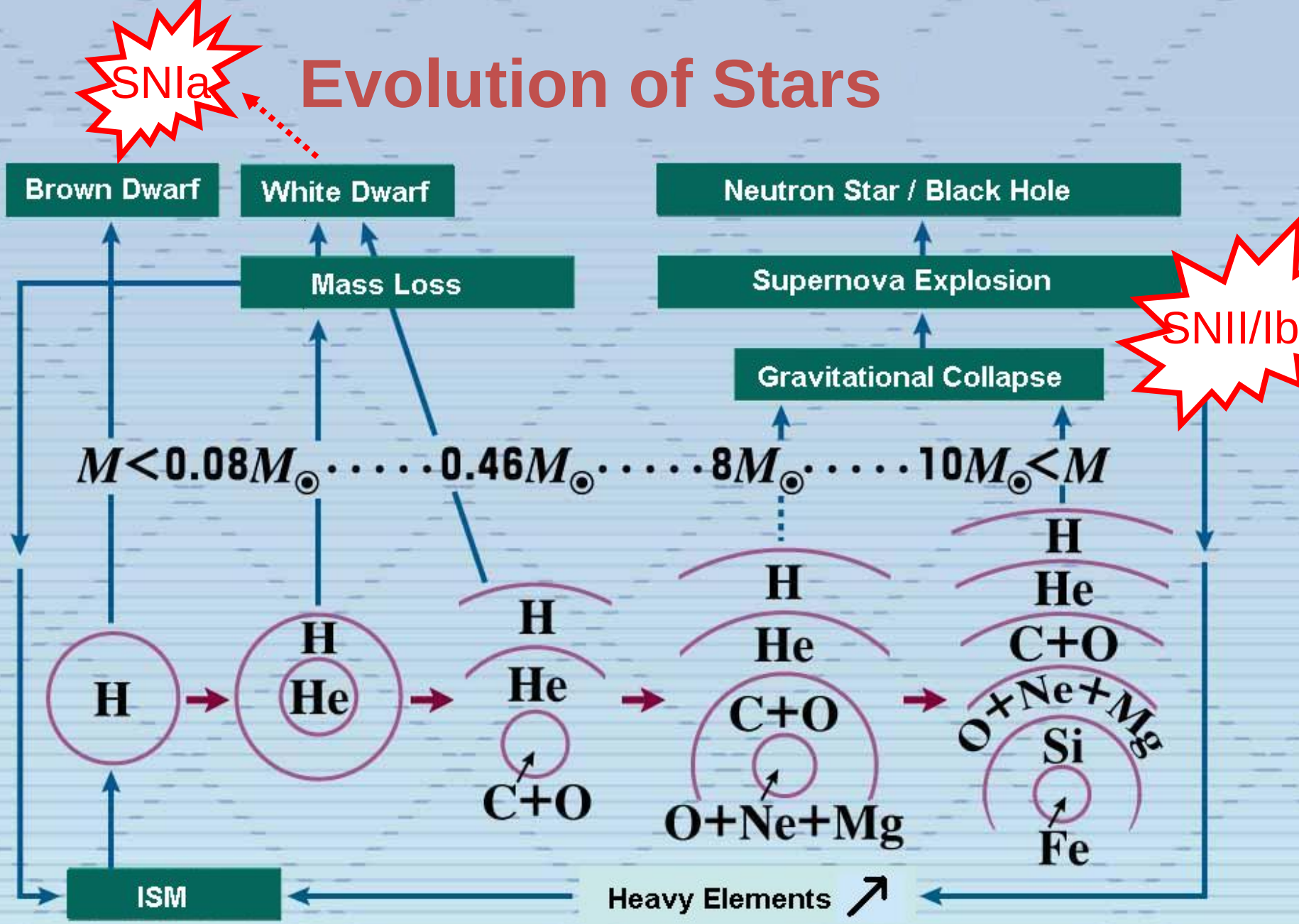
Electron Capture Supernovae from Super-AGB Stars

Ken Nomoto, Shing-Chi Leung, Alexey Tolstov

(Kavli IPMU/U. Tokyo)

Evolution of Stars

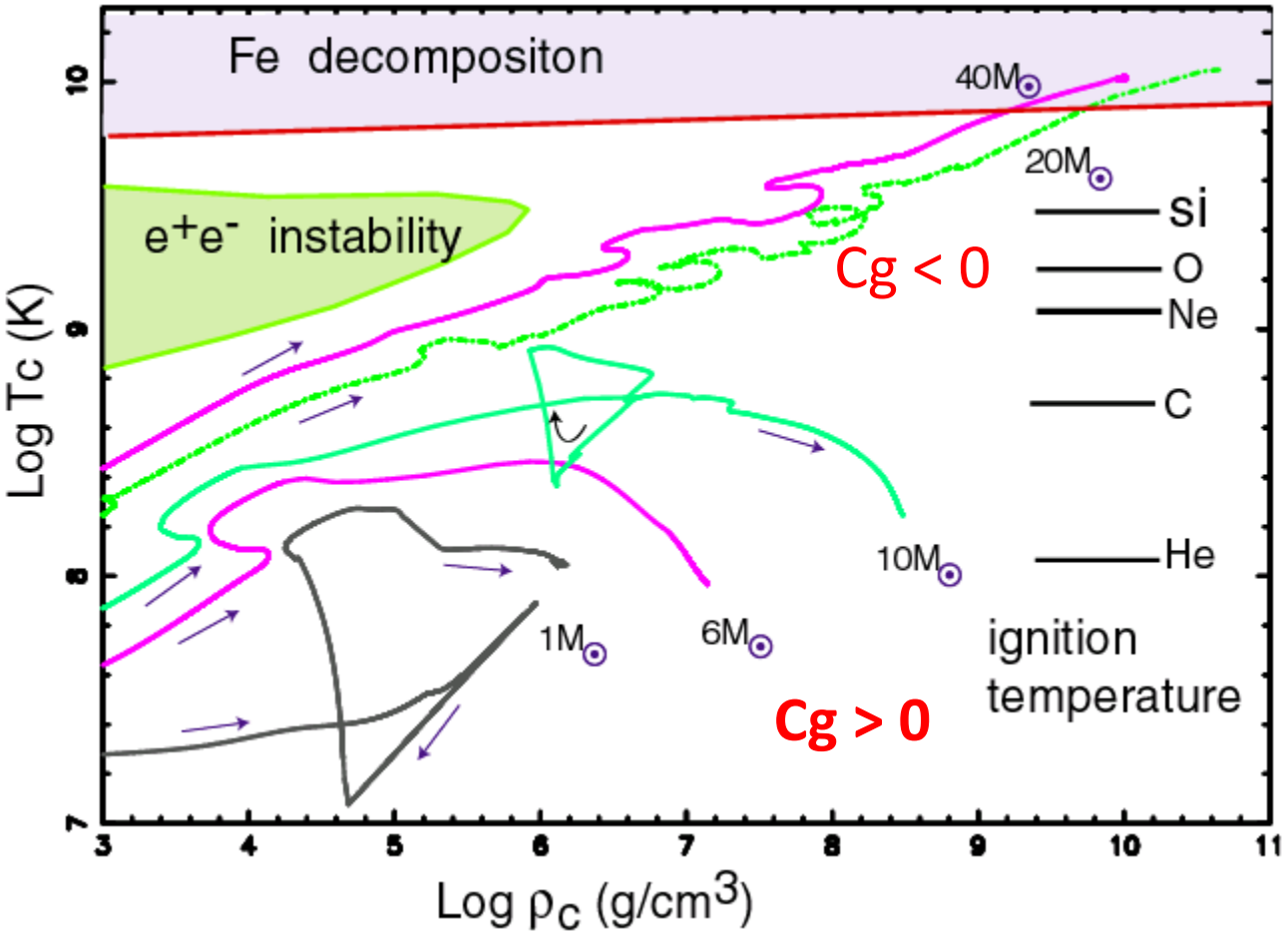


Final Fates of Stars:

$M < 8\ M_\odot$ ➔ Electron-Degenerate Core ➔ White Dwarf

$M = 8 – 10\ M_\odot$ ➔ Electron-Degenerate ONeMg Core ➔ ??

$M > 10\ M_\odot$ ➔ Fe Core ➔ Collapse (NS or BH)



$M > 10\ M_\odot$:

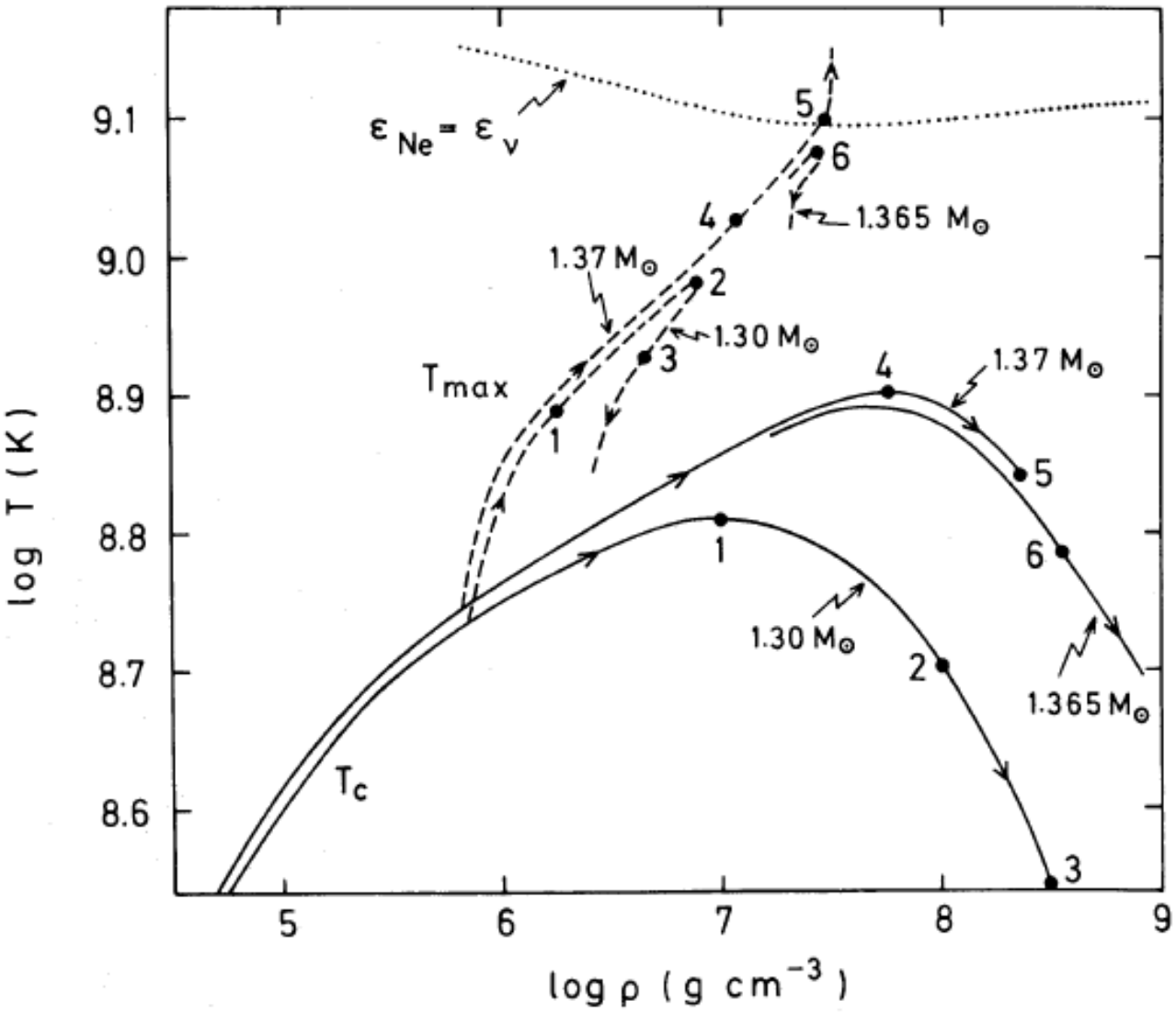
Ne ignition

$M > 8\ M_\odot$:

C ignition

Jones, Hirschi,Nomoto+2013
Toki,Suzuki,Nomoto+2013
Tominaga, Blinnikov, Nomoto+2013

Neon “star”: off-center Ne ignition



Contraction of semi-degenerate core

➔ Cooling

Outer layer

➔ Compression

➔ Ne ignition

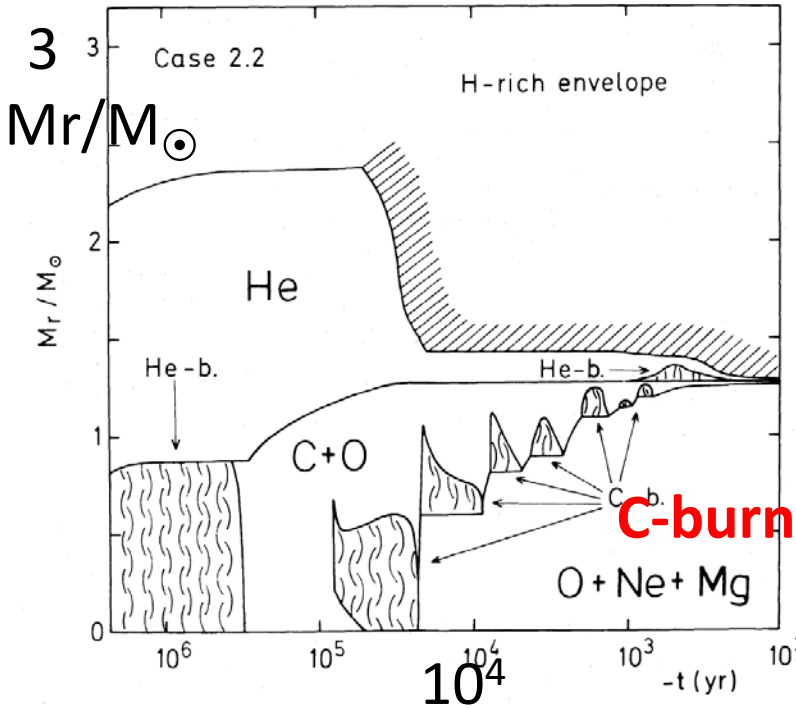
M (Ne) > 1.37 $M_\odot$

(Nomoto 1984)

Evolution of 8-10 $M_\odot$ Stars:

Formation of an electron degenerate ONeMg core

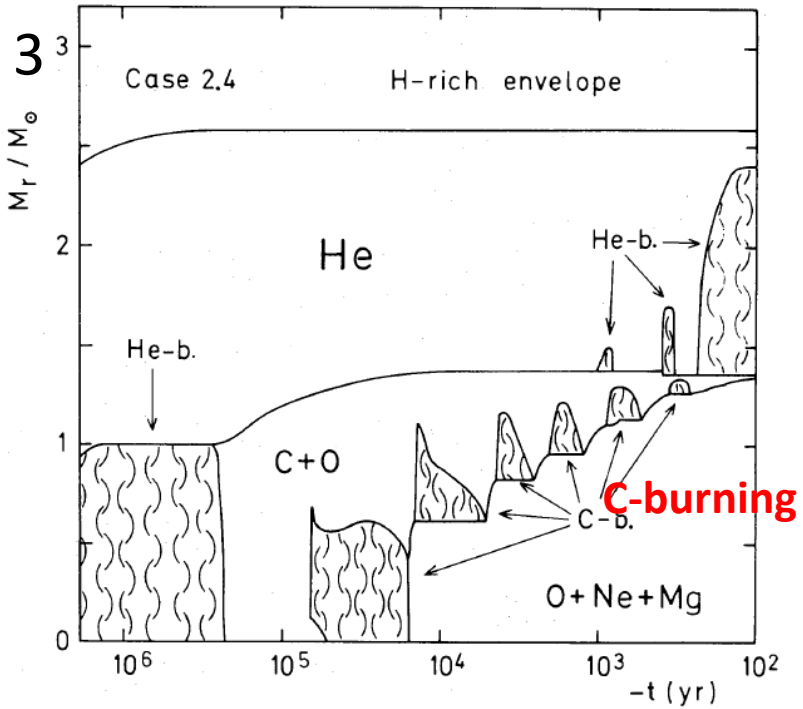
(Nomoto 1982, 84, 87)



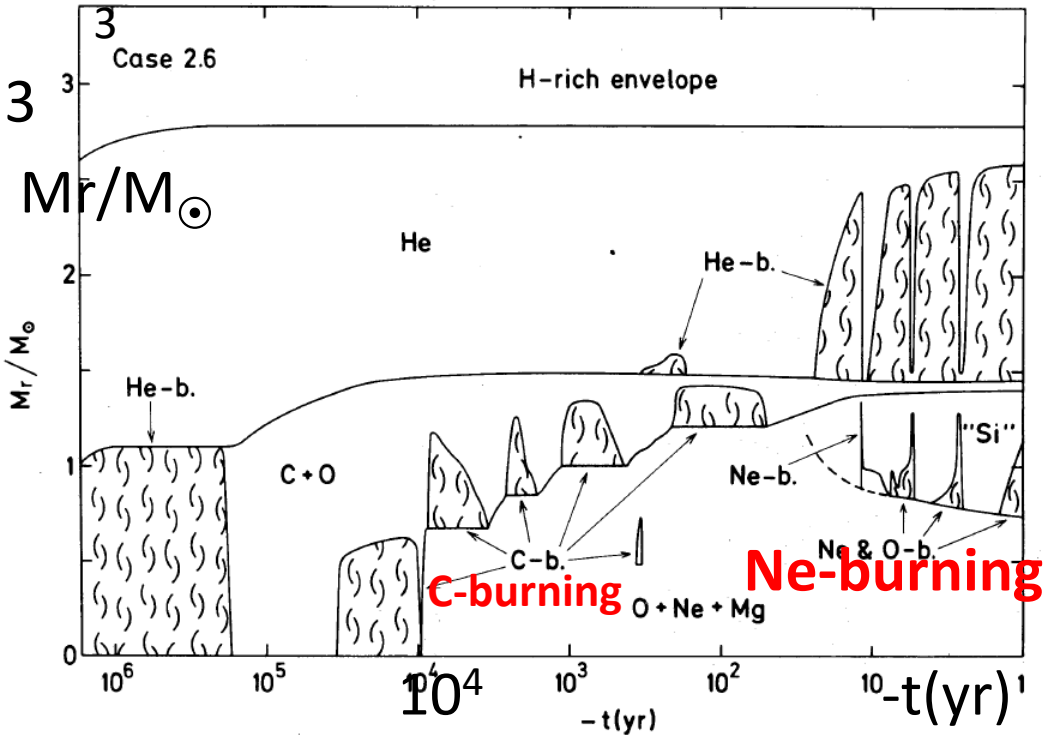
C-burning

Slow Evolution (nuclear timescale)

➔ Importance of Mass Loss



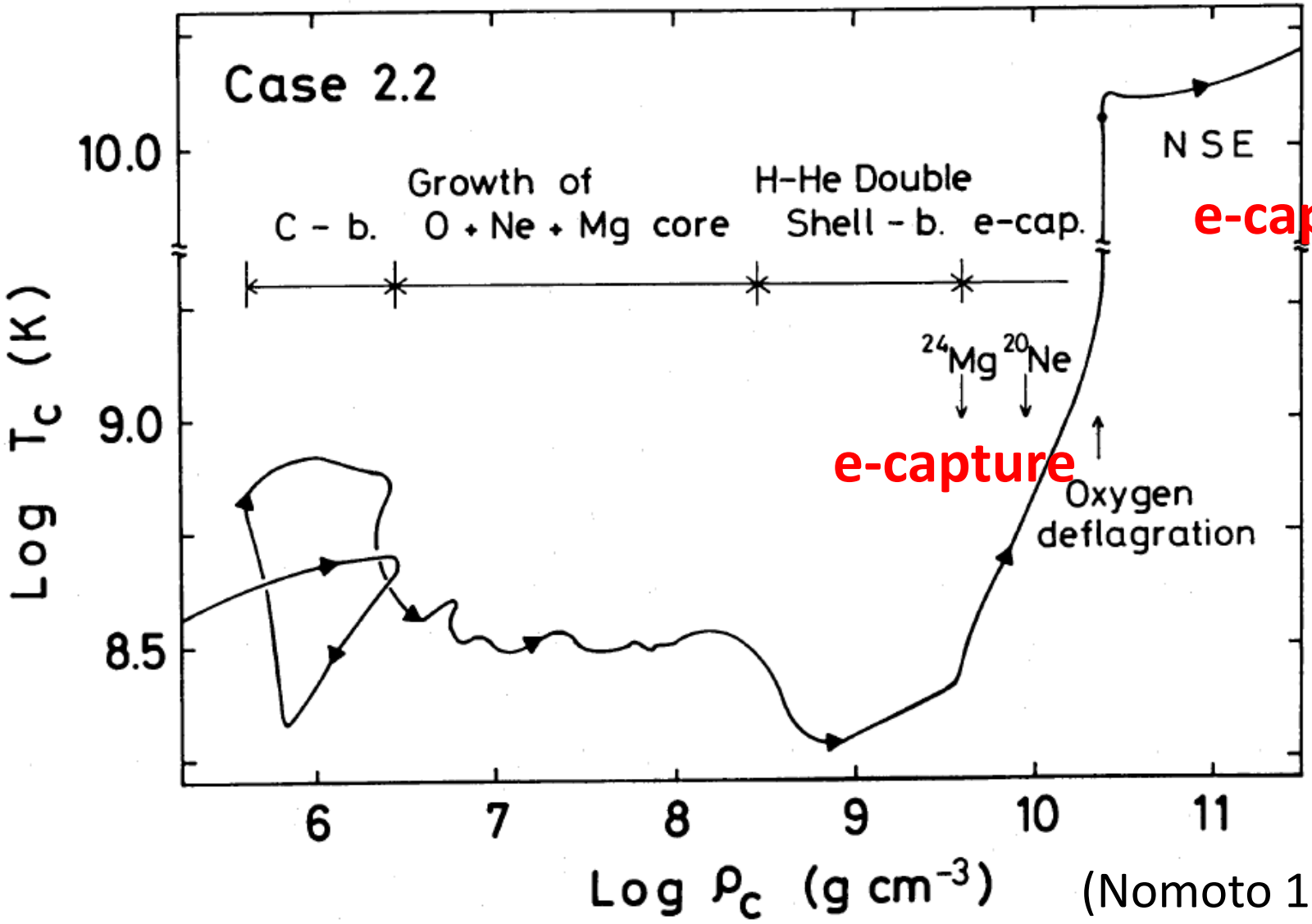
C-burning



C-burning

Ne-burning

Evolution of the central density & temperature of 8.8 $M_\odot$ star ➔ Collapse



(Nomoto 1987)

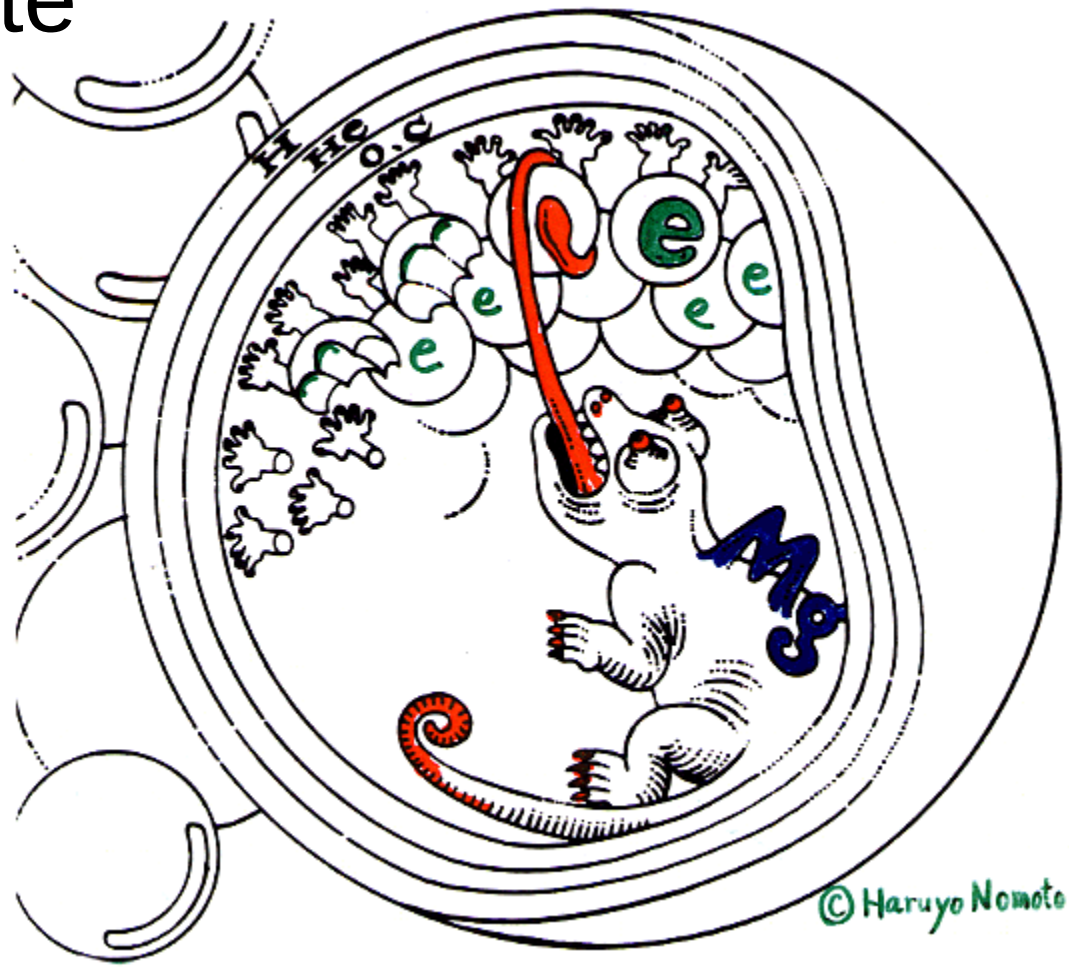
Electron Capture (EC) in 8-10 $M_\odot$ Stars

Electron-degenerate O+Ne+Mg Core

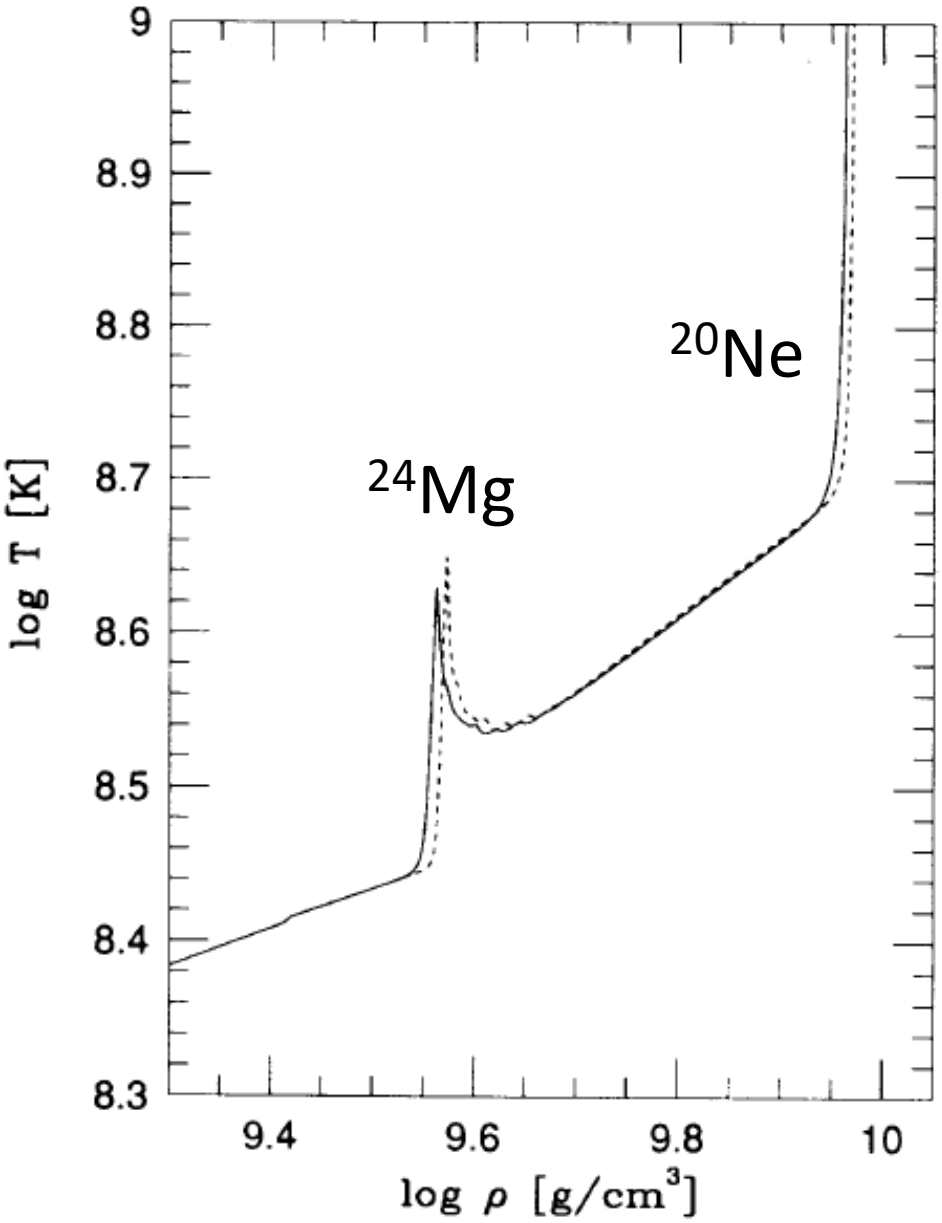
- $^{24}Mg(e^-,\nu)^{24}Na$
  $(e^-,\nu)^{24}Ne$
- $\rho > 4.0 \times 10^9 gcm^{-3}$

- $\rightarrow$collapse

(Nomoto 1984)



Electron Capture on ^{24}Mg & ^{20}Ne



Heating ➔

Convection (**Ledoux** criterion)

Semi-Convective mixing ?

Oxygen Deflagration

at log ρ_c ~ 9.95 – 10.0

➔

Explosion or Collapse ?

Hashimoto, Iwamoto, Nomoto (1993)

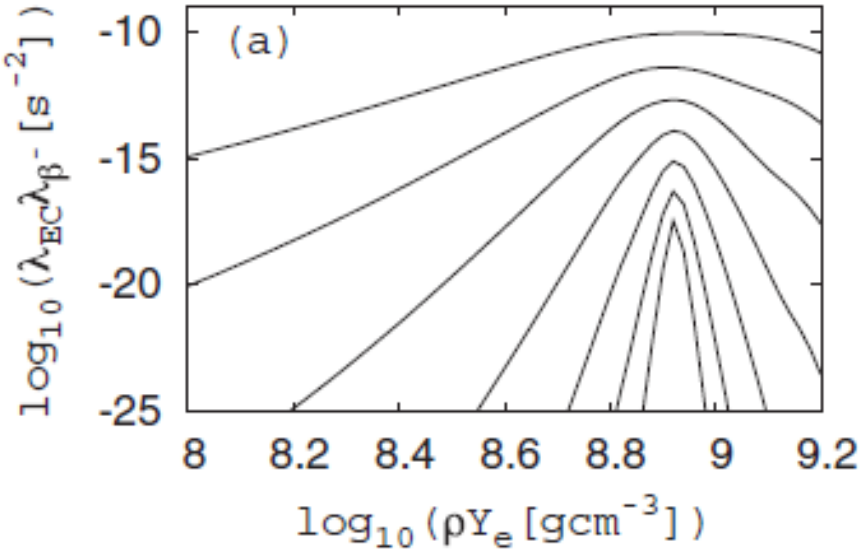
URCA Cooling ➔ ^{20}Ne E-Capture at Higher density

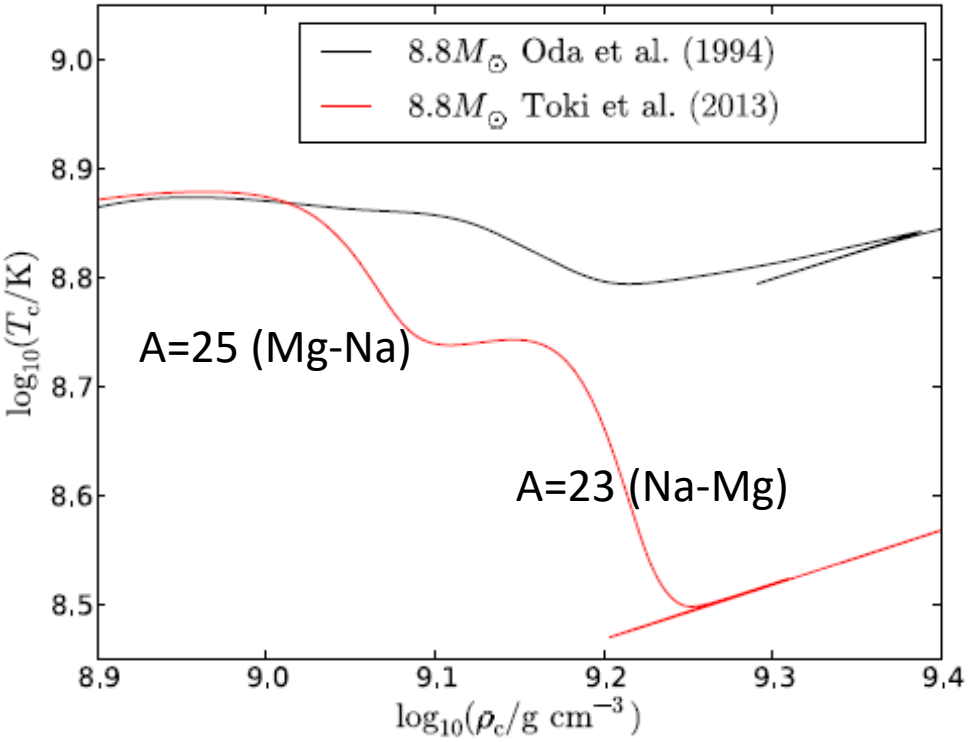
Carbon burning (^{12}C+^{12}C) ➔

X(^{16}O)=0.57, X(^{20}Ne)=0.34, X(^{23}Na)=0.06, X(^{24}Mg)=0.01, X(^{25}Mg)=0.02

URCA Cooling: **e-capture** $(i)\quad {}^{A}\mathrm{Z} + \mathrm{e}^{-} \rightarrow {}^{A}(\mathrm{Z}-1) + \nu$

Beta-decay $(ii)\quad {}^{A}(\mathrm{Z}-1) \rightarrow {}^{A}\mathrm{Z} + \mathrm{e}^{-} + \bar{\nu}$





A = 23 pair (Na – Ne)

A = 25 pair (Mg – Na)

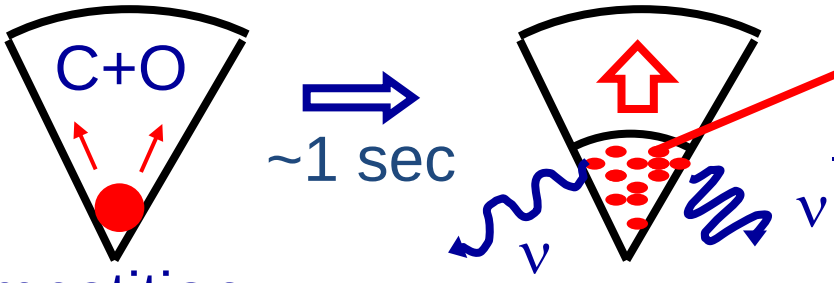
(Toki+13; Suzuki+15)

(Jones+13)

Conductive

Deflagration ⟹ **Collapse?**
Explosion?

Convective



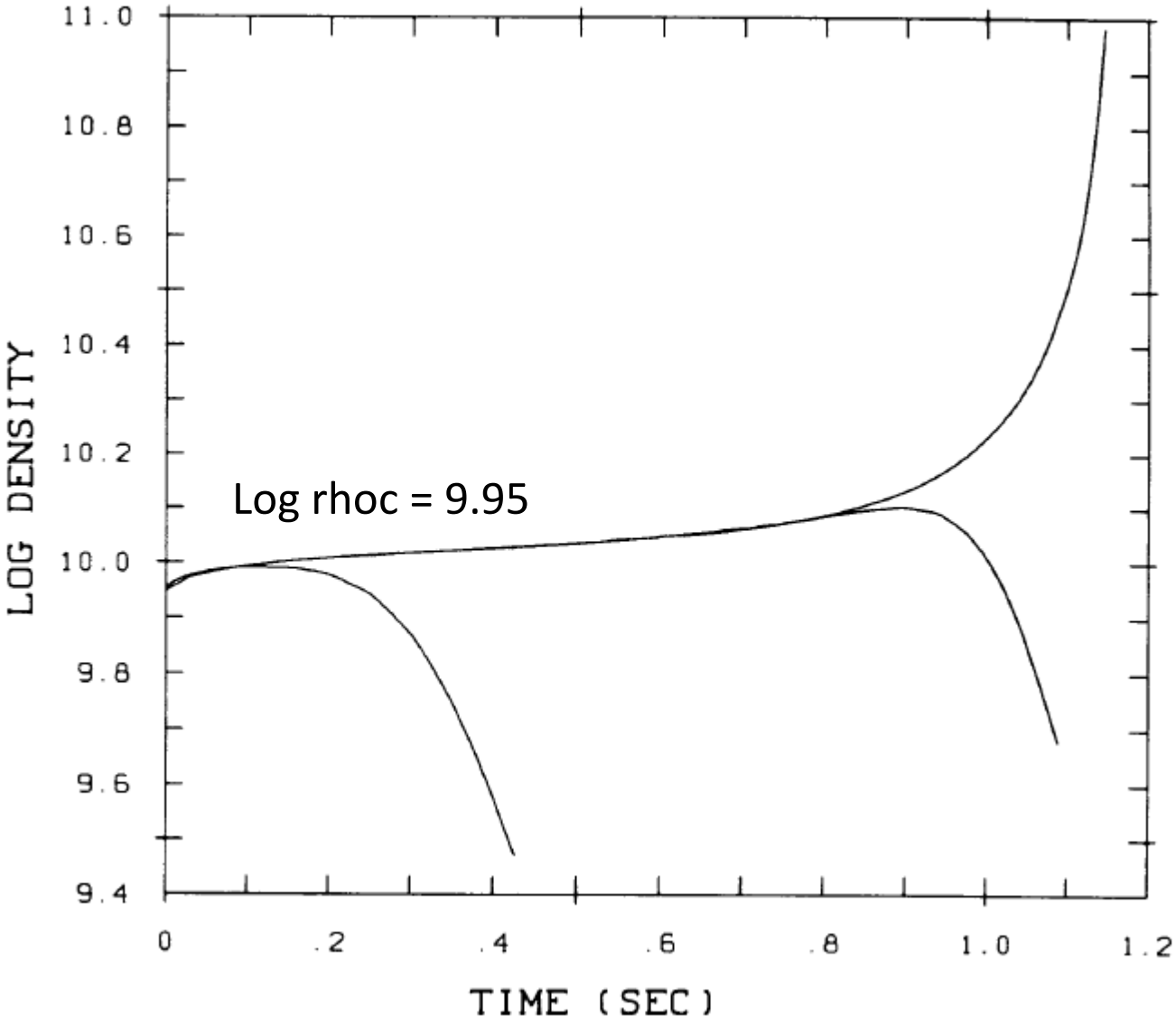
Canal et al. 90
Nomoto & Kondo 91
1991

Nuclear Statistical Equilibrium

Competition

- Electron Capture $p(e^-, \nu)n$
  - Ye ↘ ⋯⋯▸ P ↘ ⟹ Collapse
  - ν energy loss ⋯⋯▸
- Nuclear Energy Release ⋯⋯▸ P ↗ ⟹ Explosion
- Slow Propagation ⟹ Collapse
  - $v_{dif}/v_s < 0.04$
  - $v_{cond} \sim 0.007 v_s$
- Fast Propagation ⟹ Explosion
  - $v_{dif}/v_s > 0.04$ at $\rho \sim 10^{10}$ g cm^{-3} ($v_s \sim 1.2 \times 10^4$ km s^{-1})

Collapse vs. Explosion (1D)



Conductive +
Slow Convective
Deflagration
➔ Collapse

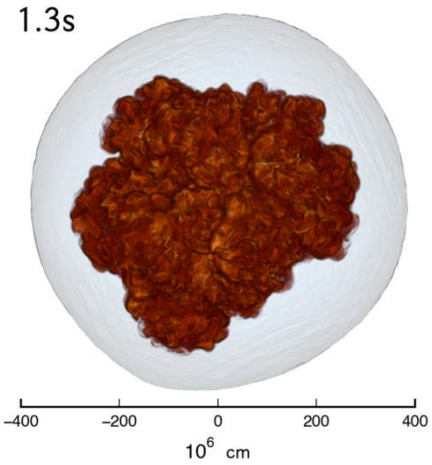
Fast Convective
Deflagration
➔ Partial Explosion

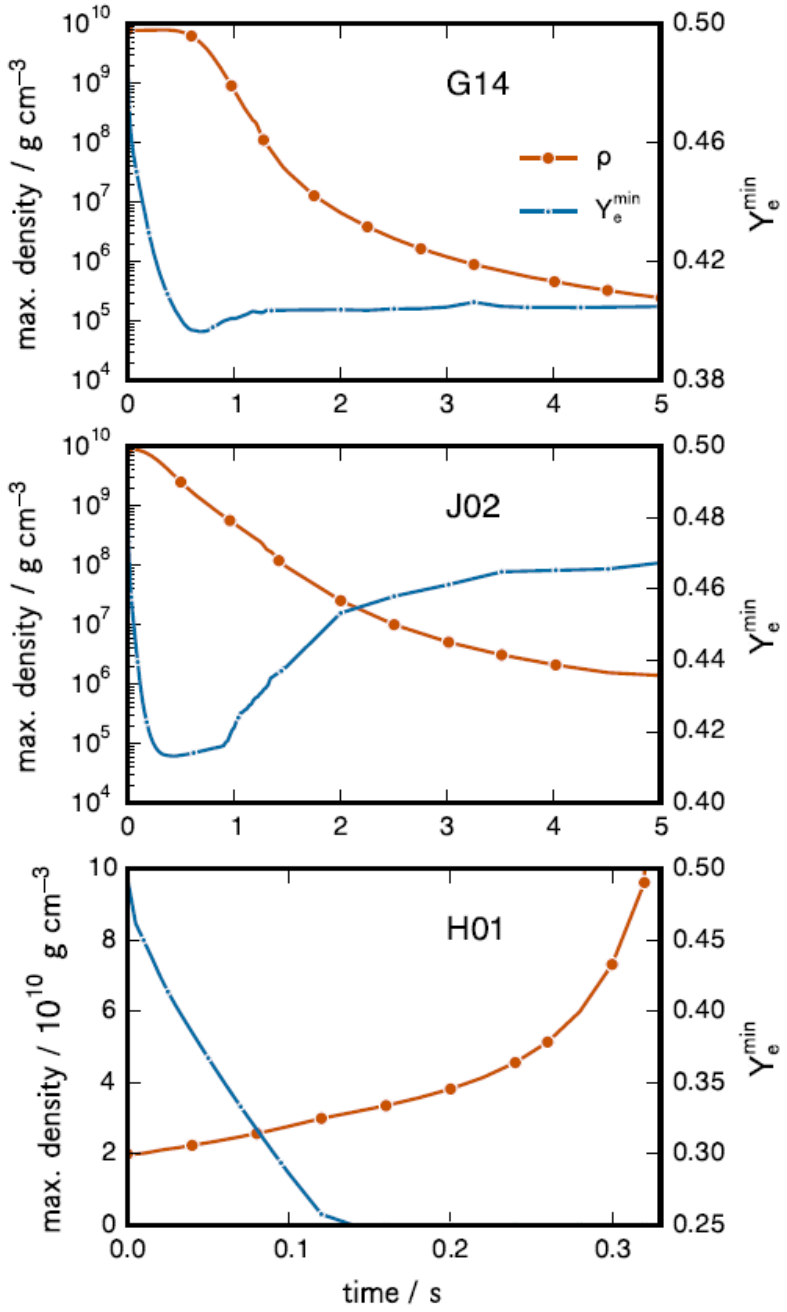
Nomoto & Kondo (1991)

Oxygen Deflagration in ONeMg Cores

3D simulations (Jones +2016)

Starting from 300 bubbles

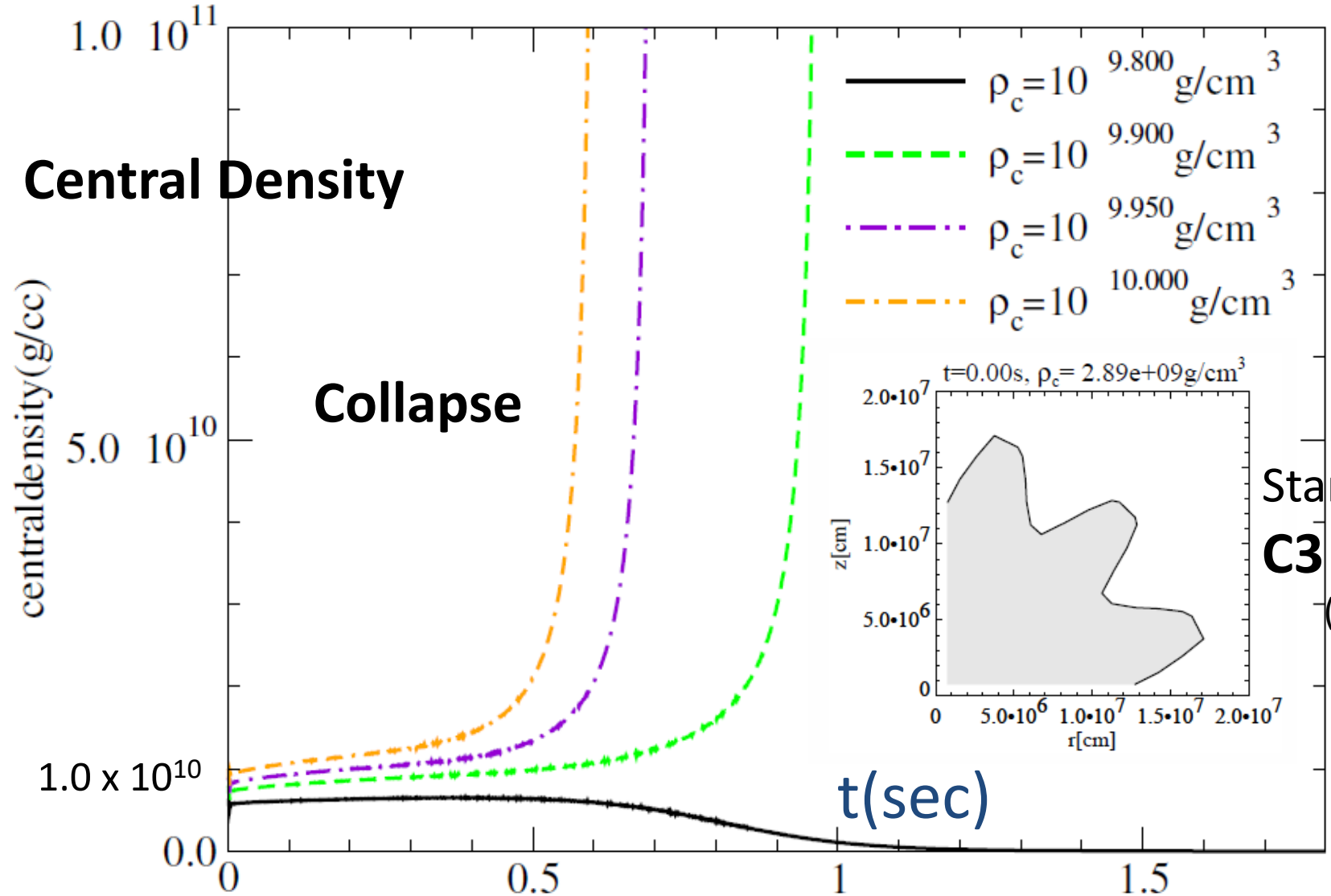




id.	res.	[a] $\log_{10}\rho_c^{ini}$ (g cm^{-3})	[b] CC (Y/N)	[c] M_{rem} (M
G13	256^3	9.90	N	0.647
G14	512^3	9.90	N	0.438
G15	256^3	9.90	Y	1.212
J01	256^3	9.95	N	0.631
J02	256^3	9.95	Y	1.291
H01*	256^3	10.3	N	1.401

Collapse of ONeMg Cores (>$10^{9.90}$ g cm^{-3})

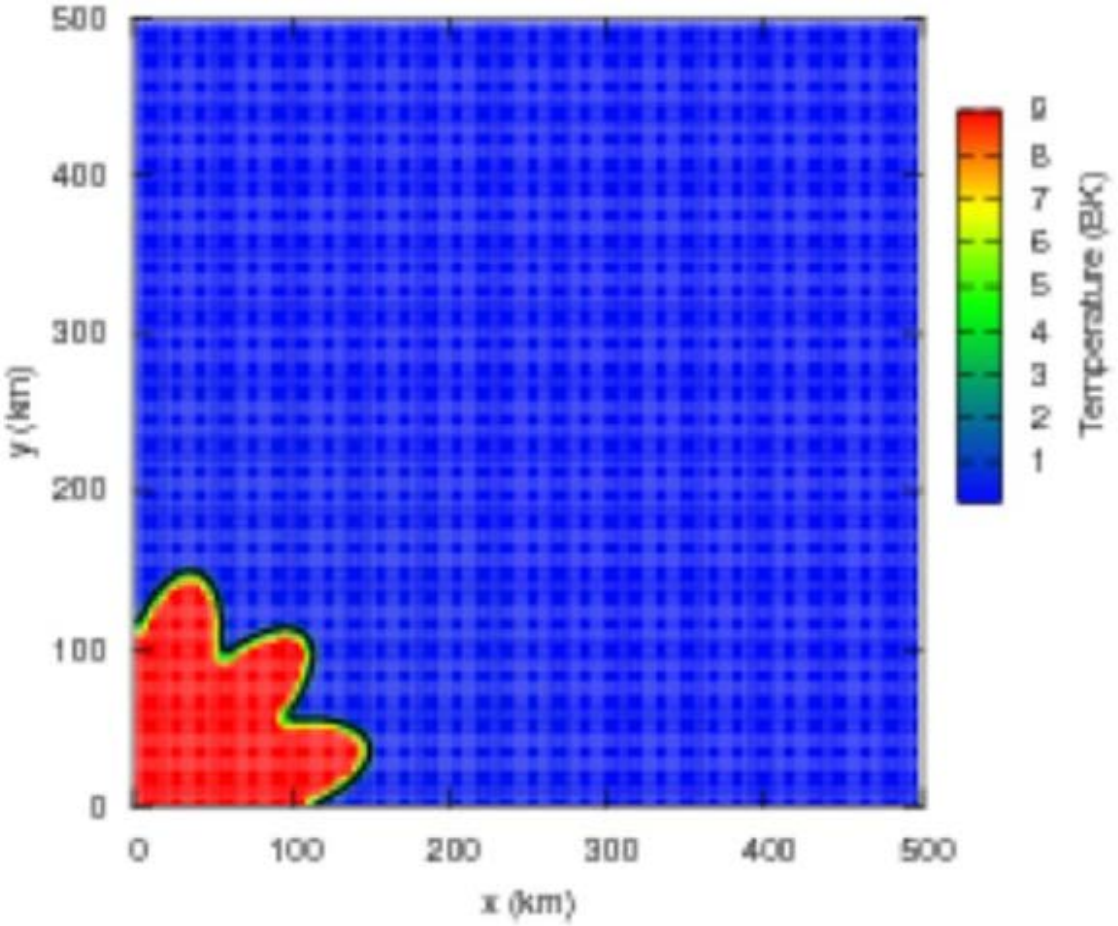
2D simulations (Leung & Nomoto 2016)



Starting from

C3 flame

(Reinecke 99)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x (km)
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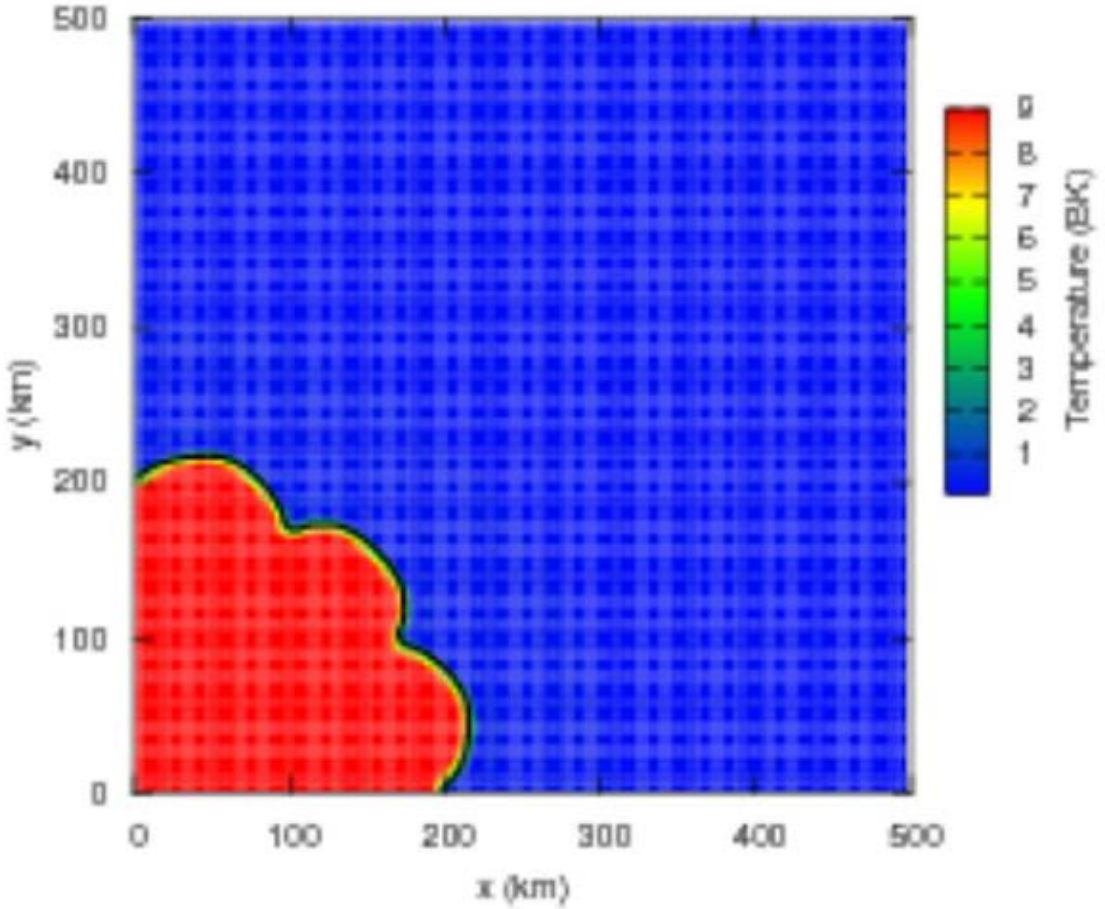
1
Temperature (BK)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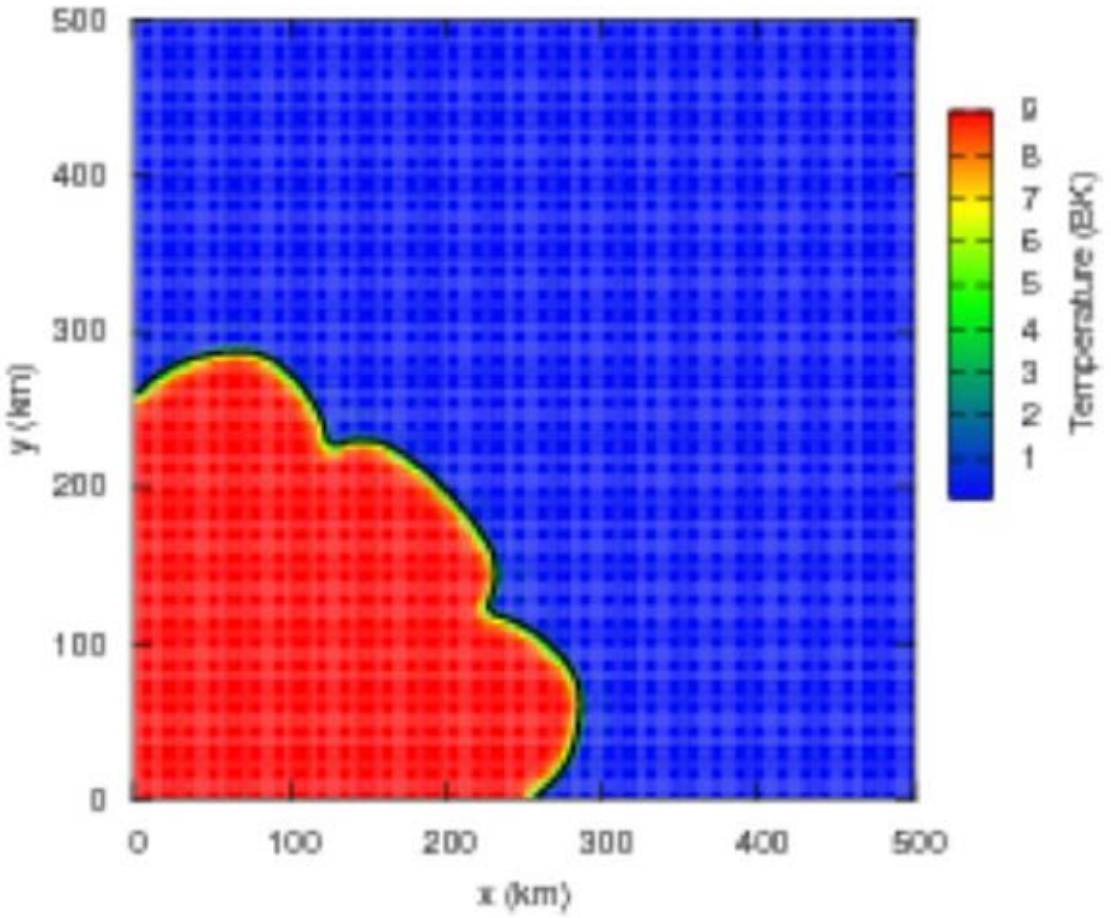
Temperature (BK)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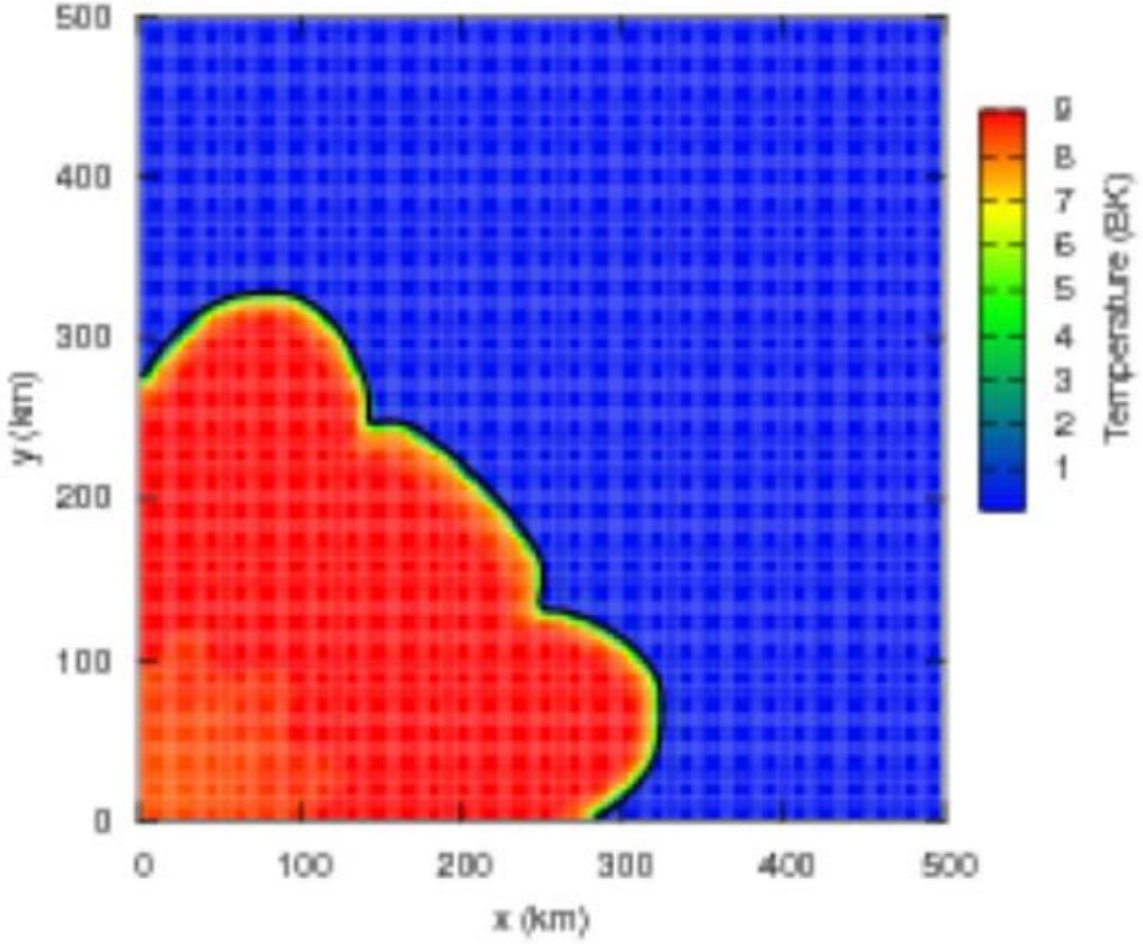
Temperature (K)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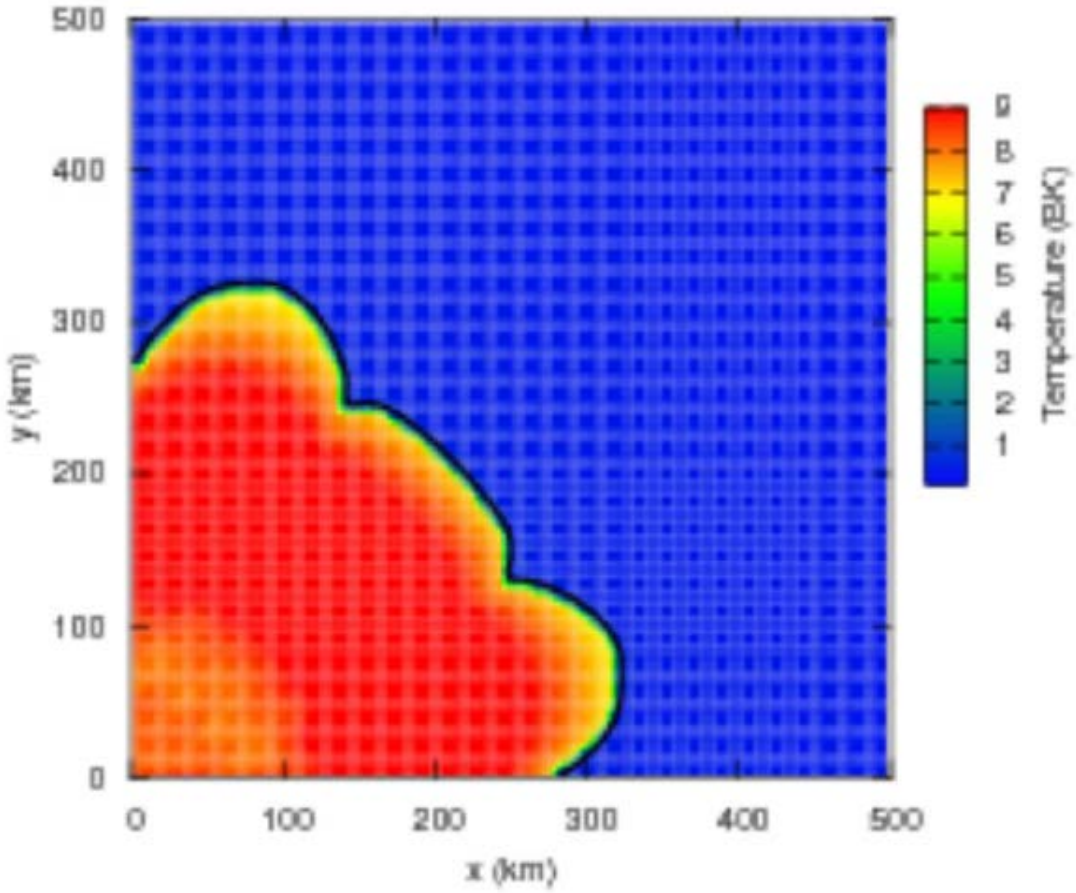
Temperature (8K)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y (km)
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x (km)
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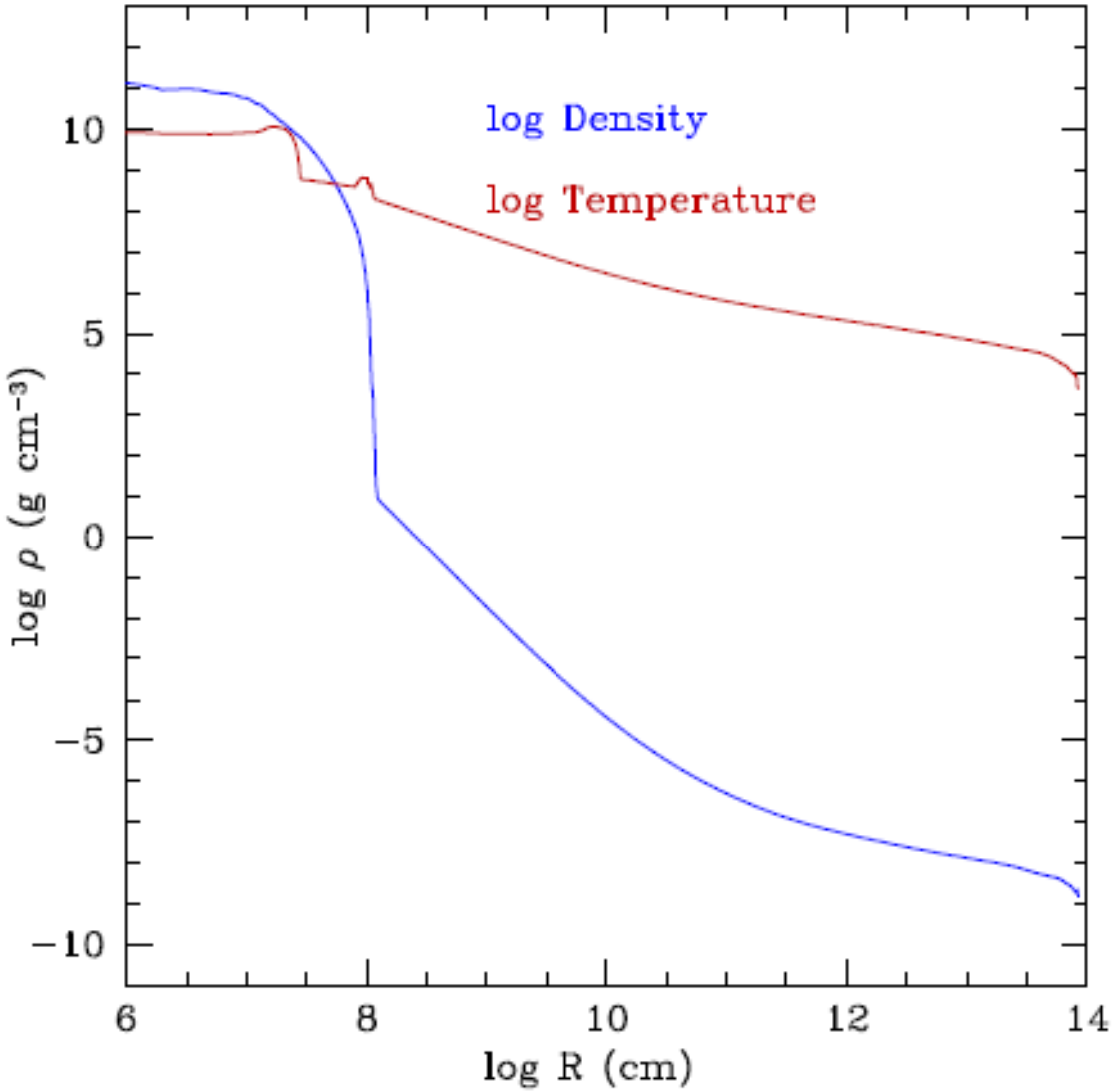
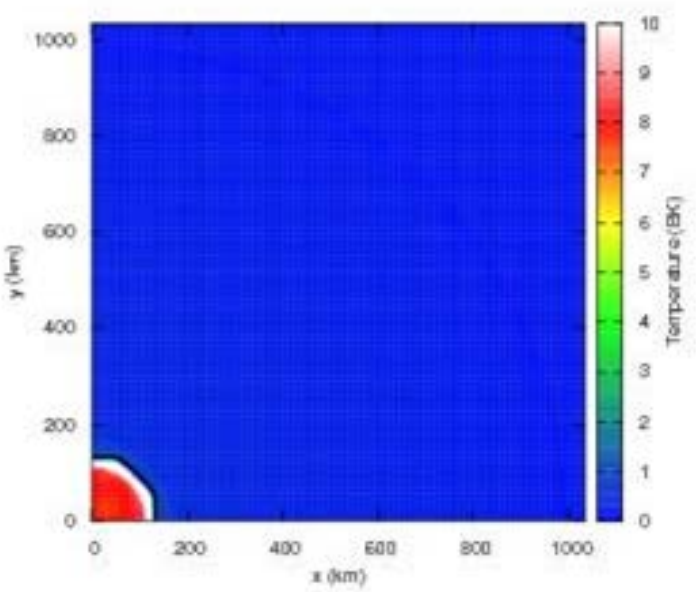
2
1
Temperature (BK)

New Initial Model of Super-AGB SN





Asymmetry has been polished during collapse.

Tolstov, Leung, Jones, Nomoto (2017)

$9M_\odot$ Star
Neutrino Heating → Weak Explosion

Steep Density Gradient

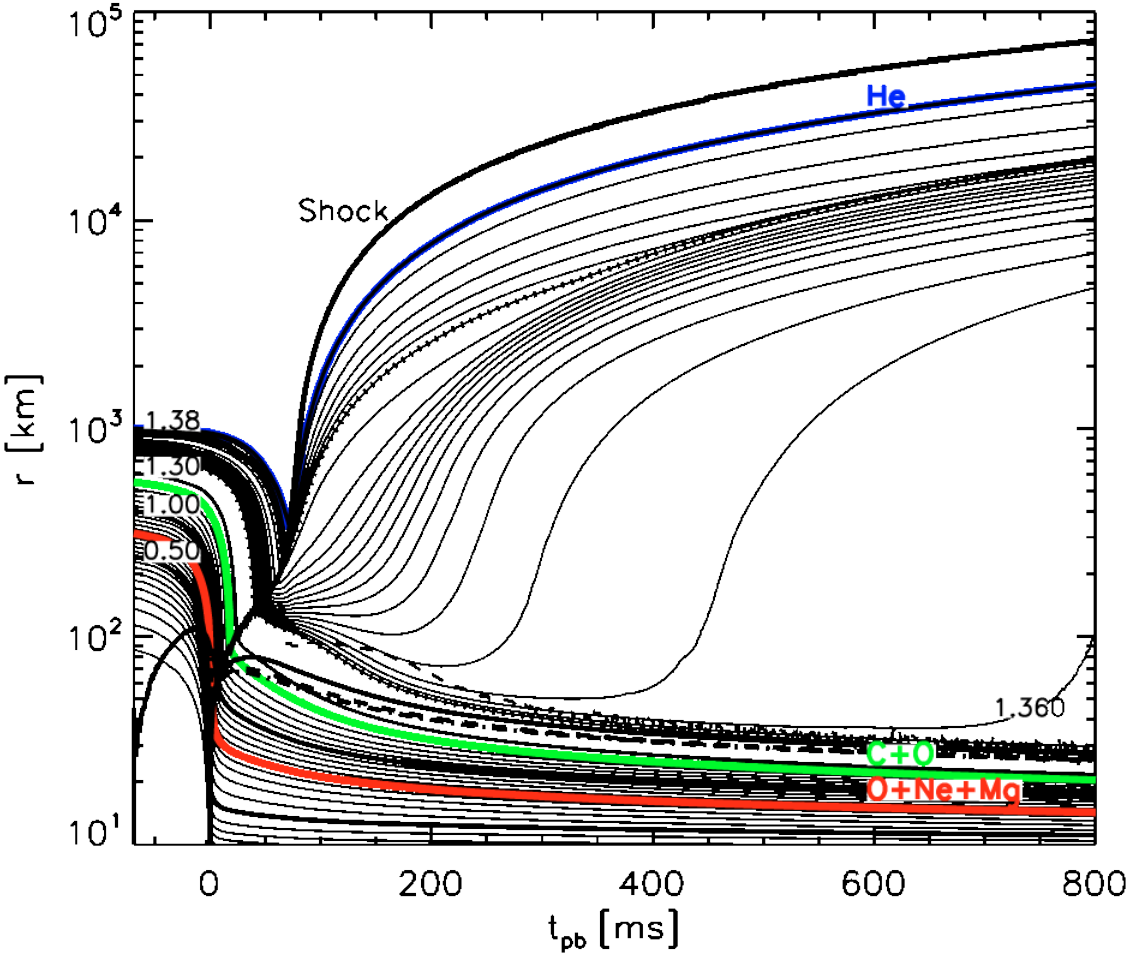
→ $E_{exp} = 1 \times 10^{50}$ erg

$M_{ej} = 0.011 M_\odot$

→ Super-AGB star's
H-He-rich Envelope
(~0.5 - $5M_\odot$)
Planetary Nebula-like

→ Nucleosynthesis Constraints

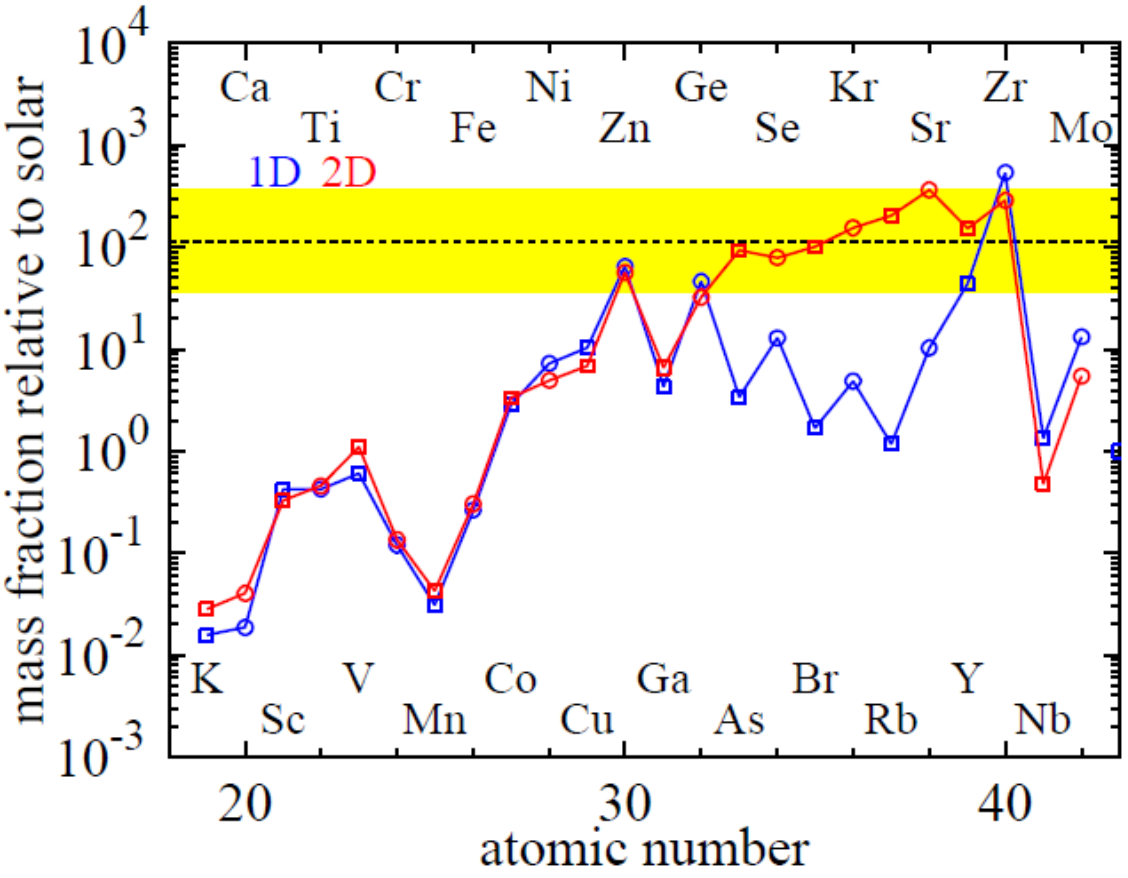
(Hoffman+ 08, Wanajo+09,11,13)



Kitaura, Janka, & Hillebrandt (2006)

$9M_\odot$ Star

Neutrino Heating → Weak Explosion Yields from EC-SNe (relative to solar)

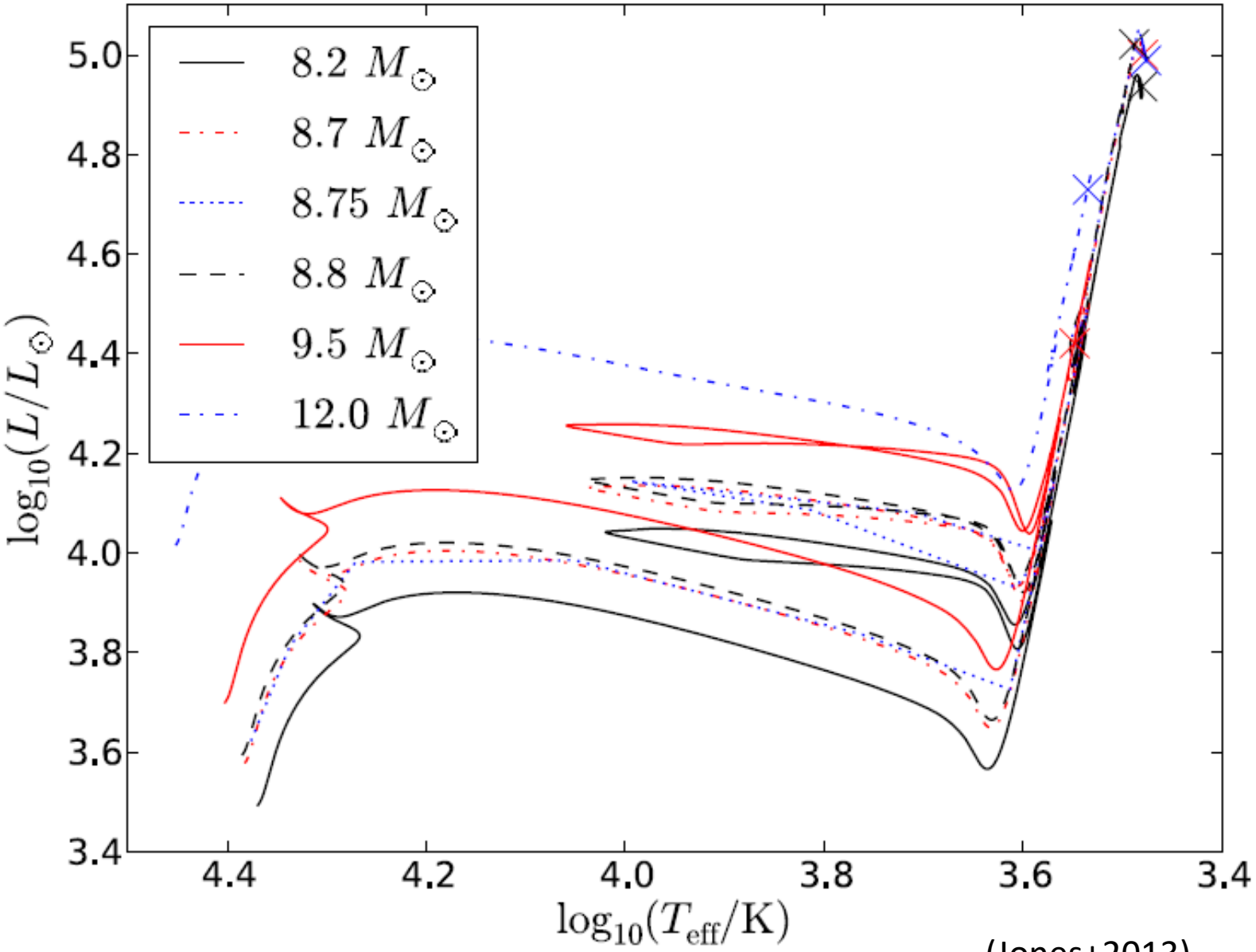


2D model (Wanajo+2011)

- still up to $N = 50$
- but can be the source of
- Zn,Ge, As, Se, Br, Rb, Sr, Y Zr
- BUT, **no r-process...**
- little Fe (^{56}Ni) mass $= 0.003\ M_\odot$
- **Faint SN (2008S?)**

→ M_{ej}=0.011$M_\odot$ E_{exp} =1×10^{50} erg

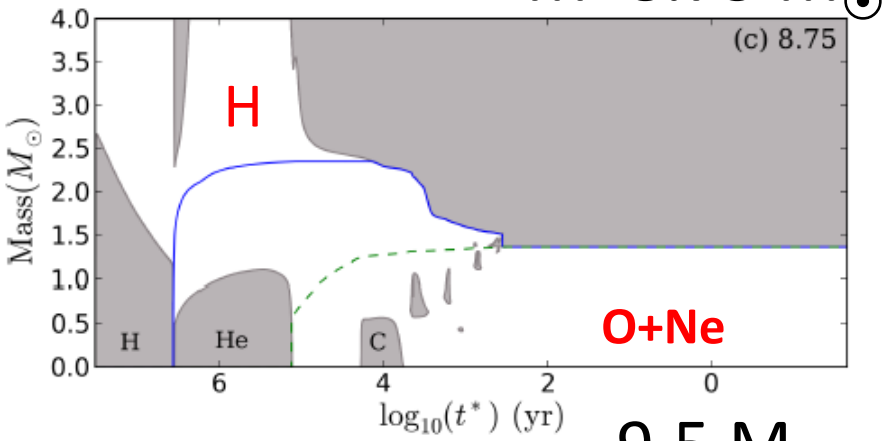
Evolution of 8 – 12 $M_\odot$ Stars



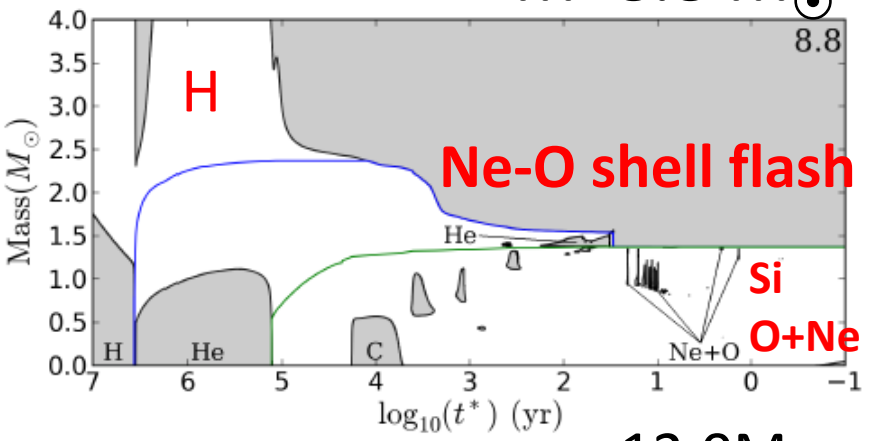
(Jones+2013)

Evolution of 8 – 12 $M_\odot$ Stars

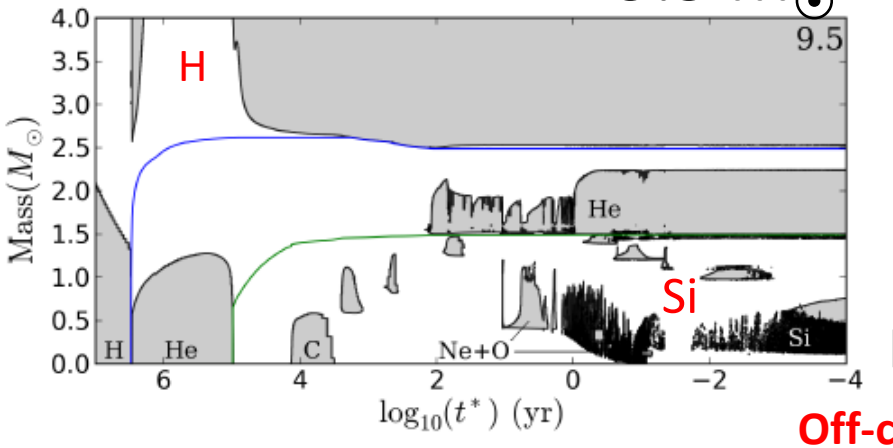
M=8.75 $M_\odot$



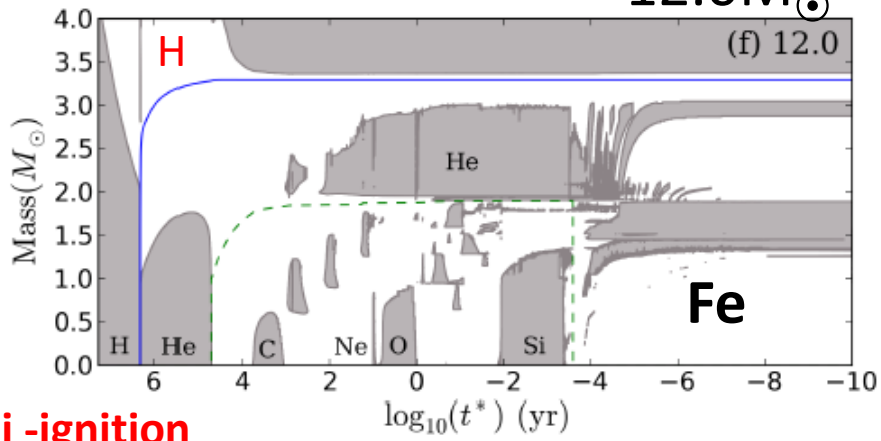
M=8.8 $M_\odot$



9.5 $M_\odot$



12.0$M_\odot$



Off-center Si -ignition

Ne-O shell flash

(Jones+ 2013; Takahashi+2013; Ritossa+99)

Final Fates of Stars:

$M < 8\ M_\odot$ ➔ Electron-Degenerate Core ➔ White Dwarf

$M = 8 – 8.8\ M_\odot$ ➔ Mass Loss ➔ O+Ne White Dwarf

➔ Electron Capture (EC) Supernova

$M \sim 8.8 – 9.5\ M_\odot$

Ne-O flame ➔ does not reach the center

formation of a degenerate O+Ne core

EC Supernova

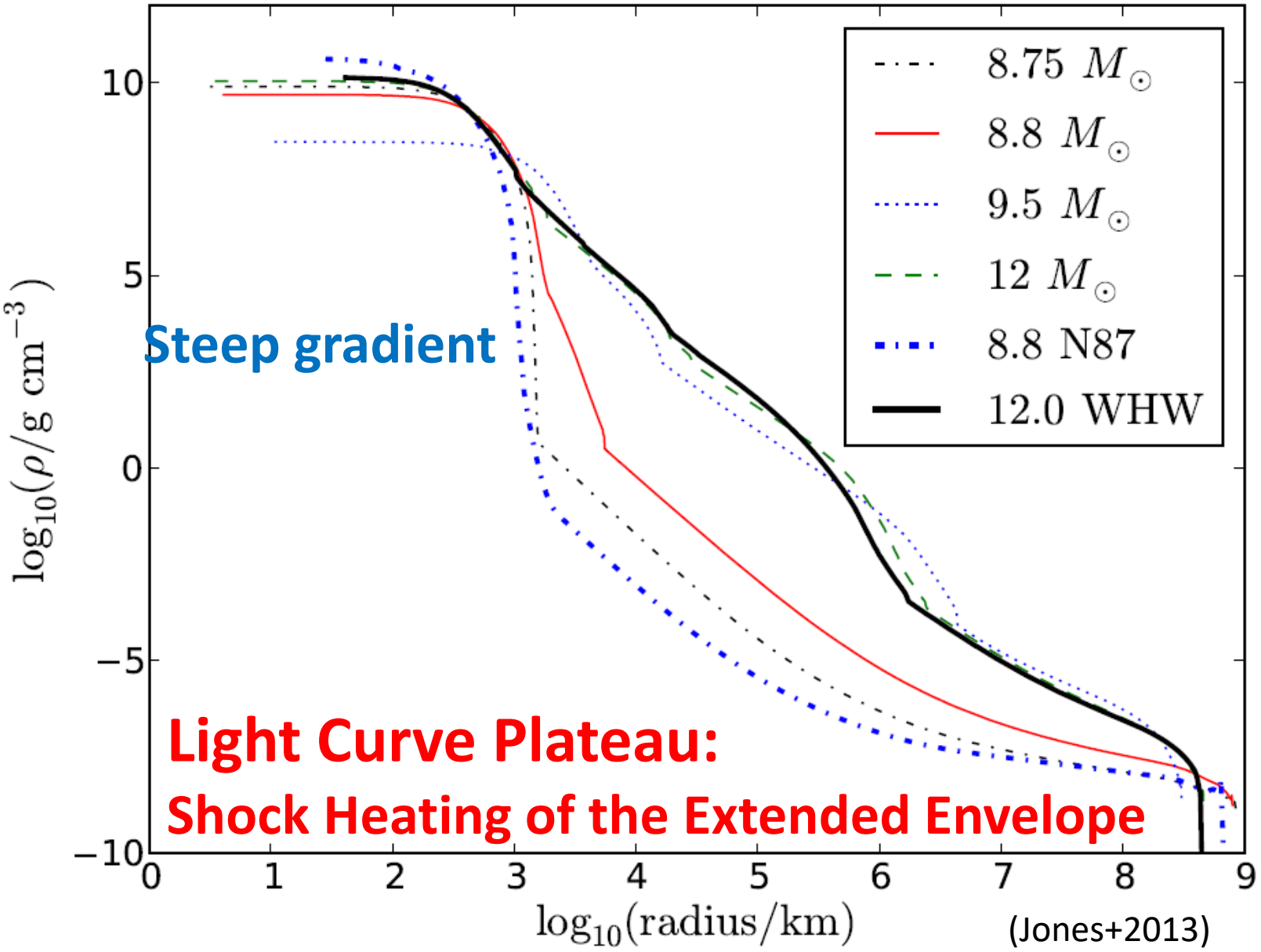
$M \sim 9.5 – 11\ M_\odot$

Ne-O flame ➔ reaches the center

formation of an Fe core

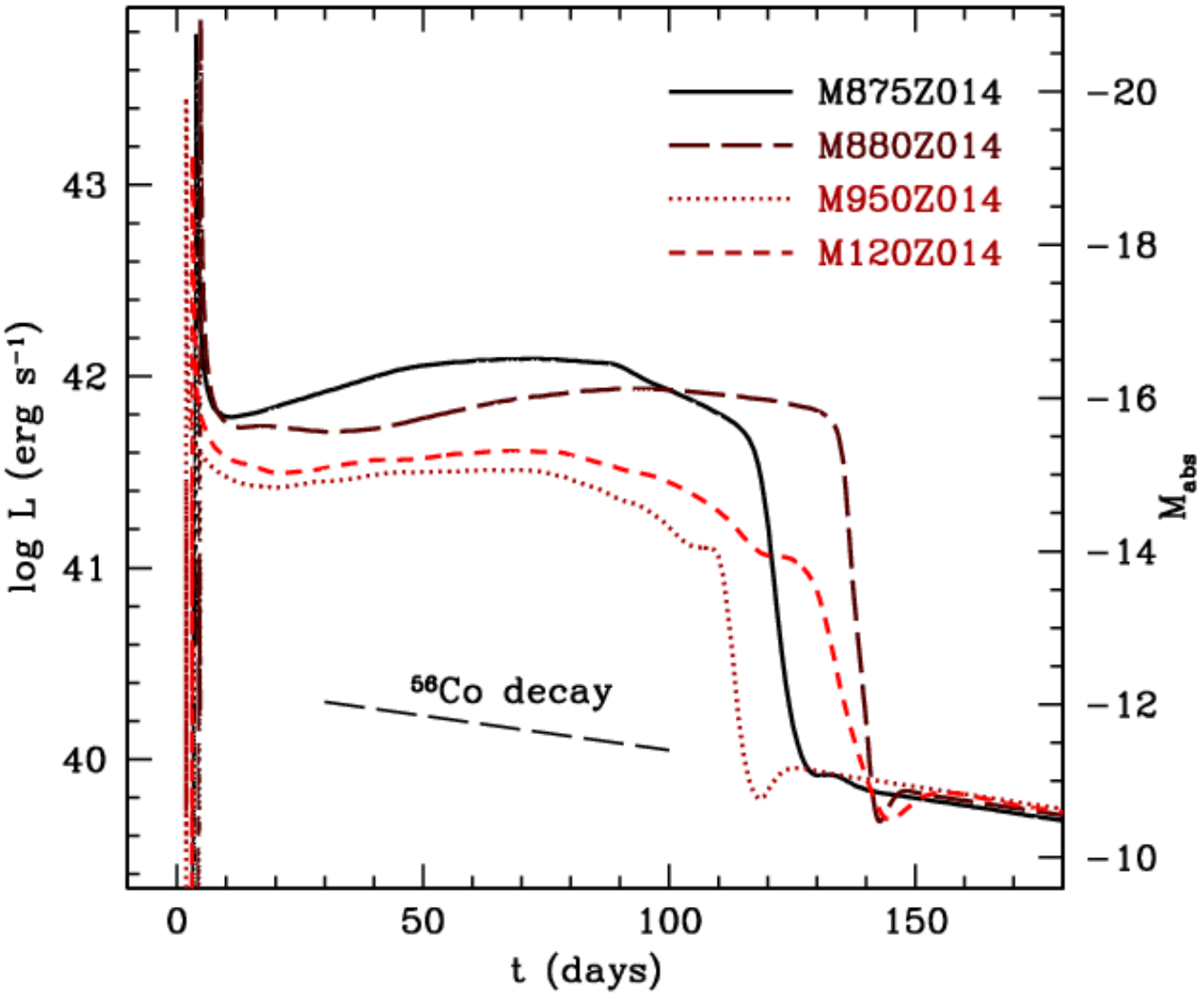
$M > 11\ M_\odot$ ➔ central Ne-burn ➔ Fe Core ➔ NS or BH

Presupernova density profiles



(Jones+2013)

Bolometric light curves (E_{51}=0.15, M(^{56}Ni)=0.002 $M_\odot$)



S-AGB:
Bright
even though
E is low.

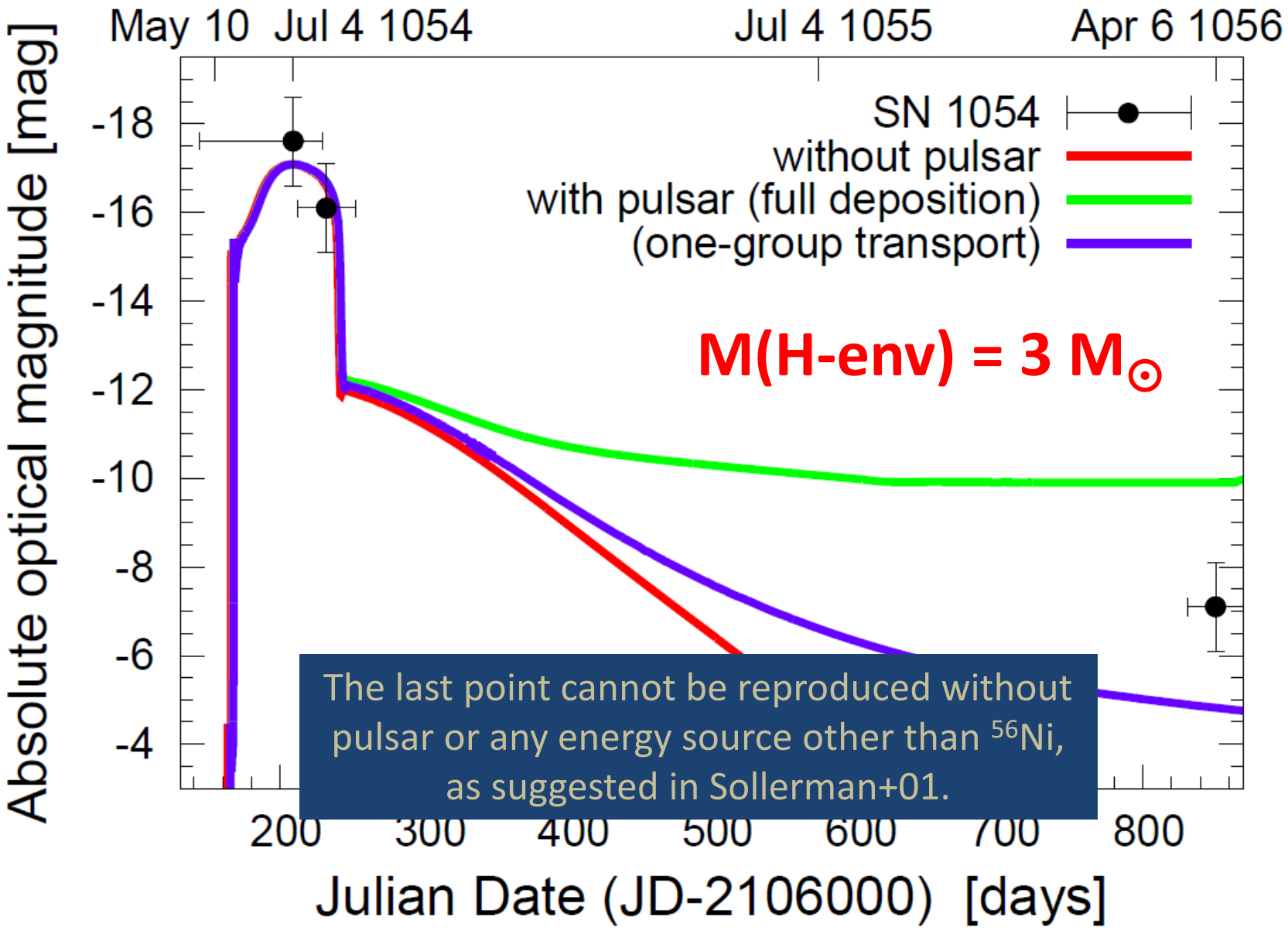
(Tolstov+2016)

The Crab Nebula（SN1054)

- Low Explosion Energy < 1e50 erg
- M_{ejecta} ~ 3 - 5$M_{\odot}$
  - Henry & McAlpine (1982)
- Helium-rich: 1.6 < X_{He}/X_{H} < 8
  - Henry & McAlpine (1982)
- Oxygen: X_{O} ~ 0.003 (X_{O}/X_{H} ~ solar)
- Carbon: 0.4 < X_{C}/X_{O} <1.1
  - Davidson et al. (1982), Pequignot & Dennefeld (1983)
- Nitrogen: moderately oversolar but X_{N}/X_{C} <1
  - Davidson et al. (1982)
- Nickel: Ni/Fe > solar
  - Dennefeld & Pequignot (1983), Henry (1984)

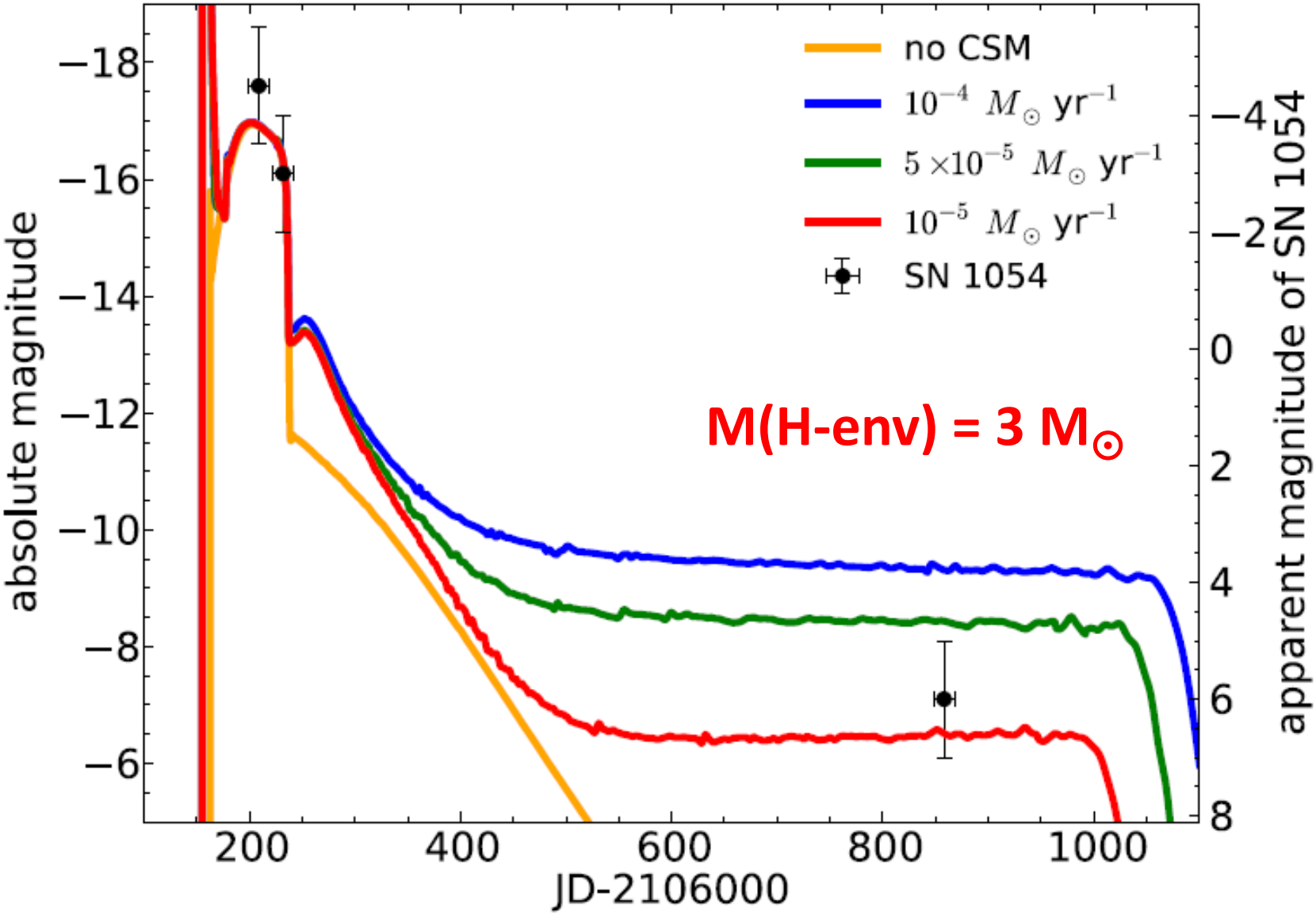
(Nomoto et al. 1982)

Light Curve with a Pulsar: SN1054?



Tominaga, Blinnikov, Nomoto (2013)

Light Curves of ECSNe with CSM Interaction



Moriya, Tominaga, Langer, Nomoto, Blinnikov, Sorokina (2014)

Signatures of Super-AGB Supernovae

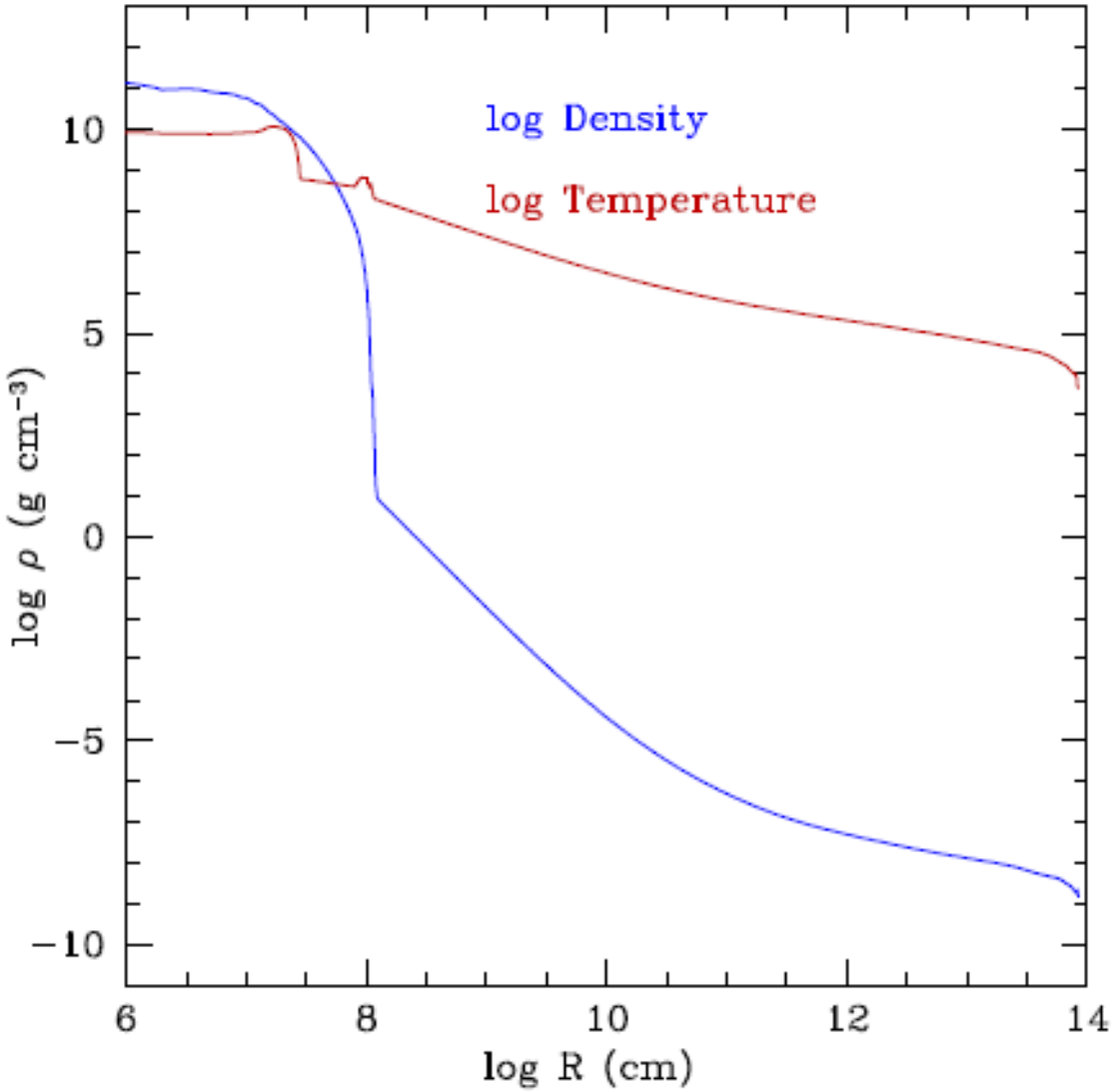
Neutron Star: $M_B \sim 1.38\ M_\odot$ ➔ $M_G \sim 1.25\ M_\odot$

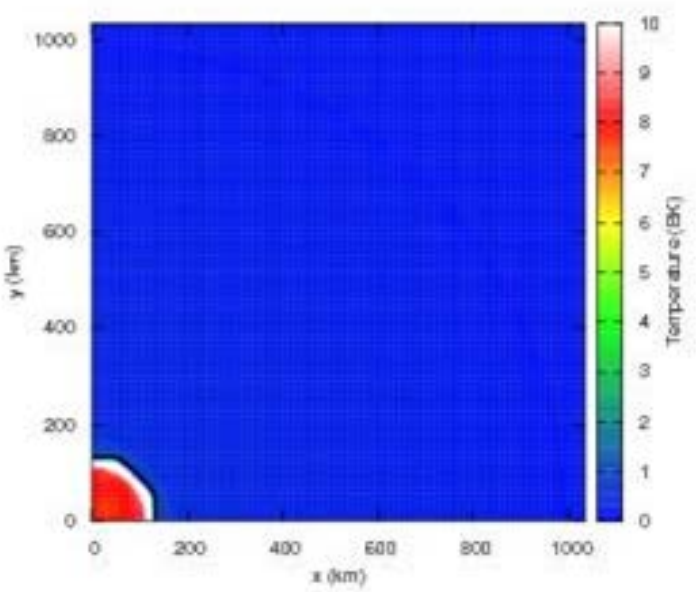
Light Curves of Electron Capture Supernovae :

- plateau with L ~ 10^{42} erg s^{-1} and t ~ 30–100 days
- faint tail (luminosity drops by ~4 mag)
- photospheric velocity at plateau of 3 - 4x10^3 km s^{-1}
- EC SNe ~ Faint SNe , SN 1054 (Crab)
-
- Circumstellar Interaction (Smith 2013; Moriya et al. 2014)

Chemical Signatures : Zn - Zr, ^{48}Ca, ^{60}Fe

New Initial Model of Super-AGB SN

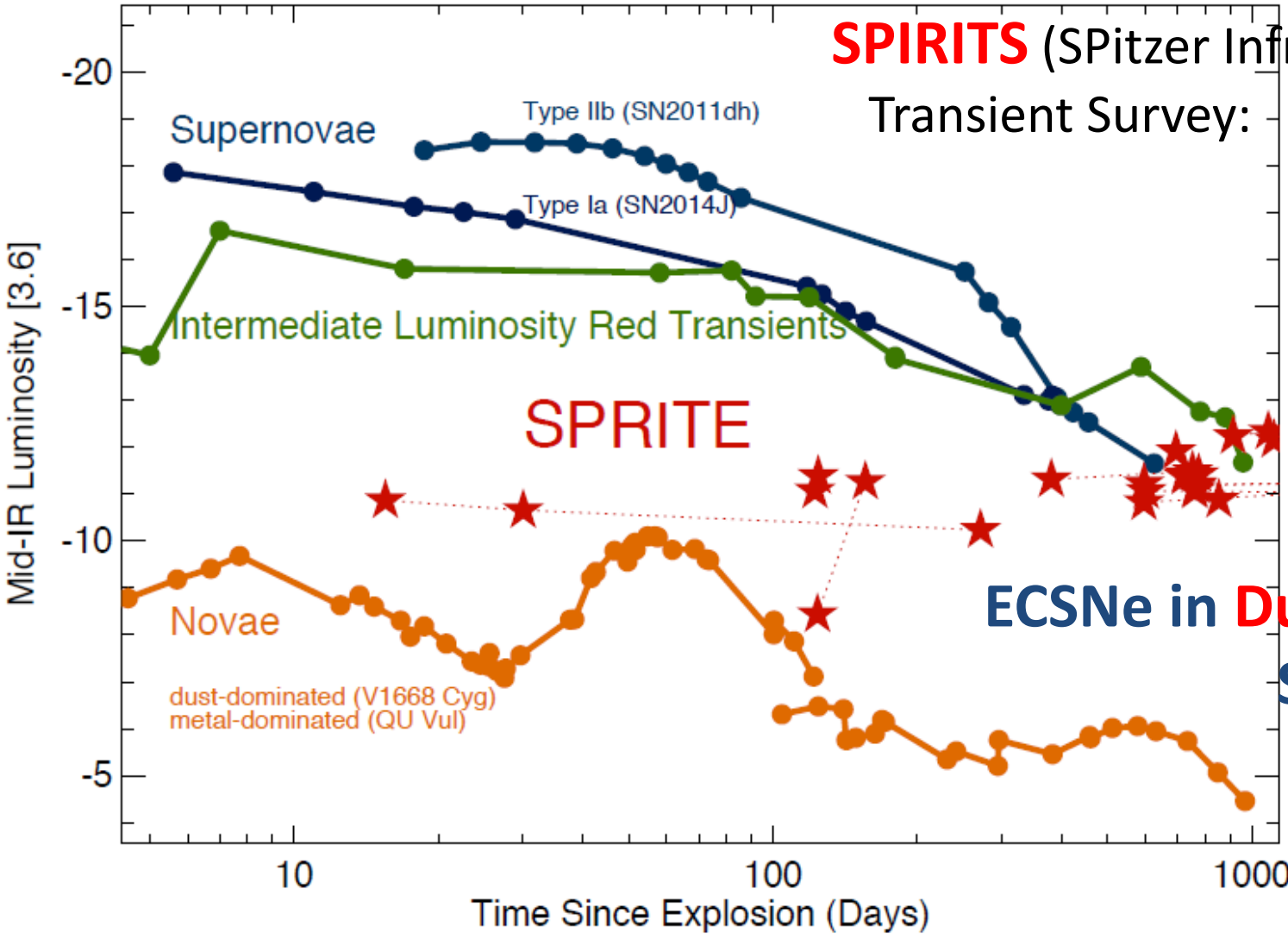




Asymmetry has been polished during collapse.

Tolstov, Leung, Jones, Nomoto (2017)

SPRITE (eSPecially Red Intermediate Luminosity Transient Events)



SPIRITS (SPitzer InfraRed Intensive Transient Survey: Kasliwal + 17)

ECSNe in Dusty CSM of Super-AGB??