An excess of mid-infrared emission from the type Iax SN 2014dt

M61 (NGC 4303)

http://www.virtualtelescope.eu/2014/10/31/supernova-psn-j122157570428185-messier-61/

Ori D. Fox et al. 2016 Jan 1,
ApJ, 816, L13

2016 May 12 (Thu)

김상철 (Sang Chul KIM)

Characteristics of Supernovae

- **Brightest objects in galaxies (M_V = -14 ~ -22)**

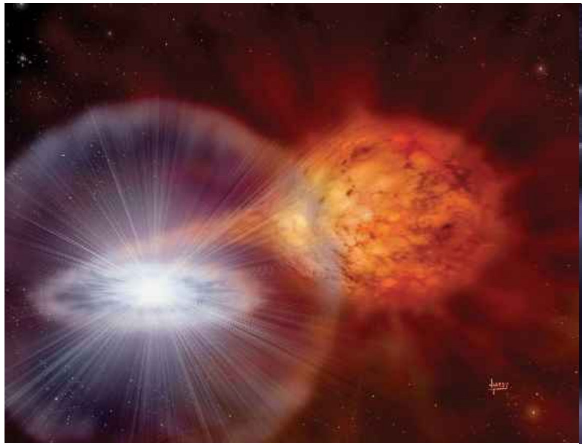
- **Typical types**

No H lines (pop II) → Type Ia

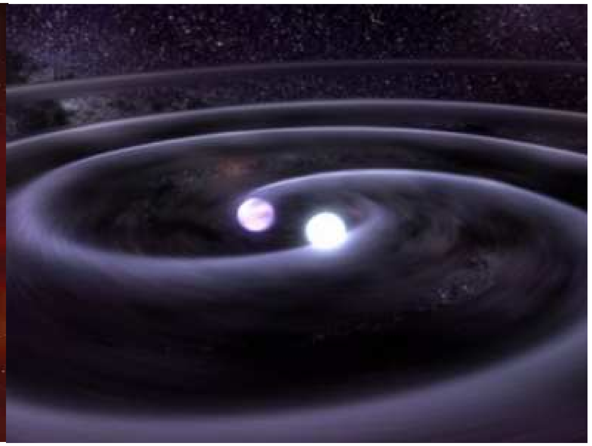
H lines (pop I) → Type II

Ib

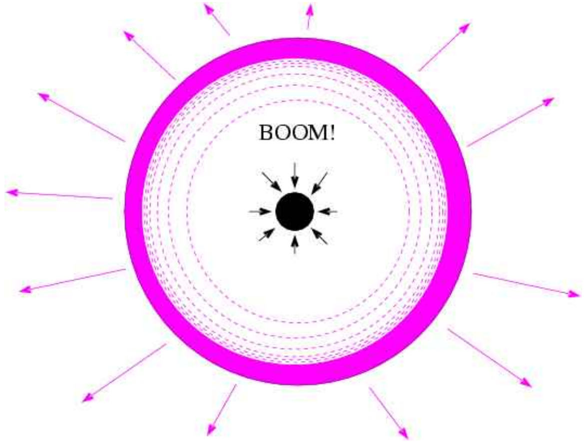
Ic



WD + Giant/MS
(Single Degenerate, SD)



WD + WD
(Double Degenerate, DD)



Core collapse

SNe Ia (thermonuclear stellar explosion)
(WD originated SNe)
백색왜성 기원 초신성

CC SNe

핵붕괴 초신성

http://dujs.dartmouth.edu/2008/05/type-ia-supernovae-properties-models-and-theories-of-their-progenitor-systems
http://wwwmpa.mpa-garching.mpg.de/mpa/research/current_research/hl2013-8/hl2013-8-en.html
http://spiff.rit.edu/richmond/sdss/sn_survey/sn_survey.html

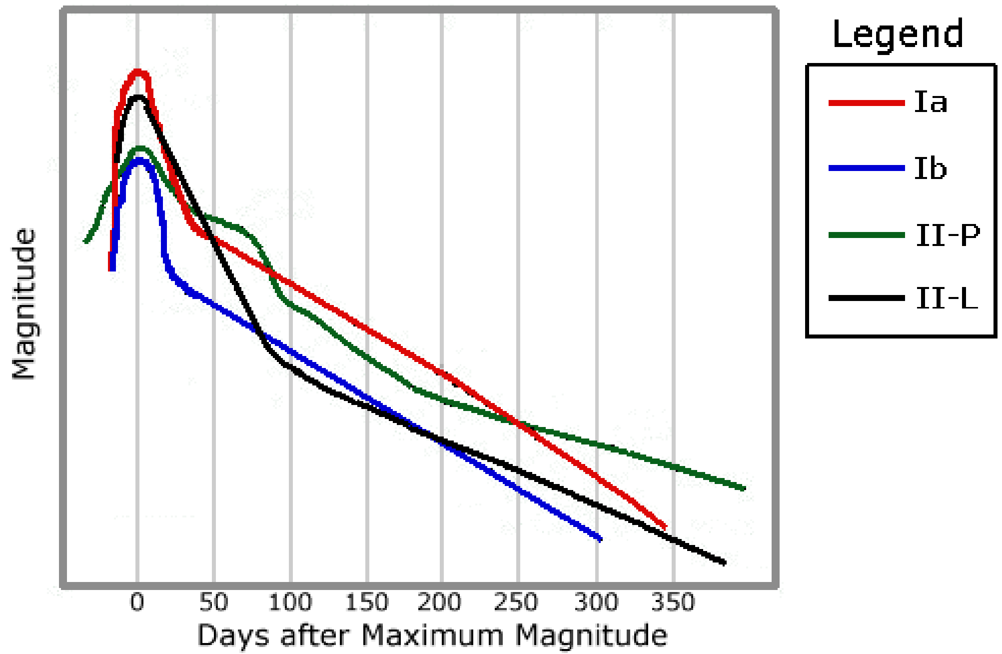
Supernovae taxonomy

- **Sub-types**

  Binary stars → Ia

  Core-collapse of massive stars → II : IIP, IIL, IIn, IIb, Ib, Ic

  Stripped-Envelope Massive Stars (Wolf-Rayet types)



Supernova taxonomy

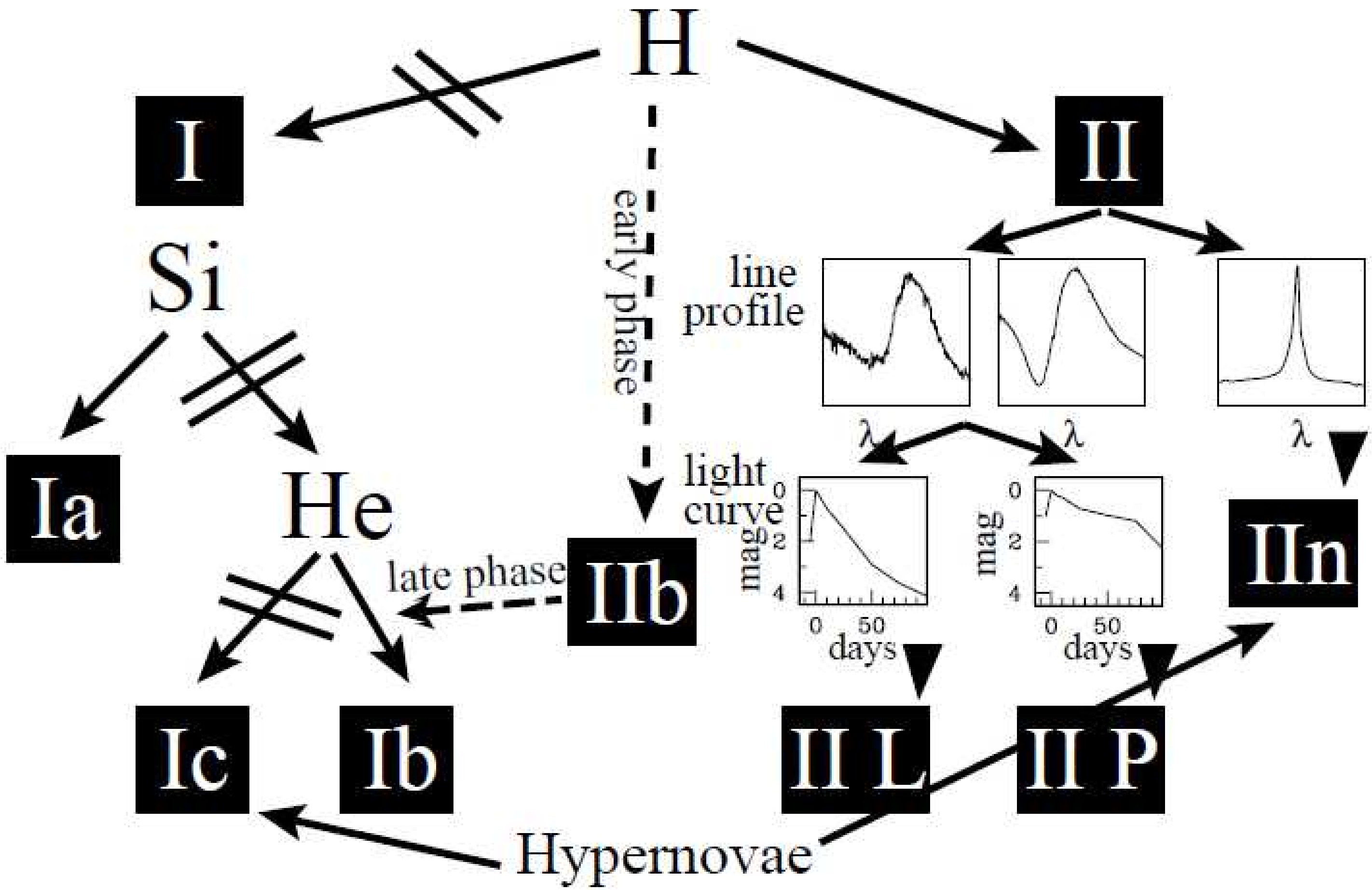


Figure 2. The detailed classification of SNe requires not only the identification of specific features in the early spectra, but also the analysis of the line profiles, luminosity and spectral evolutions

Cappellaro & Turatto (astro-ph/0012455)

SNe Iax

SN Iax

similar to SN Ia (Foley+13, ApJ, 767, 57)

comparable spectra and compositions to SNe Ia

but lower L (1% - 50% that of typical SNe Ia)

less energetic (ejecta velocities near max light ~20 – 80% that of typical SNe Ia)

ejecta - less mass (~0.1 – 0.5 $M_{\odot}$), slower velocities

may leave a bound remnant

N : 5-30% of SN Ia

found preferentially in young, star-forming galaxies

SN Iax - samples

SN 2002cx, 2005hk, 2008ge, 2008ha, 2010ae, 2010el, 2012Z

M_V=-17.63 M_V=-18.37 M_V=-17.60 M_V=-14.19 M_V≤-14.9 M_V≤-14.8 M_V≤-16.8

※ 2014dt

M_V ~ -18

SN 2012Z (McCully+14, Nature, 512, 54) → a luminous blue source in pre-explosion images → nondegenerate He companion star + CO WD

(or a massive star explosion)

※ SN 2008ge

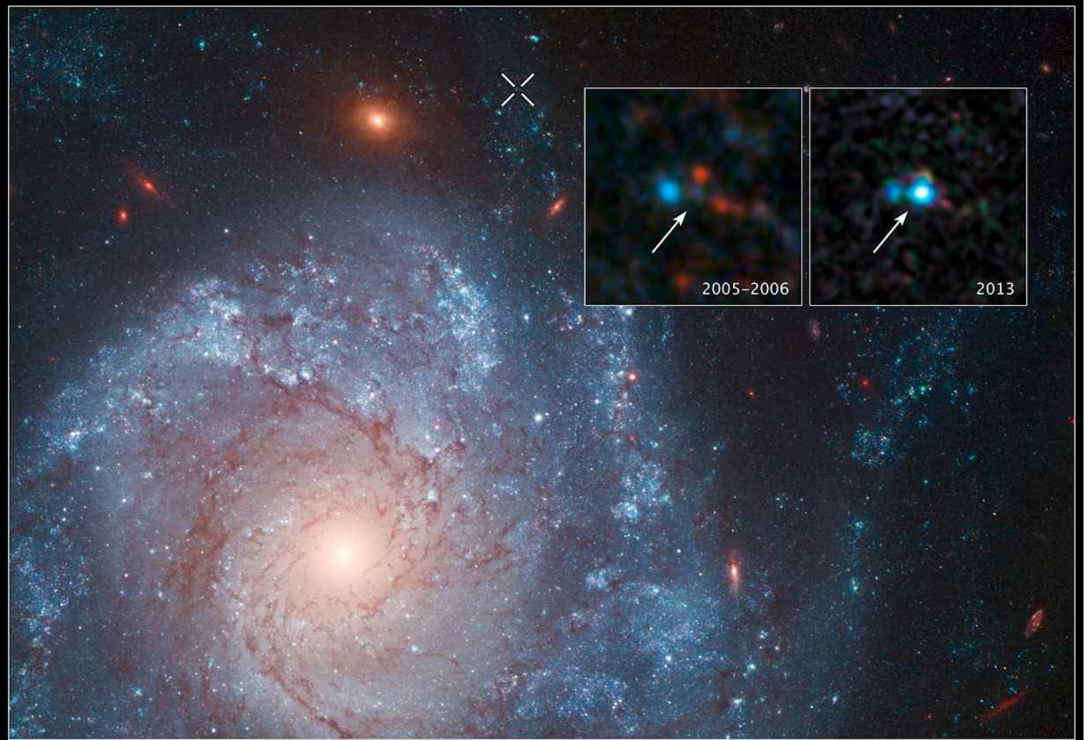
: S0 galaxy with no indication of current SF (Foley+10, AJ, 140, 1321)

: $M_i \leq 12\ M_\odot$

SN 2008ha, 4-yr post-explosion images → a red source

: thermally pulsing AGB companion

: or remnant of the WD



Supernova 2012Z in Spiral Galaxy NGC 1309
Hubble Space Telescope ▪ ACS ▪ WFC3

NASA and ESA

STScI-PRC14-32a

SNe Iax - diverse set of progenitors!

M61

Host galaxy, M61 = NGC 4303 (for SN 2014dt)

HST (http://en.wikipedia.org/wiki/Messier_61)

http://ned.ipac.caltech.edu/img/2003AJ....125..525J/2MASS_MESSIER_061_JHK.jpg

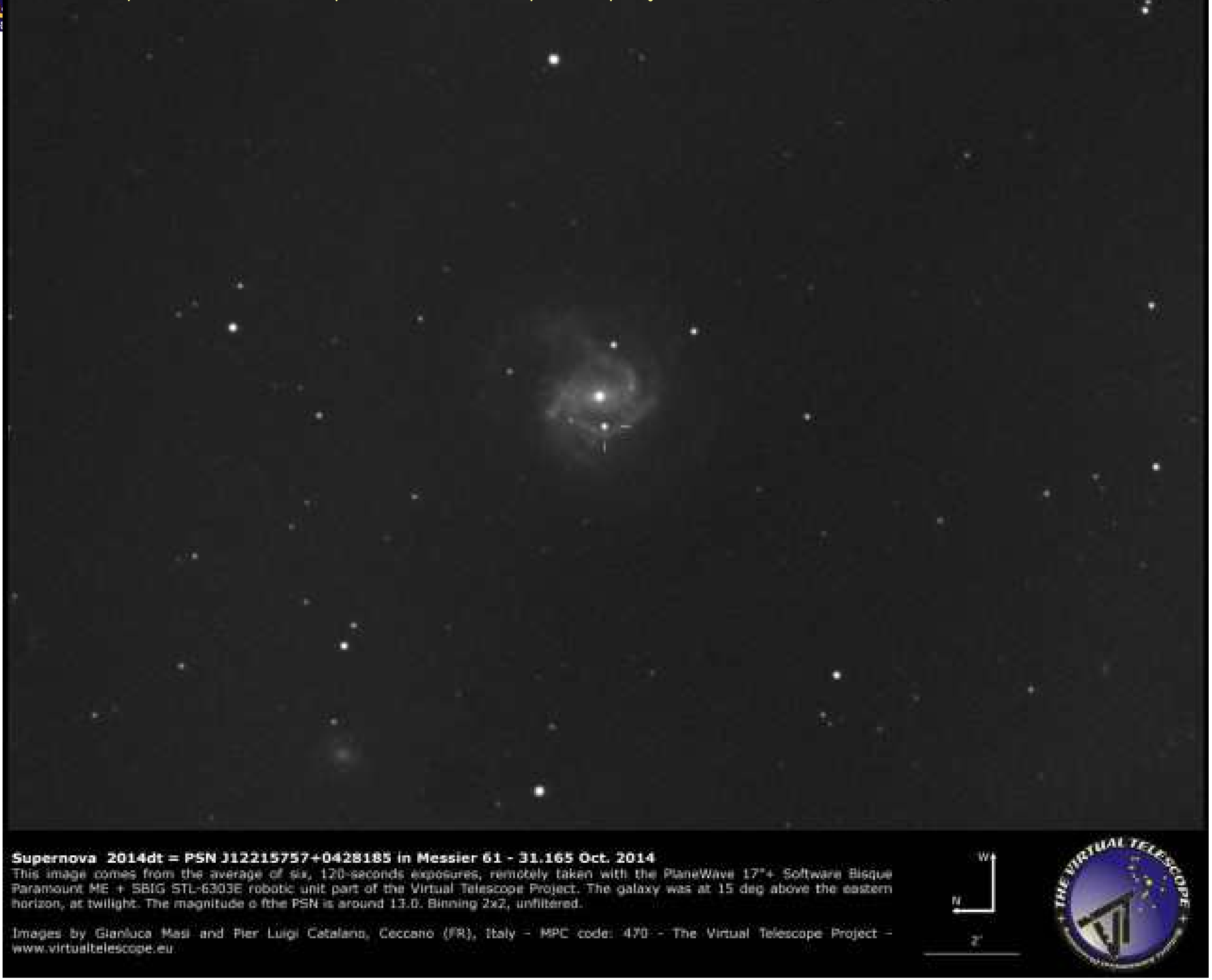
Sbc / SAB(rs)bc

α(J2000)=$12^h\ 21^m\ 54.9^s$, δ= +04° 28' 25" (Virgo)

Velocity = 1566±2 km/s

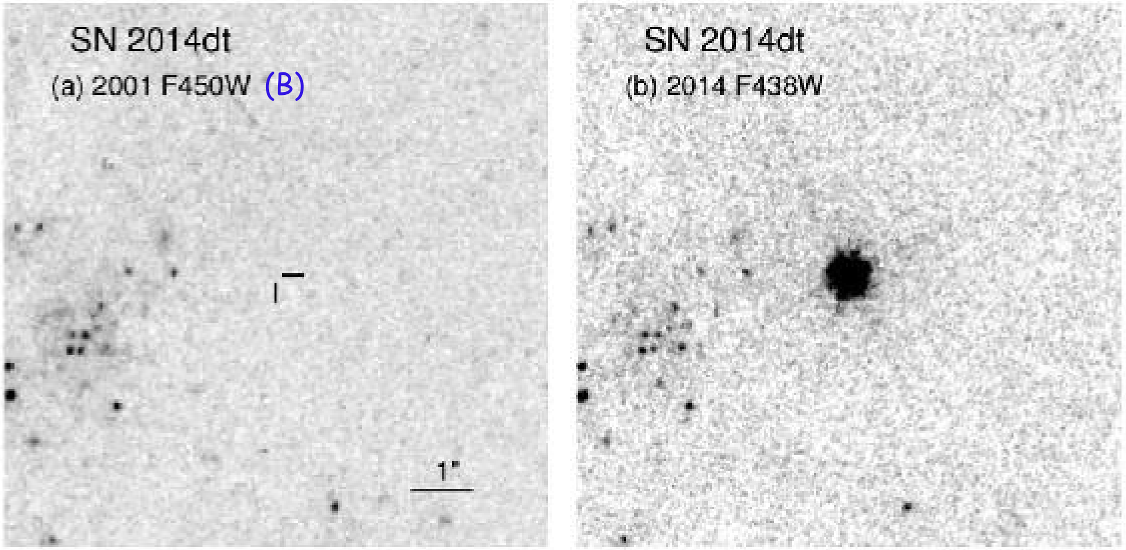
SN 2014dt (= PSN J12215757+0428185) in M61

http://www.virtualtelescope.eu/2014/10/31/supernova-psn-j122157570428185-messier-61/



SN 2014dt and HST images

Pre-explosion (2011) Supernova (2014)



Foley+15 (ApJ, 798, L37)

Detection : 2014 Oct 29.838 (UT), 13.6 mag

HST pre-imaging : 2001 Jul 27.10 HST/WFPC2 : F450W (B), F814W (I), each 460 s

Dolphot photometry

HST SN imaging : 2014 Nov 18.89 HST/WFC3/UVIS : F438W (B), 20 $\times$ 20 s

Dolphot photometry for $m_{F438W} < 16.48 \pm 0.01$ mag

SN position uncertainties : 0.13, 0.10 px (0.006", 0.005") in − and | directions

SN 2014dt

Fox + 16

(ApJ, 816, L13)

1. Observations : Spitzer + UKIRT (NIR)

SPIRITS (Spitzer InfraRed Intensive Transients Survey) program
: 194 nearby galaxies, d < 20 Mpc, IRAC 3.6/4.5 μm, depth 20 mag, cadence 1d-1yr
: 1130 hr, 3 yr (2014-2016), PID #11063, PI : M. M. Kasliwal
2014dt observations : 310-340 d post-explosion

UKIRT (United Kingdom InfraRed Telescope)
: JHK_s + PSF fitting, calibration using 2MASS stars in the field

Table 1 *Spitzer* Observations

JD −2,450,000	Epoch (days)	3.6 μm[a] (μJy)	4.5 μm[a] (μJy)
7259	309	49 (16)	52 (12)
7267	317	52 (18)	58 (13)
7286	336	75 (18)	73 (14)

Note. [a] 1σ uncertainties are given in parentheses.

Spitzer pre-explosion images

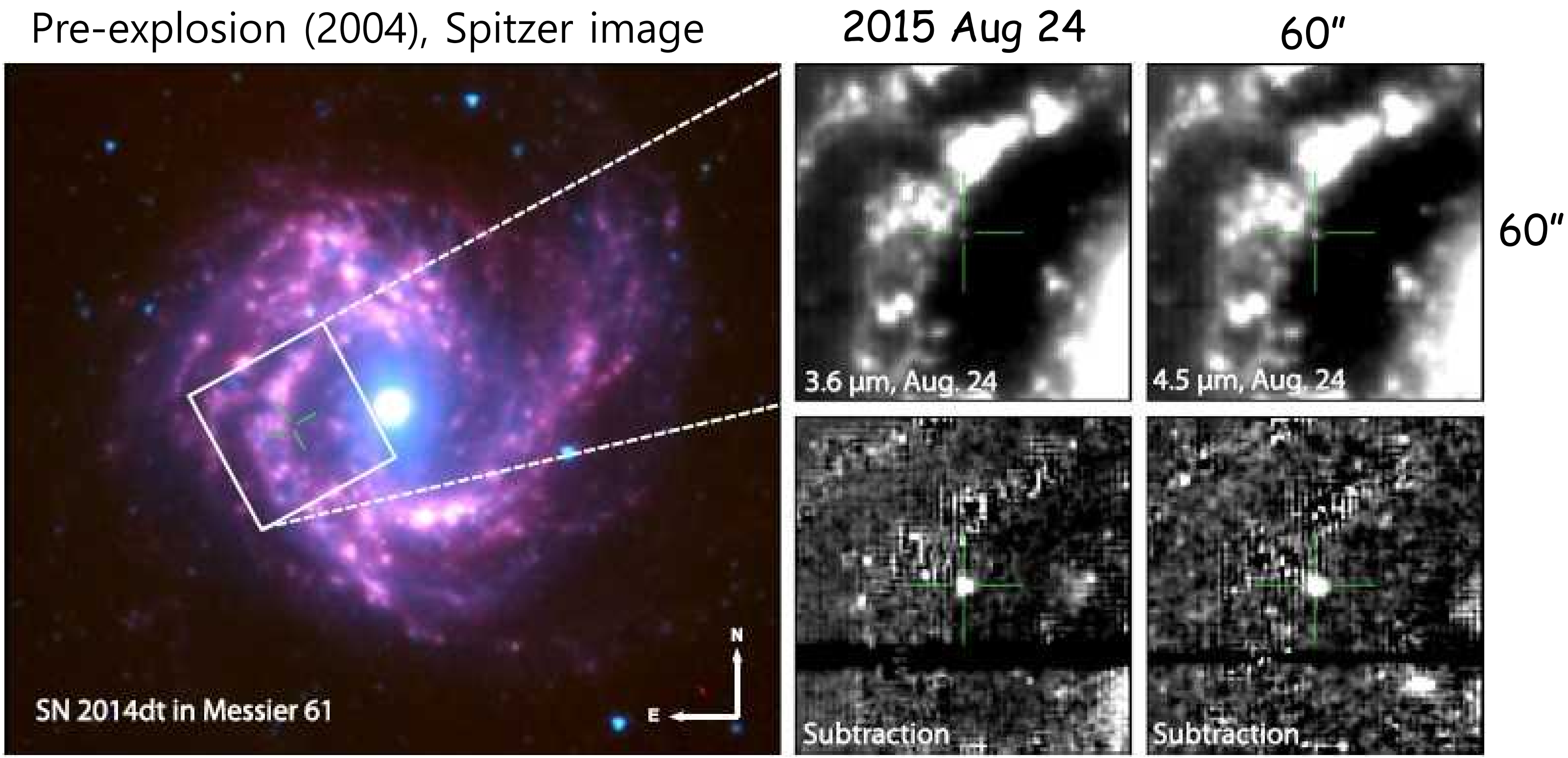


Fig. 1. pre-SN (2004) RGB composite of M61 (3.6, 4.5, 8.0 μm)

1. Observations : Optical

Las Cumbres Observatory Global Telescope (LCOGT) Network (PIs : J. Bally, E. Gomez, K. Finkelstein)

: BVI, ri

: DAOPHOT psf-fitting + calibrated using SDSS stars in the field

Palomar 48- and 60-inch

: gri, R

Swift/UVOT (Ultra-Violet/Optical Telescope)

: UBV

AAVSO (American Association of Variable Star Observers)

https://www.aavso.org/apps/webobs/results/?star=SN+2014DT

Bright Supernovae – Rocherster astronomy . Org

http://www.rochesterastronomy.org/sn2014/sn2014dt.html

distance

2 distance estimates using SN 2008in, M61 (II-P)

(1) Expanding Photosphere Method → $(m\text{-}M)_0$=30.45, d=12.3 Mpc (Bose & Kumar 14)

(2) Photospheric magnitude method → $(m\text{-}M)_0$=31.43, d=19.3 Mpc (Rodríguez+14)

[1] : similar to Tully-Fisher estimate (Schoeniger & Sofue 97)

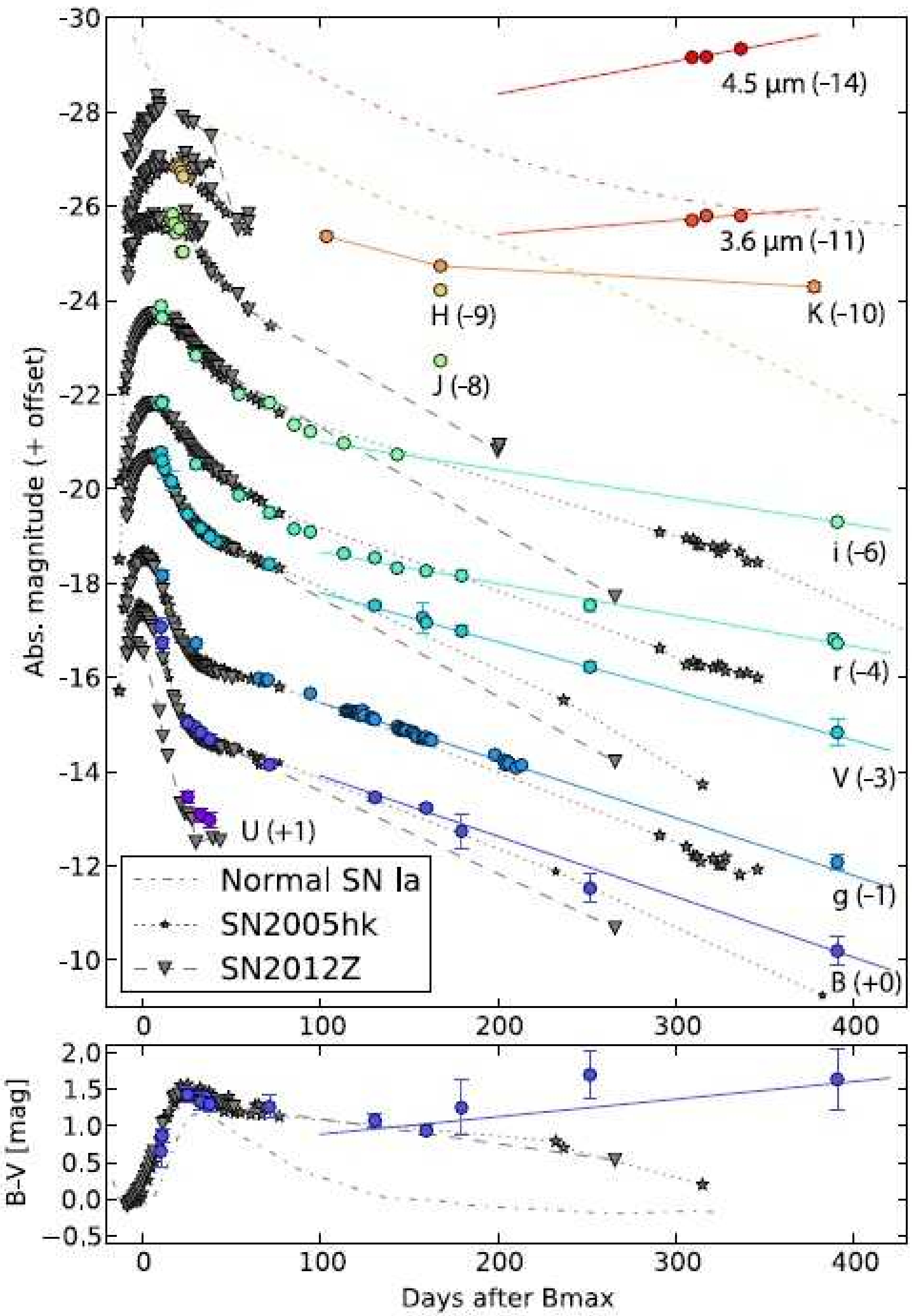
CO : $(m\text{-}M)_0$=30.02±0.92, d=10.1 Mpc

HI : $(m\text{-}M)_0$=30.21±0.70, d=11.0 Mpc

→ Adopted by Foley+15

[2] : makes SN 2014dt appear to have similar abs. mag. as SNe 2005hk and 2012Z (peak at M_V~-18)

→ adopt in this study



Light Curves (LCs)

Fig. 2. photometric LCs

Assuming $(m\text{-}M)_0$ = 31.43 mag and

$MJD_{B,max}$ = 56,950

Discovered after peak brightness

LC → peak estimate to be Oct 20
(MJD=56,950)

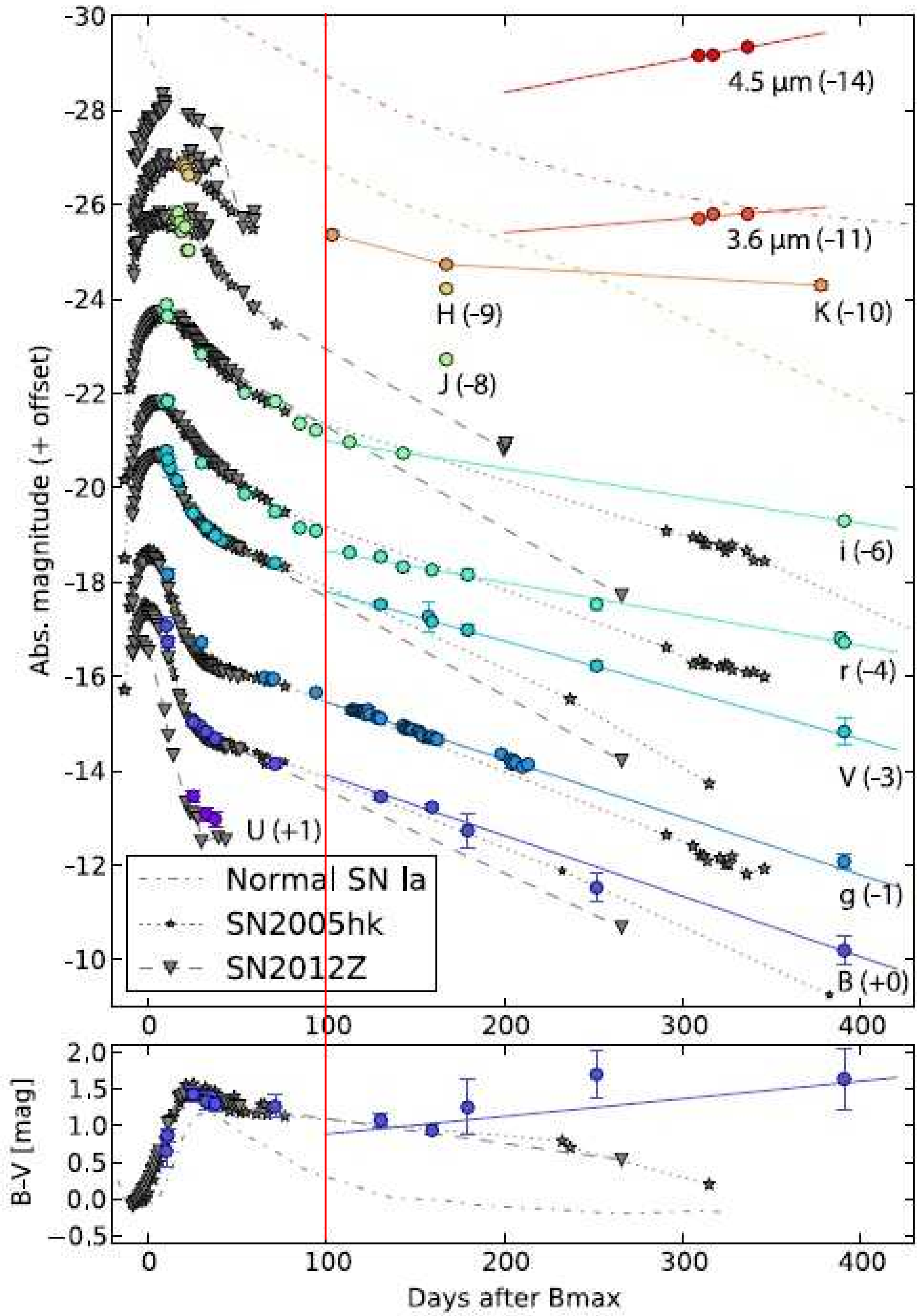
Normal Ia : Johansson+14

2005hk : Phillips+07, Sahu+08

2012Z : Stritzinger+15, Yamanaka+15

SN 2014dt → seems to follow the early evolution of 2005hk and 2012Z

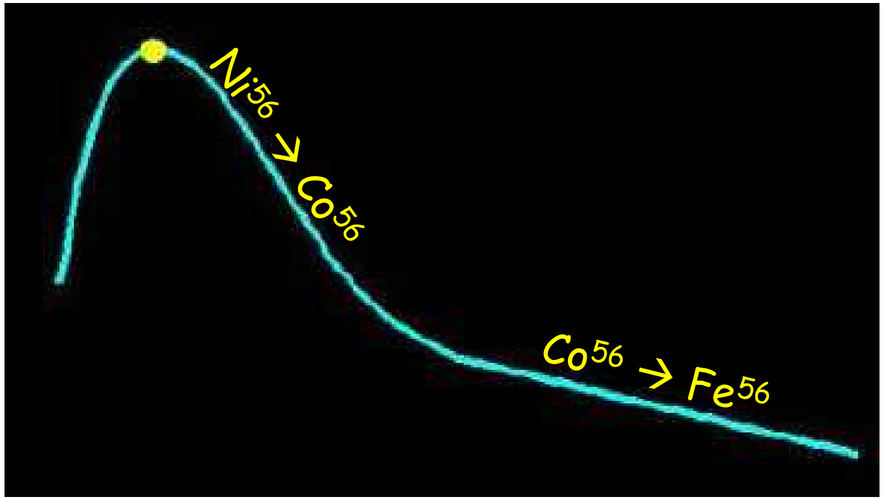
(B-V) color evolution → at ~100 d,
2014dt : redder colors than
2005hk and 2012Z



LC - plateau

LC plateau at 298 – 326 days

→ Not seen in thermonuclear SNe Ia (radioactive decay)



$Ni^{56} \rightarrow Co^{56} \rightarrow Fe^{56}$

half life : 6 77.3 days

Piro & Nakar 2013 (ApJ, 769, 67)

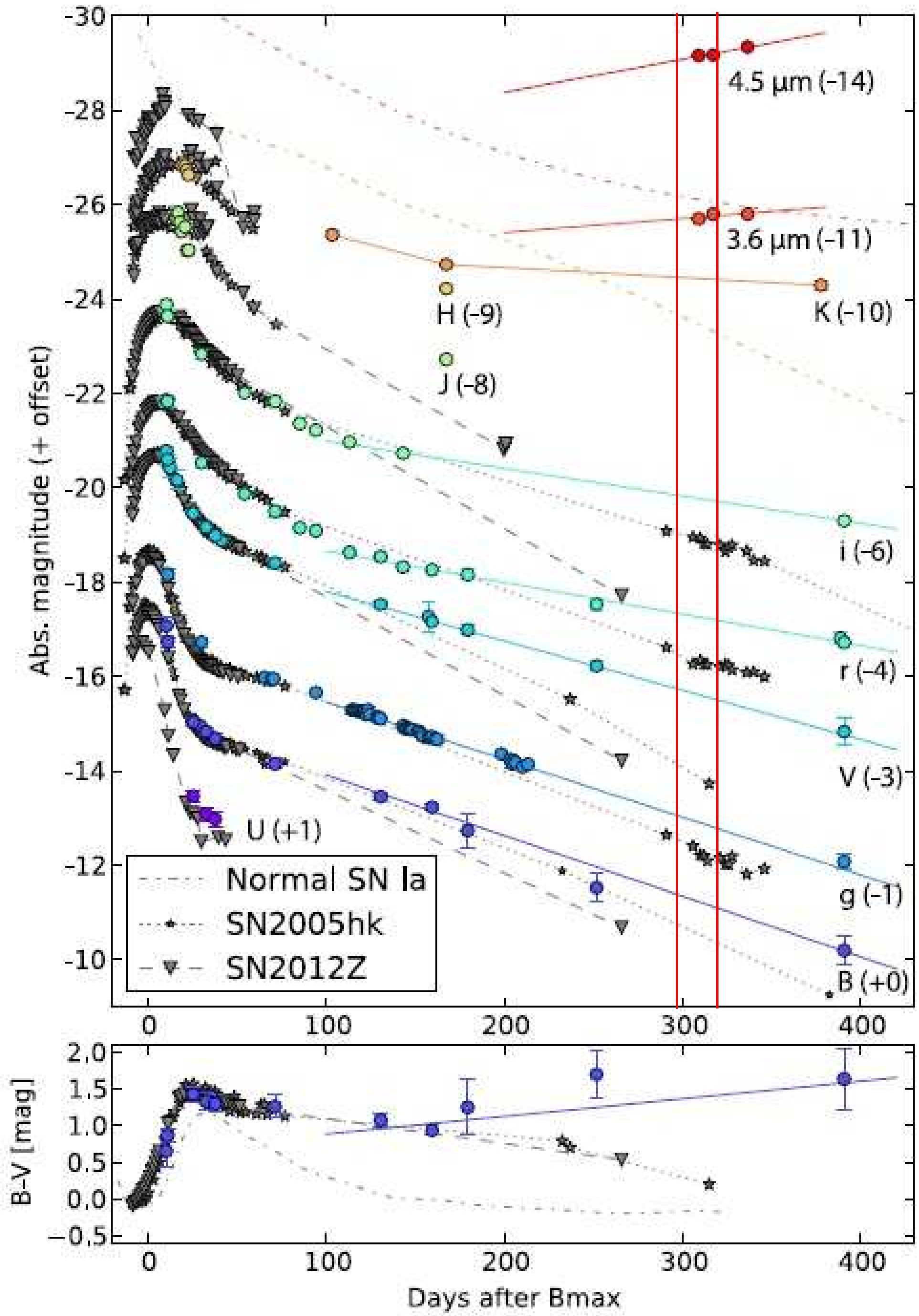
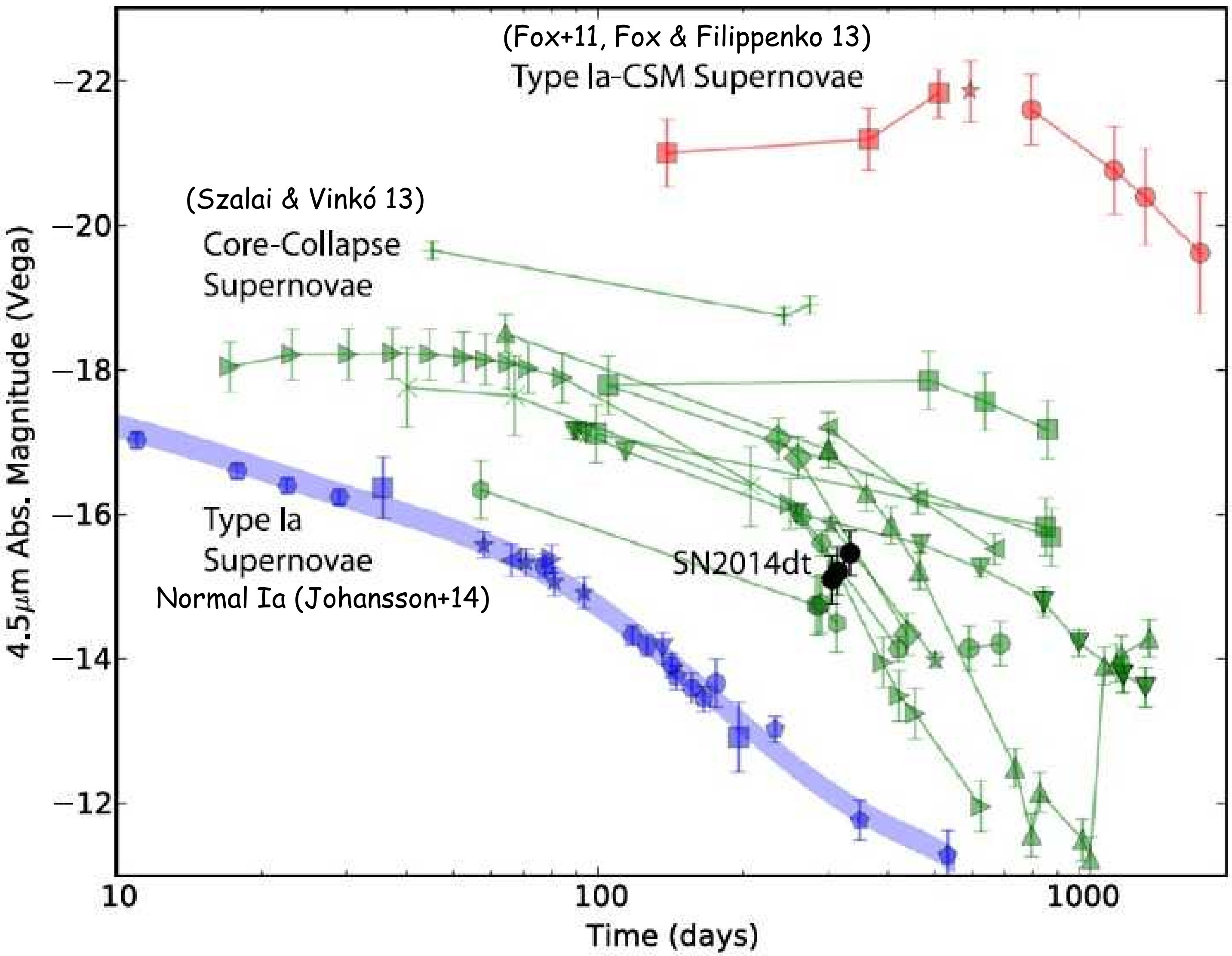


Fig. 3.

SNe Ia
and
SNe with observed dust present



SN 2014dt → clear MIR excess compared to other SNe Ia

MIR excess – probably due to warm dust

Spitzer SED fitting as a function of dust mass (M_d) and dust temperature (T_d)

$$F_\nu = \frac{M_d B_\nu(T_d) \kappa_\nu(a)}{d^2} \quad (1)$$

a = dust radius

d = distance to the dust from the observer

$\kappa_\nu(a)$ = dust absorption coefficient

assume optically thin dust, single size, single temperature, single composition of amorphous carbon (AC)

MIR excess – probably due to warm dust

Spitzer SED fitting using eq. (1)

$$F_\nu = \frac{M_d B_\nu(T_d) \kappa_\nu(a)}{d^2} \quad (1)$$

Best fitting (i.e., minimized value of χ^2)

Dust : mass, temperature, luminosity

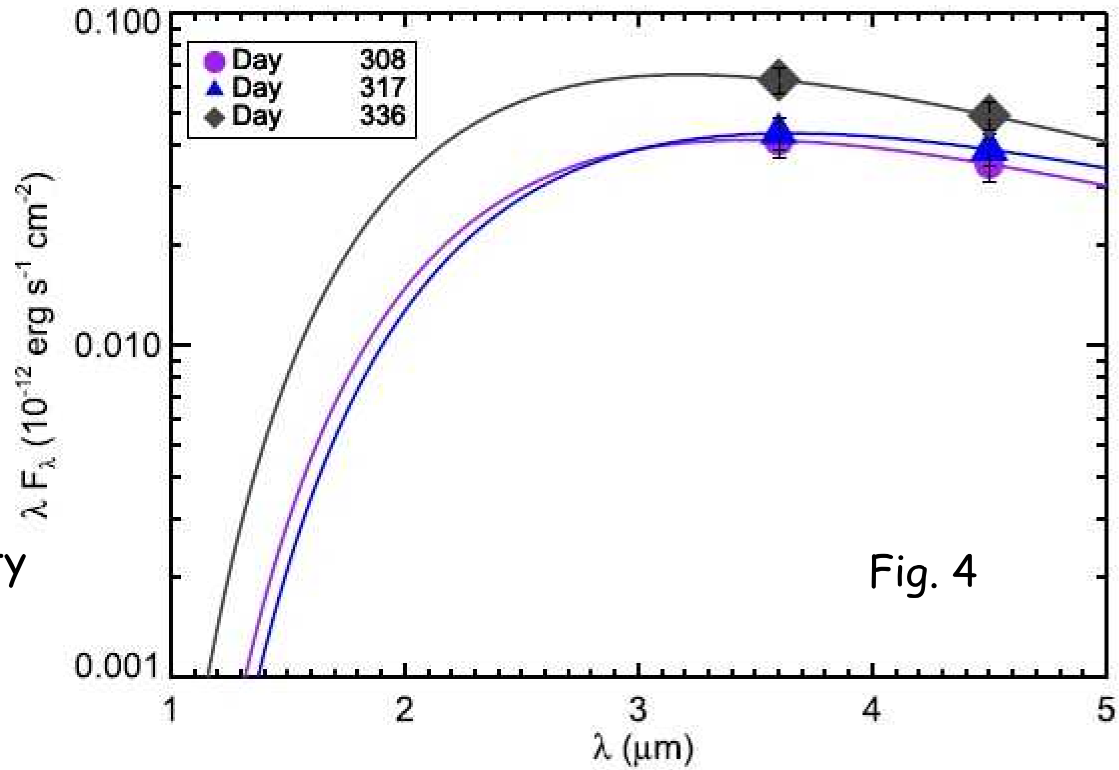


Fig. 4

Table 1 IR Fitting Parameters (a = 0.1 μm Amorphous Carbon)

JD −2,450,000	Epoch (days)	M_d ($M_\odot$)	T_d(K)	L_d ($L_\odot$)
7259	309	1.35×10^{-5}	711	4.75×10^5
7267	317	1.83×10^{-5}	679	4.98×10^5
7286	336	1.33×10^{-5}	770	7.48×10^5

Warm dust – newly formed? or pre-existing?

(1) Dust shell size calculation :

minimum radius ← BB radius $r_{\rm bb} = [L_d/(4\pi\sigma T_d^4)]^{1/2}$ ← $L_d \sim 5 \times 10^5 L_\odot$

: $r_{\rm bb} \approx 3.5 \times 10^{15}$ cm ~0.0037 ly ~230 AU T_d ~700 K

→ comparable to the distance traveled by material with a time averaged vel (~1300 km/s) over ~300 days

models suggest dust can form in SN Ia at these velocities, timescales, and total mass (Nozawa+11)

※ Newly formed dust → suggestive of a core-collapse (CC) origin

(e.g.) Valenti + (2009, Nat, 459, 674) : SNe Iax could be CC events with low-E and H-deficient due to a massive star collapsing into a BH

Warm dust – newly formed? or pre-existing?

(2) pre-existing dust?

Fox et al. (2010) result → miminum radius – approximately consistent with the distance to which such dust would have been vaporized

Dust shell at the vaporization radius = signature of a continuous mass-loss

For pre-existing dust : heating mechanism :

IR echo, shocks, radiative heating due to X-ray/UV/optical emission produced by shock interaction at an inner radius

IR echo → Too short duration

radiative heating → Require radiative heating source : $L_{\mathrm{opt/UV/X}} \approx 10^7 L_\odot$

※ Optical spectra - narrow lines existence : clear evidence of CSM interaction

→ non-degenerate companion star!

Progenitor's total mass-loss rate :

$$\dot{M} = \frac{M_d}{Z_d \Delta r} v_w = \frac{3}{4}\left(\frac{M_d}{M_\odot}\right)\left(\frac{v_w}{120\ \mathrm{km\ s^{-1}}}\right) \times \left(\frac{5 \times 10^{16}\ \mathrm{cm}}{r}\right)\left(\frac{r}{\Delta r}\right)[M_\odot\ \mathrm{yr}^{-1}] \quad (3)$$

$Z_d = M_d/M_g$ ~0.01 : dust-to-gas ratio (expected in H-rich envelope of a massive star)

v_w : progenitor (pre-SN) wind speed → assume ~10 km/s

Assuming a thin shell $\Delta r/r = 1/10$

→ mass-loss rate $< 10^{-6}\,(v_w/10\ \mathrm{km\ s^{-1}}) M_\odot\ \mathrm{yr}^{-1}$
(an upper limit)

→ Consistent with a RG/RSG (Gehrz & Woolf 71, Drout+15) or an AGB star (Marshaell+04)

Summary

SN Iax, SN 2014dt (M61)

: Spitzer 1-yr post-explosion data

→ strong MIR excess (over the expected fluxes of normal SNe Ia)

: ~10^{-5} $M_{\odot}$ of newly formed dust

: first report of newly formed dust in a SNe Ia

: dust CSM due to pre-explosion mass-loss → also possible (→ SD model)

Dust shell : less massive compared to

SNe Ia-CSM (significant shock interaction, Silverman+13, ApJS, 207, 3),

SNe IIn (interacting CC events)