The evolution of supernova progenitors

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In collaboration with:

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Outline

SN progenitor overview

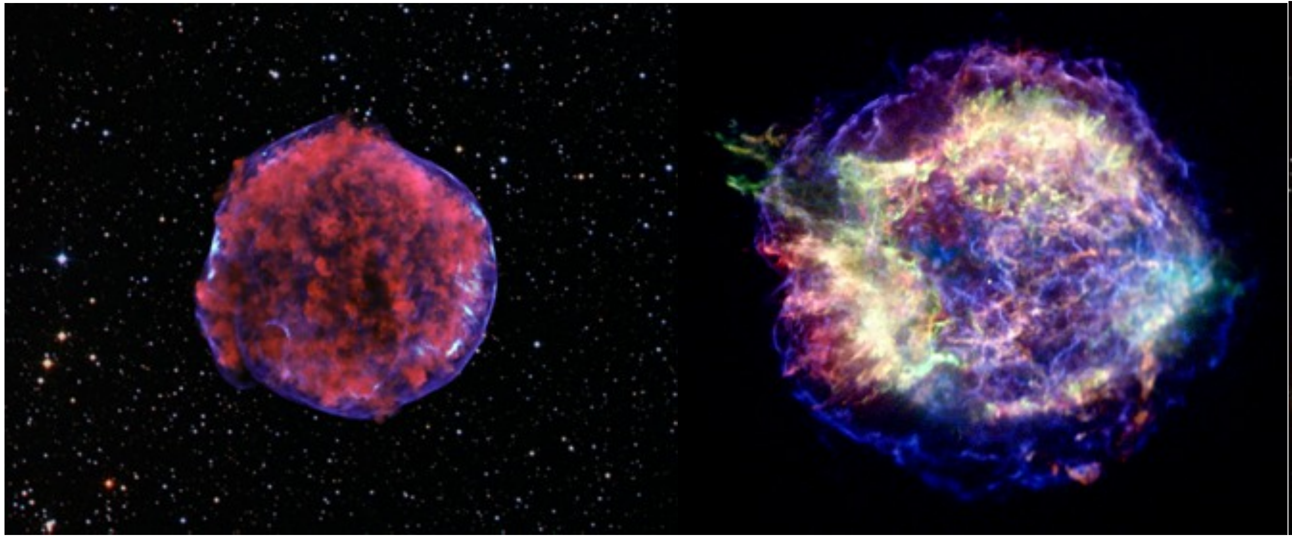
Fate of 8-10 solar-mass stars

Hybrid C-O-Ne white dwarfs and failed massive stars

Massive stars and CCSNe

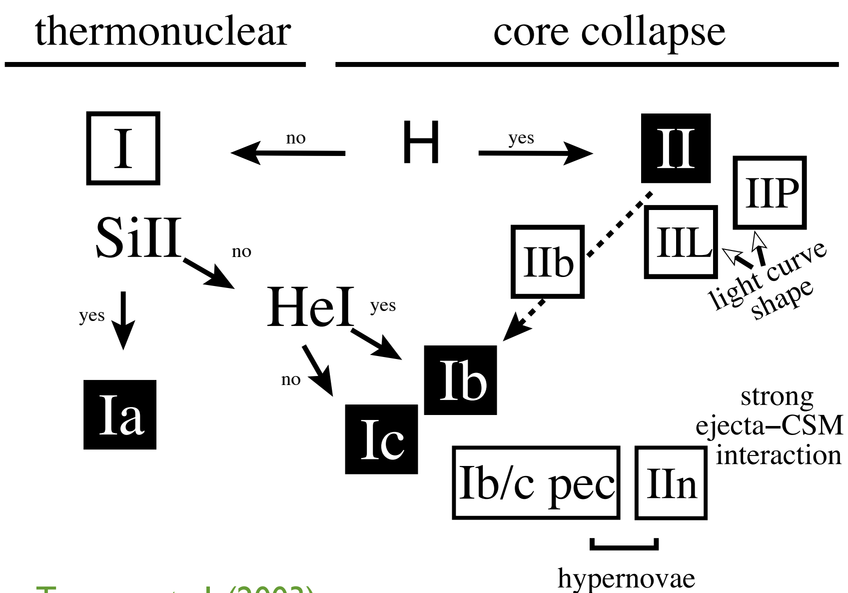
Open questions and future direction

Supernovae



Images courtesy of Hubble and Chandra

Observational Classification



Turraro et al. (2003)

Link to stellar evolution

AGB star

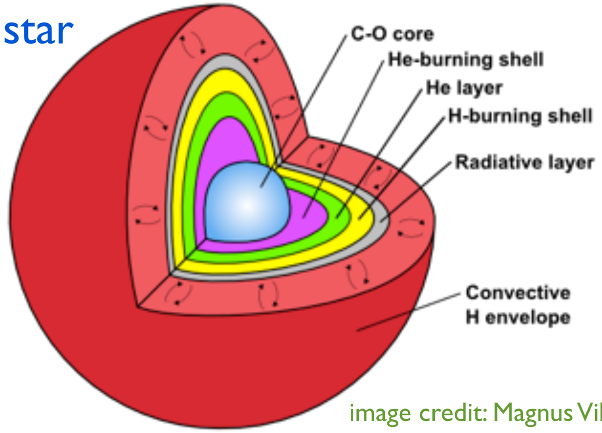
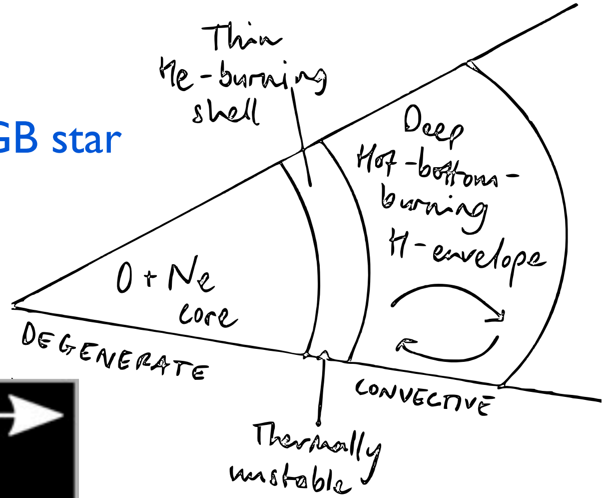


image credit: Magnus Vilhelm Persson

super-AGB star



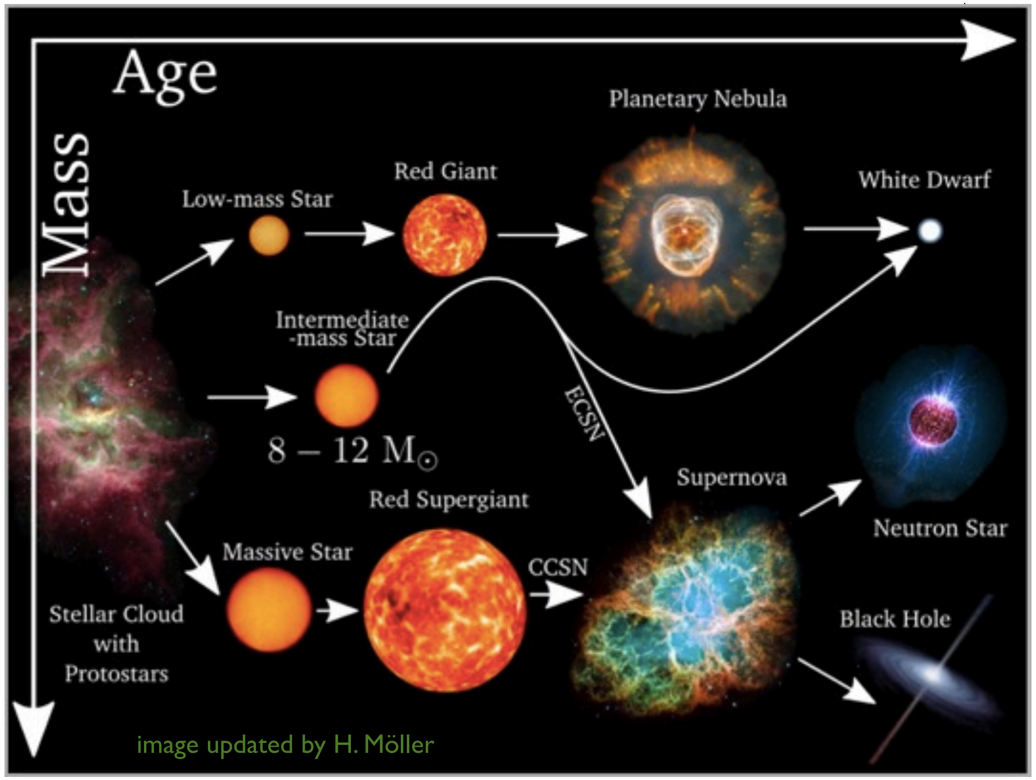
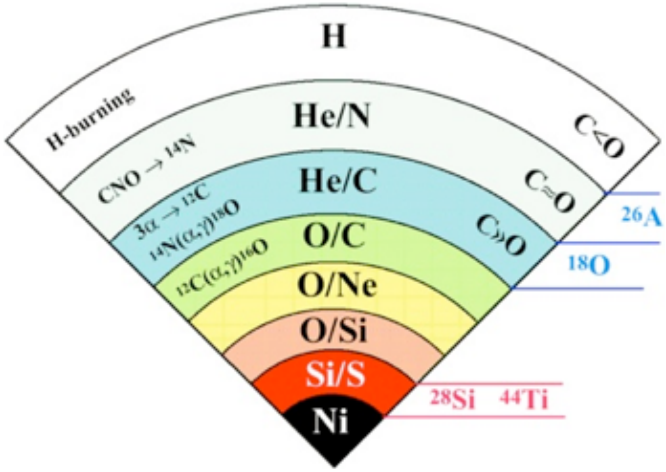


image updated by H. Möller

Massive star



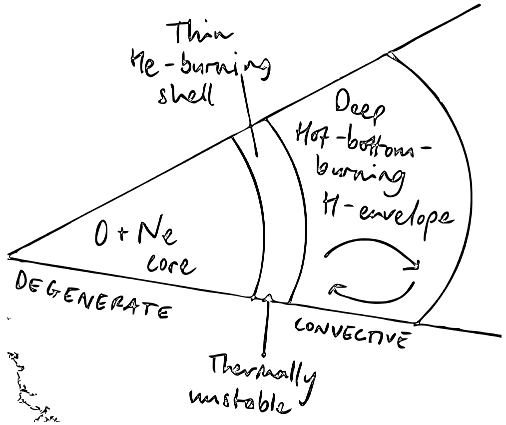
Super-AGB stars: EC-SN progenitors?

Miyaji+ (1980); Nomoto (1984, 1987); Miyaji & Nomoto (1987);
Ritossa+ (1999); Poelarends+ (2008); Takahashi+ (2013)

AGB Mass loss:

Mass loss > core growth → **ONe white dwarf**

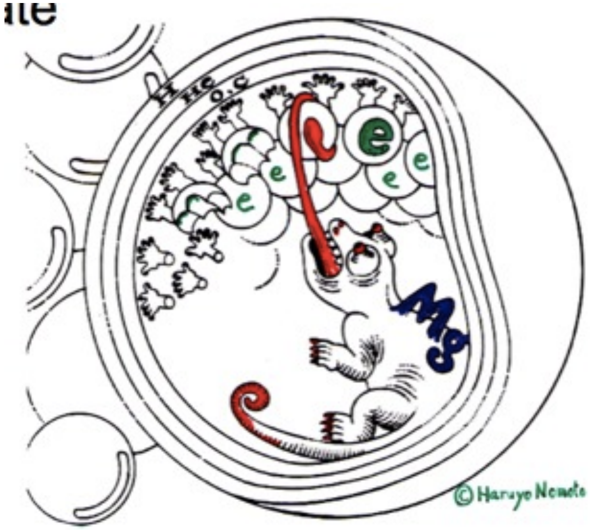
Mass loss < core growth → Oxygen deflagration → **EC-SN**



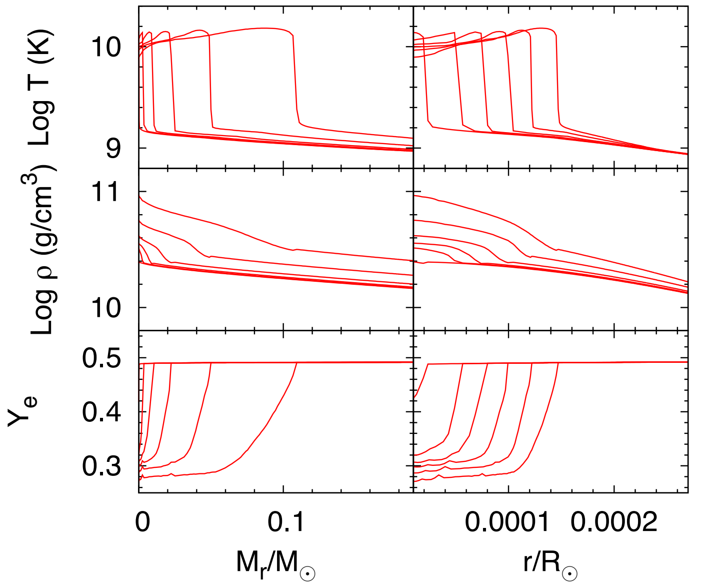
Double electron captures on even-A nuclei produce heat

^{24}Mg → ^{24}Na → ^{24}Ne $\log \rho_{crit} \approx 9.6$

^{20}Ne → ^{20}F → ^{20}O $\log \rho_{crit} \approx 9.8$



Takahashi+ (2013)

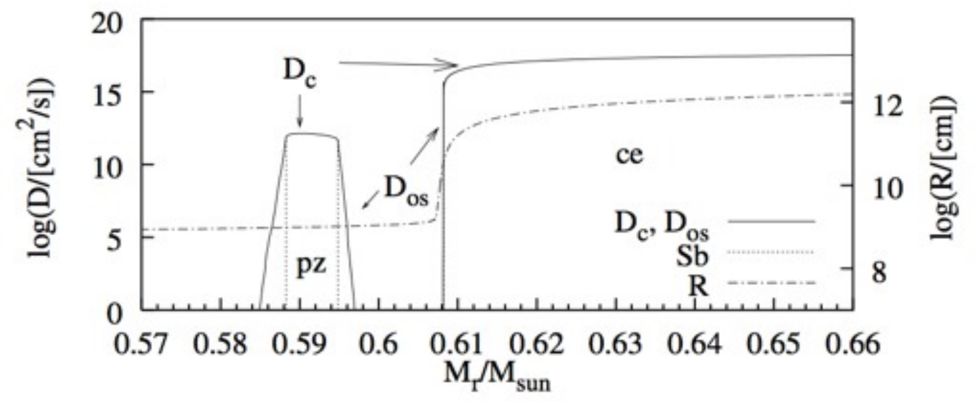


Evolution along the TP-SAGB

Convective boundary mixing modelled with exponentially decaying diffusion coefficient

(Freytag+ 1996, Herwig+ 1997)

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



f = 0.25 for shallow surface convection zones
(Freytag+ 1996)

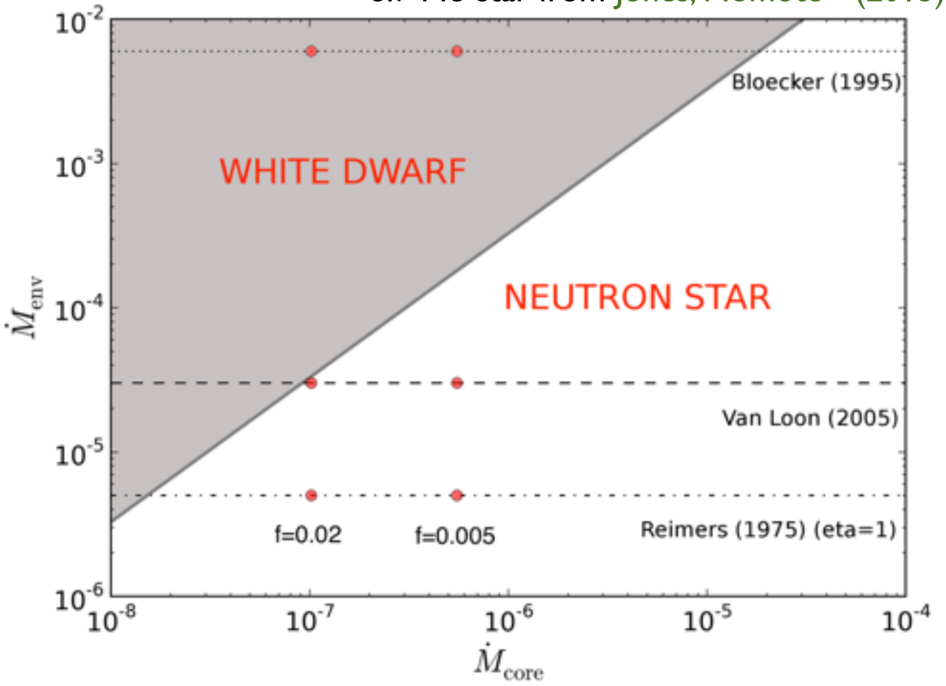
f = 0.008 below helium shell flash
(Werner & Herwig 2006, Denissenkov+ 2013)

f = 0.128 at bottom of convective envelope for 3DUP in AGB stars
(Lugaro+ 2003)

Fate of super-AGB stars depends on uncertain mass-loss rates and uncertain convective boundary mixing (CBM) efficiency

see also Poelarends (2008)

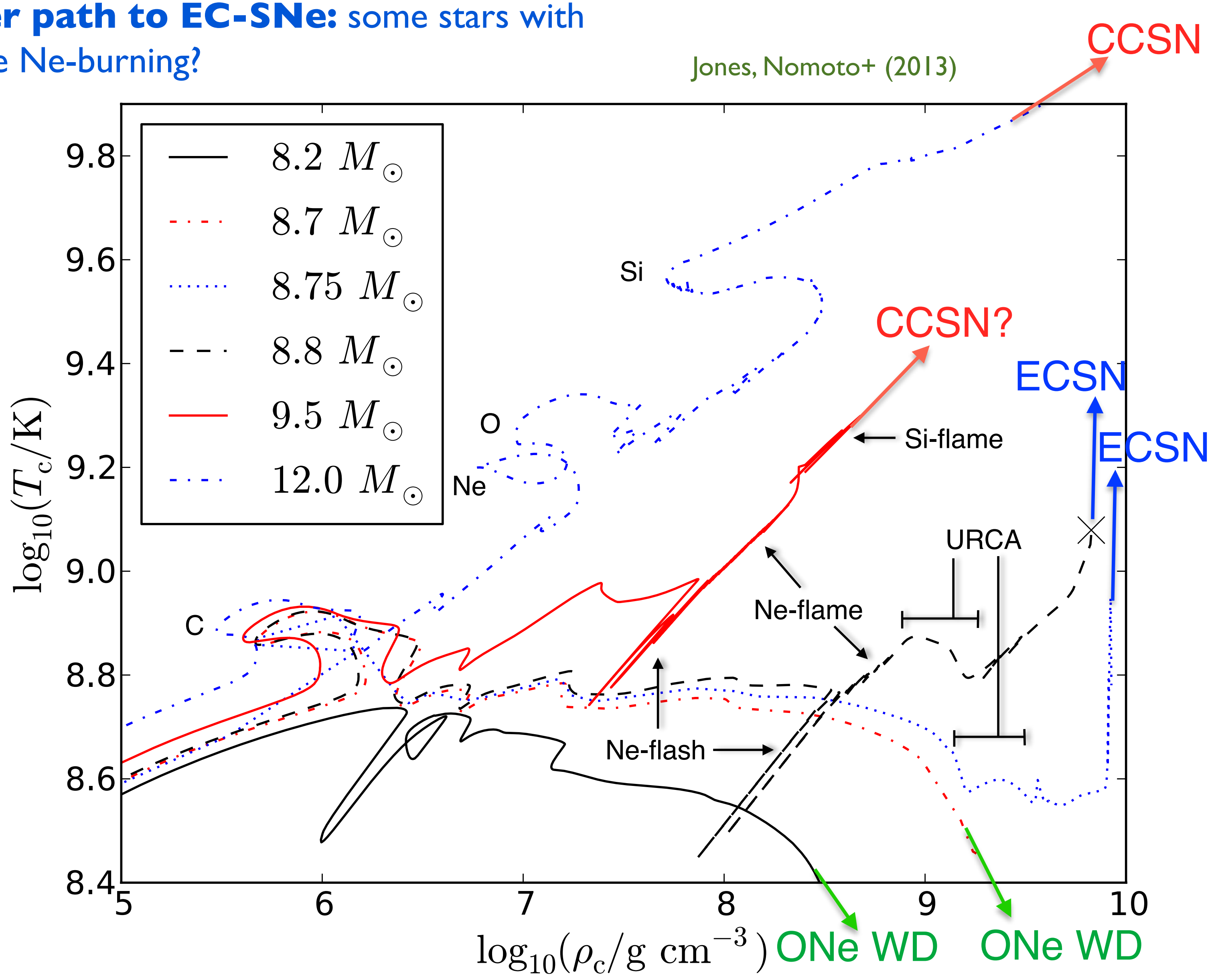
8.7 Mo star from Jones, Nomoto+ (2013)



Complex evolution of 8–12 M⊙ stars

Another path to EC-SNe: some stars with off-centre Ne-burning?

Jones, Nomoto+ (2013)



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CO White dwarfs → SN1a

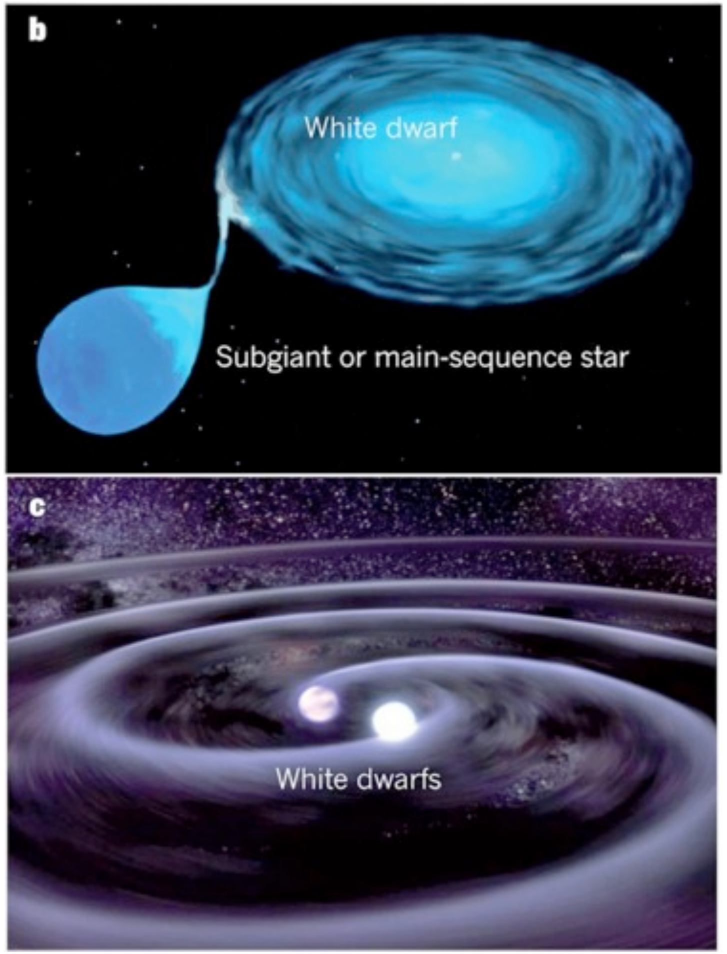
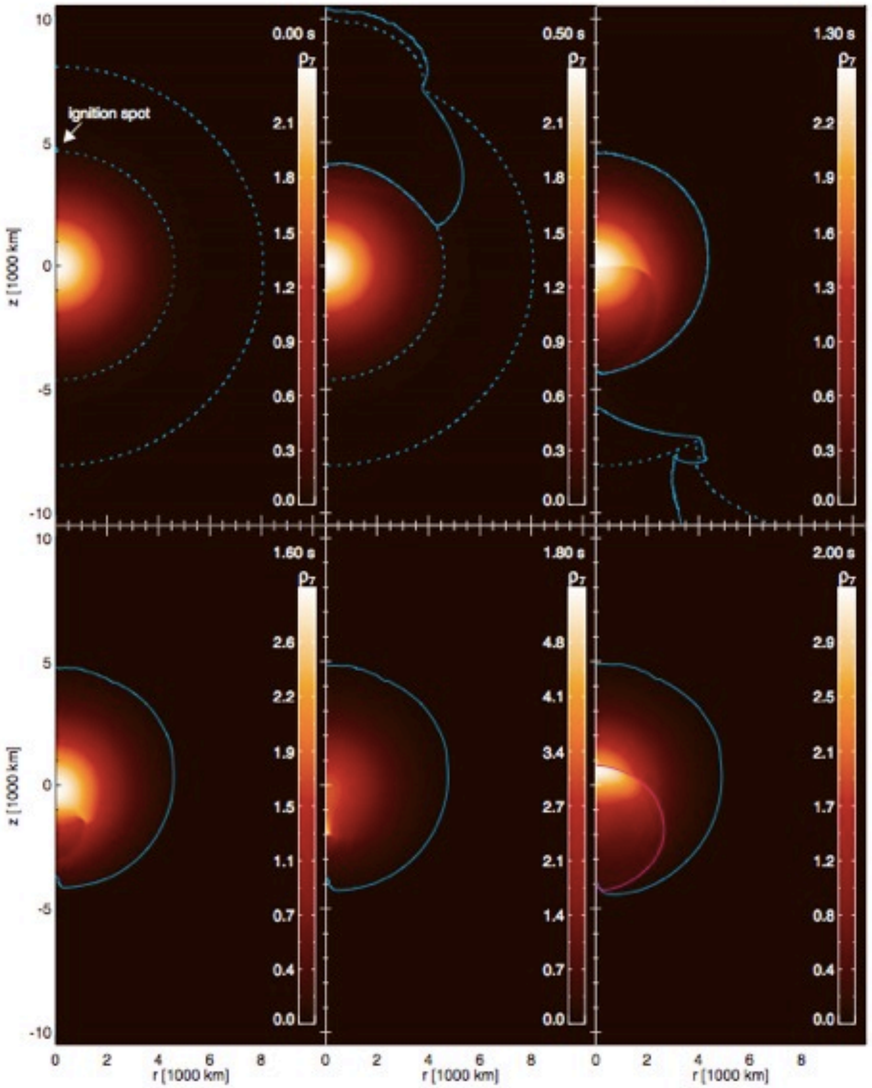


Image credit: STSCI, NASA; NASA/T. Strohmayer (GSFC)/D. Berry (Chandra).

Thermonuclear explosion
(explosive carbon burning)

Sub-Chandrasekhar explosions also possible; double-detonation
(Fink+2010)



Hybrid-core stars

Mixing across the convective boundary chokes flame propagation following off-centre ignition, leading to the formation of hybrid-core stars

Hybrid C-O-Ne white dwarfs as progenitors of type Ia supernovae: dependence on Urca process and mixing assumptions

P. A. Denissenkov[1,4,9*], J. W. Truran[2,4,9], F. Herwig[1,4,9], S. Jones[1,5,9], B. Paxton[3], K. Nomoto[6], T. Suzuki[7] and H. Toki[8]

C flame: $10^{-4} \lesssim f_{\rm CBM} \lesssim 10^{-3}.$

Ne flame: $10^{-6} \lesssim f_{\rm CBM} \lesssim 10^{-5}.$

But what should these *f*-values be???

Criterion for C-flame propagation:

$$\frac{d\log\varepsilon_{\rm nuc}}{d\log T} = \frac{d\log\rho}{d\log T} + 2\frac{d\log X(^{12}{\rm C})}{d\log T} + n. \quad < 0$$

Denisenkov+ 2013

Criterion for Ne-flame propagation:

$$\frac{\partial\ln\epsilon}{\partial\ln T} = \frac{\partial\ln Y_{20}}{\partial\ln T} + \frac{\partial\ln\lambda_{20\gamma\alpha}}{\partial\ln T} + \frac{\partial\ln\phi}{\partial\ln T} - \frac{\partial\ln\zeta}{\partial\ln T} < 0.$$

Jones, Hirschi & Nomoto (ApJ, in press)

Neon-flame quench → O-Ne-Si core → EC-SN

Carbon-flame quench → C-O-Ne core → SN1ax?

URCA process

High density

$$
\begin{array}{llllllll}
(i) & {}^{A}\mathrm{Z} & + & \mathrm{e}^{-} & \rightarrow & {}^{A}(\mathrm{Z}-1) & + & \nu \\
(ii) & & & {}^{A}(\mathrm{Z}-1) & \rightarrow & {}^{A}\mathrm{Z} & + & \mathrm{e}^{-} + \bar{\nu}.
\end{array}
$$

Low density

At critical (intermediate) density, equilibrium is achieved and strong neutrino cooling occurs

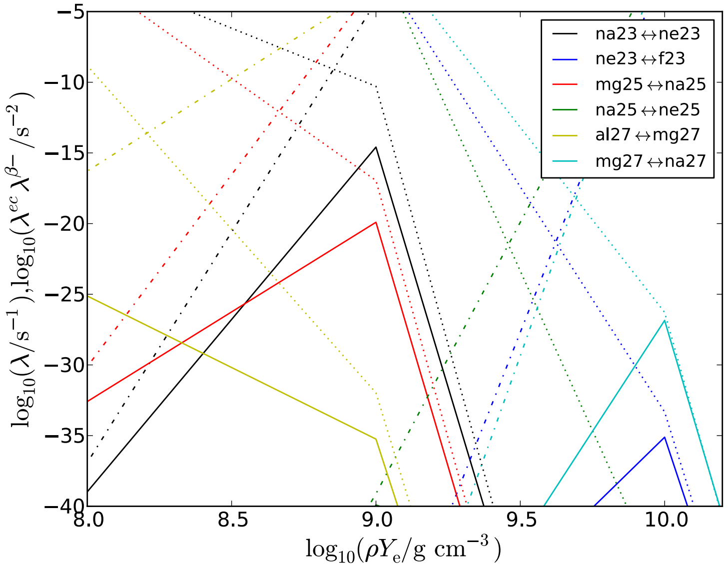
Key reactions:

^{25}Mg $\longleftrightarrow$ ^{25}Na

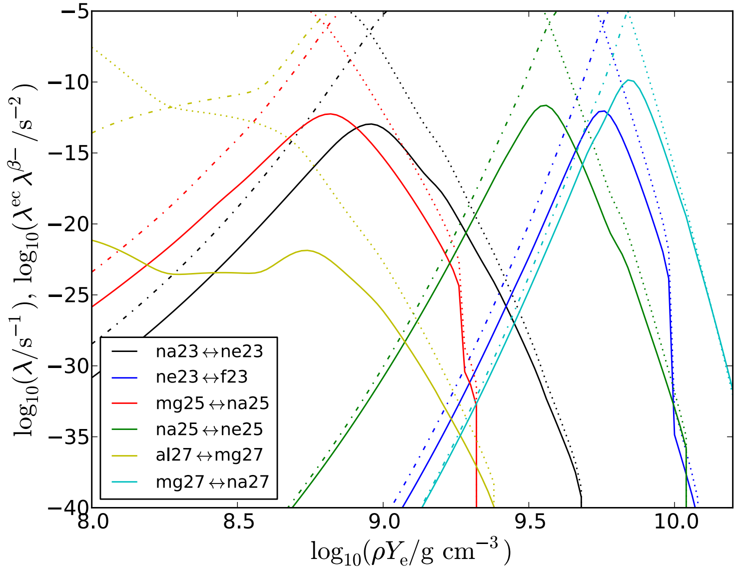
^{23}Na $\longleftrightarrow$ ^{23}Ne

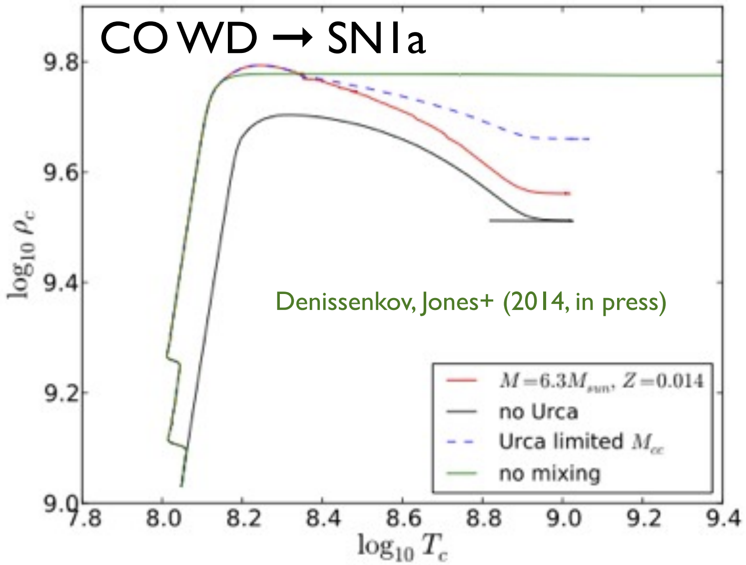
Weak reaction rates for URCA pairs

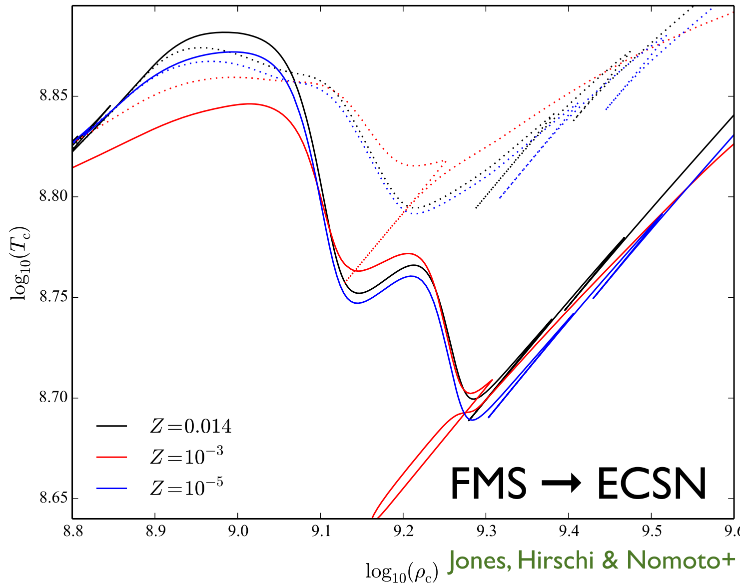
Rates from Oda+ (1994) with interpolation



Rates from Toki, Suzuki, Nomoto, Jones+ (2013) with interpolation







Jones, Hirschi & Nomoto+ (ApJ, in press)

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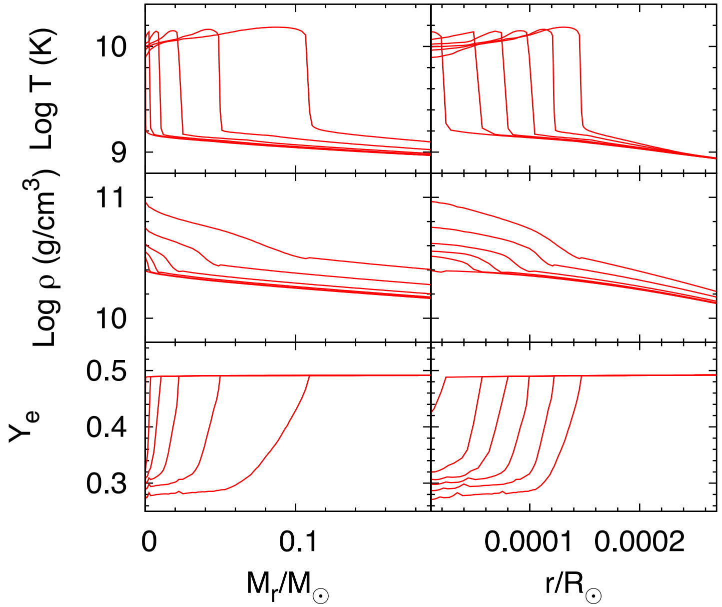
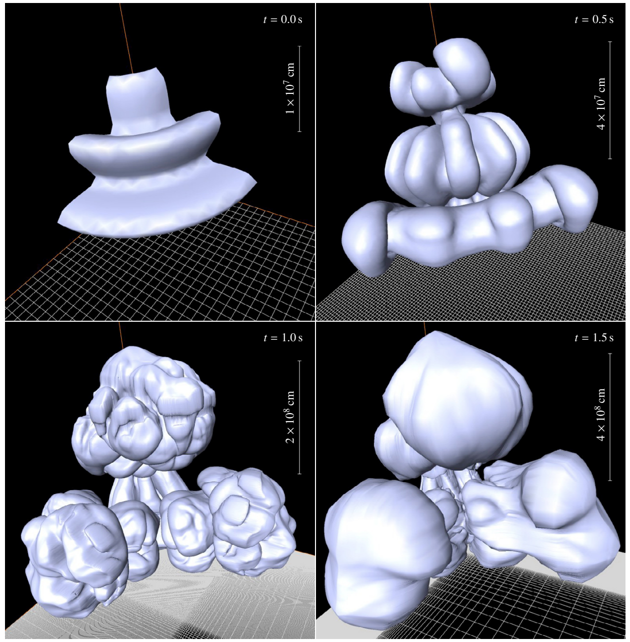
O-deflagration pre-ECSN

Takahashi+ (2013)



Carbon deflagration (Röpke+ 2006)



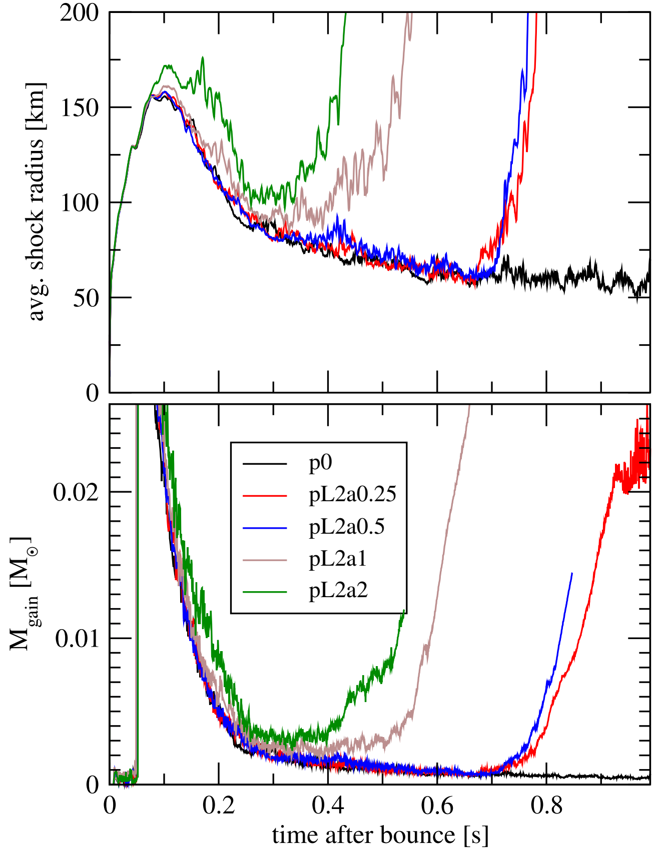
Do hydrodynamic instabilities play a role during deflagration?

What is the impact of nuclear reactions involving neutron-rich nuclei at high densities?
(H. Möller's talk at 15:30)

Does O-deflagration necessarily result in collapse?

Massive stars: CCSNe

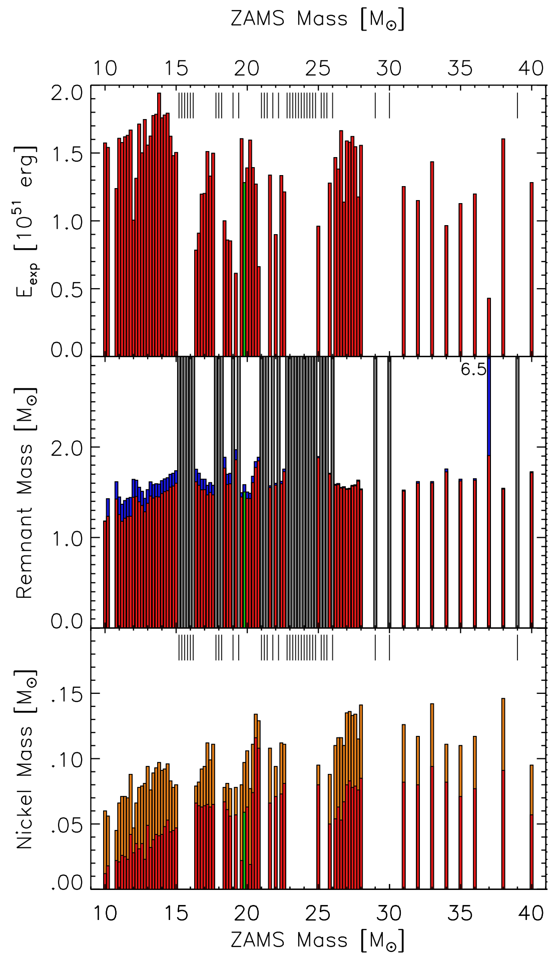
Large-scale asymmetries in progenitor structure facilitate shock revival in (2D and 3D) CCSN simulations



Müller & Janka (2014); see also Couch & Ott (2013)

Important predictions:

Nickel mass (GCE, lightcurve)
Remnant mass (NS mass distribution)
Explosion energy
Explosive nucleosynthesis

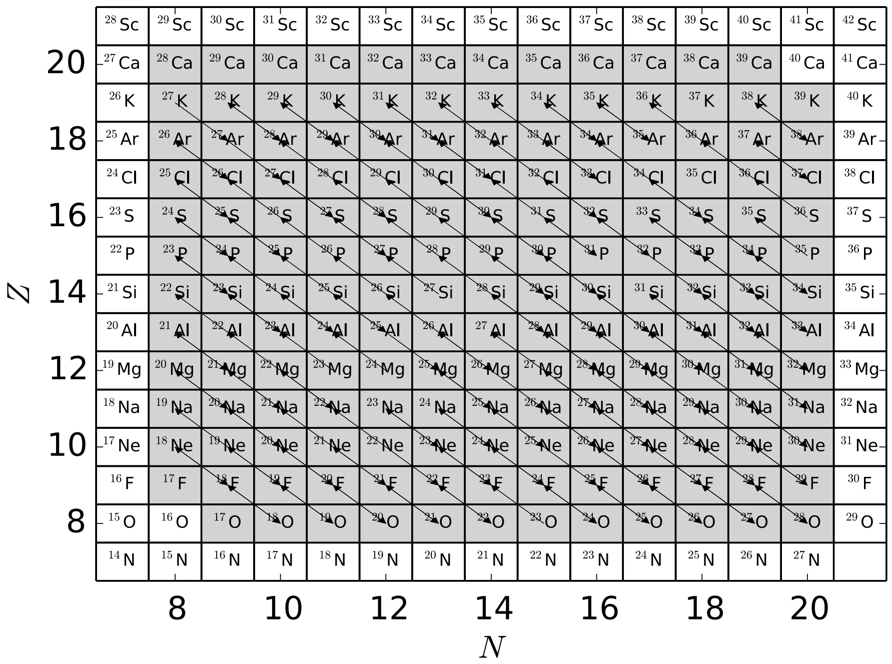


Ugliano+ (2012)

Non-monotonic behaviour of explosion properties wrt initial progenitor mass

Oxygen and silicon-burning in massive stars

Jones, Bertolli & Johnson (in prep.)



Weak interactions are critical for determining pre-SN structure and explosive nucleosynthesis

TABLE 2

OXYGEN BURNING

Basic reactions:

$$^{16}\mathrm{O}\begin{cases}(^{16}\mathrm{O},p)^{31}\mathrm{P}\\(^{16}\mathrm{O},\alpha)^{28}\mathrm{Si}\\(^{16}\mathrm{O},n)^{31}\mathrm{S}(\beta^+)^{31}\mathrm{P}\end{cases}$$

$^{31}\mathrm{P}(p,\alpha)^{28}\mathrm{Si}(\alpha,\gamma)^{32}\mathrm{S}$

$^{28}\mathrm{Si}(\gamma,\alpha)^{24}\mathrm{Mg}(\alpha,p)^{27}\mathrm{Al}(\alpha,p)^{30}\mathrm{Si}$

$^{32}\mathrm{S}(n,\gamma)^{33}\mathrm{S}(n,\alpha)^{30}\mathrm{Si}(\alpha,\gamma)^{34}\mathrm{S}$

$$^{28}\mathrm{Si}(n,\gamma)^{29}\mathrm{Si}\begin{cases}(\alpha,n)^{32}\mathrm{S}(\alpha,p)^{35}\mathrm{Cl}\\(p,\gamma)^{30}\mathrm{P}(\beta^+)^{30}\mathrm{Si}\end{cases}$$

Electron captures:

$^{33}\mathrm{S}(e^-,\nu)^{33}\mathrm{P}(p,n)^{33}\mathrm{S}$

$^{35}\mathrm{Cl}(e^-,\nu)^{35}\mathrm{S}(p,n)^{35}\mathrm{Cl}$

Massive stars ($M_* = 16\ M_\odot$):

$$^{32}\mathrm{S}(\alpha,\gamma)^{36}\mathrm{Ar}\begin{cases}(\alpha,p)^{39}\mathrm{K}\\(n,\gamma)^{37}\mathrm{Ar}(\beta^+)^{37}\mathrm{Cl}\end{cases}$$

$$^{35}\mathrm{Cl}\begin{cases}(\gamma,p)^{34}\mathrm{S}(\alpha,\gamma)^{38}\mathrm{Ar}\\(e^-,\nu)^{35}\mathrm{S}(\gamma,p)^{34}\mathrm{S}\end{cases}\begin{cases}(p,\gamma)^{39}\mathrm{K}(p,\gamma)^{40}\mathrm{Ca}\\(\alpha,\gamma)^{42}\mathrm{Ca}\begin{matrix}(\alpha,\gamma)^{46}\mathrm{Ti}\\(\alpha,p)^{45}\mathrm{Sc}(p,\gamma)^{46}\mathrm{Ti}\end{matrix}\end{cases}$$

Lower mass stars ($M_* = 4\ M_\odot$):

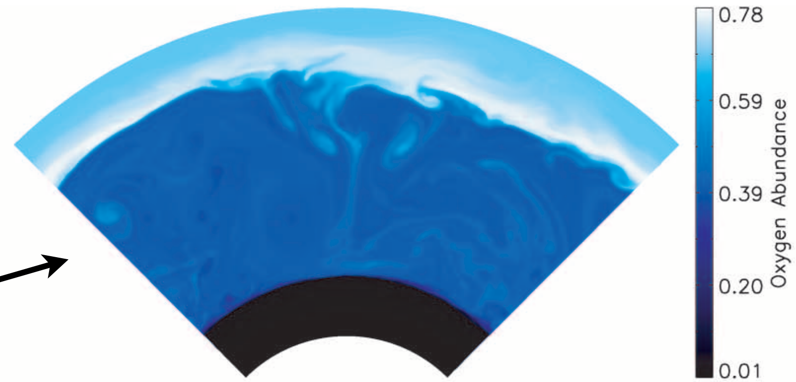
$^{31}\mathrm{P}(e^-,\nu)^{31}\mathrm{S}$ $\quad$ $^{31}\mathrm{P}(n,\gamma)^{32}\mathrm{P}$

$^{32}\mathrm{S}(e^-,\nu)^{32}\mathrm{P}(p,n)^{32}\mathrm{S}$

$^{33}\mathrm{P}(p,\alpha)^{30}\mathrm{Si}$

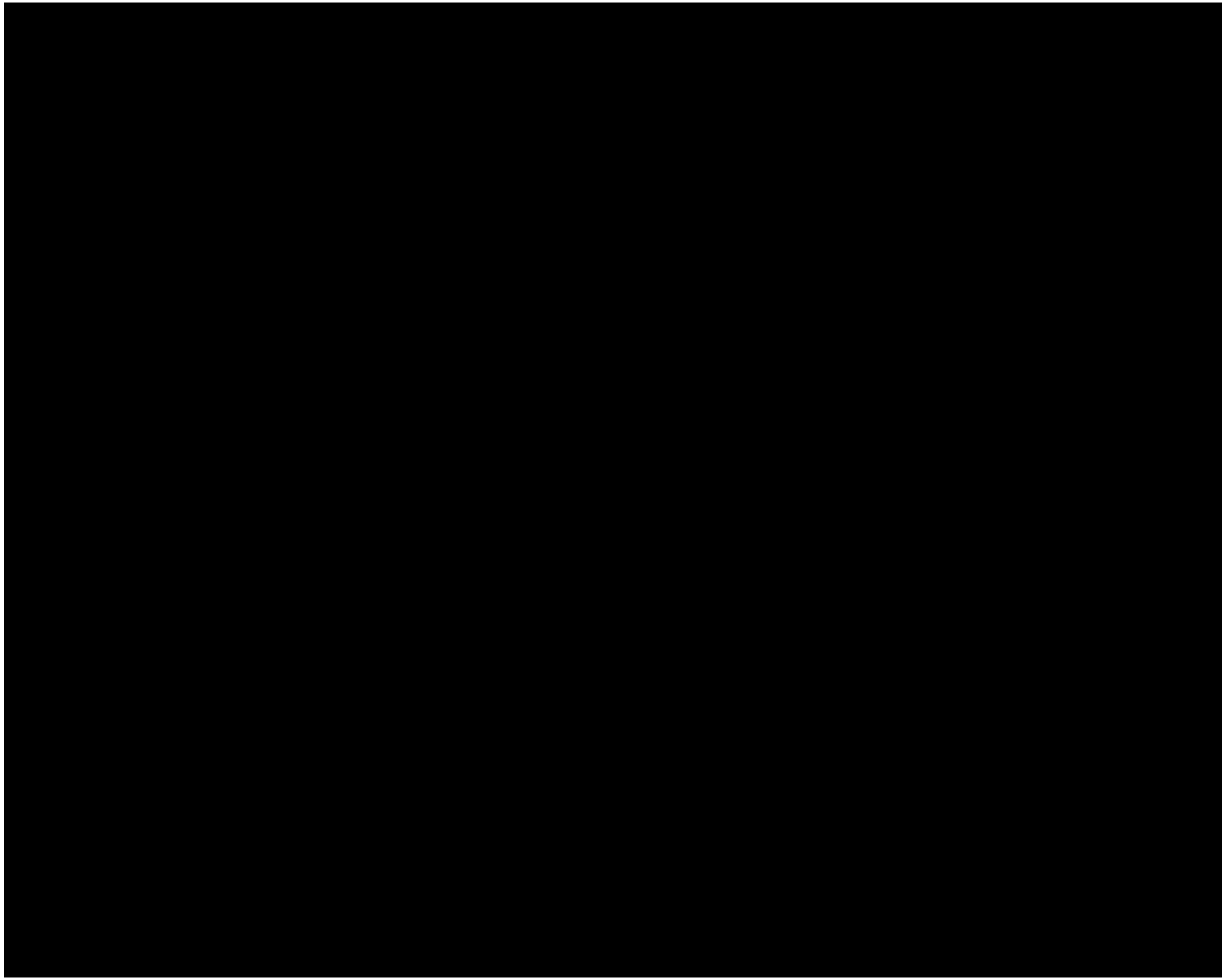
Thielemann & Arnett (1985)

Likely enhanced mass loss and eruptions during advanced burning stages (e.g. oxygen shell burning) → SN impostors, Type IIn SNe (Smith & Arnett 2014)



Meakin & Arnett (2007)

Oxygen shell burning: 25 $M_\odot$



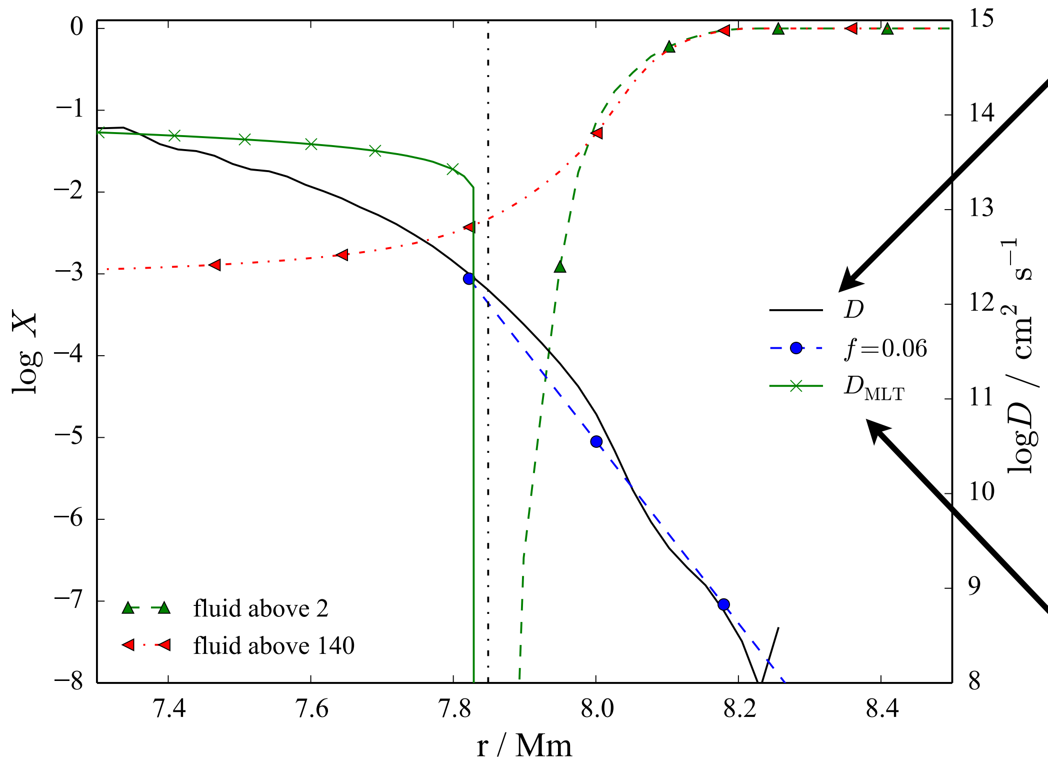
Jones, Herwig & Woodward (in prep.)

Oxygen shell burning: CBM in 1D

Jones, Bennett, Herwig, Hirschi & Woodward (in prep.)

$$x_m(X_k^n - X_k^{n+1}) = \frac{X_k^{n+1} - X_{k-1}^{n+1}}{x_l} \Delta t\, D_k + \frac{X_k^{n+1} - X_{k+1}^{n+1}}{x_r} \Delta t\, D_{k+1},$$

Sure enough, convective boundary mixing can be well approximated for O-shell burning with an exponentially decaying diffusion coefficient



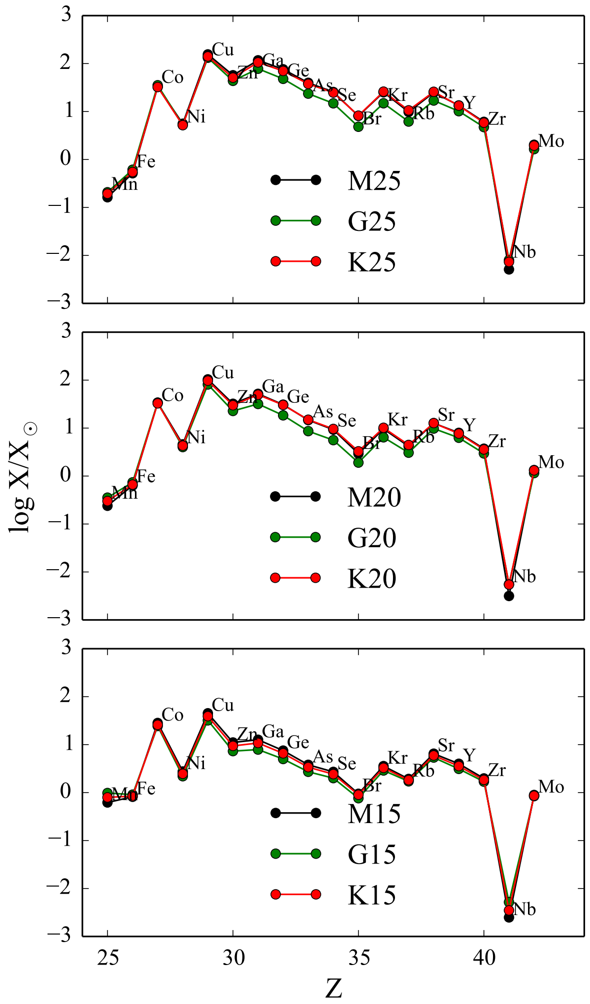
1-D diffusion coefficient profile from solving the equation above for D(r)

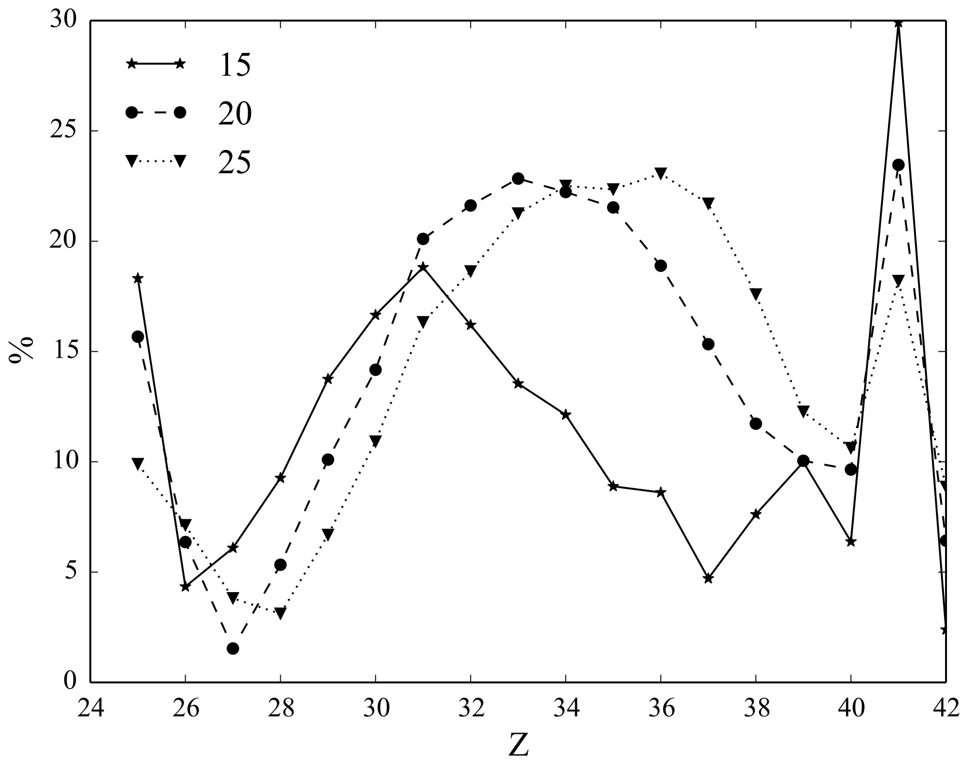
Mixing length theory breaks down at the convective boundary

Some good news: weak s-process

weak *s*-process production factors in He-core agree within 25% between 3 different stellar evolution codes despite several different physics assumptions

Jones+ (MNRAS submitted)





Open questions

What are the properties of convection and mixing at convective boundaries?

- Neon shell burning behaviour and EC-SN impact
- Hybrid C-O-Ne white dwarfs and SN1a(x) impact
- Asymmetries and coupling of mixing/burning pre-CCSN O- and Si-burning
- How does mixing behave in region of rapid electron capture?

Nuclear physics input:

- Weak reactions during O- and Si-burning in massive stars and impact on electron fraction at pre-SN stage
- URCA processes coupled with convection

What is the nucleosynthesis contribution of 8-10 Mo stars?

- Hydrogen-ingestion events could produce intermediate-neutron-density nucleosynthesis
- EC-SN yields
- Thermonuclear ONe core explosion?