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Physical characterization of Core-Collapse Supernovae with "fast" modeling procedures

S.P. Cosentino[1,2] & M.L. Pumo[1,2,3]

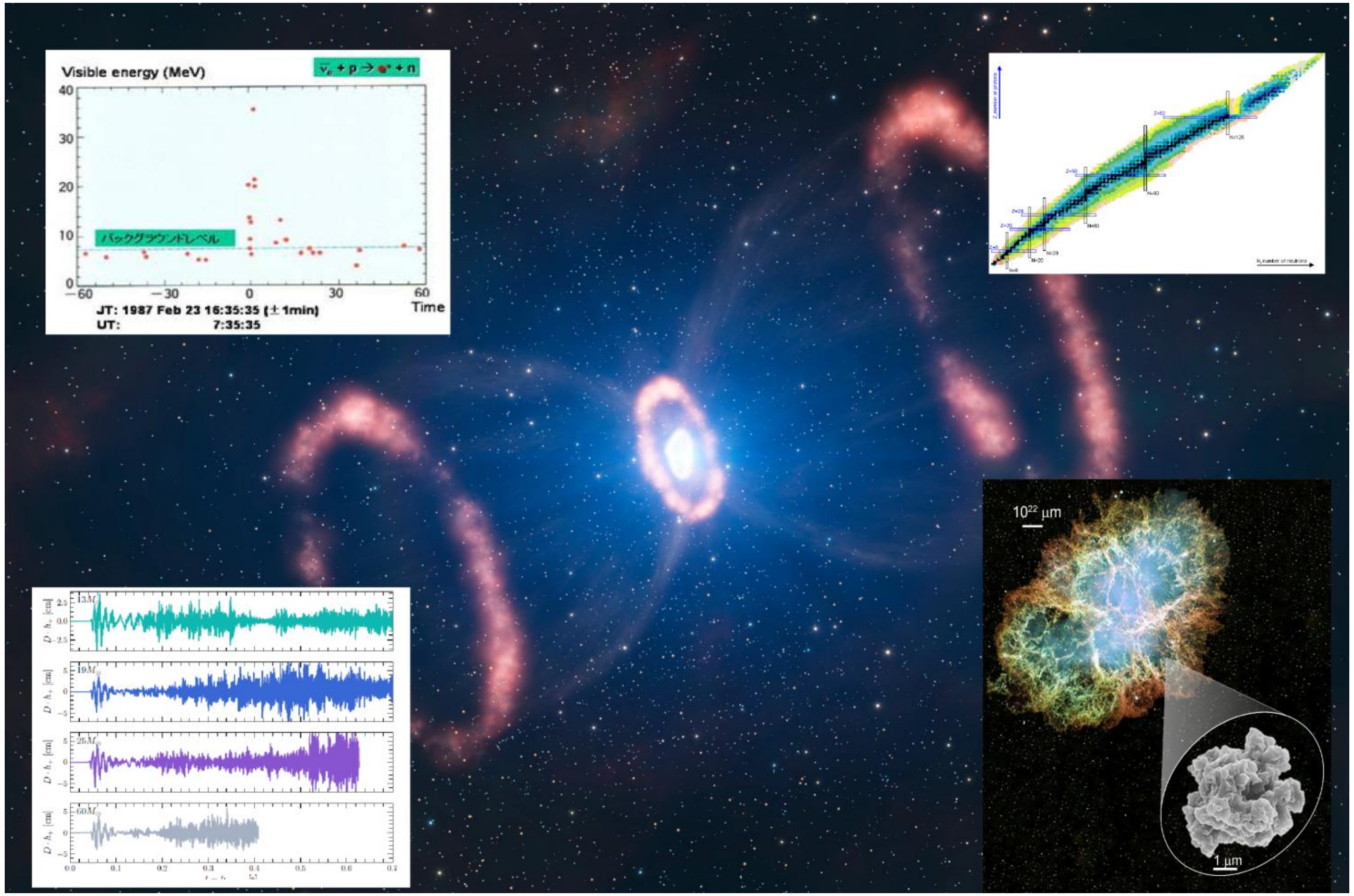
AN EXTRAORDINARY JOURNEY INTO THE TRANSIENT SKY:
from restless progenitor stars to explosive multi-messenger signals

1- UNICT, Dipartimento di Fisica e Astronomia
2- INAF, Osservatorio Astrofisico di Catania
3- INFN, Laboratori Nazionali del Sud, Catania

Core-Collapse Supernovae

Neutrino Emission

Stellar Nucleosynthesis

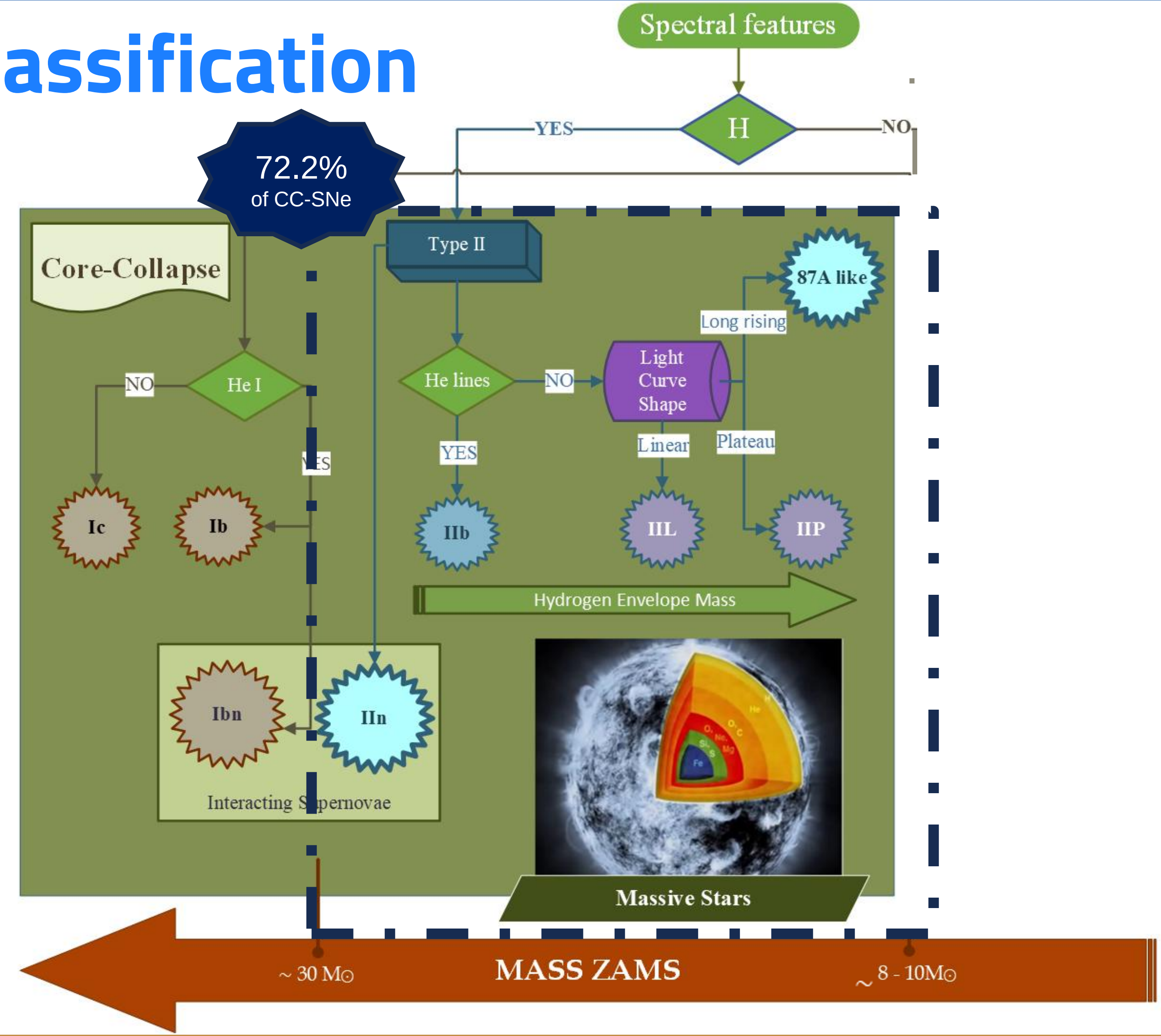


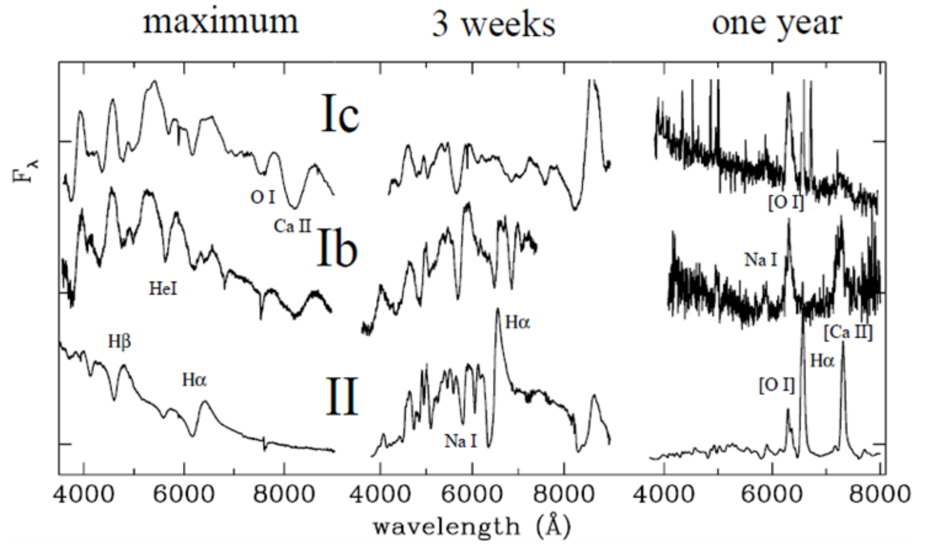
Gravitational Waves

Molecular & Dust production

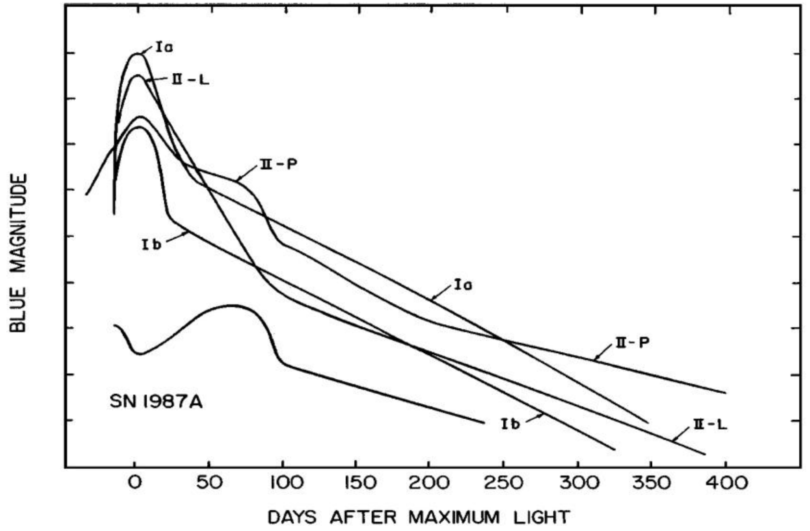
Composite image with artistic representation of SN 1987A (Ref. ESO Website)

SN classification





M. Turatto, Lecture Notes in Physics, vol. 598, p.21-36



A. V. Filippenko, ARA&A 35, 309 (1997)

Physical Characterization of Supernova events

Electromagnetic Observation:

- Light Curves → Bolometric Luminosity;
- Spectra → Photospheric Velocity.

↕

Theoretical Models:

- Hydrodynamic numerical models;
- Scaling Equations;
- Semi-/Analytical models.

→

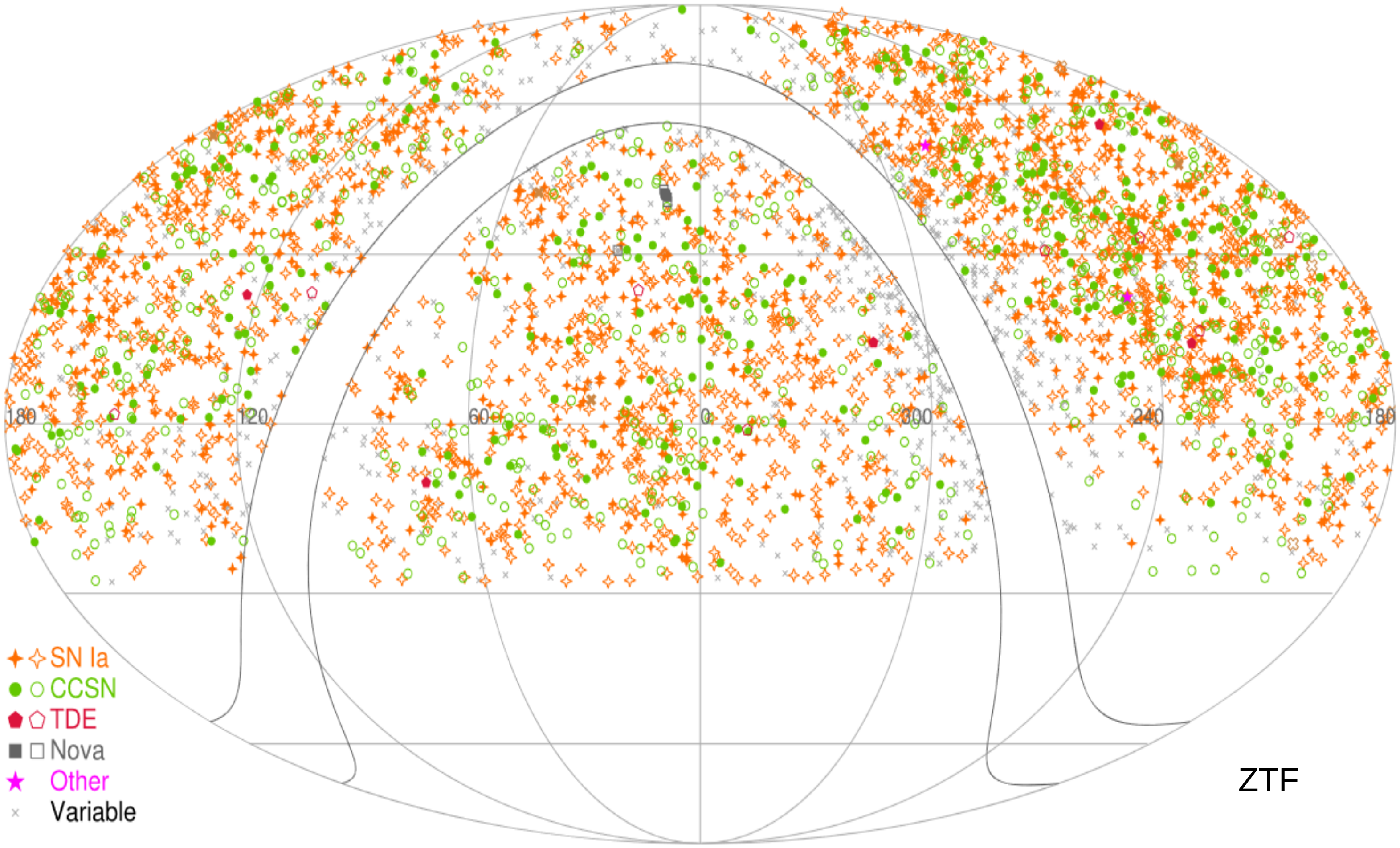
Explosion parameters:

- Explosion energy (E);
- Ejected mass (M_{ej}) ;
- Radius at explosion (R_0) ;
- Source mechanism –^{56}Ni mass, magnetar, CSM interaction, etc.– parameters (e. g. M_{Ni}, B_M, P_M, M_{CSM}, R_{CSM}, s, etc.).

Discovery, classification, characterization rates:

- Transients $\approx 10^4 yr^{-1}$
- SN Classifications $\approx 10^3 yr^{-1}$
- Type II SNe $\approx 2 \cdot 10^2 yr^{-1}$
- **Characterized** SNe II $\approx 20 yr^{-1}$

LSST survey will increase the discovery rates of $\times$ **1000 – 2000**



Ivezić, Ž et al., ApJ, Vol. 873, 2, id. 111, 44 pp. (2019).

Perley D.A., Fremling C., Sollerman et al., 2020, ApJ, 904:35

Open Issues:

- Hydrodynamical models capable of characterizing SN events are very **computationally expensive**, limiting their application to fewer SNe than those observed by the surveys (e.g. ZTF, LSST);
- **Coherent statistical studies** of SNe properties using large data samples require fast, general, and accurate post-explosion models applicable to many SN types;

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«Fast» modeling procedures for CC-SNe

«Fast» modeling procedures for CC-SNe:

- Post-explosive (semi-)analytical models;
- Modeling procedures for physical characterization of H-rich SNe.

Analytic Light Curve Model

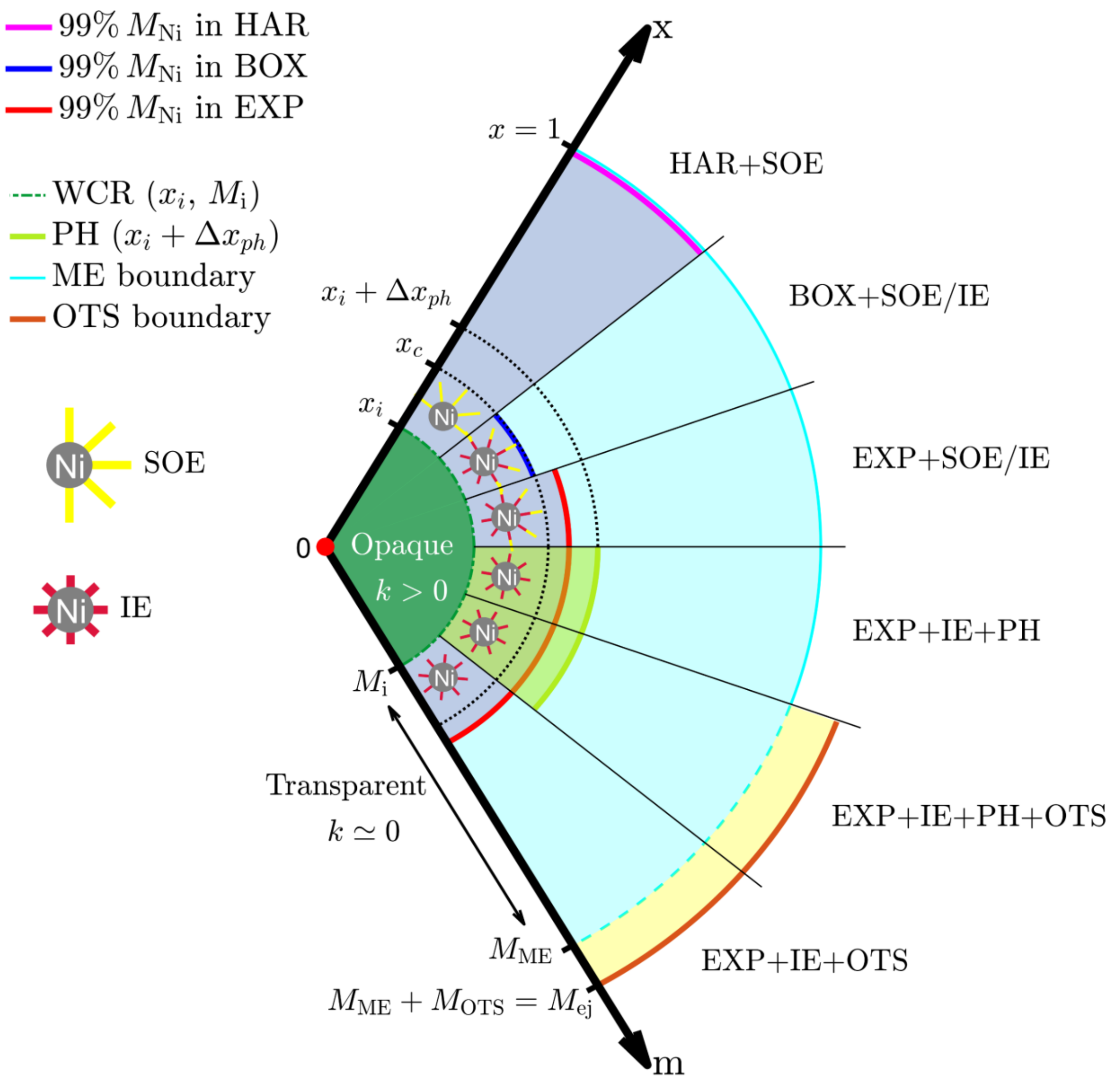
Common hypothesis for SN ejecta:

- spherical symmetry;
- homologous expansion;
- uniform density profile;
- dominant rad. pressure;
- strictly adiabatic solution (like ***Arnett 1980-1982***);
- two-zone opacity model (like ***Popov 1993***).

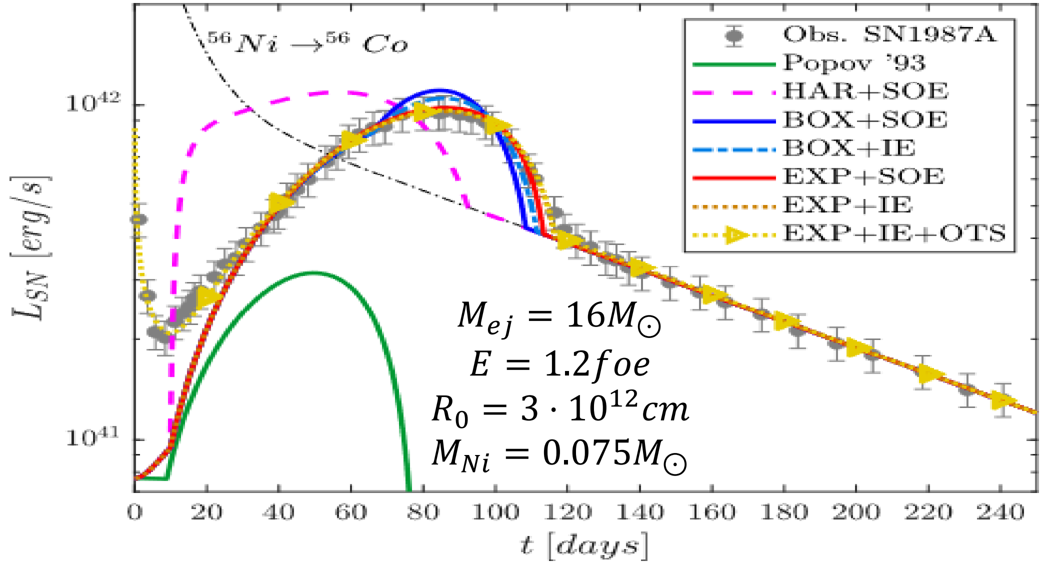
New analytical model:

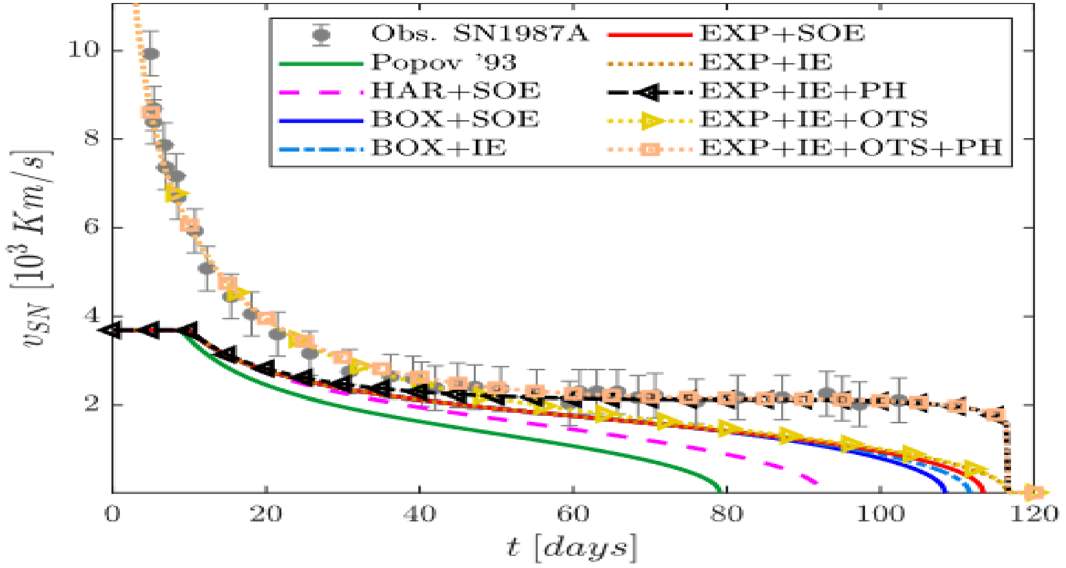
[Pumo & Cosentino, MNRAS, Vol. 538, 1, pp.223-242 (2025)]

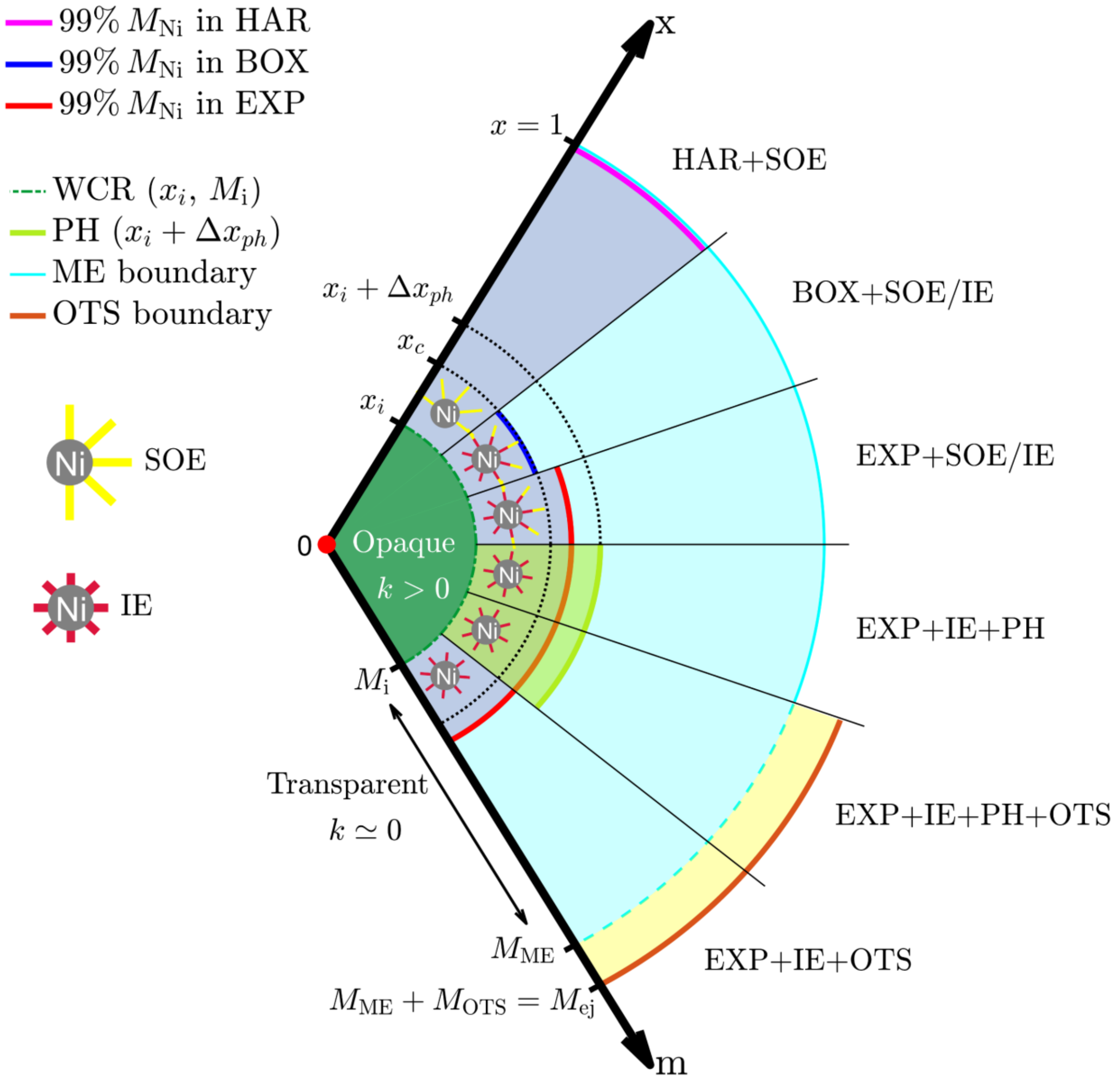
- Heating effects of **^{56}Ni decay during the recombination phase**:
  → Ni distribution and emission hypothesis (BOX, EXP, SOE, IE)
- Presence of an **Outer Thin Shell** (OTS) above the homologous ejecta:
  → further shell parameters (at least two more)



Pumo & Cosentino, MNRAS, Vol. 538, 1, pp.223-242 (2025)







Shock luminosity in interacting Supernovae

- CSM configuration

$$M_{CSM}, R_{CSM}, s, f_{\Omega}$$

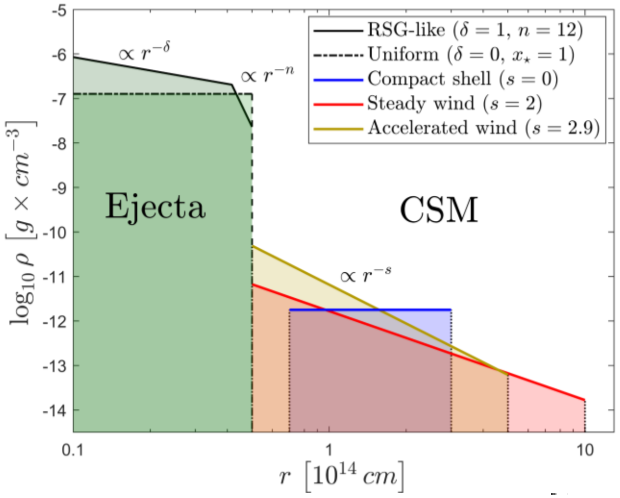
- Energy source & Diffusion time:

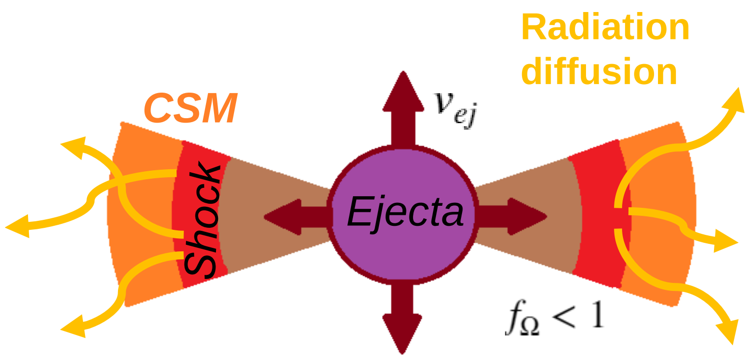
$$S_{\rm sh} \equiv \frac{9}{2}\pi f_{\Omega}\epsilon_{\rm rad}\ \rho_{\rm CSM}|_{R_{\rm sh}(t)}\ v_{\rm sh}^3(t)\,R_{\rm sh}^2(t)$$

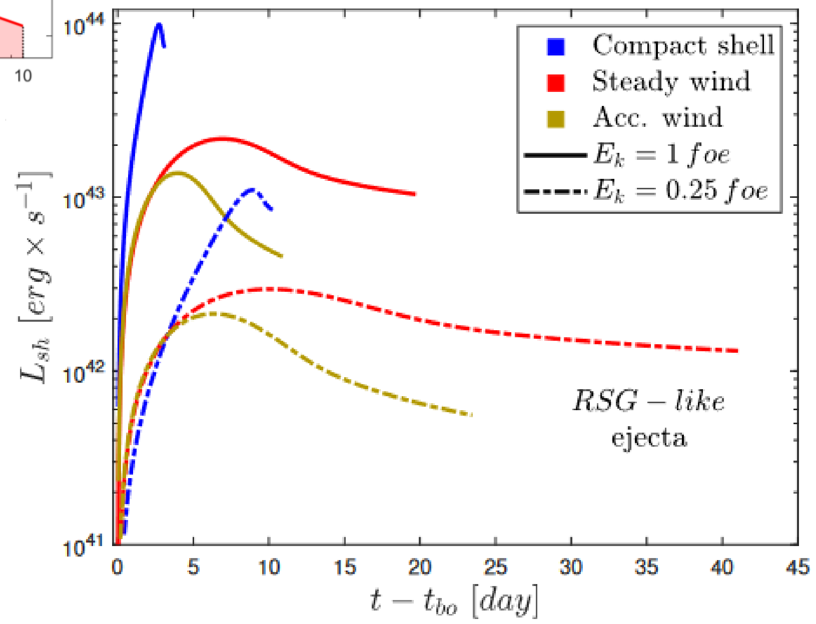
$$t_{\rm d} \equiv \frac{k_{\rm T}}{c} \times \int_{R_{\rm sh}}^{R_{\rm ph}} \rho_{\rm CSM}(r)\, d\left[(r - R_{\rm sh})^2\right]$$

- Shock luminosity:

$$L_{\rm sh}(t) = \int_{t_{\rm bo}}^{t} \frac{S_{\rm sh}(t')}{t_{\rm d}(t')} \times e^{-(t-t')/t_{\rm d}(t')}\,dt',$$







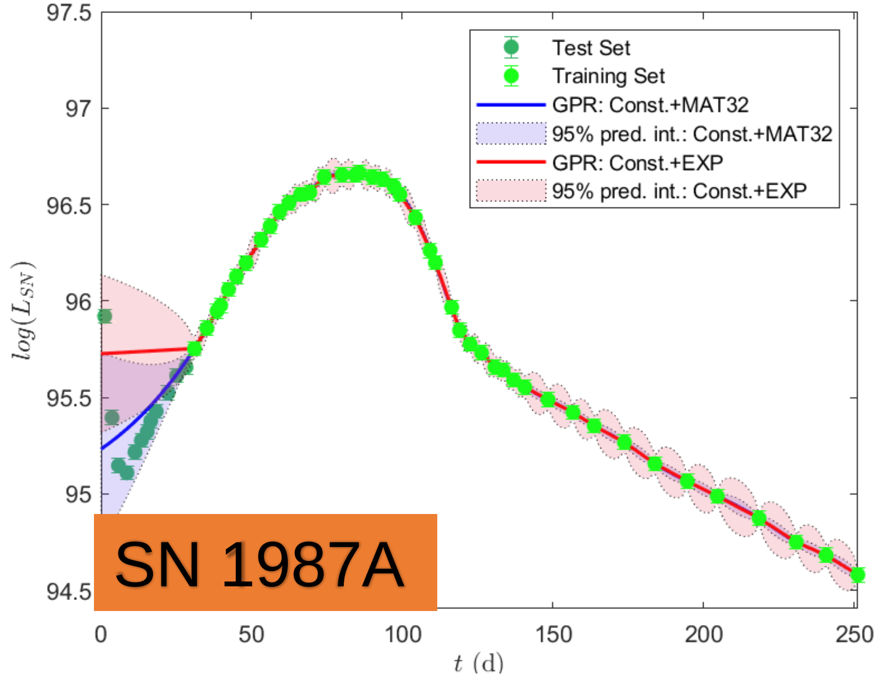
S.P. Cosentino, M.L. Pumo & S. Cherubini, MNRAS (2025, revised).

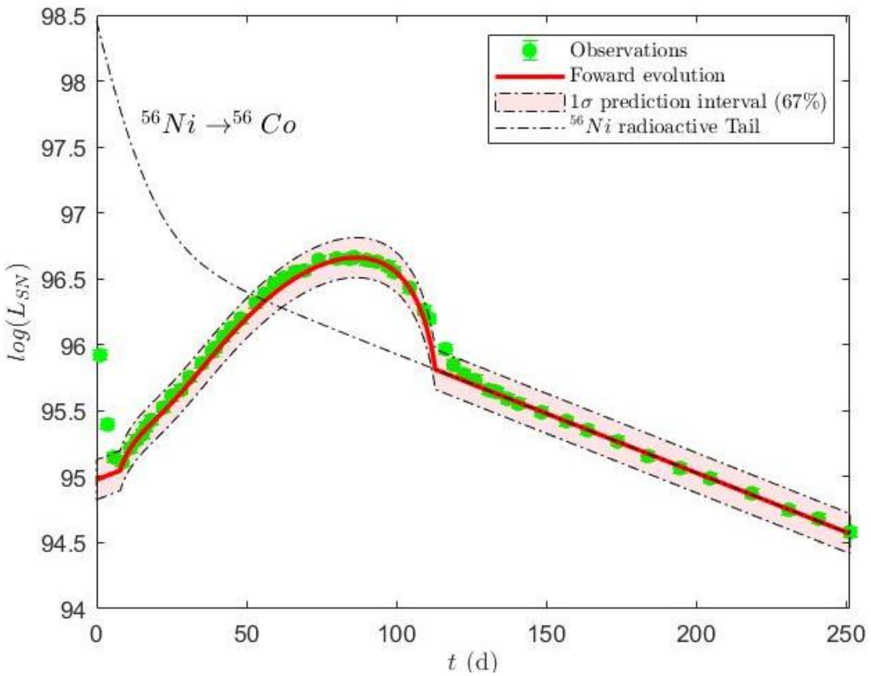
«Fast» modeling procedures for CC-SNe

S.P. Cosentino, C. Inserra, M.L. Pumo (A&A, to be submitted)

Data reduction and analysis:

- Sample choice and spectrophotometric reduction;
- Time series reconstruction (Gaussian Process).





Theoretical models and Modelling procedures:

- Development and validation of analytical models;
- Modeling parameter inference (SuperBAM).

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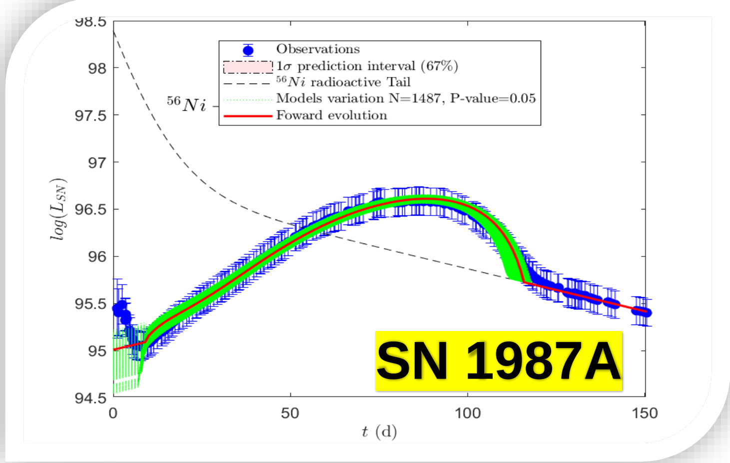
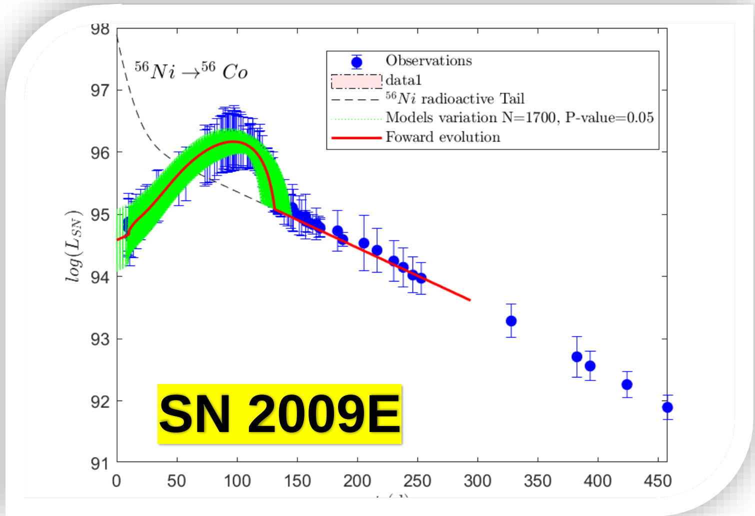
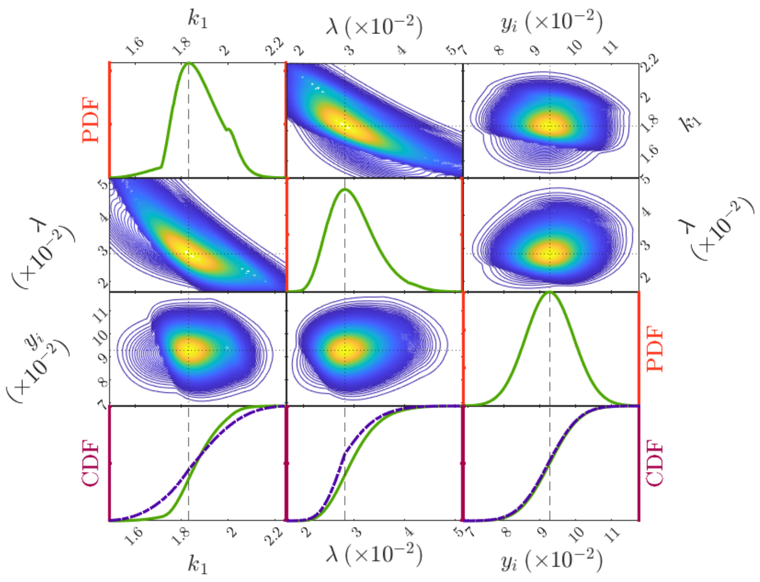
Supernova Bayesian Analytic Modeling - SuperBAM

S.P. Cosentino, C. Inserra, M.L. Pumo (A&A, to be submitted)







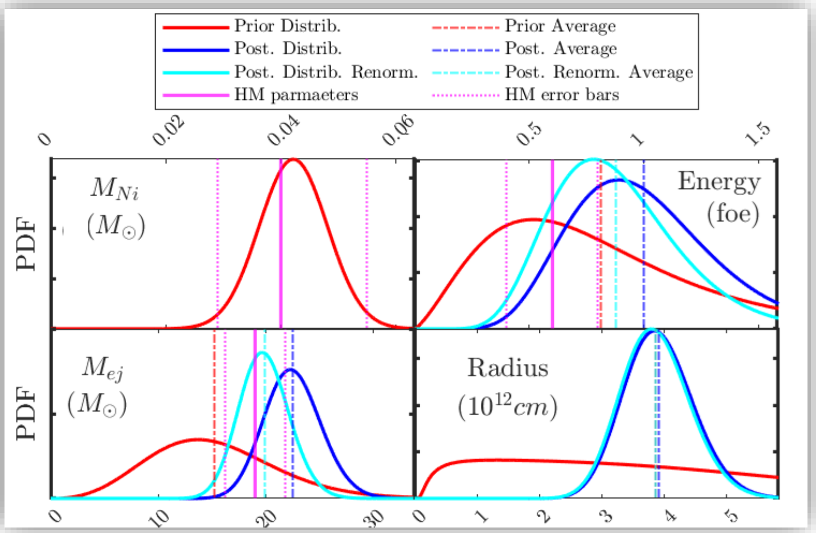
Likelihood Function

$$P(\bar{L}|\theta) = \frac{1}{\sqrt{2\pi}\,\sigma}\cdot\prod_{Obs.}\exp\left\{-\frac{\left[log\bar{L}_{Obs.} - log\bar{L}_{Mod.}(y_{Obs.},k_1,\lambda,y_{i/f})\right]^2}{2\sigma^2}\right\}$$

Posterior Probability

$$P(\theta|log\bar{L}) = N_{norm}\cdot P(log\bar{L}|\theta)\cdot P(\theta)$$

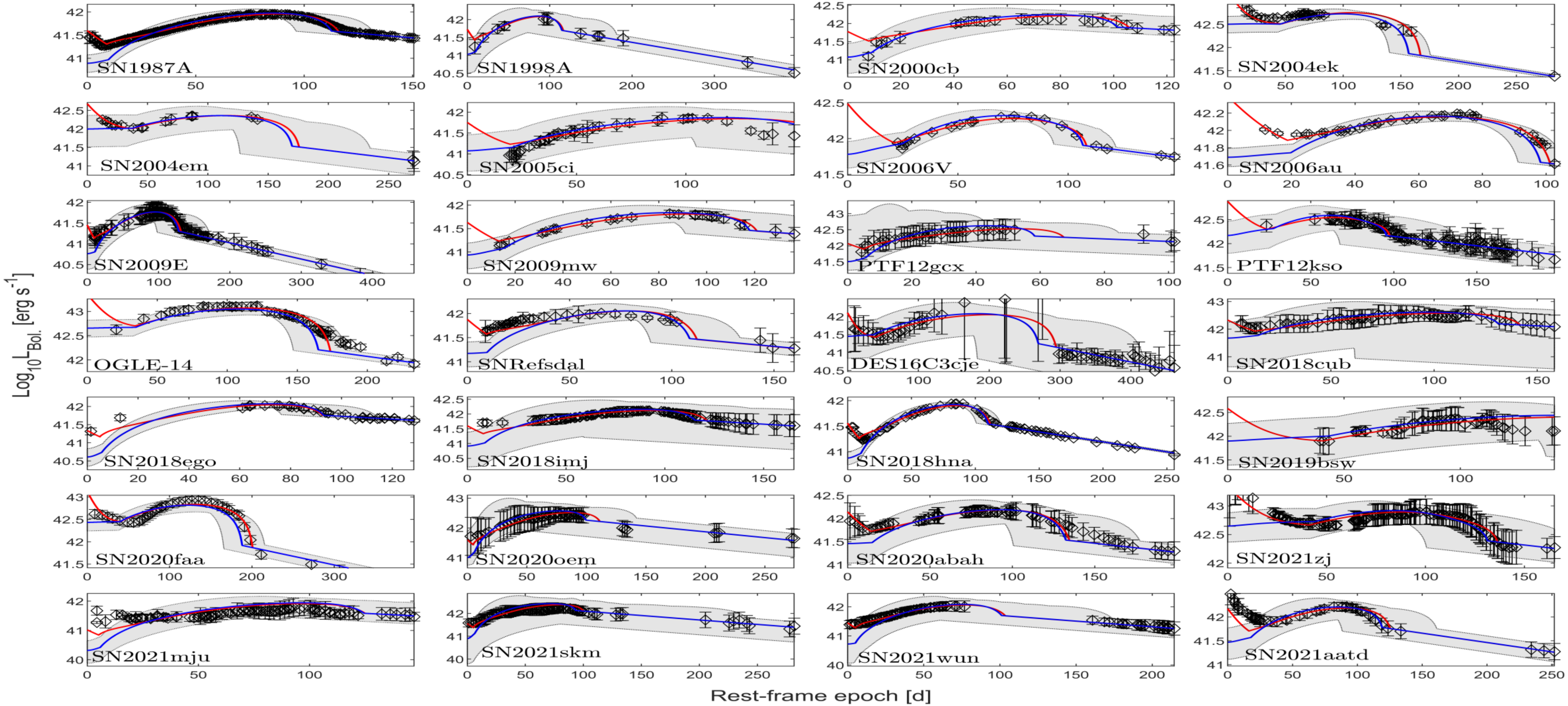
SuperBAM



Prior probabilities from scaling relation of
[Pumo, Cosentino, Pastorello et al., MNRAS 521, 4801–4818 (2023)];
Likelihood function model based on
[Pumo & Cosentino, MNRAS, Vol. 538, 1, pp.223-242 (2025)].

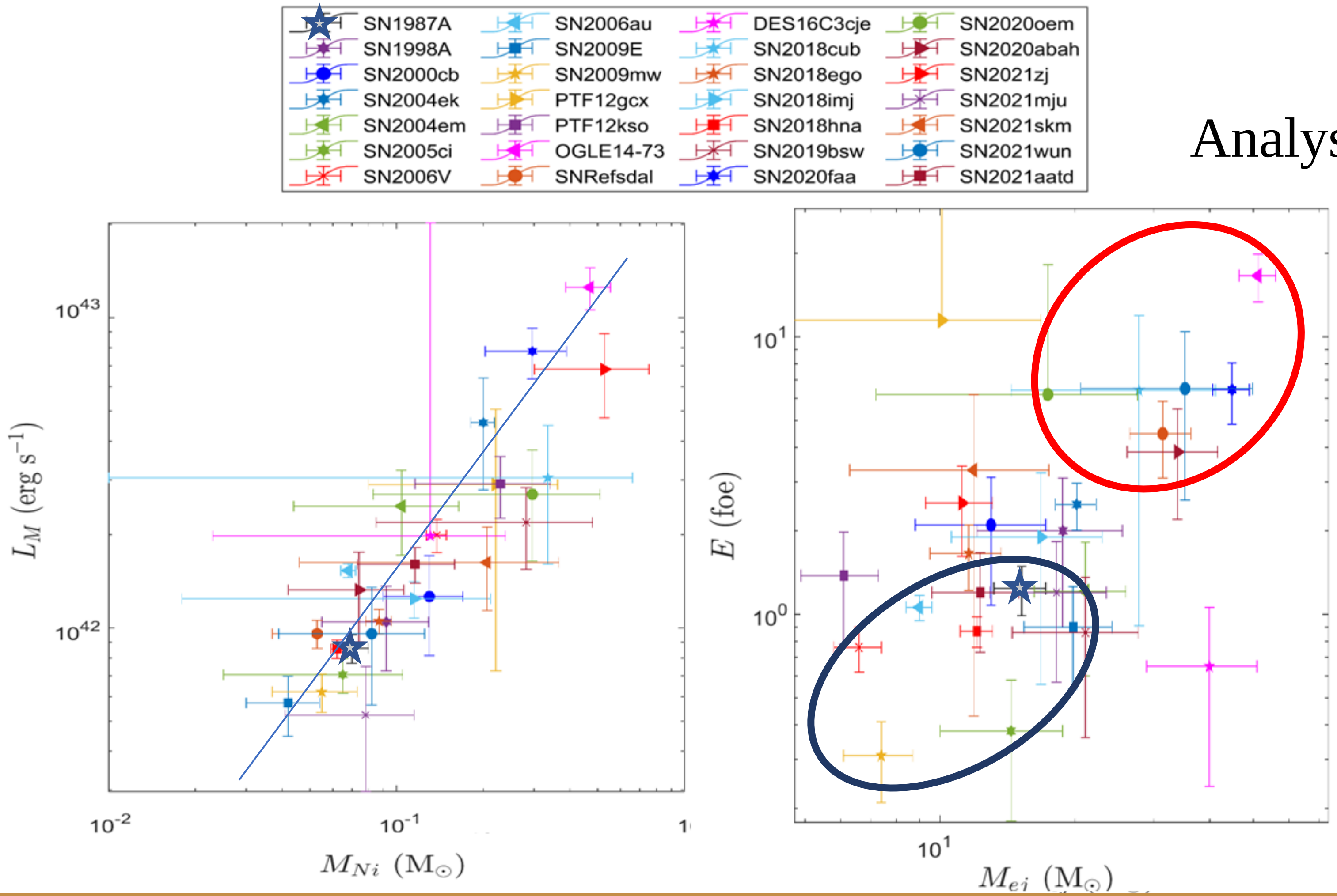
Preliminary results for 28 long-rising SNe

S.P. Cosentino, C. Inserra, M.L. Pumo (A&A, to be submitted)



87A-like SNe parameter distribution

S.P. Cosentino, C. Inserra, M.L. Pumo (A&A, to be submitted) in agreement with Pumo, Cosentino, Pastorello et al., MNRAS 521, 4801–4818 (2023);

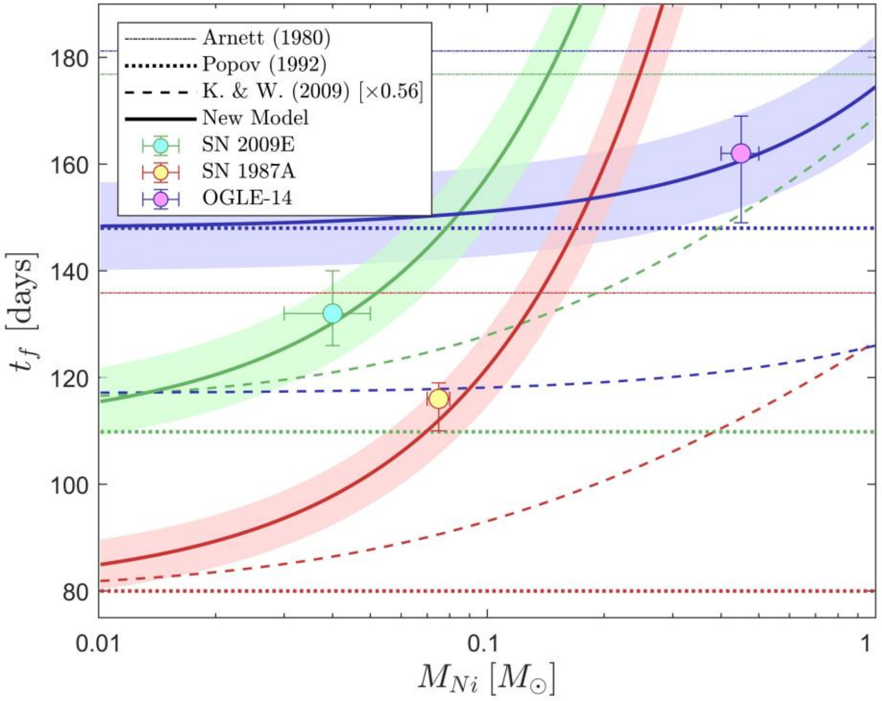


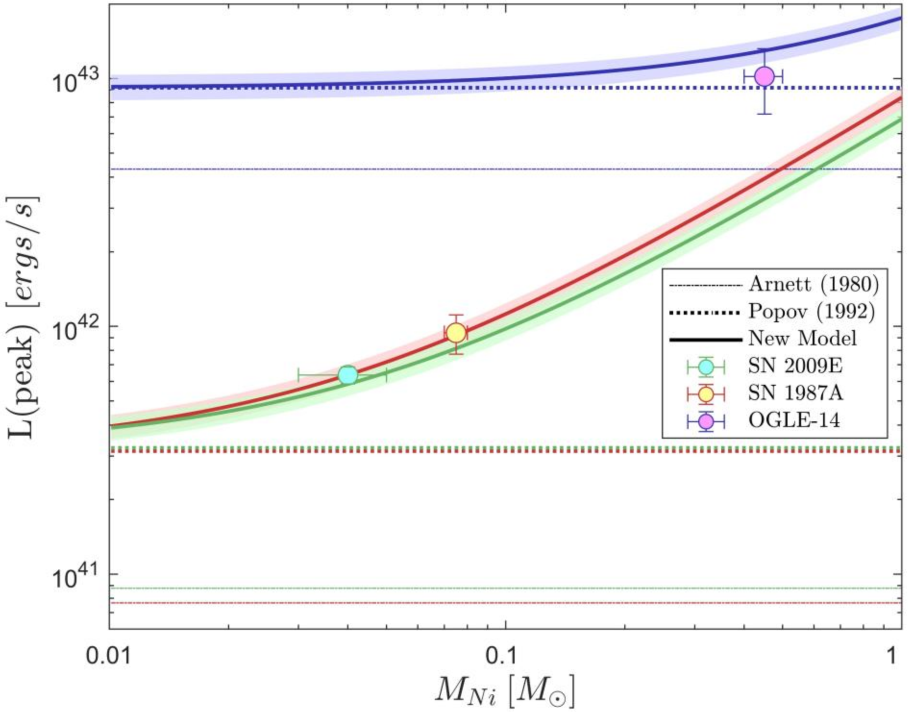
Analysis of the largest 87A-like SN sample:

- **High energetic** and no-standard Core-Collapse explosions;
- **Faint clones** of SN1987A;
- Continuous distribution in E-M_{ej} plane;
- Peak luminosity and Nickel Mass correlation;
- DES16C3cje is an enigmatic object;

New ^{56}Ni dependent scaling relations

Pumo & Cosentino, MNRAS, Vol. 538, 1, pp.223-242 (2025)



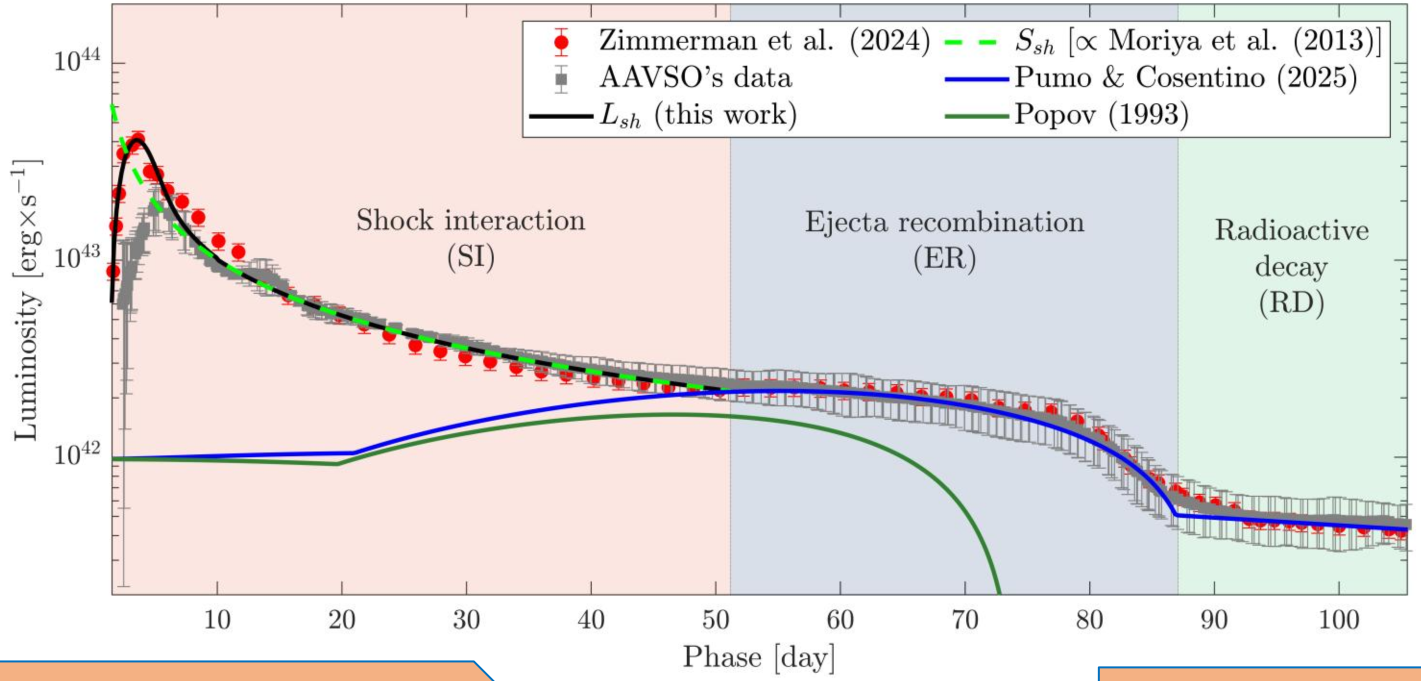


$$\begin{cases} t_f \propto R_0^{1/6}\cdot E^{-1/6}\cdot M^{1/2}\cdot[1+\mathrm{T}] \\ L_{\rm max} \propto R_0^{2/3}\cdot E^{5/6}\cdot M^{-1/2}\cdot[1+\Lambda] \end{cases} \quad \text{where:} \begin{cases} \mathrm{T} \simeq k_1\cdot M_{Ni}^{0.93}\cdot R_0^{-0.56}\cdot E^{-0.58}\cdot M^{-0.12} \\ \Lambda \simeq k_2\cdot M_{Ni}\cdot (E\cdot M\cdot R)^{-0.5} \end{cases}$$

Modeling parameters of OGLE-14-073 (OGLE-14) and SN 2009E are taken from *Terreran et al. 2017*, *Pastorello et al. 2012*, respectively, and inferred thanks to the same numerical Hydrodynamical model of SN 1987A (Pumo & Zampieri 2011).

Application to other H-rich SNe: The case of SN 2023ixf

S.P. Cosentino, M.L. Pumo & S. Cherubini, MNRAS (2025, revised)



SN ejecta parameters

$$M_{ej} = 9 \pm 0.5 M_\odot, \quad E = 1.8 \pm 0.2 foe$$

$$R_0 = (1.6 \pm 0.6) \cdot 10^{13} cm$$

$$M_{Ni} = 7.3^{+1}_{-0.5} \times 10^{-2} M_\odot$$

CSM parameters

$$M_{CSM} = 6.5^{+1.5}_{-1} \cdot 10^{-2} M_\odot$$

$$R_{CSM} = (3.6 \pm 0.5) \cdot 10^{15} cm$$

$$s = 2.90 \pm 0.03$$

Ongoing and future activities

- Development of **new modeling procedures based on Machine Learning** inference (e.g. *M. Grassia, S.P. Cosentino, M.L. Pumo, G. Mangioni, in press on IEEE PDP2025 Conf. Proc.*);
- Development of **new model for** different types of sourcing functions and ejecta composition, to describe **other class of optical transients** (e.g. ILRT, SLSNe, Ib\c);
- Simulations of **High-Energy neutrinos and gamma-ray emission** in ejecta-CSM interaction (e.g. *S.P. Cosentino, M.L. Pumo & S. Cherubini, MNRAS, 2025, revised);*
- Modeling other real SN events to **perform the observation strategies for Large Volume Neutrino Observatories** (e.g. KM3Net, IceCube);

Thanks for your attention!

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