Supernova cosmology

The quest to measure the equation of state of dark energy

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Outline

Cosmological background

Supernovae

One-stop shopping for the Hubble constant

Acceleration and Dark energy

The equation of state parameter of dark energy

The expansion of the universe

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

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

Hubble's Law **acceleration** **jerk/equation of state**

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

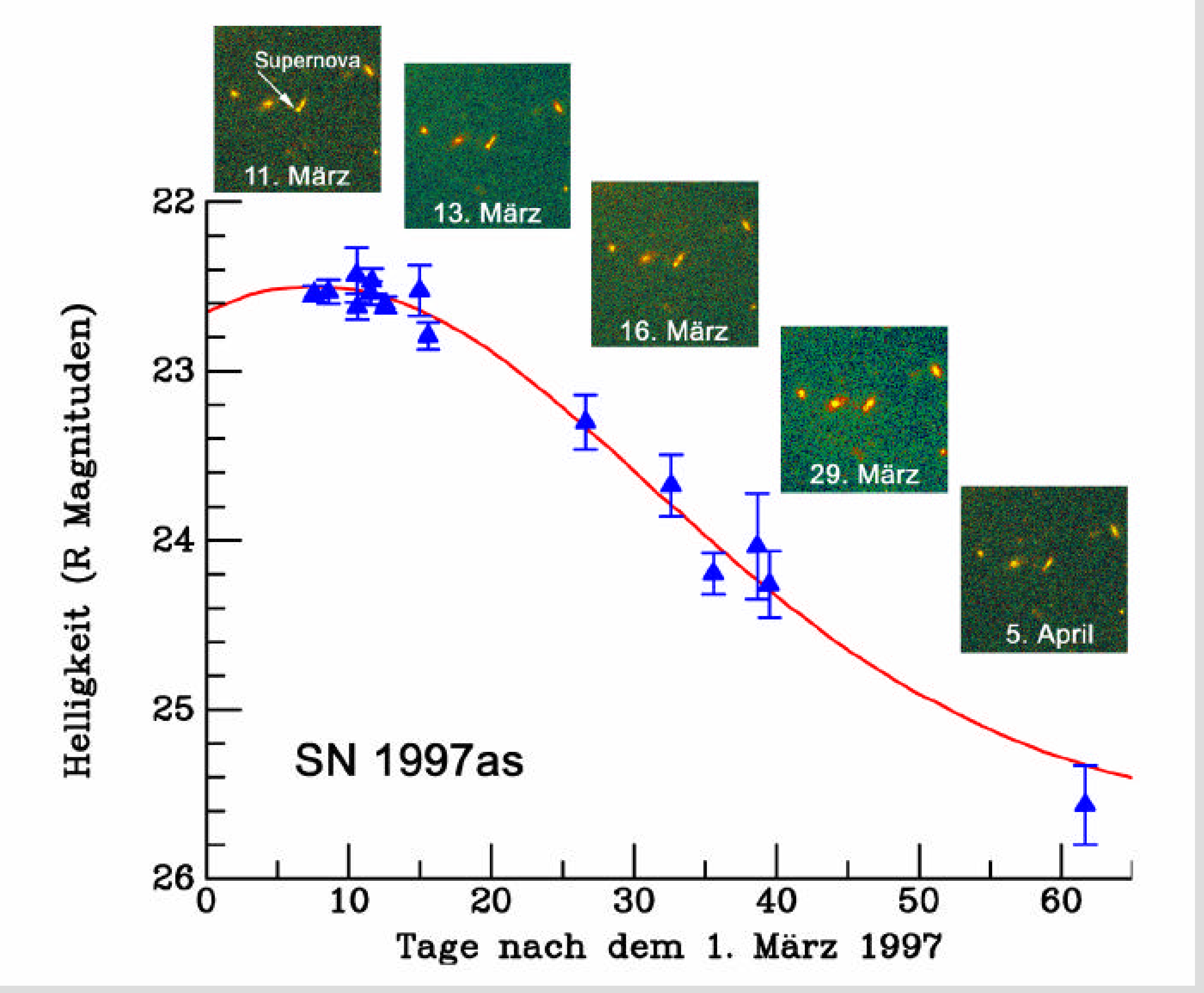
Connecting expansion to physics

Hubble law: $$D = \frac{cz}{H_0}$$

Acceleration: $$D = \frac{cz}{H_0}\left[1 + \frac{1}{2}(1 - q_0)z\right]$$

Equation of state: $$D = O(z^3)$$

Supernova light curve



Supernova classification

Based on spectroscopy

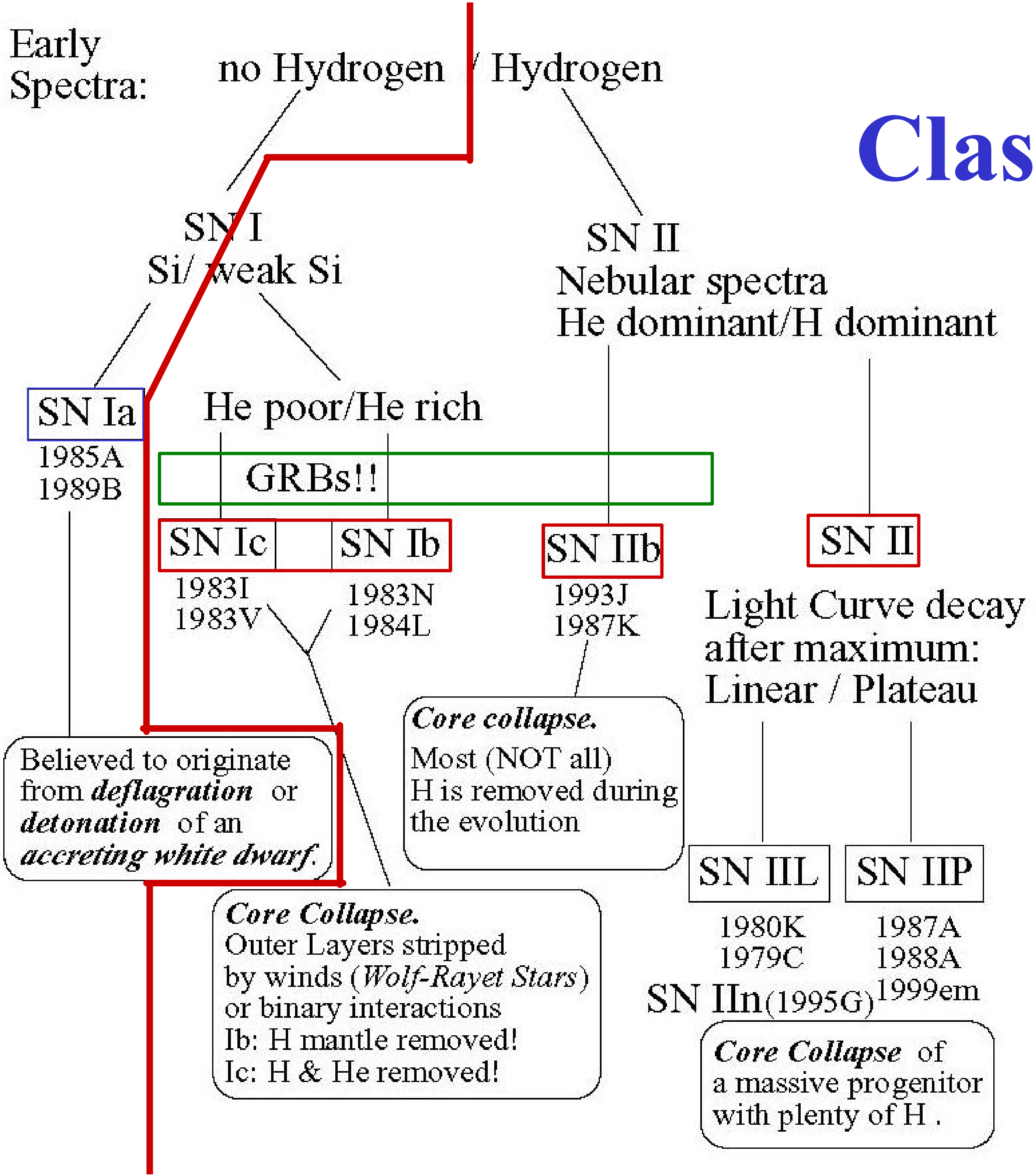
core collapse
in massive stars

SN II (H)
SN Ib/c (no H/He)
Hypernovae/GRBs

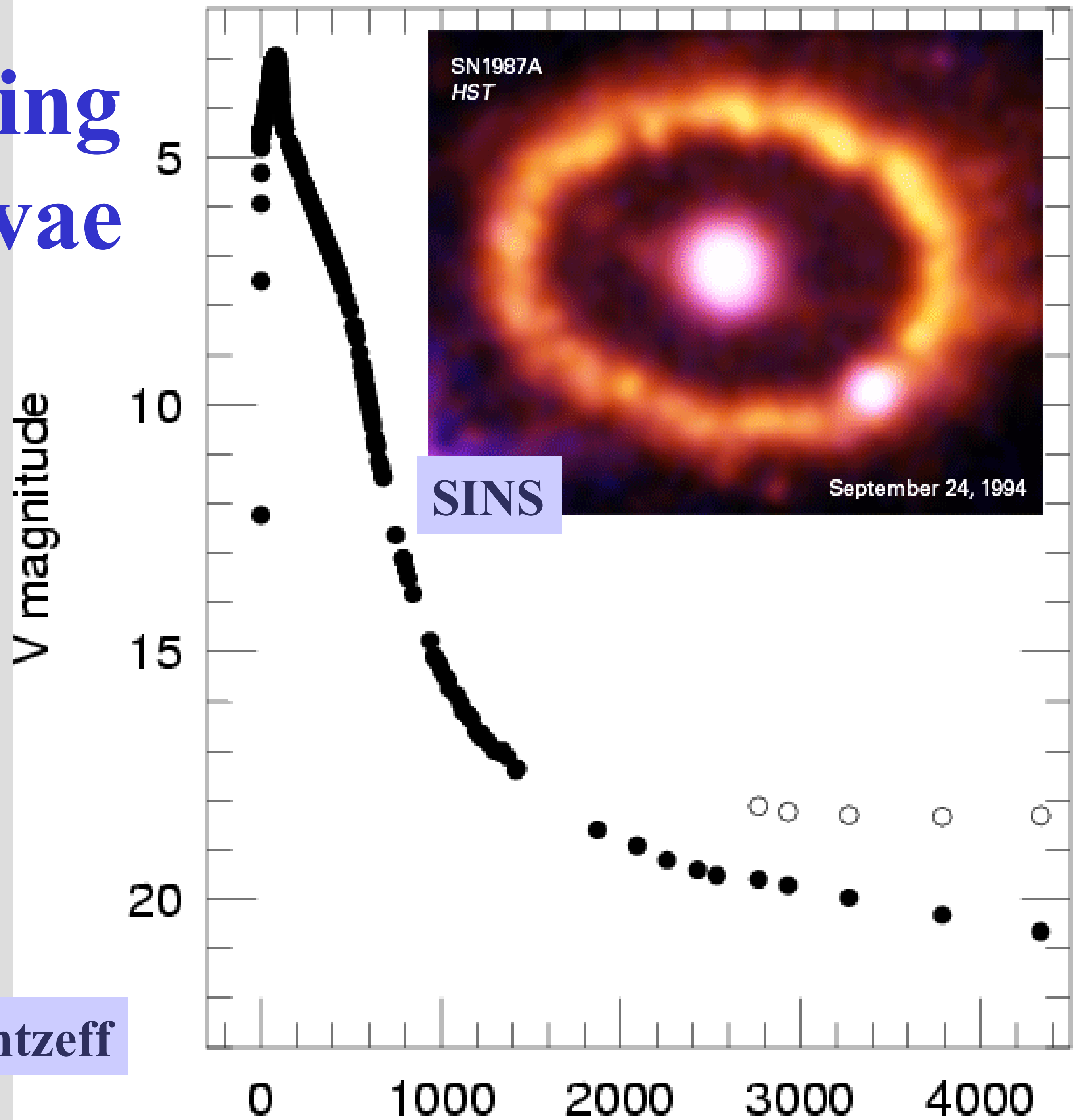
SN Ia (no H)

thermonuclear
explosions

Classification

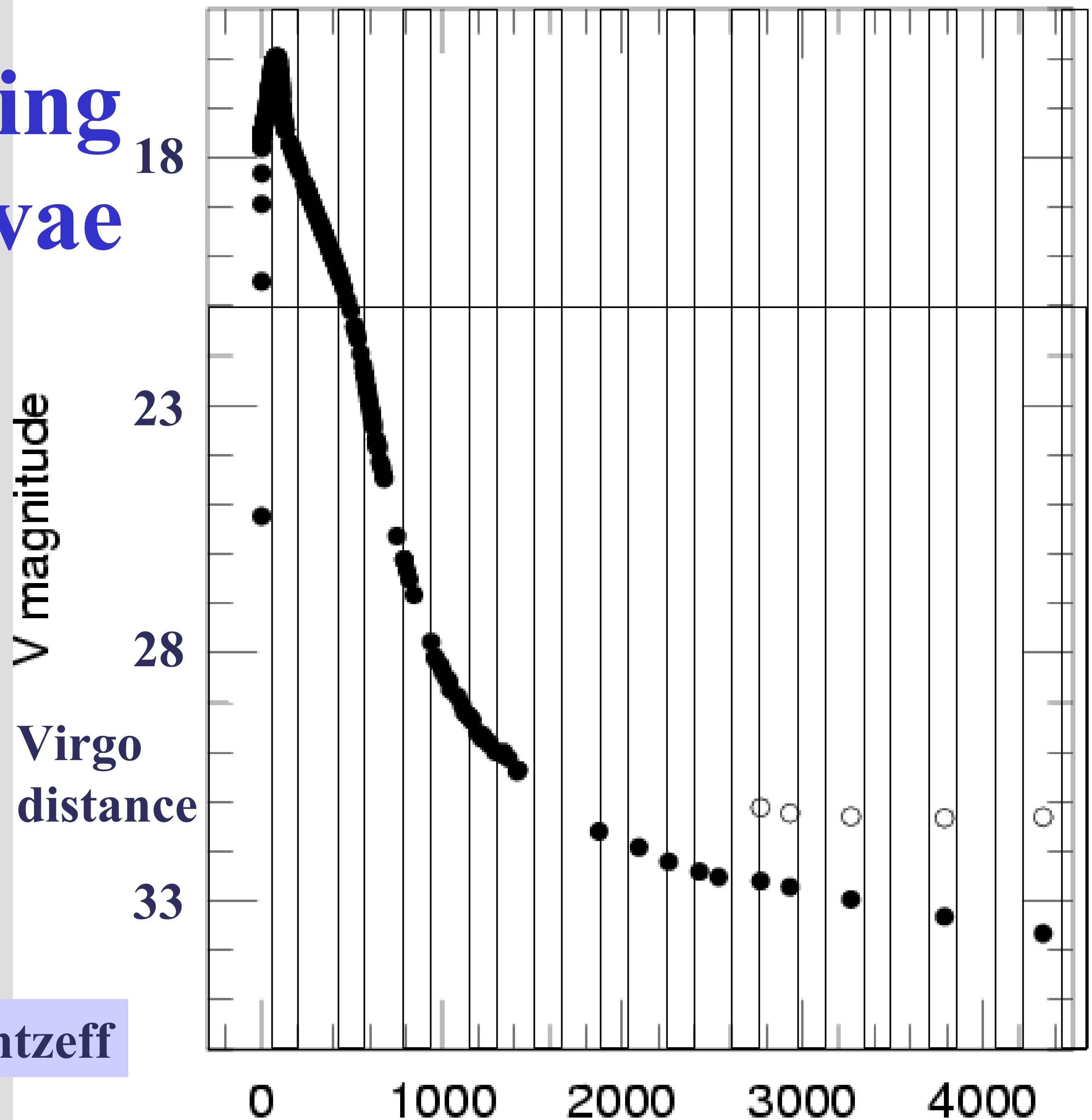


Observing supernovae



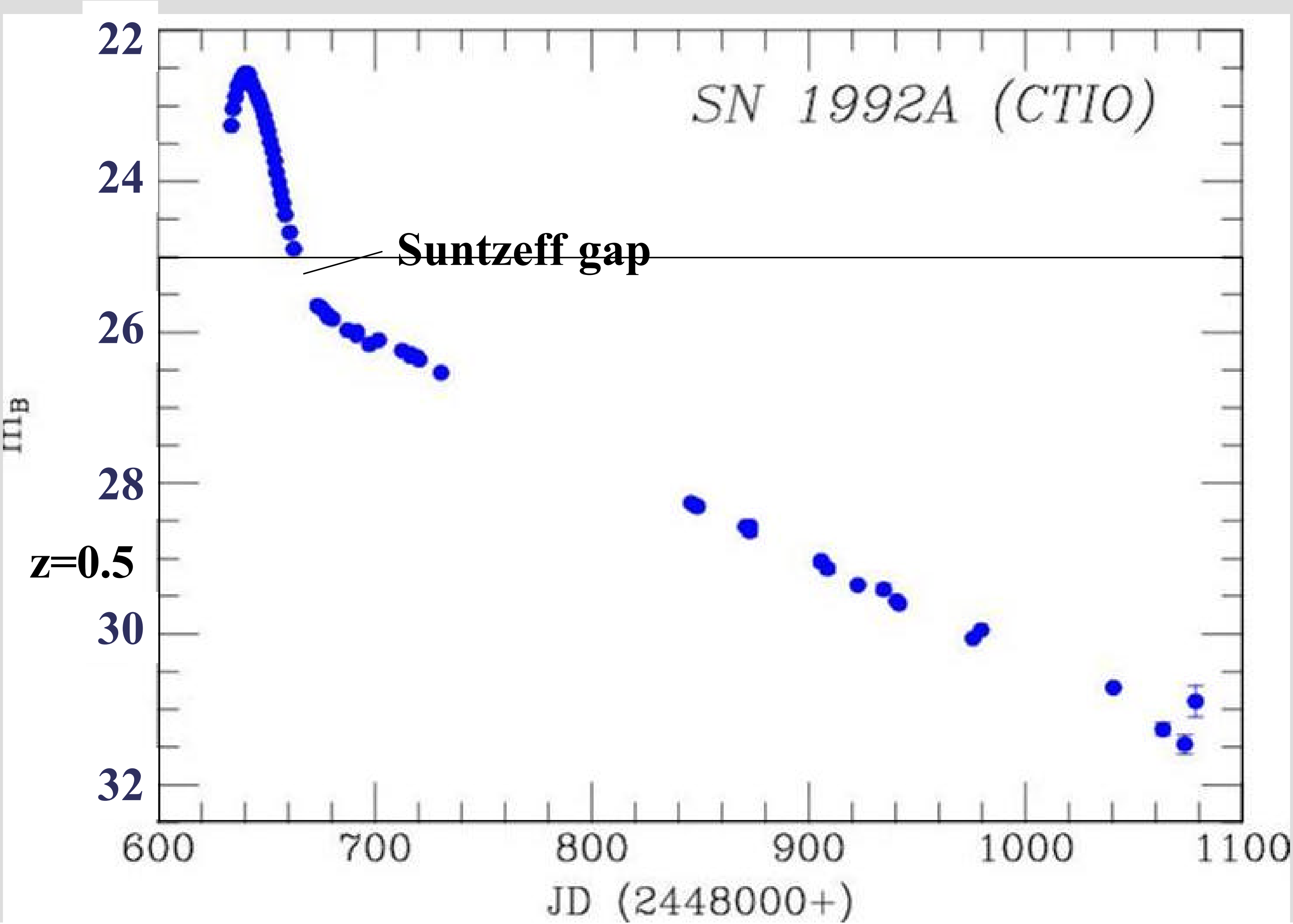
Suntzeff

Observing supernovae

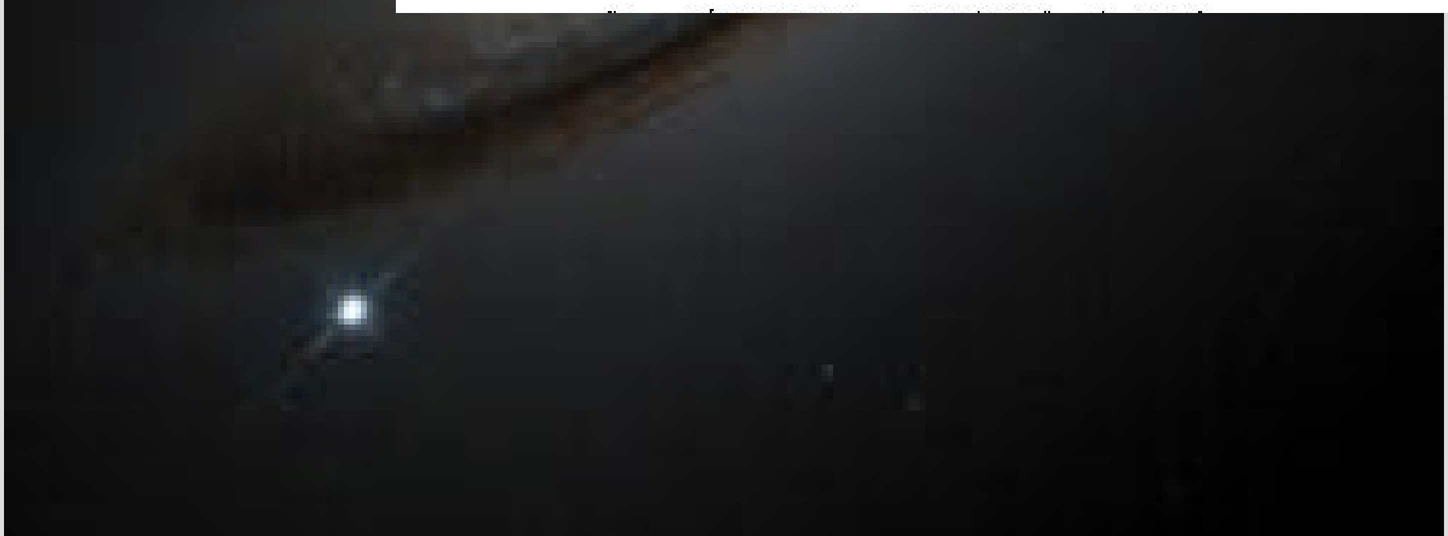


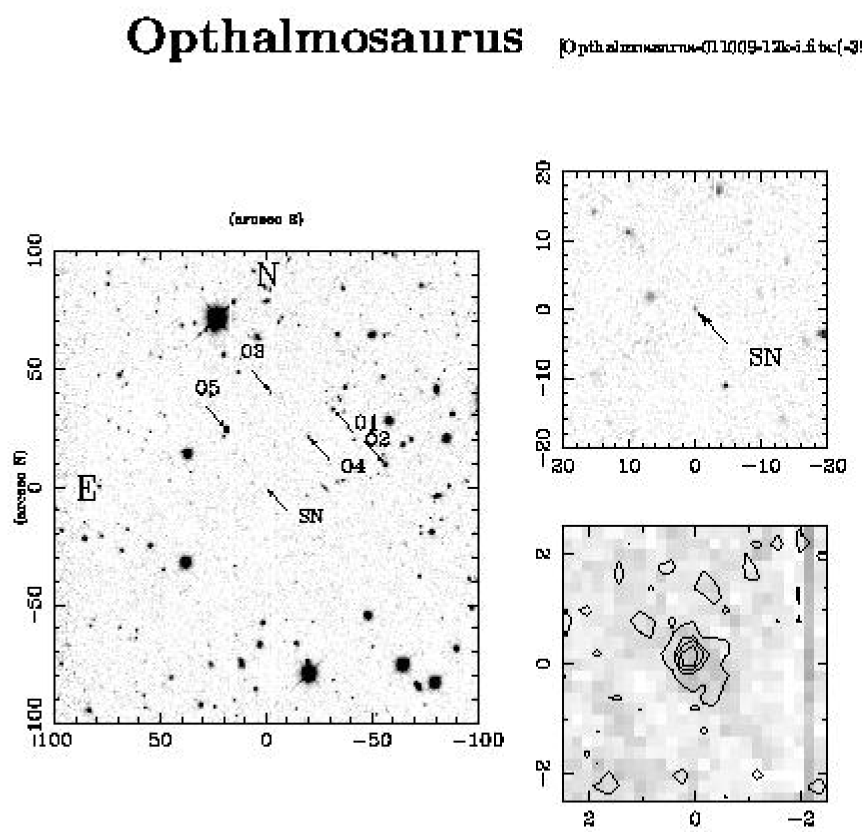
Suntzeff

Observing supernovae



SN 1994D




Opthalmosaurus
N
E
03
05
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100
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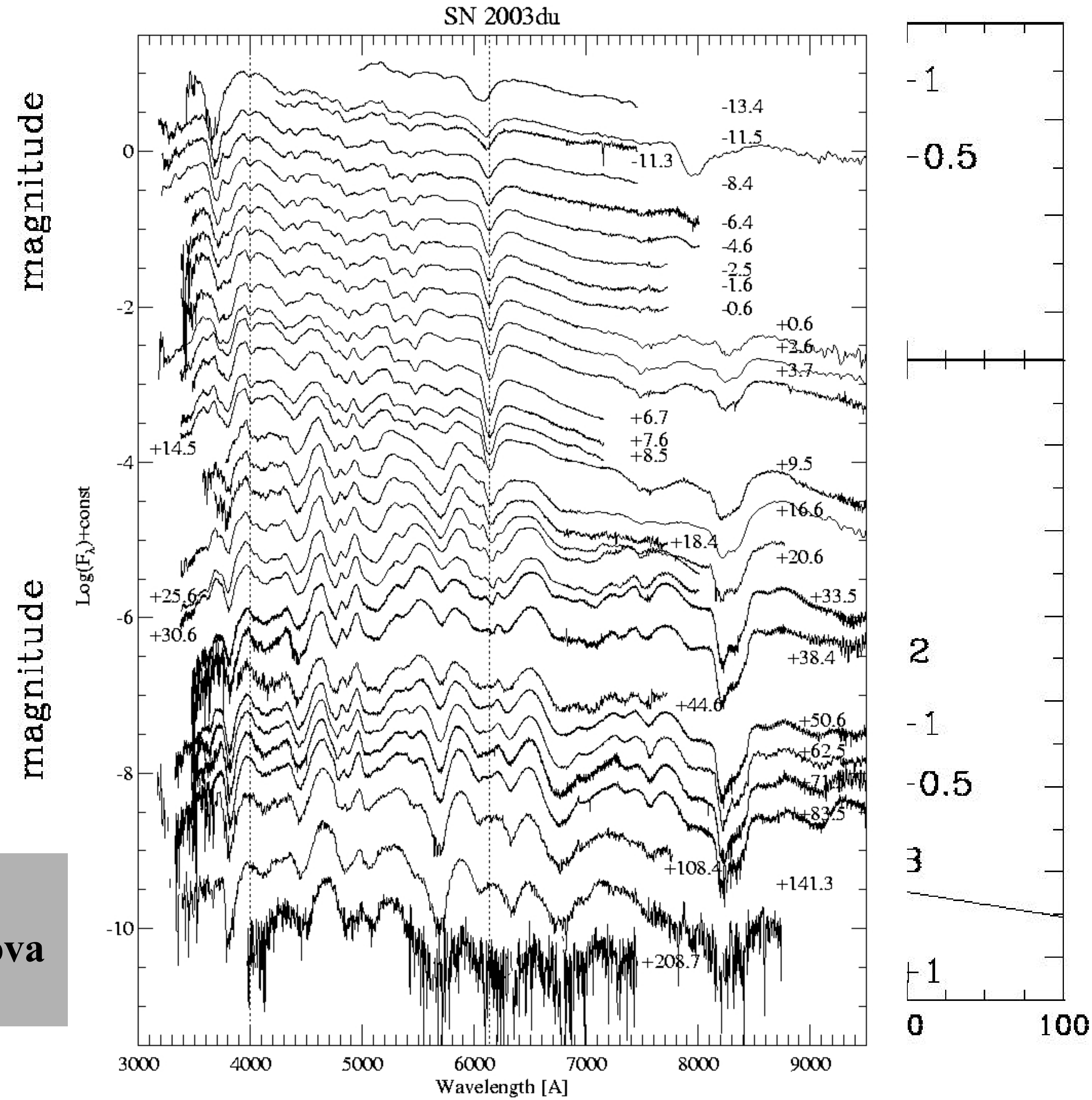
0
−2

The nearl

excellent cov
few objects

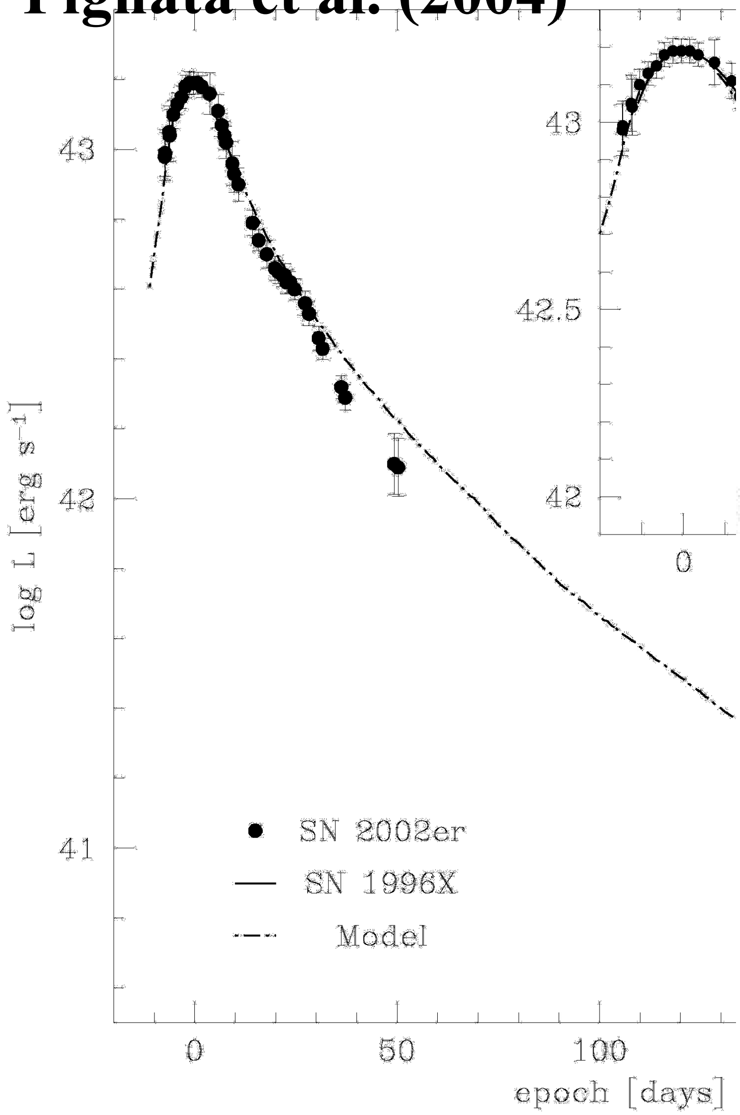
- fairly comp
- allows deta comparison

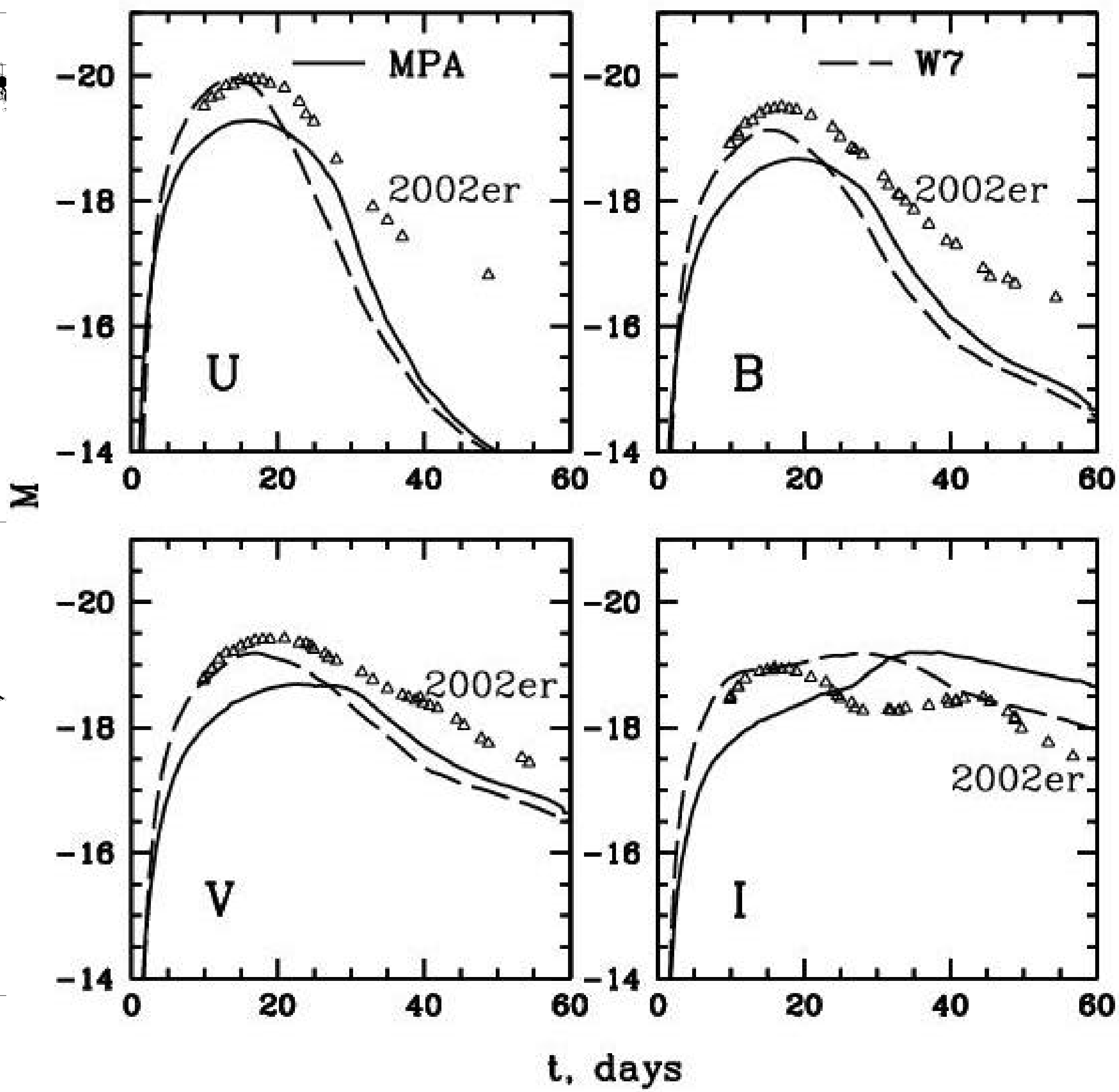


SN 2003du
European Supernova Collaboration

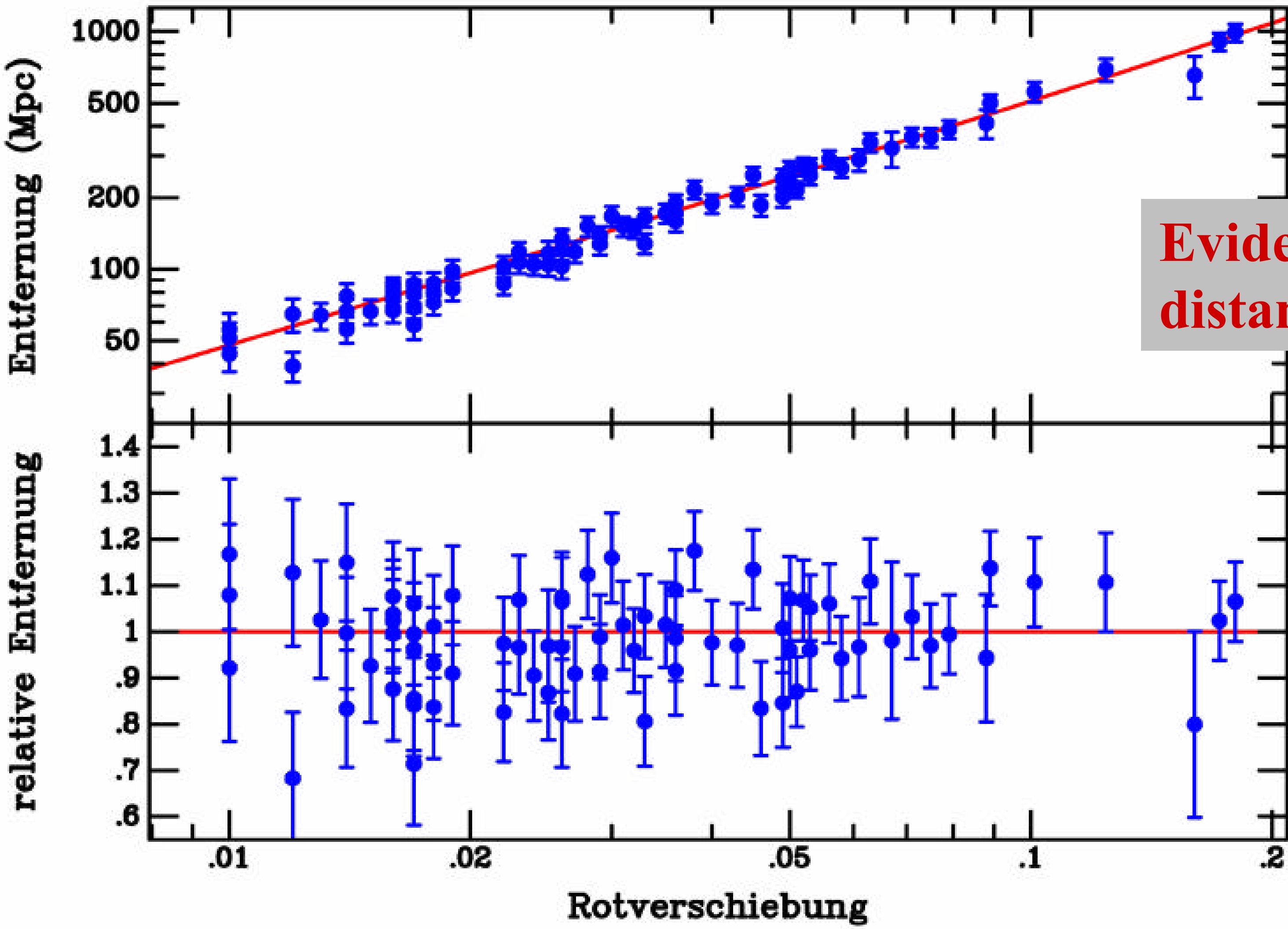
Comparison with models

Pignata et al. (2004)





The nearby SN Ia sample and Hubble's law



Evidence for good distances

Determining H_0 from models

Hubble's law

$$D = \frac{v}{H_0} = \frac{cz}{H_0}$$

Luminosity distance

$$D_L = \sqrt{\frac{L}{4pF}}$$

Ni-Co decay

$$E_{Ni} = \frac{l_{Ni}\, l_{Co}}{l_{Ni} - l_{Co}} \left\{ \left[Q_{Ni} \left(\frac{l_{Ni}}{l_{Co}} - 1 \right) - Q_{Co} \right] e^{-l_{Ni} t} + Q_{Co} e^{-l_{Co} t} \right\} N_{Ni,0}$$

H_0 from the nickel mass

$$H_0 = \frac{cz}{D} = cz\sqrt{\frac{4pF}{L}} = cz\sqrt{\frac{4pF}{aE_{Ni}}} = cz\sqrt{\frac{4pF}{ae(t)M_{Ni}}}$$

Hubble Law

Luminosity distance

Arnett's rule

Ni-Co decay and rise time

***a*: conversion of nickel energy into radiation (L=aE_{Ni})**
***e(t)*: energy deposited in the supernova ejecta**

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

Stritzinger & Leibundgut (2005)

Assumptions

Rise time (15-25 days) → about 10% uncertainty

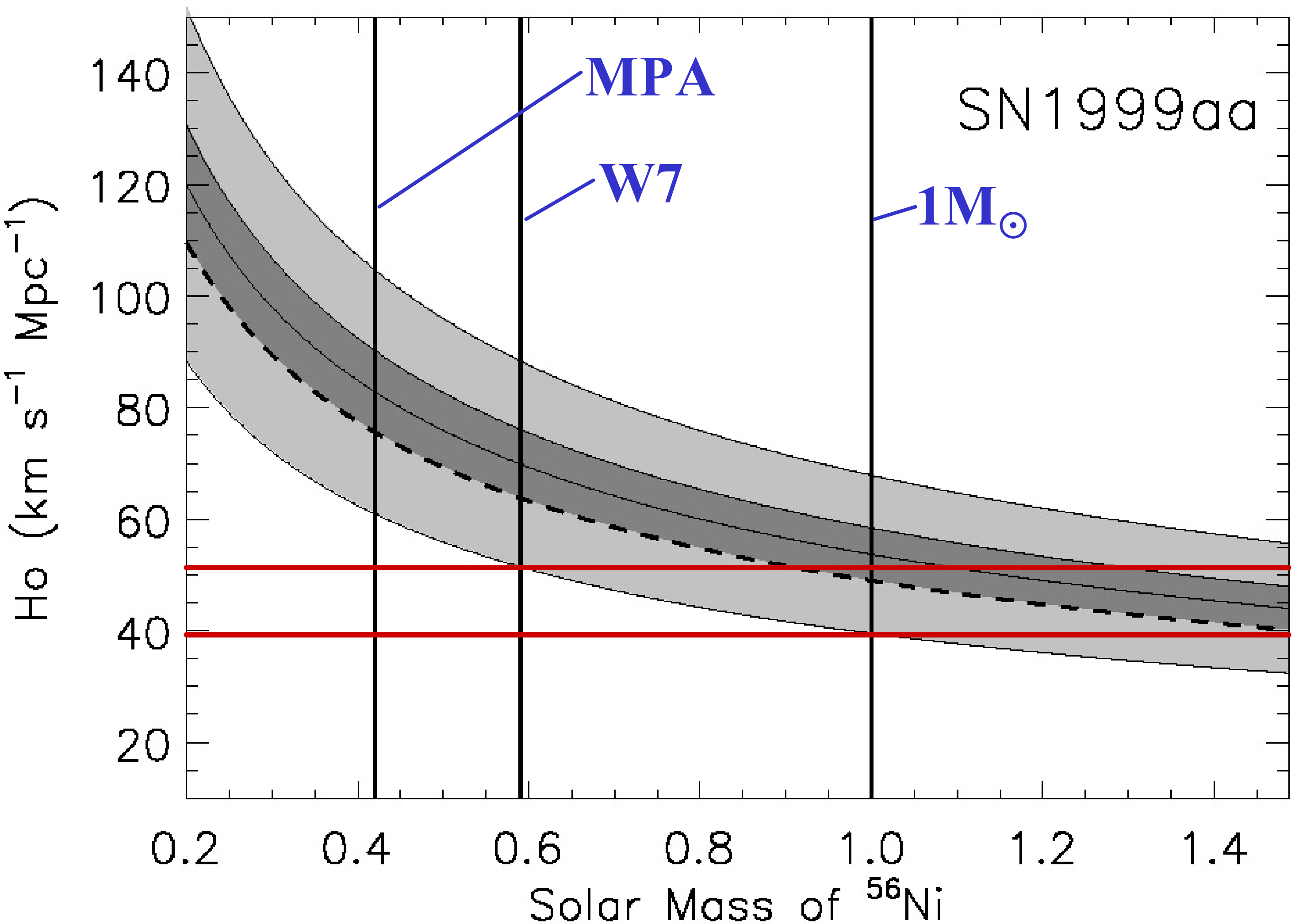
Arnett's rule

energy input at maximum equals radiated energy (i.e. a ˜ 1, $e(t_{max})$ ˜ 1)

Nickel mass from models

→ uniquely defines the bolometric peak luminosity

Comparison with models



Acceleration

Originally thought of as deceleration due to the action of gravity in a matter dominated universe

$$D = \frac{cz}{H_0}\left[1 + \frac{1}{2}(1 - q_0)z\right]$$

$$q_0 = -\frac{\ddot{a}}{a} H_0^{-2}$$


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

Friedmann cosmology

Assumption:
homogeneous and isotropic universe

Null geodesic in a Friedmann-Robertson-Walker metric:

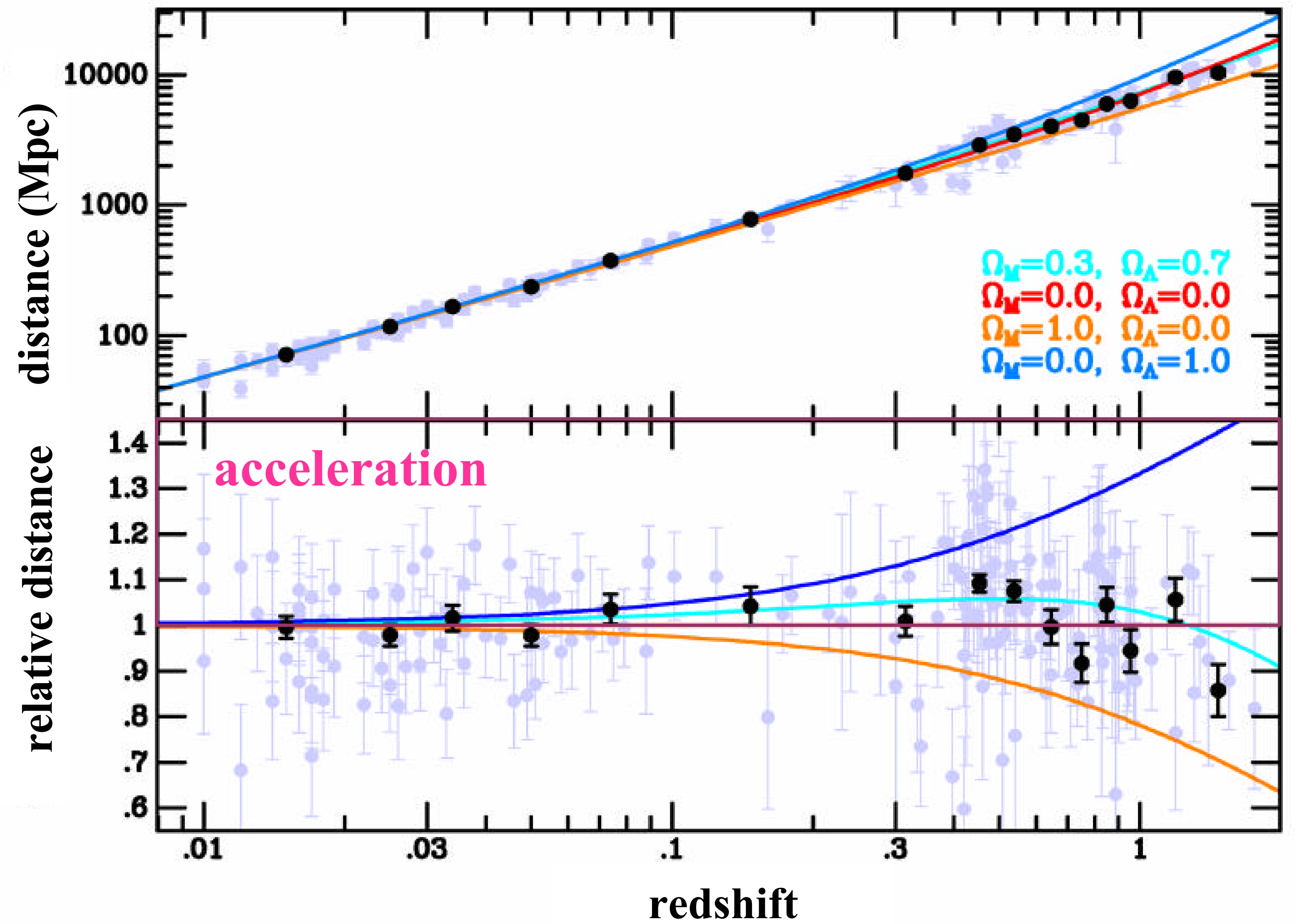
$$D_L = \frac{(1+z)c}{H_0\sqrt{|\Omega_k|}} S\left\{ \sqrt{|\Omega_k|} \int_0^z \left[\Omega_k (1+z')^2 + \Omega_M (1+z')^3 + \Omega_\Lambda\right]^{-1/2} dz' \right\}$$

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

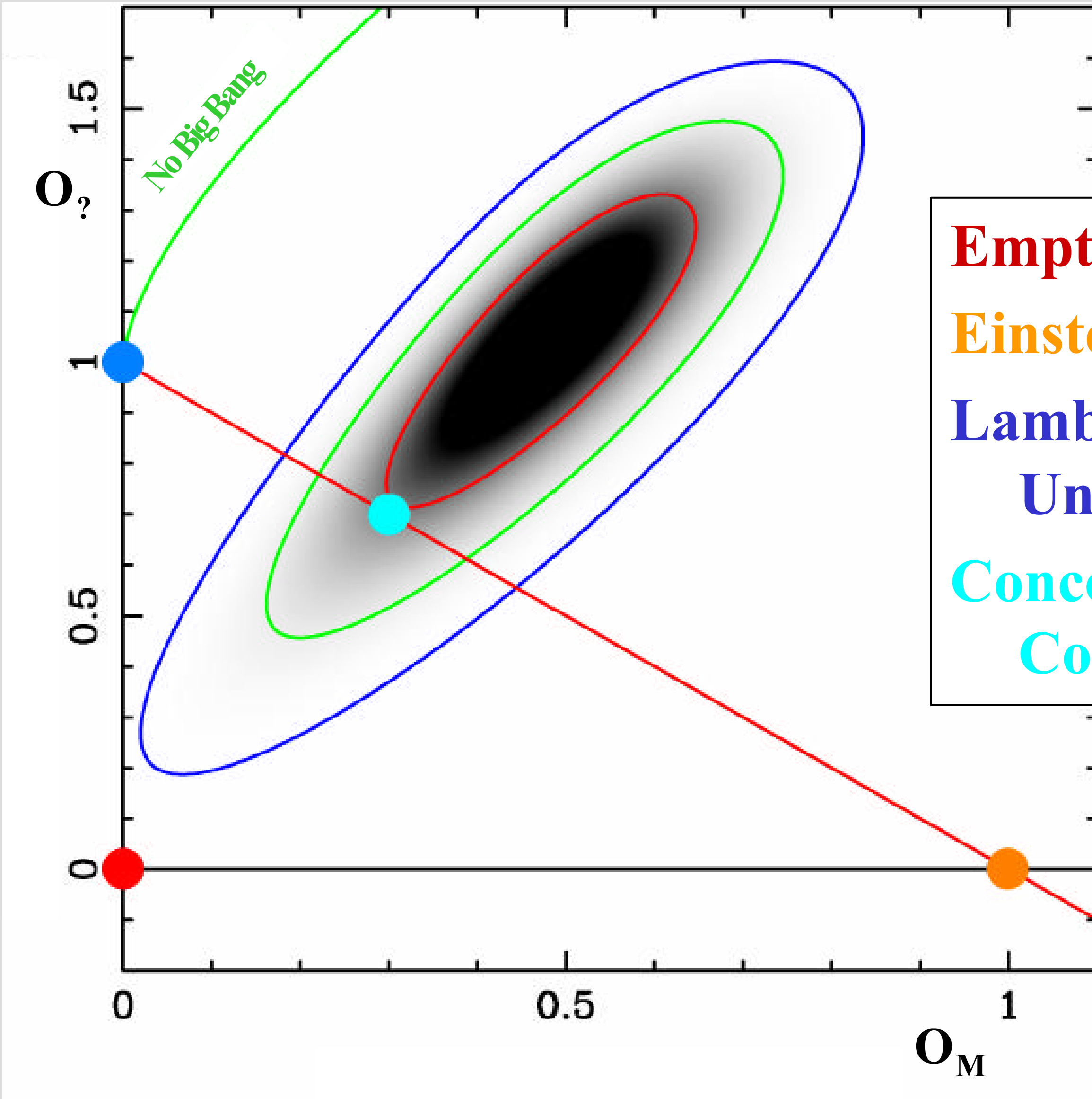
$$\Omega_k = -\frac{kc^2}{R^2 H_0^2}$$

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

Measure acceleration



Cosmological implication



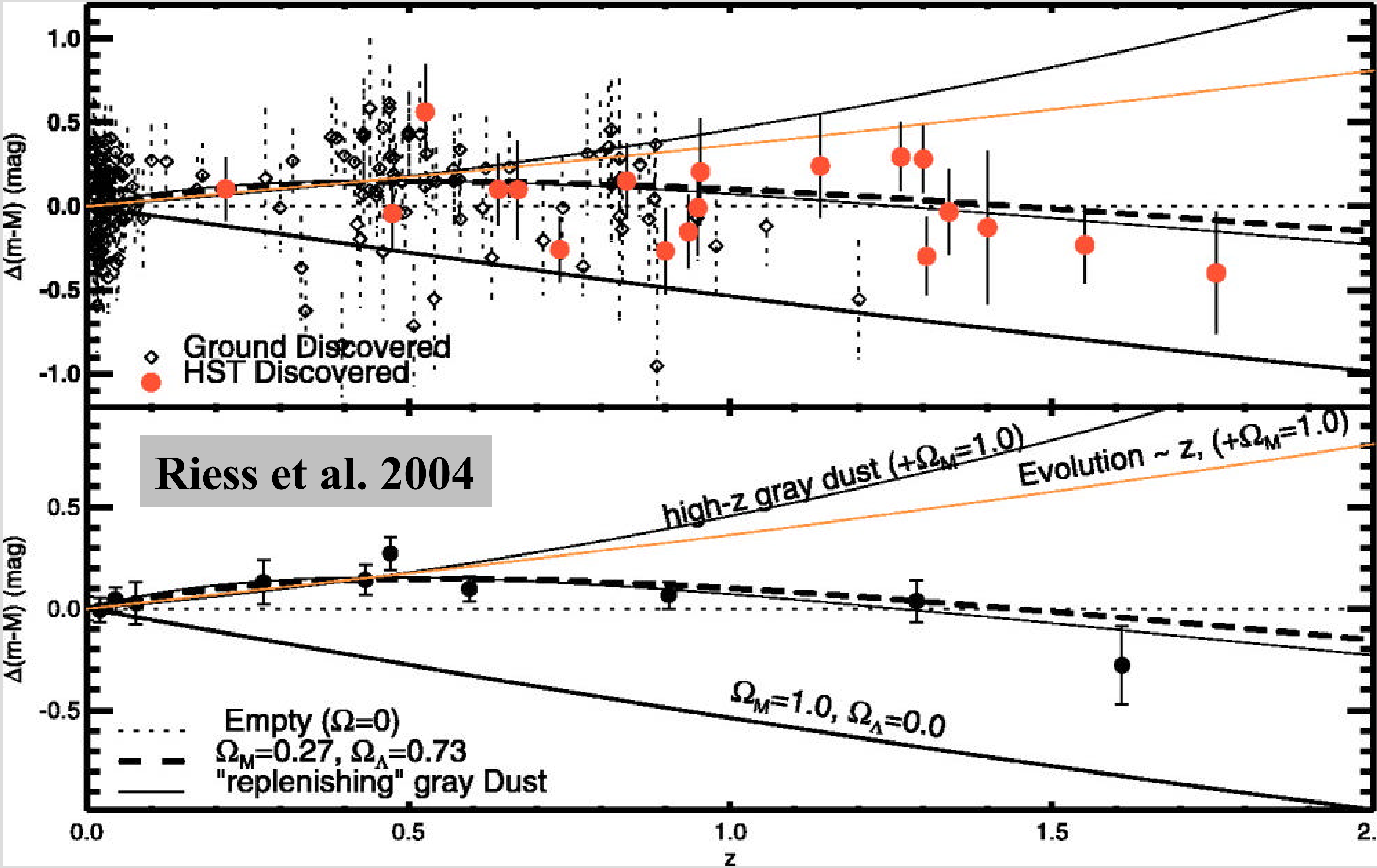
Empty Universum

Einstein – de Sitter

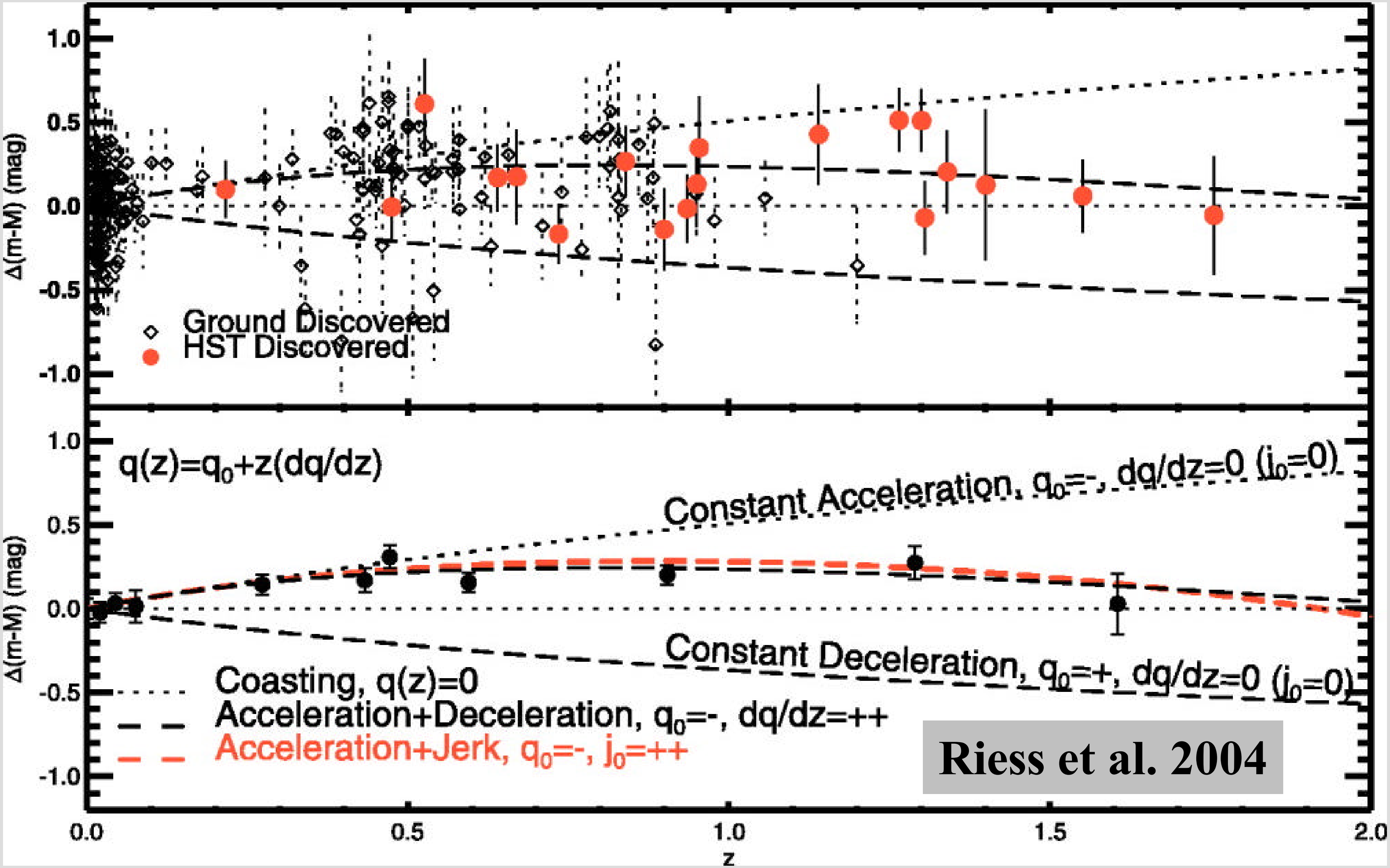
Lambda-dominated Universe

Concordance Cosmology

Evidence for the $\Omega_?$

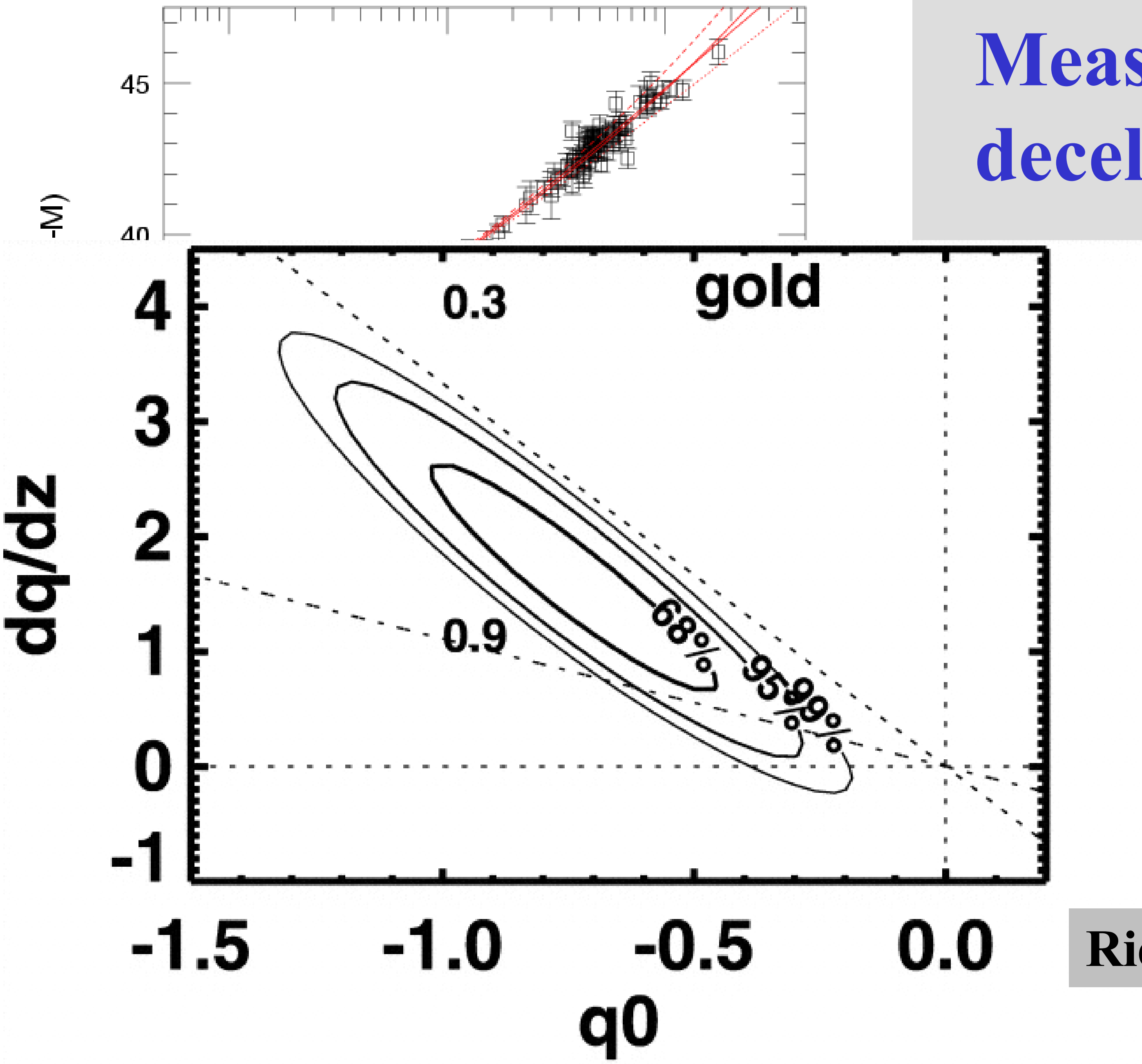


Adding jerk …



Riess et al. 2004

Measure deceleration



Riess et al. 2004

What is Dark Energy?

$$G_{\mu\nu} + f(g_{\mu\nu}) = 8\pi G \, [\, T_{\mu\nu}(\text{matter}) + T_{\mu\nu}(\text{new}) \,]$$

????

Two philosophically distinct possibilities:

- Gravitational effect, e.g. Cosmological Constant, or gravity "leaking" into extra dimensions
- A "Vacuum energy" effect, decaying scalar field

New Fundamental Physics!

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** $\Omega_k = 1 - \sum_i \Omega_i$ **and** $w_i = \dfrac{p_i}{r_i c^2}$

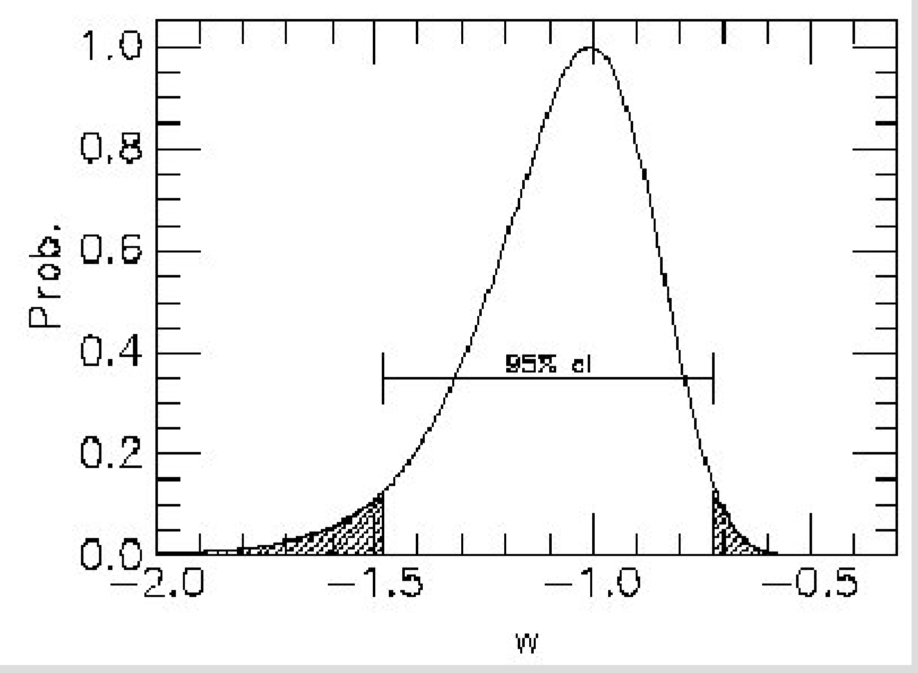
w_M= 0 (matter)

w_R= ? (radiation)

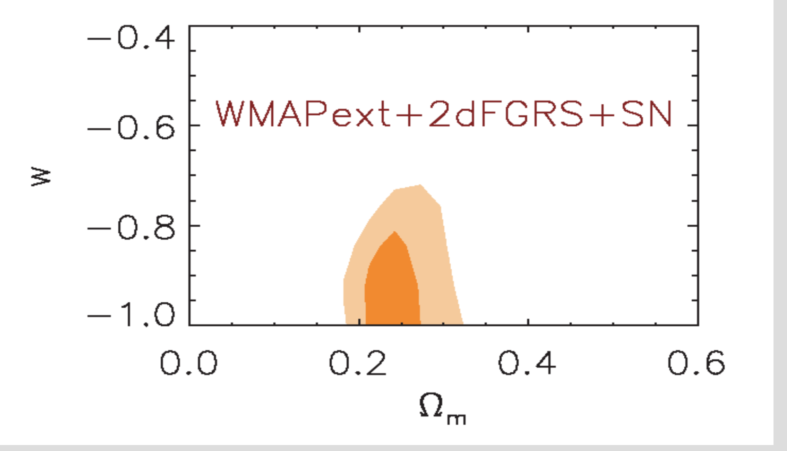
w_L= -1 (cosmological constant)

Dark Energy Equation of State

Current Limit on Dark Energy:
***w* < -0.7**



Tonry et. al. 2003



Spergel et. al. 2003

Dark Energy Models

$w > -1$ Quintessence

Gravitational, e.g. R^{-n} with n>0 (Carroll et. al. 2004)

$w = -1$ Cosmological Constant

$w < -1$ Exotic! (Carroll et. al. 2003)

In general unstable

Pair of scalars: “crossing” from w>-1 to w<-1

Physical issues

ESSENCE

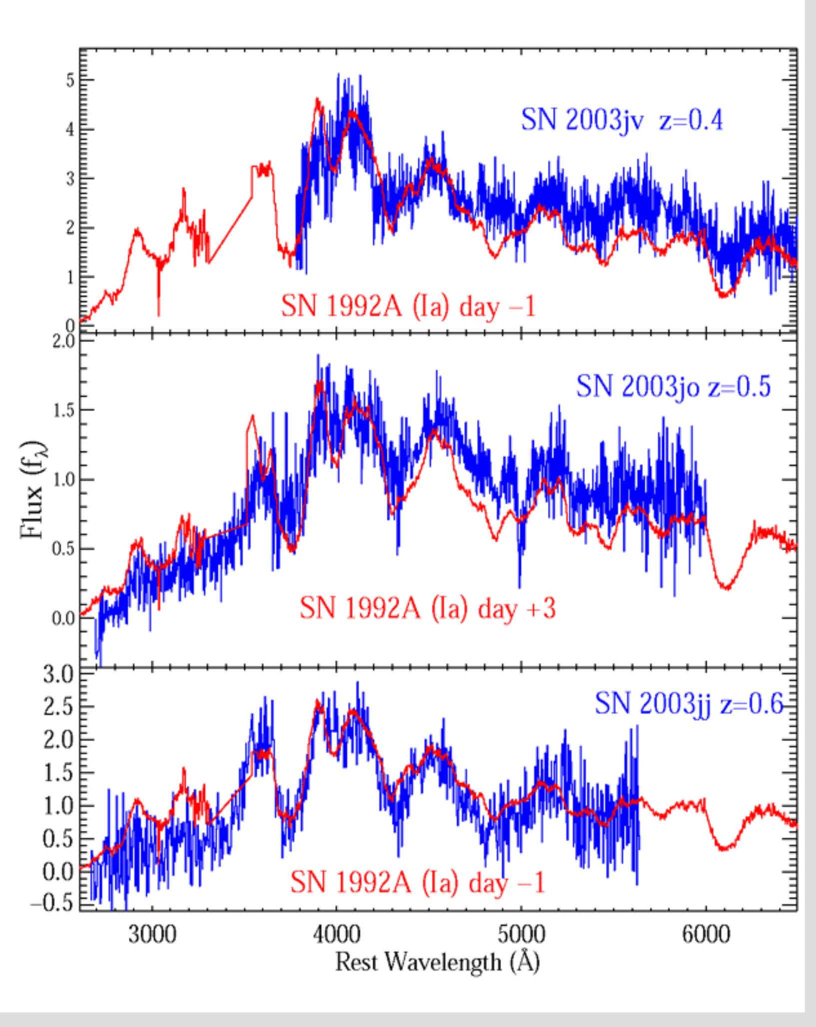
World-wide collaboration to find and characterise SNe Ia with $0.2<z<0.8$

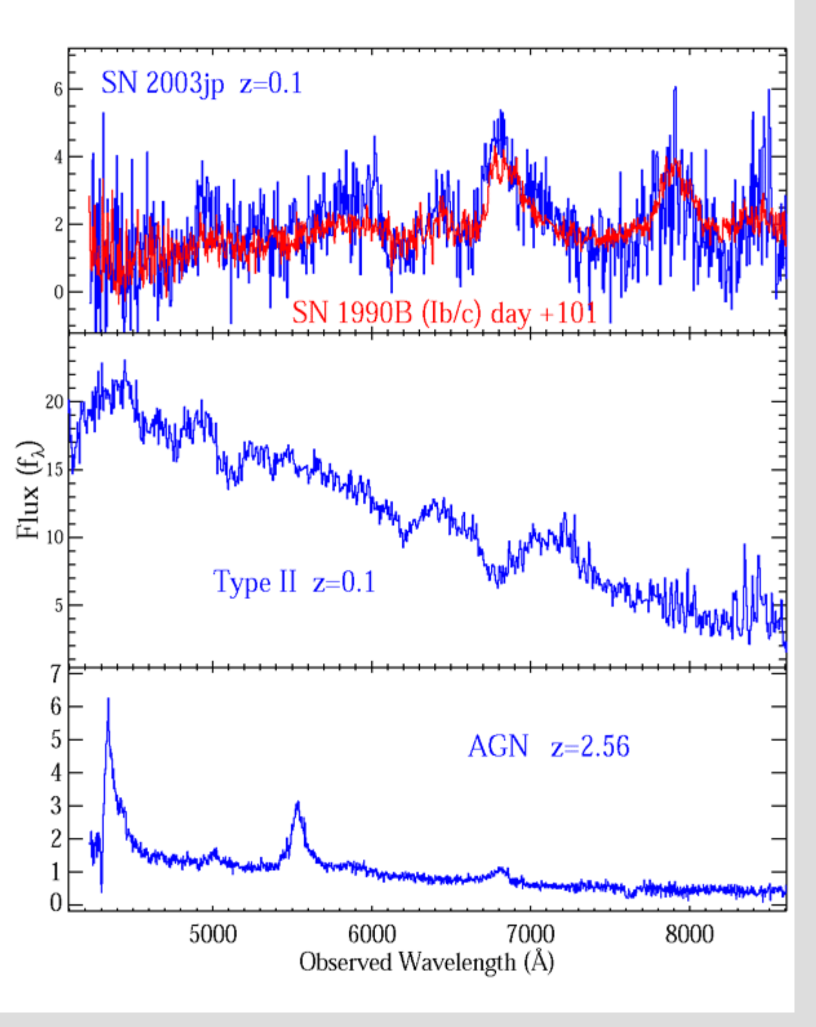
Search with CTIO 4m Blanco telescope

Spectroscopy with VLT, Gemini, Keck, Magellan

Goal: Measure distances to 200 SNe Ia with an overall accuracy of 5%
→ determine ? to 10% overall

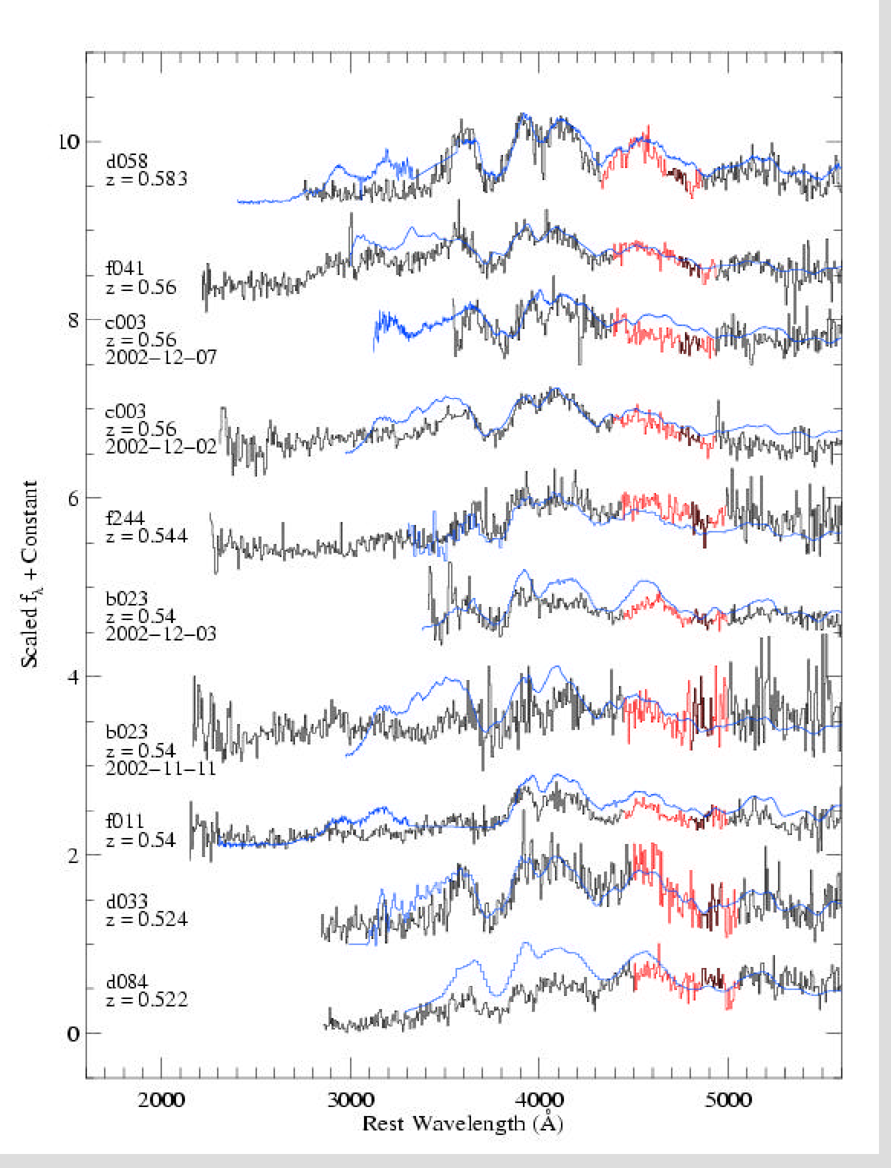
ESSENCE spectroscopy

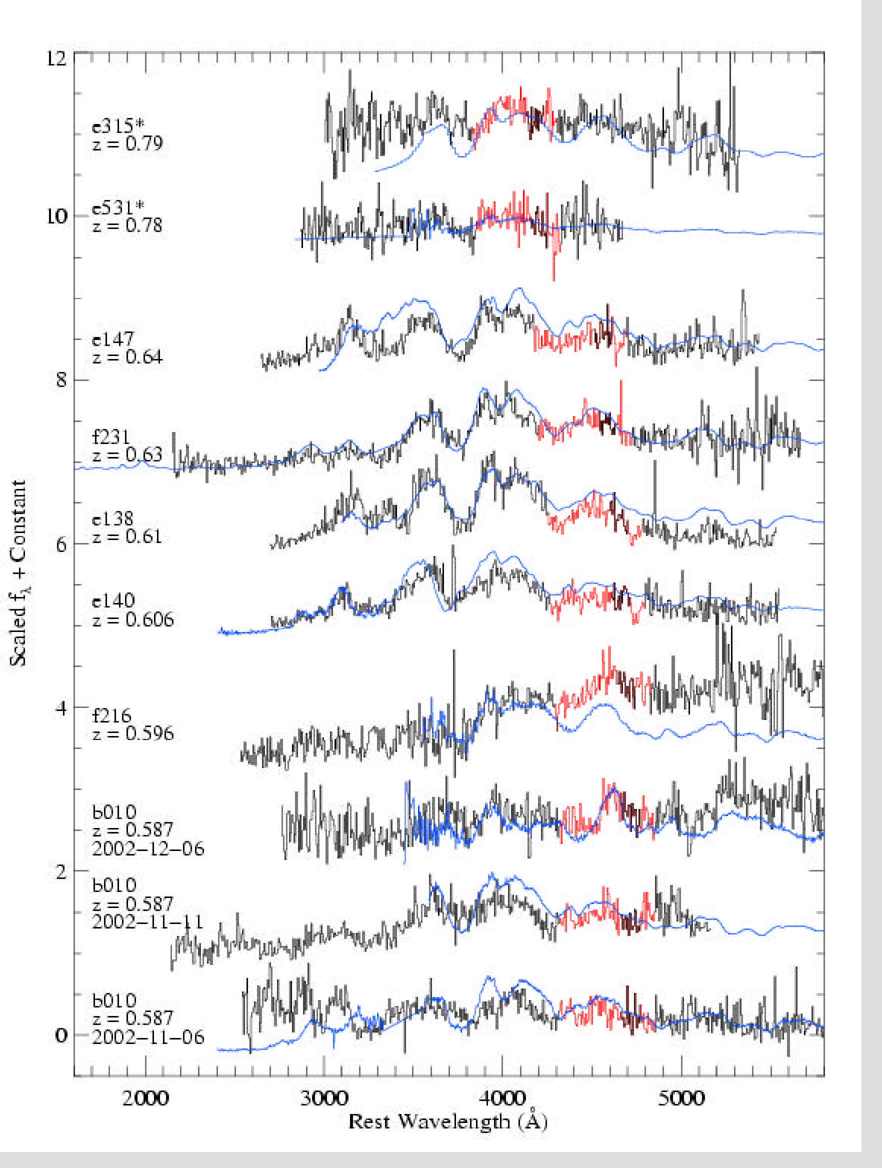




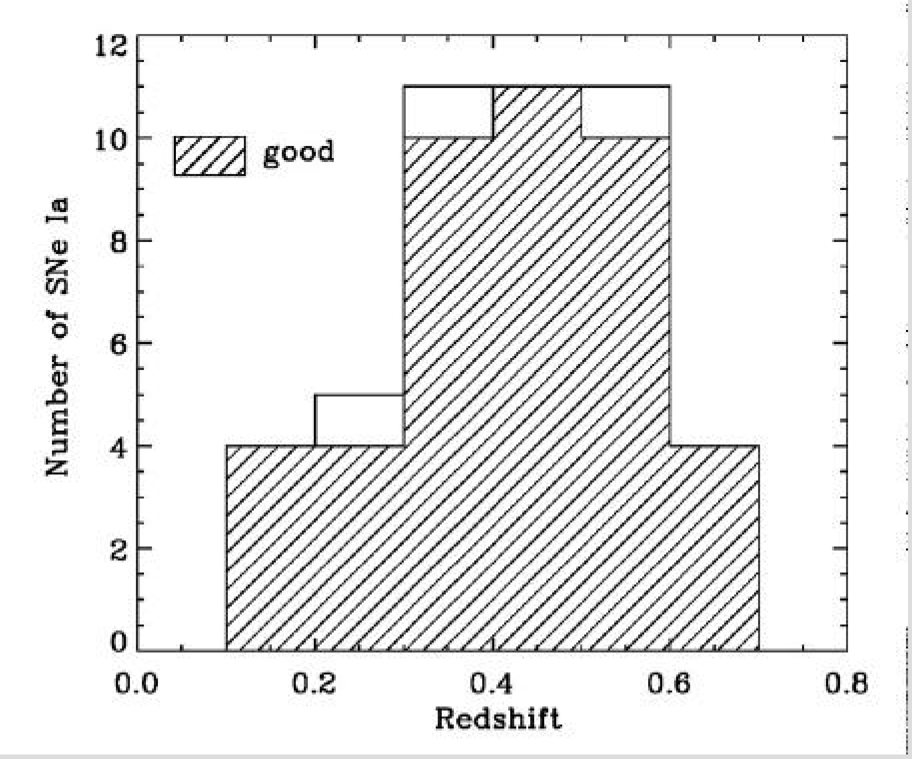
Matheson et al. 2005

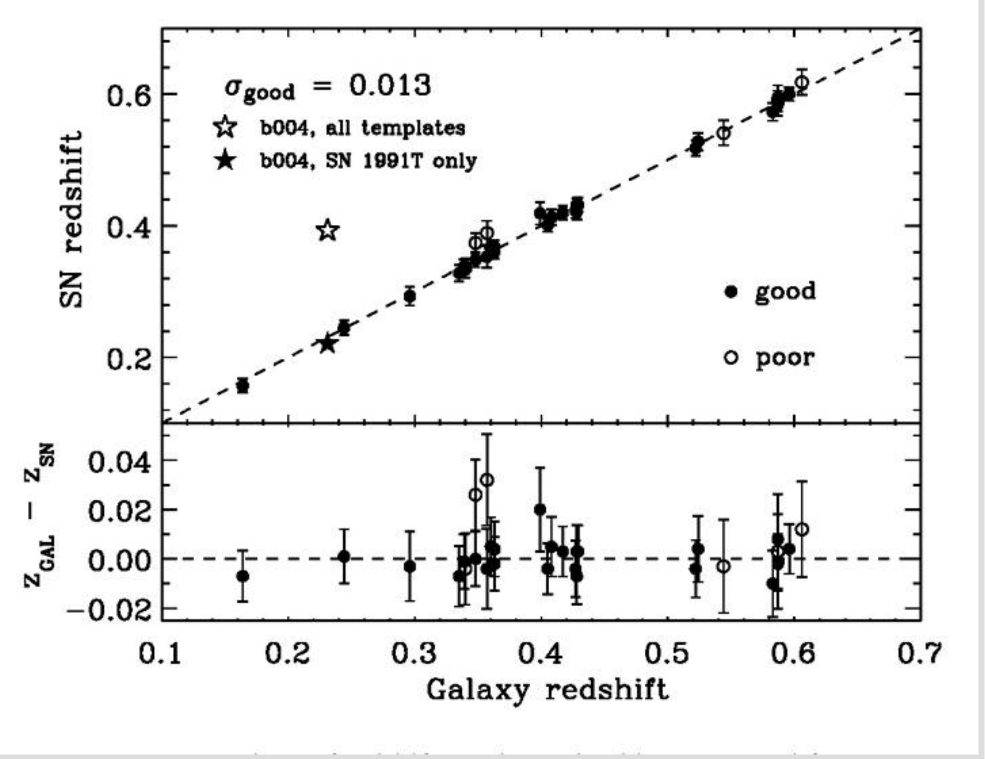
ESSENCE spectroscopy (cont.)



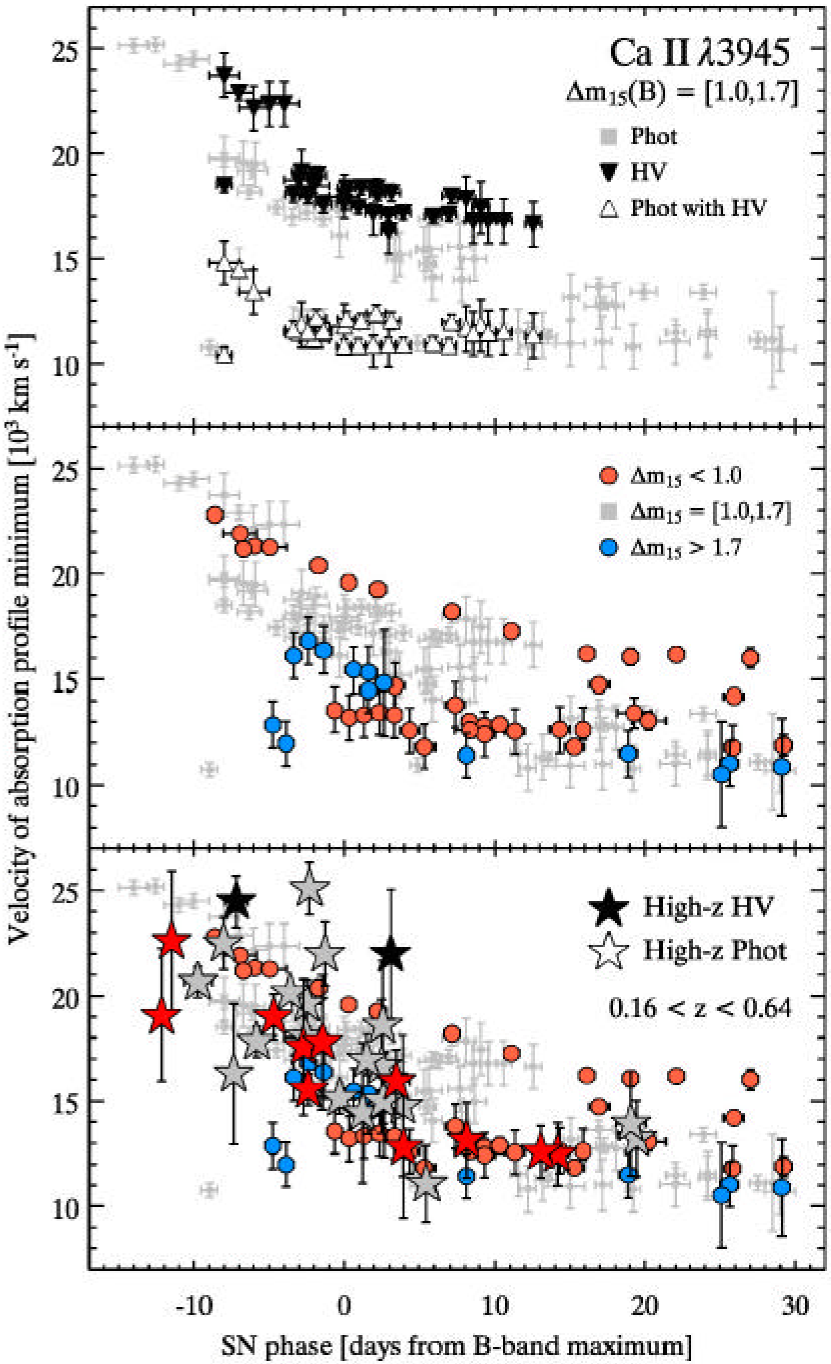


First two years of ESSENCE spectra

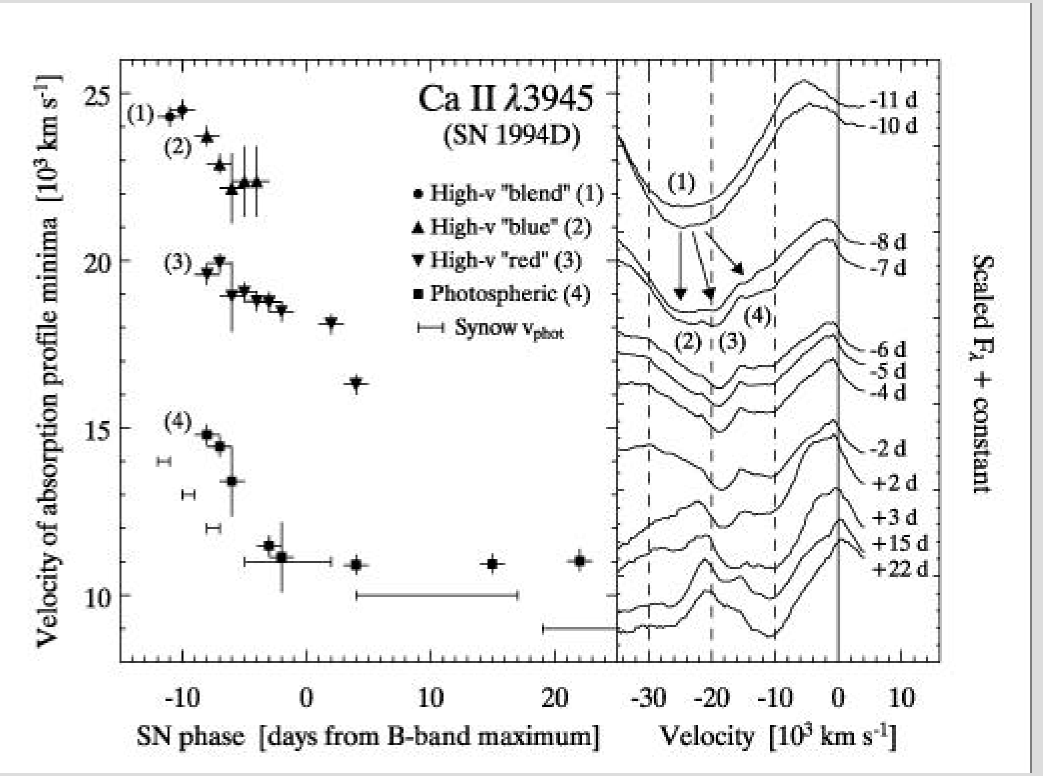




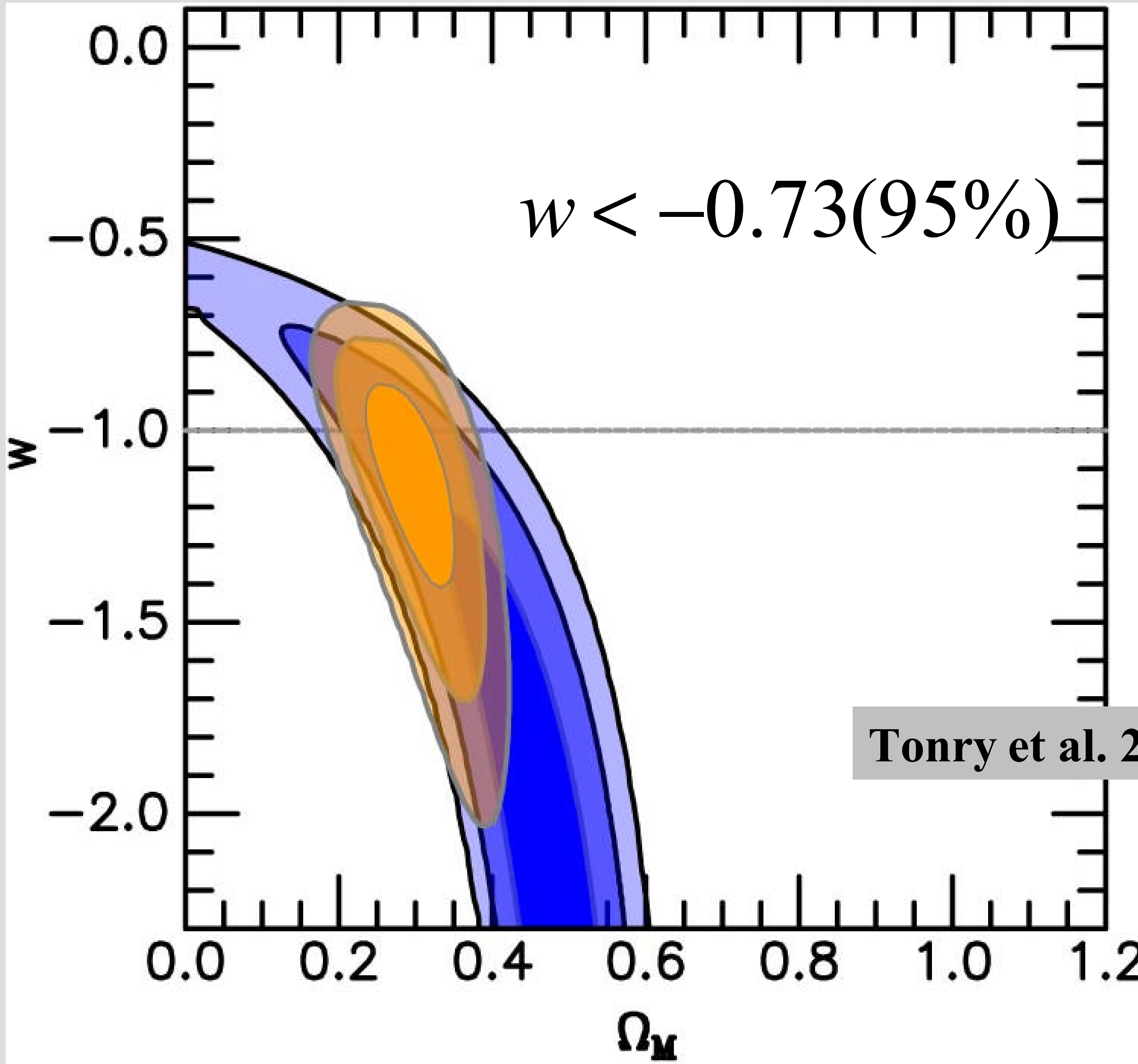
Matheson et al. 2005



Spectroscopic study



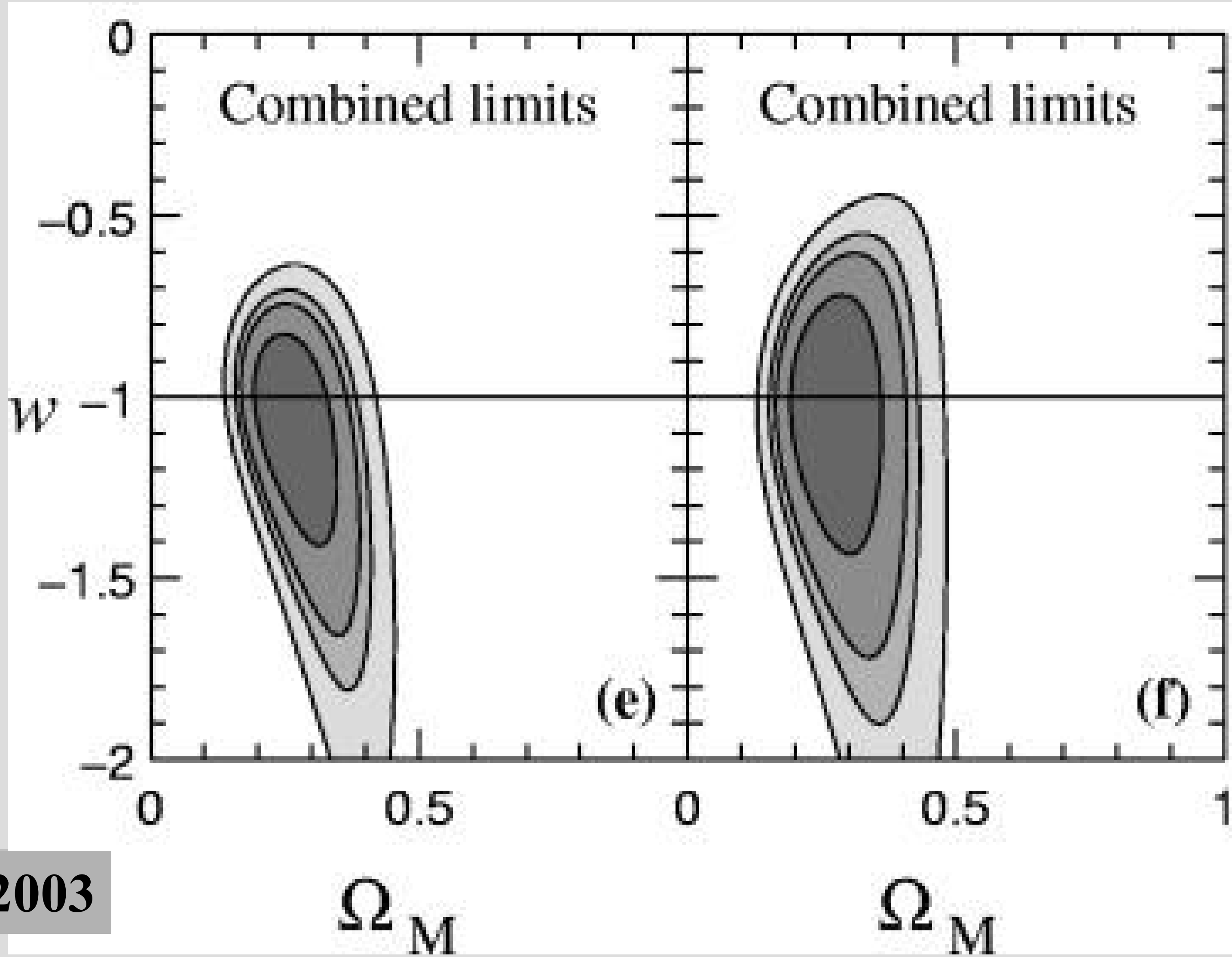
Blondin et al. 2005



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

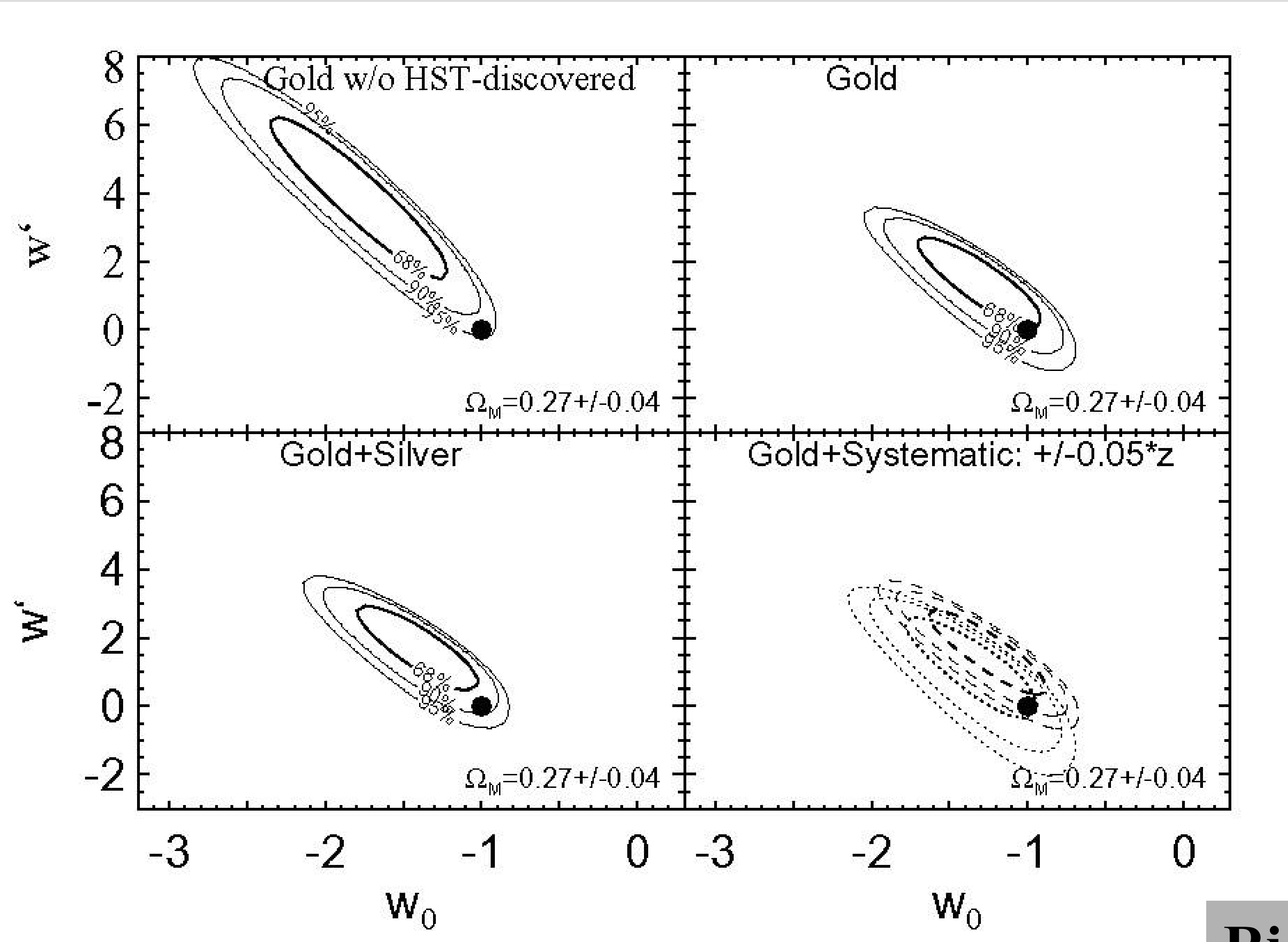
SN Ia and 2dF constraints

Use constraints from 2dF and WMAP



Knop et al. 2003

And on to a variable ?

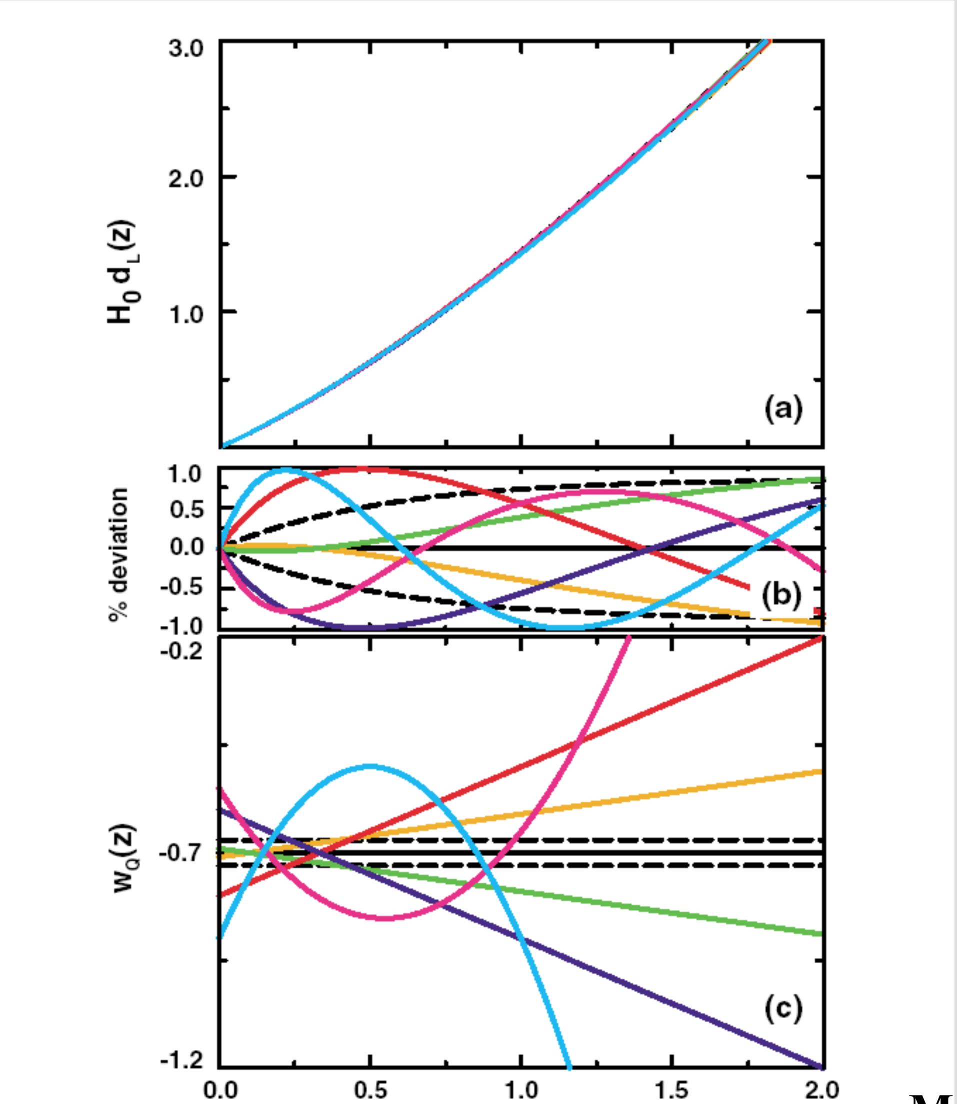


Ansatz:

? (z)= ? $_0$+ ? ’z

Riess et al. 2004

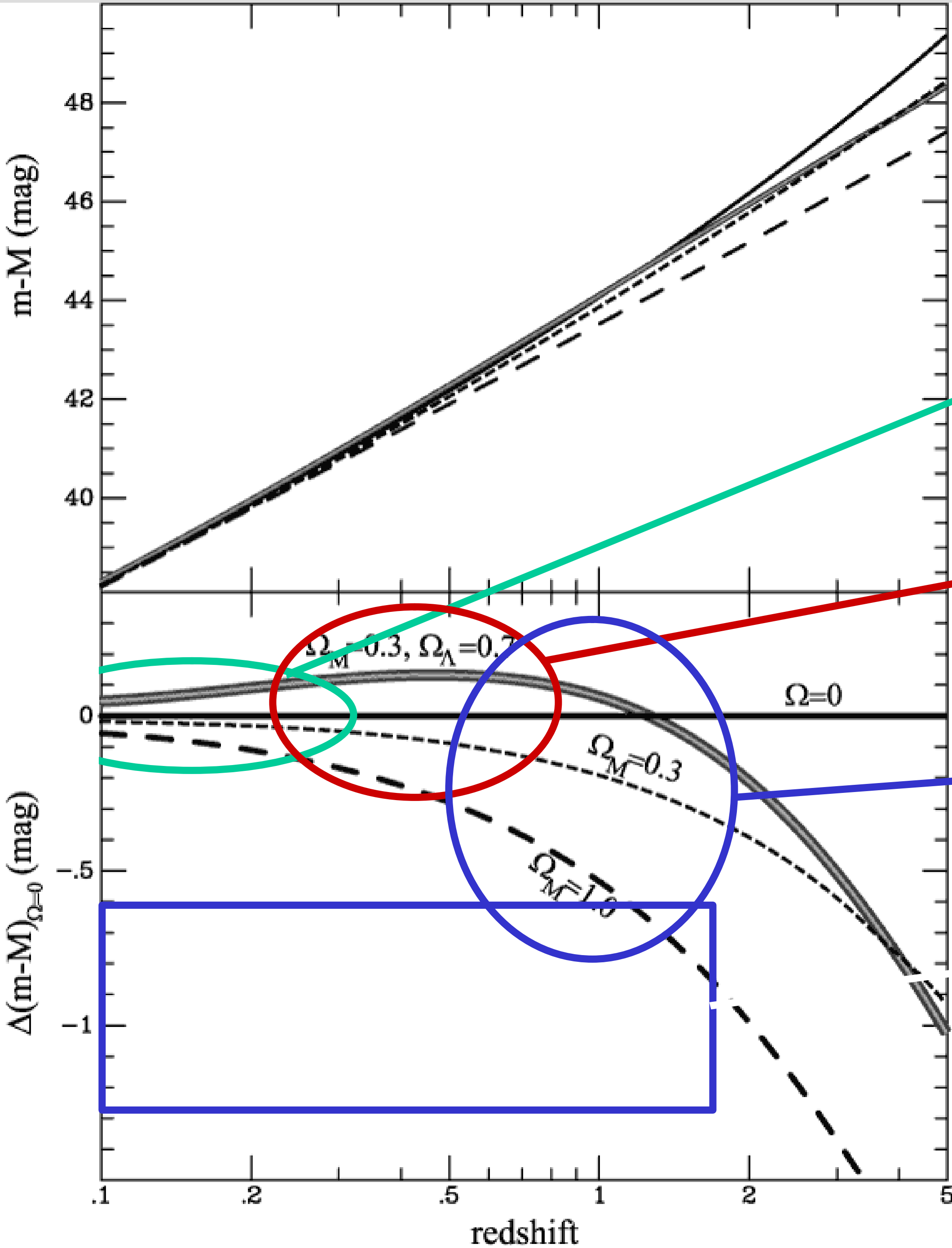
Time-dependent *w*(z)



Luminosity Distance vs redshift can be degenerate for time-varying ? (z)

Maor, Brustein & Steinhardt 2001

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 supernovae
- 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 ? are exaggerated. Current data 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**