White Dwarf Sedimentation and Phase Separation: Status of Stellar Modeling for Cooling Timescales

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HARVARD & SMITHSONIAN

KITP White Dwarfs from Physics to Astrophysics
November 14, 2022

White Dwarf Cooling Timescales

$$L \propto M T_{\rm core}^{7/2} \qquad L = -\frac{dE}{dt} = -c_V M \frac{dT_{\rm core}}{dt}$$

$$t_{\rm cool} \approx 7 \text{ Myr} \left(\frac{M}{M_\odot}\right)^{5/7} \left(\frac{L}{L_\odot}\right)^{-5/7}$$

ON THE THEORY OF WHITE DWARF STARS

I. The Energy Sources of White Dwarfs

L. Mestel

(Communicated by F. Hoyle)

(Received 1952 May 9)

Summary

Present theories of the origin of white dwarfs are discussed; it is shown that all theories imply that there can be no effective energy sources present in a white dwarf at the time of its birth. The temperature distribution of a white dwarf is then discussed on the assumption that no energy liberation occurs within the star, and that it radiates at the expense of the thermal energy of the heavy particles present. In the resulting picture, a white dwarf consists of a degenerate core containing the bulk of the mass, surrounded by a thin, non-degenerate envelope. The energy flow in the core is due to the large conductivity of the degenerate electrons, while the high opacity of the outer layer keeps down the luminosity to a low level. Estimates of the ages of observed white dwarfs are given and interpreted. Finally, it is shown that white dwarfs may accrete energy sources and yet continue to cool off, provided the temperature at the time of accretion is not too high; this suggests a possible model for Sirius B.

White Dwarf Cooling Timescales

The textbook answer: Hansen, Kawaler, & Trimble

10.2 White Dwarf Evolution 473

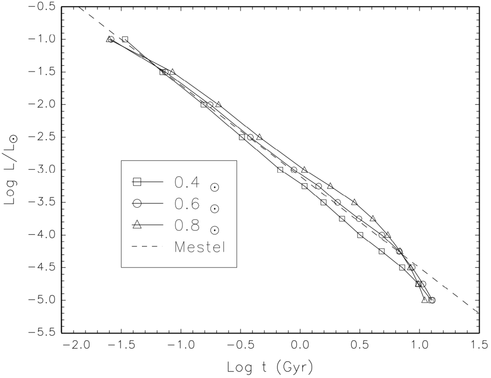


Fig. 10.1. Cooling curves for pure carbon white dwarf models as adapted from Winget et al. (1987). The dotted line is a Mestel (1952) cooling curve for a $0.6\mathcal{M}_\odot$ carbon white dwarf using (10.6).

White Dwarf Cooling Timescales

To get a precise answer for white dwarf cooling, must account for

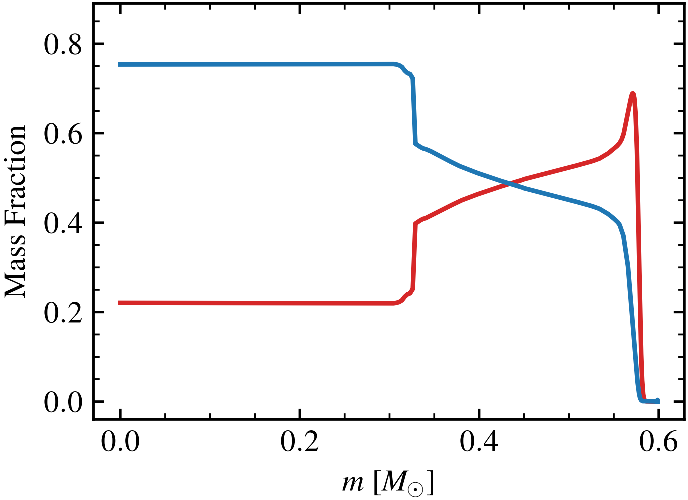
- Accurate composition profile produced by stellar evolution
- Thermodynamics: heat capacity of internal thermal reservoir
- Opacities: rate of heat transport from core to surface

along with potential residual sources of energy that can slow cooling:

- Crystallization
  - Latent heat
  - Mixing induced by phase separation
- Heavy element sedimentation
- Distillation? (Blouin et al 2021)

Phase Separation in Action in MESA

0.6 $M_\odot$ MESA White Dwarf Model



Phase Separation in Action in MESA

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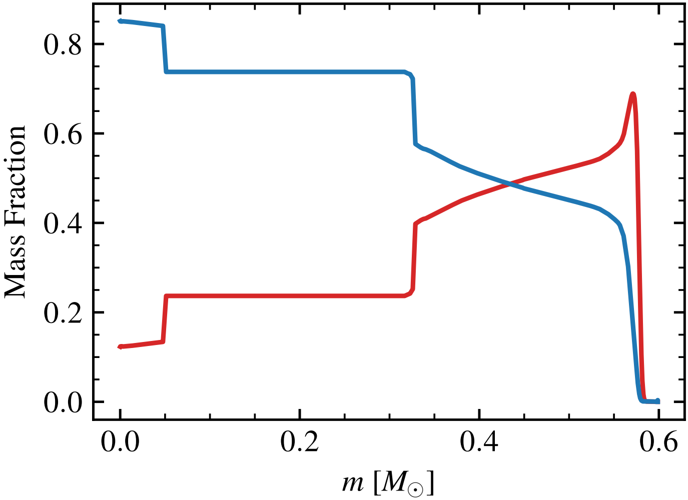
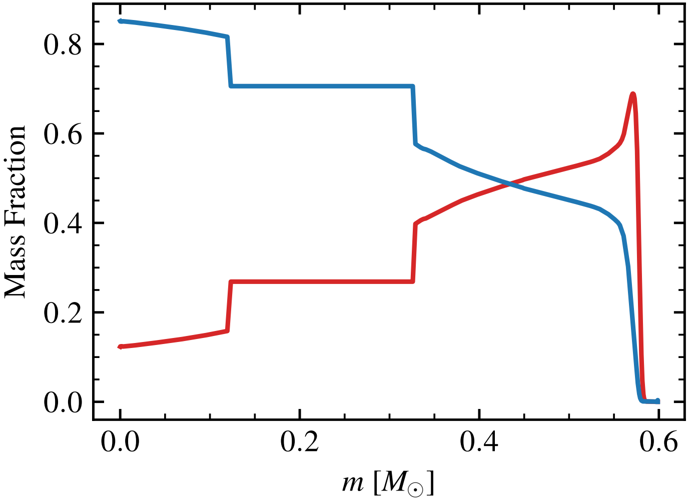


Phase Separation in Action in MESA

0.6 $M_\odot$ MESA White Dwarf Model



Phase Separation in Action in MESA

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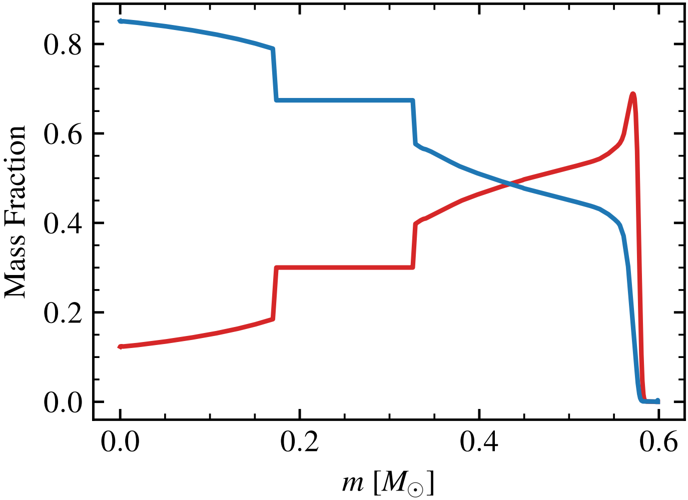
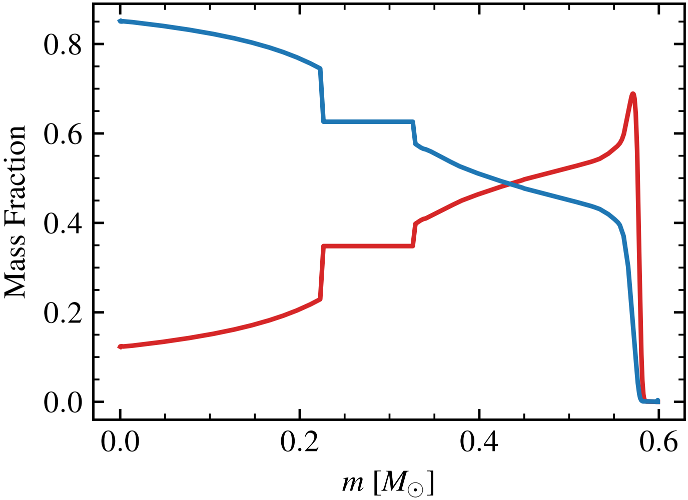


Phase Separation in Action in MESA

0.6 $M_\odot$ MESA White Dwarf Model



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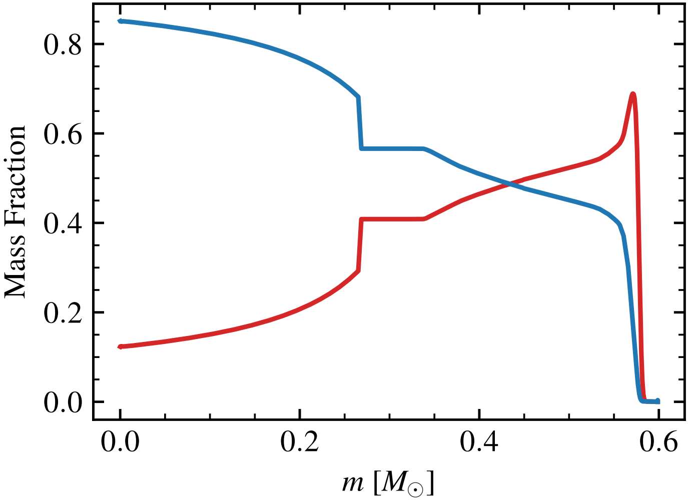
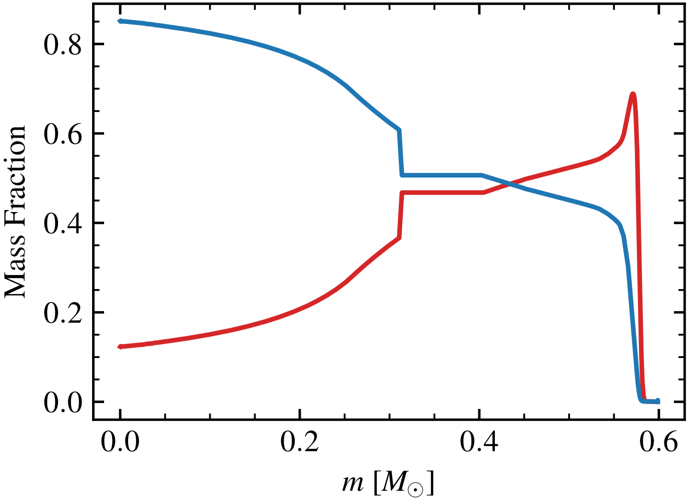


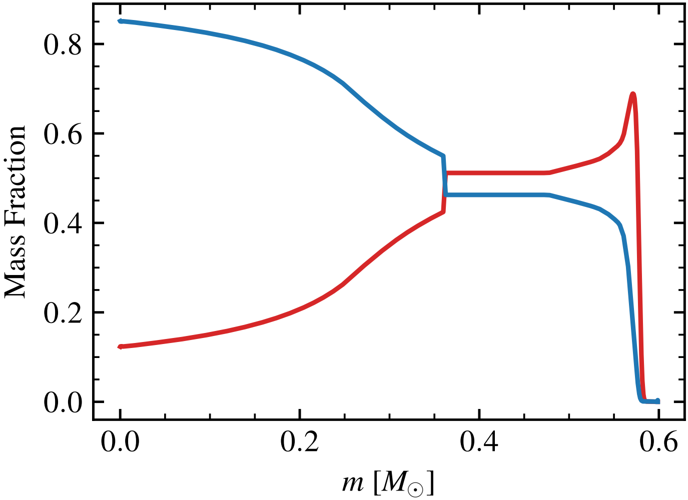
Phase Separation in Action in MESA

0.6 $M_\odot$ MESA White Dwarf Model



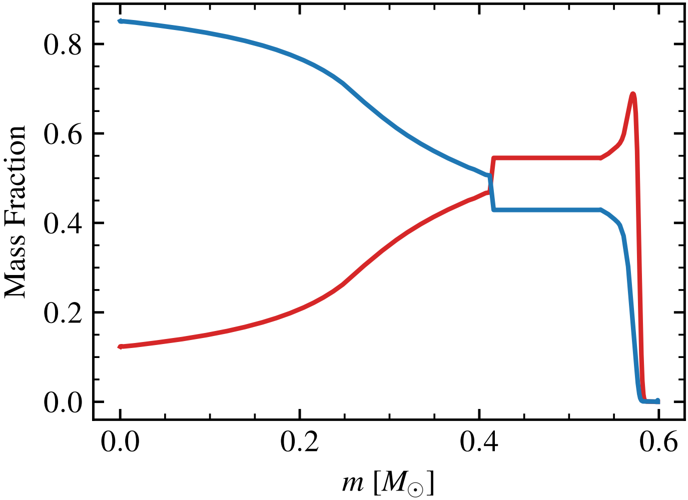
Phase Separation in Action in MESA

0.6 $M_\odot$ MESA White Dwarf Model



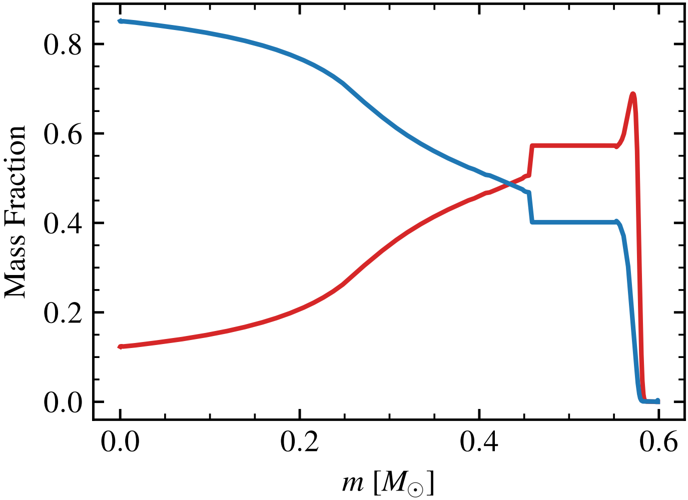
Phase Separation in Action in MESA

0.6 $M_\odot$ MESA White Dwarf Model



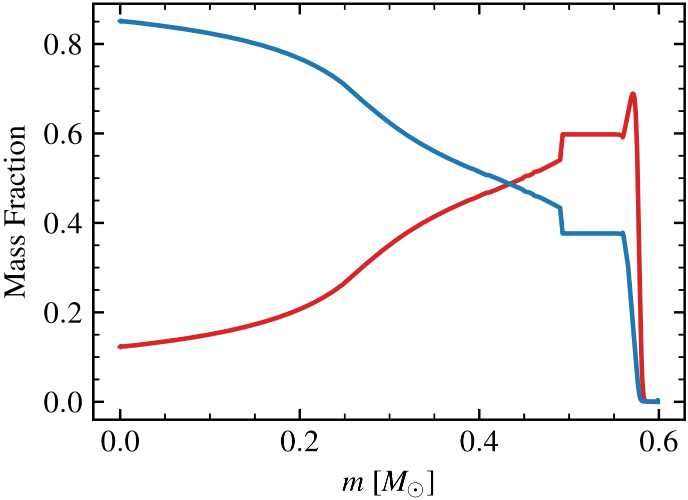
Phase Separation in Action in MESA

0.6 $M_\odot$ MESA White Dwarf Model



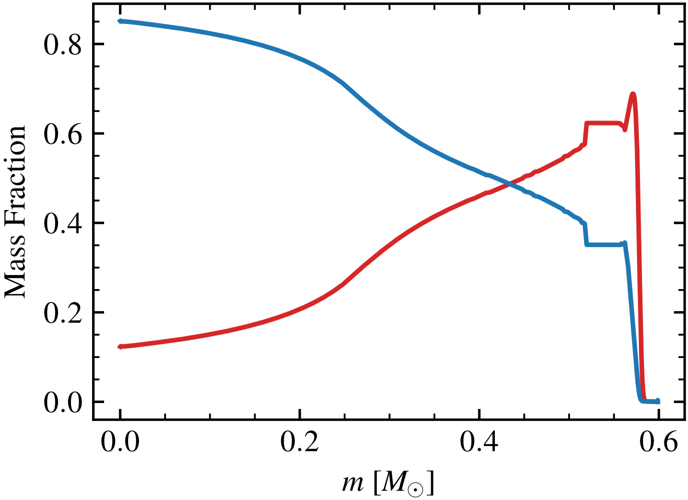
Phase Separation in Action in MESA

0.6 $M_\odot$ MESA White Dwarf Model



Phase Separation in Action in MESA

0.6 $M_\odot$ MESA White Dwarf Model



Phase Separation in Action in MESA

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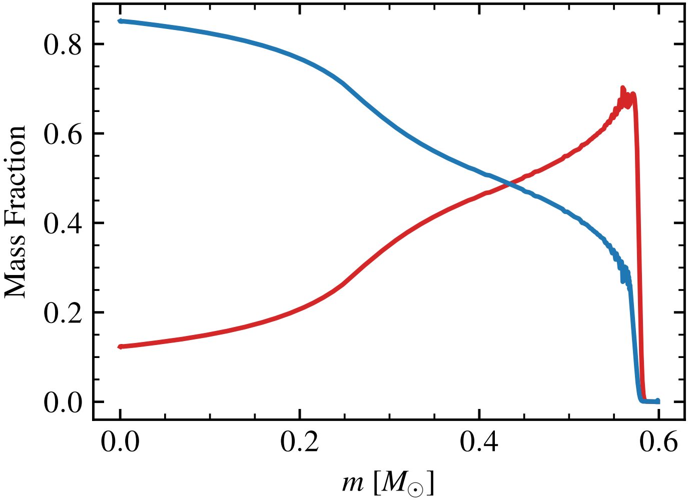
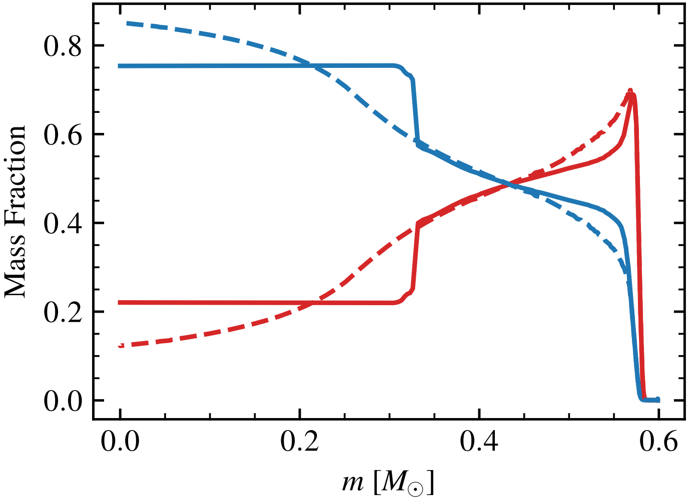


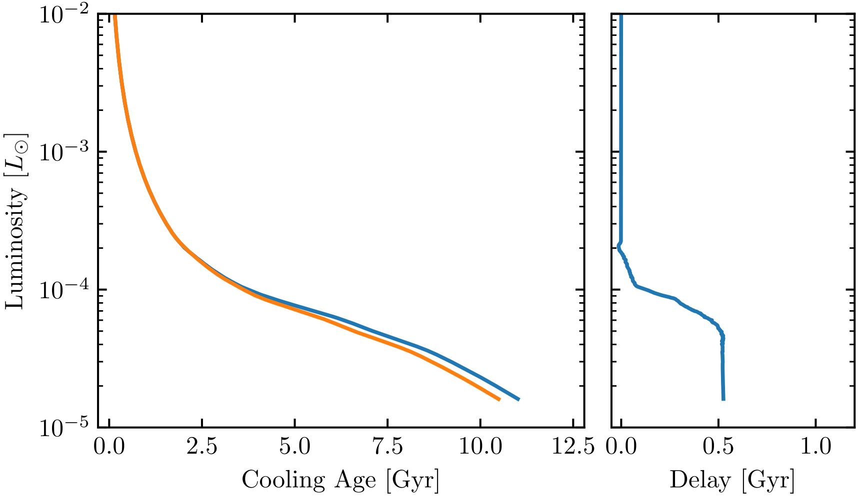
Net Result: Oxygen-Enriched Core

0.6 $M_\odot$ MESA White Dwarf Model



Cooling Delay

0.6 $M_\odot$ MESA White Dwarf Model



Cooling Delay

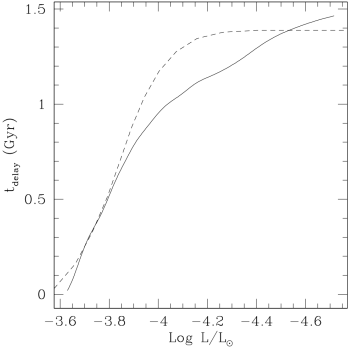


FIG. 6.—*Solid line*: Self-consistent calculation of the age difference between two 0.6 $M_\odot$ white dwarf evolutionary sequences with $Z = 0.0$, one of which is undergoing phase separation. *Dotted line*: Result of applying eq. (4) to the evolutionary sequence undergoing phase separation, which yields an asymptotic value for the age delay of $\sim$1.4 Gyr. At complete crystallization (log $L/L_\odot \sim -4.6$), the value given by the direct evolutionary calculation is within 5% of this, indicating that the basic physics that is operating is well described by eq. (3).

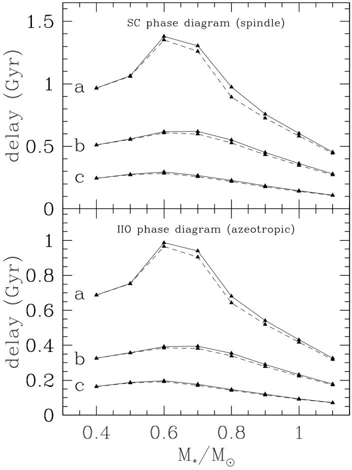


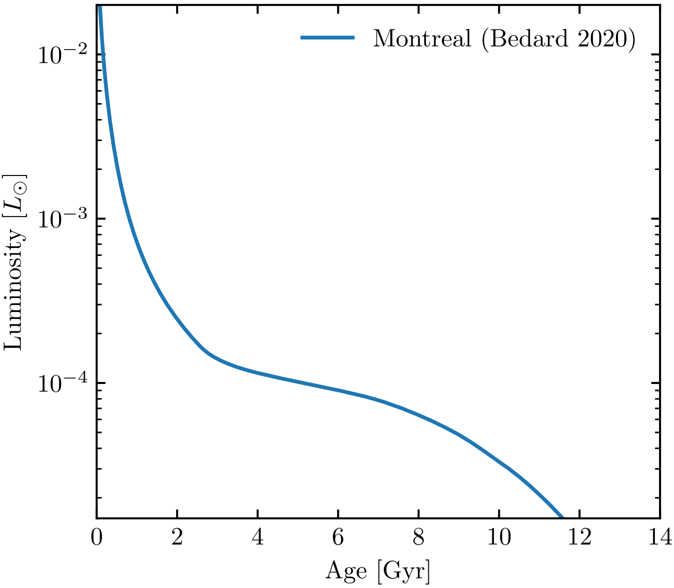
FIG. 8.—Age delay due to phase separation during crystallization as a function of total mass of the white dwarf model. Curve *a* corresponds to a 50:50 homogeneous initial C/O profile, while curves *b* and *c* are the initial profiles specified by the solid line in Fig. 4, and by eq. (3), respectively. The solid lines show zero-metallicity opacities, and the dashed lines show $Z = 0.001$, from which we can see that our result has little metallicity dependence. All models have $M_{He}/M_* = 10^{-2}$ and $M_H/M_* = 10^{-4}$.

Montgomery et al (1999)

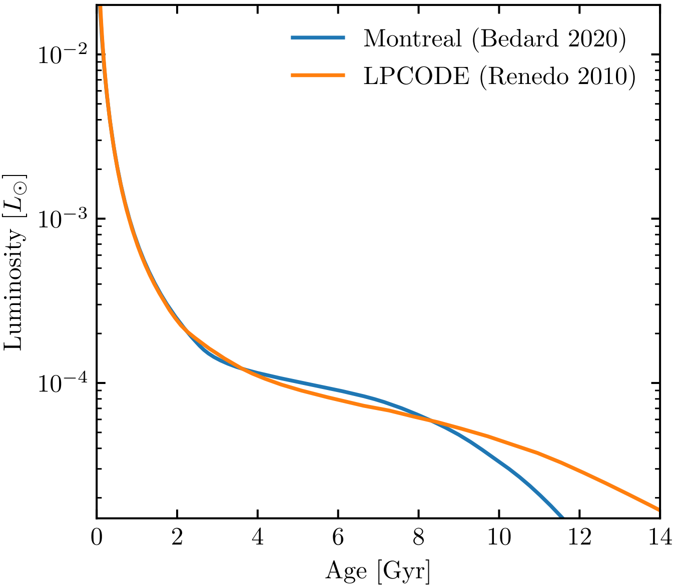
Vanilla White Dwarf Cooling

- 0.6 $M_\odot$ Carbon-Oxygen DA White Dwarf
- Standard ("thick") hydrogen envelope ($\sim 10^{-4}$ $M_\odot$)
- Core crystallization and phase separation

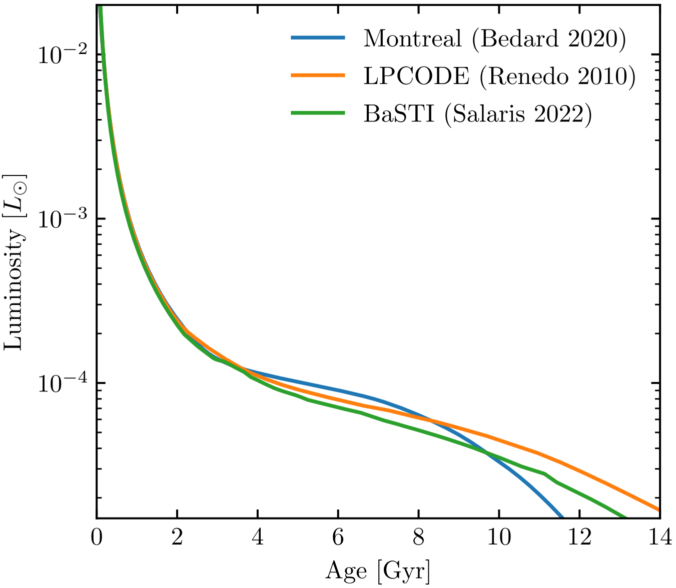
Cooling Comparisons



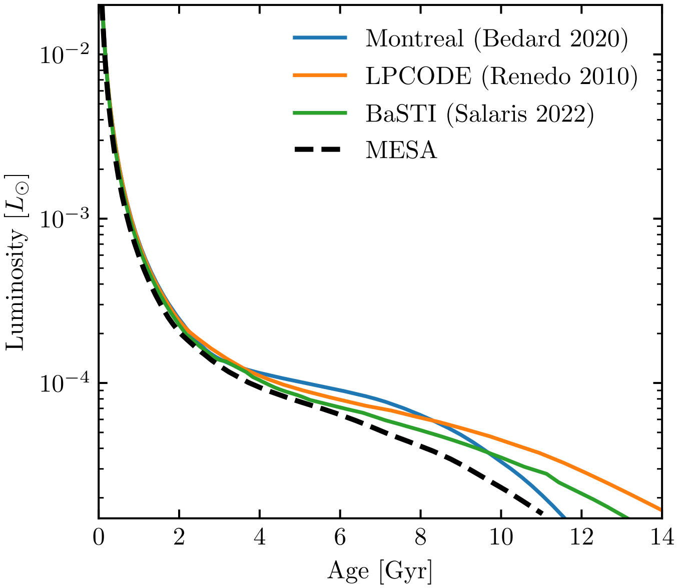
Cooling Comparisons



Cooling Comparisons



Cooling Comparisons



"Vanilla" White Dwarf Cooling?

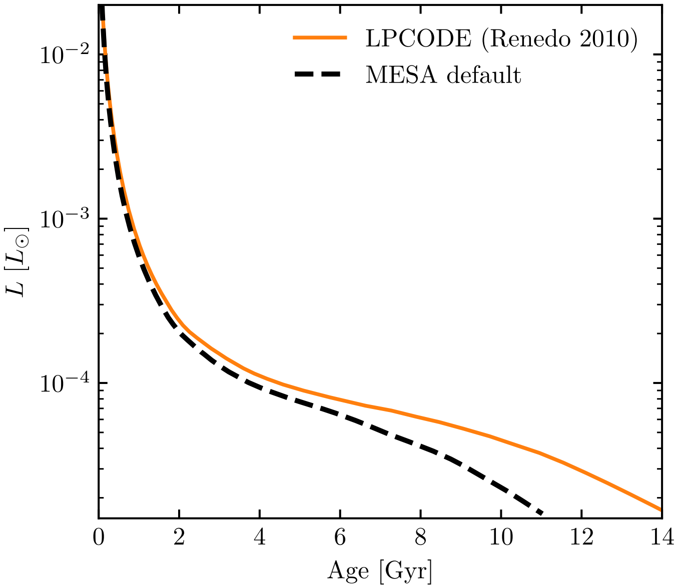
All of these tracks had:

- 0.6 $M_\odot$ Carbon-Oxygen DA White Dwarf
- Standard ("thick") hydrogen envelope ($\sim 10^{-4}$ $M_\odot$)
- Core crystallization and phase separation

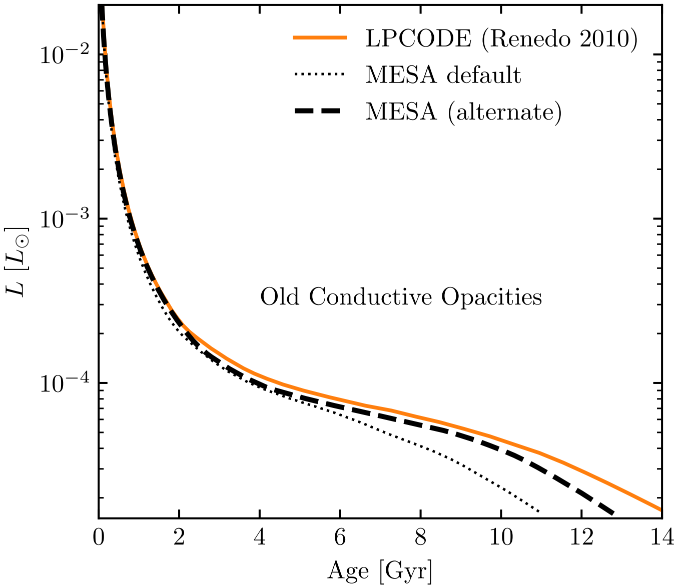
What did I forget to mention?

- Phase diagram details (Segretain 1993, Blouin & Daligault 2021)
- Conductive opacities (Cassissi 2007, Blouin 2020)
- Equation of State (Segretain 1994, Jermyn 2021)
- Interior C/O profile (50/50 vs produced by stellar evolution)

Cooling Comparisons



Cooling Comparisons



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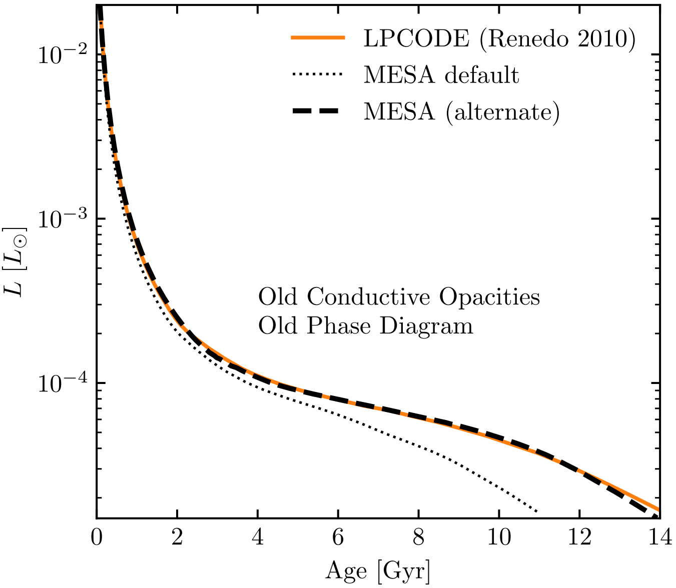
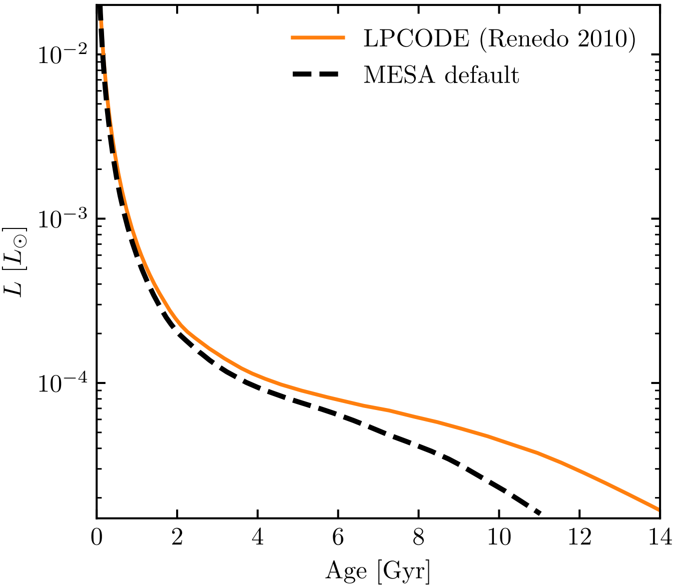
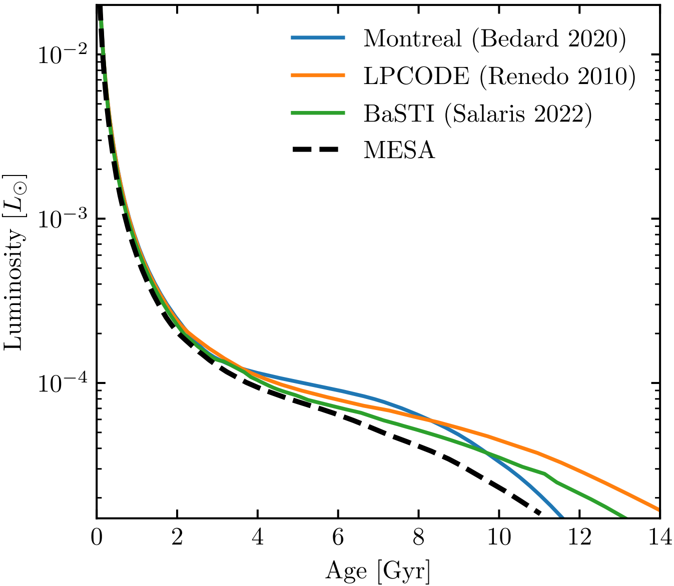


Cooling Comparisons



Cooling Comparisons



Part I Summary

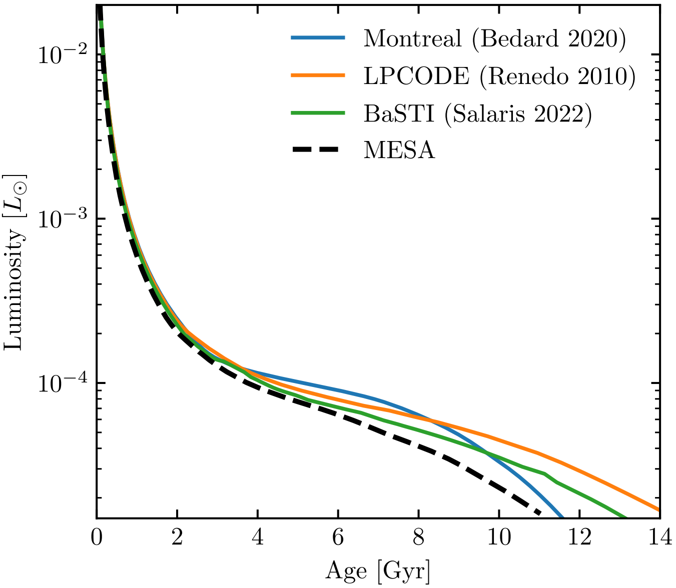
"Vanilla" white dwarf cooling comparisons raise some questions.

- What pieces of physics can we be confident we have the right answers for?
- To what extent do our models all agree as long as we implement the right physics correctly?
- What is left as inherent uncertainty in cooling timescales?

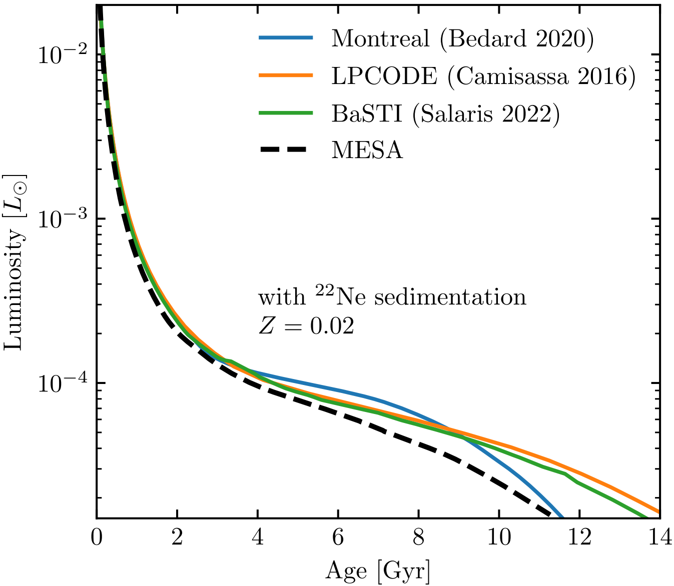
And now for Part II: making things complicated.

- ^{22}Ne (Bildsten & Hall 2001, García-Berro 2008, ...)
- The Q-branch and some metal-rich stellar populations motivate additional input physics.
- Do our code implementations show enough agreement that we can disentangle the effects of ^{22}Ne sedimentation?

Cooling Comparisons



Adding in Some ^{22}Ne



Differences

Extra cooling delays from ^{22}Ne are not consistent across codes. At $Z = 0.2$, the cooling delay is

- LPCODE: 1 Gyr
- BaSTI: 0.5 Gyr
- MESA: 0.4 Gyr

This affects proposed solutions to the Q-branch cooling delay.

- Camisasa (2021) LPCODE models suggest WDs descended from $Z = 0.06$ progenitors could experience a significant delay.
- For MESA models including standard ^{22}Ne sedimentation, an equivalent delay would require $Z > 0.15$.

NGC 6791

nature Vol 465|13 May 2010|doi:10.1038/nature09045

LETTERS

A white dwarf cooling age of 8 Gyr for NGC 6791 from physical separation processes

Enrique García-Berro[1,2], Santiago Torres[1,2], Leandro G. Althaus[1,3,4], Isabel Renedo[1,2], Pablo Lorén-Aguilar[1,2], Alejandro H. Córsico[3,4], René D. Rohrmann[5], Maurizio Salaris[6] & Jordi Isern[2,7]

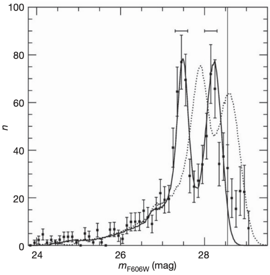
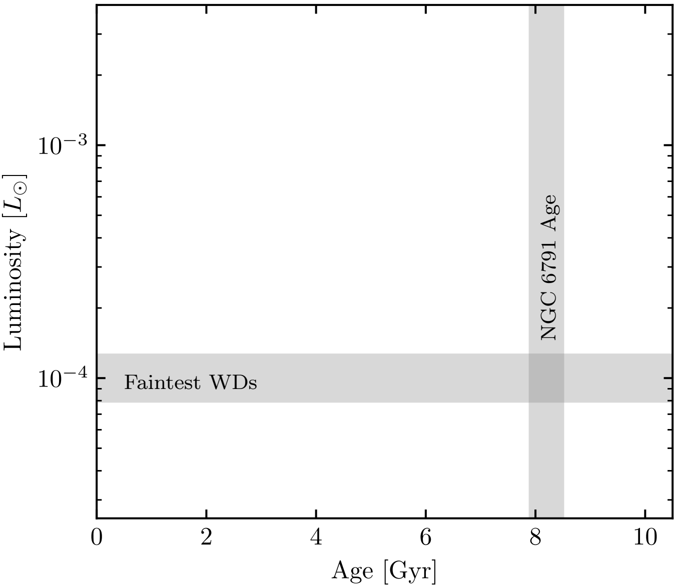
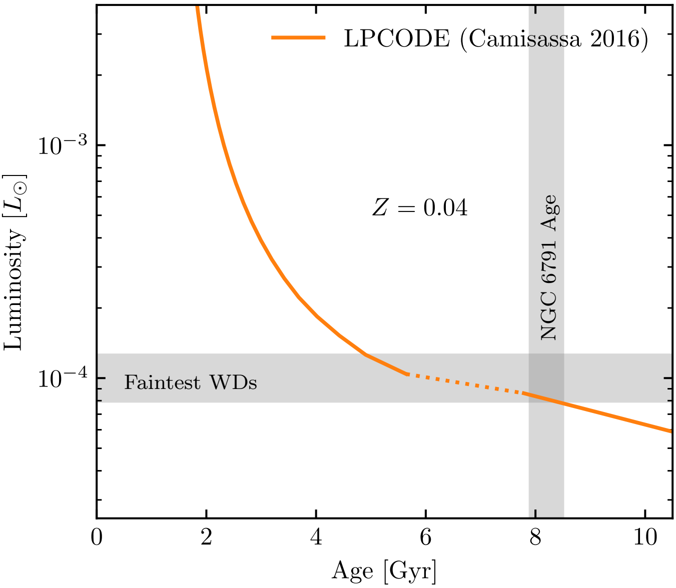


Figure 2 | White dwarf luminosity function of NGC 6791. Filled squares, the observational white dwarf luminosity function (error bars, $\pm1\sigma$; ref. 2).

NGC 6791

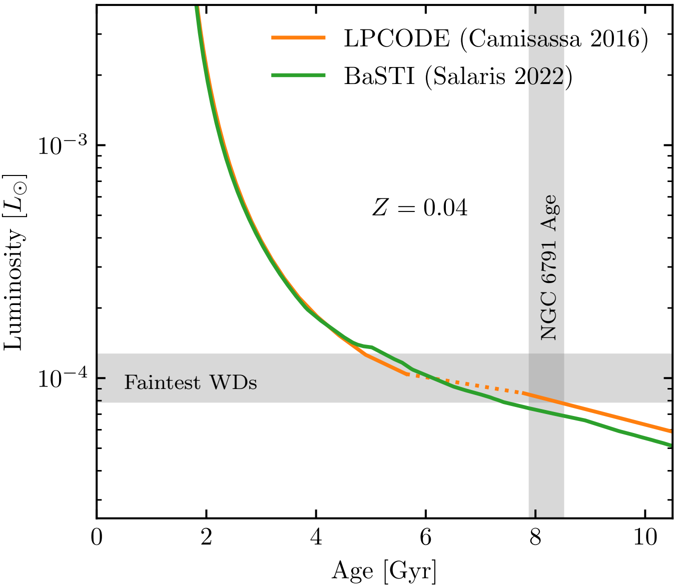

Faintest WDs
NGC 6791 Age
Luminosity $[L_\odot]$
10^{-3}
10^{-4}
0
2
4
6
8
10
Age [Gyr]

NGC 6791



LPCODE (Camisassa 2016)
$Z = 0.04$
NGC 6791 Age
Faintest WDs
10^{-3}
10^{-4}
Luminosity $[L_\odot]$
0
2
4
6
8
10
Age [Gyr]

NGC 6791



LPCODE (Camisassa 2016)
BaSTI (Salaris 2022)
$Z = 0.04$
NGC 6791 Age
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Luminosity $[L_\odot]$
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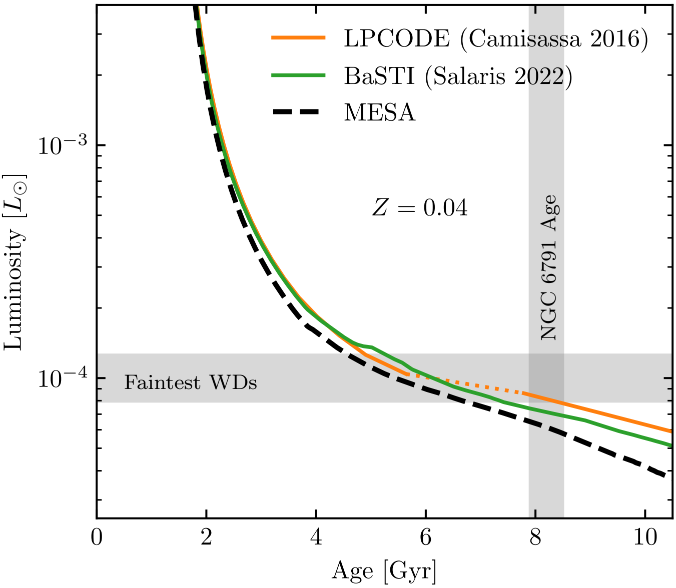
NGC 6791



LPCODE (Camisassa 2016)
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Does NGC 6791 require ^{22}Ne Distillation too?

THE ASTROPHYSICAL JOURNAL LETTERS, 911:L5 (6pp), 2021 April 10

https://doi.org/10.3847/2041-8213/abf14b

CrossMark

^{22}Ne Phase Separation as a Solution to the Ultramassive White Dwarf Cooling Anomaly

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Abstract

The precise astrometric measurements of the Gaia Data Release 2 have opened the door to detailed tests of the predictions of white dwarf cooling models. Significant discrepancies between theory and observations have been identified, the most striking affecting ultramassive white dwarfs. Cheng et al. found that a small fraction of white dwarfs on the so-called Q branch must experience an extra cooling delay of ∼8 Gyr not predicted by current models. ^{22}Ne phase separation in a crystallizing C/O white dwarf can lead to a distillation process that efficiently transports ^{22}Ne toward its center, thereby releasing a considerable amount of gravitational energy. Using state-of-the-art Monte Carlo simulations, we show that this mechanism can largely resolve the ultramassive cooling anomaly if the delayed population consists of white dwarfs with moderately above-average ^{22}Ne abundances. We also argue that ^{22}Ne phase separation can account for the smaller cooling delay currently missing for models of white dwarfs with more standard compositions.

Unified Astronomy Thesaurus concepts: Cosmochronology (332); Degenerate matter (367); Plasma physics (2089); Stellar evolution (1599); Stellar interiors (1606); White dwarf stars (1799)

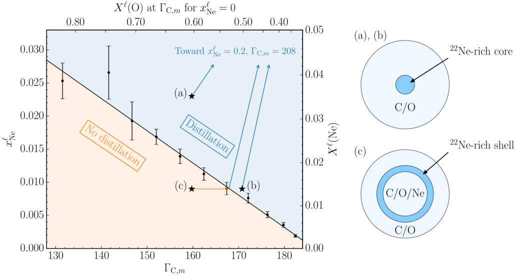
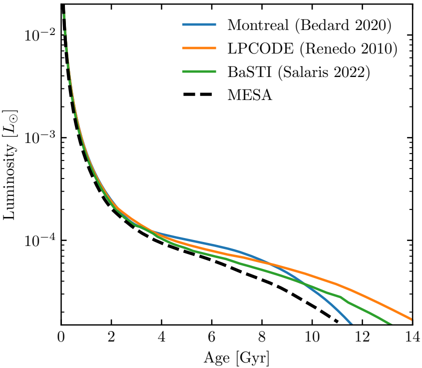


Figure 3. The circles with error bars indicate the conditions where we find that $\rho^s = \rho^\ell$ at the phase transition. The orange region below the line formed by those error bars corresponds to the regime where the solid sinks and no distillation takes place. The blue region corresponds to where the solid is lighter than the liquid, leading to ^{22}Ne distillation. The top horizontal axis gives the O mass fraction in the liquid for a C/O plasma that crystallizes at the temperature given by the bottom axis. The different scenarios (a), (b), and (c) are discussed in the text.

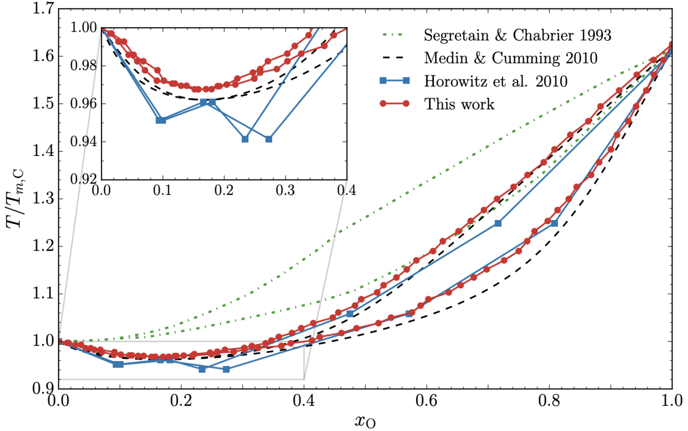
Part II Summary

- More work to do to understand the level at which different WD codes agree, inherent uncertainties in WD cooling physics.
- Latest models are cooling faster than previous generations.
- Does this require that additional cooling delays associated with crystallization operate beyond just the Q-branch?



Backup: Phase Diagrams

A&A 640, L11 (2020)



Phase diagram from Blouin et al (2020), Blouin & Daligault (2021)