Modeling nearby Core-Collapse Supernove

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SOS
Supernova
Observations & Simulations

https://sos.fcaglp.unlp.edu.ar

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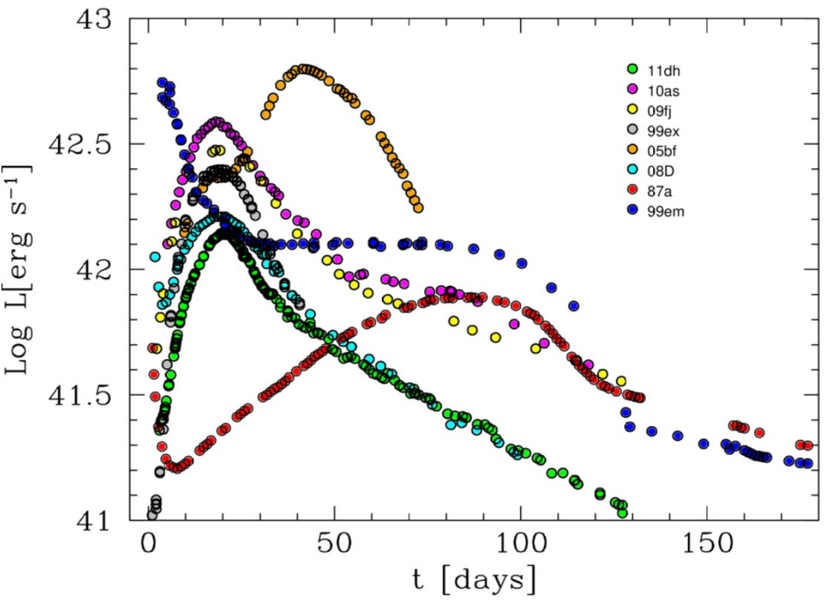
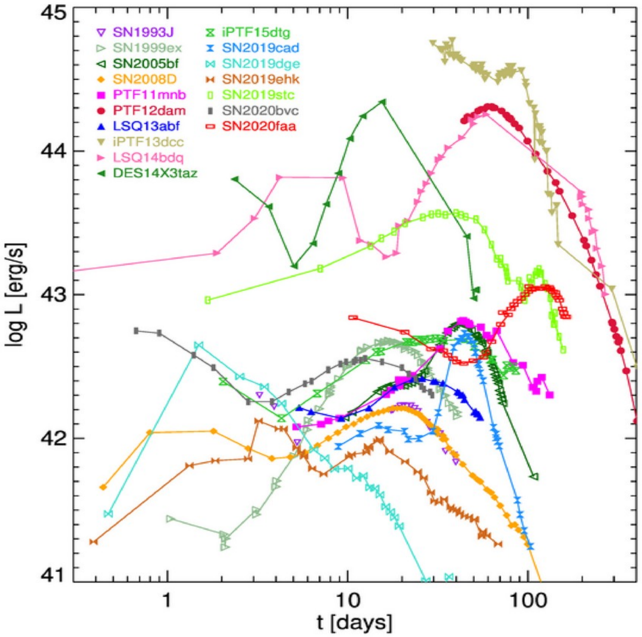
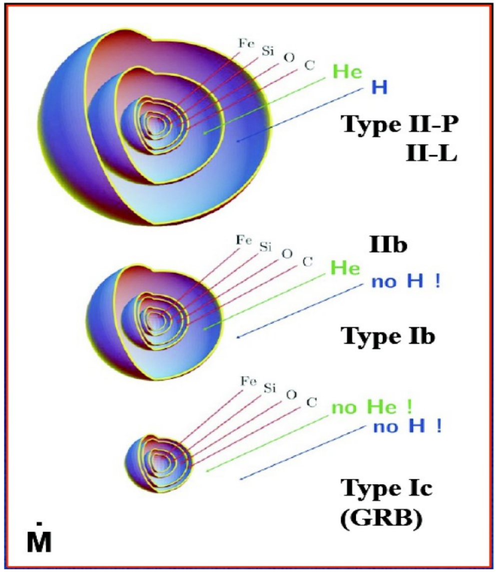
Core-collapse Supernovae

- Excellent to test stellar evolution of massive stars
- What type of progenitor corresponds to each type of SN? How do massive stars lose their envelopes?
- What power the LC of over luminous SNe (SLSNe, LGRB-SNe) ? And the multi peaks/undulations?
- SNe diversity: progenitor properties, enviroment, power source….



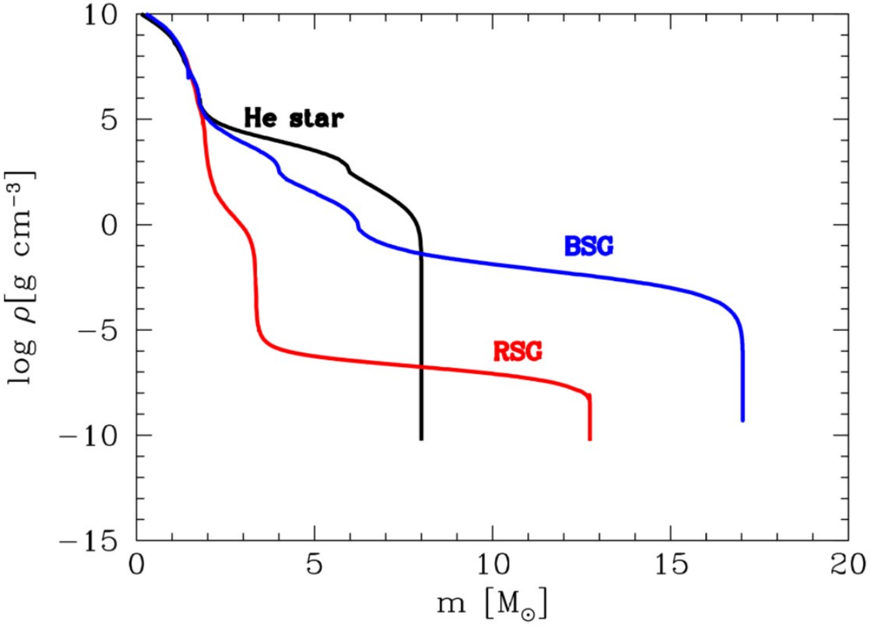




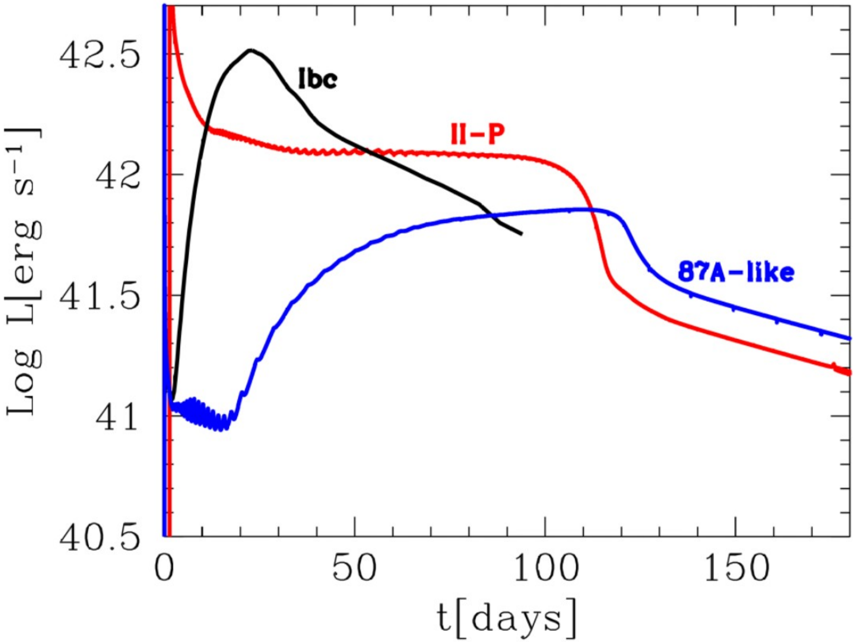
1D Hydrodynamical Models

- Useful for exploring different **properties of progenitors**, their environments and energy sources
- One-dimensional Lagrangian code with flux-limited radiation and gray transfer for gamma-rays (Bersten+11).
  A fast self-consistent model that computes shock wave propagation and complete LC evolution.
- Pre-SN structures: stellar evolution and parametric models

Initial density



Light curve



1D Hydrodynamical Models

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- One-dimensional Lagrangian code with flux-limited radiation and gray transfer for gamma-rays (Bersten+11). A fast self-consistent model that computes shock wave propagation and complete LC evolution.
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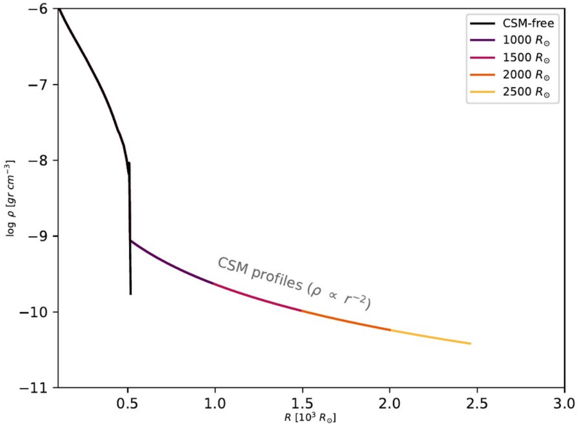
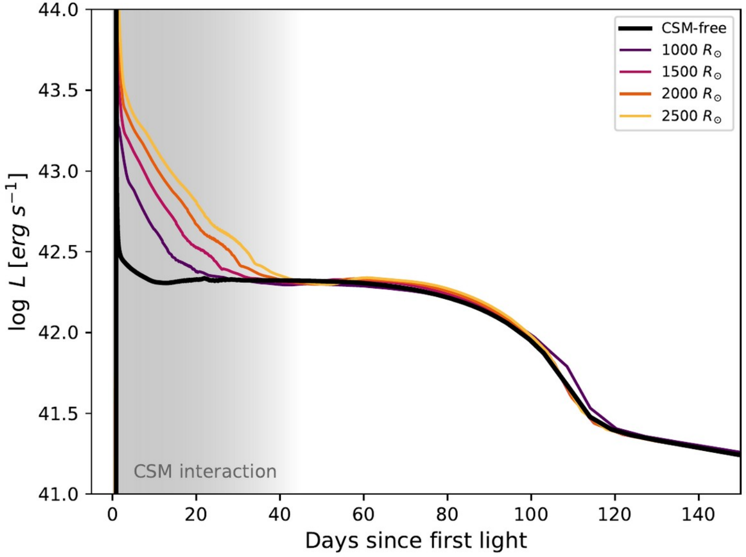
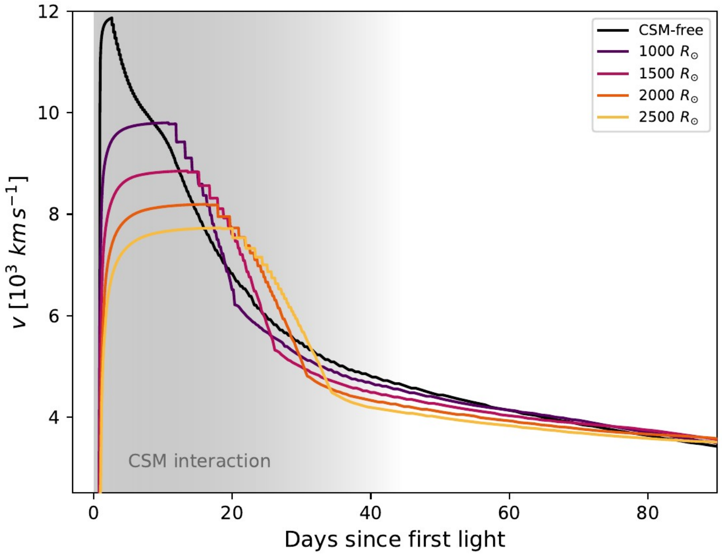
External density



Light curve

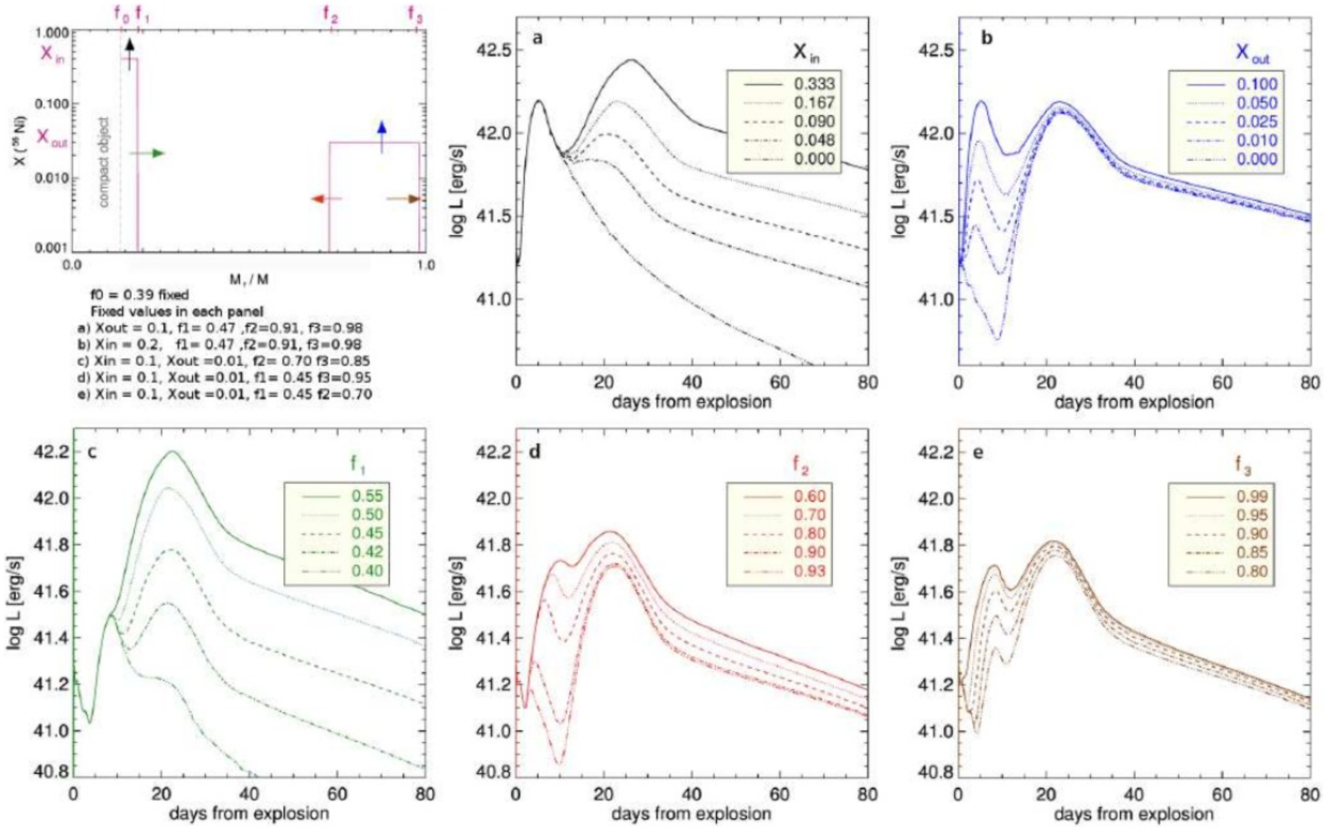


Photospheric velocity

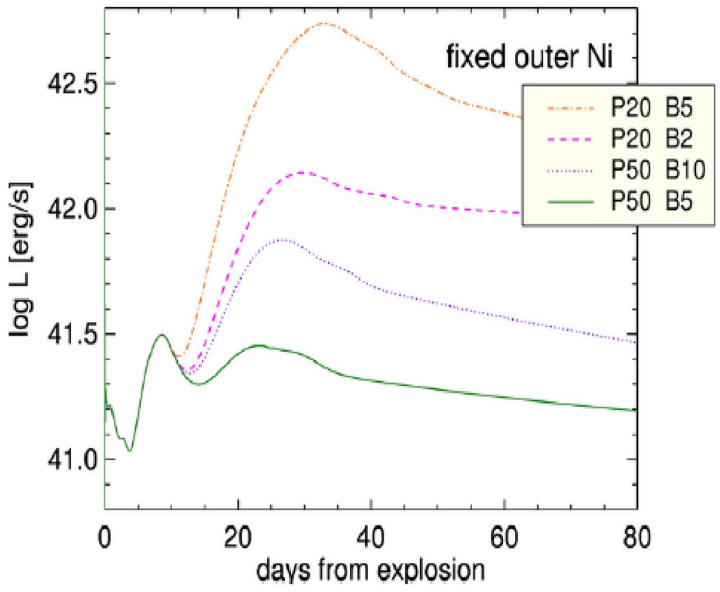


1D Hydrodynamical Models

- Useful for exploring different **properties of progenitors**, their environments and energy sources
- Double peaked SNe: double-peaked nickel distribution, hybrid model (Ni+ magnetar), ….

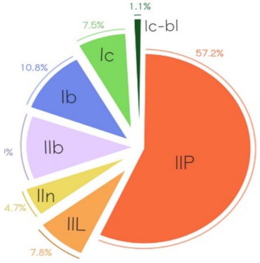


Hybrid model



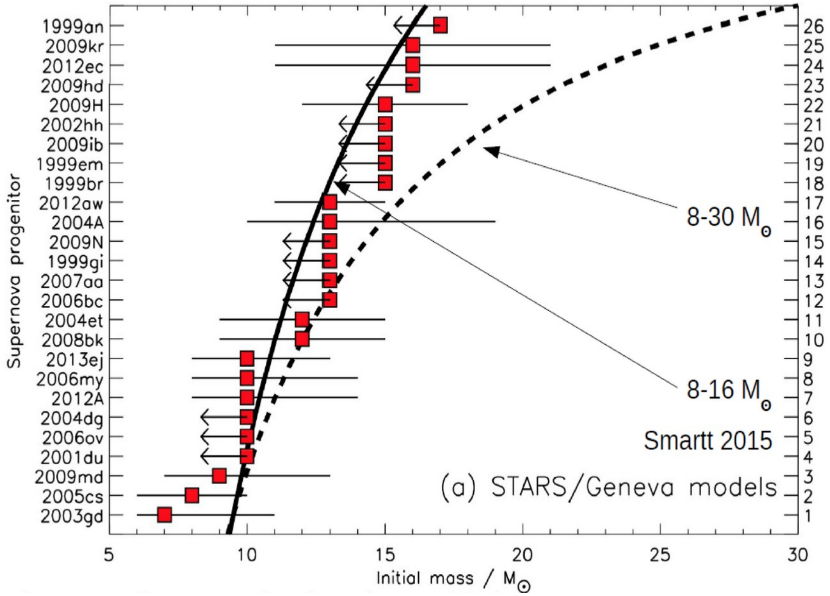
Orellana & Bersten, A&A, 2022

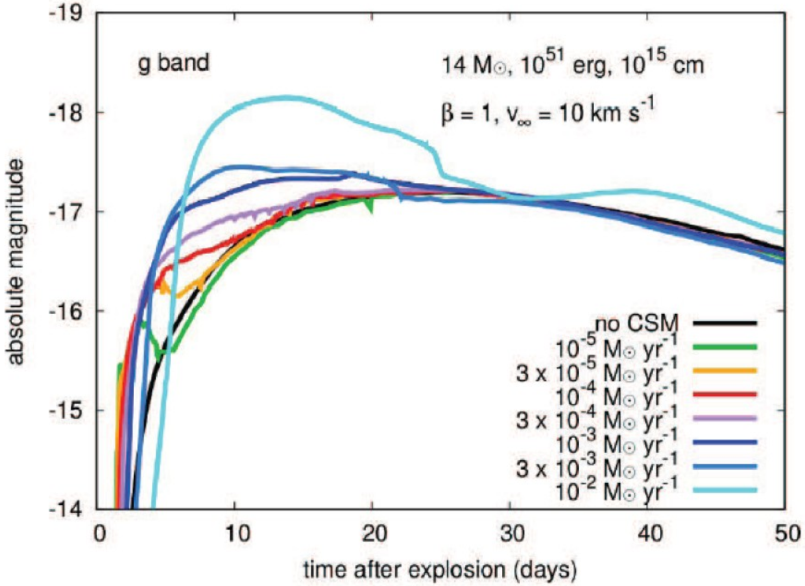
Type II Supernovae



H.F. Stevance @Sydonahi

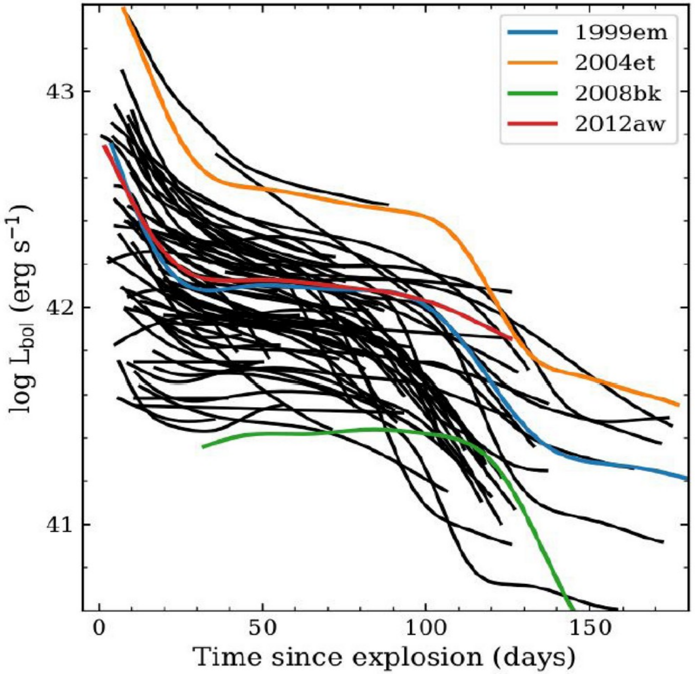
- Most common type of stellar explosion
- Pre-SN imaging + stellar evolution models: MZAMS : 8 –16 M⊙ (Smartt+15) RSG problem
- Hydro models of large SN sample: low maximum mass (M_{max} < 18 – 20 $M_{\odot}$) (Martinez, MB+22b, Silva-Farfán+24)
- Evidence of some CSM around in most SNe II (Moriya+13, Morozova+17, Förster+18,...)

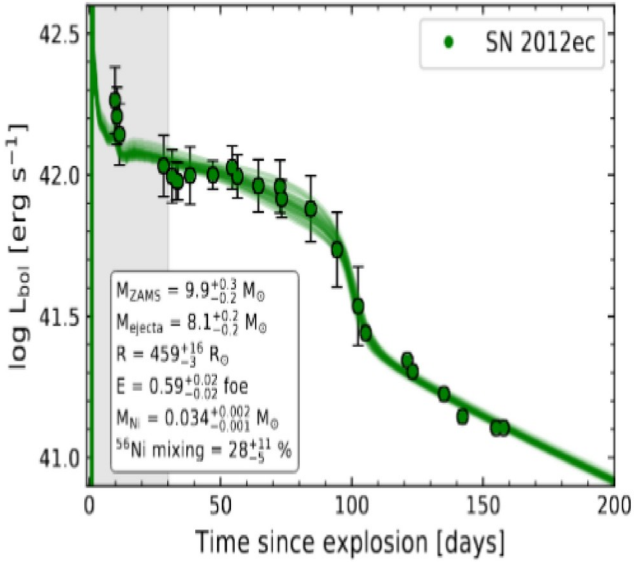


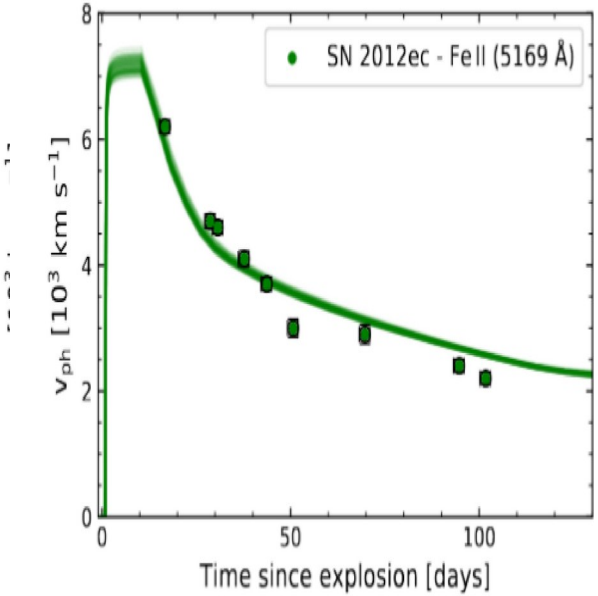


Modeling Type II Supernovae

- Physical parameters for a large sample (~80) of CSP SNe II
- Grid of hydro models based on stellar evolution progenitors (MESA+Bersten's code)
- Fitting technique based on MCMC using LC and Vph simultaneously (Martínez, MB+20)





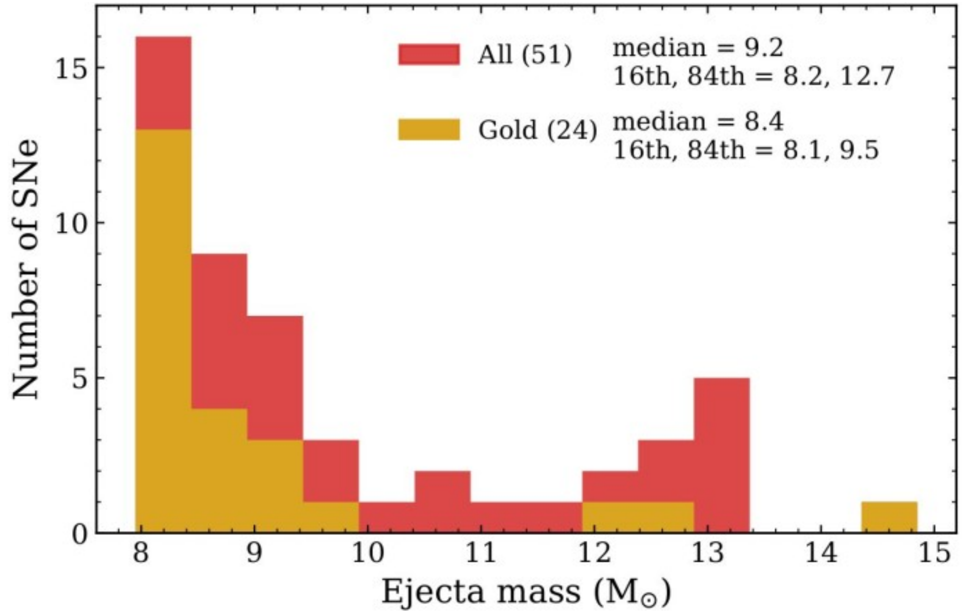


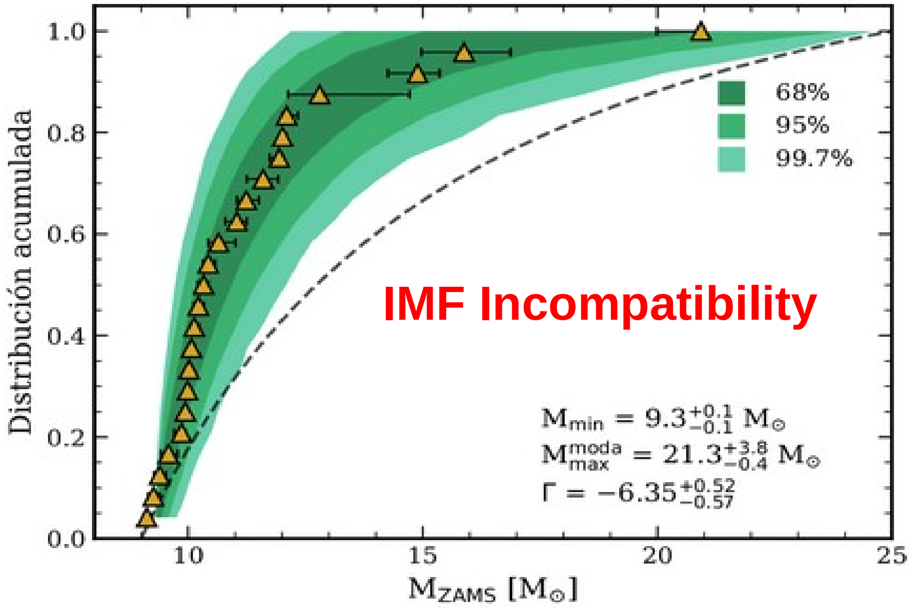
Modeling Type II Supernovae

Large sample (~ 80) of CSP SNe II

Physical Parameters + IMF of progenitors (**Martinez, MB+22a,b,c**)

- Low maximum mass(M_{max} < 18 – 20 $M_{\odot}$) ⟹ **RSG problem**
- Power law steeper than Salpeter's ⟹ **IMF incompatibility**
- IMF incompatibility due to the large number of SNs with low eyected mass

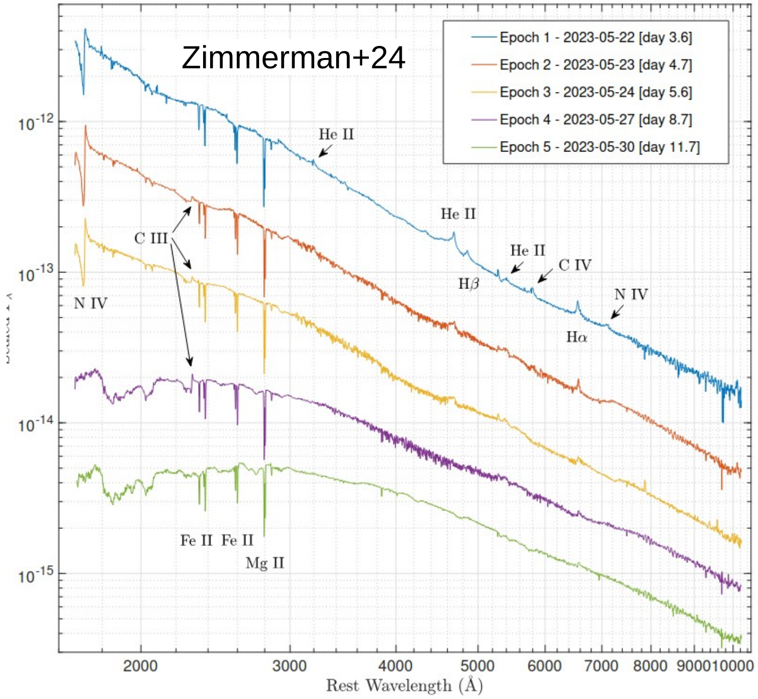


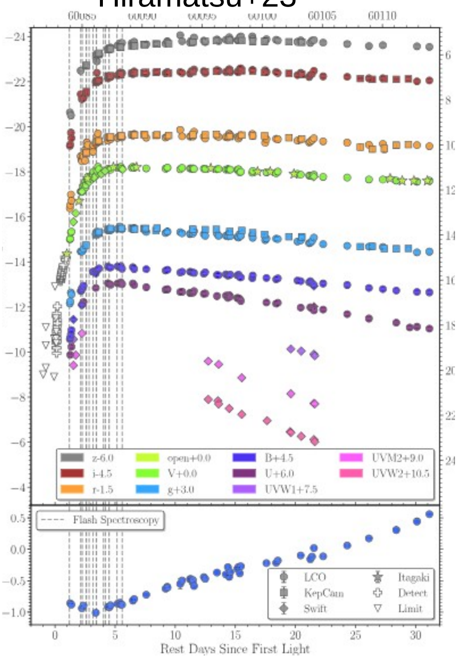


The Type II SN 2023ixf in M101

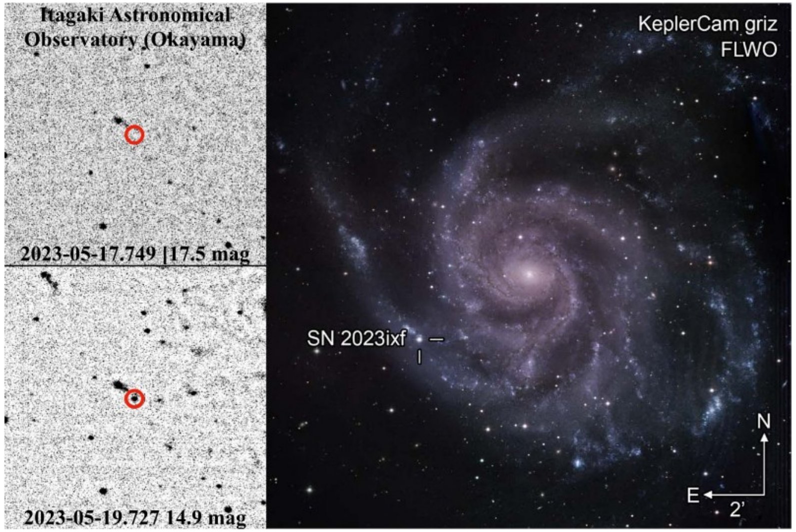
- One of the closest and most luminous CCSNe in the last decade (~7 Mpc)
- Extensive photometric and spectroscopic follow-up from radio to X-rays
- Early spectra show narrow emission lines (~ 1 week) ⇒ dense CSM

Yang+2024, Van Dyk+2024b, Moriya+2024, Fuller+2024, Van Dyk+2024a, Martí-Devesa+2024, Ferrari+2024, Singh+2024, Rest+2024, Lee+2024, Murase+2024, Sarmah+2024, Ransome+2024, Zimmerman+2024, Li+2024, Chandra+2024, Martinez+2024, Xiang+2024, Ravensburg+2024, Neustadt+2024, Bersten+2024, Liu+2023, Zhang+2023, Soraisam+2023, Dong+2023, Yamanaka+2023, Bostroem+2023, Smith+2023, Vasylyev+2023, Qin+2023, Niu+2023, Guetta+2023, Hiramatsu+2023, Jacobson-Galán+2023, Teja+2023, Flinner+2023, Koenig 2023, Soker 2023, Hosseinzadeh+2023, Pledger+2023, Jencson+2023, Sgro+2023, Kilpatrick+2023, Grefenstette+2023, Berger+2023, Davenport+2023, …





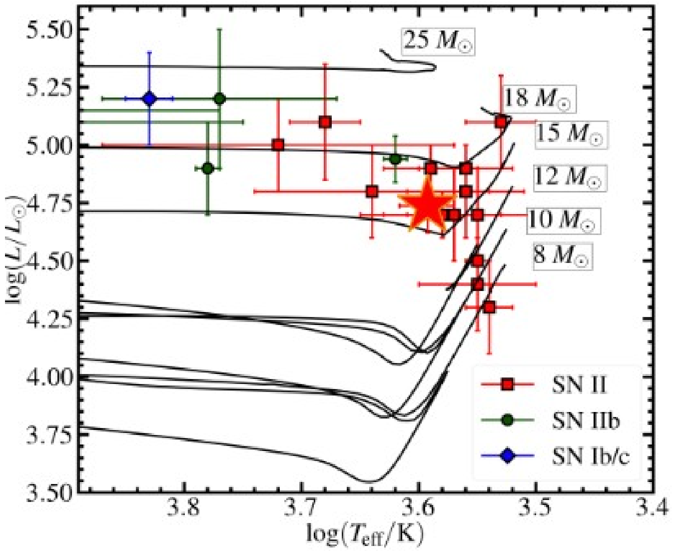
Discovered by K. Itagaki



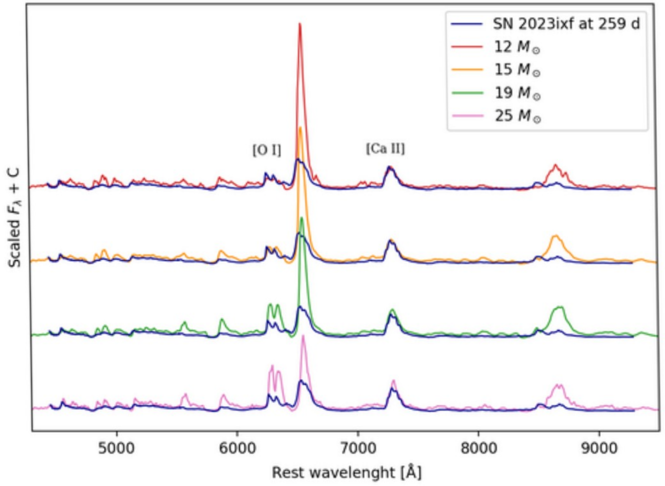
Progenitor mass estimates of SN 2023ixf

Wide rage of M_{ZAMS}

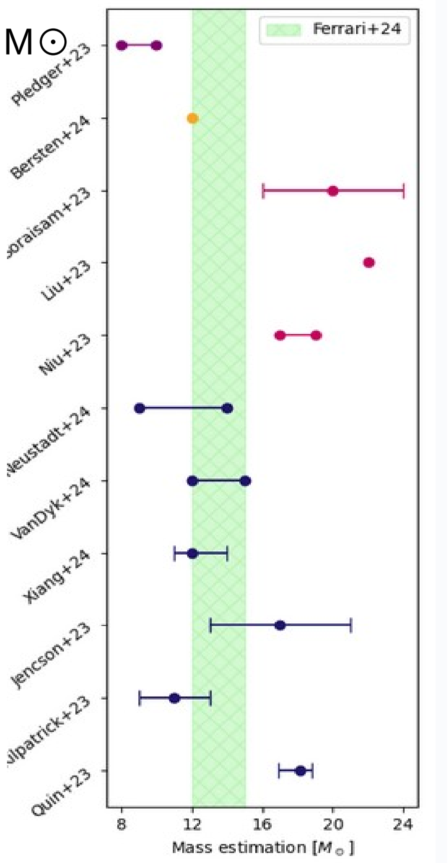
- Archival pre-explosion imaging – SED fitting ⇒ dusty RSG star. M_{ZAMS} ~ 8-22 M⊙
- Pre-explosion variability: first detection of a variable SN II progenitor: M_{ZAMS} = 16-24 M⊙
- Environmental studies: Star-forming region ⇒ M_{ZAMS}= 17-19 M⊙
- Nebular spectra at~ 240 d: M_{ZAMS} ~ 12-15 M⊙ (Ferrari+24, see also Kumar+25)
- Hydro modeling ⇒ favors M_{ZAMS} < 15 M⊙ progenitor (see next slide)



Kilpatrick+23



Ferrari+24

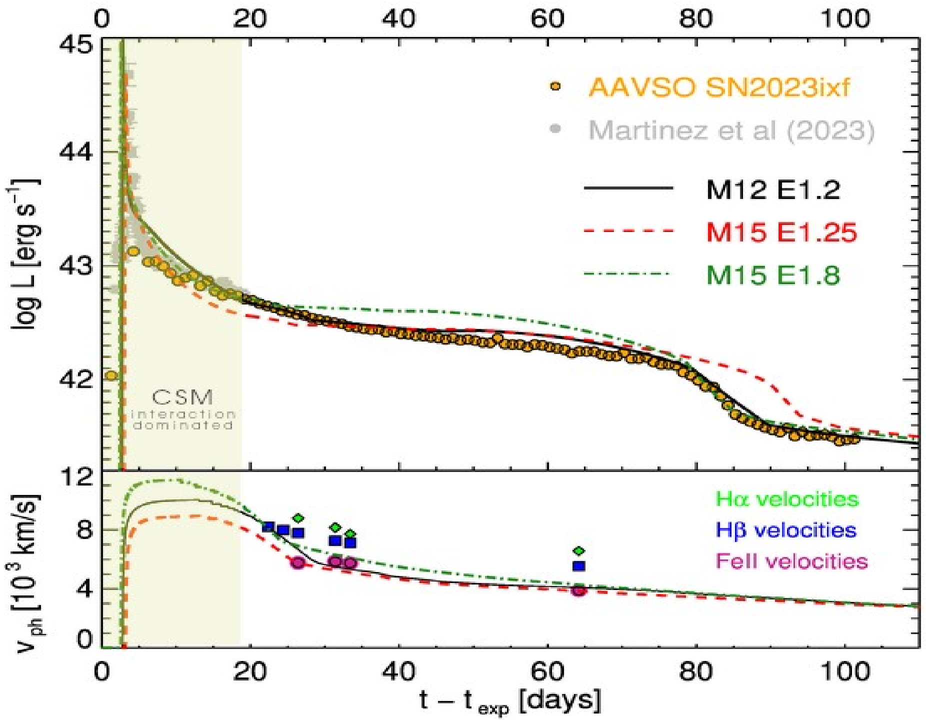


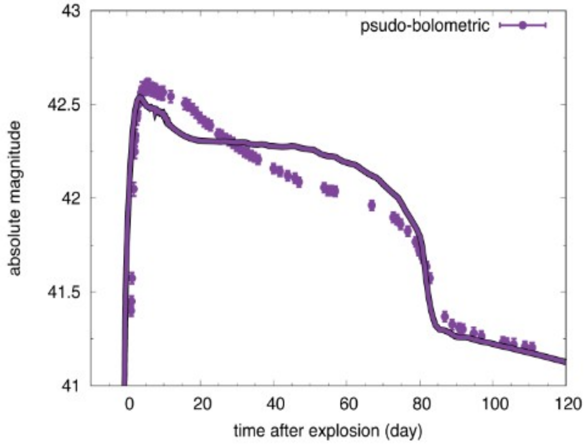
Credit L. Ferrari

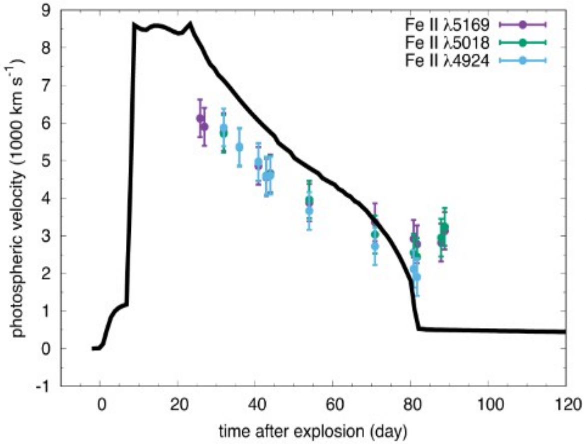
Hydro Models for SN 2023ixf

Bersten+’24

- Grid of hydro models (MESA + Bersten’s code)
- **M_{ZAMS} = 12 $M_☼$; E = 1.2 foe, M_{Ni} = 0.05 $M_☼$**
- Models favor M_{ZAMS} < 15 $M_☼$ progenitor







Moriya & Singh’24

- Pre-existing grid of LC models from Moriya+’23
- **M_{ZAMS} = 10 $M_☼$, E = 2 - 3 foe, M_{Ni}= 0.04 - 0.06 $M_☼$**
- CSM properties:

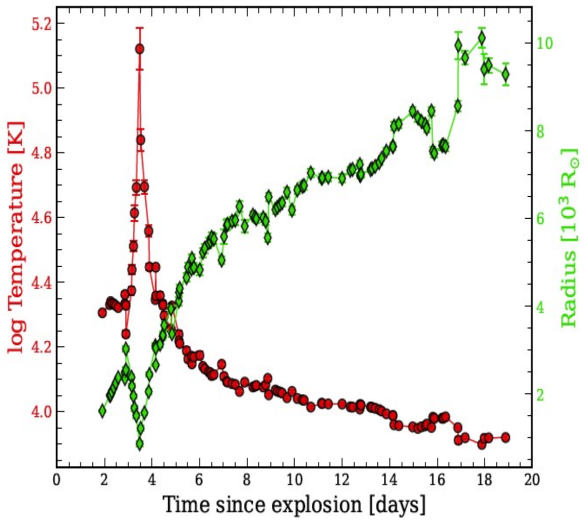
$\dot{M}$ = 10^{-3} – 10^{-2} $M_☼$ yr^{-1},

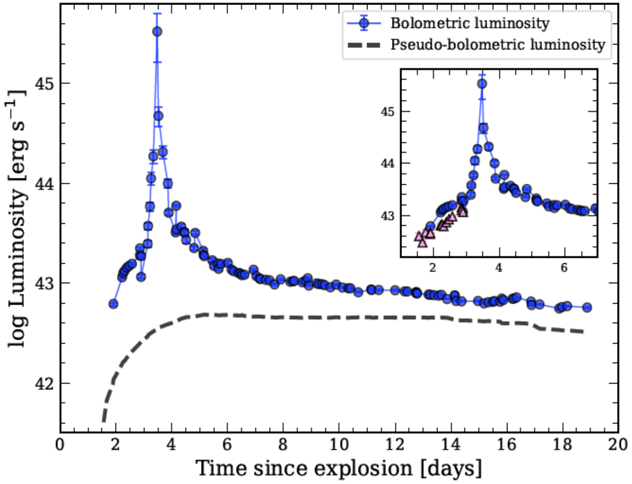
R_{CSM} = 12000 $R_☼$

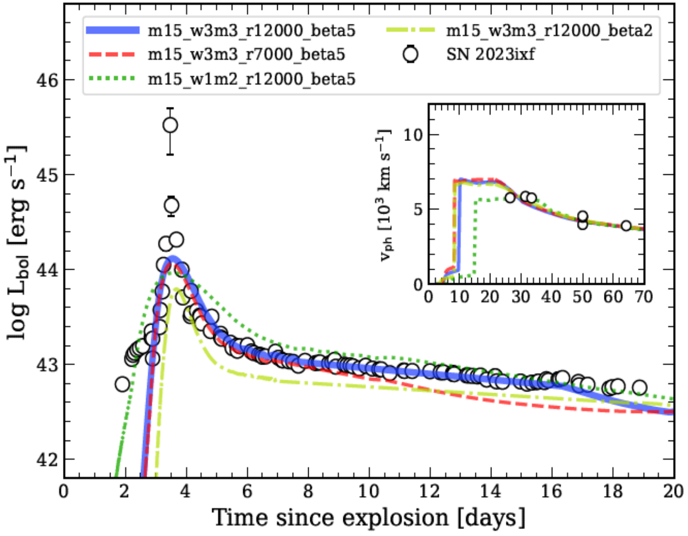
- Low-mass progenitors in both studies
- Other hydro models assuming non-standard $\dot{M}$ get large M_{ZAMS} = 15 - 17 $M_☼$ (Fang+’24 & Hsu+’24)

Early LC Modeling of SN 2023ixf

- Early bolometric ligh curve (LC): a) Initial heating phase during LC peak, b) break in rising slope and c) shock breakout from CSM structure
- Our hydro models indicated an accelerated wind with **$\dot{M} = 3\times10^{-3}\ M_{\odot}\ yr^{-1}$, 12000 $R_{\odot}$**
- Our CSM interaction models are consistent with the **duration of flash emission features and pre-SN variability**



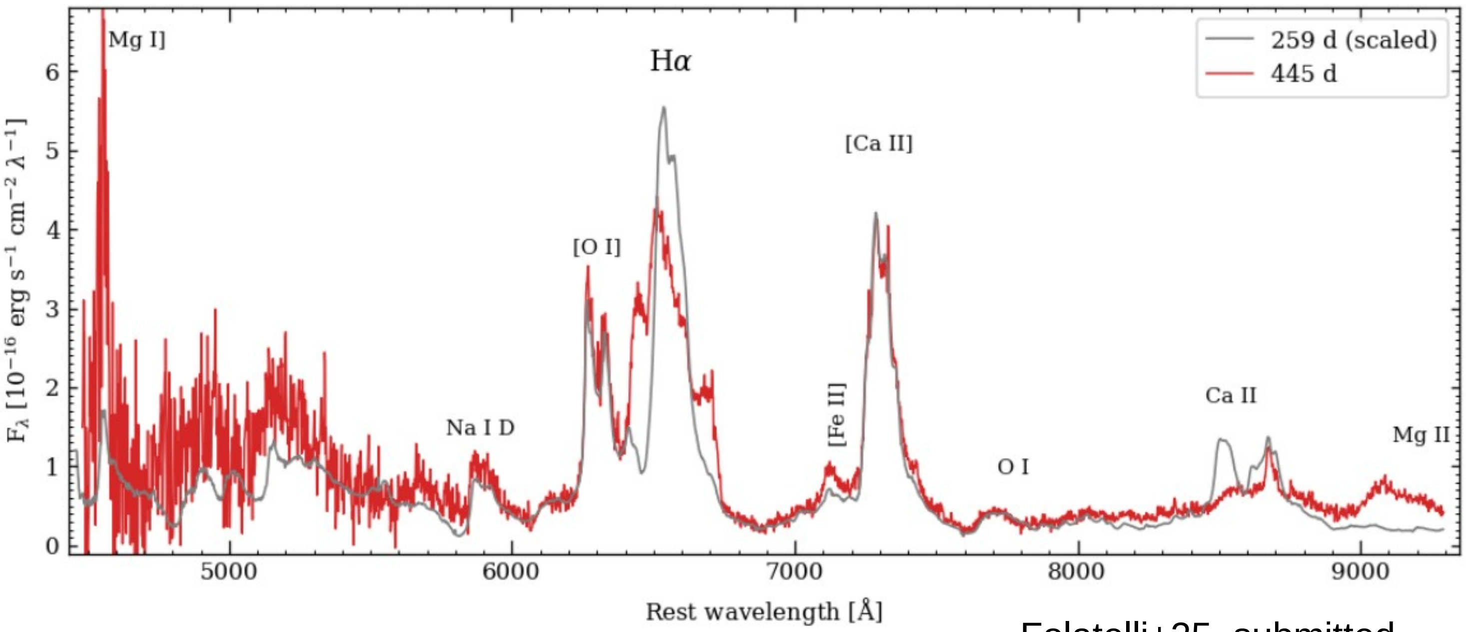


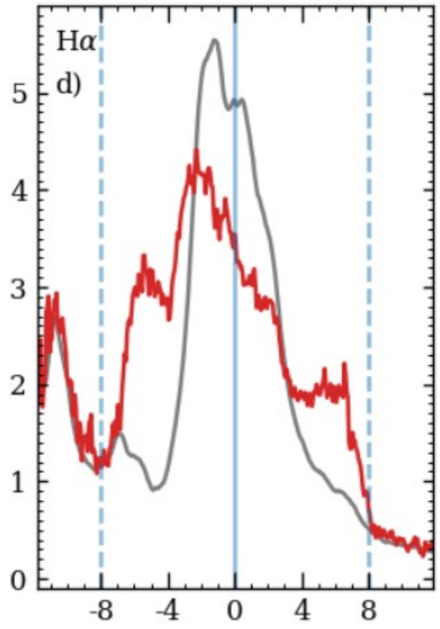


Martinez, MB + 2024

SN 2023ixf: at the nebular phase

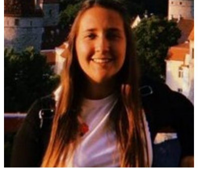
- Spectrum at 445 d show a dramatic transformation
- Complex Hα profile: a signature of CSM interaction (Folatelli+25, Kumar+25, Philip+25, Zheng+25,...).
- Belongs to a type II group with short plateaus that develop interaction features before ≈500d





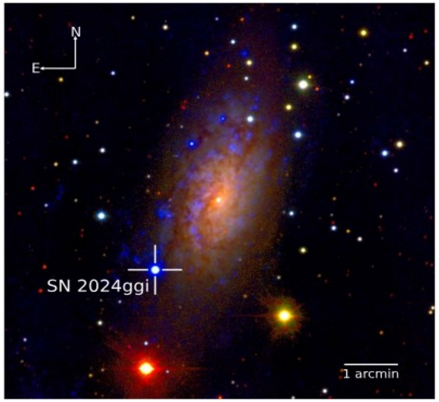
Folatelli+25, submitted

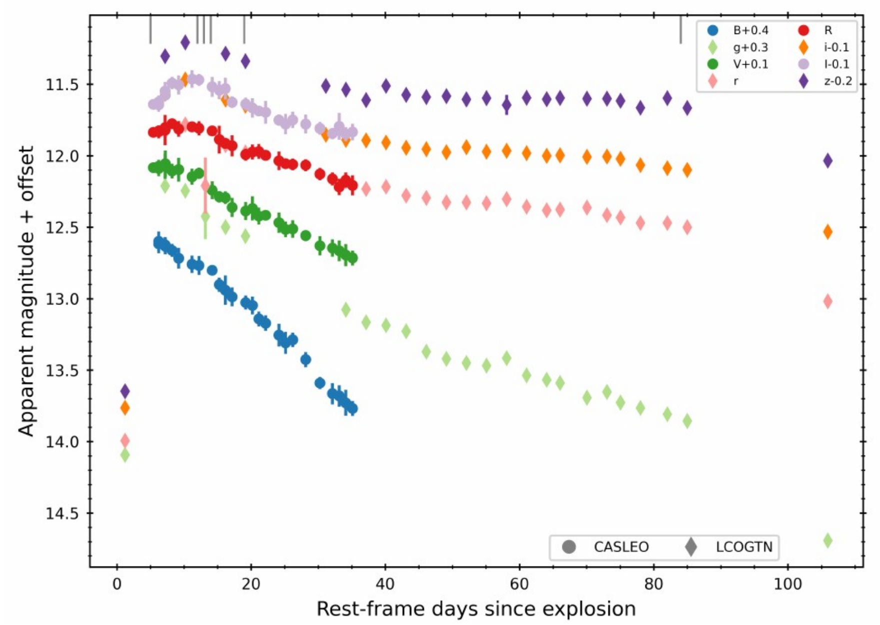
SN 2024ggi: another striking SN II



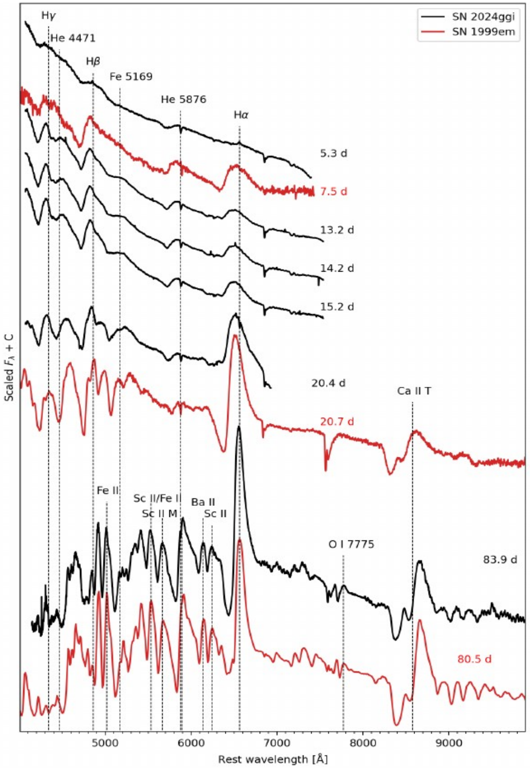
- A very nearby Type II SN (d ~6.7 Mpc)
- Extensive photometric and spectroscopic follow-up from radio to X-rays
- Early spectra show narrow emission lines (< 4 days)
- Our own follow-up campaign (CASLEO + LCOGT)

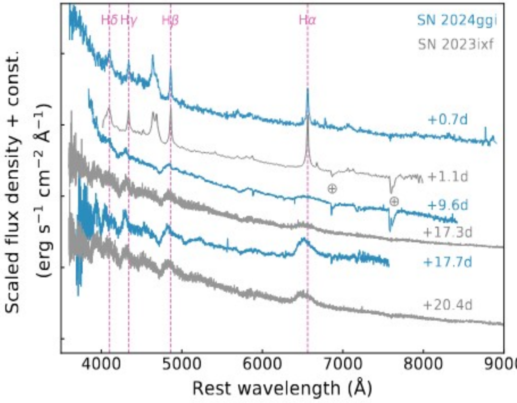
Srivastav+24, Zhai+24, Killestein+24,Hoogendam+24, Jacobson-Galán+24; Pessi+24,Chen+2024b; Shrestha+24, Zhang+2024b; Margutti &Grefenstette+24, yder+24, Chandra+24; Hu+24, Komura+24, Yang+24, Pérez-Fournon+24, Xiang+24, Hong+24 ,...





Ertini, Regna+25, submitted





Chen+24

Progenitor mass estimates of SN 2024ggi

- Archival pre-explosion imaging from HST and Spitzer – SED fitting

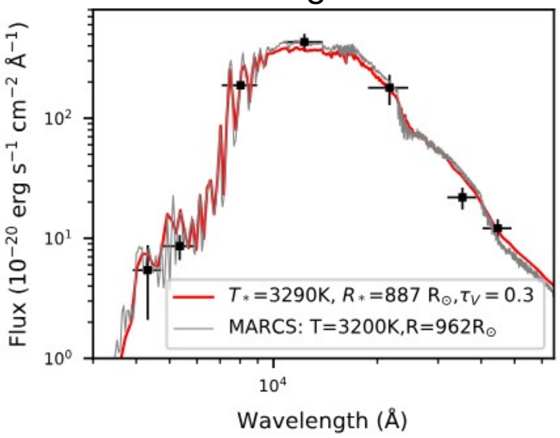
  ⇒ RSG variable star with M_{ZAMS} ~ 13 M☉

- Environmental studies: ⇒ young population M_{ZAMS} ~10 M☉

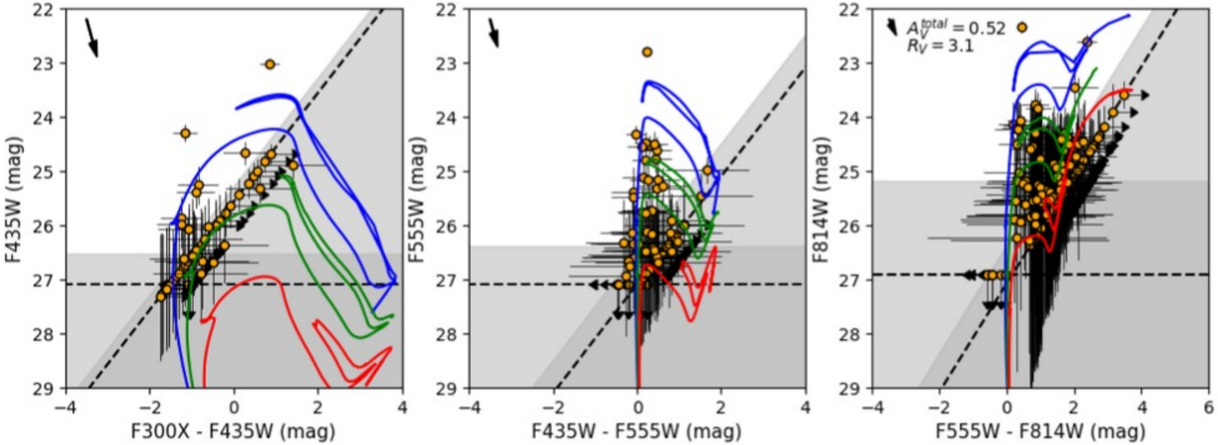
- Hydro modeling ⇒ M_{ZAMS} ~15 M☉ progenitor (see next slide)

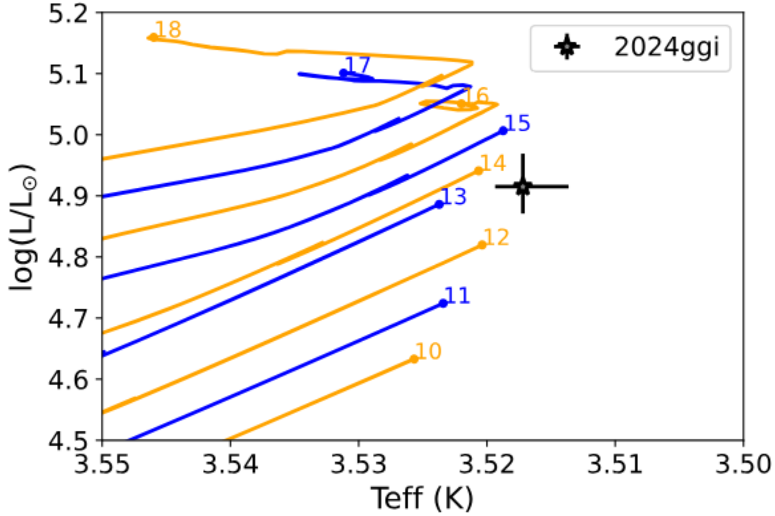
Better agreement with mass estimation

Xiang+24



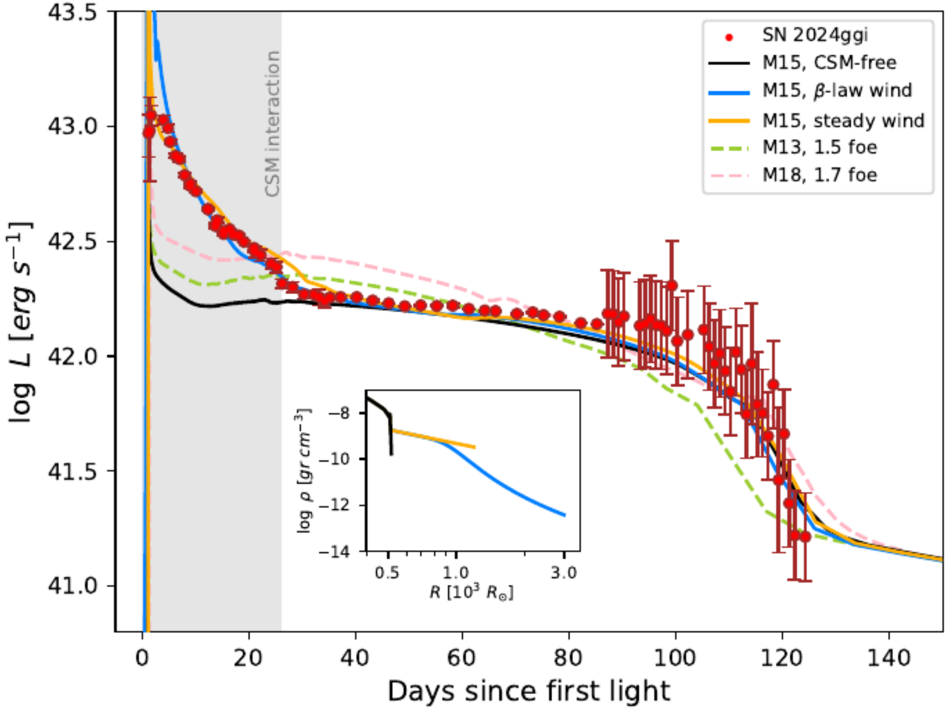
Hong+24

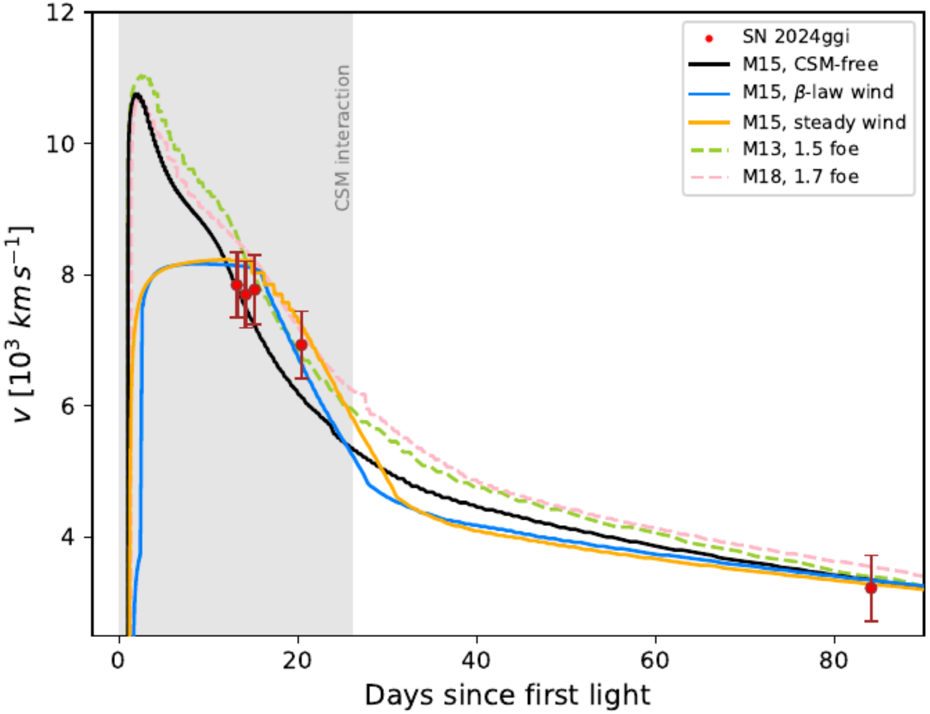




Hydro Models for SN 2024ggi

- Grid of hydro models: **M_{ZAMS} = 15 $M_\odot$; E = 1.2 foe, M_{Ni} = 0.035 $M_\odot$.**
  Lower and higher mass (M13 & M18) produce worse match to the data
- Our hydro models indicated an accelerated wind with **$\dot{M}$ = 4.6x10^{-3} $M_\odot$ yr^{-1}, Rcsm=3000 $R_\odot$, MCSM~0.5 $M_\odot$**
- Our CSM interaction models are consistent with the **duration of flash emission features**

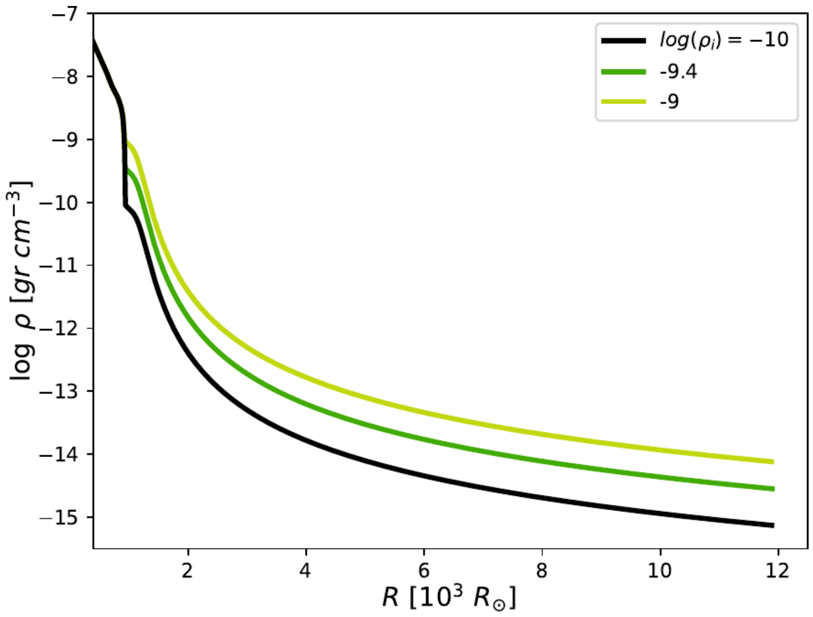


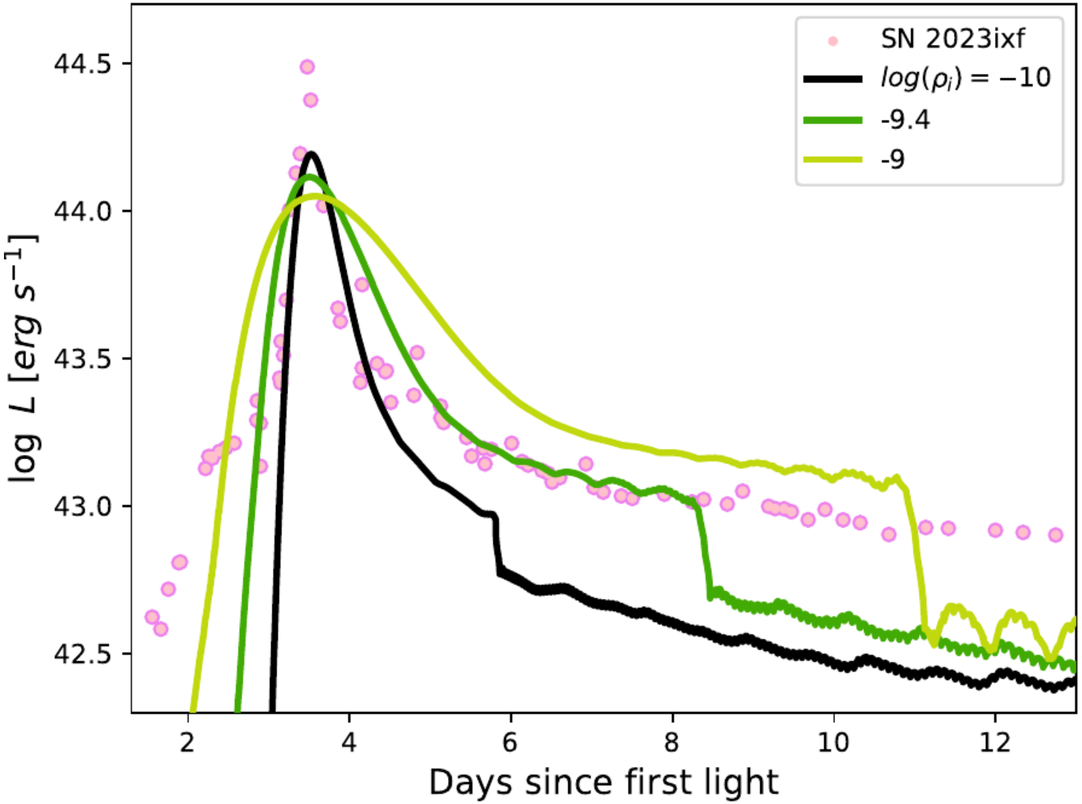


Ertini, Regna+25, sumitted

” Flat phase, continued interaction”, “sudden drop”

- Some models shows a “sudden drop” . Also present in other studies (Moriya+11, Dessart+17, Khatami & Kasen’24)
- Under what circumstances does it occur? What is the reason for this? Possible CSM constrains?

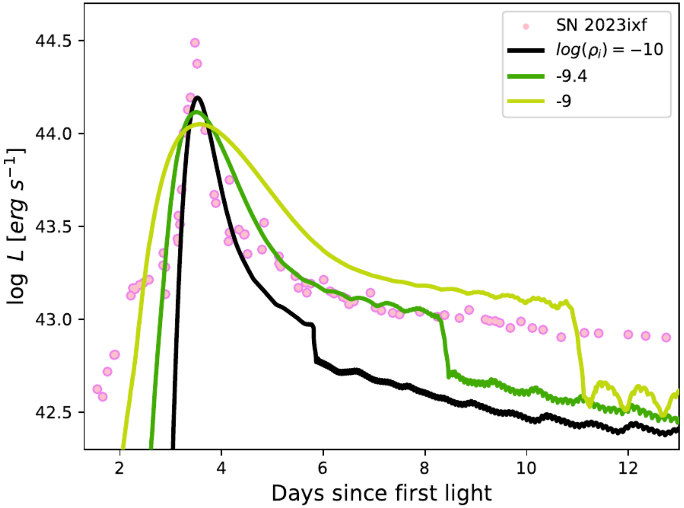




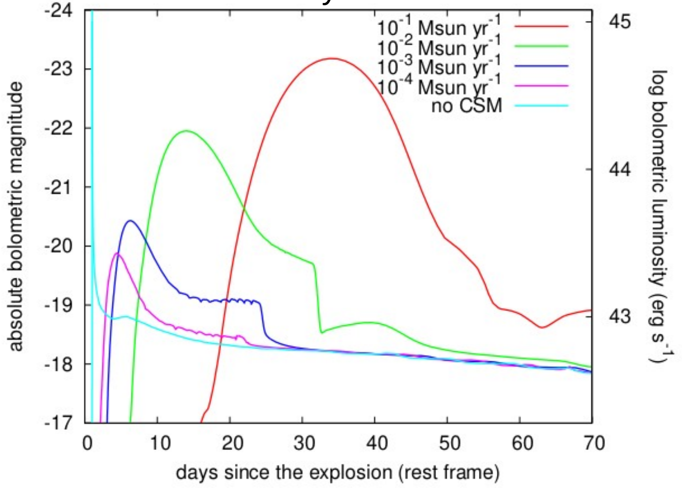
Regna, in prep

” Flat phass, continued interaction”, “sudden drop”

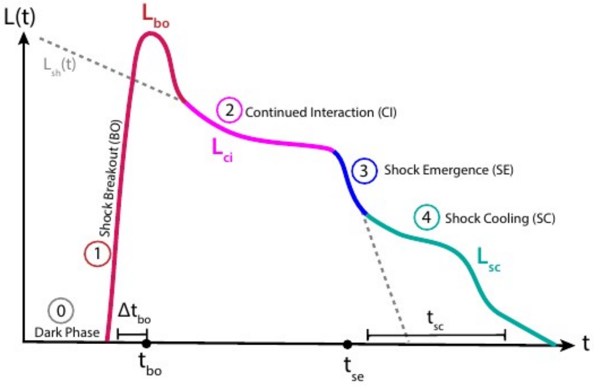
Regna, in prep



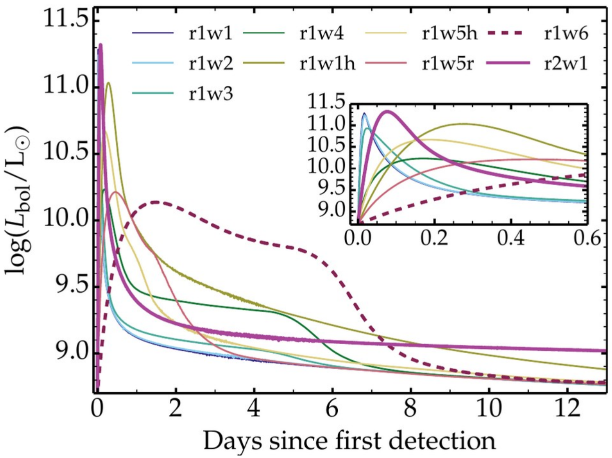
Moriya+11



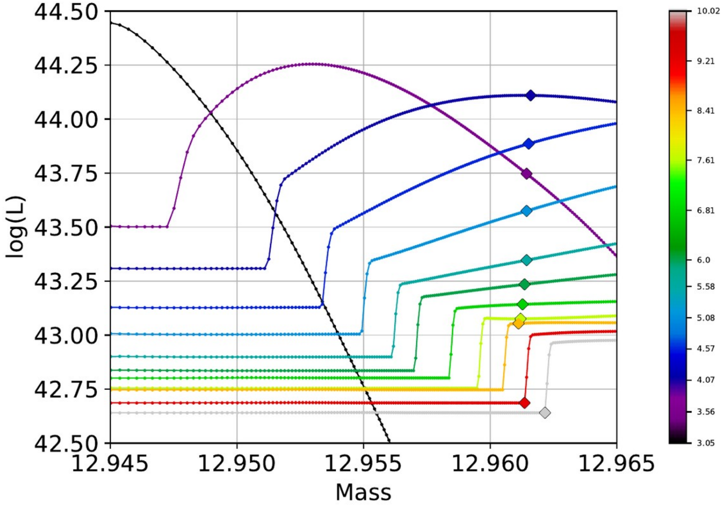
Khatami & Kasen 2024

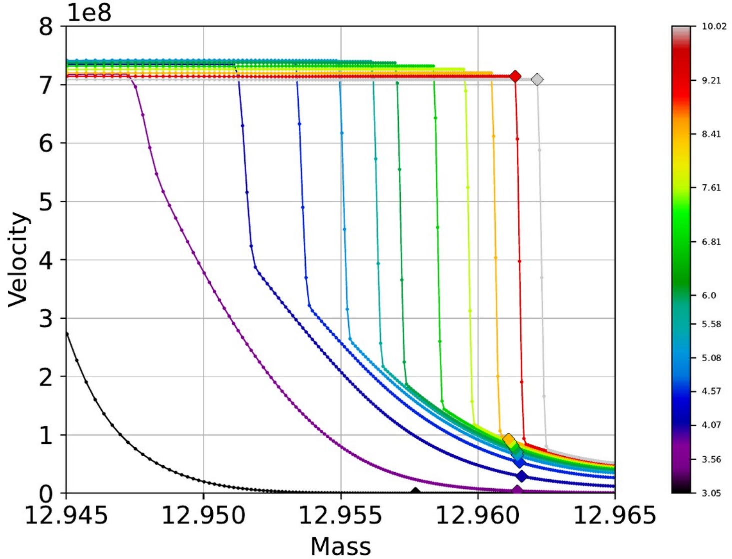


Dessart+17

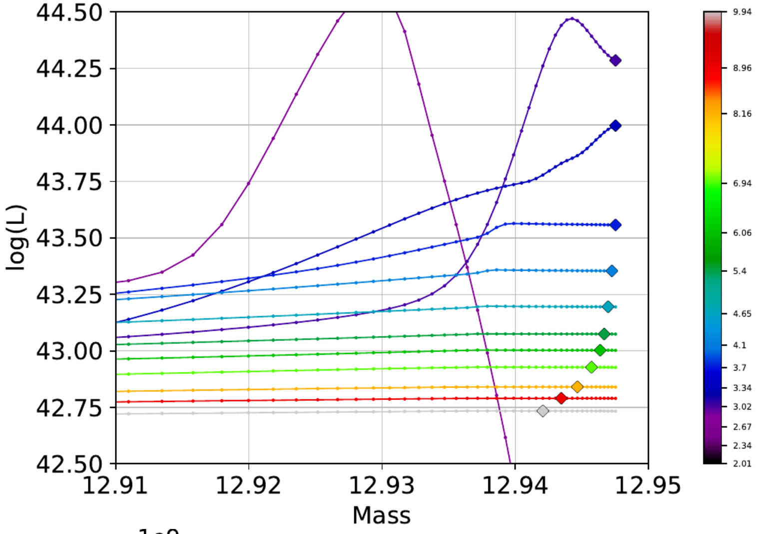


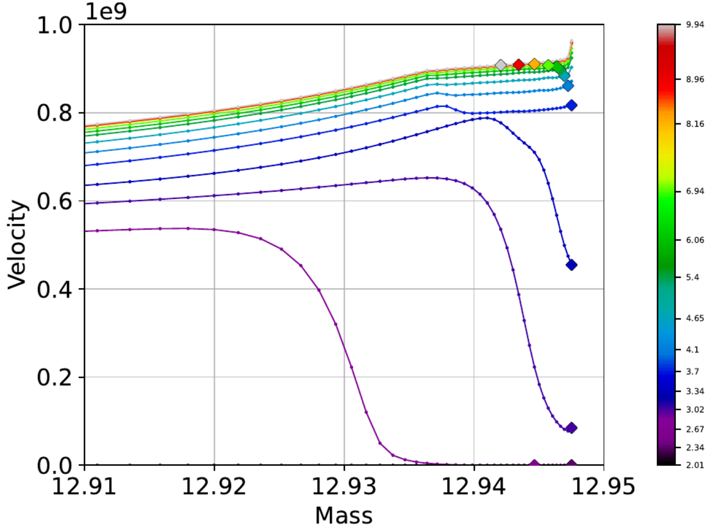
” Drop”





“Without drop”





Models with drop:

- Radiative precursor
- Delay between SBO and shock arrival
- Development of a low velocity region (narrow lines)

Regna, in prep

Summary

- **1D hydro** models useful to derive physical properties and to understand the underlying physical conditions

- The inferred progenitor mass of **SN 2023ixf** is highly uncertain (wide range of mass even using the same method)

- Low mass progenitor for **SN 2024ggi** (Mzams~10-13 Msun). Better agreement between different methods

- Early data of nearby SN: wealth of information about the mass-loss history

- Many interested featutes in the LC due to different CSM conditions