Supernova cosmology

Bruno Leibundgut
European Southern Observatory

Outline

Introduction to the Supernova Hubble diagram

Supernova physics and H_0

The ESSENCE project

Evolution of Type Ia Supernovae?

- comparing expansion velocities

Some words on variable ω

Summary

Supernova cosmology

Through (luminosity) distances

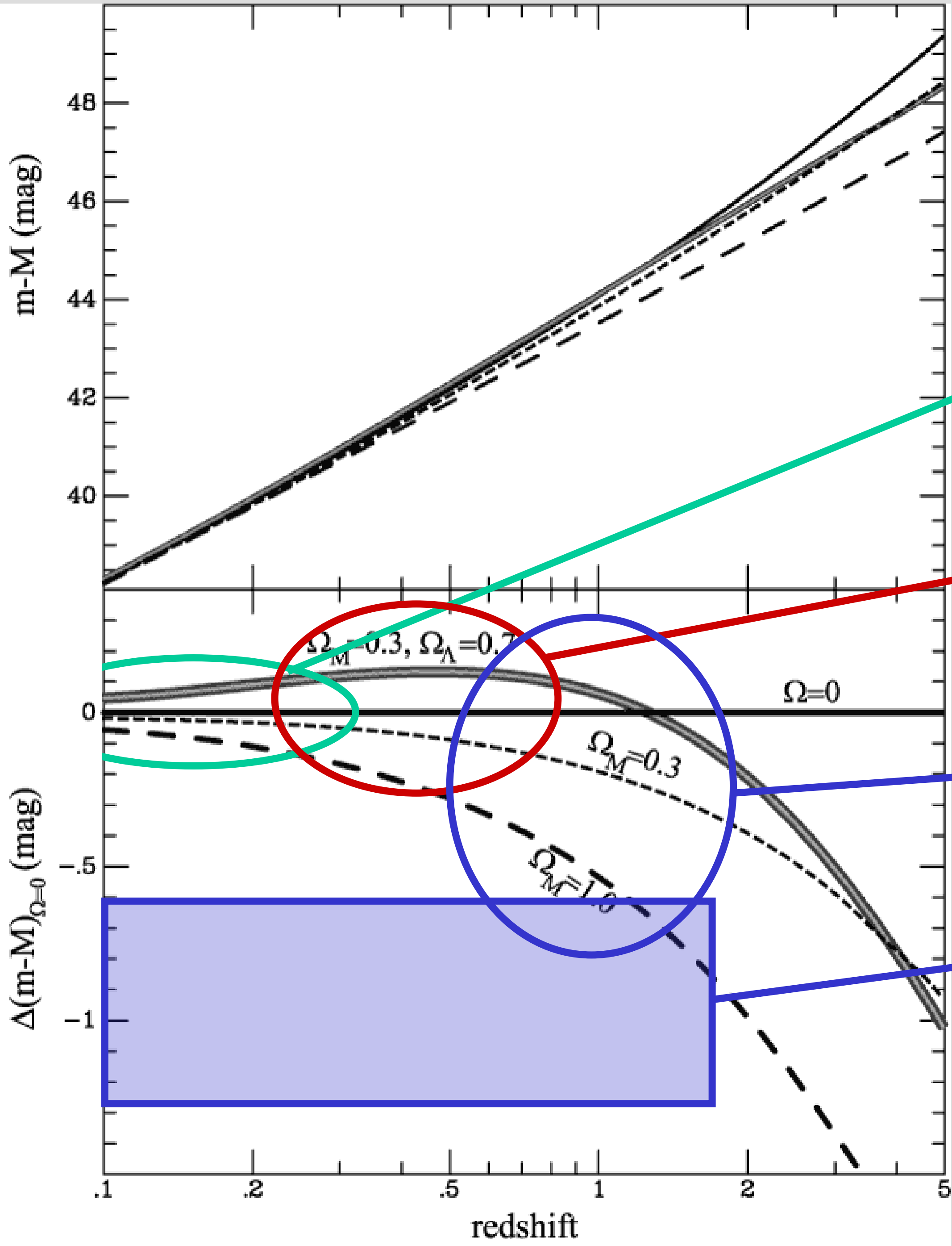
- provide distances for the determination of H_0 in the nearby universe
  - normalised peak brightness of thermonuclear supernovae (Type Ia)
    - requires knowledge of absolute luminosity
  - expanding photosphere method for core-collapse supernovae (Type II and Ib/c)
  - normalised brightness of the light curve plateau in hydrogen-rich core collapse supernovae (Type II)
- Measure expansion history
  - normalised peak brightness of Ia’s
    - relative distances are okay here

The SN 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

SN Projects



SN Factory
Carnegie SN Project

ESSENCE
CFHT Legacy Survey

Higher-z SN Search
(GOODS)

JDEM/SNAP, DUNE

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)

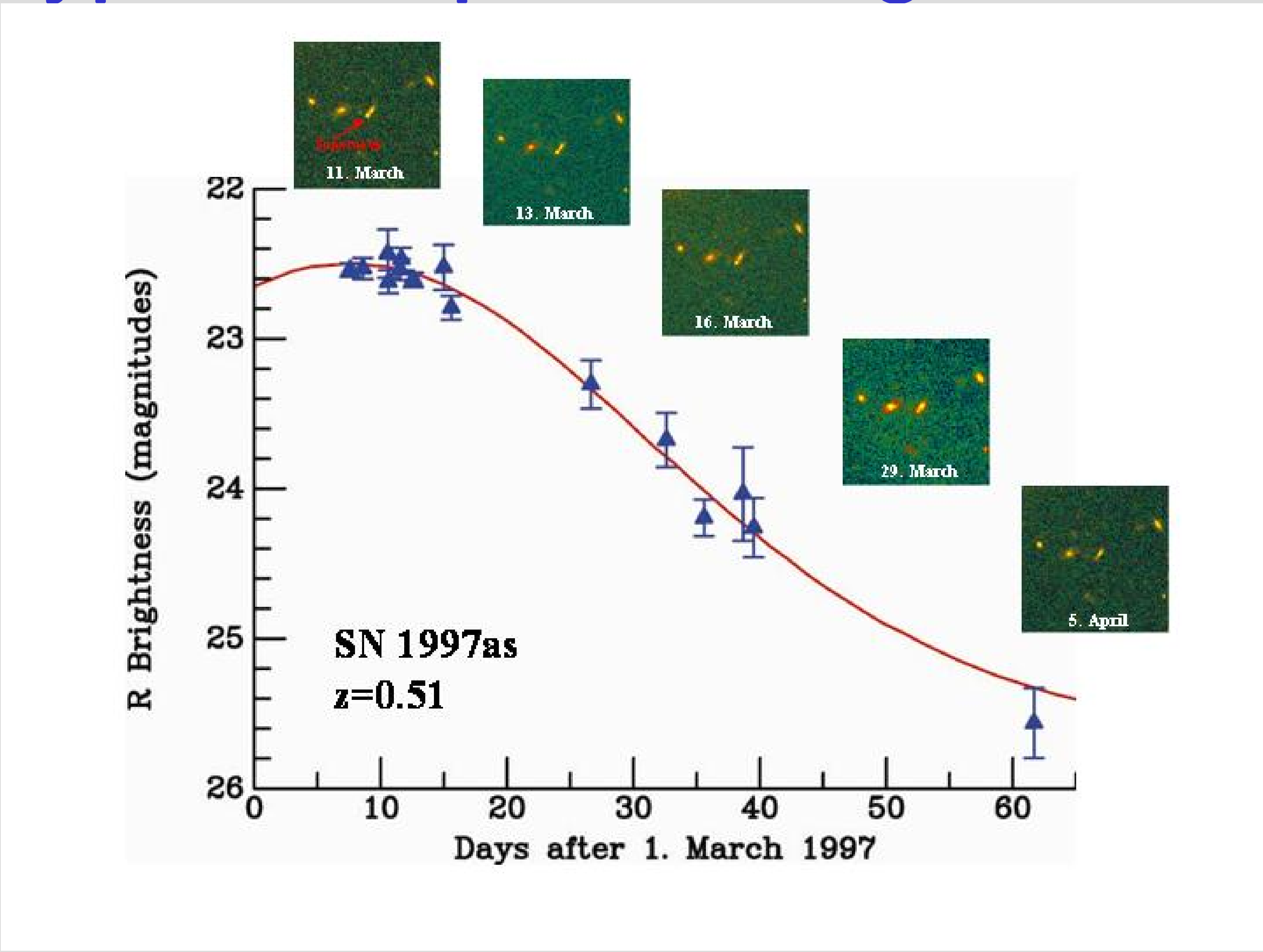
z>0.8

- break the degeneracy between Ω_M and Ω_Λ
- measure matter density

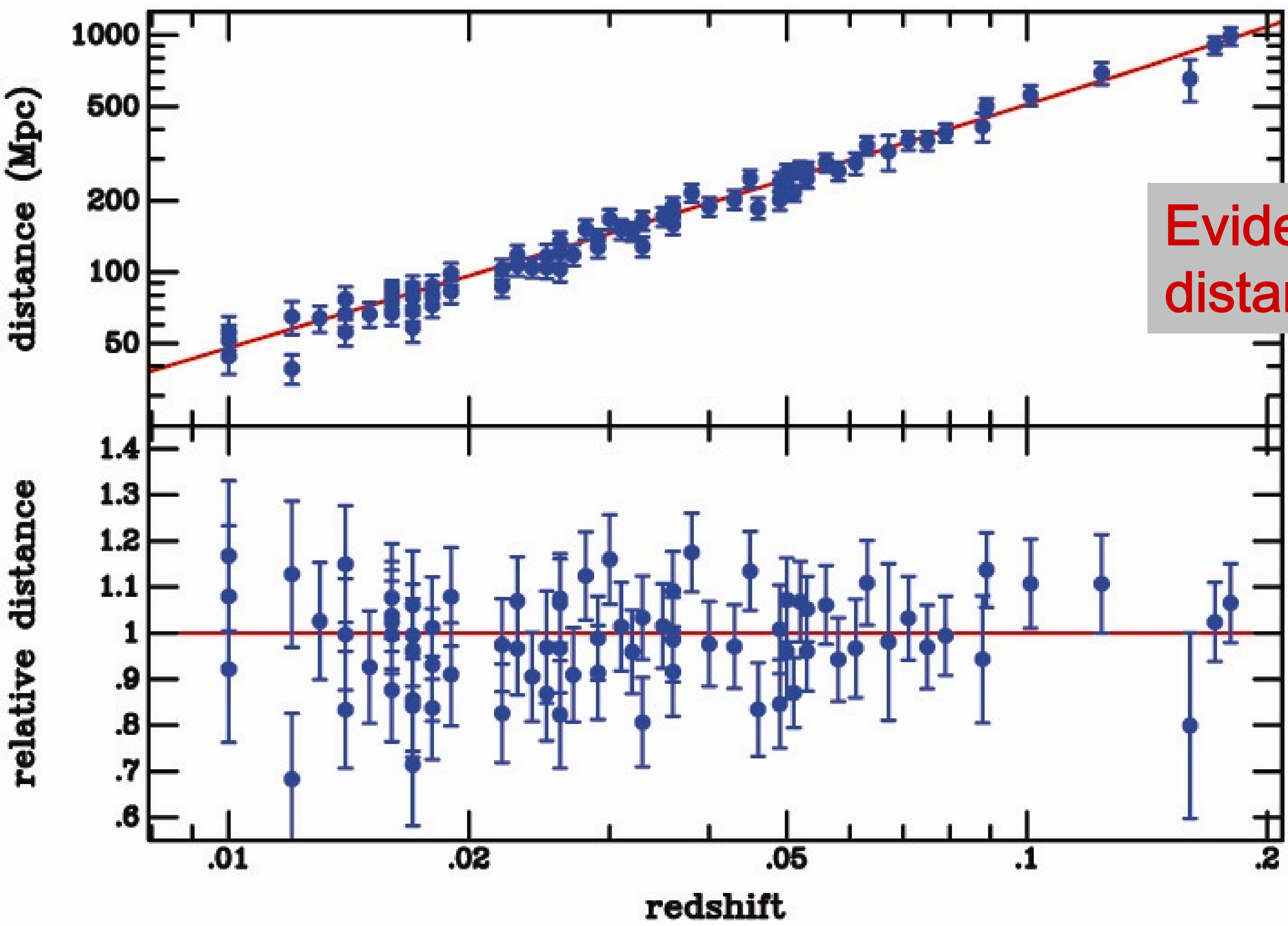
All redshifts

- Measure property of dark energy

Type Ia Supernova light curve

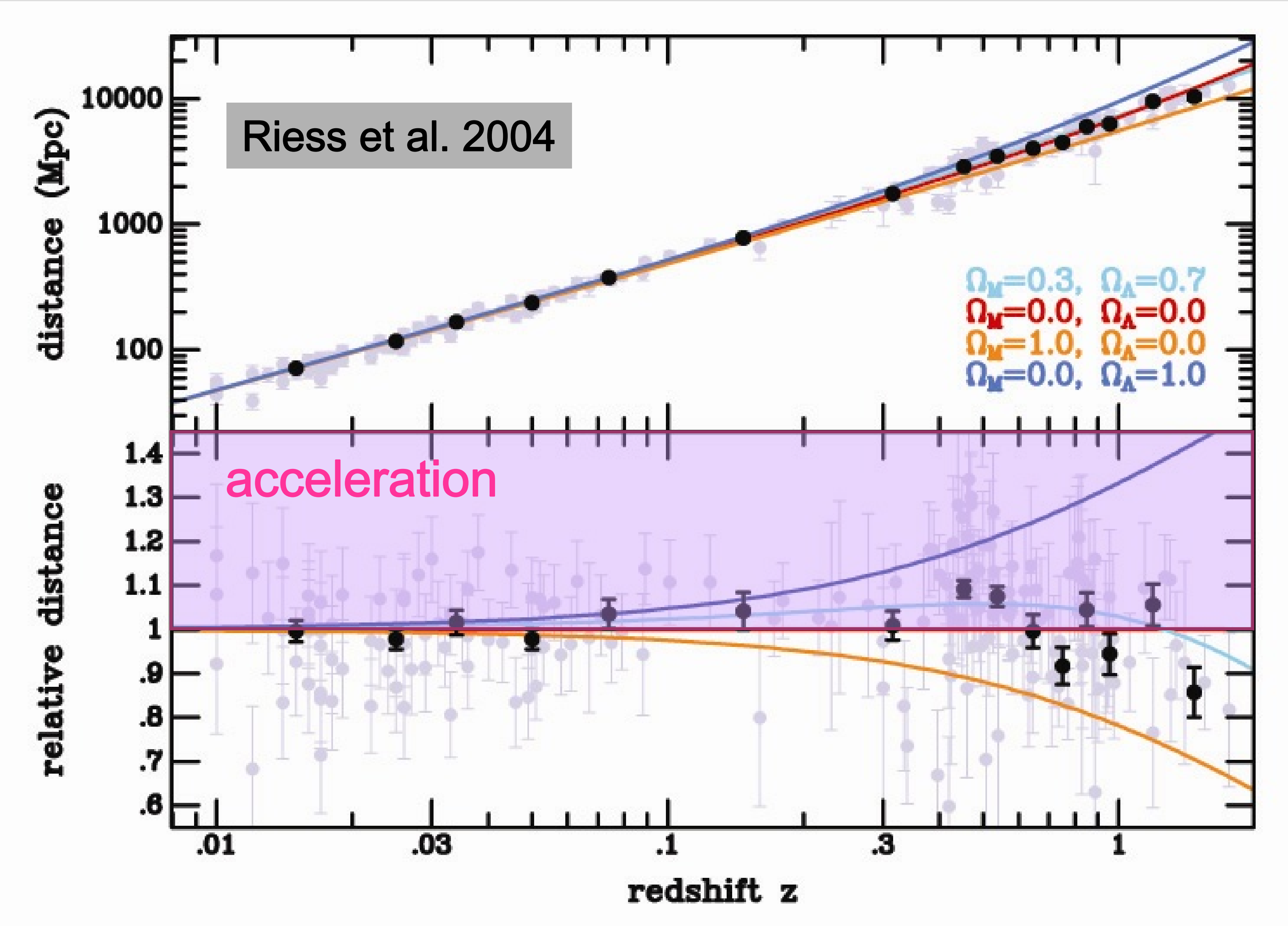


The nearby SN Ia sample and Hubble's law

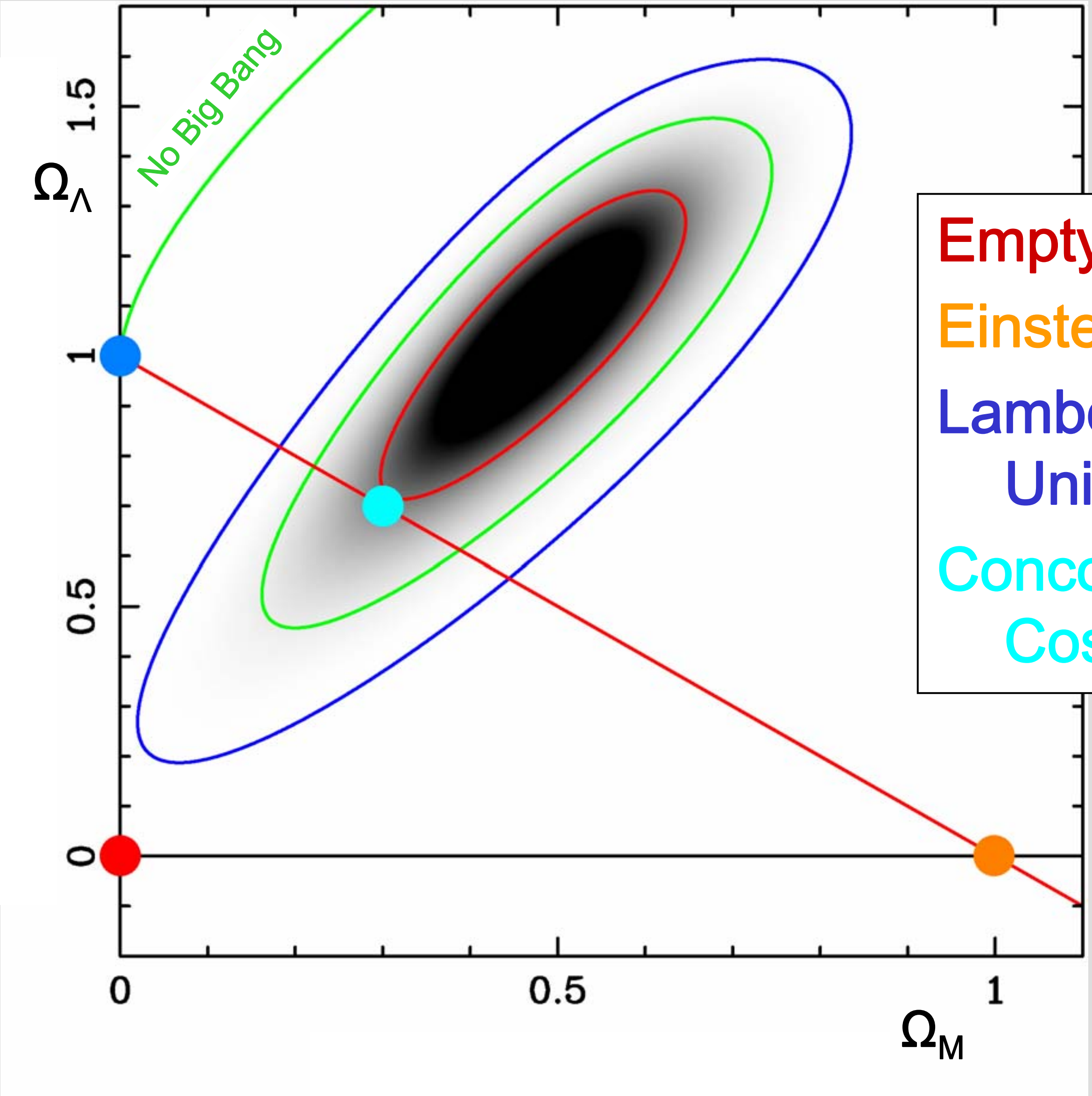


Evidence for good distances

Measure acceleration



Cosmological implication



Empty Universum

Einstein – de Sitter

Lambda-dominated Universe

Concordance Cosmology

Supernova physics

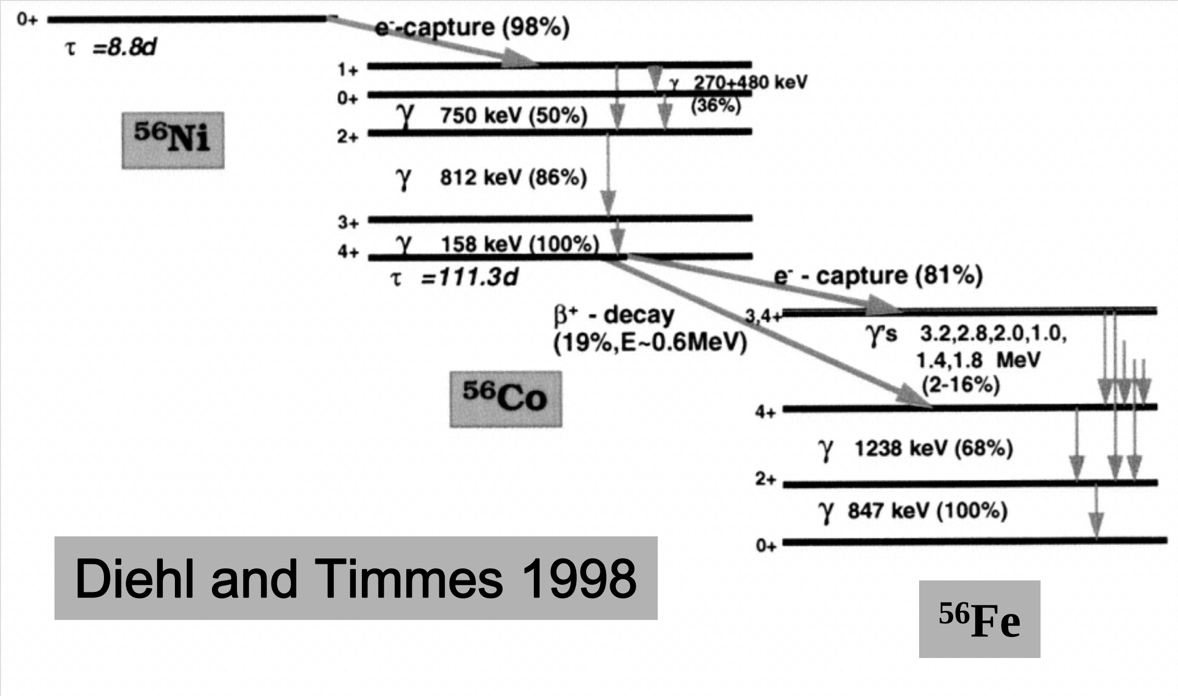
Explosion mechanism most likely explosive combustion of C and O of a white dwarf star

- Nucleosynthesis of radioactive ^{56}Ni
- Light curve is powered by the decay chain $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$

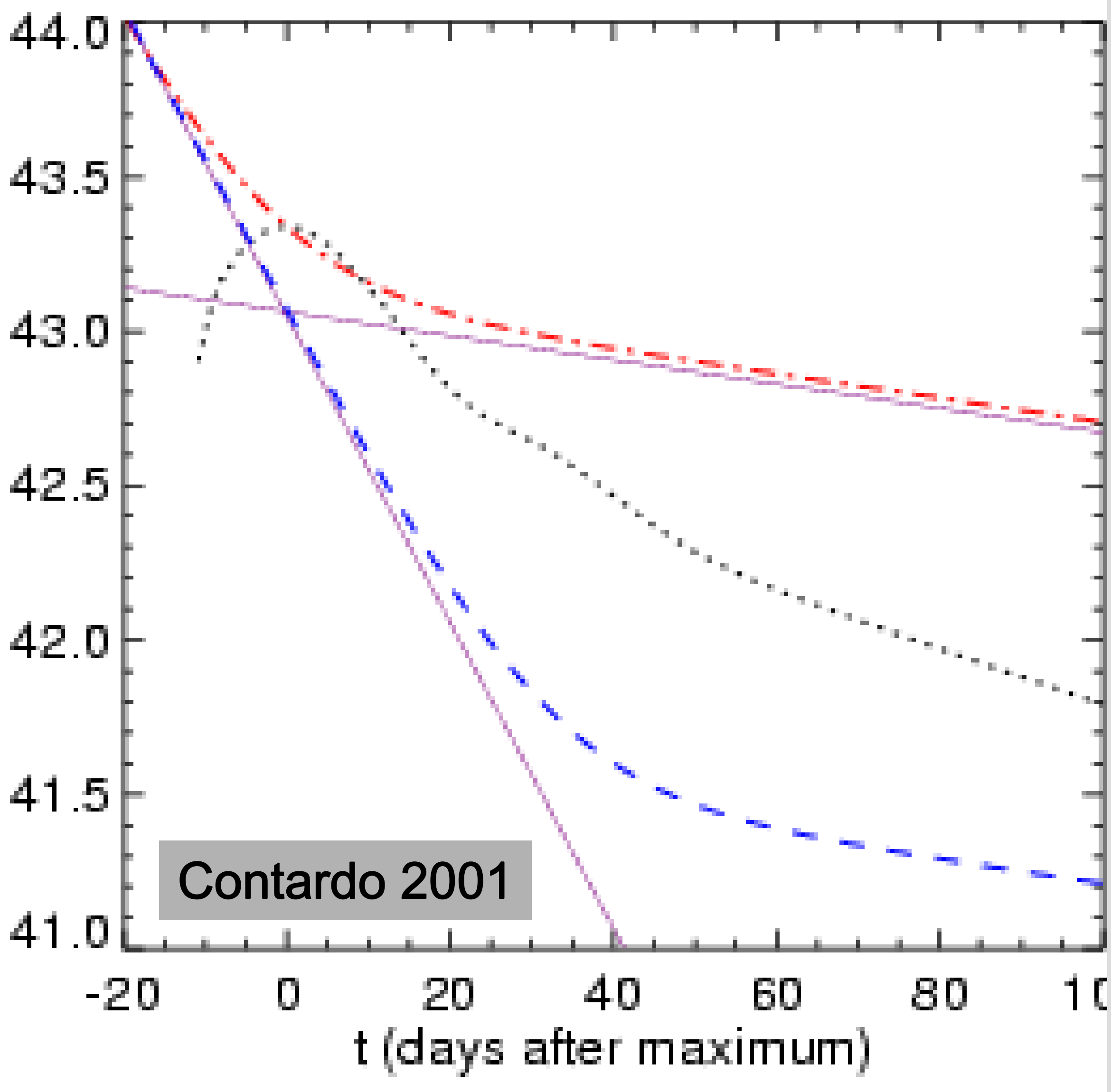
Radioactivity

Isotopes of Ni and other elements

- conversion of γ-rays and positrons into heat and optical photons



Radioactivity and light curve



- Optical depth to the γ-rays shapes the light curve
- Positron channel dominates the late phases of the light curve

Determining H_0 from explosion models

Hubble's law

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

Luminosity distance

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

Ni-Co decay

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

H_0 from the nickel mass

$$H_0 = \frac{cz}{D} = cz\sqrt{\frac{4\pi F}{L}} = cz\sqrt{\frac{4\pi F}{\alpha E_{Ni}}} = cz\sqrt{\frac{4\pi F}{\alpha\varepsilon(t)M_{Ni}}}$$

Hubble law

Luminosity distance

Arnett's rule

Ni-Co decay and rise time

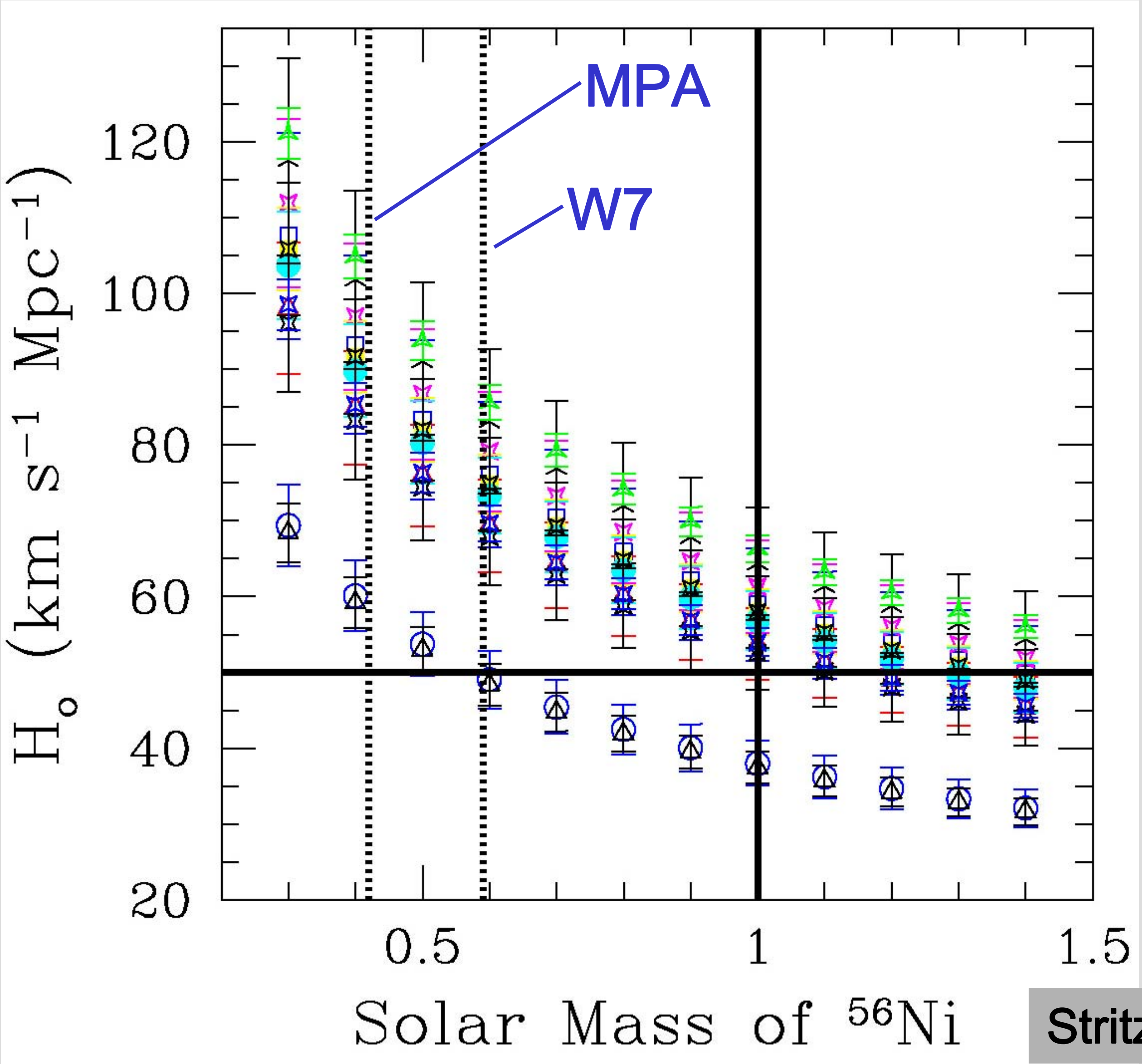
α: conversion of nickel energy into radiation ($L=\alpha E_{Ni}$)

ε(t): energy deposited in the supernova ejecta

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

Stritzinger & Leibundgut 2005

Comparison with models



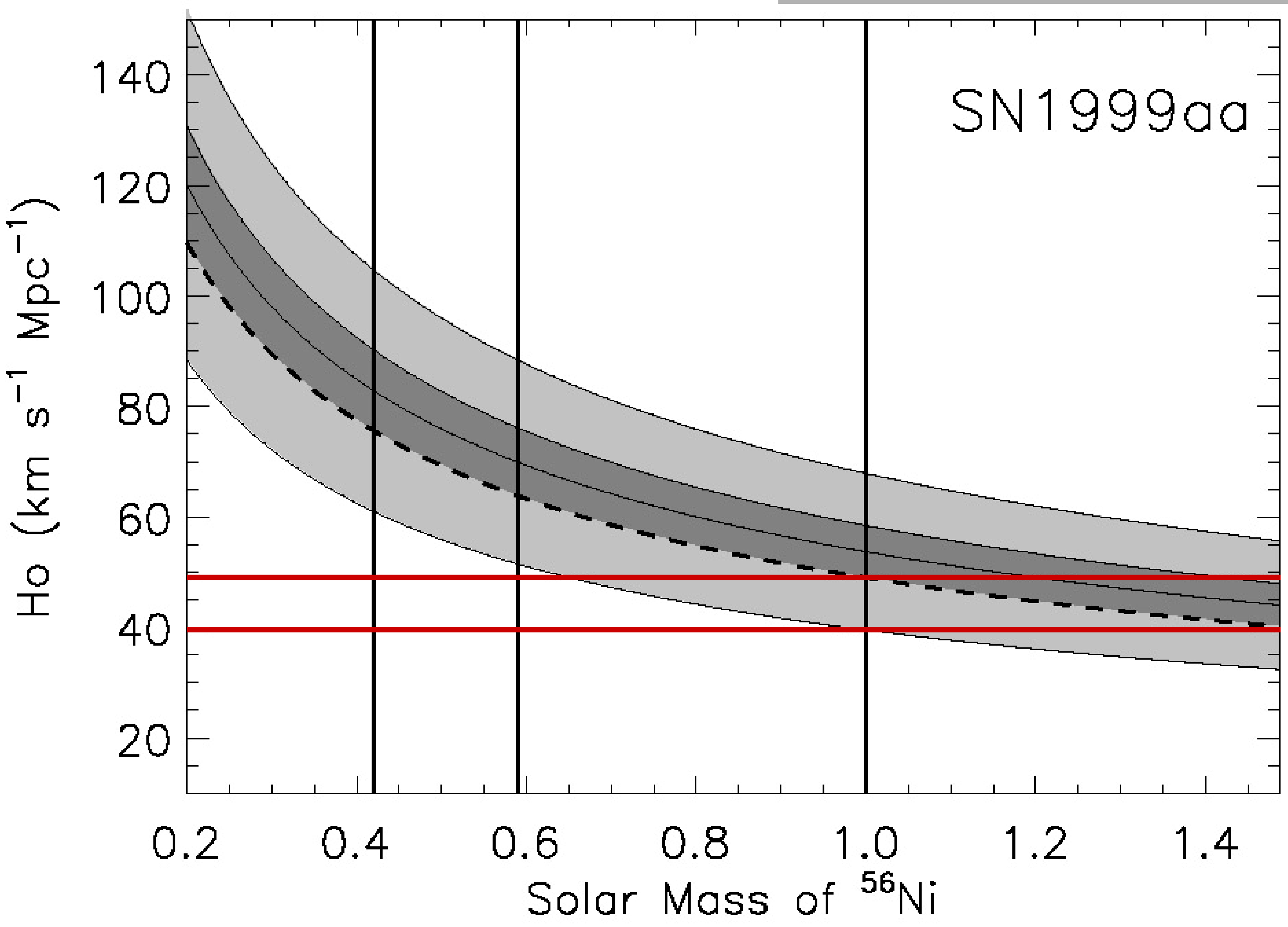
Different Ni masses for SNe Ia have been inferred

- no unique mass applicable
- only lower limit for H_0 can be derived

Stritzinger & Leibundgut 2005

Comparison with models

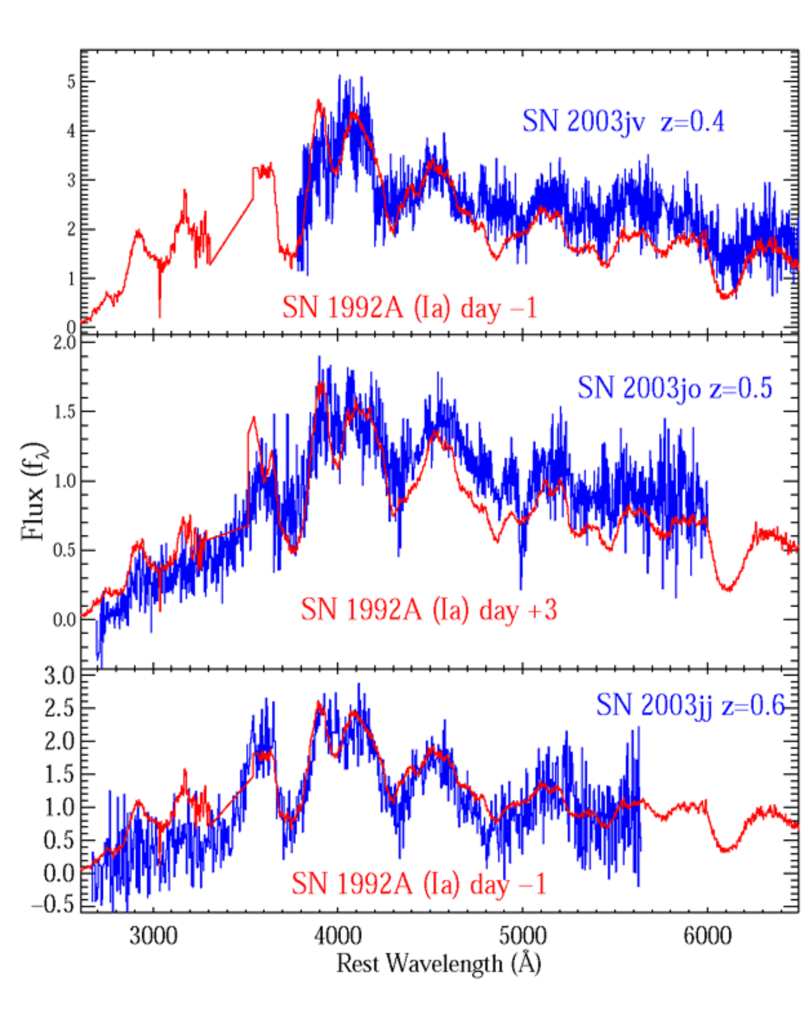
Stritzinger & Leibundgut 2005

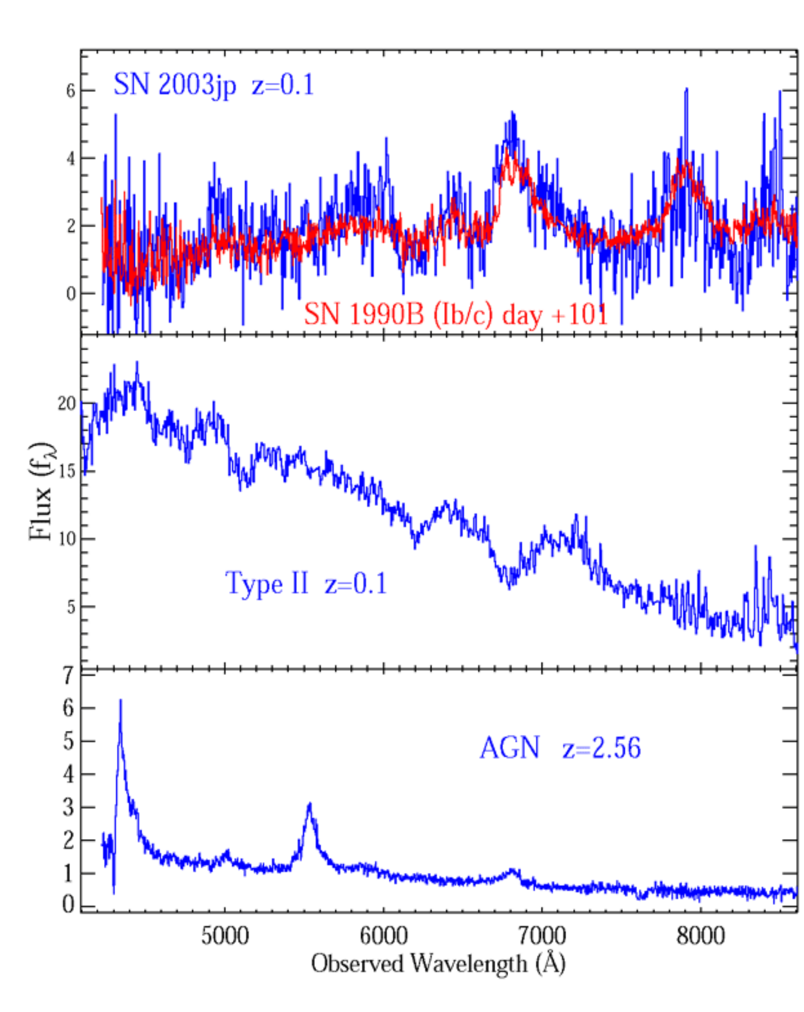


ESSENCE

- 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 ω to 10% overall

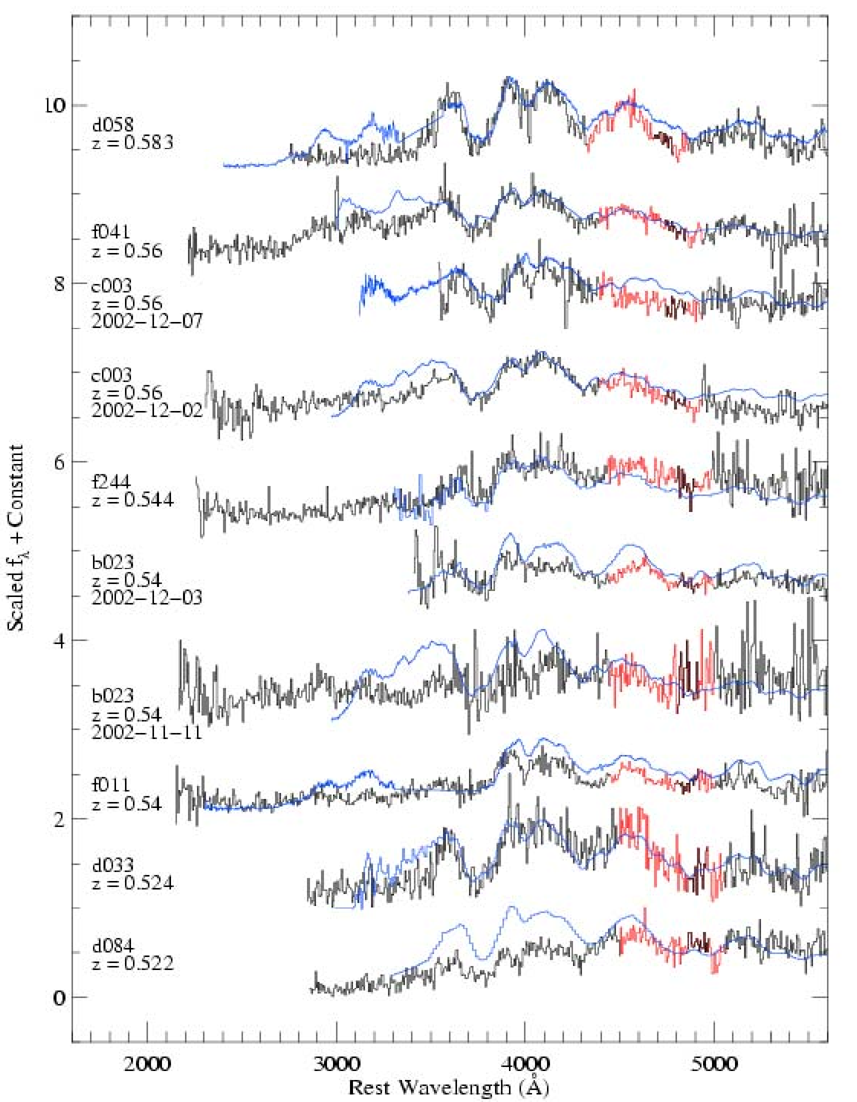
ESSENCE spectroscopy

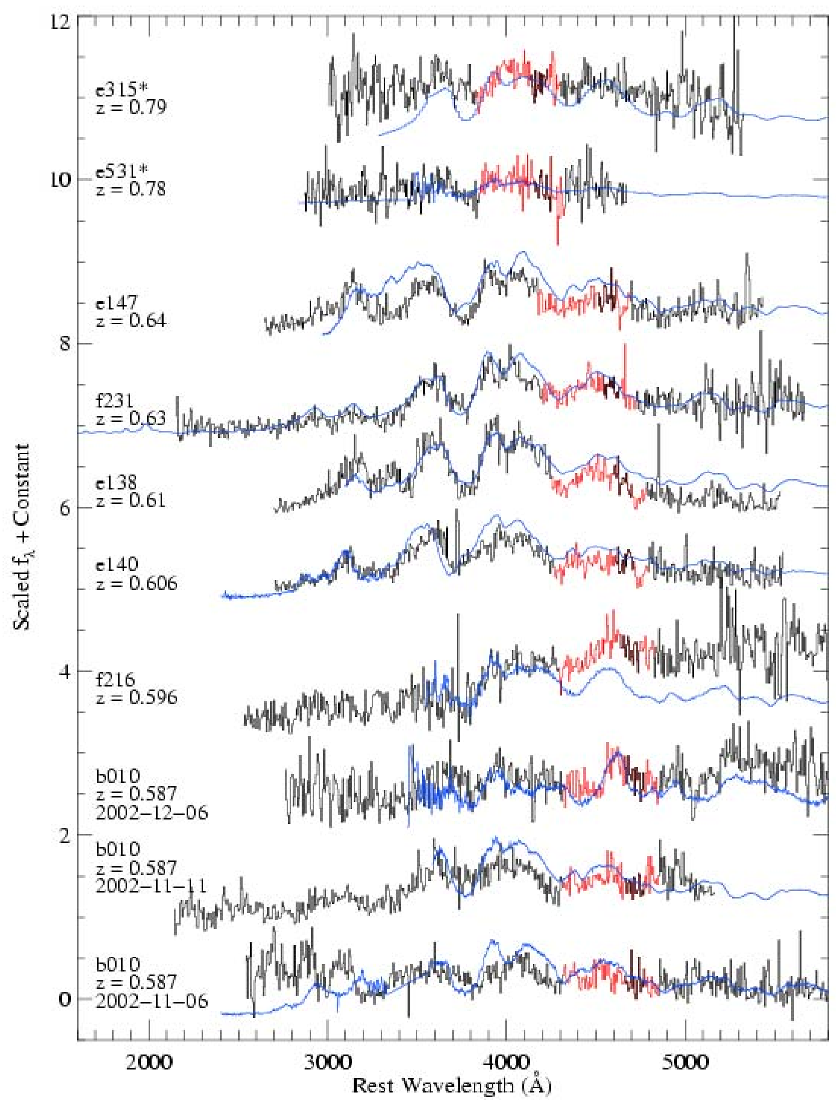




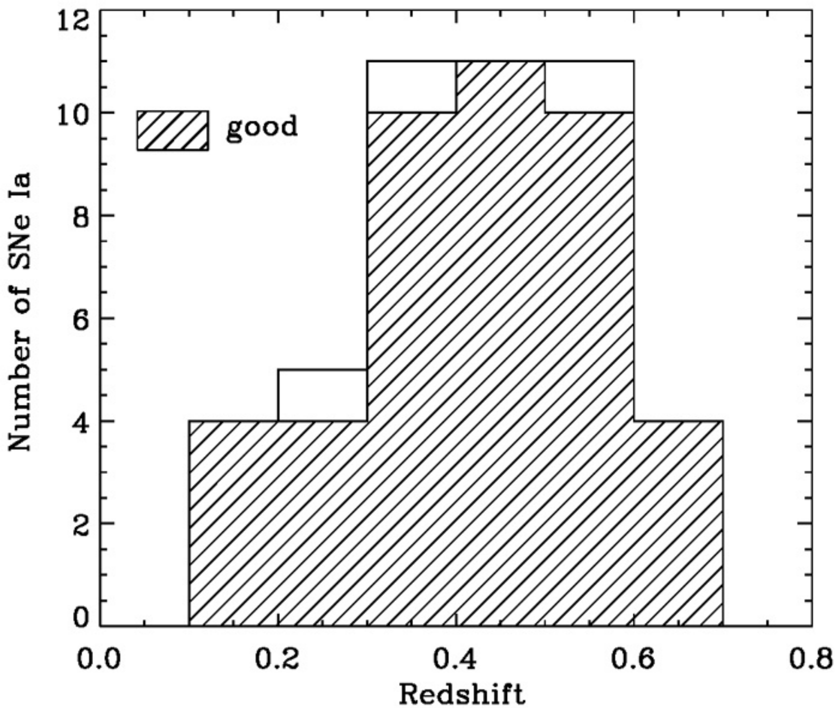
Matheson et al. 2005

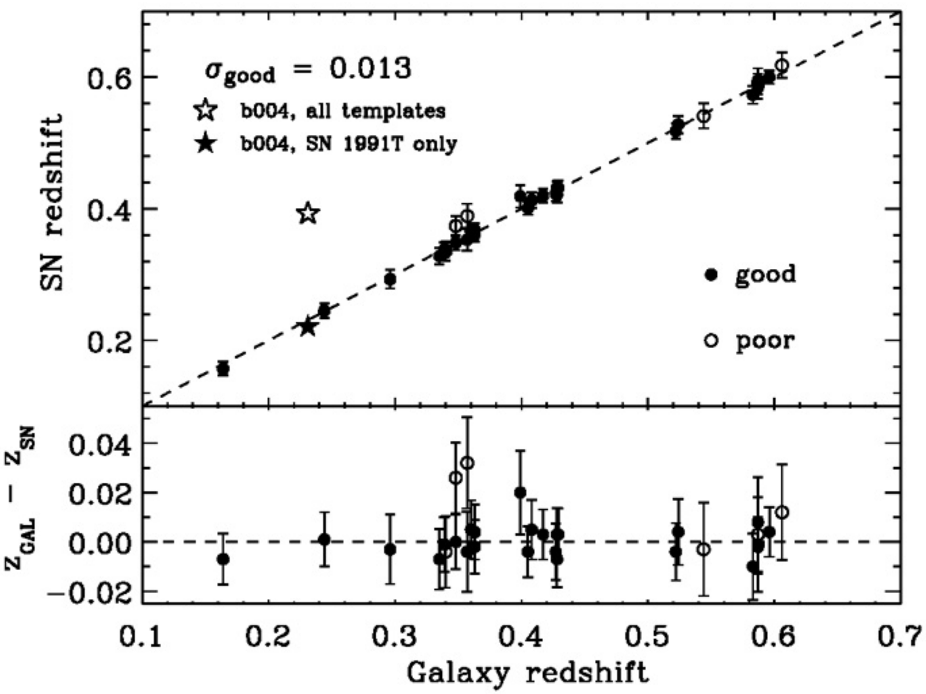
ESSENCE spectroscopy





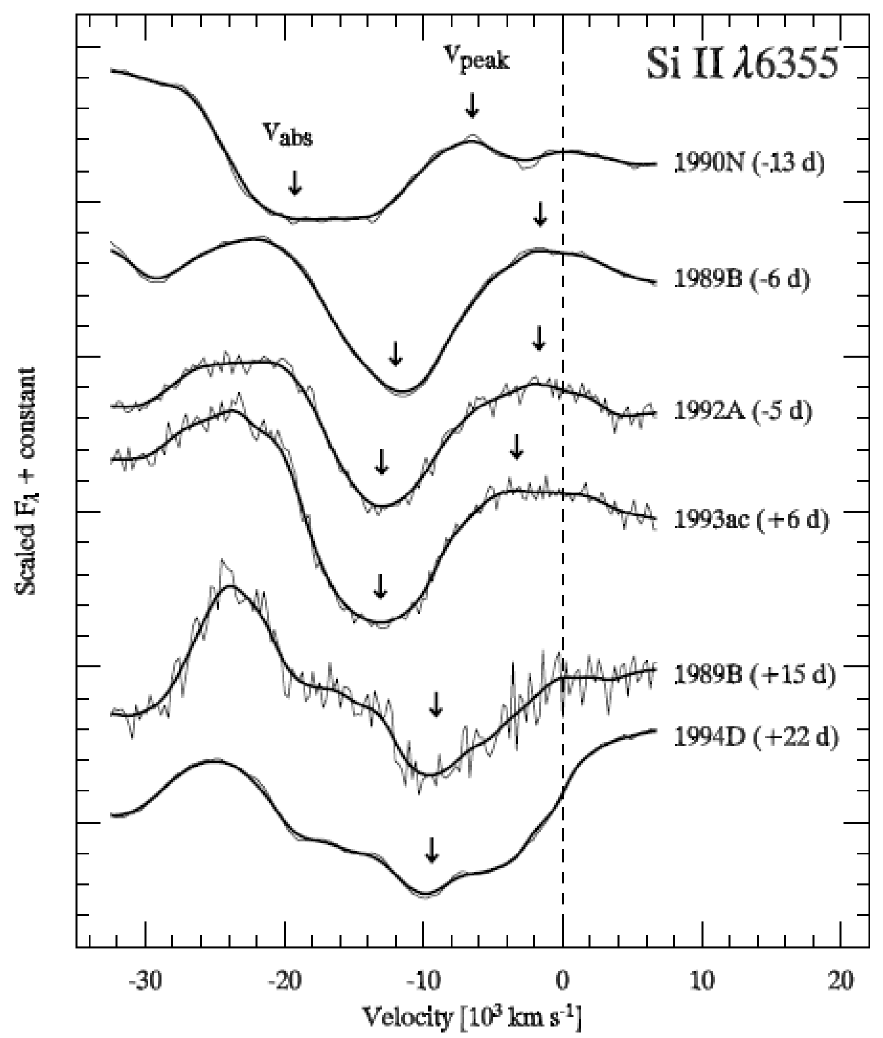
First two years of ESSENCE spectra





Matheson et al. 2005

Spectroscopic study

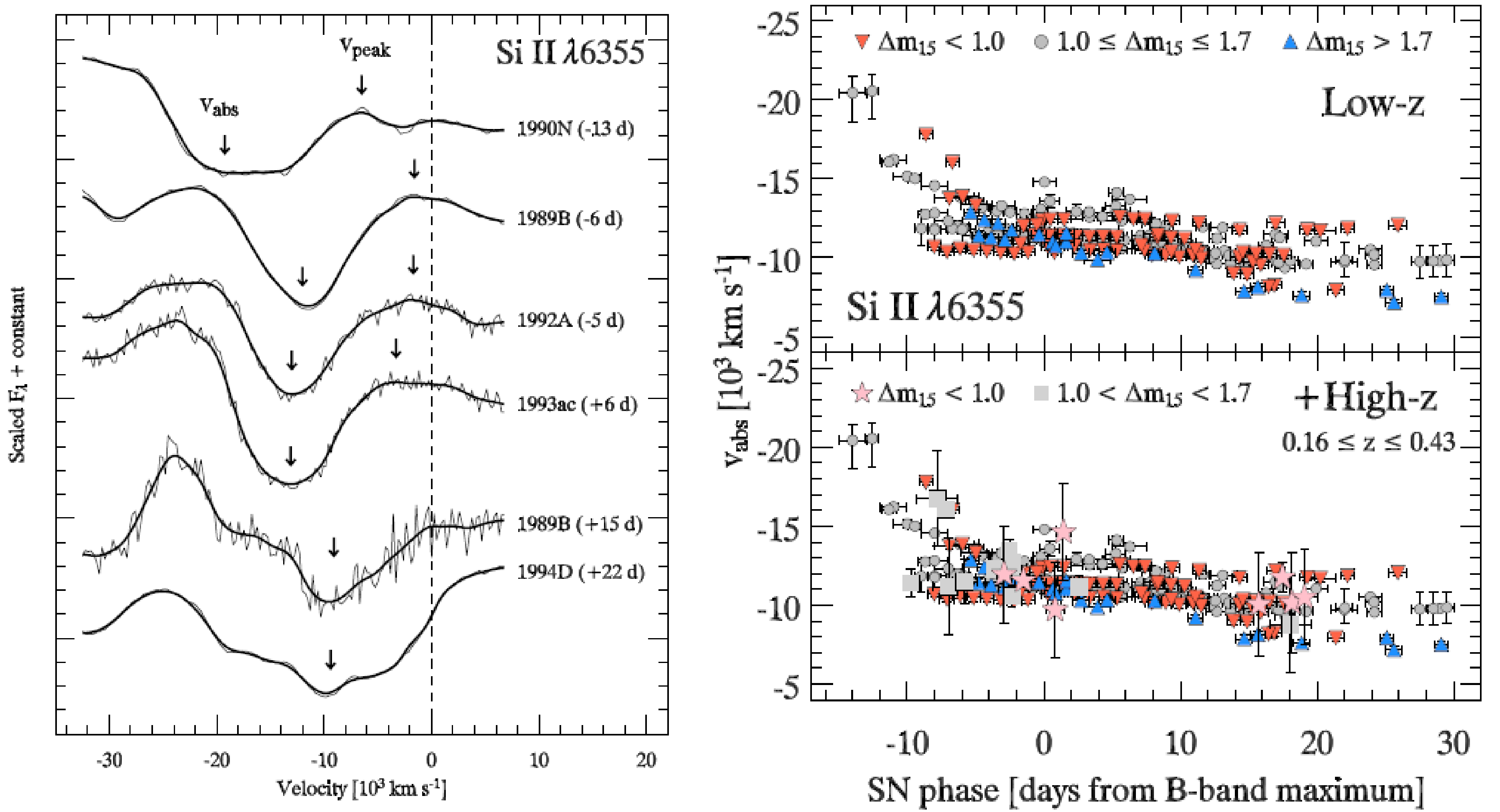


Comparing the line velocity evolution of nearby and distant SNe Ia should allow us to check for systematic differences, i.e. evolution

Blondin et al. 2005

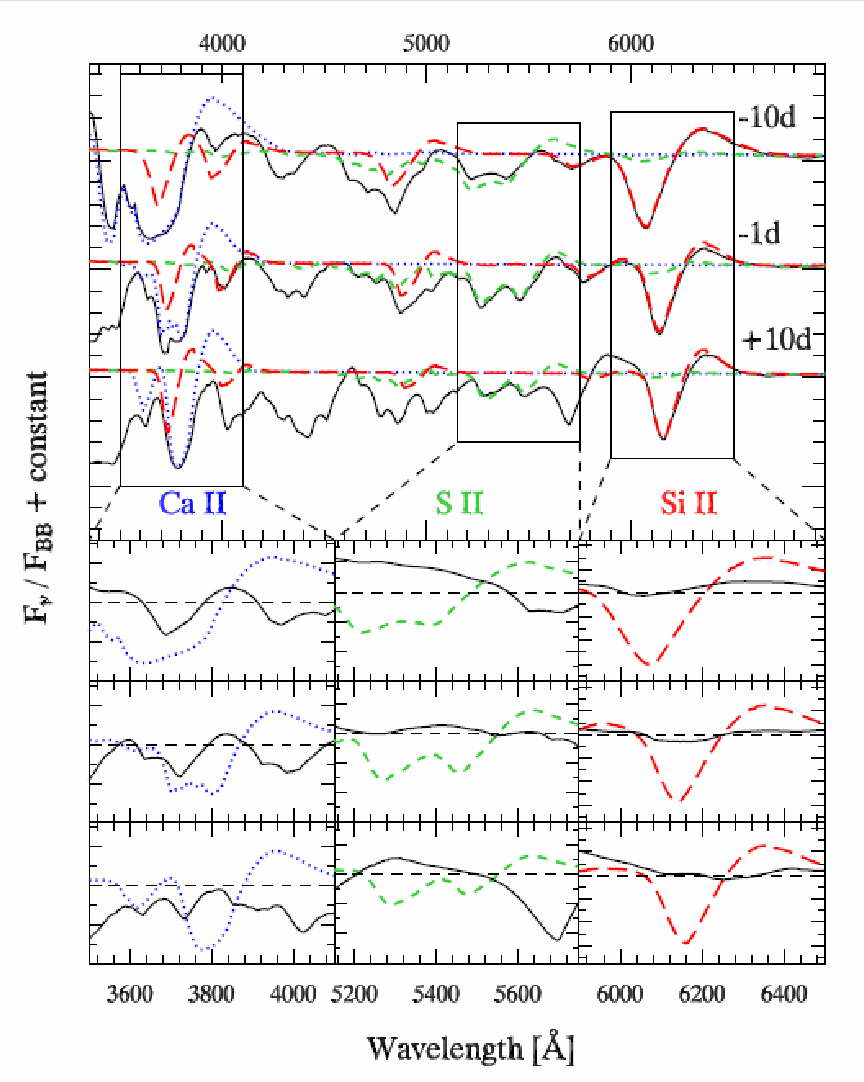
Velocity evolution of SNe Ia

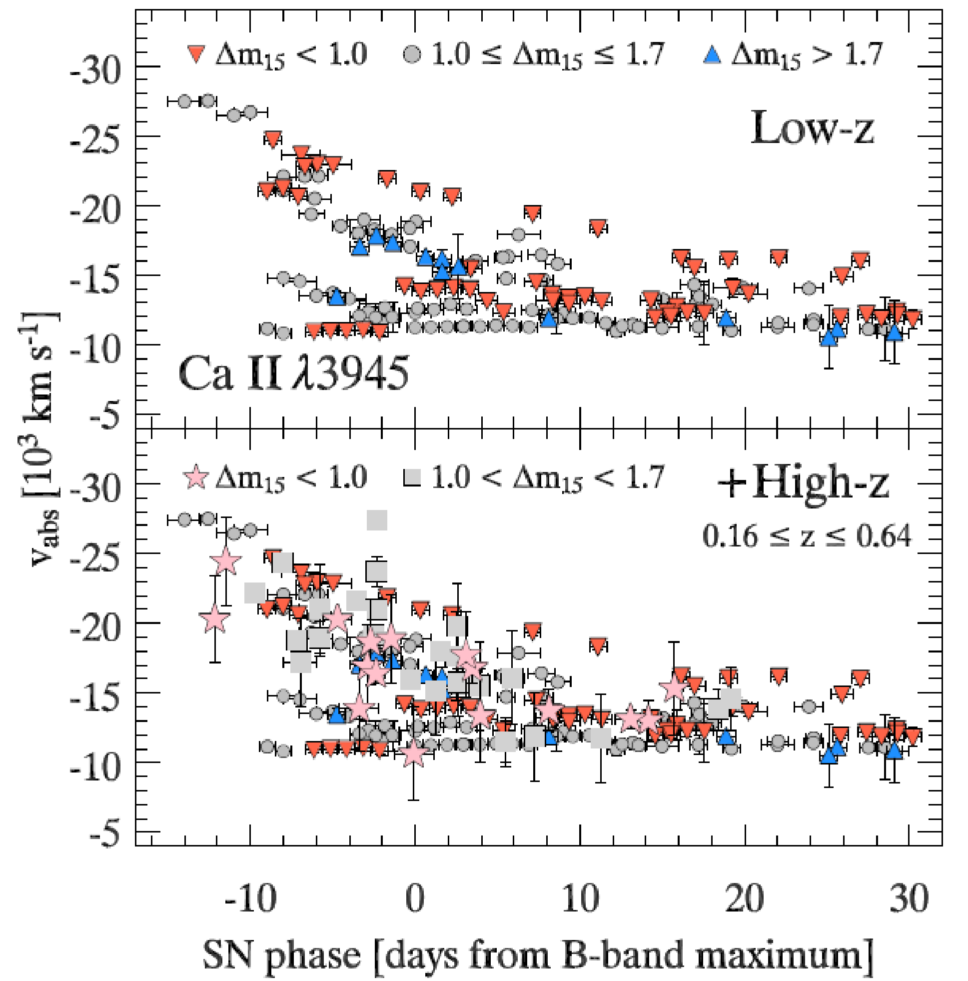
Blondin et al. 2005



Line velocities

Blondin et al. 2005





Line velocities

No significant differences in the line velocity evolution observed

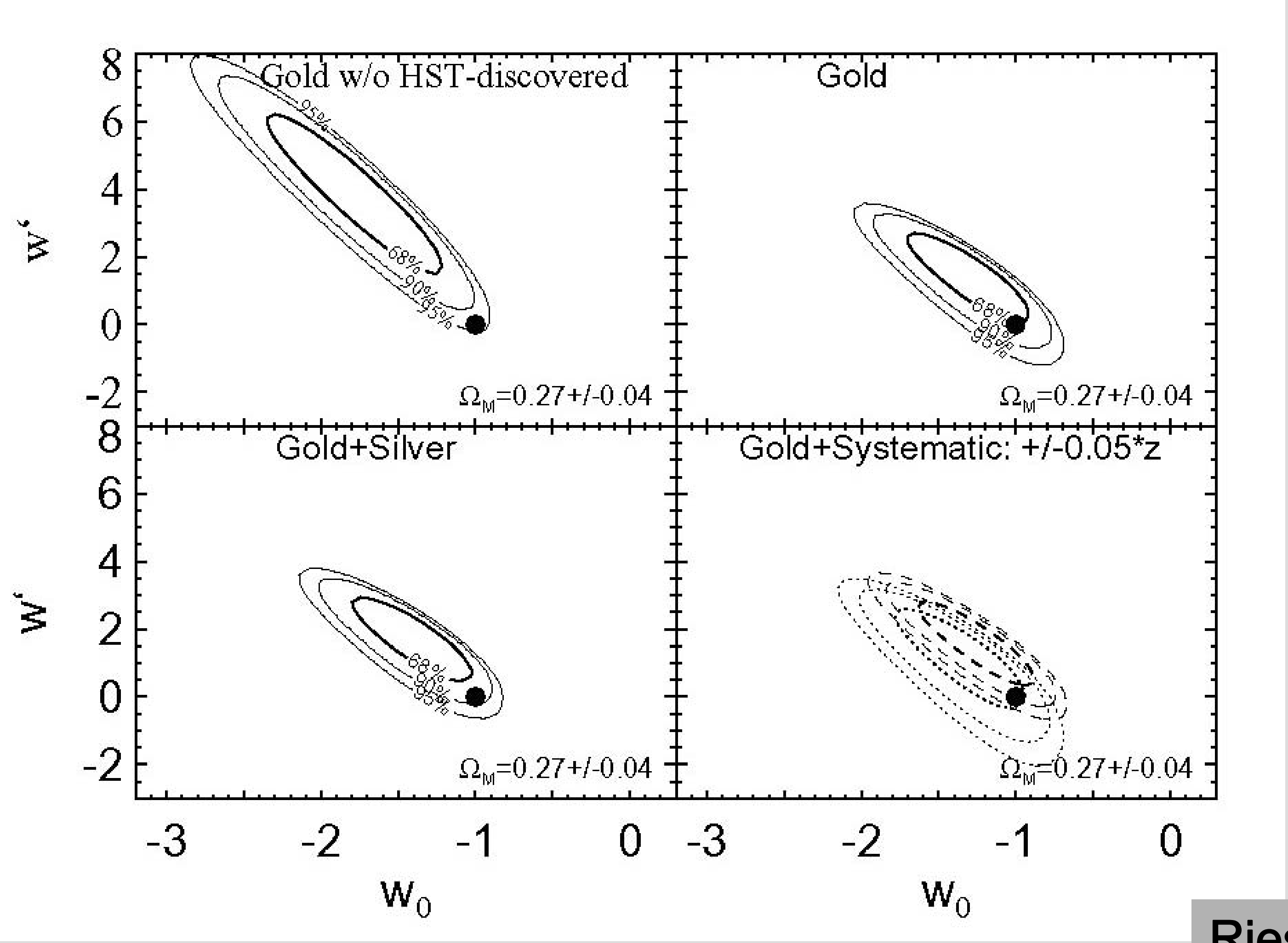
- implies similar density structure and element distribution
- explosion and burning physics similar

Peculiarities observed in nearby SNe Ia also observed in the some distant objects

- detached lines

The properties of distant SNe Ia are indistinguishable from the nearby ones with current observations

And on to a variable ω

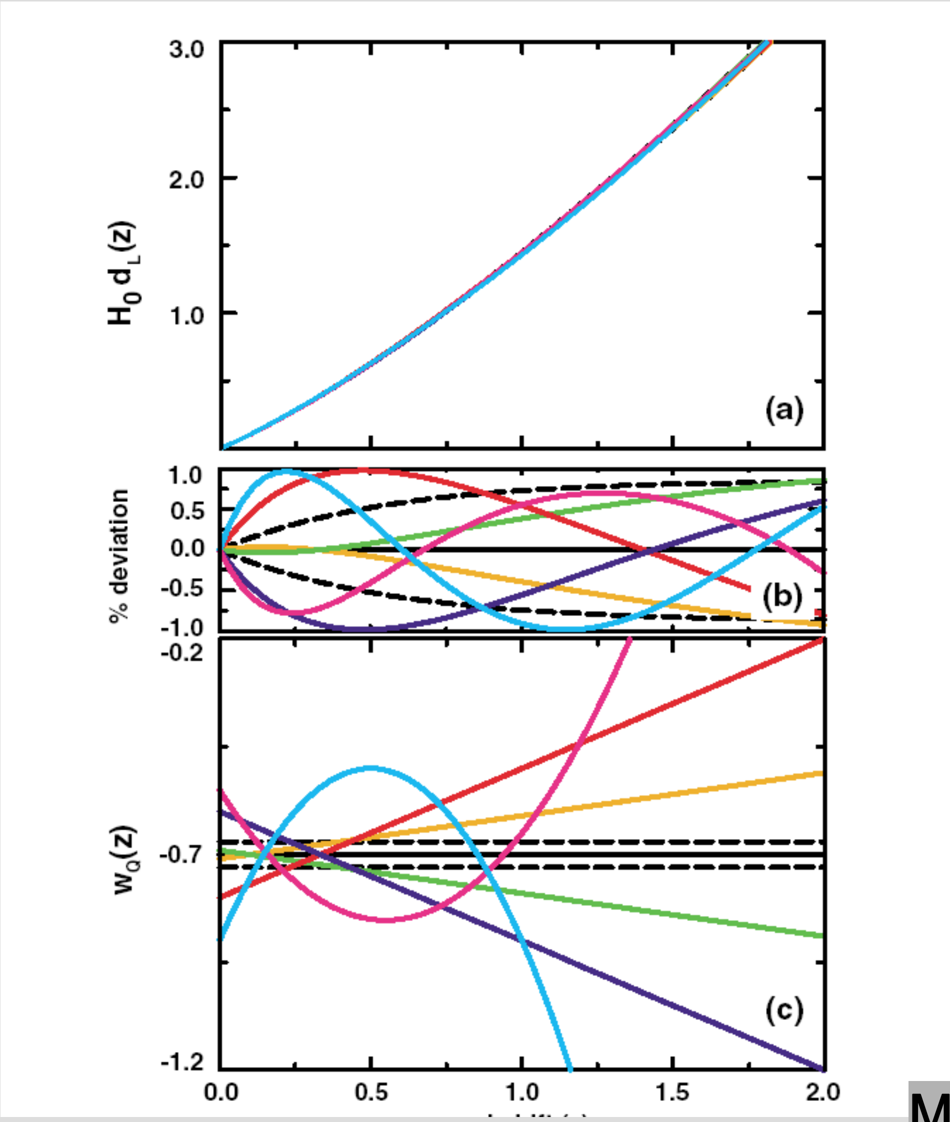


Ansatz:

$\omega(z) = \omega_0 + \omega' z$

Riess et al. 2004

Time-dependent $w(z)$



Luminosity Distance vs redshift can be degenerate for time-varying $\omega(z)$

Maor, Brustein & Steinhardt 2001

Caveat

Warning to the theorists:

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

Summary

$H_0 > 40$ km s^{-1} Mpc^{-1} (3σ), if the thermonuclear model of Type Ia supernovae is correct

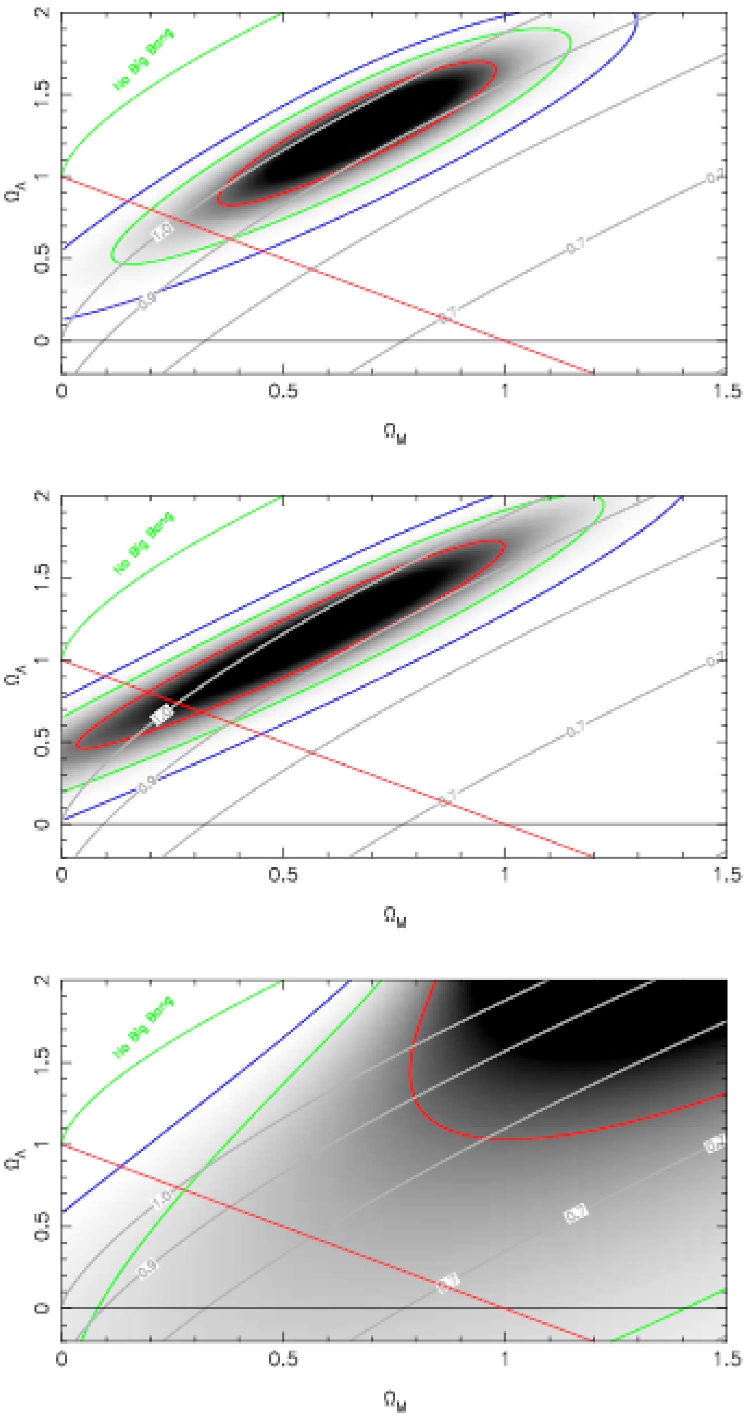
- Explosion models still under-predict the ^{56}Ni mass

Nearby SNe Ia are the source of our understanding of the distance indicator

No evolutionary effects observed so far for the distant SNe Ia

All redshifts need to be covered

- distant SNe Ia alone are useless



All SNe Ia from Tonry et al. 2003

Three highest-z objects removed

Only objects with 0.2<z<0.8

Blondin 2005

Summary

The determination of the (integrated) ω will become available in about two years

- CFHT Supernova Legacy Survey (SNLS)
  - Goal: 700 SNe Ia ⇒ Δω=7%
  - First result (one year of data) indicate ω=-1 to within almost 10%

  Finished in 2007
- ESSENCE
  - Goal: 200 SNe Ia ⇒ Δω=10%
  - Lot of work to investigate the systematics (spectroscopy)

  Finished in 2006