"Testing stellar evolutionary models from detached eclipsing binary stars"

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1. **Introduction: evolutionary models**

2. **Methodology**

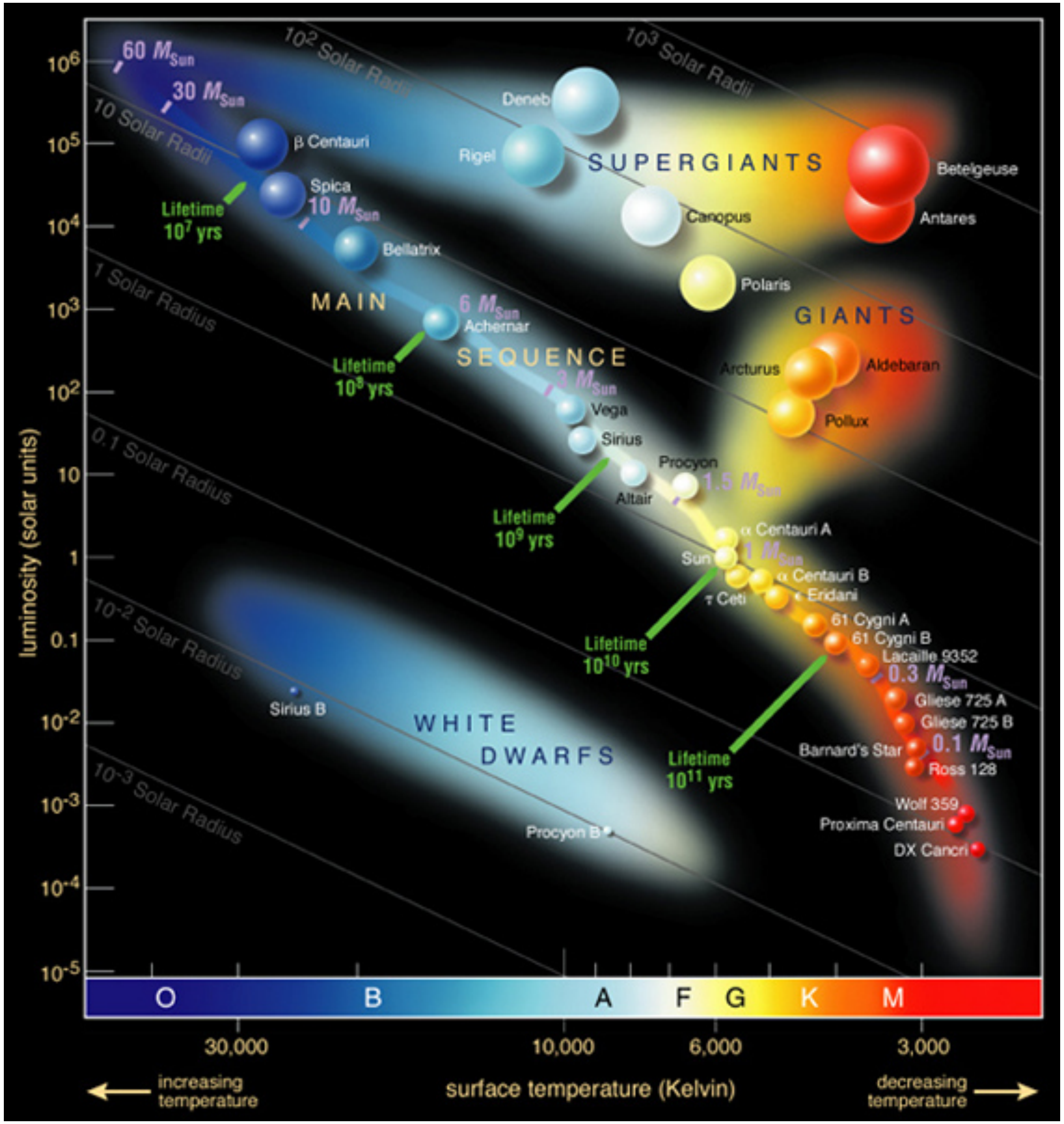
3. **An example: a solar-like star**

4. **Sample for the tests: DEB stars**

5. **Testing the models**

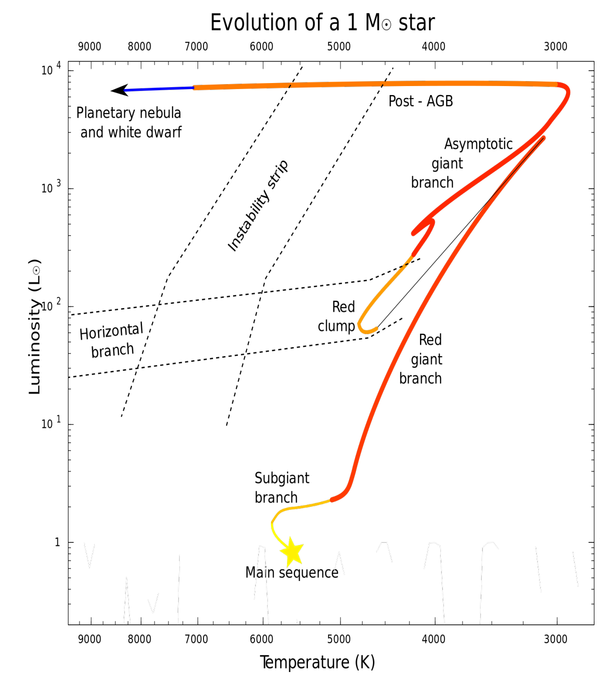
6. **Conclusions**

Stellar evolutionary models



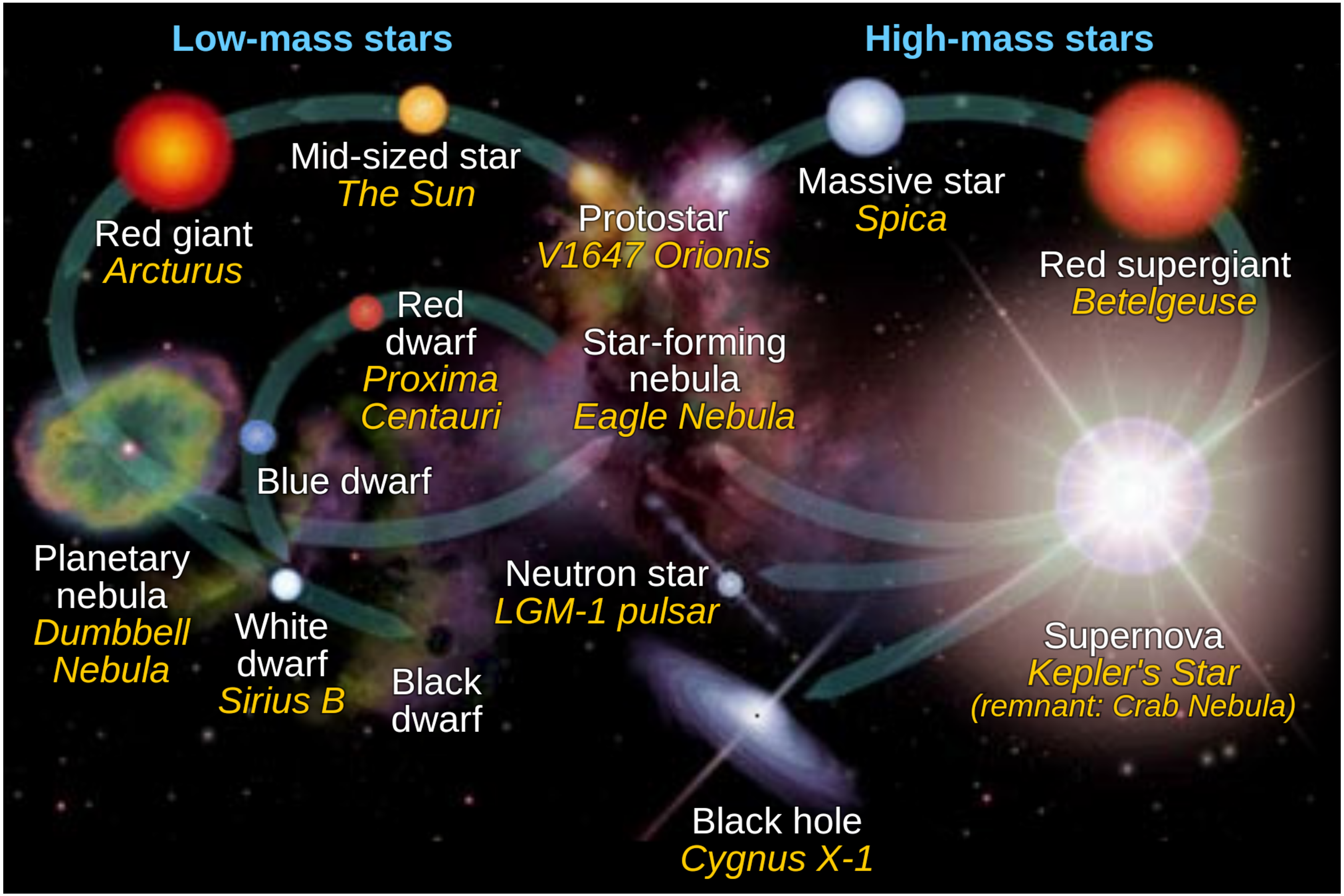
Credit: ESO

Stellar track



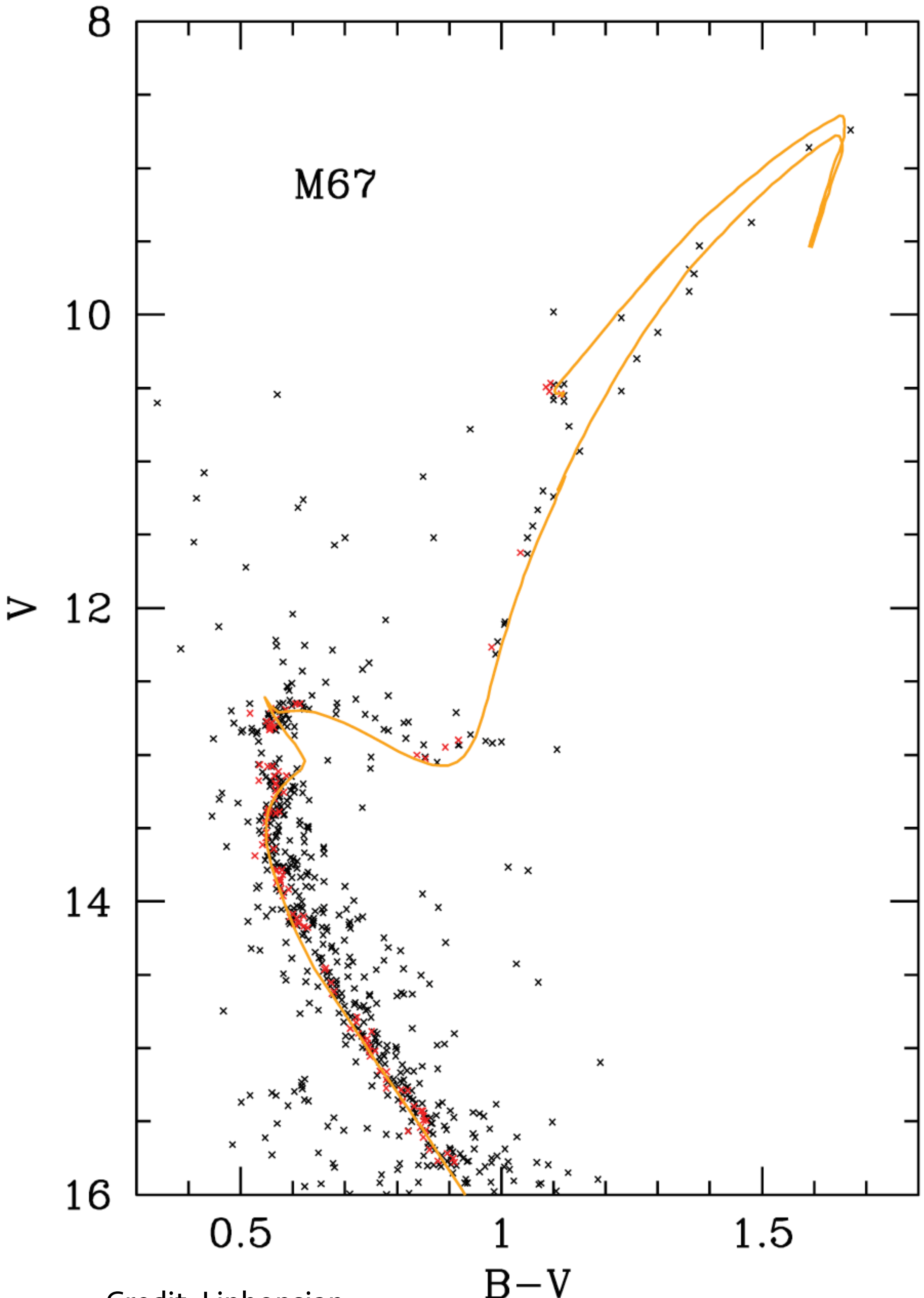
Credit: Lithopsian

Stellar evolutionary models



Credit: cmglee, NASA Goddard Space Flight Center

Stellar evolutionary models



Credit: Liphopsian

Isochrones

Example: Open cluster M67

This one is for $Z = 0.014$ and $\log(\tau/\mathrm{yr}) = 9.6$, distance modulus of $V - M_V = 9.75$ and colour excess $E(B - V) = 0.03$ (Bressan et al. 2012)

Evolutionary models

- There are different active groups developing these models (Bressan et al. 2012; Chabrier et al. 2000; Dotter et al. 2008; Meynet & Maeder 2000; Pietrinferni et al. 2004; Yi et al. 2001, etc.)

- We use PARSEC (the PAdova and TRieste Stellar Evolution Code), which provides isochrones and stellar tracks that follow the evolution of a star from its formation to the asymptotic giant branch phase for low- and intermediate-mass stars, or the carbon ignition phase for massive stars

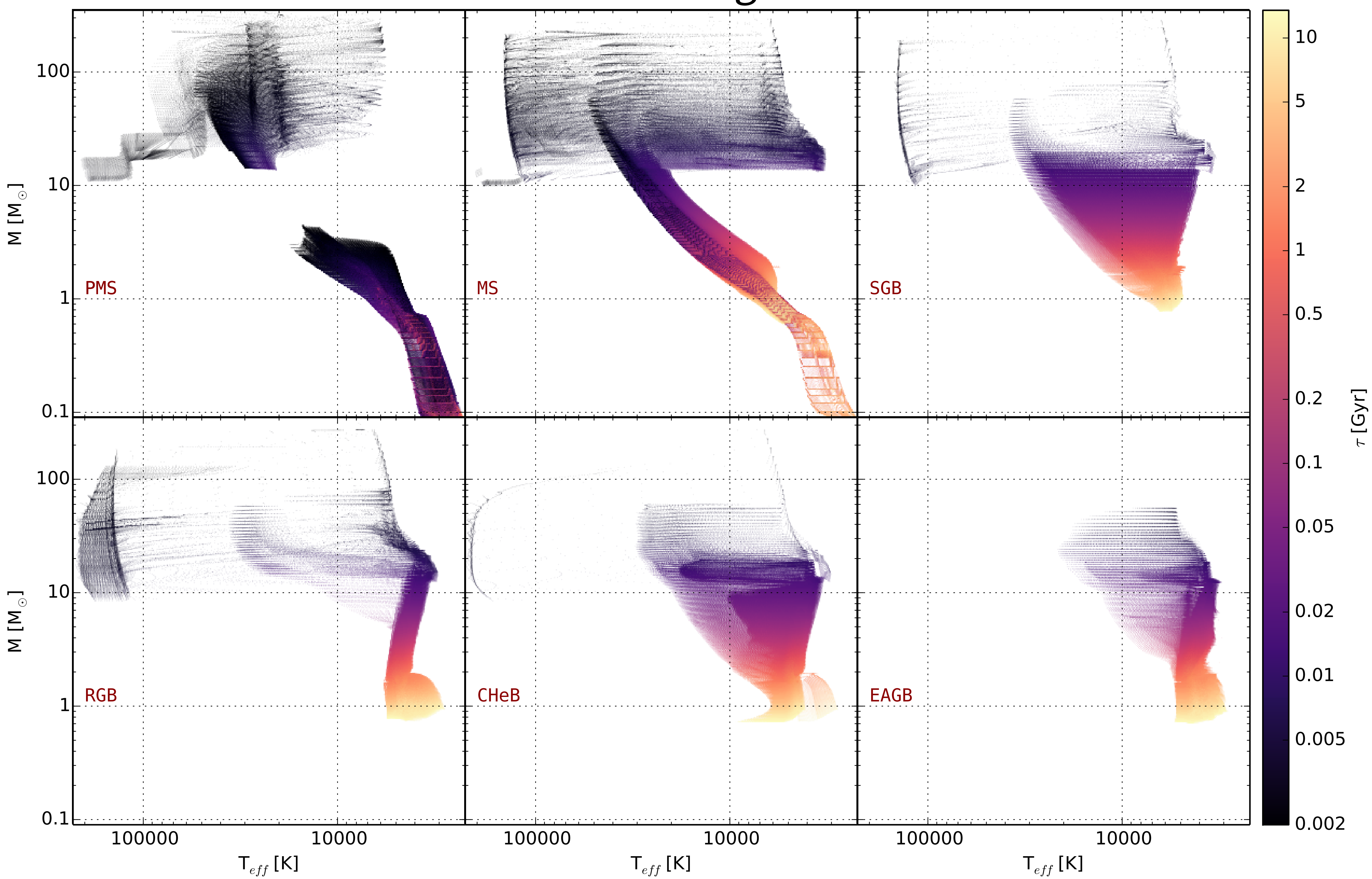
Evolutionary models

- PARSEC models (v1.2S: Bressan et al. 2012; Chen et al. 2014, 2015; Tang et al. 2014) yield, among other stellar parameters, the actual mass, luminosity, effective temperature, surface gravity, and magnitudes in a chosen photometric system (Johnson-Cousins for this research) as a function of age, initial metallicity, and initial mass. The radius can be trivially calculated from the mass and surface gravity, and the mean density from the mass and radius

Evolutionary models

[Fe/H]=-2.15 … -0.95 (0.05) -0.65 (0.03) 0.42 (0.01)

5% in age



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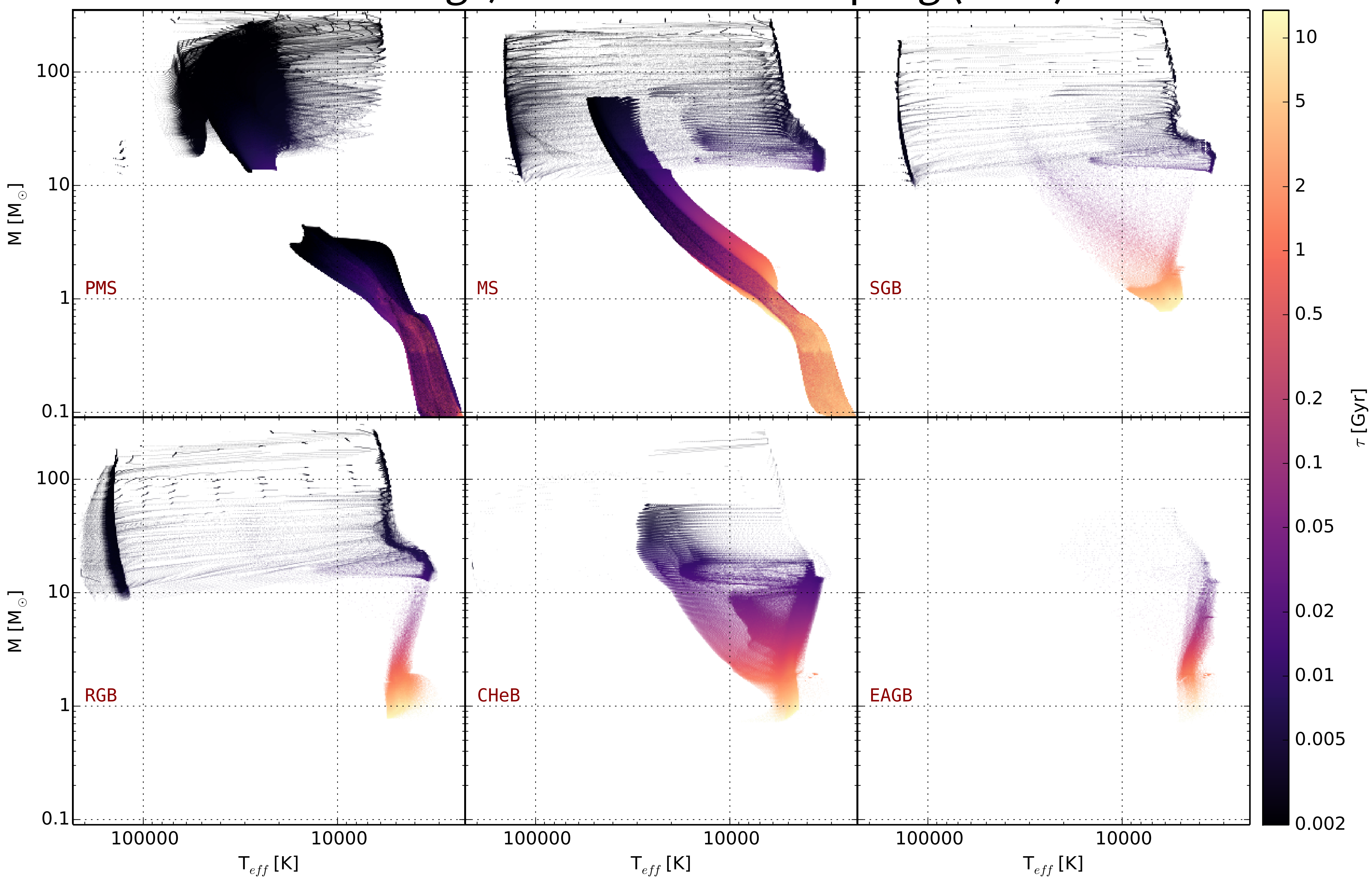
Pre-main-sequence (PMS), main-sequence (MS), sub-giant branch (SGB), red giant branch (RGB), different stages of the core helium burning (CHeB), early asymptotic giant branch (EAGB), and the thermally pulsing asymptotic giant branch (TP-AGB).

It does not include white dwarfs. The lifetime of a star ranges from a few million years to ages significantly longer than that of the Universe for very low mass dwarfs. The maximum theoretical age of the models used here is 13.5 Gyr

Evolutionary models

[Fe/H]=-2.15 … -0.95 (0.05) -0.65 (0.03) 0.42 (0.01)

5% in age; effect of mass sampling (0.1%)



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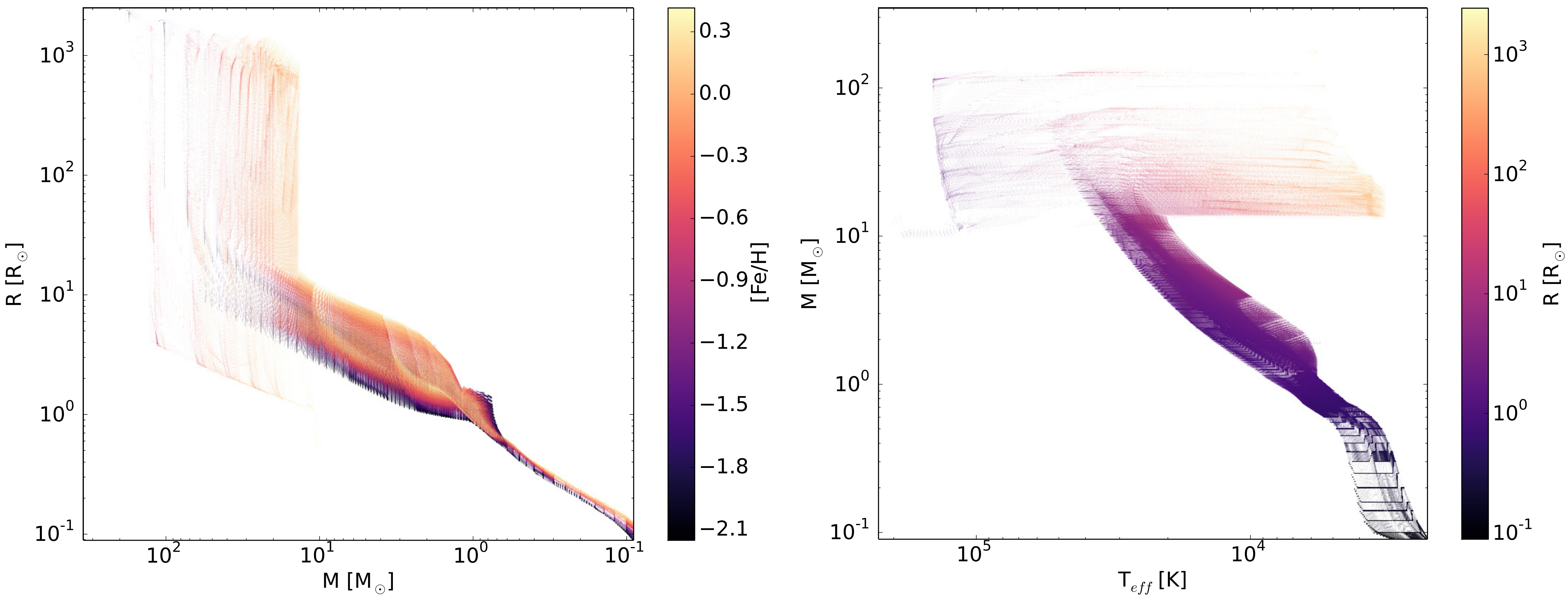
Evolutionary models



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Methodology

$$L(\tau, \zeta, m) = \left(\prod_{i=1}^{n} \frac{1}{(2\pi)^{1/2}\sigma_i} \right) \times \exp(-\chi^2/2)$$

where

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{q_i^{\mathrm{obs}} - q_i(\tau, \zeta, m)}{\sigma_i} \right)^2 .$$

- For instance, for M:

$$E(M) \propto \iiint f_0 \mathcal{L} M \,\mathrm{d}M_0 \,\mathrm{d}\tau \,\mathrm{d}[\mathrm{Fe/H}],$$

Prior f0: initial mass function of Chabrier (2001)

L: likelihood function

$$\mathrm{Var}(M) \propto \iiint f_0 \mathcal{L} [M - E(M)]^2 \,\mathrm{d}M_0 \,\mathrm{d}\tau \,\mathrm{d}[\mathrm{Fe/H}].$$

del Burgo & Allende Prieto (2016, 2018)

HD 209458: a solar-like star

Grid of models

- Zini: 0.0151 - 0.0211, in steps of 0.0005
- Age: 4.1 - 5.3, in steps of 0.01 Gyr
- Mini: 0.09 $M_\odot$ - highest mass established by the stellar lifetime, steps of 0.0001 $M_\odot$

(for calibration purposes)

- Zini: 0.0046 - 0.0246, in steps of 0.005
- Age: 0.1 - 12.1, in steps of 0.3 Gyr
- Mini: 0.09 $M_\odot$ - highest mass established by the stellar lifetime, steps of 0.002 $M_\odot$

Methodology

- We used the aforementioned grid of stellar evolution models from PARSEC v1.2S to infer the stellar properties of HD 209458 from a procedure similar to that described by Jørgensen & Lindegren (2005), but using B − V instead of T_{eff}, and with flat priors

- These models assume solar-scaled metal abundances and for their choice of the solar mixture the metal mass fraction can be computed as $Z=0.01524\ 10^{[Fe/H]}$

del Burgo & Allende Prieto (2016)

Methodology

- Input parameters: **M_V = 4.18±0.09 mag, B – V = 0.549±0.013 mag**, which were calculated from the Hipparcos parallax (**Π**=20.15±0.80 mas) and the values of B and V we derived from the CALSPEC spectrum. Also, solar metallicity (**[Fe/H]= 0.00±0.05 dex**)

- Note that HD 209458 and the Sun are very similar

- We calibrated against the Sun, i.e., PARSEC (output) is forced to reproduce solar values

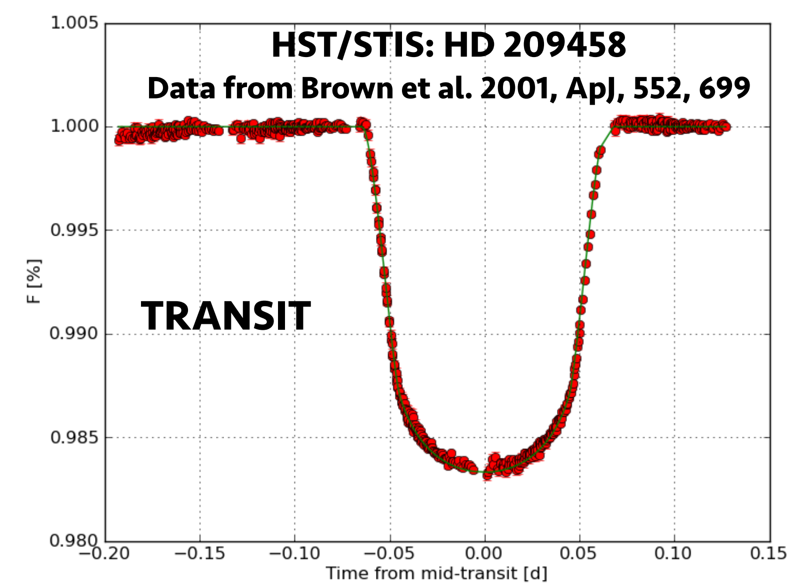
HD 209458: stellar properties

Parameter	Value±uncertainty	Note
$T_{\rm eff}$ (K)	6071±20	BF; see §3.1
"	6070±24	$f_{\rm bol}$-mod; see §3.5
"	6064±24	$f_{\rm bol}$-obs; see §3.5
"	6099±41	EM; see §3.8
θ (mas)	0.2254±0.0017	BF; see §3.3
$R_\star$ ($R_\odot$)	1.20±0.05	BF; see §3.4
"	1.20±0.06	EM; see §3.8
$L_\star$ ($L_\odot$)	1.77±0.14	$f_{\rm bol}$-mod; see §3.6
"	1.76±0.14	$f_{\rm bol}$-obs; see §3.6
"	1.77±0.14	BF; see §3.6
"	1.79±0.14	EM; see §3.8
$M_{\rm bol}$ (mag)	4.11±0.09	EM; see §3.8
$\log g$ [cm s^{-2}]	4.38±0.06	BF-LC; see §3.7
"	4.33±0.04	BF-EM; see §3.7
"	4.33±0.04	EM; see §3.8
$M_\star$ ($M_\odot$)	1.26±0.15	BF-LC; see §3.7
"	1.12±0.04	EM; see §3.8
$\rho_\star$ (g cm^{-3})	0.91±0.11	BF-EM; see §3.7
"	0.91±0.14	EM; see §3.8
τ (Gyr)	3.5±1.4	EM; see §3.8

$$T_{\rm eff} = \left(\frac{4 f_{\rm bol}}{\sigma \theta^2}\right)^{0.25}$$

$$L \propto \frac{f_{\rm bol}}{\Pi^2}$$

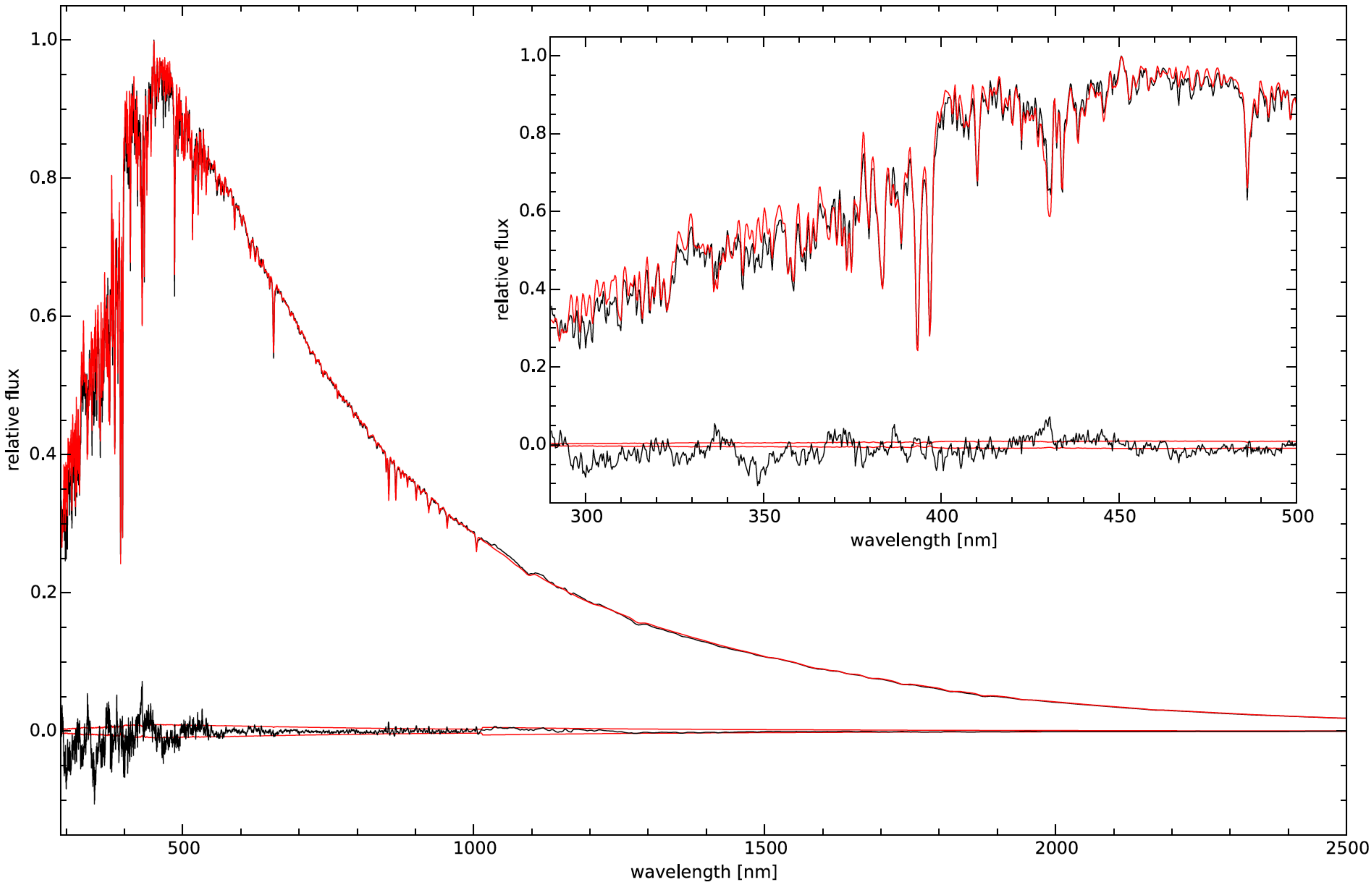
$$L/L_\odot = (R/R_\odot)^2 \, (T_{\rm eff}/T_{\rm eff,\odot})^4$$



del Burgo & Allende Prieto (2016)

ρ=1.024±0.014 gr cm^{-3}, derived from the HST transit light curve (Torres 2008)

HD 209458: stellar properties



Detached eclipsing binaries

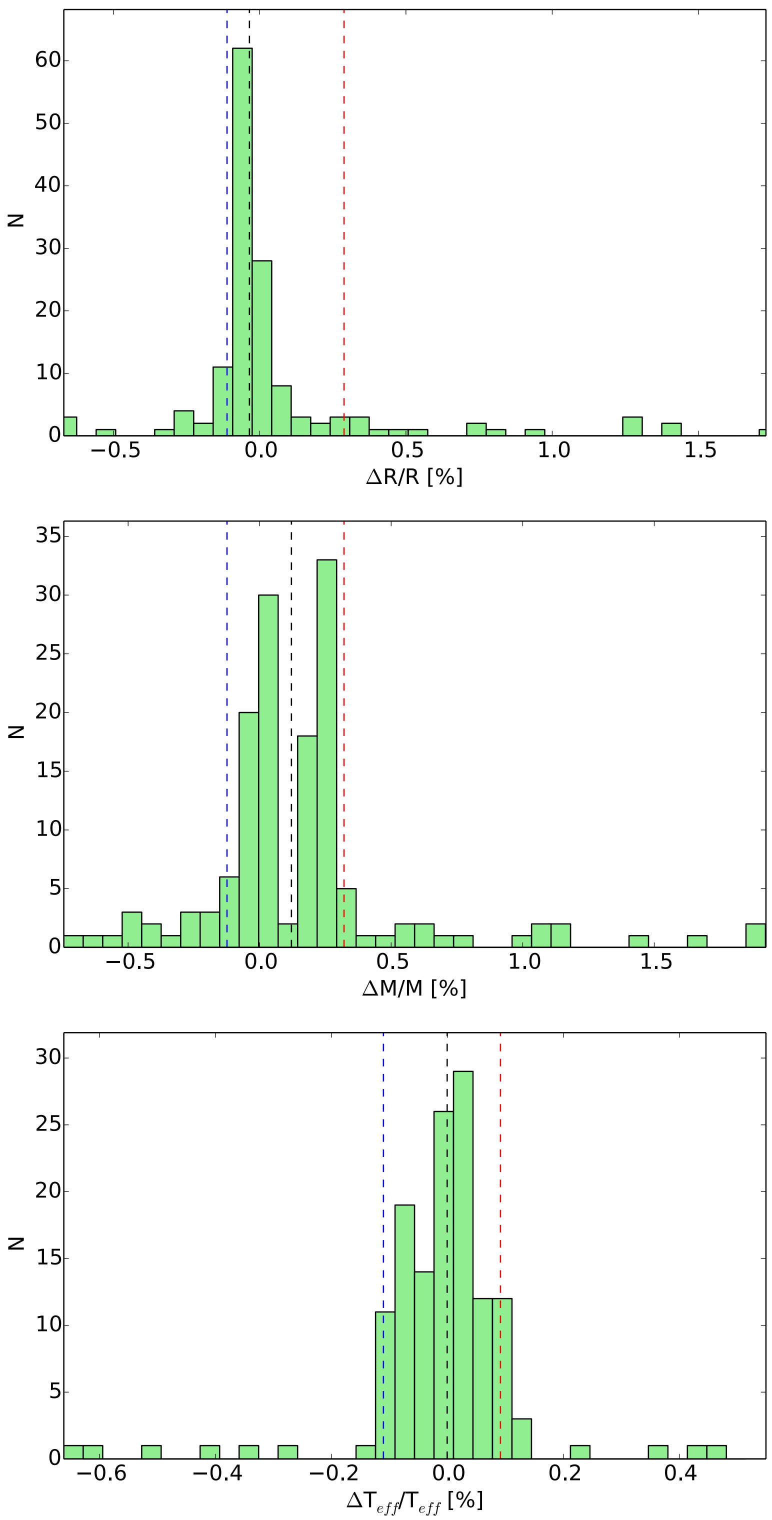
A detached eclipsing binary (DEB) system consists of two non-interacting stars that have evolved as if they were single and whose orbital plane is nearly or perfectly aligned towards the observer, so this can observe periodic eclipses

Detached eclipsing binaries

DEBCat (Southworth 2015) is a catalogue of 195 DEB systems with measurements for M and R to 2 per cent precision for most of them. It has been regularly updated to date. It presents 84 binary systems in common with (Torres et al. 2010)

DEBCat collects M, R, T_{eff}, L, and [Fe/H] (when available). There are 77 systems with known metallicities, which were obtained from abundance analysis of high-resolution spectra or, for those belonging to a stellar cluster, may be from other cluster members

DEBCat vs Torres et al.



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There is a commendable agreement between both catalogues

Relative discrepancies (%):

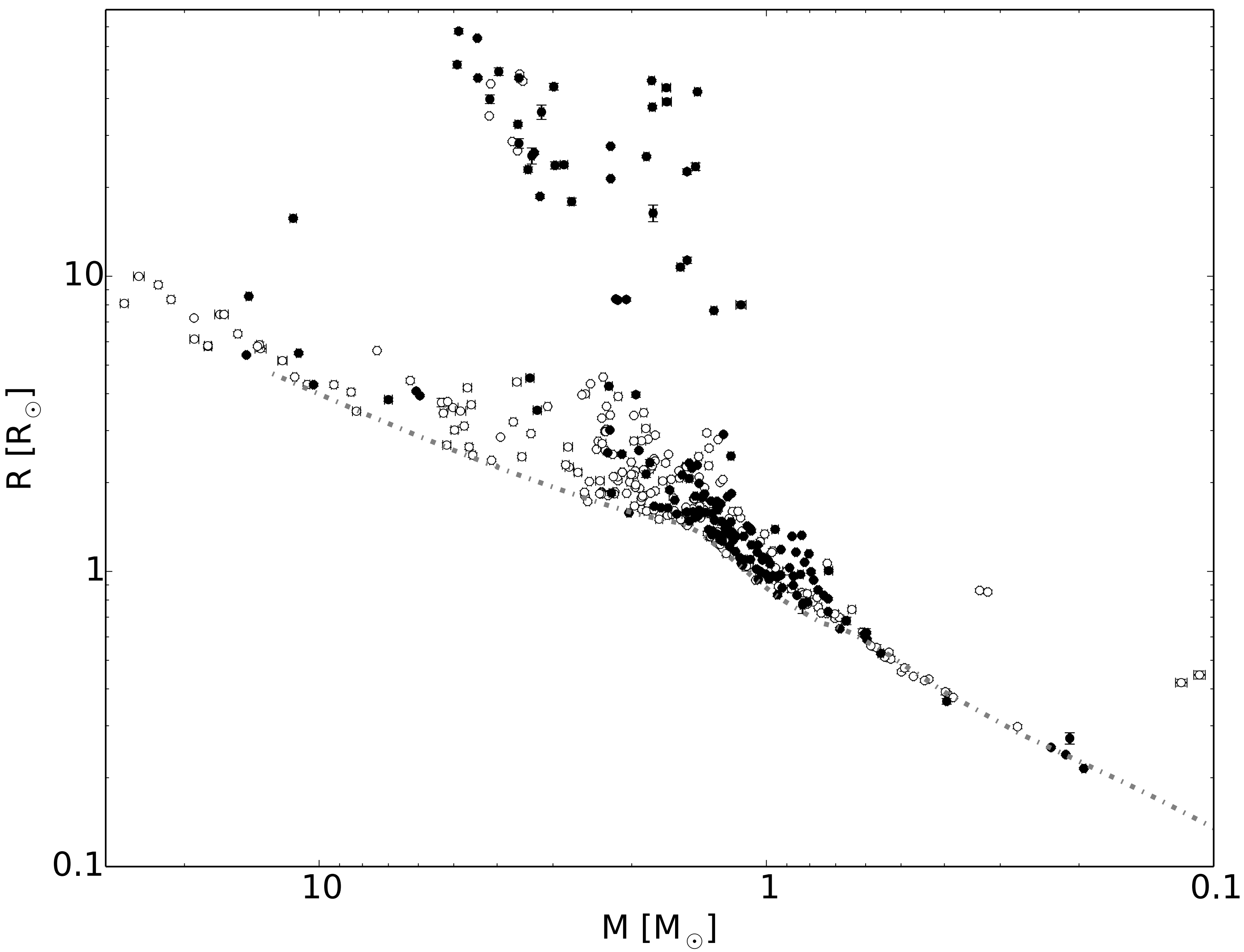
R (<>, 34th percentiles): -0.036, -0.11, 0.32

M (<>, 34th percentiles): 0.12, -0.12, 0.38

T_{eff} (<>, 34th percentiles): -0.00029, -0.11, 0.09

We employed DEBCat with additional inputs from Torres et al. (2010) and other sources as a proxy for the DEB stars to test PARSEC 1.2S models

Detached eclipsing binaries



Sample I (182)

In summary, 78 per cent of 182 stars in Sample I have relative uncertainties in radius $\leq$1 per cent, 91 per cent $\leq$2 per cent, and 96 per cent $\leq$3 per cent. Then, 86 per cent of these stars present masses accurate to 1 per cent precision, 99 per cent to 2 per cent, and all of them to 3 per cent. For effective temperature, 24 per cent are determined to 1 per cent precision, 76 per cent to 2 per cent, and 95 per cent to 3 per cent.

Sample II (136)

The resulting sample (hereafter Sample II) consists of 136 binary stars, with typical relative uncertainties for R, M, and T_{eff} of 1.0, 0.8, and 2.3 per cent, respectively. With regard to radius, 71 per cent of stars in Sample II have relative uncertainties $\leq$1 per cent, 94 per cent $\leq$2 per cent, and 99 per cent $\leq$3 per cent. Concerning mass, 79 per cent of stars have measurements to 1 per cent, 99 per cent to 1 per cent, and all of them to 3 per cent. Finally, 12 per cent of Sample II have relative uncertainties $\leq$1 per cent, 51 per cent $\leq$2 per cent, and 79 per cent $\leq$3 per cent in the case of effective temperature.

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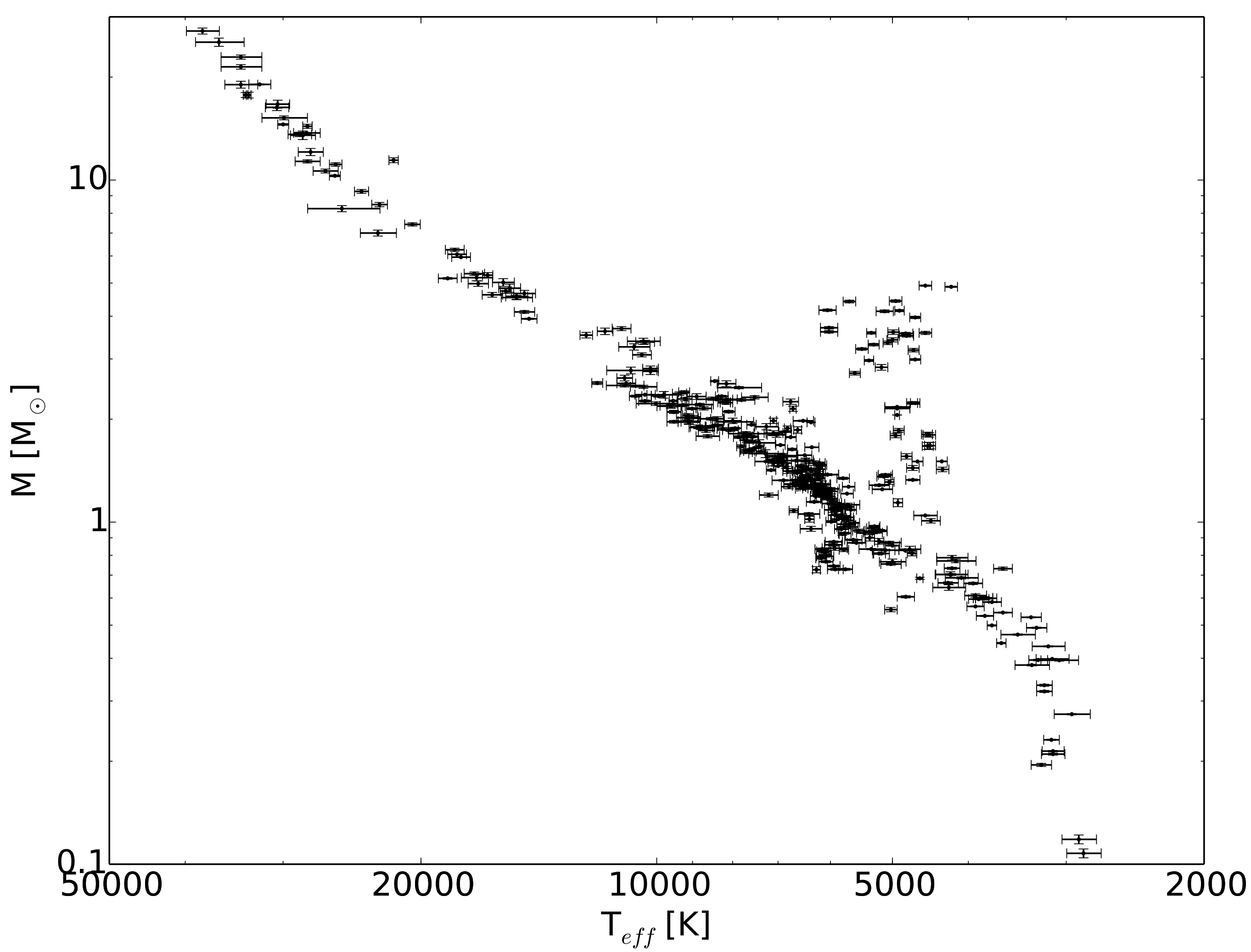
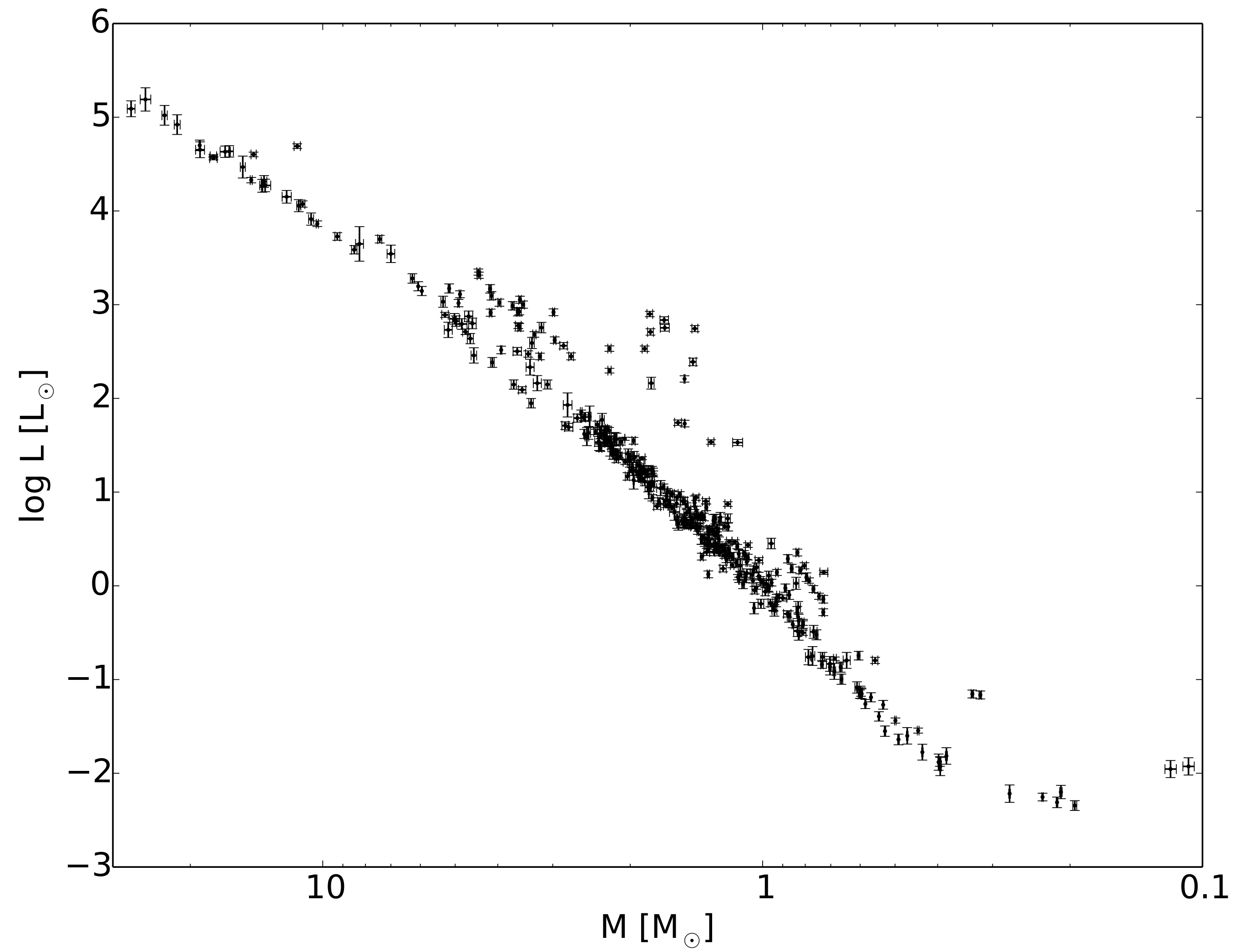
Detached eclipsing binaries





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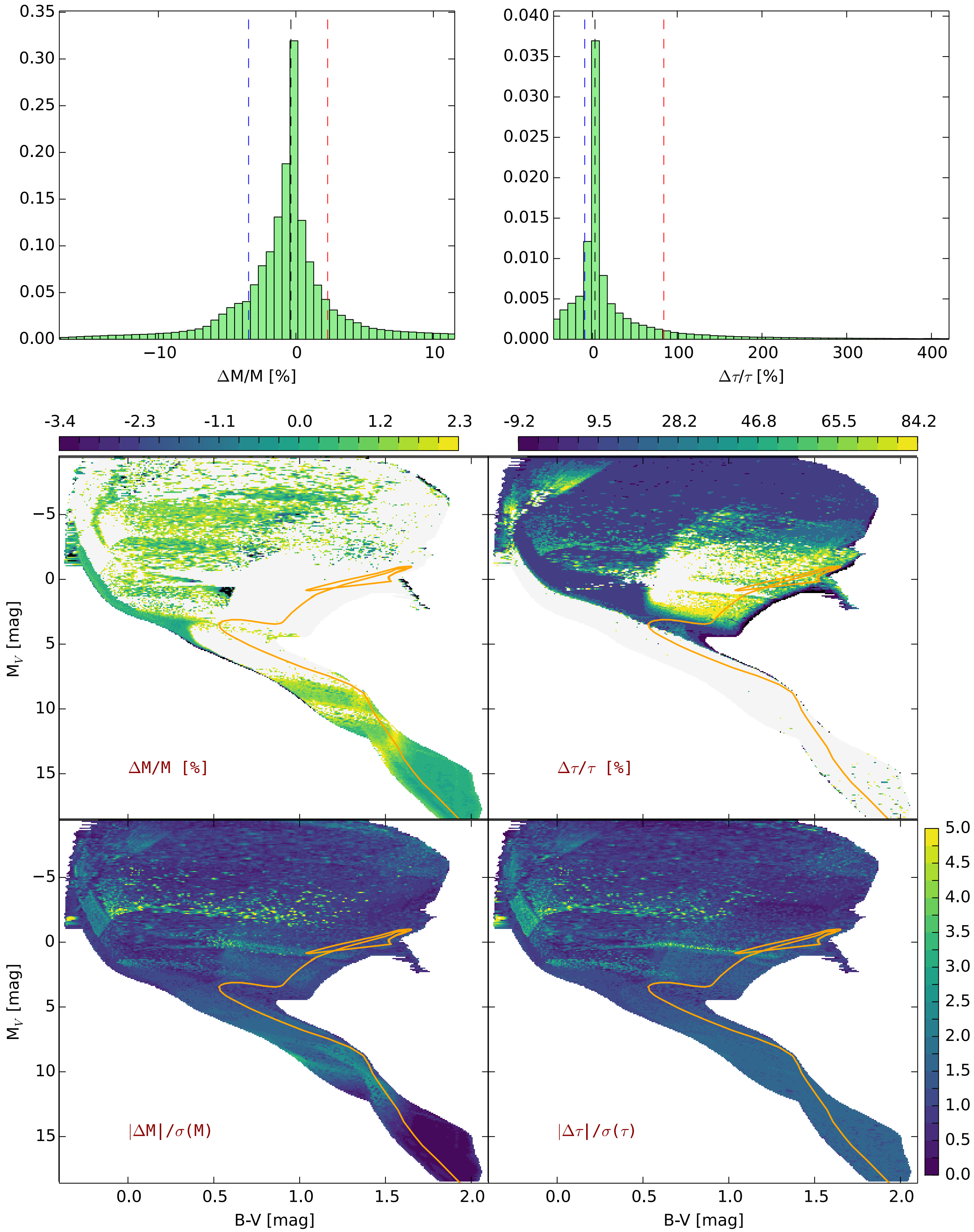
DEB stars

Grid of models

- [Fe/H]=-2.15… -0.95 (0.05)… -0.65 (0.03)… 0.42 (0.01)
- Age: 200 Myr - 13.5 Gyr, in steps of 5%
- Mini: in steps of 0.1% and irregulars

Mean values



$$E(M_V) \propto \iiint f_0 \, \mathcal{L} \, M_V \, dM_0 \, d\tau \, d[\mathrm{Fe/H}]$$

$$Var(M_V) \propto \iiint f_0 \, \mathcal{L} \, [M_V - E(M_V)]^2 \, dM_0 \, d\tau \, d[\mathrm{Fe/H}]$$

Posterior probability function

$$G(\tau) \propto \int\int L(\tau, \zeta, m)\xi(m) \, \mathrm{d}m \, \mathrm{d}\zeta.$$

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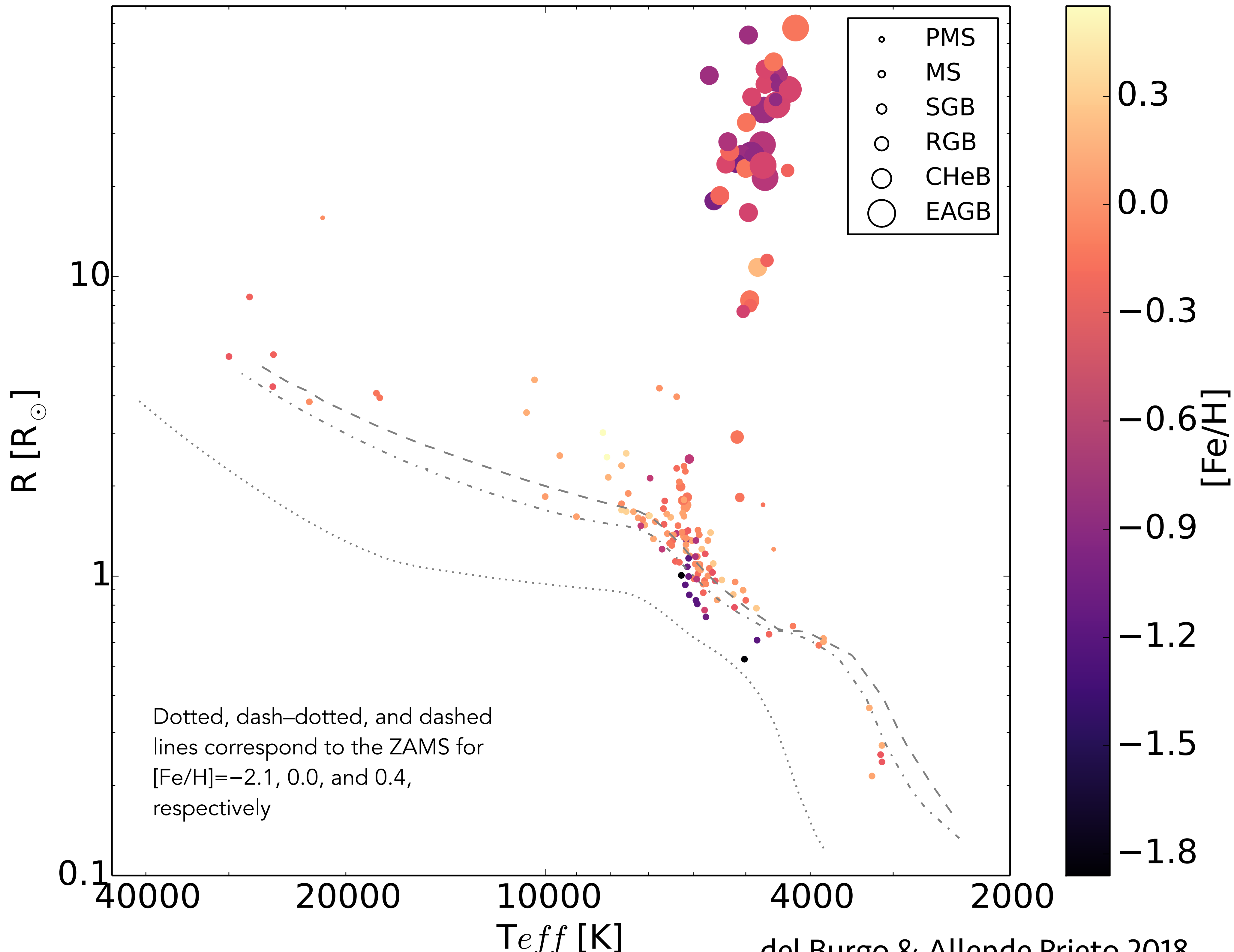
Input parameters



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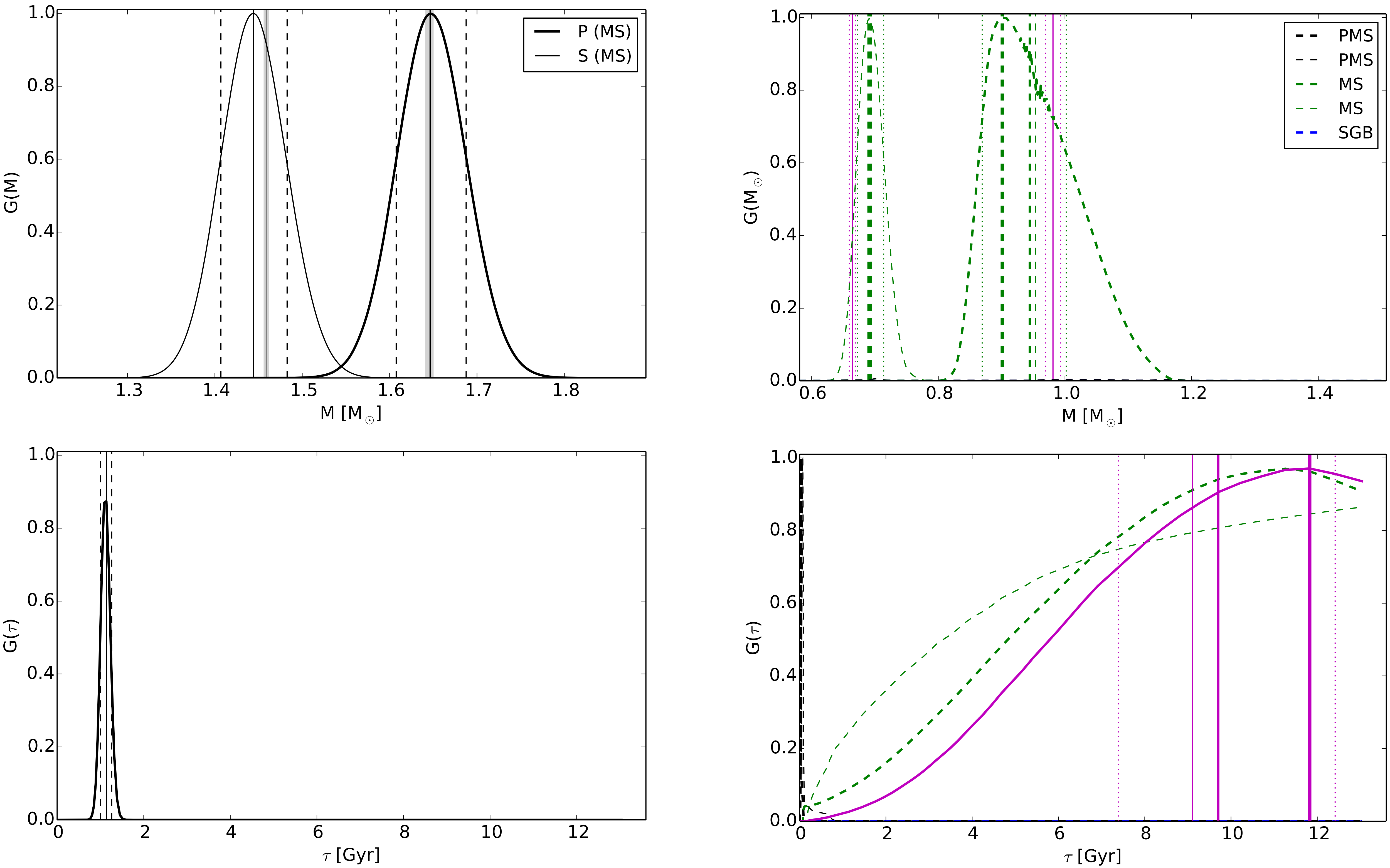
Examples: V501 Mon & IM Vir



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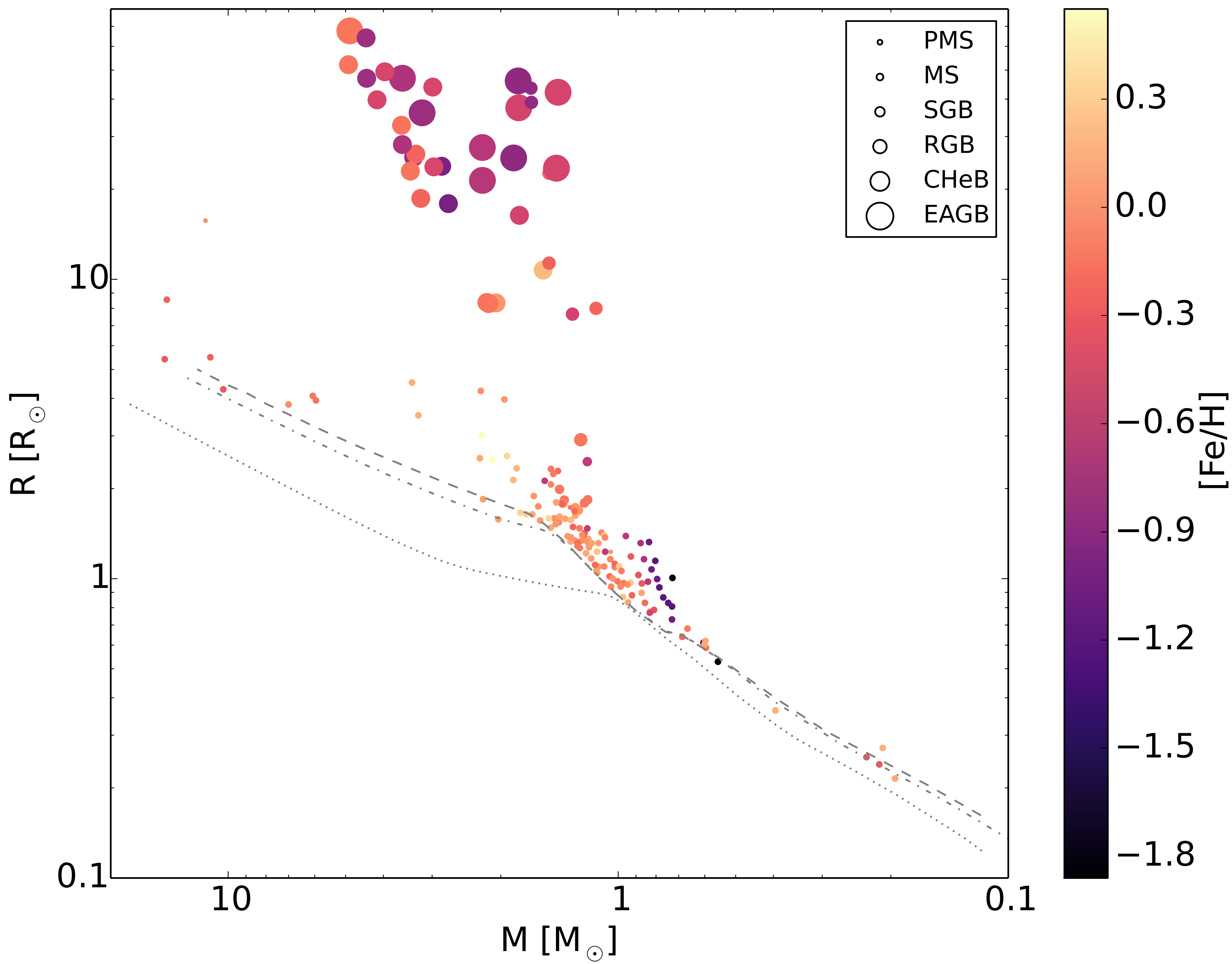
Evolution effects



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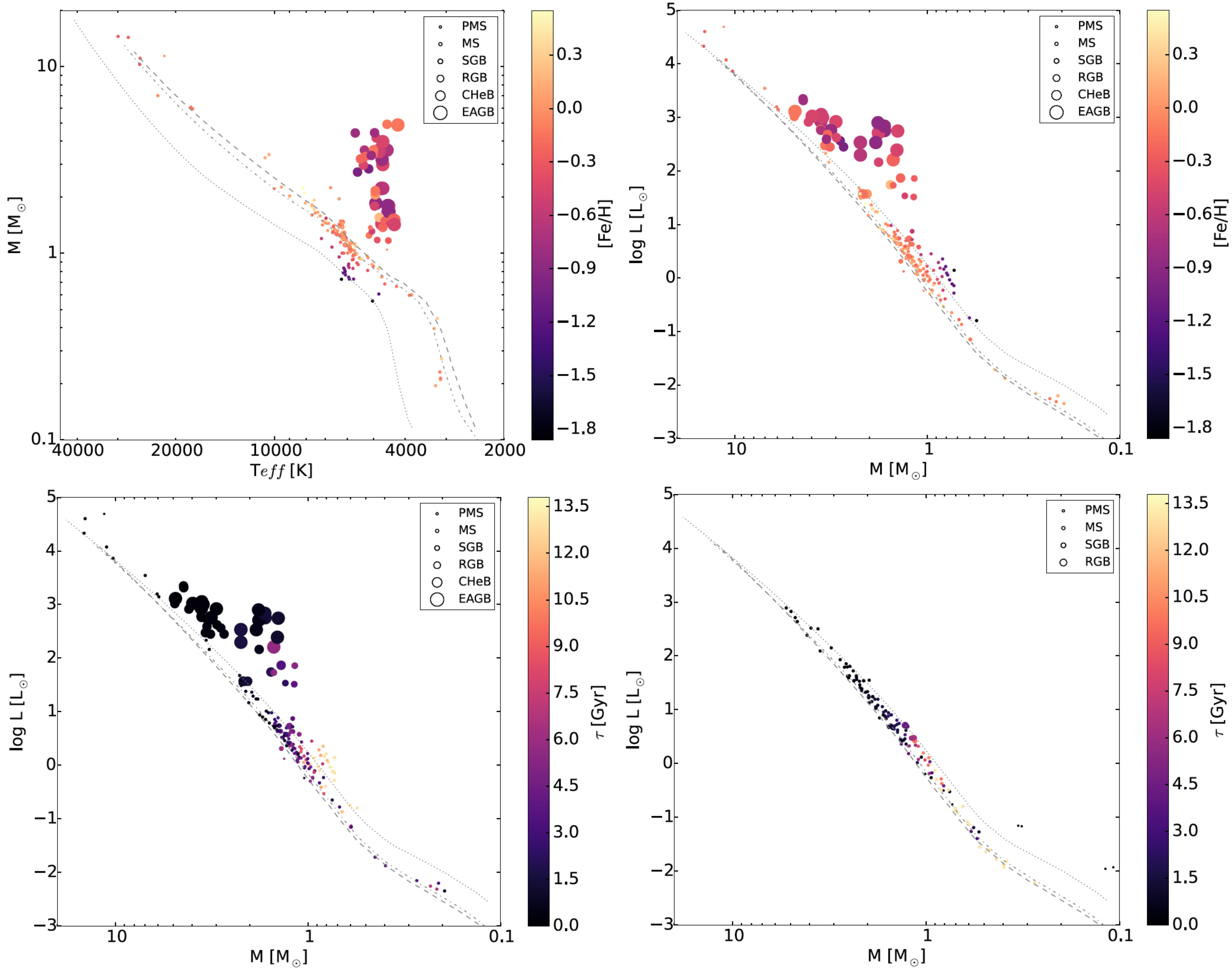
Evolution effects



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RESULTS

Table 1. Literature stellar parameters of DEB stars in Sample I, with known metallicities: radius (R), effective temperature ($T_{\rm eff}$), iron abundance [Fe/H], and mass (M), surface gravity ($\log g$), luminosity ($\log L$), spectral type (SpT)/luminosity class (LC), color excess $E(B-V)$, and distance d. References for the literature values are given in the main text.

System	R ($R_\odot$)	$T_{\rm eff}$ (K)	[Fe/H] (dex)	M ($M_\odot$)	$\log g$ (g: cm s^{-2})	$\log L$ (L: $L_\odot$)	SpT/LC	$E(B-V)$ (mag)	d (pc)
CM Dra	0.2534 ± 0.0019	3133 ± 72	-0.30 ± 0.12	0.2310 ± 0.0009	4.994 ± 0.007	-2.25 ± 0.04	M4.5V	0	14.850 ± 0.011
	0.2396 ± 0.0015	3119 ± 101	=	0.2141 ± 0.0009	5.009 ± 0.006	-2.31 ± 0.06	M4.5V	=	=
PTFEB 132.707+19.810	0.363 ± 0.008	3258 ± 90	0.14 ± 0.04	0.3953 ± 0.0020	4.915 ± 0.019	-1.87 ± 0.05	M3.5V	0	187 ± 3
	0.272 ± 0.012	3119 ± 108	=	0.2098 ± 0.0014	4.89 ± 0.04	-2.20 ± 0.07	M4.3V	=	=
HAT-TR-318-007	0.455 ± 0.004	3192 ± 110	0.30 ± 0.11	0.4480 ± 0.0010	4.774 ± 0.006	-1.71 ± 0.06	M4V	0	119.8 ± 1.1
	0.2913 ± 0.0024	3097 ± 107	=	0.272 ± 0.004	4.944 ± 0.004	-2.15 ± 0.06	M5V	=	=
YY Gem	0.620 ± 0.006	3819 ± 97	0.10 ± 0.20	0.597 ± 0.005	4.630 ± 0.008	-1.13 ± 0.04	M1Ve	0	15.098 ± 0.012
	0.604 ± 0.006	3819 ± 97	=	0.601 ± 0.005	4.66 ± 0.05	-1.16 ± 0.04	M1Ve	=	=
M55 V54	1.006 ± 0.009	6252 ± 72	-1.86 ± 0.15	0.726 ± 0.015	4.294 ± 0.010	0.144 ± 0.021		0.115 ± 0.010	5668 ± 288
	0.528 ± 0.005	5023 ± 93	=	0.555 ± 0.008	4.737 ± 0.010	-0.80 ± 0.03		=	=
M4 V69	0.866 ± 0.010	6081 ± 126	-1.20 ± 0.10	0.766 ± 0.005	4.44 ± 0.13	-0.03 ± 0.04		0.429 ± 0.004	1717 ± 82
	0.807 ± 0.008	5916 ± 136	=	0.728 ± 0.005	4.48 ± 0.12	-0.14 ± 0.04		=	=
M4 V66	0.935 ± 0.005	6166 ± 99	-1.20 ± 0.10	0.784 ± 0.005	4.39 ± 0.08	0.056 ± 0.028		0.429 ± 0.005	1717 ± 82
	0.830 ± 0.005	5943 ± 109	=	0.744 ± 0.004	4.47 ± 0.09	-0.11 ± 0.03		=	=
M4 V65	1.147 ± 0.010	6095 ± 112	-1.20 ± 0.10	0.804 ± 0.009	4.221 ± 0.014	0.21 ± 0.03		0.426 ± 0.010	1717 ± 82
	0.611 ± 0.009	4808 ± 122	=	0.605 ± 0.004	4.645 ± 0.017	-0.75 ± 0.05		=	=
NGC 6362 V41	1.074 ± 0.005	6124 ± 127	-1.07 ± 0.05	0.821 ± 0.006	4.311 ± 0.004	0.16 ± 0.04		0.0644 ± 0.0008	8095 ± 150
	0.731 ± 0.005	5741 ± 119	=	0.728 ± 0.005	4.593 ± 0.006	-0.28 ± 0.04		=	=
NGC 6362 V40	1.325 ± 0.008	6152 ± 127	-1.07 ± 0.05	0.834 ± 0.006	4.550 ± 0.005	0.36 ± 0.04		0.0636 ± 0.0009	8095 ± 150
	0.997 ± 0.013	6095 ± 154	=	0.795 ± 0.005	4.361 ± 0.011	0.09 ± 0.05		=	=
47 Tuc V69	1.315 ± 0.005	5943 ± 151	-0.71 ± 0.10	0.876 ± 0.005	4.1430 ± 0.0030	0.29 ± 0.04		0.0271 ± 0.0005	4335 ± 279
	1.162 ± 0.006	5957 ± 151	=	0.859 ± 0.006	4.2420 ± 0.0030	0.18 ± 0.04		=	=
Kepler-35	1.0285 ± 0.0019	5610 ± 142	-0.34 ± 0.20	0.888 ± 0.005	4.3623 ± 0.0020	-0.02 ± 0.04		0.121 ± 0.004	1918 ± 124
	0.7861 ± 0.0022	5200 ± 96	=	0.809 ± 0.004	4.5556 ± 0.0016	-0.39 ± 0.03		=	=
KIC 6131659	0.8800 ± 0.0028	5794 ± 53	-0.23 ± 0.20	0.922 ± 0.007	4.534 ± 0.007	-0.104 ± 0.016		0.1133 ± 0.0029	
	0.639 ± 0.006	4613 ± 42	=	0.685 ± 0.005	4.682 ± 0.009	-0.778 ± 0.018		=	
RW Lac	1.186 ± 0.004	5754 ± 106	-0.30 ± 0.19	0.928 ± 0.006	4.2570 ± 0.0030	0.14 ± 0.03	G5V	0.068 ± 0.012	208.0 ± 1.3
	0.964 ± 0.004	5559 ± 154	=	0.870 ± 0.004	4.409 ± 0.004	-0.10 ± 0.05	G7V	=	=
Kepler-453	0.833 ± 0.011	5521 ± 102	0.09 ± 0.10	0.944 ± 0.010	4.571 ± 0.015	-0.24 ± 0.03		0.056 ± 0.004	448.6 ± 2.8
	0.2150 ± 0.0014	3228 ± 97	=	0.1951 ± 0.0020	5.063 ± 0.005	-2.34 ± 0.05		=	=
Tyc 5227-1023-1	1.388 ± 0.010	6353 ± 205	-0.63 ± 0.11	0.956 ± 0.016	4.130 ± 0.010	0.45 ± 0.06		0.0749 ± 0.0012	399 ± 8
	0.977 ± 0.010	5929 ± 218	=	0.839 ± 0.012	4.380 ± 0.010	0.03 ± 0.06		=	=
IM Vir	1.061 ± 0.016	5675 ± 105	-0.10 ± 0.25	0.981 ± 0.012	4.379 ± 0.014	0.02 ± 0.03	G7V	0	83.39 ± 0.29
	0.681 ± 0.013	4246 ± 127	=	0.664 ± 0.005	4.594 ± 0.017	-0.87 ± 0.05	K7V	=	=
V565 Lyr	1.101 ± 0.007	5598 ± 90	0.28 ± 0.05	0.995 ± 0.003	4.352 ± 0.005	0.030 ± 0.029		0.1335 ± 0.0020	4067 ± 188
	0.971 ± 0.005	5433 ± 125	=	0.929 ± 0.003	4.432 ± 0.008	-0.13 ± 0.04		=	=
V530 Ori	0.980 ± 0.013	5984 ± 96	-0.12 ± 0.08	1.004 ± 0.007	4.457 ± 0.012	0.045 ± 0.030		0	102.9 ± 0.4
	0.587 ± 0.007	3882 ± 116	=	0.5955 ± 0.0022	4.676 ± 0.010	-1.15 ± 0.05		=	=
KIC 7177553	0.940 ± 0.005	5794 ± 133	-0.05 ± 0.09	1.043 ± 0.014	4.517 ± 0.008	-0.05 ± 0.04	G2V	0.0756 ± 0.0015	
	0.941 ± 0.005	5741 ± 145	=	0.986 ± 0.015	4.491 ± 0.008	-0.06 ± 0.04	G2V	=	
Kepler-34	1.1617 ± 0.0029	5916 ± 123	-0.07 ± 0.15	1.048 ± 0.003	4.3284 ± 0.0021	0.17 ± 0.04		0.167 ± 0.005	1896 ± 92
	1.0927 ± 0.0030	5861 ± 135	=	1.0207 ± 0.0021	4.3703 ± 0.0022	0.10 ± 0.04		=	=

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RESULTS

Table 3. Inferred stellar parameters of DEB stars in Sample I: absolute magnitudes in the B-band (M_B) and the V-band (M_V), bolometric correction (BC), mass (M_m), evolution stage (ES), probability Pr, distance (d_m), age (τ), and grid used.

Binary	M_B (mag)	M_V (mag)	BC (mag)	M_m ($M_\odot$)	ES	Pr	d_m (pc)	τ (Gyr)	Grid
CM Dra A	14.47 ± 0.26	12.88 ± 0.26	-2.50 ± 0.18	0.235 ± 0.004	MS	94	13.7 ± 2.8	$7\ ^{+4}_{-4}$	I
CM Dra B	14.7 ± 0.3	13.1 ± 0.3	-2.59 ± 0.23	0.219 ± 0.003	MS	95	〃	$7\ ^{+4}_{-4}$	I
PTFEB 132.707+19.810 A	13.43 ± 0.14	11.95 ± 0.14	-2.43 ± 0.08	0.359 ± 0.010	MS	80	205 ± 69	$3.2\ ^{+7}_{-0.5}$	I
PTFEB 132.707+19.810 B	14.81 ± 0.26	13.27 ± 0.26	-2.91 ± 0.13	0.254 ± 0.014	MS	96	〃	〃	I
PTFEB 132.707+19.810 A	13.37 ± 0.14	11.89 ± 0.14	-2.39 ± 0.08	0.367 ± 0.011	PMS	20	210 ± 71	$0.77\ ^{+1.2}_{-0.09}$	I
PTFEB 132.707+19.810 B	14.81 ± 0.26	13.27 ± 0.26	-2.91 ± 0.13	0.254 ± 0.014	MS	96	〃	〃	I
HAT-TR-318-007 A	12.60 ± 0.15	11.21 ± 0.16	-2.30 ± 0.11	0.456 ± 0.005	MS	90	115 ± 24	$3.3\ ^{+7}_{-1.1}$	I
HAT-TR-318-007 B	14.77 ± 0.26	13.26 ± 0.28	-3.00 ± 0.20	0.272 ± 0.006	MS	96	〃	〃	I
HAT-TR-318-007 A	12.59 ± 0.26	11.20 ± 0.26	-2.30 ± 0.17	0.455 ± 0.028	PMS	10	116 ± 26	$1.2\ ^{+0.4}_{-0.4}$	I
HAT-TR-318-007 B	14.77 ± 0.26	13.26 ± 0.28	-3.00 ± 0.20	0.272 ± 0.006	MS	96	〃	〃	I
YY Gem A	10.26 ± 0.21	8.91 ± 0.22	-1.37 ± 0.13	0.620 ± 0.012	MS	95	14.4 ± 2.2	$7\ ^{+4}_{-4}$	I
YY Gem B	10.37 ± 0.23	9.01 ± 0.24	-1.38 ± 0.14	0.604 ± 0.011	MS	92	〃	〃	I
M55 V54 A	4.87 ± 0.04	4.47 ± 0.03	-0.168 ± 0.005	0.746 ± 0.009	MS	99	4914 ± 1815	$13.0\ ^{+0.8}_{-1.0}$	I
M55 V54 B	7.68 ± 0.08	6.94 ± 0.07	-0.297 ± 0.012	0.579 ± 0.014	MS	100	〃	〃	I
M4 V69 A	5.38 ± 0.08	4.92 ± 0.07	-0.152 ± 0.006	0.764 ± 0.030	MS	100	1787 ± 394	$13.0\ ^{+0.8}_{-2.9}$	I
M4 V69 B	5.64 ± 0.08	5.15 ± 0.06	-0.157 ± 0.005	0.743 ± 0.028	MS	100	〃	〃	I
M4 V66 A	5.15 ± 0.06	4.70 ± 0.05	-0.147 ± 0.006	0.770 ± 0.025	MS	100	1786 ± 357	$13.0\ ^{+0.8}_{-2.1}$	I
M4 V66 B	5.56 ± 0.06	5.08 ± 0.05	-0.155 ± 0.005	0.741 ± 0.022	MS	100	〃	〃	I
M4 V65 A	4.65 ± 0.06	4.22 ± 0.04	-0.140 ± 0.005	0.783 ± 0.016	MS	99	1926 ± 410	$13.0\ ^{+0.8}_{-1.3}$	I
M4 V65 B	7.39 ± 0.14	6.64 ± 0.11	-0.282 ± 0.024	0.620 ± 0.014	MS	53	〃	$13.0\ ^{+0.8}_{-1.3}$	I
M4 V65 A	4.65 ± 0.06	4.22 ± 0.04	-0.140 ± 0.005	0.783 ± 0.016	MS	99	1941 ± 413	$12.2\ ^{+0.9}_{-0.9}$	I
M4 V65 B	7.89 ± 0.22	7.03 ± 0.17	-0.42 ± 0.06	0.585 ± 0.013	PMS	47	〃	$0.032\ ^{+0.004}_{-0.004}$	I
NGC 6362 V41 A	4.81 ± 0.06	4.37 ± 0.05	-0.137 ± 0.004	0.789 ± 0.022	MS	100	7498 ± 3441	$13.0\ ^{+0.8}_{-2.1}$	I
NGC 6362 V41 B	6.09 ± 0.08	5.54 ± 0.06	-0.165 ± 0.006	0.718 ± 0.025	MS	100	〃	〃	I
NGC 6362 V40 A	4.32 ± 0.07	3.89 ± 0.05	-0.132 ± 0.005	0.818 ± 0.019	MS	64	7740 ± 2798	$11.8\ ^{+0.6}_{-1.3}$	I
NGC 6362 V40 B	4.99 ± 0.08	4.54 ± 0.07	-0.139 ± 0.005	0.788 ± 0.029	MS	100	〃	〃	I
NGC 6362 V40 A	4.427 ± 0.028	3.972 ± 0.021	-0.1394 ± 0.0018	0.789 ± 0.005	SGB	36	7706 ± 2786	$13.0\ ^{+0.8}_{-0.6}$	I
NGC 6362 V40 B	4.99 ± 0.08	4.54 ± 0.07	-0.139 ± 0.005	0.788 ± 0.029	MS	100	〃	〃	I
47 Tuc V69 A	4.48 ± 0.09	3.99 ± 0.06	-0.116 ± 0.008	0.862 ± 0.028	MS	56	4332 ± 913	$11.3\ ^{+0.9}_{-1.3}$	I
47 Tuc V69 B	4.76 ± 0.09	4.27 ± 0.06	-0.118 ± 0.008	0.84 ± 0.03	MS	100	〃	〃	I
47 Tuc V69 A	4.45 ± 0.08	3.97 ± 0.06	-0.113 ± 0.008	0.871 ± 0.029	MS	31	4340 ± 915	$10.2\ ^{+1.4}_{-0.7}$	O
47 Tuc V69 B	4.76 ± 0.09	4.27 ± 0.06	-0.118 ± 0.008	0.84 ± 0.03	MS	100	〃	〃	I
Kepler-35 A	5.49 ± 0.15	4.82 ± 0.10	-0.118 ± 0.015	0.90 ± 0.05	MS	100	1601 ± 236	$13.0\ ^{+0.8}_{-3}$	I
Kepler-35 B	6.75 ± 0.15	5.92 ± 0.10	-0.239 ± 0.030	0.81 ± 0.04	MS	100	〃	〃	I
KIC 6131659 A	5.76 ± 0.06	5.12 ± 0.05	-0.120 ± 0.010	0.88 ± 0.06	MS	100	319 ± 14	$3.3\ ^{+5}_{-2.0}$	I
KIC 6131659 B	8.29 ± 0.10	7.25 ± 0.07	-0.56 ± 0.03	0.664 ± 0.018	MS	98	〃	〃	I
RW Lac A	5.08 ± 0.11	4.43 ± 0.08	-0.105 ± 0.011	0.92 ± 0.05	MS	100	187 ± 14	$13.0\ ^{+0.8}_{-2.7}$	I
RW Lac B	5.70 ± 0.16	5.01 ± 0.11	-0.128 ± 0.018	0.89 ± 0.05	MS	100	〃	〃	I
Kepler-453 A	6.35 ± 0.13	5.57 ± 0.10	-0.178 ± 0.023	0.90 ± 0.04	MS	99	408 ± 29	$0.94\ ^{+4}_{-0.15}$	I
Kepler-453 B	15.5 ± 0.3	13.9 ± 0.3	-2.95 ± 0.23	0.1883 ± 0.0026	MS	97	〃	〃	I

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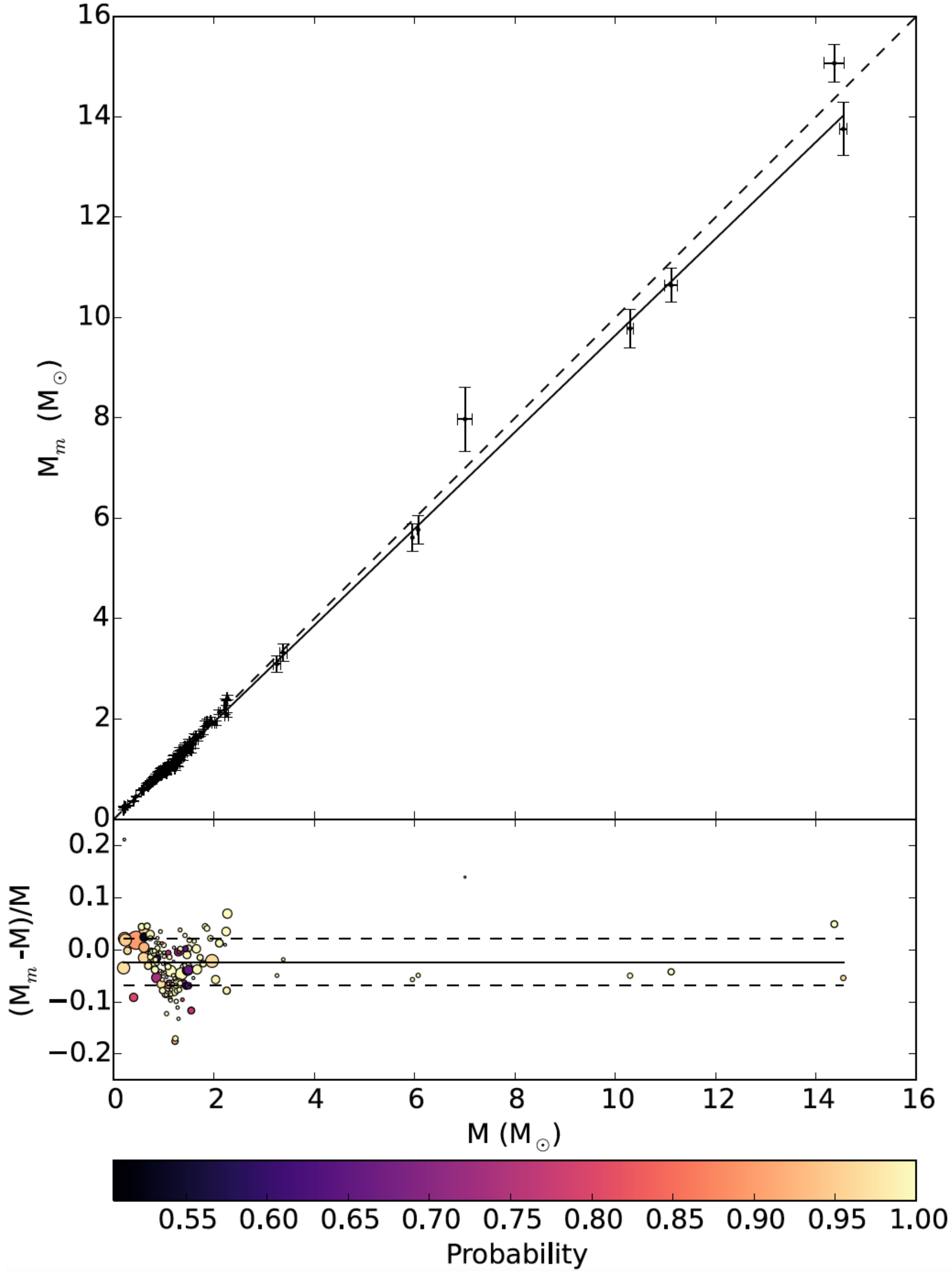
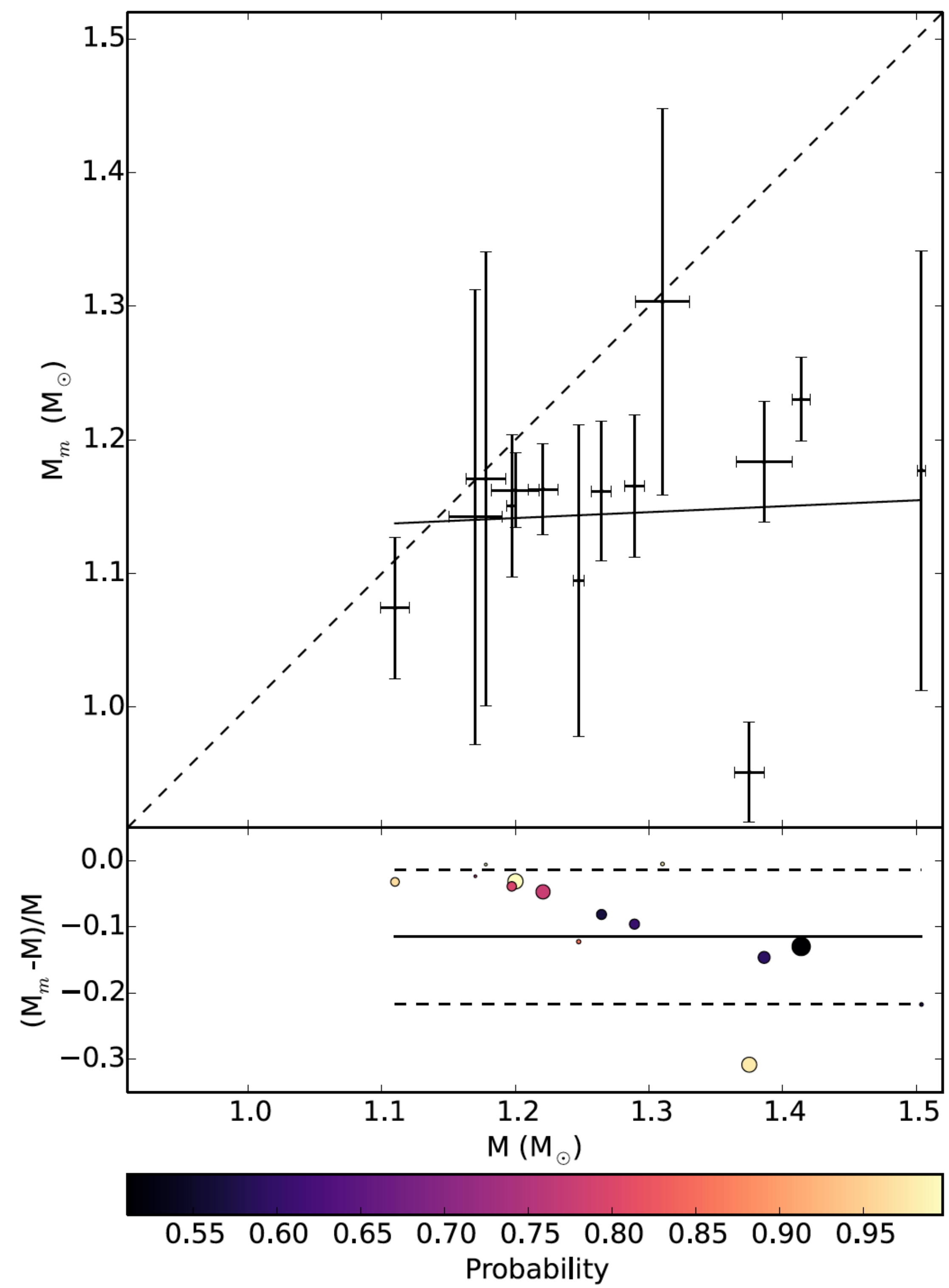
Mass





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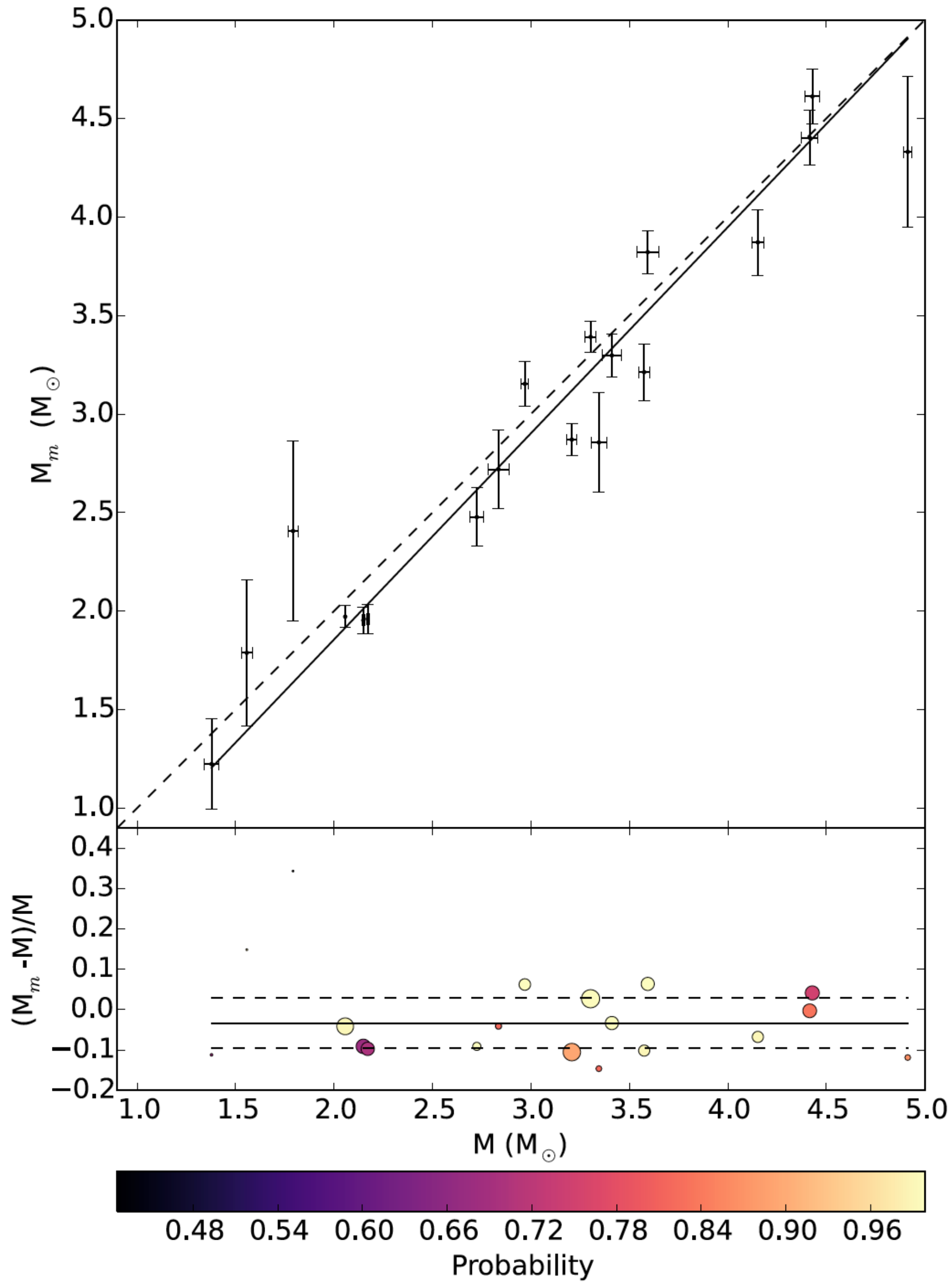
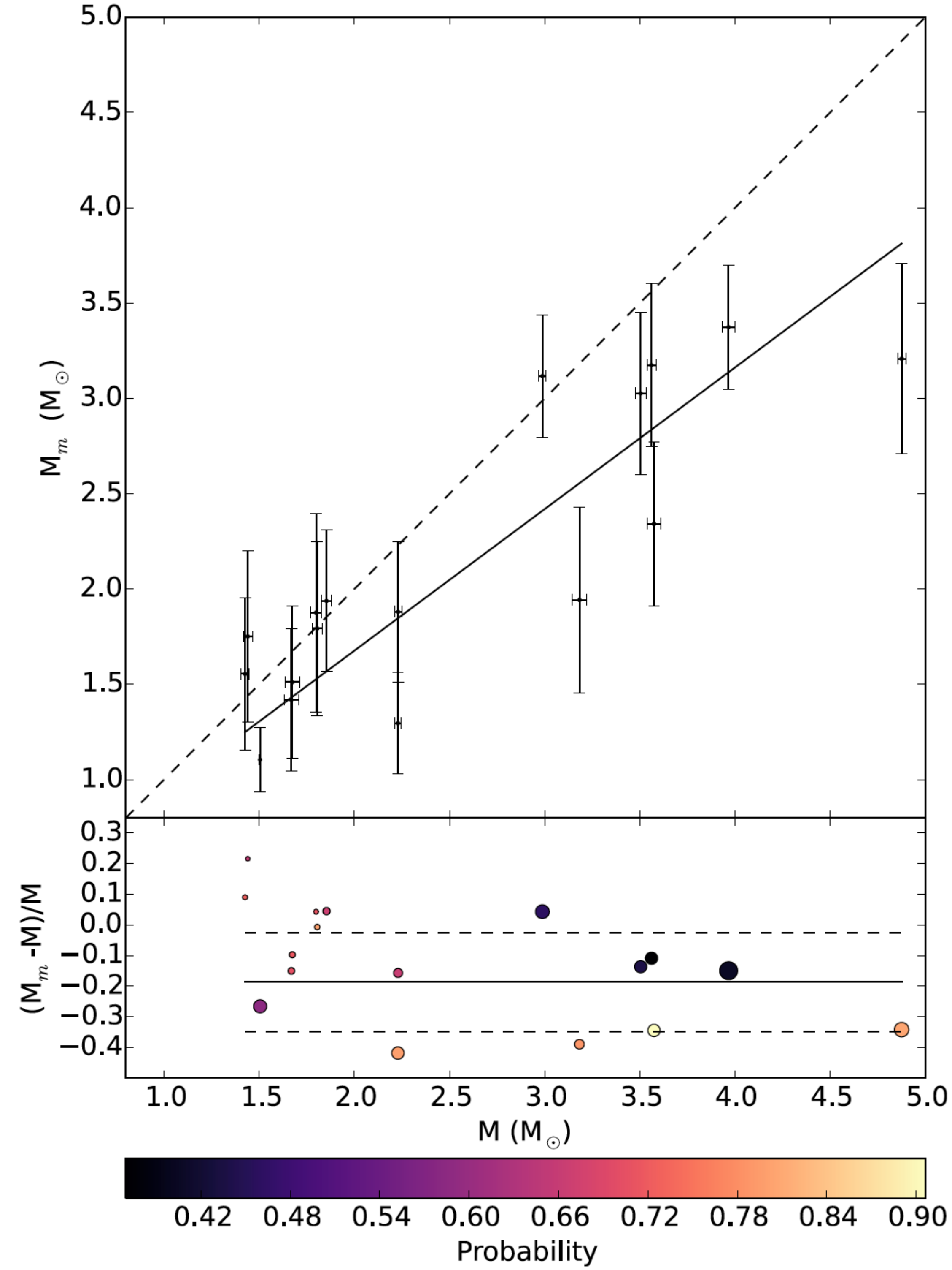
Mass





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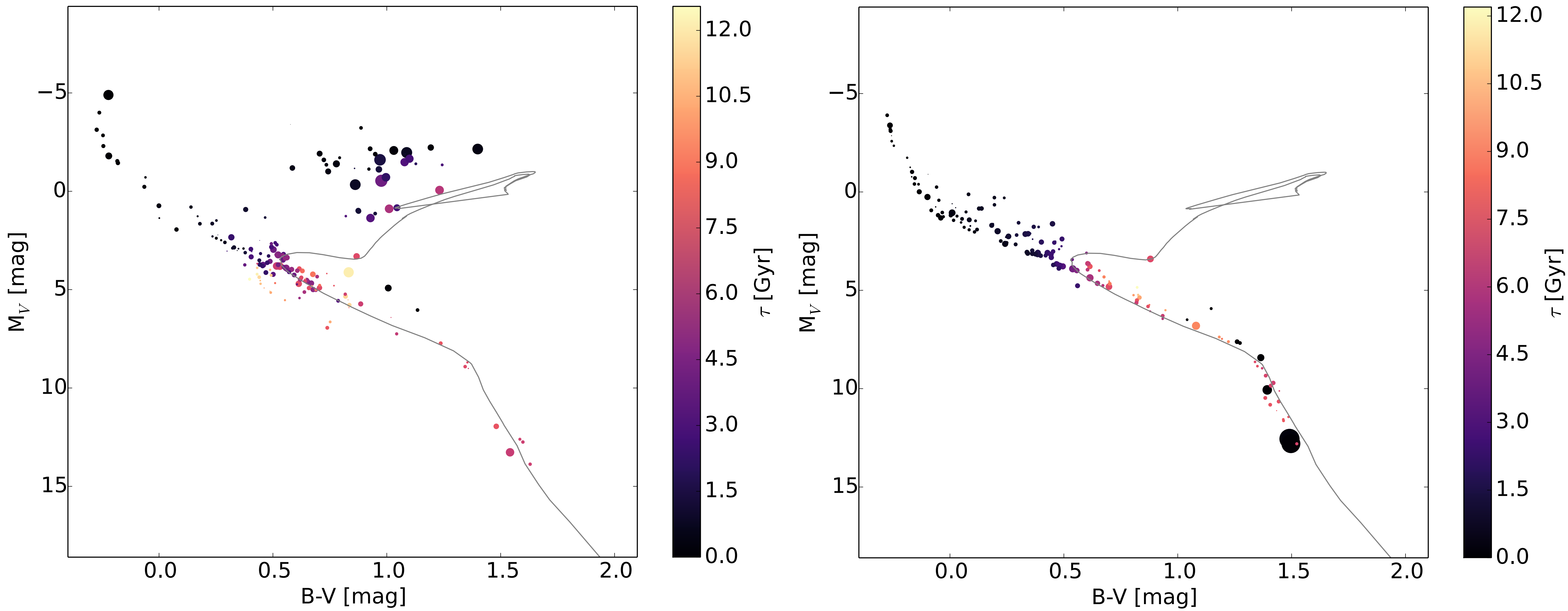
Samples I and II



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Mass

Table 5. Number of points N, mean $\pm$ standard deviation of $\frac{M_m - M}{M}$ weighted by σ^{-2} (w_1) and by normalized probability $\times$ σ^{-2} (w_2), Pearson correlation coefficient weighted by w_1, slope and offset computed using a weighted orthogonal distance regression procedure (Boggs & Rogers 1992), and mass range for different groups of DEB stars in Samples I and I + II.

Group	N	$\langle \frac{M_m - M}{M} \rangle_{w_1}$	$\langle \frac{M_m - M}{M} \rangle_{w_2}$	r_{w_1}	Slope	Offset ($M_\odot$)	Mass range ($M_\odot$)
MS (I)	129	-0.02 ± 0.04	-0.02 ± 0.04	0.998	0.964 ± 0.006	0.010 ± 0.003	0.2 – 14.5
MS (I+II)	254	-0.02 ± 0.06	-0.02 ± 0.05	0.998	0.955 ± 0.007	0.016 ± 0.004	0.1 – 14.5
S/RGB (I)	14	-0.12 ± 0.09	-0.12 ± 0.10	0.060	0.04 ± 0.24	1.1 ± 0.3	1.1 – 1.5
S/RGB (I+II)	19	-0.11 ± 0.09	-0.11 ± 0.10	0.133	0.12 ± 0.20	0.99 ± 0.25	1.1 – 1.5
CHeB (I)	19	-0.03 ± 0.06	-0.03 ± 0.06	0.973	1.05 ± 0.05	-0.24 ± 0.16	1.4 – 4.9
EAGB (I)	17	-0.19 ± 0.15	-0.21 ± 0.16	0.856	0.74 ± 0.10	0.19 ± 0.26	1.4 – 4.9

Offset±dispersion

Masses are systematically underestimated

We have added quadratically the offset and the dispersion for every evolutionary phase

We have also applied our analysis to the full sample of giants stars (RGB, CHeB, and EAGB stars), in order to compare our results with those from Ghezzi & Johnson (2015), finding consistent results

We emphasize the larger sample used in this work permits to look for differences for these stages

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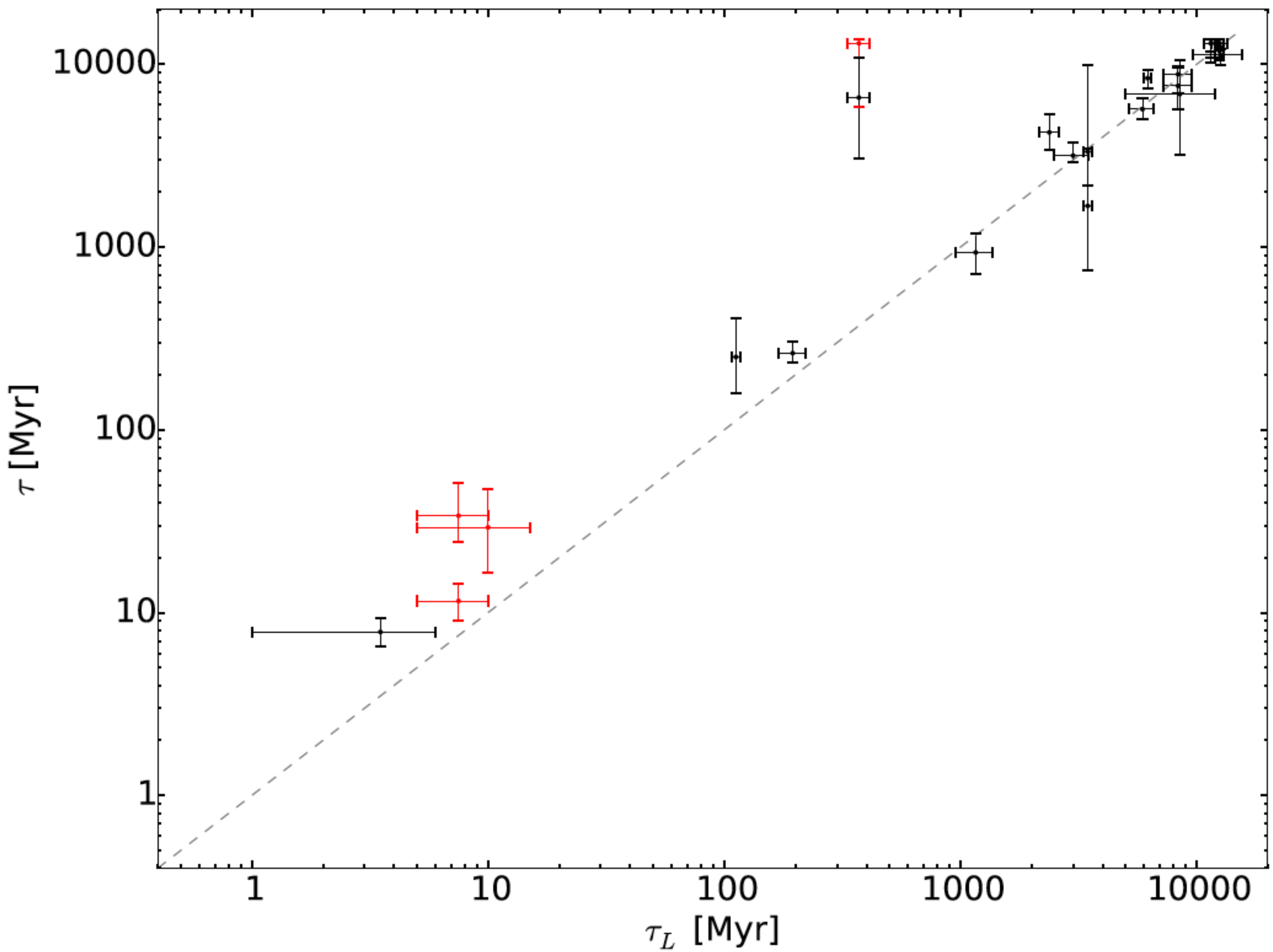
Ages



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Ages

GU Boo belongs to the globular cluster M55 (14 ± 1.2 Gyr), there are three members of M4 (11.6 ± 0.6 Gyr, Bedin et al. 2009), one binary in NGC 6362 (12.5 ± 0.5 Gyr, Kaluzny et al. 2015), and another one in 47 Tuc (10-13 Gyr, Salaris & Weiss 2002; Gratton et al. 2003; Grundahl, Stetson & Andersen 2002; Zoccali et al. 2001). Some of the eclipsing binaries are in younger, galactic clusters such as NGC 6791 (8.3 Gyr, Brogaard et al. 2012), NGC 7142 (3.0 Gyr, Straižys et al. 2014), NGC 2516 (150 Myr, Jefries, James & Thurston 1998), NGC 6819 (2.25 Gyr, Hanber
the Pleiades (112 ± 5 Myr, Dahm 2015), M
Meynet, Mermilliod & Maeder 1993), Cr 228 (
Massey et al. 2001), or NGC 2244 (1-6 Myr, B
2009).

The most discrepant cases are CU Cnc and YY Gem, for which we find uncertain but old ages, inconsistent with published estimates. The latter are based on the physical association of the YY Gem with the Castor A/B binary system, and the likely membership of CU Cnc to the same moving group, dated from the Castor A/B binary at 350 Myr (Torres & Ribas 2002; Ribas 2003). Given our success with other systems containing components with similar masses, our results speak against a common age for these systems and the Castor A/B binary, but we refer the reader to the aforementioned papers, where significant discrepancies between the parameters for the stars in these systems and stellar evolutionary models have been reported. Note that PARSEC v1.2S library introduces significant improvements for low mass dwarfs.

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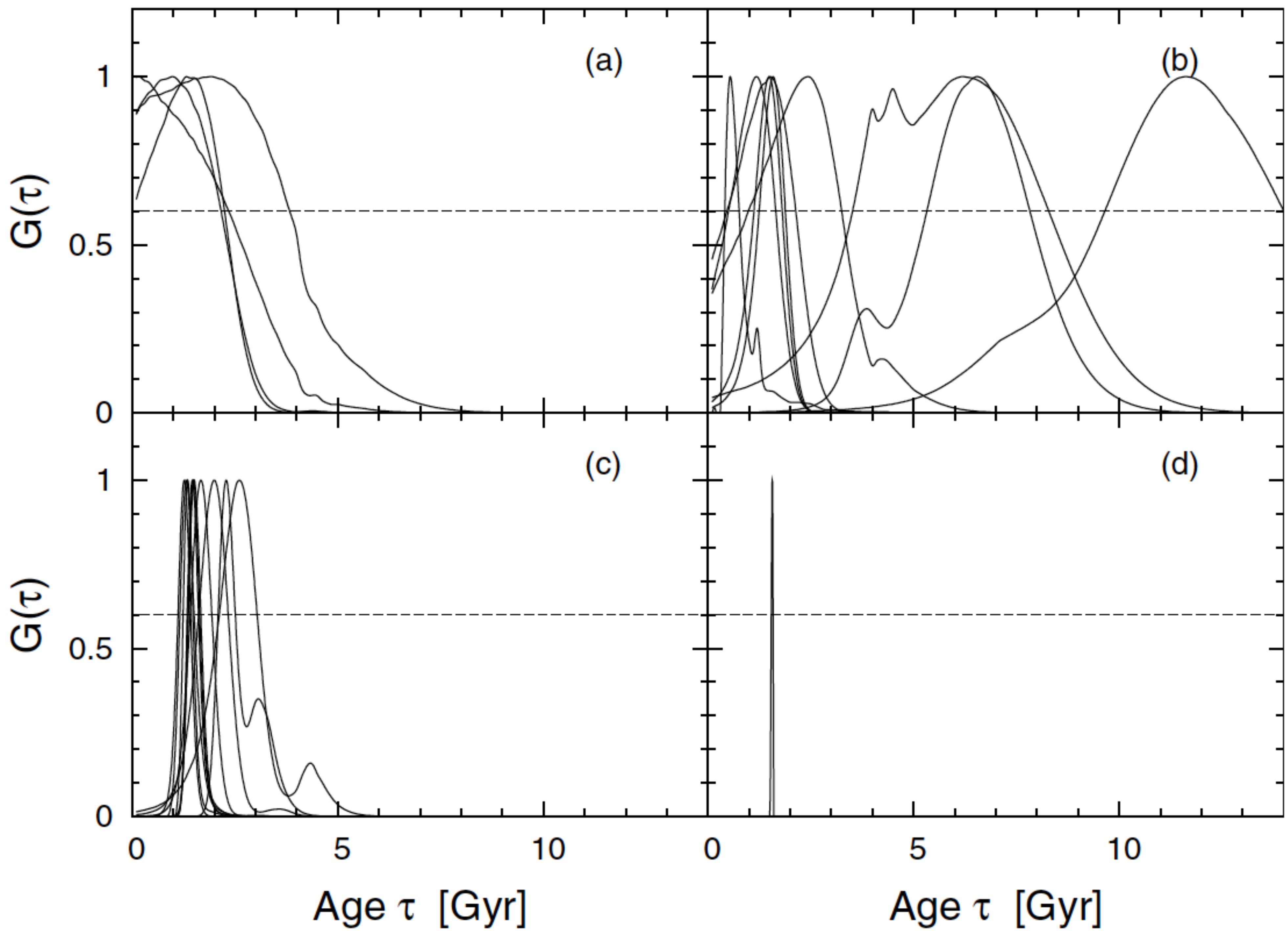
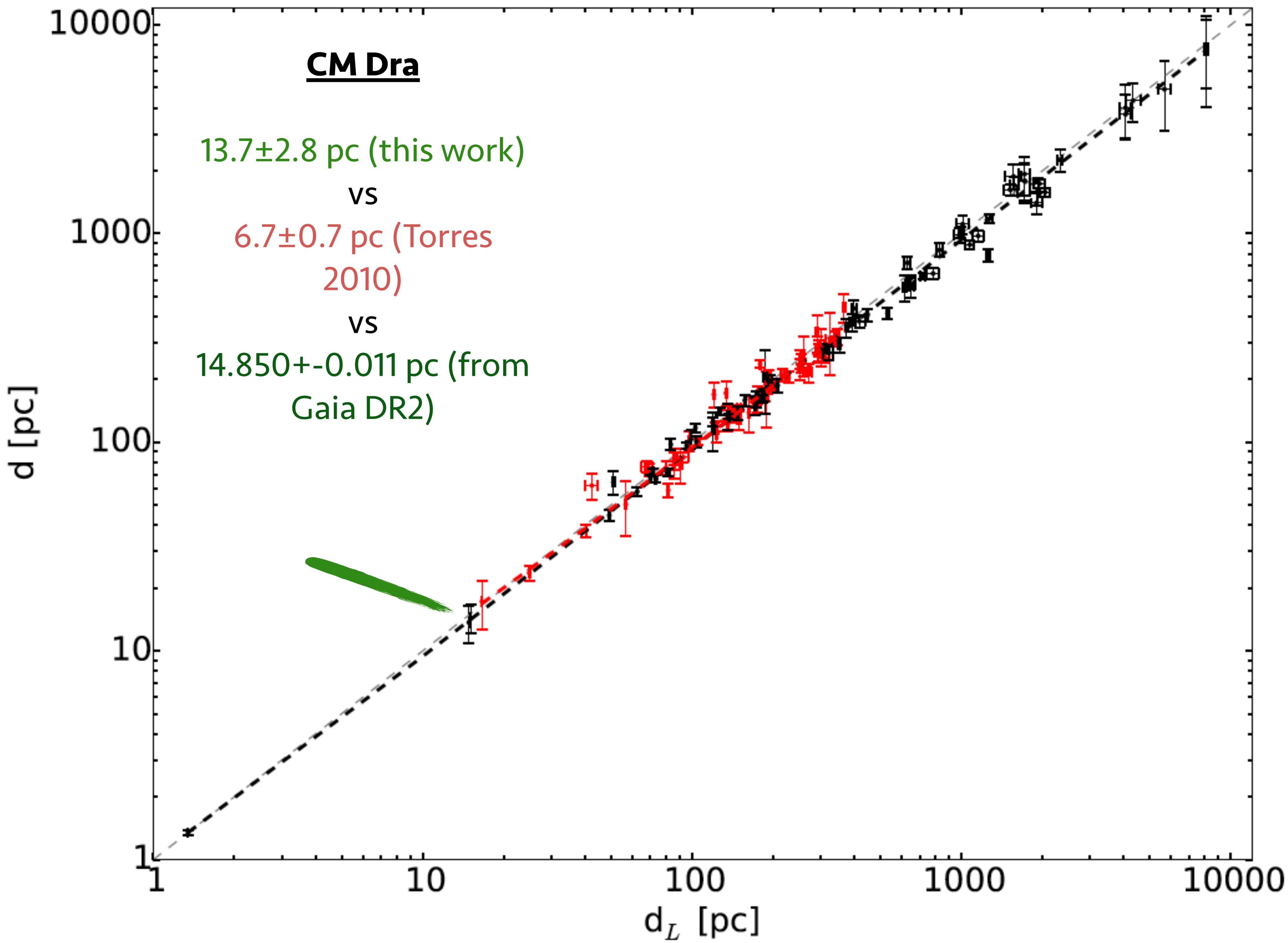
Combined $G(\tau)$



Jorgensen & Lindegren (2005)

Distances



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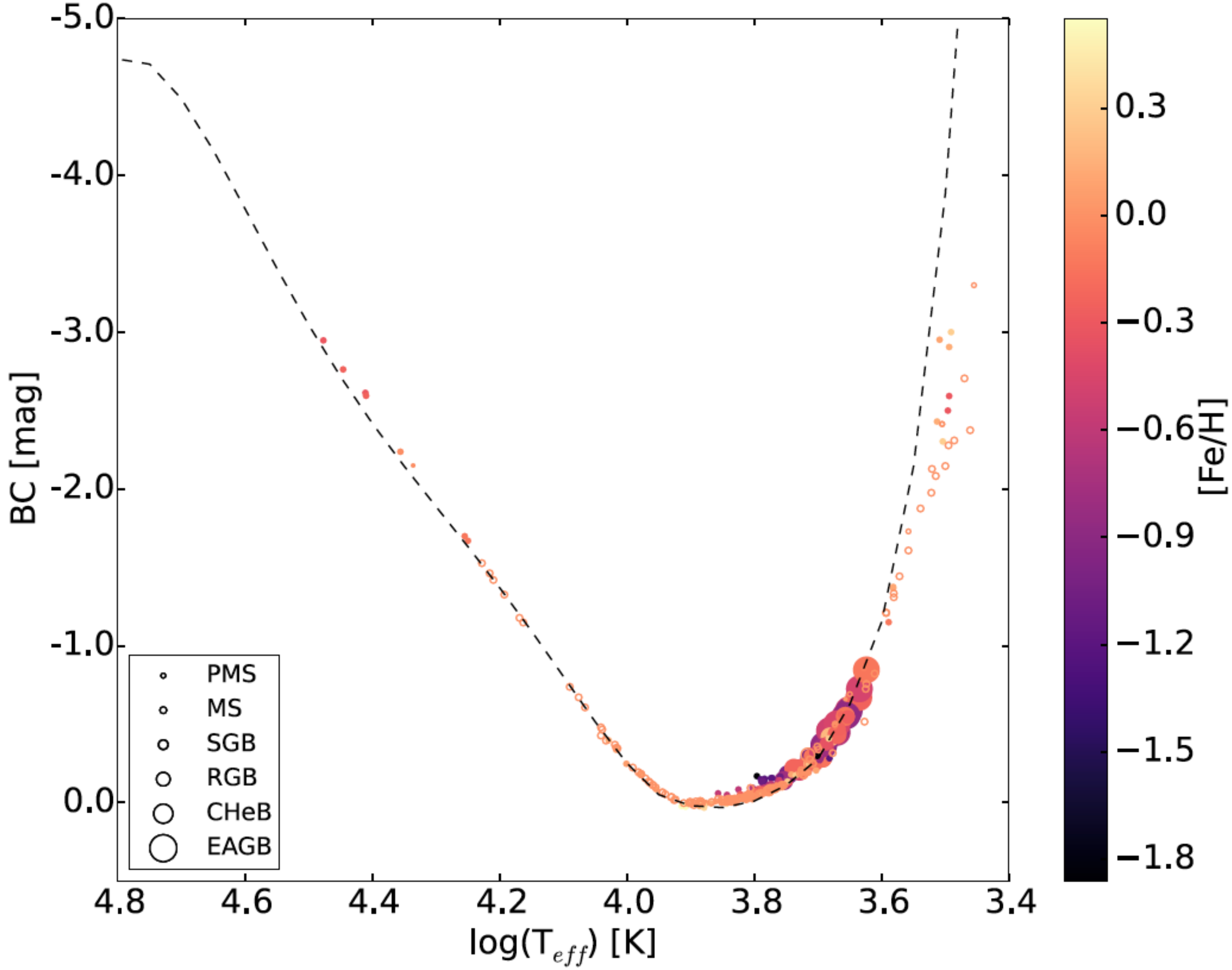
Bolometric correction



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Conclusions

This work is an endeavour to properly infer stellar parameters from evolution models using a Bayesian approach for 318 well-known DEB stars, at distances between 1.3 pc and ~8 kpc for galactic objects and ~44−68 kpc for the extragalactic ones

From the comparison with dynamical masses, we conclude that the inferred masses are precisely derived for stars on the main-sequence and in the core-helium-burning phase, with uncertainties, on average, of 4 per cent and 7 per cent, respectively.

Masses for the subgiants and red giants are predicted within 14 per cent, and those for early asymptotic giant branch stars within 24 per cent

Inferred distances agree with those from trigonometric parallaxes.
Bolometric corrections must be carefully determined

Age inference is challenging ...
Our values agree with those from the literature