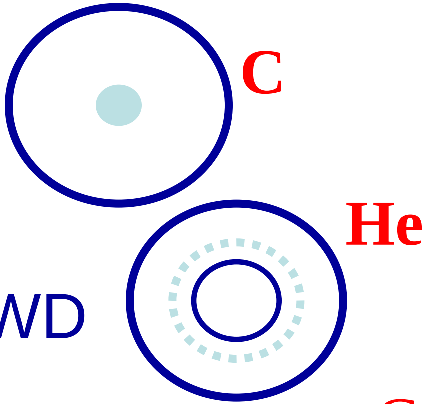
Progenitors of Type Ia Supernovae（Ia型超新星の親星）

Ken Nomoto (Kavli IPMU, U of Tokyo)

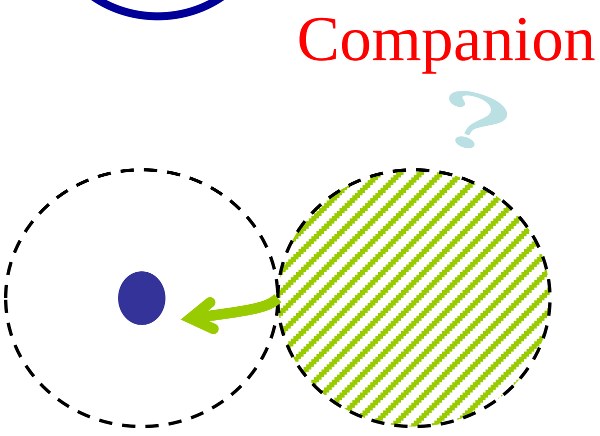
The Progenitors of Type Ia Supernovae ??

- Single Degenerate(SD)
  vs.
  Double Degenerate(DD)



- Chandrasekhar Mass WD
  vs.
  Sub-Chandrasekhar Mass WD

Core Degenerate (CD)
Collisional DD



Thermonuclear Explosions of White Dwarfs!!

Surface burning	→	Sub-Ch	Chandra
ρ (g cm^{-3}) ~10^6		10^{7-8}	10^{9-10}
DD He/C-detonation	→	C-det	
steady C-burning	→		ONeMg WD
no ignition	→		C-deflag
cDD C-detonation	→	C-det	
CD DD in common env	→	spin-up: super Ch	
SD (H-rich & He star channels)			
weak He flashes	→		C-deflag
	→	spin-up: super Ch	
He detonation	→	C-det	

Single Degenerate Scenario

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

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

➔ Central Ignition of Carbon Burning

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

(2) H & He Burning ➔ weak flashes➔M grows

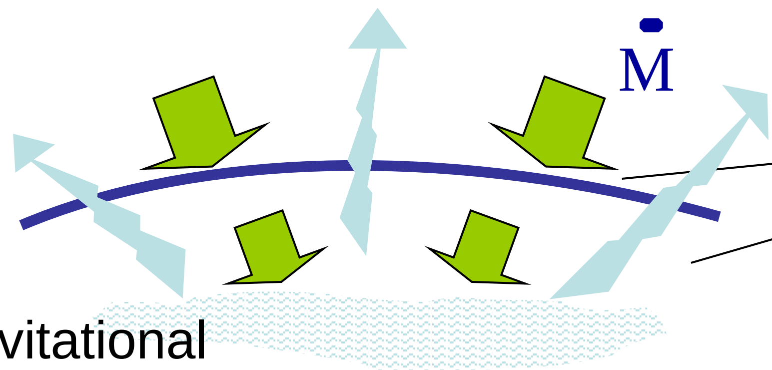
(3) Radiation-driven WD Winds ➔**SN Ia-CSM**

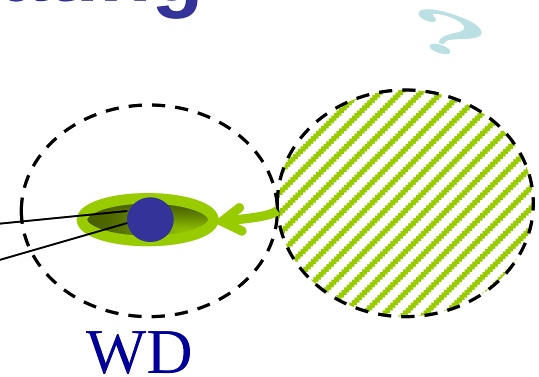
(4) Steady Hydrogen Burning ➔ **SN Ia-SSS**

(5) Recurrent Novae ➔ **SN Ia-Nova**

Single Degenerate Scenario

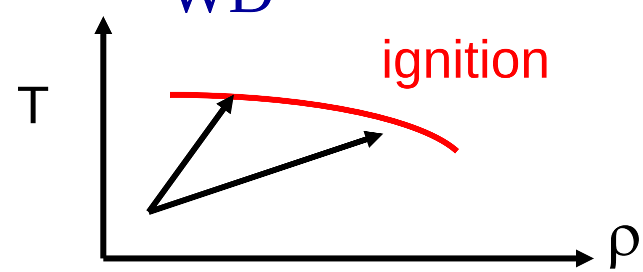
Compressional Heating





Gravitational
Energy Release

||



Compressional Heating $\propto \dot{M}$

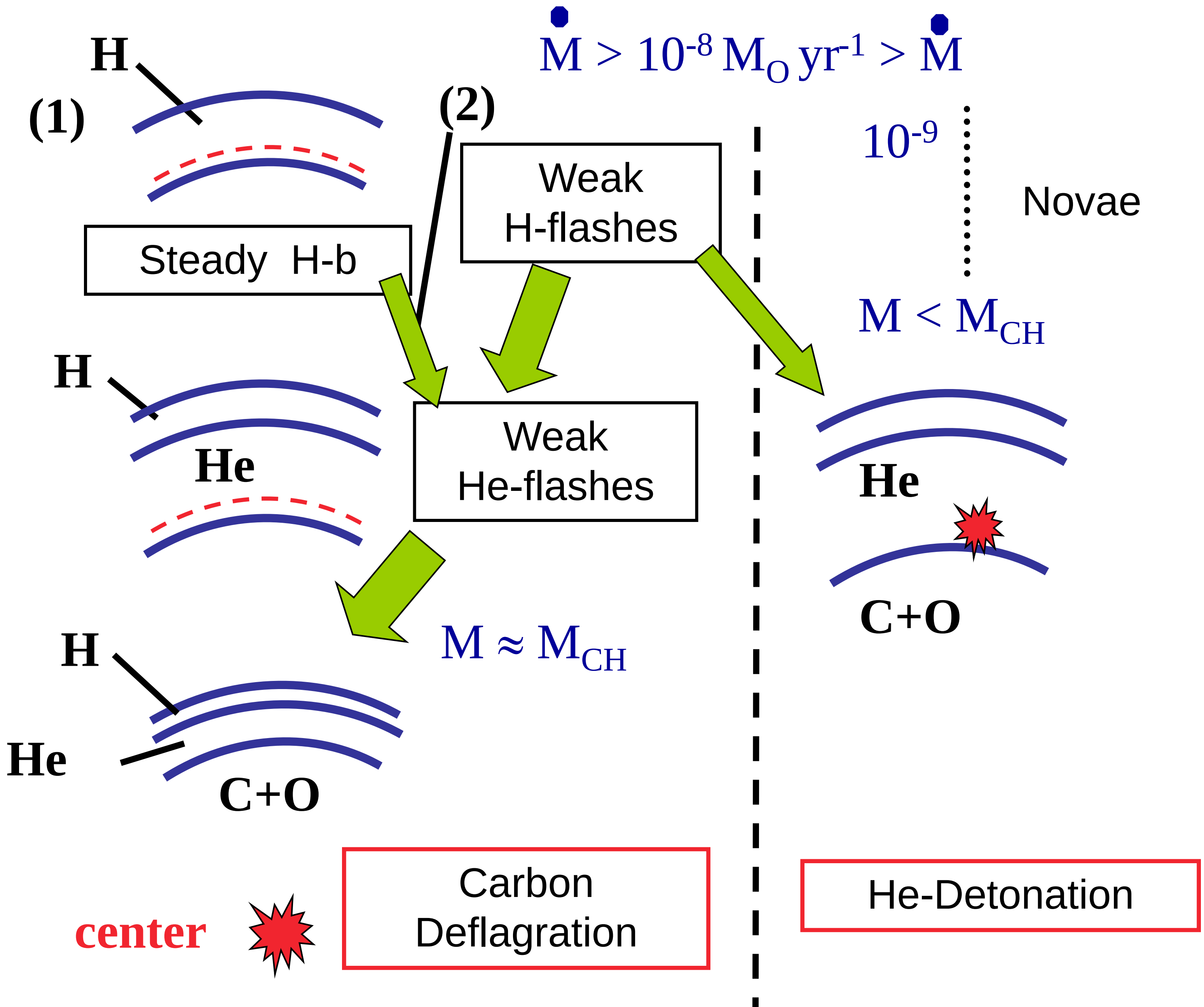
(ρ, T)

Radiative Cooling

Thermonuclear Explosions ($\dot{M}$)

$$P(H) \sim GM \cdot M(H)/R^4 \quad : R(M)$$

Deflagration & **Double Detonation**



Candidate Progenitor Systems for Carbon Ignitors

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

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

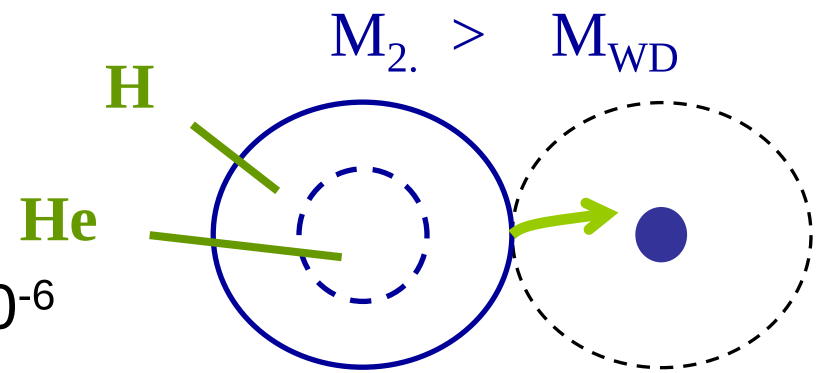
Companion

(1) H: leaving M.S.

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

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

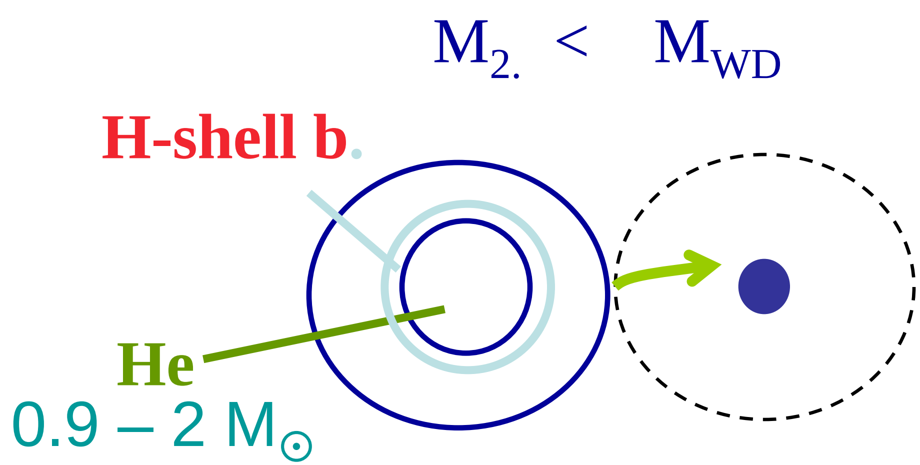
$M_{2,ms} \sim\ 1M_\odot\quad 2M_\odot\quad \sim 8M_\odot$



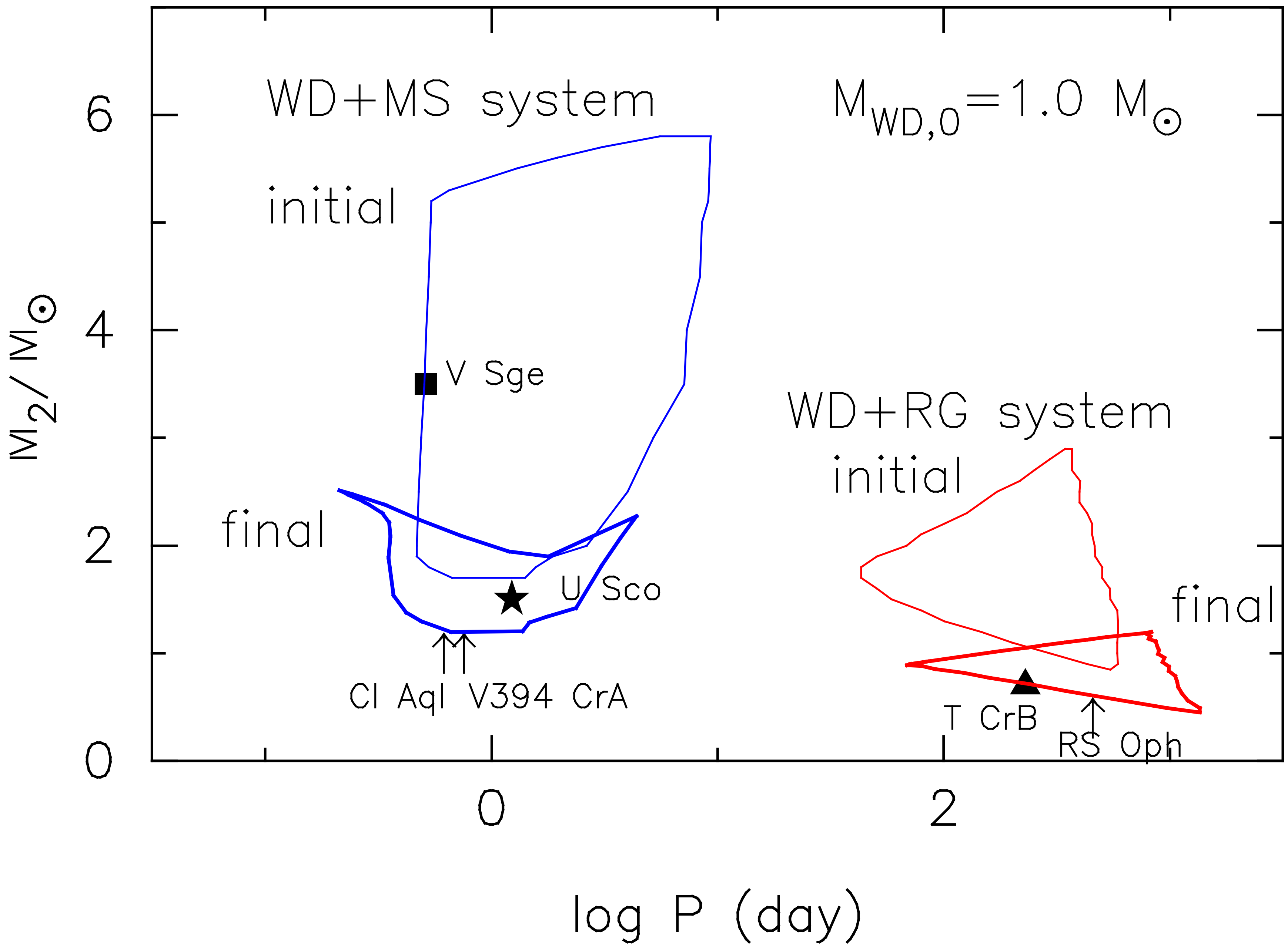
(2) H: sub giant, **red giant**

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

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

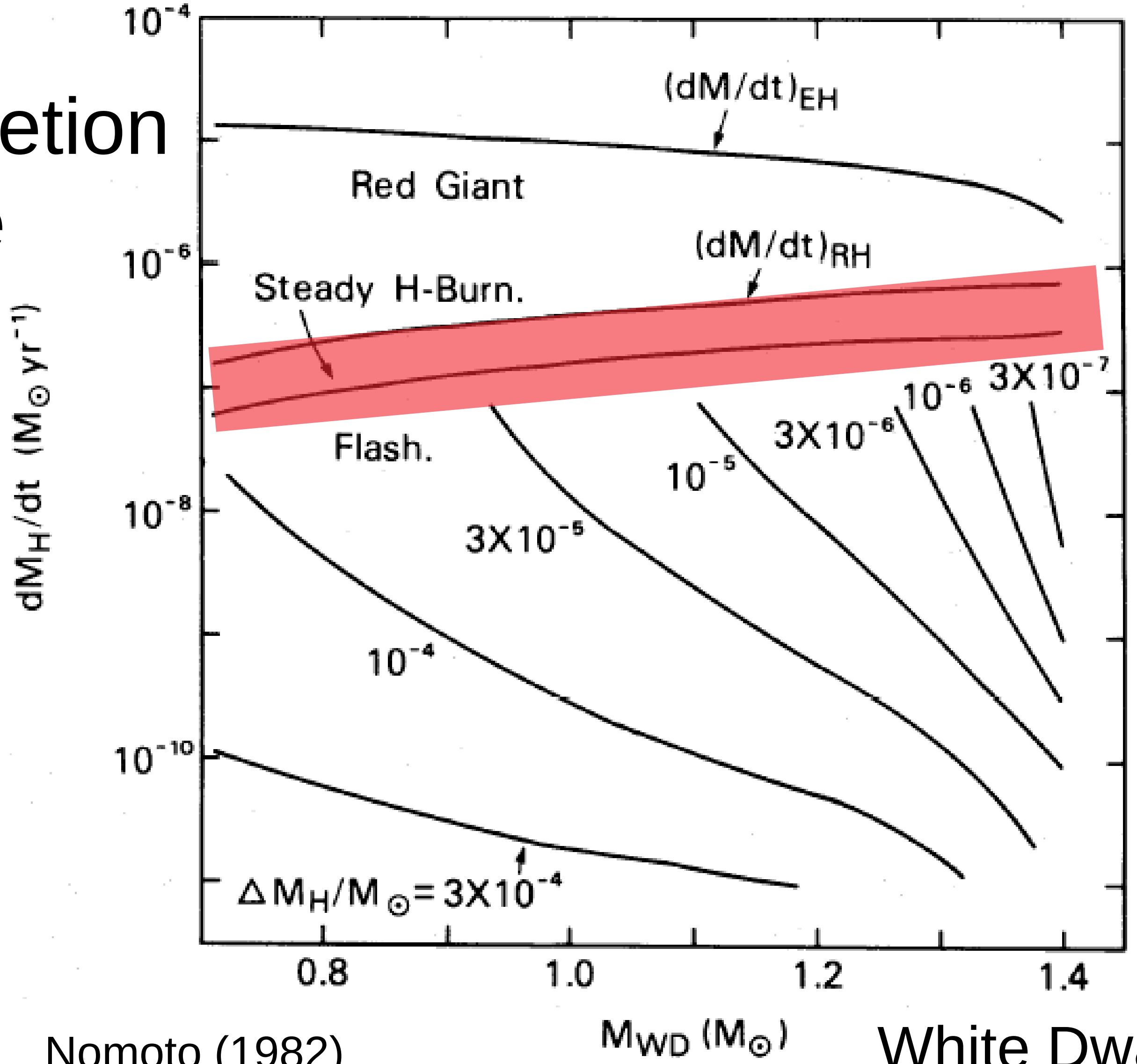


SN Ia Progenitor System(MS, RG)



Hydrogen Burning in Accreting WD

Accretion Rate



→Common env

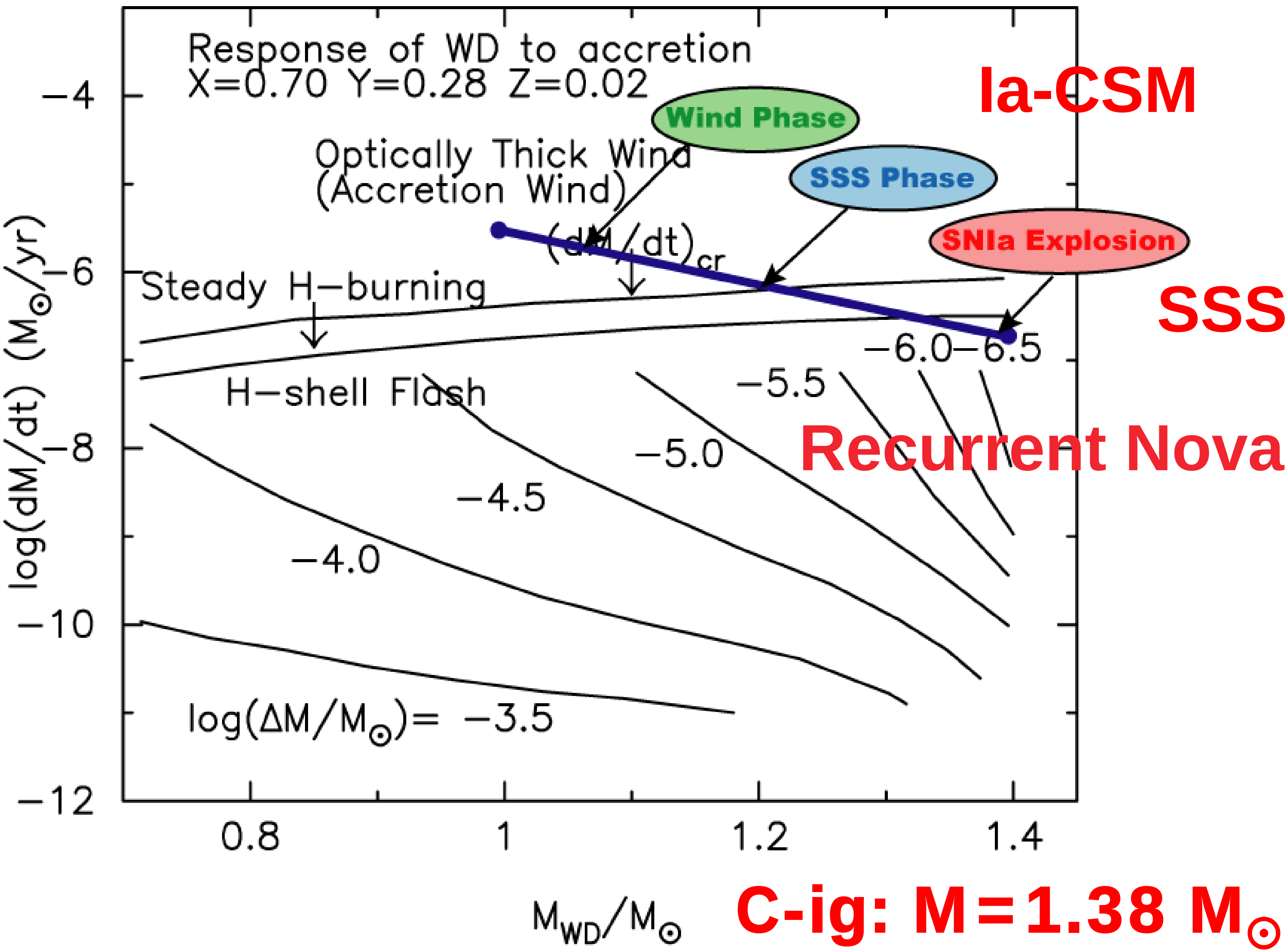
→→ DD ?

→Accretion Wind

Nomoto (1982)

White Dwarf Mass

WD Wind **[Fe/H] > -1**


Response of WD to accretion
X=0.70 Y=0.28 Z=0.02
Ia-CSM
Wind Phase
SSS Phase
SNIa Explosion
SSS
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
Recurrent Nova
$\log(\Delta M/M_\odot) = -3.5$
−4
−6
−8
−10
−12
$\log(dM/dt)\ (M_\odot/yr)$
0.8
1
1.2
1.4
$M_{WD}/M_\odot$
C-ig: M=1.38 $M_\odot$

Single Degenerate: Ia-CSM

$M(wd, 0) + M_{2,0}$: 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

Young System (with large $M_{2,0}$)

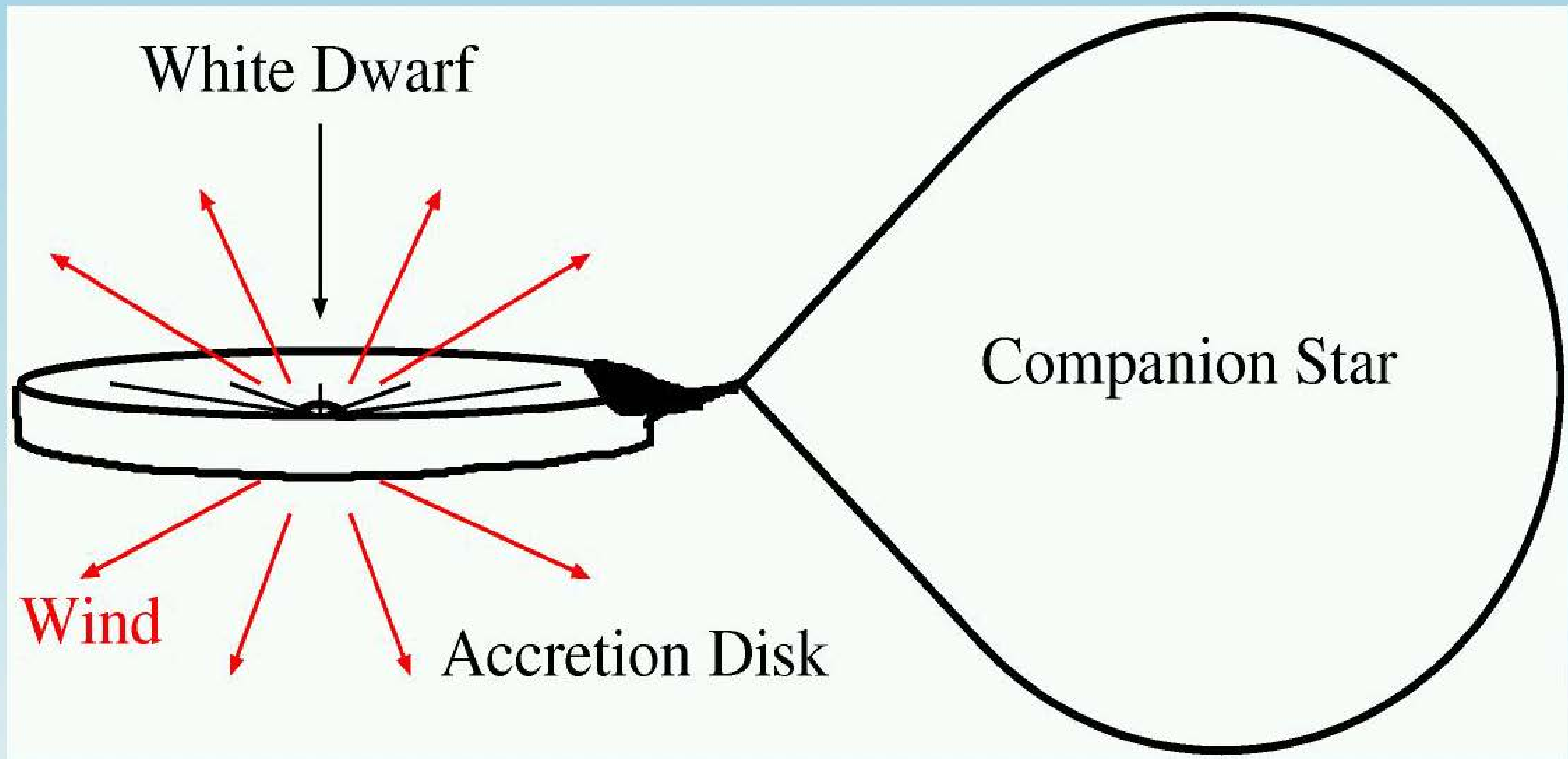
➔Central Ignition of Carbon Burning

➔SN Ia - CSM

(3) White Dwarf Wind

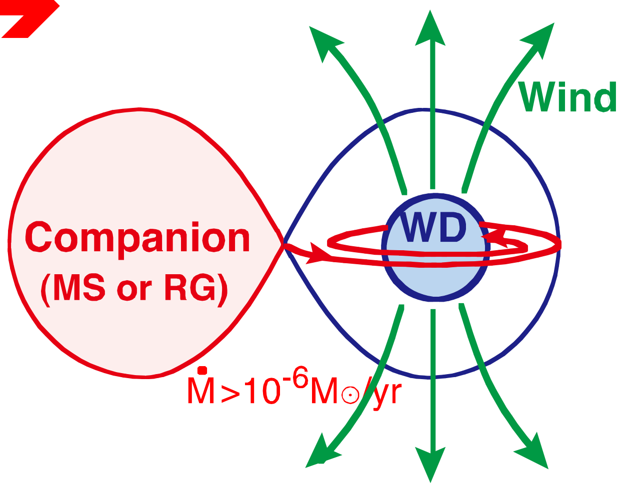
(Hachisu, Kato, & Nomoto 1996)

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



Single Degenerate: Ia-CSM

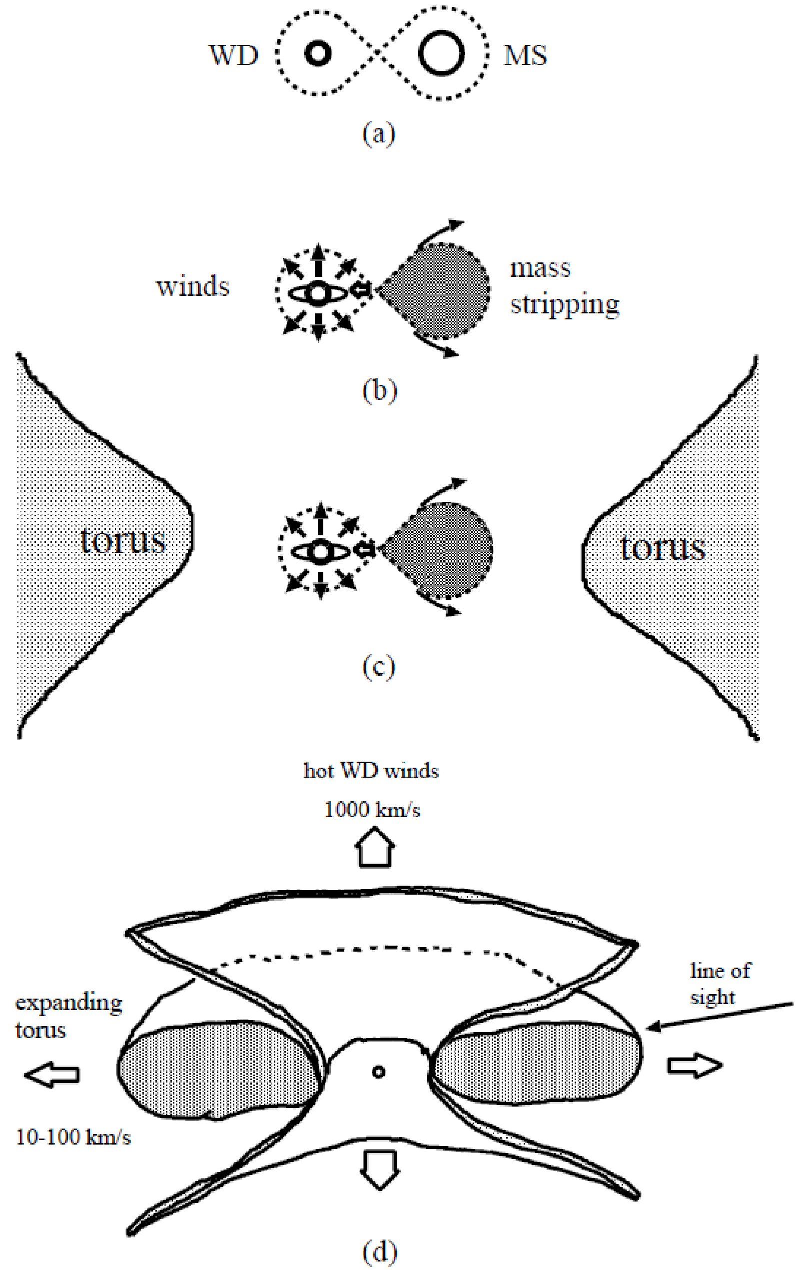
(3) Radiation-driven WD Winds →



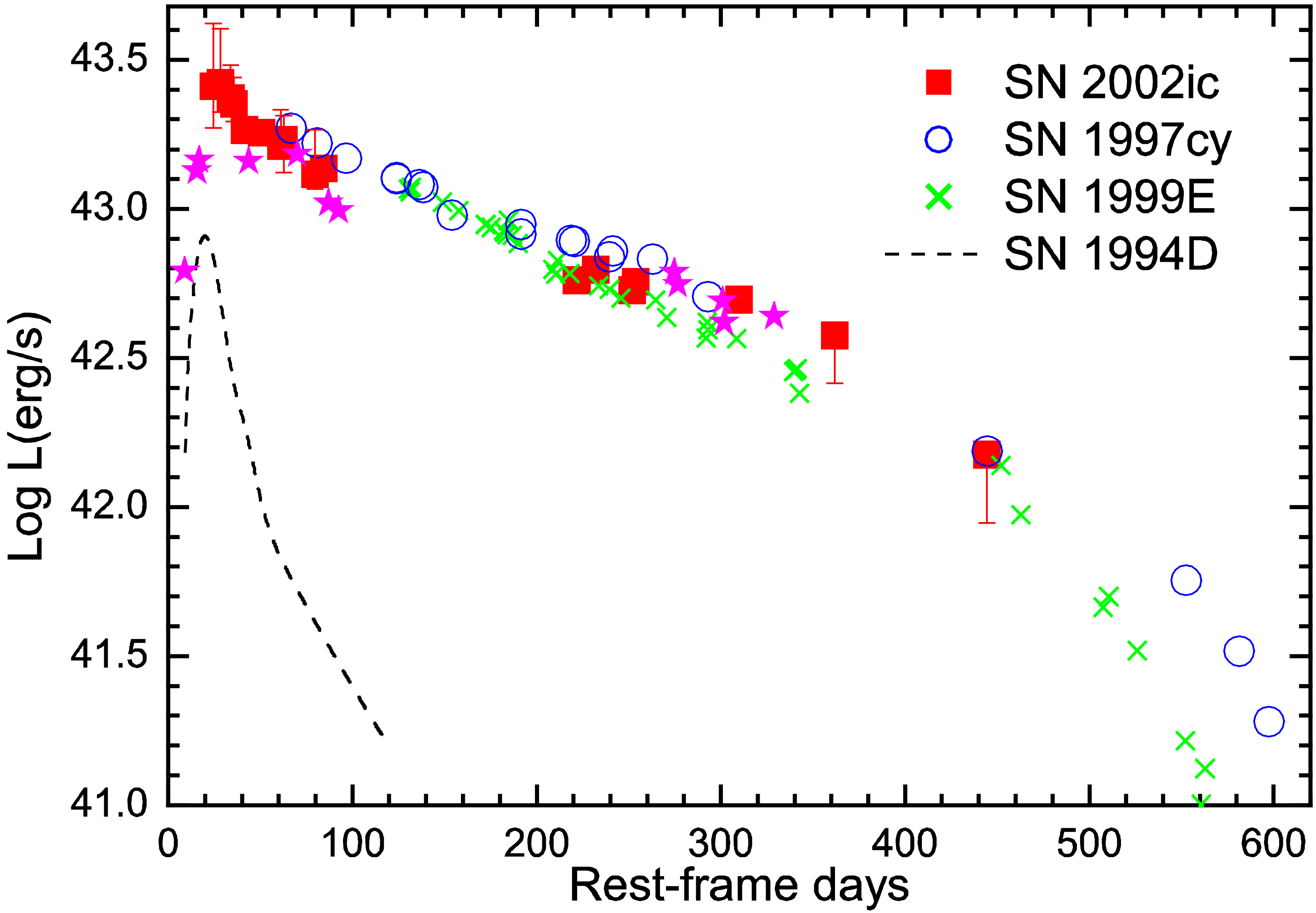
Aspherical Circumstellar Matter (~10-100 km/s)

Young System (large $M_{2,0}$)

→SN Ia-CSM

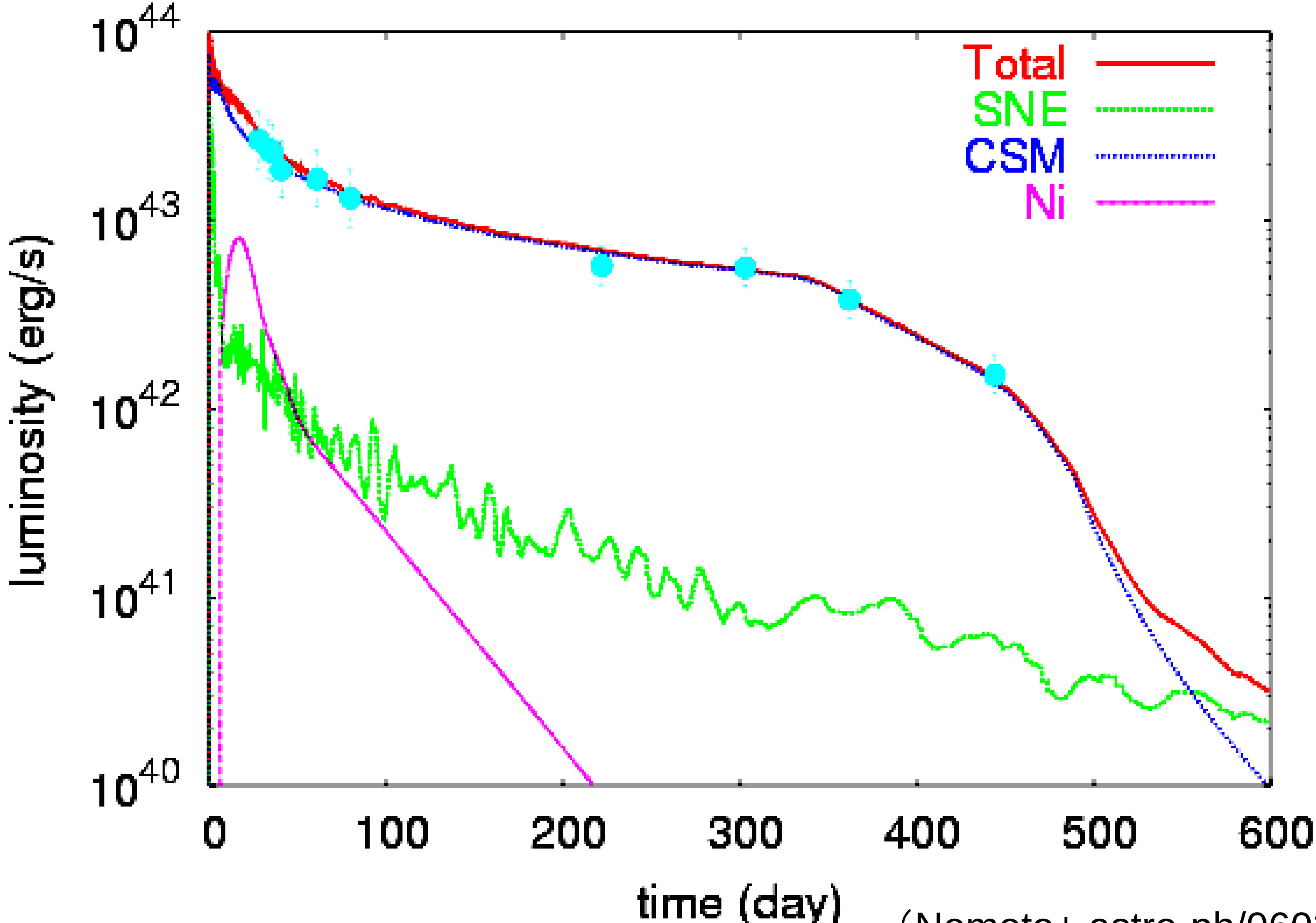


SN 02ic, 97cy, 99E: Light Curve



(Deng+04)

SN 2002ic: circumstellar interaction model



(Nomoto+ astro-ph/0603432)

Single Degenerate: SSS, Nova

$M(wd, 0) + M_{2,0}$: 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

➔ large amplitude oscillation (Teff)

(5) Recurrent Novae

➔ Central Ignition of Carbon Burning

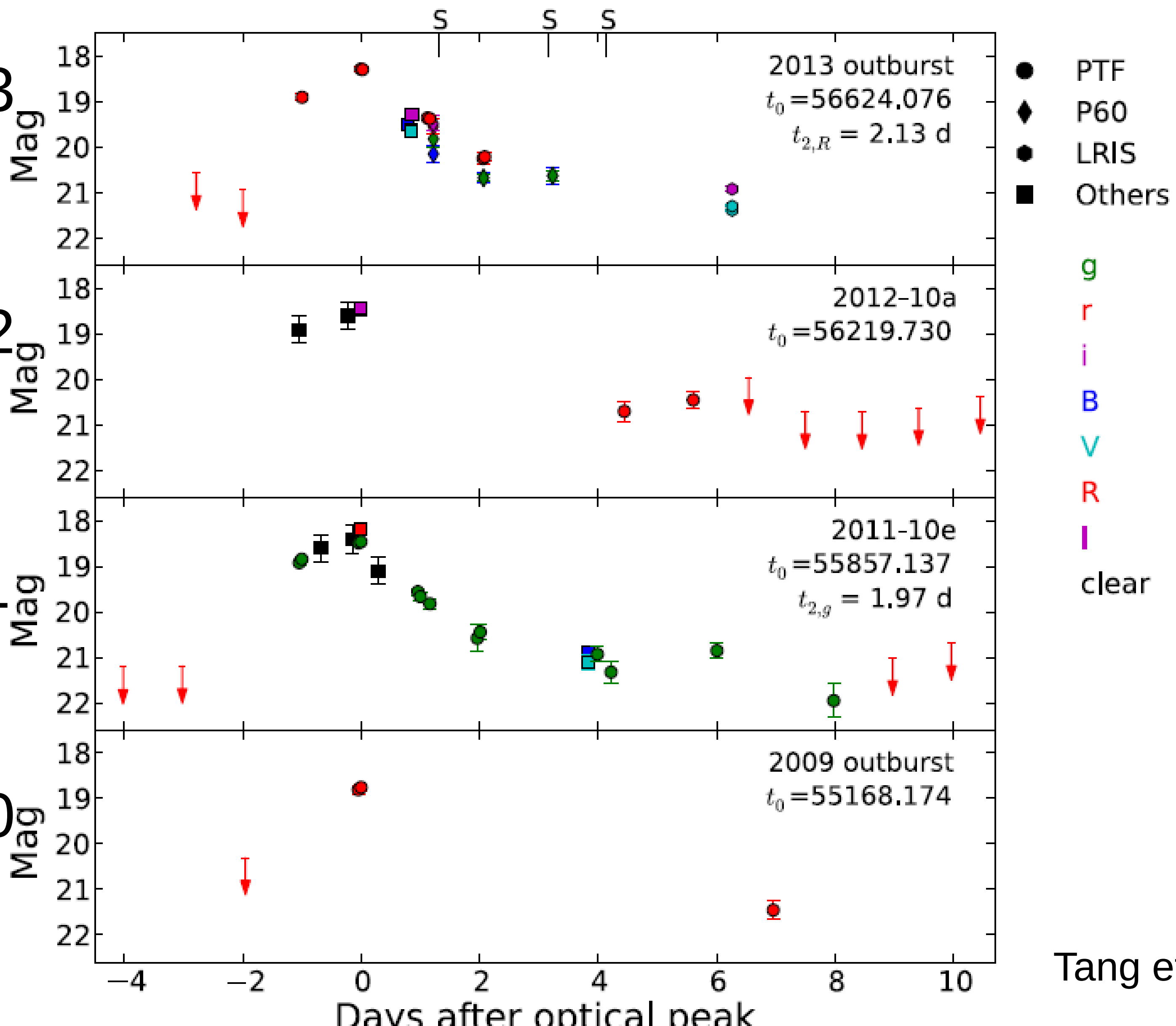
Recurrent Nova in M31: 1 yr period

2013

2012

2011

2010



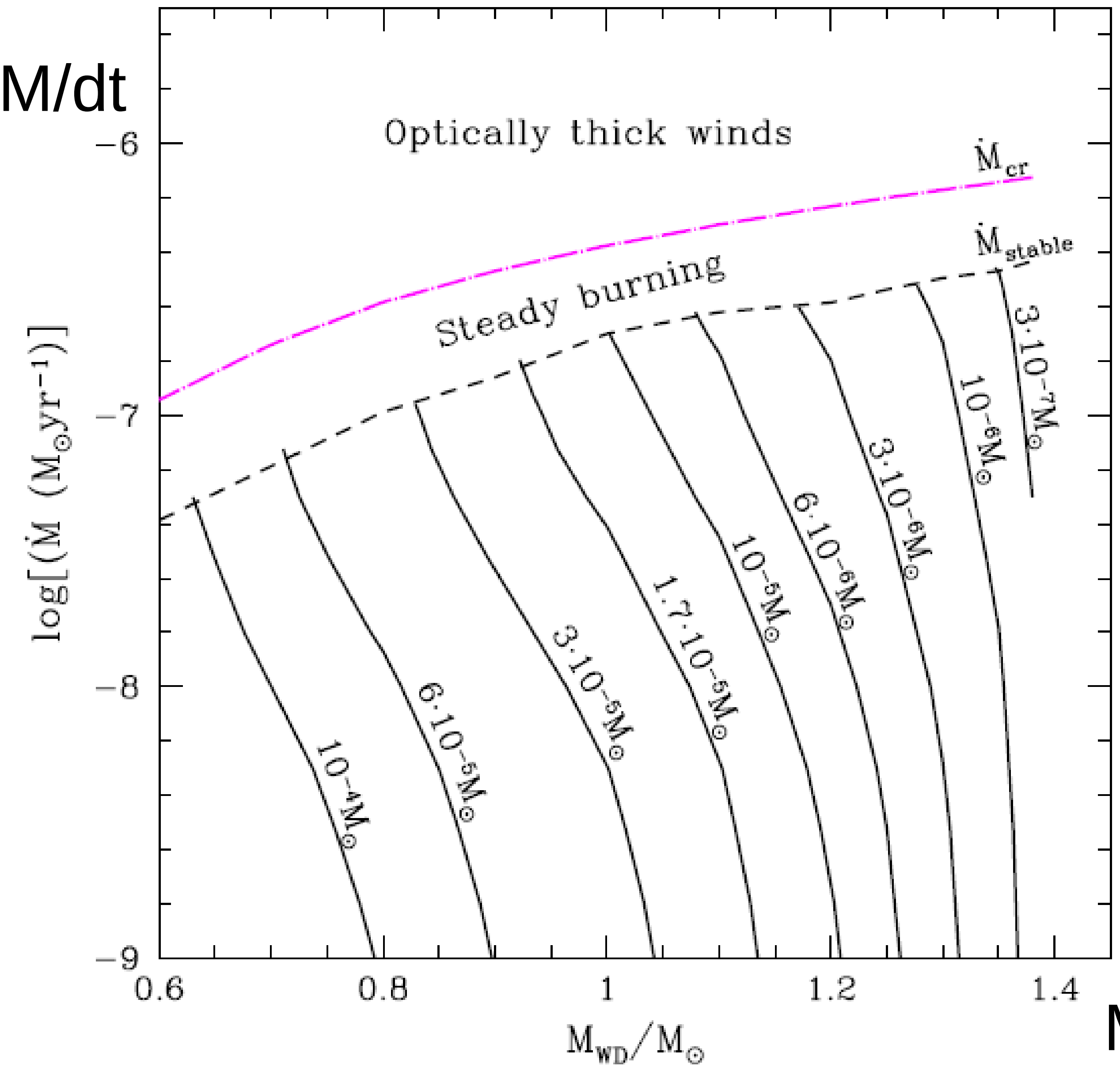
Faint!

-6.5 mag

Tang et al. (2014)

Hydrogen Mass at Ignition : M(H) ~ 1 E-7 $M_\odot$

dM/dt



M(WD)/$M_\odot$

Recurrence Period

= M(H)/(dM/dt)

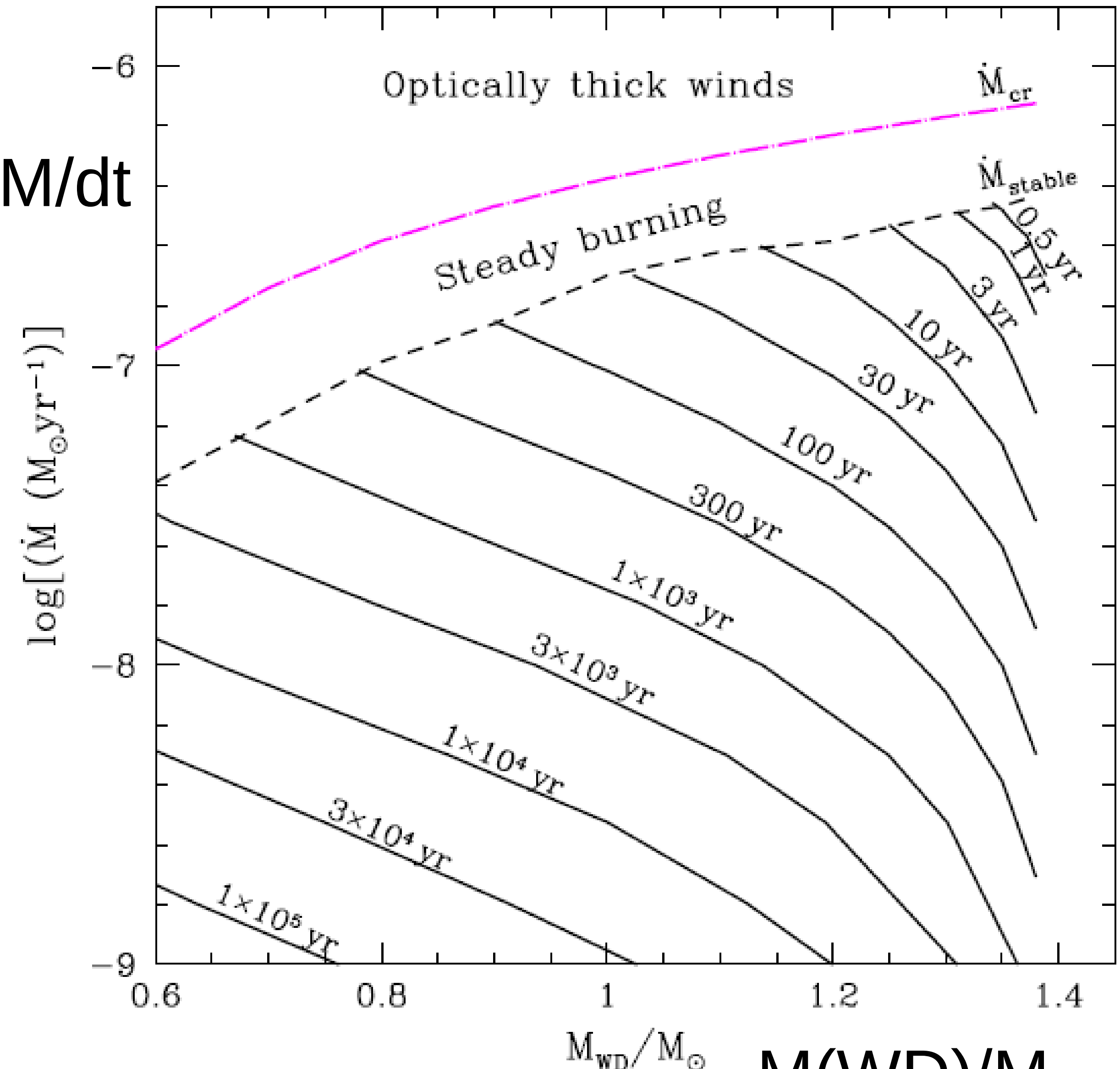
Nariai, Nomoto 1979

……………..

Wolf, Bildsten 2013

Recurrence Period

dM/dt



M(WD)/$M_\odot$

0.5 - 1 yr period

➔

M(WD) > 1.34$M_\odot$

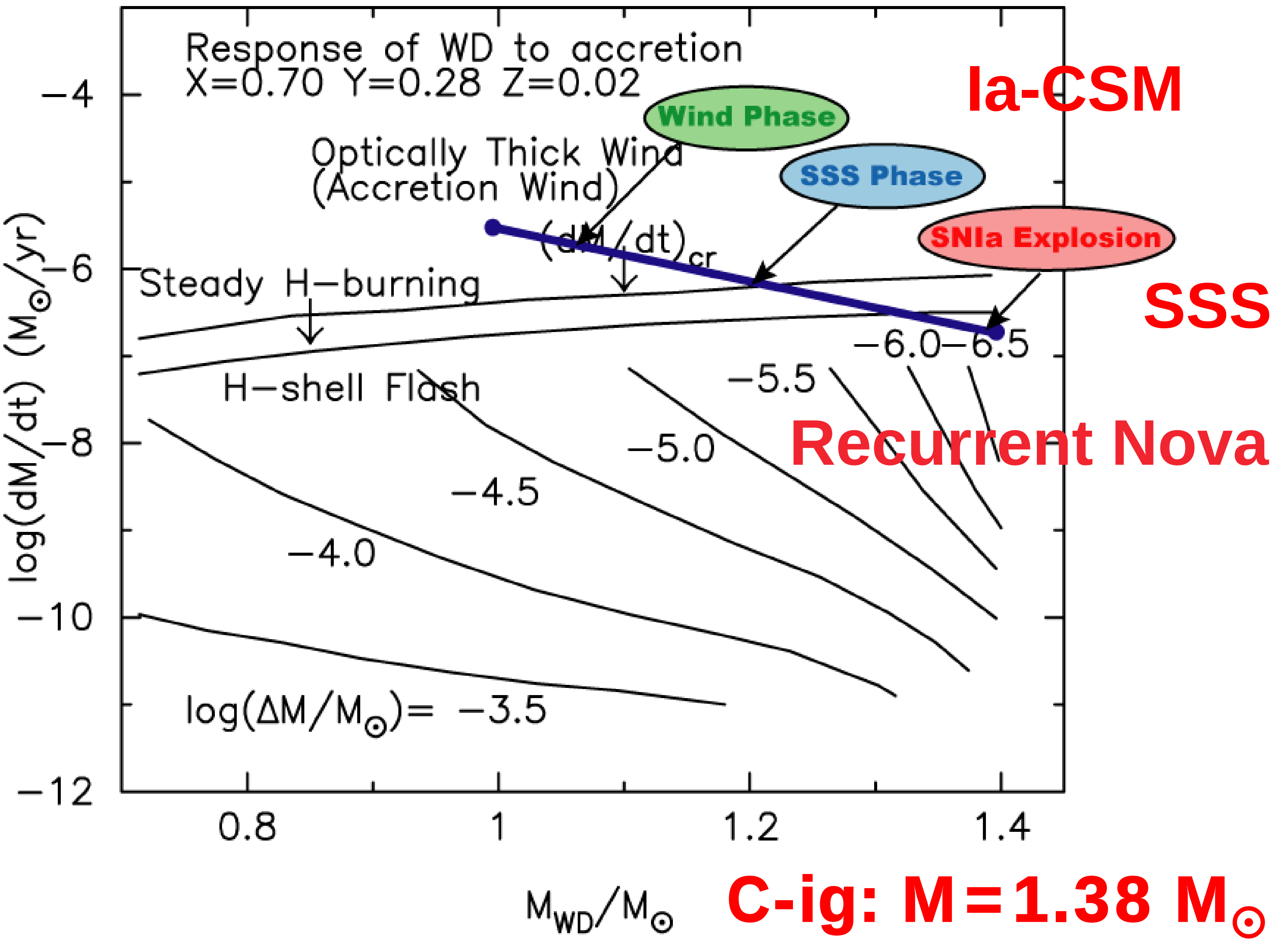
dM/dt

~2 - 4 E-7 $M_\odot$ /yr

time to SN Ia

< 1E5 yr

(Kato et al. 2014)



Response of WD to accretion
X=0.70 Y=0.28 Z=0.02
Wind Phase
SSS Phase
SNIa Explosion
Ia-CSM
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Recurrent Nova
Optically Thick Wind
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$(dM/dt)_{cr}$
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−6
−8
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0.8
1
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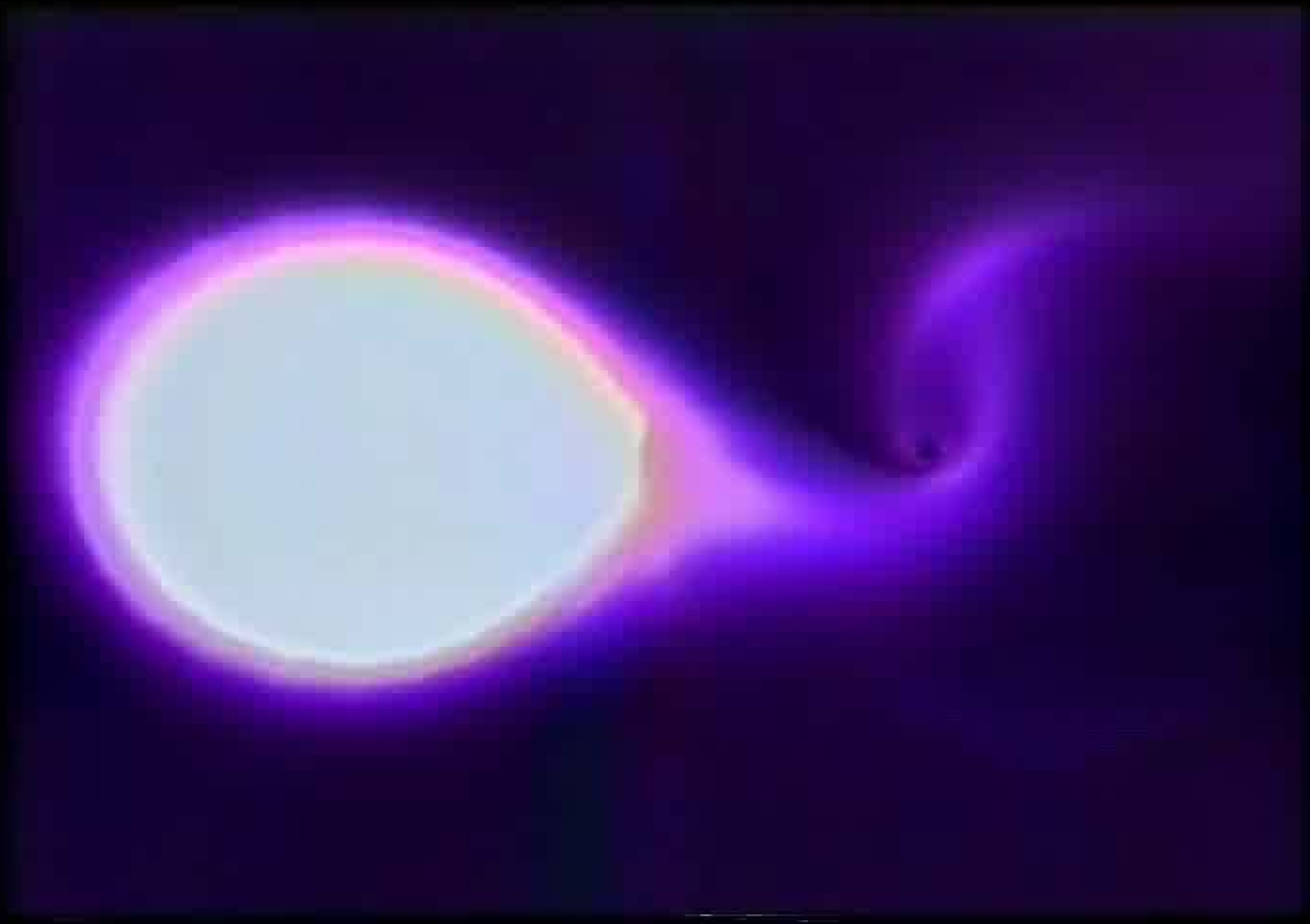
$M_{WD}/M_\odot$
C-ig: $M=1.38\ M_\odot$

Mass Transfer ➔WD Rotation



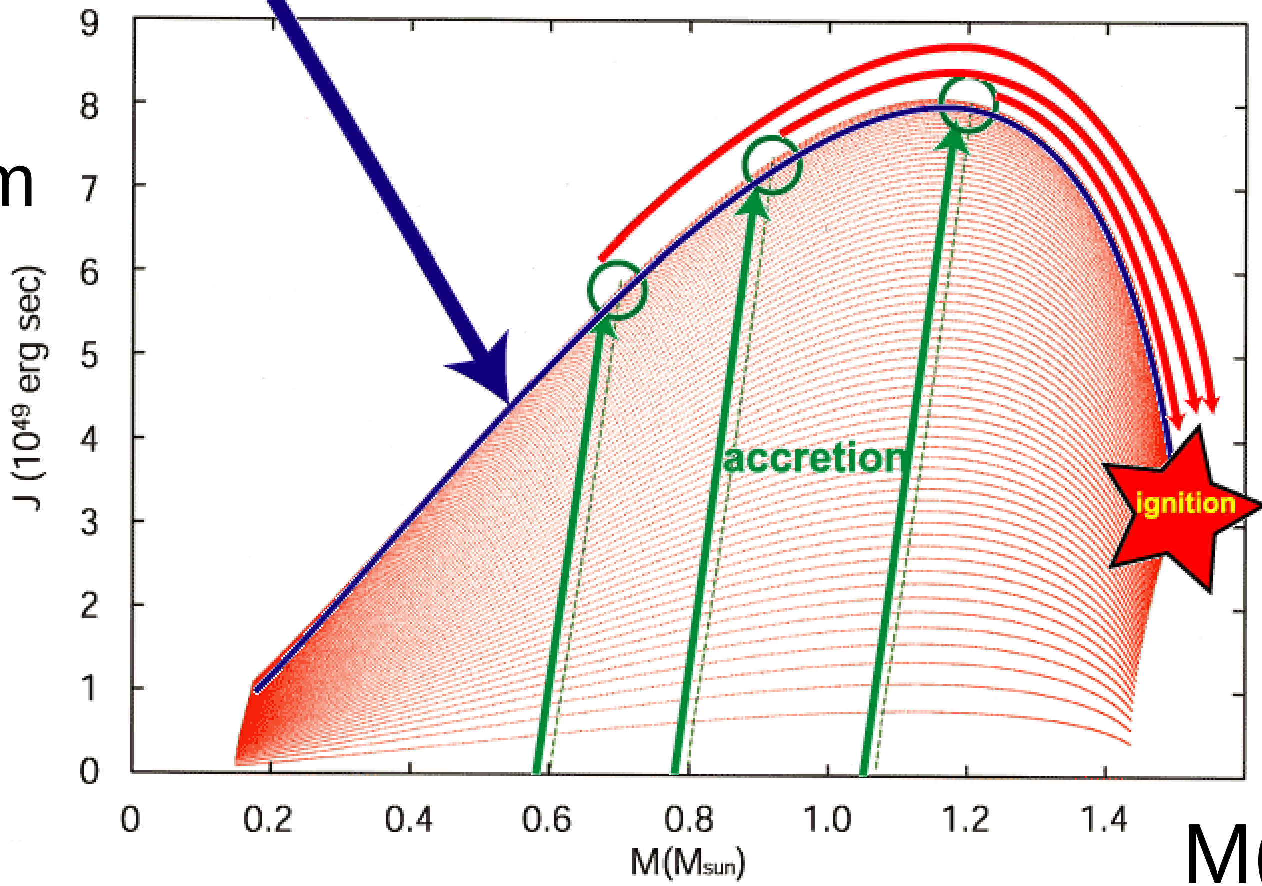
(T. Matsuda)

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)

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 $M(wd) = 1.38\ M_\odot$

(1) $M(wd, final) = 1.43\ M_\odot$ (**prompt** C-ignition)

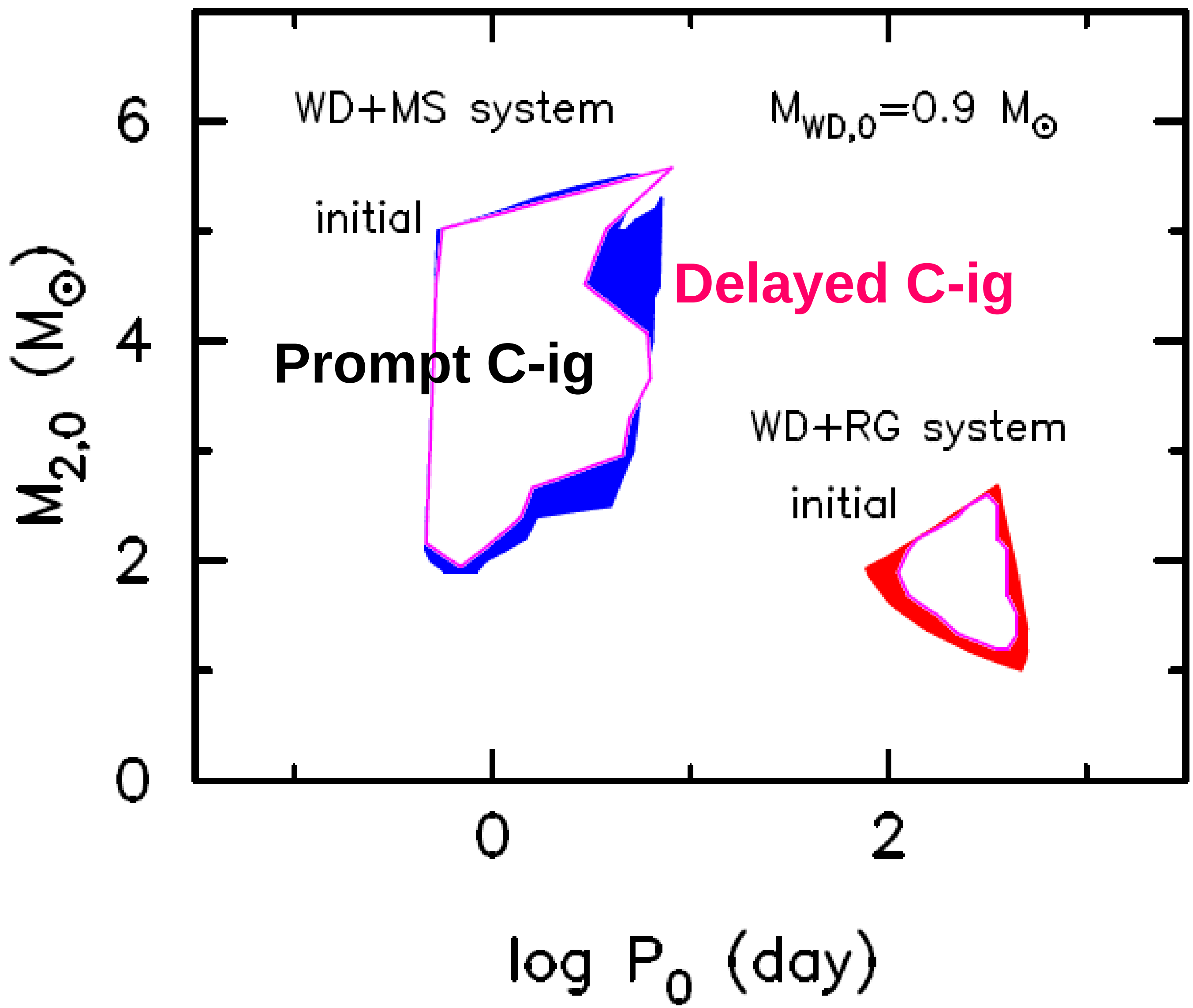
(2) $M(wd, final) = 1.38 - 1.43\ M_\odot$ (**no** C-ignition)

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

➔ strong Nova outbursts : mass ejection

➔ M(wd) does not increase

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



SNe Ia from Uniformly Rotating WDs

(1) $M_{wd,\ final}/M_{\odot} = 1.43$ (~ 65 %) :

Prompt Carbon-Ignition

(➔ e.g., PTF11kx)

(2) $M_{wd,\ final}/M_{\odot} = 1.38 - 1.43$ (~ 35 %)

Angular momentum loss

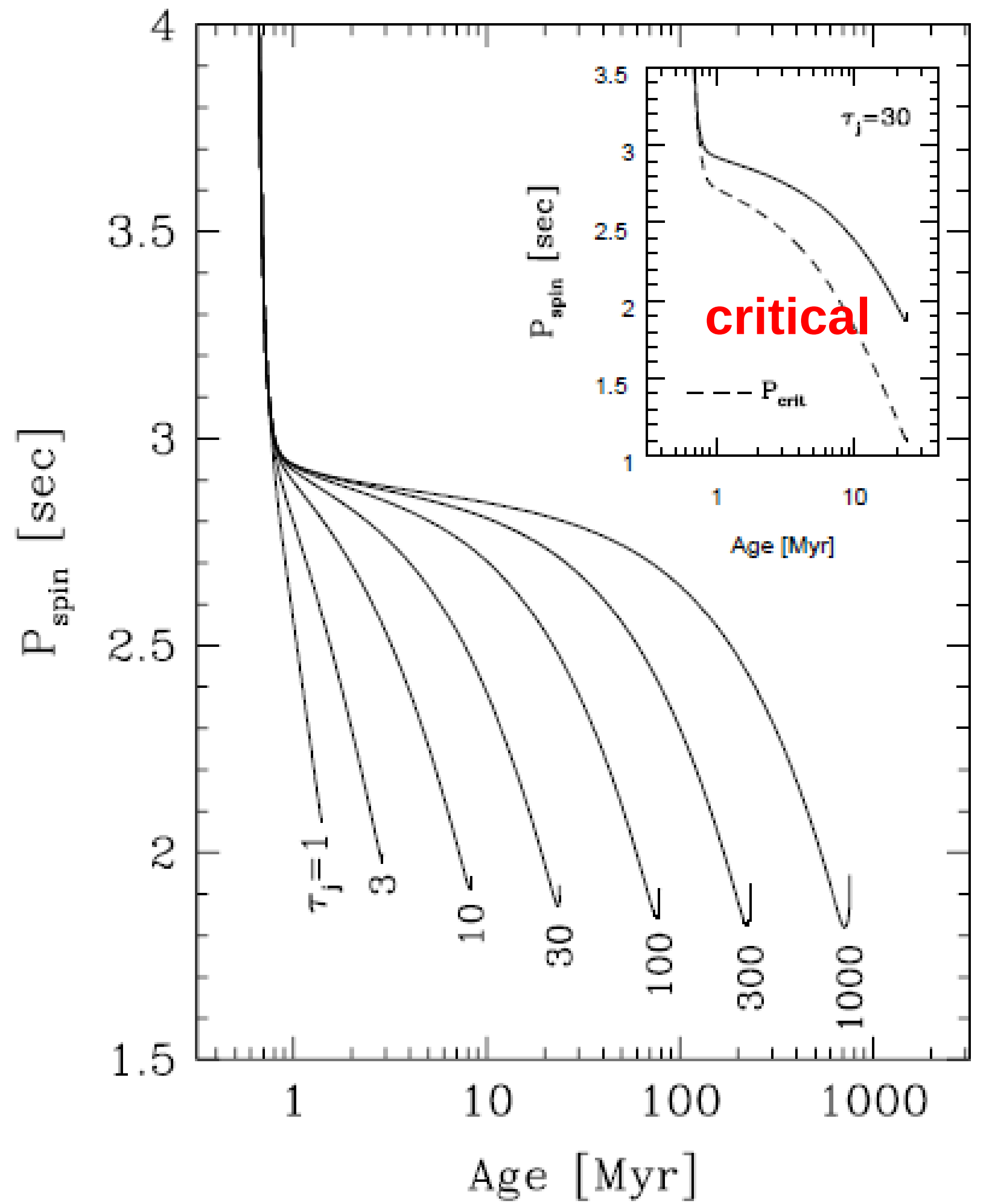
(←magnetic wind,,,,,,)

➔ **Delayed** Carbon-Ignition

Angular Momentum Loss
➔Spin-Up

$M(SN) = 1.40\ M_\odot$

P(spin, s)



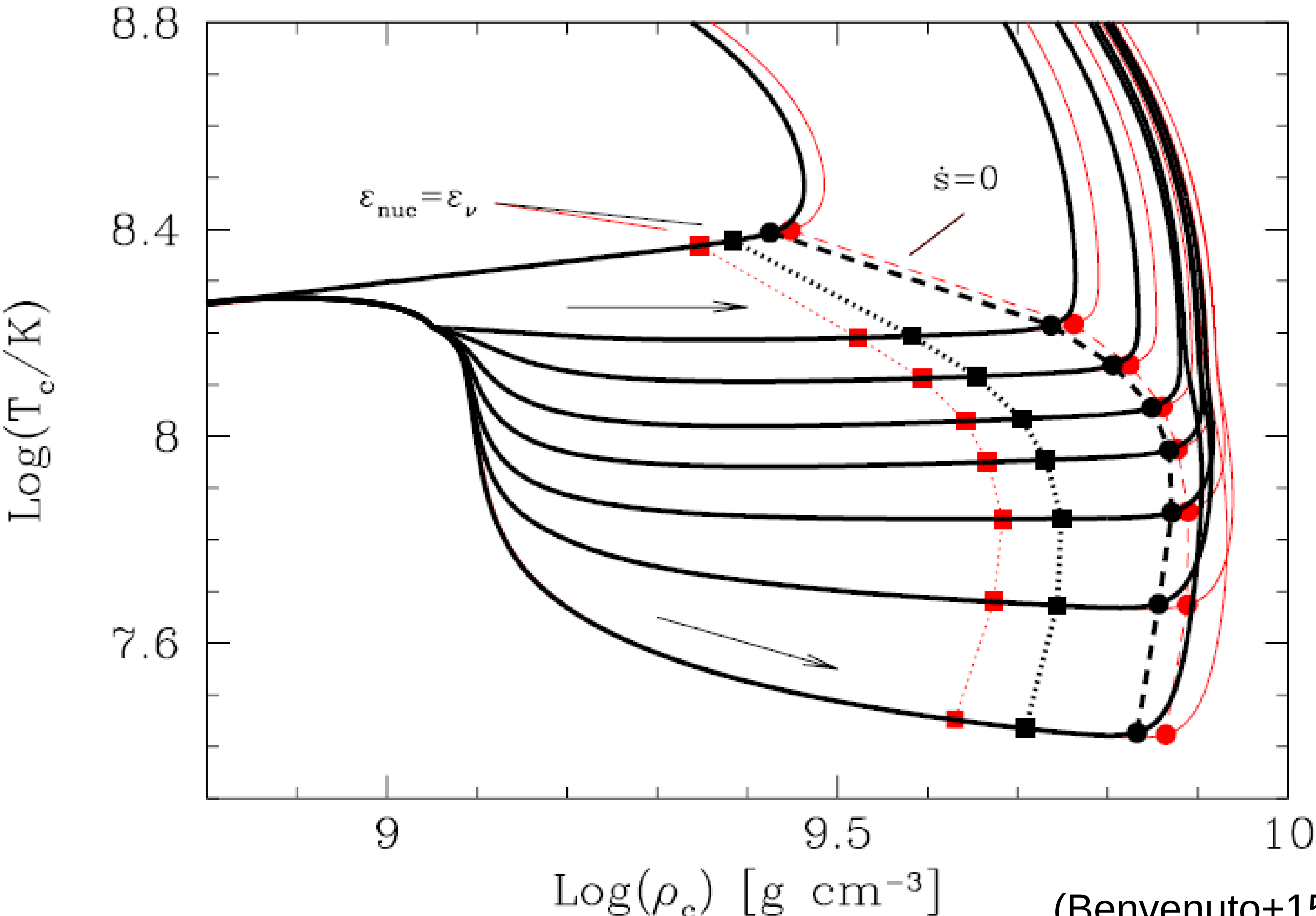
Angular momentum loss
(du to magnetic wind ?)

J /Jo = exp [-t/tau(J)]

tau (J) = 1 Myr – 1 Gyr

(Benvenuto+15 ApJL)

The central density-temperature for tau (J)= 1,3,10,30,100,300 Myr



(Benvenuto+15 ApJL)

Companions of Rotating WDs

M_2 continues to decrease by mass transfer

(~10^{-7} -10^{-8} $M_{\odot}$ y^{-1}) in 10^7 – 10^8 yrs.

(1) RG ➔ He WD by losing H-envelope

(2**)** MS ➔ He WD by losing H-envelope

Companions become He WDs :

➔ missing companions

Circumstellar matter : dispersed.

Rotating White Dwarf Models

Variations of WD masses at C-ignition

Delayed C-ig ➔ Higher ρ_c ➔ more ^{58}Ni, $^{54,56}Fe$
^{55}Mn

SN Iax (if a WD core remains) ??

If tau (J) > 3 Gyr, ➔ Collapse to NS ??

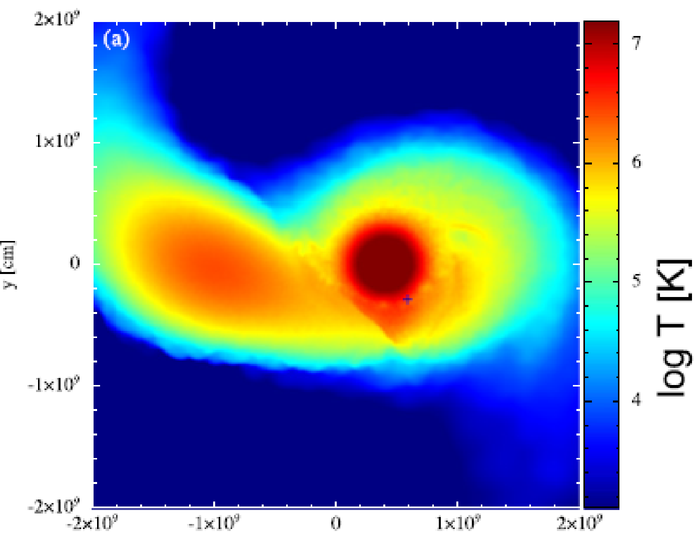
CO + CO WD Merger

M_1
$q = M_2/M_1$

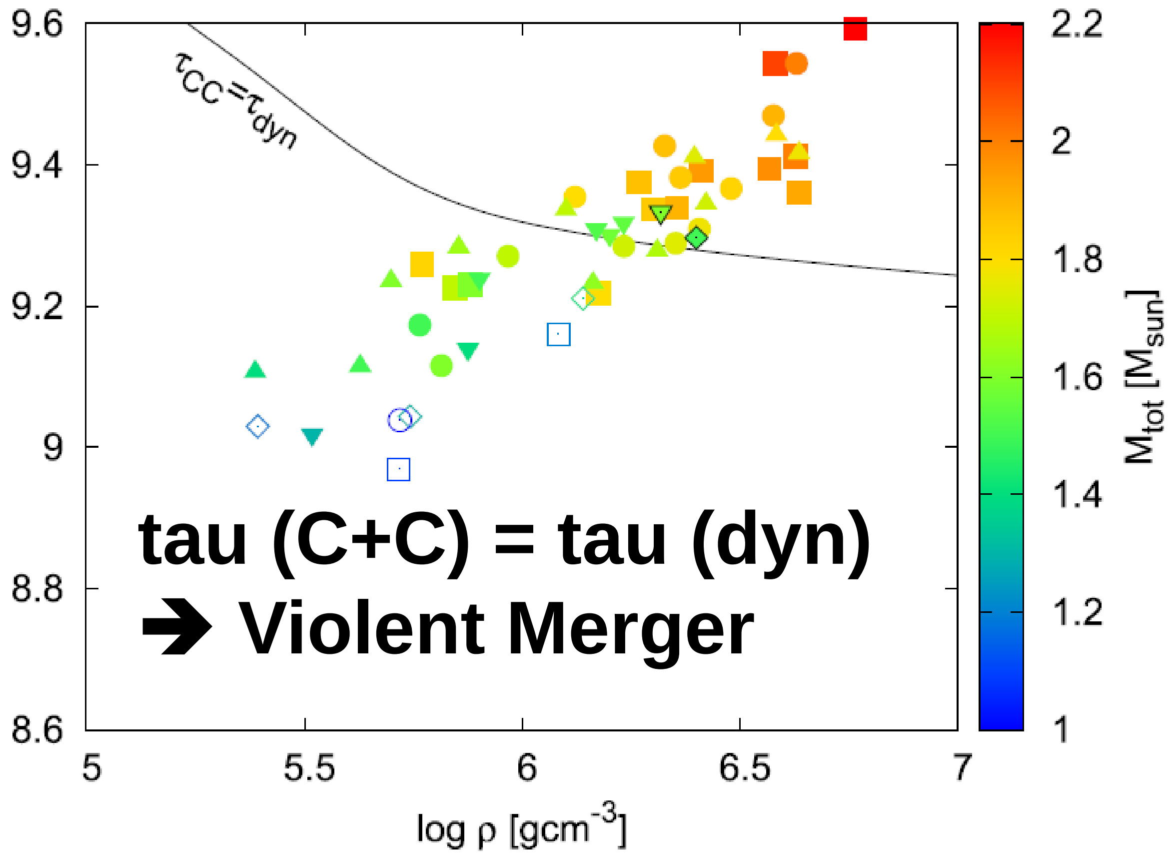
➔ **Violent Merger (sub-Ch)**

➔ **C-shell b ➔ ONeMg (Ch)**

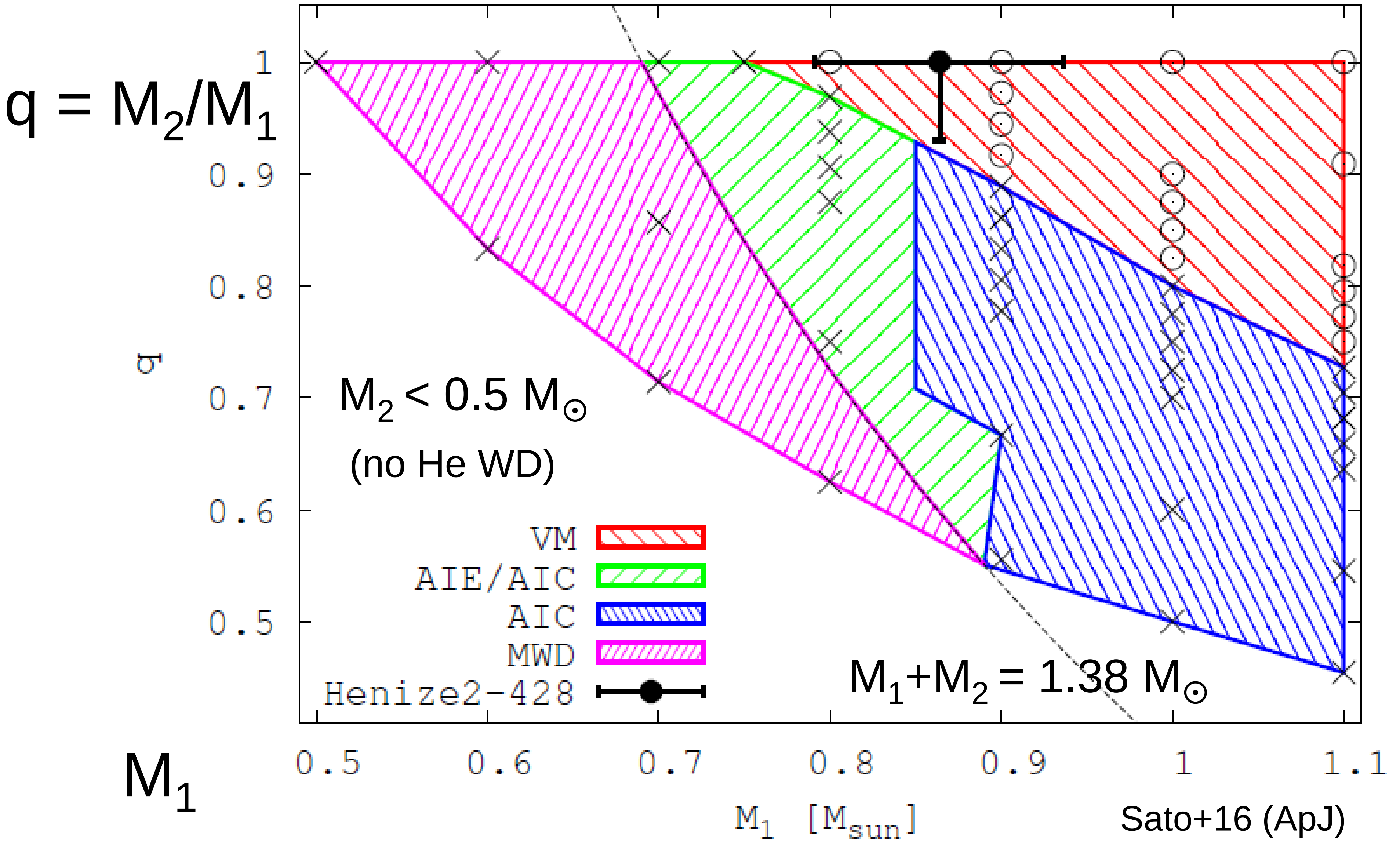
➔ **no C-shell b**



Sato+16 (ApJ)
SPH simulation

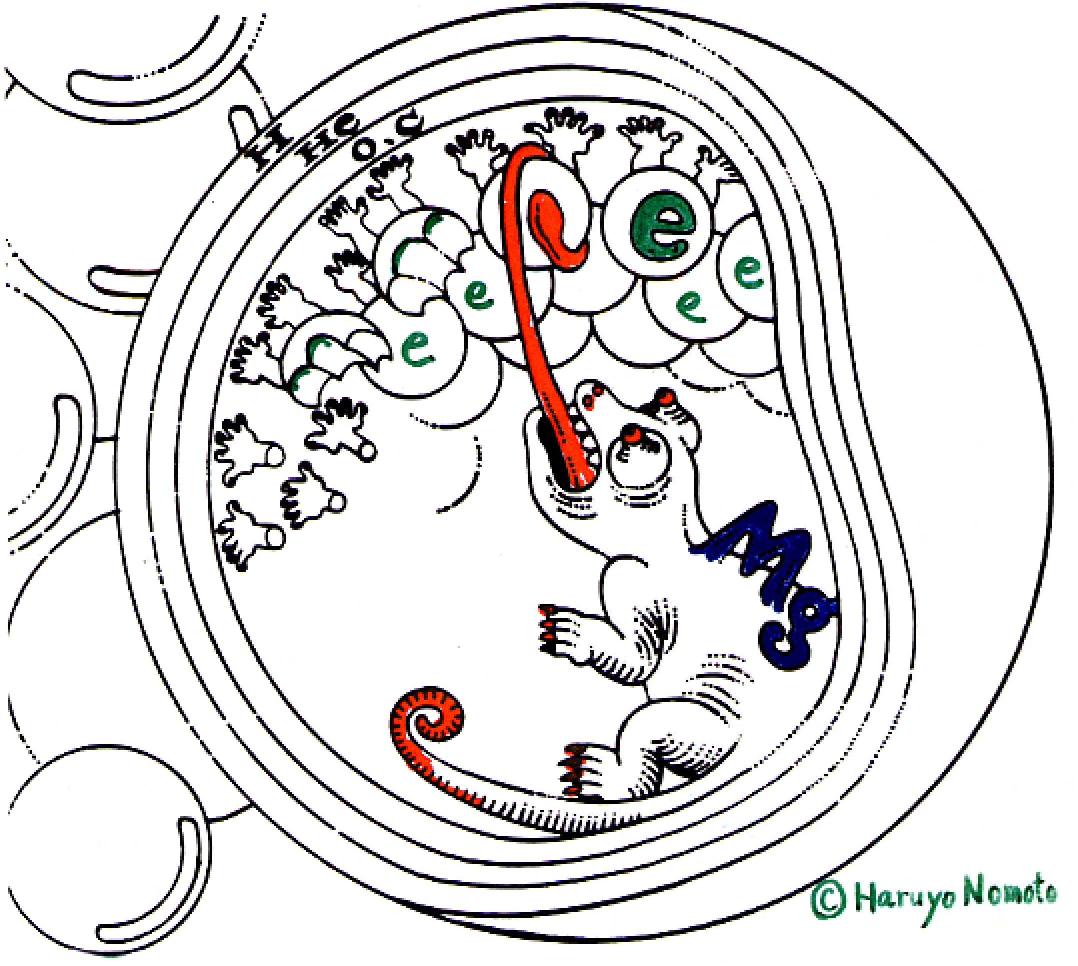


CO + CO ➔ no prompt C-shell ign.
➔ M ~M(Ch) or M < M(Ch)



Electron Capture in ONeMg WD

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



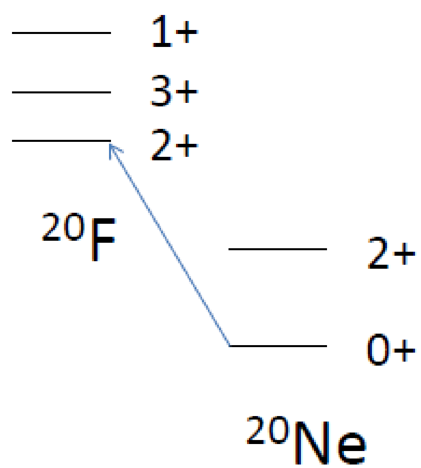
New Electron Capture Rate

Electron capture **(1) decrease in Ye ➔ Collapse (AIC)**

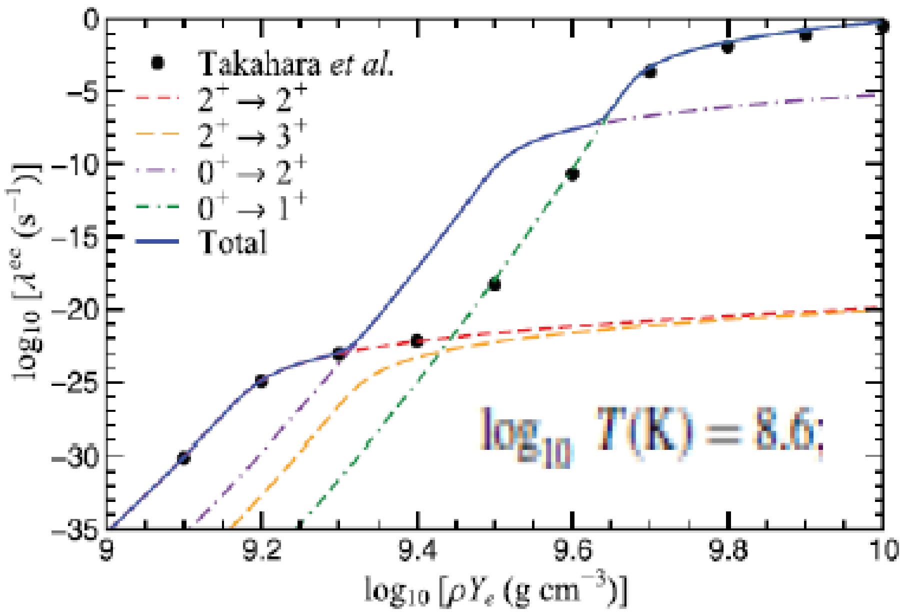
(2) heating ➔ Ne, O deflagration (➔SN Iax; Jones+19)

$^{24}Mg(e^-, \nu_e)^{24}Na(e^-, \nu_e)^{24}Ne$

$^{20}Ne(e^-, \nu_e)^{20}F(e^-, \nu_e)^{20}O$



$^{20}Ne\ (e^-, \nu)\ ^{20}F$



New Rate: 0+ ➔ 2+: 2nd forbidden transition (Kirsebom+19, Suzuki+19)

➔ Heating starts at lower density but slow. ➔Contraction

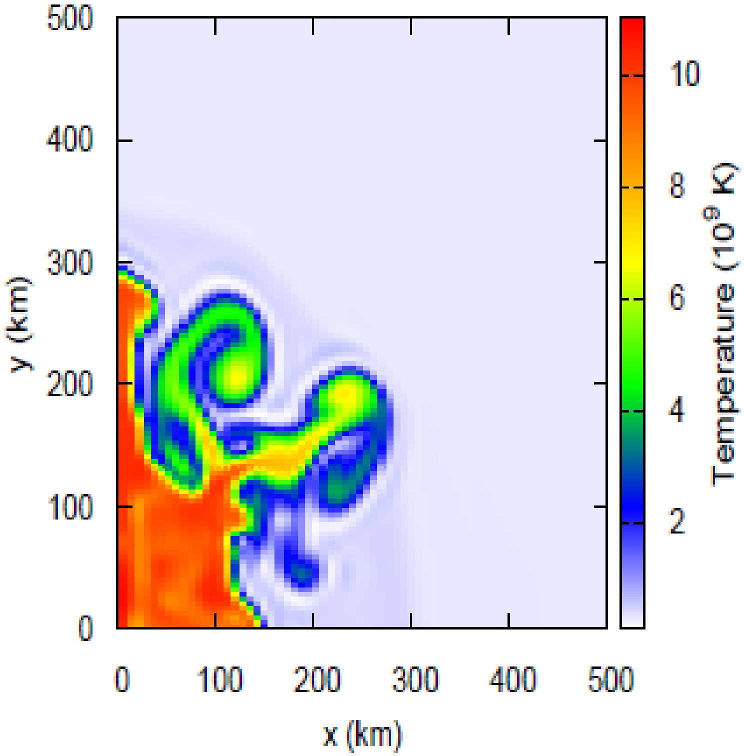
➔ Oxygen deflagration starts at $\rho_c \sim 10^{10.1 - 10.2}$ g cm^{-3} (Zha+19)

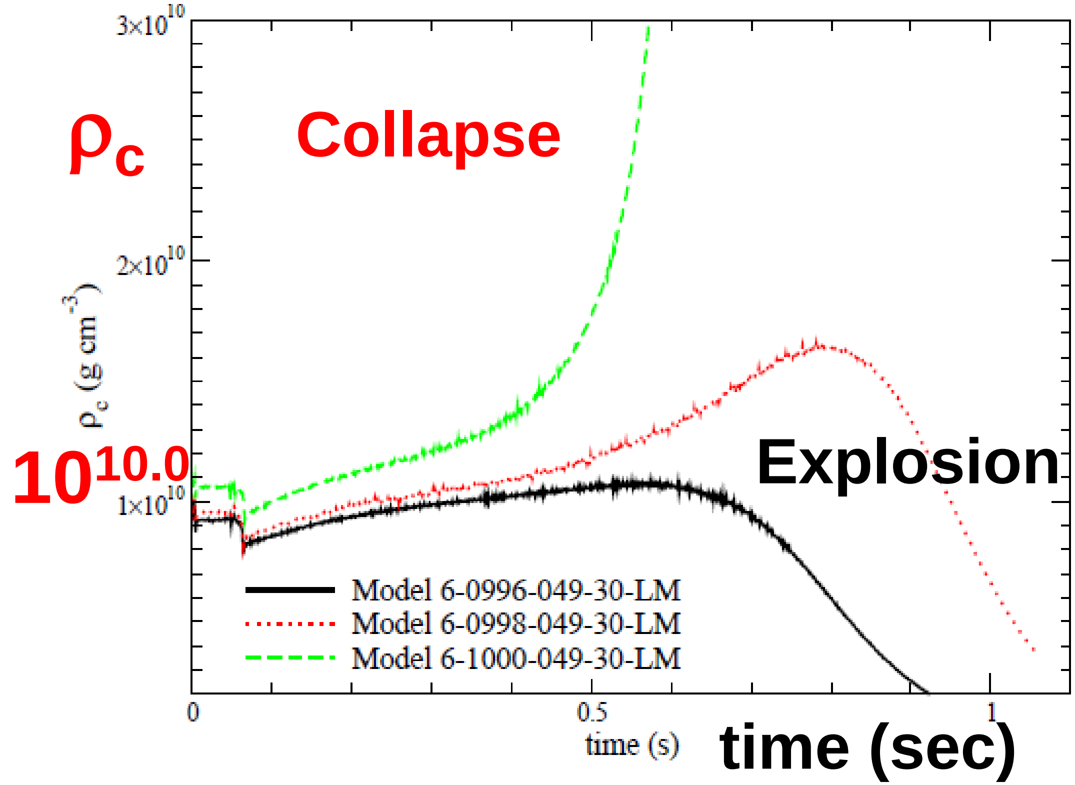
Electron capture in O-Ne-Mg WD

Heating starts at lower density but slow ➔ Contraction

➔ Oxygen deflagration starts at $\rho_c \sim 10^{10.1-10.2}$ g cm^{-3}

➔ **Collapse** (Zha+19: arXiv) **: AIC**





2D simulations: Oxygen deflagration starting from ρ_c **> (<)** $10^{10.0}$ g cm^{-3} ➔ **Collapse** **(Explosion)** (Zha+19; see, however, Kirsebom+19)

	Surface burning	→	Sub-Ch	Chandra
ρ (g cm^{-3})	~10^6		10^{7-8}	10^{9-10}
DD	He/C-detonation	→	C-det	
	steady C-burning	→		ONeMg WD
	no ignition	→		C-deflag
cDD	C-detonation	→	C-det	
CD	(DD in common env)	→	spin-up: super Ch	
SD	(H-rich & He star channels)			
	weak He flashes	→		C-deflag
		→	spin-up: super Ch	
	He detonation	→	C-det	