Supernovas con dos máximos en la curva de luz bolométrica

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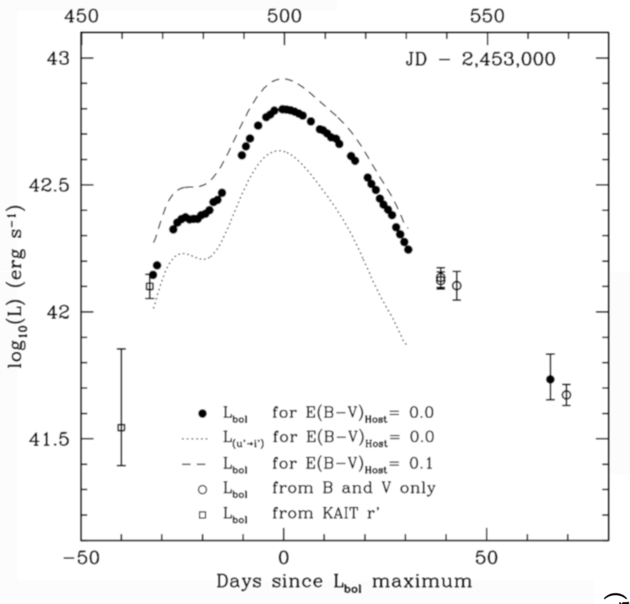
An unprecedented light curve morphology among Type Ib/c

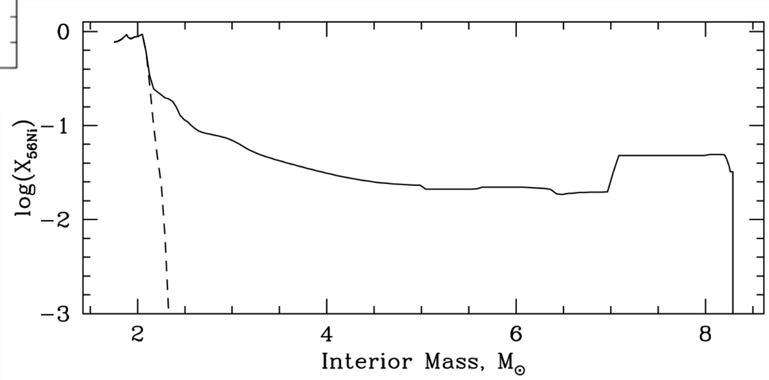
Tominaga et al. (2005)



SN2005bf

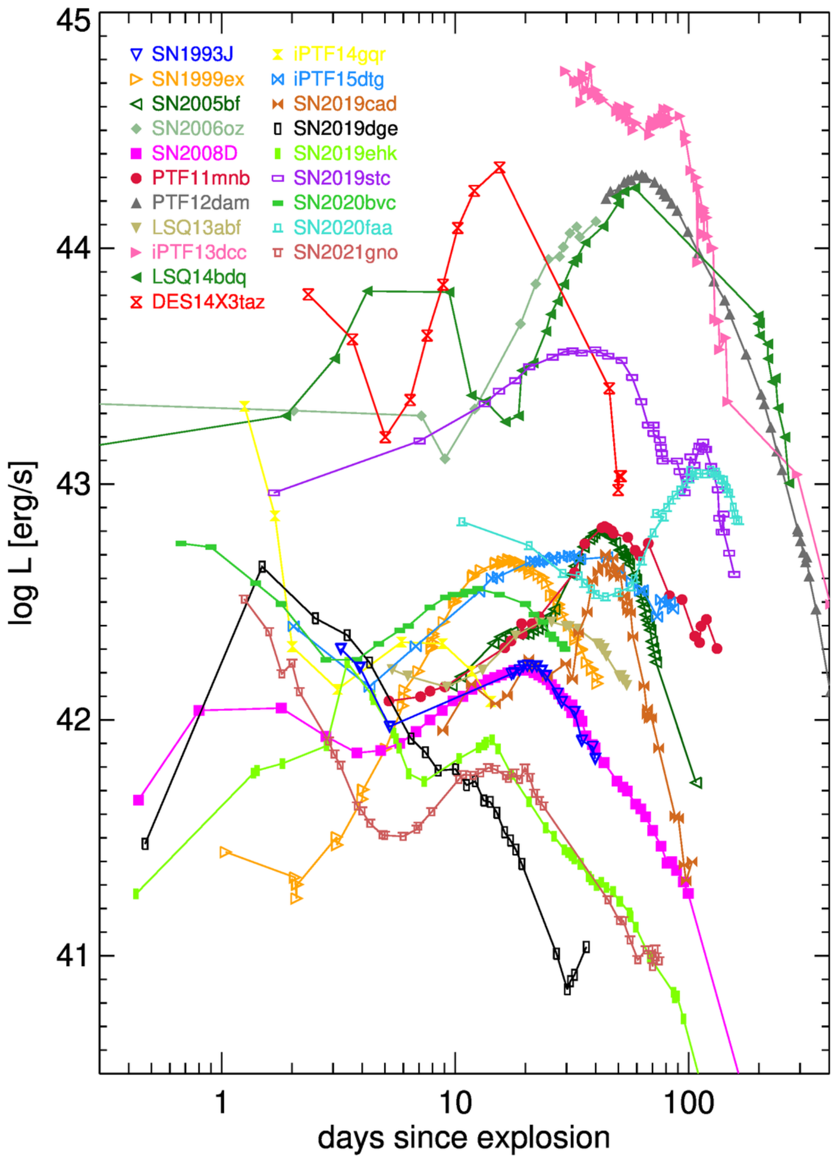
Folatelli et al. (2006)

The model propose an unusual distribution of the radioactive matter.



This is described as a mildly inverted distribution.

Magnetar as alternative proposal
Tanaka et al. (2009)



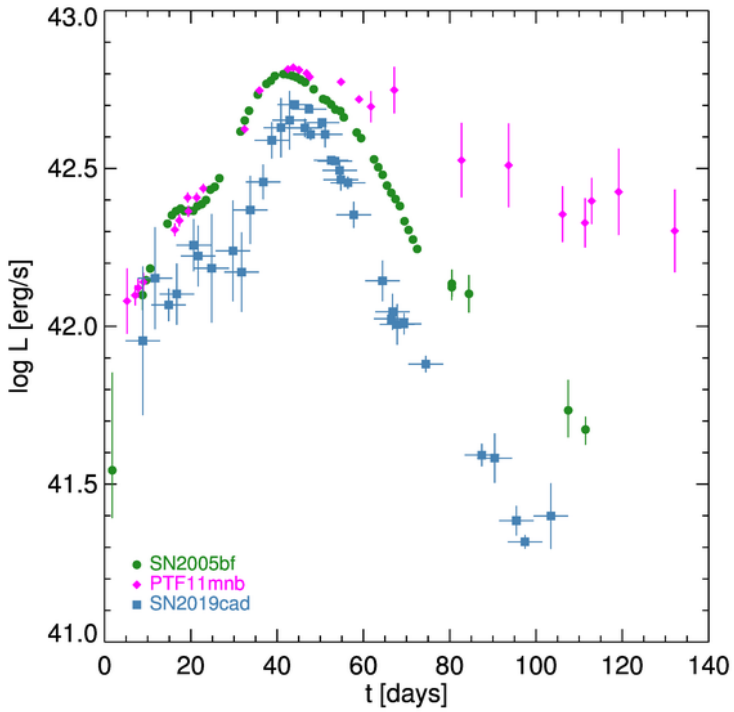
2-peaked published data

The observed morphology in both peaks is quite diverse which may indicate different physical origins.

These events are nowadays discovered more frequently.

Name	Type	Reference
SN1993J	IIb	Ray et al. (1993)
SN1999ex	Ib/c	Stritzinger et al. (2002)
SN2005bf	Ib/c	Folatelli et al. (2006)
SN2006oz	SLSN I	Leloudas et al. (2012)
SN2008D	Ib	Modjaz et al. (2009)
		Bersten et al. (2013)
		Tanaka et al. (2009c)
PTF11mnb	Ic	Taddia et al. (2018)
PTF12dam	SLSN I	Vreeswijk et al. (2017)
LSQ13abf	Ib	Stritzinger et al. (2020)
iPTF13dcc	SLSN I	Vreeswijk et al. (2017)
LSQ14bdq	SLSN Ic	Nicholl et al. (2015b)
DES14X3taz	SLSN I	Smith et al. (2016)
iPTF14gqr	Ic	De et al. (2018b)
iPTF15dtg	Ic	Taddia et al. (2016)
SN2019cad	Ic	Gutiérrez et al. (2021)
SN2019dge	Ib	Yao et al. (2020)
SN2019ehk	Ib	Jacobson-Galán et al. (2020, 2021)
	IIb	De et al. (2021)
SN2019stc	SLSN I	Gomez et al. (2021)
SN2020bvc	Ic-BL	Ho et al. (2020)
SN2020faa	SLSNII	Yang et al. (2021)
SN2021gno		Jacobson-Galán et al. (2022)
		Ertini et al. (2022)

A family of observed SNe



These have an initial rising phase.
Reasonably well-covered photometry prior to the first peak.

Original studies in this context:

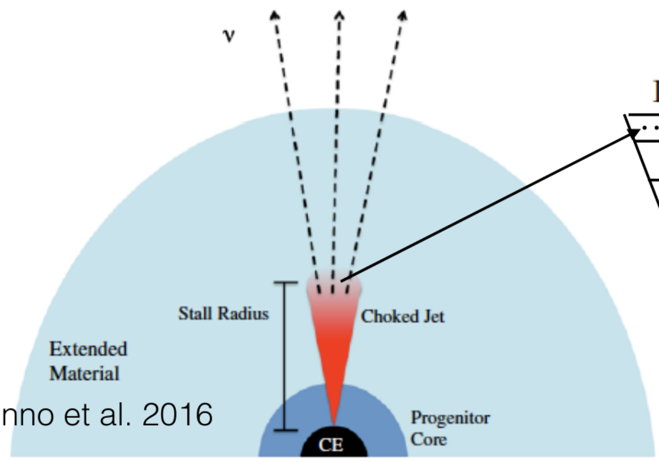
- Folatelli, G., Contreras, C., et al. 2006, ApJ, 641, 1039
- Taddia, F., Sollerman, J., et al. 2018, A&A, 609, A106
- Gutiérrez, C. P., Bersten, M. C., Orellana, M., et al. 2021, MNRAS, 504, 4907

In this study:
Models are re-investigated within a uniform prescription for the ^{56}Ni-profile.
We explore the potential of the model.

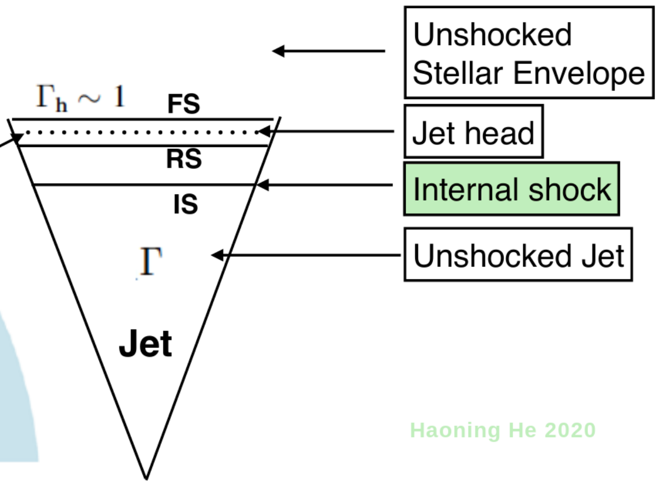
Justification: outer ^{56}Ni X_{out}

The presence of **outflows** involved in the explosion may induce nucleosynthesis of radioactive elements somewhere at the outer layers of the ejecta before the shock front of the SN arrives.

Sketch of Jet Head and Internal Shock in the Choked Jet



Senno et al. 2016

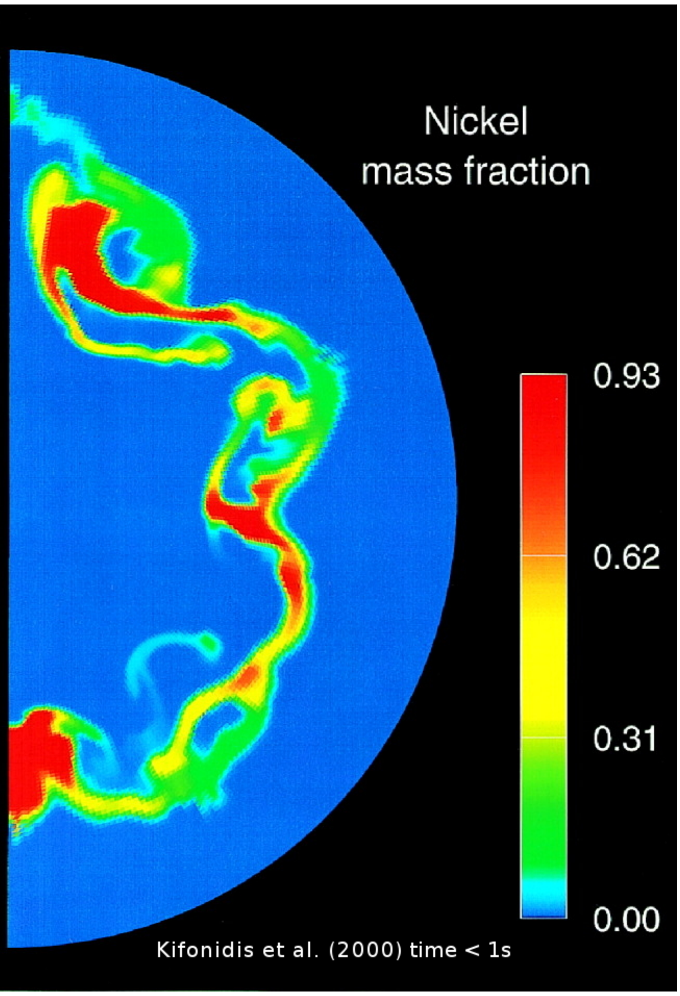


A jet choked inside the star? (inspired by Duffell & Ho, 2020)

A GRB viewed off-axis? (argued for SN2020bvc by Izzo et al. 2020)

Perhaps the outflows can transport out some material mixed with radioactive elements.

Justification: inner ^{56}Ni X_{in}



Hydrodynamical instabilities are usually invoked for the mixing.

We do not abord details like redistributing the ^{56}Ni quasi-spherically.

→ Hypothesis of a separate nickel-rich layer. Parameters as mass fraction f_n.

A double nickel distribution that is tuned in this study.

Methods

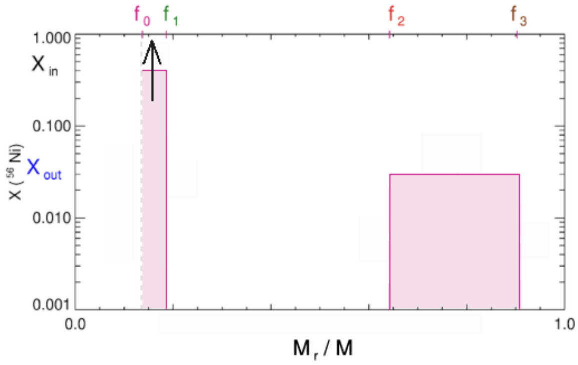
The 1D hydrodynamical code by (Bersten et al. 2011) is used to calculate bolometric LCs.

We considered different H-poor progenitors.

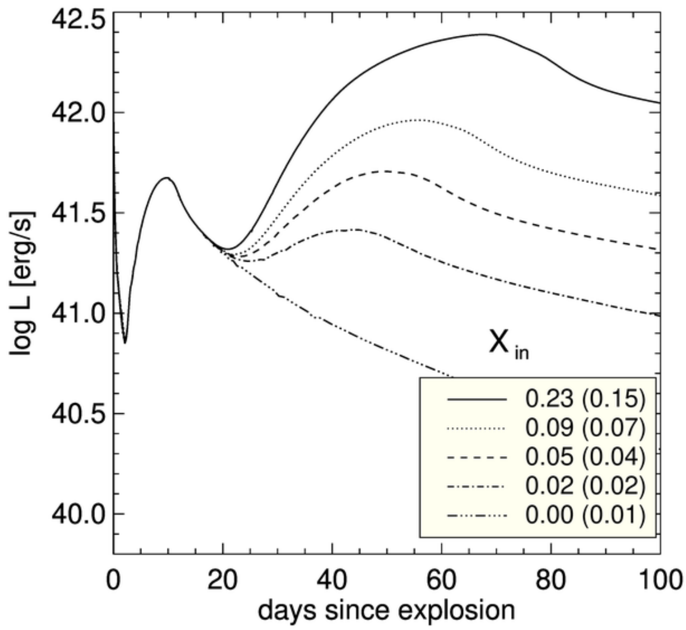
In Orellana & Bersten (2022) we present the cases that produce two well separated maxima in the LC.

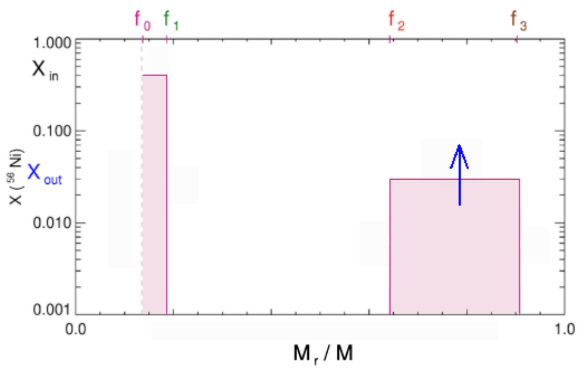
Results for He11 MESA progenitor

Varying internal abundance of nickel, with the other parameters fixed.
The total ^{56}Ni mass indicated in parentheses.
Exploded with $E_{\mathrm{exp}} = 2 \times 10^{51}$ erg.

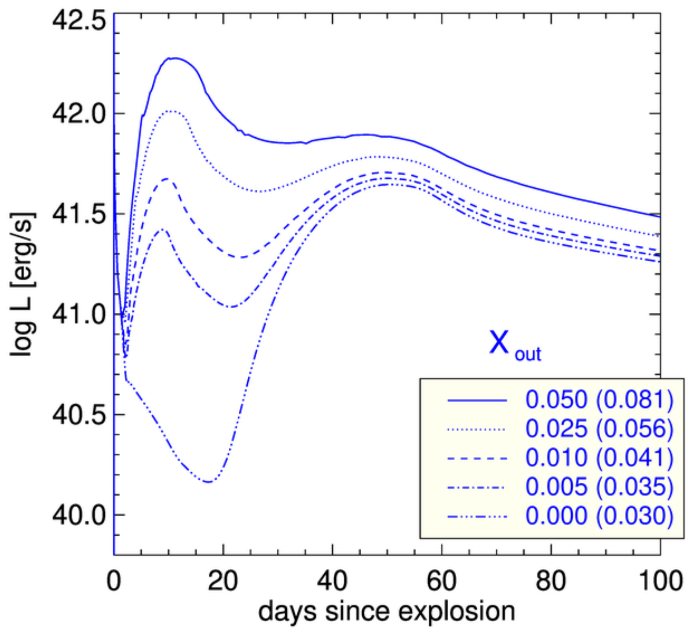


f_0=0.199 , f_1=0.25, f_2=0.91, f_3=0.991
X_out=0.01

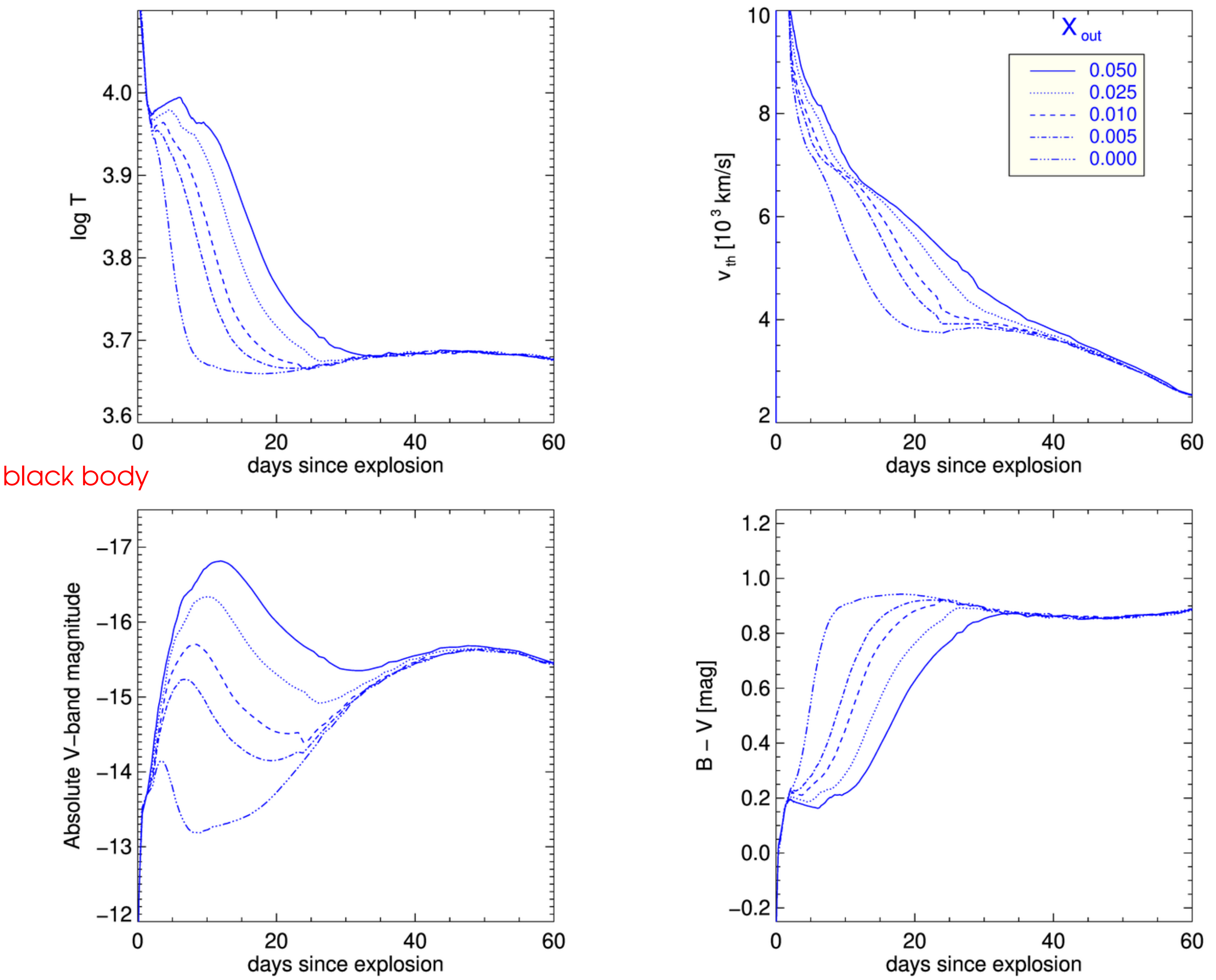


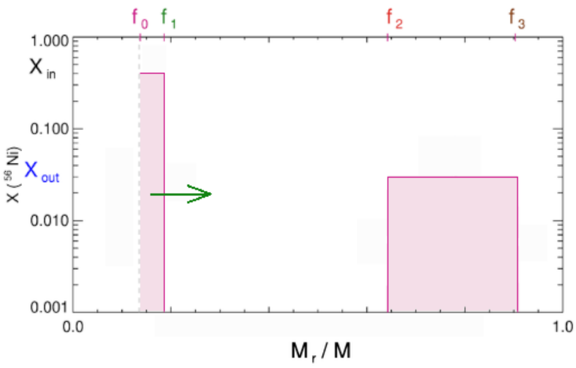


f_0=0.199 , f_1=0.25, f_2=0.91,
f_3=0.991 X_in=0.047

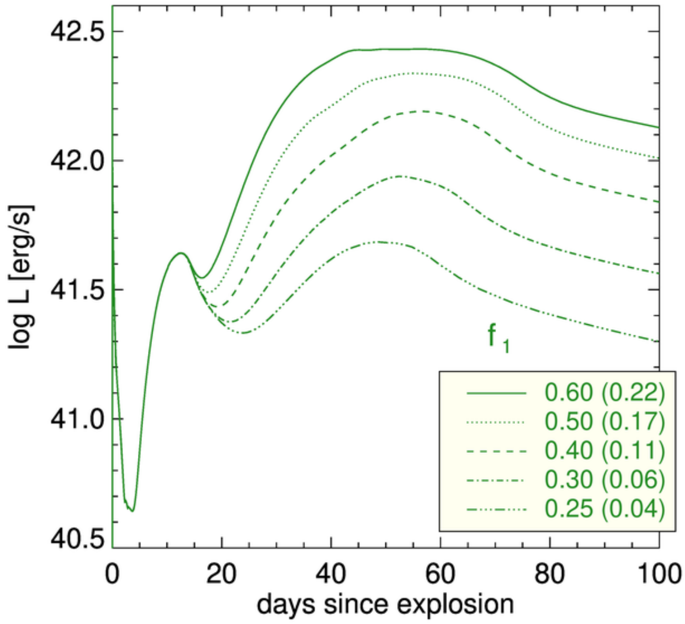


Effect of the variation in the external abundance of nickel.

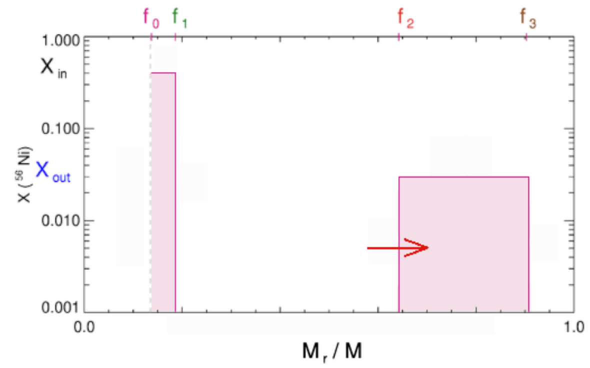

log T
days since explosion
v_{th} [10^3 km/s]
X_{out}
0.050
0.025
0.010
0.005
0.000
black body
Absolute V−band magnitude
B − V [mag]



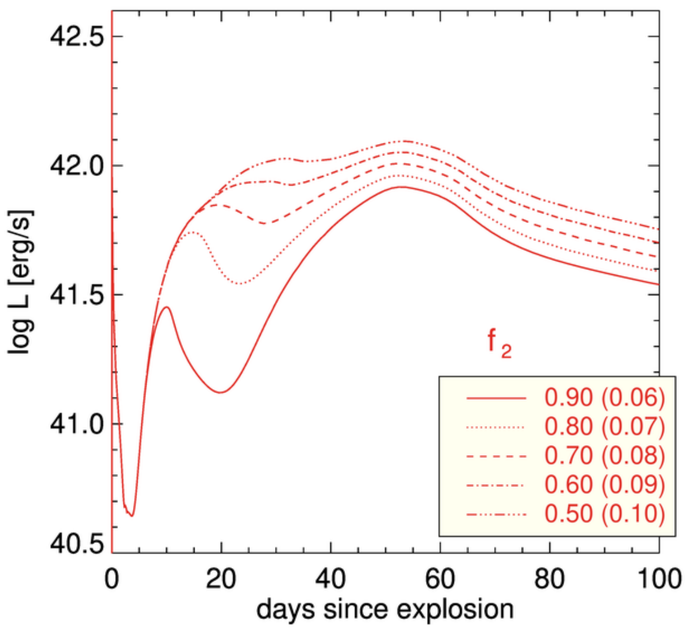
f_0=0.2, f_2=0.85, f_3=0.95
X_in=0.047 ,X_out=0.01



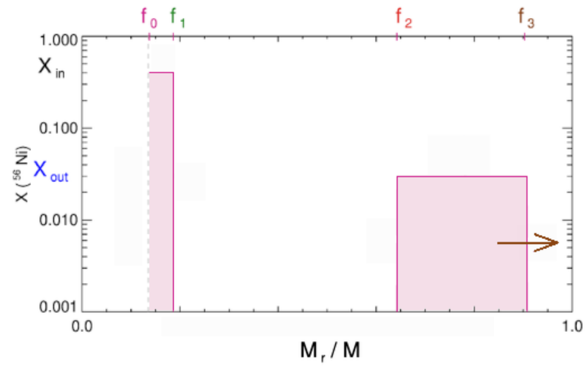
The ordinary mixing if there were no external component.



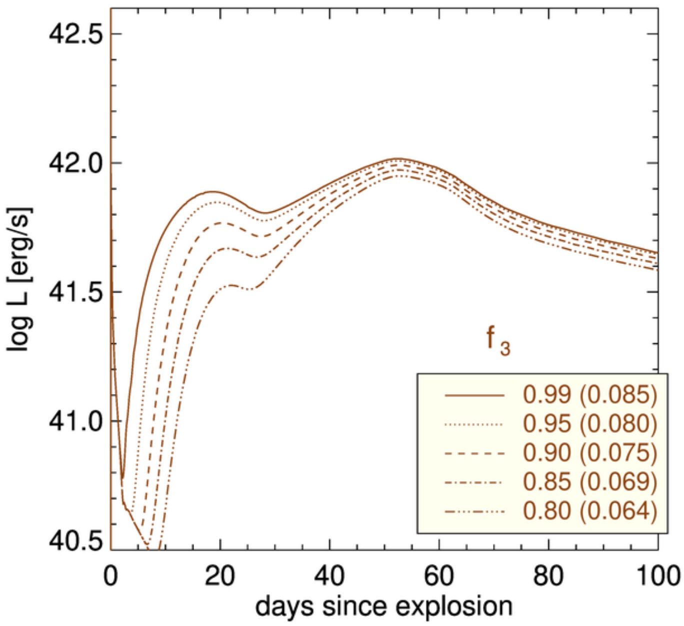
f_0=0.2, f_1=0.30, f_3=0.95
X_in=0.047 ,X_out=0.01



f_2 determines the inner border of external ^{56}Ni.

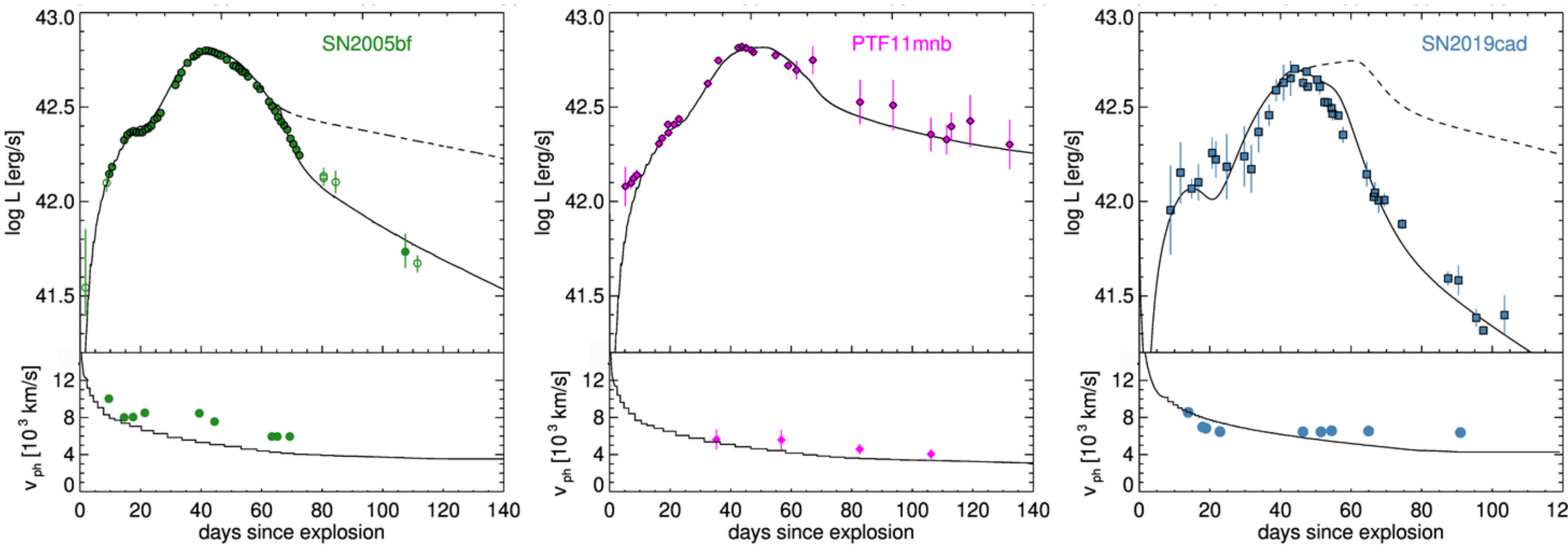


f_0=0.2, f_1=0.30, f_2=070,
X_in=0.047 ,X_out=0.01



Outermost border for the ^{56}Ni-rich mass.

Fitting parameters



Parameter	SN2005bf	PTF11mnb	SN2019cad [1]
M_{ej}	6.1 $M_\odot$	6.1 $M_\odot$	9.5 $M_\odot$
M_{preSN}	8 $M_\odot$	8 $M_\odot$	11 $M_\odot$
E_k	1.7×10^{51} erg	1.5×10^{51} erg	3.5×10^{51} erg
κ_γ [cm^2/g]	0.03 $t \leq 65$ d 0.0018 $t > 65$ d	0.03 all epochs	0.03 $t \leq 45$ d 0.0005 $t > 45$ d
f_0, f_1	0.2,0.247	0.2, 0.259	0.136, 0.165
f_2, f_3	0.524, 0.99	0.563, 1	0.724, 0.98
X_{in}, X_{out}	0.952, 0.029	0.960, 0.029	0.94, 0.014
M(^{56}Ni)in,out [a]	0.352, 0.096 $M_\odot$	0.395, 0.104 $M_\odot$	0.3, 0.041 $M_\odot$

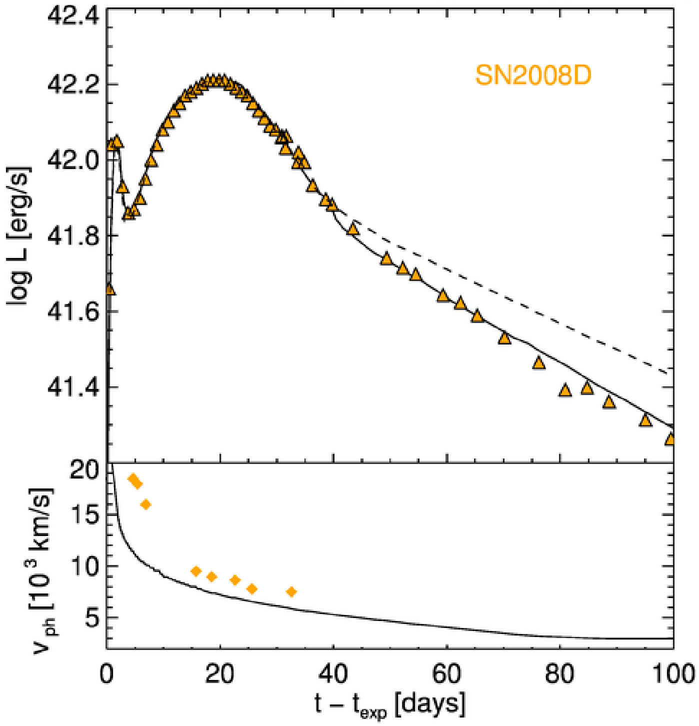
from dashed to solid line

[a] M(^{56}Ni)is afterwards computed, not an initial parameter, [1] Host-galaxy $E(U - B) = 0$

An extreme example, previously study in Bersten et al. (2013)

Parameter	SN2008D *
$M_{\rm ej}$	3,3 $M_\odot$
$M_{\rm preSN}$	5 $M_\odot$
E_k	1×10^{51} erg
κ_γ (cm^2/g)	0.03 $t \leq 40$ d
	0.015 $t > 40$ d
$f_0,\ f_1$	0.36, 0.93
$f_2,\ f_3$	0.995, 1
$X_{\rm in},\ X_{\rm out}$	0.026, 0.71
M(^{56}Ni)in,out	0.074, 0.018 $M_\odot$

* Data from Modjaz et al. (2009)



The estimated ^{56}Ni mass at the outer layer is $\sim \times 2$ larger than 0.01 $M_\odot$ in Bersten et al. (2013).
Caveats regarding the influence of external ^{56}Ni in the He lines (see, Dessart et al 2018)

General remarks

In comparison, for SN2008D the external ^{56}Ni is concentrated at the surface and heavily loaded

To do:
Double nickel could be also the case for other SNe.

- LSQ13abf (Stritzinger et al. 2019)
- SN 2020bvc (Ho et al. 2020)

General remarks

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- LSQ13abf (Stritzinger et al. 2019)
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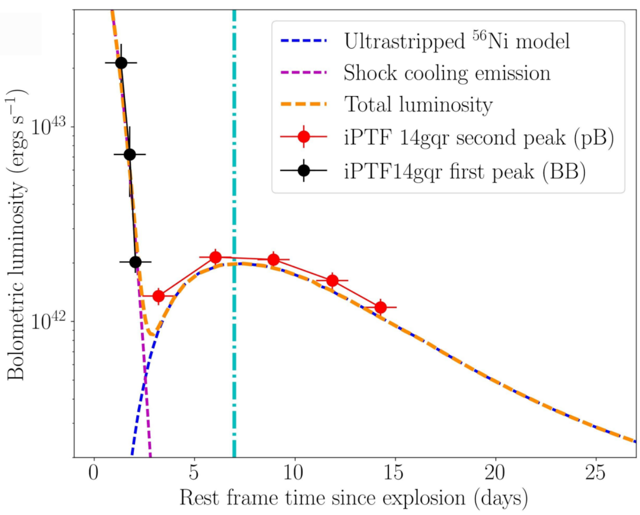
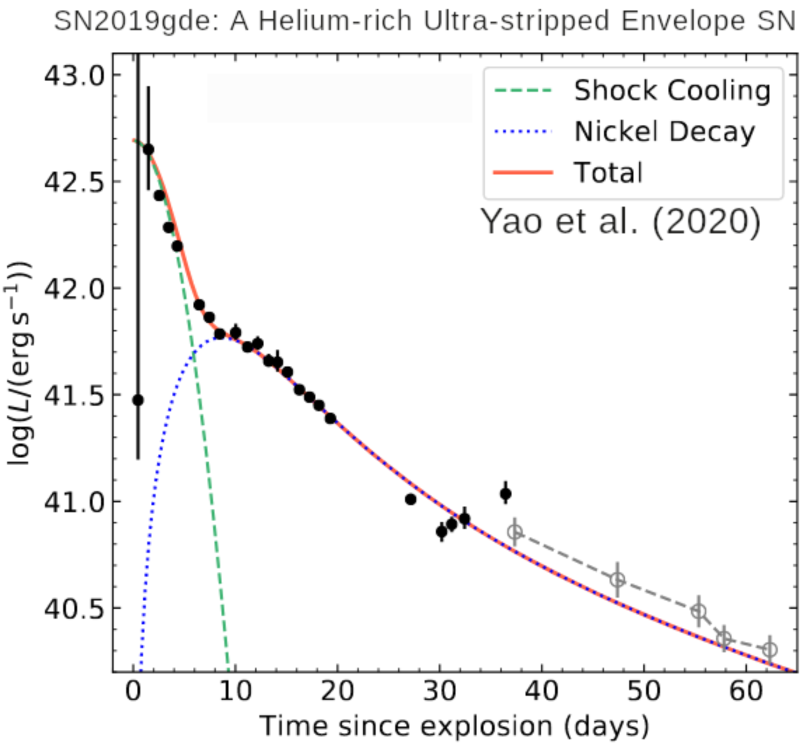
Not a likely alternative scenario for SNe with fast initial decline in the bolometric LC, such as →

A fast ultra-stripped SN, De et al. (2018)



Interaction with circumstellar matter, see, e.g. Jin, Yoon & Blinnikov (2021).

Excluded by our pre – selection



→ This is not the kind of double-peak we want to research in this work.

Calls for the fast response observational programs that follow SNe.

Even with very early data an identification of specific explosion scenarios is challenging, if only photometric observations are available (Noebauer et al. 2017).