Frozen in time

Crystallization, fractionation and distillation in white dwarf stars

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University of Victoria

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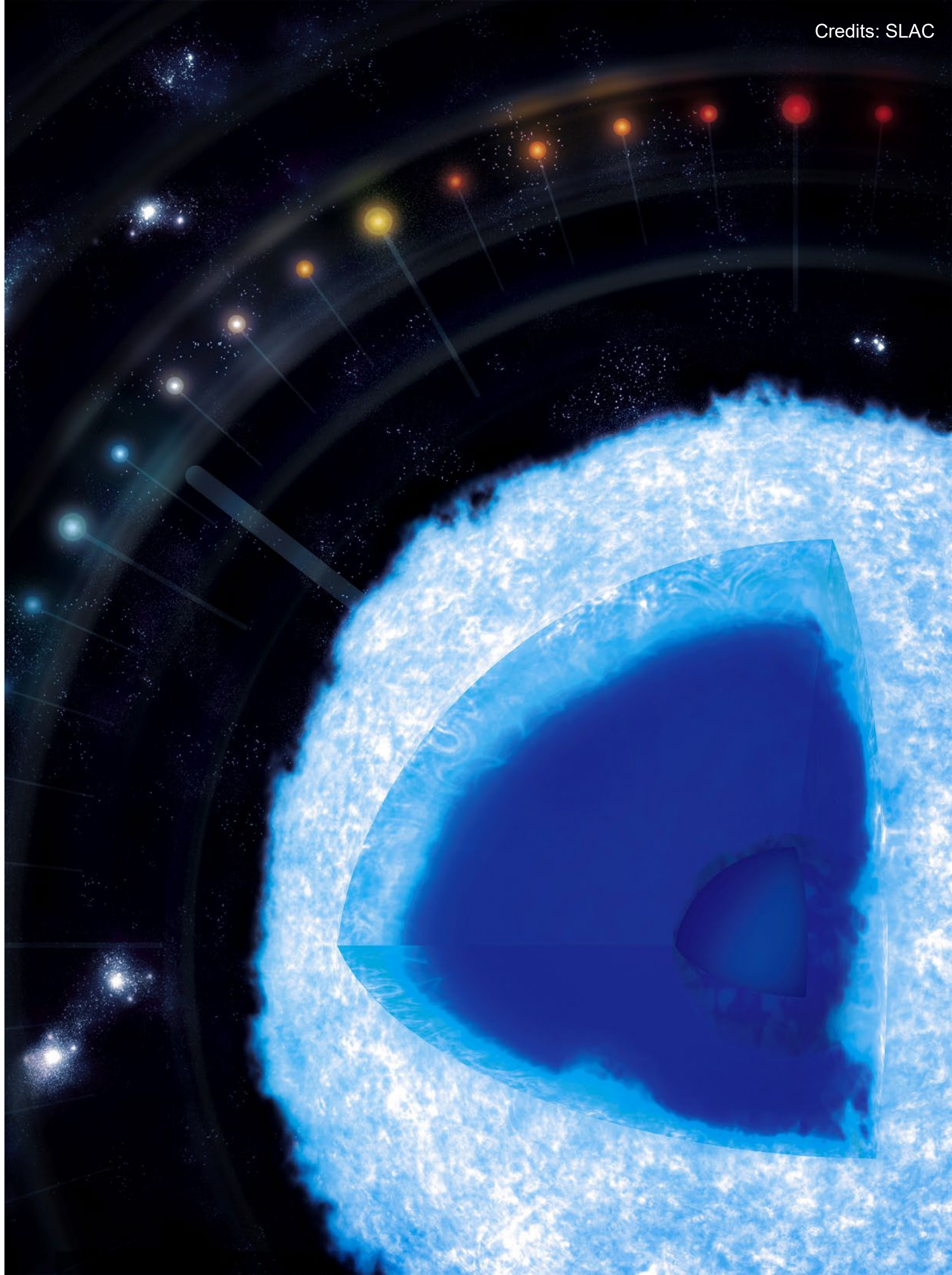

Credits: SLAC

My plan for today

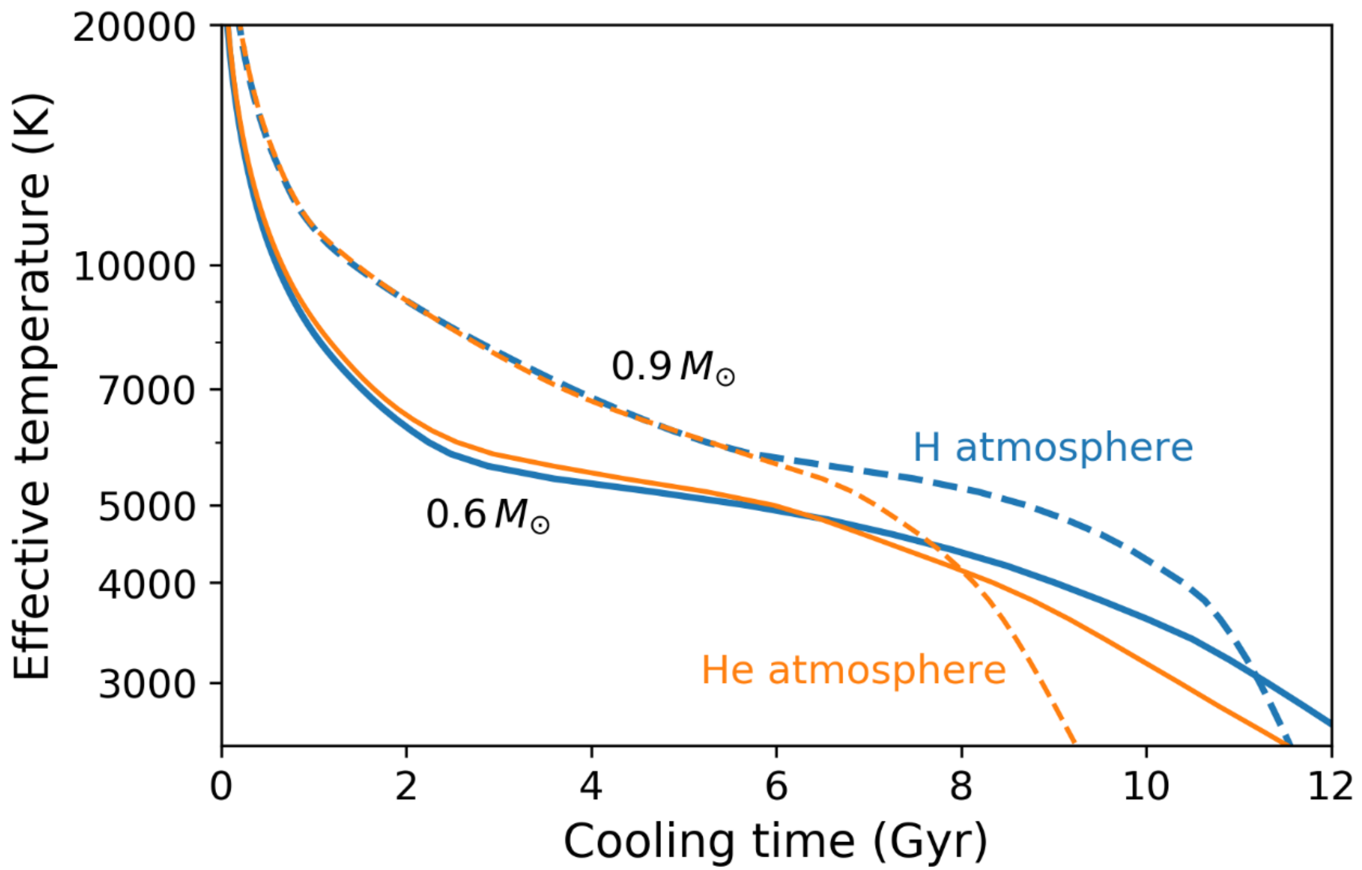
The white dwarf cooling problem

White dwarf crystallization as revealed by Gaia

^{22}Ne fractionation and distillation

Outstanding questions

White dwarf cooling



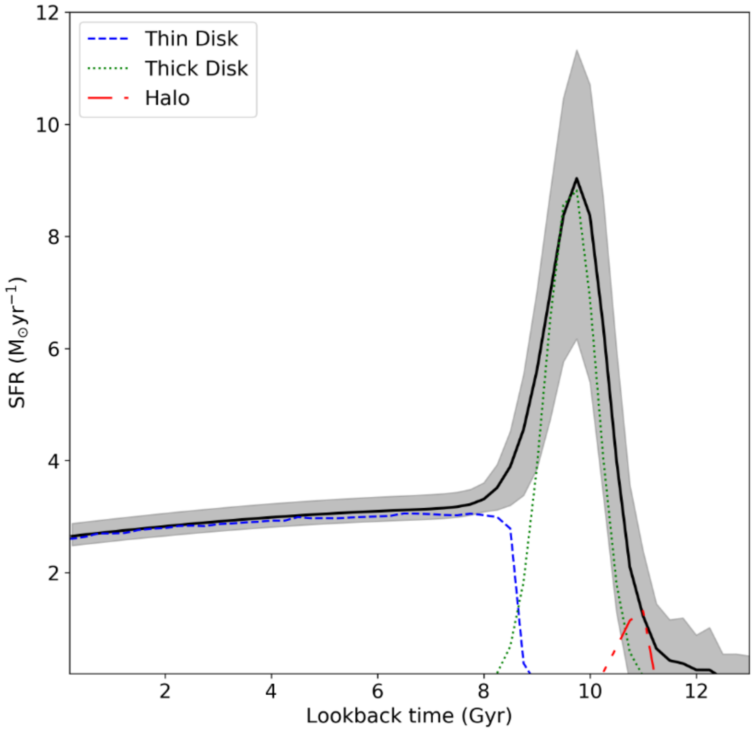
White dwarfs cool down monotonically for their entire lives

The age of a white dwarf can be obtained from its

- temperature
- mass
- atmospheric composition

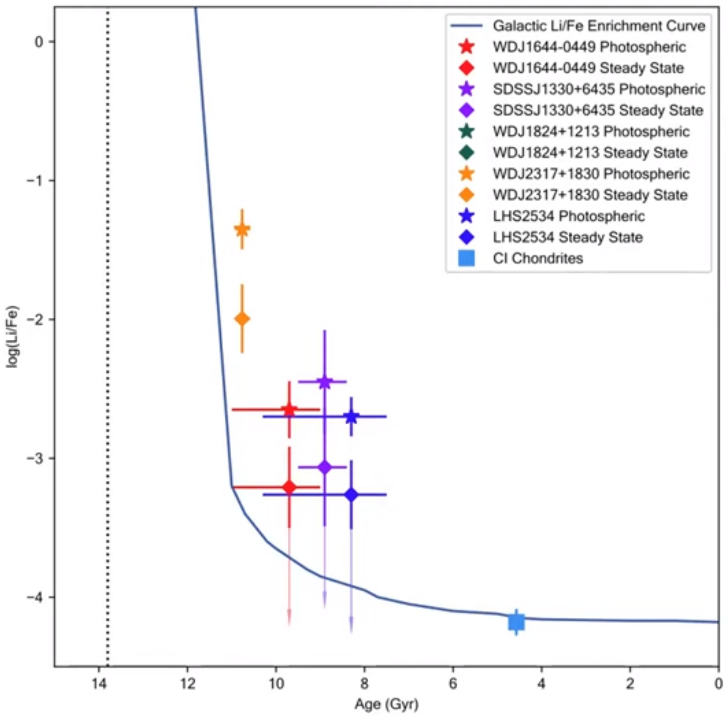
Some applications of white dwarf age dating

Stellar formation history



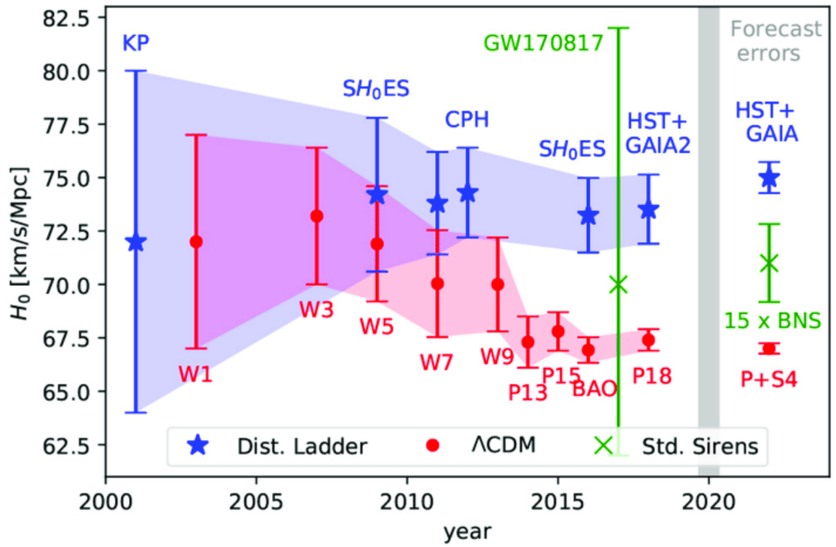
Fantin et al. 2019

Galactic chemical evolution



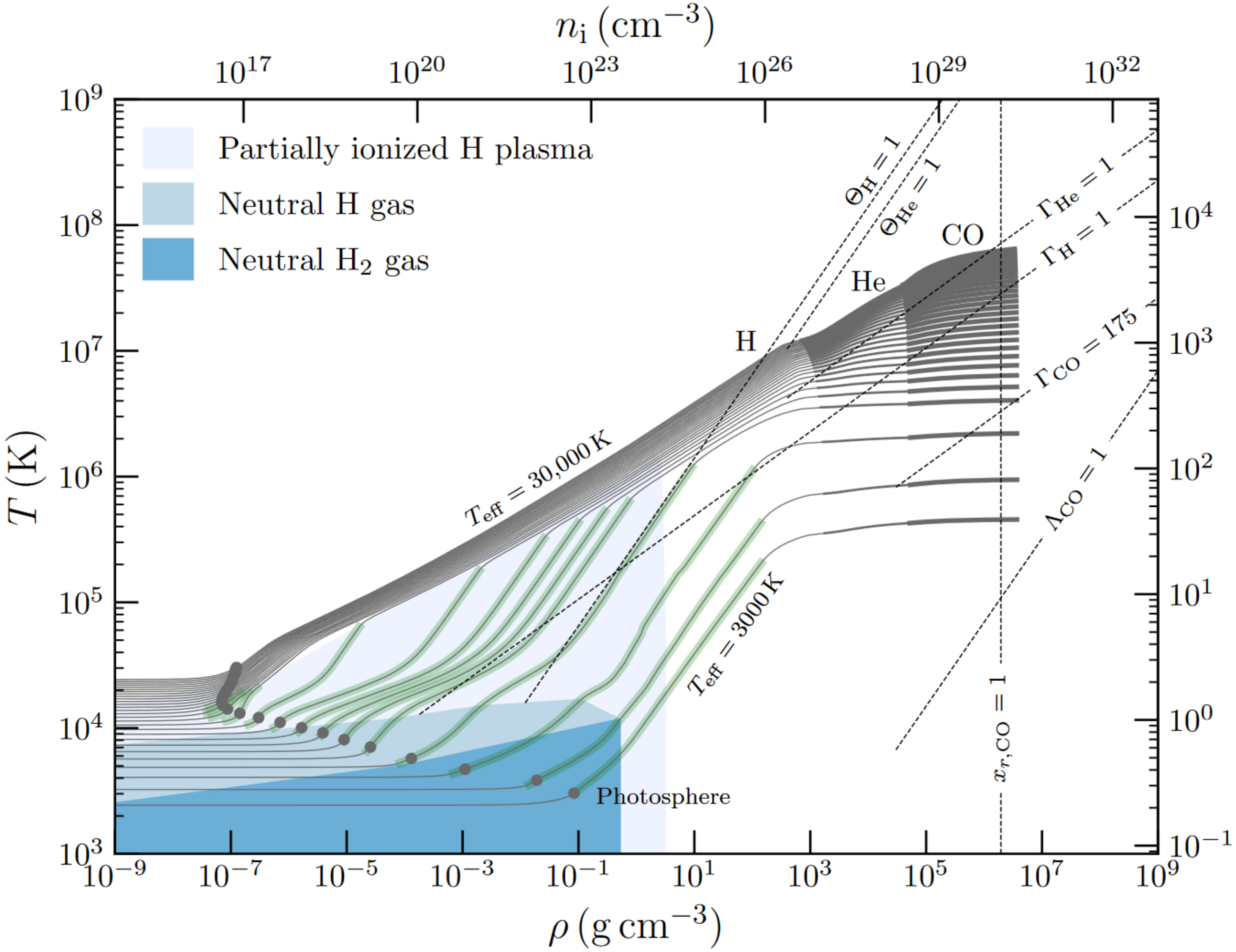
Kaiser, Clemens, Blouin, et al. 2021

Cosmology (?)



All those applications require reliable white dwarf cooling models

White dwarf physics in one figure



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The Gaia revolution

Thanks to Gaia, we now know the distances of some 250,000 white dwarfs

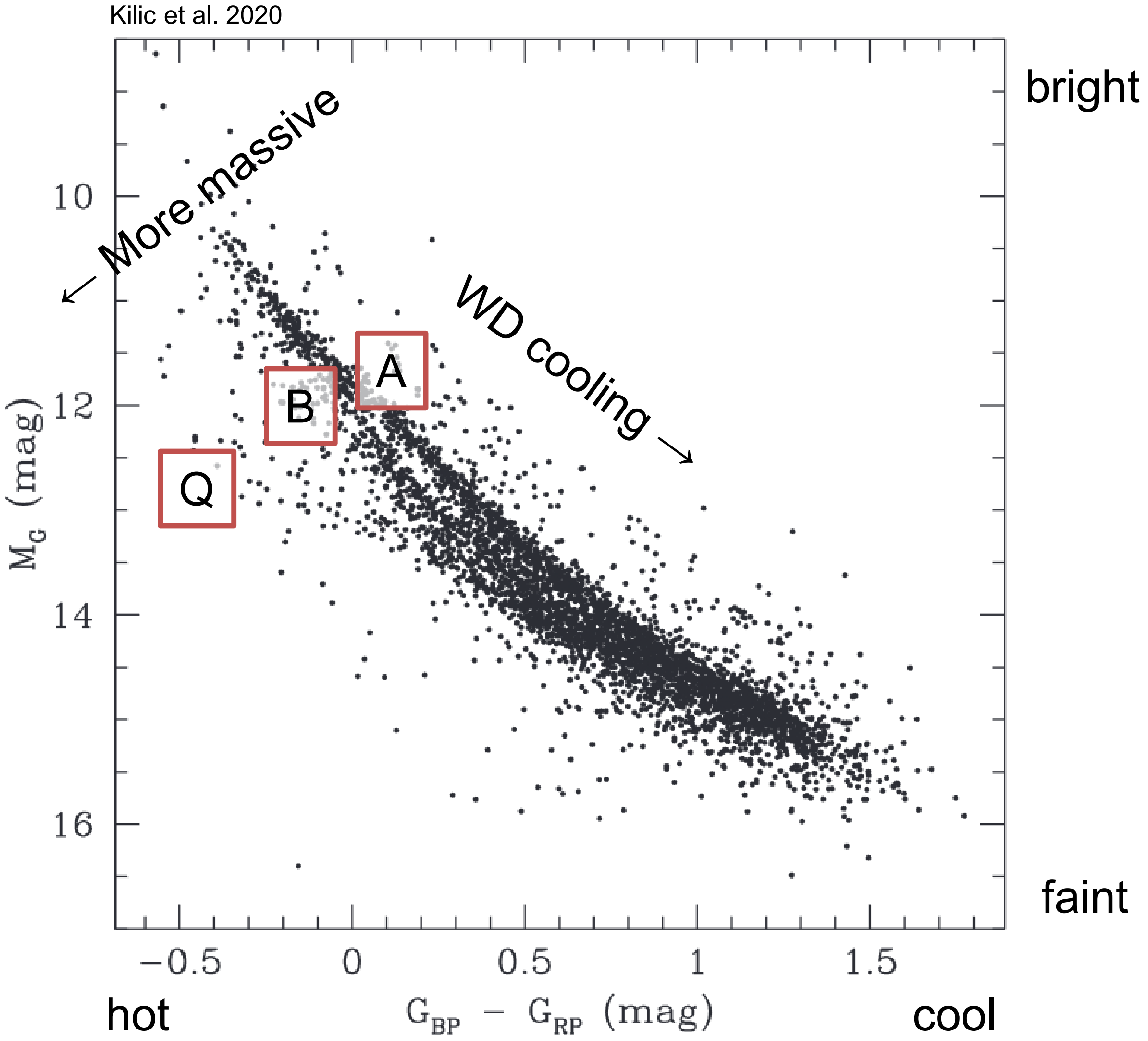
By lifting the degeneracy between *R* and *D*, Gaia provided us the masses of virtually all known white dwarfs

$$\text{Observed flux} = \frac{\pi R^2}{D^2} \times \text{Surface flux}$$

This allows to test white dwarf cooling models in unprecedented detail, and in particular the physics of core crystallization

ESA

The Gaia Hertzsprung–Russell diagram

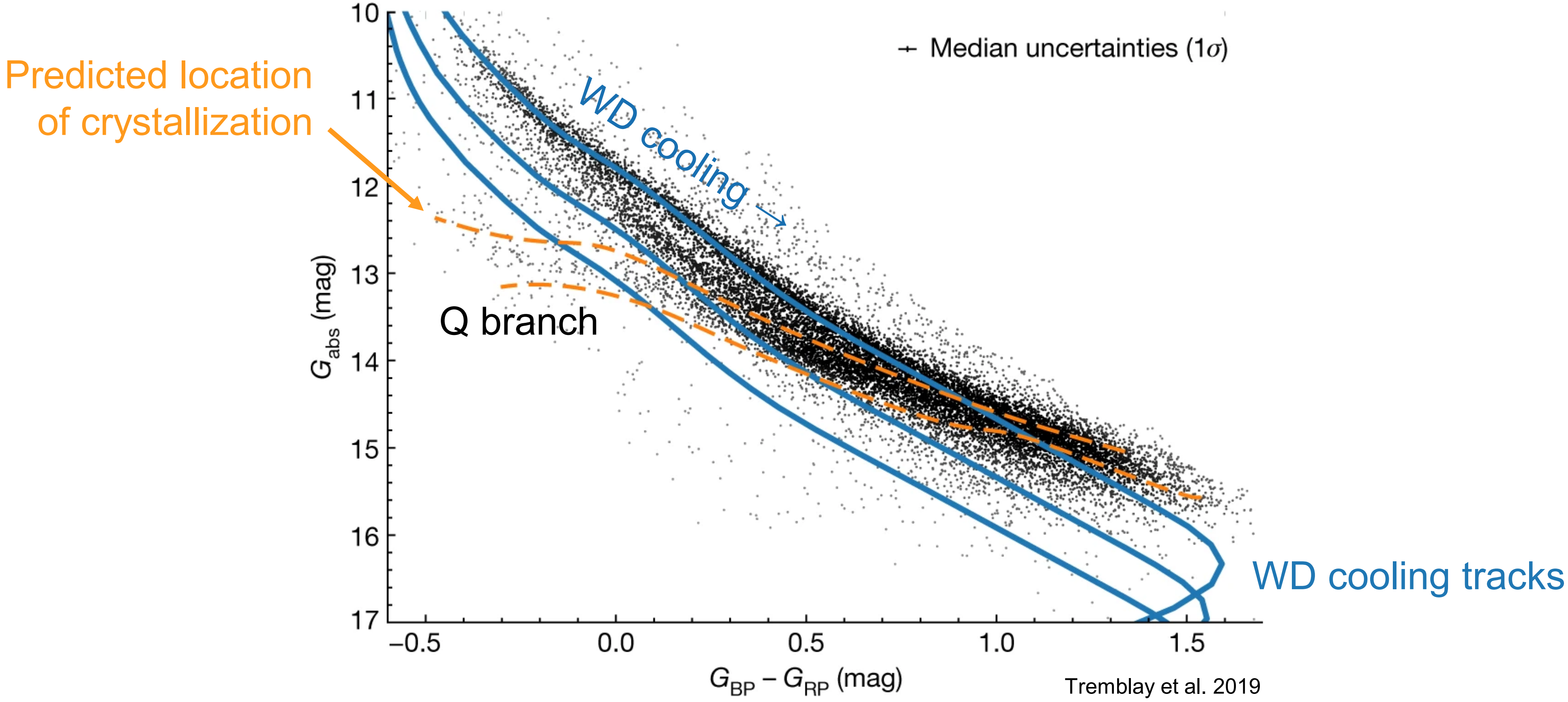

Kilic et al. 2020

A branch: tracks the evolution of H-dominated atmospheres

B branch: tracks the evolution of He-dominated atmospheres

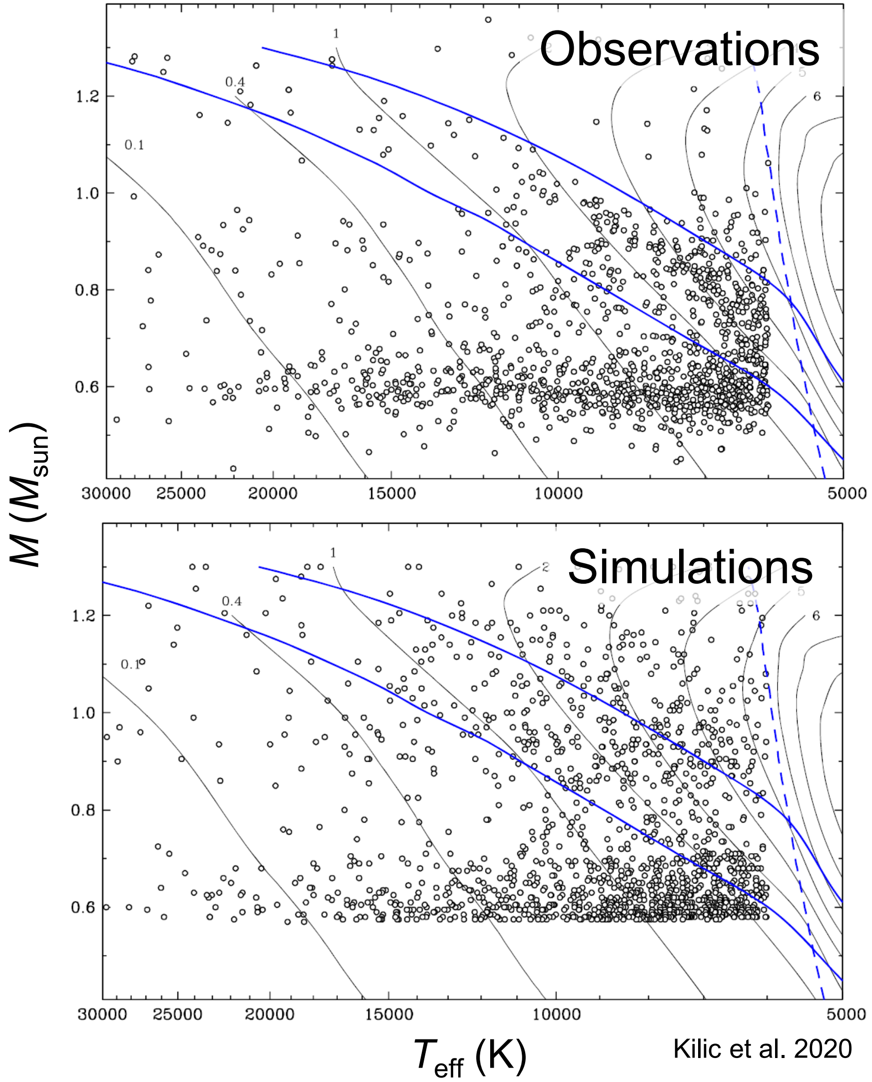
Q branch: transversal to white dwarf evolution, not an evolutionary track

The signature of crystallization in the Gaia HR diagram



Tremblay et al. 2019

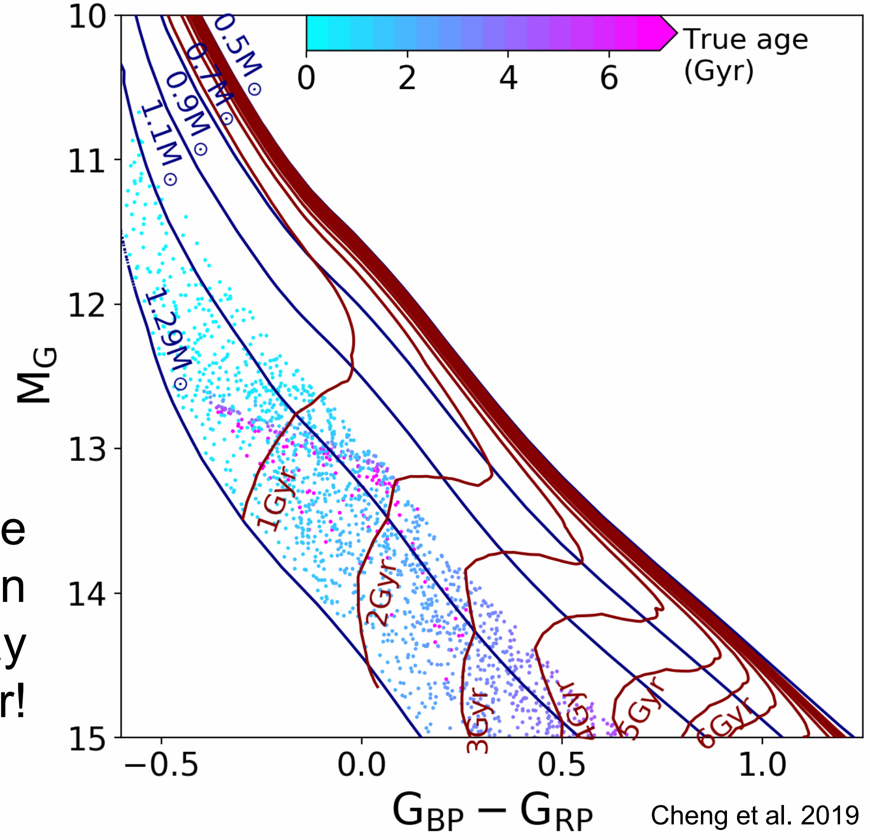
White dwarfs spend more time crystallizing than they should



Kilic et al. 2020

Standard white dwarfs experience an additional 1-2 Gyr cooling delay while crystallizing

6% of ultramassive white dwarfs experience an additional cooling delay of 8 Gyr!



Cheng et al. 2019

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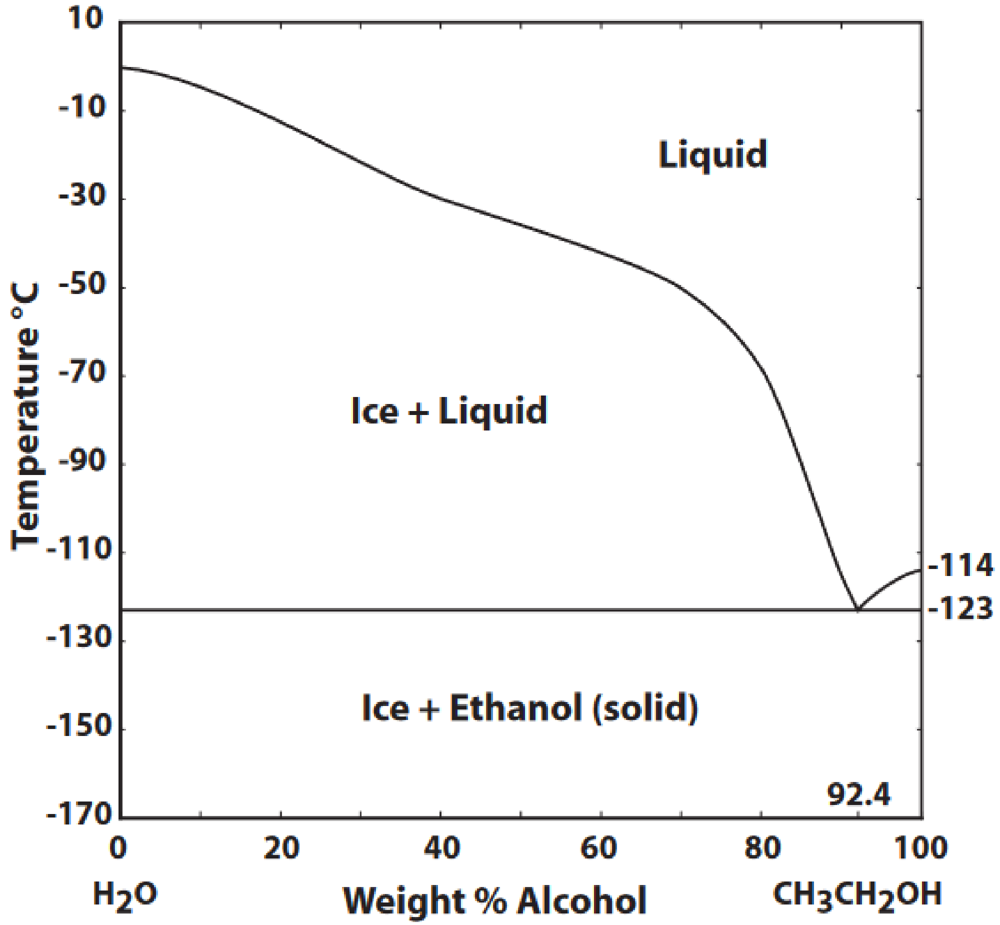
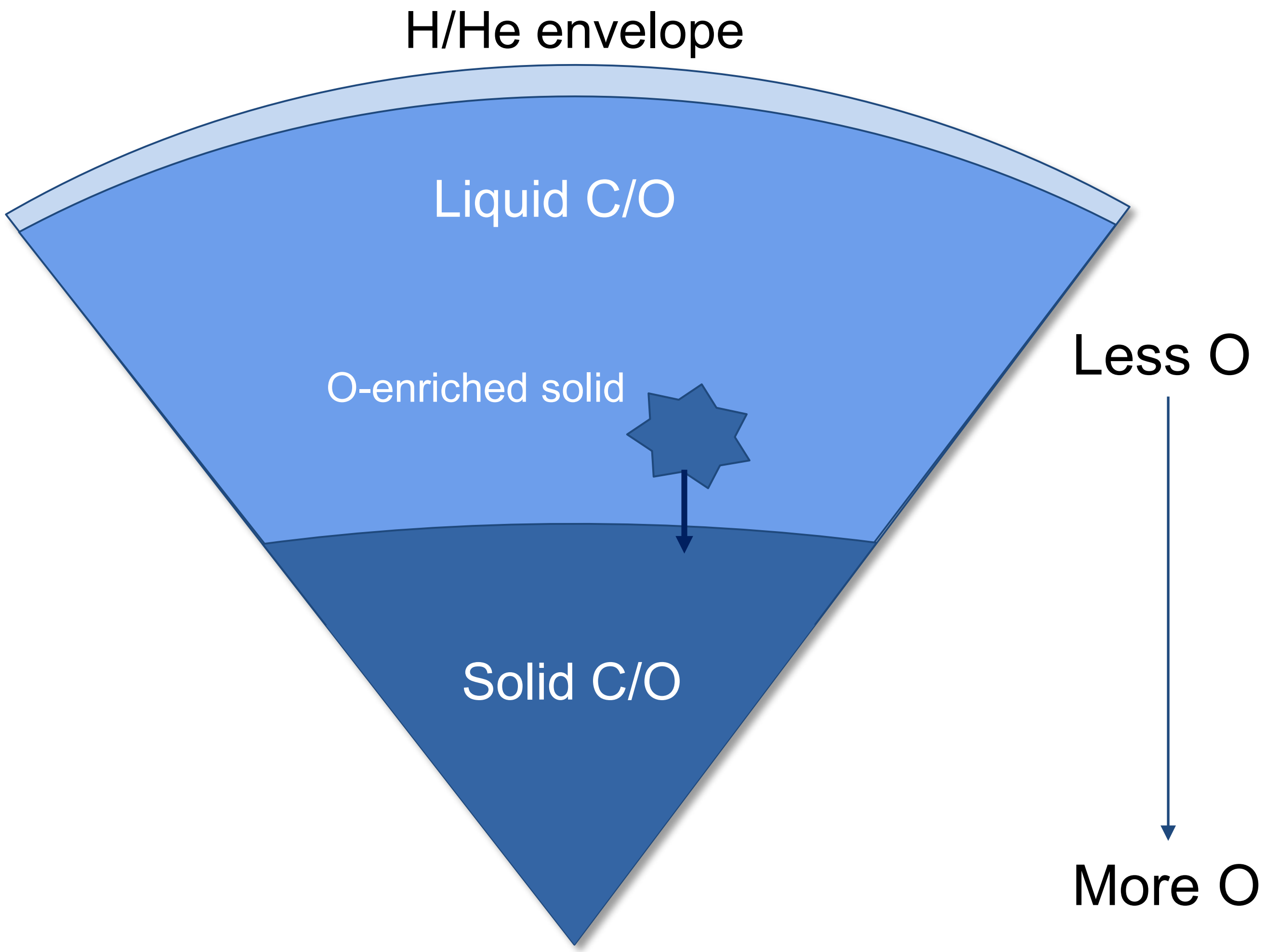
Freeze distillation



Carbon/oxygen phase separation in white dwarfs



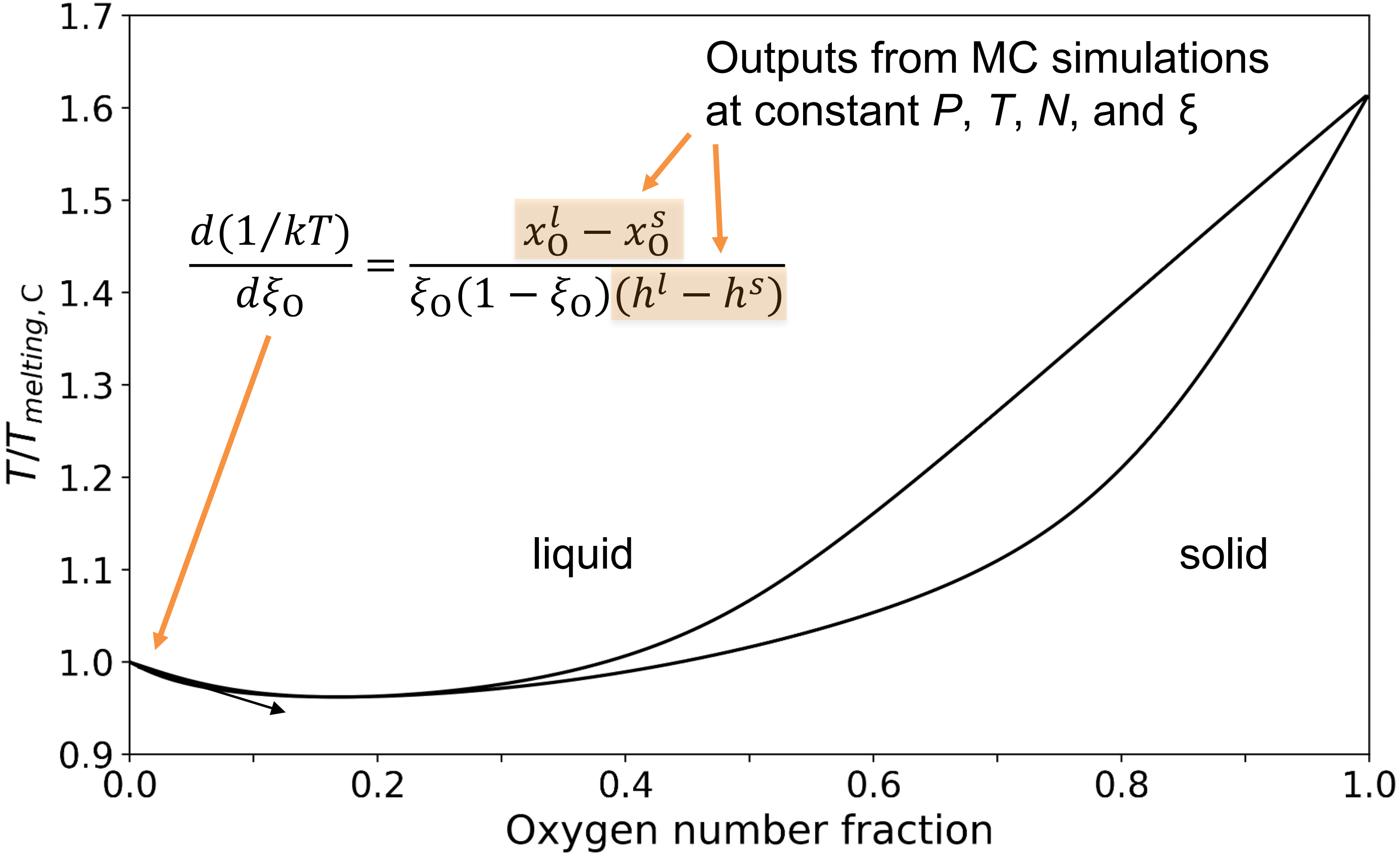
The crystallization front moves upward as the core cools down

The new crystals formed near the solid-liquid interface are O-enriched compared to the liquid

Gradually, a concentration gradient is built, thereby releasing gravitational energy

The Clapeyron technique to calculate melting curves

With Jérôme Daligault and Didier Saumon (LANL)



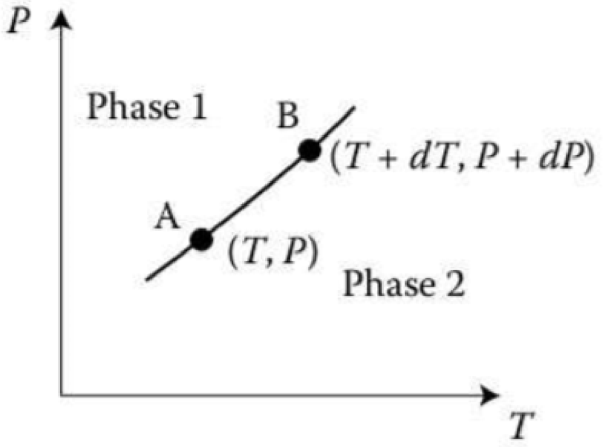
Outputs from MC simulations at constant *P*, *T*, *N*, and ξ

$$\frac{d(1/kT)}{d\xi_O} = \frac{x_O^l - x_O^s}{\xi_O(1-\xi_O)(h^l - h^s)}$$

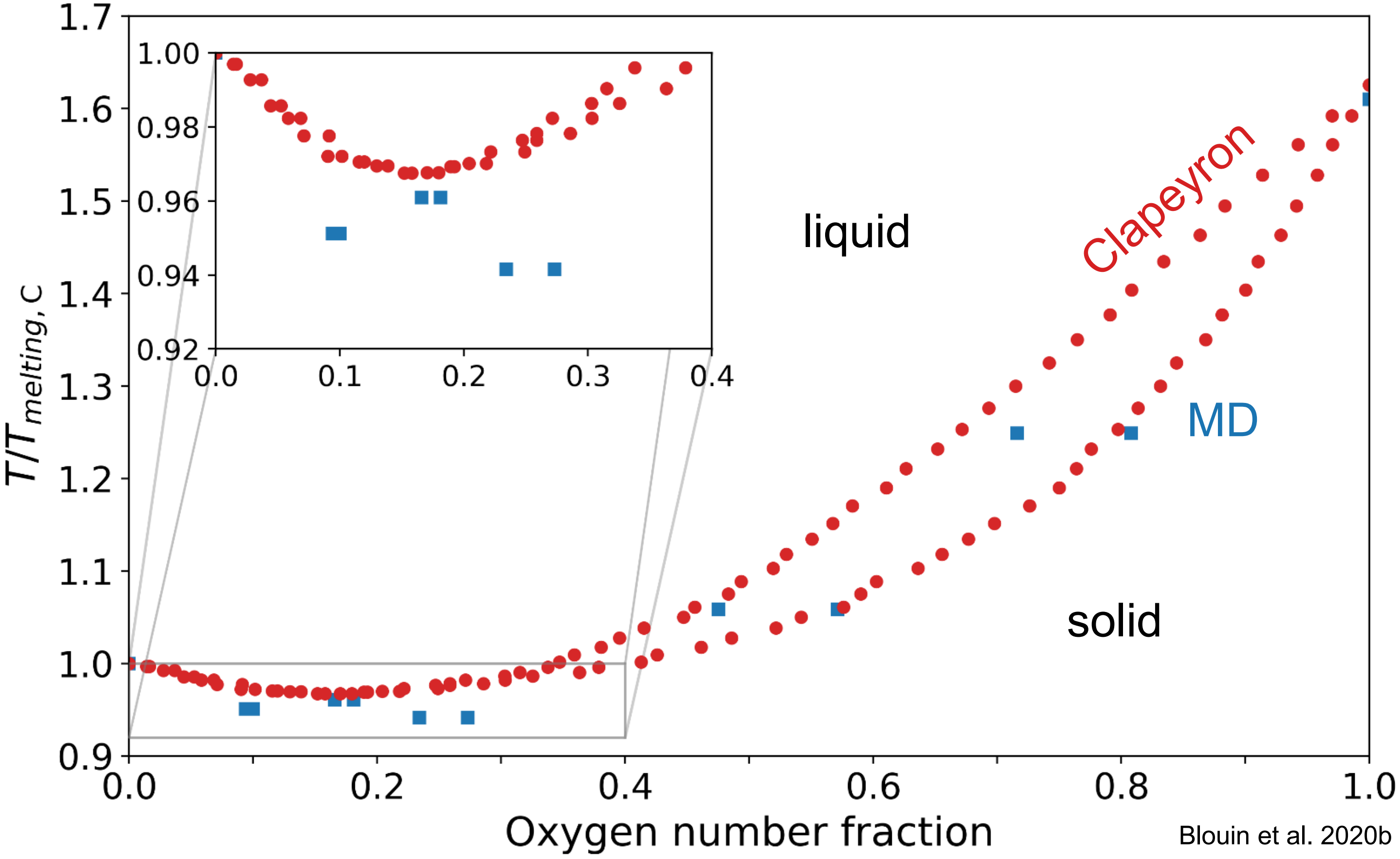
Technique previously only used for neutral mixtures; we have adapted it to plasmas

Relies on the Monte Carlo simulations and the Clapeyron equation,

$$\frac{dP}{dT} = \frac{\Delta s}{\Delta v}$$



The C/O phase diagram



Blouin et al. 2020b

The C/O phase diagram is now very well known

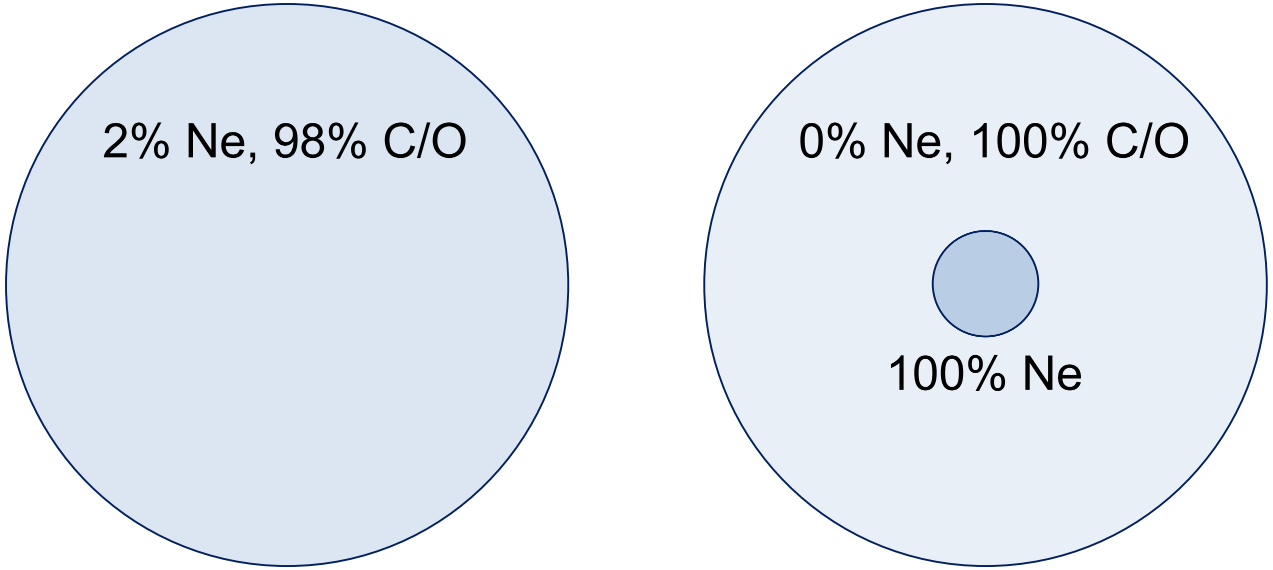
We know precisely how much energy C/O fractionation can release in crystallizing WDs, and it’s not enough to explain the Gaia observations

^{22}Ne in white dwarfs

C and O are not the only ions in WD cores: ~1-3% trace of ^{22}Ne

^{22}Ne has two extra neutrons (Z=10, A=22)

Because WDs are supported by electron degeneracy pressure, ^{22}Ne has the potential to liberate a lot of gravitational energy



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

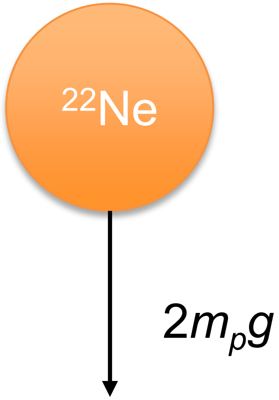
Central electron density $n_{e,0}$
Central mass density $> \rho_0$
Binding energy $< \Omega_0$

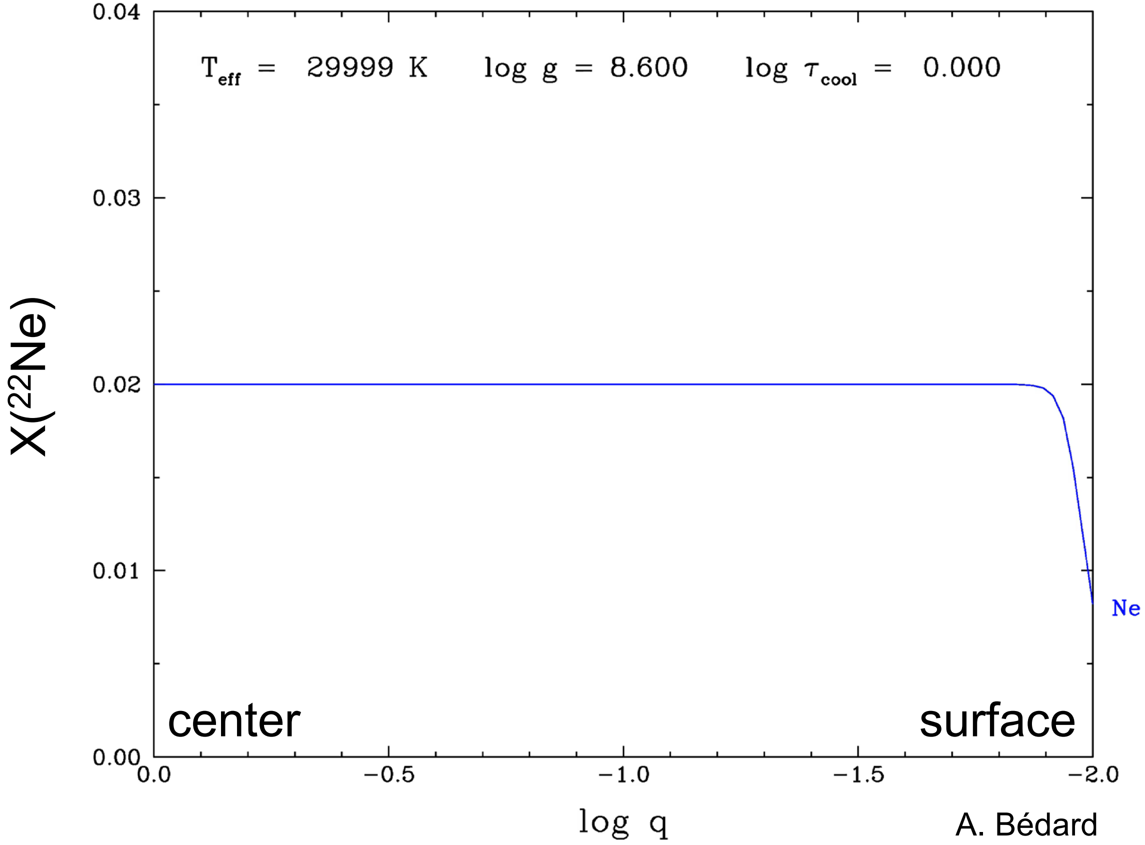
^{22}Ne gravitational settling

Standard ^{22}Ne gravitational settling leads to delays of <1 Gyr

^{22}Ne gravitational settling is *inhibited* by crystallization

Not the solution, but ^{22}Ne nevertheless contains all the gravitational energy we need…





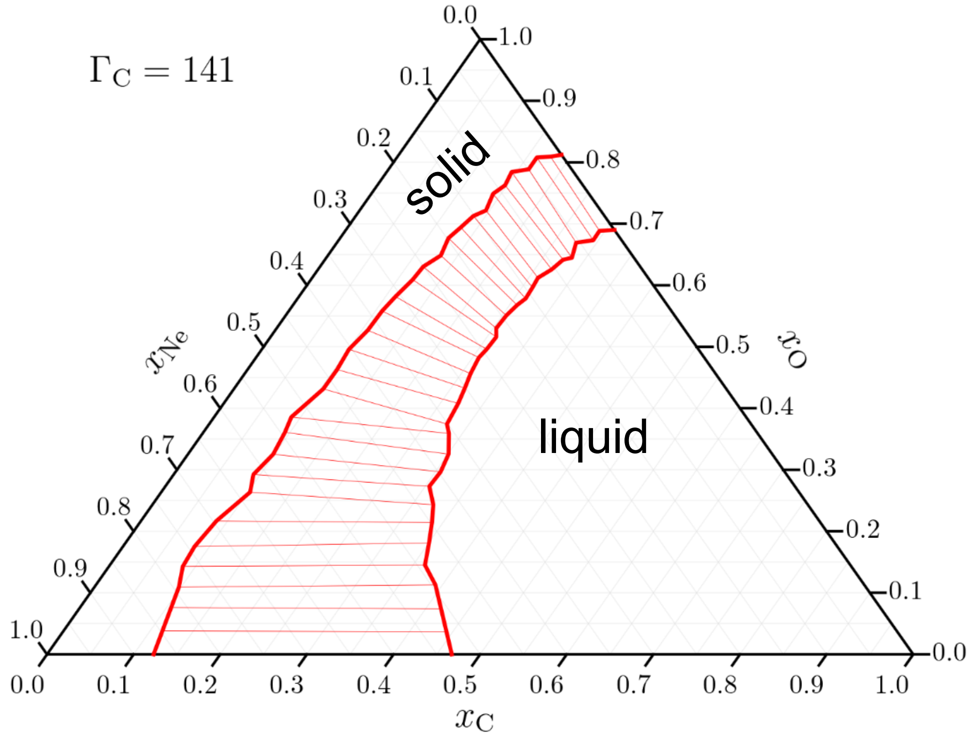
A. Bédard

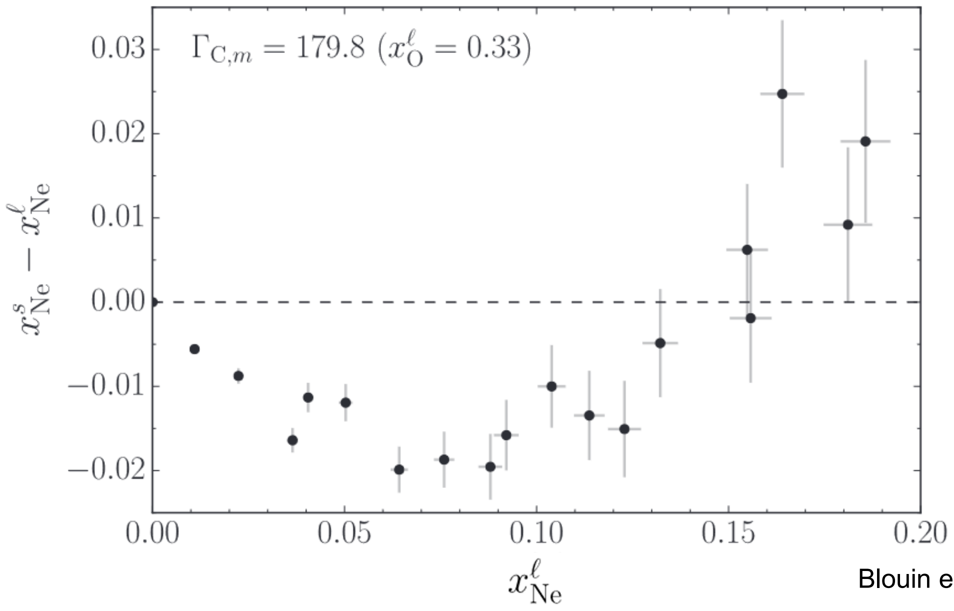
^{22}Ne phase separation

We used our Clapeyron technique to investigate phase separation in 3-component C-O-Ne mixtures

The solid phase can be impoverished in ^{22}Ne, leading to crystals that are lighter than the coexisting liquid

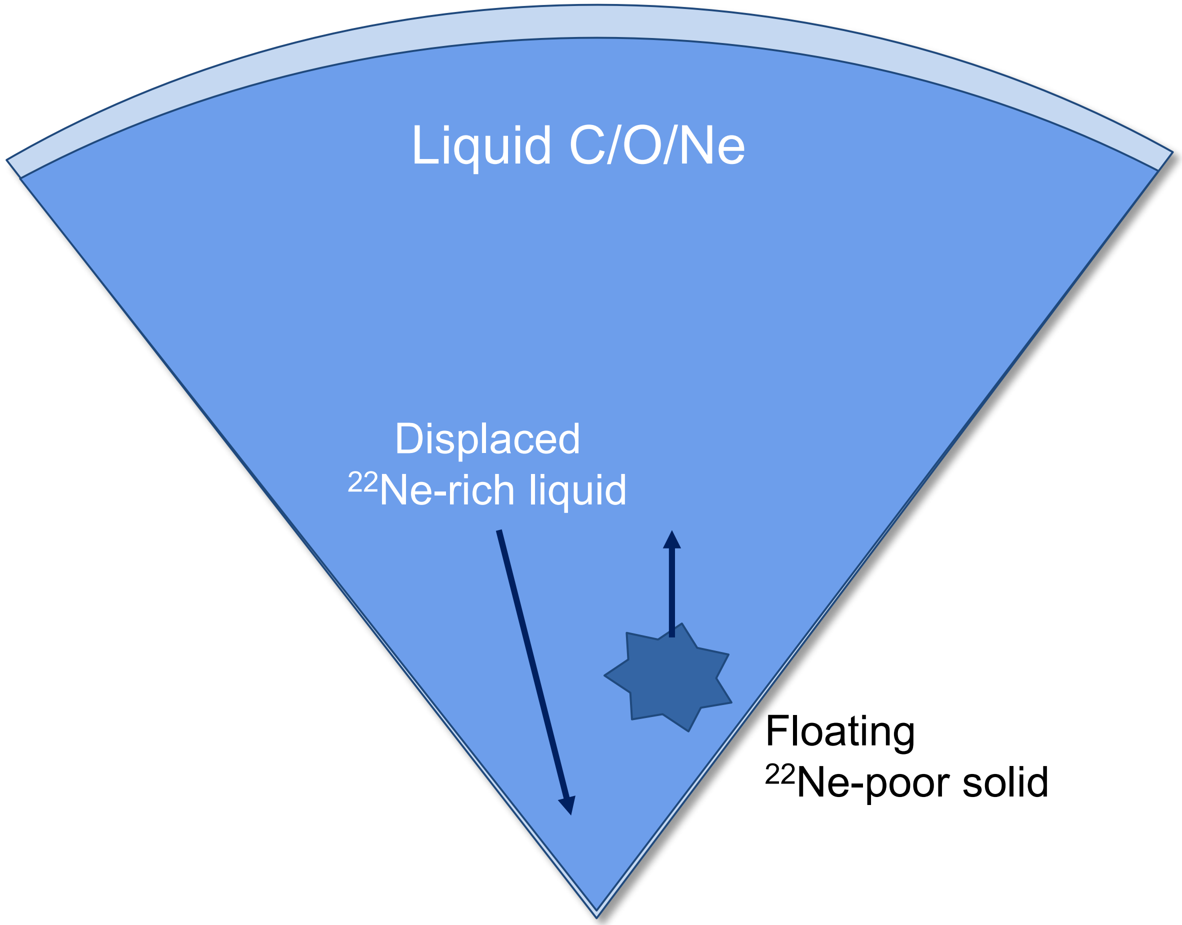
What does that mean?





Blouin et al. 2021

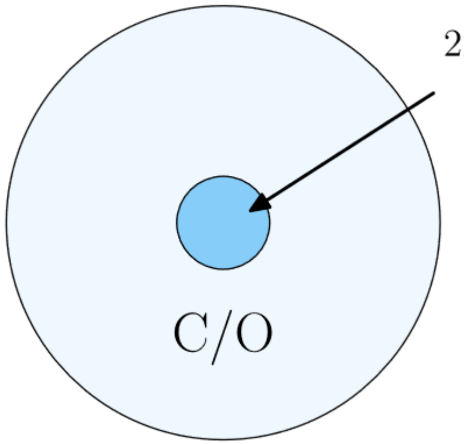
^{22}Ne distillation



Liquid C/O/Ne

Displaced
^{22}Ne-rich liquid

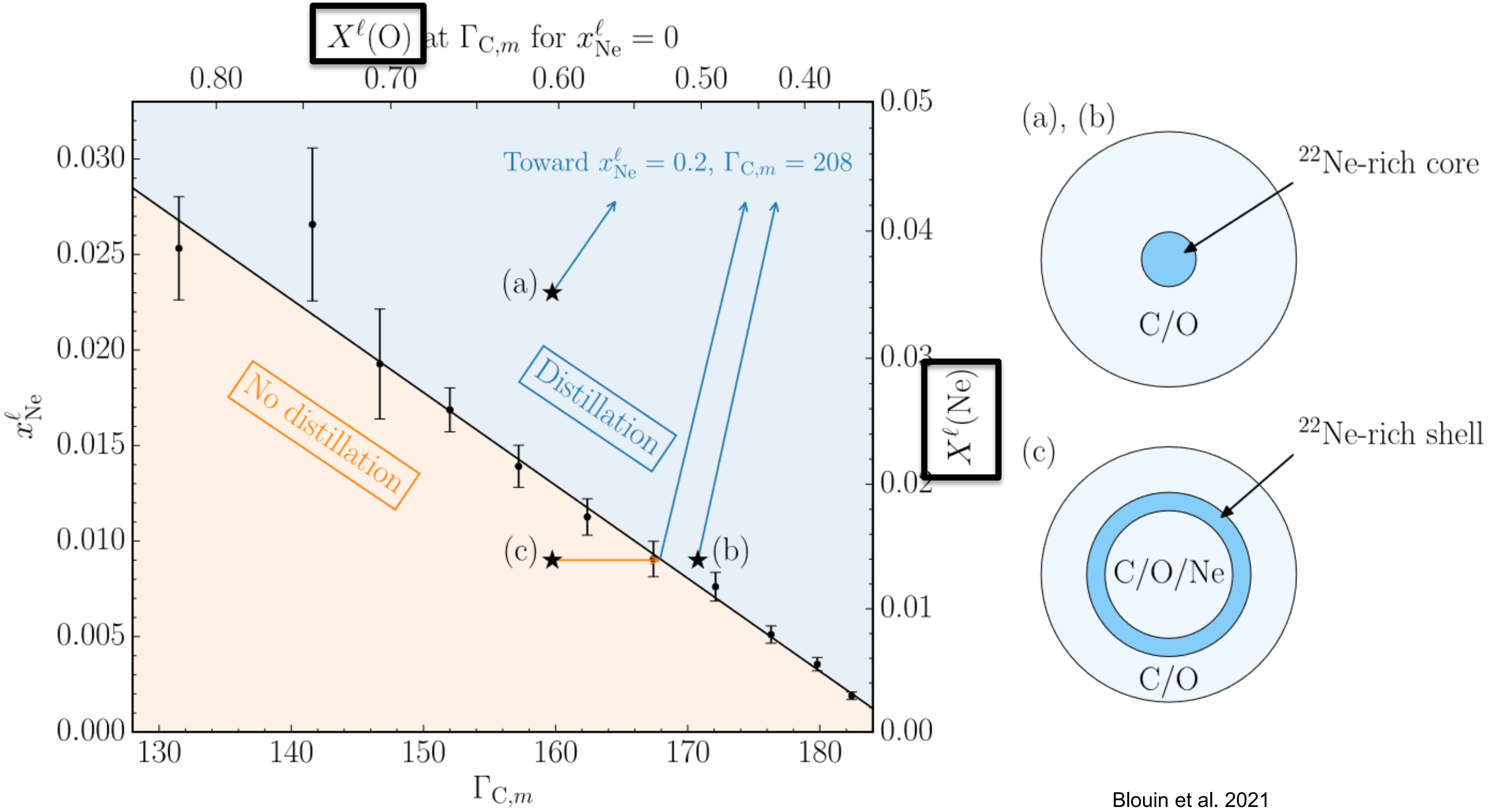
Floating
^{22}Ne-poor solid



^{22}Ne-rich core

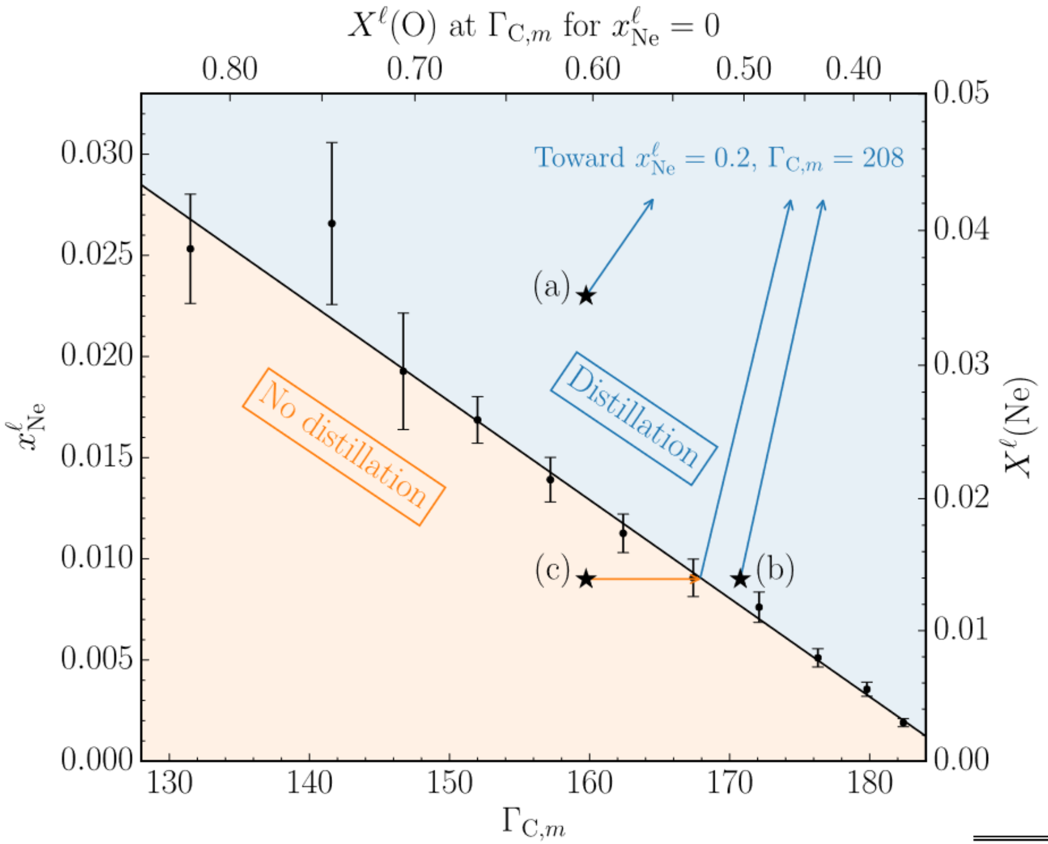
C/O

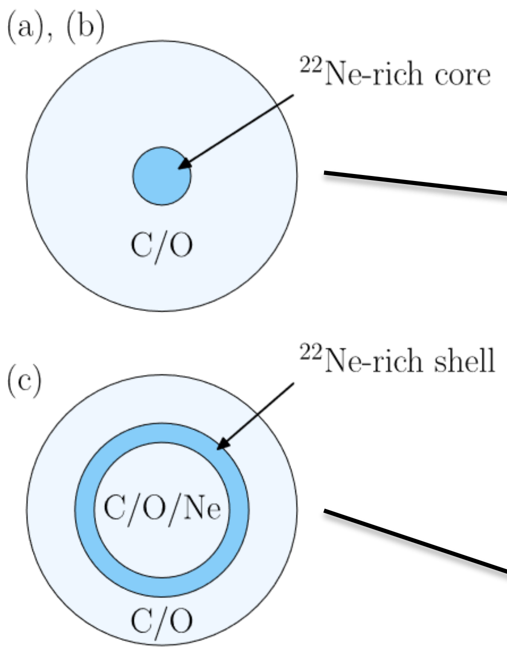
^{22}Ne distillation is a very selective process

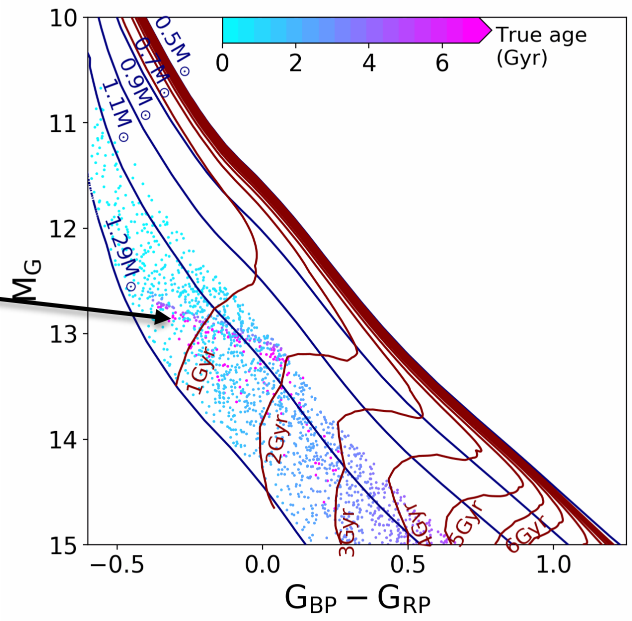


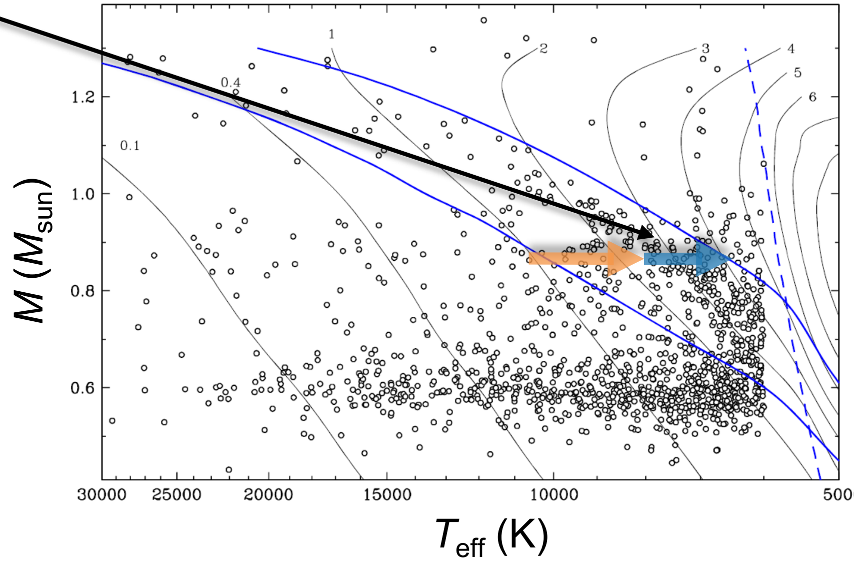
Blouin et al. 2021

^{22}Ne distillation can solve both cooling anomalies









Effect of ^{22}Ne Phase Separation

$M_\star$ ($M_\odot$)	X(O)	$X(^{22}\mathrm{Ne})$	log $L/L_\odot$ [a]	ΔB (10^{47} erg)	$\Delta\tau$ (Gyr)
Formation of a ^{22}Ne-rich central core					
1.0	0.50	0.035	−3.0	10	9.0
1.0	0.60	0.035	−2.9	10	6.4
1.1	0.50	0.035	−2.8	15	7.1
1.1	0.60	0.035	−2.6	15	5.0
1.2	0.50	0.035	−2.4	23	4.6
1.2	0.60	0.035	−2.3	23	3.6
Formation of a ^{22}Ne-rich shell					
0.6	0.60	0.014	−4.1	0.18	1.8
0.8	0.60	0.014	−3.8	0.34	2.0
1.0	0.60	0.014	−3.5	0.66	1.6

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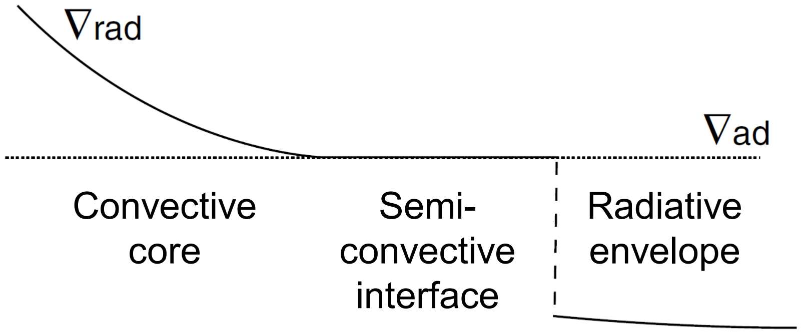
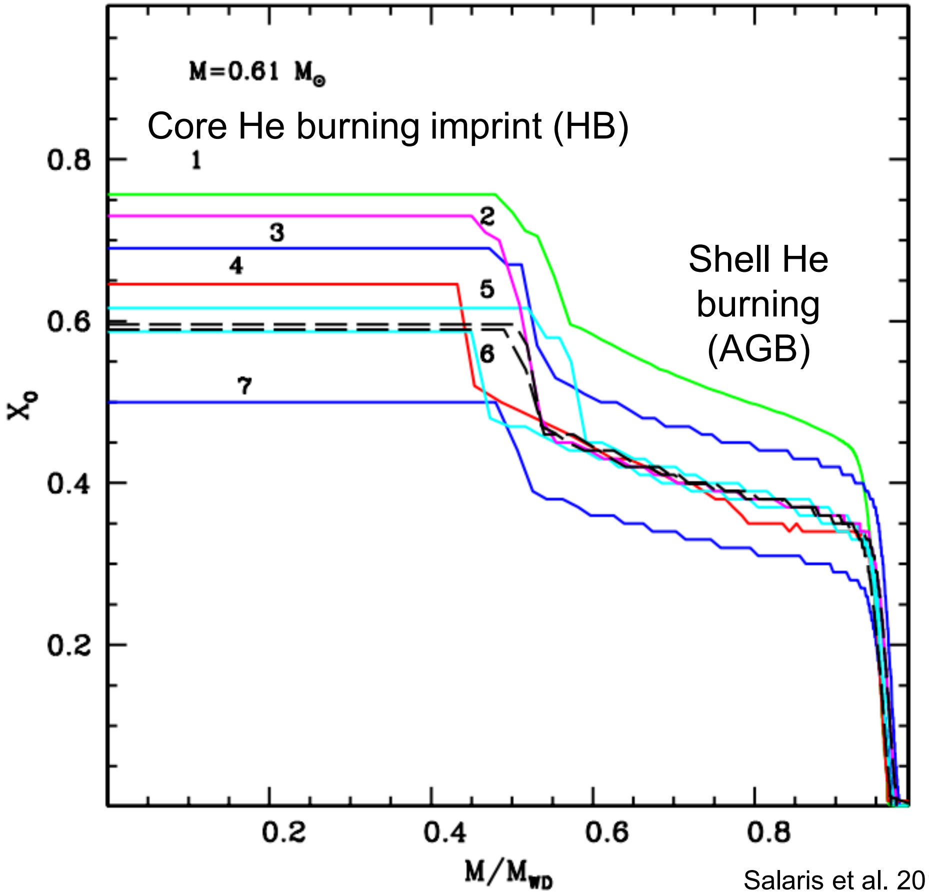
The O profile problem

^{22}Ne distillation is very sensitive to the initial O profile, which is still very uncertain mainly because of the treatment of convective boundary mixing in 1D stellar evolution codes (but also C burning cross section)

<u>Key problem</u>: mixing at the interface of the convective core of horizontal branch stars



O profiles of white dwarfs assuming different mixing schemes

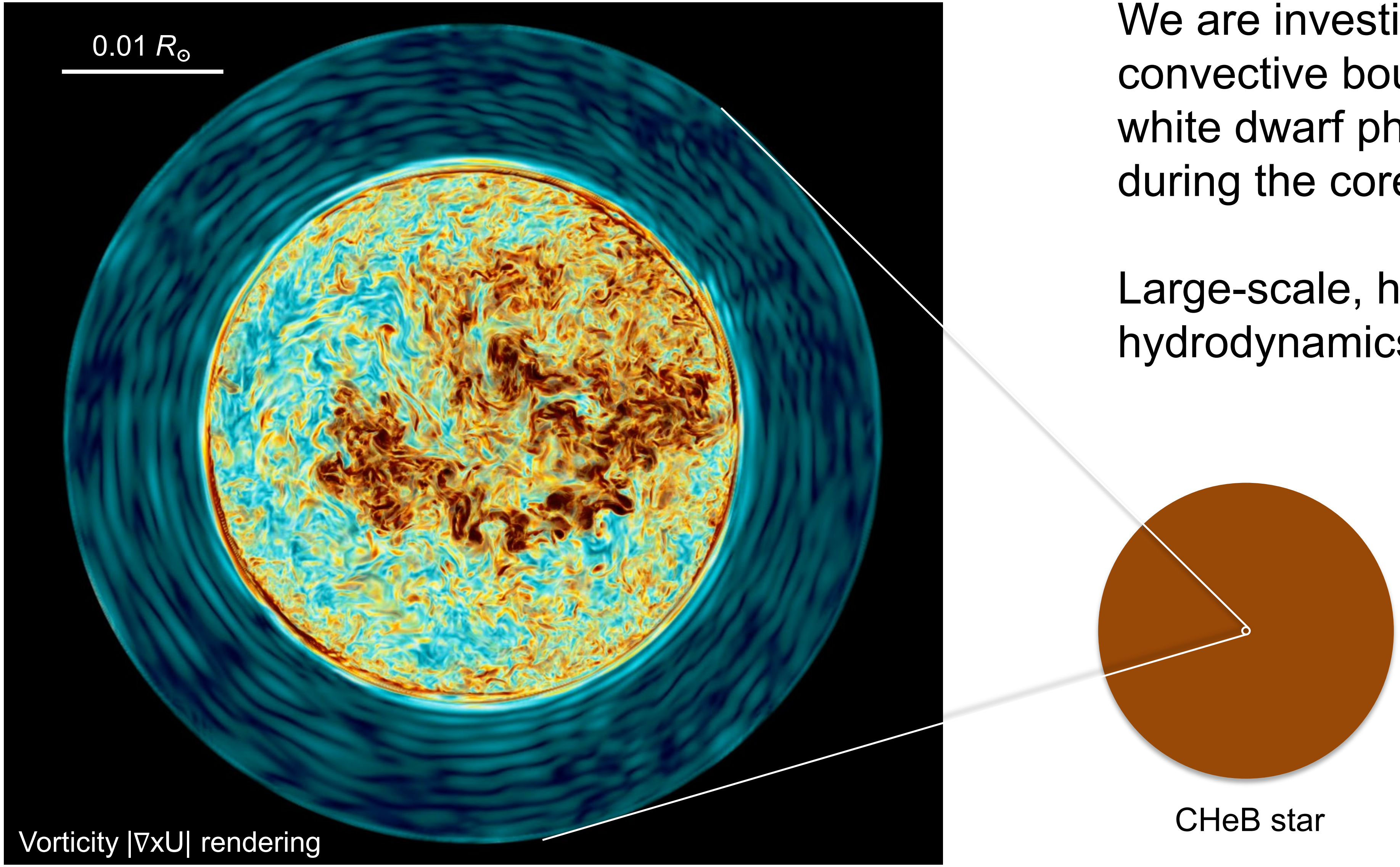


Salaris et al. 2010

Large-scale 4π 3D hydro simulations

We are investigating the efficiency of convective boundary mixing in pre-white dwarf phases, and in particular during the core-helium burning phase

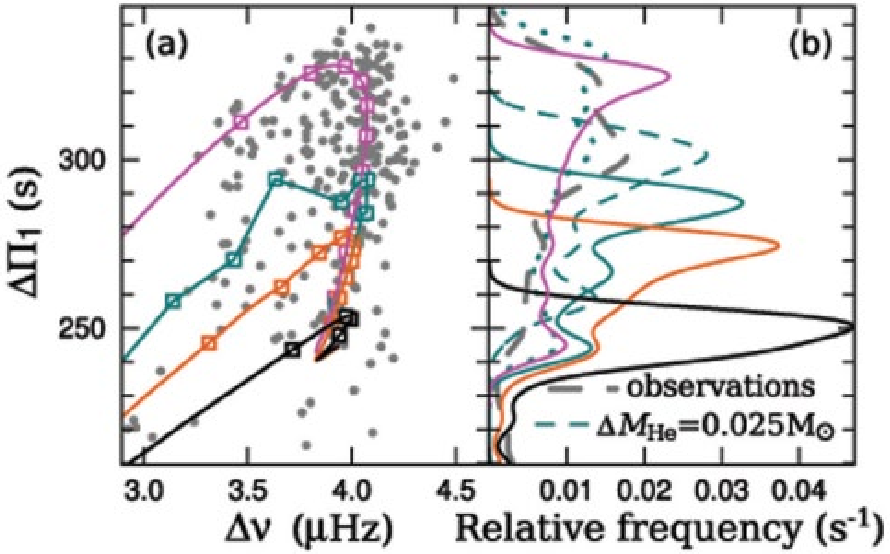
Large-scale, high-resolution 3D hydrodynamics with PPMstar



With Falk Herwig (UVic) and Paul Woodward (Minnesota)

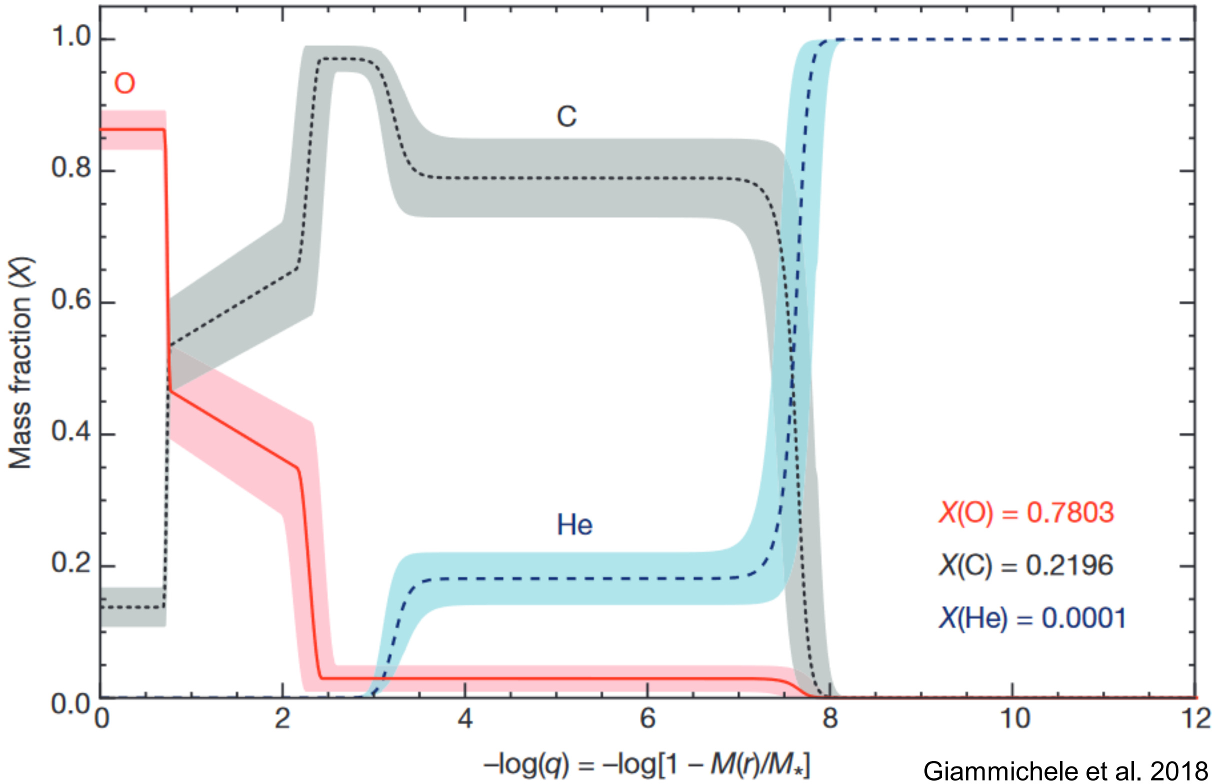
Asteroseismology is now providing useful constraints

Pulsation modes of horizontal branch stars are used to constrain the extent of their convective cores



Constantino et al. 2015

Mapping of the internal composition profile of a white dwarf with asteroseismology



Giammichele et al. 2018

Summary

White dwarf age dating is a powerful tool that has yet to reach its full potential

New observational data challenge our understanding of white dwarf evolution

^{22}Ne distillation can solve two recently identified cooling anomalies

The question of the C/O ratio of white dwarfs is the #1 uncertainty right now

Thank you! Questions?