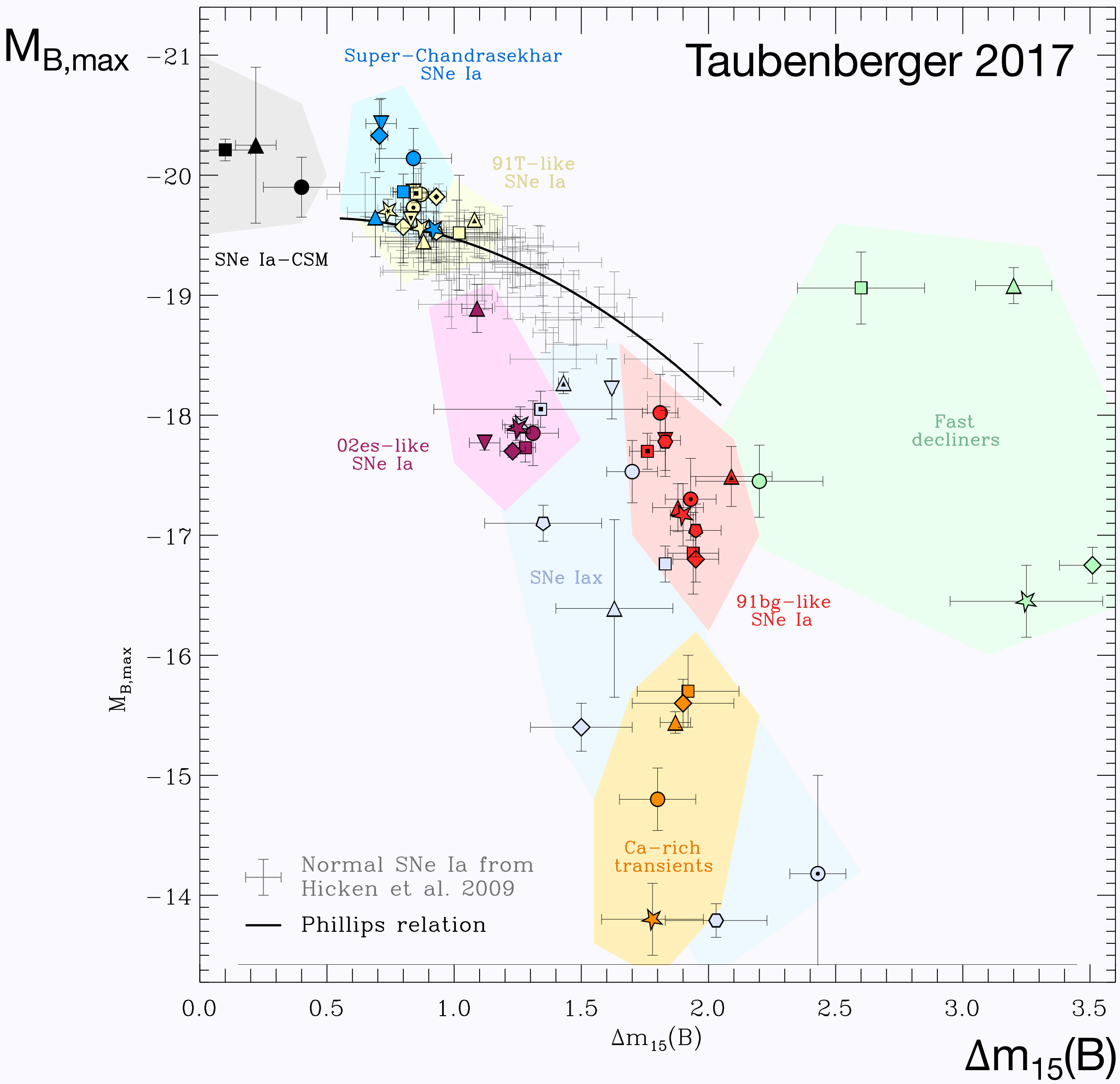
What are Type Ia Supernovae?

Bruno Leibundgut

The SN Ia variety



What is a SN Ia?

Table 1
Classification Criteria for SNe Iax

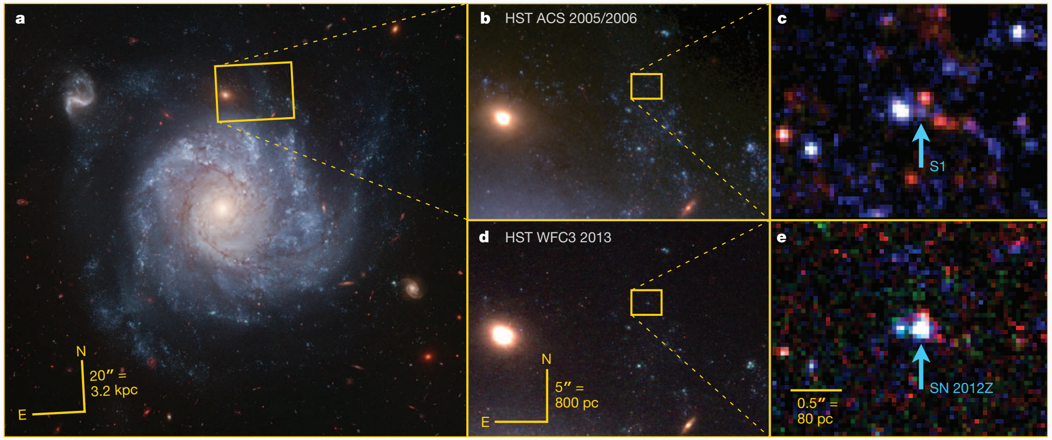
SN Class	Has Hydrogen?	$\|v\| \lesssim 8000$ km s^{-1}?	Low L for LC Shape	Spec. like SN 2002cx
SN Iax	**N**	**Y**	**Y**	**Y**
SN II	Y	Some	N/A	N
SN Ib/c	N	N	Y	N
SLSN I	N	Y	N	N
Normal SN Ia	N	N	N	N
Super-Chandra	N	Y	N	N
SN 1991T	N	N	N	Somewhat
SN 1991bg	N	N	N	N
SN 2000cx	N	N	Y	N
SN 2002bj	N	Y	N	Somewhat
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

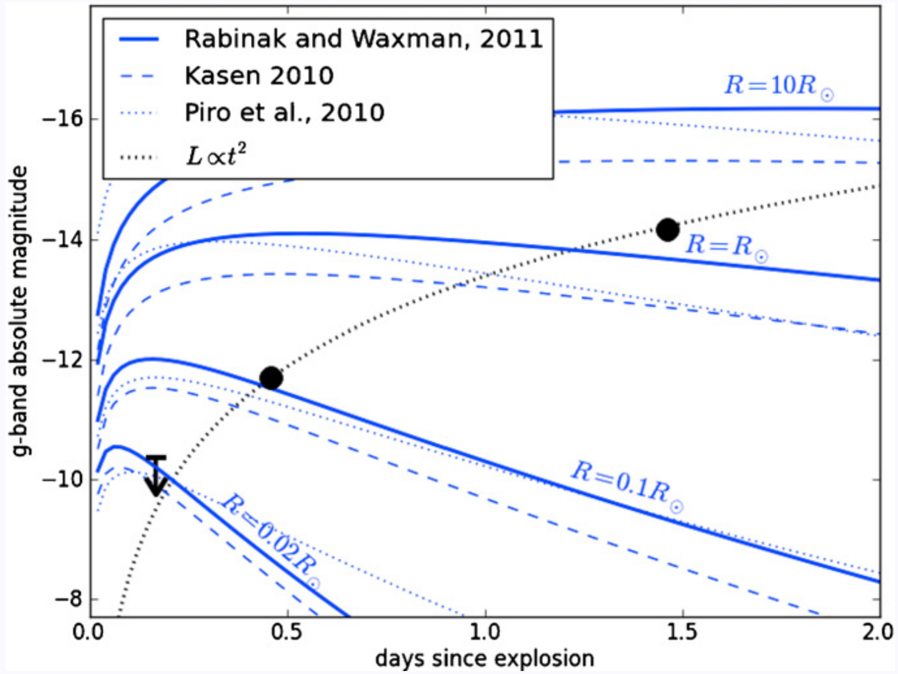
Progenitors

Direct detection

- white dwarfs about 30 magnitudes fainter than supernova → direct detection unlikely
- look for companions (binaries!)
- possible detection for a SN Iax



McCully et al. 2015

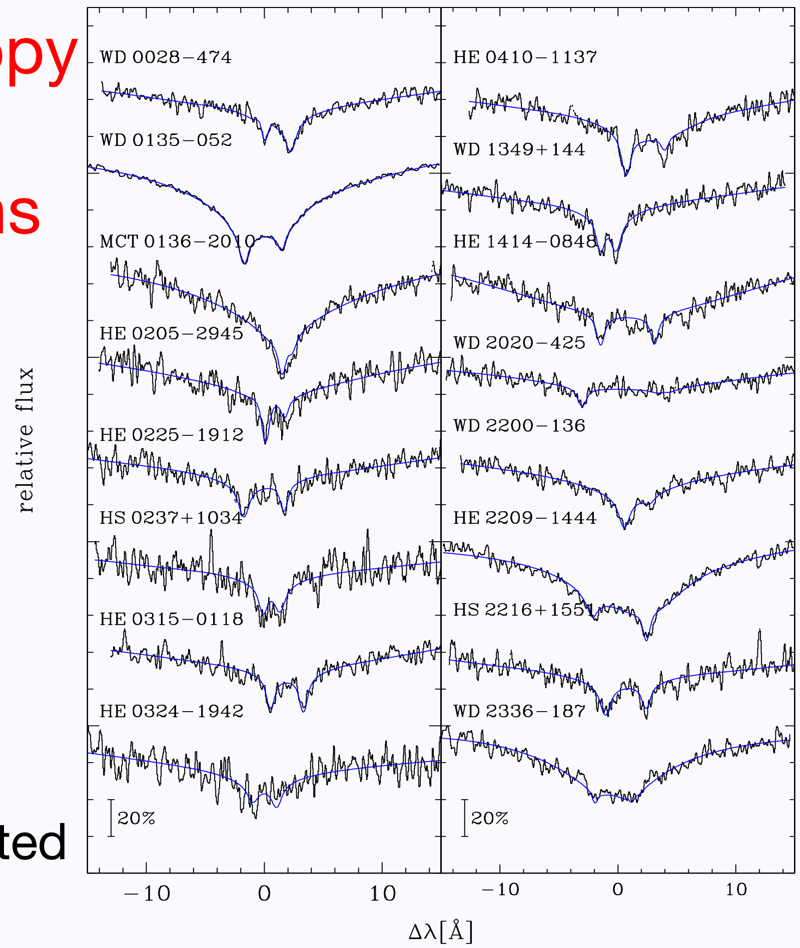


Bloom et al. 2012

Search for double degenerate systems - SPY

Supernova Progenitor surveY – SPY

- search for rapid radial velocity changes
  - high-resolution spectroscopy (UVES)
  - random phase observations
    - at least two phases with $\Delta t > 1\ day$
- 35 new DDs discovered
- complete sample
  - 20 double lined
  - 19 single lined

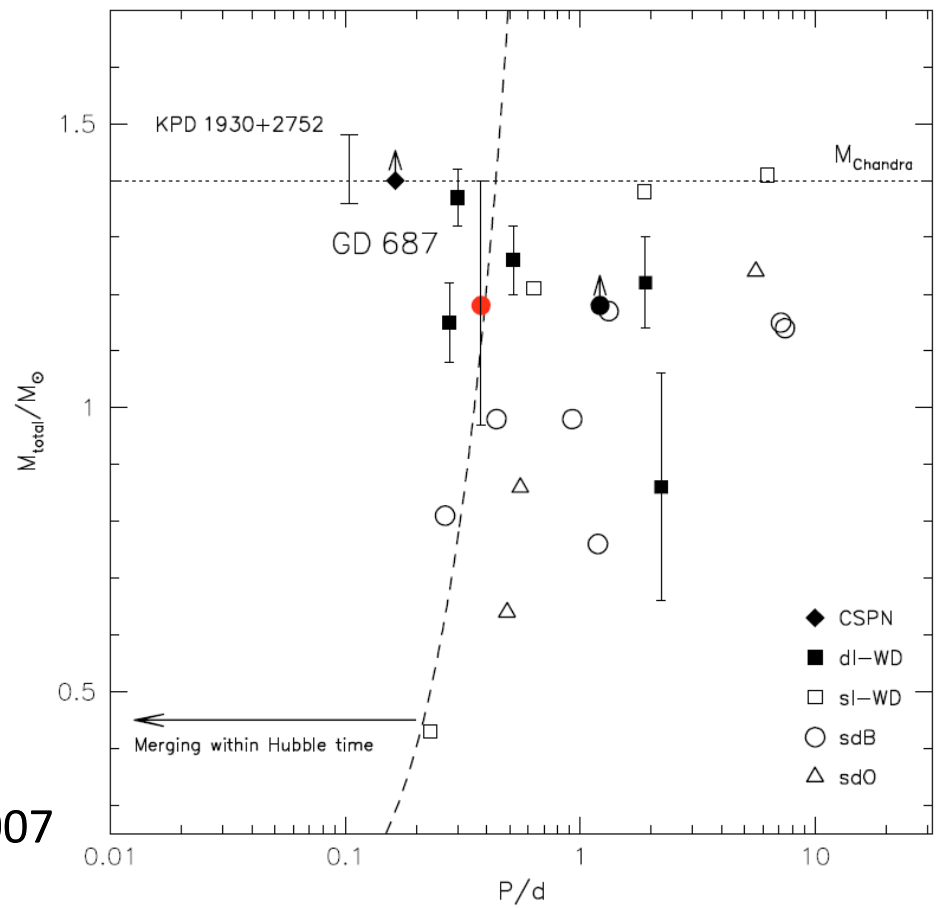


Napiwotzki et al., submitted

Supernova Progenitor surveY

644 DA white dwarfs checked for radial velocity changes

- are there double degenerate white dwarfs in the solar neighbourhood?

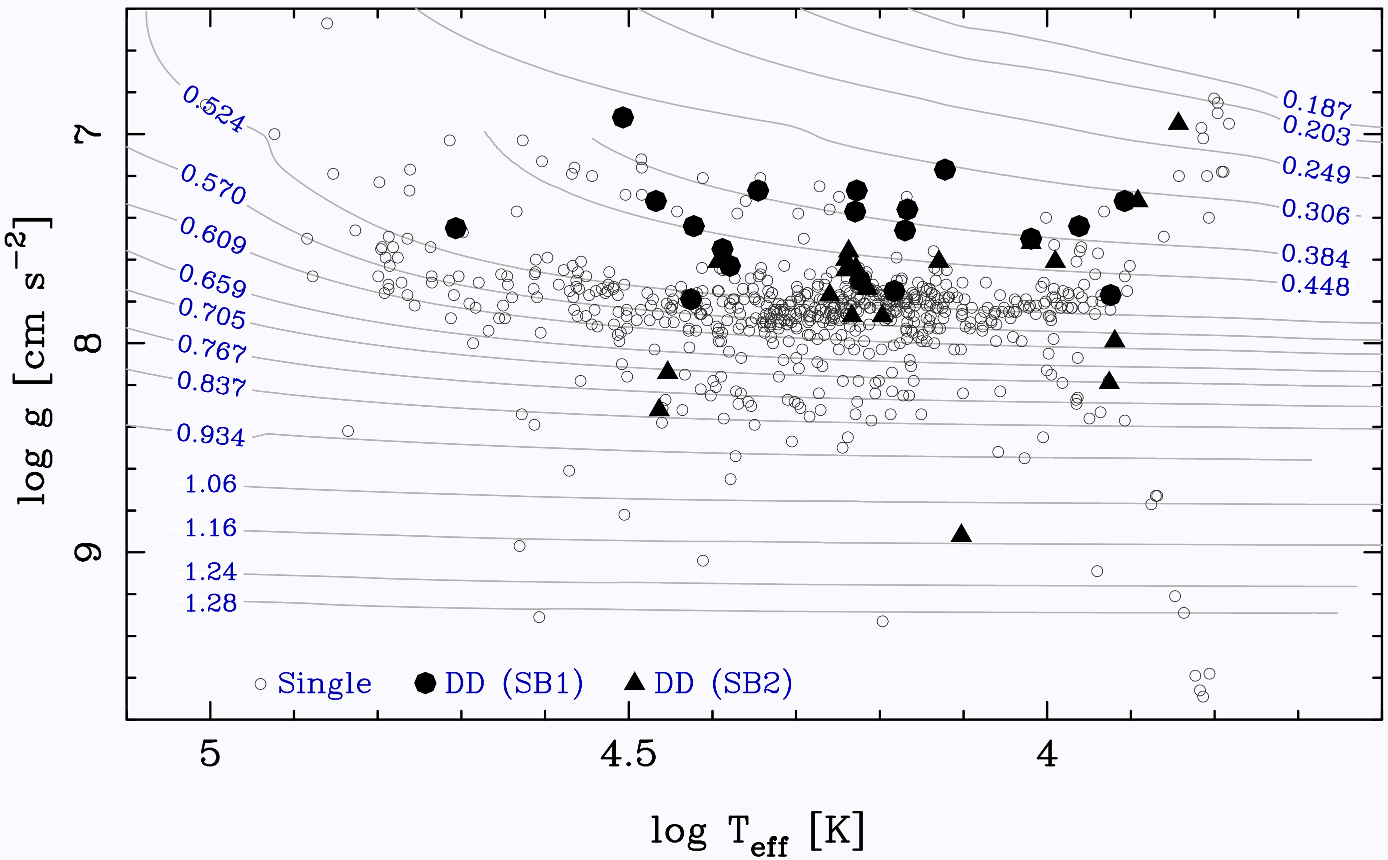


Napiwotzki et al. 2007
Geier et al. 2010

SPY results

Several massive DDs approaching M_{Chand}

Napiwotzki et al. 2017



Separate analysis

Rate analysis based on the SPY data

– Maoz & Hallakoun 2016 (arXiv:1609.02156)

– merger rate

$$R_{merge} = (7.3 \pm 2.7) \cdot 10^{-13}\ yr^{-1}\ M_{\odot}^{-1}$$

Range: $1.4 \cdot 10^{-13} < R_{merge} < 1.3 \cdot 10^{-11}\ yr^{-1} M_{\odot}^{-1}\ (2\sigma)$

– compares well with the estimated Ia rate in the Milky Way

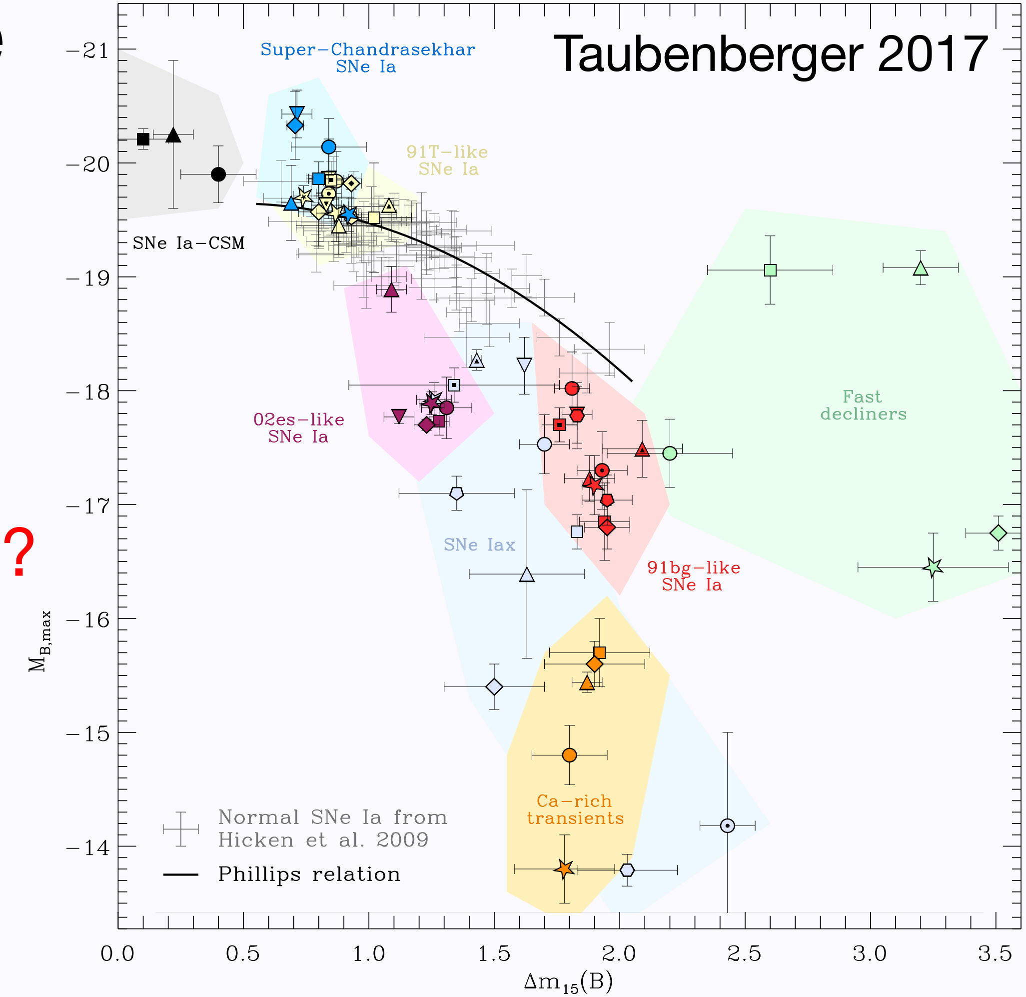
$$R_{Ia} \approx 1.1 \cdot 10^{-13}\ yr^{-1}\ M_{\odot}^{-1}$$

– together with dropping the Chandrasekhar-mass limit → could be enough double-degenerate systems to explain most SNe Ia

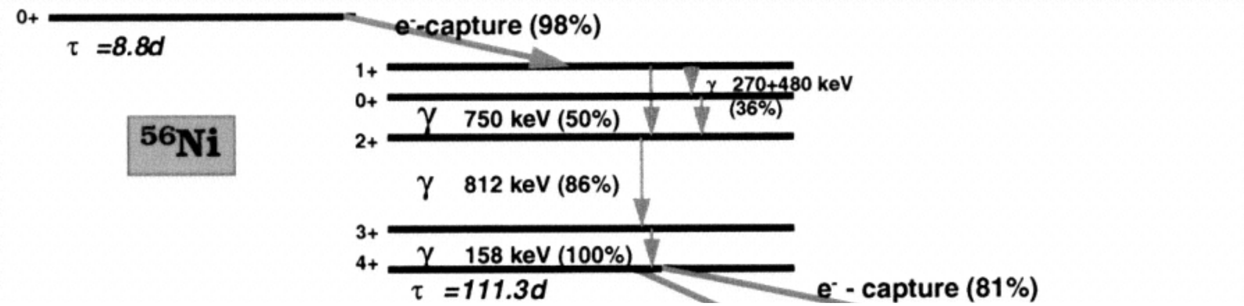
Type Ia Supernovae

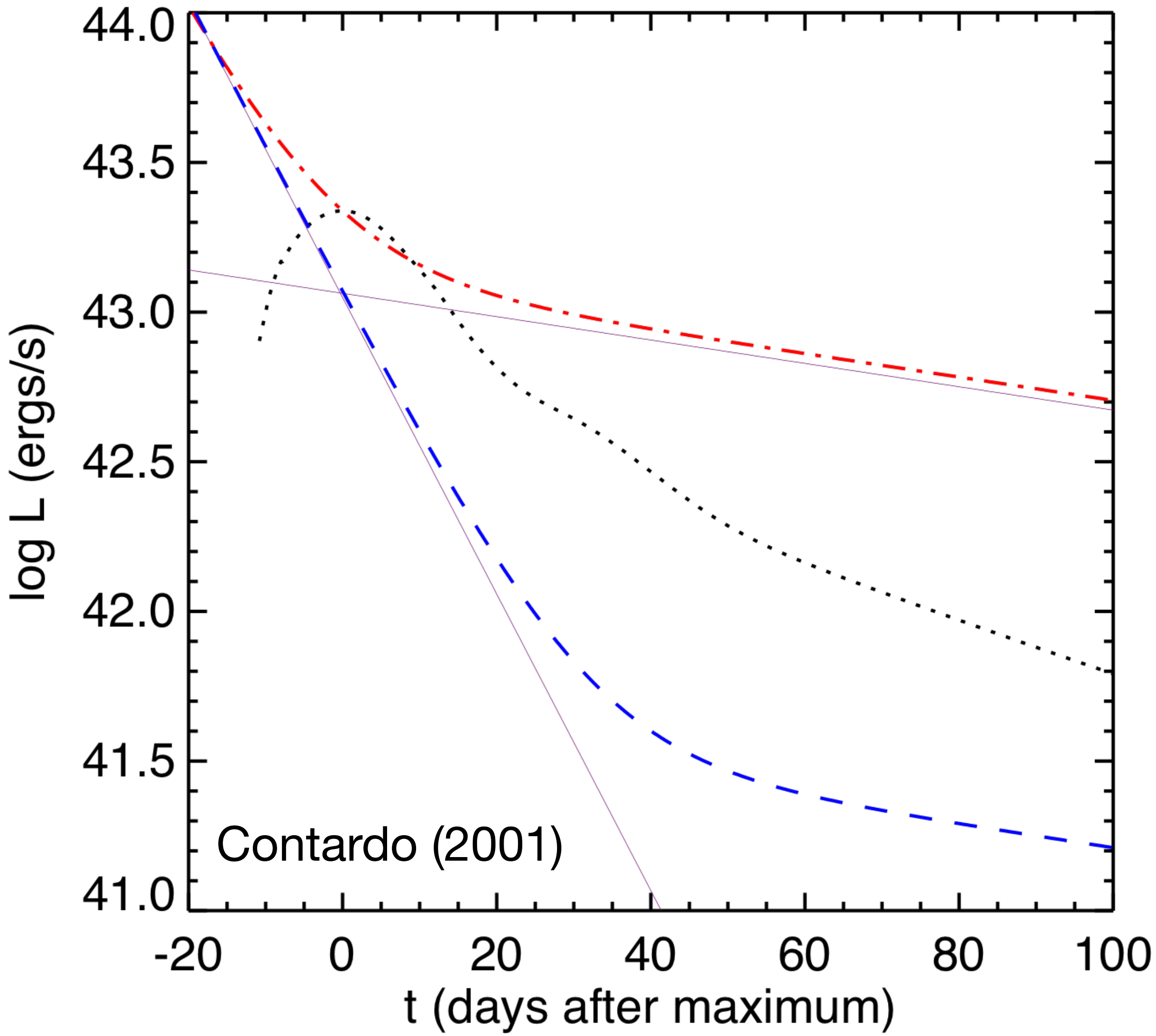
Variations on a theme

- critical parameters?
  - nickel mass
  - ejecta mass
  - explosion energy(?)
  - explosion mechanism?
  - progenitor evolution?



Radioactivity





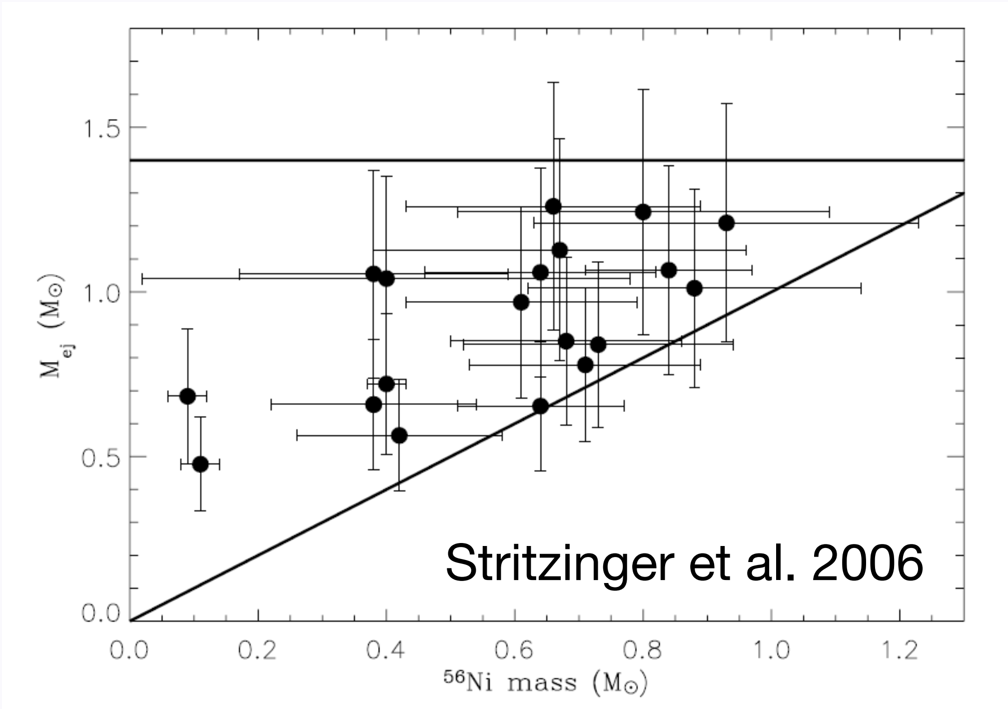
Isotopes of Ni and other elements

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

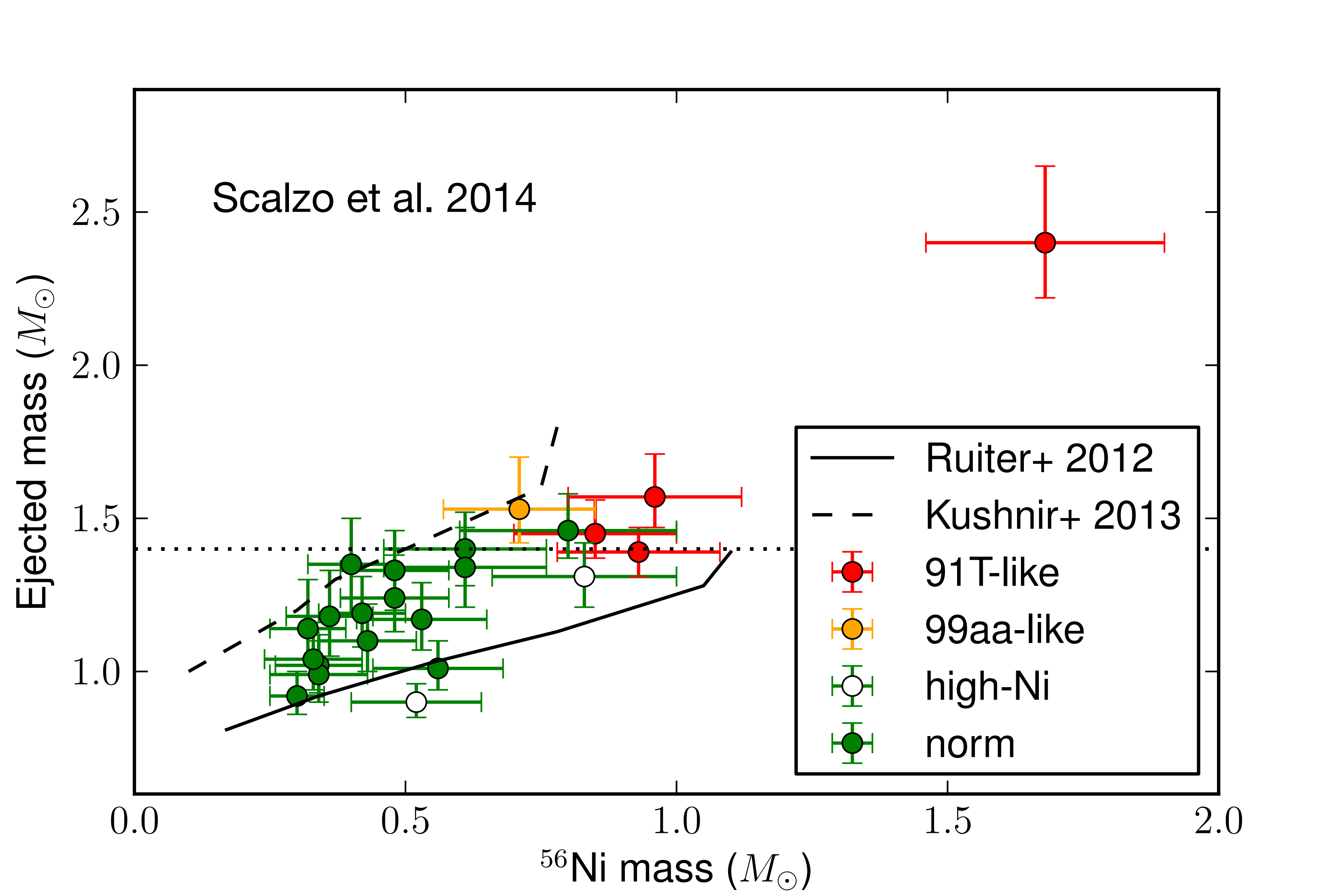
Ejecta masses

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

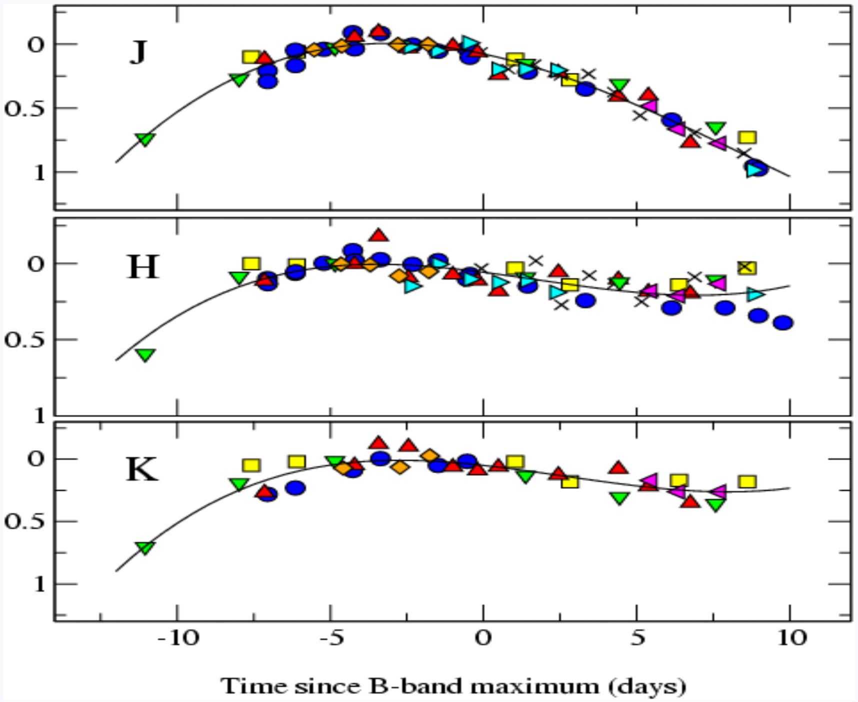


Ejecta masses



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 $\Delta m_{15}(B)$

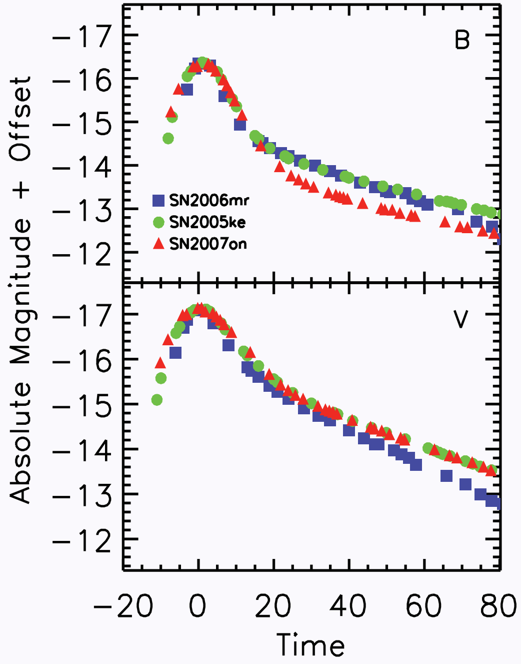
= 1980N (1.29)
= 1986G (1.79)
= 1998bu (1.05)
= 1999aw (0.81)
= 1999ee (0.94)
= 2000ca (1.01)
= 2001el (1.15)

Krisciunas et al. (2004)

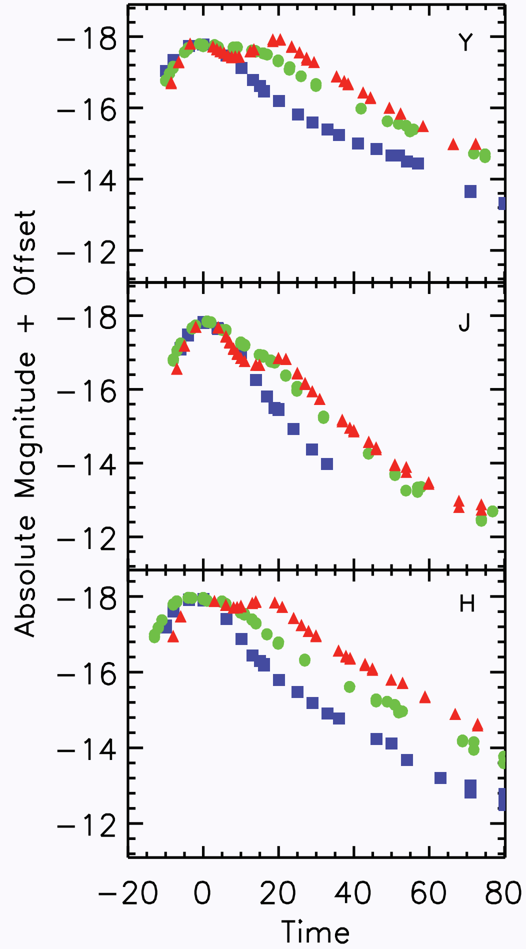
Mark Phillips

Others find this too

- Light curves in the near-IR very uniform at peak, but large differences at later times



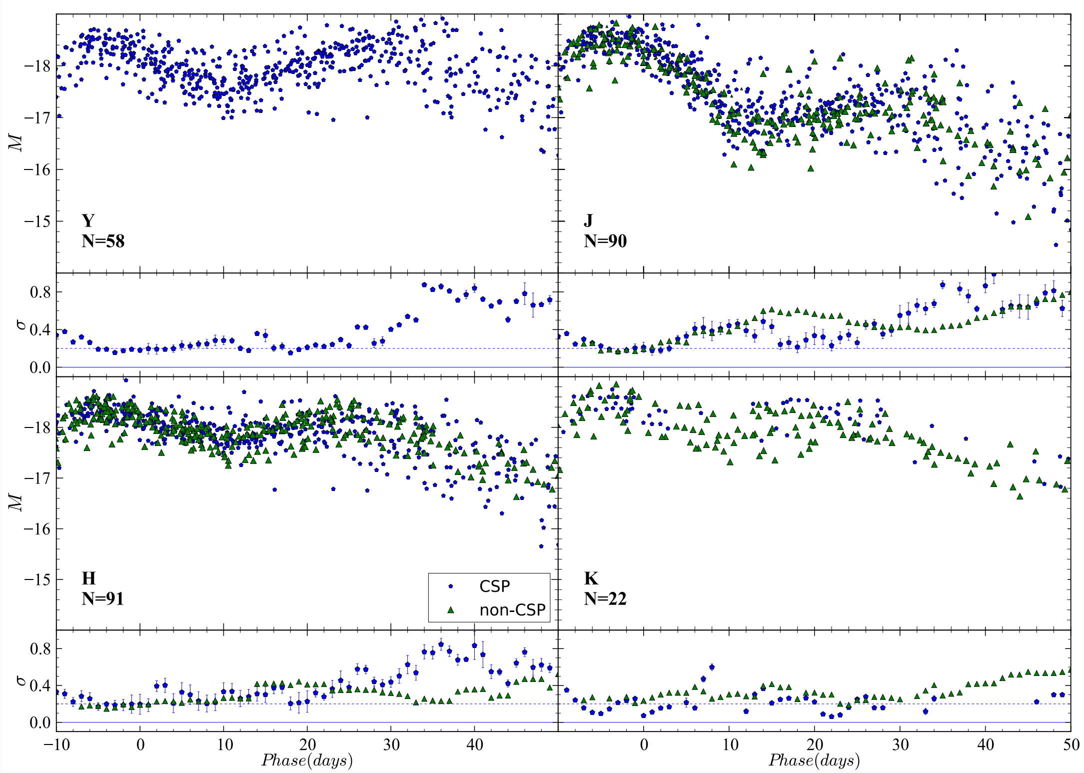
SN 2006mr
SN 2005ke
SN 2007on
Kattner et al. 2012



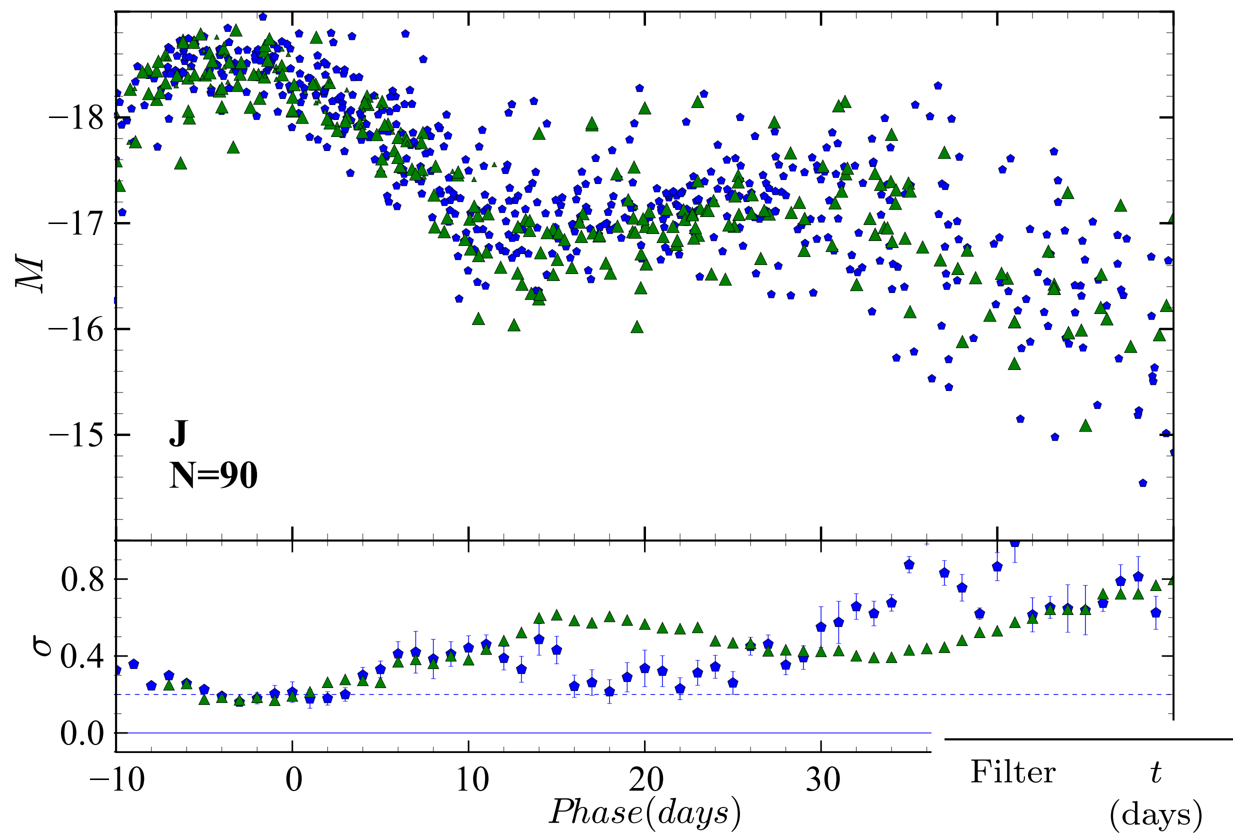
Large literature sample

- 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
  - 58in Y, 22 in K
- Mostly Carnegie SN Project data (Contreras et al. 2010, Stritzinger et al. 2011)

Dhawan et al. 2015



Infrared light curves



Dhawan et al. 2015

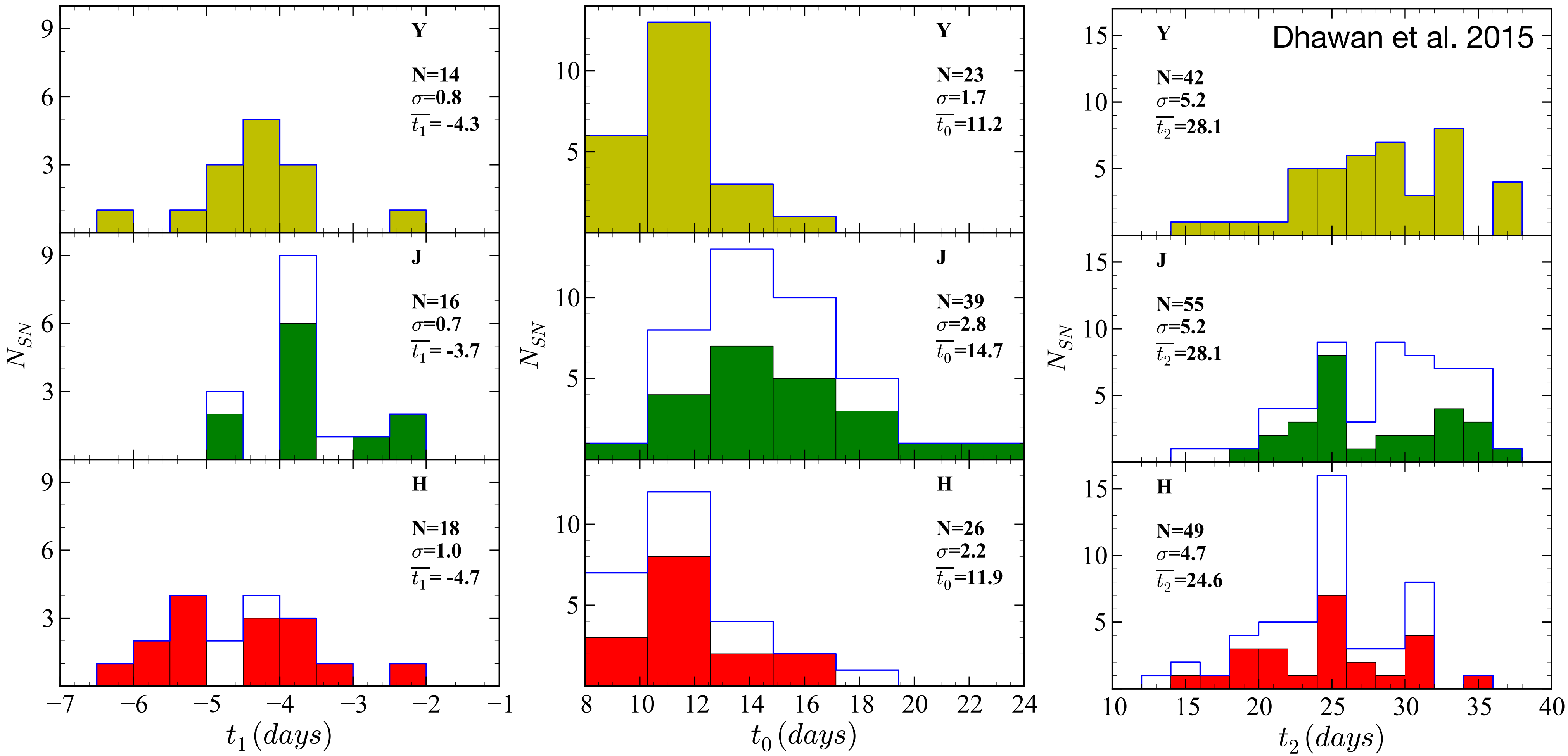
Filter	t (days)	$\sigma(M)$ (mag)	Phase range ($\sigma(M) < 0.2$ mag)	SN sample
Y	-4.4	0.15	$[-4\ ,\ +1]$	CSP
J	-3.6	0.16	$[-4\ ,\ +3]$	CSP
J	-3.8	0.17	$[-6\ ,\ +1]$	non-CSP
H	-5.1	0.17	$[-5\ ,\ +1]$	CSP
H	-4.7	0.14	$[-7\ ,\ +2]$	non-CSP

NOT after maximum

4 days

14 days

30 days

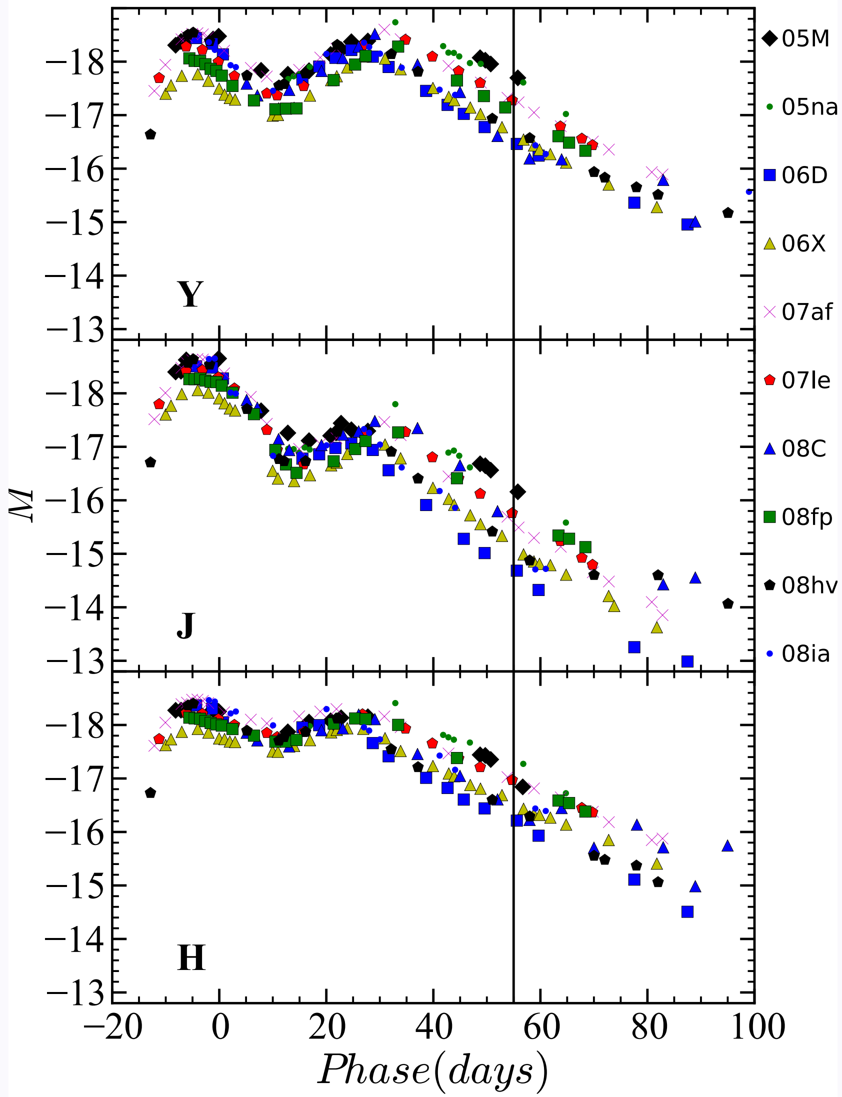


maximum

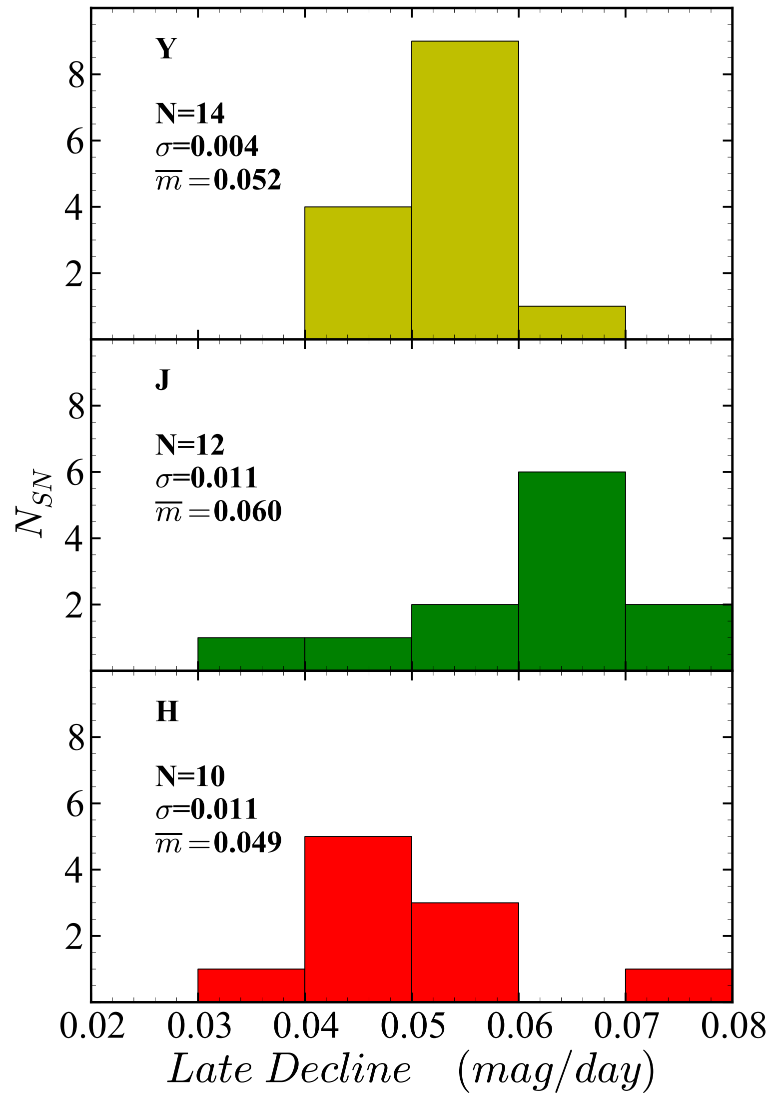
minimum

second maximum

Late decline (t>40 days)

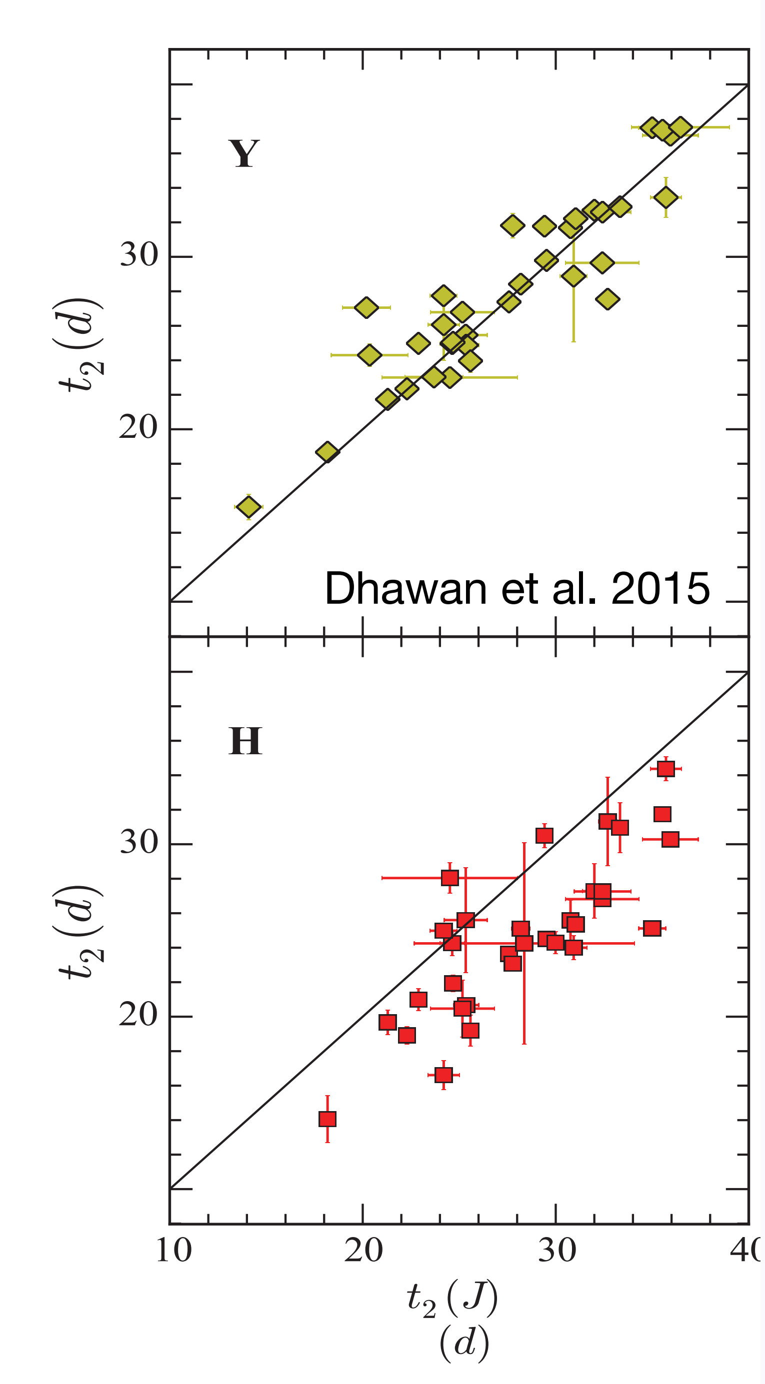


Dhawan et al. 2015



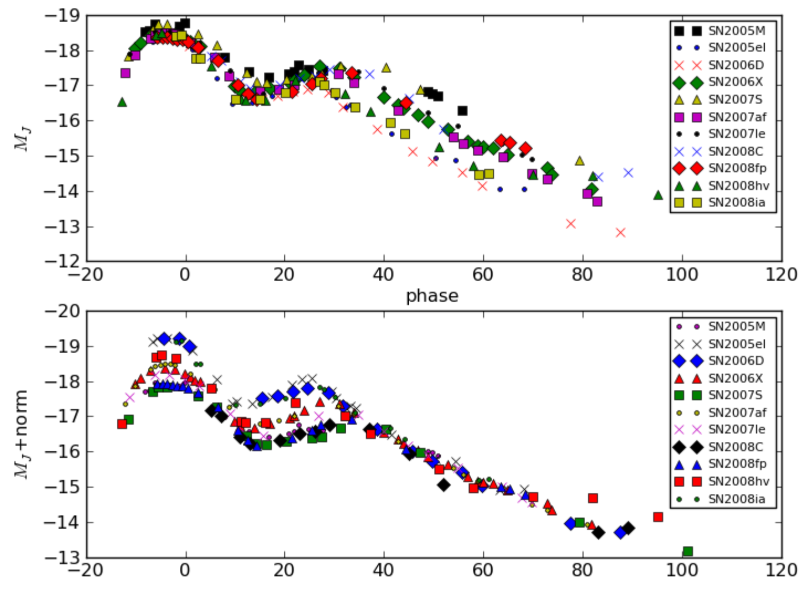
Correlations

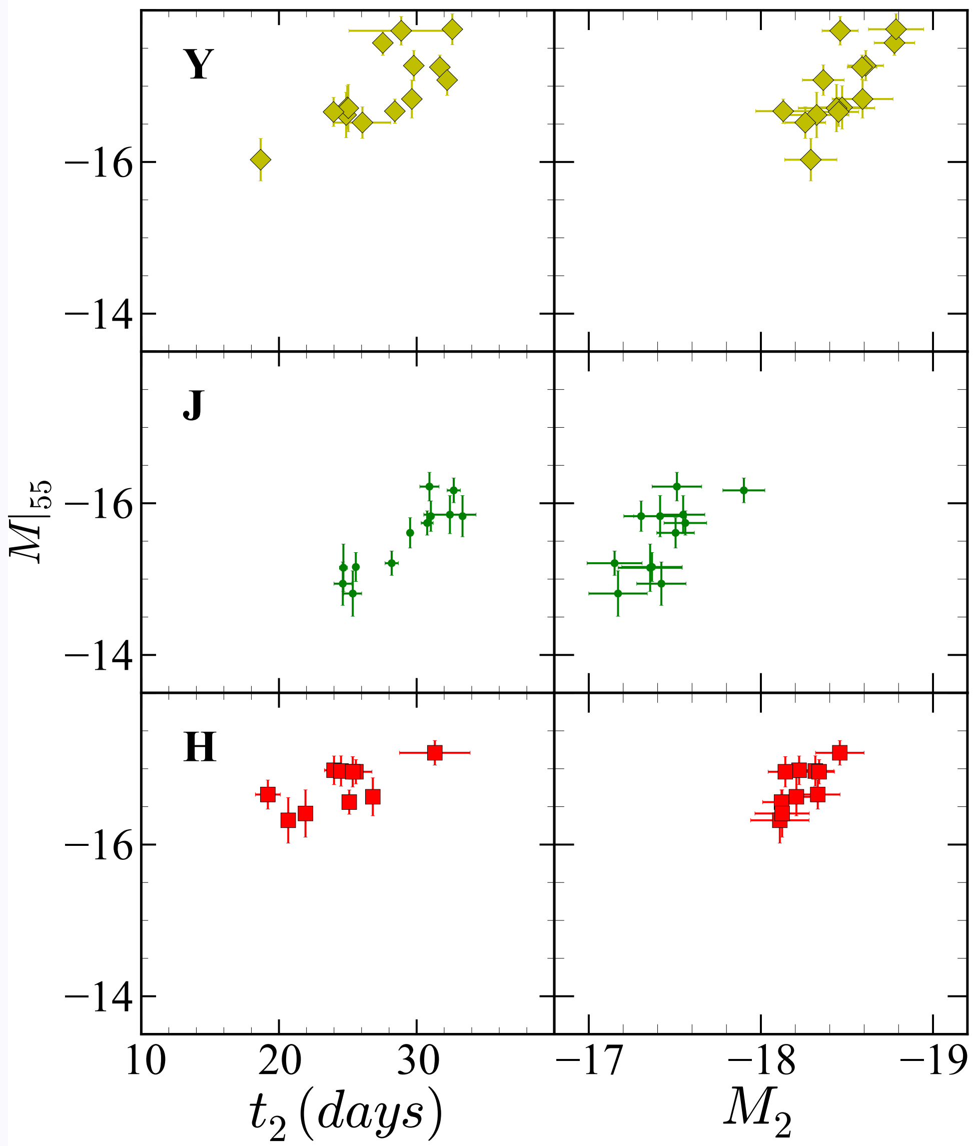
Phase of the second maximum appears to be a strong discriminator among SNe Ia



Correlations

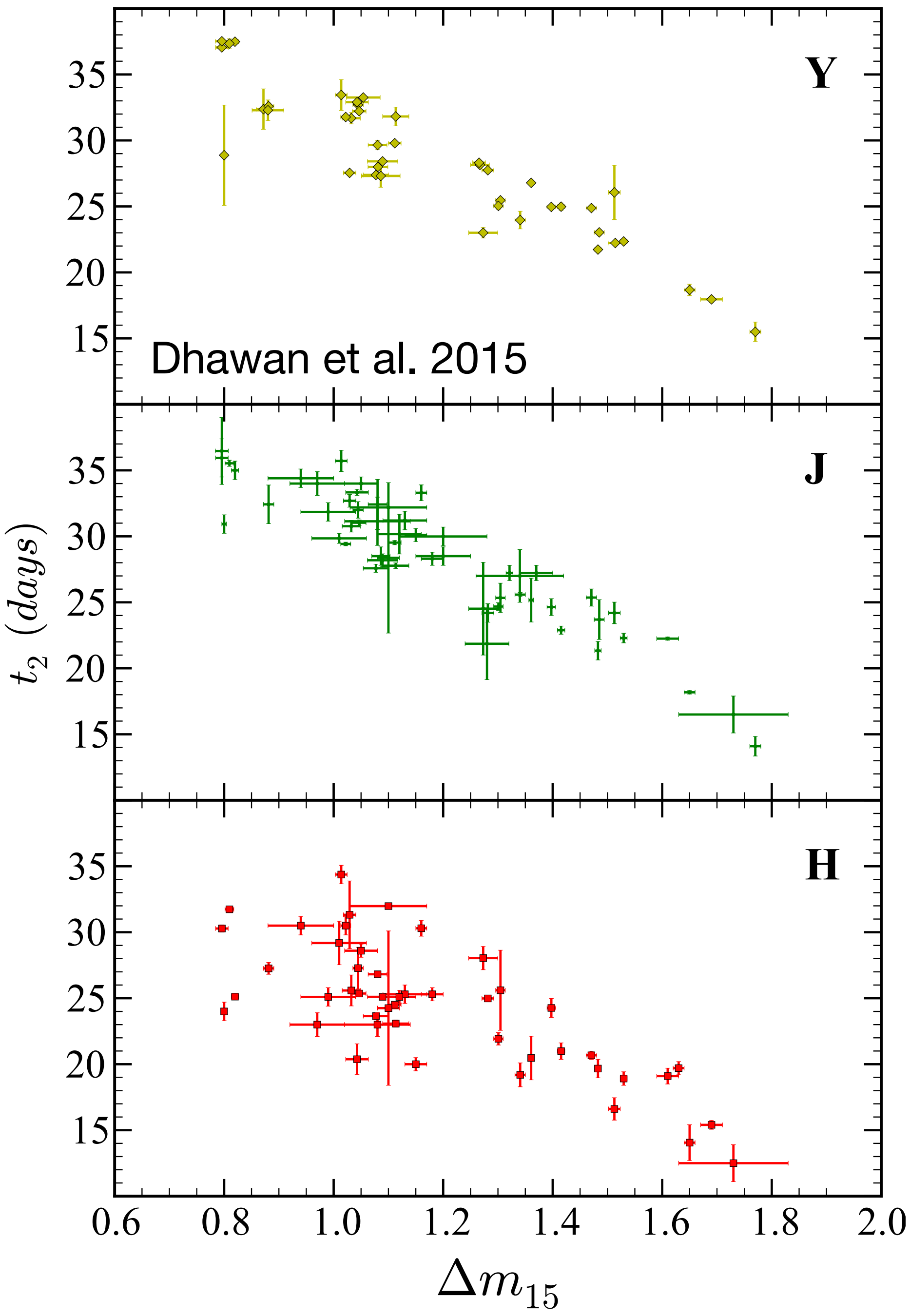
Luminosity of late decline and the phase of the second maximum are linked





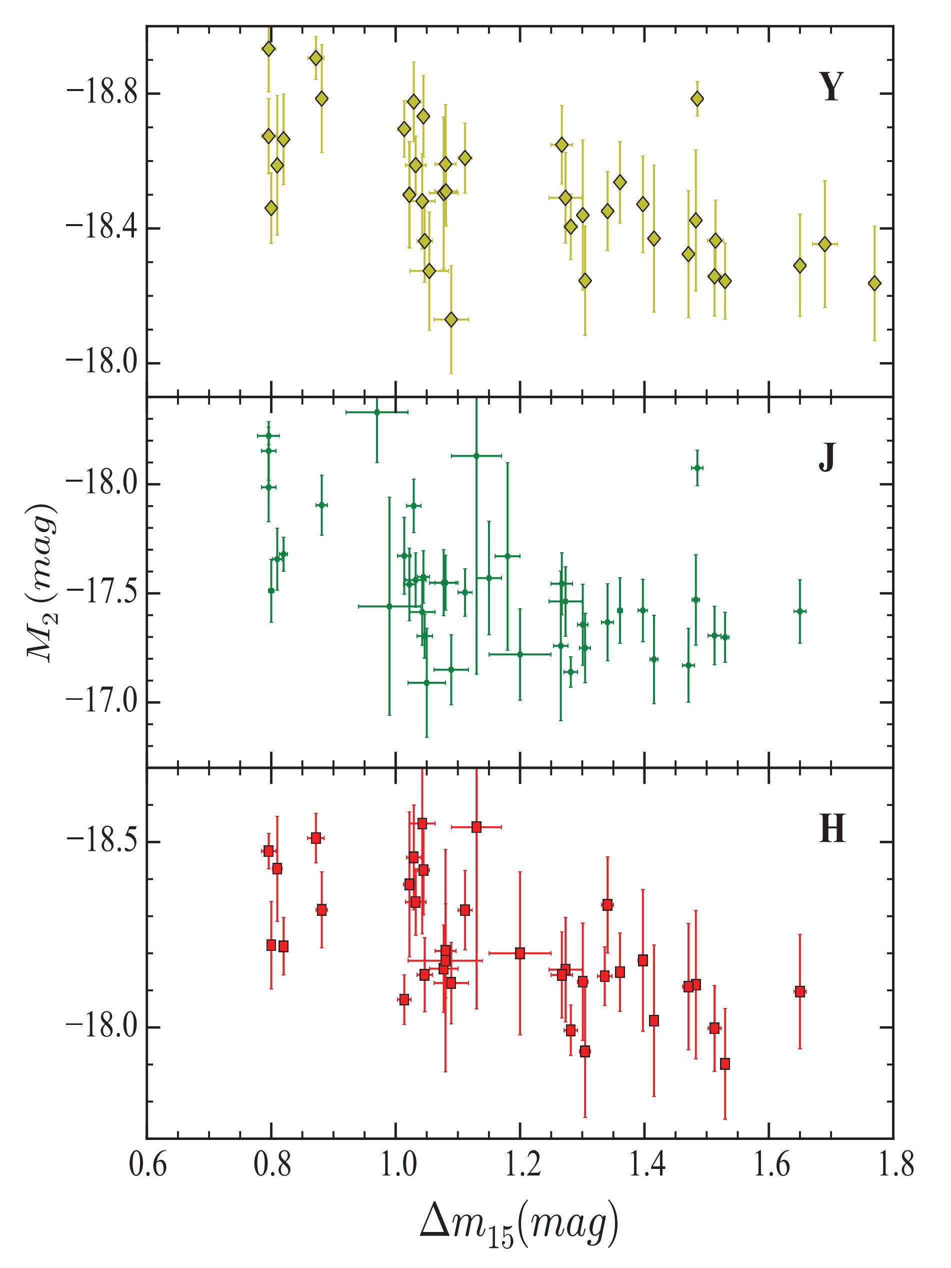
Correlations with the optical

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



Correlations

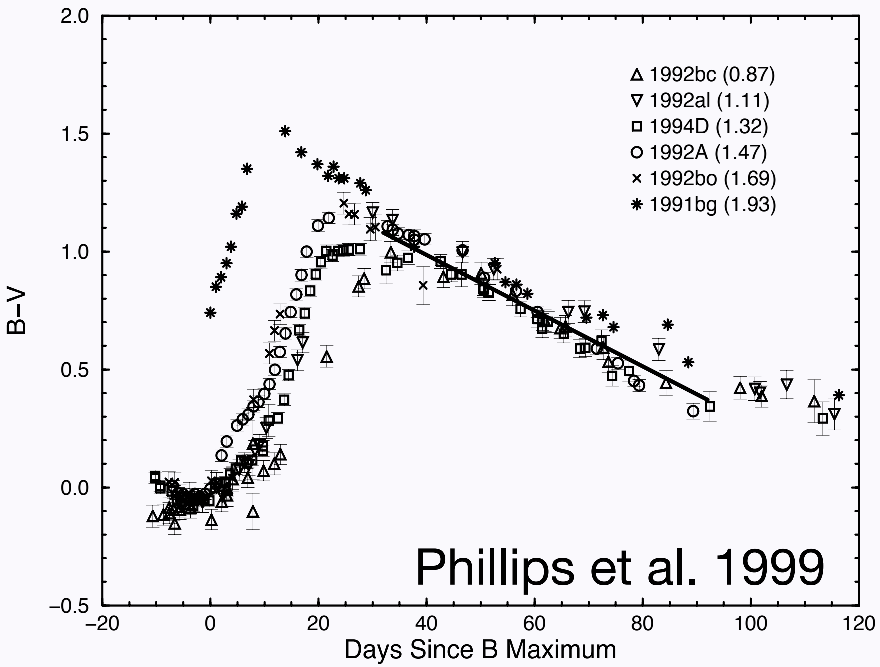
- Note very only weak correlation with the peak magnitude!

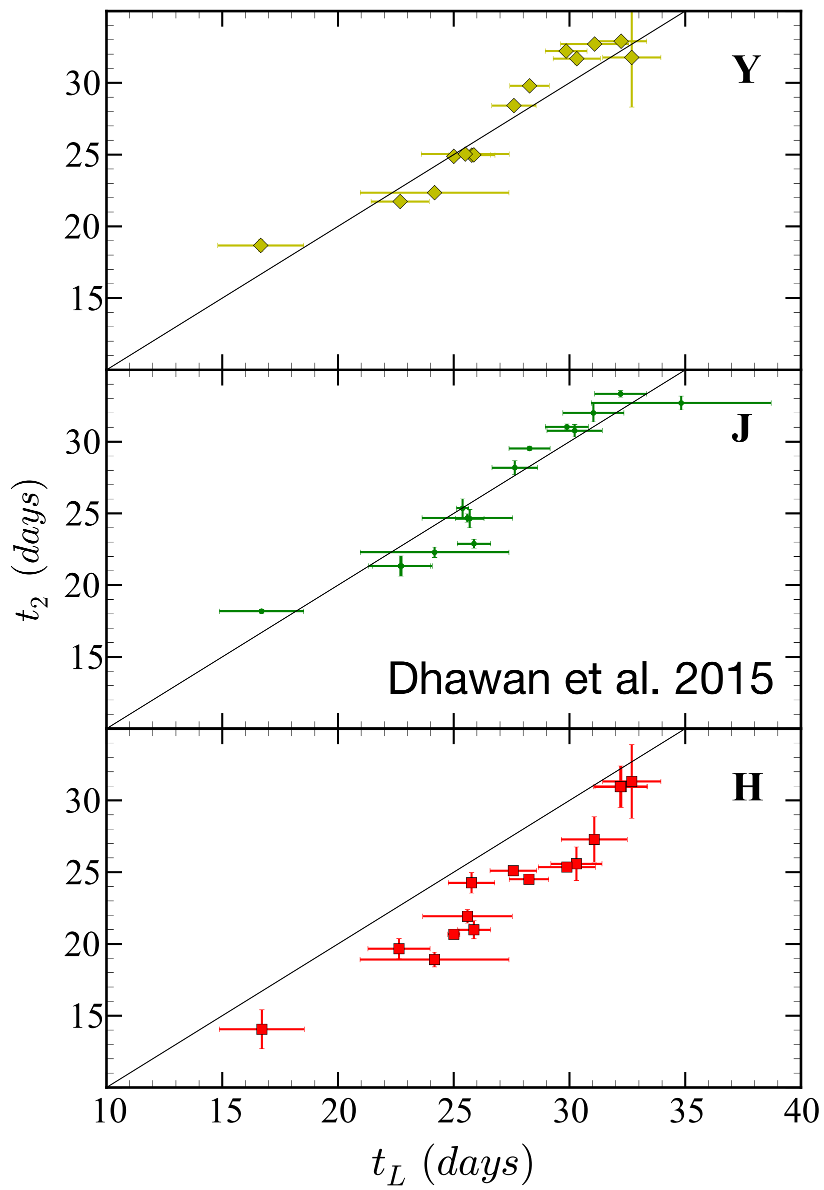


Dhawan et al. 2015

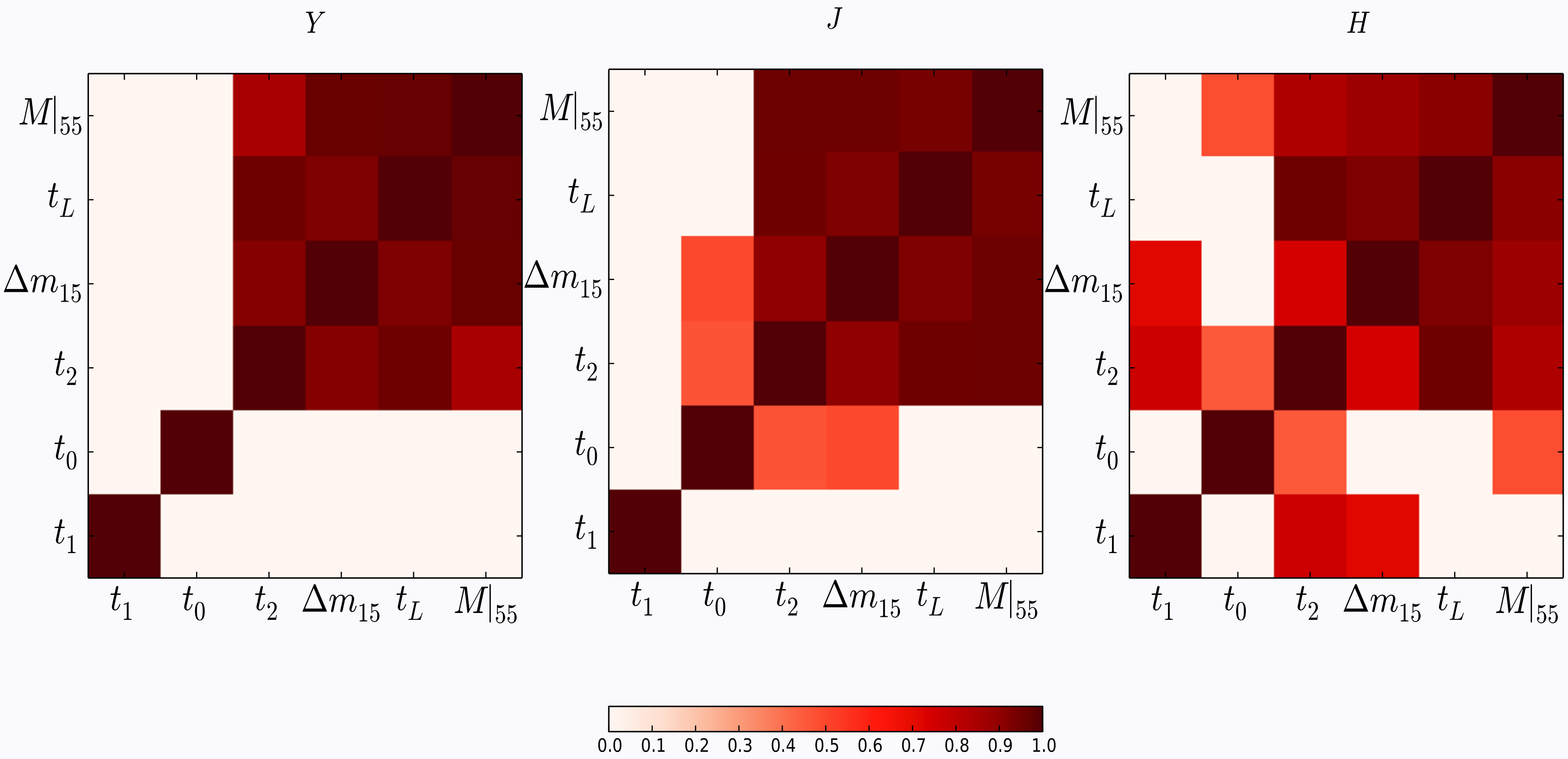
Correlation with optical colour

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





Summary

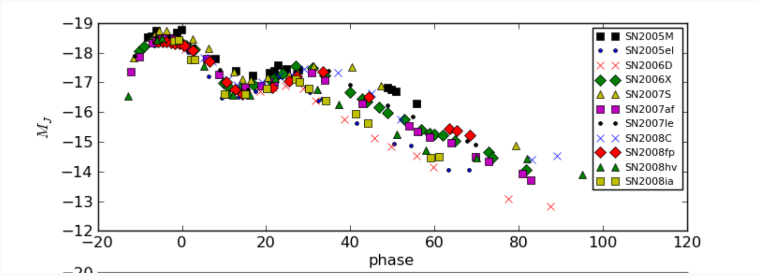


Dhawan et al. 2015

SNe Ia in the NIR

Consistent picture emerging

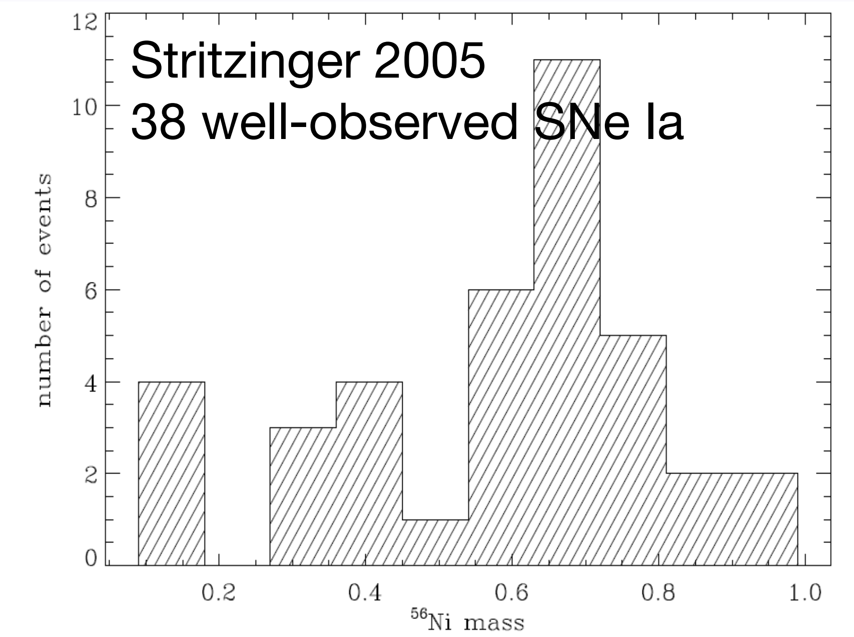
- Second peak in the near-IR is the result of the recombination of Fe^{++} to Fe^{+} (Kasen 2006)

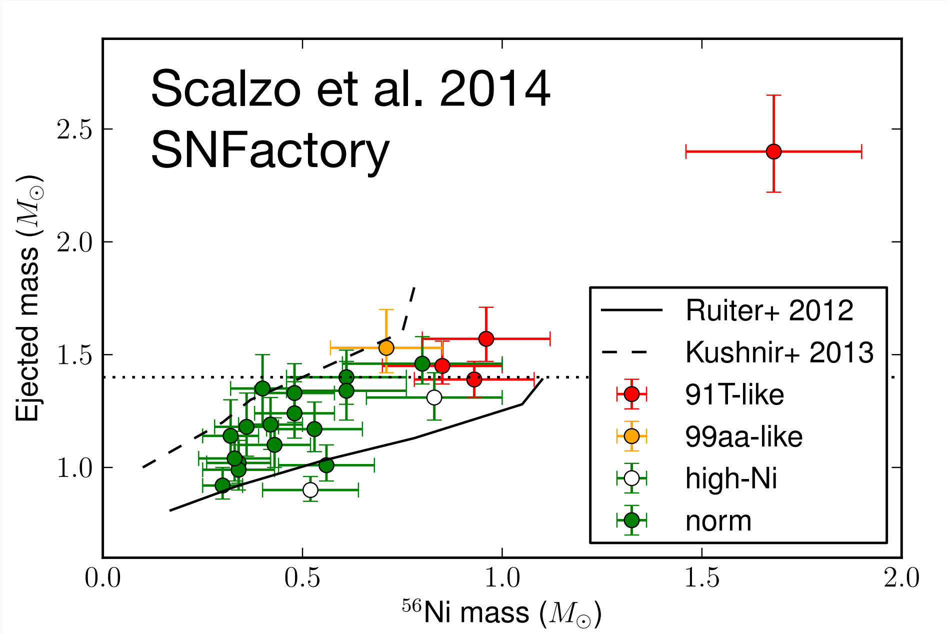


- Uniform ejecta structure
  - late declines very similar
- higher luminosity indicates higher ^{56}Ni mass
- later secondary peak also indicates higher Fe/Ni mass
- Ni mass and (optical) light curve parameters correlate (Scalzo et al. 2014)

Nickel masses directly?

- Correlate phase of second maximum with observed nickel masses
  - avoid ‘detour’ through optical light curve shape parameter (Δm_{15})

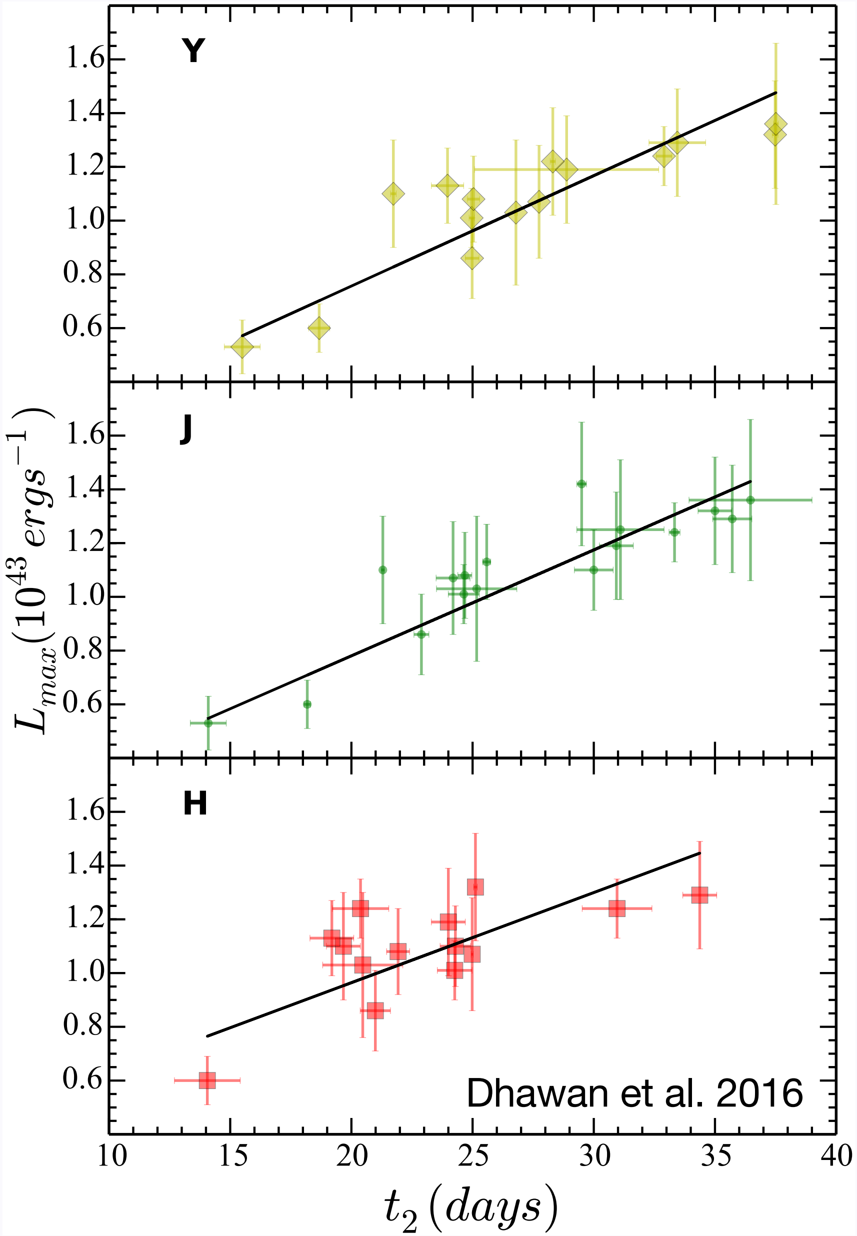




Luminosity function of SNe Ia

Use the phase of the second maximum to derive the bolometric peak luminosity

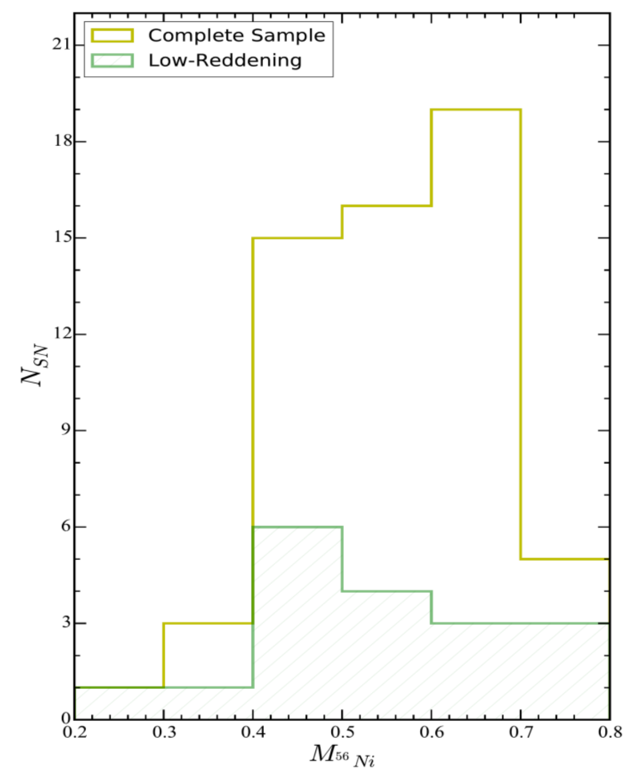
- calibrated on a sample of reddening-free SNe Ia
  - SNe with E(B-V)<0.1
  - pseudo-bolometric light curves (UBVRIYJH)
- apply to reddened objects



Luminosity function of SNe Ia

M_{Ni} (inferred)	σ	Method	Reference
0.62	0.13	γ ray lines	Churazov et al. (2014)
0.56	0.10	γ ray lines	Diehl et al. (2015)
0.37	...	Bolometric light curve $A_V = 1.7$ mag	Churazov et al. (2014), Margutti et al. (2014)
0.77	...	Bolometric light curve $A_V = 2.5$ mag	Churazov et al. (2014), Goobar et al. (2014)
0.64	0.13	NIR second maximum	this work (combined fit)
0.60	0.10	NIR second maximum + measured rise	this work

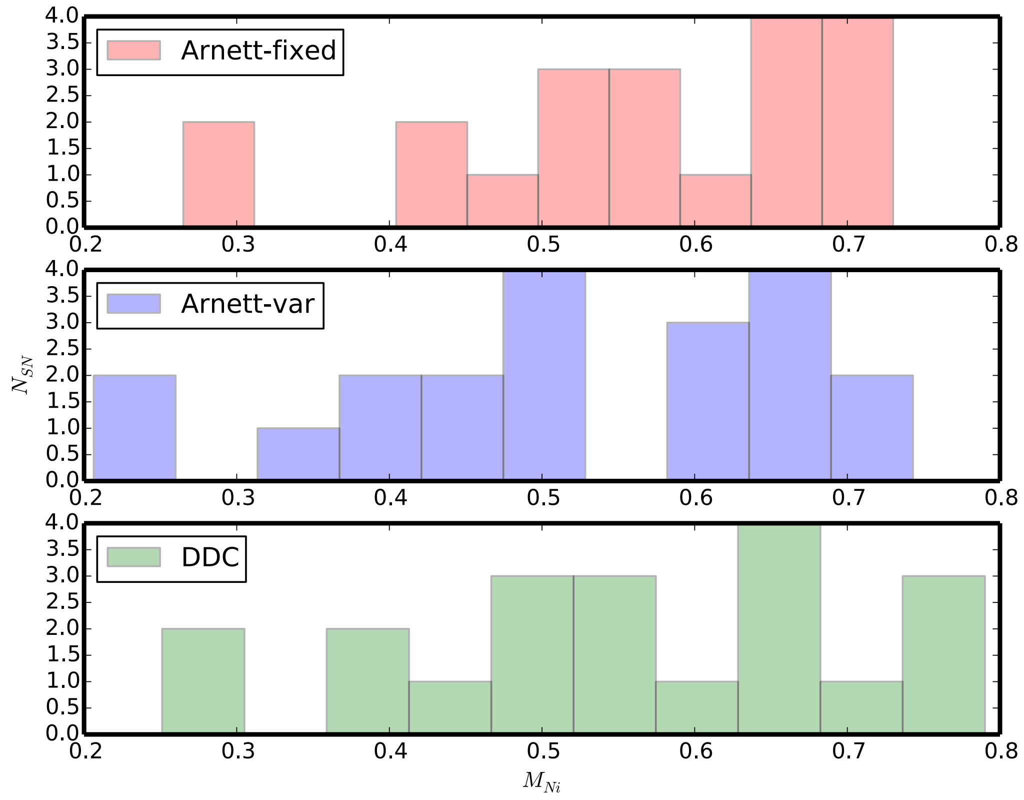
- SN 2014J test passed
- Potential to determine the luminosity function and Ni distribution



Dhawan et al. 2016

Nickel masses

- Using a timing parameter for nickel masses
  - completely independent on reddening and multiple light curves
- Explore different methods to calculate the nickel mass (currently still all Chandrasekhar-mass progenitors



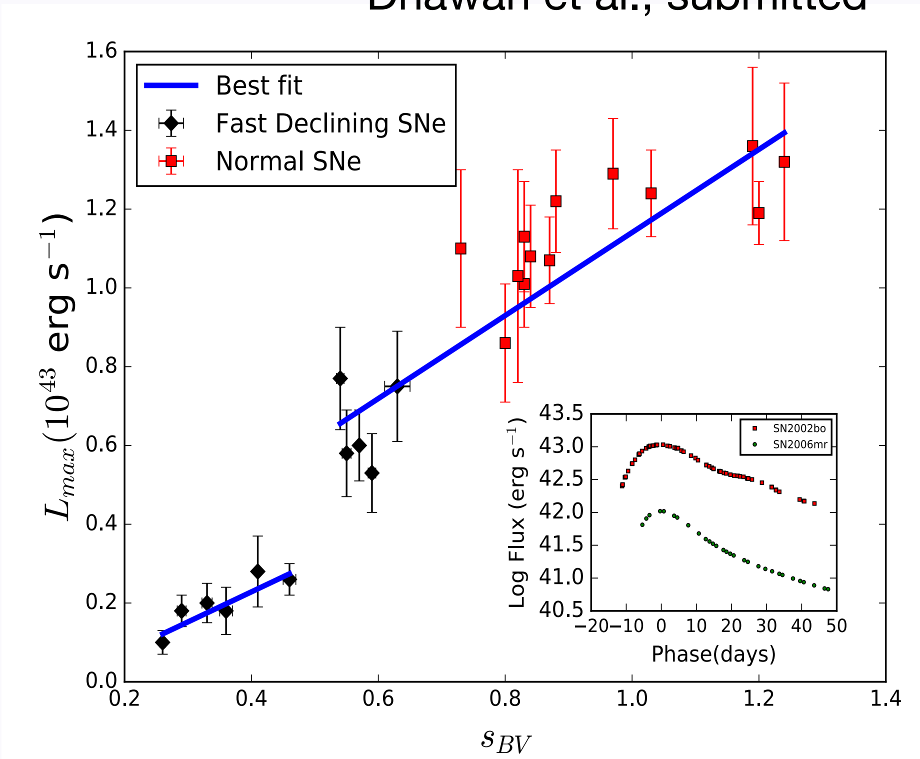
Dhawan et al. 2016

Fast-declining SNe Ia

Two groups?

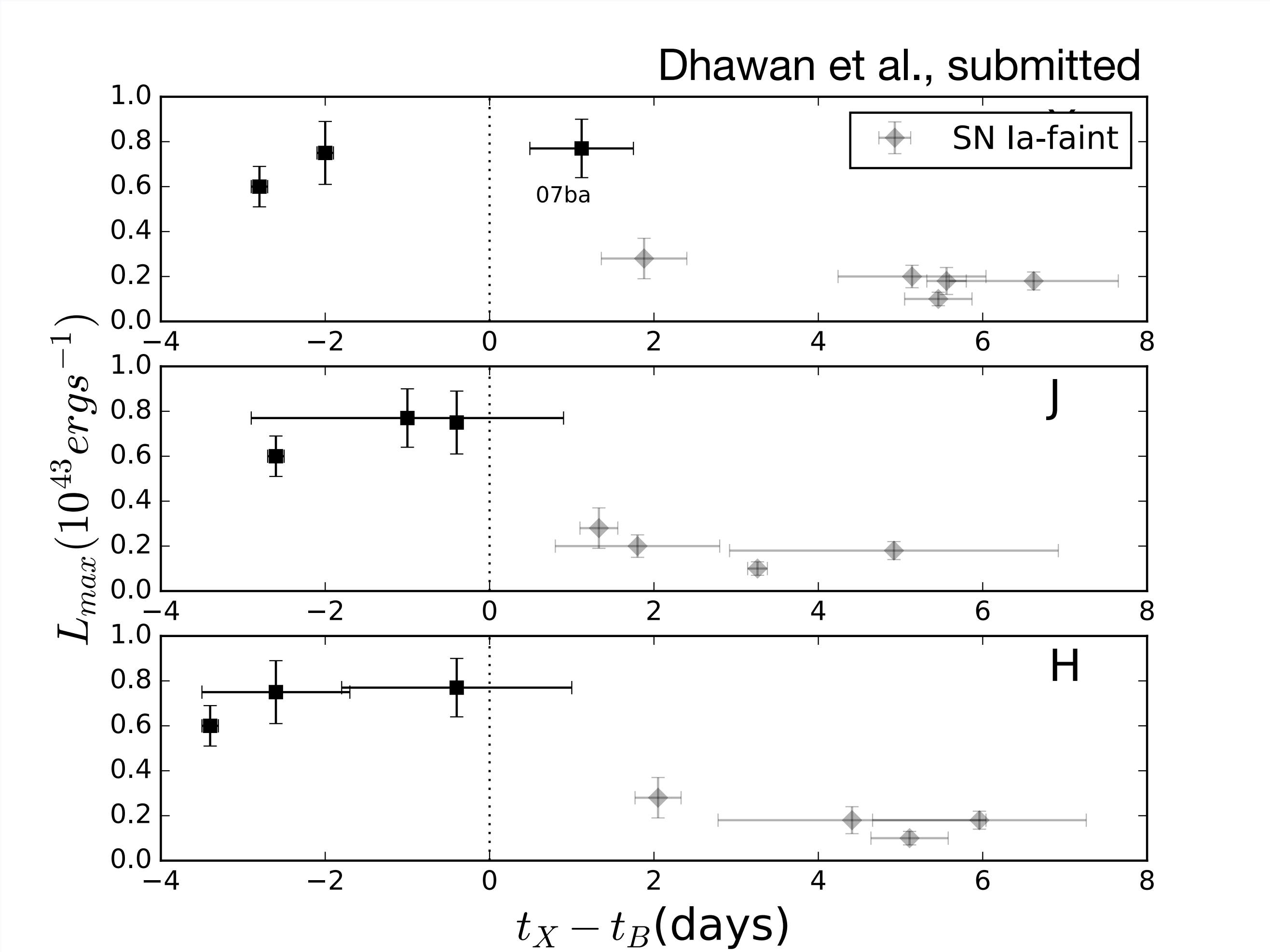
- selected SNe Ia with $\Delta m_{15}(B) > 1.6$
- separation in
  - bolometric luminosity
  - phase of NIR first peak
  - luminosity of NIR first peak
  - lack of second second NIR maximum
  - SN 1991bg-like spectrum

Dhawan et al., submitted



Fast-declining SNe Ia

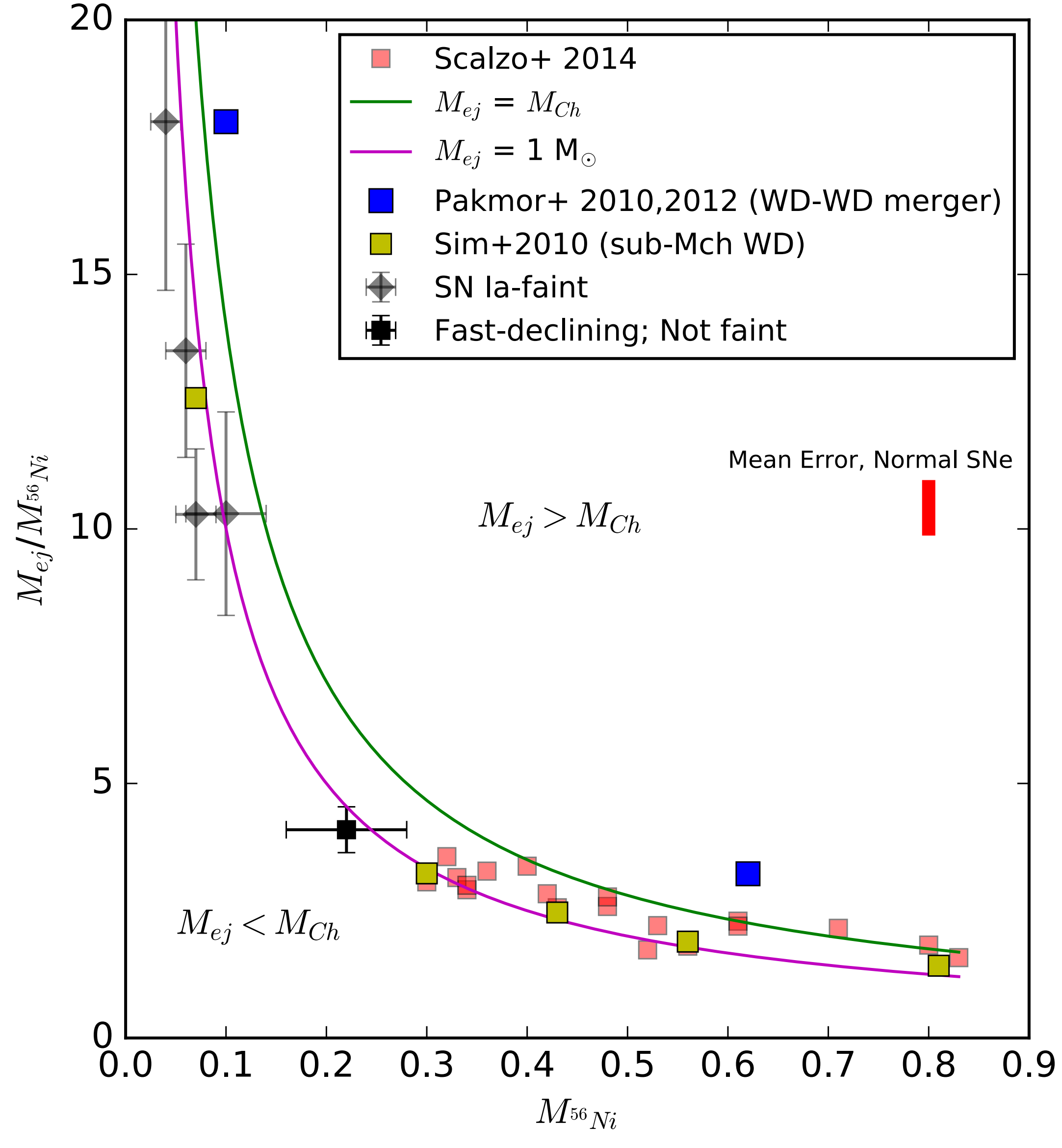
Phase of first NIR peak



Implications for the explosions

Nickel and ejecta mass

- clear indication of sub-Chandra explosions



Dhawan et al., submitted

Summary

- Double-degenerate WDs promising progenitor channel
  - SN 2011fe, DD statistics, explosion models
  - some probably through other channels
- Nickel shapes most SNe Ia
- Ejecta mass varies
- Different explosion mechanisms?