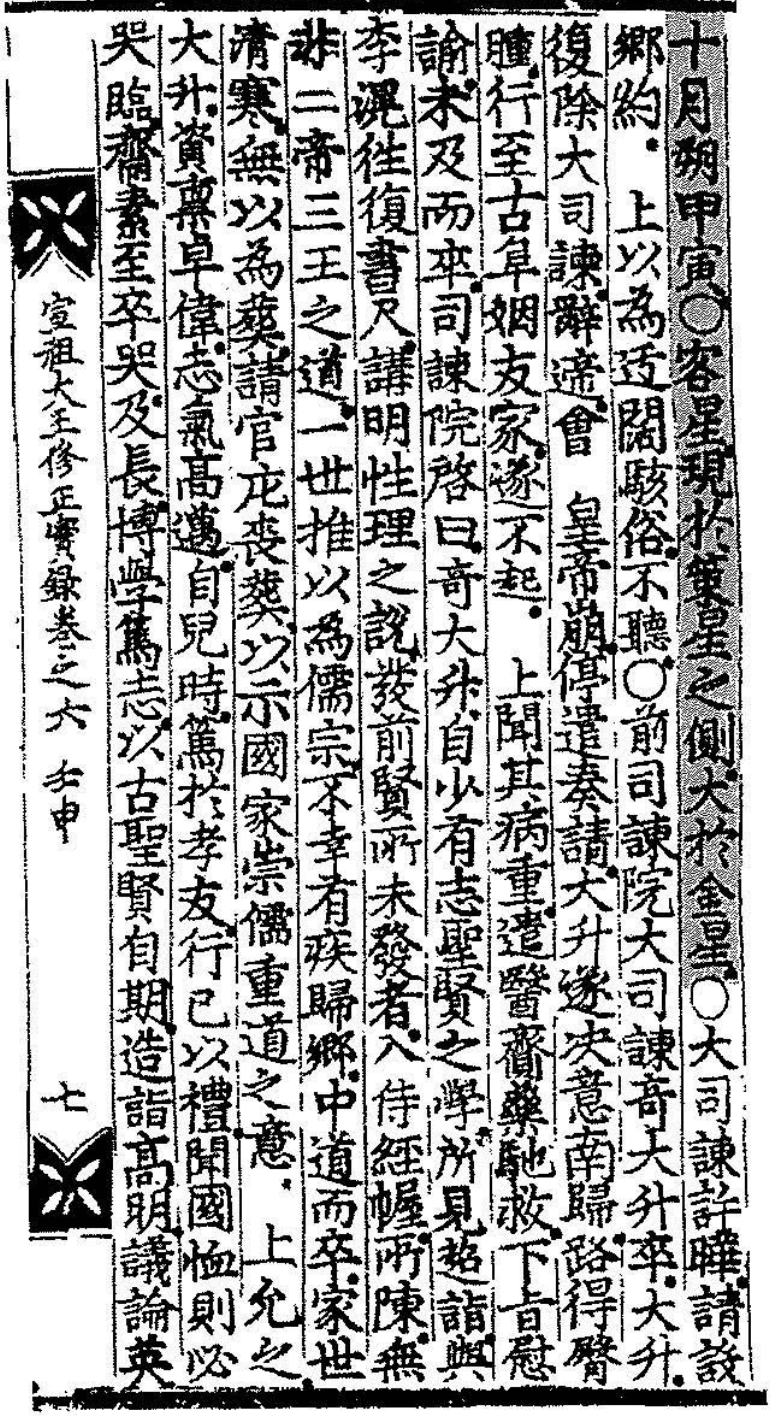
Evolution and Final Fates of Accreting White Dwarfs

Ken Nomoto
(Kavli IPMU / U. Tokyo)

AD 1572
Korean & Chinese Record

“Guest Star
as bright as Venus”

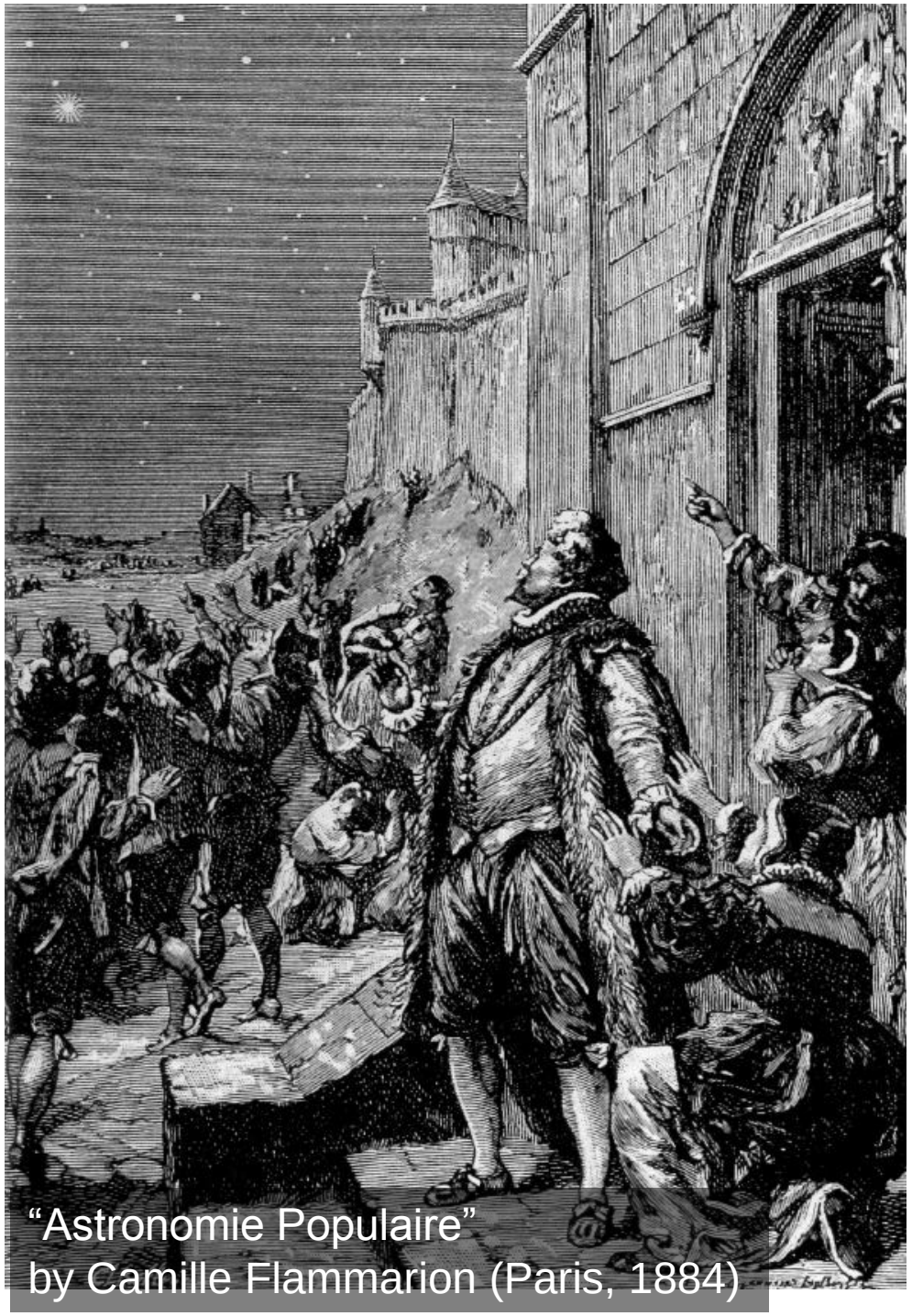
（Sonjo Sujong Sillok: Korea)


十月癸甲寅〇客星現於東方之側大於金星〇大司諫許曄請設鄉約上以為近閭駭俗不聽〇前司諫院大司諫奇大升卒大升復除大司諫辭遞會 皇帝崩停遣奏請大升遂決意南歸路得臀腫行至古阜姻友家遂不起 上聞其病重遣醫齎藥馳救下旨慰諭未及而卒司諫院啓曰奇大升自少有志聖賢之學所見超詣與李滉往復書只講明性理之說裁前賢所未發者入侍經幄所陳無非二帝三王之道一世推以為儒宗不幸有疾歸鄉中道而卒家世清寒無以為葬請官庀喪葬以示國家崇儒重道之意上允之大升資稟卓偉志氣高邁自兒時篤於孝友行已以禮閨門恂恂則必哭臨齋素至卒哭及長博學篤志以古聖賢自期造詣高明議論英

宣祖大王修正實錄卷之六 壬申 七

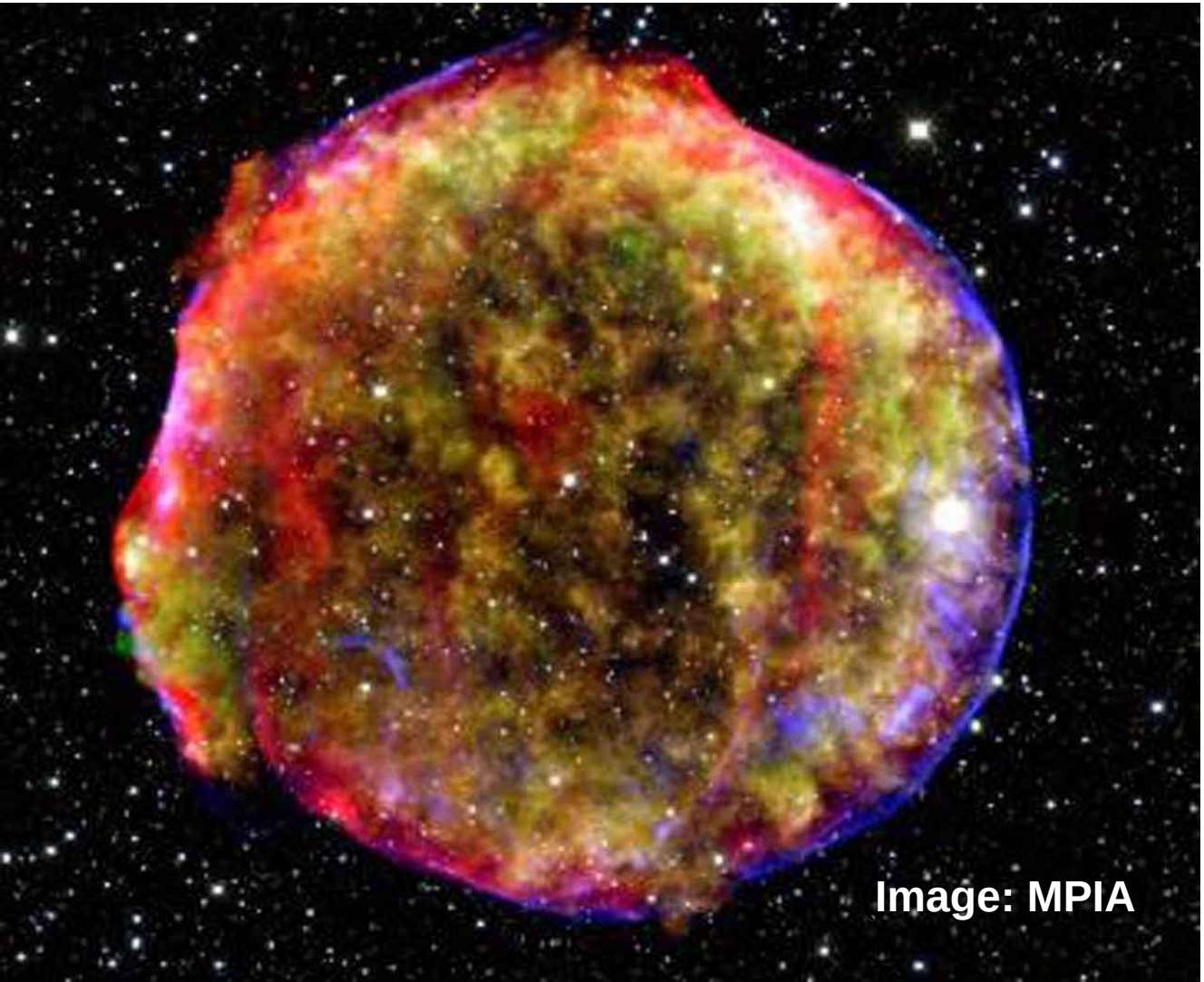
AD 1572
Tycho Brahe's Supernova

Stella Nova
(Tycho Brahe 1573)



"Astronomie Populaire"
by Camille Flammarion (Paris, 1884)

Remnant of Tycho's Supernova

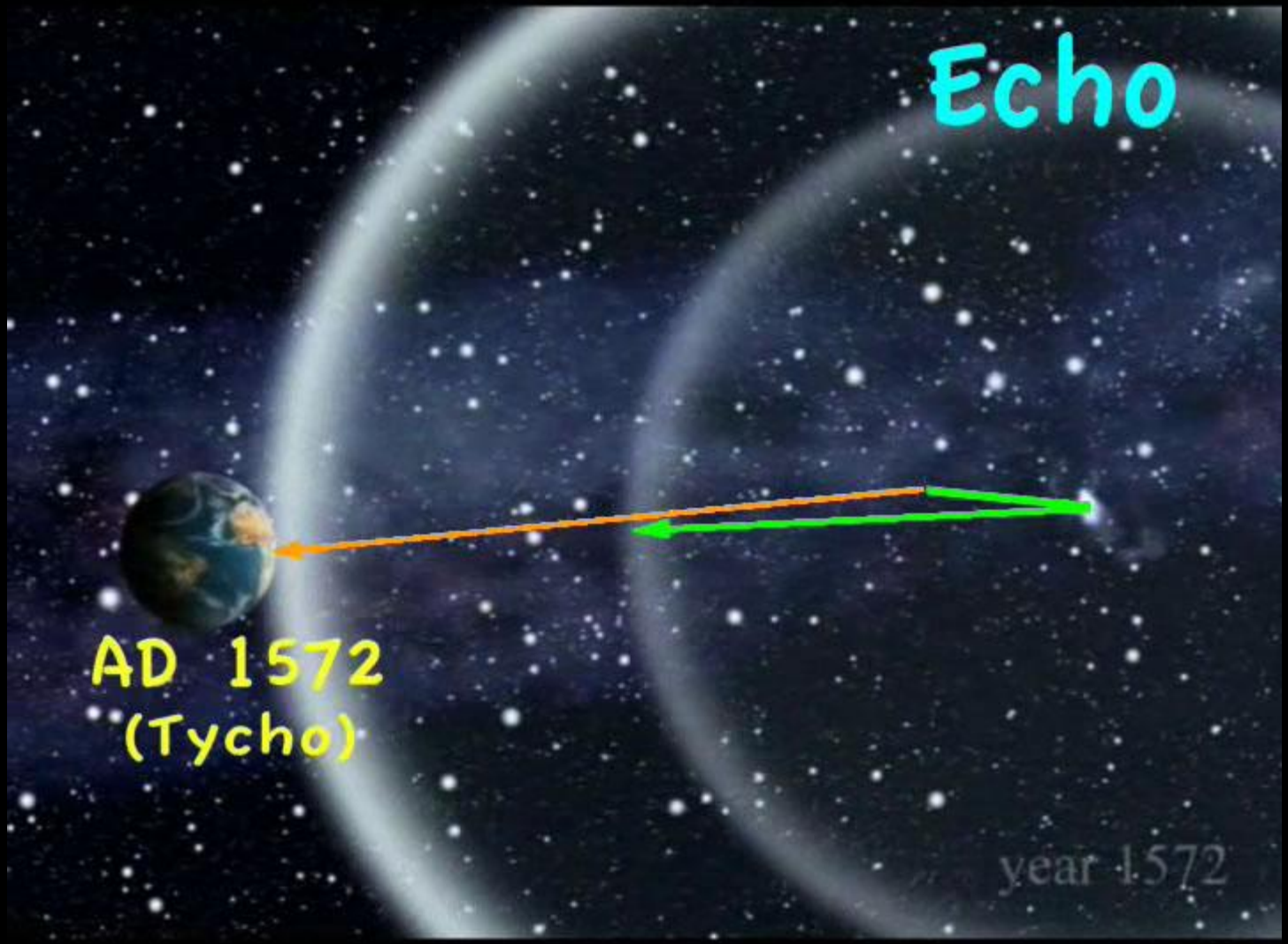


Green Yellow
Blue X-ray (Hot gas with millions of degree)

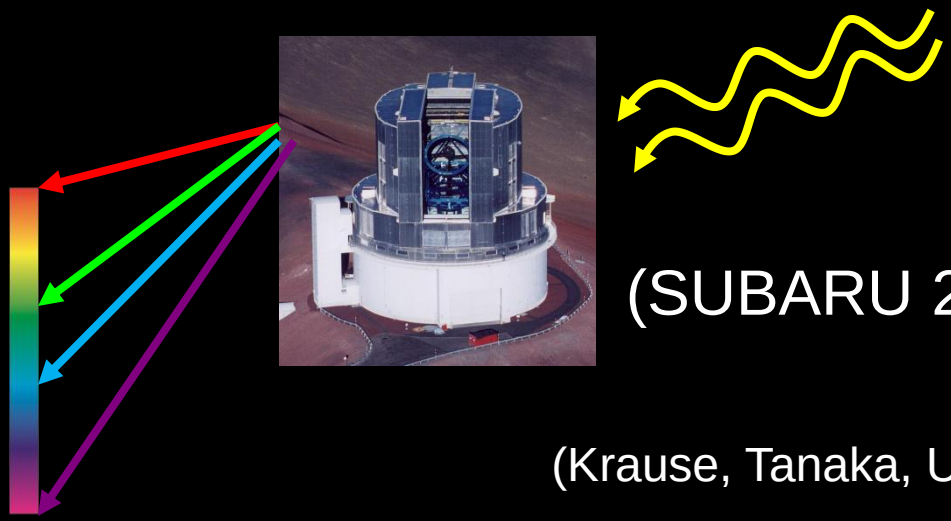
Red
Infrared (Circumstellar/ Synthesized dust)

White
Optical (Foreground/ background stars)

Light Echo of SN 1572 (Tycho)



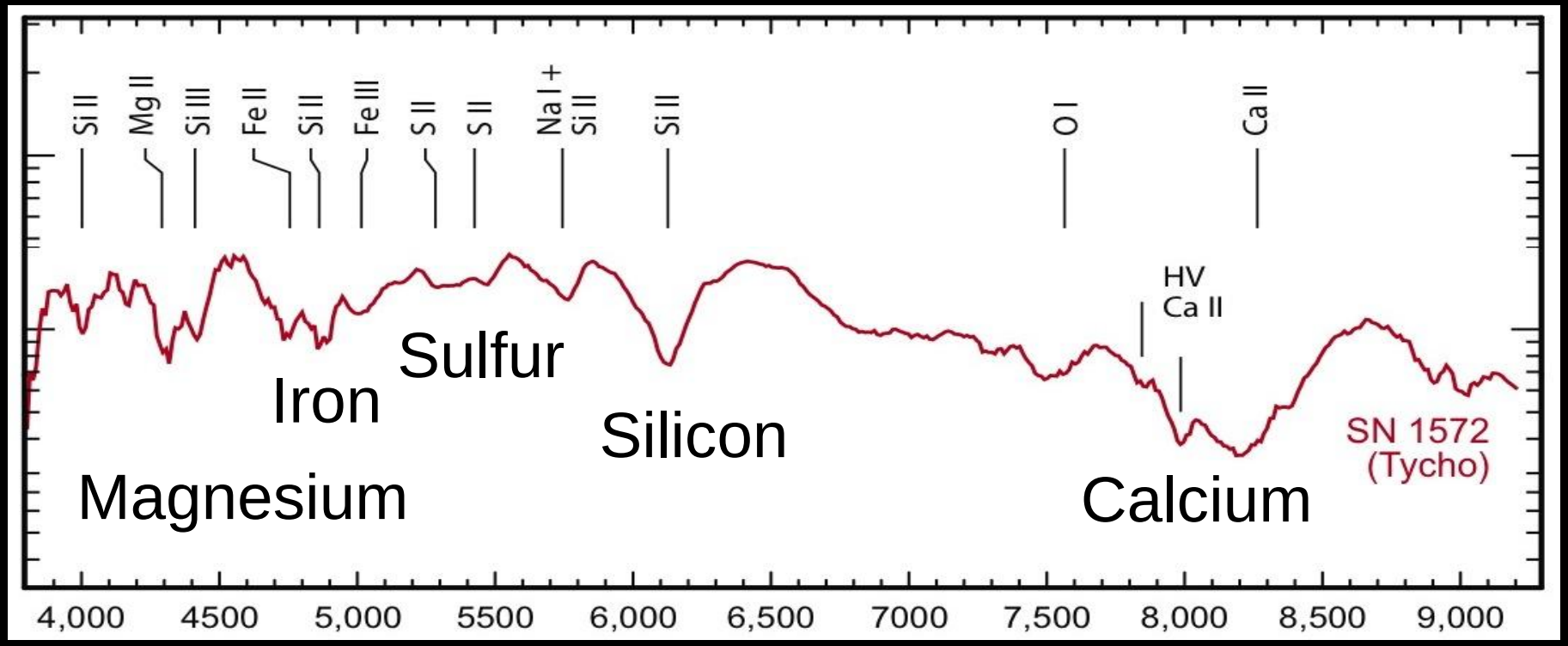
Echo: Oort, Zwicky, ,,Rest+, Krause+



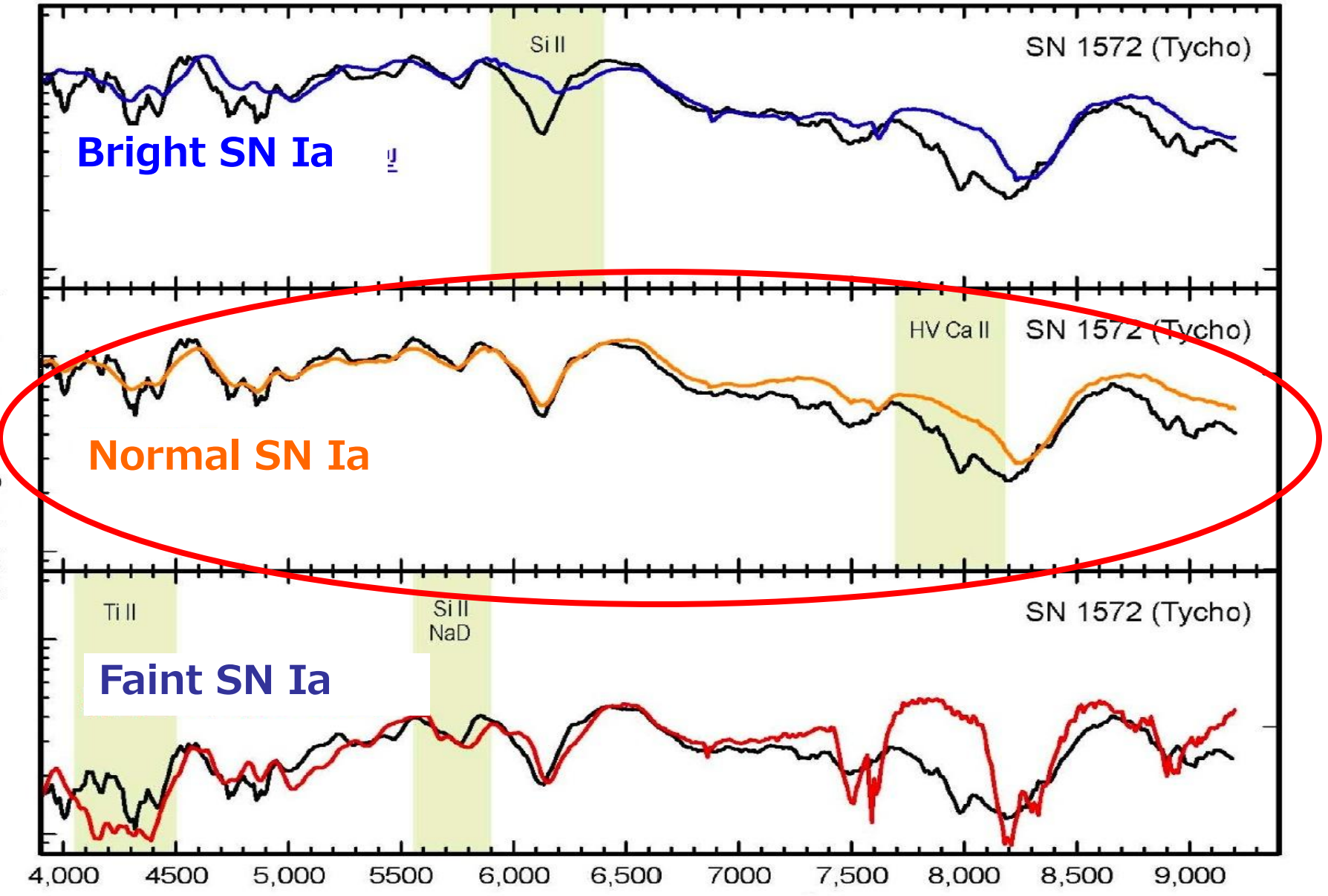
Spectrum of Echo

(SUBARU 2008)

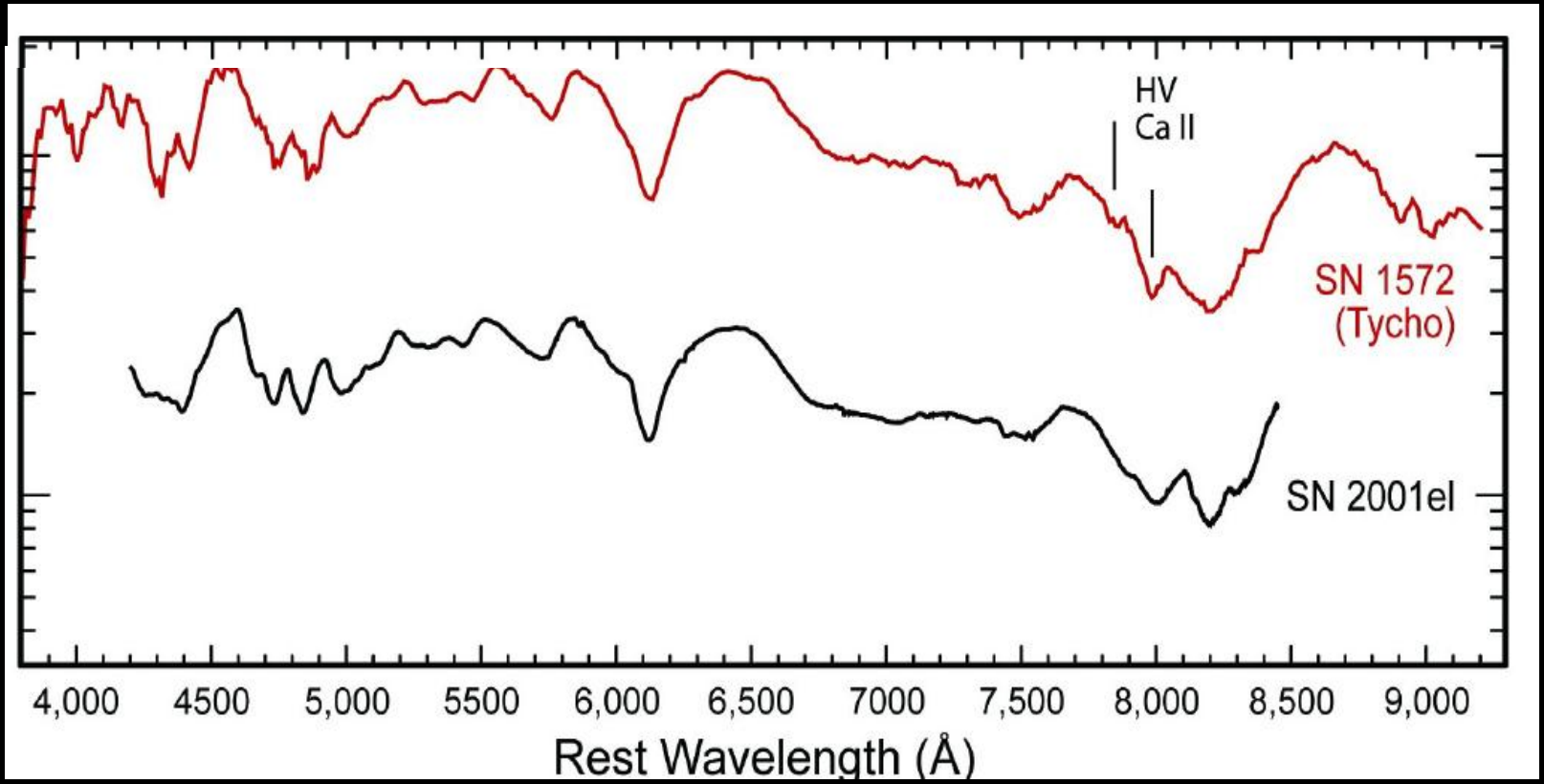
(Krause, Tanaka, Usuda, Hattori, Goto, Nomoto 2008 Nature)



Spectra

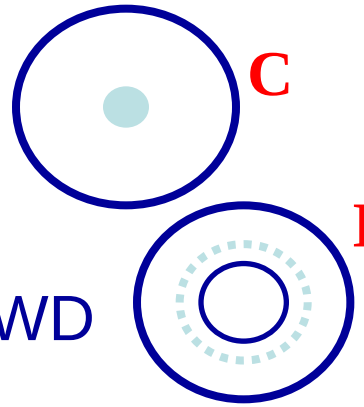

Si II
SN 1572 (Tycho)
Bright SN Ia
HV Ca II
SN 1572 (Tycho)
Normal SN Ia
Ti II
Si II
NaD
SN 1572 (Tycho)
Faint SN Ia
4,000
4500
5,000
5500
6,000
6,500
7000
7,500
8,000
8,500
9,000

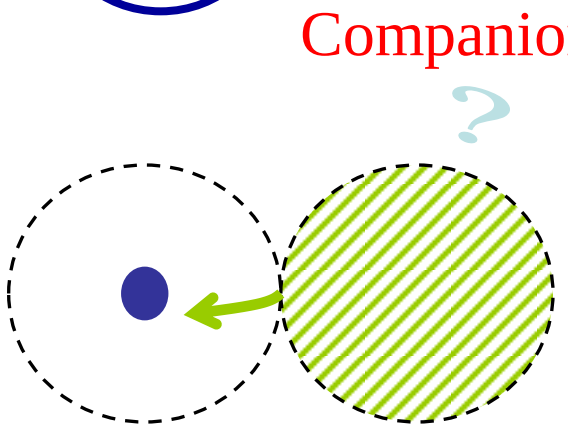
High Velocity Ca Feature



The Progenitors of Type Ia Supernovae ??

- **Single Degenerate(SD)**
  vs.
  Double Degenerate(DD)
- **Chandrasekhar Mass WD**
  vs.
  Sub-Chandrasekhar Mass WD

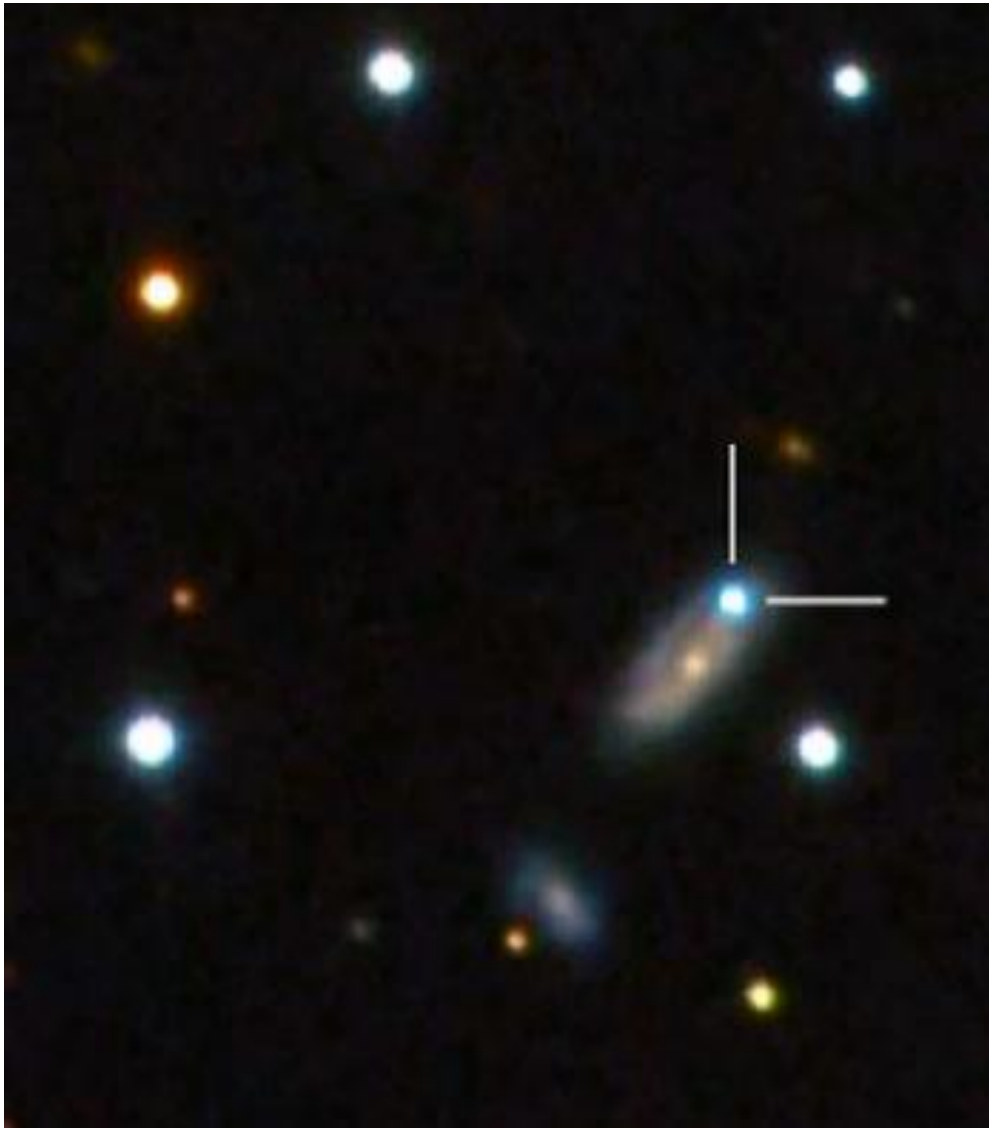


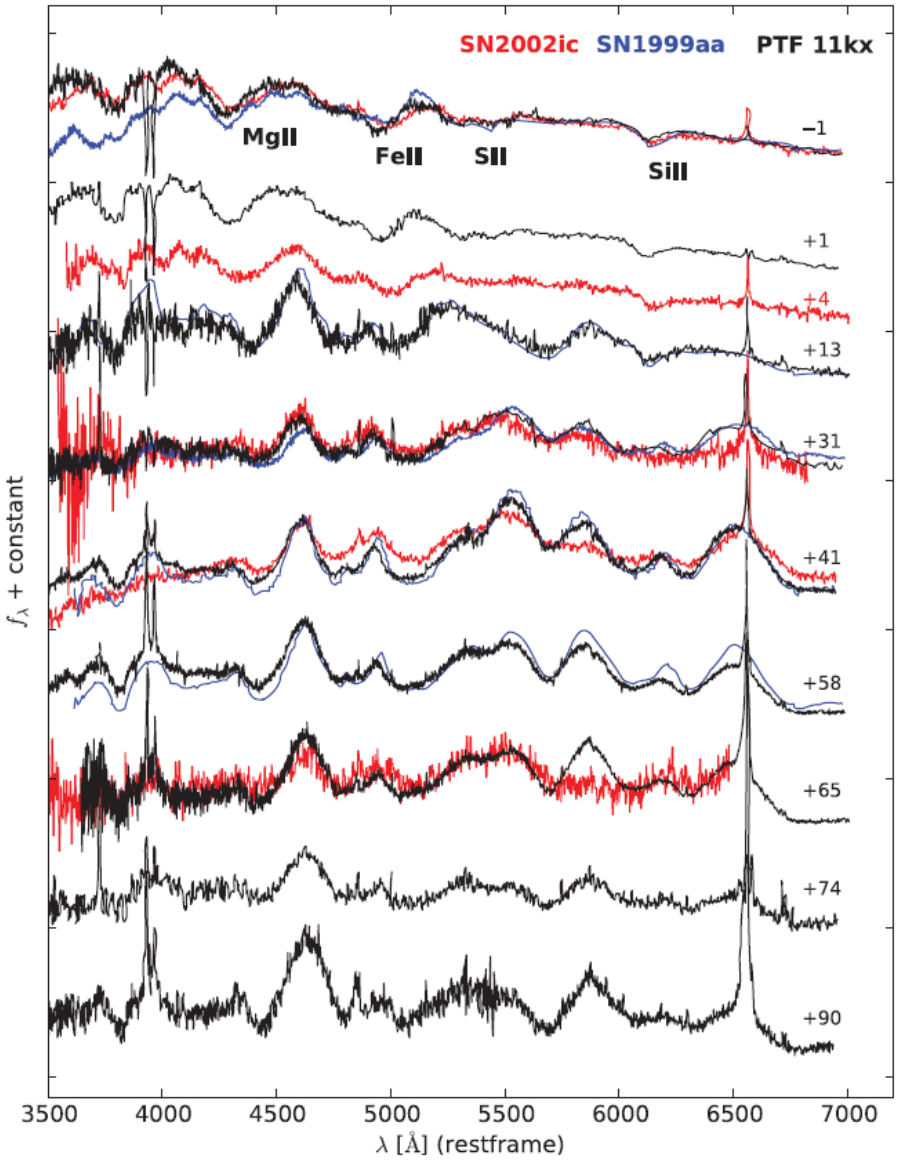


Thermonuclear Explosions of White Dwarfs!!

SN Ia: PTF11kx

(Dilday et al. 2012)



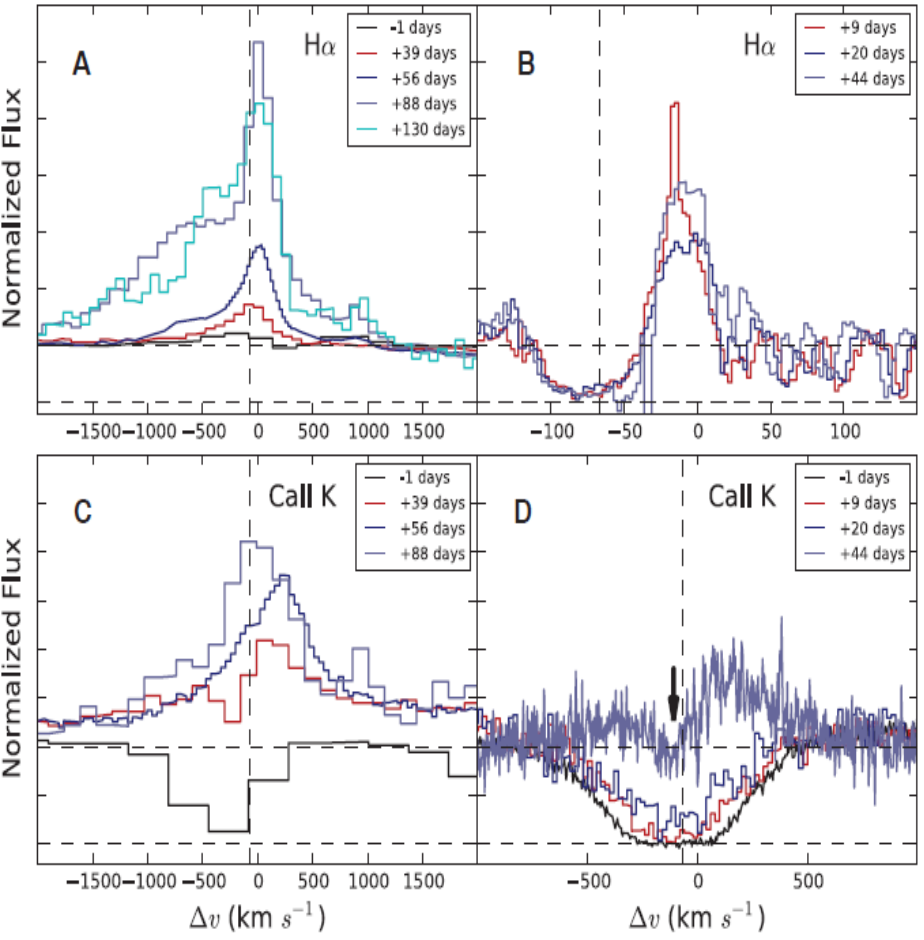


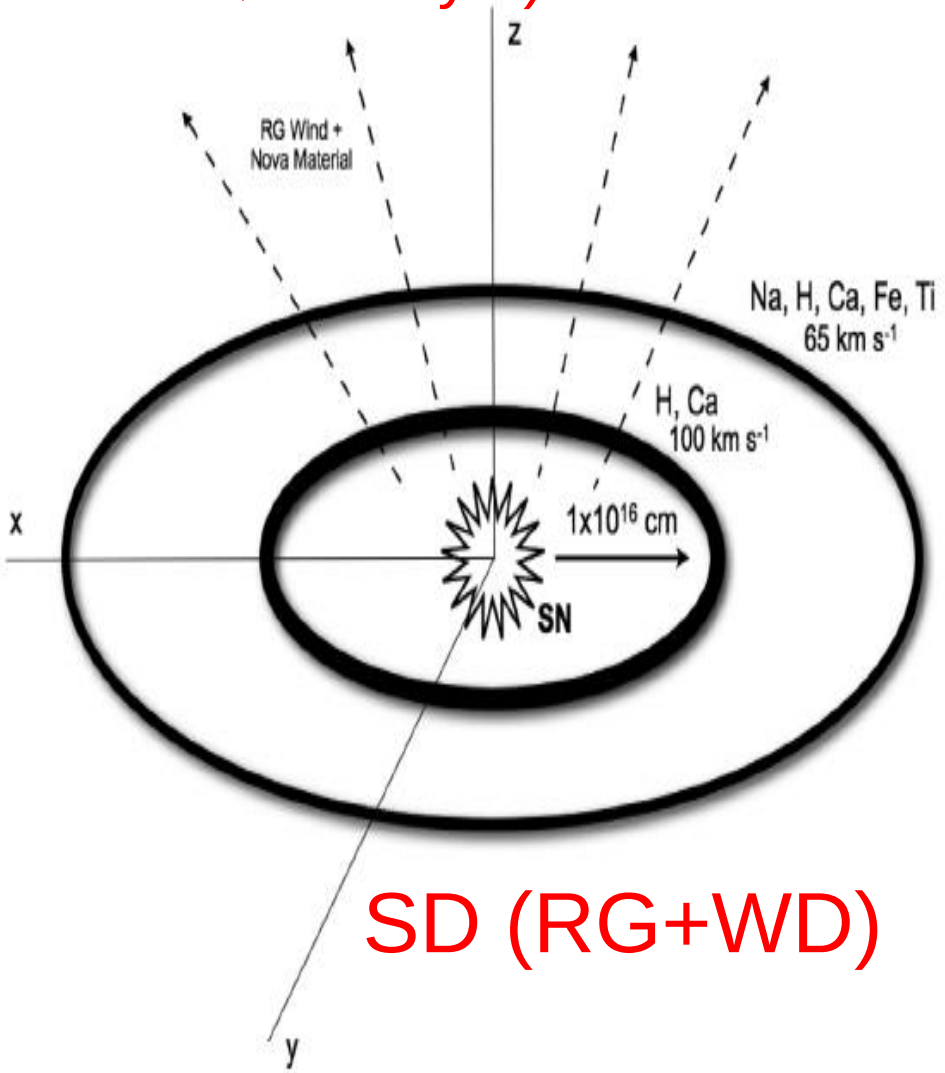
PTF11kx: Symbiotic Recurrent Nova

RG wind + Recurrent nova ejecta

(P~ 10 yrs)

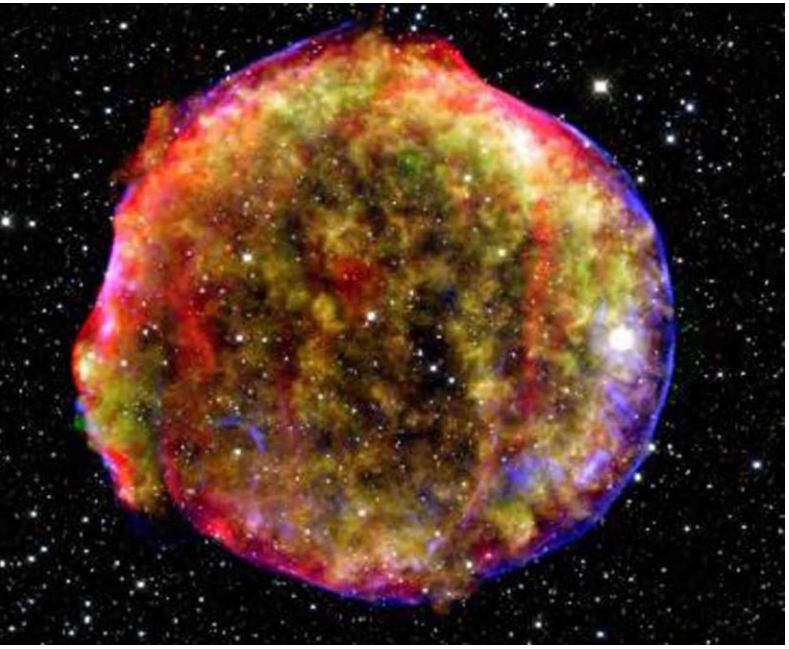
(Dilday et al. 2012)





SD (RG+WD)

SN Ia : No Companion Star ?



SNR Tycho
（Kerzendorf+ 09)
(see, however, Ruiz-Lapuente+ 04)

SNR 0509-67.5 in LMC
（Shaefer & Pagnotta 12)

SN 2011fe
in M101
（Li+ 11)

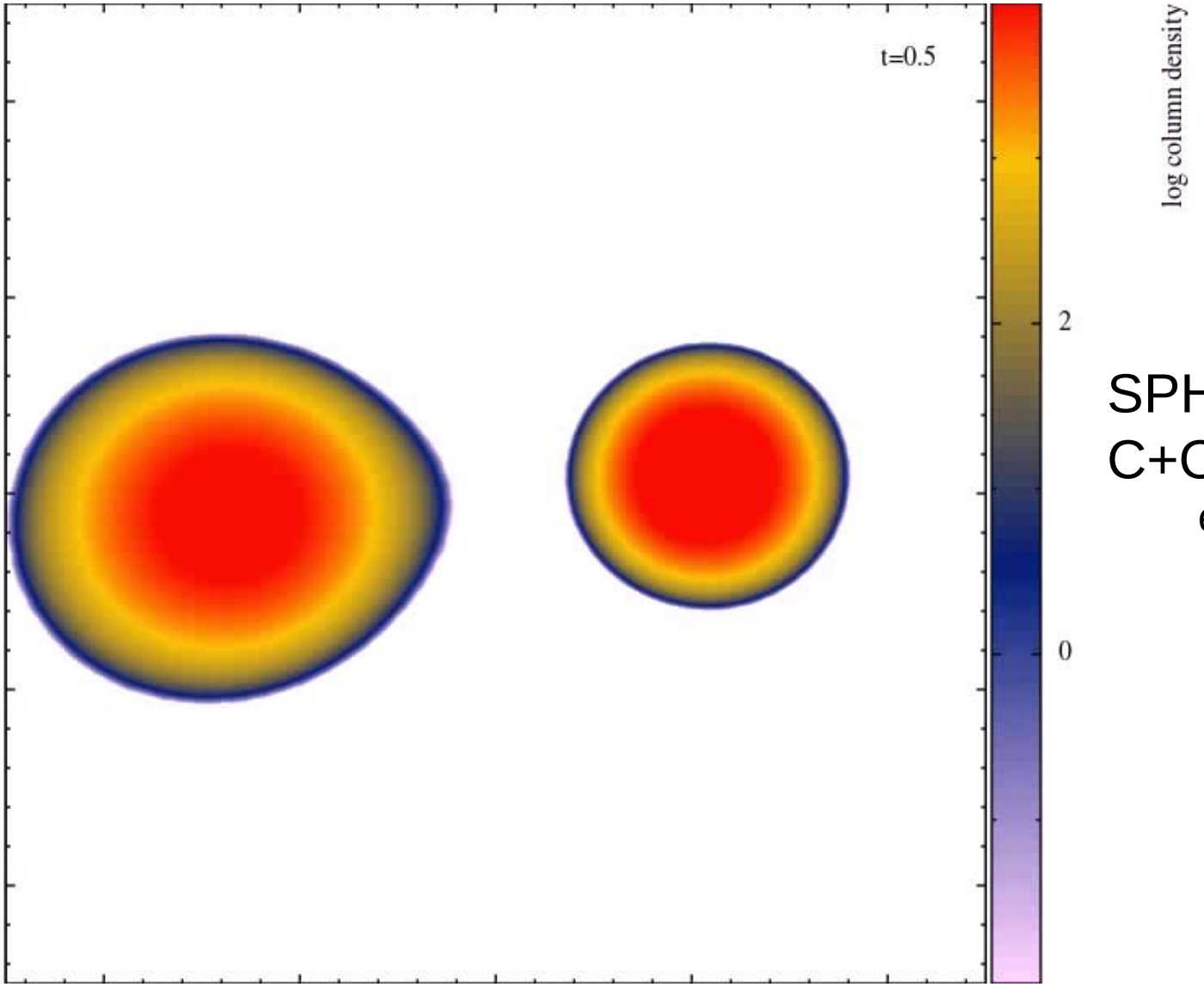
DD ? ➔

DD, SD ➔ Sub-Ch, Chandra

	surface burning	➔	sub-Ch	Chandra
ρ_c (g cm^{-3})	~10^6		$10^{7\text{-}8}$	$10^{9\text{-}10}$

DD	C-detonation ?	➔	C-det	
	steady C-burning?	➔		ONeMg WD
	no ignition ?	➔		C-deflag
SD	He flashes ?	➔		C-deflag
	He detonation ?	➔	C-det	

Double Degenerates (1.1 + 0.9 $M_\odot$)



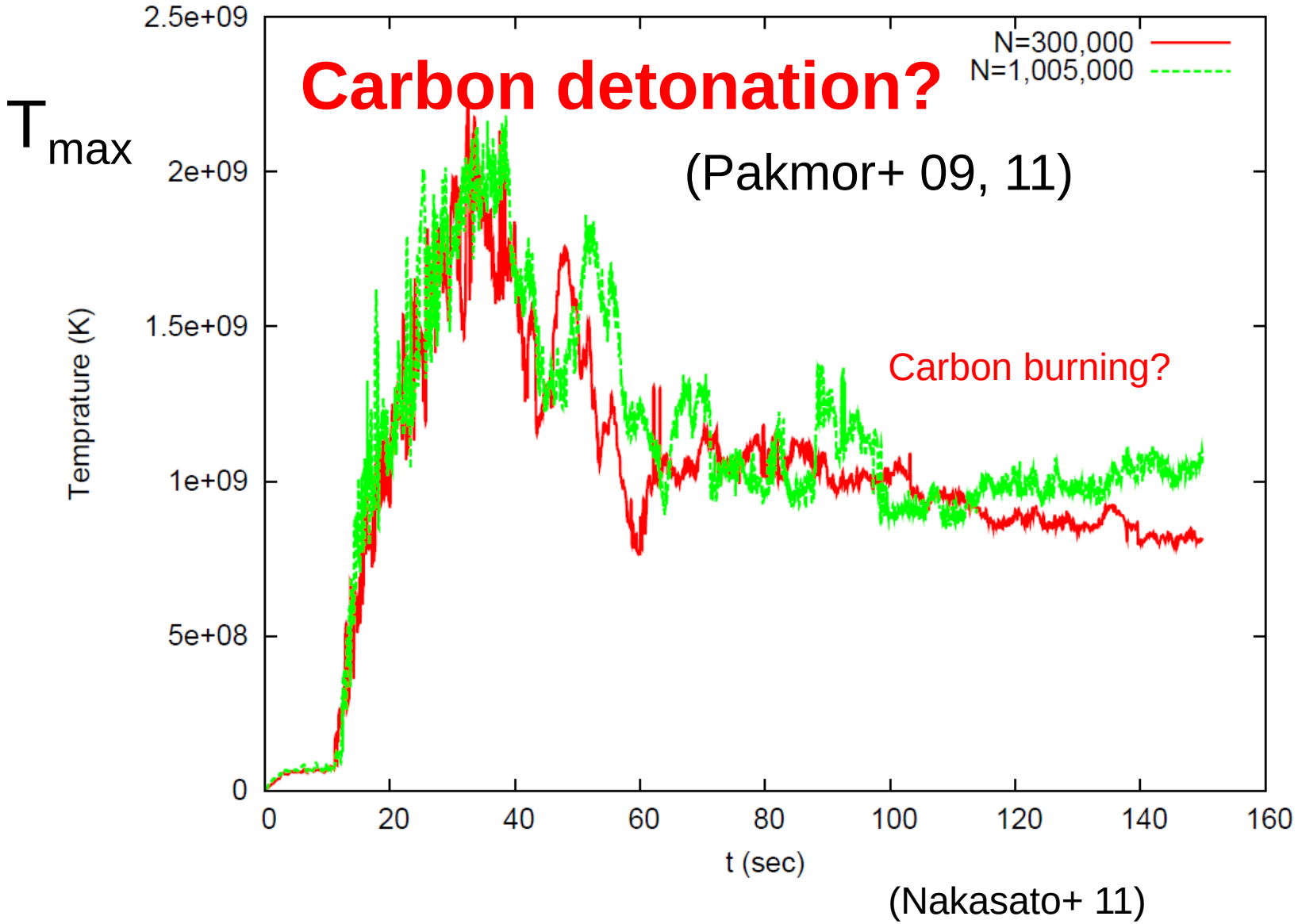
SPH Simulations of C+O WD Merging

example:

$N = 4 \times 10^6$

(Nakasato+ 12)

WD Merging (1.0+0.7)



(Nakasato+ 11)

Double Degenerate Scenario

Is C-detonation (or He detonation)

ignited near the surface ?

If yes,

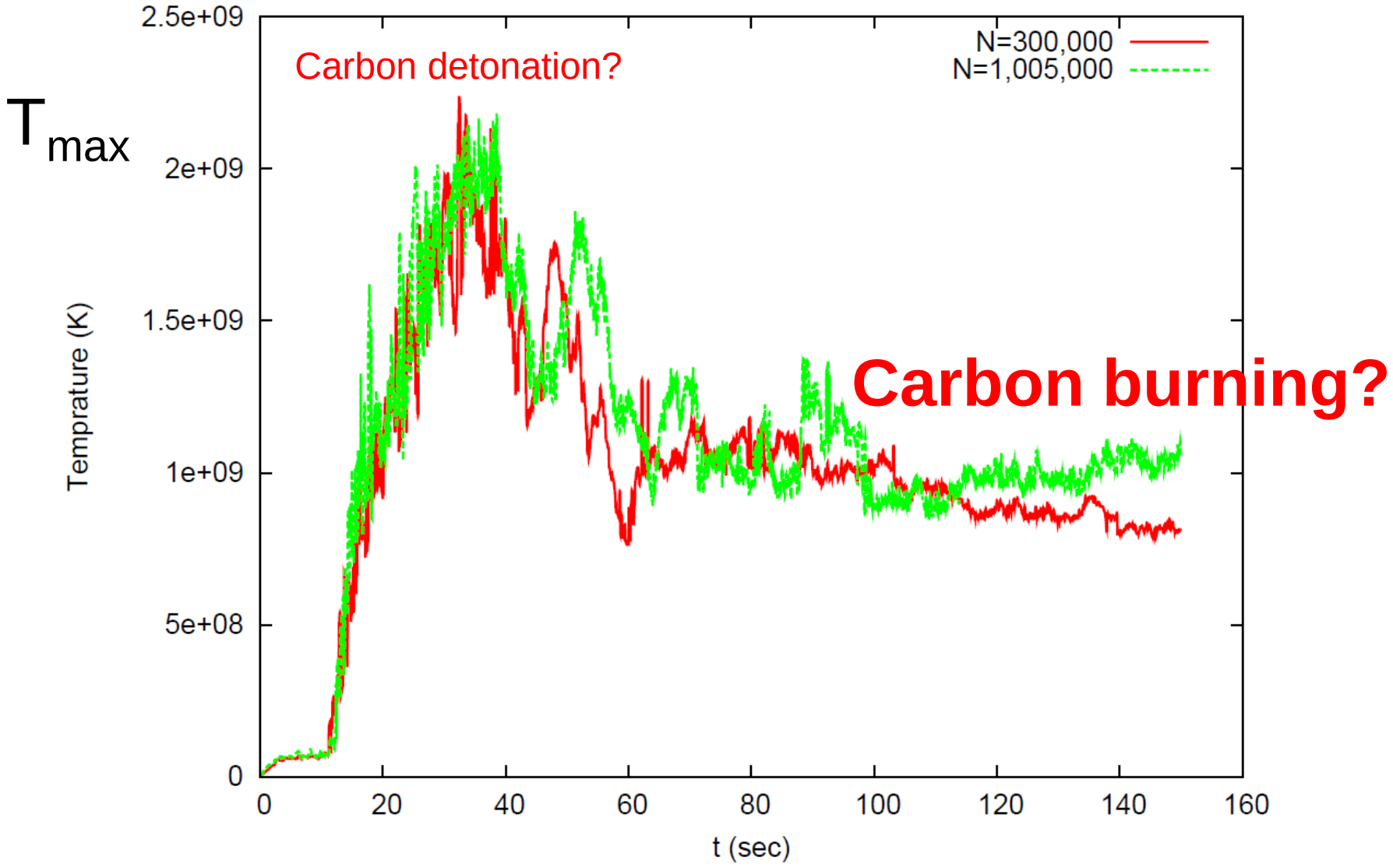
➔ central C-detonation (Pakmor+ 09, 11)

M(eff) ~ M(primary WD) ~ 0.9 – 1.1 $M_\odot$

$\rho_c \sim 10^{7-8}$ g cm^{-3} ➔ “sub-Chandra”

If not, ➔ ~ steady state

WD Merging (1.0+0.7)



(Nakasato+ 11)

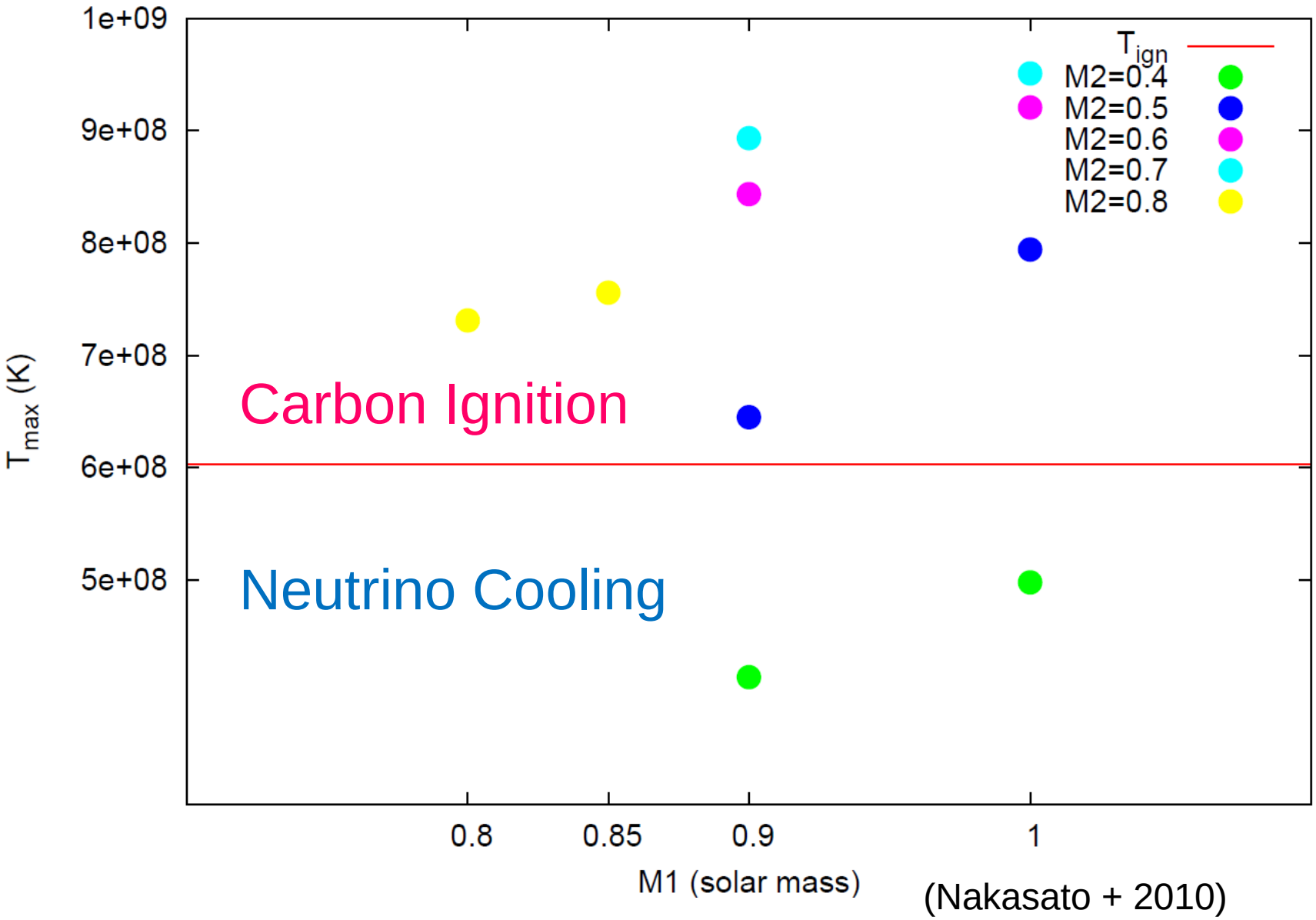
Double Degenerate Scenario

- If $T_{max} < 6 \times 10^8$ K (~ surface)
  - → C+C rate < Neutrino cooling rate
  - → no surface C-ignition (Yoon+2007)
  - ➔ central C-ignition (accretion rate?)

    ("Chandra" or "super-Chandra")

- If $T_{max} > 6 \times 10^8$ K (~ surface)
  - → C+C rate > Neutrino cooling rate
  - → surface C-Ignition (➔ inward)
  - ➔ ONeMg WD

WD Merging: T_{max} (M_1, M_2)

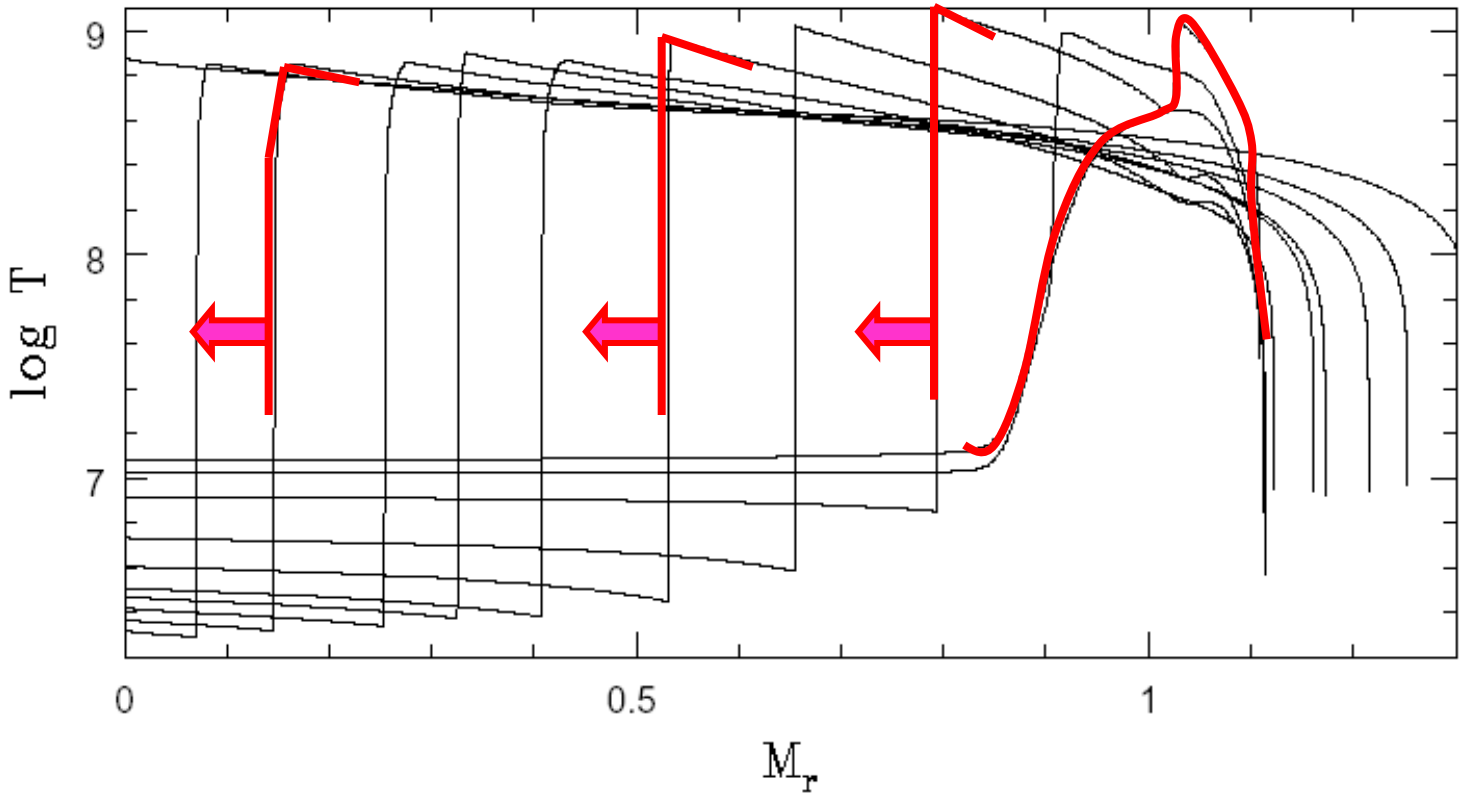


(Nakasato + 2010)

Carbon Flame

C+O WD → O+Ne+Mg WD

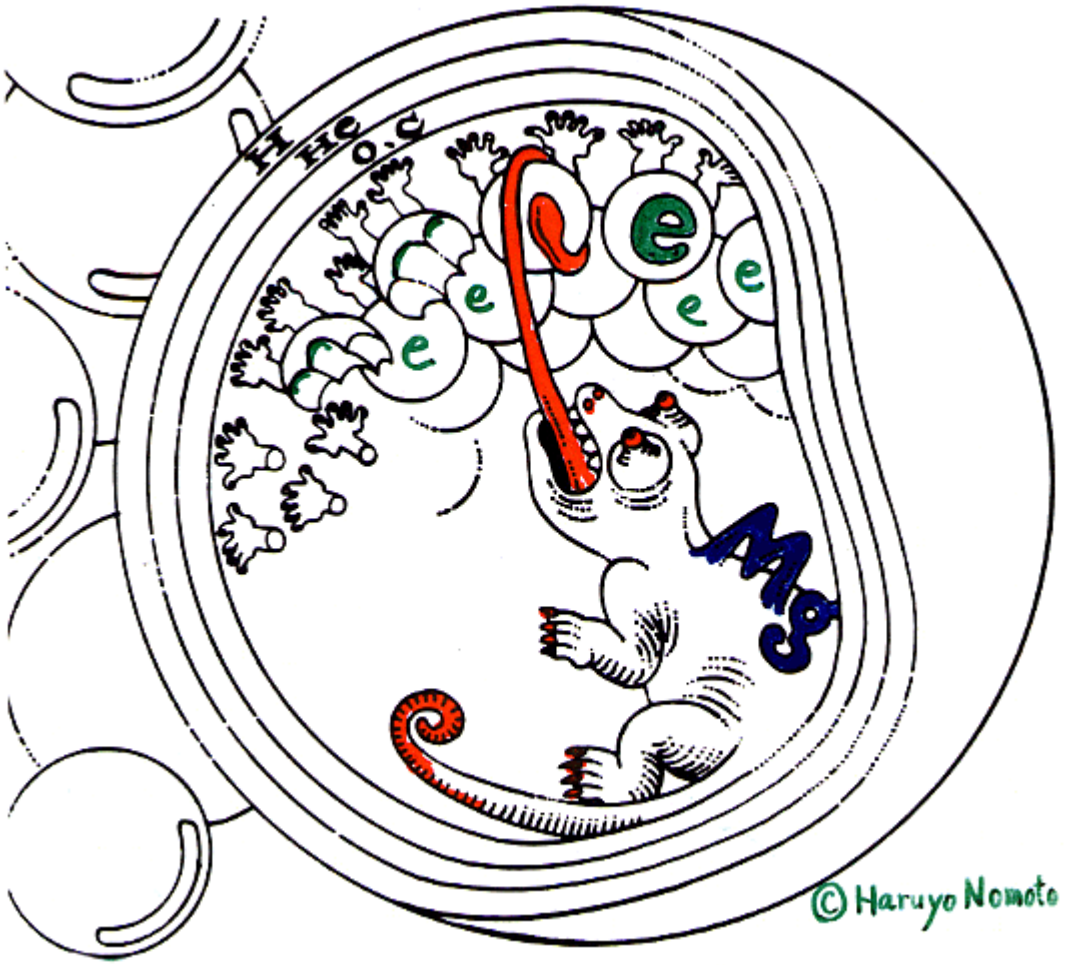
C+O → O+Ne+Mg



(Saio & Nomoto)

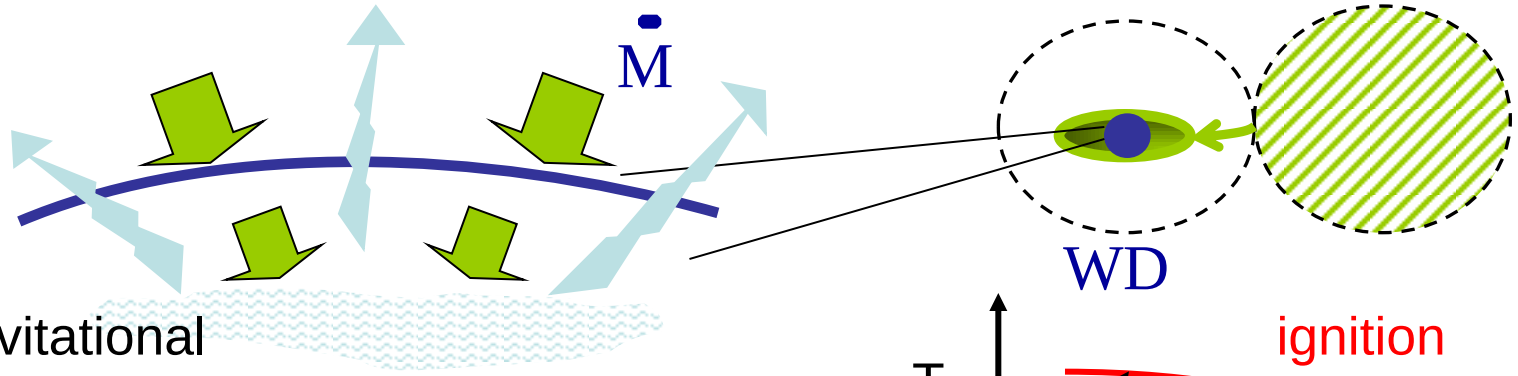
Electron Capture in ONeMg WD

- $^{24}Mg(e^-,\nu)^{24}Na$ $(e^-,\nu)^{24}Ne$
- $\rho > 4.0 \times 10^9 gcm^{-3}$
- $\rightarrow$**collapse**



Single Degenerate Scenario

(1) Compressional Heating

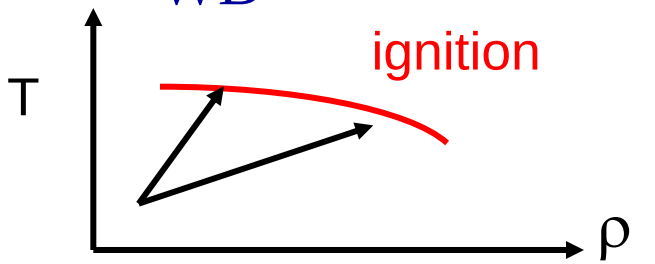


Gravitational
Energy Release

||

Compressional Heating

$\propto \dot{M}$

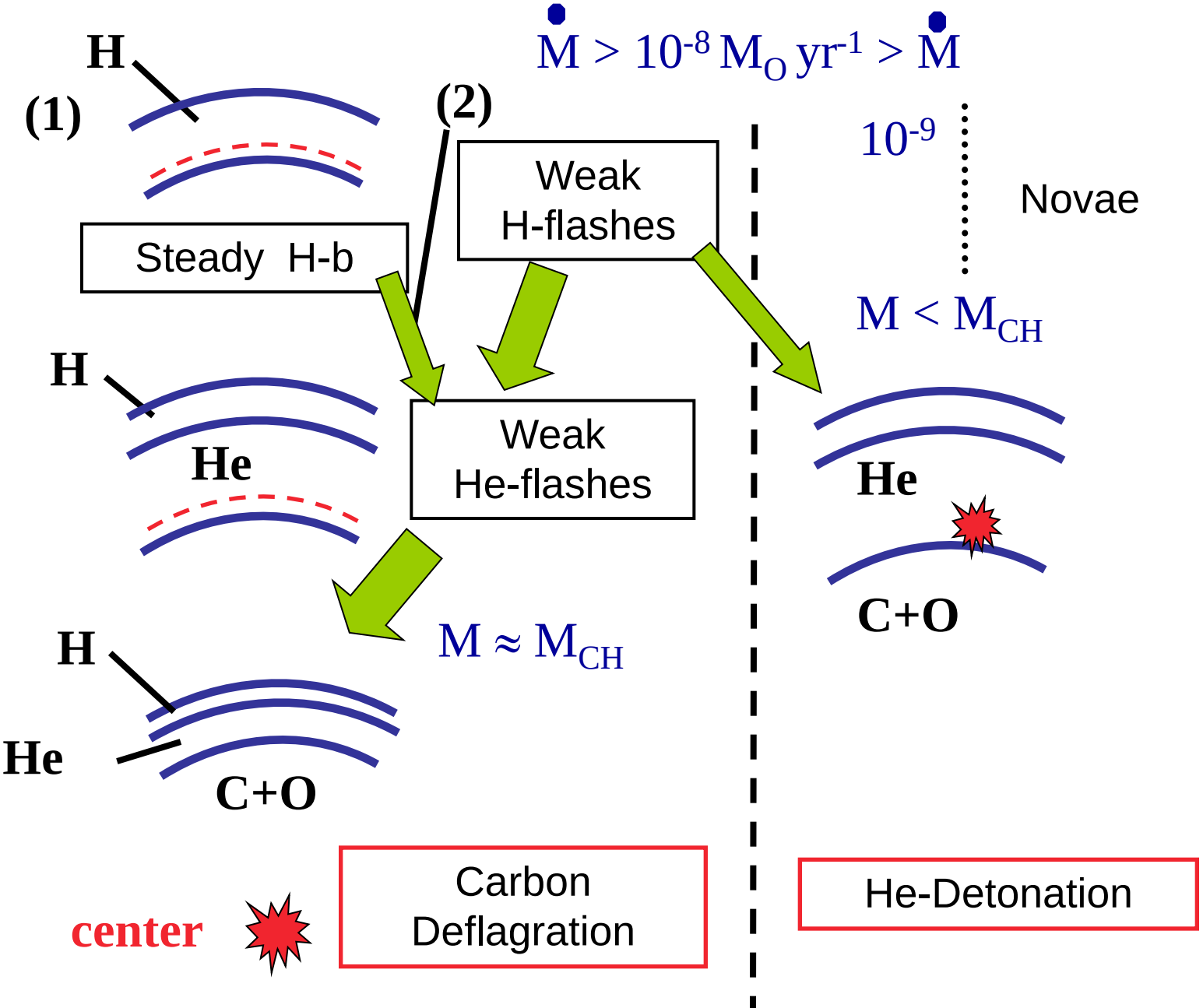


Radiative
Cooling

(ρ, T)

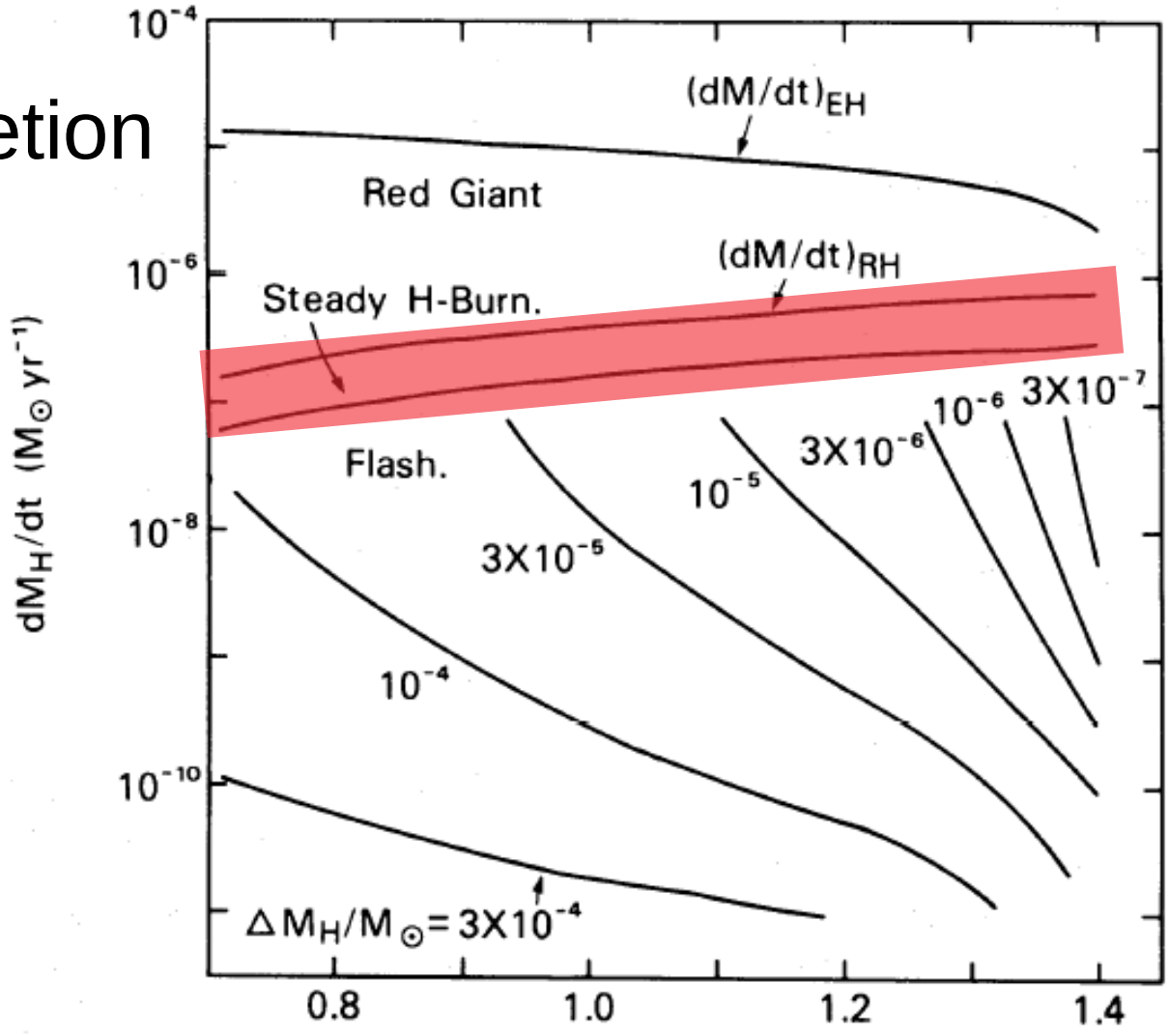
Thermonuclear Explosions ($\dot{M}$)

(2) Nuclear Burning



Hydrogen Burning in Accreting WD

Accretion Rate



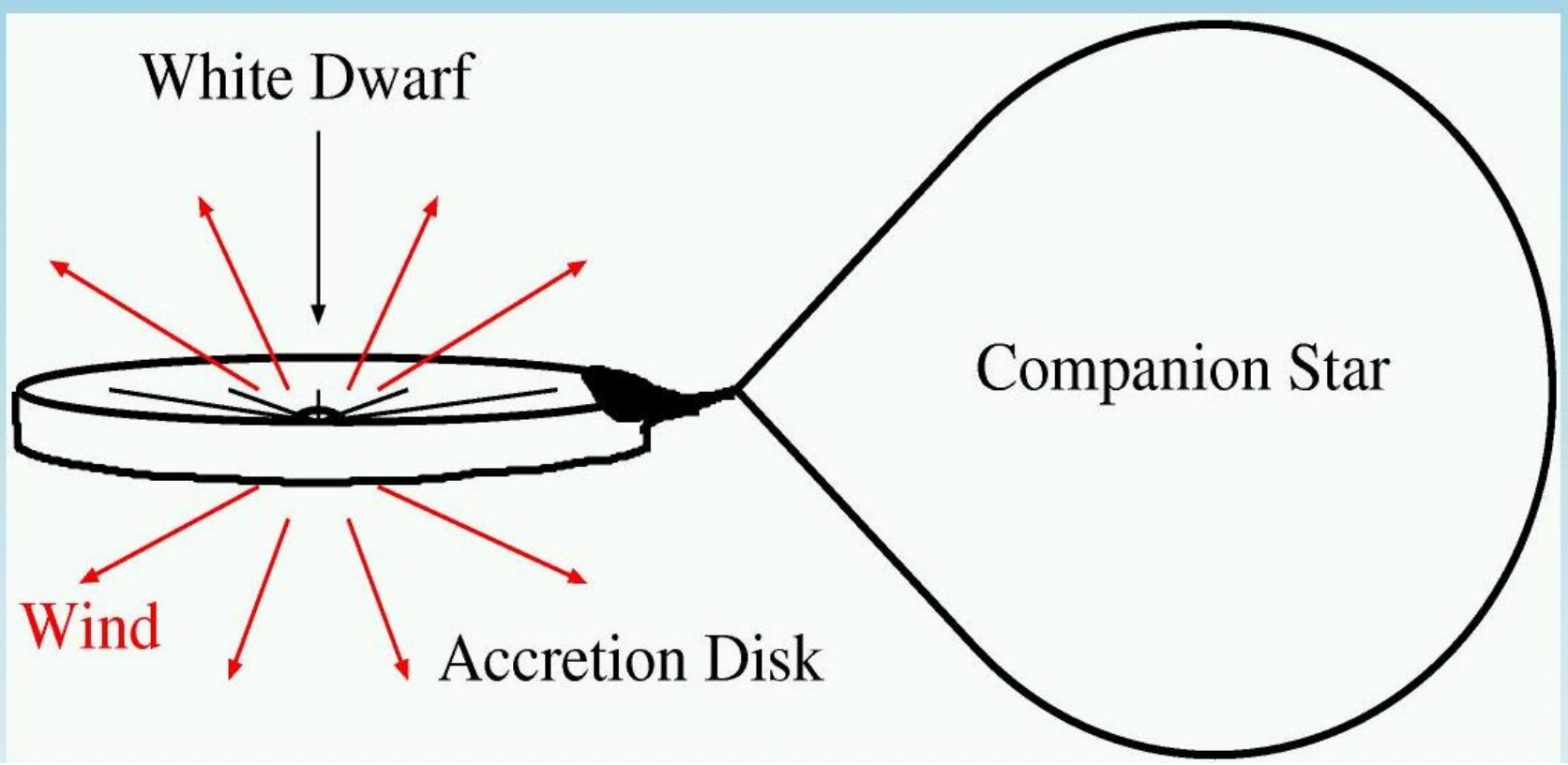
White Dwarf Mass

Nomoto (1982)

(3) White Dwarf Wind

(Hachisu, Kato, & Nomoto 1996)

$$\dot{M}_{\rm acc} > \dot{M}_{\rm cr} \rightarrow \text{Winds}$$

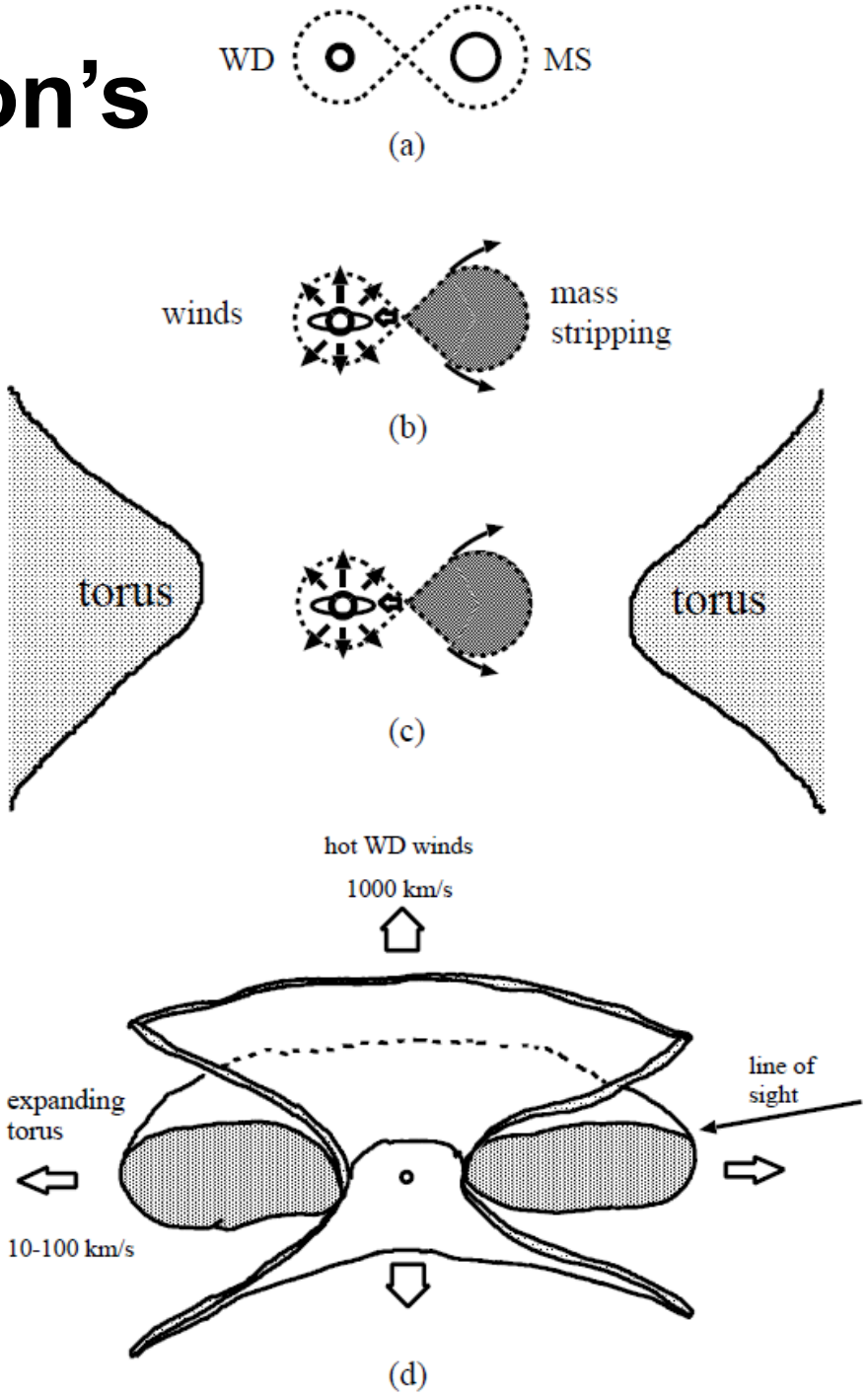


Stripping of Companion's Mass

➔ **Mass Transfer Rate reduced**

➔ **Massive (young) Companion → SN Ia**

→**Circumstellar Matter 10-100 km/S**



Hachisu, Kato, Nomoto (2008a)
ApJ 679, 1390

Candidate Progenitor Systems for Carbon Ignitors

Hachisu, Kato, Nomoto
Lee, van den Heuvel
Han, Podsiadlowski

$$4\times10^{-8} < \dot{M}\,(M_\odot\,yr^{-1}) < 2\times10^{-6}$$

Companion

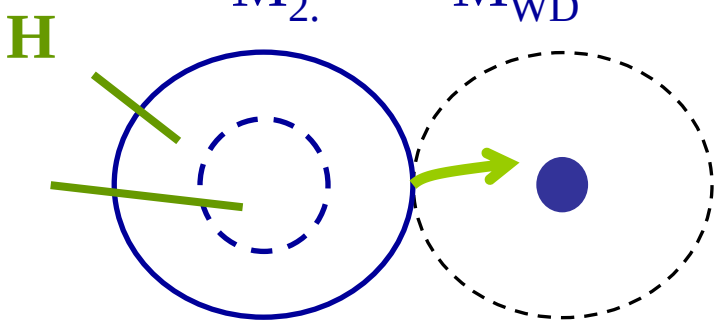
(1) H: leaving M.S.

$\dot{M}_2 \sim M_2/\tau_{KH}\ (\sim 3\times10^{-8} M_2^4)$

$\sim\ 3\times10^{-8} \quad 5\times10^{-7} \quad 2\times10^{-6}$

$M_{2,ms} \sim\ 1M_\odot \quad 2M_\odot \quad \sim 8M_\odot$

$M_{2.} > M_{WD}$

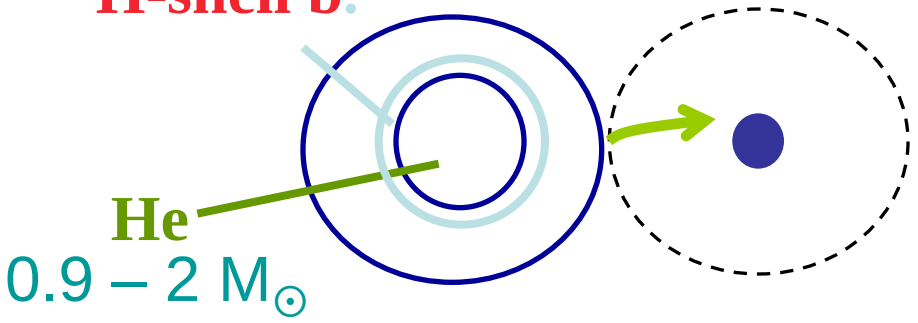


(2) H: sub giant, red giant

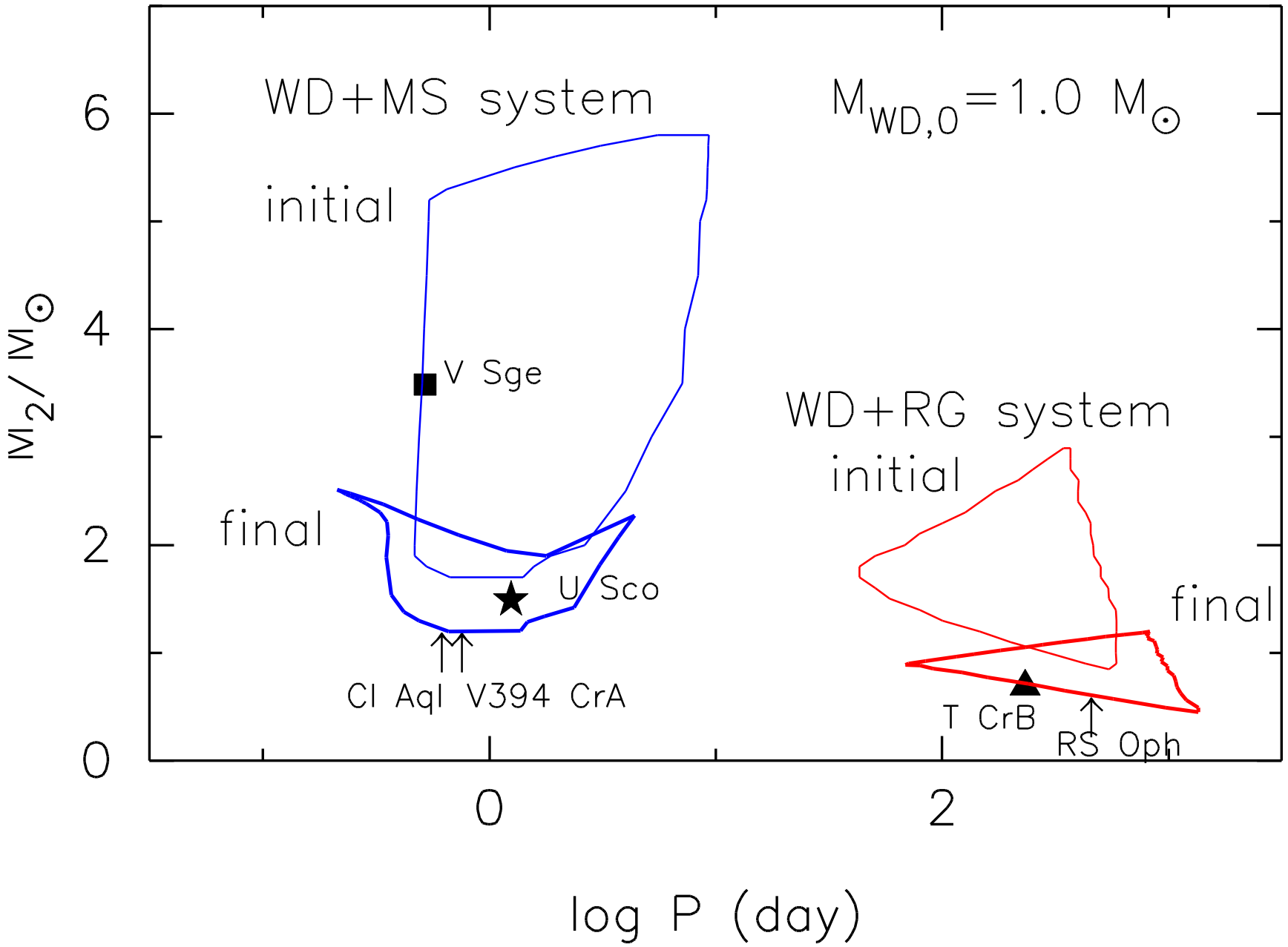
$\dot{M}_2 \sim M_2/\tau_{nuclear}$

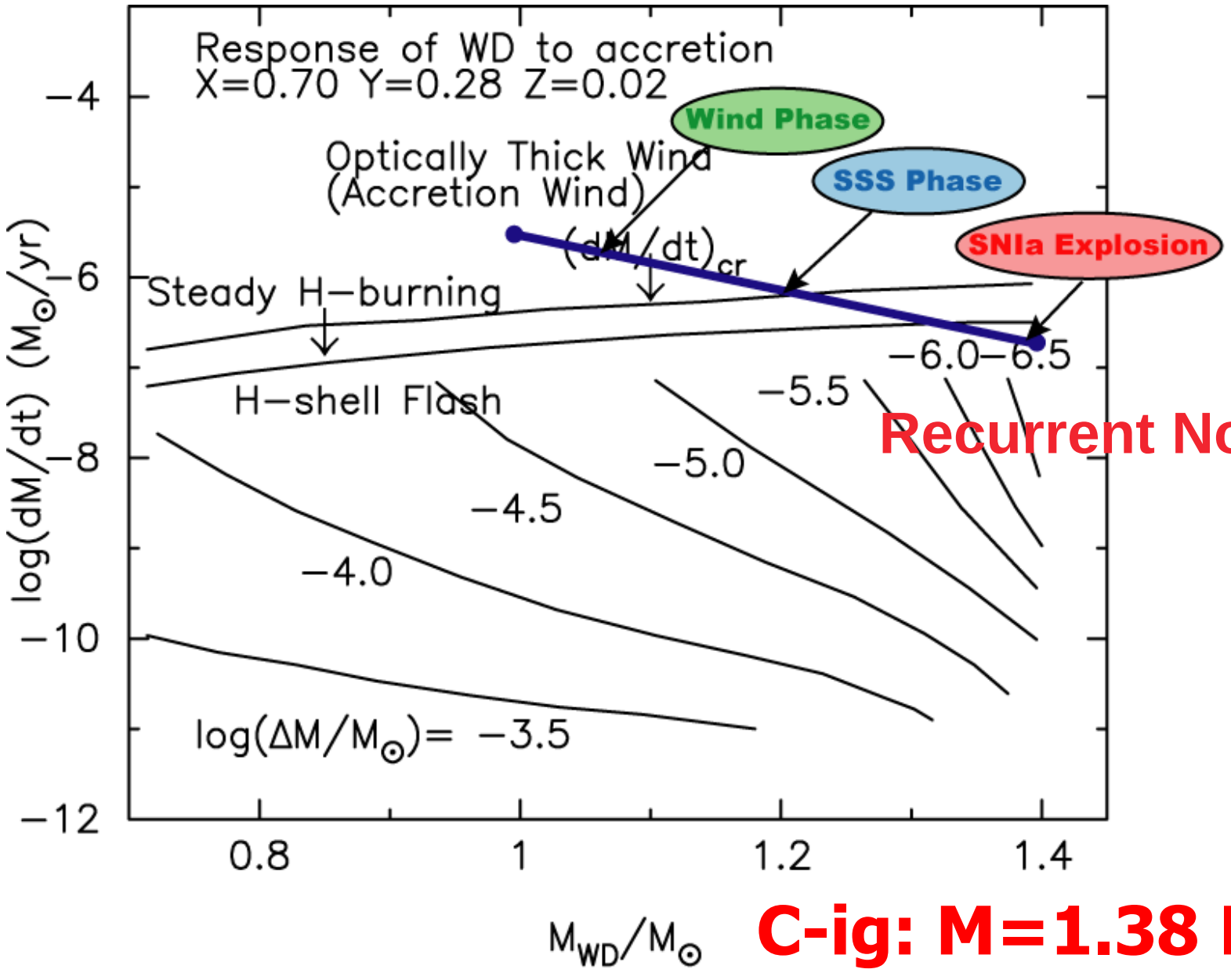
$\sim 10^{-8} \sim 10^{-6}\ M_\odot/yr$

$M_{2.} < M_{WD}$



SN Ia Progenitor System(MS, RG)




Response of WD to accretion
X=0.70 Y=0.28 Z=0.02
Wind Phase
SSS Phase
SNIa Explosion
Optically Thick Wind
(Accretion Wind)
(dM/dt)cr
Steady H−burning
H−shell Flash
−6.0−6.5
−5.5
−5.0
−4.5
−4.0
log(ΔM/M⊙)= −3.5
log(dM/dt) (M⊙/yr)
−4
−6
−8
−10
−12
0.8
1
1.2
1.4
MWD/M⊙
Recurrent Nova
C-ig: M=1.38 M⊙

Single Degenerate Scenario

M(wd, 0) + $M_{2,0}$: P_0 (initial orbital period)

➔ M(wd, final) [~ 1.38 $M_\odot$] + M_2(final)

(1) Compressional Heating ($\dot{M}$)

(2) H & He Burning

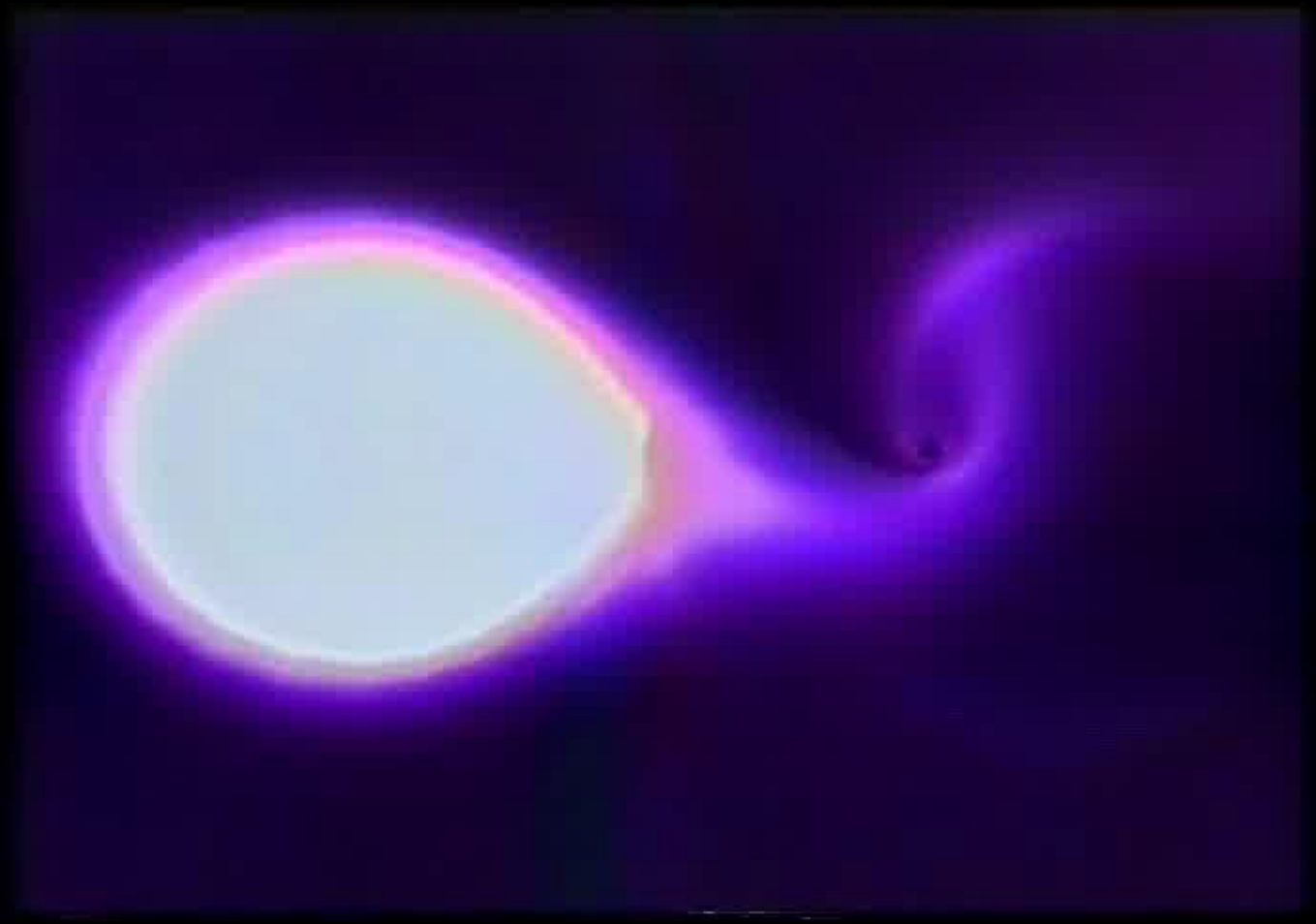
(3) Radiation-driven WD Winds

(4) Steady Hydrogen Burning

(5) **Recurrent Novae**

➔ **Central Ignition of Carbon Burning**

Mass Transfer in a SD system



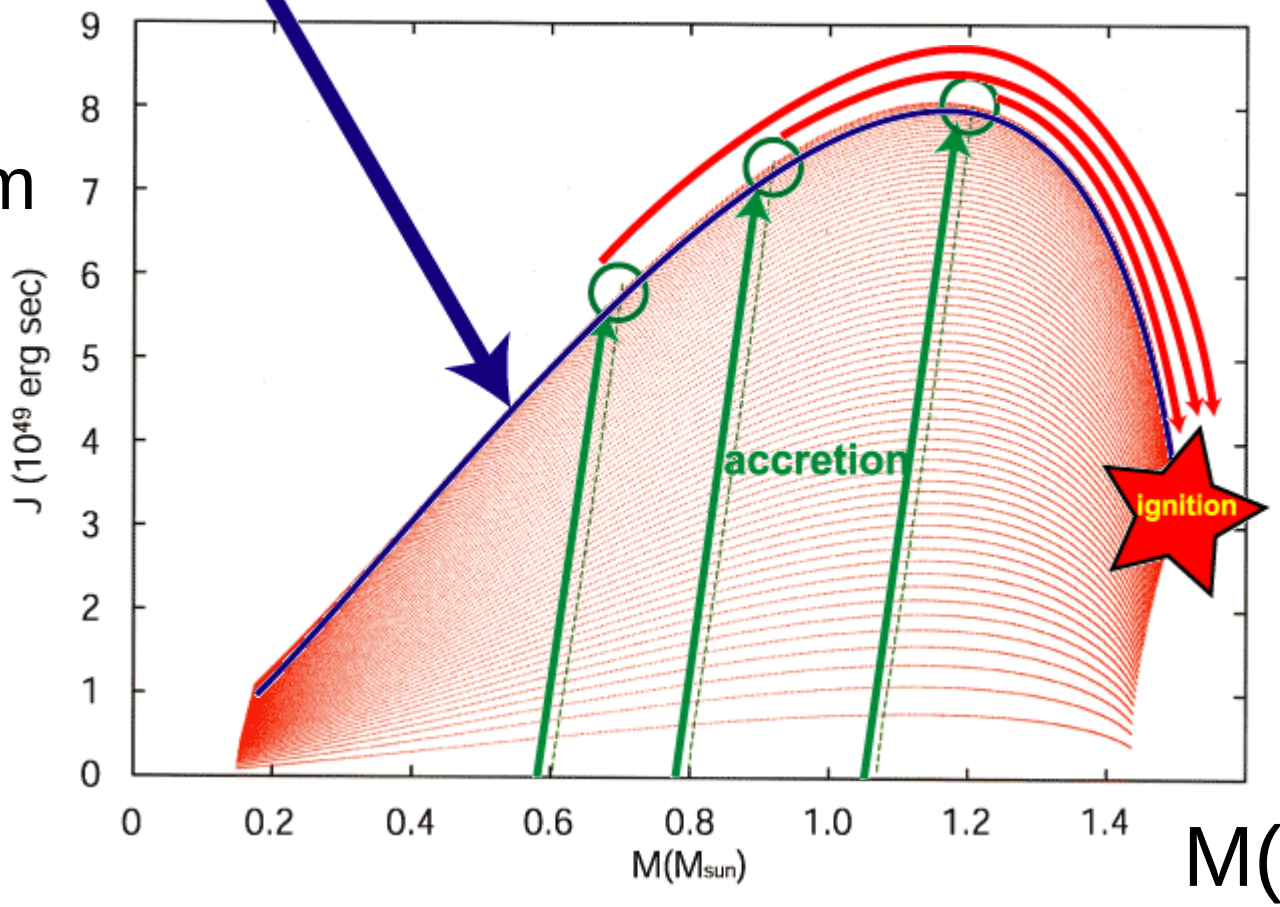
(T. Matsuda)

Evolution of Rotating White Dwarfs

Critical Rotation (Uniform rotation)

$\Omega_C=(GM/R^3)^{1/2}$

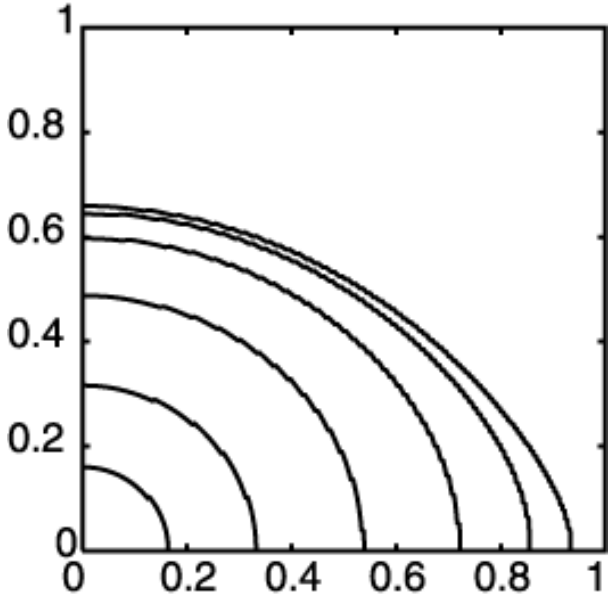
Angular Momentum



M(wd)

(e.g., Ostriker, Pacynski, Narayan, Hachisu, Piersanti, Yoon, Saio)

Structure of Rotating WDs



Uniform Rotation

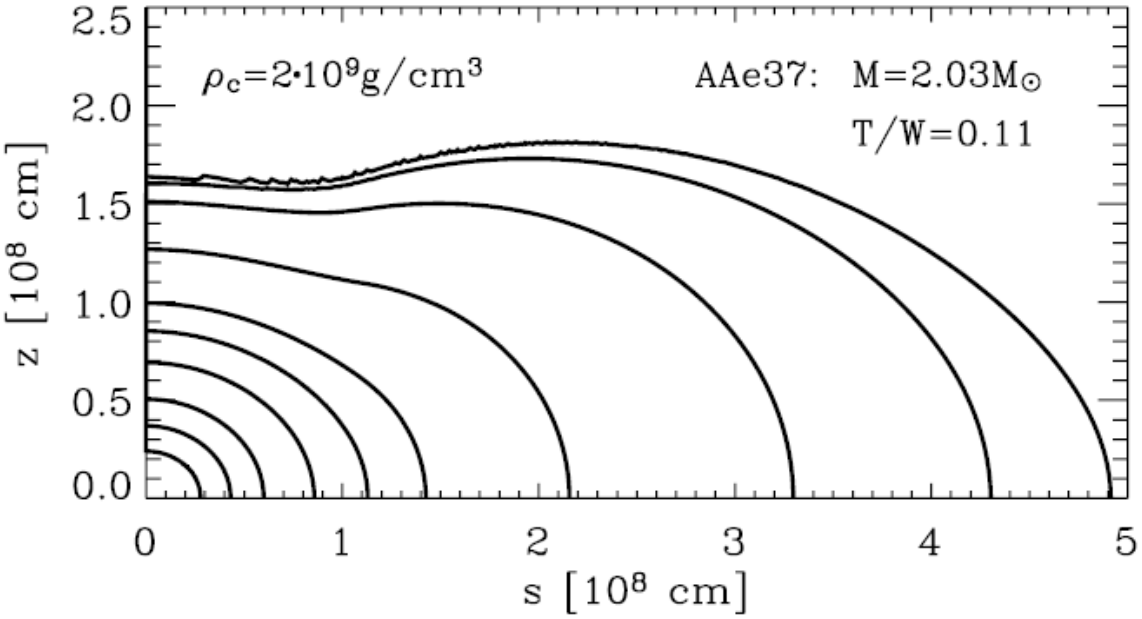
M=1.48 $M_\odot$, J=4.63

Rotation Period = 2.3sec

ρ_c=2.0e9 (Ignition)

q=0.66

(Uenishi, Nomoto, Hachisu 03)



Differential Rotation

M=2.03 $M_\odot$

ρ_c=2.0e9 (Ignition)

(Yoon, Langer 05)

SD Scenario for Rotating WDs

(**Spin-up, Spin-down scenario**: Justham 11, Di Stehano+ 11, HKN 12)

M(wd, 0) + M_2 (P_0) ➔

Accretion ➔ **Spin-Up** of WD (uniform rotation)

Accretion continues beyond M(wd) = 1.4 $M_\odot$

(1) M(wd, final) = 1.5 $M_\odot$ (**prompt** C-ignition)

(2) M(wd, final) = 1.4 - 1.5 $M_\odot$ (**no** C-ignition)

$dM/dt < 1 \times 10^{-7} M_\odot y^{-1}$

➔ strong Nova outbursts : mass ejection

➔ M(wd) does not increase

SNe Ia from Uniformly Rotating WDs

(1) $M_{wd,\ final}/M_{\odot}$ = 1.5 (~ 55 %) :

Prompt Carbon-Ignition

(➔ e.g., PTF11kx)

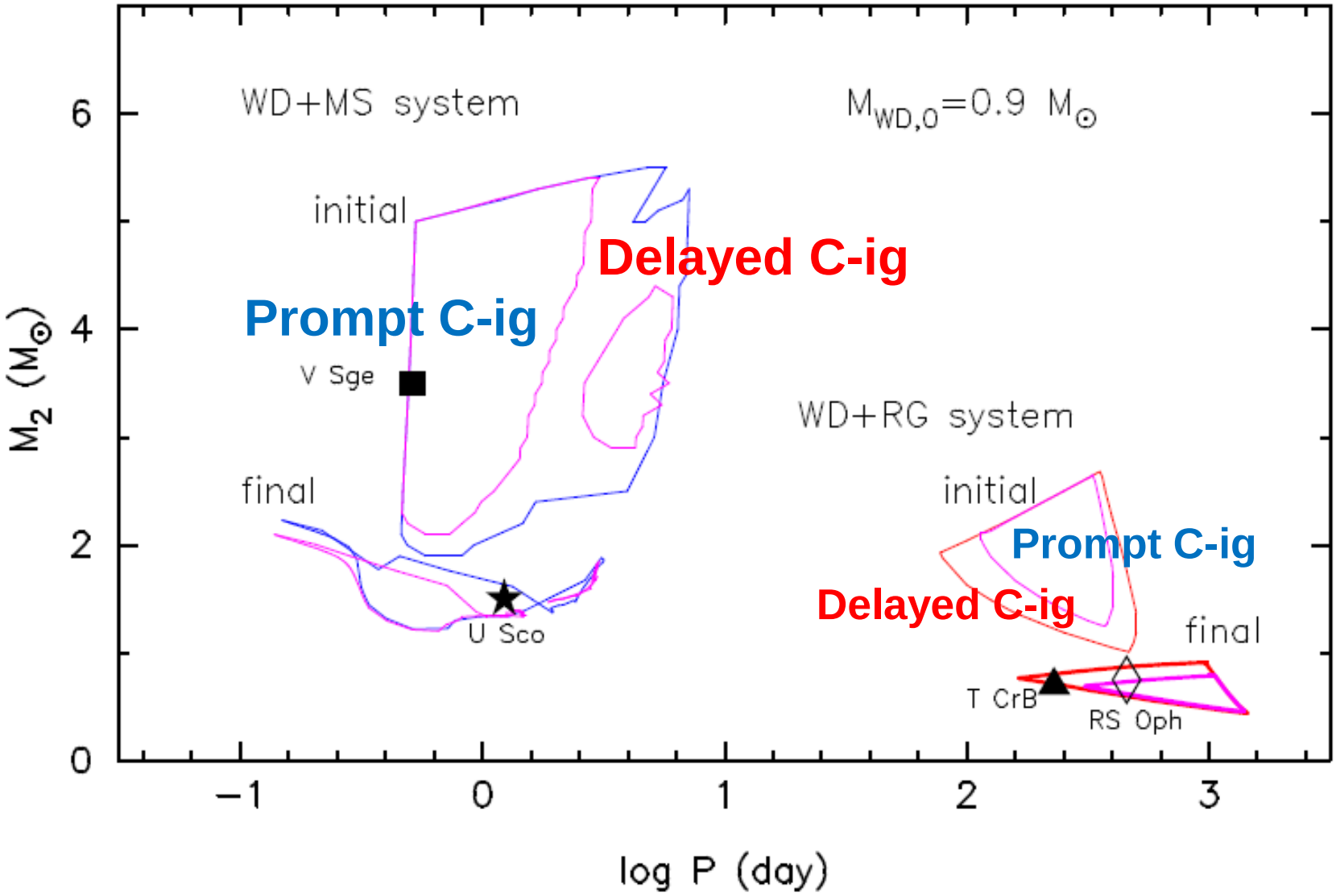
(2) $M_{wd,\ final}/M_{\odot}$ = 1.4 - 1.5 (~ 45 %)

Spin-down: angular momentum loss

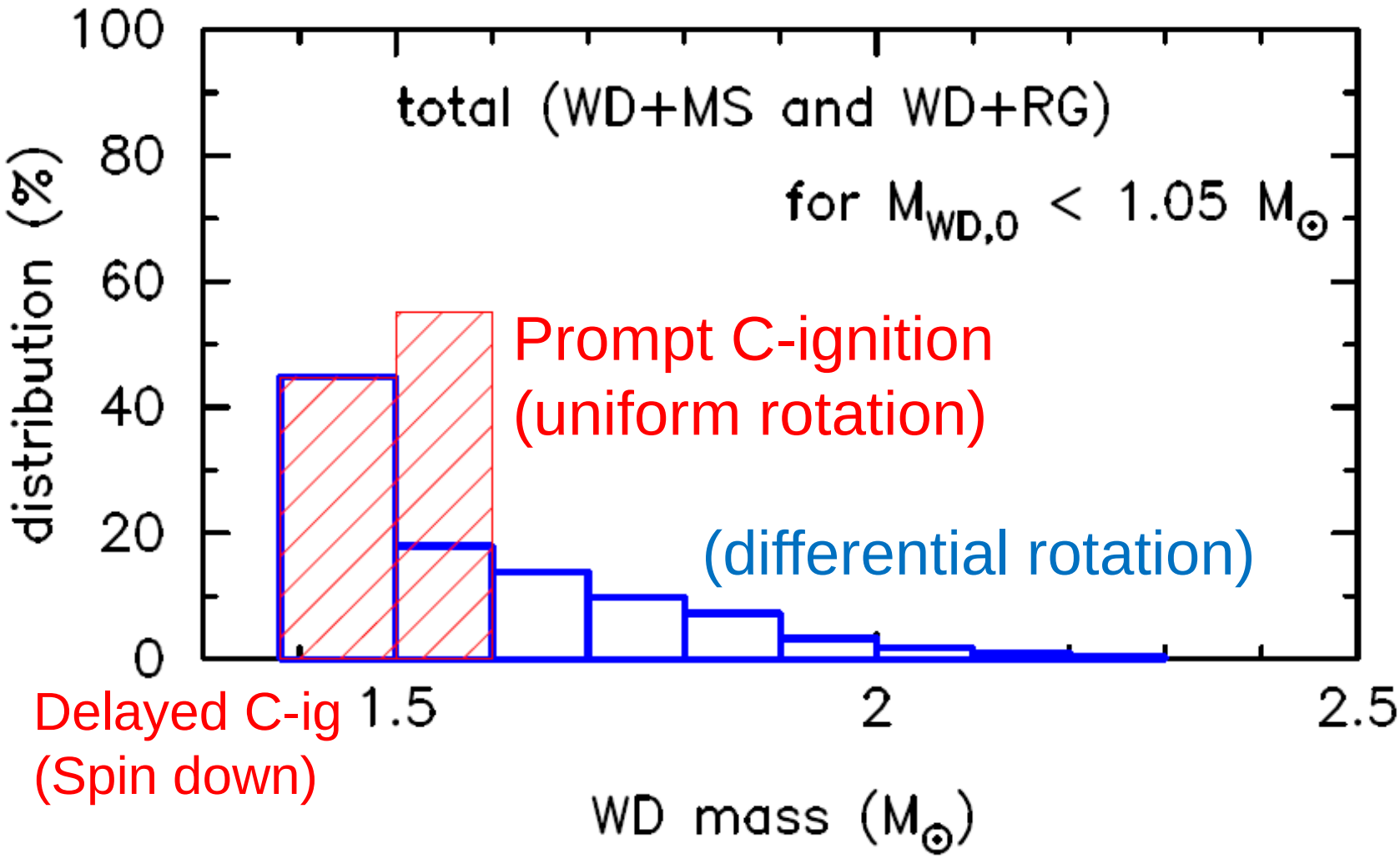
(←magnetic wind,,,,,,,)

➔ **Delayed** Carbon-Ignition

Uniformly Rotating WDs:
Prompt vs. **Delayed** Carbon-Ignition



Mass Distribution of Rotating WDs



Companions of Rotating WDs

M_2 continues to decrease by mass transfer ($\sim 1 \times 10^{-8}\ M_\odot\ y^{-1}$) during the spin-down time.

(1) RG ➔ He WD by losing H-envelope

(2) MS ➔ low mass MS ($M_2 < 1\ M_\odot$), or

➔ He WD by losing H-envelope

Companions become low mass, compact stars:

➔ missing companions

Circumstellar matter : dispersed.

Single Degenerate Scenario

Rotating White Dwarfs

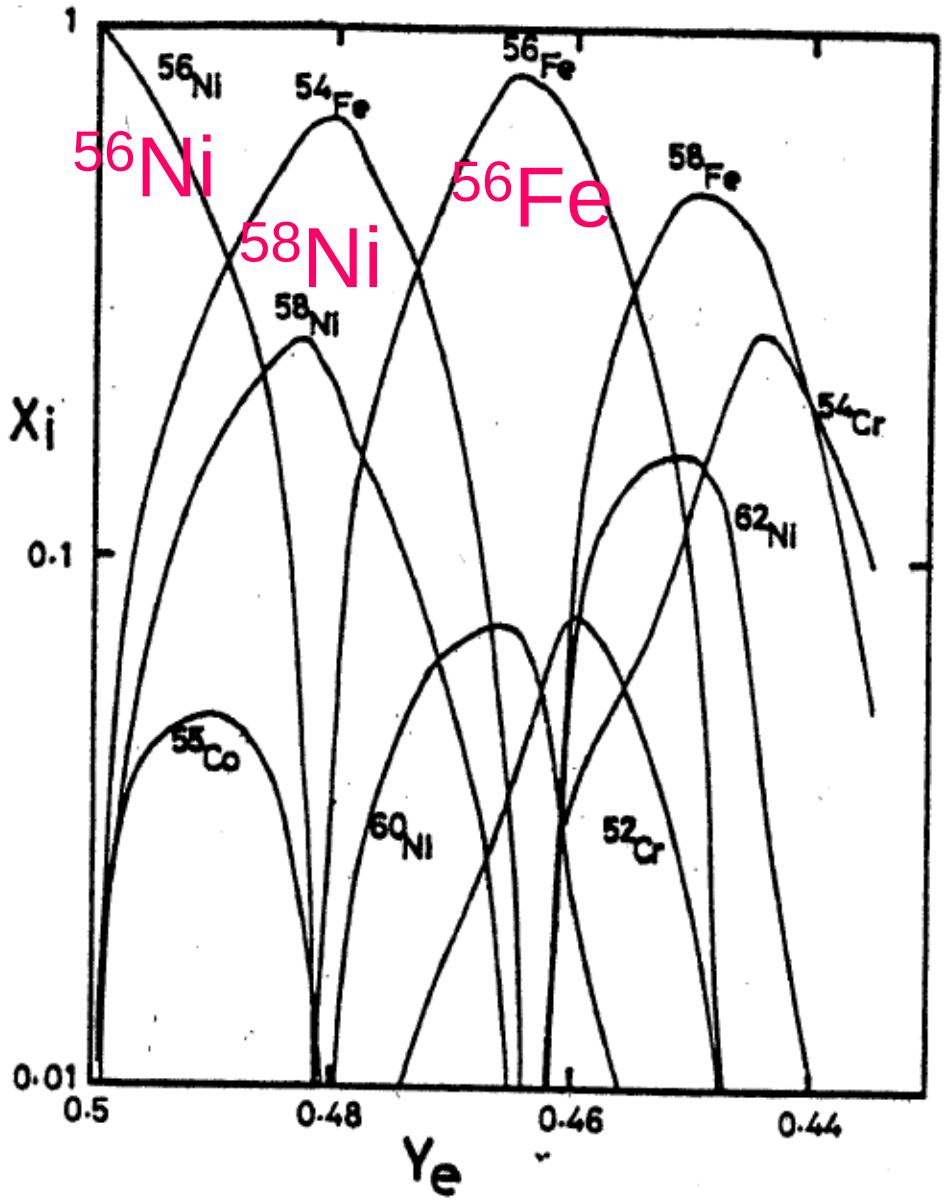
➔ Prompt & Delayed Carbon Ignition

➔ Spin-up, Spin-down scenario can solve the **missing companion** problem.

- mechanism & timescale of spin-down

(e.g., Ilkov & Soker 11)

Nucleosynthesis in Chandrasekhar Mass Models



Carbon deflagration at
$\rho_c > 10^9$ g cm^{-3}

➔ NSE & Electron Capture

➔ lower Y_e (neutron-rich)
^{58}Ni, ^{56}Fe

➔Late time spectra:
Ni, Fe

Nuclear Statistical Equilibrium (NSE: Y_e)

Chandrasekhar Mass Models

Urca cooling ➔ Higher ρ_c

$^{25}Mg <-> ^{25}Na$, $^{23}Na <-> ^{23}Ne$: high metallicity

smaller M(wd,0)

Delayed C-ig ➔ Higher ρ_c ➔ more ^{58}Ni, ^{56}Fe

➔ Late time spectra: ^{58}Ni, ^{56}Fe

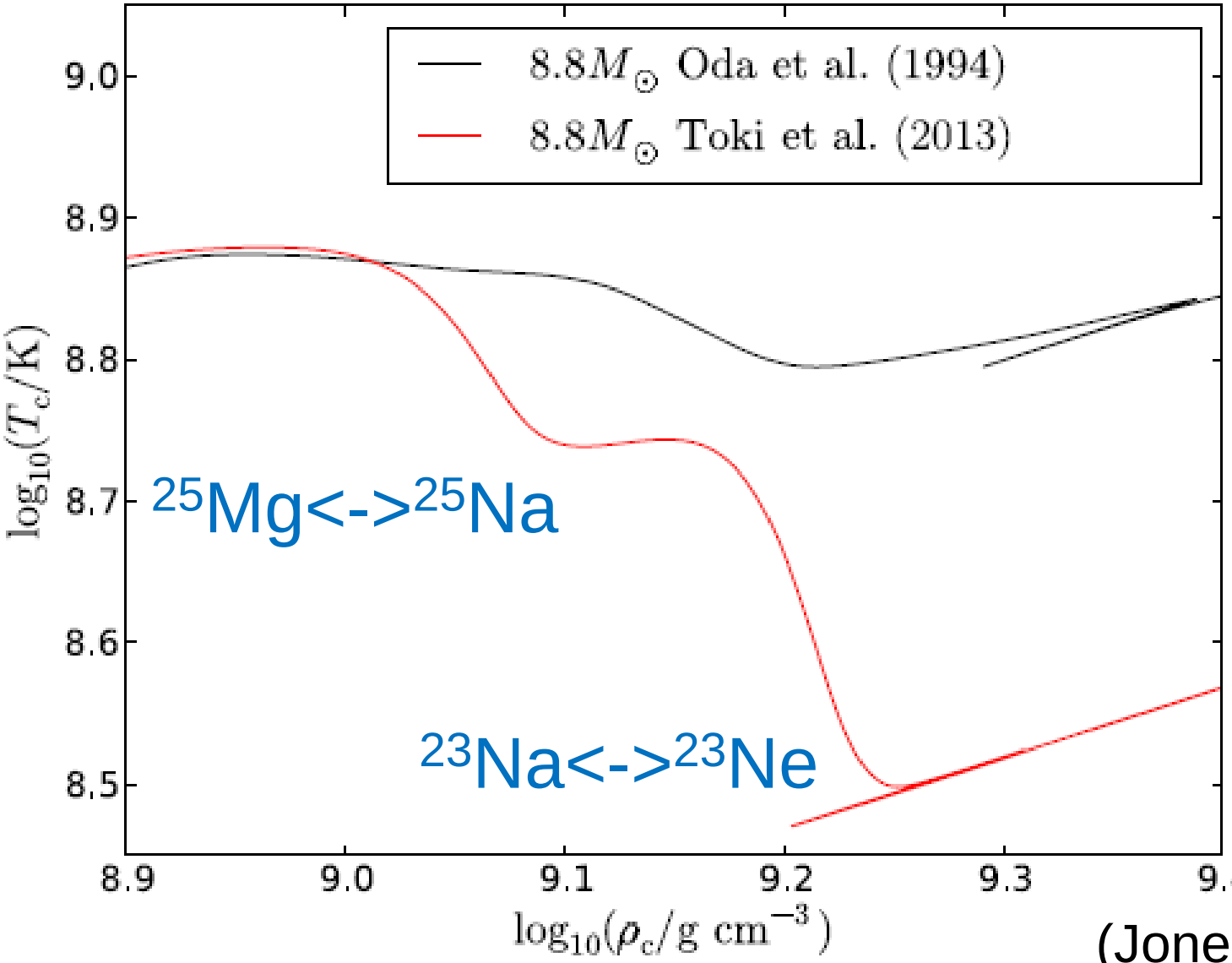
(Foley+13)

➔ Type Iax (2002cx-like) ? low M(ej), M(^{56}Ni), E

3D deflagration @ higher ρ_c ➔

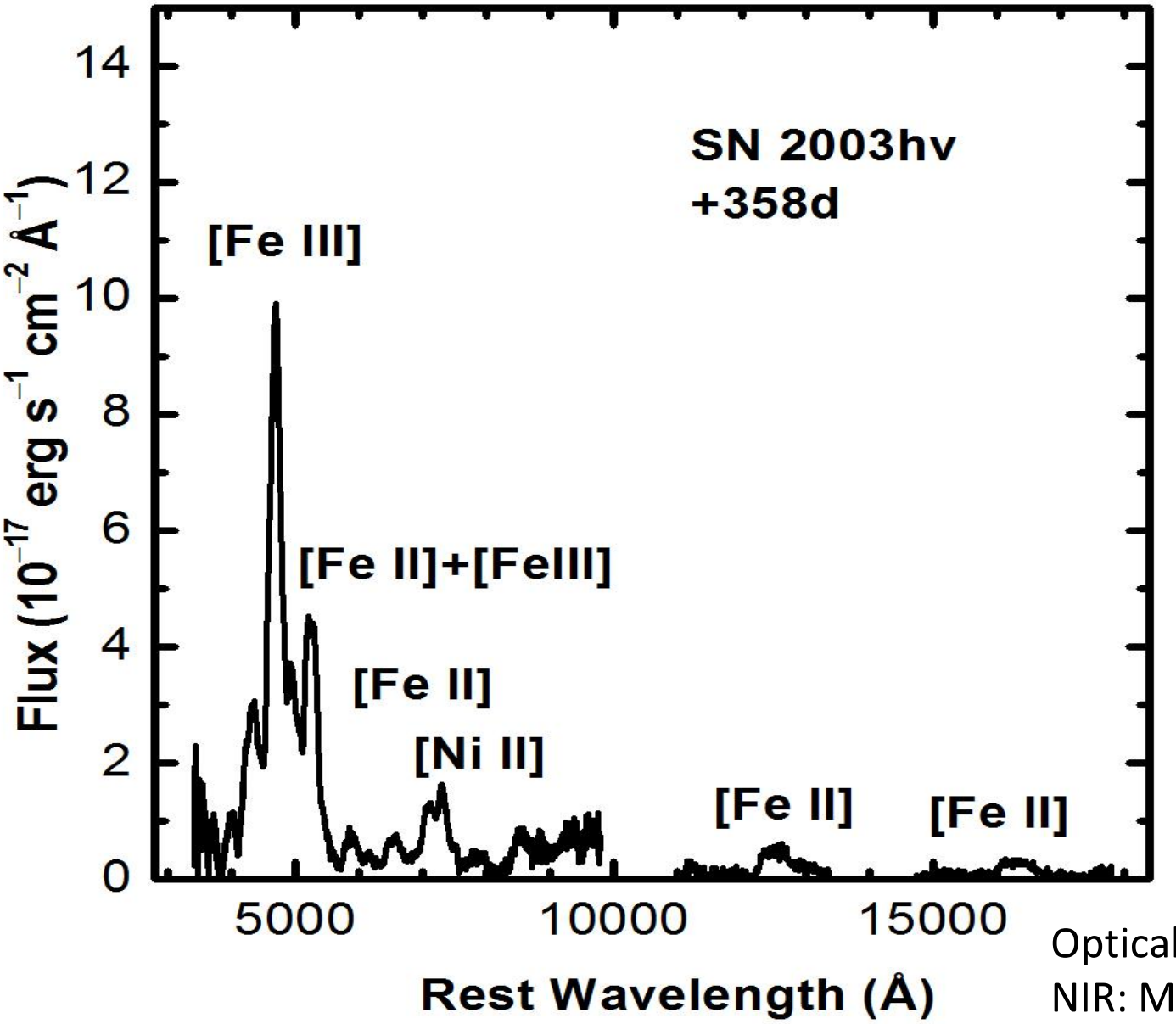
Ejecta + Bound WD remnant (Jordan+12; Kromer+13)

URCA cooling (ONeMg core)



(Jones+13)

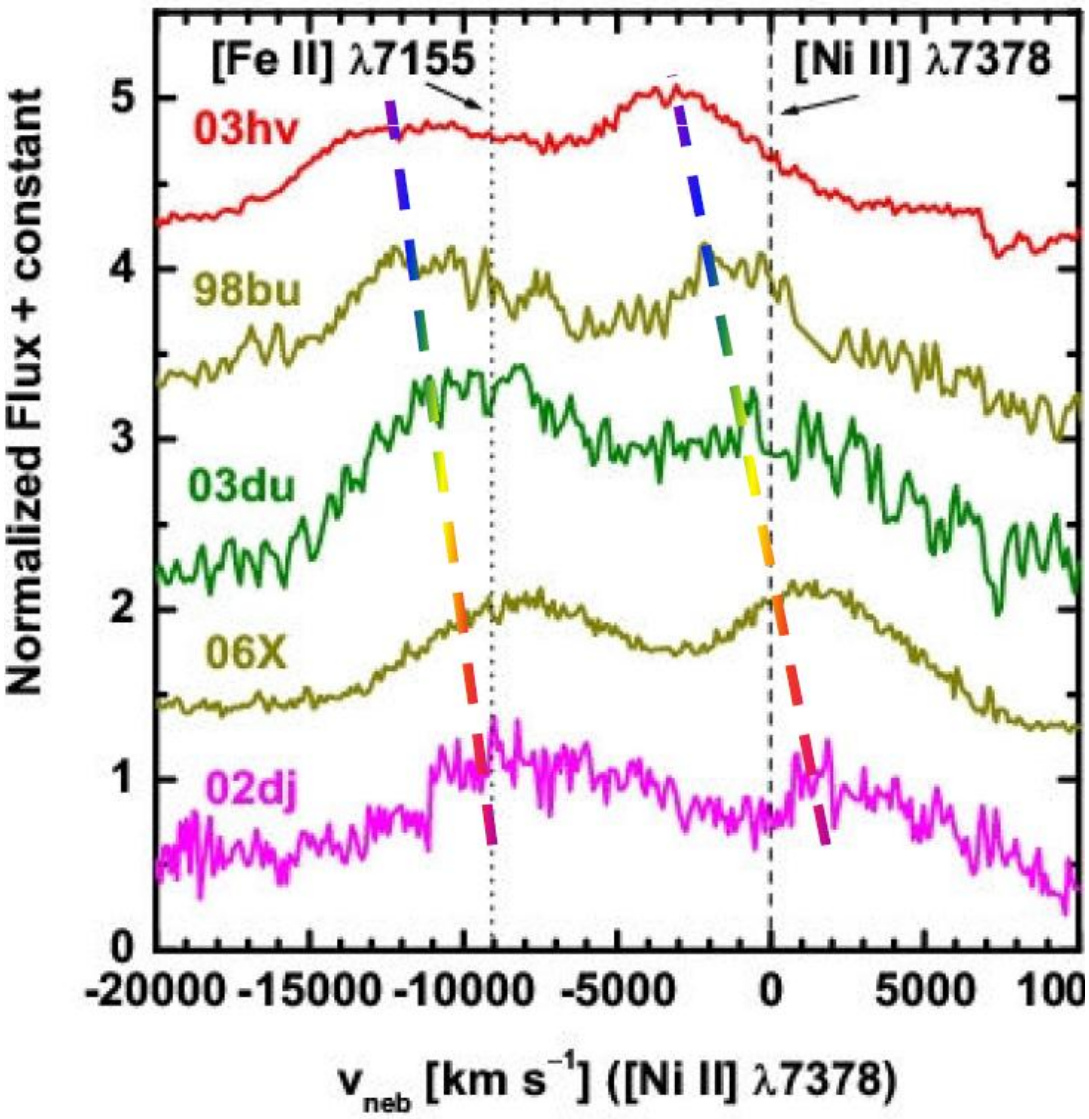
SN Ia Late-Time Spectra



Optical: Leloudas+ 09

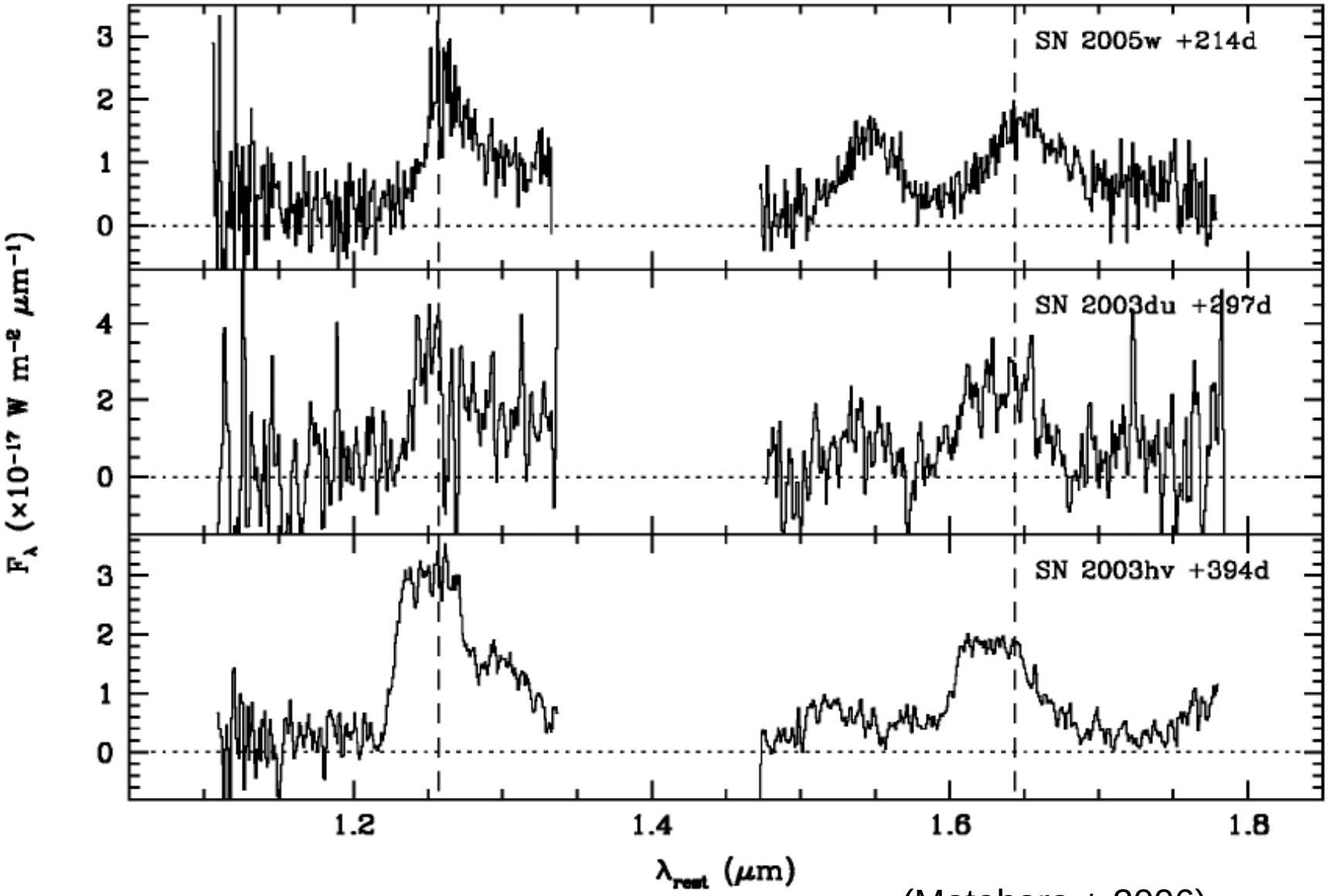
NIR: Motohara+ 06

Electron capture elements



(Maeda+ 10)

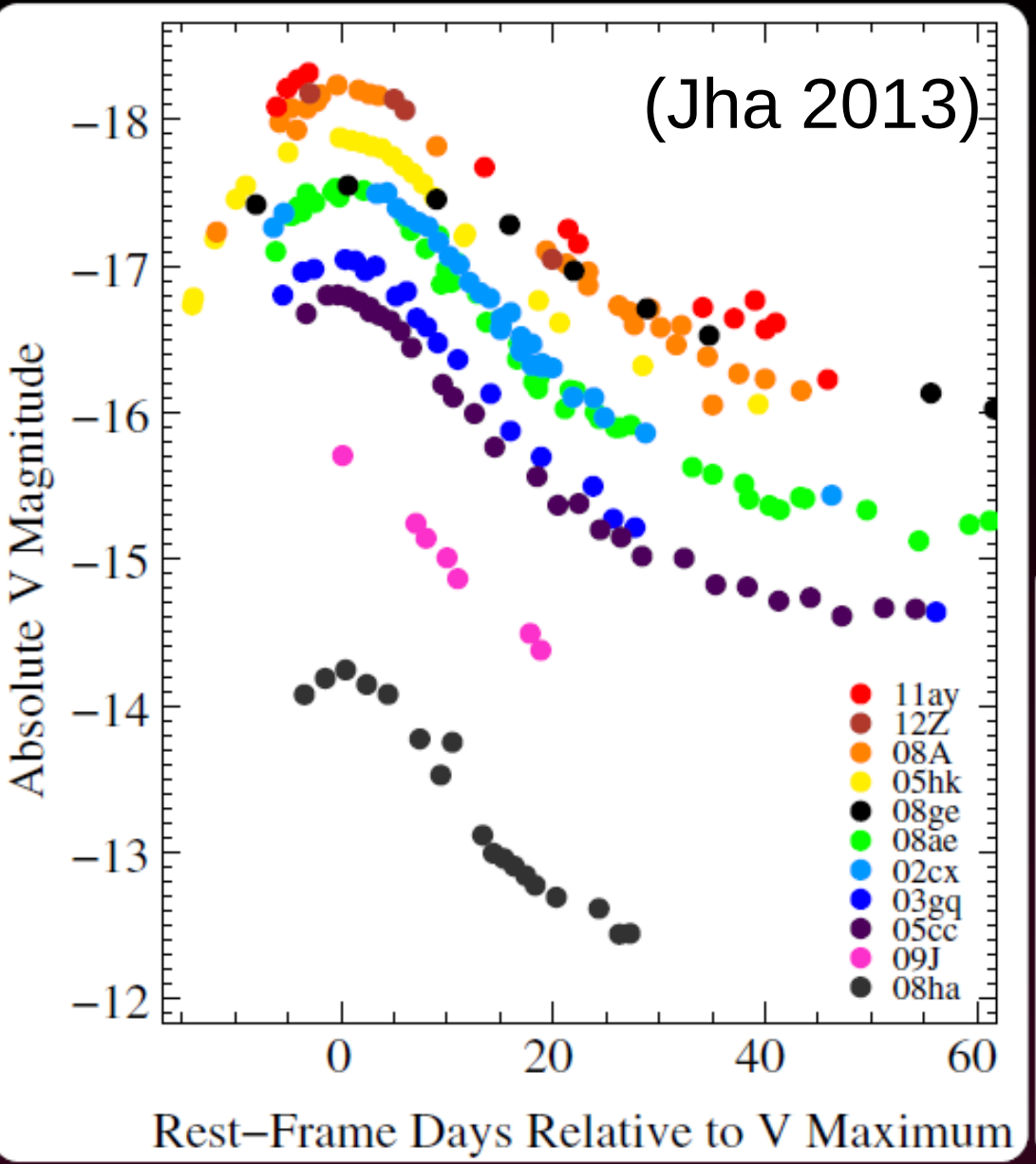
SUBARU/OHS observations of SNe Ia 05W, 03du, 03hv

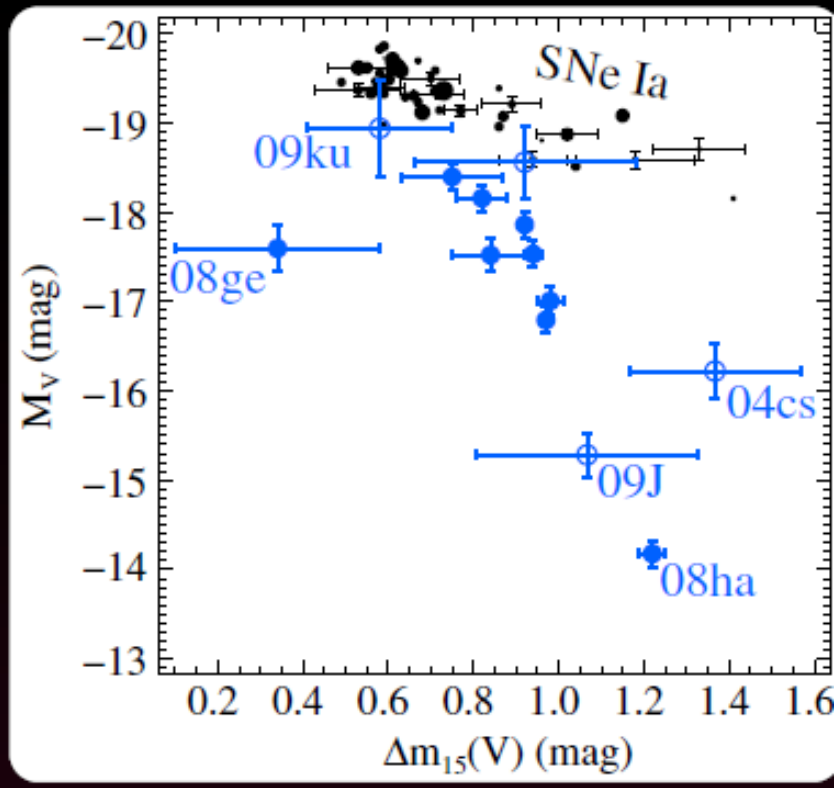


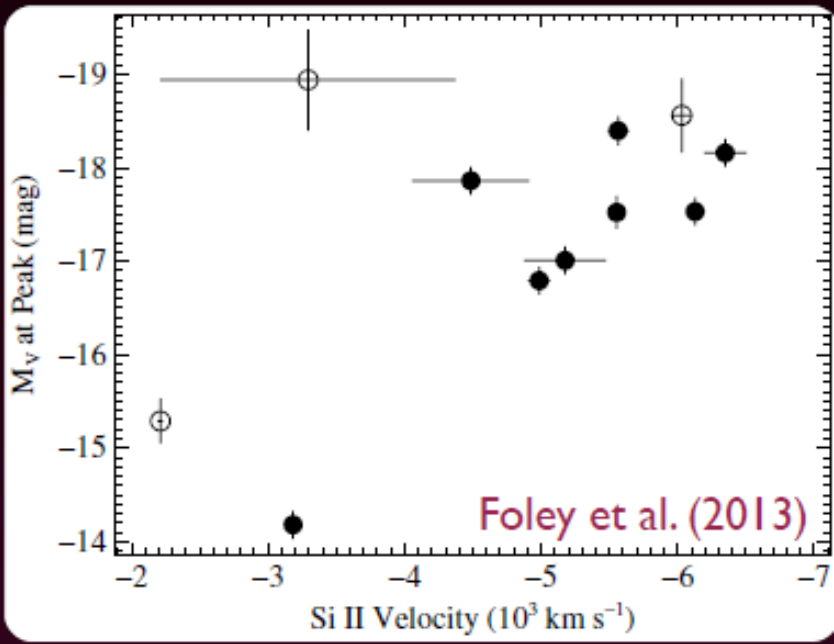
(Motohara + 2006)

Type Iax Supernovae

~25 members in the class







DD, SD ➔ Chandra, Sub-Ch

	surface burning	➔	sub-Ch	Chandra
ρ_c (g cm^{-3})	~10^6		$10^{7\text{-}8}$	$10^{9\text{-}10}$

[late time ^{58}Ni, ^{56}Fe]

DD	C-detonation ?	➔	C-det
	steady C-burning?	➔	ONeMg WD
	no ignition ?	➔	C-deflag

Prompt and Delayed C-ignition

SD	He flashes ?	➔	C-deflag
	He detonation ?	➔	C-det