The importance of mixing in white dwarfs evolving towards explosion

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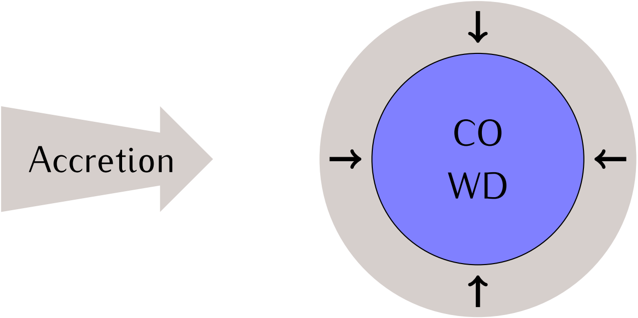
The single degenerate channel for Type Ia SNe is a CO WD growing to the Chandrasekhar mass.



SN Type Ia progenitor systems remain enigmatic.

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- The nearby Ia SN 2011fe did not show evidence for the existence of a luminous companion star (Li et al. 2011) nor signs of interaction with a non-degenerate companion (Kasen 2010; Nugent et al. 2011).
- Nucleosynthetic constraints, both from galactic chemical evolution and individual supernova remnants, suggest a near-Chandrasekhar mass progenitor (Seitenzahl et al. 2013; Yamaguchi et al. 2015).

Recent progress has been made in understanding a peculiar variant of thermonuclear supernovae.

Type Iax SNe are broadly similar to Ias

- have lower velocities and are generally fainter
- don't obey a tight width-luminosity relation
- spectra more likely to show carbon features
- favor star-forming, late-type host galaxies
- rate is $\gtrsim$ 10% Ia rate

e.g., Foley et al. (2013), Jha (2017)

There are intriguing observations of both Iax progenitors and postgenitors.

- An object consistent with an $\approx 2\,M_\odot$ He star was observed in pre-explosion imaging in the SN Iax 2012Z (McCully et al. 2014) and continues to be present after the explosion.

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- An object consistent with an $\approx 2\,M_\odot$ He star was observed in pre-explosion imaging in the SN Iax 2012Z (McCully et al. 2014) and continues to be present after the explosion.
- Late time spectra of SN Iax do not become fully nebular (e.g., Foley et al. 2016). This can be interpreted as the presence of a surviving object that is launching an optically-thick wind.

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- Kepler et al. (2016) discovered an 0.56 ± 0.09 $M_{\odot}$ WD with an oxygen atmosphere.
- Vennes et al. (2017) found a high proper motion, 0.14 ± 0.01 $M_{\odot}$ WD with atmosphere dominated by oxygen and neon.

There is an emerging picture of the Type Iax supernovae that "repurposes" existing Ia models.

- Accretion from a He-star companion is a way to grow a WD to the Chandrasekhar mass.

e.g., Yoon & Langer (2003)

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- Accretion from a He-star companion is a way to grow a WD to the Chandrasekhar mass.

  e.g., Yoon & Langer (2003)

- Models of the deflagration of a WD match many properties of the explosion and leave behind a peculiar bound remnant.

  e.g., Jordan et al (2012); Kromer et al. (2013)

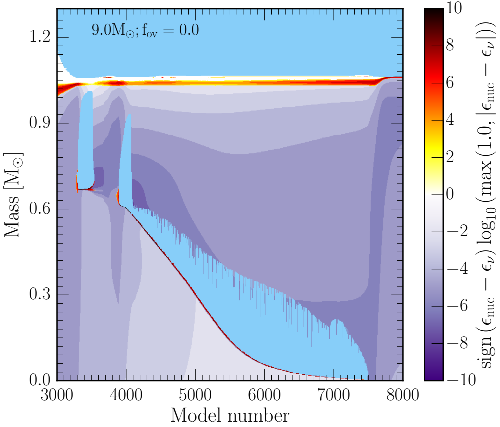
Why do we care about Chandrasekhar mass WDs?

Formation and evolution of Hybrid C/O/Ne WDs

Simmering phase and the convective Urca process

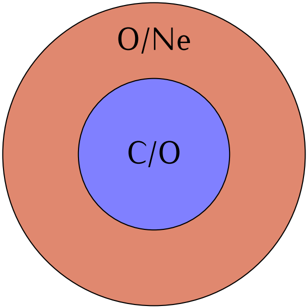
Summary

S-AGB stars experience off-center carbon ignition; the carbon-burning front propagates inwards.



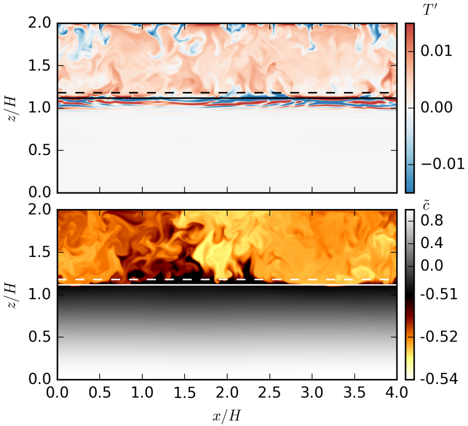
from Farmer et al. (2015)

If mixing quenches the carbon flame,
then you produce a "hybrid" C/O/Ne WD.



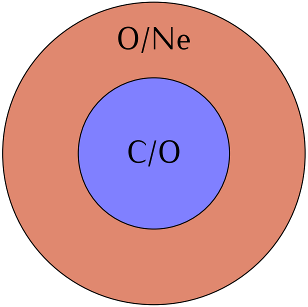
Siess (2009), Denissenkov et al. (2013)

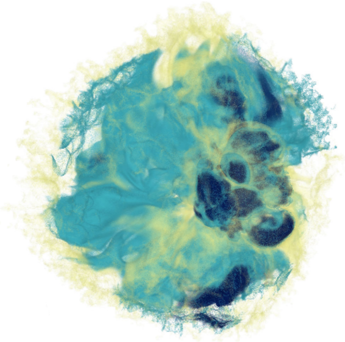
Hydrodynamics simulations suggest that it is unlikely that the flame quenches.



from Lecoanet, JS, et al. (2016)

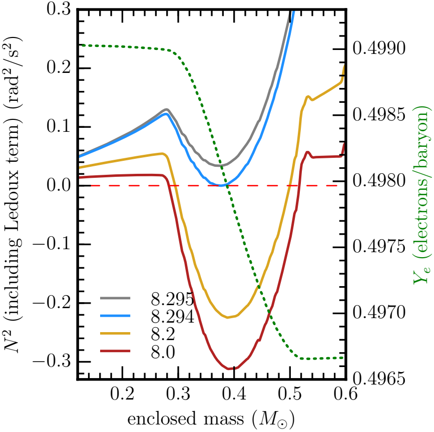
Operating under the assumption these objects form, people then perform simulations of the explosion.





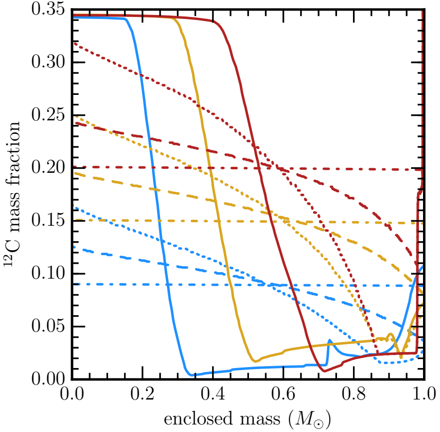
e.g., Bravo et al. (2016); Fig. from Kromer et al. (2015)

Hybrid WD are unstable to mixing as they cool, and they have time to cool as they grow to M_{Ch}.



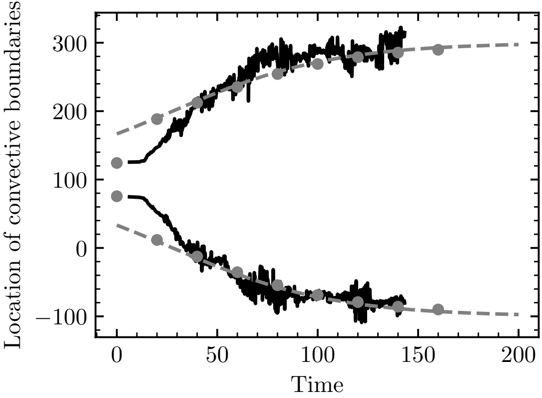
Brooks, JS, et al. (2017)

Evolving the models indicates they would be fully mixed at the time they would explode.



Brooks, JS, et al. (2017)

Direct numerical simulations of an idealized problem give similar mixing behavior.



JS & Garaud (in prep.)

The central carbon fraction affects the density at which the WD reaches carbon ignition conditions.

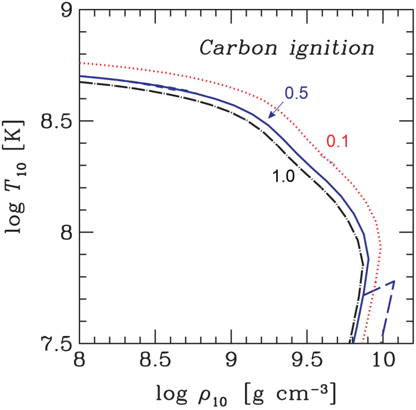


Fig. adapted from Yakovlev et al. (2006)

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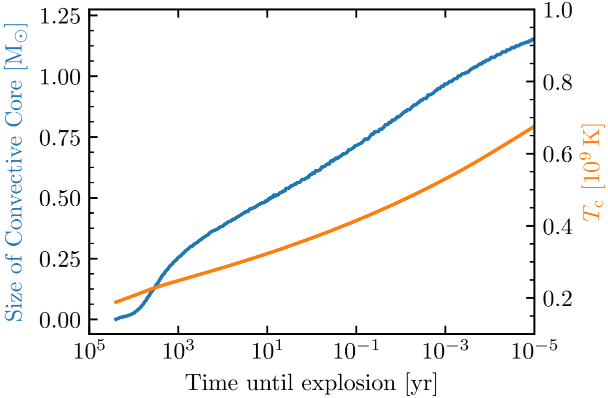
Summary

After carbon ignites, a "simmering" phase of convective core carbon burning follows.



Carbon burning increases the neutronization of the material, affecting the eventual nucleosynthesis.

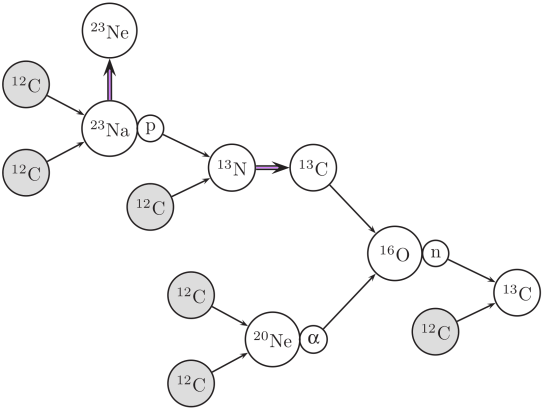
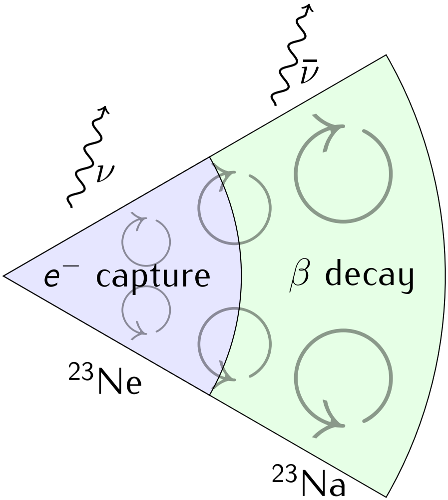
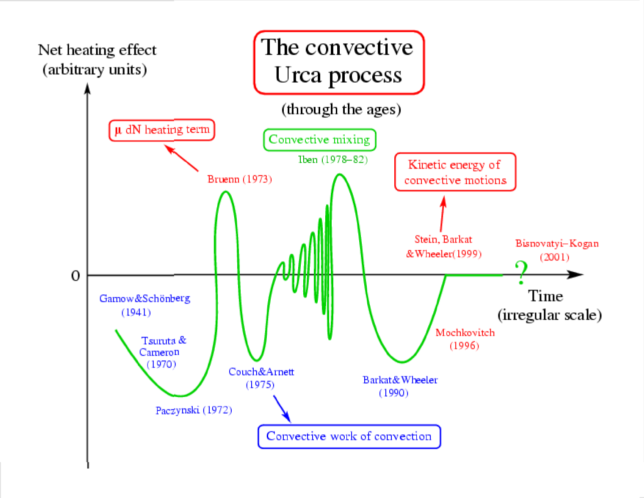


Fig. adapted from Förster et al. (2010)

How much carbon burns depends on the net energetics of the convective Urca process.

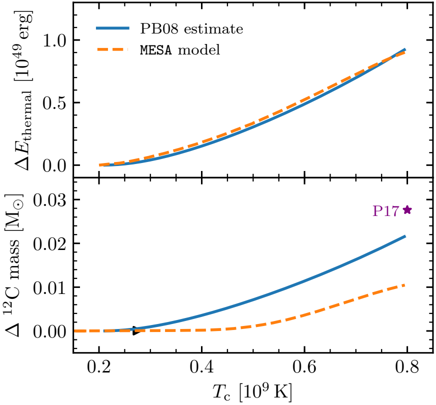


The convective Urca process through the litterature



slide from P. Lesaffre; Talk at KITP Conference (2007)

Several recent studies disagree about how much carbon is burned on the way to explosion.



from JS et al. (2017)

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- Observations of Type Iax supernovae (and possibly their remnants) are proving evidence that at least some WDs reach the Chandrasekhar mass and explode.

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- The evolution of the progenitor WDs is important and needs to be incorporated into the initial conditions of explosion simulations.
- The details of the simmering phase are particularly important for understanding the nucleosynthesis of near-Chandrasekhar explosion models.