Supernova Cosmology

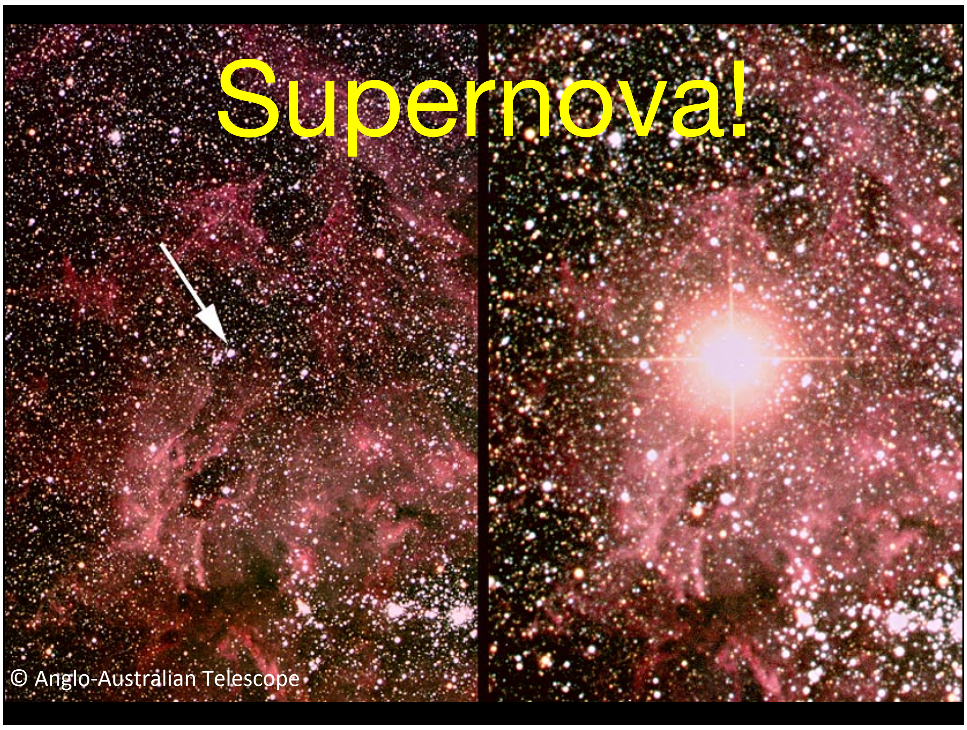
Bruno Leibundgut
European Southern Observatory

Take away messages

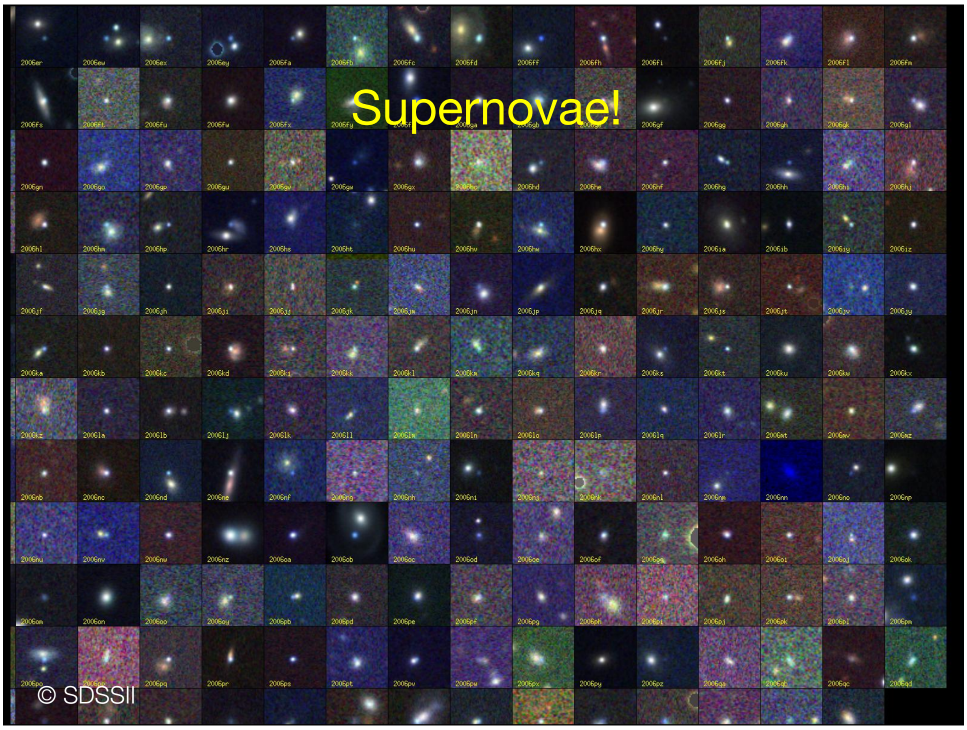
- Supernovae are complicated astrophysical objects
  - explosions!
  - old stars, i.e. end of stellar evolution
  - this also applies to Type Ia supernovae
- The universe experiences accelerated expansion
  - measured through cosmological distances by Type Ia Supernovae
    - SNe Ia can be used to determine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

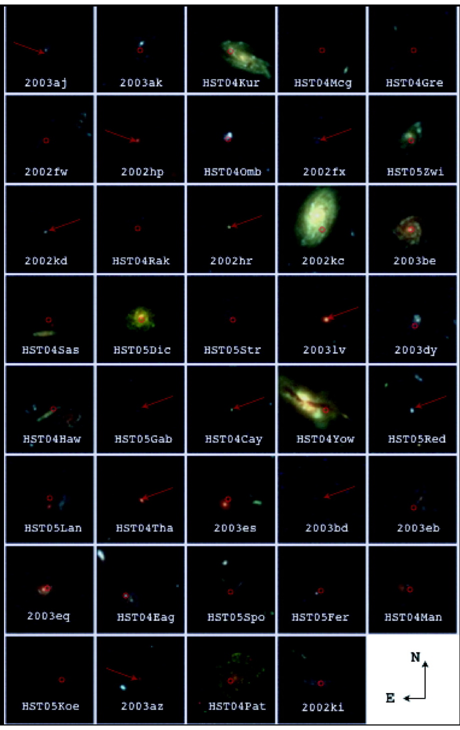
Presentation in two parts

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




SN 1994D

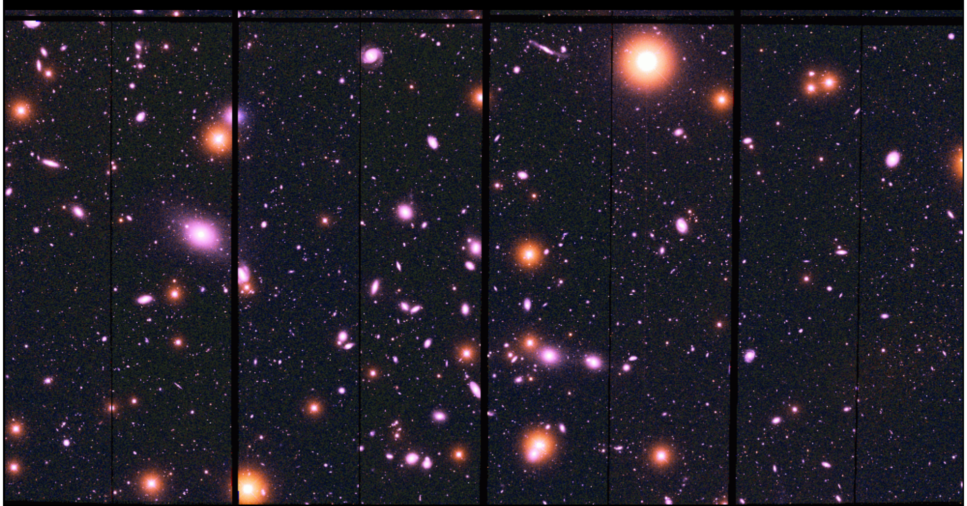

Supernovae!
© SDSSII



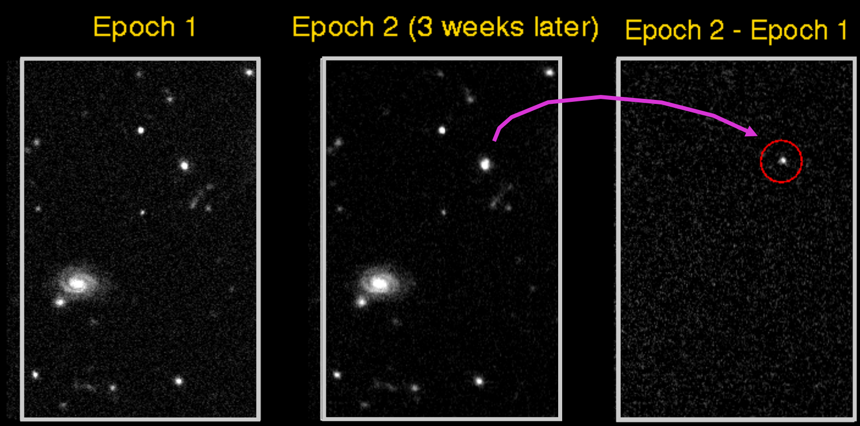
Supernovae!

Riess et al. 2007

Supernova Search



Supernova Search



(High-z Supernova Team)

Supernova classification

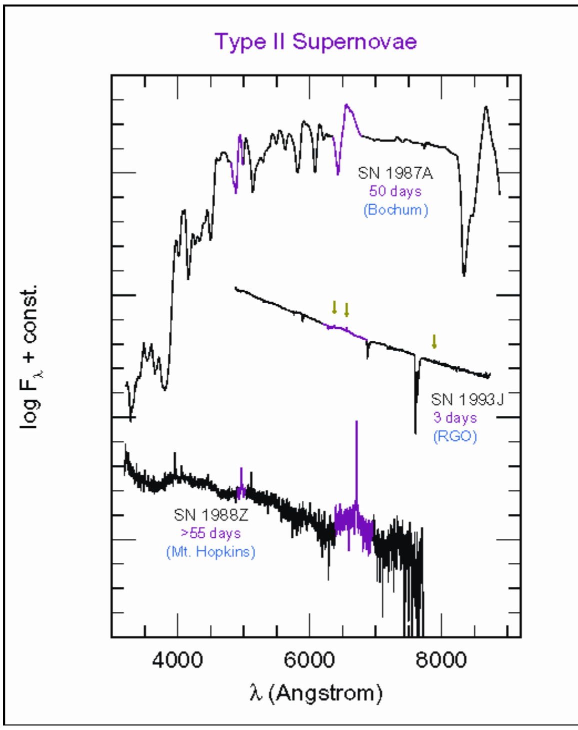
Based on spectroscopy

core collapse
in massive stars

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

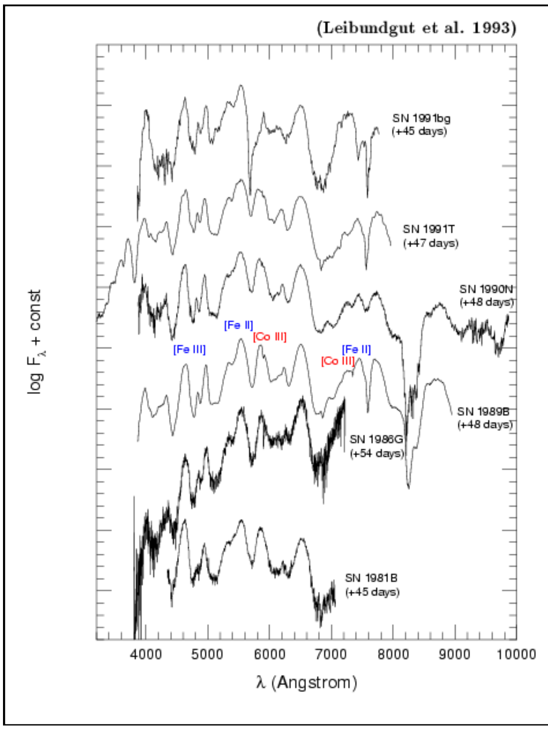
SN Ia (no H)

thermonuclear
explosions



Supernova Spectroscopy

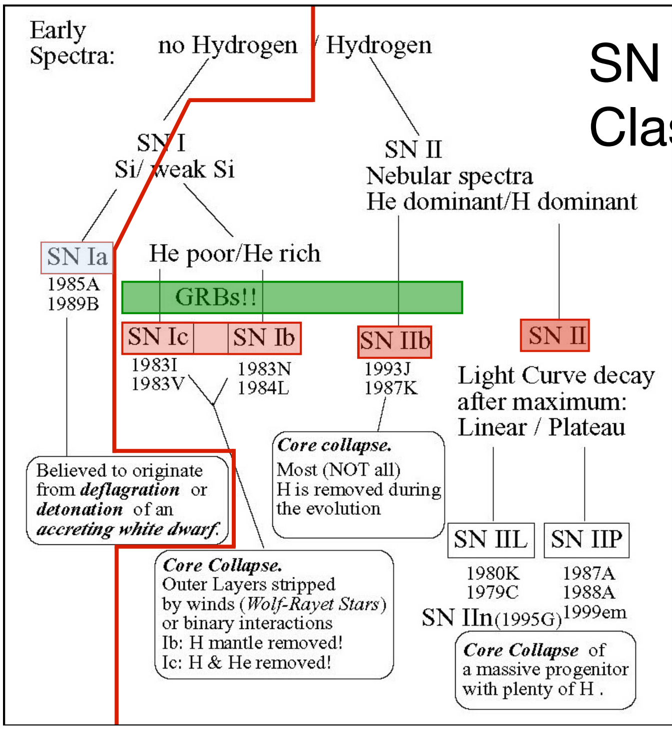
Type II



Supernova Spectroscopy

Type Ia

SN Classification



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

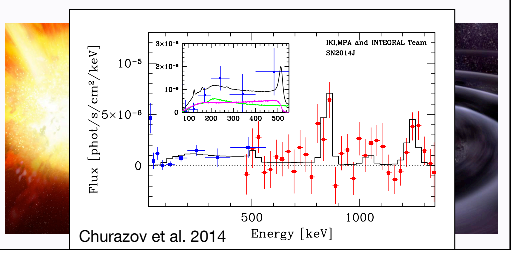
Supernova Types

Thermonuclear SNe
- Progenitor stars have small mass ($<8M_{\odot}$)
- highly developed stars (white dwarfs)
- Explosive C 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

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



Churazov et al. 2014

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

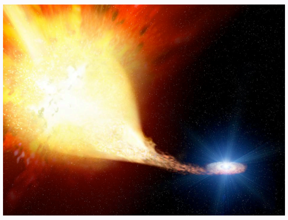
Possible progenitors

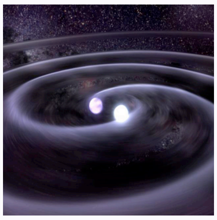
Single Degenerate

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

Double Degenerate

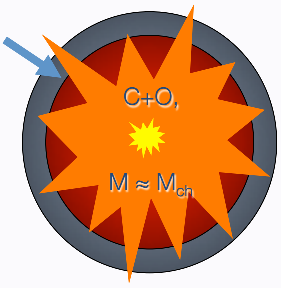
- 2 'dead' stars
  - Old systems (>10^9 yr)
- mergers
- 'clean' environment
- no companion remnant





The "standard model"

He (+H) from binary companion



Density ~ 10^9 - 10^{10} g/cm

Temperature: a few 10^9 K

Radii: a few 1000 km

<u>Explosion energy:</u>

Fusion of

C+C, C+O, O+O

⇒ "Fe"

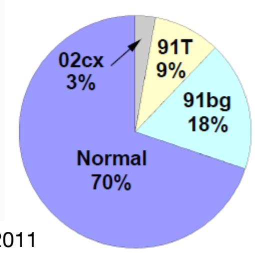
There is a lot more to this – you need to contact your explosive theory friends

Type Ia Supernovae

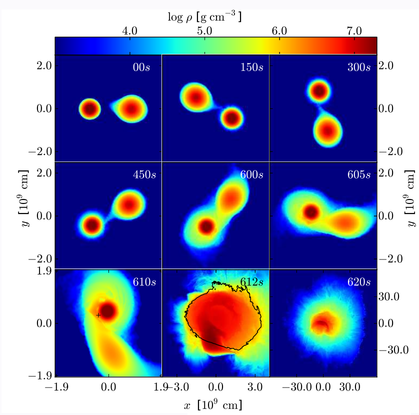
Complicated story

- observational diversity
- many models

→ need more constraints



Wang et al. 2011



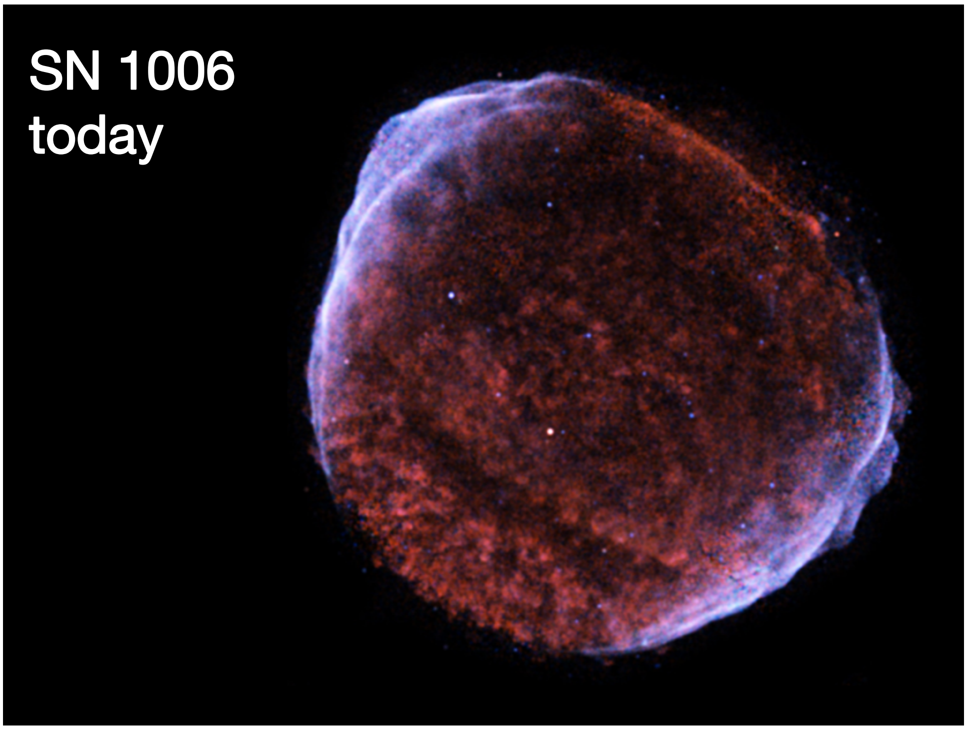
Pakmor et al. 2012

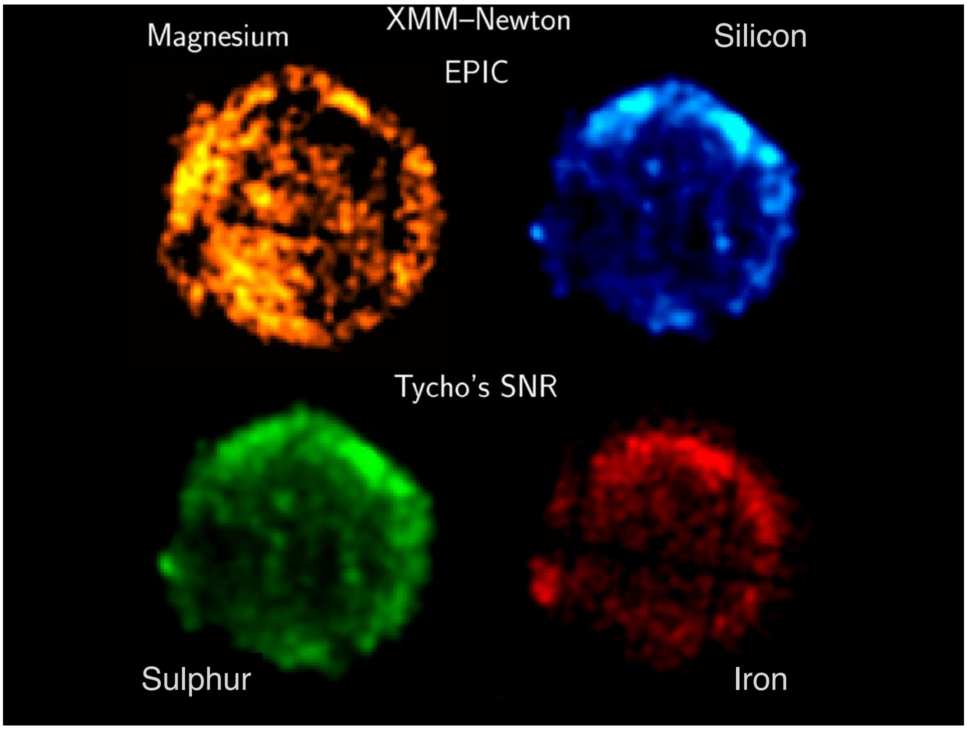
Historical importance of supernovae

- 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 ot the Ptolemaic world view with the heavenly spheres

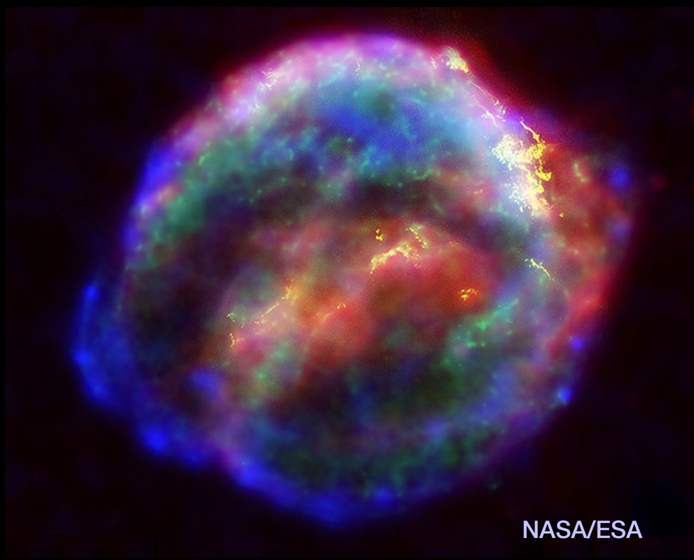
Historical importance of supernovae

- 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

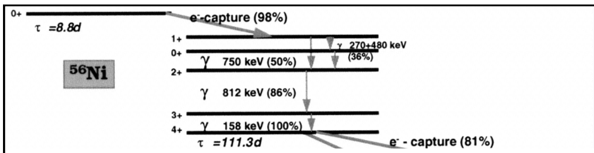

SN 1006
today


Magnesium
XMM–Newton
EPIC
Silicon
Tycho's SNR
Sulphur
Iron

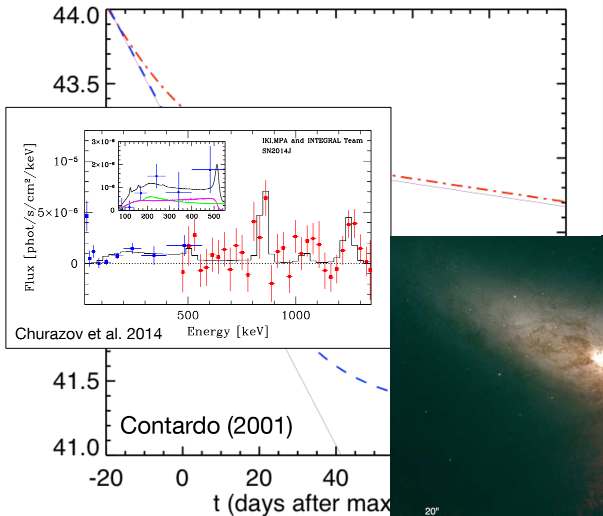
Kepler's Supernova today



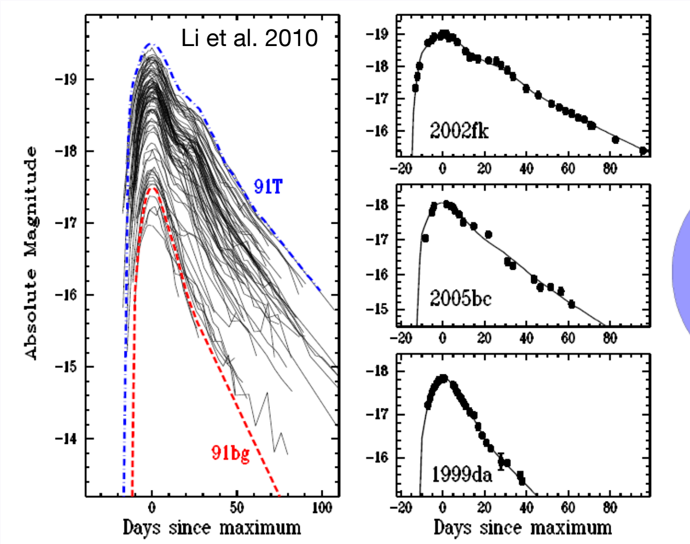
Radioactivity

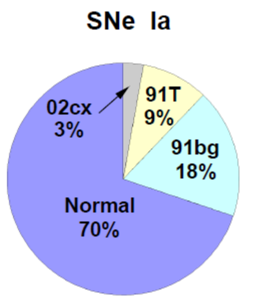


- Isotopes of Ni and other elements
  – conversion of γ-rays and



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

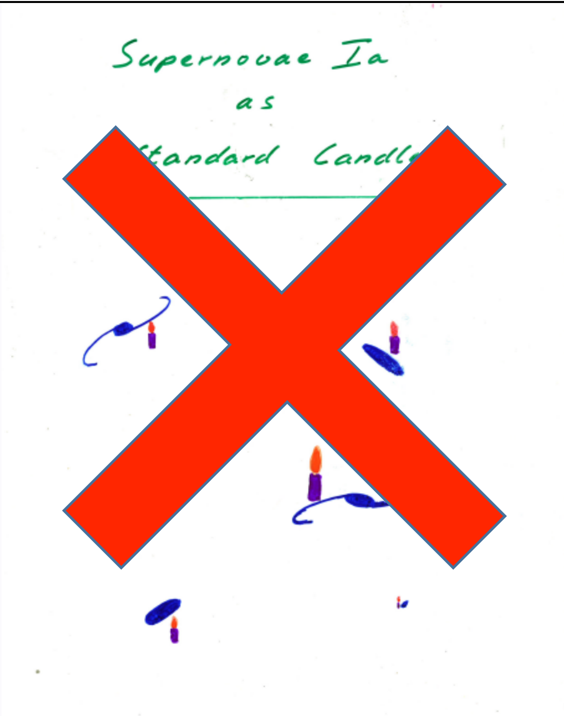
→What should we give up?

→evidence for multiple progenitor channels
→indications for several explosion mechanisms
→uniform metalicity

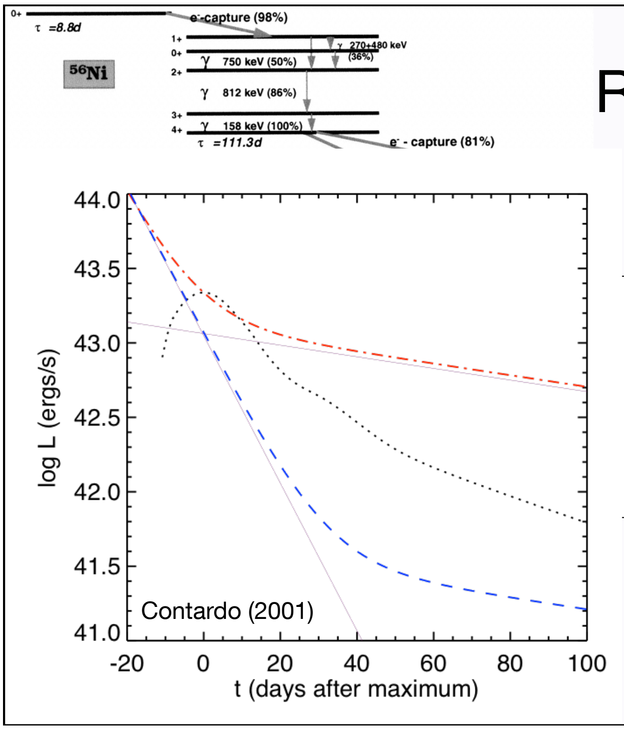
Type Ia SNe are not standard candles

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 γ-rays and positrons into heat and optical photons

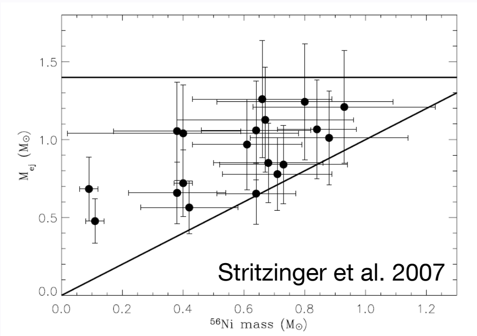
Ejecta masses

Large range in nickel and ejecta masses

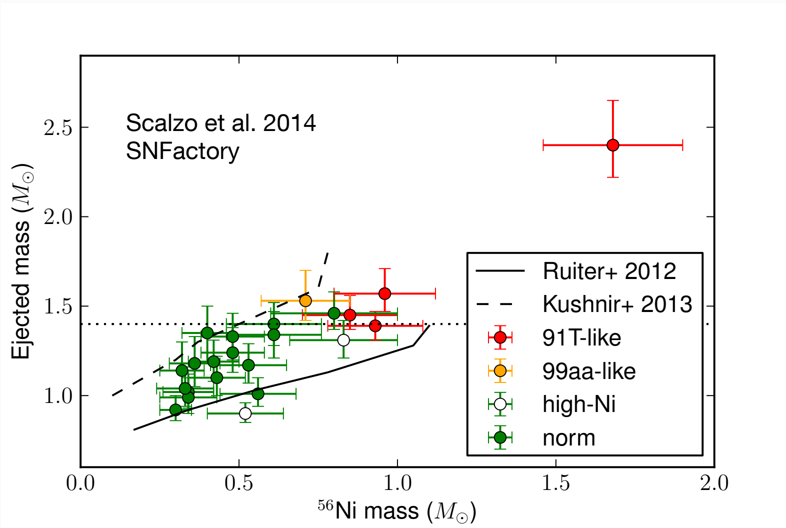
– no ejecta mass at 1.4$M_\odot$

– factor of 2 in ejecta masses

– some rather small differences between nickel and ejecta mass

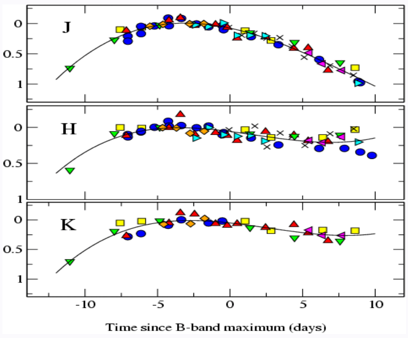


Ejecta masses



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



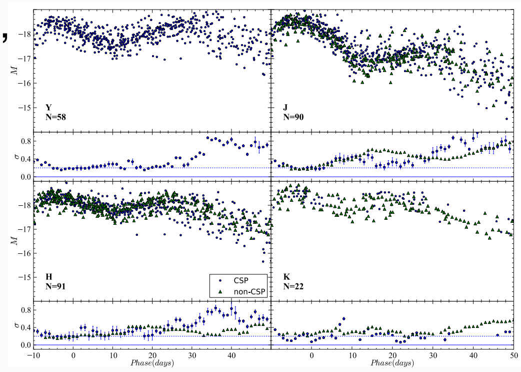
SN	$\Delta m_{15}(B)$
1980N	1.29
1986G	1.79
1998bu	1.05
1999aw	0.81
1999ee	0.94
2000ca	1.01
2001el	1.15

Krisciunas et al. (2004)
Mark Phillips

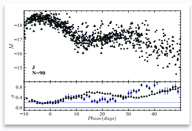
Large literature sample

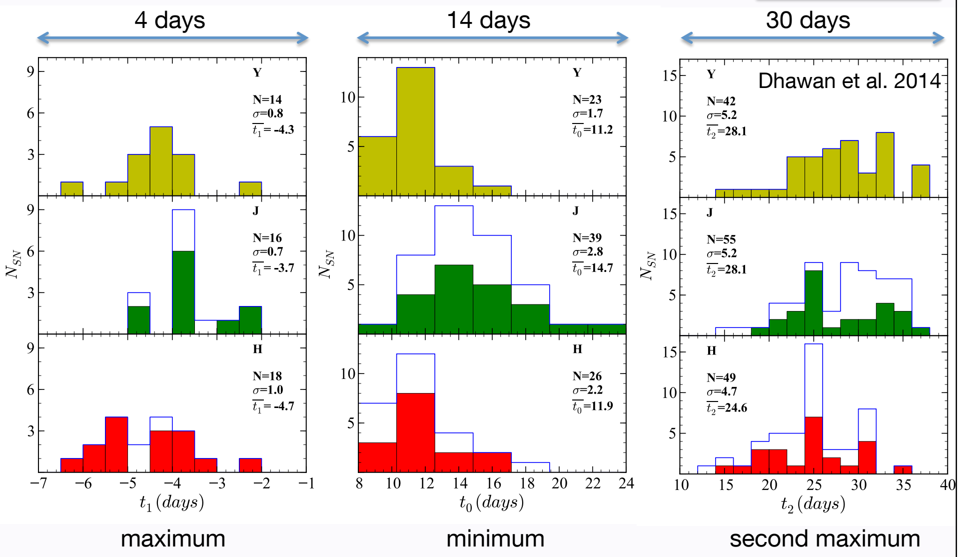
- Scatter minimal at first maximum in Y (1.04μm), J (1.24μm), H (1.63μm) and K (2.14μm)
- ~90 objects in J and H
  - 58 in Y, 22 in K
- Mostly Carnegie SN Project data (Contreras et al. 2010, Stritzinger et al. 2011)

Dhawan et al. 2015

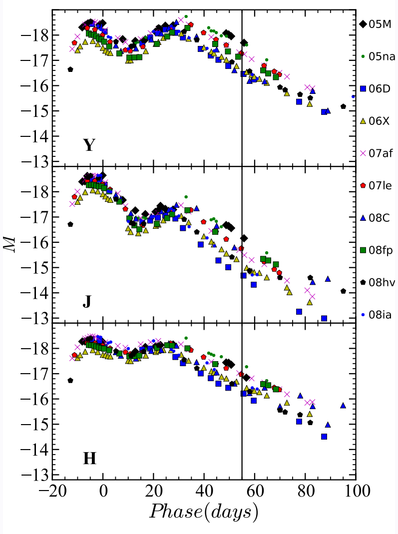


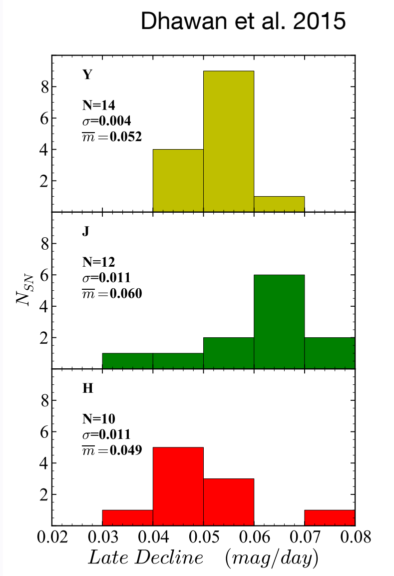
Diversity after maximum





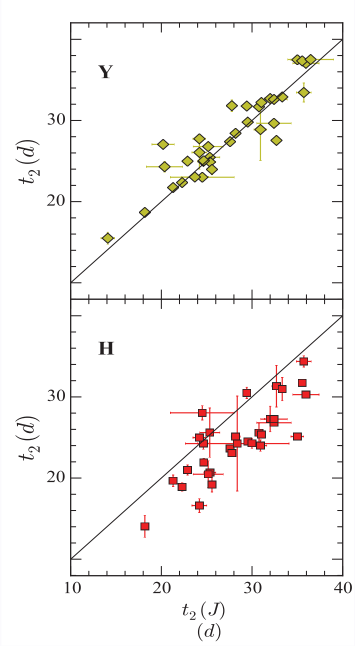
Late decline (t>40 days)





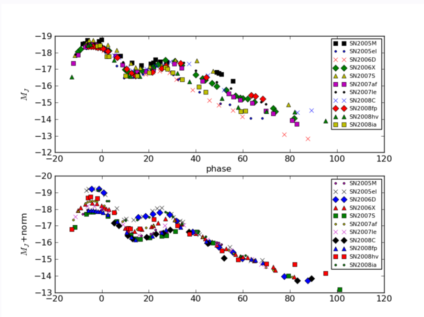
Correlations

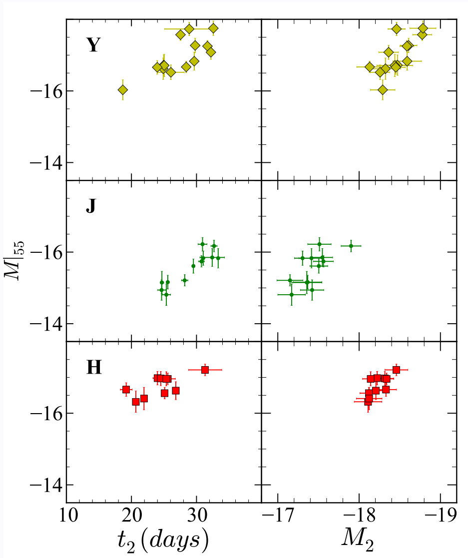
Phase of the second maximum appears to be a strong discriminator among SNe Ia



Correlations

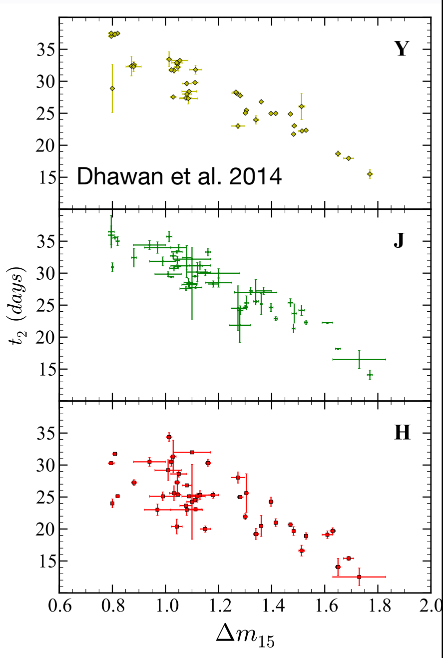
Luminosity of late decline and the phase of the second maximum are linked





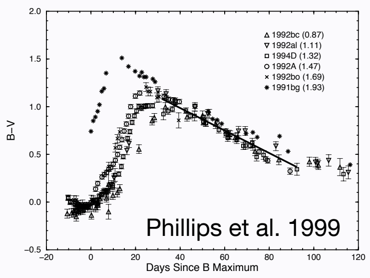
Correlations with the optical

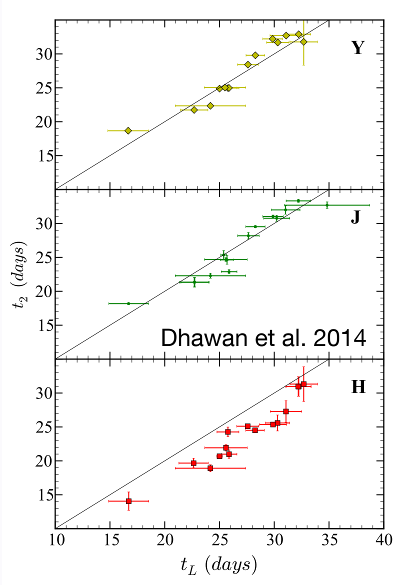
- IR properties correlate with optical decline rate
- Phase of secondary maximum strongly correlated with Δm_{15}



Correlation with optical colour

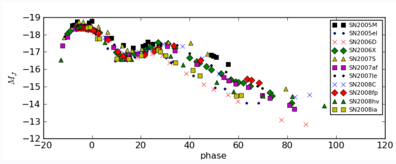
Phase of second maximum and beginning of the Lira relation are also tightly linked





Consistent picture emerging

- Second peak in the near-IR is the result of the recombination of Fe++ to 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

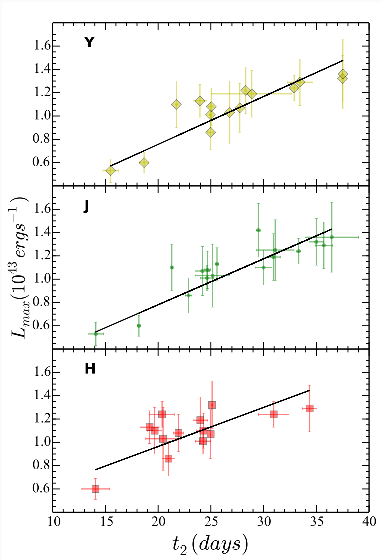
➔ later secondary peak also indicates higher Ni mass

➔ Ni mass and (optical) light curve parameters correlate (Scalzo et al. 2014)

Nickel masses

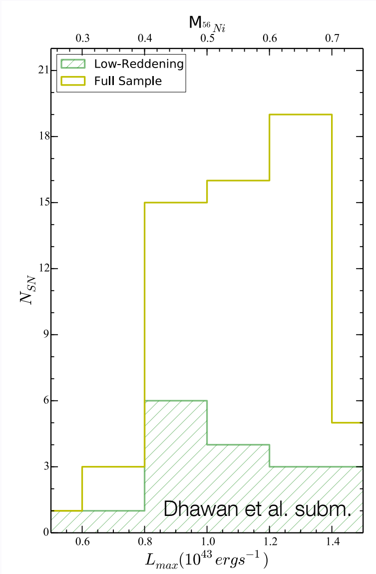
Dhawan et al. subm.

- 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 (Δm_{15}), luminosity of the late decline phase
- Second maximum in the IR light curves strong parameter for SN Ia characterisation → simple way to measure nickel mass

Type Ia supernova cosmology

Excellent distance indicators!

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:

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

$$\Omega_M = \frac{8\pi G}{3H_0^2}\rho_M \qquad \Omega_k = -\frac{kc^2}{R^2 H_0^2} \qquad \Omega_\Lambda = \frac{\Lambda c^2}{3H_0^2}$$

Ω_M: matter density Ω_k: curvature Ω_Λ: cosmological constant

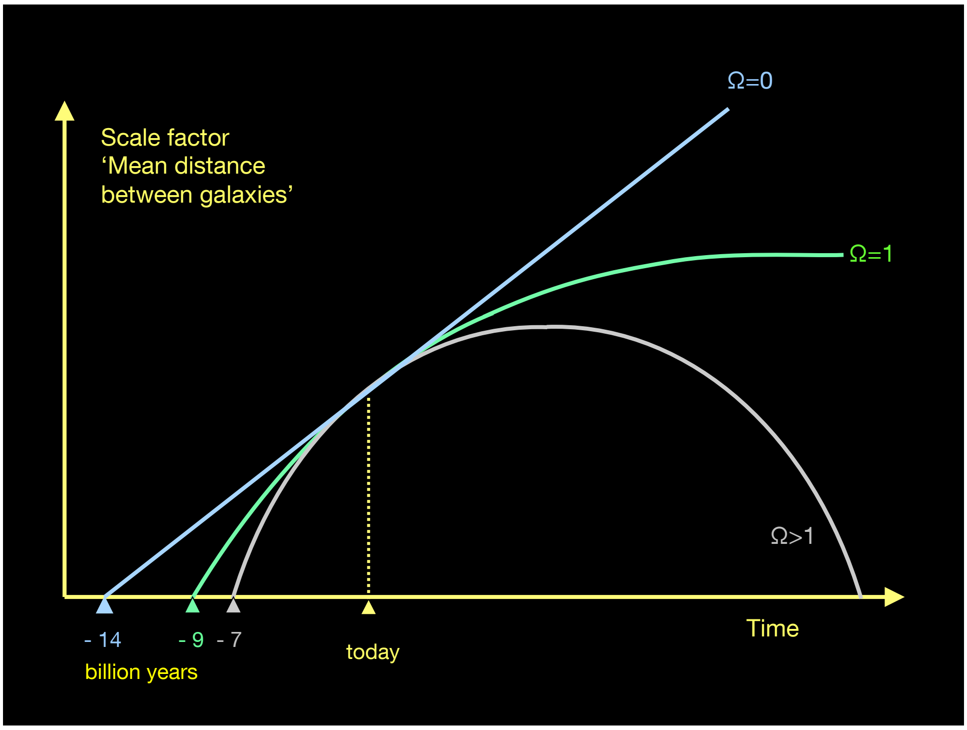
The equation of state parameter ω

General luminosity distance

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

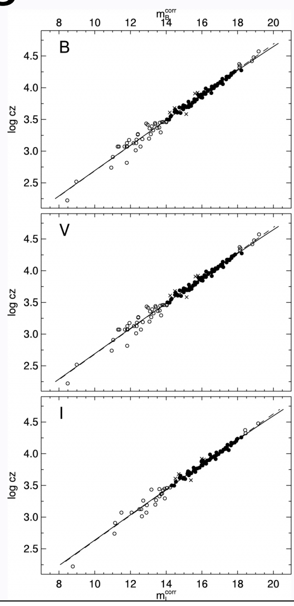
– with $\Omega_\kappa = 1 - \sum_i \Omega_i$ and $\omega_i = \frac{p_i}{\rho_i c^2}$

ω_M= 0 (matter)
ω_R= ⅓ (radiation)
ω_Λ= -1 (cosmological constant)



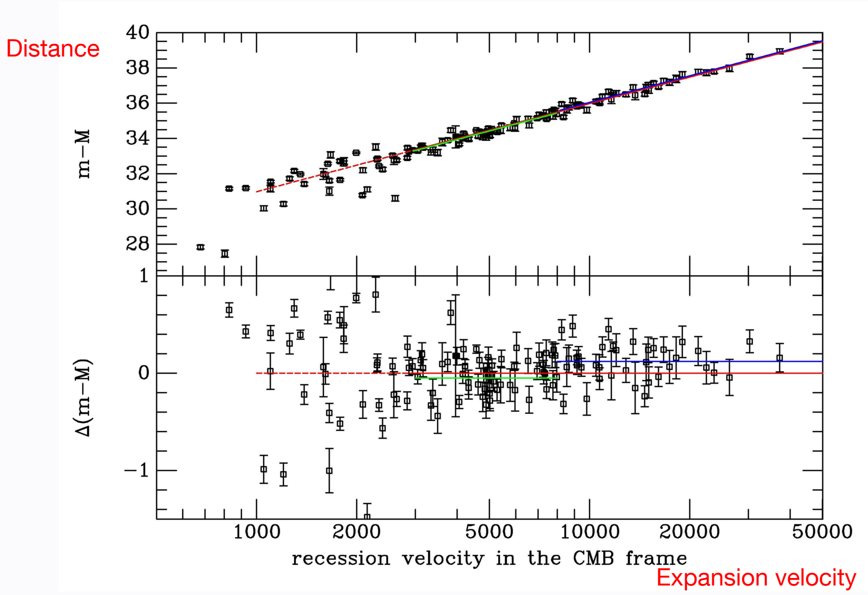
SN Ia Hubble diagram

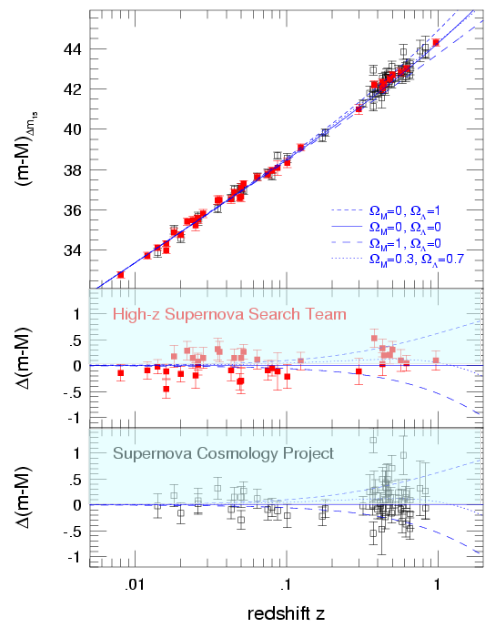
- Excellent distance indicators
- Experimentally verified
- Work of several decades
- Best determination of the Hubble constant



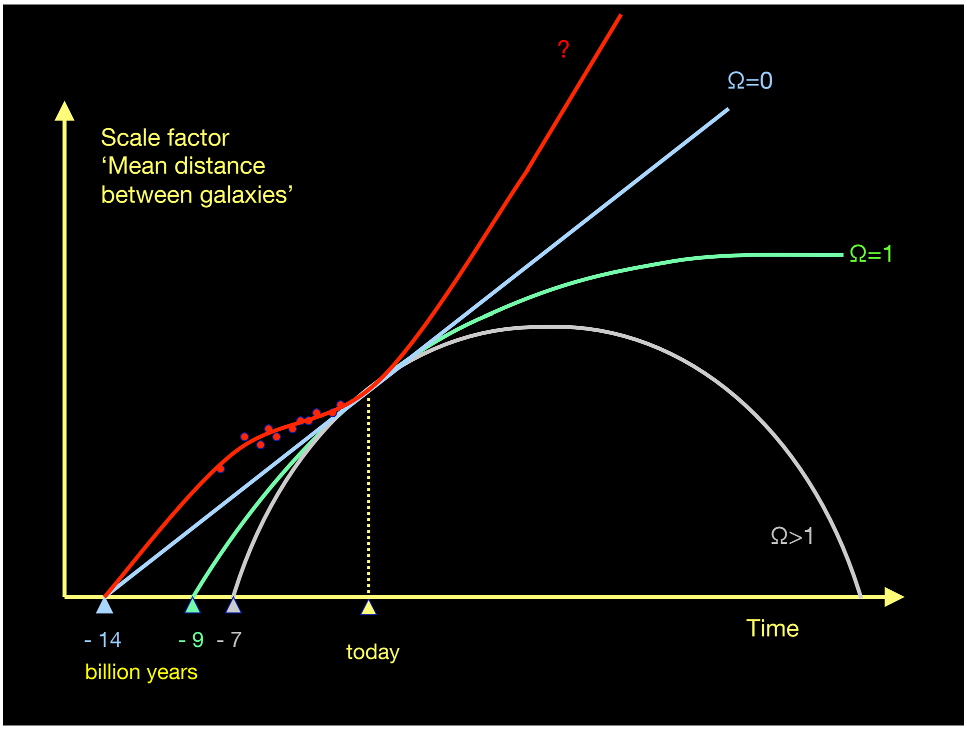
Reindl et al. 2005

Distance indicator!

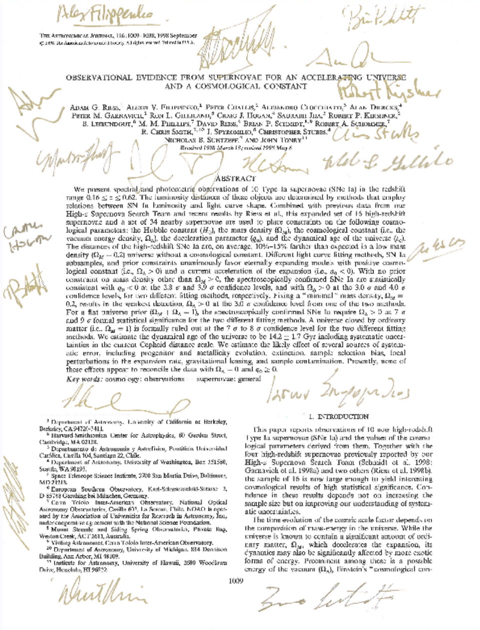




The SN Hubble Diagram



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

ABSTRACT

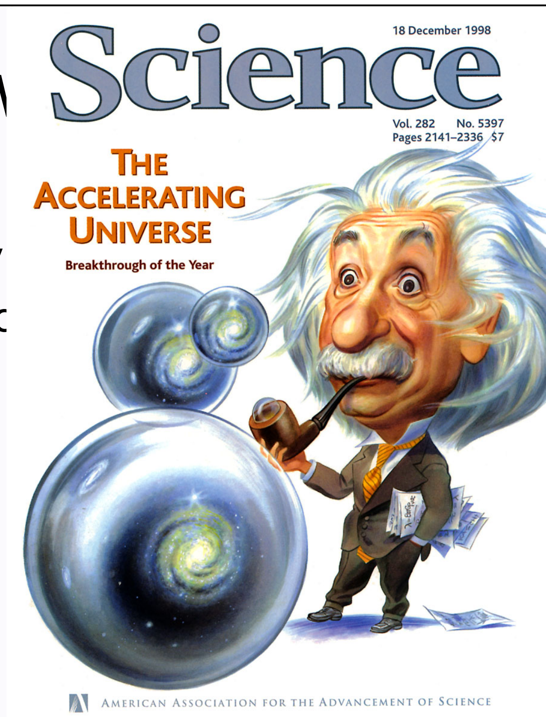
1. INTRODUCTION

?

Distant … than in

a freely

This rec… t



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

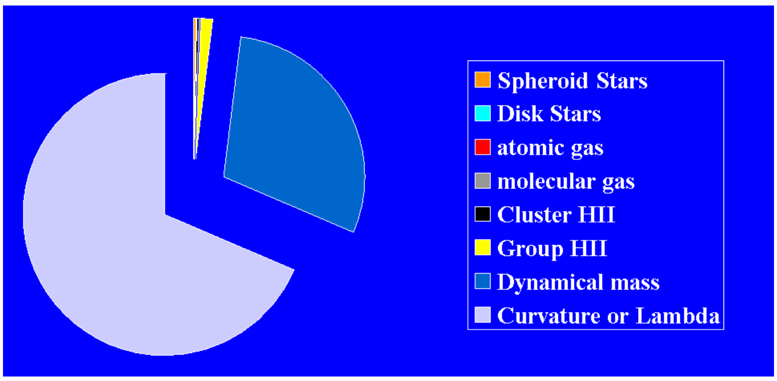
[Die Kosmologische Konstante] haben wir nur nötig, um eine quasi-statische Verteilung der Materie zu ermöglichen, wie es der Tatsache der kleinen Sterngeschwindigkeiten entspricht.

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.

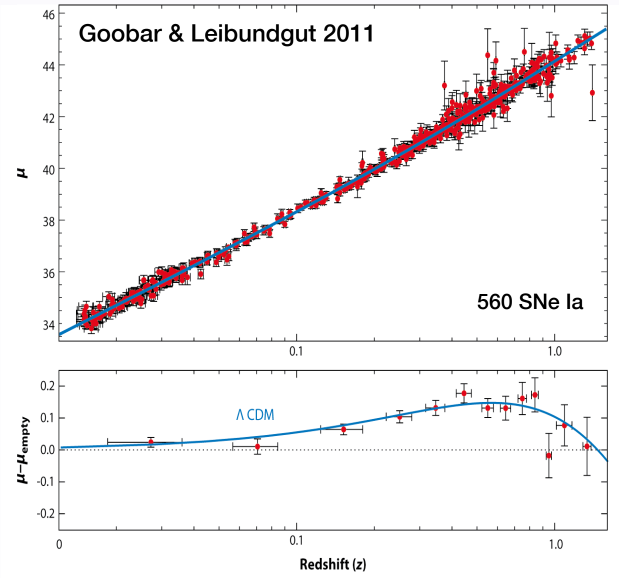
Einstein (1917)

Contents of the universe

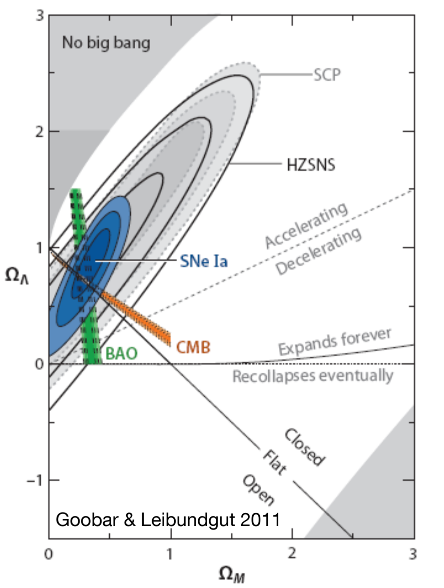
Dark Matter and Dark Energy are the dominant energy components in the universe.



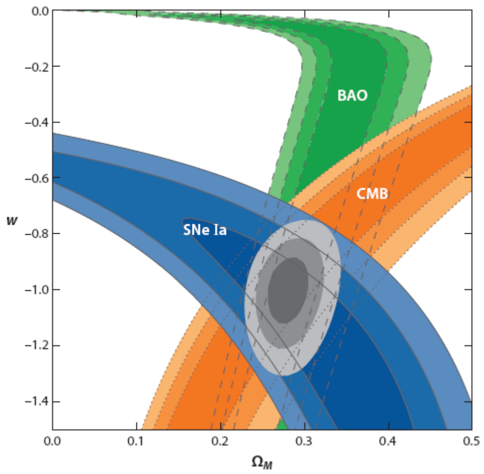
Supernova Cosmology



et voilà ...



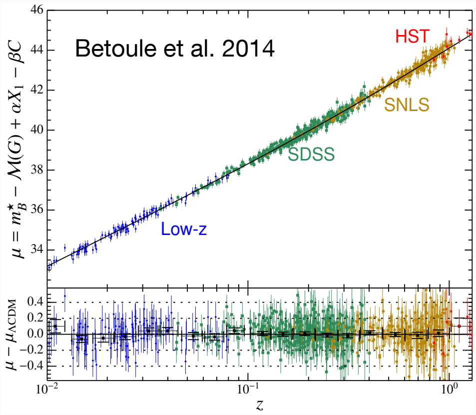
10 years of progress

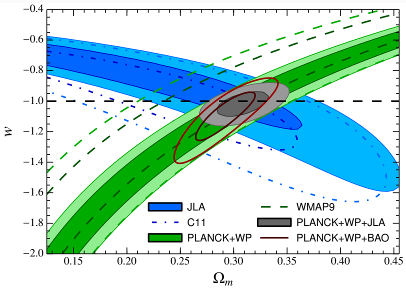


Constant ω firmly established

N_{SN}	Ω_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		$-0.91^{+016\ \pm 0.07}_{-0.20\,-0.14}$	SiFTO/SALT2	Conley et al. 2011
472	0.269 ± 0.015	$-1.061^{+0.069}_{-0.068}$	SALT2	Sullivan et al. 2011
580	0.271 ± 0.014	$-1.013^{+0.077}_{-0.073}$	SALT2	Suzuki et al. 2011
740	0.295 ± 0.034	-1.018±0.057 CMB	SALT2	Betoule et al. 2014
		-1.027±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?

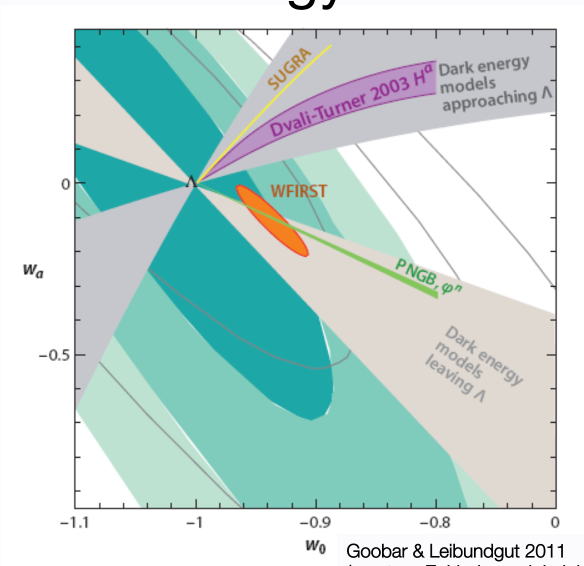
Already in hand

- >1000 SNe Ia for cosmology
- constant 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

Cosmology – more?



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

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 cosmologal 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 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

- 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