Accretion-Induced Collapse and its Progenitors

with L. Bildsten, J. Brooks, E. Quataert, & others

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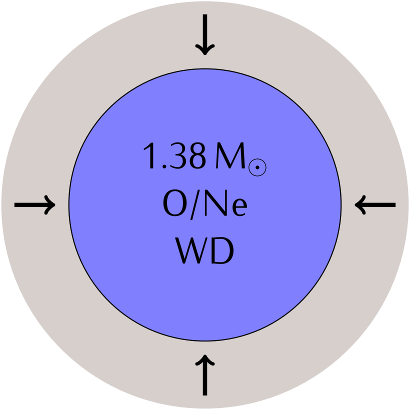
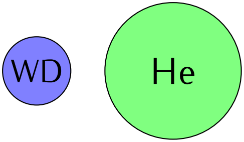
26 May 2017

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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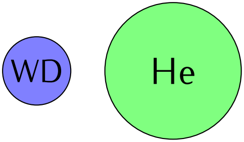
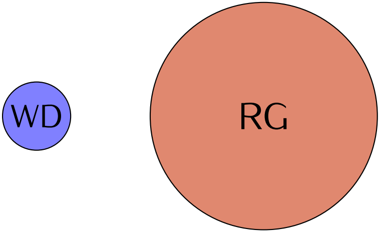


or



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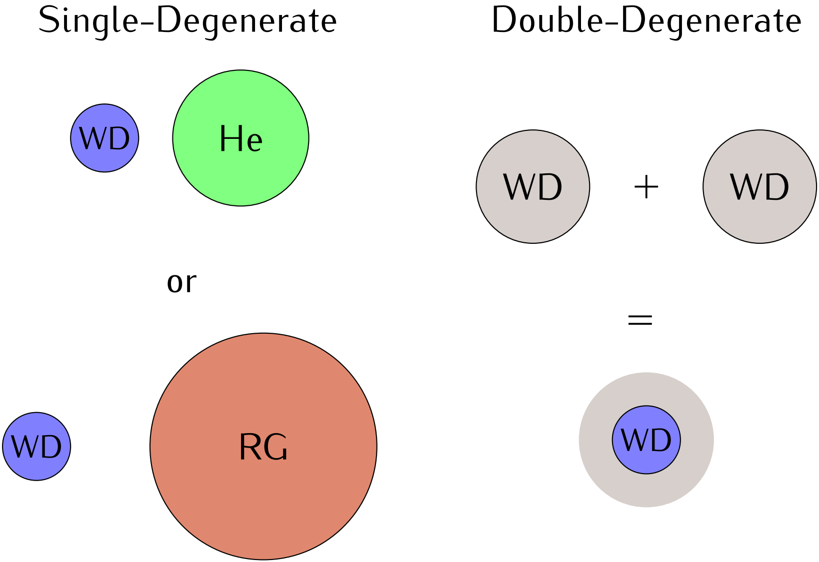

No direct observations of AIC have yet been made.

- 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

  e.g. Piro & Kulkarni (2013), Metzger & Bower (2014)

The strongest (indirect) evidence for AIC is the presence of young NSs in GCs.

Globular clusters have:

- old stellar populations ($\sim$ 10 Gyr)
- low escape velocities ($<$ 50 km/s)
- some young NSs (P ~ 300 ms, B ~ 10^{11} G)

Lyne et al. (1996); Boyles et al. (2011)

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AIC:

- takes a long time
- produces NSs with low natal kicks

Weak reactions will drive the evolution.

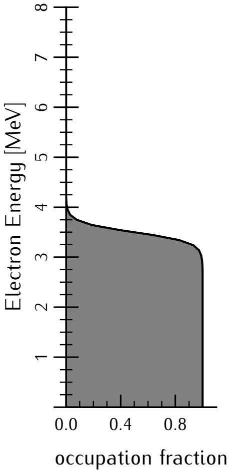
Electron capture

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

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.



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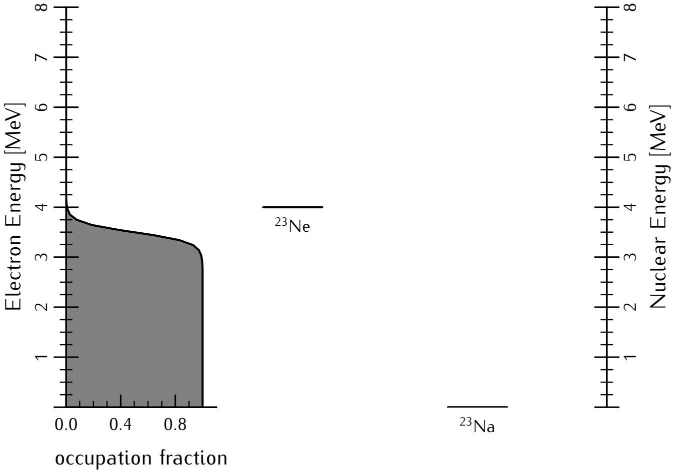
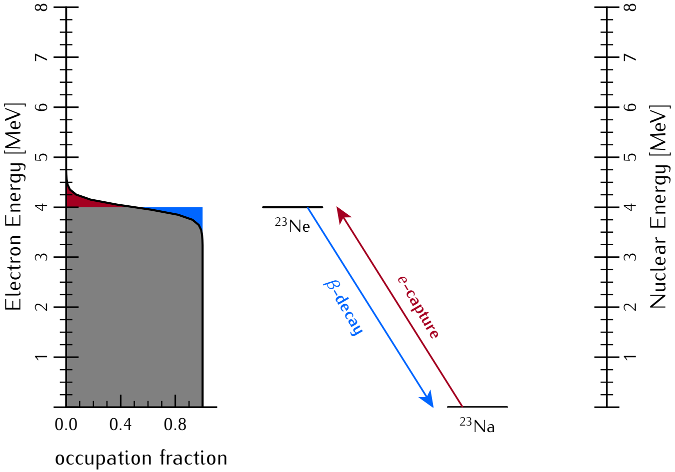
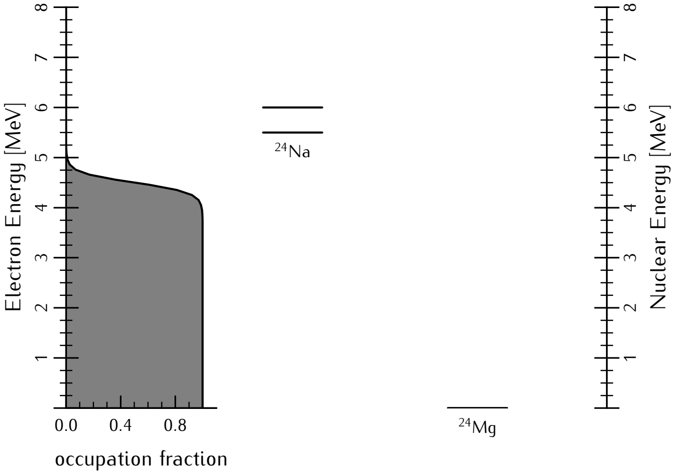


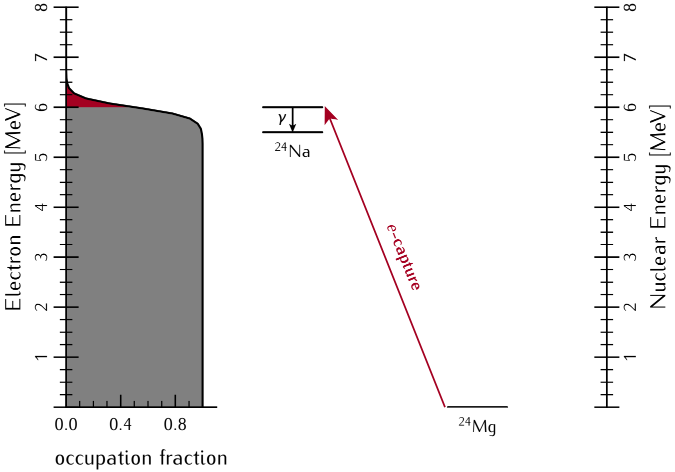
At some particular densities the plasma is cooled by emission of Urca-process neutrinos.



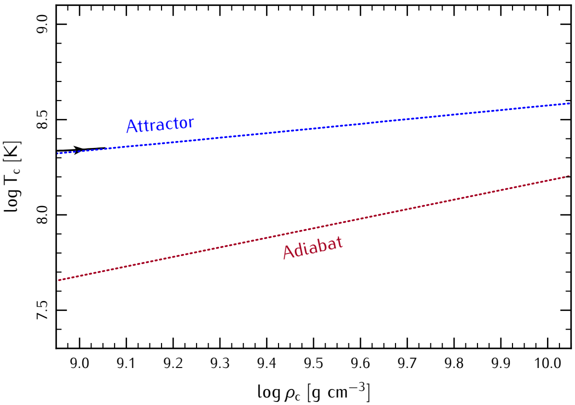


Electron Energy [MeV]
occupation fraction
0.0
0.4
0.8
1
2
3
4
5
6
7
8
^{24}Na
^{24}Mg
Nuclear Energy [MeV]

At some particular densities the plasma is heated by emission of gamma-rays.

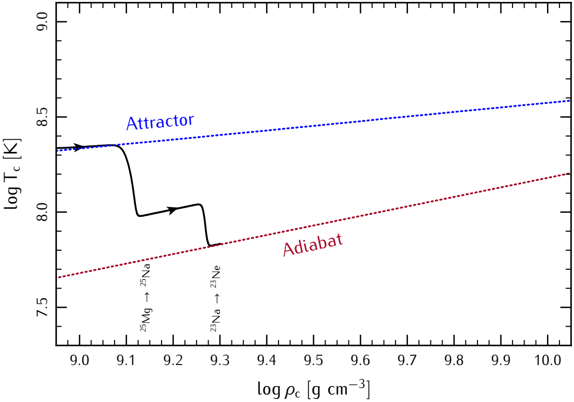


Initially, the temperature is set by a balance between compression and neutrino cooling.



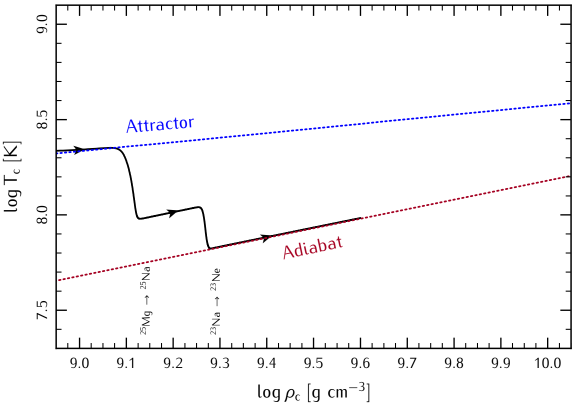
Paczyński (1971); JS et al. (2015)

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

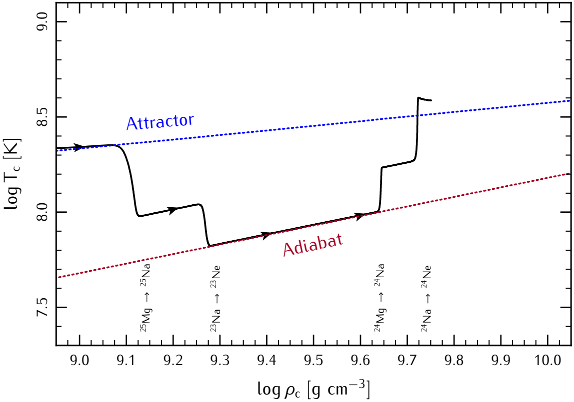


Paczyński (1973); JS et al. (2017)

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

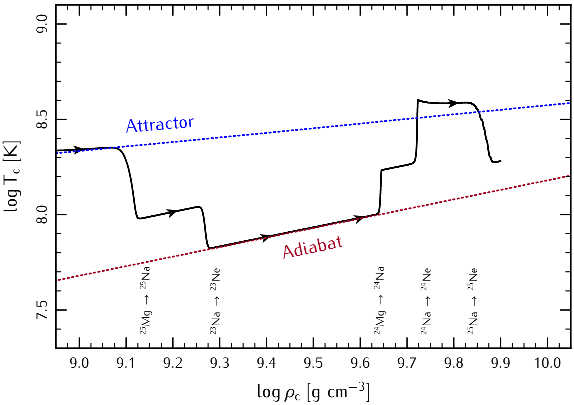


Substantial heating also occurs associated with the $A = 24$ isotopes.



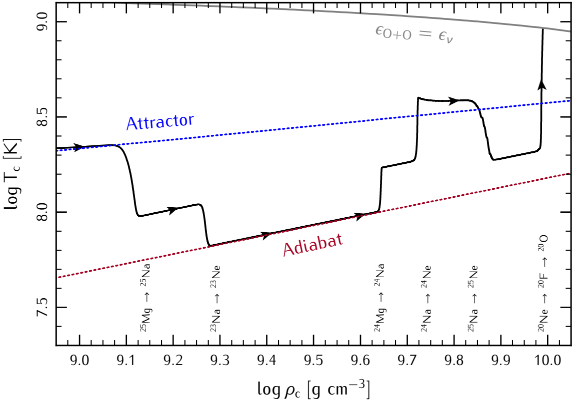
Miyaji et al. (1980, 1987); JS et al. (2015)

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



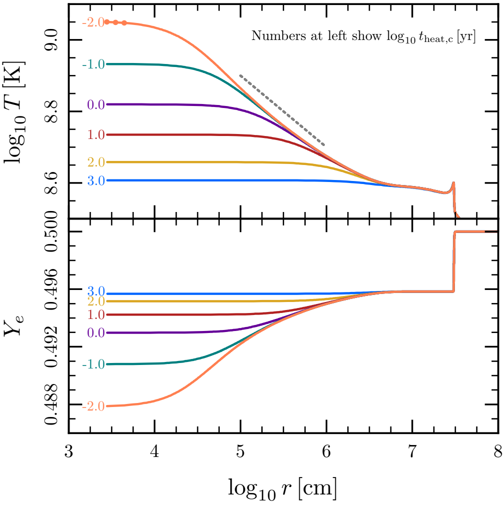
JS et al. (2017)

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

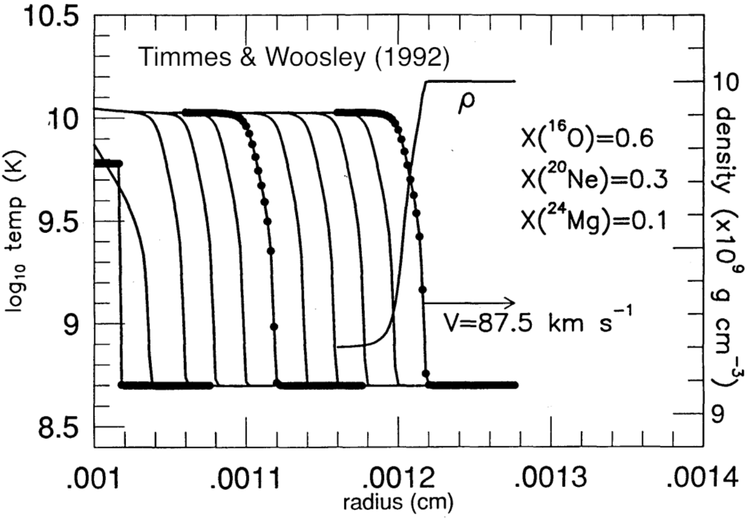


Miyaji et al. (1980, 1987); JS et al. (2015)

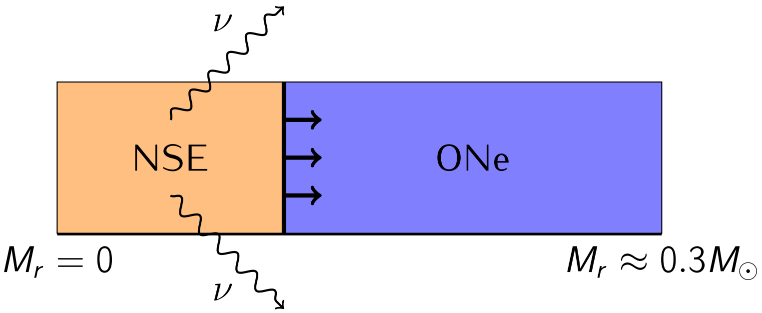
A thermal runaway develops in the core;
but convection is not triggered in the core.



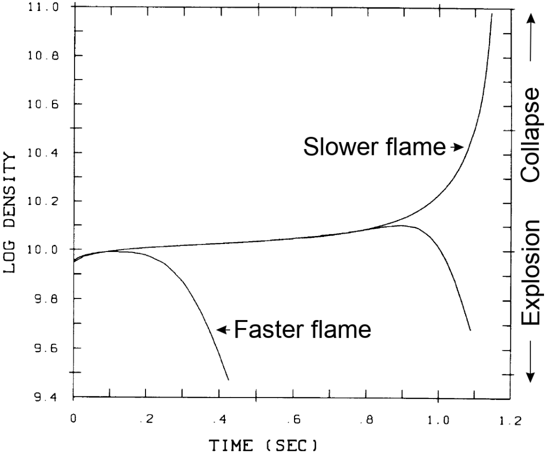
This will lead to the formation
of an outgoing oxygen deflagration wave.



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



The models are uncomfortably close to the boundary between collapse and explosion.



e.g. Nomoto & Kondo (1991)

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

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- We have evolved full-star models that include Urca cooling and resolve the length-scale of the birth of the oxygen deflagration.

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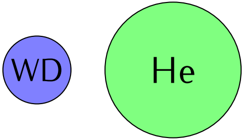
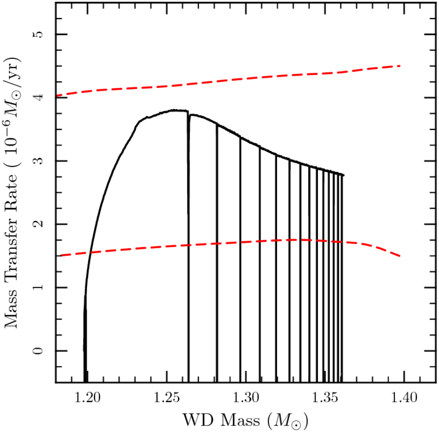
- We have evolved full-star models that include Urca cooling and resolve the length-scale of the birth of the oxygen deflagration.
- These models provide important input for the multi-D simulations necessary to determine whether these WDs collapse or explode.

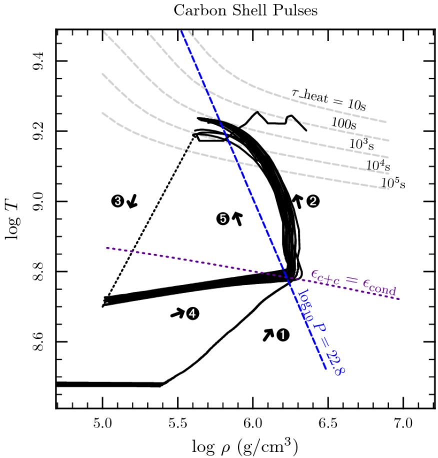
Mass transfer after core He-burning gives $\dot{M}$ in the regime for stable He burning on the WD.





Yoon & Langer (2003); Brooks et al. (2016, 2017)

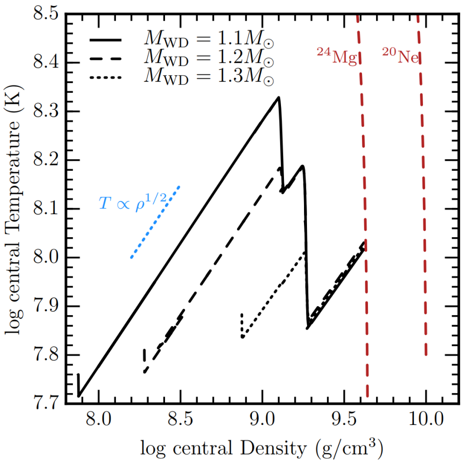
We evolve both stars plus their orbit;
there is stable He burning, plus carbon flashes.



Brooks et al. (2017)

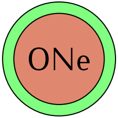
The models reach the conditions for AIC;

Urca cooling erases some of the initial differences.



Brooks et al. (2017)

Not only do He + O/Ne WD models reach AIC, but some He + C/O WD models do too.



$\longrightarrow$ AIC

Brooks et al. (2017)

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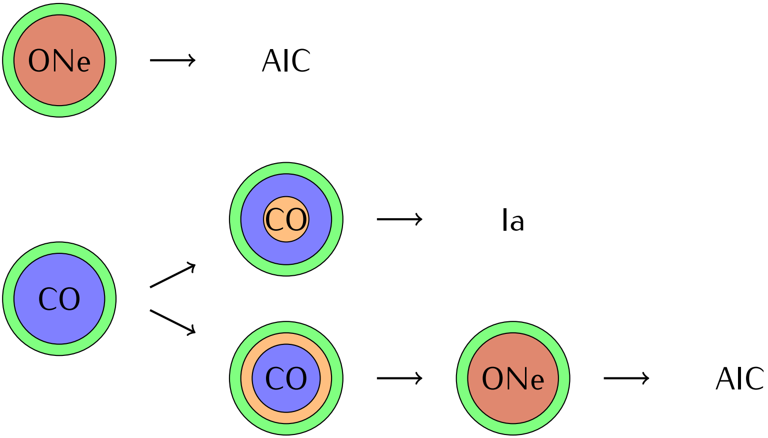
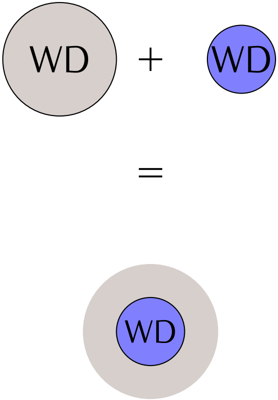
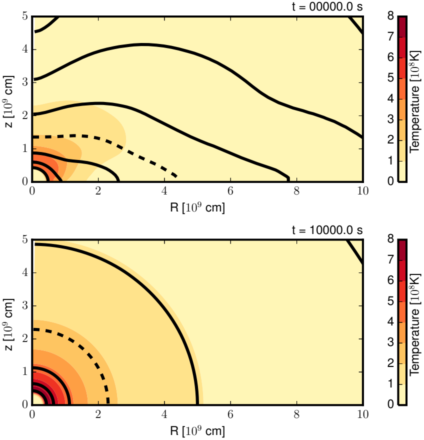


Brooks et al. (2017)

Double white dwarf mergers evolve towards a thermally-supported, spherical state.





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

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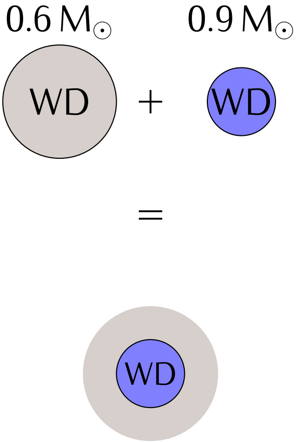
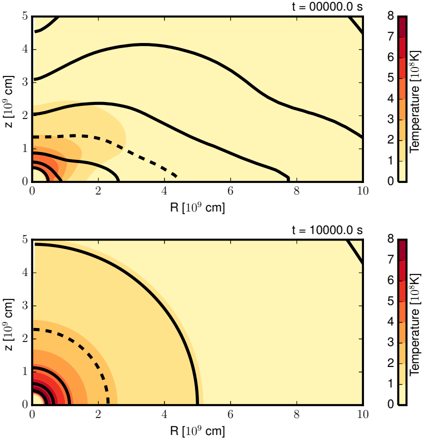
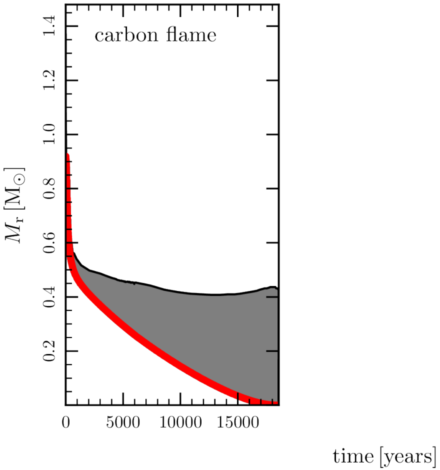


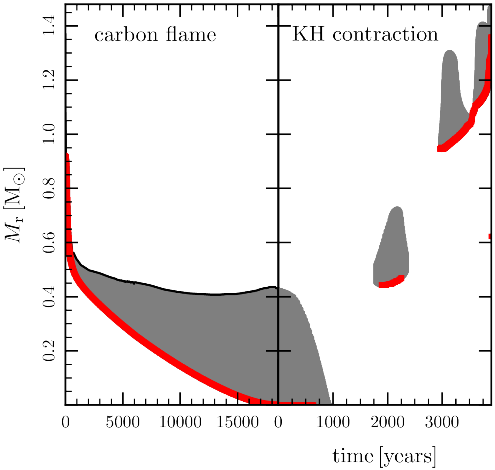


see Shen et al. (2012); Schwab et al. (2012)

A convectively-bounded carbon deflagration forms and propagates inward, reaching the center.



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



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

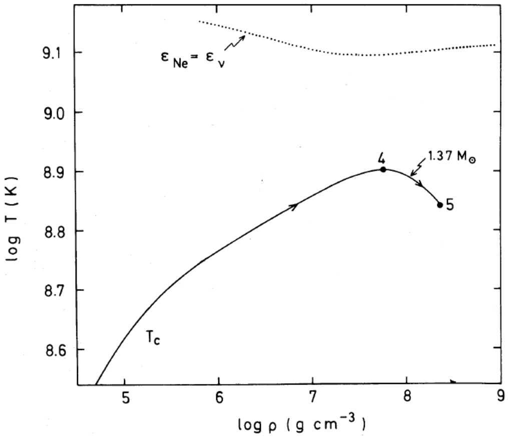


Fig. adapted from Nomoto (1984)

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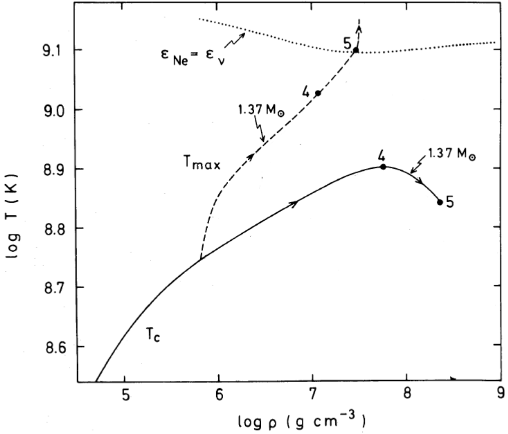
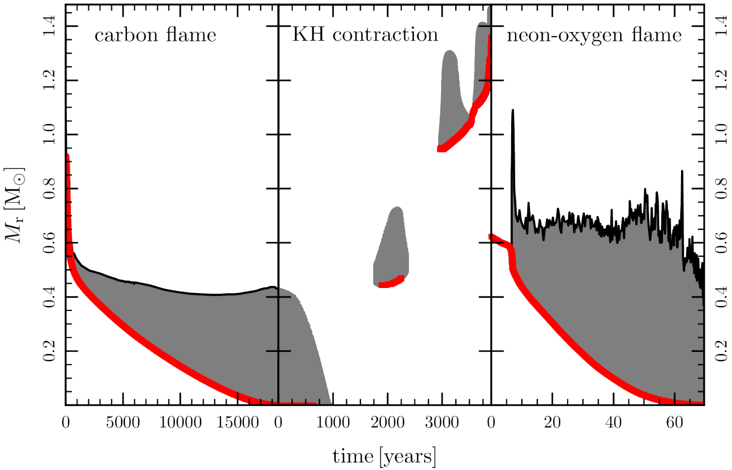
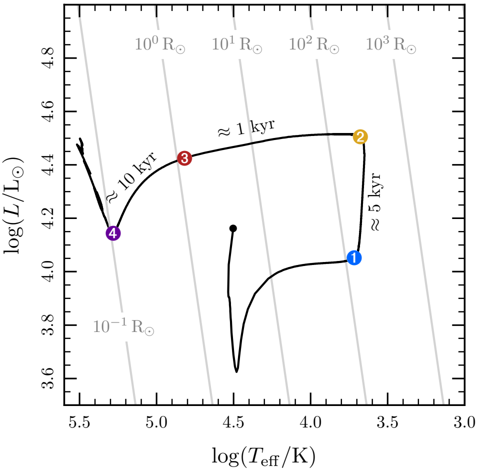


Fig. adapted from Nomoto (1984)

A convectively-bounded neon deflagration forms and propagates inward, destroying O/Ne core.



Post-merger there is a cool, giant phase,
but the carbon-burning is too deep to sustain it.



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- For He star + WD binaries, we explored a channel where an initially CO WD is converted to ONe during the accretion phase.
- For super-Chandrasekhar WD mergers, the likely fate is collapse to a neutron star, though the collapse may not occur via an O/Ne core.

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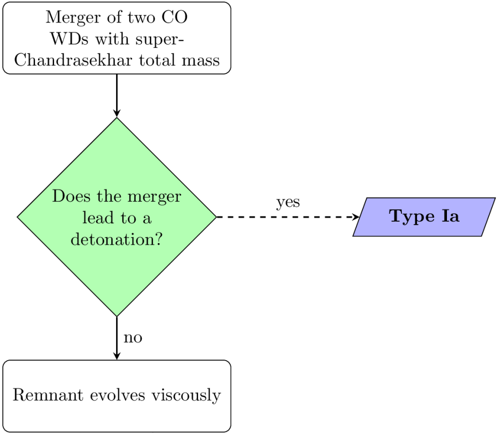
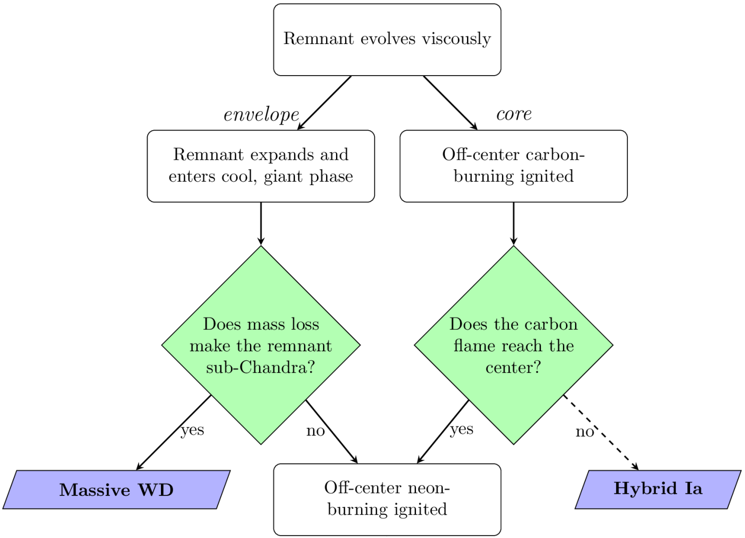
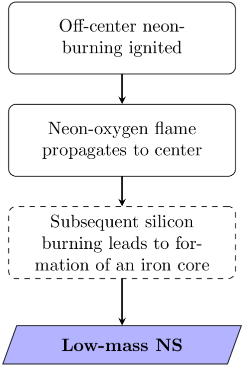
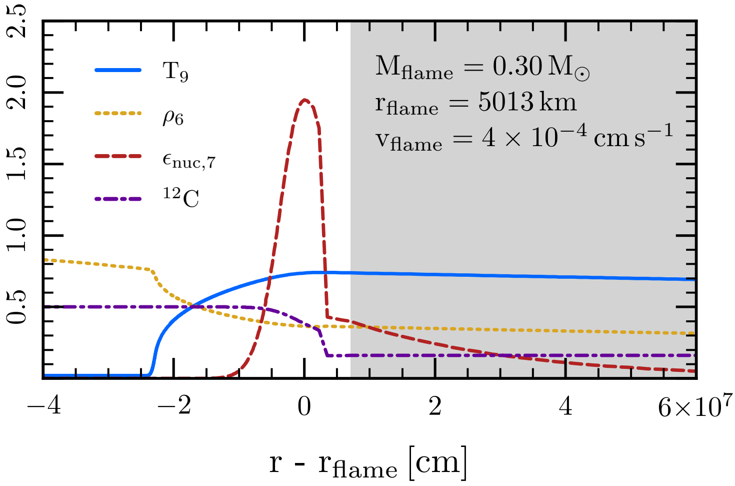
- Our work provides much-needed initial models necessary for multi-D work that can probe the collapse/explosion and make predictions for the signatures of the AIC event itself.
- A better understanding of the systems that undergo AIC can predict signatures useful for finding a Galactic AIC progenitor system.

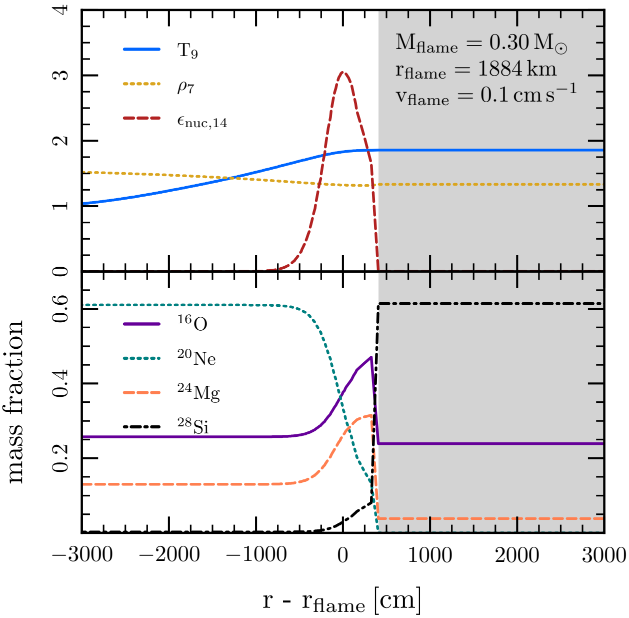

Merger of two CO WDs with super-Chandrasekhar total mass
Does the merger lead to a detonation?
yes
Type Ia
no
Remnant evolves viscously


Remnant evolves viscously
envelope
core
Remnant expands and enters cool, giant phase
Off-center carbon-burning ignited
Does mass loss make the remnant sub-Chandra?
Does the carbon flame reach the center?
yes
no
yes
no
Massive WD
Off-center neon-burning ignited
Hybrid Ia


Off-center neon-burning ignited
Neon-oxygen flame propagates to center
Subsequent silicon burning leads to formation of an iron core
Low-mass NS



T9
ρ6
ε nuc,7
12C
M flame = 0.30 M⊙
r flame = 5013 km
v flame = 4 × 10−4 cm s−1
2.5
2.0
1.5
1.0
0.5
−4
−2
0
2
4
6×10^7
r - r flame [cm]



T_9
ρ_7
$\epsilon_{\rm nuc,14}$
$M_{\rm flame} = 0.30\,M_\odot$
$r_{\rm flame} = 1884\,{\rm km}$
$v_{\rm flame} = 0.1\,{\rm cm\,s^{-1}}$
^{16}O
^{20}Ne
^{24}Mg
^{28}Si
mass fraction
0 1 2 3 4
0.2 0.4 0.6
−3000 −2000 −1000 0 1000 2000 3000
r - $r_{\rm flame}$ [cm]