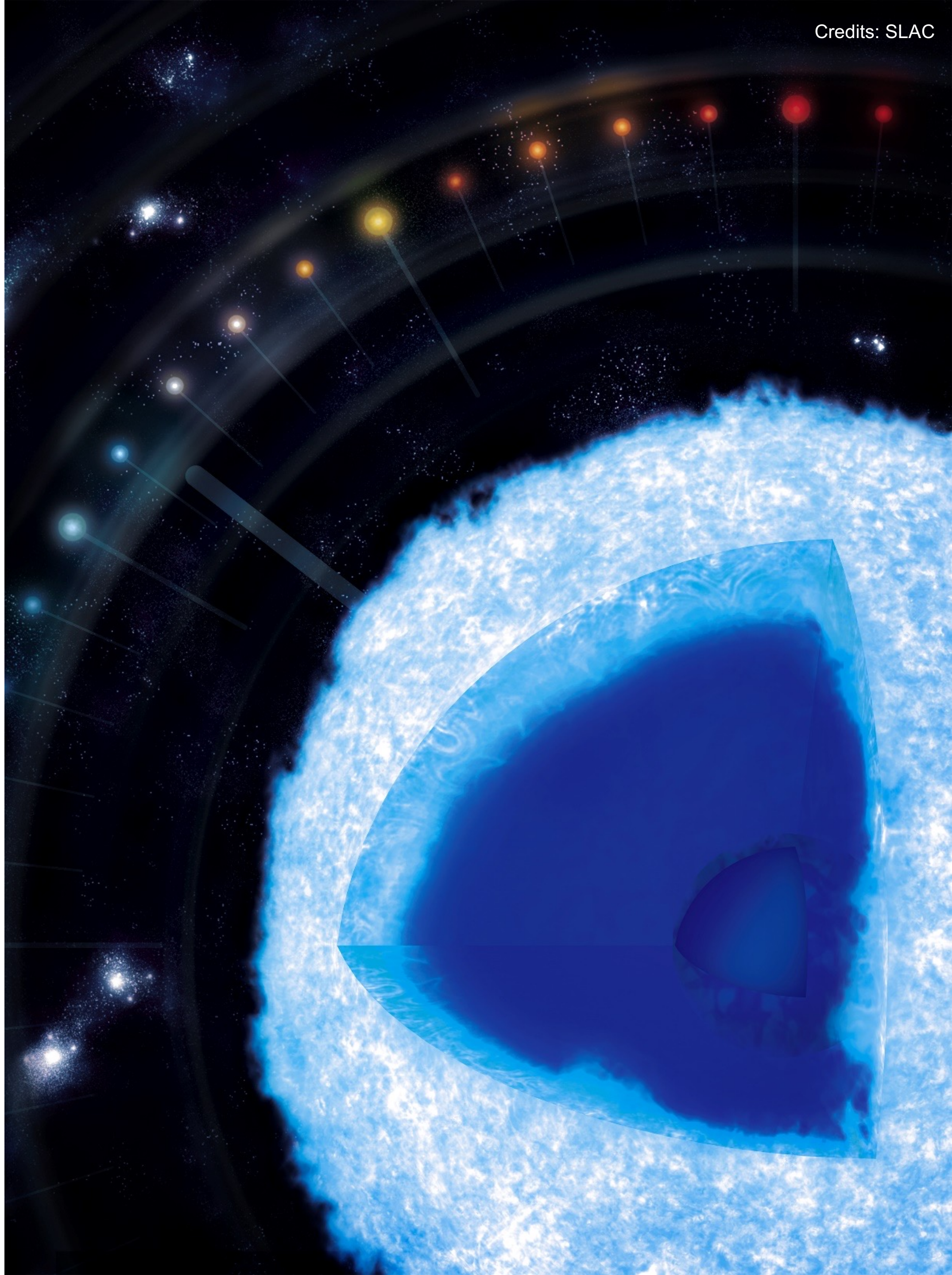
Fractionation processes in crystallizing white dwarfs

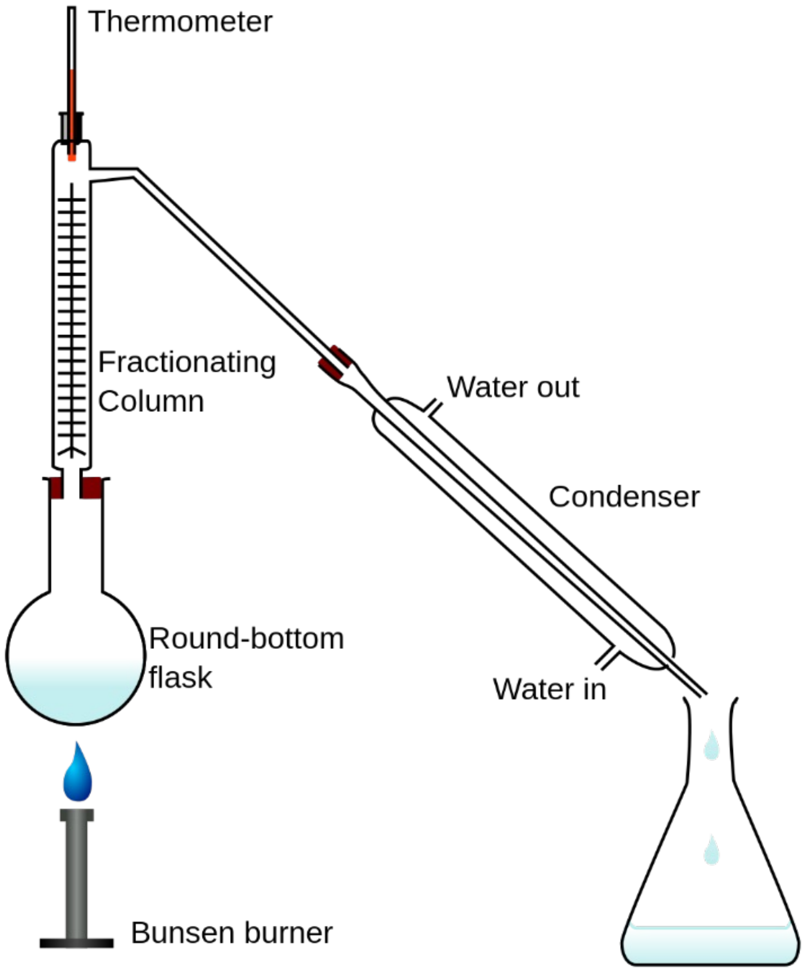
Simon Blouin
Banting and CITA National Fellow
University of Victoria

White Dwarfs from Physics to Astrophysics
KITP
November 14, 2022

University of Victoria
Los Alamos NATIONAL LABORATORY
Bourses postdoctorales Banting Postdoctoral Fellowships
IReNA
CITA | ICAT Canadian Institute for Theoretical Astrophysics L'institut Canadien d'astrophysique théorique



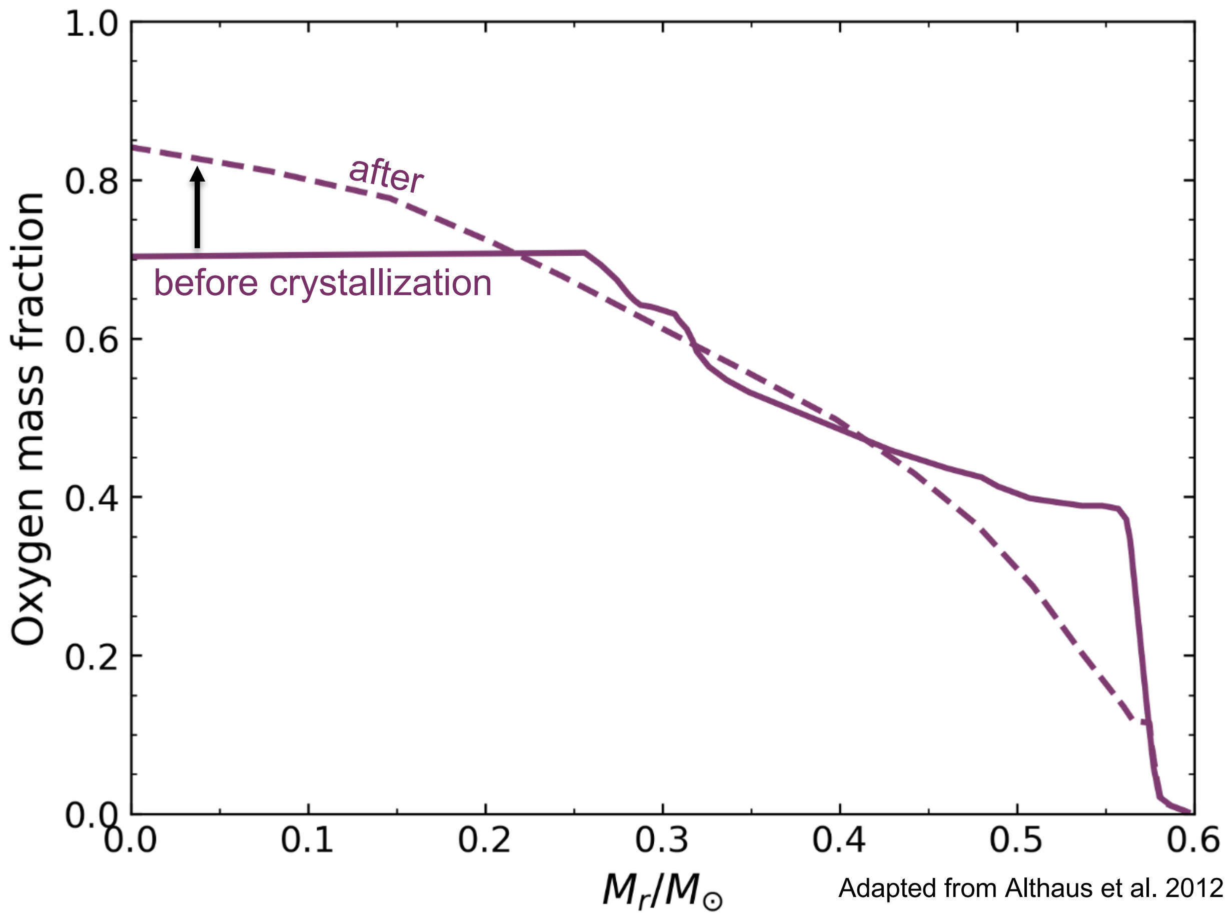
What is fractionation?



In general, the two coexisting phases of a multi-component mixture have different compositions

This is known as fractionation (or phase separation)

Fractionation impacts WD cooling



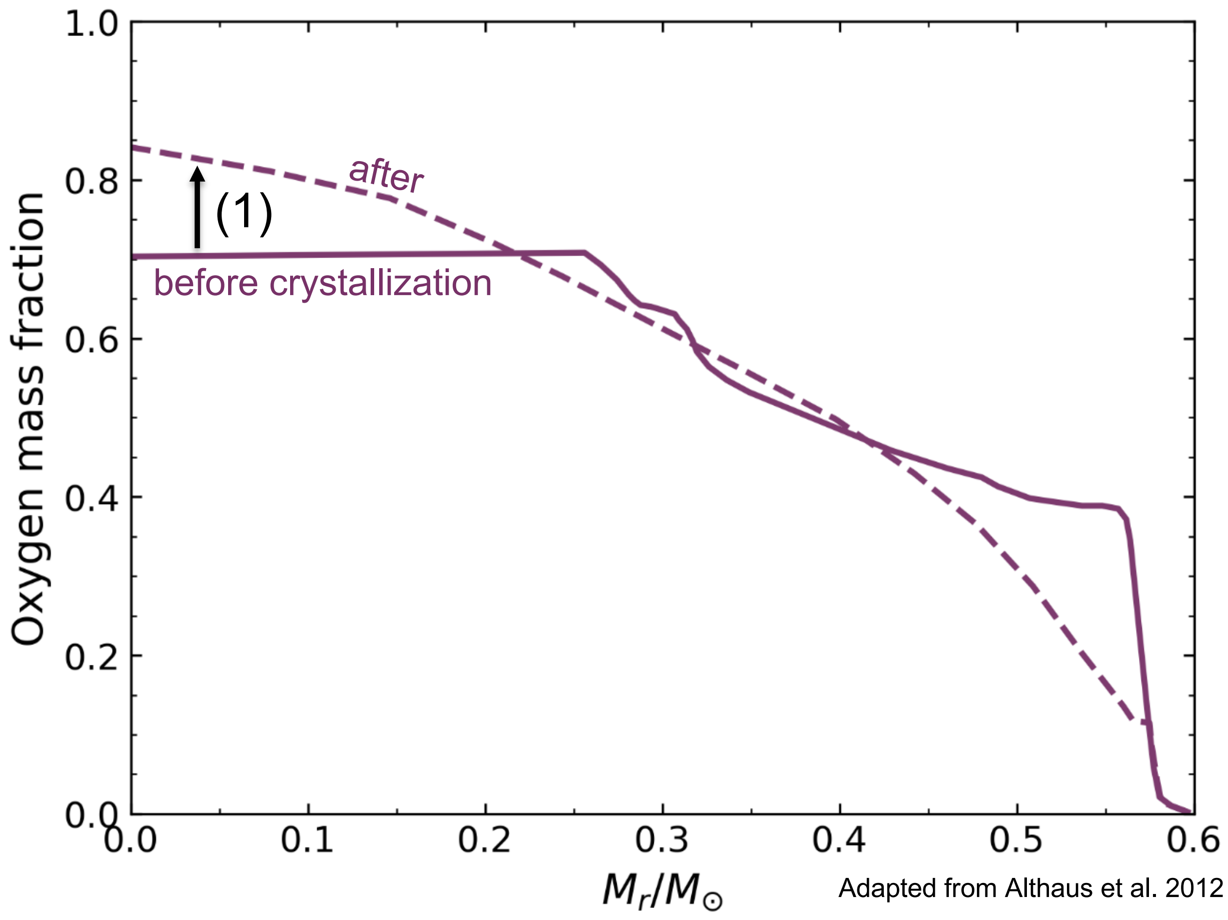
Adapted from Althaus et al. 2012

The separation of O and C during WD crystallization releases gravitational energy, delays the cooling

Effect comparable to the release of latent heat

Analogous process in O-Ne WDs

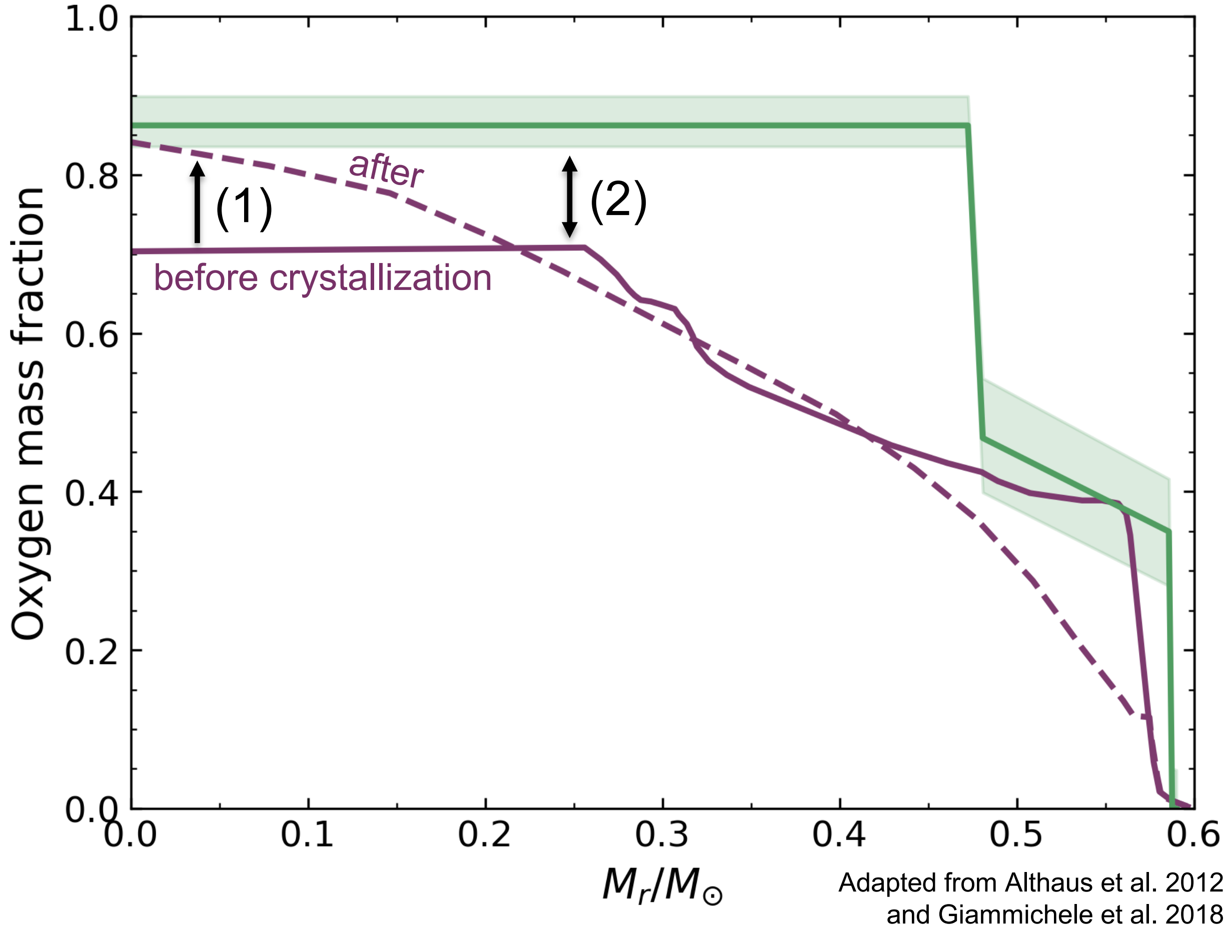
What we need to know to get this right



Adapted from Althaus et al. 2012

(1) How strong is the separation process? → phase diagrams

What we need to know to get this right



Adapted from Althaus et al. 2012 and Giammichele et al. 2018

(1) How strong is the separation process? → phase diagrams

(2) What is the initial composition profile on which fractionation operates?

The initial composition problem (very quickly)

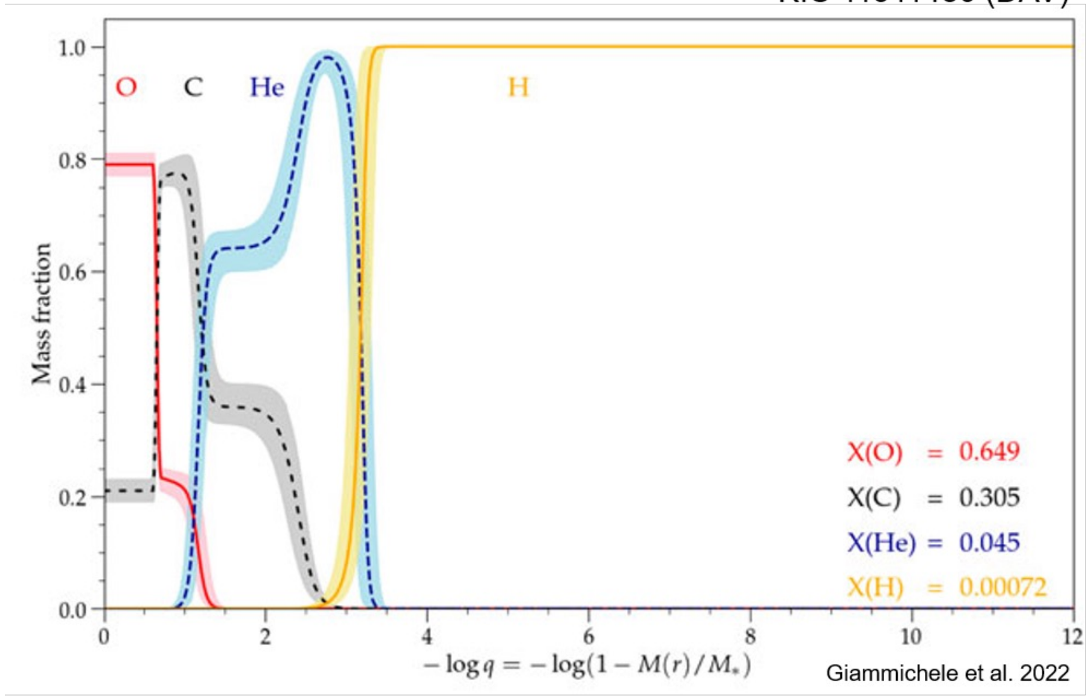
Initial WD composition predicted using 1D stellar evolution (MESA, LPCODE, BaSTI)

All codes have their own recipes to treat convective boundary mixing: affects the WD composition

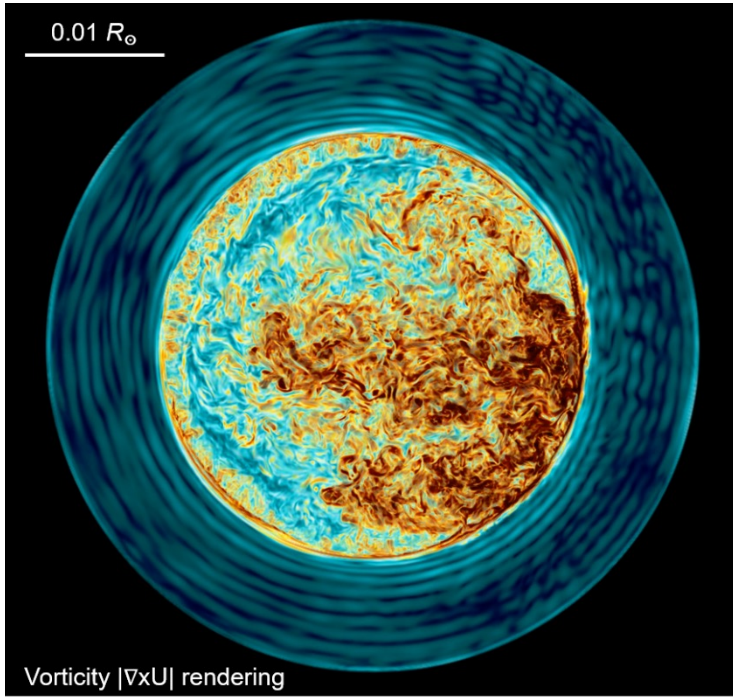
Core He-burning phase especially uncertain: ∇_{rad} develops a local minimum, breathing pulses

Asteroseismology and 3D hydrodynamics simulations provide avenues to solve this problem

KIC 11911480 (DAV)

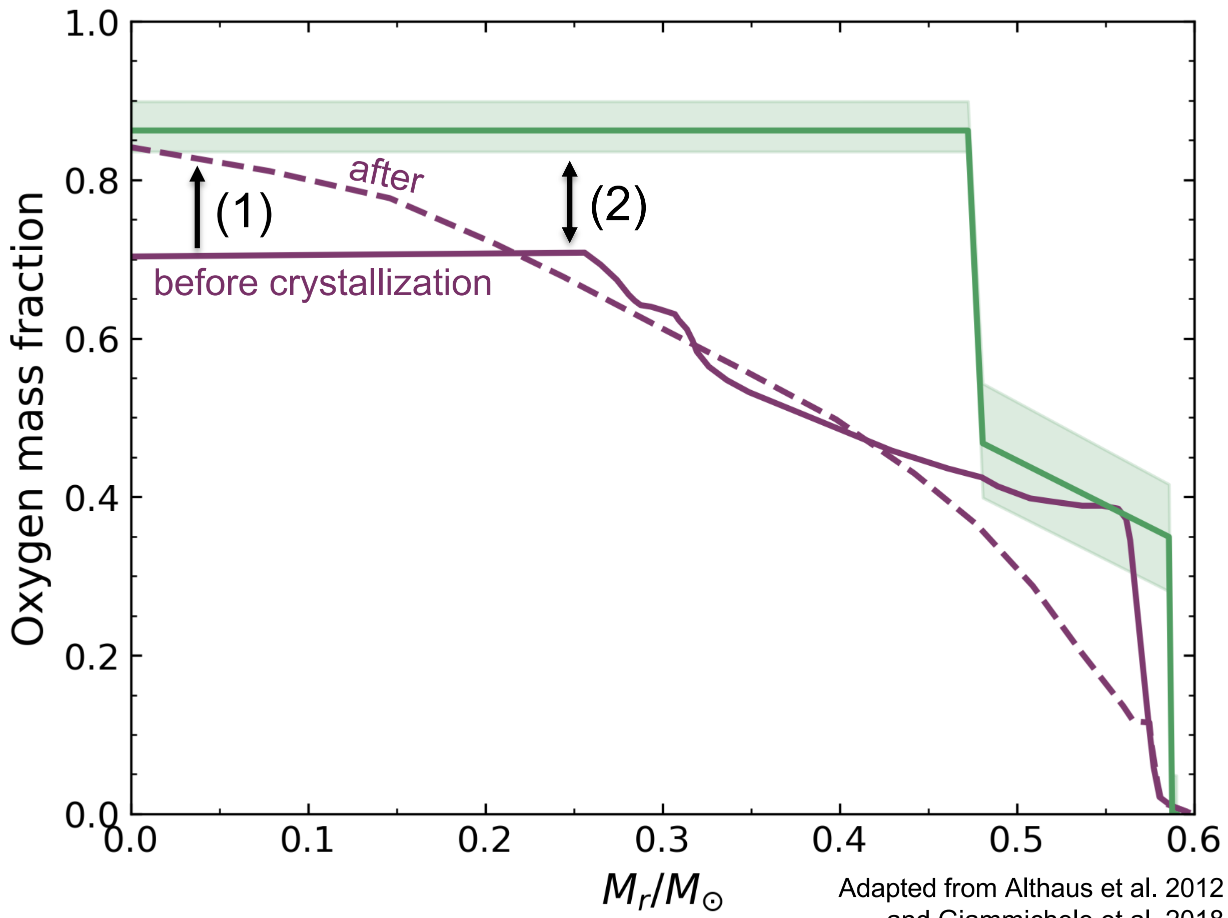


Giammichele et al. 2022



Vorticity |∇xU| rendering

What we need to know to get this right

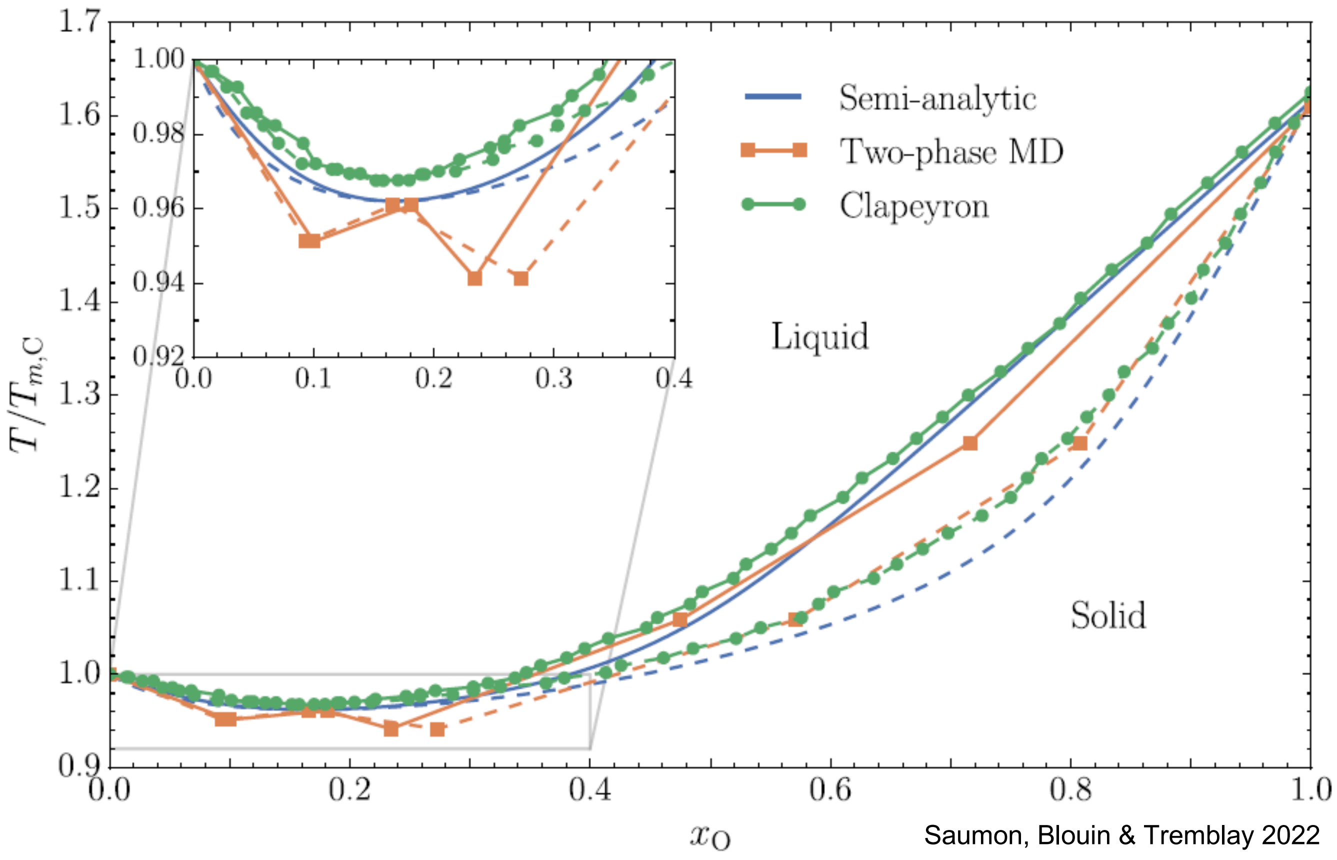


Adapted from Althaus et al. 2012
and Giammichele et al. 2018

(1) How strong is the separation process? → phase diagrams

(2) What is the initial composition profile on which fractionation operates?

Phase diagram calculations



Saumon, Blouin & Tremblay 2022

Semi-analytic: fast but uncertain (arbitrary choices in free energy functional forms + super-heated solid / super-cooled liquid problem, see Ogata+93, DeWitt+96, Jermyn+21)

Molecular dynamics: first-principles → accurate but costly. More useful for “spot checks”. See Horowitz+10, Hughto+12, Caplan+21

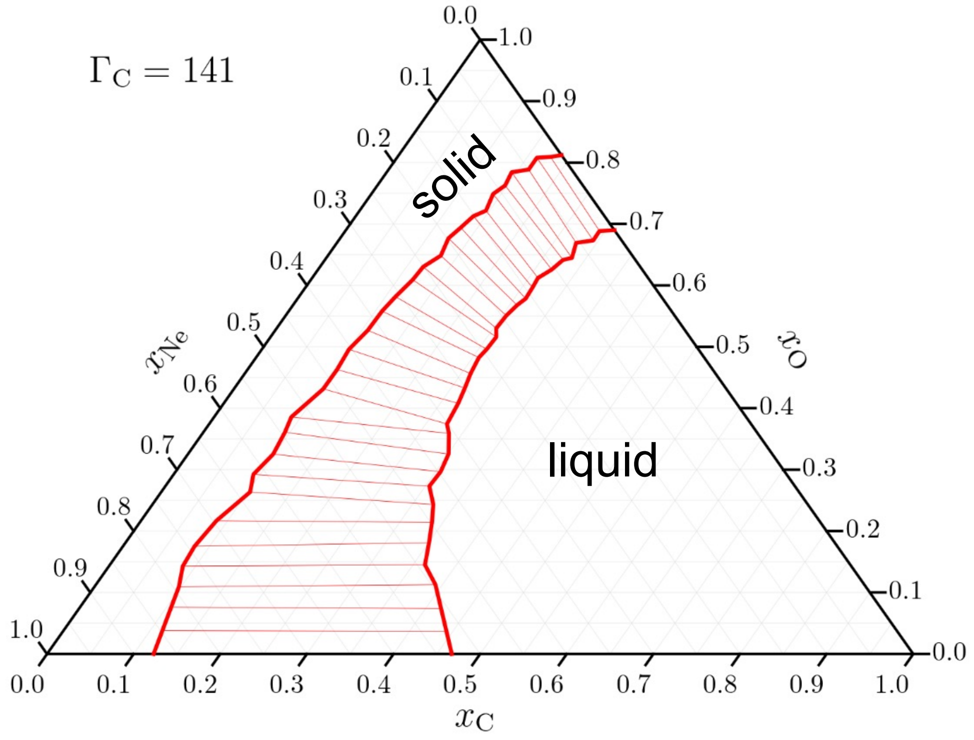
Clapeyron: uses first-principles Monte Carlo simulations. Accurate and relatively cheap, see Blouin & Daligault 2022

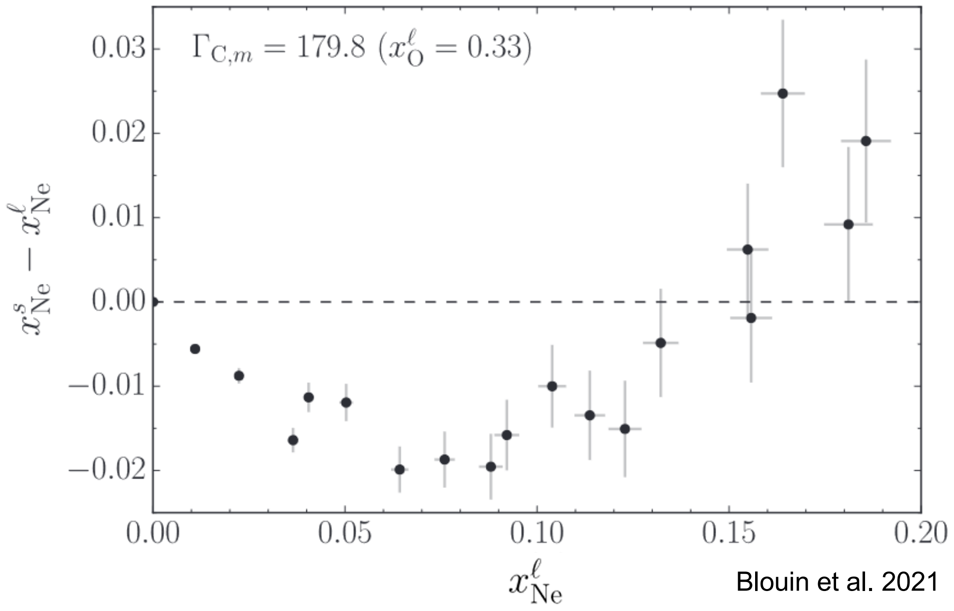
Overall, good agreement: the physics is well understood and we have reliable simulation methods

Recent result #1: ^{22}Ne distillation

The C-O-Ne phase diagram predicts that crystals are impoverished in ^{22}Ne compared to the liquid phase

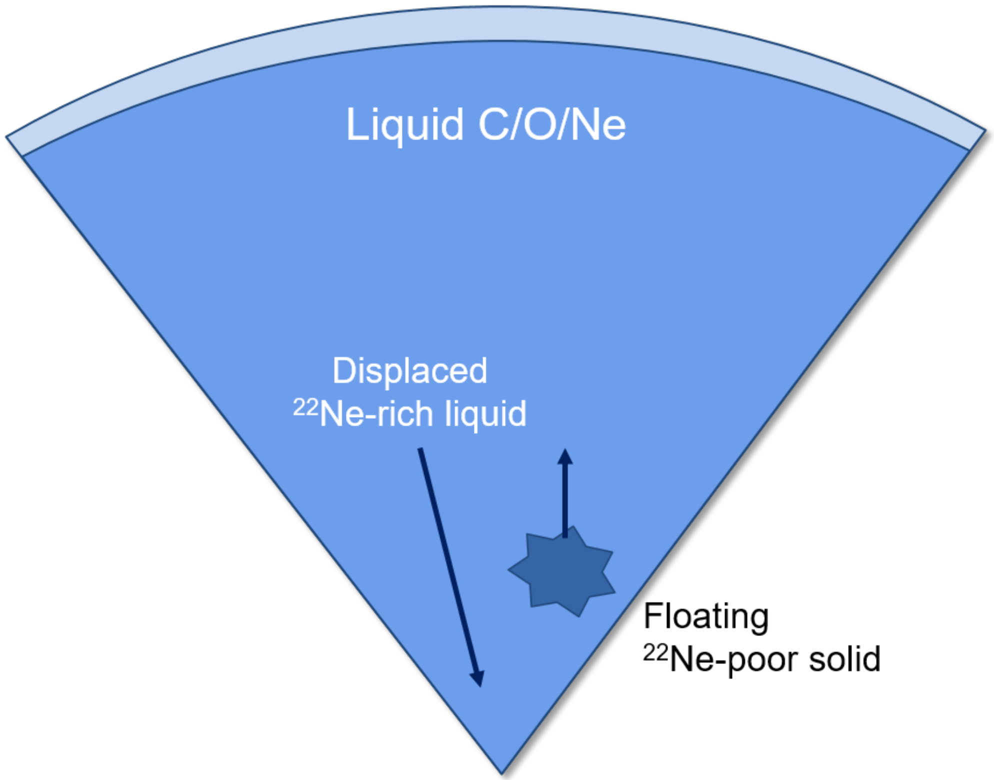
Result found both using the Clapeyron and the semi-analytic approach (also consistent with constraints from molecular dynamics)





Blouin et al. 2021

Recent result #1: ^{22}Ne distillation



Astron. Astrophys. 241, L29–L32 (1991)

ASTRONOMY AND ASTROPHYSICS

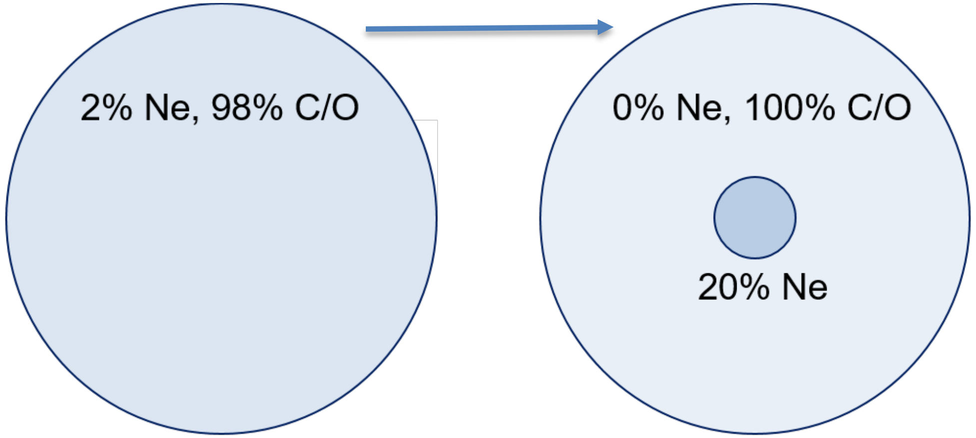
Letter to the Editor

The role of the minor chemical species in the cooling of white dwarfs

J. Isern[1,4], R. Mochkovitch[2], E. García-Berro[3,1,4], and M. Hernanz[1,4]

[1] Centre d'Estudis Avançats de Blanes (CSIC), Camí de Santa Bárbara, E-17300 Blanes, Spain
[2] Institut d'Astrophysique de Paris, 98bis Bd. Arago, F-75014 Paris, France
[3] Departament de Física Aplicada (UPC), Jordi Girona Salgado 31, E-08034 Barcelona, Spain
[4] Laboratori d'Astrofísica (IEC), Carme 15, E-08001 Barcelona, Spain

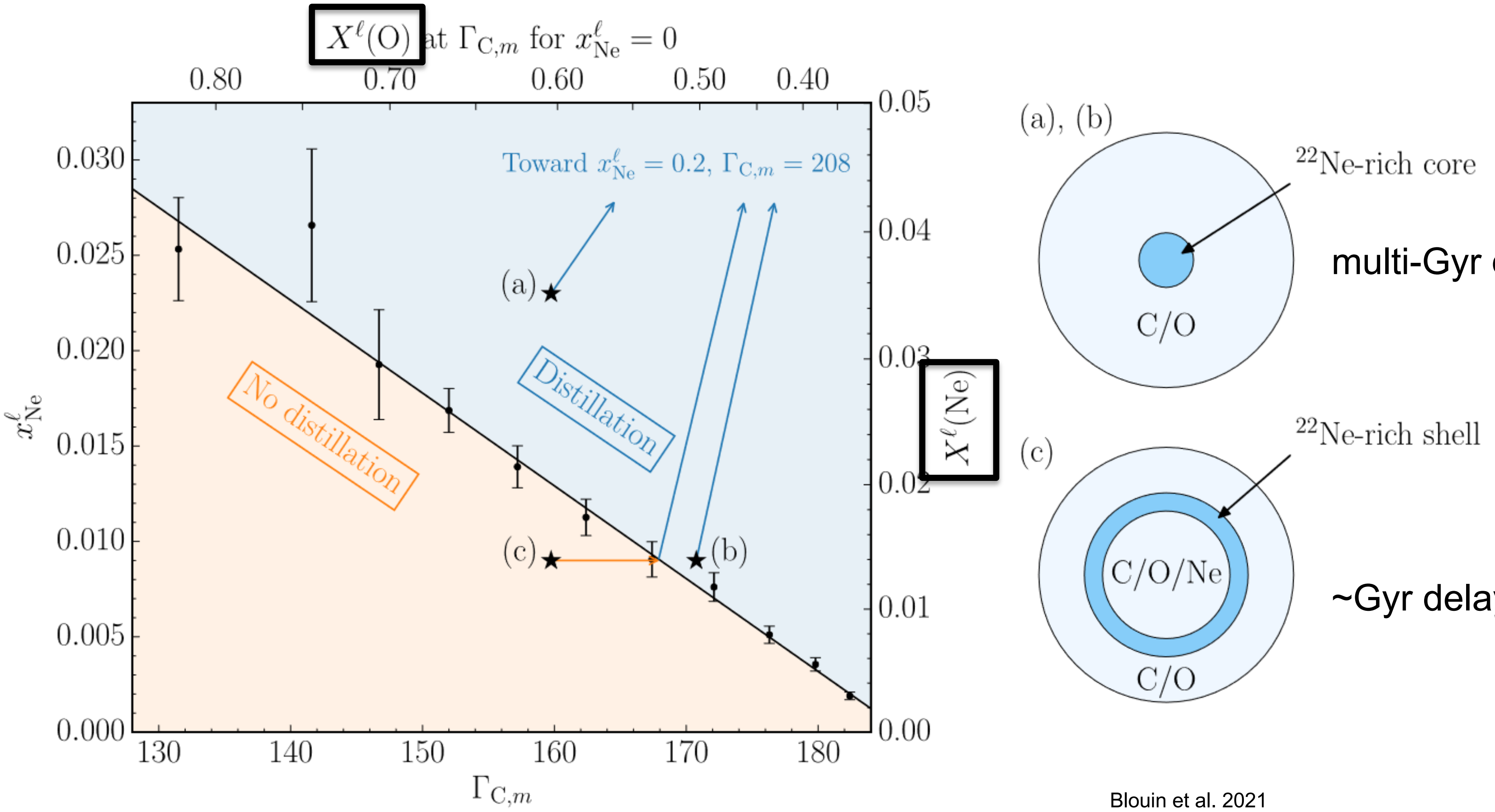
Received August 7, accepted September 27, 1990



Central electron density $n_{e,0}$
Central mass density ρ_0
Binding energy Ω_0

Central electron density $n_{e,0}$
Central mass density $> \rho_0$
Binding energy $< \Omega_0$

Recent result #1: ^{22}Ne distillation



multi-Gyr delays

~Gyr delays

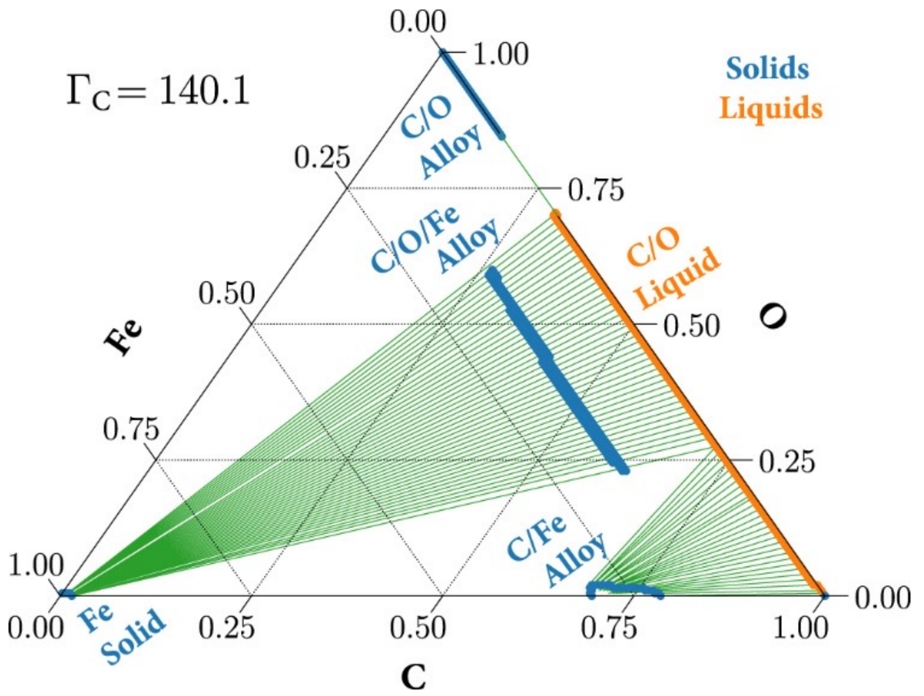
Blouin et al. 2021

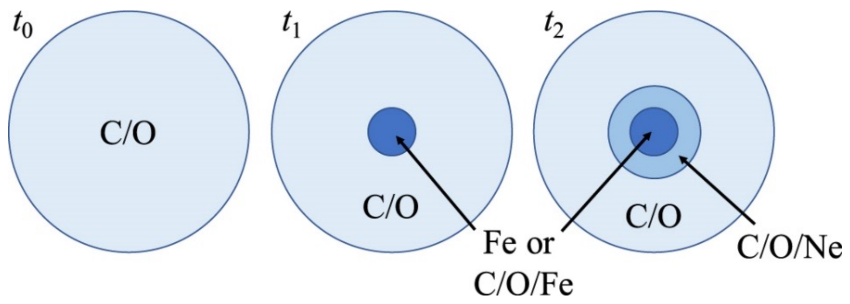
Recent result #2: ^{56}Fe precipitation

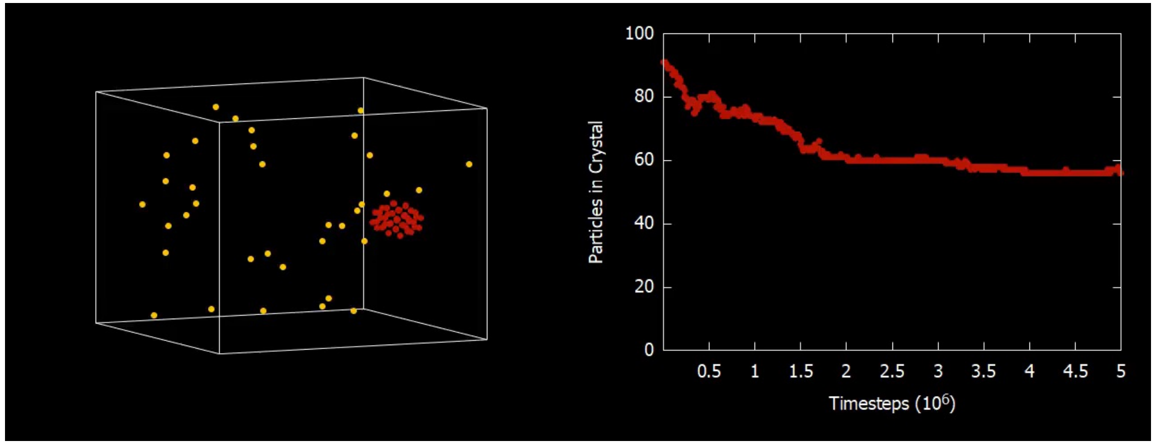
Fe-rich crystals predicted to form before the C-O mixture crystallizes (Caplan+21)

Molecular dynamics consistent with semi-analytic calculations

Slows down WD cooling by <0.2 Gyr (Salaris+22)







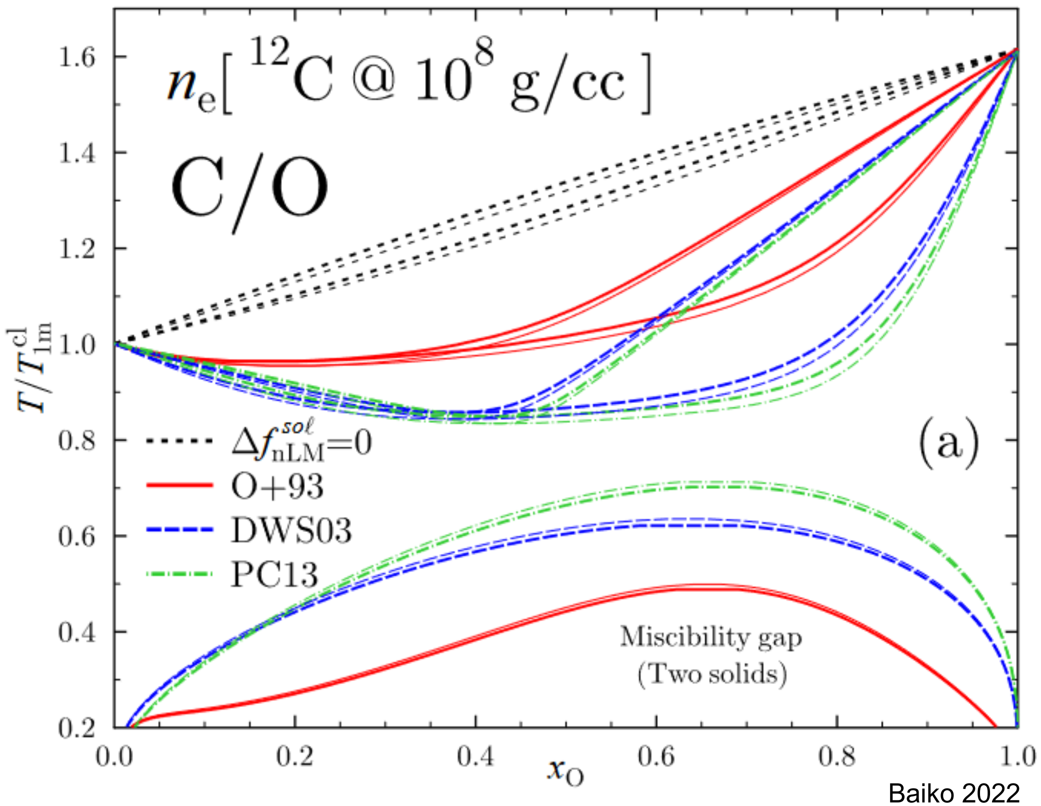
Caplan et al. 2021

Recent result #3: solid-solid fractionation

Solid-solid separation predicted in C-O and O-Ne cores

Could affect WD cooling significantly, as it would happen when the star is quite dim

Very uncertain: mixture of grains/lamellae with different compositions or large-scale separation?



Baiko 2022

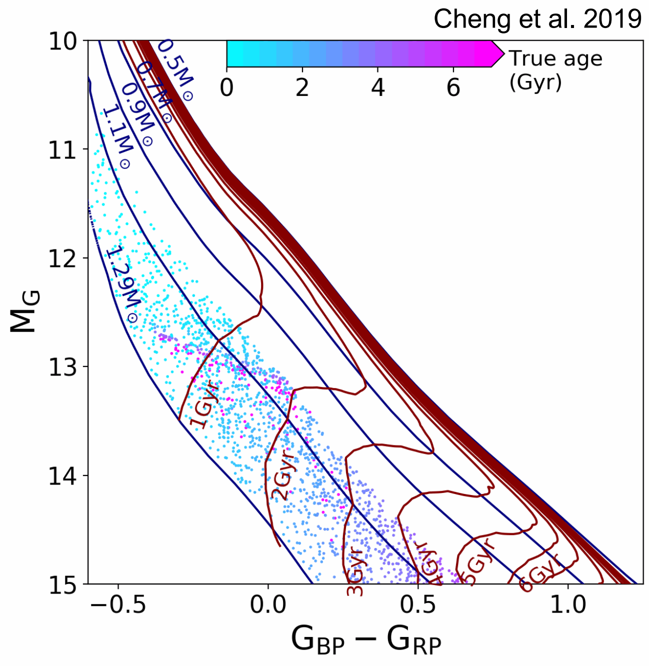

Antiperthite, Eurico Zimbres

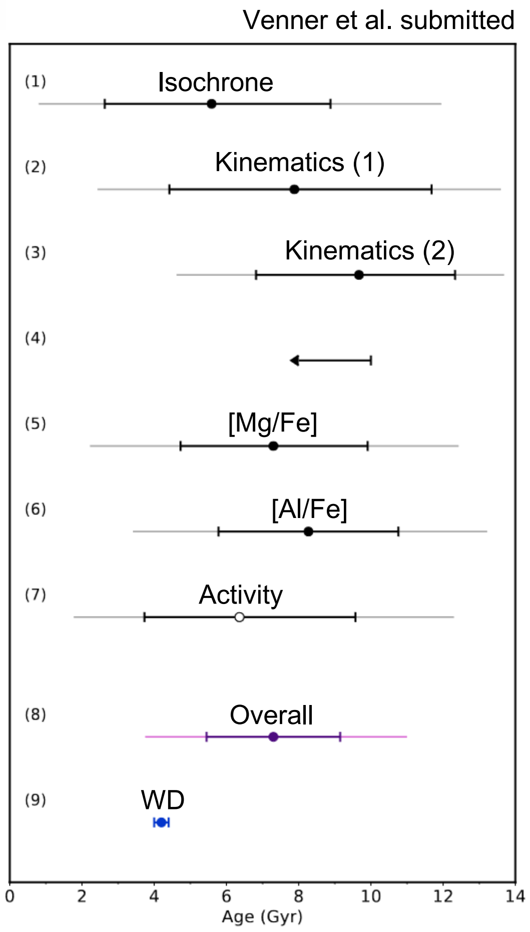
Observational constraints

Gaia allows statistical constraints on fractionation-induced cooling delays: seems to imply that ^{22}Ne distillation is required

A more direct test would be to use wide binaries with a crystallized/ing WD and a companion for which a precise age can be inferred (similar to previous works on clusters, e.g., Garcia-Berro+10)

Asteroseismology: *g* modes cannot probe the crystallized portion, but can be used to measure the fraction of the core that is crystallized





Summary

The solid and liquid phases don't have the same composition during crystallization → fractionation

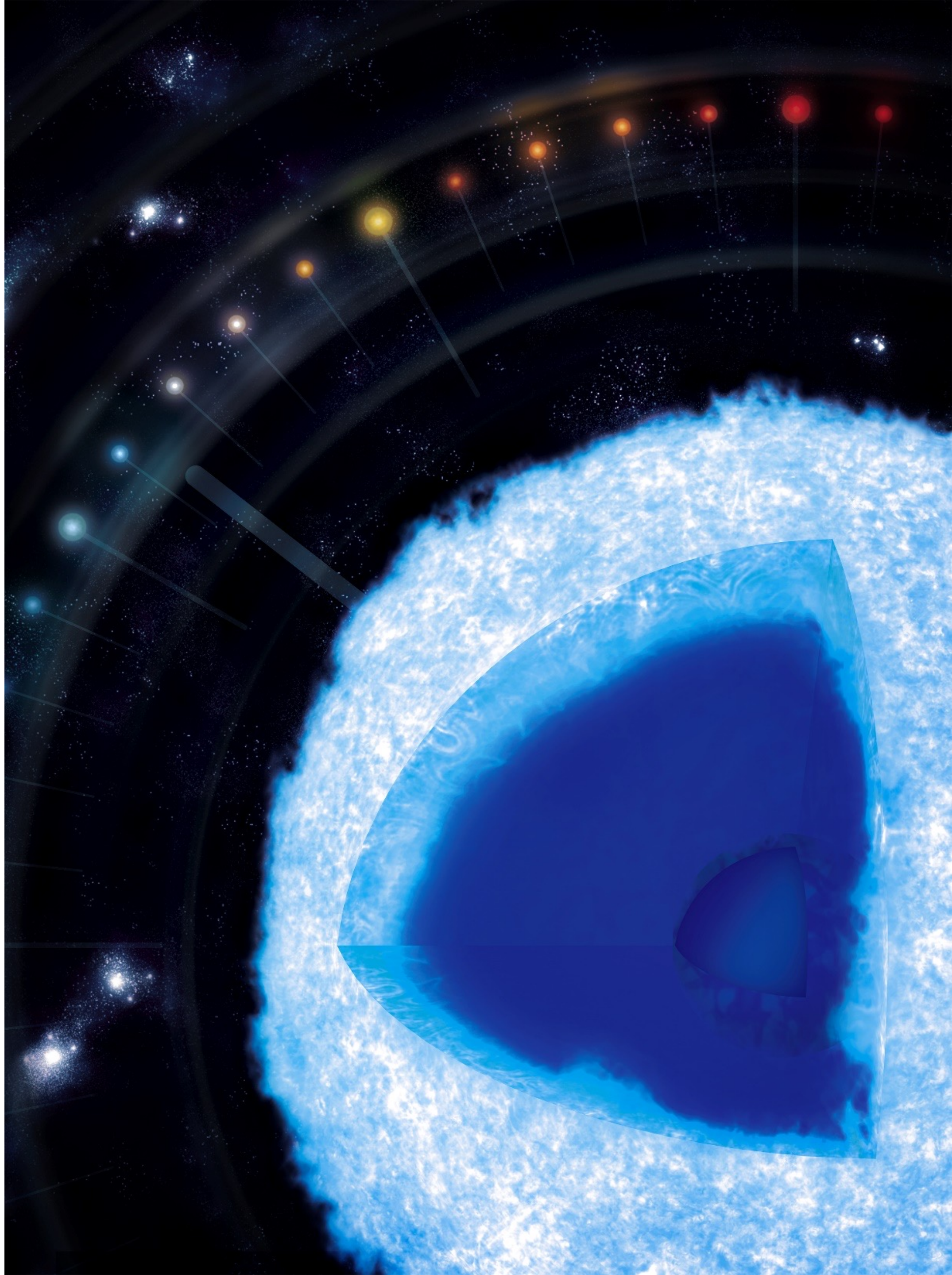
To understand the effect of fractionation on WD evolution, we need to know:

(1) Phase diagrams
(2) Initial WD composition

New fractionation processes have been recently proposed (^{22}Ne distillation, ^{56}Fe precipitation, solid-solid separation)

Observational constraints would be useful, especially from wide binaries with well-known ages

Thanks! Questions?



References

Althaus et al. 2012, A&A, 537, 33
Baiko 2022, MNRAS, 517, 3962
Blouin et al. 2021, ApJL, 911, L5
Blouin & Daligault 2021, PRE, 103, 043204
Caplan et al. 2021, ApJL, 919, L12
Cheng et al. 2019, ApJ, 886, 100
DeWitt et al. 1996, Physica B, 228, 21
Garcia-Berro et al. 2010, Nature, 465, 194
Giammichele et al. 2018, Nature, 554, 73
Giammichele et al. 2022, FrASS, 9, 879045
Horowitz et al. 2010, PRL, 104, 231101
Hughto et al. 2012, PRE, 86, 066413
Isern et al. 1991, A&A, 241, L29
Jermyn et al. 2021, ApJ, 913, 72
Ogata et al. 1993, PRE, 48, 1344
Salaris et al. 2022, MNRAS, 509, 5197
Saumon et al. 2022, Physics Reports, 988, 1