Dark Energy:
Present and Future Observations

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The *History* of Cosmic Expansion

Observations
- The Universe is Expanding.
- CMB -> Hot Big Bang! (inflation)

Theory & Principles (corroborated by observations)
- General Relativity
- Homogeneous & isotropic on large scales

Friedman Equation: Equation of Motion for Universe

$$H^2 \equiv \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3}\rho_M + \frac{\Lambda}{3} - \frac{k}{R^2}$$

(Dark) Matter

$$\Omega_{\mathrm{M}} \equiv \frac{8\pi G}{3\mathrm{H}_0^2}\rho_{\mathrm{M},0} \quad \Omega_\Lambda \equiv \frac{\Lambda}{3\mathrm{H}_0^2} \quad \Omega_k \equiv -\frac{k}{\mathrm{R}_0^2\mathrm{H}_0^2}$$

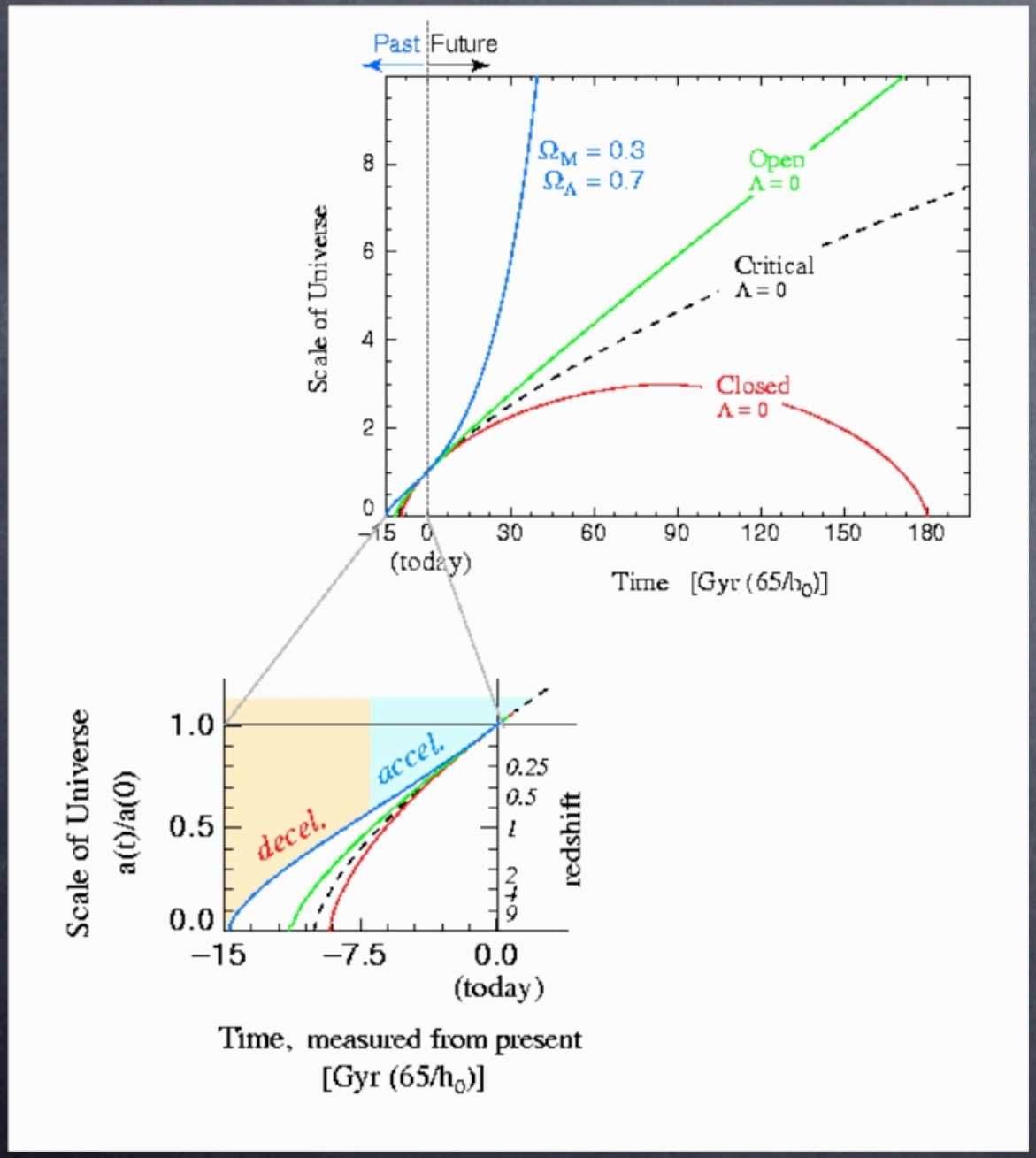
(Dark) Energy
Einstein's blunder?

$$\Omega_{\mathrm{M}} + \Omega_\Lambda + \Omega_k = -1, 0, +1$$

Geometry (Curvature)

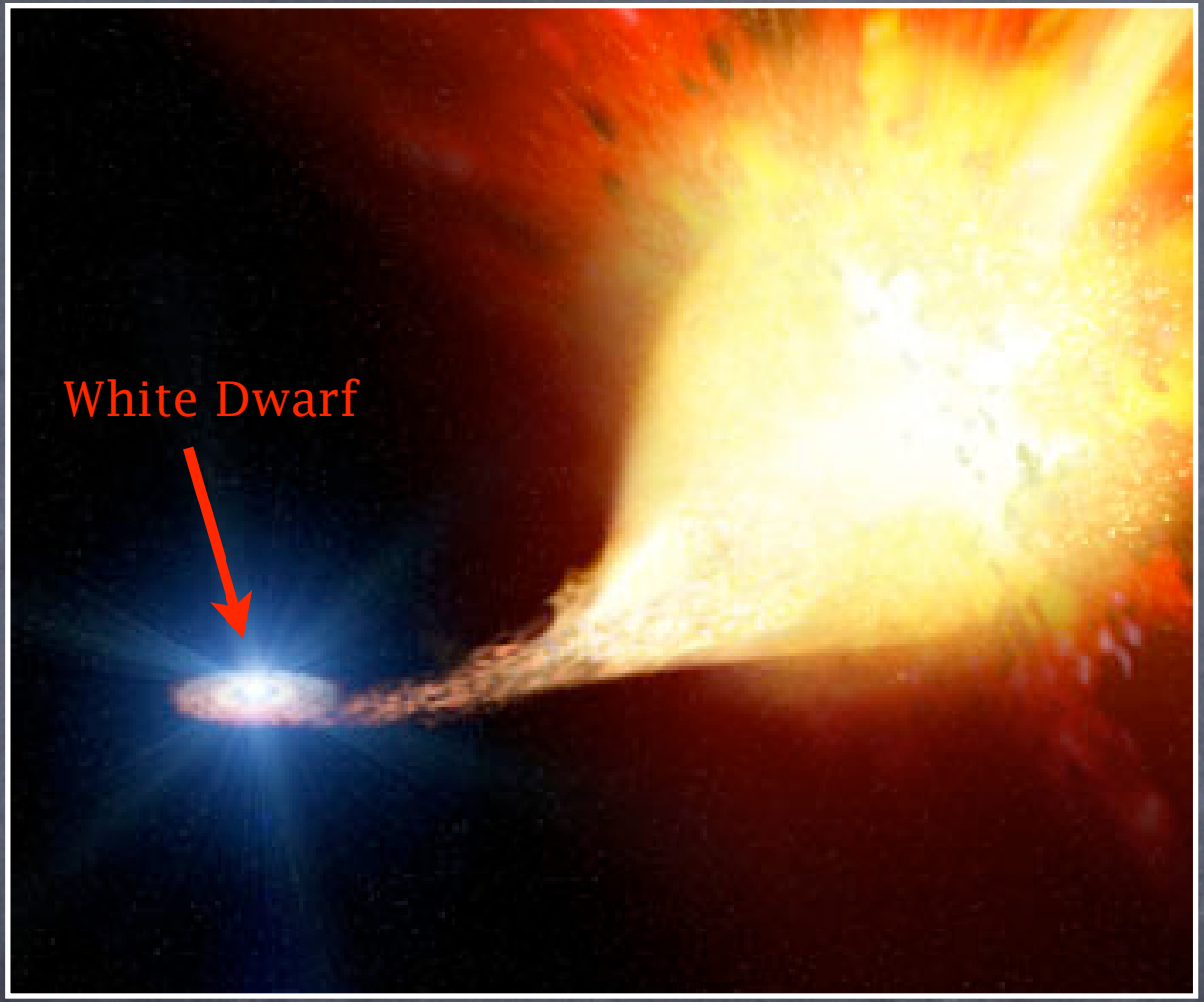
The Expansion History of the Universe

$$D_L = cH_0^{-1}(1+z)|\Omega_k|^{-1/2} S\left\{|\Omega_k|^{1/2}\int_0^z dz'[(1+z)^2(1+\Omega_M z)-z(2+z)\Omega_\Lambda]^{-1/2}\right\}$$

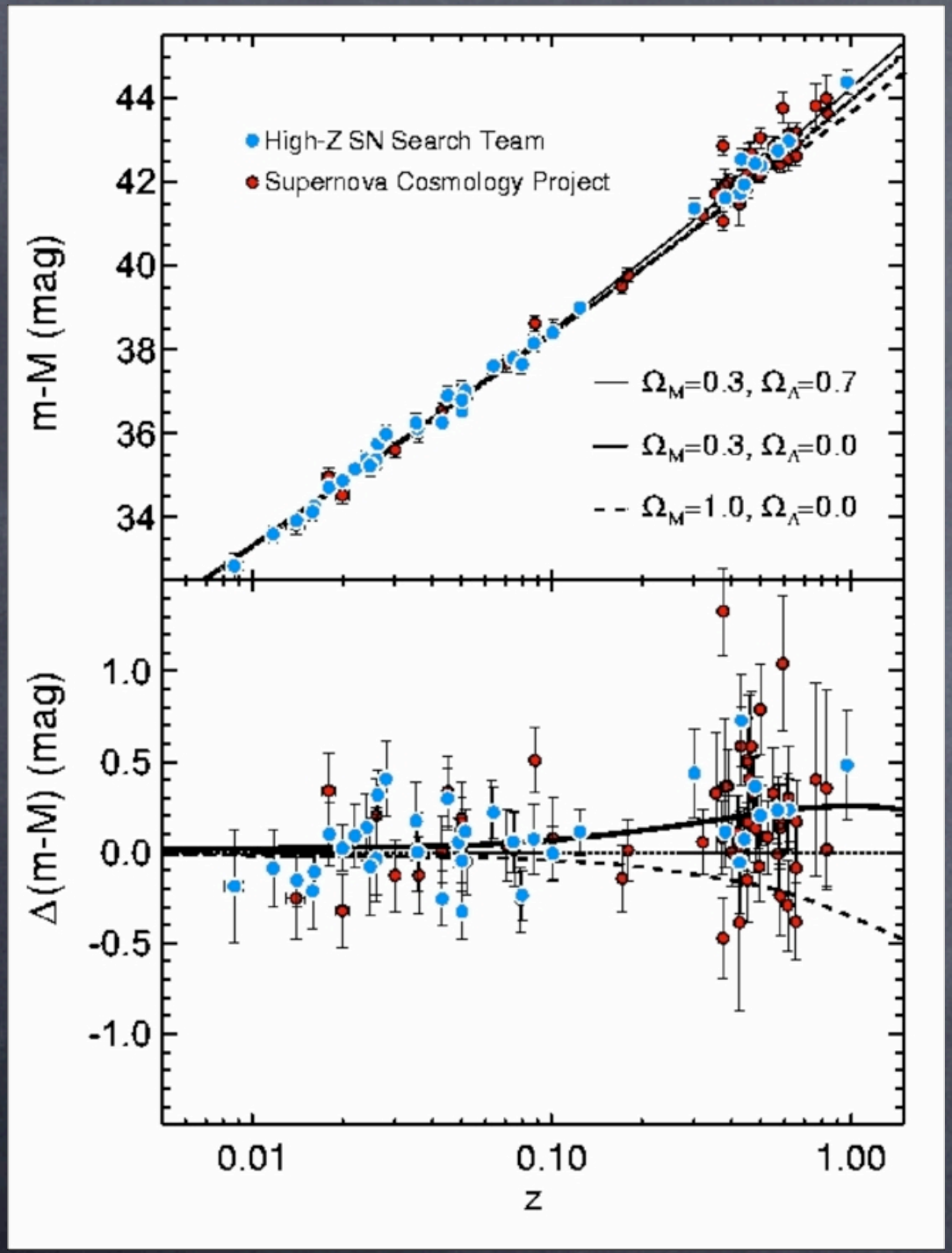


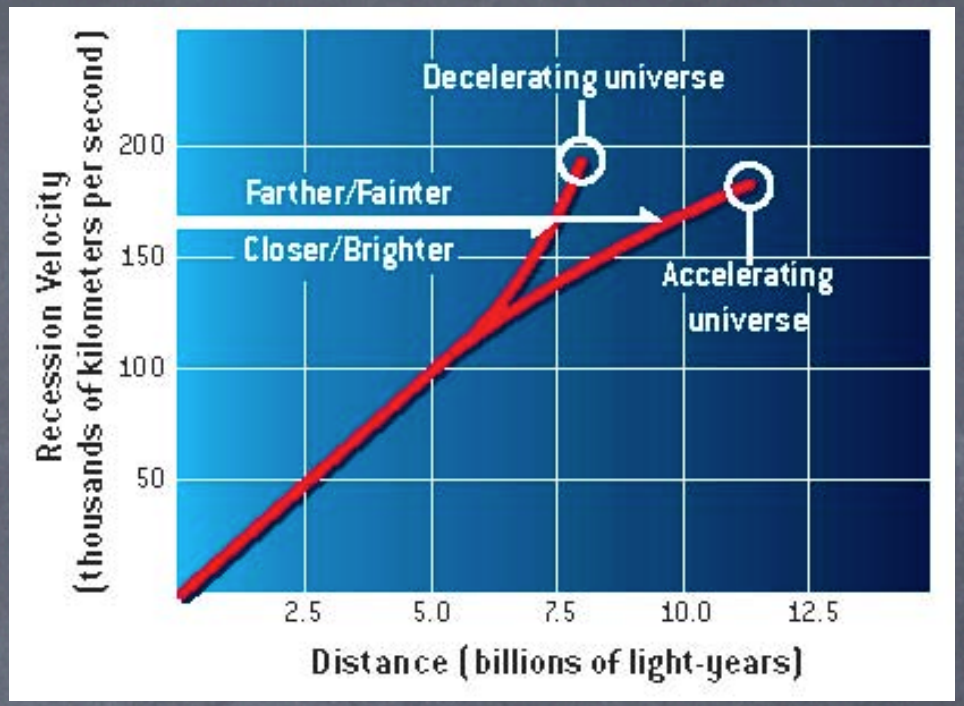
Mass is Destiny

How (we think) Nature Makes a Type Ia Supernova



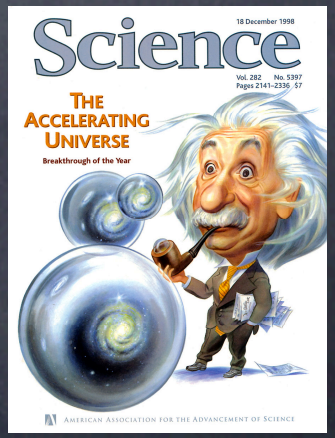
- Homogeneity: 1.4 $M_\odot$, 10^{51} ergs
- Negligible hydrogen, lots of Intermediate Mass Elements
- Mature progenitors
- Models (delayed-detonation) good fit to observations





↕ 25% fainter than

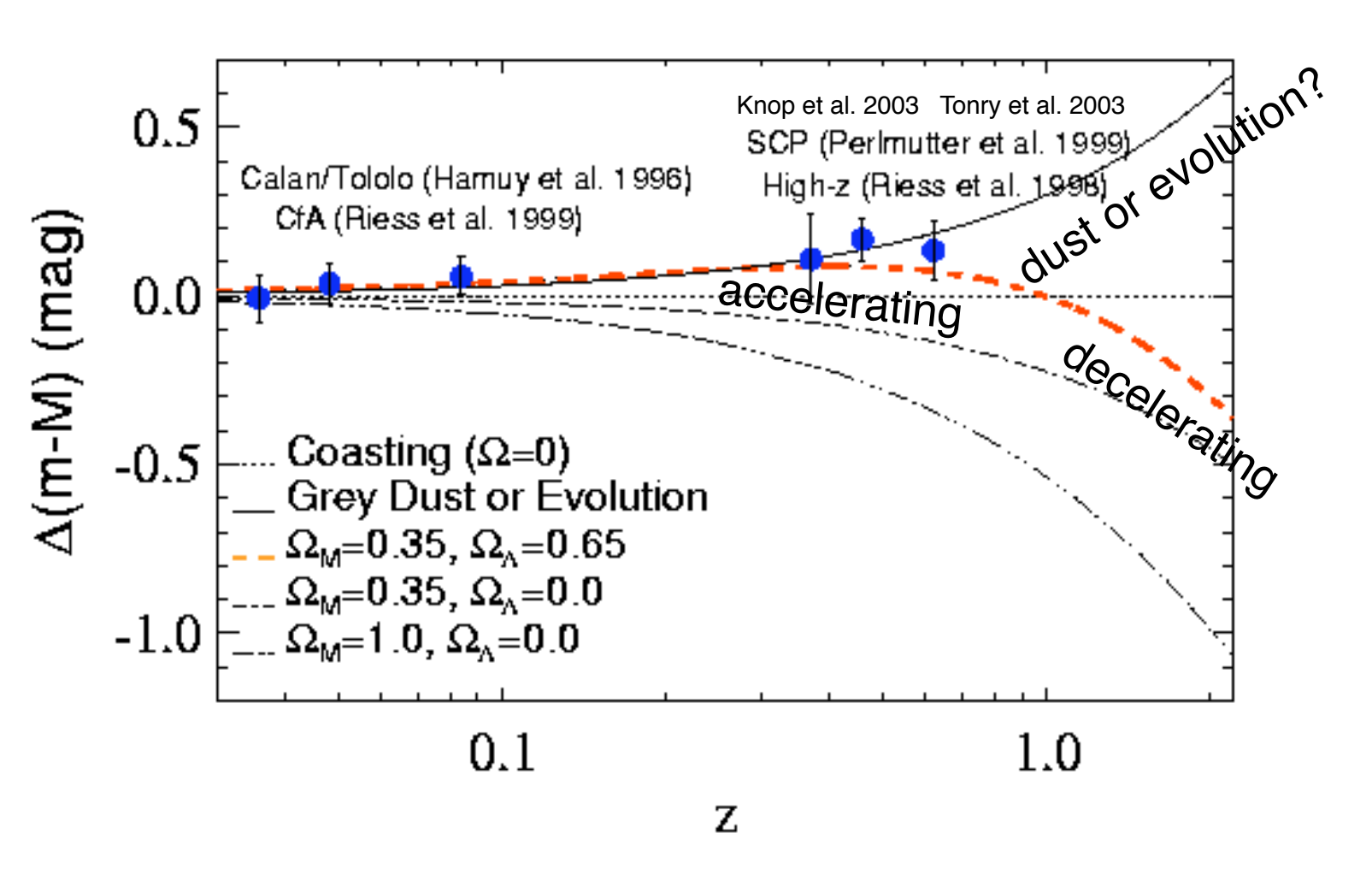
$\Omega_M = 0.3 \quad \Omega_\Lambda = 0.0$



Searching for the Epoch of Deceleration

$$\frac{\rho_M}{\rho_\Lambda} = \frac{\rho_{M,0}}{\rho_\Lambda}(1+z)^3$$

z	$\frac{\rho_M}{\rho_\Lambda}$
0.0	0.4
0.4	1.0
0.8	2.3
1.2	4.3
1.7	8.0



The GOODS ACS Treasury Program…

Type Ia Supernova Discoveries at $z > 1$ From the *Hubble Space Telescope*: Evidence for Past Deceleration and Constraints on Dark-Energy Evolution[1]

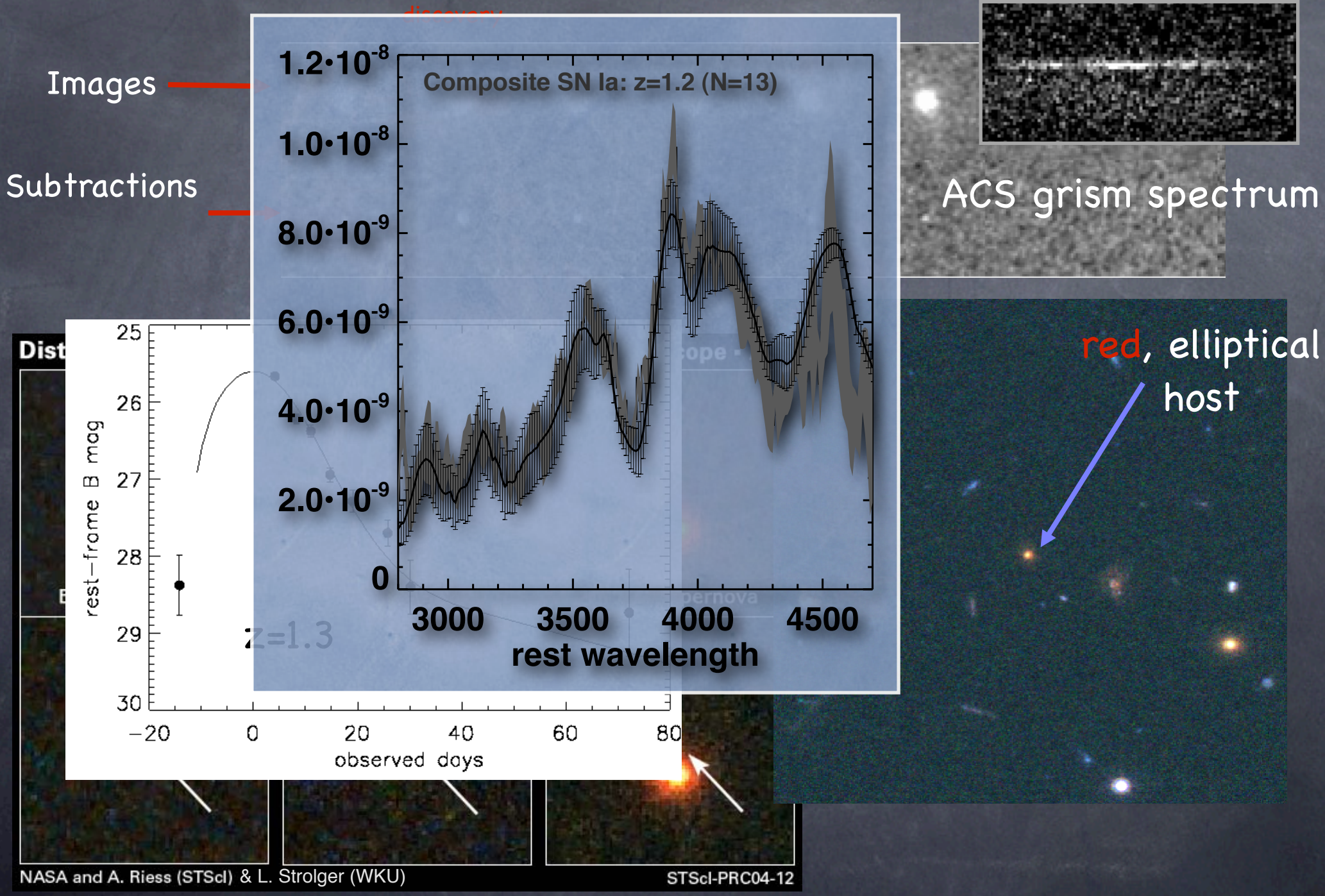
Adam G. Riess[2], Louis-Gregory Strolger[2], John Tonry[3], Stefano Casertano[2], Henry C. Ferguson[2], Bahram Mobasher[2], Peter Challis[4], Alexei V. Filippenko[5], Saurabh Jha[5], Weidong Li[5], Ryan Chornock[5], Robert P. Kirshner[4], Bruno Leibundgut[6], Mark Dickinson[2], Mario Livio[2], Mauro Giavalisco[2], Chuck Steidel[7], Txitxo Benitez[8] and Zlatan Tsvetanov[8]

THE HUBBLE HIGHER-z SUPERNOVA SEARCH: SUPERNOVAE TO $z \approx 1.6$ AND CONSTRAINTS ON TYPE Ia PROGENITOR MODELS [a]

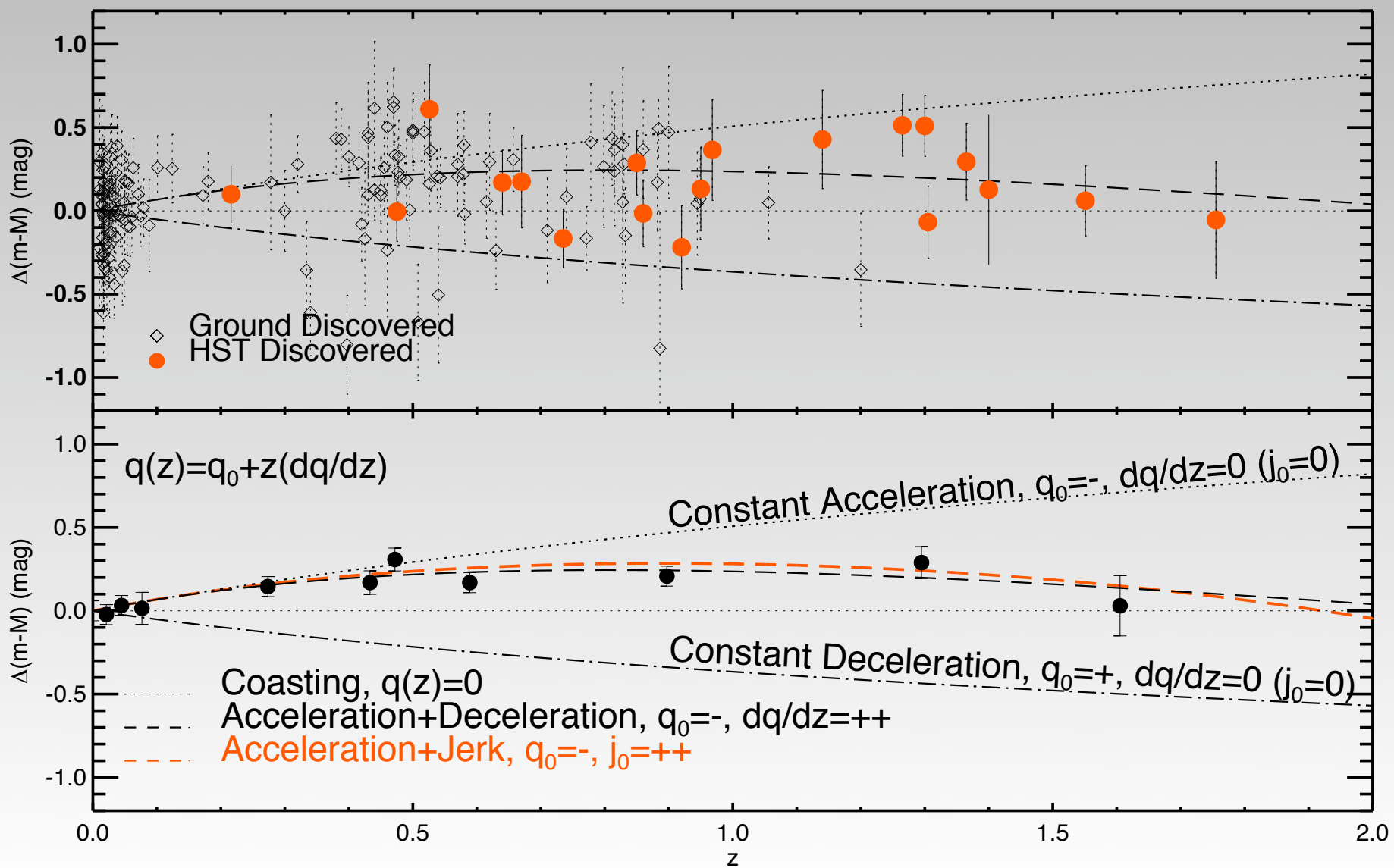
Louis-Gregory Strolger[2], Adam G. Riess[2], Tomas Dahlen[2], Mario Livio[2], Nino Panagia[2,3], Peter Challis[4], John L. Tonry[5], Alexei V. Filippenko[6], Ryan Chornock[6], Henry Ferguson[2], Anton Koekemoer[2], Bahram Mobasher[2,3], Mark Dickinson[2], Mauro Giavalisco[2], Stefano Casertano[2], Richard Hook[7], Stephane Blondin[8], Bruno Leibundgut[8], Mario Nonino[9], Piero Rosati[8], Hyron Spinrad[6], Charles C. Steidel[10], Daniel Stern[11], Peter M. Garnavich[12], Thomas Matheson[4], Norman Grogin[13], Ann Hornschemeier[13], Claudia Kretchmer[13], Victoria G. Laidler[14], Kyoungsoo Lee[13], Ray Lucas[2], Duilia de Mello[13], Leonidas A. Moustakas[2], Swara Ravindranath[2], Marin Richardson[2], and Edward Taylor[15]

Year 1	399 orbits: Deep extragalactic studies 134 orbits: ToO 6 - 8 SNe at 1.2 < z < 1.8
Year 2	260 orbits w/ Supernova Cosmology Project!
Year 3	360 orbits for supernova studies.
Year 4	parallel data survey (incl. UDF)
Year 5	186 orbits for high-z SNe AND H_0!

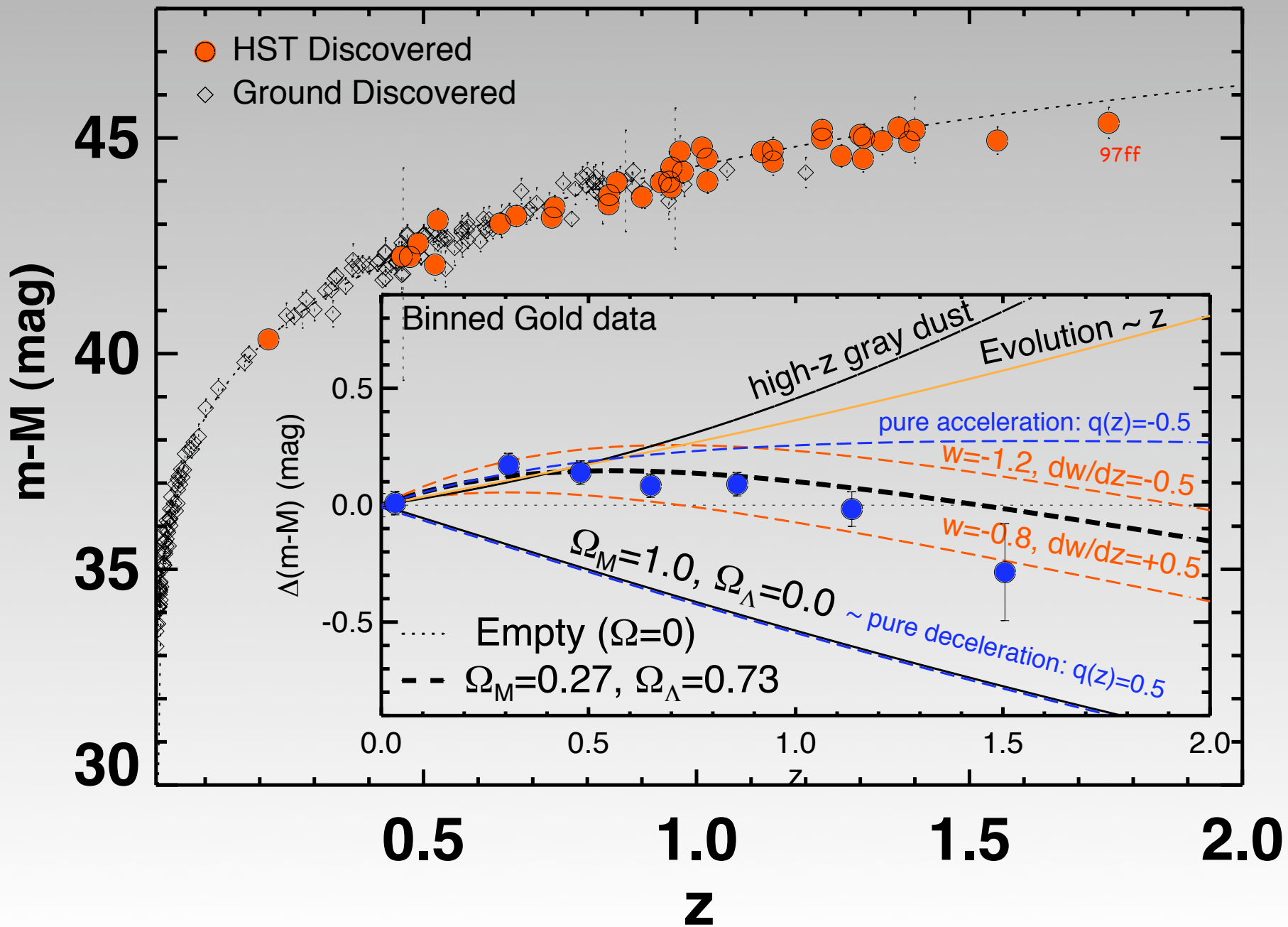
18% of HST time

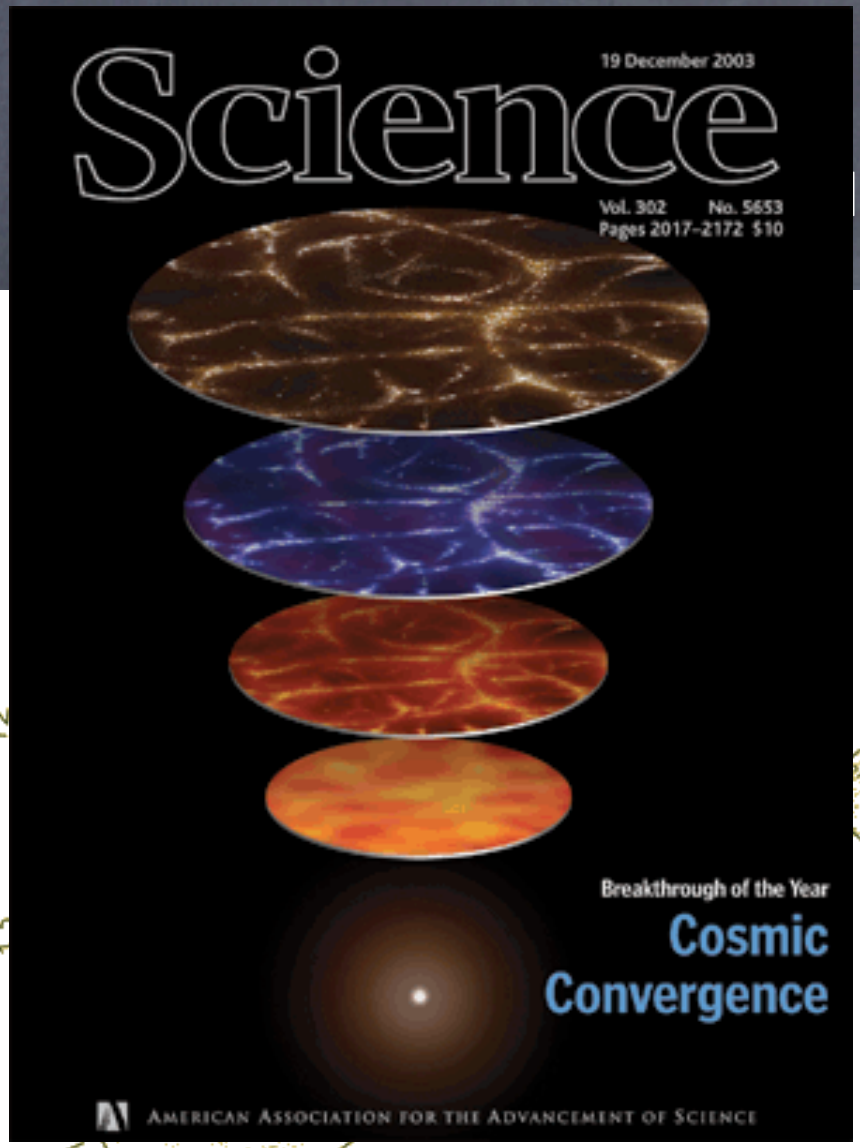

Images
Subtractions
Composite SN Ia: z=1.2 (N=13)
1.2·10^-8
1.0·10^-8
8.0·10^-9
6.0·10^-9
4.0·10^-9
2.0·10^-9
0
3000
3500
4000
4500
rest wavelength
ACS grism spectrum
red, elliptical host
rest−frame B mag
25
26
27
28
29
30
−20
0
20
40
60
80
observed days
z=1.3
NASA and A. Riess (STScI) & L. Strolger (WKU)
STScI-PRC04-12

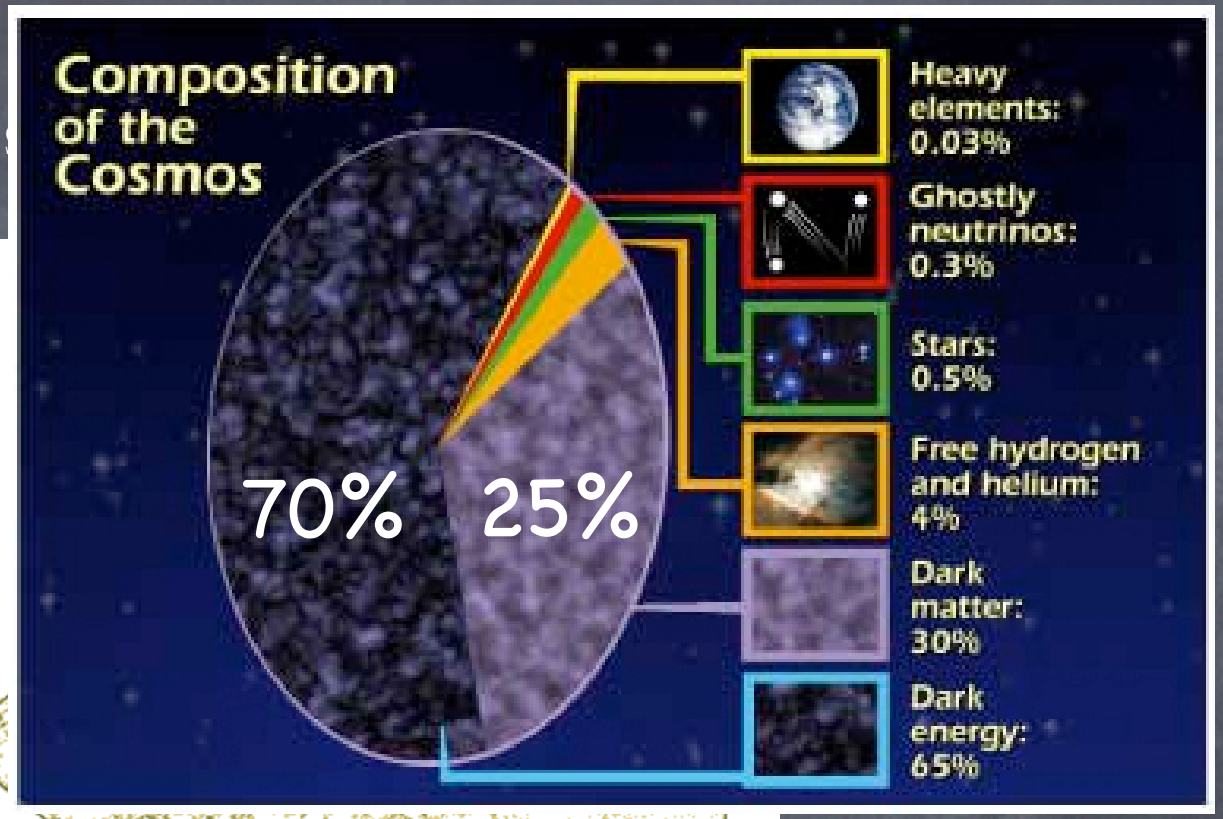
A Cosmic Jerk:
Deceleration gave way to Acceleration,



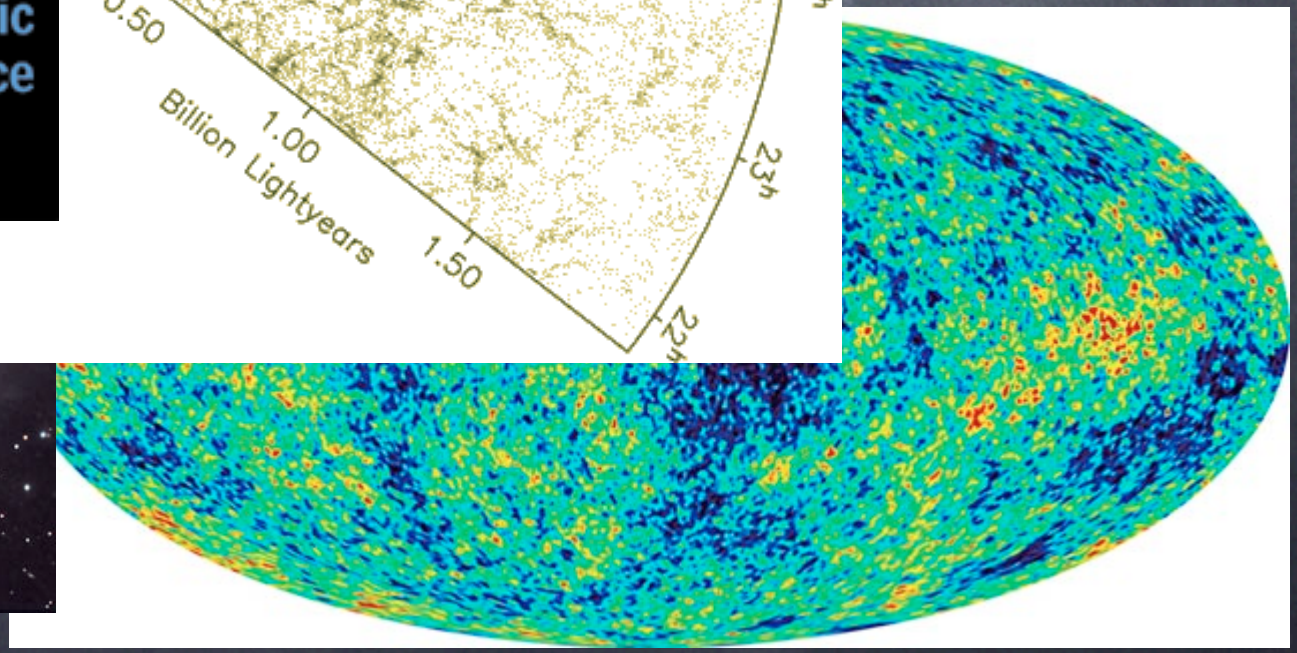
The New SN Ia Hubble Diagram

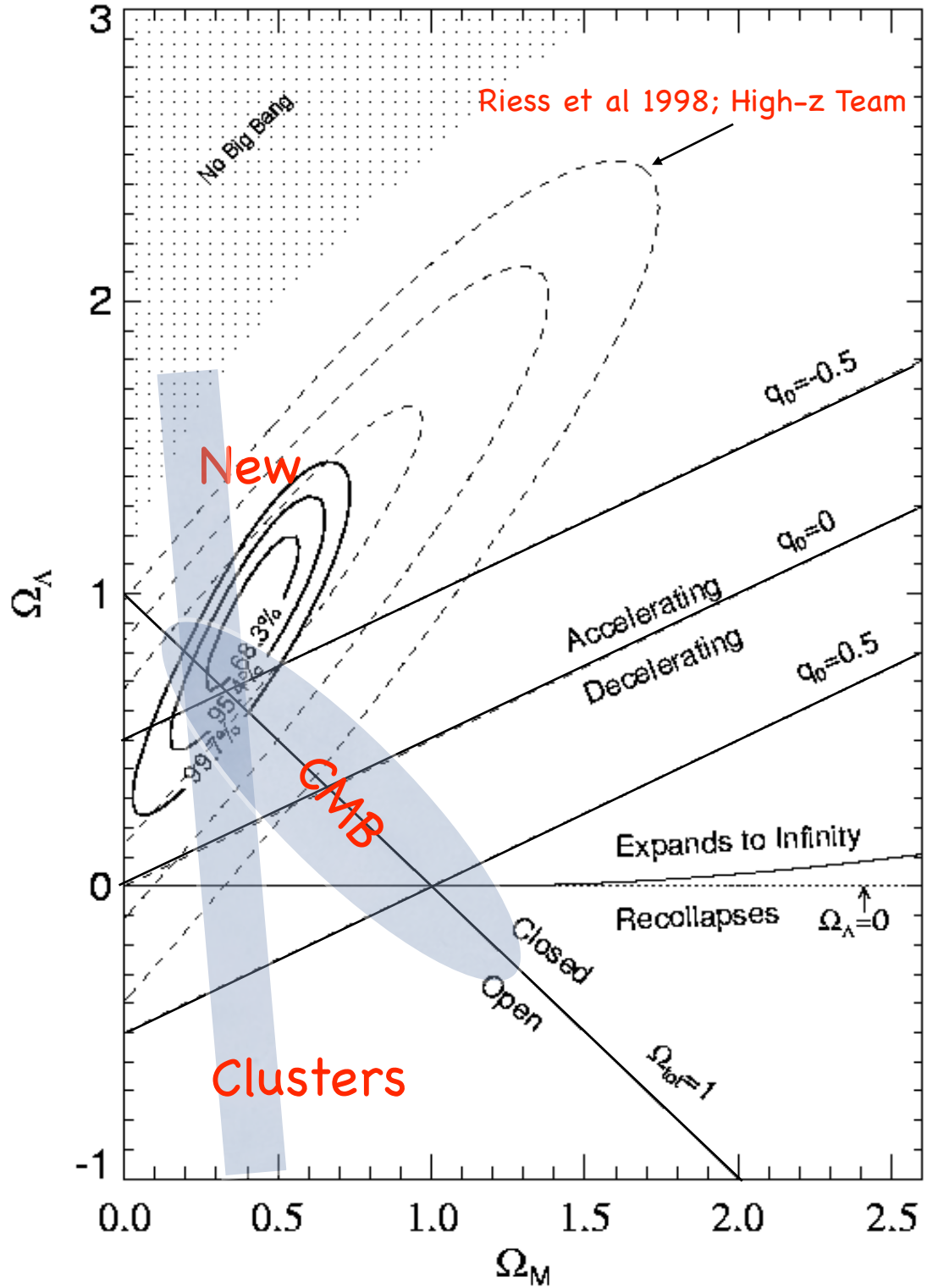



Science
19 December 2003
Vol. 302 No. 5653
Pages 2017–2172 $10
Breakthrough of the Year
Cosmic Convergence
American Association for the Advancement of Science


Composition of the Cosmos
70%
25%
Heavy elements: 0.03%
Ghostly neutrinos: 0.3%
Stars: 0.5%
Free hydrogen and helium: 4%
Dark matter: 30%
Dark energy: 65%


0.50
1.00
1.50
Billion Lightyears




Riess et al 1998; High-z Team
No Big Bang
New
CMB
Clusters
q_0=-0.5
q_0=0
q_0=0.5
Accelerating
Decelerating
Expands to Infinity
Recollapses
Ω_Λ=0
Closed
Open
Ω_{tot}=1
68.3%
95.4%
99.7%
Ω_Λ
Ω_M
3
2
1
0
-1
0.0
0.5
1.0
1.5
2.0
2.5

Ω_Λ only describes $\rho_{\rm vac}$

If a perfect fluid (and constant),

then $U = P\Delta V$ says

$$P_{\rm vac} = -\rho_{\rm vac} c^2$$

Equation of state parameter reveals nature of Dark Energy!

$$w \equiv \frac{1}{c^2}\left(\frac{P}{\rho}\right)_{\rm vac}$$

$$w(z) = w_0 + w' z;\ w' \equiv \frac{dw}{dz} \qquad w(z) = w_0 + \frac{w_a z}{1+z}$$

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Dr. Suzanne Staggs
Princeton University

Dr. Nicholas Suntzeff
Texas A&M University

The Next Step: critical observations

- Galaxy Cluster counts (# of large structures)
- Baryon Acoustic Oscillations (BAO)
- Supernovae
- Weak Lensing

<u>And somewhat later:</u>

- Integrated Sachs-Wolfe effect
- GRBs as standard candles
- Gravitational Wave experiments

The Future...
Is NOW!

- SNLS, ESSENCE -- Constrains on **w** via supernovae <z>=0.5. SNLS already a 100's!
- SDSS -- constraints on Ω_M/growth of structure via CL & weak lensing, SN result expected.
- WMAP -- BAO, SZ, & critical distance to z=1089
- SHOES -- Simultaneous constraints on H_0 and w'(w_a) via supernovae & cepheids.

A little further down the road... < 5 yrs.

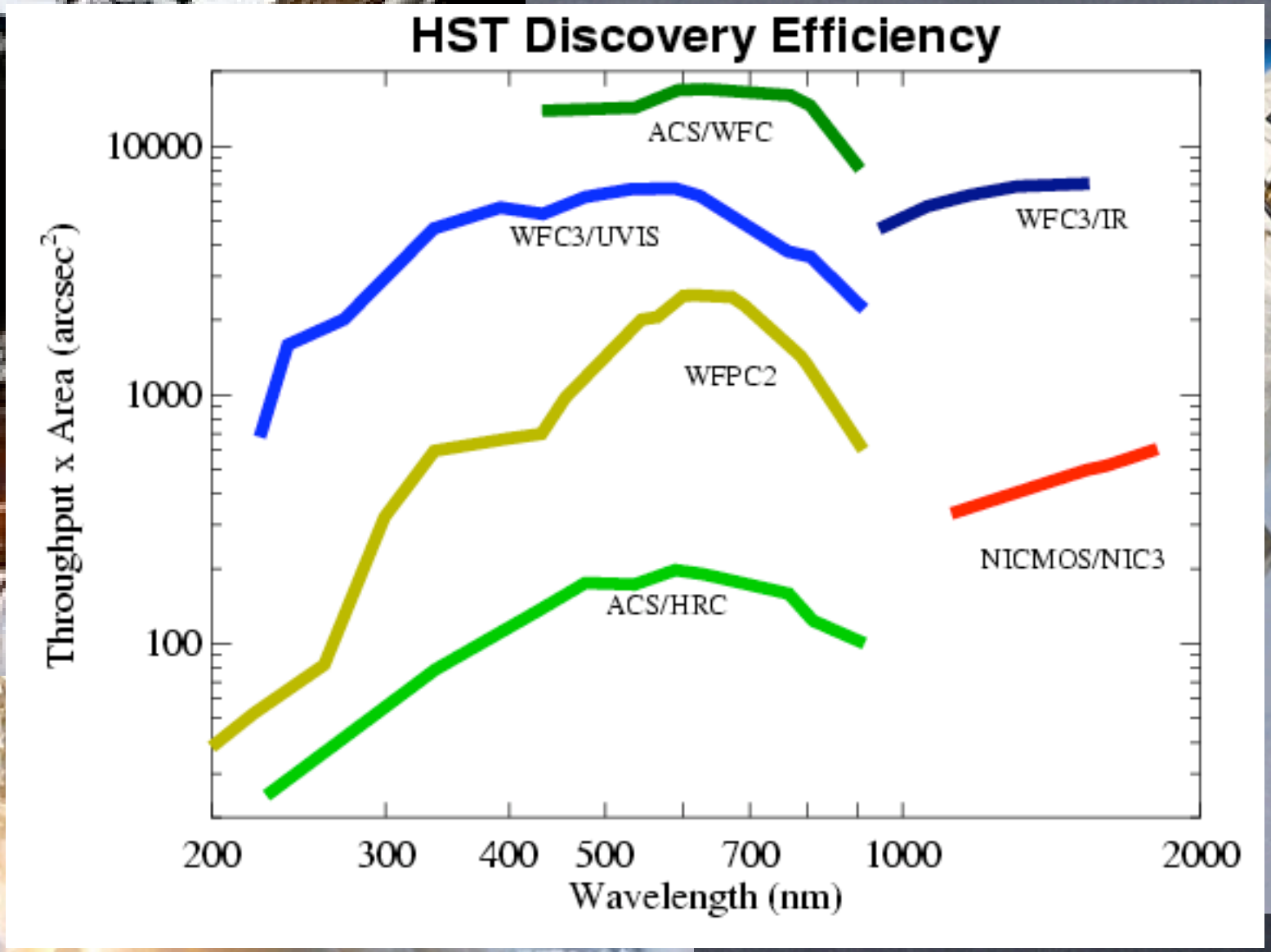
- Dark Energy Survey
- Pan-STARRS-4
- ALPACA

approx. 1000°'s

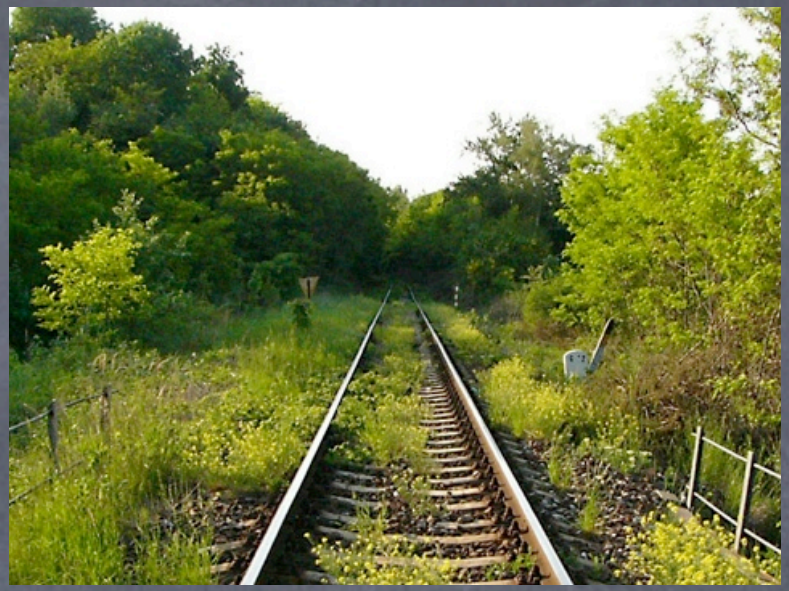
- Cornell-Caltech Atacama Telescope
- Cluster Imaging eXperiment (CIX)

SZ cluster detection

HST + WFC3 & COS!


HST Discovery Efficiency
ACS/WFC
WFC3/UVIS
WFC3/IR
WFPC2
NICMOS/NIC3
ACS/HRC
10000
1000
100
Throughput x Area (arcsec^2)
200
300
400
500
700
1000
2000
Wavelength (nm)

Still further yet...
approx. 10 yrs.



LSST: 8-m "all sky" surveyor.
10,000°'s! Hemisphere every week!

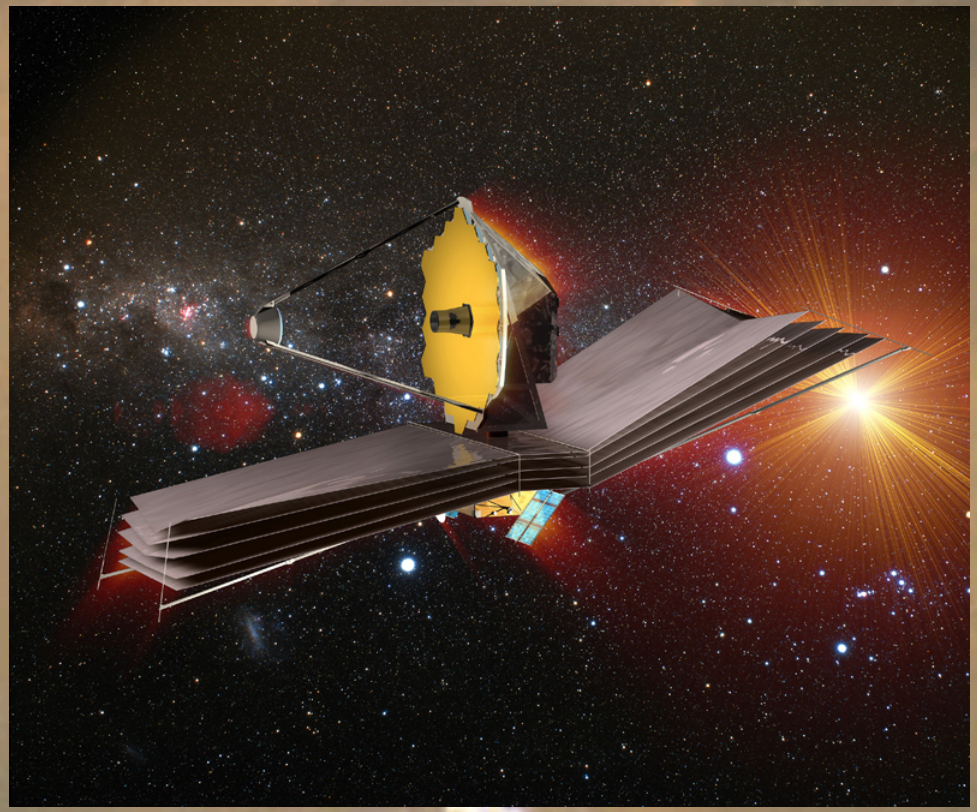
GSMT: ultra deep optical & IR.
- Giant Magellan Telescope
- Thirty-Meter Telescope

- SKA- Next logical step beyond ALMA, approx. 2 orders of mag. more sens. than VLA!

The distant, uncertain future...

space-based projects

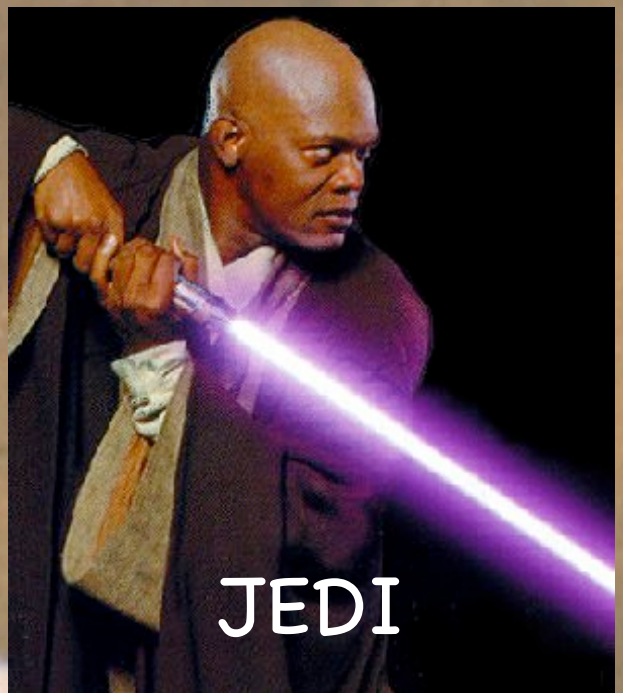
- Constellation-X: Next logical step from Chandra
- JWST



The distant, uncertain future...

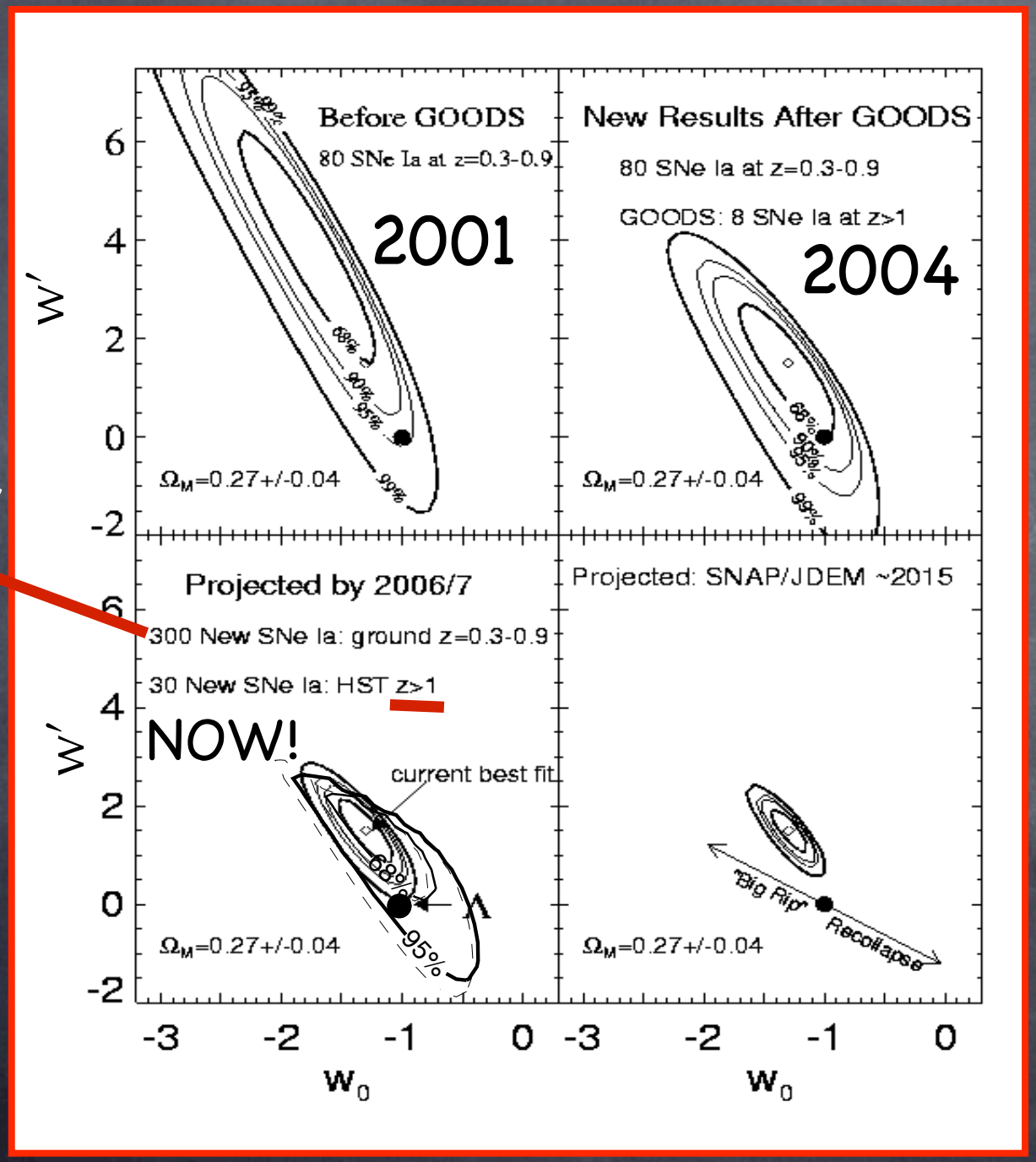
space-based projects

Joint Dark Energy Mission (NASA/DOE)



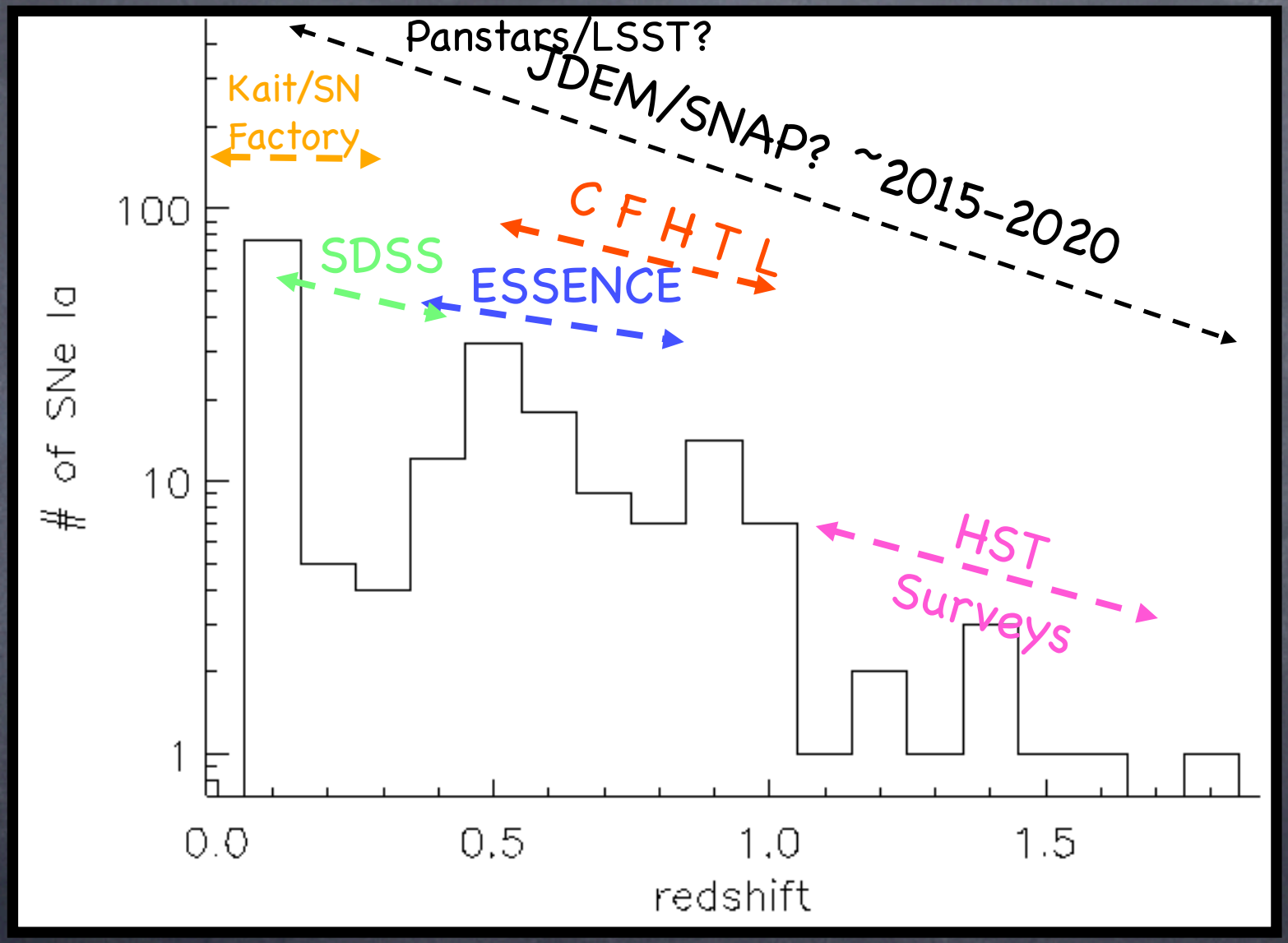
Closing in on Dark Energy: The Near Future

CFHT L, ESSENCE, Sloan DSS, Carnegie



Rejection of Λ :
i.e., wo ≠ -1 or w′ ≠ 0
would be a tremendous breakthrough!

Phase Space of Supernova Dark Energy Surveys



The End