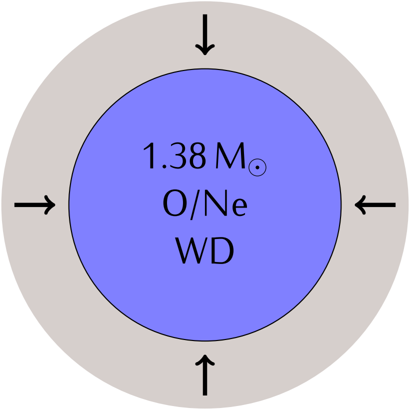
Single and Double Degenerate Pathways towards Accretion-Induced Collapse

with L. Bildsten, E. Quataert & others

Josiah Schwab

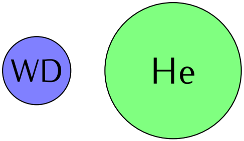
06 November 2015

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



Multiple channels are thought to lead to AIC.

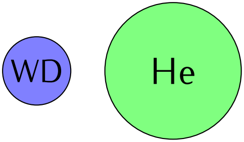
Single-Degenerate



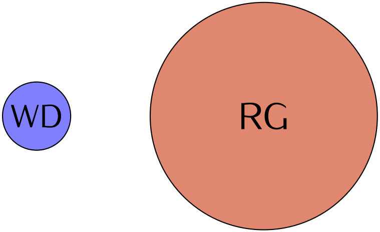
Double-Degenerate

Multiple channels are thought to lead to AIC.

Single-Degenerate



or

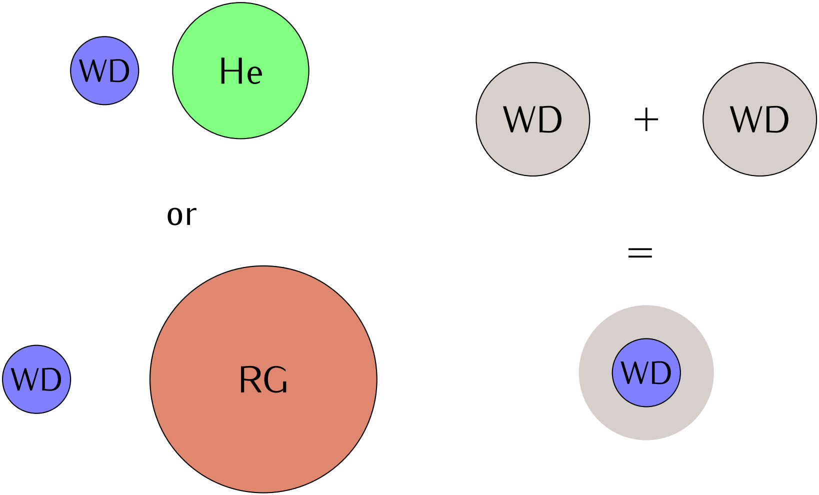


Double-Degenerate

Multiple channels are thought to lead to AIC.

Single-Degenerate

Double-Degenerate



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);

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);

- 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)

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.

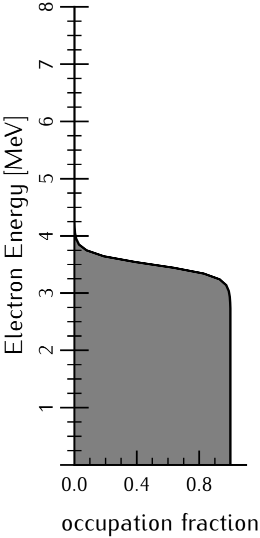
Electron capture

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

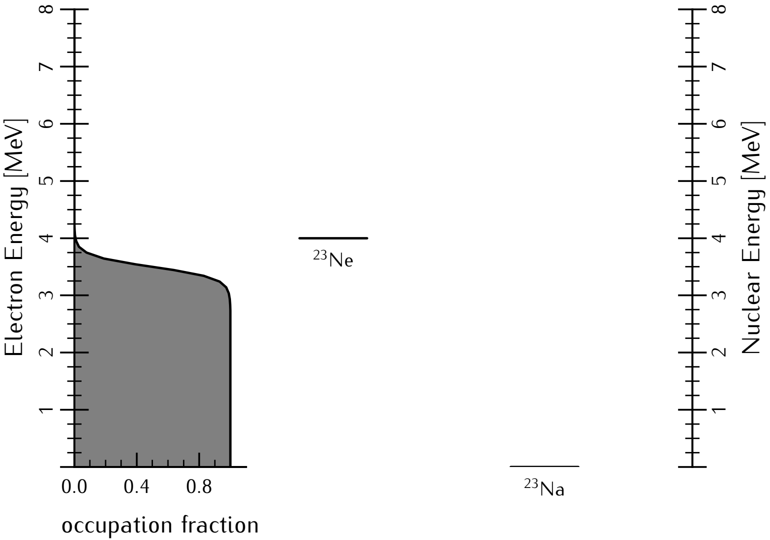
Beta decay

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

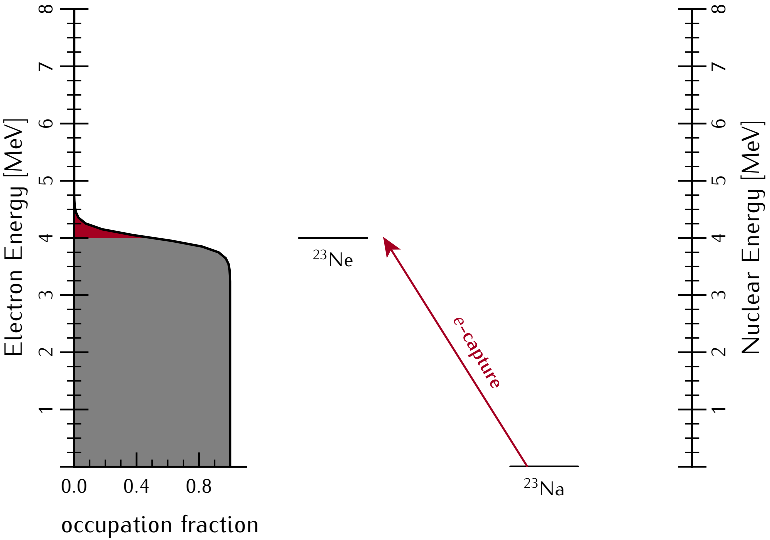
The WD is a cold, electron-degenerate plasma.



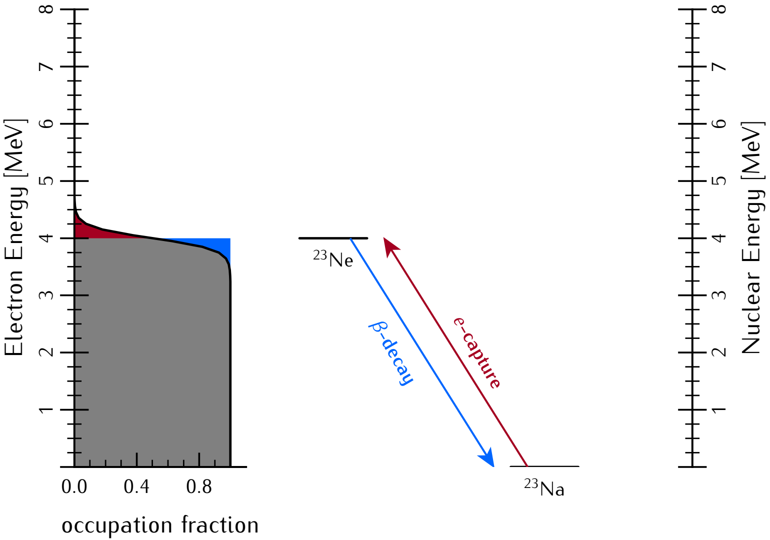
The electron Fermi energy is $\sim$ MeV and rising.



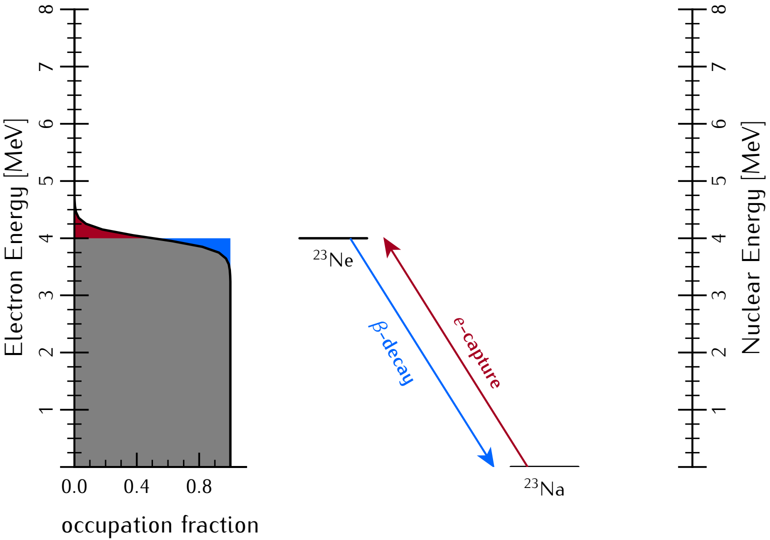
Electron-capture reactions can now occur.



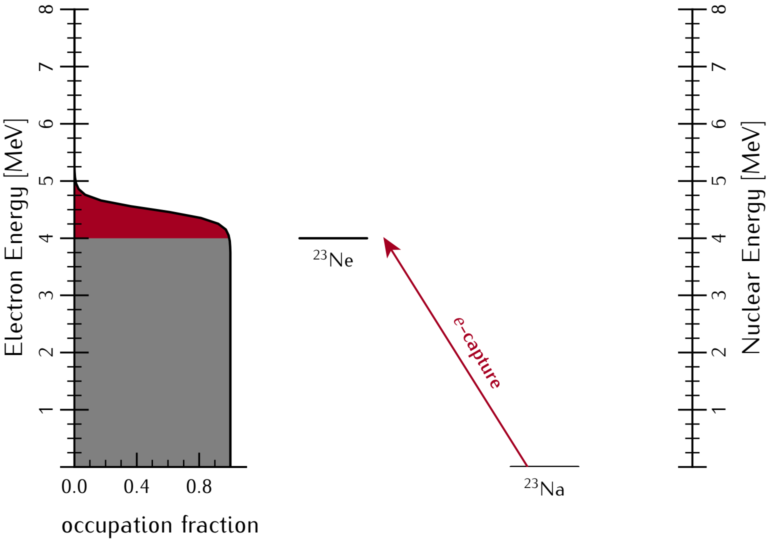
Beta-decay reactions can also still occur.

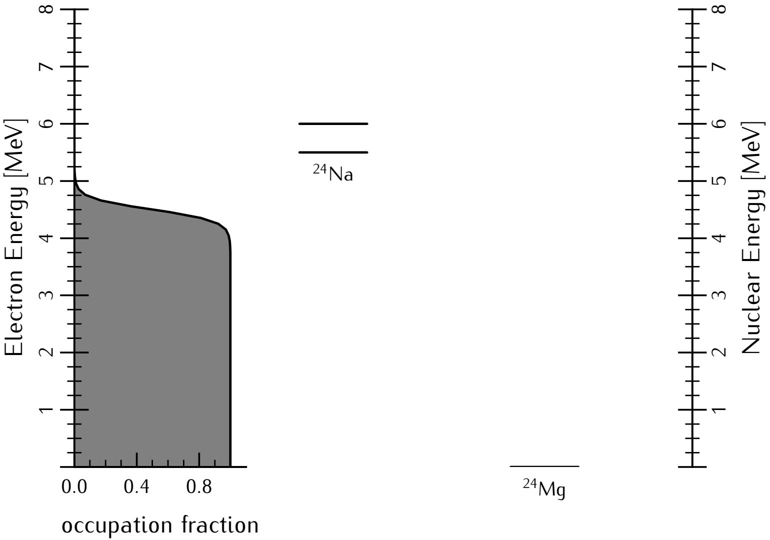


This "Urca process" cools the plasma.



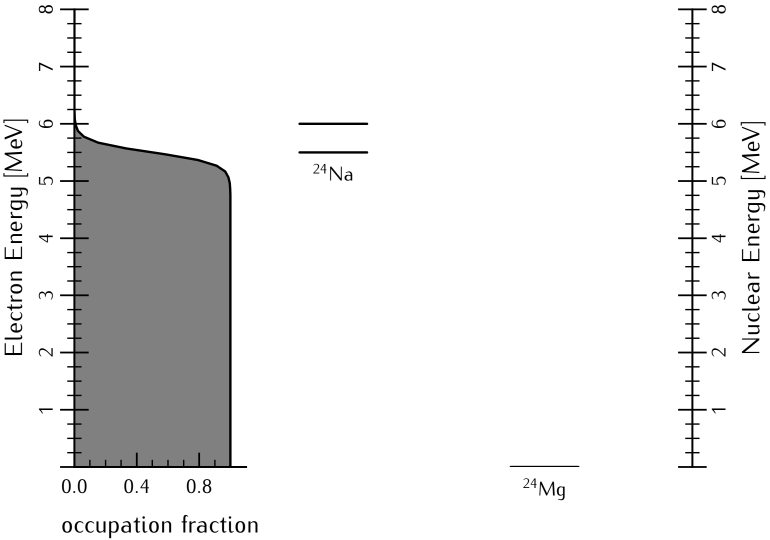
It shuts off above the threshold density.



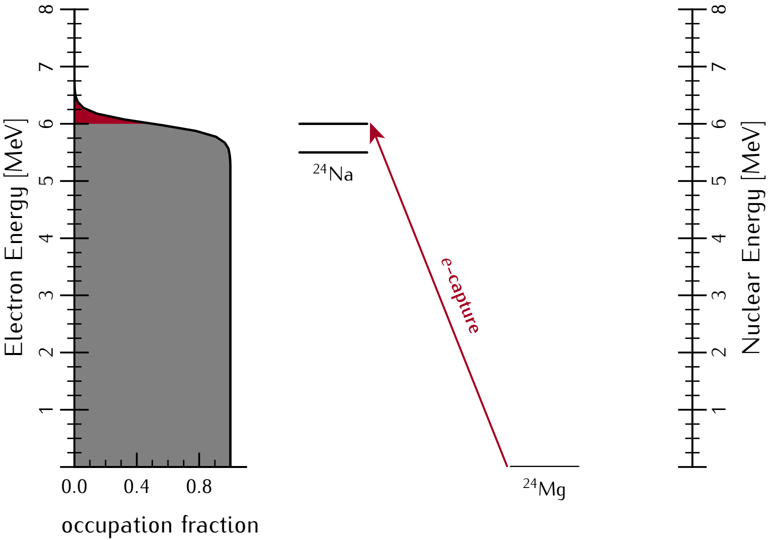


Electron Energy [MeV]
1
2
3
4
5
6
7
8
0.0
0.4
0.8
occupation fraction
^{24}Na
^{24}Mg
Nuclear Energy [MeV]

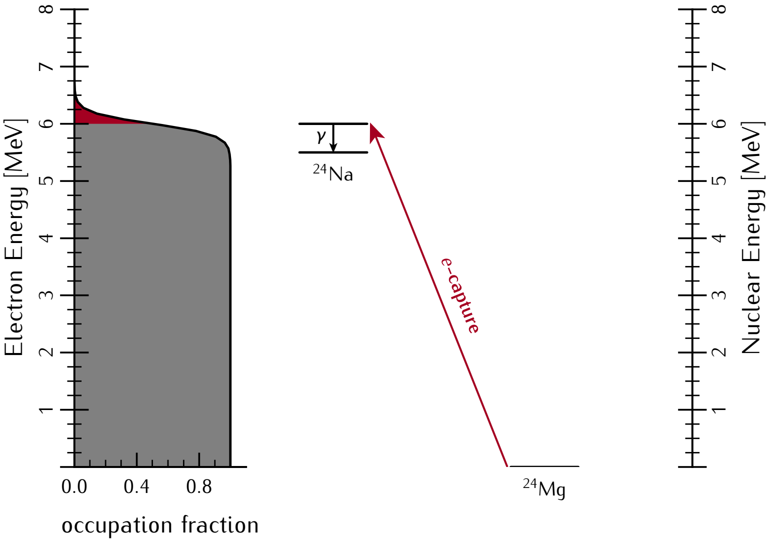
The ground state transition is highly forbidden.



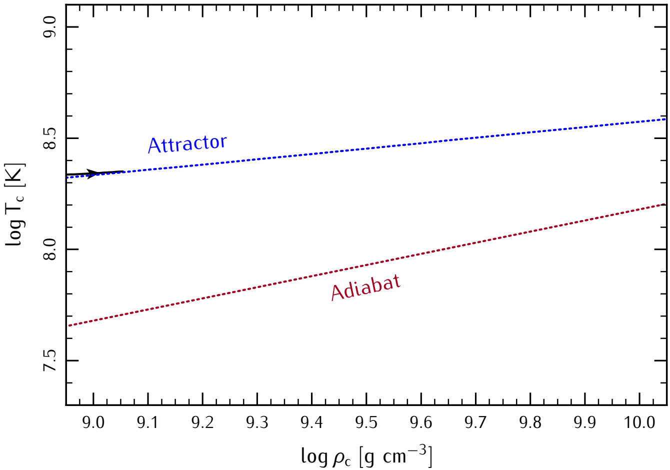
Electron-captures are into an excited state.



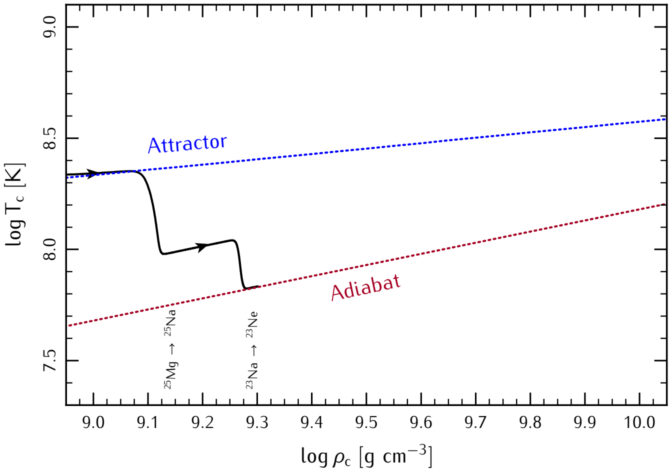
Emission of a gamma-ray heats the plasma.



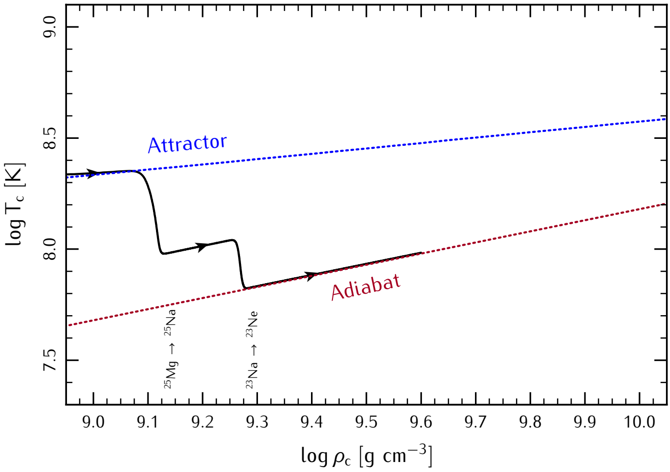
Initially, the temperature is set by a balance between compression and neutrino cooling.



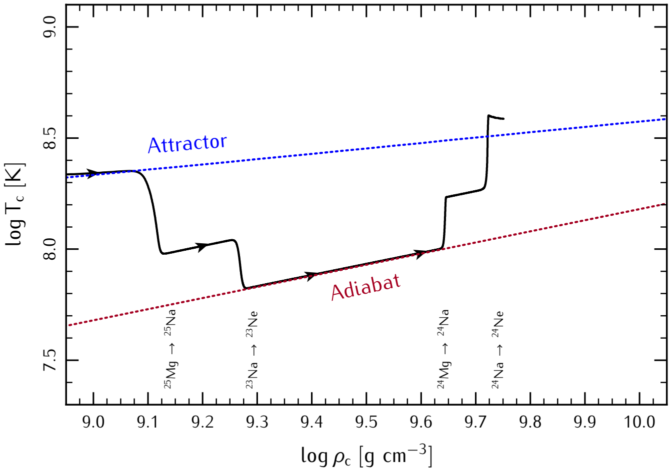
Substantial Urca-process cooling occurs associated with the $A = 23$ and $A = 25$ isotopes.



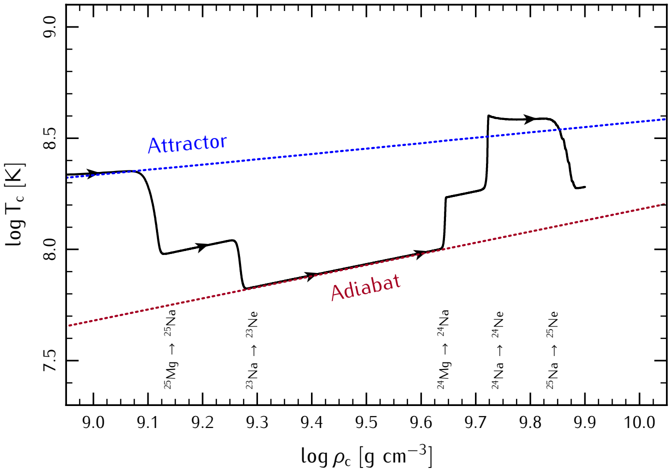
This shuts off neutrino cooling
and the material evolves along an adiabat.



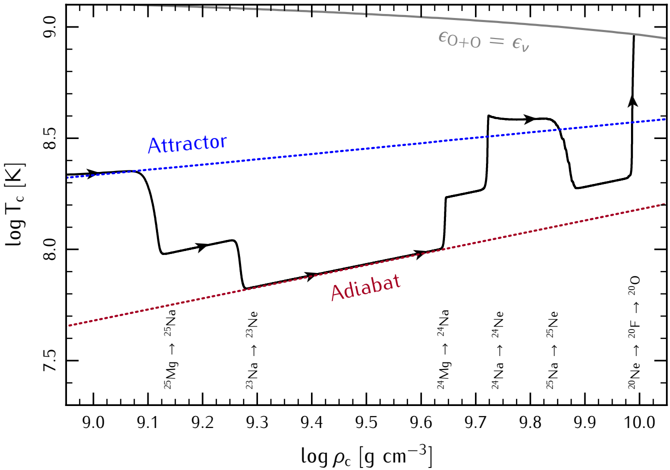
Substantial heating also occurs associated with the $A = 24$ isotopes.



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.



Overview

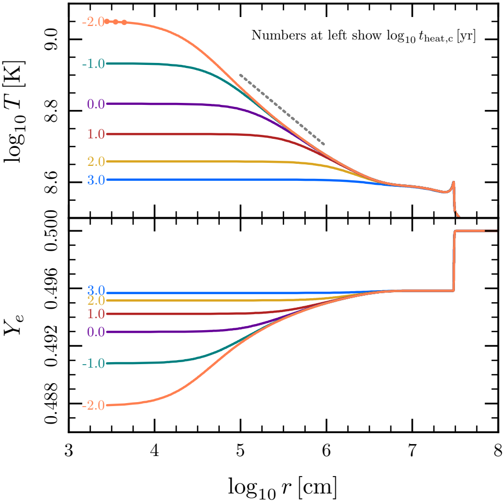
Single Degenerates

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

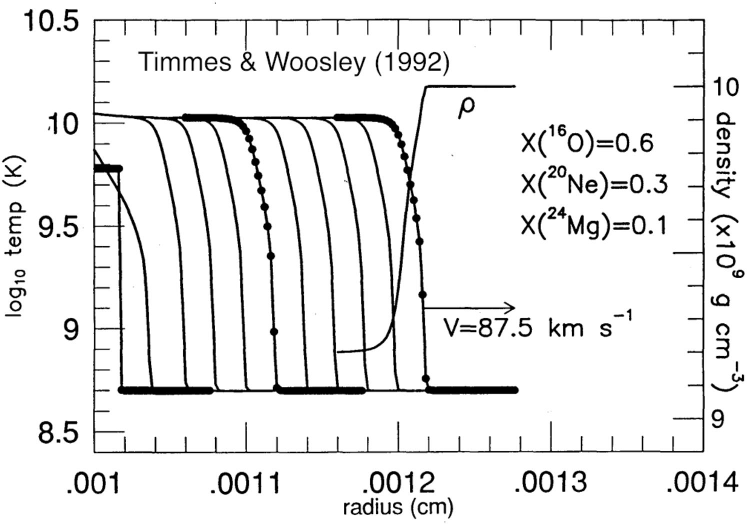
Double Degenerates

Summary and Conclusions

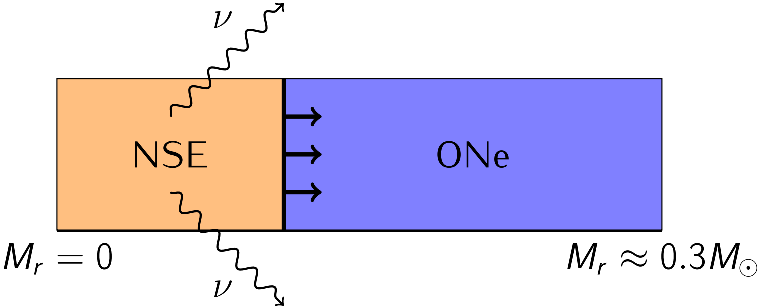
A thermal runaway develops in the core; but convection is not triggered in the core.



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.

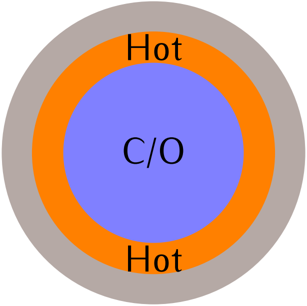


- This work provides an analytic understanding of the evolution of ONe WDs evolving towards accretion-induced collapse.

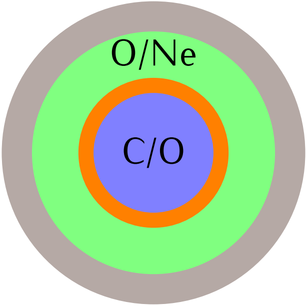
- This work provides an analytic understanding of the evolution of ONe WDs evolving towards accretion-induced collapse.
- We demonstrated the presence of a thermal runaway in the core, which will trigger an oxygen deflagration at a density such that collapse to a neutron star is likely.

- This work provides an analytic understanding of the evolution of ONe WDs evolving towards accretion-induced collapse.
- 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.

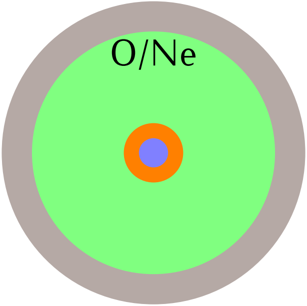
How would a WD merger evolve towards AIC?



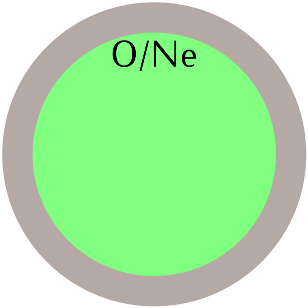
How would a WD merger evolve towards AIC?



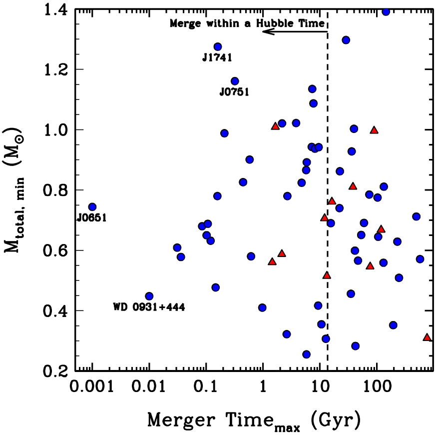
How would a WD merger evolve towards AIC?



How would a WD merger evolve towards AIC?

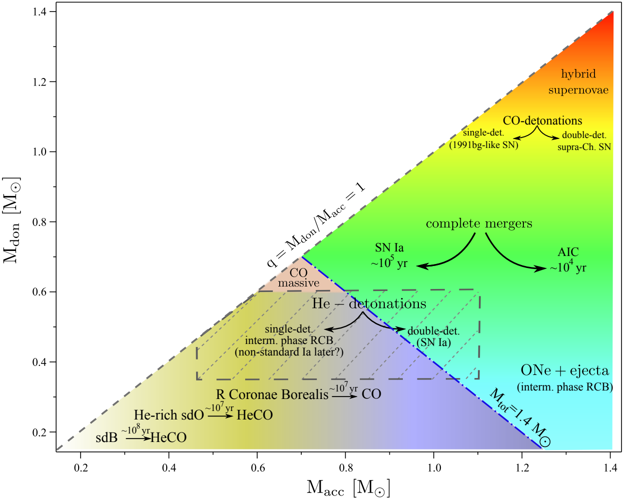


There are WD+WD binaries that will merge; the rate in the Milky Way is ~1 per century.



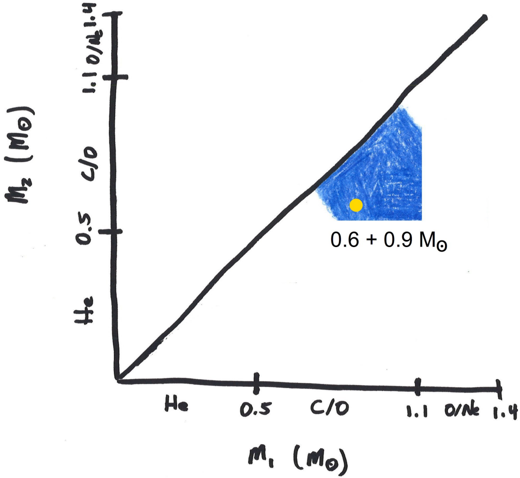
Badenes & Maoz (2012); ELM: Gianninas et al. (2015)

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.

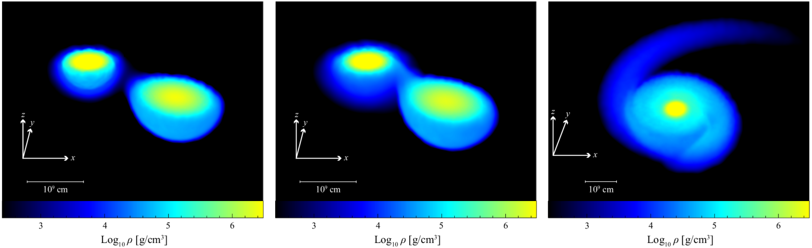


Fig. from Dan et al. (2011)

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

Dynamical Time (min)

Completion of merger

Viscous Time (hr)

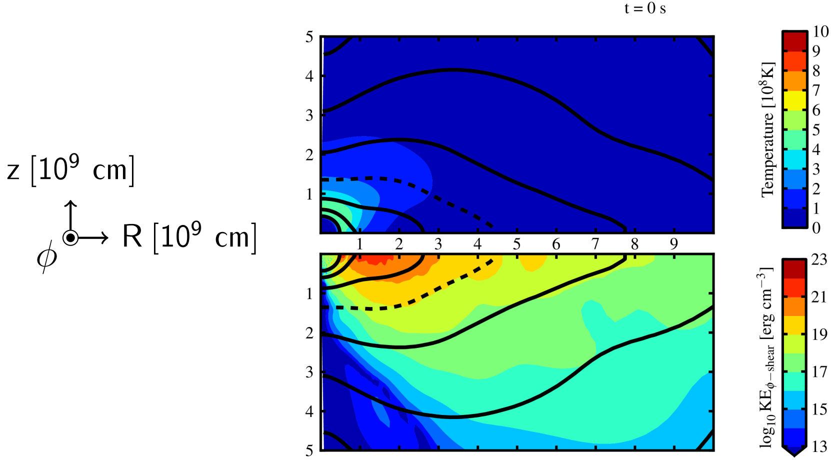
Redistribute ang. mom.

Thermal Time (kyr)

Radiate away energy

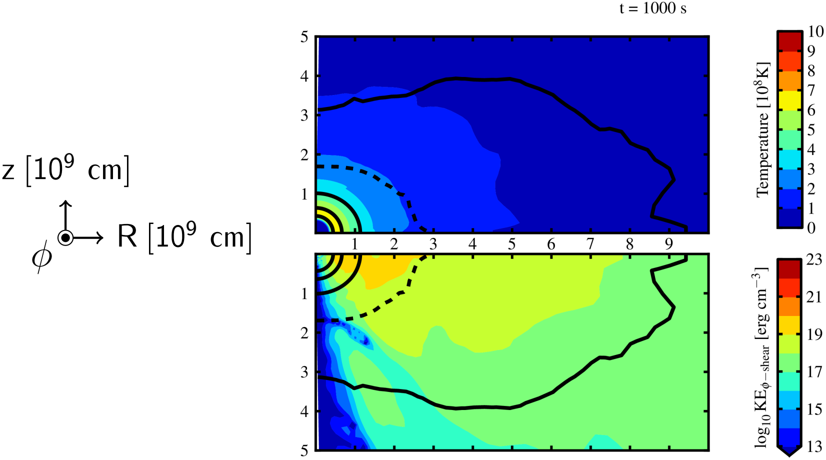
Shen et al. (2012); Schwab et al. (2012)

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



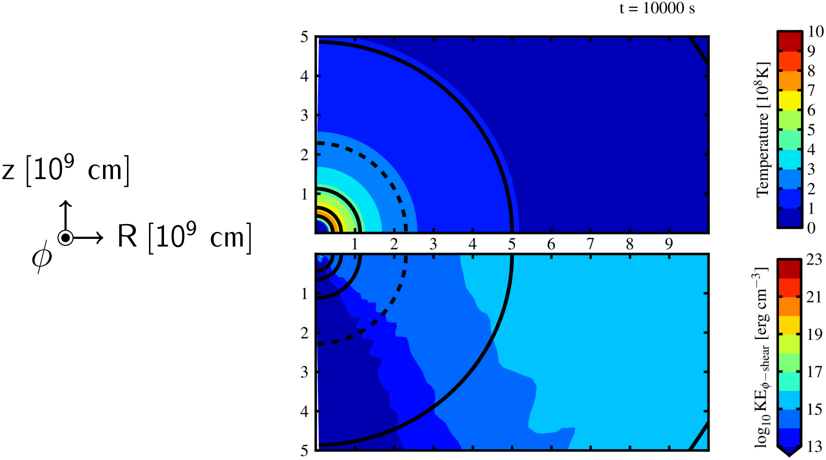
Schwab et al. (2012)

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



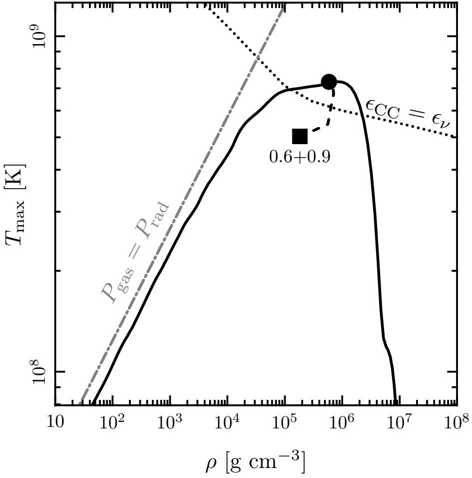
Schwab et al. (2012)

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



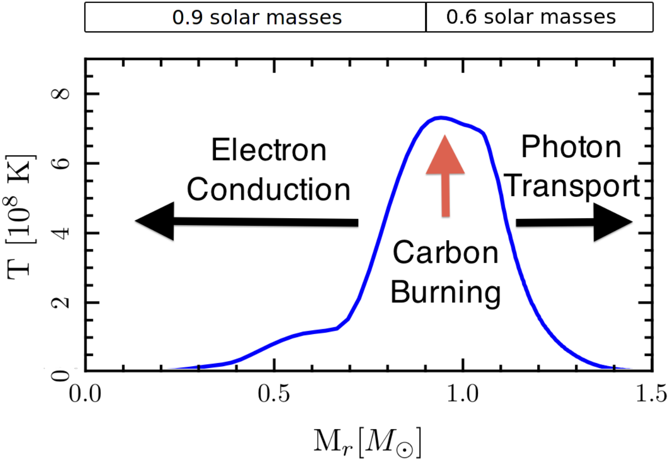
Schwab et al. (2012)

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

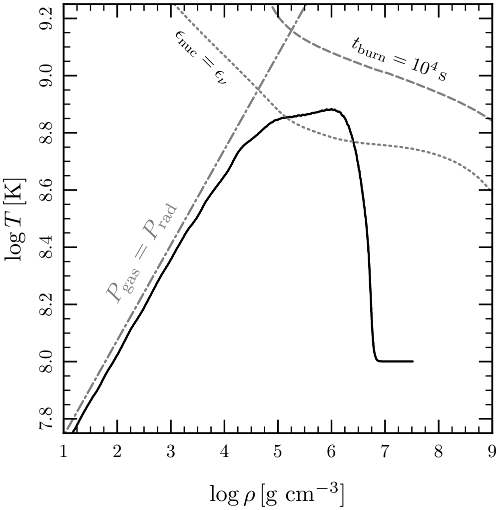


Schwab et al. (2012)

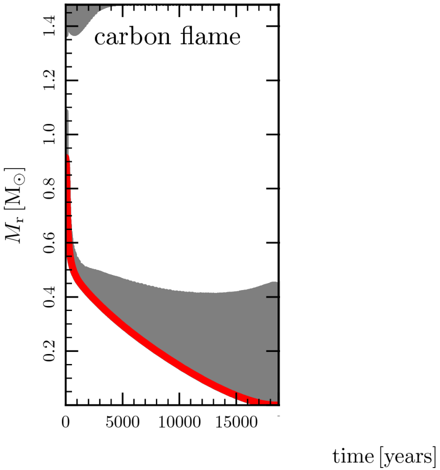
Energy generation and heat transport will drive the next phase of evolution.



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

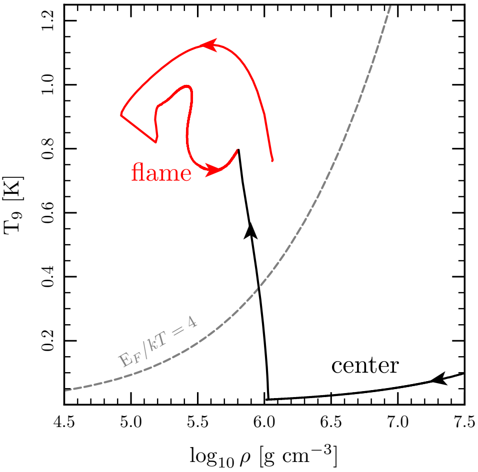


A convectively-bounded carbon deflagration forms and propagates inward.

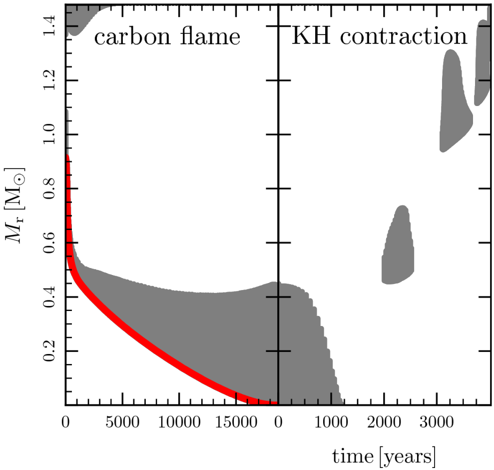


The flame reaches the center;

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.

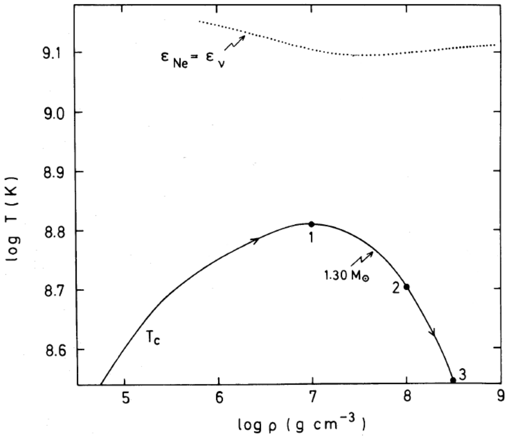


Fig. adapted from Nomoto (1984)

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

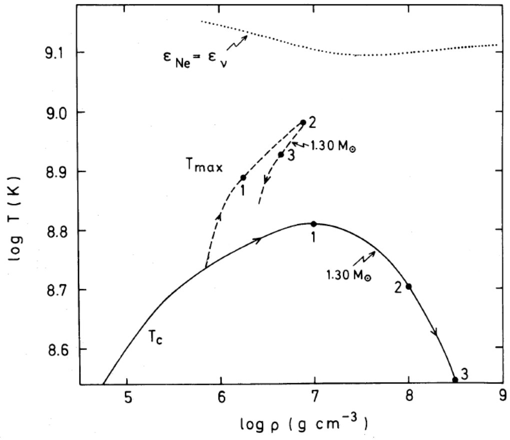


Fig. adapted from Nomoto (1984)

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

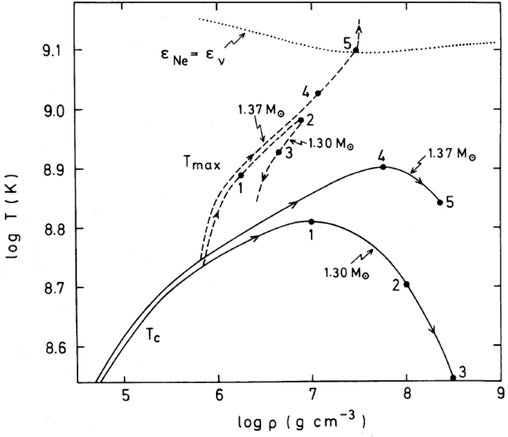
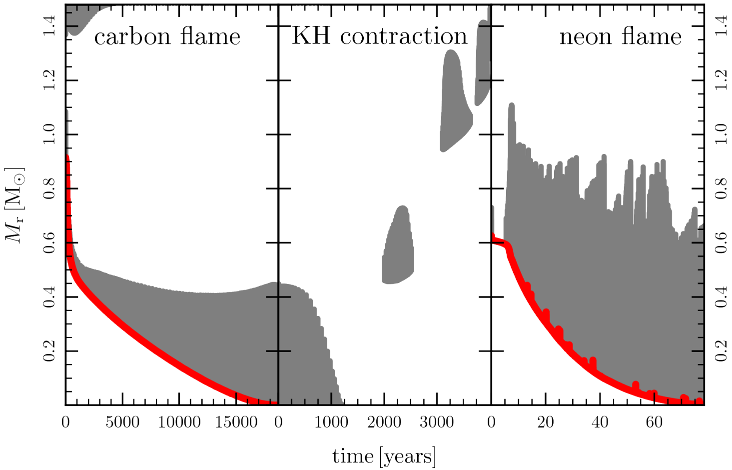


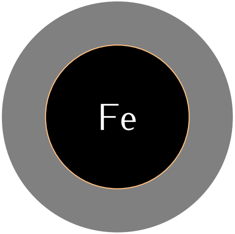
Fig. adapted from Nomoto (1984)

A convectively-bounded neon deflagration forms and propagates inward.



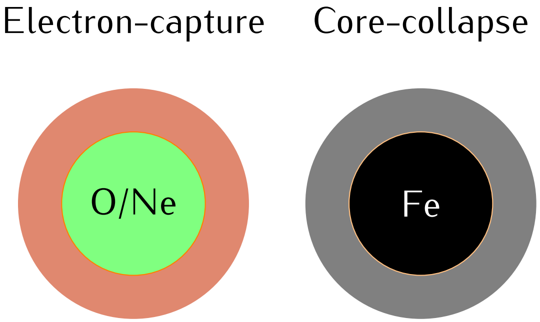
The outcome depends on the central composition; does the off-center burning reach the center?

Core-collapse



Schwab+ (in prep)

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

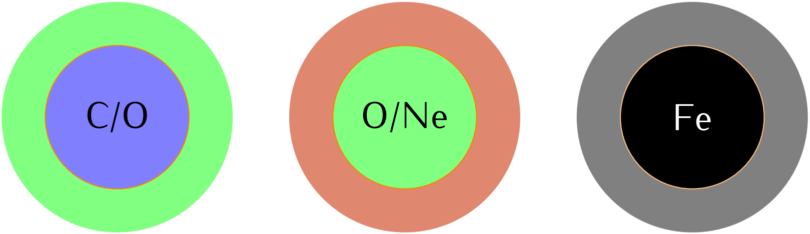


Schwab+ (2015)

Schwab+ (in prep)

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

Hybrid Ia Electron-capture Core-collapse



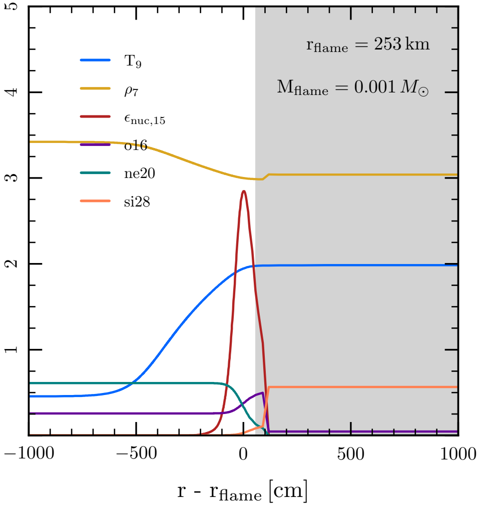
Denissenkov+ (2013) Schwab+ (2015) Schwab+ (in prep)

- A double white dwarf system that merges goes through three phases:
  - **dynamical** phase (merger)
  - **viscous** phase (rapid redistribution of ang. mom.)
  - **thermal** phase (readjustment and stellar evolution)

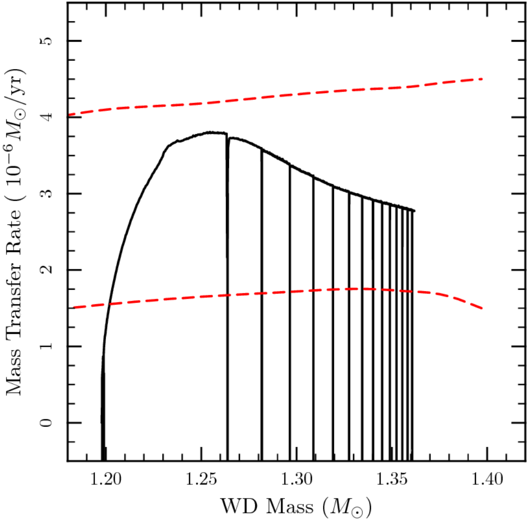
- A double white dwarf system that merges goes through three phases:
  - **dynamical** phase (merger)
  - **viscous** phase (rapid redistribution of ang. mom.)
  - **thermal** phase (readjustment and stellar evolution)
- Connecting simulations of each phase enables studies of the long-term evolution.

- A double white dwarf system that merges goes through three phases:
  - **dynamical** phase (merger)
  - **viscous** phase (rapid redistribution of ang. mom.)
  - **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.

Neon flame structure



He + ONe Binares (Jared Brooks)



He + ONe Binares (Jared Brooks)