# Type Ia Supernovae as Distance Indicators

Bruno Leibundgut

# What do we want to learn about supernovae?

- What explodes?
  - progenitors, evolution towards explosion
- How does it explode?
  - explosion mechanisms
- Where does it explode?
  - environment (local and global)
  - feedback
- What does it leave behind?
  - remnants
  - compact remnants
  - chemical enrichment
- Other use of the explosions
  - light beacons
  - distance indicators
  - chemical factories

# What do we know about supernovae Ia?

- What explodes?
  - progenitors, evolution towards explosion
    - white dwarfs (?), several channels
- How does it explode?
  - explosion mechanisms
    - several channels
      - deflagrations, detonations, delayed detonations, He detonations, mergers
- What does it leave behind?
  - remnants
    - Tycho, LMC
  - compact remnants
    - none, companion (?)
  - chemical enrichment
    - the usual suspects

# What do we know about supernovae Ia?

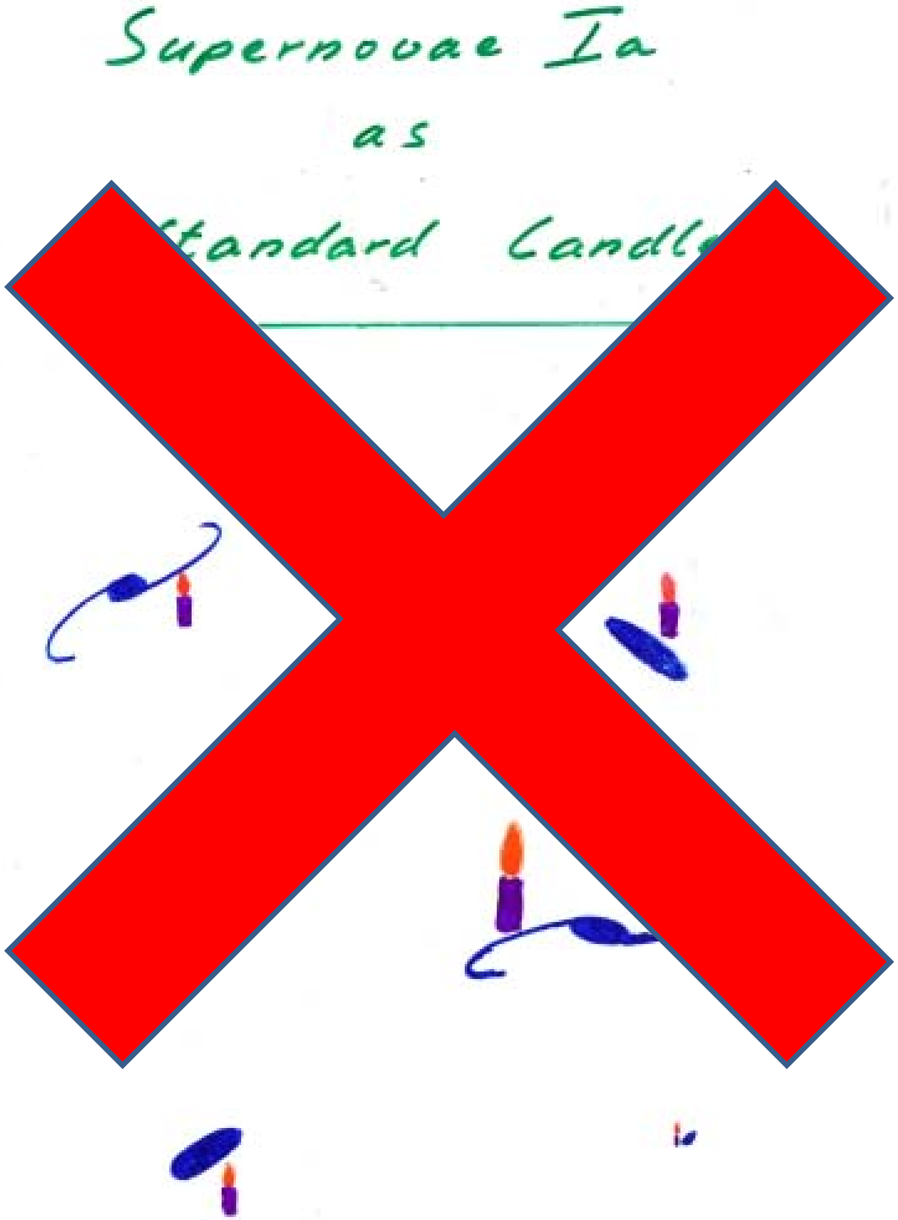
- Where does it explode?
  - environment (local and global)
    - some with CSM (?)
    - all galaxy morphologies
    - dependencies on host galaxies?
  - feedback
    - little
- Other use of the explosions
  - light beacons
    - little use as background source
  - distance indicators
    - ha!
  - chemical factories
    - no significant dust

It is time to give up some cherished paradigms

# Type Ia SNe are not standard candles

They are not even standardizable

Maybe some of them can be normalised to a common peak luminosity

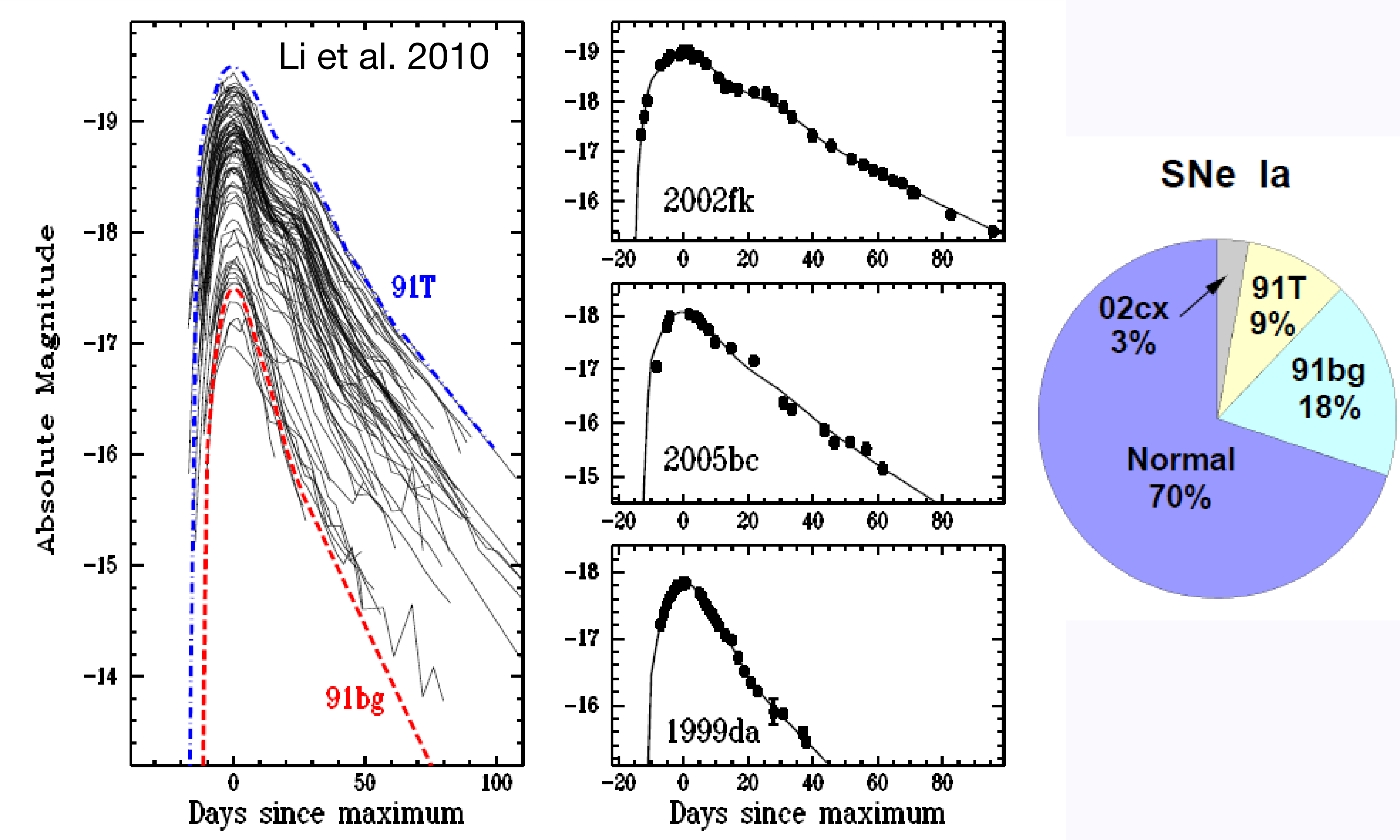


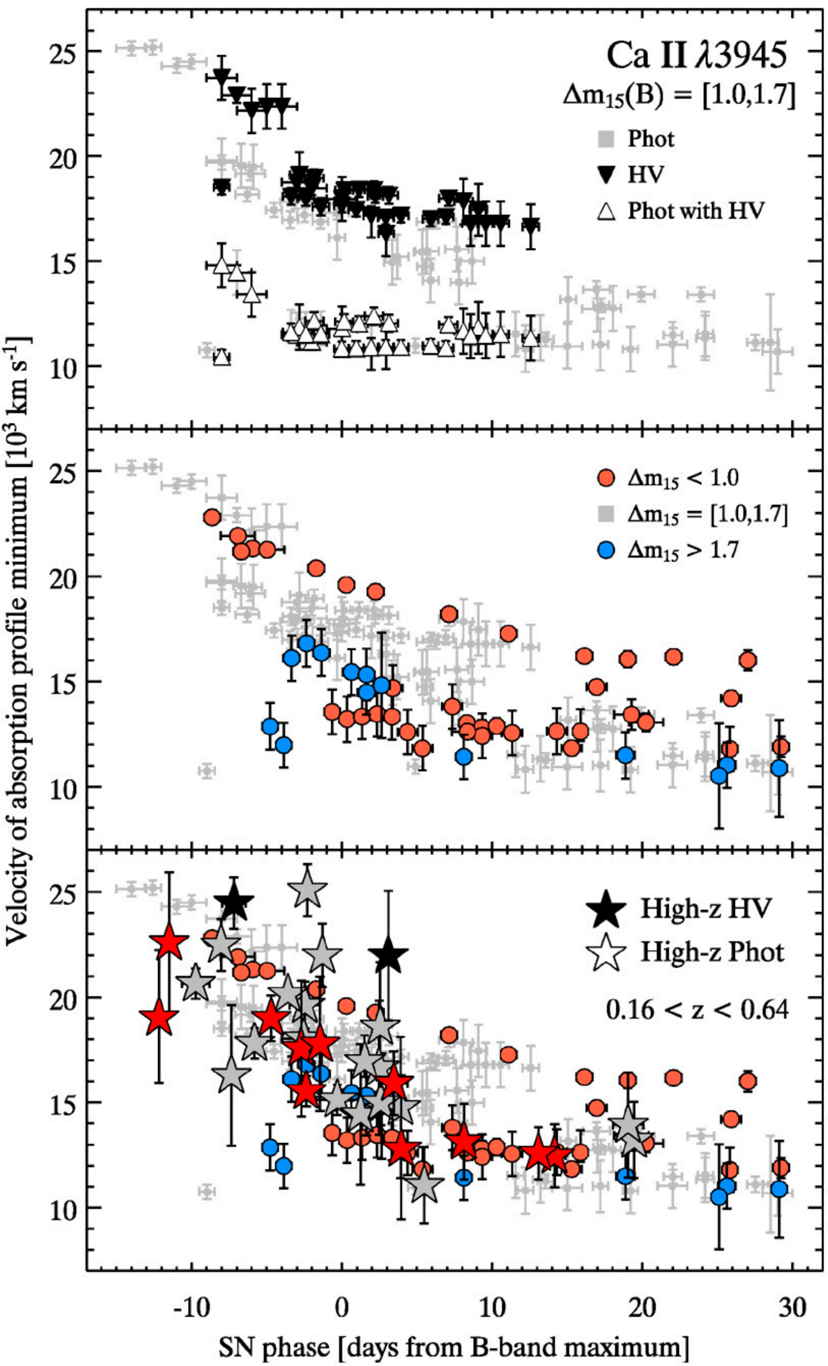

Paradigm 1

# Why no standard candle?

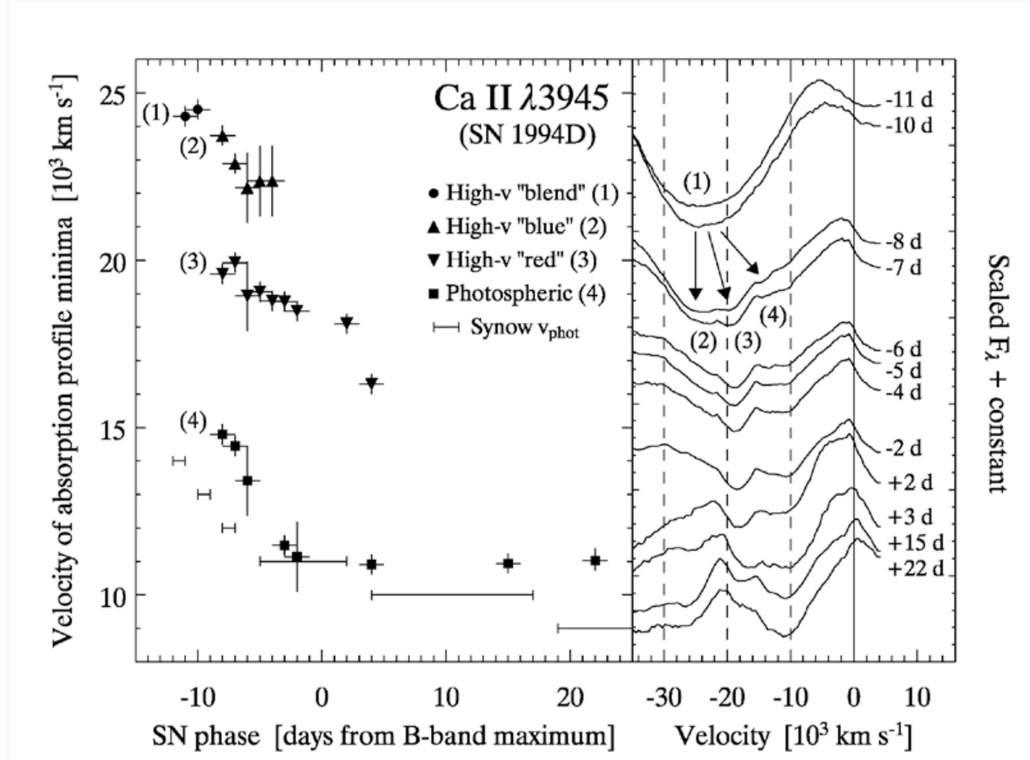
- Large variations in
  - luminosity
  - light curve shapes
  - colours
  - spectral evolution
  - polarimetry
- Some clear outliers
  - what is a type Ia supernova?
- Differences in physical parameters
  - Ni mass

# Luminosity distribution






# Spectral evolution




Blondin et al. 2006

also Garavini et al. 2007

Bronder et al. 2008

# What is a SN Ia?

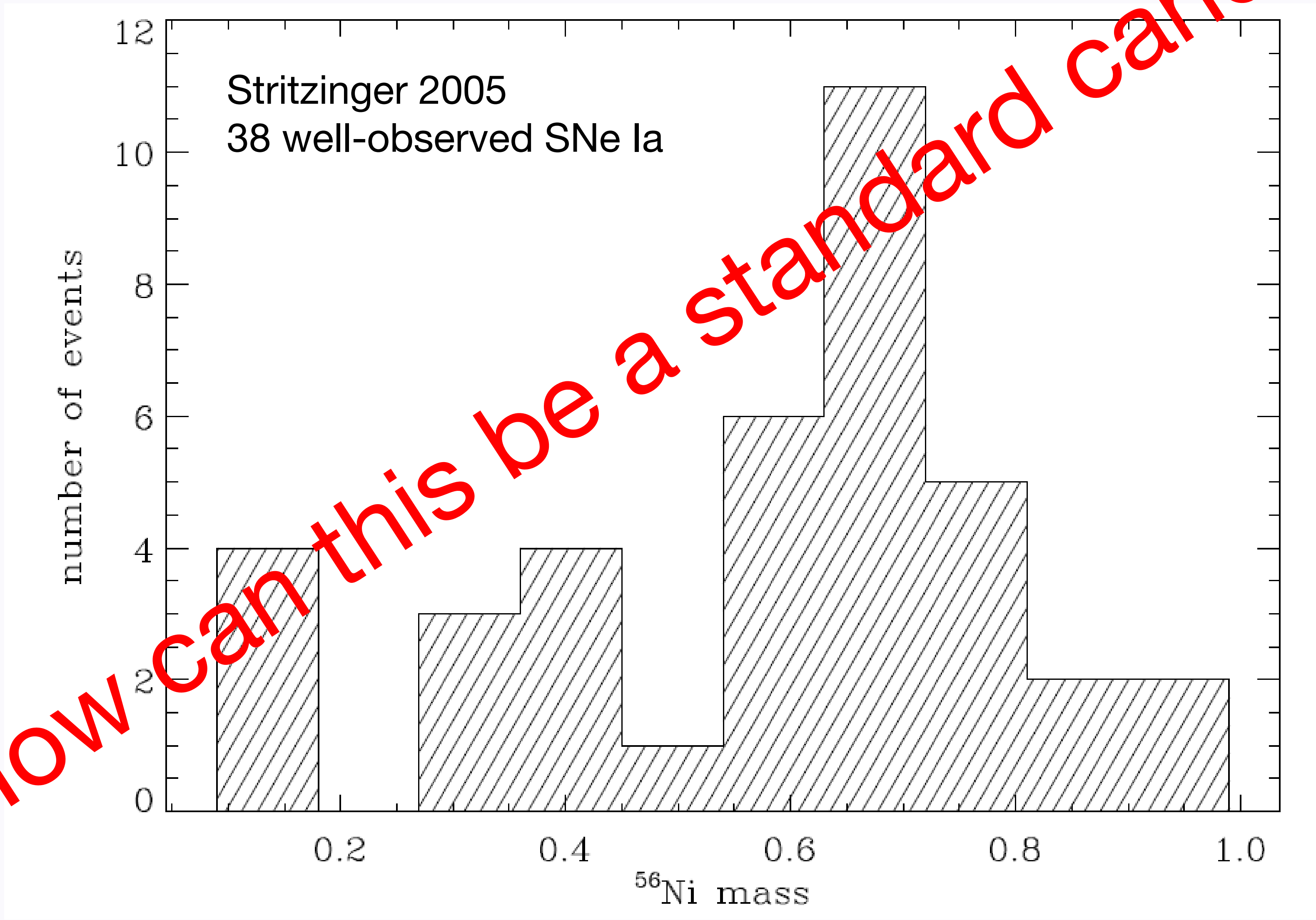
**Table 1**
Classification Criteria for SNe Iax

| SN Class | Has Hydrogen? | $\lvert v \rvert \lesssim 8000$ km $s^{-1}$? | Low $L$ for LC Shape | Spec. like SN 2002cx |
|---|---|---|---|---|
| **SN Iax** | N | Y | Y | Y |
| SN II | Y | Some | N/A | N |
| SN Ib/c | N | N | Y | N |
| SLSN I | N | Y | N | N |
| Normal SN Ia | N | N | N | N |
| Super-Chandra | N | Y | N | N |
| SN 1991T | N | N | N | Somewhat |
| SN 1991bg | N | N | N | N |
| SN 2000cx | N | N | Y | N |
| SN 2002bj | N | Y | N | Somewhat |
| SN 2002es | N | Y | Y | Somewhat |
| SN 2002ic | Y | N | N | N |
| SN 2005E | N | Y | Y | N |
| SN 2006bt | N | N | Y | N |
| SN 2010X | N | N | Y | N |
| PTF 09dav | Y | Y | Y | Somewhat |

Foley et al. 2013

What is the standard candle?

# Ni masses from bolometric light curves




How can this be a standard candle?

# Type Ia SNe do not all come from Chandrasekhar-mass white dwarfs

Annu. Rev. Astron. Astrophys. 2000. 38:191–230
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## TYPE IA SUPERNOVA EXPLOSION MODELS

Wolfgang Hillebrandt[1] and Jens C. Niemeyer[2]
[1]Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85740

There are good reasons to believe that perhaps most type Ia supernovae are the explosions of white dwarfs that have approached the Chandrasekhar mass, $M_{\rm chan} \approx 1.39\ M_{\odot}$, and are disrupted by thermonuclear fusion of carbon and oxygen.

■ **Abstract** Because calibrated light curves of type Ia supernovae have become a major tool to determine the local expansion rate of the universe and also its geometrical structure, considerable attention has been given to models of these events over the past couple of years. There are good reasons to believe that perhaps most type Ia supernovae are the explosions of white dwarfs that have approached the Chandrasekhar mass, $M_{\rm chan} \approx 1.39\ M_{\odot}$, and are disrupted by thermonuclear fusion of carbon and oxygen. However, the mechanism whereby such accreting carbon-oxygen white dwarfs explode continues to be uncertain. Recent progress in modeling type Ia supernovae as well as several of the still open questions are addressed in this review. Although the main emphasis is on studies of the explosion mechanism itself and on the related physical processes, including the physics of turbulent nuclear combustion in degenerate stars, we also discuss observational constraints.

Paradigm 2

# Supernova theory

**Models of Supernova Explosions: Where Do We Stand?**

Wolfgang Hillebrandt

Max-Planck-Institut für Astrophysik, 85748 Garching, Germany;
wfh@mpa-garching.mpg.de

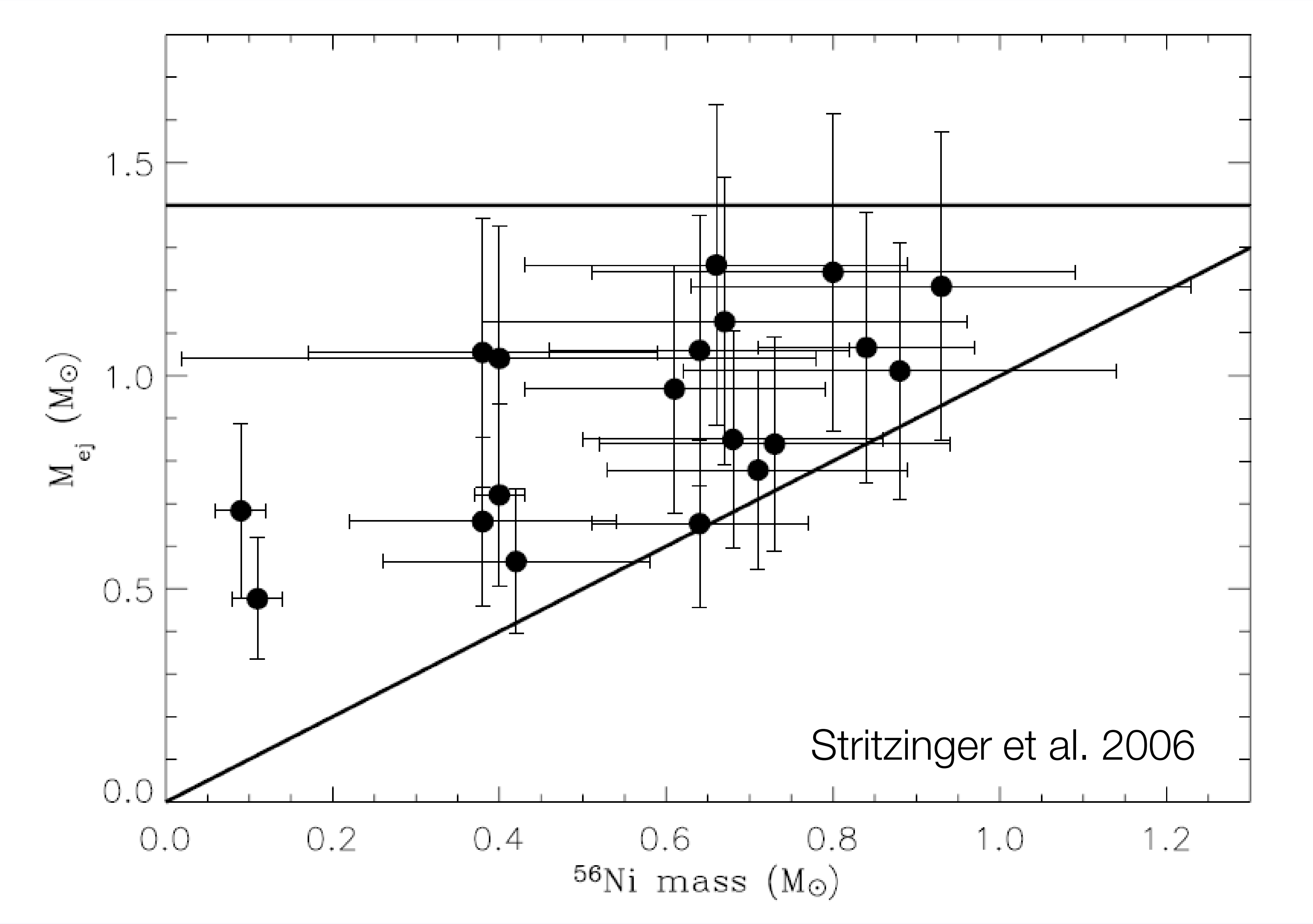
**Summary.** The present status of our understanding of core-collapse and of thermonuclear supernovae is reviewed. It will be argued that the failure of numerical simulations of the collapse of massive stars to produce explosions is probably caused by our incomplete knowledge of the (micro-) physics involved. In contrast, for thermonuclear (type Ia) supernovae the basic physics seems to be well under control and, therefore, it is not surprising that model predictions and observations are in good agreement.

(2003)

"Type Ia Supernova progenitors are not Chandrasekhar-mass white dwarfs"

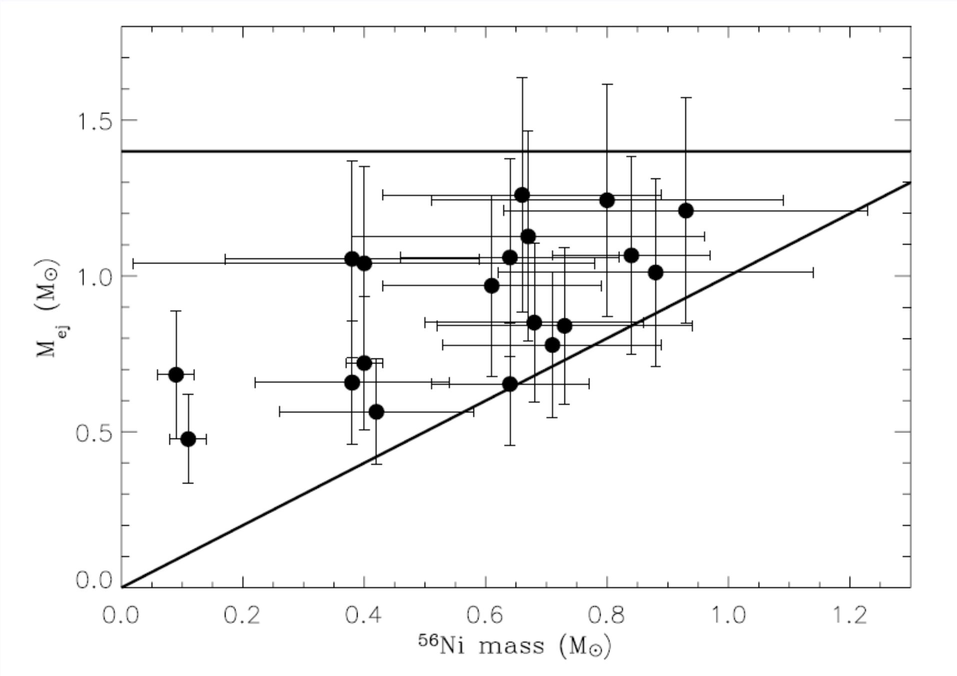
(2012)

# Ejecta masses



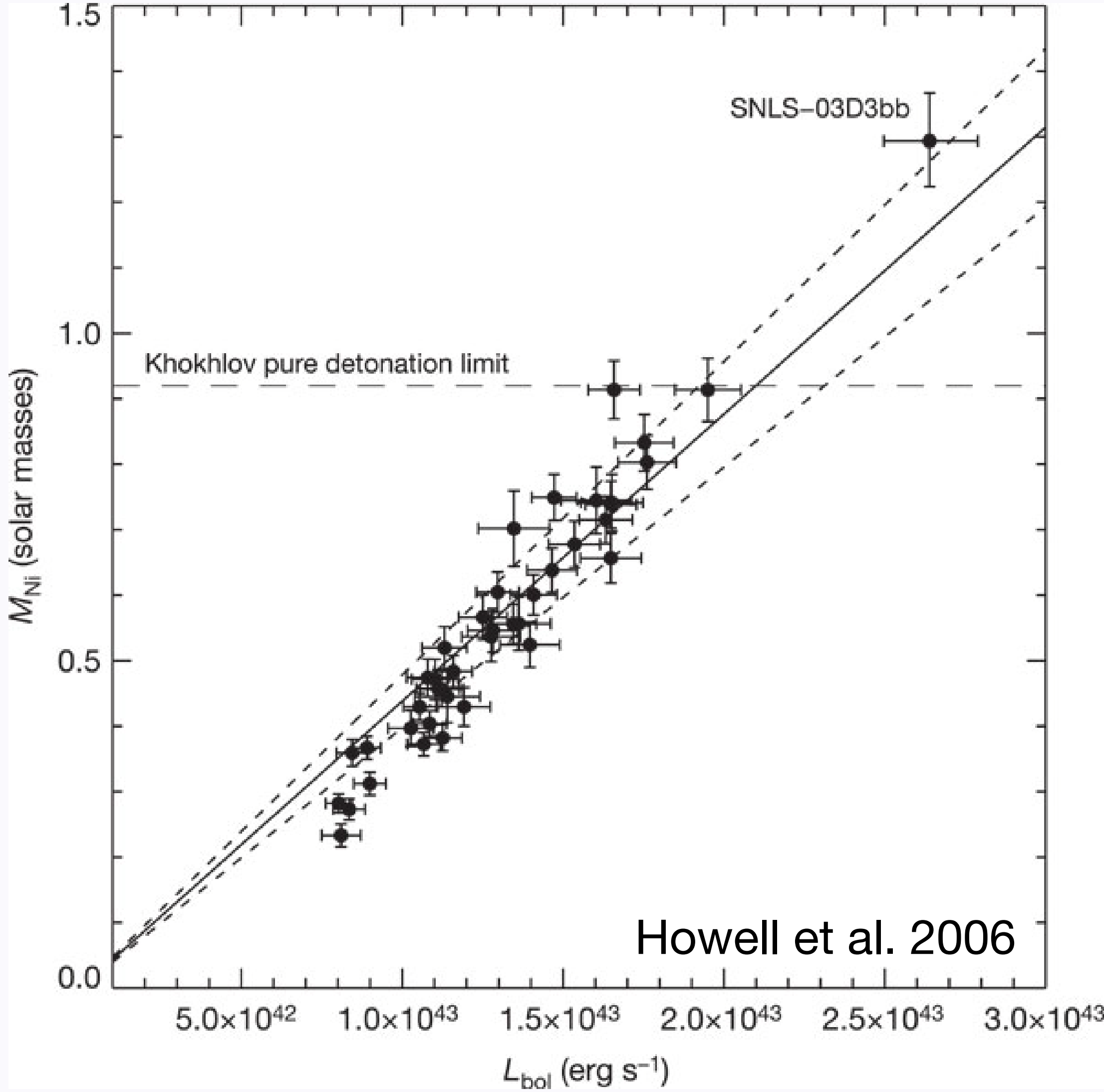
# Ejecta masses

- Large range in nickel and ejecta masses
  - no ejecta mass at 1.4$M_\odot$
  - factor of 2 in ejecta masses
  - some rather small differences between nickel and ejecta mass



# Ejecta masses

- Super-Chandrasekhar explosions?
  - also SN 2006gz, 2007if, 2009dc
  - inferred Ni mass > 1 $M_\odot$



# SNe Ia are not a homogeneous class

- Proliferation of information
  - Large samples produce many peculiar and special objects
  - Difficulty to assess what are generic features of the class and what are peculiar modifications to the norm
    - Subluminous
    - Superluminous
    - CSM/no CSM
    - Environmental effects

→What should we give up?

→multiple progenitor channels

→multiple explosion mechanisms

→uniform metalicity

Paradigm 3

# SN Ia Correlations

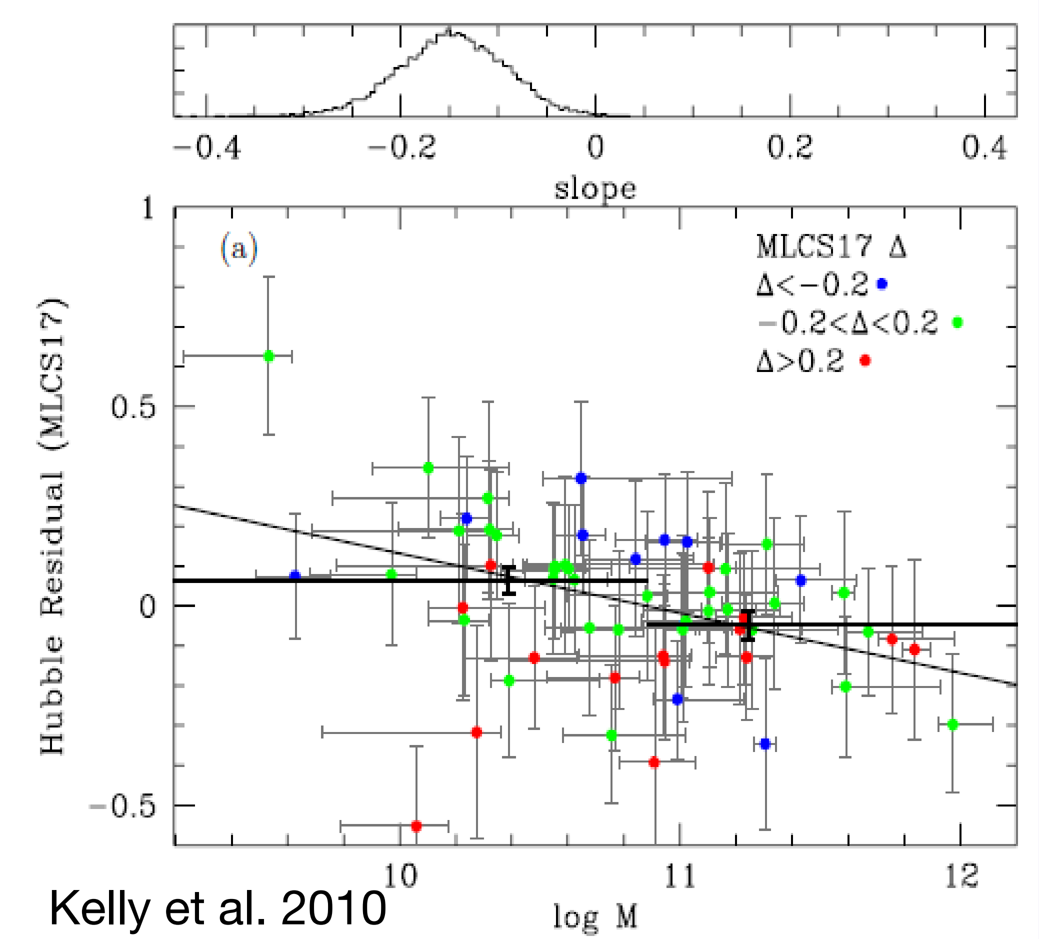
- Luminosity vs. decline rate
  - Phillips 1993, Hamuy et al. 1996, Riess et al. 1996, 1998, Perlmutter et al. 1997, Goldhaber et al. 2001
- Luminosity vs. rise time
  - Riess et al. 1999
- Luminosity vs. color at maximum
  - Riess et al. 1996, Tripp 1998, Phillips et al. 1999
- Luminosity vs. line strengths and line widths
  - Nugent et al. 1995, Riess et al. 1998, Mazzali et al. 1998
- Luminosity vs. host galaxy morphology
  - Filippenko 1989, Hamuy et al. 1995, 1996, Schmidt et al. 1998, Branch et al. 1996

**Warning! Historic slide**

# SN Ia Correlations

Luminosity with host galaxy mass and star formation

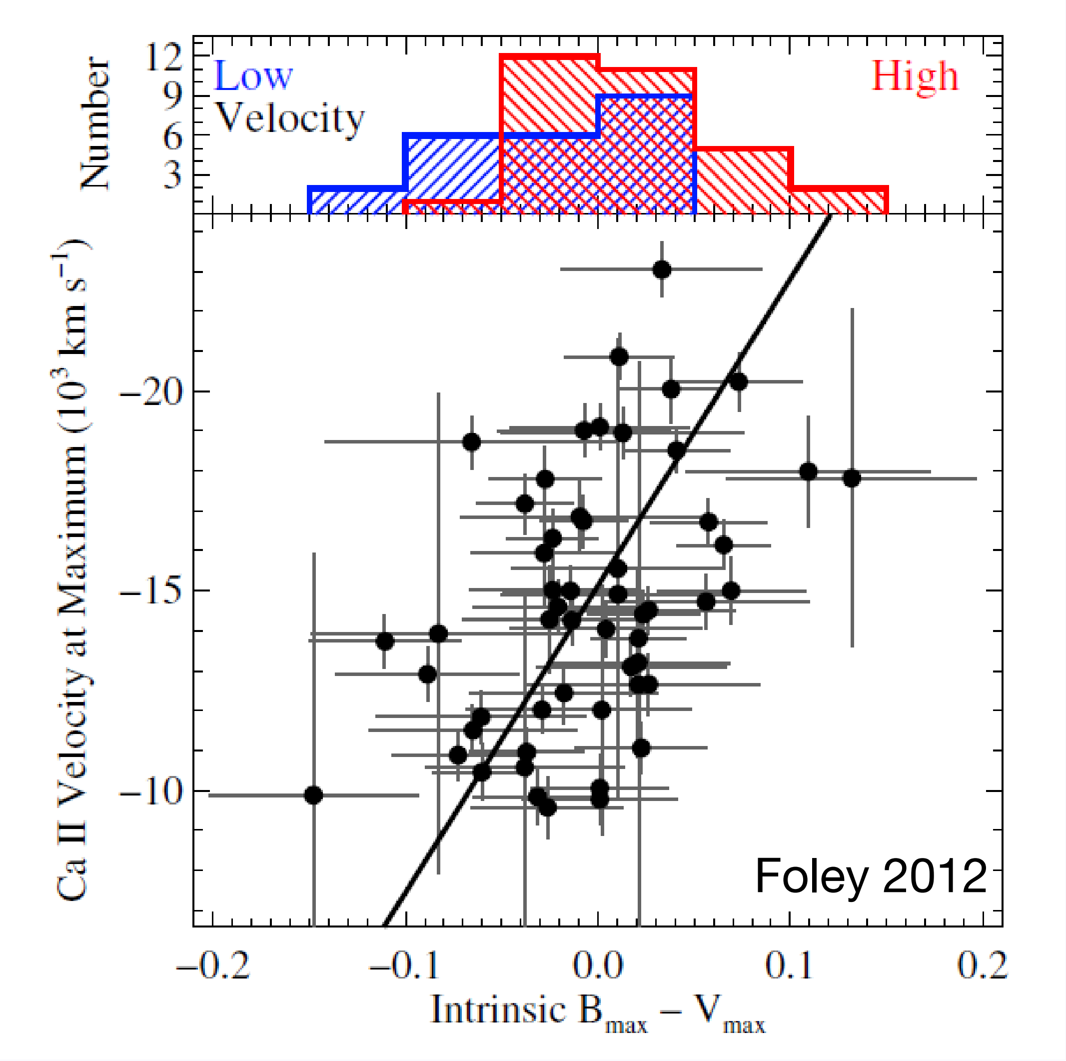
- Hicken et al. 2009, Kelly et al. 2010, Lampeitl et al. 2010, Sullivan et al. 2010



Kelly et al. 2010

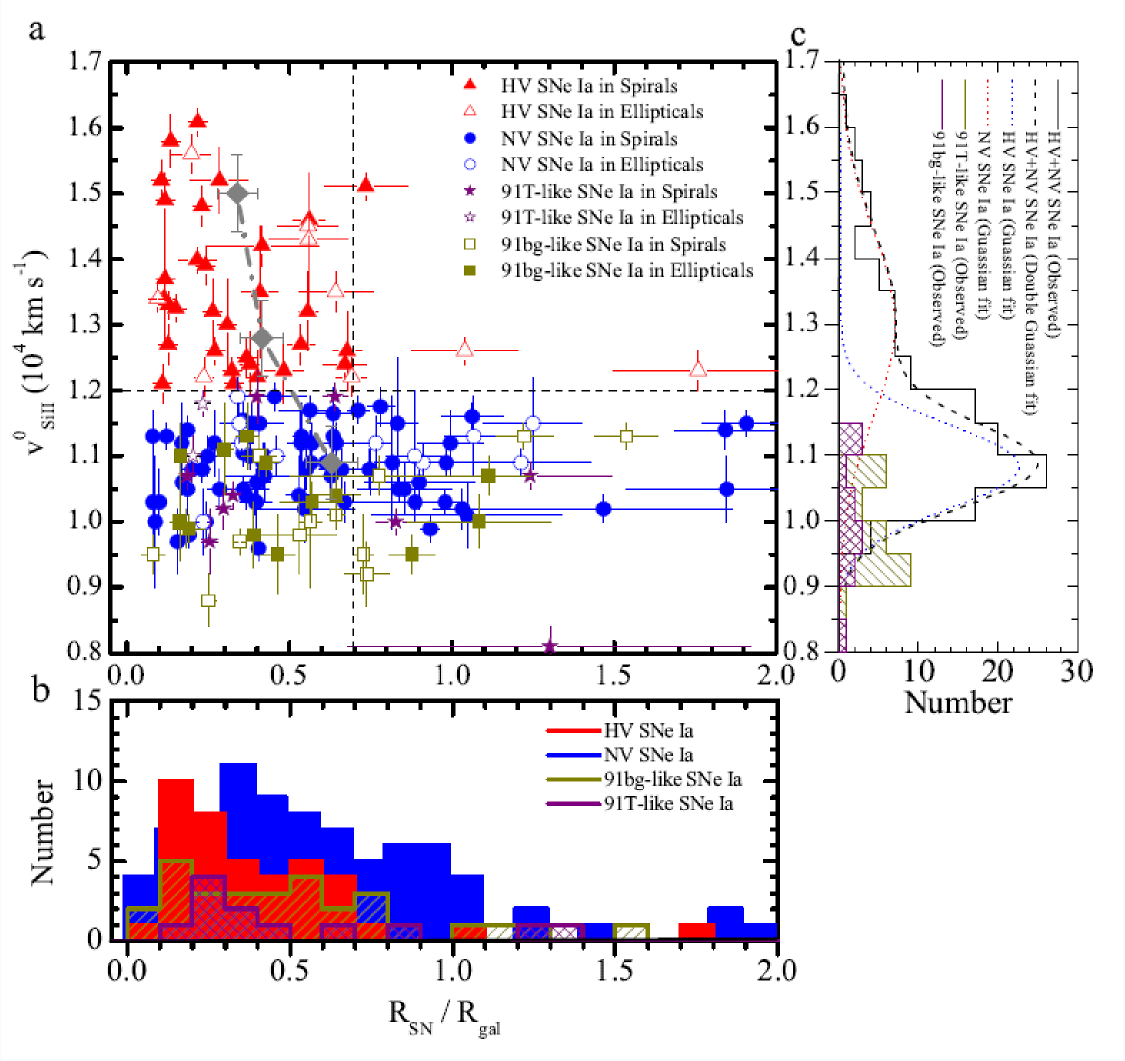
# SN Ia Correlations

- Expansion velocity with colour



# SN Ia Correlations

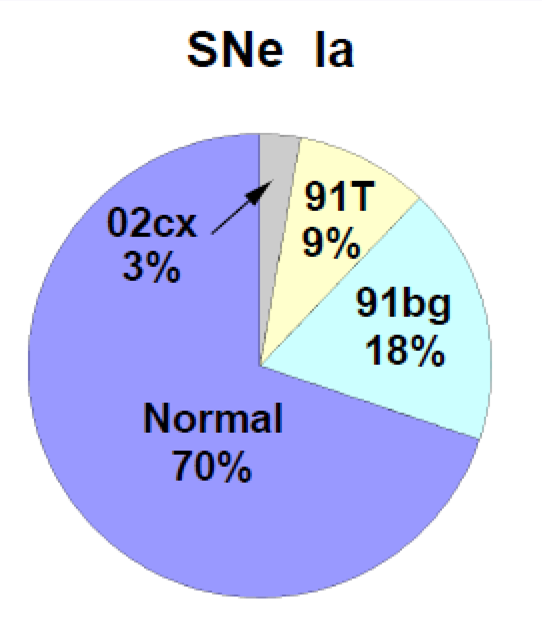
Expansion velocity with position within host galaxy




Wang et al. 2013

# Type Ia Supernovae

- Complicated story
  - observational diversity
  - many models
  - → need more constraints



# Type Ia Supernovae as distance indicators

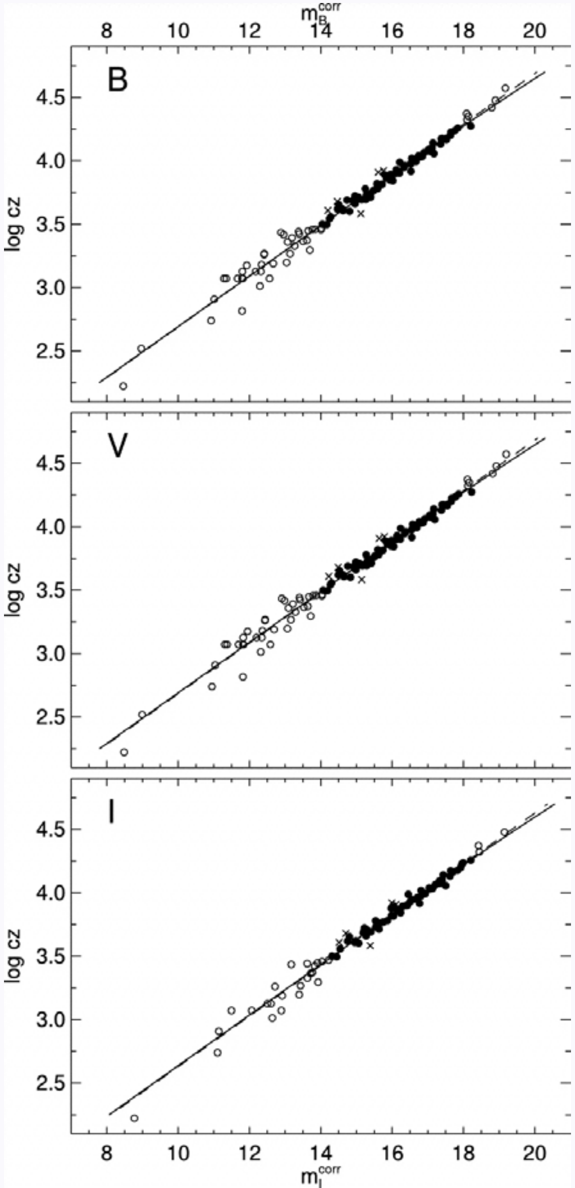
Excellent distance indicators!

# Supernova cosmology

- Stellar explosions
  → systematics!
- SNe Ia currently the best known individual cosmic distance indicator
  – ~5-10% accuracy on individual SN
- Absolute calibration relies on external sources
  – Cepheids

# SN Ia Hubble diagram

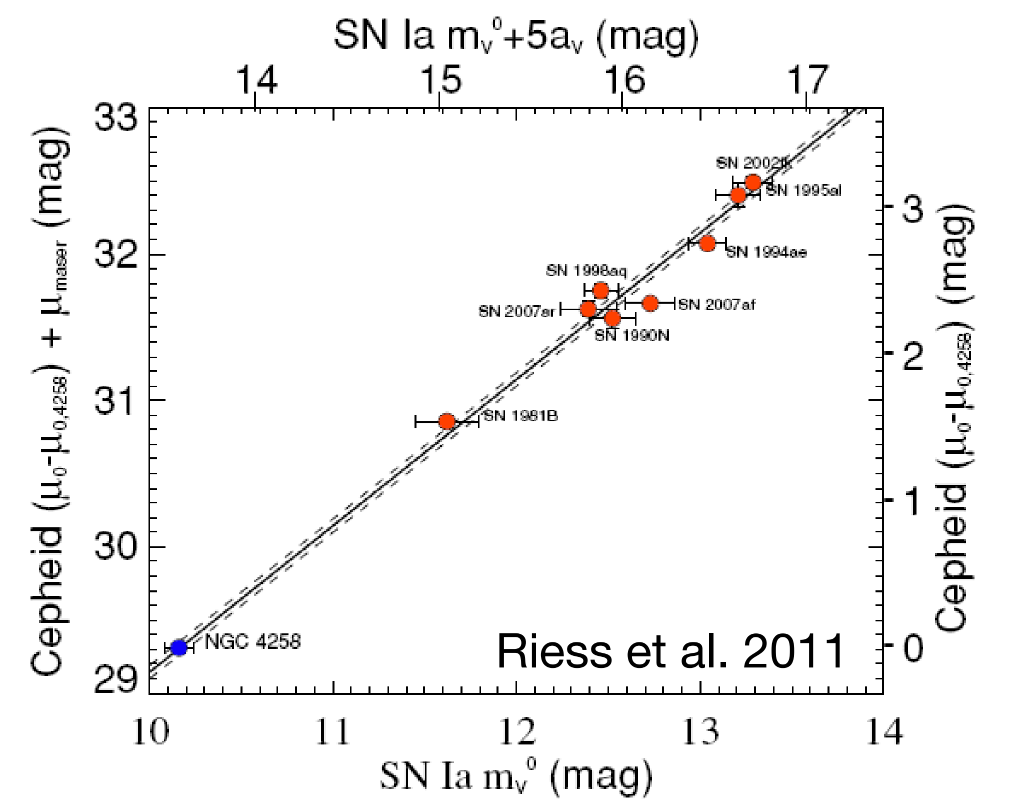
- Excellent distance indicators
- Experimentally verified
- Work of several decades
- Best determination of the Hubble constant




Reindl et al. 2005

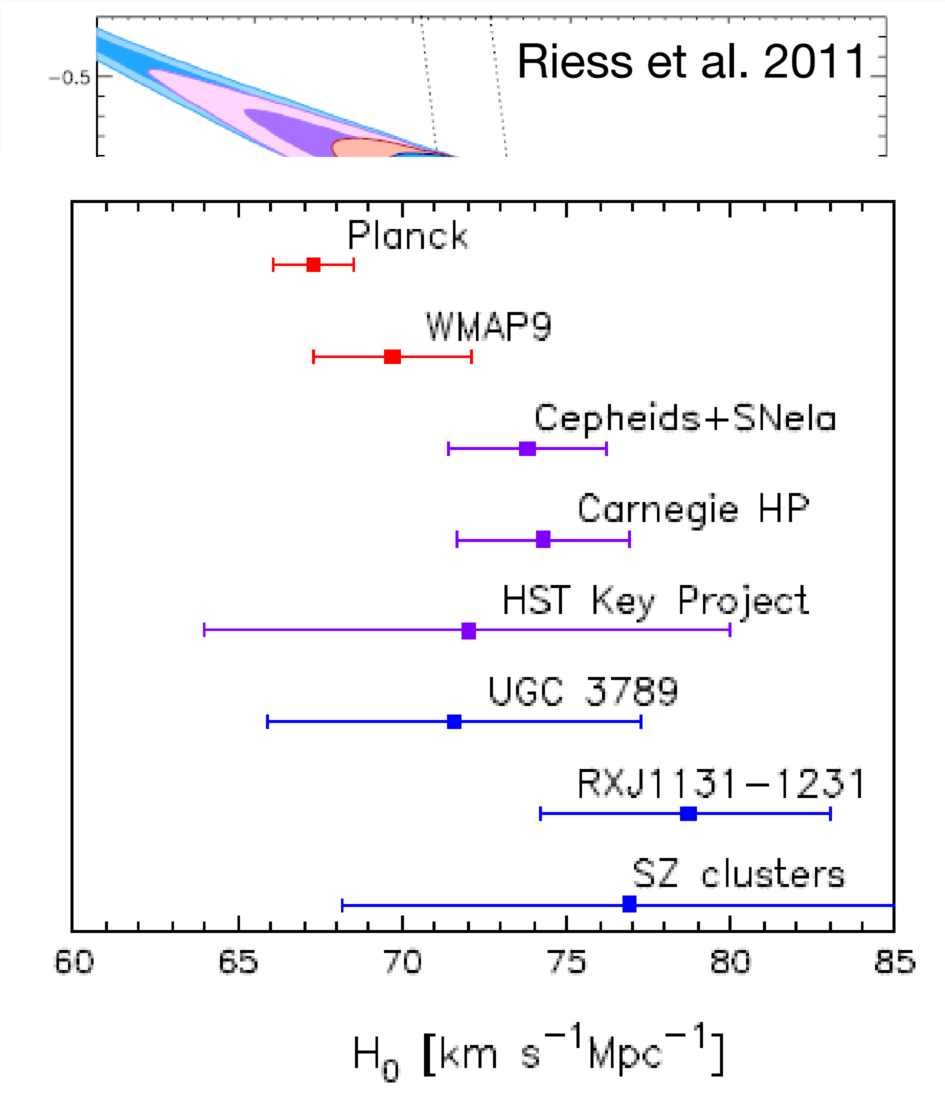
# $H_0$ from supernovae

- Measure the local Hubble diagram
- Calibrate the luminosity of the distance indicator
  - Cepheids
    - LMC
    - NGC 4358
  - nearby SNe Ia



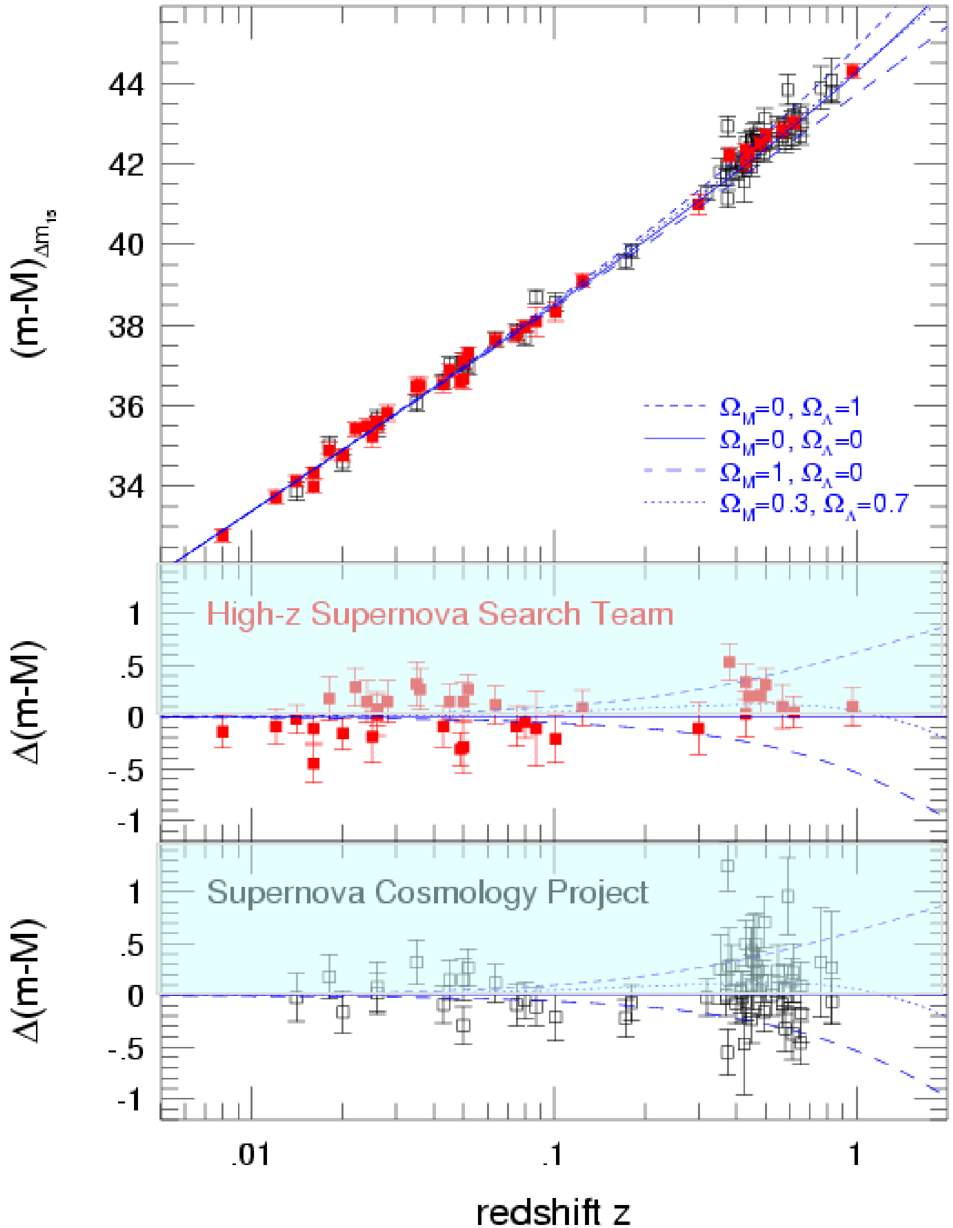
# The importance of $H_0$

- Sets the absolute scale
  - size and age of the universe
- In combination with CMB measurements
  - constrains *w*
  - neutrino mass
  - number of relativistic species



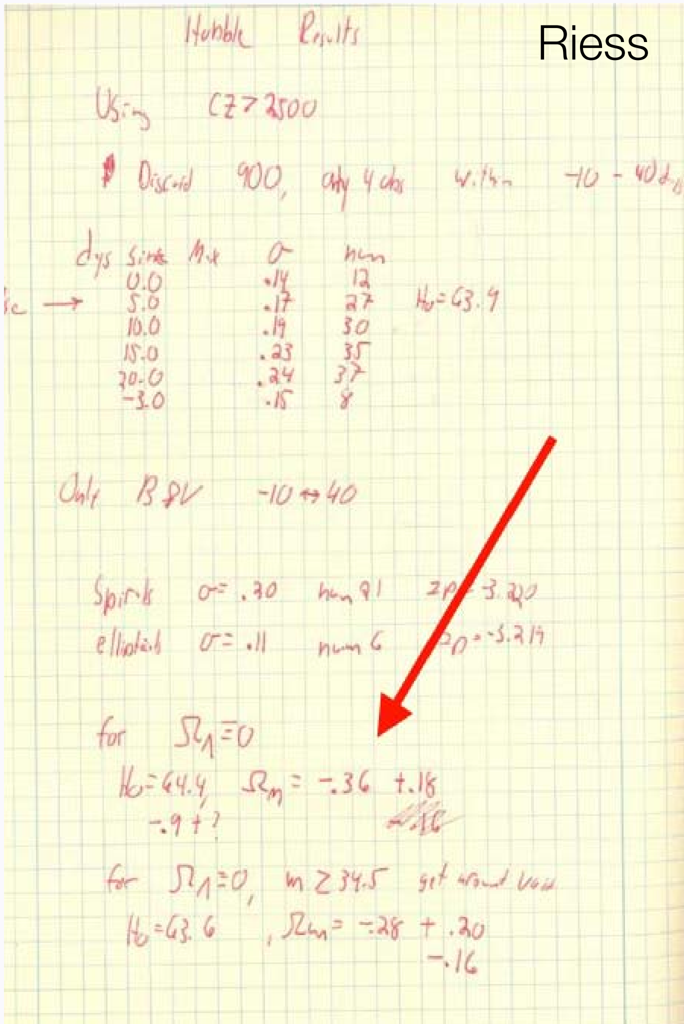
# Supernova Cosmology

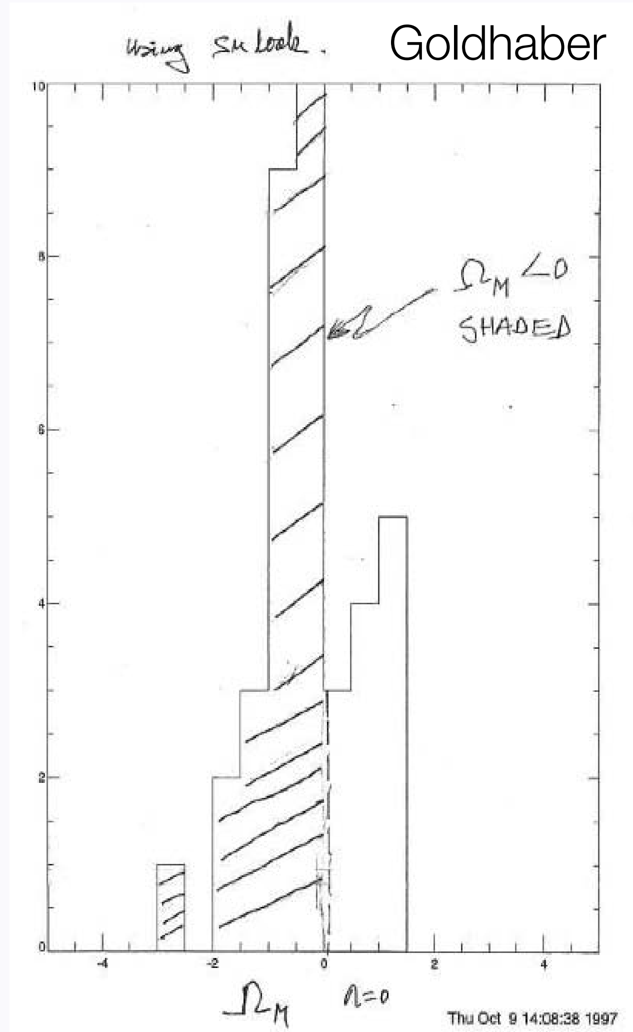
# The SN Hubble Diagram



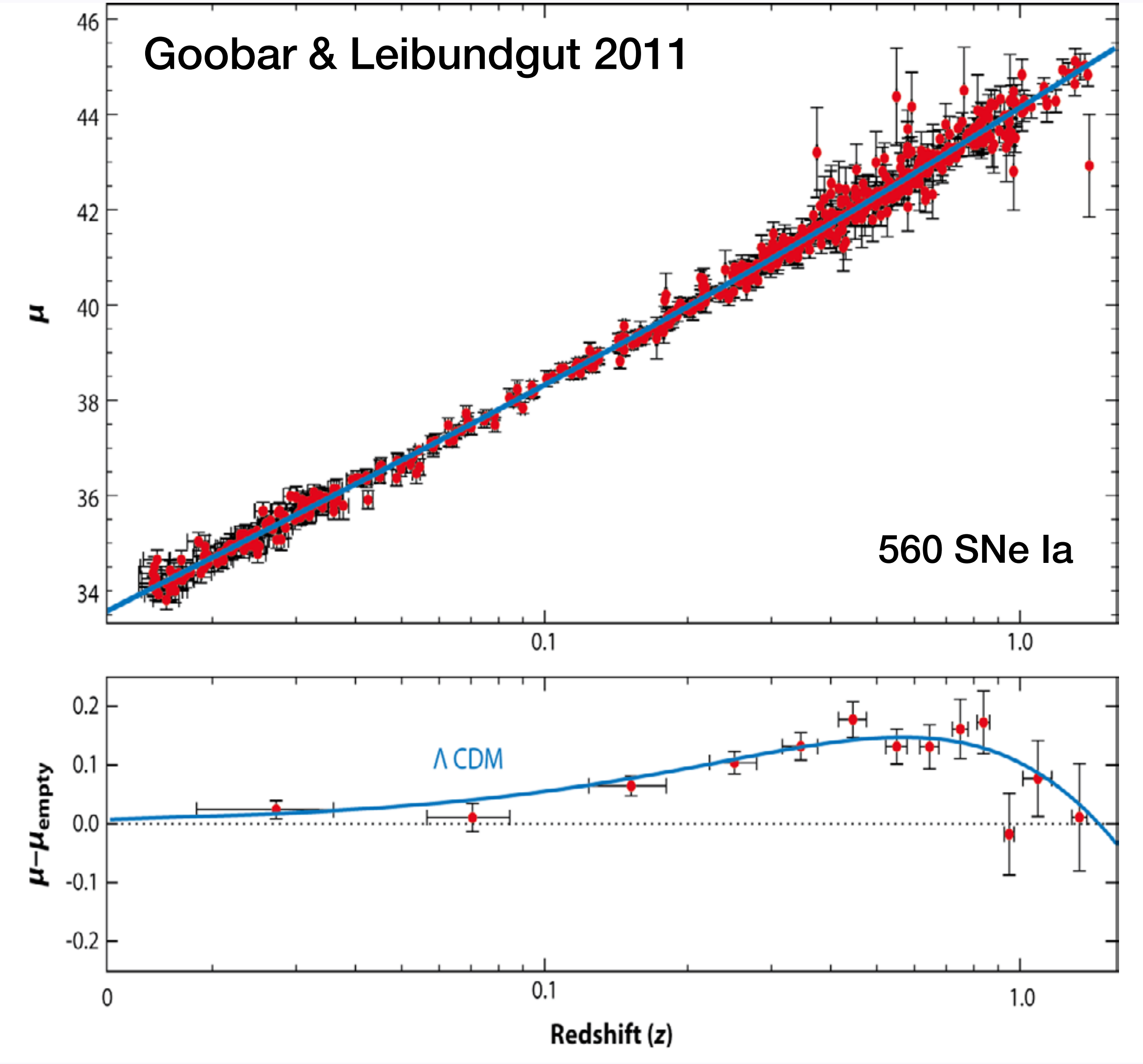

# Absurd result

## negative matter density

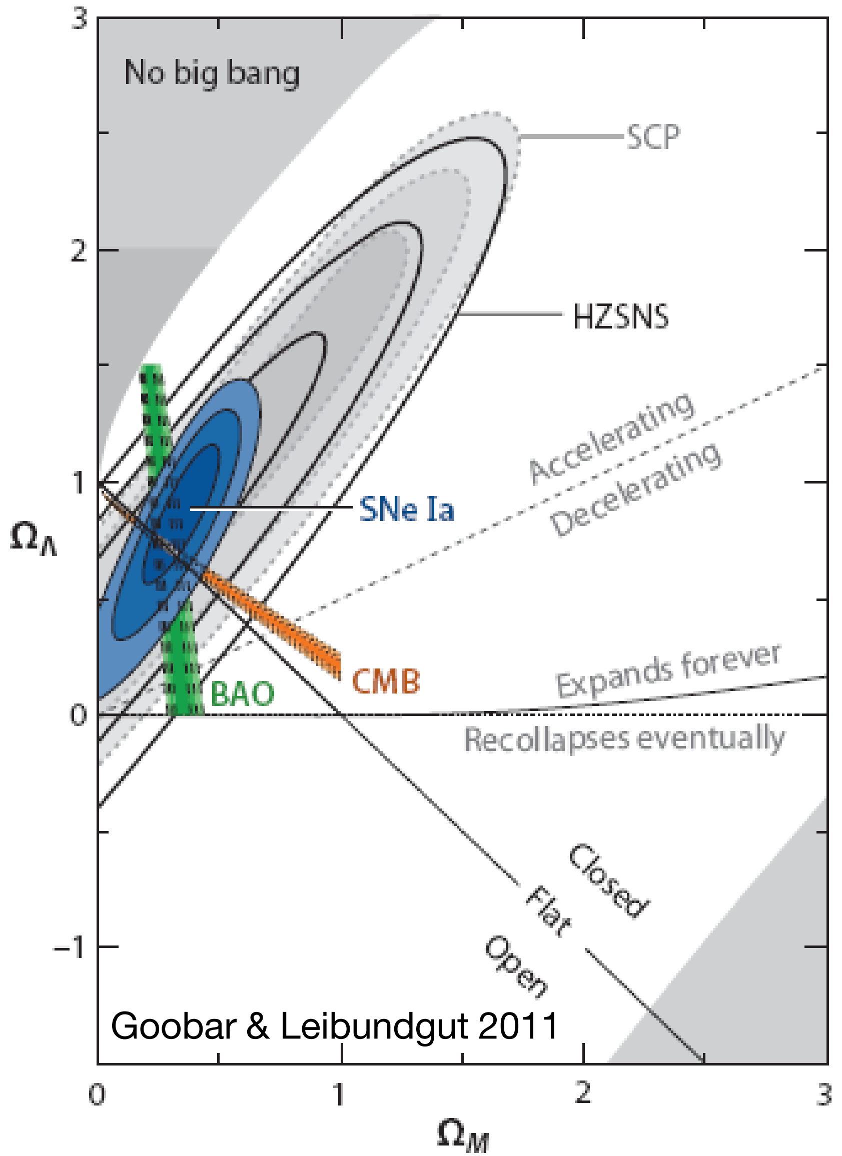


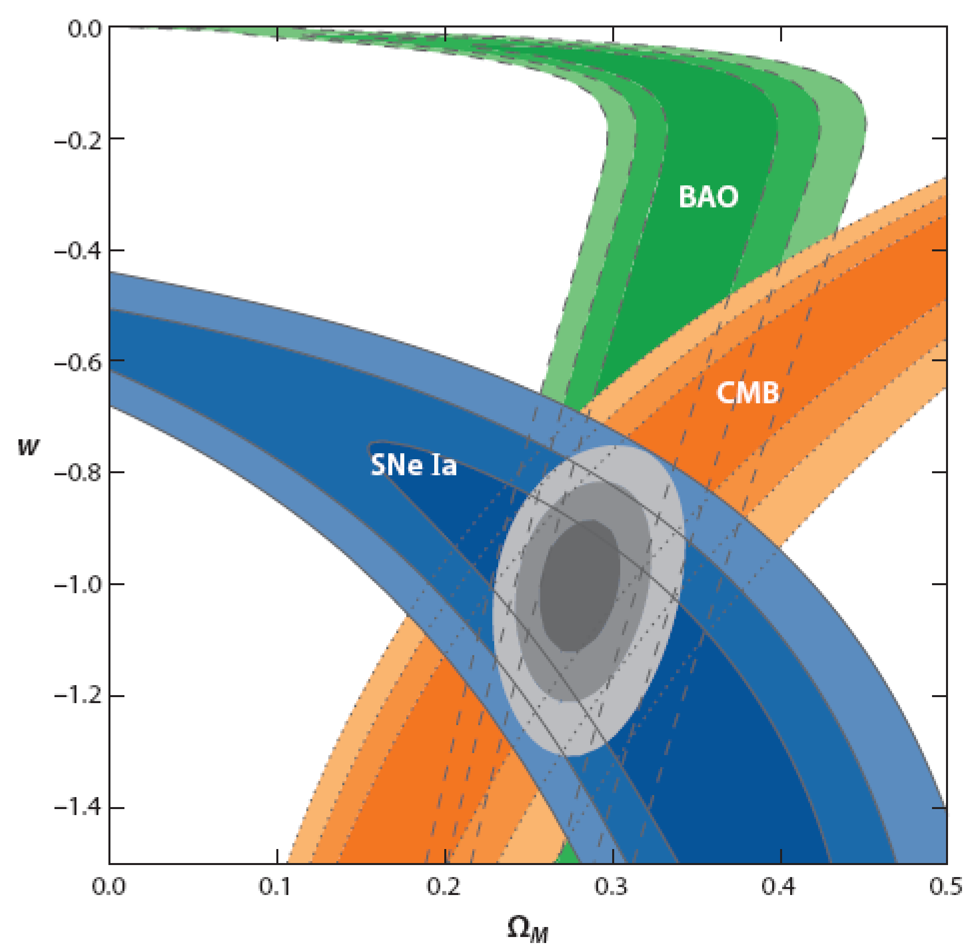
# Supernova Cosmology 2011



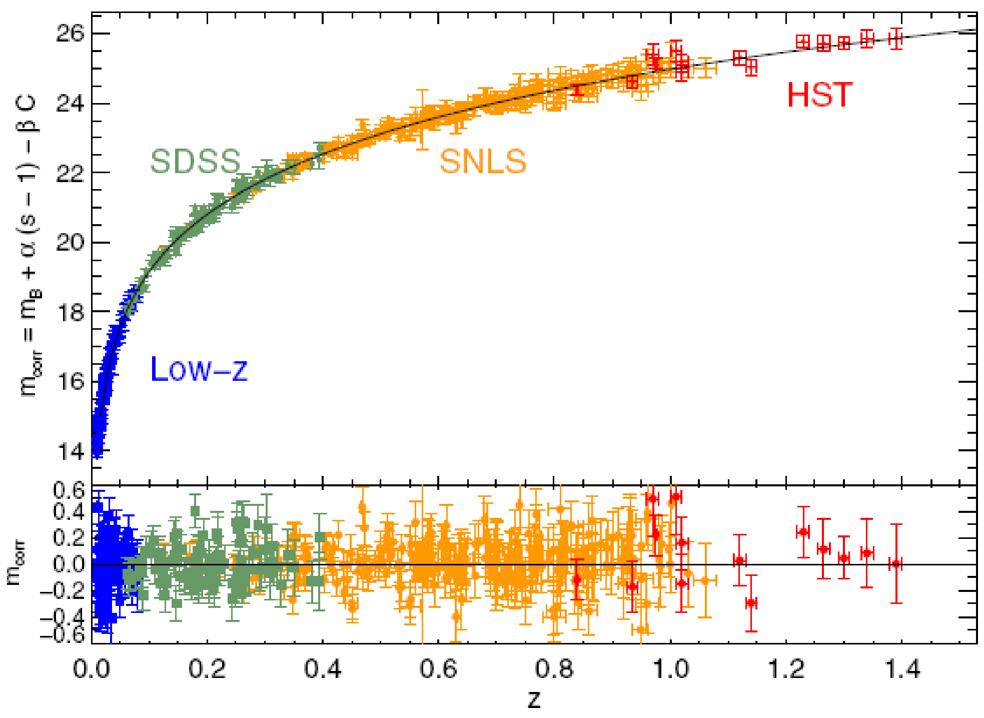
# et voilà ...




10 years of progress

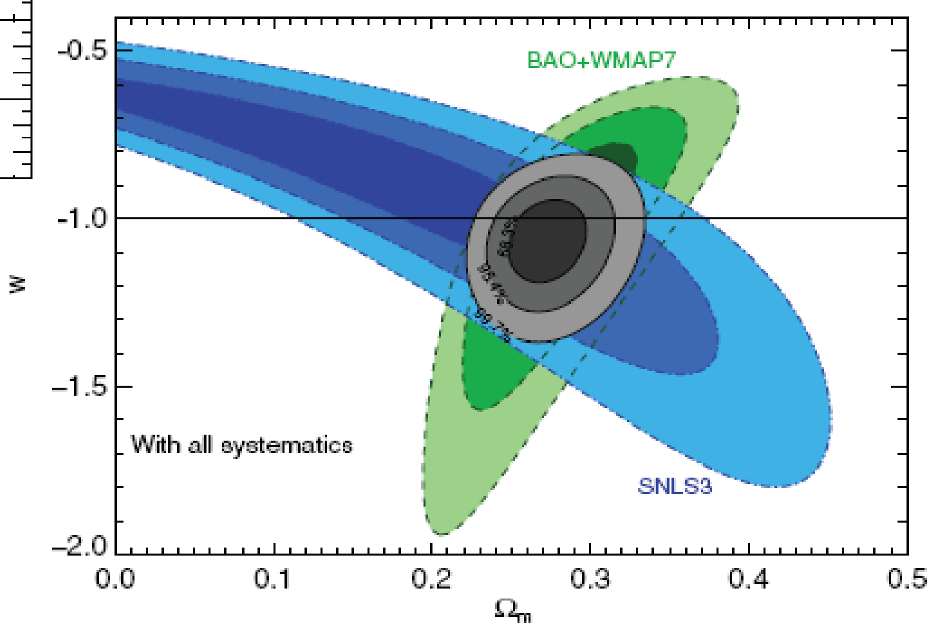


# Recent SNLS results




Conley et al. 2011

Sullivan et al. 2011



# Supernova cosmology

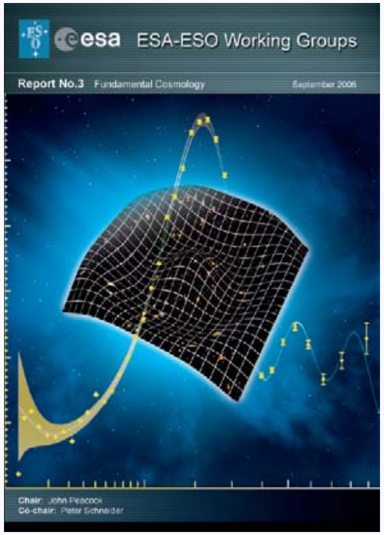
- ω firmly established
  - general agreement between different experiments

| $N_{SN}$ | $\Omega_M$(flat) | $w$ (constant, flat) | Light curve fitter | Reference |
|---|---|---|---|---|
| 115 | $0.263^{+0.042\,+0.032}_{-0.042\,-0.032}$ | $-1.023^{+0.090\,+0.054}_{-0.090\,-0.054}$ | SALT | Astier et al. 2006 |
| 162 | $0.267^{+0.028}_{-0.018}$ | $-1.069^{+0.091\,+0.13}_{-0.083\,-0.13}$ | MLCS2k2 | Wood-Vasey et al. 2007 |
| 178 | $0.288^{+0.029}_{-0.019}$ | $-0.958^{+0.088\,+0.13}_{-0.090\,-0.13}$ | SALT2 | |
| 288 | $0.307^{+0.019\,+0.023}_{-0.019\,-0.023}$ | $-0.76^{+0.07\,+0.11}_{-0.07\,-0.11}$ | MLCS2k2 | Kessler et al. 2009 |
| 288 | $0.265^{+0.016\,+0.025}_{-0.016\,-0.025}$ | $-0.96^{+0.06\,+0.13}_{-0.06\,-0.13}$ | SALT2 | |
| 557 | $0.279^{+0.017}_{-0.016}$ | $-0.997^{+0.050\,+0.077}_{-0.054\,-0.082}$ | SALT2 | Amanullah et al. 2010 |
| 472 | | $-0.91^{+016\,\pm0.07}_{-0.20\,-0.14}$ | SiFTO/SALT2 | Conley et al. 2011 |
| 472 | $0.269 \pm 0.015$ | $-1.061^{+0.069}_{-0.068}$ | SALT2 | Sullivan et al. 2011 |
| 580 | $0.271^{+0.014}_{-0.014}$ | $-1.013^{+0.077}_{-0.073}$ | SALT2 | Suzuki et al. 2011 |

# Systematics

- Contamination
- Photometry
- K-corrections
- Malmquist bias
- Normalisation
- Evolution
- Absorption
- Local expansion field

**“[T]he length of the list indicates the maturity of the field, and is the result of more than a decade of careful study.”**



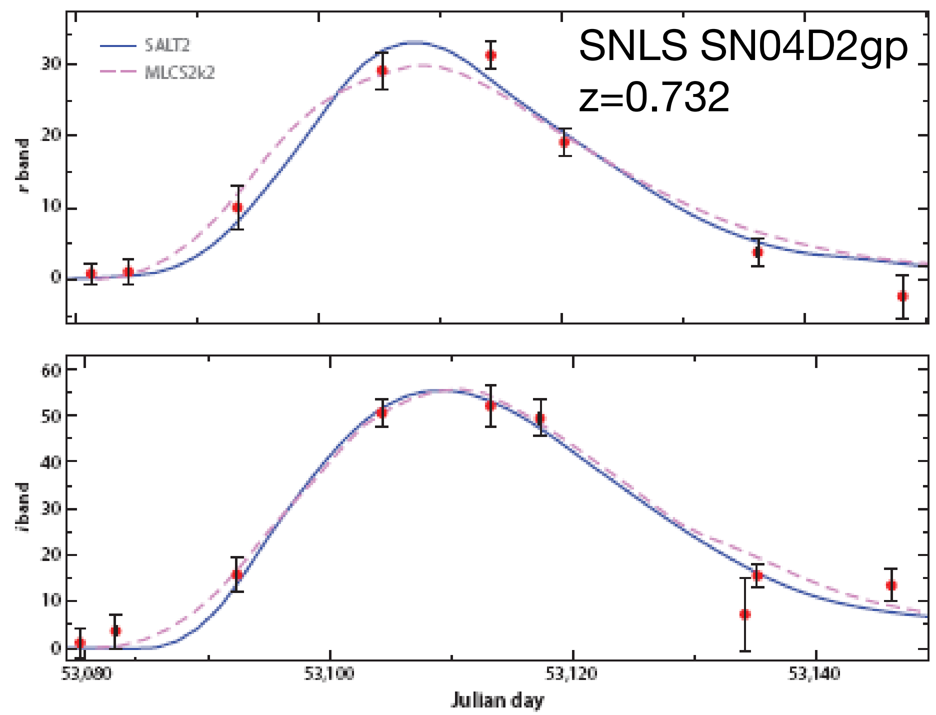
# Systematics

- Current questions
  - calibration
  - restframe UV flux
    - redshifted into the observable window
  - reddening and absorption
    - detect absorption
      - through colours or spectroscopic indicators
    - correct for absorption
      - knowledge of absorption law
  - light curve fitters
  - selection bias
    - sampling of different populations
  - gravitational lensing
  - brightness evolution

# Required phenomenology

- photometric calibration
- normalisation
  - ("standardizable candle"; "standard crayon")
  - different light curve fitters
    - $\Delta m_{15}$,SALT, SiFTO, MLCS

Goobar & Leibundgut 2011

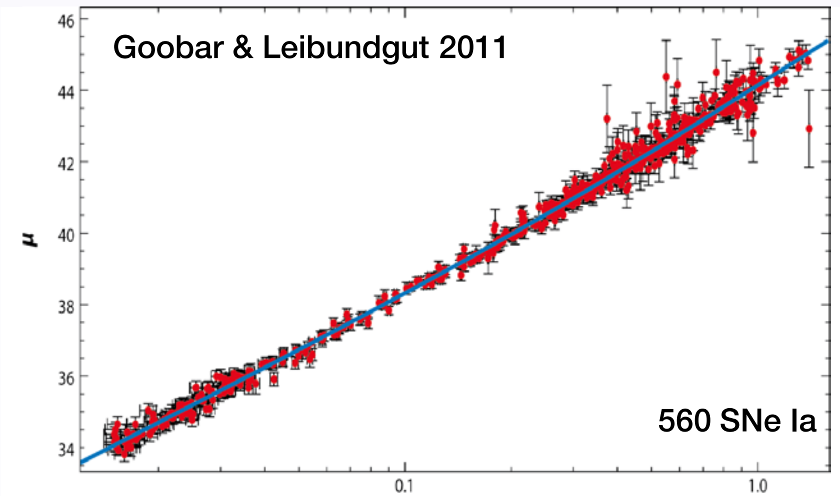


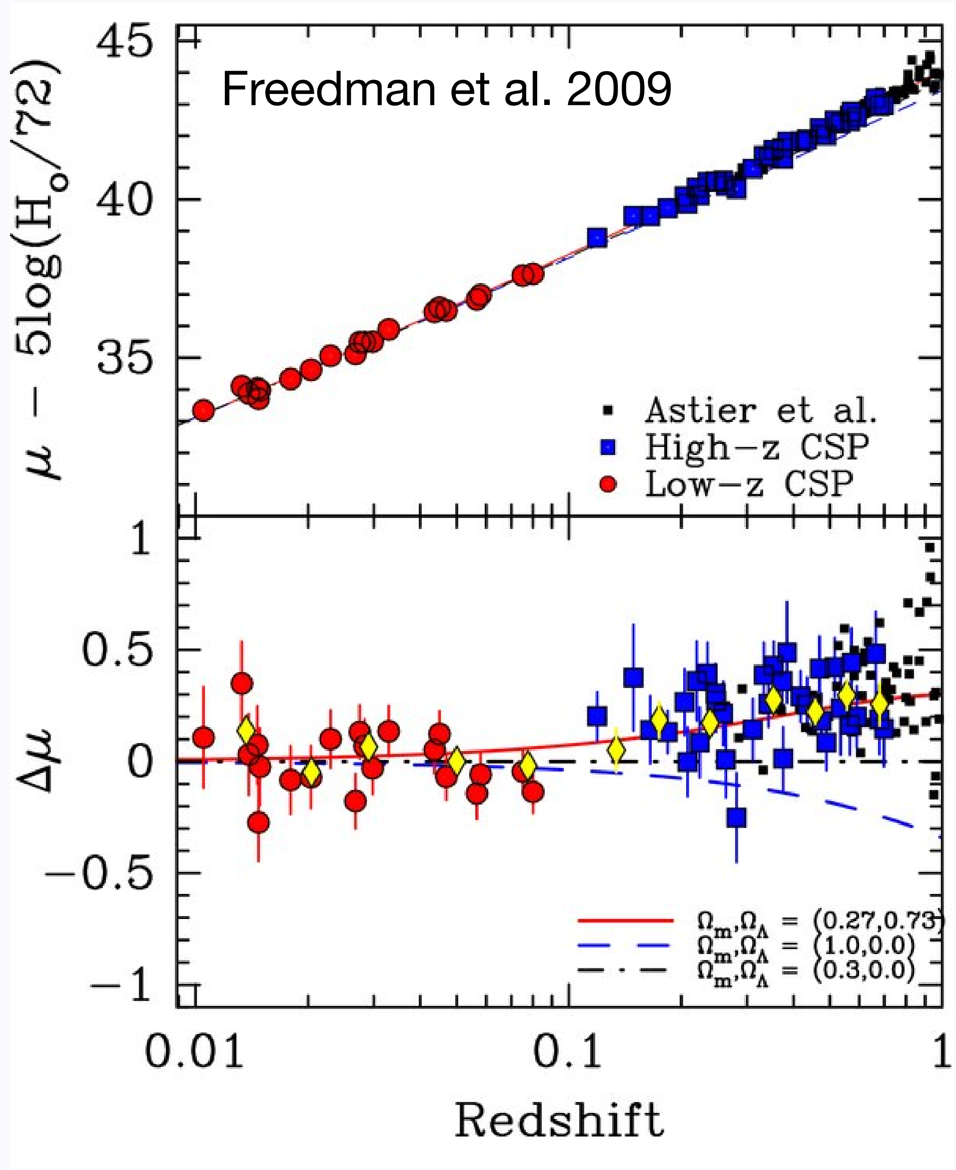
# What next?

- Already in hand
  - >1000 SNe Ia for cosmology
  - constant ω determined to 5%
  - accuracy dominated by systematic effects
- Missing
  - good data at z>1
    - light curves and spectra
  - good infrared data at z>0.5
    - cover the restframe B and V filters
    - move towards longer wavelengths to reduce absorption effects
  - restframe near-infrared Hubble diagram
    - Nobili et al. 2005, Freedman et al. 2009, Barone-Nugent et al. 2012, Kattner et al. 2012

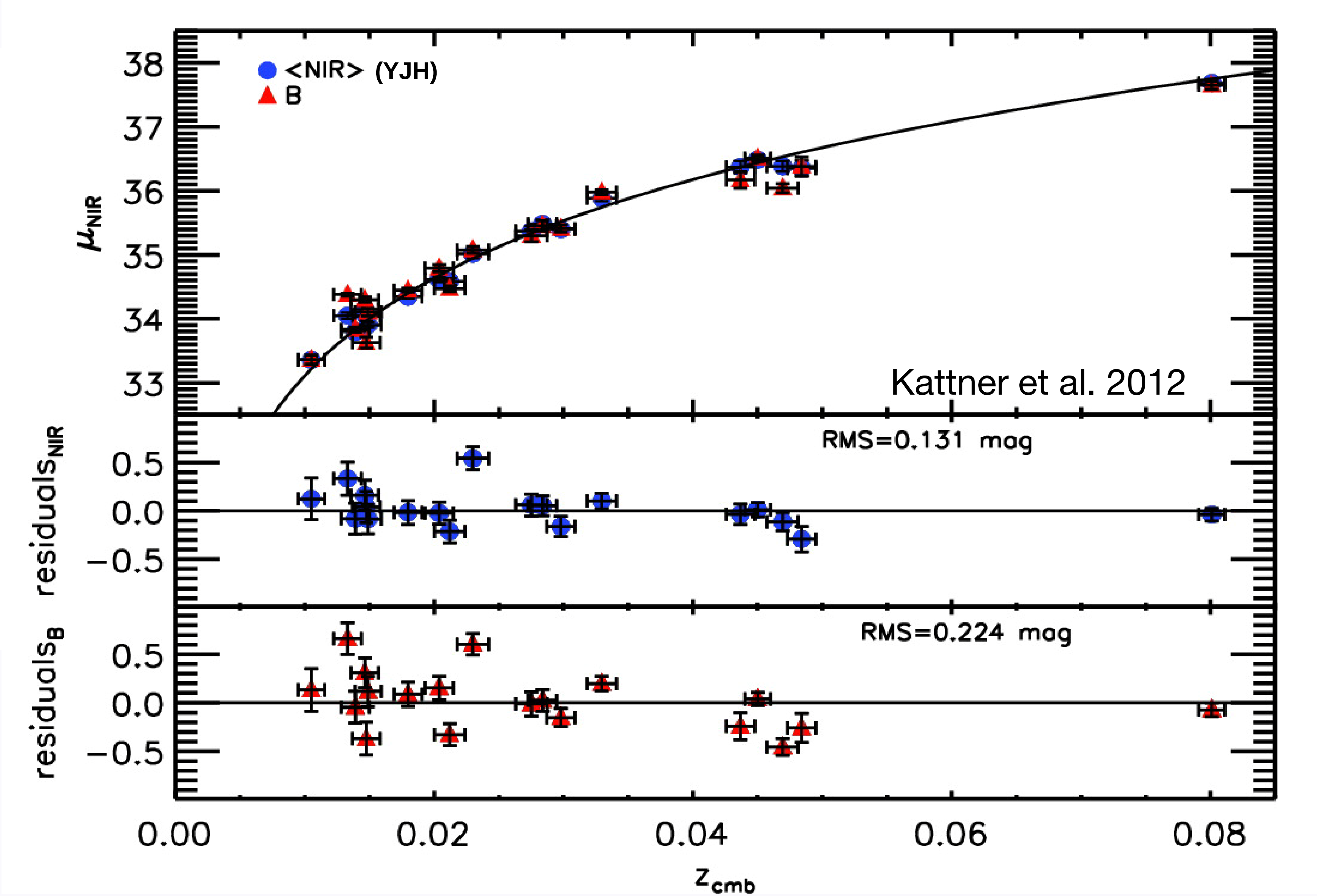
# I-band Hubble diagram

- Currently only 35 SNe  Ia



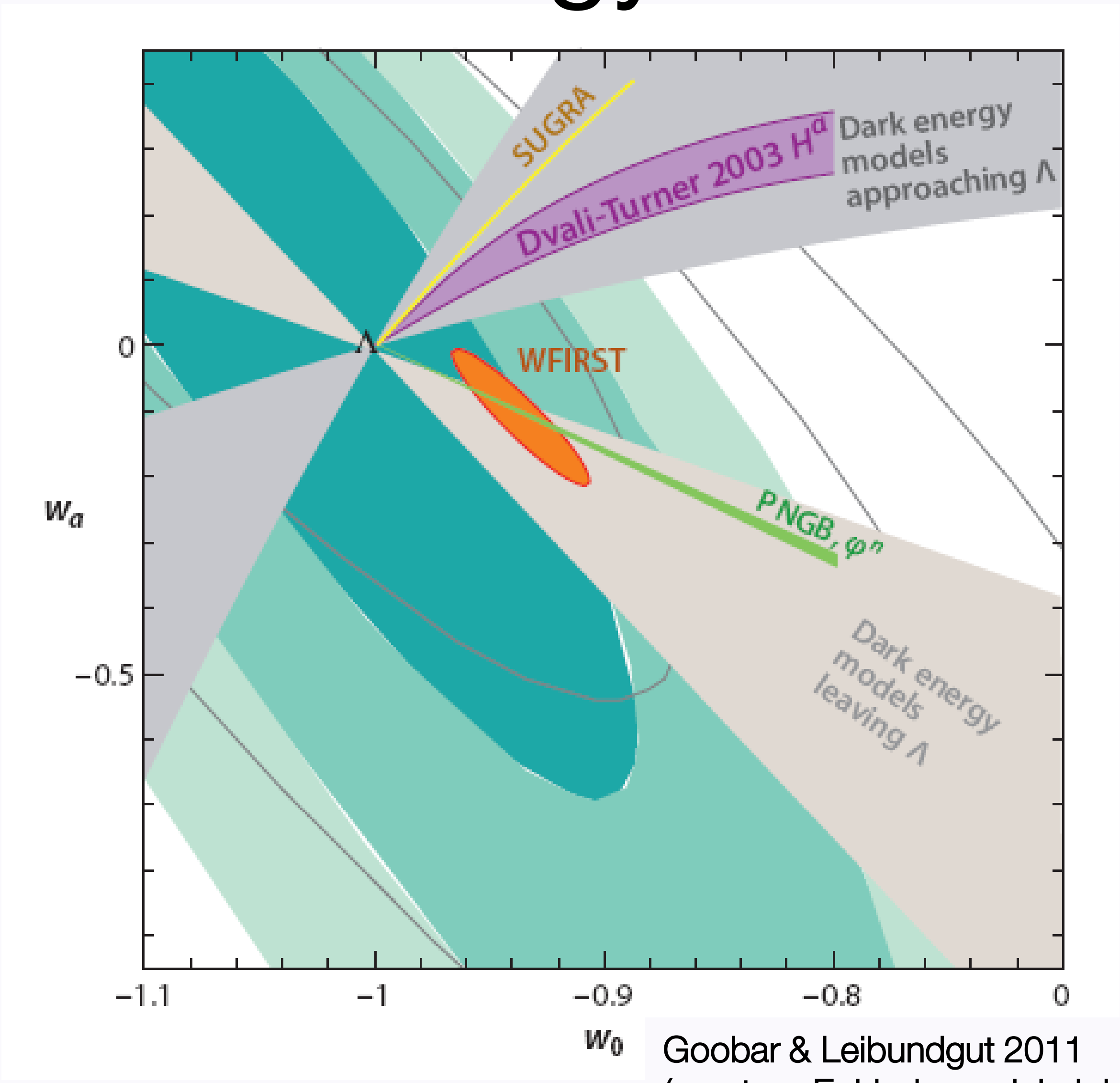
# J- and H-band Hubble diagrams



# Supernova Cosmology – do we need more?

- Test for variable ω
  - required accuracy ~2% in *individual* distances
  - can SNe Ia provide this?
    - can the systematics be reduced to this level?
    - homogeneous photometry?
    - further parameters (e.g. host galaxy metalicity)
    - handle >100000 SNe Ia per year?
- Euclid
  - 3000 SNe Ia to z<1.2 with IR light curves (deep fields) → restframe I-band Hubble diagram
  - 16000 SNe discovered

# Cosmology – more?




Goobar & Leibundgut 2011
(courtesy E. Linder and J. Johansson)

# Distant SNe with CANDELS and CLASH

- Multi-cycle HST Treasury Programs

PIs: S. Faber/H. Fergusson

PI: M. Postman

## HST MCT SN Survey

PI: A. Riess

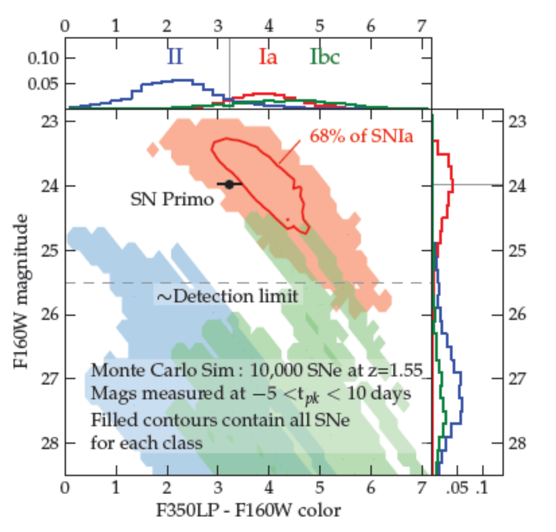
SN discoveries and target-of-opportunity follow-up
SNe Ia out to z≈2
Determine the SN rate at z>1 and
constrain the progenitor systems

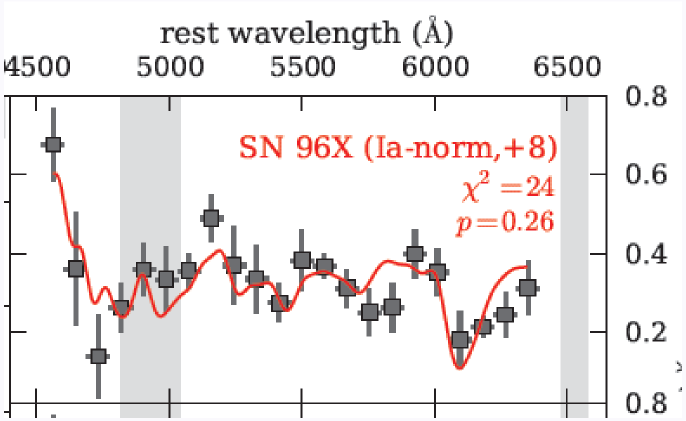
# SNe Ia at high redshifts ($z>1.5$)

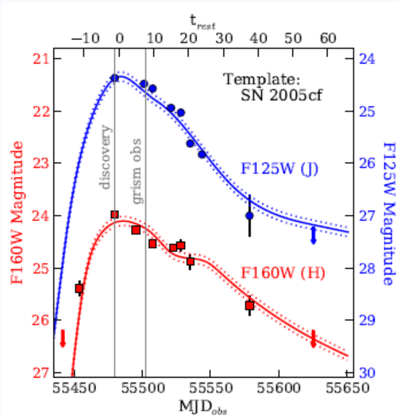
- ratio $(\Omega_{DE}/\Omega_M)_0=2.7$; $(\Omega_{DE}/\Omega_M)_{z=1.5}=0.173$ with $w_0=-1\pm0.2$ and $w_a=-1\pm1$; $w=w_0+w_a(1-a)$
- within these uncertainties the observed magnitudes change less than 0.1m
  - direct test for evolution!
- at $z>1.5$ age of the universe is $<4$Gyr
  - low-mass stars are still on the main sequence
  - SN Ia progenitors from more massive progenitor stars
  - constrain progenitor models of SNe Ia

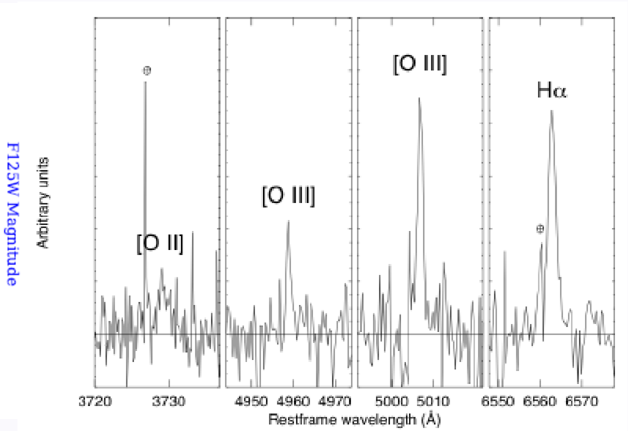
# 4 arguments for a SN Ia @ z=1.55

1. color and host galaxy photo-z
2. host galaxy spectroscopy
3. light curve consistent with normal SN Ia at z=1.55
4. SN spectrum consistent



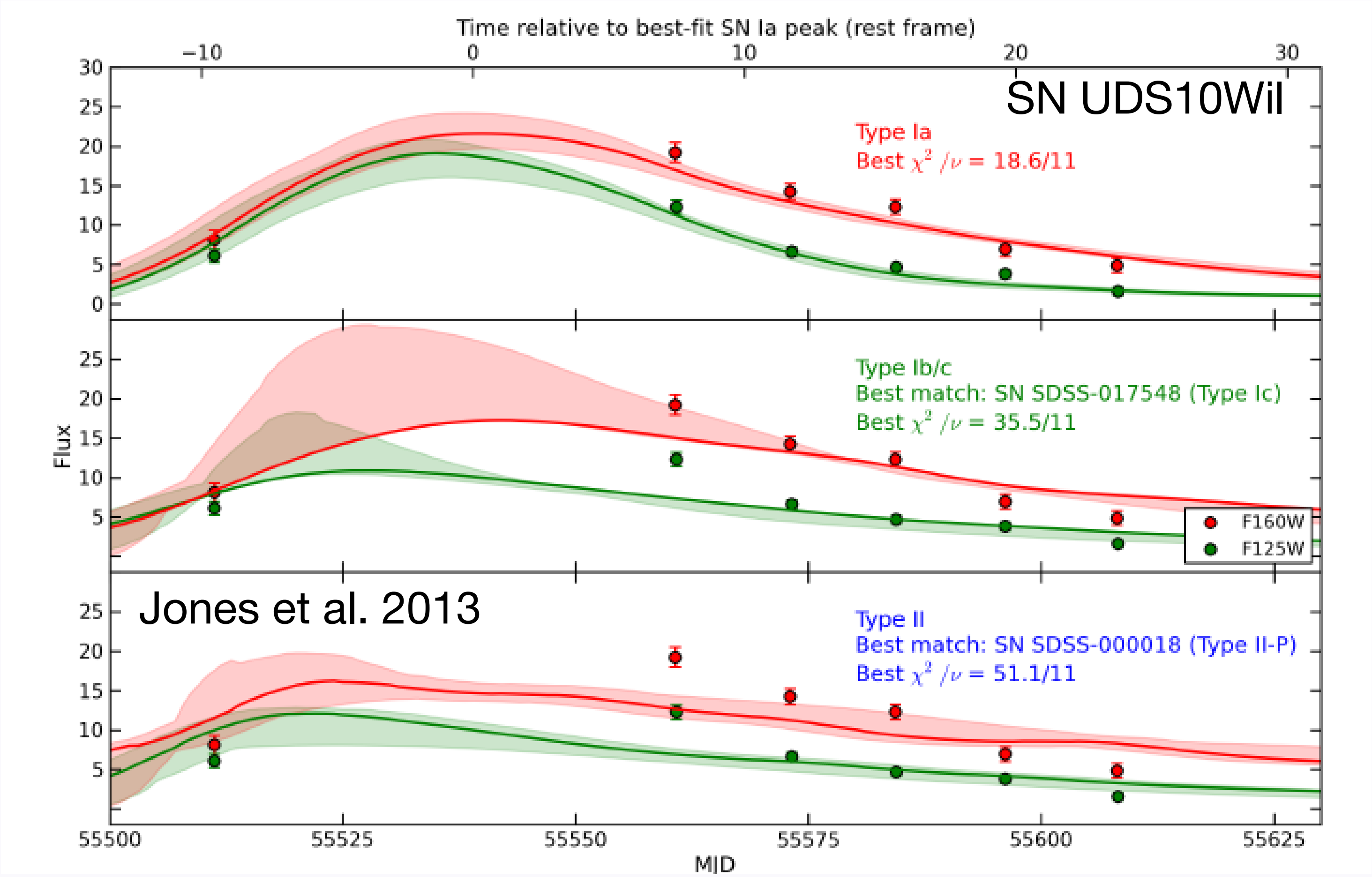



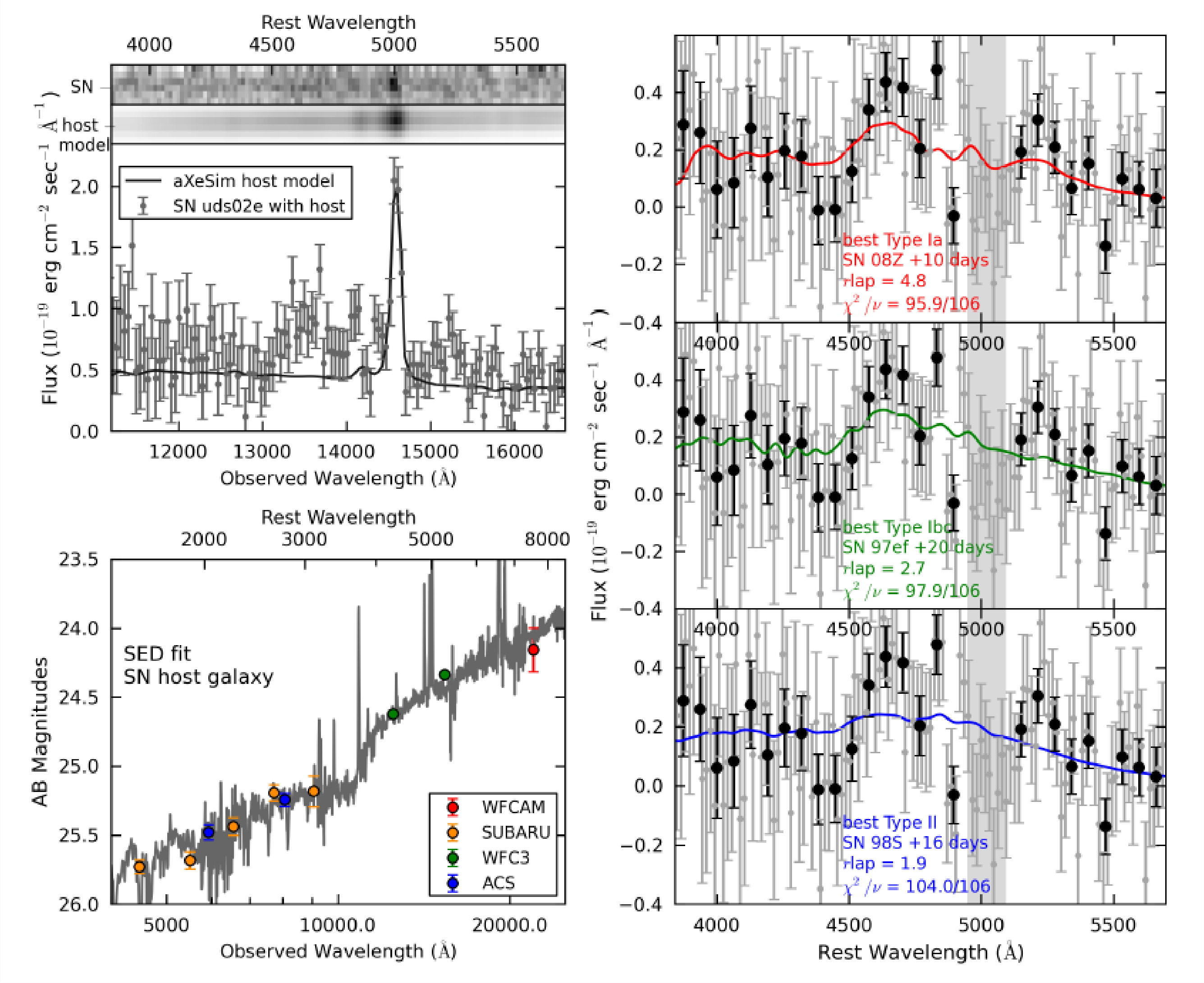



# SNe Ia at z>1

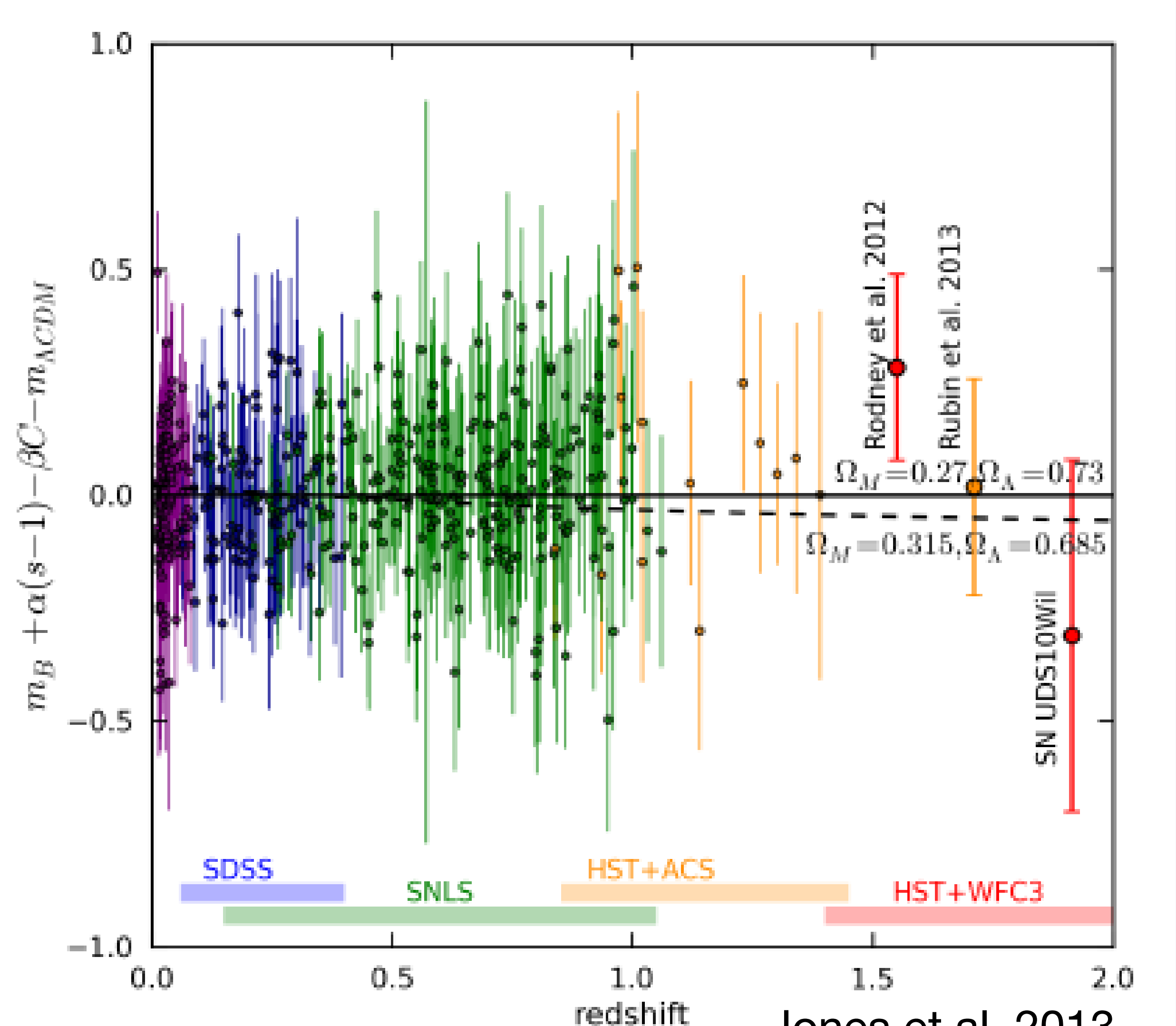
- SN Ia at z=1.91



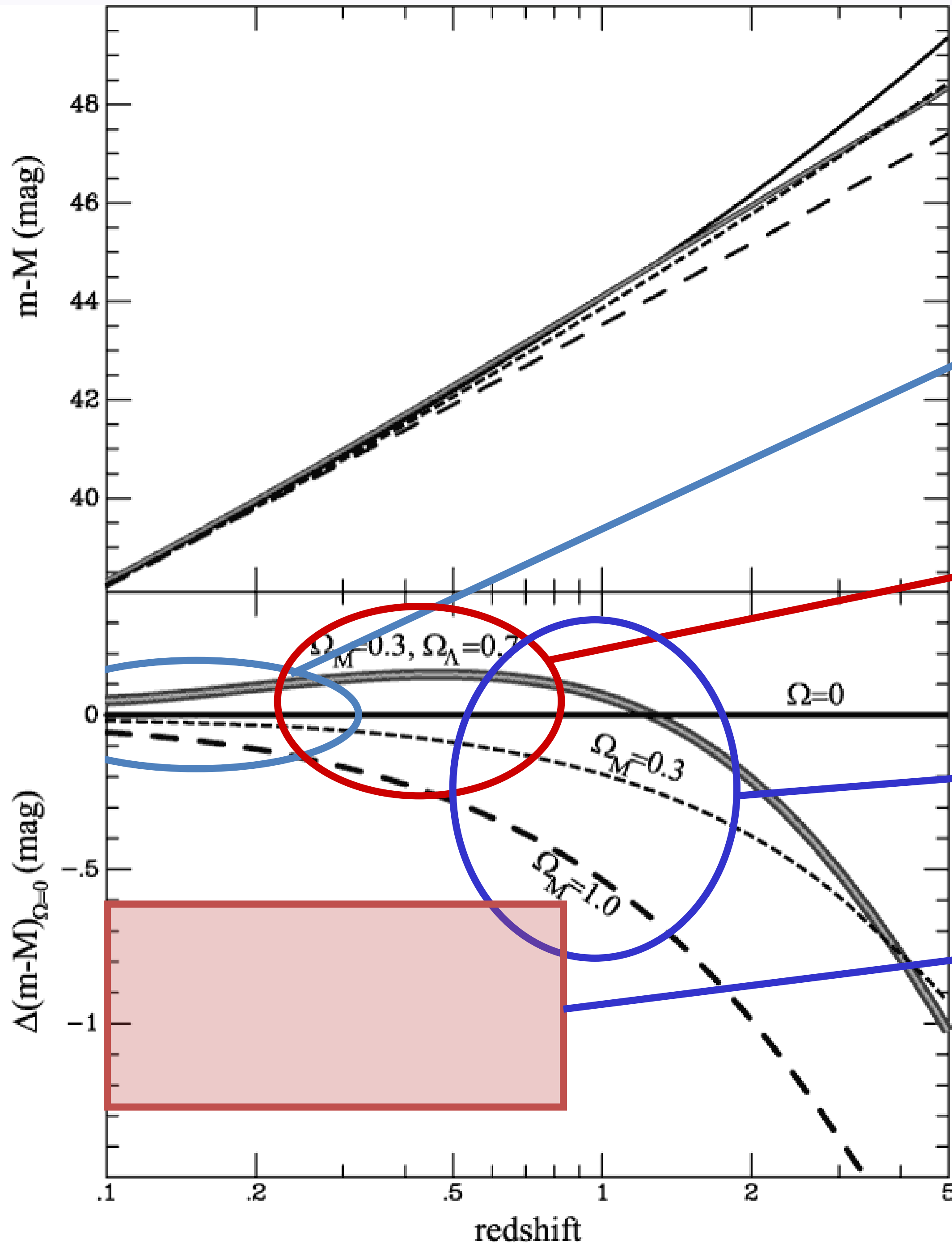
# SN UDS10Wil at z=1.91



# SNe at z>1




Jones et al. 2013




# Where are we …

SN Factory
Carnegie SN Project
SDSSII

ESSENCE
CFHT Legacy Survey

Higher-z SN Search (GOODS)

Euclid/WFIRST/LSST

Plus the local searches: LOTOSS, CfA, ESC

# Summary

- Concentrate on $\lambda$ not covered so far
  - particular IR is interesting
    - reduced effect of reddening
    - better behaviour of SNe Ia(?)
- Understand the SN zoo
  - many (subtle?) differences observed in recent samples (PanSTARRS and PTF)
    - subluminous and superluminous
  - understand potential evolutionary effects
    - spectroscopy important → PESSTO
    - DES?, LSST?, Euclid follow-up?