

# Supernova Cosmology

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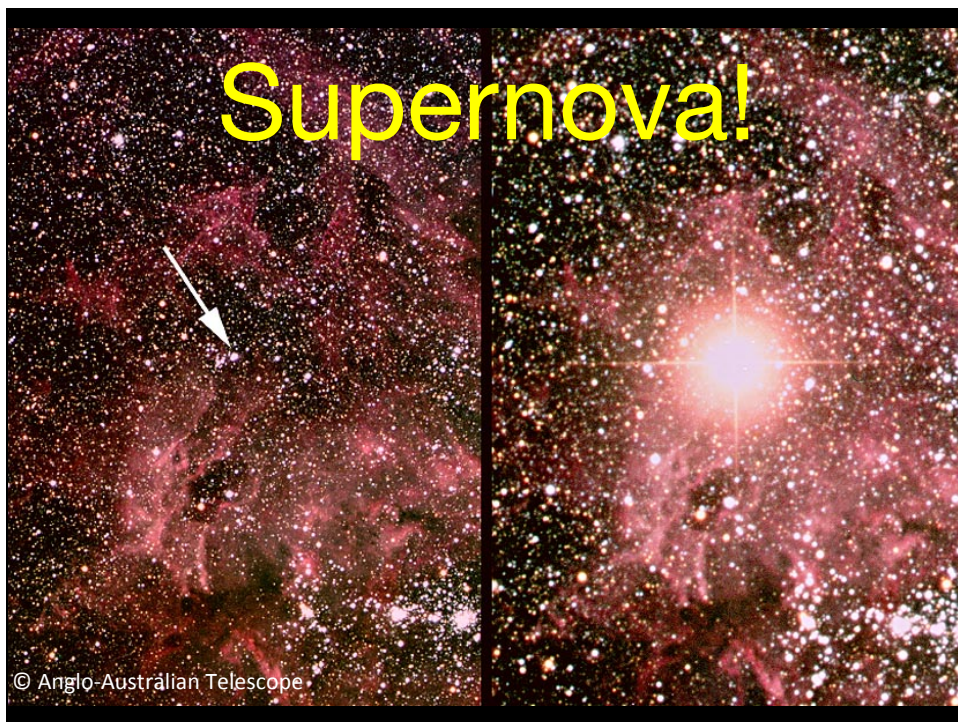


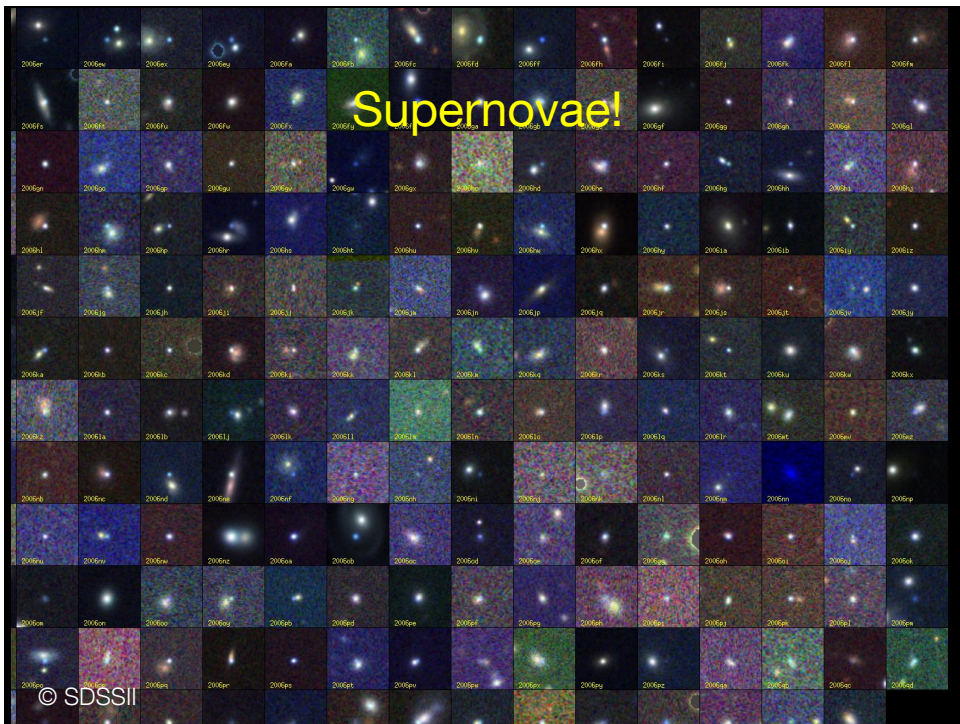
## Take away messages

- Supernovae are complicated astrophysical objects
  - explosions!
  - old stars, i.e. end of stellar evolution
  - this also applies to Type Ia supernovae
- The universe experiences accelerated expansion
  - measured through cosmological distances by Type Ia Supernovae
    - SNe Ia can be used to determine accurate distances

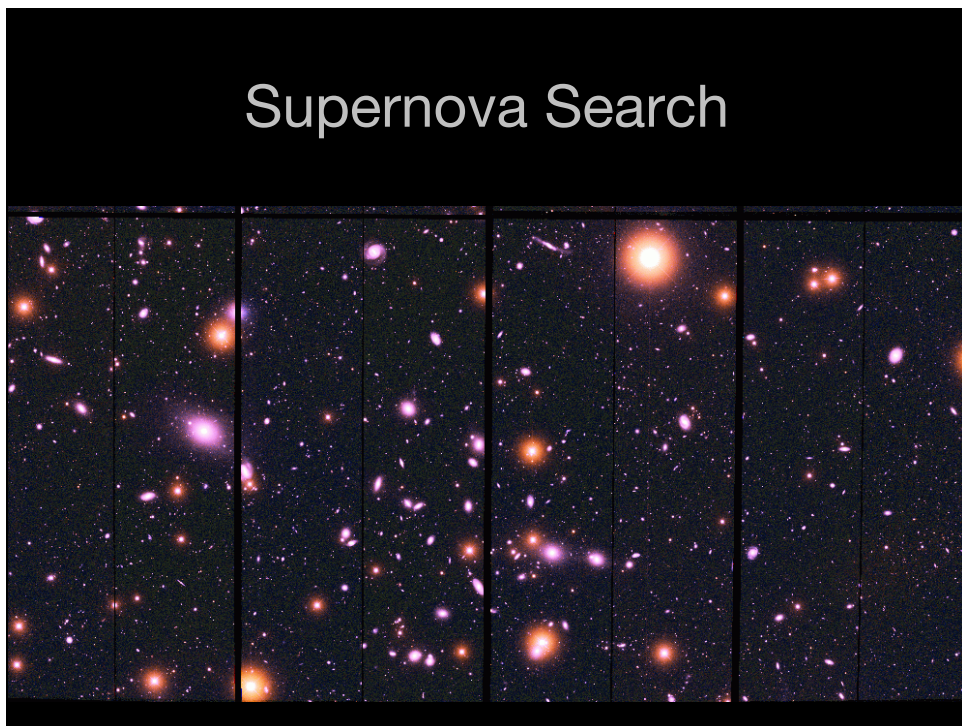
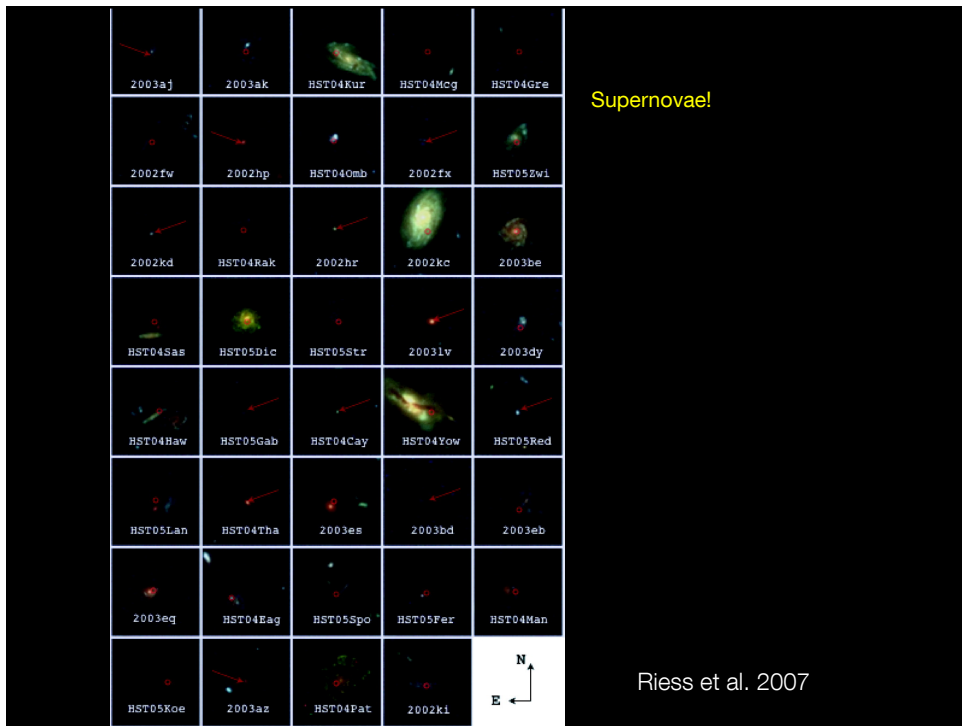
## Presentation in two parts

1. Physics of (Type Ia) supernovae
  - latest results on evolutionary path towards supernovae
  - explosion physics
2. Cosmology with Type Ia supernovae
  - SNe Ia as distance indicators
  - cosmological consequences
    - accelerated expansion

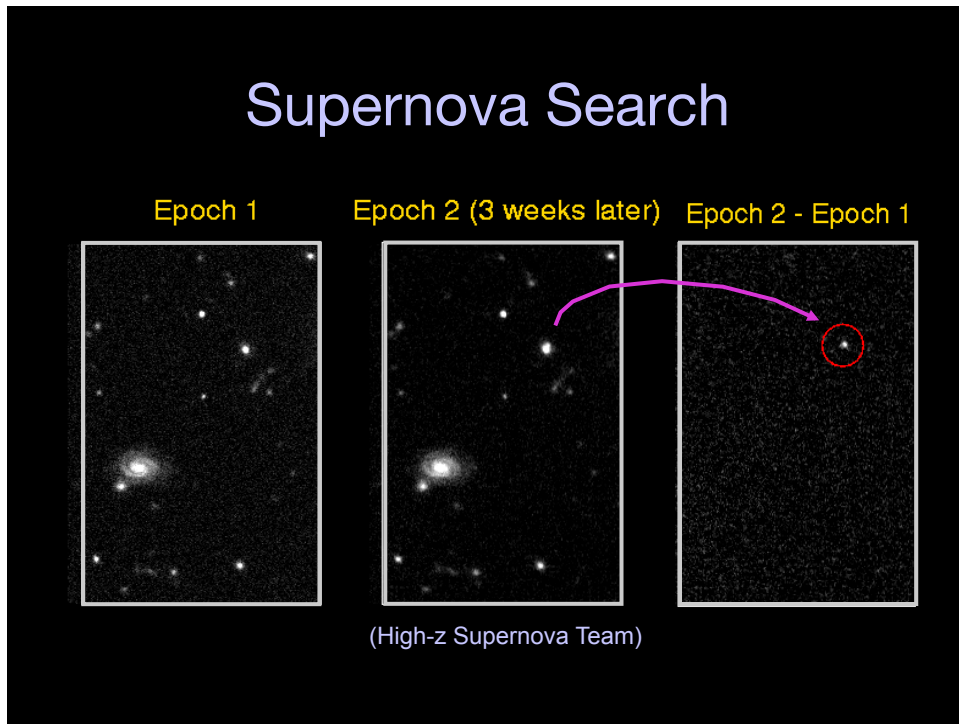












## Supernova classification

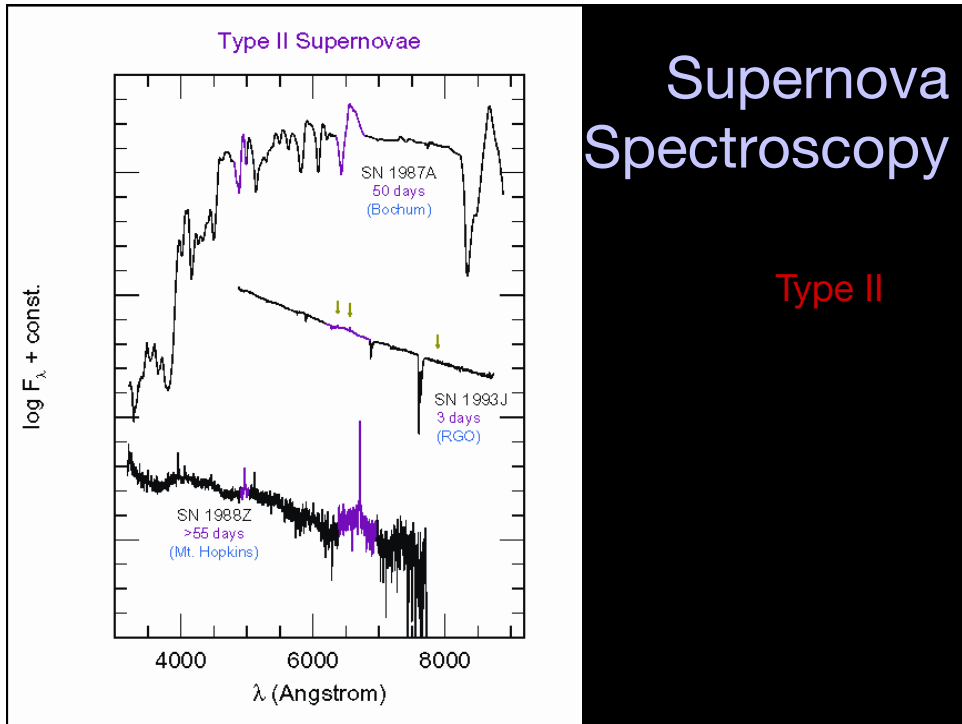
Based on spectroscopy

core collapse  
in massive stars

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

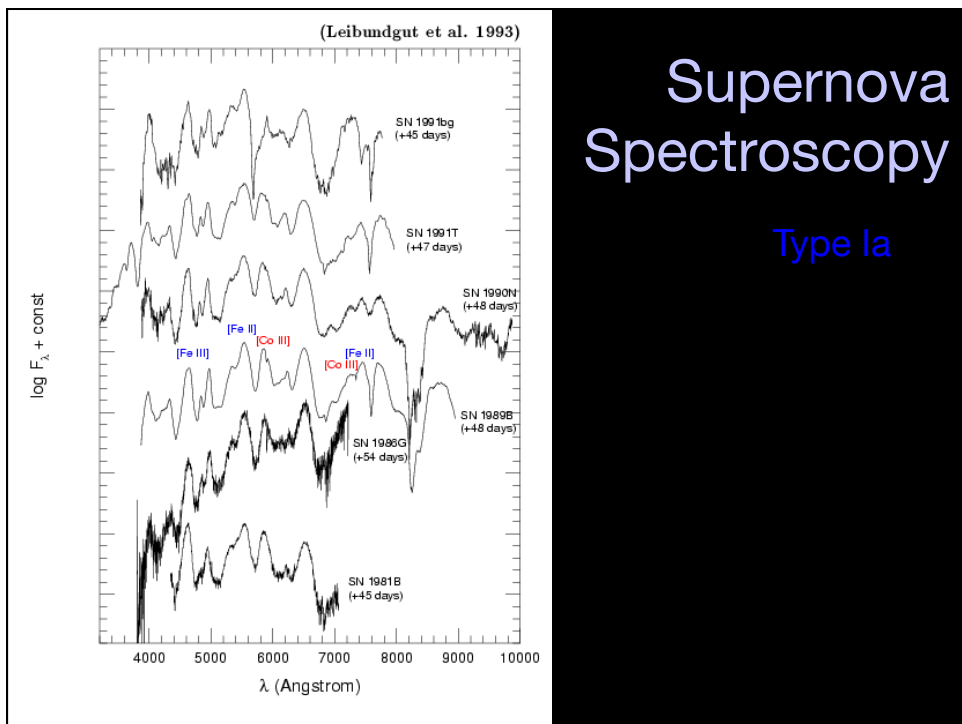
SN Ia (no H)

thermonuclear  
explosions



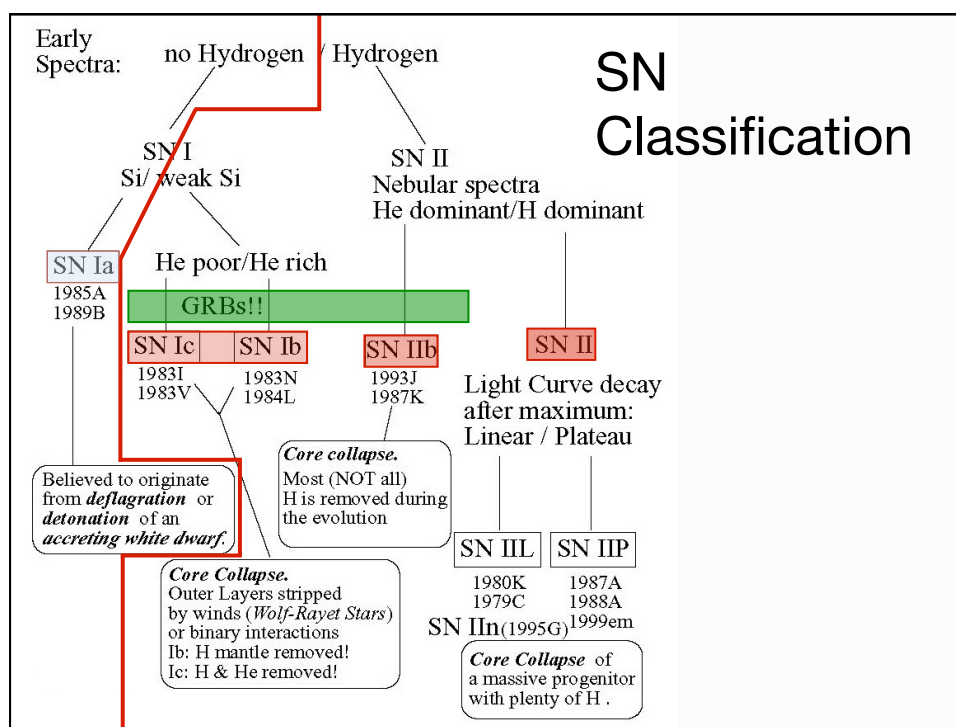
# Supernova Spectroscopy

Type II



# Supernova Spectroscopy

Type Ia



## 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 is left behind?**
  - remnants
  - compact remnants
  - chemical enrichment
- **Other uses of the explosions**
  - light beacons
  - distance indicators
  - chemical factories



## Supernova Types

### Thermonuclear SNe

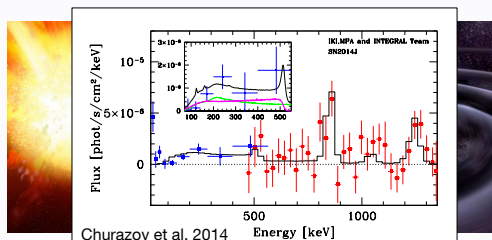
- Progenitor stars have small mass ( $<8M_{\odot}$ )
- highly developed stars (white dwarfs)
- Explosive C and O burning
- Binary star systems
- Complete destruction

### 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

## What do we **know** about Type Ia supernovae?

- **What explodes?**
  - progenitors, evolution towards explosion
    - white dwarfs, several channels
- **How does it explode?**
  - explosion mechanisms
    - thermonuclear explosions
    - several channels
      - deflagrations
      - detonations
      - delayed detonations
      - He detonations
      - mergers
- **What is left behind?**
  - remnants
    - Tycho, SN 1006, LMC
  - compact remnants
    - none, companion (?)
  - chemical enrichment
    - Fe group elements



## What do we **know** about Type Ia supernovae?

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

## Possible progenitors

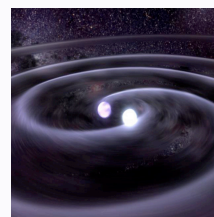
### Single Degenerate

- ‘life’ star
  - young systems ( $>10^8$  yr)
- ‘long’ mass transfer
- ‘messy’ environment
  - expect hydrogen, helium, oxygen, dust
- companion left behind



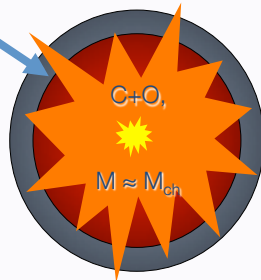
### Double Degenerate

- 2 ‘dead’ stars
  - Old systems ( $>10^9$  yr)
- mergers
- ‘clean’ environment
- no companion remnant



## The “standard model”

He (+H)  
from binary  
companion



Density  $\sim 10^9 - 10^{10}$  g/cm

Temperature: a few  $10^9$  K

Radii: a few 1000 km

Explosion energy:

*Fusion of*

*C+C, C+O, O+O*

*⇒ "Fe"*

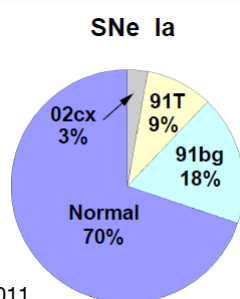
There is a lot more to this – you need to contact your explosive theory friends

## Type Ia Supernovae

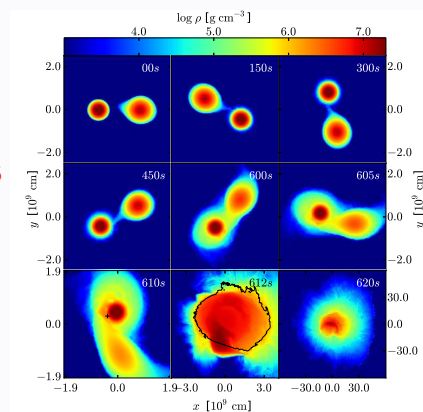
Complicated story

- observational diversity
- many models

→ need more constraints



Wang et al. 2011



Pakmor et al. 2012

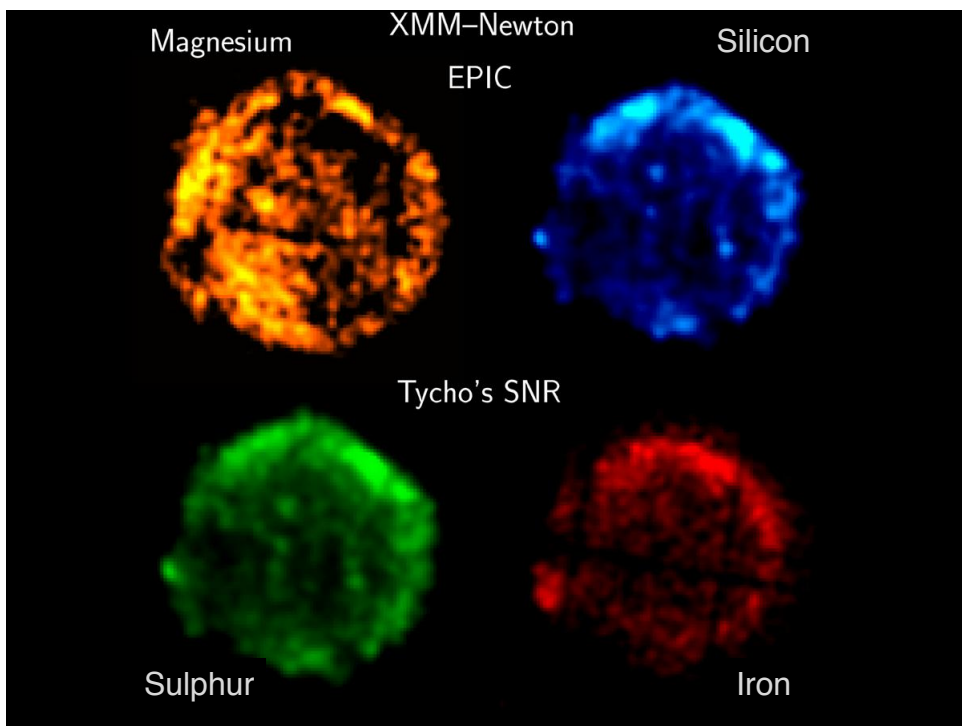


## Historical importance of supernovae

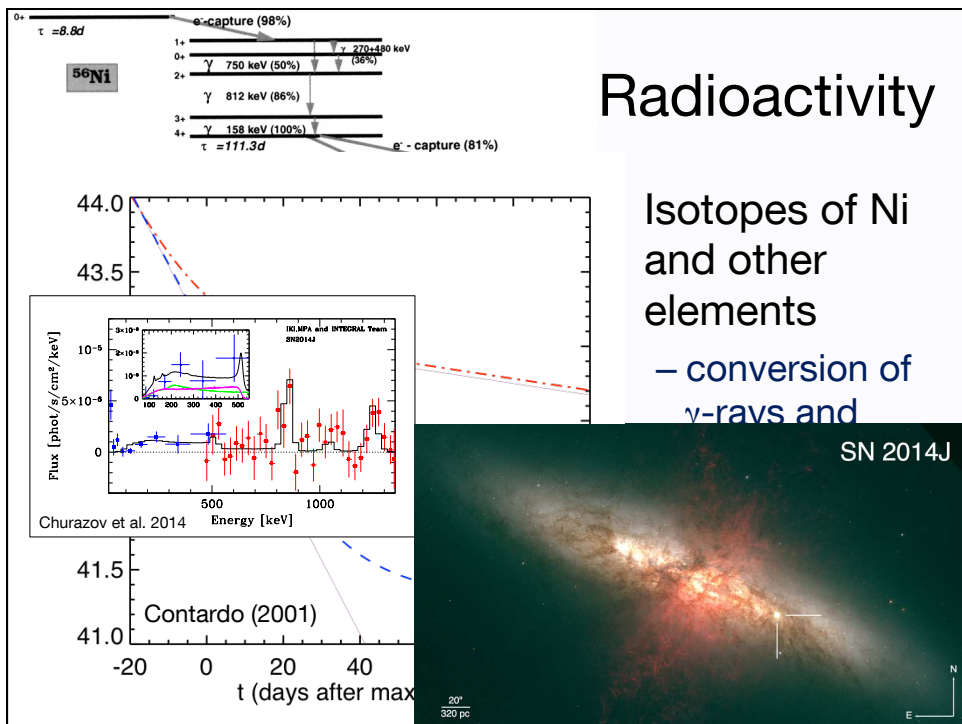
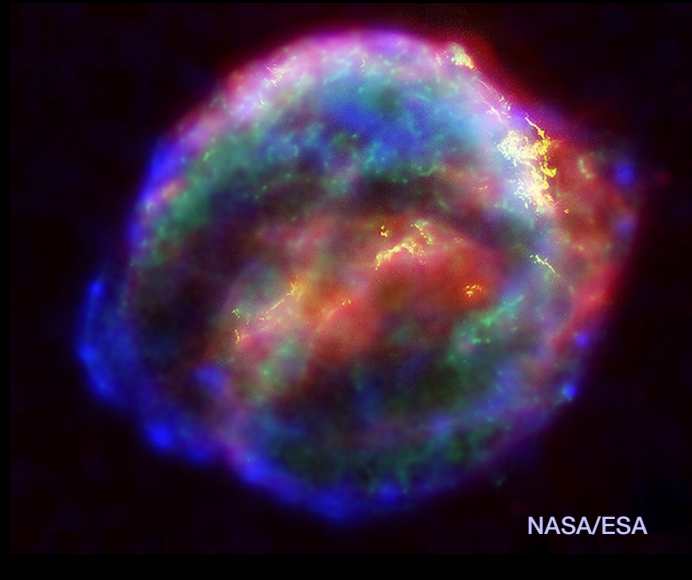
- Historical supernova observations in Asia (China, Korea)
  - Interpreted (together with comets) as heavenly signs (typically as bad omens)
- Appeared in the part of the fixed stars
  - In contradiction of the Ptolemaic world view with the heavenly spheres

## Historical importance of supernovae

- SN1572 observed by Tycho Brahe
  - De stella nova
  - No measurable parallax → outside of the solar system
- SN1604 Kepler's Supernova
- Observations of S Andromeda (SN1885B) in the Andromeda galaxy
  - Lundmark (1925) proposed that Andromeda is outside our Milky Way

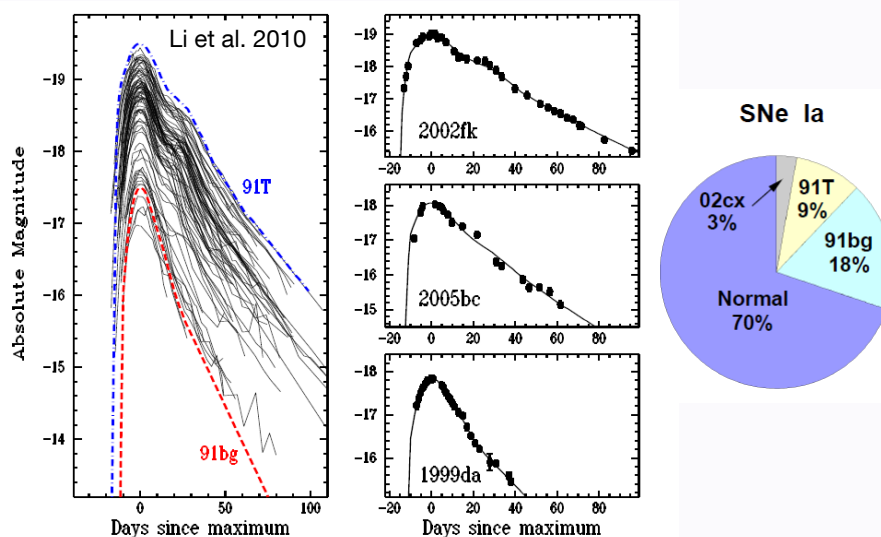


# Kepler's Supernova today





## Luminosity distribution



## SNe Ia are not a homogeneous class

### Proliferation of information

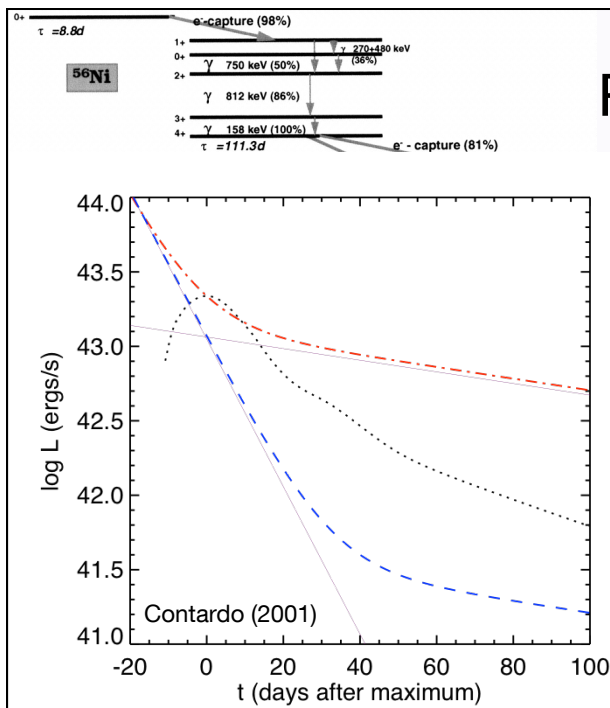
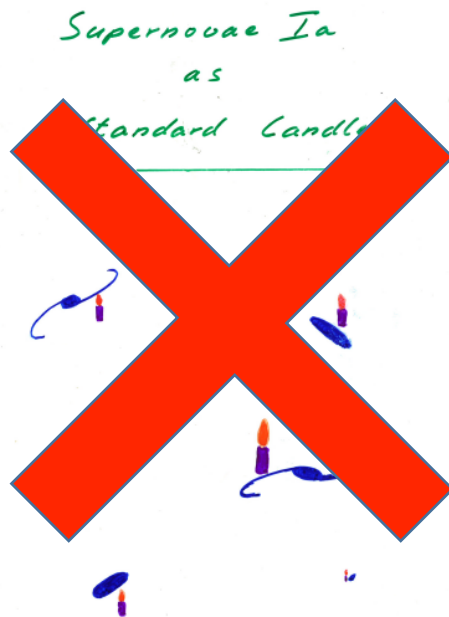
- Large samples produce many peculiar and special objects
- Difficulty to assess what are generic features of the class and what are peculiar modifications to the norm
  - Subluminous
  - Superluminous
  - CSM/no CSM
  - Environmental effects

### →What should we give up?

- evidence for multiple progenitor channels
- indications for several explosion mechanisms
- uniform metallicity

Type Ia SNe  
are not  
standard  
candles

They are not even  
standardizable  
Maybe some of  
them can be  
normalised to a  
common peak  
luminosity



## Radioactivity

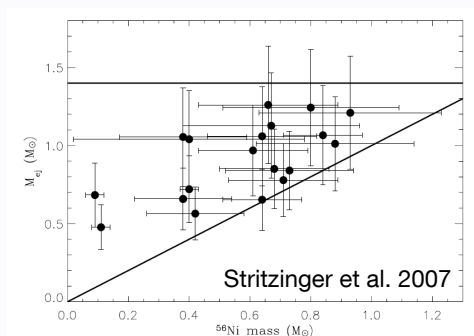
Isotopes of Ni  
and other  
elements

– conversion of  $\gamma$ -  
rays and  
positrons into  
heat and optical  
photons

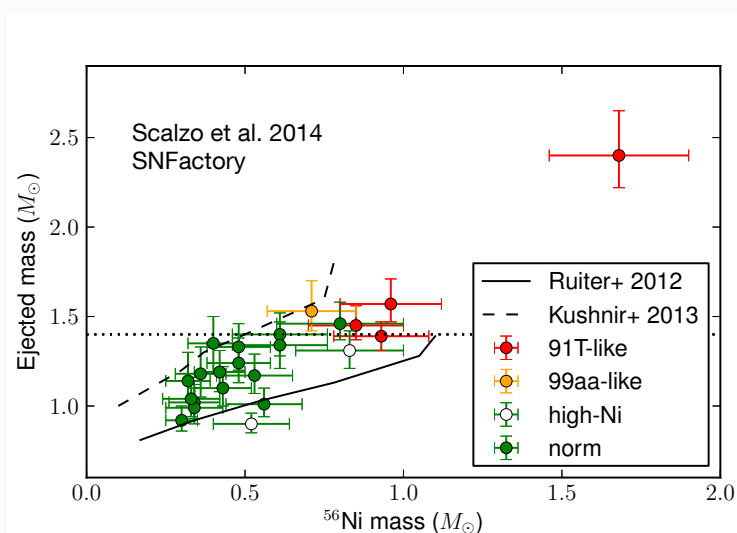
## Ejecta masses

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

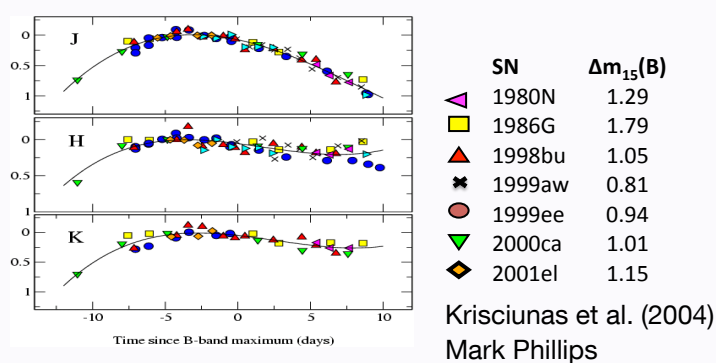


## Ejecta masses



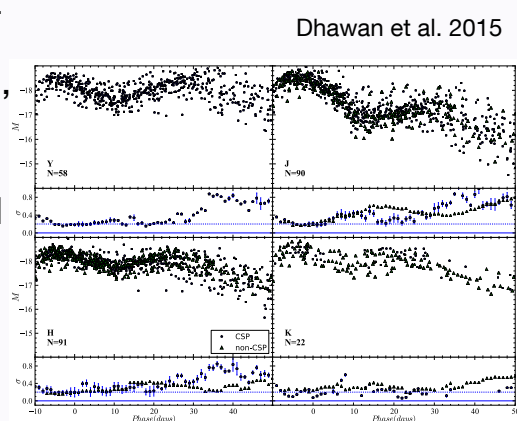
## The promise of the (near-)infrared

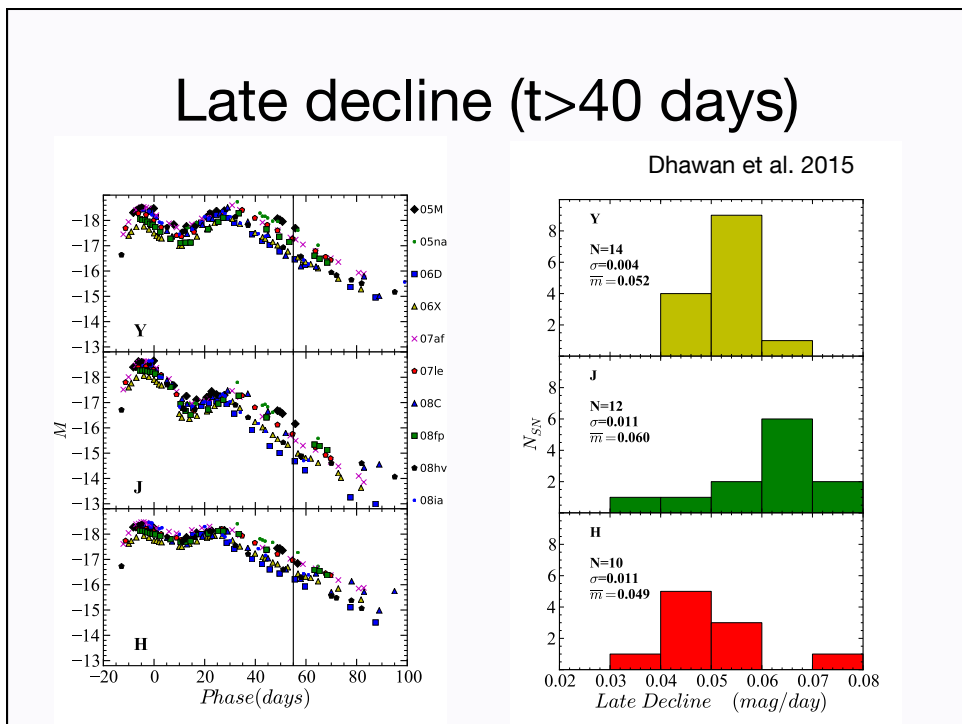
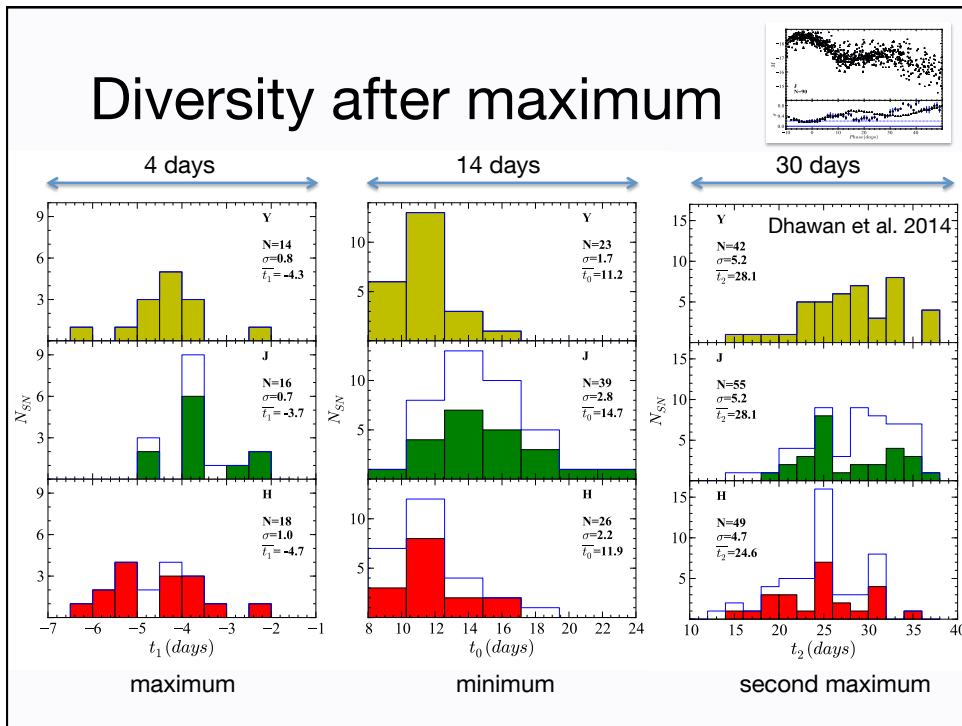
- Extinction is much reduced in the near-IR  
–  $A_H/A_V \cong 0.19$  (Cardelli et al. 1989)
- SNe Ia much better behaved



## Large literature sample

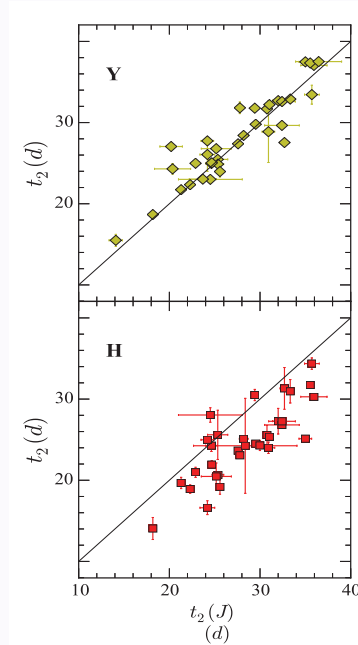
- Scatter minimal at first maximum in  
Y (1.04 $\mu$ m), J (1.24 $\mu$ m),  
H (1.63 $\mu$ m) and  
K (2.14 $\mu$ m)
- ~90 objects in J and H  
– 58 in Y, 22 in K
- Mostly Carnegie SN  
Project data  
(Contreras et al. 2010,  
Stritzinger et al. 2011)





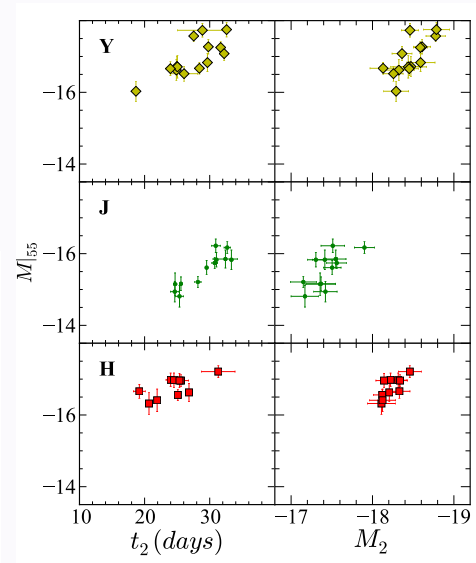
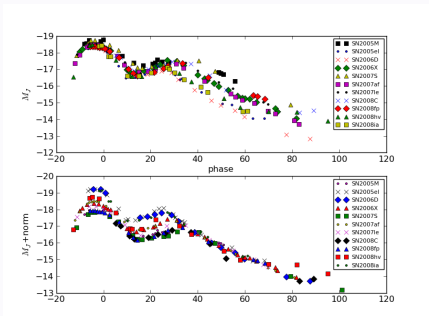
# Correlations

Phase of the second maximum appears to be a strong discriminator among SNe Ia



# Correlations

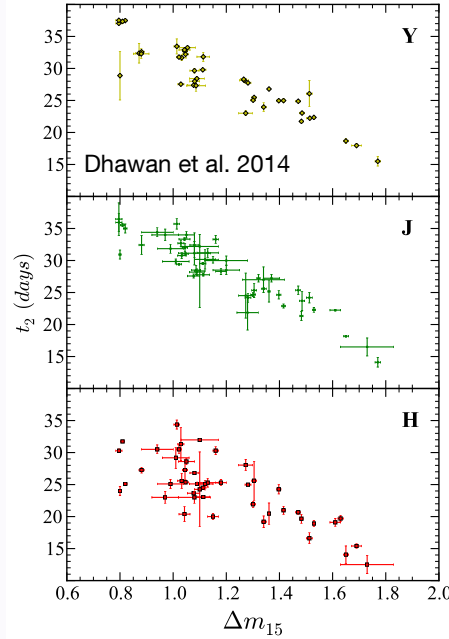
Luminosity of late decline and the phase of the second maximum are linked





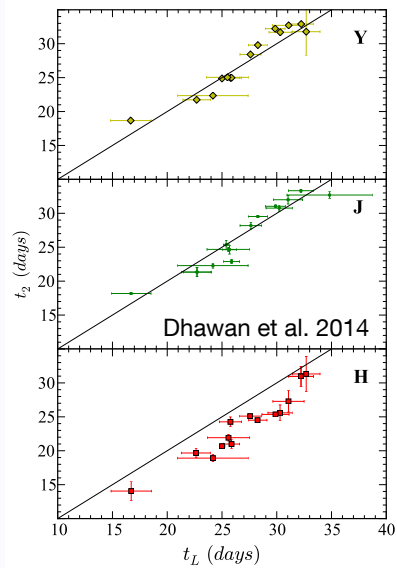
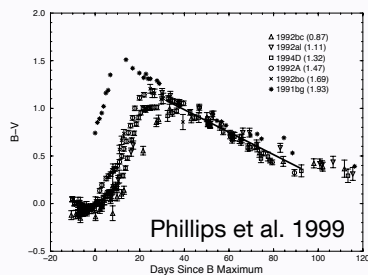
## Correlations with the optical

- IR properties correlate with optical decline rate
- Phase of secondary maximum strongly correlated with  $\Delta m_{15}$



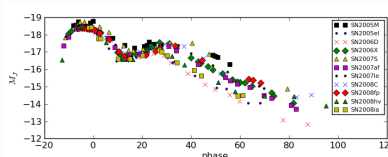
## Correlation with optical colour

Phase of second maximum and beginning of the Lira relation are also tightly linked



## Consistent picture emerging

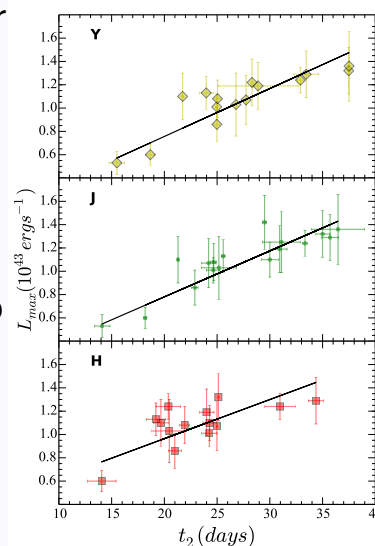
- Second peak in the near-IR is the result of the recombination of  $\text{Fe}^{++}$  to  $\text{Fe}^+$  (Kasen 2006)
    - he predicted a later second maximum for larger Ni masses
  - Optical colour evolution faster for objects with lower nickel mass (Kasen & Woosley 2007)
  - Ejecta structure uniform
    - late declines very similar
- higher luminosity indicates a higher Ni mass  
 → later secondary peak also indicates higher Ni mass  
 → Ni mass and (optical) light curve parameters correlate (Scalzo et al. 2014)



## Nickel masses

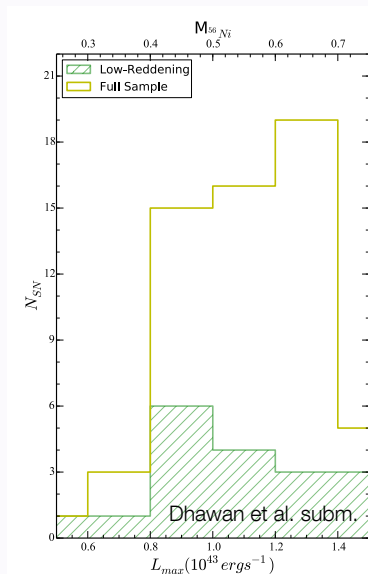
Dhawan et al. subm.

- Using a timing parameter for nickel masses
  - completely independent on reddening and multiple light curves
- Test with a sample of unreddened SNe Ia
- Explore different methods to calculate the nickel mass (currently still all Chandrasekhar-mass progenitors)



## Luminosity and mass functions

- Reddening independent distribution functions
  - fails for super-Chandra objects
    - SN 2007if
  - potential shock interaction at peak might create additional luminosity



## Summary

- Nickel seems the dominant parameter for the light curves of SNe Ia
  - phase of second maximum, start of uniform B-V colour evolution (Lira law), optical light curve shape ( $\Delta m_{15}$ ), luminosity of the late decline phase
- Second maximum in the IR light curves strong parameter for SN Ia characterisation  $\rightarrow$  simple way to measure nickel mass

# Type Ia supernova cosmology

Excellent distance indicators!



## 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

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

## Friedmann cosmology

**Assumption:**  
homogeneous und isotropic universe

Friedmann-Robertson-Walker-Lemaître metric:

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

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

$\Omega_M$ : matter density

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

$\Omega_k$ : curvature

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

$\Omega_\Lambda$ : cosmological constant

## The equation of state parameter $\omega$

General luminosity distance

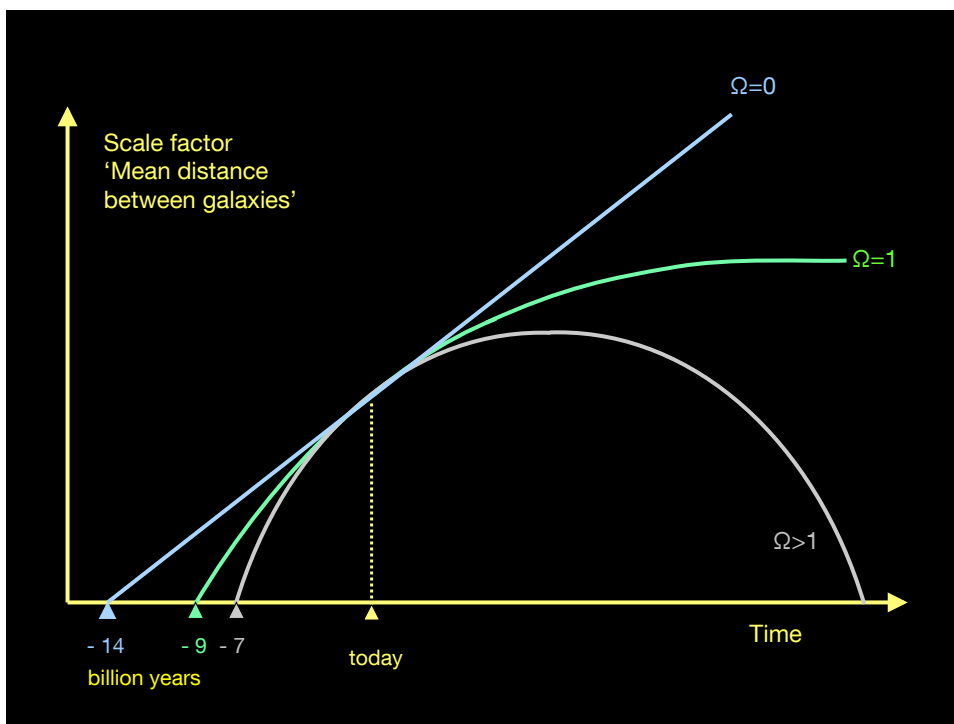
$$D_L = \frac{(1+z)c}{H_0 \sqrt{|\Omega_\kappa|}} S \left\{ \sqrt{|\Omega_\kappa|} \int_0^z \left[ \Omega_\kappa (1+z')^2 + \sum_i \Omega_i (1+z')^{3(1+\omega_i)} \right]^{-1/2} dz' \right\}$$

– with  $\Omega_\kappa = 1 - \sum_i \Omega_i$  and  $\omega_i = \frac{p_i}{\rho_i c^2}$

$\omega_M = 0$  (matter)

$\omega_R = \frac{1}{3}$  (radiation)

$\omega_\Lambda = -1$  (cosmological constant)

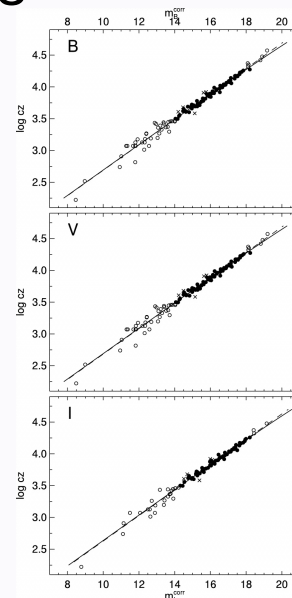




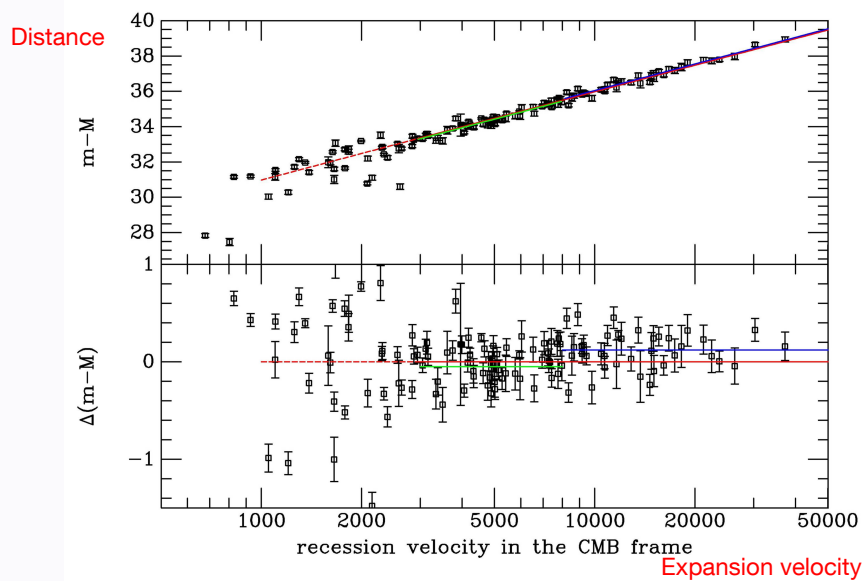
## SN Ia Hubble diagram

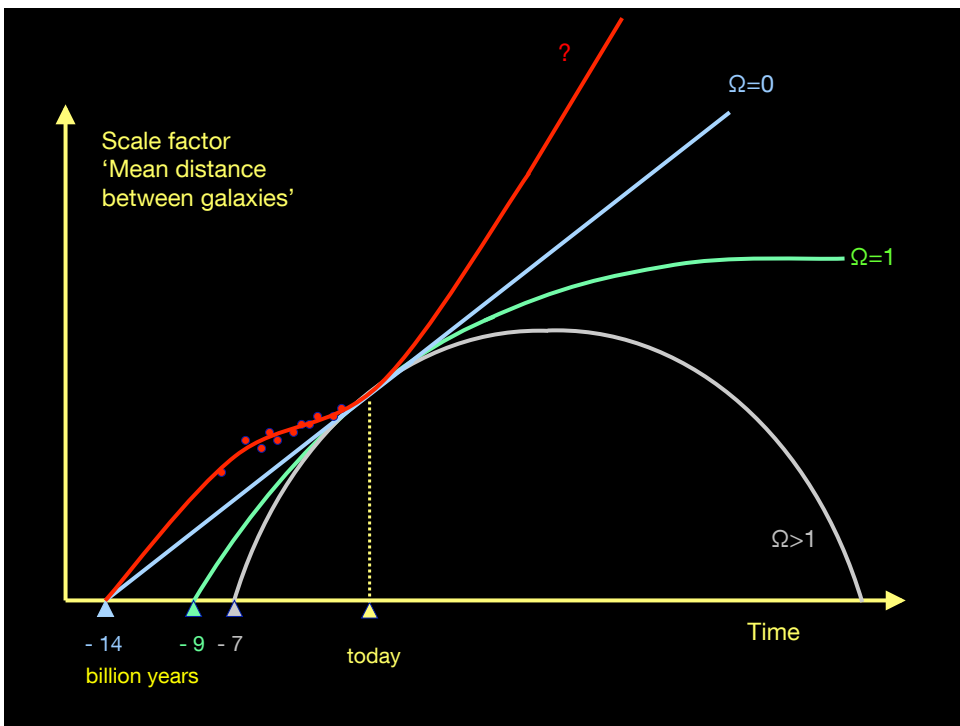
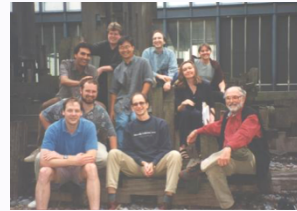
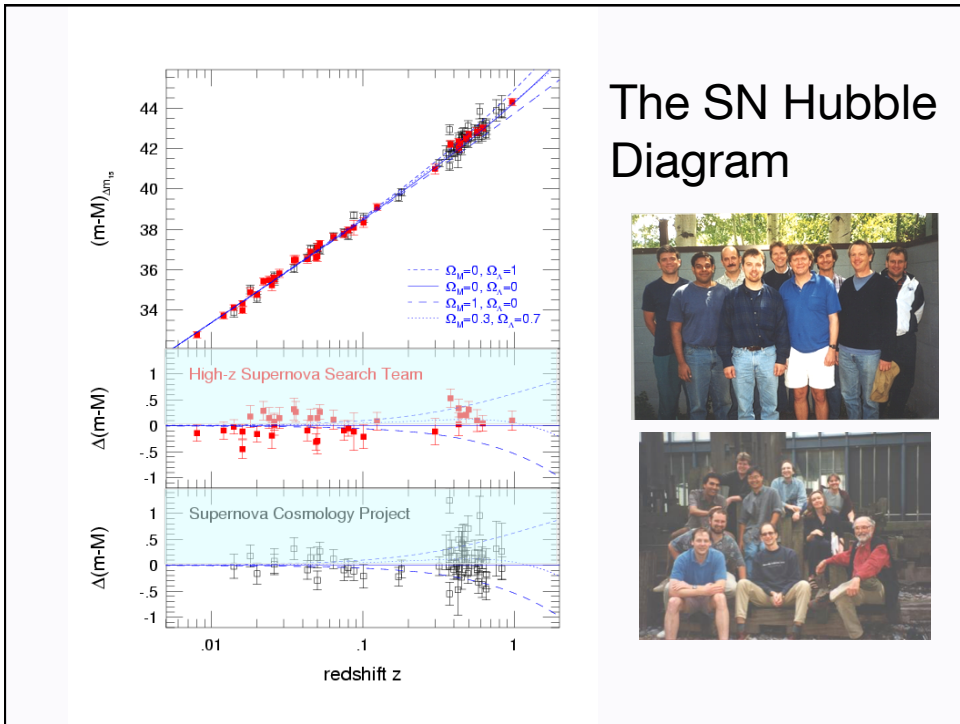
- Excellent distance indicators
- Experimentally verified
- Work of several decades
- Best determination of the Hubble constant

Reindl et al. 2005



## Distance indicator!





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.

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

**ABSTRACT**

We present spectral and photometric observations of 10 type Ia supernovae (SN Ia) in the redshift range  $0.18 < z < 0.82$ . The luminosity distances of these objects are determined by methods that employ relations between SN Ia luminosity and light curve shape. Combined with previous data from our High-Z Supernova Search Team and recent results by Riess et al., this expanded set of 16 high-redshift supernovae and a set of 58 nearby supernovae are used to place constraints on the following cosmological parameters: the Hubble constant  $H_0$ , the mass density  $\Omega_M$ , the cosmological constant  $\Omega_\Lambda$ , the vacuum energy density  $\Omega_\Lambda$ , the deceleration parameter  $q_0$ , and the dynamical age of the universe  $t_H$ . The elements of the high-redshift SN Ia data, on average, show that light is not in a low field density  $\Omega_M \approx 0.2$  universe without a cosmological constant. Different light curve fitting methods, SN Ia calibration, and prior constraints observational bias errors, including results with prior constraints on  $H_0$ ,  $\Omega_M$ ,  $\Omega_\Lambda$ ,  $q_0$ , and  $t_H$  are used a current acceleration of the expansion (i.e.,  $a > 0$ ). With no prior constraint on mass density other than  $\Omega_M > 0$ , the spectroscopically confirmed SN Ia fit parameters, constrained with  $q_0 < 0$  at the 2.5  $\sigma$  and 5.0  $\sigma$  confidence levels, and with  $\Omega_M > 0$  at the 3.0  $\sigma$  and 5.0  $\sigma$  confidence levels, for two different fitting methods, respectively. Fitting a "minimal" mass density,  $\Omega_M = 0.2$ , results in the weakest detection,  $q_0 < 0$  at the 2.0  $\sigma$  confidence level from one of the two methods. For a flat universe prior  $(\Omega_M + \Omega_\Lambda = 1)$ , the cosmologically constrained SN Ia require  $\Omega_M > 0.2$  at 7  $\sigma$  and 5  $\sigma$  (local statistical significance) for the two different fitting methods. A reference curve by ordinary means in the current Copernican era. We estimate the dynamical age of the universe to be  $12.7 \pm 1.5$  Gyr including systematic uncertainties in the current Copernican era. We estimate the likely effect of several sources of systematic error, including projection and magnification biases, systematic sample selection bias, local perturbations in the expansion rate, gravitational lensing, and sample contamination. Presently, none of these effects appear to threaten the data with  $1\sigma$ ,  $2\sigma$ , and  $3\sigma$ .

**Key words:** cosmology: observations — supernovae: general

**1. INTRODUCTION**

This paper reports observations of 10 new high-redshift type Ia supernovae (SN Ia) and the values of the cosmological parameters derived from them. Together with the first high-redshift supernovae previously reported by our High-Z Supernova Search Team (Flintheart et al. 1998; Courvoisier et al. 1999) and two others (Riess et al. 1999), the sample of 16 is now large enough to yield interesting cosmological results of high statistical significance. Comparison of these results depends not on decreasing the sample size but on improving our understanding of systematic uncertainties.

The time evolution of the cosmic scale factor depends on the composition of matter-energy in the universe. While the universe is known to contain a significant amount of ordinary matter,  $\Omega_M$ , which decelerates the expansion, its dynamics may also be significantly affected by more exotic forms of energy. From our new results, it is possible to study the vacuum ( $\Omega_\Lambda$ ),  $\Lambda$ -like "cosmological con-

18 December 1998

# Science ?

Vol. 282 No. 5397  
 Pages 2141-2336 57

## THE ACCELERATING UNIVERSE

Breakthrough of the Year

Distant a freely This rec

than in

t

AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

## Einstein zur Kosmologischen Konstante

Wir geben hierfür zunächst einen Weg an, der an sich nicht beansprucht, ernst genommen zu werden; er dient nur dazu, das Folgende besser hervortreten zu lassen.

Im folgenden führe ich den Leser auf dem von mir selbst zurückgelegten, etwas indirekten und holperigen Wege, weil ich nur so hoffen kann, daß er dem Endergebnis Interesse entgegenbringe. Ich komme nämlich zu der Meinung, daß die von mir bisher vertretenen

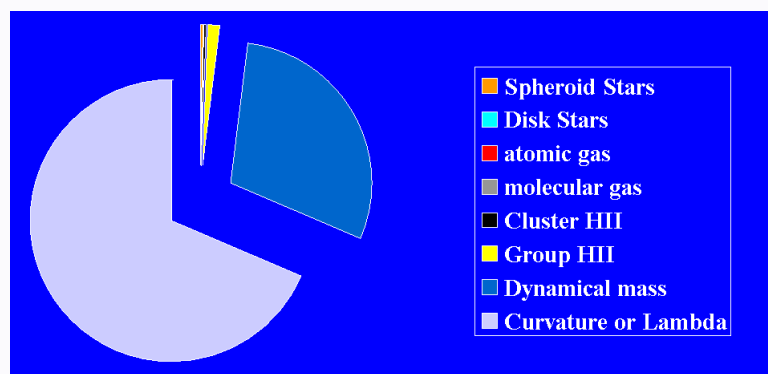
[Die Kosmologische Konstante] haben wir nur nötig, um eine quasi-statische Verteilung der Materie zu ermöglichen, wie es der Tatsache der kleinen Sternengeschwindigkeiten entspricht.

zeitlich und örtlich variabel, läßt sich aber im großen durch einen sphärischen Raum approximieren. Jedenfalls ist diese Auffassung logisch widerspruchsfrei und vom Standpunkte der allgemeinen Relativitätstheorie die naheliegendste; ob sie, vom Standpunkt des heutigen astronomischen Wissens aus betrachtet, haltbar ist, soll hier nicht untersucht werden. Um zu dieser widerspruchsfreien Auffassung zu gelangen, mußten wir allerdings eine neue, durch unser tatsächliches Wissen von der Gravitation nicht gerechtfertigte Erweiterung der Feldgleichungen der Gravitation einführen.

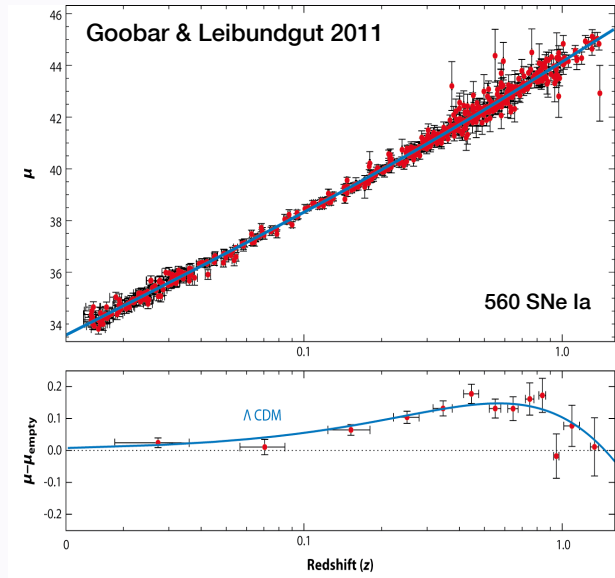
Einstein (1917)

## Contents of the universe

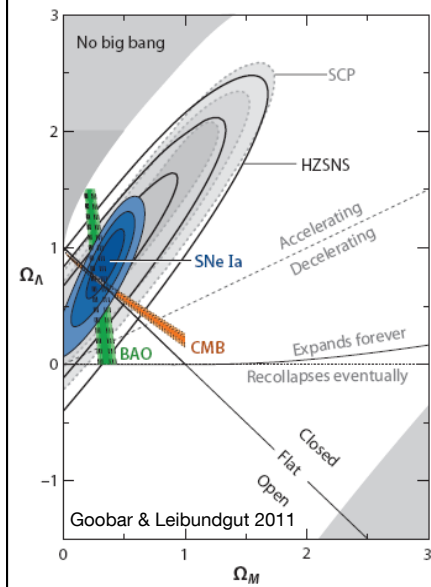
Dark Matter and Dark Energy are the dominant energy components in the universe.



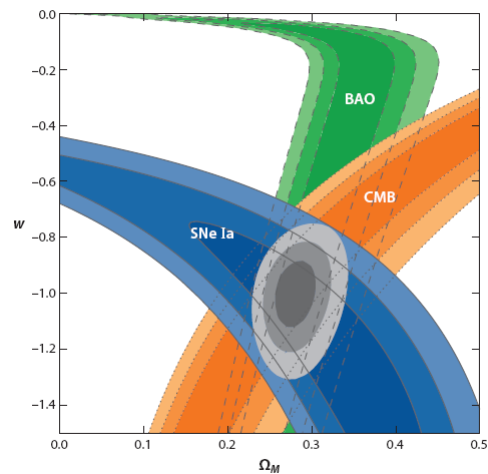
# Supernova Cosmology



et voilà ...



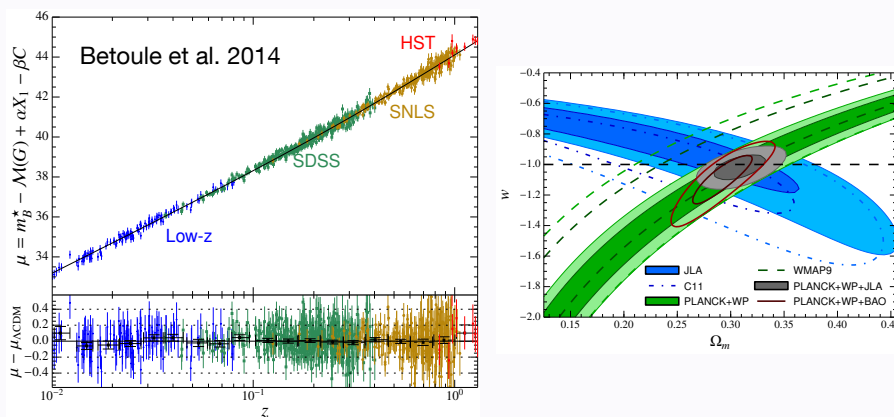
10 years of progress



# Constant $w$ firmly established

$N_{SN}$	$\Omega_M(\text{flat})$	$w$ (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		$-0.91^{+0.16 \pm 0.07}_{-0.20-0.14}$	SiFTO/SALT2	Conley et al. 2011
472	$0.269 \pm 0.015$	$-1.061^{+0.069}_{-0.068}$	SALT2	Sullivan et al. 2011
580	$0.271 \pm 0.014$	$-1.013^{+0.077}_{-0.073}$	SALT2	Suzuki et al. 2011
740	$0.295 \pm 0.034$	$-1.018 \pm 0.057$ CMB	SALT2	Betoule et al. 2014
		$-1.027 \pm 0.055$ CMB+BAO		

# Status 2014





## Systematic uncertainties

### Current questions

- calibration
- reddening and absorption
  - detection
    - through colours or spectroscopic indicators
  - correction
    - knowledge of absorption law
- light curve fitting
- selection bias
  - sampling of different populations
- gravitational lensing
- brightness evolution

## What next?

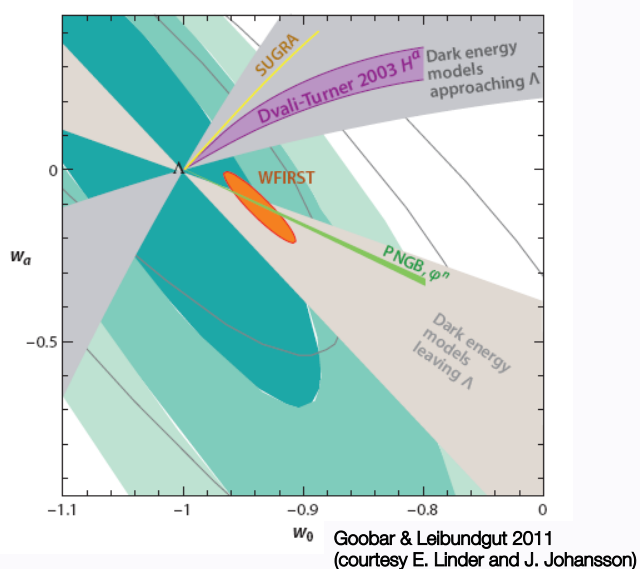
### Already in hand

- >1000 SNe Ia for cosmology
- constant  $\omega$  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

## Cosmology – more?



## Speculations

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

### Einstein's cosmological constant

No explanation in particle physics theories

### Quintessence

Quantum mechanical particle field releasing energy into the universe

### Signatures of high dimensions

Gravity is best described in theories with more than four dimensions

### Phantom Energy

Dark Energy dominates and eventually the universe end in a **(Big Rip)**

## Supernova Cosmology – do we need more?

### Test for variable $\omega$

- required accuracy  $\sim 2\%$  in *individual* distances
- can SNe Ia provide this?
  - can the systematics be reduced to this level?
  - homogeneous photometry?
  - further parameters (e.g. host galaxy metallicity)
  - handle  $>100000$  SNe Ia per year?

### Euclid

- SNe Ia with IR light curves (deep fields)
  - restframe I ( $z < 1.2$ ), J ( $z < 0.8$ ) and H ( $z < 0.4$ )
- several thousand SNe to be discovered