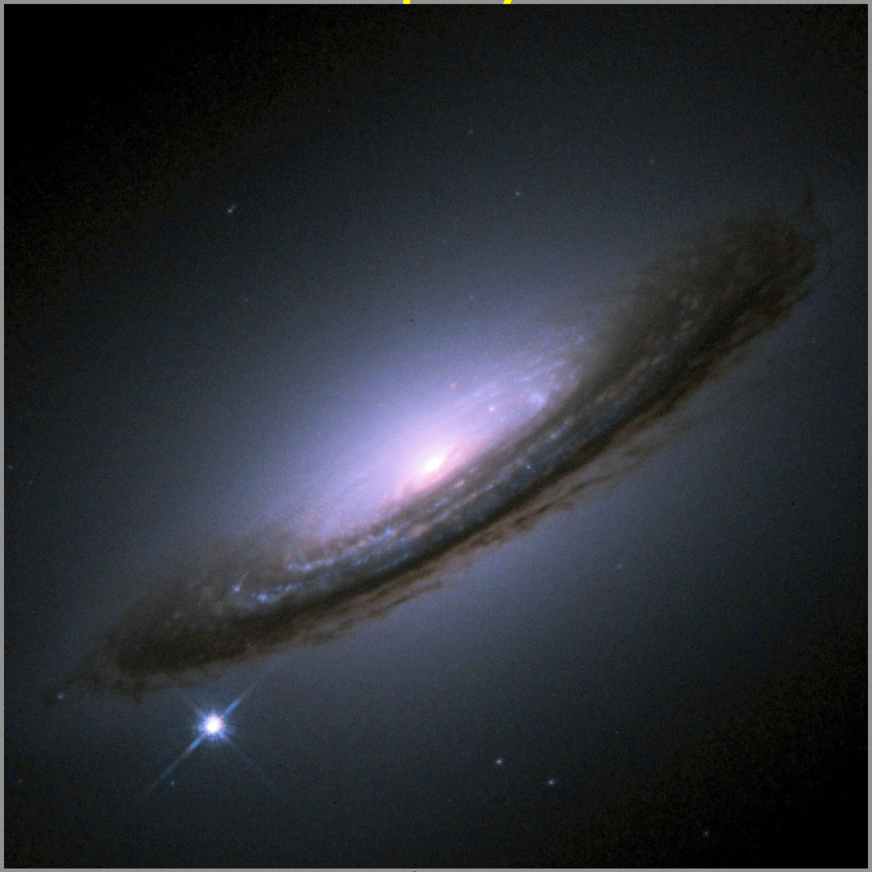
Bright Stars, Dark Energy

Robert P. Kirshner
Harvard-Smithsonian Center for Astrophysics



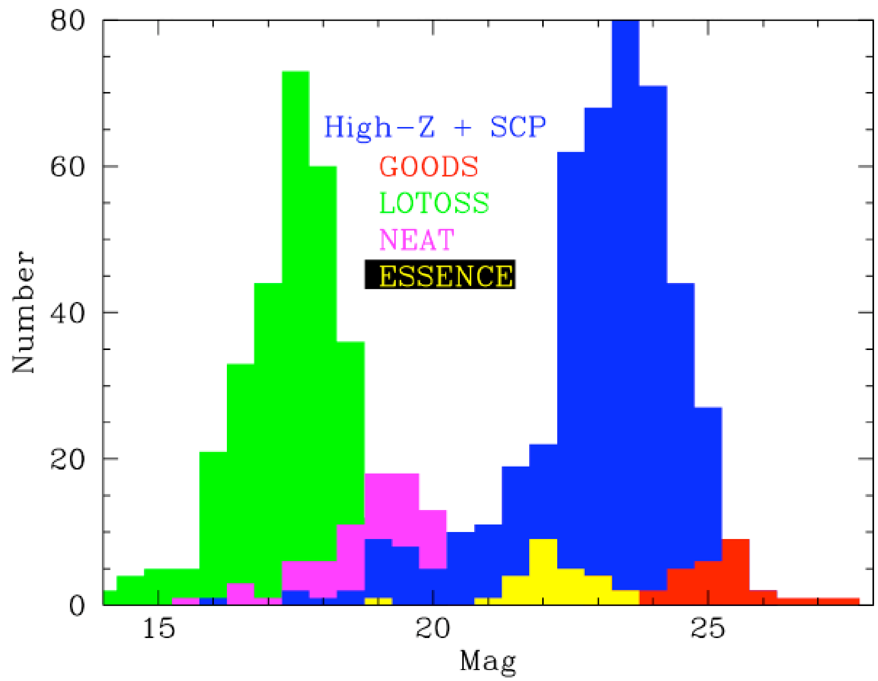
Type Ia supernova $\sim 4 \times 10^9$ Suns

~1 SNIa /century

Le

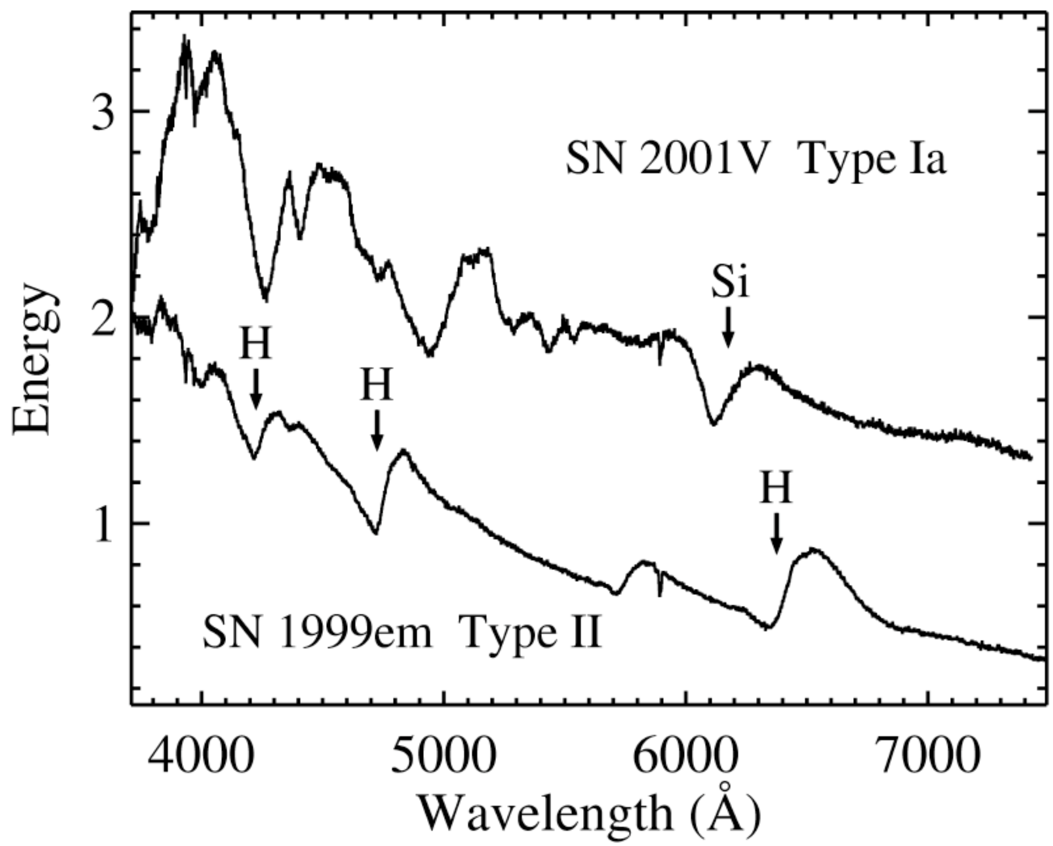
The KAIT Search

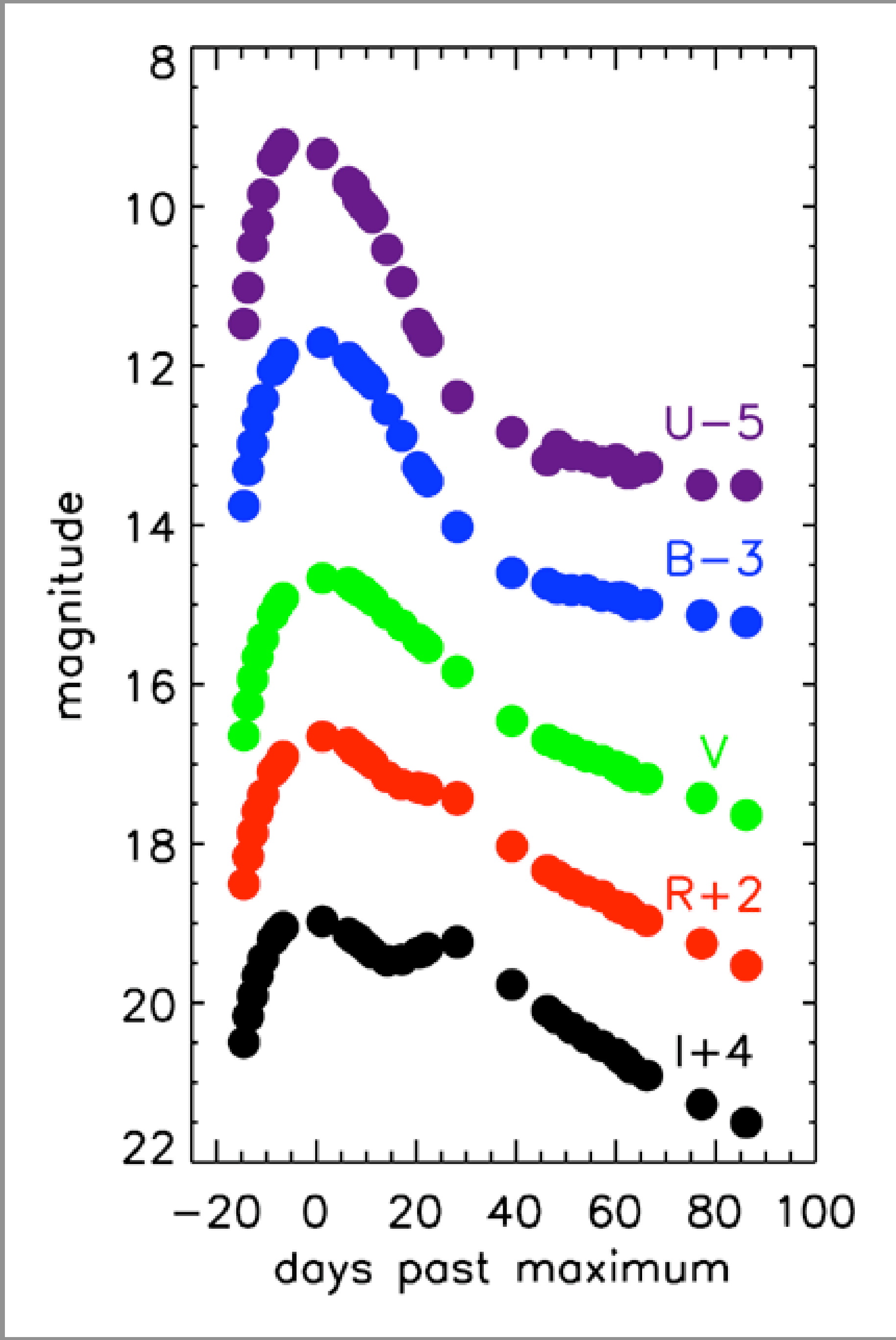
Supernova Discoveries



F.L. Whipple Observatory: Following up

Determining the Type





Light Curves: Clues to Luminosity

Mark Phillips

Mario Hamuy

Adam Riess

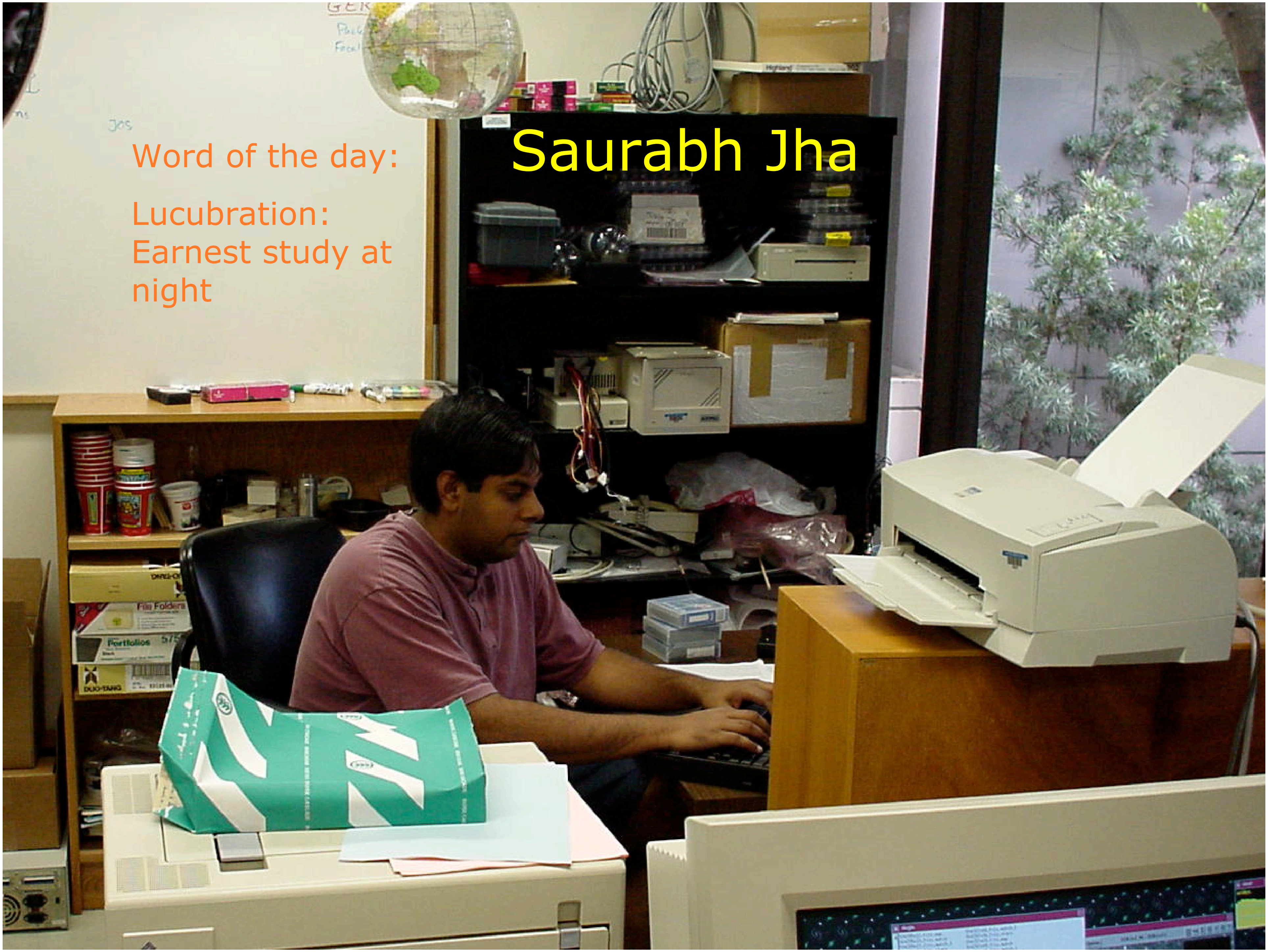
Saurabh Jha

Perlmutter & Co.

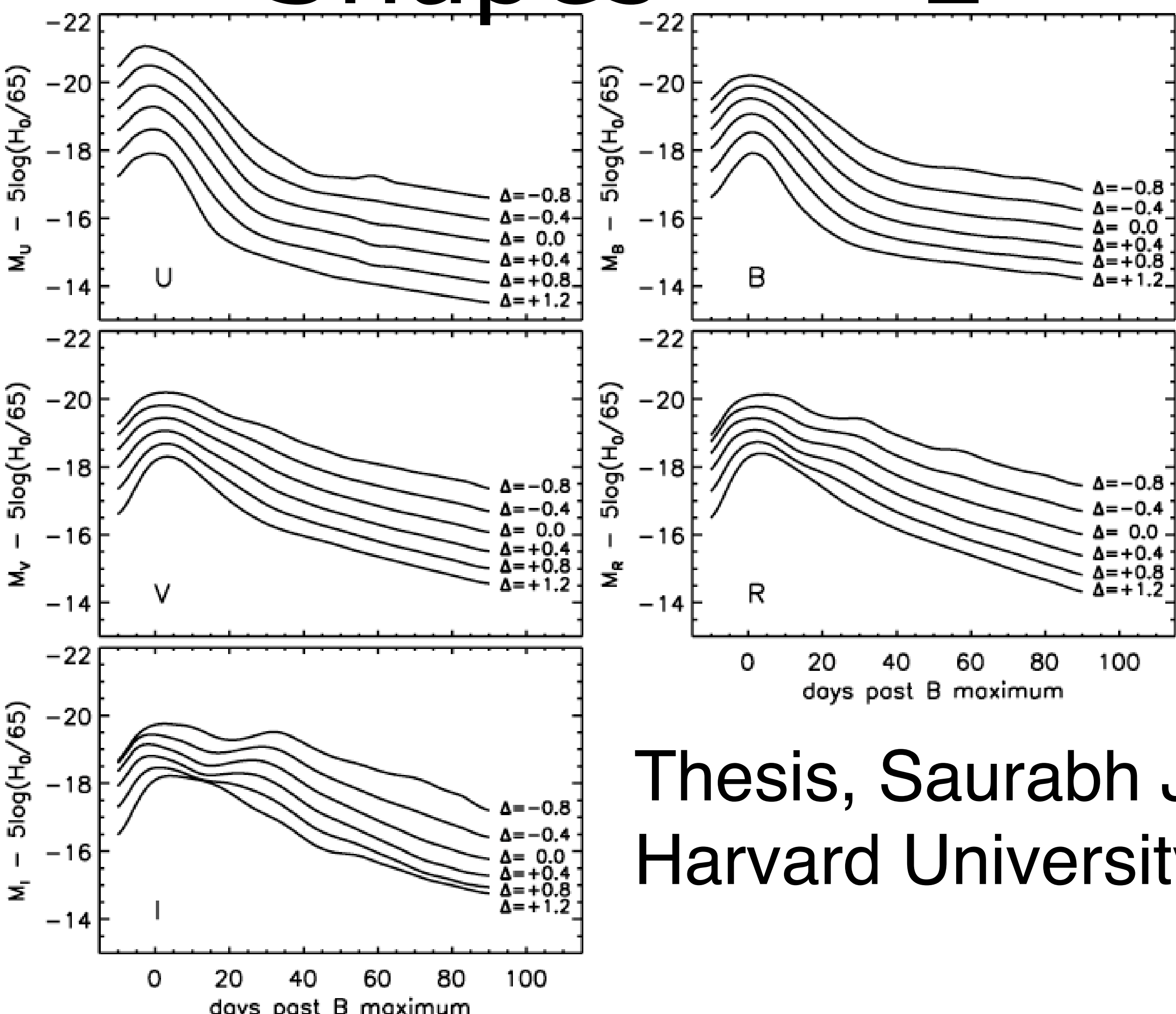
Saurabh Jha

Word of the day:

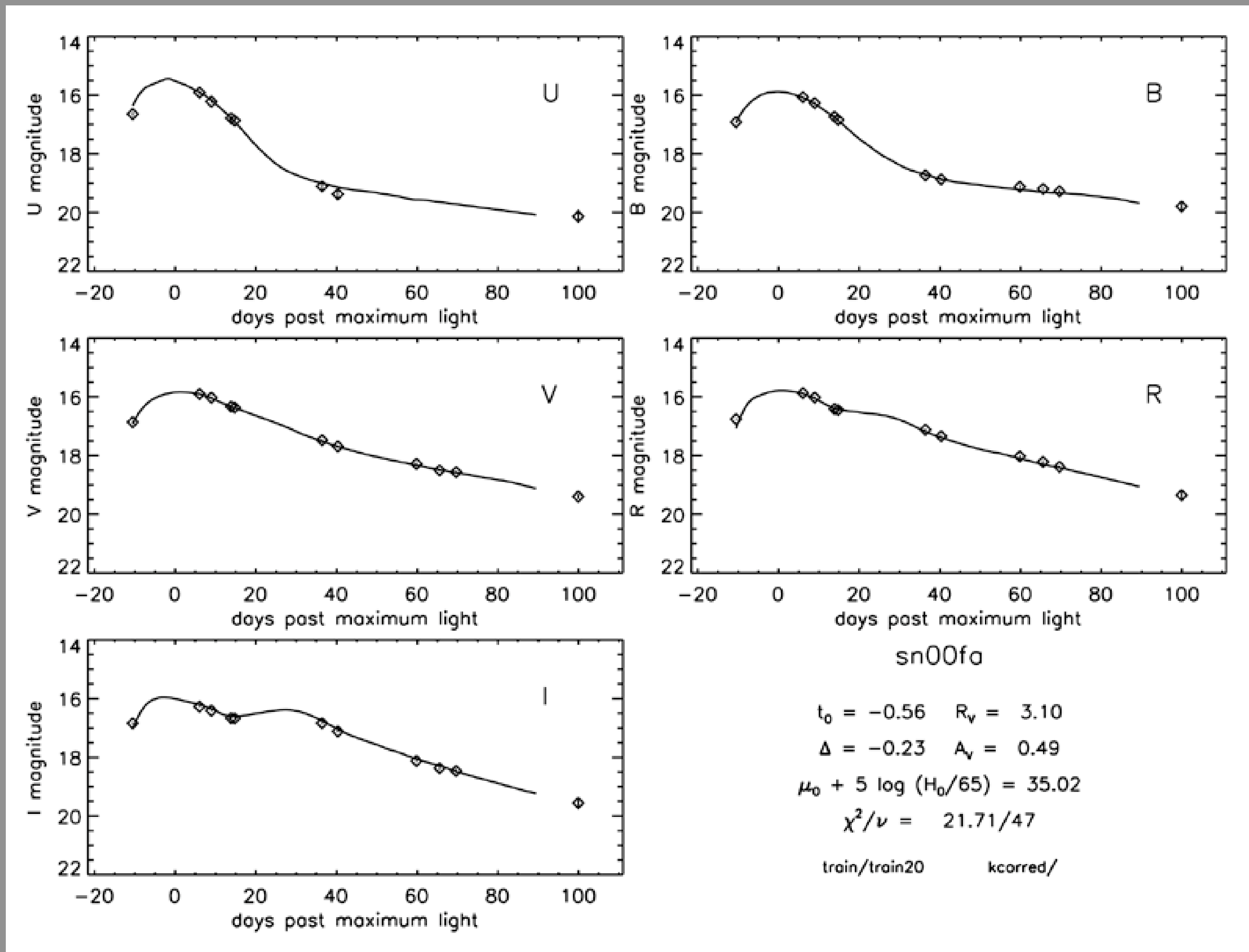
Lucubration: Earnest study at night

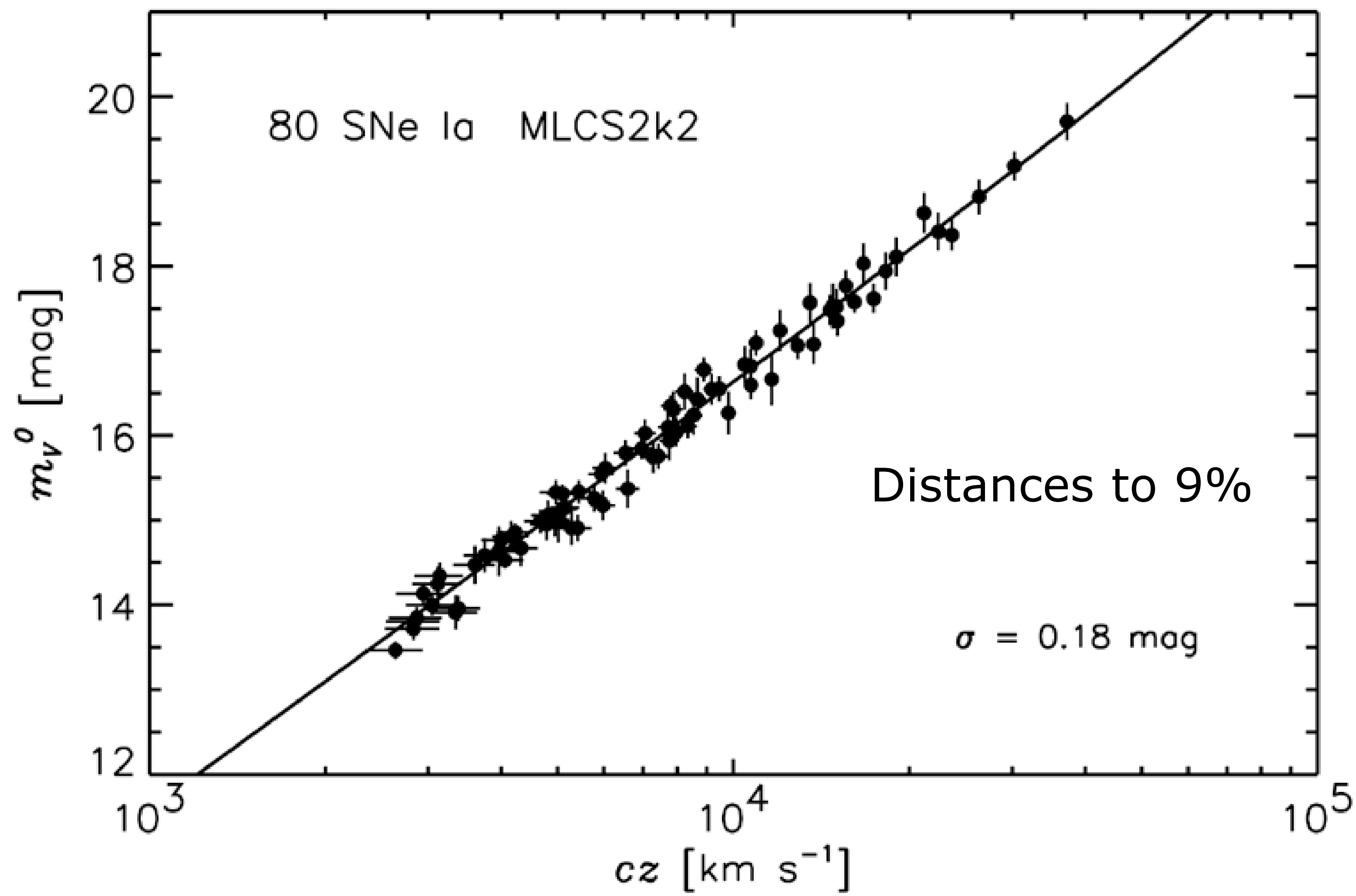


Light Curve Shapes => L



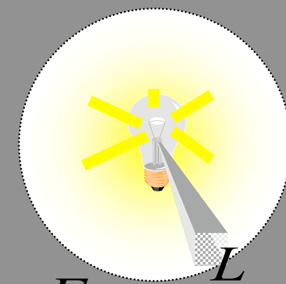
Thesis, Saurabh Jha, Harvard University


U magnitude
U
B magnitude
B
V magnitude
V
R magnitude
R
I magnitude
I
days past maximum light
sn00fa
t_0 = −0.56 R_V = 3.10
Δ = −0.23 A_V = 0.49
μ_0 + 5 log (H_0/65) = 35.02
χ^2/ν = 21.71/47
train/train20 kcorred/


80 SNe Ia MLCS2k2
Distances to 9%
σ = 0.18 mag
m_V^0 [mag]
cz [km s⁻¹]
20
18
16
14
12
10³
10⁴
10⁵

Luminosity Distance

$$D_L = \sqrt{\frac{L}{4\pi F}}$$



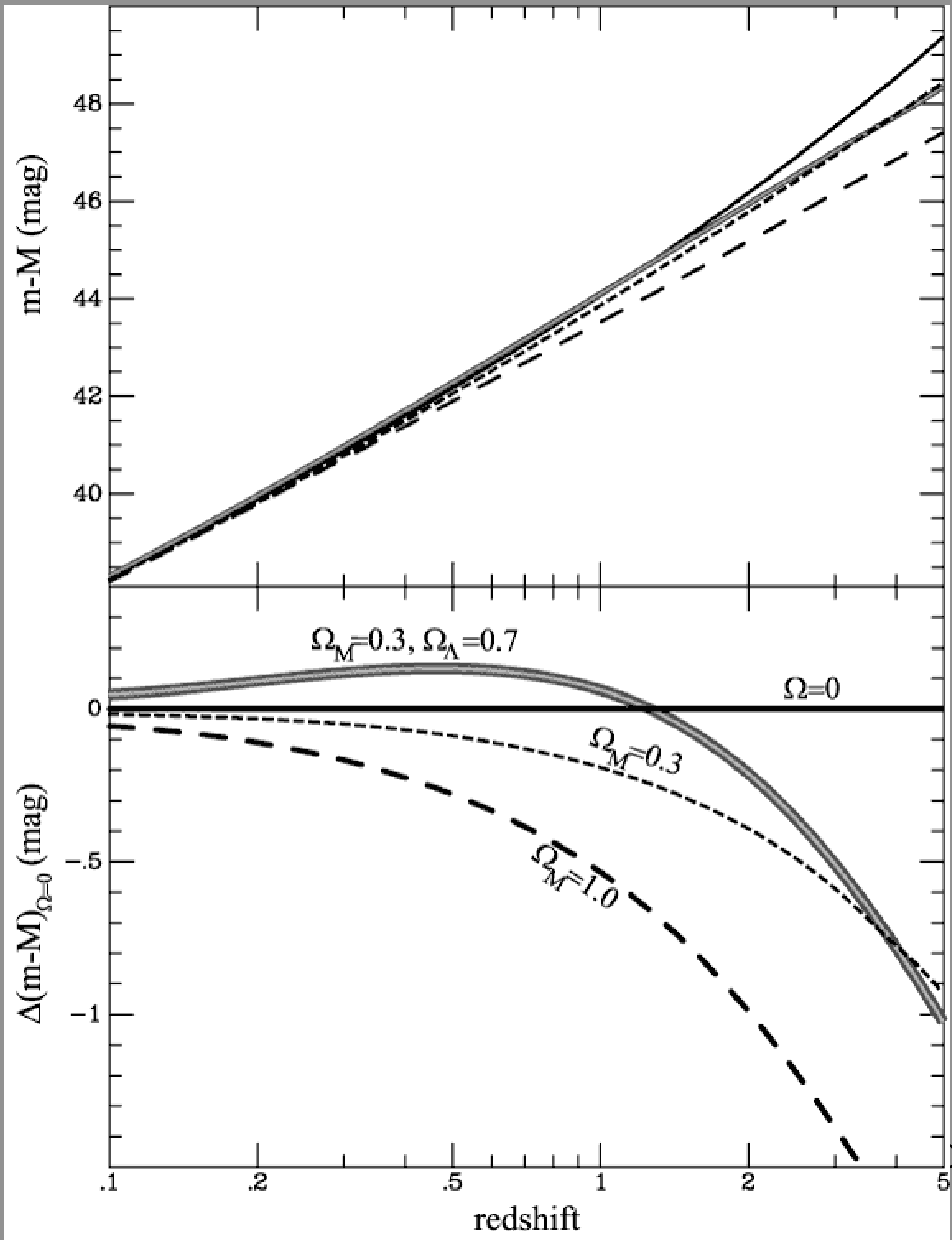
$$F = \frac{L}{4\pi D^2}$$

Observer infers distance to an object with redshift z from the observed flux.

$$D_L = \frac{c}{H_0}(1+z)\left|\Omega_0\right|^{-1/2} S\left[\left|\Omega_0\right|^{1/2}\int_0^z dz'\left[\sum_i \Omega_i \left(1+z'\right)^{3+3w_i} - \Omega_0\left(1+z'\right)^2\right]^{-1/2}\right]$$

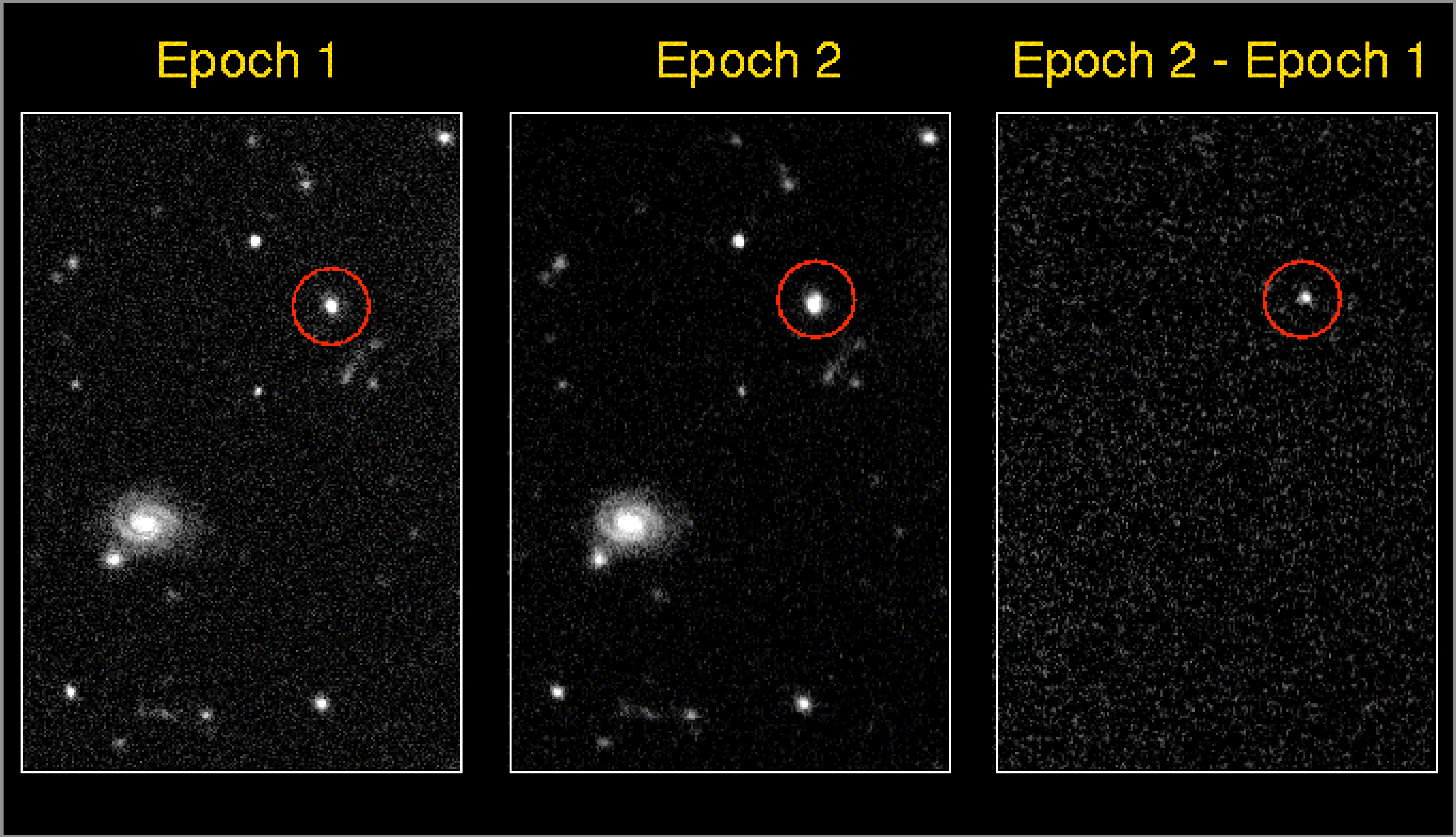
$$\Omega_0 = \left(\Omega_{tot} = \sum_i \Omega_i\right) - 1$$

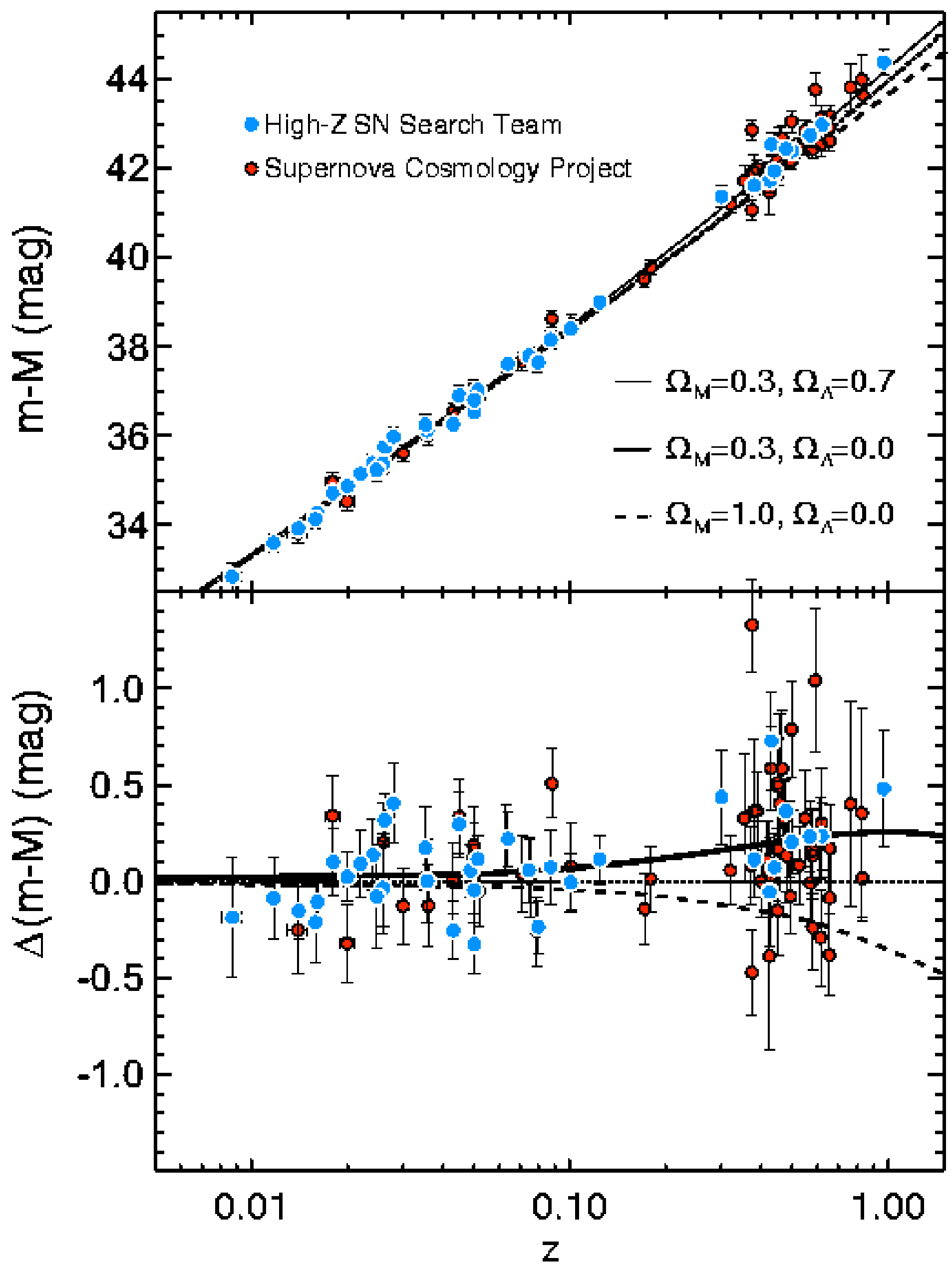
$$S(x) = \begin{cases} \sin(x) & \mathrm{k} = 1 \\ x & \mathrm{k} = 0 \\ \sinh(x) & \mathrm{k} = -1 \end{cases}$$



History of Cosmic Expansion D(z) is encoded in the Hubble Diagram

Searching by Subtraction

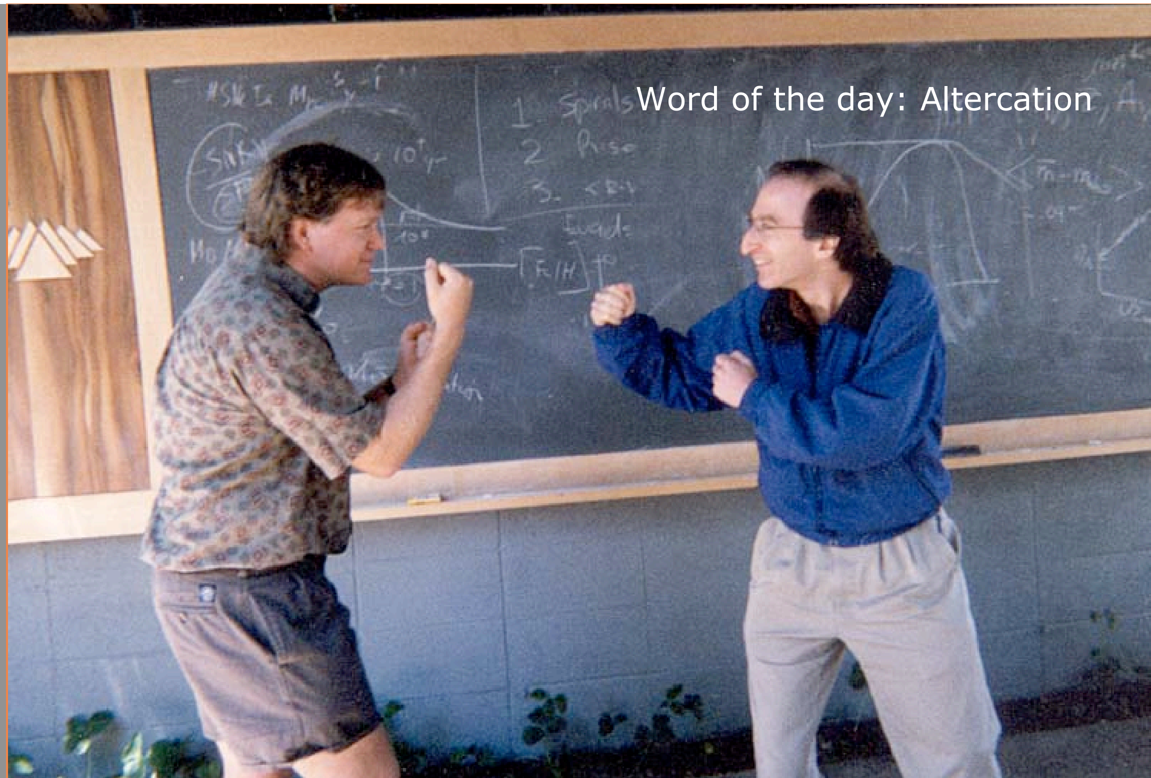




1998 Data:

Riess et al. (1998)

Perlmutter et al. (1999)



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)
- Alex Filippenko, Weidong Li, Saurabh Jha (Berkeley)
- Peter Garnavich, Stephen Holland (Notre Dame)
- Chris Stubbs (UW)
- John Tonry, Brian Barris (University of Hawaii)
- Adam Reiss (Space Telescope)
- Alejandro Clocchiatti (Catolica Chile)
- Jesper Sollerman (Stockholm)

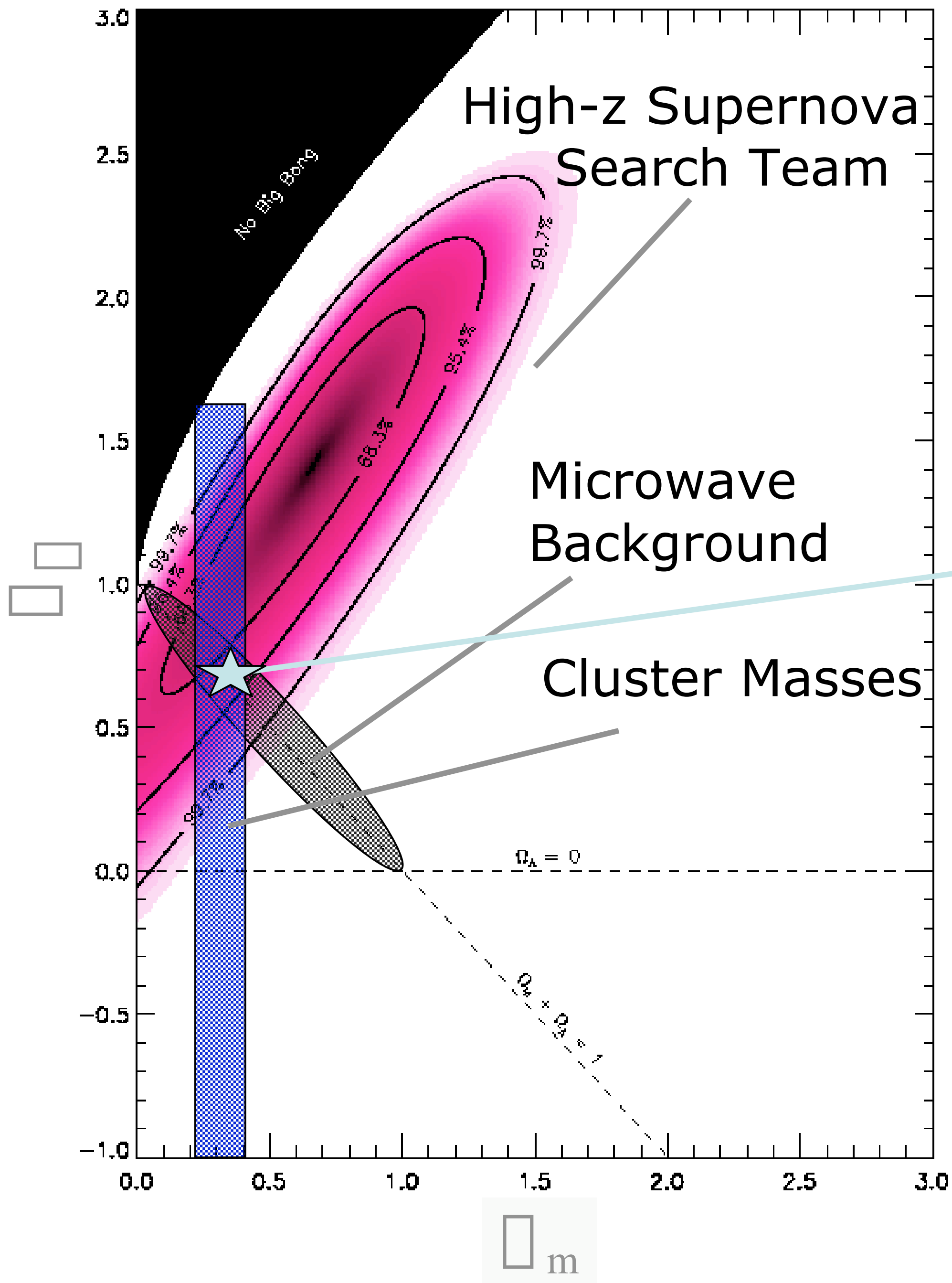
The High-Z SN Search

on Photon

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



Best fit:

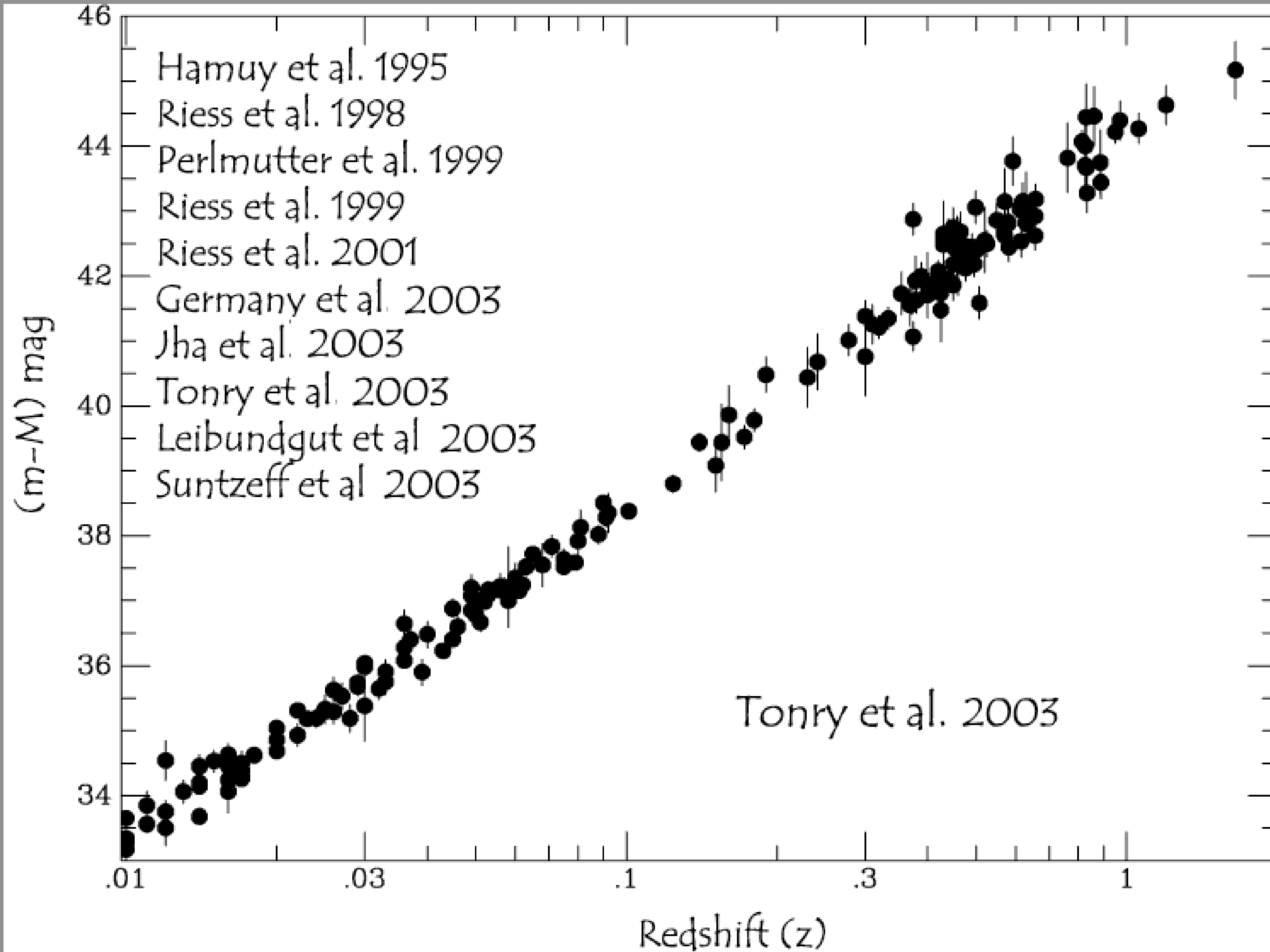
$\Omega_{mass} \sim 0.3$

$\Omega_{\Lambda} \sim 0.7$

Λ?

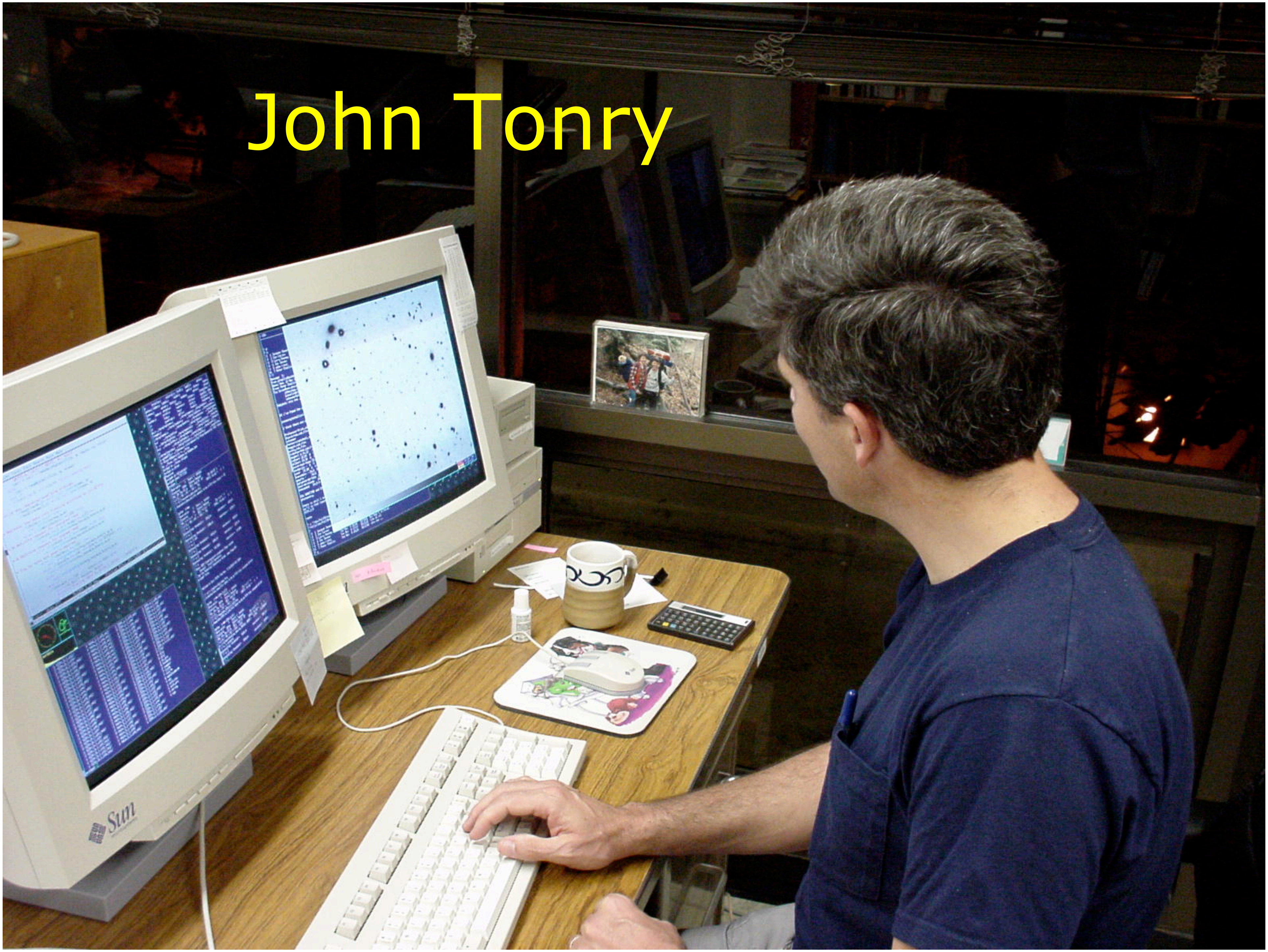
Einstein’s View on □

“An increase in the precision of data derived from observation will enable us in the future to fix its sign and determine its value.” 1932

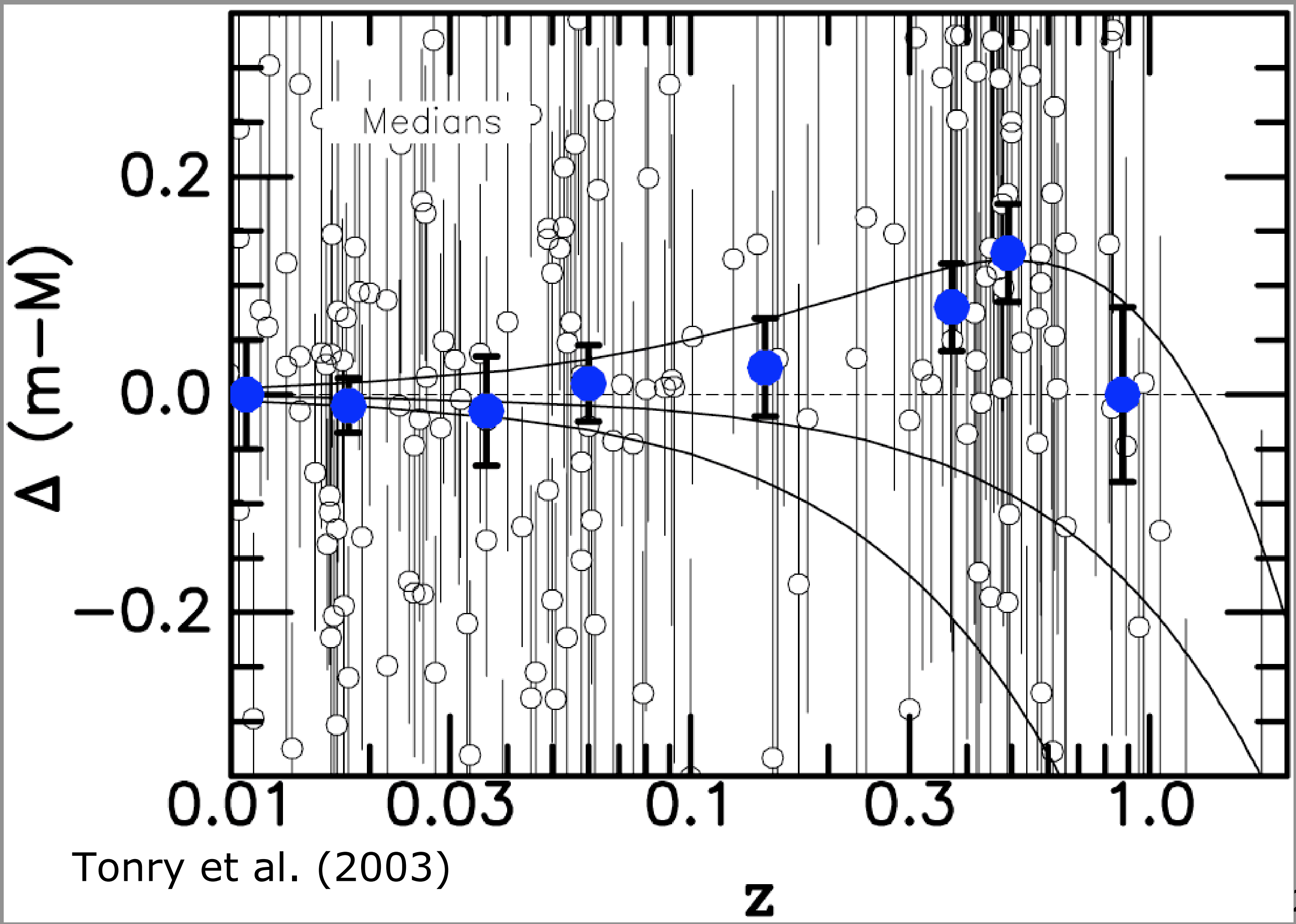


Hamuy et al. 1995
Riess et al. 1998
Perlmutter et al. 1999
Riess et al. 1999
Riess et al. 2001
Germany et al. 2003
Jha et al. 2003
Tonry et al. 2003
Leibundgut et al 2003
Suntzeff et al 2003
(m−M) mag
46
44
42
40
38
36
34
.01
.03
.1
.3
1
Redshift (z)
Tonry et al. 2003

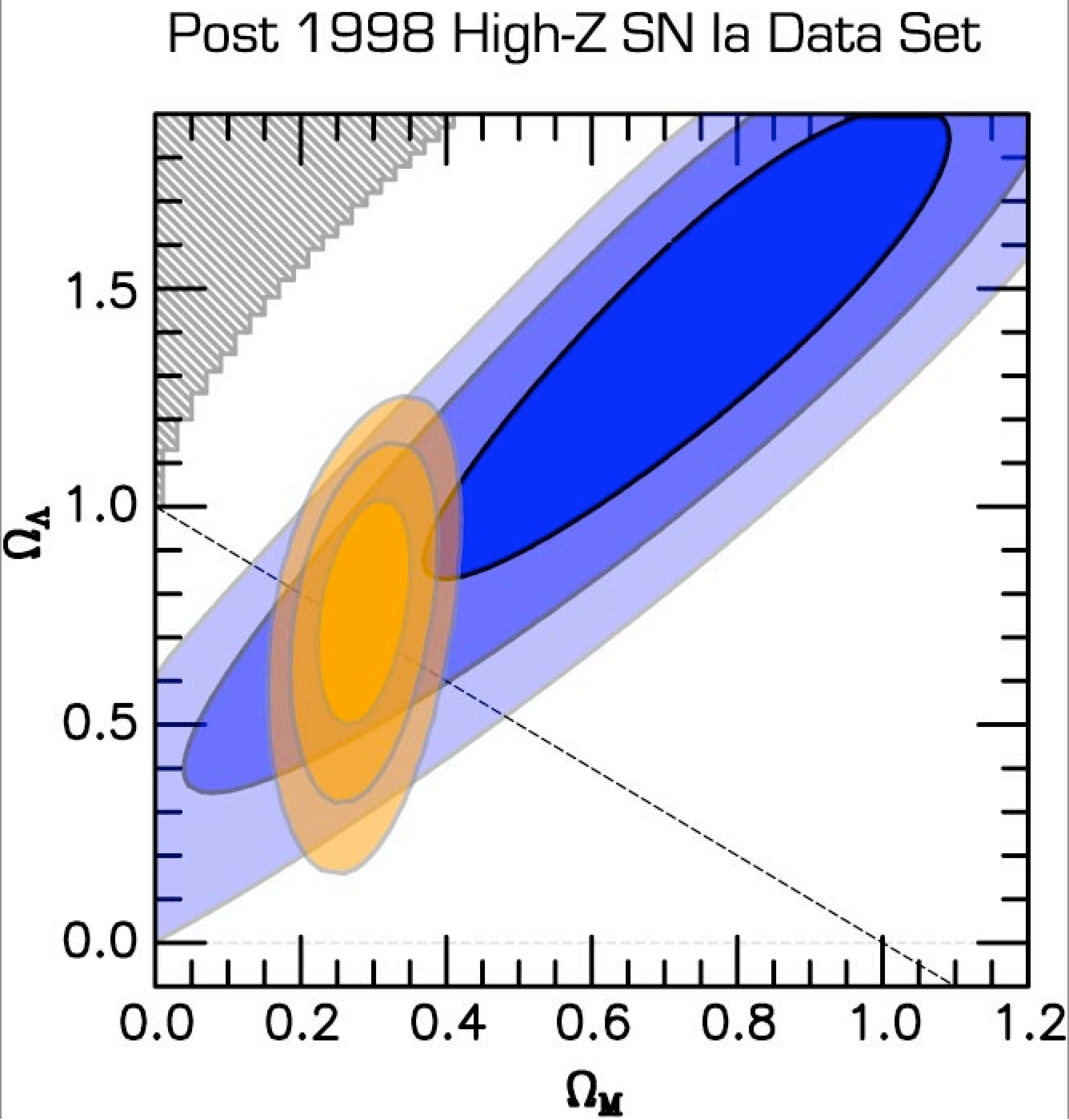
John Tonry



Acceleration/Deceleration

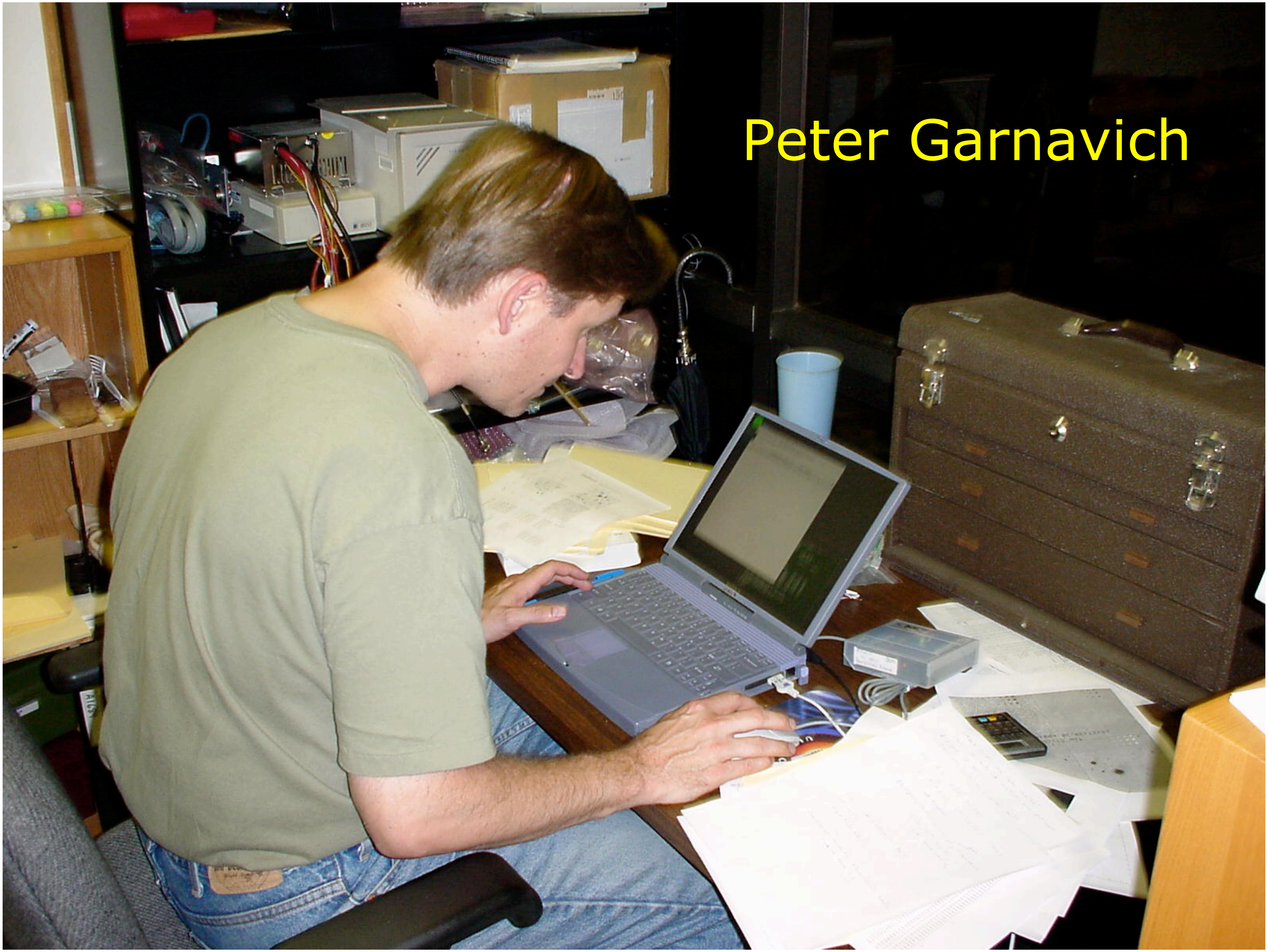


Tonry et al. (2003)



Still

Accelerating!

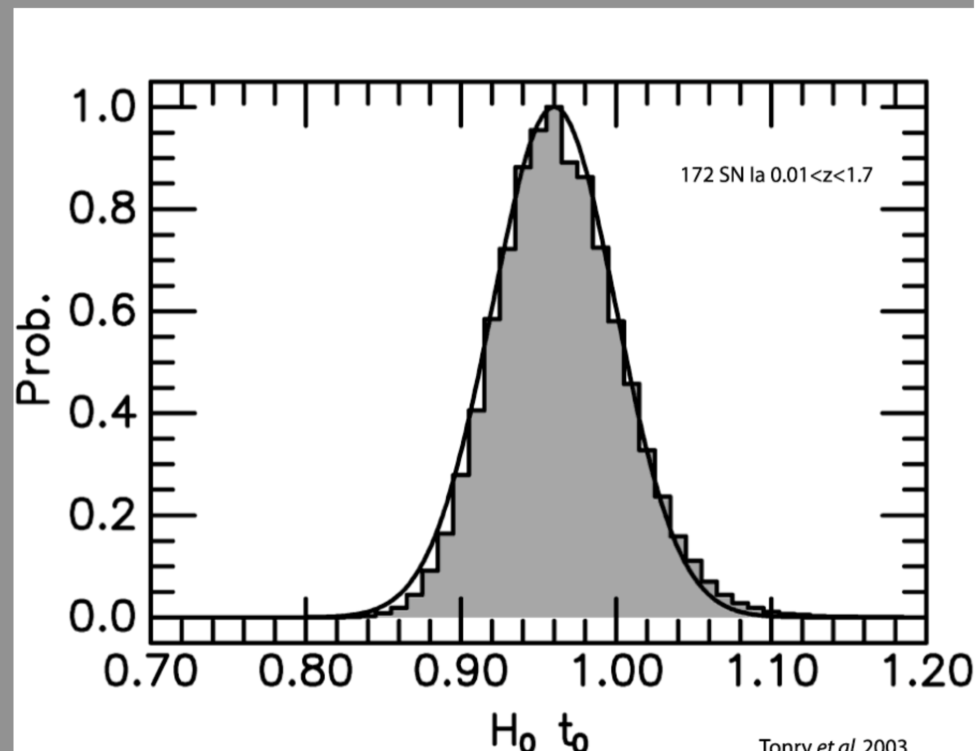

Peter Garnavich

□ Cosmology

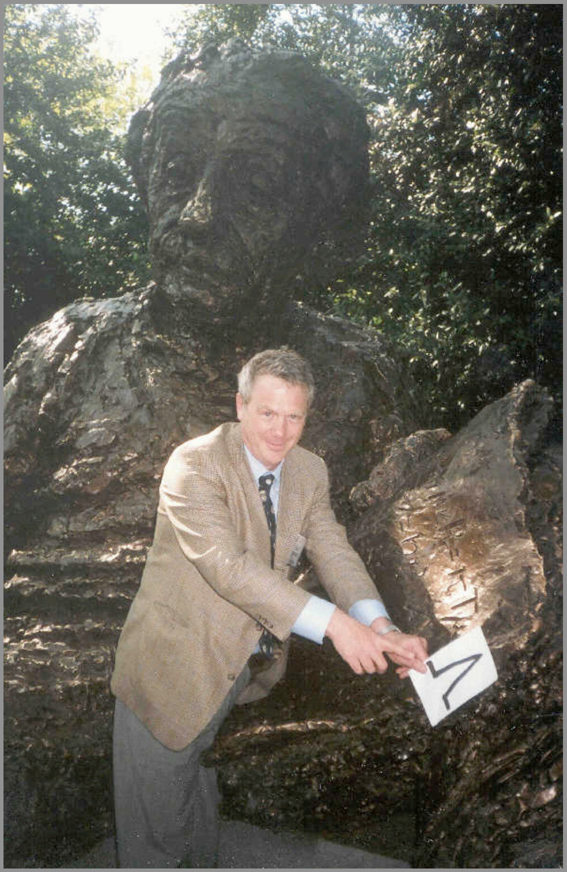
- SN: $H_o t_o$=0.96+/-0.04
- For H_o=72+/-8,

t_o=13.6 +/- 1.5 Gyr

$□_m$=0.28, $□_□$=0.72

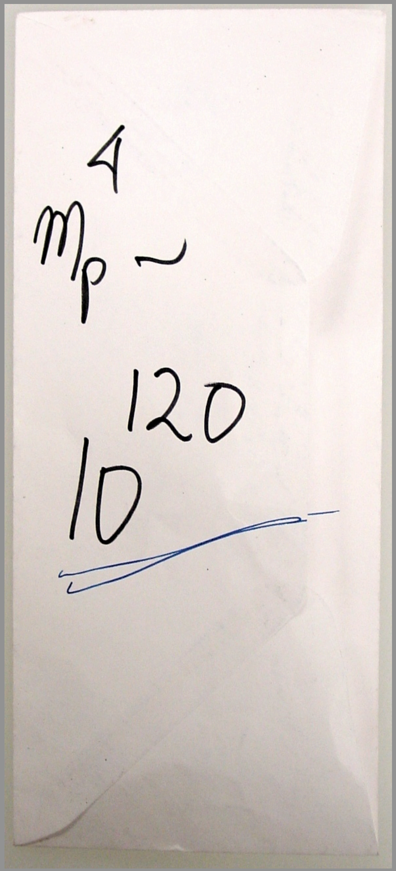


Putting Λ on the Right Hand Side



The Cosmological Constant?

- Not good quantitative agreement!
- "A bone in the throat."--S. Weinberg



Equation of State for Matter & Energy

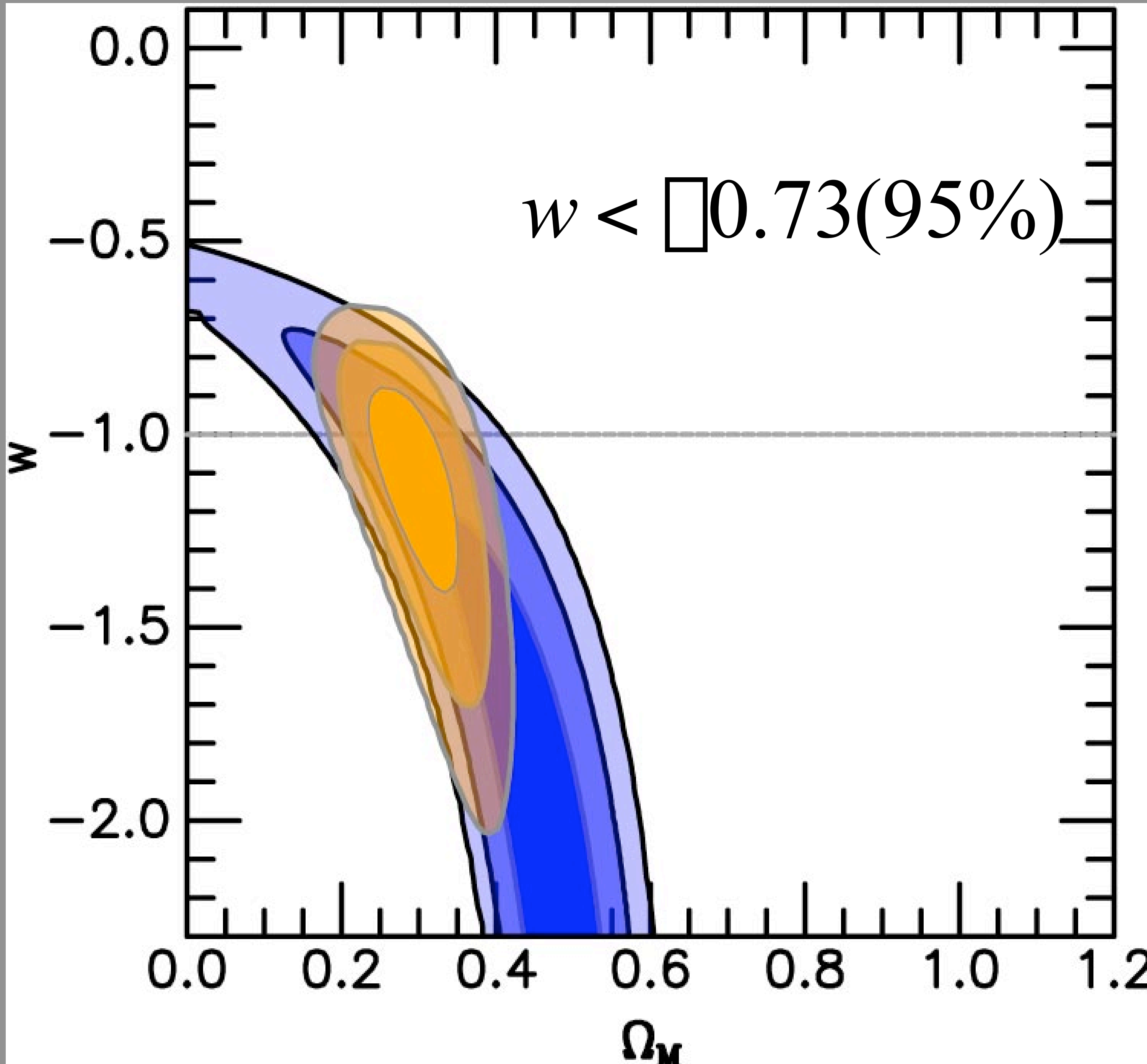
$$w_i \equiv \frac{P_i}{\rho_i} \qquad \rho_i \propto (\text{Volume})^{-(1+w_i)}$$

w $= 0$ for normal matter $\qquad \rho \propto V^{-4/3}$

w=1/3 for photons

w=-1 for Cosmological Constant

Λ or quintessence?


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

Testing the Model

- More precise measurements at z~0.5 to pin down w
- Measurements at z>1 to observe the era of deceleration and to constrain w’
- Independent methods--Sachs-Wolfe effect (Scranton et al.astro-ph/0307335)

ESSENCE

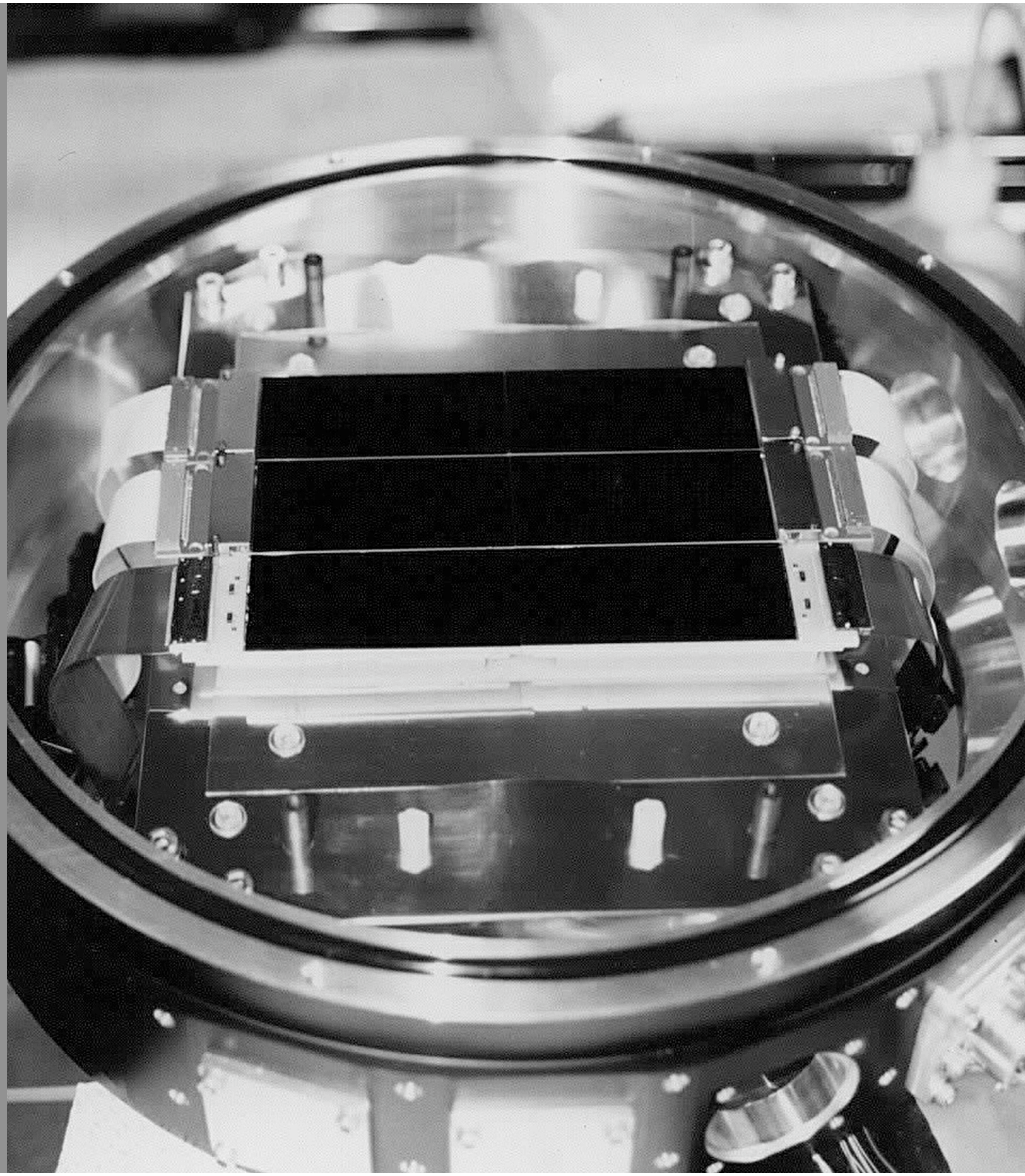
Equation of ***S***tate: ***S***up***E***r***N***ovae Trace ***C***osmic ***E***xpansion

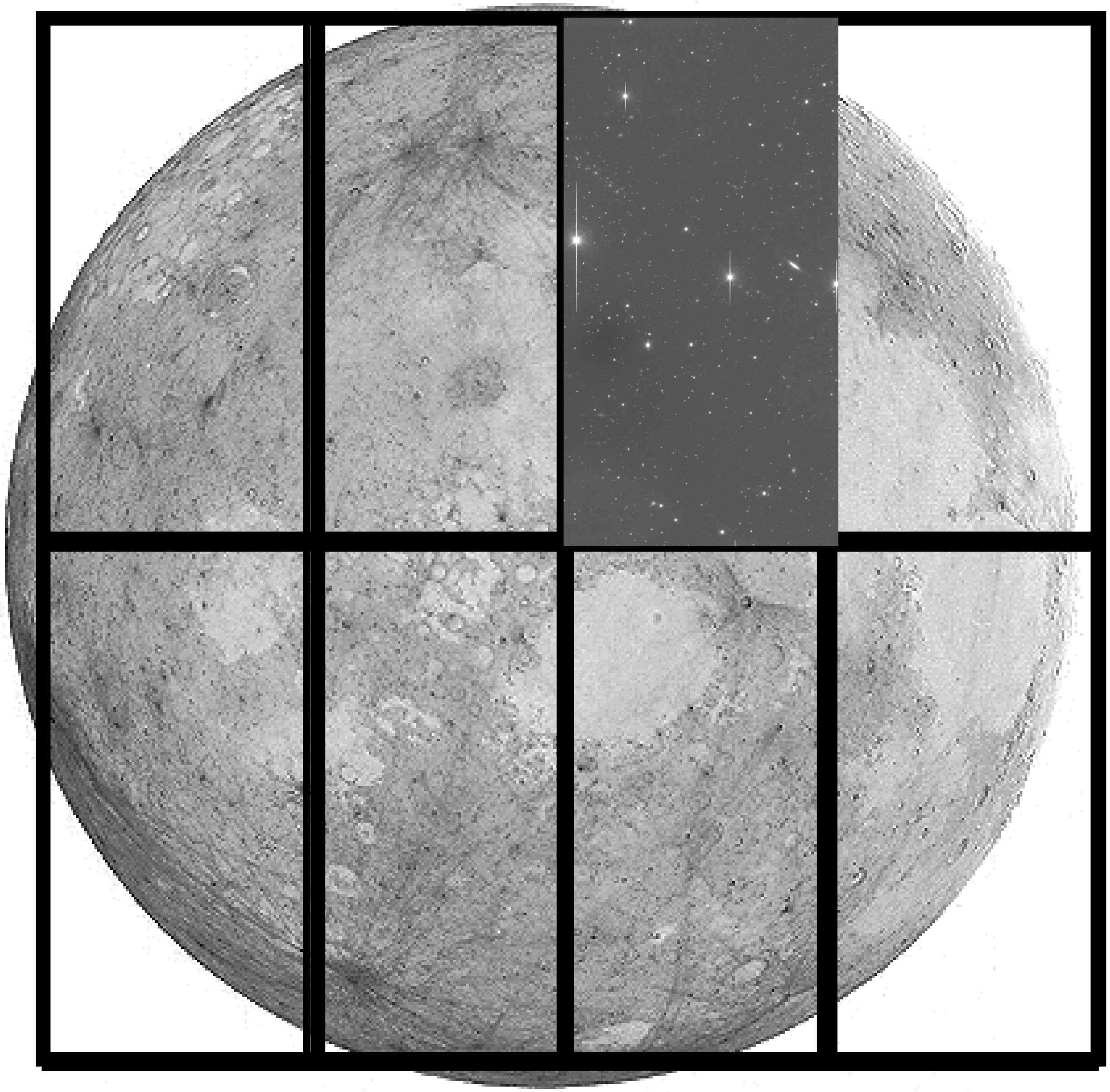
- NOAO Survey on CTIO 4m, MOSAIC for 5 years
- Shares frame subtraction pipeline with SuperMacho project, Chris Stubbs, P.I.
- Expect ~ 200 supernovae with $0.1 < z < 0.8$
- 3 band photometry: V,R,I (observer frame)
- 2 sets of fields, so $\Delta t = 4$ days
- Goal is to determine the distance to each redshift bin ($\Delta z = 0.1$) to 2%
- ~3% photometry at peak SN brightness

ESSENCE Survey Team

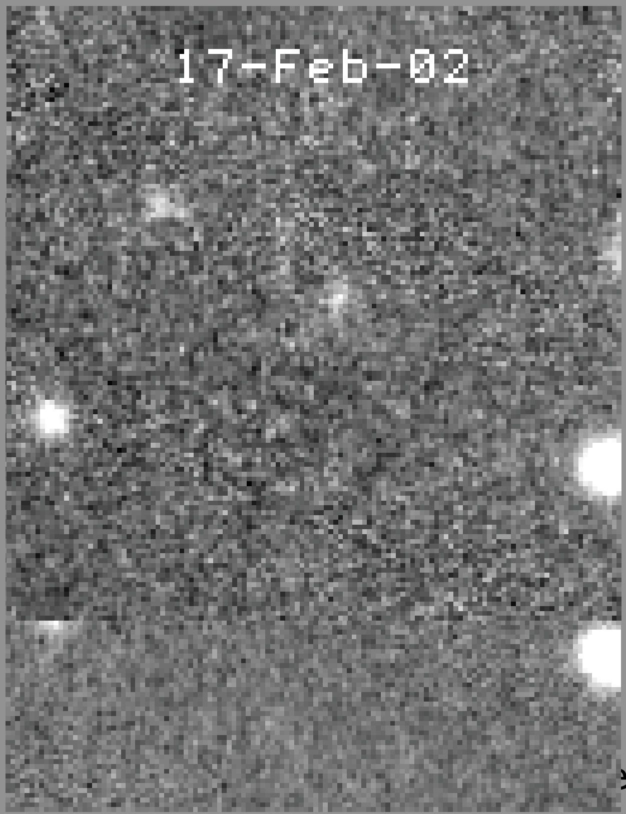
Claudio Aguilera --- CTIO/NOAO
Brian Barris --- Univ of Hawaii
Andy Becker --- Bell Labs/Univ. of Washington
Peter Challis --- Harvard-Smithsonian CfA
Ryan Chornock --- Harvard-Smithsonian CfA
Alejandro Clocchiatti --- Univ Catolica de Chile
Ricardo Covarrubias --- Univ of Washington
Alex V. Filippenko --- Univ of Ca, Berkeley
Peter M. Garnavich --- Notre Dame University
Stephen Holland --- Notre Dame University
Saurabh Jha --- Harvard-Smithsonian CfA
Robert Kirshner --- Harvard-Smithsonian CfA
Kevin Krisciunas --- CTIO/NOAO

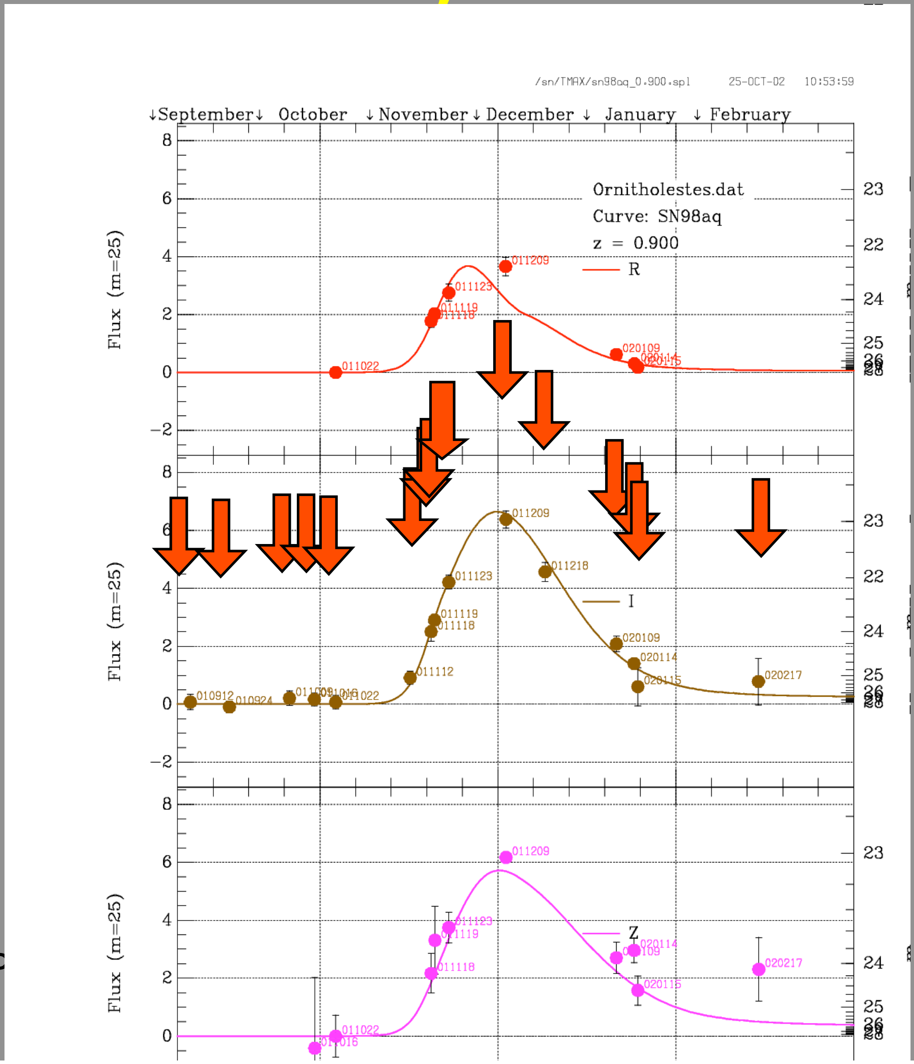
Bruno Leibundgut --- European Southern Observatory
Weidong D. Li --- Univ of California, Berkeley
Thomas Matheson --- Harvard-Smithsonian CfA
Anthony Miceli --- Univ of Washington
Gajus Miknaitis --- Univ of Washington
Armin Rest --- Univ of Washington/CTIO
Adam G. Riess --- Space Telescope Science Institute
Brian P. Schmidt --- Mt. Stromlo Siding Springs Observatories
Chris Smith --- CTIO/NOAO
Jesper Sollerman --- Stockholm Observatory
Jason Spyromilio --- European Southern Observatory
Christopher Stubbs --- Univ of Washington
Nicholas B. Suntzeff --- CTIO/NOAO
John L. Tonry --- Univ of Hawaii



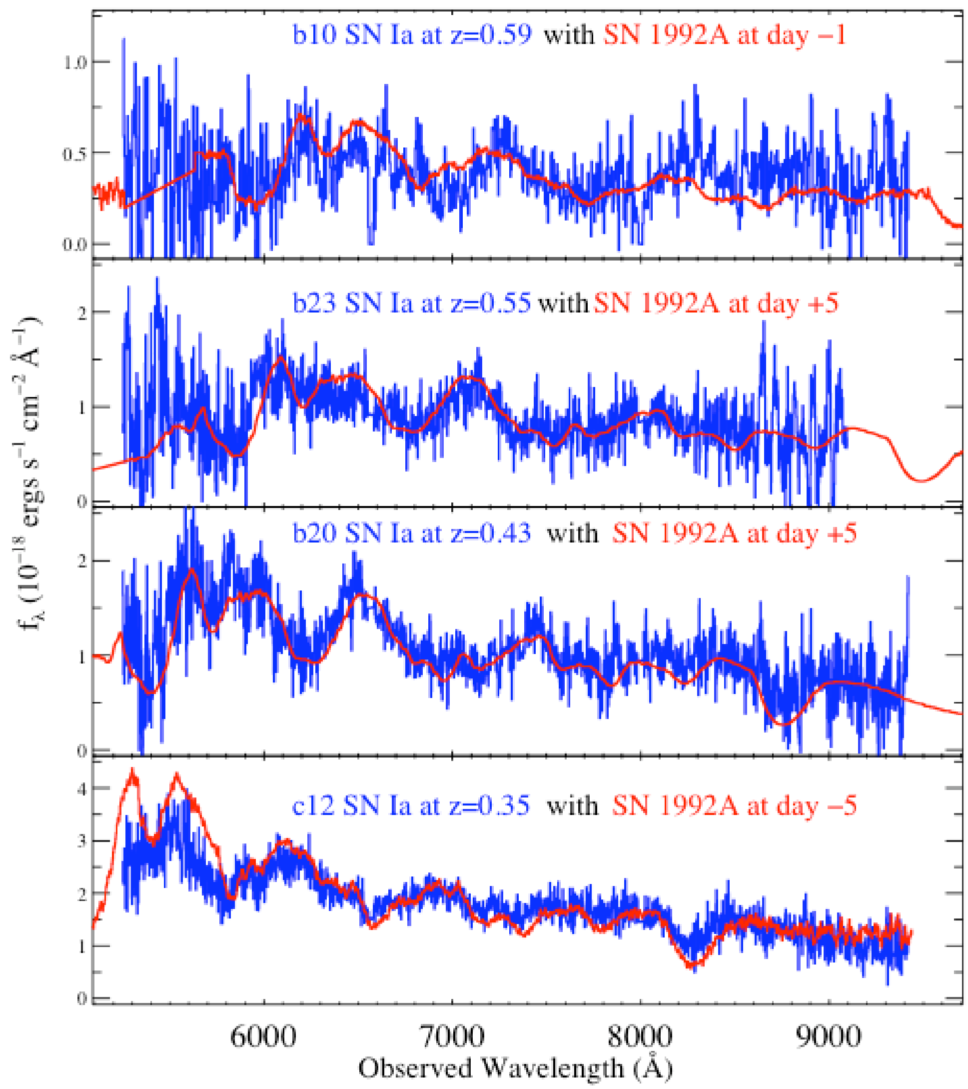


Continuous Searching: 2001-Brian Barris, UH



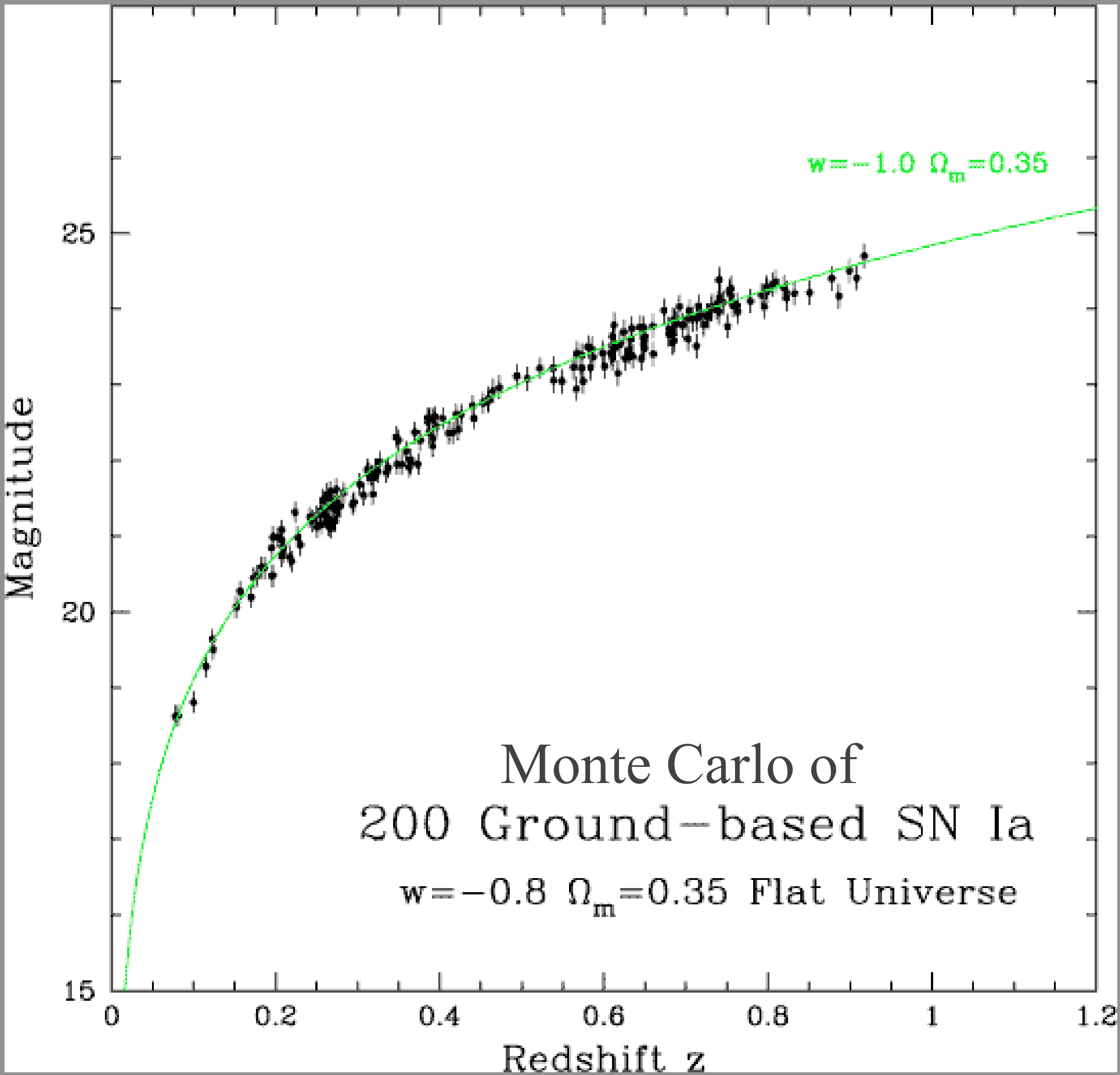


epton P



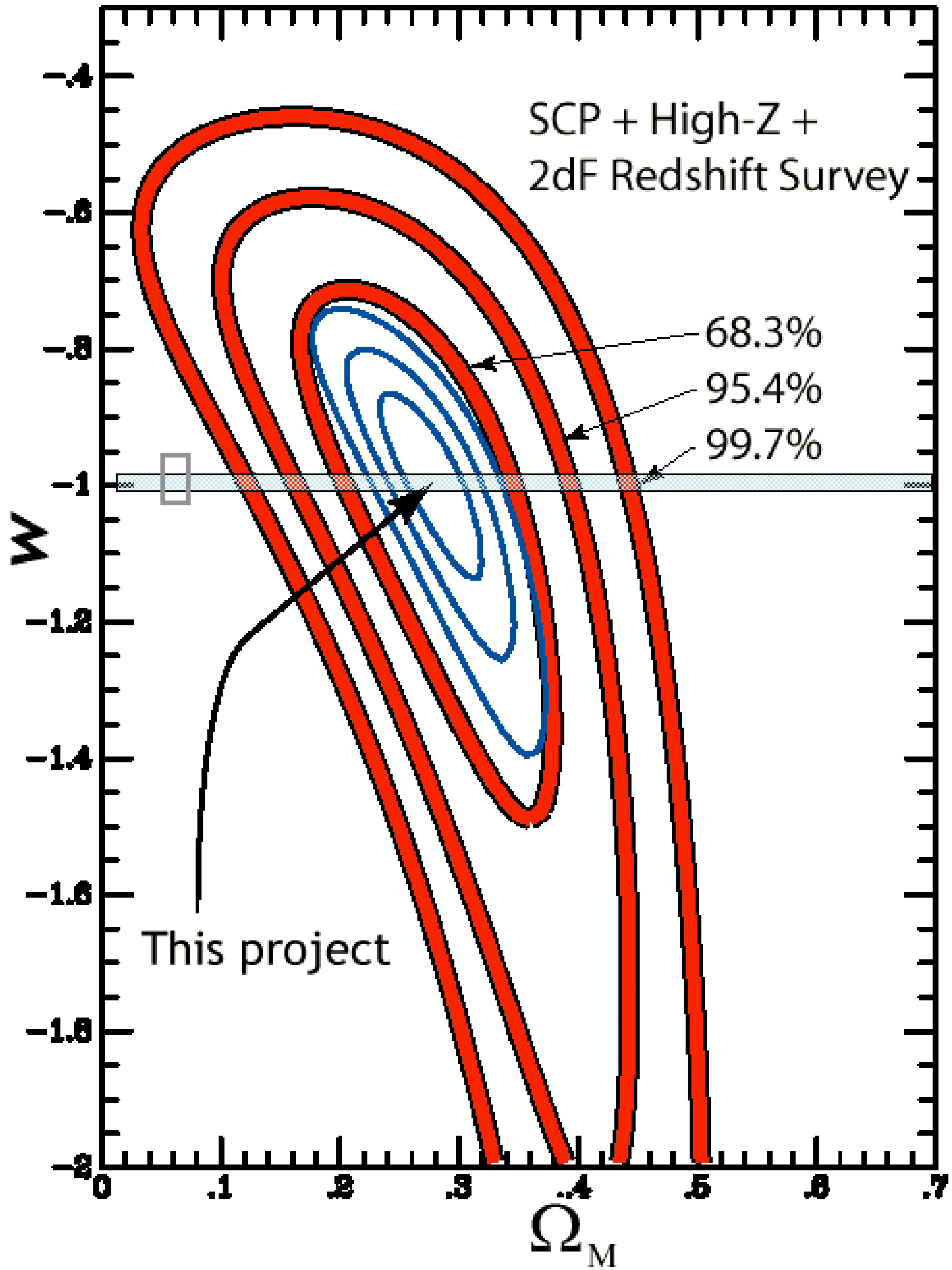
Spectra of distant SN Ia just like those nearby

Essence Survey Goal: w



Supernovae, CMB, and large scale structure will determine w to 10%

This cannot fail to be interesting! [illegible] or something else.



Lep

ESSENCE survey SNe (as of Jan 2003)

Z	Ia's	II's
0.1	1	0
0.2	2	3
0.3	5	3
0.4	4	0
0.5	4	0
0.6	2	0
Totals	18	6

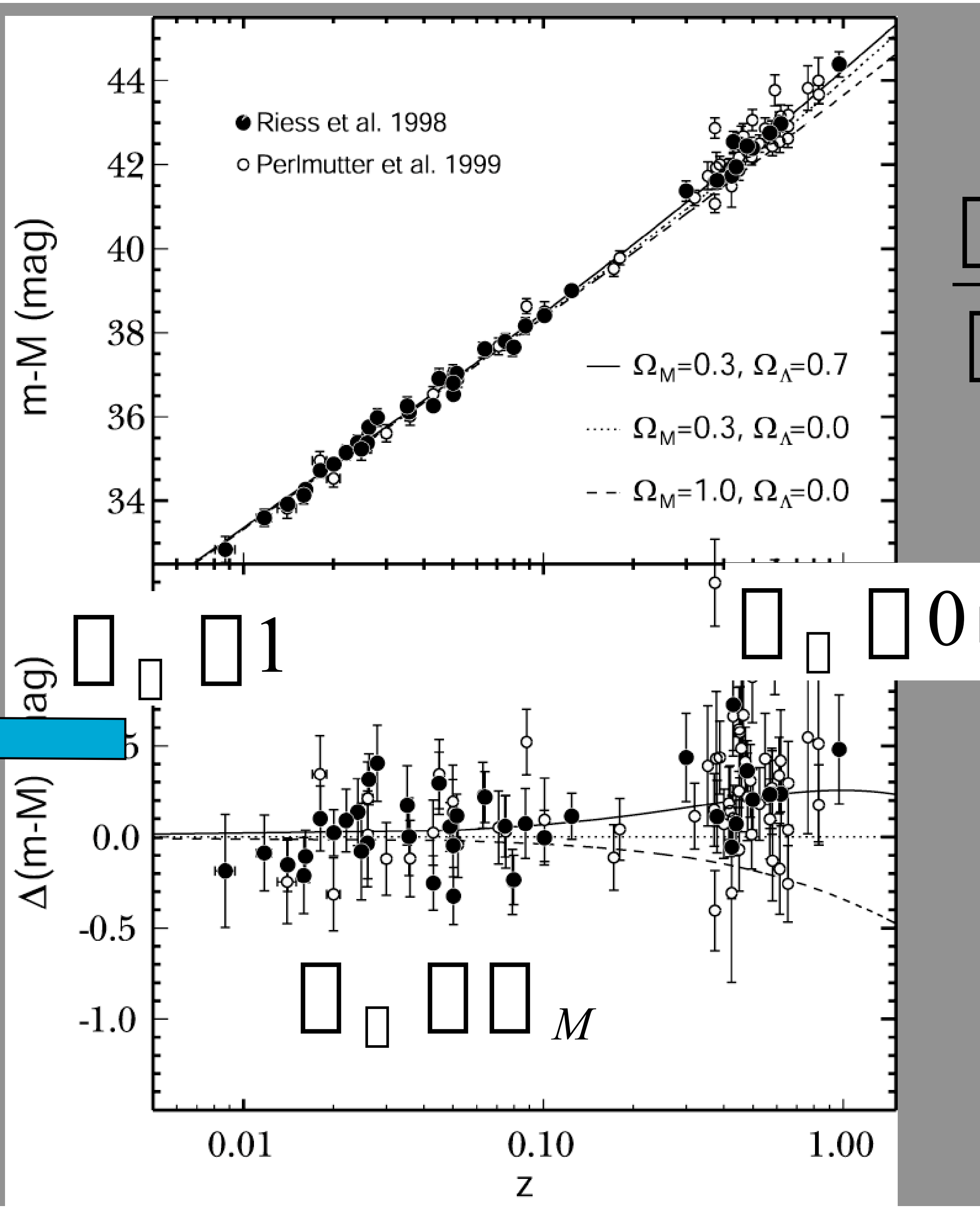
SN types and redshifts from
- Keck
- Magellan
- VLT
- Gemini

18 are SN type Ia's
6 are SN type II
5 uncertain

Good light curves from CTIO 4m on 14 type Ia's

Searching for Supernovae with HST

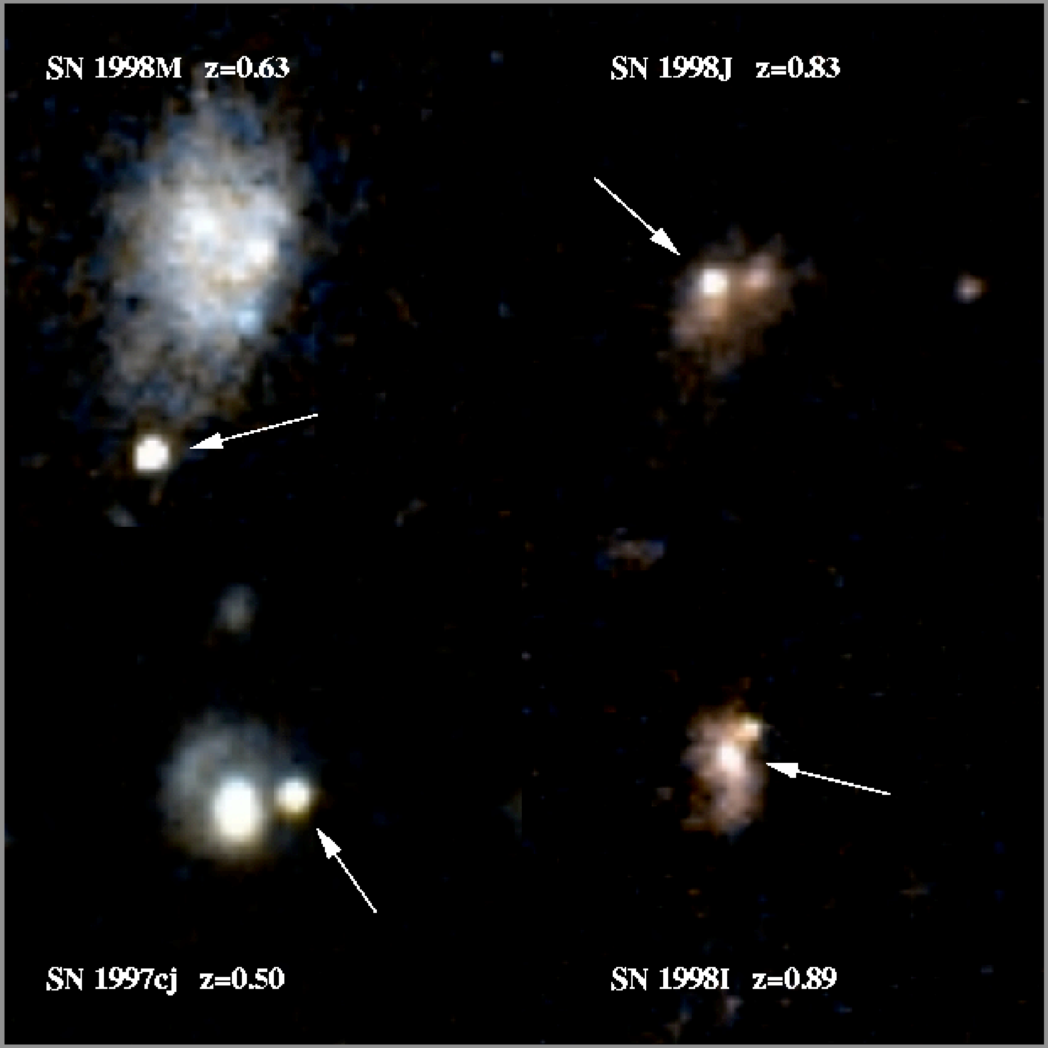
Back to the age of ***de***celeration



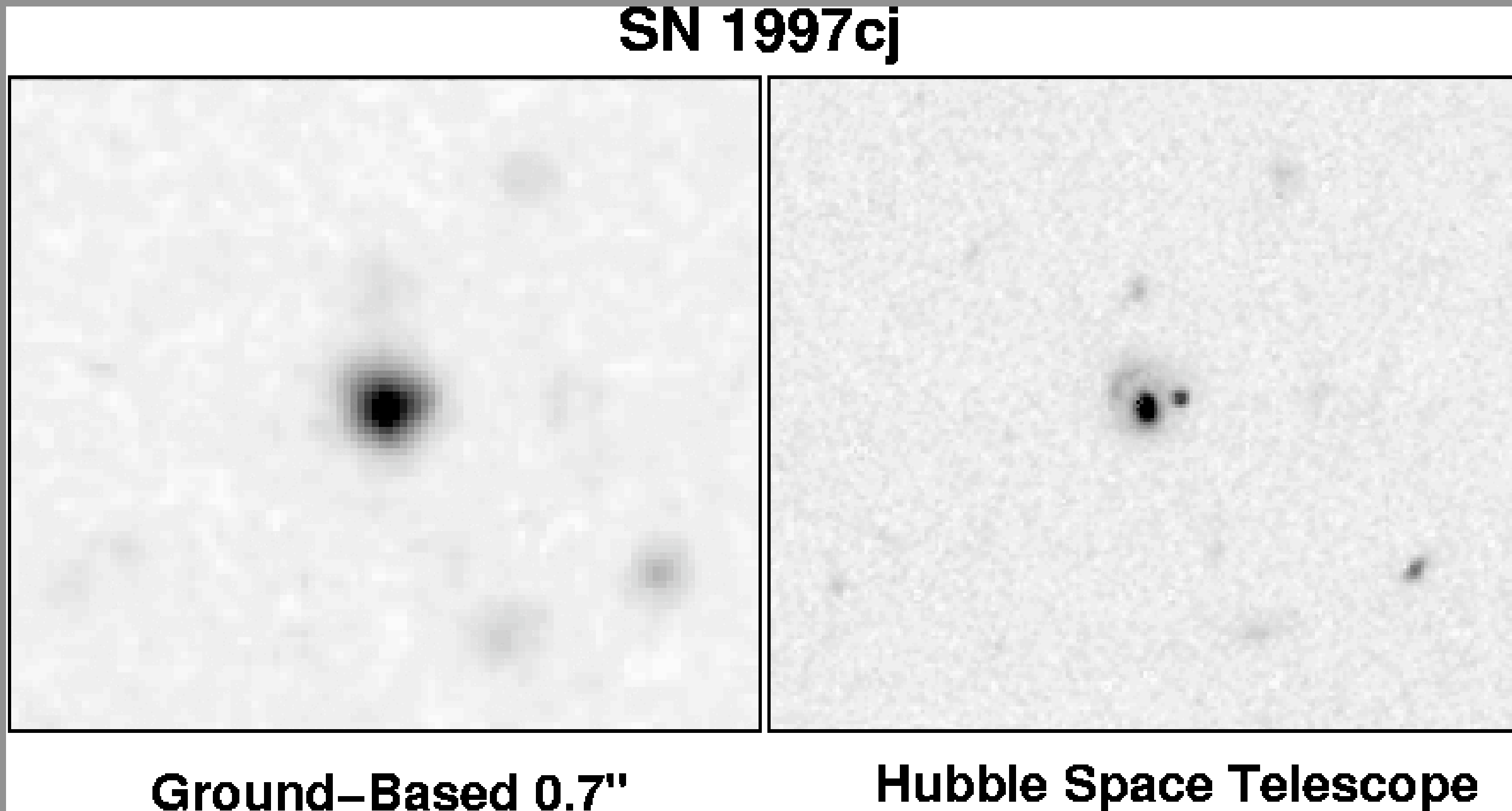
Riess et al. 1998
Perlmutter et al. 1999
Ω_M=0.3, Ω_Λ=0.7
Ω_M=0.3, Ω_Λ=0.0
Ω_M=1.0, Ω_Λ=0.0
m-M (mag)
44
42
40
38
36
34
Δ(m-M) (mag)
0.0
-0.5
-1.0
0.01
0.10
1.00
z

$(1+z)^3$

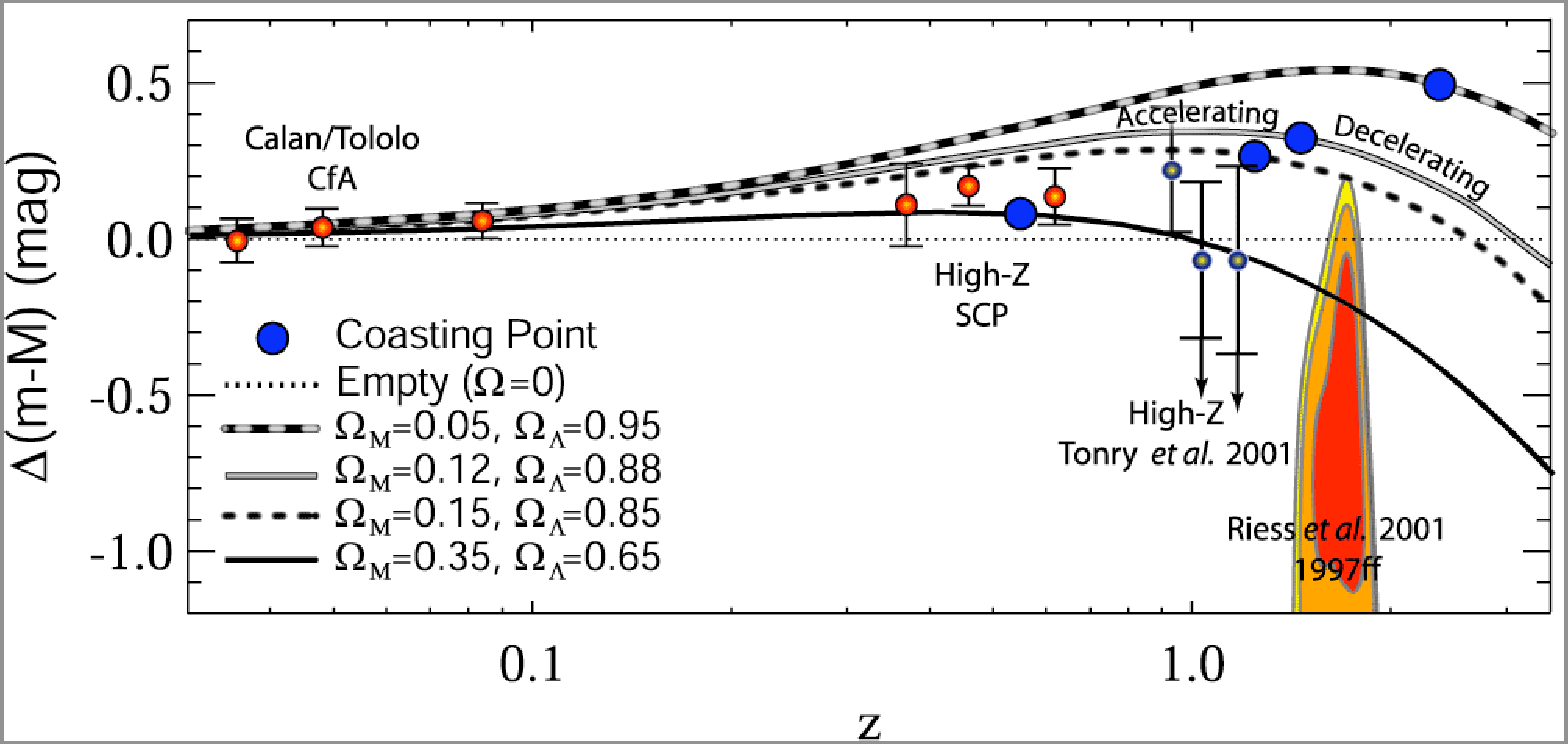
High-z Supernovae with HST



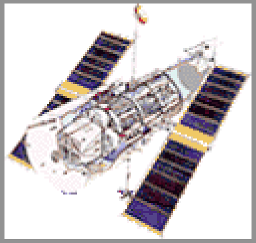
The sharper image!



The Era of Deceleration? One Lucky Glimpse by Riess et al. (2001)



The GOODs ACS Treasury Program &



The Higher-Z Supernova Search Team

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

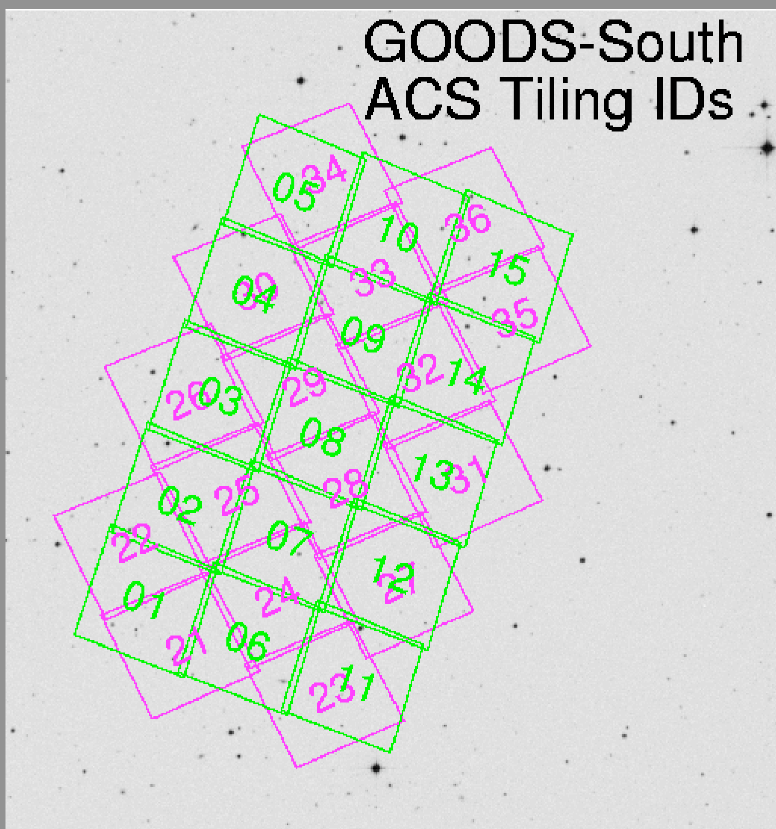
Adam Riess

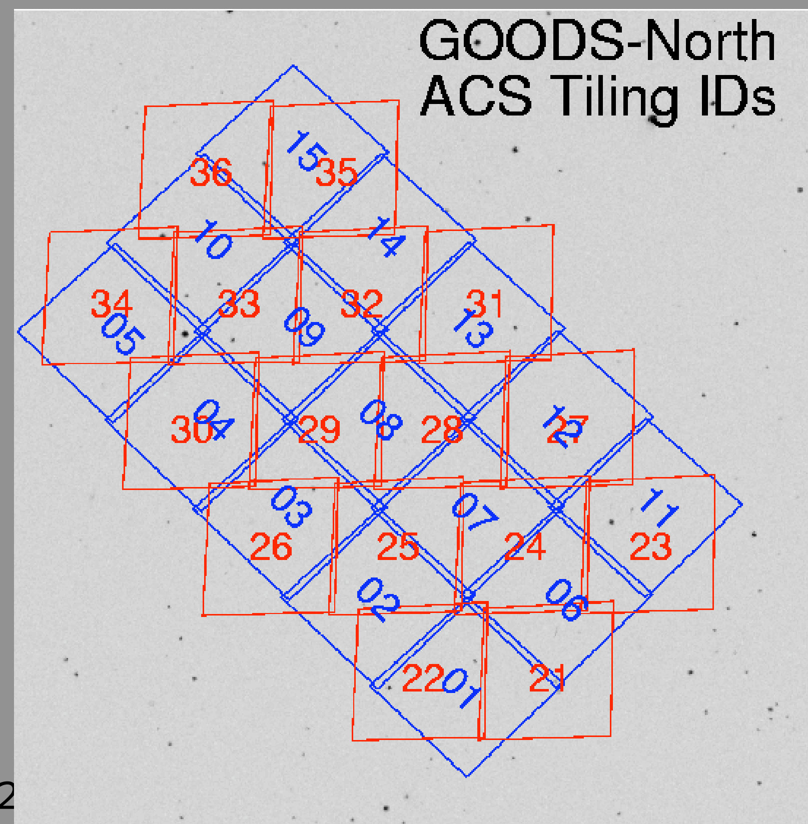
1.2< z < 1.8
supernovae

Searching for SNe Ia with ACS

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

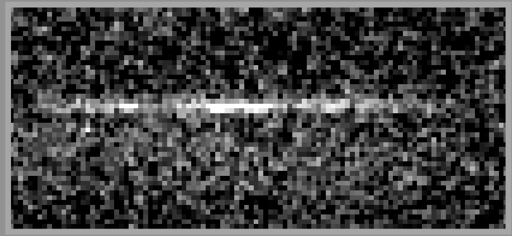
CDFS=08/02-02/03 HDFN=11/02-05/03



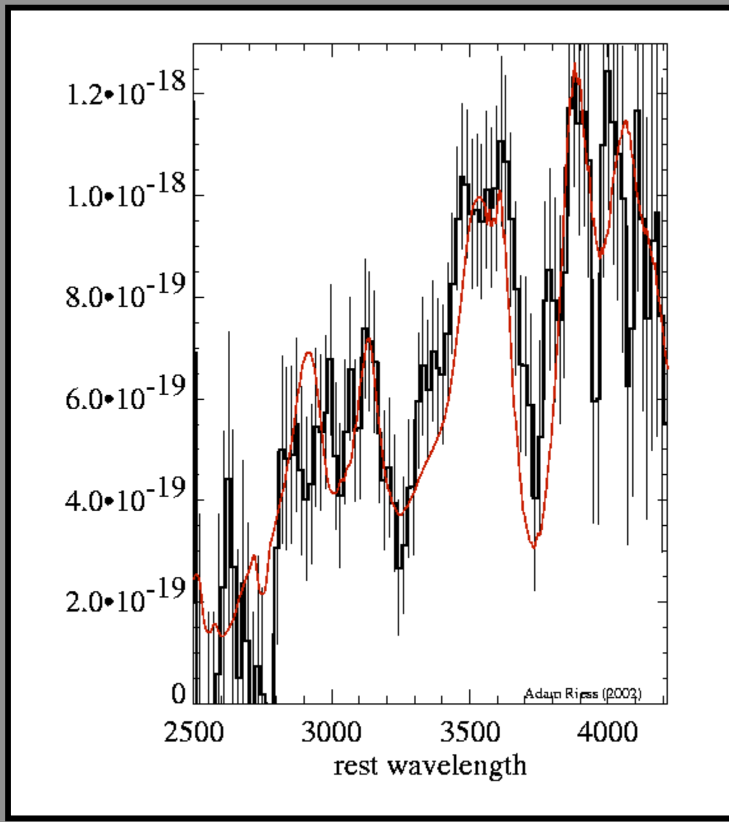


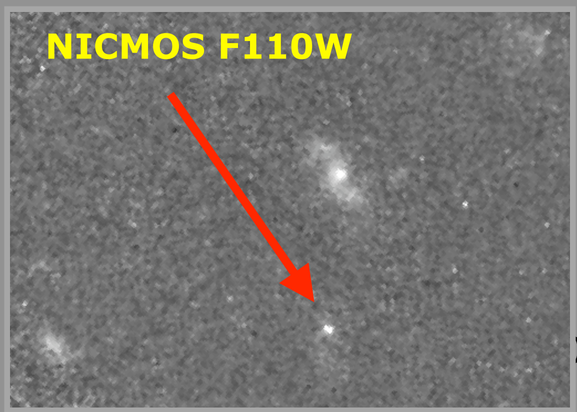
Our first higher-z SN Ia, Aphrodite

Aphrodite ($1<z<1.5$)



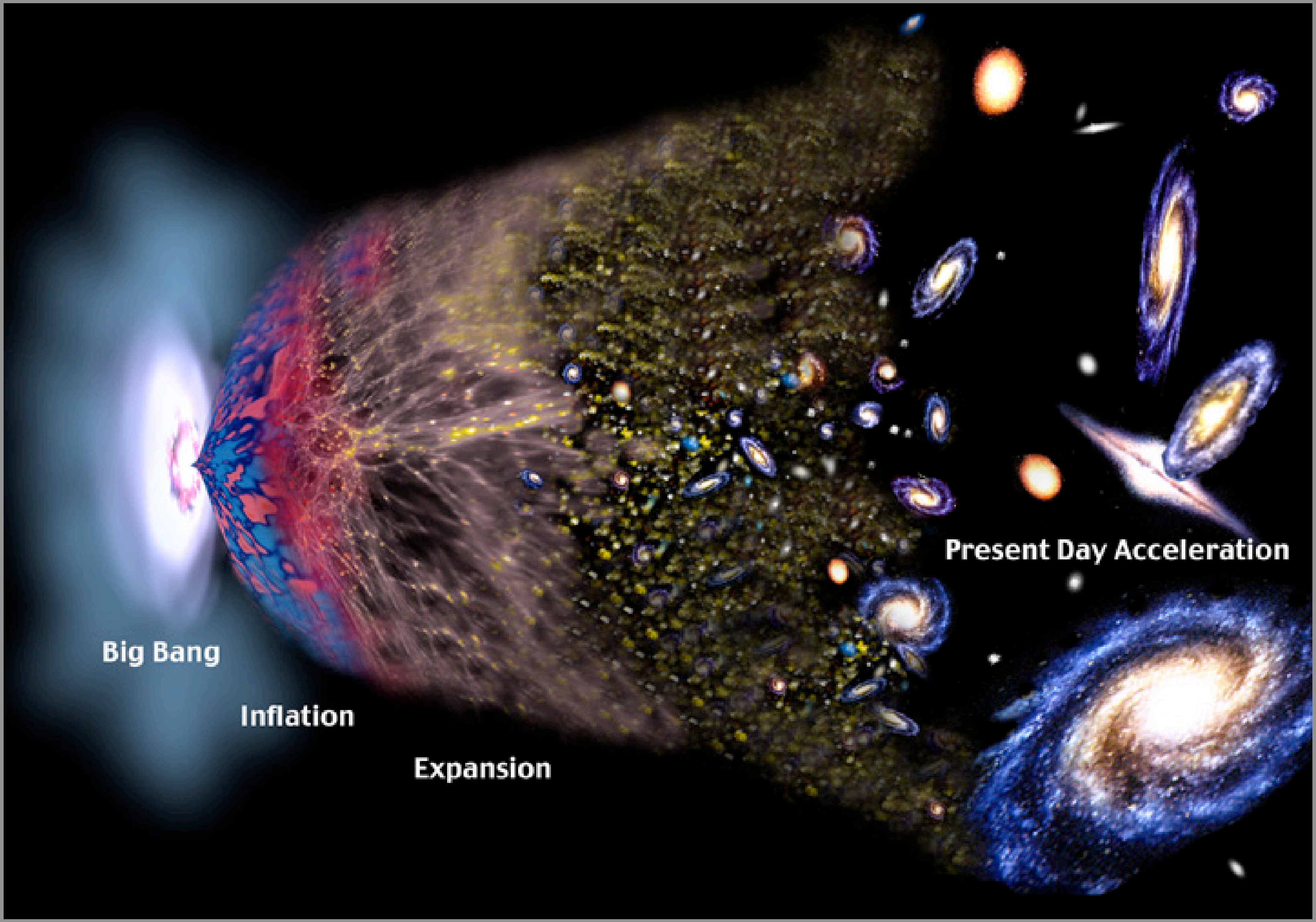
ACS grism spectrum





03

Facts first, then the conclusions!



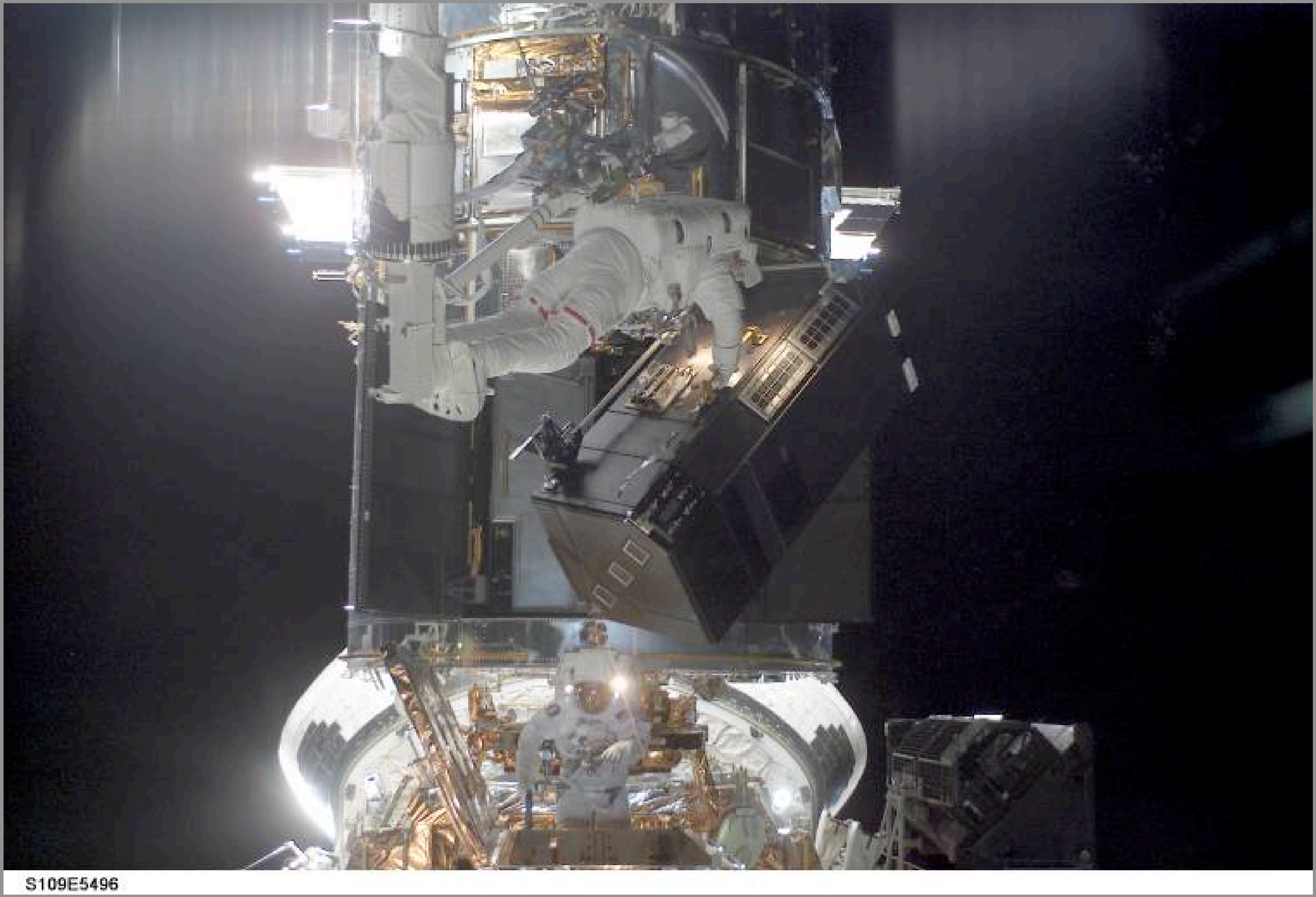
Higher-Z Scorecard

- Discovery with HST in 2002
- 42 Supernovae reported to IAU
- 10 SN Ia in the interesting range 1.2 >z >1.8
- Lightcurves and spectra from HST
- See Riess et al. astro-ph/0308185
- Renewed search in 2003

Present and Future

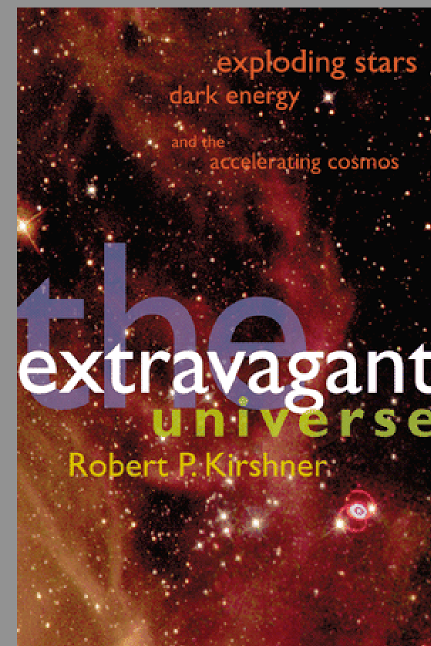
- Low-z: the nature of SN Ia--KAIT, FLWO, SN Factory
- Mid-z: measuring w-- ESSENCE, CFHT Legacy
- Higher-z: era of deceleration, w' HST with ACS, SNAP, HST w/SM5?

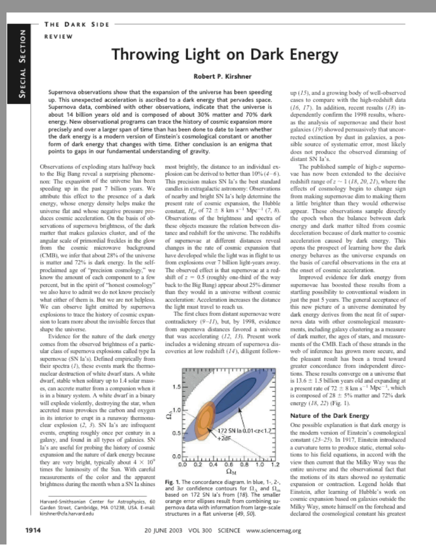
A New Instrument for Hubble?



To Learn More

- The Extravagant Universe
- *Science:* 300, 1914 (2003)
- Tonry, J. & High-Z Team astro-ph/0305008





THE DARK SIDE

SPECIAL SECTION

REVIEW

Throwing Light on Dark Energy

Robert P. Kirshner

Supernova observations show that the expansion of the universe has been speeding up. This unexpected acceleration is ascribed to a dark energy that pervades space. Supernova data, combined with other observations, indicate that the universe is about 14 billion years old and is composed of about 30% matter and 70% dark energy. New observational programs can trace the history of cosmic expansion more precisely and over a larger span of time than has been done to date to learn whether the dark energy is a modern version of Einstein's cosmological constant or another form of dark energy that changes with time. Either conclusion is an enigma that points to gaps in our fundamental understanding of gravity.

Observations of exploding stars halfway back to the Big Bang reveal a surprising phenomenon: The expansion of the universe has been speeding up in the past 7 billion years. We attribute this effect to the presence of a dark energy, whose energy density helps make the universe flat and whose negative pressure produces cosmic acceleration. On the basis of observations of supernova brightness, of the dark matter that makes galaxies cluster, and of the angular scale of primordial freckles in the glow from the cosmic microwave background (CMB), we infer that about 28% of the universe is matter and 72% is dark energy. In the self-proclaimed age of "precision cosmology," we know the amount of each component to a few percent, but in the spirit of "honest cosmology" we also have to admit we do not know precisely what either of them is. But we are not helpless. We can observe light emitted by supernova explosions to trace the history of cosmic expansion to learn more about the invisible forces that shape the universe.

Evidence for the nature of the dark energy comes from the observed brightness of a particular class of supernova explosions called type Ia supernovae (SN Ia's). Defined empirically from their spectra (*1*), these events mark the thermonuclear destruction of white dwarf stars. A white dwarf, stable when solitary up to 1.4 solar masses, can accrete matter from a companion when it is in a binary system. A white dwarf in a binary will explode violently, destroying the star, when accreted mass provokes the carbon and oxygen in its interior to erupt in a runaway thermonuclear explosion (*2, 3*). SN Ia's are infrequent events, erupting roughly once per century in a galaxy, and found in all types of galaxies. SN Ia's are useful for probing the history of cosmic expansion and the nature of dark energy because they are very bright, typically about 4×10^9 times the luminosity of the Sun. With careful measurements of the color and the apparent brightness during the month when a SN Ia shines most brightly, the distance to an individual explosion can be derived to better than 10% (*4–6*). This precision makes SN Ia's the best standard candles in extragalactic astronomy: Observations of nearby and bright SN Ia's help determine the present rate of cosmic expansion, the Hubble constant, H_o, of 72 ± 8 km s^{-1} Mpc^{-1} (*7, 8*). Observations of the brightness and spectra of these objects measure the relation between distance and redshift for the universe. The redshifts of supernovae at different distances reveal changes in the rate of cosmic expansion that have developed while the light was in flight to us from explosions over 7 billion light-years away. The observed effect is that supernovae at a redshift of $z = 0.5$ (roughly one-third of the way back to the Big Bang) appear about 25% dimmer than they would in a universe without cosmic acceleration: Acceleration increases the distance the light must travel to reach us.

The first clues from distant supernovae were contradictory (*9–11*), but, by 1998, evidence from supernova distances favored a universe that was accelerating (*12, 13*). Present work includes a widening stream of supernova discoveries at low redshift (*14*), diligent follow-up (*15*), and a growing body of well-observed cases to compare with the high-redshift data (*16, 17*). In addition, recent results (*18*) independently confirm the 1998 results, whereas the analysis of supernovae and their host galaxies (*19*) showed persuasively that uncorrected extinction by dust in galaxies, a possible source of systematic error, most likely does not produce the observed dimming of distant SN Ia's.

The published sample of high-z supernovae has now been extended to the decisive redshift range of $z \sim 1$ (*18, 20, 21*), where the effects of cosmology begin to change sign from making supernovae dim to making them a little brighter than they would otherwise appear. These observations sample directly the epoch when the balance between dark energy and dark matter tilted from cosmic deceleration because of dark matter to cosmic acceleration caused by dark energy. This opens the prospect of learning how the dark energy behaves as the universe expands on the basis of careful observations in the era at the onset of cosmic acceleration.

Improved evidence for dark energy from supernovae has boosted these results from a startling possibility to conventional wisdom in just the past 5 years. The general acceptance of this new picture of a universe dominated by dark energy derives from the neat fit of supernova data with other cosmological measurements, including galaxy clustering as a measure of dark matter, the ages of stars, and measurements of the CMB. Each of these strands in the web of inference has grown more secure, and the pleasant result has been a trend toward greater concordance from independent directions. These results converge on a universe that is 13.6 ± 1.5 billion years old and expanding at a present rate of 72 ± 8 km s^{-1} Mpc^{-1}, which is composed of 28 ± 5% matter and 72% dark energy (*18, 22*) (Fig. 1).

Nature of the Dark Energy

One possible explanation is that dark energy is the modern version of Einstein's cosmological constant (*23–25*). In 1917, Einstein introduced a curvature term to produce static, eternal solutions to his field equations, in accord with the view then current that the Milky Way was the entire universe and the observational fact that the motions of its stars showed no systematic expansion or contraction. Legend holds that Einstein, after learning of Hubble's work on cosmic expansion based on galaxies outside the Milky Way, smote himself on the forehead and declared the cosmological constant his greatest

Fig. 1. The concordance diagram. In blue, 1-, 2-, and 3σ confidence contours for Ω_Λ and Ω_m based on 172 SN Ia's from (*18*). The smaller orange error ellipses result from combining supernova data with information from large-scale structures in a flat universe (*49, 50*).

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1914 20 JUNE 2003 VOL 300 SCIENCE www.sciencemag.org

Conclusions

- Supernovae trace the history of cosmic expansion to infer the properties of the dark energy
- Coming soon: more precise data on era of acceleration (z <1)
- Also coming soon: data on era of deceleration (z >1)
- A bright future for dark energy