# Numerical studies of supernovae

context & some results + work in progress

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LICA
Laboratorio de Investigación Científica en Astronomía

CONICET

**Madrid – Escuela Técnica Superior de Ingenieros Navales, UPM – 2023**

# Laboratorio de Investigación Científica en Astronomía

6/03/2023 - **RES UNRN CSPyGE No009-23**

Centro Interdisciplinario de Telecomunicaciones, Electrónica, Computación y Ciencia Aplicada

3 Inv. Sede Andina
+ Inv. Sede Atlántica

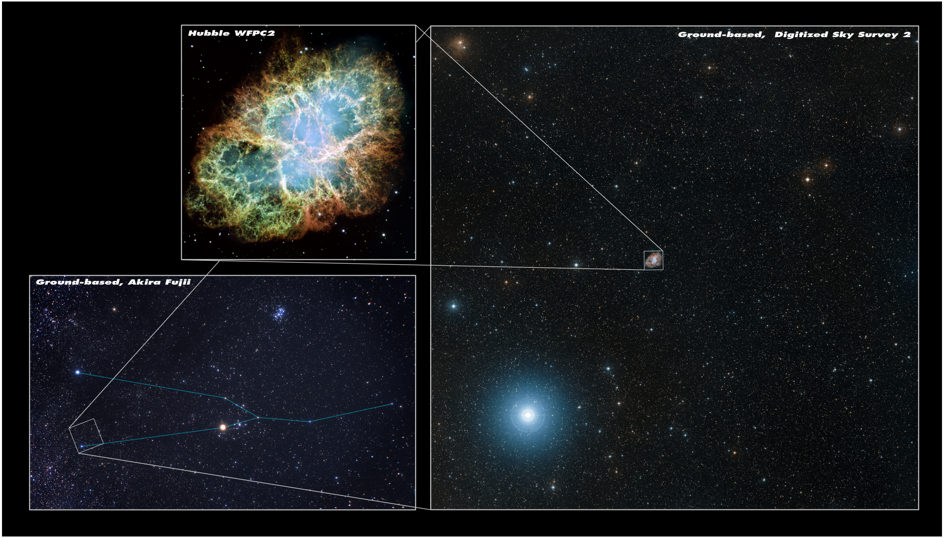

**Bariloche – Buenos Aires** $\approx 1500$ **km.**

# The changing skies: a historic supernova $\sim 2$ kpc away


According to Chinese records: visible at daytime for 23 days

and at night for 653 days.

# ∼1000 year later, the Crab



# SNe discovery frequencies

SNR G1.9+0.3


exploded circa 1870

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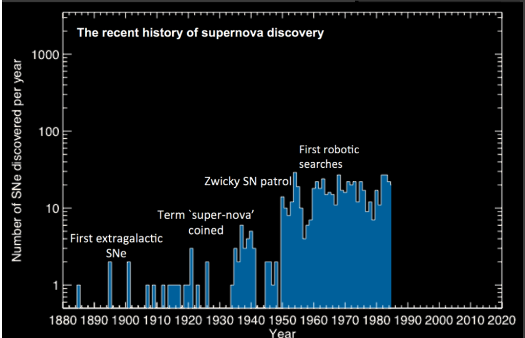
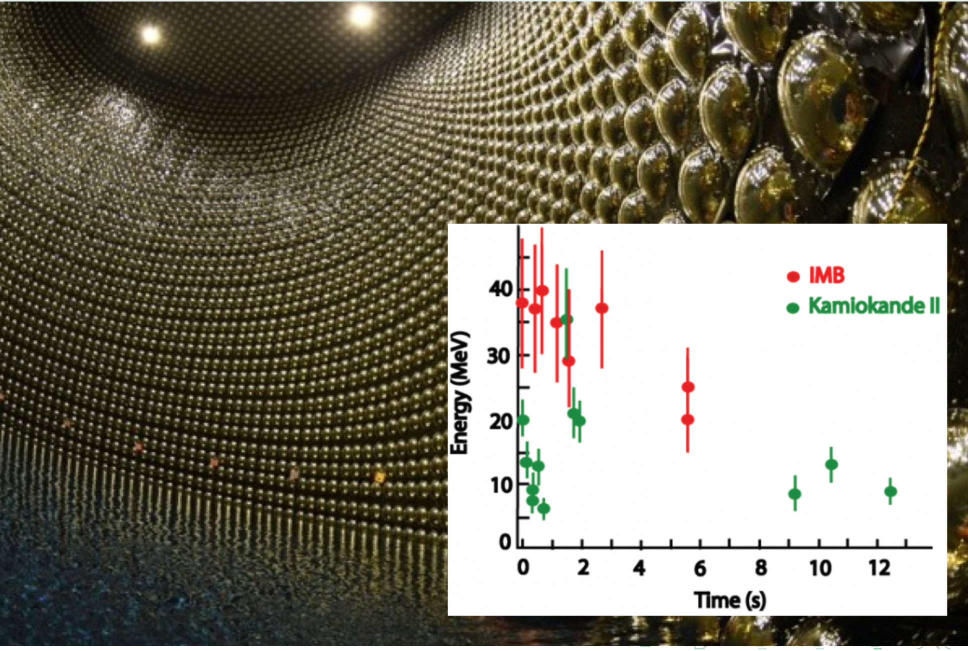
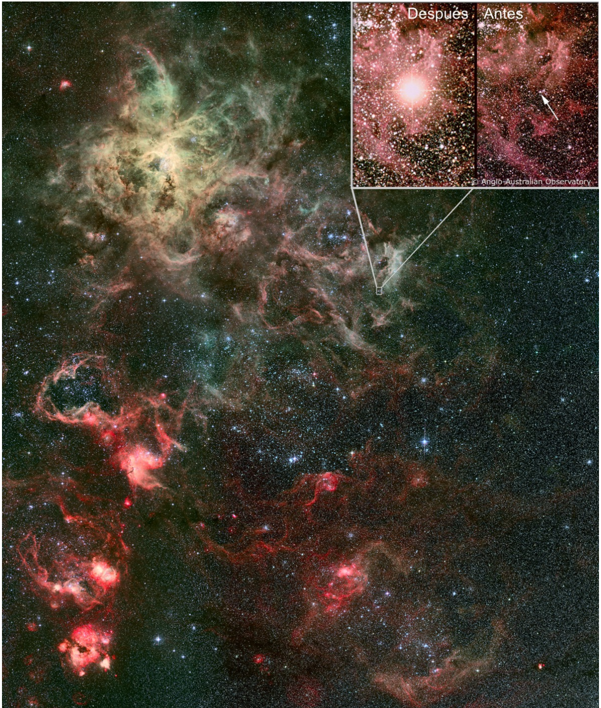


# Neutrinos from the Large Magellanic Cloud



# Tarantula nebula and neighborhood



# SNe status of discoveries nowadays

More than 20.000 SNe discovered over 130 years

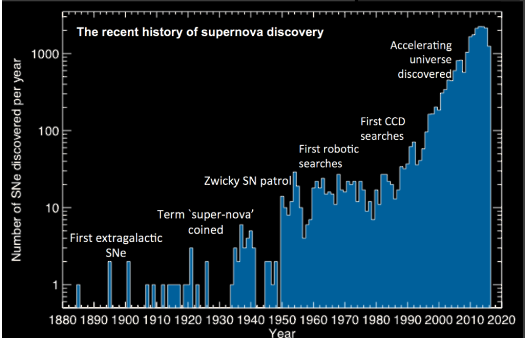

TNS Transients Statistics

**PUBLIC** TNS transients reported by year

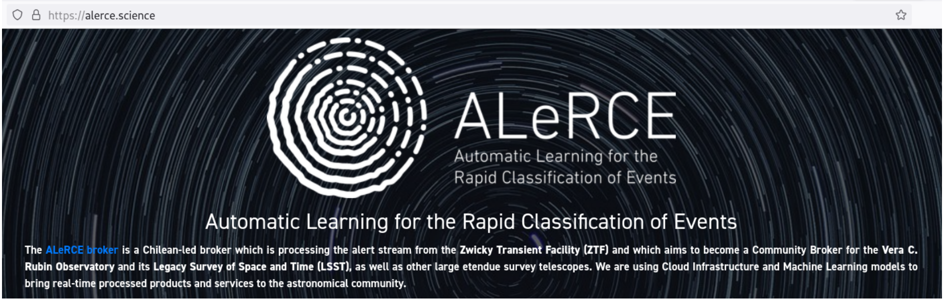
| | |
|---|---|
| 2009 | 7 |
| 2010 | 5 |
| 2011 | 8 |
| 2013 | 104 |
| 2014 | 95 |
| 2015 | 136 |
| 2016 | 7076 |
| 2017 | 7621 |
| 2018 | 9066 |
| 2019 | 19161 |
| 2020 | 21830 |
| 2021 | 23601 |
| 2022 | 21378 |
| 2023 | 11937 |

**PUBLIC** TNS classified SNe reported by year

| | |
|---|---|
| 2009 | 1 |
| 2010 | 1 |
| 2011 | 3 |
| 2013 | 2 |
| 2014 | 6 |
| 2015 | 24 |
| 2016 | 642 |
| 2017 | 748 |
| 2018 | 1507 |
| 2019 | 2139 |
| 2020 | 2105 |
| 2021 | 2349 |
| 2022 | 2151 |
| 2023 | 1069 |



# In the survey era and the potential discoveries



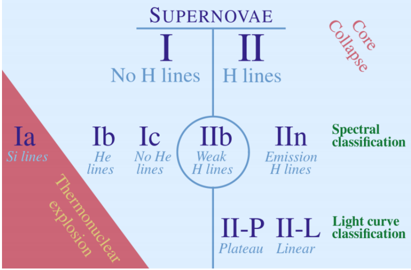

## After succesful discovery

Time for ambitious programmes dedicated to transient follow-up.
Carnegie Supernovae Project: 2004 – 2009

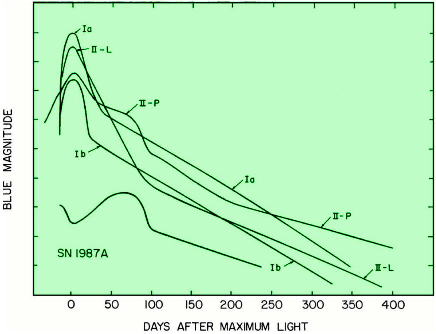
POISE
Precision Observations of Infant Supernova Explosions

# Ordering: two main techniques

Classification: Filippenko (1997).



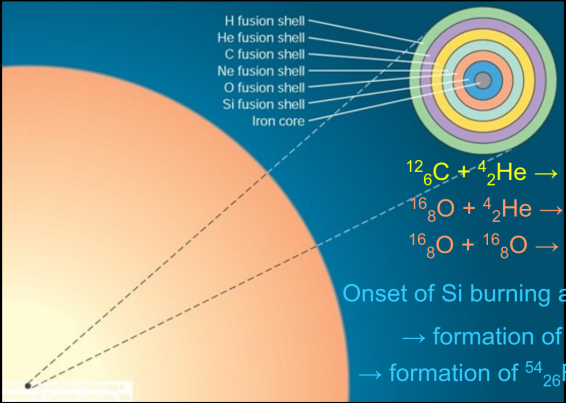

Light curves




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

# Just before the destruction of massive stars

## Fusion of Heavier Elements




$^{12}_{6}C + ^{4}_{2}He \rightarrow ^{16}_{8}O + \gamma$

$^{16}_{8}O + ^{4}_{2}He \rightarrow ^{20}_{10}Ne + \gamma$

$^{16}_{8}O + ^{16}_{8}O \rightarrow ^{28}_{14}Si + ^{4}_{2}He$

Onset of Si burning at $T \sim 3 \times 10^9$ K

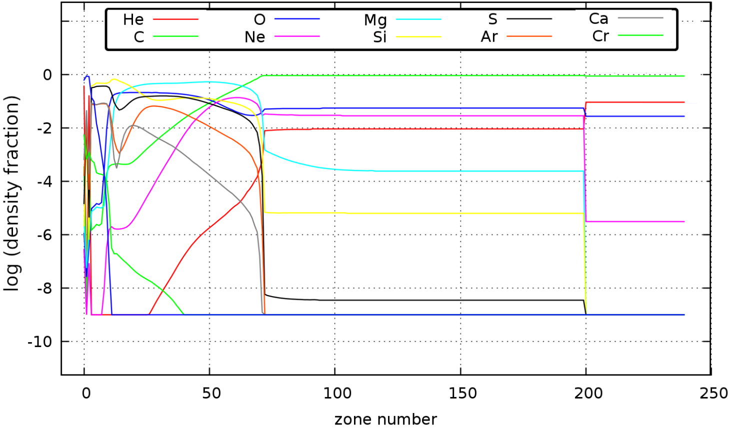
$\rightarrow$ formation of S, Ar, …;

$\rightarrow$ formation of $^{54}_{26}Fe$ and $^{56}_{26}Fe$

$\rightarrow$ iron core

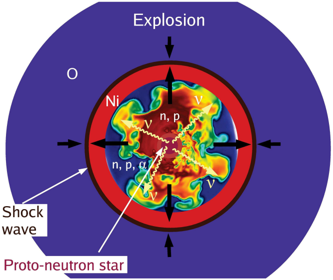
**Final stages of fusion happen extremely rapidly:**
**Si burning lasts only for ~ 2 days.**

# In more detail




The zones are traslated to mass coordinate.
Composition mostly rules over the opacities.
Radioactive elements are added manually.

# Neutrino-driven scenario, advances in the topic




Explosion phases in the $\nu$-driven scenario.
Neutrinos ***revive*** stalled shock by energy deposition.

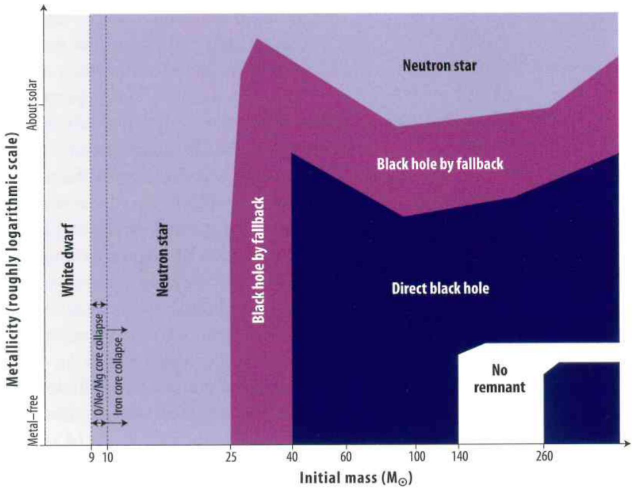
Convective processes & hydrodynamic instabilities play an important role
$\rightarrow$ multi-dimensional treatment.

Computationally expensive.

See Janka (2008) in Handbook of Supernovae

Alternative context of magnetorotationally powered SNe, see Obergaulinger & Reichert (2023)

# Problem splitted: inner mass



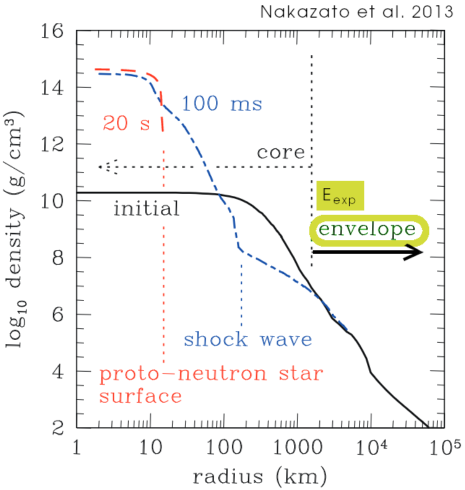

**Heger +2003**

Hereafter, the inner mass only affects through its gravity.

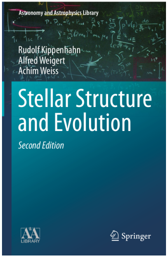
# Problem splitted: outer mass

Our SN has initial energy injection $E_{\rm exp} \sim 10^{51}$ erg above the core of mass $M_{\rm CO}$ that forms a compact object.

This energy is fully deposited and thermalized in the innermost layers of the envelope.



# Hydrodynamics with radiative transfer 1 D




## Time and $m$ are the independent variables.

Assumptions:

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

Lagrangian specification of the flow field (the observer follows an individual fluid parcel as it moves through space and time).

More lessons from 1987A: earlier than expected **hard X-rays**

Mixing of $^{56}$Ni required.

# Finite differences to track of the SN shock

Bersten, M.C. PhD thesis, 2010

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

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

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

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

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

**Equations** + Initial and boundary conditions, and constituent equations

The code uses a space-centering discretization with the extensive quantities evaluated at the interfaces and the intensive quantities in the midpoints of the grid zones.

# Basic of our methods

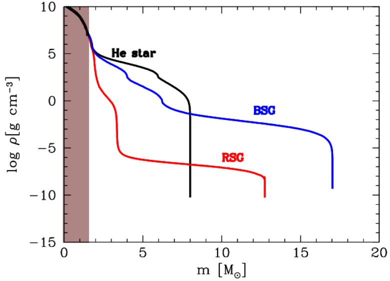
The 1D Lagrangian hydrodynamical code by **Bersten et al. (2011)** is used to track the supernova shock through the ejected envelope by solving the differential equations.

→ We can estimate Black Body emission at photospheric depth.

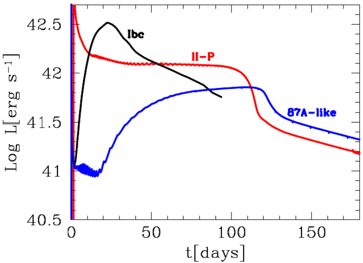
Total $L_{\rm bol}(t)$

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

Initial density




Light curve




With different progenitor stars.

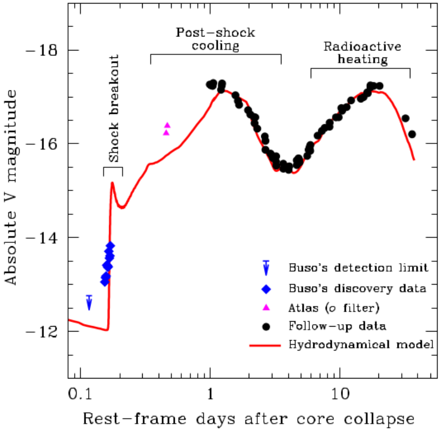
# A type IIb SNe: shocking external matter


↓

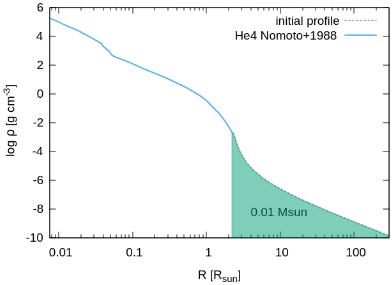
The optical LC evolution during the first hours and days after the explosion is crucial to understand the SN progenitor star.

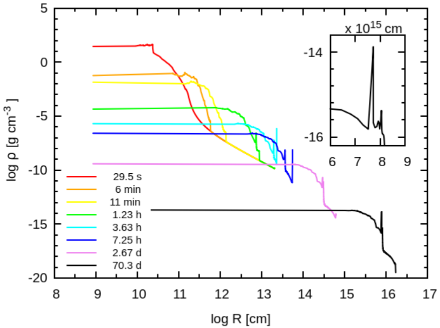
SN2016gkg, was detected **briefly** after the explosion

Modeled by our group: $R_* \sim 320 R_\odot$
$E_{\rm exp} \sim 1{,}2 \times 10^{51}$ erg, $M_{\rm Ni} = 0{,}09\, M_\odot$,
ejected mass $\sim 3{,}5\, M_\odot$




Bersten, Folatelli, Garcia, van Dyk, Benvenuto, Orellana, et al. Nature (2018)




External material comes from late stellar $dM/dt$

An overdense thin shell is impulsed.
SN2016gkg, was radio loud!
- Nayana et al. (2022)

Model non-thermal emission is
work in progress

# Physical constraints: an important data set

Results on the sample of SNe IIL and IIP by the CPS project

- Paper I: Bolometric light curves Martinez et al. 2022, A&A Vol. 660, A40
- Paper II: Derive physical parameters Martinez et al. 2022, A&A Vol. 660, A41

$E_{\rm exp}$, $M_{\rm ej}$, $^{56}{\rm Ni\,mass}$, $^{56}{\rm Ni\,mix}$

- Paper III: Correlations and further analysis Martinez et al. 2022, A&A Vol. 660, A42

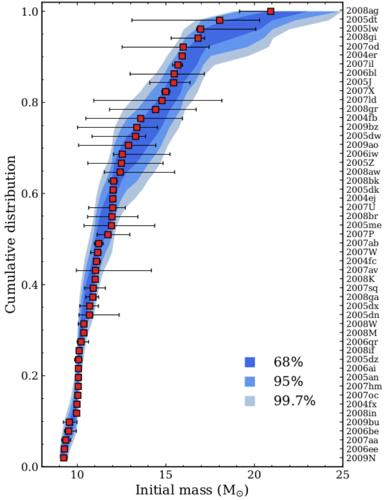
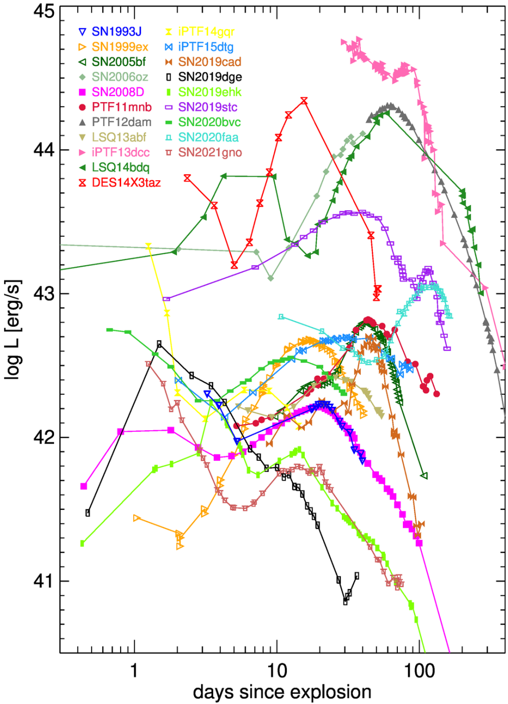



**Fig. 5.** Cumulative distribution of the $M_{\rm ZAMS}$ for the SN II progenitors in the entire sample. The shaded contours show the confidence regions. The derived masses are shown in red squares.




# 2-peaked published data

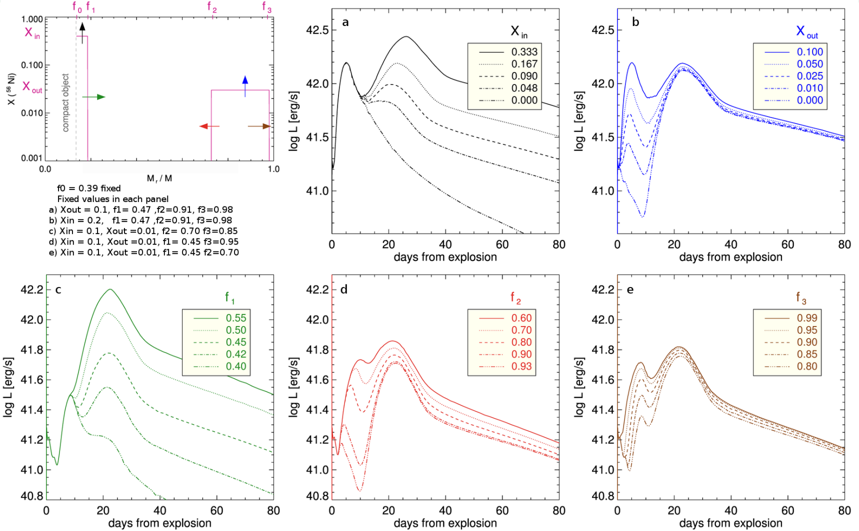
The observed morphology in both peaks is quite diverse which may indicate different physical origins.

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) |

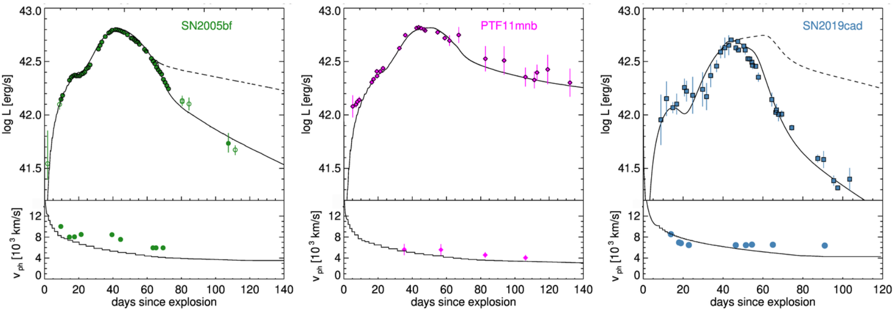
# Model dependences

## Results for He4, Nomoto & Hashimoto (1988) progenitor




Orellana & Bersten, BAAA (2020)

# Fitting parameters, Orellana & Bersten (2022)




| 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 $M_\odot$ |
| $E_k$ | $1.7 \times 10^{51}$ erg | $1.5 \times 10^{51}$ erg | $3.5 \times 10^{51}$ erg |
| $\kappa_\gamma$ [cm$^2$/g] | 0.03 $t \leq 65$ d<br>0.0018 $t > 65$ d | 0.03 all epochs | 0.03 $t \leq 45$ d<br>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 $E(U-B) = 0$

# Detected **briefly** after the explosion, on 19 May 2023

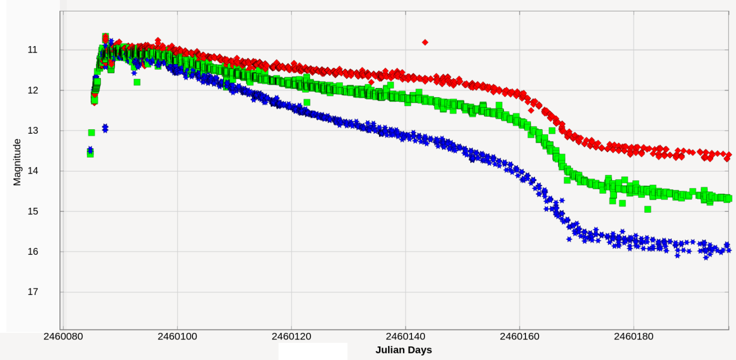
**Hosseinzadeh, G. et al. (2023)**


**Figure 1.** SN 2023ixf occurred in a spiral arm of the Pinwheel Galaxy near several star-forming regions. This image was made using 12 hours of small telescope data on the nights of 2023-05-20, 21, and 22. Image credit: Travis Deyoe, Mount Lemmon SkyCenter, University of Arizona.

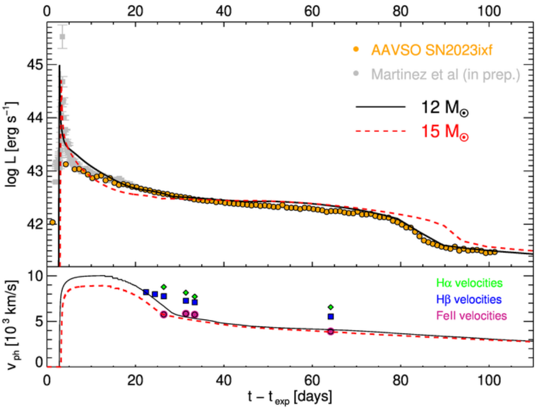
# SN2023ixf a new largely studied supernova. $D = 6{,}7$ Mpc

**$>$ 30 papers on arxiv**

American Association of Variable Star Observers (AAVSO)
An organization of amateur and professional astronomers.



# Preliminary results, submitted by S.O.S




*Circumstellar interaction models for the early bolometric light curve of SN 2023ixf*

**L. Martinez, M. C. Bersten, G. Folatelli, M. Orellana, K. Ertini, A&A, [astro-ph/2310.08733]**

*The progenitor of SN 2023ixf from hydrodynamical modelling*

**M. C. Bersten, M. Orellana, G. Folatelli, L. Martinez, M. P. Piccirilli, T. Regna, L.M. Román Aguilar, K. Ertini, A&A, [astro-ph/2310.14407]**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