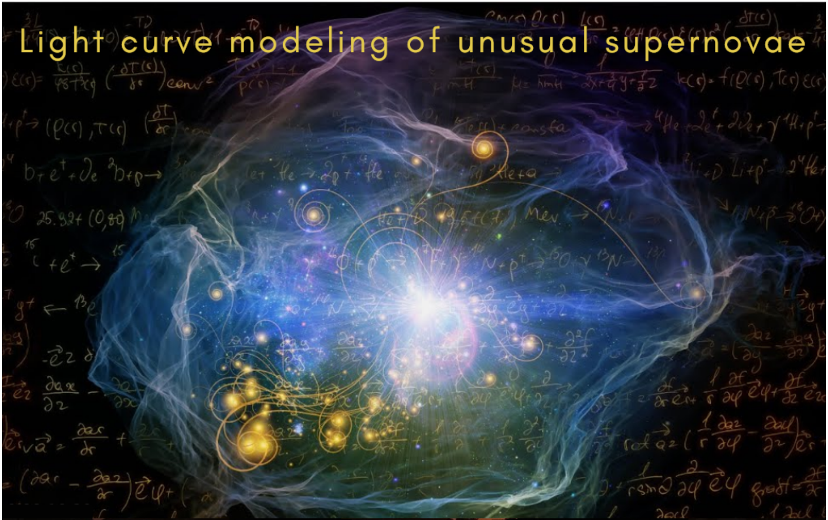
Light curve modeling of unusual supernovae



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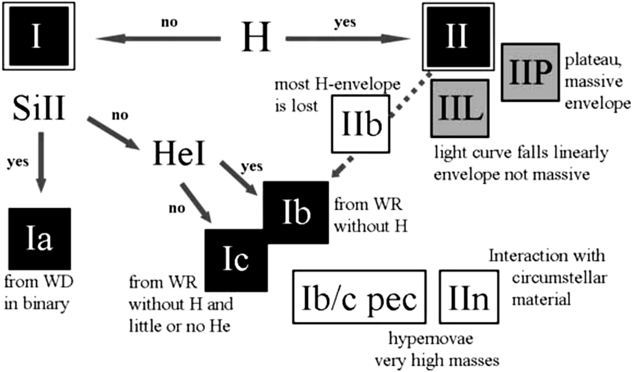
CONICET

Order from optical data

Classification: Filippenko (1997). Main groups in black squares, Maeder (2009)

WD explosion Core collapse

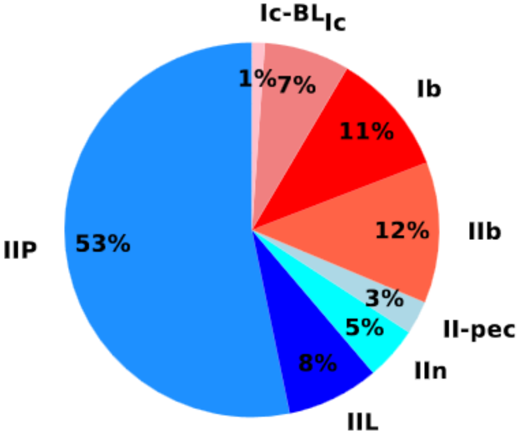


Classification sometimes can be nontrivial: some objects can be time dependent (e.g., Milisavljevic et al. 2013)

Core Collapse and no H : stripped envelope SNe.

We focus on destruction of massive stars

More interesting statistics at TNS - `https://www.wis-tns.org/stats-maps`



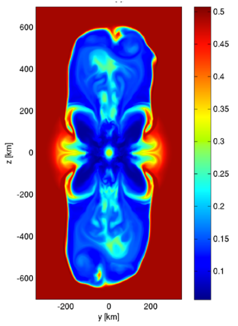
Observed fractions of CCSN types in a volume-limited sample.

CCSNe explosion mechanisms

1. neutrino-driven

$E_\nu \sim 3\text{x}10^{53}$ erg $(M_{ns}/M_{sun})^2/R_{ns}$ for NS

2. magneto-rotational



? GRB [a]

? Modified mixing [b]

? Magnetar [c]

3. other

pair instability, etc

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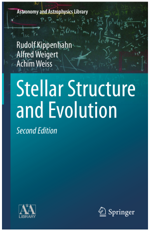
[a] e.g. Román Aguilar et al. BAAA65
[b] e.g. Folatelli et al. (2006); Gutierrez et al. (2019); Orellana & Bersten (2022)
[c] e.g. Bersten et al. (2016); Orellana, Bersten & Moriya (2018)

Hydrodynamics with radiative transfer 1 D



Assumptions:

- Simplifications: spherical symmetry, diffusion approximation.
- Nucleosynthesis of radioactive elements ALREADY DONE.
- Gray approx. for the gamma-rays from ^{56}**Ni**
- Complete Opal tables at $\sim$ visible λ.
- Problem splitted: initial energy injection $\sim 10^{51}$ erg above the mass $M_{\rm CO}$

Using Lagrangian coordinates:

$$V = \frac{4\pi}{3}\frac{\partial r^3}{\partial m} \quad \Longrightarrow \text{Mass conservation}$$

$$\frac{\partial r}{\partial t} = u \quad \Longrightarrow \text{Velocity}$$

$$\frac{\partial u}{\partial t} = -4\pi r^2 \frac{\partial}{\partial m}(P+q) - \frac{Gm}{r^2} \quad \Longrightarrow \text{Momentum conservation}$$

$$\frac{\partial E}{\partial t} = \epsilon - \frac{\partial L}{\partial m} - (P+q)\frac{\partial V}{\partial t} \quad \Longrightarrow \text{Energy conservation}$$

$$L = -(4\pi r^2)^2 \frac{ac}{3\kappa}\frac{\partial T^4}{\partial m} \quad \Longrightarrow \text{Radiative energy transport}$$

Equations + Initial and boundary conditions, and constituent equations

Methods

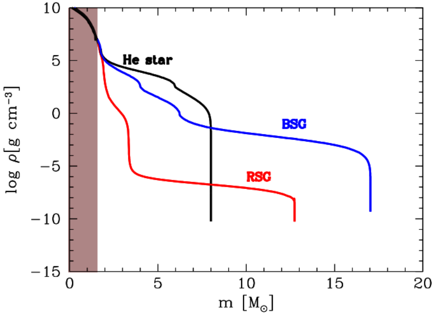
The code by **Bersten et al. (2011)** is used to track the supernova shock through the ejected envelope by solving the differential equations.

→ We can estimate Black Body emission at photospheric depth.

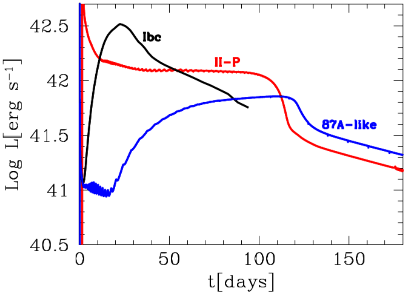
Total $L_{\text{bol}}(t)$

$$\text{Mag}(t) = -2{,}5 \log \frac{\int d\lambda F(\lambda,t) S(\lambda)}{\int d\lambda S(\lambda)}$$

Initial density

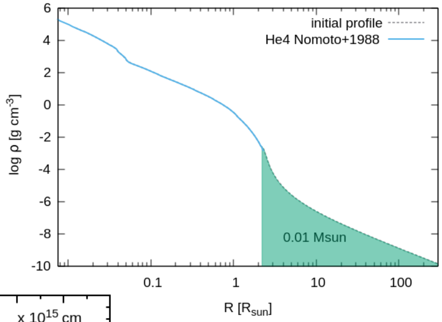


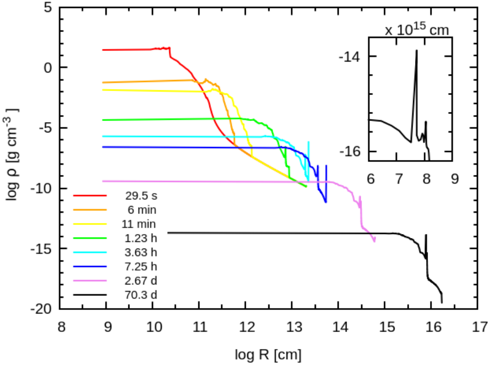
Light curve



With different progenitor stars.

Massive stars mass loss





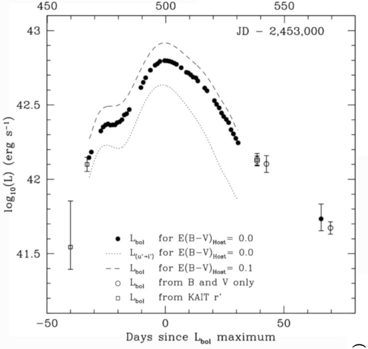
Initially for the SN the external material comes from late stellar dM/dt

The shock breakout is delayed

An overdense thin shell is impulsed → Particle acceleration
We don't consider **yet**, B=0 in our studies.

The unprecedented light curve morphology

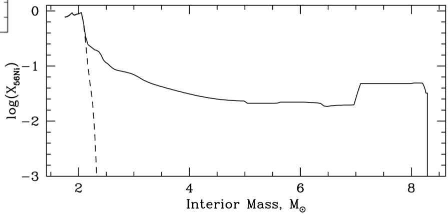
Tominaga et al. (2005)



SN2005bf

Folatelli et al. (2006)

The model propose an unusual distribution of the radioactive matter.

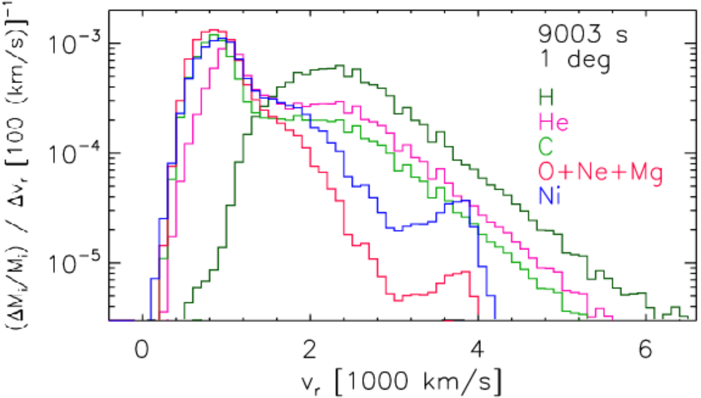


This is described as a mildly inverted distribution.

Magnetar as alternative proposal
Tanaka et al. (2009)

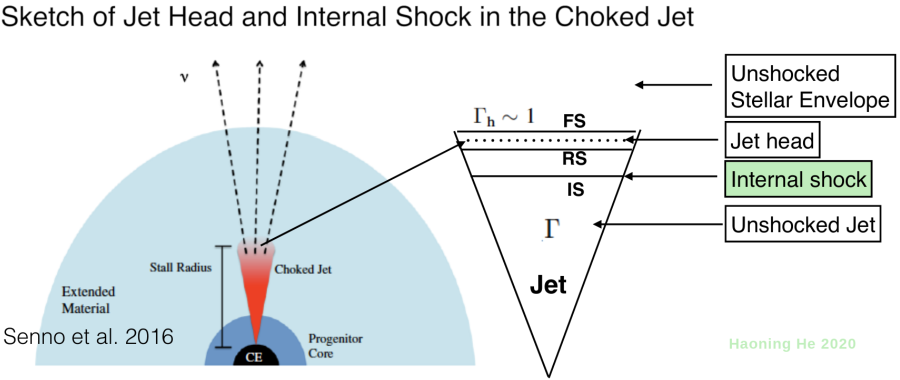
Double location for the radioactive material

3D simulations of core-collapse SNe: from shock revival to shock breakout
Wongwathanarat, A. ; Müller, E. ; Janka, H. -Th. A&A Vol. 577, id.A48 (2015)



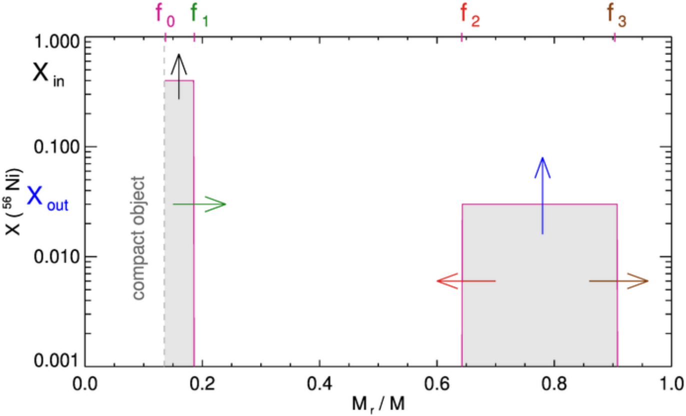
Justification: outer ^{56}Ni X_{out}

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. Or they may transport out some material mixed with radioactive elements.



A jet choked inside the star? (inspired by **Duffell & Ho, 2020**)
A GRB viewed off-axis? (argued for SN2020bvc by **Izzo et al. 2020**)

Hypothesis of a separate nickel-rich layer

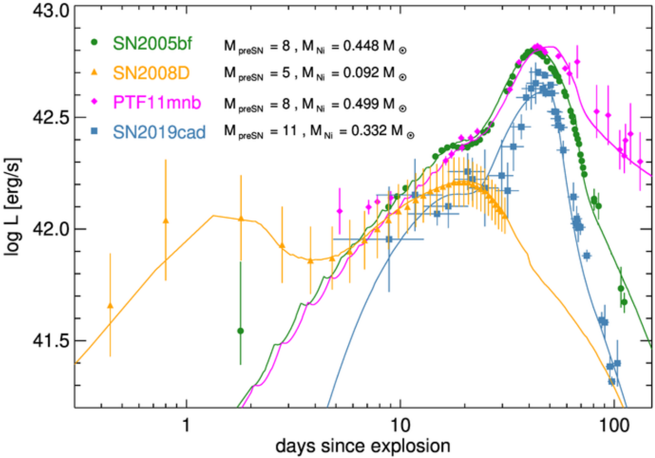


Arrows indicate freedom degrees of the model.

Peculiar double-peaked SNe

A small family resembling SN 2005bf

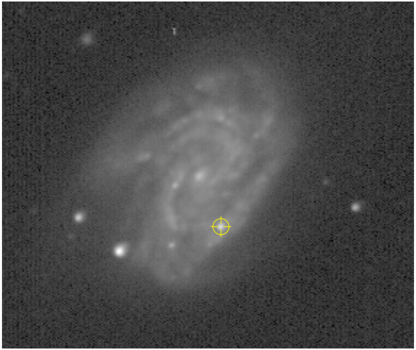
The characteristic rise in luminosity detected prior to the first peak is uneasy to conciliate with other models.



The fitting parameters for the bolometric data were provided in Orellana & Bersten (2022). Models were re-investigated **within a uniform prescription** for the ^{56}Ni-profile.

A new member of the sample? SN 2022jli

Light curve first reported by Moore et al. (2023): a type Ic SN at 23 Mpc
L_{bol} data investigated with MOSFiT code – **no** hydrodynamic calculations.



A **rebrigthening** started around one month after discovery.

The explosion time is not well constrained.

Catching attention - Chen et al. (2024) Nature

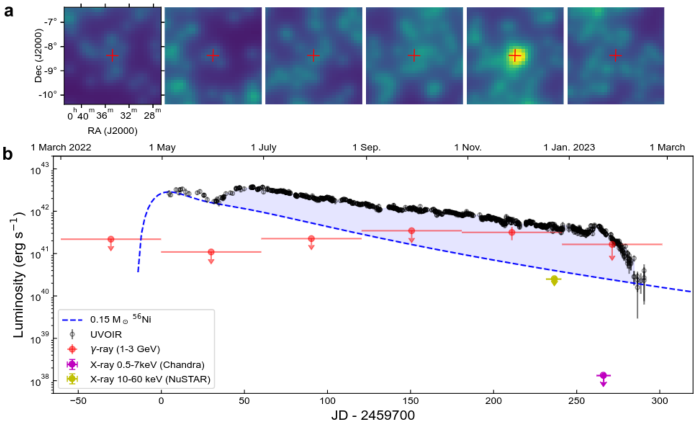
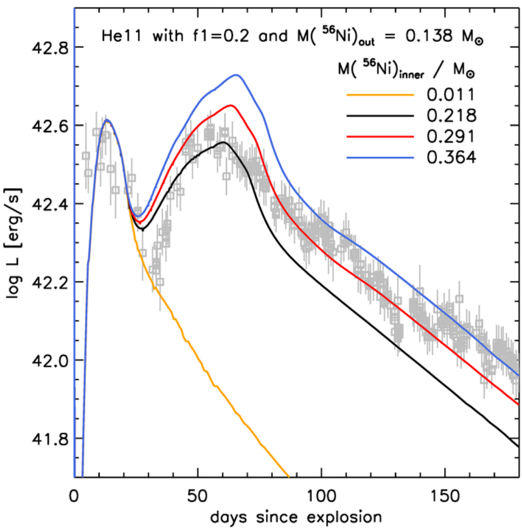
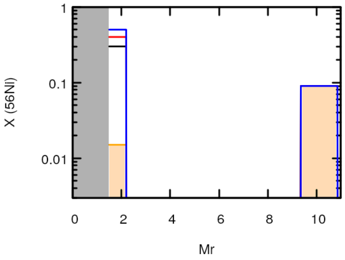


Figure 4: **The pseudo-bolometric light curve and multi-frequency data of SN 2022jli. (a)** The γ-ray source detection map generated with bimonthly Fermi-LAT observation in the energy band of $1-3$ GeV using the Poisson noise matched filter method

Double Ni trials for SN2022jli

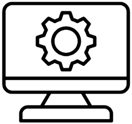




Not so good, requires a radioactive mass content $M(^{56}Ni) \gtrsim 0{,}35 M_\odot$.
The minimum around 30d does not reproduce the data.

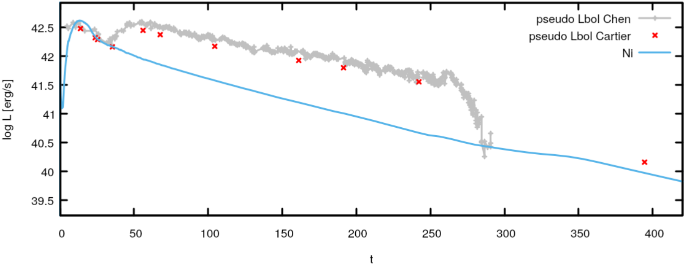
Preliminary idea: hybrid power source

- First peak is powered by nickel, i.e. a total M(^{56}Ni) of 0.15M$_\odot$
- Second peak by a central engine: a new-born magnetar powering the hydrodynamic code through spin-down.



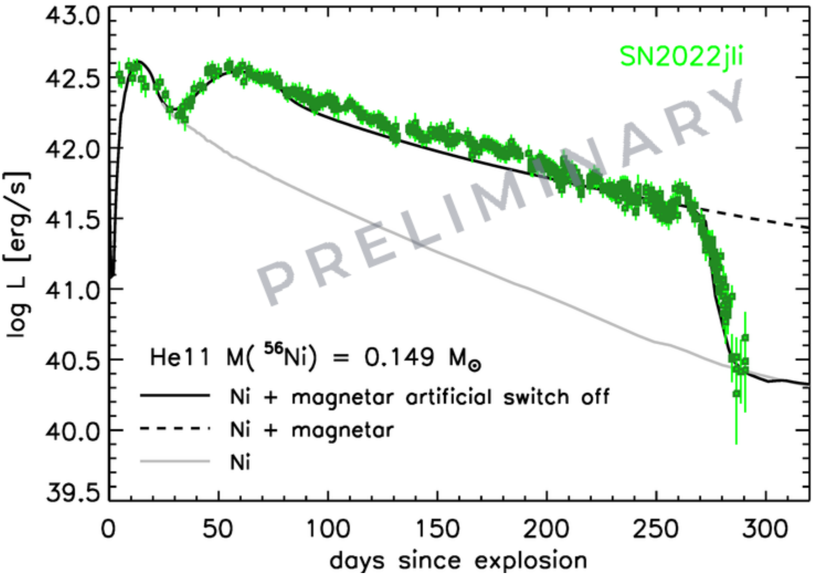
$P \simeq 22$ ms por the rotational initial period of the neutron star, and a bipolar magnetic field $B \simeq 5 \times 10^{14}$ G.
Thus $E_{\rm rot} \sim 4 \times 10^{49}$ erg, is considerably less than the explosion energy, and the spin-down timescale is $t_p \sim 92$ days.

- Energy deposition by the magnetar must be drastically switched off ~ 270 d.



Late data : Cartier et al. arXiv:2410.21381

Results for the overall light curve (Orellana et al. in prep.)



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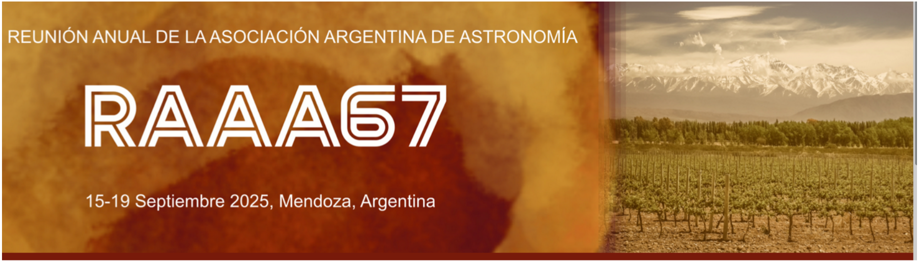
Supernova Observations and Simulations (S.O.S) research group:
http://sos.fcaglp.unlp.edu.ar/



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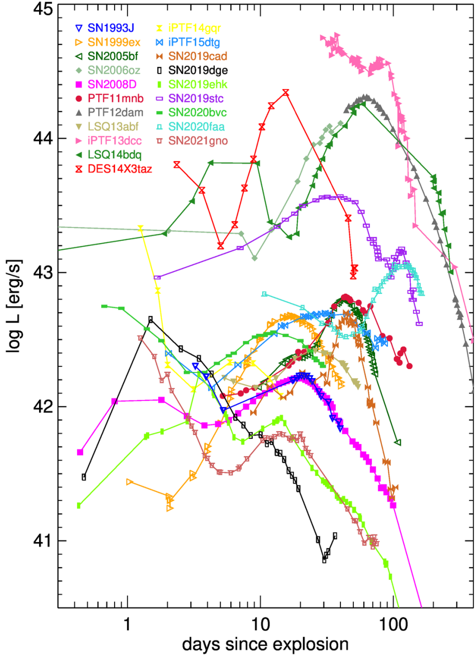
Extra slide



2-peaked published data < 2022

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)