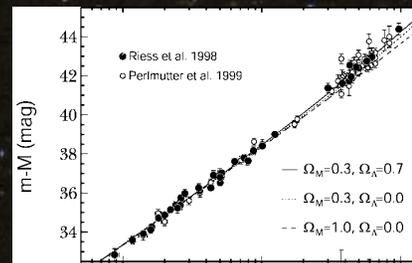


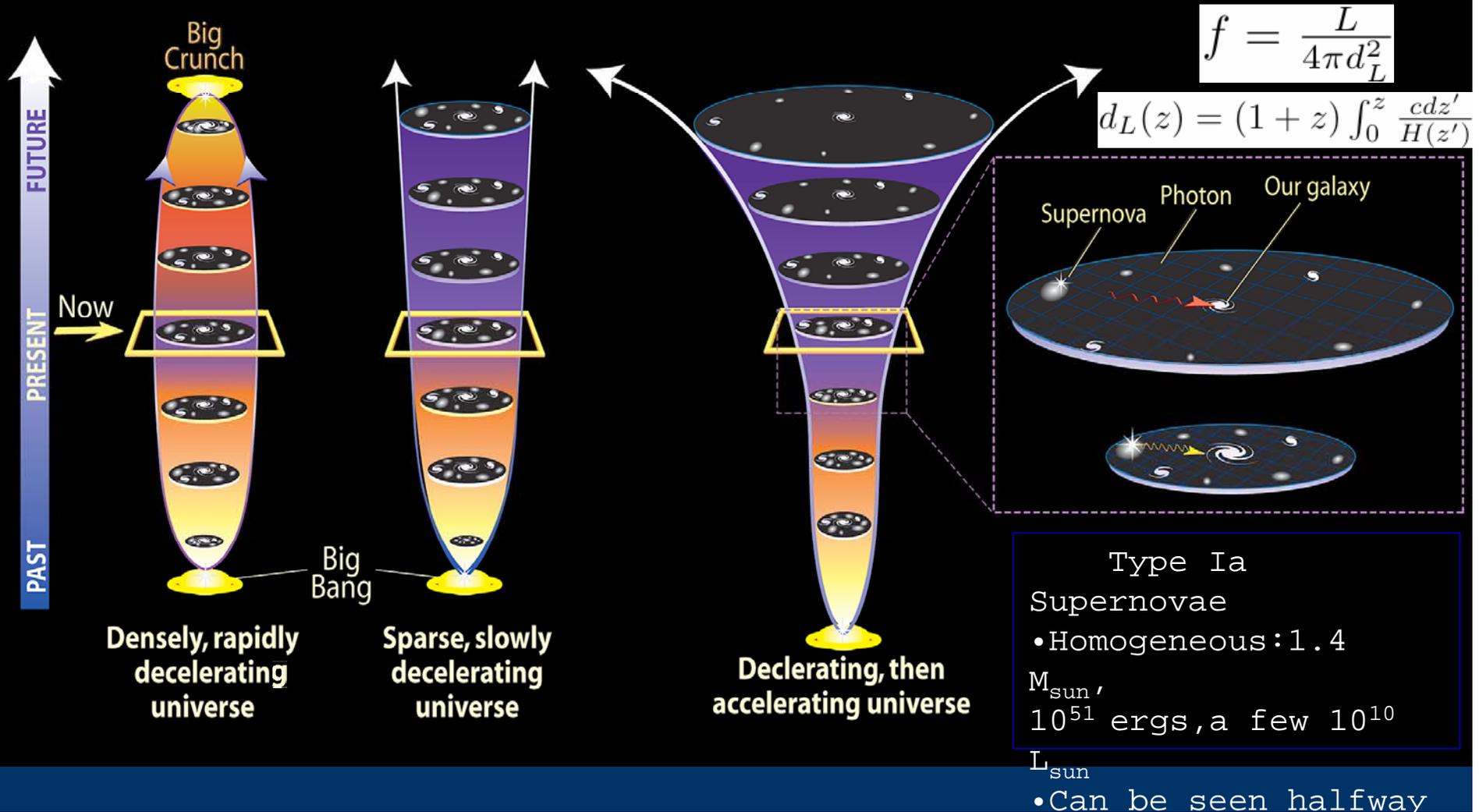
The History of Cosmic Expansion from Supernovae Near and Far

Adam G. Riess

*Johns Hopkins University and
Space Telescope Science Institute*



Models of the Expanding Universe



The Accelerating Universe

By 1998 two teams measured >100 SNe Ia at $0.01 < z < 1.0$
Surprise!

The U

THE ASTRONOMICAL JOURNAL, 116:1009–1038, 1998 September
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High-z

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

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Received 1998 March 13; revised 1998 May 6

THE ASTROPHYSICAL JOURNAL, 517:565–586, 1999 June 1
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SCP

MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

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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
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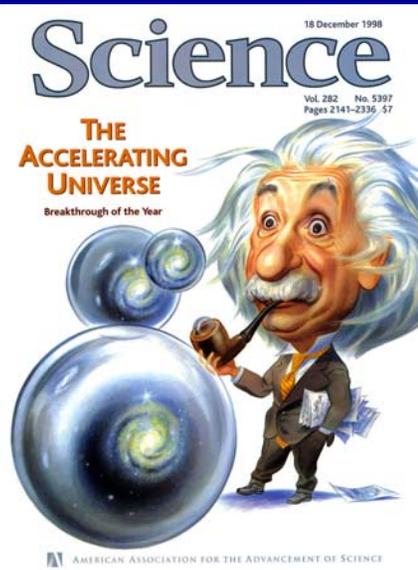
R. S. ELLIS, M. IRWIN, AND R. G. McMAHON
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Department of Astronomy, University of Barcelona, Barcelona, Spain

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Hubble *Higher-z* Team

- Using HST, find and measure type Ia supernovae at $0.9 < z < 1.7$
- To look for evidence of preceding deceleration (i.e., **conf**)
 - Characterize the nature of dark energy (i.e., its equation)

**Awarded 134 (+399 with GOODS) orbits in 2002-2003,
90 orbits in 2003-2004 and 270 Orbits in 2004-2005**

P.I. Riess (STScI),
Ferguson (STScI)
Strolger (STScI), Tonry (UH)
Filippenko (UCB), Jha (UCB),
Li (UCB), Kirshner, (CfA)
Challis, (CfA), Casertano,
(STScI)
Dickinson (STScI), Giavalisco



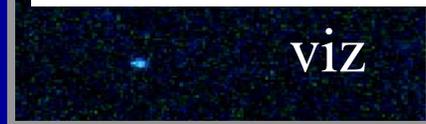
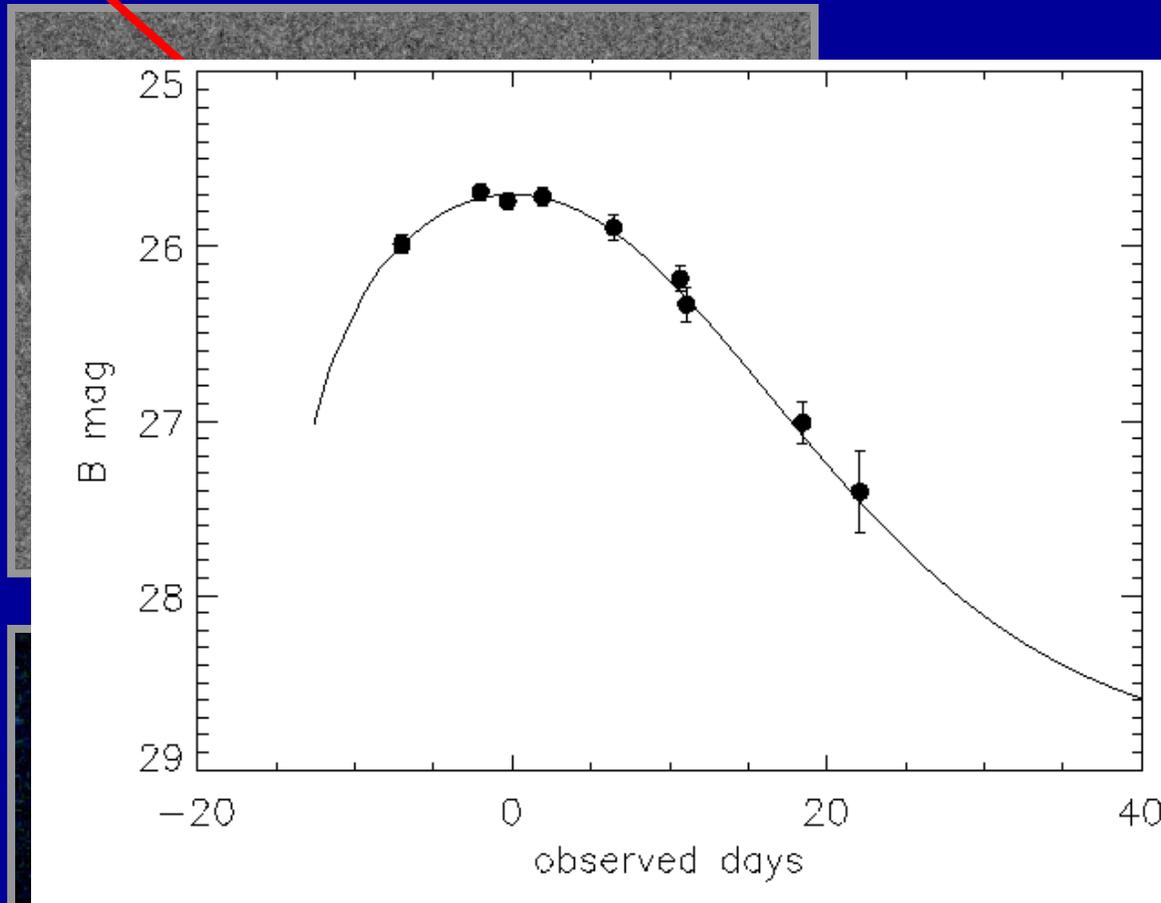
Innovations Required: ToO without spectral confirmation via
host phot-z's, U-band LC, grism spectroscopy with HST (Ries

Our first higher-z SN Ia, Aphrodite

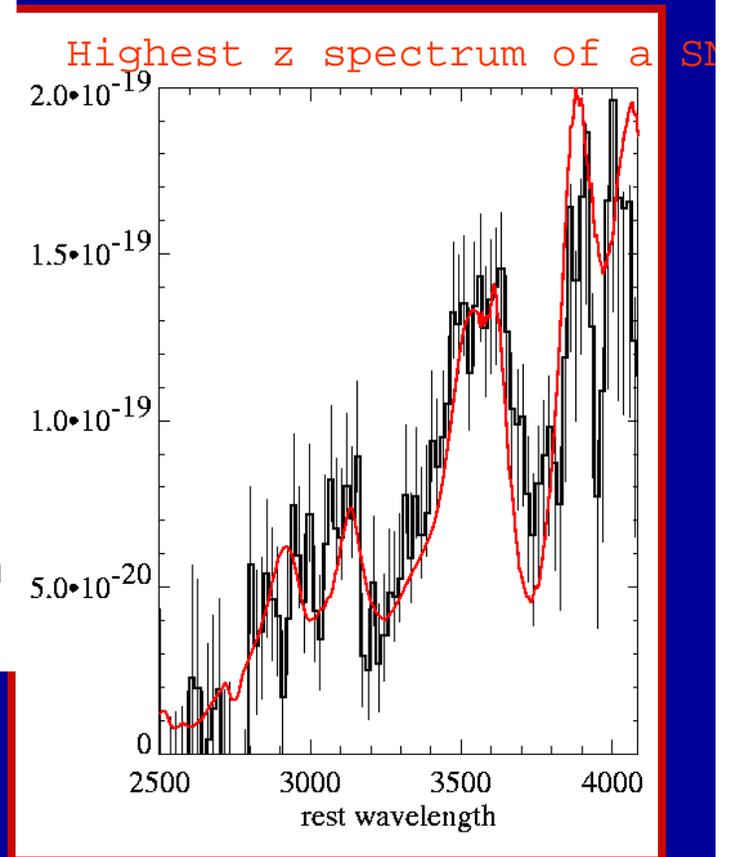
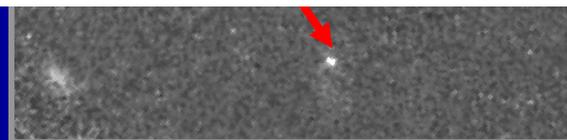
Aphrodite ($z=1.3$)



ACS grism spectrum



viz

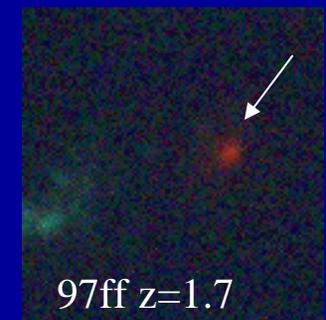
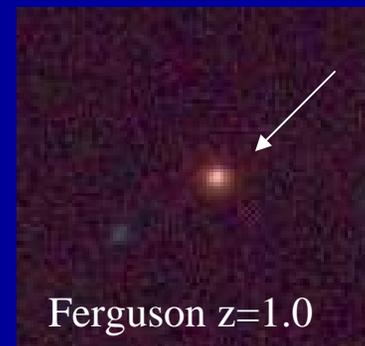
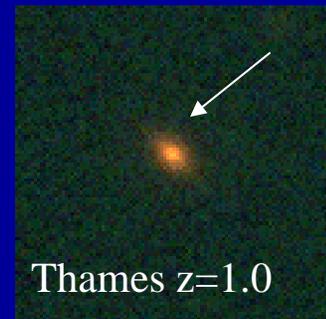
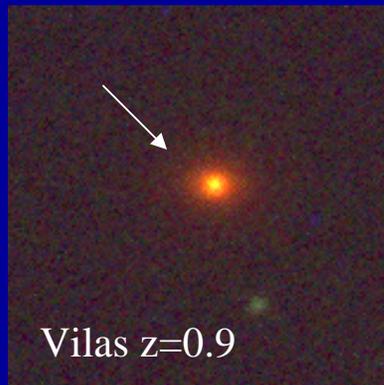
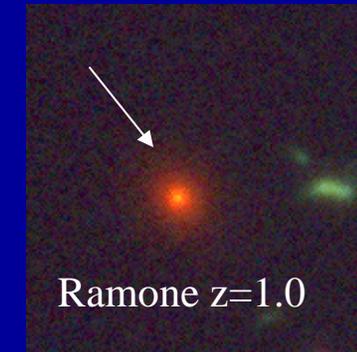
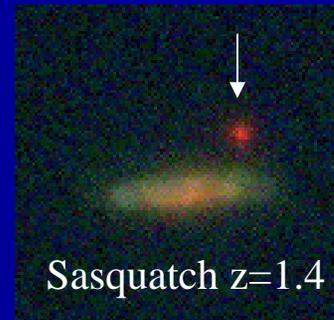
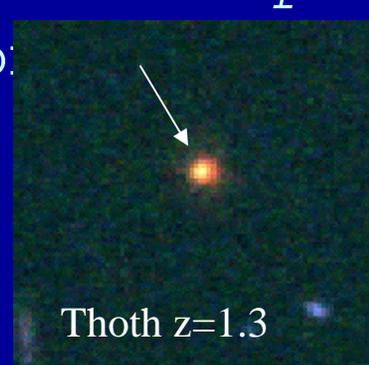
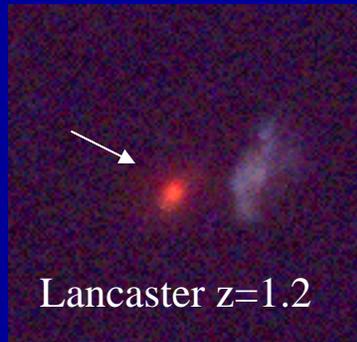


3 cycles

135 SNe of all types, ~50 SNe Ia, ~25 SNe Ia at $z > 1$

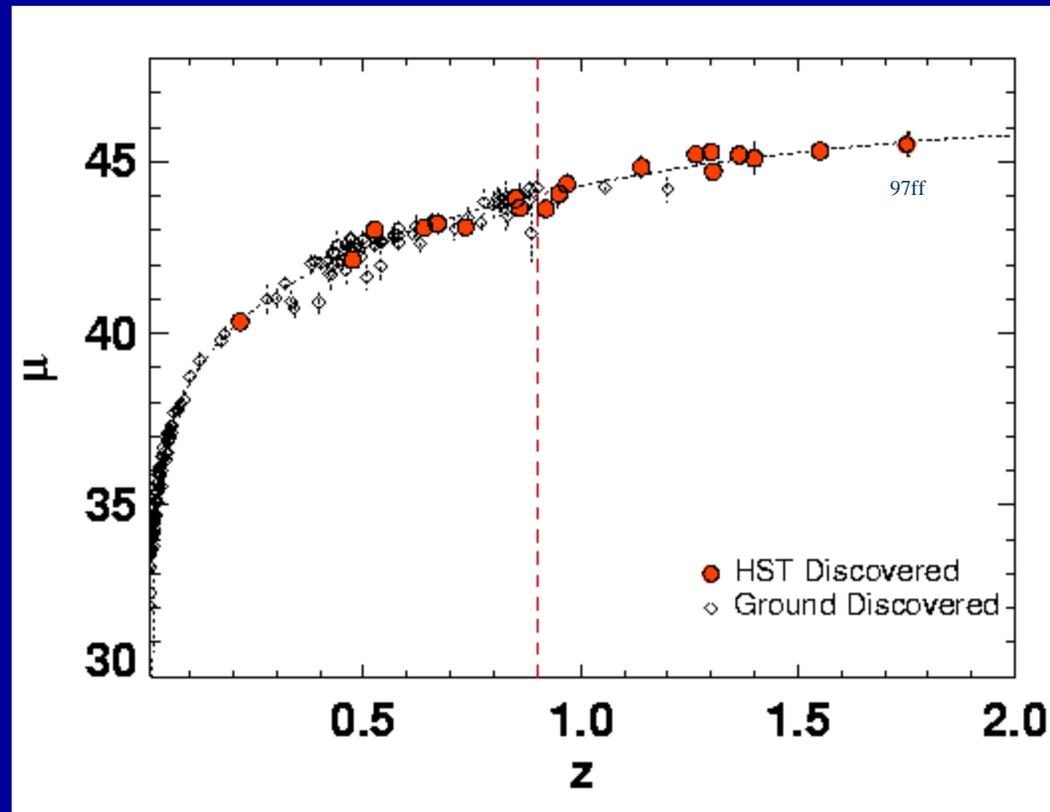
~10 SN Ia in *Elliptical* Hosts (low dust

content) in the redshift range $0.9 < z < 1.7$



The New SN Ia Hubble Diagram (Riess et al. 2004)

6 of the 7
highest
redshift
SNe Ia
(2003)

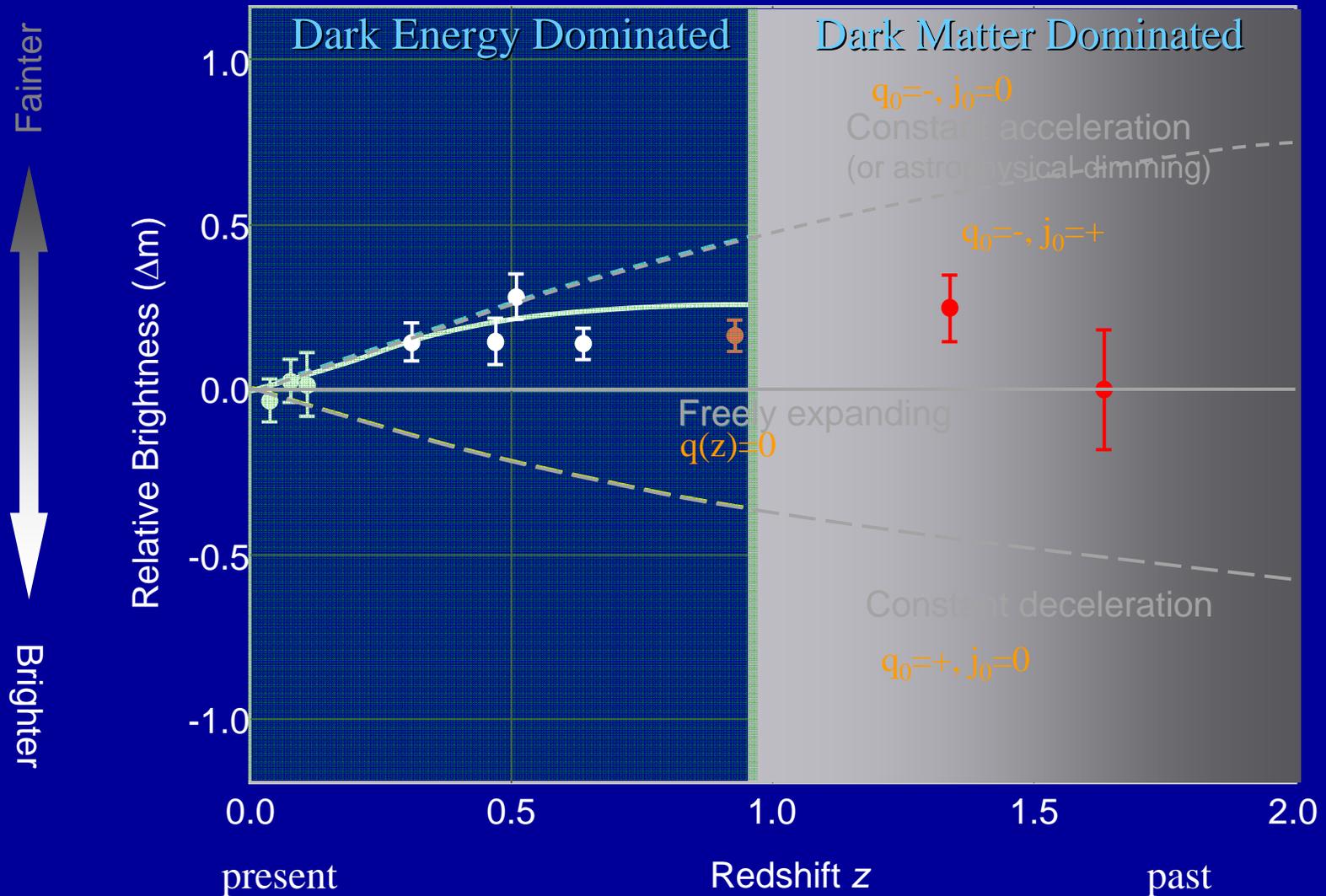


2005: 19
of the
20 highest
Redshift
SNe known

High Redshift SN and Expansion

History

Taylor Expansion of the left handside of the Friedman Eq: $a(t)$
 $d_l(z, H_0, q_0, j_0) = \frac{cz}{H_0} \left[1 + \frac{1}{2}(1-q_0)z - \frac{1}{6}(1-q_0-3q_0^2+j_0)z^2 + O(z^3) \right]$ $H(t) = \dot{a}/a, q(t) = -(\ddot{a}/a)(\dot{a}/a)^{-2}, j(t) = (\dddot{a}/a)(\dot{a}/a)^{-3}$



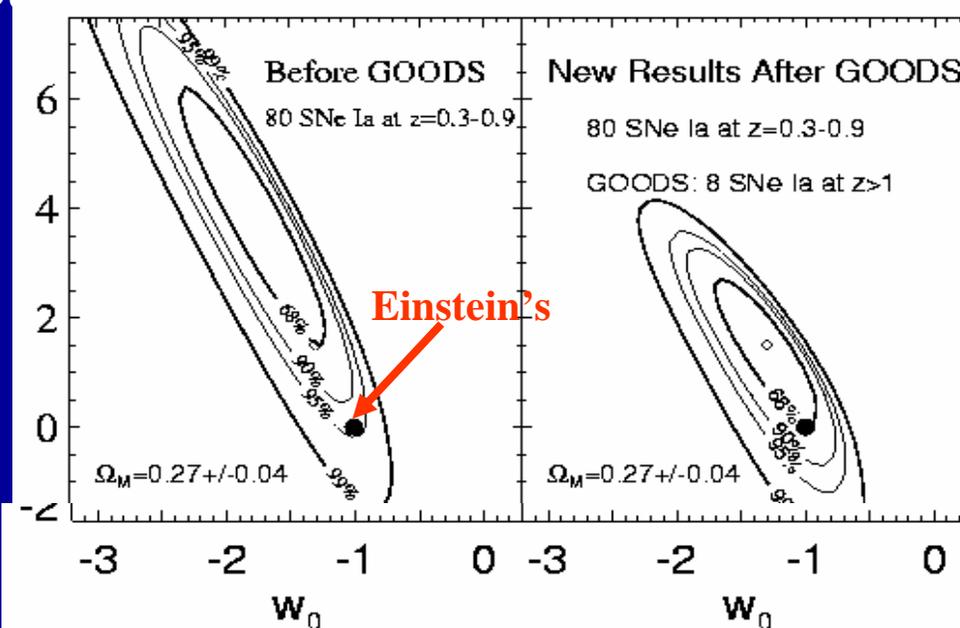
Probing Dark Energy

Two fundamental properties/clues of dark energy:
 its strength, $w_0=w(z=0)$ AND is it dynamic or static
 i.e. is $w'=dw/dz=0$?

$$d_L = \frac{c}{H_0} (1+z) \left\{ \int_0^z dz' \left[(1+z')^3 \Omega_M + (1-\Omega_M)(1+z')^{3(1+w_0-w')} e^{3w'z'} \right]^{-1/2} \right\}$$

- We have doubled our knowledge of w_0 and w' in 1 year with HST
- Einstein's model now looks better than ever,
- We should double our current progress again in upcoming publication of latest SNe stay tuned!

w'



Two SN-based Routes to Constraining Dark Energy

More SNe Ia

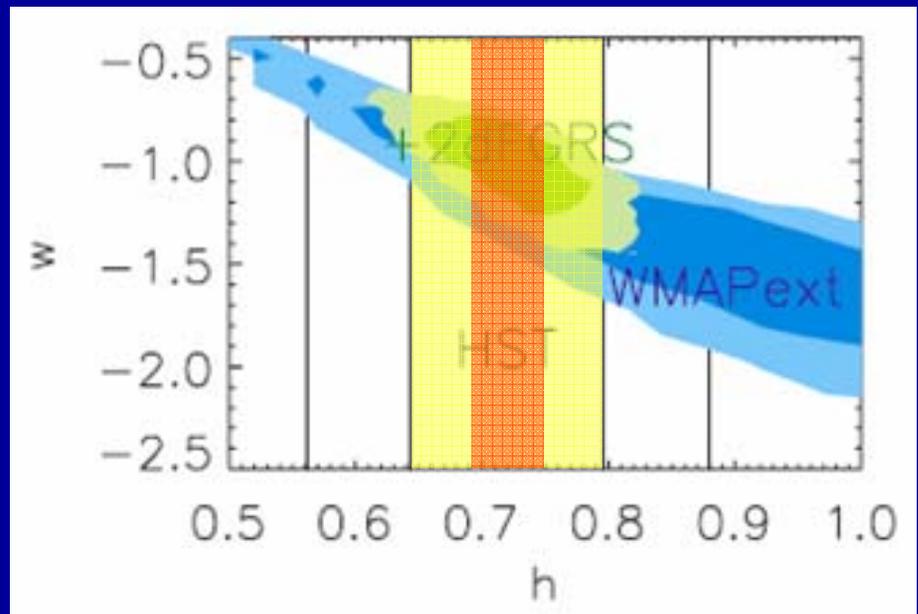
More precise

H_0
"Single most important complement to the CMB for measuring the dark energy equation of state is a determination of H_0 Constant to better than a few percent." Wayne Hu, astro

Projected
ESSENCE
5 yrs

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

.8

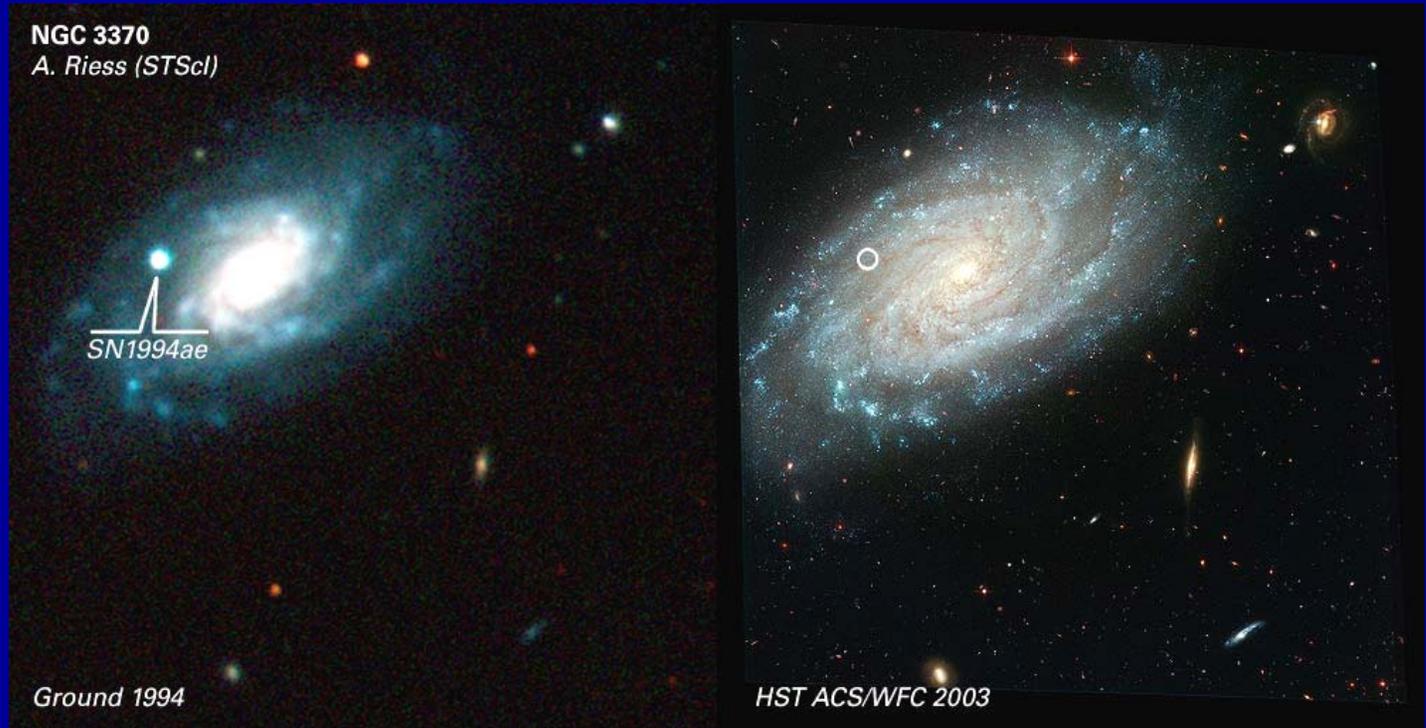


- updating SN Ia $M_{V,B}$ calibration
- replace LMC with NGC4258

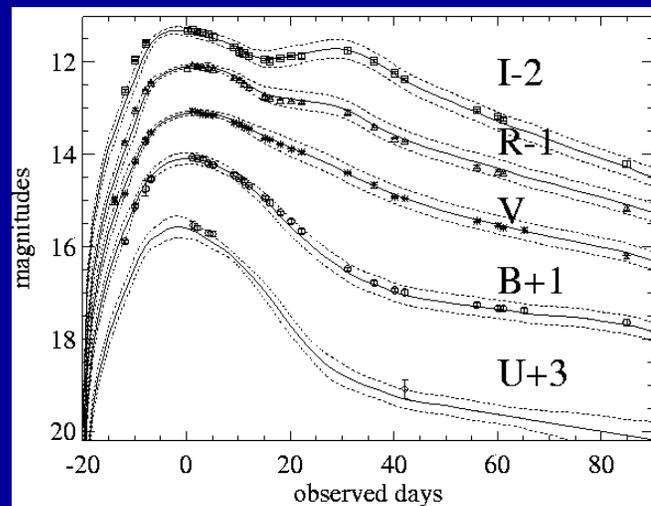
's SN-
Calibration
of H_0 from
1937C!

ACS
Provides
for a
Reliable
Recalibrati
on of H_0
from *Modern*
SNe Ia

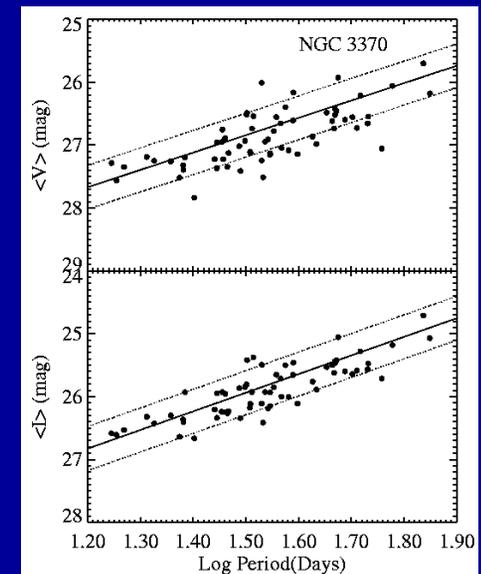
With HST we
are now
calibrating
4 from
1990's and



Ground: SN 1994ae

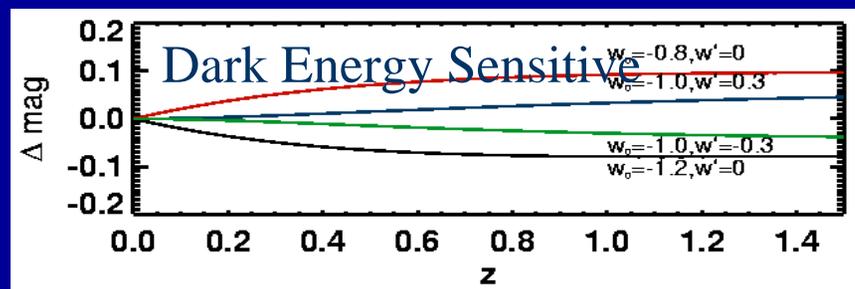


ACS: Cepheids

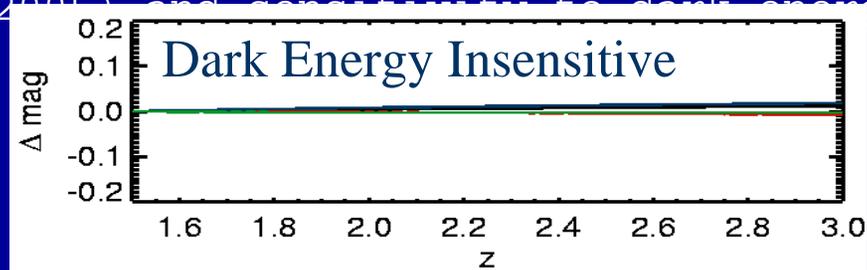


A New Approach to Taming Possible SN Ia Evolution in JDEM SN-Dark Energy Studies (Riess and Livio, *in prep*)

- JDEM mission concepts (e.g., SNAP) propose to average 1000's of SNe Ia at $0 < z < 1.5$ to measure the eq. of state of DE



- Such measurements will rely on our ability to detect and calibrate possible SN Ia evolution to $\sim 1\%$
- A powerful method to do this is to observe SNe Ia at even higher redshifts, $1.5 < z < 3.0$, where sensitivity to evolution is *increased* (e.g., global metallicity evolves by at least as much as at $z < 1.5$, Kulkarni et al. 2005) and sensitivity to dark energy is *decreased*



- Such observations require flux measurements at $25 < H \ \& \ K < 27$ mag, well within reach of JWST, JWST should be able to measure 100's such SNe Ia

Summary :

- SNe Ia are being used to trace the history of cosmic expansion; they reveal present, cosmic acceleration and the need for Dark Energy
- With HST we have discovered the highest redshift SNe Ia; they show a preceding epoch of decelerating expansion (as predicted by the Λ CDM model) thus confirming the reality of acceleration
- With growing precision, SNe Ia at all redshifts are being used to determine the equation of state of dark energy (value and evolution) and should, in the future, help determine the nature of Dark Energy and perhaps the fate of the Universe.
- Additional studies of SNe Ia locally to improve the calibration and at the ever higher redshifts to trace evolution are important for continued progress in Dark Energy studies