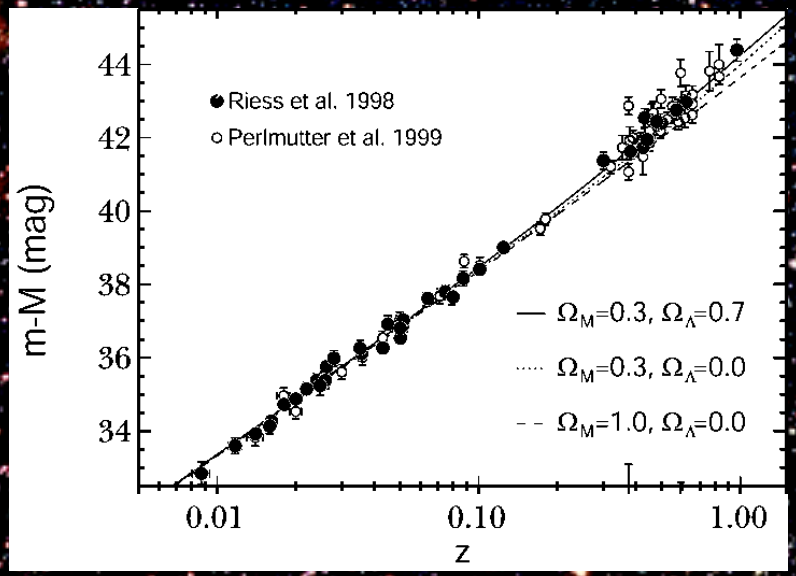
Evidence from Type Ia Supernovae for an

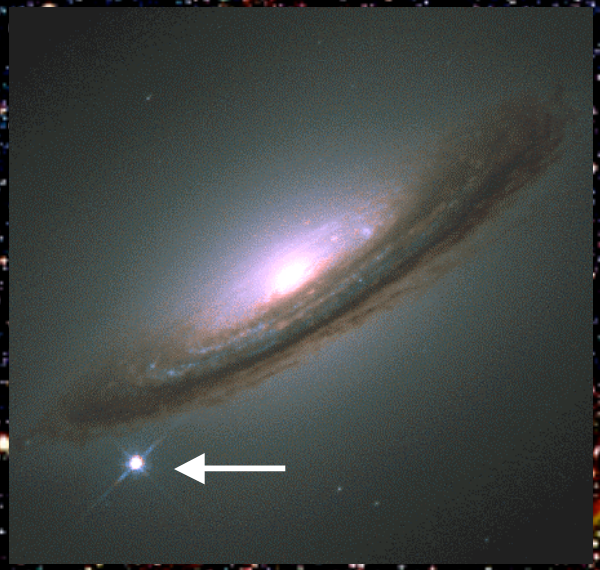
Accelerating Universe

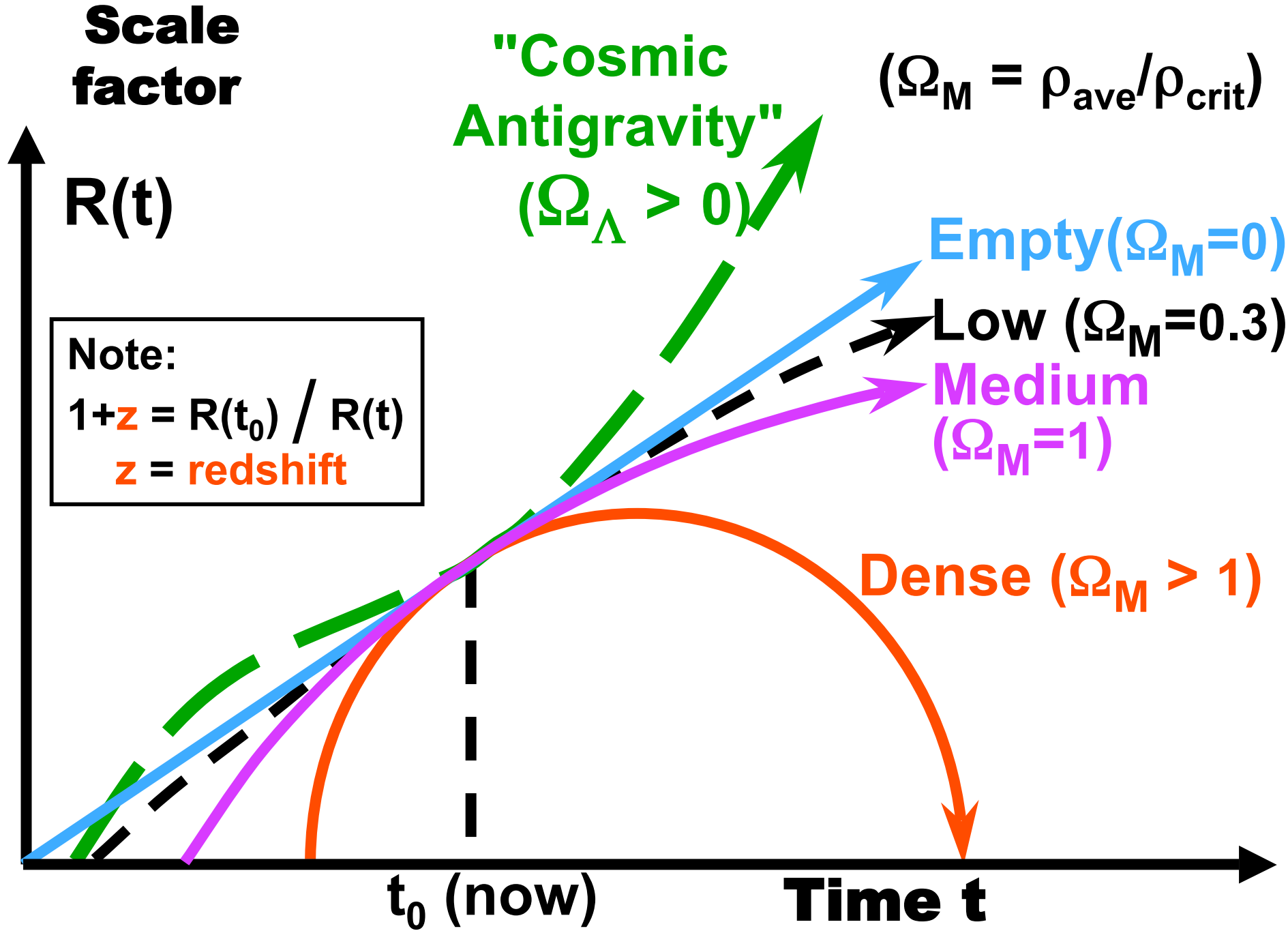
... and Dark Energy

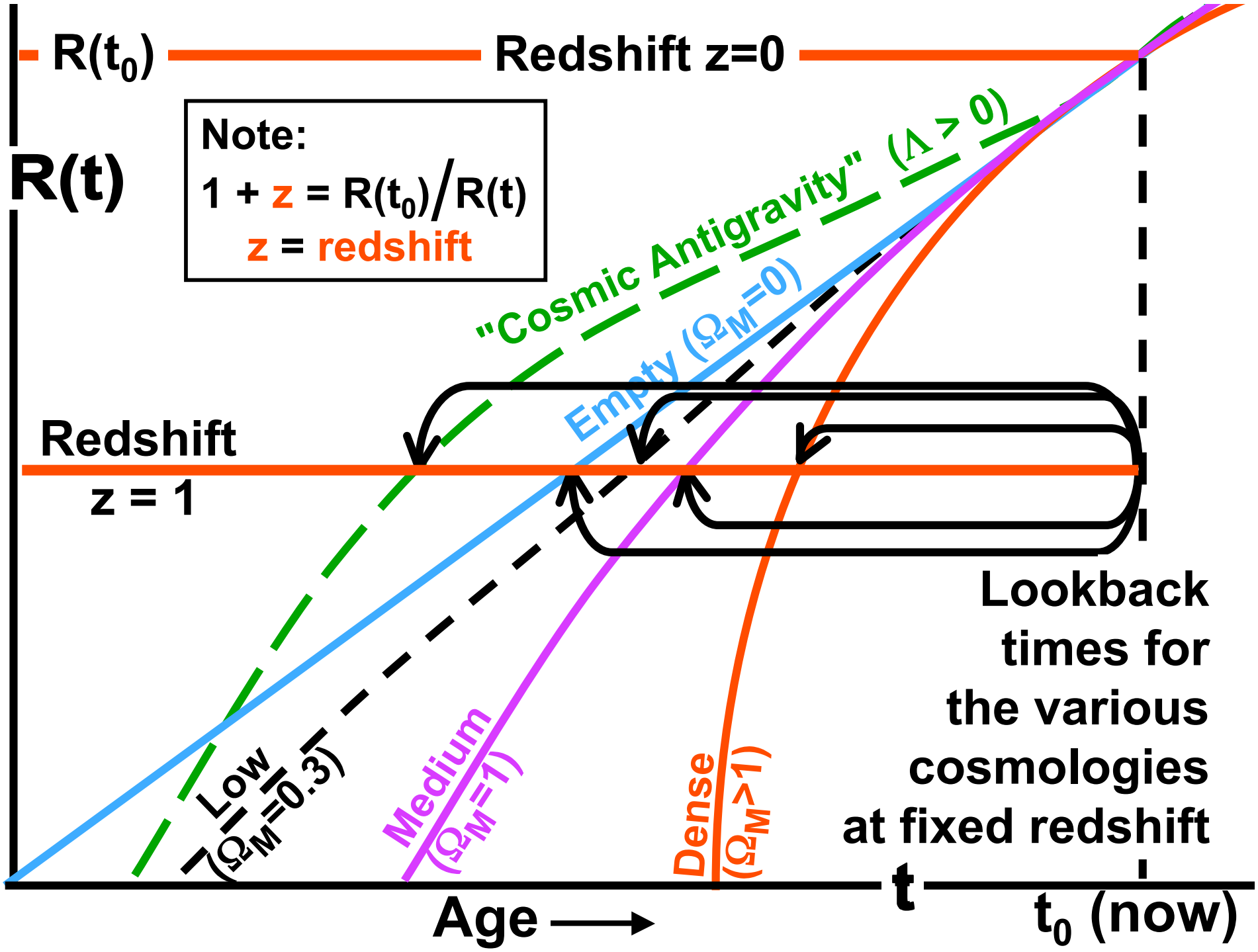
Alex Filippenko

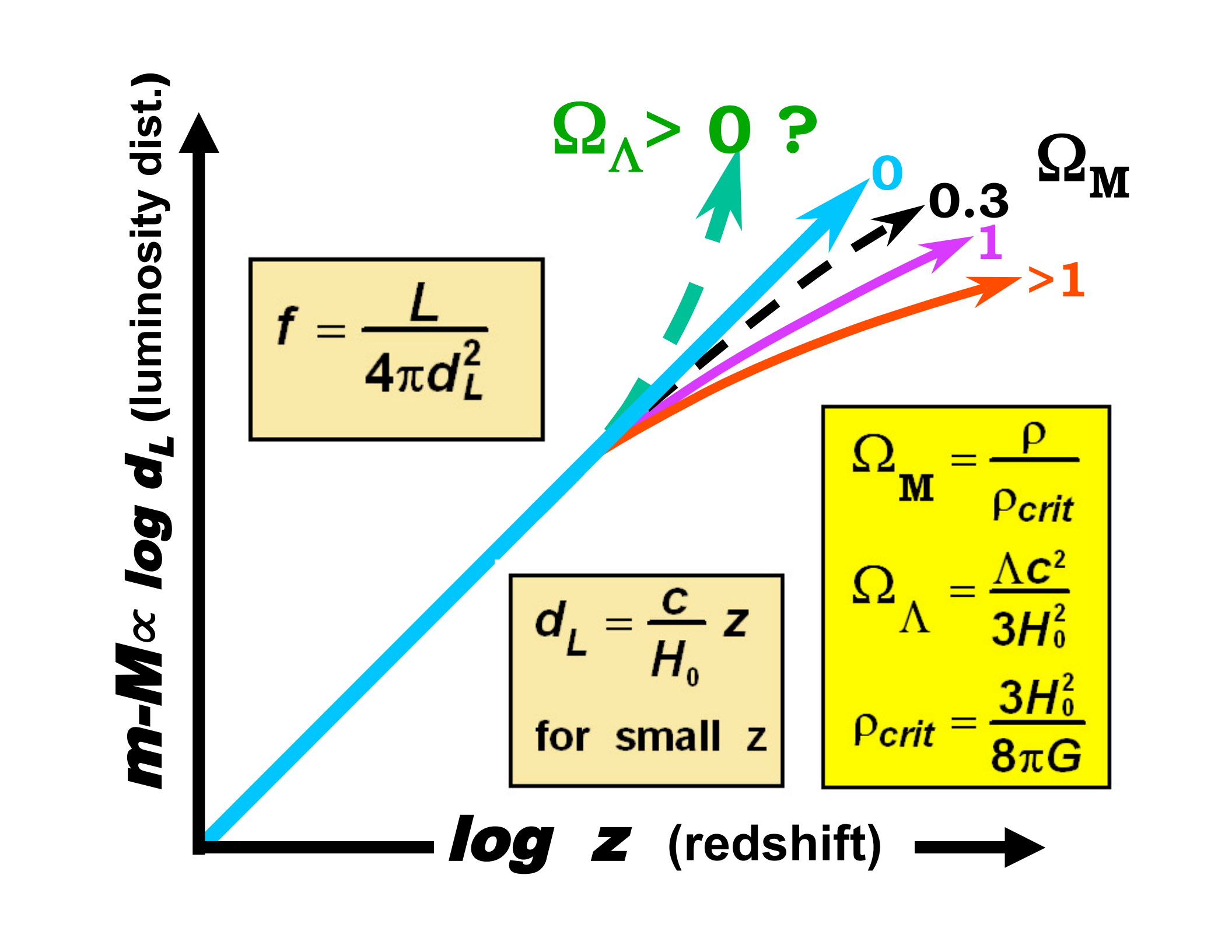
University of California, Berkeley






Scale factor
R(t)
"Cosmic Antigravity"
($\Omega_\Lambda > 0$)
($\Omega_M = \rho_{ave}/\rho_{crit}$)
Empty(Ω_M=0)
Low (Ω_M=0.3)
Medium
(Ω_M=1)
Dense ($\Omega_M > 1$)
Note:
1+z = R(t_0) / R(t)
z = redshift
t_0 (now)
Time t


R(t0)
Redshift z=0
R(t)
Note:
1 + z = R(t0)/R(t)
z = redshift
"Cosmic Antigravity" (Λ > 0)
Empty (ΩM=0)
Redshift
z = 1
Lookback
times for
the various
cosmologies
at fixed redshift
Low
(ΩM=0.3)
Medium
(ΩM=1)
Dense
(ΩM>1)
t
Age
t0 (now)


m-M∝ log d_L (luminosity dist.)
log z (redshift)
$\Omega_\Lambda > 0$?
Ω_M
0
0.3
1
>1
$f = \frac{L}{4\pi d_L^2}$
$d_L = \frac{c}{H_0} z$
for small z
$\Omega_M = \frac{\rho}{\rho_{crit}}$
$\Omega_\Lambda = \frac{\Lambda c^2}{3H_0^2}$
$\rho_{crit} = \frac{3H_0^2}{8\pi G}$

Measuring Cosmological Parameters

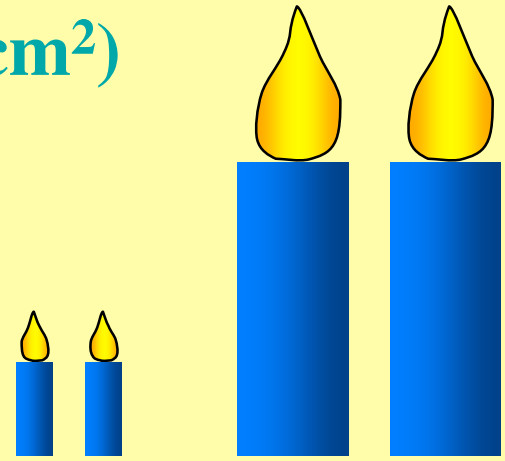
- **Redshift: easy to measure from galaxy spectrum**
- **Distance:**

  "Luminosity distance" d_L

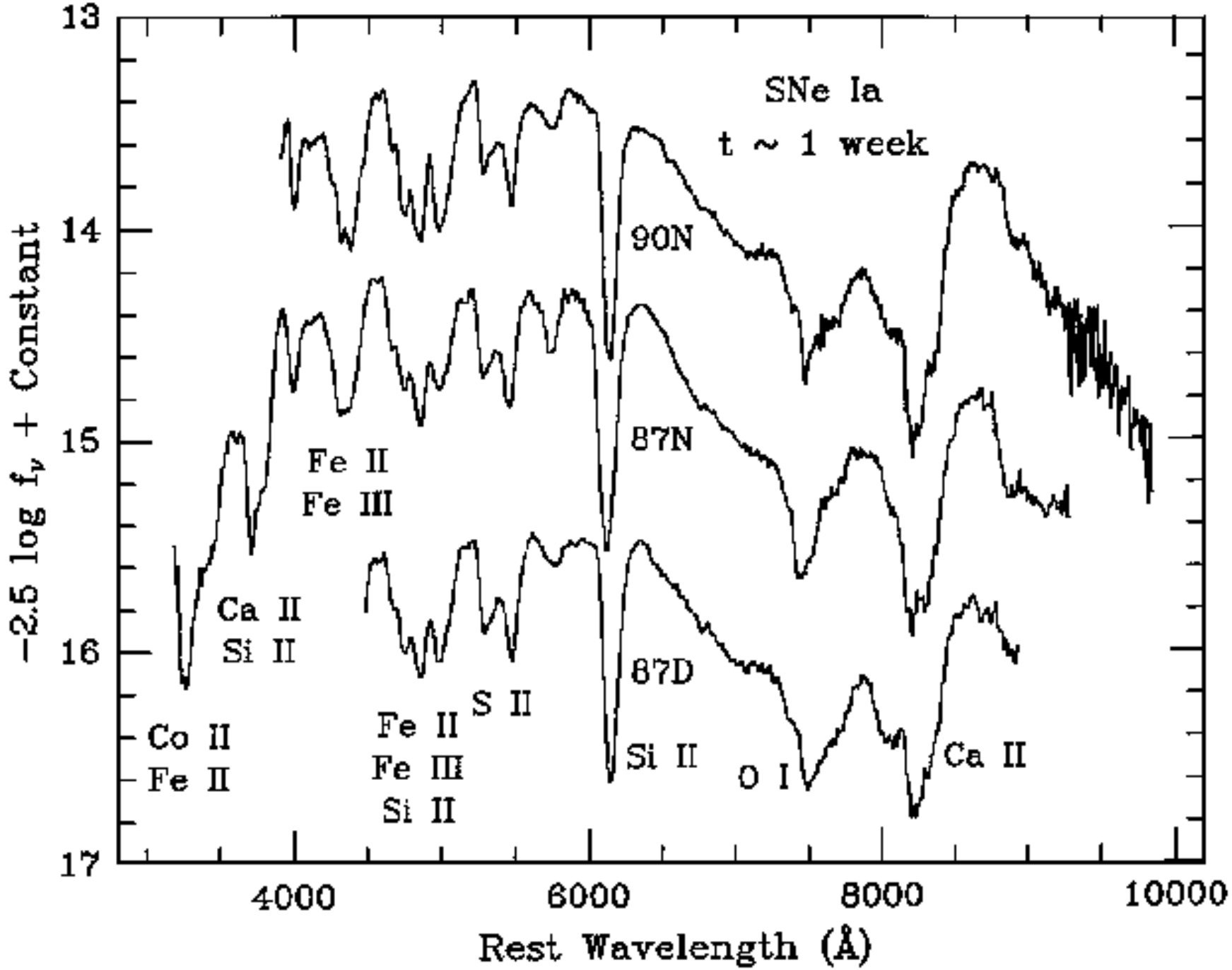
$$f = \frac{L}{4\pi d_L^2}$$

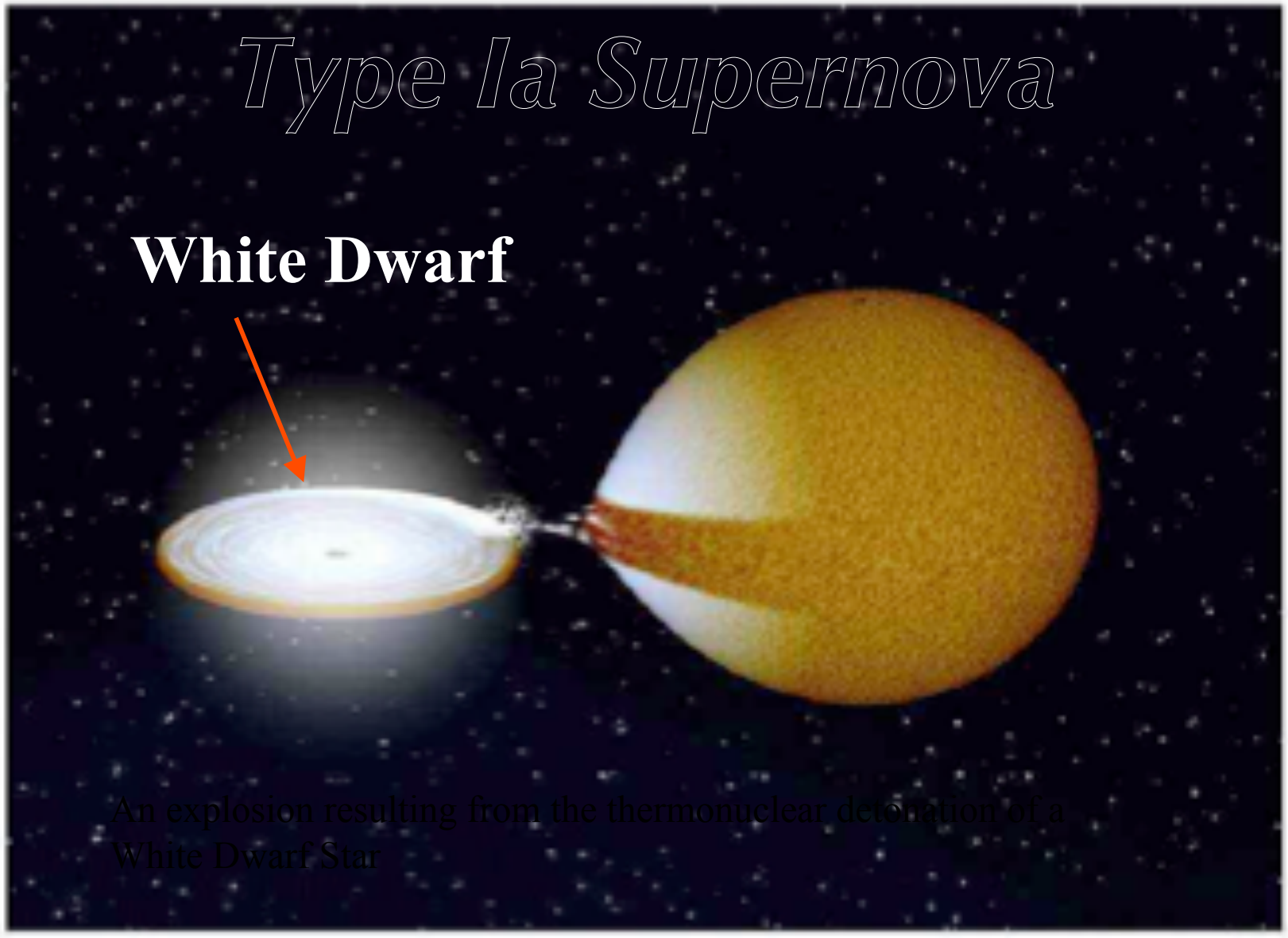
f = flux (erg/s-cm^2)

L = luminosity (erg/s)



- **Measure f, "know" L**
  - **NOT SO EASY !**
  - **Need a "standard candle"**


SNe Ia
t ~ 1 week
90N
87N
87D
Fe II
Fe III
Ca II
Si II
Co II
Fe II
Fe II
Fe III
Si II
S II
Si II
O I
Ca II
−2.5 log f_ν + Constant
Rest Wavelength (Å)
13
14
15
16
17
4000
6000
8000
10000

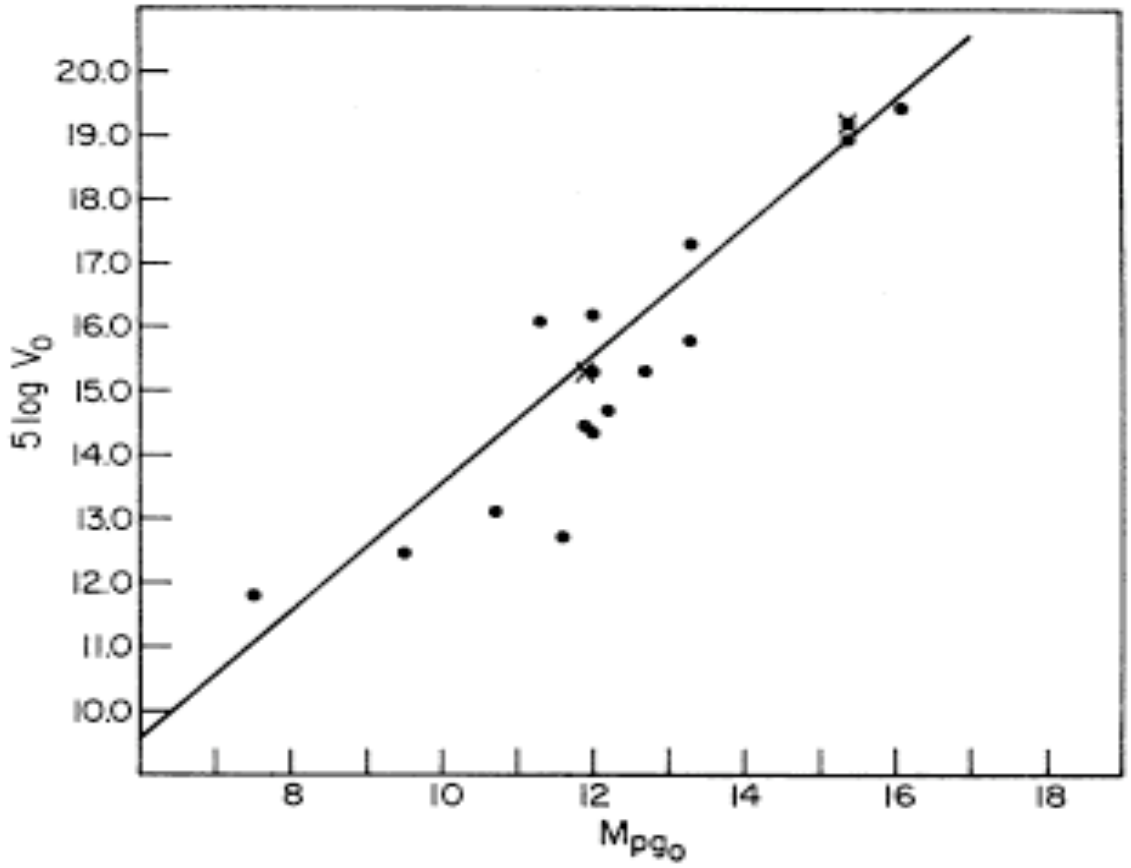


An explosion resulting from the thermonuclear runaway of a white dwarf star at M(Chandra).

Absolute Magnitudes of Supernovae

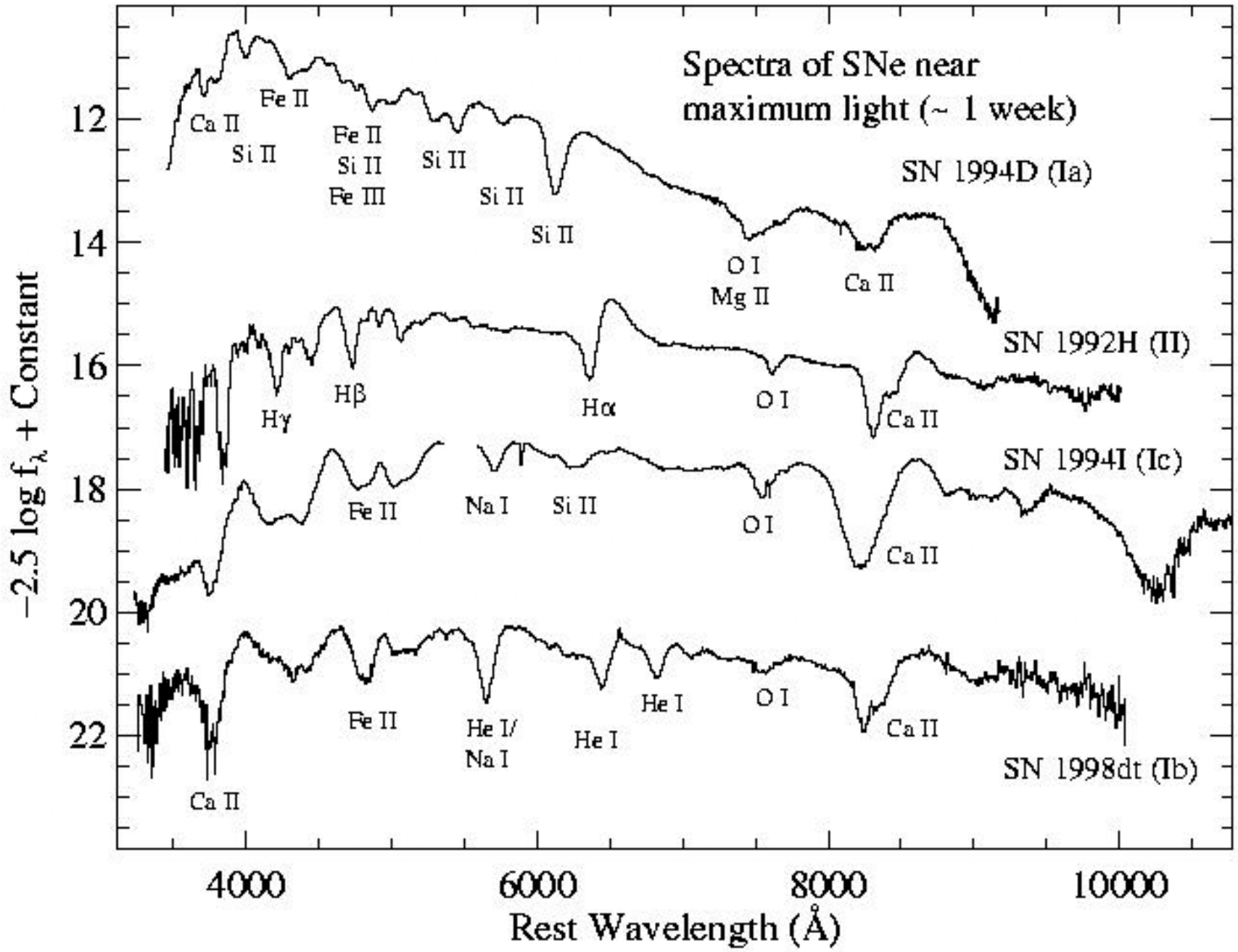
CHARLES T. KOWAL

(1968)



Charles Kowal:

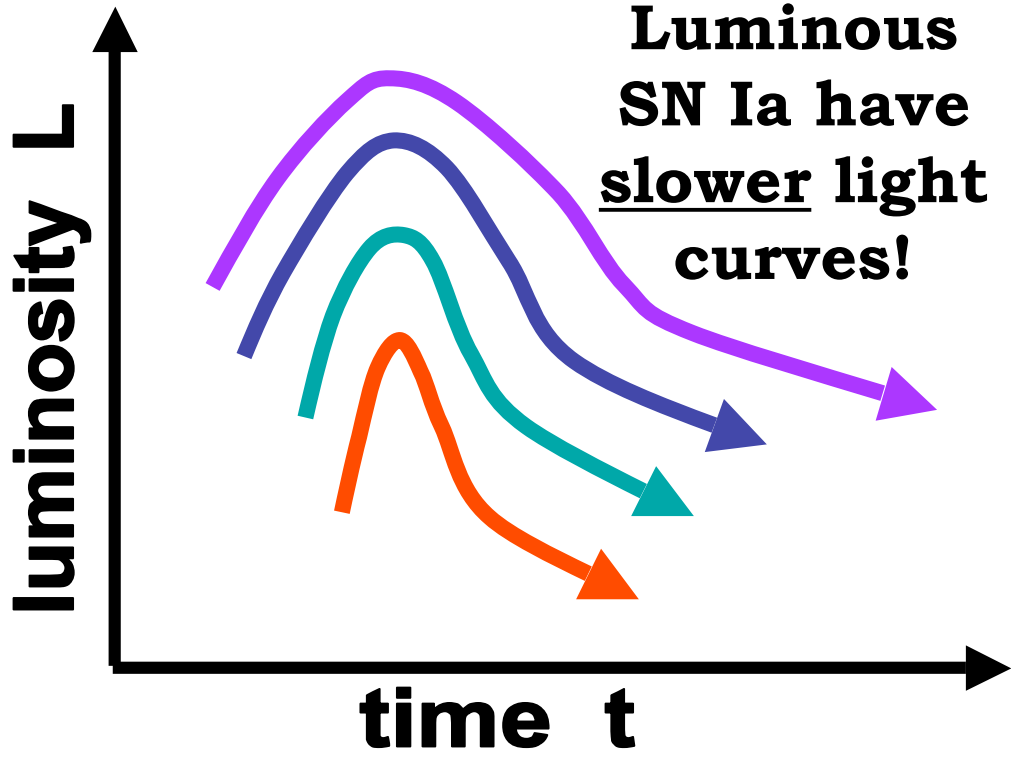
SN I are relatively good "standard candles" with $\sigma \approx 50\%$ in distance


Spectra of SNe near
maximum light (~ 1 week)
SN 1994D (Ia)
SN 1992H (II)
SN 1994I (Ic)
SN 1998dt (Ib)
Ca II
Si II
Fe II
Fe II
Si II
Fe III
Si II
Si II
Si II
O I
Mg II
Ca II
Hγ
Hβ
Hα
O I
Ca II
Fe II
Na I
Si II
O I
Ca II
Ca II
Fe II
He I/
Na I
He I
He I
O I
Ca II
12
14
16
18
20
22
4000
6000
8000
10000
−2.5 log f$_\lambda$ + Constant
Rest Wavelength (Å)

Calibrating the Nearly Standard Candle

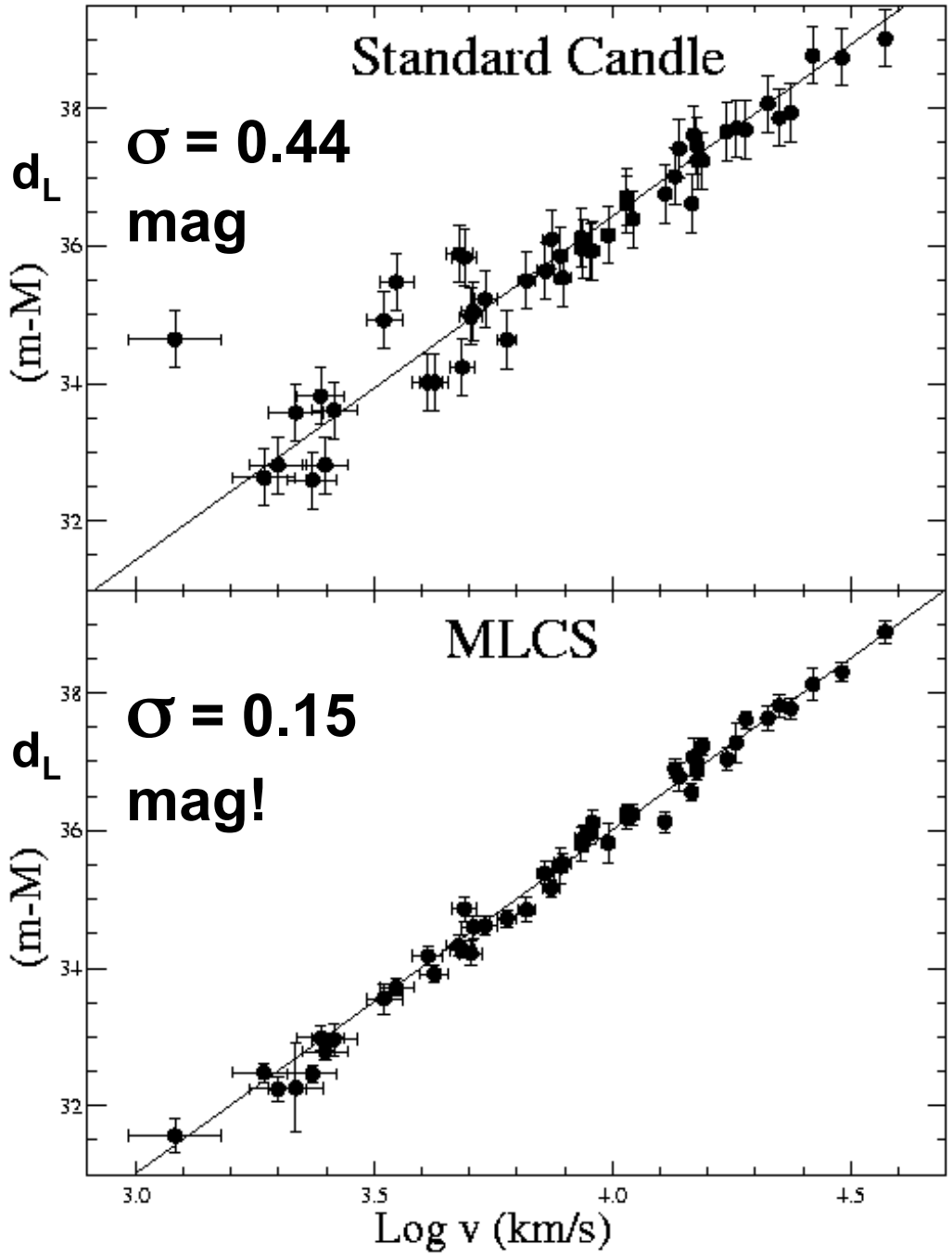
- **Phillips (93), Riess et al. (95), Hamuy et al. (95): established L vs. light-curve shape correlation with ~ 10 nearby SN Ia.**
- **Use it to standardize other SN Ia.**
- **Measured colors give reddening and extinction.**
- **Accurately calibrate individual SN!**

Absolute light curves of SN Ia in galaxies of known distance



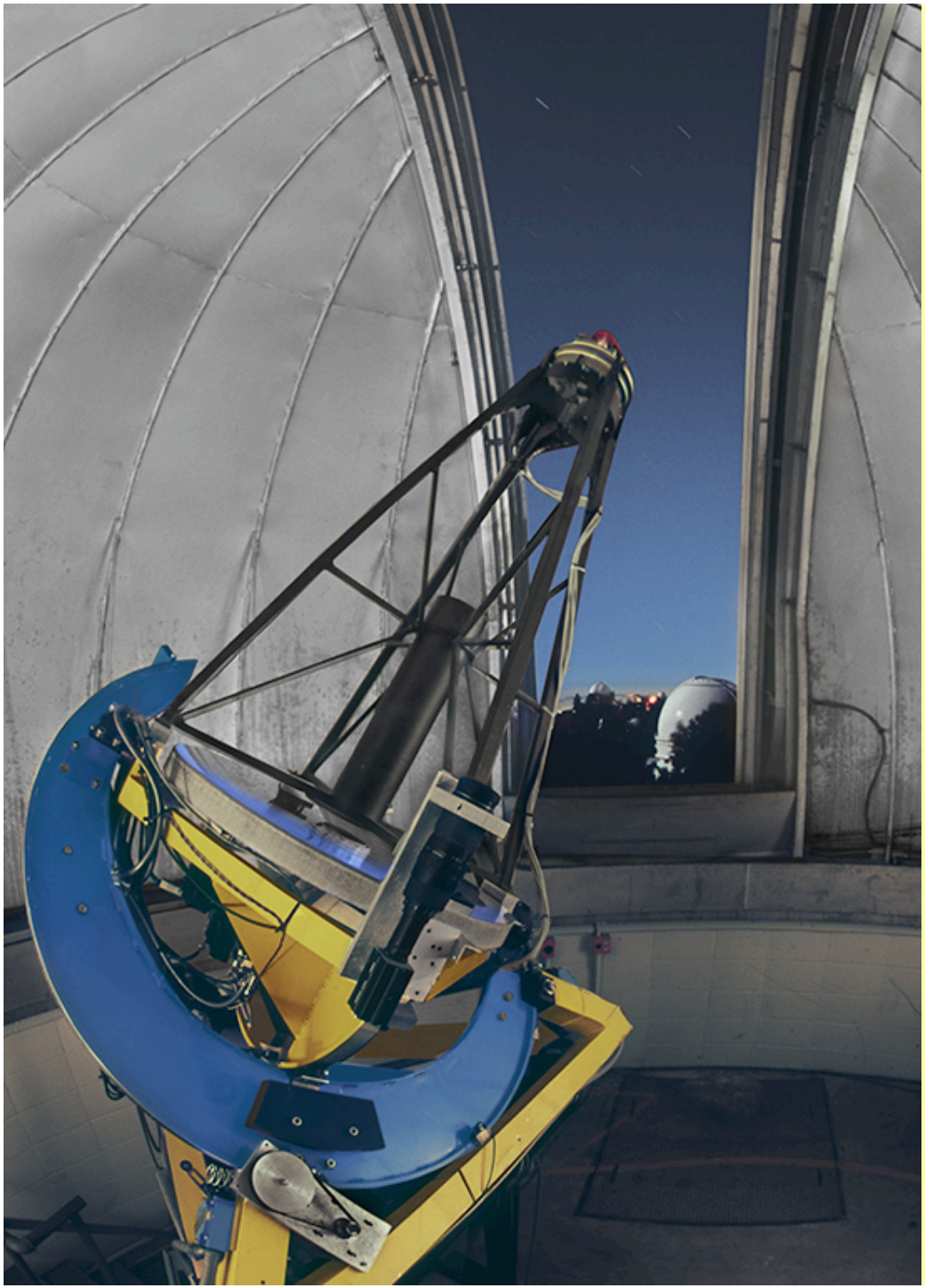
MLCS: Multi-color Light-Curve Shape (Riess et al.)

∝ log d_L



∝ log d_L

(Riess et al. 1995, 1996, 1999)

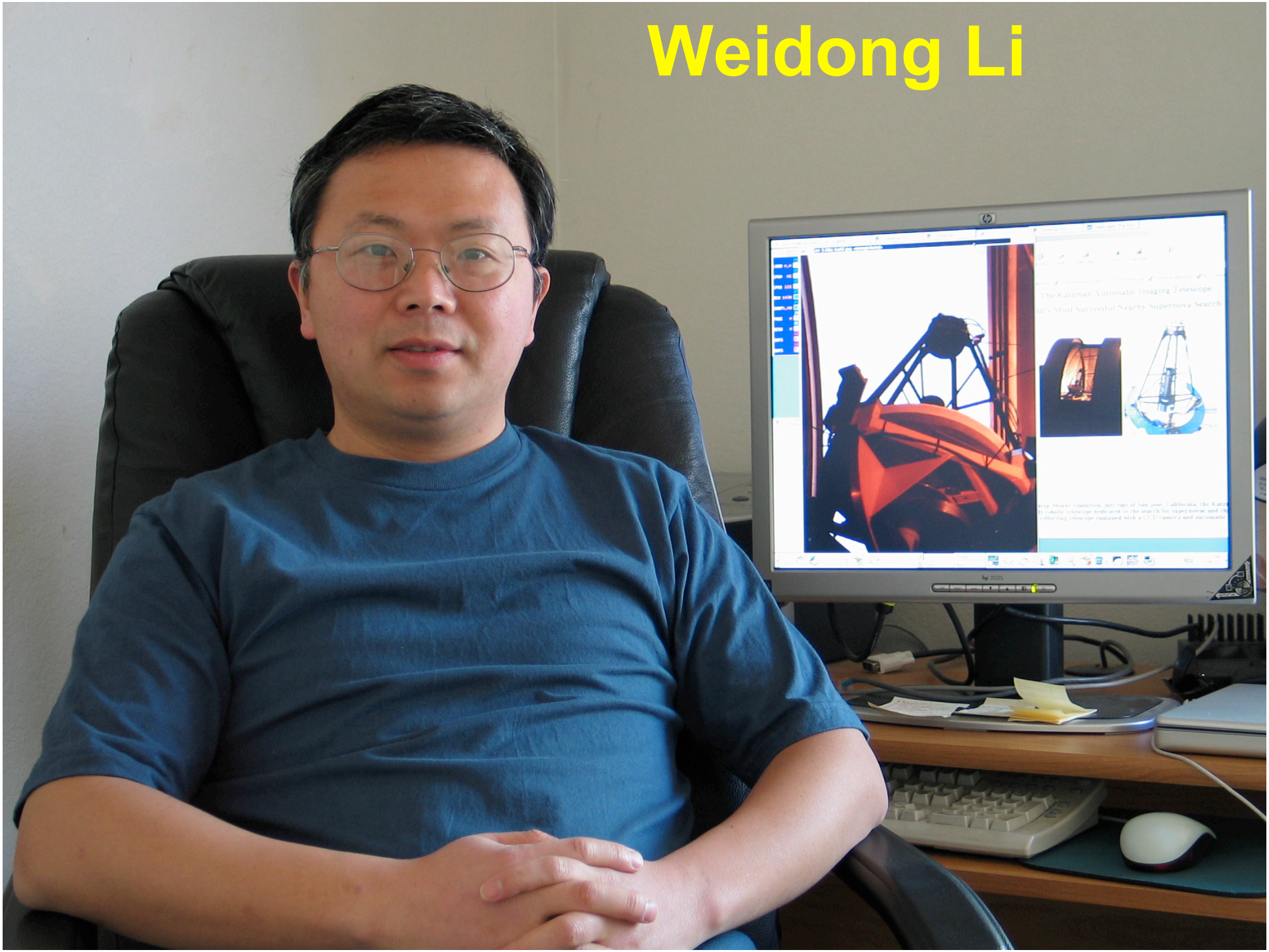


KAIT,

the Katzman Automatic Imaging Telescope; 0.76 m mirror.

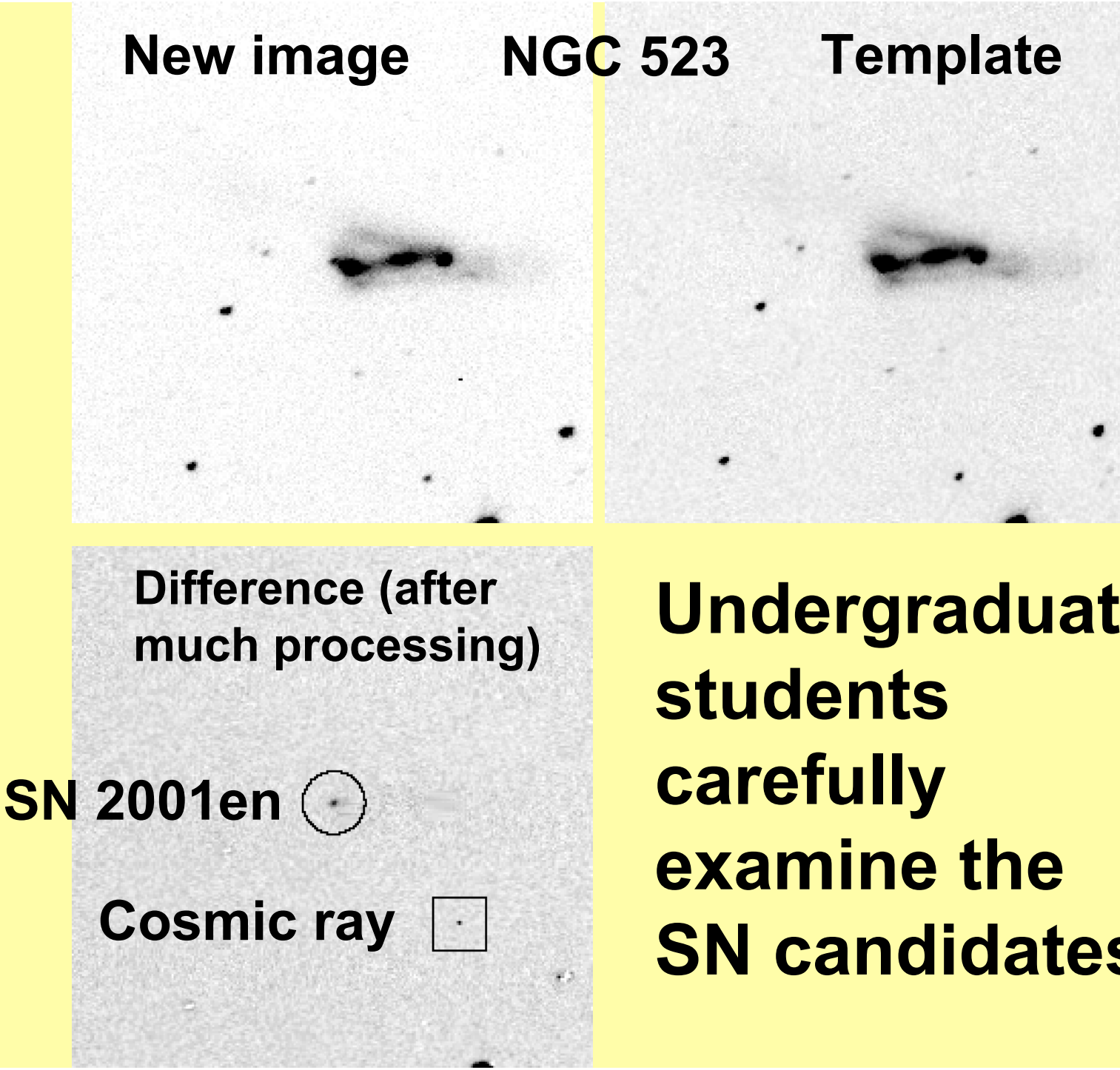
Lick Observatory, near San Jose, CA

(AF & Weidong Li)


Weidong Li

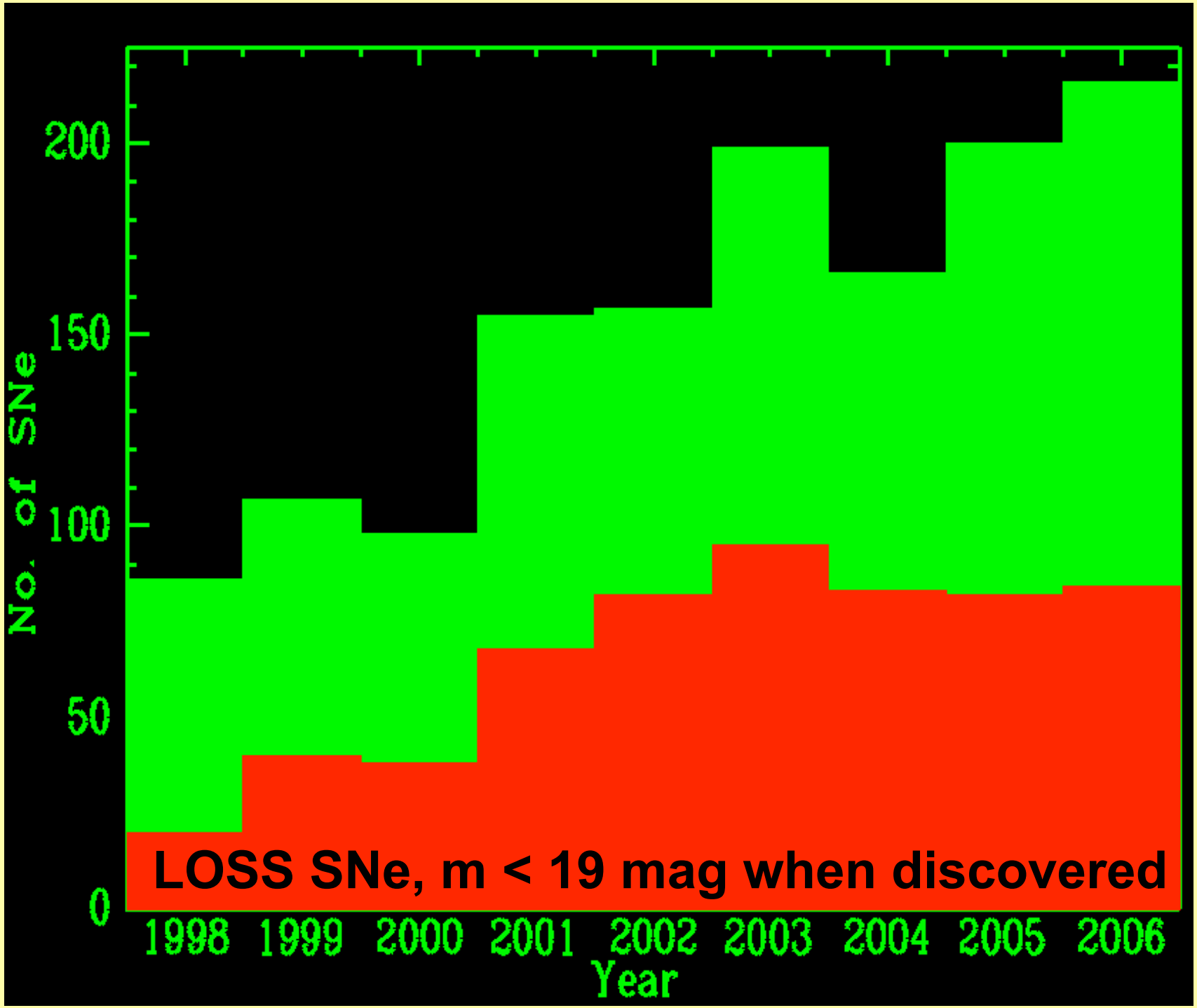
Discovered over 600 SNe with KAIT

http://astron.berkeley.edu/~bait/kait.html



Undergraduate students carefully examine the SN candidates!

KAIT Supernova Search & Analysis Team, May 2005


No. of SNe
0
50
100
150
200
1998
1999
2000
2001
2002
2003
2004
2005
2006
Year
LOSS SNe, m < 19 mag when discovered

SN 1998dh

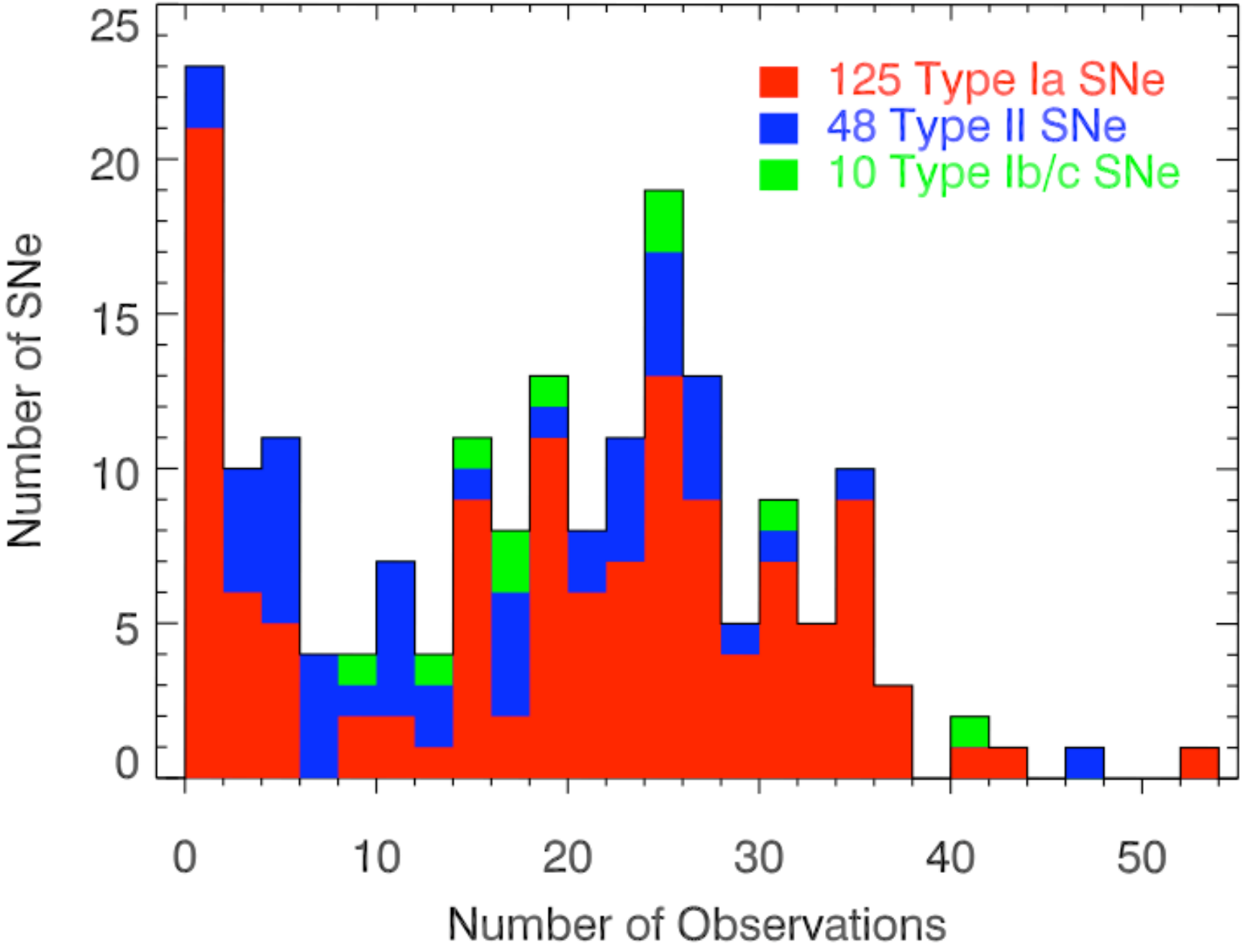
Age:
-6 days

Maximum

+26 days

+47 days

+102 days

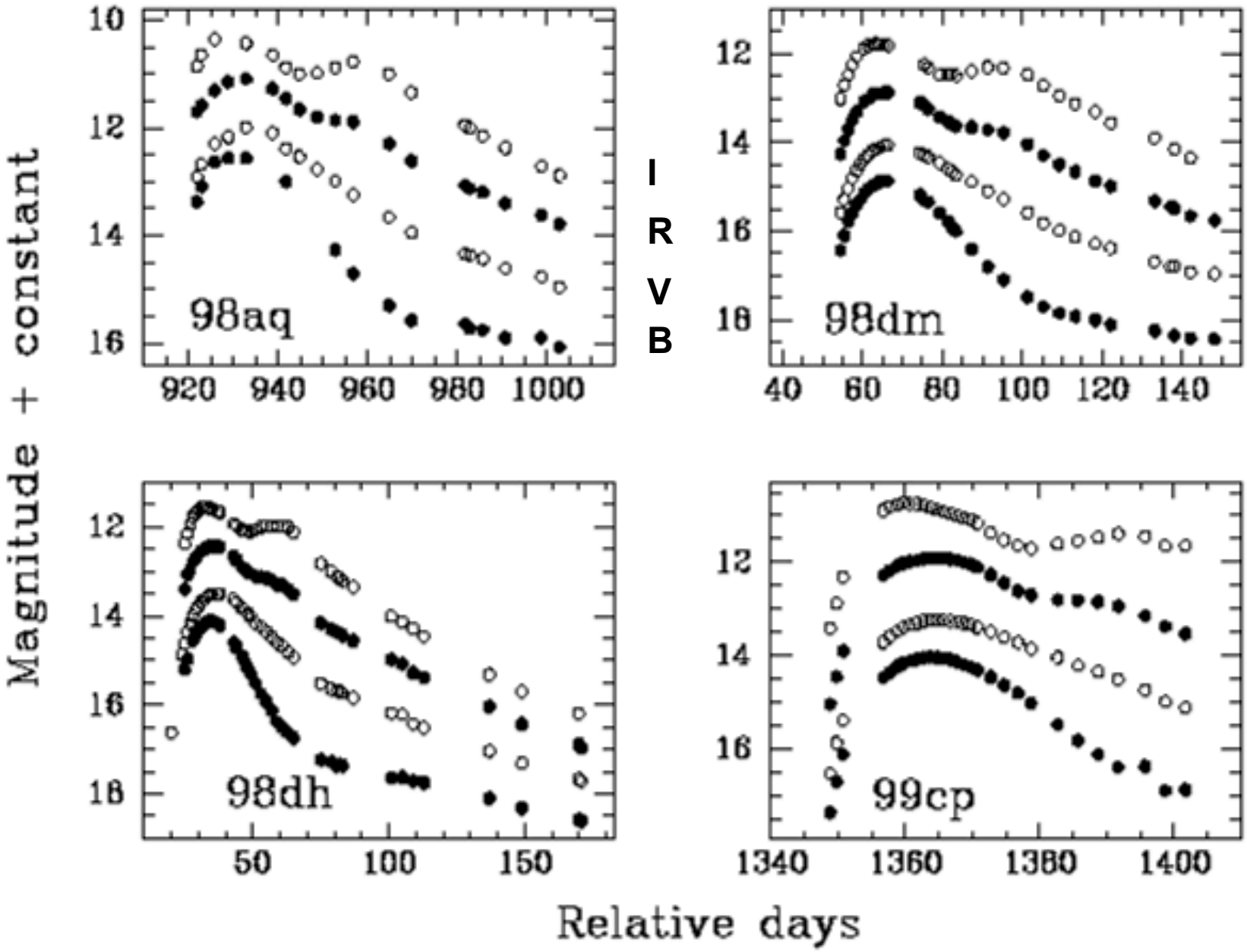

125 Type Ia SNe
48 Type II SNe
10 Type Ib/c SNe
Number of SNe
Number of Observations
0
5
10
15
20
25
0
10
20
30
40
50

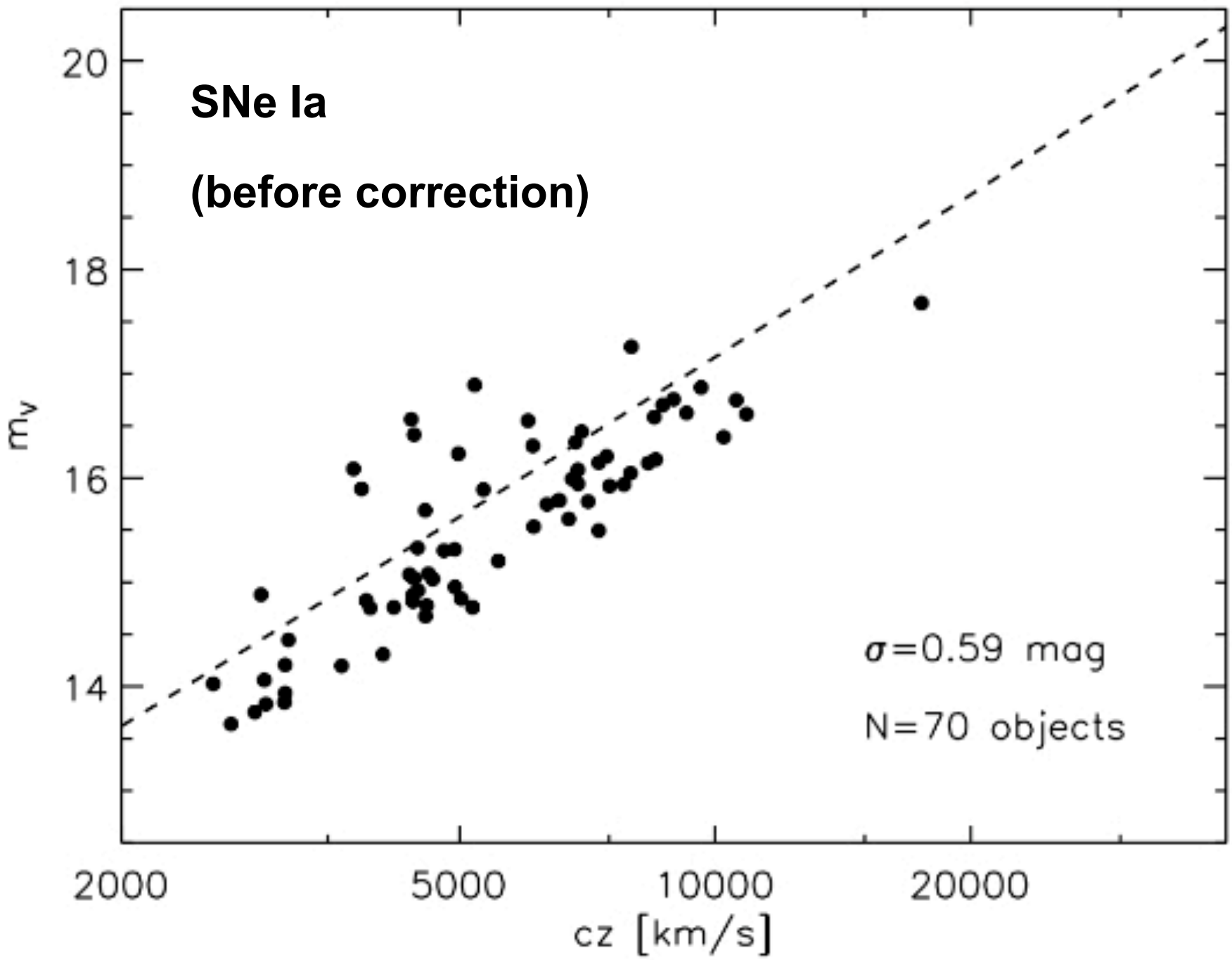
Mohan
Ganeshalingam

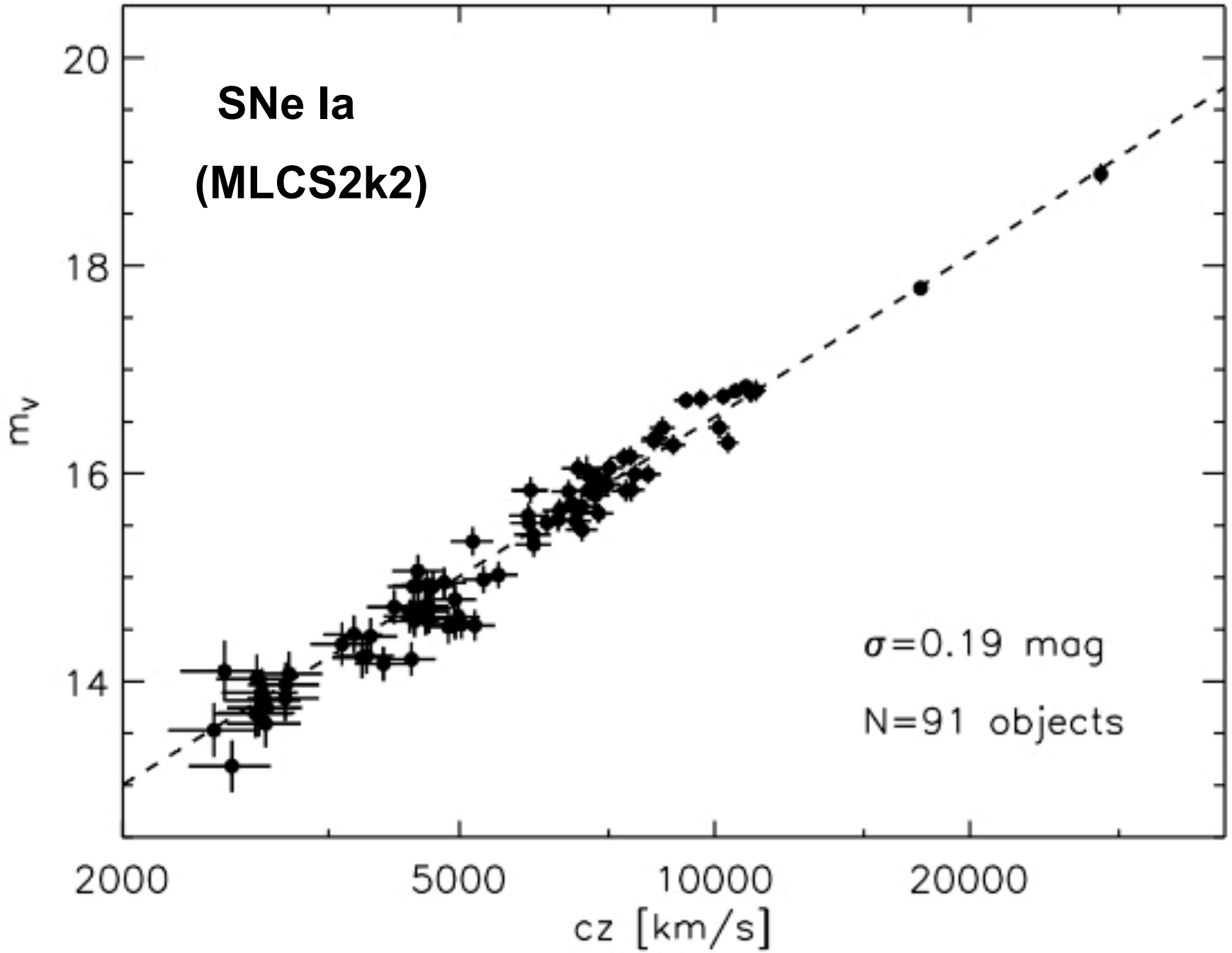
Template subtraction; SN photometry

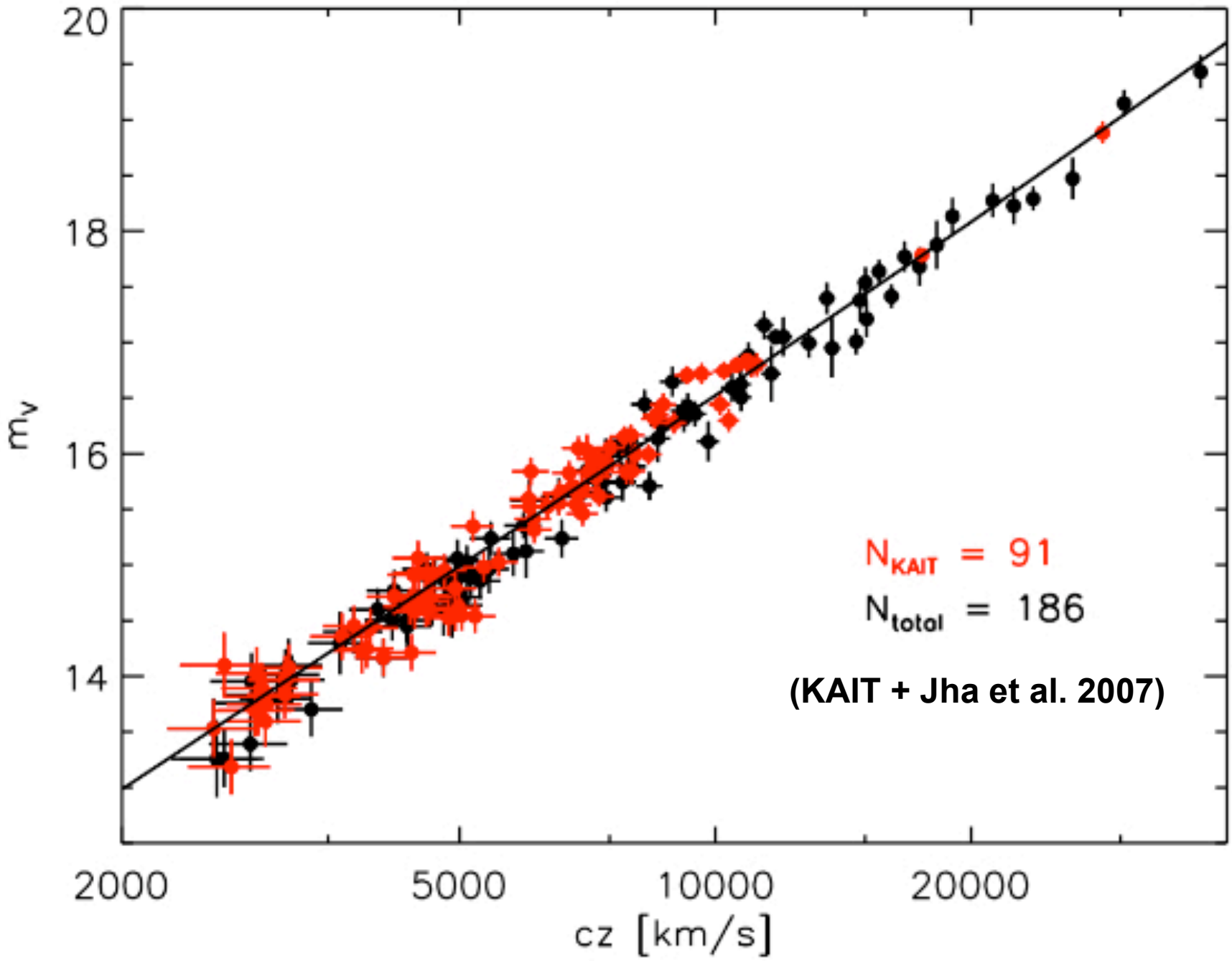
(Automatic pipeline)

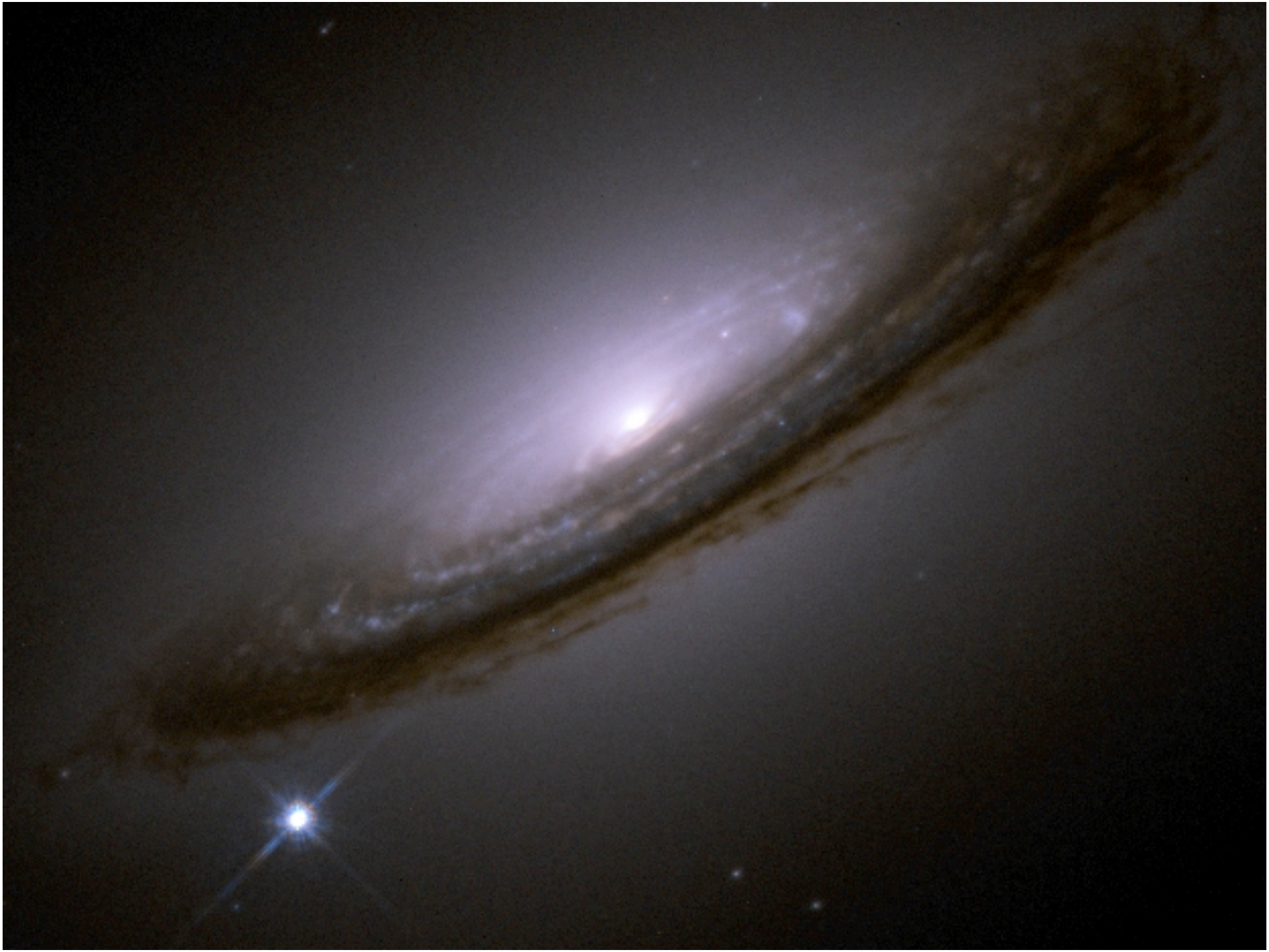
KAIT (U)BVRI follow-up of bright SN Ia

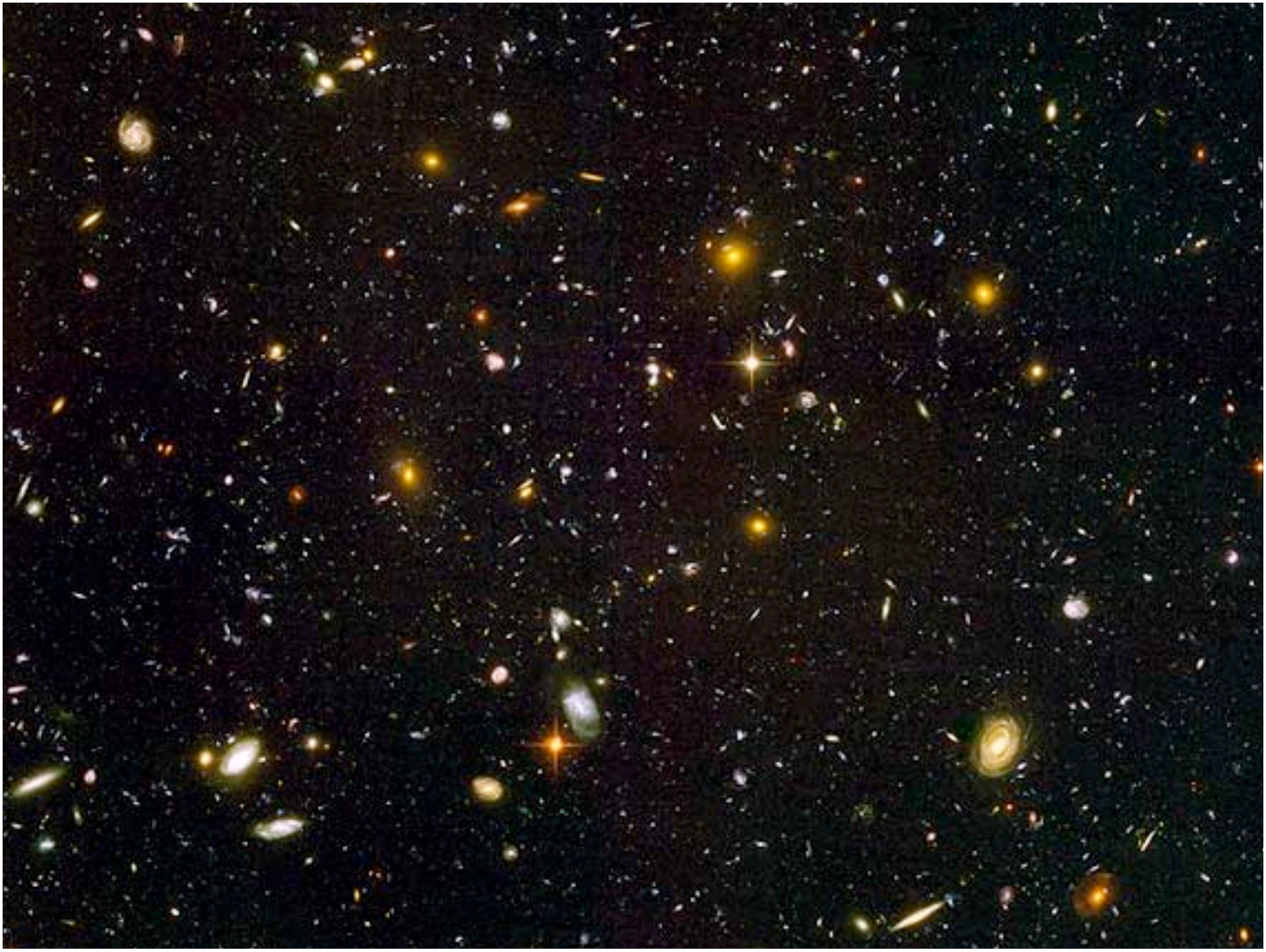


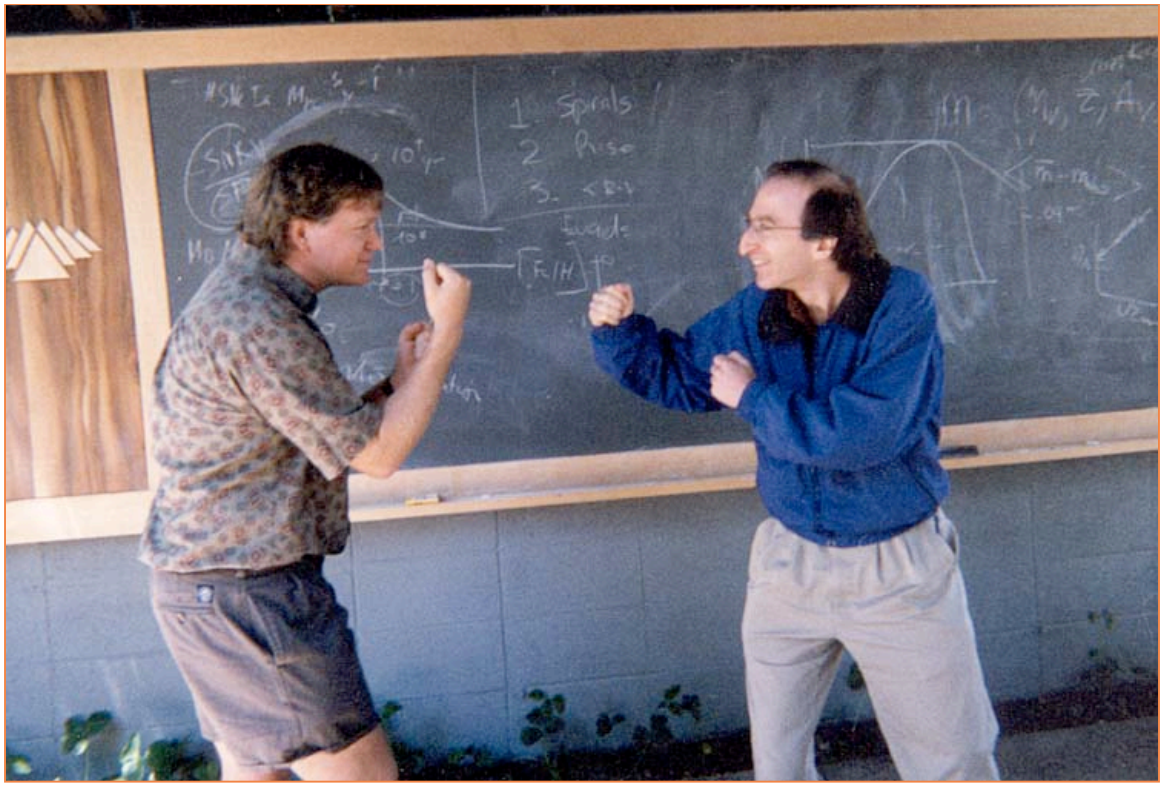

SNe Ia
(before correction)
20
18
16
14
m_v
2000
5000
10000
20000
cz [km/s]
σ=0.59 mag
N=70 objects


SNe Ia
(MLCS2k2)
20
18
16
14
m_v
2000
5000
10000
20000
cz [km/s]
σ=0.19 mag
N=91 objects


20
18
16
14
m_v
2000
5000
10000
20000
cz [km/s]
N_{KAIT} = 91
N_{total} = 186
(KAIT + Jha et al. 2007)







The High-Z Team

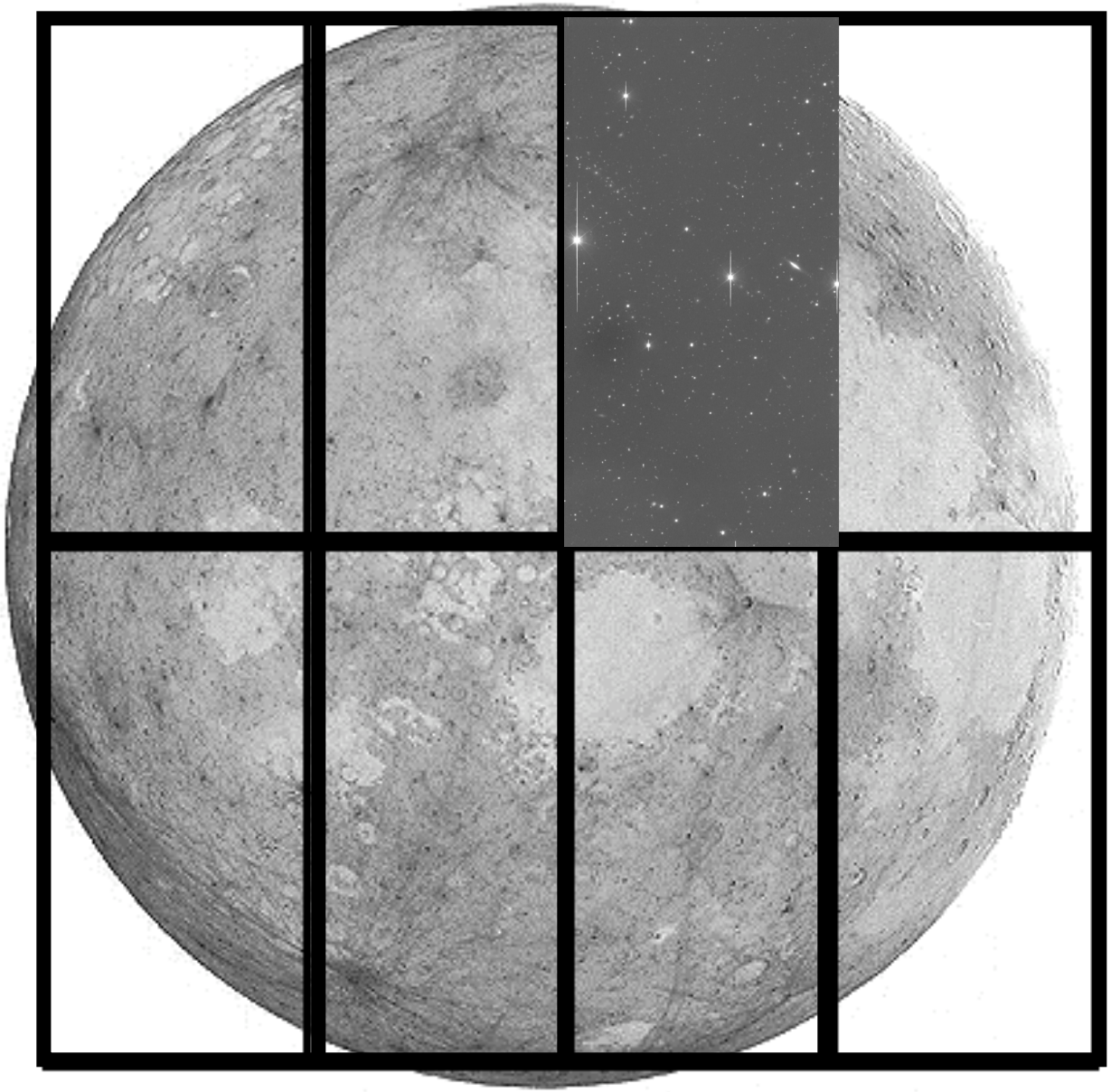
- Brian Schmidt (ANU)
- Nick Suntzeff, Bob Schommer, Chris Smith (CTIO)
- Mark Phillips (Carnegie)
- Bruno Leibundgut and Jason Spyromilio (ESO)
- Bob Kirshner, Peter Challis, Tom Matheson (Harvard)
- AlexFilippenko, Weidong Li, Saurabh Jha (Berkeley)
- PeterGarnavich, Stephen Holland (Notre Dame)
- Chris Stubbs (UW)
- John Tonry, Brian Barris (University of Hawaii)
- Adam Reiss (Space Telescope)
- AlejandroClocchiatti (CatolicaChile)
- Jesper Sollerman (Stockholm)

The High-Z SN Search

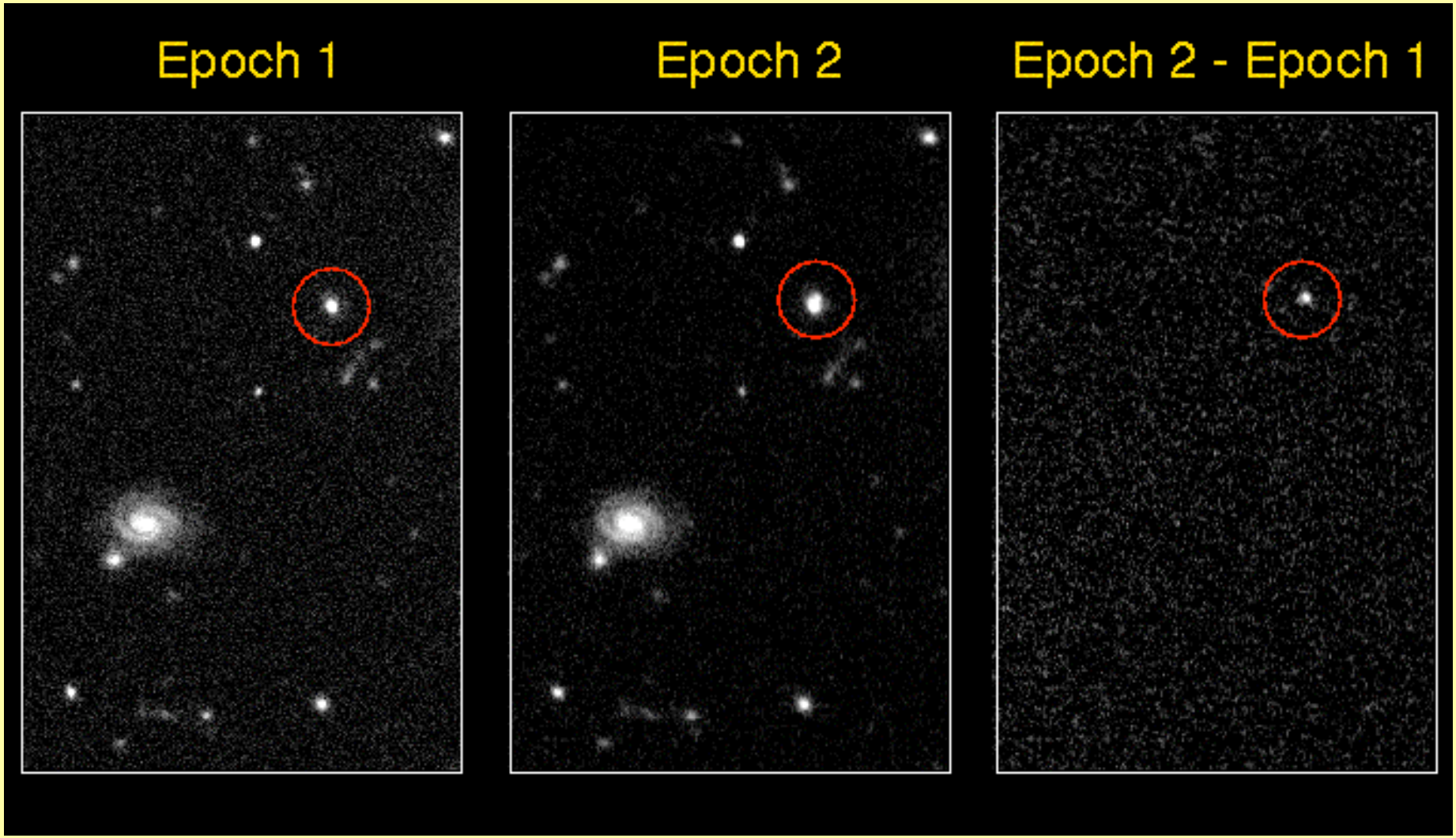
The Supernova Cosmology Project

S. Perlmutter, G. Aldering, S. Deustua, S. Fabbro, G. Goldhaber, D. Groom,
A. Kim, M. Kim, R. Knop, P. Nugent, (LBL & CfPA)
N. Walton (Isaac Newton Group)
A. Fruchter, N. Panagia (STSci)
A. Goobar (Univ of Stockholm)
R. Pain (IN2P3, Paris)
I. Hook, C. Lidman (ESO)
M. DellaValle (Univ of Padova)
R. Ellis (CalTech)
R. McMahon (IofA, Cambridge)
B. Schaefer (Yale)
P. Ruiz-Lapuente (Univ of Barcelona)
H. Newberg (Fermilab)
C. Pennypacker

The High-Z SN Search



Searching by Subtraction



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BMARSDEN@CFA.HARVARD.EDU or DGREEN@CFA.HARVARD.EDU (science)
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SUPERNOVAE

The High-Z Supernova Search Team reports the discovery of seventeen supernovae on CCD images taken at the Victor Blanco 4-m telescope at Cerro Tololo Interamerican Observatory (CTIO) by N. Suntzeff, A. Clocchiatti, and R. Schommer (CTIO); and B. Schmidt (Mount Stromlo and Siding Spring Observatories). Each supernova is within 2″ of its host galaxy's nucleus, except for SN 1996bg, which is 3″.9 south and 0″.3 west of its host galaxy, and all objects were observed at more than one epoch. The following are given for each supernova: the date of their discovery image, position, R magnitude at discovery, redshift, supernova type, and telescope (T) that provided the redshift and spectral-typing information.

SN	1996 UT	α_{2000}	δ_{2000}	R	z	type	T
1996at	Sept. 15	1h08m17s.63	−0°58′25″.5	20.5	0.09	Ic	A
1996au	Sept. 15	3 12 47.79	+0 45 11.9	22.5	0.52	Ia	K
1996av	Sept. 15	1 53 54.22	+0 15 30.6	22.4	0.51	Ia	K
1996aw	Oct. 8	21 53 47.10	+0 02 47.3	21.7	0.21	Ia	M
1996ax	Oct. 8	21 53 52.93	−0 02 36.4	23.3	0.23	?	M/K
1996ay	Oct. 8	0 09 57.41	+0 53 37.9	23.9	0.62	Ia	K
1996az	Oct. 8	0 15 10.84	+1 06 34.6	24.0	0.84	?	K
1996ba	Oct. 8	1 08 39.87	−0 56 38.9	23.5	0.66	Ia	K
1996bb	Oct. 8	2 57 06.06	−2 42 17.4	23.6	0.56	Ia?	K
1996bc	Oct. 8	3 12 06.58	+0 38 17.1	22.5	0.46	Ia	K
1996bd	Oct. 9	23 59 26.98	−0 56 16.6	21.6	0.28	Ia	M
1996be	Oct. 9	2 12 02.83	+1 22 39.1	22.2	0.22	II	K
1996bf	Oct. 9	2 12 15.39	+1 27 48.9	21.5	0.25	Ia	M
1996bg	Oct. 9	0 52 52.38	−0 04 31.1	22.0	0.12	II	M/K
1996bh	Oct. 9	1 11 31.53	−0 57 38.1	22.8	0.43	Ia	K
1996bi	Oct. 9	1 52 35.84	+0 02 43.3	23.0	0.60	Ia	K
1996bj	Oct. 9	2 11 49.53	+1 24 51.0	22.6	0.57	Ia	K

The Anglo-Australian Telescope (A) observations were made by R. Stathakis (Anglo-Australian Observatory) on Oct. 9–10; The Keck Telescope (K) observations were made Oct. 11–12 by A. V. Filippenko, D. C. Leonard, and A. J. Barth (University of California, Berkeley); and the Multiple-Mirror Telescope (M) observations were made on Oct. 10–12 by R. Kirshner, Harvard-Smithsonian Center for Astrophysics. Finder charts may be requested by sending electronic mail to pgarnavi.ch@cfa.harvard.edu.

1996 October 14 © Copyright 1996 CBAT *Daniel W. E. Green*

17 SNe,
z = 0.09-0.84

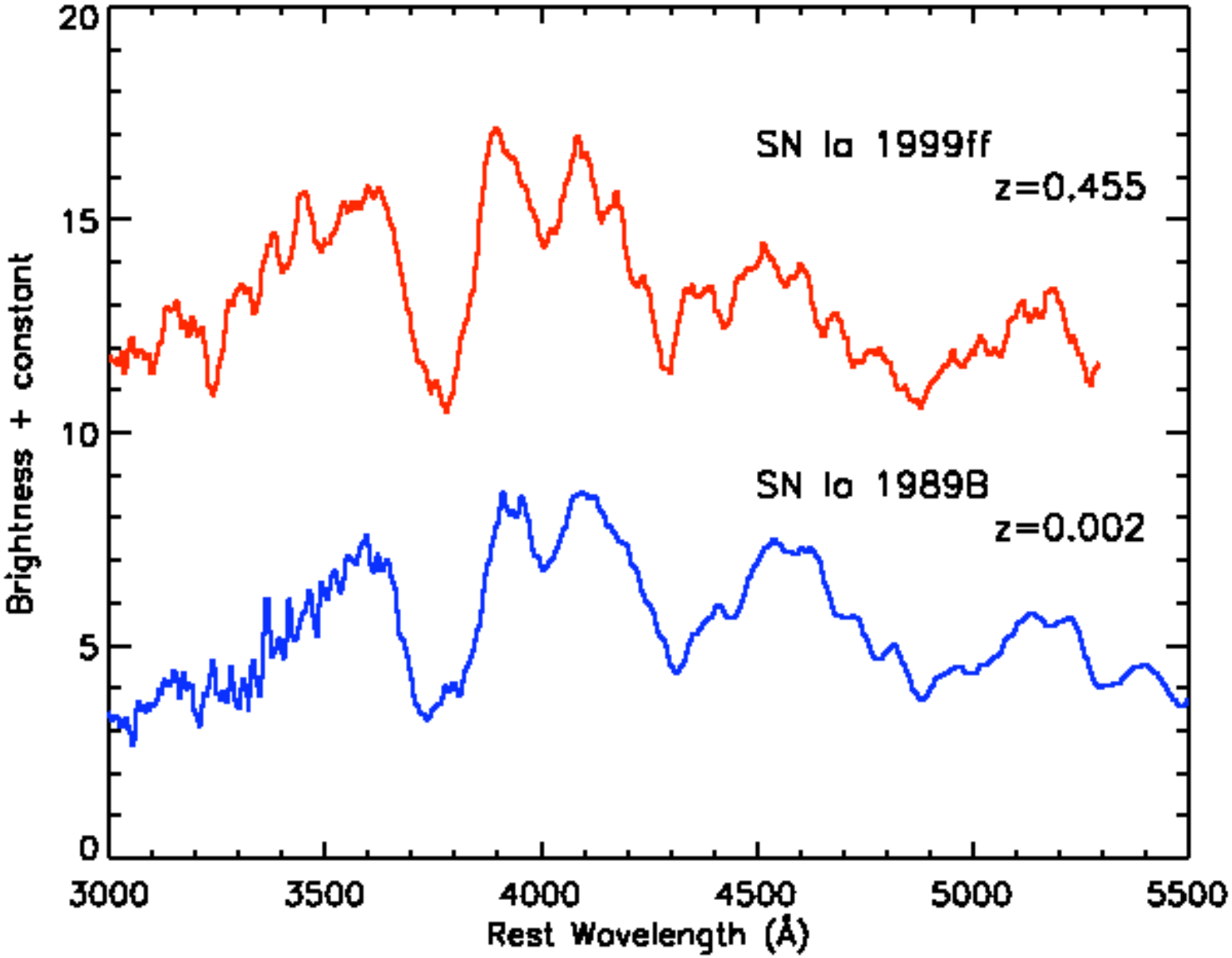
Schmidt,
Suntzeff, et al.

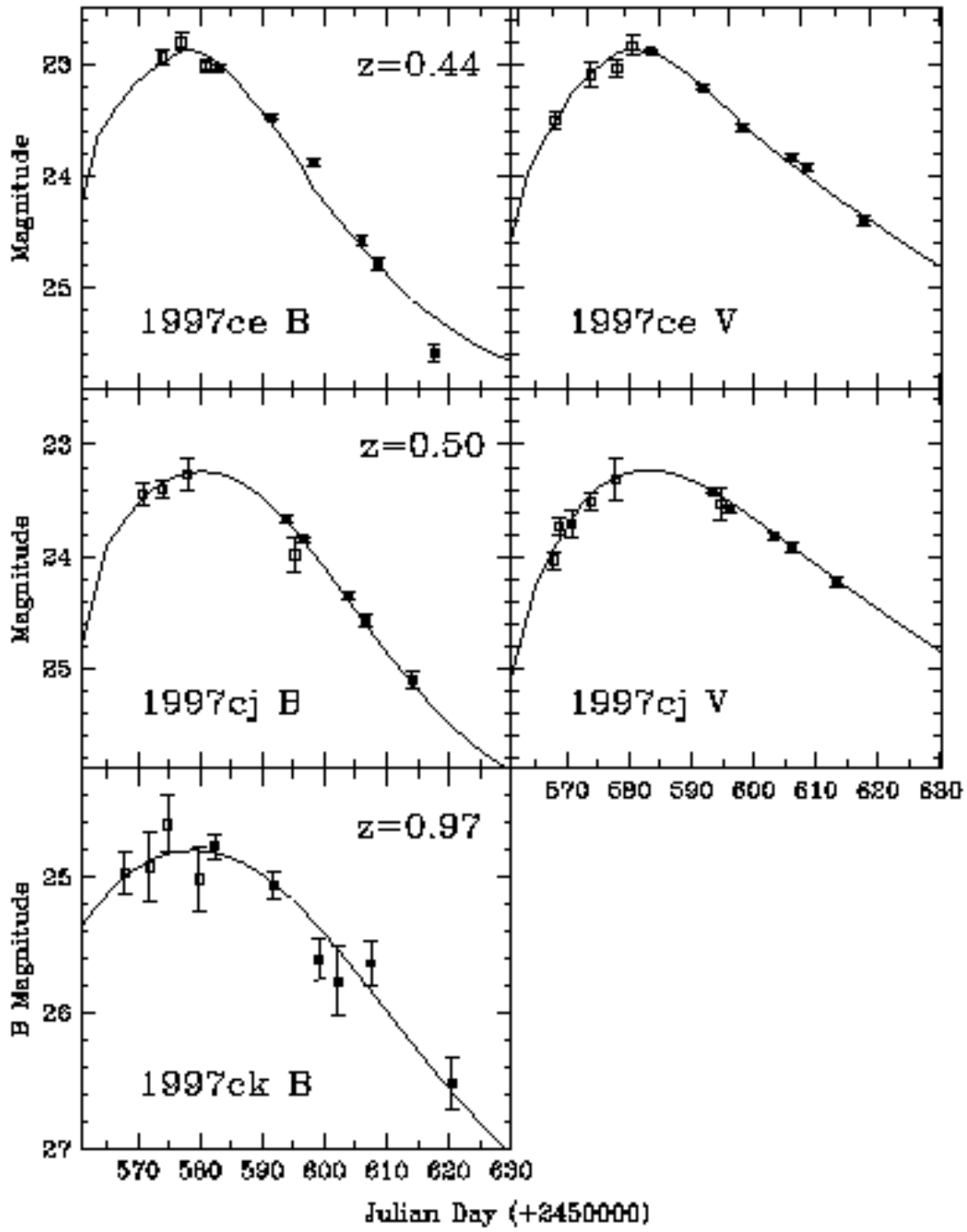
Mostly Keck spectra.

Oct. 1996

IAUC 6490

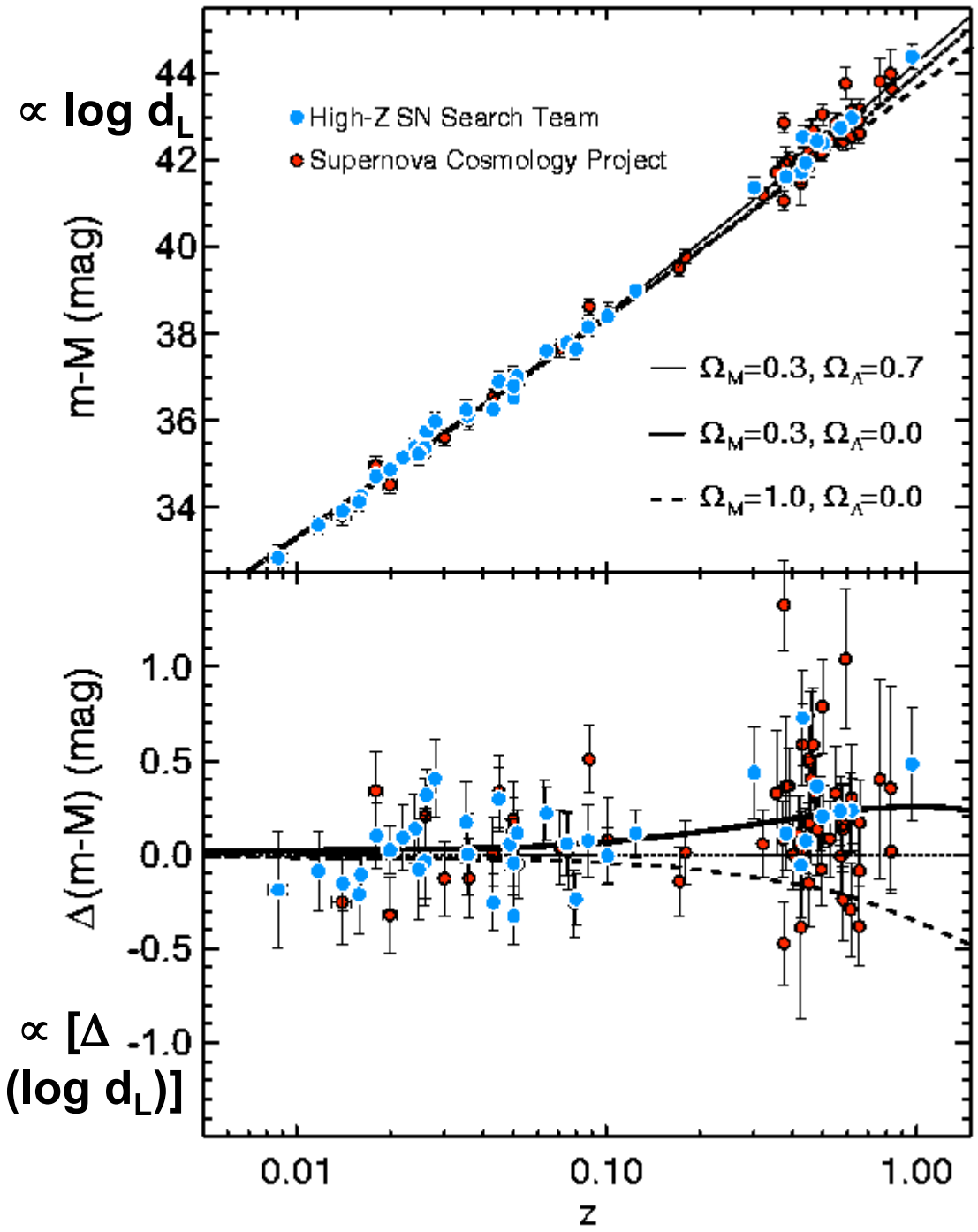
Keck LRIS, 1 hour





High-z SN Ia light curves (Garnavich et al. 1998a)

Two filters: get color, so can deal with reddening and intrinsic dimness.

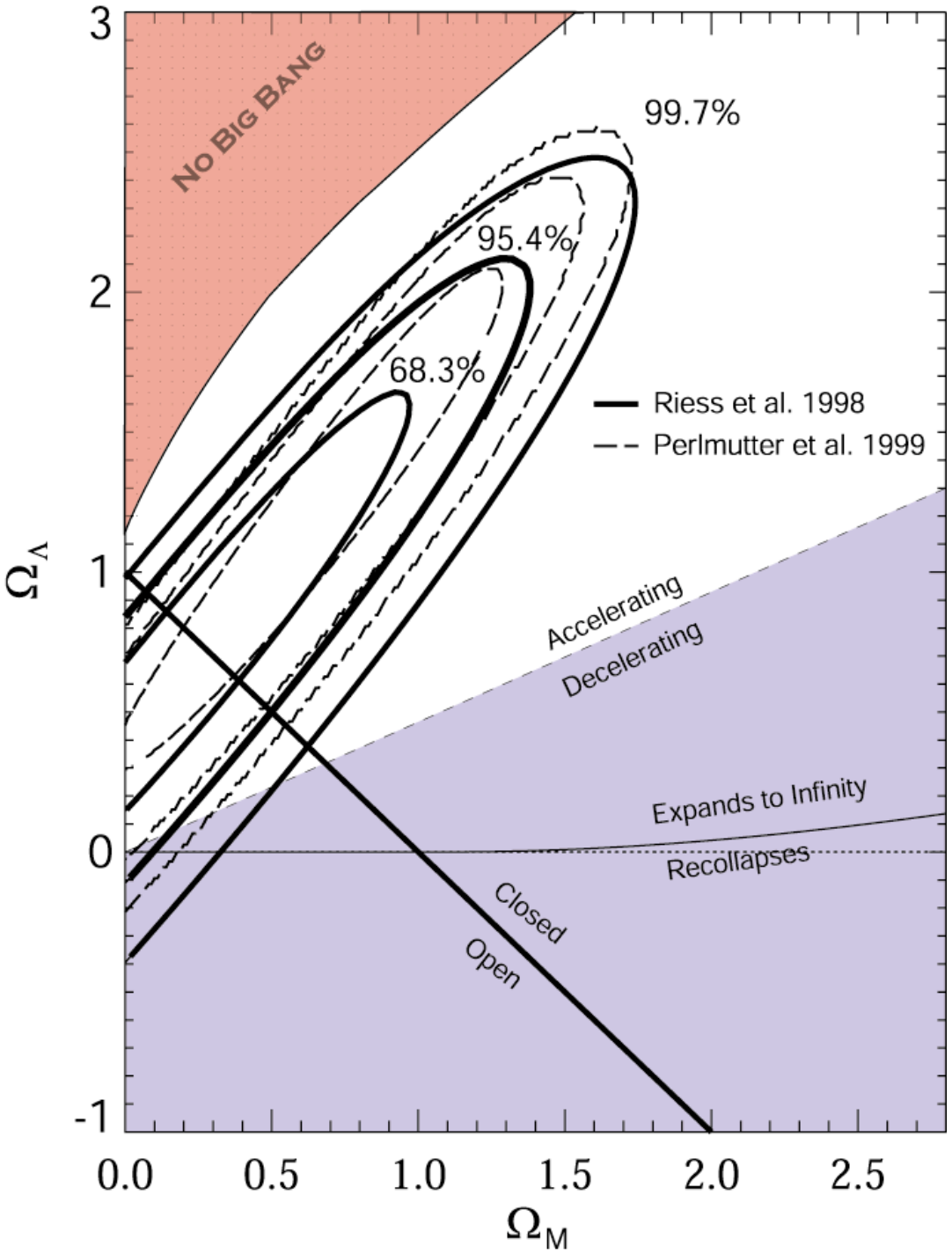


<1998 data:

Riess et al. (1998) – blue dots

Perlmutter et al. (1999) – red dots

Conclude $\Lambda > 0$!



<1998 data: Riess et al. (1998) Perlmutter et al. (1999)

A non-zero cosmological constant!?

THE ASTRONOMICAL JOURNAL, 116:1009–1038, 1998 September
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High-z team (Sep. 1998)

OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

ADAM G. RIESS,[1] ALEXEI V. FILIPPENKO,[1] PETER CHALLIS,[2] ALEJANDRO CLOCCHIATTI,[3] ALAN DIERCKS,[4] PETER M. GARNAVICH,[2] RON L. GILLILAND,[5] CRAIG J. HOGAN,[4] SAURABH JHA,[2] ROBERT P. KIRSHNER,[2] B. LEIBUNDGUT,[6] M. M. PHILLIPS,[7] DAVID REISS,[4] BRIAN P. SCHMIDT,[8,9] ROBERT A. SCHOMMER,[7] R. CHRIS SMITH,[7,10] J. SPYROMILIO,[6] CHRISTOPHER STUBBS,[4] NICHOLAS B. SUNTZEFF,[7] AND JOHN TONRY[11]
Received 1998 March 13; revised 1998 May 6

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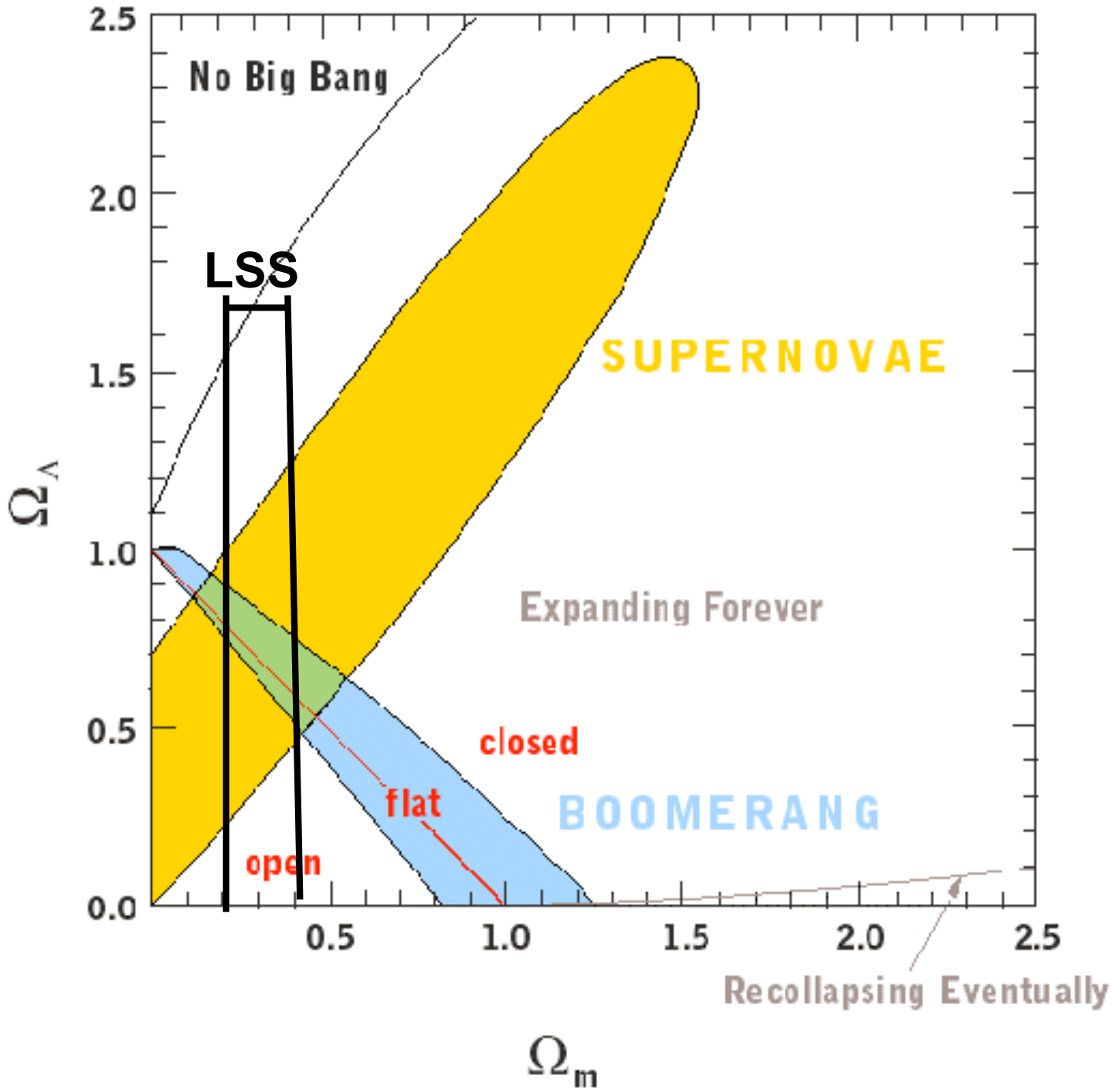
SCP (June 1999)

MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

S. PERLMUTTER,[1] G. ALDERING, G. GOLDHABER,[1] R. A. KNOP, P. NUGENT, P. G. CASTRO,[2] S. DEUSTUA, S. FABBRO,[3] A. GOOBAR,[4] D. E. GROOM, I. M. HOOK,[5] A. G. KIM,[1,6] M. Y. KIM, J. C. LEE,[7] N. J. NUNES,[2] R. PAIN,[3] C. R. PENNYPACKER,[8] AND R. QUIMBY
Institute for Nuclear and Particle Astrophysics, E. O. Lawrence Berkeley National Laboratory, Berkeley, CA 94720
C. LIDMAN
European Southern Observatory, La Silla, Chile
R. S. ELLIS, M. IRWIN, AND R. G. MCMAHON
Institute of Astronomy, Cambridge, England, UK
P. RUIZ-LAPUENTE
Department of Astronomy, University of Barcelona, Barcelona, Spain
N. WALTON
Isaac Newton Group, La Palma, Spain

et al. (AF, …)

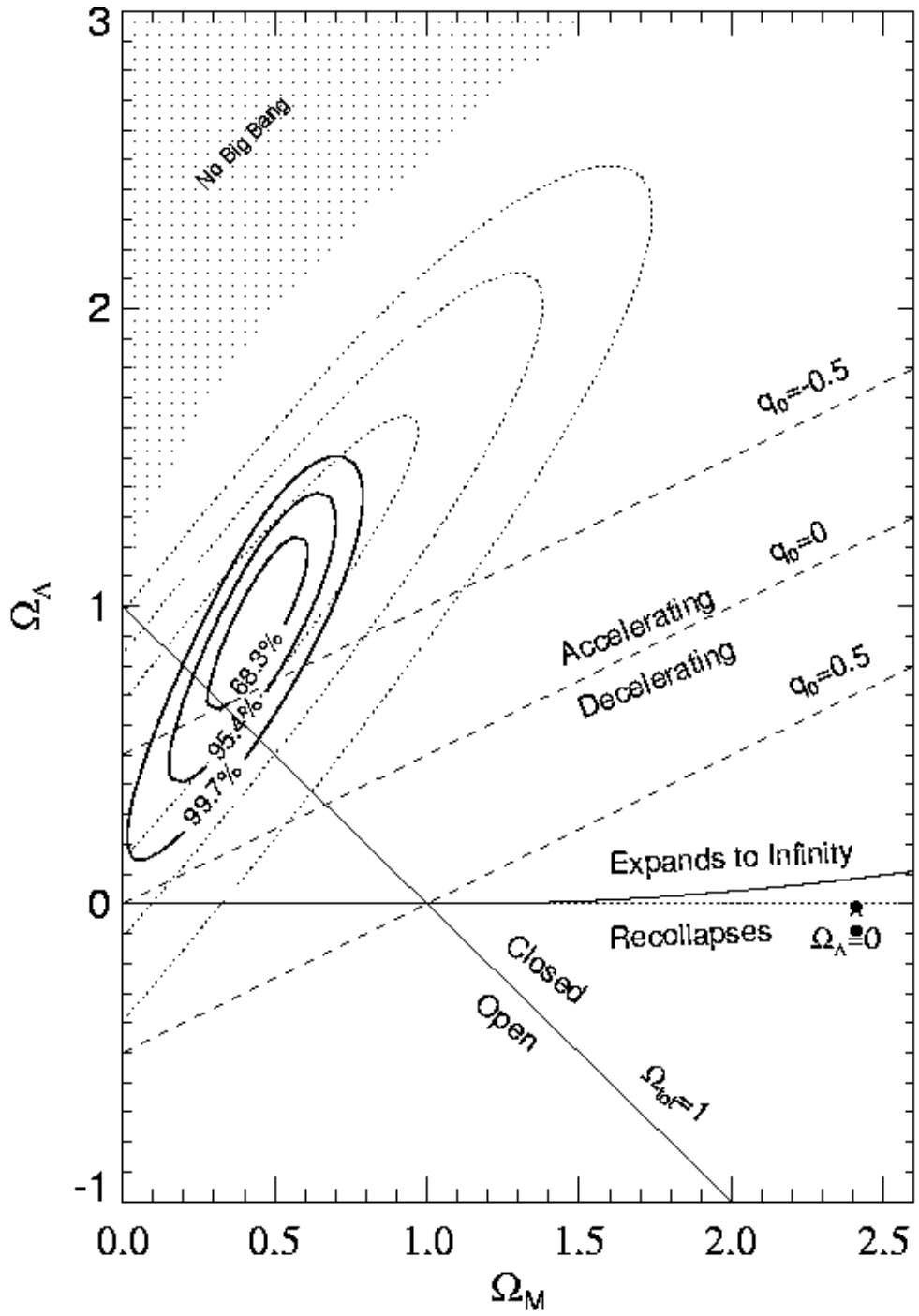


(2000/ 2001)

Clusters, LSS: Ω_M = 0.3 ± 0.1

Concor- dance: (0.3, 0.7)

WMAP + LSS 2003: (0.27, 0.73)

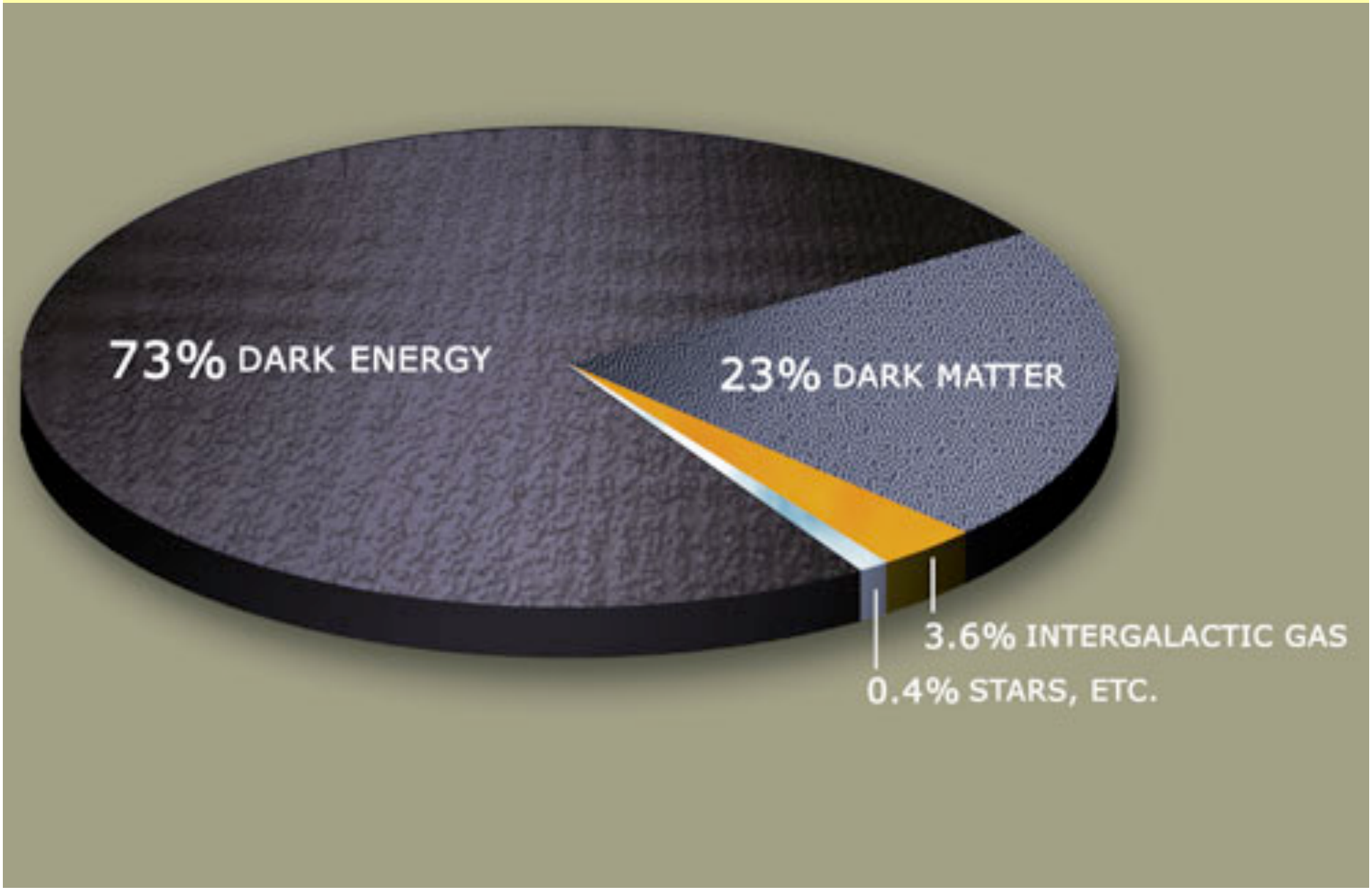


Riess et al. (2004), using all published high-z SN Ia data.

(SN Ia + LSS: $\Omega_M = 0.28$, $\Omega_\Lambda = 0.72$, with precision ~ CMB + LSS)

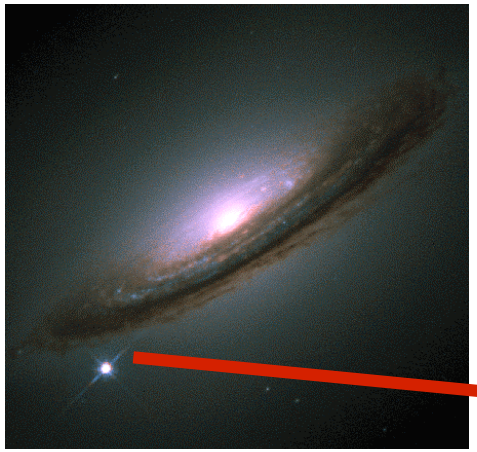
Ω_M=1 ruled out at very many σ!

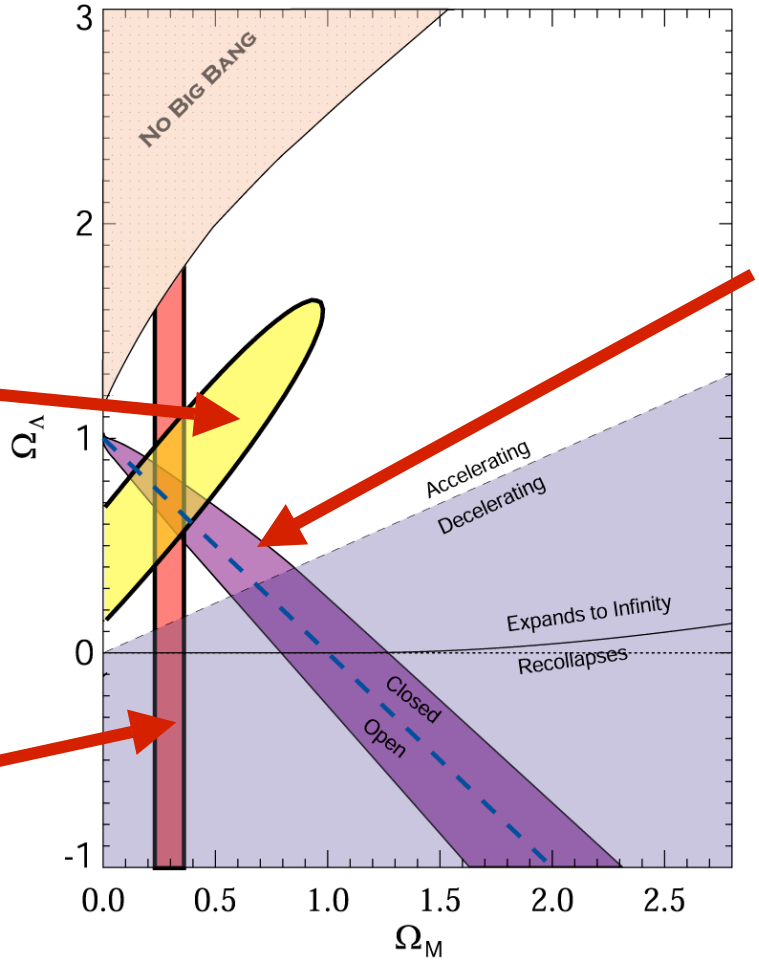
Composition of the Universe



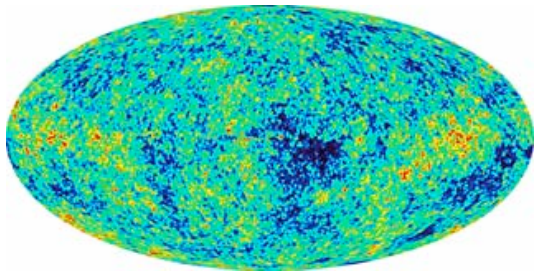
Since “dark energy” seems real…

SN Ia



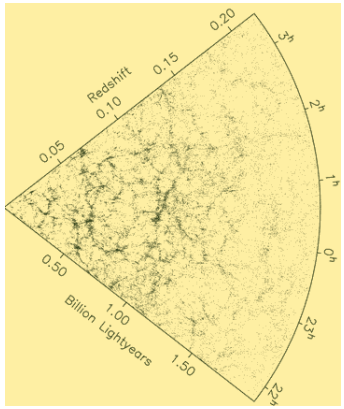


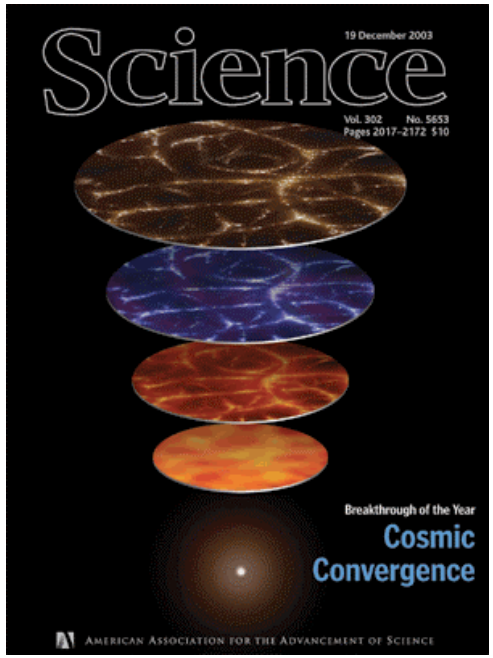
CMB(WMAP)



+ ISW, X-ray Clusters

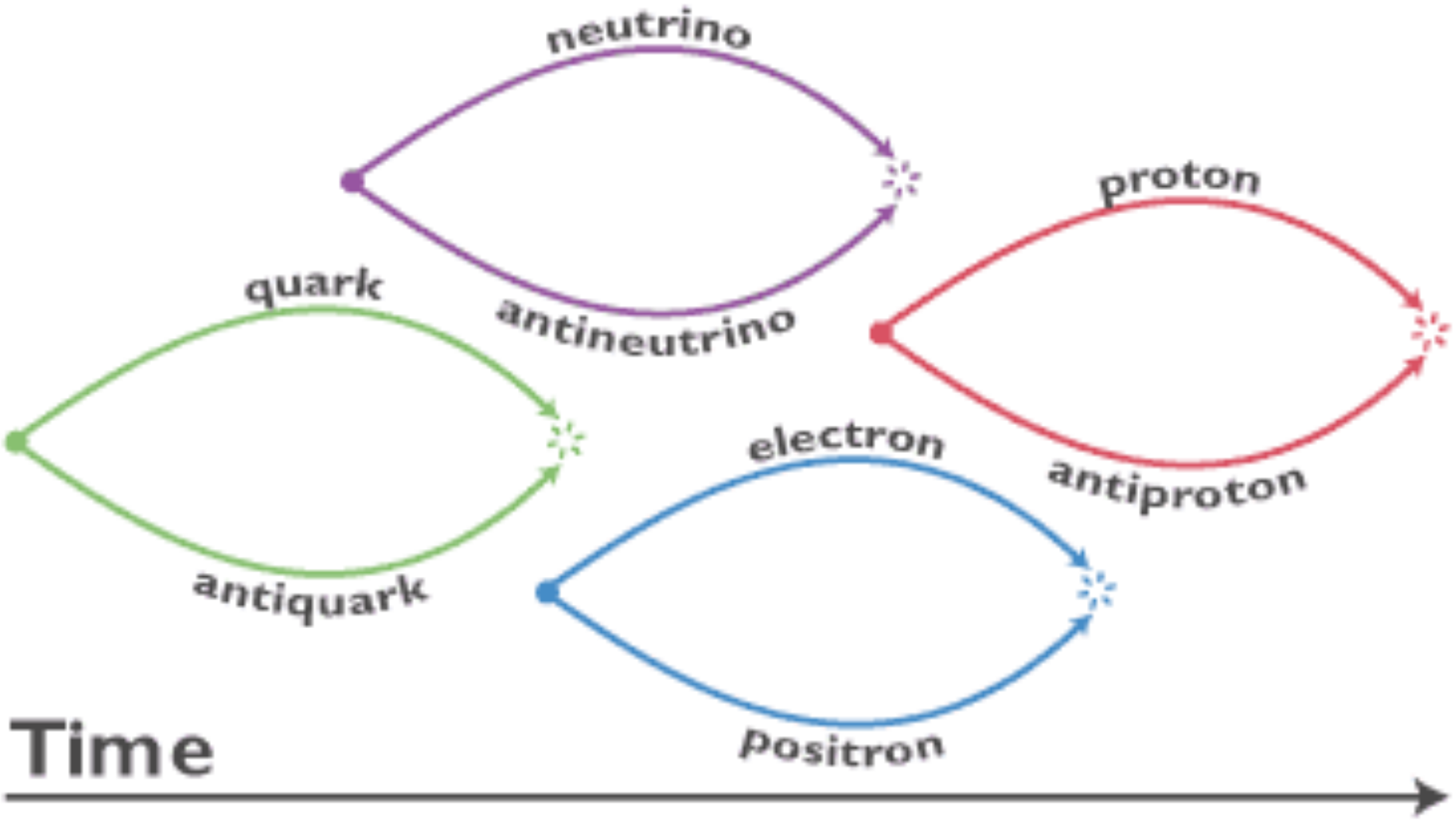
LSS





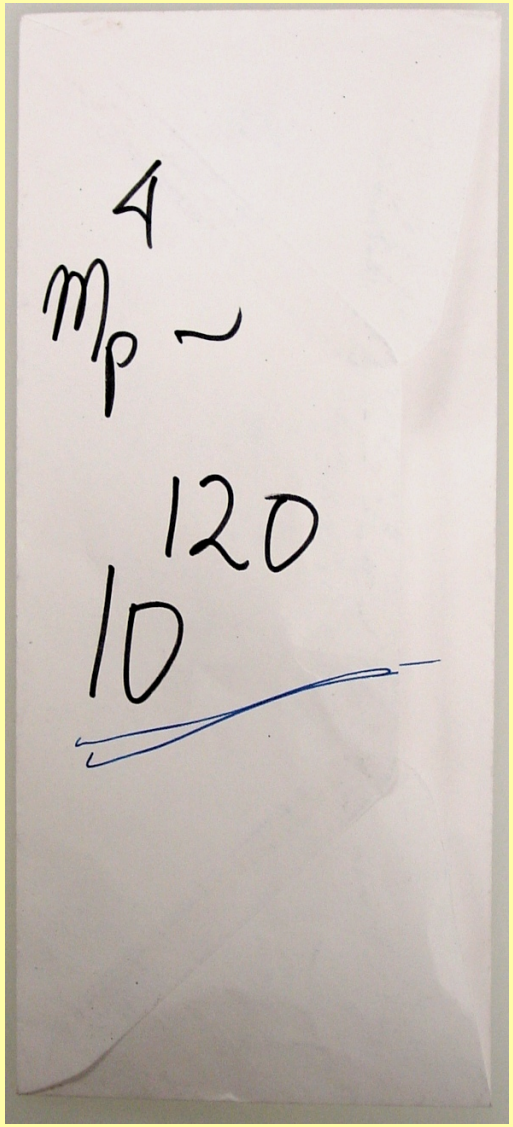
what is it?

Quantum fluctuations: virtual particles



Λ, the Cosmological Constant?

- **Not good quantitative agreement with theoretical expectations!**
- **Way too small. "Why now?"**
- **"A bone in the throat." – S. Weinberg**



Define $w = P/(\rho c^2)$

- **Equation-of-state parameter**
- $\rho \propto (\text{volume})^{-(1+w)}$

$w = 0$ for normal non-relativistic matter

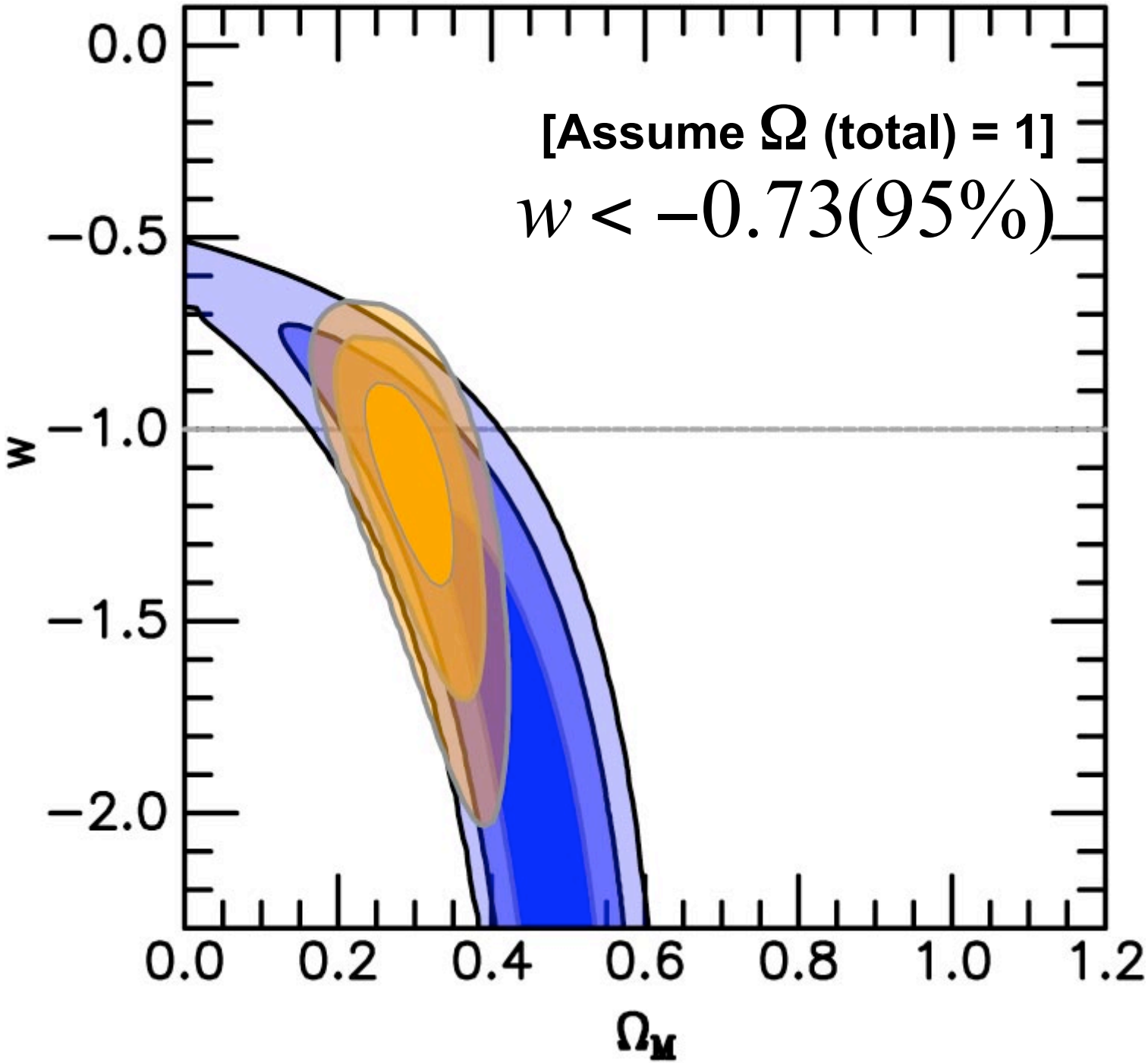
$w = 1/3$ for photons

$w = -1$ for Λ

$w \neq -1$ for "*quintessence*," etc. (rolling scalar field, etc.; –1/3 for cosmic strings).

In GR, gravitational acceleration $\propto -(\rho c^2 + 3P)$.

If $w < -1/3$, the Universe accelerates!


[Assume Ω (total) = 1]
w < –0.73(95%)
0.0
–0.5
–1.0
–1.5
–2.0
w
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Ω_M

From Space, a New View of Doomsday

By DENNIS OVERBYE

Published: February 17, 2004

Once upon a time, if you wanted to talk about the end of the universe you had a choice, as Robert Frost put it, between fire and ice.

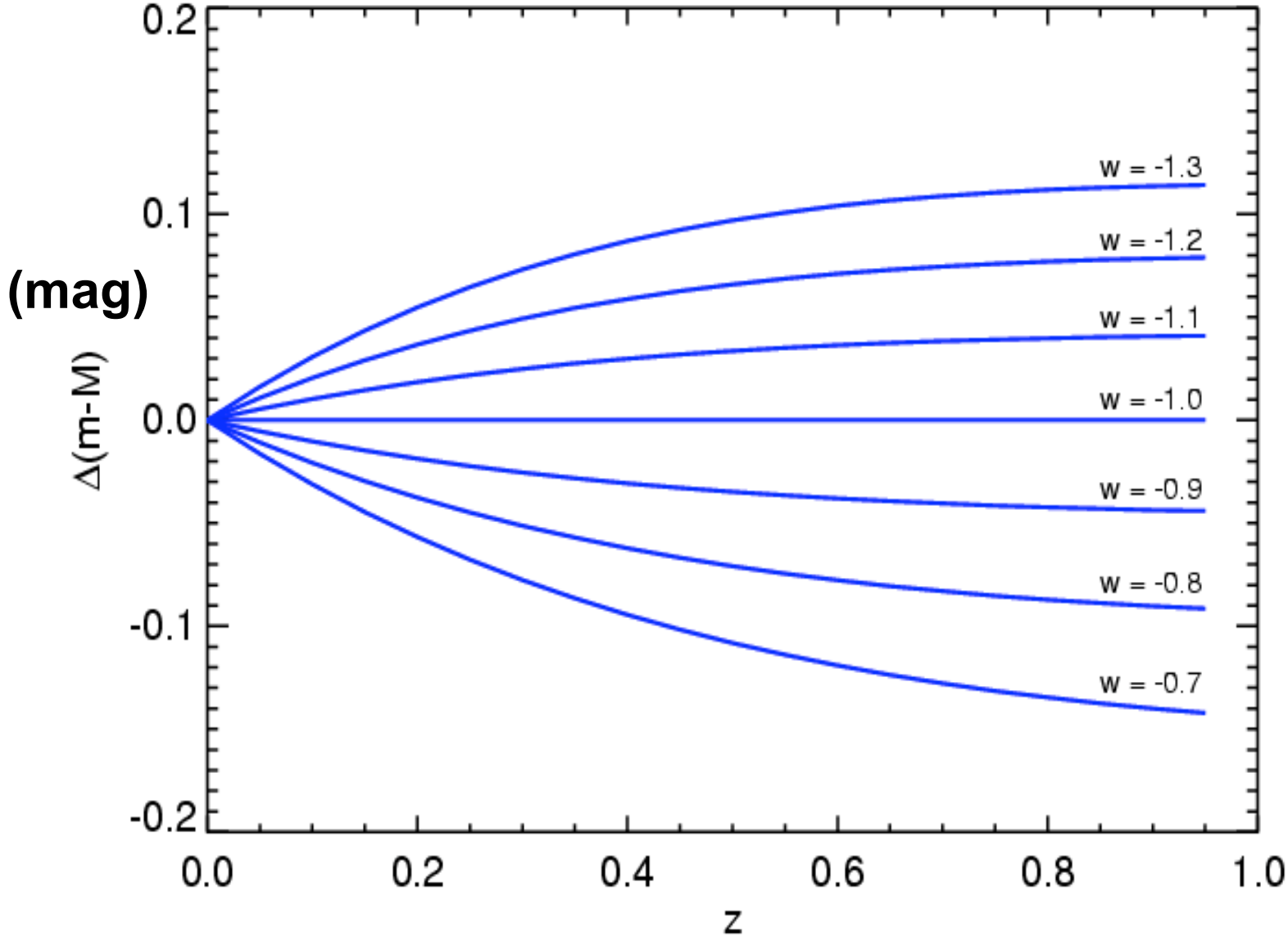
Either the universe would collapse under its own weight one day, in a fiery "big crunch," or the galaxies, now flying outward from each other, would go on coasting outward forever, forever slowing, but never stopping while the cosmos grew darker and darker, colder and colder, as the stars gradually burned out like tired bulbs.

Now there is the Big Rip.

Recent astronomical measurements, scientists say, cannot rule out the possibility that in a few billion years a mysterious force permeating space-time will be strong enough to blow everything apart, shred rocks, animals, molecules and finally even atoms in a last seemingly mad instant

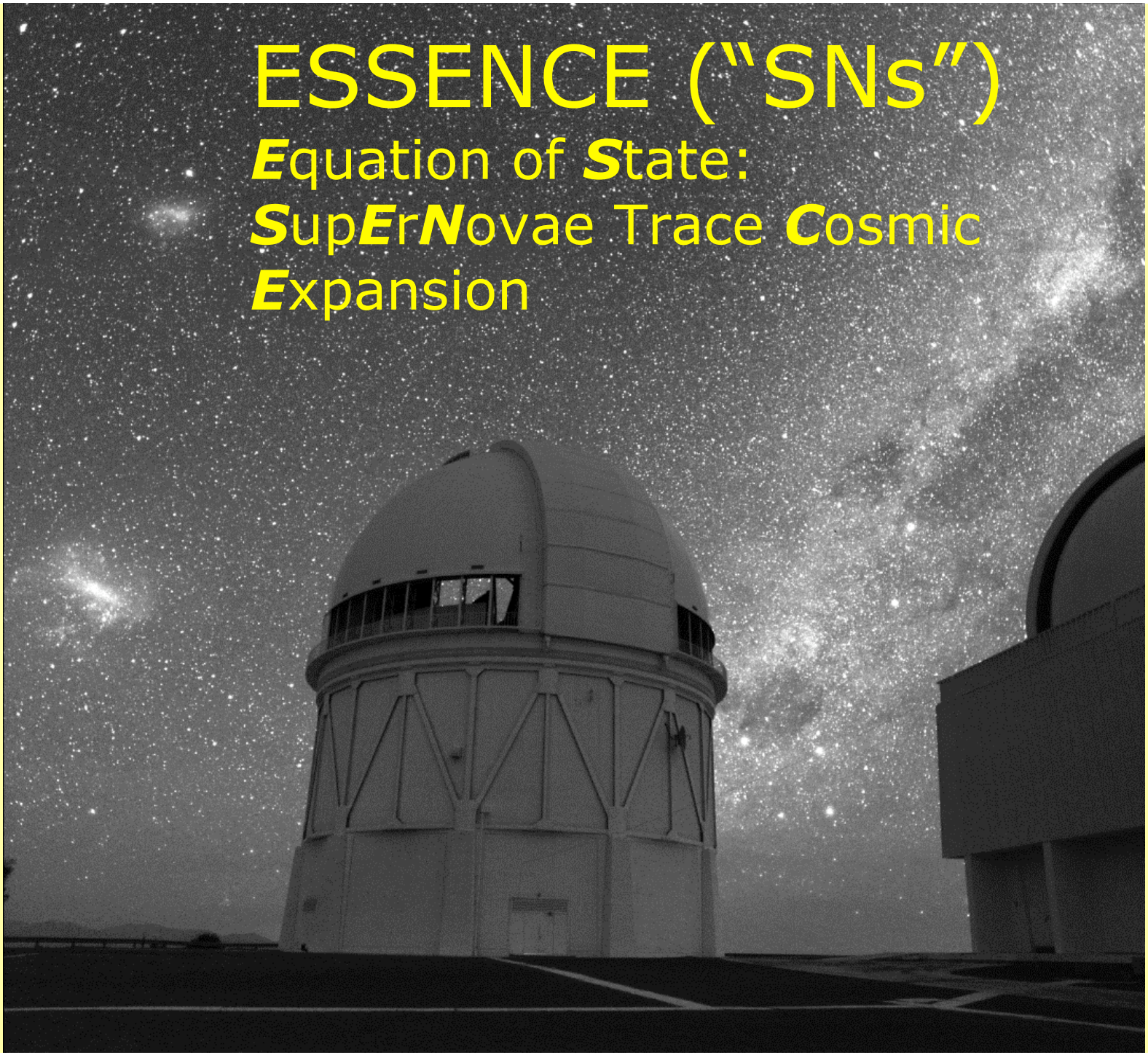
Advertisement

Rick Friedman; Peter DaSilv
Marty Katz for The New Yo
Tim



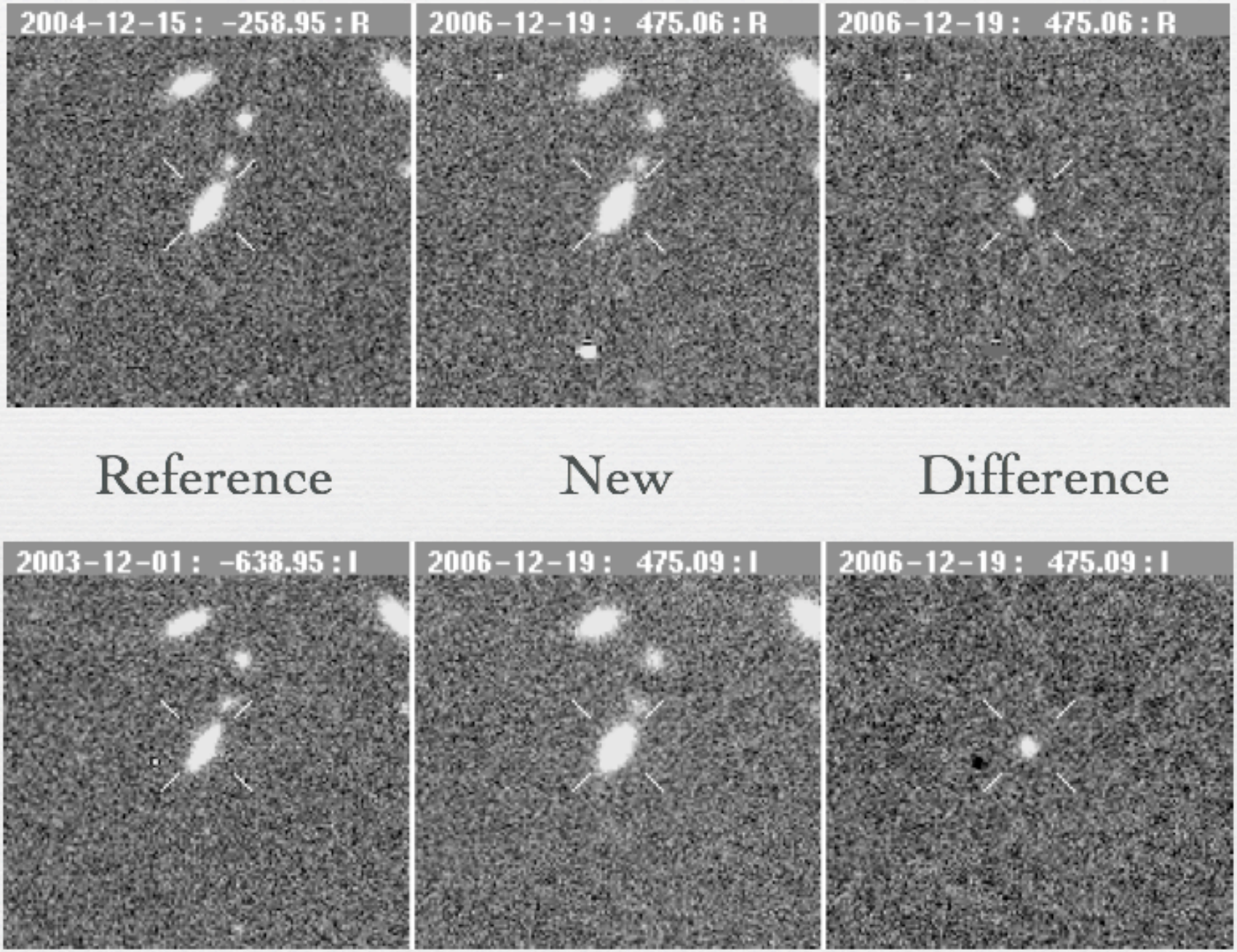
Difference in apparent SN brightness vs. z

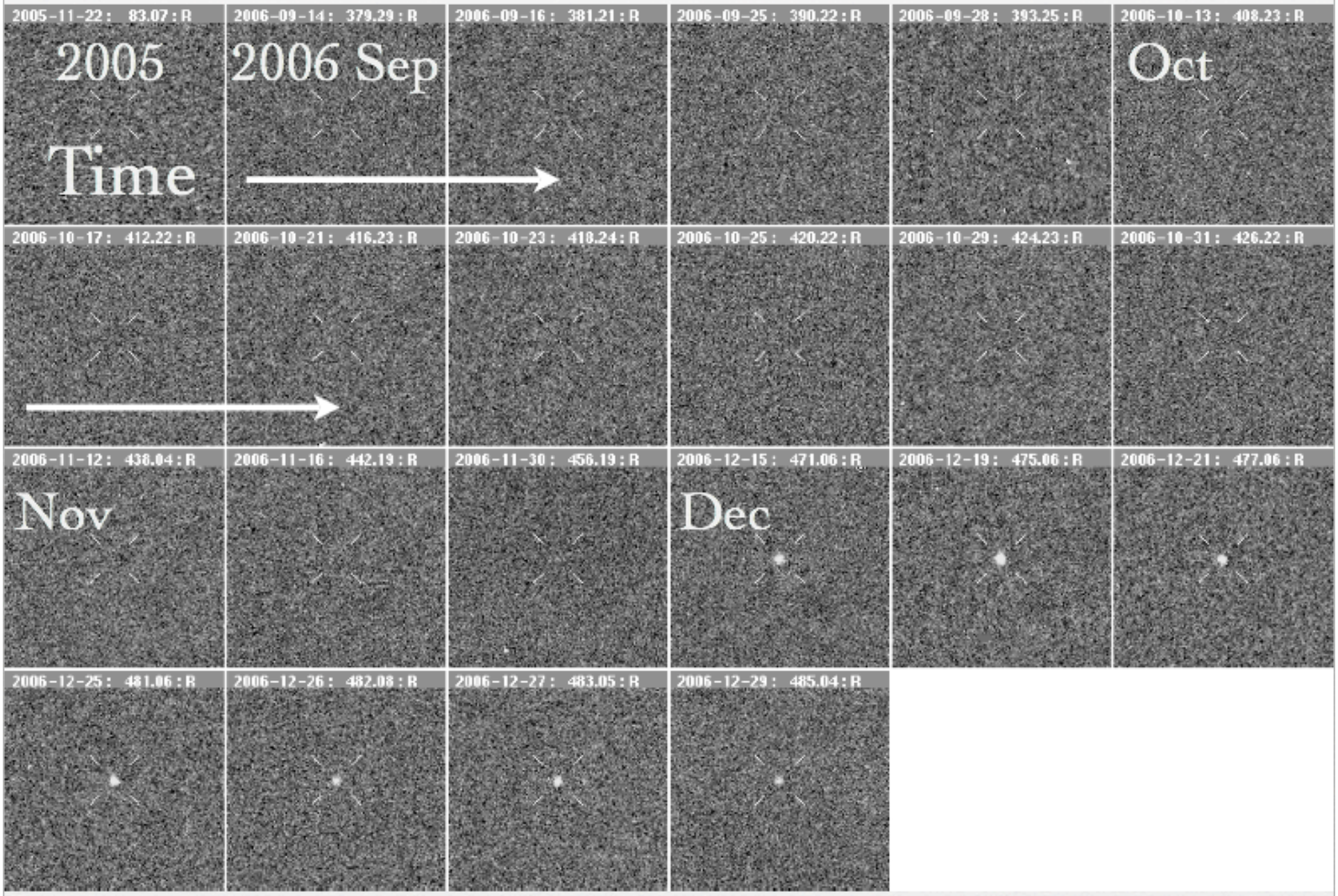
$\Omega_\Lambda = 0.70$, flat universe


ESSENCE ("SNs")
*E*quation of *S*tate:
*S*up*E*r*N*ovae Trace *C*osmic
*E*xpansion

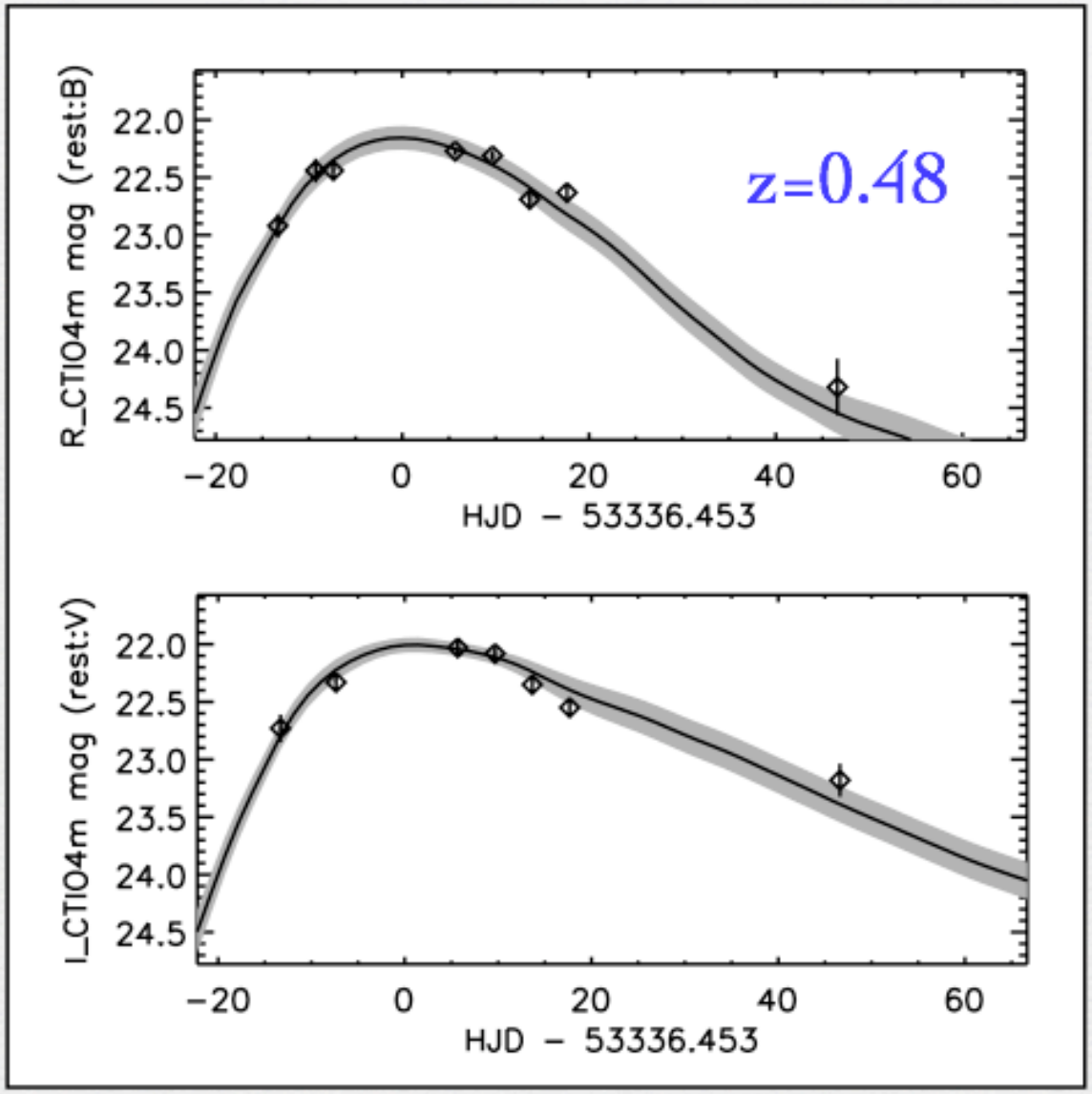
ESSENCE (Miknaitis et al. 2007, Wood-Vasey et al. 2007)

- Determine w to 10%.
- 6-year project on CTIO 4m; 12 sq. deg.; MOSAIC II.
- Wide-field images in 2 bands.
- Same-night detection of SN.
- Spectroscopy:
  - Keck, VLT, Gemini, Magellan.
- ~200 SN Ia, $0.2 < z < 0.8$
- Data and SN Ia public.


2004-12-15 : -258.95 : R
2006-12-19 : 475.06 : R
2006-12-19 : 475.06 : R
R
Reference
New
Difference
2003-12-01 : -638.95 : I
2006-12-19 : 475.09 : I
2006-12-19 : 475.09 : I
I


2005-11-22 : 83.07 : R
2005
Time
2006-09-14 : 379.29 : R
2006 Sep
2006-09-16 : 381.21 : R
2006-09-25 : 390.22 : R
2006-09-28 : 393.25 : R
2006-10-13 : 408.23 : R
Oct
2006-10-17 : 412.22 : R
2006-10-21 : 416.23 : R
2006-10-23 : 418.24 : R
2006-10-25 : 420.22 : R
2006-10-29 : 424.23 : R
2006-10-31 : 426.22 : R
2006-11-12 : 438.04 : R
Nov
2006-11-16 : 442.19 : R
2006-11-30 : 456.19 : R
2006-12-15 : 471.06 : R
Dec
2006-12-19 : 475.06 : R
2006-12-21 : 477.06 : R
2006-12-25 : 481.06 : R
2006-12-26 : 482.08 : R
2006-12-27 : 483.05 : R
2006-12-29 : 485.04 : R

Apparent Brightness



$m_v^0 = 22.75 \pm 0.20$

$\Delta = -0.15 \pm 0.07$

$A_v = 0.19 \pm 0.17$

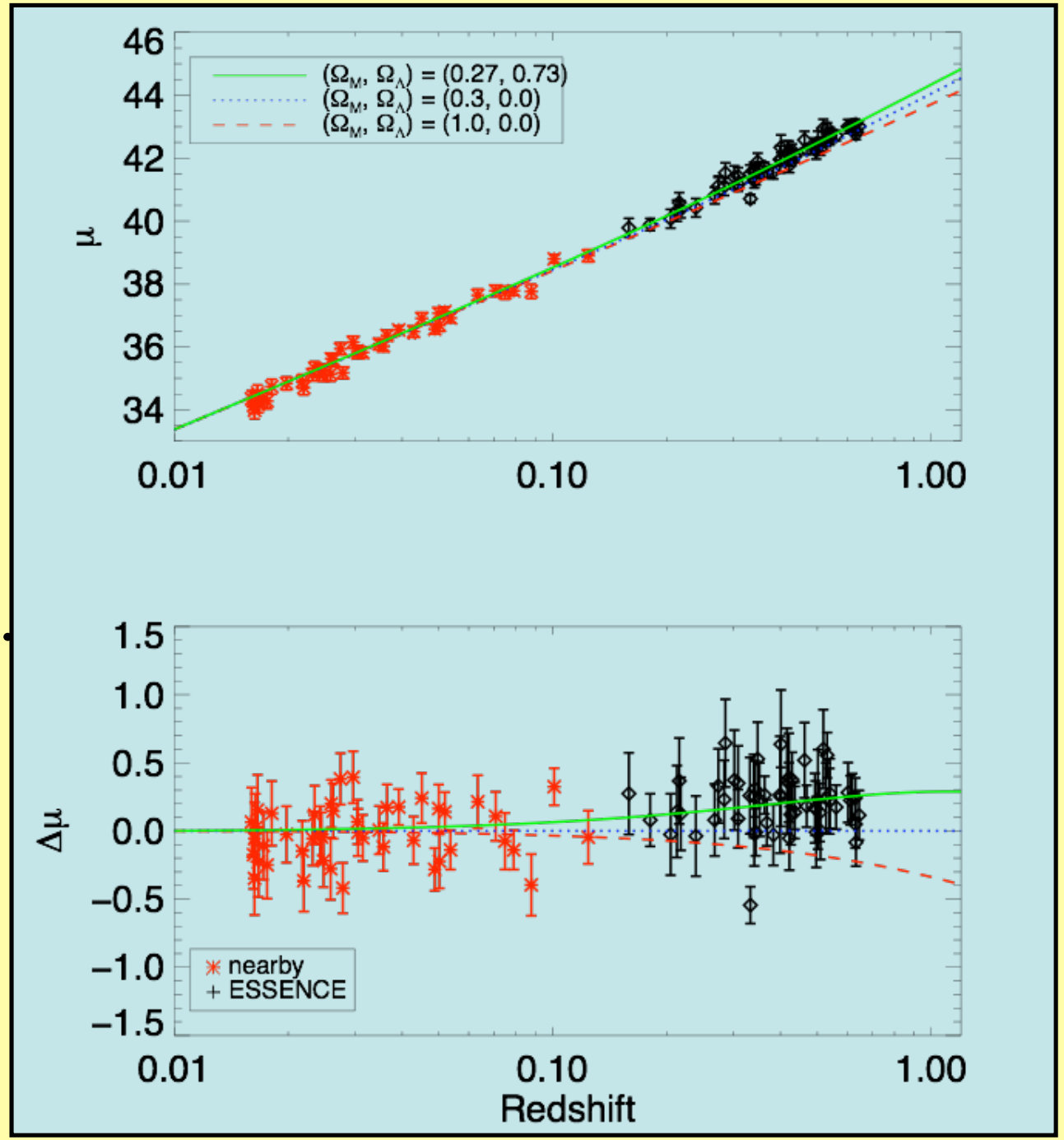
$R_v = 3.10 \pm 0.00$

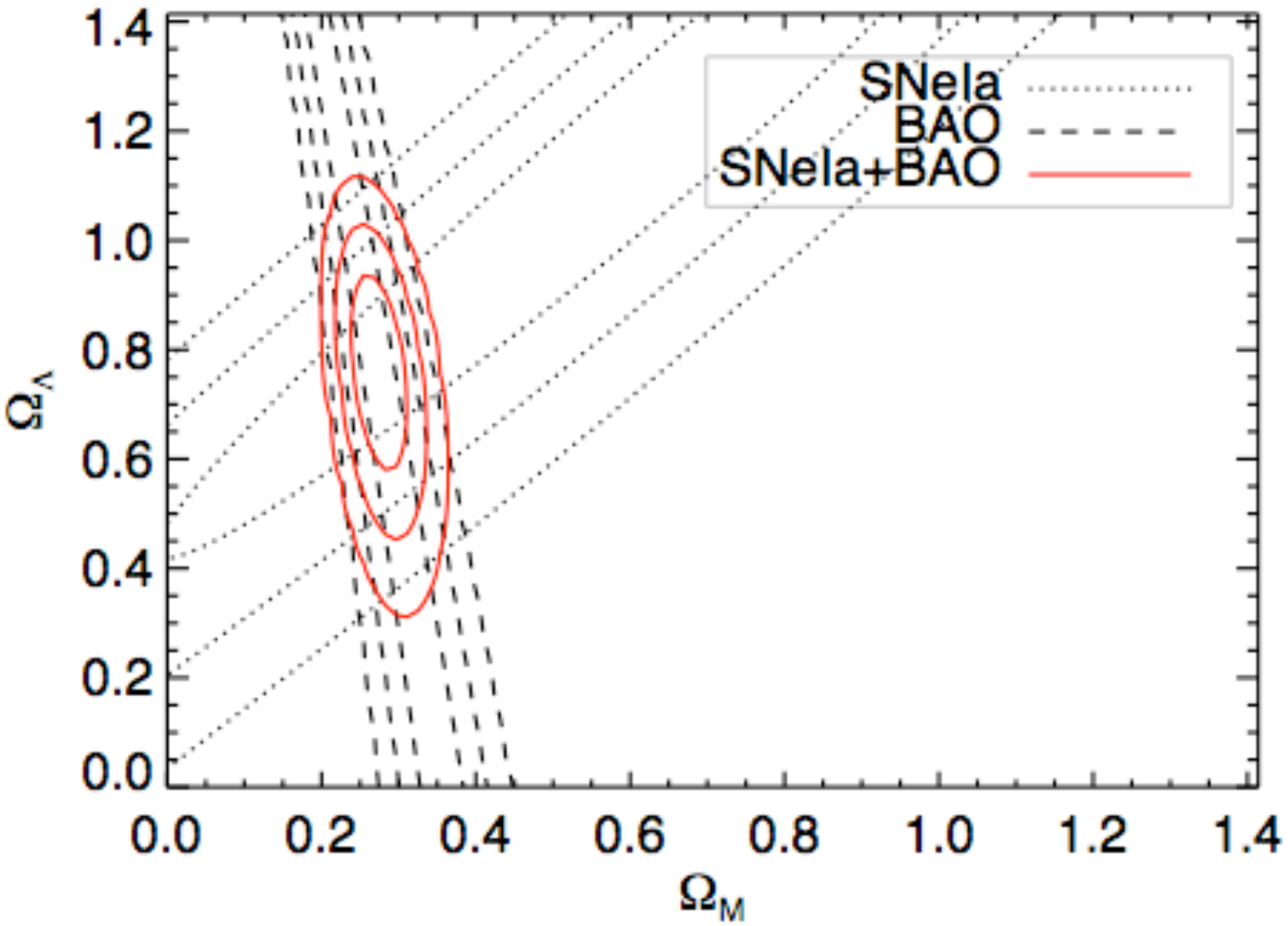
$\mu_0 = 42.25 \pm 0.20$

ESSENCE Hubble diagram

(Wood-Vasey et al. 2007, ApJ)

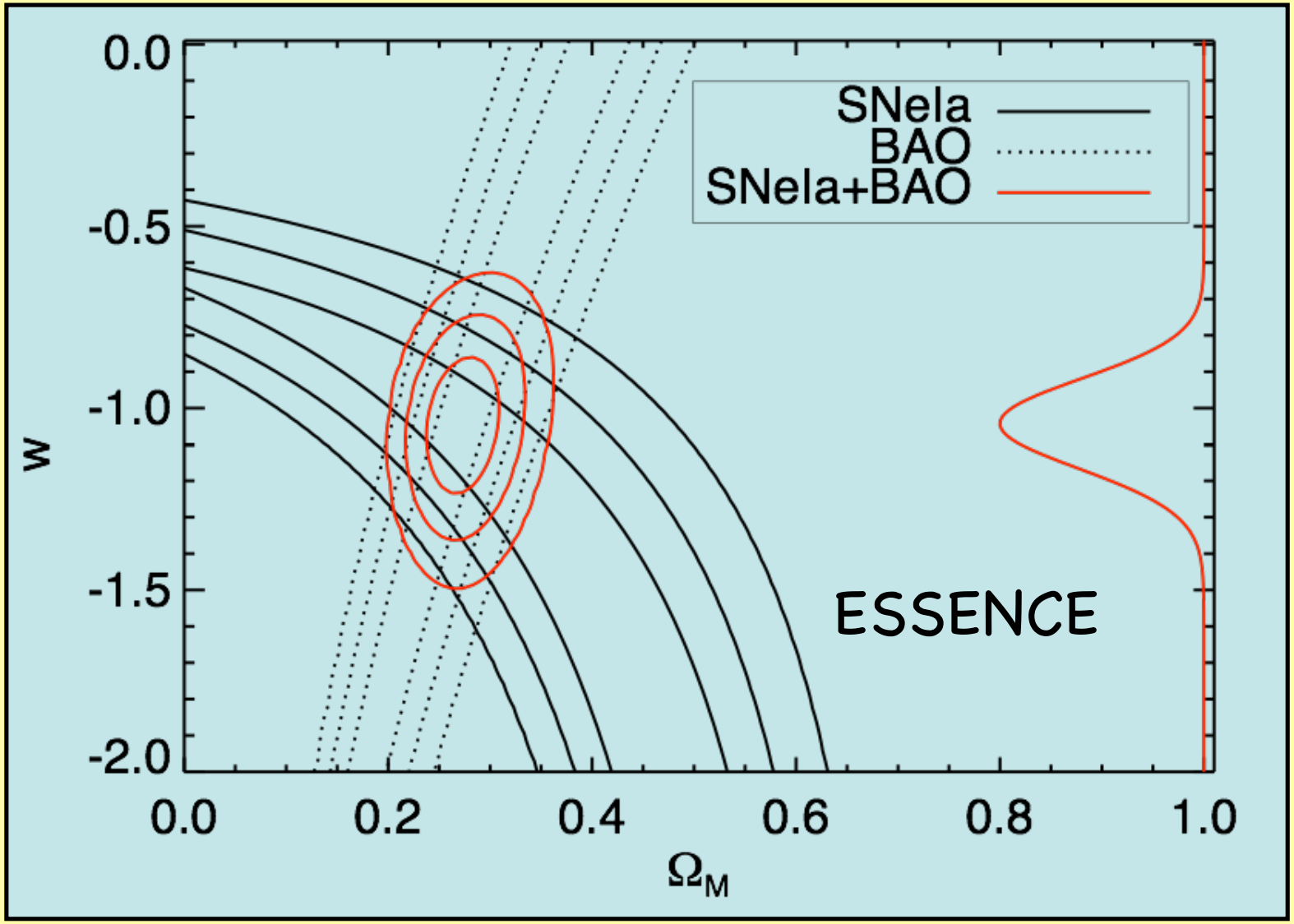
(For nearby SNe, see
Hamuy et al. 1996, AJ
Riess et al. 1999, AJ
Jha et al. 2006, AJ)




SNela
BAO
SNela+BAO
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Ω_Λ
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Ω_M

Flat, isotropic, constant-w

$w = -1.05 \pm 0.11 \pm 0.13$



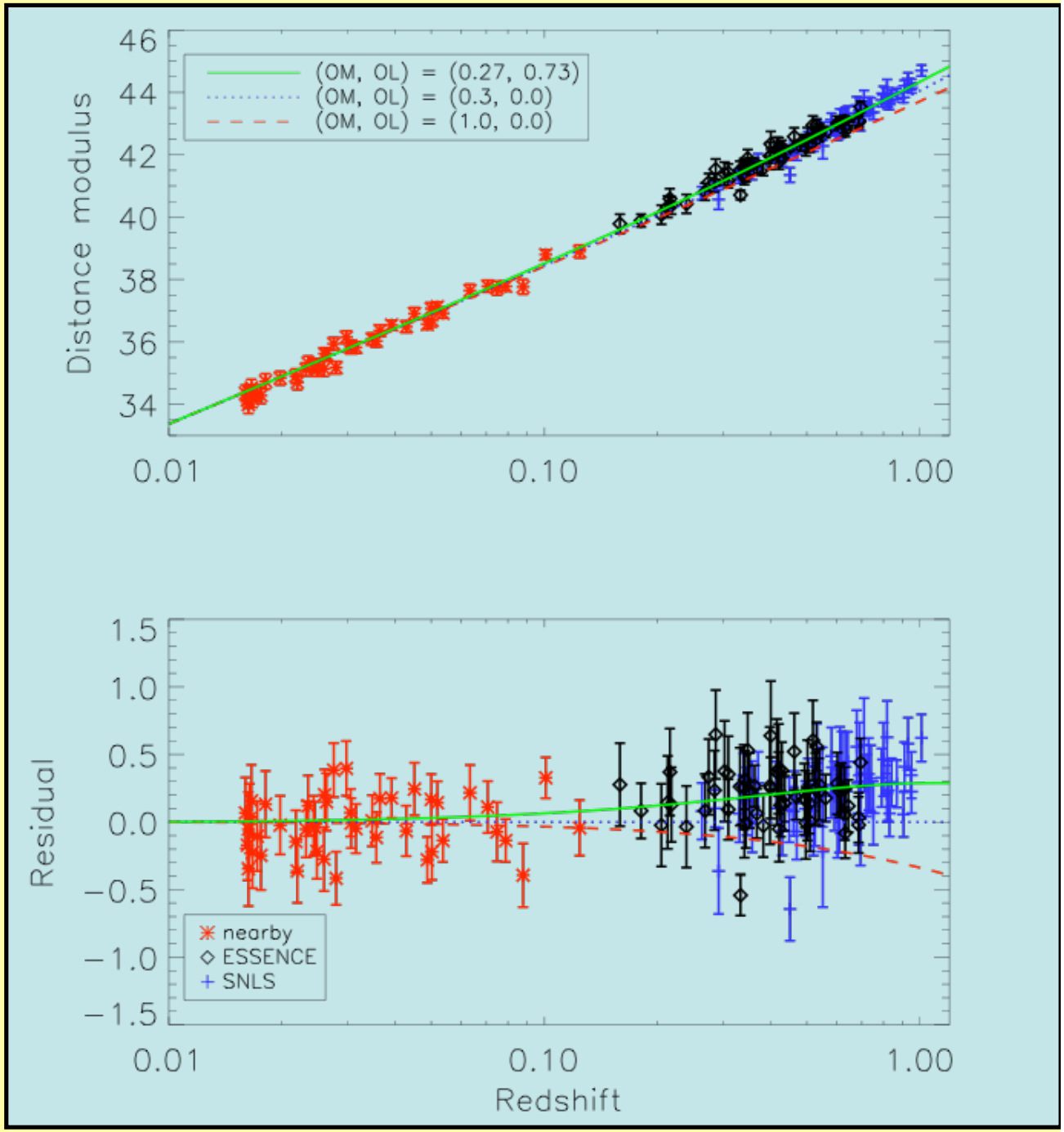
(Wood-Vasey et al. 2007, ApJ)

CFHT: SN Legacy Survey
(Astier et al. 2006)

ESSENCE +SNLS Hubble diagram

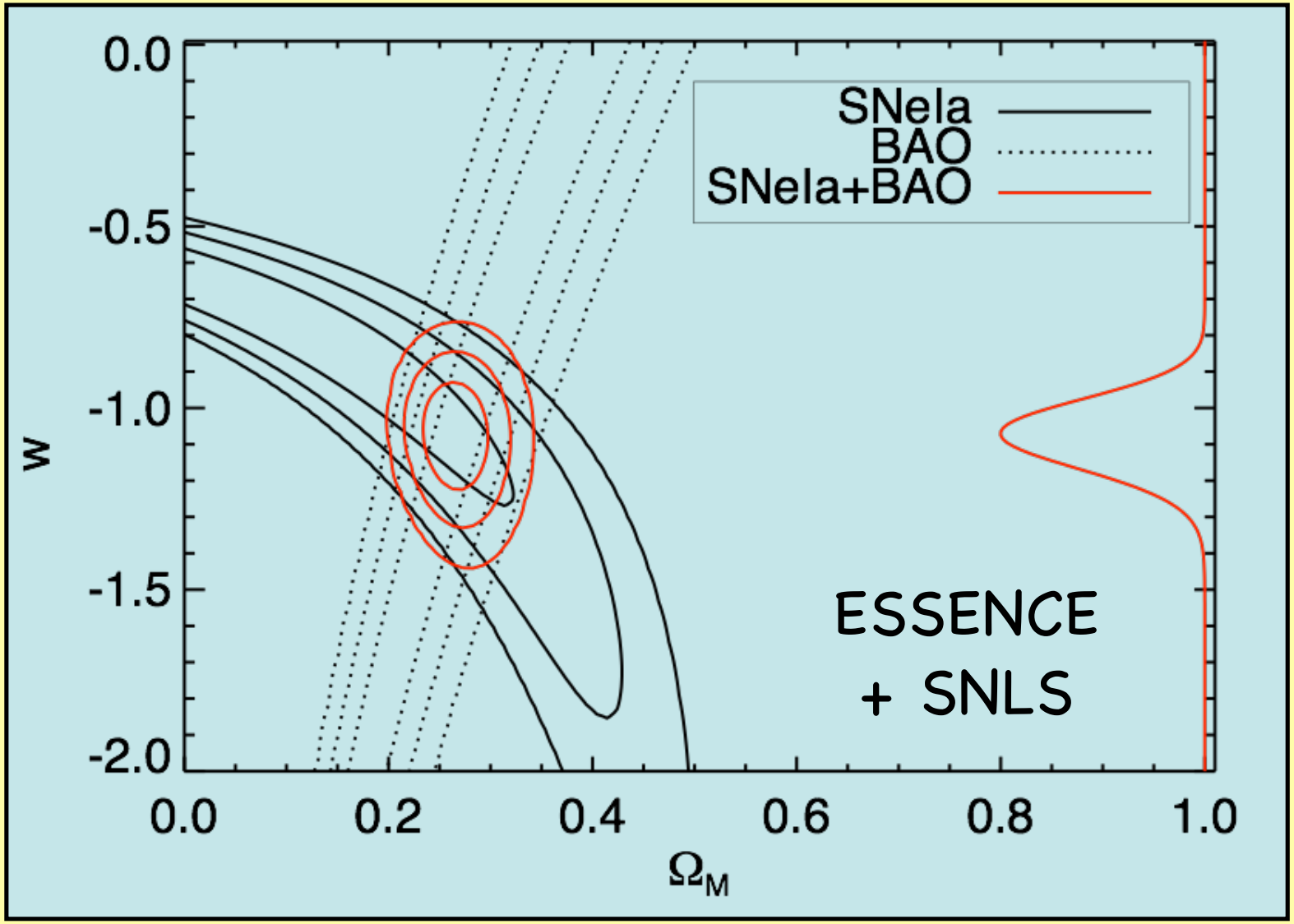
(Wood-Vasey et al. 2007; Astier et al. 2006)

(For nearby SNe, see Hamuy et al. 1996, AJ
Riess et al. 1999, AJ
Jha et al. 2006, AJ)



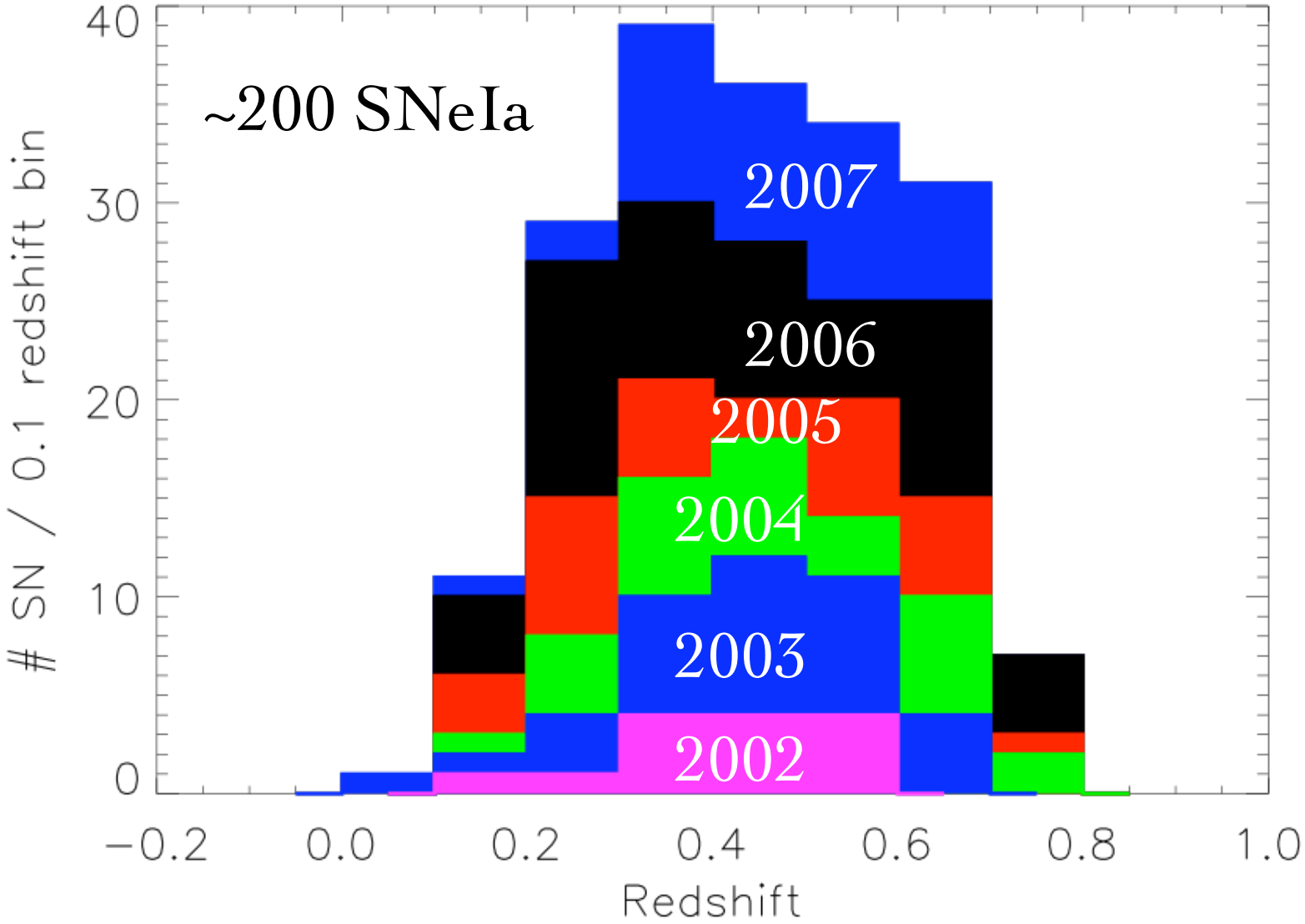
Flat, isotropic, constant-w

$w = -1.07 \pm 0.09 \pm 0.13$

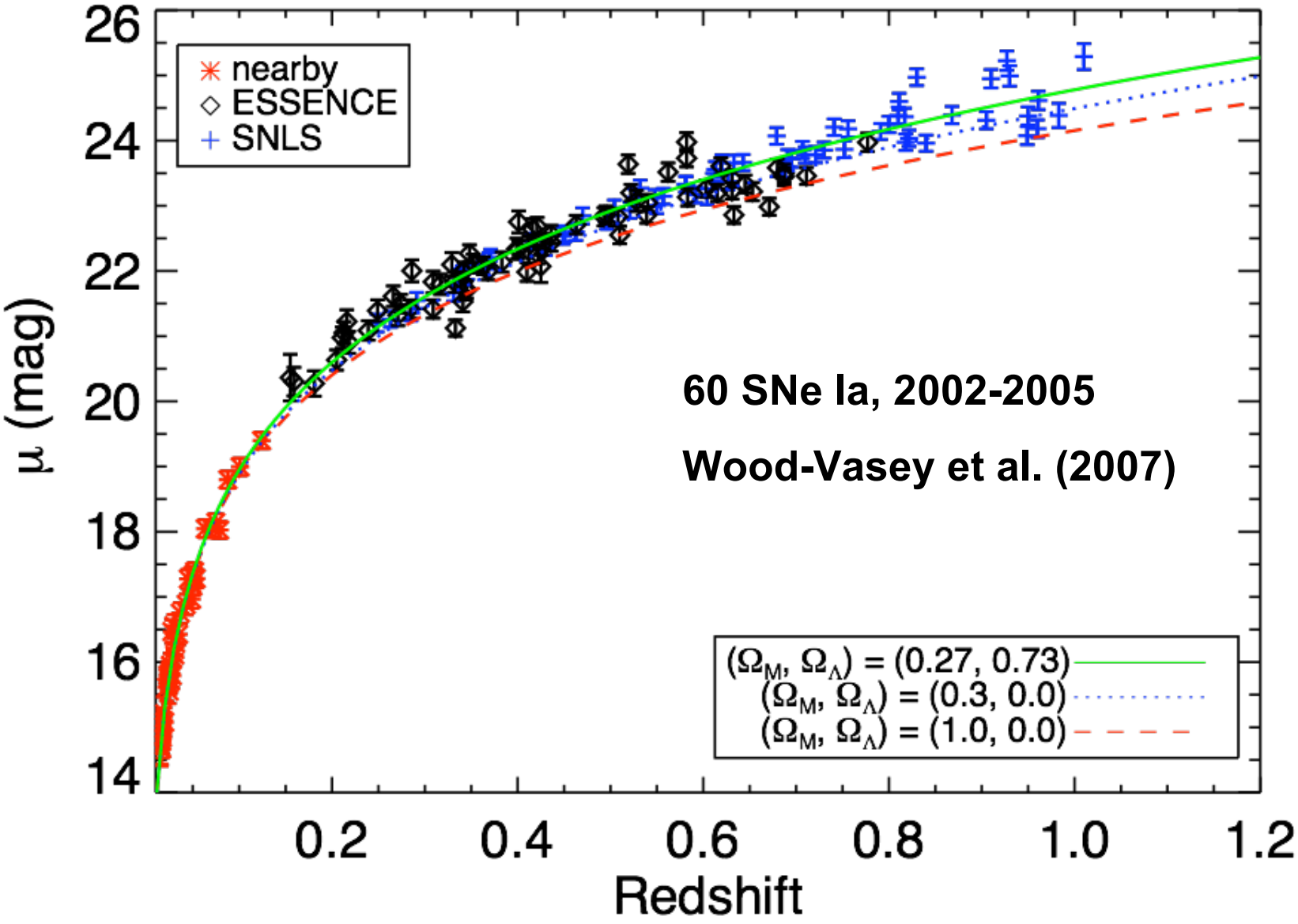


(Wood-Vasey et al. 2007, ApJ)

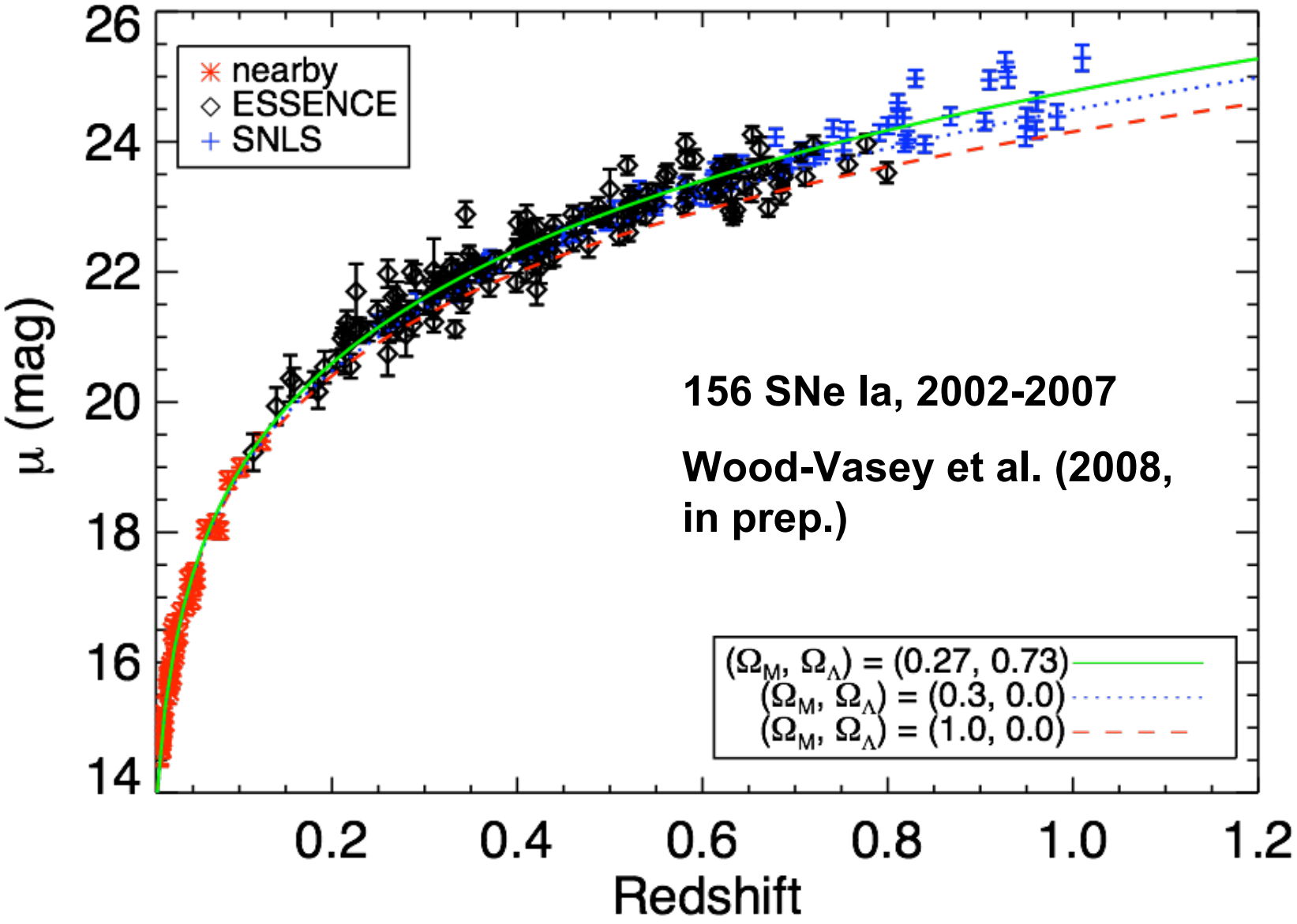
ESSENCE SNeIa From All 6 Years

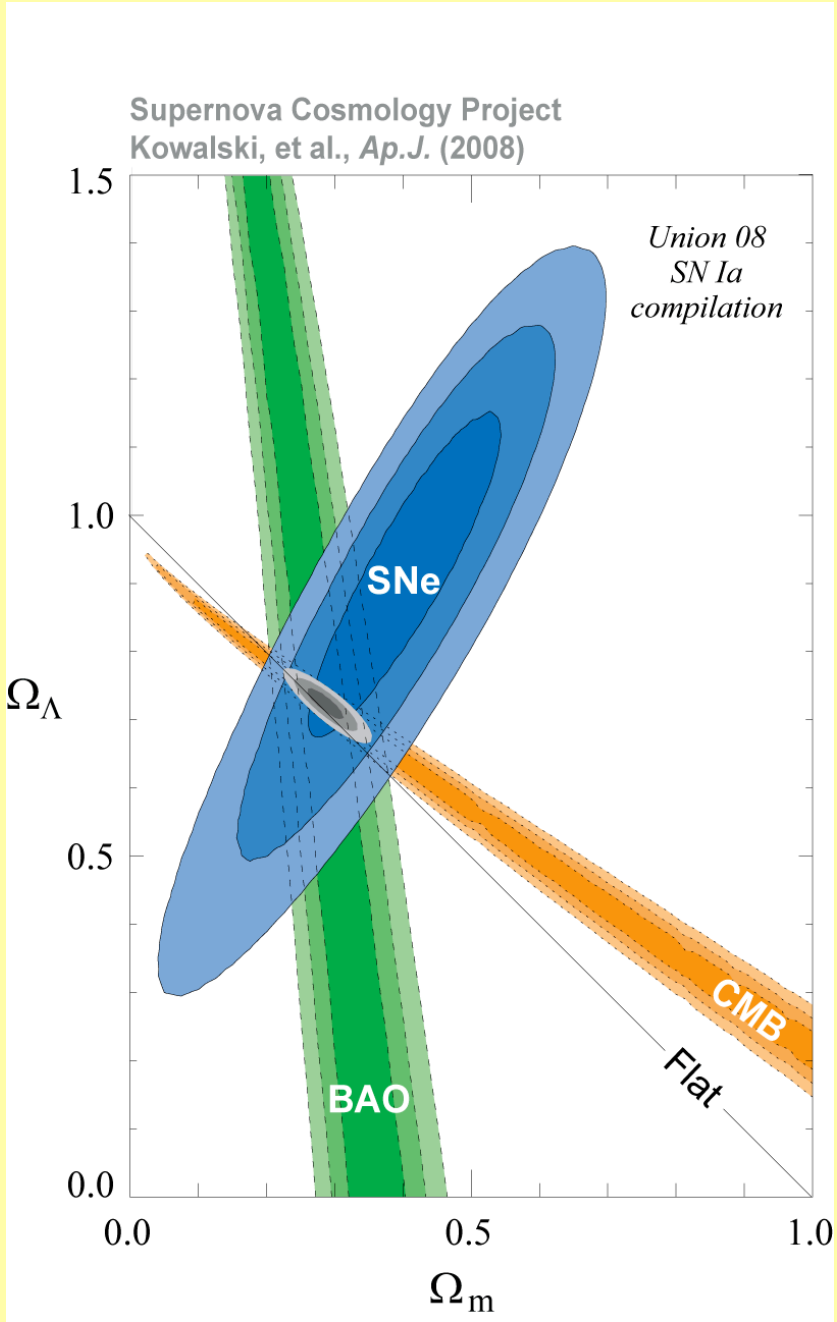


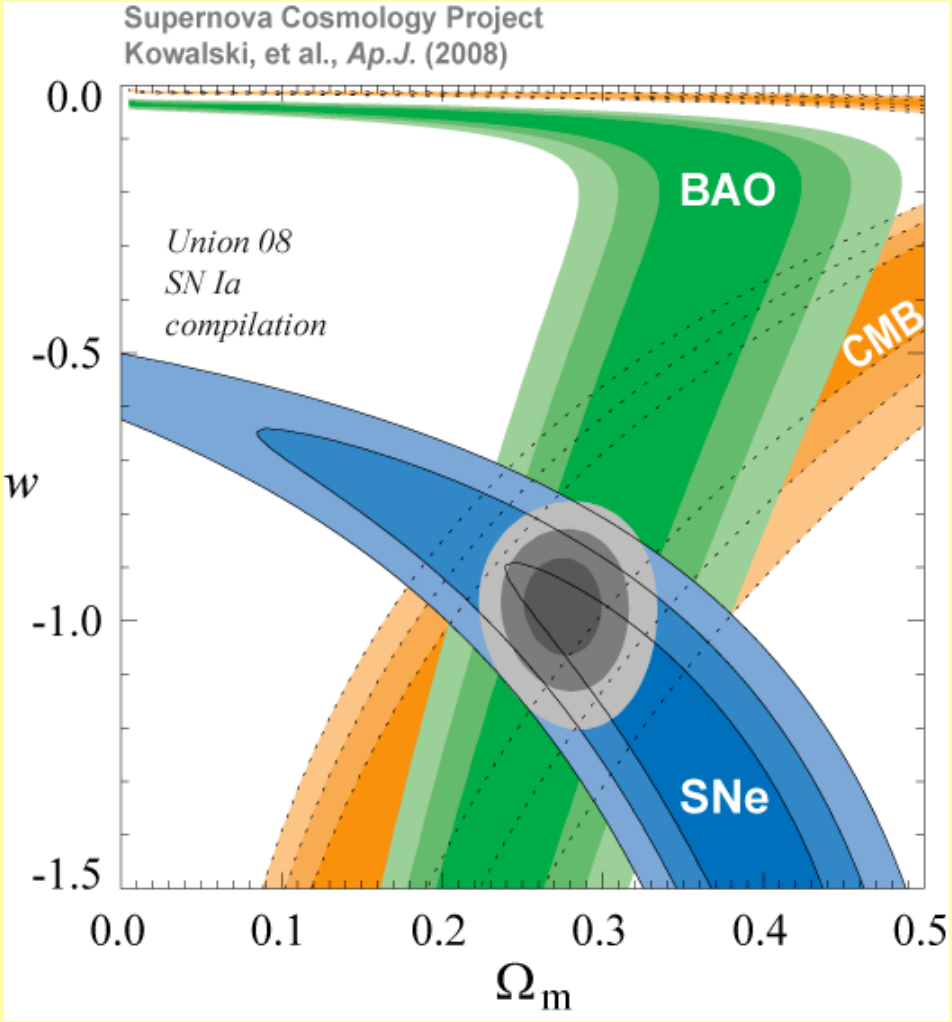
Previous ESSENCE Hubble Diagram



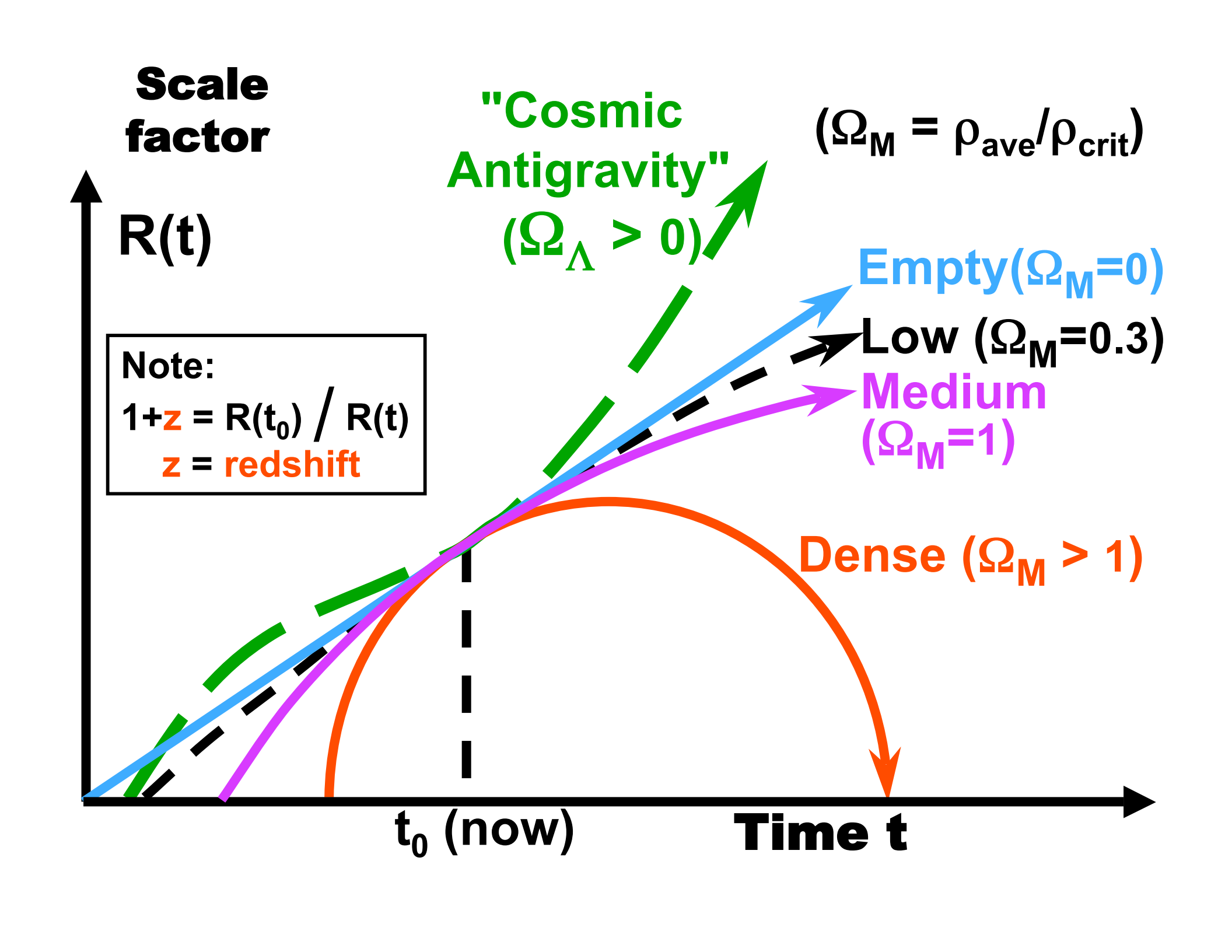
Preliminary Current ESSENCE Hubble Diagram




Supernova Cosmology Project
Kowalski, et al., Ap.J. (2008)
Union 08
SN Ia
compilation
SNe
BAO
CMB
Flat
1.5
1.0
0.5
0.0
0.0
0.5
1.0
Ω_Λ
Ω_m


Supernova Cosmology Project
Kowalski, et al., Ap.J. (2008)
Union 08
SN Ia
compilation
BAO
CMB
SNe
0.0
-0.5
-1.0
-1.5
w
0.0
0.1
0.2
0.3
0.4
0.5
Ωm

Probing the era of *deceleration*


Scale factor
R(t)
"Cosmic Antigravity"
($\Omega_\Lambda > 0$)
($\Omega_M = \rho_{ave}/\rho_{crit}$)
Empty(Ω_M=0)
Low (Ω_M=0.3)
Medium
(Ω_M=1)
Dense ($\Omega_M > 1$)
Note:
1+z = $R(t_0)$ / R(t)
z = redshift
t_0 (now)
Time t

Cycle 11: GOODS ACS Treasury Program and

The Hubble Higher-z Supernova Search Team

"A Higher-z Supernova Search Piggybacking on the ACS Survey"

Riess (STScI)
Strolger (STScI)
Tonry (UH)
Filippenko (UCB)
Kirshner (CfA)
Challis (CfA)
Casertano (STScI)
Dickinson (STScI)
Giavalisco (STScI)
Ferguson (STScI)

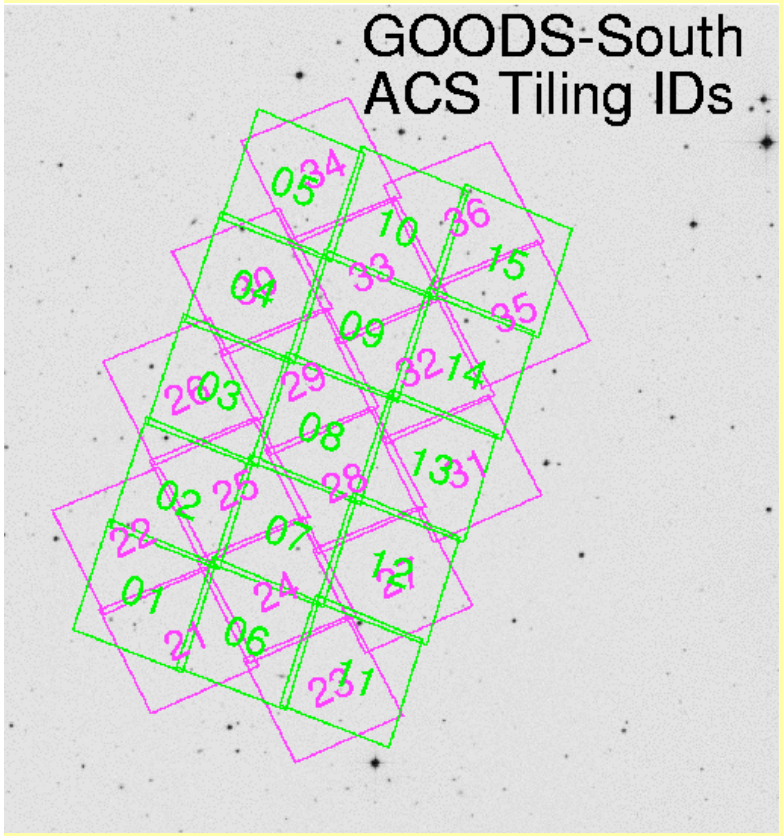
134 orbits ToO for 6-8 SNe Ia at 1.2<z<1.8

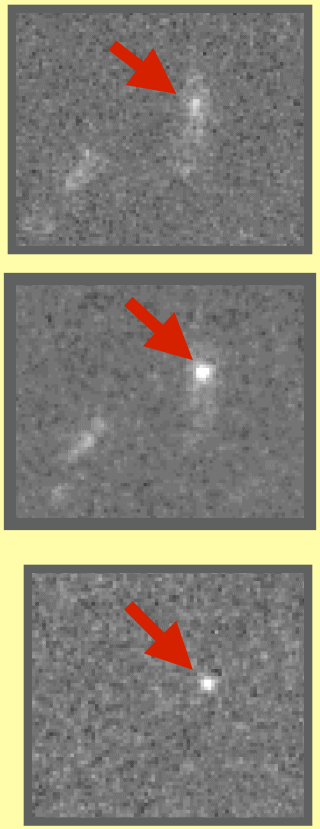
399 orbits of deep imaging for extragalactic studies

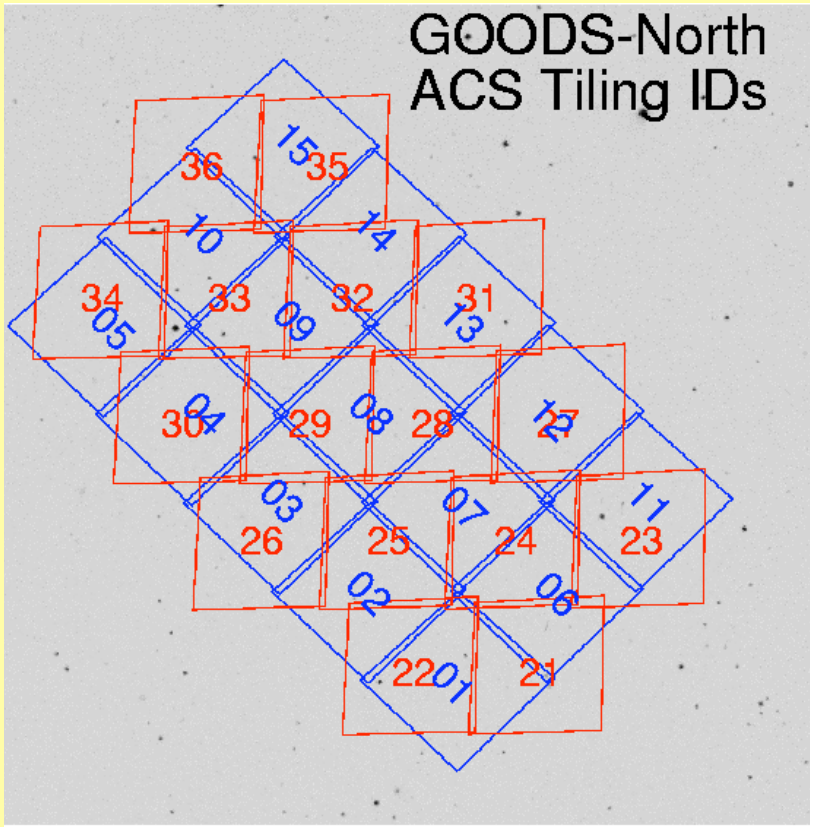
Searching for SN Ia with ACS

5 z-band epochs, spaced by 45 days;
simultaneous v,i band; 120 tiles

CDFS=08/02-02/03 **HDFN=11/02-05/03**

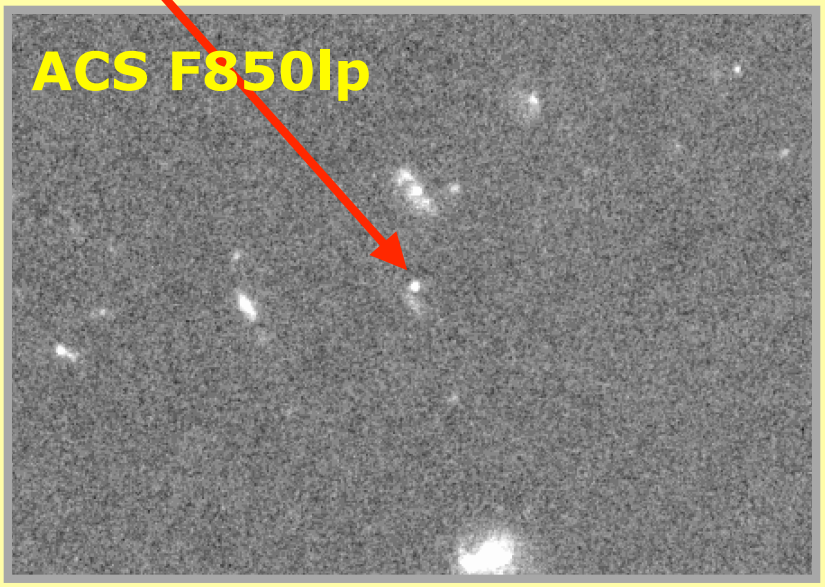


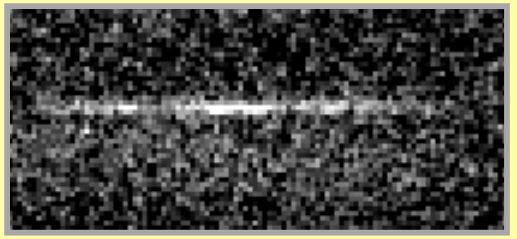




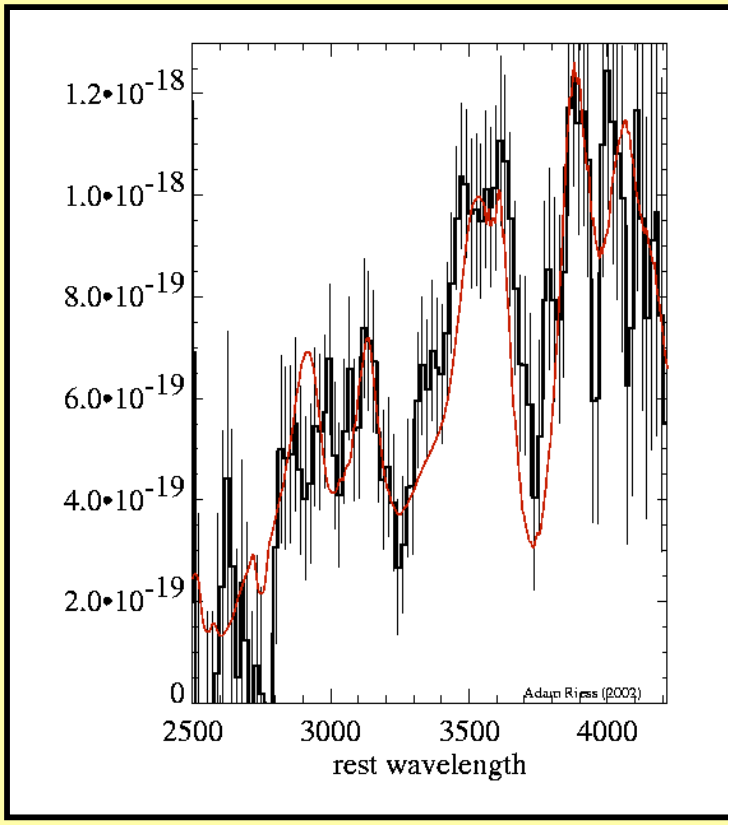
Our first higher-z SN Ia, Aphrodite

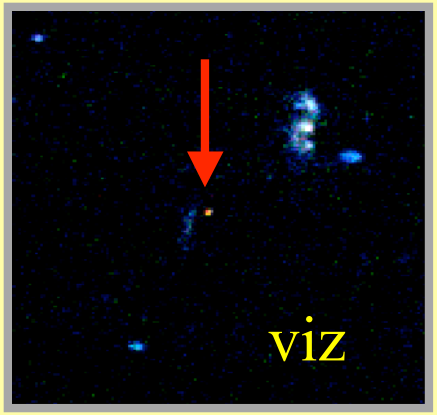
Aphrodite (1<z<1.5)

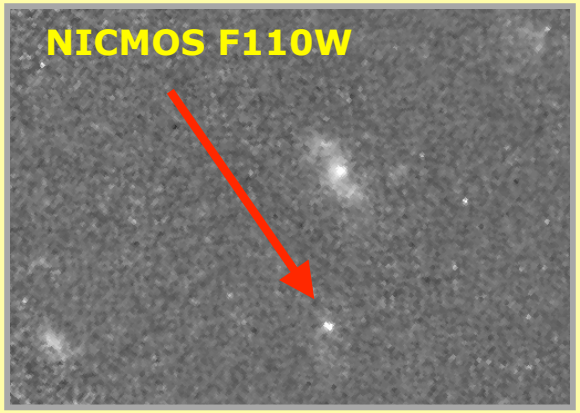




ACS grism spectrum

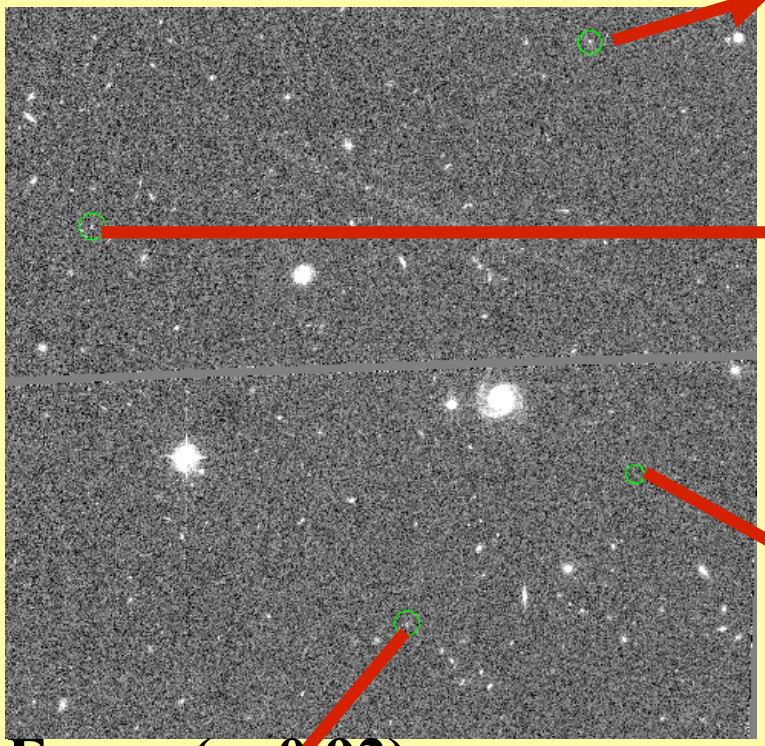






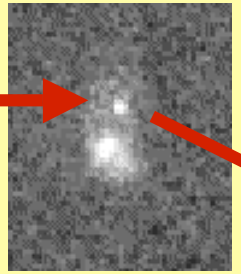
Rich Field of 4 SN Ia

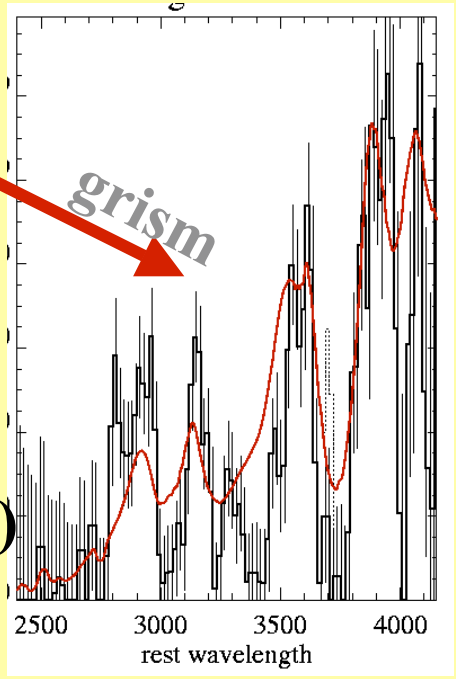
HDFN, tile n4z_26/29



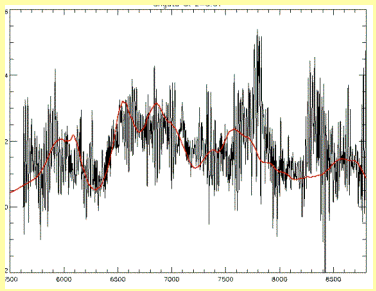
Vilas (z=0.86)

Borg (z=1.37)

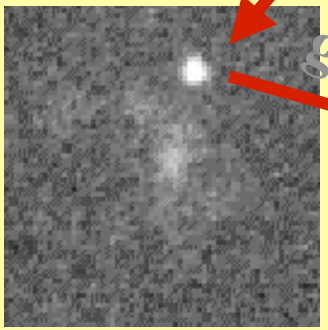


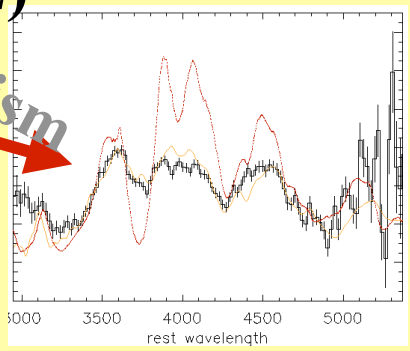


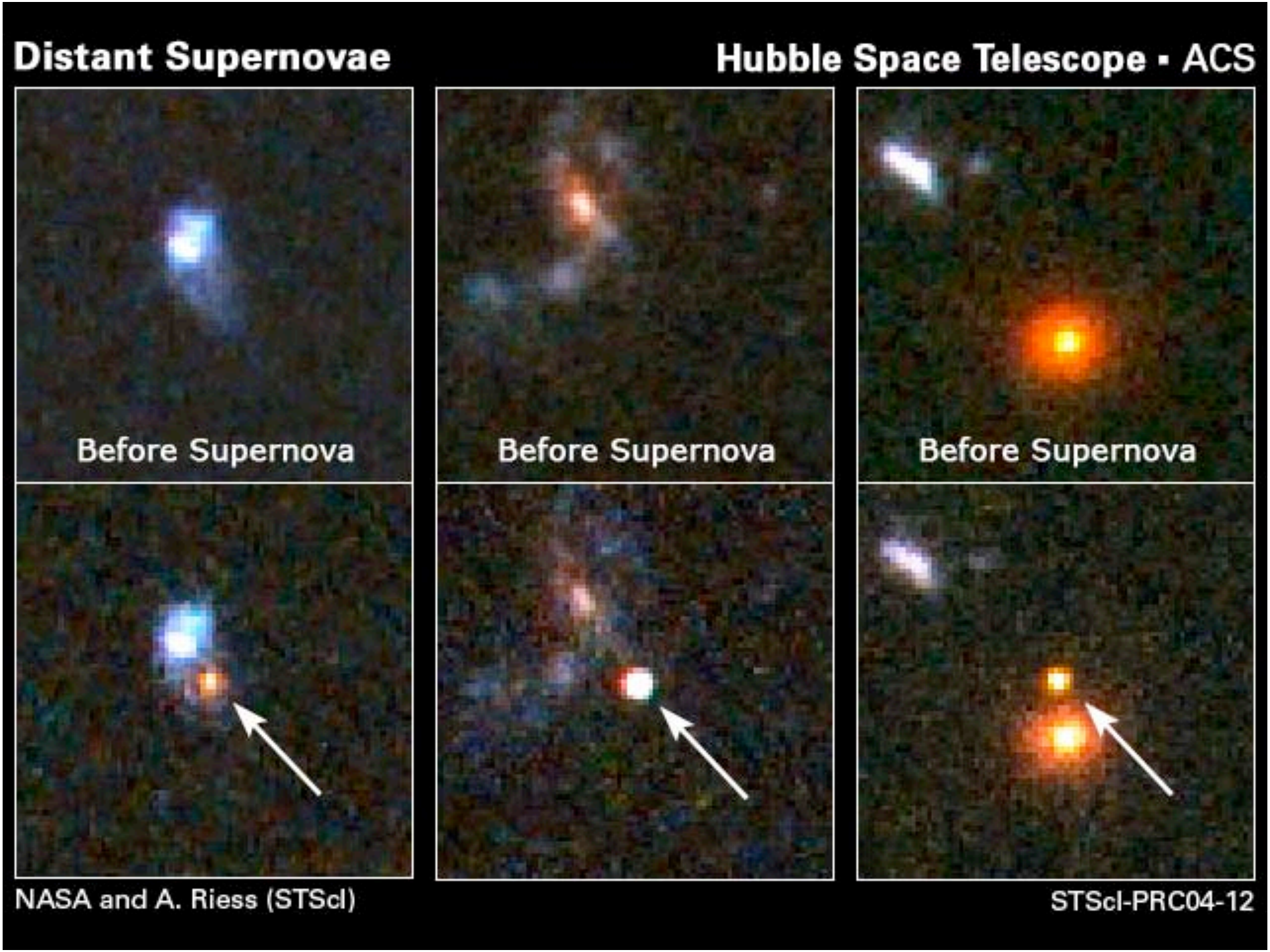
Anguta (z=0.67)



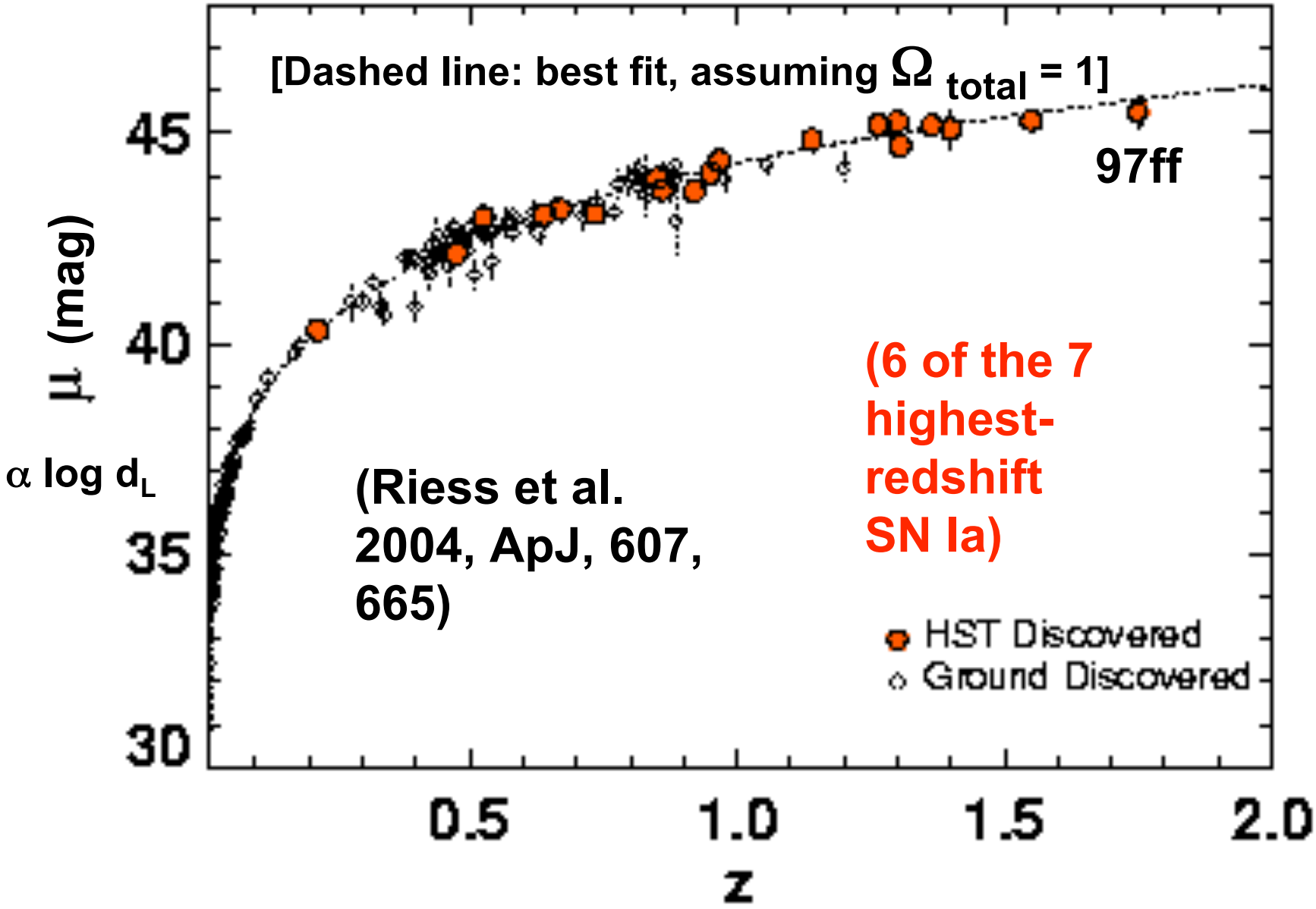
McEnroe (z=0.92)



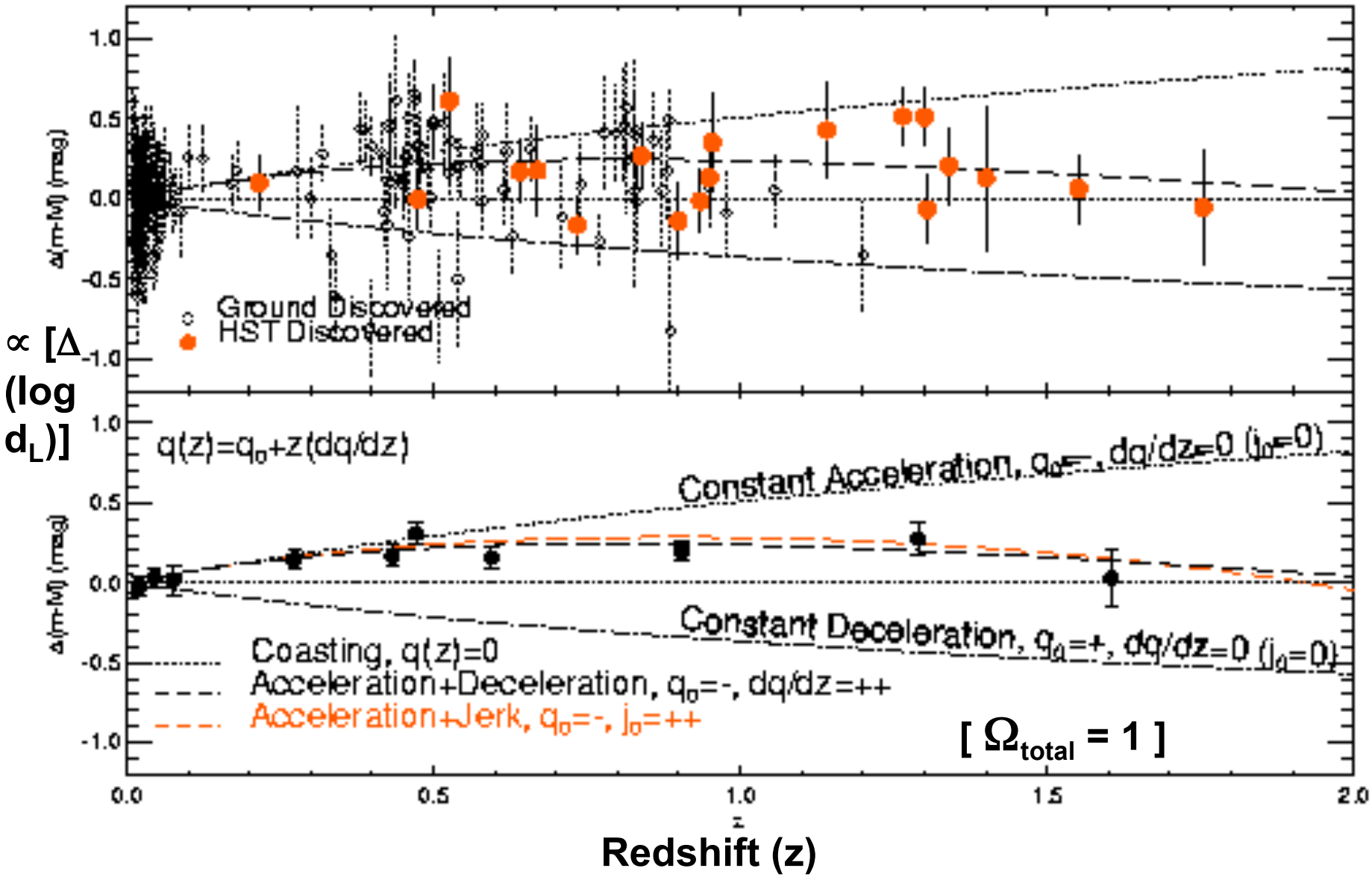



Distant Supernovae
Hubble Space Telescope • ACS
Before Supernova
Before Supernova
Before Supernova
NASA and A. Riess (STScI)
STScI-PRC04-12

SN Ia Hubble Diagram



Residual Hubble Diagram (Riess et al. 2004, ApJ, 607, 665)



$\propto [\Delta(\log d_L)]$

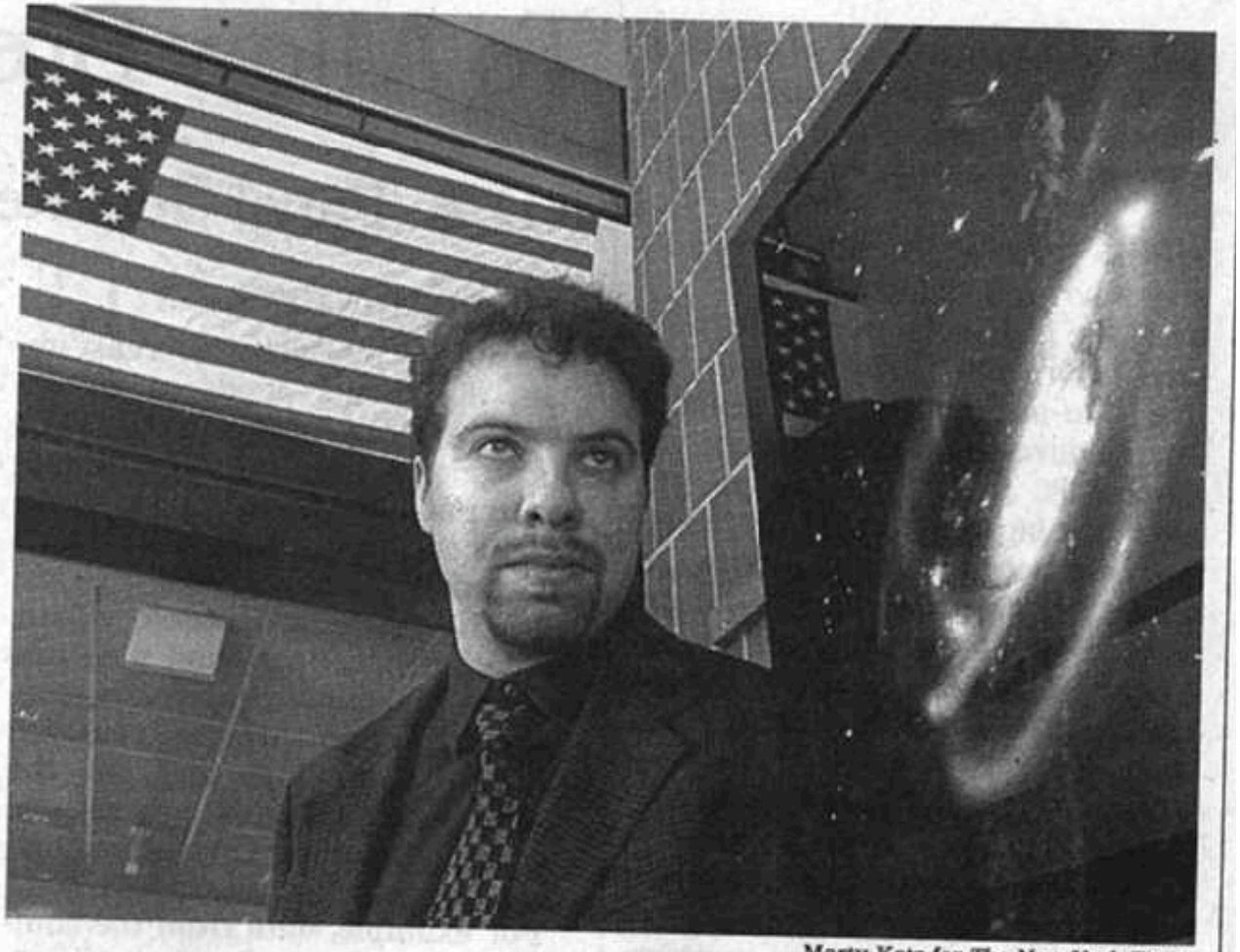
A 'Cosmic Jerk' That Reversed the Universe

By DENNIS OVERBYE

CLEVELAND, Oct. 10 — Astronomers said on Friday that they had determined the time in cosmic history when a mysterious force, "dark energy," began to wrench the universe apart.

Five billion years ago, said Dr. Adam Riess, an astronomer at the Space Telescope Science Institute in Baltimore, the universe experienced a "cosmic jerk." Before then, Dr. Riess said, the combined gravity of the galaxies and everything else in the cosmos was resisting the expansion, slowing it down. Since the jerk, though, the universe has been speeding up.

The results were based on observations by a multinational team of astronomers who used the Hubble Space Telescope to search exploding stars known as Type 1a supernovas, reaching back in time three-quarters of the way to the Big Bang, in which the universe was born. The results should help quell remaining doubts that the expansion of the universe is

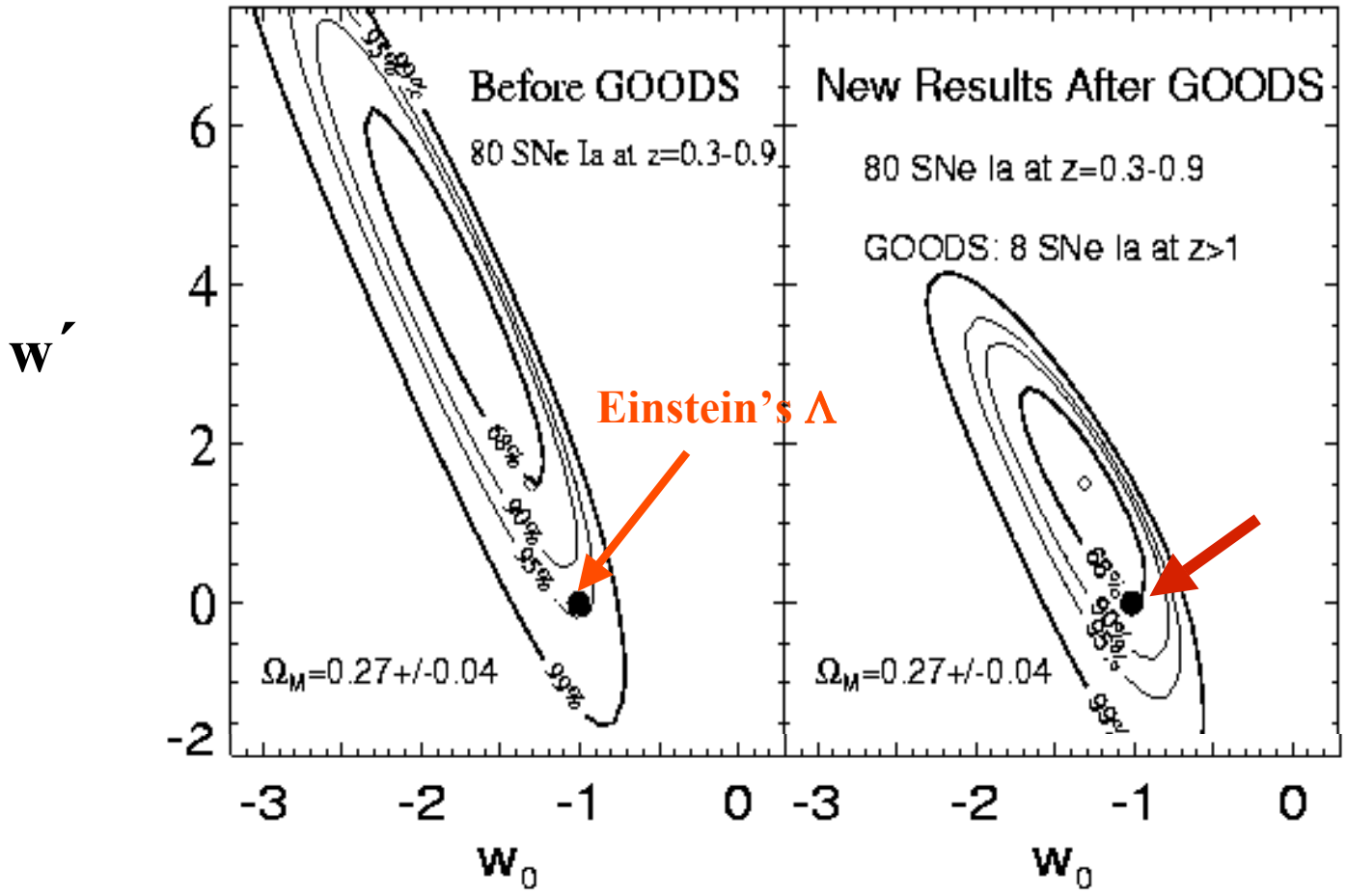


Marty Katz for The New York Times

Dr. Adam Riess, who reported yesterday on the speeding and expanding universe, at the Space Telescope Science Institute in Baltimore.

Probing Dark Energy (Riess et al. 2004)

Two clues to the nature of dark energy: strength now (w_0), and whether it is static or dynamic (is dw/dz = w′ = 0?).



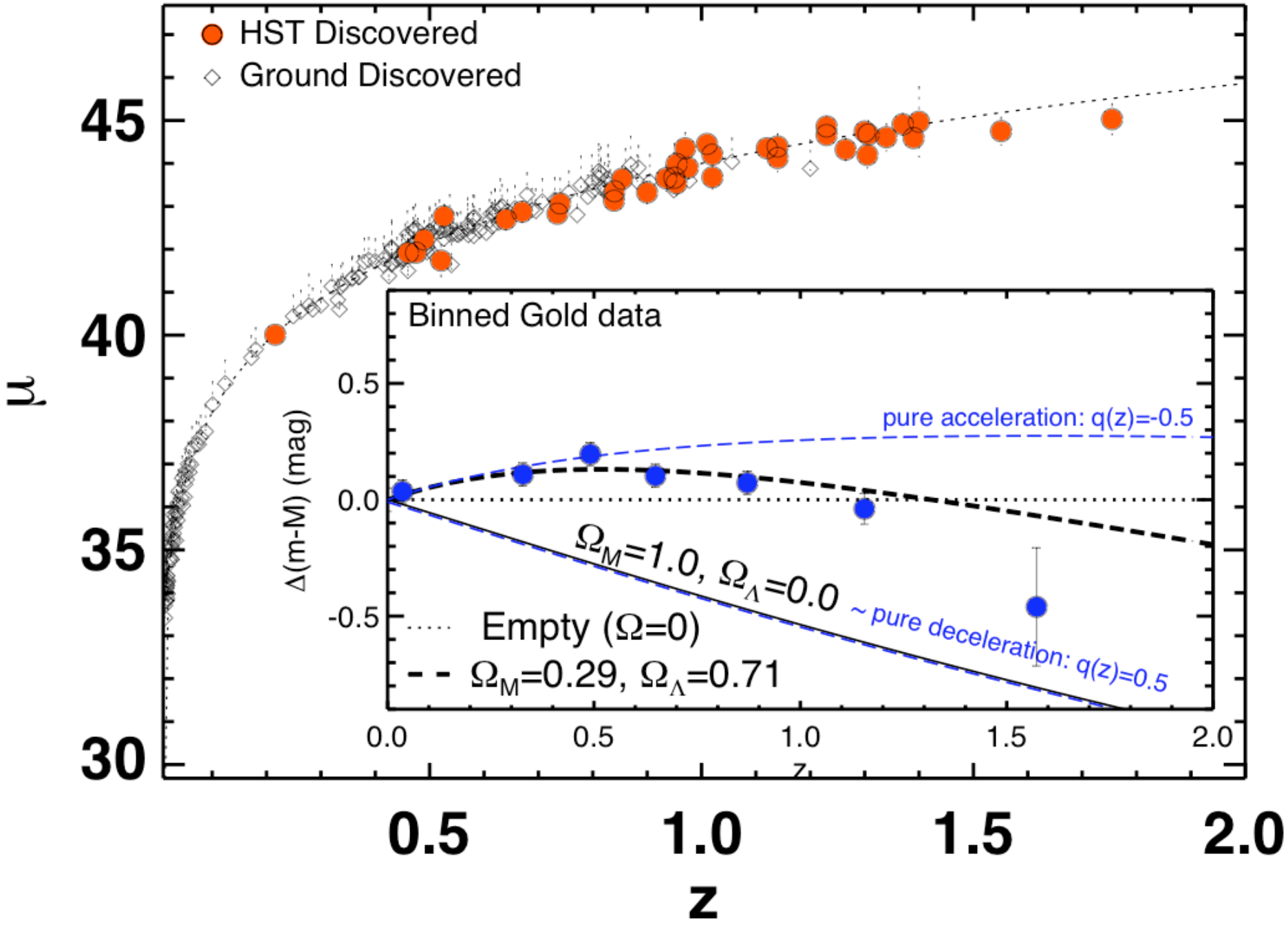
We doubled our knowledge of w_0 and w′ in 1 year with HST; Λ looks better than ever, but still uncertain.

PANS: Probing Acceleration *Now* with Supernovae

Awarded 270 orbits in Cycle 13 with HST.
Found >20 SNe Ia at z > 0.8.

Most recent results (Riess et al. 2007, ApJ, 659, 98 -- April)

We found and studied 19 of the 20 highest redshift SNe Ia known.


HST Discovered
Ground Discovered
μ
45
40
35
30
0.5
1.0
1.5
2.0
z
Binned Gold data
Δ(m-M) (mag)
0.5
0.0
-0.5
pure acceleration: q(z)=-0.5
Ω_M=1.0, Ω_Λ=0.0
~ pure deceleration: q(z)=0.5
Empty (Ω=0)
Ω_M=0.29, Ω_Λ=0.71
0.0
0.5
1.0
1.5
2.0
z

Detect dark energy at $z > 0.7$

Dark energy affected the expansion of the Universe even during the first 9 Gyr, when he Universe was still decelerating.

Data remain consistent with $w' = 0$ (e.g., cosmological const.)

Joint Dark Energy Mission (JDEM) ~2015?

Studying the dark energy of the Universe…

Systematic effects:
we will need to
control them to ~1%

HST (2.4 m) should continue to find SNe Ia at z > 1, for at least a few more years.

Summary & Future

- The State of LCDM is Strong
- Tackle Extinction vs. Intrinsic Color
  - UV - Optical - NIR data
- More nearby SNeIa: +300 from KAIT, CSP, CfA
- SDSS-II, ESSENCE, SNLS joint analysis
- Pan-STARRS1, Dark Energy Survey, LSST
- JDEM with supernovae