Gamma Ray Emission from Type Ia Supernovae

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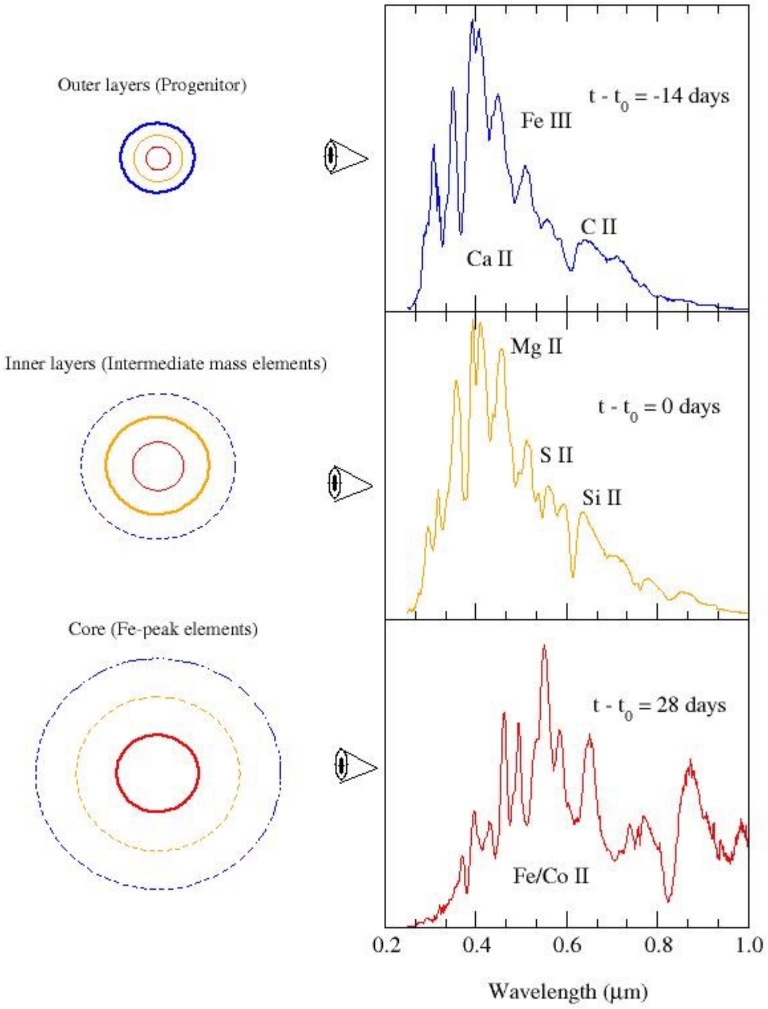
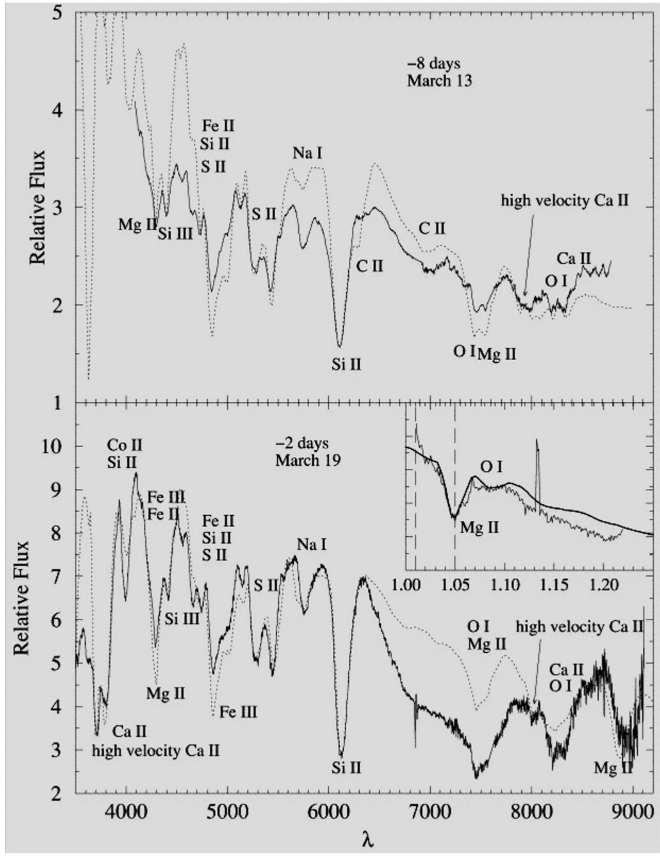
 # For a long time there is a consensus that Type Ia supernovae are caused by the thermonuclear explosion of a C/O white dwarf near the Chandrakhar’s mass in a close binary system.

(He white dwarfs are completely incinerated to iron, and O/Ne white dwarfs probably collapse)

As the supernova expands, the atmosphere becomes more and more transparent.
The different layers become exposed as the time goes on
This allows to study the structure as a function of time



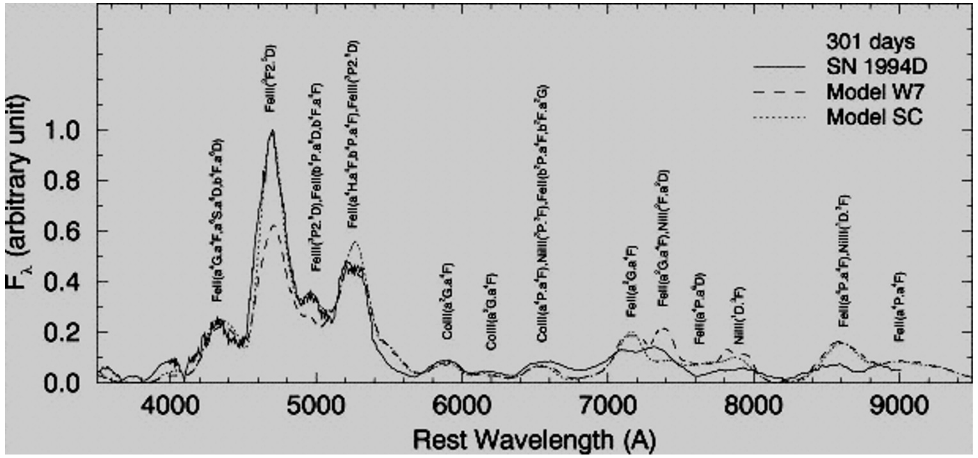


H is absent

Spectrum at maximum light. Incomplete burning (C, Si, Ca,Mg). V≳ 10,000 km/s

Hattano et al 1999

#Nebular phase spectrum. Complete incineration (Co, Fe), V< 10,000 km/s



Arguments favouring such hypothesis were:

- Progenitors should be long lived to account for their presence in all galaxies, including ellipticals

 # Arguments favouring such hypothesis were:

- The short risetime of the light curve indicates that the exploding star is a compact object
- The explosion should produce at least ~ 0.3 M_0 of ^{56}Ni to account for the light curve and late time spectrum (via the radioactive chain ^{56}Ni -> ^{56}Co -> ^{56}Fe). Arnett’s rule: $L \propto M_{56Ni}$

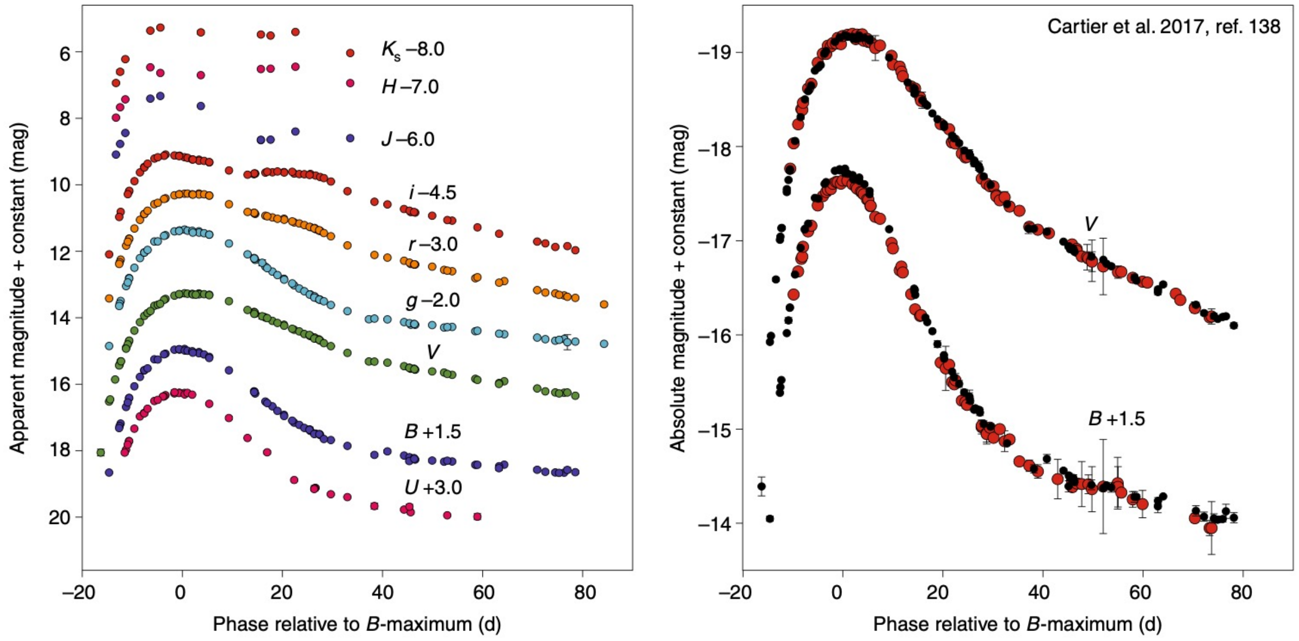
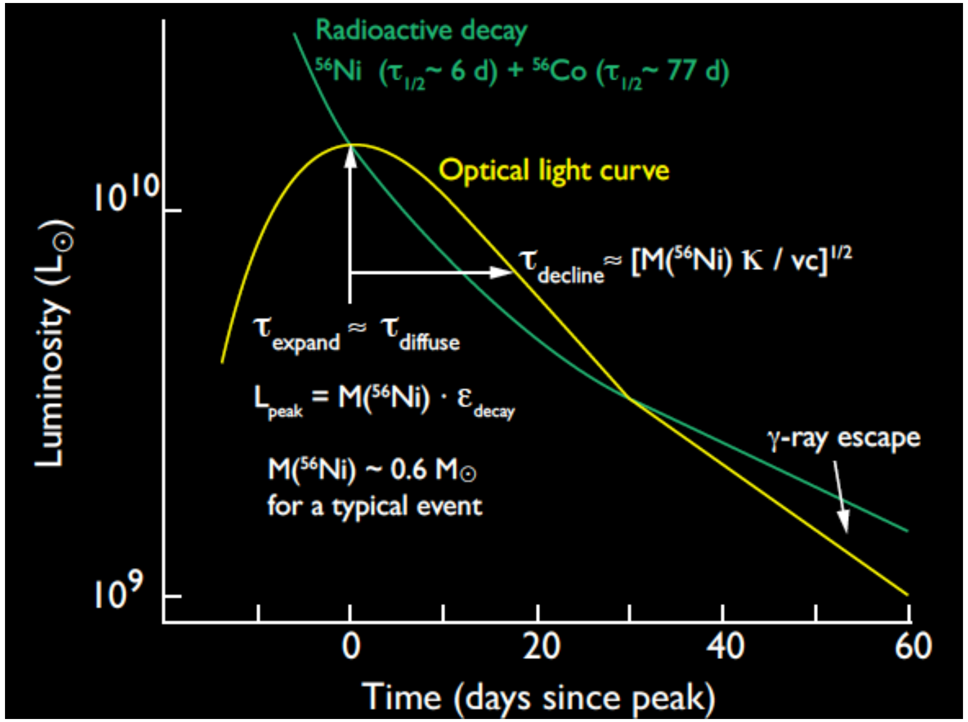


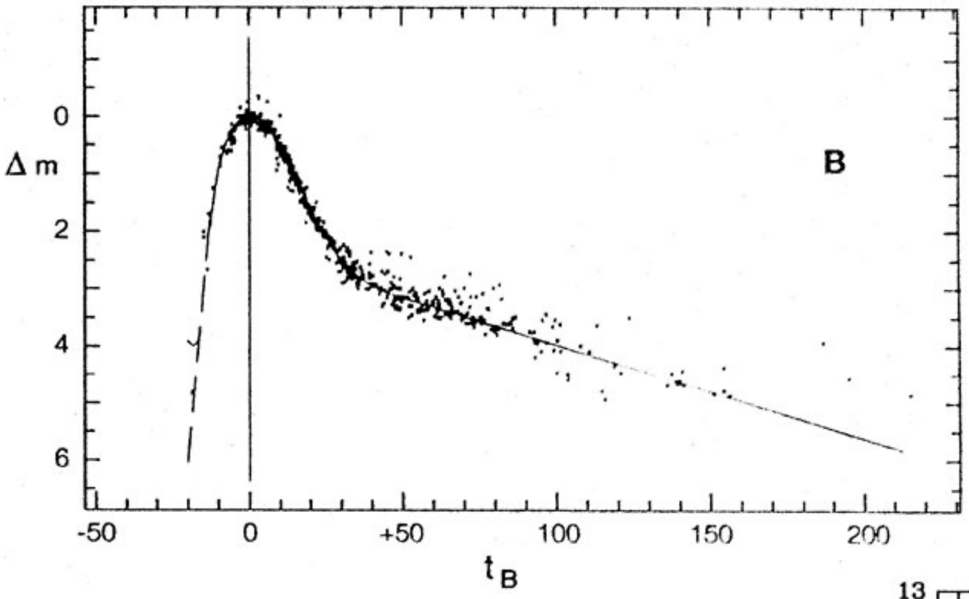
Fig. 1 | Lightcurves of SNe Ia. Left: optical and near-infrared lightcurve of the type-Ia SN 2015F. Right: comparison of the *B*- and *V*-band lightcurves of SN 2015F (black points) and SN 2004eo (red points) showing the similarity between these two SNe Ia. The error bars displayed are 1σ uncertainties. Adapted from ref. [138], OUP.



Jha+’19

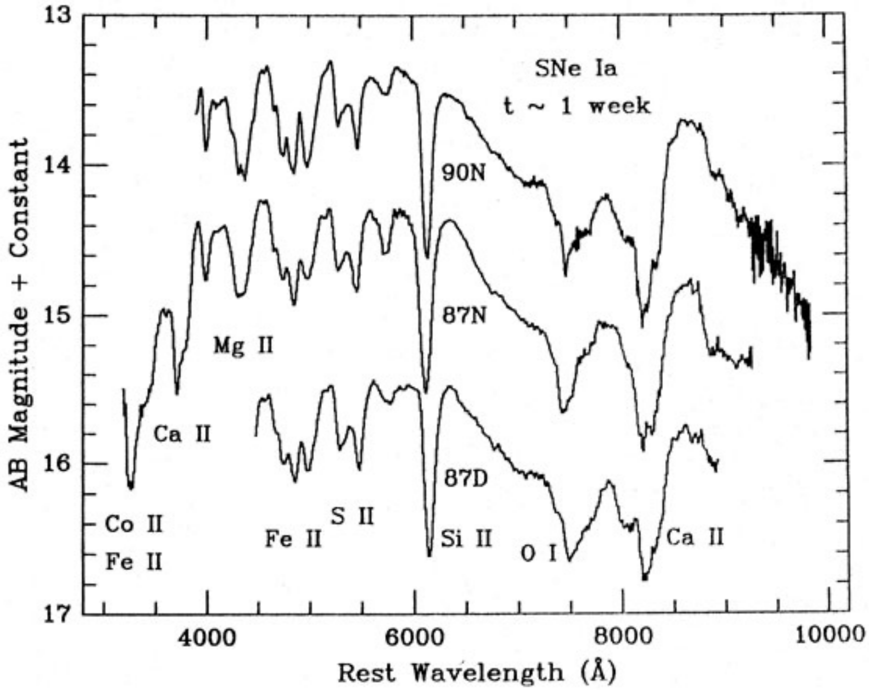
Timmes

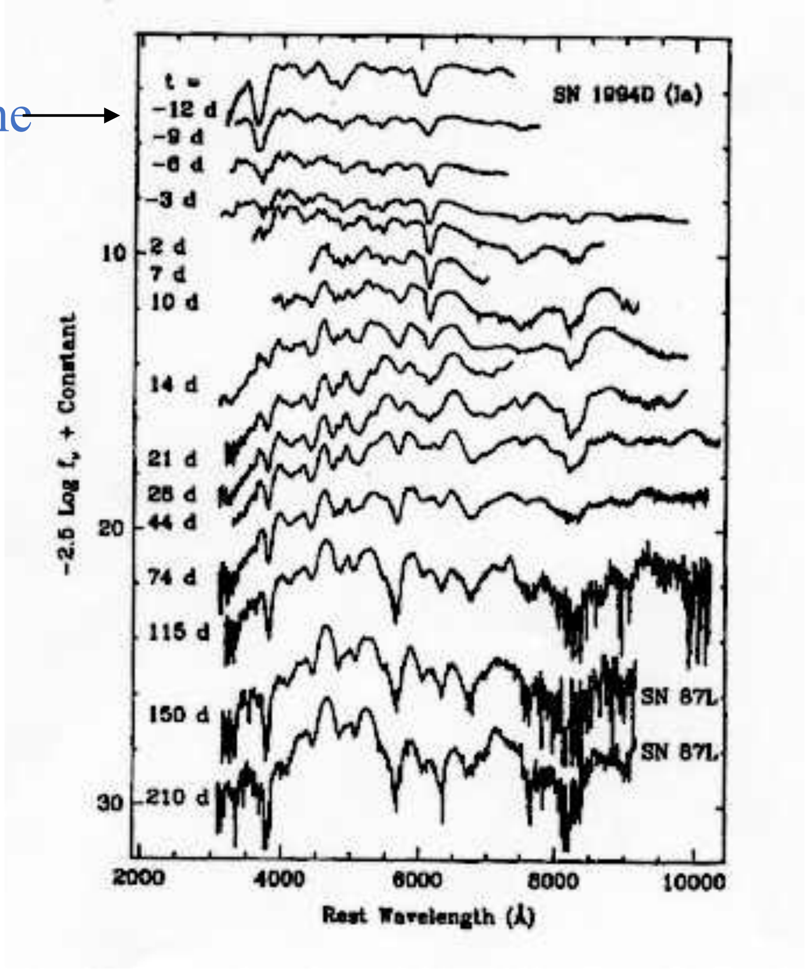
Additional arguments were the spectral and photometric homogeneity



The B-light curve of 22 SNIA, showing the similarity among them (Cadonau '87)

Spectral homogeneity near the maximum light & over the time (Fillipenko)





More recent examples of spectral SNIa homogeneity

Jha+’2019

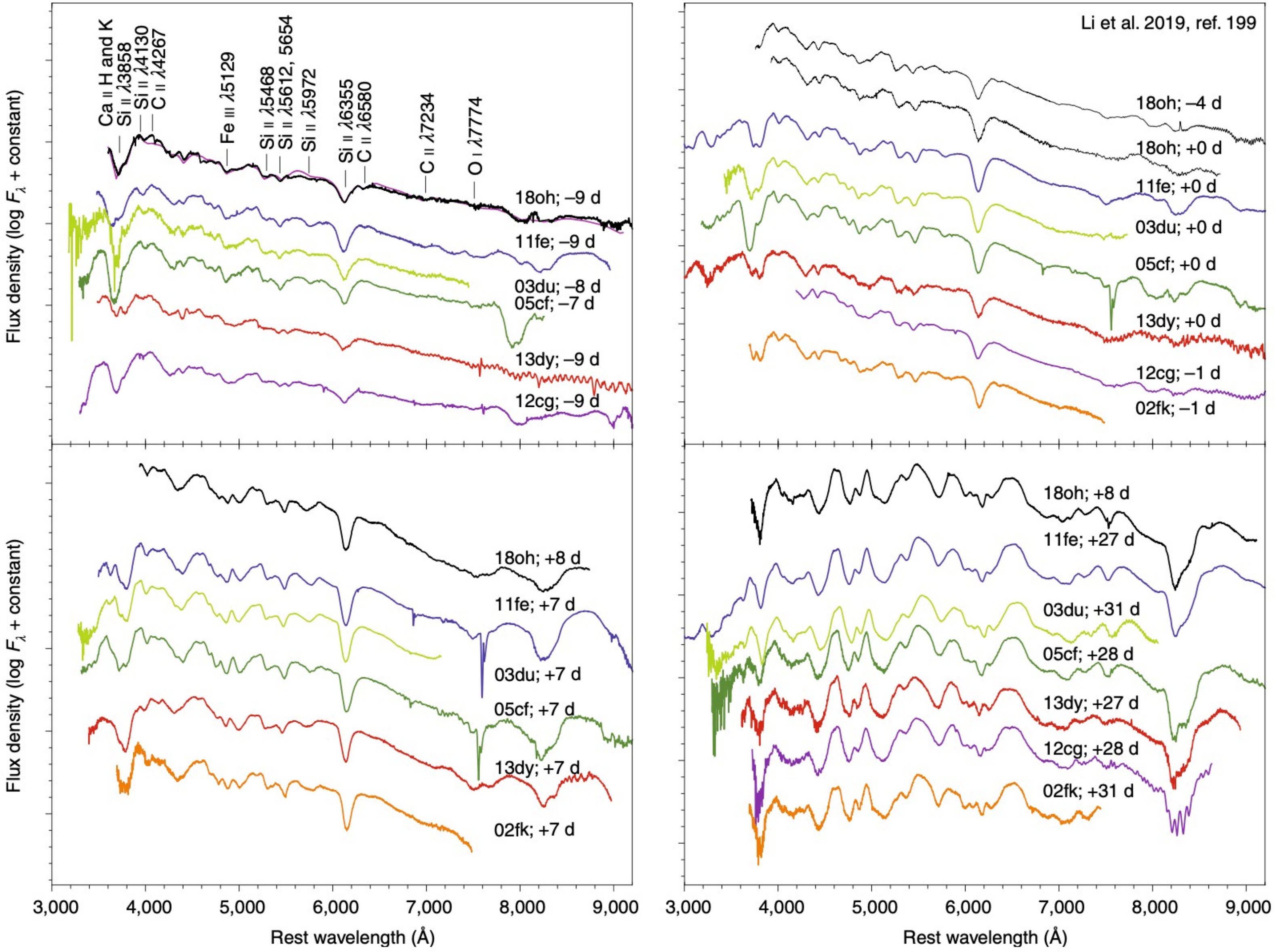
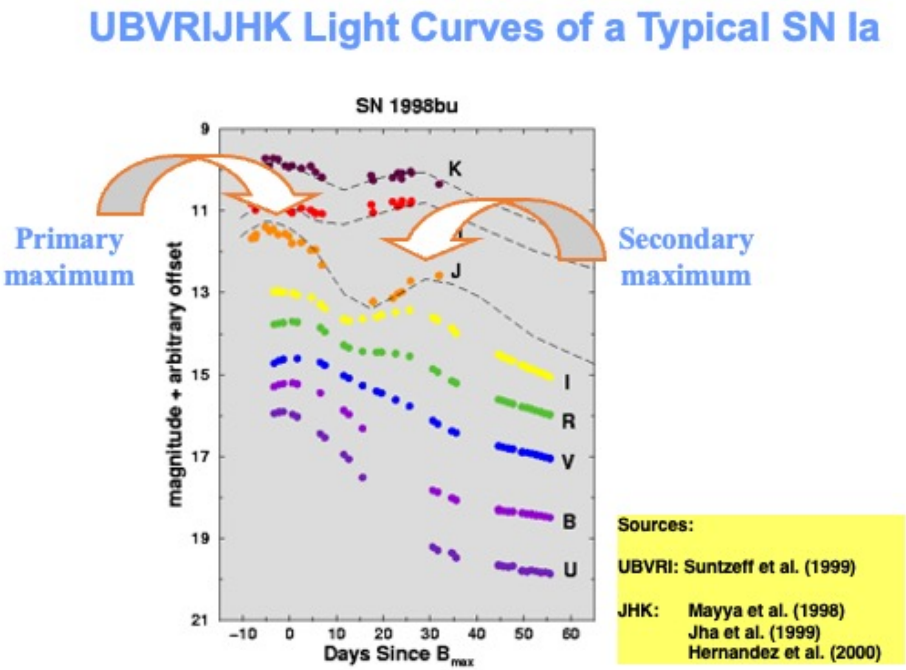


Fig. 2 | Homogeneous optical spectra of SNe Ia. A sample of SNe Ia is shown at four epochs from –9 days to +1 month after *B*-maximum light. The main contributing features are shown via a model fit (dark magenta) in the upper-left panel. F_λ, flux per unit wavelength. Adapted from ref. [199], AAS/IOP.

Bolometric light curves

- provide global parameters
    - size
    - nickel mass (Arnett’s rule)
    - ejecta mass
    - explosion energy
    - (distances)
- indicate the total energy output/conversion from γ-rays

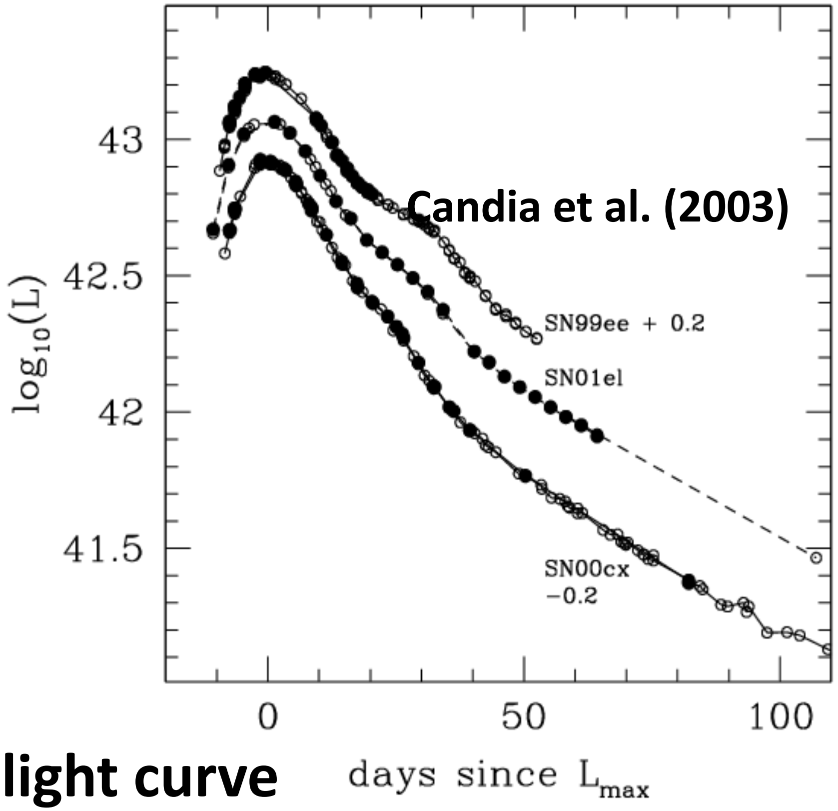


UBVRIJHK Light Curves of a Typical SN Ia

Sources:

UBVRI: Suntzeff et al. (1999)

JHK: Mayya et al. (1998)
Jha et al. (1999)
Hernandez et al. (2000)



Candia et al. (2003)

Bolometric light curve

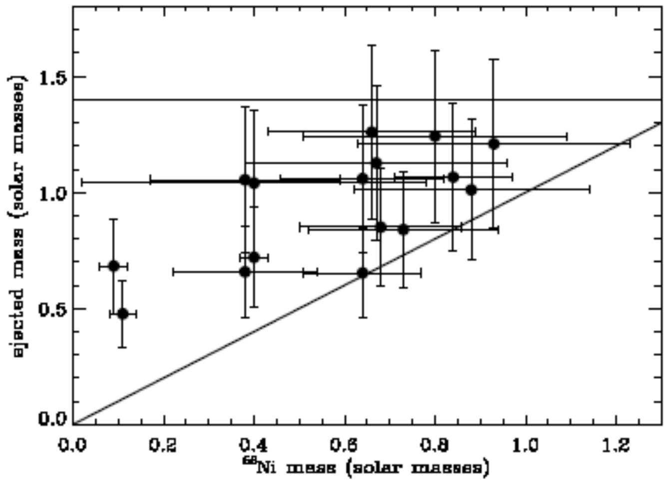


Figure 4 Ejected mass plotted vs. ^{56}Ni mass for 16 SNe Ia. Units are in solar mass. See text for comments concerning the error bars.
Solid horizontal line indicates the Chandrasekhar mass. Slanted line has a slope of 1.

Stritzinger et al 2006

Explosion mechanisms

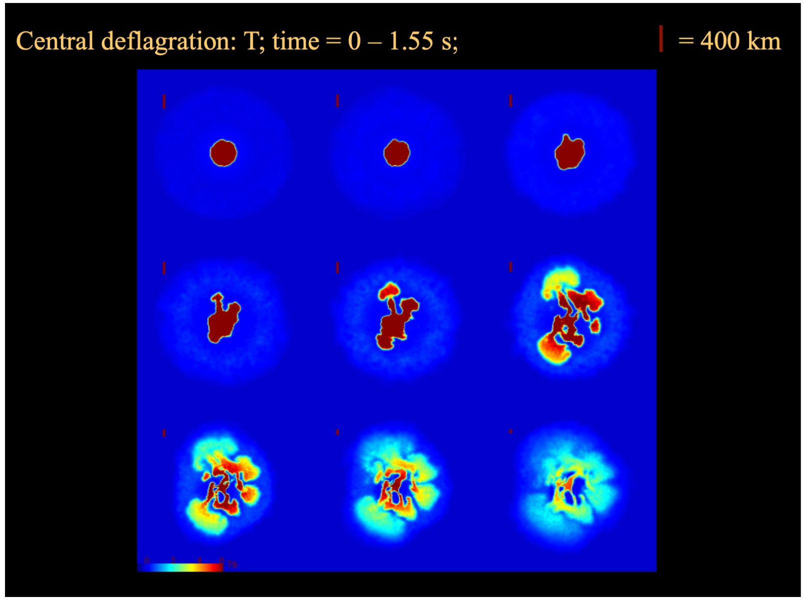
The presence of intermediate elements, the absence of important amounts Fe-peak elements at máximum indicates that the burning has to be subsonic (deflagration) and that the supersonic fronts (detonation) must be confined to regions with $\varrho \lesssim 10^7$ g cm^{-3} if fuel is C/O

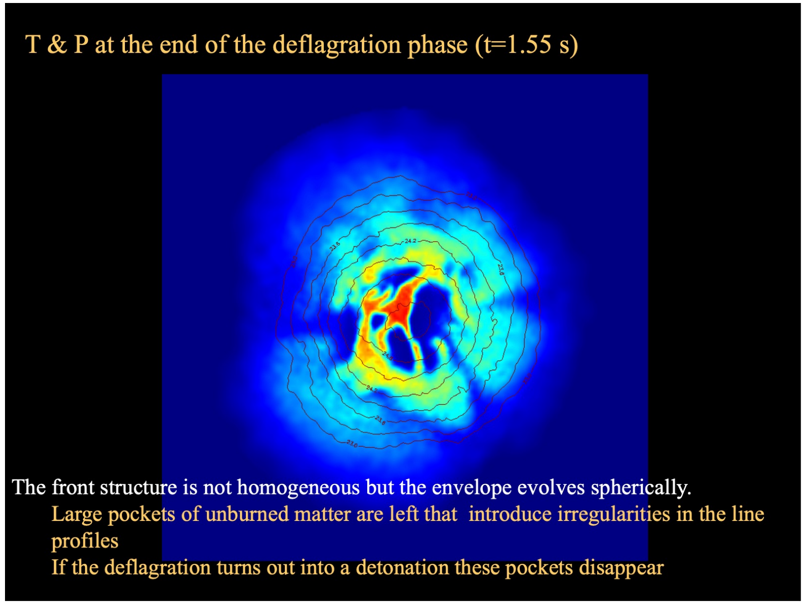
Possibilities:

* Detonation in the outer layers of a near-Ch WD or a sub-Ch triggers central ignition.
* Deflagration can start in the central regions
* Delayed detonation: deflagration followed by a detonation
* Pulsational delayed detonation

The equivalent in 3D also exists

Deflagration - detonation


Central deflagration: T; time = 0 – 1.55 s;


T & P at the end of the deflagration phase (t=1.55 s)

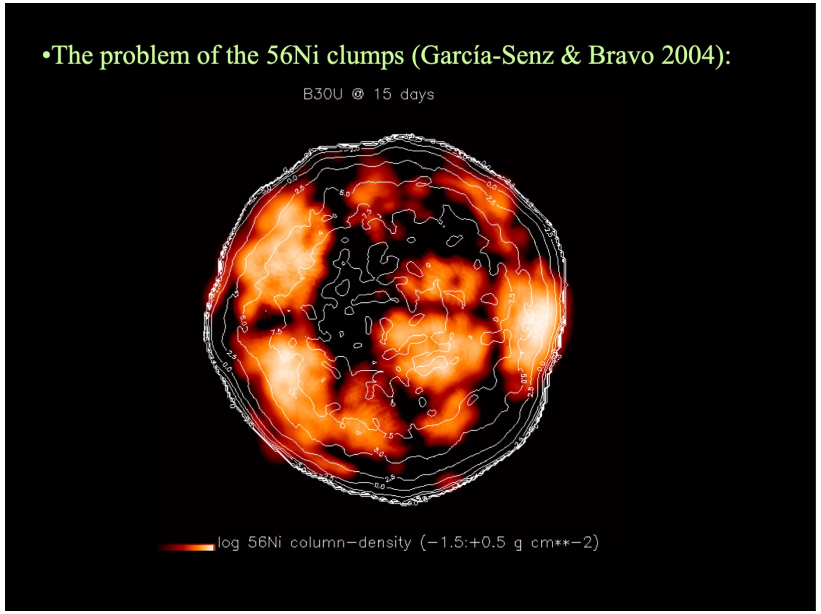
The front structure is not homogeneous but the envelope evolves spherically.

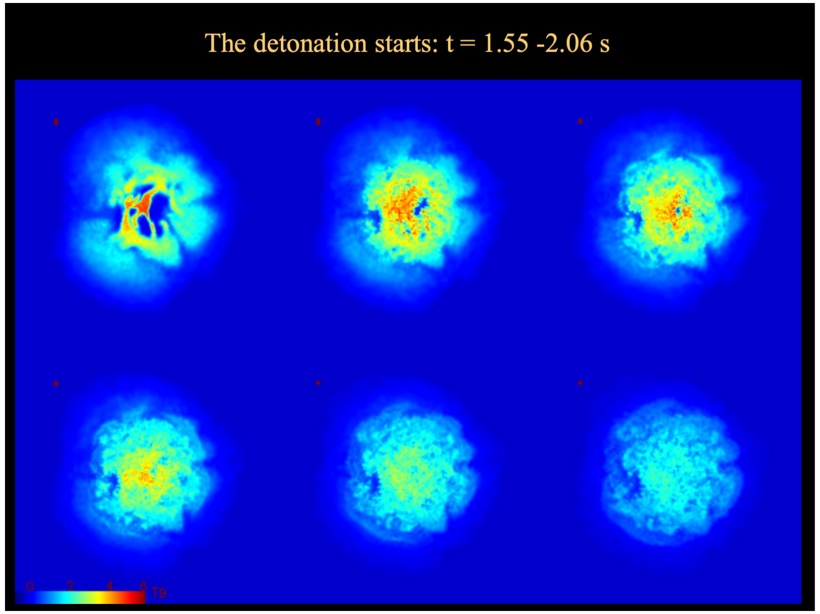
Large pockets of unburned matter are left that introduce irregularities in the line profiles

If the deflagration turns out into a detonation these pockets disappear

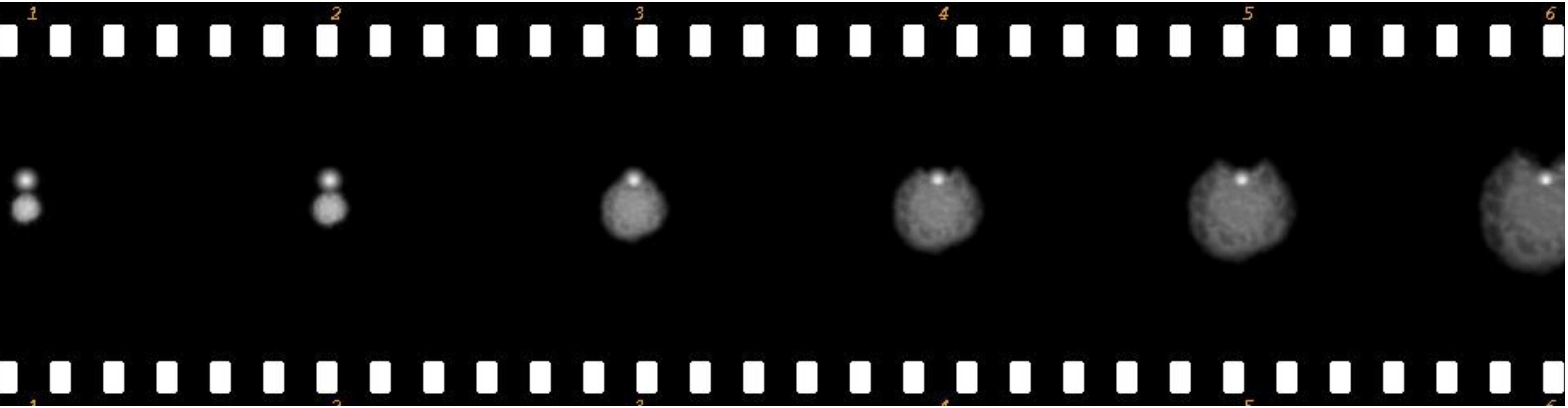
Deflagration introduces irregularities that are erased by the detonation (Garcia-Senz & Brav0’04)

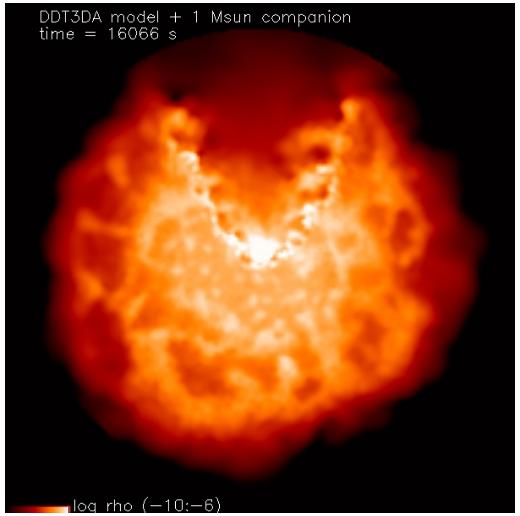
The velocity structure suggests stratification (Ashell+’14) SN14J at odds with a pure deflagration

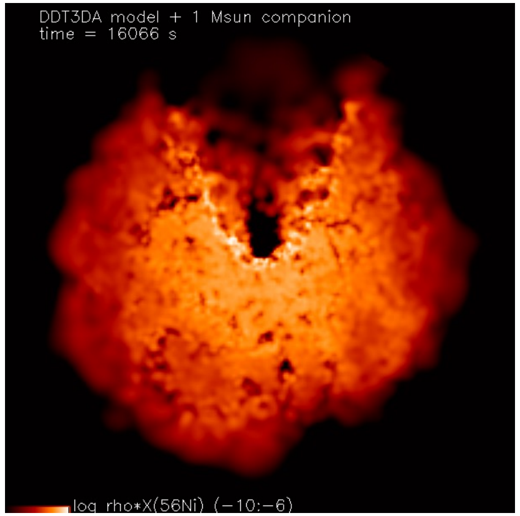

•The problem of the 56Ni clumps (García-Senz & Bravo 2004):

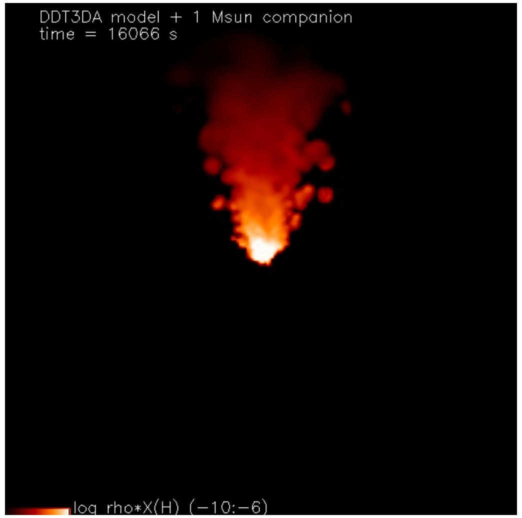

The detonation starts: t = 1.55 -2.06 s

Interaction with the companion. Dependence on the visual







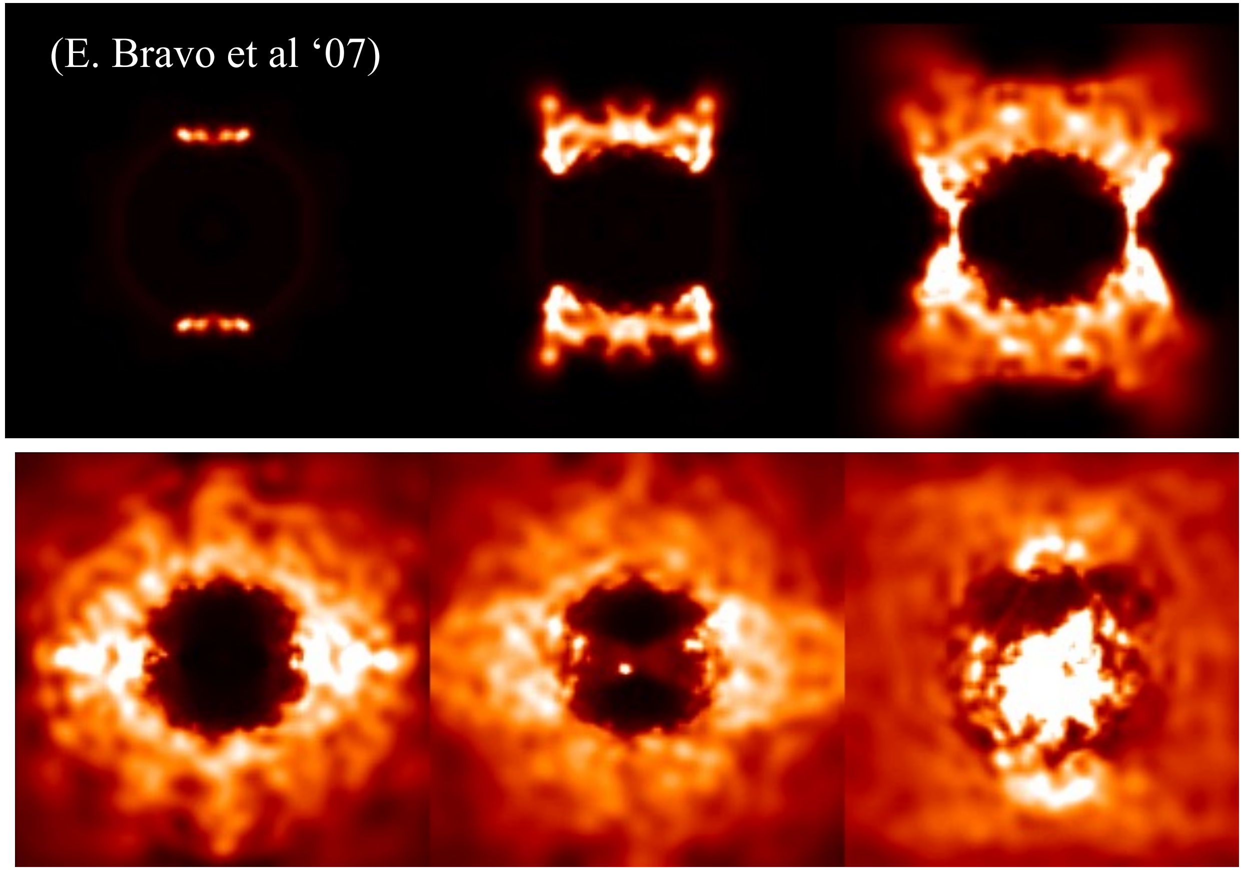


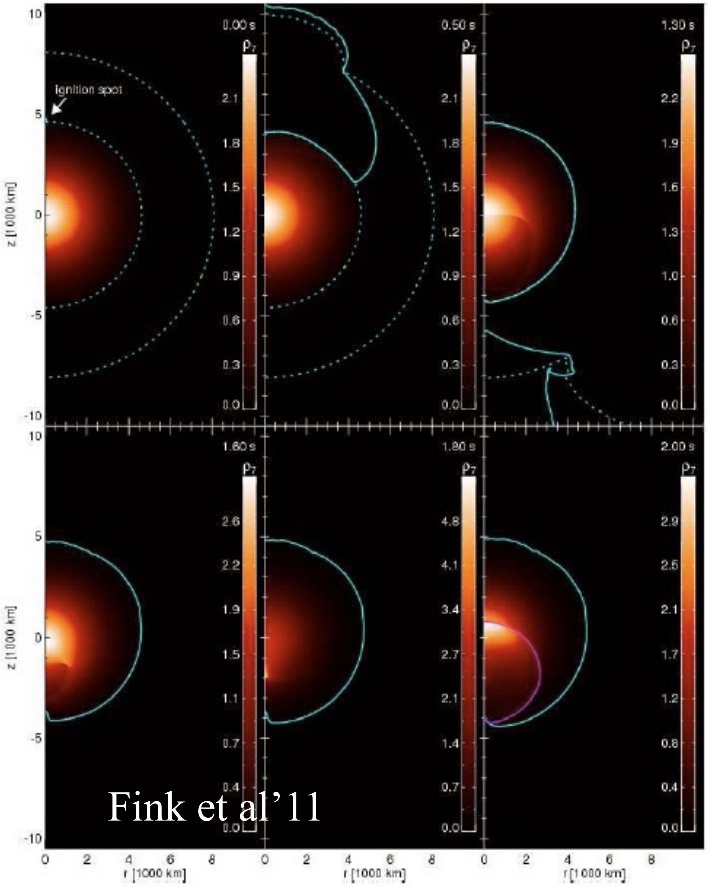
Stripped mass: 0.15-0.53 M_o
Depends on tha mass, separation and evolutionary status of the secondary

(Bravo+’07)

Double detonations

(temperature)


(E. Bravo et al ‘07)



Fink et al’11

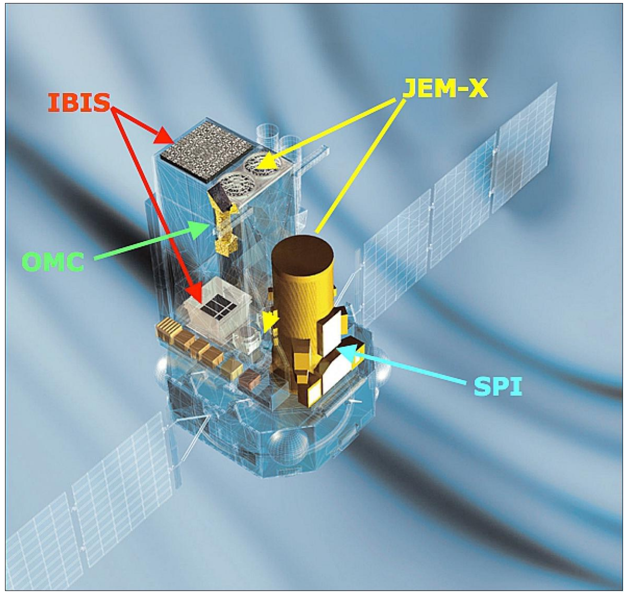
Initially it was thought that it was necessary to detonate 0.2-0.3 $M_{\odot}$ to induce the central detonation.

Incompatible with observations: excess of Fe at high velocities,

Fink+’11 showed that only a very small amount of He

The detonation can ignite the companion and even produce the double detonation of the secondary WD (triple and quadruple detonation)

INTEGRAL observations of SN2014J in M82 confirmed the main lines of this scenario!



Churazov et al. 2014
Diehl et al.2015

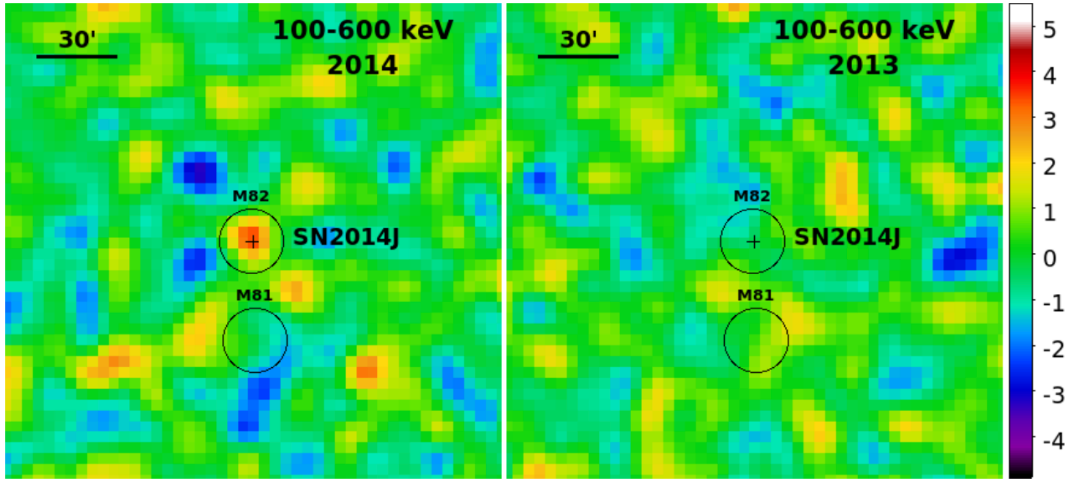
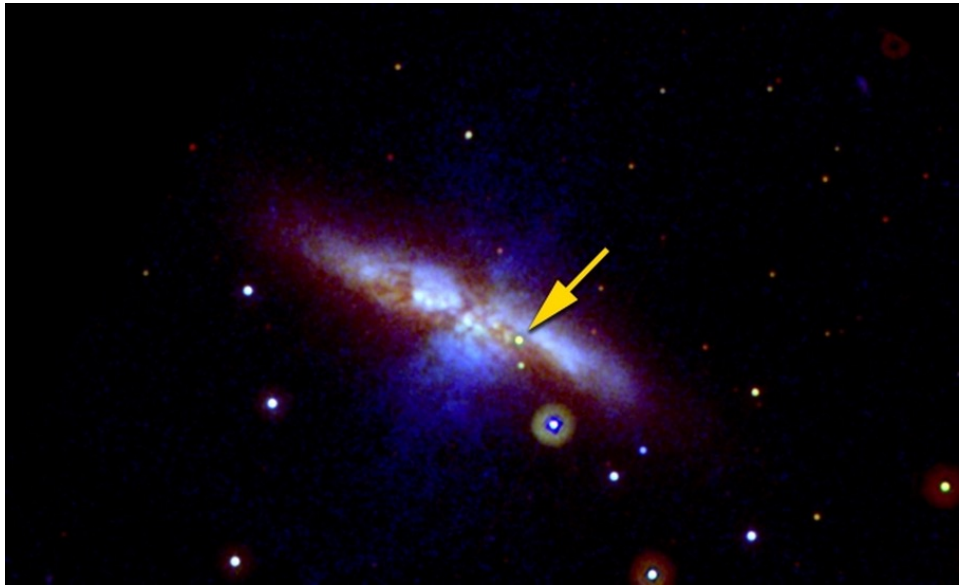


Figure 3 ***Appearance of a new hard (100–600 keV) X-ray source at the position of SN 2014J.*** *In the ISGRI image of the M82 field taken in 2013 the source is absent. Colours show the signal-to-noise ratio at a given position. SN 2014J is detected in this image at ~3.7 s.d.*



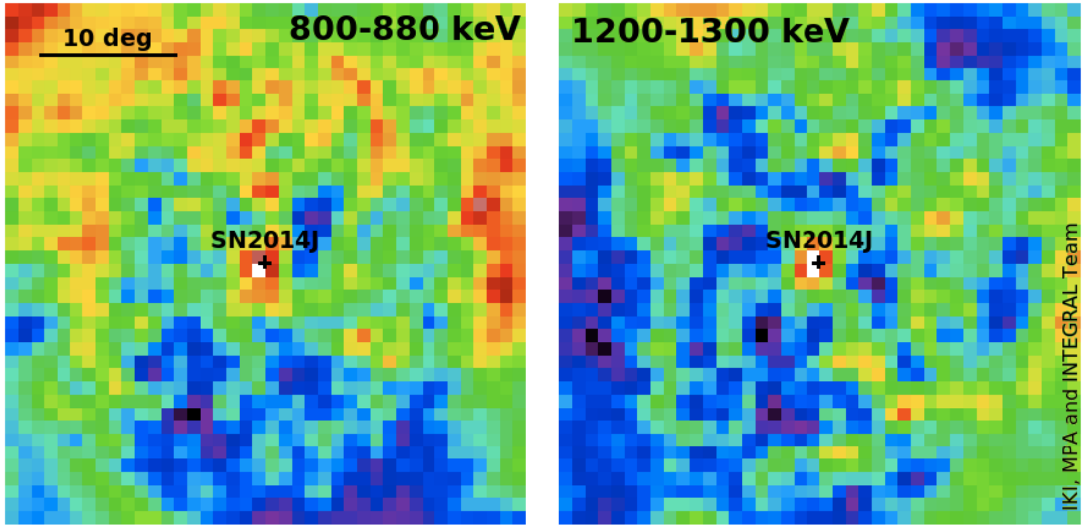
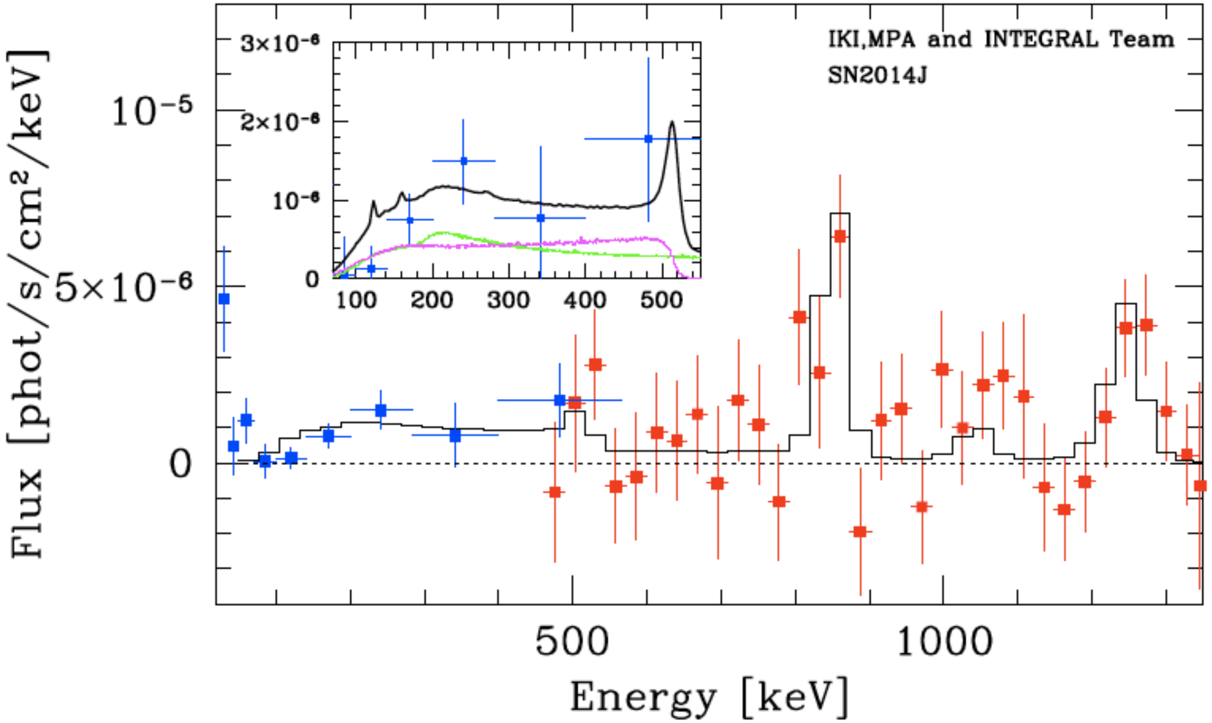


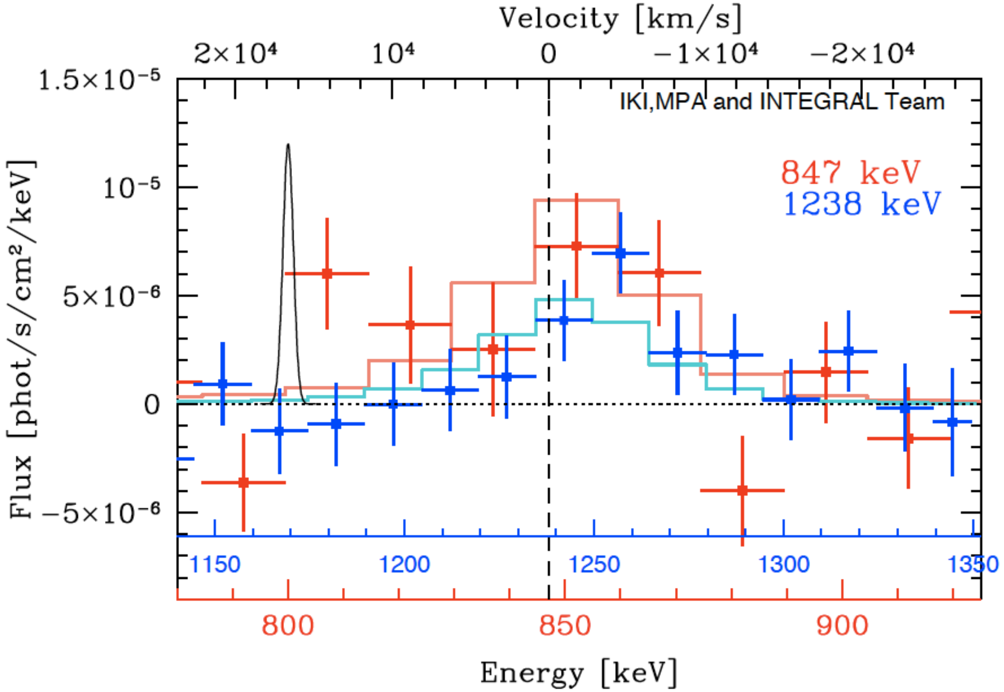
FIG. 2.— Signatures of ^{56}Co lines at 847 and 1238 keV in SPI images. Broad bands 800-880 keV and 1200-1300 keV are expected to contain the flux from these lines with account for expected broadening (and shift) due to the ejecta expansion and opacity effects. The source is detected at 3.9 and 4.3 σ in these two bands.

INTEGRAL observations of SN2014J in M82 confirmed the main lines of this scenario!

$$M_{56Ni} = 0.56^{+0.14}_{-0.06}\ M_{\odot}$$

$$M_{ej} = 1.2^{+1.9}_{-0.5}\ M_{\odot} \qquad v_{exp} = 3{,}000 \pm 800\ km/s$$

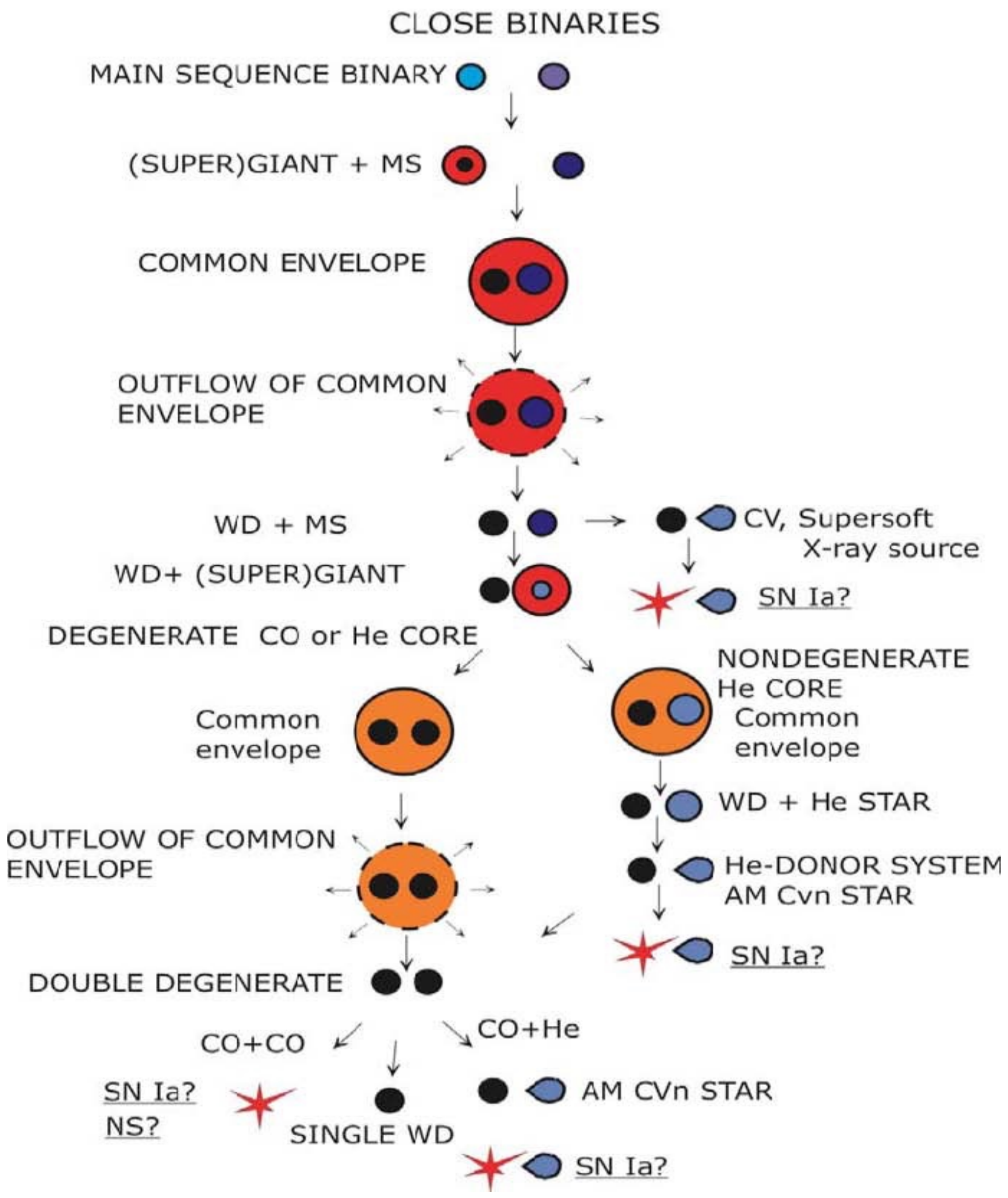


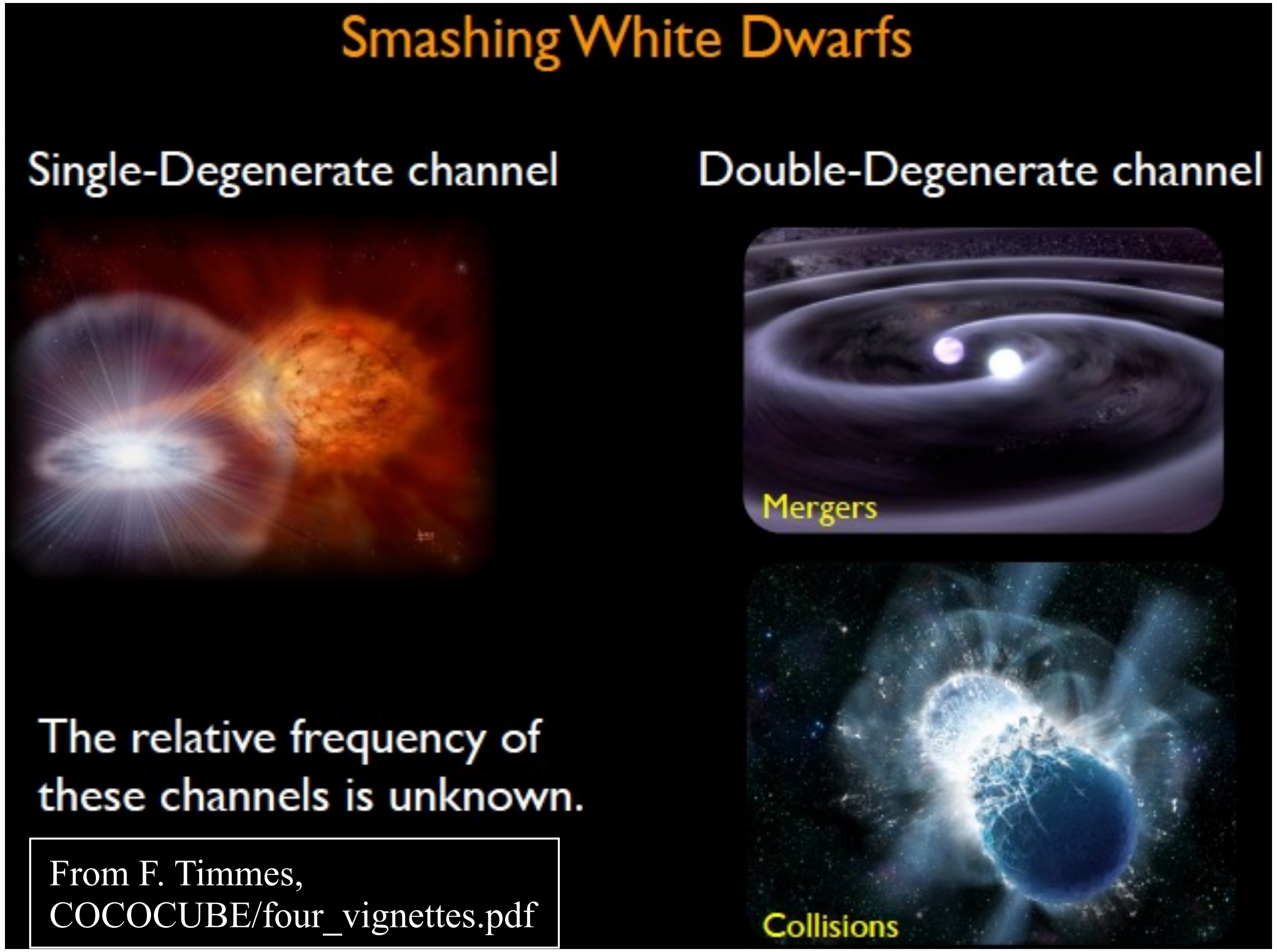


Churazov et al. 2014

FIG. 4.— Broadening of the 847 and 1238 keV lines. Red points show the SPI spectrum in the 720-920 keV range. Red histogram shows the line profile in the fiducial model. The blue points show the SPI spectrum of the 1238 keV line. For comparison a Gaussian line at 800 keV with the width, corresponding to the SPI intrinsic energy resolution is shown with a black line. Both observed lines are clearly broadened. Upper axis shows the velocity needed to shift the line to a given energy.

Scenarios leading to a SNIa





Smashing White Dwarfs

Single-Degenerate channel

Double-Degenerate channel

Mergers

Collisions

The relative frequency of these channels is unknown.

From F. Timmes, COCOCUBE/four_vignettes.pdf

Progenitor system still elusive!

At a first glance both scenarios SD & DD can coexist!

Everything able to explode eventually does it!

The questions are:

Is there anything preventing the explosion?

Is there anything preventing the detection?

Accreted matter:
H, He or C+O

There are multiple scenarios that are potentially explosive

Z. Liu et al.: SN Ia explosion in binary systems 5

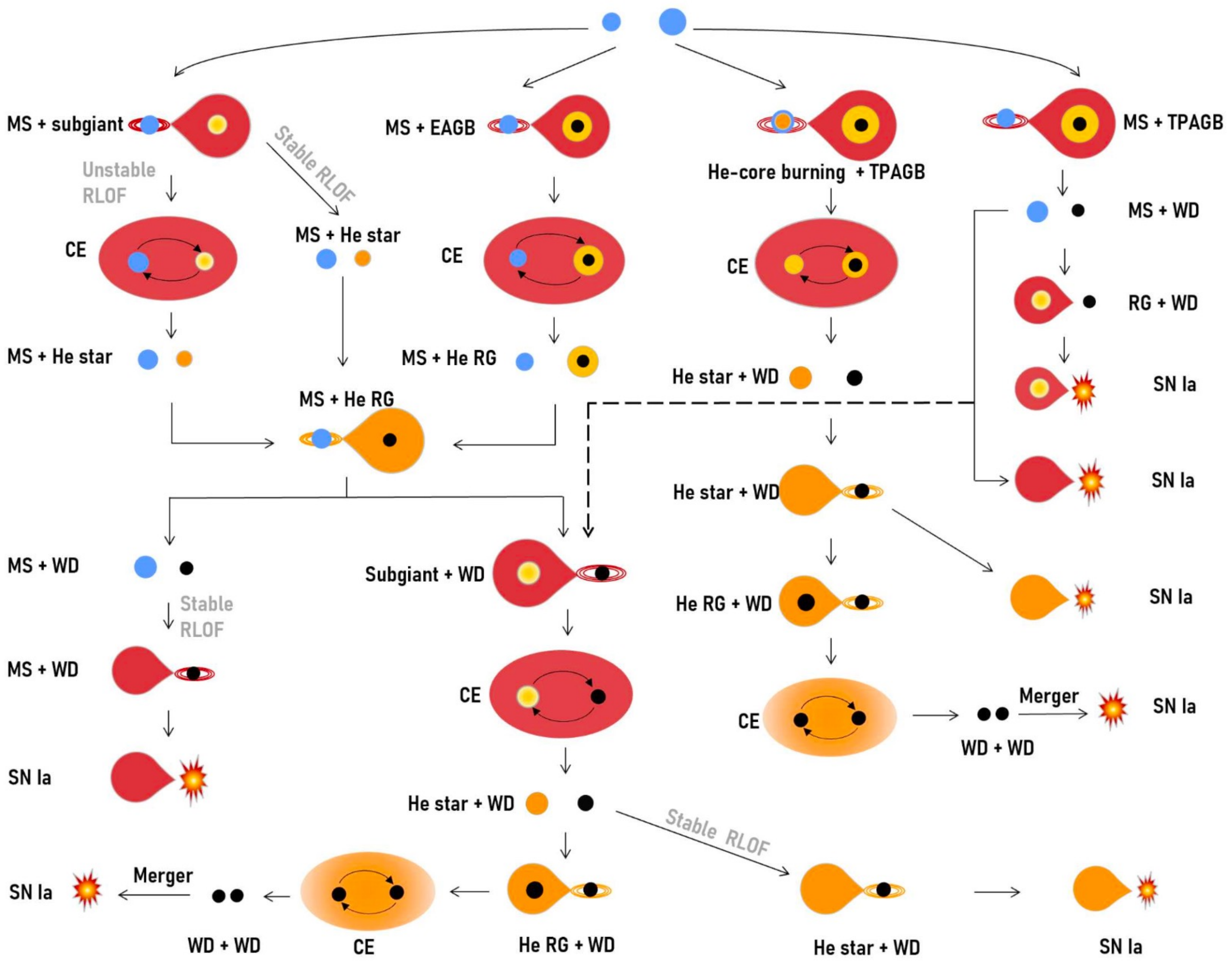


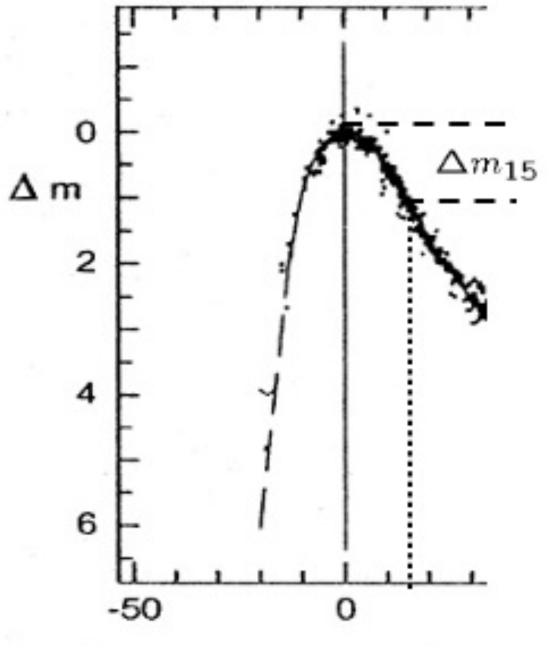
Fig. 2 Schematic illustration of binary evolutionary paths for SNe Ia in the SD and DD scenario (see also Wang 2018). Note that evolutionary channels here are not complete and that new channels may still be proposed in the future.

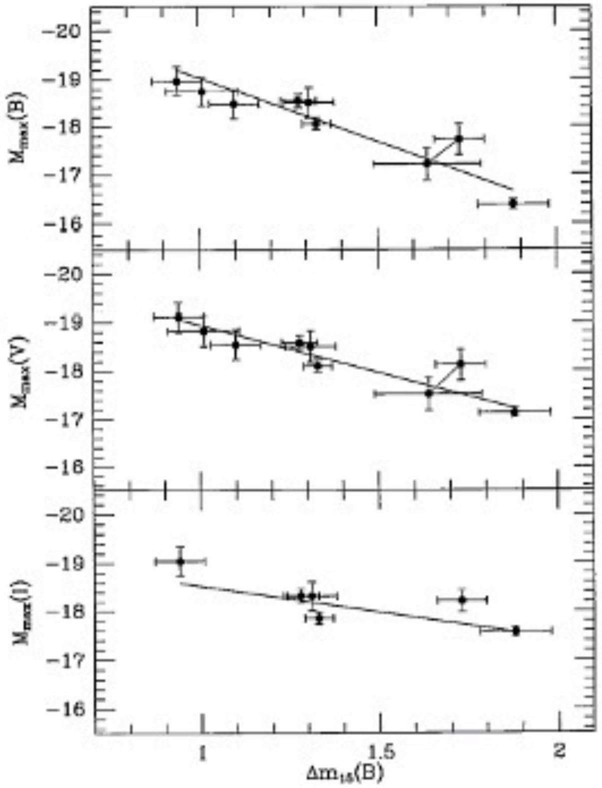
- **Single degenerate scenario** (Whelan & Iben’73, Nomoto’82, Han & Podsialowski’04)
- **Double degenerate scenario** (Webbink’84, Iben & Tutukov’84)
- **Core degenerate scenario** (Livio & Riess’03, Kashi & Soaker’11, Soker’11)
- **WD-WD collision scenario** (Kushnir et al’13)
- **Sub-Chandrasekhar scenario** (Woosley & Weaver’94, Livne & Arnet’95, Shen et al’13)

The unicity of SNIa was early questioned

Barbon+’74 divided SNIa into ‘Fast’ & ‘Slow’
Pskovskii’77,’84; Branch’81
Phillips’93; Phillips+’99 found a correlation between peak magnitude and width

Phillips (1993; ApJ 413, L105)





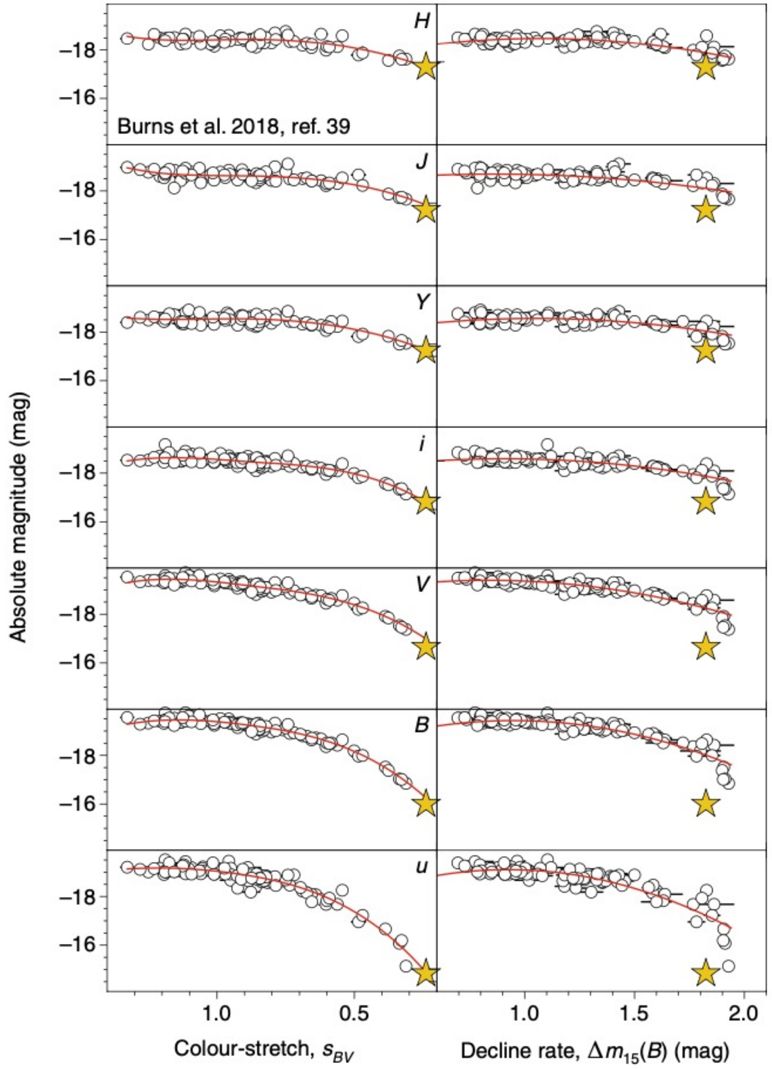
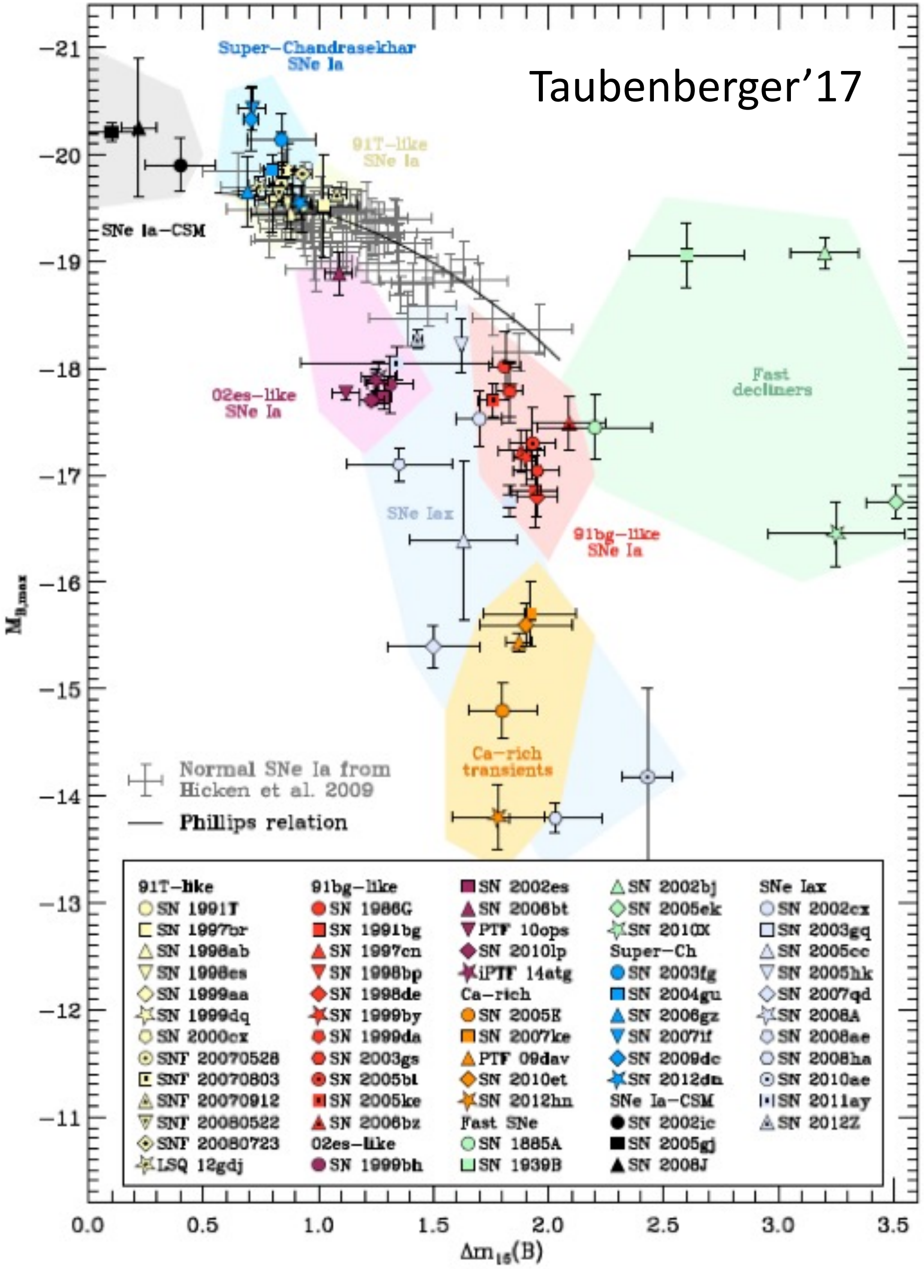


Fig. 3 | Lightcurve shape standardization of SNe Ia. Modern versions of the Phillips relation[8] from the Carnegie Supernova Project[39]. The right panels use the original $\Delta m_{15}(B)$ parameterization, while the left panels use s_{BV}, the lightcurve colour-stretch[40]. Note the tight scatter around the mean relations ($\sigma \lesssim 0.15$ mag, except in u) and the flattening at longer wavelengths, showing that SNe Ia are excellent standard (not just standardizable) candles in the near-infrared. 1σ error bars are shown

A peculiar object is just a better observed object!: The SNIa zoo


Taubenberger’17

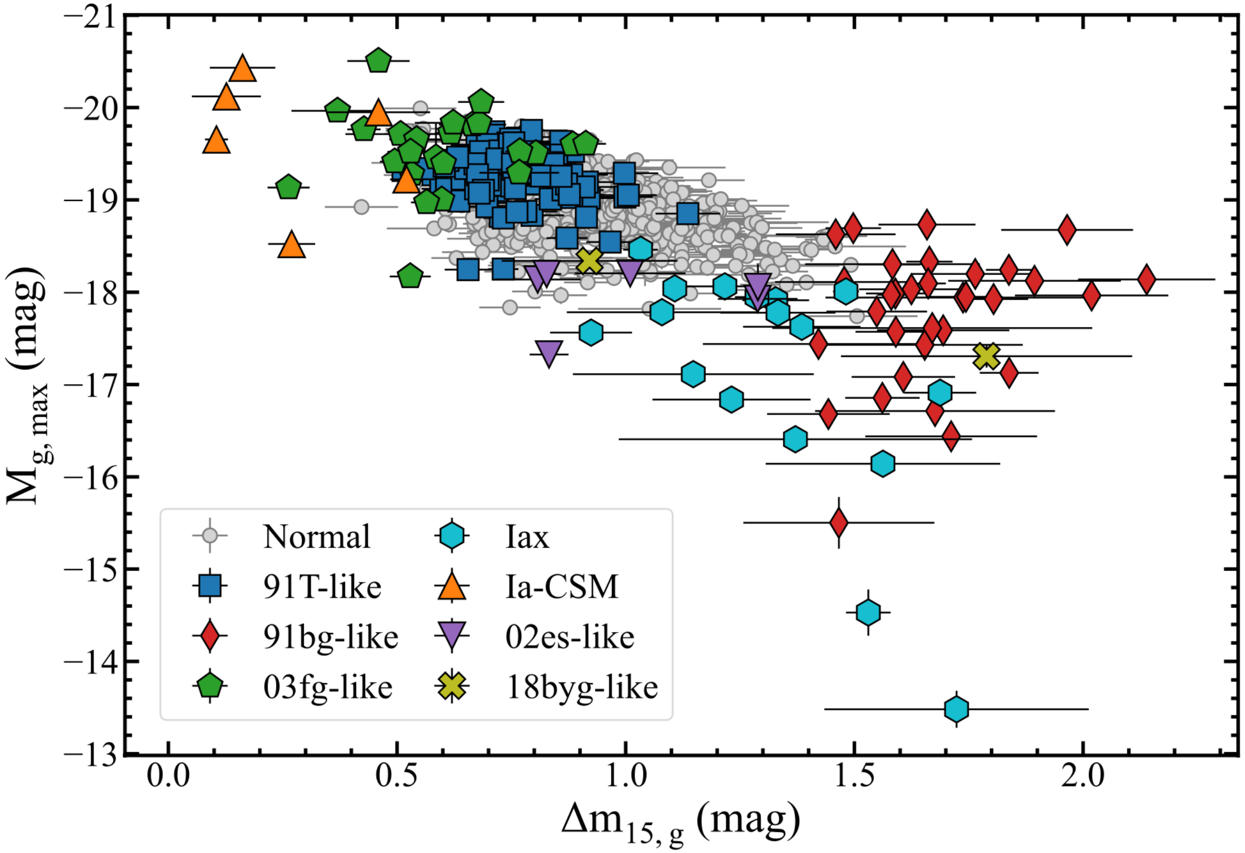


Fig. 5. Absolute *g*-band magnitude at peak versus the decline rate within 15 days from peak in the *g* band of the “gr” sample. The different subtypes are presented in different symbols and colors, as shown in the legend.

Thermonuclear subtypes in the ZTF catalogue
Dimitriadis+24 (arxiv 2409.04200v1)

#Therefore, the question is to assign a progenitor and an explosion mechanism to each subtype

Early behaviour of SNIa

Observations at early epochs after the explosion are crucial since they provide an information about the progenitor that disappears at later epochs.

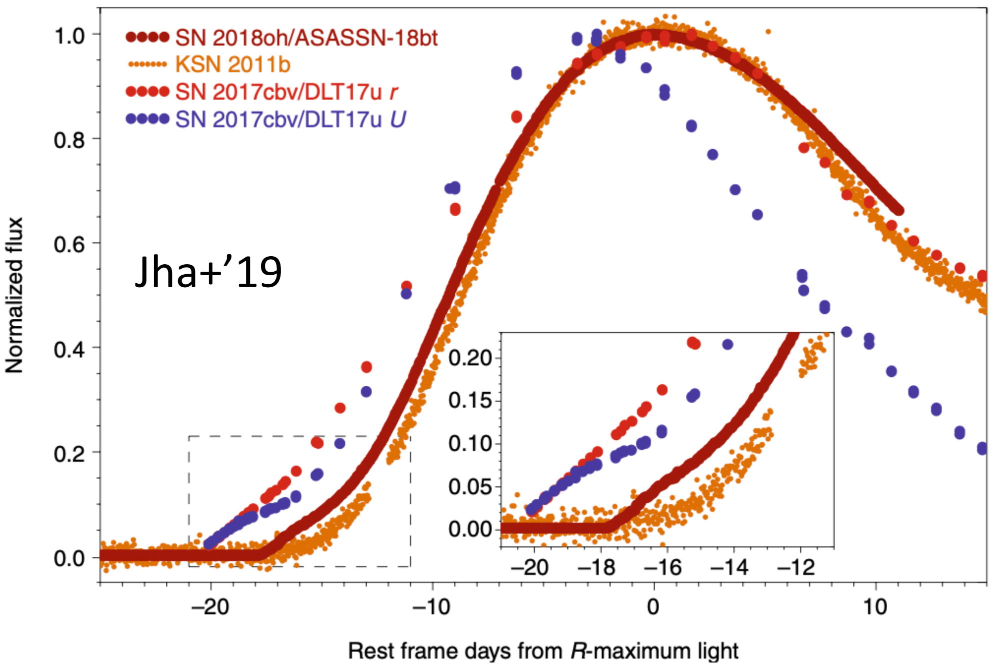
The shape of the light curve depends initially on the energy deposited by the shock break-out, which is proportional to the radius of the progenitor ($E \propto R_*$), and on the amount and distribution of ^{56}Ni

The light curve of exploding stars with $\mathrm{R} \leq 10 - 100\ R_\odot$ is mostly powered by radioactive material. These events mainly consist of exploding white dwarfs (SNIa) or core collapse of hydrogen stripped massive stars (SNIb/c).

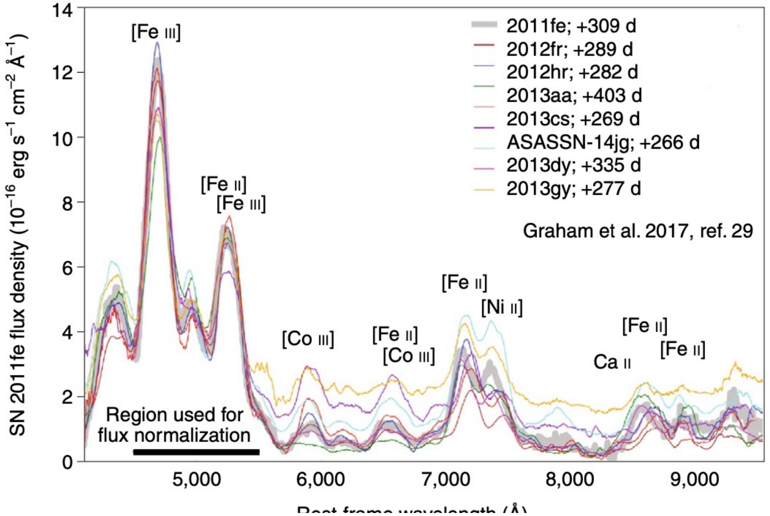
In the case of SNIa, the analysis of the rise time to maximum shows significant variations that range from ~16 to 25 days and some of them are rising more sharply then others (Firsth +'15). These differences, together with the diversity in colours are interpreted as being due the existence of asymmetries (Maeda+'11;Cartier+'11) or to differences in the distribution of ^{56}Ni (Piro & Nakar'13,14) or both (Magee+'18).

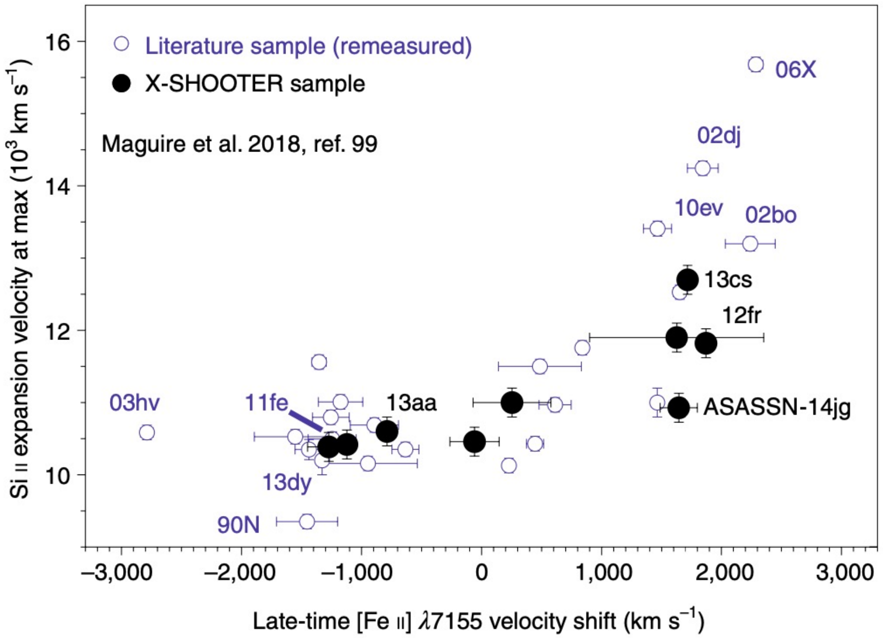
The early detection and characterization of the ^{56}Ni would be of the highest importance!

Early light curves



Light curves obtained by Kepler. Deviations from a smooth early rise have been interpreted as a shock interaction with a ND companion but it can be due to presence of shallow radioactive isotopes





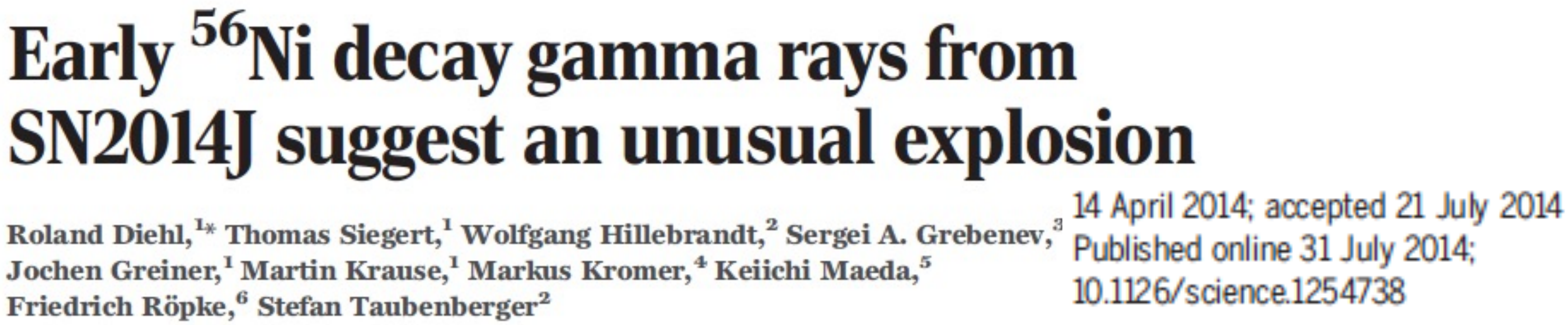
SNIa nebular (top) and Si velocities at maximum. SNIa with redshifted features have higher Si velocities, Caused by asymmetries (Jah+'19)?

Early observations (Rev 1380-86)
Jan 31/Feb 18 (17 – 35 days after explosion).

Optical Max: 17-20 d a.e.

INTEGRAL
IBIS/ISGRI: Max efficiency 50-200 keV
SPI: 70 keV – 3 MeV

Two detection claims: Diehl et al’14 (SPI), Isern et al’14 (SPI & ISGRI)



Early ^{56}Ni decay gamma rays from SN2014J suggest an unusual explosion

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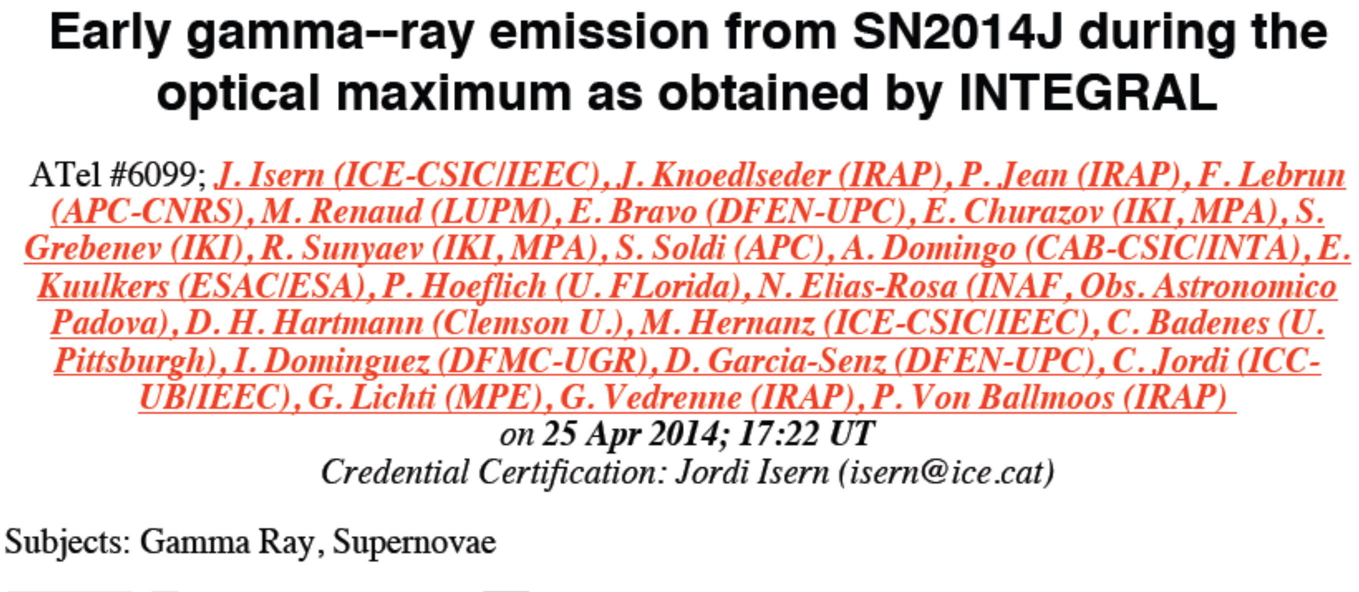
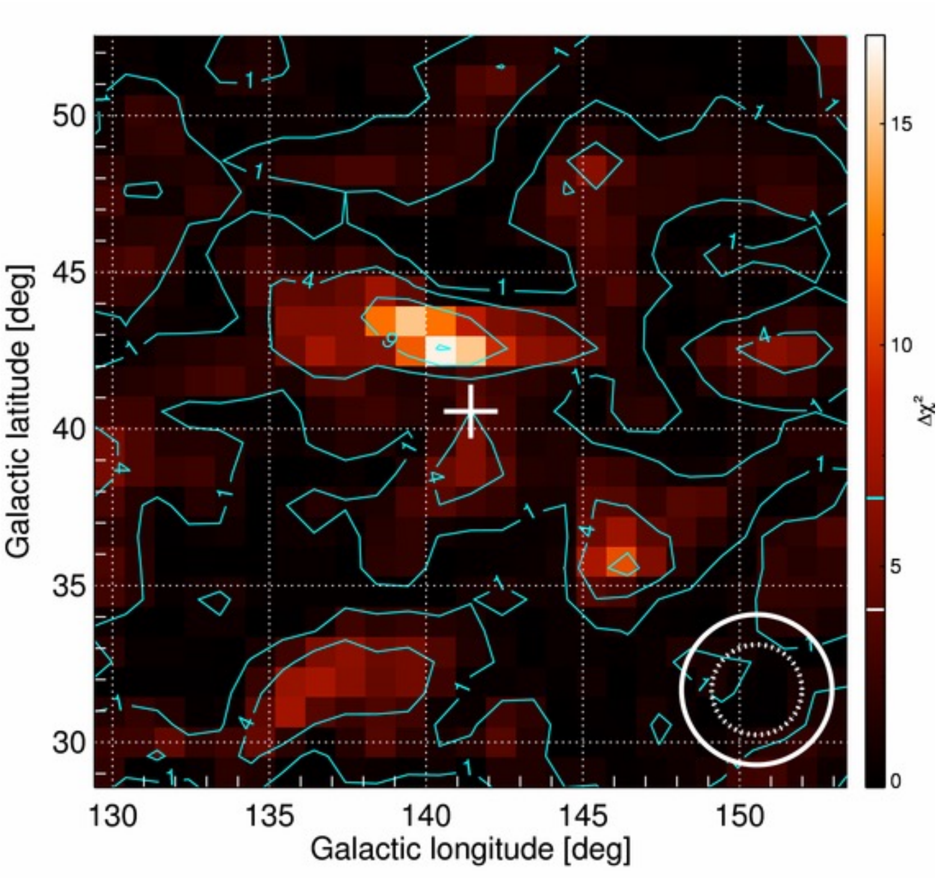


Early gamma--ray emission from SN2014J during the optical maximum as obtained by INTEGRAL

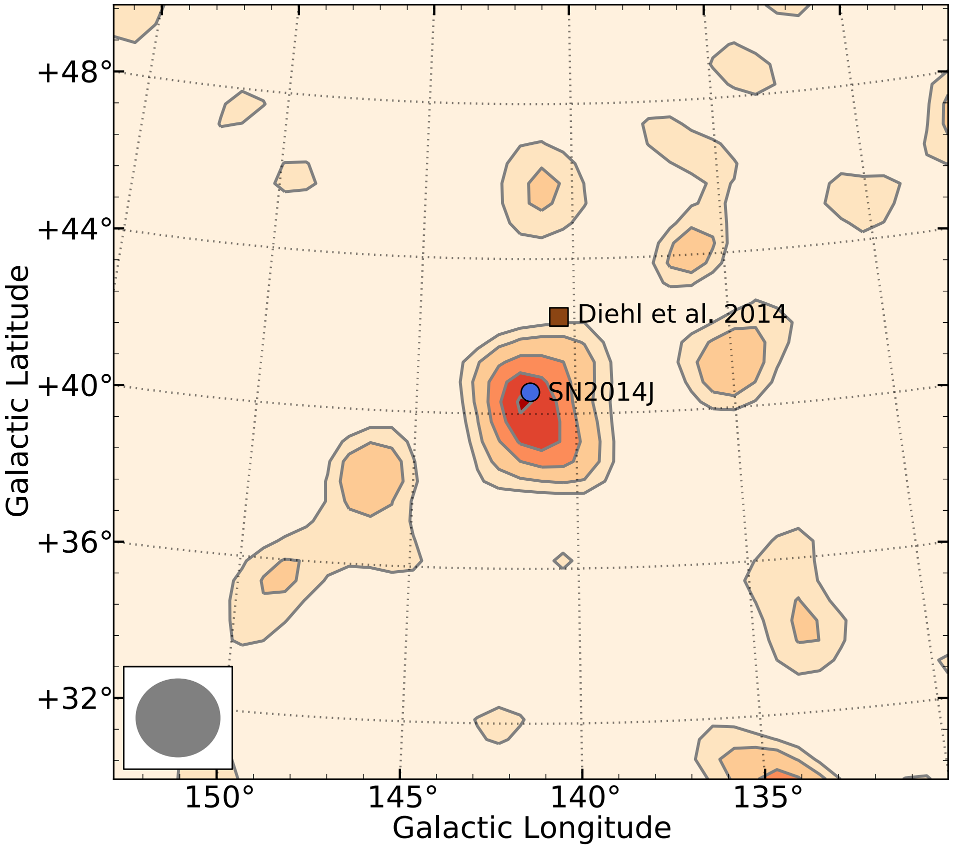
ATel #6099; J. Isern (ICE-CSIC/IEEC), J. Knoedlseder (IRAP), P. Jean (IRAP), F. Lebrun (APC-CNRS), M. Renaud (LUPM), E. Bravo (DFEN-UPC), E. Churazov (IKI, MPA), S. Grebenev (IKI), R. Sunyaev (IKI, MPA), S. Soldi (APC), A. Domingo (CAB-CSIC/INTA), E. Kuulkers (ESAC/ESA), P. Hoeflich (U. FLorida), N. Elias-Rosa (INAF, Obs. Astronomico Padova), D. H. Hartmann (Clemson U.), M. Hernanz (ICE-CSIC/IEEC), C. Badenes (U. Pittsburgh), I. Dominguez (DFMC-UGR), D. Garcia-Senz (DFEN-UPC), C. Jordi (ICC-UB/IEEC), G. Lichti (MPE), G. Vedrenne (IRAP), P. Von Ballmoos (IRAP)
on 25 Apr 2014; 17:22 UT
Credential Certification: Jordi Isern (isern@ice.cat)

Subjects: Gamma Ray, Supernovae

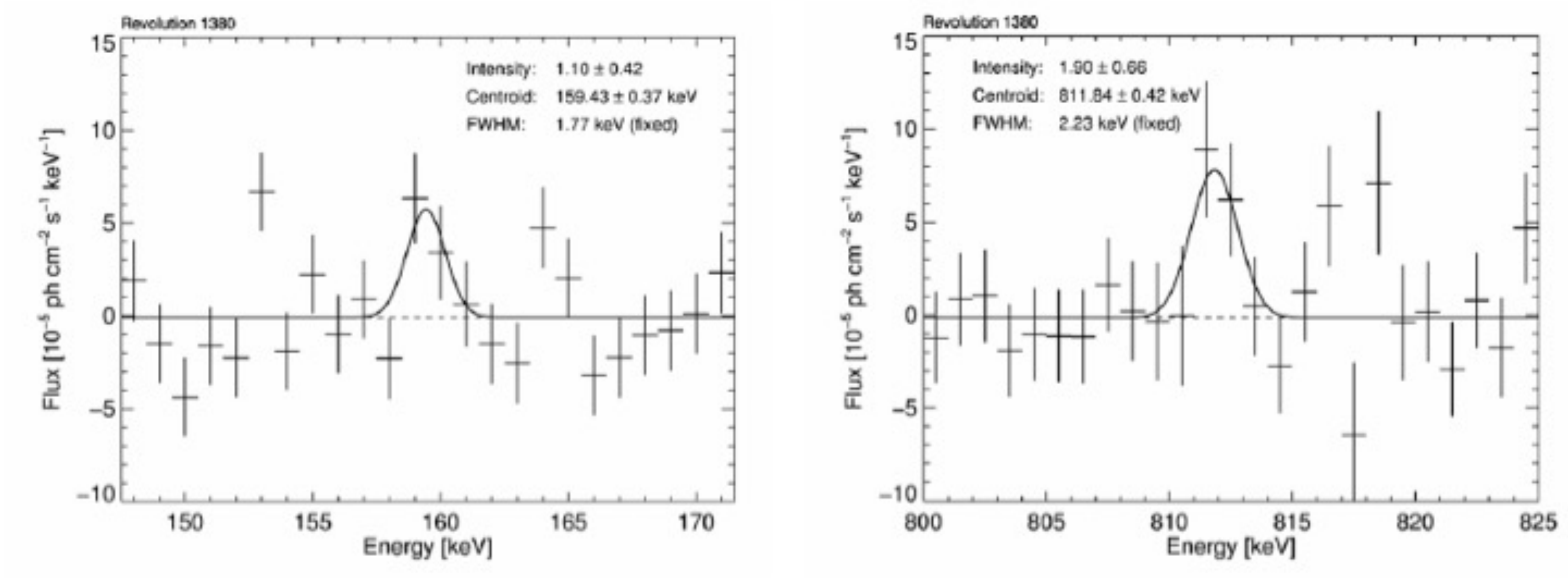
SN2014J early emission



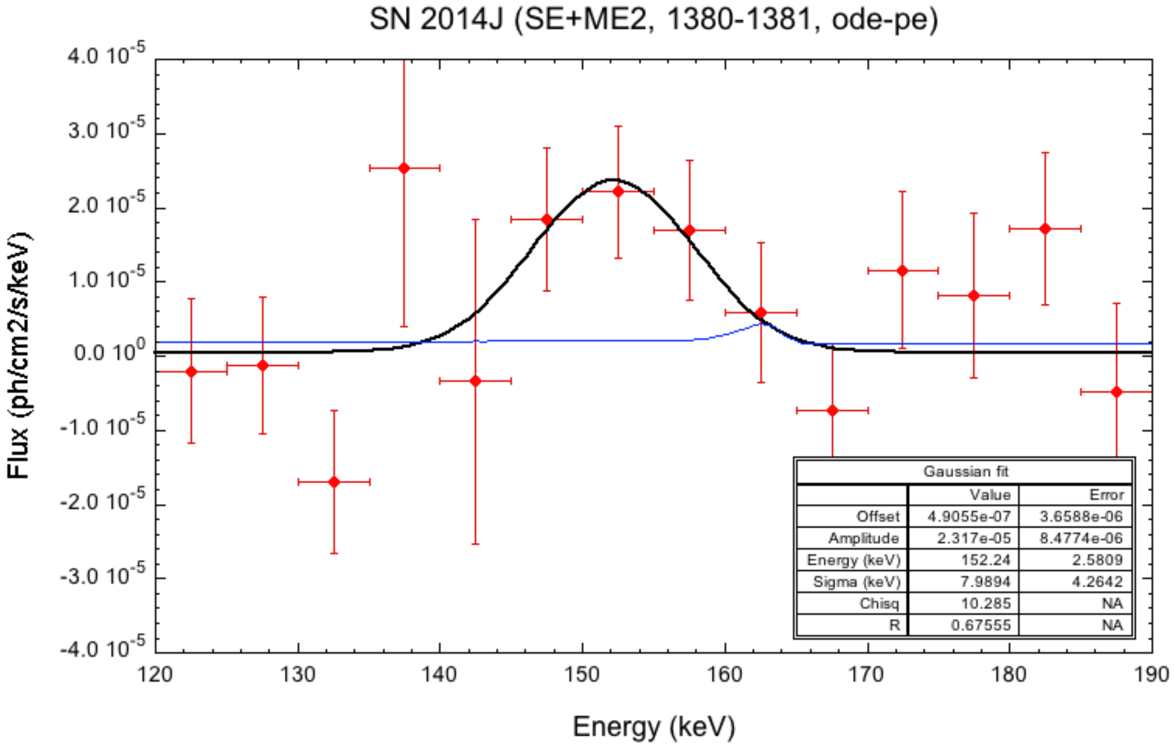
Emission of ^{56}Ni (158 & 812 keV) mapped onto the position of SN2014J (cross). (Diehl+'14)



145-165 band/ 16-35 days a.e.
Excess in the SN2014J position
5σ (Isern+'16)



Diehl +’14



	Value	Error
Offset	4.9055e-07	3.6588e-06
Amplitude	2.317e-05	8.4774e-06
Energy (keV)	152.24	2.5809
Sigma (keV)	7.9894	4.2642
Chisq	10.285	NA
R	0.67555	NA

Isern+’16

Broad line

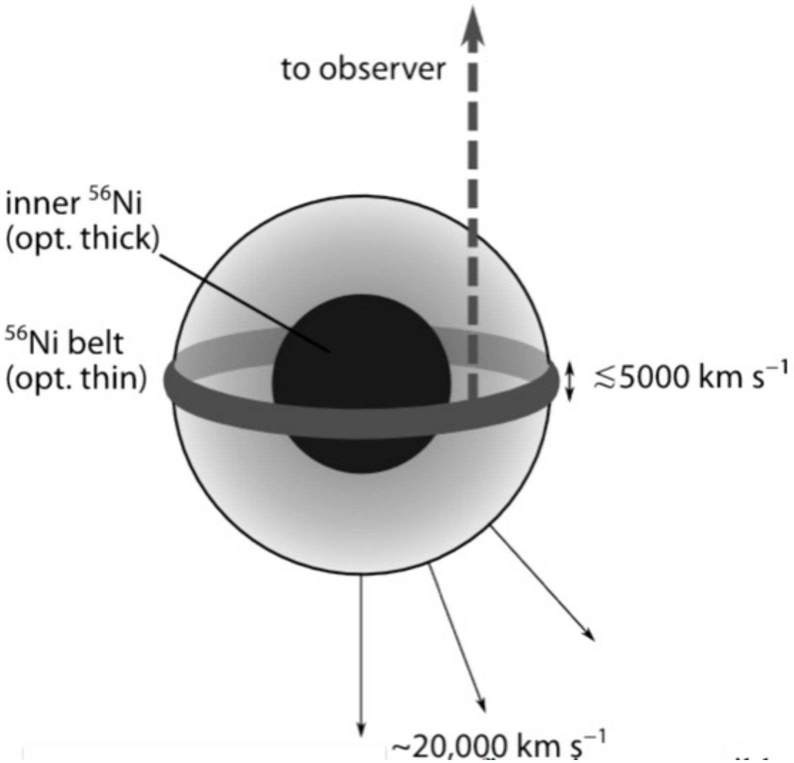
Center: 155.0 ±1.9 keV;

FWHN: 5.3 ± 3.9 keV; Transient

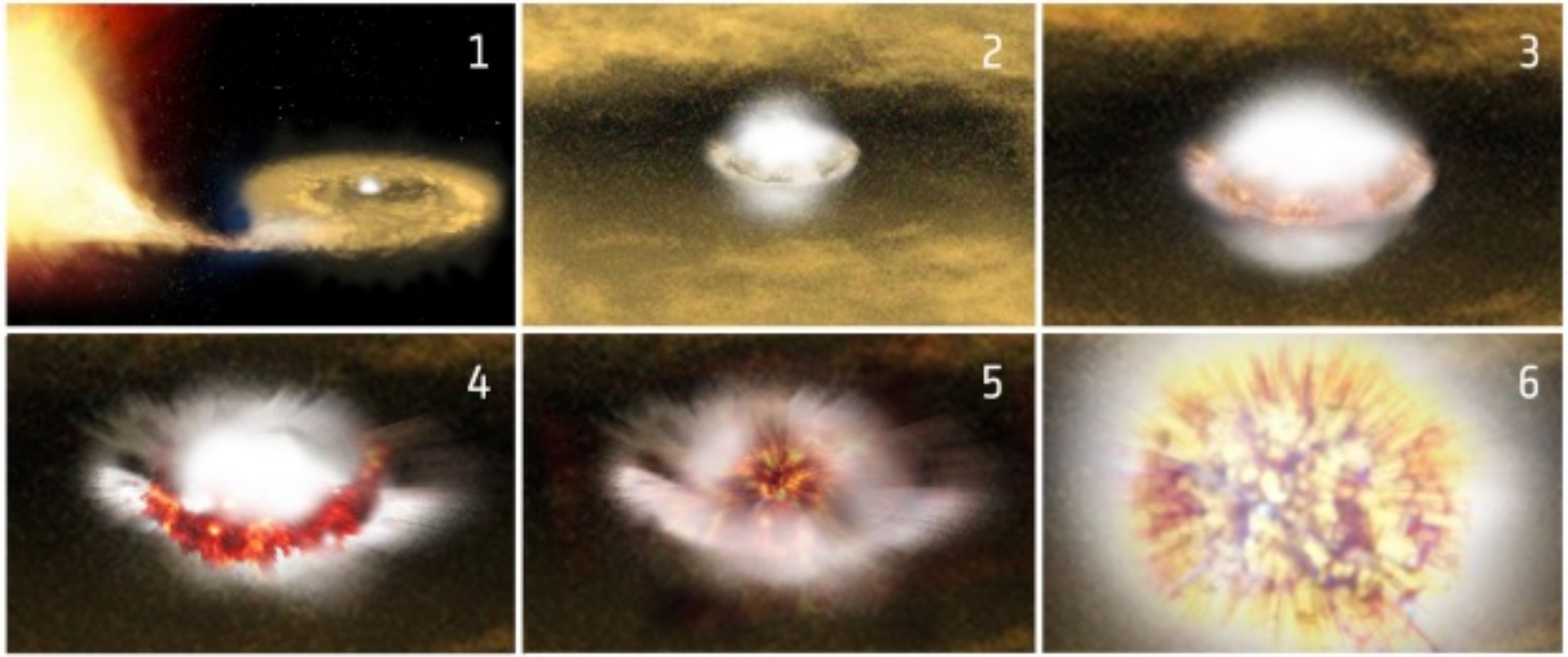
Flux: (2.4 ±1.6) x 10^{-4} cm^{-2} s^{-1} (3.5 σ)

The analysis of this emission is controversial:

- Diehl+'14 found a narrow emission at the ^{56}Ni lab value with indications of blue and red-shifted emission



They proposed the ignition of an equatorial He-belt perpendicular to the observer

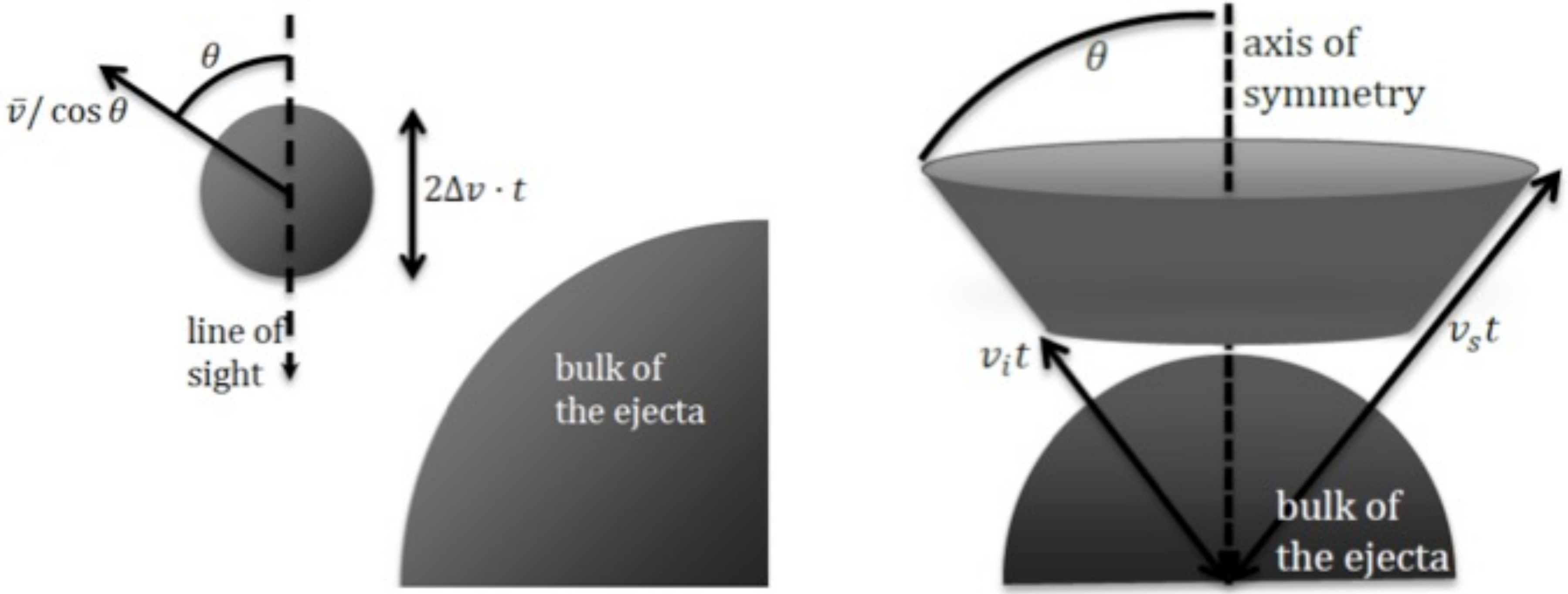


ESA credit

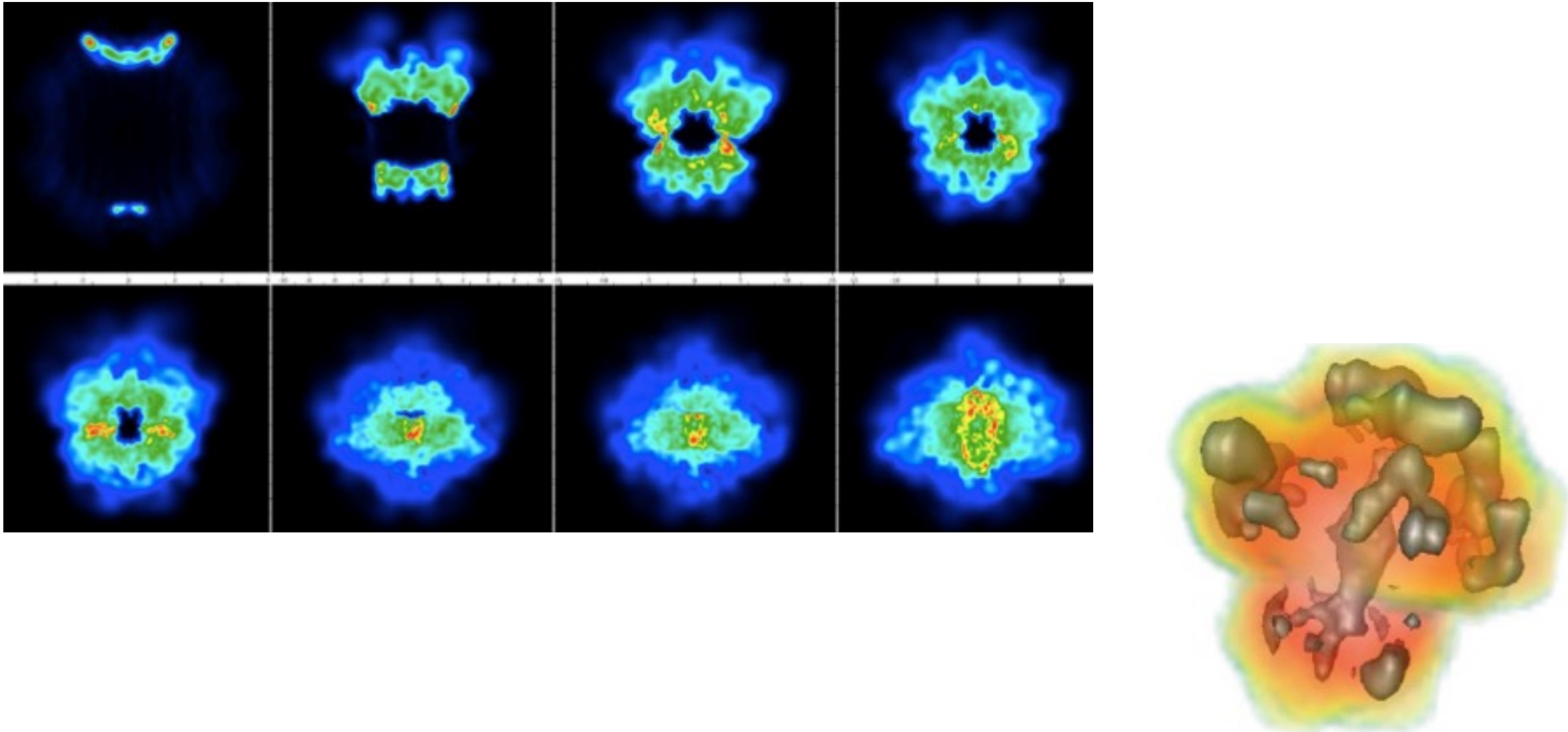
The analysis of this emission is contrversial: Isern+’16 found a redshifted broad ^{56}Ni line with centroid at 154.5±0.64 keV and width 3.7±1.5 keV

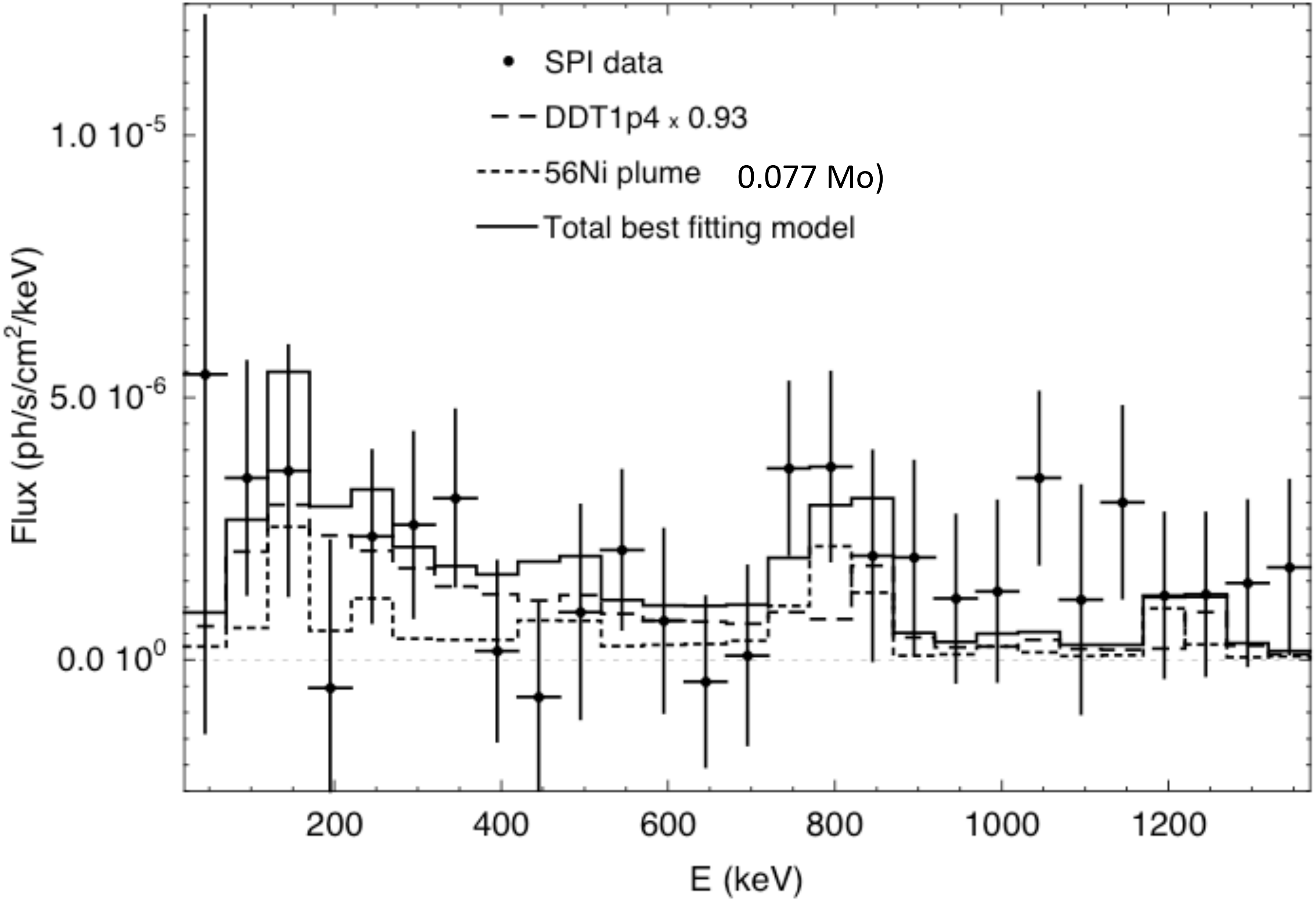
A blob should be visible in the optical

^{56}Ni distributed over a conical structure tilted versus the observar could fit the data.



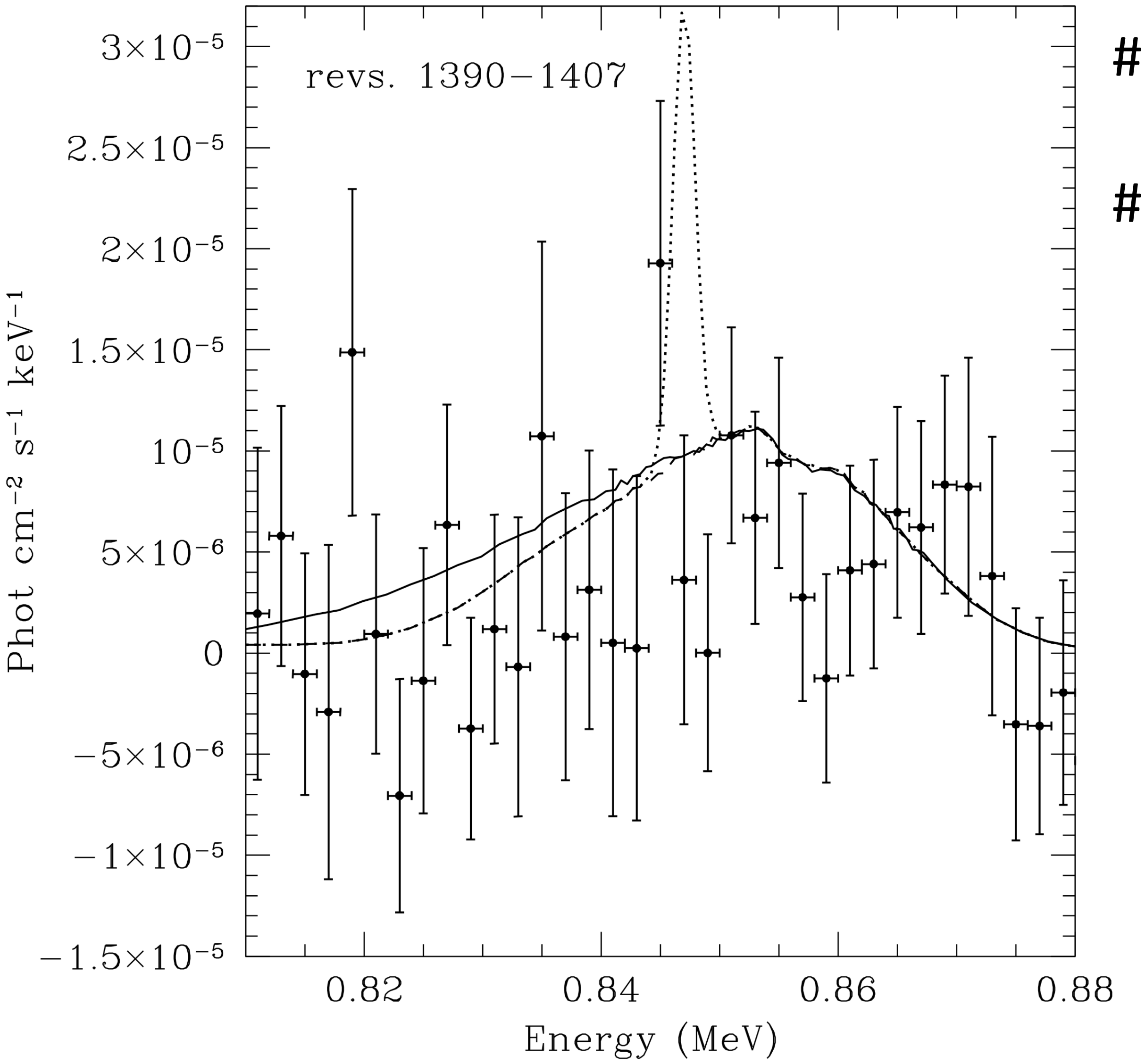
Asynchronous ignition of a He layer (Isern et al’17)





Gamma-ray spectrum
Rev: 1380-1386
(16.5 – 35.2 days a.e.)
Bins 50 keV

The inclusion of ‘bullets’ has to be compatible with the late time gamma spectrum



High resolution gamma-ray spectrum 50-100 days after explosion

Bins 2 keV wide

Dashed: DDT1p4 model

Solid: DDT1p4 + 0.07 $M_o$non equatorial plume

Dotted: DDT1p4 + 0.06 M_o equatorial plume

Max mass eq: 0.02 M_o (2 sigma)

Conclusions

INEGRAL has succeeded to detect SNIa the gamma lines 158 keV ^{56}Ni & 847, 1238 keV ^{56}Co lines and proved that these eruptions are the outcome of the thermonuclear explosion of a white dwarf in a binary system

Lines are broad (~ 3%) and variable, as expected, and have allowed to determine the total amount of ^{56}Ni and to provide constraints to its distribution.

Early observations before the maximum light could be extremely important to solve this problem

Observations around the maximum of SN2014J strongly suggest the presence of ^{56}Ni in the outer layers ($M_{Ni} \sim 0.03\text{-}0.08\ M_{\odot}$) either in the form of a plume or a ring

Detonation triggered by a thin He layer could be responsible but…

A statistically representative sample of SNIa must be observed

The necessary sensitivity is challenging: $\sim 10^{-7}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{keV}^{-1}$

Wide field monitor?

Royal Academy of Sciences & Arts of Barcelona (RACAB)- 1764

Fabra Observatory 1904