EXCELENCIA MARÍA DE MAEZTU

White Dwarf Crystallization & Associated Phenomena

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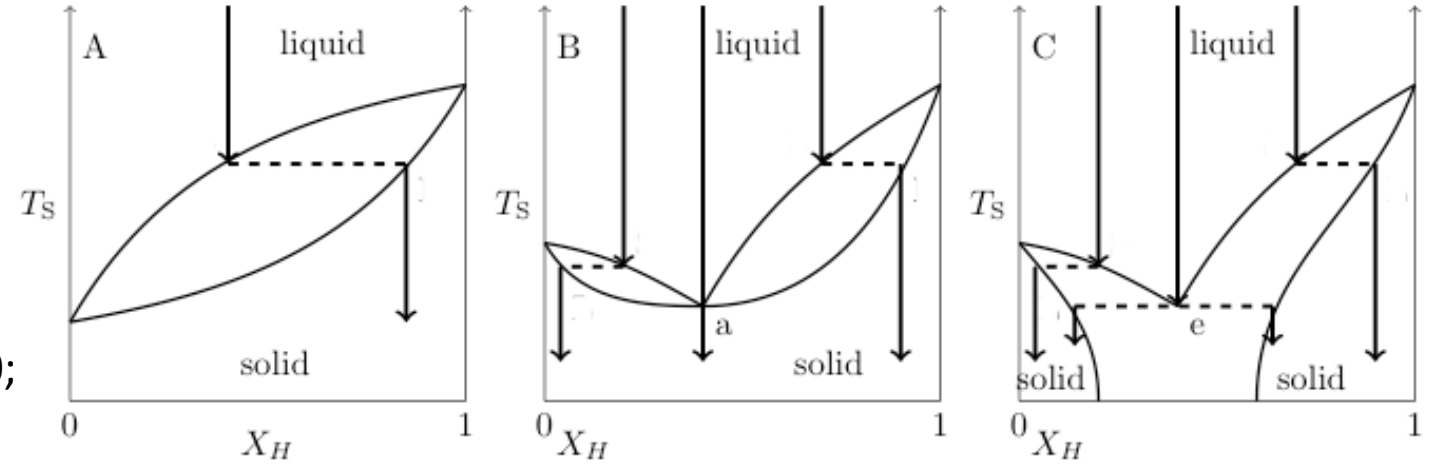
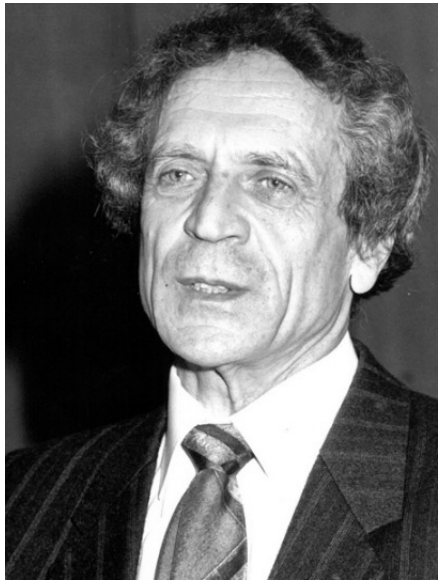
Stellar magnetic fields from protostars to supernovae
Garching, October 24th, 2023

Coulomb plasmas
(Binary mixtures)

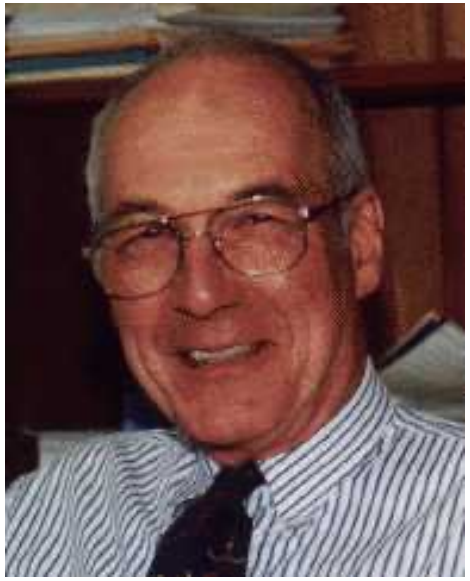


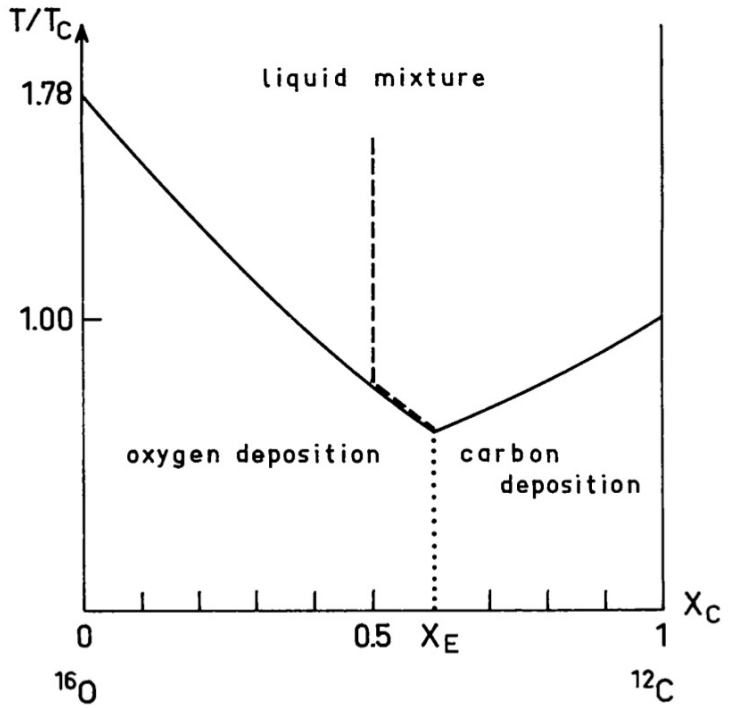
The first to wonder about crystallization & sedimentation:
Schatzman 1958; Kirzhnitz 1960; Abrikosov 1960; Salpeter 1961; Van Horn 1968

Evry Schatzman
(1920-2010)



Hugh Van Horn
(



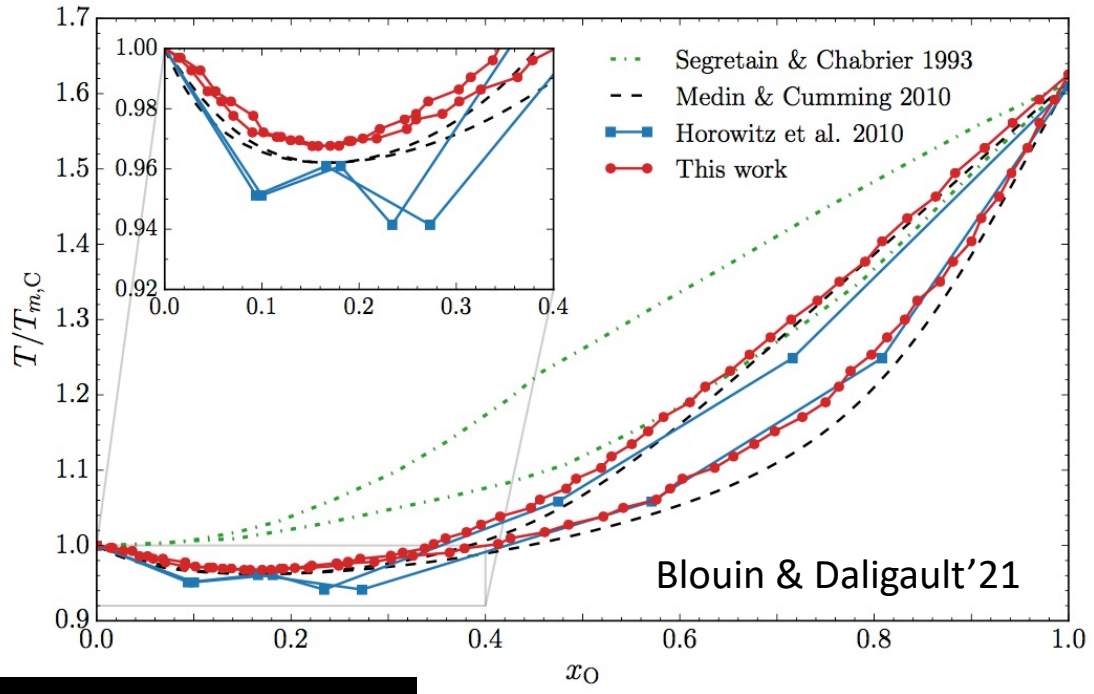


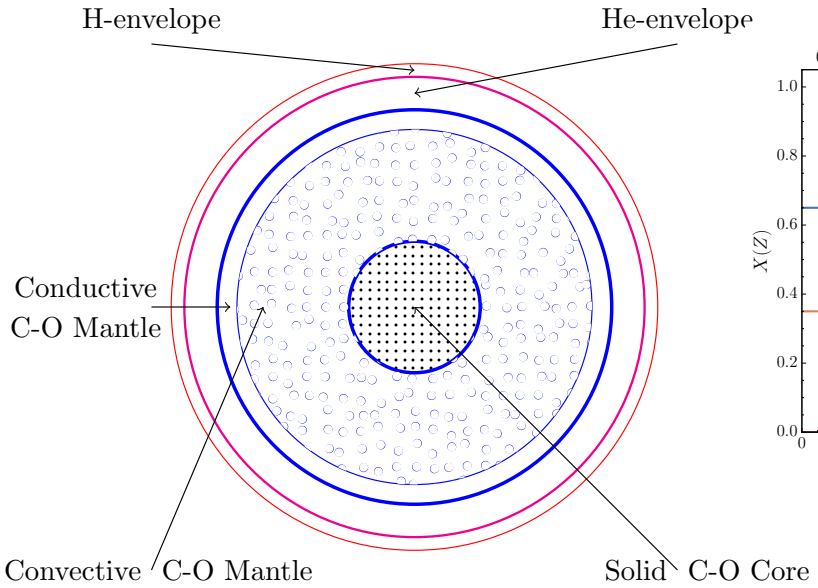
Stevenson's diagram
(1980) J. Phys. Col.

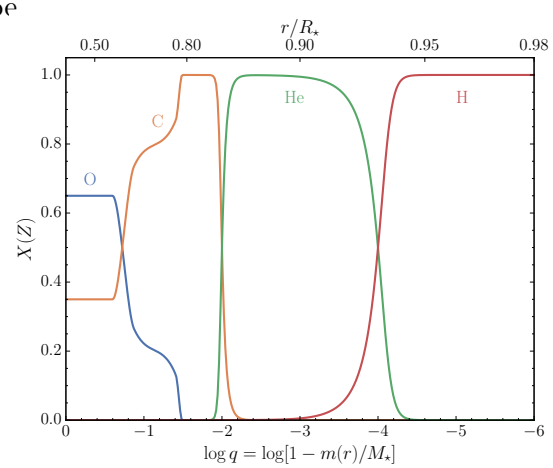
David J. Stevenson
(1948-)

Behaviour under crystallization: C/O plasma

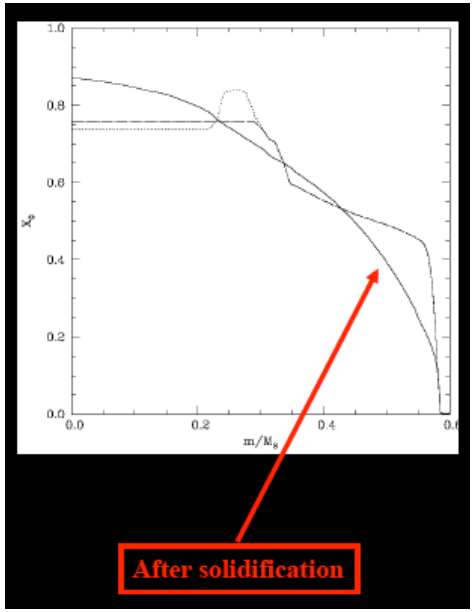
$T_S \propto \rho^{1/3}$







Salaris et al (2010)

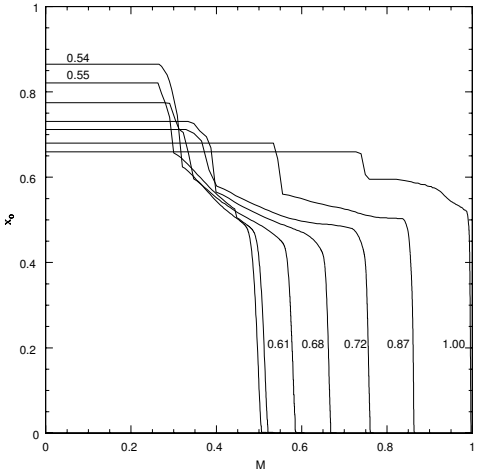


$$\Delta t = \int_0^{M_{WD}} \frac{\varepsilon_g(T_c)}{L(T_c)} dm$$

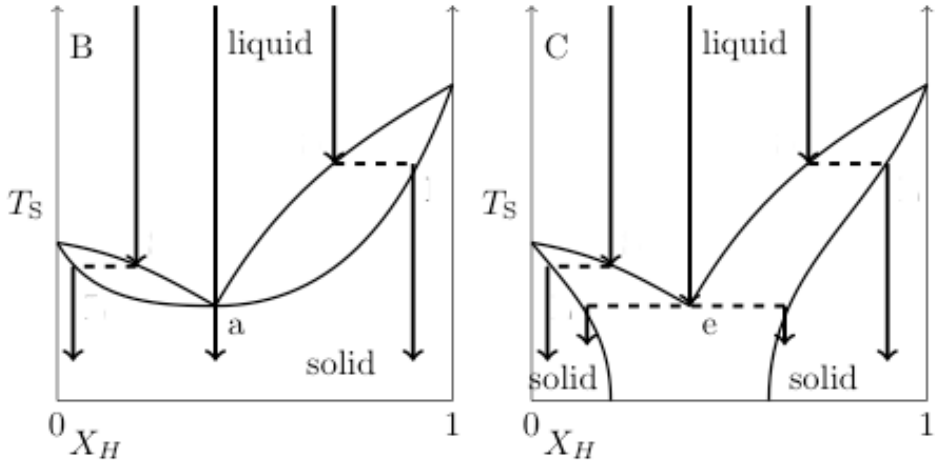
(Isern et al., (1998) J. Phys, Cond. Matter)

Energy release ~ 2×10^{46} ergs
(M_{WD}=0.6 $M_\odot$, X_C=X_O=0.5)
Energy & delay depend on:
- Oxygen profile
- Temperature of solidification
- Transparency of the envelope
(M_{He} ,M_H)

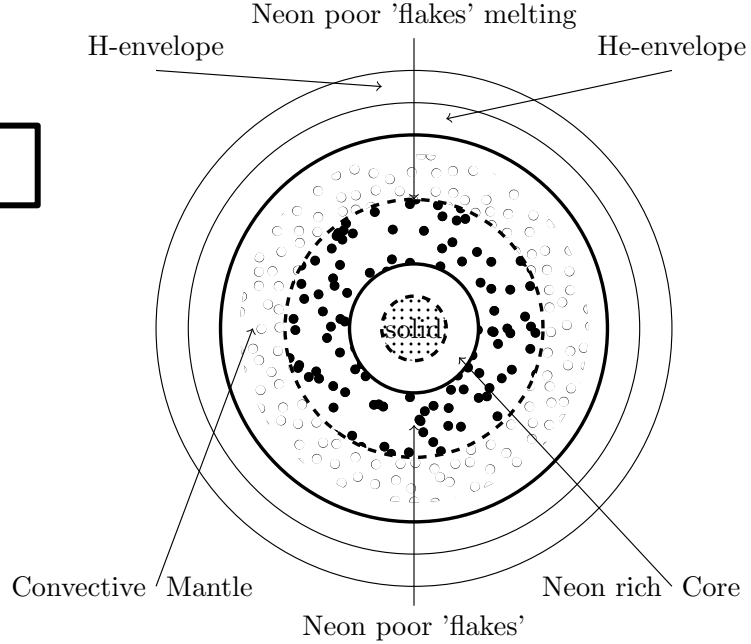
Typically $\lesssim$ 1 Ga



The distillation process

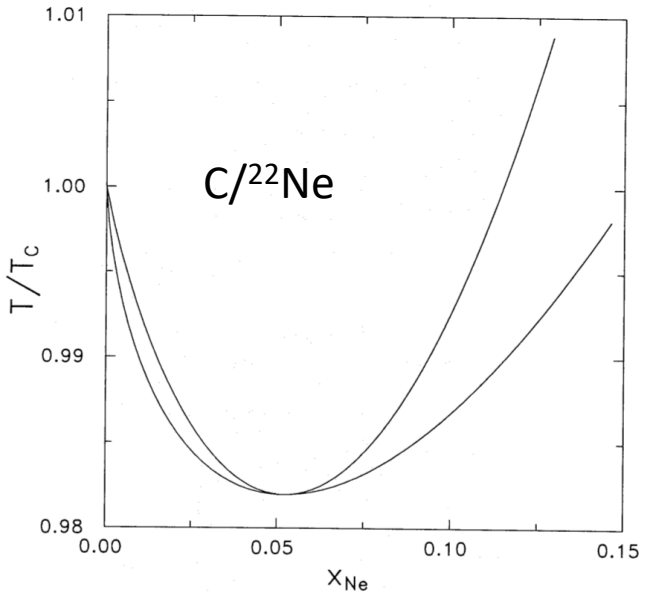


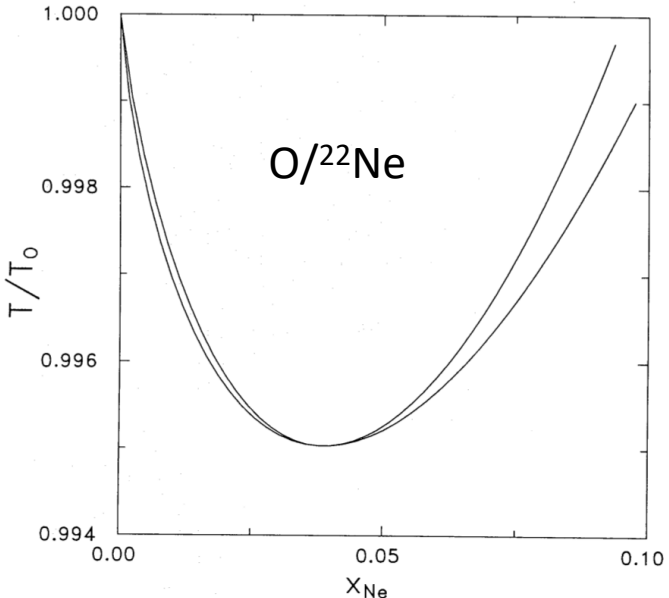
$T_S \propto \rho^{1/3}$



The minor species

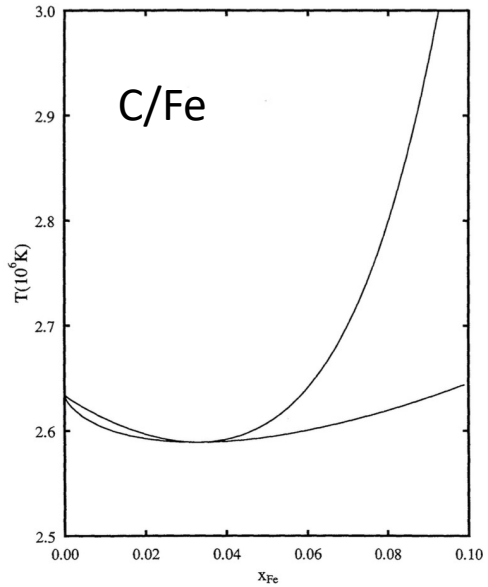
Isern et al'1991





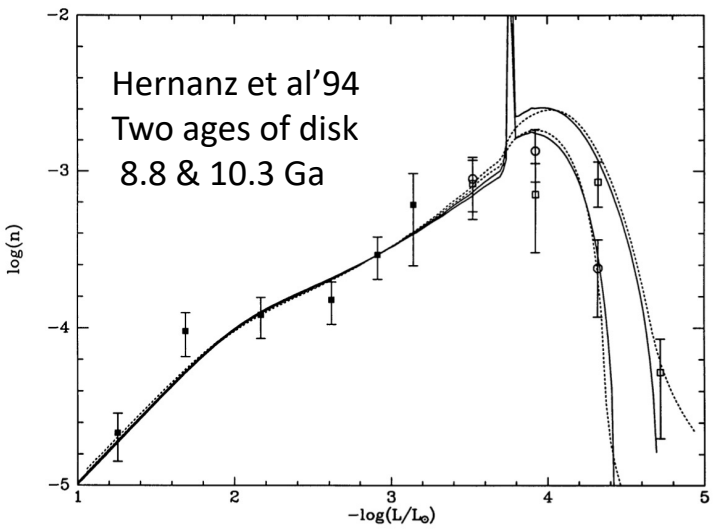
Energy release 2-10x10^{46} erg
Delays of several Ga
Shape & position of the azeotrope
Role of other minor species →
Influence on the WDLF (metallicity dependence)

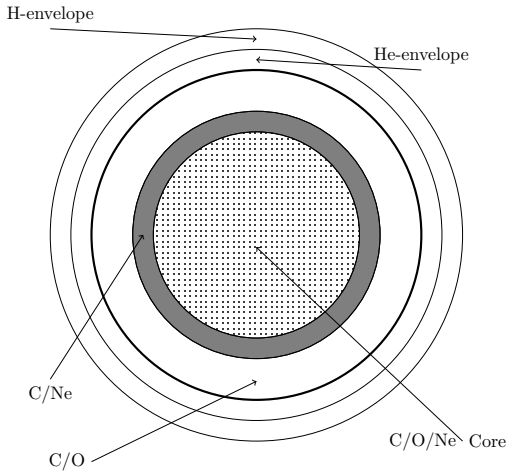
Xu & an Horn 1992



Energy released by crystallization induced separation 0.6 M_o

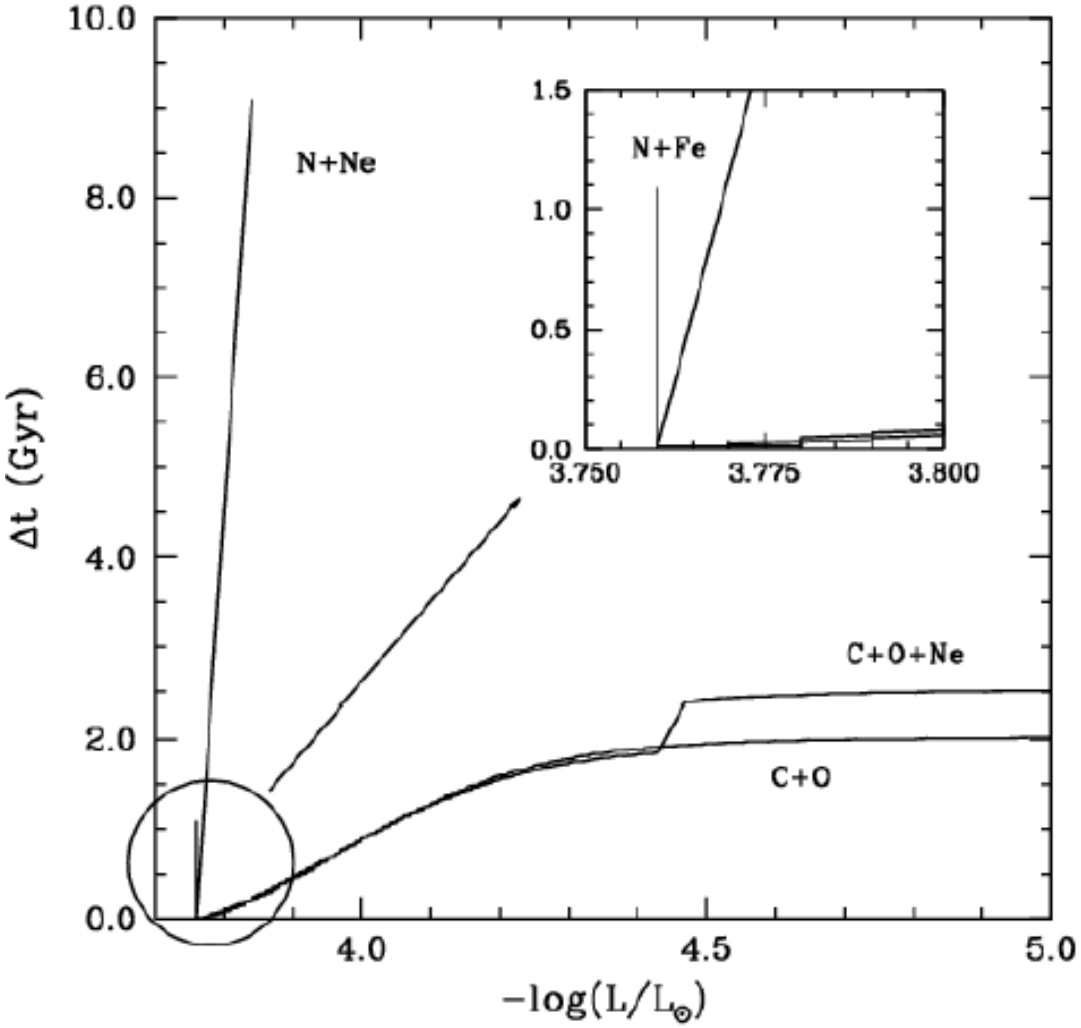
Mixture	ΔE(erg)	Phase diagram
C/O	1.95×10^{46}	Segretain+'94
A/Ne	1.52×10^{47}	Segretain+'94
A/Fe	2.00×10^{46}	Segretain+'94
C/O/Ne	0.20×10^{46}	Segretain'96





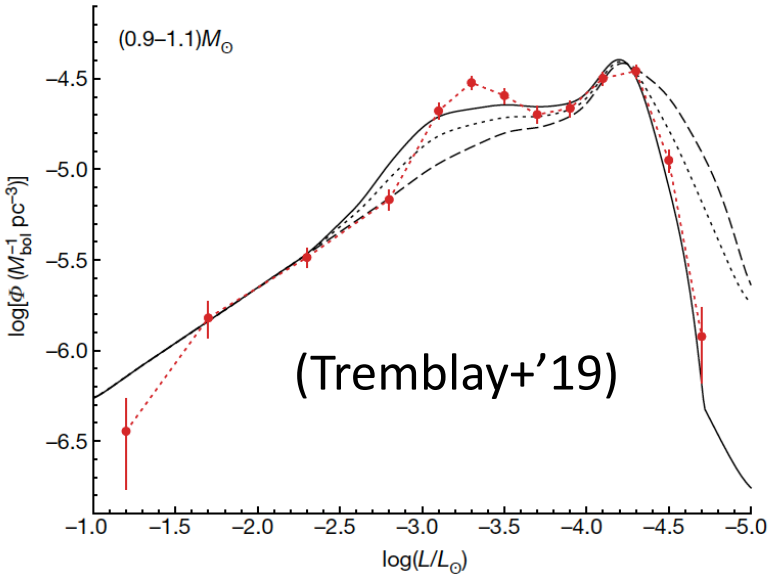
Segretain'96

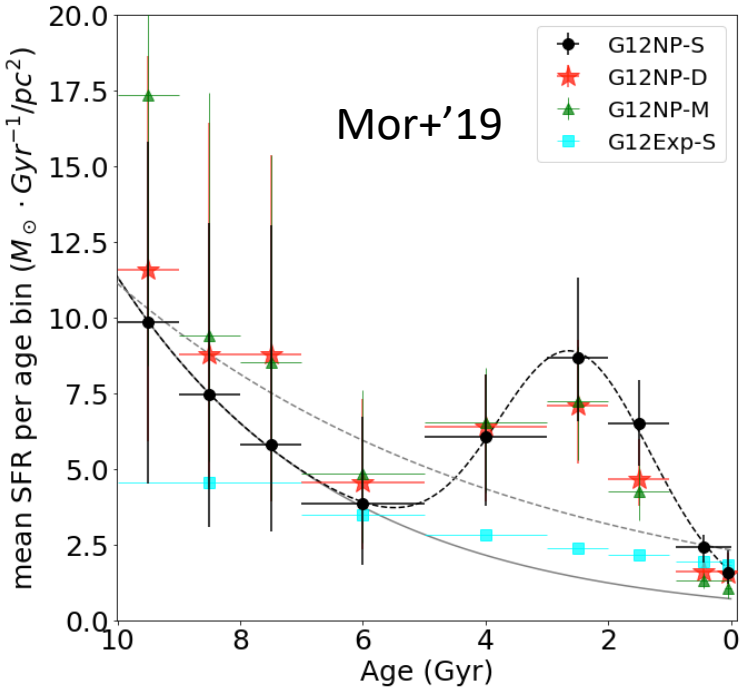
(Isern et al. (1998) in
Strongly Coupled Coulomb Systems)-Springer

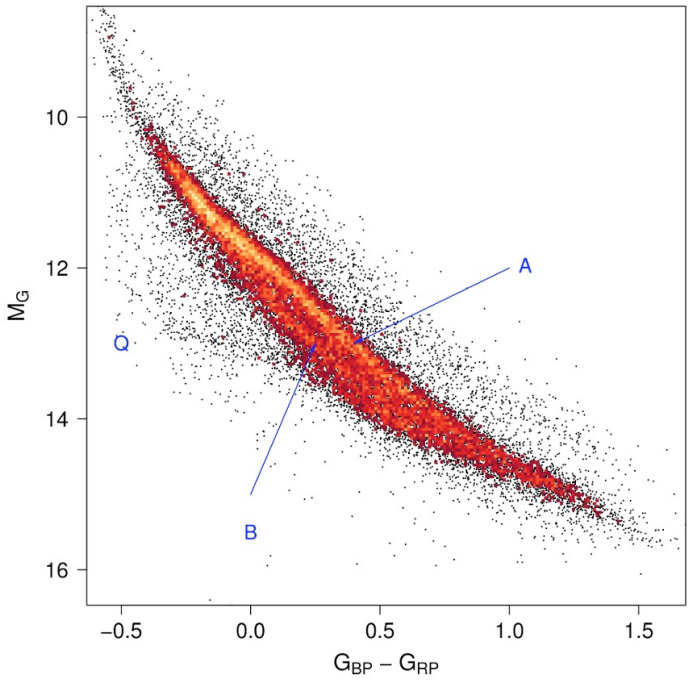


Delays depend on the transparency of the atmosphere and T_{eff} when crystallization occurs!

Two facts introduced by Gaia DR2:







LF of massive WDs demands a delay in the cooling (crystallization: latent heat+sedimentation)
Q-branch could be the consequence of the migration of minor species (22Ne, 56Fe,...)
But degeneracy between galactic properties and WD evolution could provide a different explanation
External information or better physical models are necessary to solve the degeneracy
Analysis of Mor+'19 (Gaia + Besançon model

Metallicity is important

- Lifetime of the progenitor
- Changes in the initial-final mass relationship
- Changes in the C/O profile: Z↓C↑
  - Larger especific heat
  - Larger sedimentation energy upon crystallization
  - Different T_{eff} at which crystallization starts
- Energy released by impurities: ^{22}Ne & ^{56}Fe
  - Gravitational diffusion
  - Sedimentation induced by crystallization

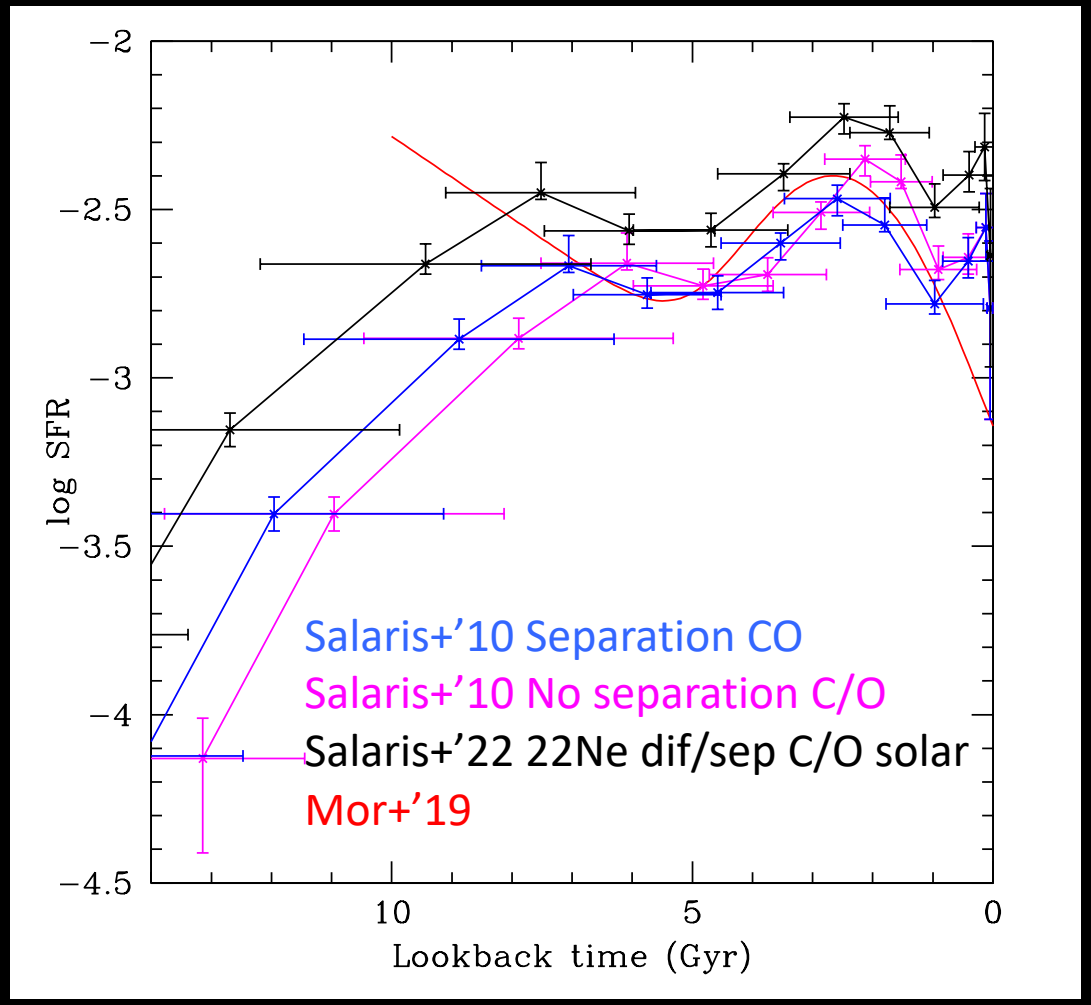
$$n(L) = \int_{M_l}^{M_u} \Phi(M)\Psi\left(T_G - t_{cool}(m_{WD}, Z) - t_{ps}(Z)\right)\tau_{cool}(Z)\,dM$$

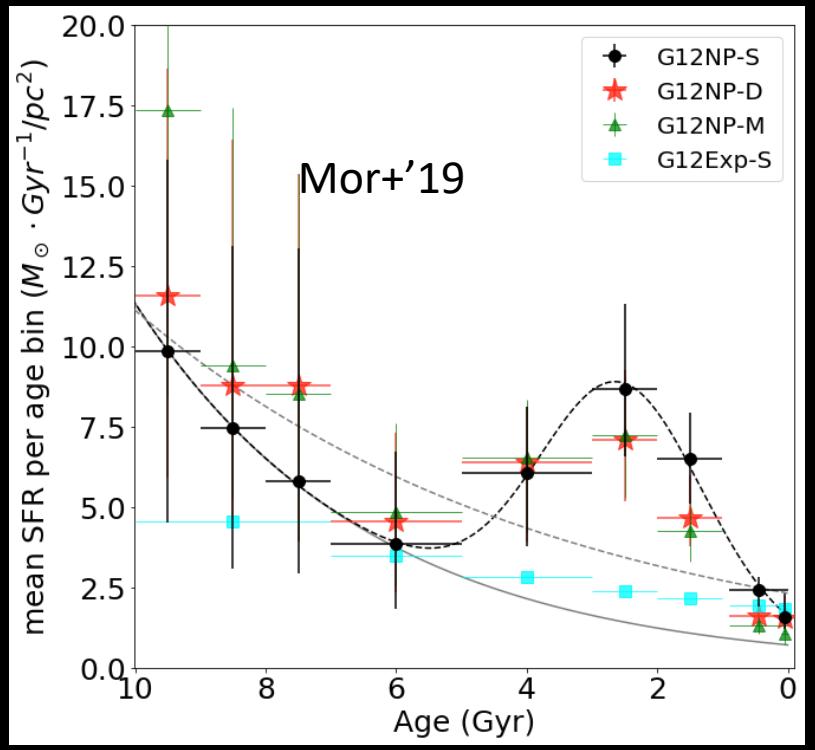
$$m_{WD} = IFMR(M_{ps}, Z)$$

The dependence on Z, with few exceptions (Isern+'05,Cojocaru+'14,Tononi+'19), has been very often neglected

RACAB

Luminosity function massive white dwarfs





$$N(l,T) \simeq \langle \Psi \rangle \int_{\Delta M} \Phi(M)\, \Delta t_{cool}(l,M)\, dM$$

$$\Delta t_{cool} = t_{cool}(l+0.5\Delta l, M) - t_{cool}(l-0.5\Delta l, M)$$

$$\langle \Psi \rangle = \frac{N(l,T)}{\int_{\Delta M} \Phi(M)\, \Delta t_{cool}(l,M)\, dM}$$

Degeneracy between galactic properties and WD evolution!
Different models provide different solutions to the SFH
External information is necessary to break the degeneracy
Analysis of Mor+'19 (Gaia + Besançon model) [*pc^{-2}]

^{22}Ne distillation upon crystallization

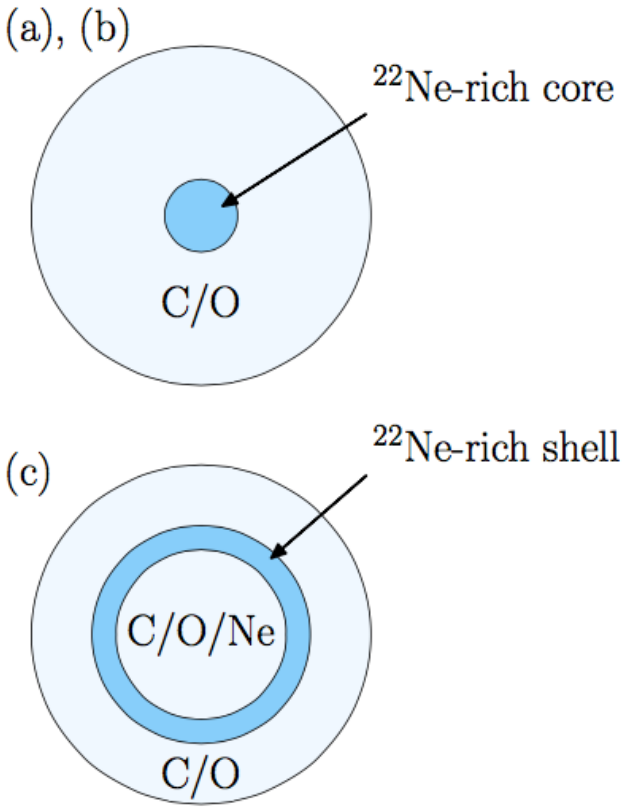


Table 1. Effect of ^{22}Ne phase separation.

$M_\star$ ($M_\odot$)	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

Blouin+'21

THE ASTROPHYSICAL JOURNAL LETTERS, 919:L12 (6pp), 2021 September 20

Caplan et a 2021l

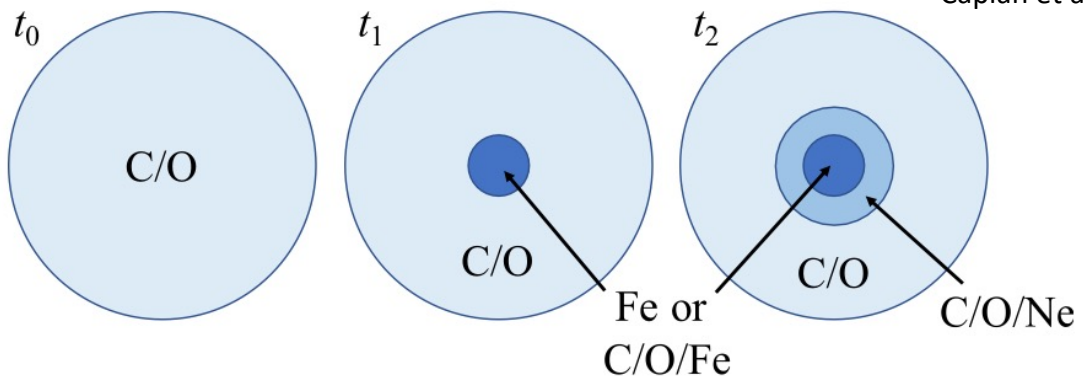


Figure 3. Schematic illustration of the time evolution of the WD from formation (left), to Fe precipitation (center), through Ne shell formation (right). Not to scale.

C-O white dwarfs

THE ASTROPHYSICAL JOURNAL, 946:78 (6pp), 2023 April 1

Caplan, Blouin, & Freeman

O-Ne white dwarfs

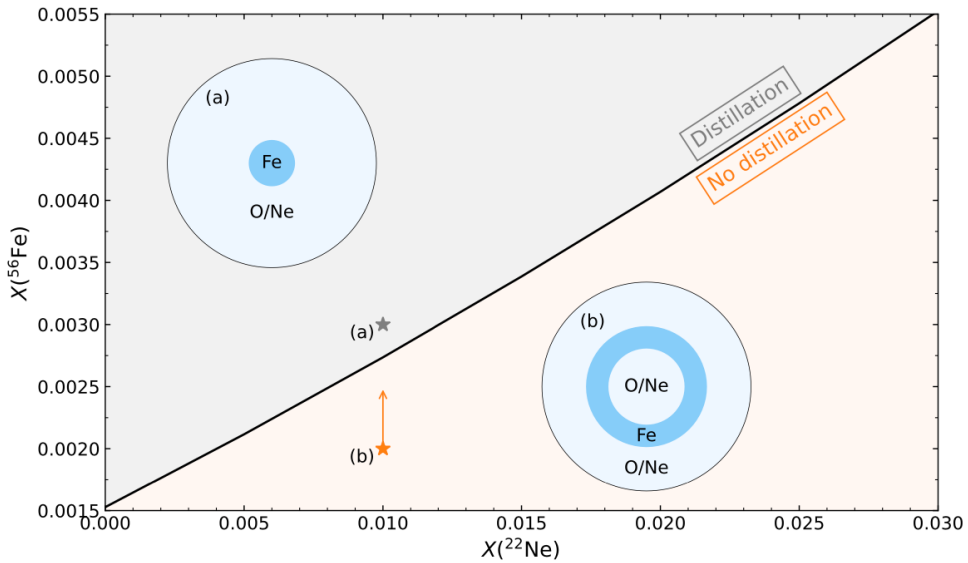


Figure 3. The black line indicates composition where the solid phase has neutral buoyancy ($\rho^s = \rho^\ell$). In the gray region above this boundary, the ^{56}Fe depletion in the solid phase makes the crystal lighter than the liquid, leading to distillation. In the orange region below, the change in ^{56}Fe abundance between both phases is too small to make the crystal buoyant. As in Figure 2, $X(^{20}\mathrm{Ne})$ is fixed to 0.30, and $X(^{16}\mathrm{O}) = 1 - X(^{20}\mathrm{Ne}) - X(^{22}\mathrm{Ne}) - X(^{56}\mathrm{Fe})$. Two scenarios are illustrated. In scenario (a), a ^{56}Fe-rich WD forms an Fe central core through distillation. In scenario (b), the WD initially forms a solid Fe-depleted core. As this central solid core is formed, the ^{56}Fe abundance in the liquid increases (orange arrow). This enrichment ultimately allows distillation to take place, leading to the formation of an Fe shell.

Type Ia supernovae from frozen white dwarfs

The migration of neutron rich species towards the inner regions modifies the yields of neutron rich isotopes synthesized during SNIa explosions

Neutrons are provided by the initial content of the WD (^{22}Ne, ^{56}Fe,…) and by e^-captures in the inner regions. If these isotopes migrate towards the center, the outer layers have a deficit of neutrons

In general the energetics and ^{56}Ni yields are not strongly affected.

- Yields in the region Ca – S are modified
- In sub-Chandra explosions the abundances of Co and Cu increase and those of Mn decrease.
- In Chandra explosions the synthesis of the majority of iron-group elements is harmed. For instance the synthesis of ^{55}Mn is reduced by a factor 4

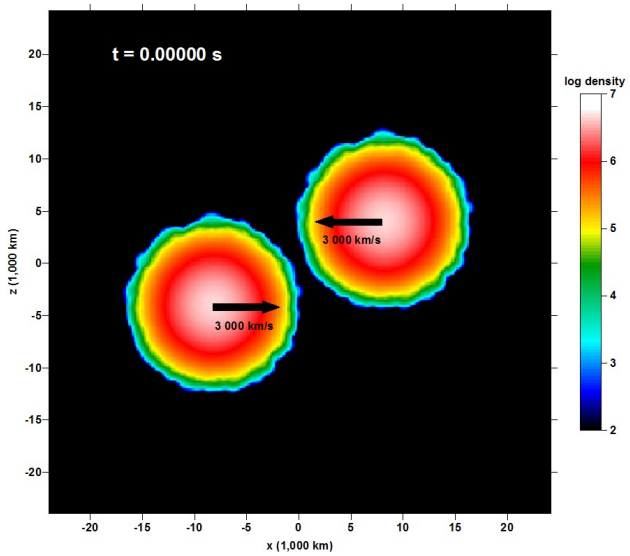
The influence of this effect depends on the degree of sedimentation

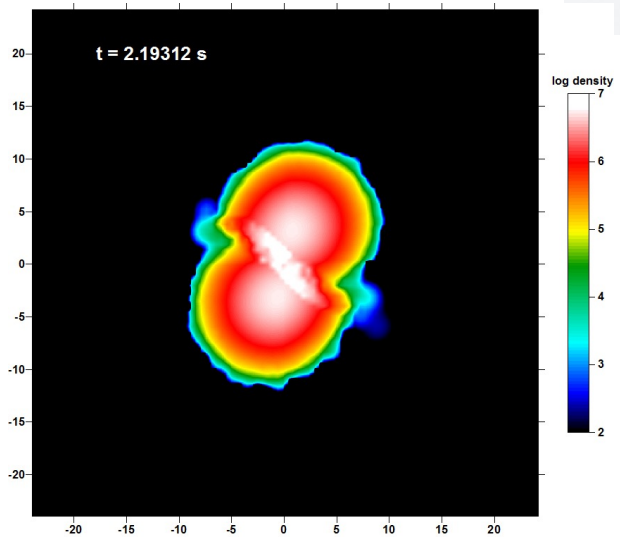
Bravo, Isern, Piersanti, A&A, submitted

The Ne-E problem

Table 1. Inventory of Presolar Grains (Adapted from José'16)

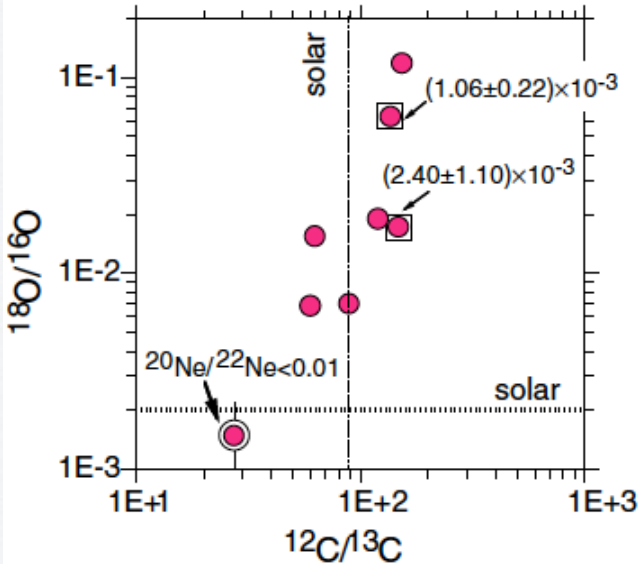
Grain type	Size	Stellar source
Nanodiamonds	2 nm	SN (?)
SiC	0.1-20 μm	AGB,SN,CN,C-stars
Graphites	1- 20 μm	SN,AGB,CN
Oxides[2]	0.2 - 3 μm	RGB,AGB,SN,CN
Si_3N_4	0.3 - 1 μm	SN
Silicates[3]	0.1 - 0.3 μm	RGB, AGB, SN





Murchison meteorite

The solar abundance $(^{20}Ne/^{22}Ne)_{solar}$ ~ 13.6



Amari'09

Collision (Kodai-Lidov cycle in triple systems, clústers,...)

During the collision 3-8x10^{-4} M_o of C+^{22}Ne are ejected
Is the Ne-E anomaly the outcome of such collisions?

Isern & Bravo RNAAS (2018)
Isern& Bravo EUROWD21, 2018arXiv180908789I

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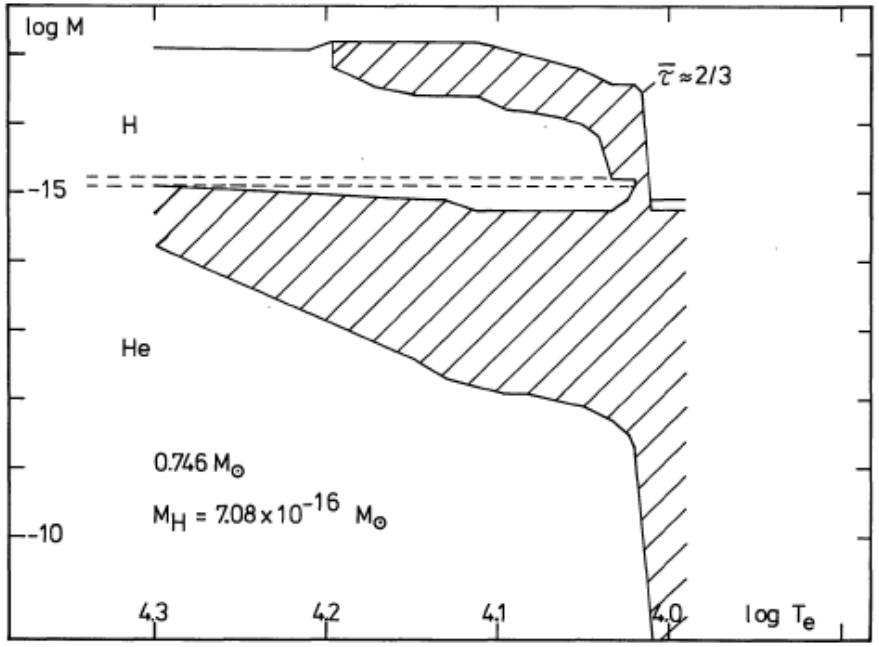
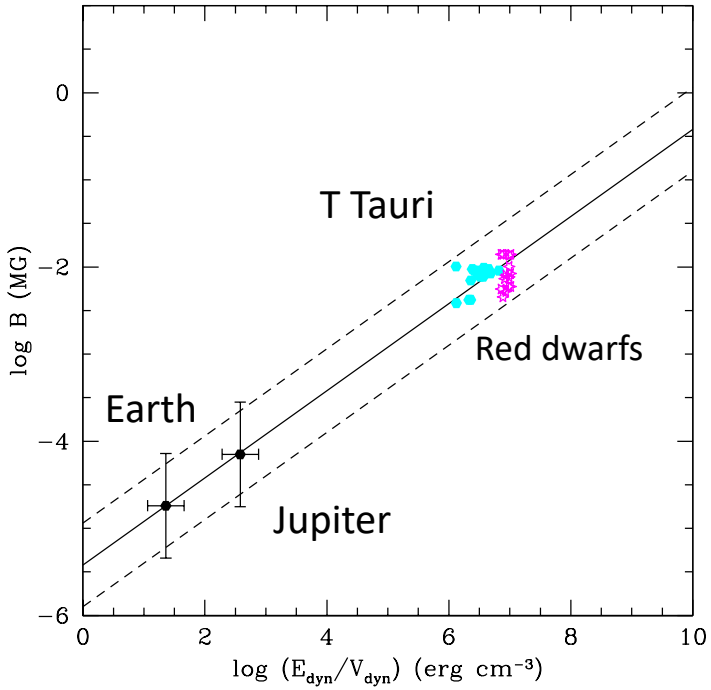
Crystallization and white dwarf magnetism?

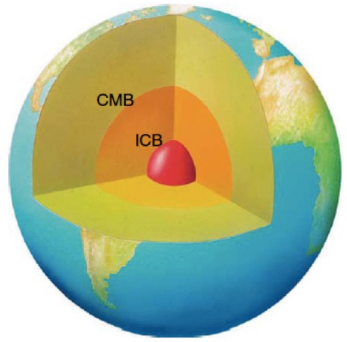
Cool WDs develop deep convection zones due to recombination of H and He that deepens as they cool down.
If turnover convective time ≈ Rotation period a dynamo can work
Limited by the equipartition $B_{eq} \leq 10$ kG (Fontaine+'73; Wendall+'87; Tremblay+'15)
A more energetic source was necessary !



Evolution of outer convective layers (Koester'76)

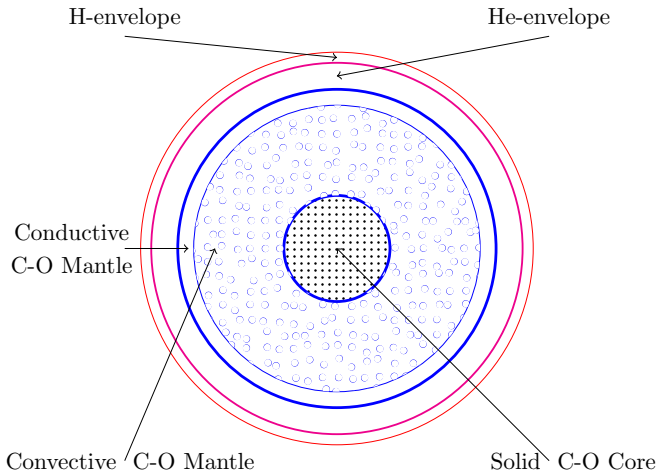
Using scaling laws, Christensen'09,'10 found a relationship between the dynamo energy and field intensity





Given the similitude between the Earth and crystallizing WDs it was natural to wonder if a similar scaling law could be valid in WDs

This relationship is only valid for saturated dynamos



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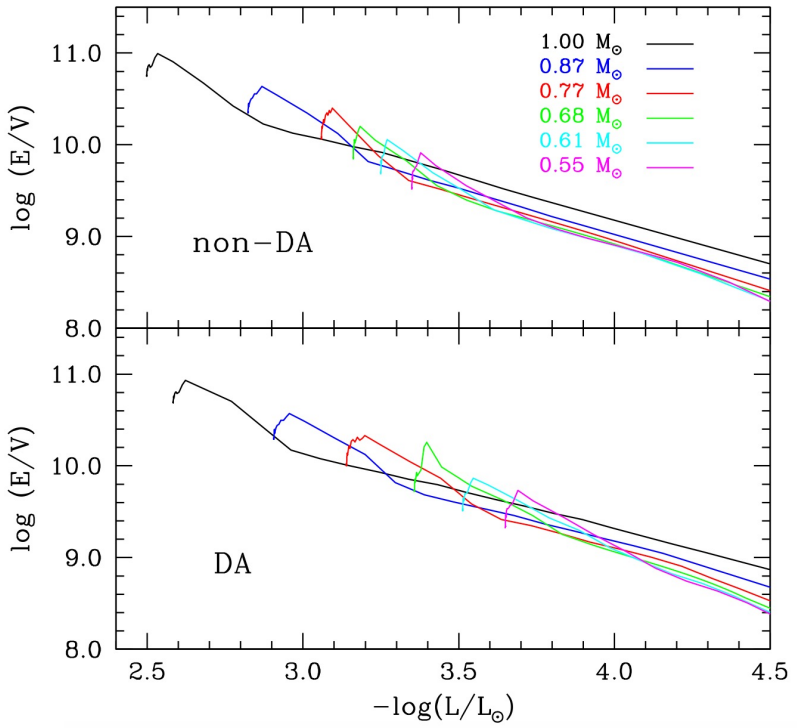
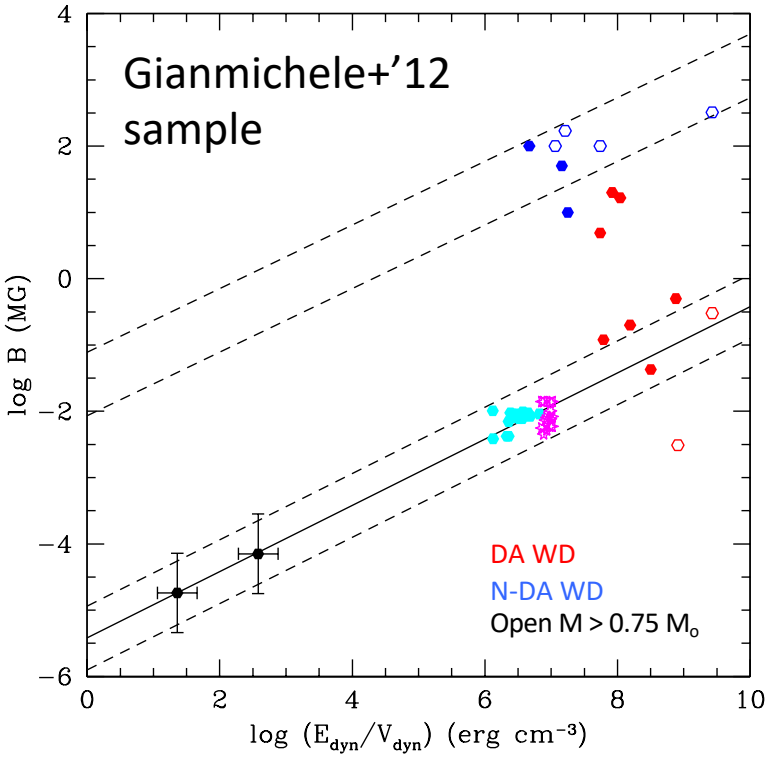
Energy density within the convective zone

R.h.s: f_{ohm}fraction Ohm dissitation
x Characteristic magnetic difusion time
x convective flux
/thermal length scale

$$E_m = \frac{B^2}{2\mu_0} \propto f_{Ohm} \frac{l_B^2}{\eta} \frac{q_c}{H_T}$$

In the saturation regime and taking into account variations of scale height and density





$$\frac{B^2}{2\mu_0} = cf_\Omega \frac{1}{V} \int_{r_i}^{r_o} \left[\frac{q_c(r)\lambda(r)}{H(r)} \right]^{2/3} \rho(r)^{1/3} 4\pi r^2 dr,$$

q_c convected flux
H scale height
λ mixing length

Can these scaling laws be applied to white dwarfs?

DA with B< ~ 0.1 MG follow the Earth/Jupiter relationship
non-DA follow a dynamo scaling law, but different from the E/J one
An independent block

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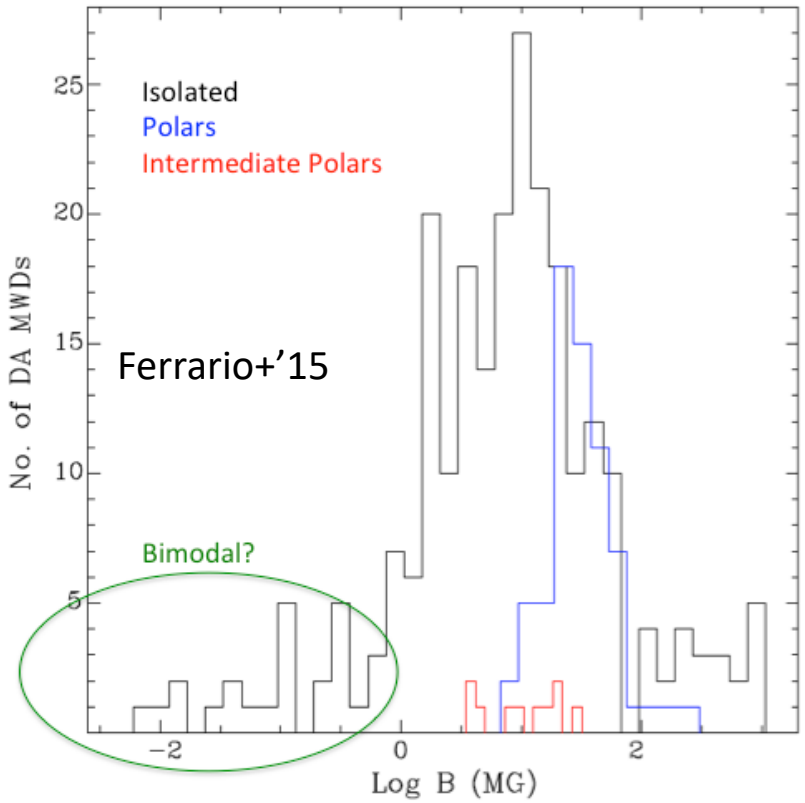


Are the present values of luminosity representative of the dynamo that produced the magnetic field?
τ_{diff} > Age universe

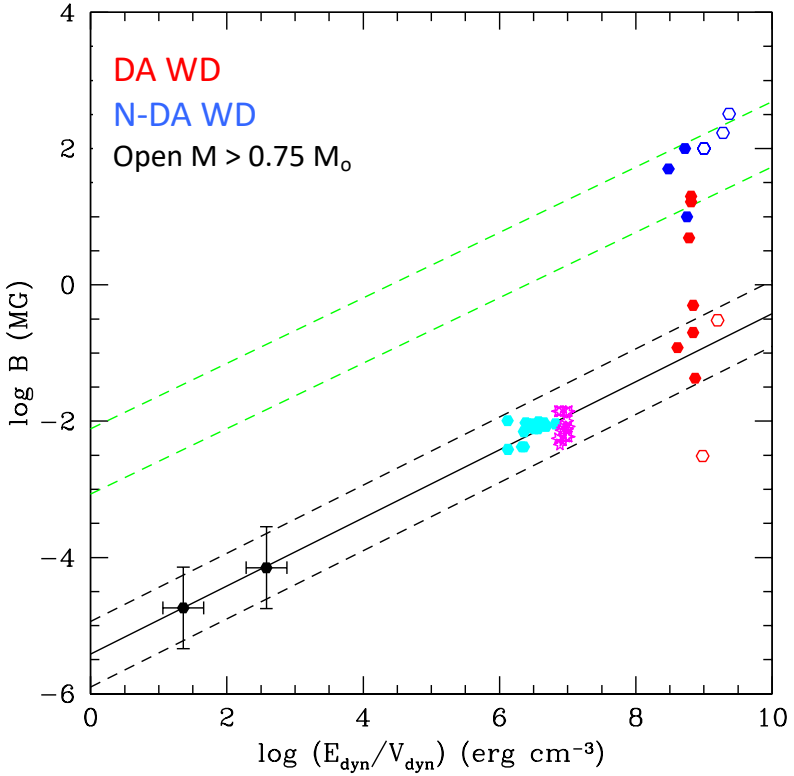
Assume B was created at the maximum efficiency of the dynamo

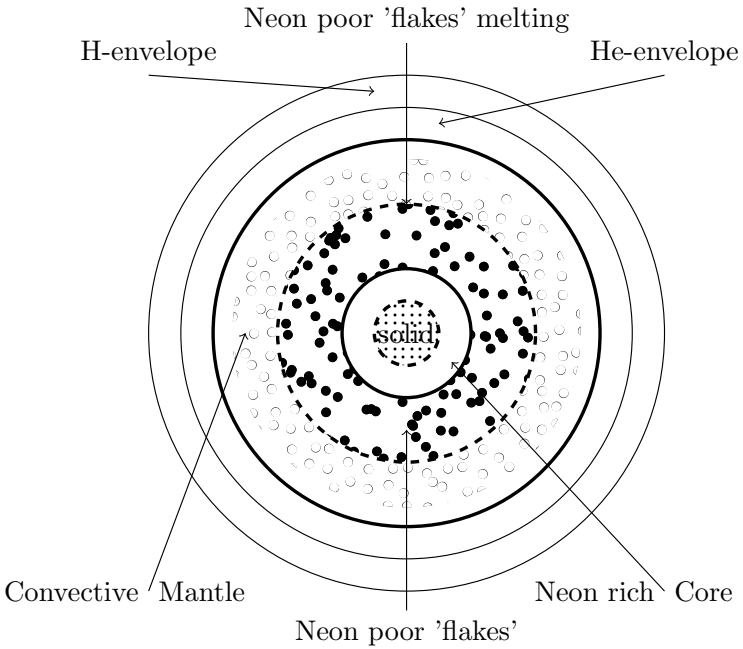
Are ^{22}Ne and other neutron rich impurities playing a role?

Field distribution

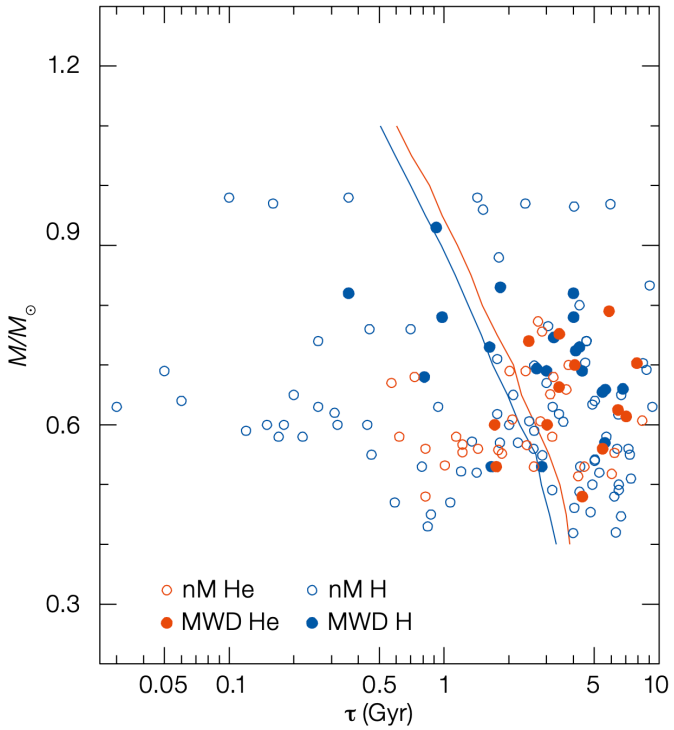
1 kG < B < 1 GG
- Uncertain lower limit
- Upper limit relatively safe

Majority in the range 1.5 MG < B < 75 MG
Difference between single and binary WDs
Is there a population of weak field WDs?
See Bagnulo and Landstreet'21, Amorin+'23 for a recent work

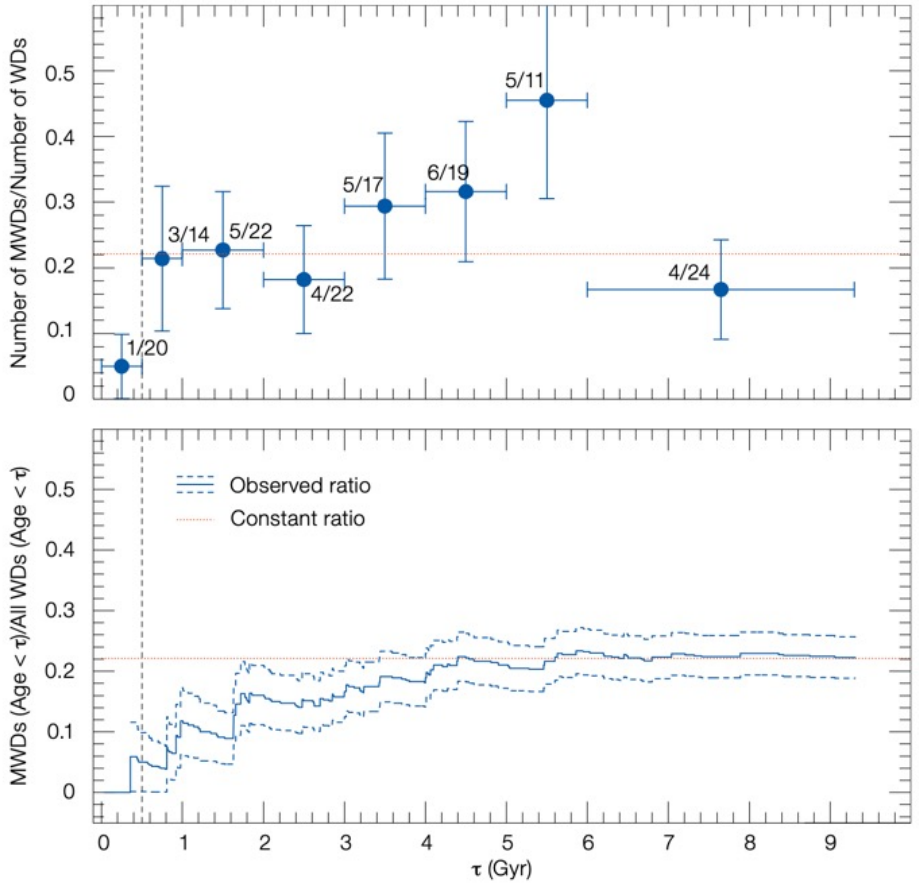




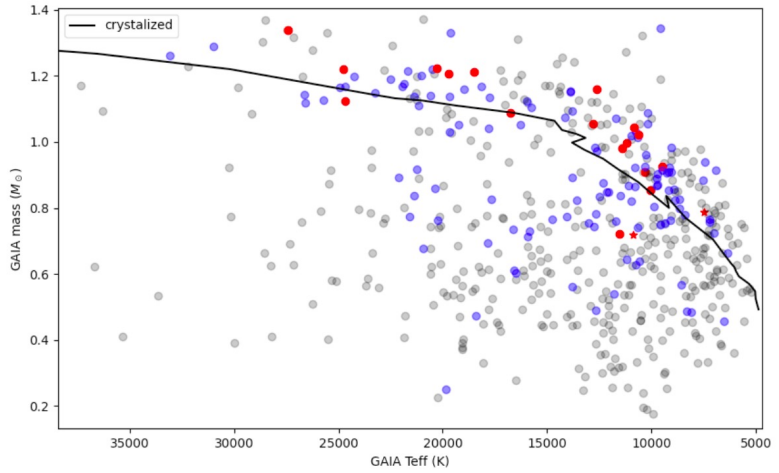
In 2017 the feeling was that crystallization-induced-magnetism appears appear too late in stellar evolution, however we now see



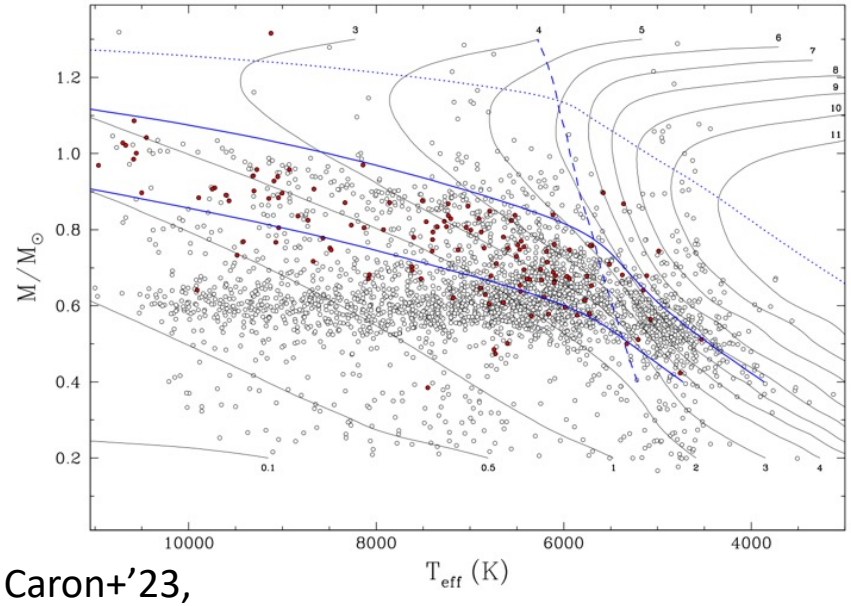
Bagnulo & Landstreet'22



There is a clear shortage of WMDs younger than 0.5 Gyr (Bagnulo & Landstreet'21,22)



Amorim+'23
black(<10MG),blue (10-100MG),re(>100MG)



Caron+'23,
red MWDs, blue lines (start-80% crystallized)

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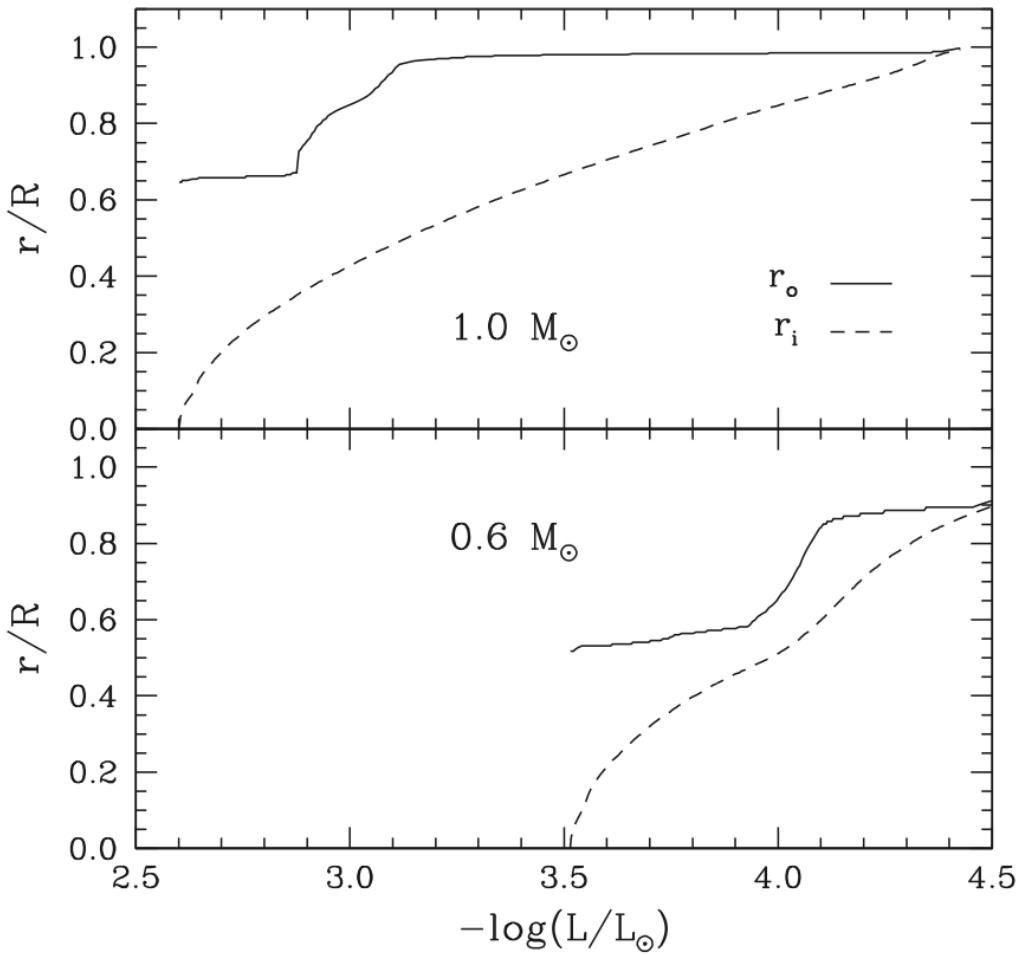
Difficult to emerge at the surface



Boundaries of the convective zone induced by crystallization (Isern+'17)

This problem is shared by the fossile origin

Because of thr differences in the chemical profile, the convective zone of massive WDs can reach more external regions that low mass WDs

This favours massive white dwarfs

Incidence of magetism in single stars and binaries

Small fraction of white dwarfs with strong magnetic fields in detcahed binaries (precursors of CV)
All members of this fraction are cold white dwarfs
A large fraction (~35%) of white dwarfs in CV binaries have strong magnetic fields

This tension can be solved if it is postulated that white dwarfs are able to create a strong magnetic field when they are cool enough (Schreiber+'21)

Unable to reach the strongest observed strengths?

In Isern+’17 it was assumed that this occurred when all the heavy species were in the solid and only the lighter species were remaining -> Strong buoyancy -> rapid turbulent flows -> low efficiency of the dynamo -> weak magnetic fields unless rapid rotation

In Ginzburg +’22 after a crtical time determined by the size of the crystallizing region and conductivity -> Lower buoyancy -> slower turbulent flows -> high efficiency of the dynamo -> strong magnetic fields even with low rotation velocities

Fuentes+23 have modelled the compositional-driven convection associated to crystallization in NS & WD. In WD they have found fingering regime -> low velocities -> Not enough kinetic energy to activate the dynamo

A unique mechanism?

Not necessarily (Bagnulo & Landstreet'22):
- Massive, young MWDs are the result of the merger of two white dwarfs
- The weak field of young low mass MWDs has probably a fossil origin which emerge during the cooling process
- Crystallization induces an increase of MWDs

Crystallization plays a role!
If CO mixtures cannot activate the dynamo, which is the action mechanism?
* ^{22}Ne ? In this case the dynamo would be metallicity dependent.
* An Increase of the migration velocity towards the outer layers of internal fields induced by convection associated to crystallization?

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Fabra Observatory 1904