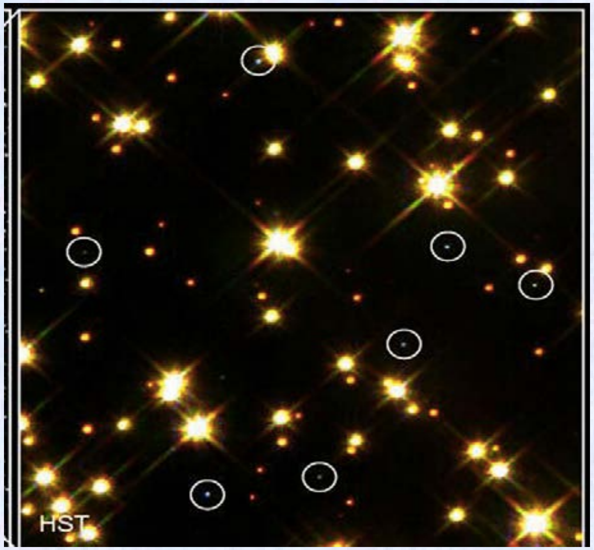
WHITE DWARFS IN GLOBULAR CLUSTERS: PRESENT AND FUTURE



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THE ASTROPHYSICAL JOURNAL, 434:641–651, 1994 October 20

COOLING THEORY OF CRYSTALLIZED WHITE DWARFS

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ABSTRACT

We examine extensively the effect of the different crystallization processes, related to the presence of major and minor chemical species, on the binding energy and the cooling time of old white dwarfs. We use improved equations of state for the solid and the liquid, and crystallization diagrams calculated within the modern theory of freezing. We show that, in spite of their small abundance, trace elements severely alter the cooling process and lengthen the cooling time of the star for a given luminosity by several gigayears. In particular, ^{22}Ne is shown to provide enough gravitational energy at crystallization to sustain the star at the same luminosity for a time larger than the one due to the crystallization of C/O itself. These calculations demonstrate the necessity of including a proper treatment of crystallization in modern white dwarf cooling theory. We also consider the effect of an initial composition gradient in the distribution of carbon and oxygen throughout the star. Finally, we show that a substantial portion of the interior of massive white dwarfs is already in a quantum state in the *fluid* phase and that Debye cooling probably occurs prior to crystallization in these stars.
Subject headings: stars: interiors — stars: luminosity function, mass function — white dwarfs

THE ASTROPHYSICAL JOURNAL, 434:652–661, 1994 October 20

THE INFLUENCE OF CRYSTALLIZATION ON THE LUMINOSITY FUNCTION OF WHITE DWARFS

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Received 1993 August 2; accepted 1993 December 30

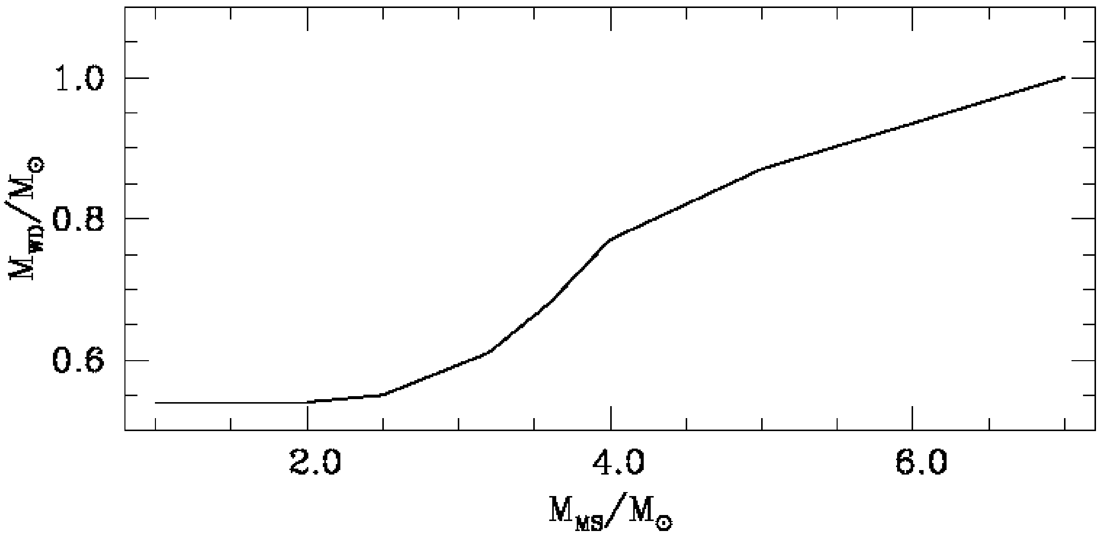
ABSTRACT

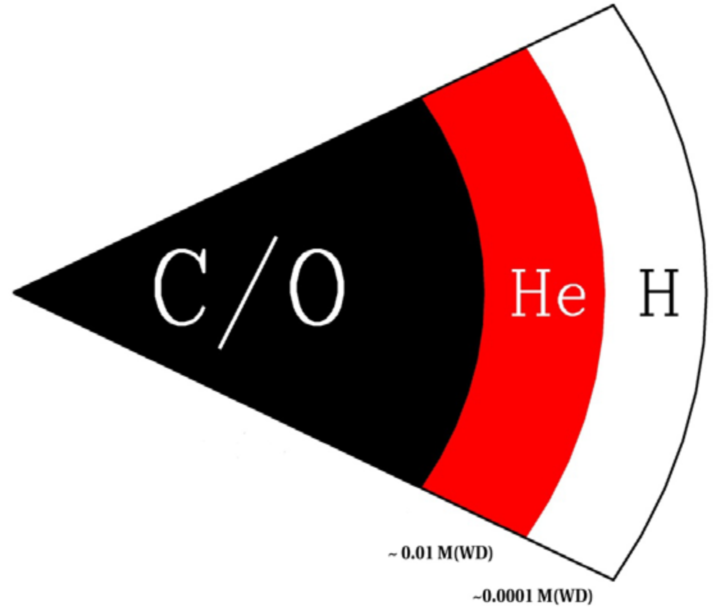
The inclusion of a detailed treatment of solidification processes in the cooling theory of carbon-oxygen white dwarfs is of crucial importance for the determination of their luminosity function. Carbon-oxygen separation at crystallization yields delays larger than 2 Gyr in the cooling time for a white dwarf to cool down to the observed cutoff luminosity, i.e., $\log (L/L_\odot) \sim -4.5$. When calculating the luminosity function, this leads to estimates of the age of the Galactic disk 1.5–2 Gyr older than the ones obtained when ignoring such separation processes. Furthermore, the presence of minor chemical species, in particular, ^{22}Ne and ^{56}Fe, alters significantly the crystallization process and the cooling time and produces extra delays of 2–3 Gyr. However, the detailed computation of the theoretical white dwarf luminosity function, taking into account galactic chemical evolution, shows that, for minor species, this effect does not modify significantly the location of the cutoff, and thus the estimated age of the disk. The effect of ^{22}Ne crystallization is shown to produce a sharp peak in the luminosity function at $\log (L/L_\odot) \sim -3.8$. Though nondetectable with present-day observations, this peak can be used as a future observational test of the crystallization of minor chemical species in white dwarf interiors.
Subject headings: equation of state — stars: interiors — white dwarfs

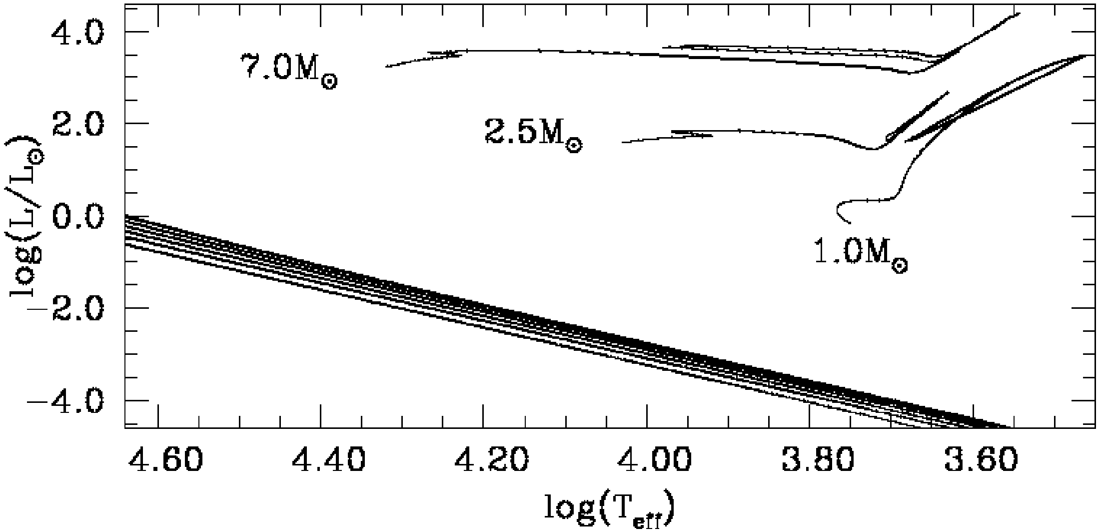
OUTLINE

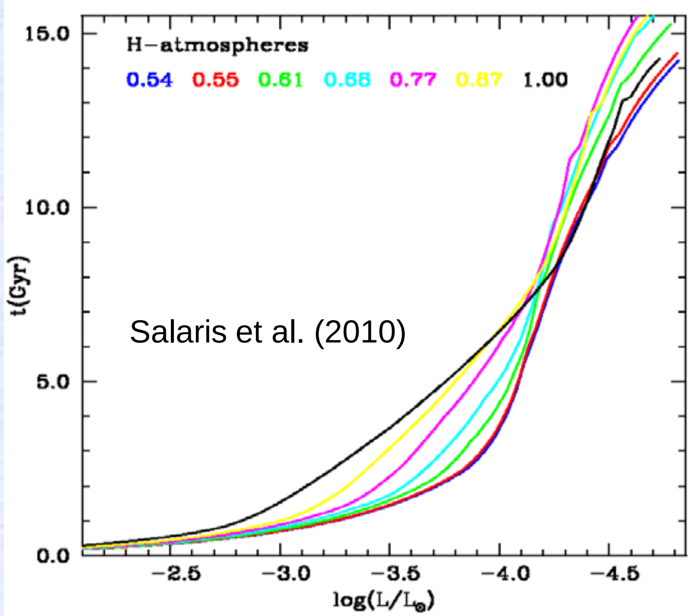
- **WD isochrones and cluster CMDs**
- **Main results about globular cluster WDs**
- **IR is the future (JWST and ELT)**

White dwarfs







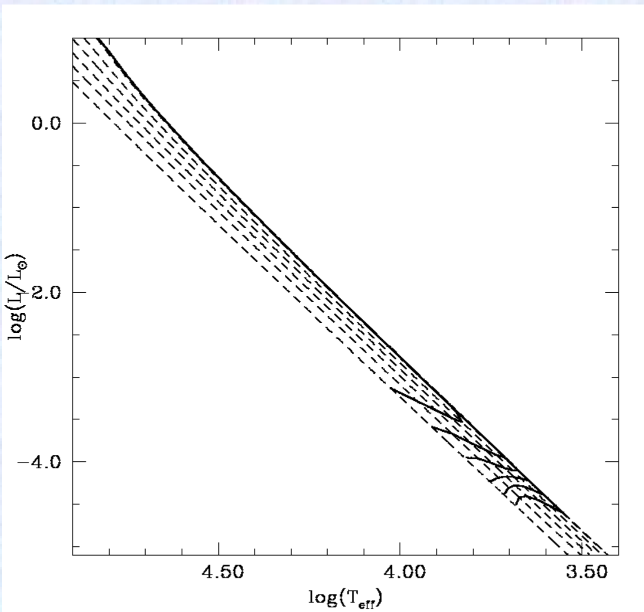


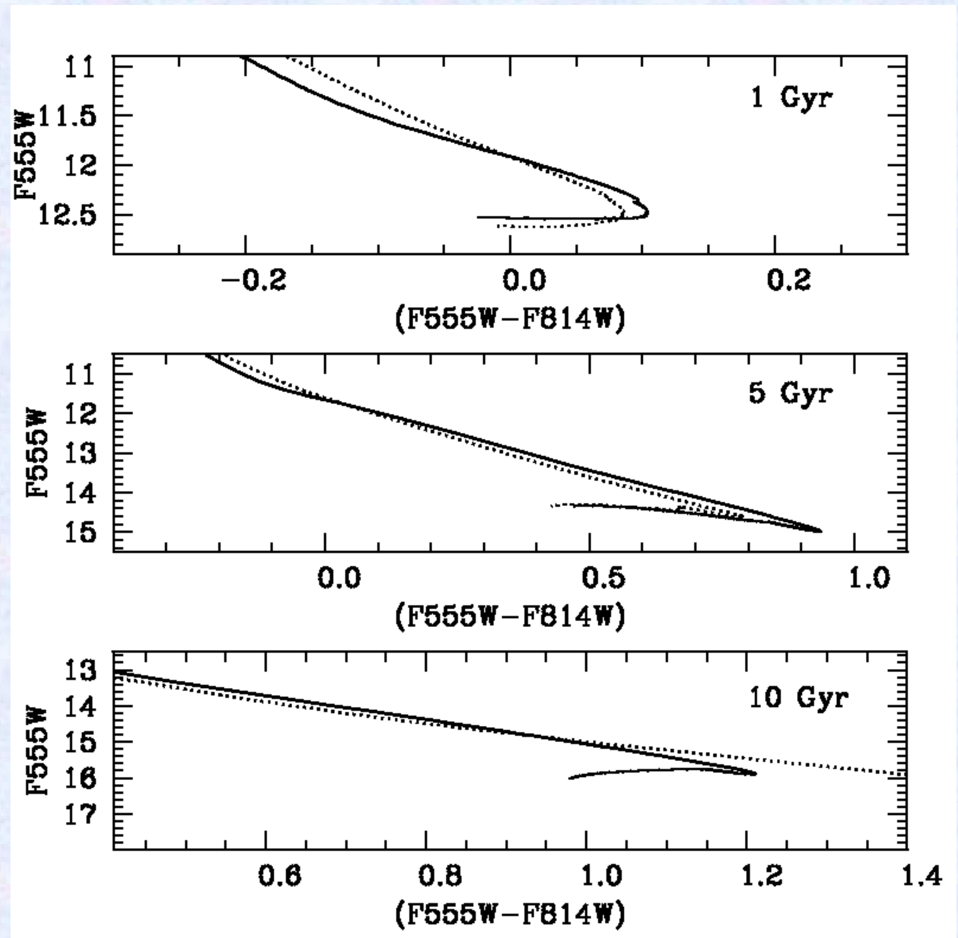
WD cosmochronology

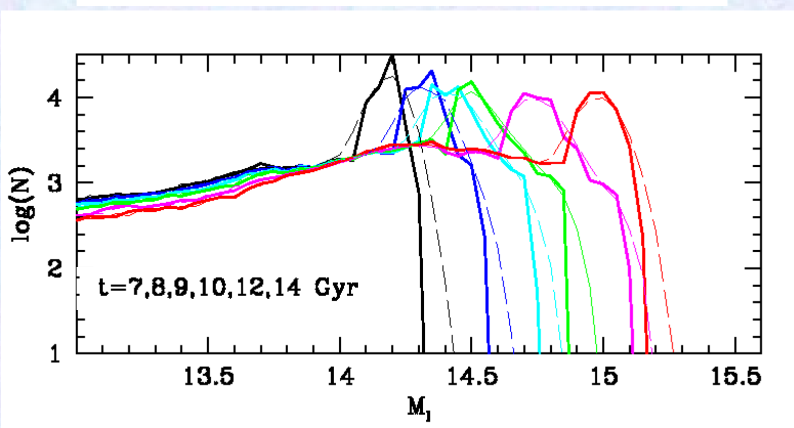
Ingredients: WD cooling models – Initial-final mass relationship – progenitor ages − bolometric corrections

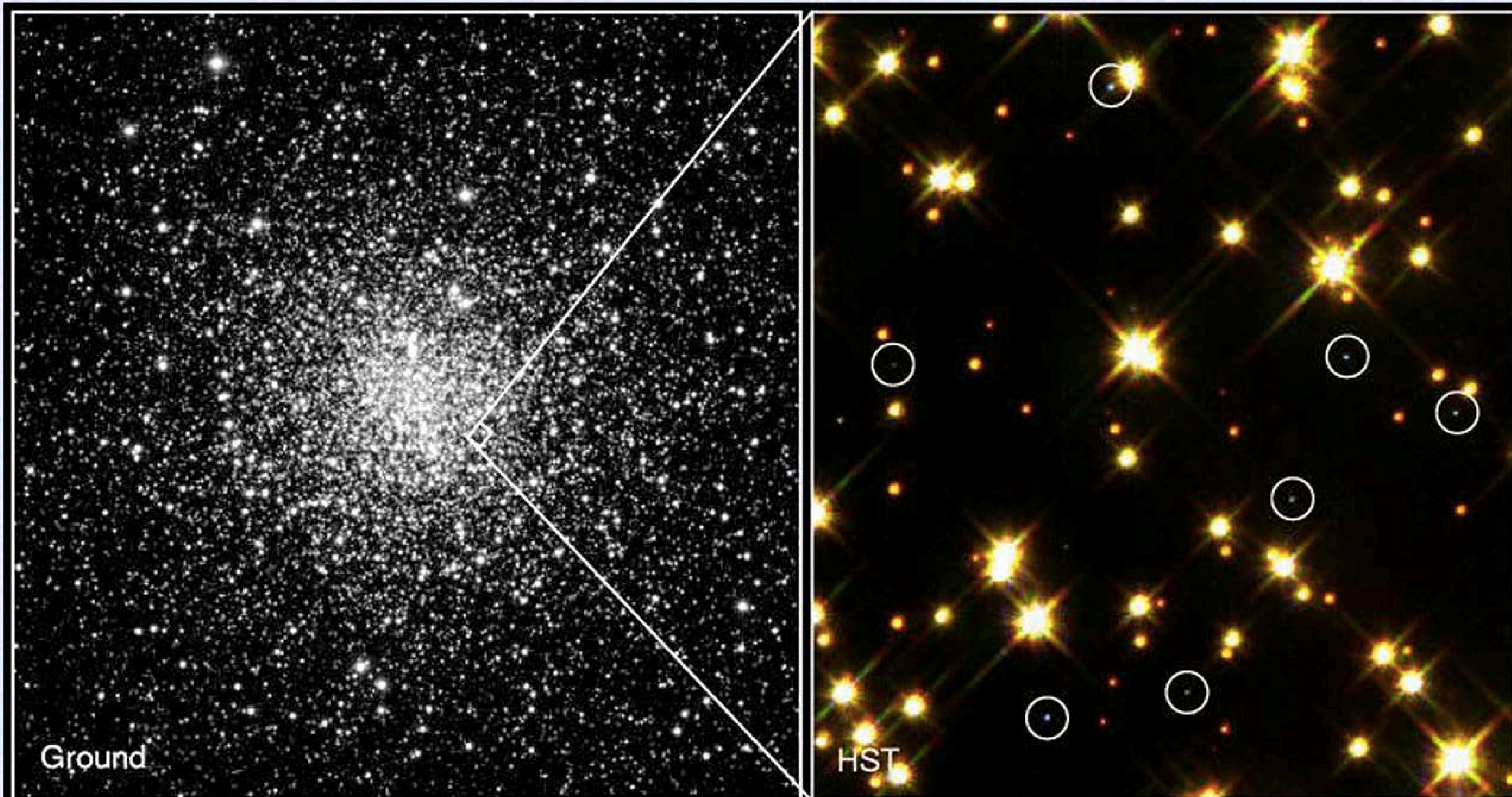
$$t(iso) = t(WD) + t(prog)$$

Salaris et al. (2010)









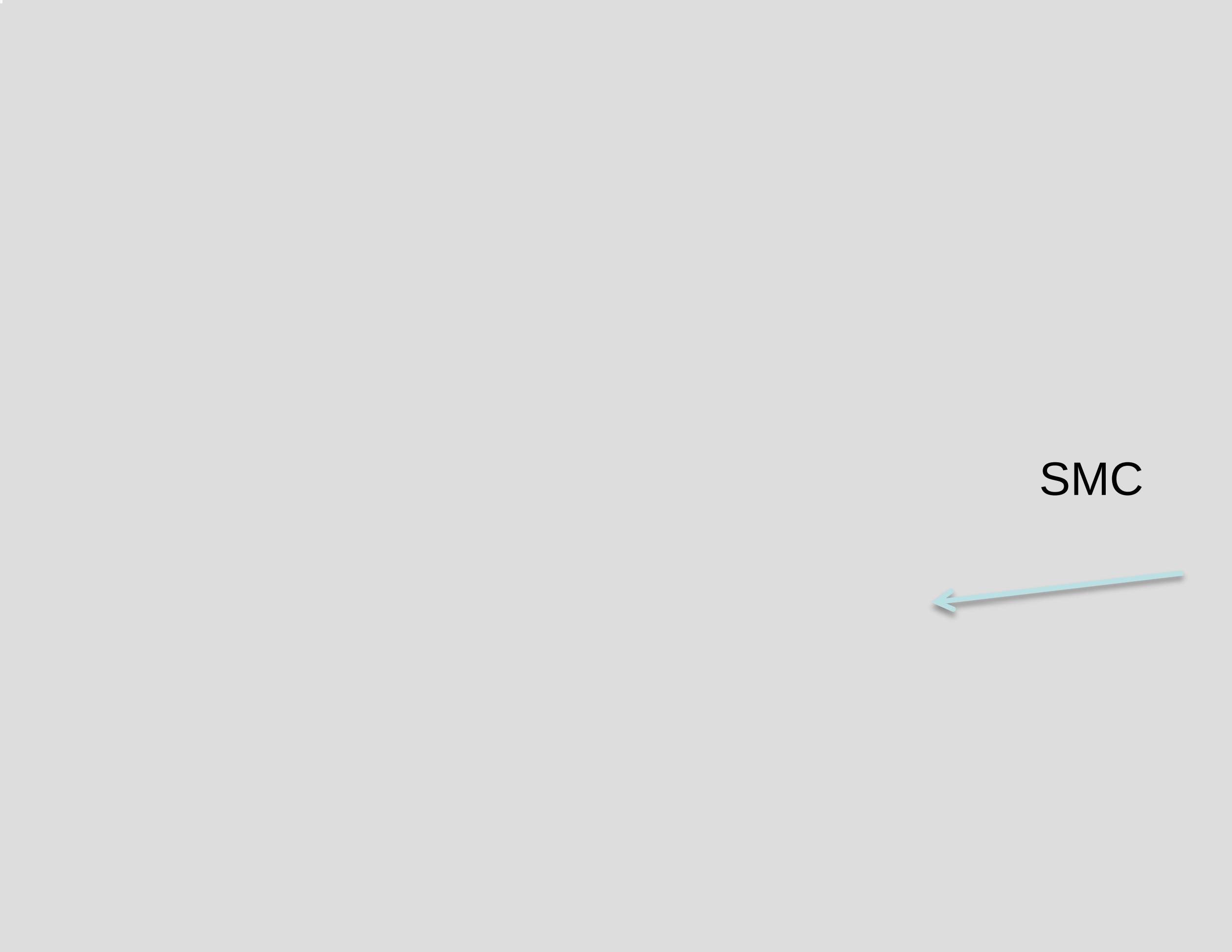
White Dwarf Stars in M4 HST · WFPC2

PRC95-32 · ST ScI OPO · August 28, 1995 · H. Bond (ST ScI), NASA

Hot WDs observed in

M71 (GB) **NGC6752 (HST)** **NGC2808 (HST)** **M15 (HST)**
M80 (HST) **NGC3201 (GB)** **ω Cen (HST)**

Complete WD (DA) sequences observed (HST) in



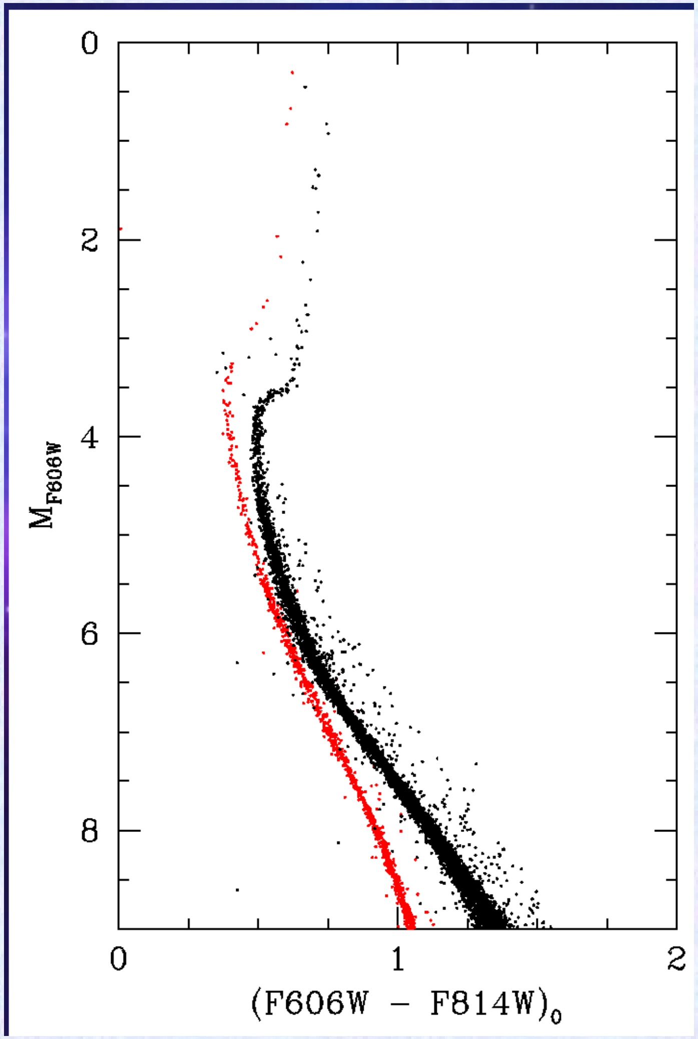
WD ages for

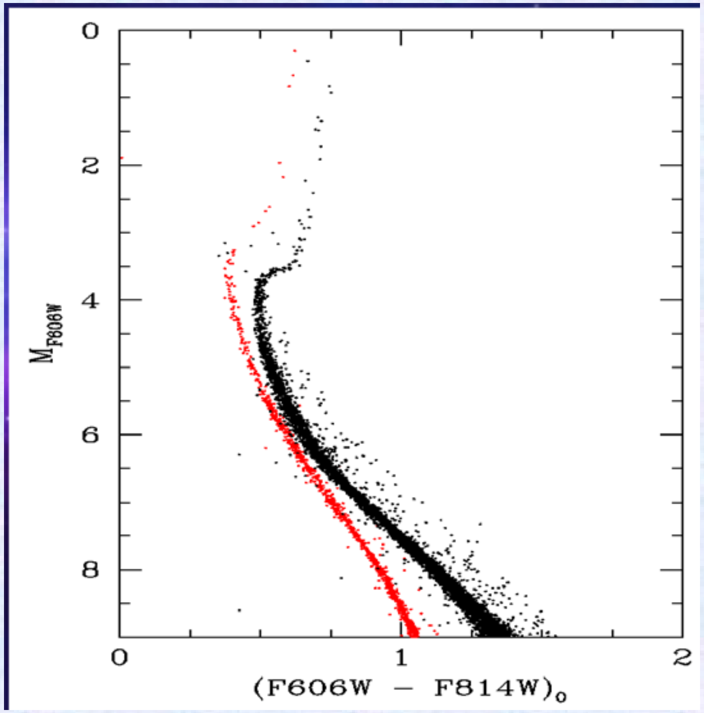
NGC6397
Hansen et al.(2007)
Torres et al. (2015)
Campos et al. (2016)

M4
Hansen et al (2004),
Bedin, Salaris et al. (2009)
Campos et al. (2016)

47 Tuc
Hansen et al. (2013)
Garcia-Berro et al. (2014)
Campos et al. (2016)

47 Tuc and NGC6397

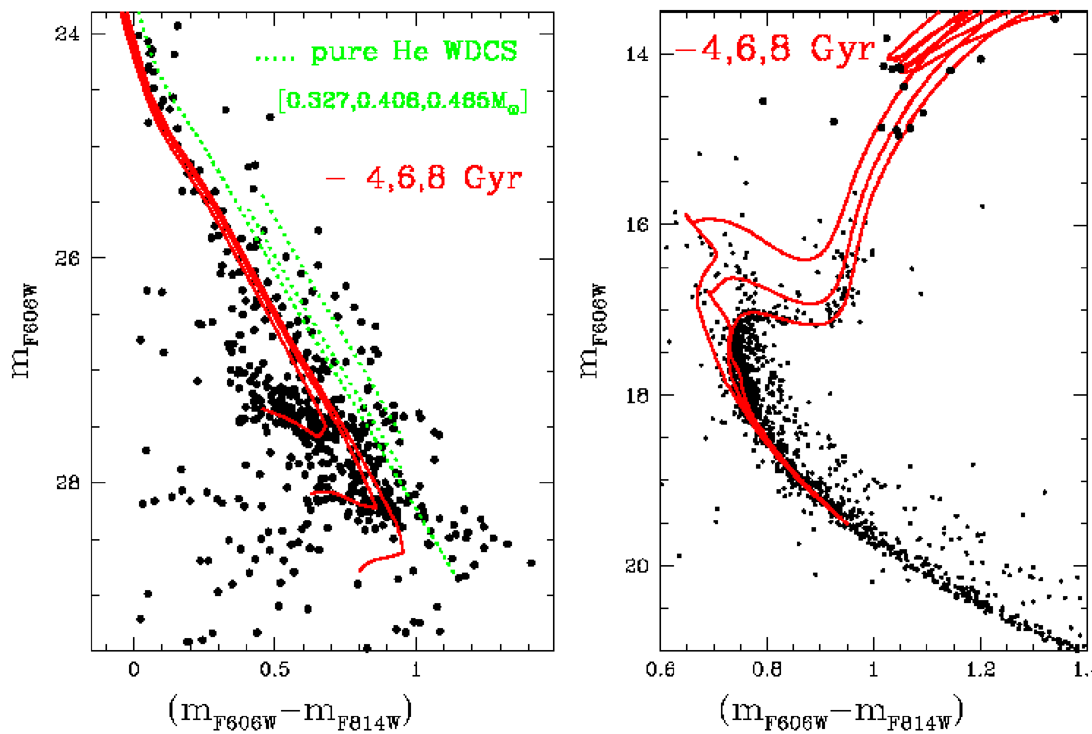


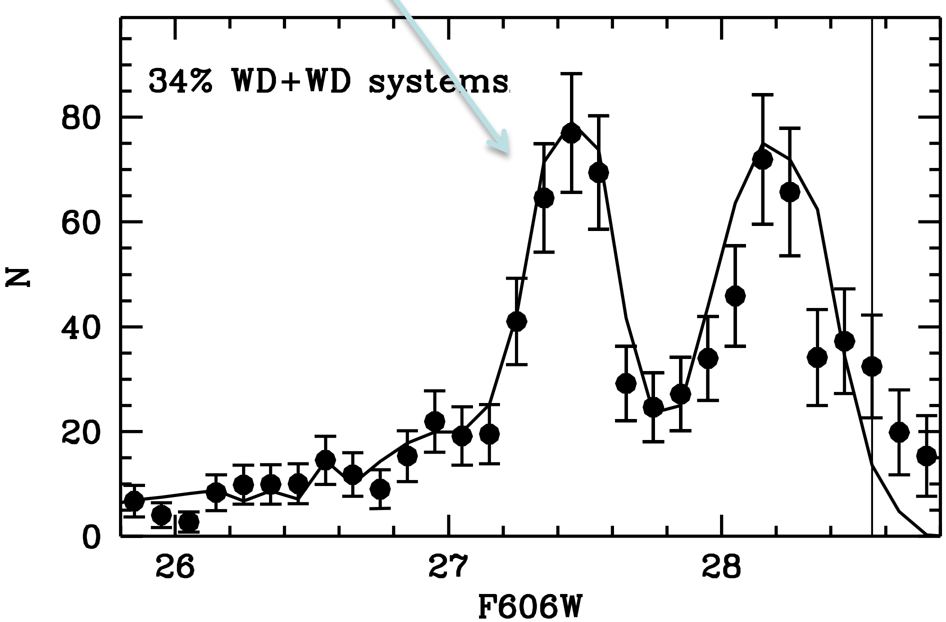


Richer et al. (2013)

NGC 6791

50% initial fraction of binaries
+
^{22}Ne diffusion



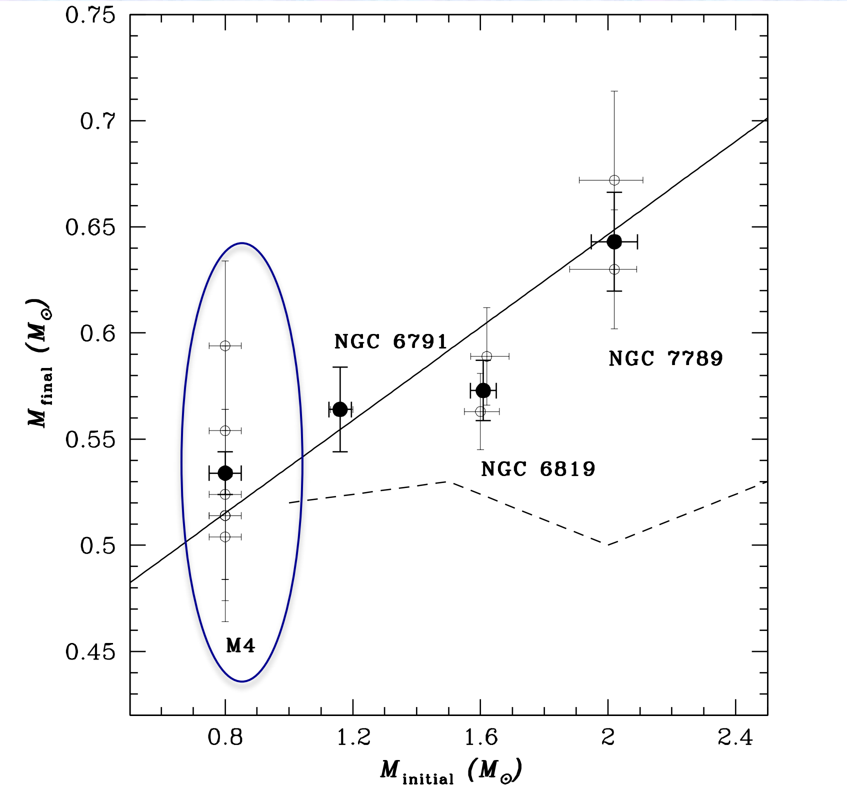


Bedin, Salaris et al. (2005, 2008a, b)

Garcia Berro et al. (2010, 2011)

Mass of bright WDs in M4

Kalirai et al. (2009) 6 members



Average
0.53 ± 0.01 $M_\odot$

Keck spectra to determine T_{eff} and surface gravity *g* from Balmer lines' fitting

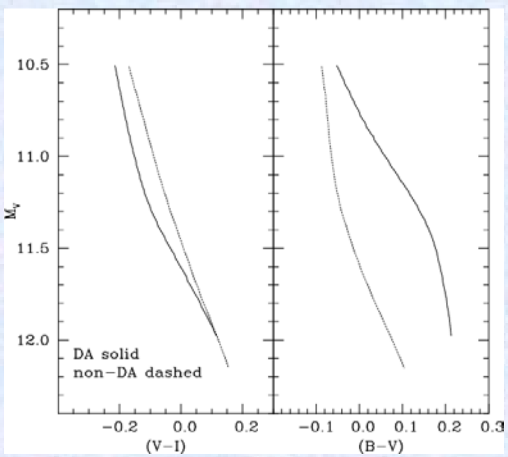
Once *g* is known, using of a theoretical M-R relationship provides the WD mass

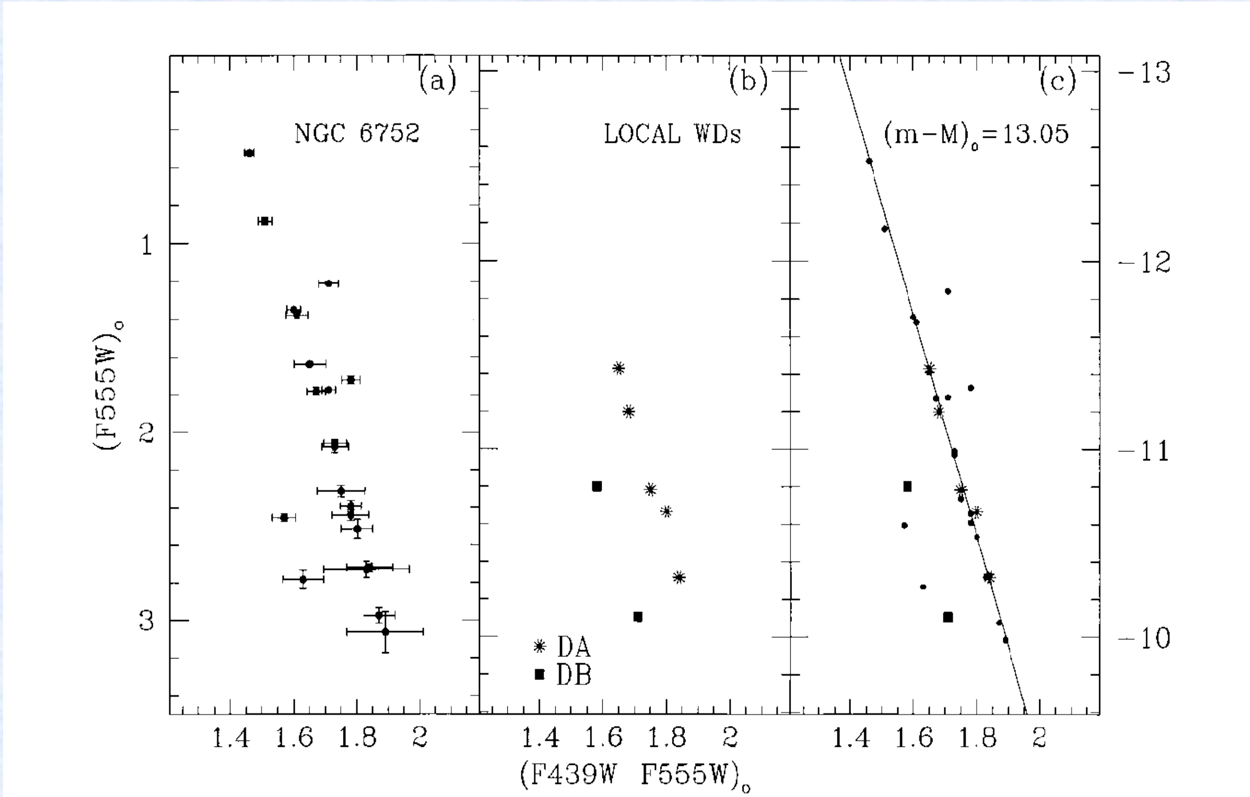
With a different method Moehler et al. (2004) estimate 0.53 ± 0.03 $M_\odot$ for a total of 8 WDs in NGC6752 and NGC6397

Distance from WD-fitting

NGC6752

Salaris et al. (2001)





Assumed a value for E(B-V)

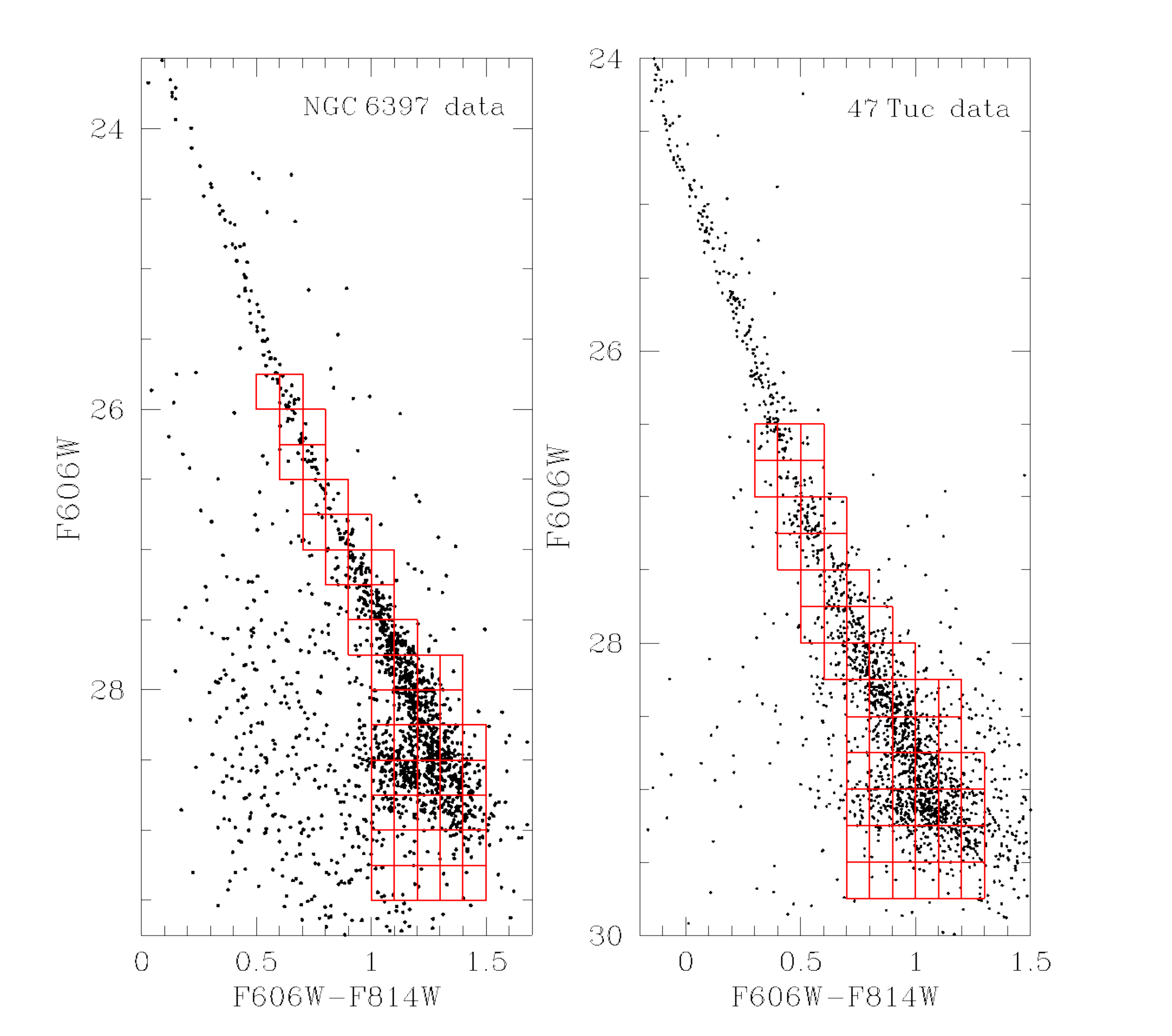
$\Delta M_V / \Delta(M/M_\odot) \cong 2.3$

$\Delta M_V / \Delta \log q(\mathrm{H}) \sim -0.035$

NGC6752 (Renzini et al. 1996)
47 Tuc (Zoccali et al. 2001)
M5 (Layden et al. 2005)

Salaris et al. (2001) have investigated uncertainties of this method

Hansen et al. (2004, 2007, 2013), Garcia-Berro et al. (2014), Torres et al. (2015), Campos et al. (2016)



Campos et al. (2016)

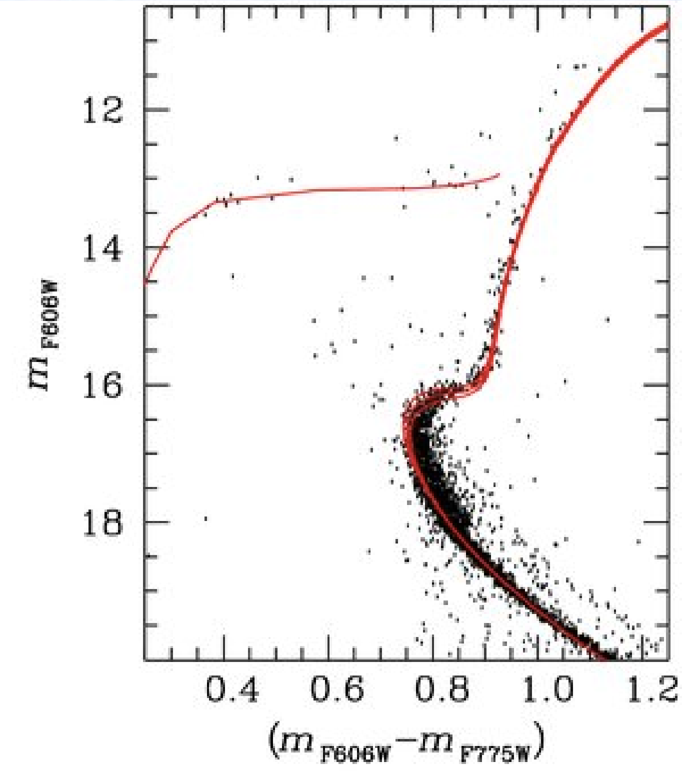
MC simulations of the WD CMD, including photometric errors and completeness

Bright part of the sequence to constrain distance modulus and reddening

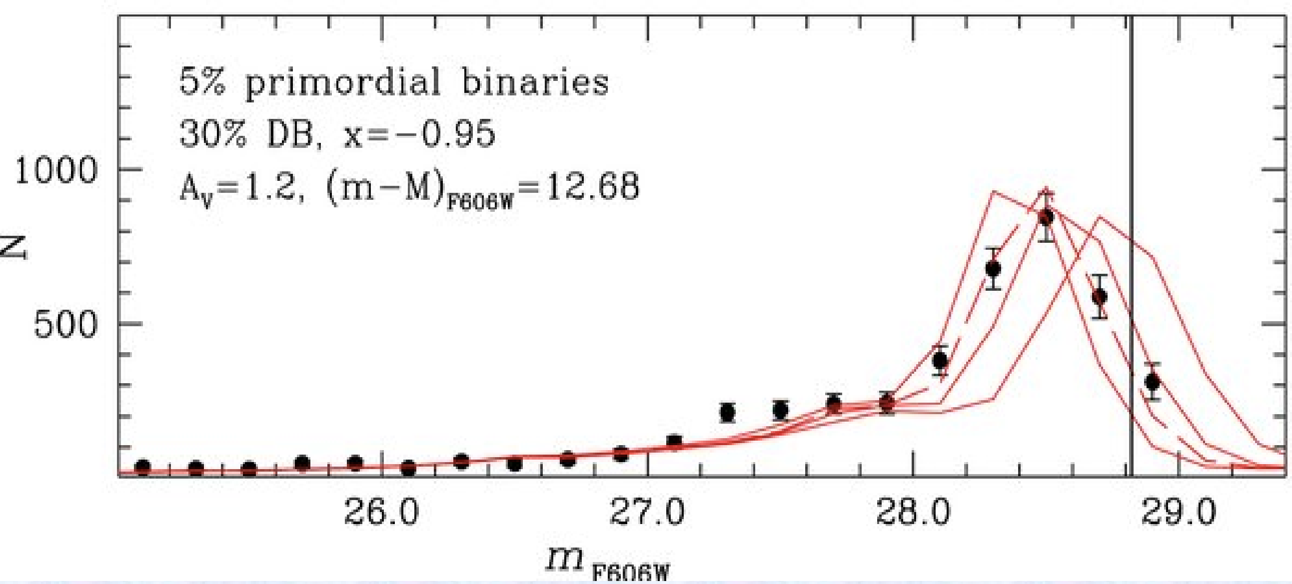
MF exponent as a free parameter. Fraction of DB WDs (and unresolved WD+WD binaries) can also be included

Use of the WD luminosity function, simulated with a MC technique, including photometric errors and completeness

11, 12, and 13 Gyr



11, 11.6 (dashed line), 12, and 13 Gyr

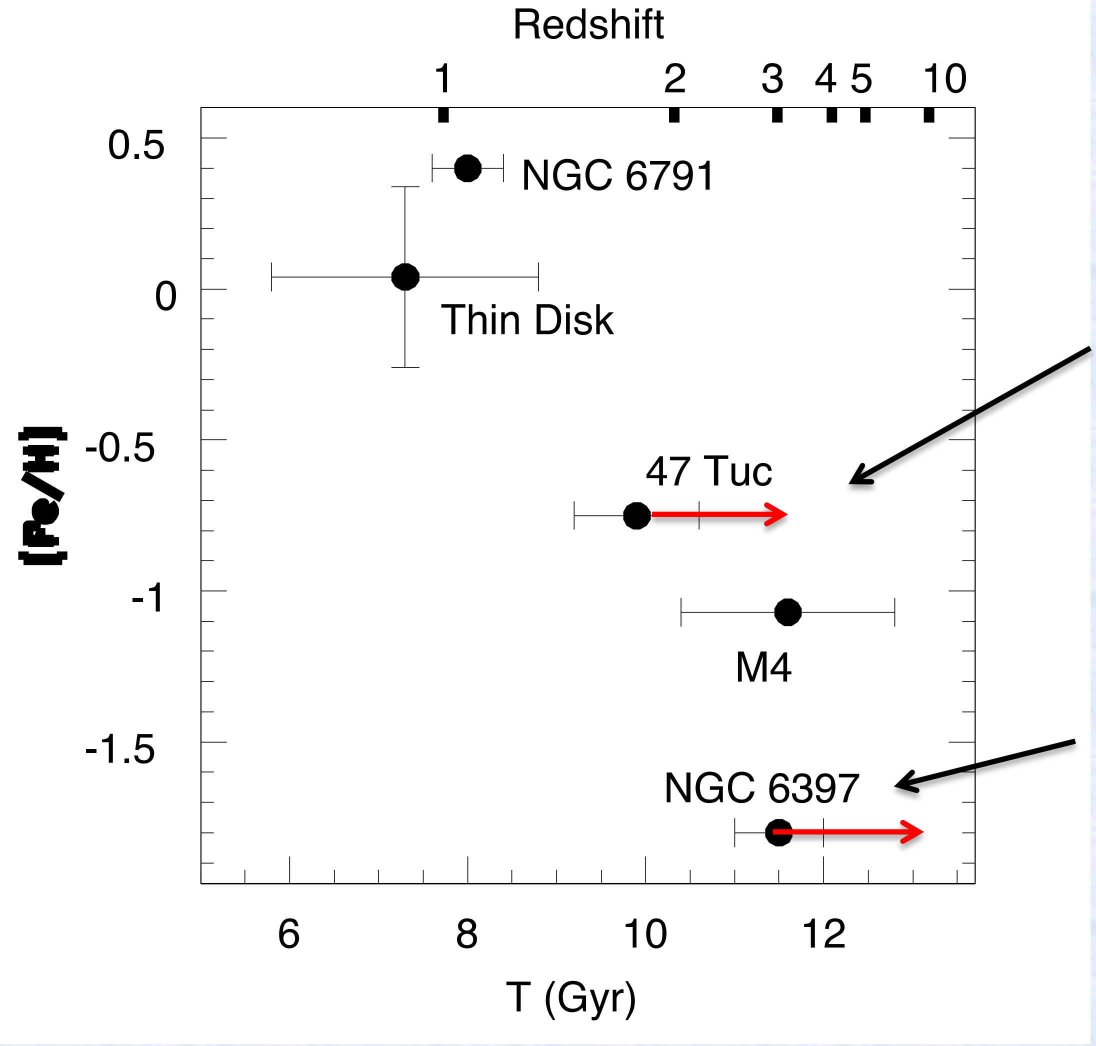


M4

Bedin, Salaris et al. (2009)

Garcia-Berro et al. (2014) remarkably found an additional episode of star formation separated by ~40 Myr from the older one

Link with the GC multiple-population phenomenon



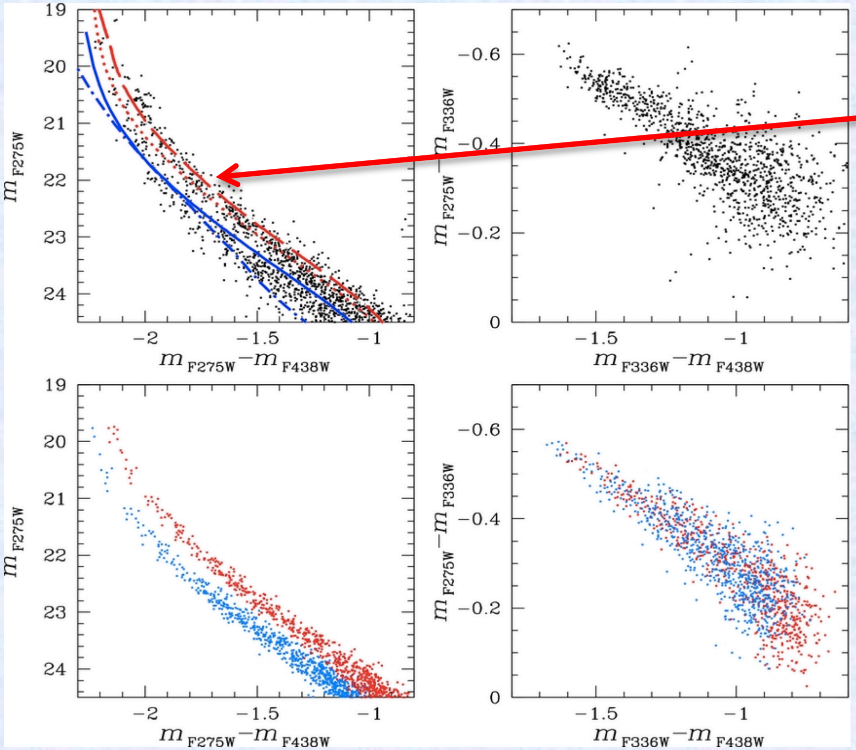
Different methodologies and/or different implementations of the same methods, but especially different cooling models

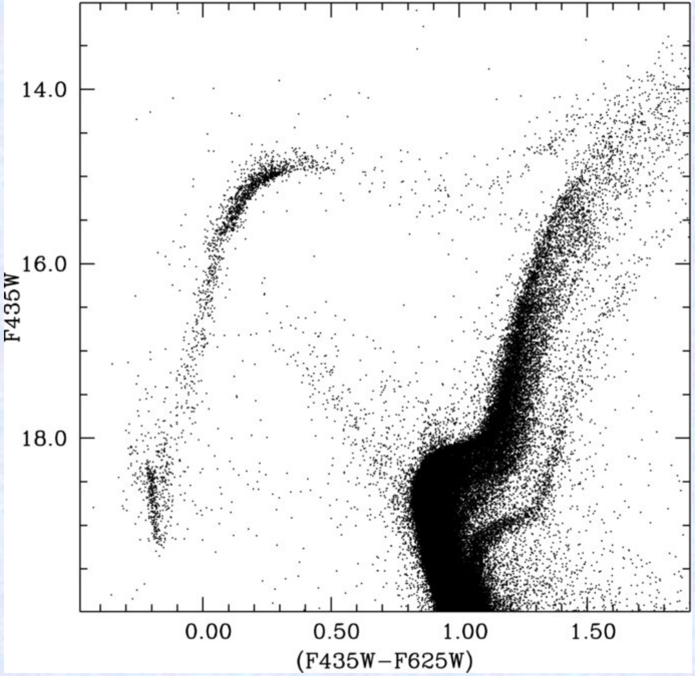
Original figure from Hansen et al. (2013)

Hot WDs in ω Centauri

Bellini et al. (2013)

Double bright WD sequence !





Cassisi et al. (2009)

Progeny of He-rich (Y=0.40) subpopulation in the cluster

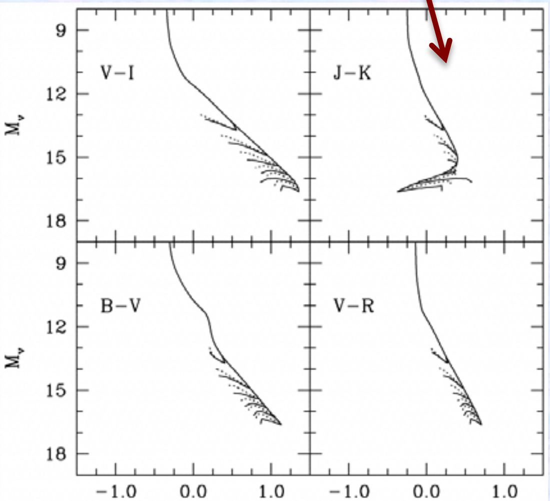
The blue WDCS is populated by the evolved stars of the He-normal component ($\sim 0.55 M_{\odot}$ CO-core DA objects) while the red WDCS hosts the end-products of the He-rich population ($\sim 0.46 M_{\odot}$ objects, ~ 10 % CO-core and ~ 90 % He-core WDs).

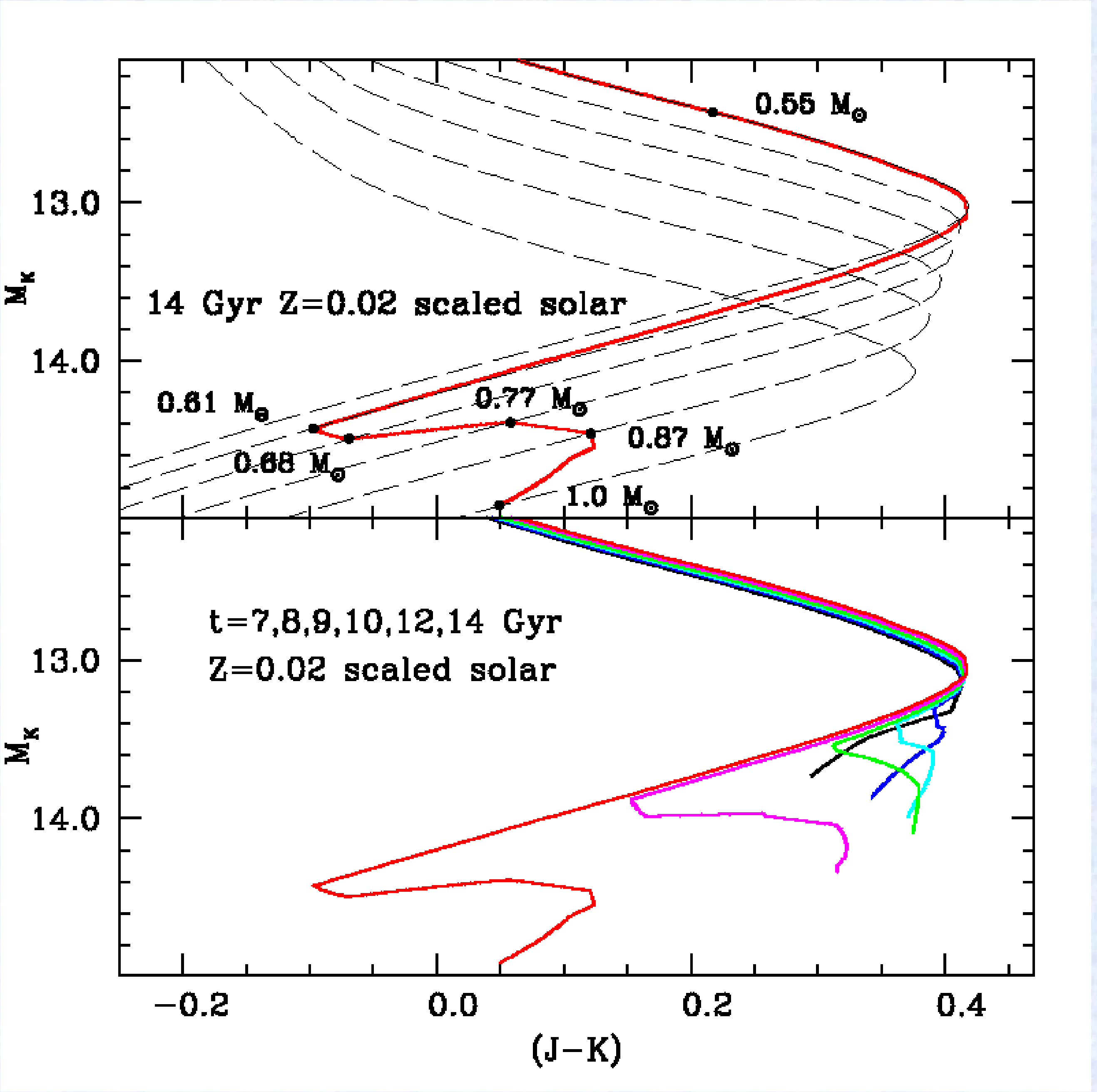
WD tracks for CO-core 0.55 $M_{\odot}$ DA (blue solid) and DB models (blue dash-dotted), and 0.46 $M_{\odot}$ DA CO-core (red dotted) and He-core (red dashed) models are fit to the observed CMD.

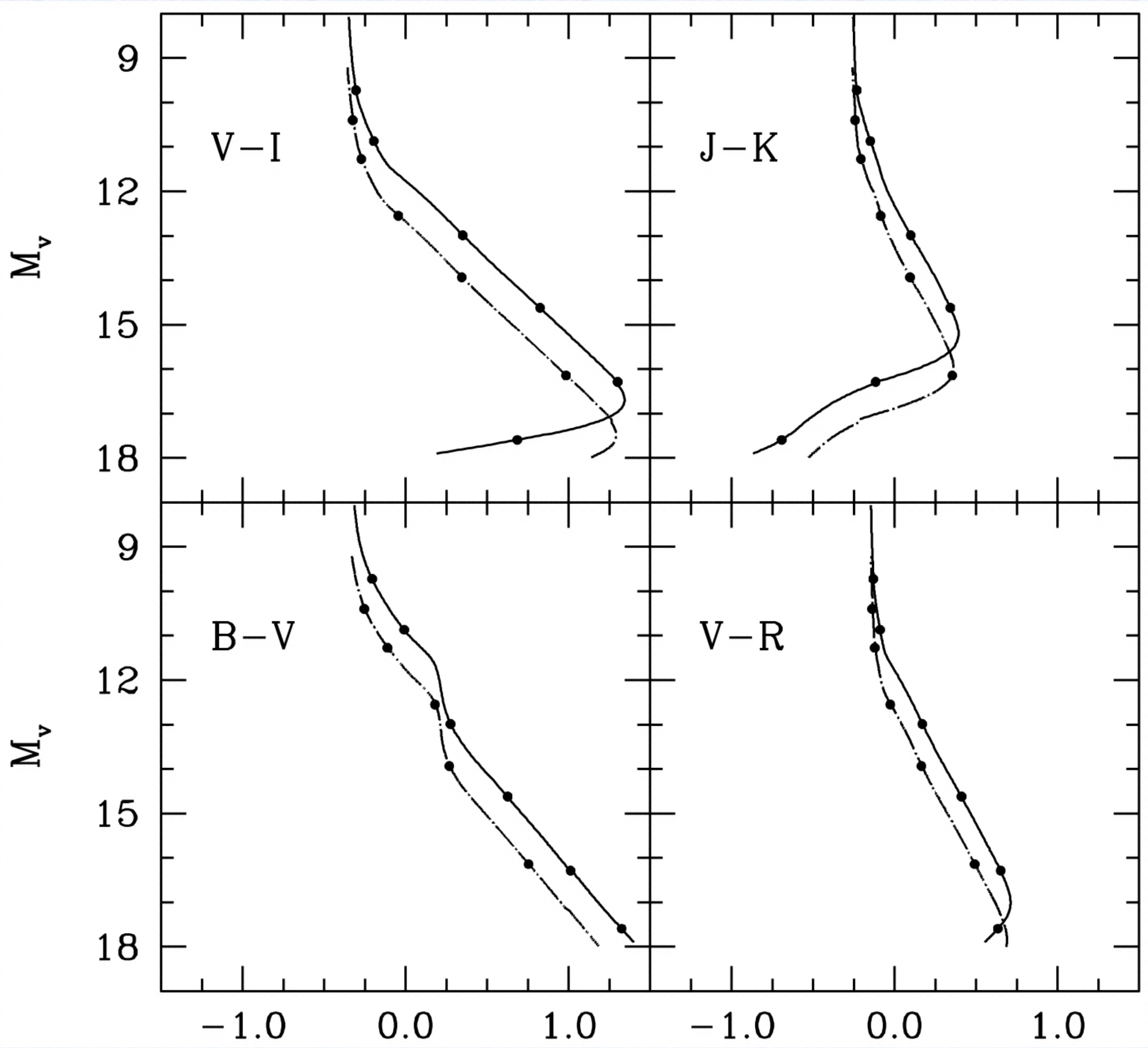
WD cluster ages in the IR (JWST, ELT)

Bono, Salaris & Gilmozzi (2012)

Already shown by Salaris et al. (2000)







0.6 and
1.0 $M_{\odot}$
WD
tracks

Salaris et al.
(2000)

Log(t) = 7.0, 8.0, 9.0, 9.5, 10.0 and 10.2

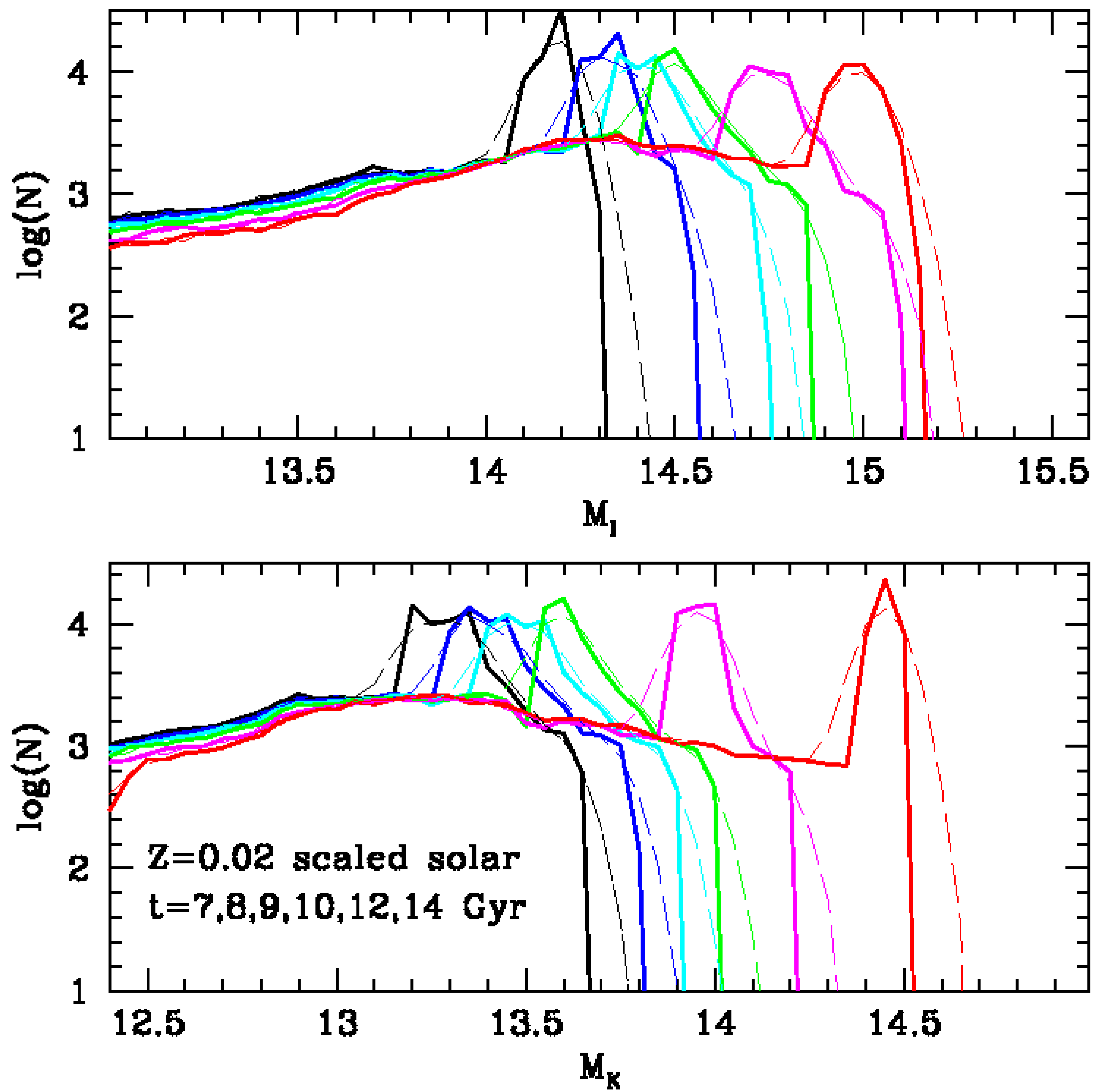
12 → 13 Gyr

ΔK ~0.22 mag

Δ(I,V) ~0.15 mag

MICADO camera on ELT

1σ photometric error 0.05 mag at the bottom of WD sequence for clusters with (m-M) < 15.0-15.5

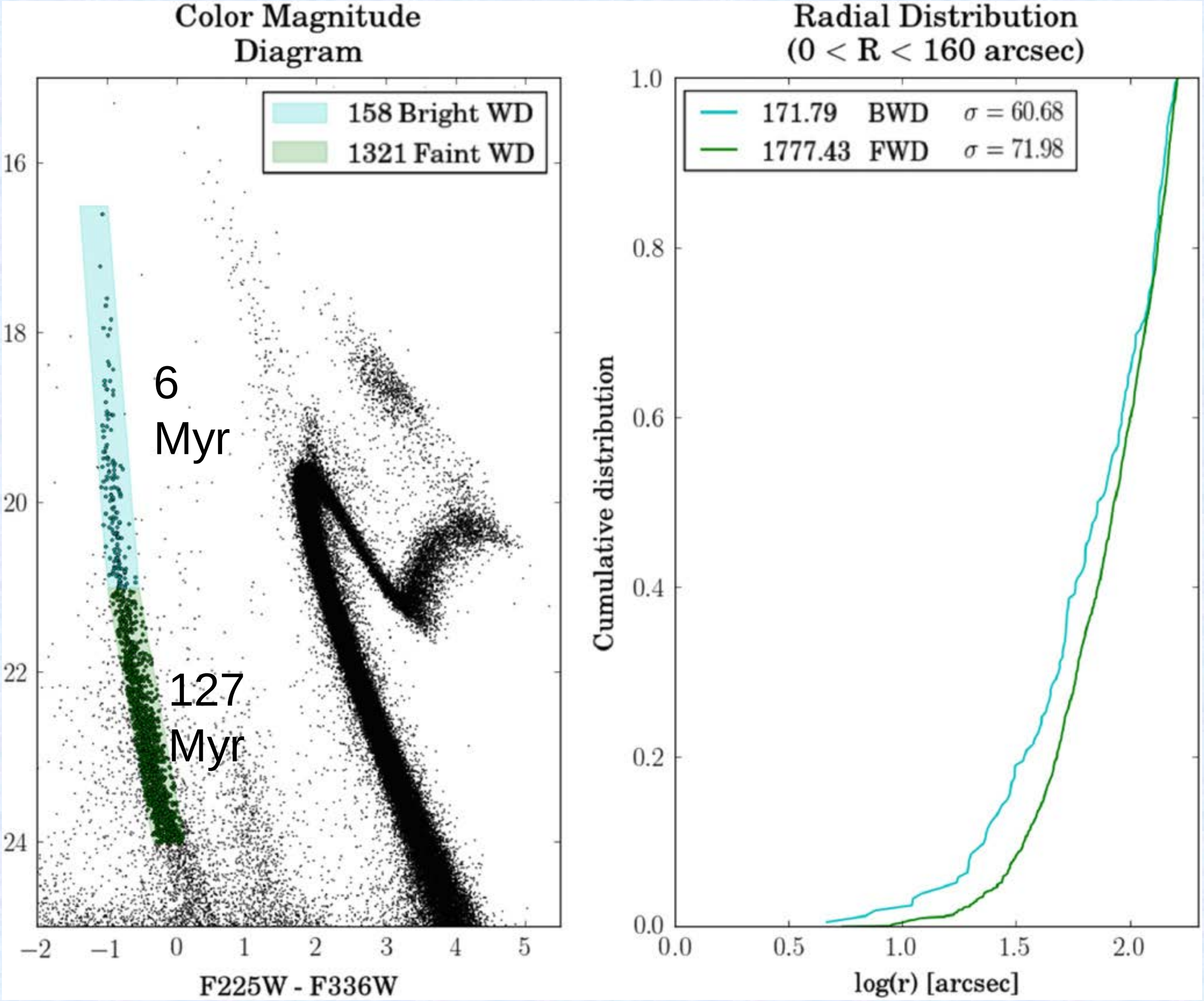


A JWST Survey of White Dwarfs in Globular Clusters

Cluster	$(m-M)_0$	A_{F814W}	Target Mag F814W	F090W Exp Time (hr)	F150W Exp Time (hr)
NGC 6121 (M4)	11.7	0.54	27.4	1	1.5
NGC 6397	11.8	0.27	27.4	1	1.5
NGC 104 (47 Tuc)	13.2	0.06	28.5	6.9	10.6
NGC 6656 (M22)	12.5	0.53	28.2	4	6.1
NGC 6752	13	0.06	28.3	4.9	7.4
NGC 6838 (M71)	13	0.37	28.6	8.3	12.6
NGC 6254 (M10)	13.2	0.41	28.8	12.5	18.3
NGC 6218 (M12)	13.5	0.28	29	17.2	26.4
NGC 3201	13.5	0.34	29	17.2	26.4
NGC 5139 (Ω Cen)	13.6	0.18	29	17.2	26.4
NGC 6809 (M55)	13.6	0.12	28.9	14.4	21.9

Rate of diffusion of stars through the cluster core

$$\kappa \approx 10-13$$

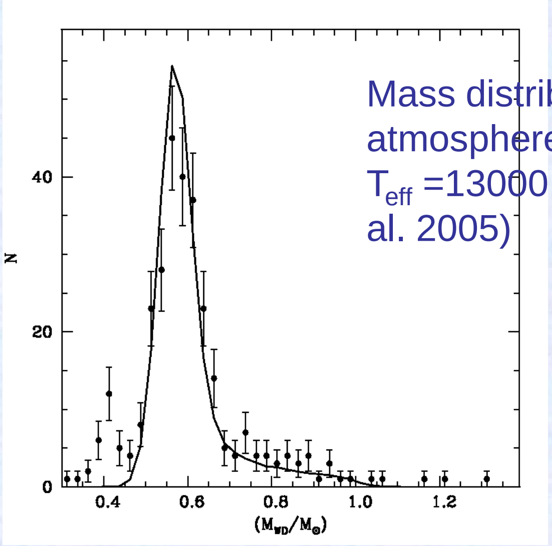


47 Tuc

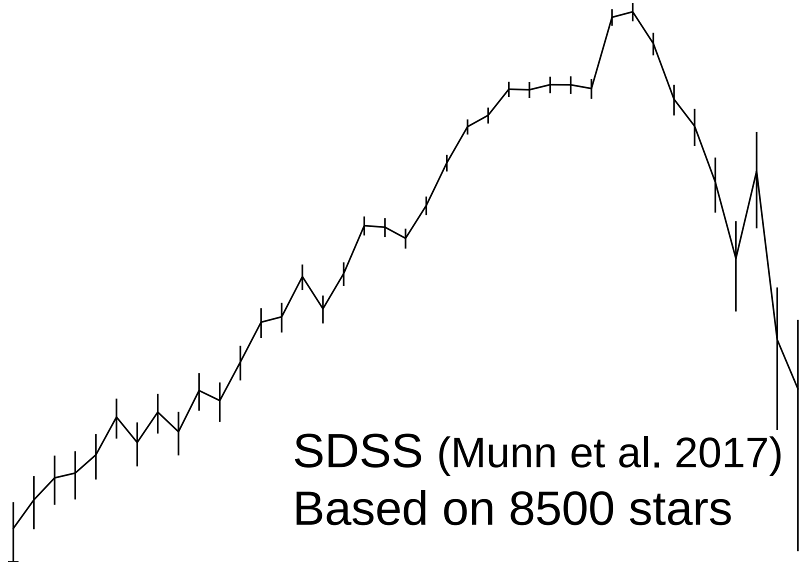
Heyl et al. (2015)

Age of the oldest population of the solar neighbourhood

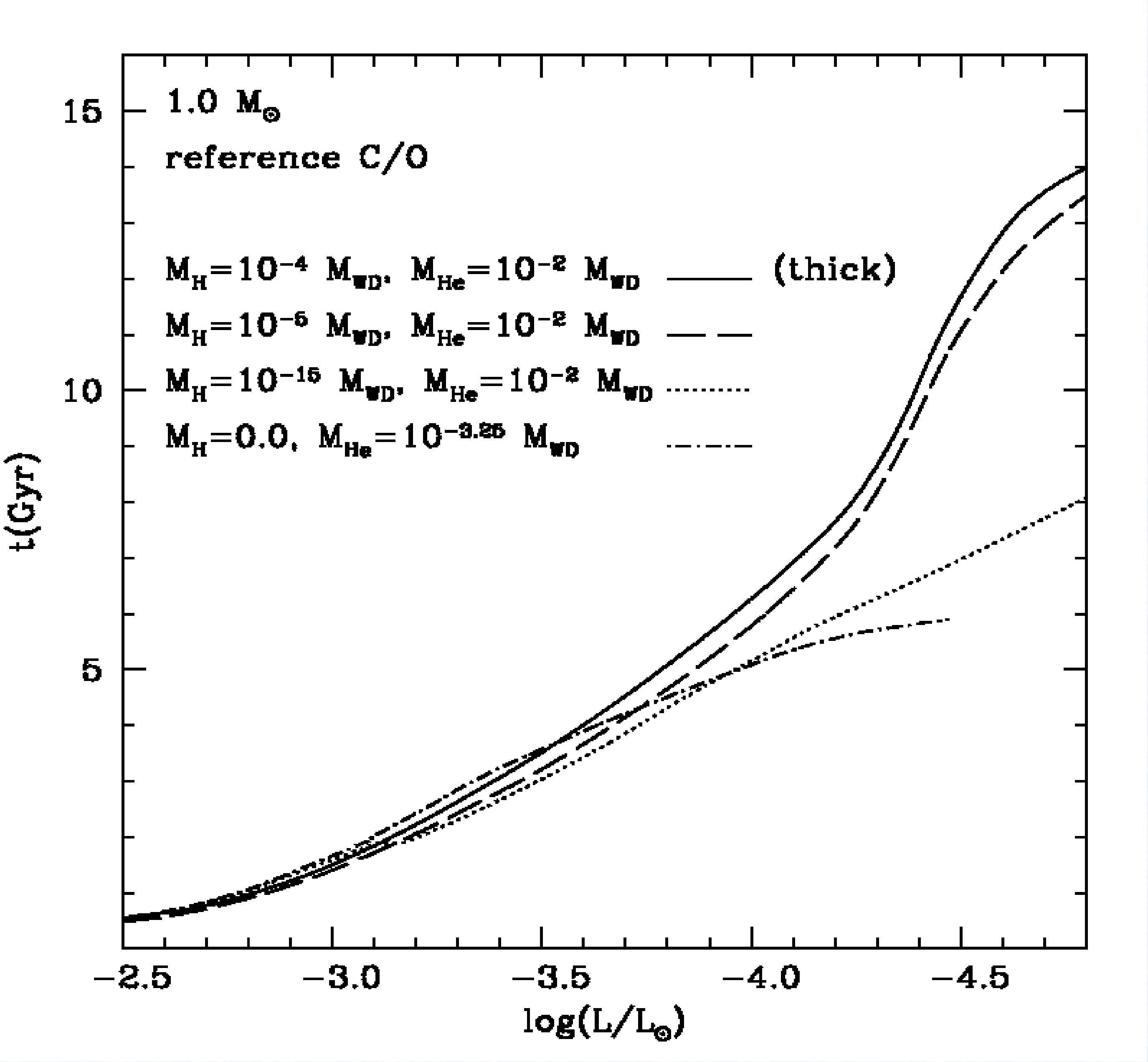
Salaris et al. (2010)



Mass distribution of H-atmosphere objects hotter than T_{eff} =13000 (data from Liebert et al. 2005)

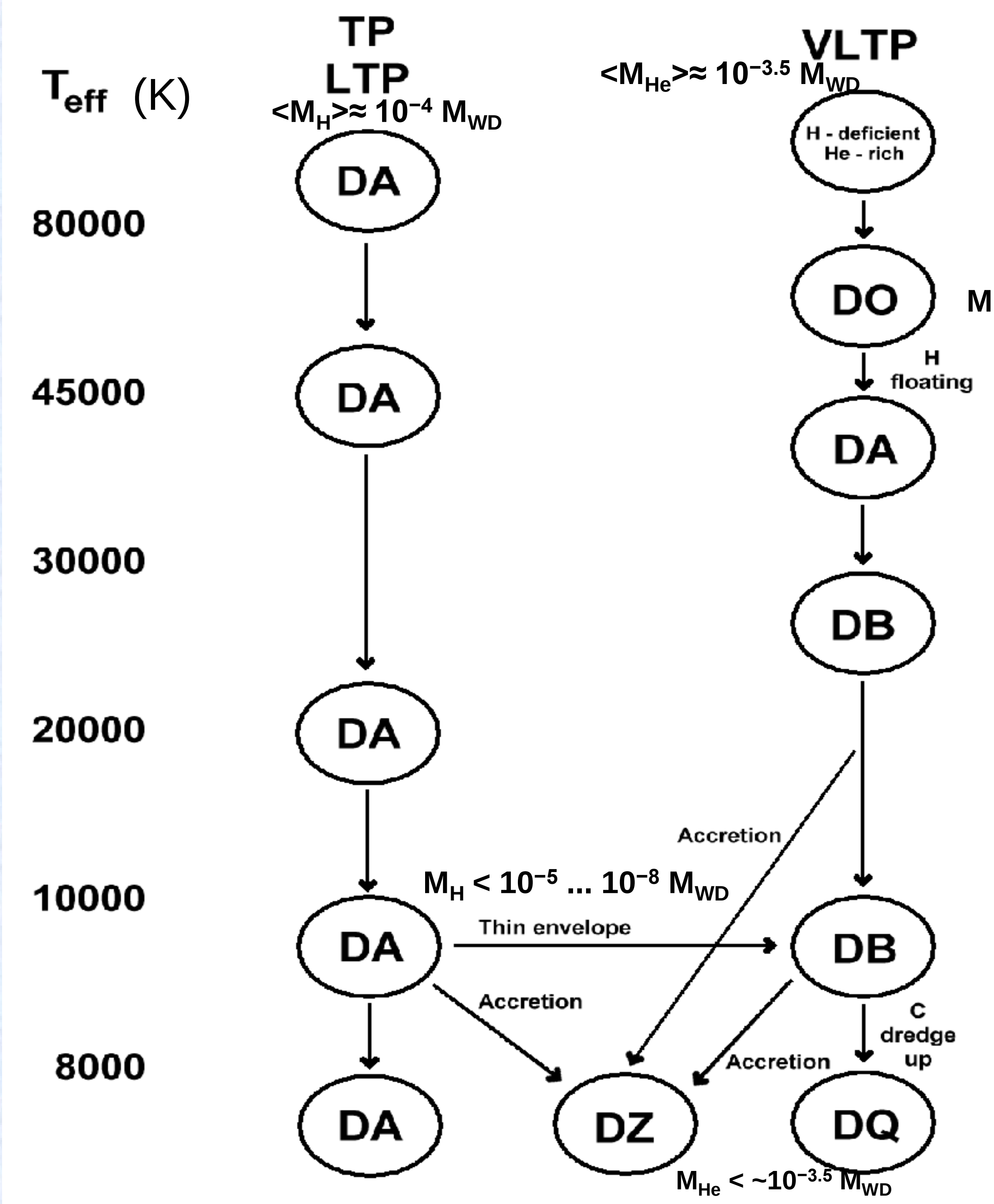


SDSS (Munn et al. 2017)
Based on 8500 stars



1.0 M$_\odot$
reference C/O
$M_H=10^{-4}\ M_{WD},\ M_{He}=10^{-2}\ M_{WD}$ (thick)
$M_H=10^{-6}\ M_{WD},\ M_{He}=10^{-2}\ M_{WD}$
$M_H=10^{-15}\ M_{WD},\ M_{He}=10^{-2}\ M_{WD}$
$M_H=0.0,\ M_{He}=10^{-3.25}\ M_{WD}$
t(Gyr)
15
10
5
−2.5
−3.0
−3.5
−4.0
−4.5
log(L/L$_\odot$)

Range of envelope thickness for Field Disk WDs

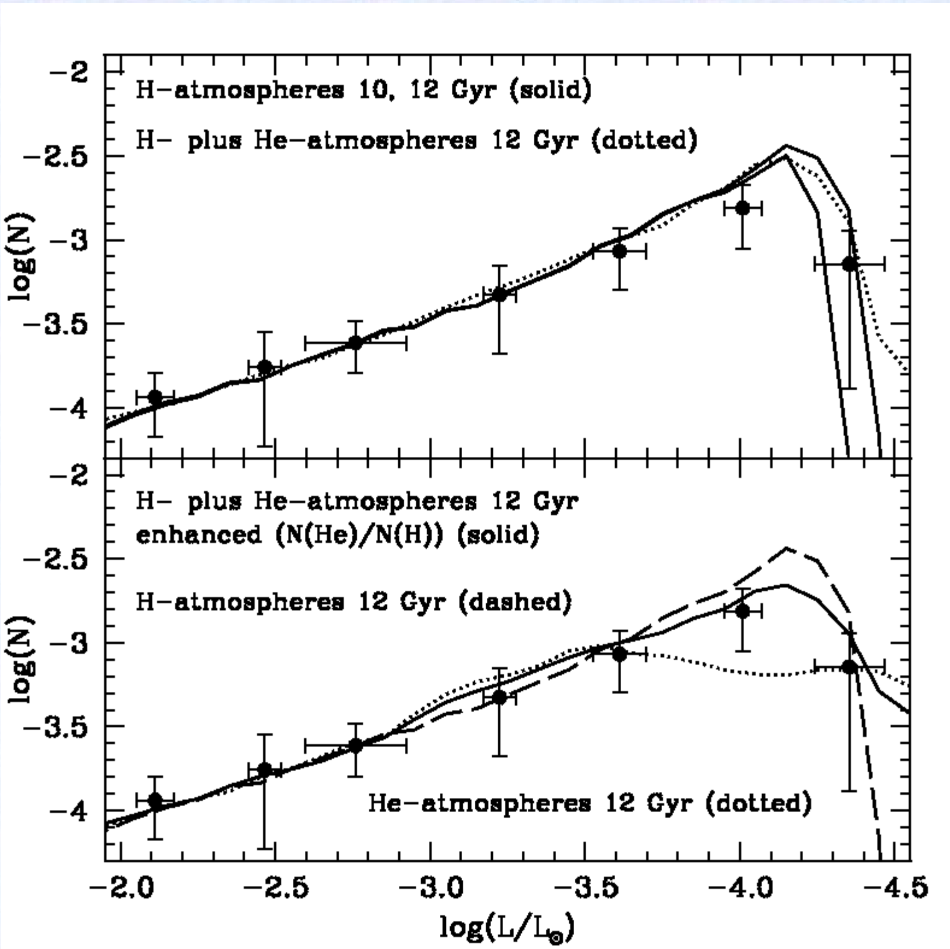


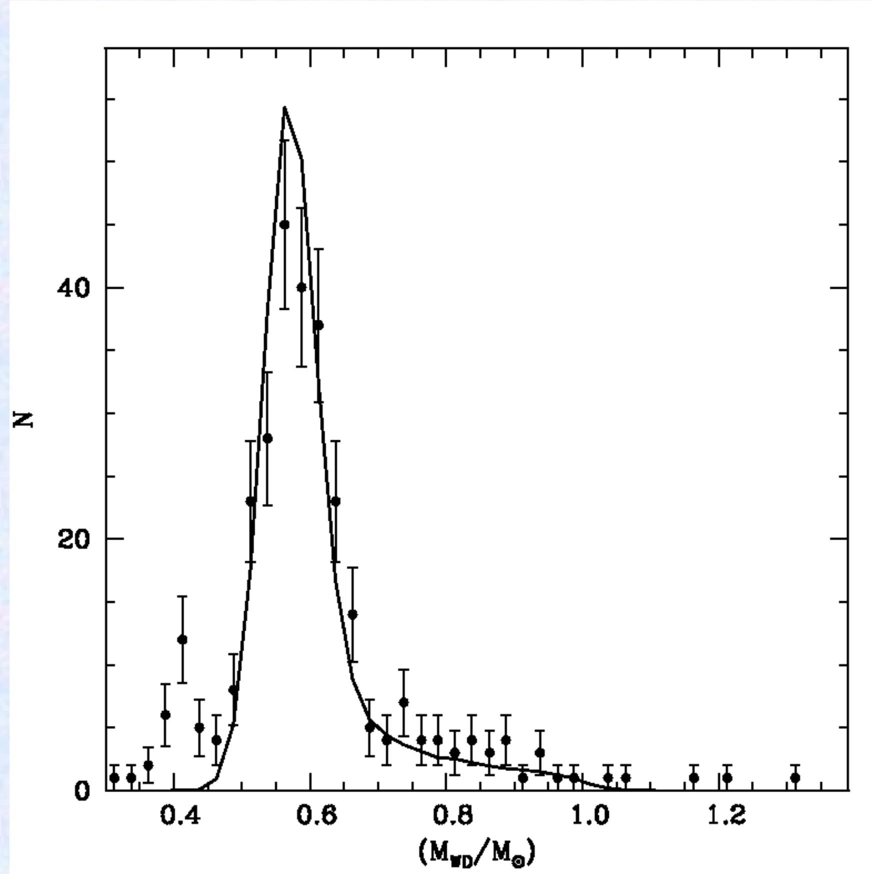
$M_H < 10^{-10}\ M_{WD}$

WDs in the solar neighbourhood

Mass distribution of H-atmosphere objects hotter than T_{eff} =13000 (data from Liebert et al. 2005)

Salaris et al. (2010)





WD LF from Catalan et al. (2008)