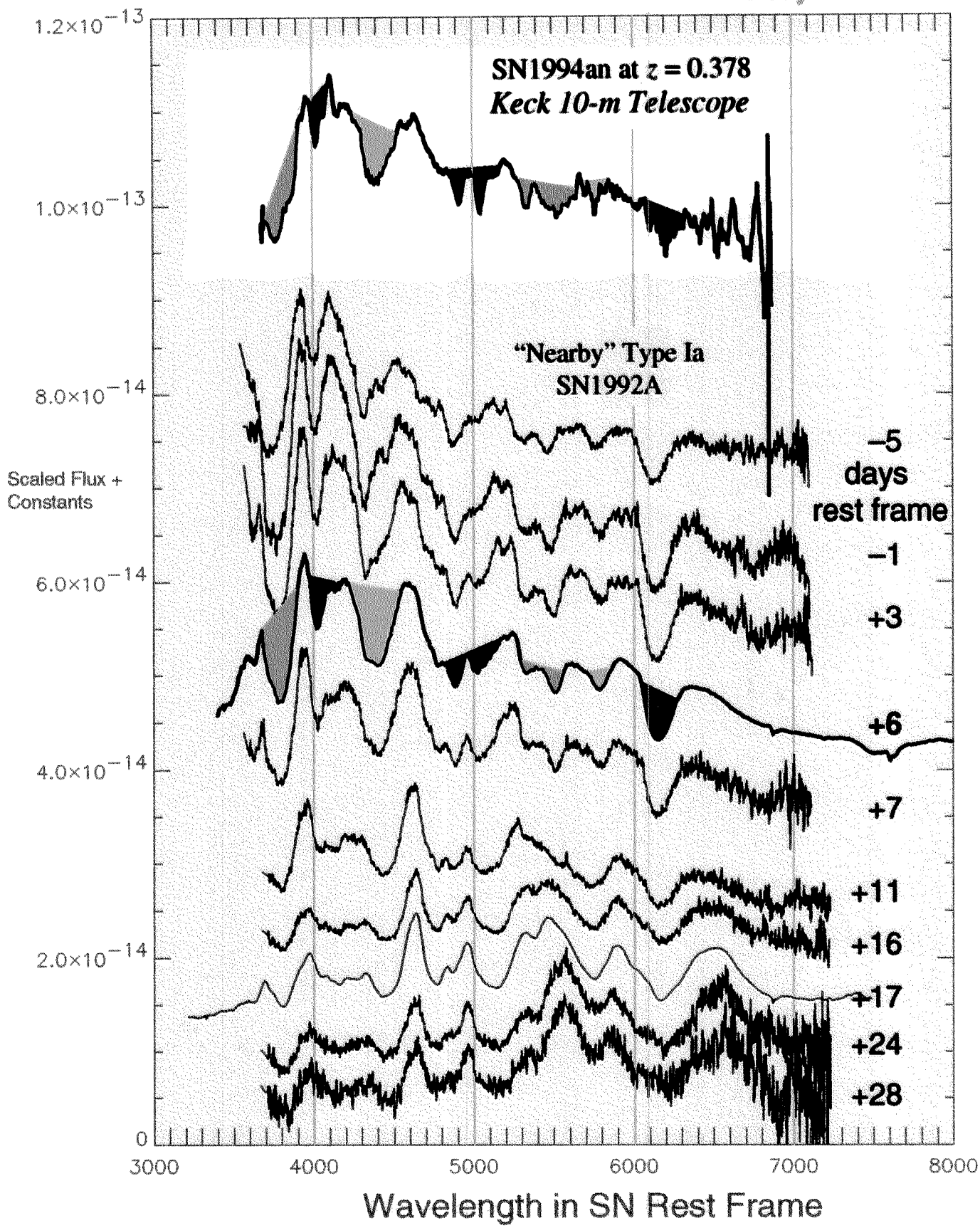




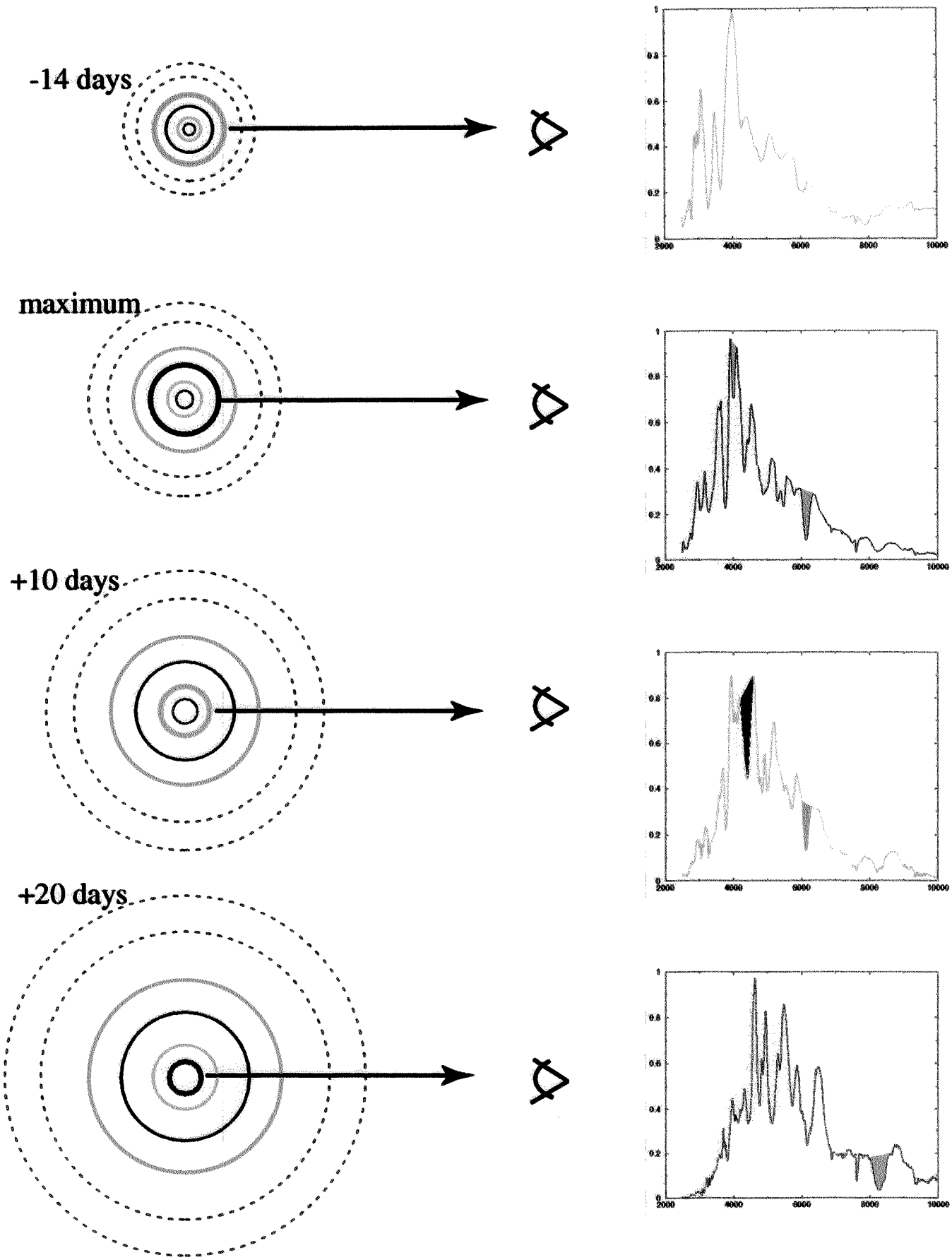
Spectra

An Example: SN1994an

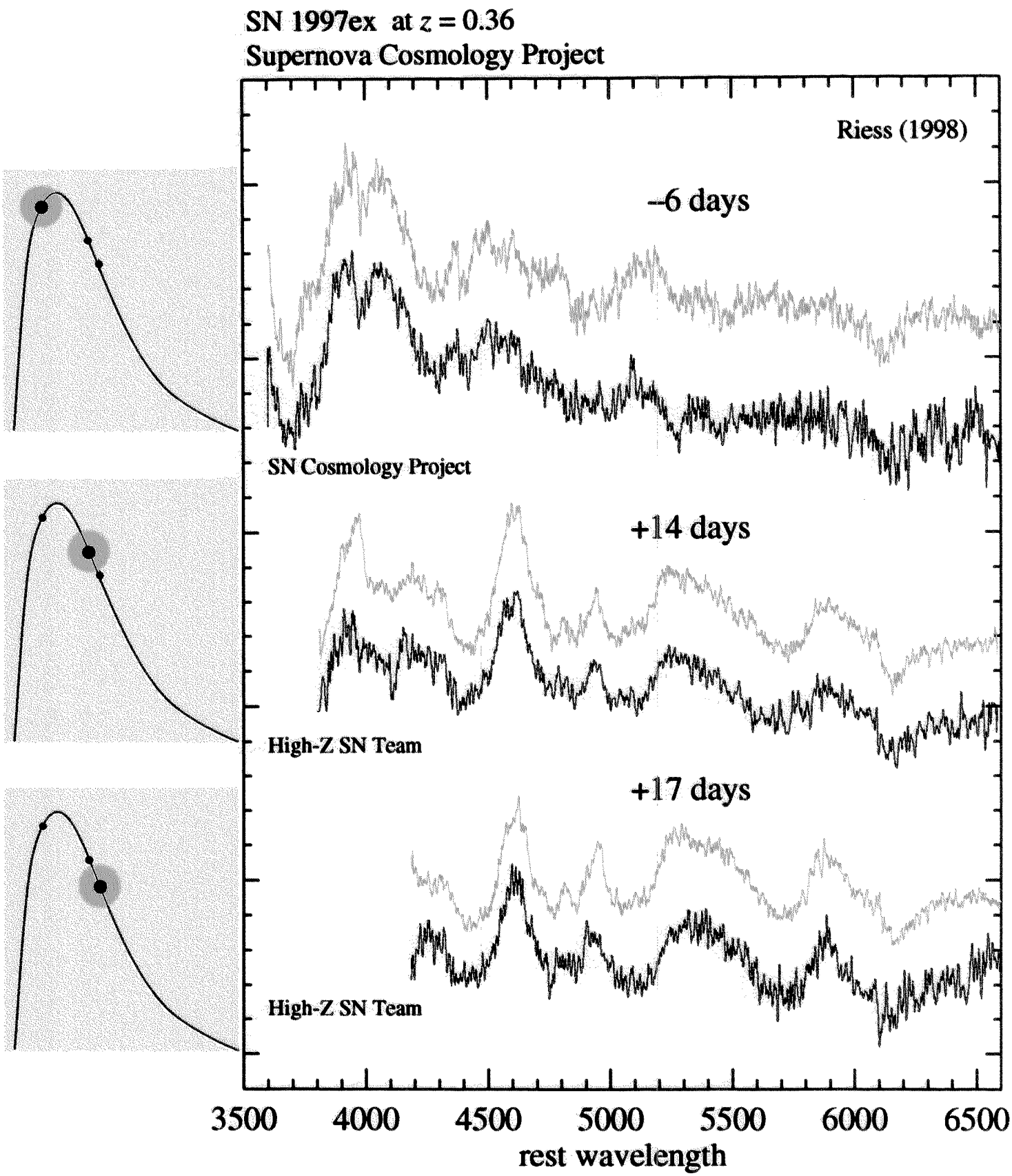
at $z = 0.378$
+9 days past max observer frame
= +6 days rest frame



The time series of spectra are a "CAT Scan" of the Supernova

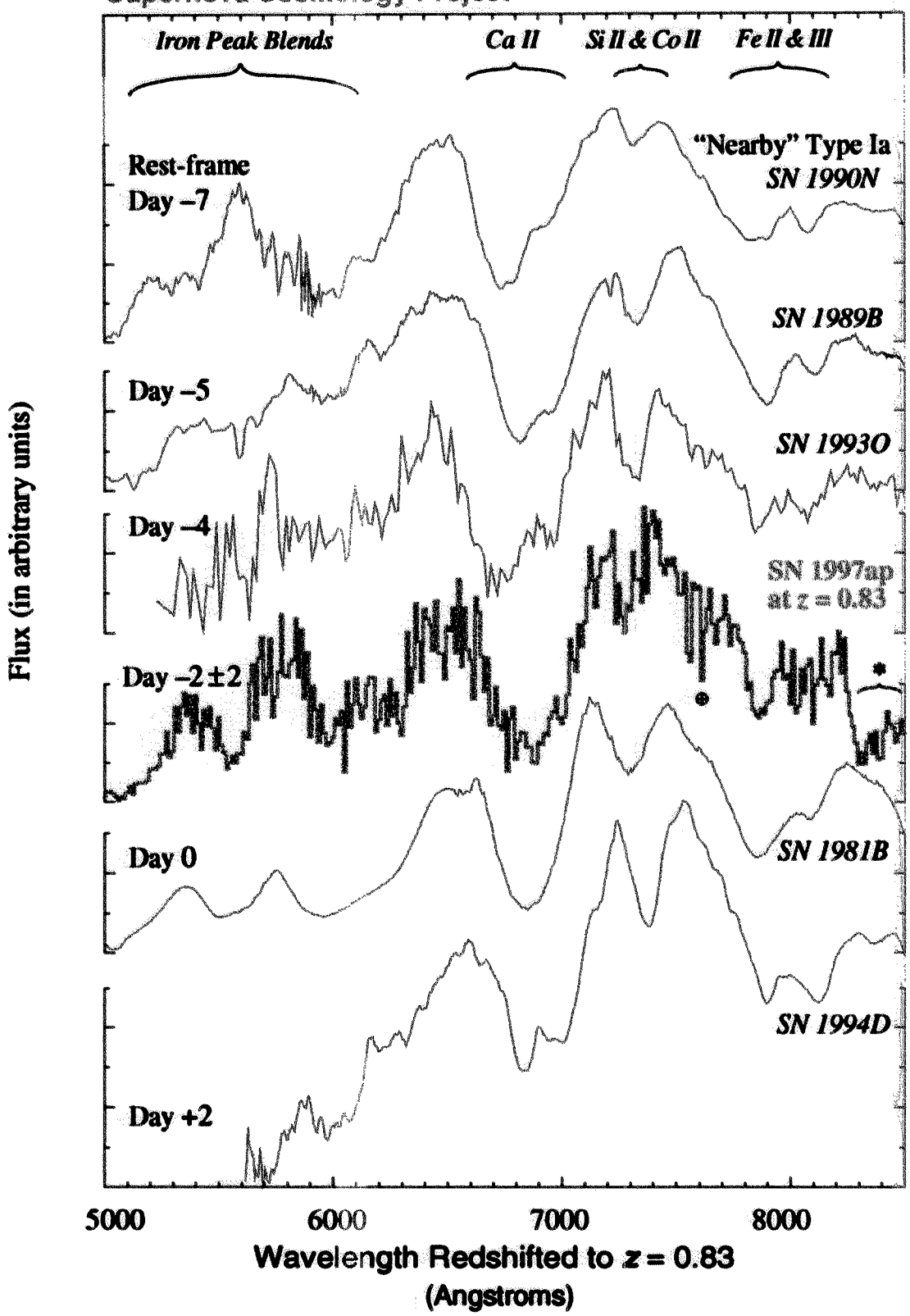


Time Series of Low-Redshift and High-Redshift Spectra



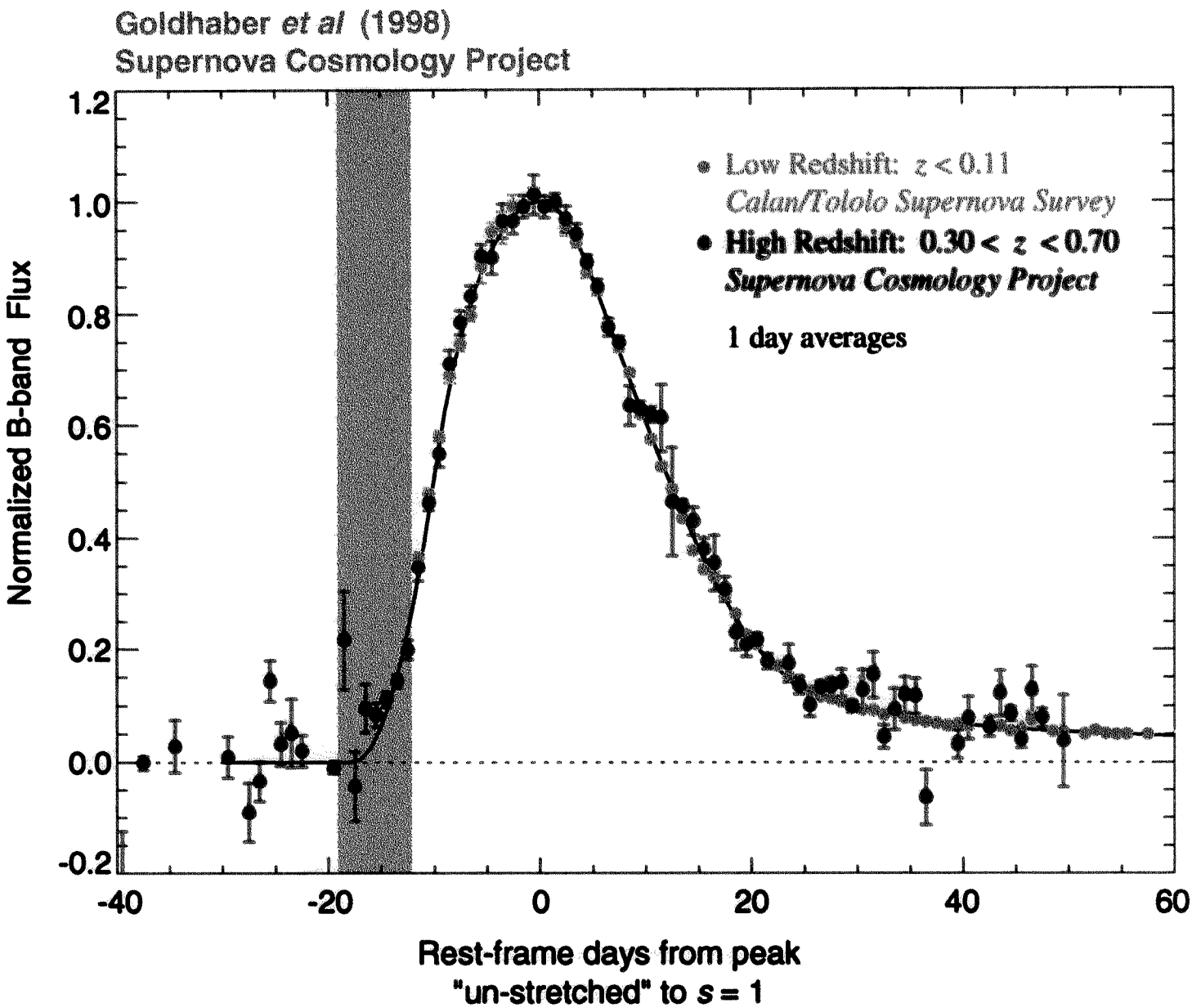
Supernova 1997ap at $z = 0.83$

Perlmutter, *et al.*, Nature (1998)
Supernova Cosmology Project



Note: –4 days (before) max observer frame = –2 days rest frame

Lightcurves Match between Low-Redshift and High-Redshift Type Ia Supernova



Score Card of Uncertainties on $(\Omega_{M,}^{flat}\ \Omega_{\Lambda}^{flat}) = (0.28, 0.72)$

Statistical

☑	high-redshift SNe	0.05
☑	low-redshift SNe	0.065
	Total	***0.085***

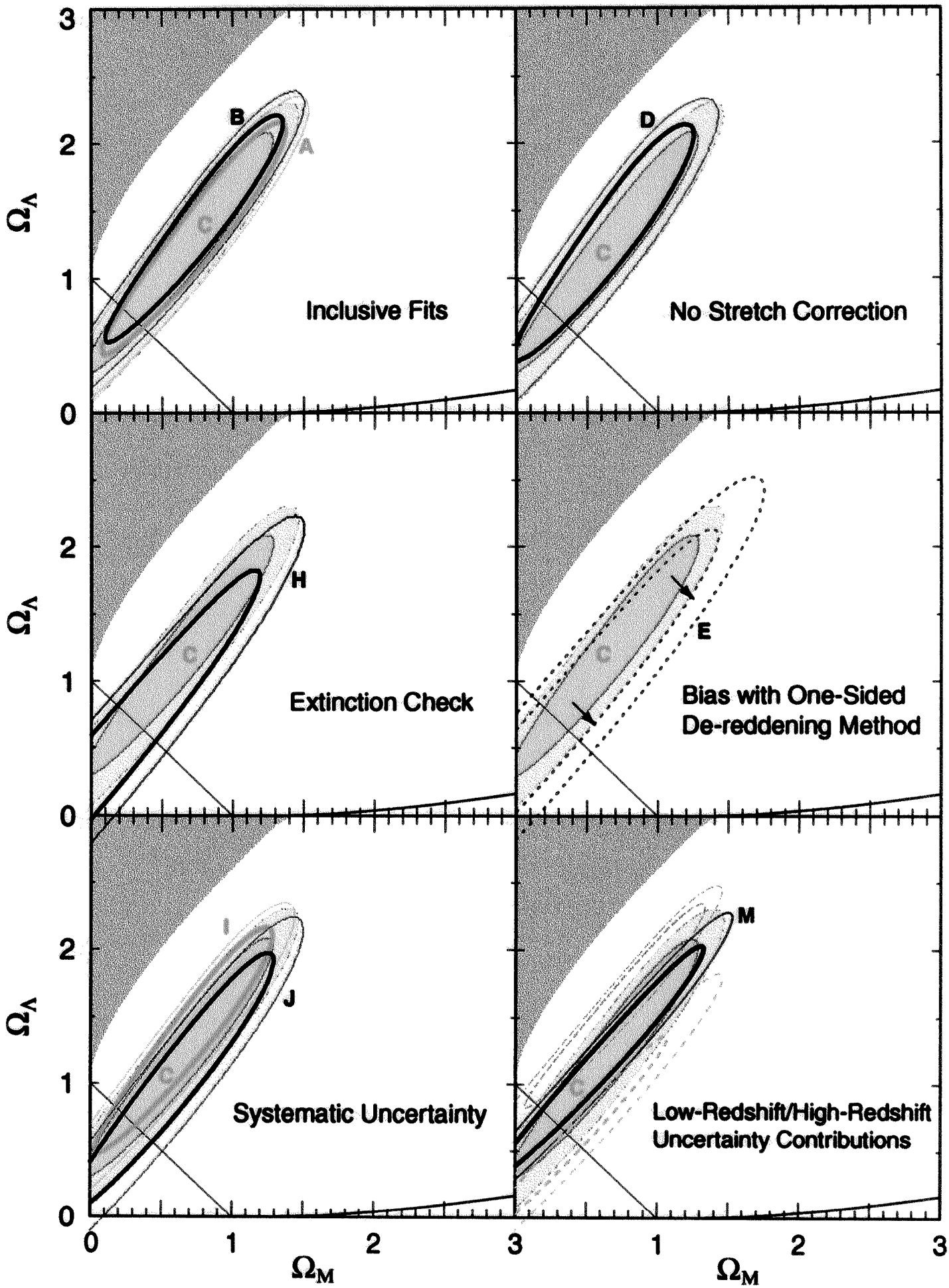
Systematic

☑	dust that reddens $R_B(z{=}0.5) < 2\ R_B(\text{today})$	< 0.03	4 of 4 high-z lens galaxies
?	evolving grey dust clumpy		< 0.14 or would increase σ
?	same for each SN		
☑	Malmquist bias difference	< 0.04	
?	SN Ia evolution shifting distribution of prog mass/metallicity/C-O/..		< 0.13, lightcurve rise-times • Test range of low-z SNe. • Compare ellipticals/spirals...
☑	K-correction uncertainty including zero-points	< 0.025	
	Total identified entities/processes	***0.05***	

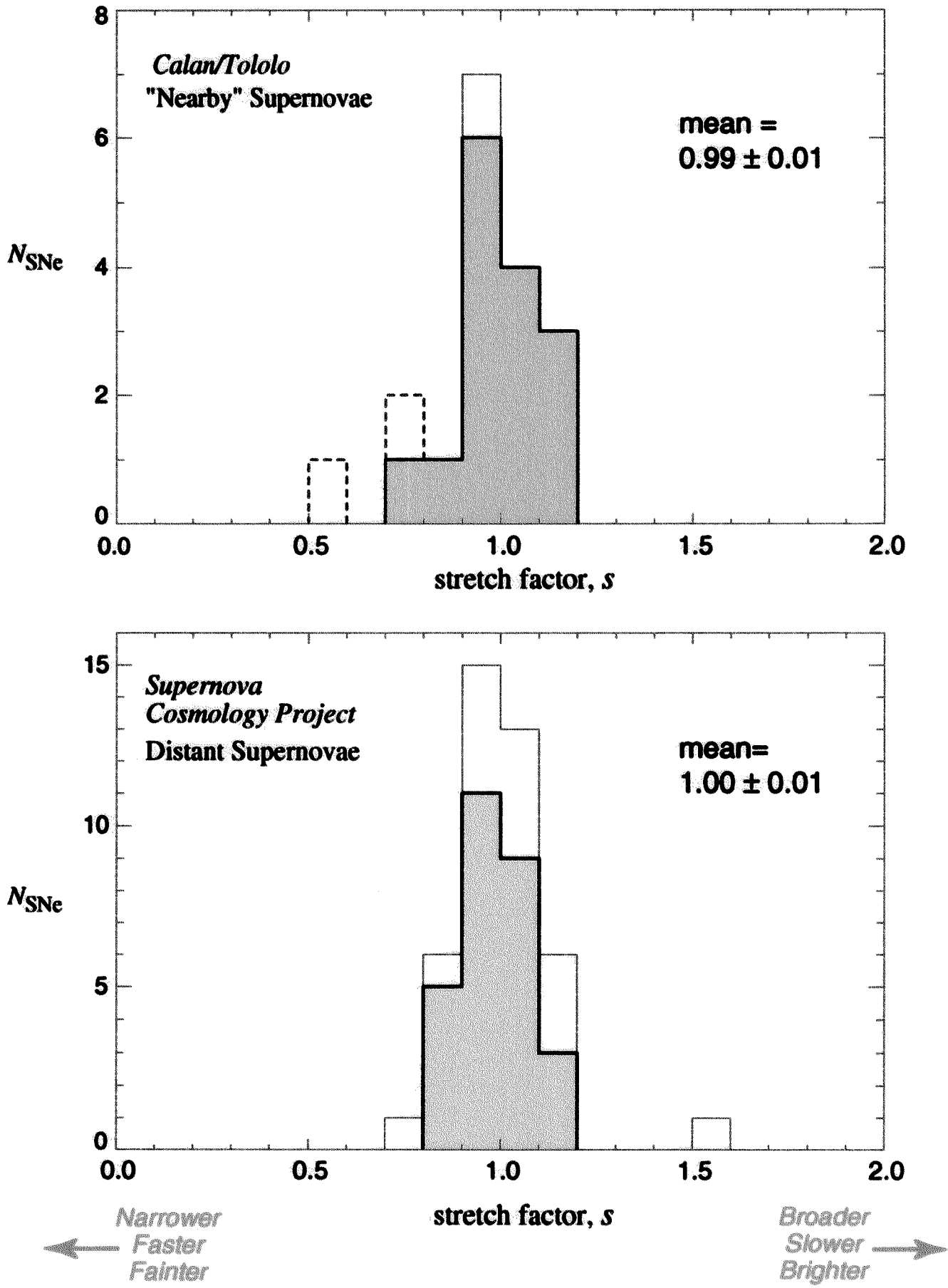
Cross-Checks of sensitivity to

☑	Width-Luminosity Relation	< 0.03
☑	Non-SN Ia contamination	< 0.05
☑	Galactic Extinction Model	< 0.04
☑	Gravitational Lensing by clumped mass	< 0.06

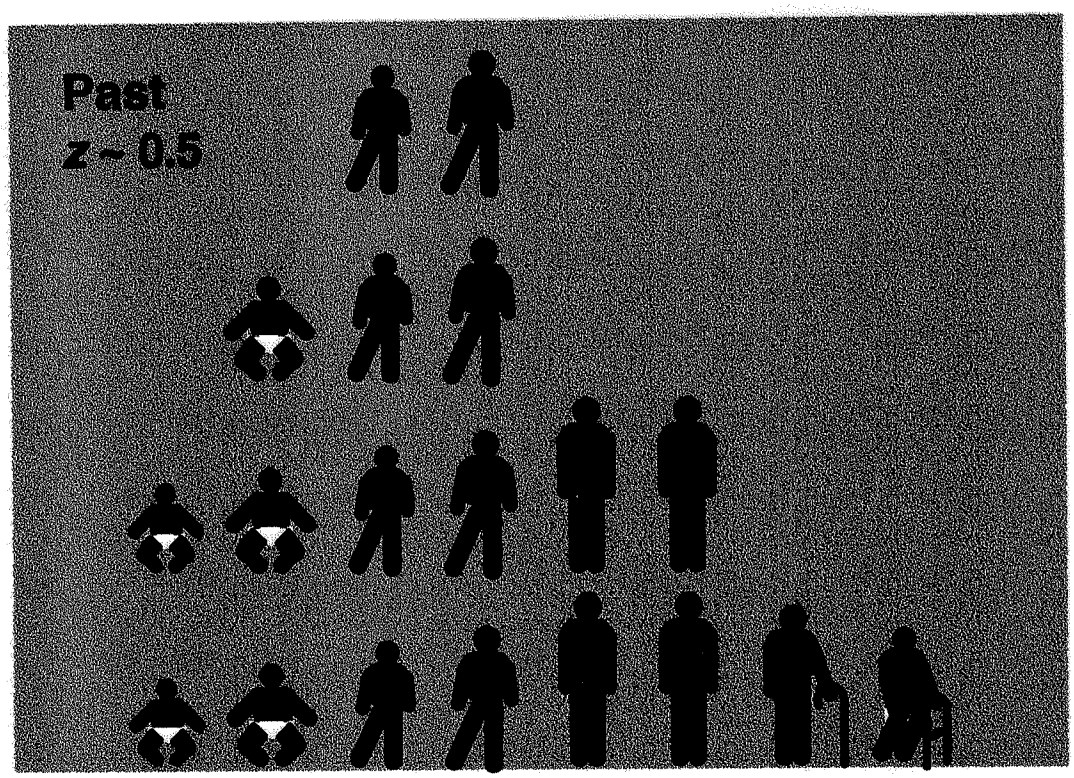
Perlmutter *et al.* (1998)
astro-ph/9812133

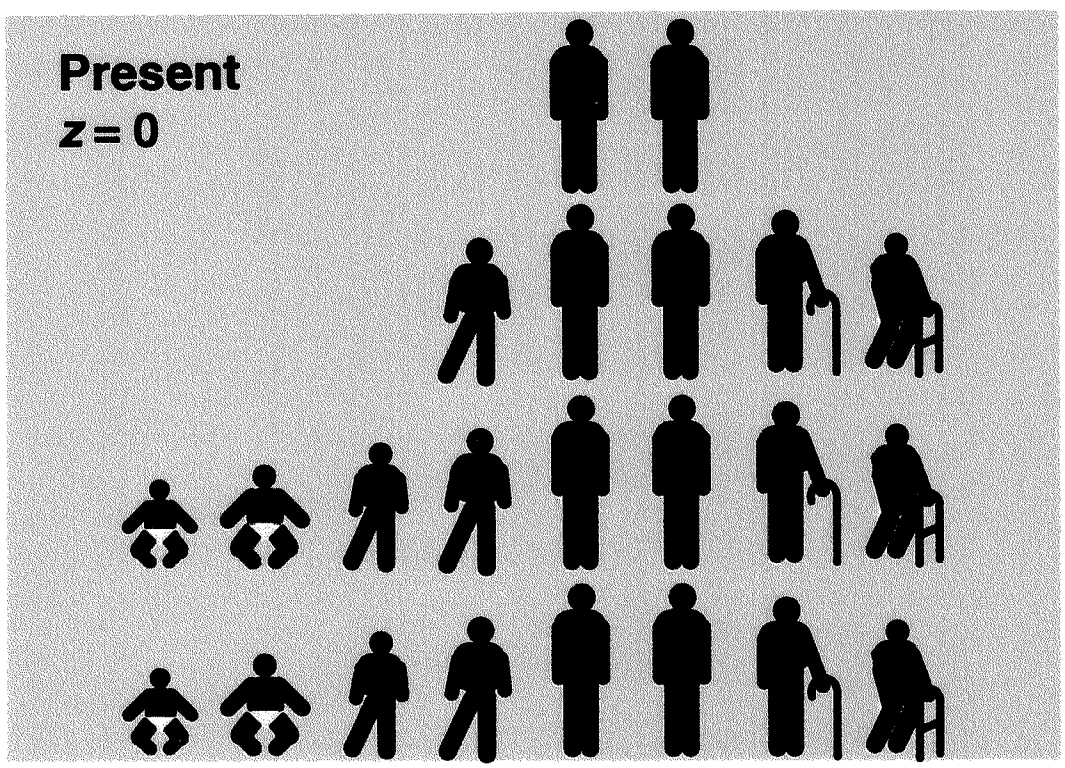

Inclusive Fits
No Stretch Correction
Extinction Check
Bias with One-Sided
De-reddening Method
Systematic Uncertainty
Low-Redshift/High-Redshift
Uncertainty Contributions
A
B
C
D
E
H
I
J
M
Ω_Λ
Ω_M
0
1
2
3

Lightcurve Width Distributions



Supernova Demographics





Galaxy Environment Age

← *Younger* *Older* →

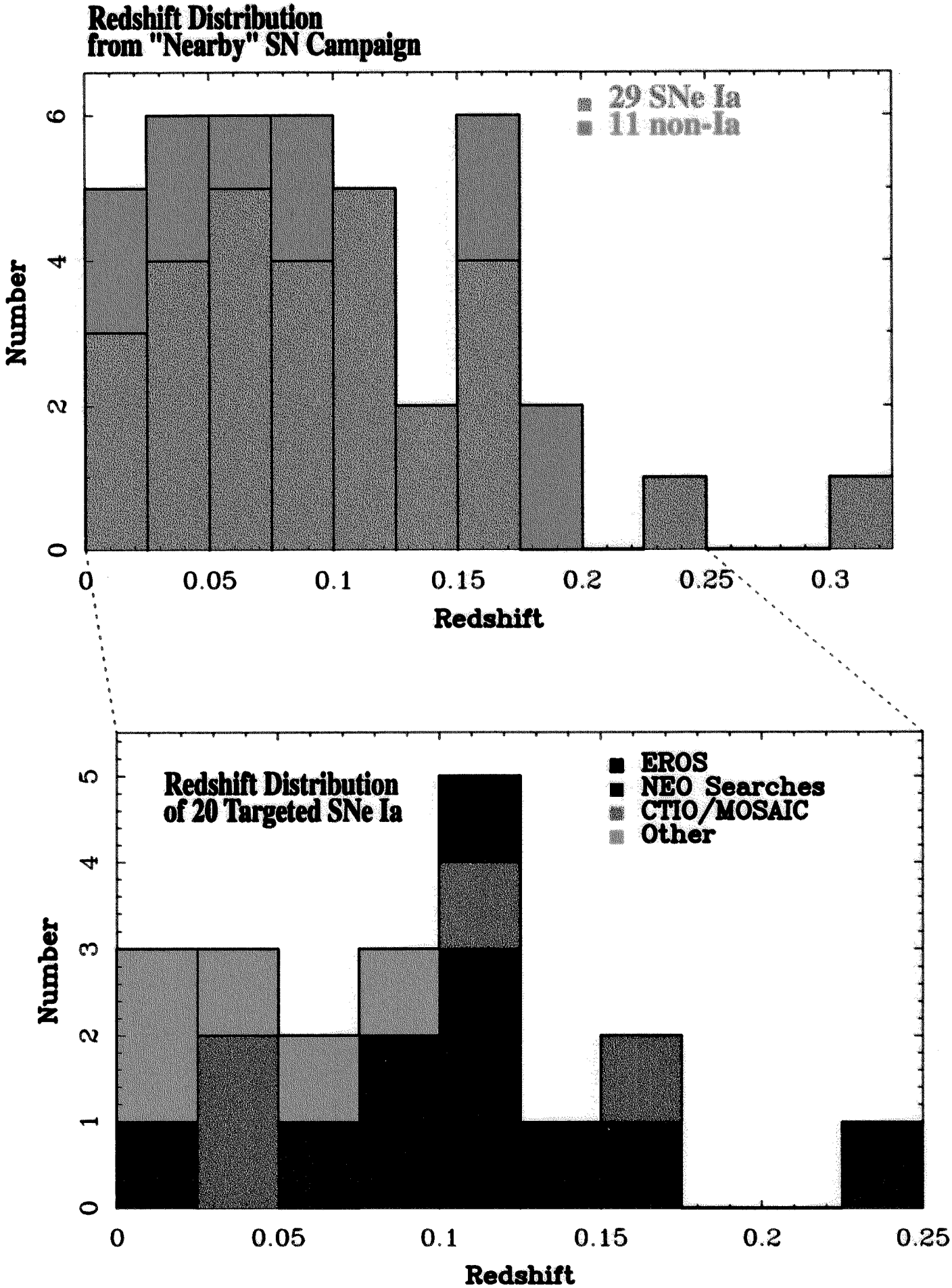
New "Nearby" Supernova Search

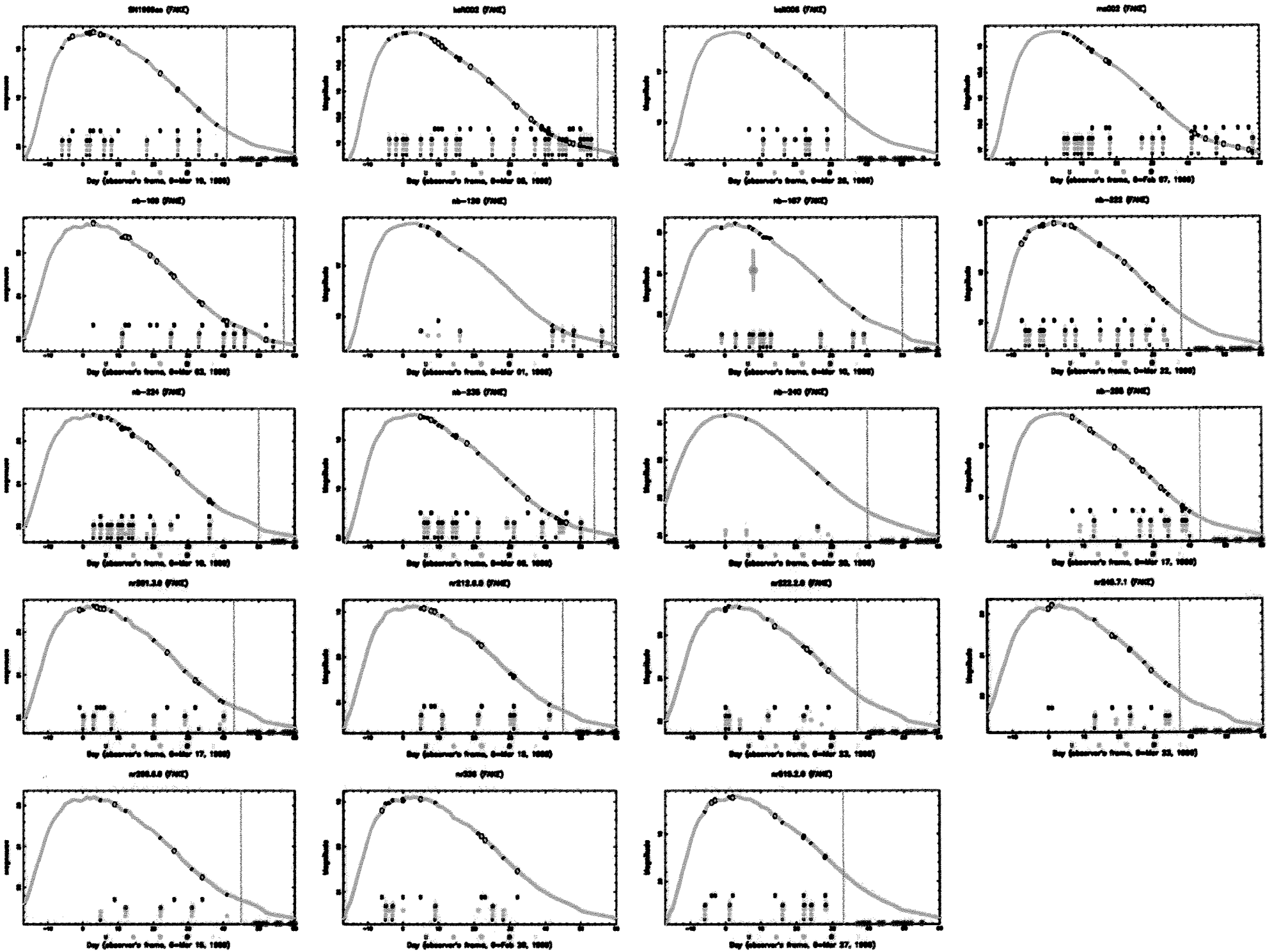
Find and study ~60 SNe at $z < 0.1$ in ~3 years.

Goals:

- Determine intrinsic luminosity function of SNe Ia.
- Study relationships between lightcurve timescale, spectral features, luminosity, etc. as function of progenitor environment.
- UBVRI lightcurves beginning well before maximum.
- Spectral time series (to improve/test K corrections).
- Study search-selection effects in nearby samples.

February/March 1999 Search Telescopes		Ia	II/Ic
EROS in Chile 1 meter	~450 sq. deg.	11	3
Mosaic (8K x 8K) Camera on Kitt Peak 0.9 meter	~175 sq. deg.	6	2
NEAT on Haleakala, Maui	~425 sq. deg.	3	2
Yale/QUEST Venezuela Schmidt	~140 sq.deg.	0	0
Spacewatch (2K x 2K) on Kitt Peak	~150 sq. deg.	3	0

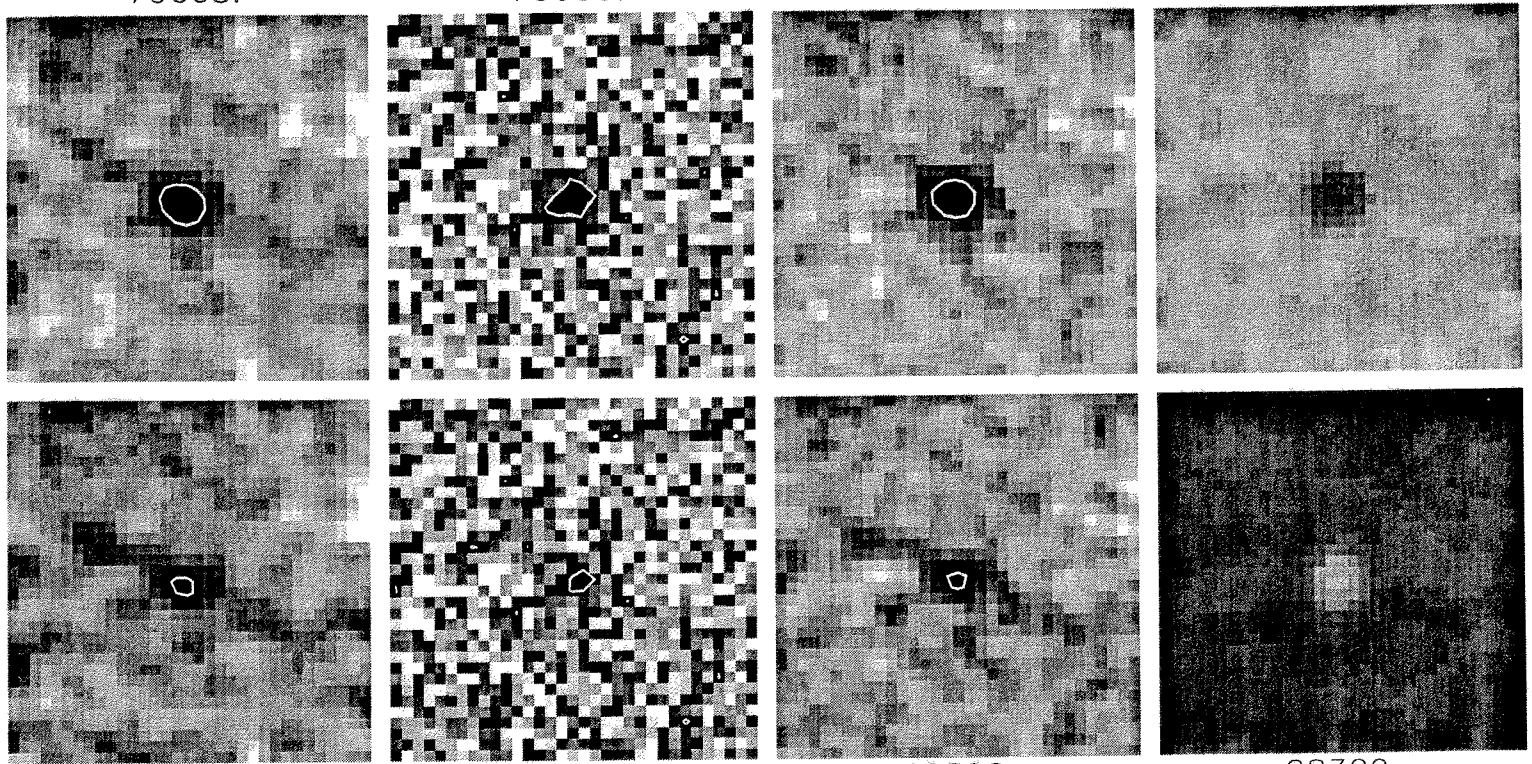

Redshift Distribution
from "Nearby" SN Campaign
29 SNe Ia
11 non-Ia
Number
0
2
4
6
0
0.05
0.1
0.15
0.2
0.25
0.3
Redshift
Redshift Distribution
of 20 Targeted SNe Ia
EROS
NEO Searches
CTIO/MOSAIC
Other
Number
0
1
2
3
4
5
0
0.05
0.1
0.15
0.2
0.25
Redshift



K98-001

"Albinoni"

NEW1	NEW2	NEW	REF
79668.	70035.	75219.	28329.



51338.	41706.	46890.	28329.

REF
- sep1598keck27csg.fts
- sep1598keck28csg.fts
- sep1598keck29csg.fts
- sep1598keck36csg.fts
- sep1598keck37csg.fts
- sep1598keck38csg.fts

NEW1
- oct1598keck33csg.fts
- oct1598keck34csg.fts
- oct1598keck35csg.fts

NEW2
- oct1598keck46csg.fts
- oct1598keck47csg.fts
- oct1598keck52csg.fts

Ap.Sig	=	5.591
%Inc	=	165.5
PCyg.Sig	=	2.307
MaxPixSig	=	0.000
MXY	=	0.007617
FWX	=	4.731
FWY	=	3.497
NeighDist	=	36.65
NeighMag	=	22.97
Mag	=	24.77
Theta	=	27.47
New1Sig	=	8.276
New2Sig	=	8.258
Sub1Sig	=	4.661
Sub2Sig	=	4.159
Sub2−Sub1	=	0.6467
DSub1Sub2	=	1.386

Subtraction: Keck031_1

RA : 23:17:56.91

Dec : +15:39:17.6

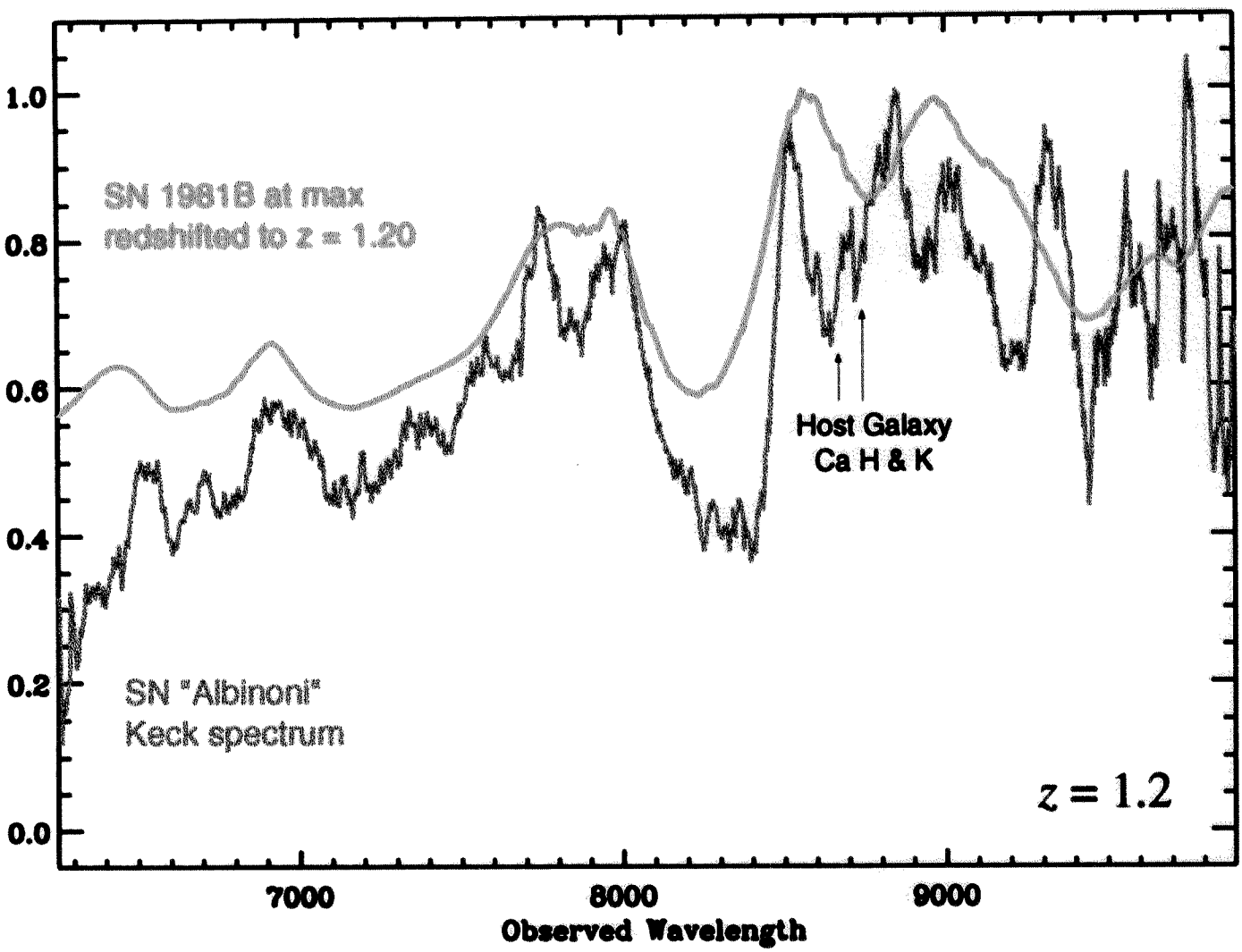
Refsys= sep1598keck27csg.fts

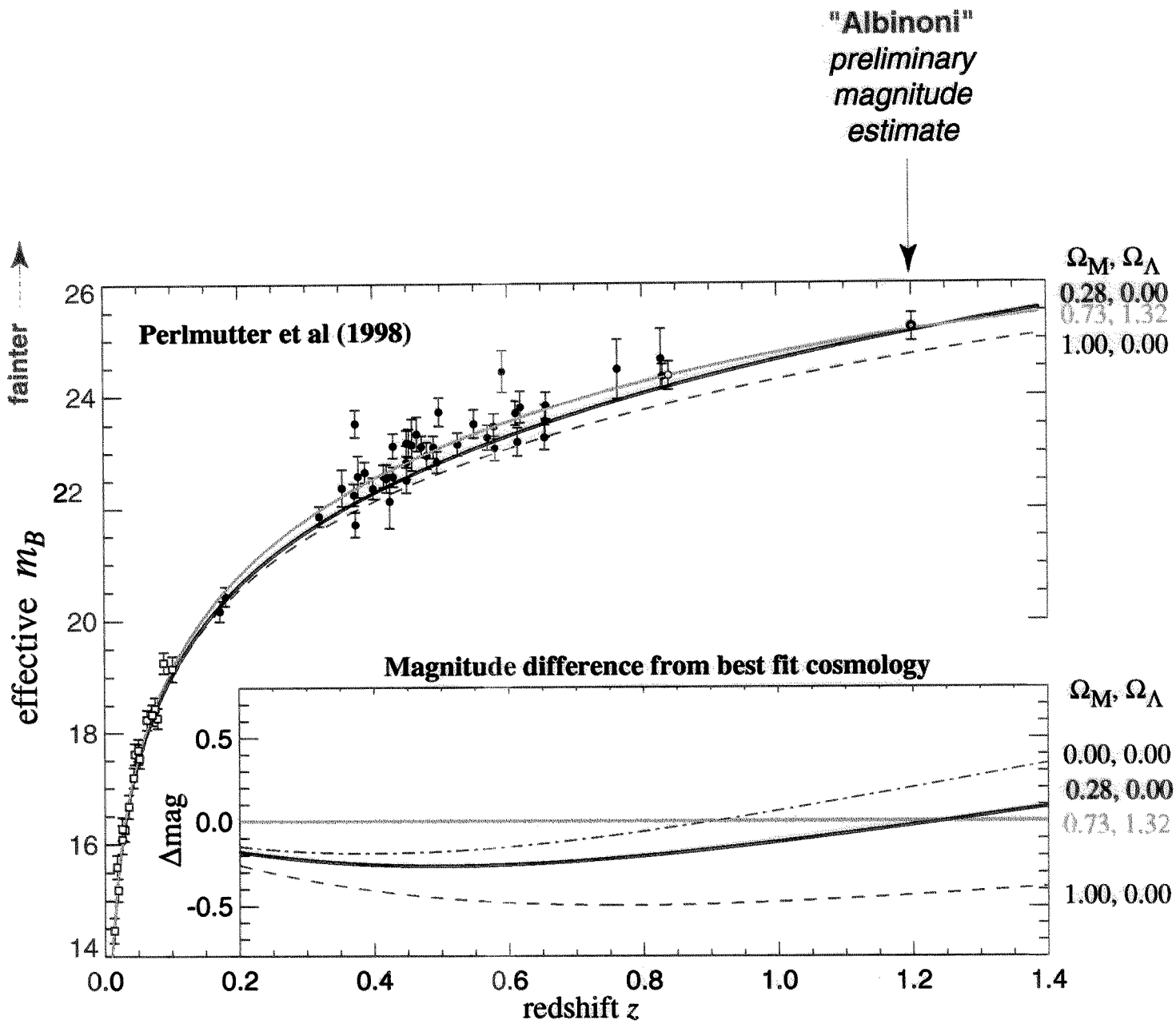
Pos on refsys: (456.2,1179.5)

Scanner: gerson

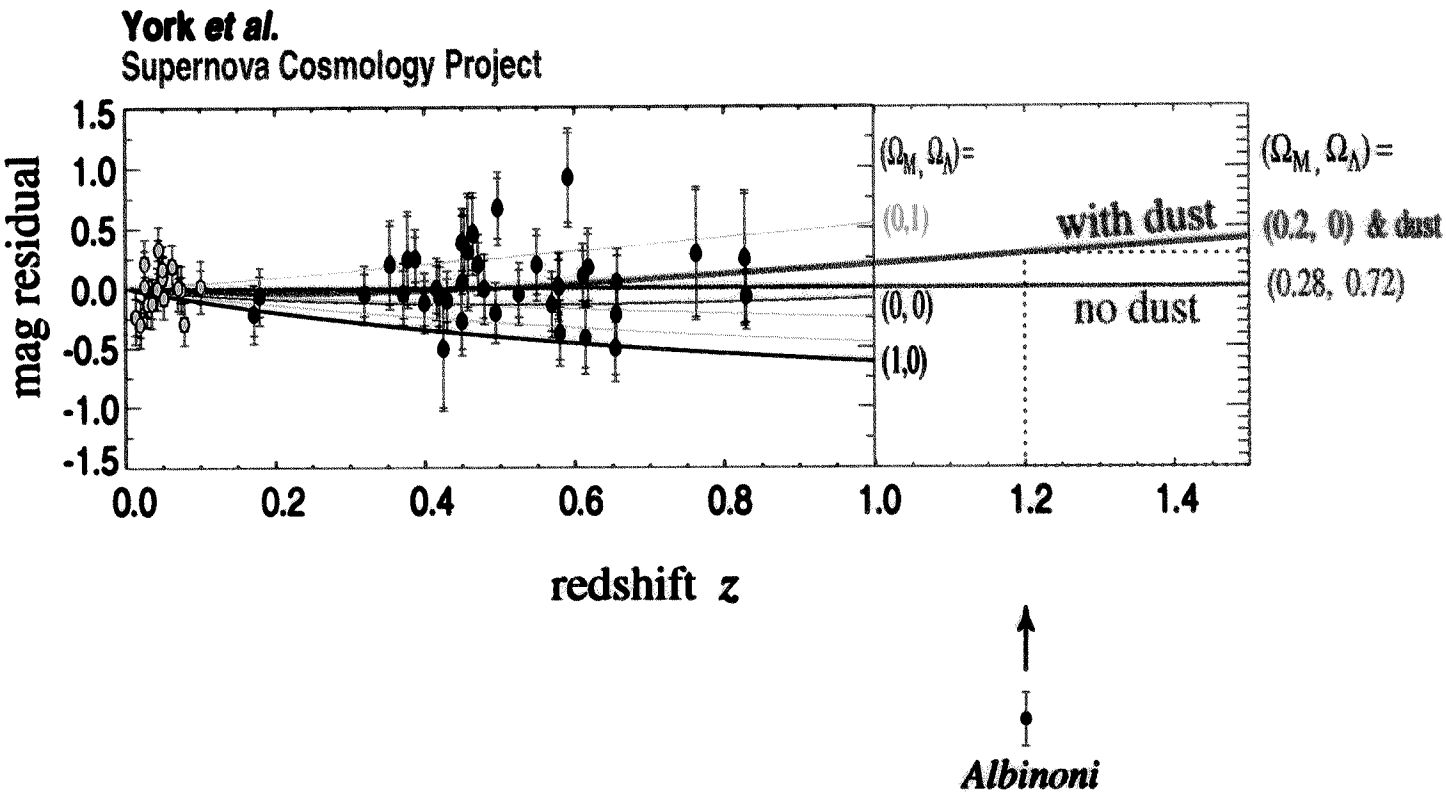
Subtractions :	4
Host :	3
Shape :	2
Position :	−4
Motion :	−4
Overall :	2

1998−10−15 17:30:04.00


SN 1981B at max
redshifted to z = 1.20
SN "Albinoni"
Keck spectrum
Host Galaxy
Ca H & K
z = 1.2
1.0
0.8
0.6
0.4
0.2
0.0
7000
8000
9000
Observed Wavelength

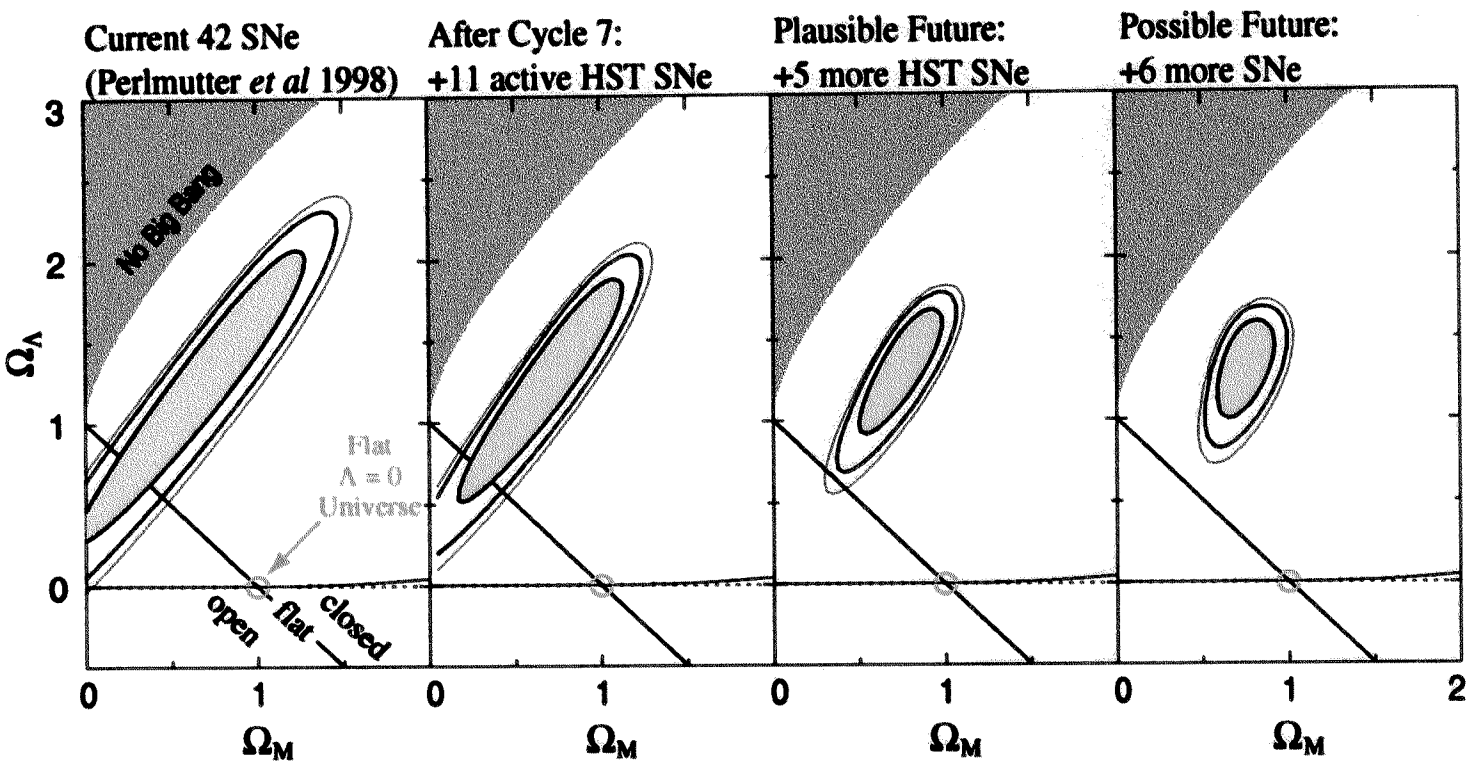

"Albinoni"
preliminary
magnitude
estimate
fainter
Perlmutter et al (1998)
effective m_B
Ω_M, Ω_Λ
0.28, 0.00
0.73, 1.32
1.00, 0.00
Magnitude difference from best fit cosmology
Δmag
0.00, 0.00
0.28, 0.00
0.73, 1.32
1.00, 0.00
redshift z

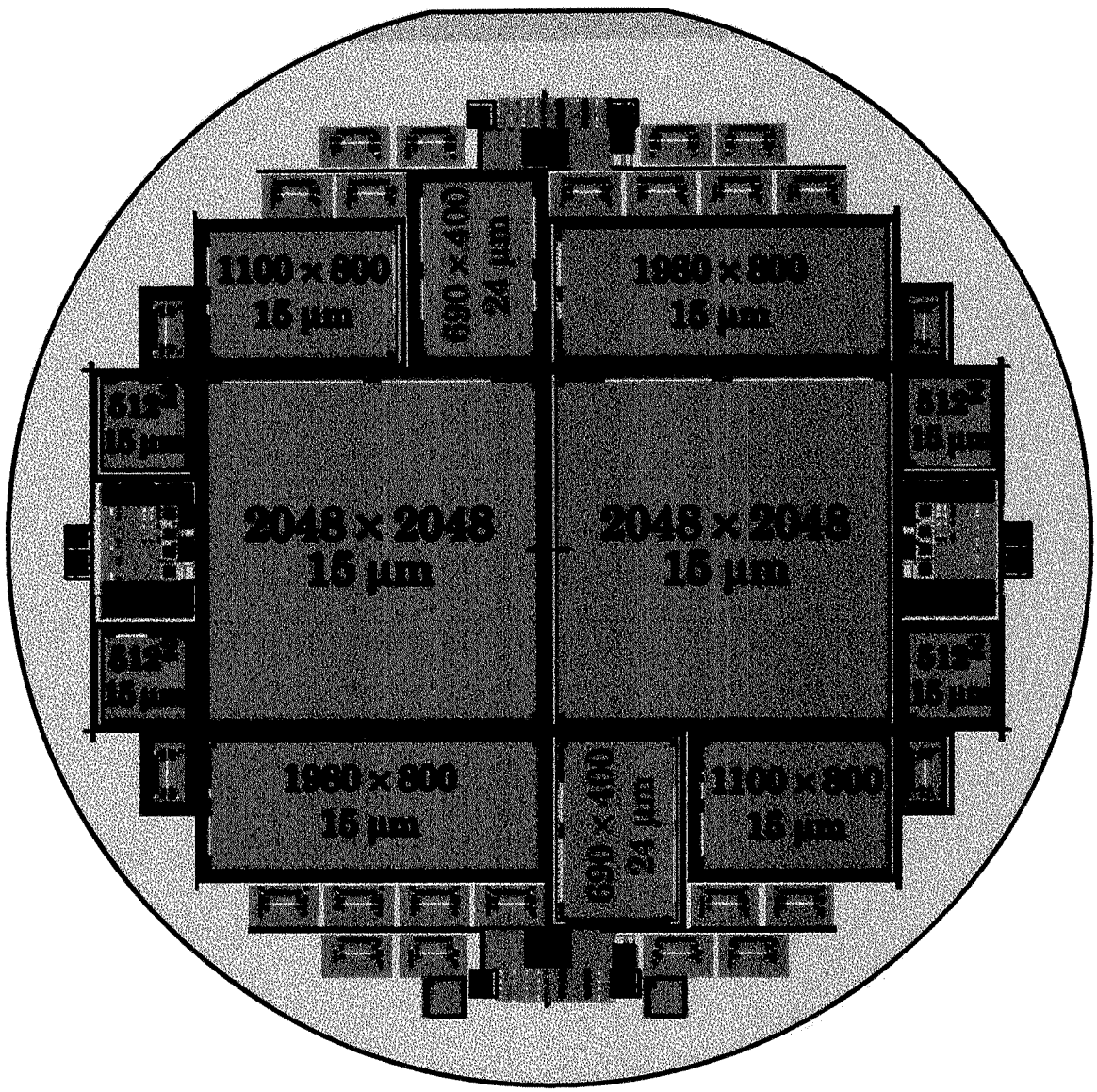
Recognizing
Intergalactic Grey Dust
Using SNe at Redshifts > 1



see Aguirre (1999)
astro-ph/9904319

If future results were to narrow in on current best fit...



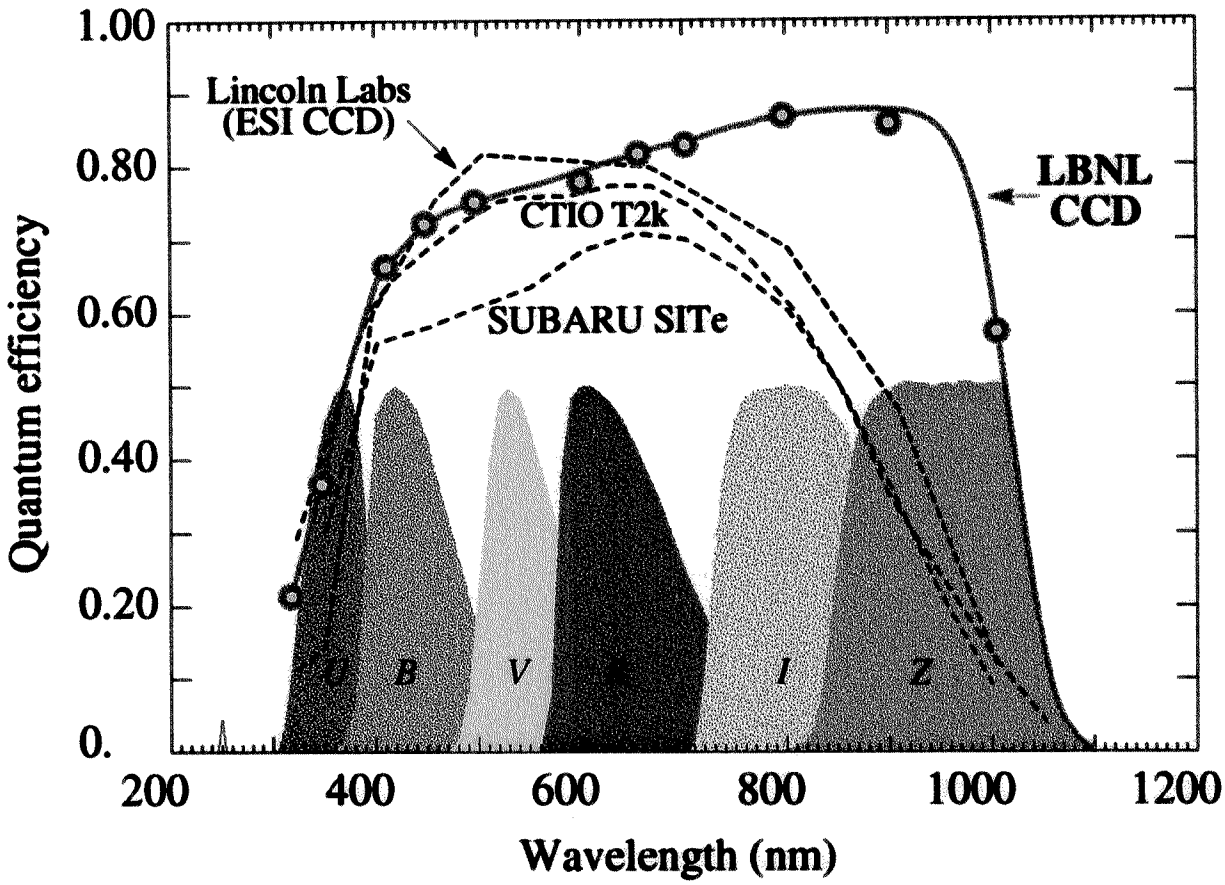


0 cm 5

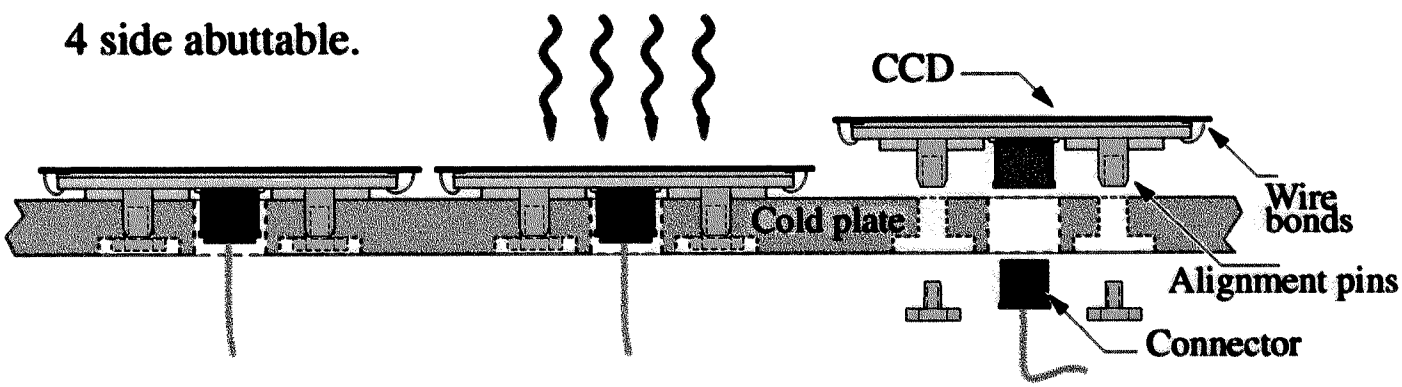
Steve Holland
(LBNL)

LBNL CCD Technology

High quantum efficiency from near UV to near IR
No thinning, no fringing.
High yield.
Radiation hard.



4 side abuttable.



What's wrong with a non-zero cosmological constant / vacuum energy ?

Two coincidences :

- WHY SO SMALL ?

  Might expect $\frac{\Lambda}{8\pi G} \sim m^4_{\text{symmetry breaking}}$.

  This is off by ~51 ORDERS OF MAGNITUDE !

- "WHY NOW" ?

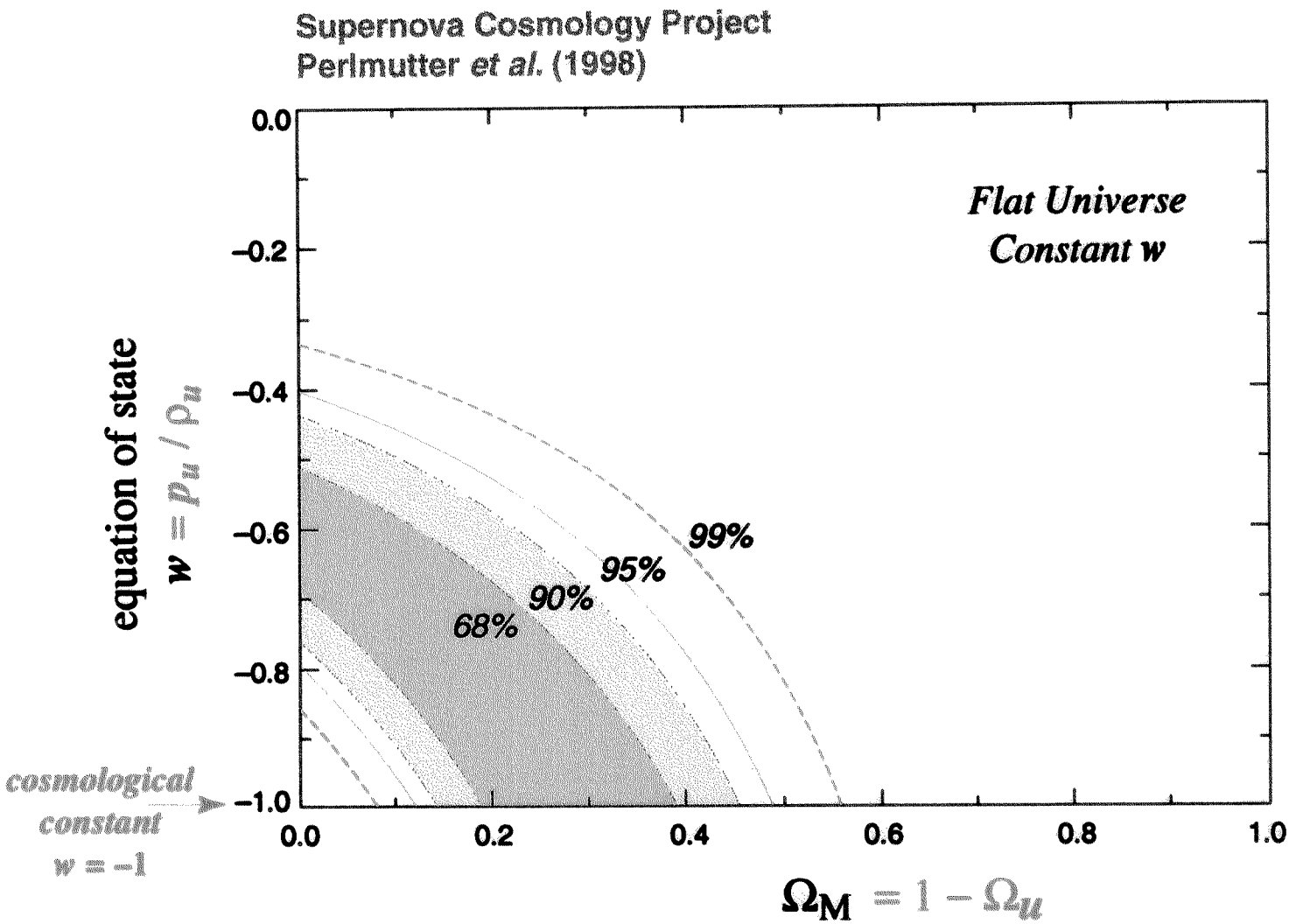
$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}(\rho + 3p)$$

MATTER: $p = 0 \Rightarrow \rho \propto R^{-3}$

VACUUM ENERGY: $p = -\rho \Rightarrow \rho = \underline{\text{const.}}$

"Dark Energy"

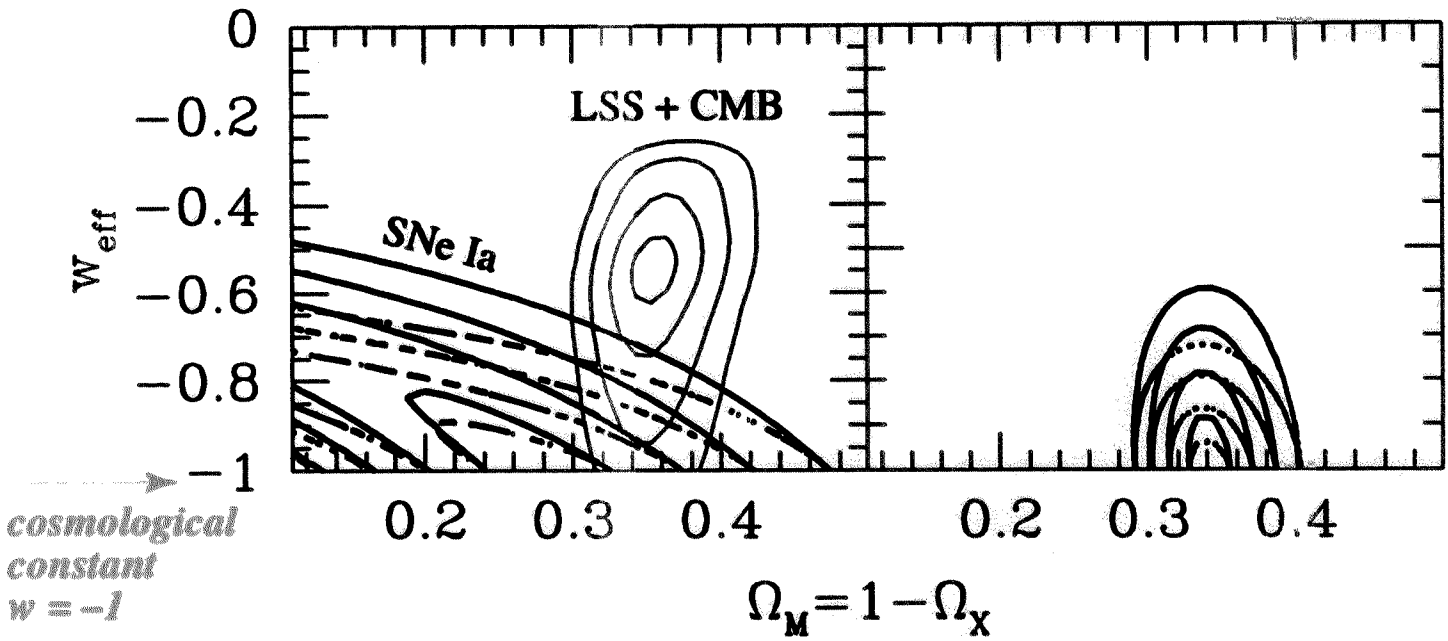
Unknown Component Ω_u of Energy Density



cf. Garnavich et al. (1998)

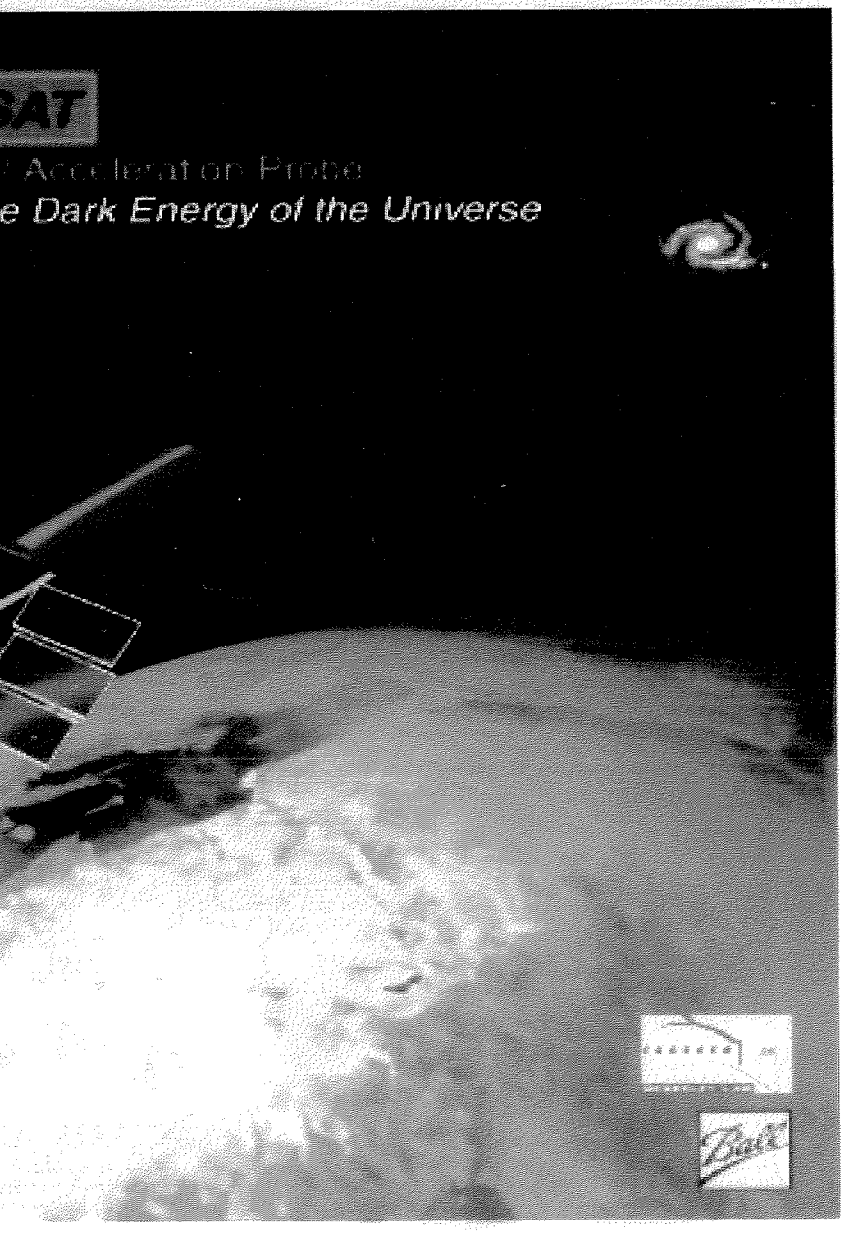
astro-ph/9901052

CONSTRAINTS ON EQUATION OF STATE OF "DARK ENERGY"



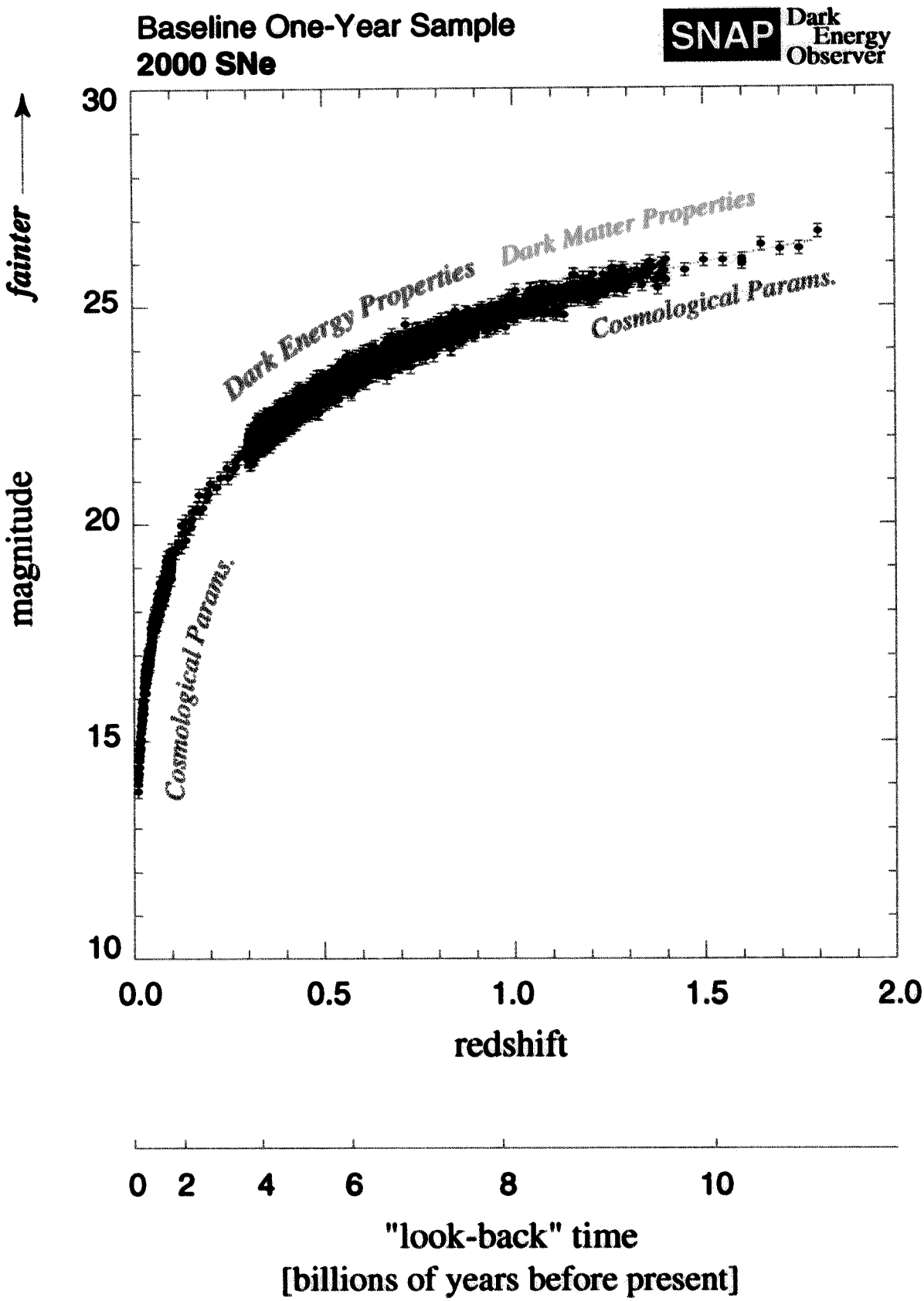
S.P., Turner, & White (1999)
Phys. Rev. Lett.

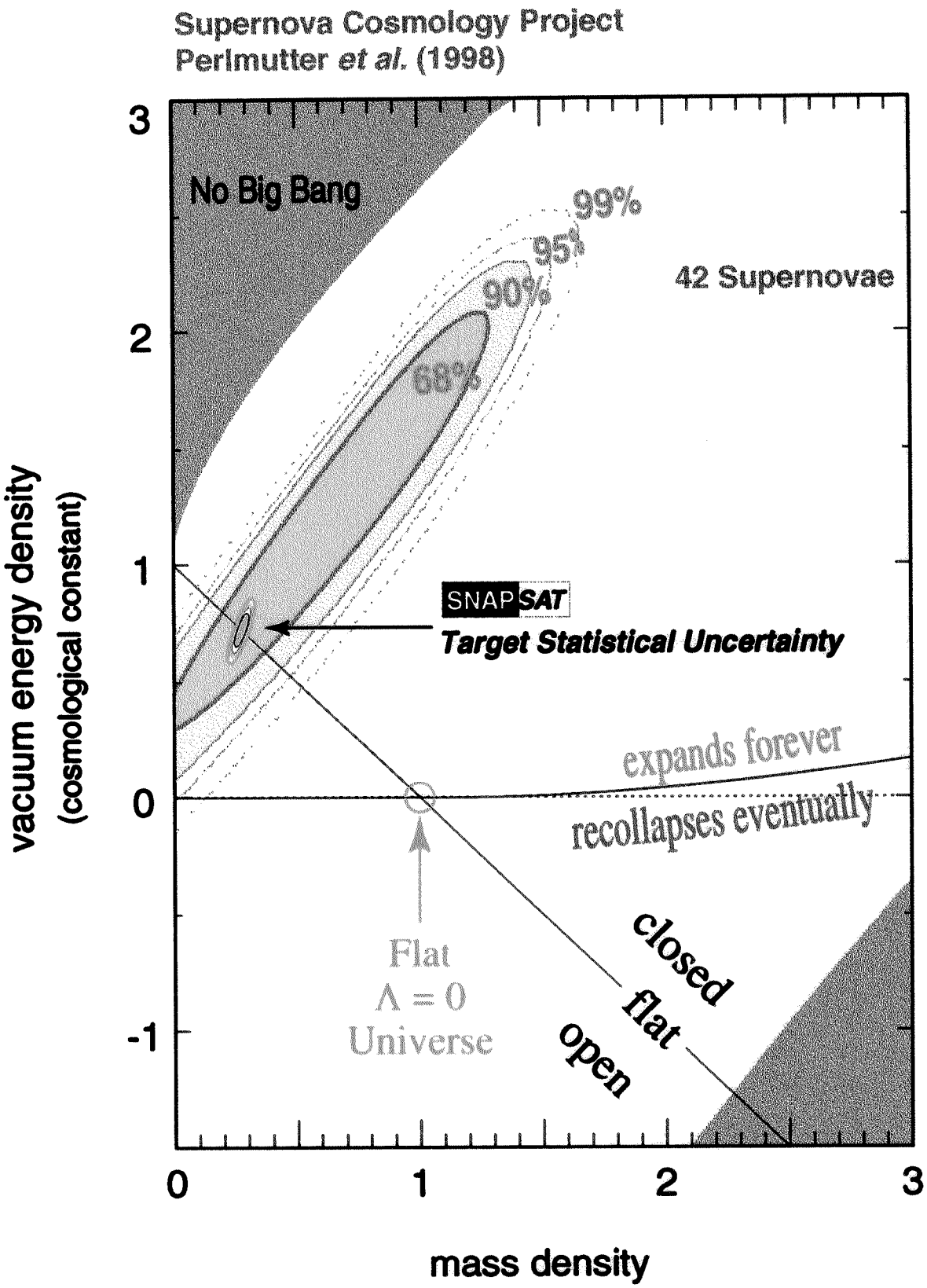
ed Satellite Probe of the Fundamental Properties of the Universe

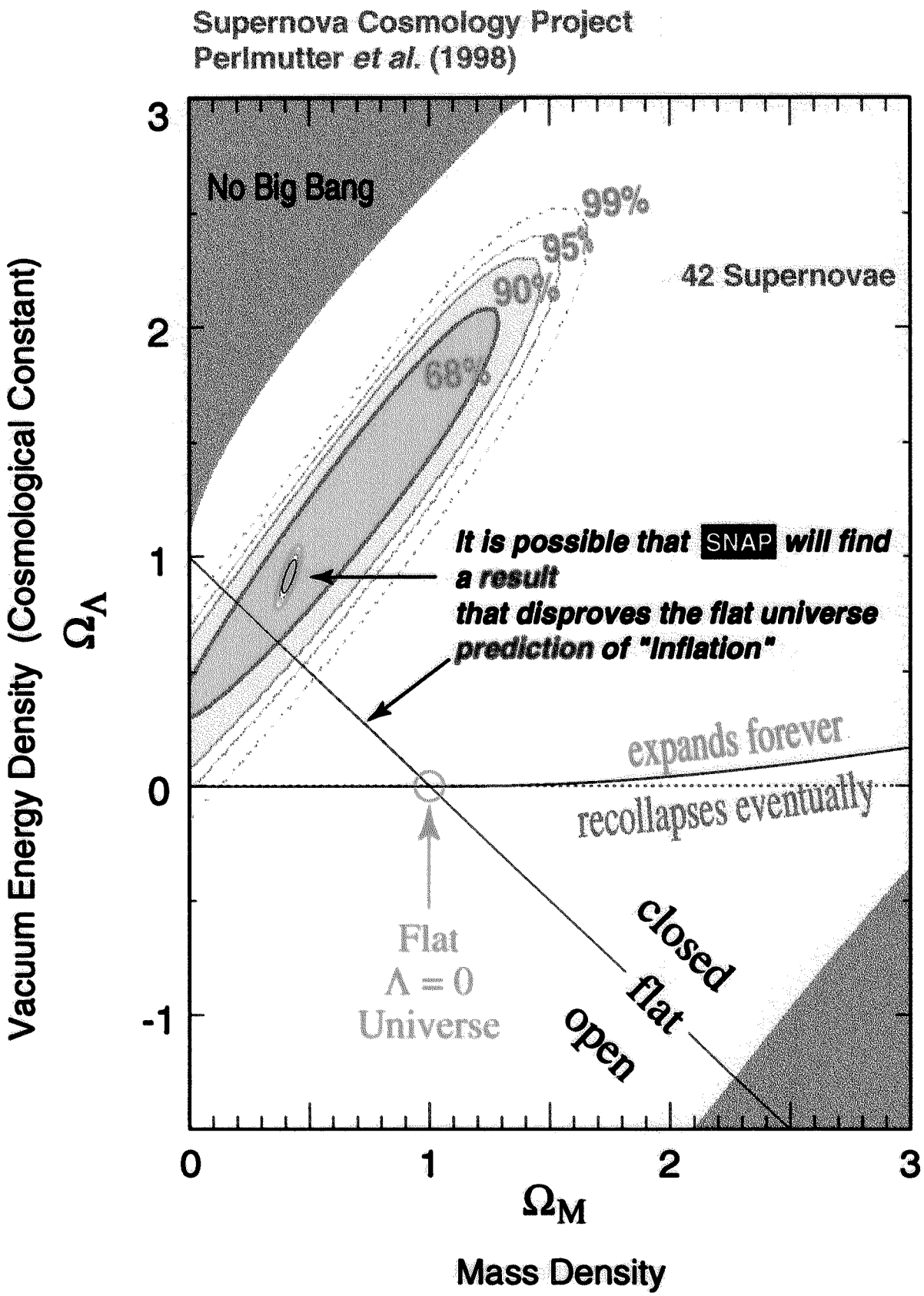


Scope

- 1.8 meter aperture
- 1 square degree mosaic camera (1 billion pixels)
- 3 channel spectroscopy 0.3 μm-1.8 μm

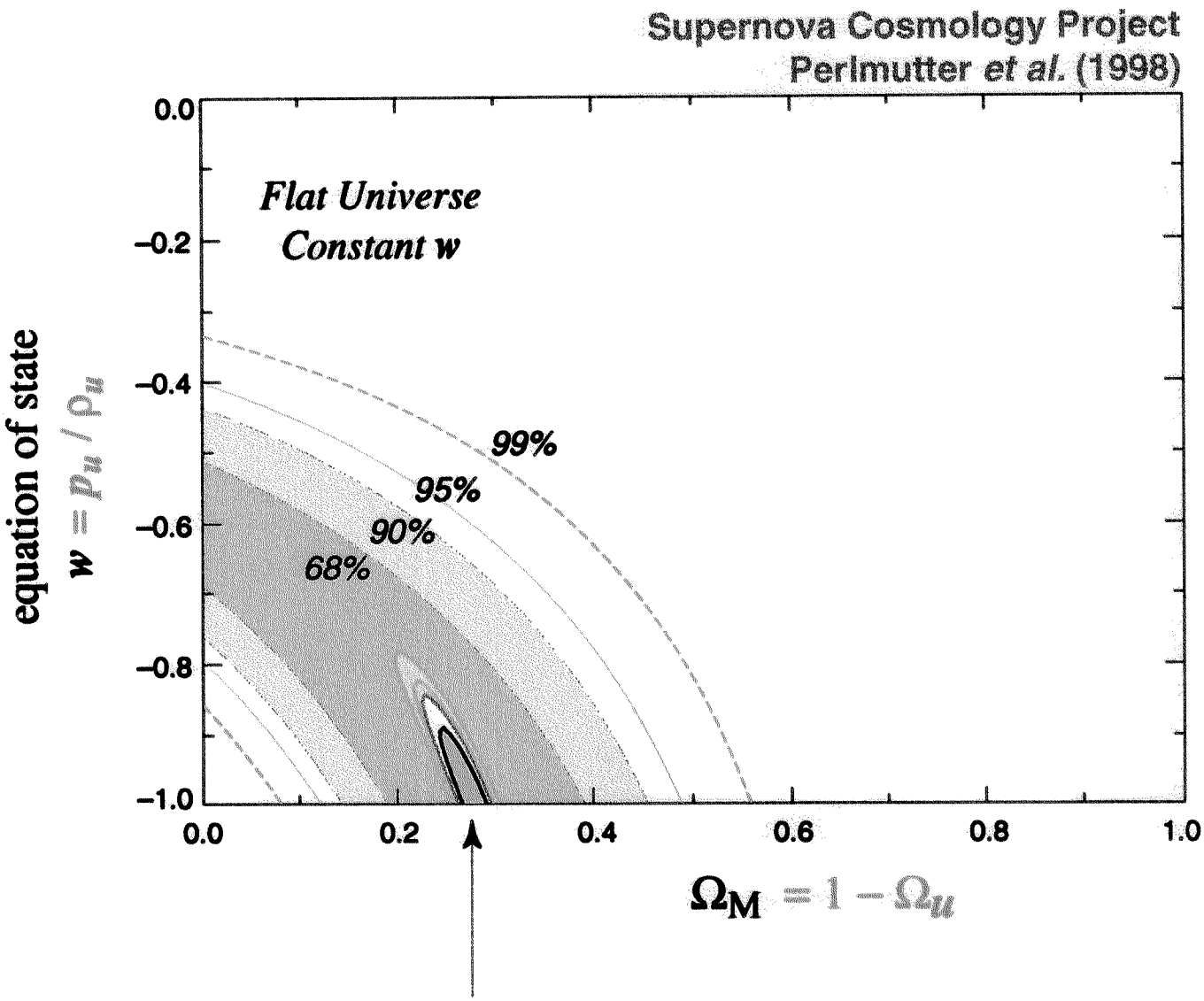

Baseline One-Year Sample
2000 SNe
SNAP
Dark Energy Observer
fainter
magnitude
30
25
20
15
10
Dark Energy Properties
Dark Matter Properties
Cosmological Params.
Cosmological Params.
0.0
0.5
1.0
1.5
2.0
redshift
0
2
4
6
8
10
"look-back" time
[billions of years before present]


Supernova Cosmology Project
Perlmutter et al. (1998)
No Big Bang
99%
95%
90%
68%
42 Supernovae
SNAP SAT
Target Statistical Uncertainty
expands forever
recollapses eventually
closed
flat
open
Flat
Λ = 0
Universe
vacuum energy density
(cosmological constant)
mass density
3
2
1
0
-1
0
1
2
3

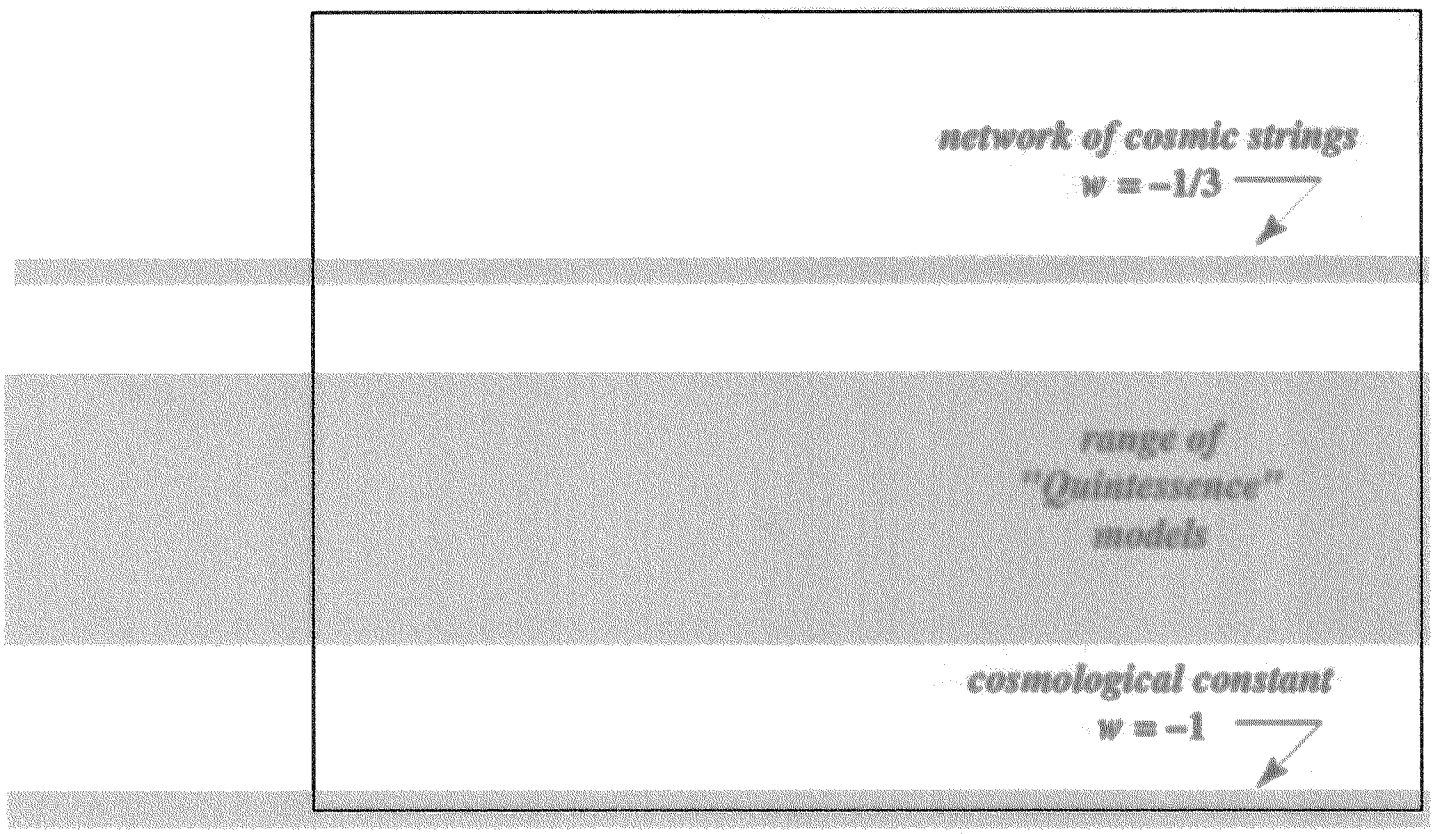

Supernova Cosmology Project
Perlmutter et al. (1998)
No Big Bang
99%
95%
90%
68%
42 Supernovae
It is possible that SNAP will find a result that disproves the flat universe prediction of "Inflation"
expands forever
recollapses eventually
Flat
Λ = 0
Universe
closed
flat
open
Vacuum Energy Density (Cosmological Constant)
Ω_Λ
Ω_M
Mass Density
3
2
1
0
-1
0
1
2
3

Dark Energy

Unknown Component, Ω_u, of Energy Density



SNAP Satellite
Target Statistical Uncertainty


network of cosmic strings
w = −1/3
range of
"Quintessence"
models
cosmological constant
w = −1

Conclusions

- SNe Ia are useful, usable cosmological tools.

- The Universe is Accelerating, Λ is positive

Flat Universe
(or not very open)

Very Strong Confidence

$\Omega_M = 0.28$
$\Omega_\Lambda = 0.72$ $\pm 0.085 \pm 0.05$

Open Universe

Statistically Strong Confidence (99%)

None of Identified Systematics can provide ~0.15 mag needed.

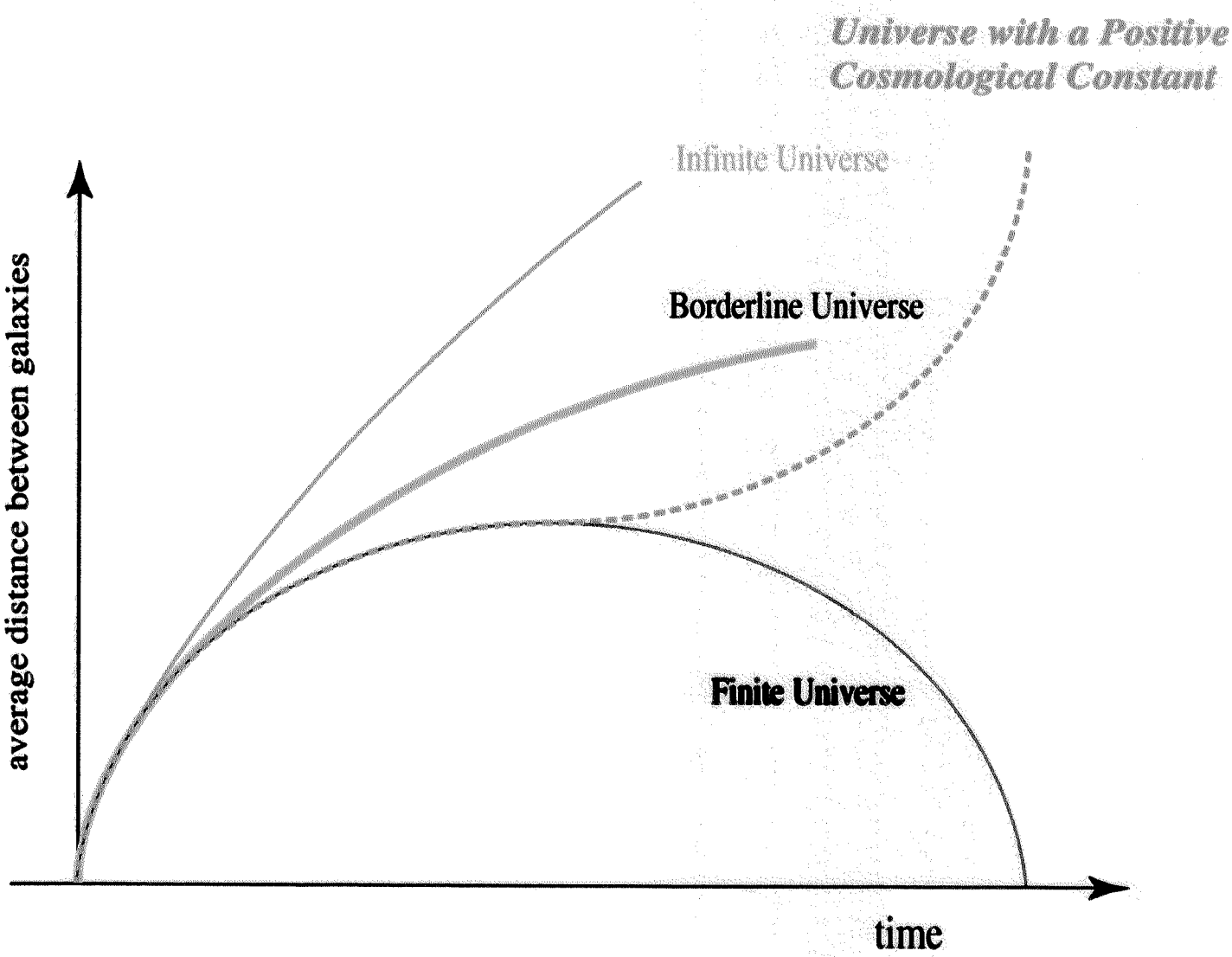
- Equation of State of "Dark Energy" near $p/\rho = -1$ → like Cosmological Constan

Coming Soon

- Add remaining 40 SNe to analysis, with 12 HST SNe out to $z = 1.2$

- New Low Redshift SN studies
  - study subsets for evolution
  - improve U data

- New Higher Redshift SN studies
  - separate $\Omega + \Lambda$ without CB
  - test evolution / dust


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

Supernova Cosmology Project: selected publications

• **Wide-field search** plan. for high-redshift SNe.	Automated supernova discoveries: Status of the Berkeley project. Pennypacker et al, In *Particle Astrophysics (Berkeley, 1988)*, ed. Norman, 1989.
• First high-redshift SN caught near peak (SN 1992bi).	A supernova at z=0.458 and implications for measuring the cosmological deceleration. Perlmutter et al, ***Ap.J.Lett.*** 440,L41, 1995. **astro-ph/9505023**
• **"Batch" technique** for *scheduled* discovery of multiple SNe on the rise. • & **"Stretch-factor"** lightcurve parameterization.	Scheduled discoveries of 7+ high-redshift supernovae. Perlmutter et al, In *Thermonuclear Supernovae, (Aiguablava, June 1995)*, eds.Ruiz-Lapuente, Canal, Isern, 1997. **astro-ph/9602122**
• **"Cross-filter" *K* correction** limits uncertainty.	A generalized *K* correction for type Ia supernovae. Kim, Goobar, & Perlmutter ***P.A.S.P.***, 108, 190, 1996. **astro-ph/9505024**
• Proposal to **separate Ω_M and Λ** using SNe at a range of redshifts.	Feasibility of measuring the cosmological constant Λ and mass density Ω using supernovae. Goobar & Perlmutter, ***Ap. J.***, 450, 14, 1995. **astro-ph/9505022**
• **Rates** of high-redshift SNe & **search efficiency** study.	The type Ia supernova rate at $z = 0.4$, Pain et al, ***Ap. J.***, 473, 356, 1996. **astro-ph/9602125**
• Results from first 7 SNe & techniques for full analysis of Ω_M, Λ, and statistical and systematic uncertainties.	Measurements of the cosmological parameters Ω and Λ from the first seven supernovae at $z > 0.35$. Perlmutter et al, ***Ap. J.***, 483, 565, 1997. **astro-ph/9608192**
• First *scheduled* **HST observation** of SN & demo of Ω_M — Λ separation **suggests low-Ω_M**.	Discovery of a supernova explosion at half the age of the universe. Perlmutter et al, ***Nature***, 391, 51, 1998. **astro-ph/9712212**
• **Evidence for $\Lambda > 0$.**	Cosmology from type Ia supernovae. AAS meeting presentation *(Washington, January 1998)*. **astro-ph/9812473**
	Measurements of Ω and Λ from 42 high-redshift supernovae. Perlmutter et al, ***Ap. J.***, 516, (in press) **astro-ph/9812133**