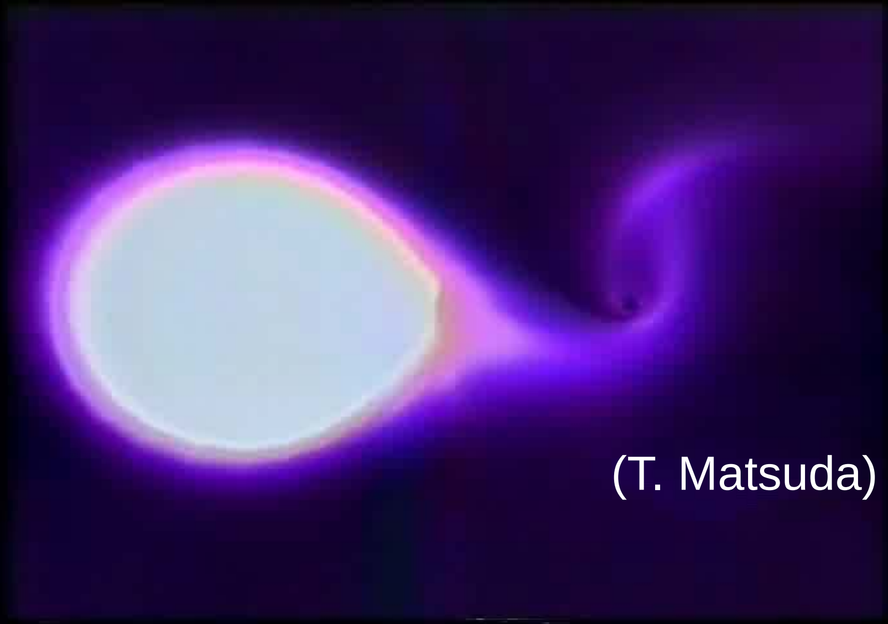
Progenitors of Type Ia Supernovae



Abundance Profiling of Extremely Metal Poor Stars

Ken Nomoto (Kavli IPMU, U. Tokyo)


Francesca, Welcome to the Red Vest Club !!

Recent Members 1

Recent Members 2

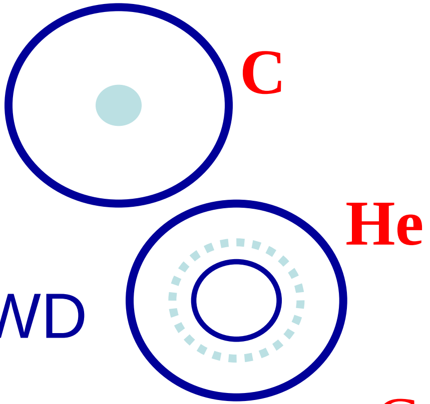
30 Years Ago! (1983) Erice → W7 & DD (Icko)

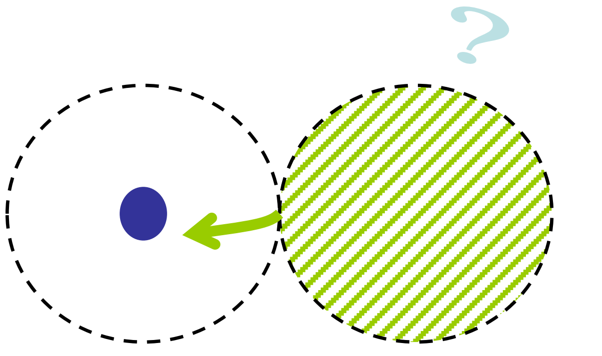
(SN Ia → Chemical Evolution: Francesca)

Francesca in Tokyo (2005 OMEG)

The Progenitors of Type Ia Supernovae ??

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

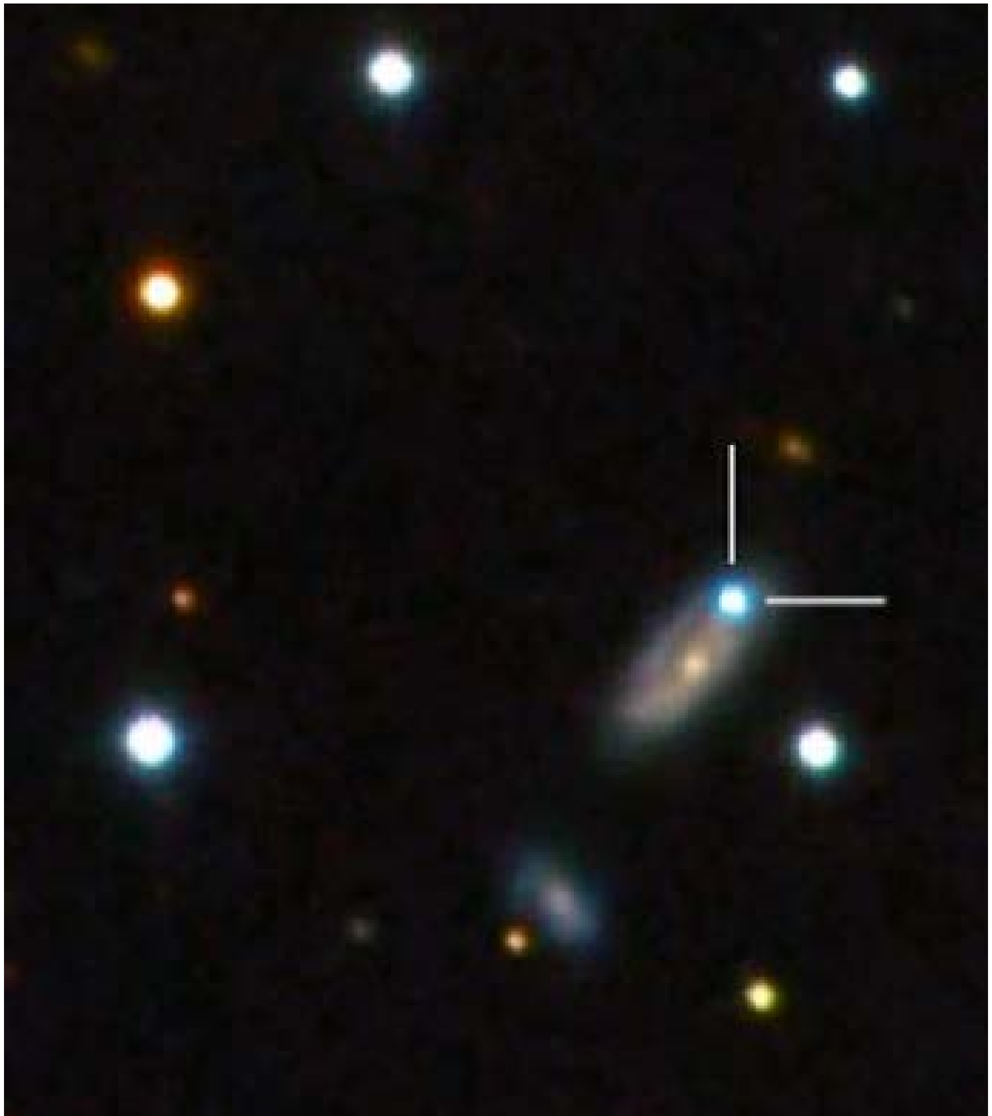


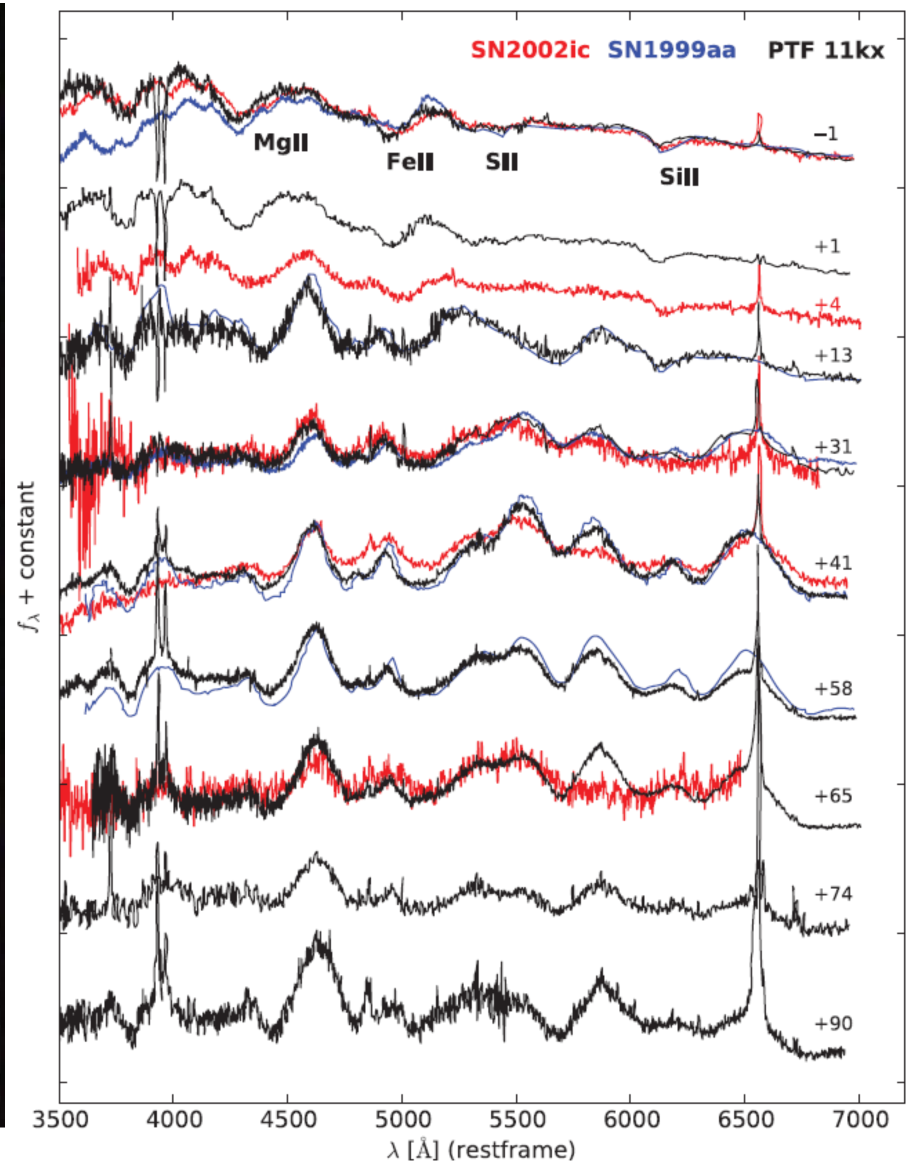


Thermonuclear Explosions of White Dwarfs!!

SN Ia: PTF11kx

(Dilday et al. 2012)

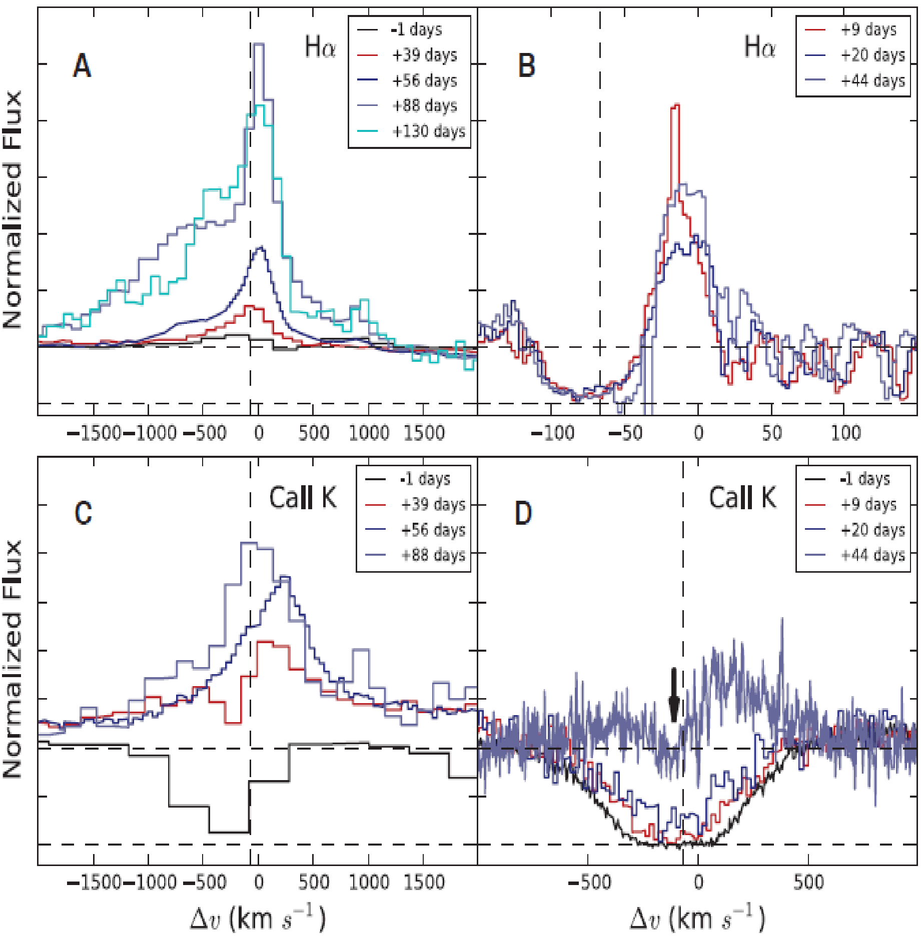


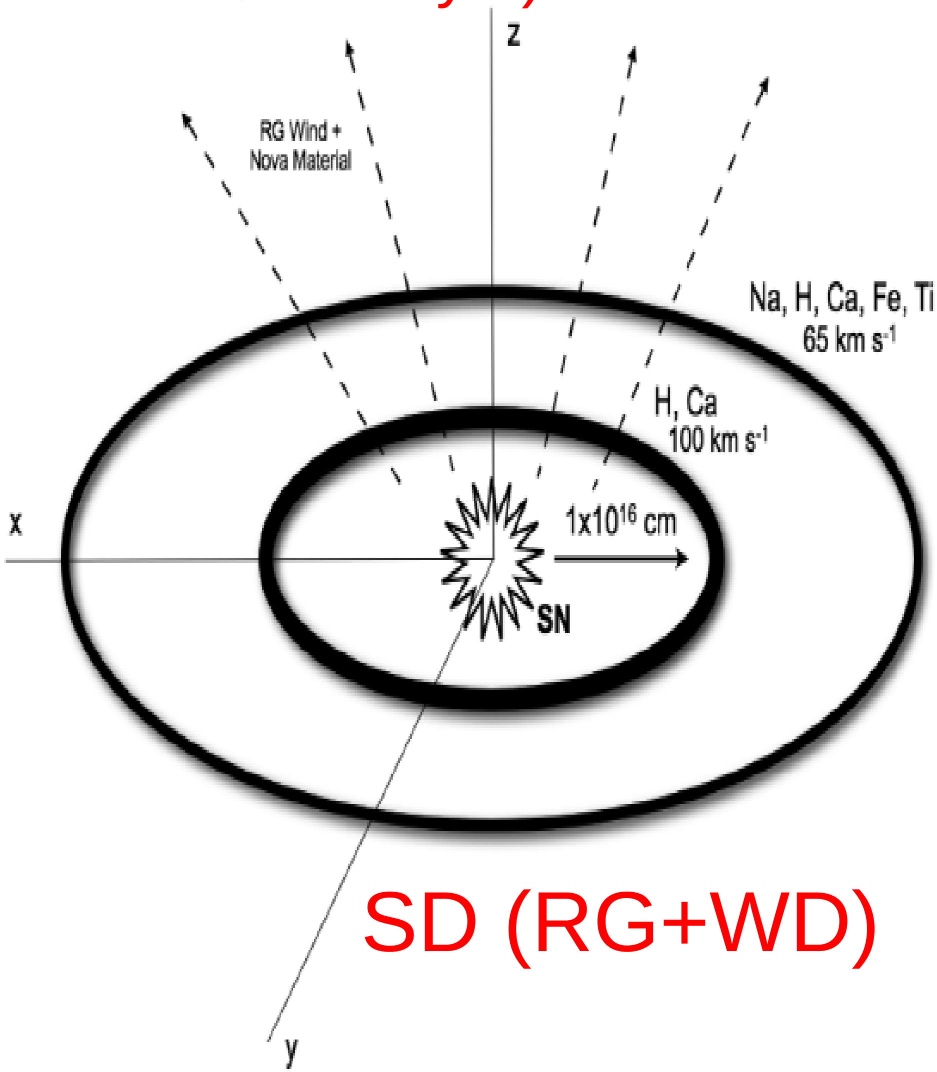


PTF11kx: Symbiotic Recurrent Nova

RG wind + Recurrent nova ejecta
(P~ 10 yrs)

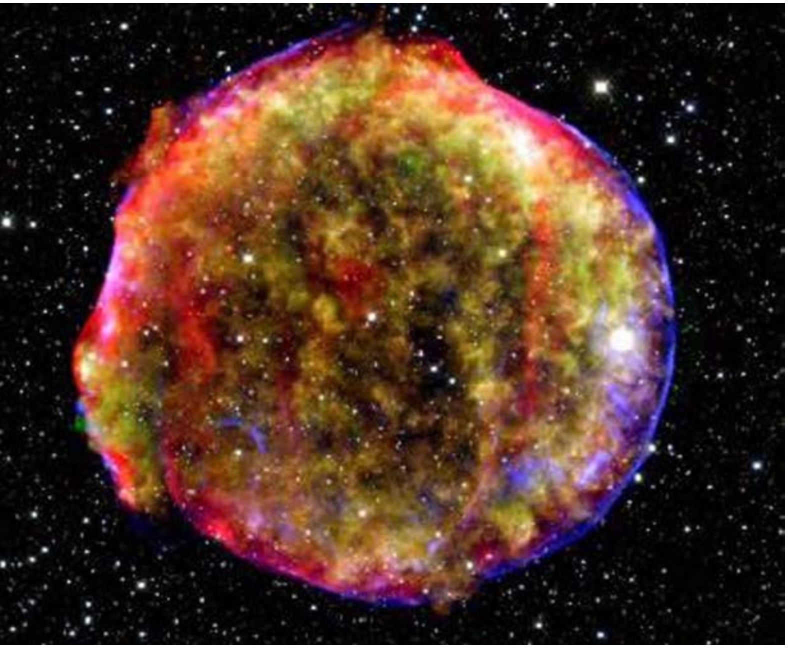
(Dilday et al. 2012)





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)

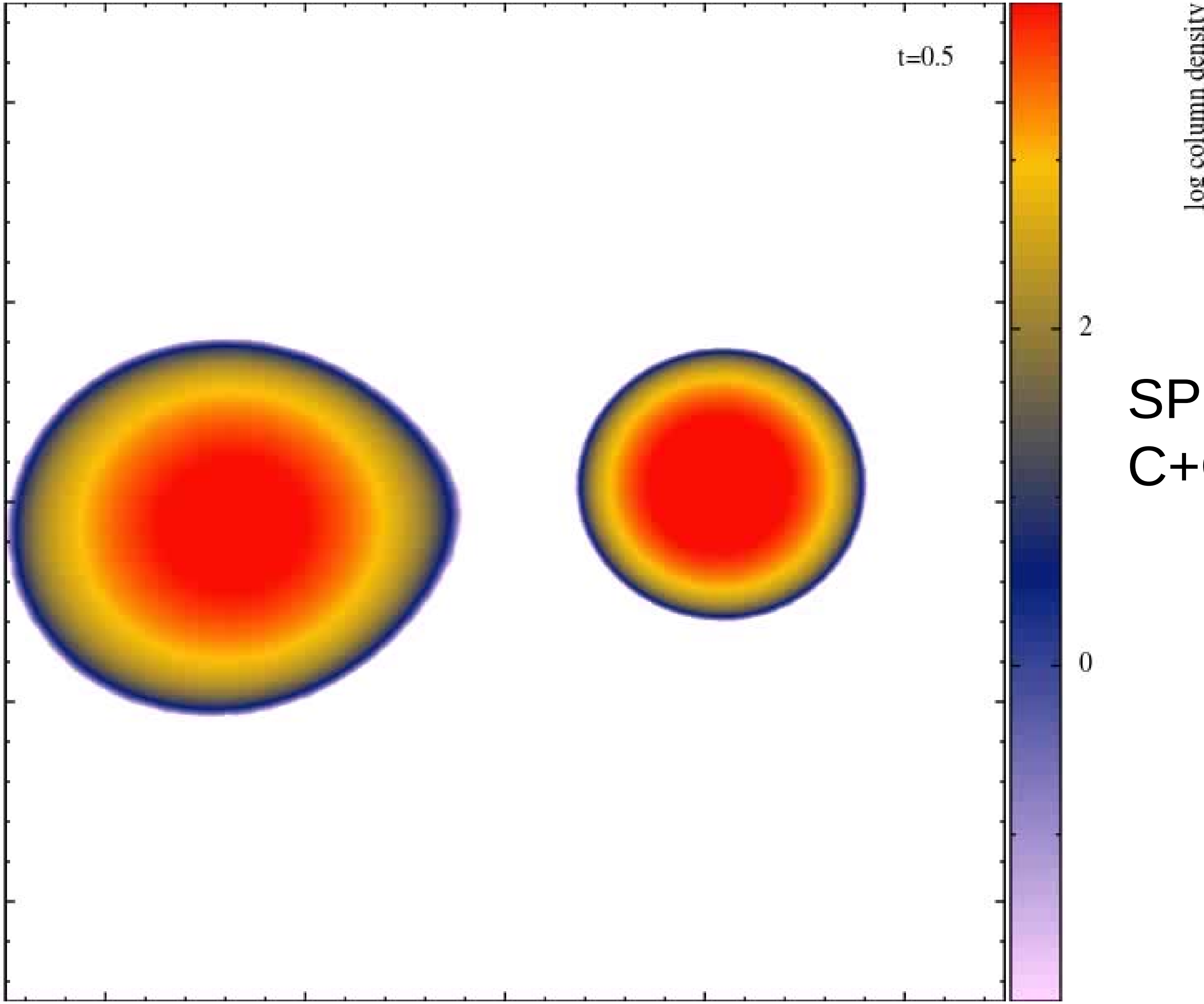
SN 2011fe
in M101
（Li+ 11)

DD ? ➔

DD, SD ➔ Sub-Ch, Chandra

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



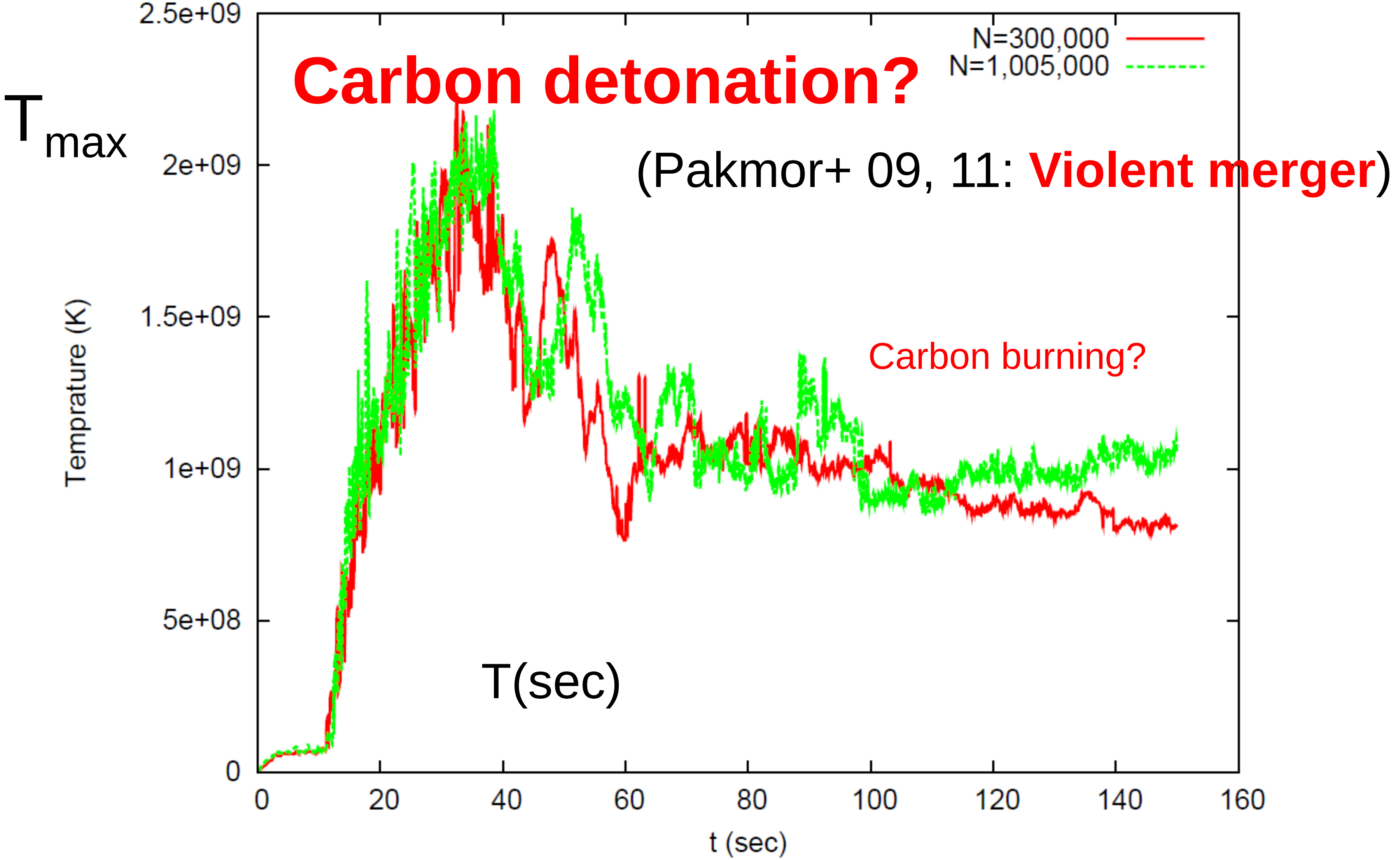
SPH Simulations of C+O WD Merging

example:

N = 4 x 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 (violent merger) ?

If yes,

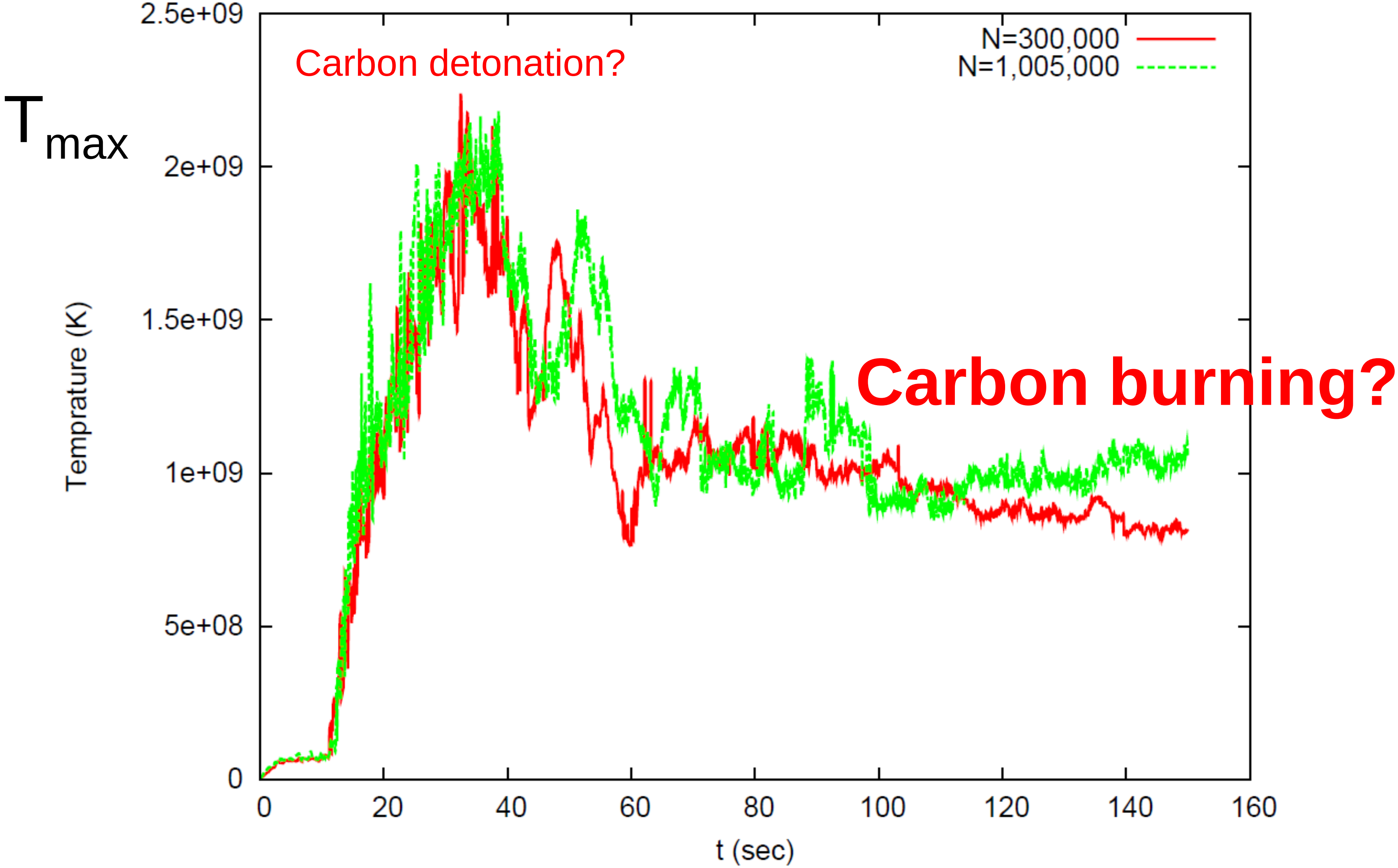
➔ central C-detonation (Pakmor+ 09, 11)

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 (Yoon+ 07)

WD Merging (1.0+0.7)

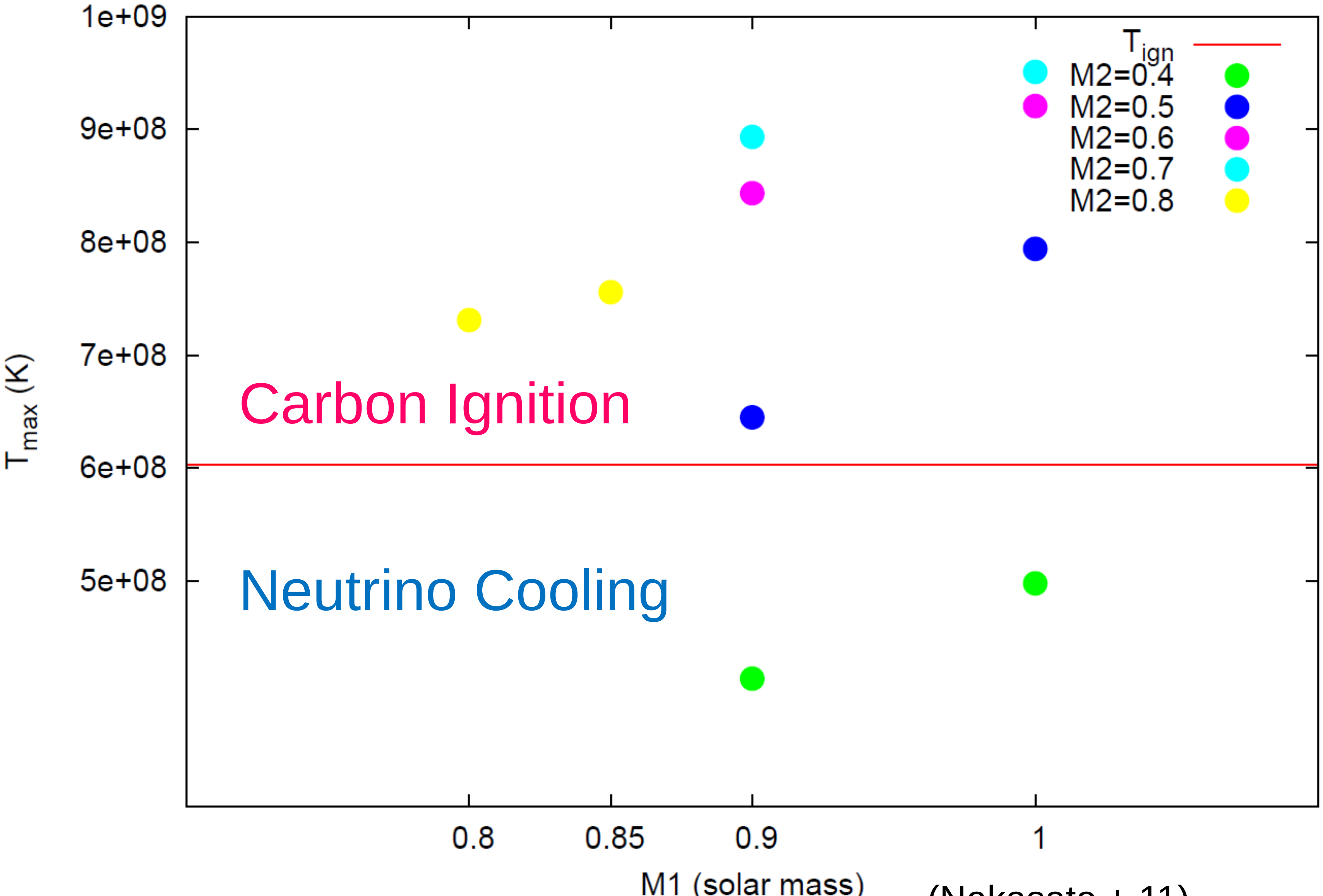


(Nakasato+ 11)

Double Degenerate Scenario

- If $T_{max} < 6 \times 10^8$ K (~ surface)
  → C+C rate < Neutrino cooling rate
  → no surface C-ignition (Yoon+ 07)
  ➔ central C-ignition (if accretion rate is low)
  ("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

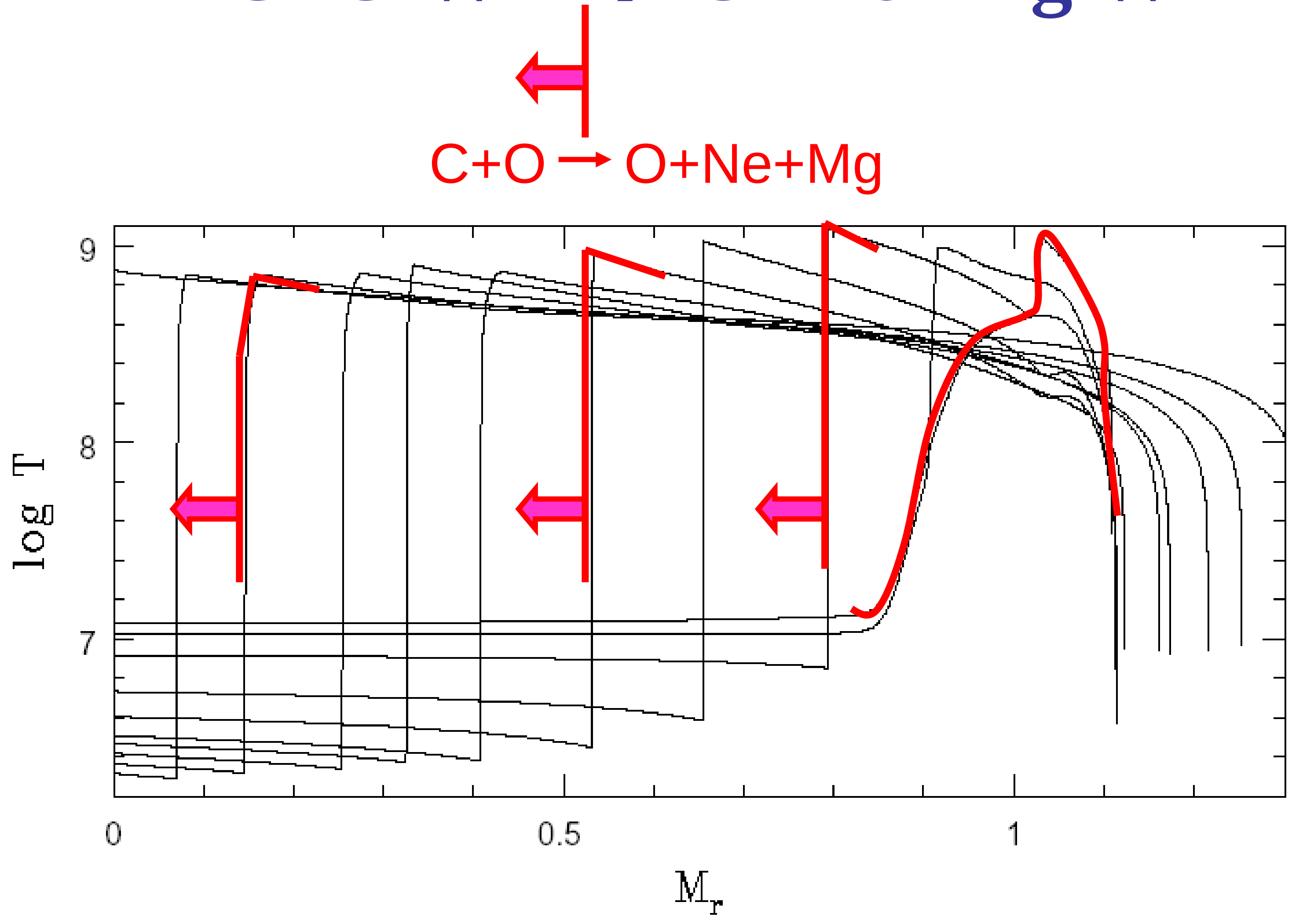
WD Merging: T_{max} (M_1, M_2)



(Nakasato + 11)

Carbon Flame

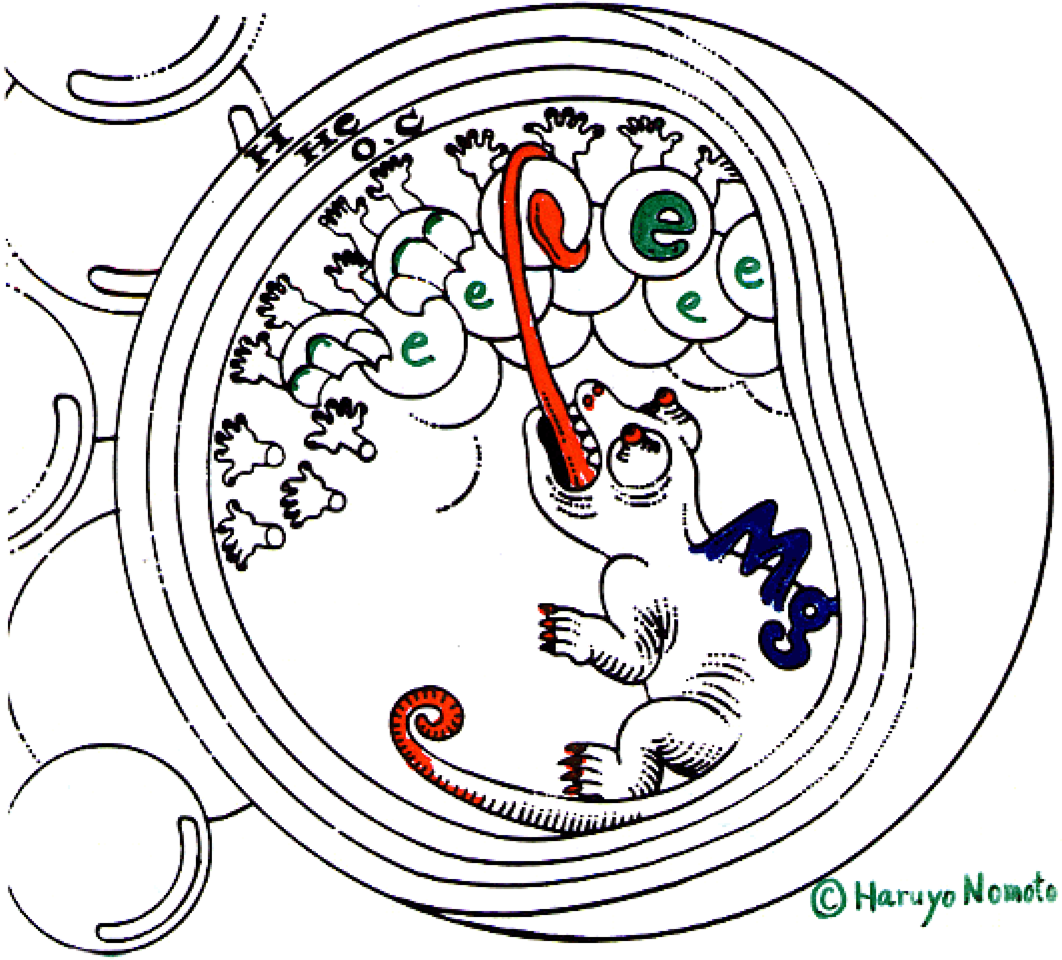
C+O WD → O+Ne+Mg WD



(Saio & Nomoto)

Electron Capture in ONeMg WD

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

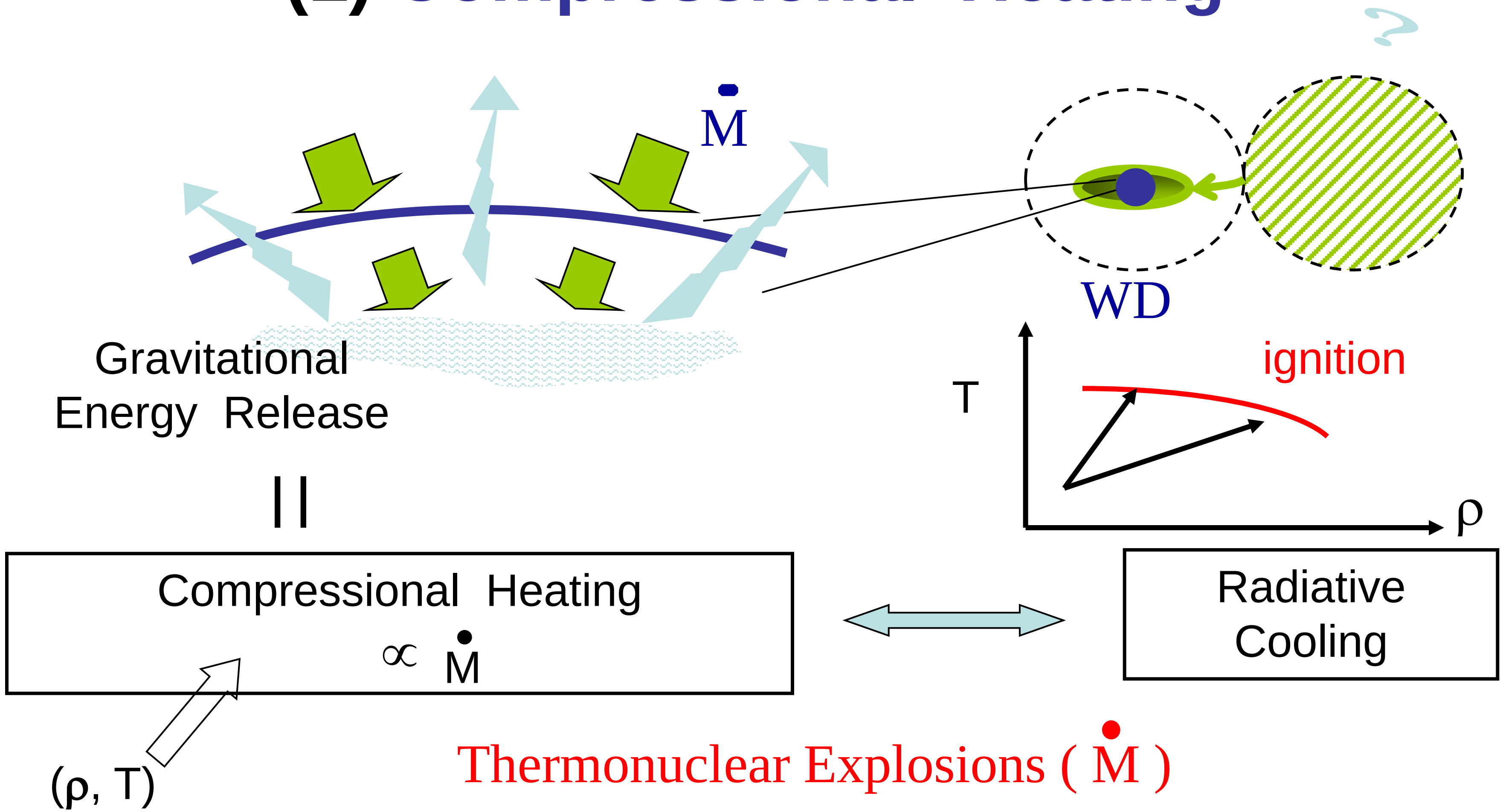


DD, SD ➔ Sub-Ch, Chandra

	surface burning	➔	sub-Ch	Chandra
ρ_c (g cm^{-3})	$\sim 10^6$		$10^{7\text{-}8}$	$10^{9\text{-}10}$
DD	C-detonation ?	➔	C-det	
	steady C-burning?	➔		ONeMg WD
SD	He flashes ?	➔		C-deflag
	He detonation ?	➔	C-det	

Single Degenerate Scenario

(1) Compressional Heating



Candidate Progenitor Systems for Carbon Ignitors

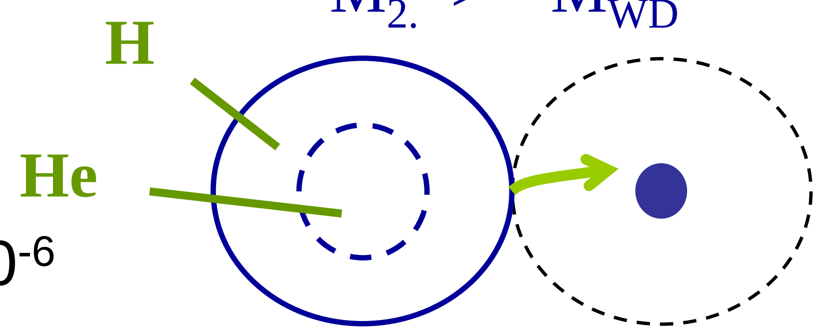
Hachisu, Kato, Nomoto
Lee, van den Heuvel
Han, Podsiadlowski

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

Companion

(1) H: leaving M.S.

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



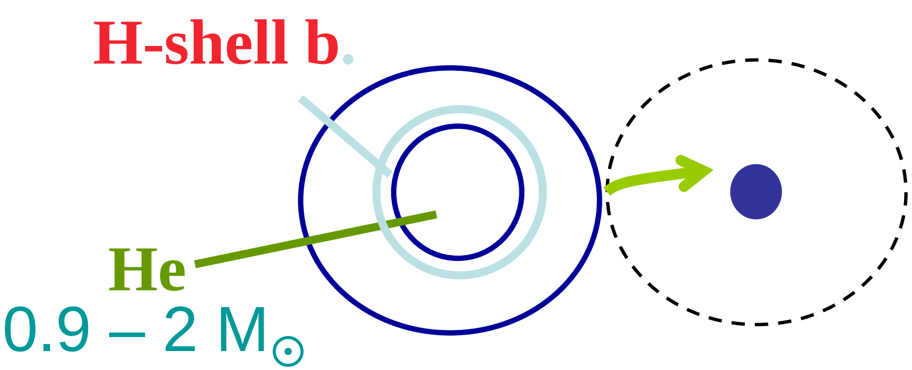
$\dot{M}_2 \sim M_2/\tau_{KH}\ (\sim 3\times10^{-8} M_2^{\,4})$

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

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

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

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



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

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

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 ($\dot{M}$)

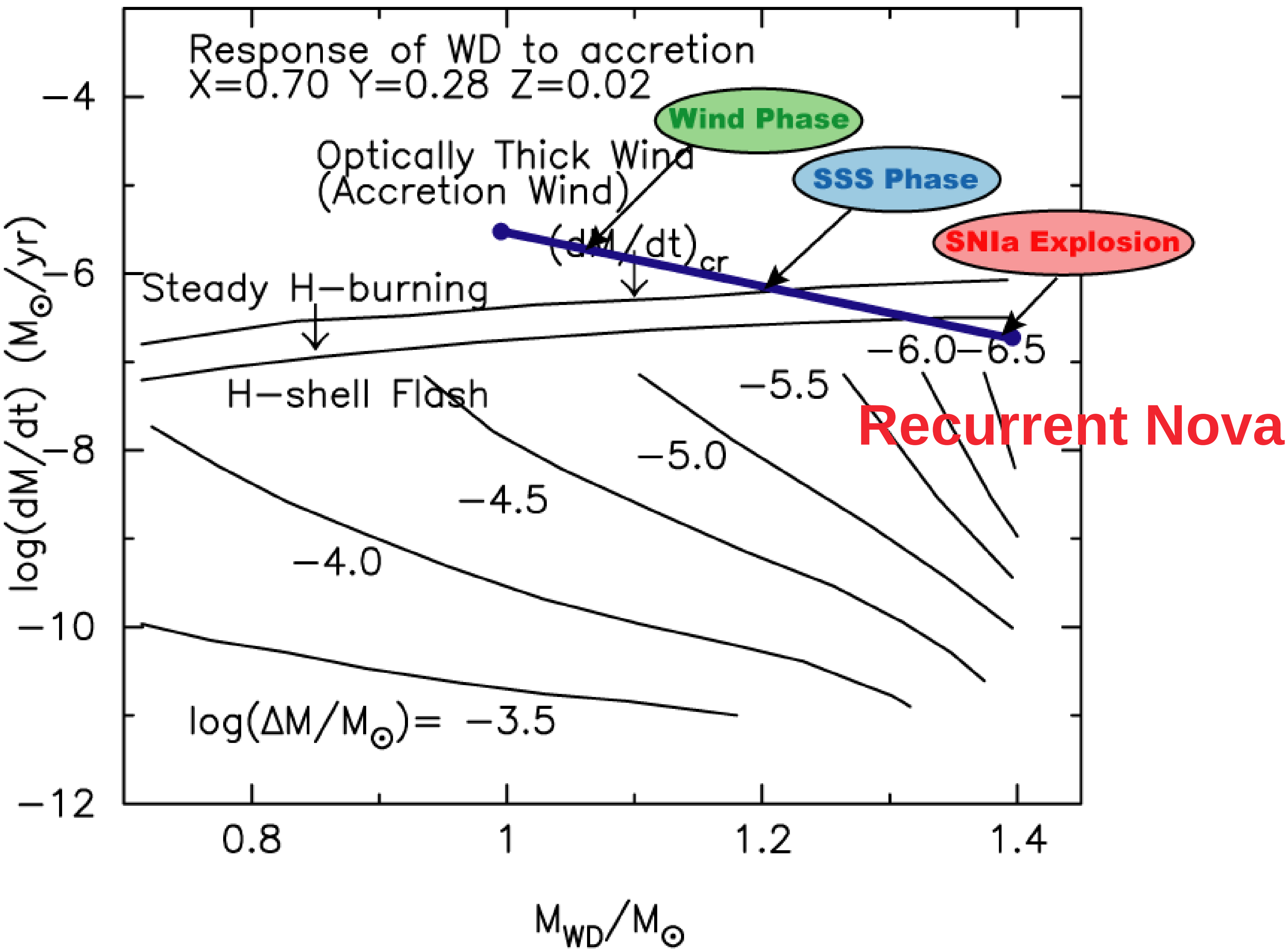
(2) H & He Burning

(3) Radiation-driven WD Winds

(4) Steady Hydrogen Burning

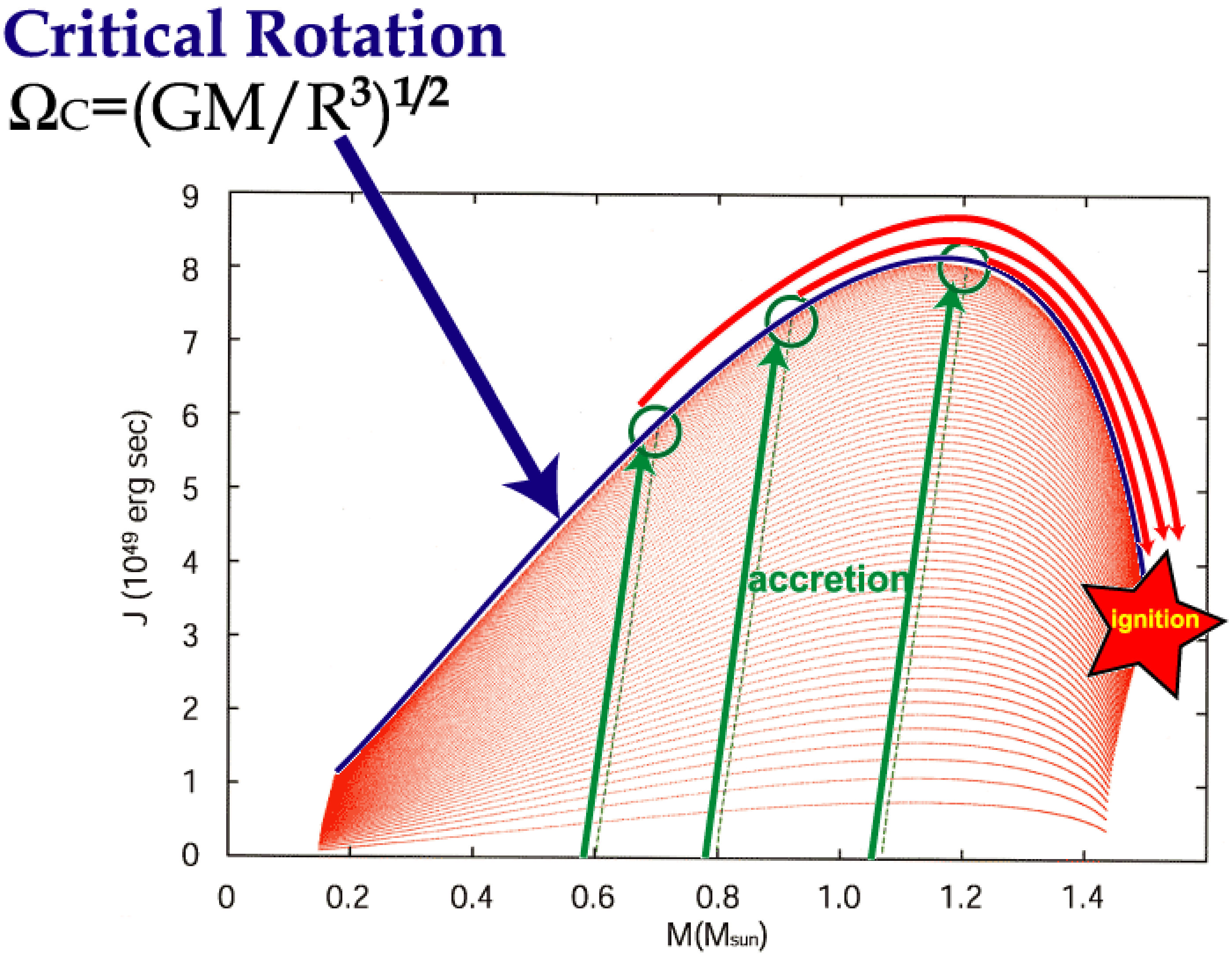
(5) **Recurrent Novae**

➔ **Central Ignition of Carbon Burning**



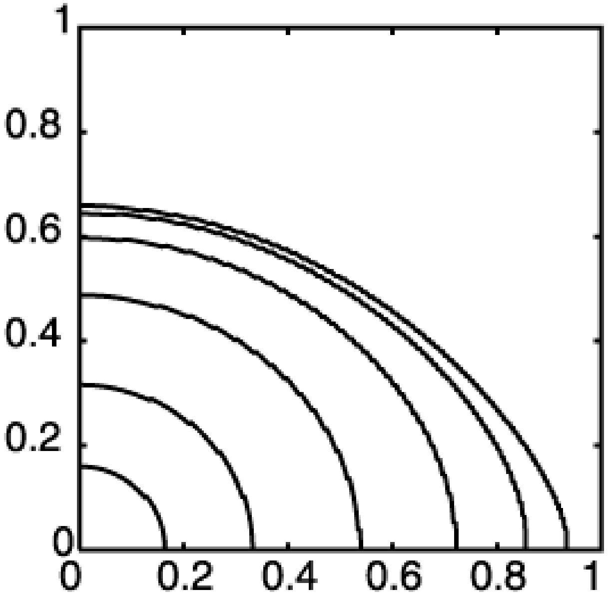
Response of WD to accretion
X=0.70 Y=0.28 Z=0.02
Wind Phase
SSS Phase
SNIa Explosion
Optically Thick Wind
(Accretion Wind)
$(dM/dt)_{cr}$
Steady H−burning
H−shell Flash
−6.0
−6.5
−5.5
−5.0
−4.5
−4.0
$\log(\Delta M/M_\odot) = -3.5$
Recurrent Nova
−4
−6
−8
−10
−12
$\log(dM/dt)\ (M_\odot/yr)$
0.8
1
1.2
1.4
$M_{WD}/M_\odot$

Evolution of Rotating White Dwarfs



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

Structure of Rotating WDs



Uniform Rotation

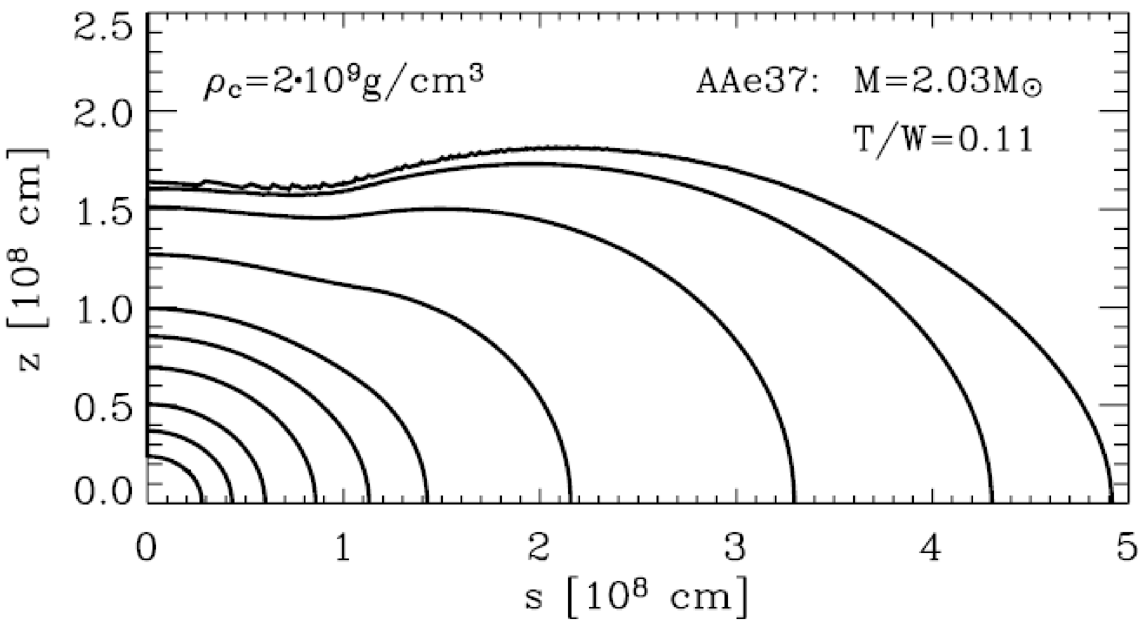
$M=1.48\ M_\odot$, $J=4.63$

Rotation Period = 2.3sec

$\rho_c=2.0e9$ (Ignition)

$q=0.66$

(Uenishi, Nomoto, Hachisu 03)



Differential Rotation

$M=2.03\ M_\odot$

$\rho_c=2.0e9$ (Ignition)

(Yoon, Langer 05)

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

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

$M(wd) > 1.38\ M_\odot$ without C-ignition

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

➔ strong Nova outbursts : mass ejection

➔ M(wd) does not increase

➔ $M(wd, final) > 1.38\ M_\odot$

SNe Ia from Rotating WDs

- $M_{wd,\,final}/M_{\odot} > 2.4$: T / W > 0.14

  secular instability

- $M_{wd,\,final}/M_{\odot} = 1.5 - 2.3$:

  differential → uniform rotation

  (←meridional circulation,,,,,)

- $M_{wd,\,final}/M_{\odot} = 1.4 - 1.5$:

  uniform rotation

  Spin-down: angular momentum loss

  (←magnetic wind,,,,,,,)

→ Carbon Ignition

Companions of Rotating WDs

M_2 continues to decrease by mass transfer
(~1 x 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

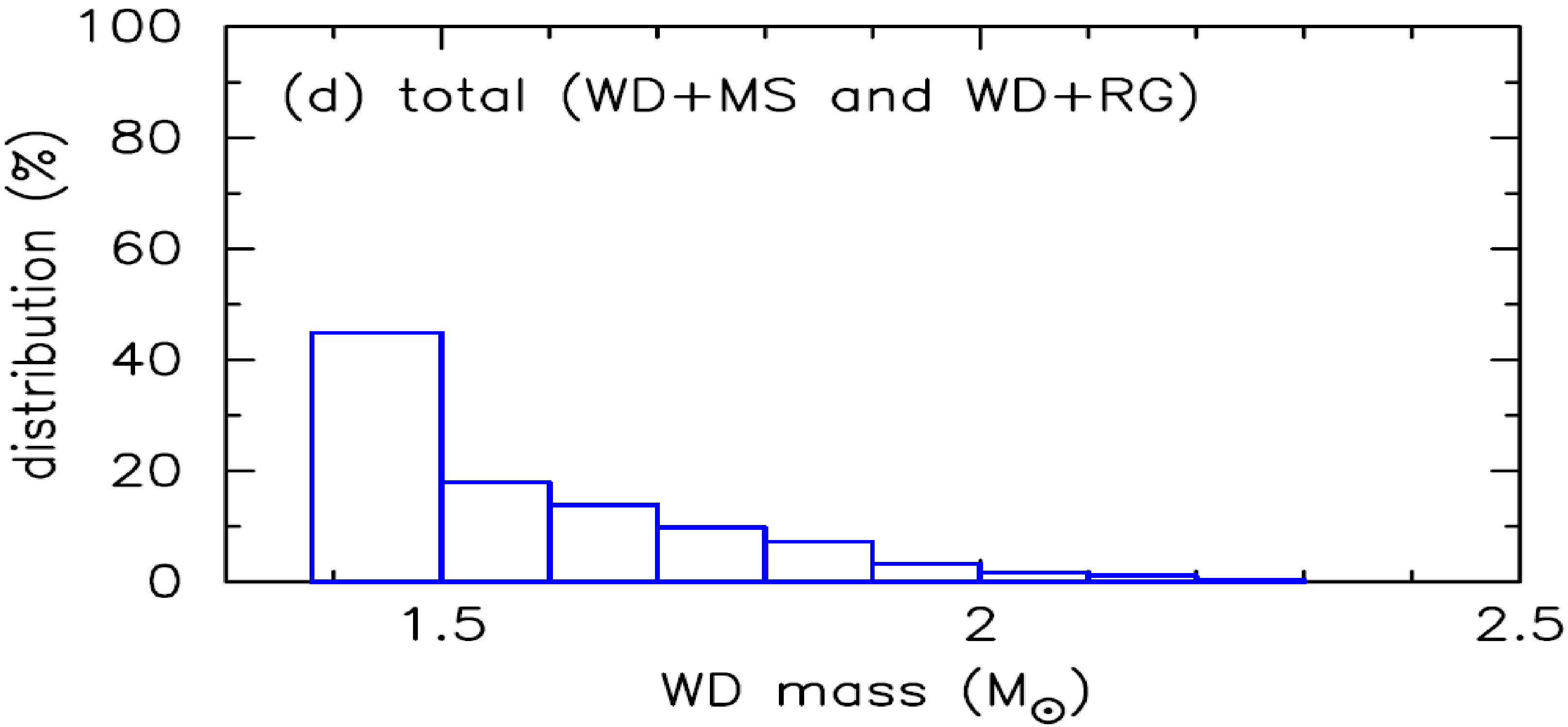
➔ He WD by losing H-envelope

Low mass, compact companion stars:

➔ missing companions

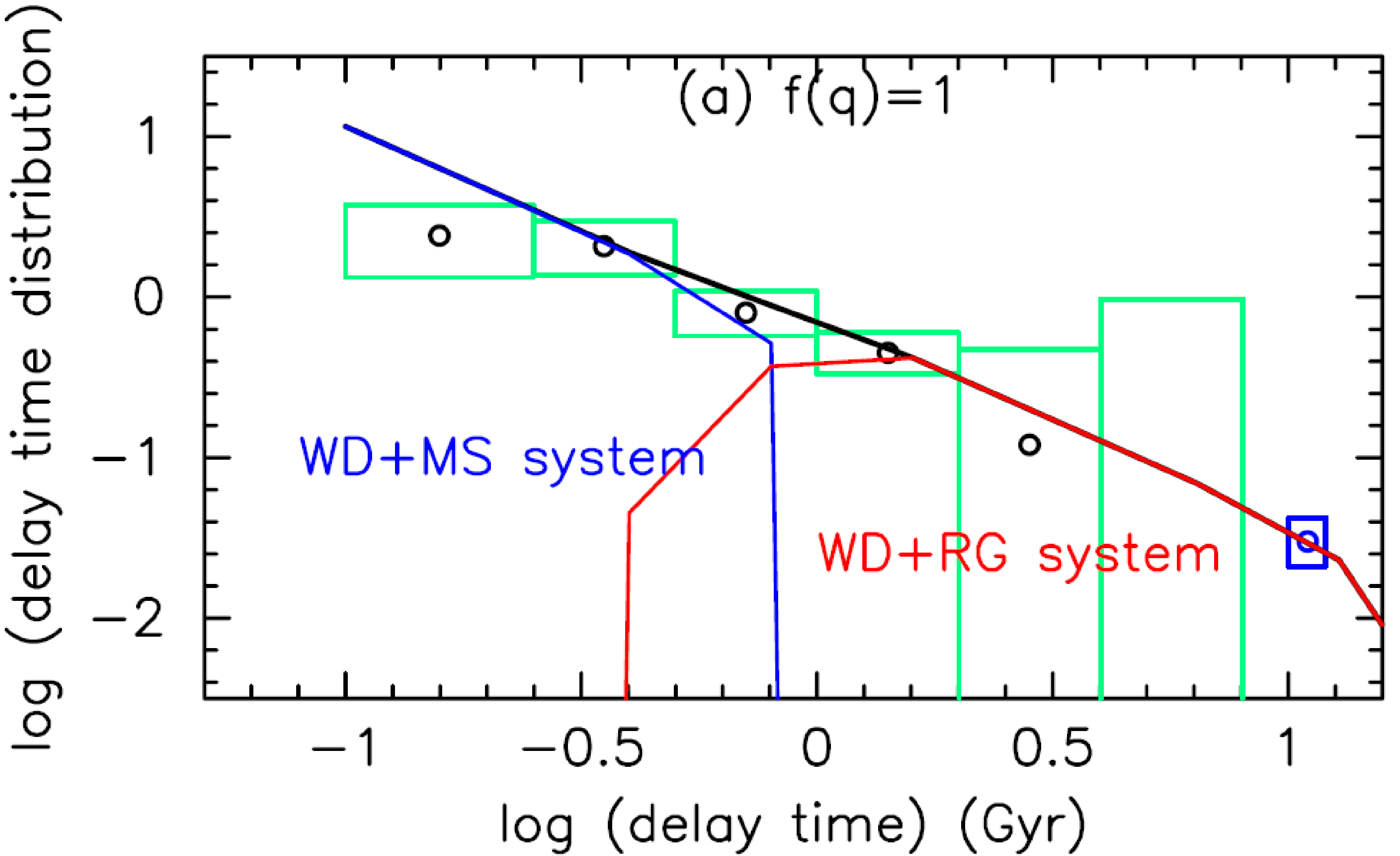
Circumstellar matter is dispersed.

Mass Distribution of Rotating WDs



WD Mass ($M_\odot$)	Ratio (%)	$\Delta m_{15}(B)$ (mag)	(Blondin+12) 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

SD: Delay Time Distribution



Single Degenerate Scenario

Rotating WDs (➔mass distribution)

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

- mechanism & timescale of spin-down

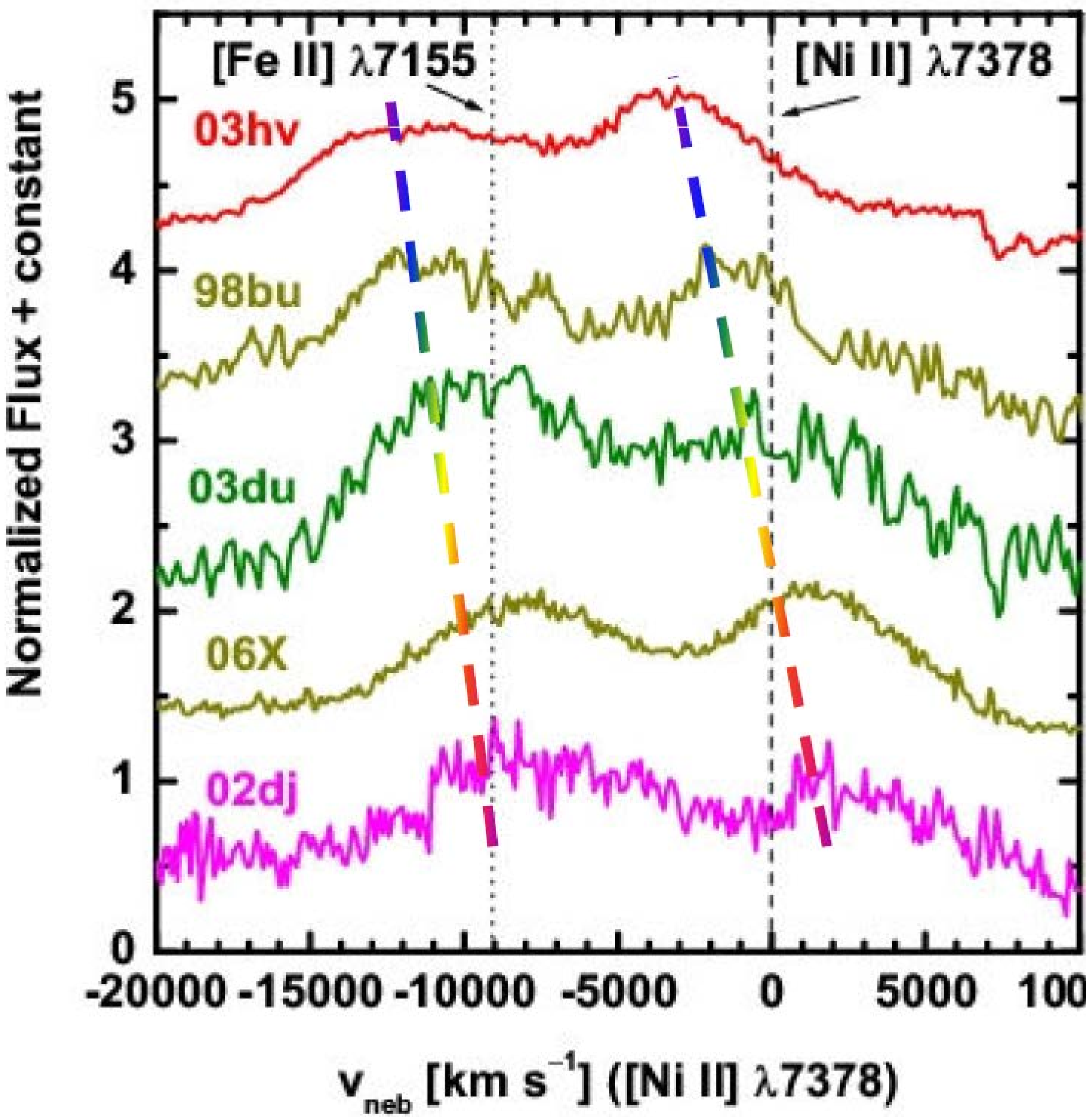
(e.g., Ilkov & Soker 11)

Uniformly Rotating WDs (➔M~1.5 $M_{\odot}$)

➔ Pre-supernova ~ recurrent novae(PTF11kx)

Electron capture elements (Fe, Ni nebular lines) ← Chandra Mass

($\rho_c \sim 10^{9-10}$ g cm^{-3})



(Maeda+ 10)

Nucleosynthesis in Stars and the Chemical Enrichment of Galaxies

K. Nomoto, C. Kobayashi, N. Tominaga

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(Annual Review Astron. Astrophys. 2013/08/19)

Abundance Profiling of Extremely Metal Poor Stars (Tominaga + 2013)
48 stars

Nucleosynthesis in Stars and the Chemical Enrichment of Galaxies

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Keywords

first star, galactic archaeology, gamma-ray burst, hypernova, metal-poor star, supernova

Abstract

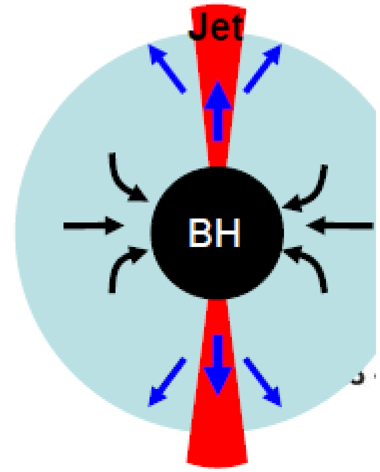
After the Big Bang, production of heavy elements in the early Universe takes place starting from the formation of the first stars, their evolution, and explosion. The first supernova explosions have strong dynamical, thermal, and chemical feedback on the formation of subsequent stars and evolution

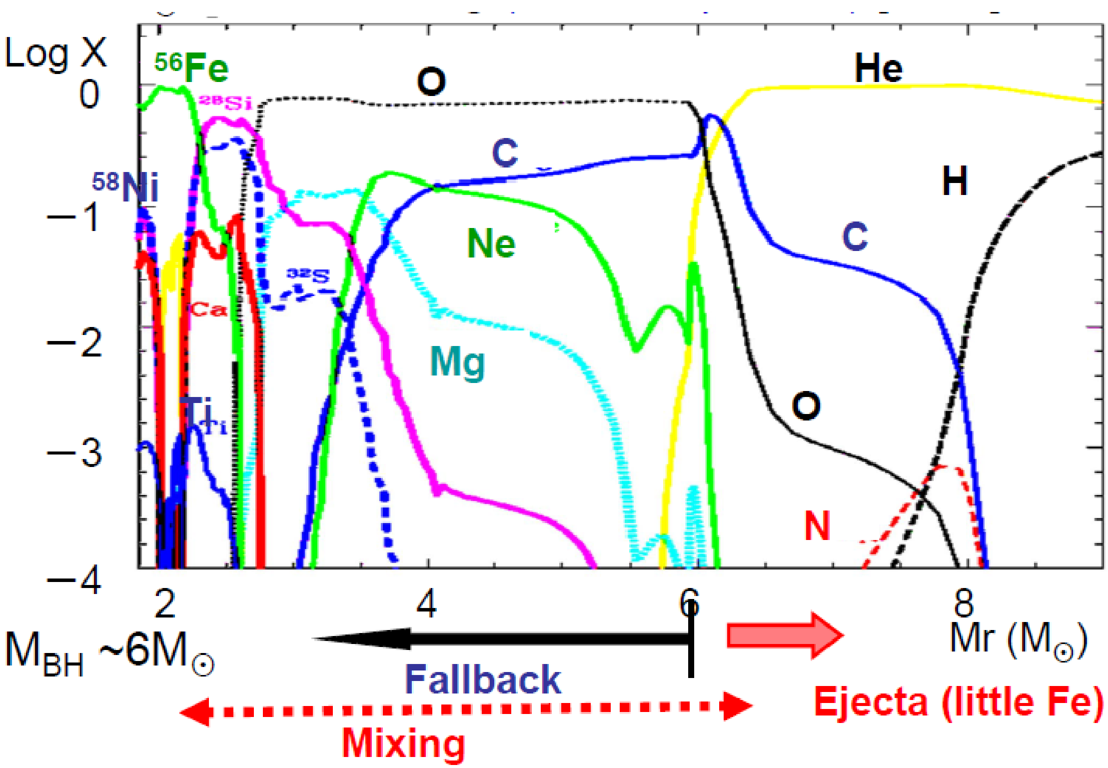
Mixing & Fallback Supernova

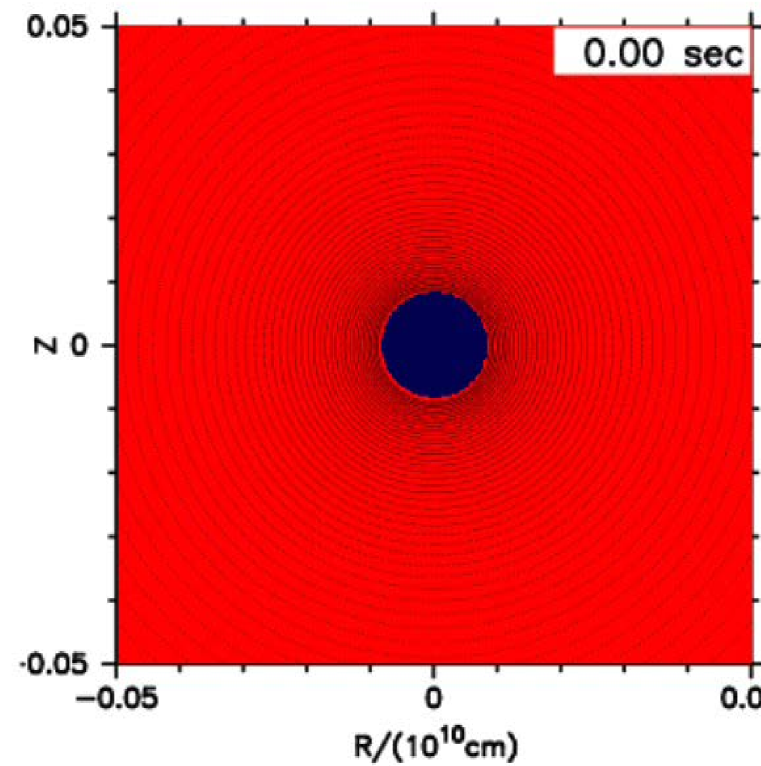
➔ Carbon Enhanced Metal Poor **(CEMP)** Stars

➔ M(Fe), M(BH)

(Jet-induced)

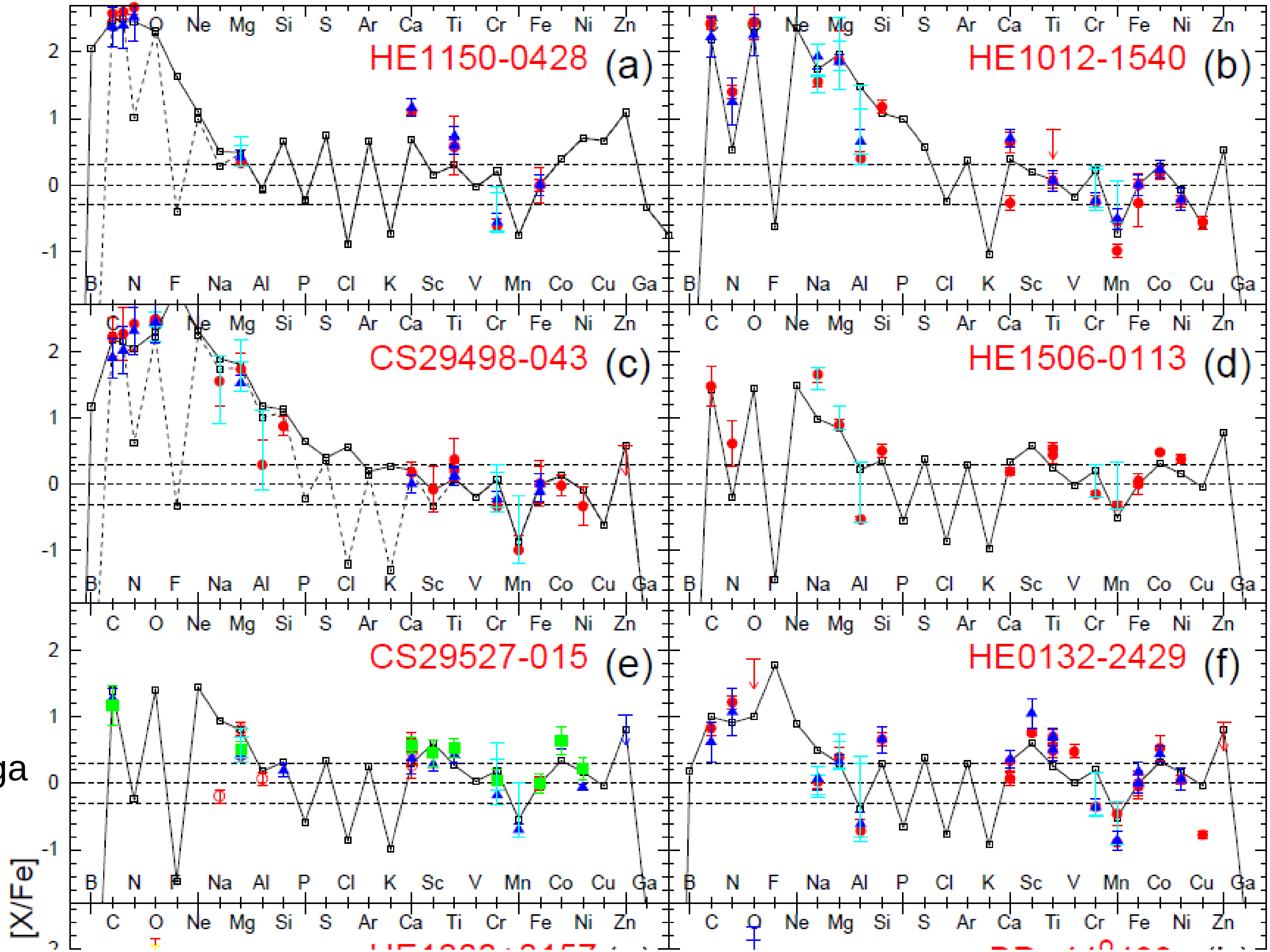






CEMP Stars ← Mixing & Fallback SNe

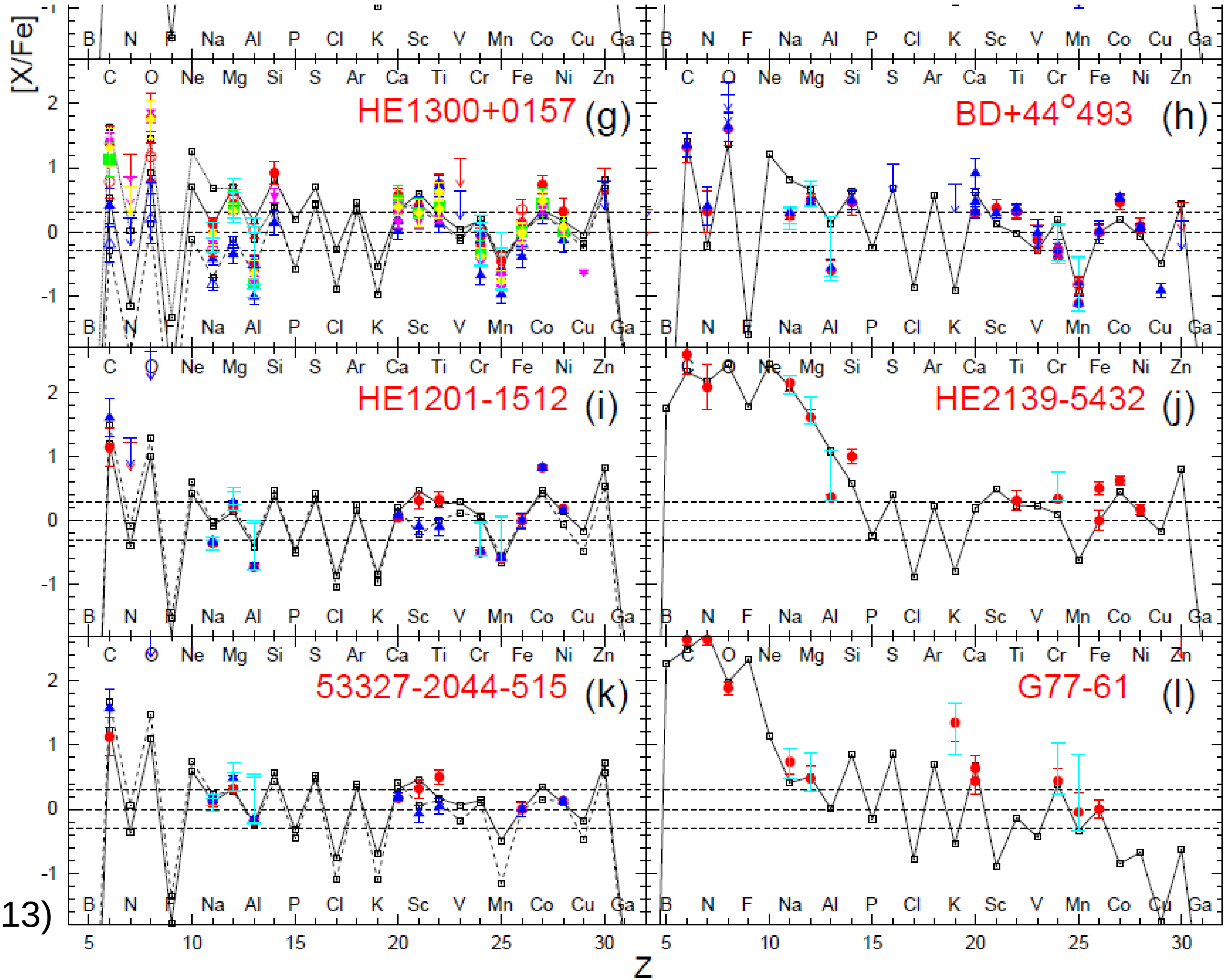
[X/Fe]



(Tominaga +13)

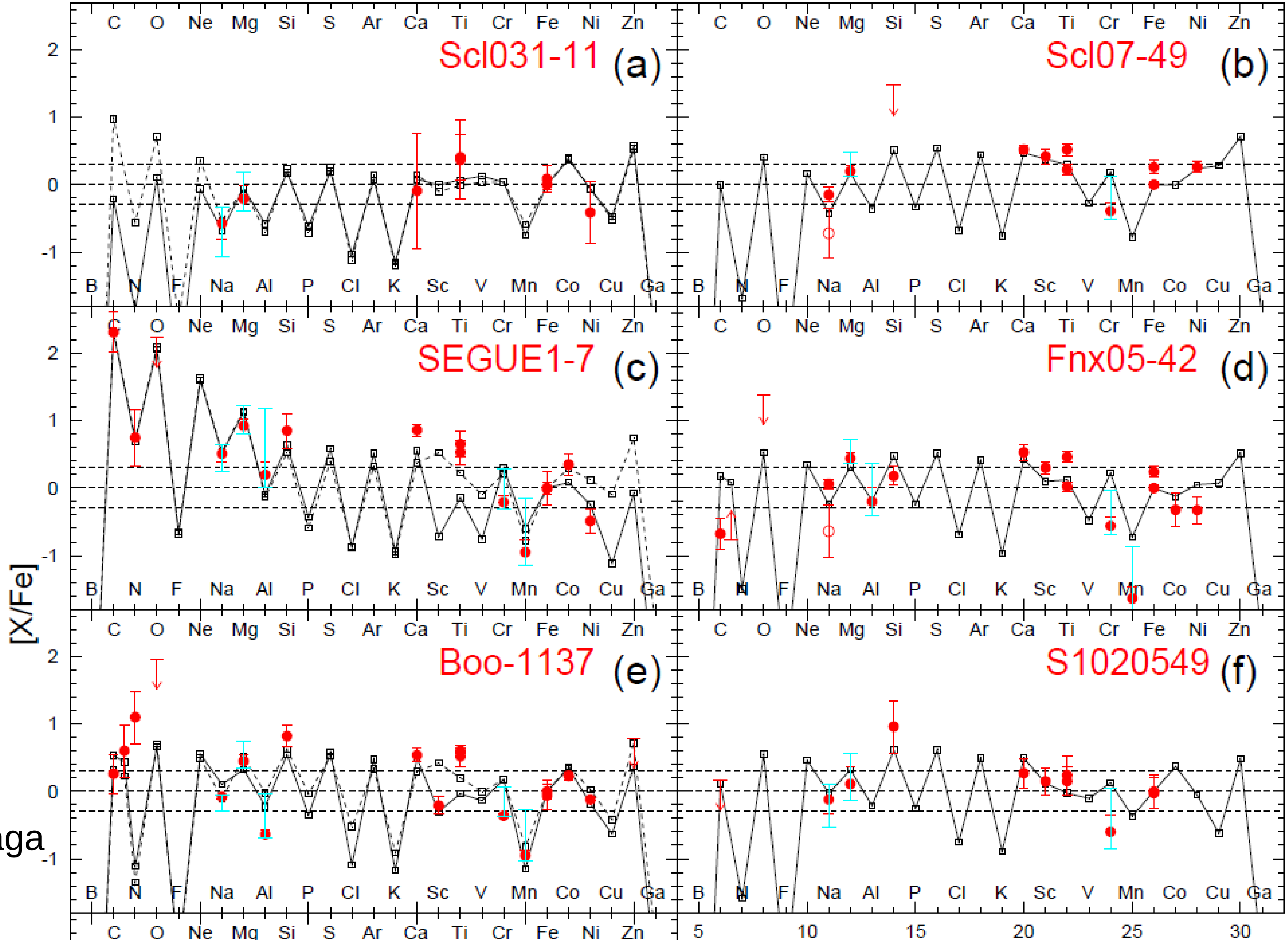
CEMP Stars 🡐 Mixing-Fallback SNe

[X/Fe]



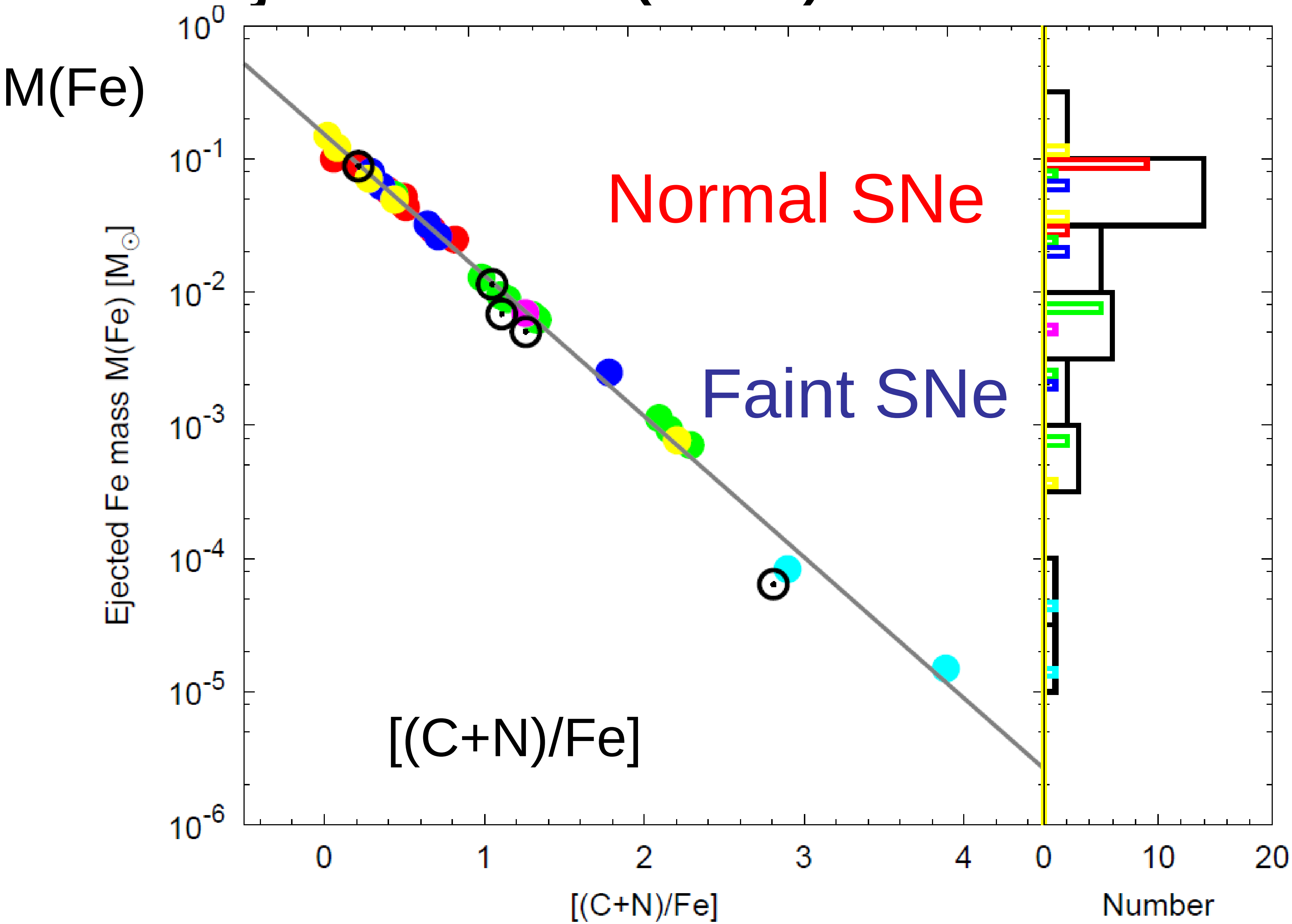
(Tominaga+13)

EMP Stars in dwarf galaxies



(Tominaga +13)

Ejected Fe (^{56}Ni) Mass



Black Hole Mass Function