Detected or undetected ? -- The progenitors of SNe Ia based on the SD model

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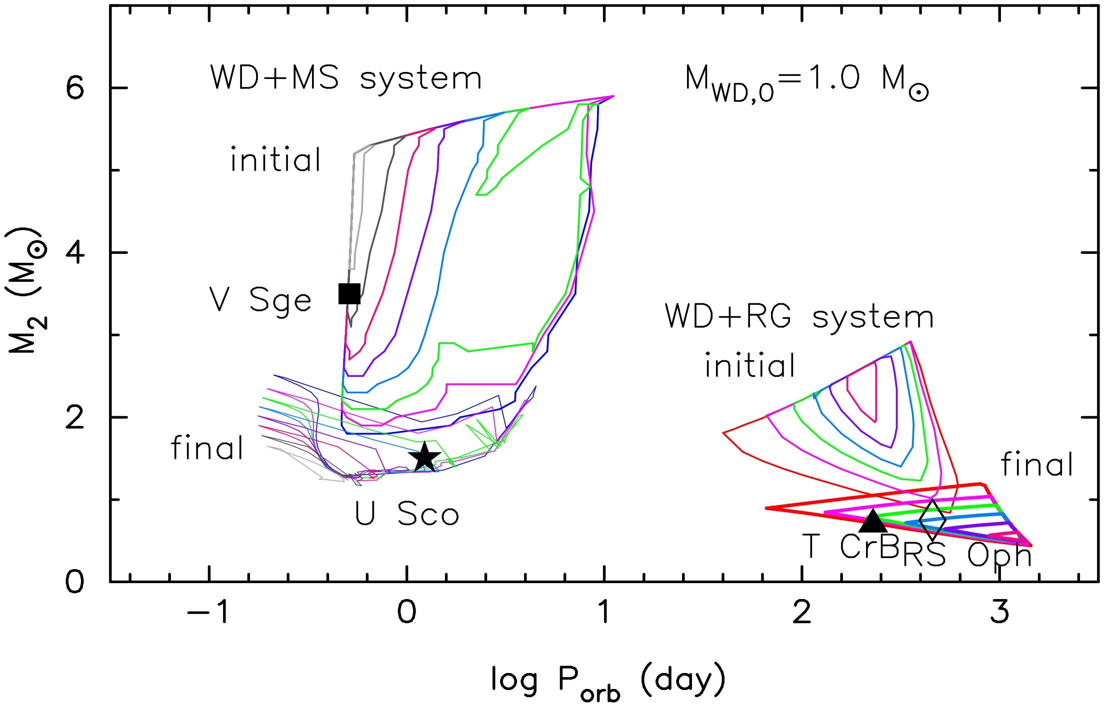
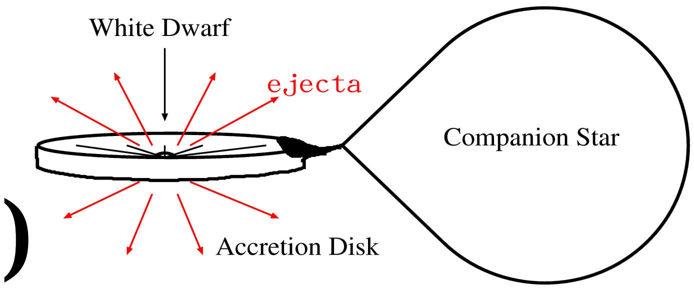


Hachisu, Kato, Saio, & Nomoto, 2012, ApJ, 744, 69
Hachisu, Kato, & Nomoto, 2012, ApJ, 756, L4

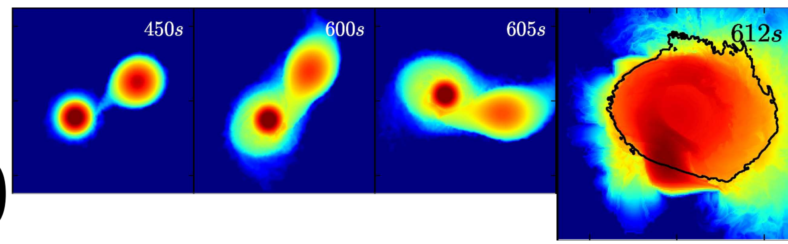
Binary Evolution Models -- SD vs. DD

○ Single Degenerate (SD)



A White Dwarf (WD) gets mass from its normal star companion
→ The WD mass reaches 1.38 Mo
→ carbon ignites at the center/the WD explodes as an SN Ia

○ Double Degenerate (DD)



Pakmor+ 2012

Two WDs merge due to orbital angular momentum loss
→ If the total mass exceeds 1.38 Mo, it explodes as an SN Ia

Serious Problems against SD model

1 - Unseen companions in some SNe Ia

- Red Giant (RG) companions are rejected
- Main-sequence (MS) companions are rejected
- undetected circumstellar matter

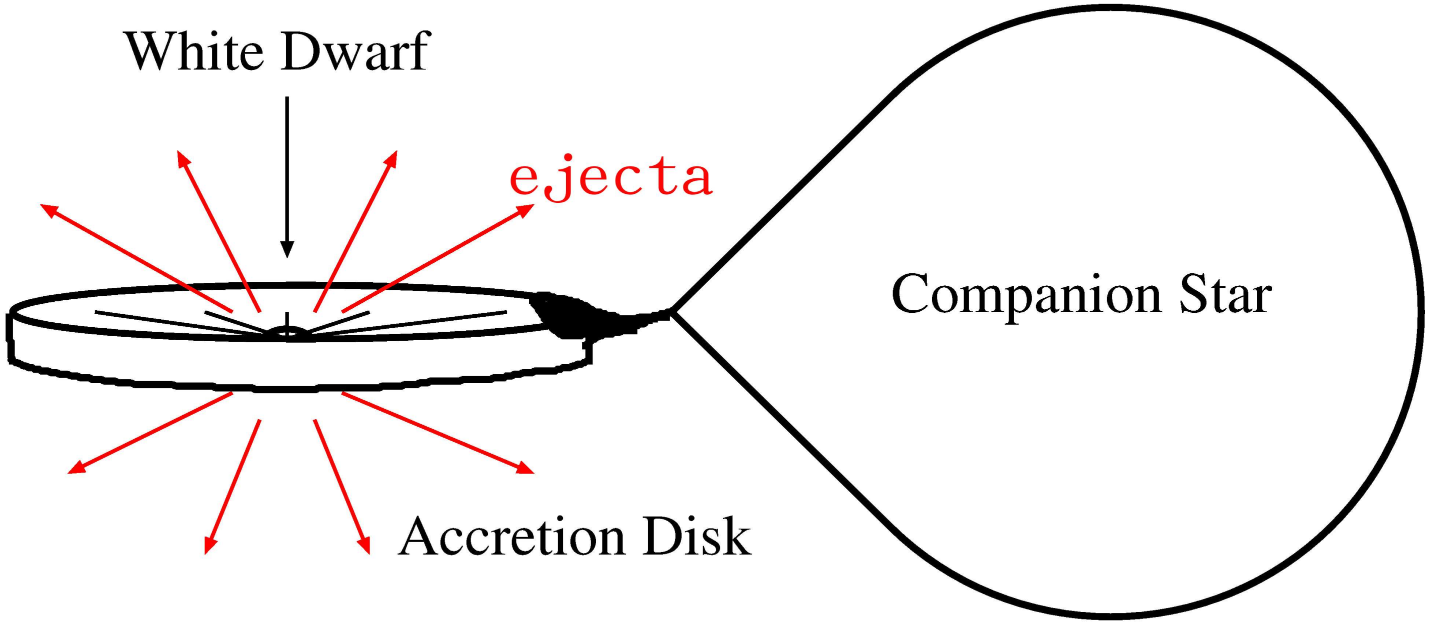
2 - Super-Chandarasekhar mass SNe Ia

- Very bright SNe Ia (～2 Mo or more massive WDs)
  → origin of diversity in brightness

3 - Delay Time Distribution (DTD)

- Standard SD models do not reproduce t^{-1} distribution

Unseen Companion Stars



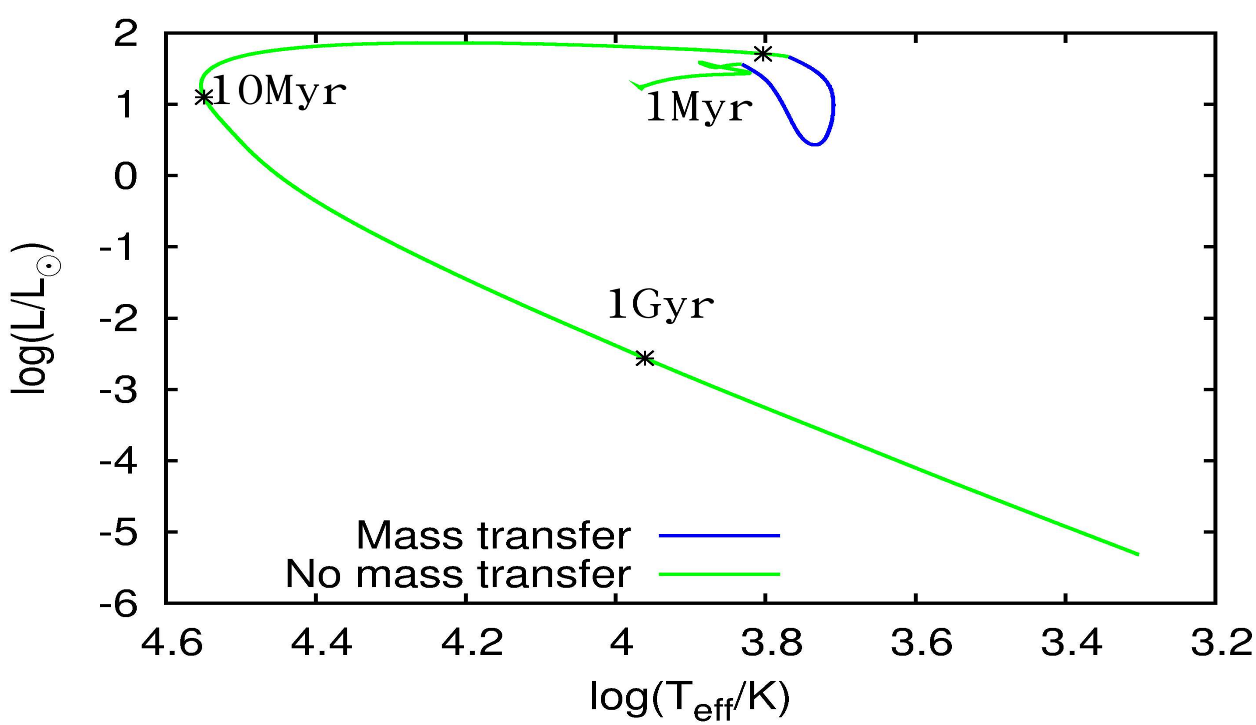
○ Strong constraints on SN 2011fe in M101

not brighter than ∽3.5 Mo MS before explosion (Li + 2011)

less massive than ∽1 Mo MS from no-shocking feature (Brown + 2012)

undetected circumstellar matter (Patat + 2011)

Spin-up/spin-down of rotating WDs



(de Stefano + 2011)

- **WD was once spun up/not exploded, even if M > 1.38 Mo, until it spins down**

  → delayed (1 Gyr or so)

- **not detected at explosion**

  → the companion star evolved to a He WD

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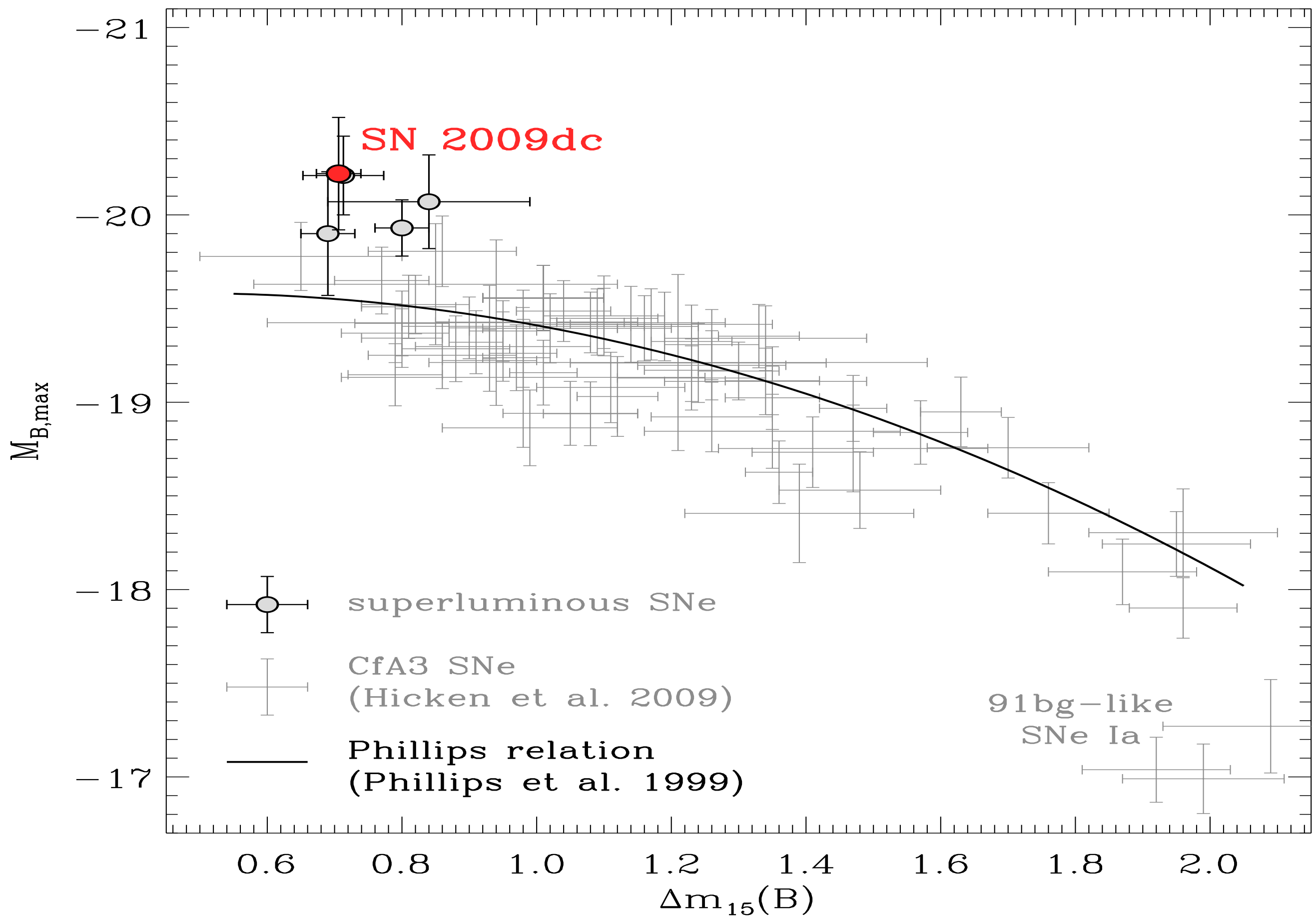
Super-bright Type Ia Supernovae

- **SNe 2003fg, 2006gz, 2007if, 2009dc**
  → **0.5-0.8 mag brighter than Phillips law**
  → super-Chandrasekhar mass SNe Ia

Taubenberger et al. (2011, MNRAS, 412, 2735)



Very Massive Ni56 and Ejecta Mass

○ **Ni mass as massive as 1.4 Mo or more**
Ejecta more massive than 2.0 Mo

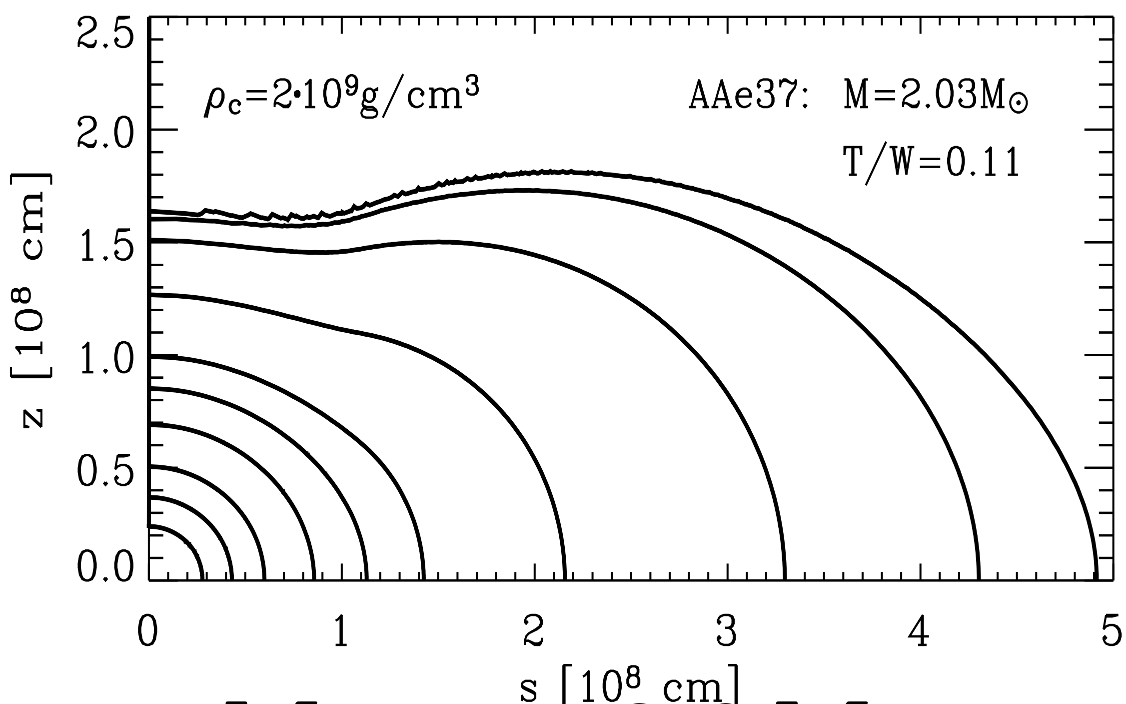
→ super-Chandrasekhar mass SNe Ia

object	^{56}Ni mass	ejecta mass	ref.
SN 2003fg	$1.29 \pm 0.07\ M_\odot$	$\sim 2.1\ M_\odot$	Howell et a1.(2006)
SN 2006gz	$\sim 1.2\ M_\odot$	—	Hicken et al.(2007)
SN 2007if	$1.6 \pm 0.1\ M_\odot$	$2.4 \pm 0.2\ M_\odot$	Scalzo et al.(2010)
SN 2009dc	$1.4 - 1.7\ M_\odot$	$> 2.0\ M_\odot$	Silverman et al.(2011)
	$\sim 1.8\ M_\odot$	$\sim 2.8\ M_\odot$	Taubenberger et al.(20

Differentially Rotating WDs

- differential rotation supports WDs
  → super-Chandrasekhar mass

e.g., Yoon & Langer (2005)



$$M_{\rm WD} > 2.0 M_\odot$$

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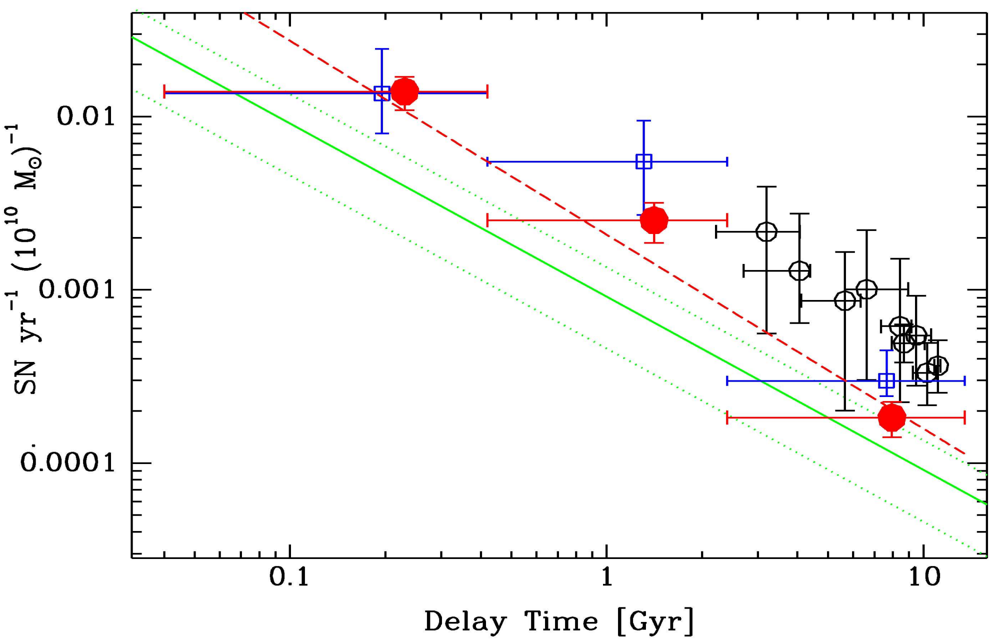
Delay Time Distribution

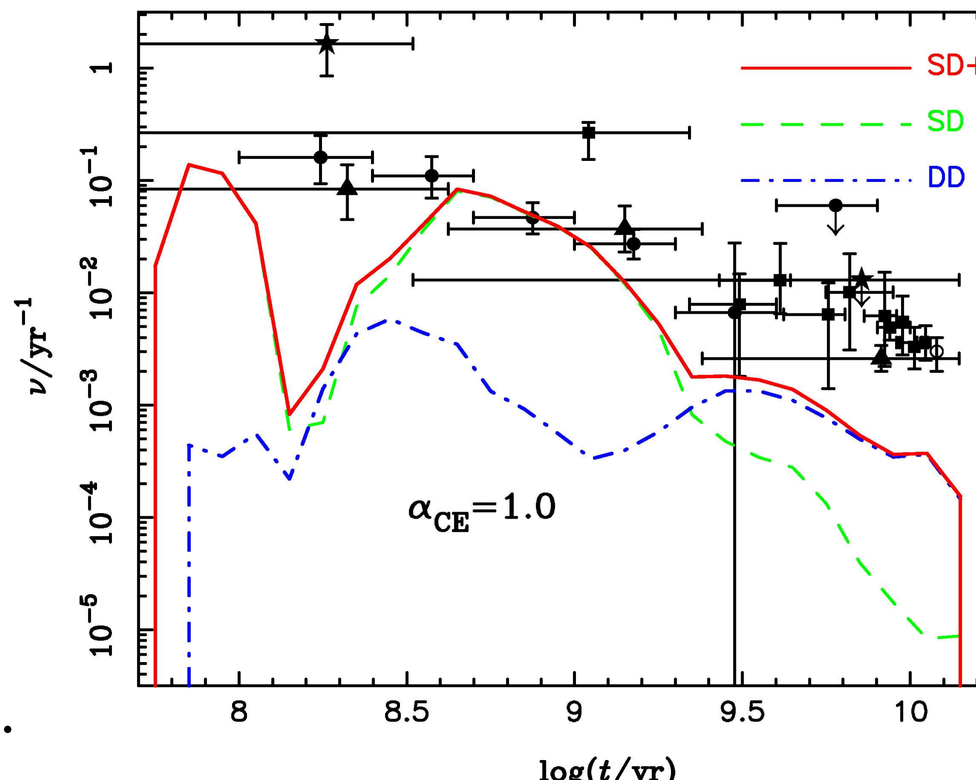
○ **previous SD models cannot reproduce**

$$\propto t^{-1}$$

Maoz + 2012



Meng & Yang 2012



→ including mass stripping effect → resolved

Basic Assumptions of our new Model

- **Our SD model includes three effects in binary evolutions**

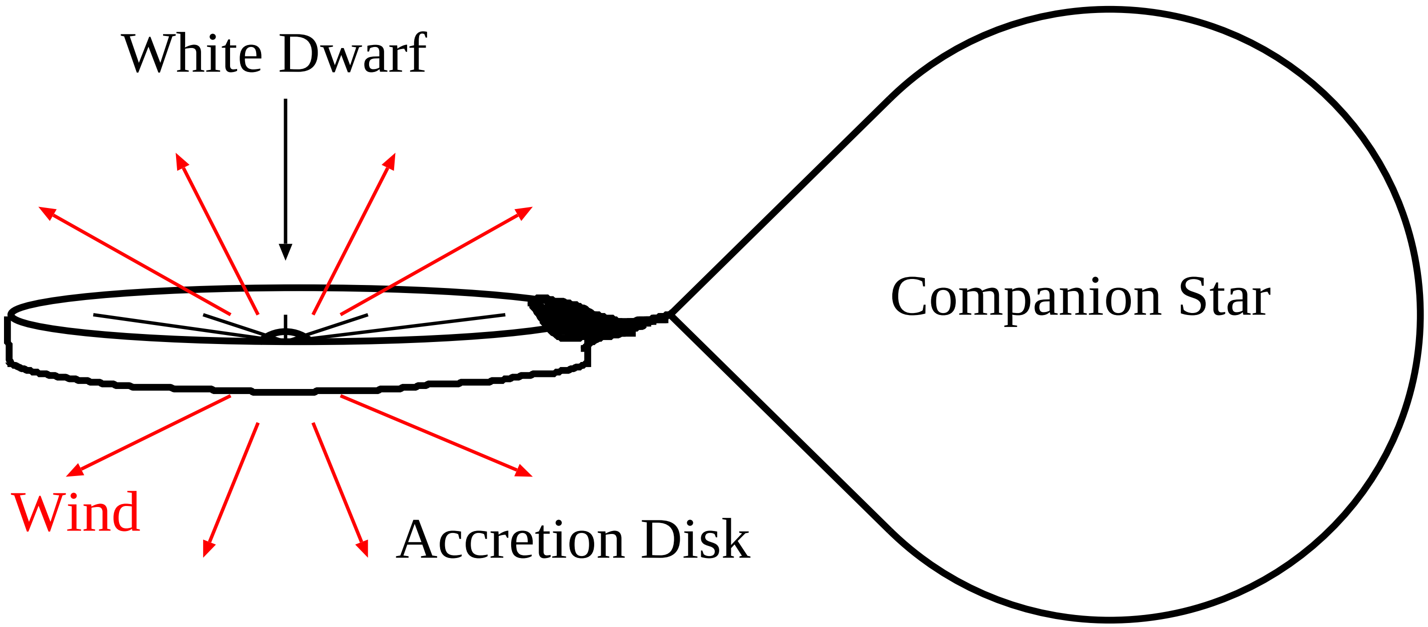
(1) WD winds (accretion winds)
(2) mass stripping of companion
(3) differentially rotating WD

Accretion Wind Evolution (1)

1 . **WDs blow strong winds when the mass accretion rate exceeds a critical rate**

$$\dot{M}_{\rm acc} > \dot{M}_{\rm cr} = 6.68 \times 10^{-7} \left(\frac{M_{\rm WD}}{M_\odot} - 0.445 \right) M_\odot \ {\rm yr}^{-1}$$

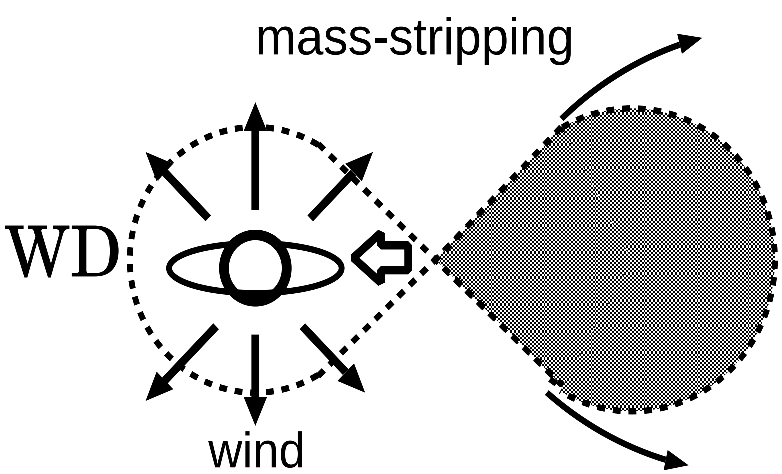
(Hachisu, Kato, & Nomoto 1996, ApJ, 470, L97)



Mass Stripping Effect (2)

2. Winds collide with the companion and strip off the surface

(Hachisu & Kato 2003, ApJ,590,445)



$$\dot{M}_{2,\mathrm{strip}} = c_1 \dot{M}_{\mathrm{wind}}$$

$$c_1 = \frac{\eta_{\mathrm{eff}} \cdot g(q)}{\phi_1 - \phi_3} \frac{1}{2} v_{\mathrm{wind}}^2 \frac{a}{GM}$$

$$c_1 \approx 0.1 \left(\frac{v_{\mathrm{wind}}}{v_{\mathrm{orb}}} \right)^2 = 0.1 \left(\frac{4000\ \mathrm{km/s}}{400\ \mathrm{km/s}} \right)^2 \sim 10$$

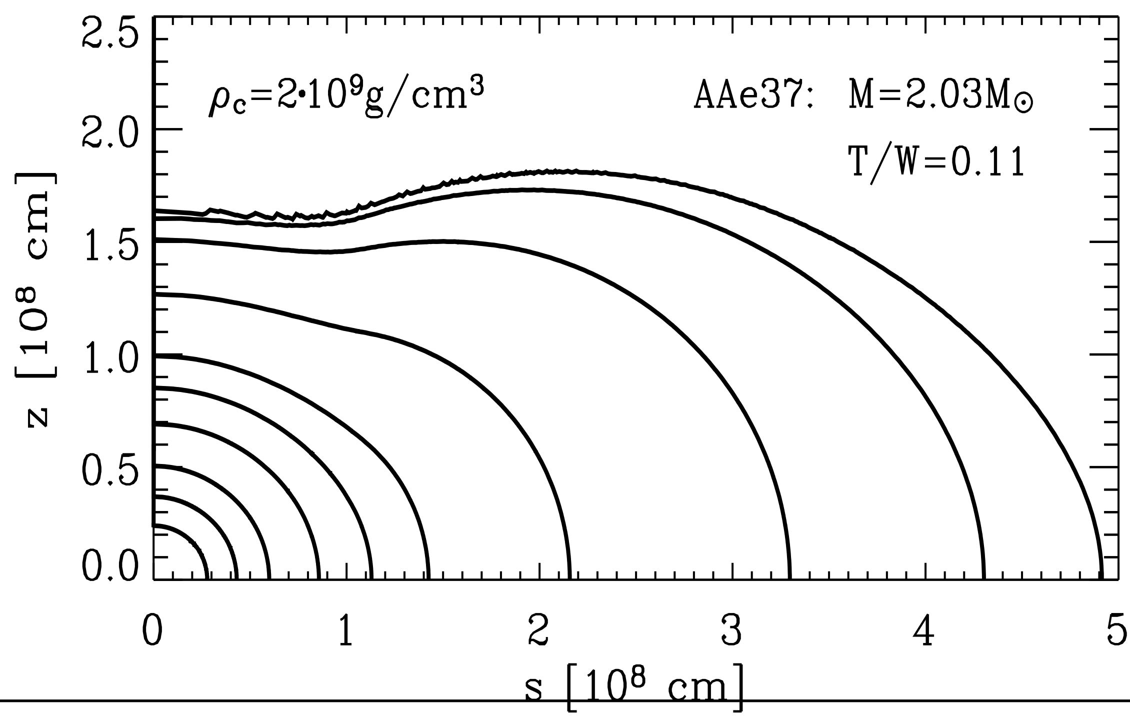
Differentially Rotating WDs (3)

3. Mass-accretion timescale is shorter than timescale of angular momentum transfer

→ differential rotation → super-Ch mass

Yoon & Langer (2005)

$$\dot{M}_{\rm acc} > 1 \times 10^{-7} M_\odot \ {\rm yr}^{-1}$$

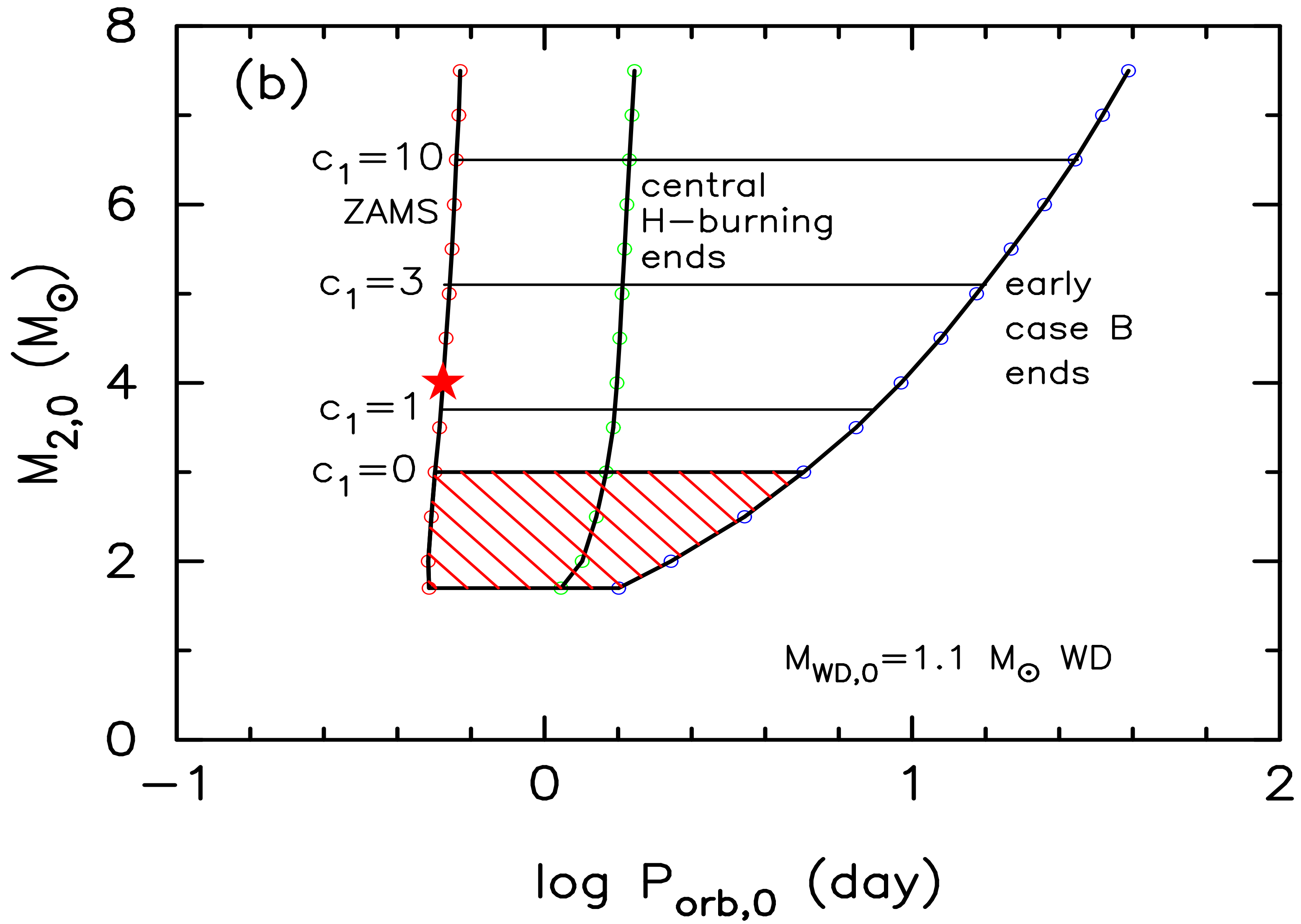


$$M_{\rm WD} > 2.0 M_\odot$$

Initial State of Binary Evolution

○ 1.1 Mo WD + 4.0 Mo MS (ZAMS)

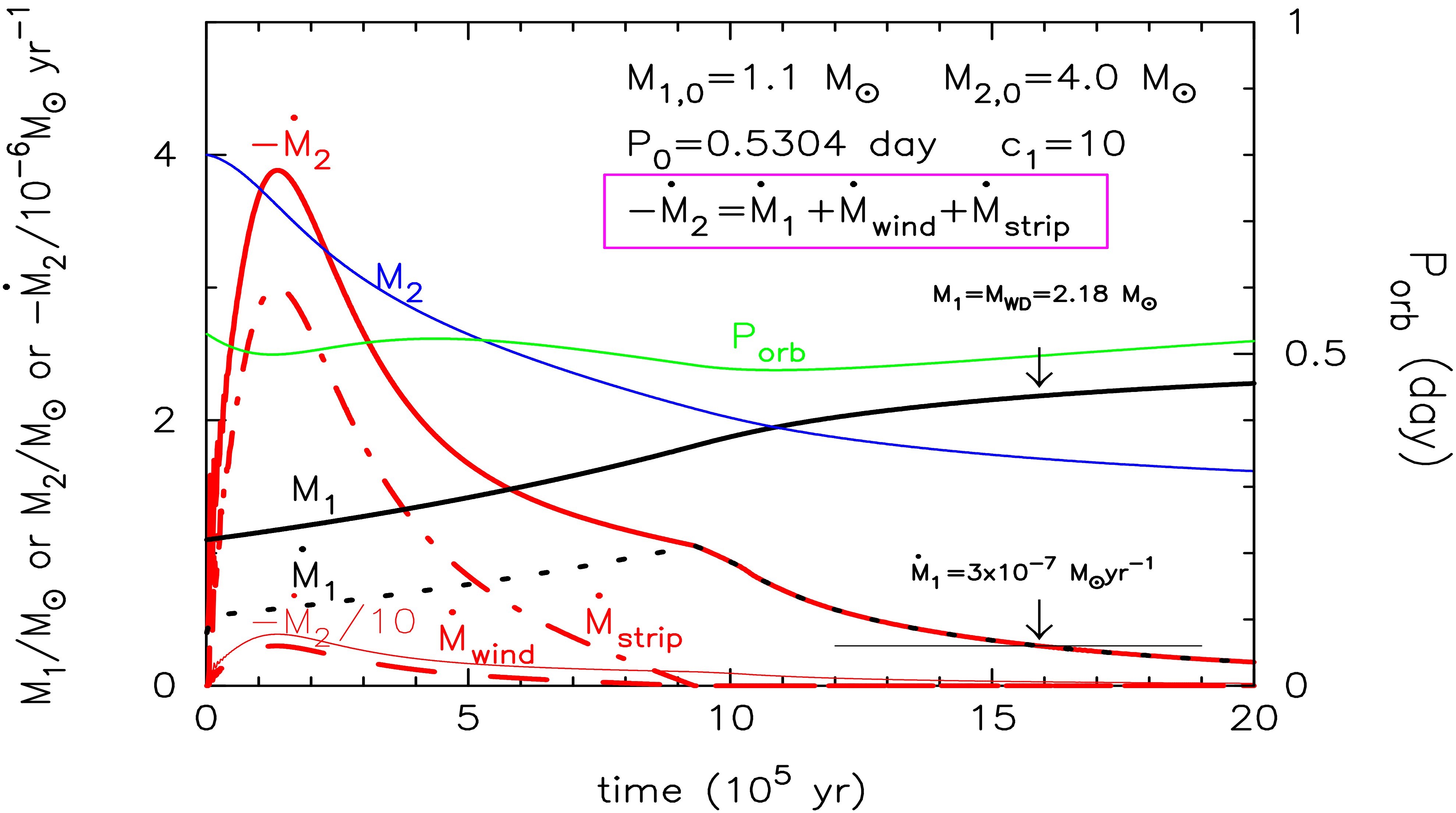
Hachisu et al. (2011)



Binary Evolution of 1.1 Mo WD + MS

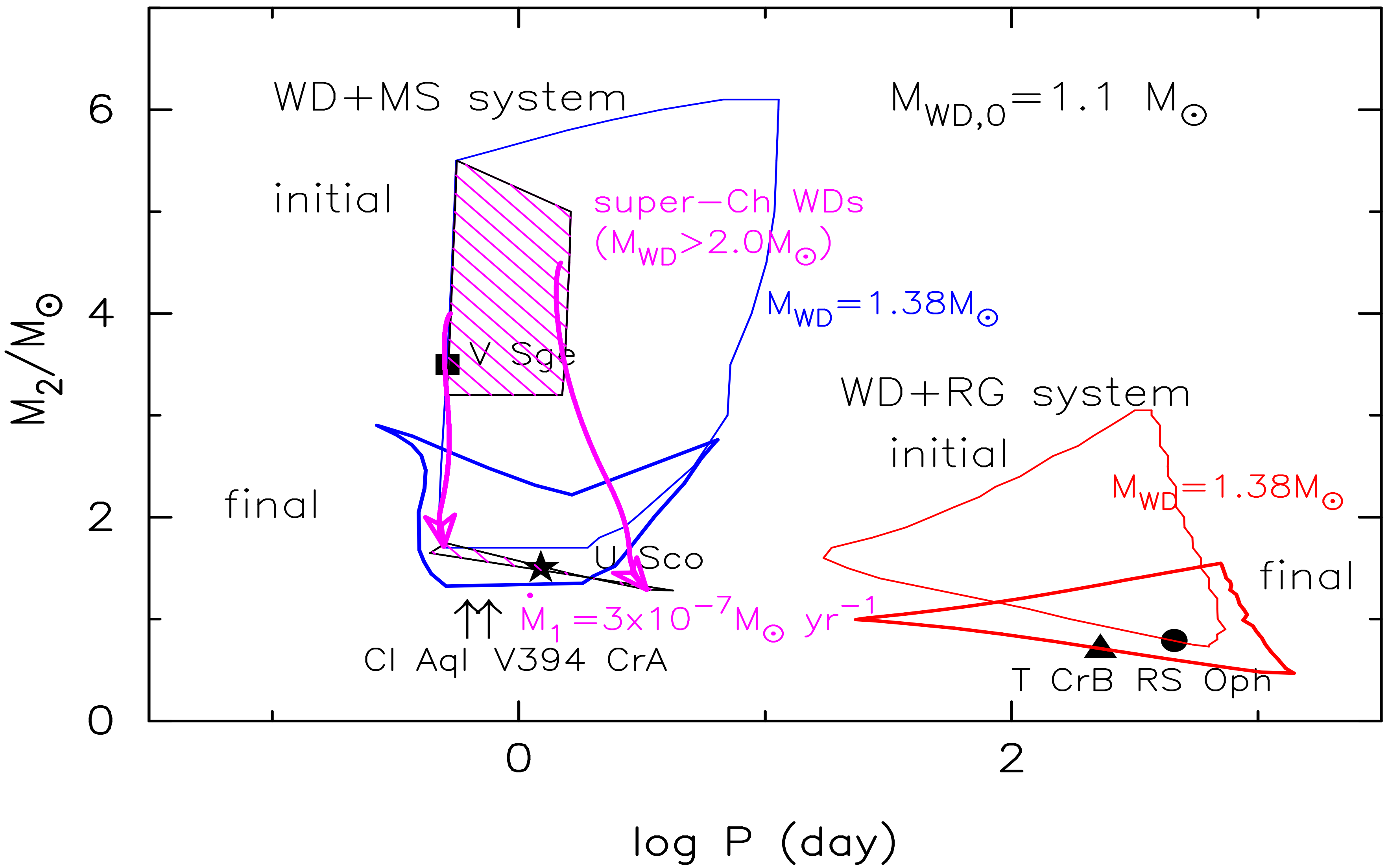
→ maximum WD mass = 2.2 Mo (c1=10)

Hachisu et al. (2011)



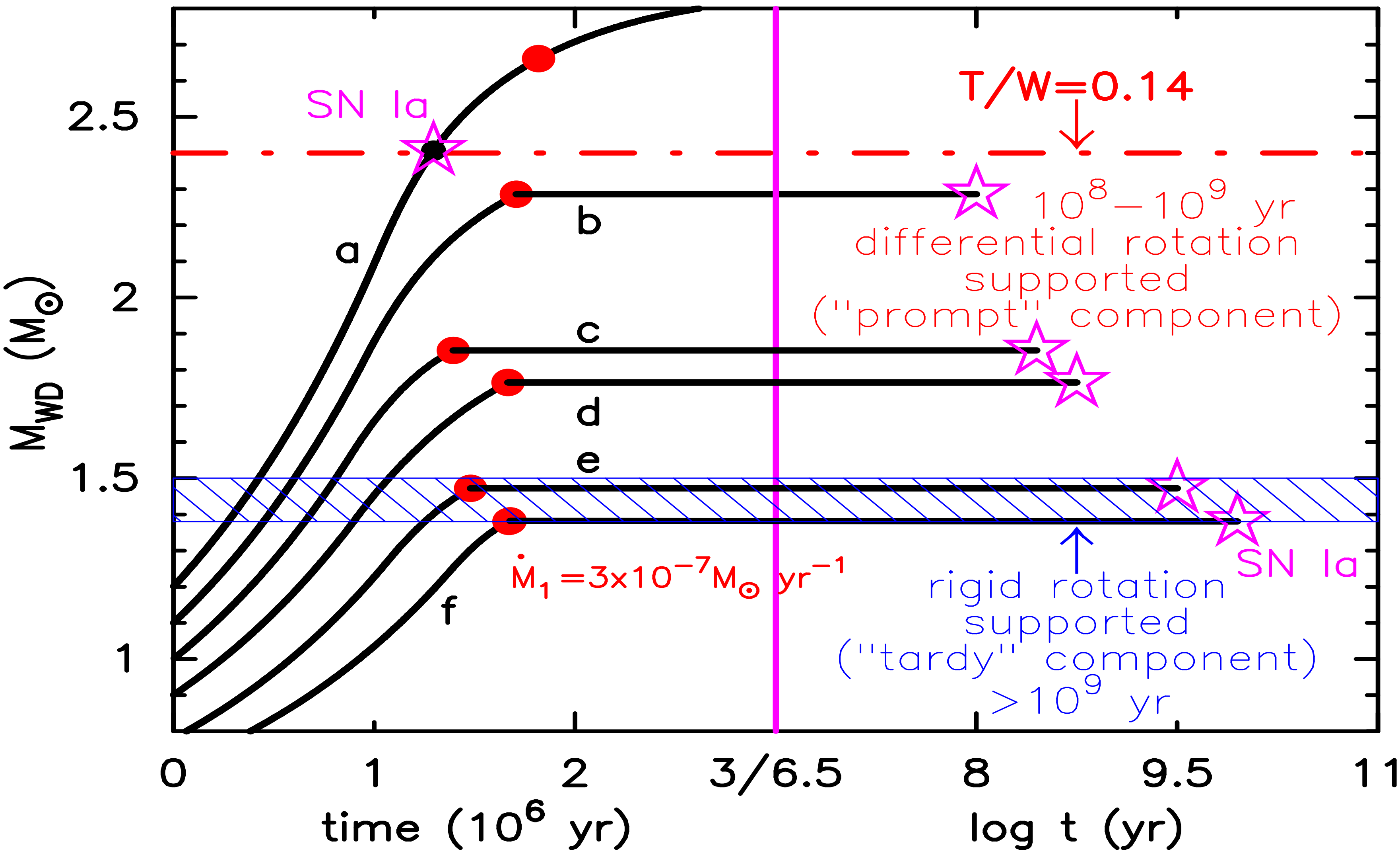
Binary Evolution Paths

- 2.2 Mo WD mass is reached



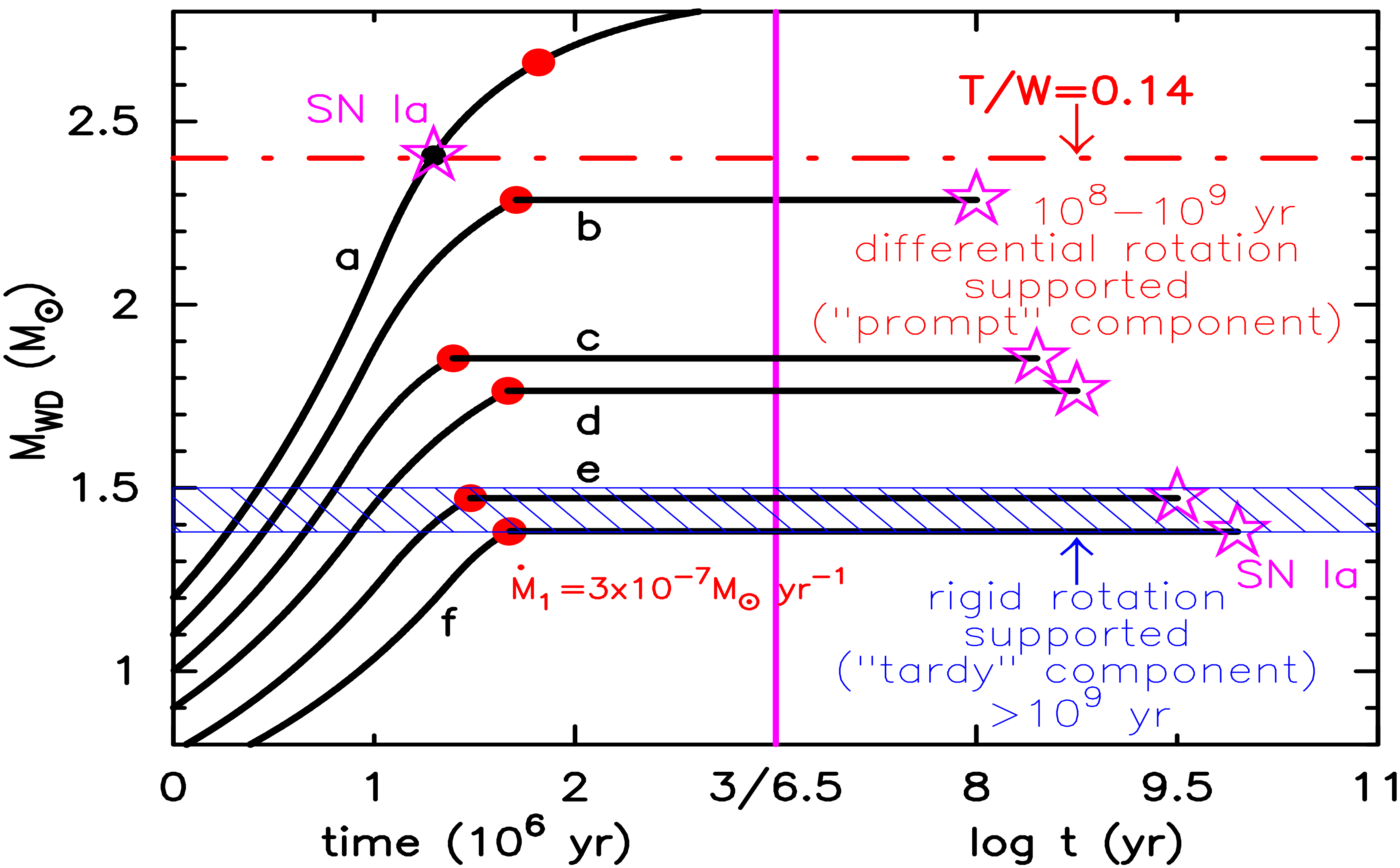
(1) Final Mwd > 2.4 Mo

- Case a: WD explodes immediately after reaching Mwd=2.4 Mo



(2) Final 1.5 < Mwd < 2.4 Mo

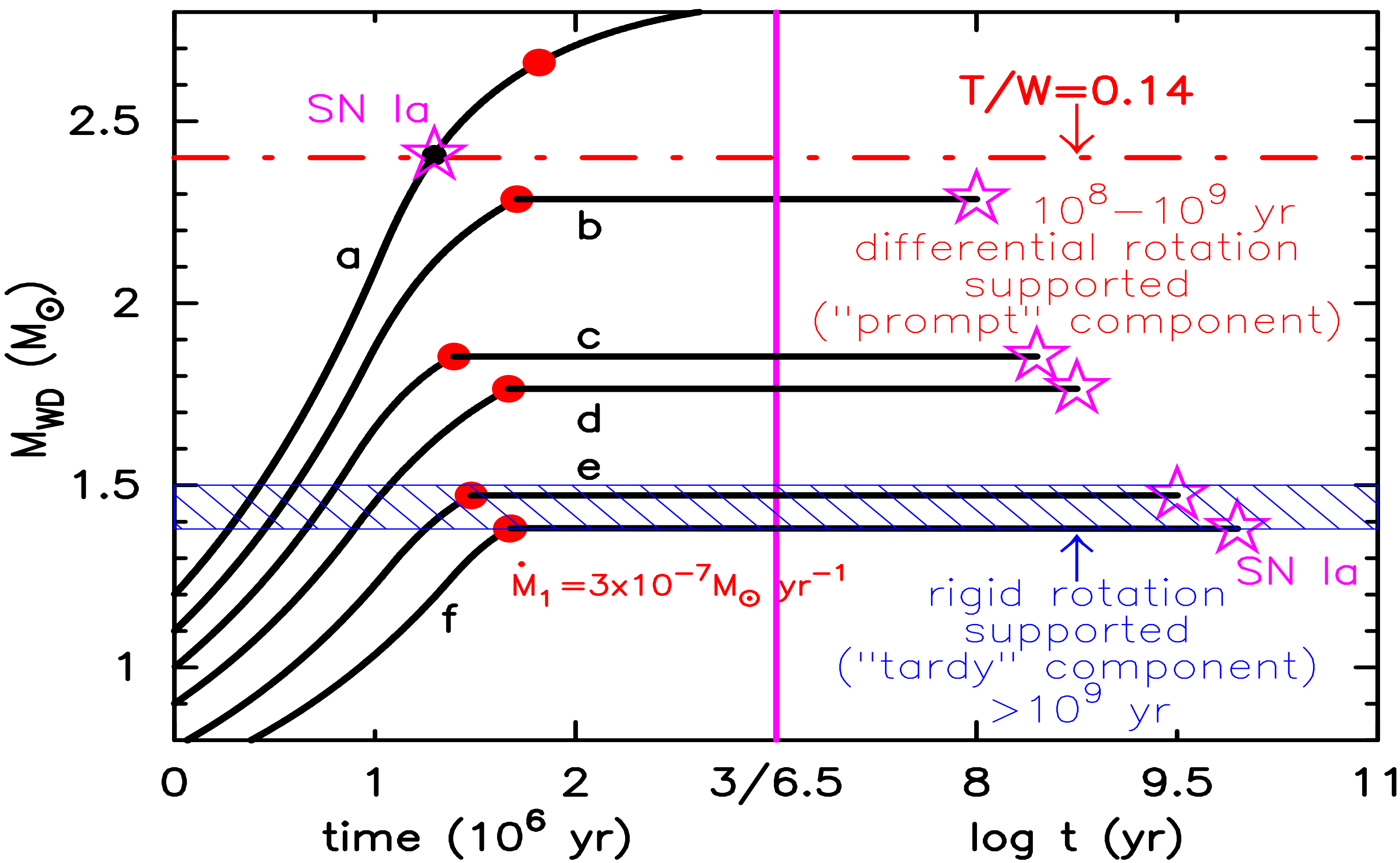
- Case b,c,d: differential rotation 10^8--10^9 yr to explode as an SN Ia



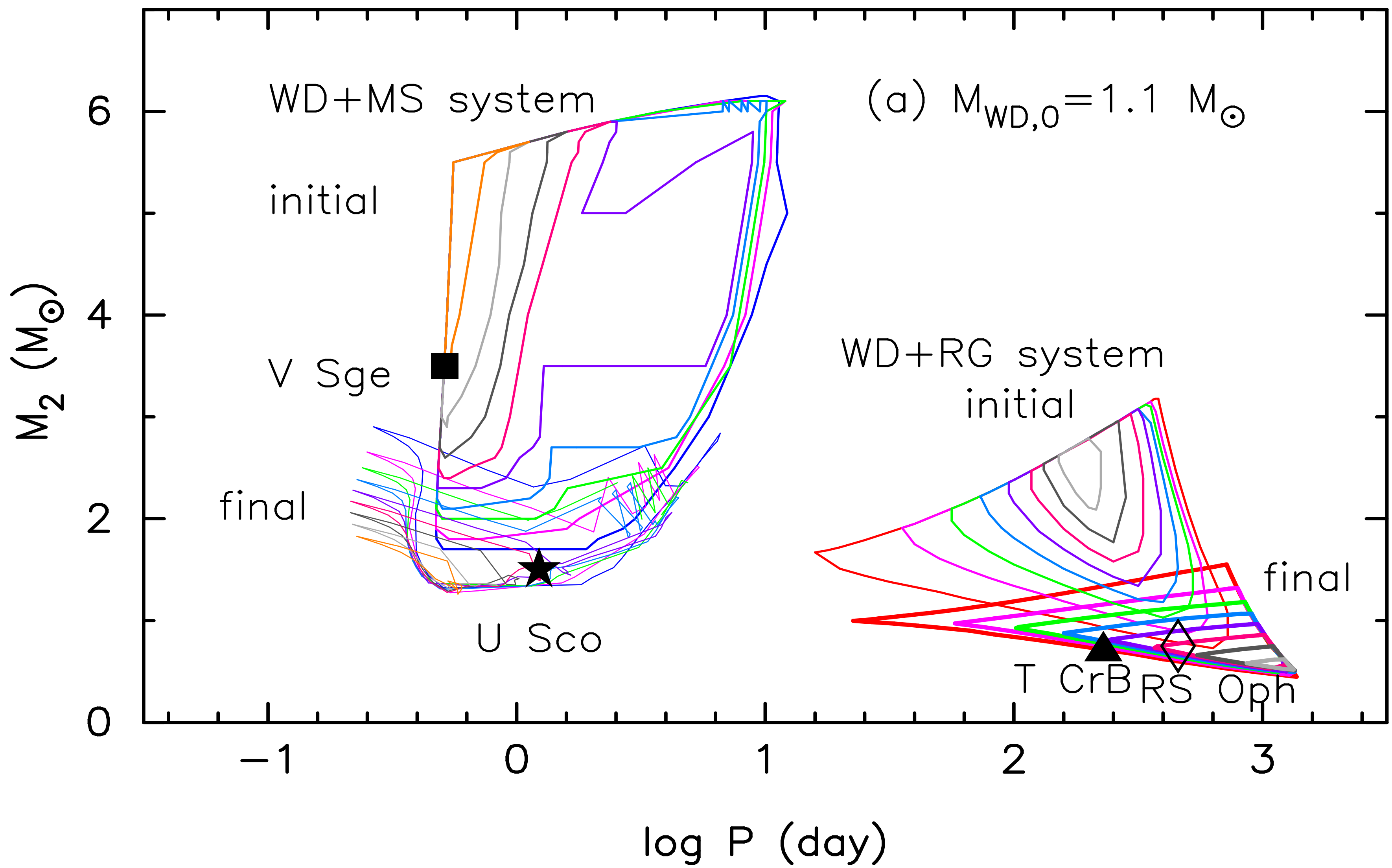
(3) Final 1.38 < Mwd < 1.5 Mo

- Case e,f: rigid rotation
  > 10^9 yr to explode as an SN Ia

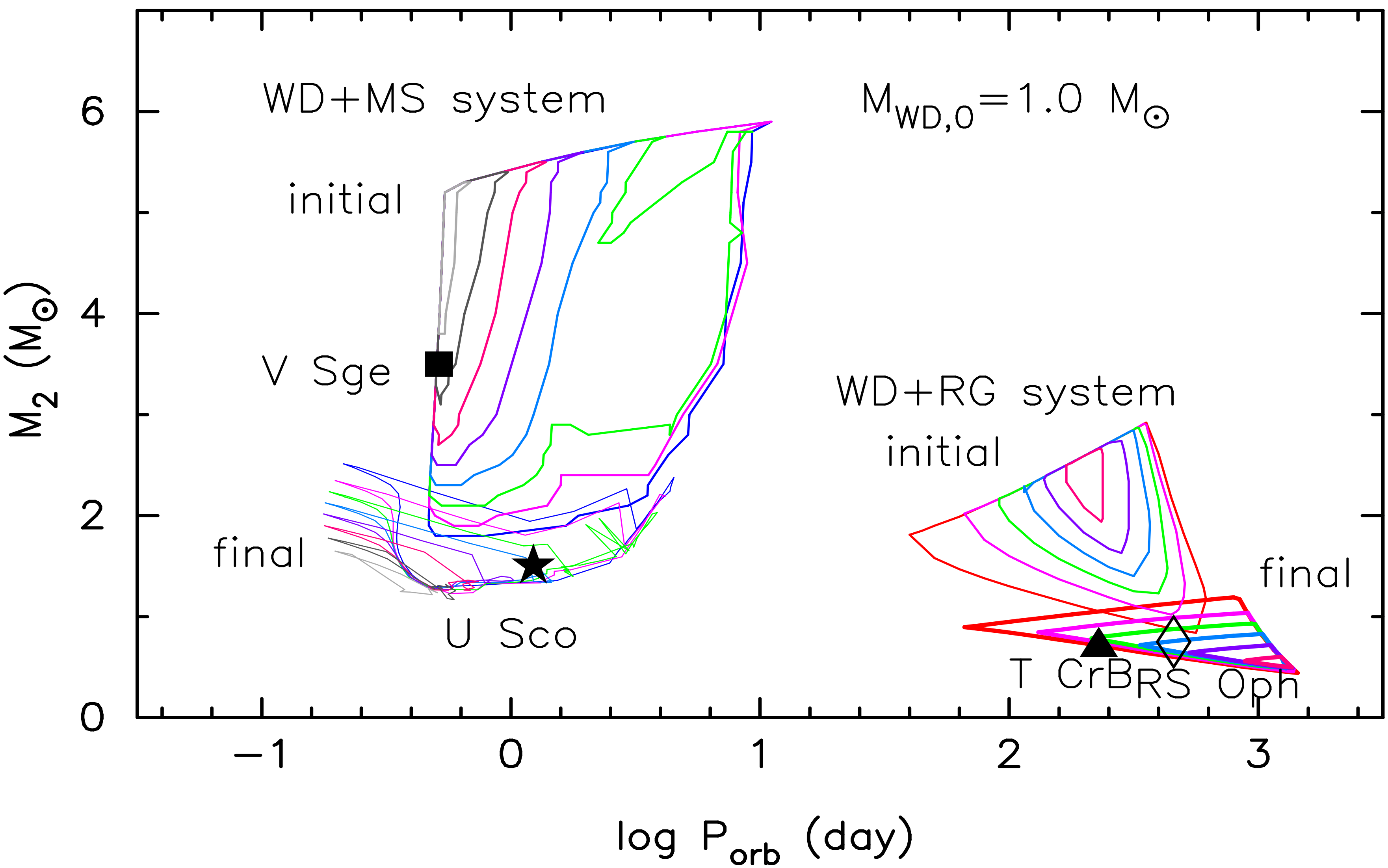
(e.g., Justham 2011, Di Stefano et al. 2011, Ilkov & Soker 2011)



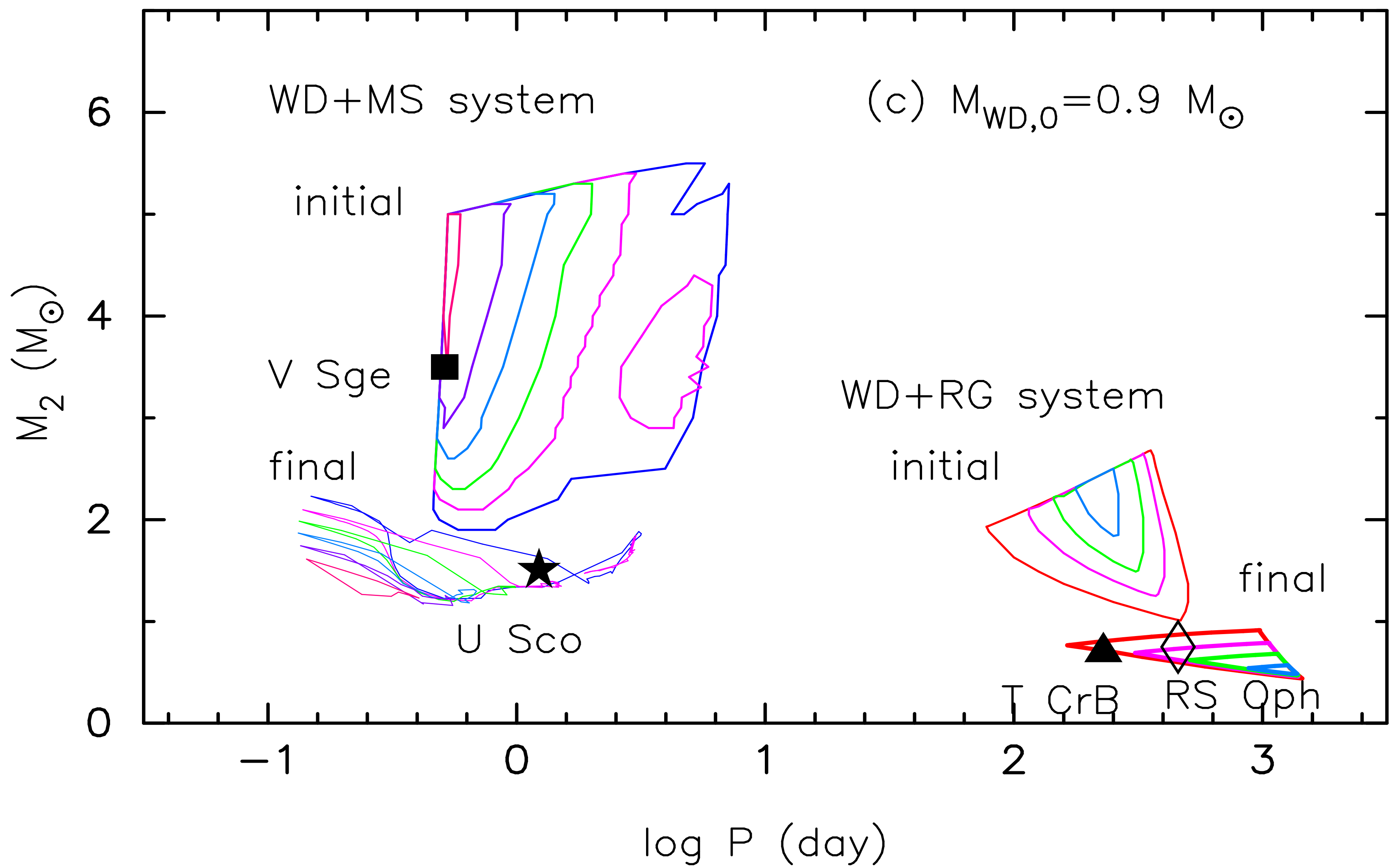
Growth of WD Mass (initial 1.1 Mo)



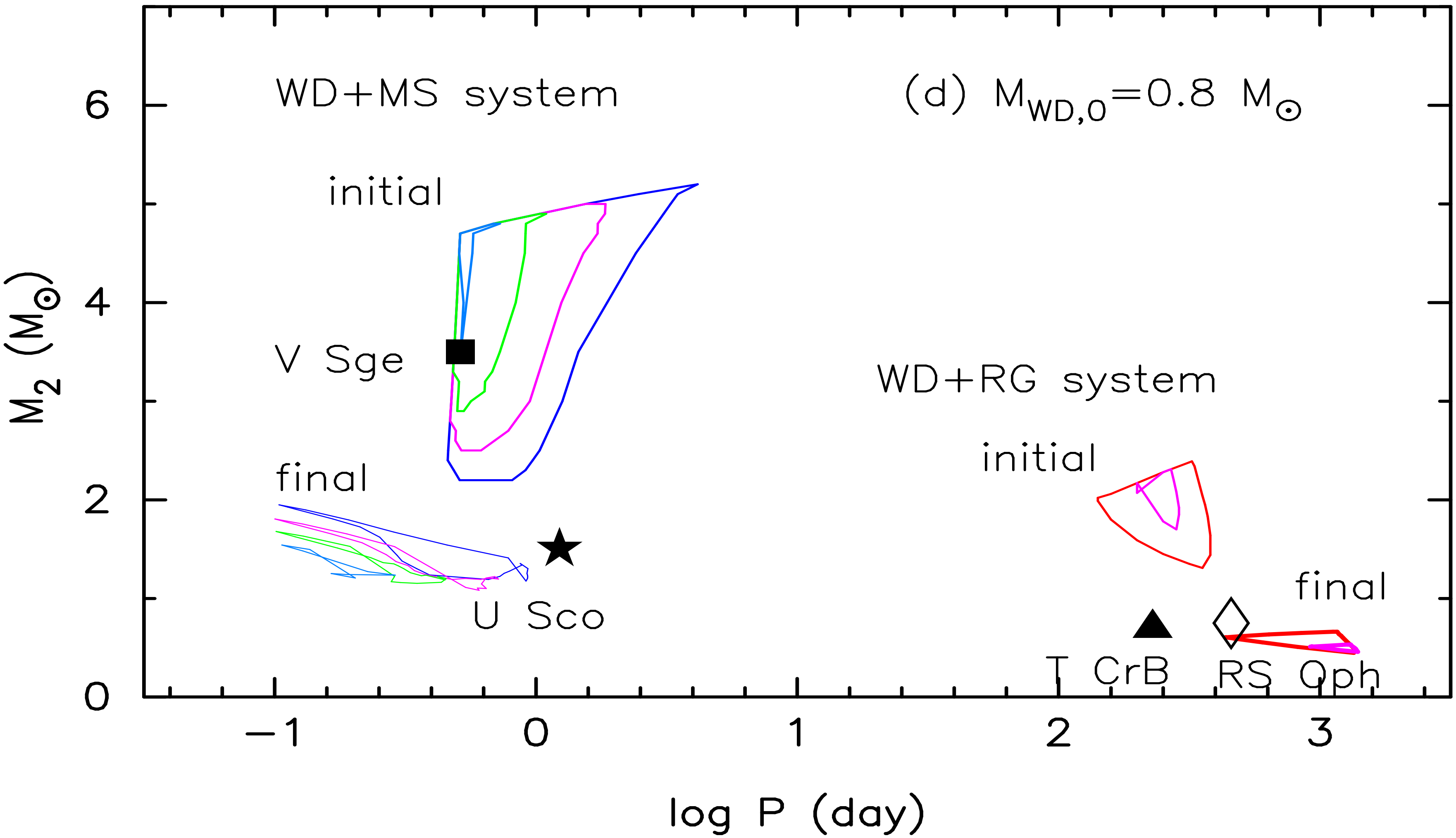
Growth of WD Mass (initial 1.0 Mo)



Growth of WD Mass (initial 0.9 Mo)

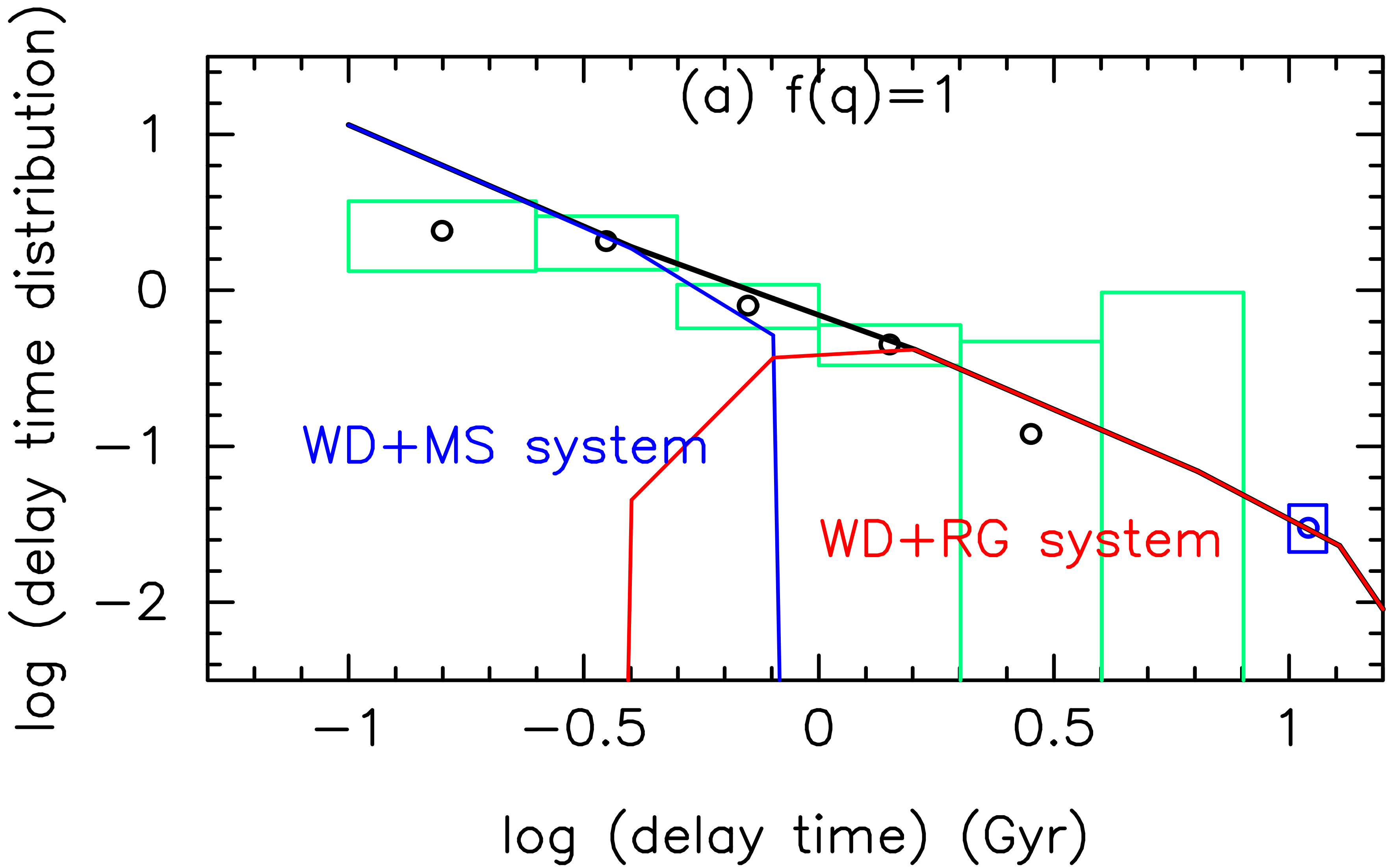


Growth of WD Mass (initial 0.8 Mo)

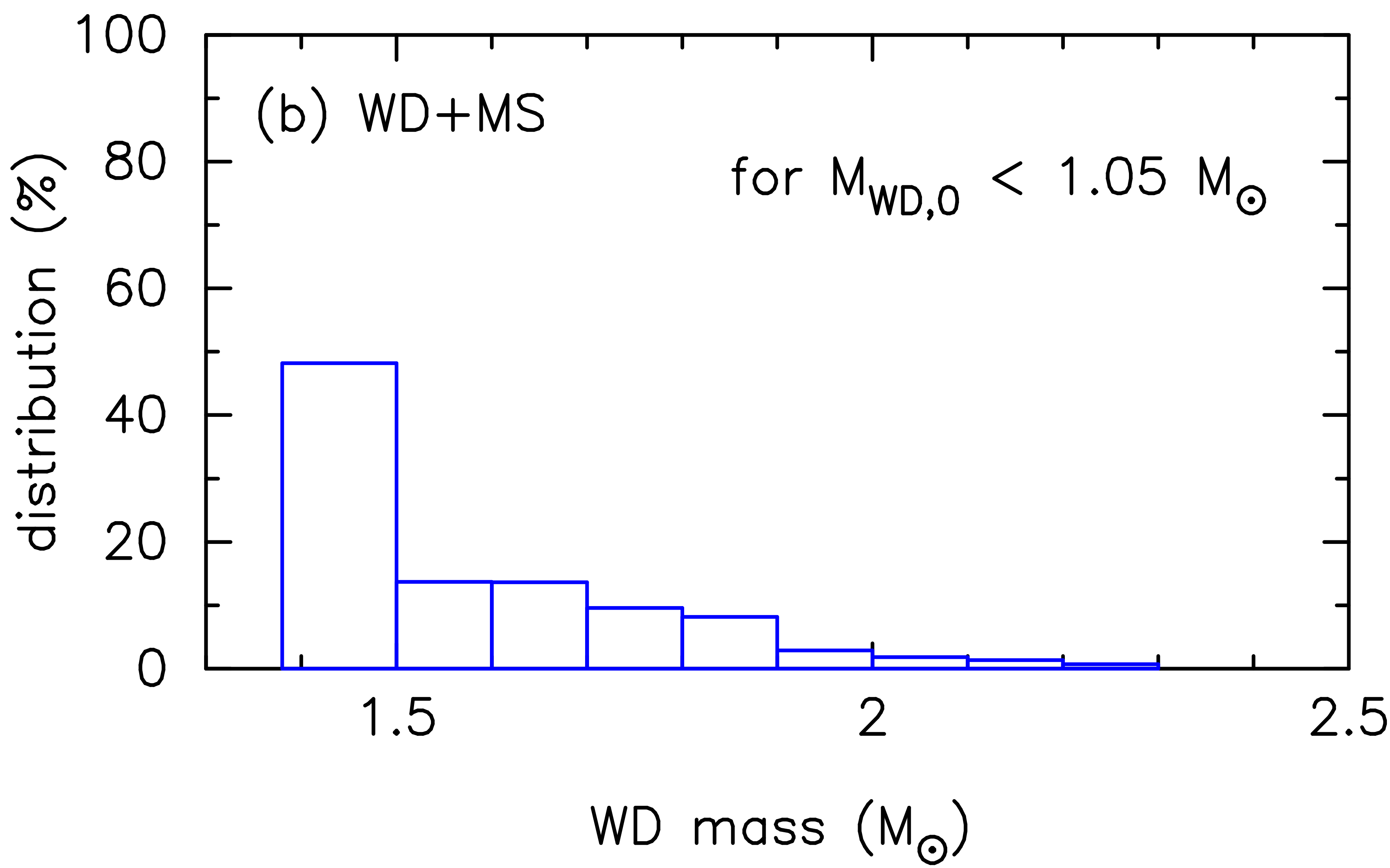


log P (day)

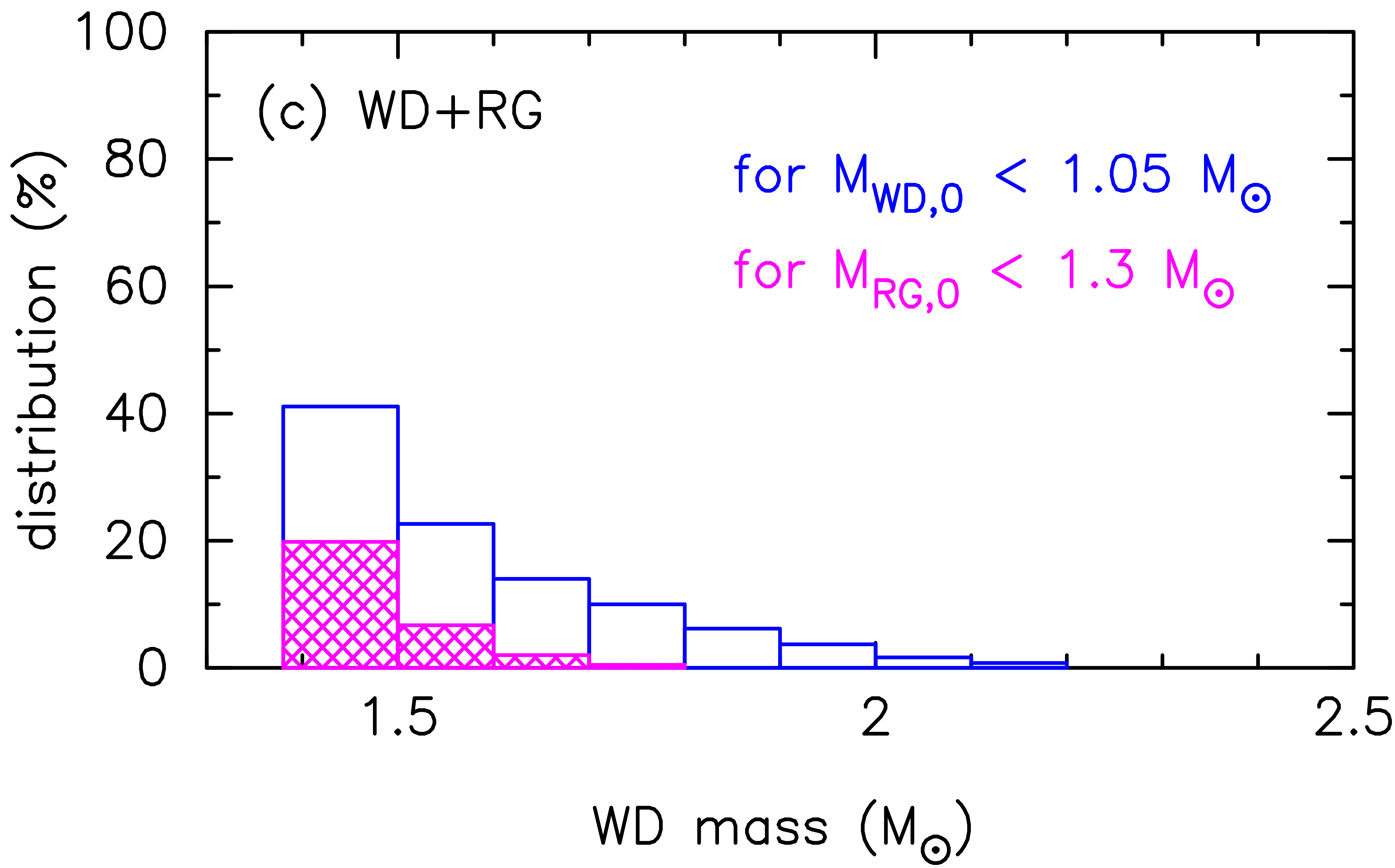
Delay Time Distribution



Mass Distribution of WDs (MS)



Mass Distribution of WDs (RG)

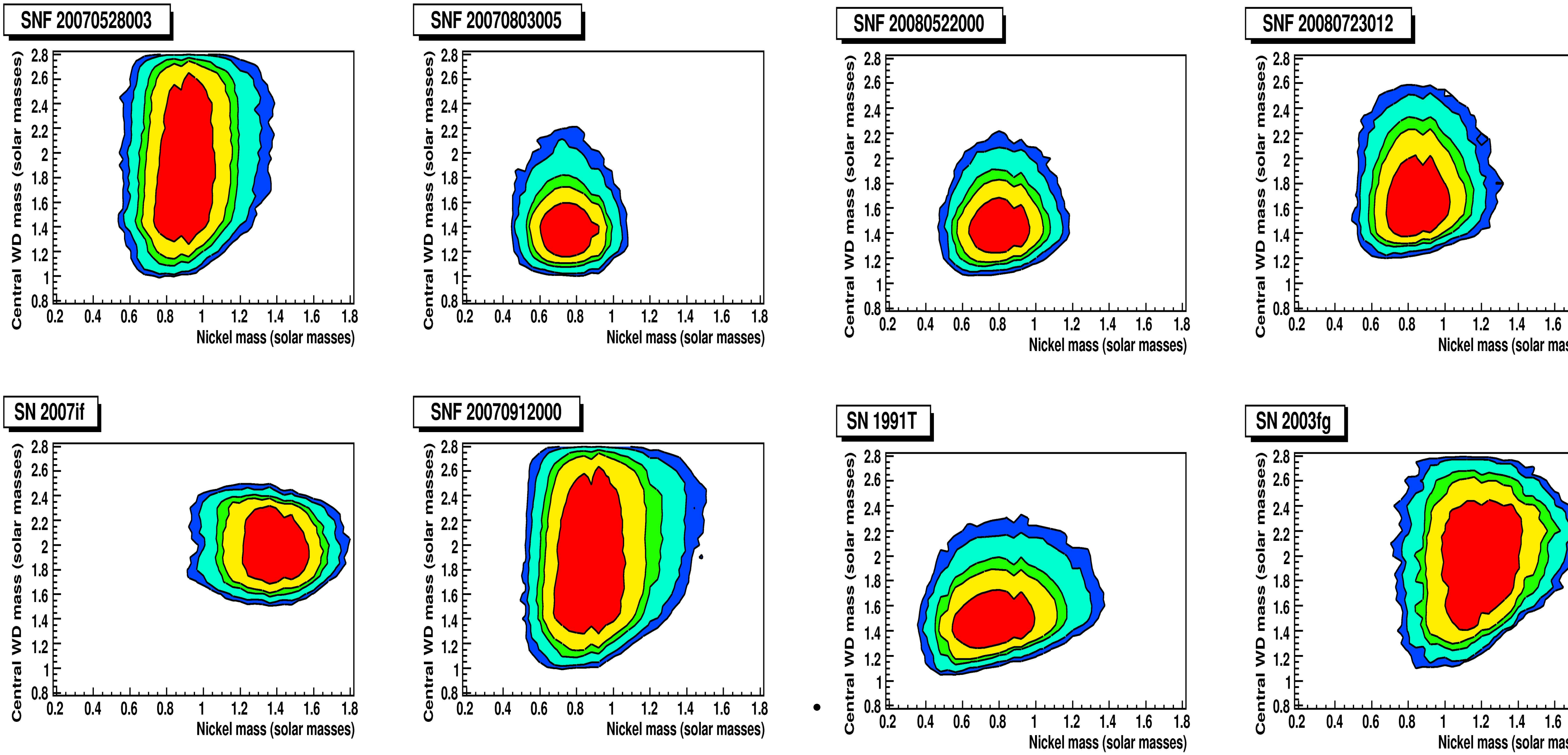


○ companions evolved to a He WD at explosion

→ No detection of companions

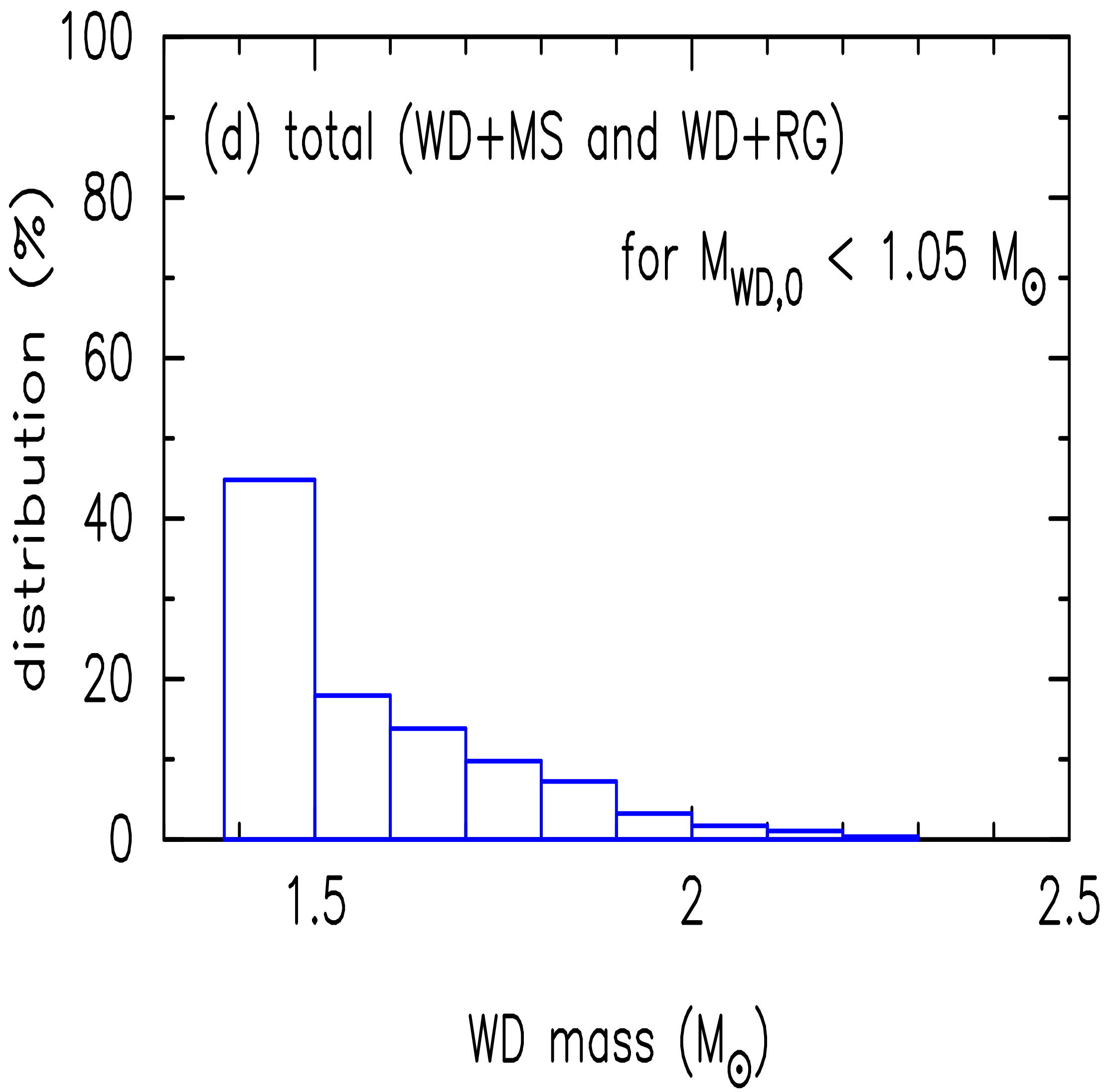
Mass Distribution of WDs

e.g., Scalzo + 2012

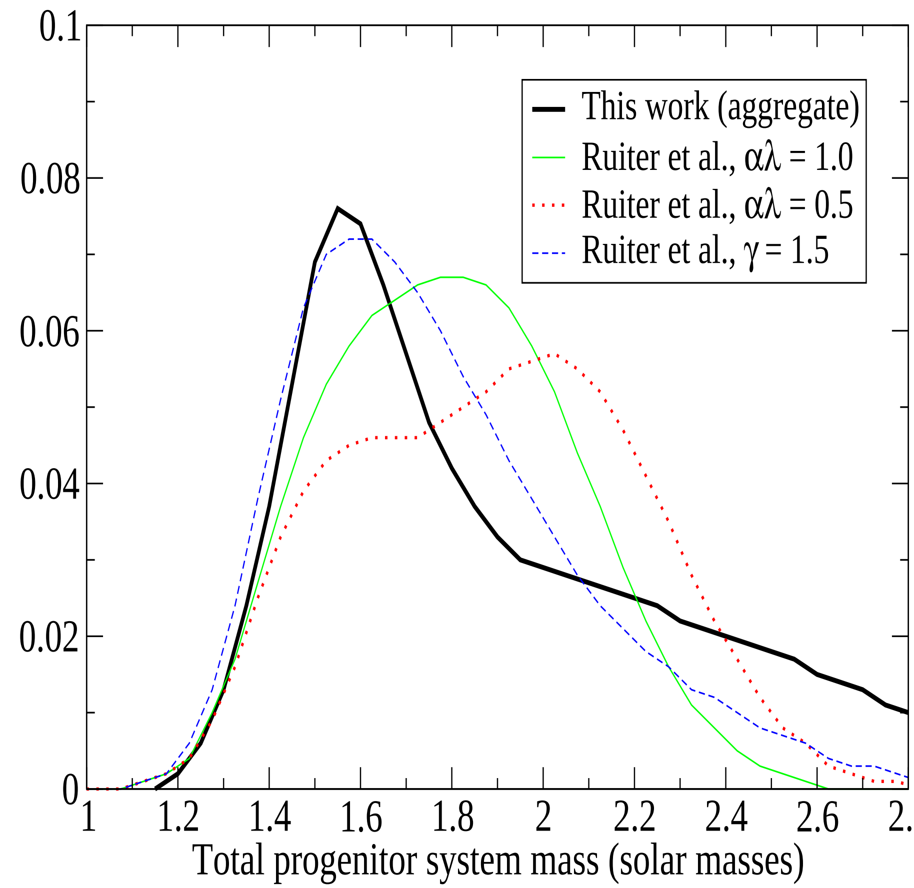


Comparison between Obs. and Model

Our model



Scalzo + 2012 (black line)



Luminosity Distribution of SNe Ia

Table 2

WD Mass versus Maximum Luminosity Distribution

WD Mass ($M_\odot$)	Ratio (%)	$\Delta m_{15}(B)$ (mag)	Ratio[a] (%)
1.38–1.6	62.7	1.1–2.1	67.4
1.6–1.8	23.6	1.0–1.1	17.3
1.8–2.0	10.5	0.9–1.0	10.2
2.0–2.3	3.2	0.7–0.9	5.1

Note. [a] Taken from Blondin et al. (2012).

Summary

1 - Unseen companion

→ Companion becomes a He WD during spin-down time

2 - Brightness distribution

→ Mass distribution of WDs at explosion

3 - Delay Time Distribution (DTD)

→ Both WD+MS and WD+RG contribute t^{-1}