White Dwarf Cosmochronology

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MW-Gaia Workshop
Naples, September 20-23th 2022

Introduction

The relatively simple structure of white dwarfs and their long characteristic cooling time make them the ideal stellar object to:

- Test new ideas in Physics
- To characterize the properties of Galactic substructures
- To trace the evolution of the Galaxy

Furthermore, they are responsible of many violent events like supernovae, novae, cataclysmic variables,...

The stellar age is a fundamental parameter hard to obtain!

There are several methods:

- Chromospheric activity
- Isochrones
- Spectroscopy & Asteroseismology
- Cooling of white dwarfs

The evolution of white dwarfs is a gravothermal process of cooling but is far of being simple and well understood (Isern+'22; Saumon+'22)

Furthermore, the age of the white dwarf **is $t = t_{cool} + t_{PS}$** (unless $t_{ps} << t_{cool}$)

White dwarf cooling

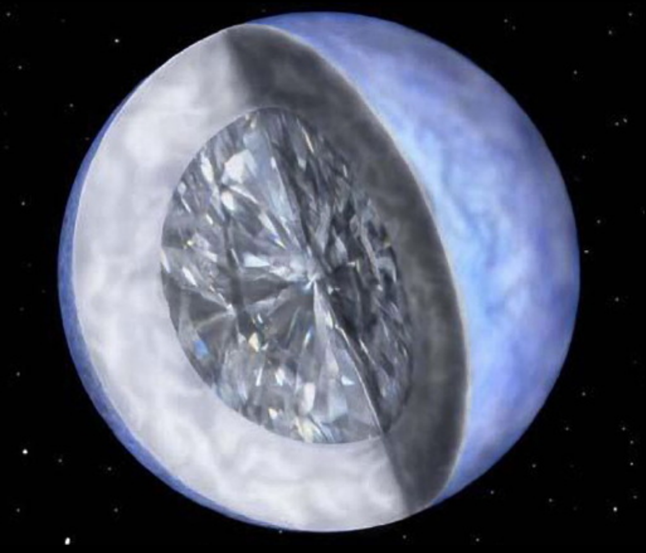
$$L+L_\nu+\left(L_e\right)=-\int_{M_{WD}} c_V \frac{dT_C}{dt}\,dm-\int_{M_{WD}} T\left(\frac{\partial P}{\partial T}\right)_{V,x}\frac{dV}{dt}\,dm+\left(l_s+e_s\right)\dot{m}_e+\dot{d}_Z+\left(\varepsilon_e\right)$$

A L(T_C) relationship is necessary to solve this equation
It depends on the properties of the envelope.

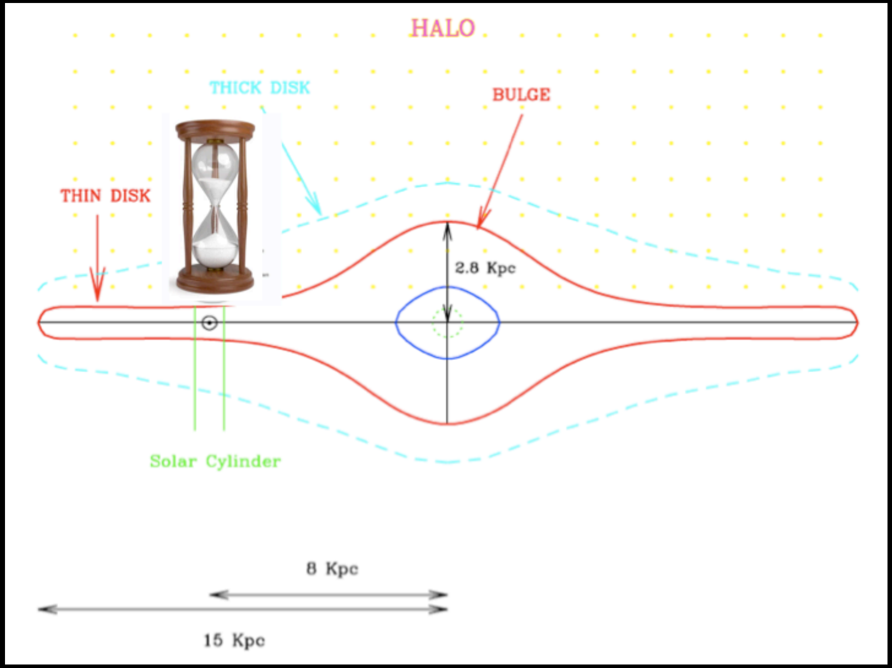
$$L \propto T^{\alpha}$$

$$\alpha \approx 2.5-2.7$$

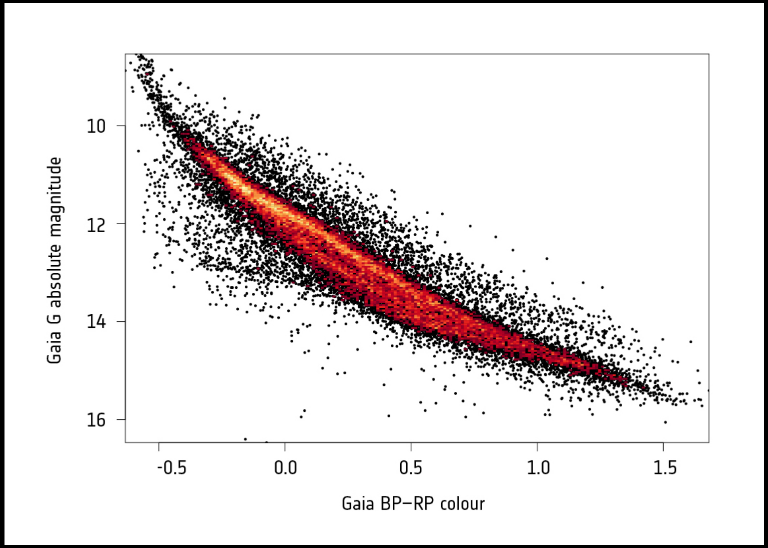
$$L = L(t)$$



CO.core/He-envelope/H-envelope

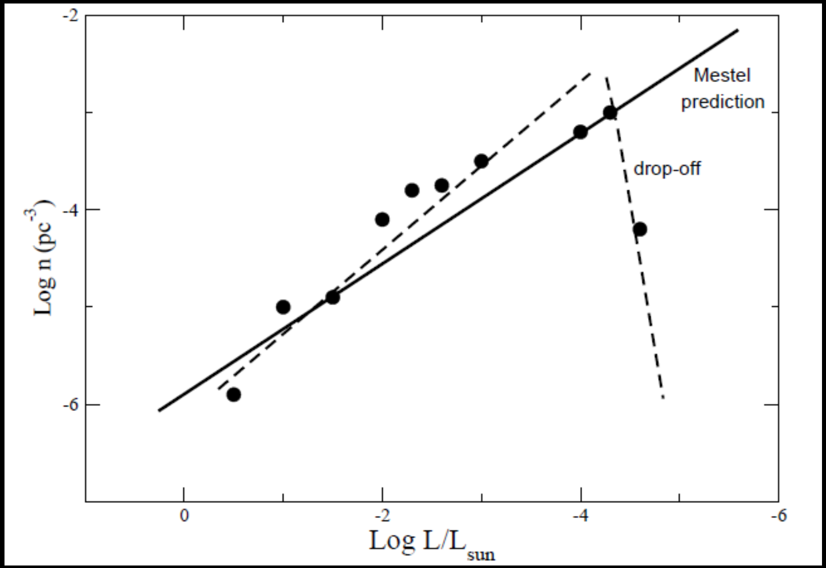


Tools to extract information



Structures in the HR-diagram

Piling at a given region can be caused by population or by internal physical properties



Luminosity distribution

Cooling implies o monotonic behavior with a cut off caused by finite age of Galaxy

Slope changes can be caused by population or by internal physical properties

The luminosity function

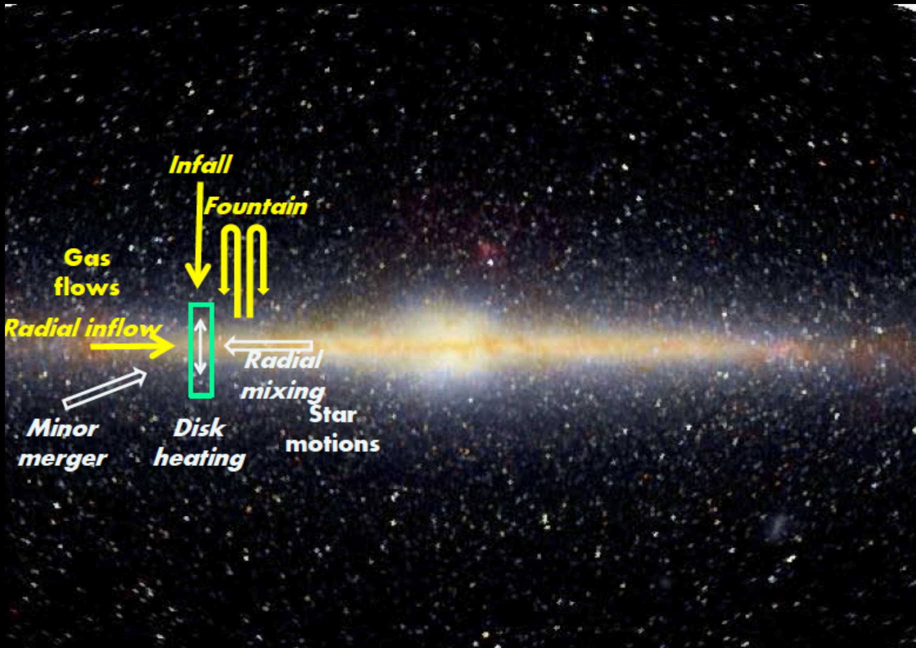
Number of white dwarfs per unit magnitude versus luminosity, i.e. the number of MS stars born at a given time able to produce a white dwarf of luminosity L per unit of magnitude at present

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

1.- n(L) is the observed distribution

2.- Φ,Ψ are the IMF and SFR respectively.
  T_G is the age of the Galaxy

3.- t_{cool} is the cooling time
  t_{PS} is the lifetime of the progenitor
  τ_{cool} is the characteristic cooling time
  M is the mass of the progenitor
  Hidden an m_{WD}= IFMR (M)



But radial and vertical motions &
DD mergers, supernovae, if WDs in binaries not excluded

There is a degeneracy between the physics of WD and Galactic properties

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

Are under control all the ingredients that determine the cooling of white dwarfs?

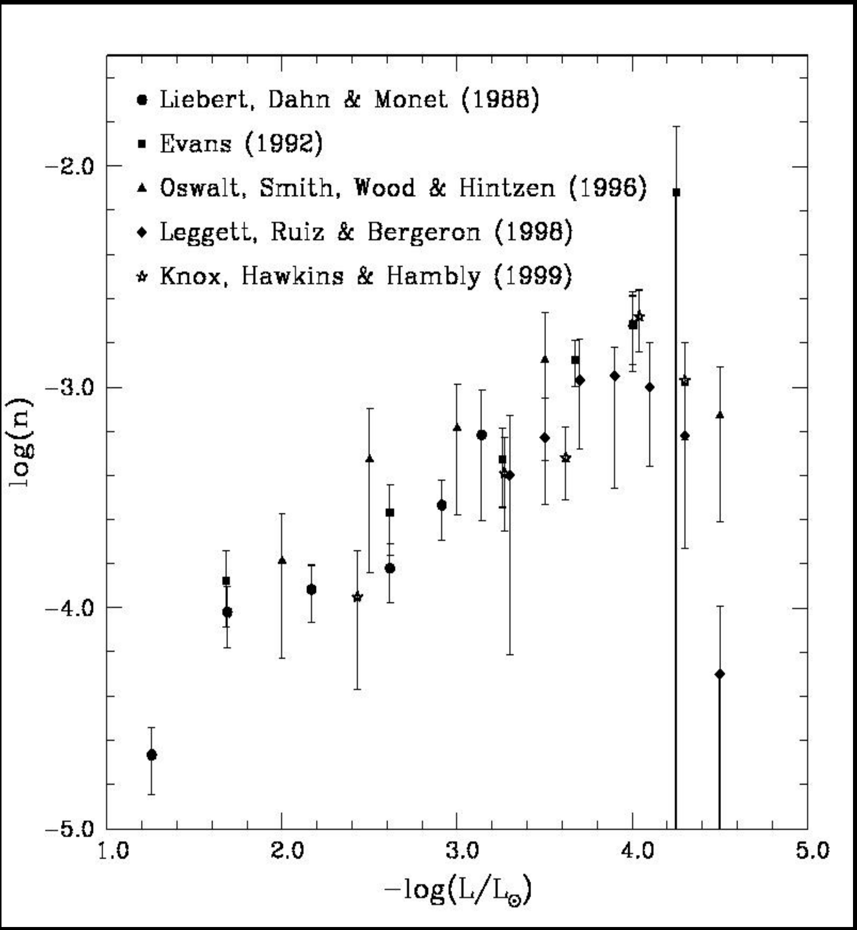
- EOS, opacities, convection..., progenitors, metallicity...

Do we know which is the structure and evolution of the Galaxy? Is the Solar neighborhood representative of the entire Galaxy?

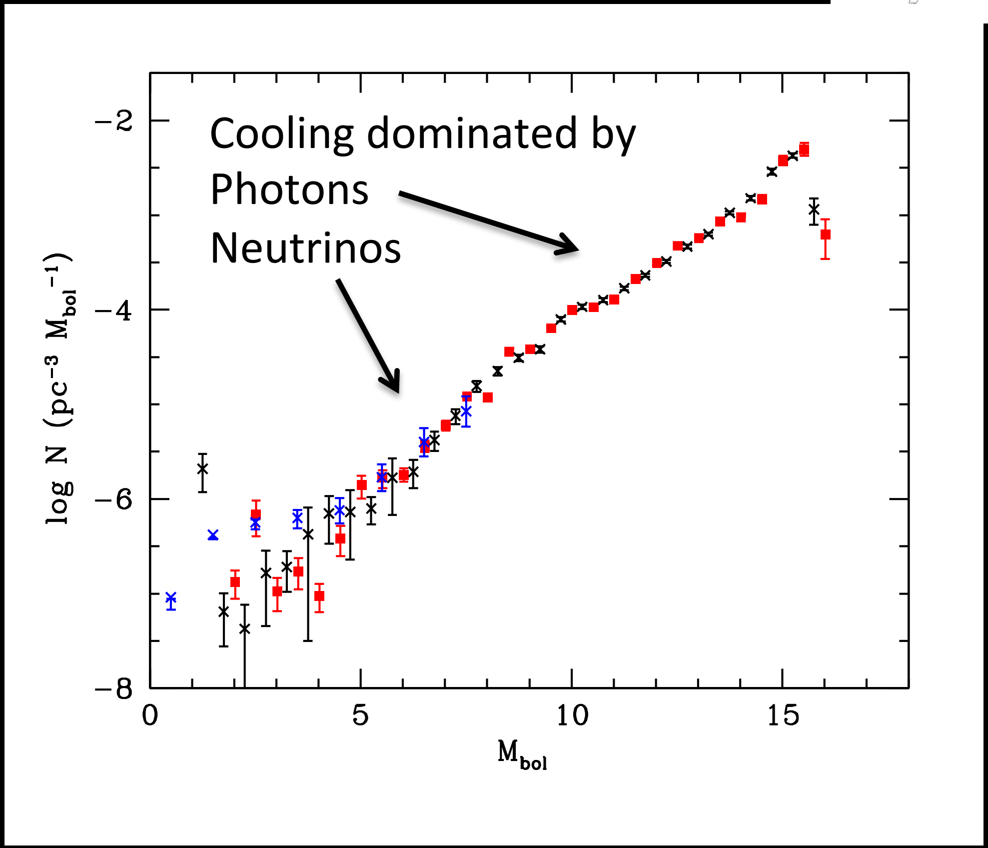
- The conventional picture is seriously challenged by the results of Gaia, APOGEE,...
- The universality of the IMF is being questioned
- ...

(Isern+'22, Saumon+'22)

White dwarf catalogues are more and more complete and accurate

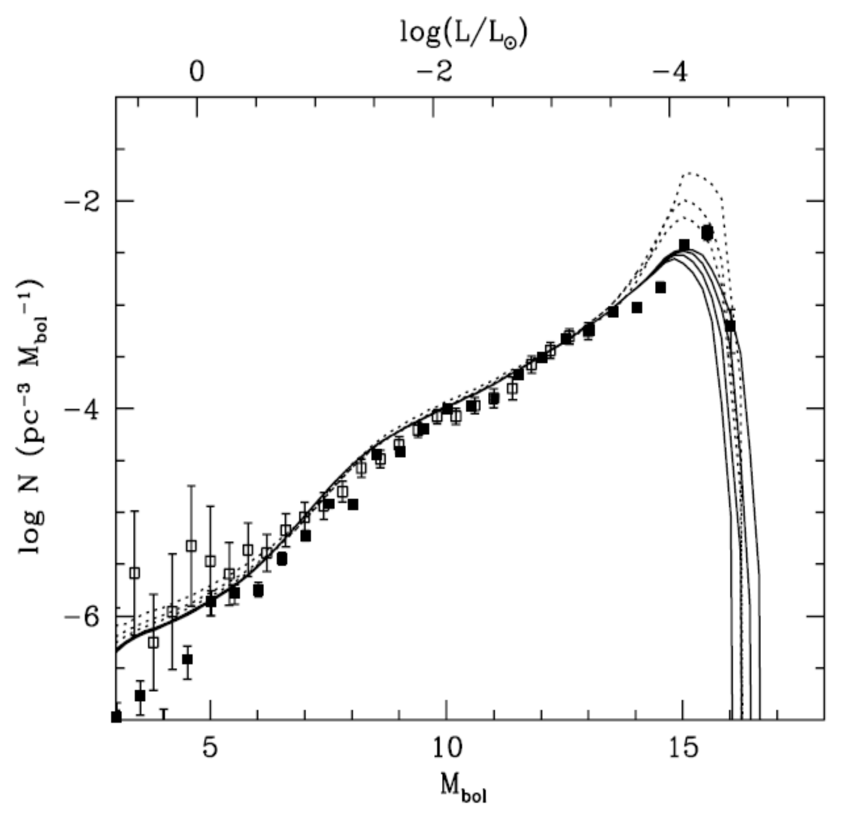


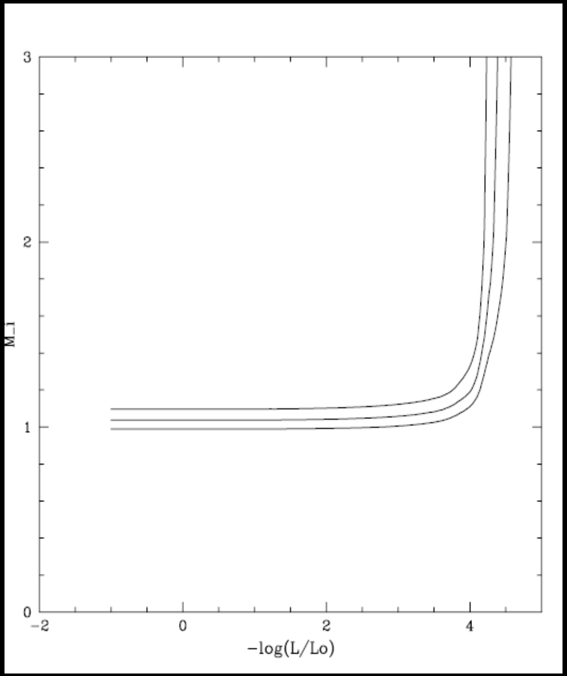
~ 100s stars (before 2000)

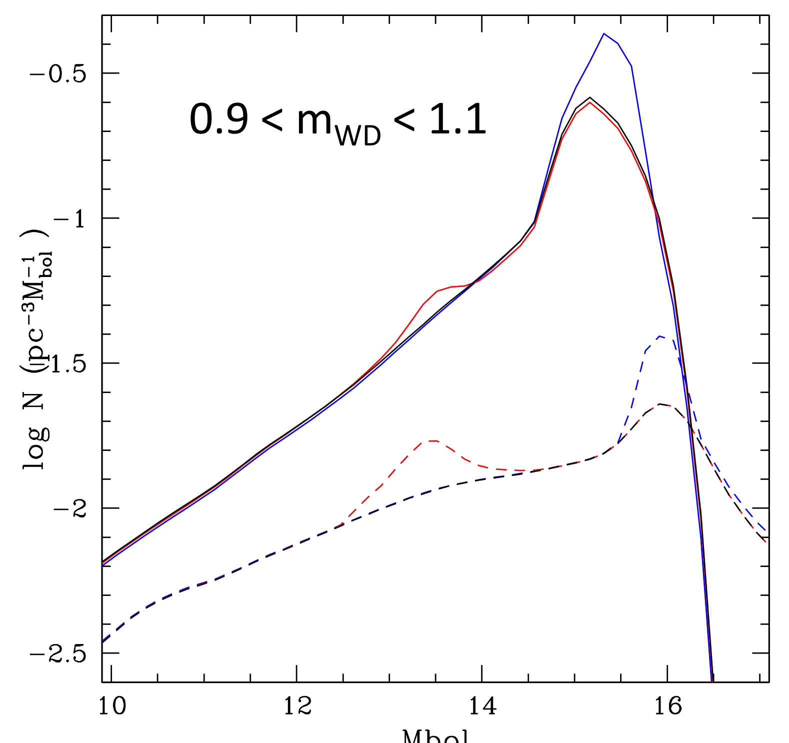


Cooling dominated by
Photons
Neutrinos

- New catalogues obtained from SDSS, SCSS, LSS-GAC, PanSTARS... contain ~ 1000s stars
- Obtain information about the physical properties of WDs







$0.9 < m_{WD} < 1.1$

$$n(l) \propto \langle \tau_{cool} \rangle \int_{M_i}^{M_{\max}} \Phi(M)\Psi(\tau)dM$$

Blue: SFR pic at t ~ 2 Gyr (old) + cnt
Red: SFR pic at t ~11 Gyr (young) + cnt
Black: SFR cnt

Two ways to measure the cooling rate of WD:

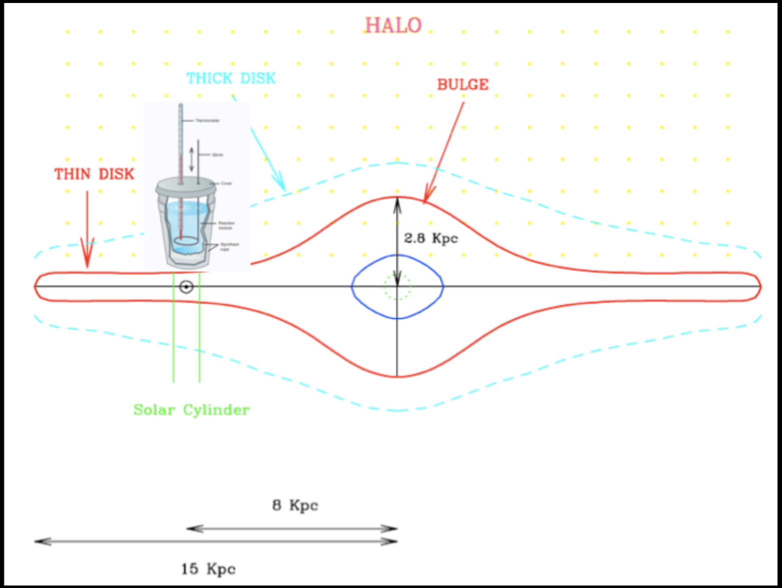
From their luminosity function

From the secular drift of the period of pulsation of variables

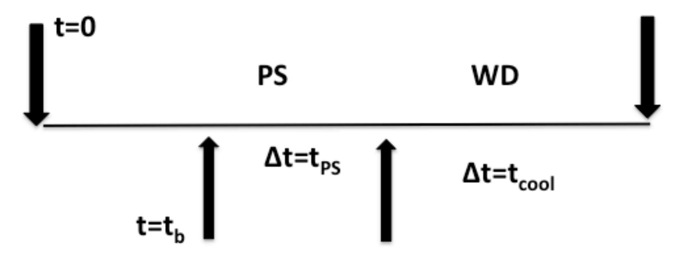
Some exemples of using WD to bound physical theories:

- **Axion [Raffelt'86; Isern+'92,08;Isern&Garcia-Berro'08,Miller-Bertolami+'14 Isern+'18]**
- Secular drift of G_N [Vila'69; Garcia-Berro+'95; Benvenuto+'04]
- Magnetic monopoles [Freese'84]
- Neutrino magnetic momentum [Blinnikov & Dunina-Barkovskaya'94]
- Extradimensions [Malec & Besiada'01]
- Formation bh by high energy collisions [Giddings & Mangano'08]
- WIMPS [Bertone'07]
- Dark forces [Dreiner+'13]
- Modified gravity [Saltas+'18]

WDs can be used as galactic calorimeters



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



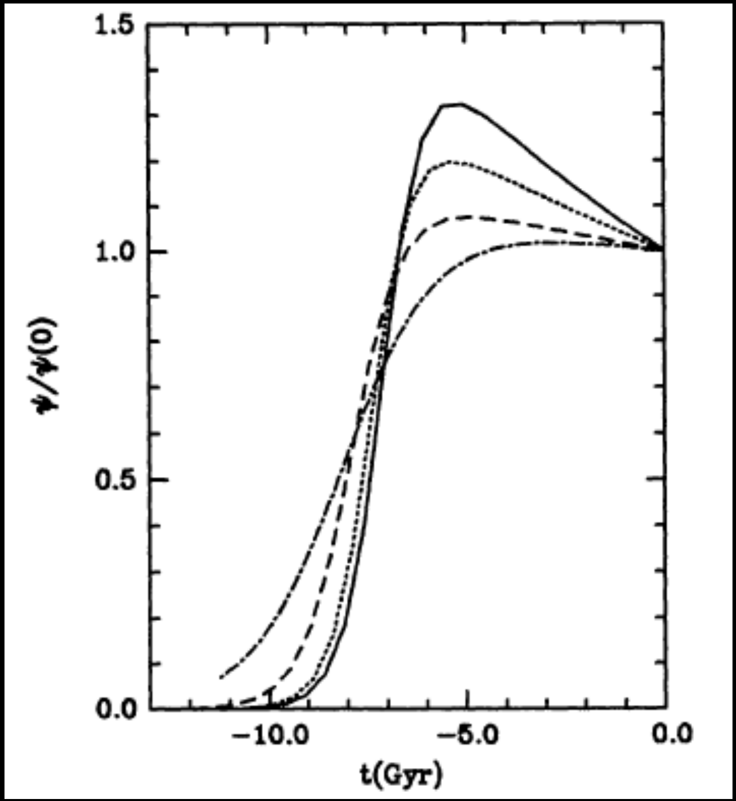
$$n(l)=\int_0^{t_b^{up}}K\left(l,t_b\right)\Psi\left(t_b\right)dt_b$$

The kernel is not symmetric no directly inverted

(Picard's theorem)

Models of chemical evolution of the galaxy provide natural trial function (Isern+'99)

$$\Psi(t)=\frac{\Sigma(t)}{h(t)}\propto\frac{e^{-t/\tau_s}}{h_1+h_0e^{-t/\tau_h}}$$



It can be adjusted bin by bin (Rowell'13)
Results are sensitive to the assumed metallicity and IMF

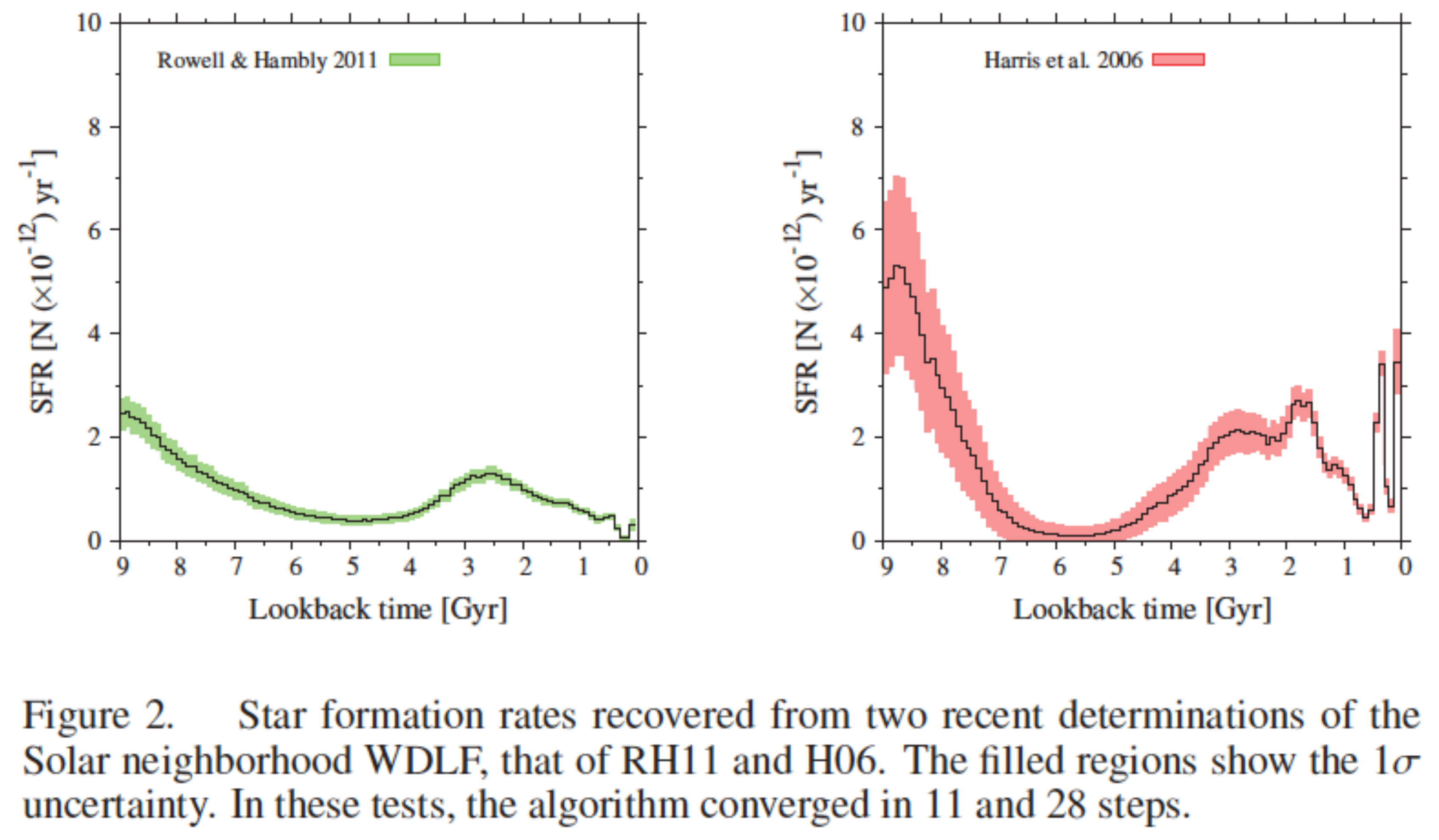


Figure 2. Star formation rates recovered from two recent determinations of the Solar neighborhood WDLF, that of RH11 and H06. The filled regions show the 1σ uncertainty. In these tests, the algorithm converged in 11 and 28 steps.

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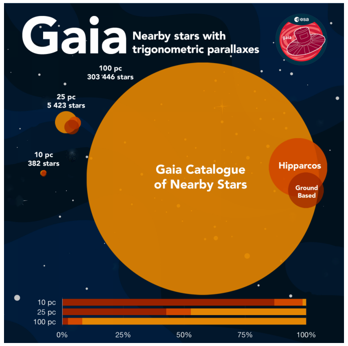
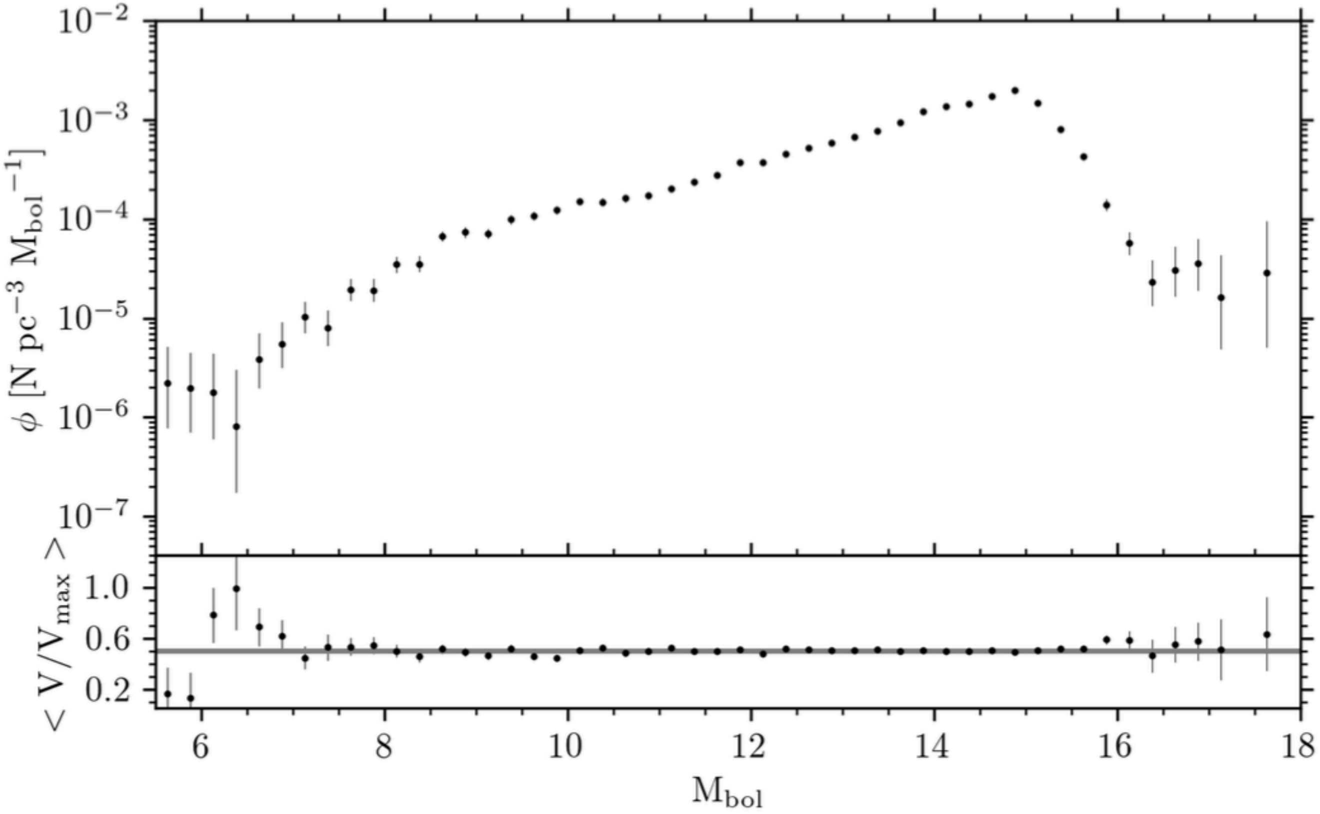
Is the correct one? Additional information is necessary



\# Gaia DR2 & DR3 have allowed to identify ~360,000 WDs (Talksby Gentille-Fusillo and Jiménez-Esteban)

\# This allowed to obtain detailed luminosity functions like



\# ~1900 Wds around the peak at M_{bol} ~ 14.85

Broader peak than previously found

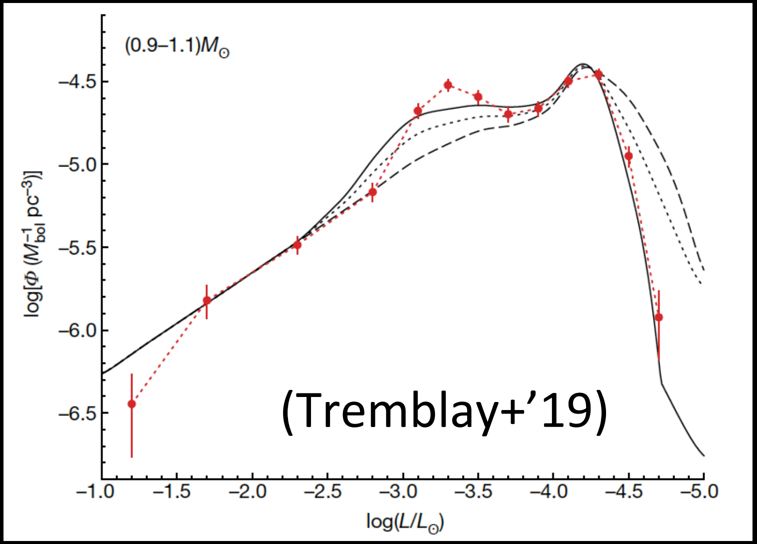
\# Features at:

M_{bol} = 10.5 (Limoges+15)

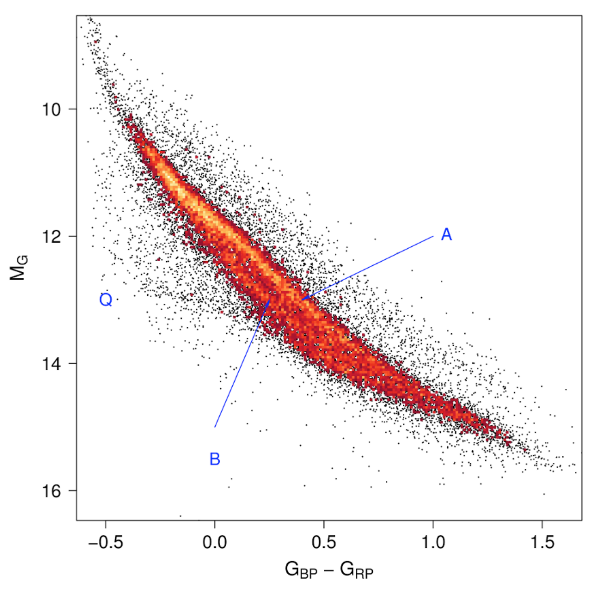
M_{bol}=14.25

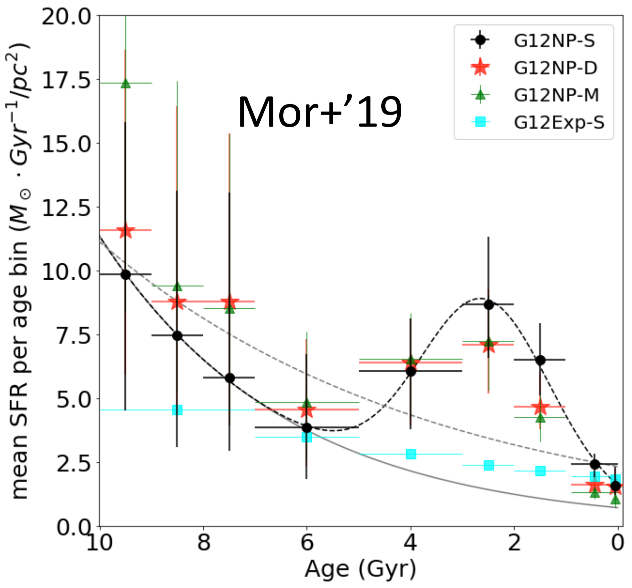
The WDLF from the GCNS_GEDR3 (Smart+'21)

Two questions introduced by Gaia DR2



(Tremblay+’19)





Mor+’19

- # 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 models are necessary to solve the degeneracy
- # Analysis of Mor+’19 (Gaia + Besançon model)

Metallicity is important

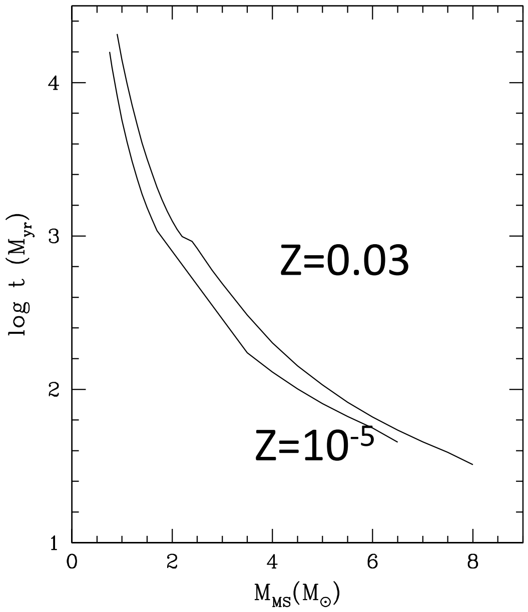
- Lifetime of the progenitor
- Changes in the initial-final mass relationship
- Changes in the C/O profile: Z↓C↑
  - Larger especific heat
  - Larger sedimentation energy upon crystallization
  - Different T_{eff} at which crystallization starts
- Energy released by impurities: ^{22}Ne & ^{56}Fe
  -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

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

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

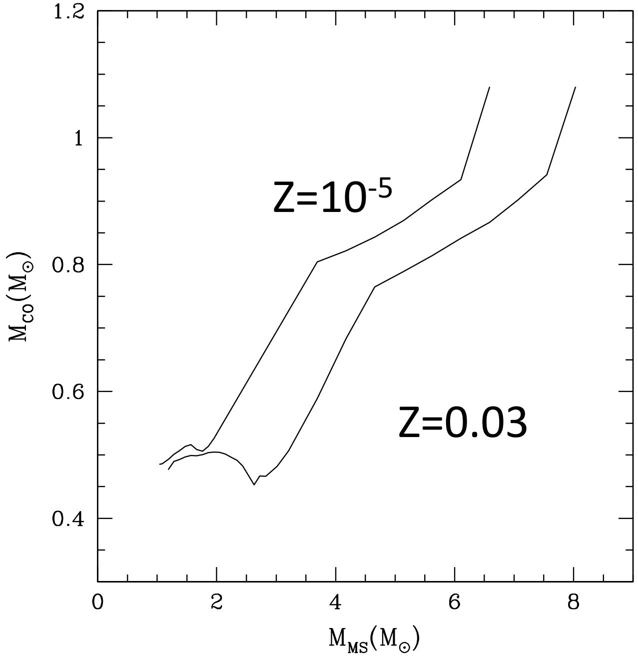
The dependence on Z, with few exceptions (Isern+'05,Cojocaru+'14,Tononi+'19), has been neglected very often

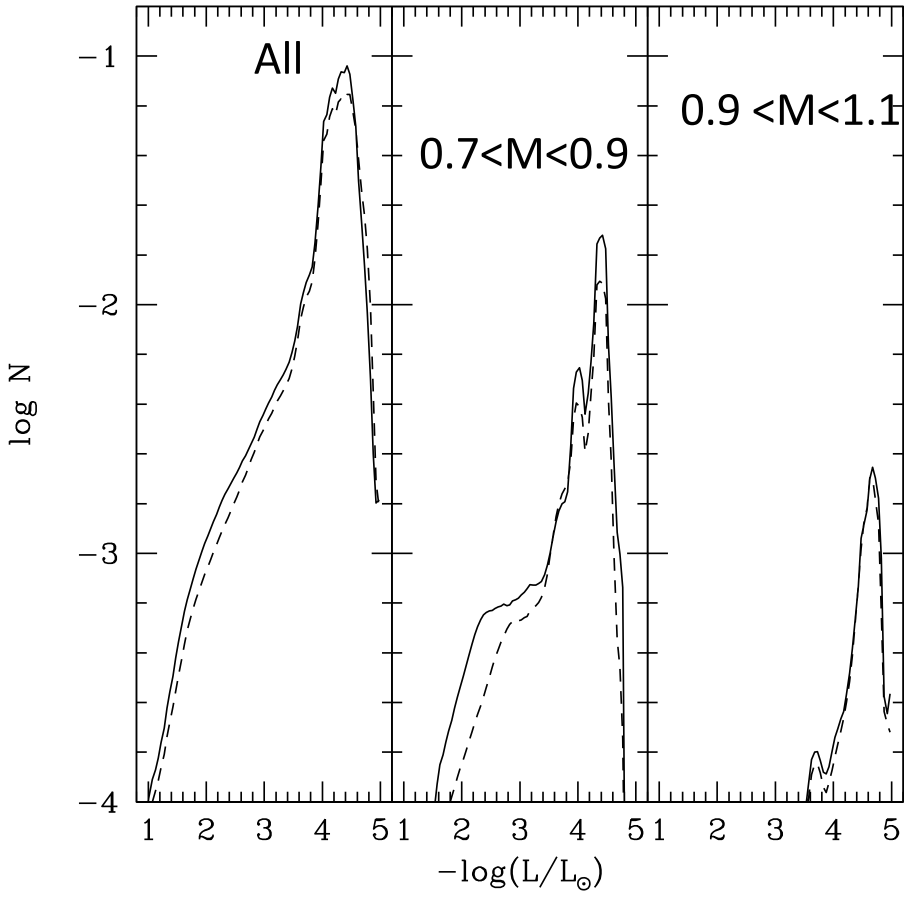
Influence of Z via parent star



Pietrinferni+’04

Dashed: Solar metallicity
Continuous: Z(t) Twarog’80
WD models: Salaris+’10
C/O sedimentation & DA/nDA





Stratified C/O profiles

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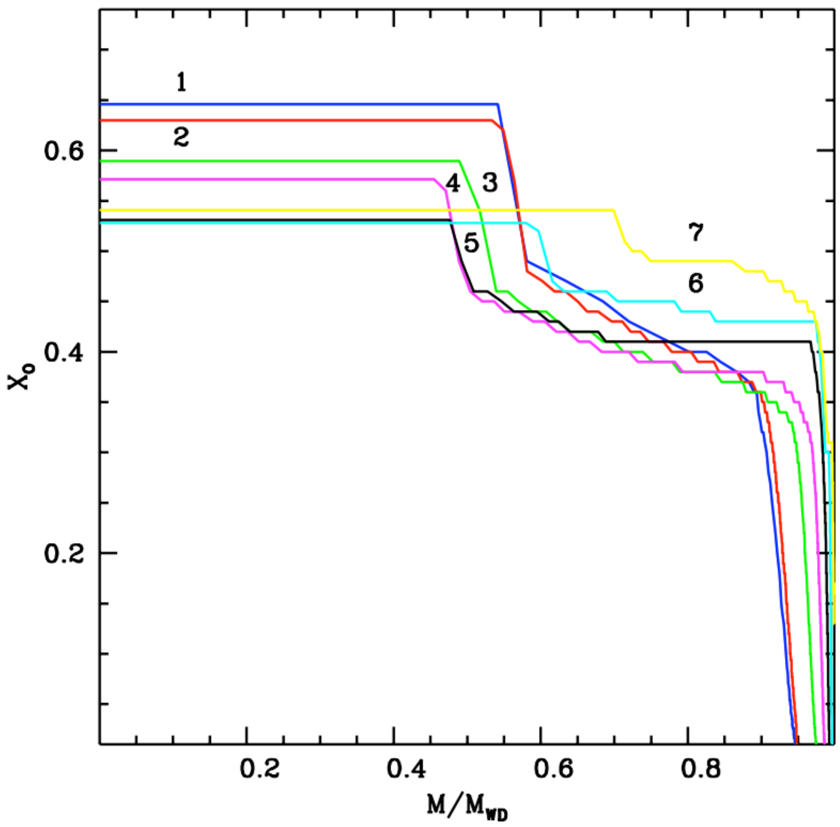


Figure 2. Reference oxygen stratification (in mass fraction) for our WD models. Labels denote, in order of increasing number, the abundances for the 0.54, 0.55, 0.61, 0.68, 0.77, 0.87, and 1.0 $M_\odot$ models, respectively.

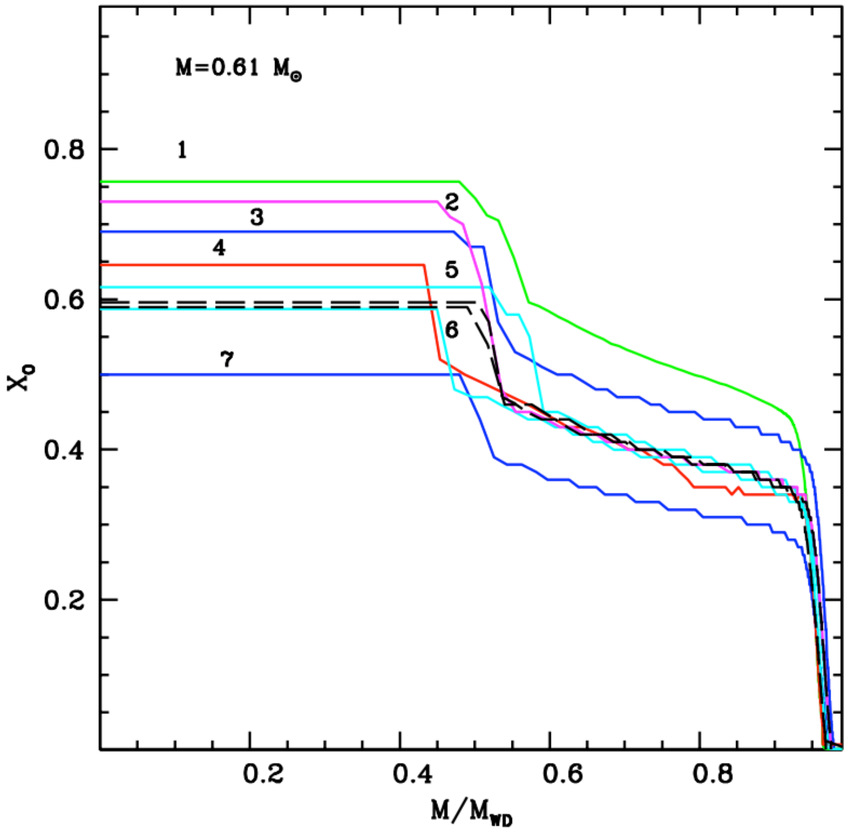
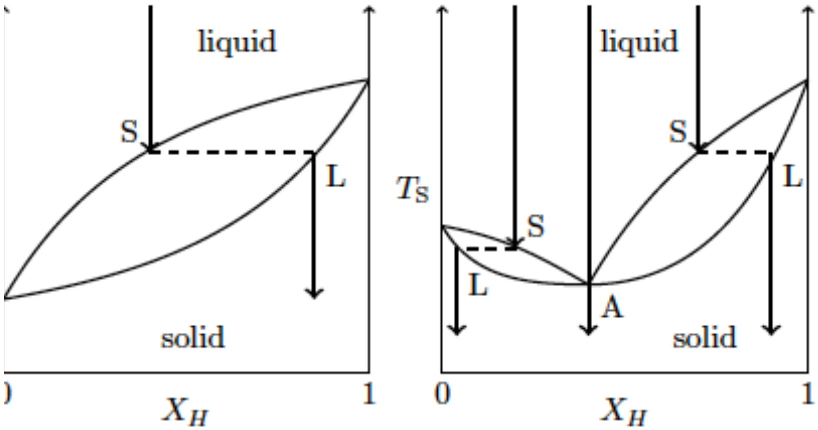


Figure 3. Several different oxygen stratification (in mass fraction) tested on a 0.61 $M_\odot$ WD model. See the text for details.

The WD C/O profile is stratified. The abundance and extension of the oxygen rich core depends on the mass, carbon-alpha rate, metallicity and treatement of convection (D'Antonna & Mattizelli'79; Salaris+'97,10)

Behavior upon crystallization Coulomb plasmas

$$\Gamma = \frac{(Ze)^2}{a k_B T} = 170 - 180$$



Schatzman’82
Mochkovitch’83
Segretain & Chabrie’93
Hernanz+’94
Segretain+’94
Isern+’91
Isern+’97
Isern+’00

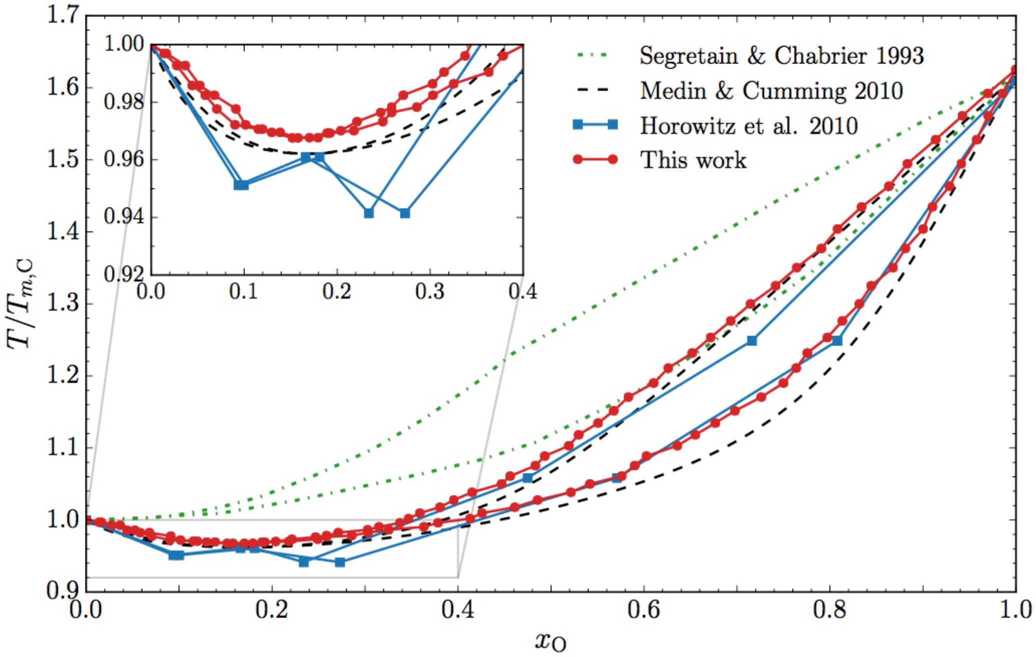


Fig. 1. C/O phase diagram. Both the liquidus (above which the plasma is entirely liquid) and the solidus (below which it is entirely solid) are shown. The horizontal axis gives the number fraction of O, $x_O = N_O/(N_C + N_O)$, and the vertical axis corresponds to the ratio between the temperature and the melting temperature of a pure carbon plasma. Our results, in red, are compared to those of Segretain & Chabrier (1993), Medin & Cumming (2010) and Horowitz et al. (2010). The region where an azeotrope is predicted is enlarged in the upper-left corner.

Sink of heavy neutronized species

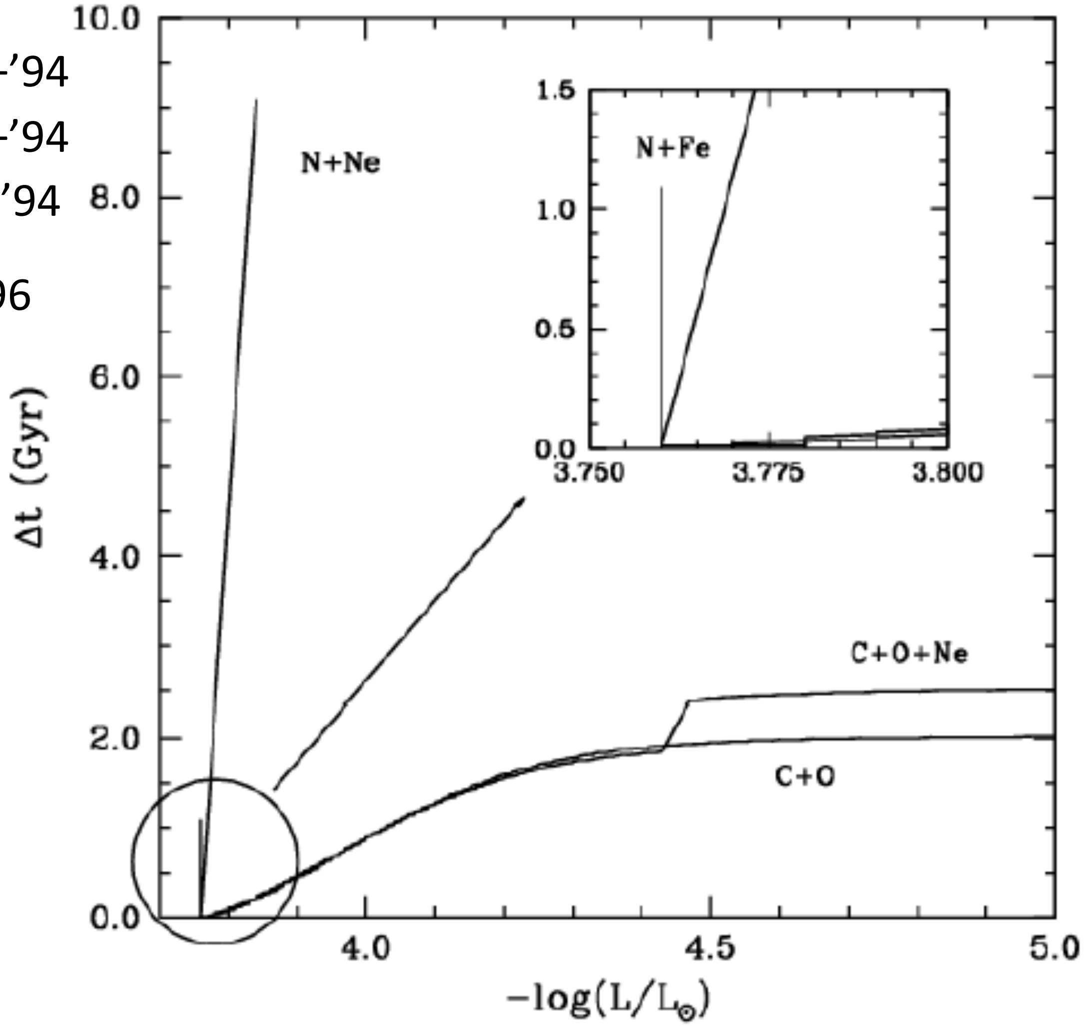
Because of the extreme dependence of degenerate structures on the Ye distribution, the sink of rich neutron species like ^{22}Ne and ^{56}Fe can release important amounts of energy (see Althaus+'10, Isern+'22 for a review)

Migration of heavy species towards the central regions is a consequence of

- Gravitation induced diffusion (Bravo+'92, Bildsten & Hall'02, Deloye & Bildsten'02, Garcia-Berro'08, among others).
- Solubility change upon crystallization and associated precipitation of heavier species.
  *Minor species: ^{22}Ne (Isern+'91) and ^{56}Fe (Xu & Van Horn '92)

Energy released by crystallization induced separation 0.6 $M_{\odot}$

Mixture	ΔE(erg)	
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

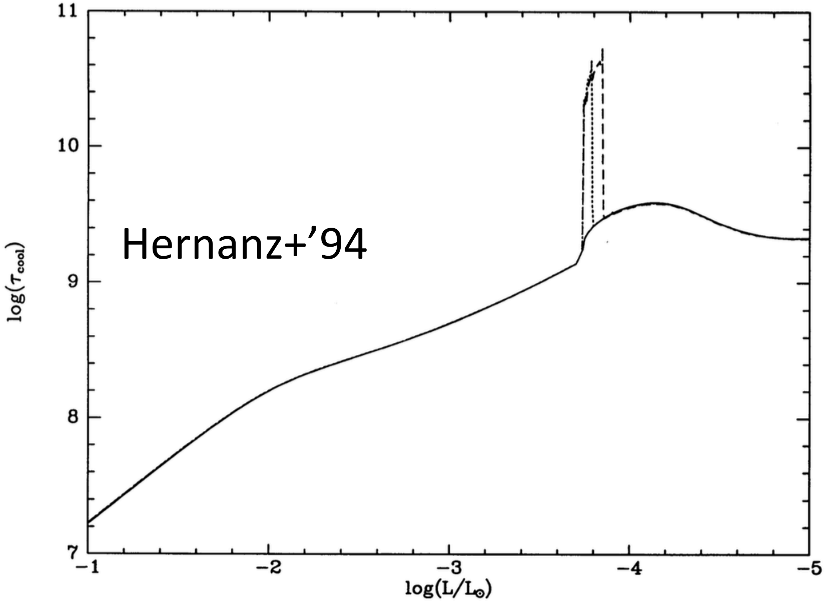


$$\Delta t = \int_{0}^{M_{WD}} \frac{\varepsilon_g\left(T_c\right)}{L\left(T_c\right)} dm$$

(Isern+’98a,b)

The delay depends on the transparency of the atmosphere

^{22}Ne distillation upon crystallization



Hernanz+’94

#Obtained with the phase diagrams of Isern+91 and Chabrier+94 and Z solar

These diagrams assume that the C/O mixtures behaves like a plasma with average atomic mas A (~14)

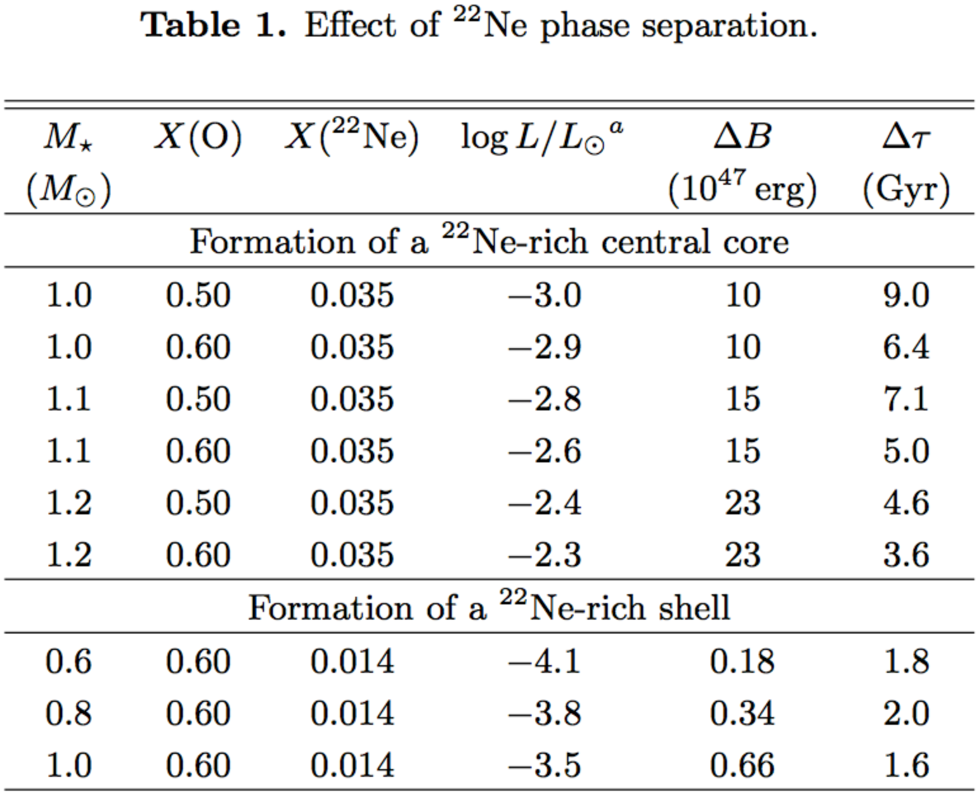
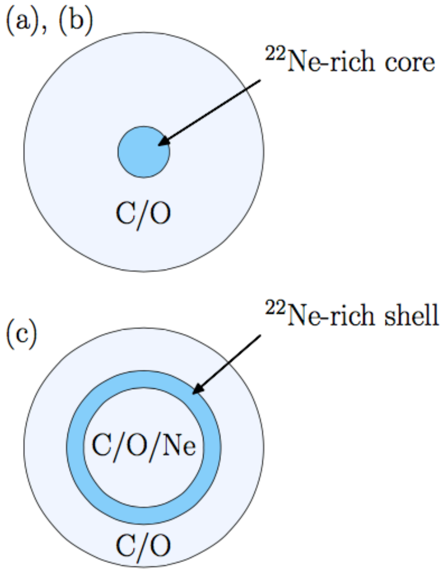


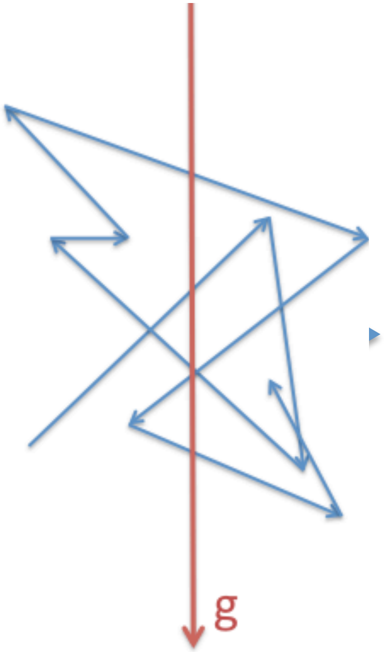
Table 1. Effect of ^{22}Ne phase separation.

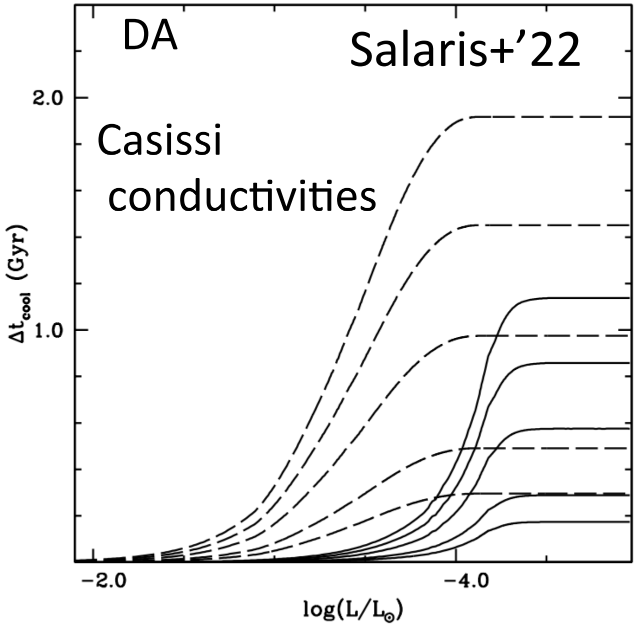
$M_\star$ $(M_\odot)$	$X(\mathrm{O})$	$X(^{22}\mathrm{Ne})$	$\log L/L_\odot{}^a$	ΔB $(10^{47}$ erg)	$\Delta\tau$ (Gyr)
Formation of a ^{22}Ne-rich central core					
1.0	0.50	0.035	−3.0	10	9.0
1.0	0.60	0.035	−2.9	10	6.4
1.1	0.50	0.035	−2.8	15	7.1
1.1	0.60	0.035	−2.6	15	5.0
1.2	0.50	0.035	−2.4	23	4.6
1.2	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

Diffusion





Salaris+’22

Casissi conductivities

Figure 6. Cooling time delay $\Delta t_{\rm cool}$ (in Gyr) as a function of the luminosity, caused by the diffusion of Ne in 0.61$M_\odot$ (solid lines) and 1.0$M_\odot$ (dashed lines) H-atmosphere WD models, from progenitors with Z=0.006 0.01, 0.017, 0.03, 0.04 (in order of increasing maximum $\Delta t_{\rm cool}$) respectively

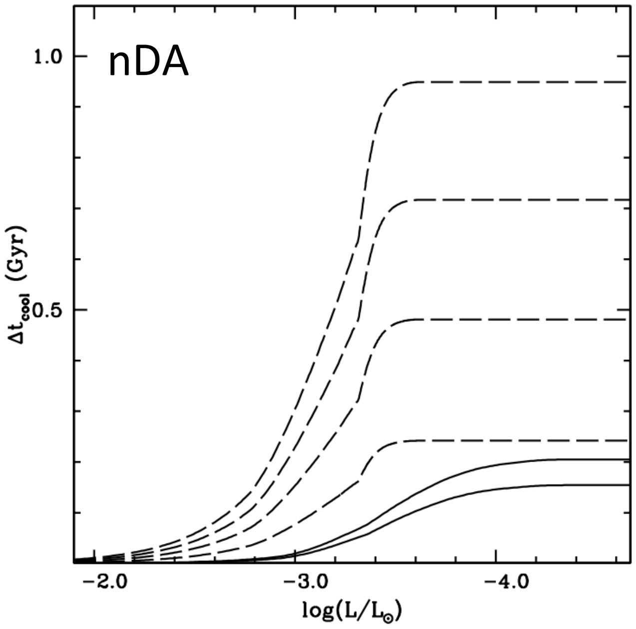
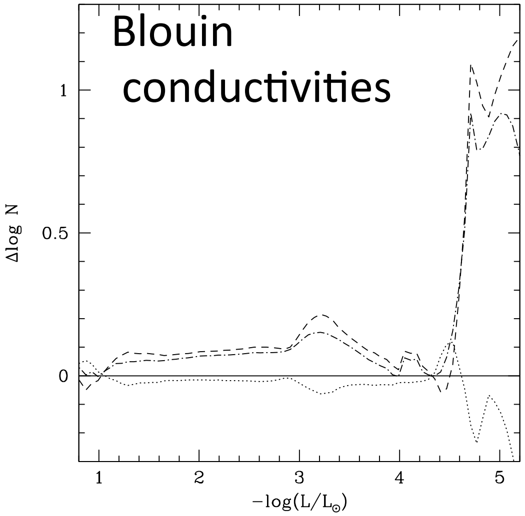


Figure 7. As Fig. 6 but for the corresponding He-atmosphere models. The displayed 0.61$M_\odot$ calculations are for progenitors with Z=0.03 and 0.04; the 1.0$M_\odot$ calculations are for progenitors with Z=0.01, 0.017, 0.03, 0.04 (in order of increasing maximum $\Delta t_{\rm cool}$). The cooling delay for models from lower metallicity progenitors are negligible.



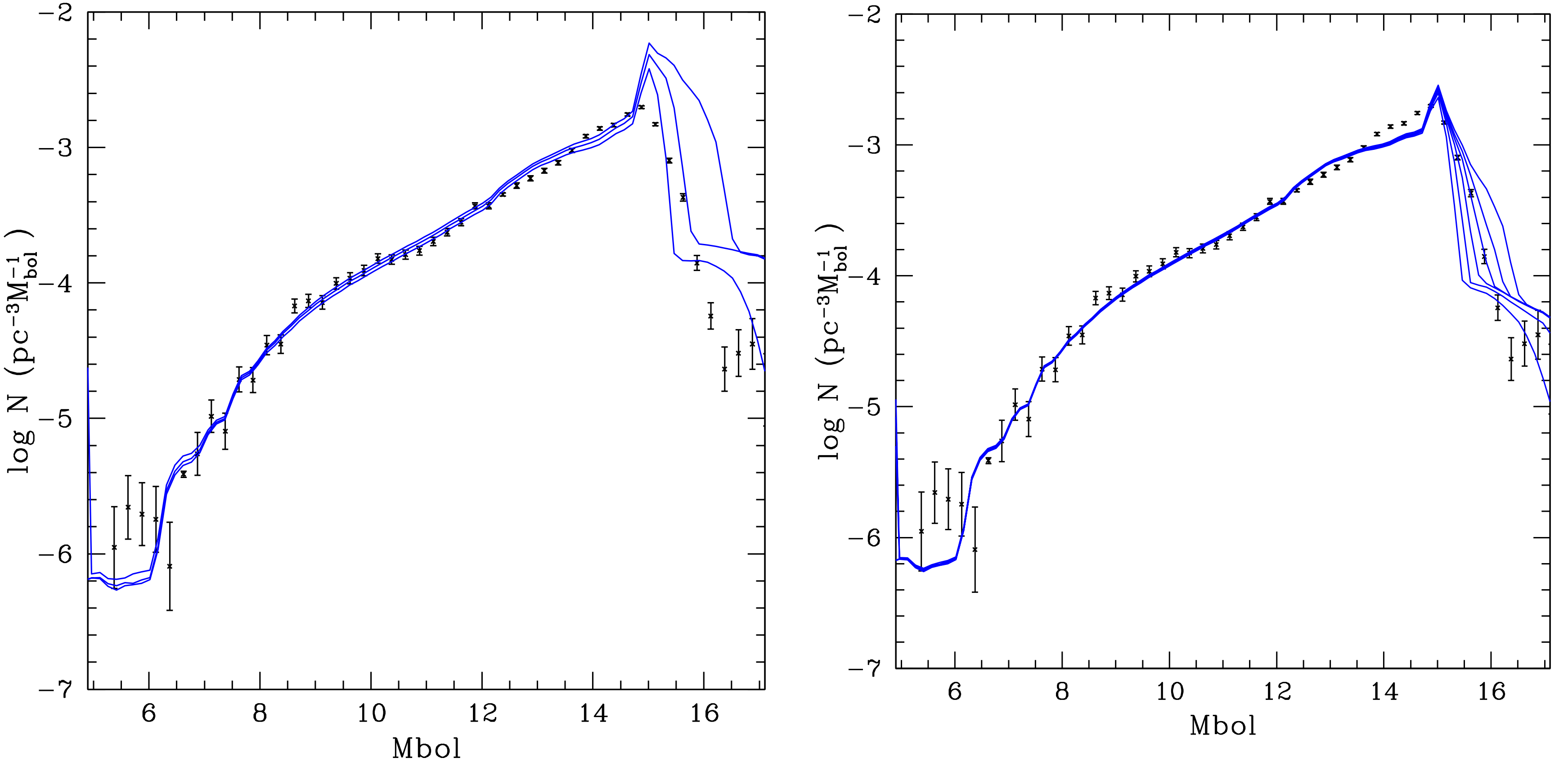
Blouin conductivities

Dash-dotted: $\log N_Z - \log N_0$

Dashed: $\log N_\odot - \log N_0$

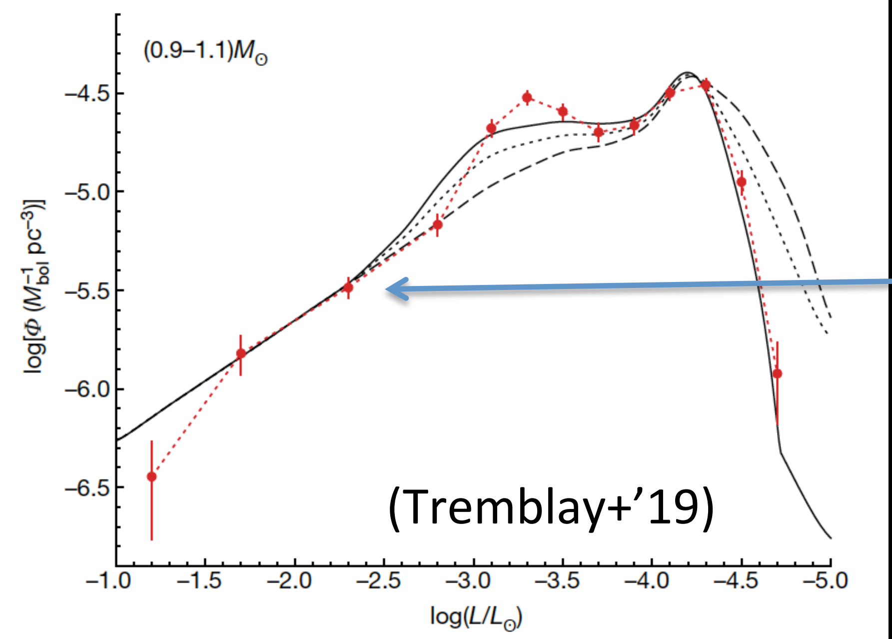
Dotted: $\log N_Z - \log N_\odot$

Salaris+'22 cooling models
#Solar metallicity
WDLF from Smart+21

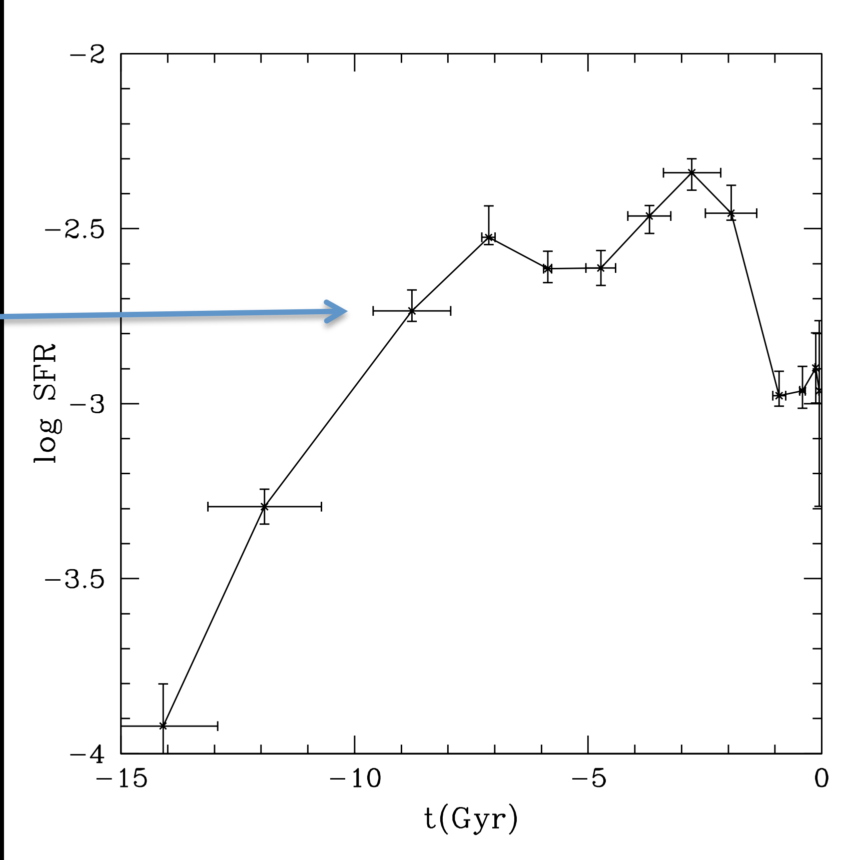


It is necessary to introduce a scale height. Here, that of Mira stars
(Wyatt & Cahn'83)

SFH from massive white dwarfs



(Tremblay+’19)

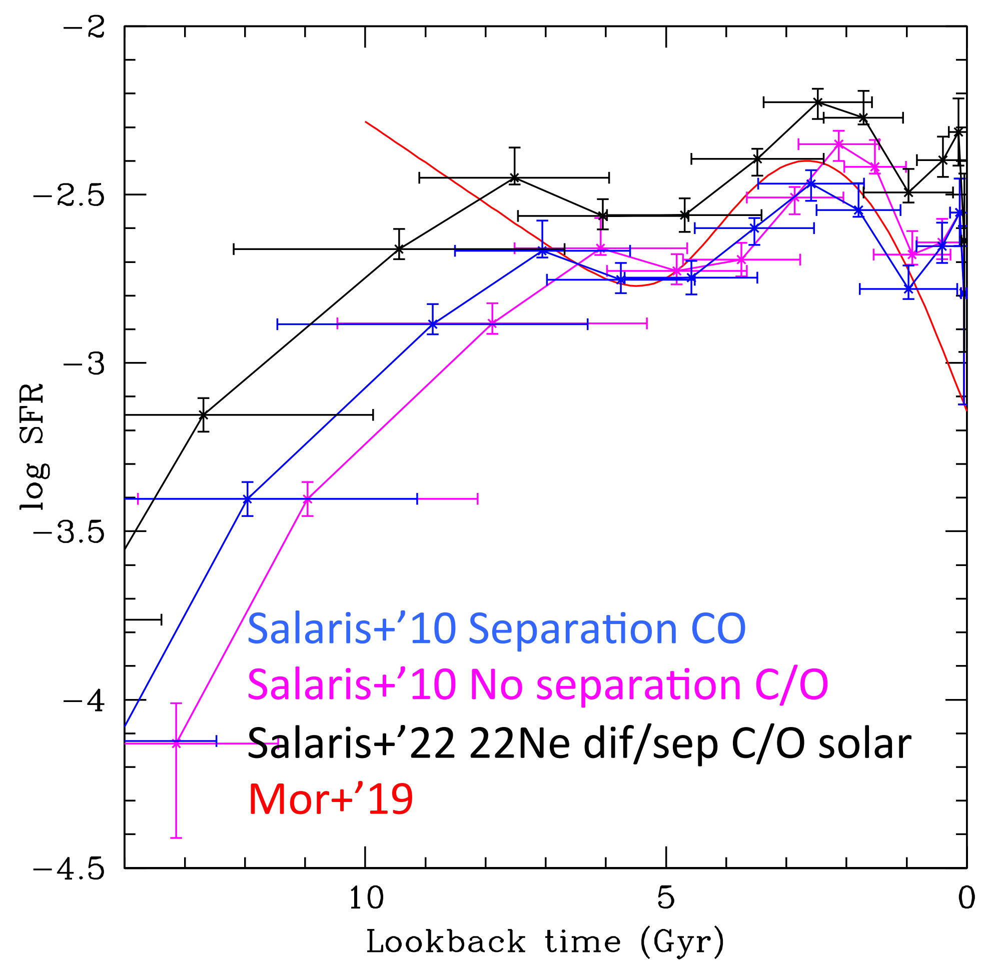


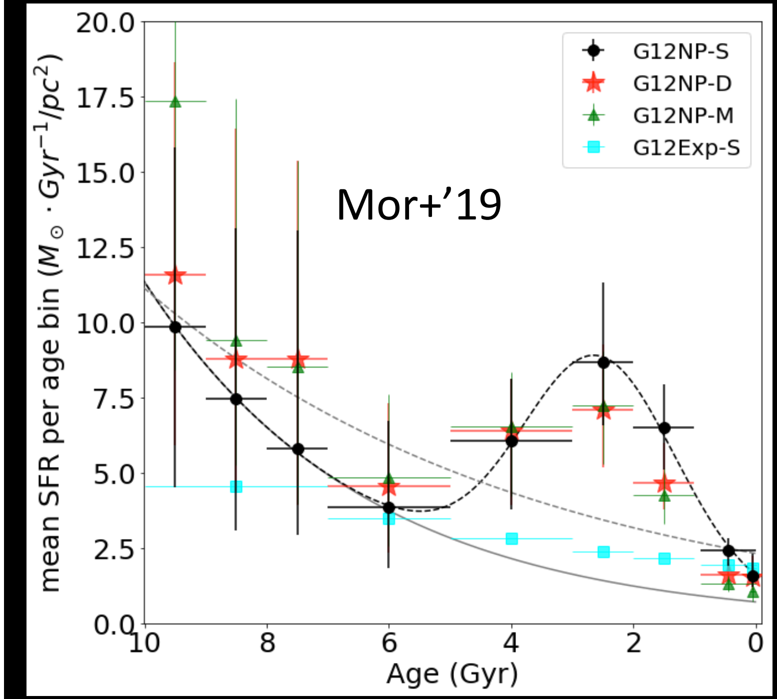
$$N(l,T) \simeq \langle \Psi \rangle \int_{\Delta M} \Phi(M)\,\Delta t_{cool}(l,M)\,dM$$

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

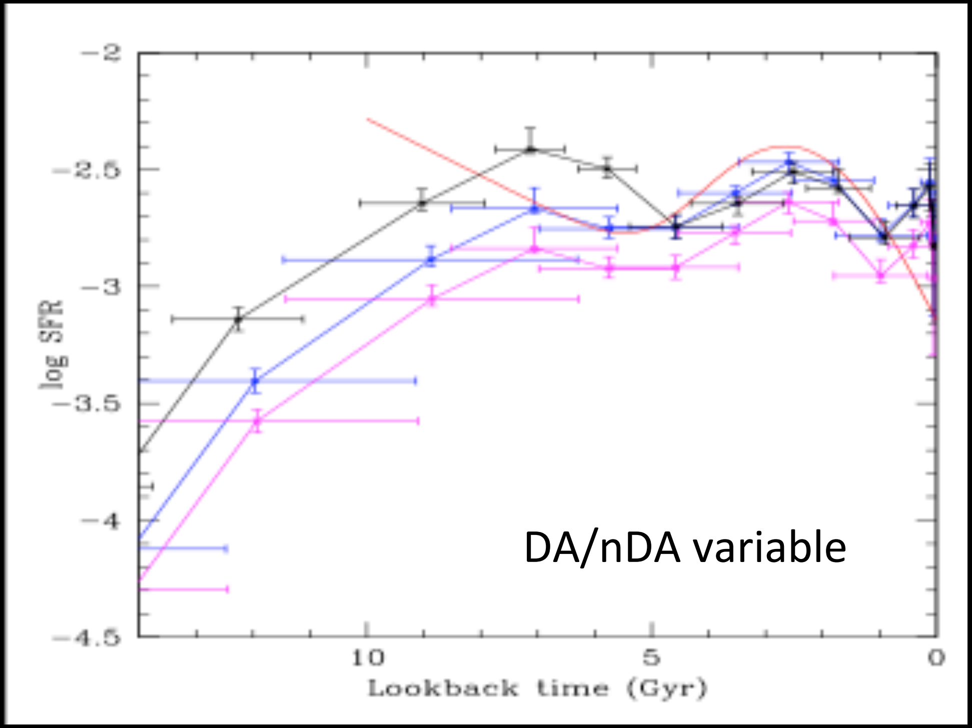
$$\langle \Psi \rangle = \frac{N(l,T)}{\int_{\Delta M} \Phi(M)\,\Delta t_{cool}(l,M)\,dM}$$

Isern+’98; Isern’19



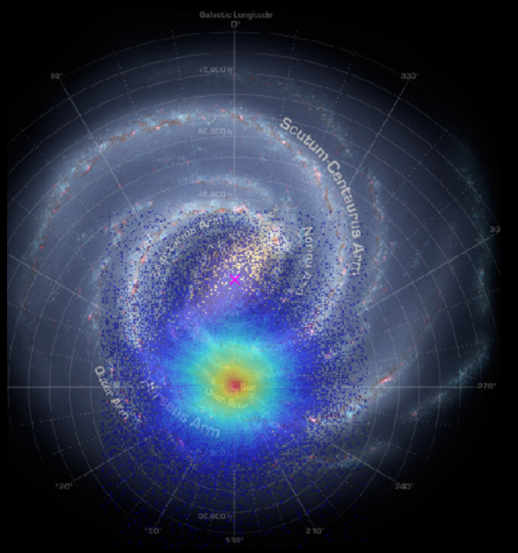


Degeneracy between galactic properties and WD evolution!
Different models provide different solutions to the SFH
External information is necessary to break the degeneracy
Analysis of Mor+’19 (Gaia + Besançon model) [*pc^{-2}]



Different origins of the discrepancy

- DA-nDA conversion
- DD-mergers
- …



- Inside-out formation of the disc + migrations (Kubryc+’15,Frankel +18)?
- Thick disk formation (Haywood+19)
- Intermitent galactic flows (Noguchi+19)
- Disk inflation induced by Gaia-Enceladus like events (Helmi+18)?

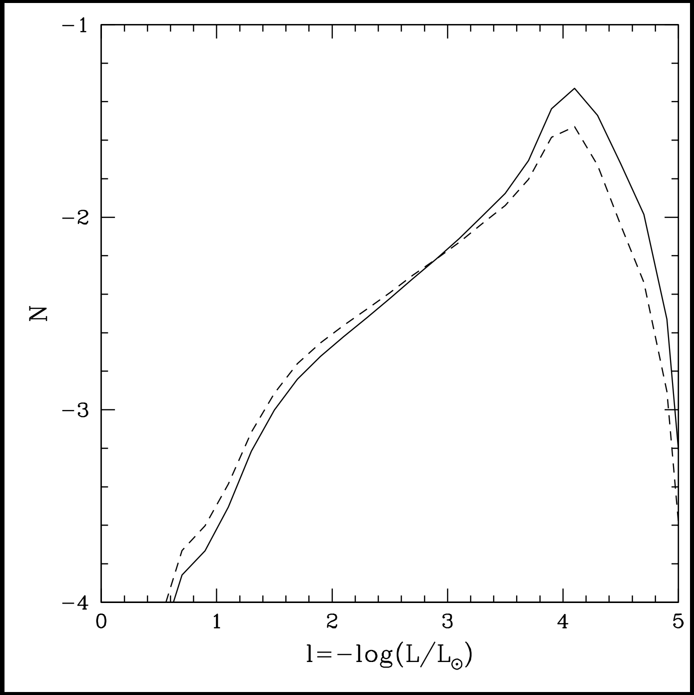
Conclusions

It is evident that the influence of metallicity cannot be avoided

The information about the initial metallicity is not retained by the atmosphere of single white dwarfs

The relationship between age-metallicity do not follow a simple, unique relationship but displays a noticeable dispersion

How to proceed? Obviously through chemodynamical models of the Galaxy. But the paradigm is changing! and we need a solid anchor.



Empirical determination of the WDLF in no-ninteracting binary systems:

- Mass of the WDs (massive in particular!)
- Age of the binary system
- Age-metallicity relationship
- Effective SFH

The solid line represents the LF of WD in non-interacting binarie. The dashed line that of single WD. Both normalized at l=3 and Z(t)=Zo