3D Hydrodynamical Simulations of Ejecta-Companion Interaction for Type Iax Supernovae

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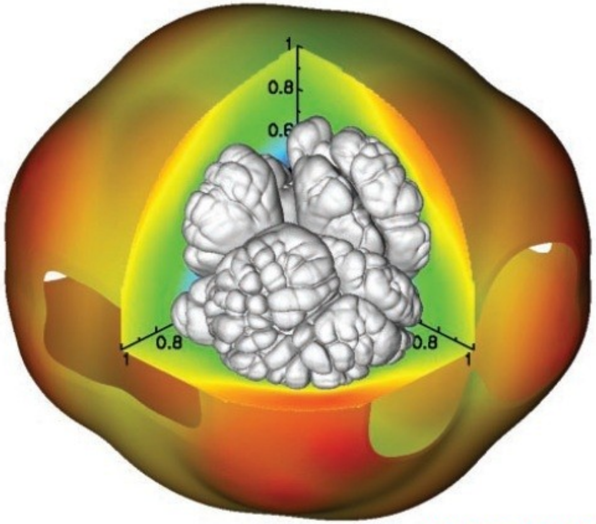
Contents

1.Introduction

What we know about SN Ⅰa？

- **Thermonuclear explosion**
- **Mass of the WD ~ 1.4 $M_\odot$**

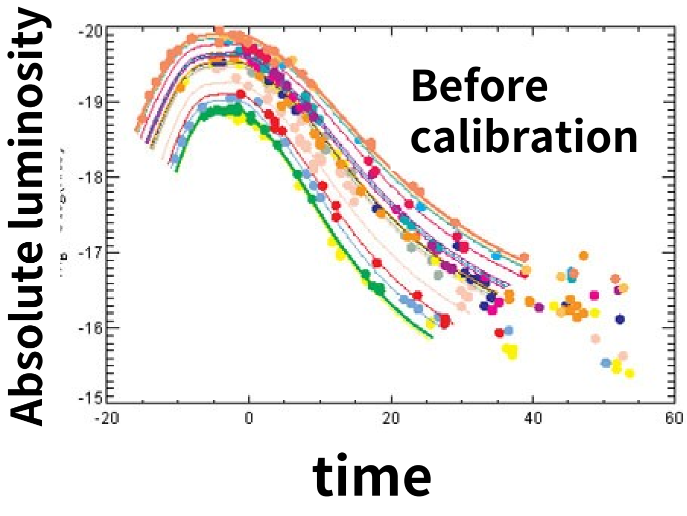


Gamezo et al. (2003)

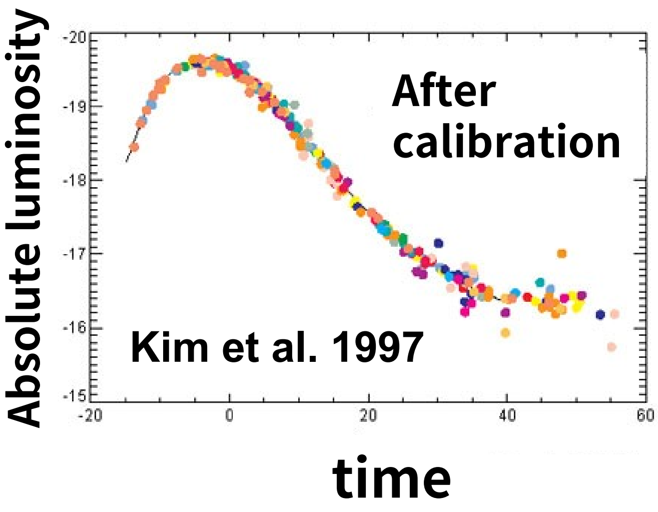
What we still not know about SN Ⅰa？

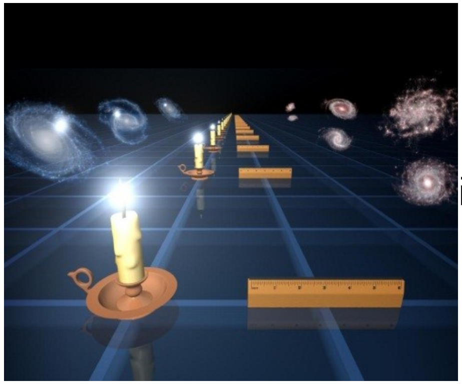
- ✓ **The progenitor system？**
- ✓ **The explosion mechanism？**

The importance of SN Ⅰa

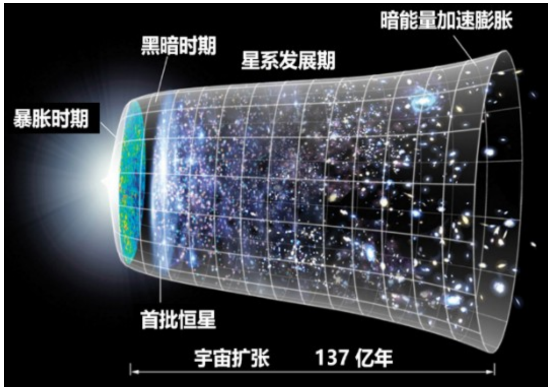


Phillips relationship

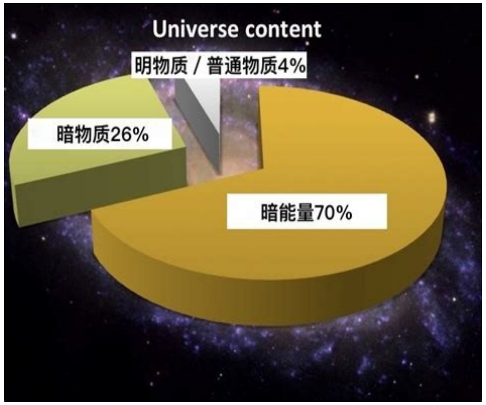




Standard candles



Accelerating



Dark energy

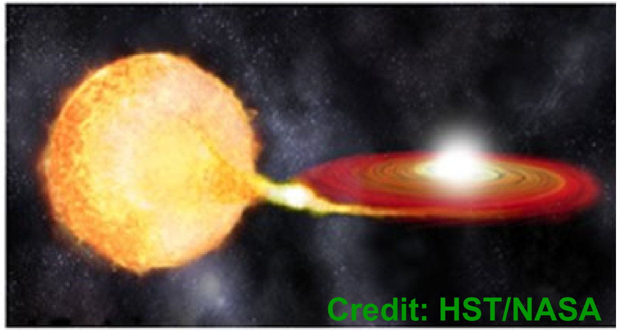
the Nobel Prize in Physics 2011

Progenitor model

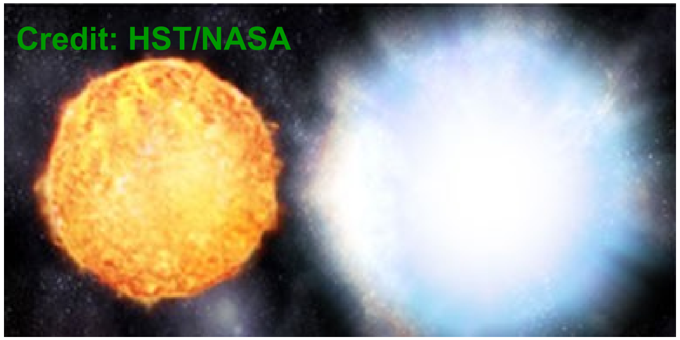
- **Single-degenerate (SD) model**

(Whelan & Iben 1973; Nomoto 1982; Han & Podsiadlowski 2004…)

degenerate star	non-degenerate star
CO WD +	MS SG He star RG



Accreting mass



Progenitor model

- **Double-degenerate (DD) model**

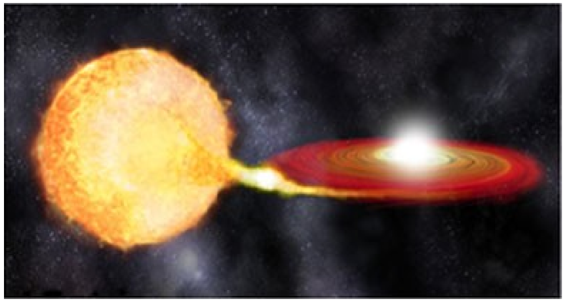
(Iben & Tutukov 1984; Webbink 1984…)

degenerate star **degenerate star**

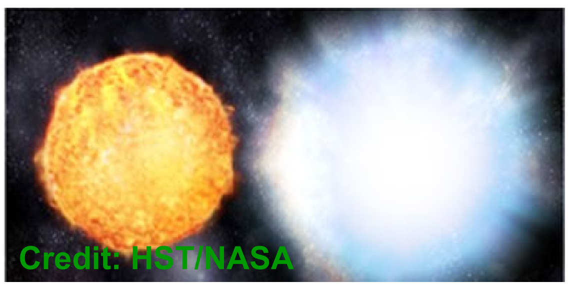
WD + WD

Merger →

SD model:

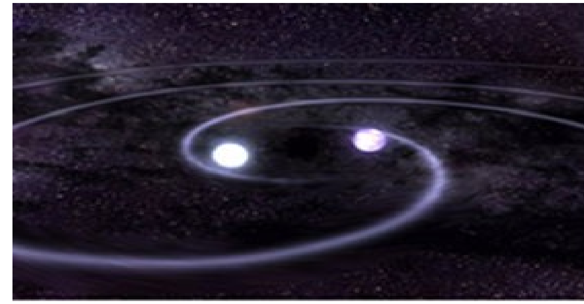


Bright source

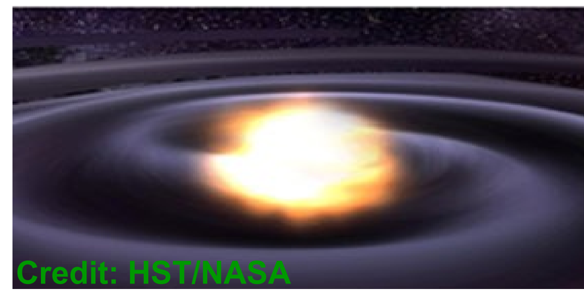


Surviving companion star

DD model：



No Bright source



No surviving companion star

Searching { Bright source / Surviving companion star } → SD? DD?

SN Iax

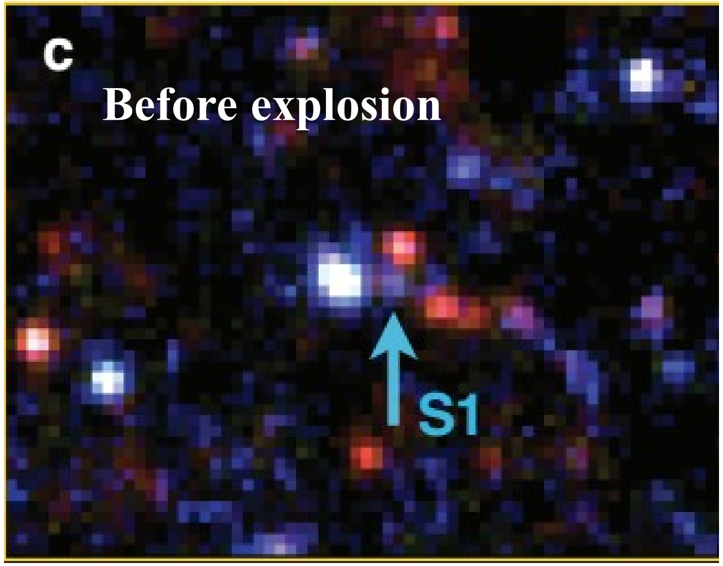
	Normal Ia	Iax
Peak luminosity	~ -19.3 mag	-14.2 ~ -18.4 mag
Explosion energy	~ 10^{51} erg	~ 10^{50} erg
Ejecta velocity	~ 10^4 km/s	2000 ~ 8000 km/s
Ejecta mass	~ 0.7 $M_\odot$	0.15 ~0.5 $M_\odot$

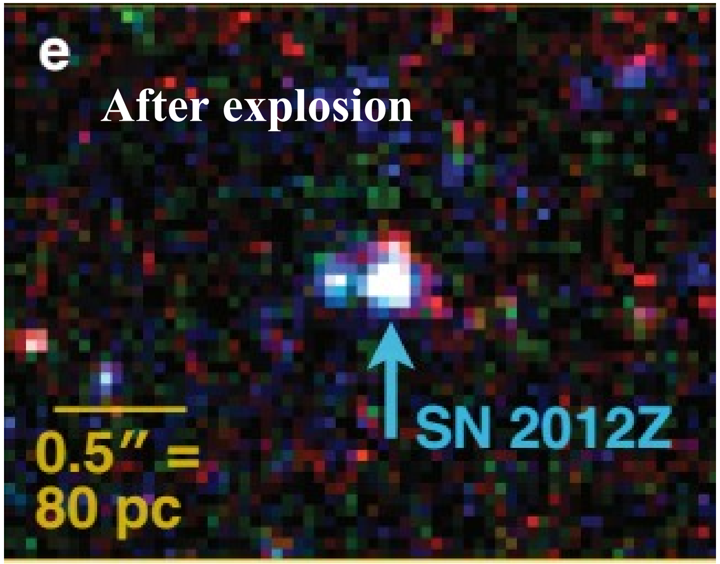
(Foley et al. 2013)

Three observations suggest a SD progenitor system for SN Iax

- Bright source : SN 2012Z
  (McCully et al. 2014)
- He lines in early-time spectra : 2004cs, 2007J
  (Jacobson-Galan et al. 2019)
- Short delay time (<100Myr)
  (Foley et al. 2009; Lyman et al. 2013, 2018)

Bright source



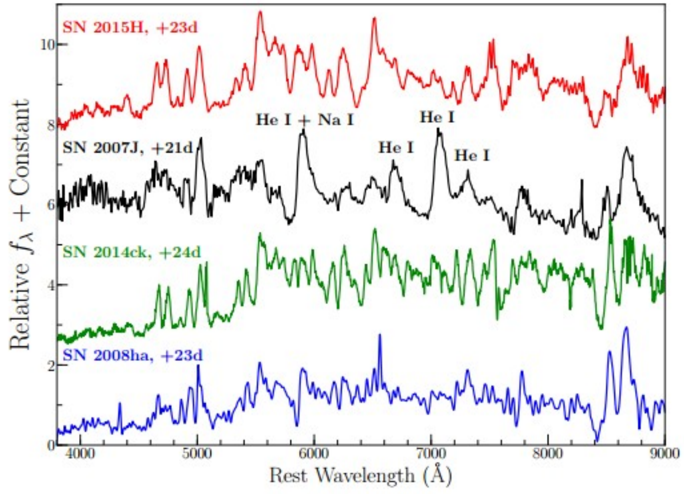


(McCully et al. 2014. Nature)

↓

WD + He star

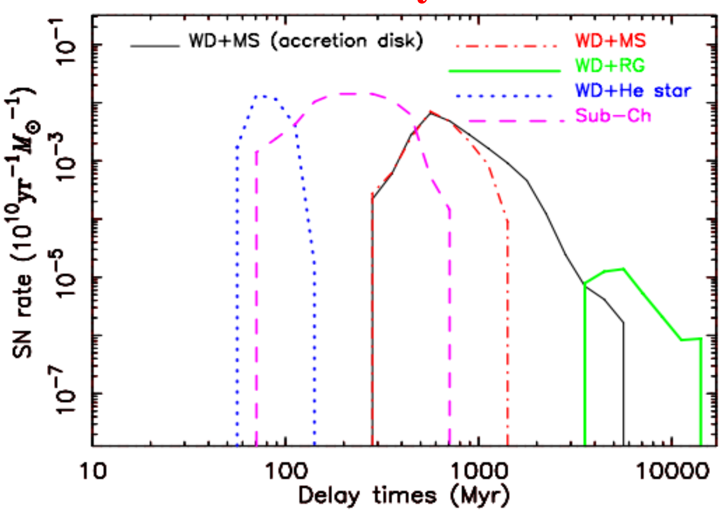
He line in SN 2007J



(Jacobson-Galan et al. 2019)

→ **WD + He star**

Short delay time



(Liu et al. 2015； see also Wang et al 2013)

+ **Short delay time (<100Myr)**

(Foley et al. 2009; Lyman et al. 2013, 2018)

↓

WD + He star

2.Simulation models

If SN Iax is from WD + He star channel

Question：

(1) **Ejecta VS the Companion star?**

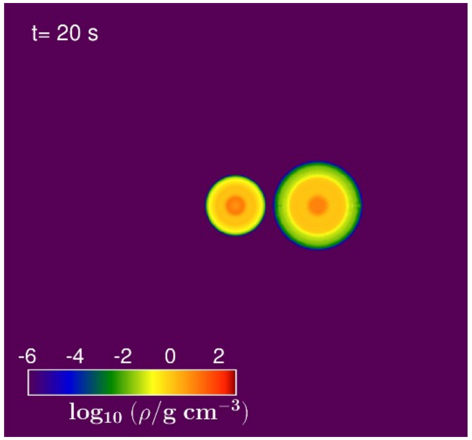
(2) **Surviving companion star?**

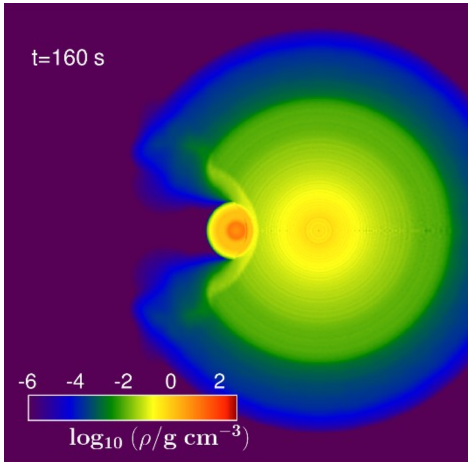
◆ **To Simulate SN ejecta impact He star**

Progenitor model ： CO WD + He star

Explosion model ： a weak deflagration

(N5def in Kromer et al. 2013)

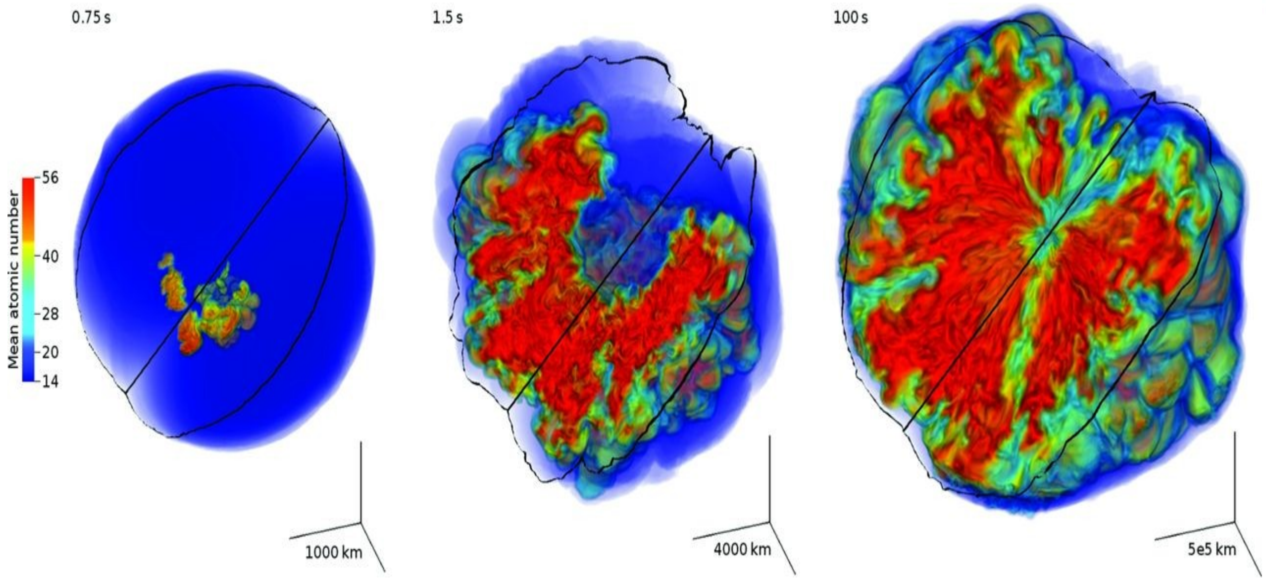




Liu et al. (2012, 2013)

N5def Model

(Kromer et al. 2013)



The hydrodynamic evolution of N5def model

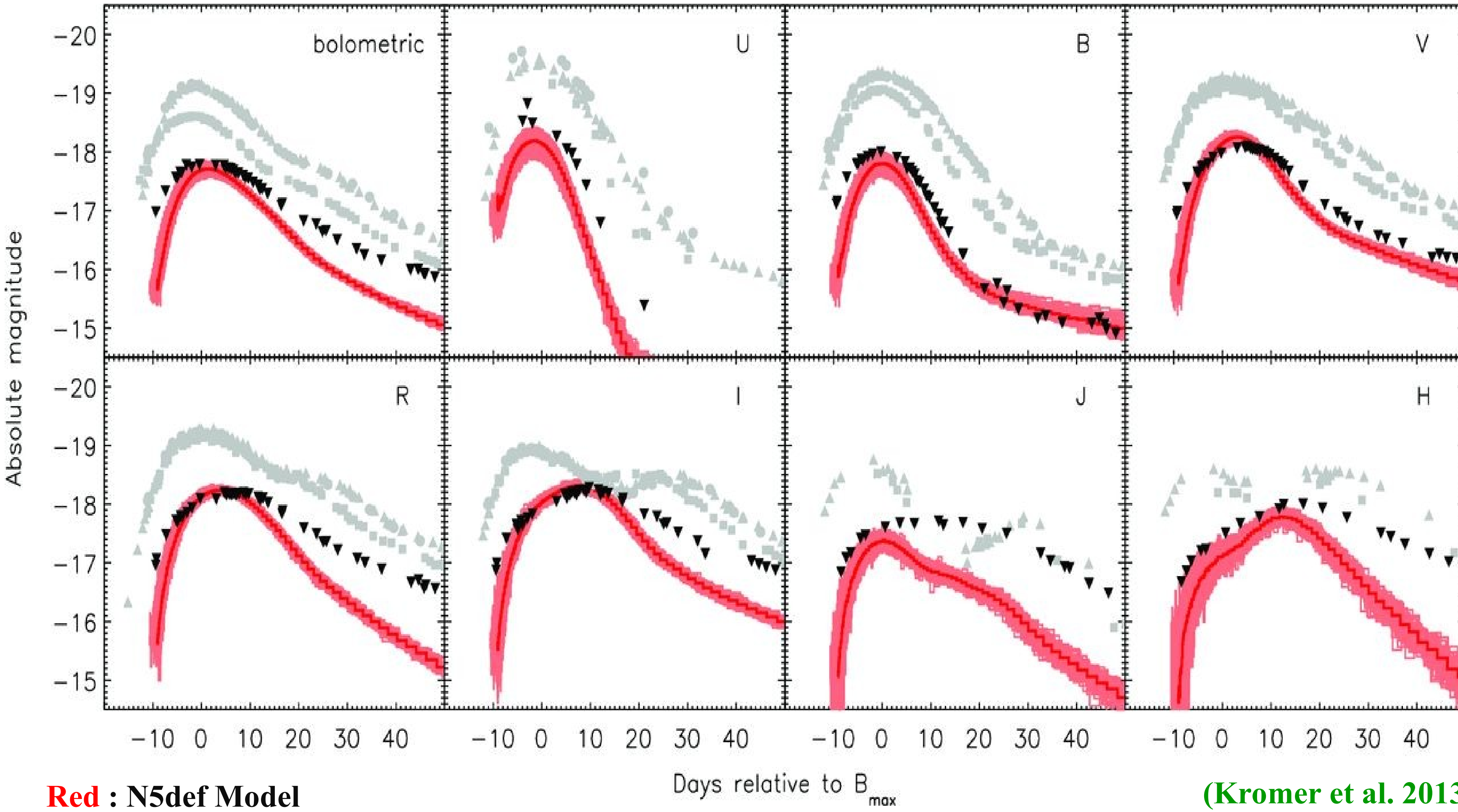
Yields of select species for model N5def.

	Bound remnant ($M_\odot$)	Ejecta ($M_\odot$)
Total	1.028	0.372
C	0.422	0.043
O	0.484	0.060
Ne	0.054	0.005
Mg	0.004	0.013
Si	0.015	0.025
S	0.004	0.009
Ca	0.0003	0.001
Fe	0.004	0.031
Ni	0.025	0.187
^{56}Ni	0.022	0.158

N5def Model

Compared with observation

Light curves



Red : N5def Model

Black upside-down triangles : SN Iax (SN 2005hk)

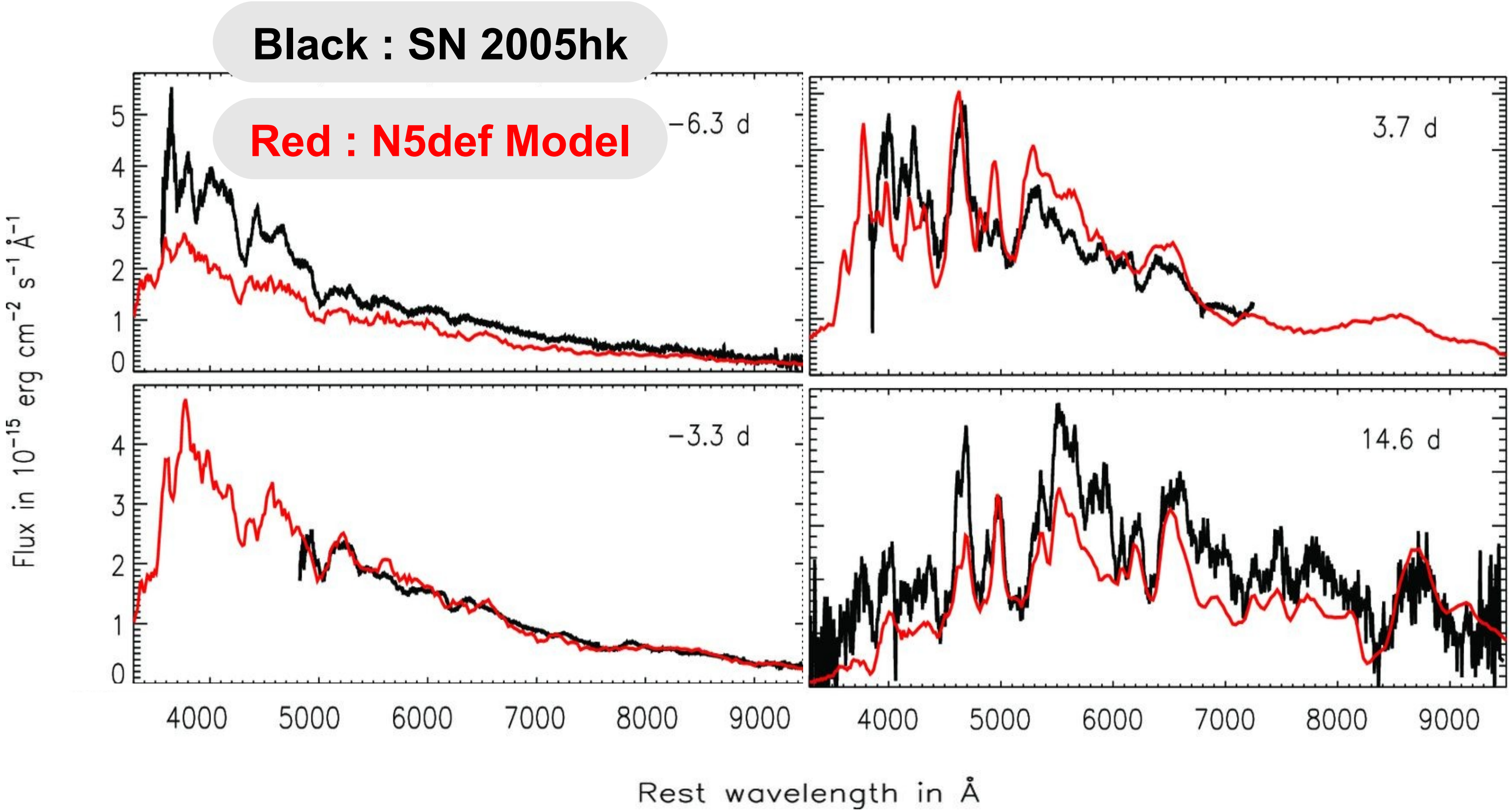
Grey symbols : Normal Ia (SNe 2003du, 2004eo, 2005cf)

(Kromer et al. 2013)

N5def Model

Compared with observation

Spectral evolution from -6.3 to 14.6 days



(Kromer et al. 2013)

3. Method

One-dimensional stellar evolution (MESA)

(Paxton et al. 2013)

↓

Three-dimensional smoothed particle hydrodynamics method (GADGET)

(Springel et al. 2001)

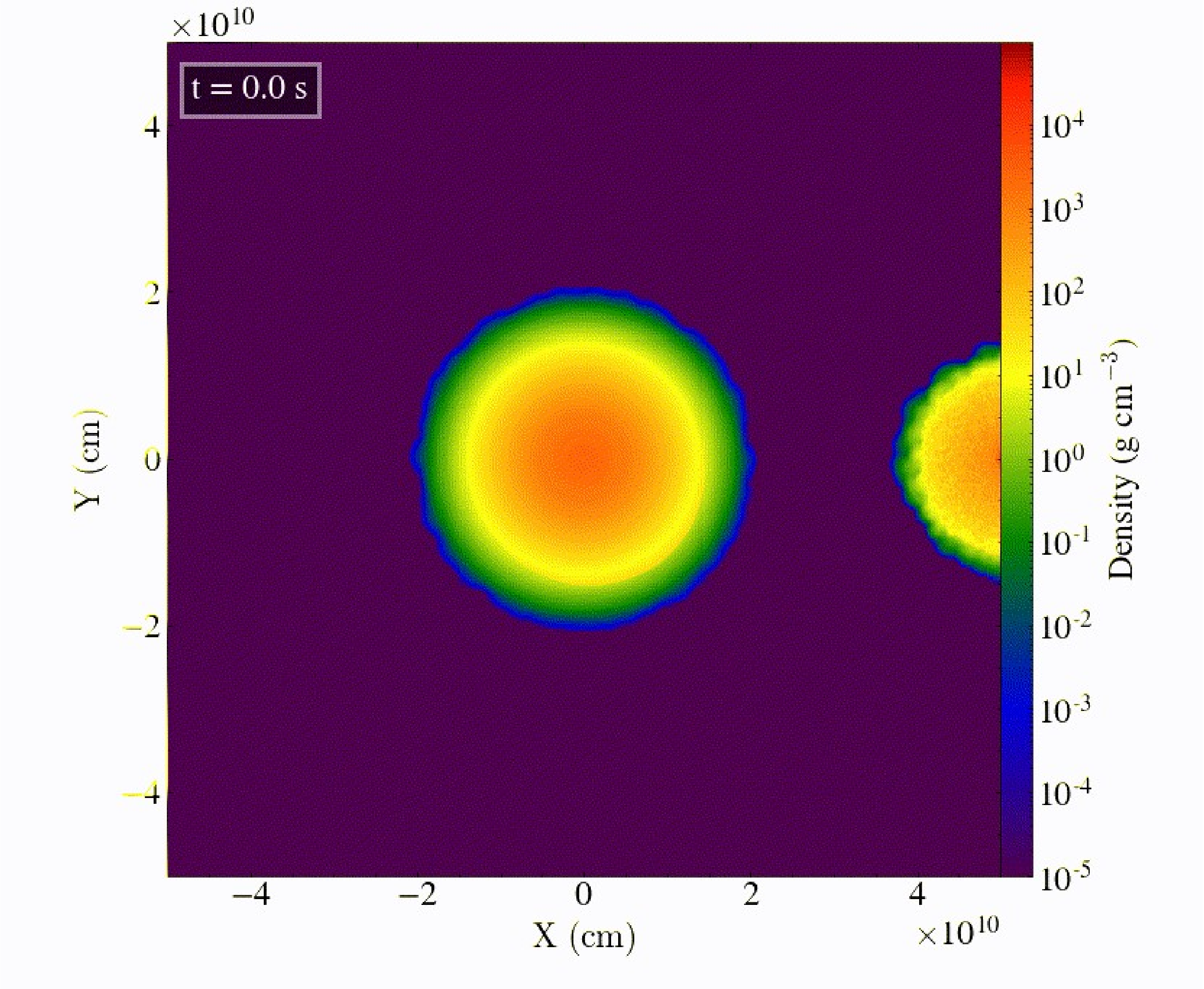
Mass ($M_\odot$)	Radius R_2(10^{10}cm)	Separation A(10^{10}cm)	A/R_2
1.24	1.91	5.16	2.70

(He01 in Liu et al. 2013)

→ **The influence of ejecta on companion star**

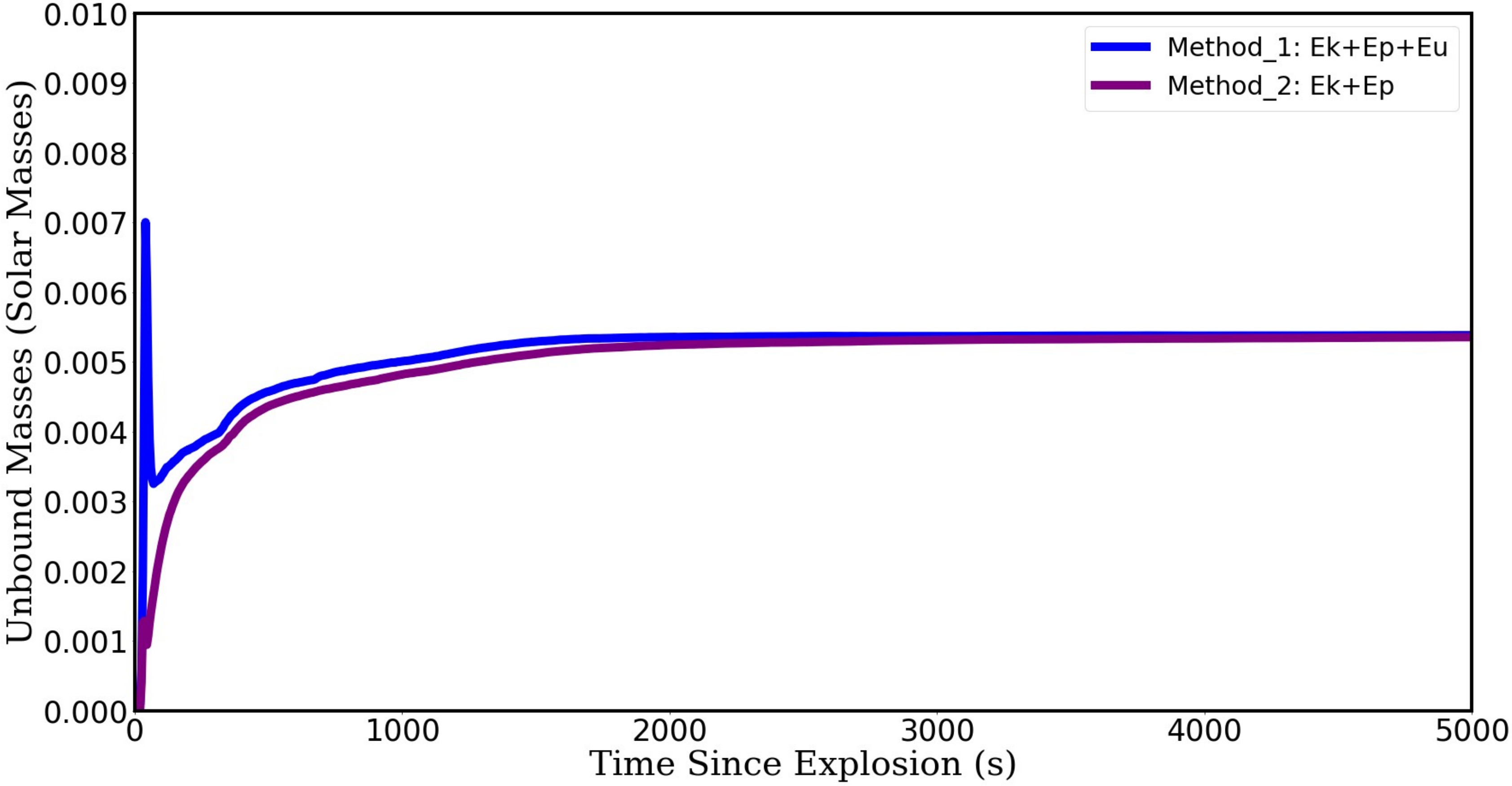
- stripped material
- heavy element
- …

4. Results



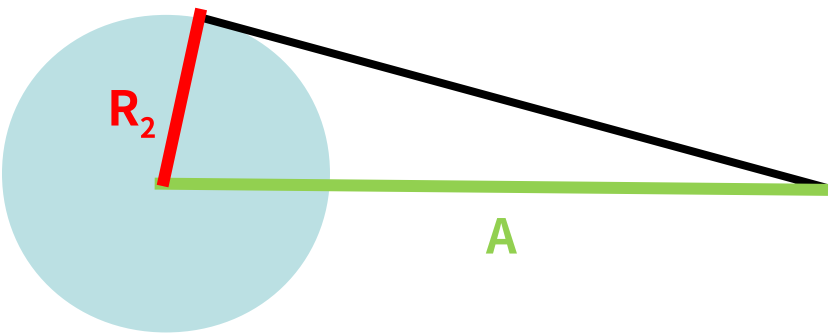
×10^10
t = 0.0 s
4
2
0
−2
−4
Y (cm)
−4
−2
0
2
4
X (cm)
×10^10
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
Density (g cm^-3)

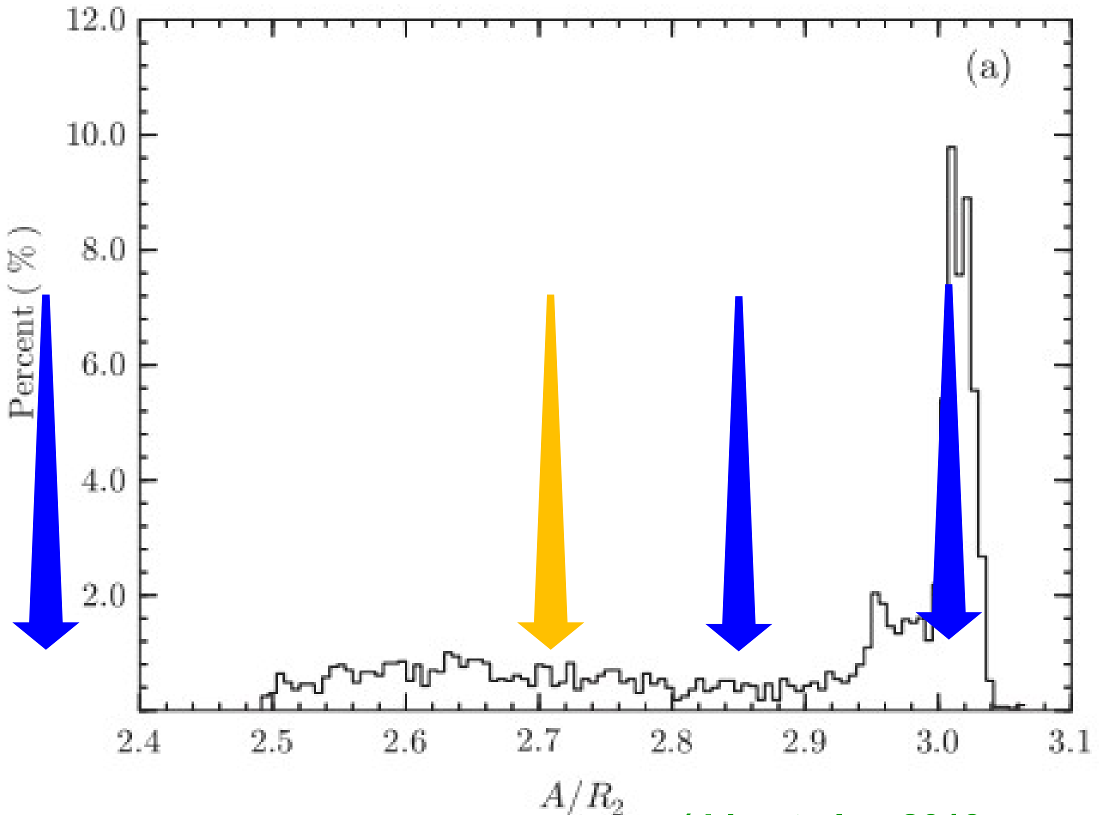
Unbound masses —— time



Unbound mass ~ 0.005M$_{\odot}$

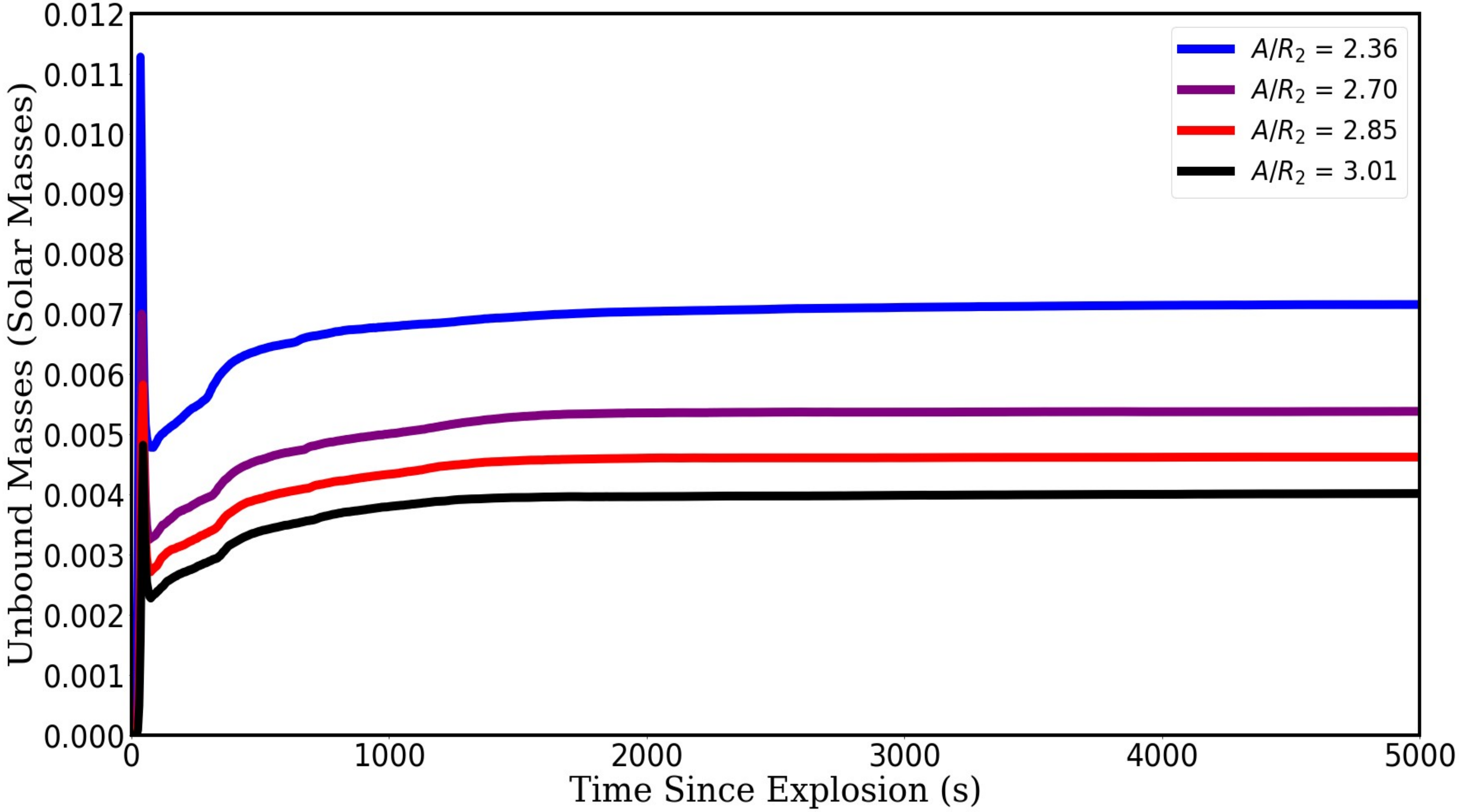
Different initial setup





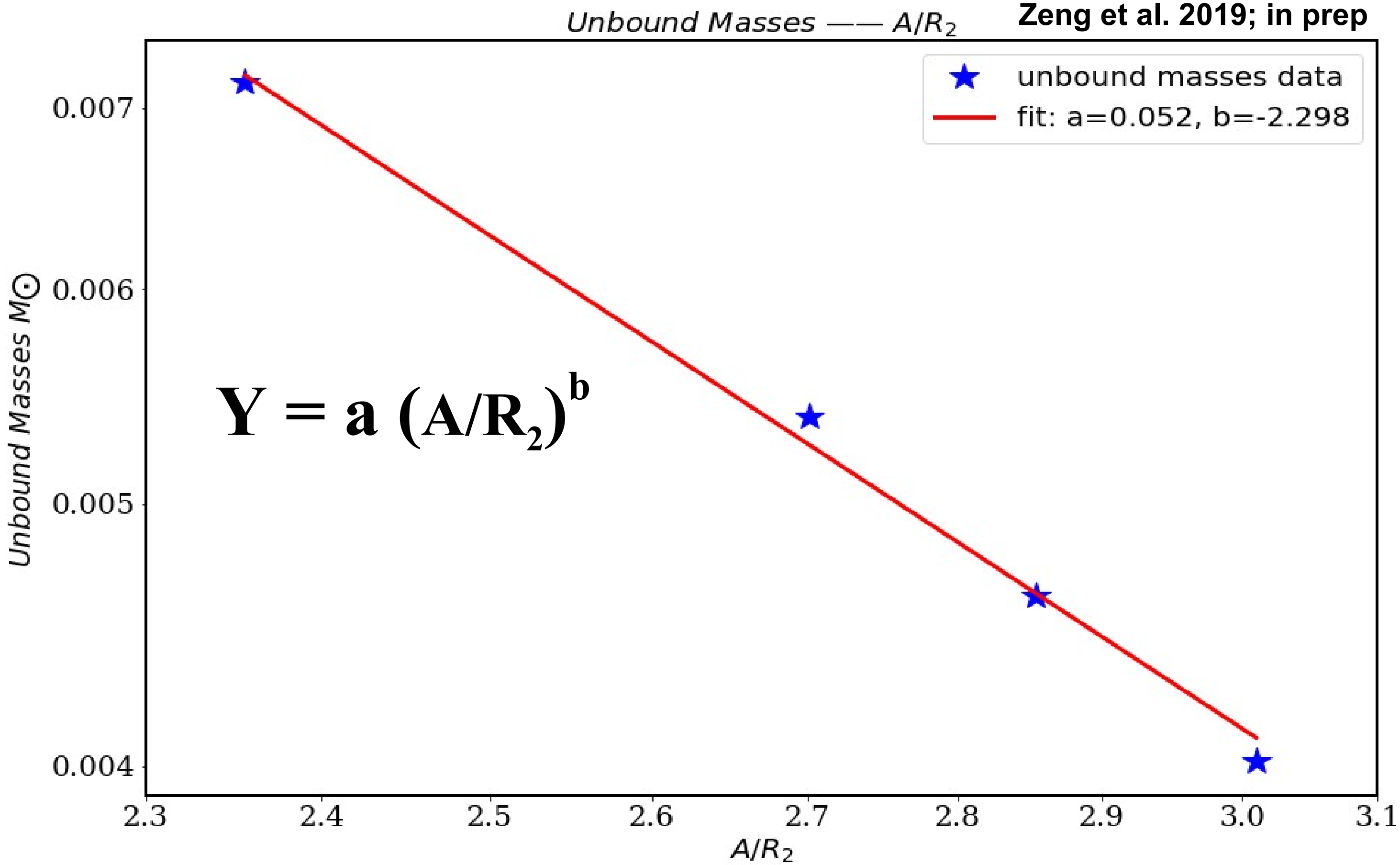
(Liu et al， 2013； see also Wang et

Zeng et al. 2019; in prep



A/R_2	Unbound Masses($M_\odot$)
2.36	0.0072
2.70	0.0054
2.85	0.0046
3.01	0.0040

Zeng et al. 2019; in prep



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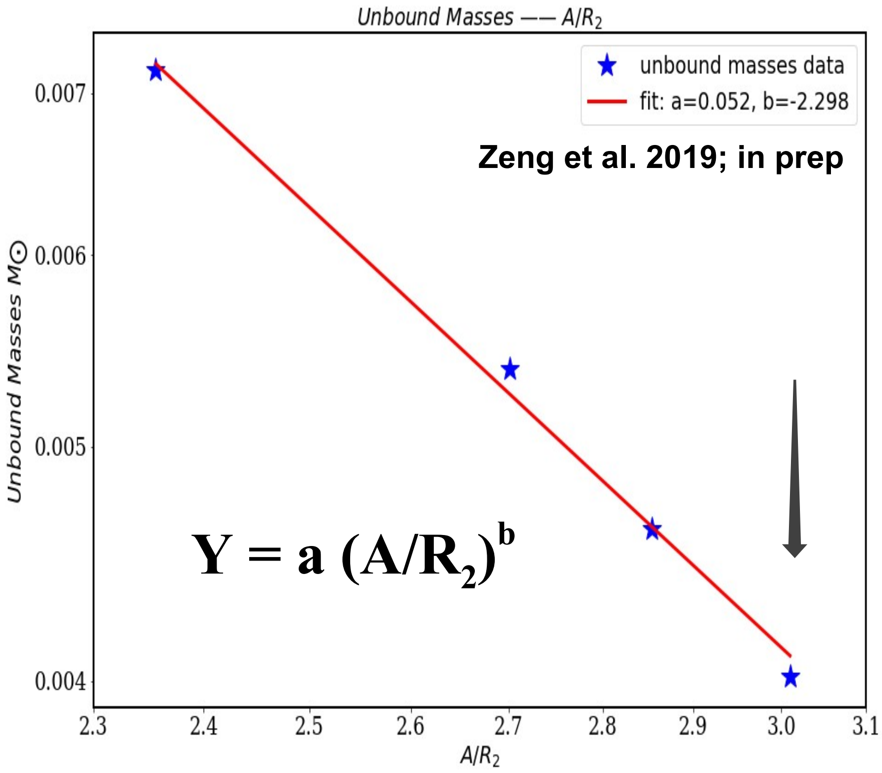

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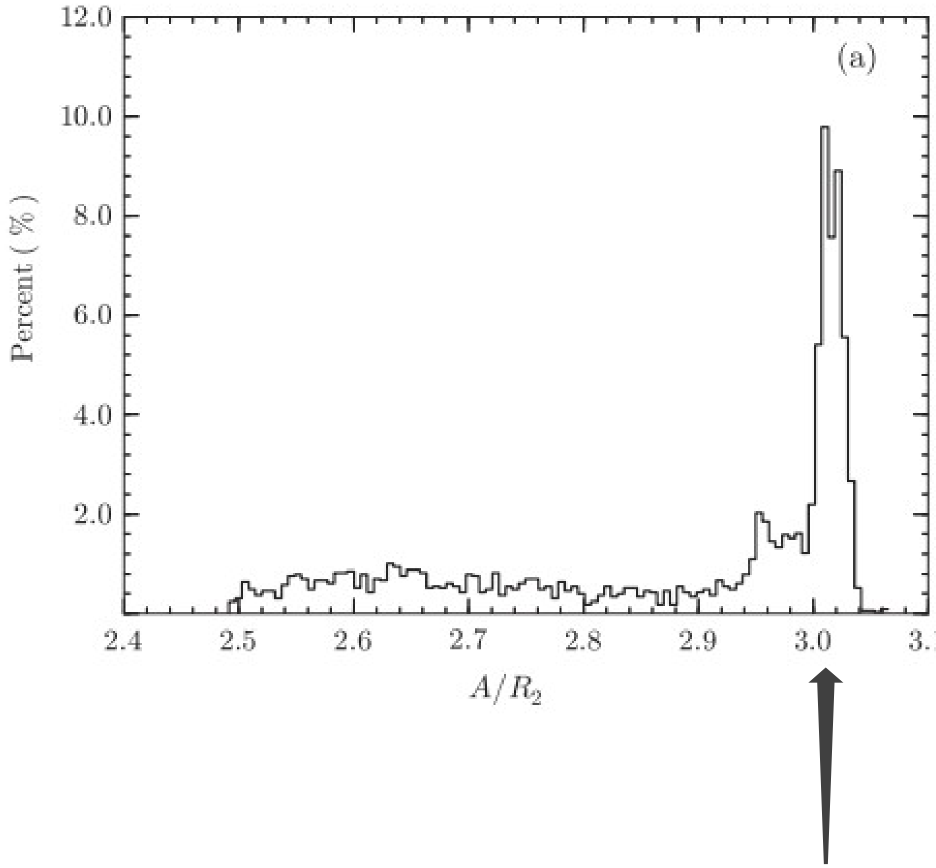
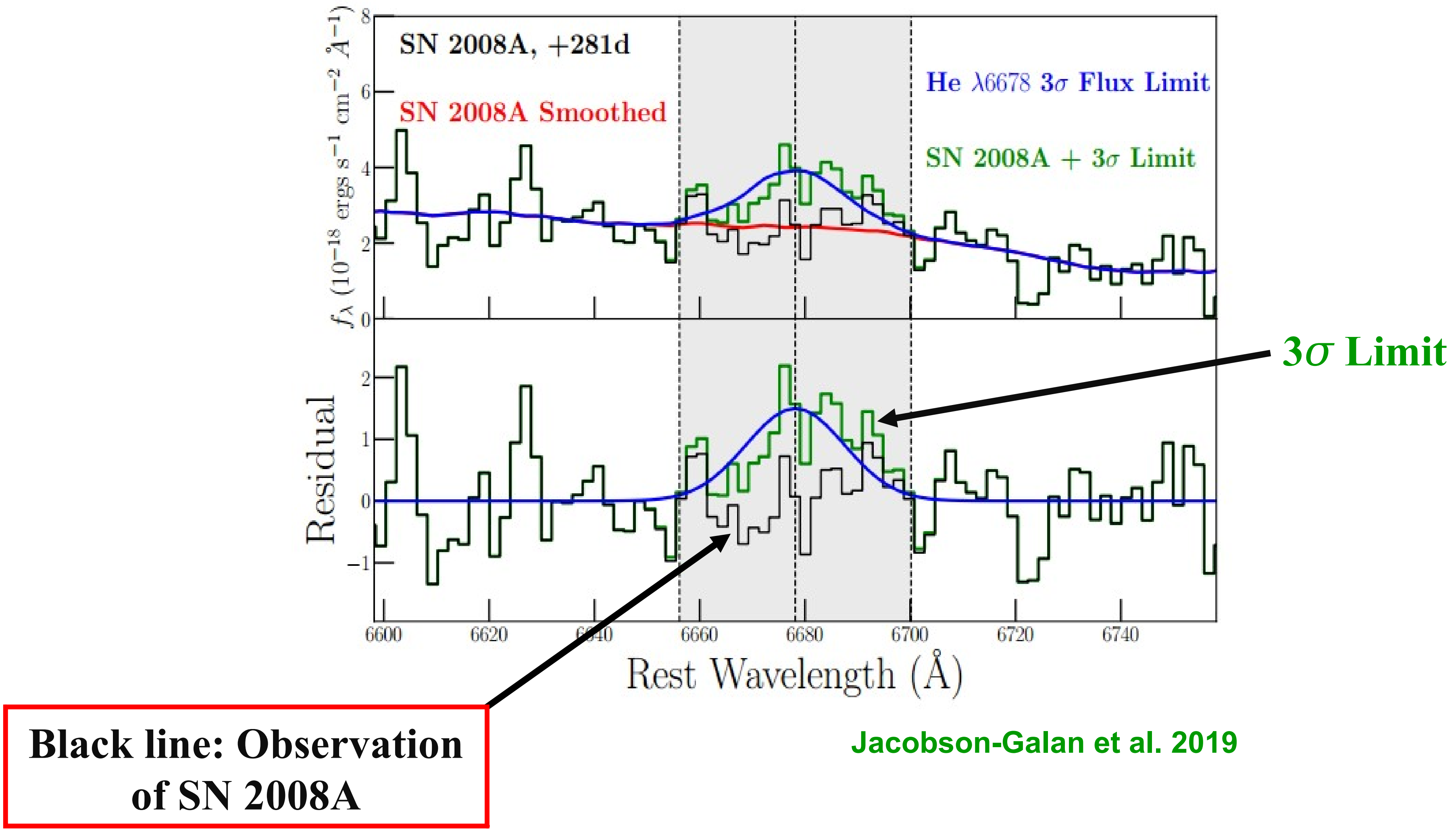


- As the ratio increases, the amount of stripped He mass will decrease.
- For the most system, the stripped He mass ~ 4 X $10^{-3}M_\odot$

Non-detection He lines in SNe Iax **late-time spectra**

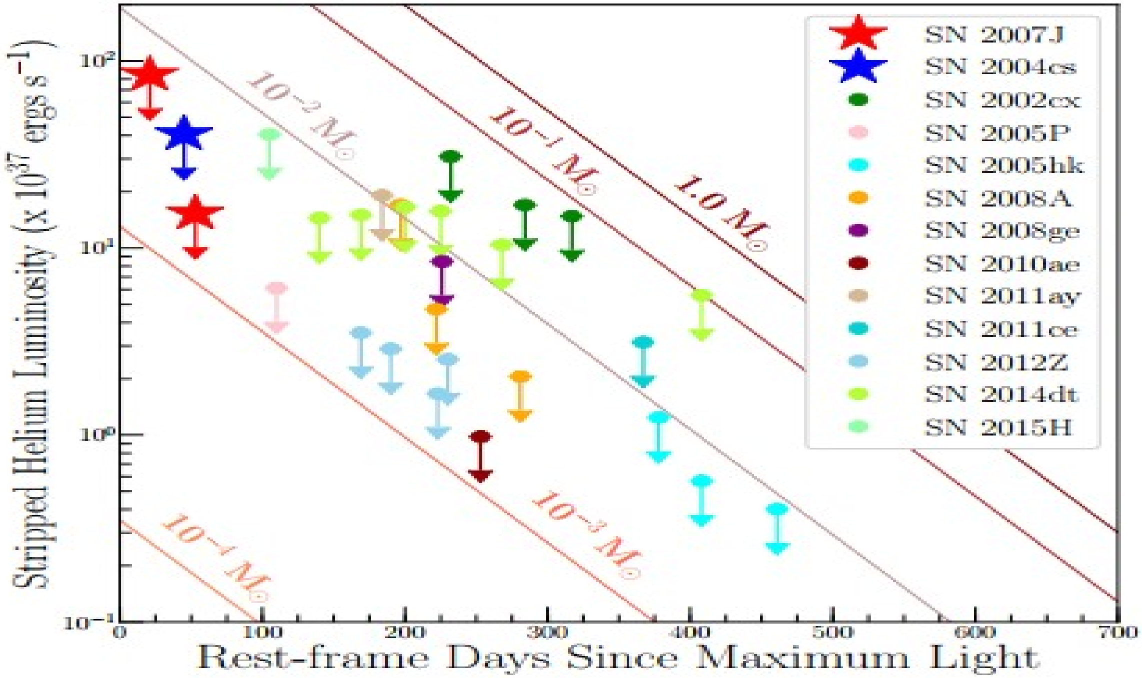
Different groups search for the He line:

(e.g., Foley et al. 2013; Jacobson-Galan et al. 2019； Tucker et al. 2019)



Jacobson-Galan et al. 2019

Why non-detection He lines in SNe Iax late-time spectra ？



(Jacobson-Galan et al. 2019)

<0.01 $M_{\odot}$ (typical upper limits) He-rich material can be stripped from companion star

+

Our simulations : ~ 0.004 $M_{\odot}$ (most system)

Naturally explain non-detection He lines in late-time spectra of SNe Iax.

5. Summary

- **Get unbound masses for different initial separation ratio setups, such unbound masses as a faction of the ratio follow a power law**
- **Unbound masses : 0.004 $M_{\odot}$ (for most system of WD + He channel)**
- **Naturally explain non-detection He lines in late-time spectra of SNe Iax.**

6. Future work

Long-term evolution of surviving companion star

Three-dimensional smoothed particle hydrodynamics method (GADGET) (Springel et al. 2001)

→ ◆ **The influence of ejecta on companion star**

↓

One-dimensional stellar evolution (MESA) (Paxton et al. 2013)

→ ◆ **Surviving companion star**

Thank you !

Yields of select species for model N5def.

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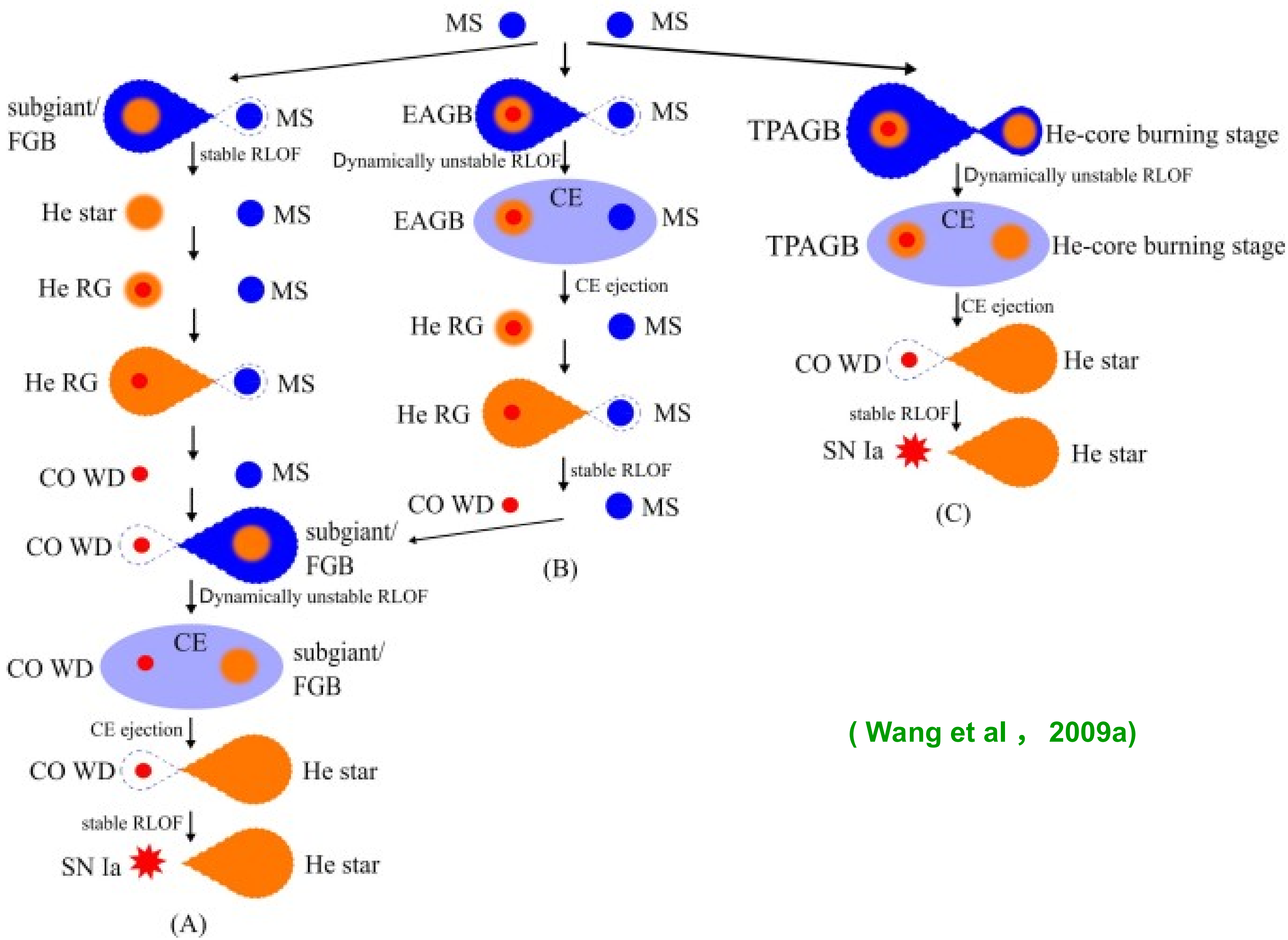

(Wang et al， 2009a)