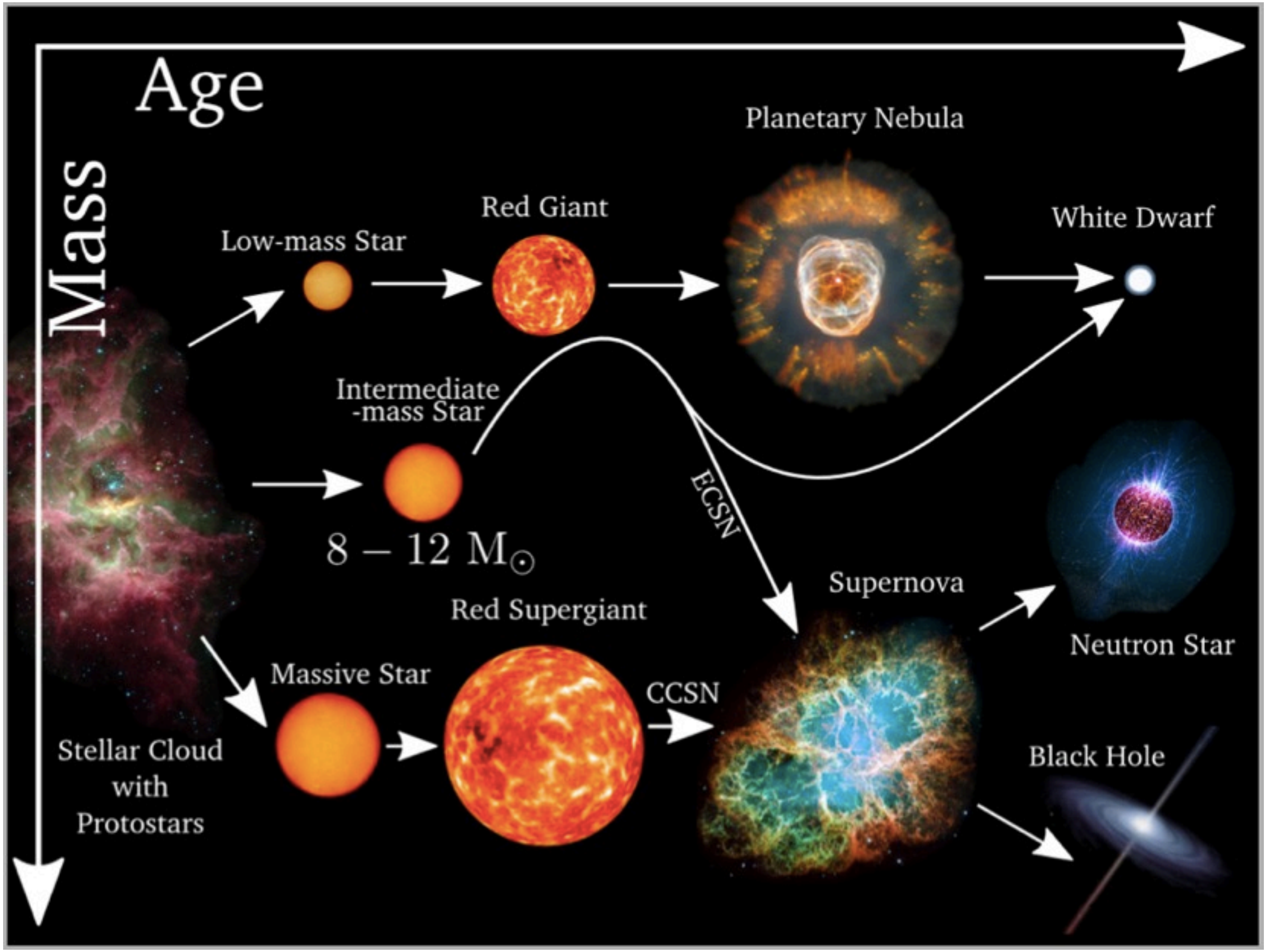
Progenitors of electron-capture supernovae

Samuel Jones
University of Victoria

In collaboration with:
R. Hirschi (Keele U), K. Nomoto (Kavli IPMU), F. Herwig (UVic), G. Martínez-Pinedo (TU Darmstadt), T. Fischer (U Wrocław), H. Toki (Osaka U), T. Suzuki (Nihon U), M. Pignatari (U Basel), M. Bertolli (ORNL), P. Denissenkov (UVic), F. X. Timmes (ASU), B. Paxton (KITP), H. Möller (TU Darmstadt),

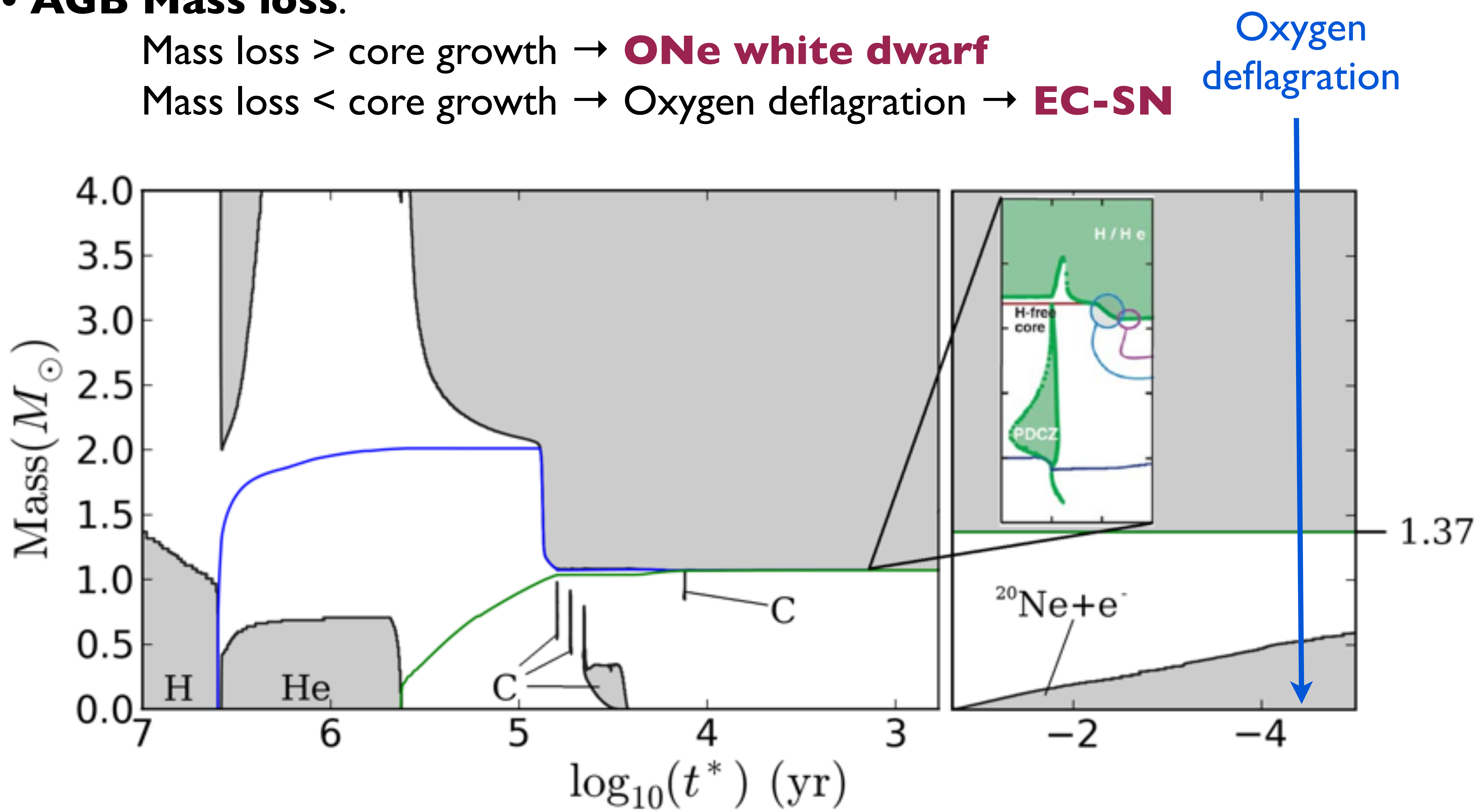
Stellar evolution overview



Super-AGB stars: EC-SN progenitors?

- Off-centre carbon ignition → O + Ne core, thin pulsing helium shell, hydrogen envelope

- **AGB Mass loss**:
  Mass loss > core growth → **ONe white dwarf**
  Mass loss < core growth → Oxygen deflagration → **EC-SN**



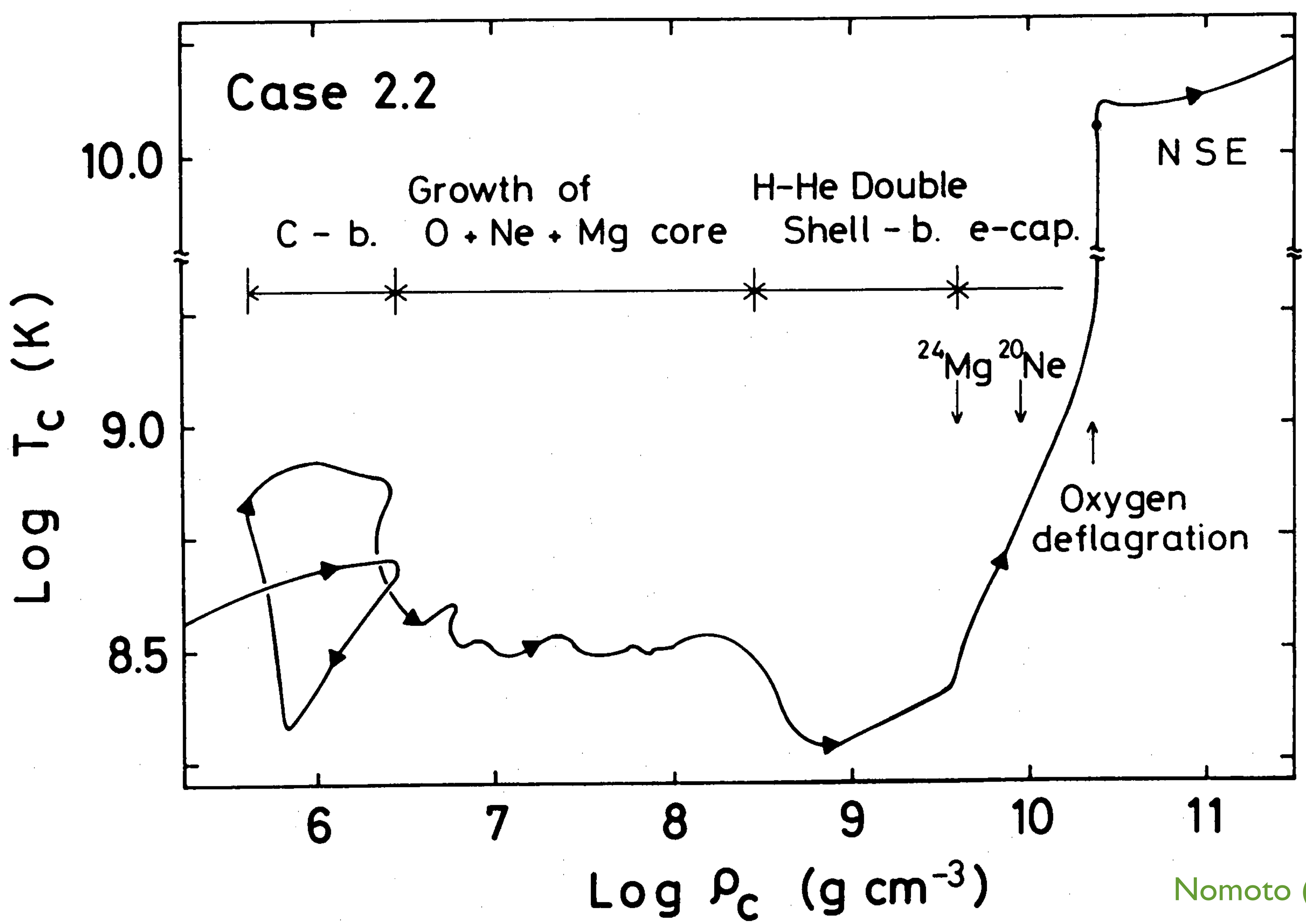
Miyaji+ (1980); Nomoto (1984, 1987); Miyaji & Nomoto (1987); Ritossa+ (1999); Poelarends+ (2008); Takahashi+ (2013)

Super-AGB stars: EC-SN progenitors?

Electron captures on even-A nuclei produce heat

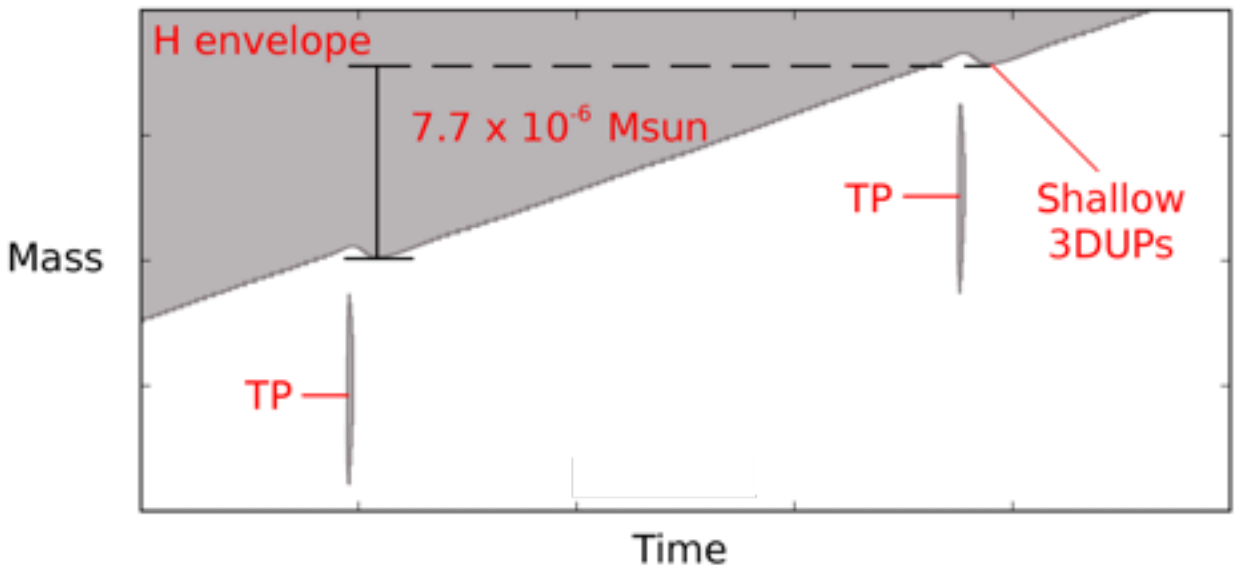
$^{24}Mg + e^-$ $\log \rho_{crit} \approx 9.6$

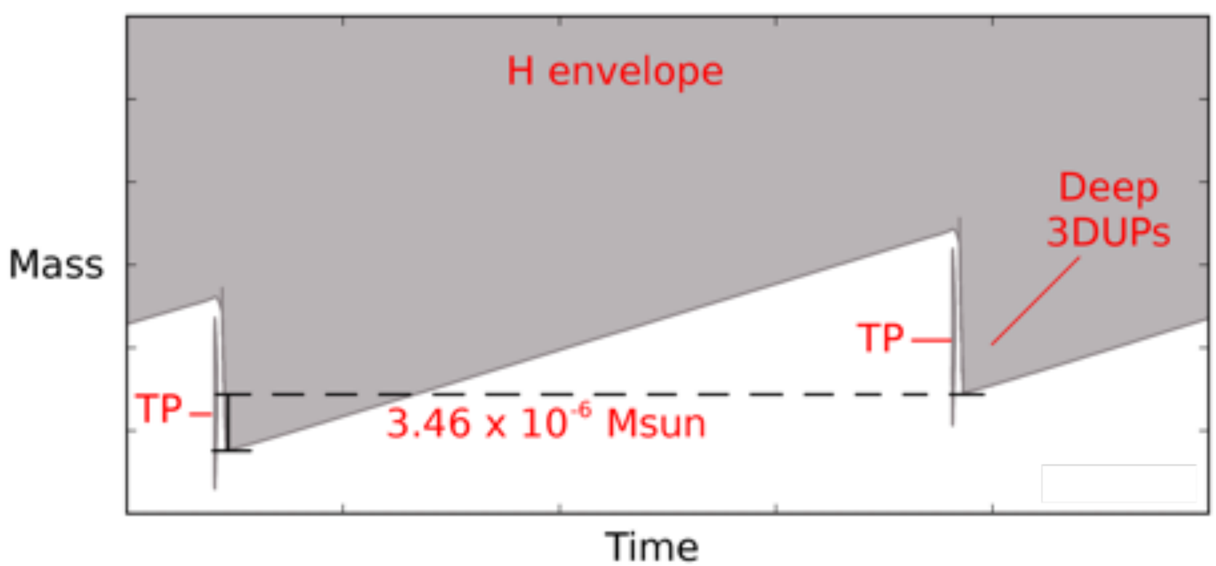
$^{20}Ne + e^-$ $\log \rho_{crit} \approx 9.8$



Nomoto (1987)

Evolution along the TP-SAGB

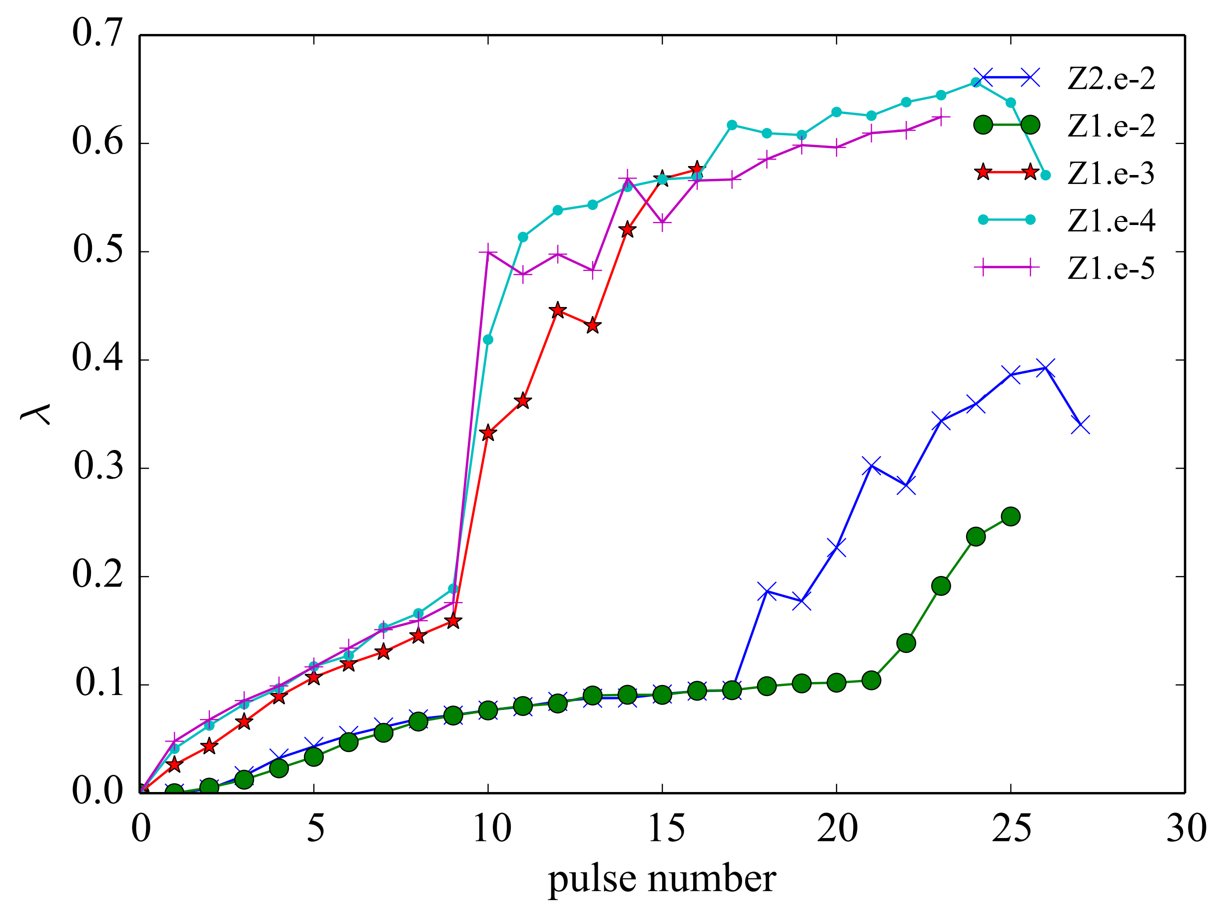




Sensitivity of λ to convective boundary mixing parameter *f*

3DUP efficiency

$$\lambda = \frac{\text{mass dredged up}}{\text{mass increase of He core}}$$



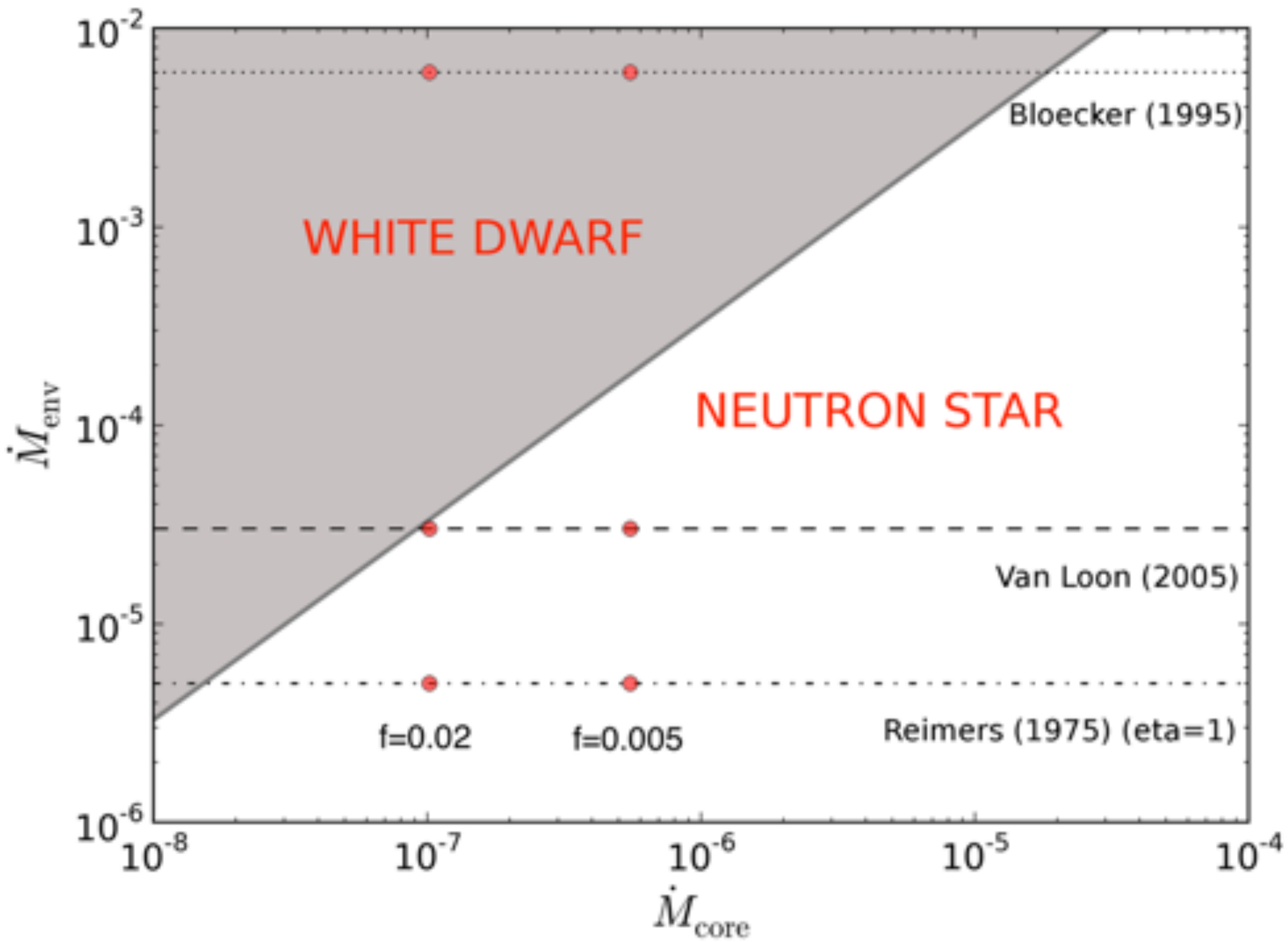
λ increases along TP-SAGB

ONe White dwarf or neutron star?

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

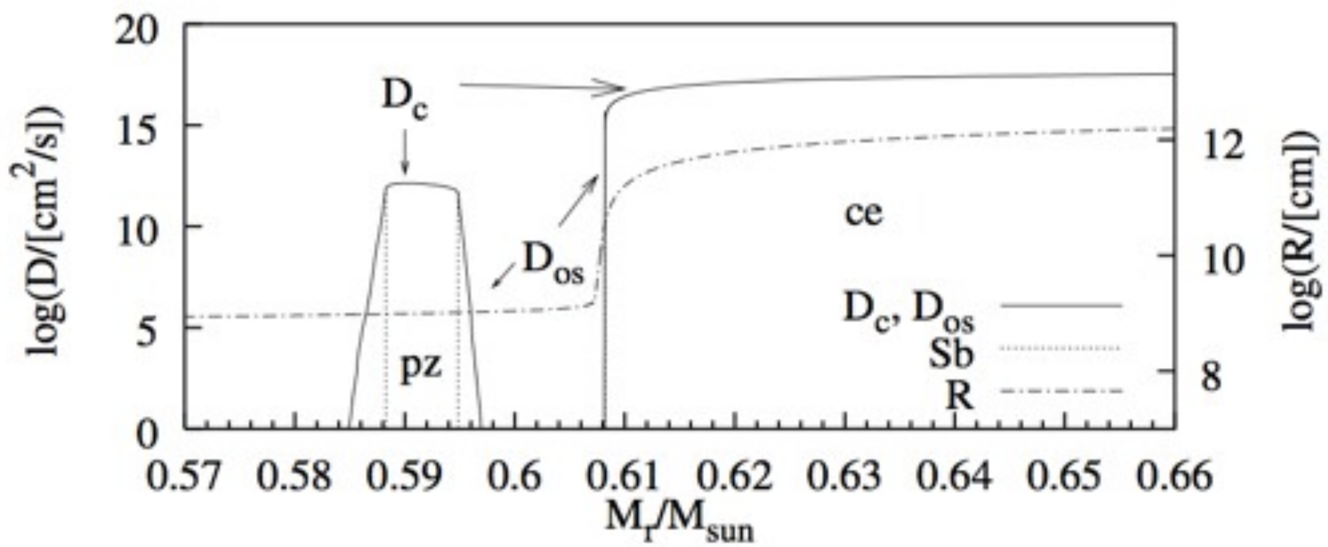
see also Poelarends (2008)

8.7 Mo star from Jones+ (2013)



Convective boundary mixing modelled with exponentially decaying diffusion coefficient

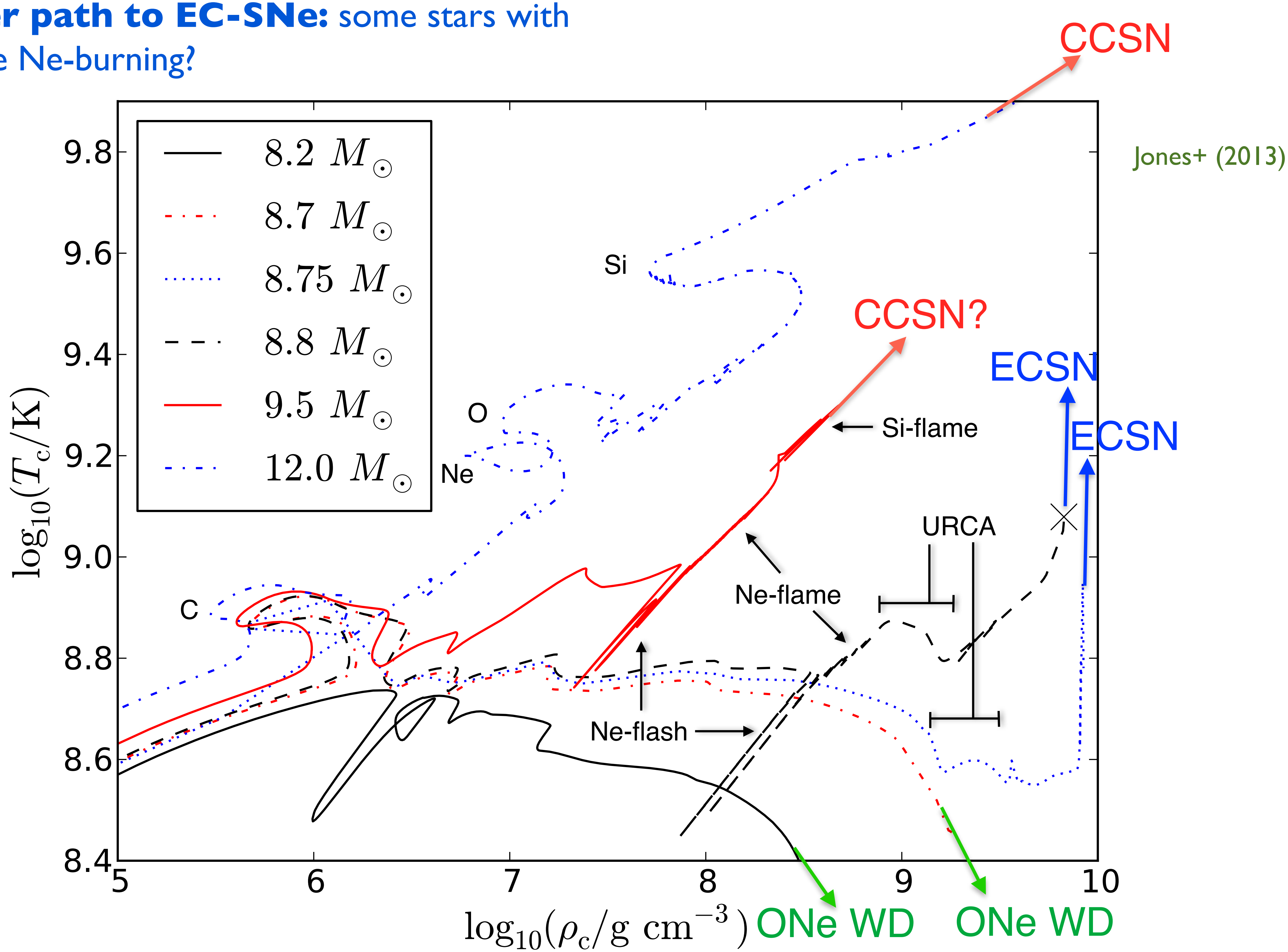
(Freytag+ 1996, Herwig+ 1997)



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)

Complex evolution of 8--12 Mo stars

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



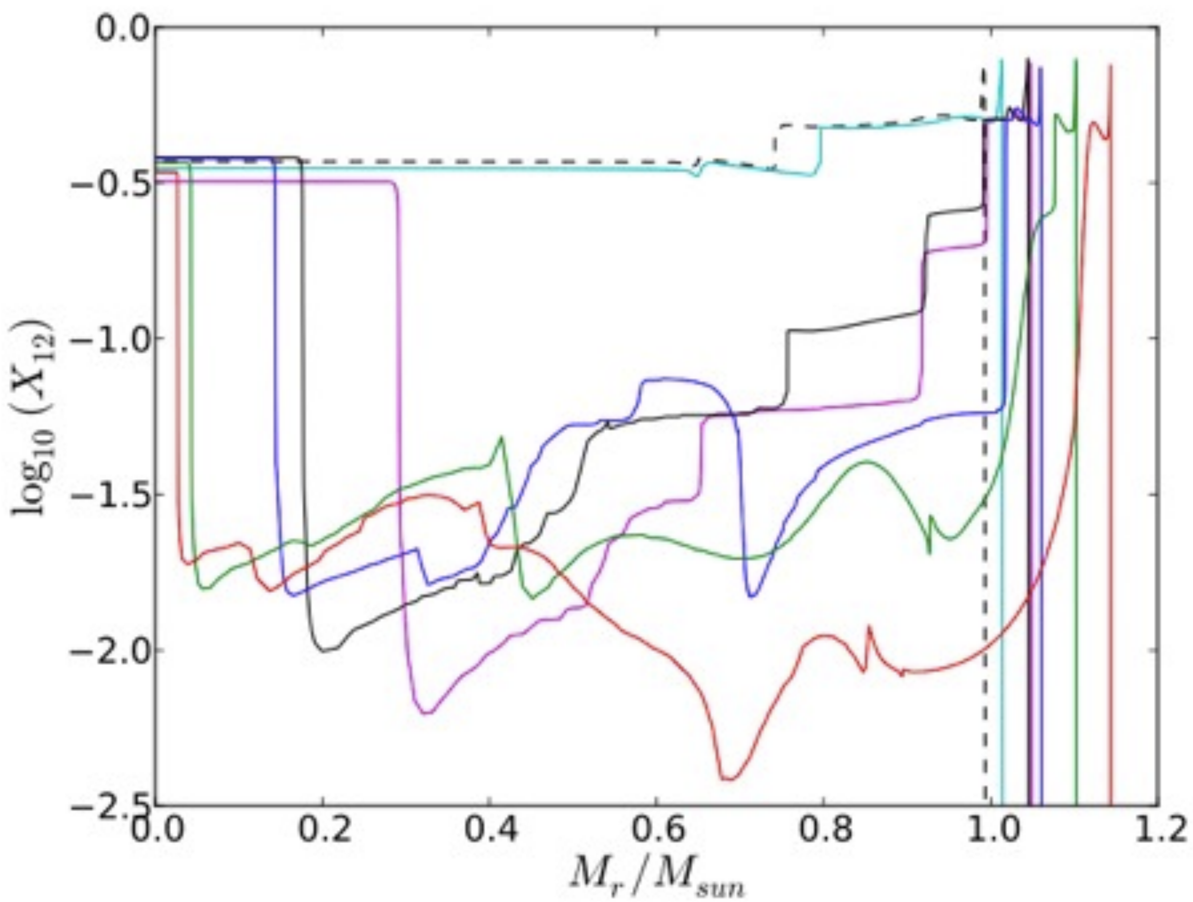
Hybrid white dwarfs and failed massive stars

CBM chokes flame propagation following off-centre ignition

arXiv:1407.0248

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

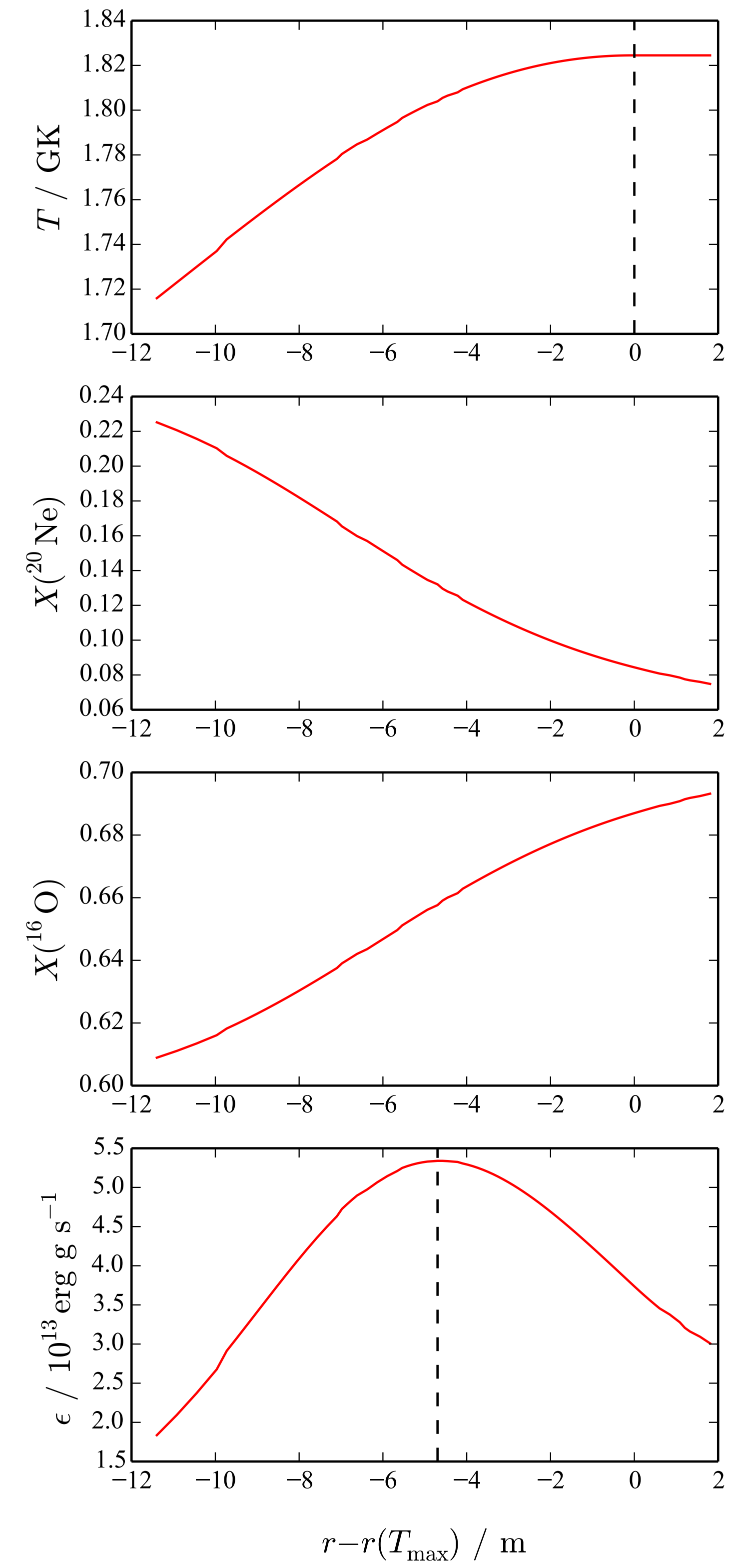
P. A. Denissenkov[1,4,9⋆], J. W. Truran[2,4,9], F. Herwig[1,4,9], S. Jones[1,5,9], B. Paxton[3], K. Nomoto[6], T. Suzuki[7] and H. Toki[8]



^{12}C abundance profiles at the end of carbon burning in models of **hybrid C-O-Ne WDs** with convective boundary mixing

Choking of neon flame would produce "failed massive stars"

Jones+ (submitted to ApJ)



URCA process

High density

$$(i) \quad {}^{A}\mathrm{Z} + \mathrm{e}^{-} \rightarrow {}^{A}(\mathrm{Z}-1) + \nu$$

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

Low density

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

Key reactions:

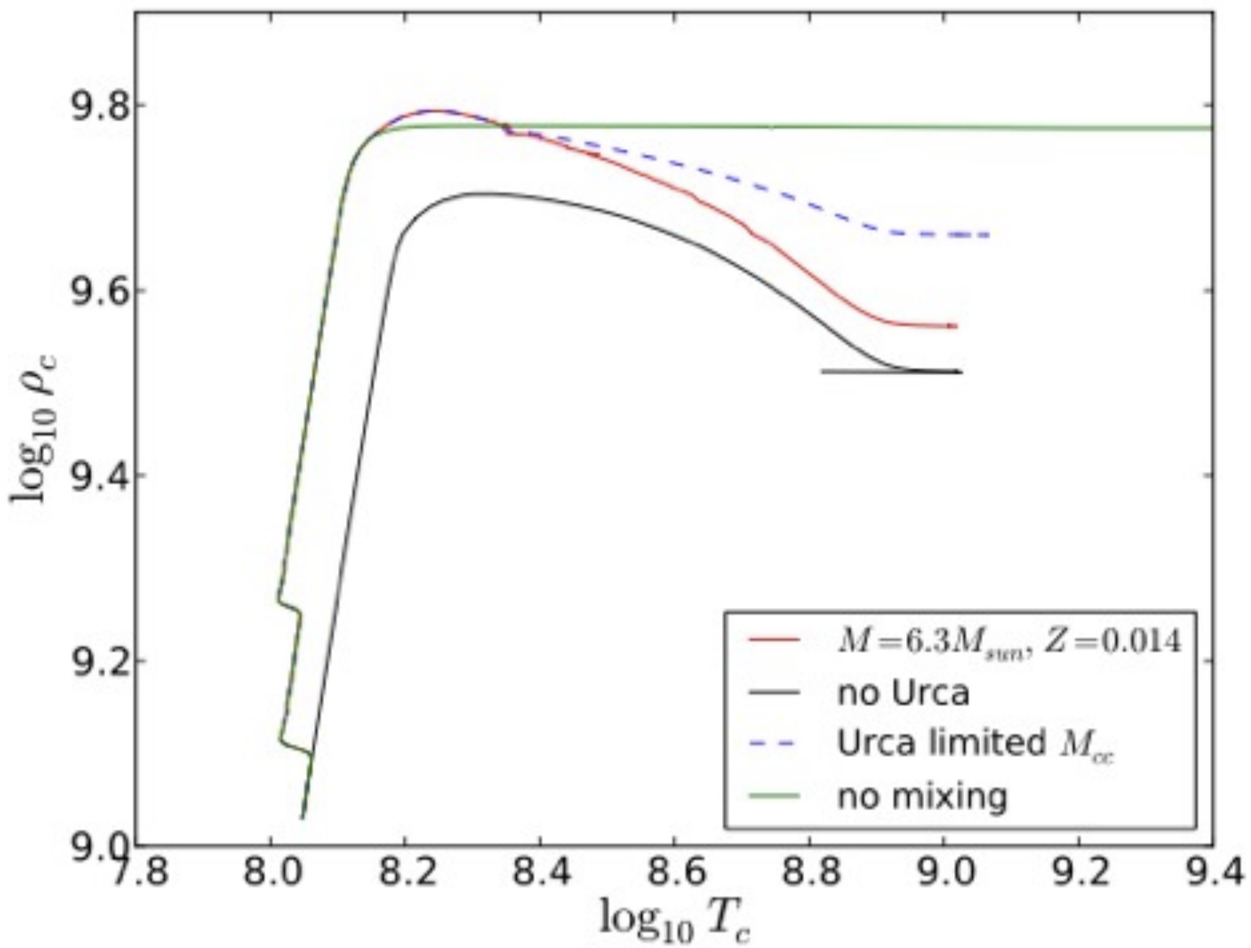
$^{25}\mathrm{Mg} \longleftrightarrow {}^{25}\mathrm{Na}$

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

Impact of new URCA rates

CO WDs (Type Ia)

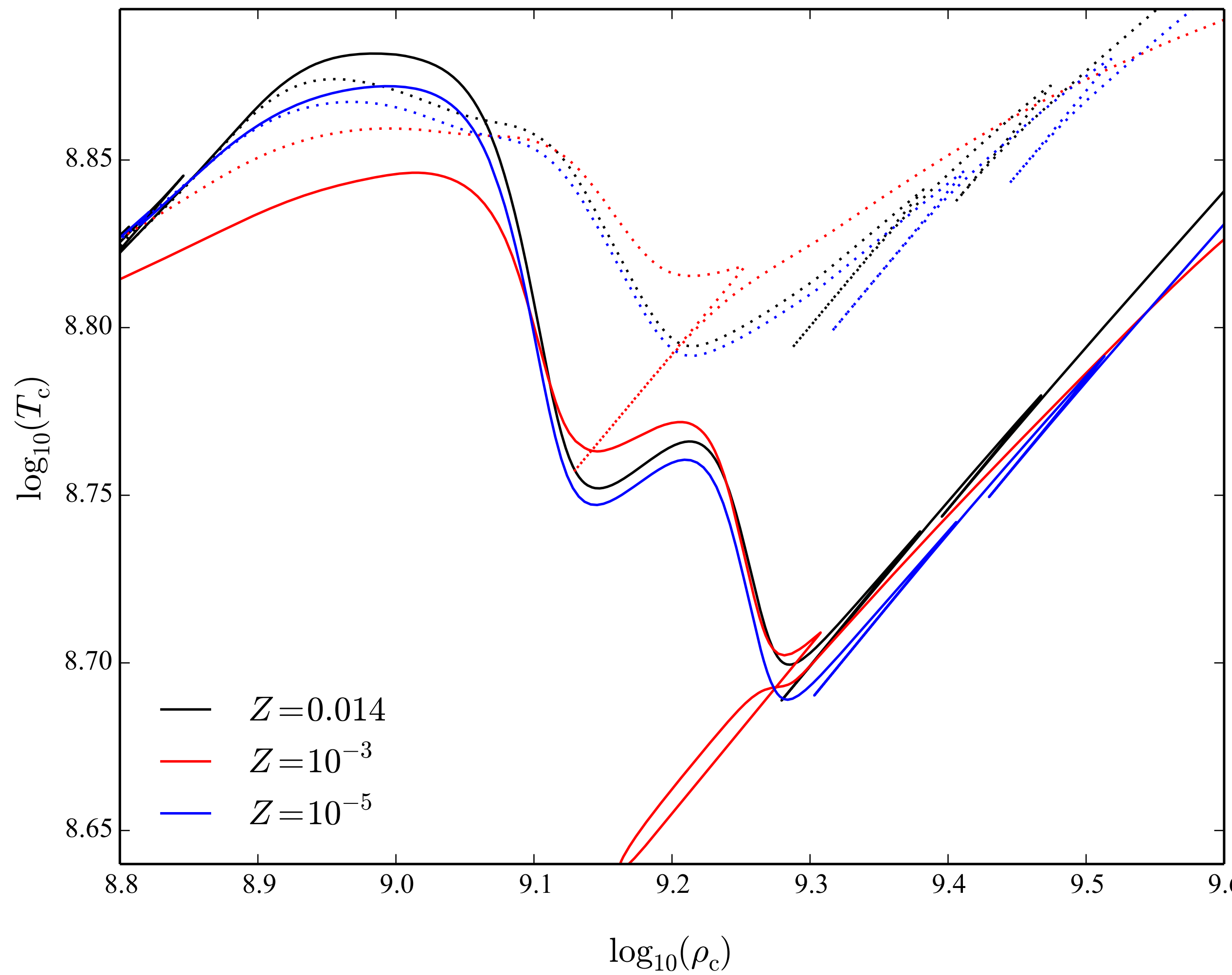
Denissenkov+ (2014, in press)



In the hybrid C-O-Ne WDs, URCA is stronger and can lead to **off-centre ignition of the C-deflagration**

Failed massive stars

Jones+ (submitted to ApJ)

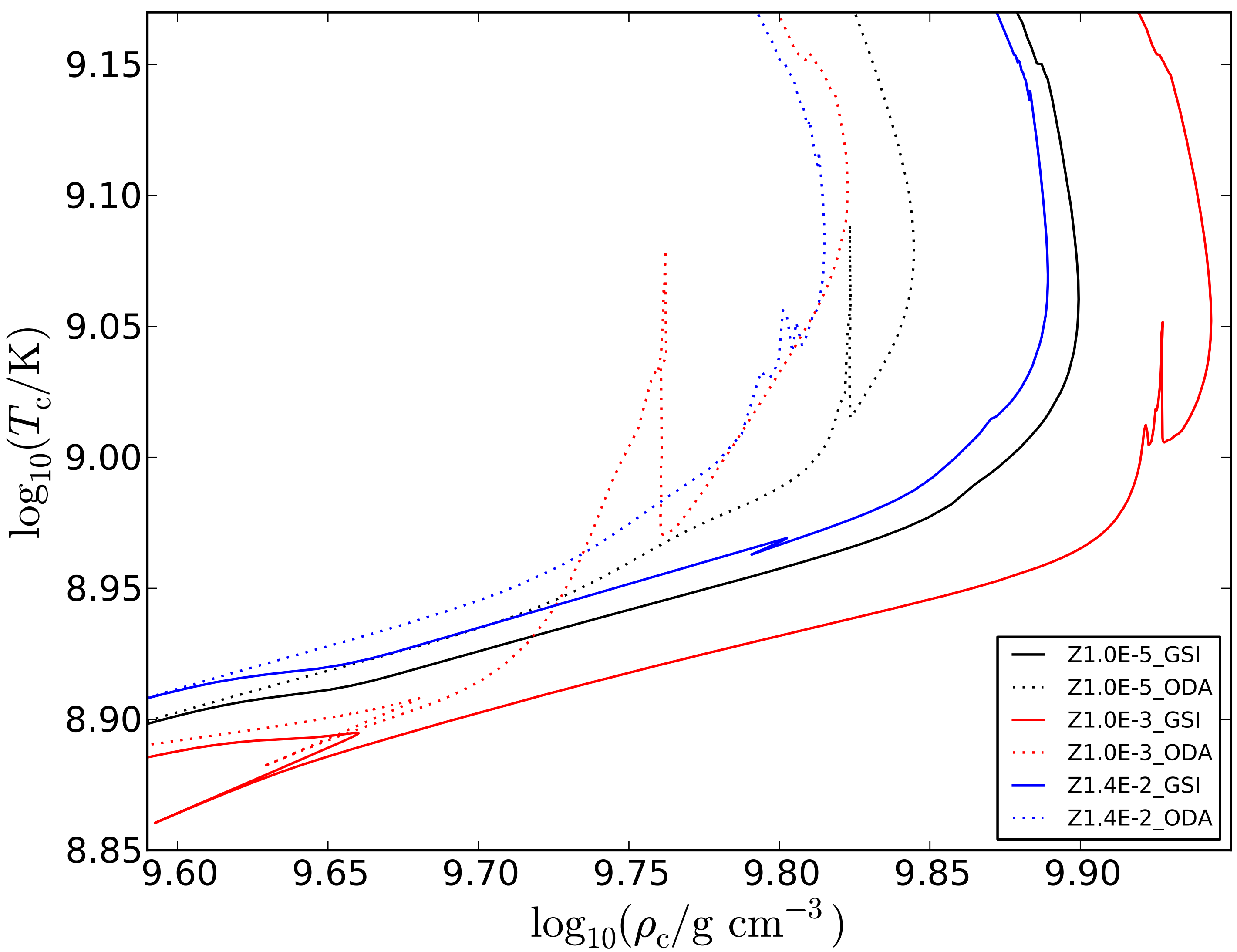


rates:
Oda+ (1994) - dashed
Toki+ (2013) - solid

Impact of new $^{20}Ne + e^-$ rate

Rate by Lam, Martínez-Pinedo+ (2013)

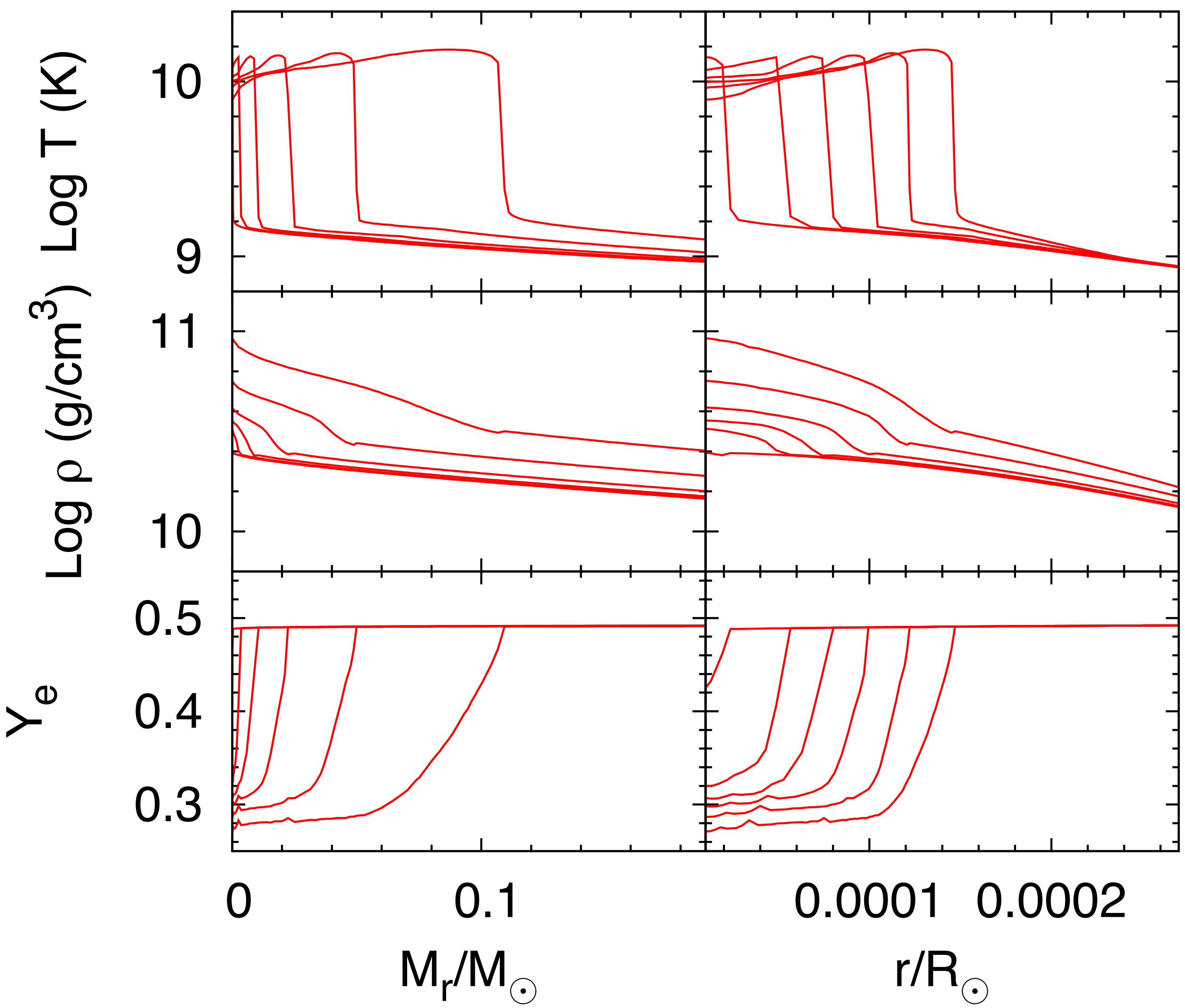
Oxygen deflagration ignites at higher density with appropriately resolved reaction rate including Coulomb corrections



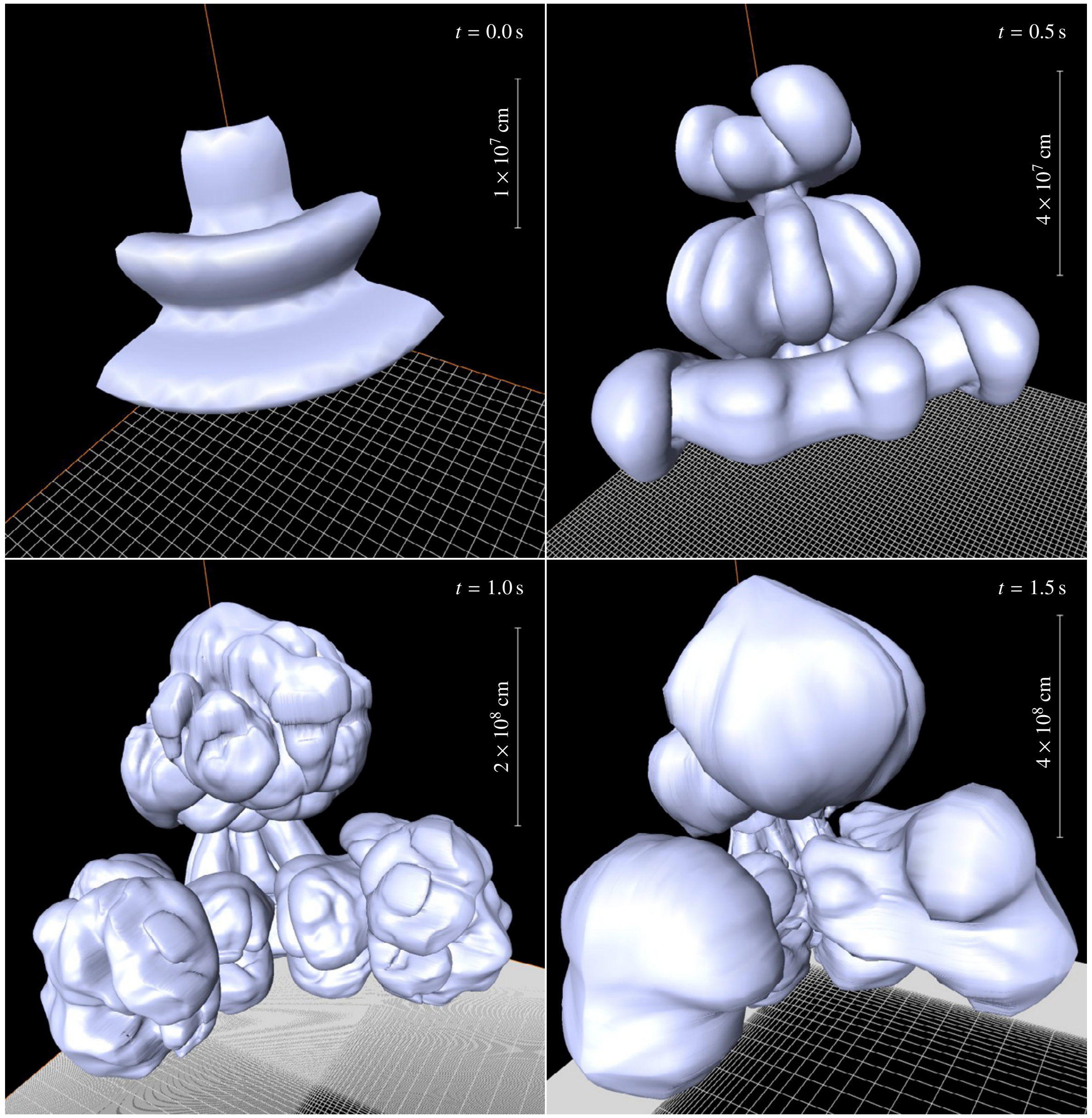
Evolutionary time scale becomes similar to convective time scale; electron capture leads to increase in μ

O-deflagration pre-ECSN

Takahashi+ (2013)



Carbon deflagration (Röpke+ 2006)

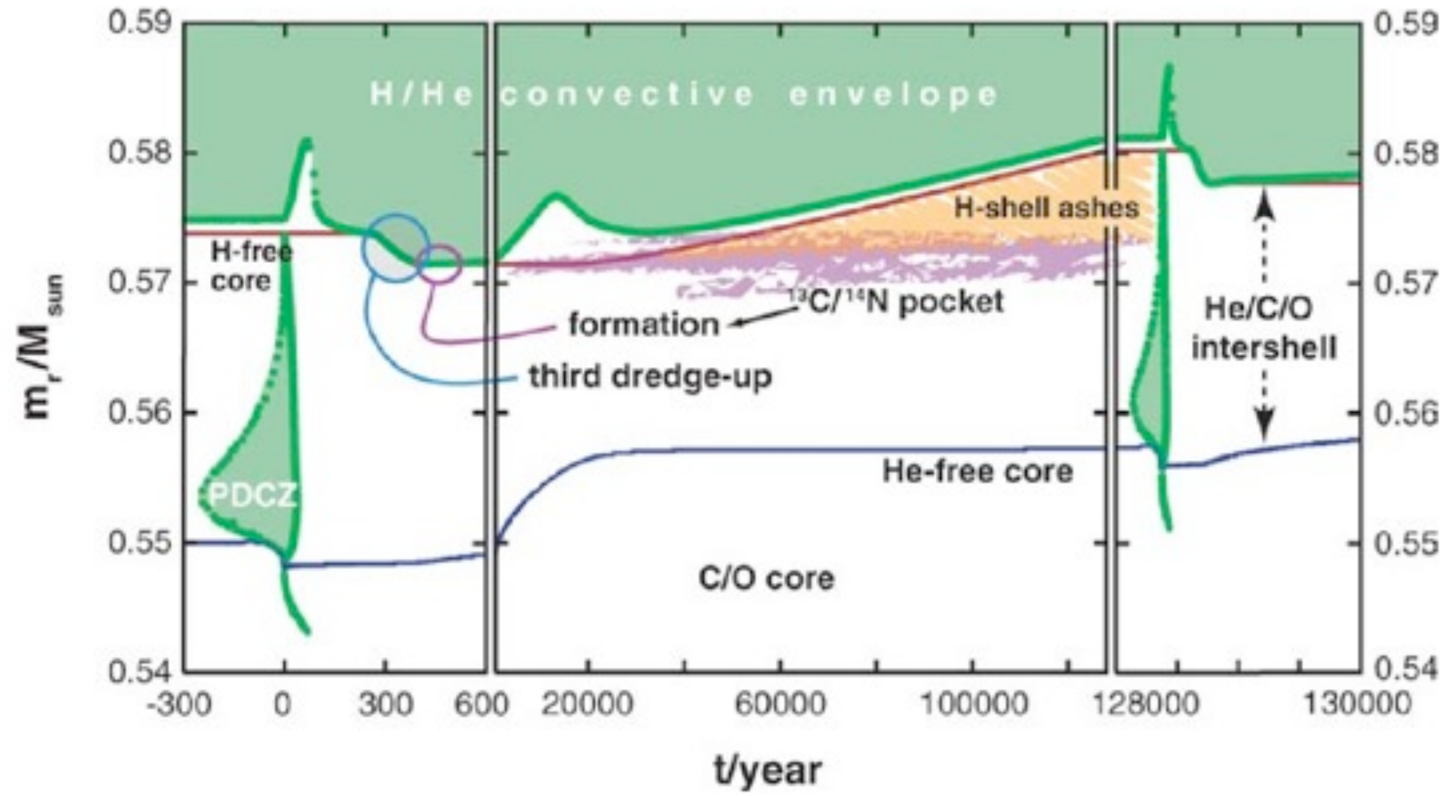


Do hydrodynamic instabilities and high-density nuclear reactions play a role during deflagration?

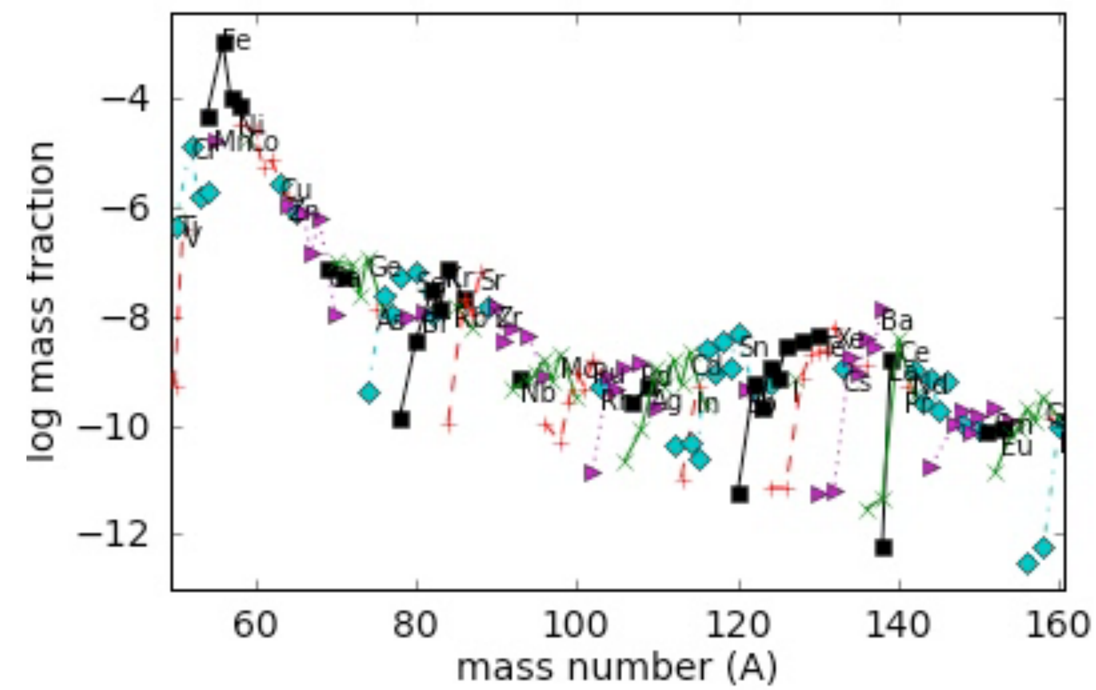
Does O-deflagration necessarily result in collapse?

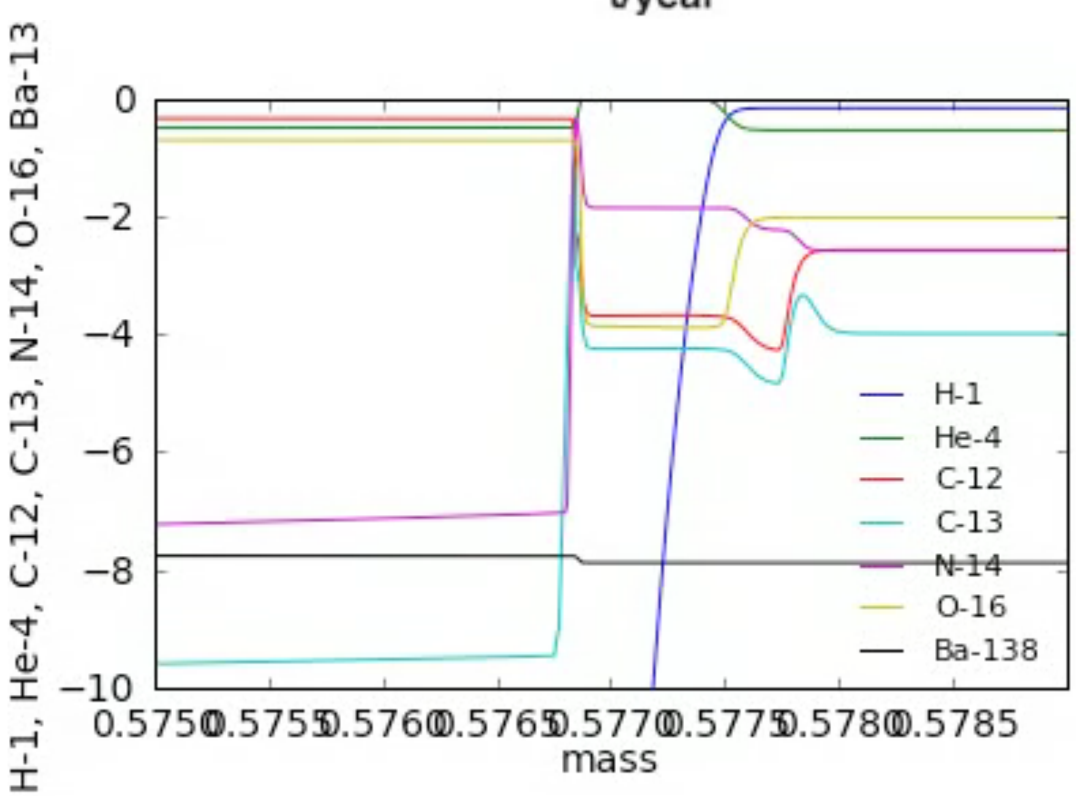
Main s-process component

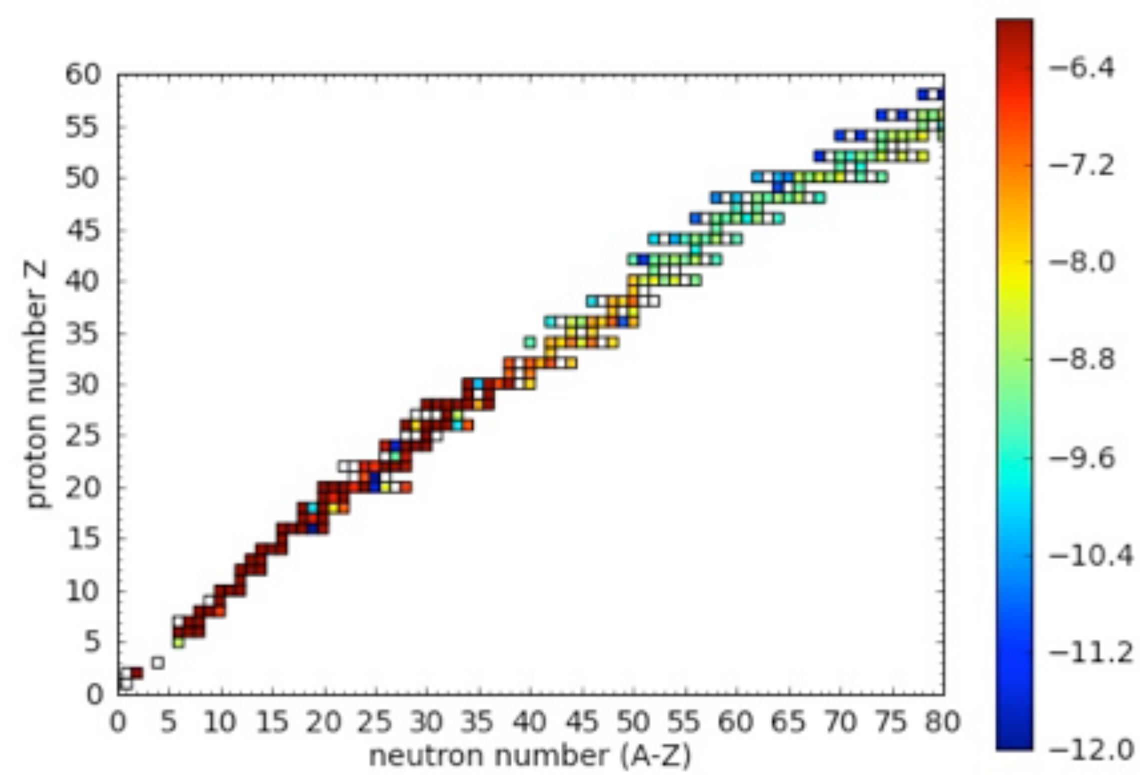
Herwig (2005)



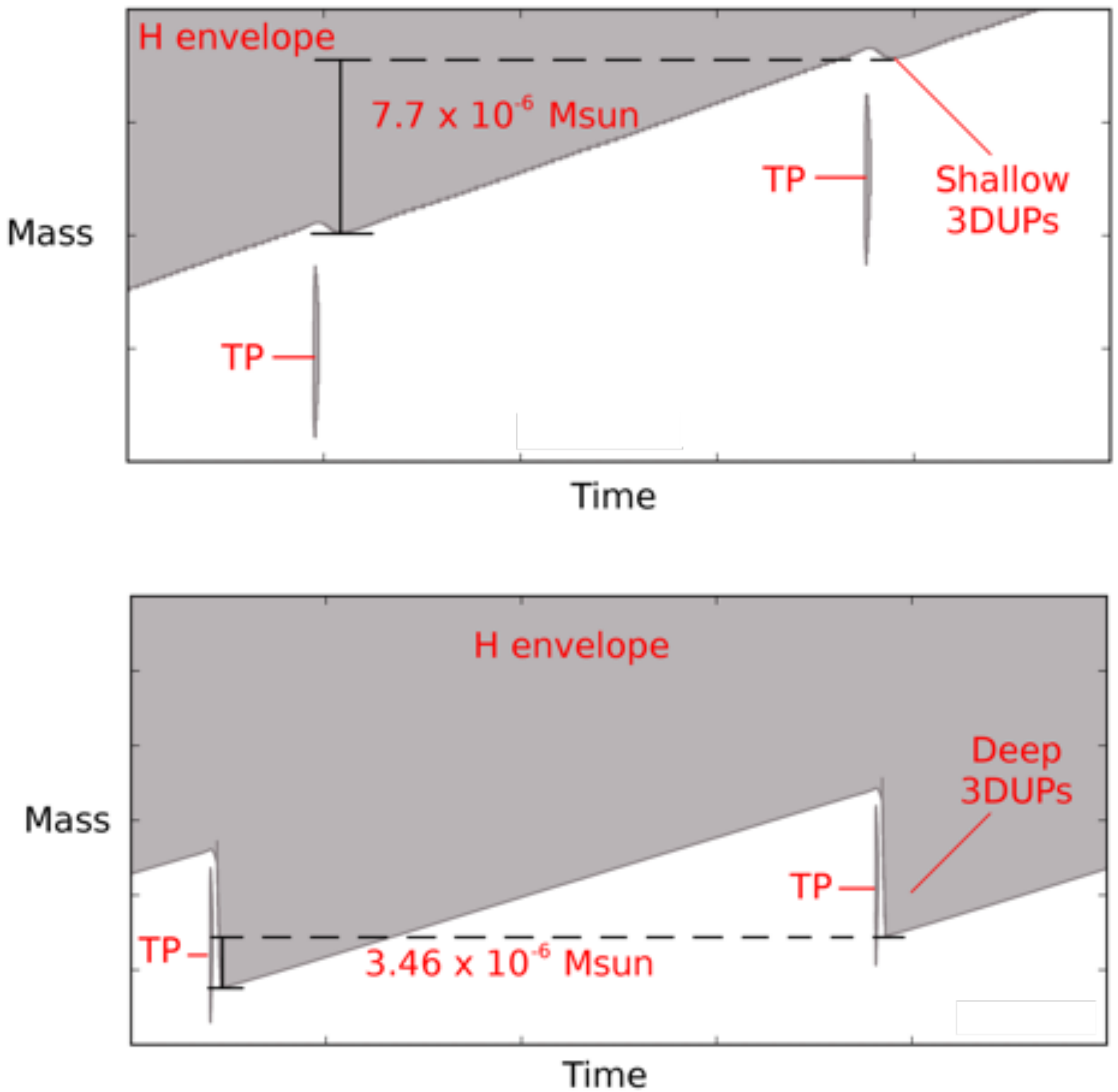
$^{13}C(a,n)^{16}O$







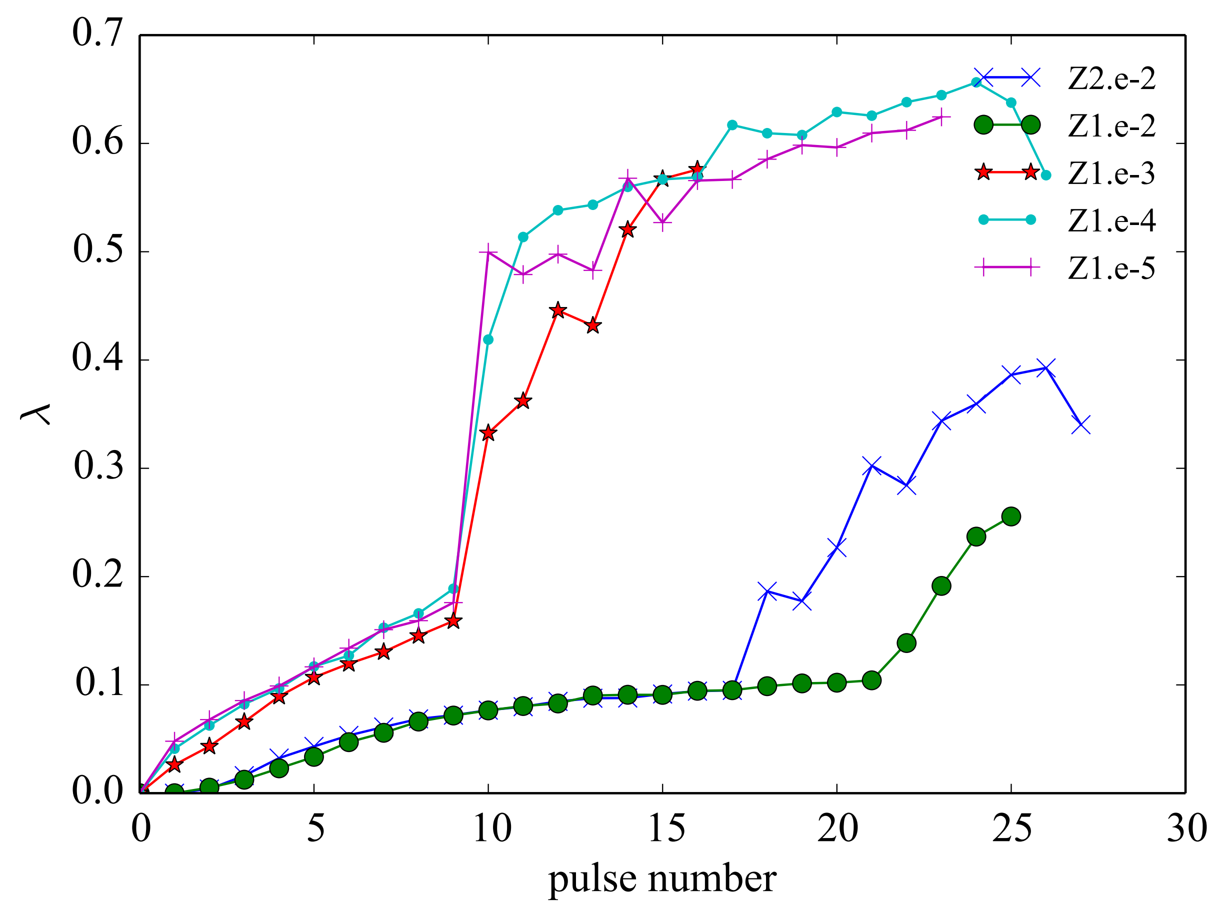
Evolution along the TP-SAGB



Sensitivity of λ to convective boundary mixing parameter *f*

3DUP efficiency

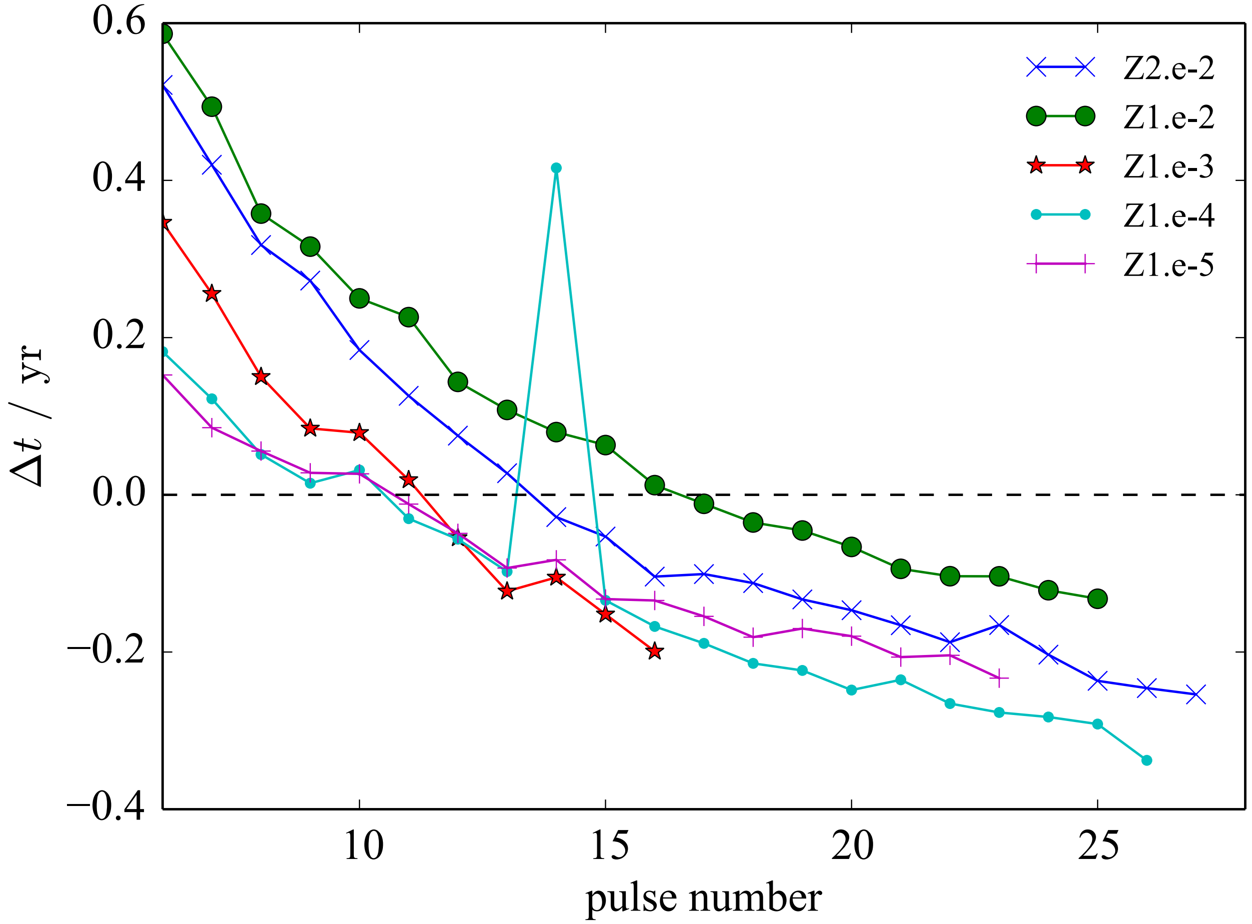
$$\lambda = \frac{\text{mass dredged up}}{\text{mass increase of He core}}$$



λ increases along TP-SAGB

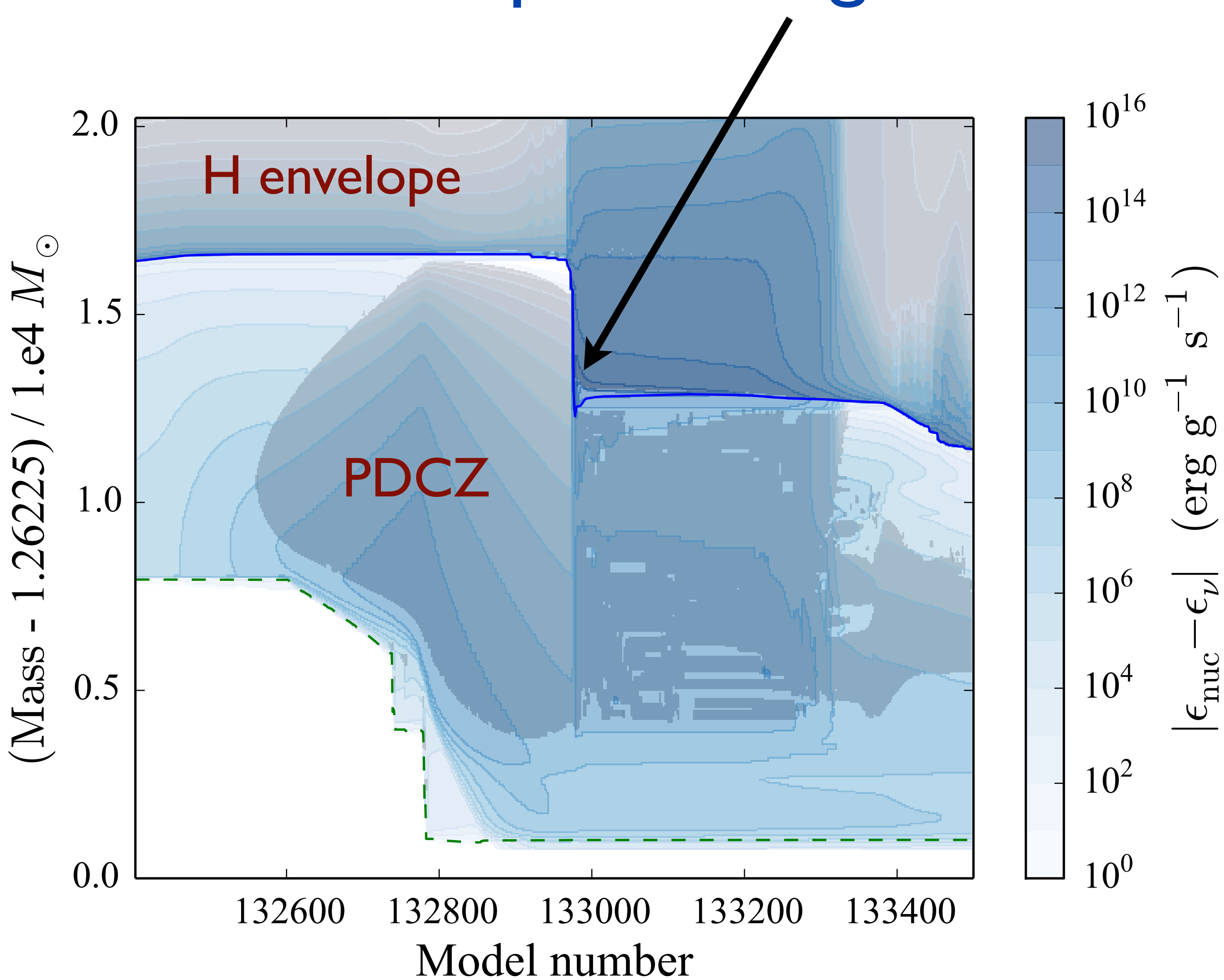
Hydrogen-ingestion thermal pulses

Δt = time between extinction of pulse-driven convection zone (PDCZ) and beginning of third dredge-up (3DUP)



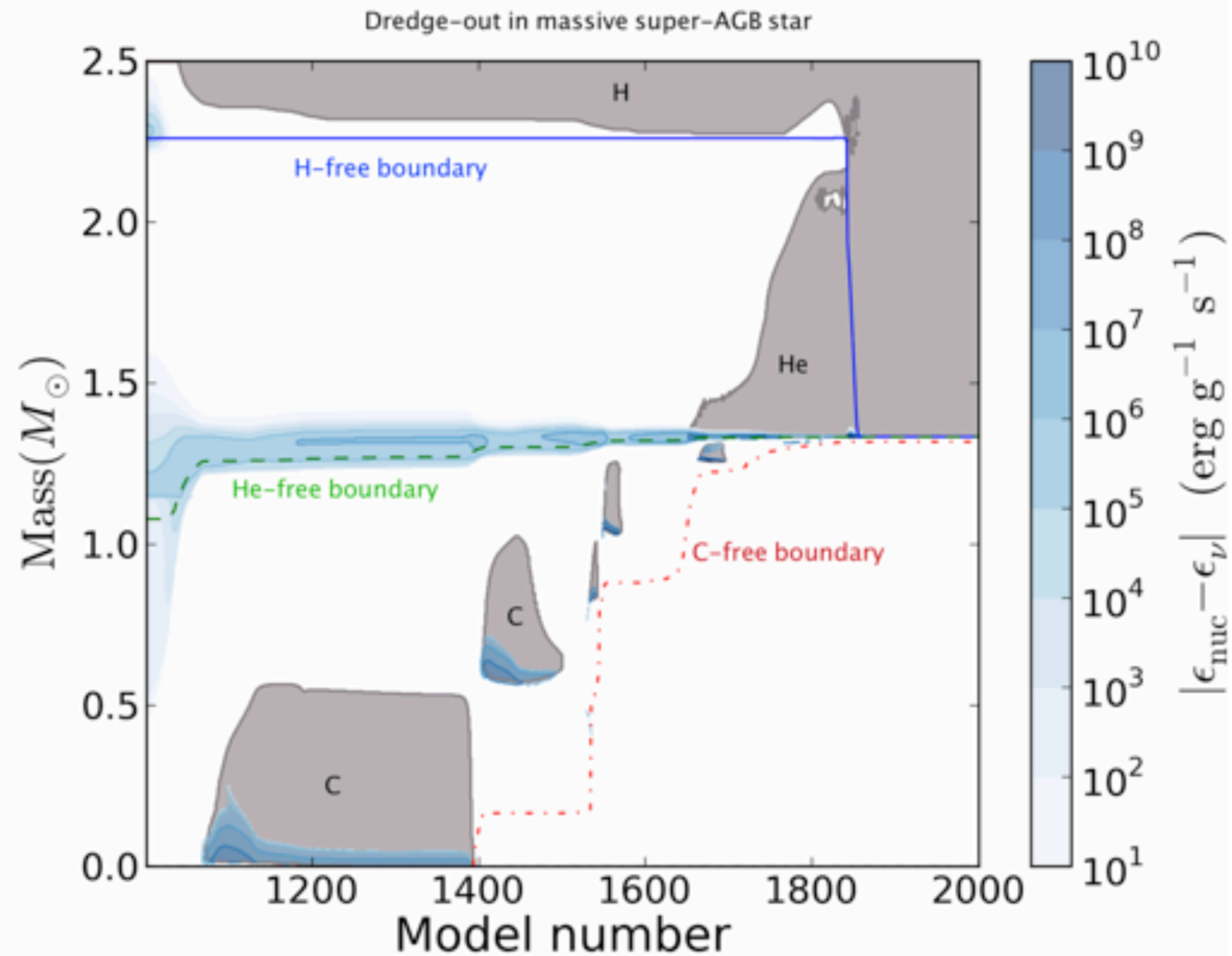
Jones+, in prep.

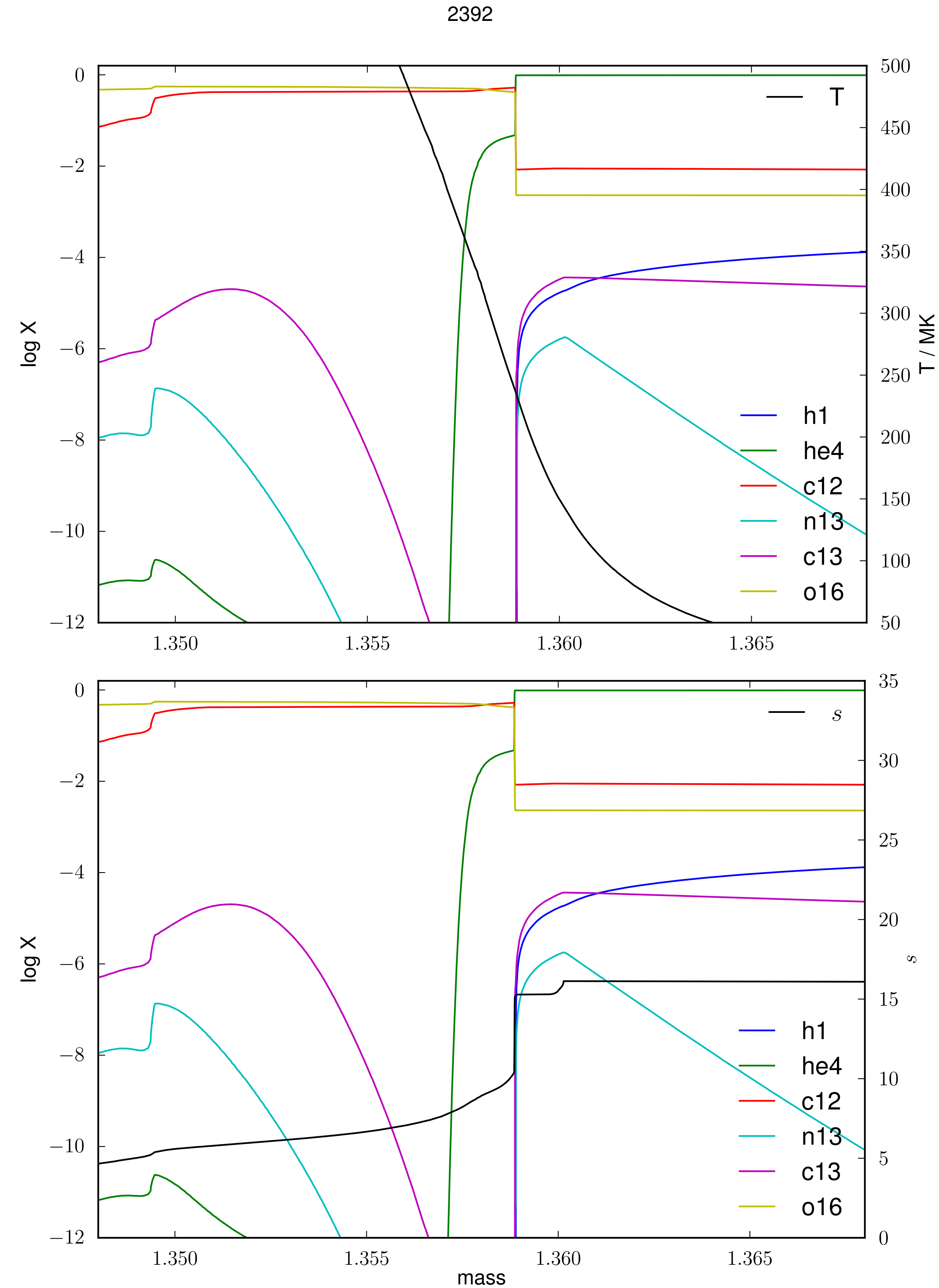
proton ingestion



Mass ejection → type IIn supernova?

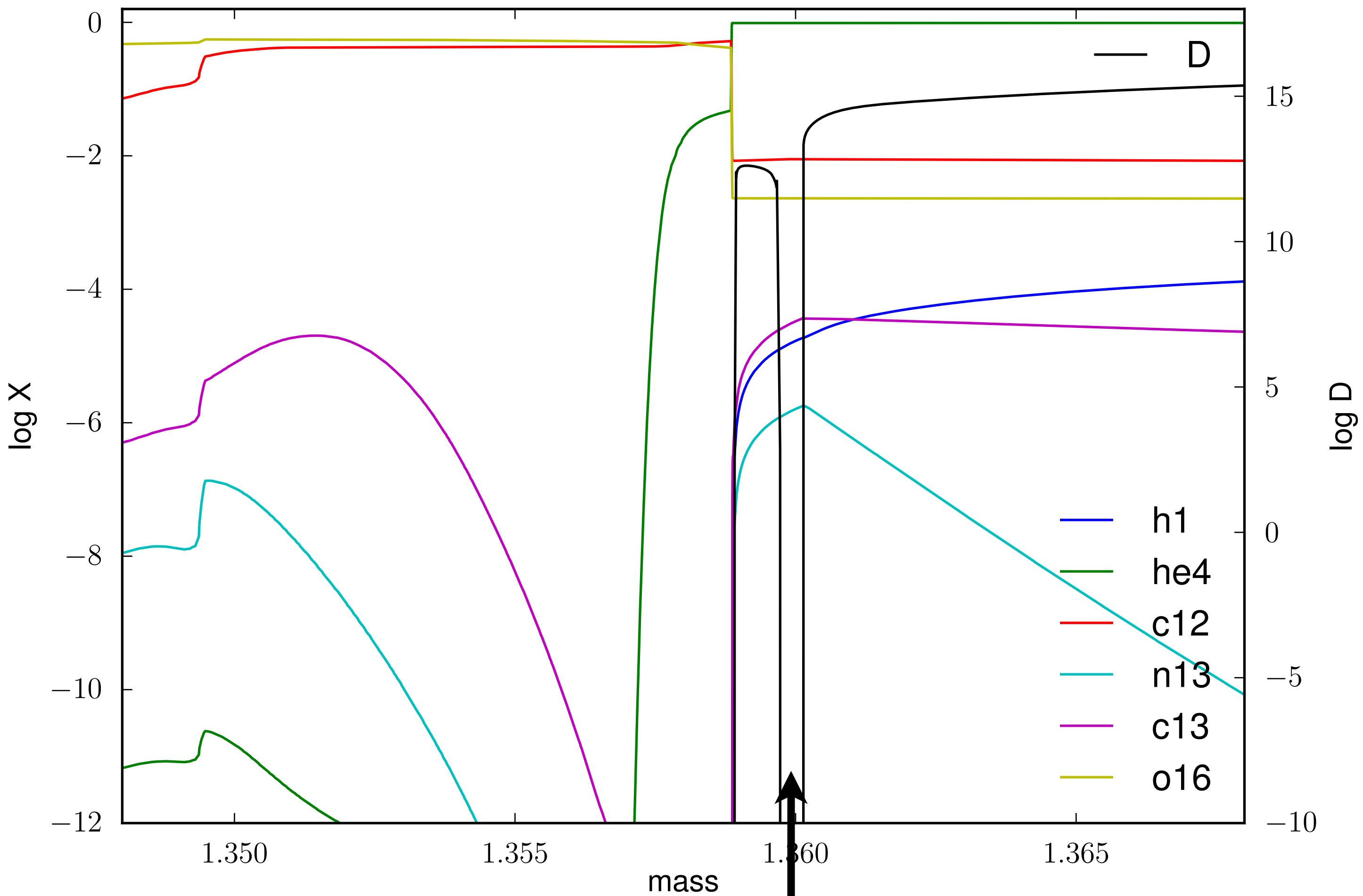
H-^{12}C combustion during dredge-out





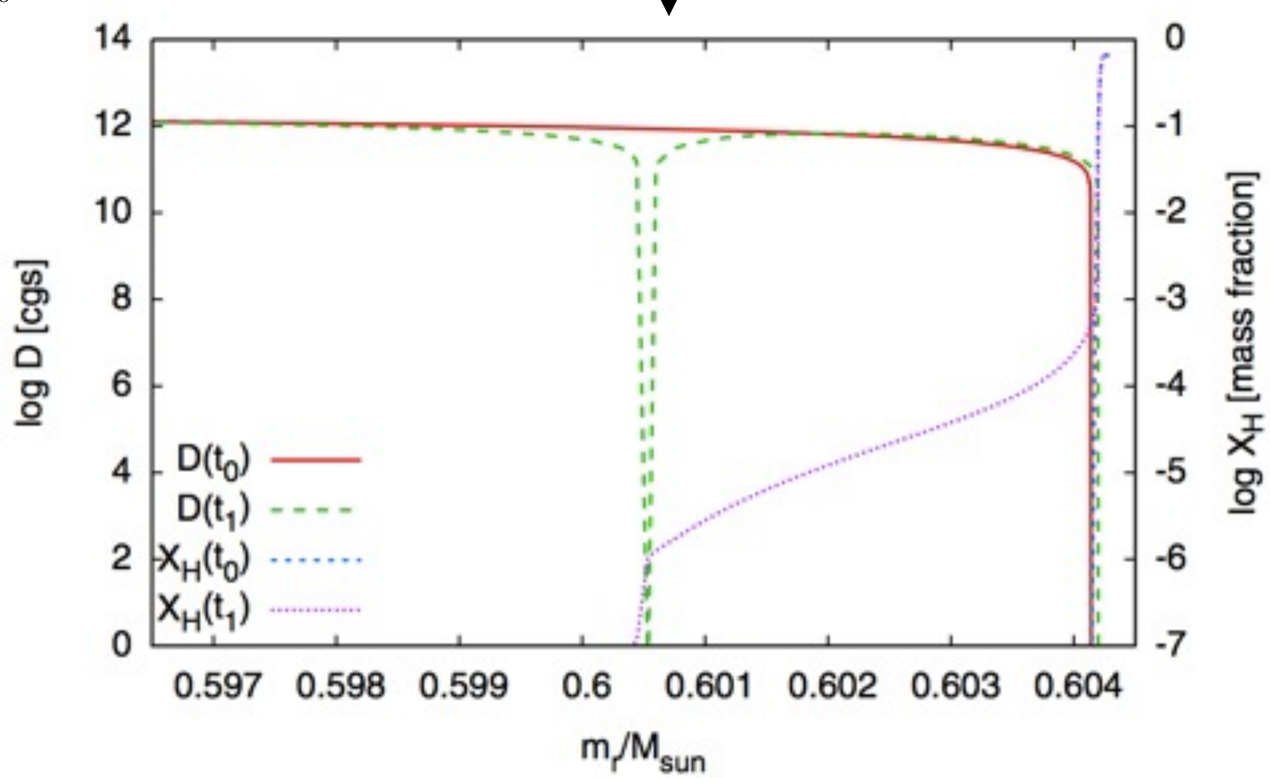
Jones+, in prep.

Validity of 1-D stellar models

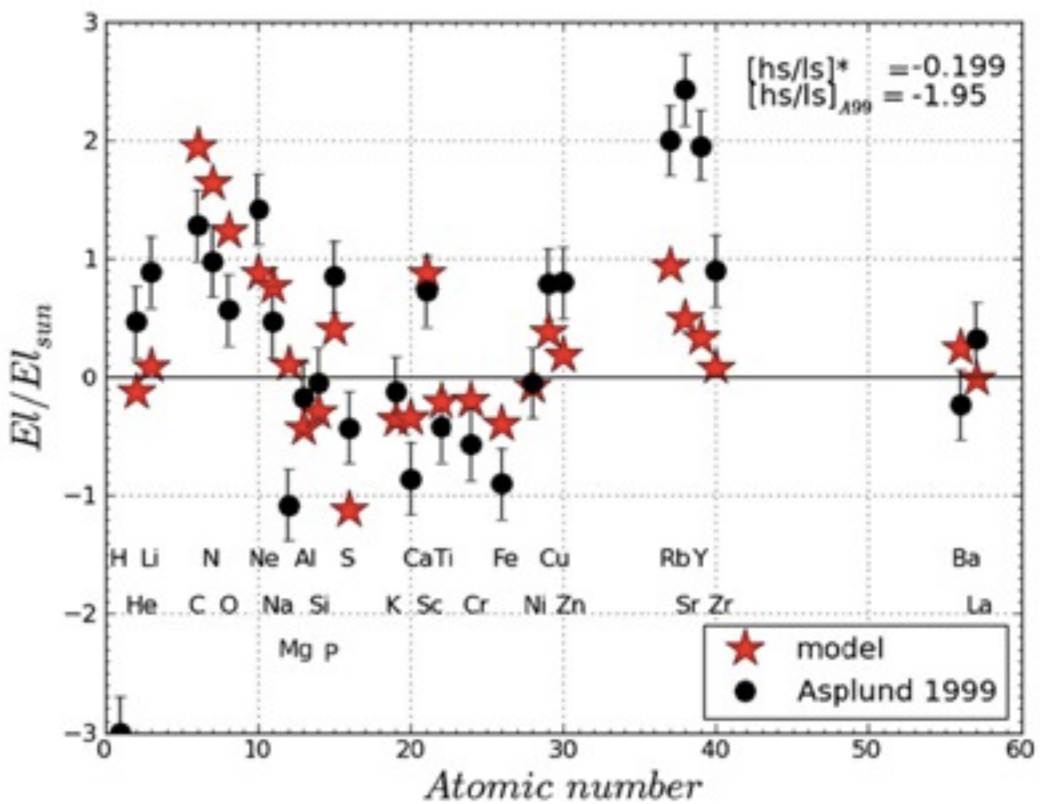


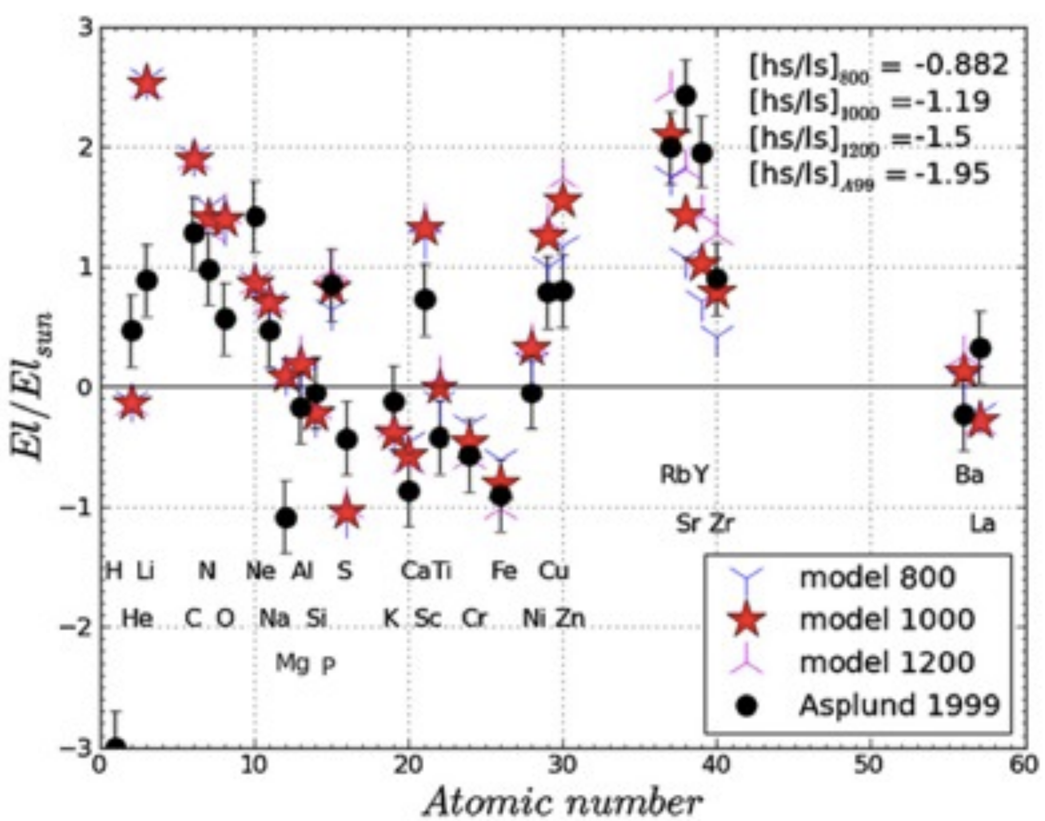
Entropy jump due to burning of protons prohibits further transport of protons in 1D stellar models

Similar situation to post-AGB helium-shell flash in Sakurai's object (Herwig+ 2011)



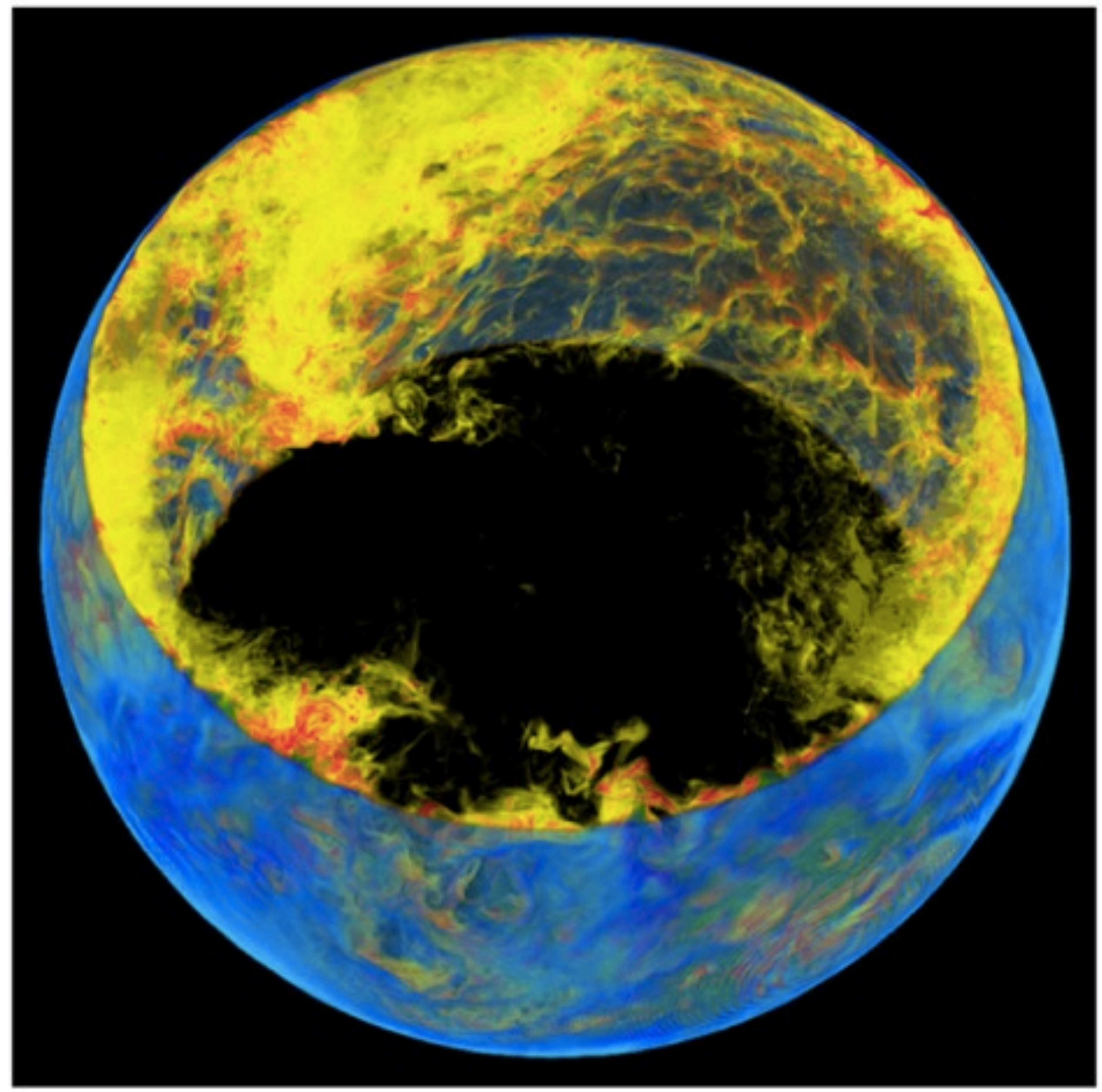
"Delayed-split" model informed by 3D simulation





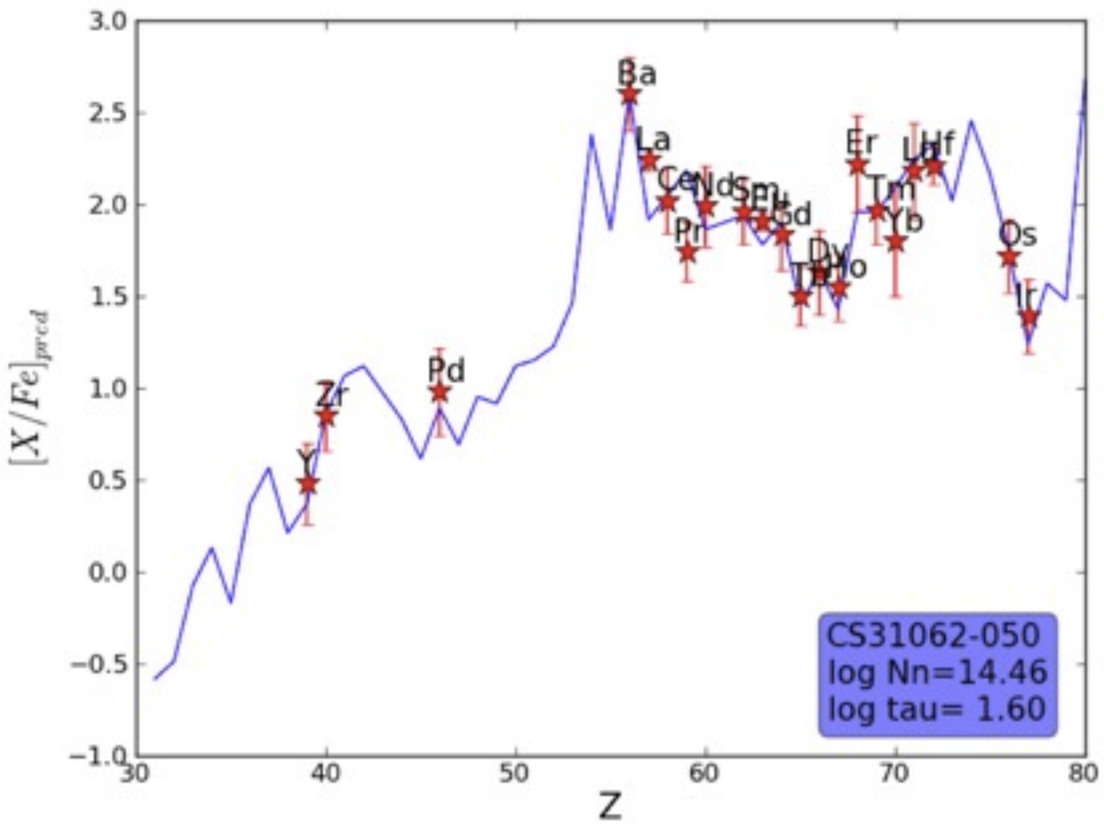
3D PPM simulation of very-late thermal pulse (VLTP) in post-AGB star Sakurai's Object

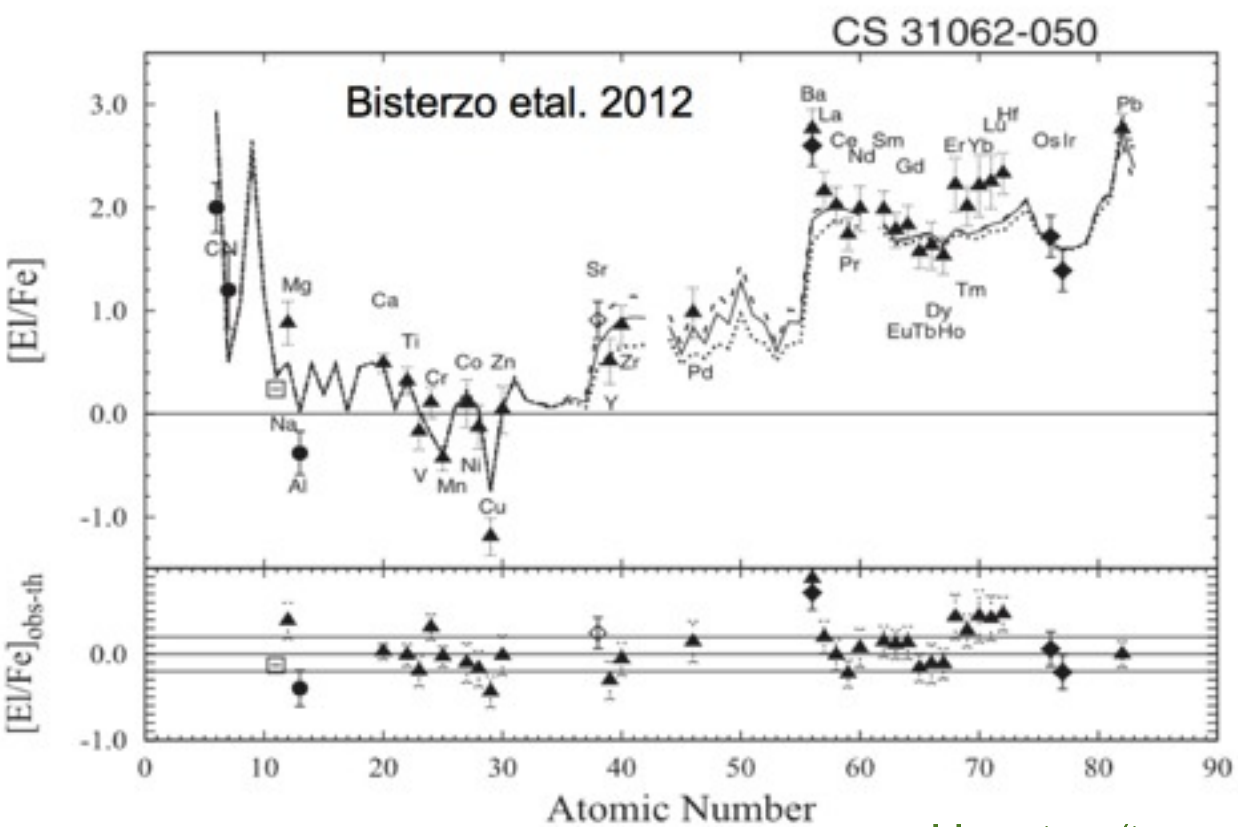
Herwig+ (2011)



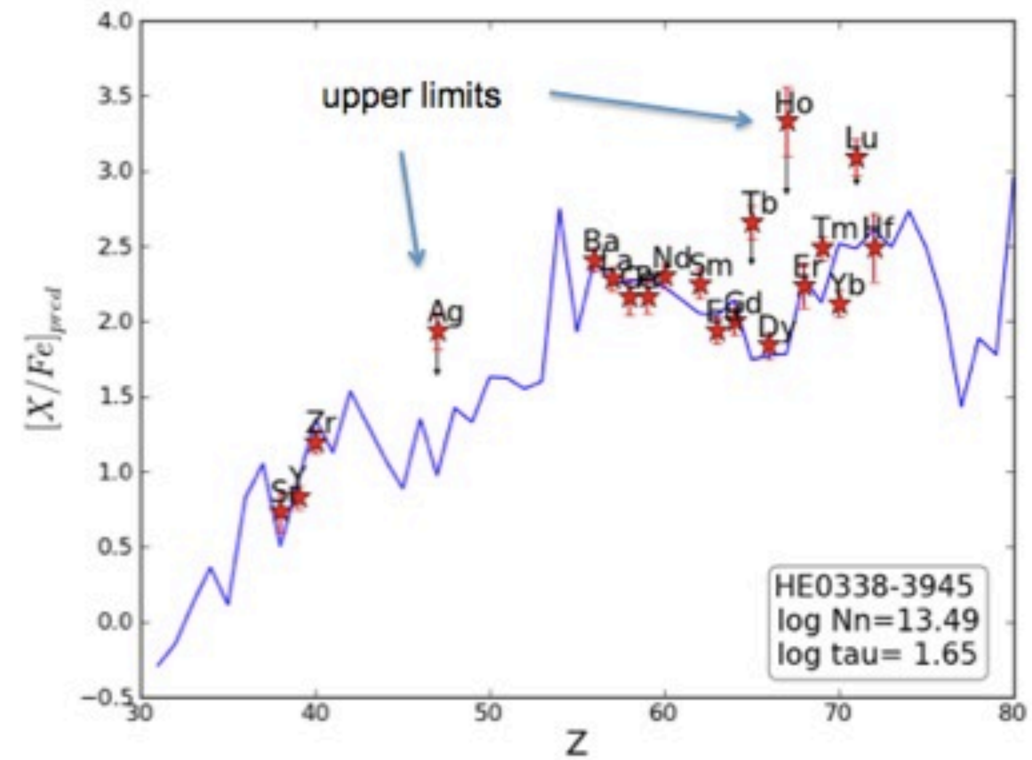
Colour :: proton abundance: 1% (blue) -- 0.01% (yellow)

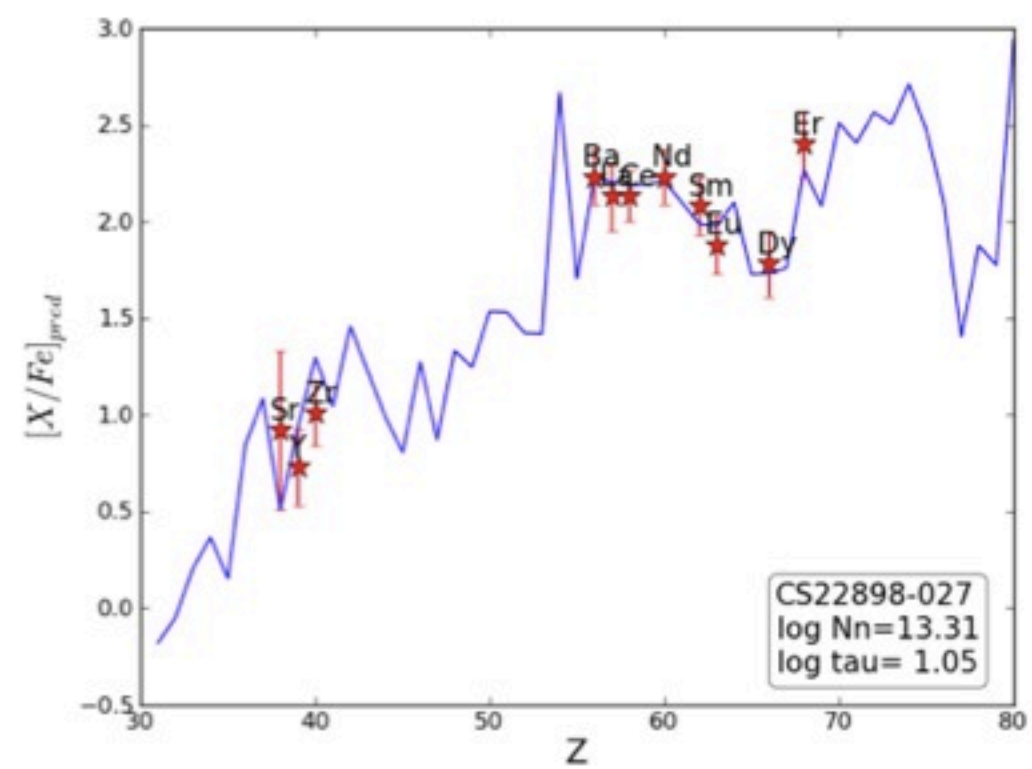
One-zone model





Could proton-ingestion events produce some CEMP-r/s stars?





Herwig+ (in prep.)

Open questions

What are the properties of mixing at convective boundaries?

- Neon shell burning behaviour and EC-SN impact
- Hybrid C-O-Ne white dwarfs and SN1a impact
- Efficiency of 3DUP in super-AGB stars - can these stars become EC-SNe?
- How does mixing behave in region of strong electron capture?

Mass loss vs core growth - more EC-SNe at low metallicity?

Are EC-SNe core-collapse or thermonuclear supernovae?

- New weak interaction rates increase O-deflagration ignition density
- Convection and turbulence during deflagration (cf. C-deflagration in Type Ia supernovae)

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

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

CANFAR Software-as-a-service for NuGrid data exploration

S. Jones(UVic, NuGrid), F. Herwig(UVic, JINA, NuGrid), L. Siemens(UVic), S. Fabbro(UVic, CANFAR), S. Gaudet(NRC-Herzberg, CANFAR), M. Pignatari(Basel, NuGrid), R. Trappich(Chicago, NuGrid) and the NuGrid Collaboration

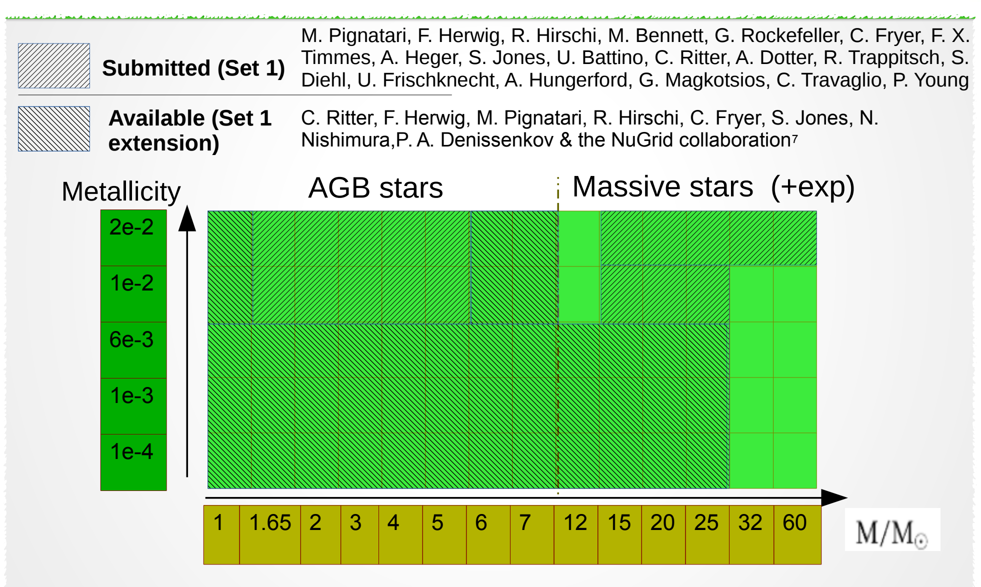
JINA

CANFAR Canadian Advanced Network for Astronomical Research

One-Zone Numerical Experiments (OZoNE) - explore a library of thermodynamic trajectories from stellar production sites

Interactive Python front-end for one-zone nucleosynthesis simulations (PyPPN)

NuGrid Yields: all stable isotopes for up to 14 initial masses at 5 metallicities



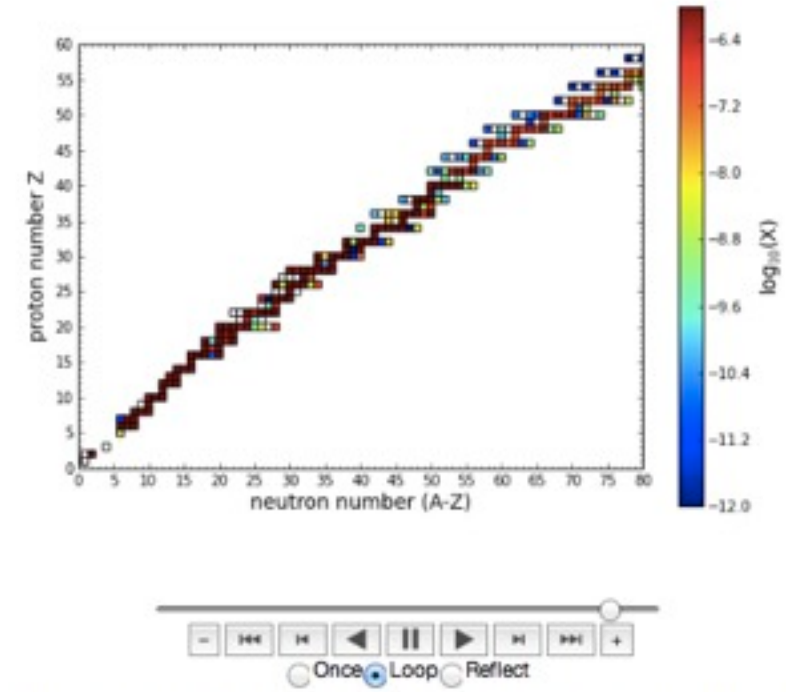
You explore and analyse data

network

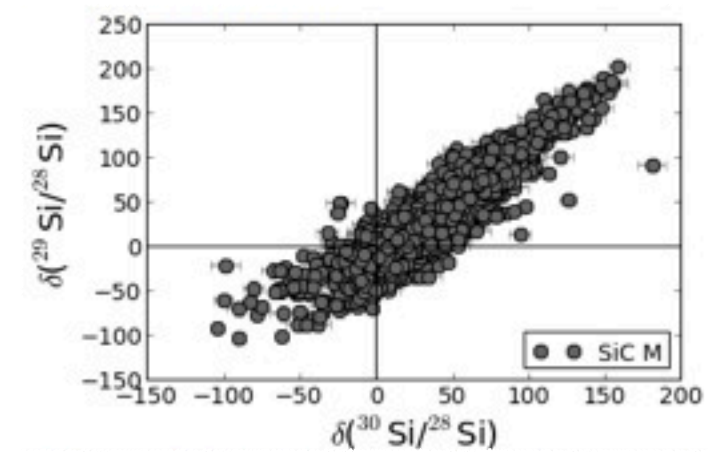
CANFAR Software-as-a-service on virtual machine in CANFAR cloud

network

NuGrid data on VOspace



Data exploration: make plots and movies with a web-based interactive Python framework



Interactive framework for U of Washington pre-solar grain database