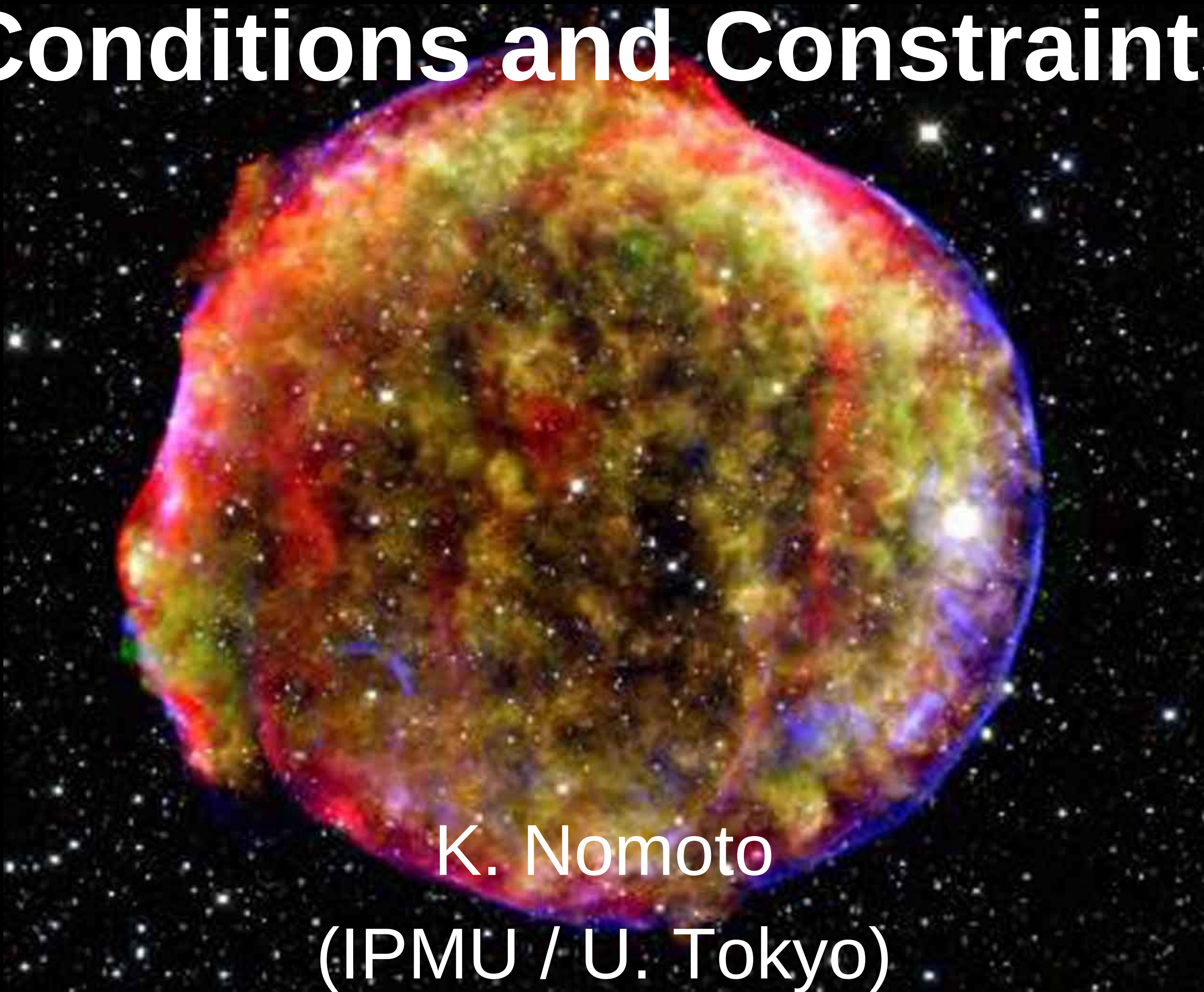
Single Degenerate Ignition Conditions and Constraints



K. Nomoto
(IPMU / U. Tokyo)

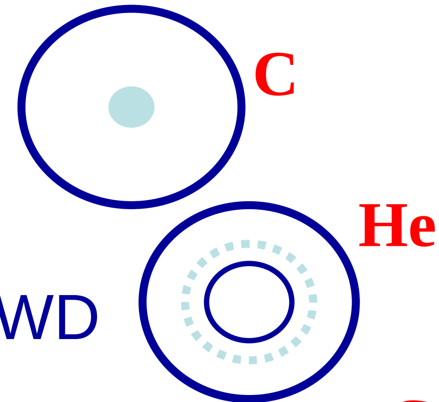
KITP 2007 March

Bob, Welcome to the Red Vest Club !!

The Progenitors of Type Ia Supernovae

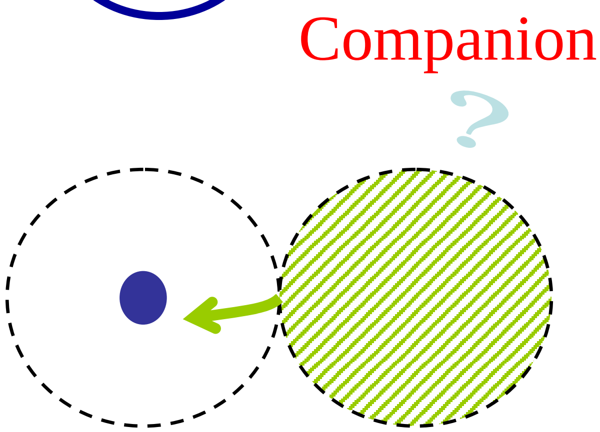
- **Single Degenerate**
  vs.
  Double Degenerate

- **Chandrasekhar Mass WD**
  vs.
  Sub-Chandrasekhar Mass WD



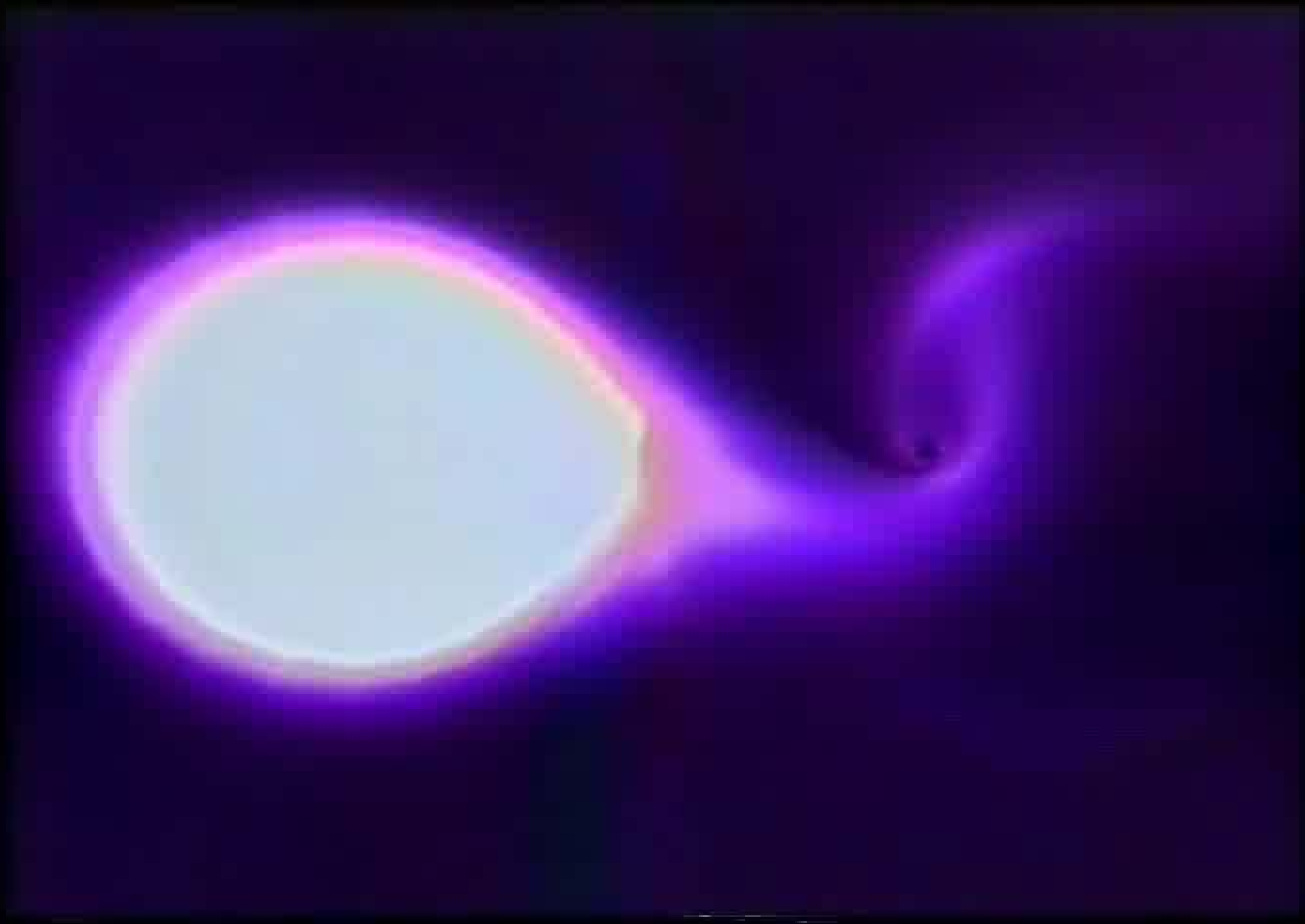
Single Degenerate Scenario

Hurdles, Constraints,
Observational Tests



SN 1572 (Tycho)

SN 2009dc (Super Chandra Candidate)



(T. Matsuda)

Single Degenerate Scenario

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

(2) H & He Burning

(3) Radiation-driven WD Winds

(4) Mass-Stripping of Companion Star

(5) Reduction of Mass Transfer Rate

➔ **Ignition of Carbon Burning**

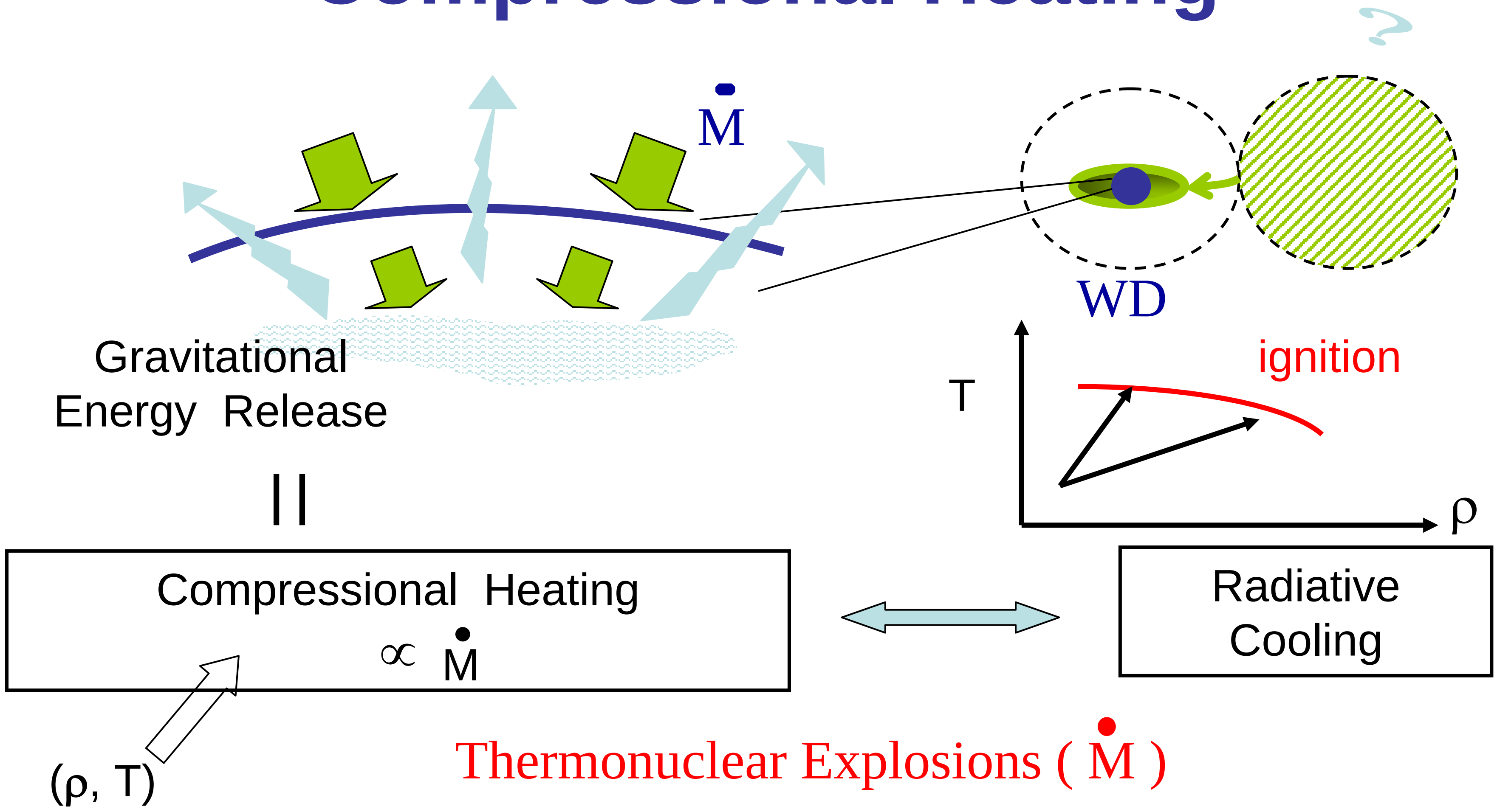
➔ Hurdles, Constraints, Observational Tests

Population(M_2,P); Delay Time Distribution

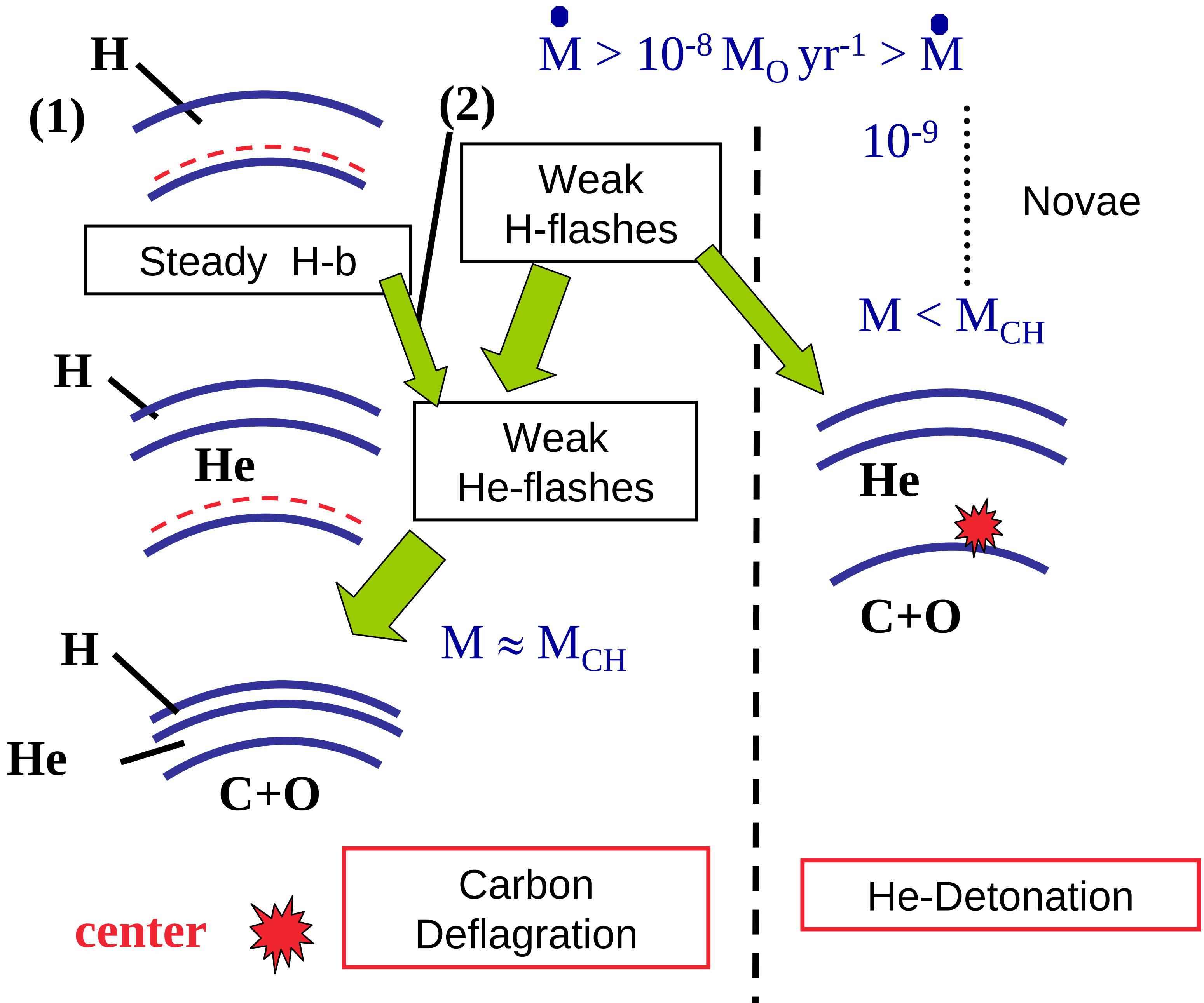
Circumstellar Matter, etc.

(1) Accreting White Dwarf Models

Compressional Heating

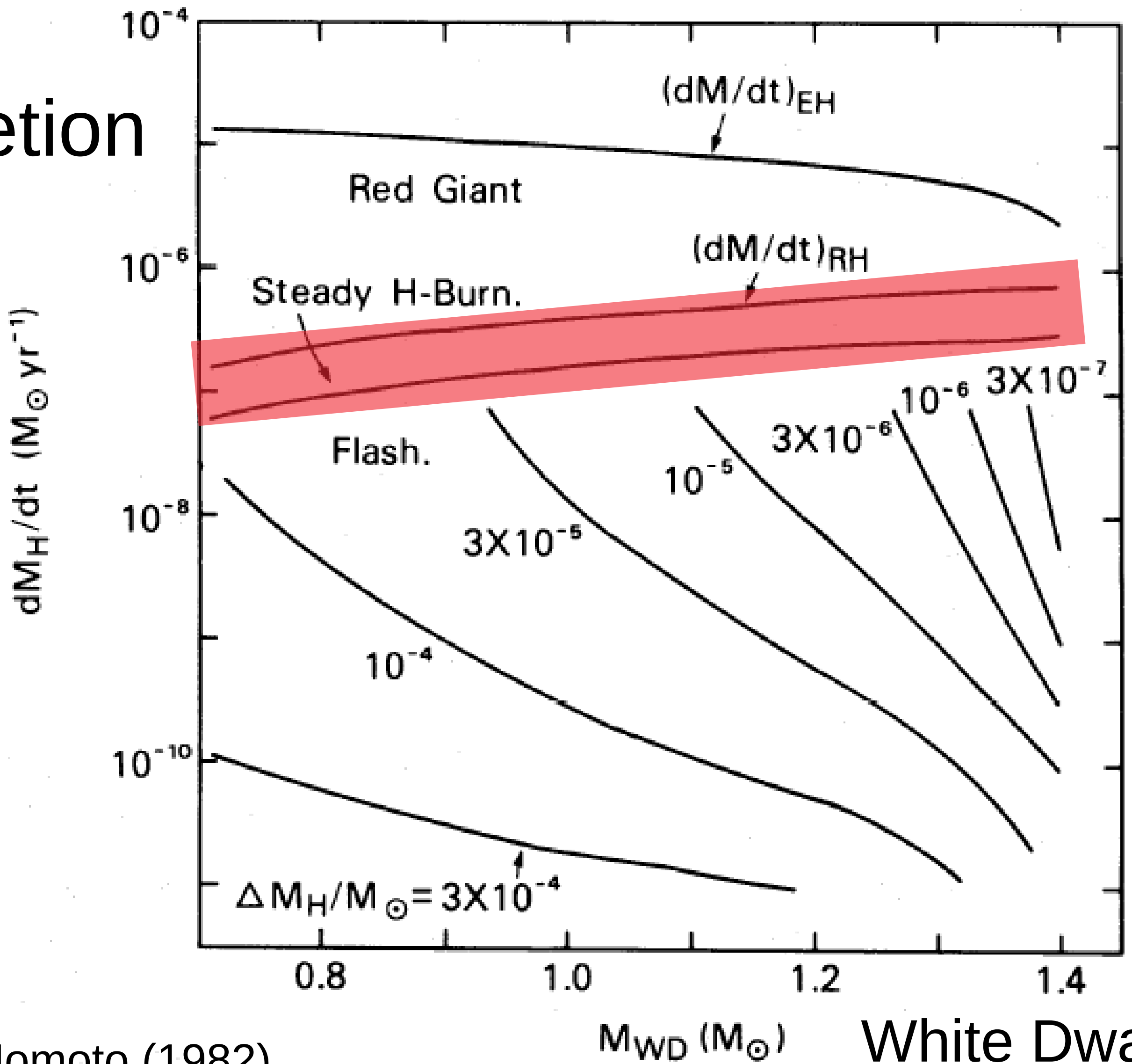


(2) Nuclear Burning



Hydrogen Burning in Accreting WD

Accretion Rate



White Dwarf Mass

Nomoto (1982)

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

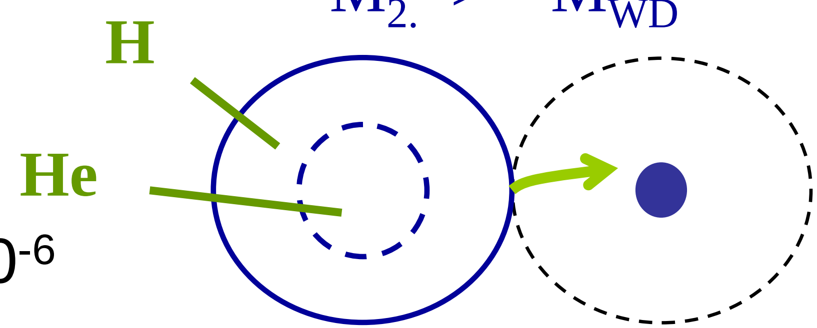
(1) H: leaving M.S.

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

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

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

$M_2 > M_{WD}$



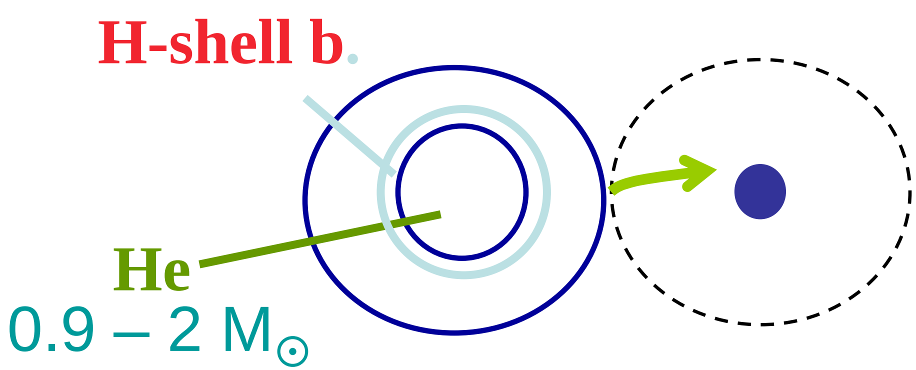
Super-Soft X-ray Source

$M_2 < M_{WD}$

(2) H: sub giant, red giant

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

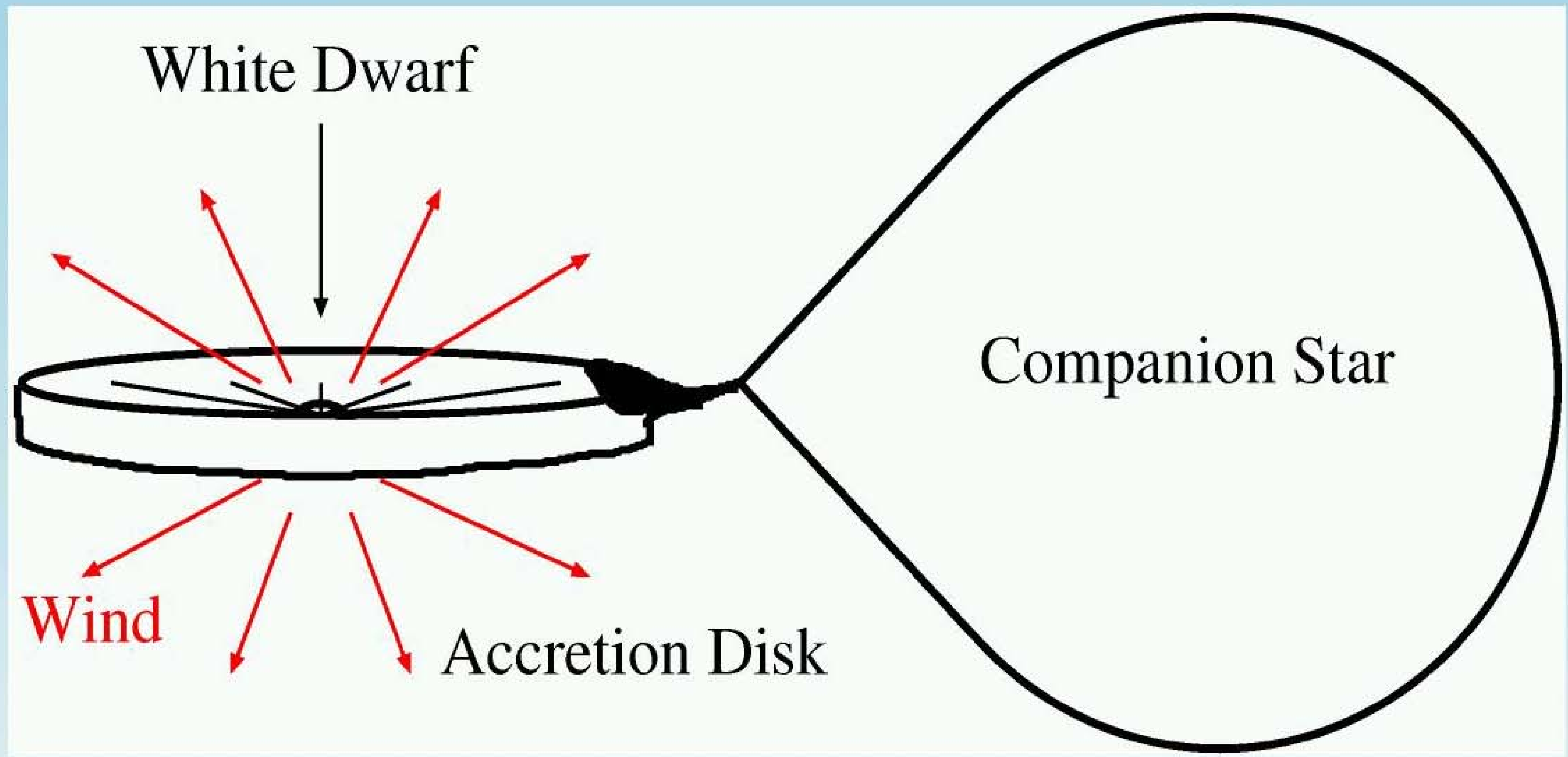
$\sim 10^{-8} \sim 10^{-6}\ M_\odot/yr$



(3) White Dwarf Wind

(Hachisu, Kato, & Nomoto 1996)

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



White Dwarf Wind

(1) Suppress of WD Radius Expansion

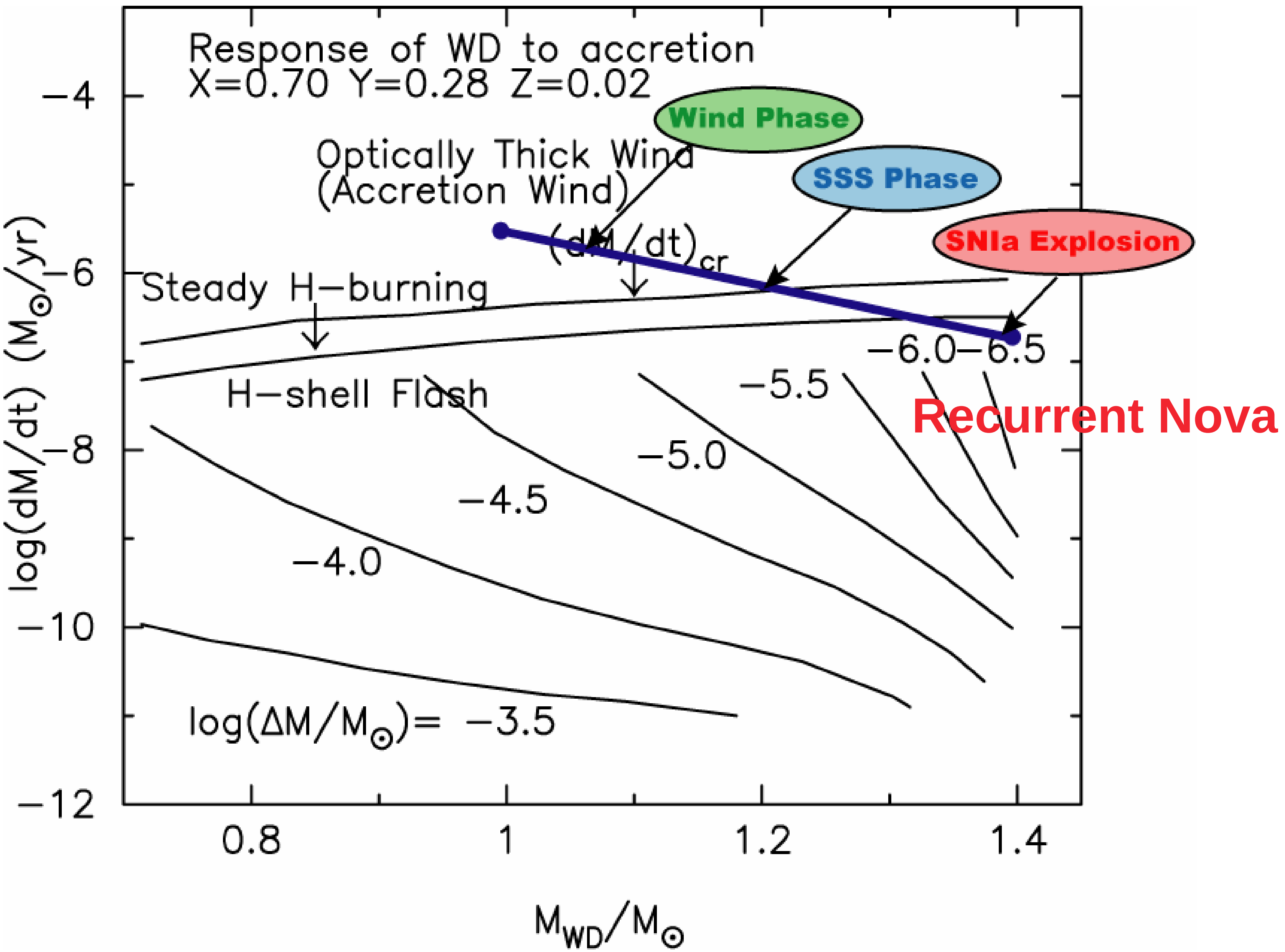
➔ Super Soft X-ray Sources

➔ $\dot{M} > \dot{M}_{RG}$ is allowed

(2) Mass Stripping from the Companion

➔ Reduction of Mass Transfer Rate

➔ $M_2 \sim 6 - 8\ M_\odot$ (Young Population) is allowed


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
Recurrent Nova
−6.0−6.5
−5.5
−5.0
−4.5
−4.0
log(ΔM/M⊙)= −3.5
log(dM/dt) (M⊙/yr)
MWD/M⊙
−4
−6
−8
−10
−12
0.8
1
1.2
1.4

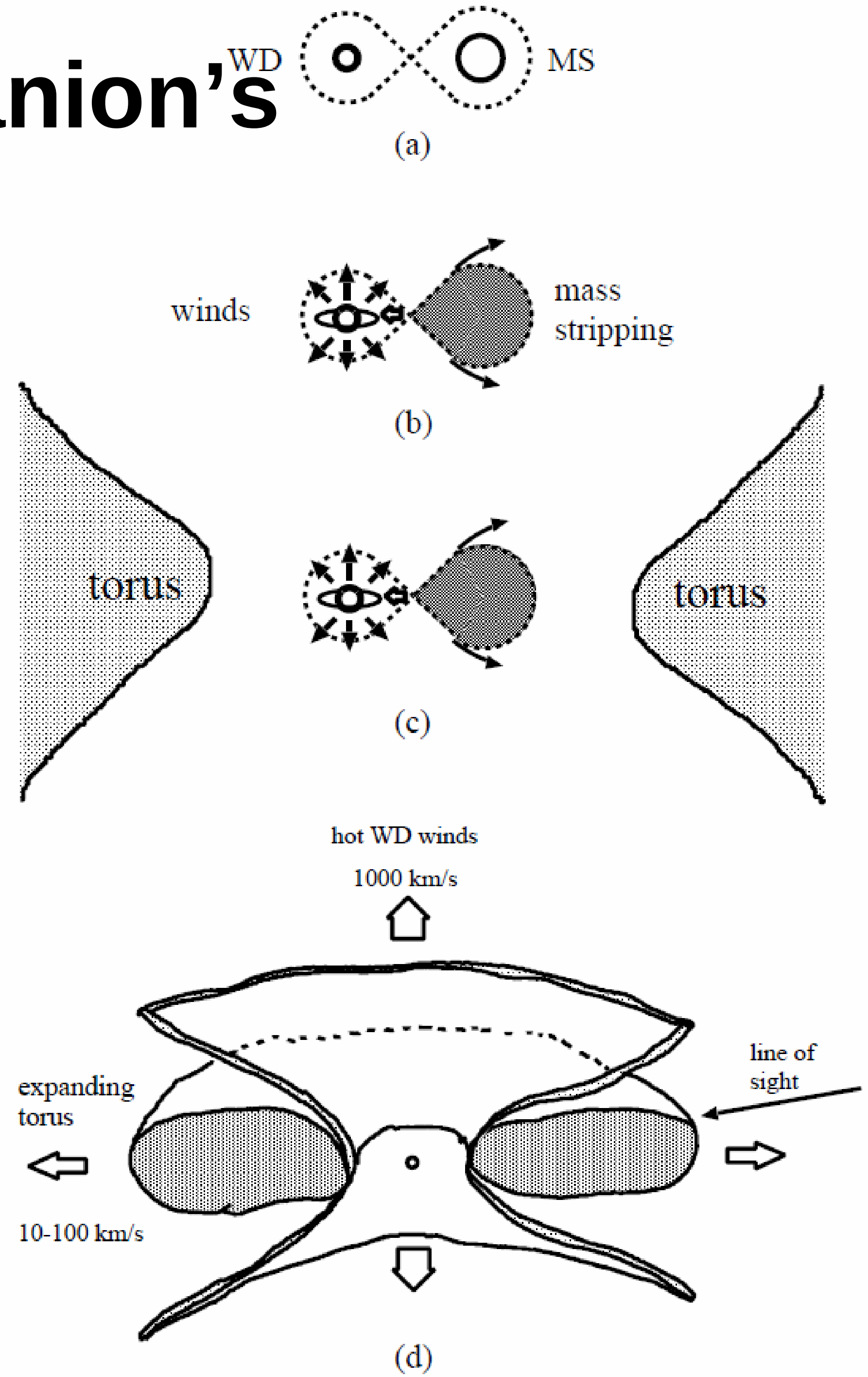
(4)Stripping of Companion's Mass

➔ **Mass Transfer Rate reduced**

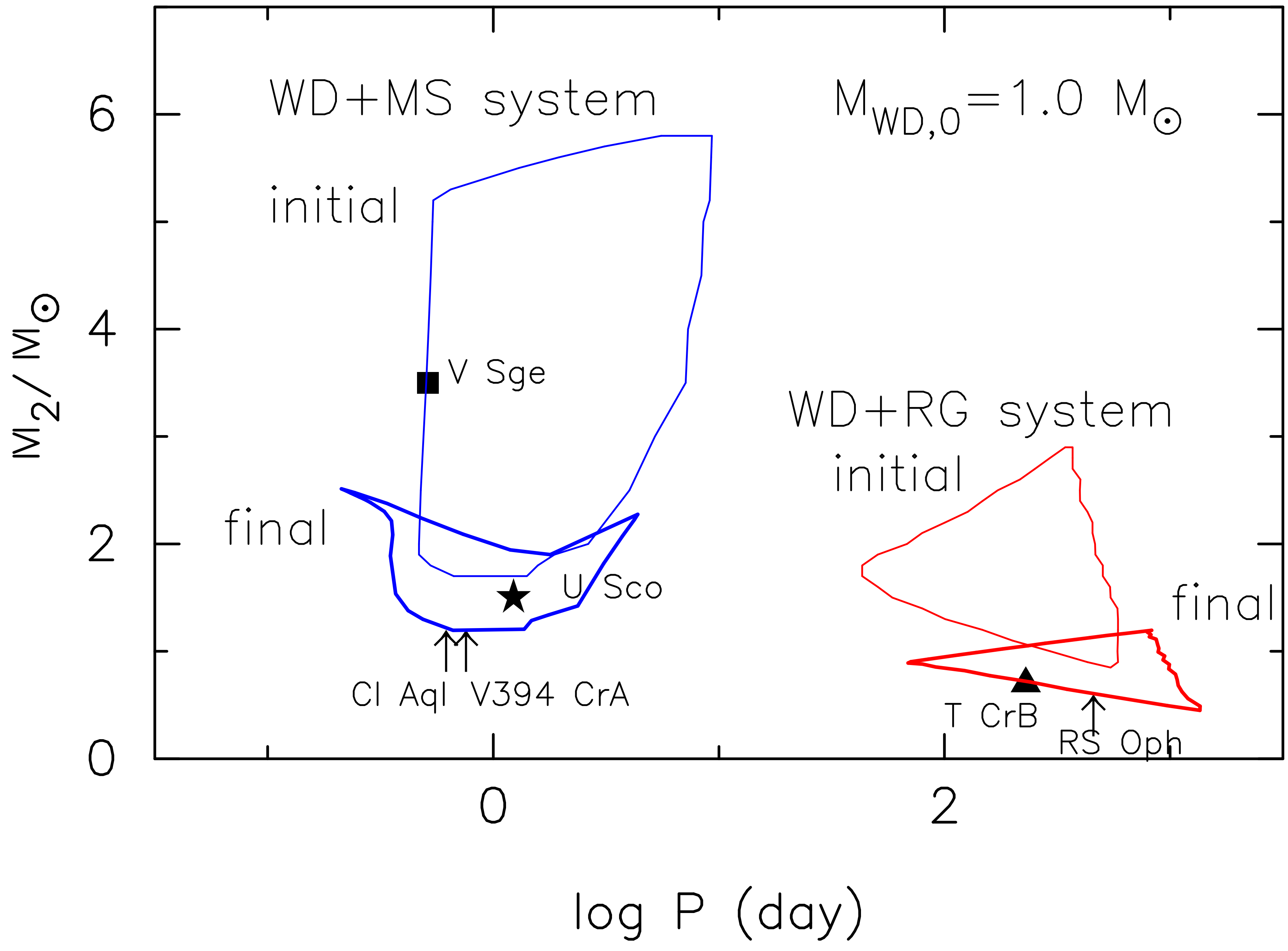
➔ **Massive (young) Companion → SN Ia**

➔ **Circumstellar Matter 10-100 km/s**

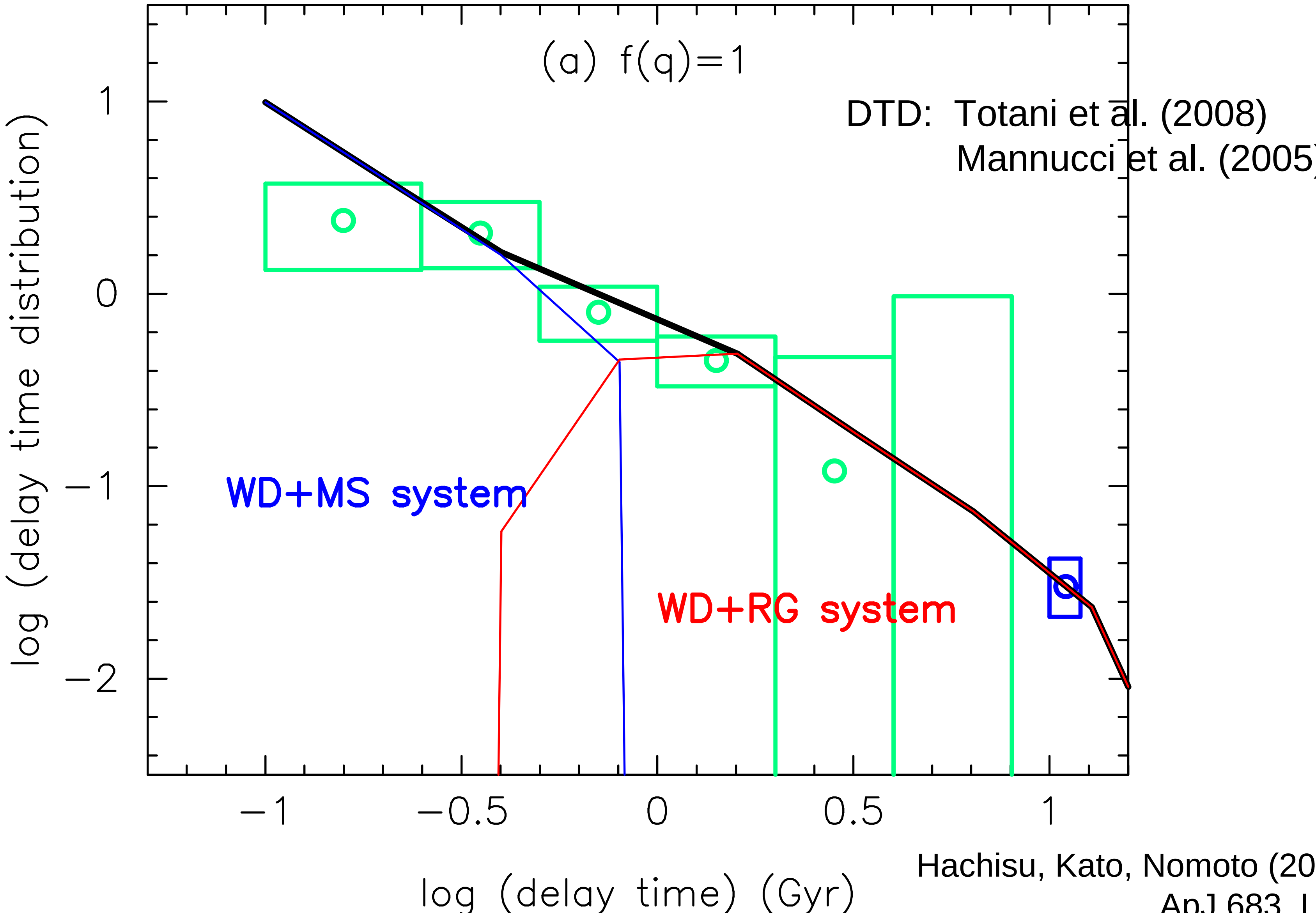
Hachisu, Kato, Nomoto (2008a) ApJ 679, 1390



SN Ia Progenitor System(MS, RG)

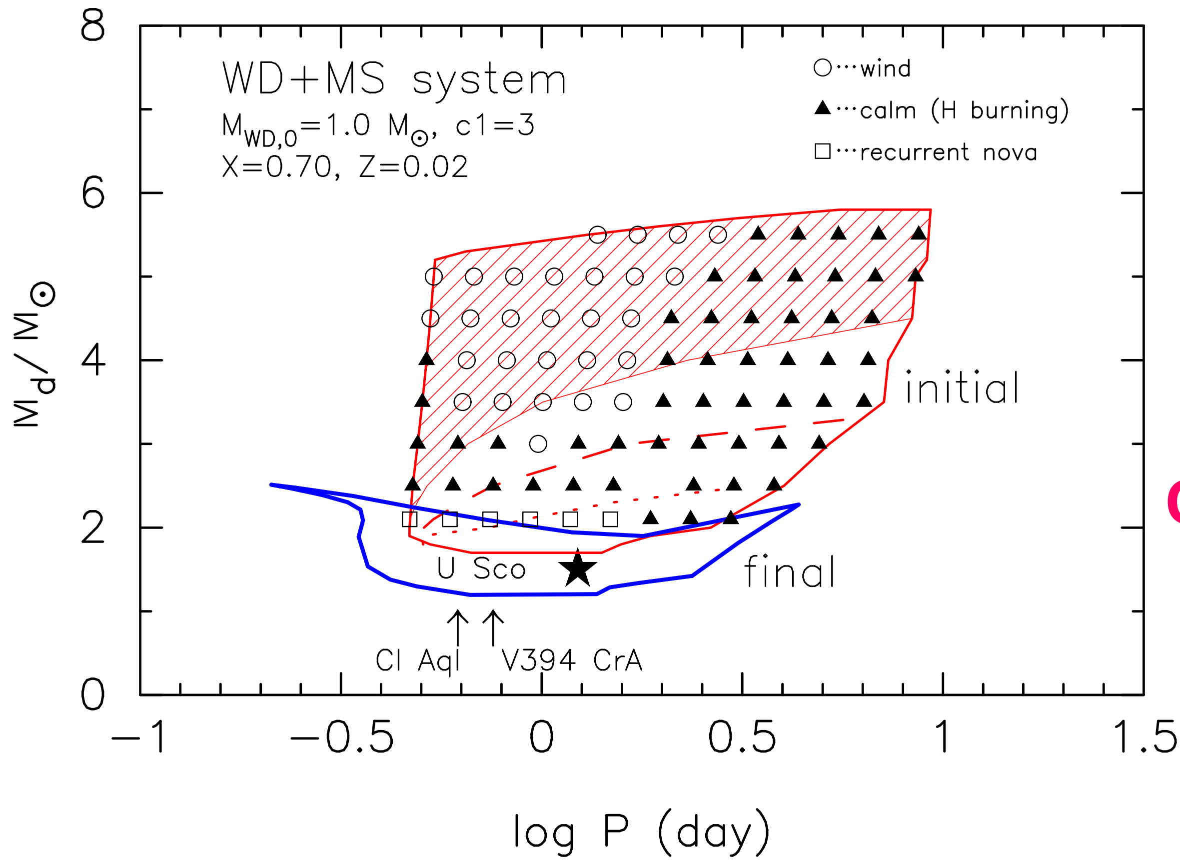


Delay Time Distribution



Hachisu, Kato, Nomoto (2008b)
ApJ 683, L127

Pre-SN Winds & CSM



WIND

CSM Interaction

SN Ia/IIn (IIa)
2002ic, 2005gj

SN 1604 (Kepler) ?

CALM

CSM

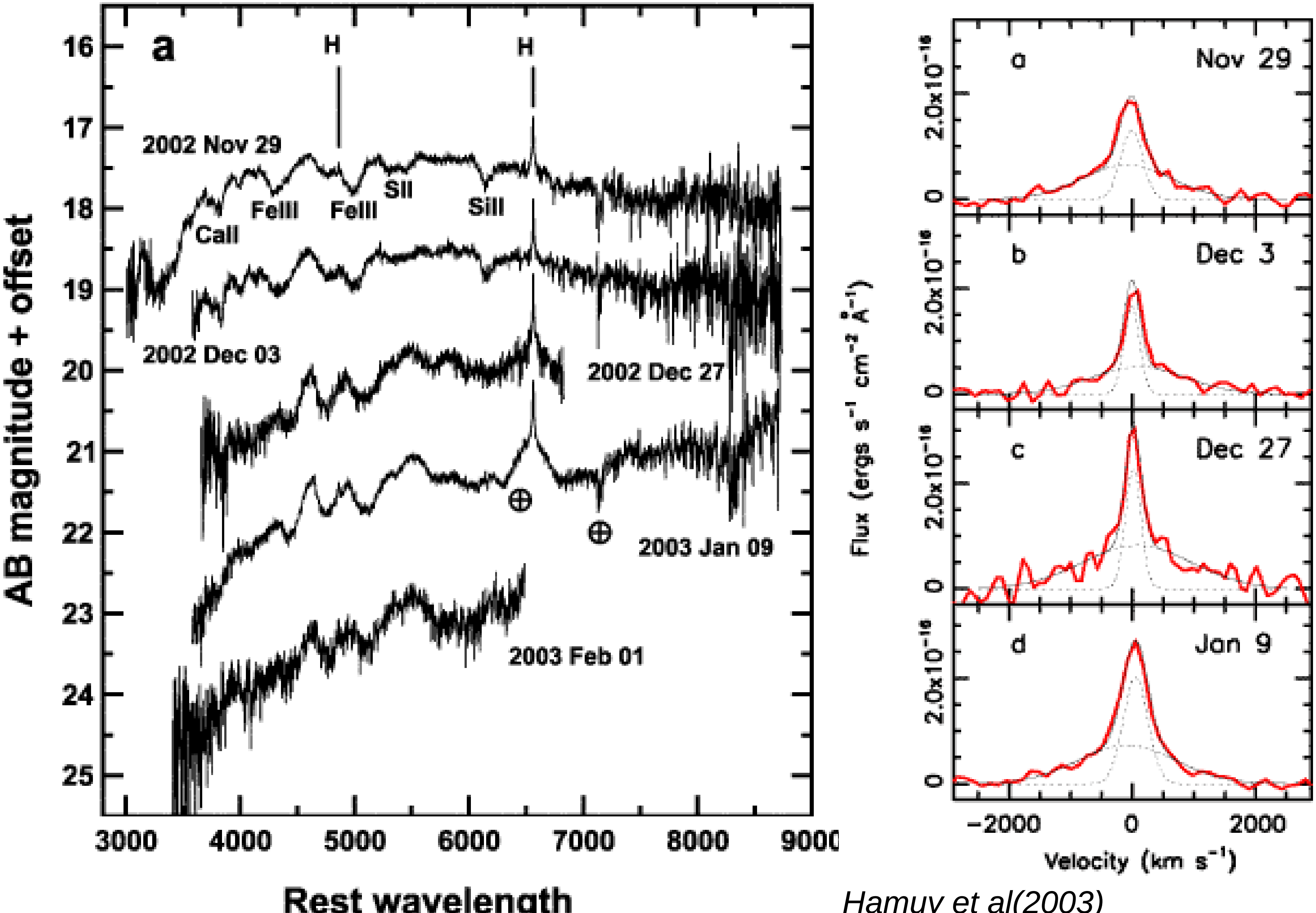
SN 2006X (Patat et al.)

no CSM(geometry?)

SN 200af

RN (Recurrent Nova)

SN Ia/IIn 2002ic

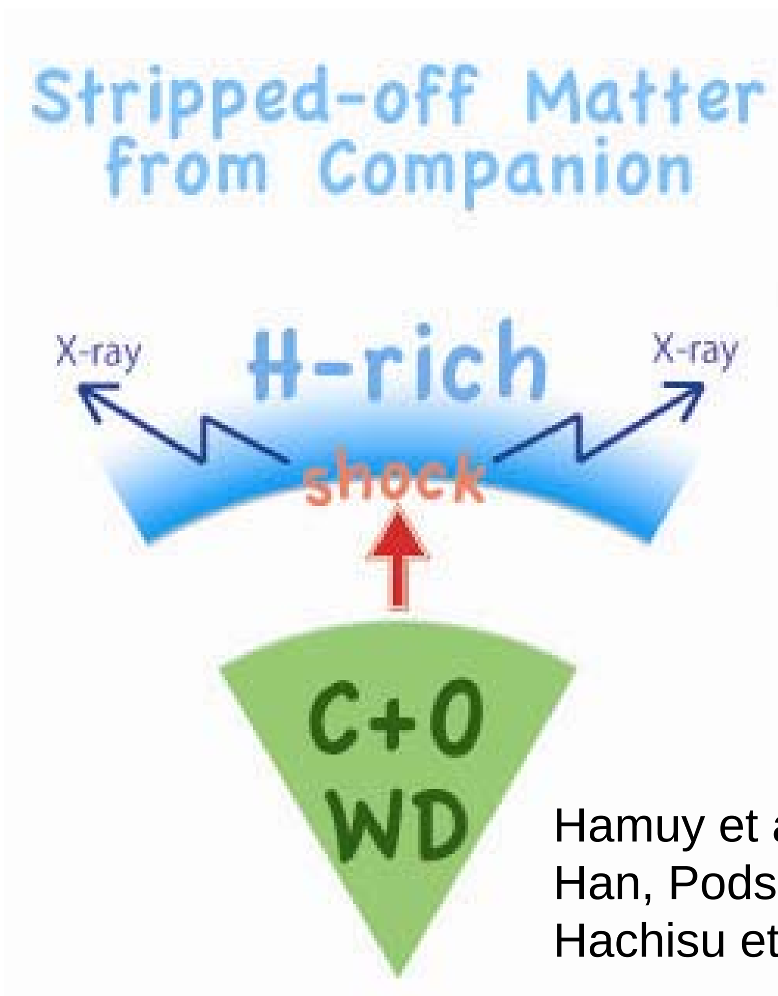


Hamuy et al(2003)

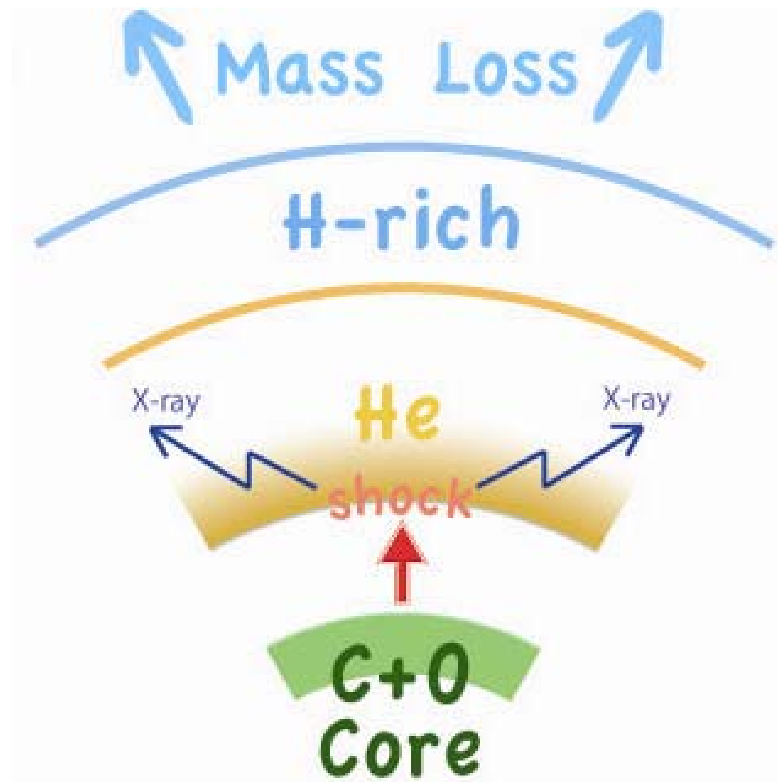
Models for 2002ic-like SNe

SN Ia/IIn

SN Ic/Ibn/IIn (He line?) 2006jc-like ?

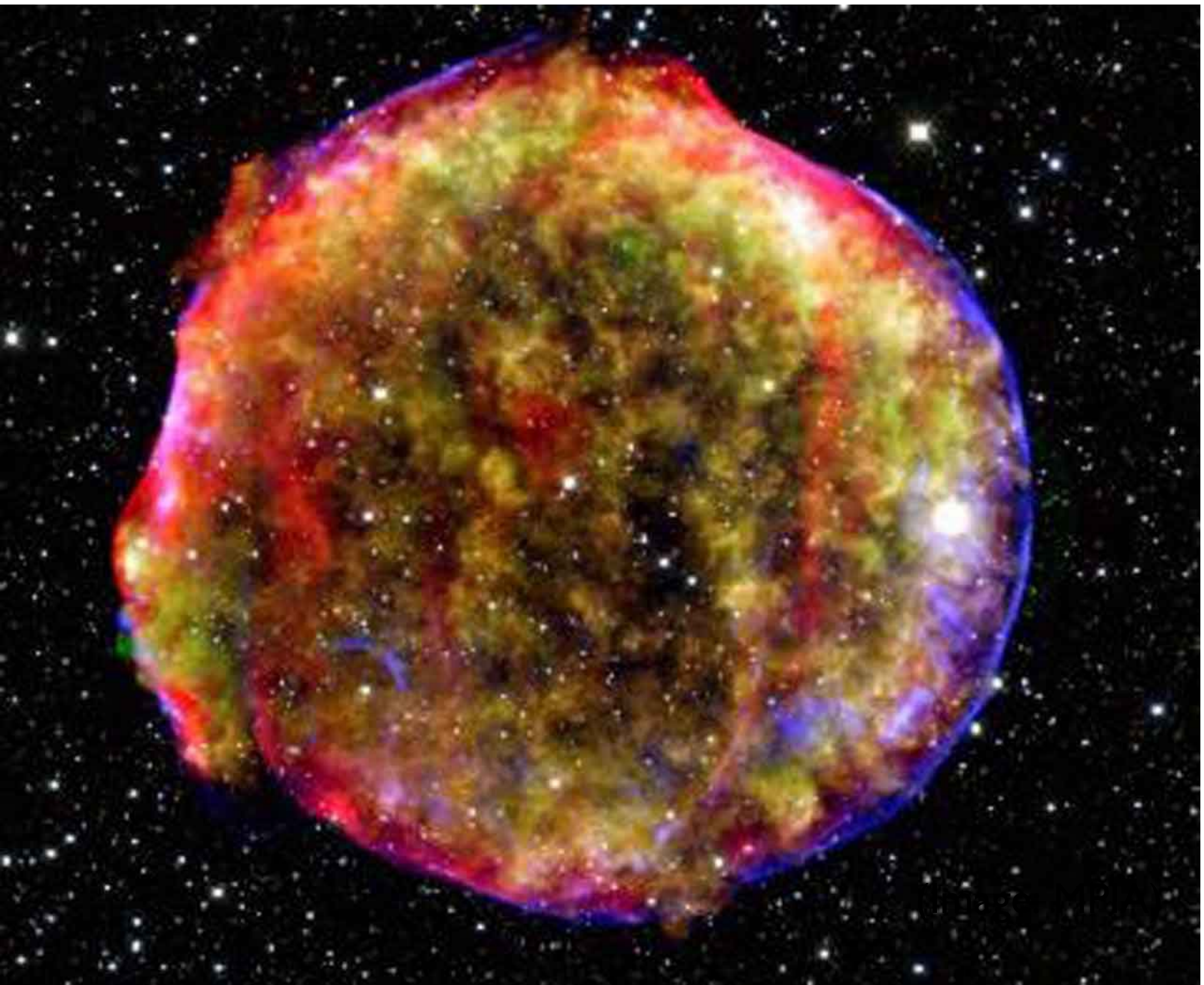


Hamuy et al.
Han, Podsiadlowski
Hachisu et al.



Benetti et al.

AD 2008
Remnant of Tycho's Supernova

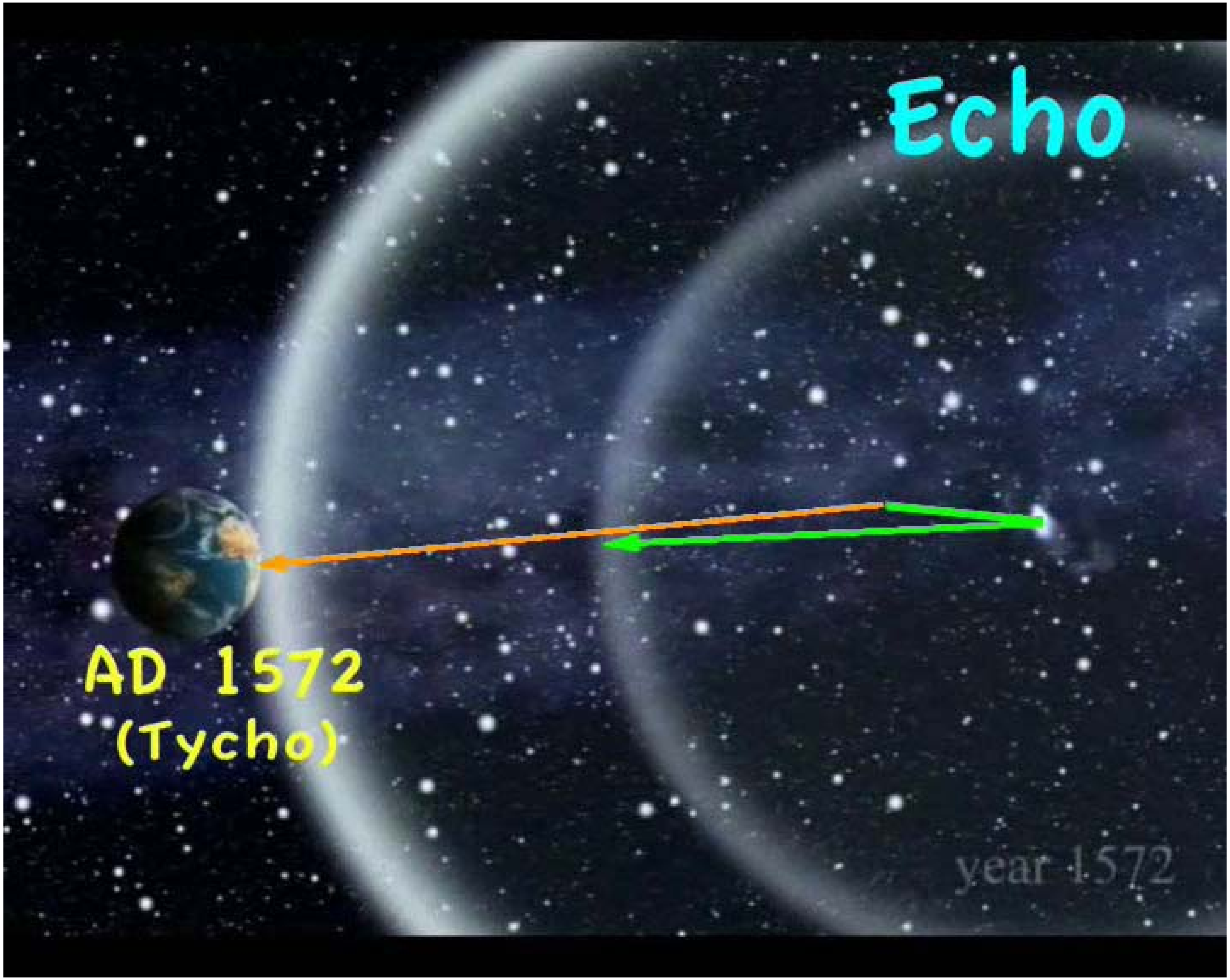


Green Yellow Blue
X-ray (Hot gas with millions of degree)

Red
Infrared (Circumstellar/ Synthesized dust)

White
Optical (Foreground/ background stars)

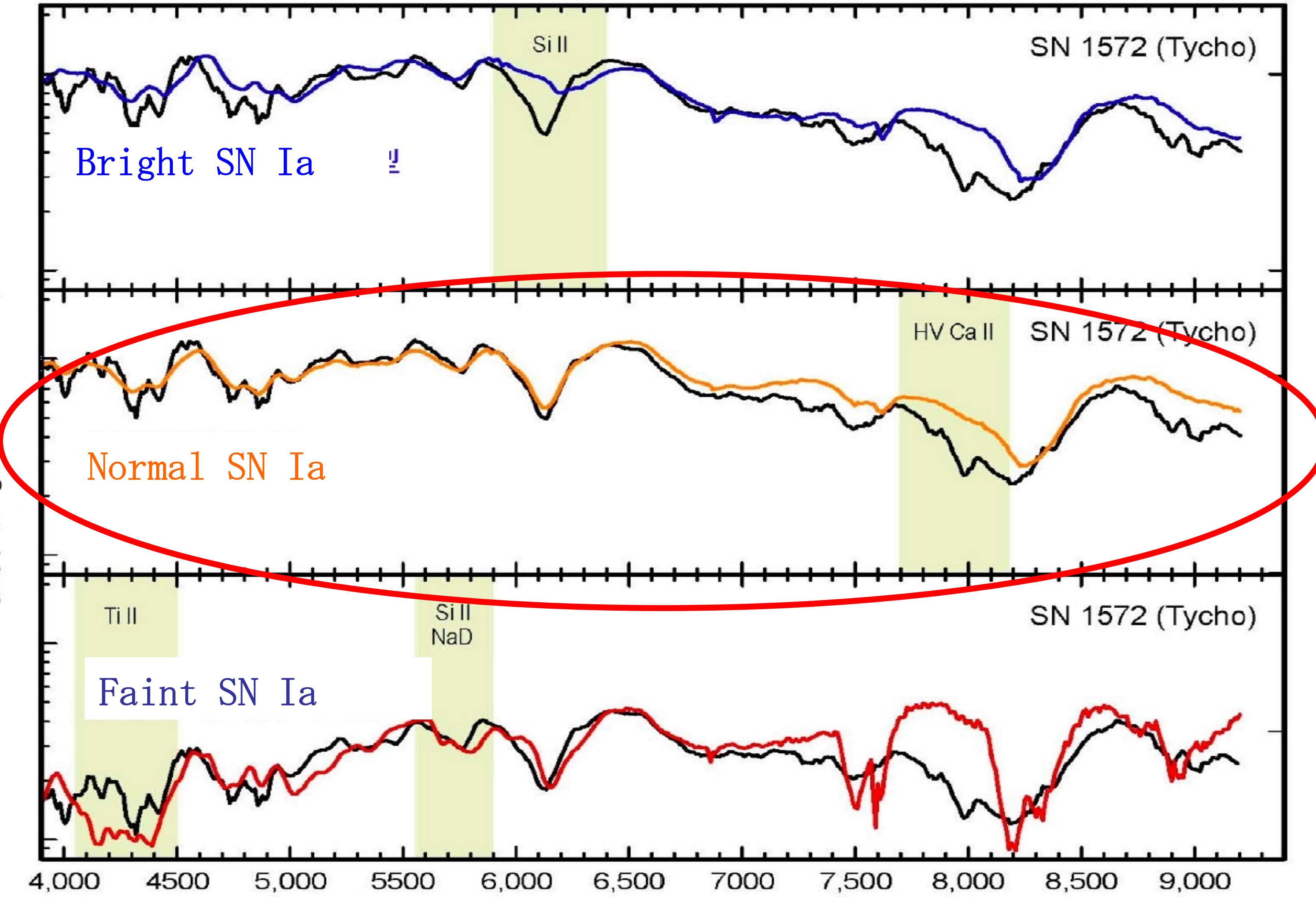
Observations of “SN Echo”



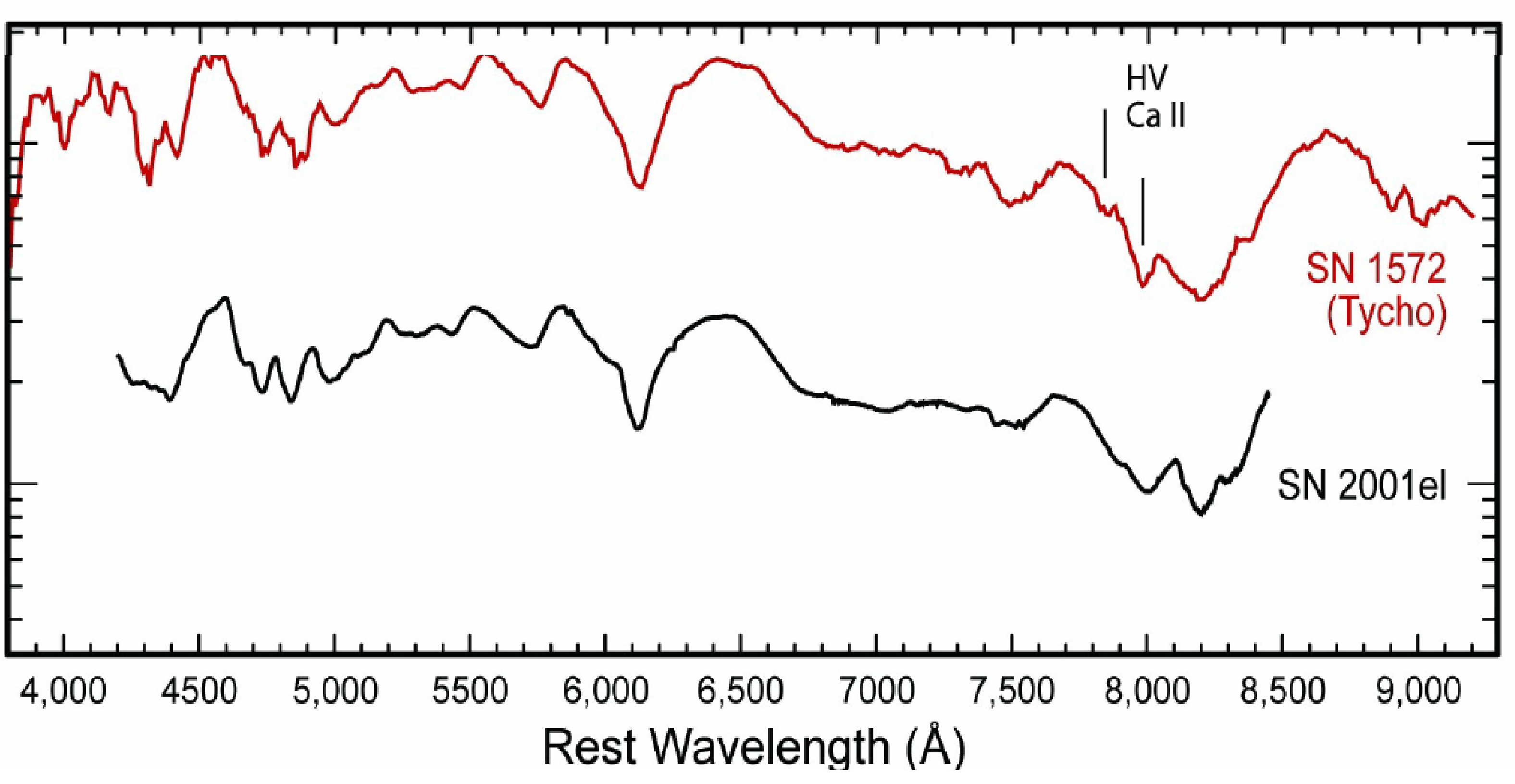
(Oort, Zwicky, ,,, Rest et al., Krause et al.)

Spectra

(Krause, Tanaka, Goto, Usuda, Hattori, Birkmann, Nomoto '08)



High Velocity Ca Feature

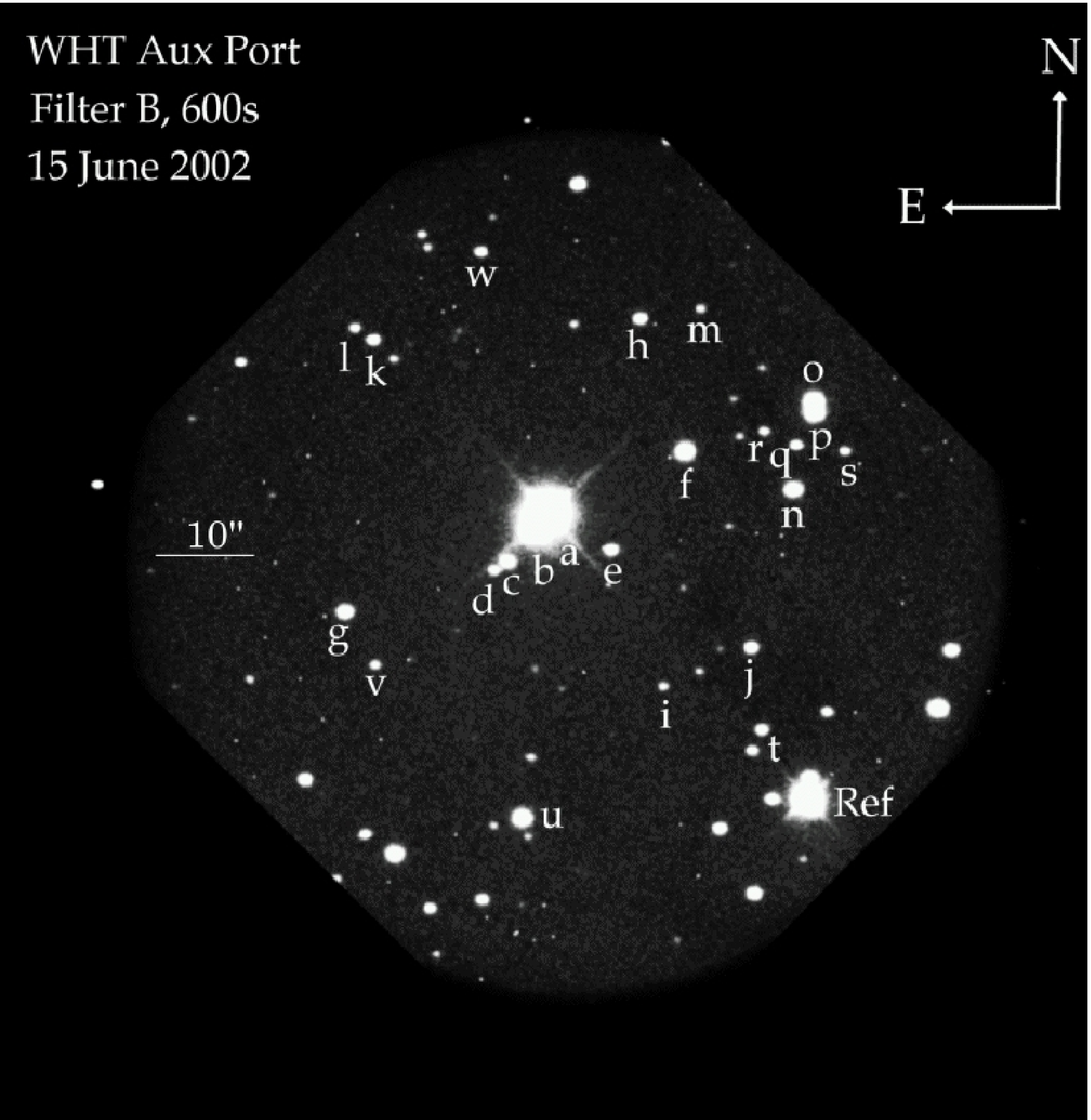


Origin of high velocity Ca ?

-- Circumstellar interaction ? (Gerardy+, Mazzali+)

-- Asphericity ? (← Echo)

SN 1572: Companion Candidate (Star G)



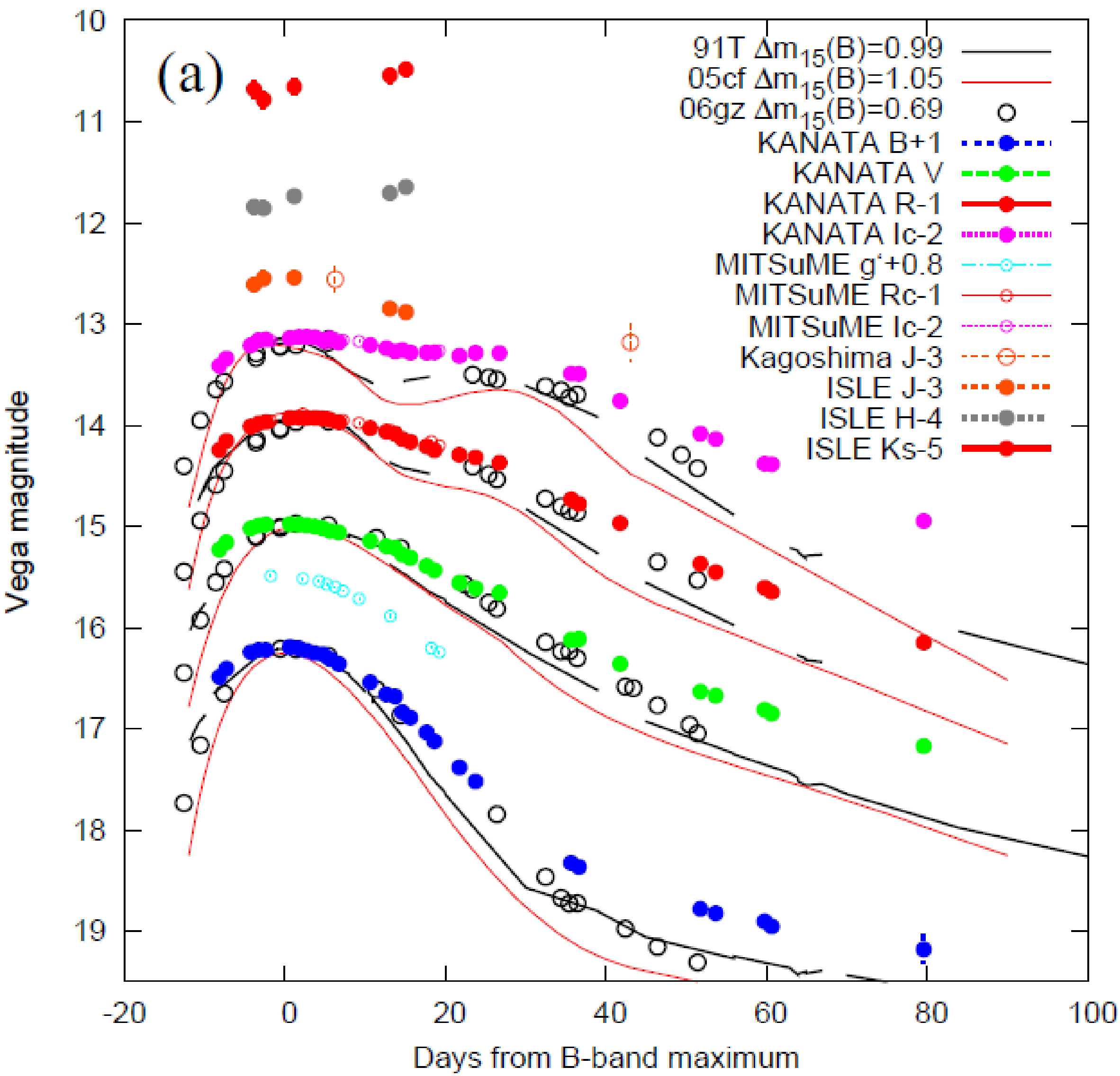
SN in Binary → High Velocity Proper Motion (~100km/s)
(Ruiz-Lapuente et al.)

Peculiar Abundances Ni, Li
(Hernandez et al.)

Star G: Non-rotating WD+RG system ?
(Subaru HDS obs.)
(Kerzendorf et al.)

Star E ?(Subaru:Ihara et al.)

Super-Chandra candidate SN 2009dc



Very bright

M_V= - 19.9 mag

Very slow

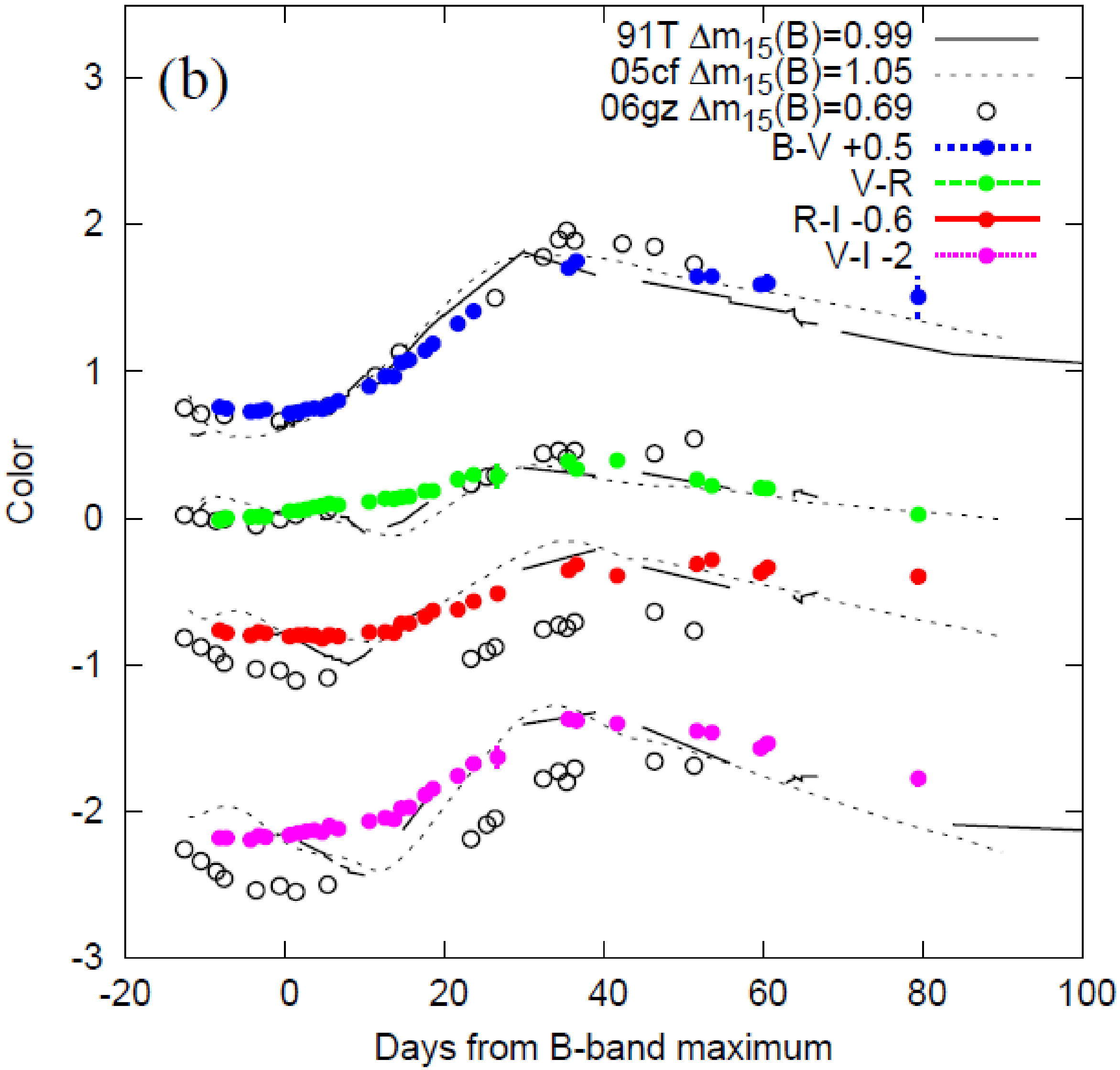
Δm_{15} = 0.65 mag

(Hiroshima U., Okayama Obs. Gunma Obs., Kagoshima U., SUBARU)

Yamanaka, Kawabata, Tanaka, Kinugasa, Imada, Maeda, Nomoto et al. (arXiv:0908.2059)

SN 2003fg (Howell et al.)
SN 2006gz (Hicken et al.)

SN 2009dc: Color Evolution

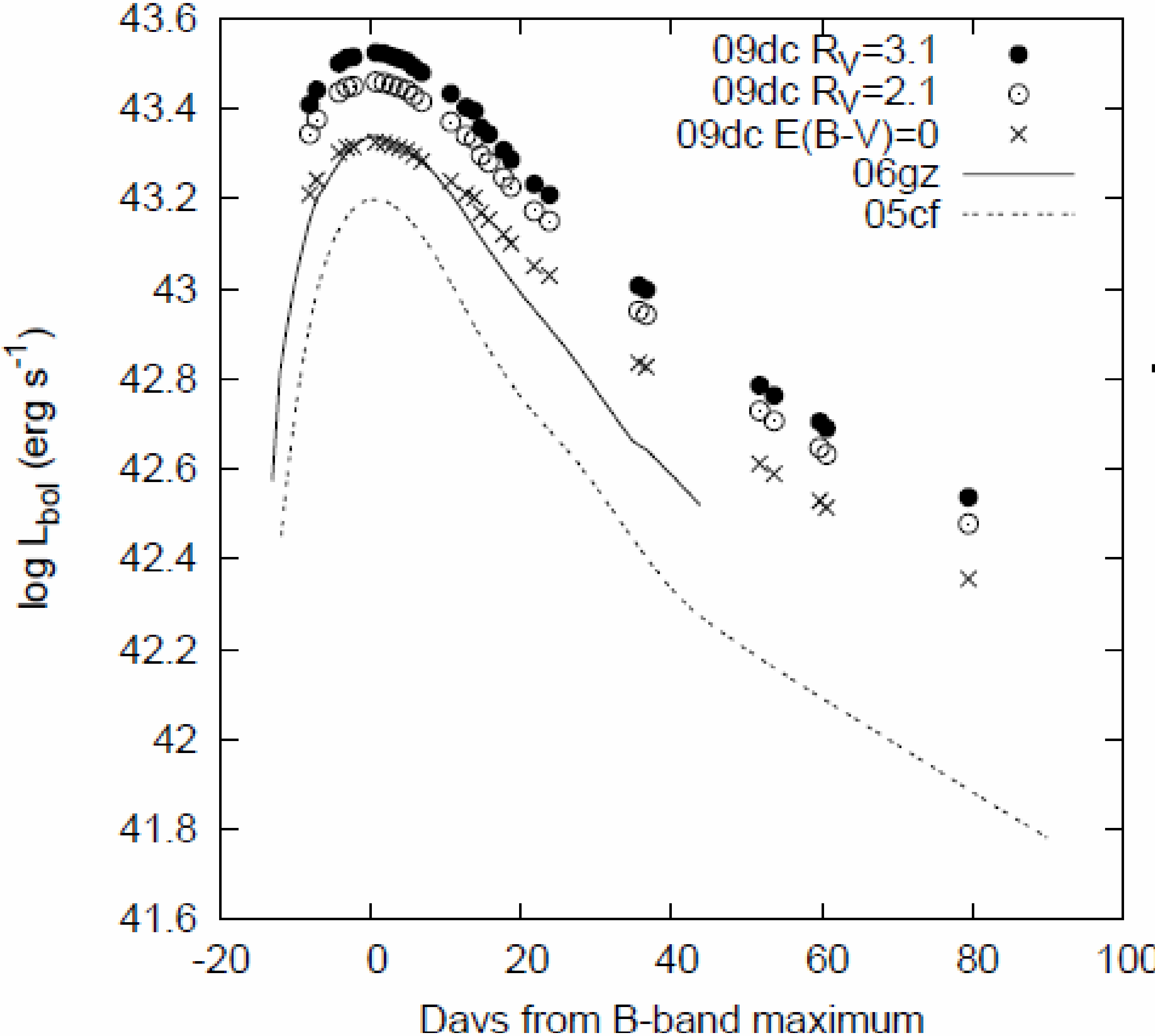


E(B-V) = 0.14

(host)

Na I D line abs.

SN 2009dc Bolometric Luminosity



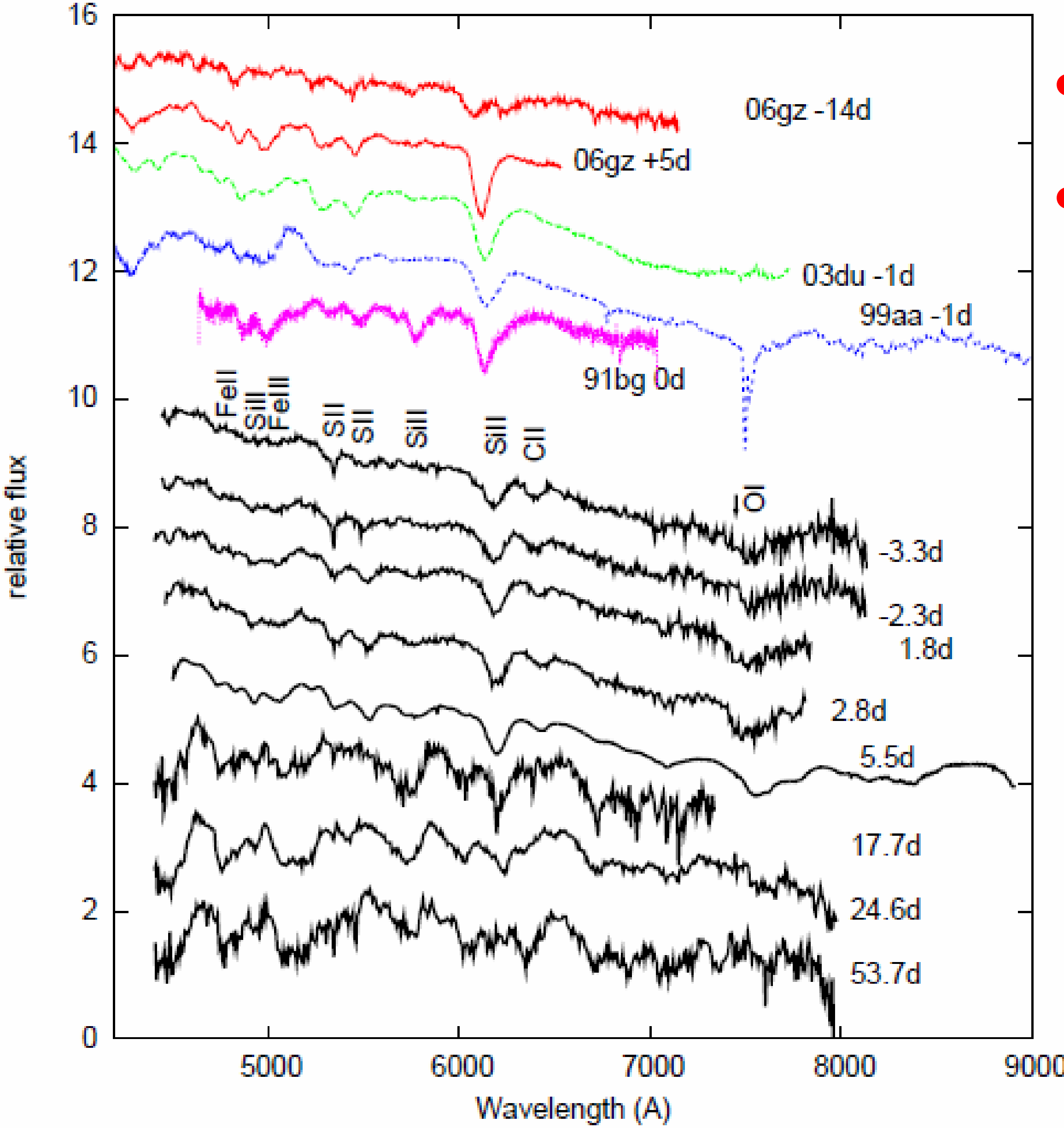
$M(^{56}Ni) > 1.2\ M_\odot$

→ Super-Chandra. SN candidate

Yamanaka et al. (2009)

E($B-V$) (mag) Galactic	host	R_V	Total A_V (mag)	$M_{V,\max}$ (mag)	$L_{\max}$ (erg s^{-1})	^{56}Ni mass $M_\odot$
0.07	0	3.1	–	-19.90 ± 0.15 mag	$(2.1 \pm 0.5) \times 10^{43}$ erg s^{-1}	$1.2 \pm 0.3\ M_\odot$
0.07	0.14	2.1	0.29	-20.19 ± 0.19 mag	$(2.9 \pm 0.8) \times 10^{43}$ erg s^{-1}	$1.6 \pm 0.4\ M_\odot$
0.07	0.14	3.1	0.43	-20.32 ± 0.19 mag	$(3.3 \pm 0.9) \times 10^{43}$ erg s^{-1}	$1.8 \pm 0.5\ M_\odot$

SN 2009dc: Spectroscopy



- Carbon line
- Slow velocity

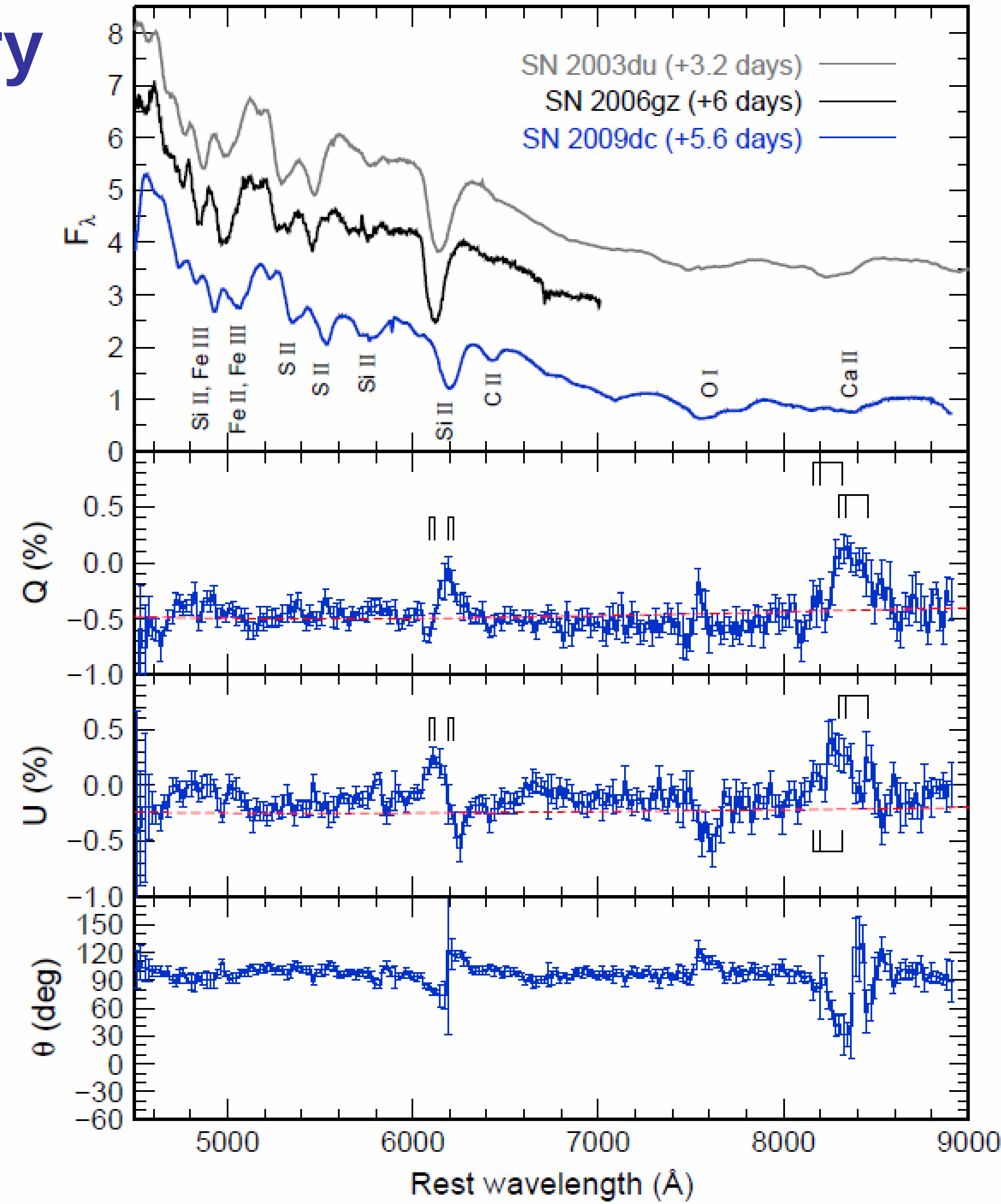
V(Si) ~ 8000 km/s

V(C) ~ 8000 km/s

Yamanaka et al. (2009)

Spectropolarimetry with Subaru

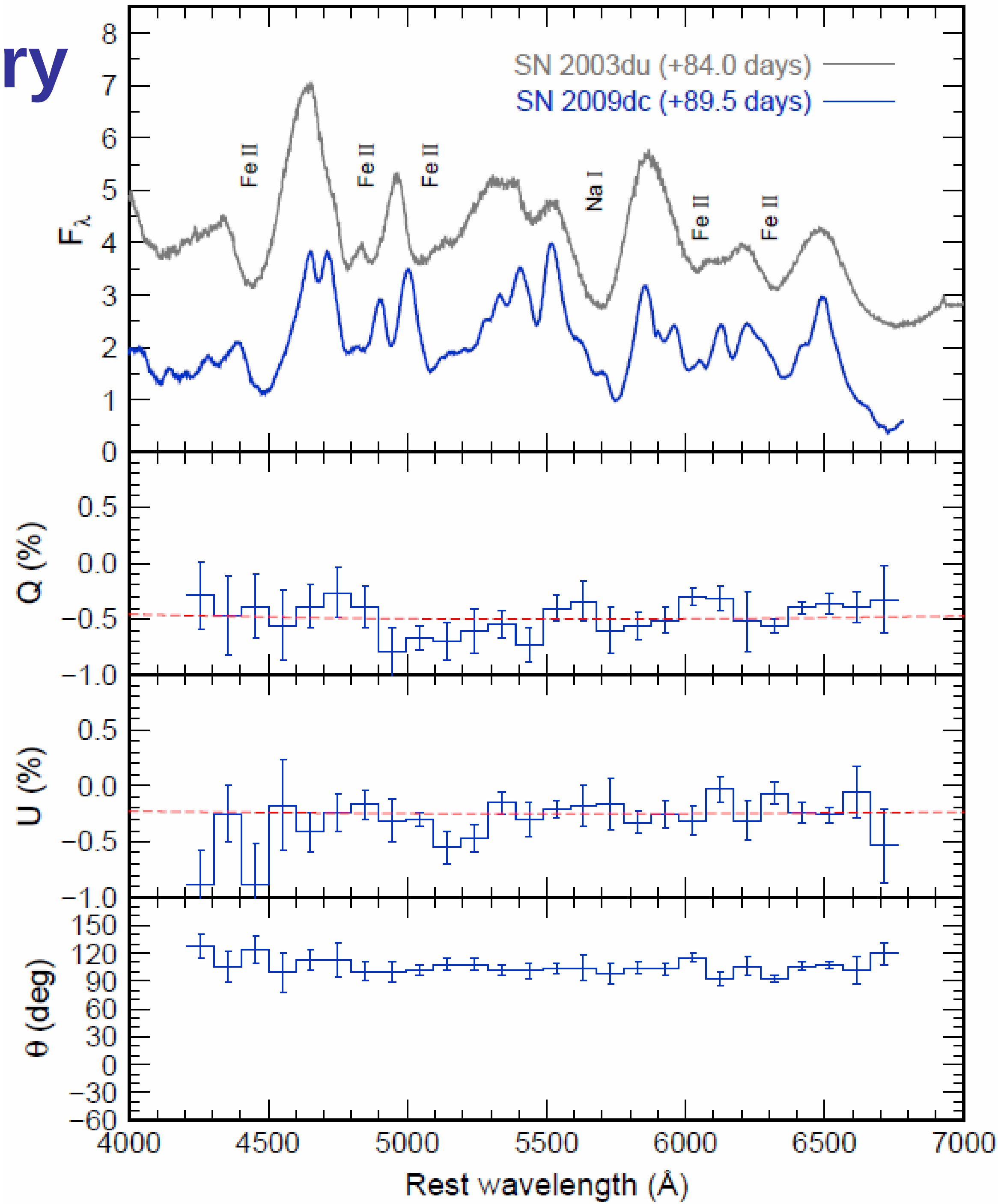
- 2009 May 1
(day +5.6)
- Small continuum polarization
→ not very
aspherical!
- Line polarization at Si and Ca lines ~0.5%



Tanaka, et al. (arXiv:0908.2057)

Spectropolarimetry with Subaru (2)

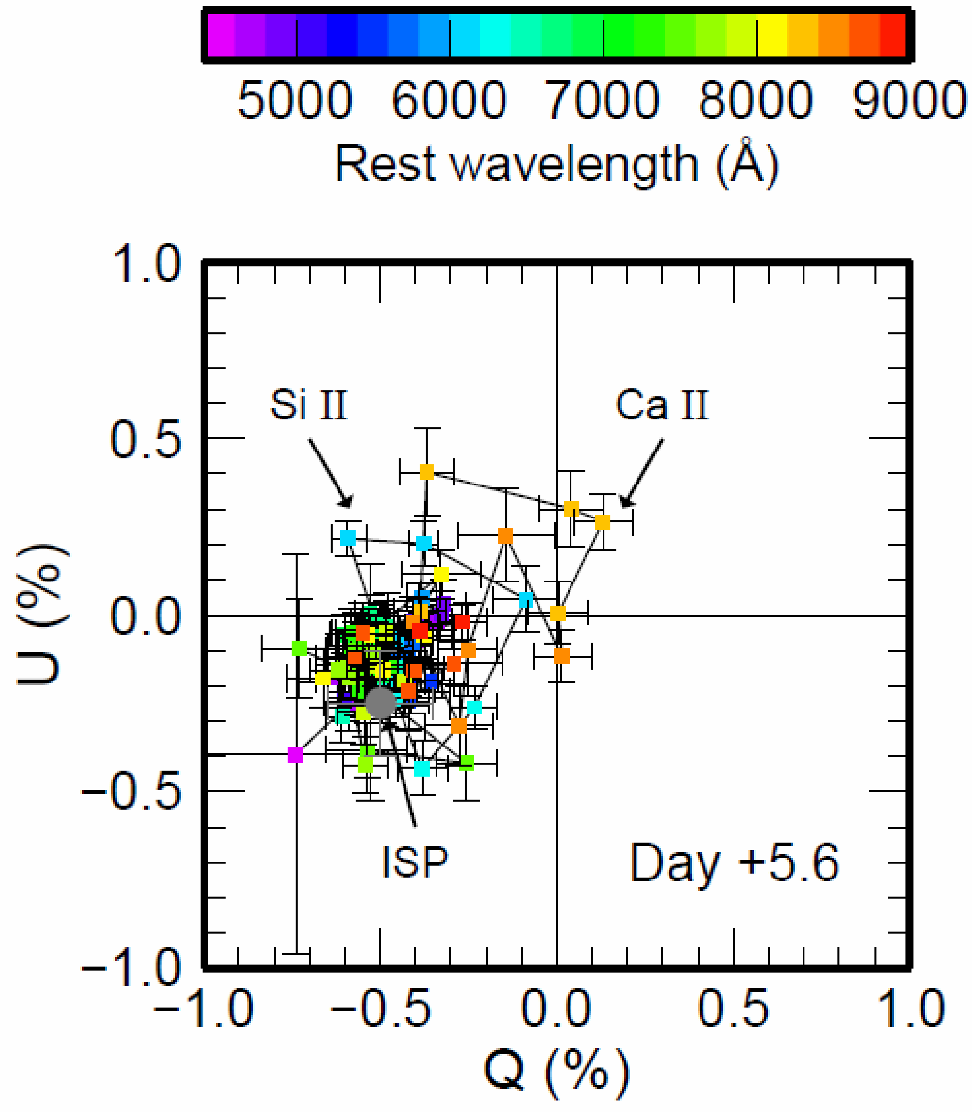
- 2009 July 24 (day +89.5)
- Determination of interstellar polarization



Tanaka et al. (2009)

SN 2009dc: Data in Q-U plane

- Distinguished polarization feature at Si and Ca
- Not straight line in Q-U plane
  → Clumpy structure

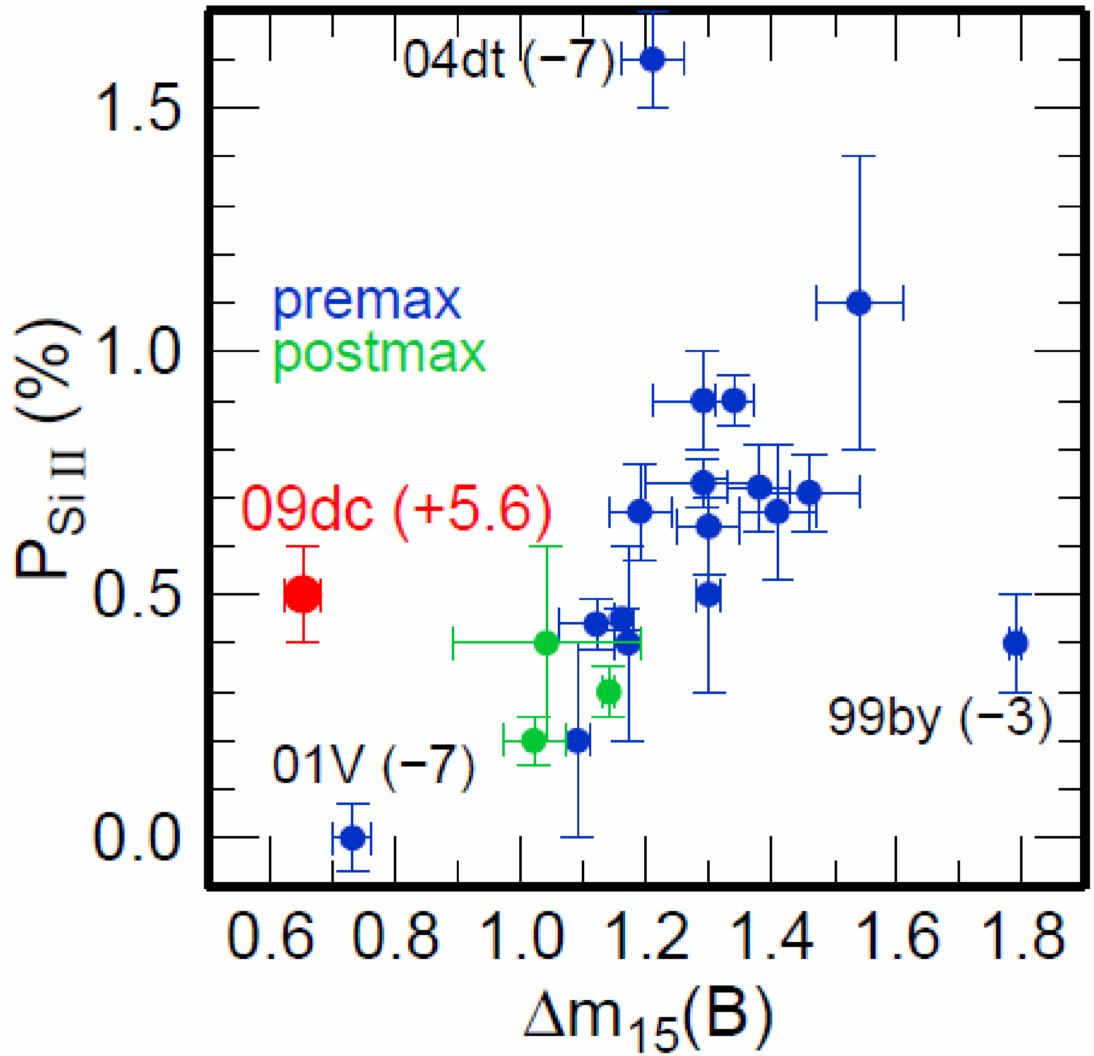


Tanaka et al. (2009)

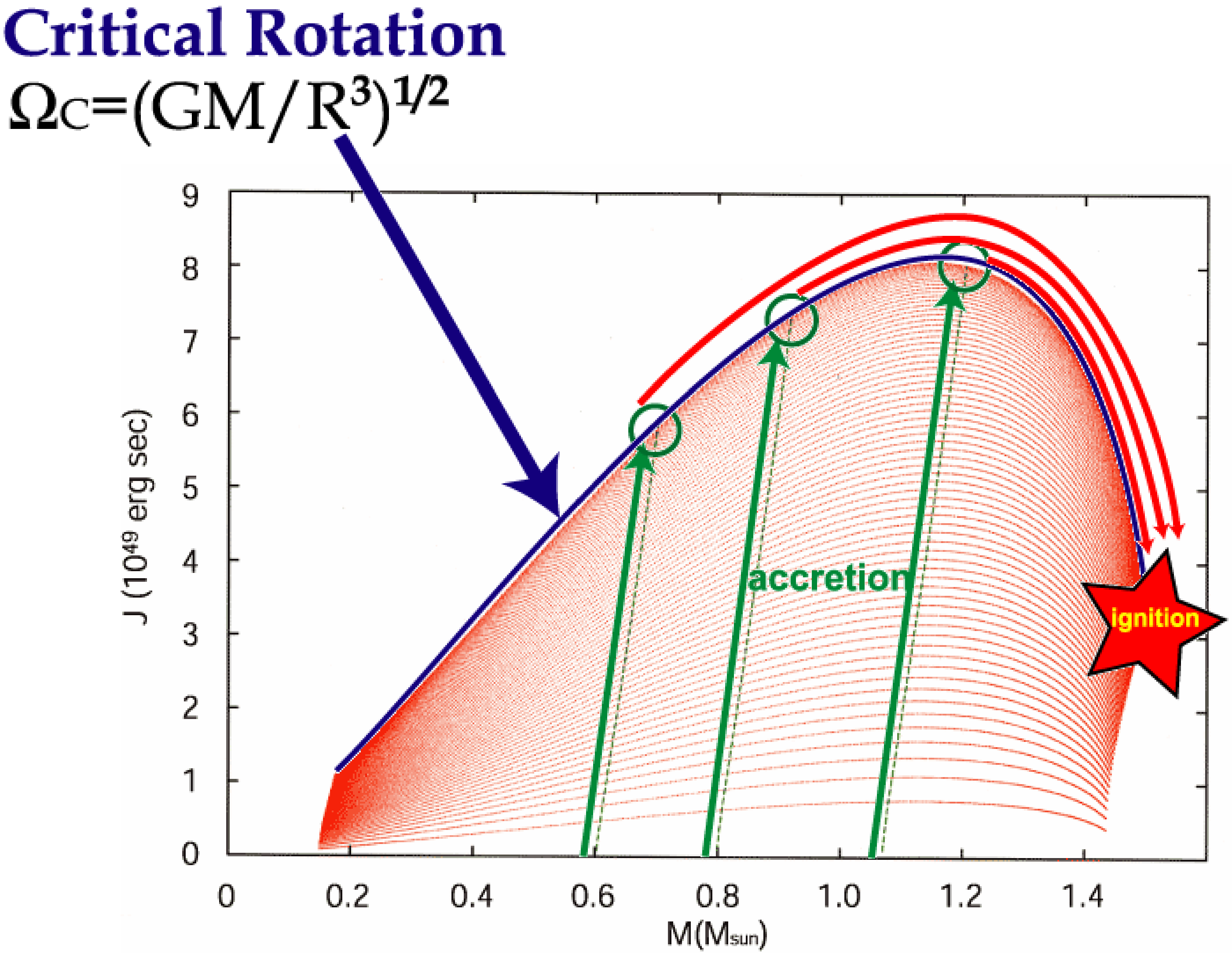
Δm_{15} vs. P(Si II)

- Normal polarization
- But larger than expected from its extreme brightness (Δm_{15})

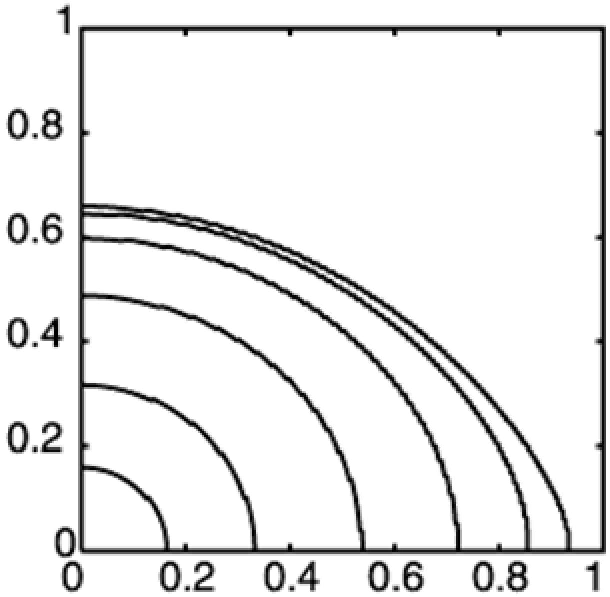
Tanaka et al. (2009)



Evolution of Rotating White Dwarfs



Structure of Rotating WDs



Uniform Rotation

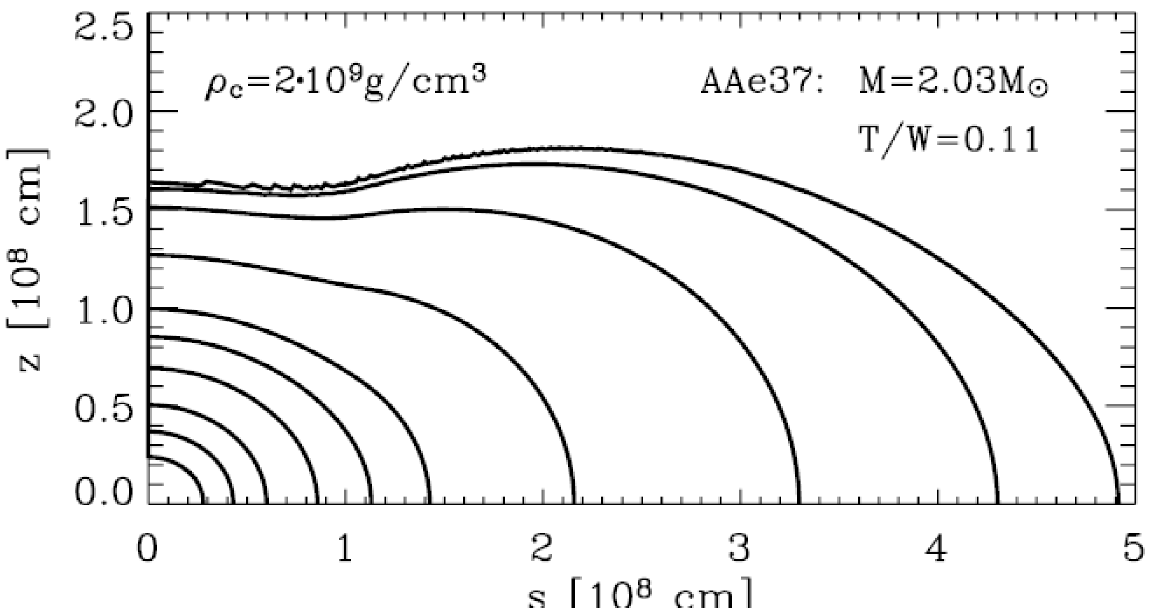
M=1.48 $M_\odot$, J=4.63

Rotation Period = 2.3sec

ρ_c=2.0e9 (Ignition)

q=0.66

(Uenishi, Nomoto, Hachisu 2003)



Differential Rotation

M=2.03 $M_\odot$

ρ_c=2.0e9 (Ignition)

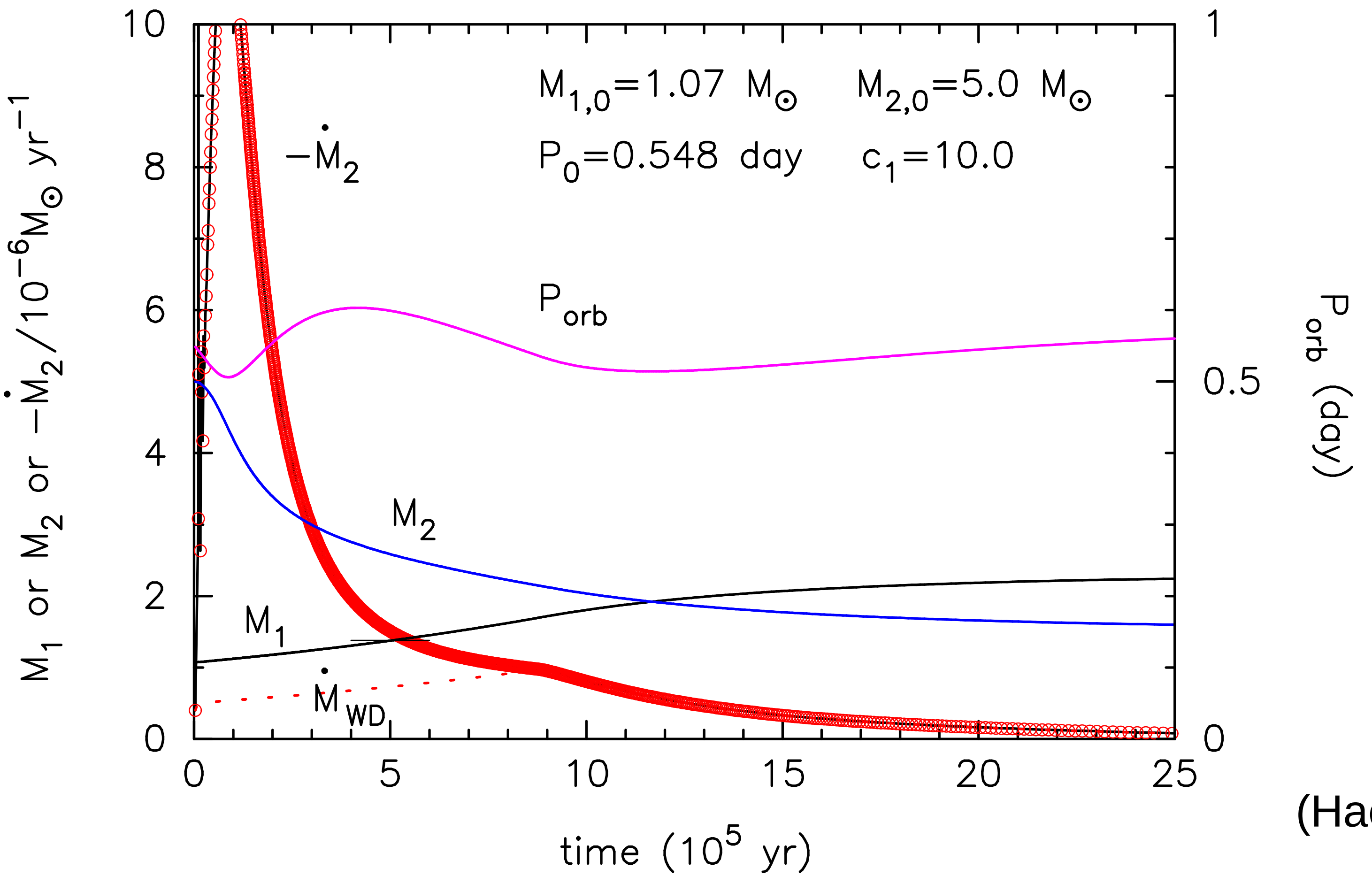
(Yoon, Langer 2005)

If M ~ 2 $M_\odot$, small polarization ?

Super Chandra Mass in SDs

$M_{WD} < 1.7\ M_\odot$ (Chen & Li)

$M_{WD} < 2.2\ M_\odot$ (Hachisu et al.; mass stripping)



(Hachisu et al.)

Progenitors of Type Ia Supernovae

Single Degenerate

WD winds & Mass Stripping

→ Young Population

Delay Time Distribution

Circumstellar Matter (10 – 1000 km/s)

H, He ?

SN 1572 (Tycho) : Companion Star ?

SN 2009dc : Super-Chandra Candidate

but ~Spherical; Mass ?