Evolution of electron capture supernova progenitors: new models, improved nuclear physics and hydrodynamic mixing uncertainties

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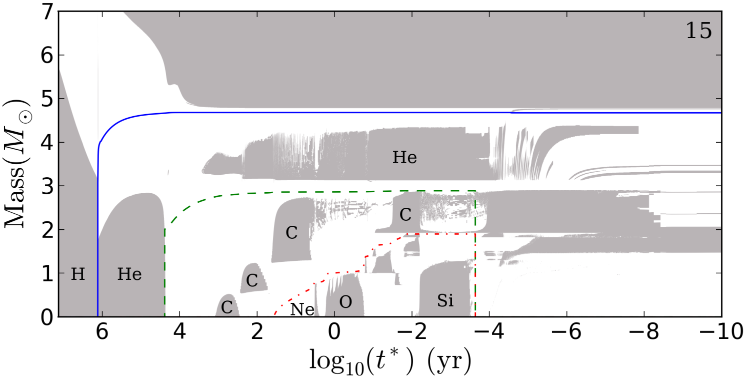
Outline

- SN-II progenitor evolution overview
- Motivation for and importance of studying $8 - 12\, M_{\odot}$ stars
- Modelling stars
- new ECSN progenitor models
- Improvements to nuclear physics considerations for weak reaction rates

Massive stars - CCSN progenitors

$M \gtrsim 10 M_\odot$:

Central H, He, C, Ne, O, Si burning $\rightarrow$ Fe core $\rightarrow$ e^--captures $\rightarrow$ collapse $\rightarrow$ explosion



see e.g. Heger et al. 2003

Massive stars - CCSN progenitors

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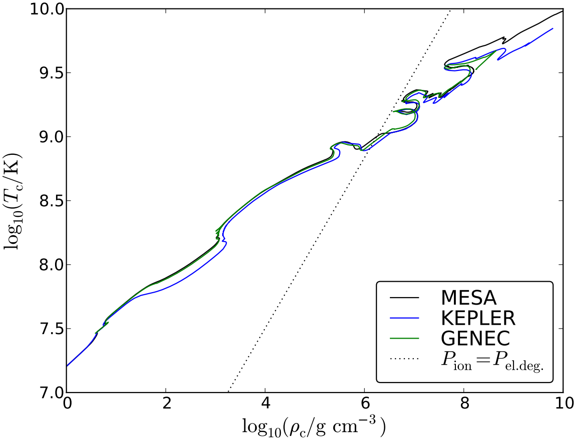
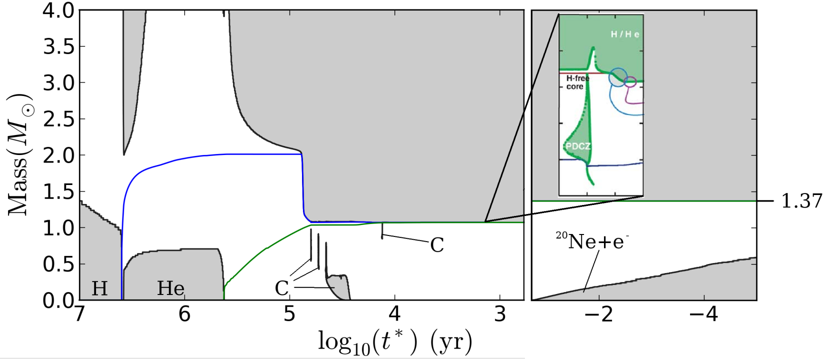


Super-AGB stars - EC-SN progenitors?

H, He, C burning → ONe core growth → e$^-$-captures → O delfagration → Fe core → e$^-$-captures → collapse → explosion



Miyaji et al. (1980), Nomoto (1984, 1987), Miyaji & Nomoto (1987), Ritossa et al. (1999), Poelarends et al. (2008), Takahashi et al. (2013)

Super-AGB stars - EC-SN progenitors?

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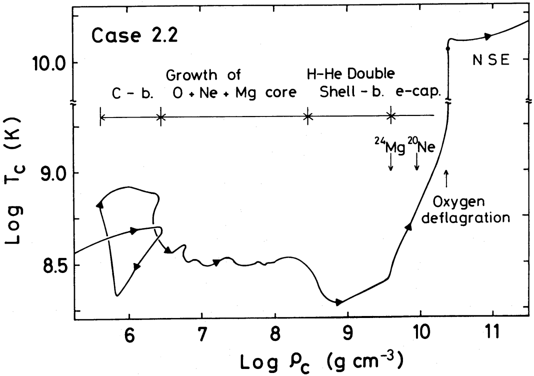
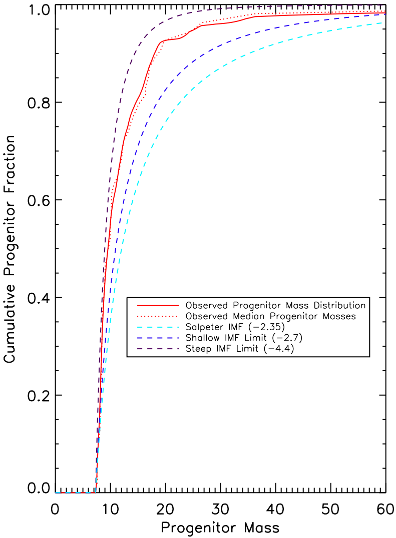


Nomoto (1987)

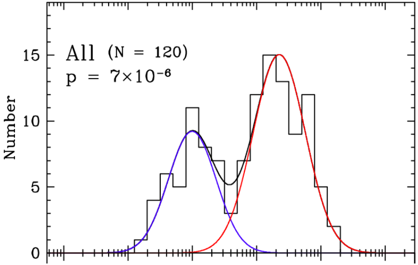
Motivation – Statistical

- $N(8 - 12\ M_{\odot})/N(M > 8\ M_{\odot}) = 0.42$ $(\alpha = -2.35)$
- Jennings et al. (2012, see figure right)
- Distinct lack of low mass SNII progenitor models (Nomoto '84, '87; Takahashi et al. 2013; Mueller et al. 2012)
- Many challenges!



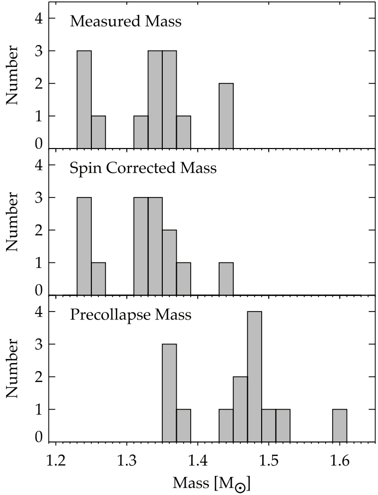
Motivation – Compact objects

- BeX spin period and orbital eccentricity bimodality (Knigge et al., 2011 Nature)



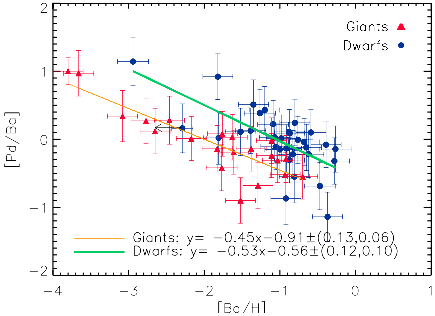
Spin period distribution, $0.1 - 10^4 s$

- Bimodal NS mass distribution (Schwab et al., 2012)



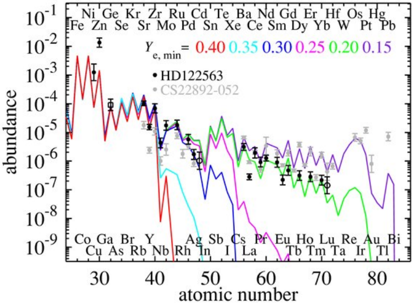
Motivation – Nucleosynthesis

- Abundance anti-correlations - second (weak) r-process?



Hansen et al. 2012

- Electron capture supernovae → weak r-process?
- 2-D simulations produce n-rich pockets with Ye,min ∼ 0.4



Wanajo et al. (2011)

- no r-process (not even Pd or Ag)

Modelling Stars – the MESA code

$$\frac{dm}{dr} = 4\pi r^2 \rho(r)$$ mass conservation

$$\frac{dP}{dm} = -\frac{GM_r}{4\pi r^4}$$ hydrostatic equilibrium

$$\frac{dL}{dm} = \epsilon_{\rm nuc} - \epsilon_\nu + \epsilon_{\rm grav}$$ energy conservation

$$\frac{dT}{dm} = -\frac{GmT}{4\pi r^4 P}\nabla$$ energy transport

$$\nabla = \frac{\partial \ln T}{\partial \ln P};$$

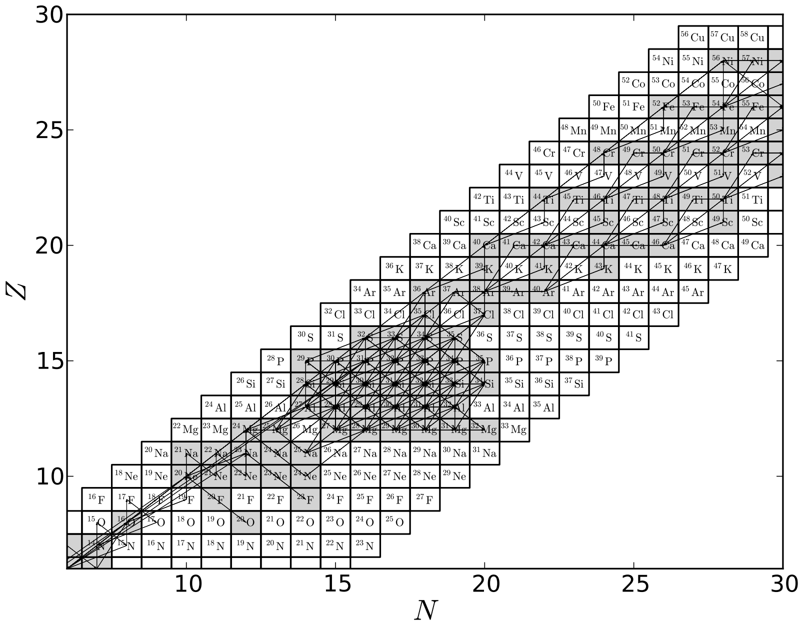
$\nabla = \nabla_{\rm rad}$ (radiative); $\nabla = \nabla_{\rm ad}$ (deep interior convection)

$$P^\alpha = \frac{\rho}{\mu^\varphi} k T^\delta$$ EOS

$$\nabla_{\rm rad} > \nabla_{\rm ad} \left(+ \frac{\phi}{\delta} \right)$$ Convection criteria

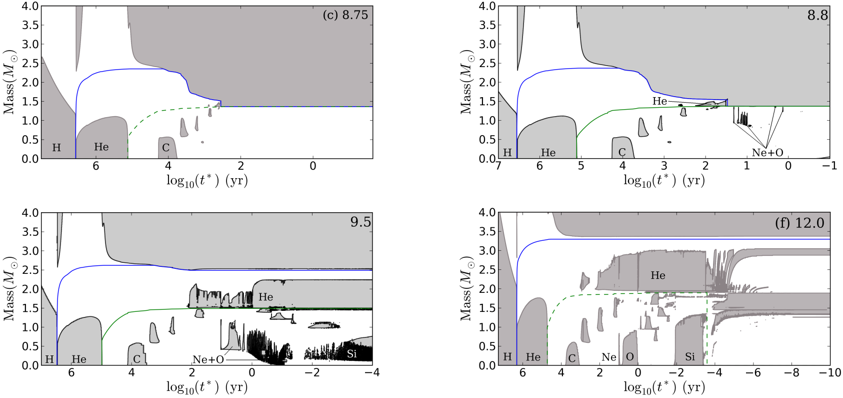
$$D = D_0 \exp\left(- \frac{2z}{f_{\rm CBM} \lambda_{P,0}} \right)$$ boundary mixing

$$\dot{Y}_i = \sum_j N^i_j \lambda_j Y_j + \sum_{j,k} N^i_{j,k} \lambda_{i,j} \rho Y_j Y_k + \sum_{j,k,l} N^i_{j,k,l} \lambda_{i,j,l} \rho^2 Y_j Y_k Y_l \quad {\rm s}^{-1}$$

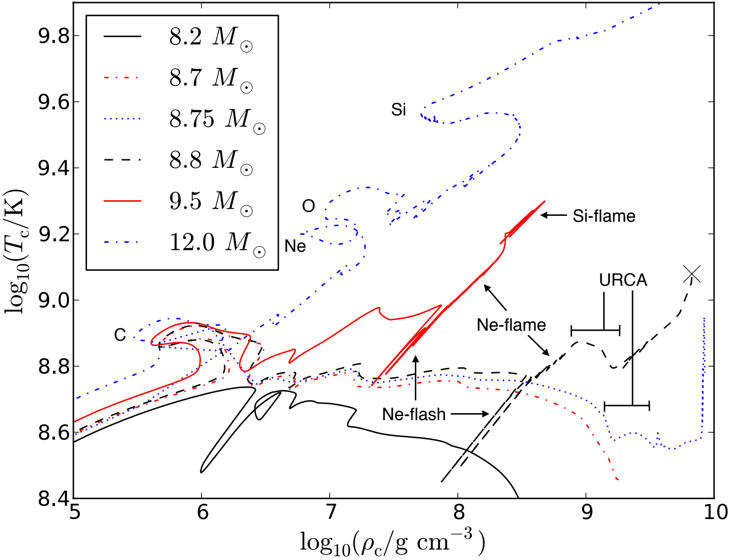


56 Cu 57 Cu 58 Cu
54 Ni 55 Ni 56 Ni 57 Ni
52 Co 53 Co 54 Co 55 Co 56 Co
50 Fe 51 Fe 52 Fe 53 Fe 54 Fe 55 Fe
48 Mn 49 Mn 50 Mn 51 Mn 52 Mn 53 Mn 54 Mn
46 Cr 47 Cr 48 Cr 49 Cr 50 Cr 51 Cr 52 Cr 53 Cr
44 V 45 V 46 V 47 V 48 V 49 V 50 V 51 V 52 V
42 Ti 43 Ti 44 Ti 45 Ti 46 Ti 47 Ti 48 Ti 49 Ti 50 Ti 51 Ti
40 Sc 41 Sc 42 Sc 43 Sc 44 Sc 45 Sc 46 Sc 47 Sc 48 Sc 49 Sc 50 Sc
38 Ca 39 Ca 40 Ca 41 Ca 42 Ca 43 Ca 44 Ca 45 Ca 46 Ca 47 Ca 48 Ca 49 Ca
36 K 37 K 38 K 39 K 40 K 41 K 42 K 43 K 44 K 45 K 46 K 47 K
34 Ar 35 Ar 36 Ar 37 Ar 38 Ar 39 Ar 40 Ar 41 Ar 42 Ar 43 Ar 44 Ar 45 Ar
32 Cl 33 Cl 34 Cl 35 Cl 36 Cl 37 Cl 38 Cl 39 Cl 40 Cl 41 Cl 42 Cl 43 Cl
30 S 31 S 32 S 33 S 34 S 35 S 36 S 37 S 38 S 39 S 40 S 41 S
28 P 29 P 30 P 31 P 32 P 33 P 34 P 35 P 36 P 37 P 38 P 39 P
26 Si 27 Si 28 Si 29 Si 30 Si 31 Si 32 Si 33 Si 34 Si 35 Si 36 Si 37 Si
24 Al 25 Al 26 Al 27 Al 28 Al 29 Al 30 Al 31 Al 32 Al 33 Al 34 Al 35 Al
22 Mg 23 Mg 24 Mg 25 Mg 26 Mg 27 Mg 28 Mg 29 Mg 30 Mg 31 Mg 32 Mg 33 Mg
20 Na 21 Na 22 Na 23 Na 24 Na 25 Na 26 Na 27 Na 28 Na 29 Na 30 Na 31 Na
18 Ne 19 Ne 20 Ne 21 Ne 22 Ne 23 Ne 24 Ne 25 Ne 26 Ne 27 Ne 28 Ne 29 Ne
16 F 17 F 18 F 19 F 20 F 21 F 22 F 23 F 24 F 25 F 26 F 27 F
15 O 16 O 17 O 18 O 19 O 20 O 21 O 22 O 23 O 24 O 25 O
14 N 15 N 16 N 17 N 18 N 19 N 20 N 21 N 22 N 23 N
30
25
20
15
10
Z
10
15
20
25
30
N

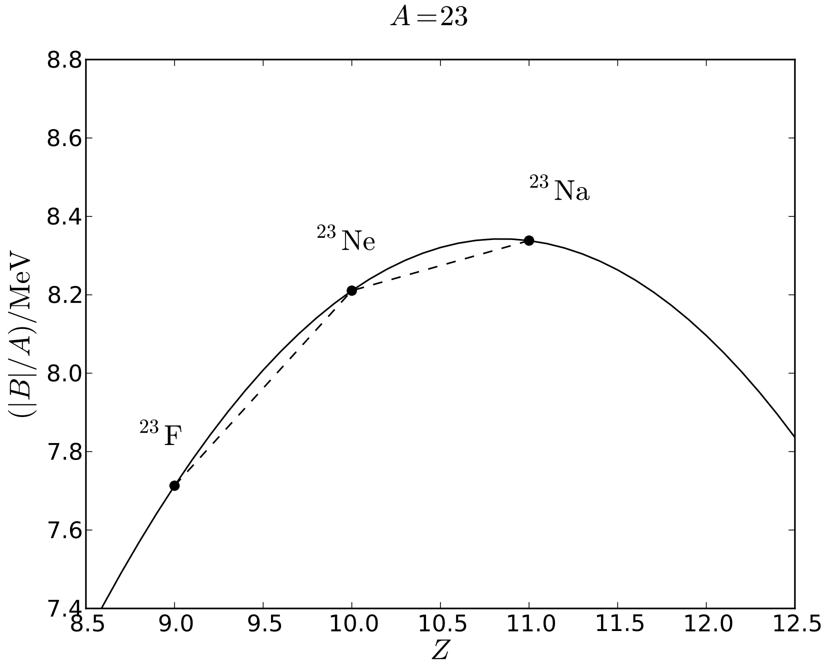
Transition evolution: super-AGB $\rightarrow$ massive star

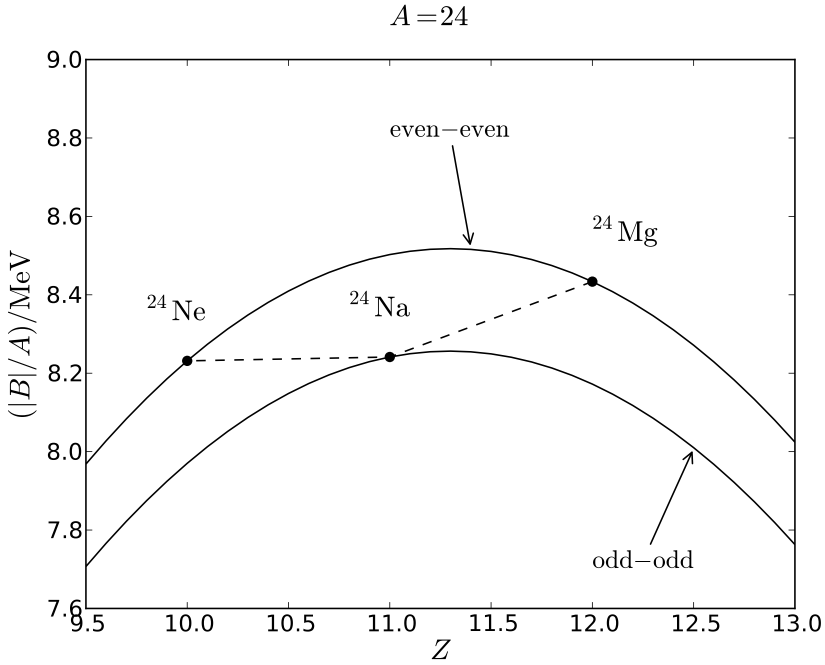


Convection is a 3D phenomenon!



8.2 $M_\odot$
8.7 $M_\odot$
8.75 $M_\odot$
8.8 $M_\odot$
9.5 $M_\odot$
12.0 $M_\odot$
Si
O
Ne
C
Si-flame
URCA
Ne-flame
Ne-flash
$\log_{10}(T_c/\mathrm{K})$
$\log_{10}(\rho_c/\mathrm{g\ cm^{-3}})$


$A = 23$
$(|B|/A)/\mathrm{MeV}$
8.8
8.6
8.4
8.2
8.0
7.8
7.6
7.4
8.5 9.0 9.5 10.0 10.5 11.0 11.5 12.0 12.5
Z
$^{23}\mathrm{Na}$
$^{23}\mathrm{Ne}$
$^{23}\mathrm{F}$

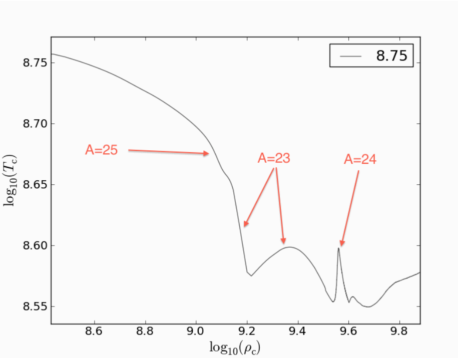


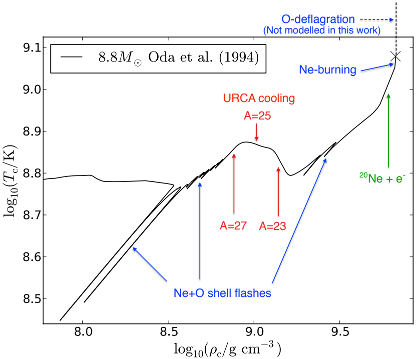
$A = 24$
9.0
8.8
8.6
8.4
8.2
8.0
7.8
7.6
9.5
10.0
10.5
11.0
11.5
12.0
12.5
13.0
Z
$(|B|/A)/\mathrm{MeV}$
even−even
odd−odd
$^{24}\mathrm{Ne}$
$^{24}\mathrm{Na}$
$^{24}\mathrm{Mg}$

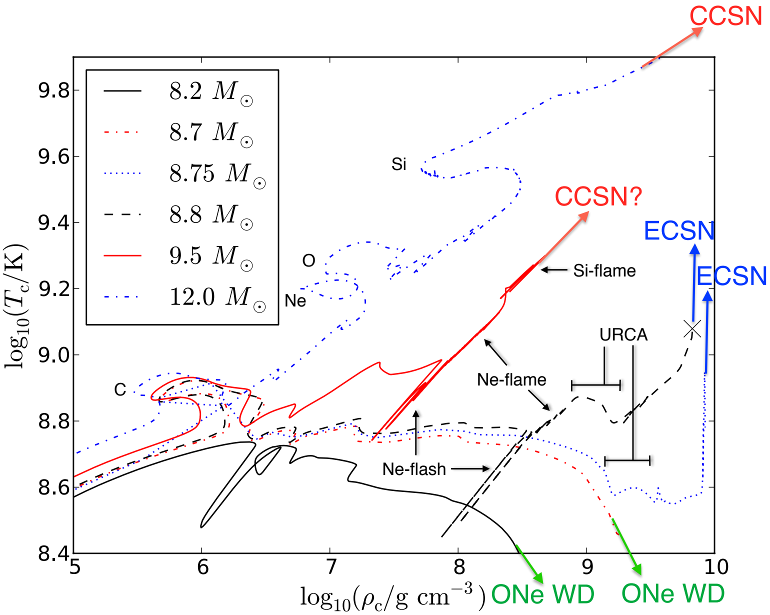
8.75 and 8.8 $M_\odot$ models - weak interactions

- Both SAGB (8.75 Mo) and failed massive stars (8.8 Mo) may produce an ECSN

URCA pairs: $^{27}\mathrm{Al} \leftrightarrow {}^{27}\mathrm{Mg}$; $^{25}\mathrm{Mg} \leftrightarrow {}^{25}\mathrm{Na}$; $^{23}\mathrm{Na} \leftrightarrow {}^{23}\mathrm{Ne}$






CCSN
CCSN?
ECSN
ECSN
Si
O
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C
Si-flame
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URCA
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8.2 $M_\odot$
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$\log_{10}(T_c/\mathrm{K})$
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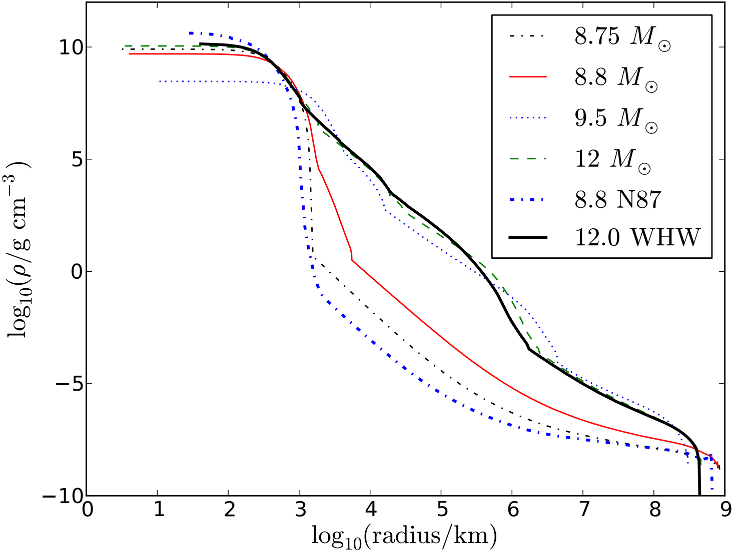
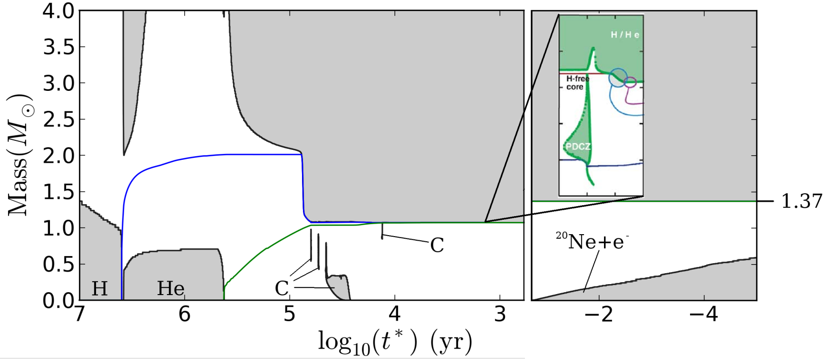
9.8
9.6
9.4
9.2
9.0
8.8
8.6
8.4
5
6
7
8
9
10

Progenitor structures



Convective Boundary Mixing (CBM) in super-AGB stars - 3DUP efficiency

H, He, C burning → ONe core growth → e$^-$-captures → O delfagration → Fe core → e$^-$-captures → collapse → explosion



Miyaji et al. (1980), Nomoto (1984, 1987), Miyaji & Nomoto (1987), Ritossa et al. (1999), Poelarends et al. (2008), Takahashi et al. (2013)

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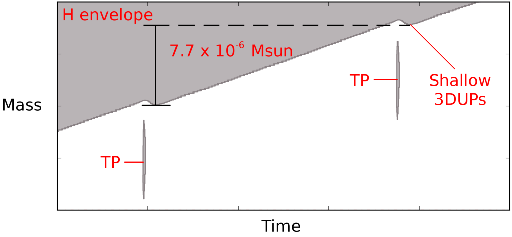
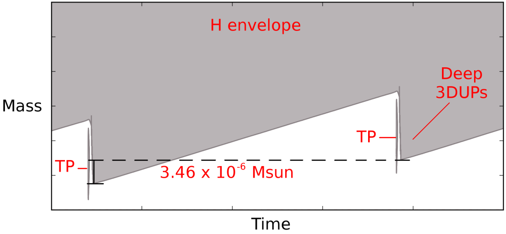
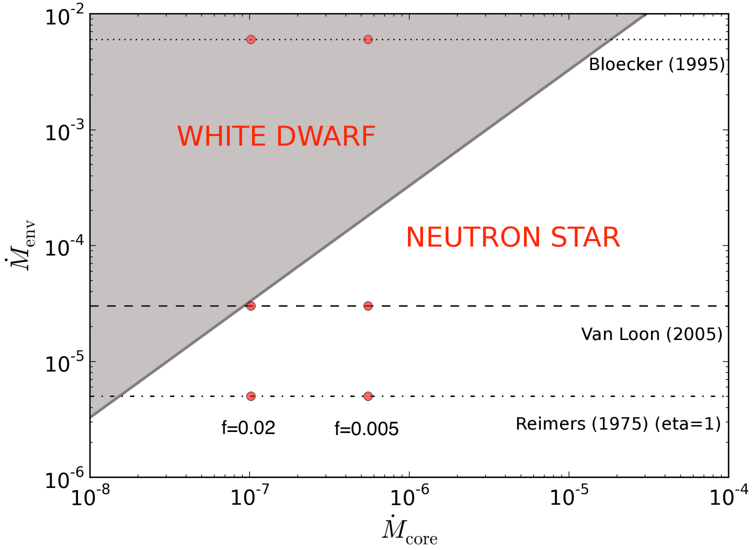


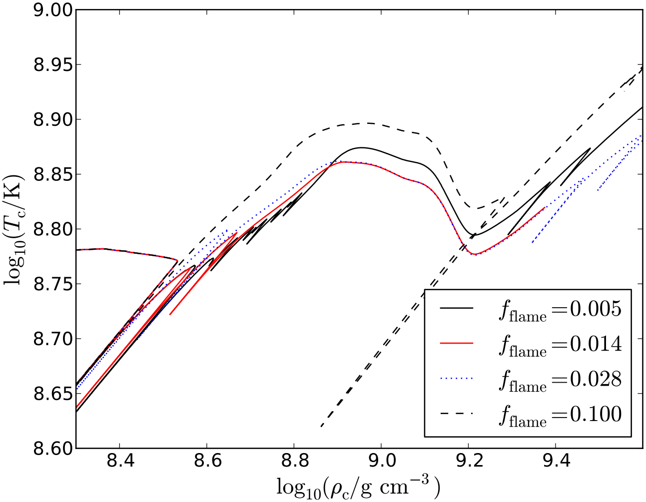




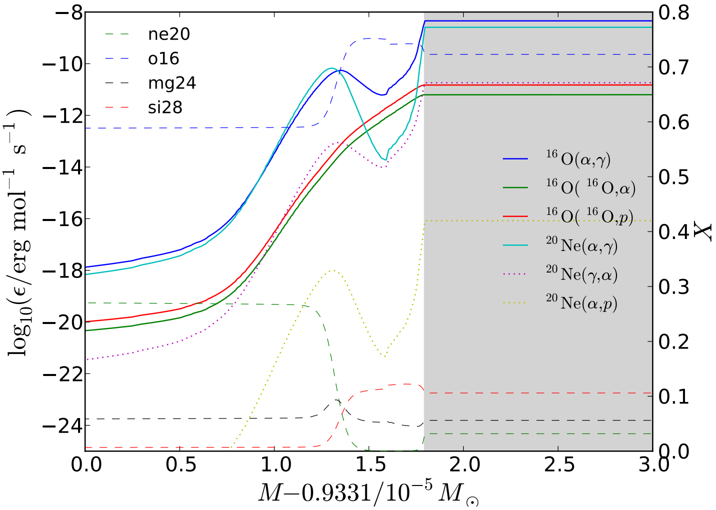
WHITE DWARF
NEUTRON STAR
Bloecker (1995)
Van Loon (2005)
Reimers (1975) (eta=1)
f=0.02
f=0.005
$\dot{M}_{\mathrm{env}}$
$\dot{M}_{\mathrm{core}}$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}

Boundary mixing and NeO flame propagation

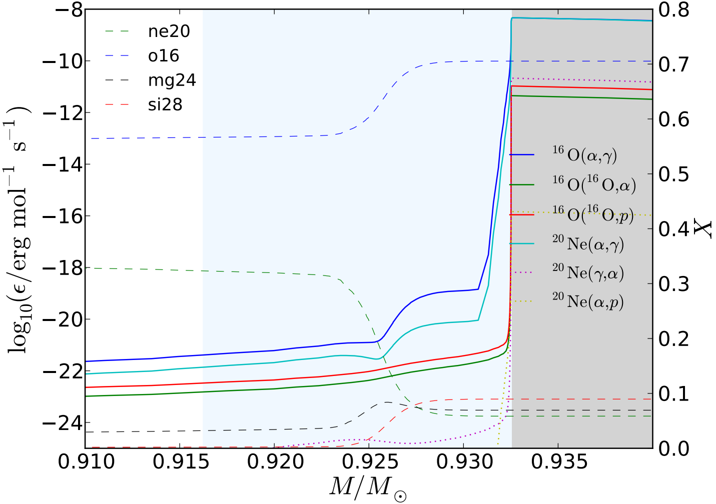
- Stronger mixing at interface: different behaviour, same fate of 8.8 $M_\odot$ model (EC-SN)



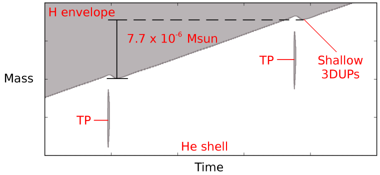
- No mixing at interface: conductive propagation – NO CONTRACTION

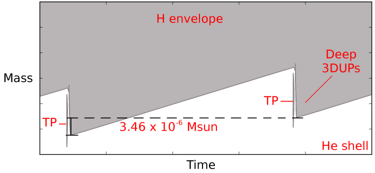


- Mixing at interface characterised by $f_{\rm CBM} = 0.005$: compressional propagation (periodic contraction)

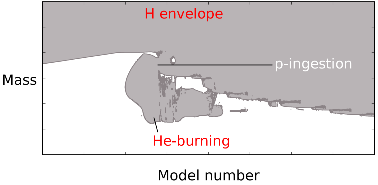


(S-)AGB thermal pulse ('TP')

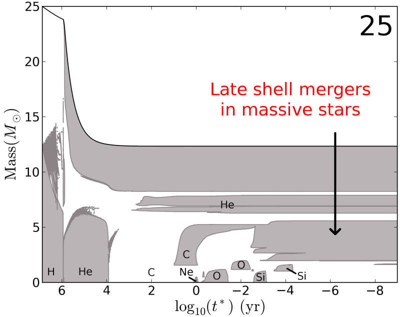


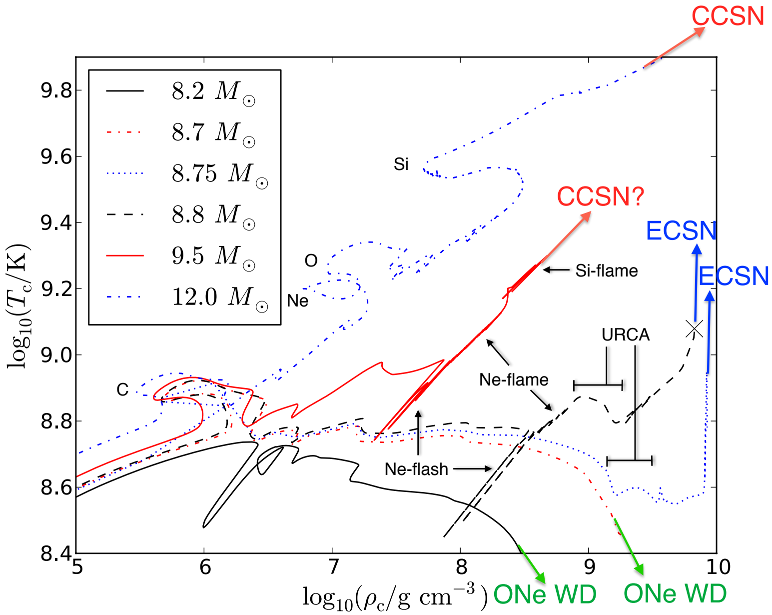


(S-)AGB hydrogen ingestion



$$^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}(\beta^{+}\nu)^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$$

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Si
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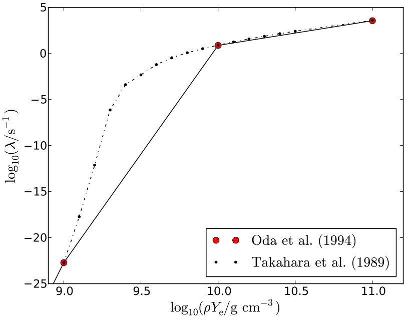
Si-flame
URCA
Ne-flame
Ne-flash
$\log_{10}(T_c/\mathrm{K})$
$\log_{10}(\rho_c/\mathrm{g\ cm^{-3}})$
ONe WD
ONe WD

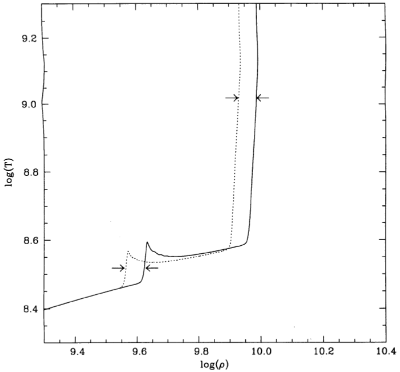
Weak rates - problems and solutions

- $\log\langle ft\rangle$
- Sufficient resolution to determine threshold densities.

$\lambda(^{24}\mathrm{Mg}(\mathrm{e}^-,\bar{\nu})^{24}\mathrm{Na})$ at $T_9 = 0.4$



- Consistent $e^{\pm}$-capture, $\beta^{\pm}$-decay, ν-loss rates.
- Coulomb corrections.



Gutierrez et al. (1996) - only rate corrections.

8.75 and 8.8 $M_\odot$ models - weak interactions

- Both SAGB (8.75 Mo) and failed massive stars (8.8 Mo) may produce an ECSN

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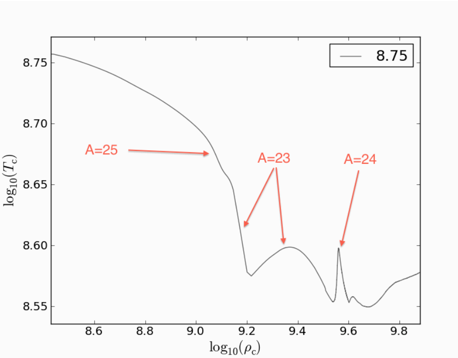
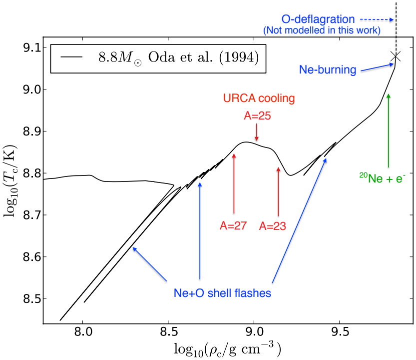
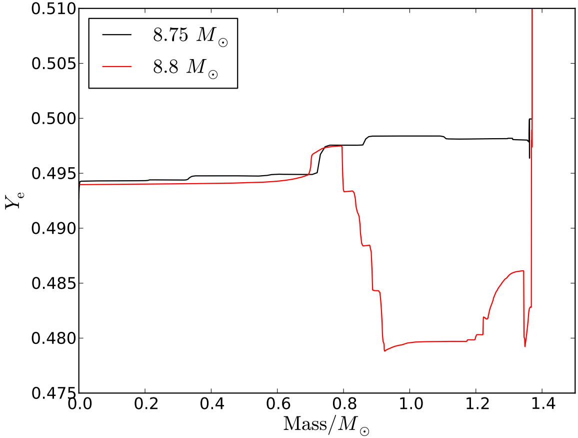




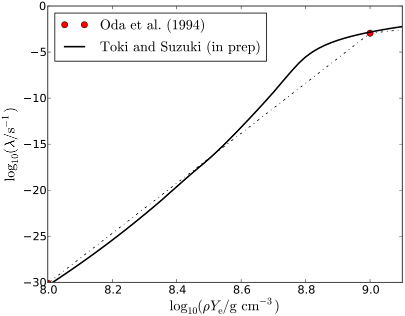
8.8 $M_\odot$: Y_e-driven contraction ($Y_{\mathrm{e,min}} < 0.48$)



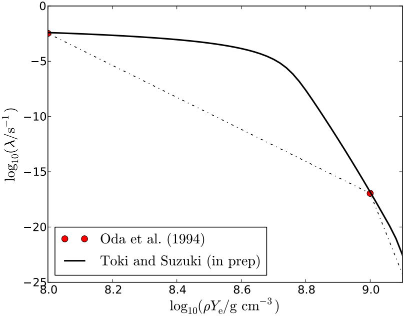
8.75 $M_\odot$: $\dot{M}_{\mathrm{core}}$-driven contraction (time for ν-losses)

New SD-shell rates (URCA pairs)

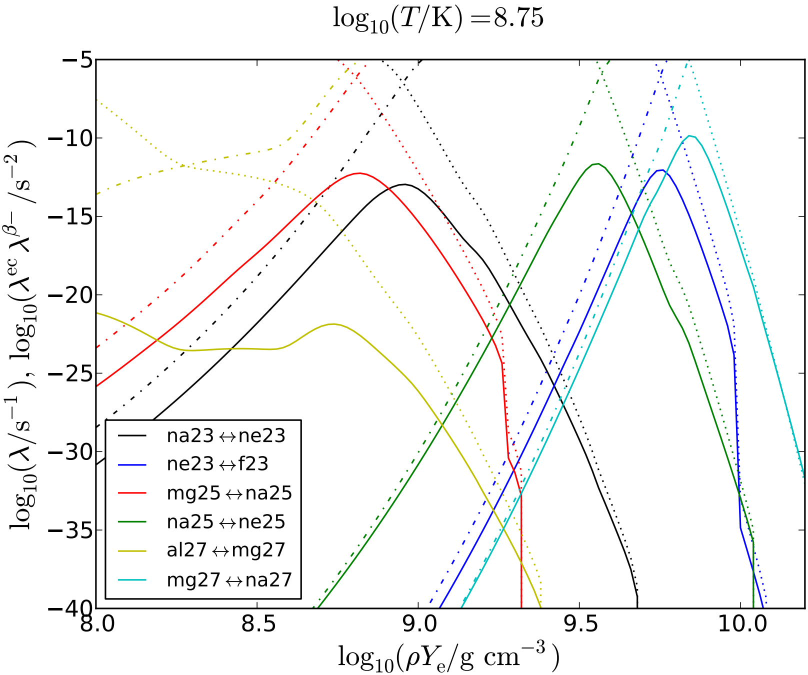
- Results for A=25 URCA pair (Toki et al., 2013), USDB



^{25}Mg + e$^-$ $\rightarrow$ ^{25}Na + ν_e

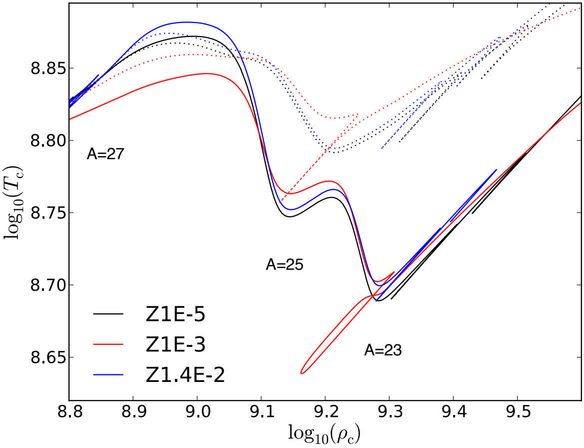


^{25}Na $\rightarrow$ ^{25}Mg + e$^-$ + $\bar{\nu}_e$


$\log_{10}(T/\mathrm{K}) = 8.75$
$\log_{10}(\lambda/\mathrm{s}^{-1})$, $\log_{10}(\lambda^{\mathrm{ec}}\lambda^{\beta-}/\mathrm{s}^{-2})$
$\log_{10}(\rho Y_{\mathrm{e}}/\mathrm{g\ cm}^{-3})$
−5
−10
−15
−20
−25
−30
−35
−40
8.0
8.5
9.0
9.5
10.0
na23 ↔ ne23
ne23 ↔ f23
mg25 ↔ na25
na25 ↔ ne25
al27 ↔ mg27
mg27 ↔ na27

New SD-shell rates (URCA pairs)

- Results using A=23, 25, 27 pairs (Toki et al. 2013) in MESA

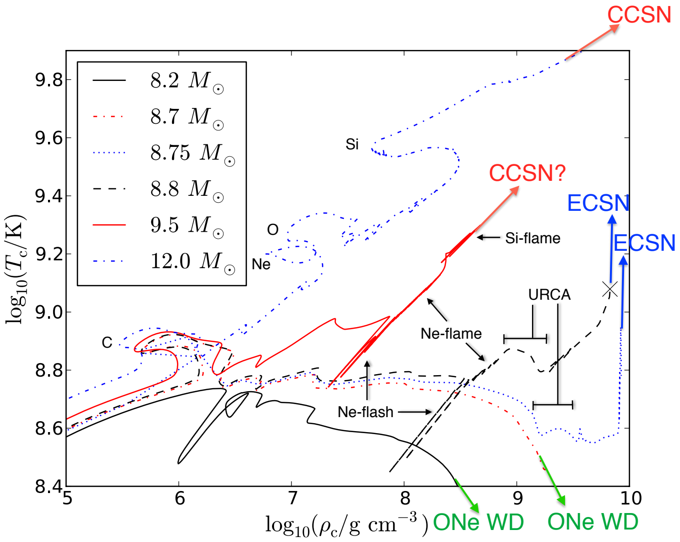


Summary

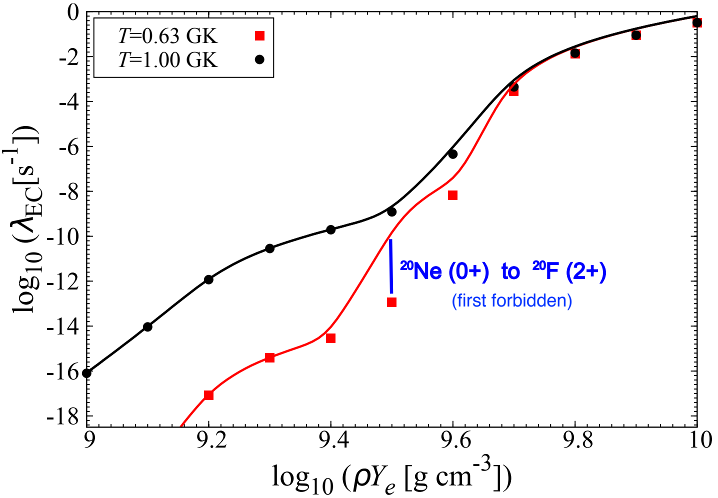
- ECSN progenitor models from 2 evolutionary paths. (well known SAGB and new 'failed massive star').
- Mass loss still very uncertain for super-AGB phase.
- 3D simulations of stellar regimes are cruicial to constrain boundary behaviour (e.g. Herwig et al. (2011), Mocák et al. (2011)).
- Well resolved grids of weak rates, especially *sd*-shell nuclei. Coulomb corrections to both the rate and the energy production/loss should be included.

Summary

Jones et al. (2013), ApJ 772, 150



New $^{20}\mathrm{Ne}(\mathrm{e}^-,\nu)^{20}\mathrm{F}$ rate



G. Martinez-Pinedo, Y. H. Lam et al. (in prep.)