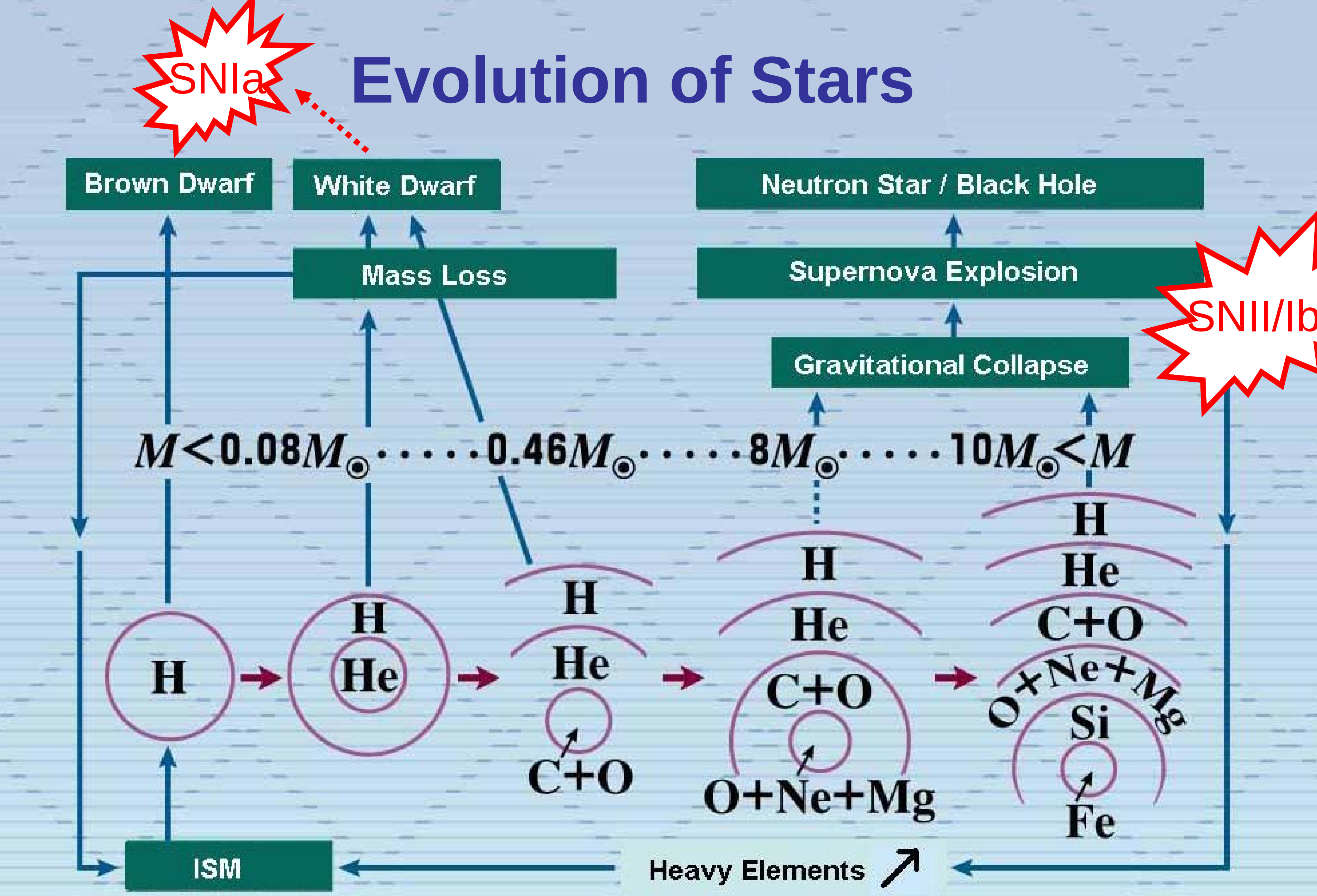
Short History of Supernova Research

Ken Nomoto (Univ. of Tokyo)

Evolution of Stars



Progress of Theoretical Physics, Vol. 48, No. 1, July 1972

Mixing between Stellar Envelope and Core in Advanced Phases of Evolution. IV

—*Effect of Super-Adiabaticity in Convective Envelope*—

Ken-ichi NOMOTO* and Daiichiro SUGIMOTO

College of General Education, University o
Meguro, Komaba, Tokyo
**Department of Astronomy, University of To*

(Received December 28, 1971)

Super-Adiabatic Envelope

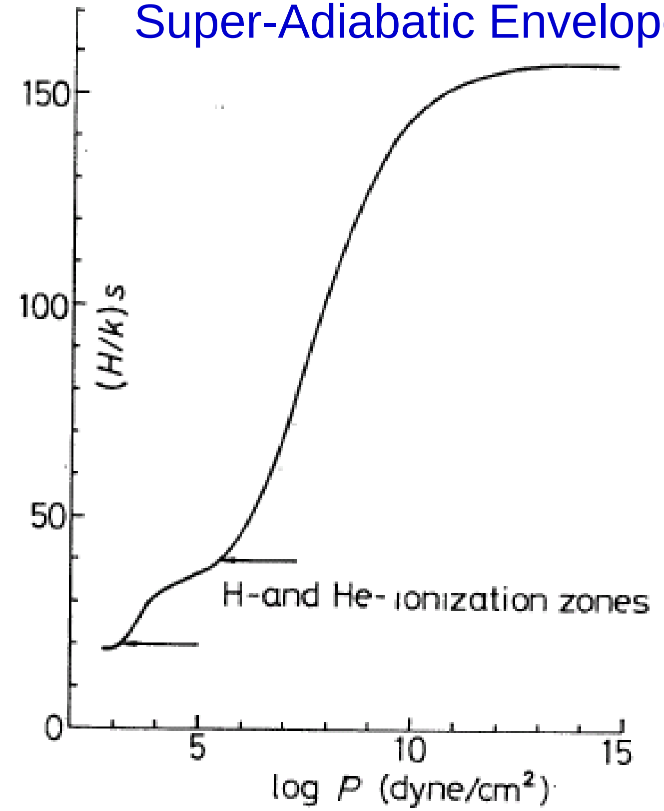
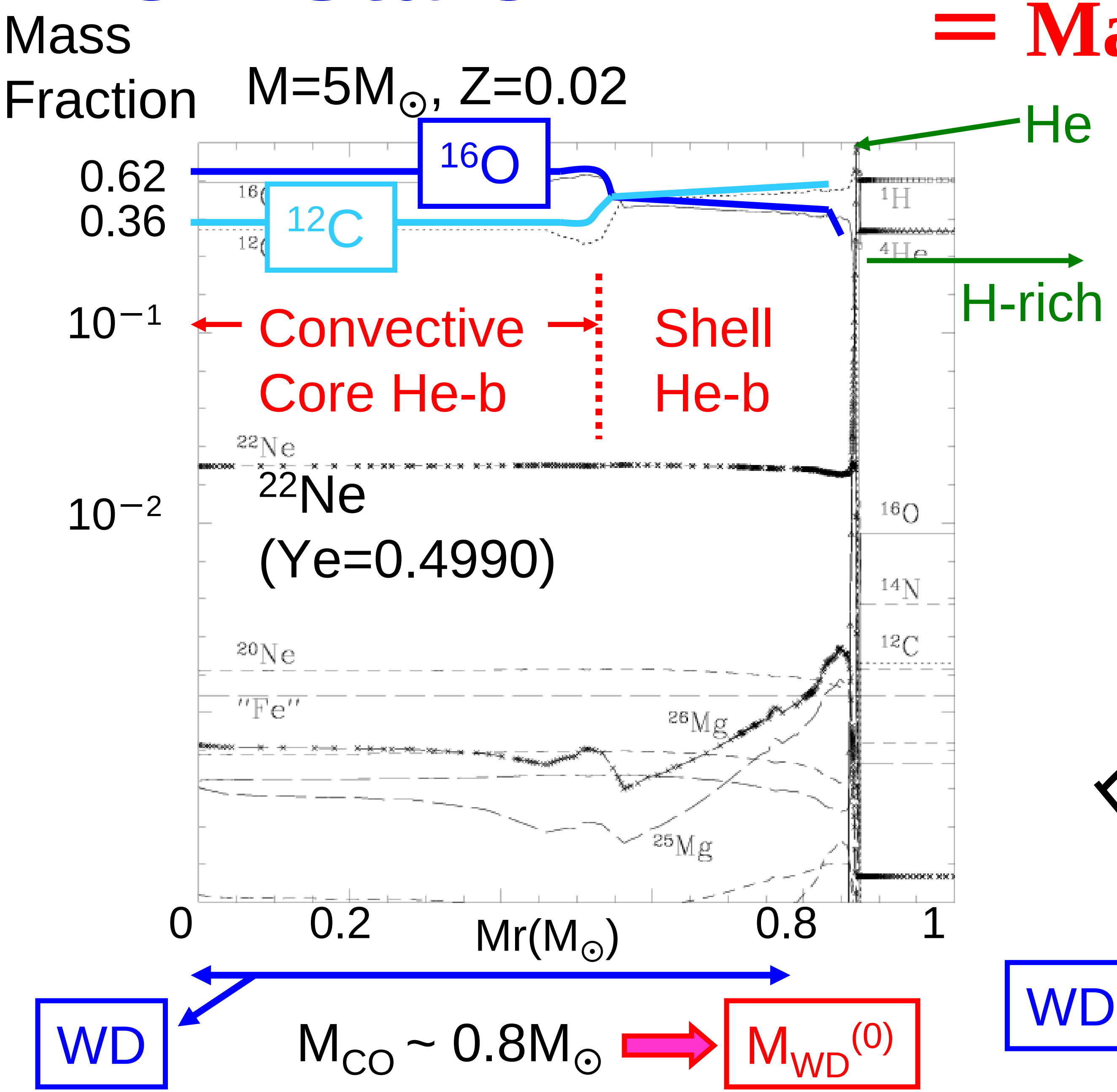


Fig. 8. Entropy distribution in the enve-

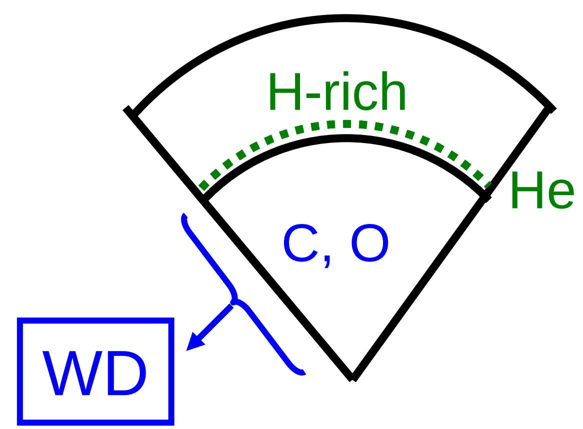
Dredge-up of the He Layer in AGB Stars

AGB Stars

Dredge-up of He Layer = Mass Loss



$M_{CO} \sim 0.8 M_\odot$ ⇒ $M_{WD}^{(0)}$

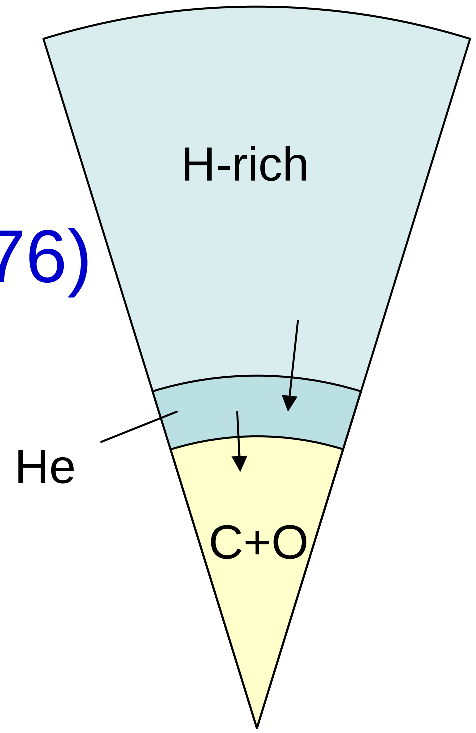


Thermonuclear Explosion Models for 3-8$M_\odot$ AGB Stars

Carbon Detonation (Arnett 1971)

→ Too much Fe
Too small Neutron Stars } → Collapse?

Carbon Deflagration (Nomoto et al 1976)



1976 Astrophys Space Sci

CARBON DEFLAGRATION SUPERNOVA, AN ALTERNATIVE TO CARBON DETONATION

(*Letter to the Editor*)

KEN'ICHI NOMOTO and DAIICHIRO SUGIMOTO

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and

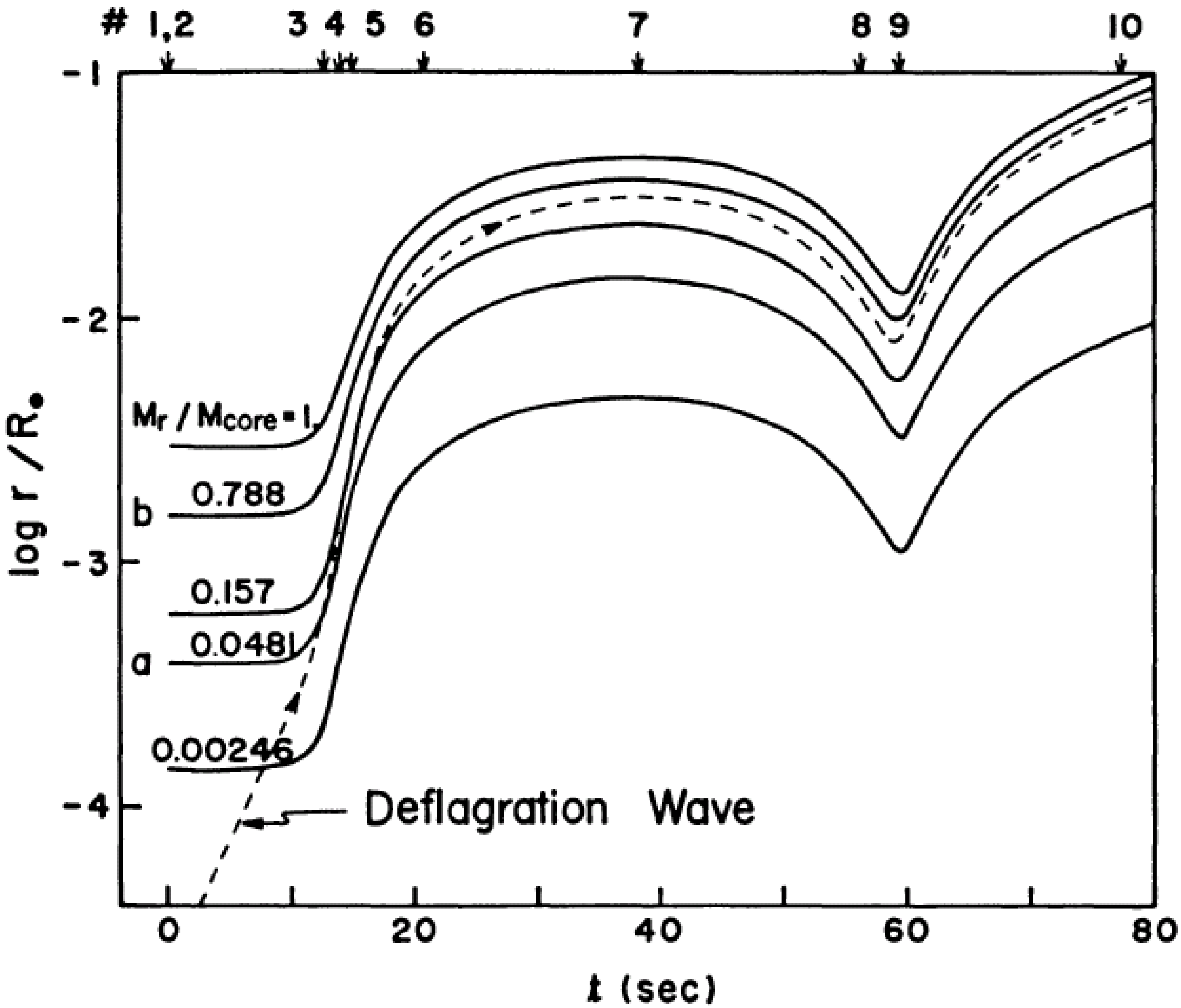
SADAYUKI NEO

Dept. of Physics, Kyoto University, Kyoto, Japan

(Received 16 October, 1975)

CARBON DEFLAGRATION SUPERNOVA

Nomoto et al.(1976)

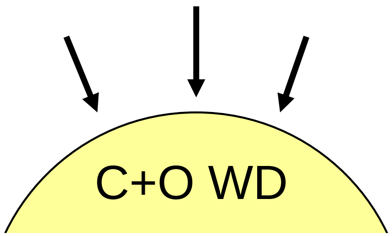


From AGB Stars to Close Binaries

Approximation : Core ~ Single star

– C+O Core growth ~ Accretion onto C+O WDs

$M_{WD} \longrightarrow M_{ch}$

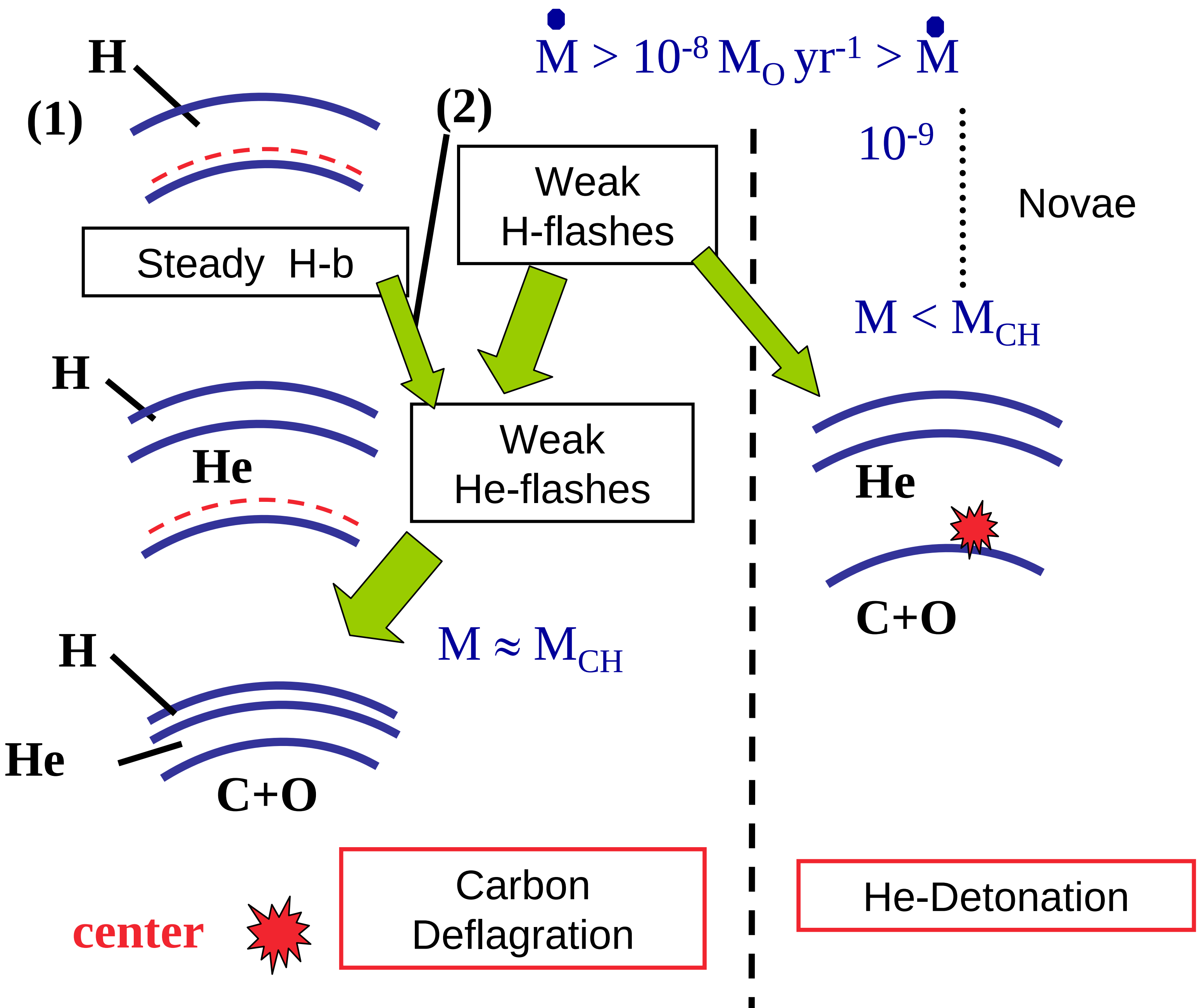


Accreting WD evolution (M, dM/dt)

Accretion of H, He, C+O (separately)

Novae

Thermonuclear Supernovae



$\dot{M} > 10^{-8} M_O yr^{-1} > \dot{M}$
H
(1)
(2)
Weak
H-flashes
Steady H-b
10^{-9}
Novae
$M < M_{CH}$
H
He
Weak
He-flashes
He
C+O
$M \approx M_{CH}$
H
He
C+O
center
Carbon
Deflagration
He-Detonation

Observations in Japan

- Little observational information on Type I SN was available in Japan.
- no SN observational group

- Abundance:
  - Si feature (Mustel & Chugai 1975)

Observations vs. Models

NASA/GSFC (1980-81)
Meetings @ La Jolla, Austin, Santa Cruz
Los Alamos, Kyoto

Type I Supernova

- Light Curves
- Spectra

— Consistent with Deflagration Models

"Reality" .

W7: parameter: $\ell/H_p=0.7$

AIP Conference Proceedings
Series Editor: Hugh C. Wolfe
Number 63

Supernovae Spectra

(La Jolla Institute, 1980)

Editors
Roland Meyerott and George H. Gillespie
La Jolla Institute

American Institute of Physics
New York 1980

La Jolla Workshop on Supernovae Spectra (1980)

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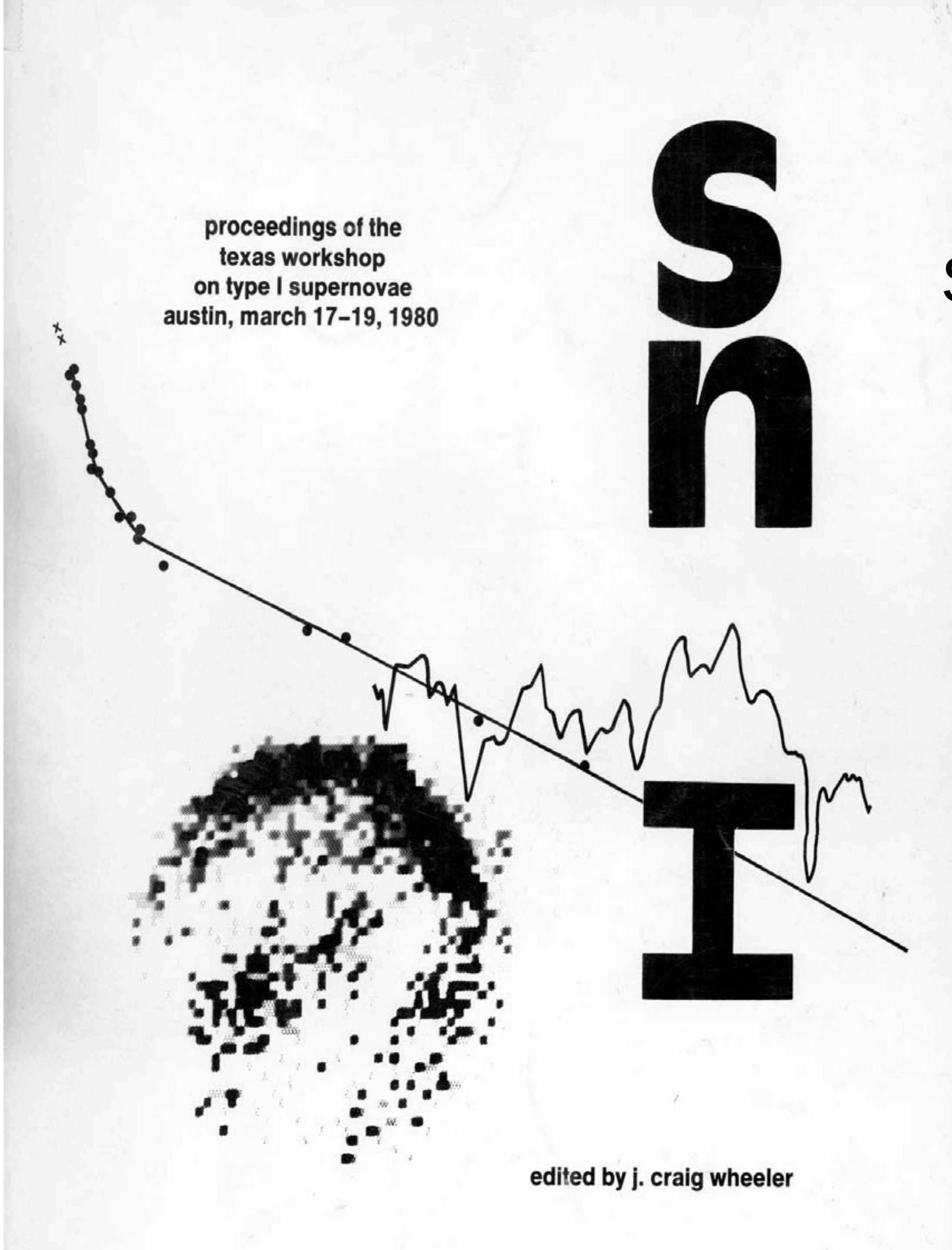


SN I Workshop
(1980 March, Austin)

Austin 1981

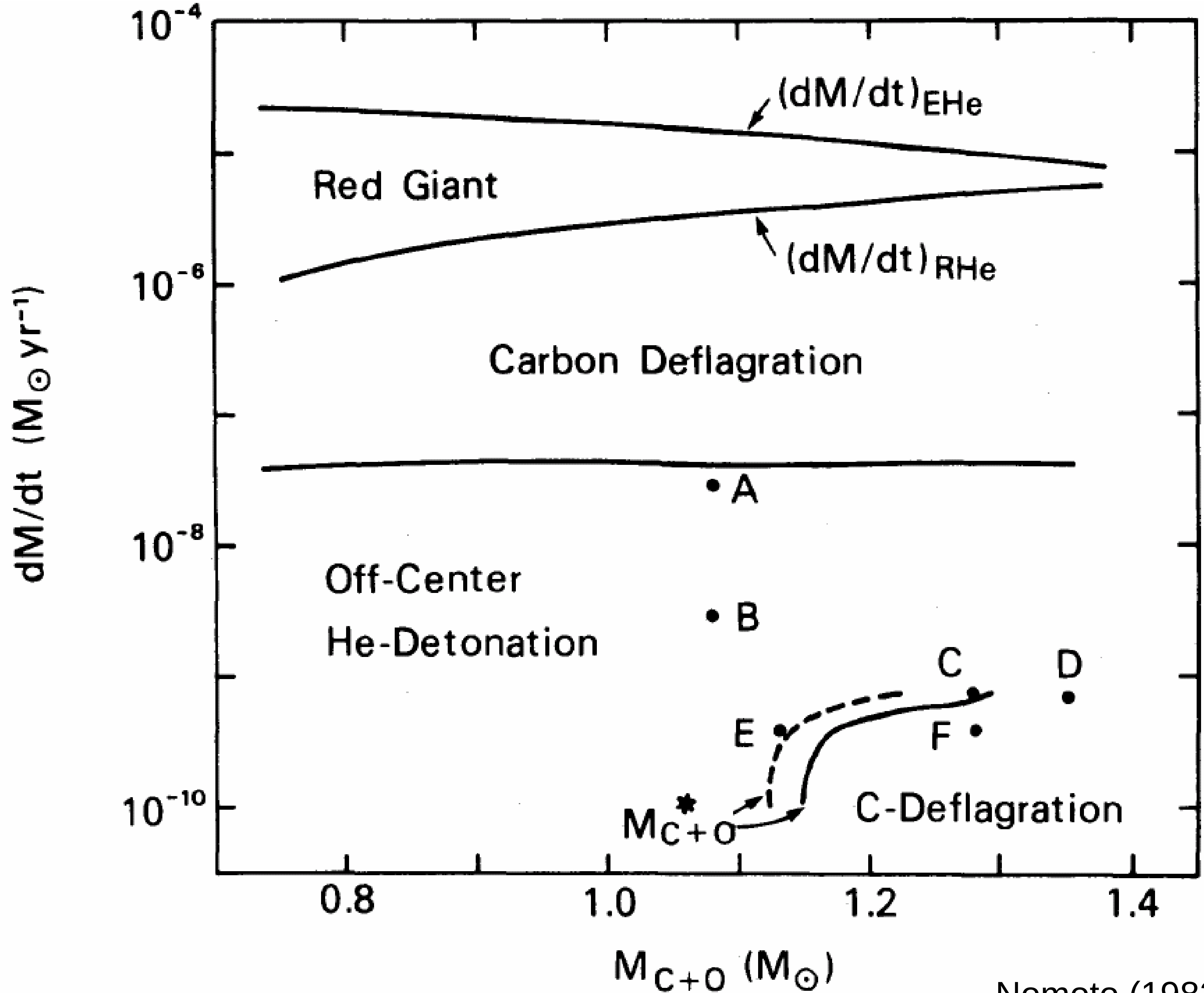
Supernovae in Accreting White Dwarfs

Table 1. Supernovae in Accreting White Dwarfs

Nomoto (1980: Austin Proceedings)

dM/dt

Composition of WD \ dM/dt	High ($\sim 4 \times 10^{-8} M_\odot y^{-1}$)	Intermediate	Low ($\sim 1 \times 10^{-9} M_\odot y^{-1}$)
He **He**	Weak He Shell-Flash ⇒	(recurrence)	He Detonation (Center) ⇓ total disruption (Ni)
C+O **C+O**	Weak He Shell-Flashes (recurrence) ⇓ ....growth toward the Chandrasekhar limit......... ⇓ Carbon Deflagration ⇒	Off-Center Detonations: total disruption {Ni; (Ni+C+O)}; (white dwarf + Ni) — total disruption ("Ni", Ca-Si-C, He)	$M_O \lesssim 1.2 M_\odot$ (Off-Center Detonations); $M_O \gtrsim 1.2 M_\odot$: He-Accumulation (no He-ignition) ↙ growth toward the Chandrasekhar limit
O+Ne+Mg **ONeMg**	Electron Capture ⇒	neutron star	



10^{-4}
10^{-6}
10^{-8}
10^{-10}
dM/dt ($M_\odot$ yr^{-1})
$(dM/dt)_{EHe}$
Red Giant
$(dM/dt)_{RHe}$
Carbon Deflagration
A
Off-Center
B
He-Detonation
C
D
E
F
M^*_{C+O}
C-Deflagration
0.8
1.0
1.2
1.4
M_{C+O} ($M_\odot$)

Nomoto (1982)

Erice (1983) W7

Carbon Deflagration

Kippenhahn & Weigert

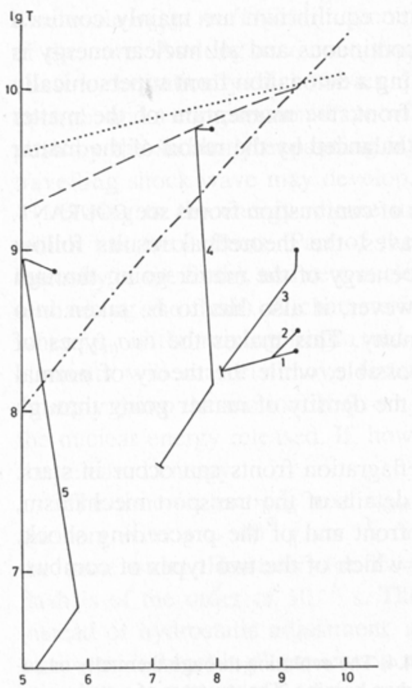


Fig. 34.5. The evolution of a stellar core during carbon deflagration. Ignition starts with model 1. Then the centre moves as in the case of detonation. But after model 3 the outer layers of the core are also involved. At the same time, a deflagration front develops. Note that the density decreases in the inward direction in the front (after NOMOTO et al., 1976). The dot-dashed and dotted lines correspond to those of Fig. 34.4

(stage 6 in Fig. 34.4) all of the core mass is at a temperature of about 5×10^9 K. Then the iron peak elements are formed in statistical equilibrium.

The corresponding evolution of the core in the case of a deflagration front is shown in Fig. 34.5. One can see that the layers ahead expand long before the front arrives, a sign of the subsonic motion of the deflagration front. The increase of T in the front is accompanied by a decrease of ϱ. A basic difference to the result of a detonation front is that only the innermost part of the core is heated to $T \approx 5 \times 10^9$ K, where iron peak elements can be formed. Because of the expansion these high temperatures are no longer reached when the front has moved a bit further outwards.

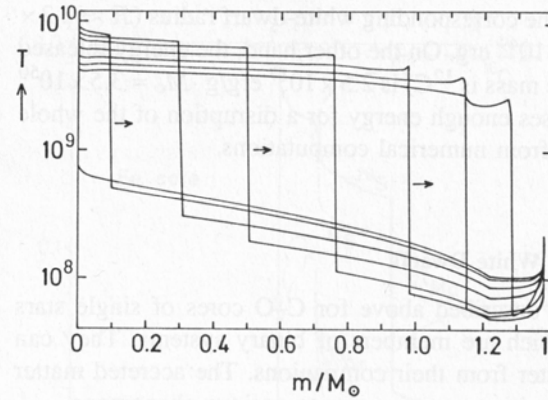
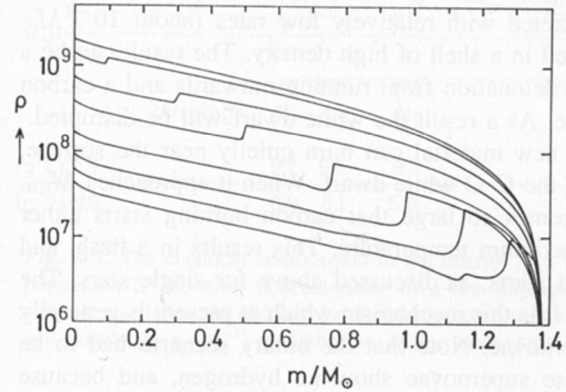


Fig.
distr
a car
MOTO
going
ward
ted i
0.6,
and



$$v_D = \alpha \left(\frac{Gm}{4r^2} \ell_m \Delta \lg \varrho \right) ,$$

where α is a free parameter and ℓ_m the mixing length difference in density ahead and behind the deflagration

Calculations by NOMOTO et al. (1984) used the mode dependent convection. Their results are displayed in Fig the core for 8 consecutive stages of evolution. Note that burning) and the last only 3.22 s have elapsed. One

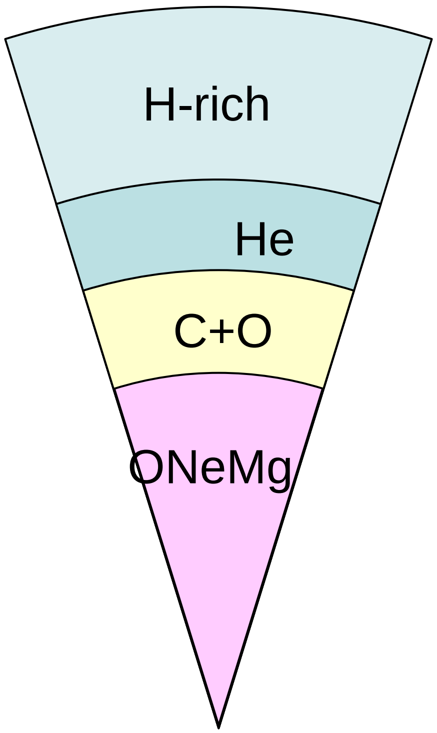
Massive Star Evolution (NASA, MPA)

- 8-10$M_{\odot}$ stars ⟶ degenerate ONeMg cores

Evolution of He-cores (Approximation)

- Electron Capture Core Collapse
- NASA : IUE observations of the Crab Nebula

Crab SN ⟵ 9$M_{\odot}$ star explosion?



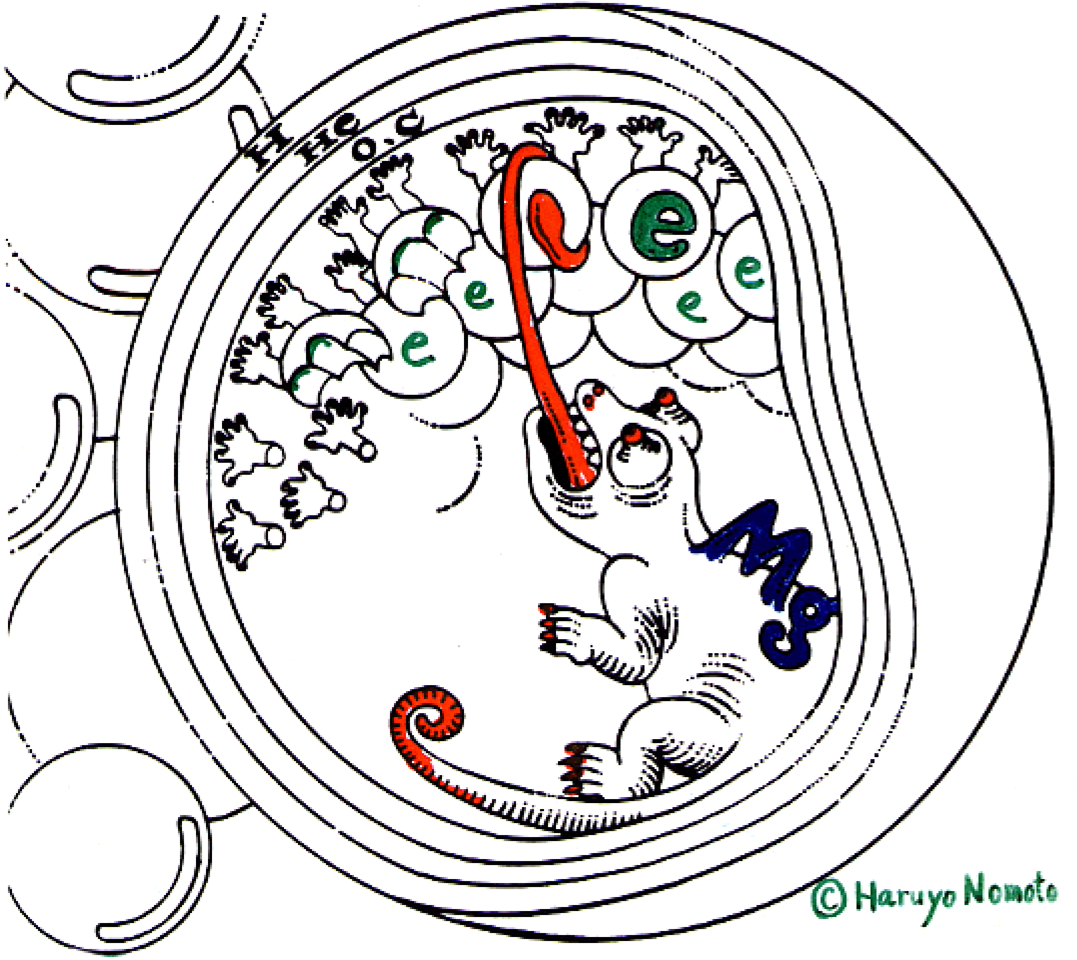
MPA 1983

Electron Capture

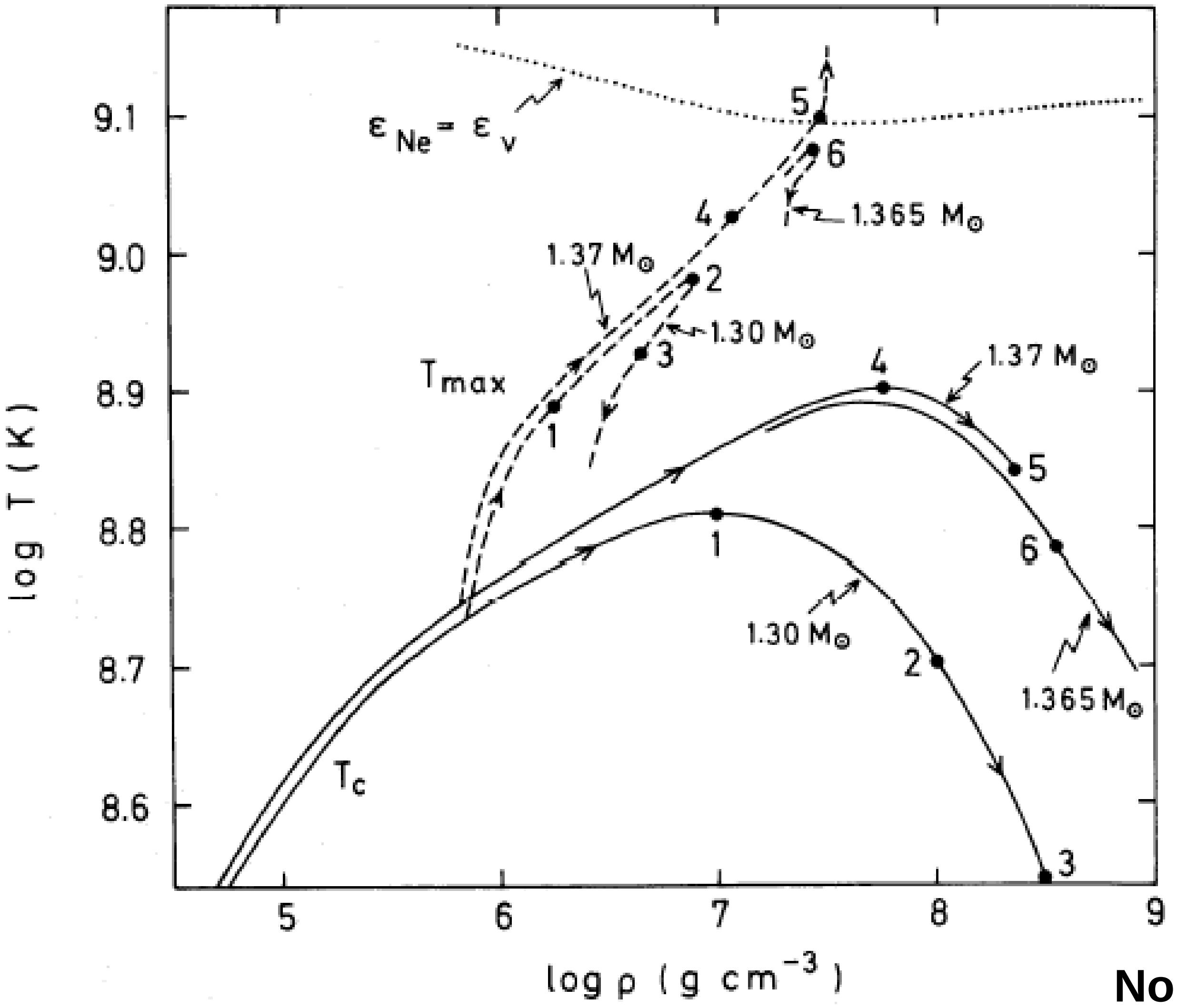
- $^{24}Mg(e^-,\nu)^{24}Na$ $(e^-,\nu)^{24}Ne$

$\rho > 4.0 \times 10^9 gcm^{-3}$

- $\rightarrow$ collapse



Contraction of a Neon Star

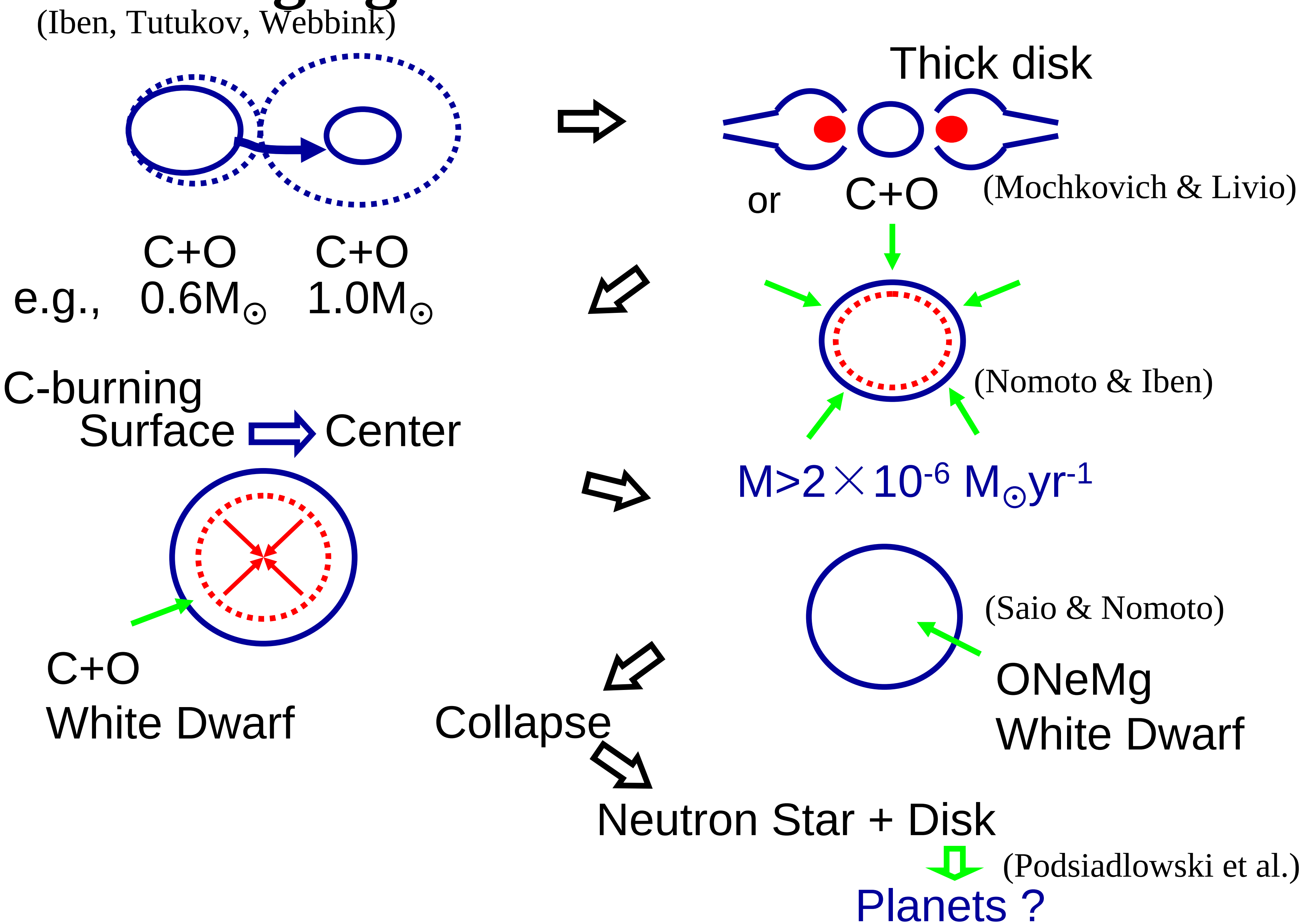


$M_{Ne} > 1.37 M_{\odot}$

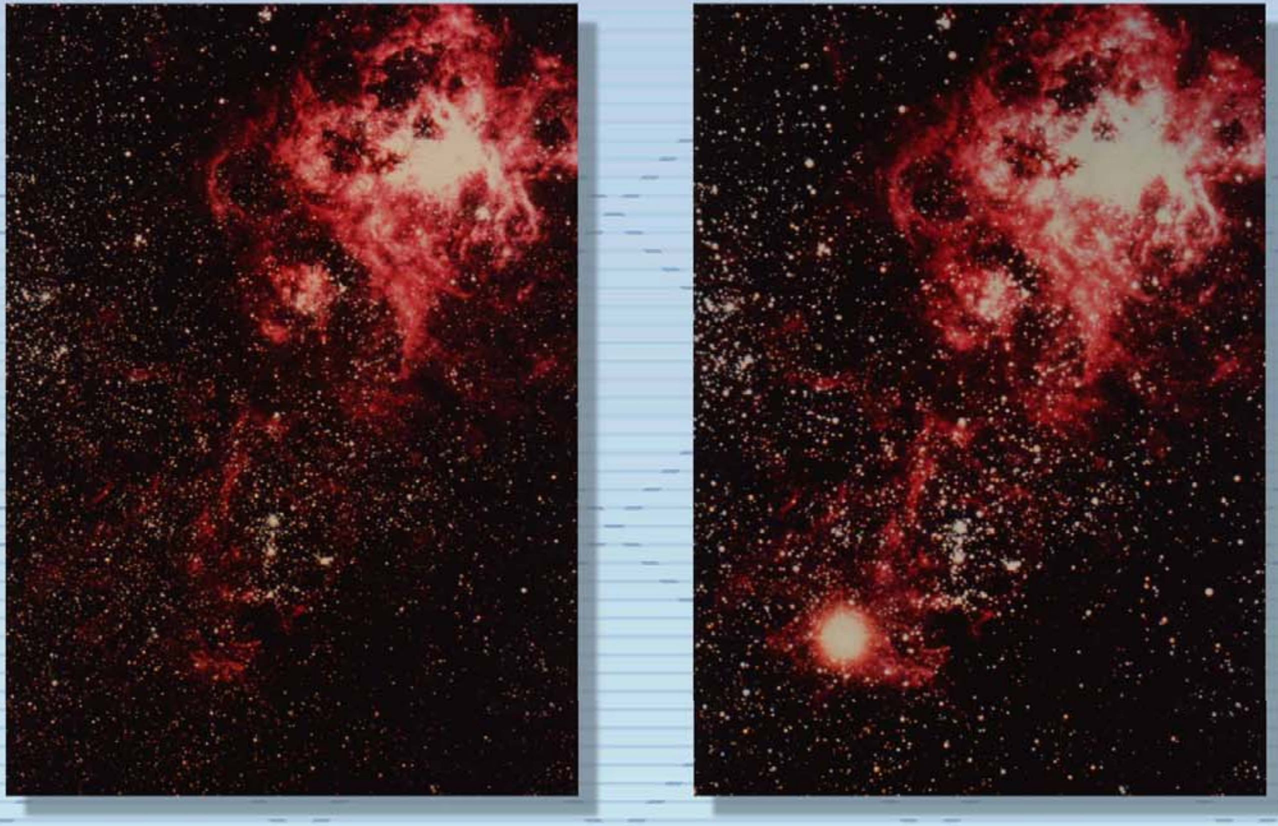
Ne-ignition

Nomoto (1984)

Merging of Double White Dwarfs

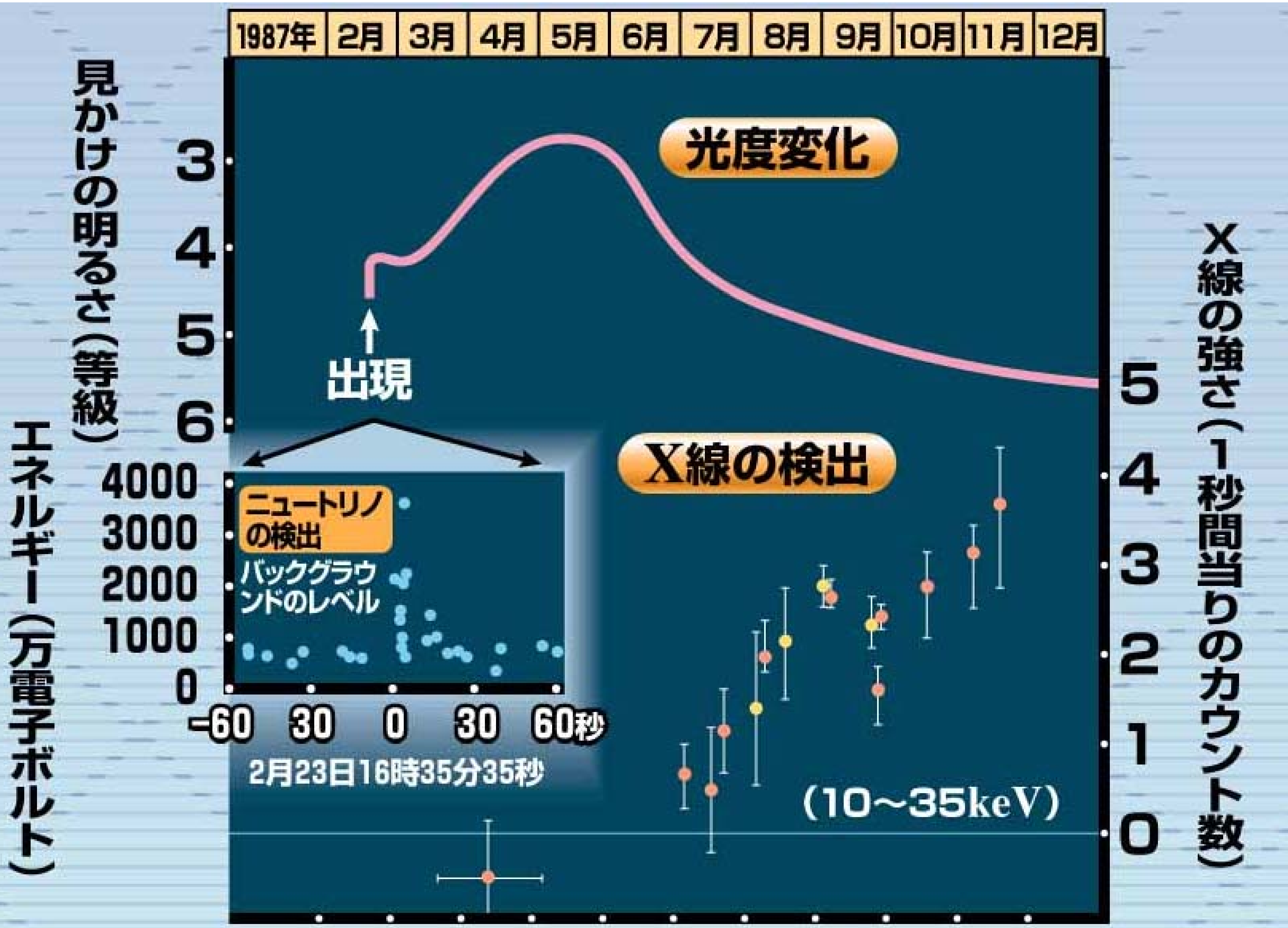


超新星1987A



撮影／アングロオーストラリアン天文台

SN1987A



1987年
2月
3月
4月
5月
6月
7月
8月
9月
10月
11月
12月
見かけの明るさ（等級）
3
4
5
6
光度変化
出現
X線の検出
X線の強さ（1秒間当りのカウント数）
5
4
3
2
1
0
エネルギー（万電子ボルト）
4000
3000
2000
1000
0
ニュートリノの検出
バックグラウンドのレベル
−60
30
0
30
60秒
2月23日16時35分35秒
（10〜35keV）

SN 1987A

- Observations: (Japanese Contribution)
  - Neutrinos (Kamiokande)
  - X-rays (Ginga Satellite) → Mixing !
- Models
  - Progenitor (why Blue Supergiant?)
  - Rings (formation, Collision)
  - Nucleosynthesis
  - Light curves (Optical, X-ray, γ-ray)
  - Mixing (multi-D hydrodynamics)

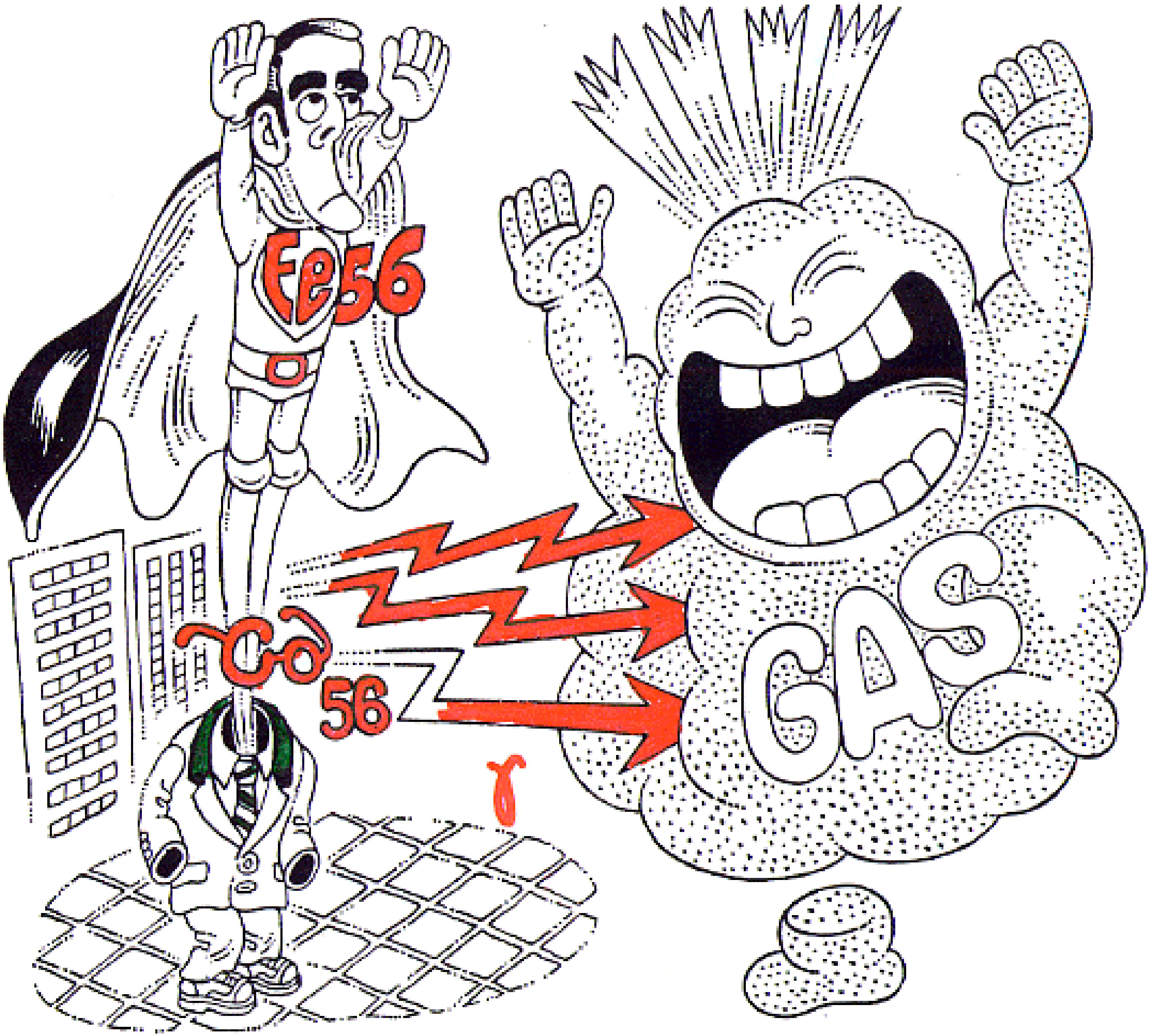
  Dust formation

Big Collaboration !!

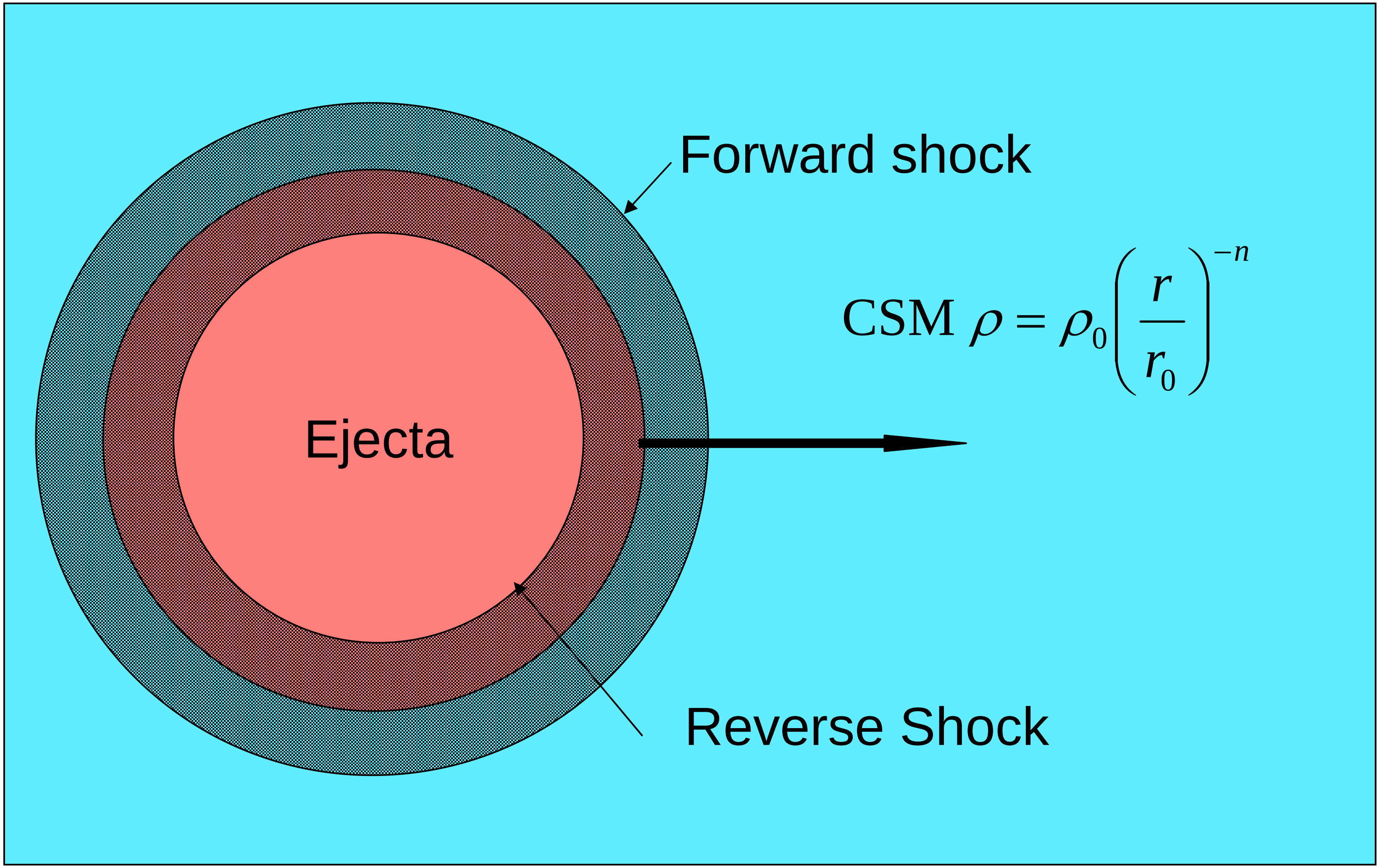
IAU Colloq. 108 (Sep. 1987, Univ of Tokyo)

SN 1987A @Tokyo (1987)

Small house

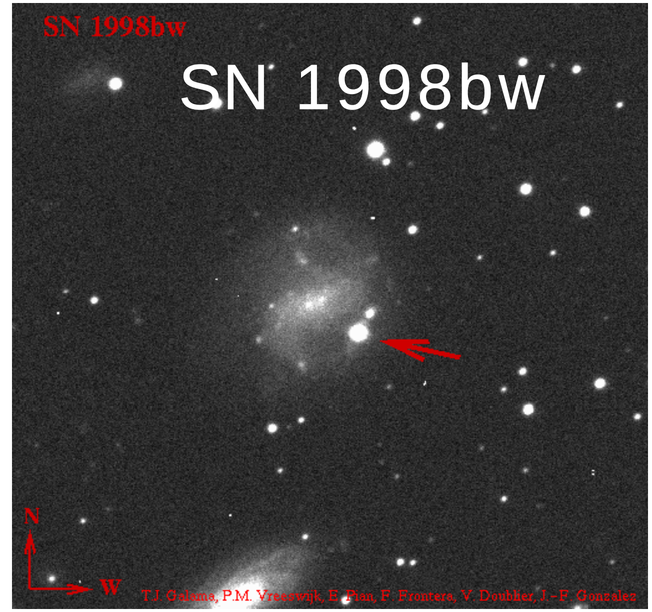

Fe56
Co 56
γ
GAS

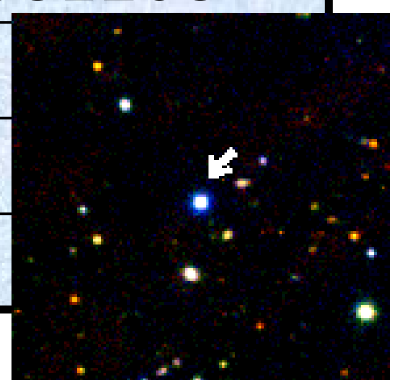
Type Ib SN 1993J:
Circumstellar Interaction



GRB-associated Supernovae

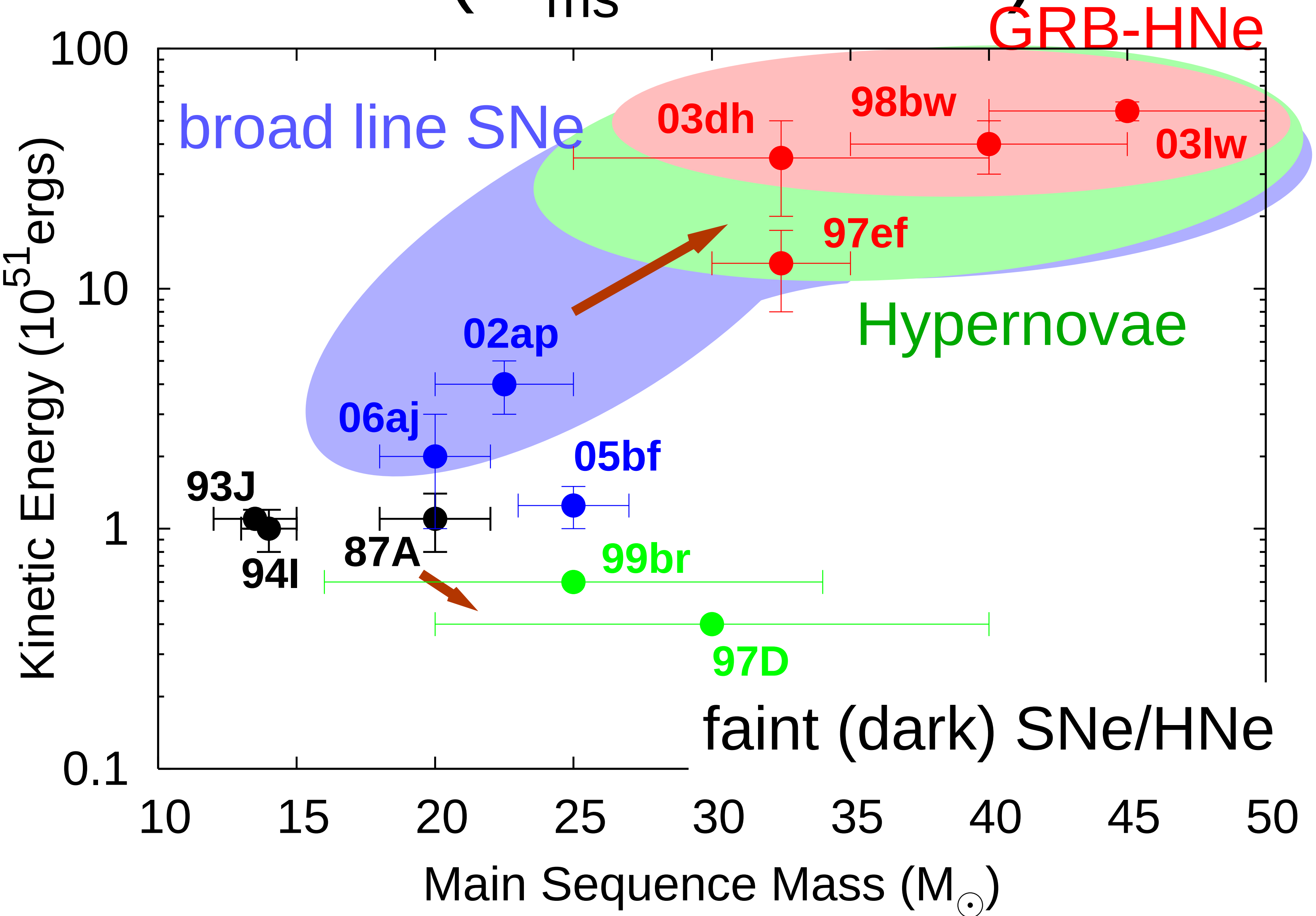
SNe Ic	
SN	GRB
1998bw	980425
1997ef	(971115)
2002ap	
2003dh	030329
2003lw	031203





Hypernova in Prague

SNe (M_{ms}-E relation)



First Stars & Extremely (Hyper) Metal-Poor Stars

[Fe/H]<-2.5

Zn/Fe ↗ ⟷ Hypernovae

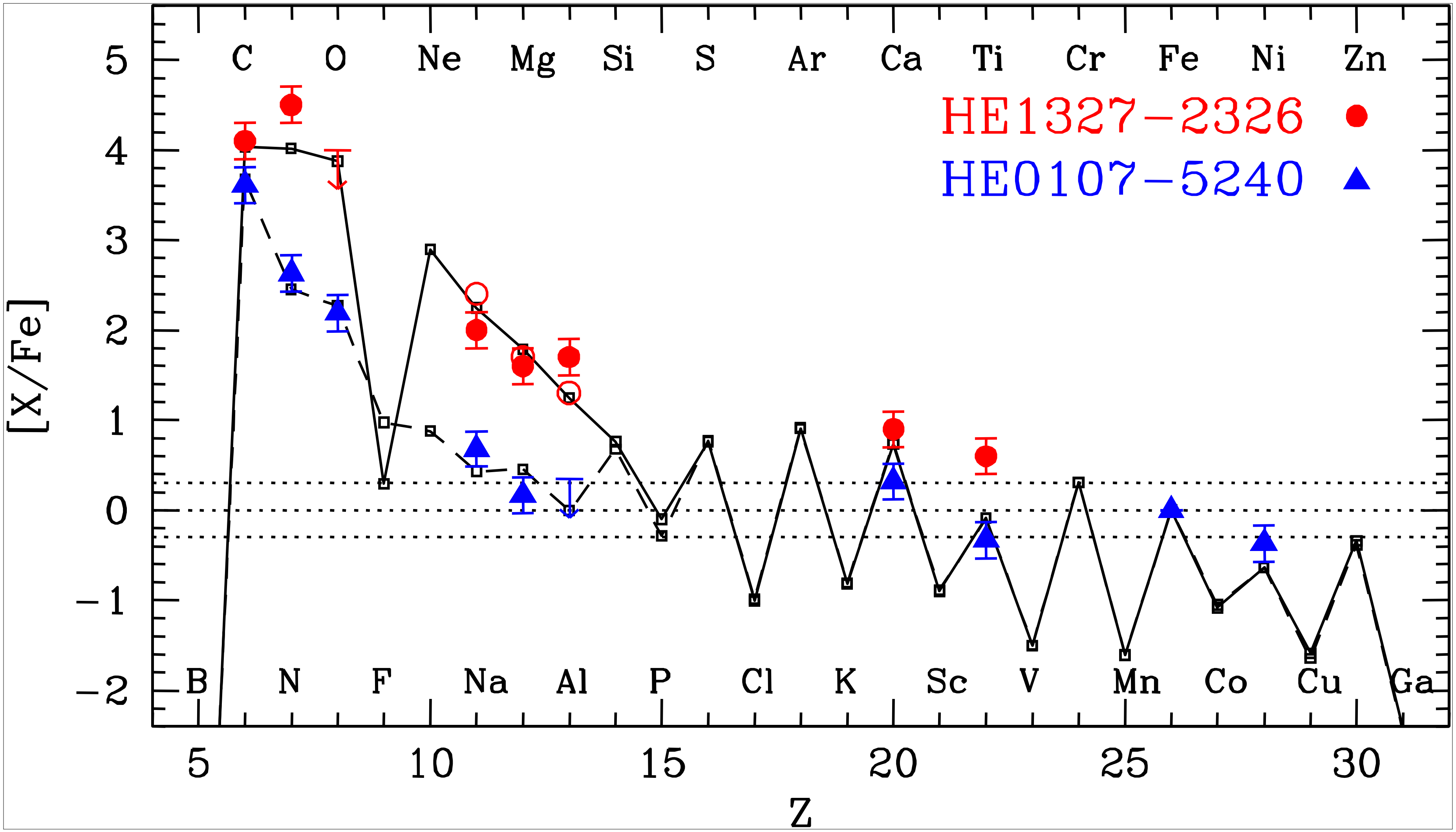
- Mixing & Fallback with low E

(Approximation, Parameters)

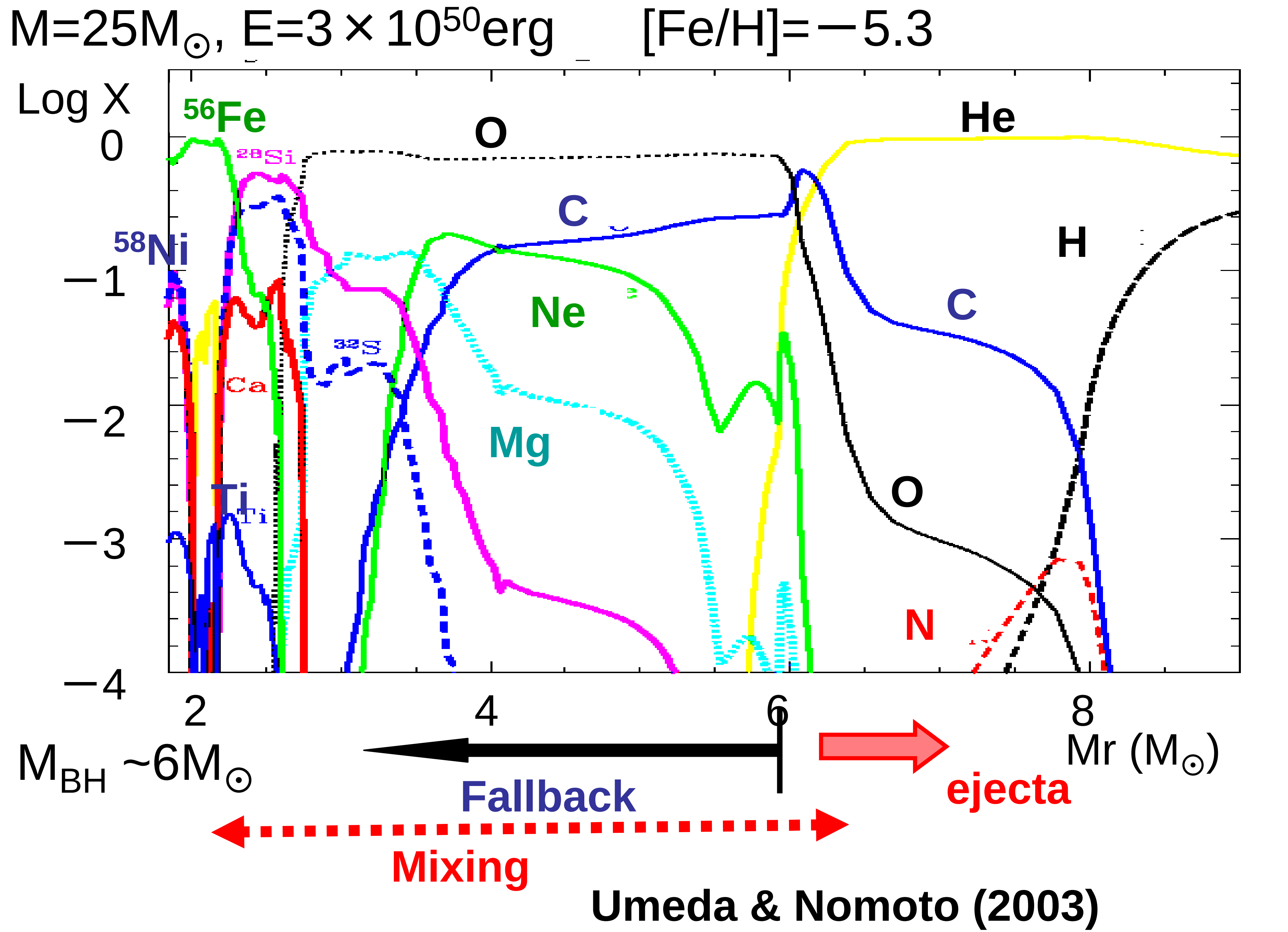
↓

- Jet-induced Nucleosynthesis & Explosion with high E

Hyper Metal Poor (HMP) stars

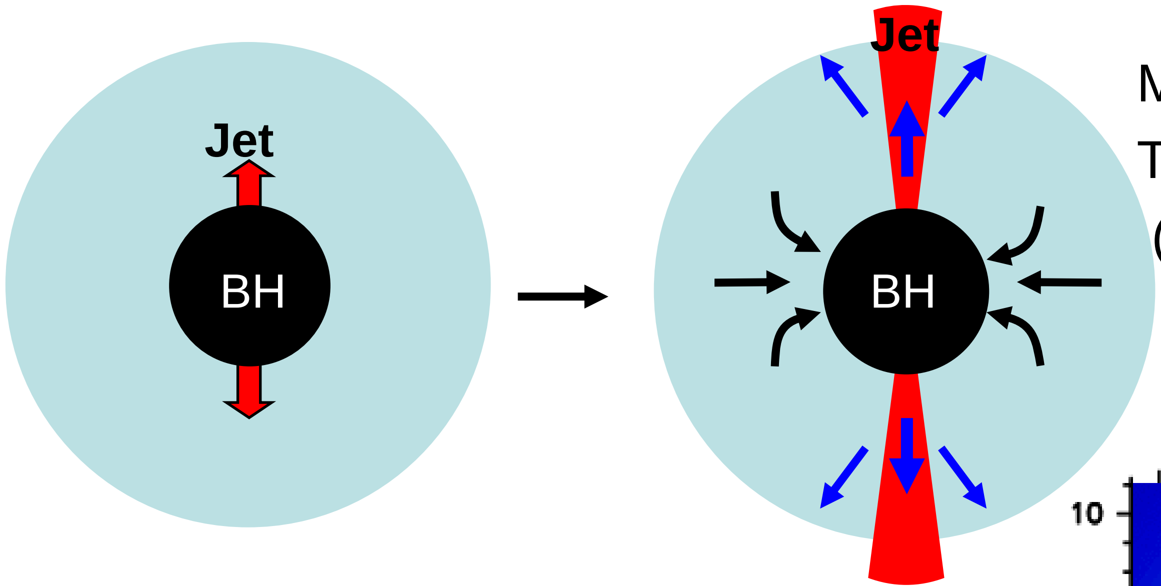


Iwamoto et al. (Science 2005)

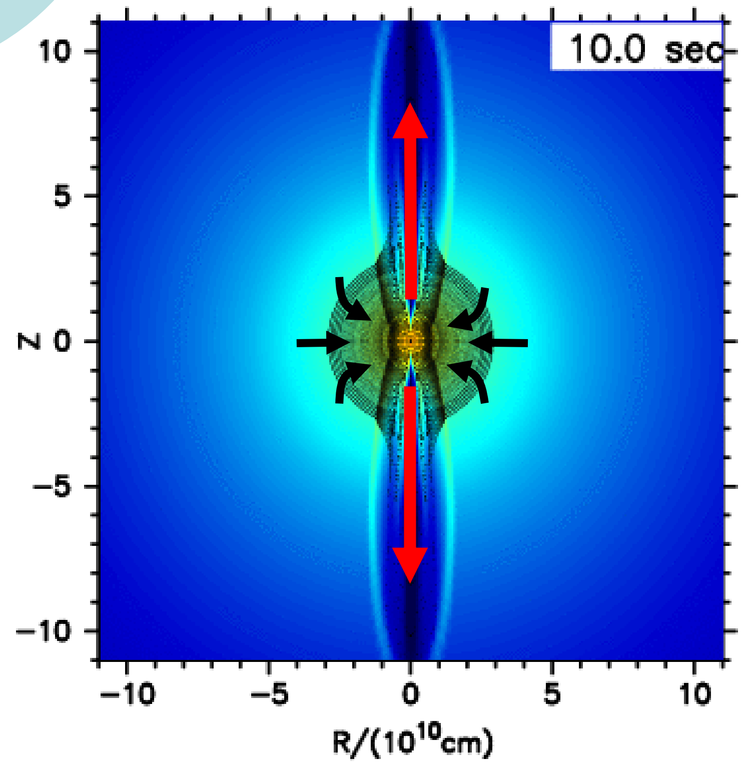


M=25M$_\odot$, E=3×10^{50}erg [Fe/H]=−5.3
Log X
0
−1
−2
−3
−4
^{56}Fe
^{28}Si
^{58}Ni
Ca
Ti
Ti
^{32}S
O
C
Ne
Mg
He
H
C
O
N
2
4
6
8
Mr (M$_\odot$)
M$_{BH}$ ~6M$_\odot$
Fallback
ejecta
Mixing
Umeda & Nomoto (2003)

Jet-induced Nucleosythesis



Maeda, Nomoto (2003)
Tominaga, Umeda, Nomoto (2006)

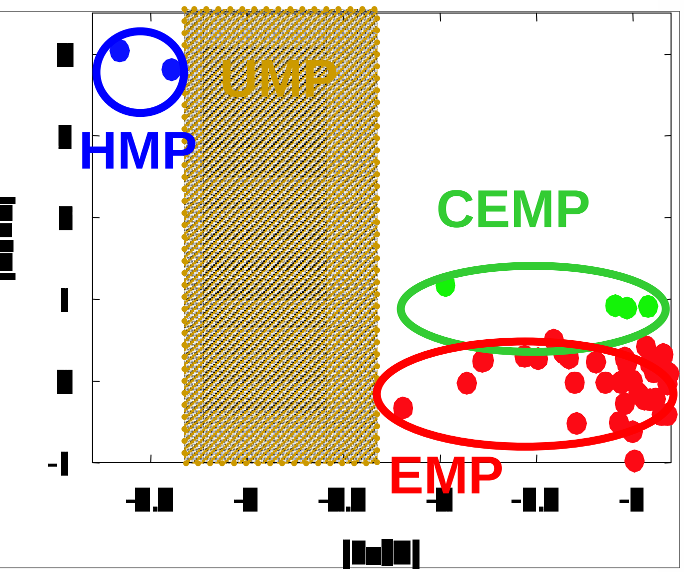


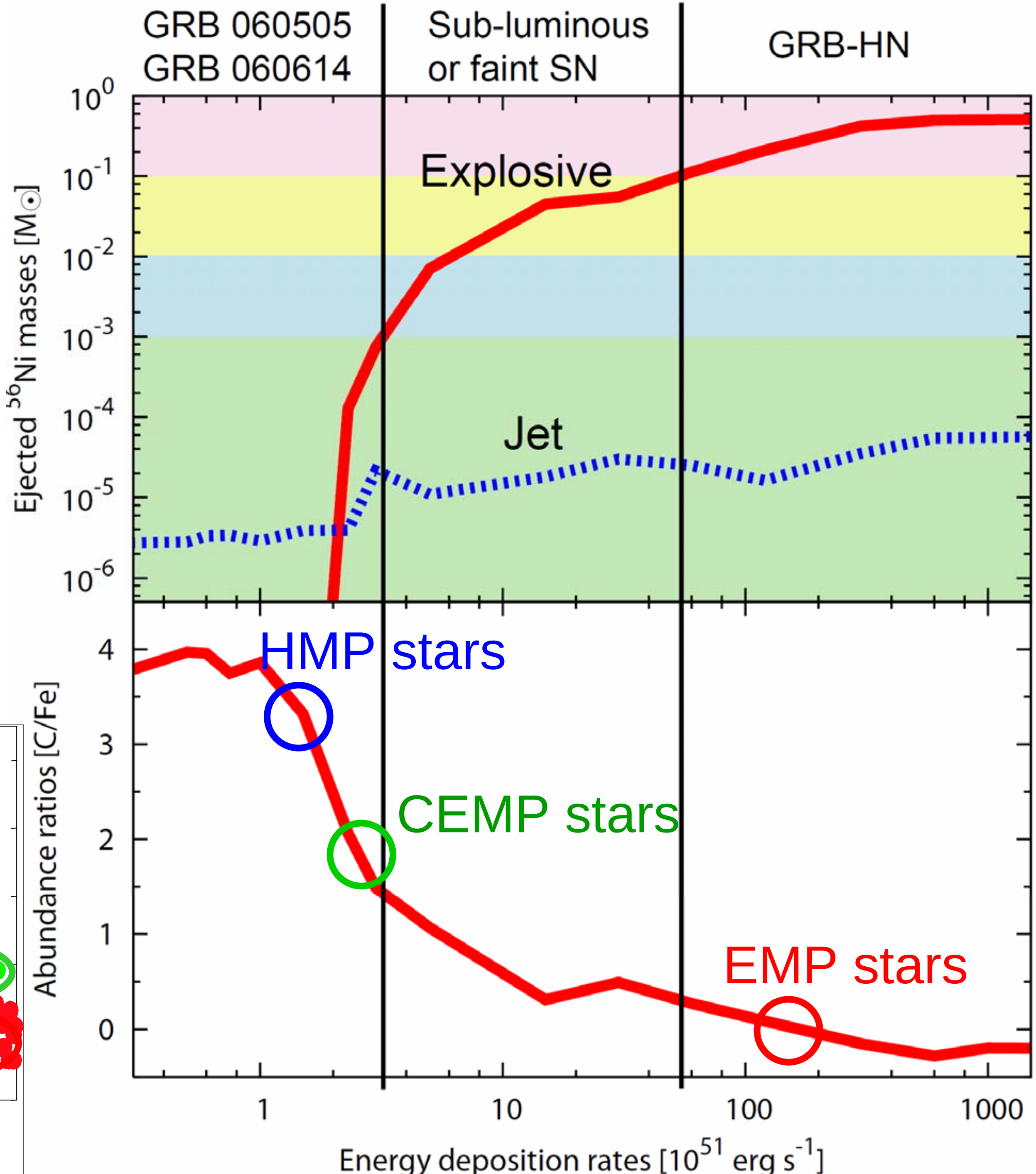
$\dot{E}_{jet}$:
Energy injection rate
(Rotation etc.)

$40M_\odot$ 1.5×10^{52} erg

[C/Fe]

Smaller $\dot{E}_{dep}$ leads smaller $M(^{56}Ni)$ and larger [C/Fe]





Small Workshop vs. Big Enterprise

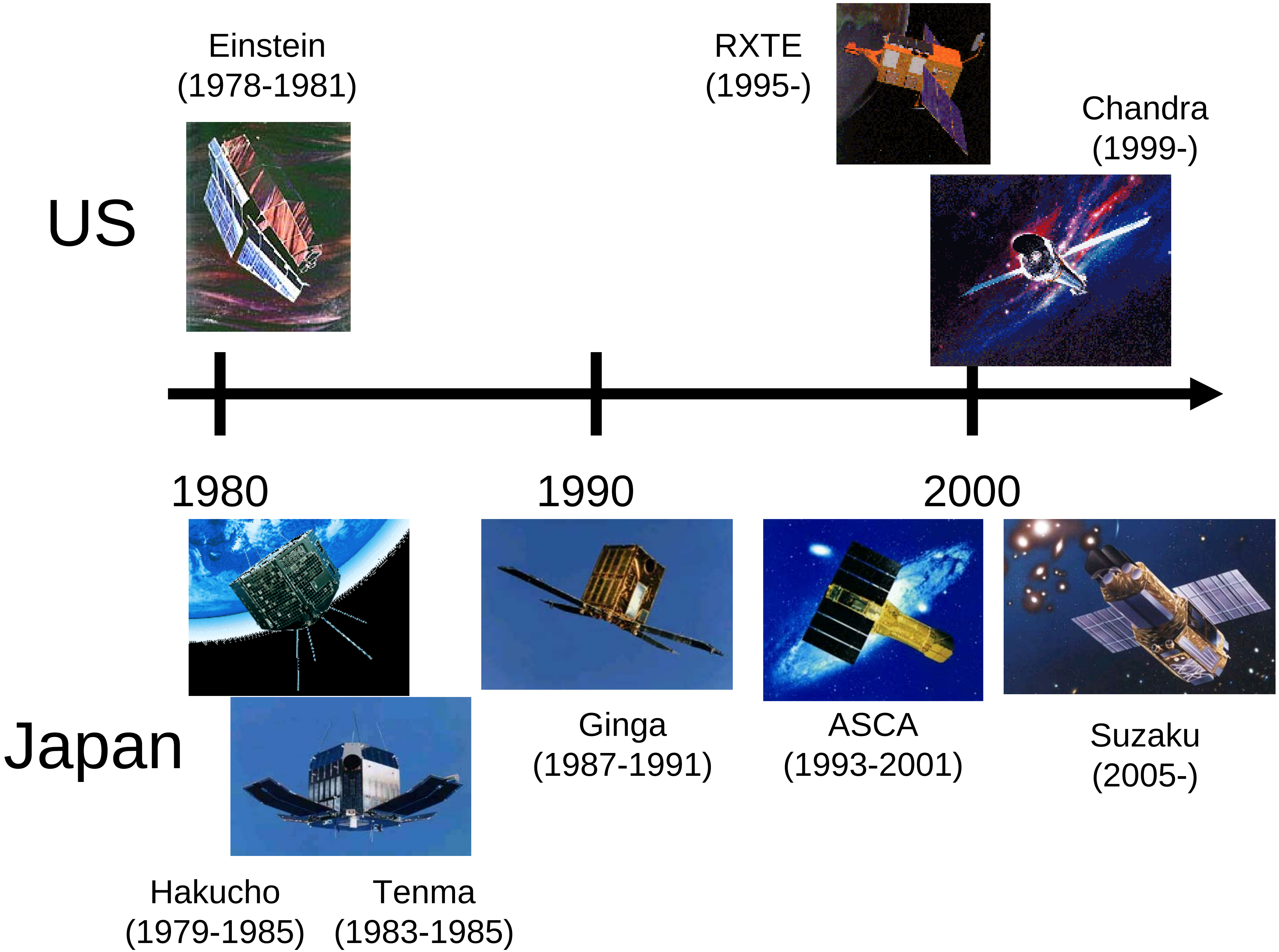
Approximate Models

– One Zone Models: Analytic Solutions, Linear Stability,
Basic Physics

– **1D Models** for Evolution, Explosions
– Structure, Non-equilibrium
– **Parameters** for Convection, etc.

– 2D Models
– 3D Models

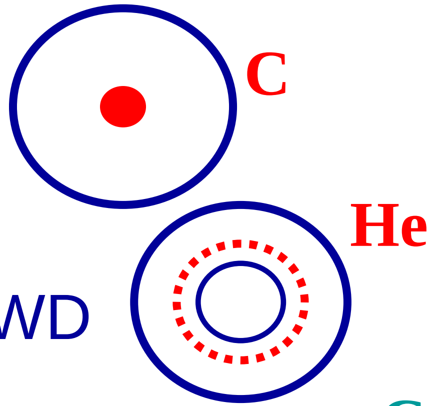
↓ Higher Resolution


Einstein
(1978-1981)
RXTE
(1995-)
Chandra
(1999-)
US
1980
1990
2000
Japan
Ginga
(1987-1991)
ASCA
(1993-2001)
Suzaku
(2005-)
Hakucho
(1979-1985)
Tenma
(1983-1985)

The Progenitors of Type Ia Supernovae

- Single Degenerate
  vs.
  Double Degenerate

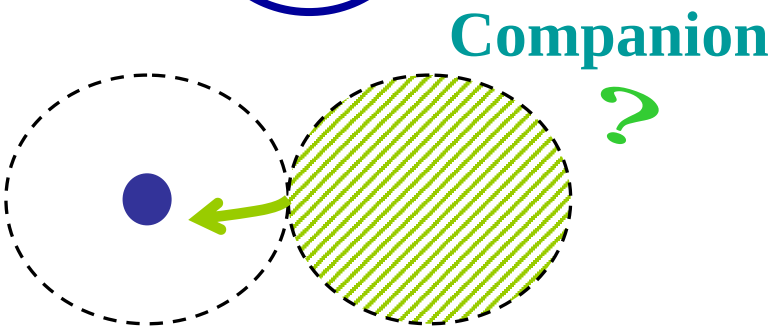
- Chandrasekhar Mass WD
  vs.
  Sub-Chandrasekhar Mass WD



$M^{(0)}_{WD} \sim 0.6 - 1.1\ M_{O}$

?

$M_{CH} \sim 1.4\ M_{O}$



(1) White Dwarf (Mass$^{(0)}$, Metallicity, Rotation)
(2) Companion (Age, Metallicity)

⇒ SNe Ia (E vs. Spiral; **Redshift**) • Rate • **Evolution** ?

- **Circumstellar Interaction : SNe 2002ic, 2005ke**

Candidates of the SN Ia Progenitors

- **Main-Sequence (MS):**
  Slightly Evolved 2-3$M_\odot$ stars
  ⇒Young, Spiral
  ($t \lesssim 0.5$Gyr)
  →Supersoft X-ray Source
  →Recurrent Nova (USCo)

- **Red Giant (RG):**
  1-2$M_\odot$ stars
  ⇒Old, Spiral & Elliptical
  ($t \gtrsim 3$Gyr)
  →Symbiotic Stars?
  →Recurrent Novae (TCrB)

Remnant ?

Double Degenerate ?

Search; Hydrodynamics of Merging

Sub-Chandrasekhar Mass SN Ia? He ?

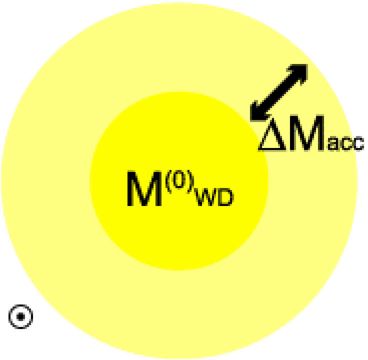
Circumstellar matter ?

Rotation of accreting WDs → Fate, Diversity ?

SN rate (z)

Ellipticals vs. Spirals

- Ellipticals
  - Red Giant Companion
  - $M^{(0)}_{WD} \sim 1.0\text{-}1.1 M_\odot$; $\Delta M_{acc} \sim 0.3\text{-}0.4 M_\odot$
    - Smaller C/O ratio
    - Smaller Angular Momentum



$\Delta M_{\ cc} + M + {}^{(0)}_{WD} = 1.4 M_\odot$

$M(^{56}Ni) \downarrow$

- Spirals
  - RG&MS Companion
  - $M^{(0)}_{WD} \sim 0.6\text{-}1.1 M_\odot$; $\Delta M_{acc} \sim 0.3\text{-}0.8 M_\odot$
    - Larger C/O ratio
    - Larger Angular Momentum

$M(^{56}Ni) \uparrow$

Circumstellar Medium of SN Ia

White Dwarf Steady Wind

$v_W > 1{,}000$ km s^{-1}

$\dot{M} \sim 10^{-6} - 10^{-7}\ M_\odot yr^{-1}$

$$\frac{\dot{M}}{v_{10}} \sim 10^{-8}\ M_\odot yr^{-1}$$

Recurrent Nova Wind

$v_W \sim 4{,}000$ km s^{-1}

➔ Nova Cavity

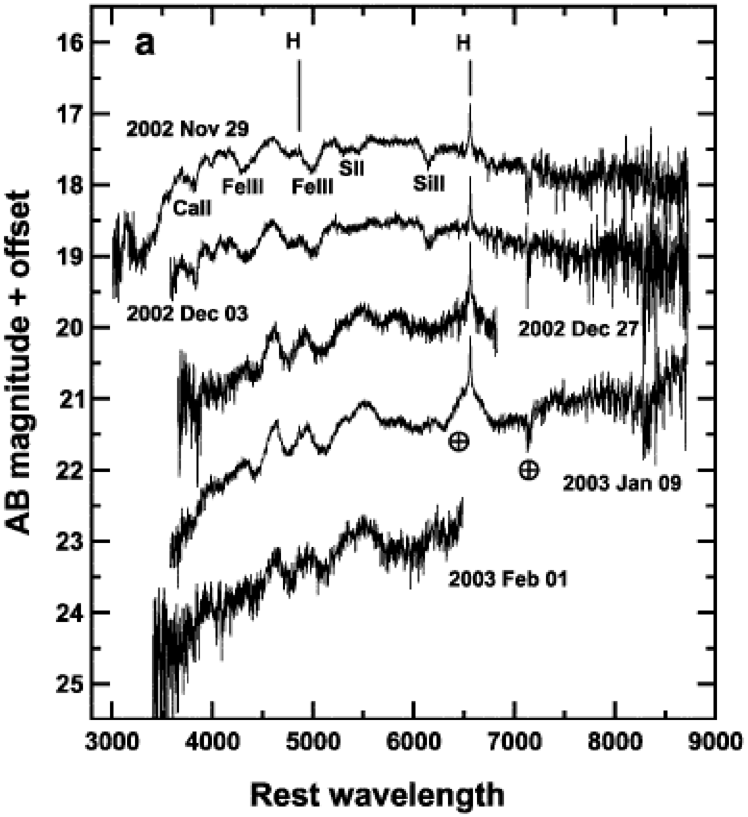
(Wood-Vasey & Sokoloski)

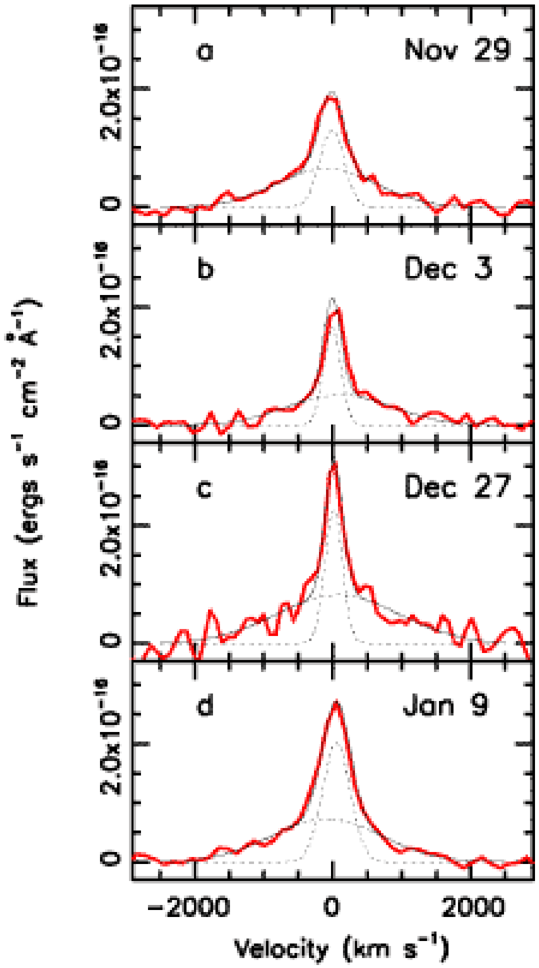
Companion Star Wind

- Radio
- High velocity H
  - Hα, …
  - He lines (*e.g., Lundqvist et al.)*

⇨ **Circumstellar Interaction in SNe Ia**

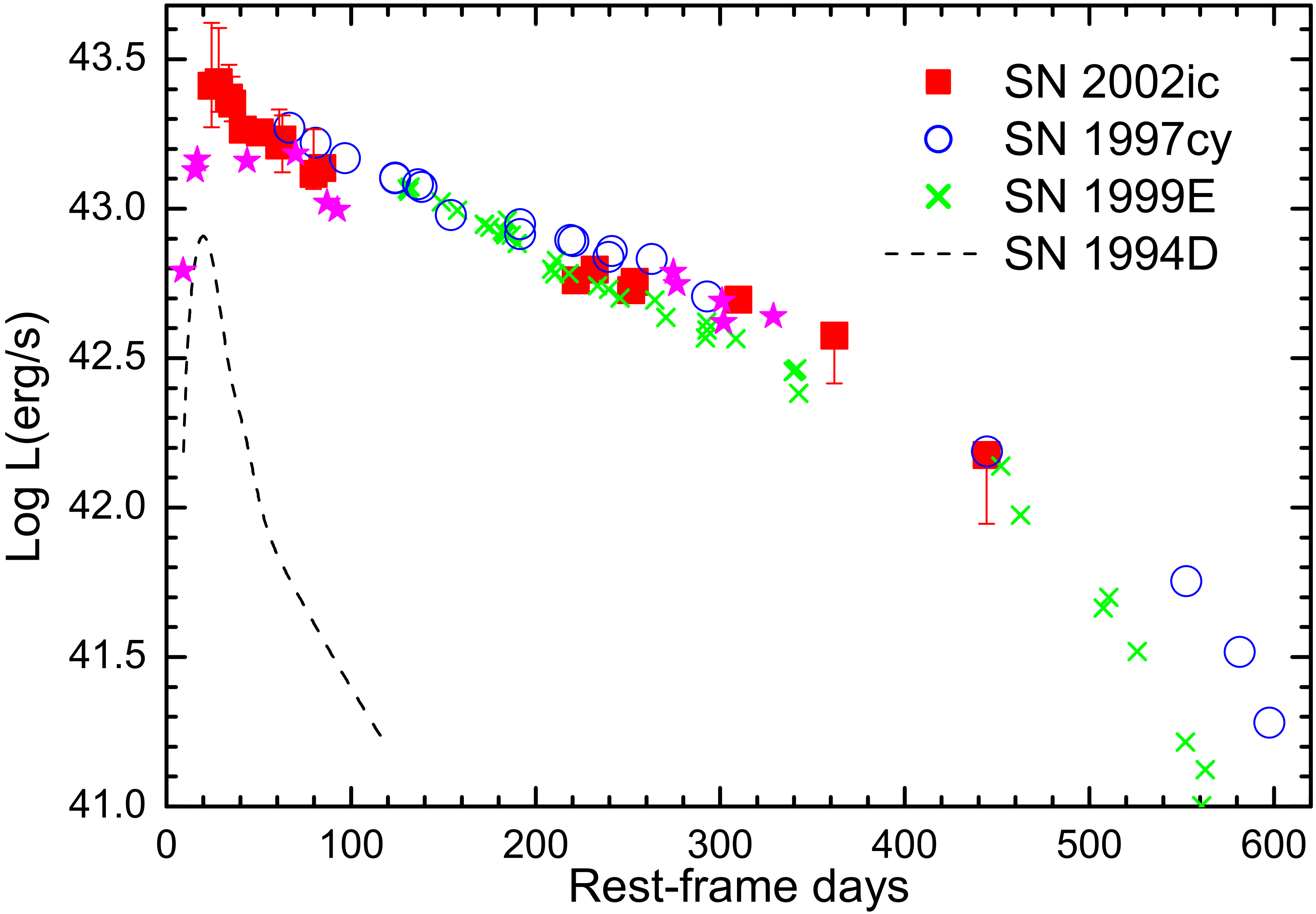
Discovery of H-lines in SN2002ic





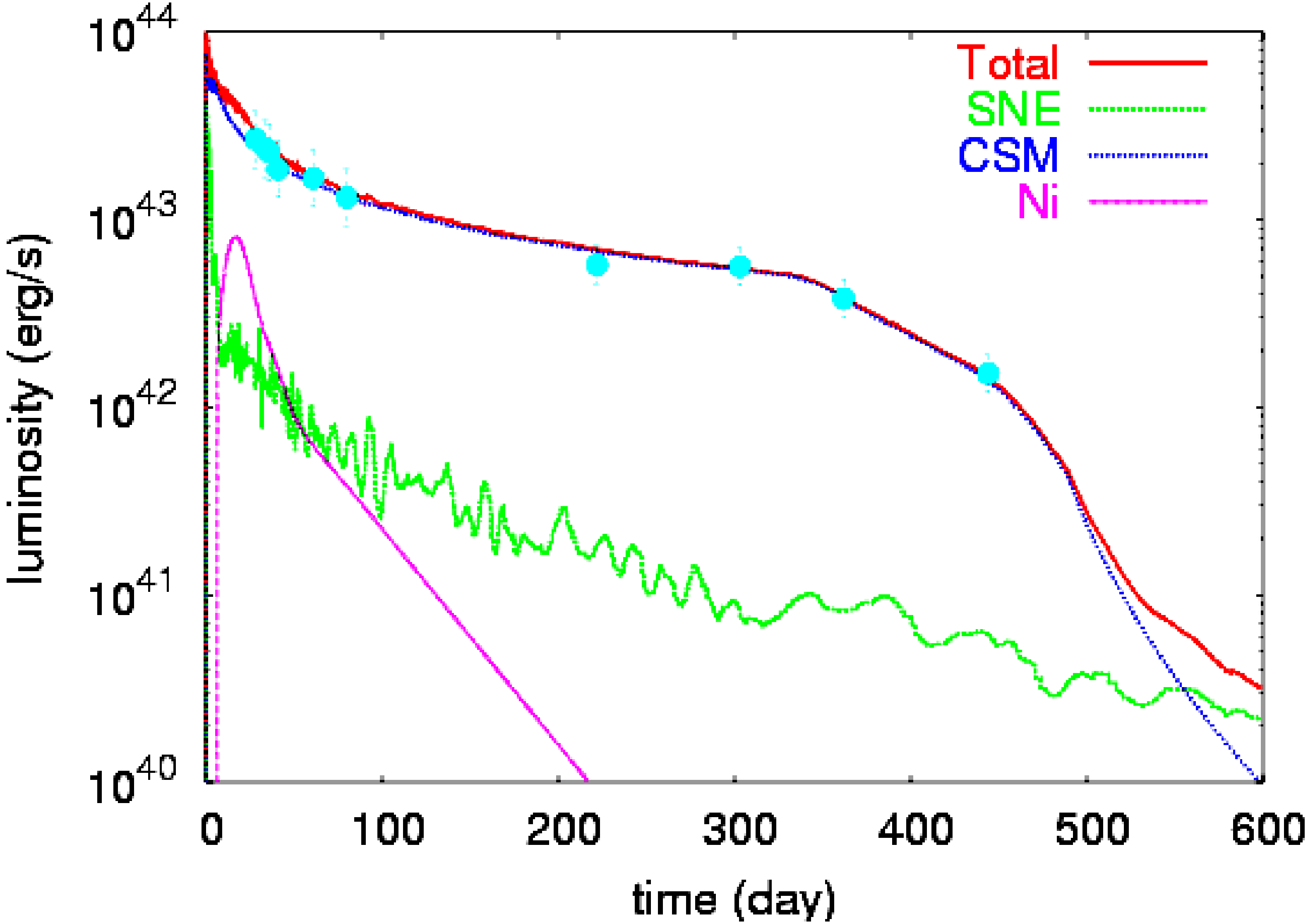
Hamuy et al(2003)

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



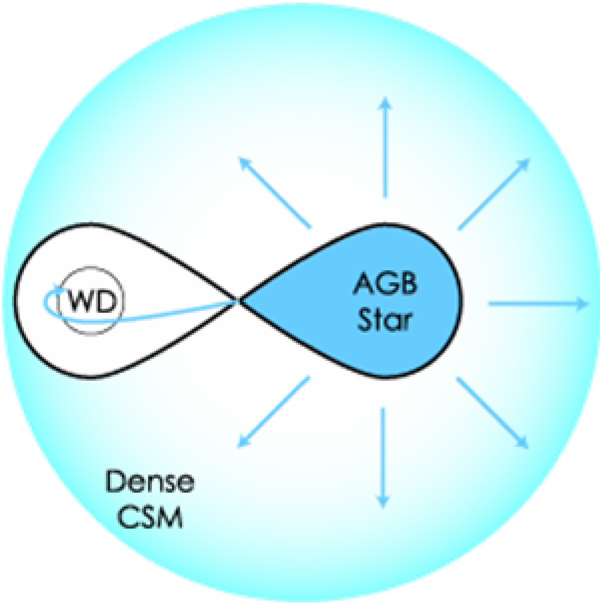
Turatto, Rigon, Hamuy, Deng, Wood-Vasey

SN 2002ic: Circumstellar Interaction Model

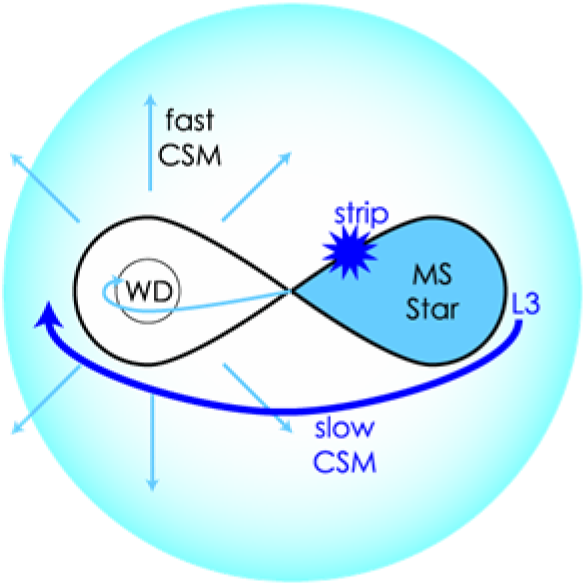


Suzuki et al. (also Chugai, Wood-Vasey)

Circumstellar Medium of SN Ia



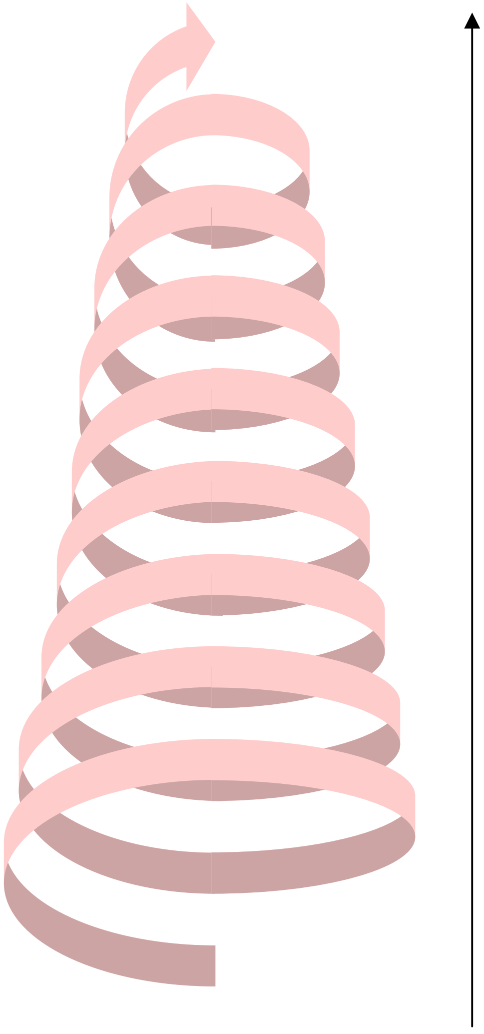
WD+RG?



WD+MS?

WD wind (fast)
Companion star wind (slow)

Spiraling Approach



Hypothetical Model
(parameters)

↓

Observational Constraints

↓

Partial Truth

↓

1st Principle Approach

Collaboration !

Norman 1985

Exploring Culture !

Kyoto 1990

Fun !

Santa Barbara 1997

Tokyo Nov 30/Dec 1, 2006

Welcome to Japan:
21st Century COE, Tokyo Think Tank