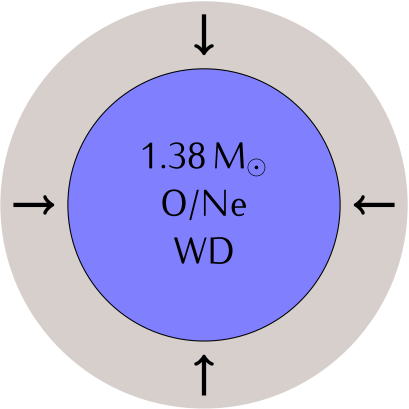
Single and Double Degenerate Pathways towards Accretion-Induced Collapse

with L. Bildsten, E. Quataert & others

Josiah Schwab

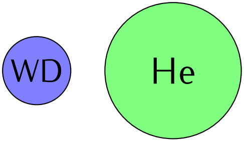
10 November 2015

Accretion-induced collapse (AIC) occurs when an O/Ne WD reaches a critical mass.



Multiple channels are thought to lead to AIC.

Single-Degenerate



Double-Degenerate

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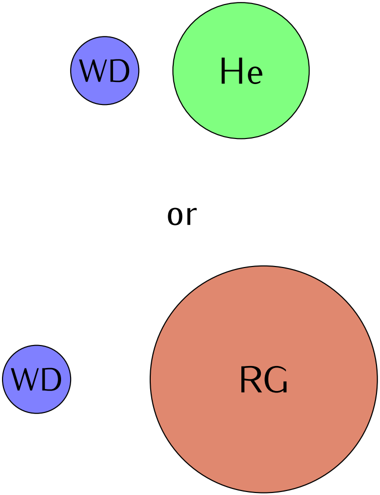

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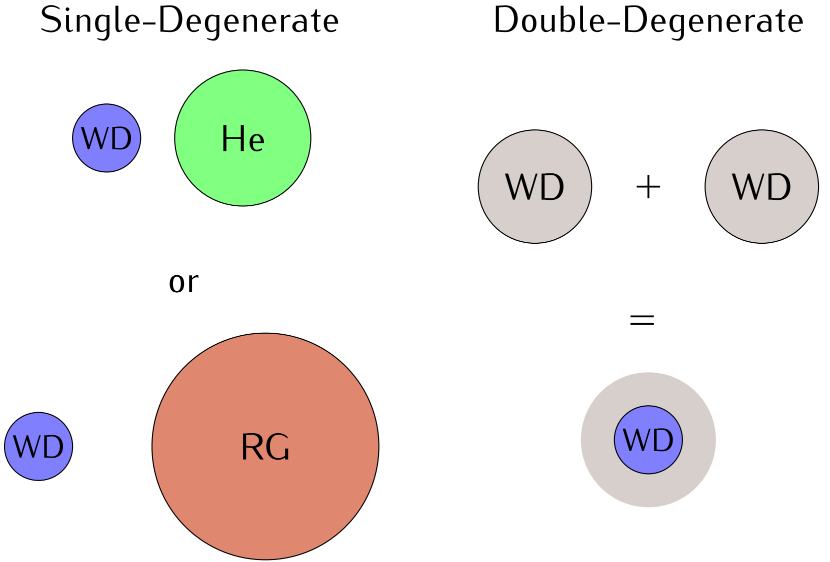

No direct observations of AIC have yet been made.

- Models of the collapse of a massive WD to form a neutron star (NS) produce a weak explosion and $\sim 10^{-3}\,M_\odot$ of Ni-rich ejecta.

  Woosley & Baron (1992); Dessart et al. (2006);

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- Other radio, optical, and X-ray signatures have been predicted, but depend on whether
  - the progenitor systems have surrounding material
  - other aspects of the evolution synthesize Ni-56
  - the newly formed NS is a magnetar

  Piro & Kulkarni (2013); Metzger & Bower (2014)

The goal of this work is to improve our understanding of the signatures of AIC by improving the modeling of the evolution preceeding the collapse to a neutron star.

Overview

Single Degenerates
- The physics of the key weak reactions
- Thermal evolution of accreting ONe WDs
- Collapse to a neutron star

Double Degenerates

Summary and Conclusions

Weak reactions will drive the evolution.

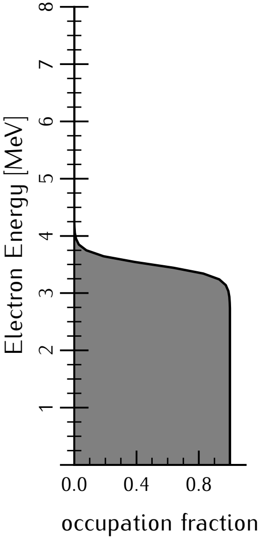
Electron capture

$$(Z, A) + e^- \rightarrow (Z - 1, A) + \nu_e$$

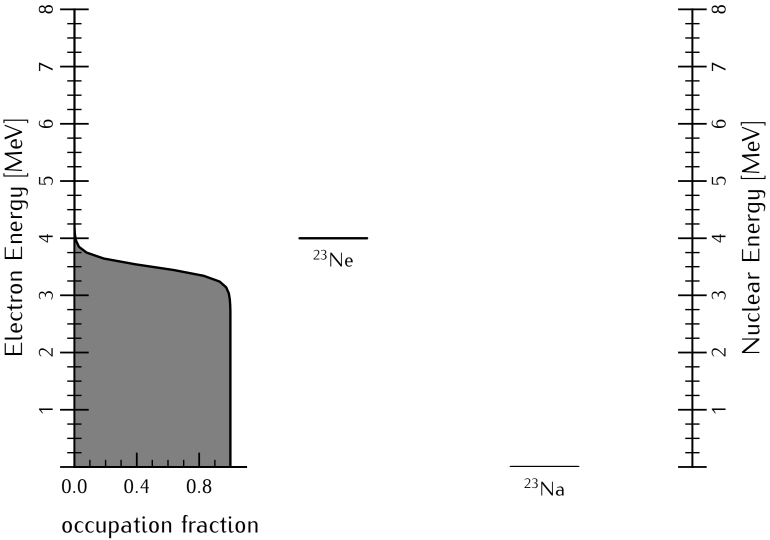
Beta decay

$$(Z - 1, A) \rightarrow (Z, A) + e^- + \bar{\nu}_e$$

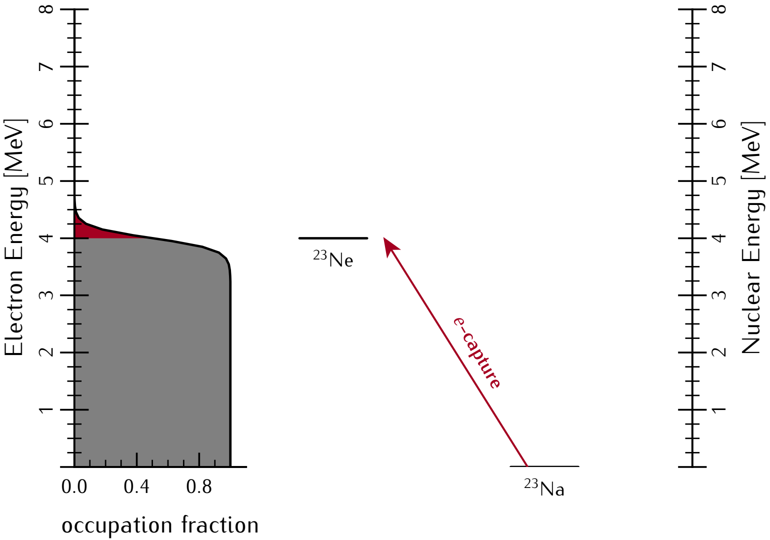
The WD is a cold, electron-degenerate plasma.



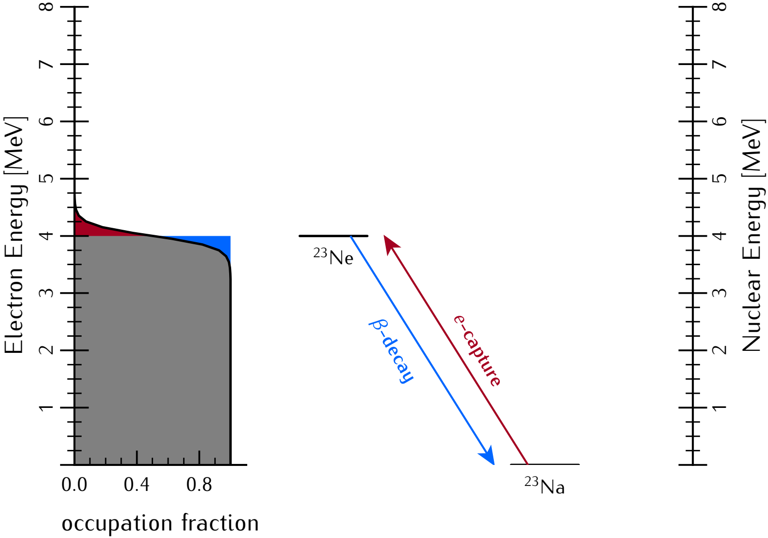
The electron Fermi energy is $\sim$ MeV and rising.



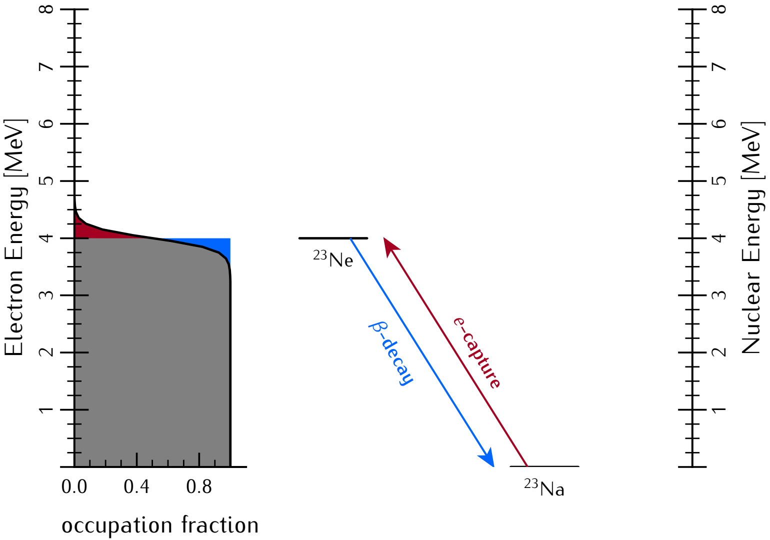
Electron-capture reactions can now occur.



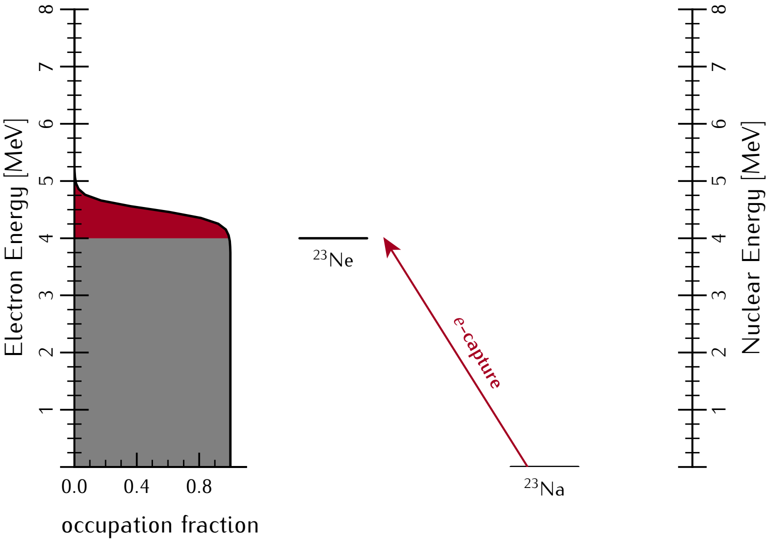
Beta-decay reactions can also still occur.

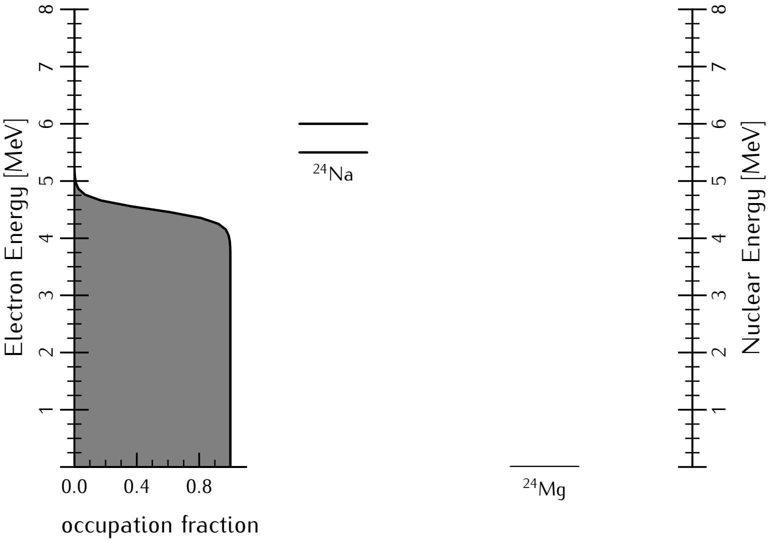


This "Urca process" cools the plasma.



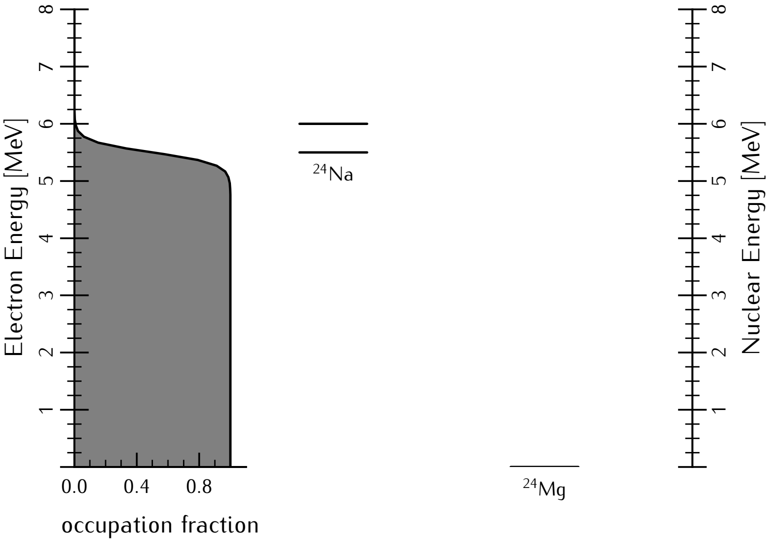
It shuts off above the threshold density.



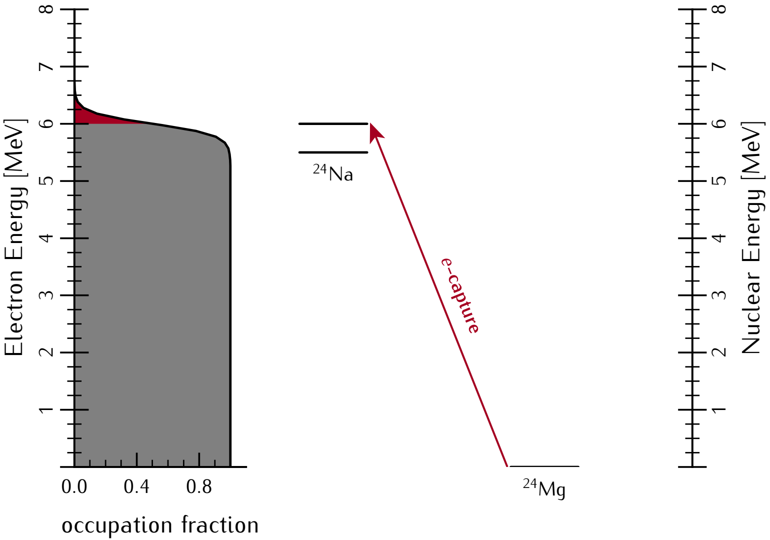


Electron Energy [MeV]
8
7
6
5
4
3
2
1
0.0
0.4
0.8
occupation fraction
^{24}Na
^{24}Mg
Nuclear Energy [MeV]

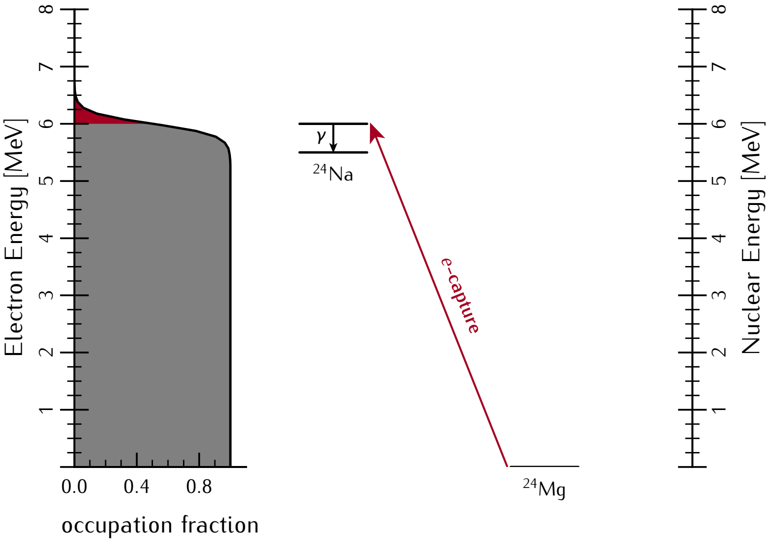
The ground state transition is highly forbidden.



Electron-captures are into an excited state.



Emission of a gamma-ray heats the plasma.



Overview

Single Degenerates

The physics of the key weak reactions

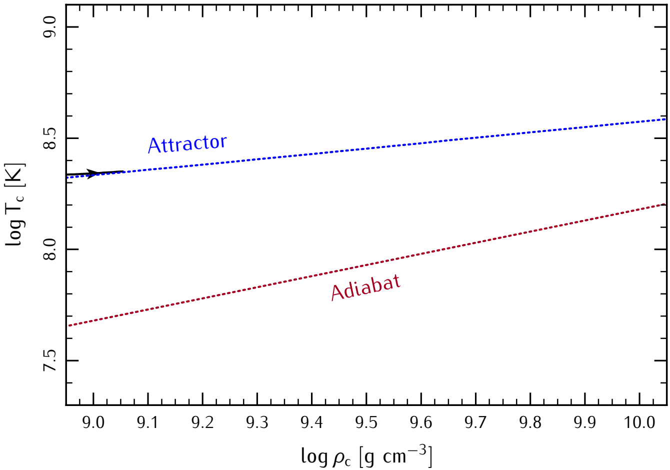
Thermal evolution of accreting ONe WDs

Collapse to a neutron star

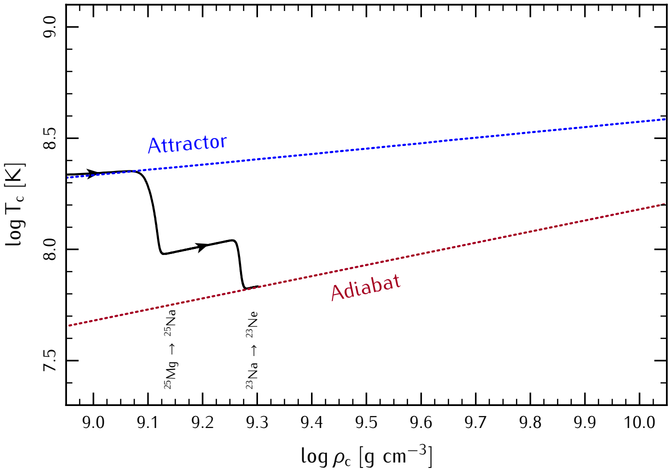
Double Degenerates

Summary and Conclusions

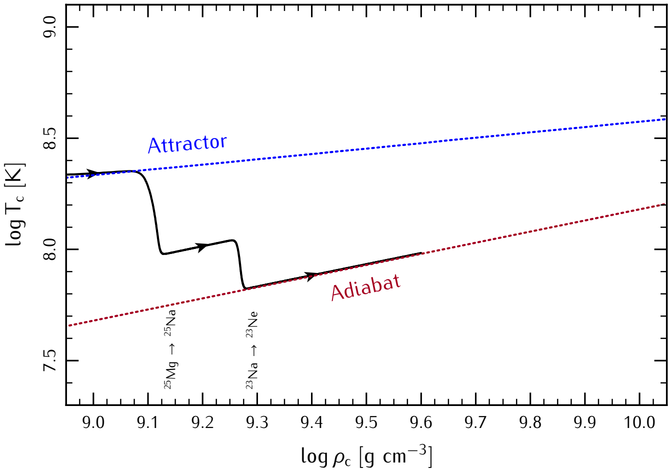
Initially, the temperature is set by a balance between compression and neutrino cooling.



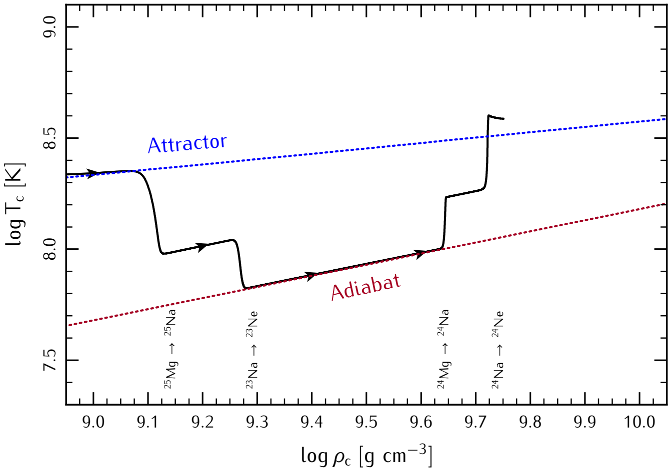
Substantial Urca-process cooling occurs associated with the $A = 23$ and $A = 25$ isotopes.



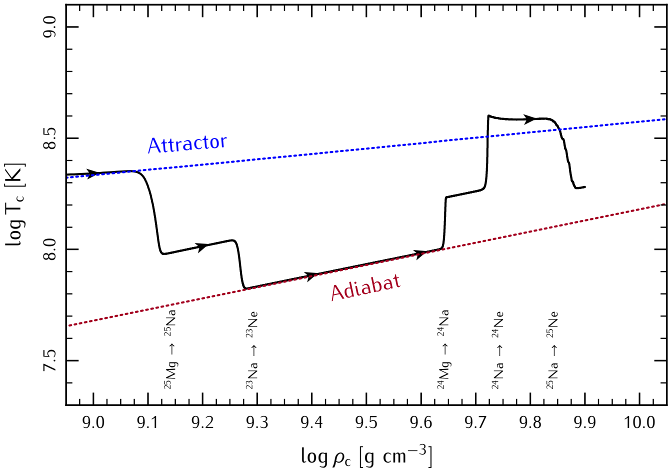
This shuts off neutrino cooling
and the material evolves along an adiabat.



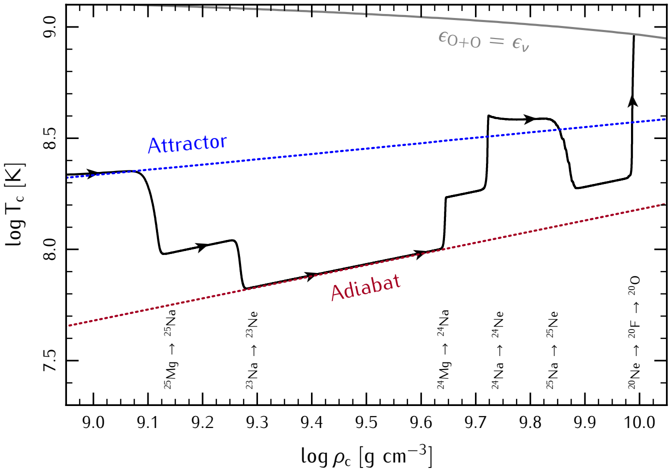
Substantial heating also occurs associated with the $A = 24$ isotopes.



Urca-process cooling will set the temperature at the onset of captures on ^{20}Ne.



Captures on ^{20}Ne are exothermic;
this heating will ignite oxygen fusion.



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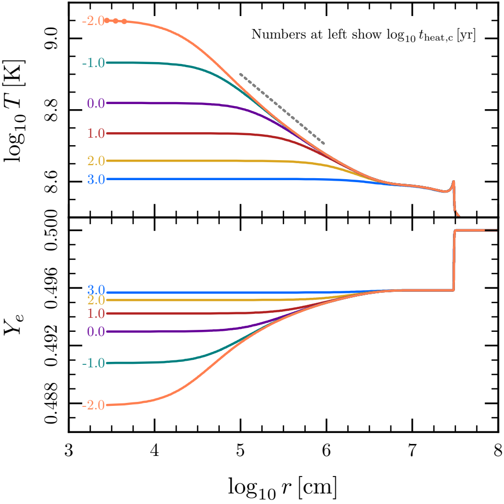
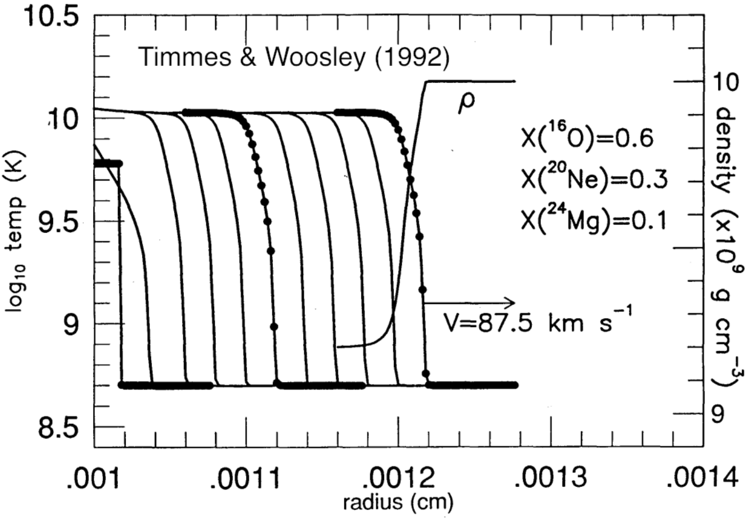
A thermal runaway develops in the core;

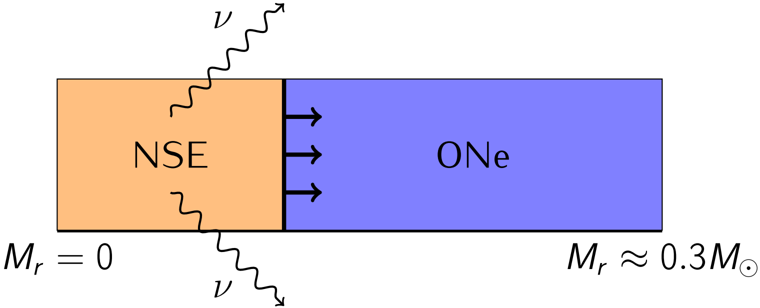
but convection is not triggered in the core.



This will lead to the formation
of an outgoing oxygen deflagration wave.



There is a competition between the deflagration and the weak reactions occurring in its ashes.



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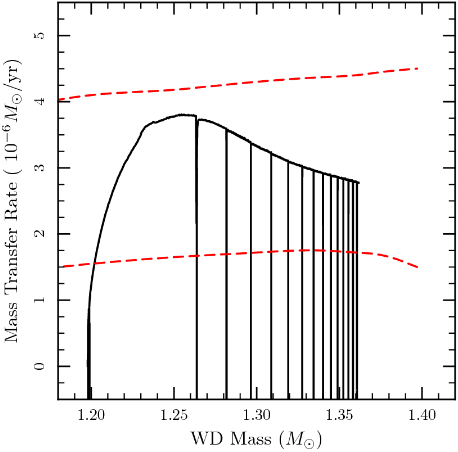
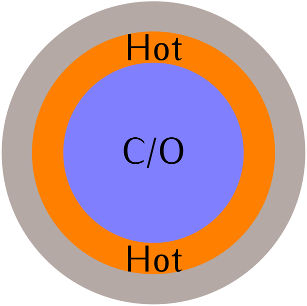
- We demonstrated the presence of a thermal runaway in the core, which will trigger an oxygen deflagration at a density such that collapse to a neutron star is likely.
- This enables the generation of more realistic progenitor models for studies of the observational signatures of AIC.

This understanding is being applied to simulations of He star + ONe WD binaries.



work by Jared Brooks

How would a WD merger evolve towards AIC?



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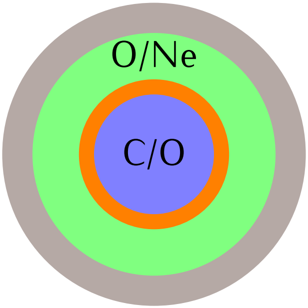

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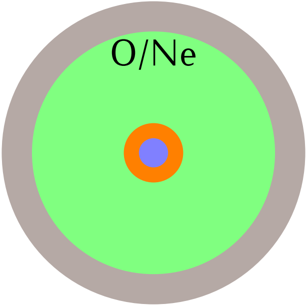

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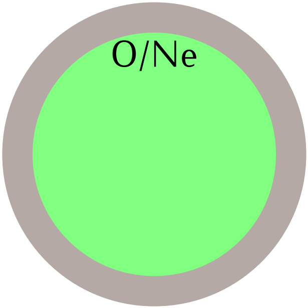
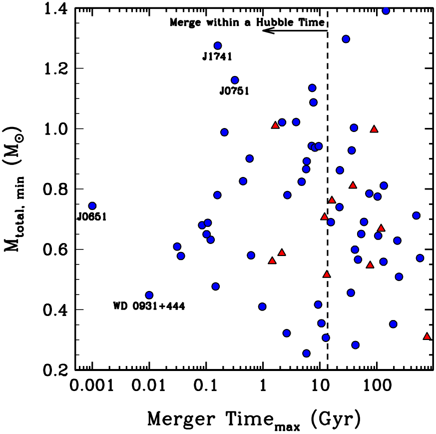
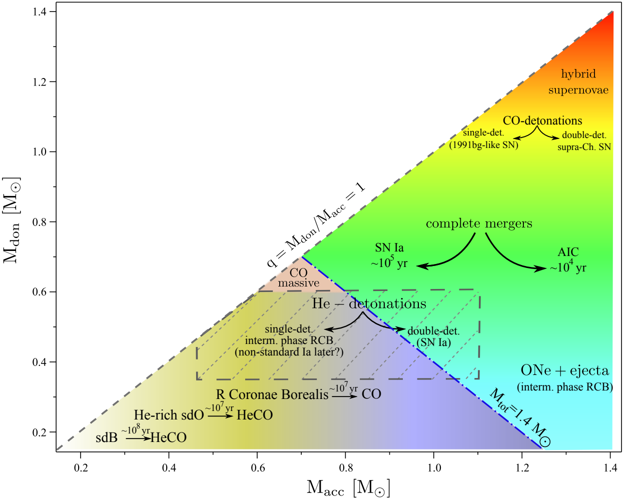


There are WD+WD binaries that will merge; the rate in the Milky Way is ~1 per century.



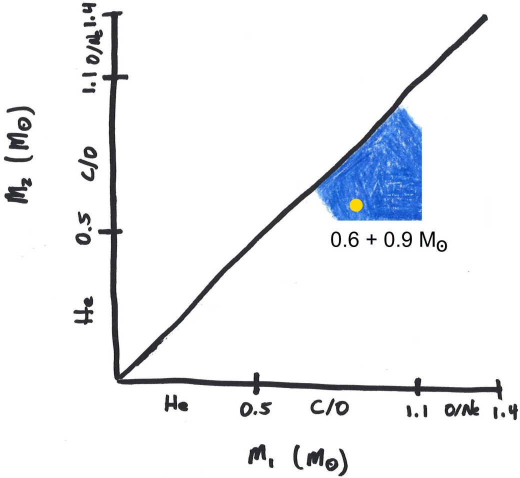
Badenes & Maoz (2012); ELM: Gianninas et al. (2015)

There are a wide variety of post-merger outcomes.



e.g., Webbink (1984), … ; Fig. from Dan et al. (2014)

Today, I will focus on the merger of two CO WDs, with a total mass above the Chandrasekhar mass.



The primary WD remains relatively undisturbed;
The secondary WD is disrupted, forming a disk.

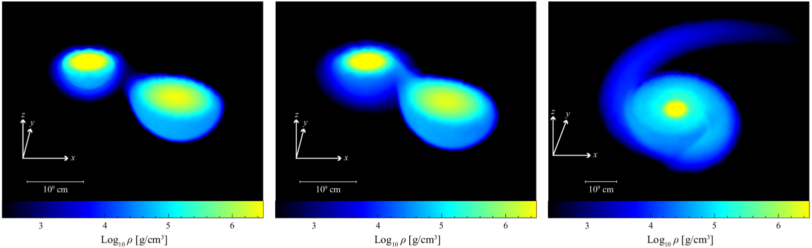


Fig. from Dan et al. (2011)

The evolution can be divided into three phases with well-separated timescales.

Dynamical Time (min)

Completion of merger

Viscous Time (hr)

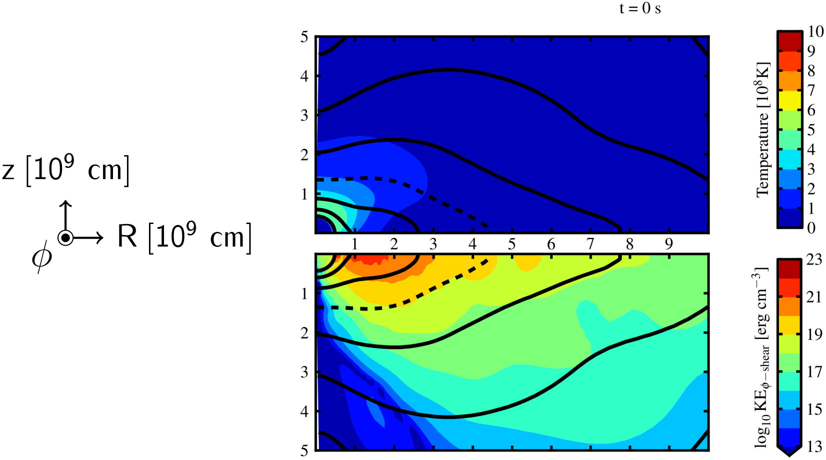
Redistribute ang. mom.

Thermal Time (kyr)

Radiate away energy

Shen et al. (2012); Schwab et al. (2012)

The remnant is unstable to the MRI and evolves viscously before cooling significantly.



Schwab et al. (2012)

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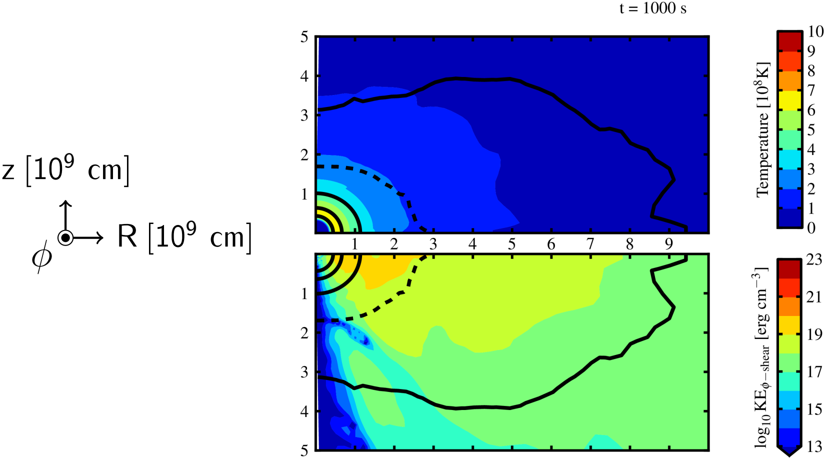

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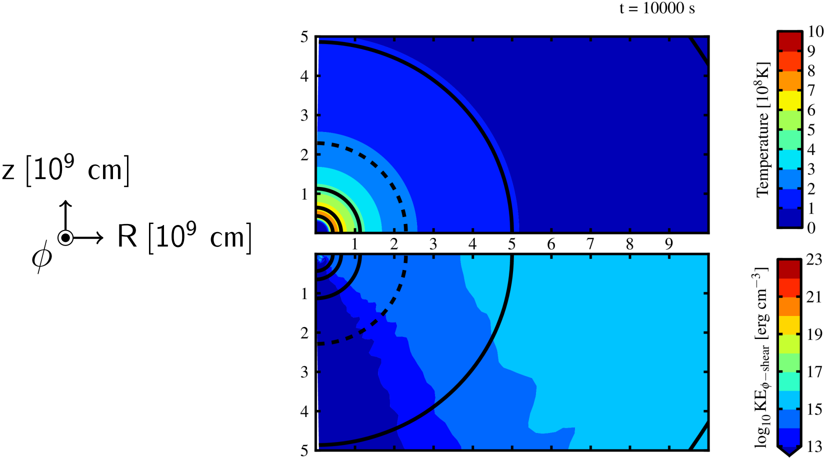
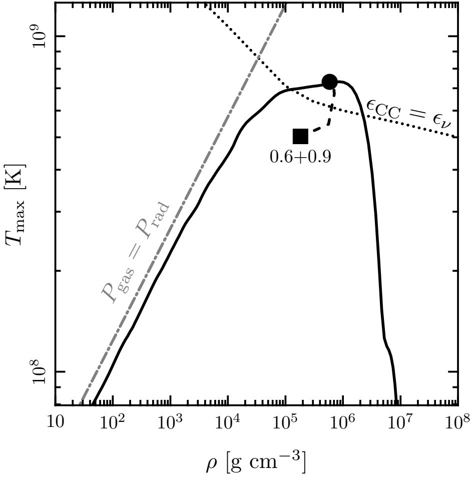


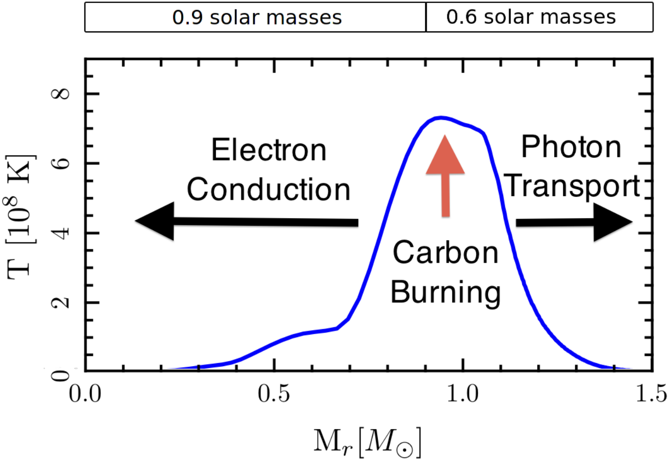
Schwab et al. (2012)

The viscous heating ignites carbon fusion off-center in the remnant.

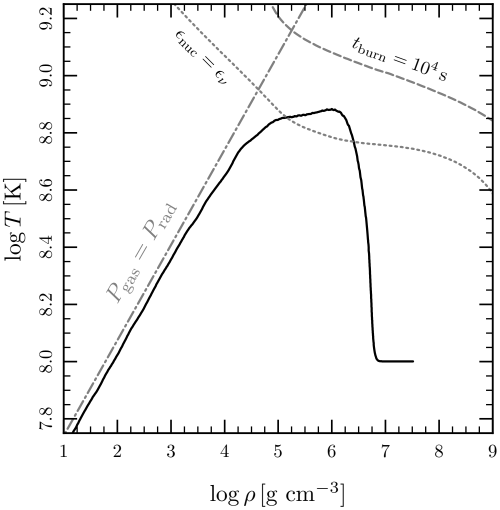


Schwab et al. (2012)

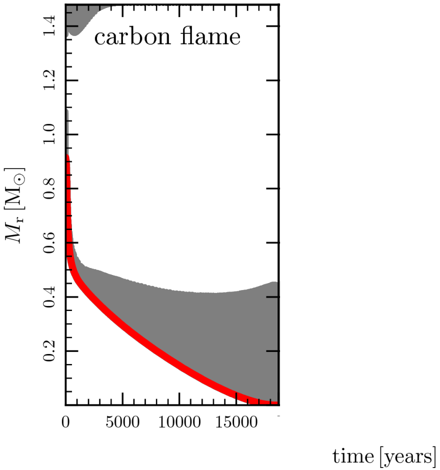
Energy generation and heat transport will drive the next phase of evolution.



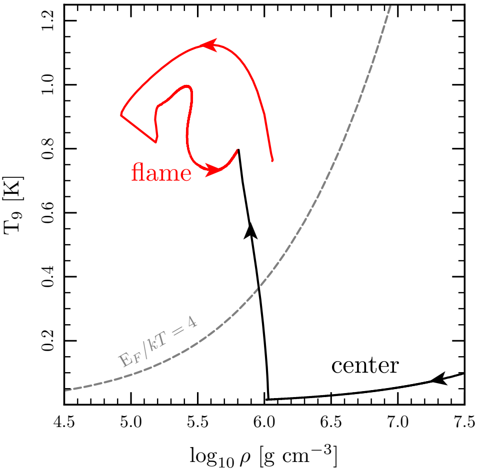
I map the output of the hydro simulations into the MESA stellar evolution code.



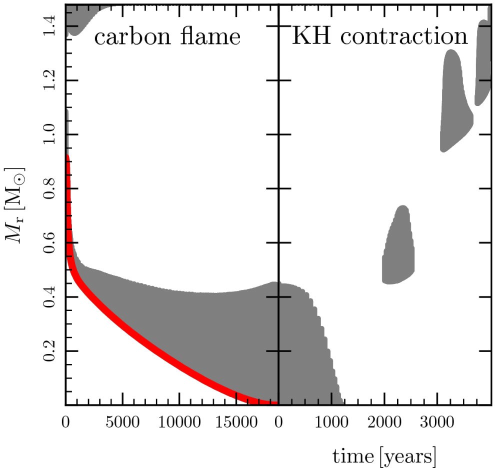
A convectively-bounded carbon deflagration forms and propagates inward.



The flame reaches the center;
the material is oxygen-neon and non-degenerate.



Then the remnant undergoes a phase of Kelvin-Helmholtz contraction.



The KH contraction is neutrino-cooled and leads to off-center neon ignition.

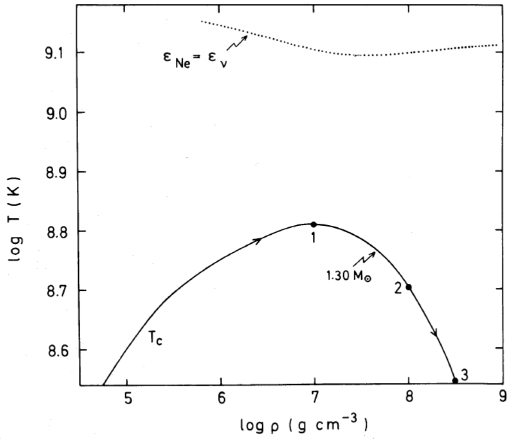


Fig. adapted from Nomoto (1984)

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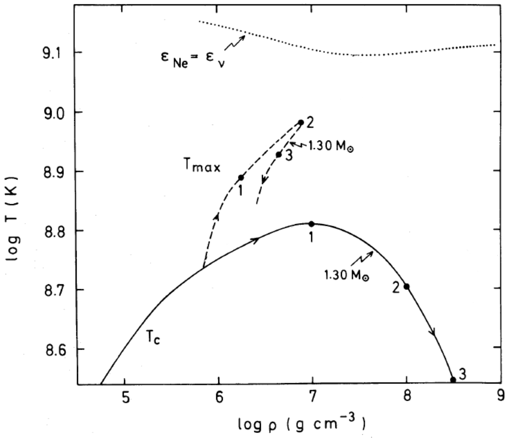

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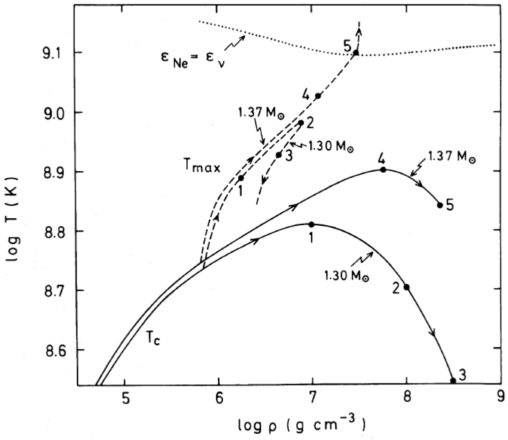

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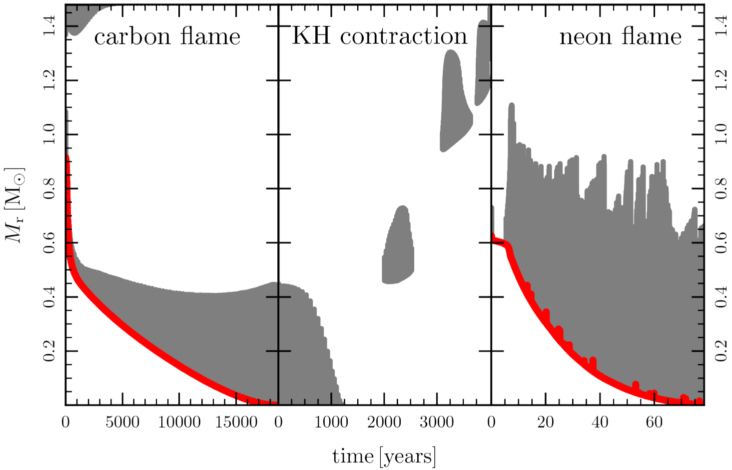
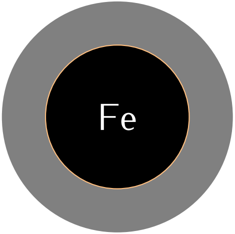
A convectively-bounded neon deflagration forms and propagates inward.



The outcome depends on the central composition; does the off-center burning reach the center?

Core-collapse



Schwab+ (in prep)

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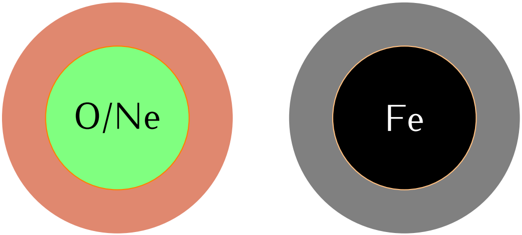
Electron-capture Core-collapse



Schwab+ (2015) Schwab+ (in prep)

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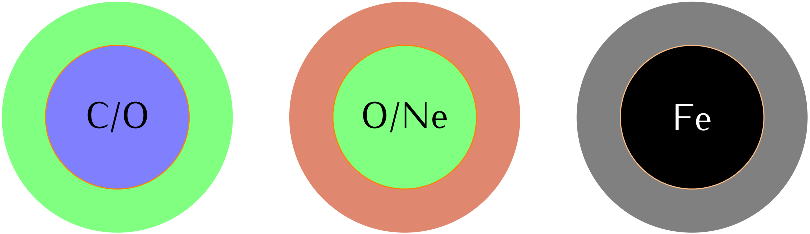
Hybrid Ia | Electron-capture | Core-collapse



Denissenkov+ (2013) | Schwab+ (2015) | Schwab+ (in prep)

- A double white dwarf system that merges goes through three phases:
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  - **thermal** phase (readjustment and stellar evolution)
- Connecting simulations of each phase enables studies of the long-term evolution.
- For super-Chandrasekhar WD mergers, the likely fate is collapse to a neutron star; the evolution towards collapse appears to be more complicated than previously understood.

- This work enables evolution of systems with an accreting ONe WD in MESA.

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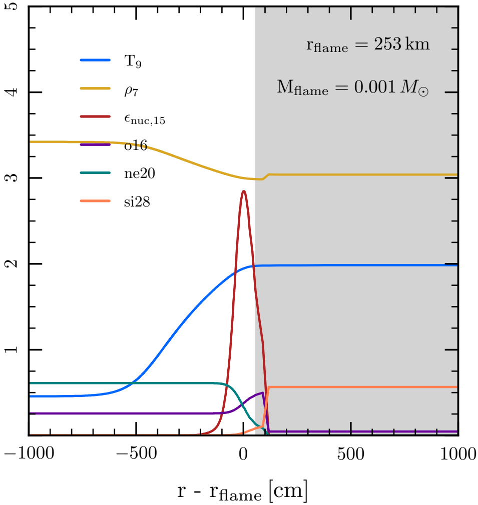
- This work makes predictions about the observable properties of WD merger remnants during the phase preceeding the collapse to a neutron star.

Neon flame structure



He + ONe Binares (Jared Brooks)