The Type Ia Supernova Hubble Diagram

Bruno Leibundgut

European Southern Observatory

The original Hubble Diagram (Galaxies)

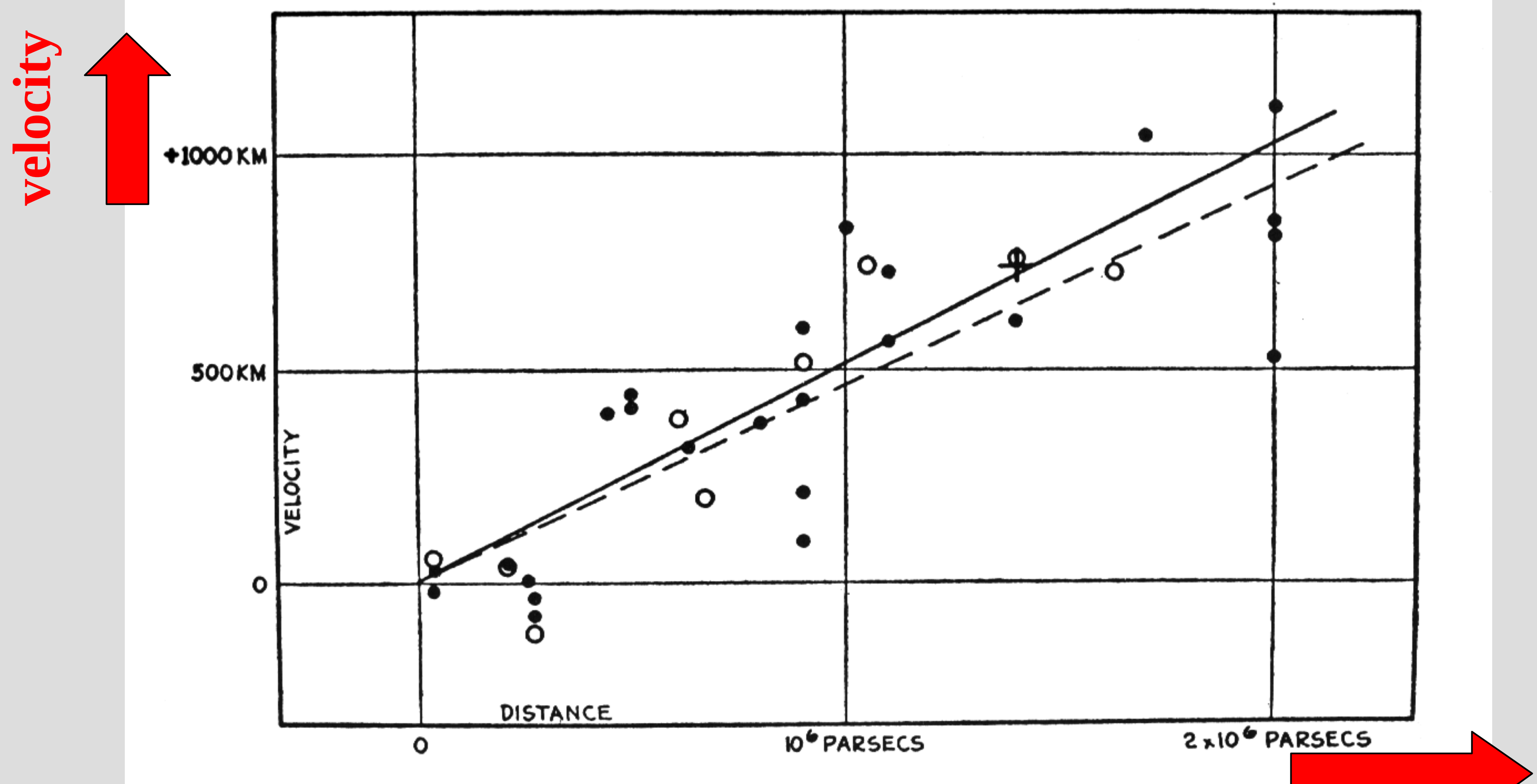
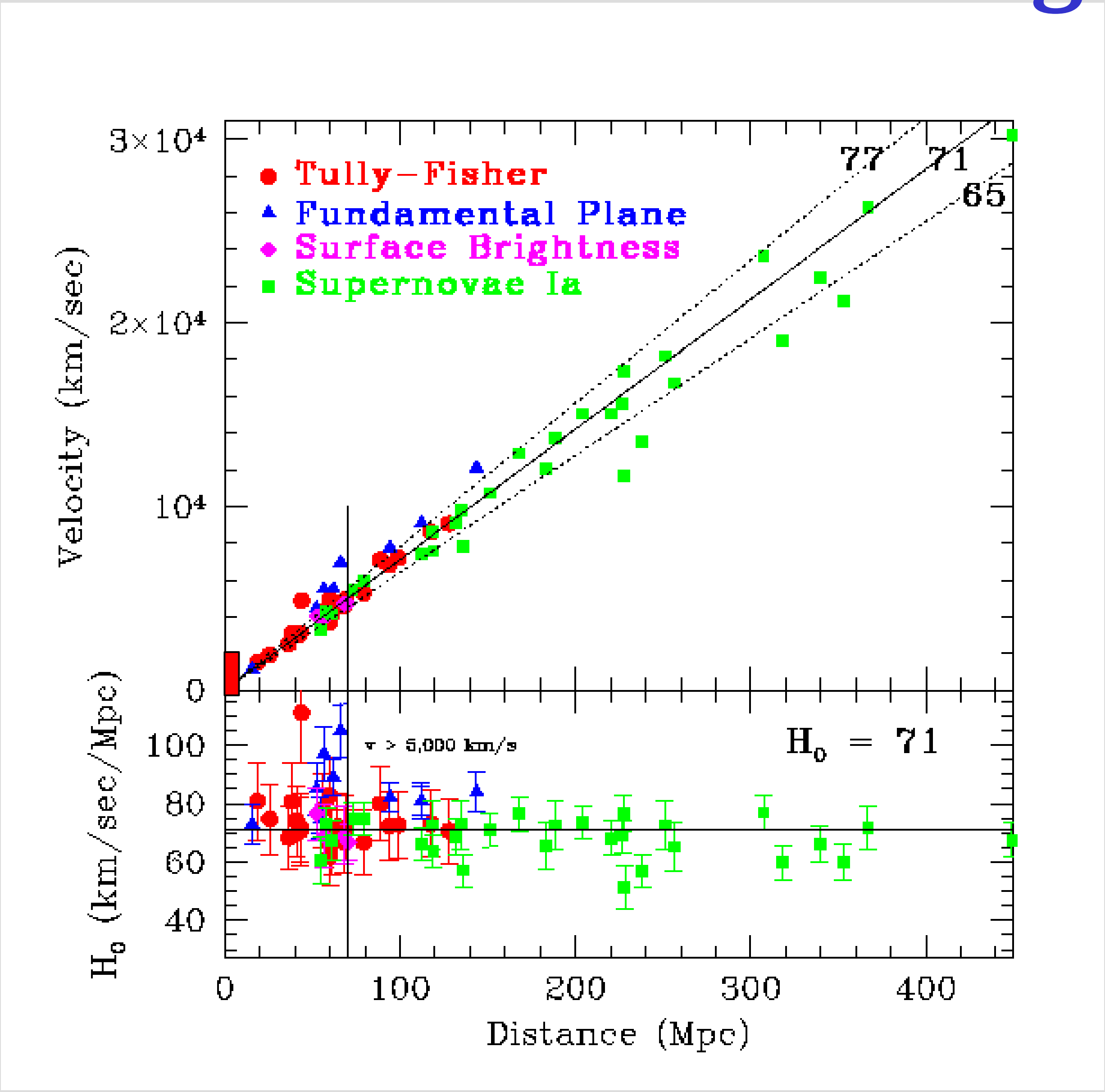


FIG. 9. *The Formulation of the Velocity-Distance Relation.*

A modern Hubble Diagram



The expansion of the universe

Luminosity distance in an isotropic, homogeneous universe as a Taylor expansion

$$D_L = \frac{cz}{H_0}\left\{1+\frac{1}{2}(1-q_0)z-\frac{1}{6}\left[1-q_0-3q_0^2+j_0\pm\frac{c^2}{H_0^2R^2}\right]z^2+O(z^3)\right\}$$

$$H_0=\frac{\dot{a}}{a} \qquad q_0=-\frac{\ddot{a}}{a}H_0^{-2} \qquad j_0=\frac{\dddot{a}}{a}H_0^{-3}$$

Supernovae

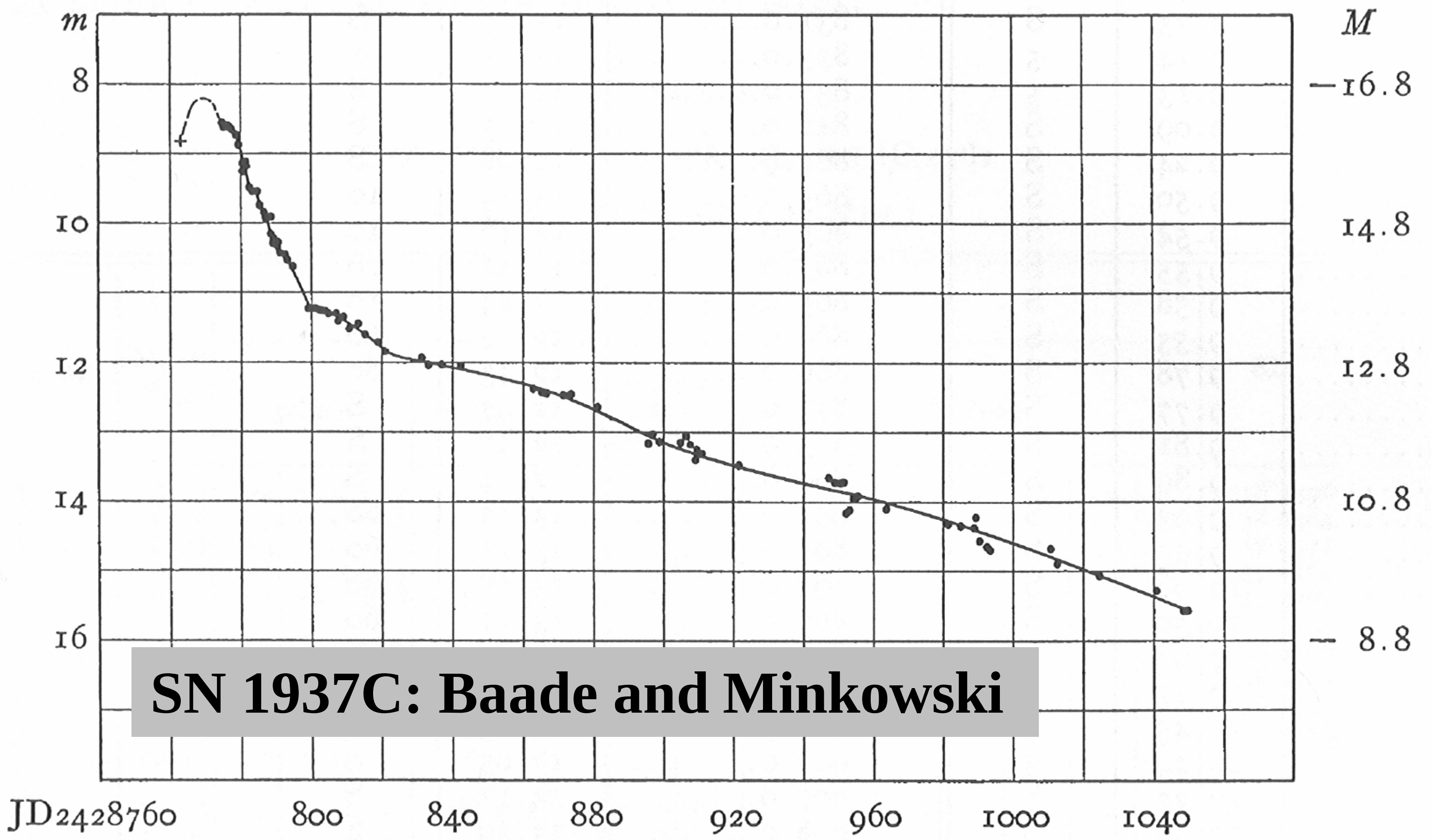
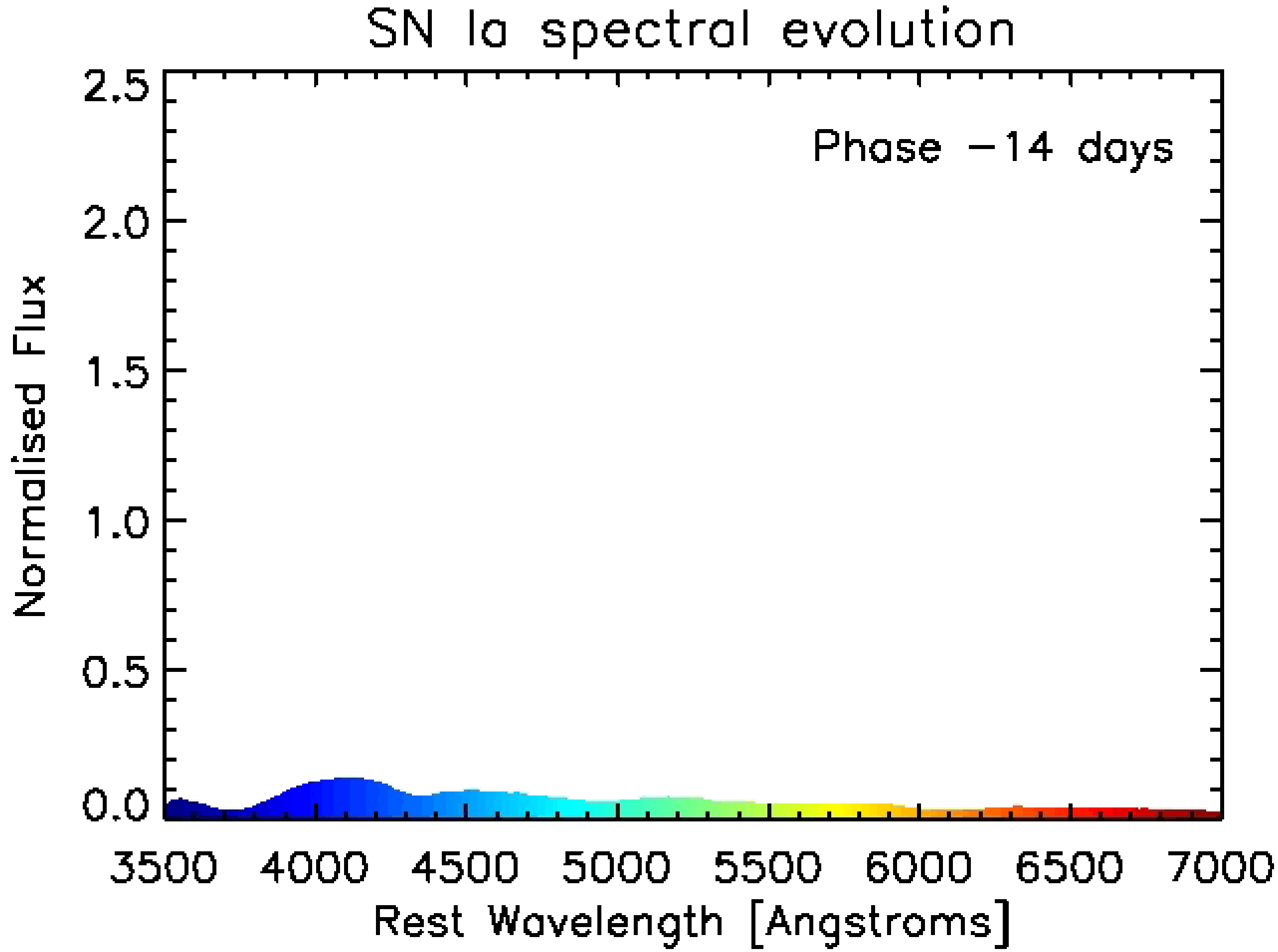


FIG. 1.—Photographic light-curve of supernova in IC 4182

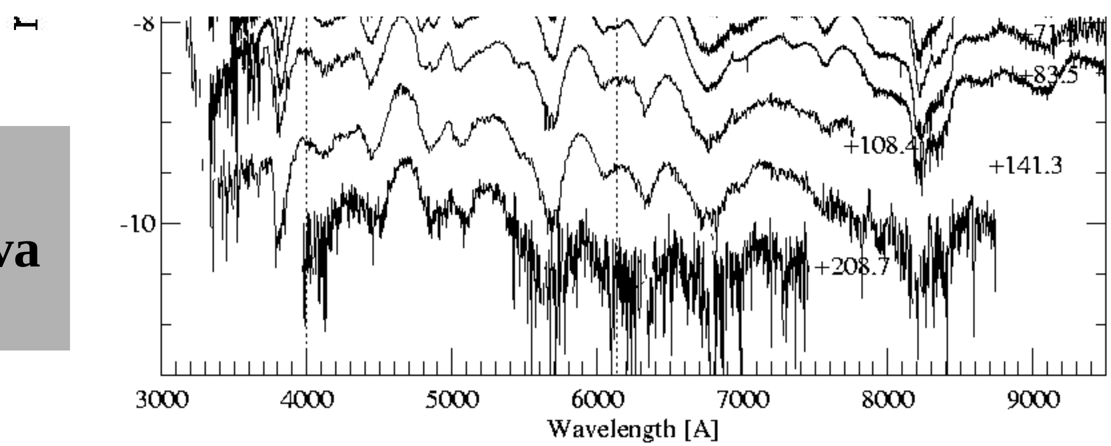
The nearl

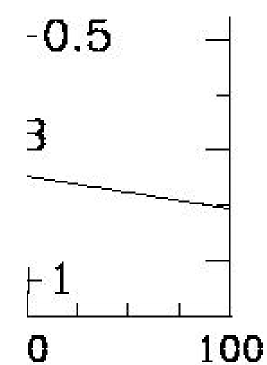
excellent cov
few objects

- fairly comp
- allows deta
  comparison

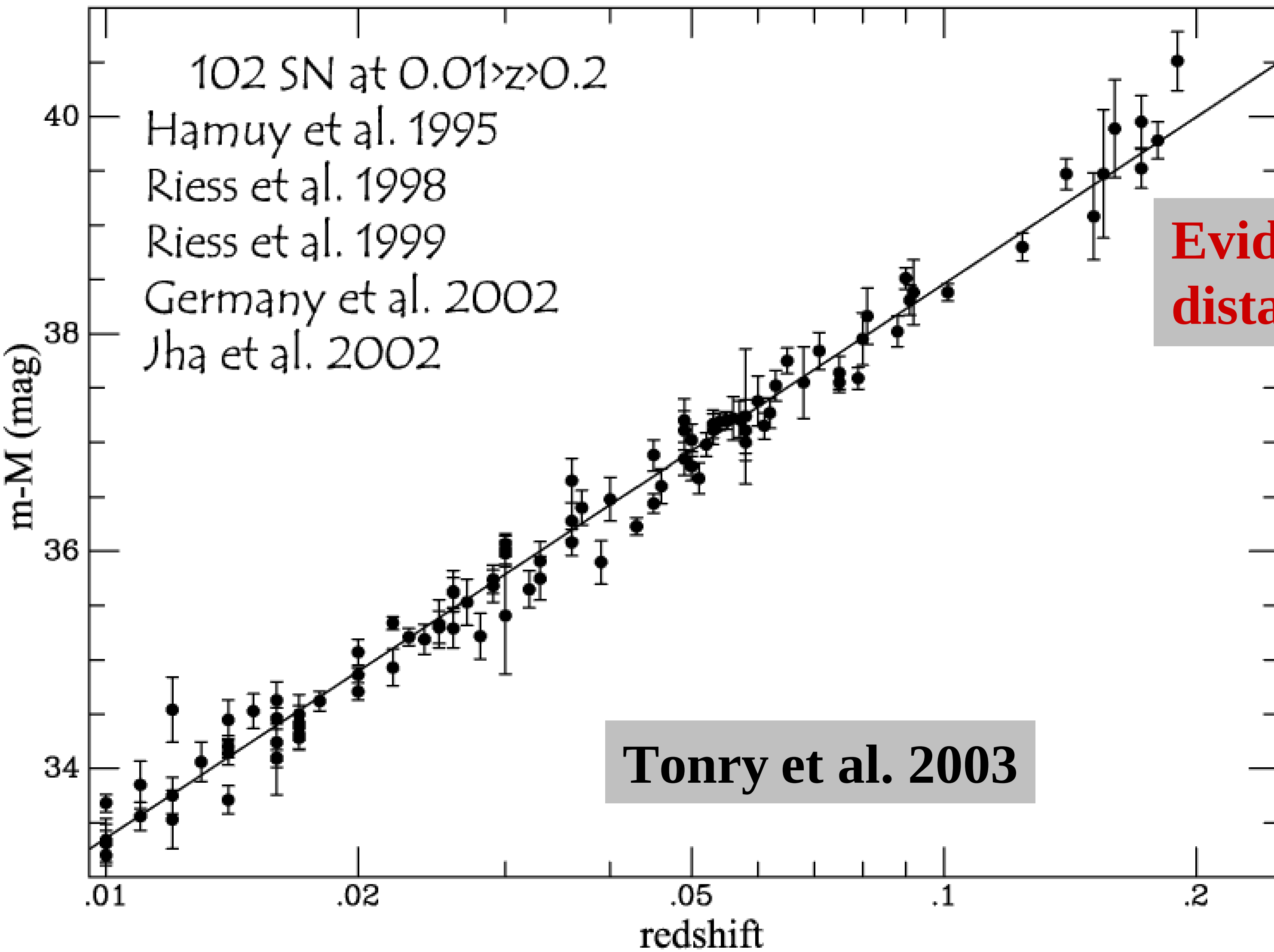


SN 2003du
European Supernova Collaboration



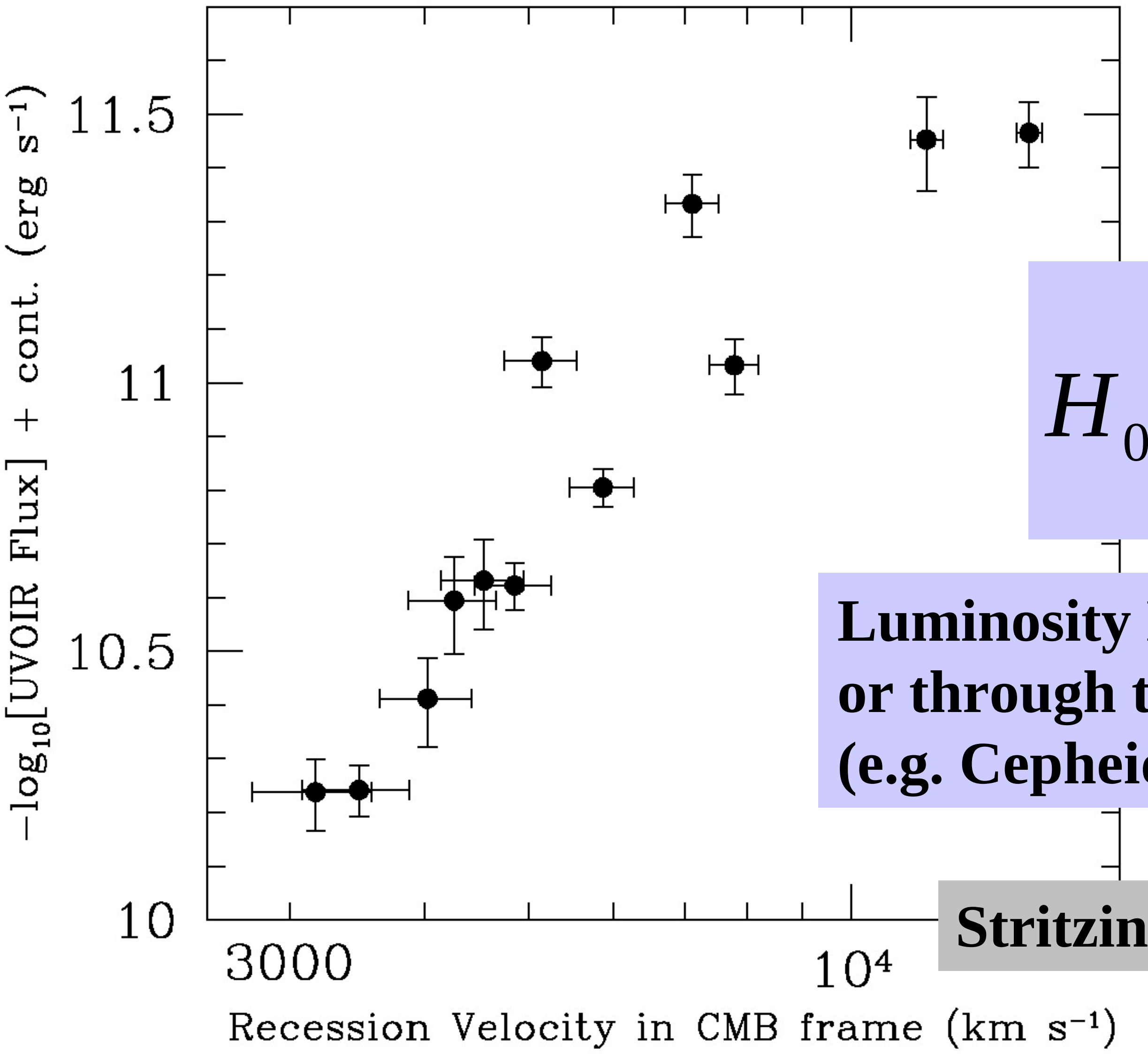


The nearby SN Ia sample



Evidence for good distances

The nearby SN Ia Hubble diagram



$$H_0 = cz\sqrt{\frac{4pF}{L}}$$

Luminosity L either from models or through the distance ladder (e.g. Cepheids)

Stritzinger & Leibundgut 2005

H_0 from the nickel mass

$$H_0 = \frac{cz}{D} = cz\sqrt{\frac{4pF}{L}} = cz\sqrt{\frac{4pF}{E_{Ni}}} \propto cz\sqrt{\frac{4pF}{M_{Ni}}}$$

Hubble Law

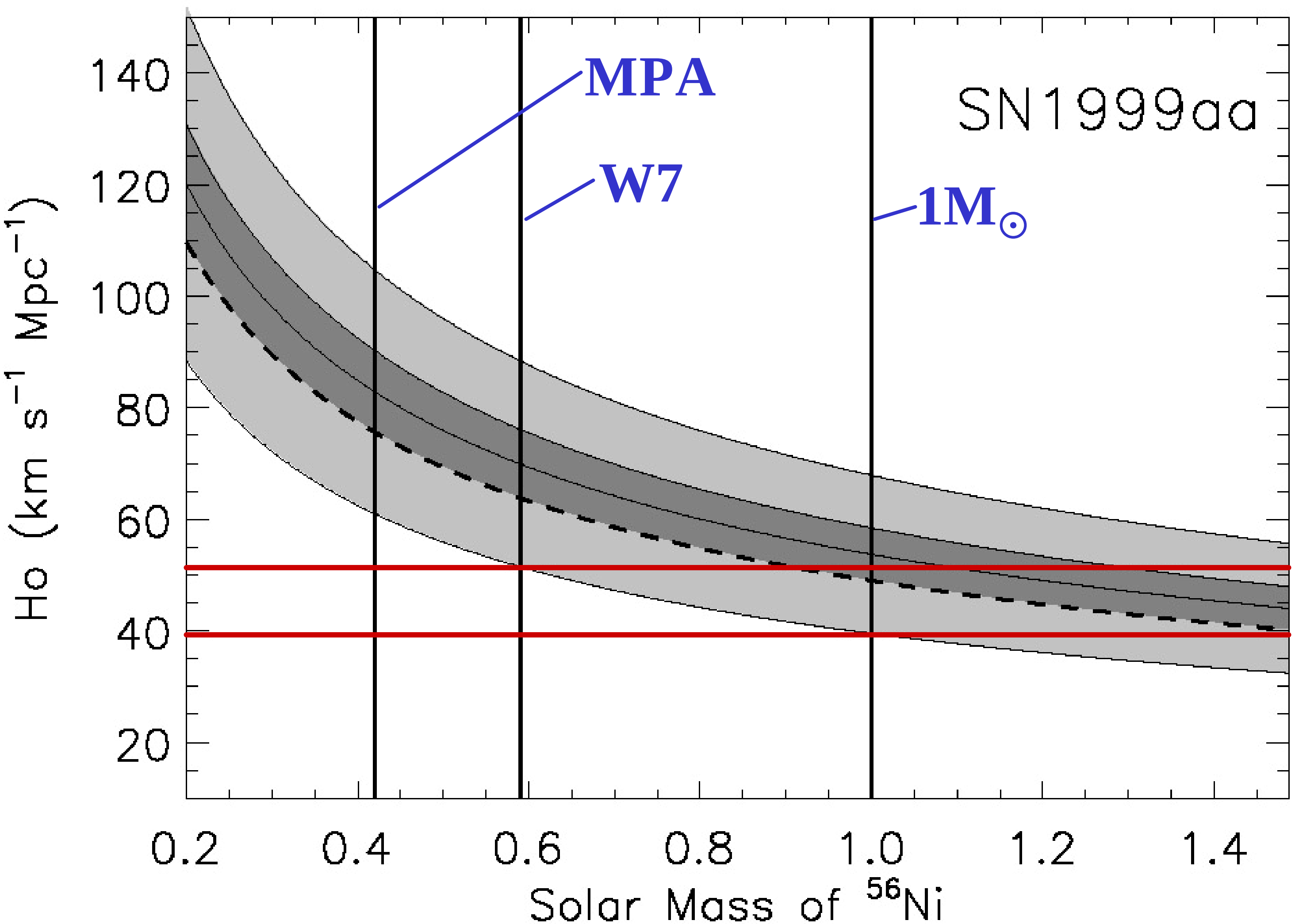
Luminosity distance

Arnett’s rule

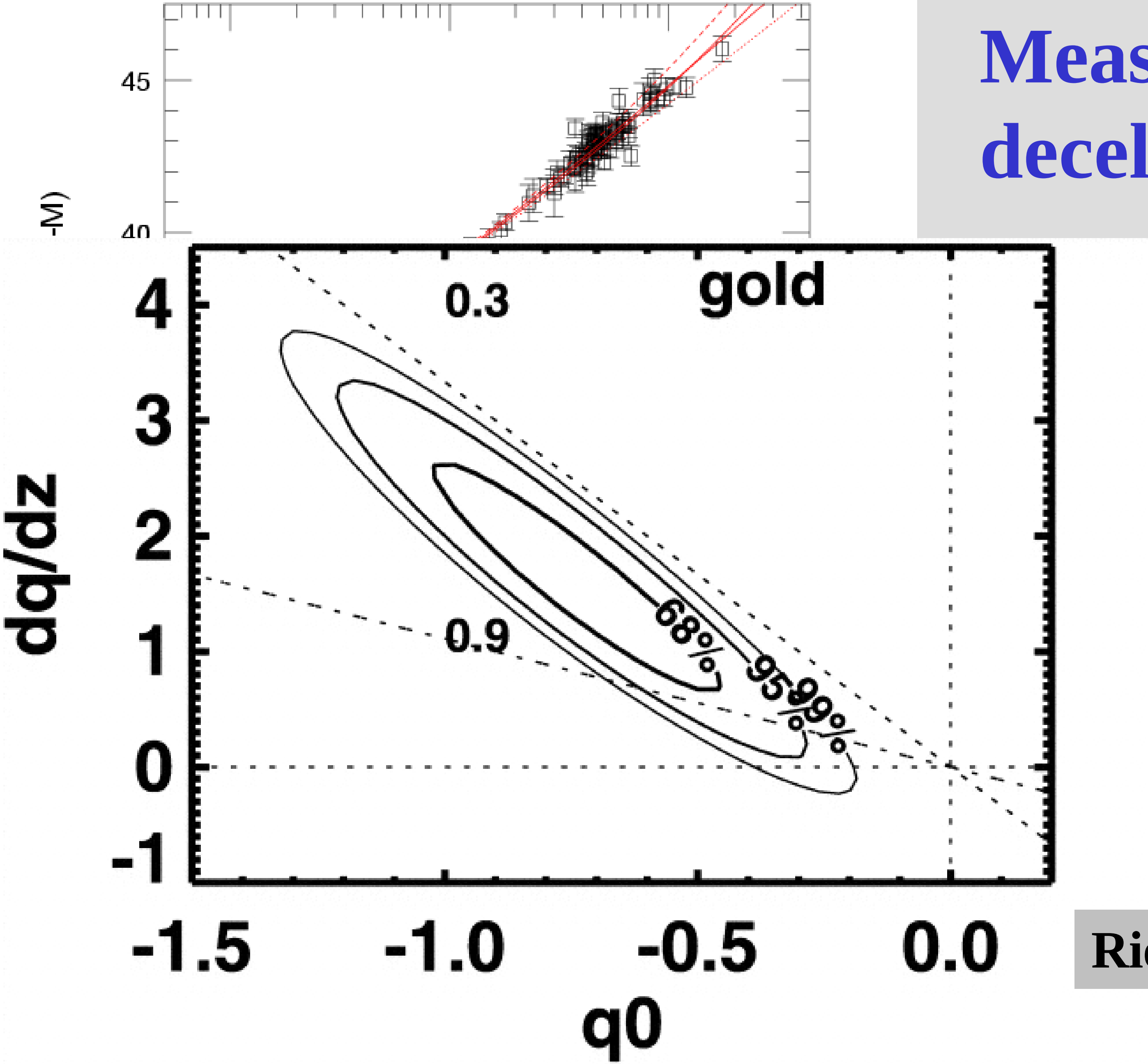
Ni-Co decay and rise time

Need bolometric flux at maximum F and the redshift *z* as observables

Comparison with models

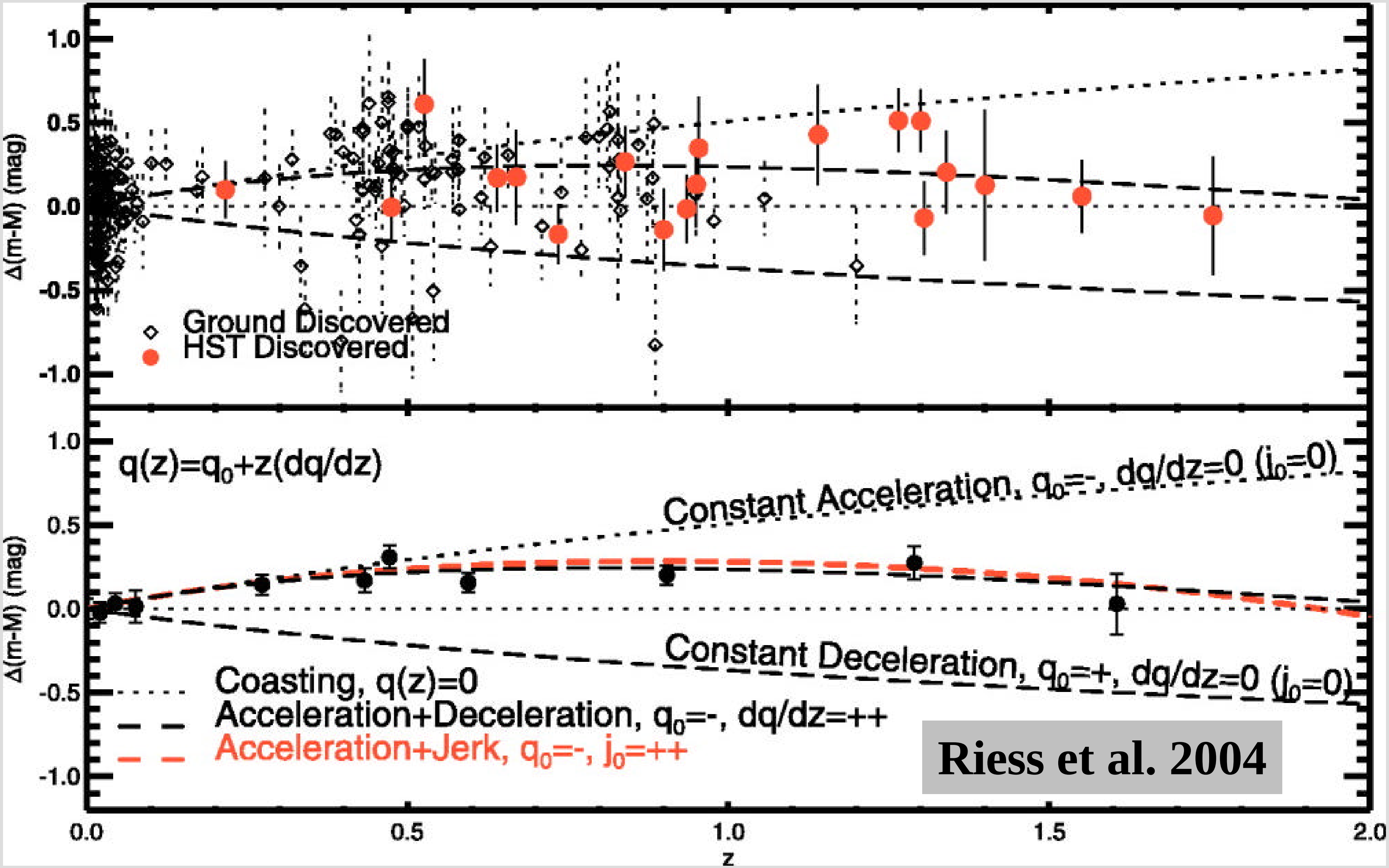


Measure deceleration



Riess et al. 2004

Adding jerk …



Ground Discovered
HST Discovered
Δ(m-M) (mag)
q(z)=q0+z(dq/dz)
Constant Acceleration, q0=-, dq/dz=0 (j0=0)
Constant Deceleration, q0=+, dq/dz=0 (j0=0)
Coasting, q(z)=0
Acceleration+Deceleration, q0=-, dq/dz=++
Acceleration+Jerk, q0=-, j0=++
Riess et al. 2004
z


$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\frac{8\pi G}{c^4} T_{\mu\nu}$
A. EINSTEIN

Friedmann cosmology

Assumption:
homogeneous and isotropic universe

Null geodesic in a Friedmann-Robertson-Walker metric:

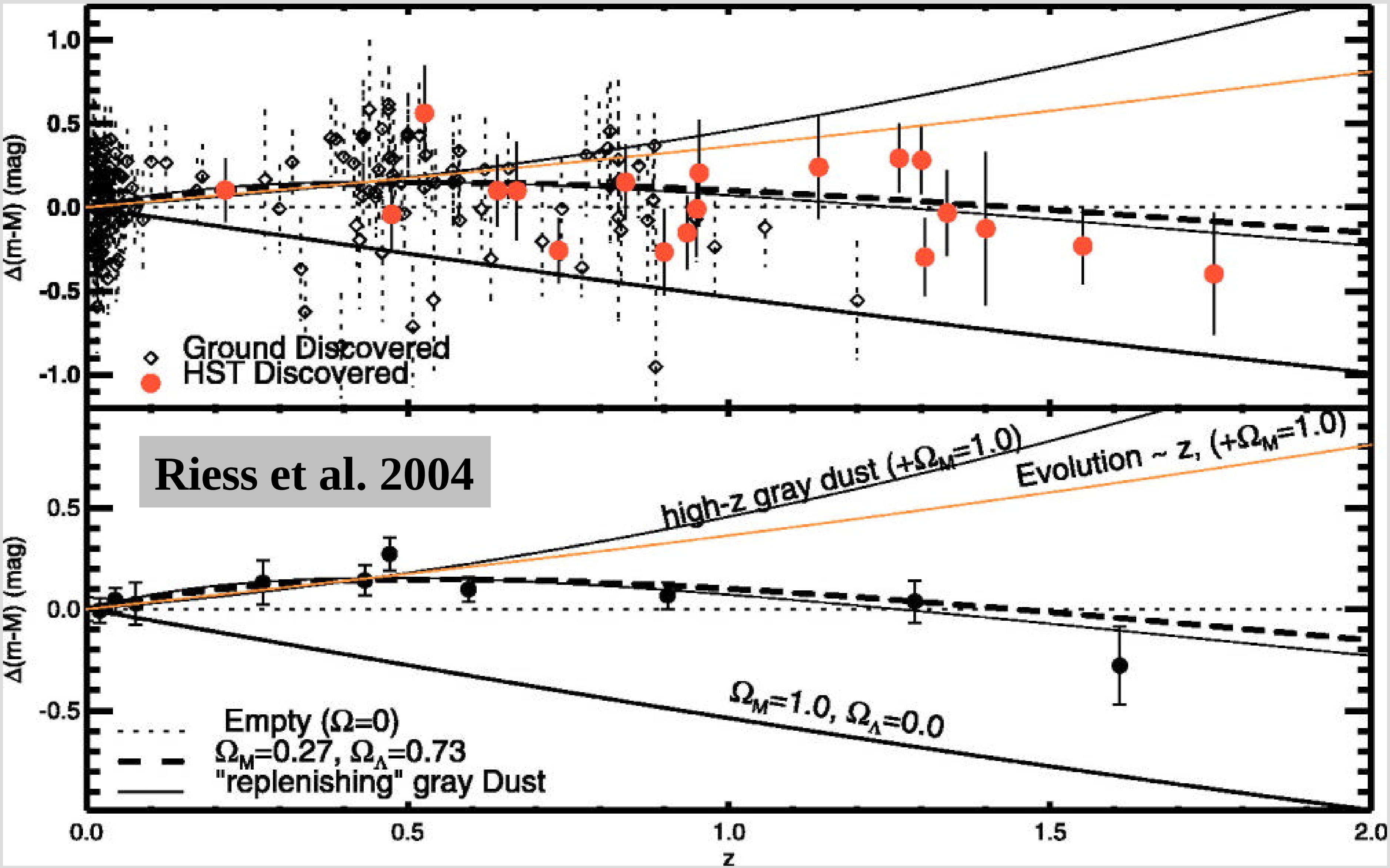
$$D_L = \frac{(1+z)c}{H_0\sqrt{|\Omega_k|}} S\left\{ \sqrt{|\Omega_k|} \int_0^z \left[\Omega_k (1+z')^2 + \Omega_M (1+z')^3 + \Omega_\Lambda \right]^{-1/2} dz' \right\}$$

$$\Omega_M = \frac{8pG}{3H_0^2} r_M$$

$$\Omega_k = -\frac{kc^2}{R^2 H_0^2}$$

$$\Omega_\Lambda = \frac{\Lambda c^2}{3H_0^2}$$

Evidence for the O?



The equation of state parameter w

General luminosity distance

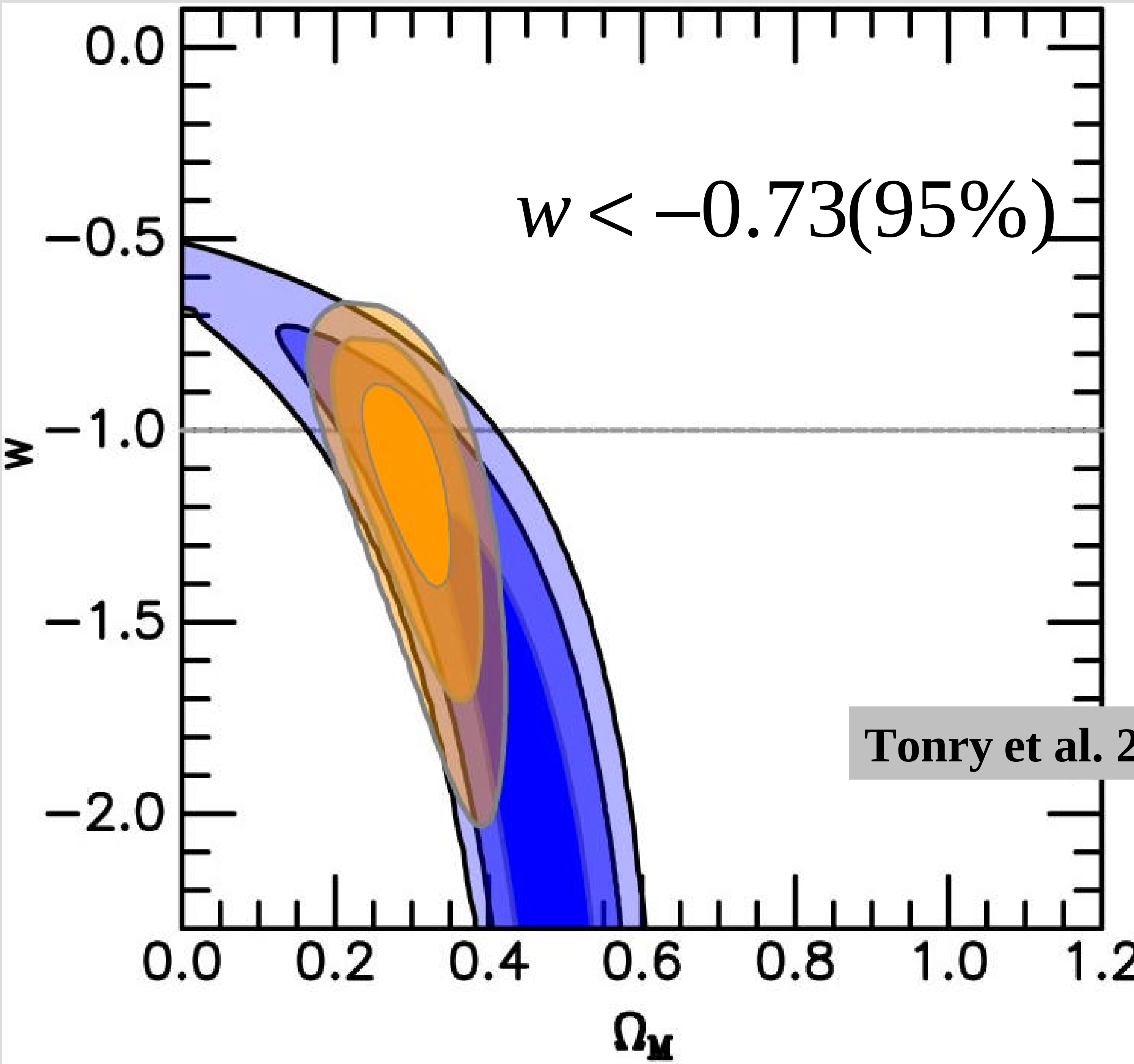
$$D_L = \frac{(1+z)c}{H_0\sqrt{|\Omega_k|}} S\left\{\sqrt{|\Omega_k|}\int_0^z \left[\Omega_k (1+z')^2 + \sum_i \Omega_i (1+z')^{3(1+w_i)}\right]^{-1/2} dz'\right\}$$

- **with** $k = 1 - \sum_i \Omega_i$ **and** $w_i = \frac{p_i}{r_i c^2}$

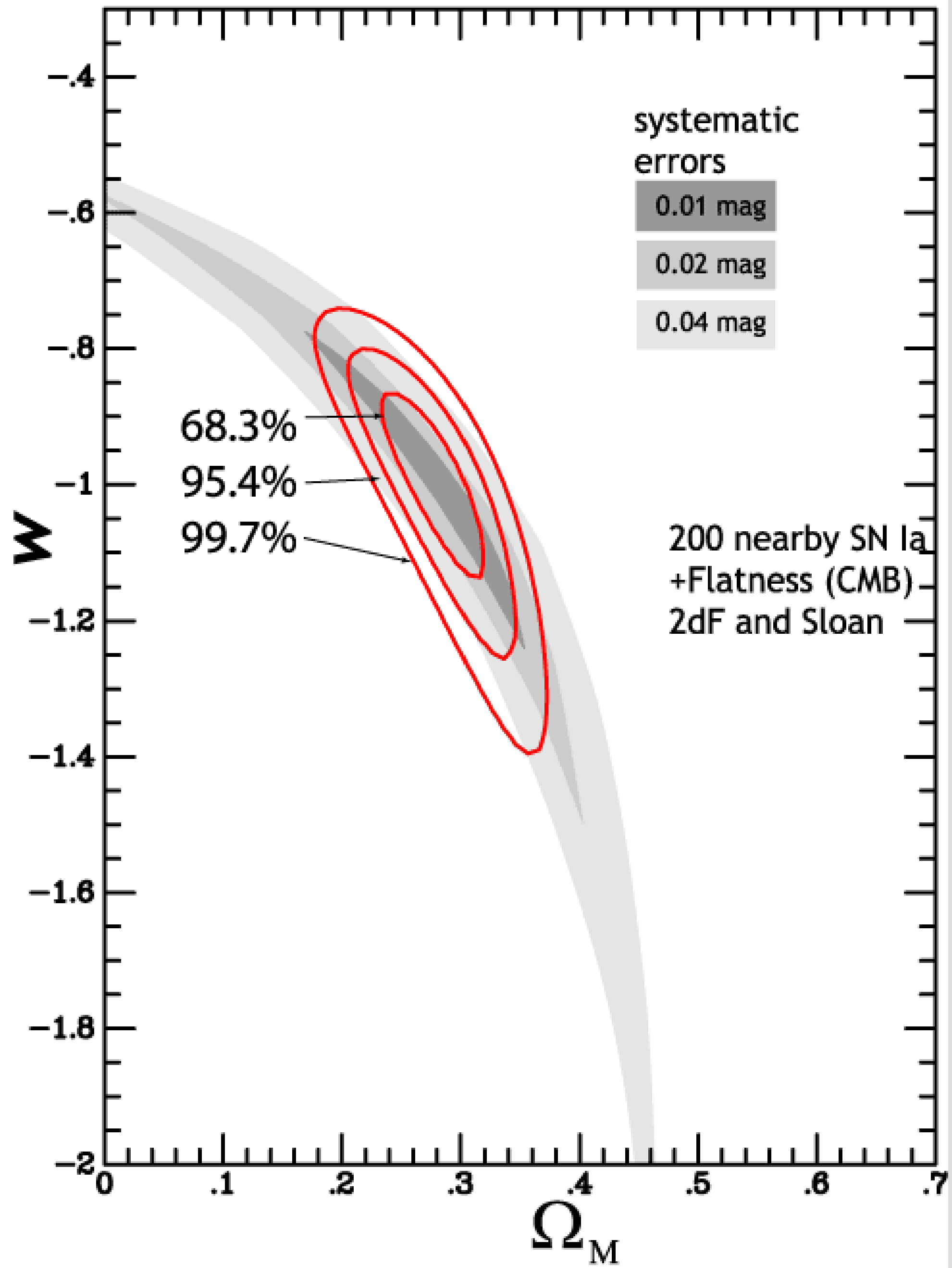
w_M= 0 (matter)

w_R= ? (radiation)

w_L= -1 (cosmological constant)

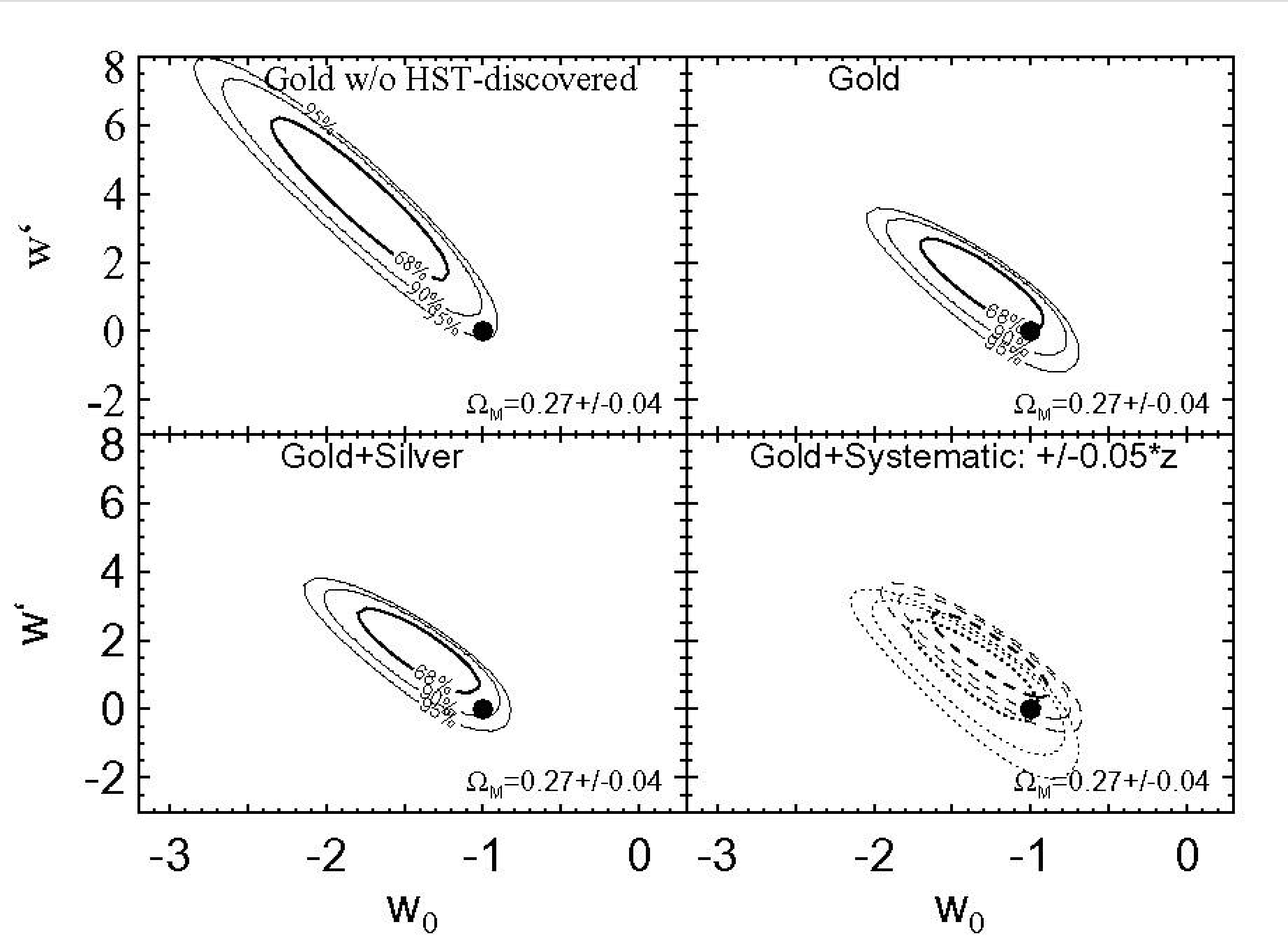


0.0
−0.5
−1.0
−1.5
−2.0
w
0.0 0.2 0.4 0.6 0.8 1.0 1.2
Ω_M
w < −0.73(95%)
Tonry et al. 2003



systematic errors
0.01 mag
0.02 mag
0.04 mag
68.3%
95.4%
99.7%
200 nearby SN Ia
+Flatness (CMB)
2dF and Sloan
w
-.4
-.6
-.8
-1
-1.2
-1.4
-1.6
-1.8
-2
0
.1
.2
.3
.4
.5
.6
.7
Ω_M

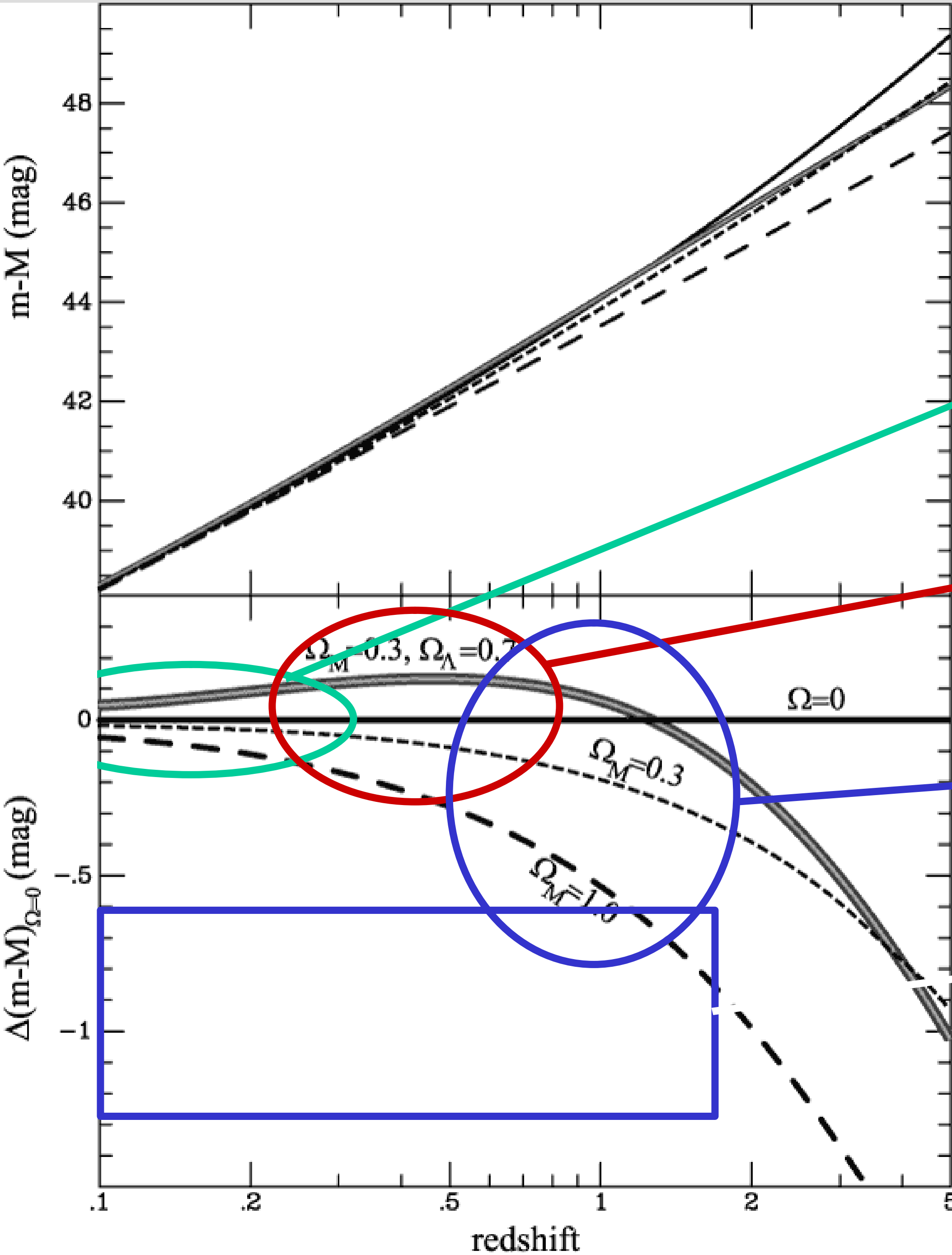
And on to a variable ?



Ansatz:

? (z)= ? $_0$+ ? ’z

SN Projects



SN Factory
Carnegie SN Project

ESSENCE
CFHT Legacy Survey

Higher-z SN Search
(GOODS)

SNAP

Four redshift regimes

z<0.05

- Define the characteristics of Type Ia Supernova
- Understand the explosion and radiation physics
- Determination of H_0

z<0.3

- Explore the systematics of SNe Ia
- Establish distance indicator

Four redshift regimes (cont.)

0.2<z<0.8

- Measure the strength of the cosmic acceleration (dark energy)

z>0.8

- break the degeneracy
- measure matter density

All redshifts

- Measure details of dark energy

The SN Ia Hubble diagram

- **powerful tool to**
  - **measure the absolute scale of the universe H_0**
  - **measure the expansion history (q_0)**
  - **determine the amount of dark energy**
  - **measure the equation of state parameter of dark energy**

Caveats

Warning to the theorists:

Claims for a measurement of a change of the equation of state parameter w are exaggerated. Current accuracy is inadequate for too many free parameters in the analysis.

Summary

Type Ia supernovae appear currently the most promising route to provide a possible answer to what the Dark Energy is.

All redshifts need to be covered

- distant SNe Ia alone are useless
- nearby SNe Ia are the source of our understanding of the distance indicator