Supernova Cosmology

Bruno Leibundgut
ESO


Supernova!
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Supernovae!

2006er 2006ew 2006ex 2006ey 2006fa 2006fb 2006fc 2006fd 2006ff 2006fh 2006fi 2006fj 2006fk 2006fl 2006fm
2006fs 2006ft 2006fu 2006fw 2006fx 2006fy 2006fz 2006ga 2006gb 2006ge 2006gf 2006gg 2006gh 2006gk 2006gl
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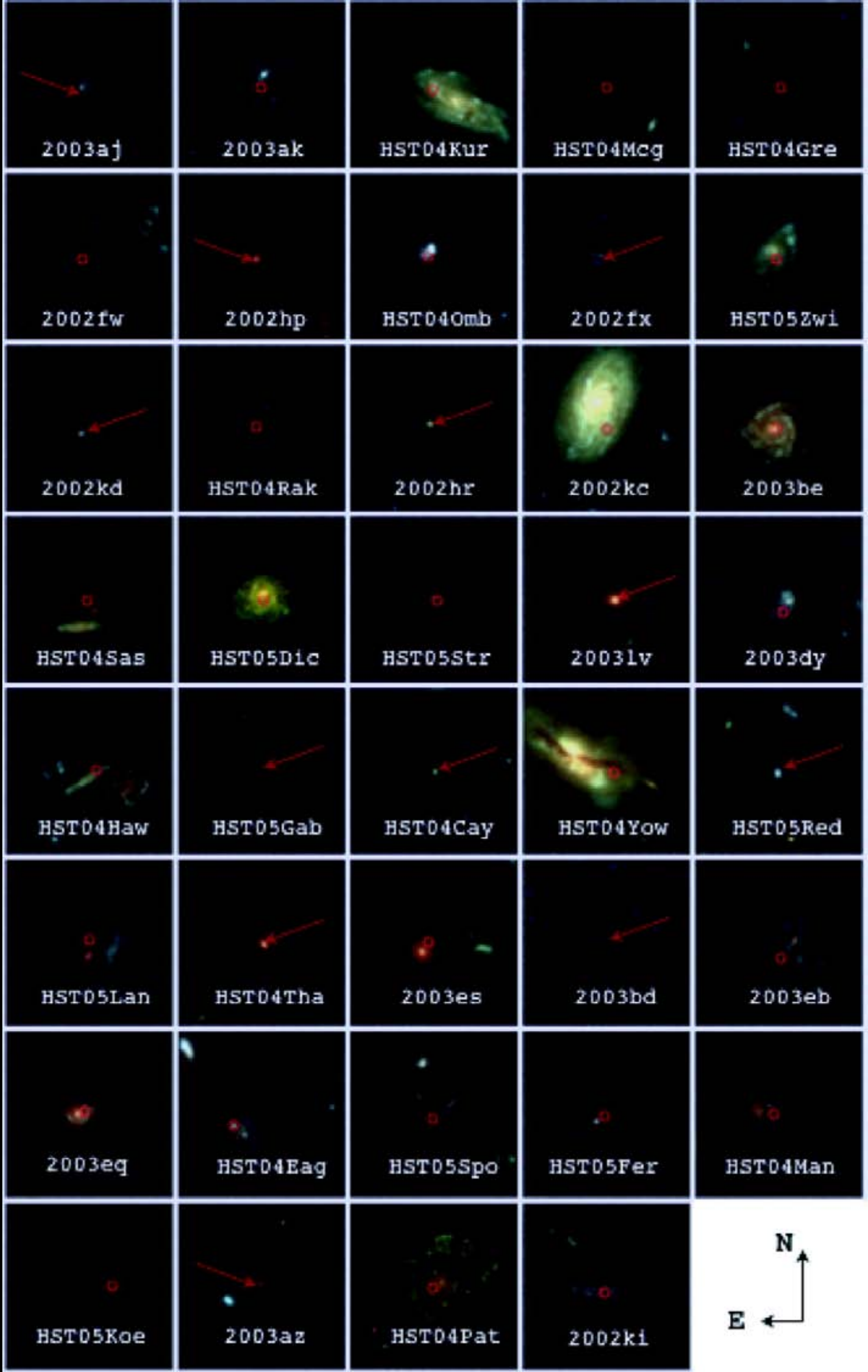


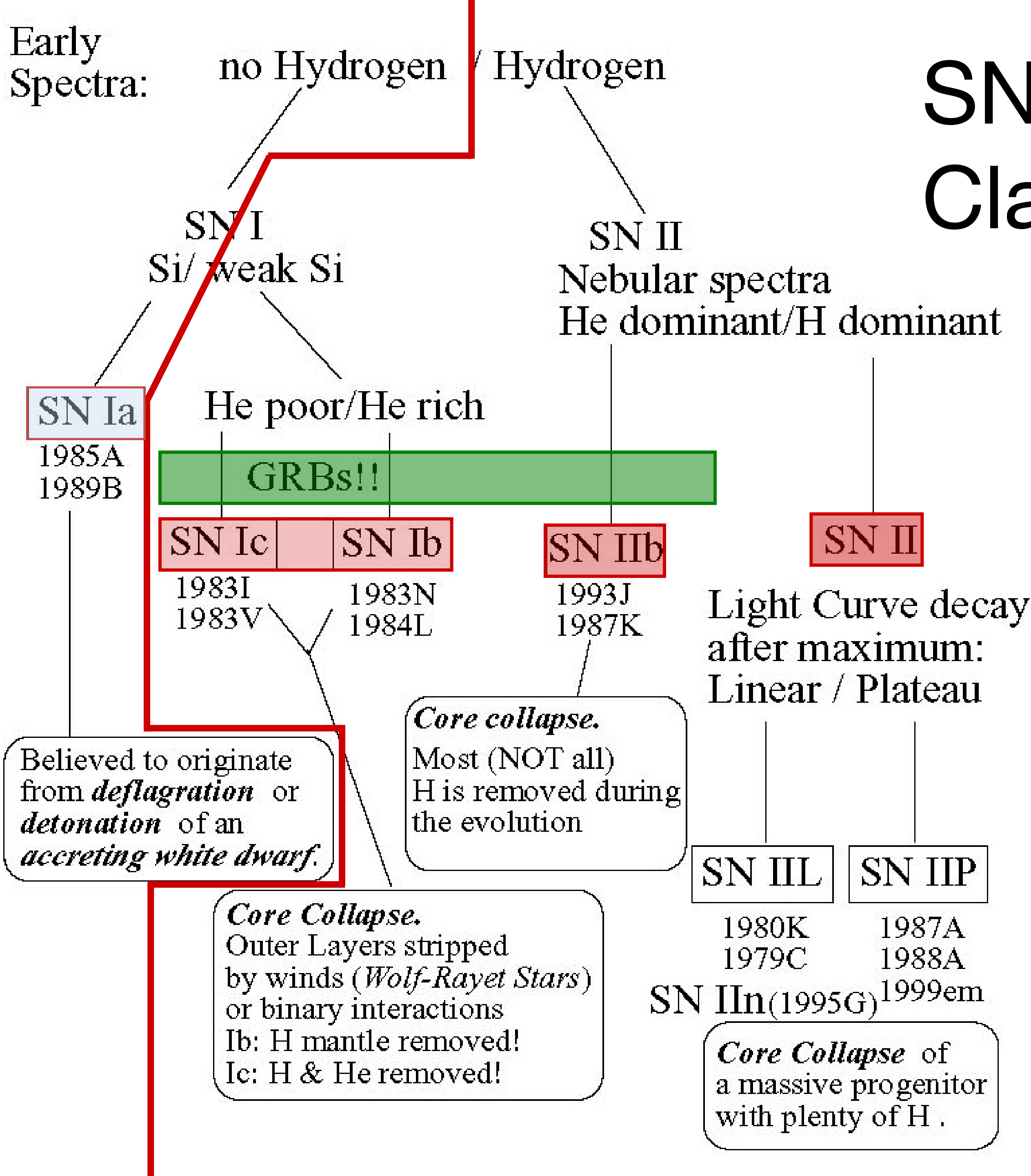
Supernovae!

Riess et al. 2007

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

SN Classification



Supernova Types

Thermonuclear SNe

- Progenitor stars have small mass ($<8M_{\odot}$)
- highly developed stars (white dwarfs)
- Explosive C und O burning
- Binary star systems
- Complete destruction

Core collapse SNe

- Progenitor stars have large mass ($>8M_{\odot}$)
- large envelope (Fusion still ongoing)
- Burning because of the high density and compression
- Single stars (double stars for SNe Ib/c)
- Neutron star as remnant

Supernova Astrophysics

- To measure cosmological parameters (distances) you need to
  - understand your source
  - understand what can affect the light on its path to the observer (‘foregrounds’)
  - know your local environment

Supernova Cosmology

The expansion of the universe

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

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

Hubble's Law deceleration jerk/equation of state

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

Friedmann cosmology

Assumption:
homogeneous und isotropic universe

Friedmann-Robertson-Walker-Lemaître metric:

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

$$\Omega_M = \frac{8\pi G}{3H_0^2}\rho_M$$

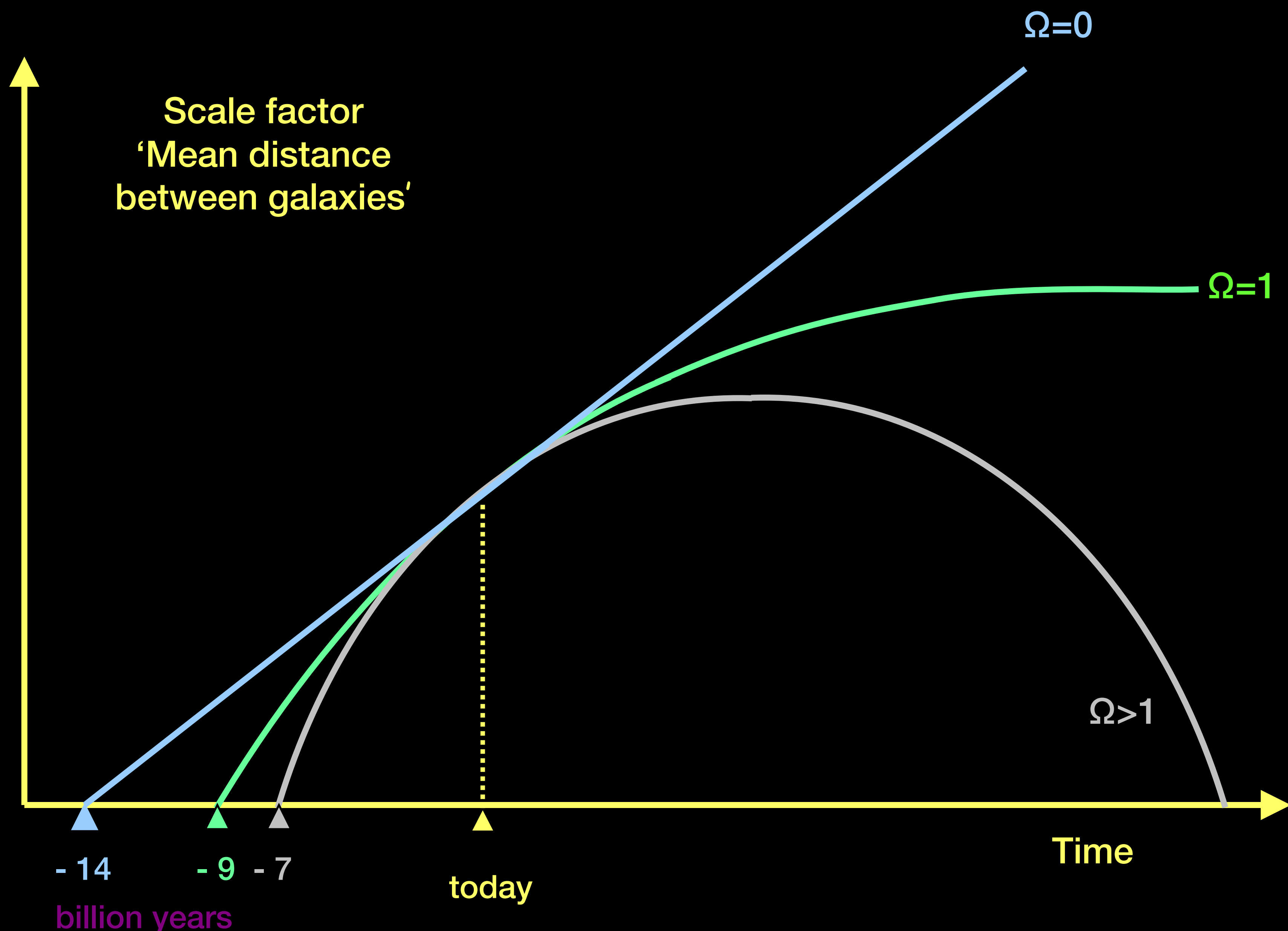
$$\Omega_k = -\frac{kc^2}{R^2 H_0^2}$$

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

Ω_M: matter density

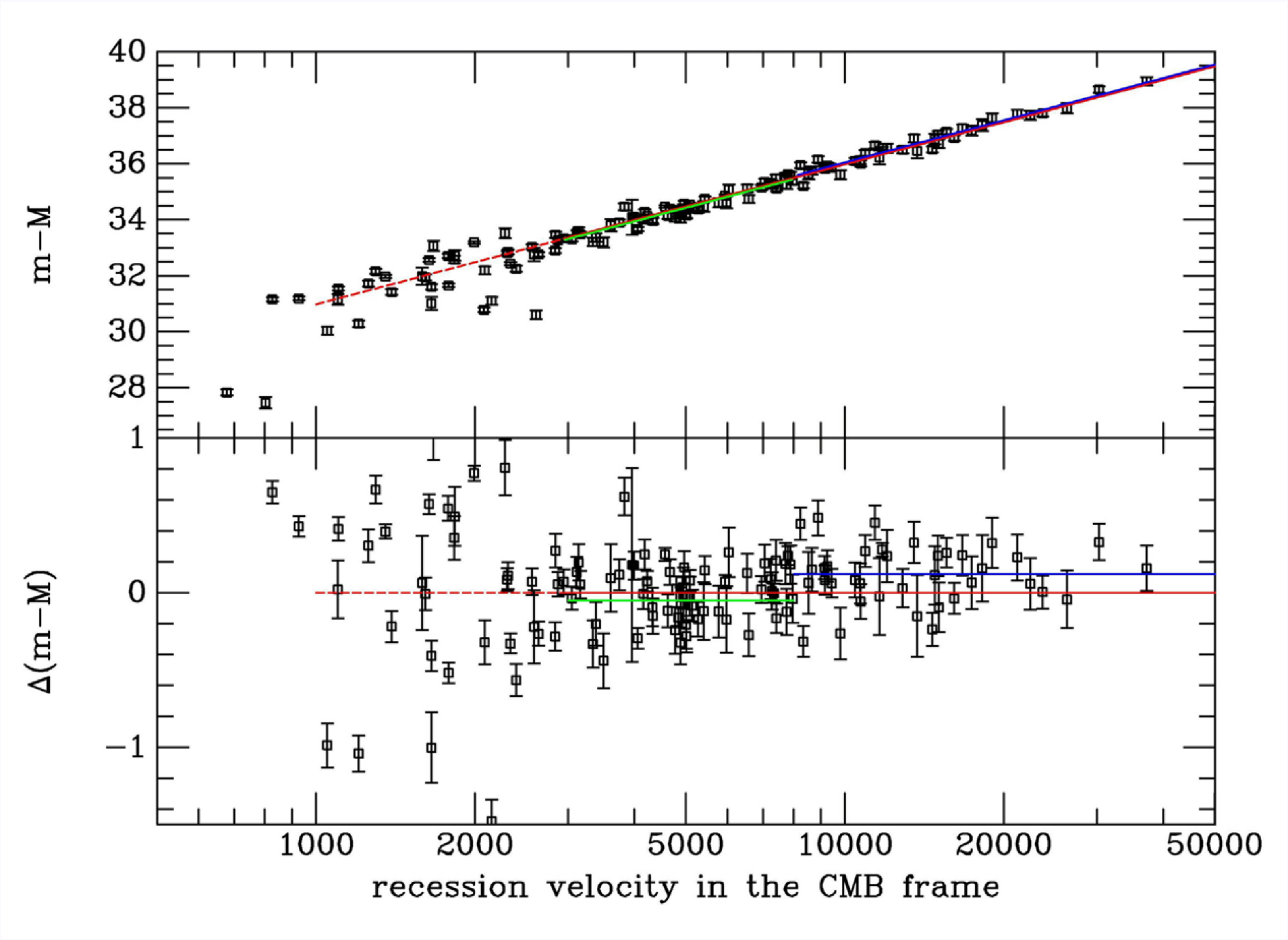
Ω_k: curvature

Ω_Λ: cosmological constant



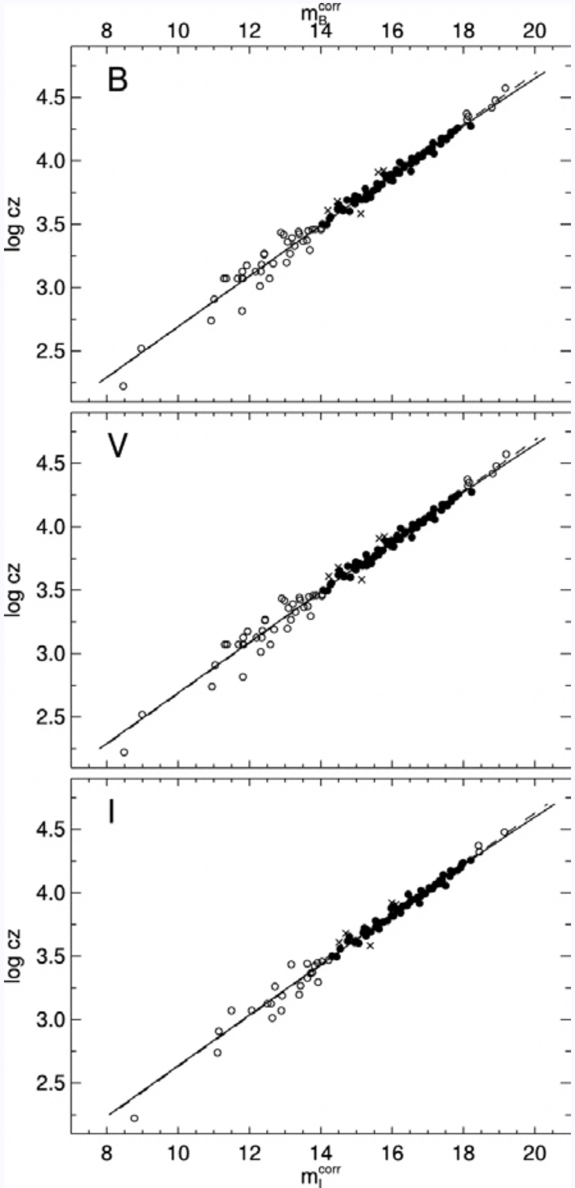
Ω=0
Scale factor
'Mean distance
between galaxies'
Ω=1
Ω>1
Time
- 14
- 9
- 7
today
billion years

Distance indicator!



SN Ia Hubble diagram

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

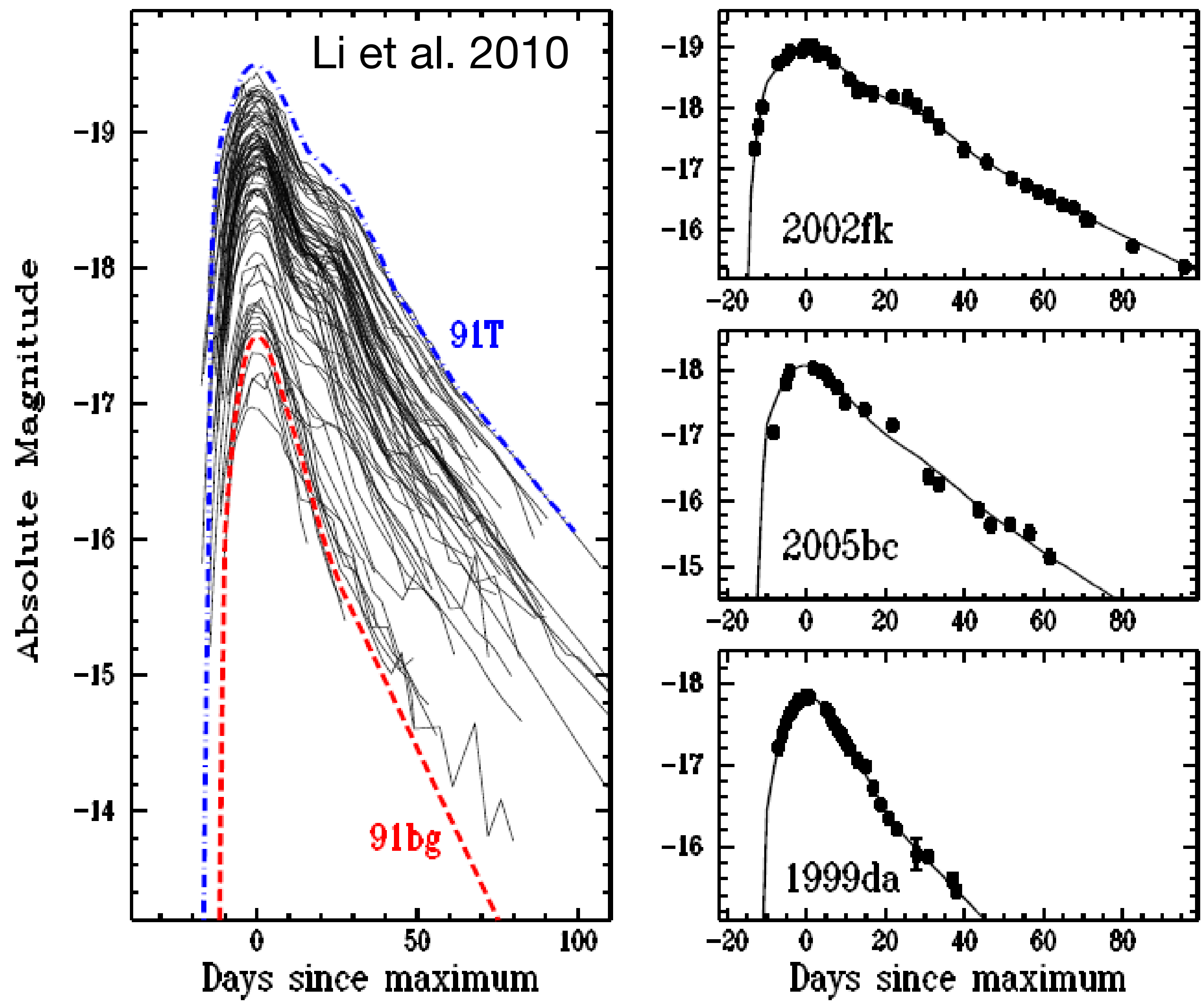


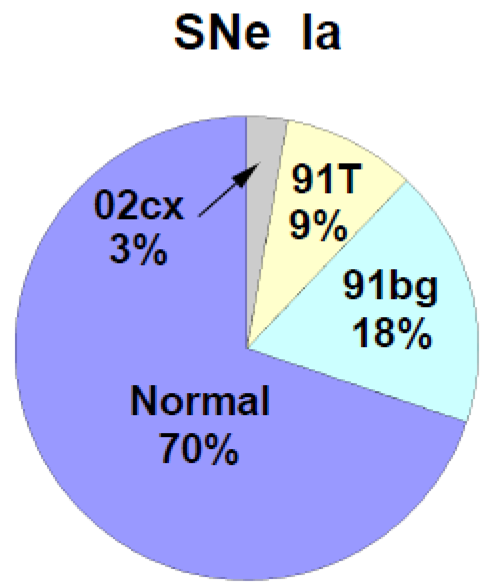
Reindl et al. 2005

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

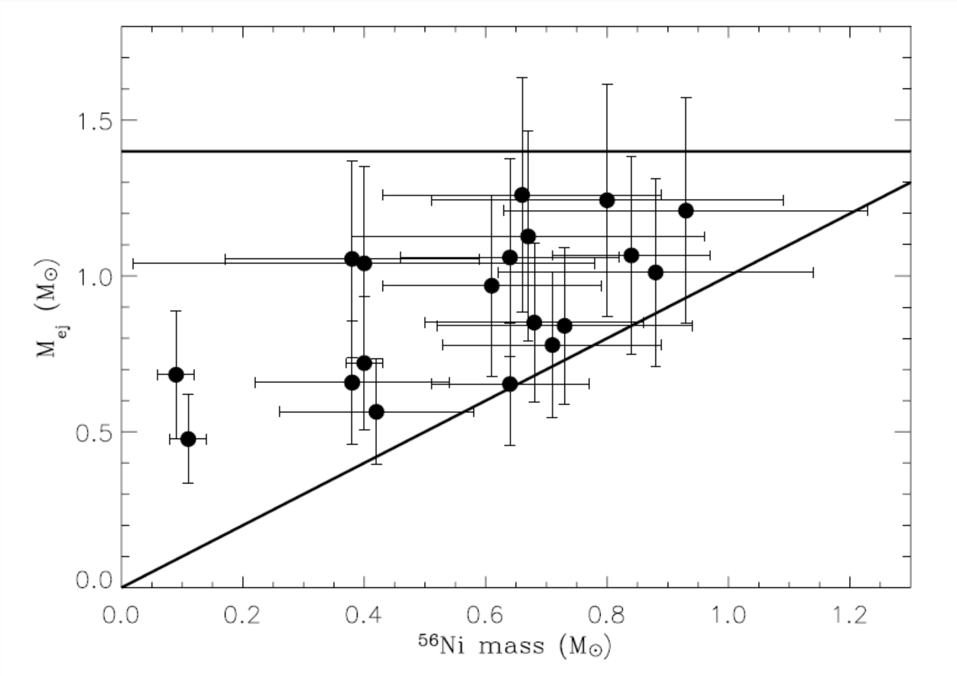
Luminosity distribution





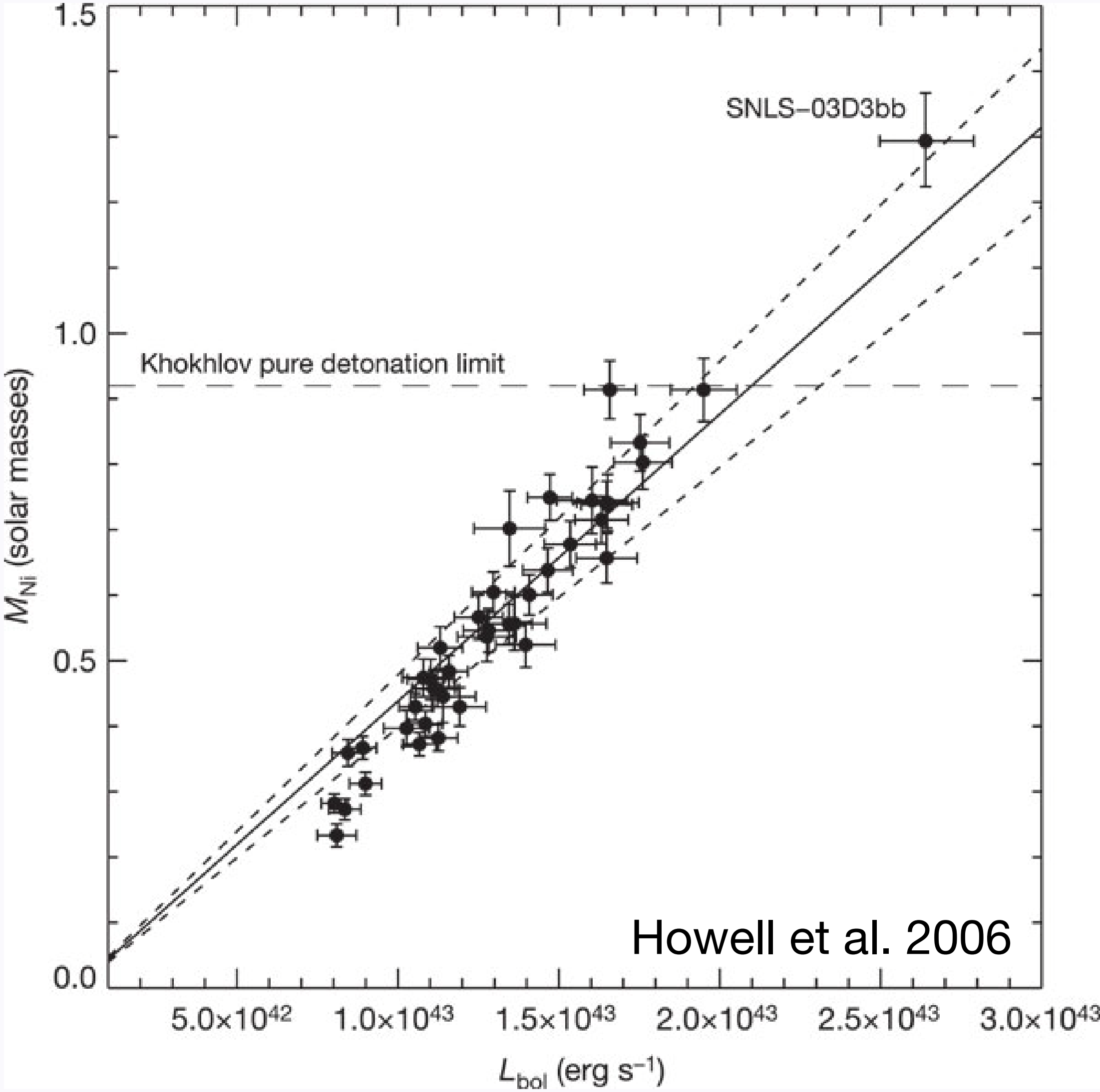
Ejecta masses

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



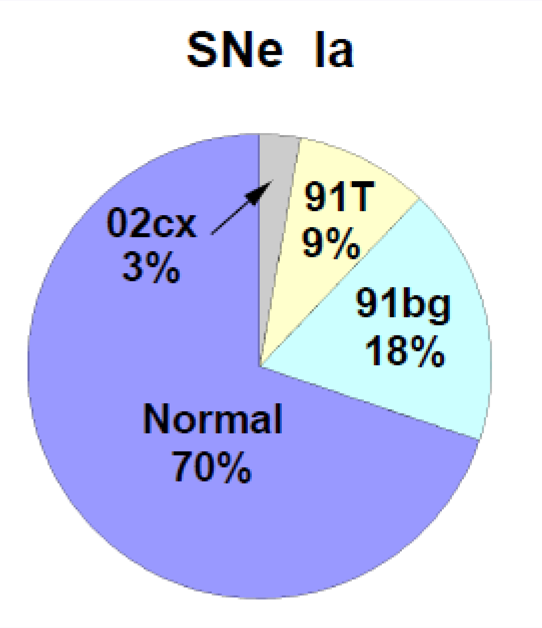
Ejecta masses

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



Type Ia Supernovae

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

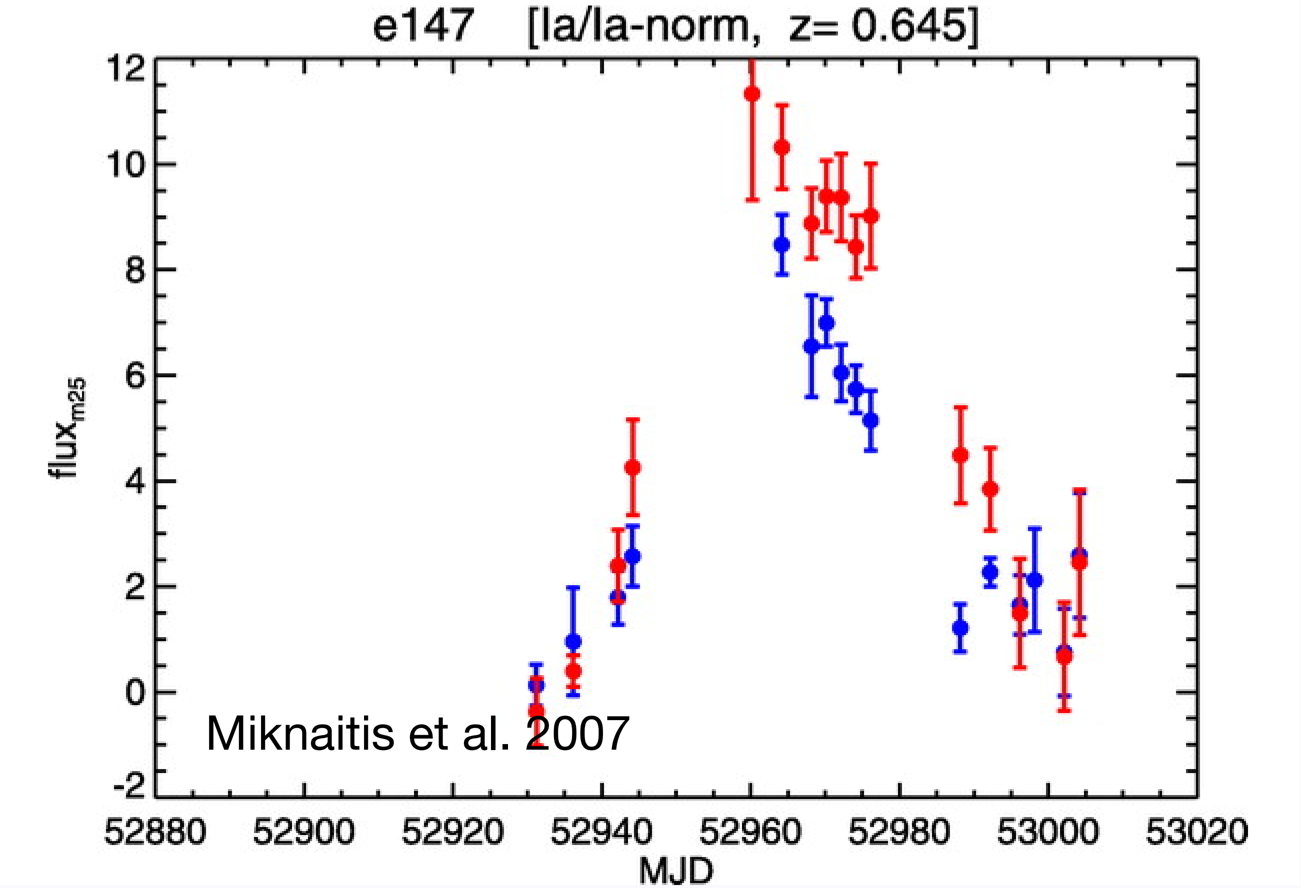


Supernova Cosmology

- Required observations
  - light curve
  - spectroscopic classification
  - redshift
- Required theory
  - cosmological model
  - (supernova explosions and light emission)
- Required phenomenology
  - calibrations (photometric systems)
  - normalisations (light curve fitters)

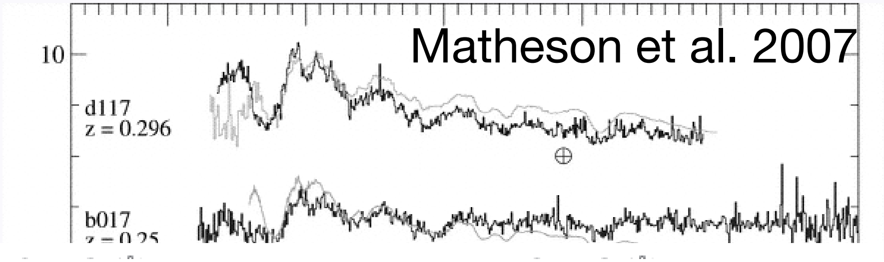
Required observations

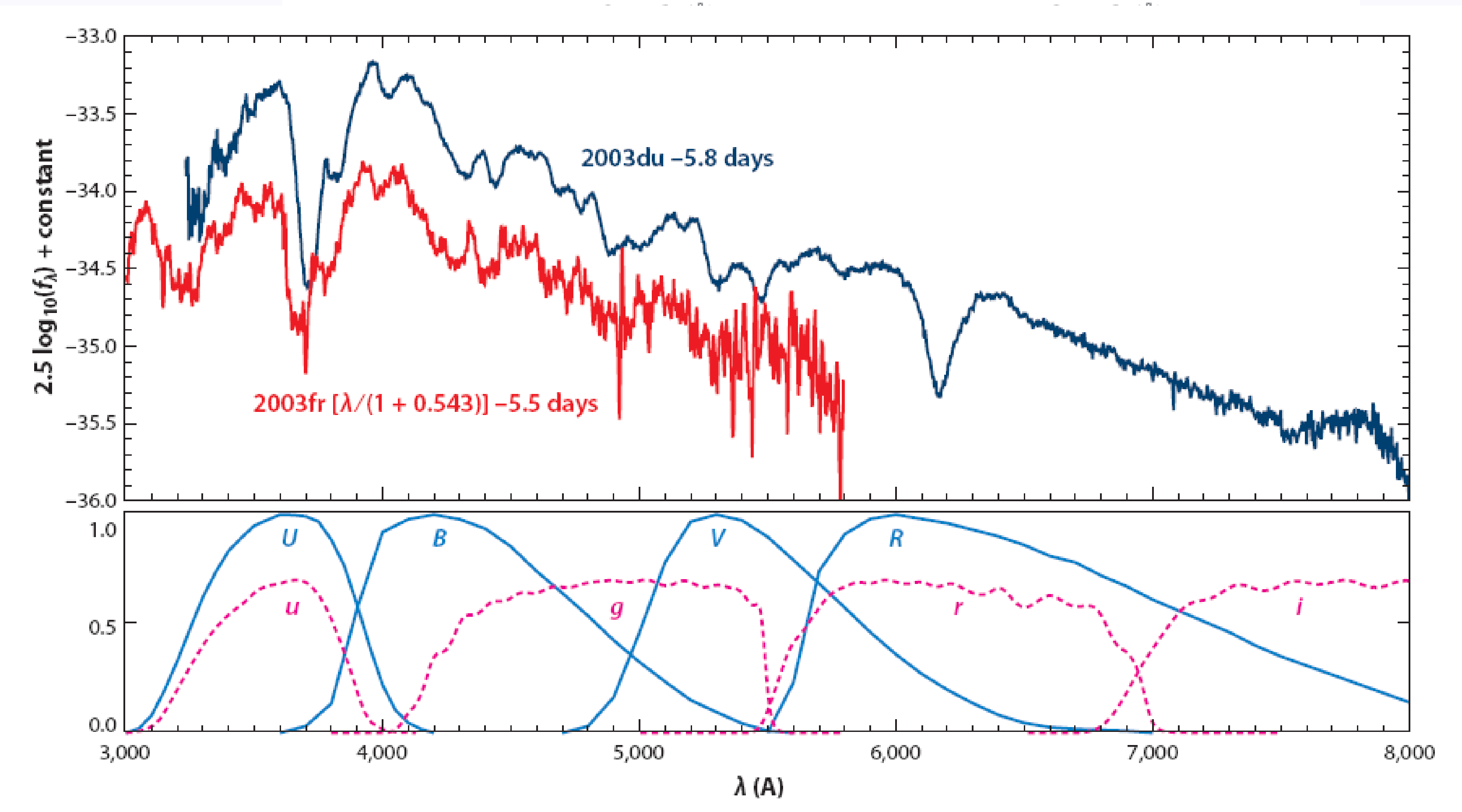
- Light curves



Required observations

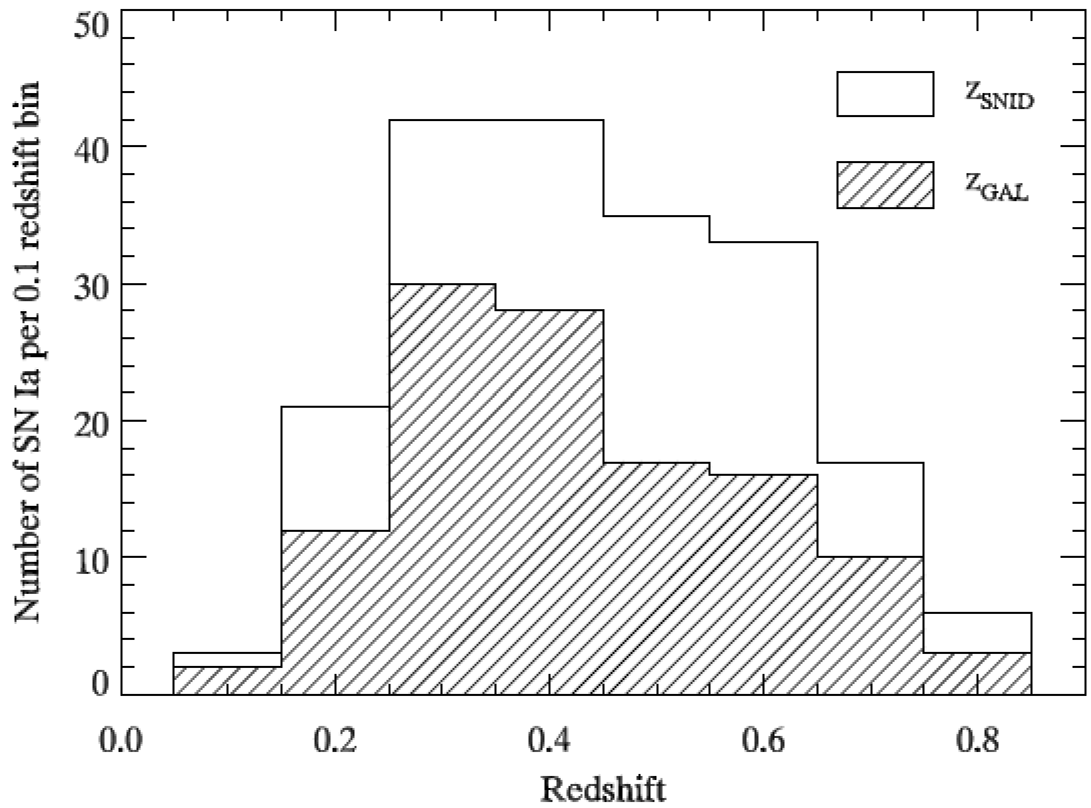
- Spectroscopic classification





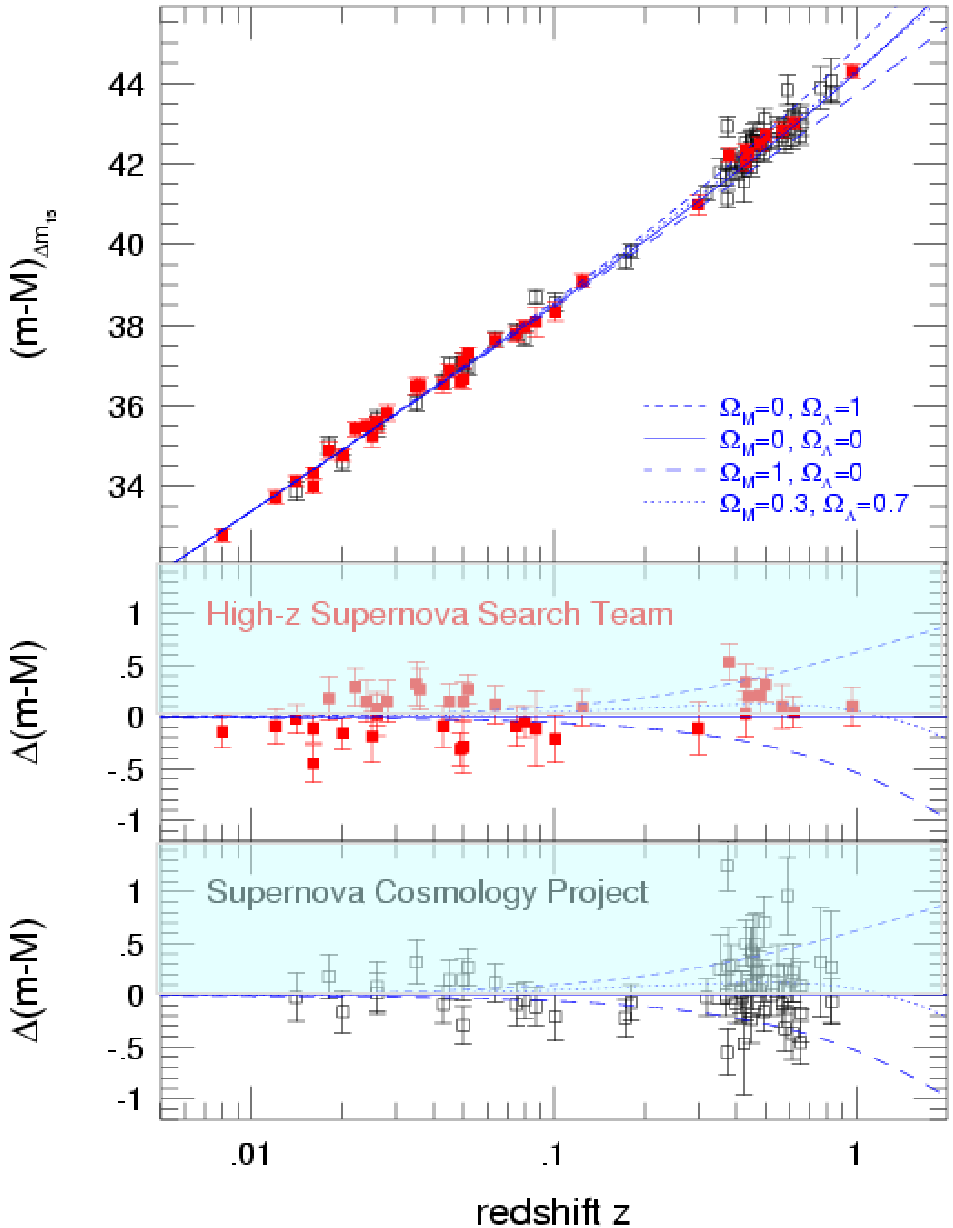
Required observations

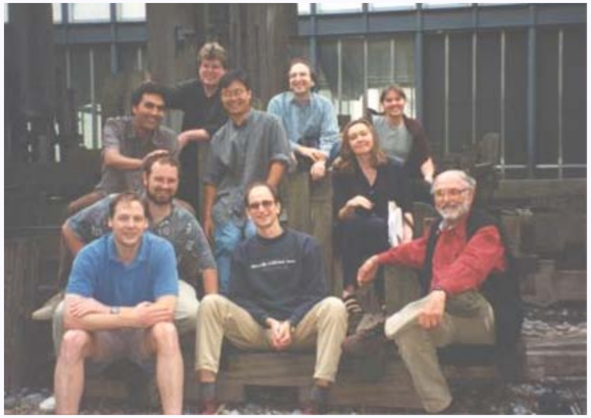
- Redshifts



Blondin et al., in prep.

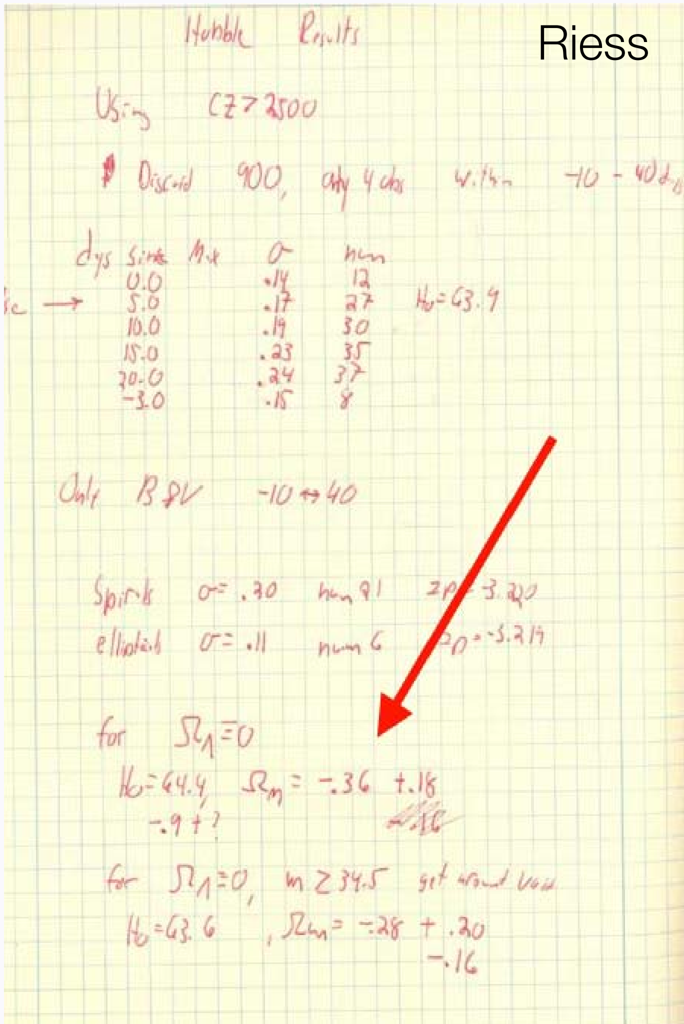
The SN Hubble Diagram

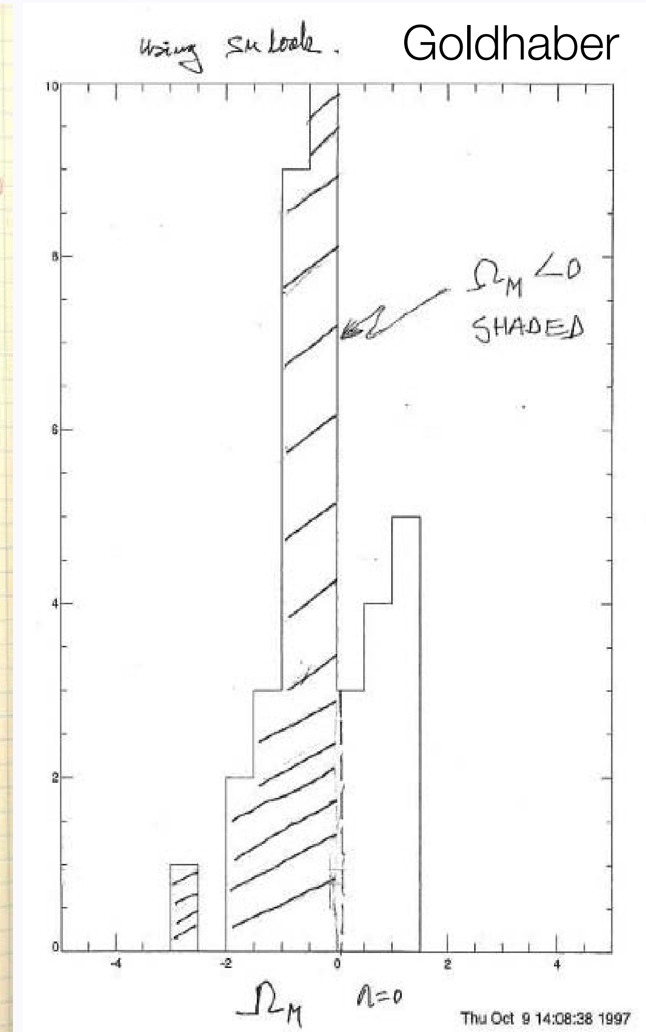




Absurd result

negative matter density

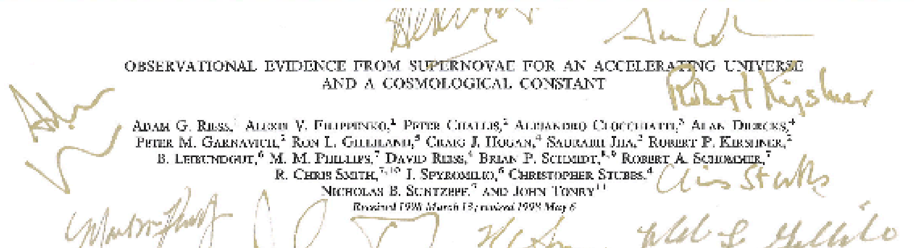




If the observational evidence upon which these claims are based are reinforced by future experiments, the implications for cosmology will be incredible.

Preprint August 1999

This is a very interesting paper that makes me very nervous. Ultimately the solution is to publish it and let the world take its shots.

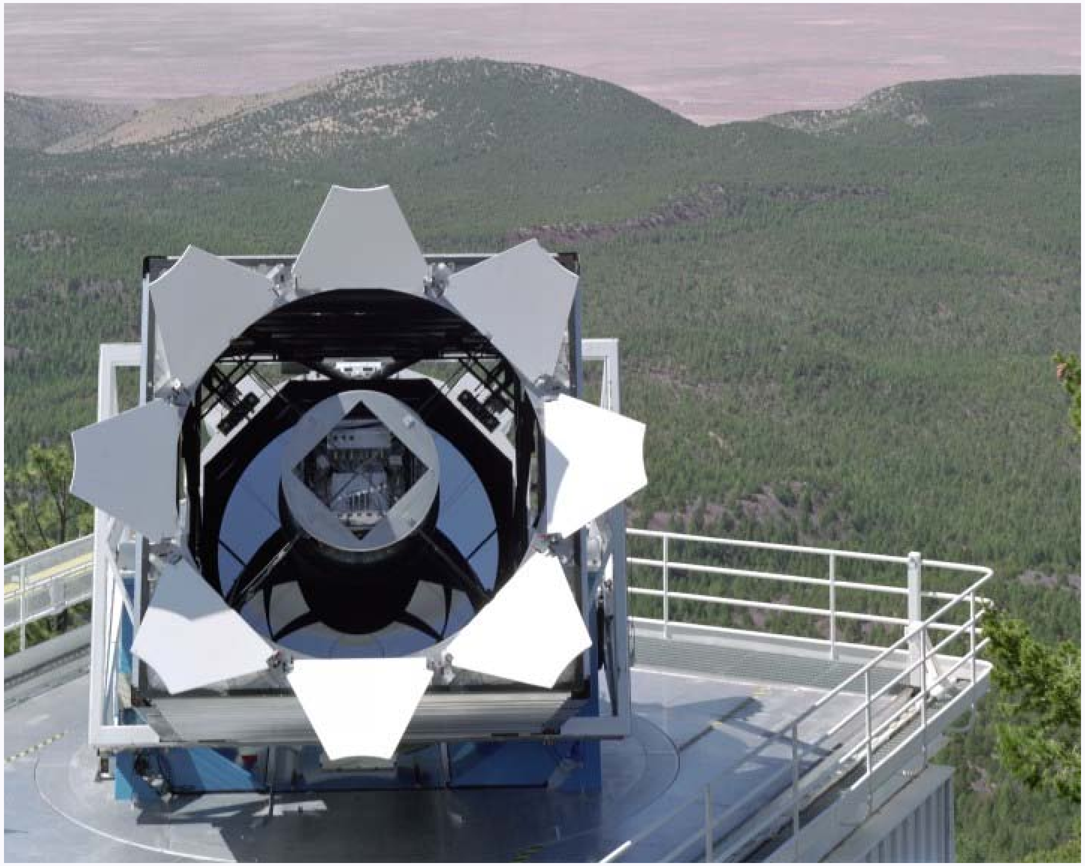

OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

Adam G. Riess,[1] Alexei V. Filippenko,[1] Peter Challis,[2] Alejandro Clocchiatti,[3] Alan Diercks,[4] Peter M. Garnavich,[2] Ron L. Gilliland,[5] Craig J. Hogan,[4] Saurabh Jha,[2] Robert P. Kirshner,[2] B. Leibundgut,[6] M. M. Phillips,[7] David Reiss,[4] Brian P. Schmidt,[8,9] Robert A. Schommer,[7] R. Chris Smith,[7,10] J. Spyromilio,[6] Christopher Stubbs,[4] Nicholas B. Suntzeff,[7] and John Tonry[11]

Received 1998 March 13; revised 1998 May 6

... and the consequences

SDSS-II Supernova Search



World-wide collaboration to find and characterise SNe Ia with $0.04 < z < 0.4$

Search with Sloan 2.5m telescope

Spectroscopy with HET, ARC, Subaru, MDM, WHT, Keck, NTT

Goal: Measure distances to 500 SNe Ia to bridge the intermediate redshift gap

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

SNLS – The SuperNova Legacy Survey

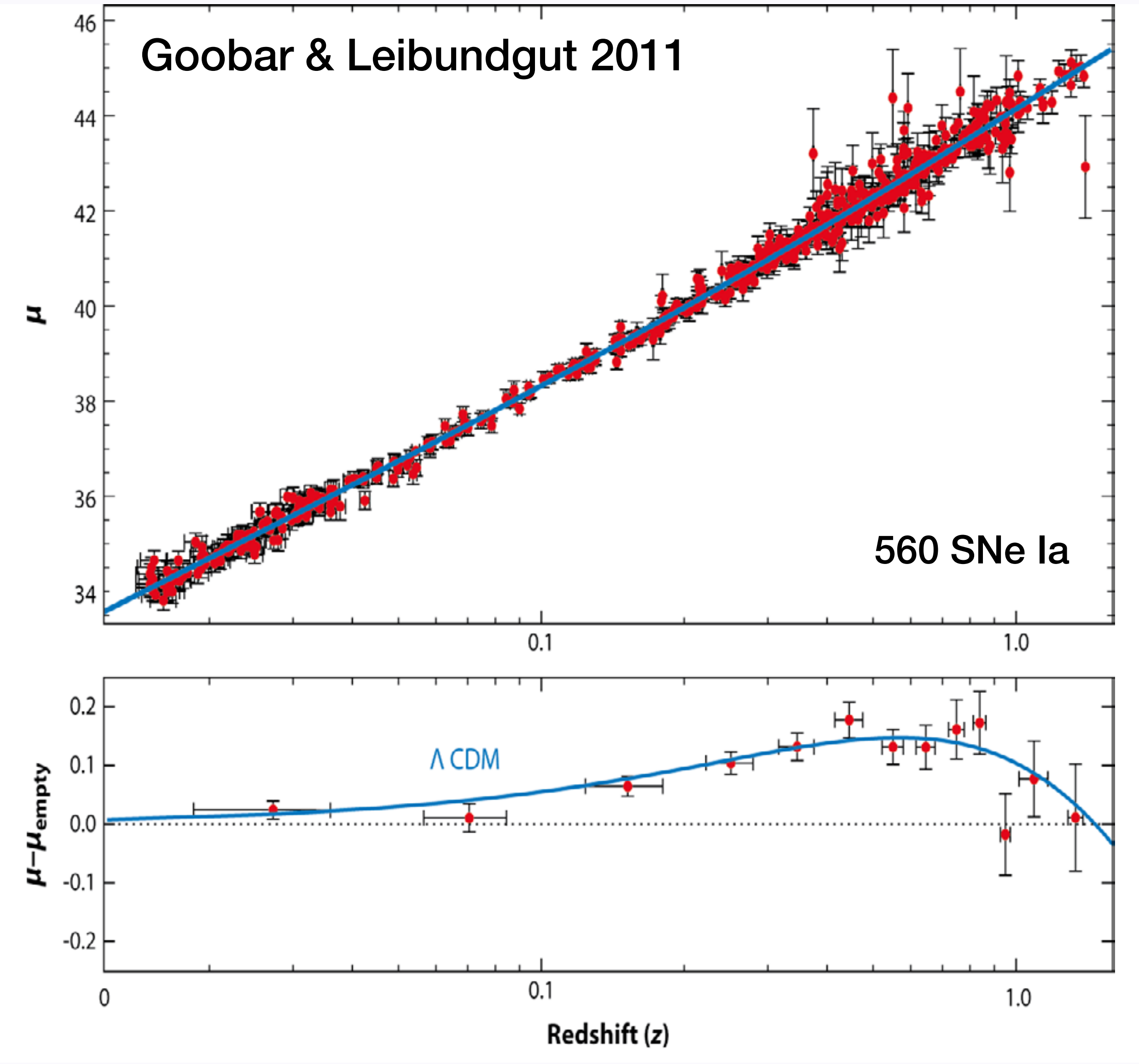
World-wide collaboration to find and characterise SNe Ia with $0.2 < z < 0.8$

Search with CFHT 4m telescope

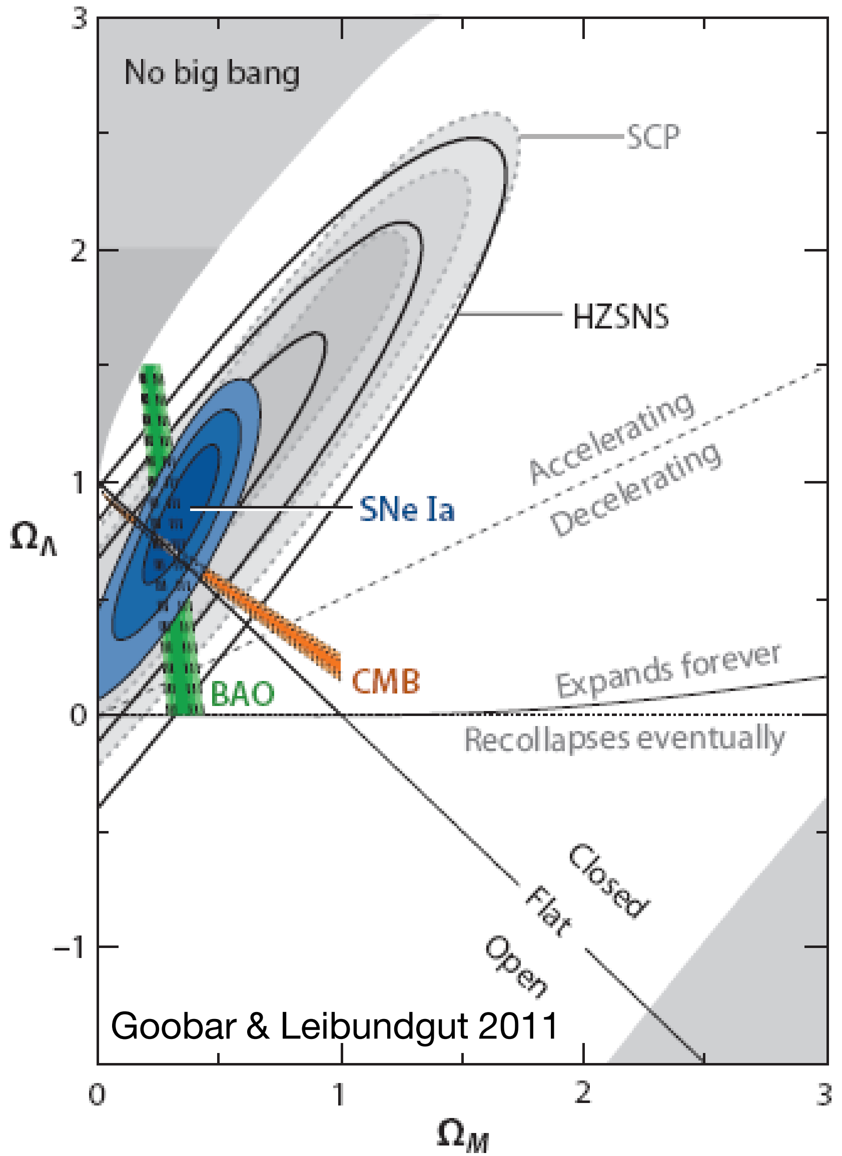
Spectroscopy with VLT, Gemini, Keck, Magellan

Goal: Measure distances to 700 SNe Ia with an overall accuracy of 5%
→ determine ω to 7% overall

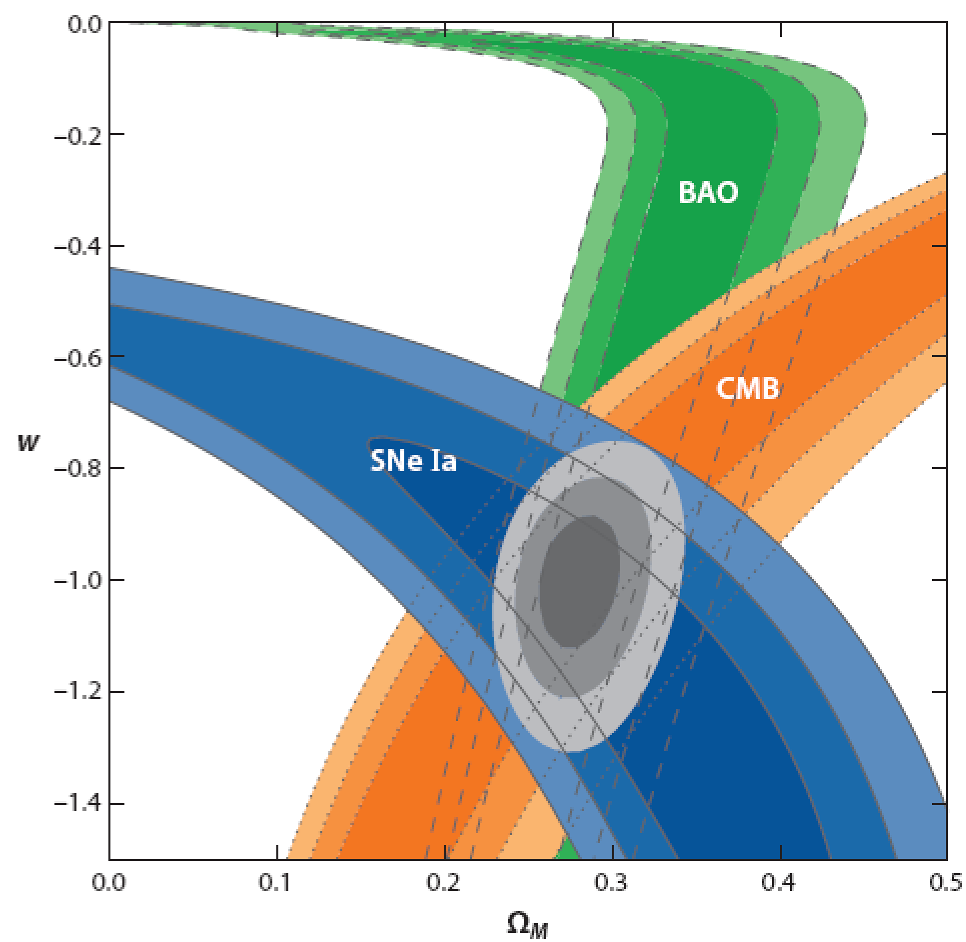
Supernova Cosmology 2011



et voilà ...



10 years of progress



Supernova cosmology

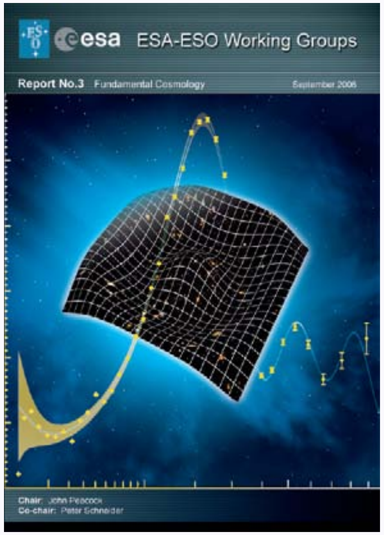
- ω firmly established
  - general agreement between different experiments

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

Systematics table

Wood-Vasey et al. 2007

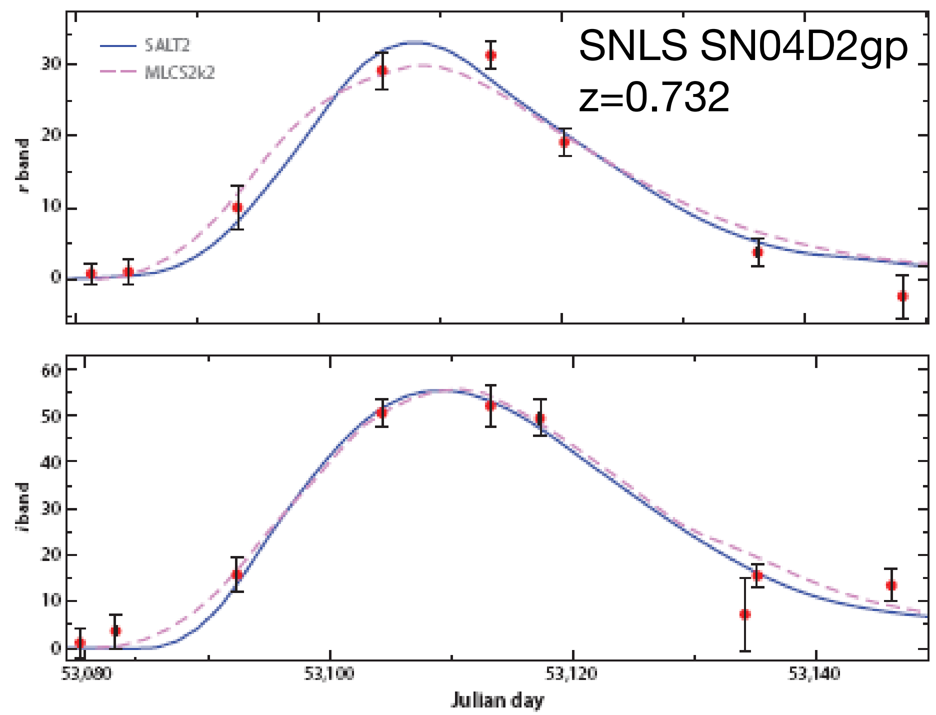
Table 5. Potential Sources of Systematic Error on the Measurement of w

Source	dw/dx	Δx	Δ_w	Notes
Phot. errors from astrometric uncertainties of faint objects	1/mag	0.005 mag	0.005	
Bias in differential image photometry	0.5 / mag	0.002 mag	0.001	
CCD linearity	1 / mag	0.005 mag	0.005	
Photometric zeropoint differences in R, I	2 / mag	0.02 mag	0.04	
Zeropoint offset between low and high z	1 / mag	0.02 mag	0.02	
K-corrections	0.5 / mag	0.01 mag	0.005	
Filter passband structure	0 / mag	0.001 mag	0	
Galactic extinction	1 / mag	0.01 mag	0.01	
Host-galaxy R_V	0.02 / R_V	0.5	0.01	"glosz"
Host-galaxy extinction treatment	0.08	prior choice	0.08	different priors
Intrinsic color of SNe Ia	3 / mag	0.02 mag	0.06	interacts strongly with prior
Malmquist bias/selection effects	0.7 / mag	0.03 mag	0.02	"glosz"
SN Ia evolution	1 / mag	0.02 mag	0.02	
Hubble bubble	$3/\delta H_{\mathrm{effective}}$	0.02	0.06	
Gravitational lensing	$1/\sqrt{N}$ / mag	0.01 mag	< 0.001	Holz & Linder (2005)
Grey dust	1 / mag	0.01 mag	0.01	
Subtotal w/o extinction+color	···	···	0.082	
Total	···	···	0.13	
Joint ESSENCE+SNLS comparison	···	···	0.02	photometric system
Joint ESSENCE + SNLS total	···	···	0.13	

Required phenomenology

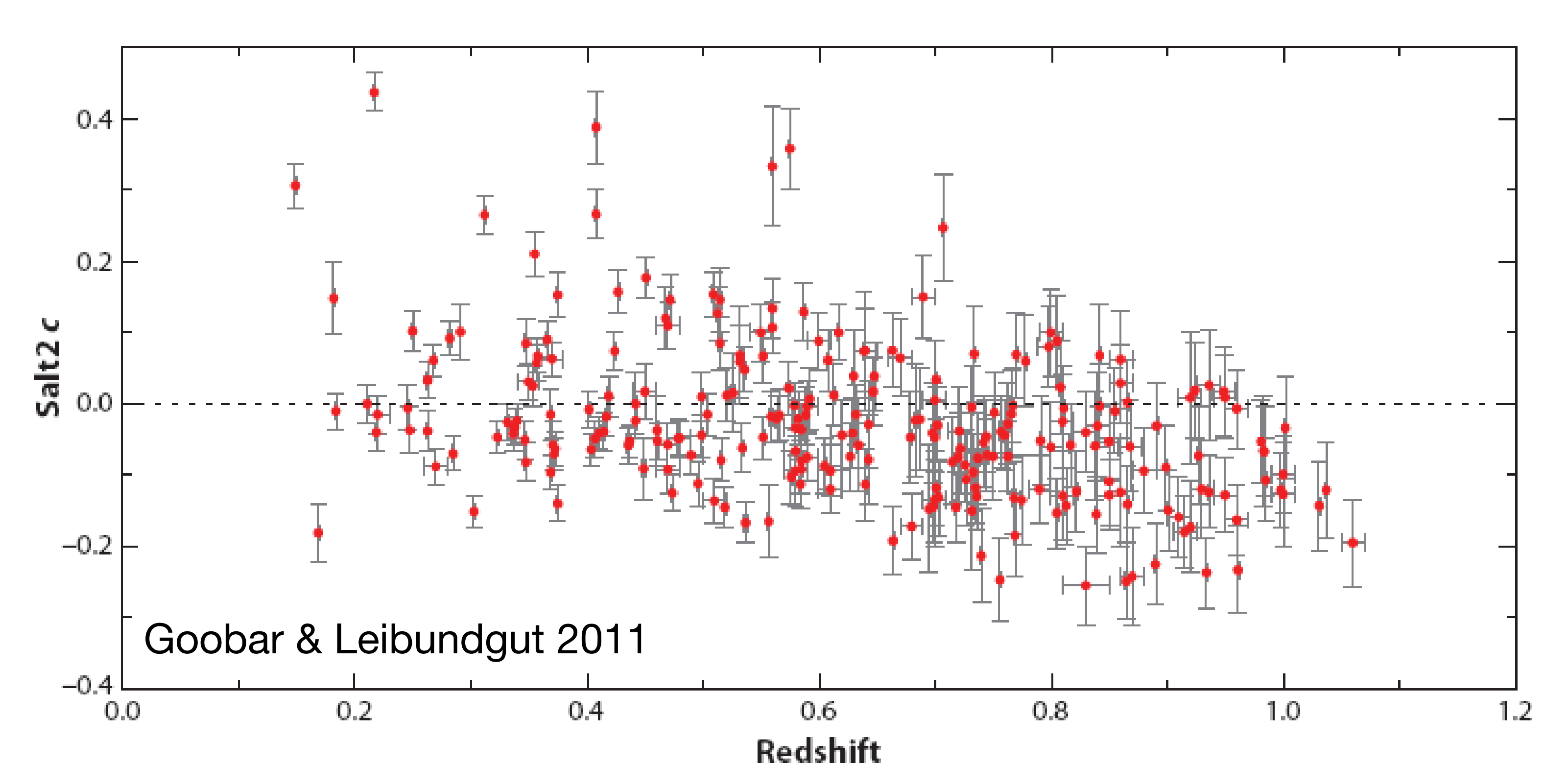
- photometric calibration
- normalisation
  - (“standardizable candle”; “standard crayon”)
  - different light curve fitters
    - Δm_{15},SALT, SiFTO, MLCS

Goobar & Leibundgut 2011



Required phenomenology

- Checks
  - – selection effects? evolution?

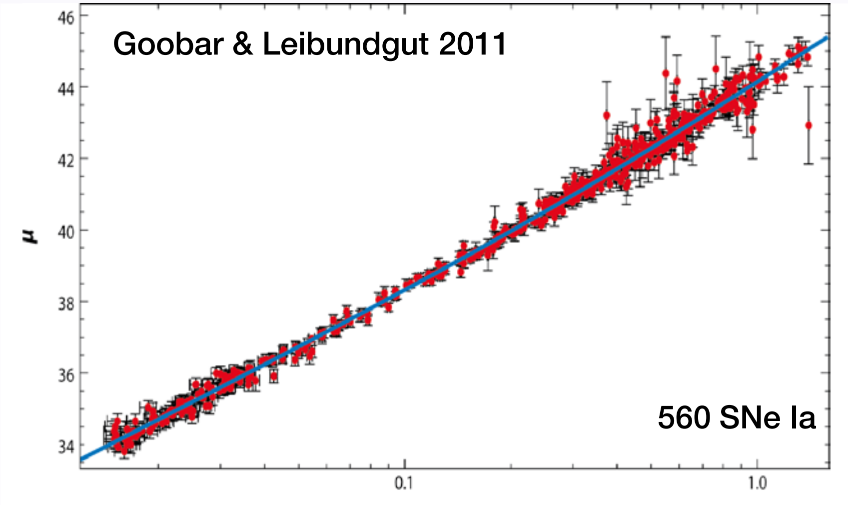


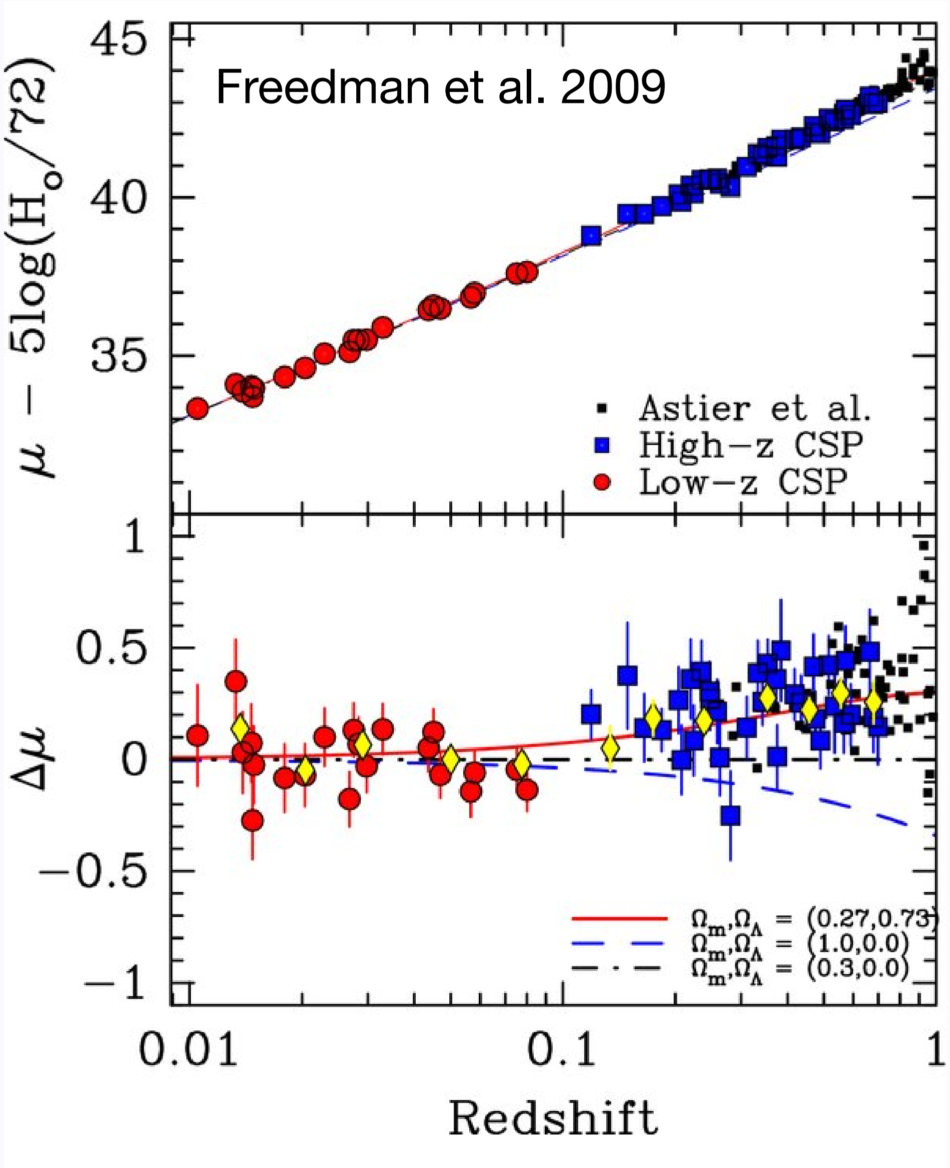
What next?

- 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
  - I-band Hubble diagram
    - Freedman et al.
    - Nobili et al.

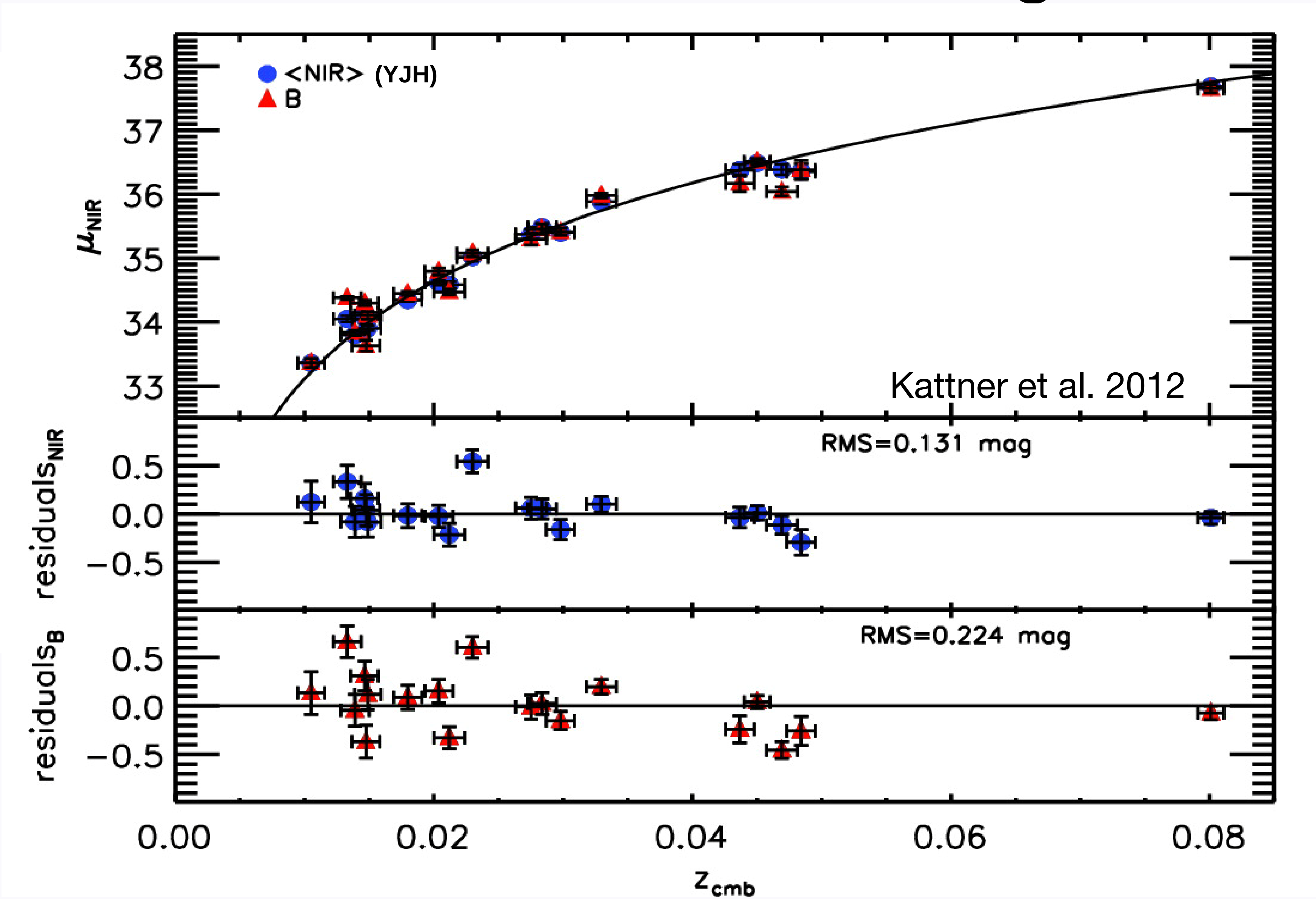
I-band Hubble diagram

- Currently only 35 SNe Ia





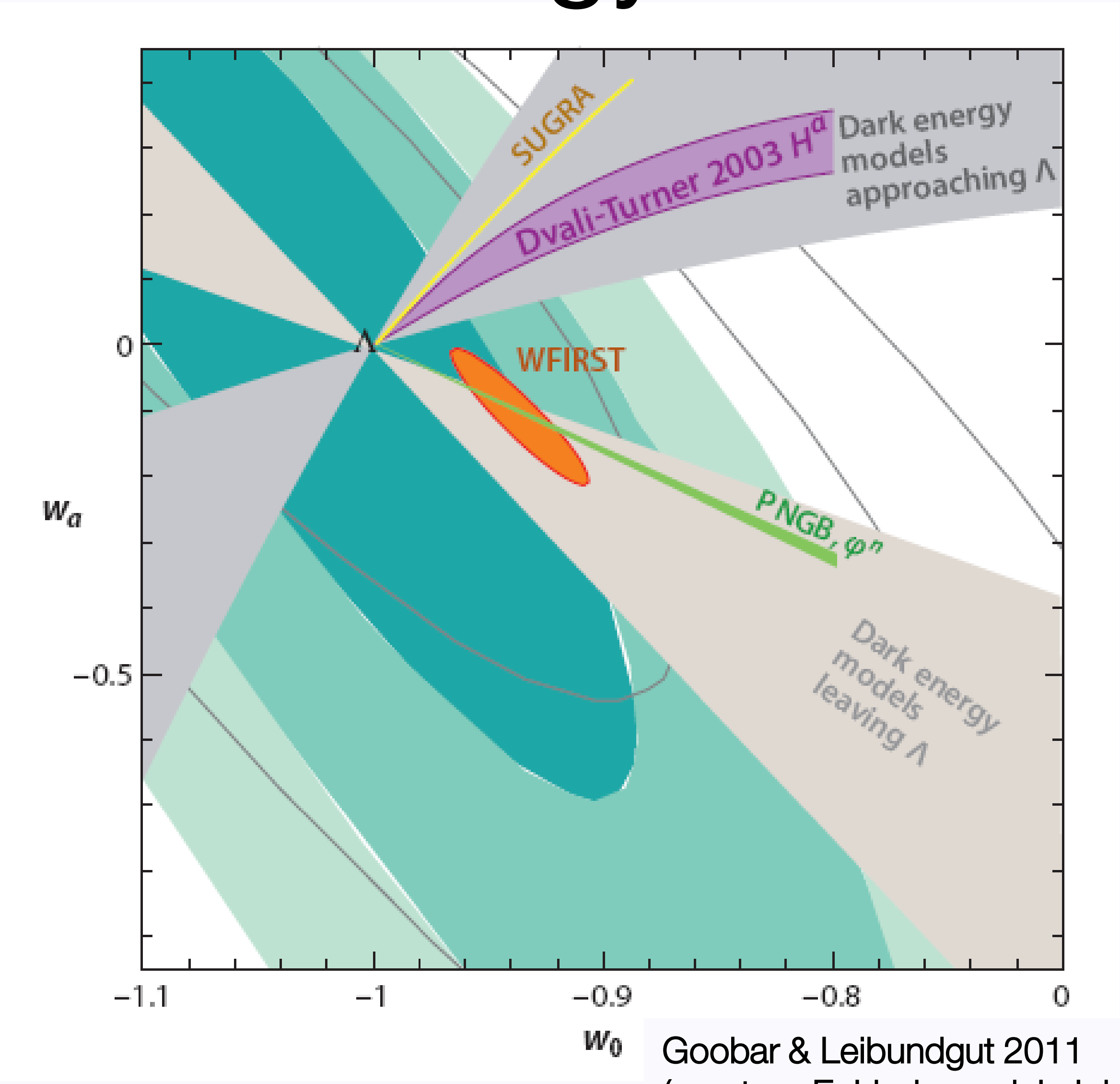
J- and H-band Hubble diagrams



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) → 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 $z \approx 2$

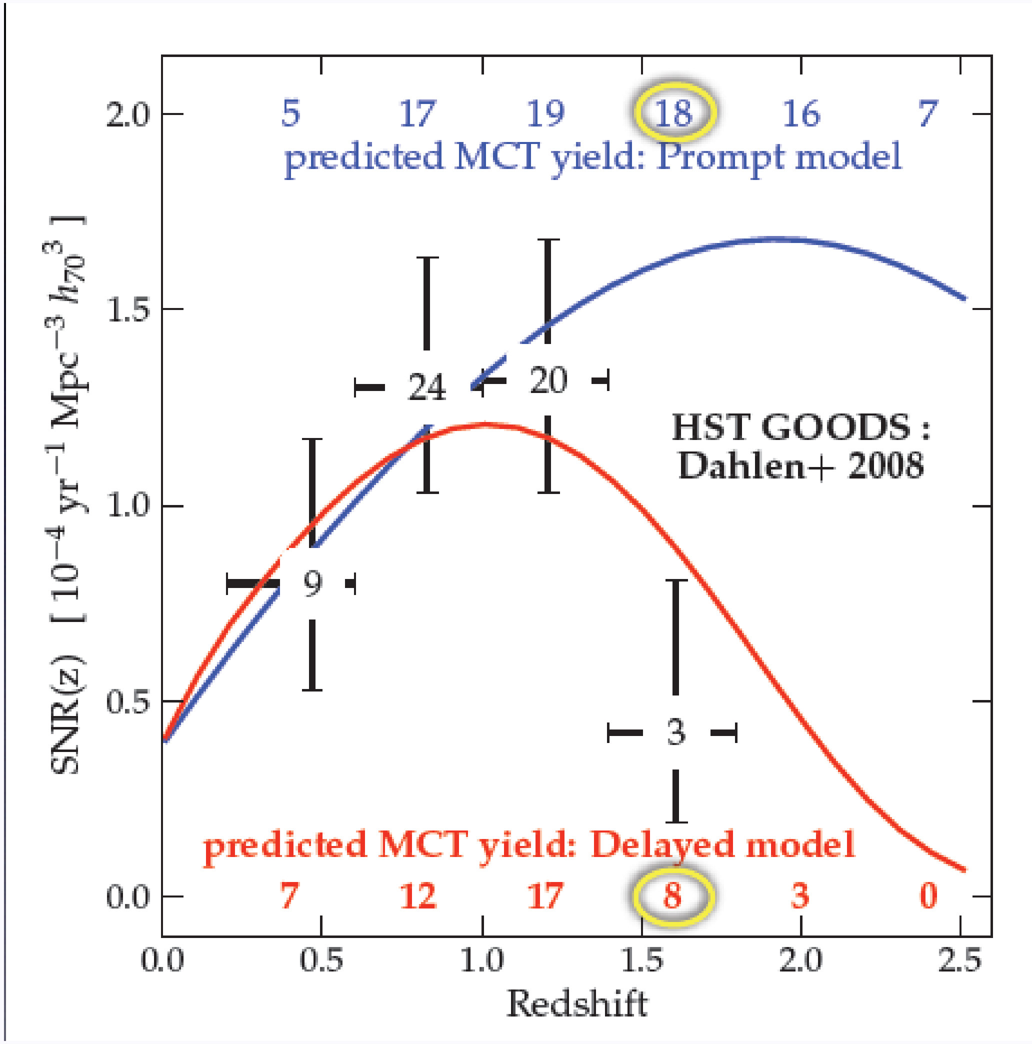
Determine the SN rate at $z>1$ and constrain the progenitor systems

SNe Ia at high redshifts (z>1.5)

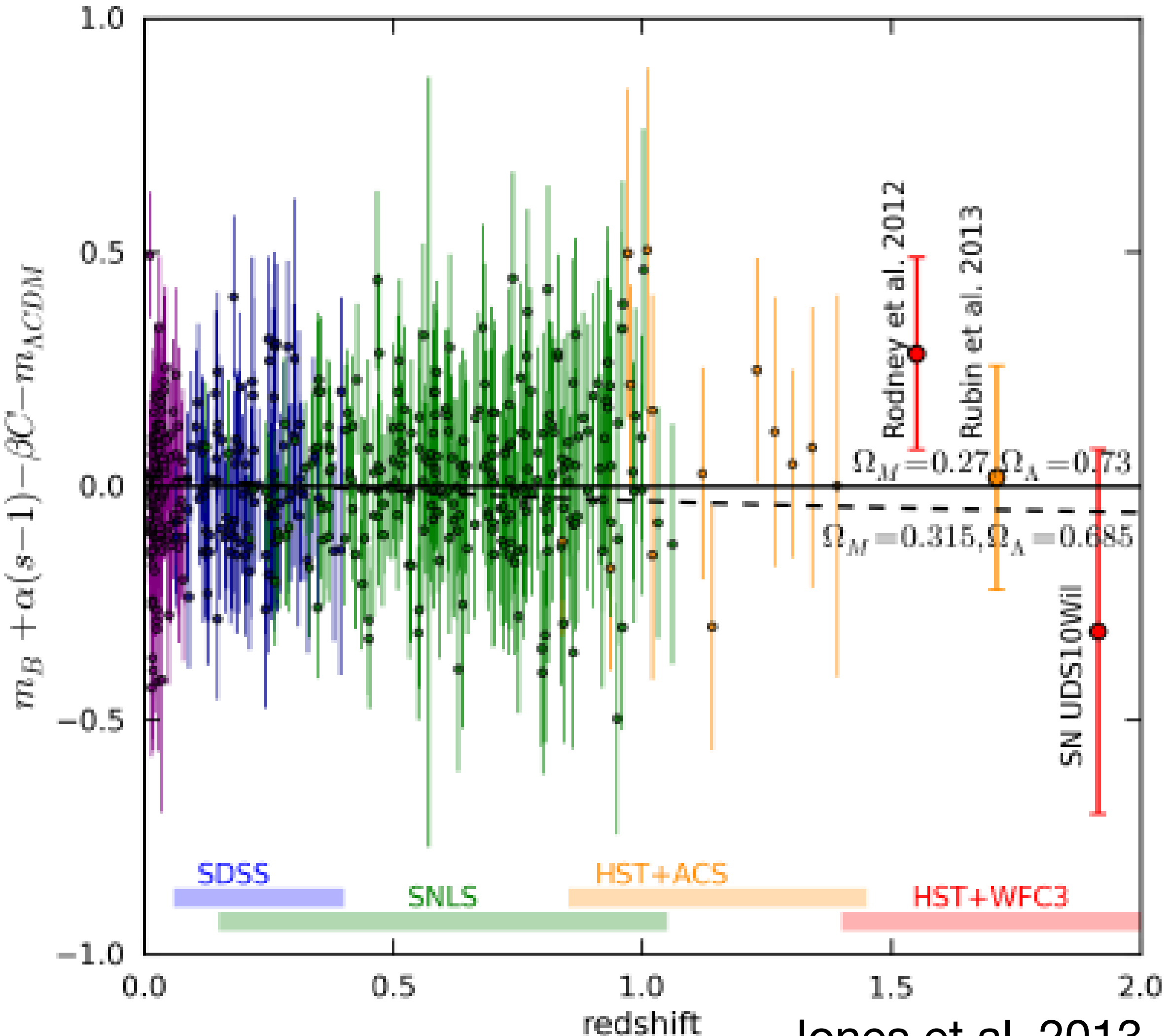
- ratio $(\Omega_{DE}/\Omega_M)_0$=2.7; $(\Omega_{DE}/\Omega_M)_{z=1.5}$=0.173 with w_0=-1±0.2 and w_a=-1±1; $w=w_0+w_a(1-a)$
- within these uncertainties the observed magnitudes change less than 0.1m
  - direct test for evolution!
- at z>1.5 age of the universe is <4Gyr
  - low-mass stars are still on the main sequence
  - SN Ia progenitors from more massive progenitor stars
  - constrain progenitor models of SNe Ia

SN rates and what they can tell us

Steve Rodney; MCT SN Survey

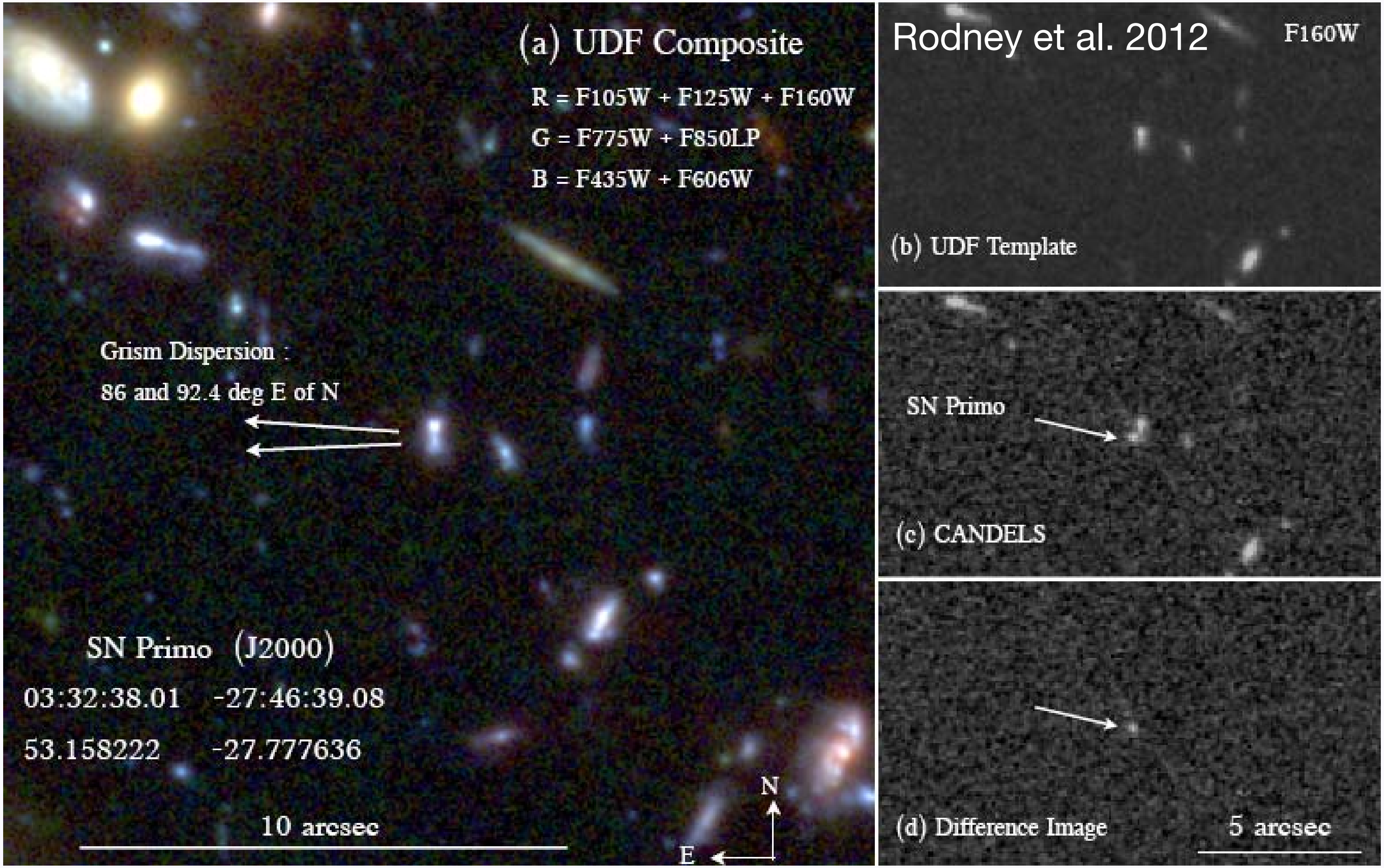


SNe at z>1



Jones et al. 2013

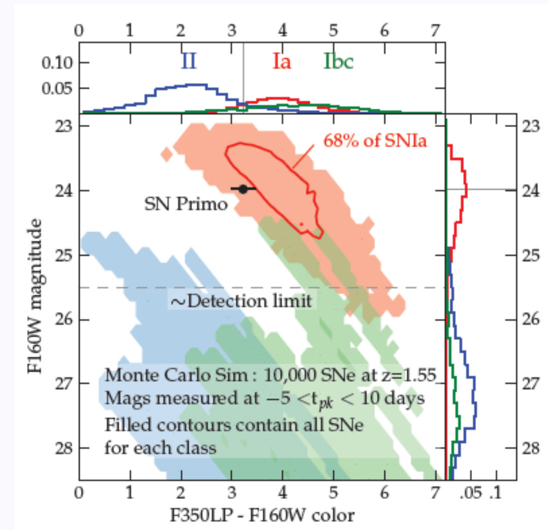
Discovery

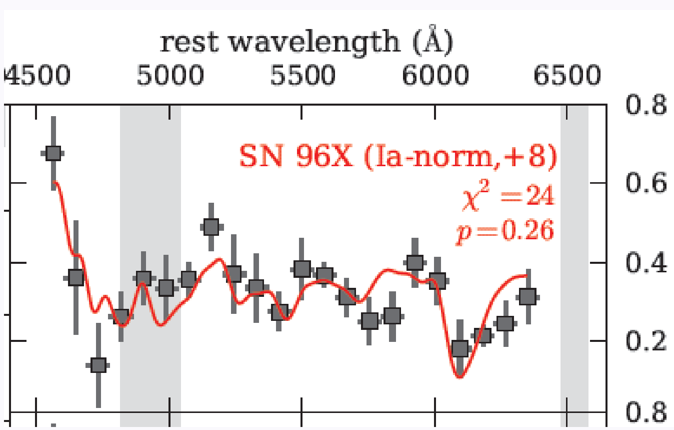


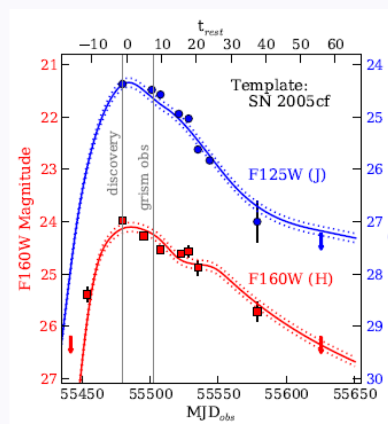
(a) UDF Composite
R = F105W + F125W + F160W
G = F775W + F850LP
B = F435W + F606W
Grism Dispersion :
86 and 92.4 deg E of N
SN Primo (J2000)
03:32:38.01 -27:46:39.08
53.158222 -27.777636
10 arcsec
N
E
Rodney et al. 2012
F160W
(b) UDF Template
SN Primo
(c) CANDELS
(d) Difference Image
5 arcsec

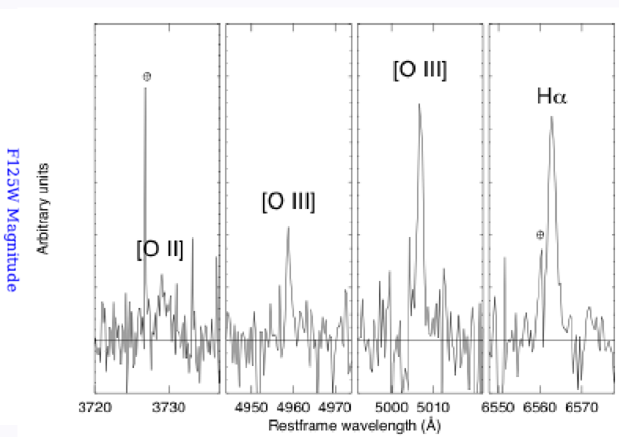
4 arguments for a SN Ia @ z=1.55

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



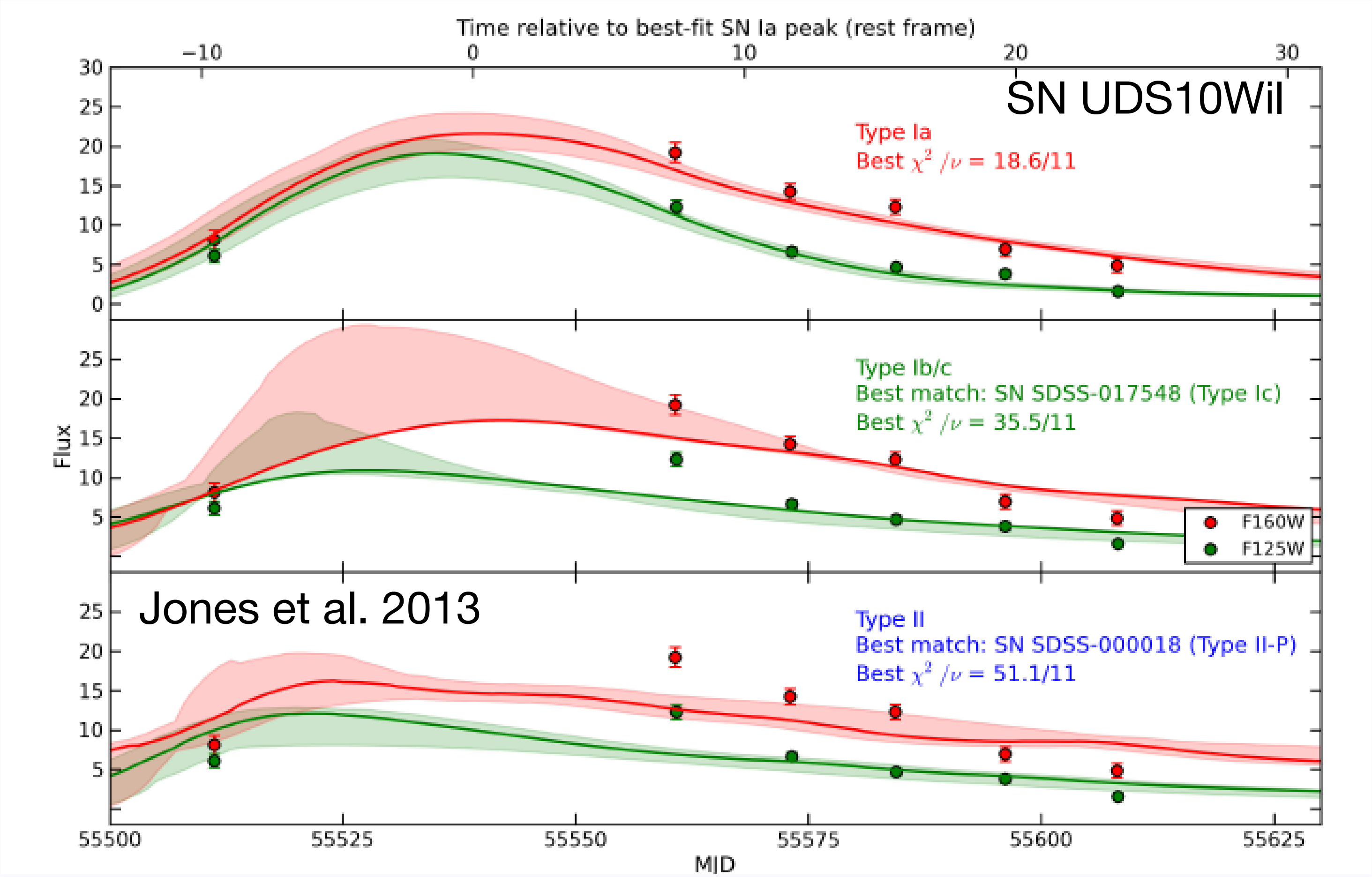




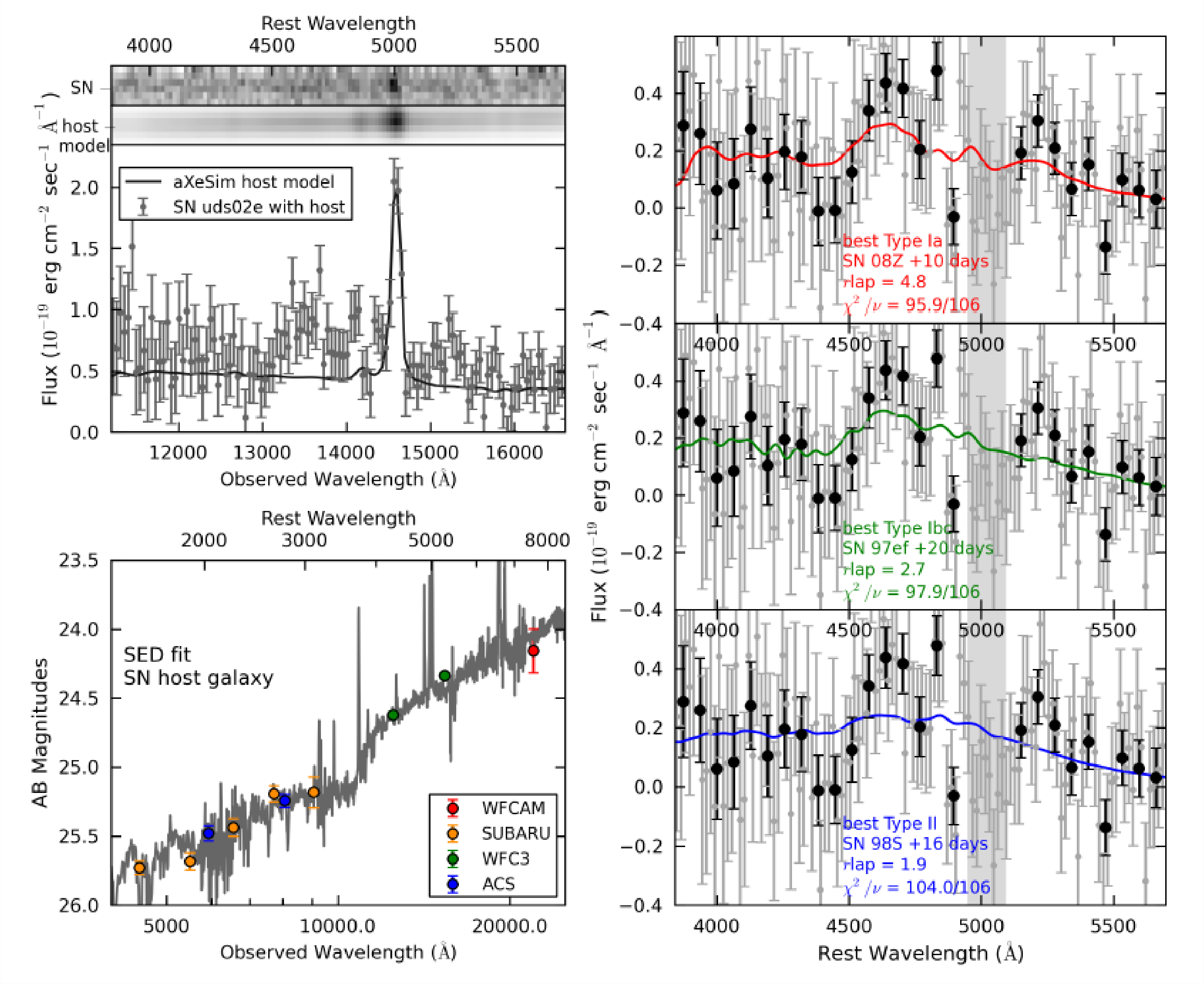


SNe Ia at z>1

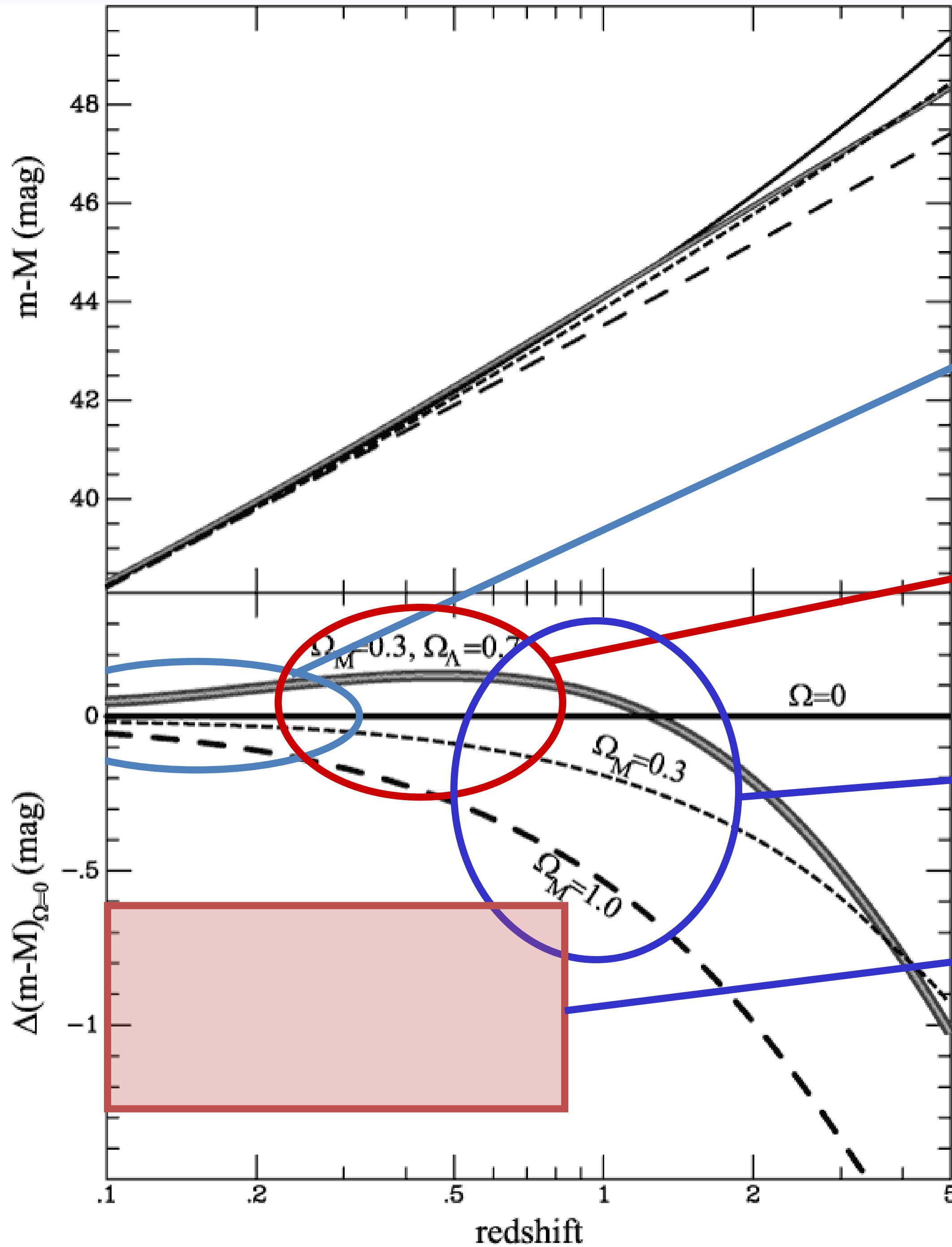
- SN Ia at z=1.91



SN UDS10Wil at z=1.91



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

Tasks for the coming years

- Concentrate on wavelengths 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 → public spectroscopic survey
    - Dark Energy Survey?, Large Synoptic Survey Telescope?, Euclid follow-up?