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大質量星の爆発間際の大規模な質量放出とその後の超新星の光度曲線の研究

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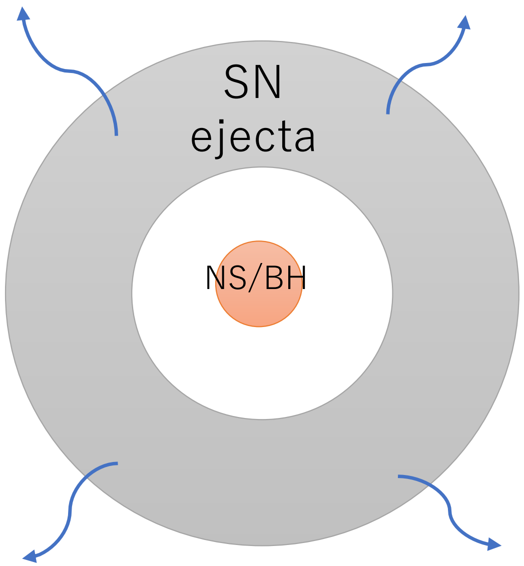
https://github.com/DTsuna/CHIPS

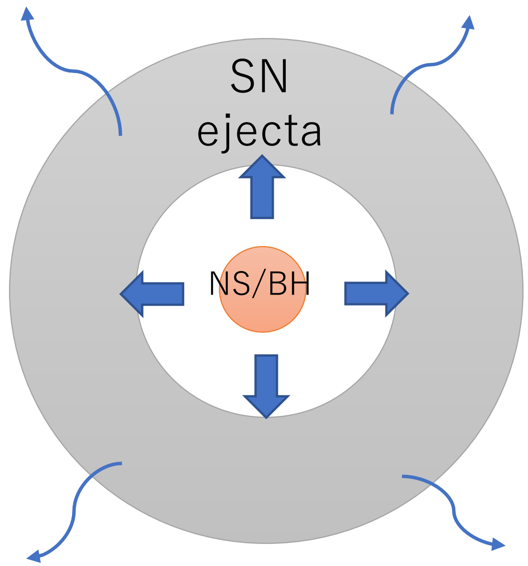
WHAT POWERS THE SUPERNOVAE?

Ejecta powered



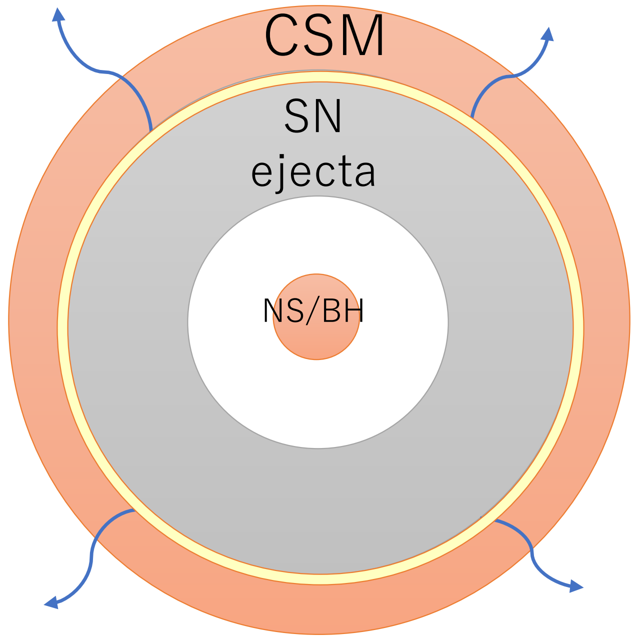
Internal energy/Ni56 inside SN ejecta (Type IIP/IIL, Type I)

Central engine powered



Energy injection to ejecta from inside. Powered by central compact object (Type I SLSN?)

Interaction powered



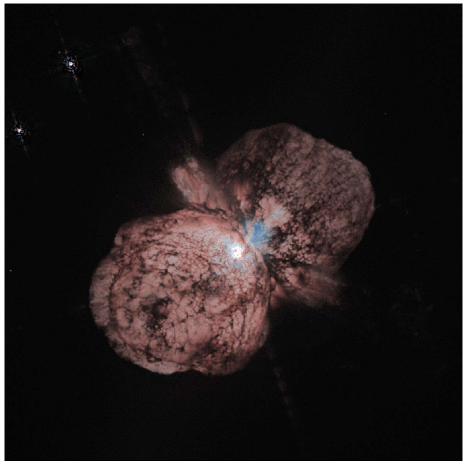
Collision of ejecta & “wall”. Powered by ejecta’s kinetic energy (SN IIn, Type II SLSN)

HOW TO MAKE DENSE CSM?

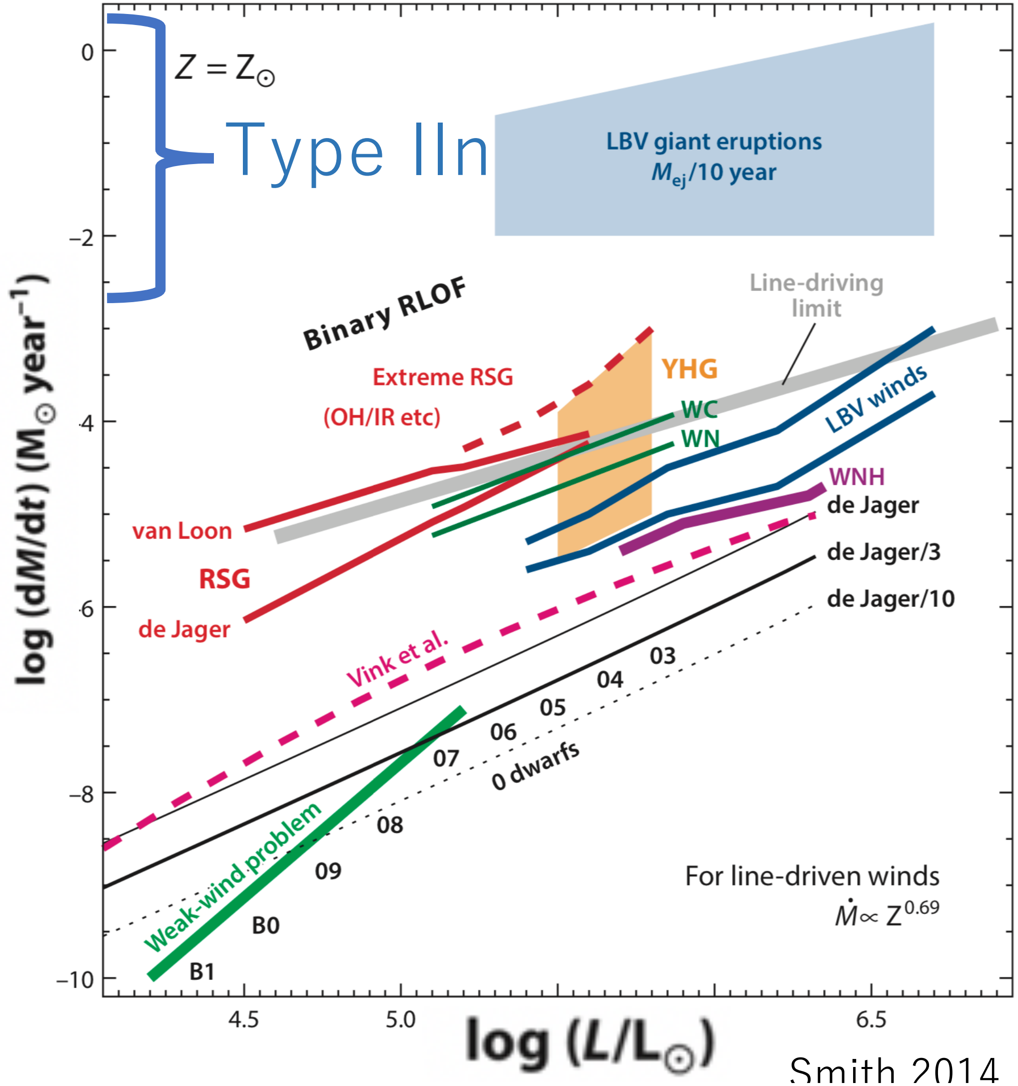
Standard “stellar wind” seen in massive stars: $\lesssim 10^{-4} M_{\odot}/\mathrm{yr}$

➢Too low to explain Type IIn

(LBV-like) mass eruption just before core-collapse?



https://en.wikipedia.org/wiki/Eta_Carinae

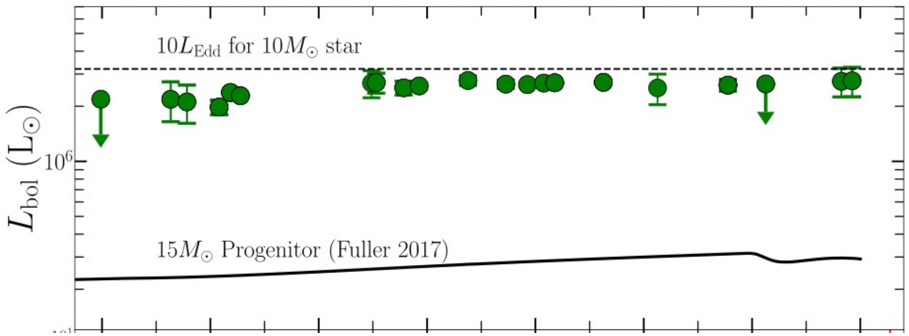


Smith 2014

SN 2020tlf

- Terminal explosion 130 days after mass eruption (~10^{40} erg/s) (Jacobson-Galán+22)
- ZAMS mass：10-12Msun
- RSG

観測の結果、爆発が起きた時点で恒星を取り巻く物質が存在していたことが判明。夏の間にこの恒星から激しく放出された明るいガスだった。



https://www.cnn.co.jp/fringe/35181793.html

MASS ERUPTION MODELING

- Kuriyama & Shigeyama 2020
- Inject energy at the base of the stellar envelope (~few 10 % of envelope's binding energy)
- Assume that the injected energy source is the nuclear burning.

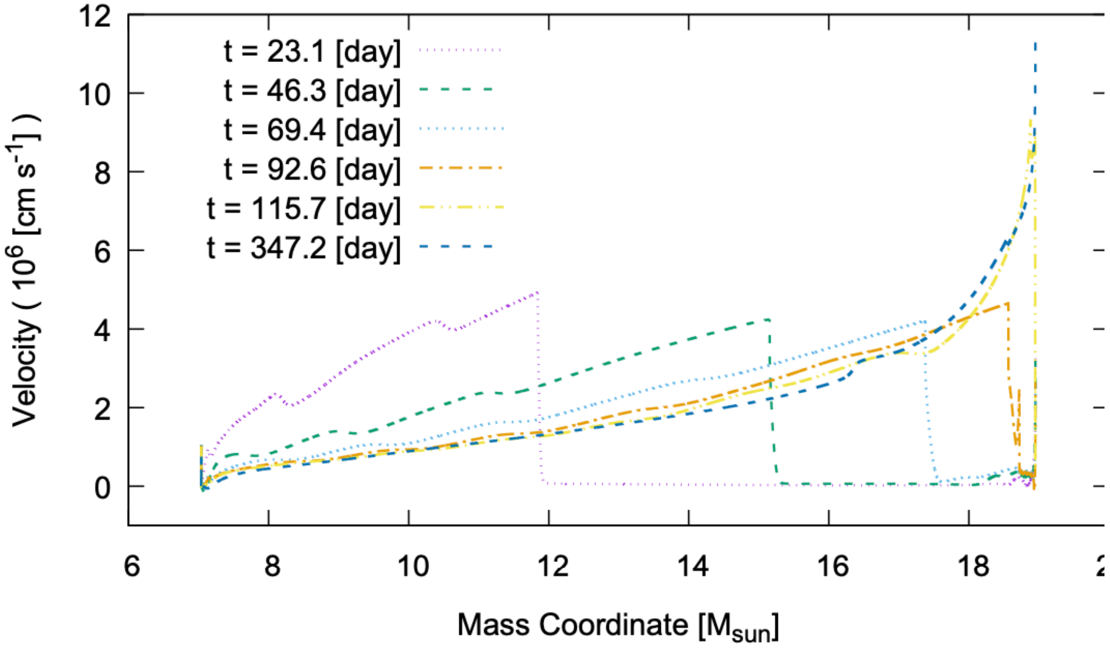
Table 2. Injected energies and duration of injection.

Model	Injected energy $E_{\rm inject}$	Duration of injection τ [s]
RSG1	0.8, 1.0, 1.2, 1.4, 1.6 [$\times 10^{47}$ erg]	700
RSG2	1.5, 2.0, 2.5, 3.0, 3.5 [$\times 10^{47}$ erg]	5000
BSG	5.0, 7.0, 10.0, 13.0 [$\times 10^{48}$ erg]	1.85×10^4
YSG	5.0, 7.0, 9.0, 11.0 [$\times 10^{46}$ erg]	2.84×10^5
WR1	1.0, 2.0, 3.0, 4.0 [$\times 10^{50}$ erg]	1
WR2	1.0, 2.0, 3.0, 4.0, 5.0 [$\times 10^{50}$ erg]	1

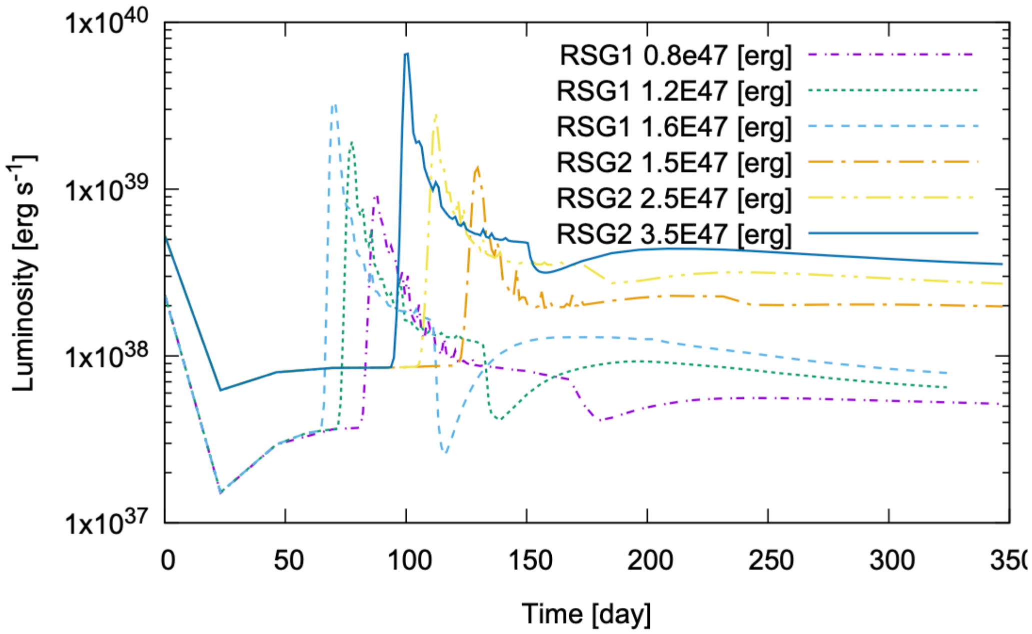
Table 1. Properties of SNe progenitors.

Model	$M_{\rm ZAMS}$	Z	R	$T_{\rm eff}$	$M_{\rm He\ core}$	$M_{\rm H\ env}$	$E_{\rm outer}$ $^{(a)}$	Time to CC	Burning stage	SN type $^{(b)}$
RSG1	$11 M_\odot$	0.02	$730 R_\odot$	3400 K	$3.9 M_\odot$	$6.1 M_\odot$	-2.2×10^{47} erg	10 yr	Ne burning	IIn
RSG2	$20 M_\odot$	0.02	$1085 R_\odot$	3500 K	$6.3 M_\odot$	$12.7 M_\odot$	-4.7×10^{47} erg	0.8 yr	Ne burning	IIn
BSG	$15 M_\odot$	2×10^{-4}	$58 R_\odot$	11000 K	$3.7 M_\odot$	$10.3 M_\odot$	-1.9×10^{49} erg	8 yr	Ne burning	IIn
YSG	$50 M_\odot$	0.01	$1380 R_\odot$	4700 K	$20.6 M_\odot$	$0.5 M_\odot$	-3.1×10^{46} erg	10 yr	C burning	IIn
WR1	$50 M_\odot$	0.01	$0.7 R_\odot$	220000 K	$19.8 M_\odot$	$-^{(c)}$	-5.3×10^{50} erg	0.5 yr	C burning	Ibn
WR2	$50 M_\odot$	0.01	$0.6 R_\odot$	240000 K	$19.8 M_\odot$	$-^{(c)}$	-6.0×10^{50} erg	15 day	C burning	Ibn

MASS ERUPTION MODELING



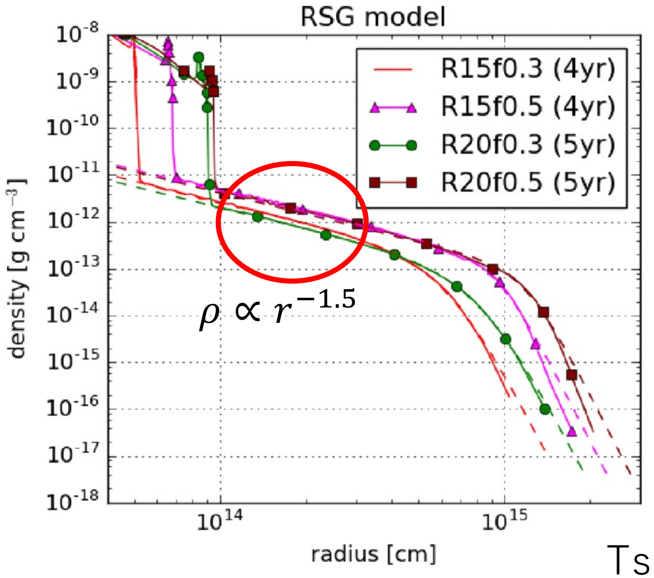
Shock propagation in stellar envelope

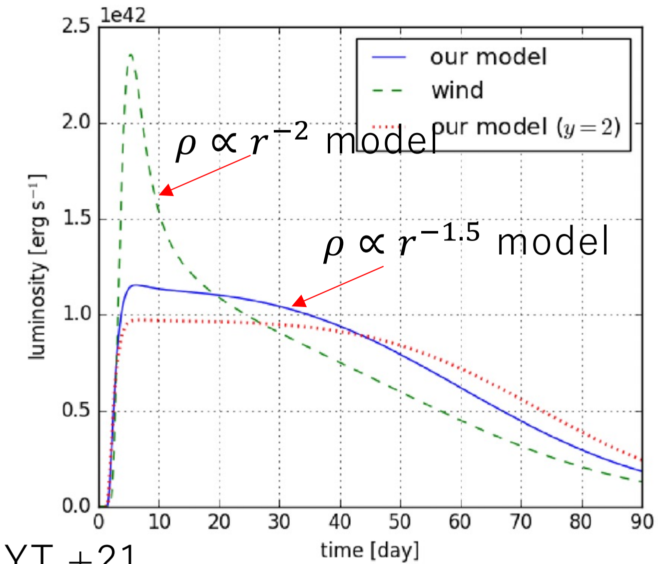


Light curve of precursor

WHY IIN LC MODELING?

- Most of previous studies focus on SNe IIn interacting with dense CSM whose density profile is proportional to r^{-2} (steady wind) or single power-law profile (e.g. Moriya+11, Chevalier & Irwin 11, Chatzopoulos+12, Ginzburg & Balberg 12, Moriya+13, Tsuna+19, Takei & Shigeyama 20, Suzuki+20…)
- CSM density structure affects the light curve (right figure)
- More realistic modeling of CSM leads to better understanding of SNe IIn.





Tsuna, YT,+21

CHIPS PROJECT

YT, Tsuna, Kuriyama, Ko, Shigeyama

https://github.com/DTsuna/CHIPS

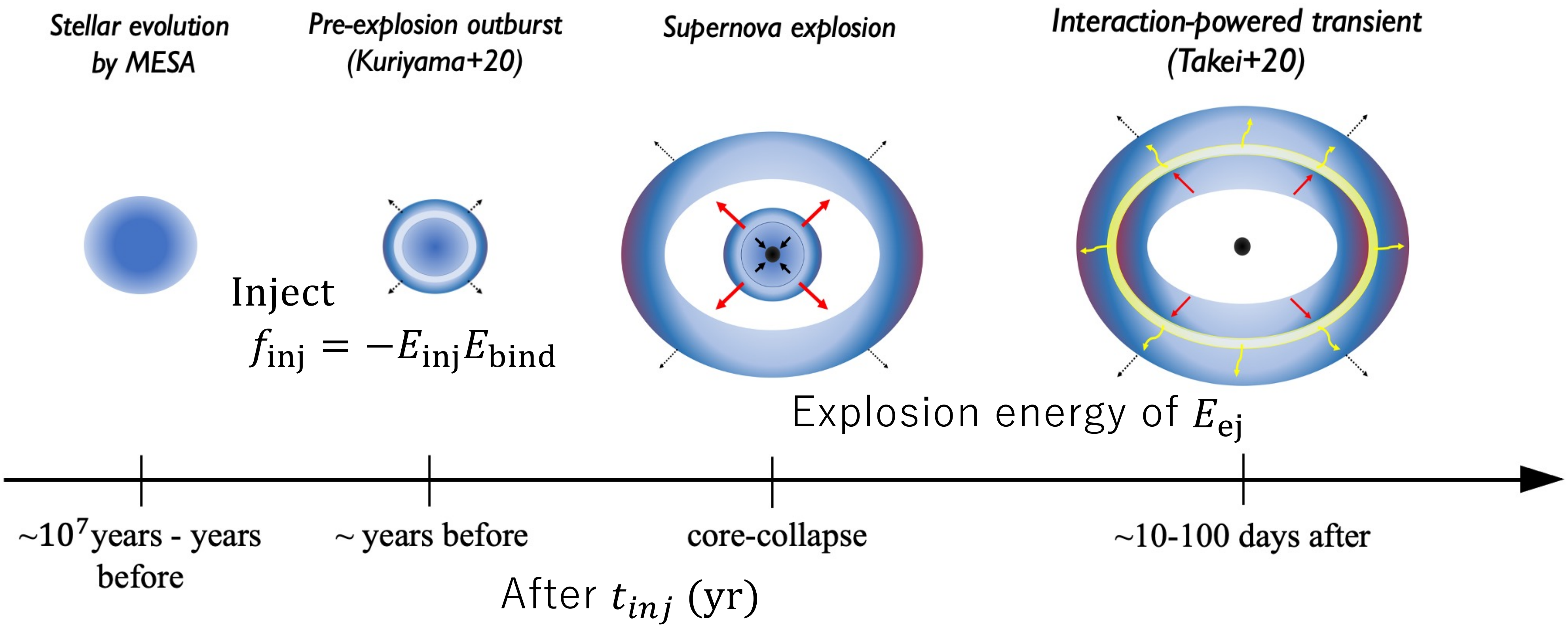
Open-source code aimed to unveil the
Complete History of Interaction-Powered Supernovae

PARAMETERS

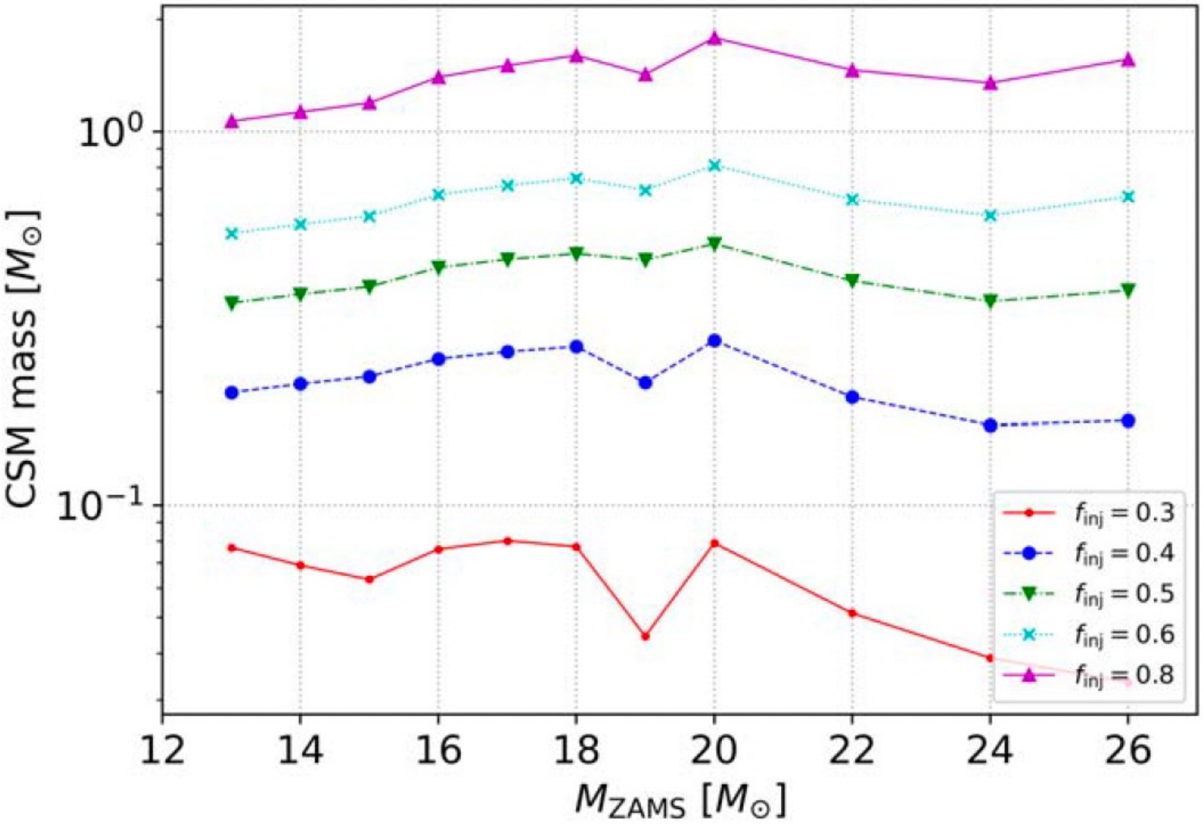
CHIPS

- M ($M_{\odot}$): Initial mass (we have sample models of 13, 14, ⋯, 26 solar masses)
- f_{inj}: Energy injected at the base of the stellar envelope, scaled with the envelope's binding energy (order of 0.1-1)
- t_{inj} (yr): Time from energy injection to core-collapse
- E_{ej} (ergs): Explosion energy of supernova

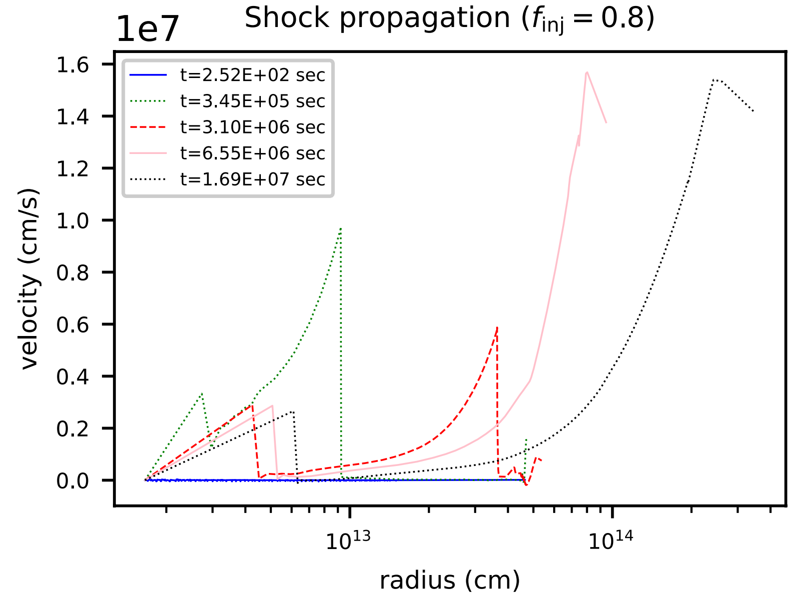
PARAMETERS

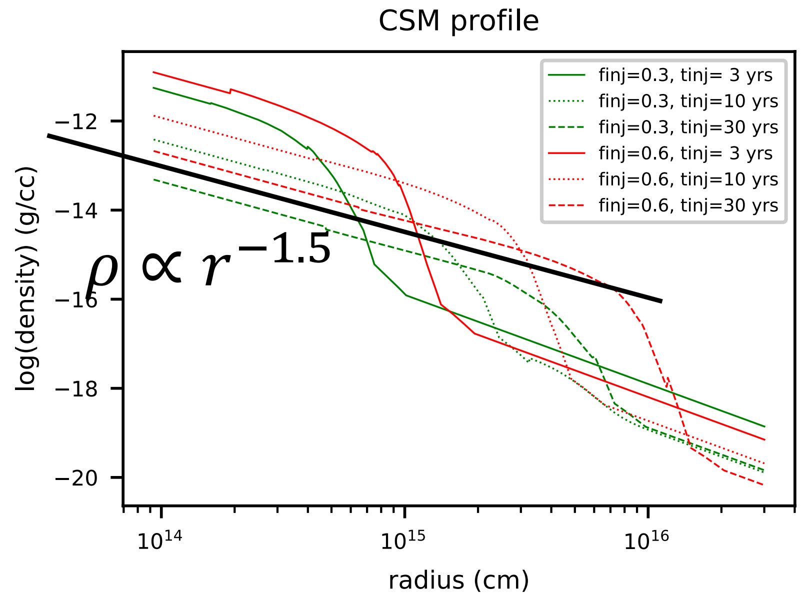

Stellar evolution by MESA
Pre-explosion outburst (Kuriyama+20)
Supernova explosion
Interaction-powered transient (Takei+20)
Inject
$f_{\rm inj} = -E_{\rm inj} E_{\rm bind}$
Explosion energy of $E_{\rm ej}$
~10^7 years - years before
~ years before
core-collapse
~10-100 days after
After t_{inj} (yr)

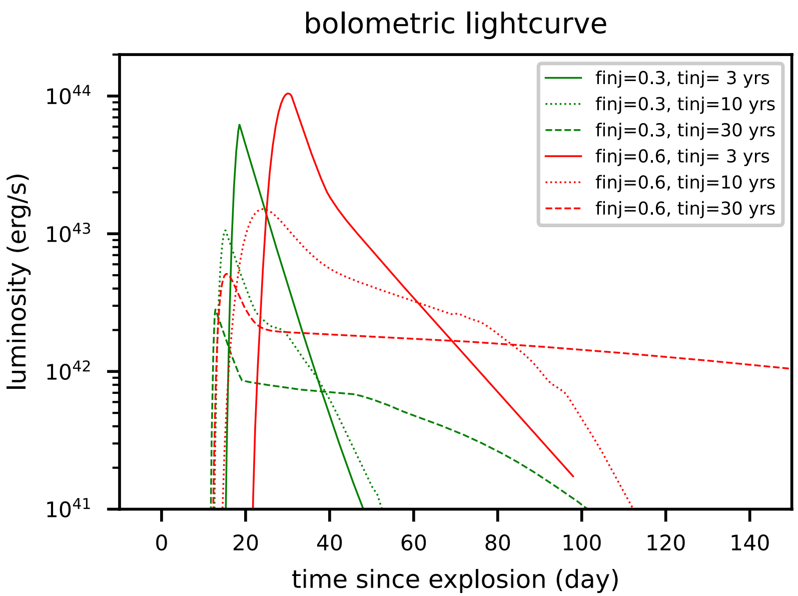
CSM MASS


CSM mass [$M_\odot$]
10^0
10^{-1}
12
14
16
18
20
22
24
26
M_{ZAMS} [$M_\odot$]
$f_{inj} = 0.3$
$f_{inj} = 0.4$
$f_{inj} = 0.5$
$f_{inj} = 0.6$
$f_{inj} = 0.8$

$15M_\odot$
model

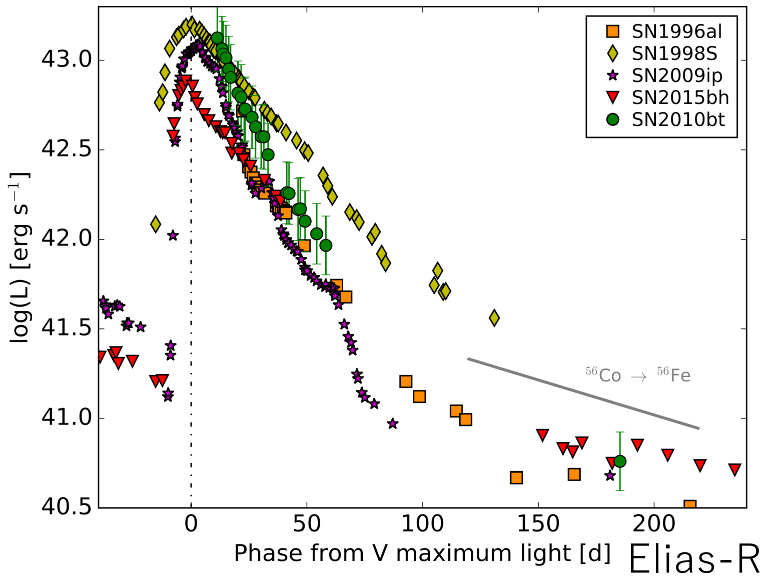




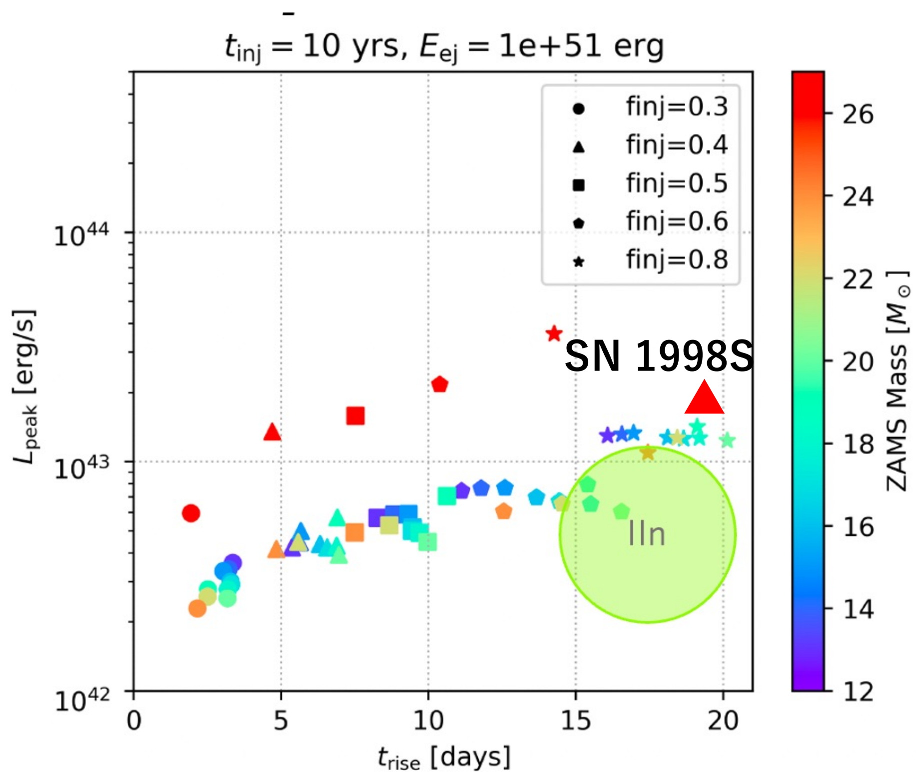


COMPARISON WITH OBSERVATION

- SN 1998S
- t_{rise}~20 days, L_{peak}~$2{\times}10^{43}$erg/s
- Corresponding parameter space:
  - ➢ $E_{\text{ej}} \sim 10^{51}$erg, $t_{\text{inj}} \sim 10$ yrs, $f_{\text{inj}} \sim 0.8$



Elias-Rosa+18



COMPARISON WITH OBSERVATION

- $f_{inj} = 0.7, t_{inj} = 11\,\mathrm{yr}, E_{ej} = 2.5\times10^{51}\mathrm{erg}, M_* = 20M_\odot$
- Well reproduce each light curve (*BVR*, bolometric)
- Tail: radioactive decay of ^{56}Co with mass of 0.15Msun
- Large explosion energy → large nickel mass (Hamuy 2003)

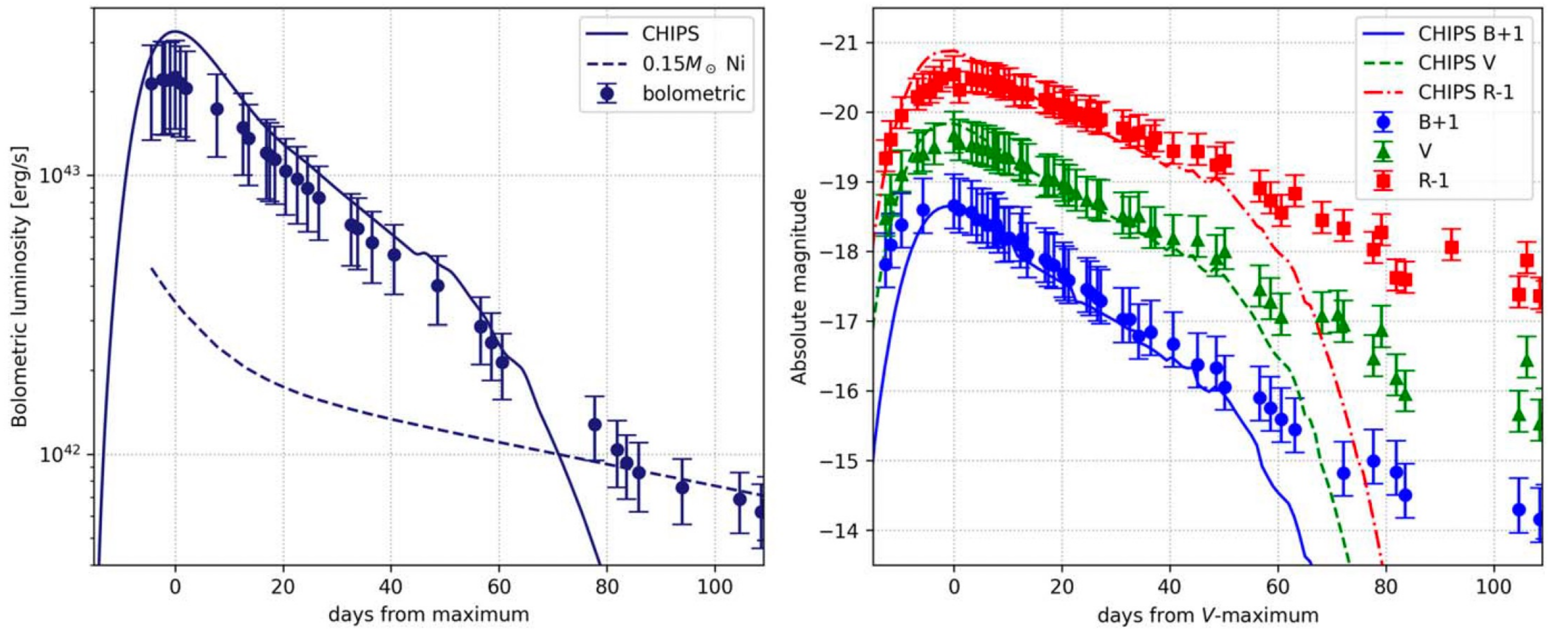
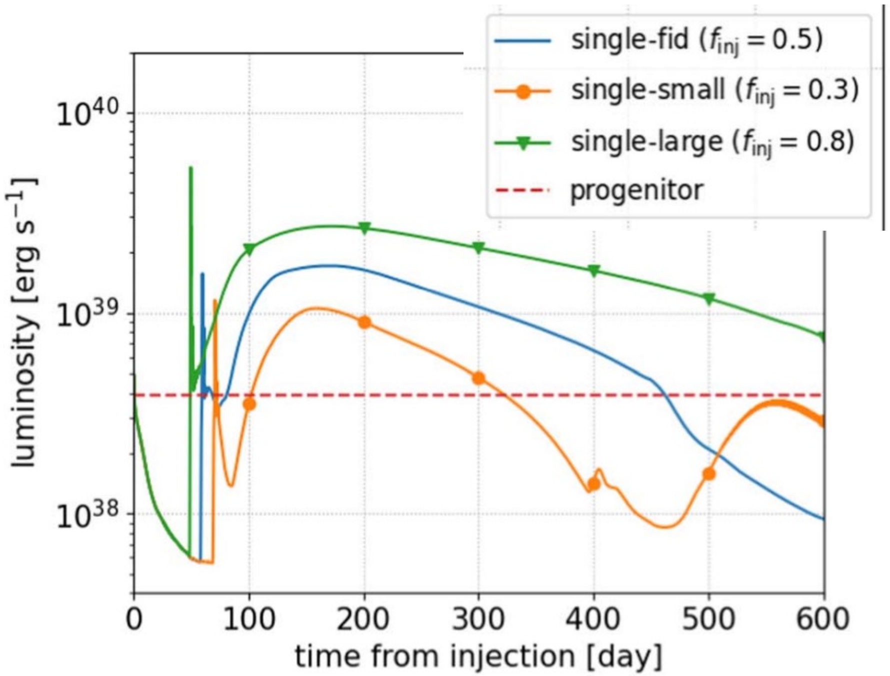


Figure 13. Left-hand panel: Comparison of the bolometric LC of SN 1998S with that of a CHIPS model. The dashed line shows the luminosity of ^{56}Ni and ^{56}Co. Right-hand panel: Comparison of the multiband (B, V, R) LCs with those of a CHIPS model. The data are corrected for extinction using the color excess

PRECURSOR LIGHT CURVE

- 1D radiation hydrodynamics simulation with CHIPS including H/He ionization calculation (Tsuna, YT, Shigeyama 2022)



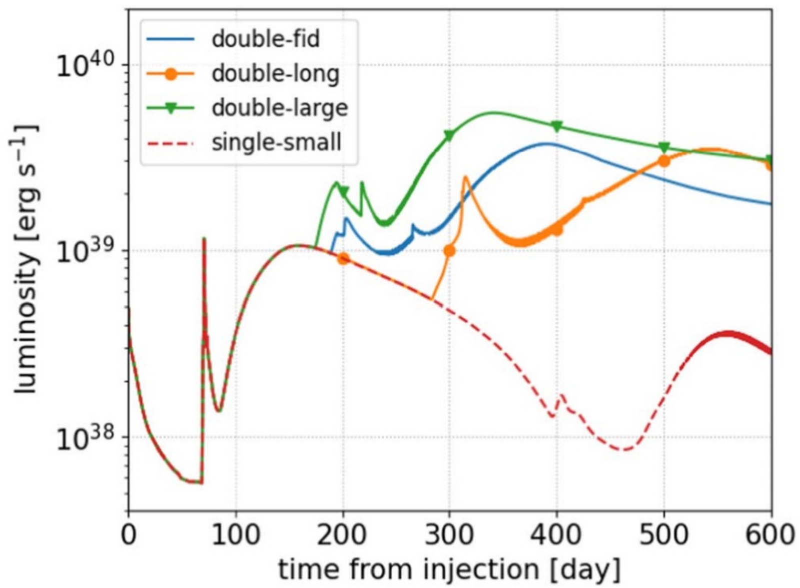
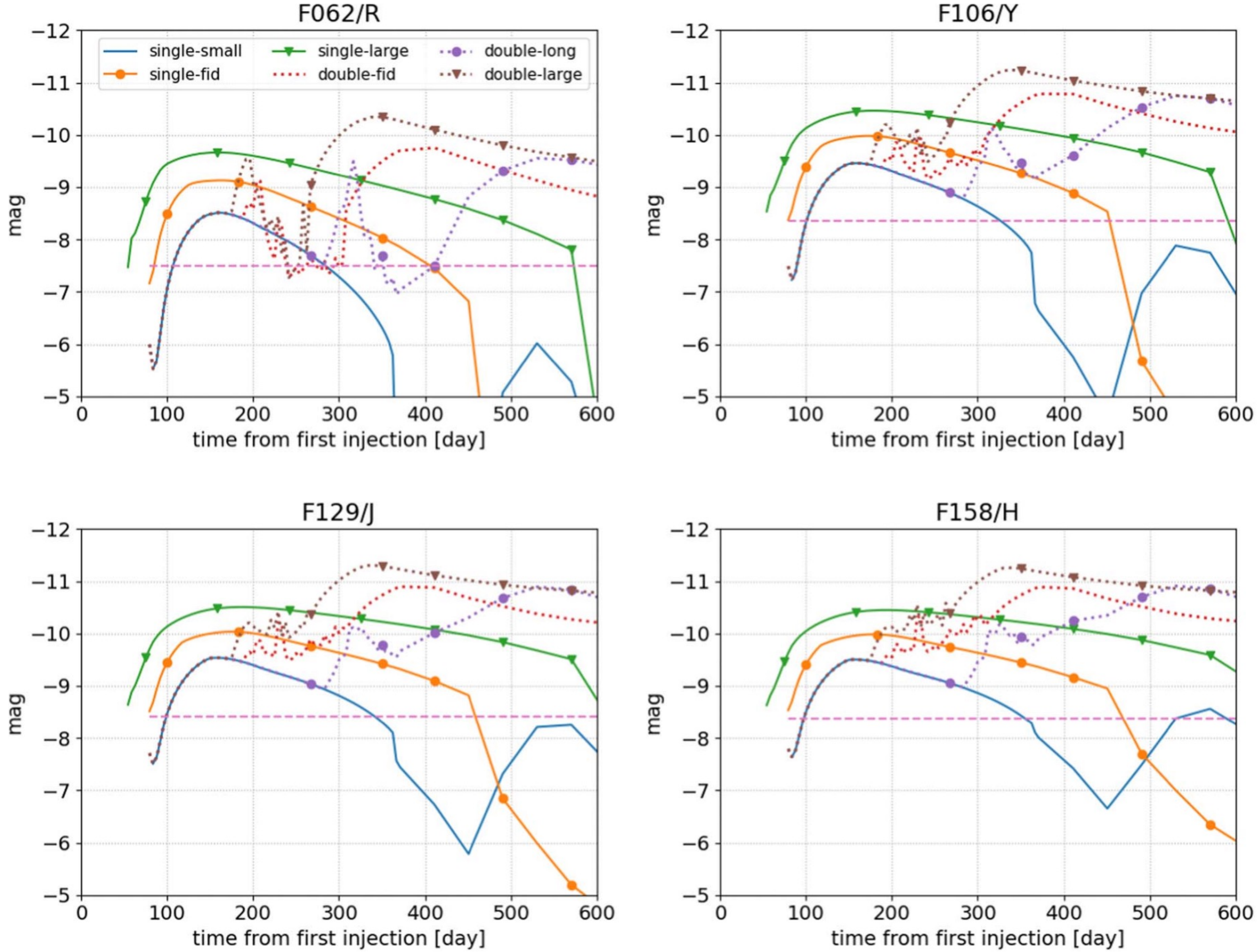
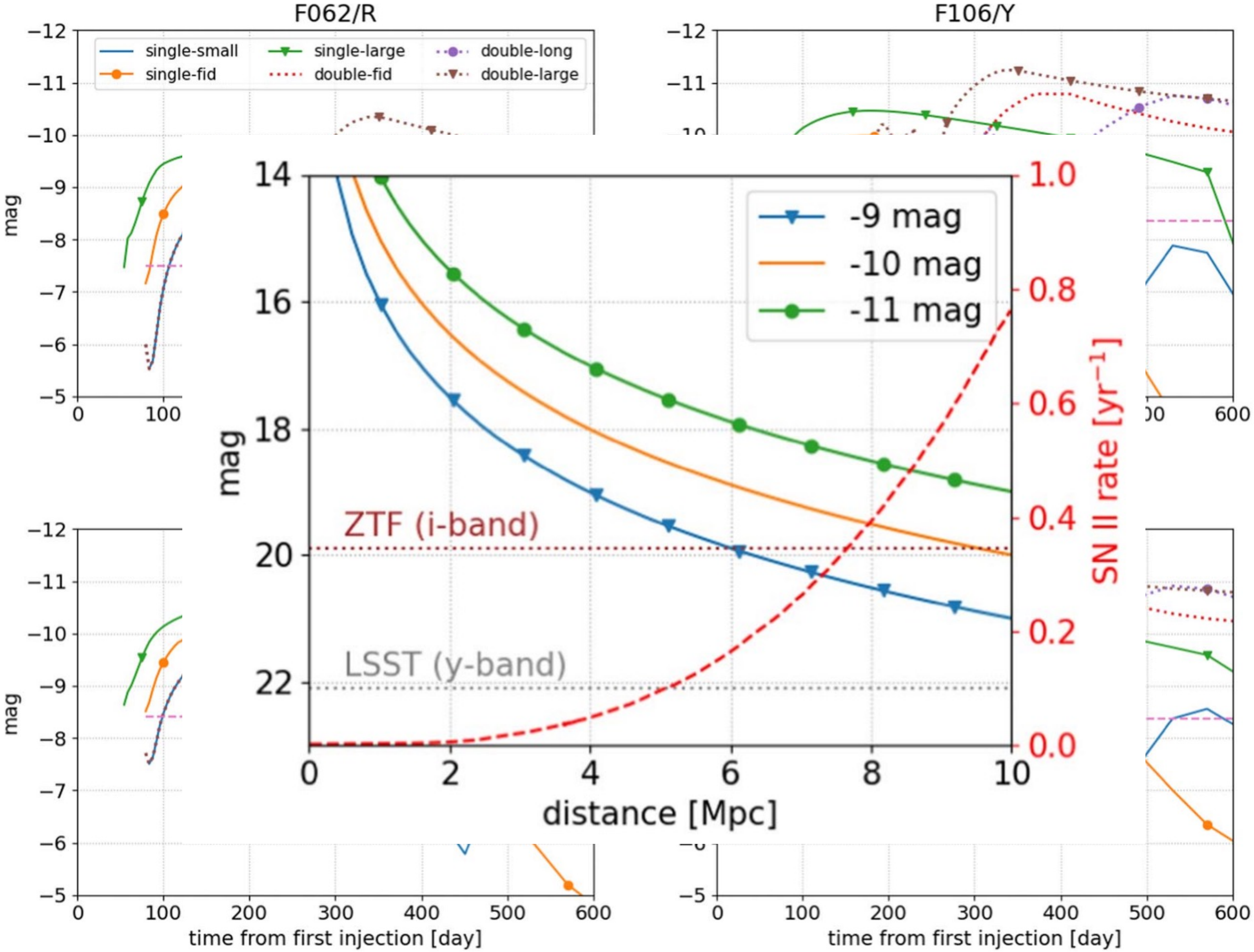


Figure 5. Bolometric light curves for models with two energy injections. The dashed line shows the $f_{inj} = 0.3$ model in Figure 3.



F062/R
F106/Y
F129/J
F158/H
single-small
single-fid
single-large
double-fid
double-long
double-large
mag
time from first injection [day]


F062/R
F106/Y
single-small
single-fid
single-large
double-fid
double-long
double-large
mag
time from first injection [day]
-9 mag
-10 mag
-11 mag
ZTF (i-band)
LSST (y-band)
SN II rate [yr^{-1}]
distance [Mpc]

Summary

- Previous works focus on simple CSM density profile of $\rho \propto r^{-s}$
- Some massive stars are known to experience mass eruption(s), which forms dense CSM.
- CHIPS code simulates both the creation of CSM from mass eruption and subsequent SN light curve (**https://github.com/DTsuna/CHIPS**).
- We can reproduce LC features of interaction-powered transients by CHIPS.

Future work

- Spectral modeling (Ishii, YT+, in prep.)
- Expand CHIPS code to Ibn modeling (YT+, in prep.)