Young, (metal-)rich and not alone: Formation of thin-disc RR Lyrae stars through binary evolution

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&

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Based on:

- Bobrick&Iorio+2022, arXiv:2208.04332 (https://arxiv.org/abs/2208.04332)
- Iorio&Belokurov, 2021, MNRAS, 502, 5686 (https://academic.oup.com/mnras/article/502/4/5686/6066514)

Stellar Variability, Stellar Multiplicity: Periodicity in Time & Motion, Sofia, 6 June 2023

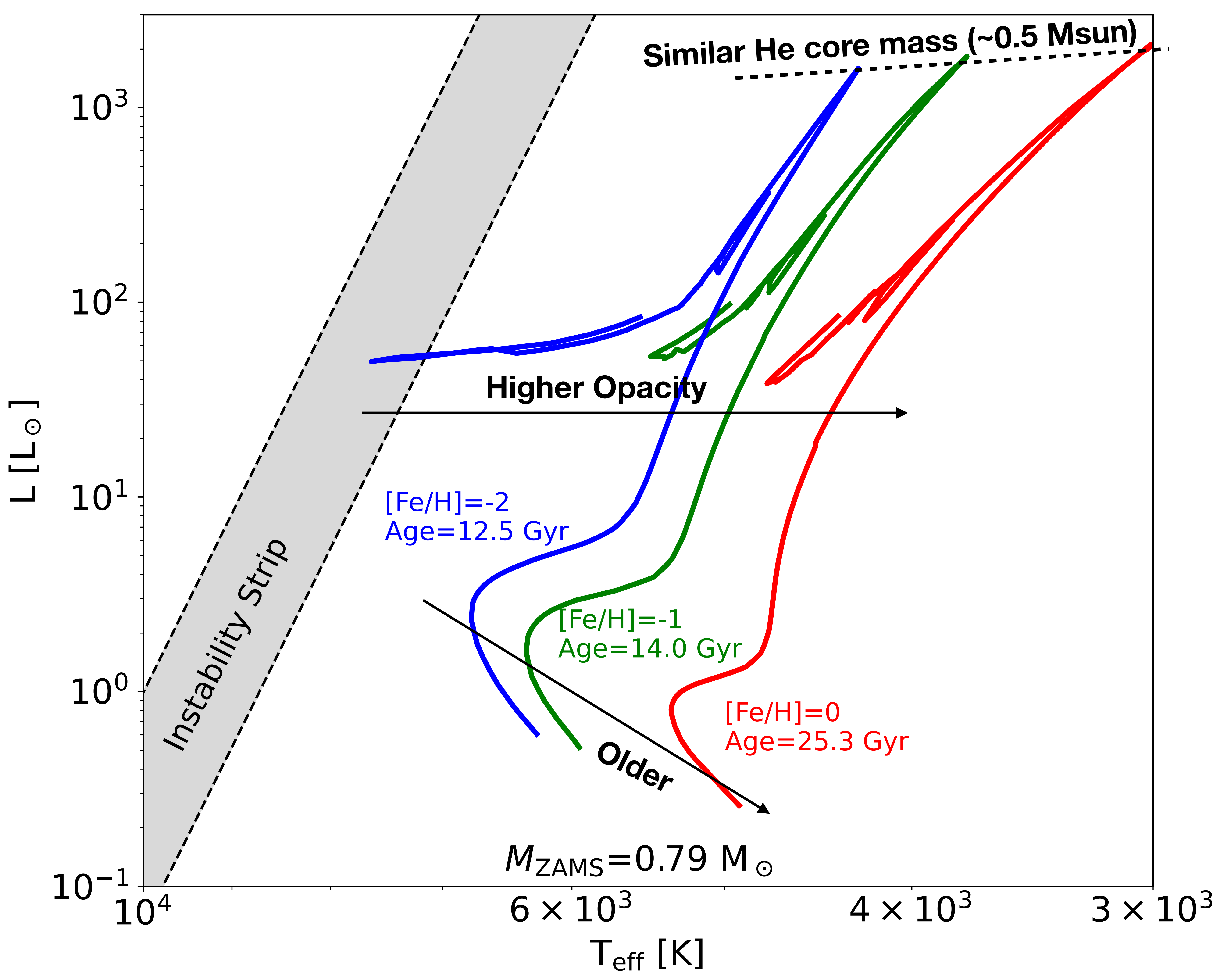
The RR Lyrae in the Milky Way

The "Classical textbook definition"

(e.g. Catelan09, Smith04)

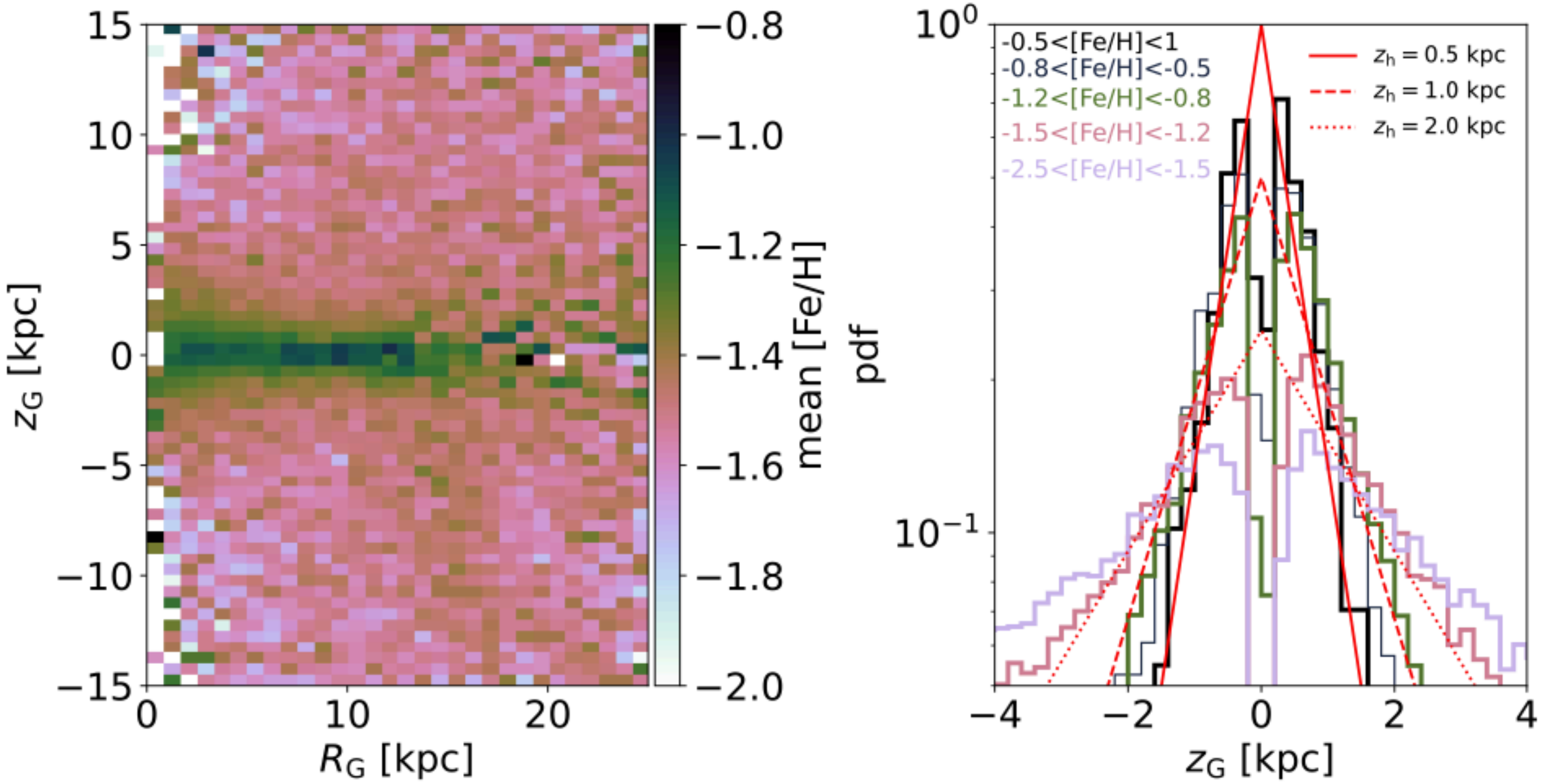
- **Low-mass** (<1 Msun) core He burning stars
- **Old** (>10 Gyr) and **metal-poor** ([Fe/H]<-1) **popII** stars
- Tracers of old populations (Halo, Globular clusters, Thick disc, Streams)

Single stellar evolution from MOBSE (Giacobbo+18)



A Gaia view of the RR Lyrae in the Milky Way

Data: Gaia DR 3 RR Lyrae (Bobrick&Iorio+22)



Metal-rich RR Lyrae stars exist

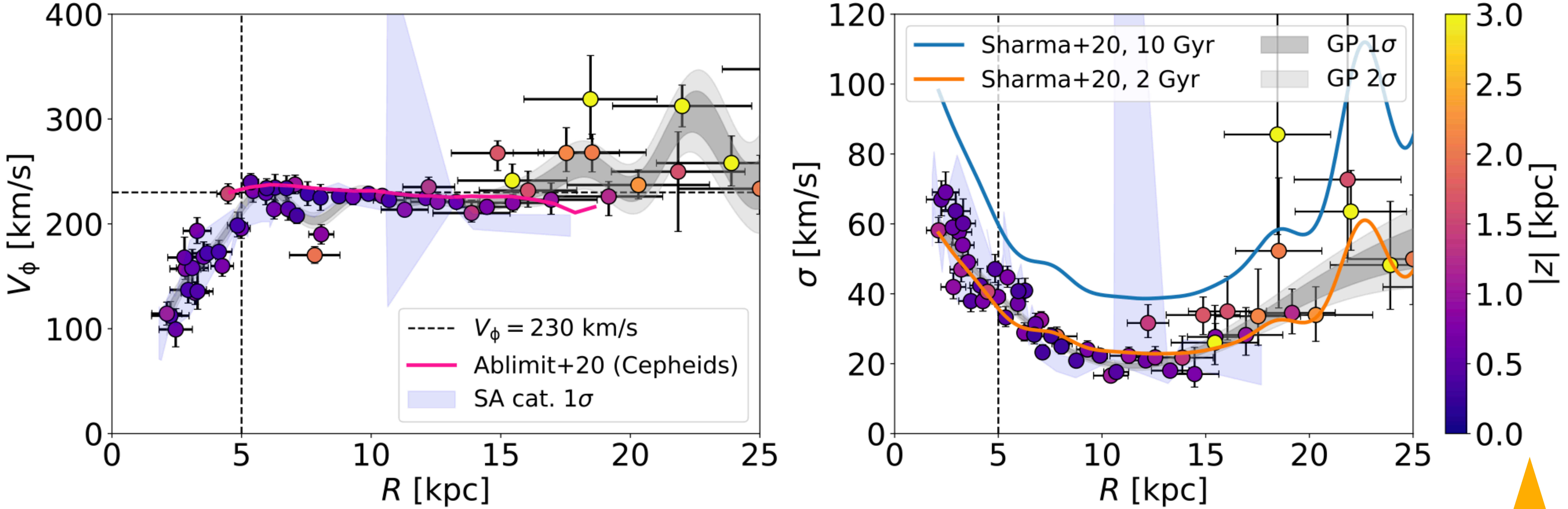
They have a flattened disc-like distribution

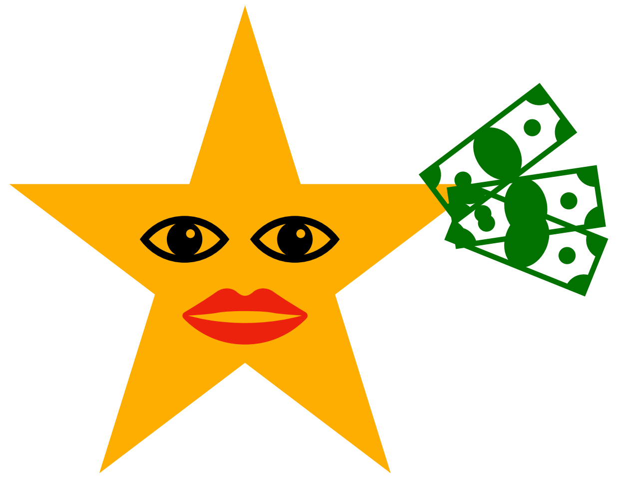
(See also Layden+95,Prudil+20,Zinn+20,Crestani+21)

A Gaia view of the RR Lyrae in the Milky Way

Data: Gaia DR 2 RR Lyrae (Iorio&Belokurov21)

Note: each point shows the best kinematical model for RR Lyrae binned on R-z





Kinematics of Metal-rich RR Lyrae
consistent with intermediate-young (< 10 Gyr) Thin-Disc populations

Confirm and extend what we already found in the solar neighbourhood (Layden+94, Prudil+20,Zinn+21)

How to form a metal-rich RR Lyrae star?

To balance the higher envelope opacity metal-rich RR Lyrae should have less massive envelope with respect to the metal-poor ones (see e.g. Bono+98).

$$\dot{M}_{\rm RGB} \propto \eta \frac{RL}{M}$$ (Kudritzki&Reimers78)

Higher wind mass loss during RGB (>0.4-0.5 Msun)

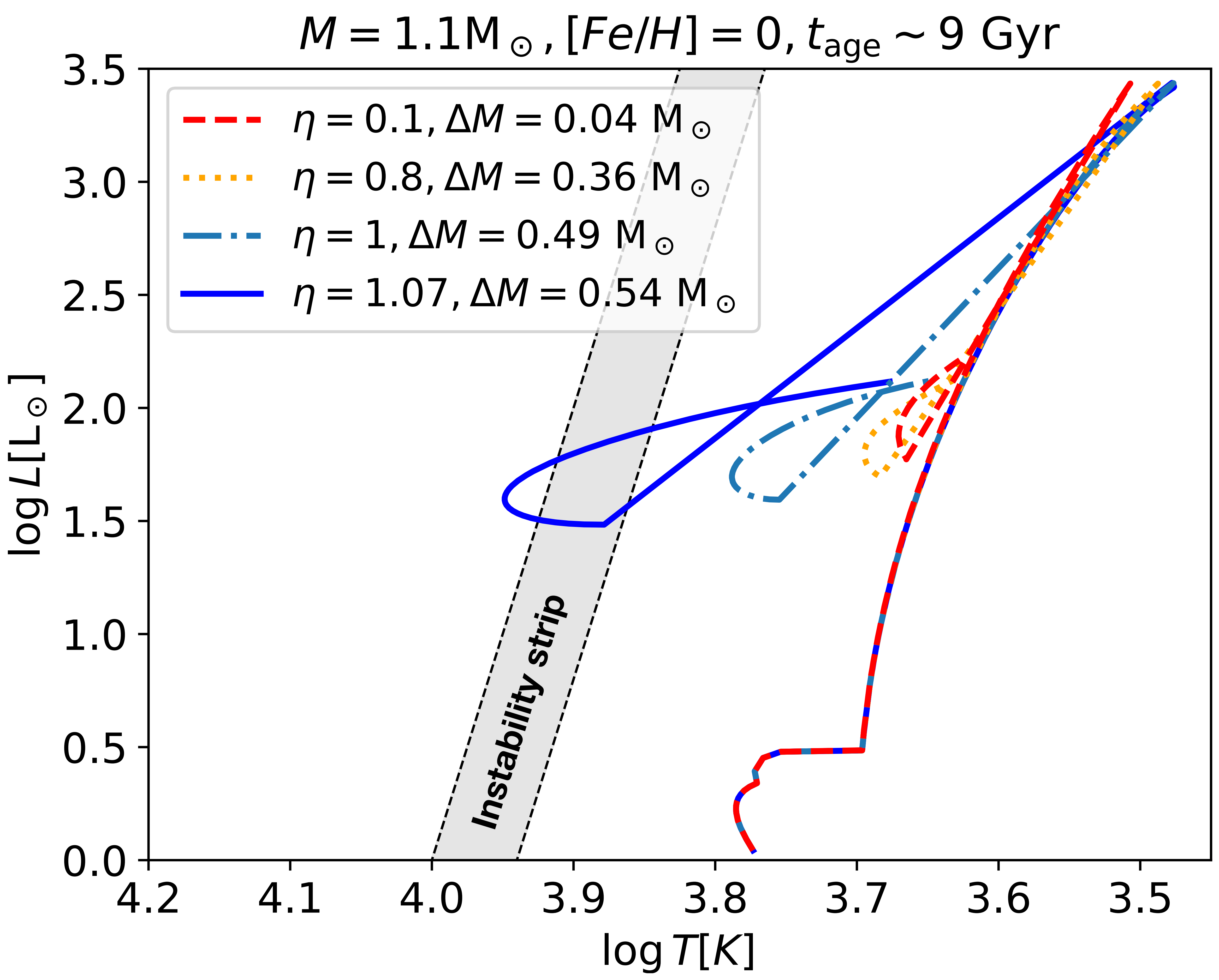
↓

Hotter core He burning stars

Challenge:

- **High RGB mass loss not supported by observations (<0.3 Msun,eta<0.6)**
(See e.g. Salaris+13, Origlia+14, Savino+19, Tailo+22)

- **Most of the RR Lyrae in the MW should be metal-rich**

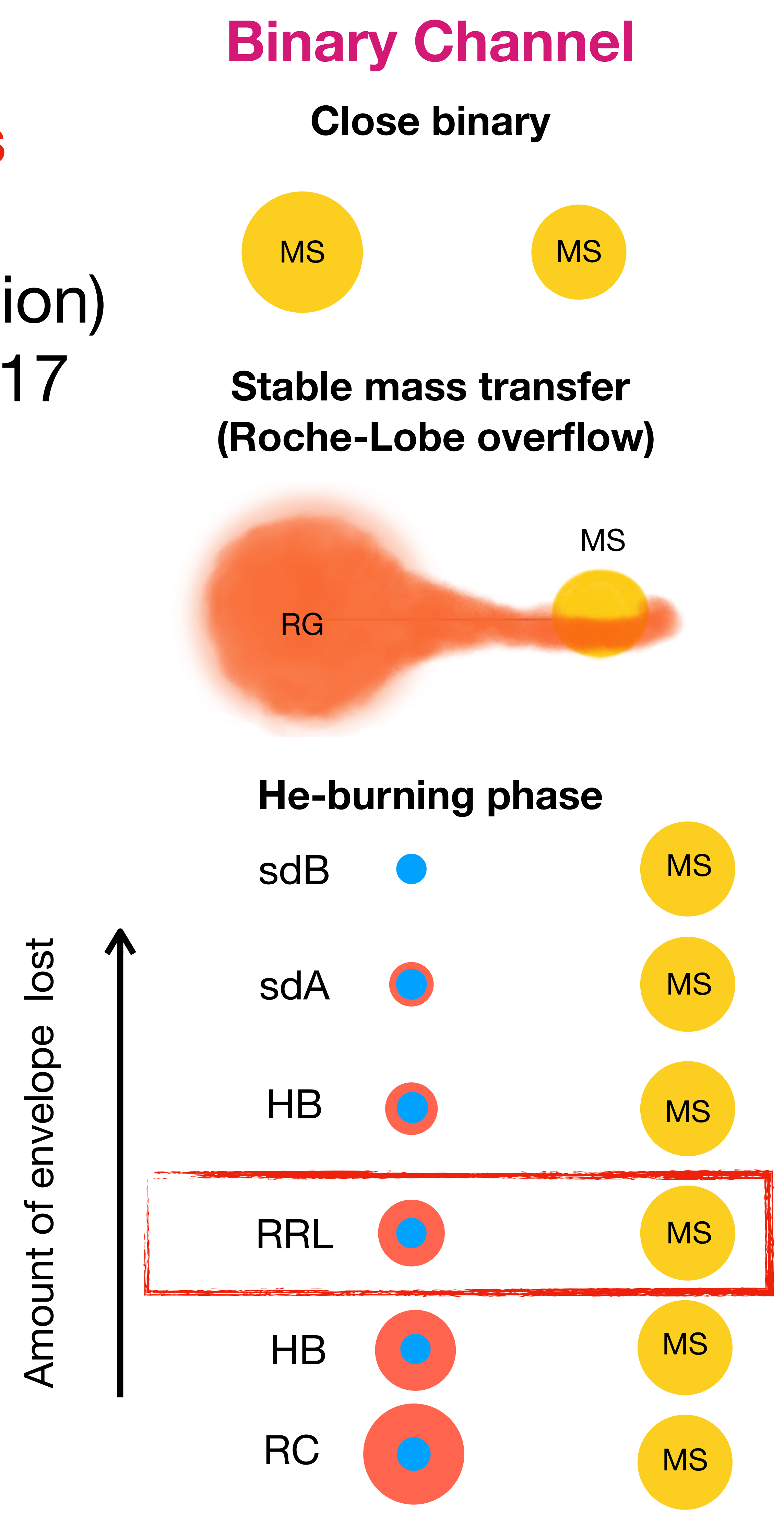


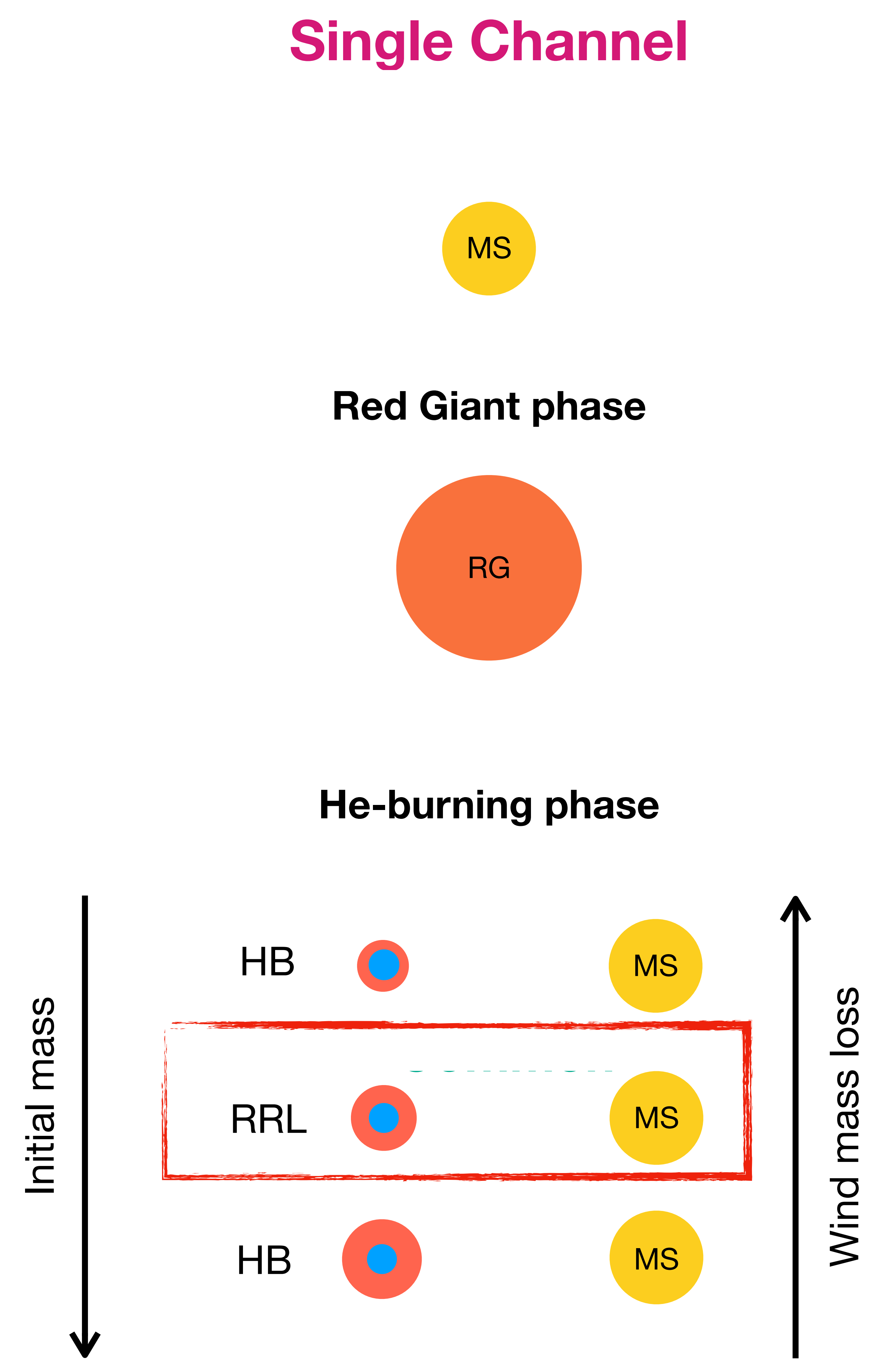
Single stellar evolution from MOBSE (Giacobbo+18)

An alternative formation channel: Binary mass loss

To balance the higher envelope opacity metal-rich RR Lyrae should have less massive envelope with respect to the metal-poor ones (see e.g. Bono+98).

~30% of Sun-like stars are in a binary system
(with a lower mass companion)
Offner+22,Moe&Distefano17



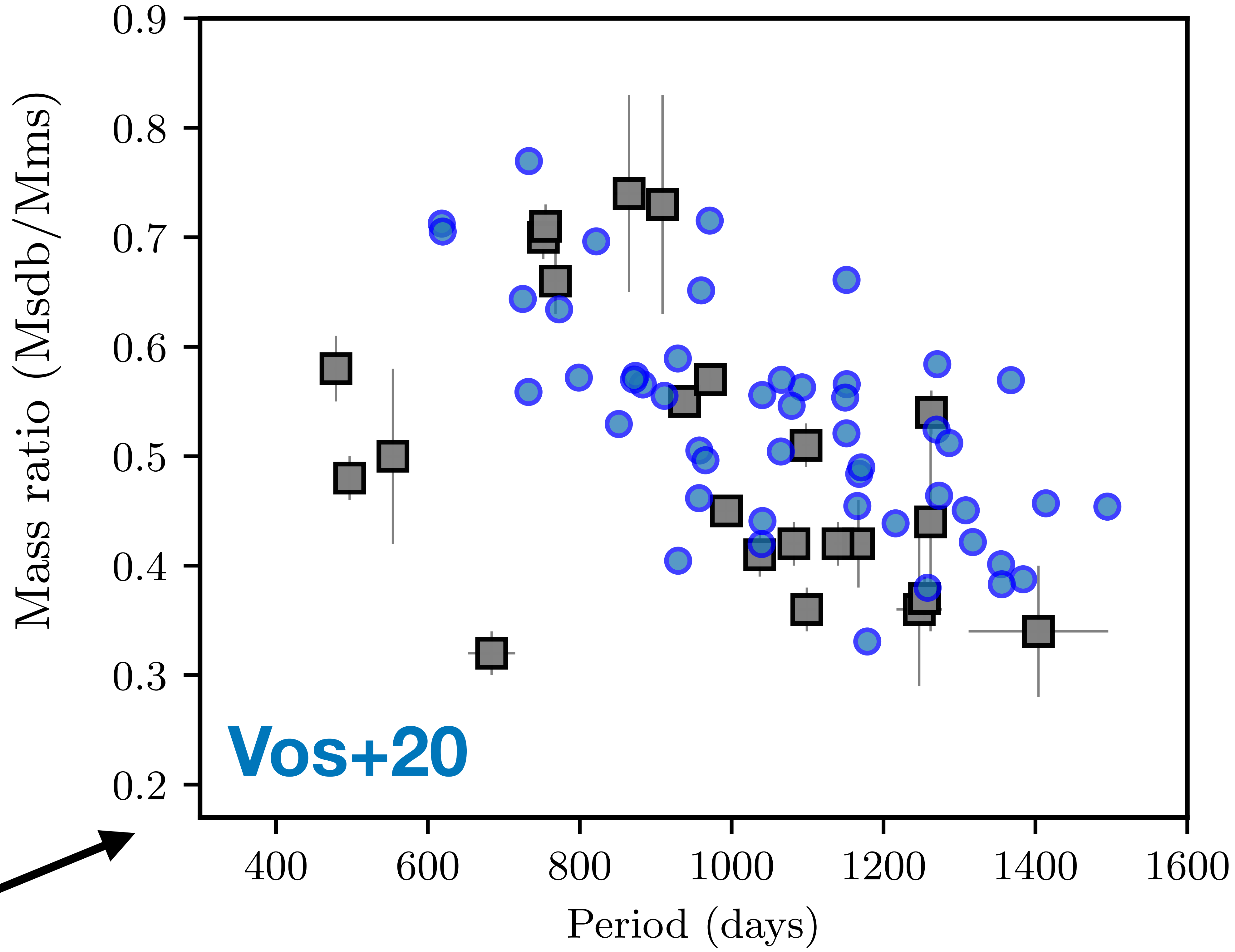


Credit: Bobrick&Iorio+22, see also Karzmarek+17

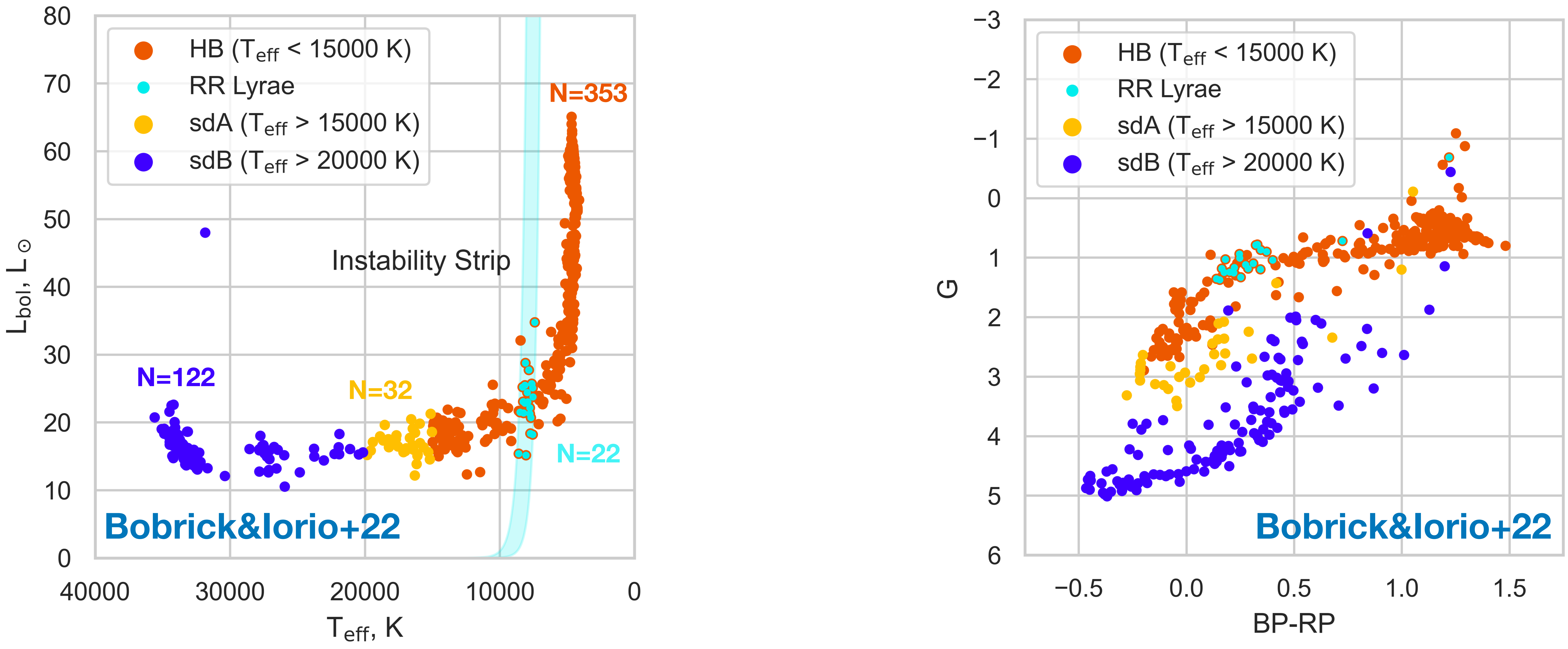
An alternative formation channel: Binary mass loss

Simulation setup (Vos+20): 2060 binaries

- Detailed stellar evolution models by MESA (Paxton+13-19)
- Standard RLO mass transfer model
- Close binary (100<P/days<700)
- Solar like stars (0.7<M/Msun<2)
- Besancon Galactic population (Robin+03) Close binary fraction 25%
- The simulations reproduce the Galactic population of long Period sdBs



Binary made RR Lyrae stars



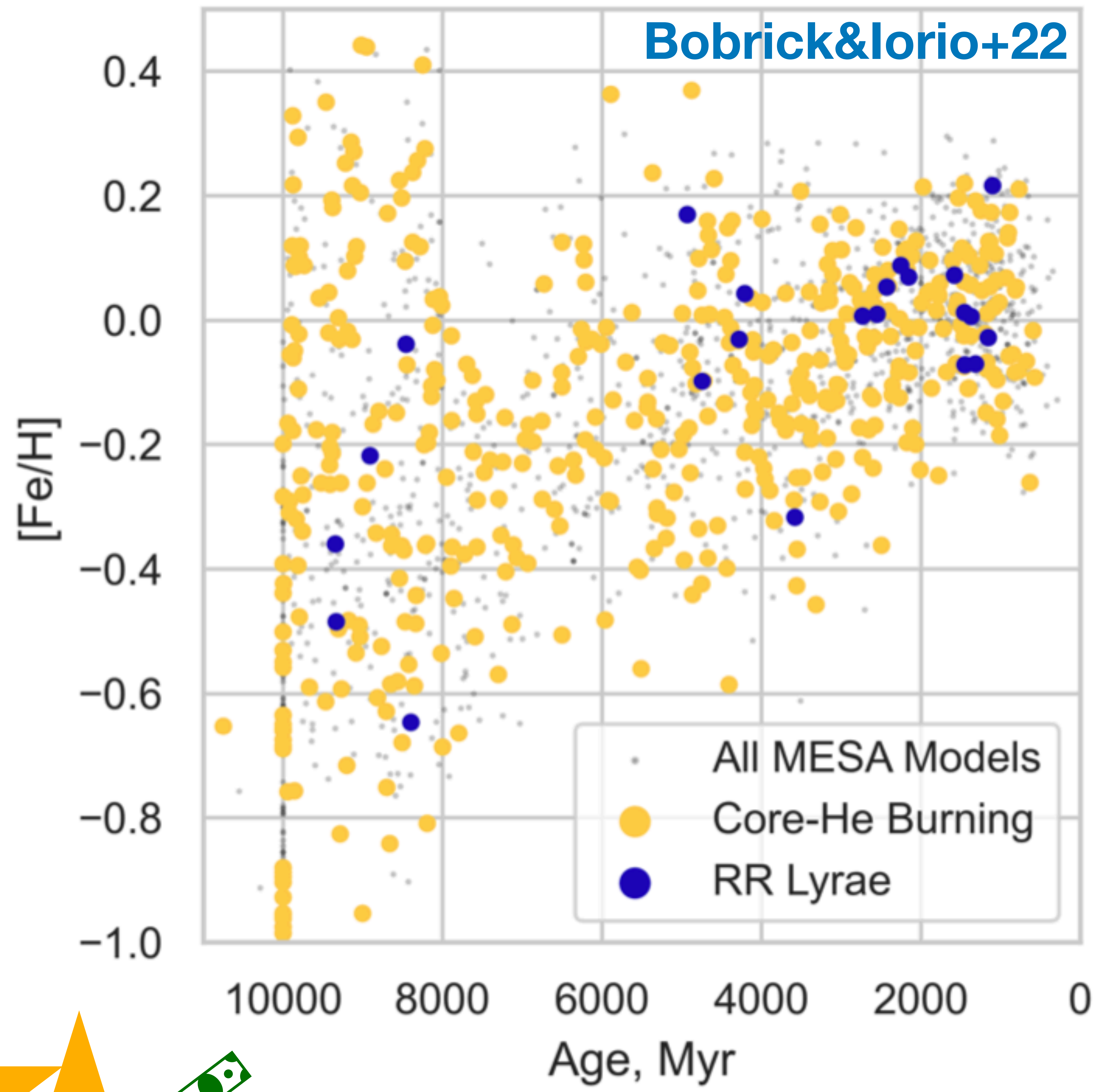
Consistent with Luminosity-metallicity relation of RRLs: Binary made RRL are fainter than metal-poor ones

(See e.g. Muraveva+20, Garofalo+23)

Galactic population of binary made RR Lyrae stars

Considering the Besancon model:

- ~ 50,000 in the Thin-Disc
- 0 in the Halo and Thick-Disc
- ~12,000 in the Bulge
- **Consistent with the RRL Metal-rich population**
- **Consistent with intermediate-young populations**



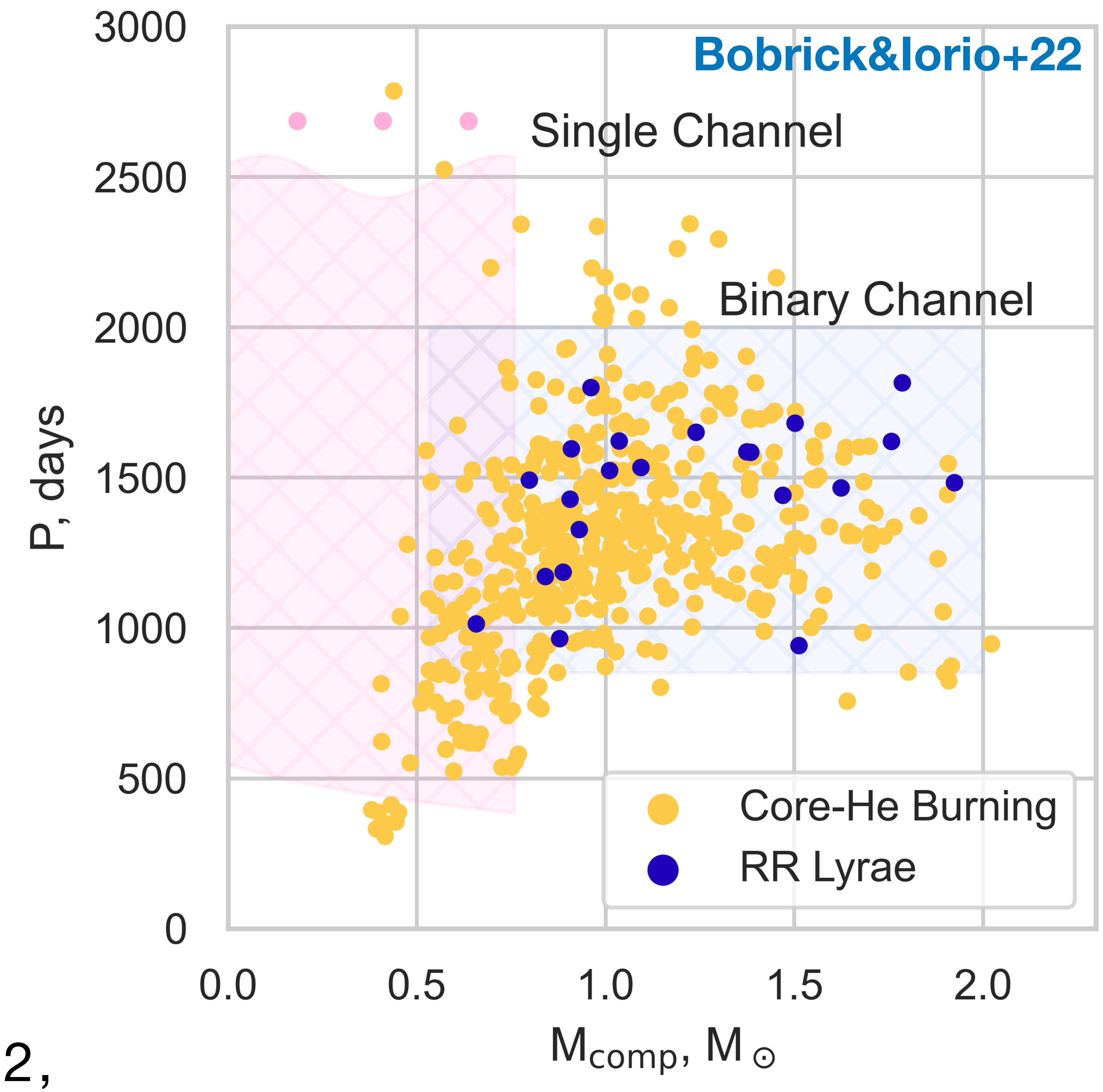
Finding the elusive companion

Metal-rich RR Lyrae have a companion

- ~1 order of magnitude fainter
- P ~1000-2000 days
  (Most of Gaia binaries < 1000 days)
- Low orbital velocity (< 10 km/s)
  (RRL pulsations ~50 km/s)

Challenging to observe!

Only two confirmed RRL in binary systems:
- Tu Uma (halo RRL, wide orbit P~8000 days)
  (see e.g. Liska+16)
- BEP, peculiar object
  (see e.g. Soszynski+09, Pietrzynski+12, Smolec+13)



Conclusions

- **Metal-rich RR Lyrae are ubiquitous in the Galactic Thin-Disc.**
- **Their kinematics is consistent with an intermediate-young population.**
- **Young Metal-rich RR Lyrae can be produced in binaries**
- **Stripped HBs, RR Lyrae, sdAs, sdBs belong to the same family**

Questions/Comments?

- Send me an email: giuliano.iorio.astro@gmail.com

To download the slides →

He-enriched RR Lyare

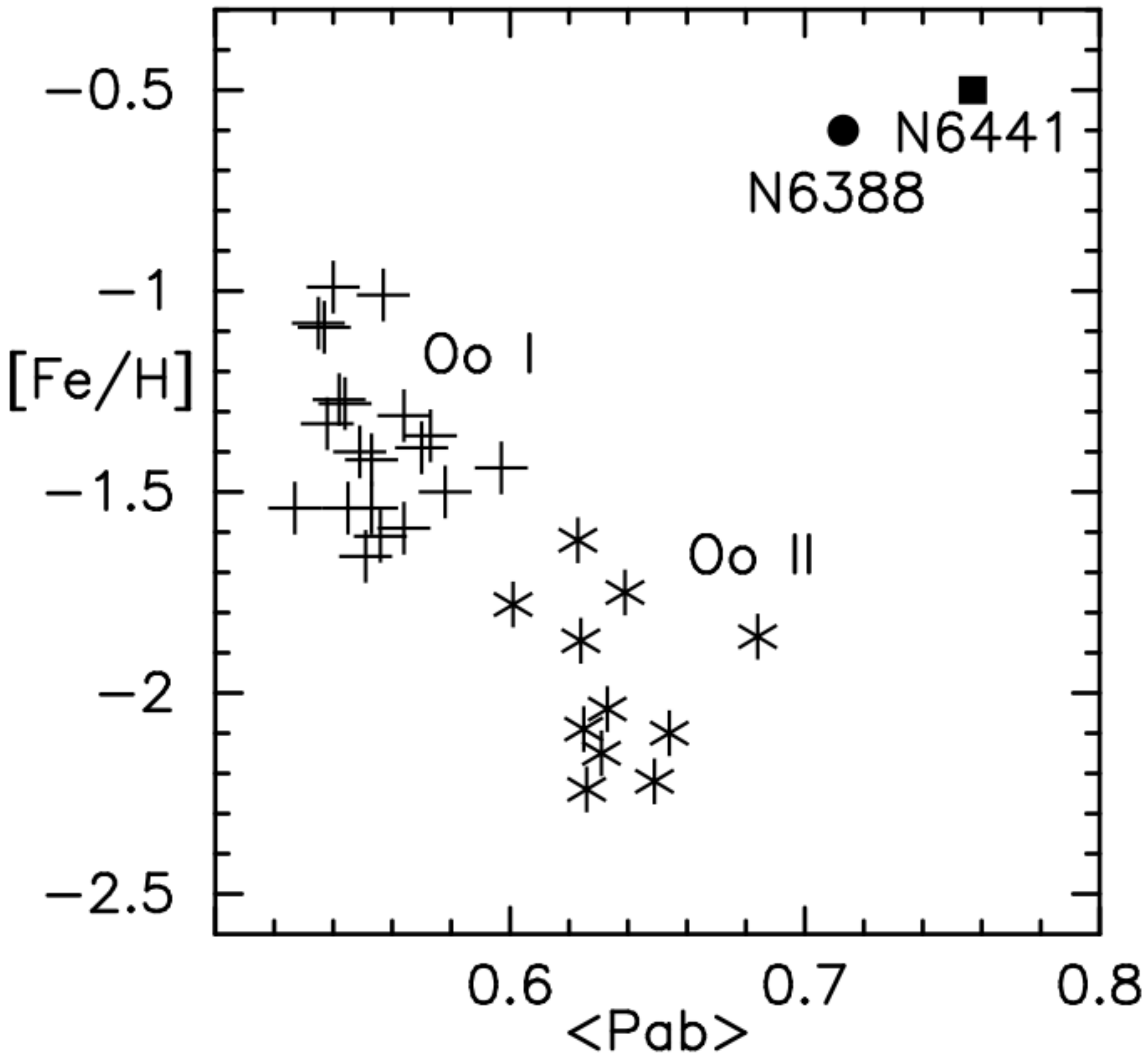
He-enriched envelopes produce hotter stars and can help (in combination with stellar winds) metal-rich star to enter in the IS.

This what actually observed in metal-rich He-enriched GCs: NGC6441, NGC 6338

Challenge:

- RR Lyrae Period not consistent with metal-rich RRL in the field

- How can we explain that the disc is “filled” by a population of highly He-enhanced stars?



RR Lyrae in metal-rich GCs

Why we do not see RR Lyrae in metal-rich GCs

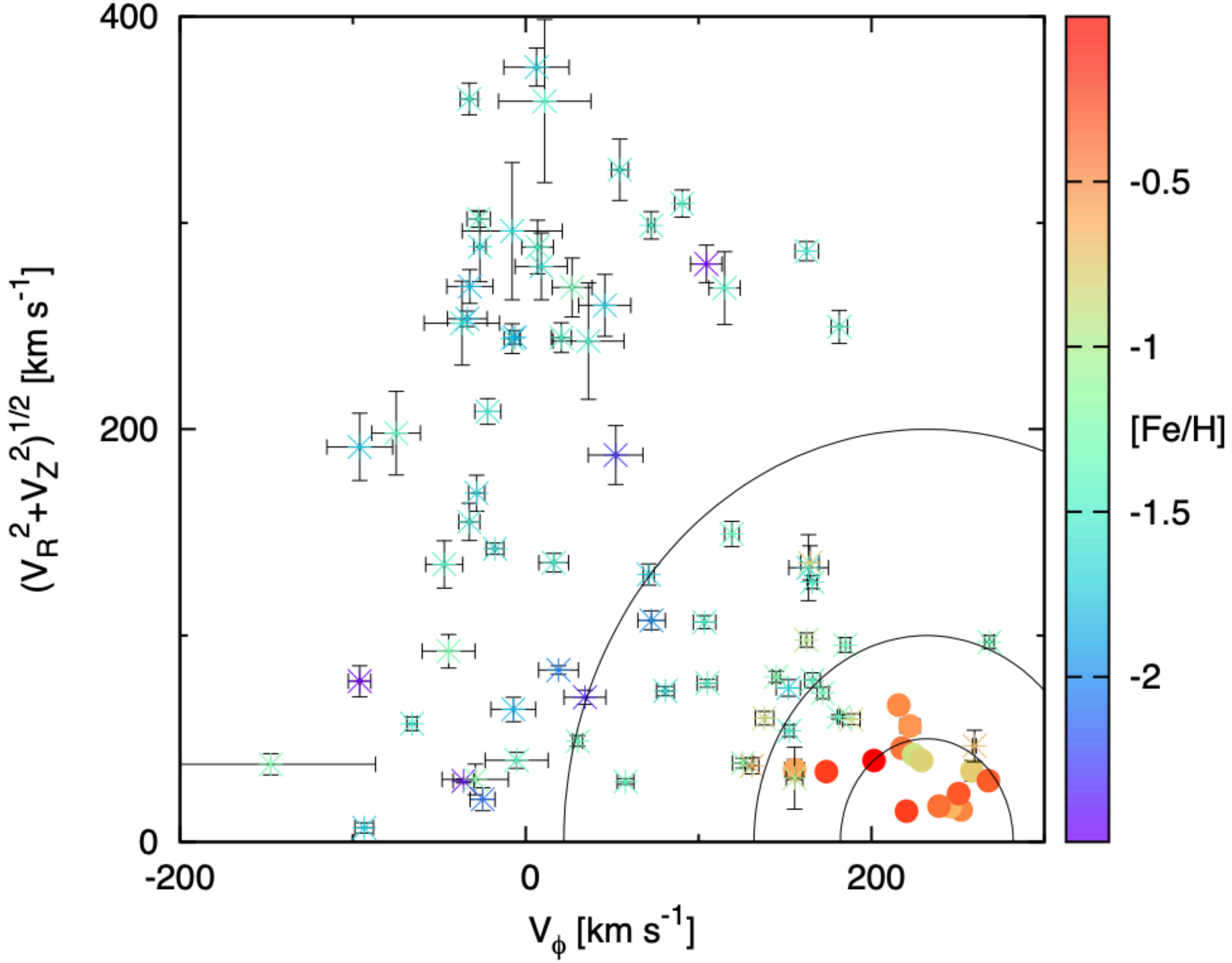
Following our prediction: ~1E4 binary made RRLs over 1E10-1E11 solar masses in the disc

This mean a formation efficiency of 1E-6 - 1E-7 1/Msun

GC mass is 1E5-1E6, we expect 0 or a few RRLs that is actually consistent with the observations:

- **NGC5927, NGC6352, NGC6496, NGC6838, no candidates**
- **47Tuc, NGC6304, NGC6366, NGC6624, NGC6337, few candidates**
- **Only exceptions: several RRLs in NGC6441, NGC 6338 but they are He-enriched clusters**

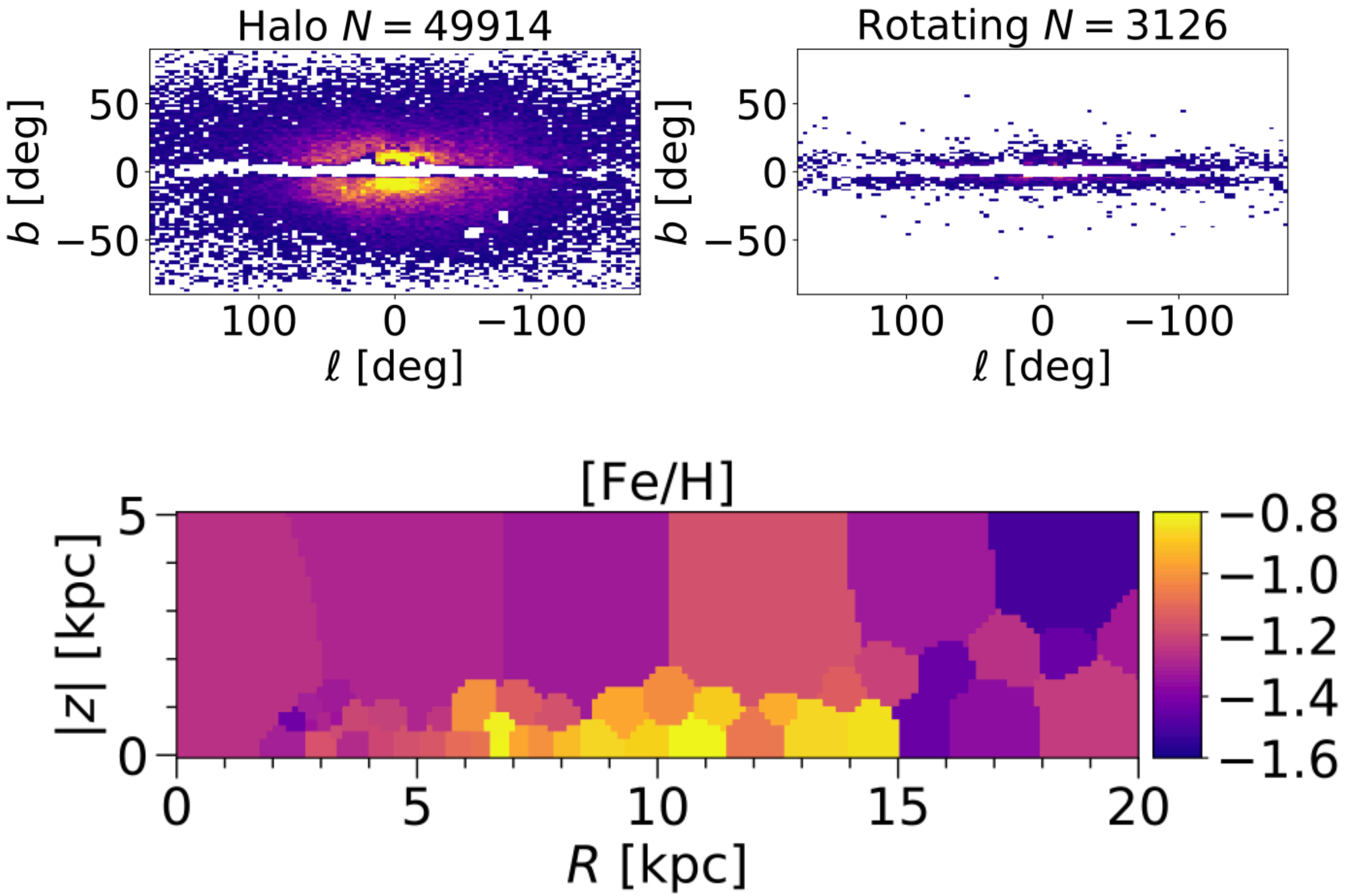
Metal-rich RR Lyrae in the solar neighborhood



Zinn+20

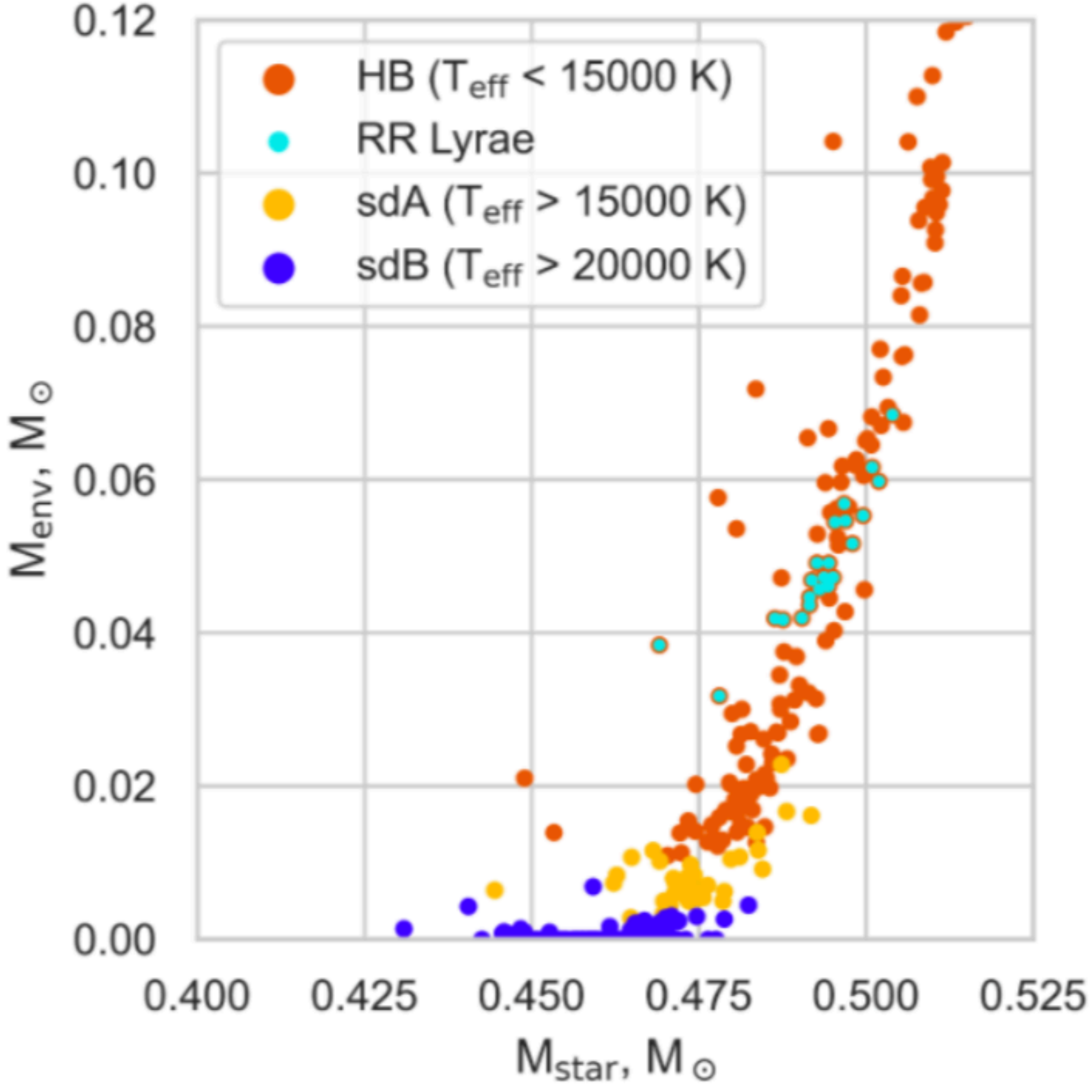
Circle: alpha-poor
Asterisk: alpha-rich

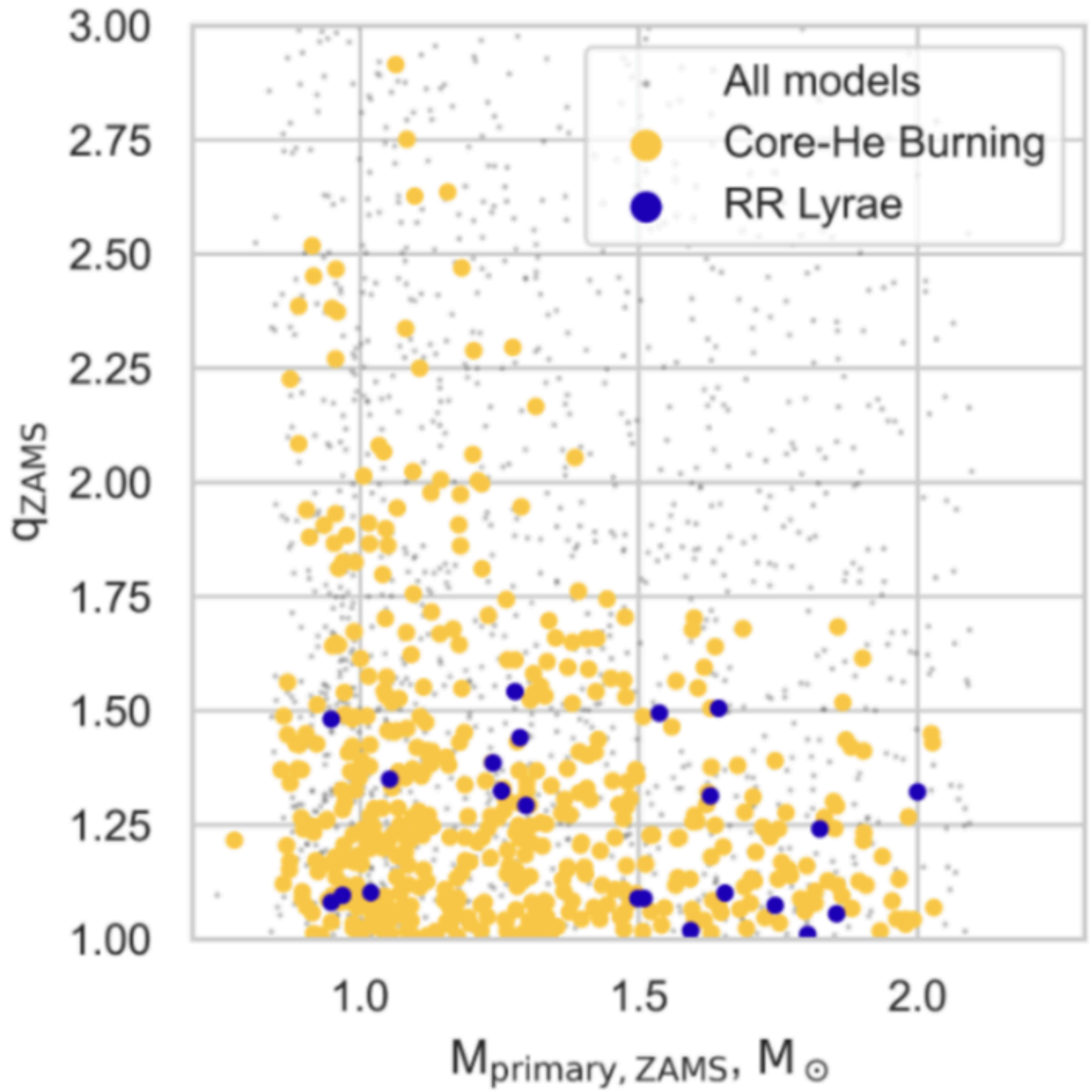
Metal-rich RR Lyrae in the stellar disc from Gaia (DR2)



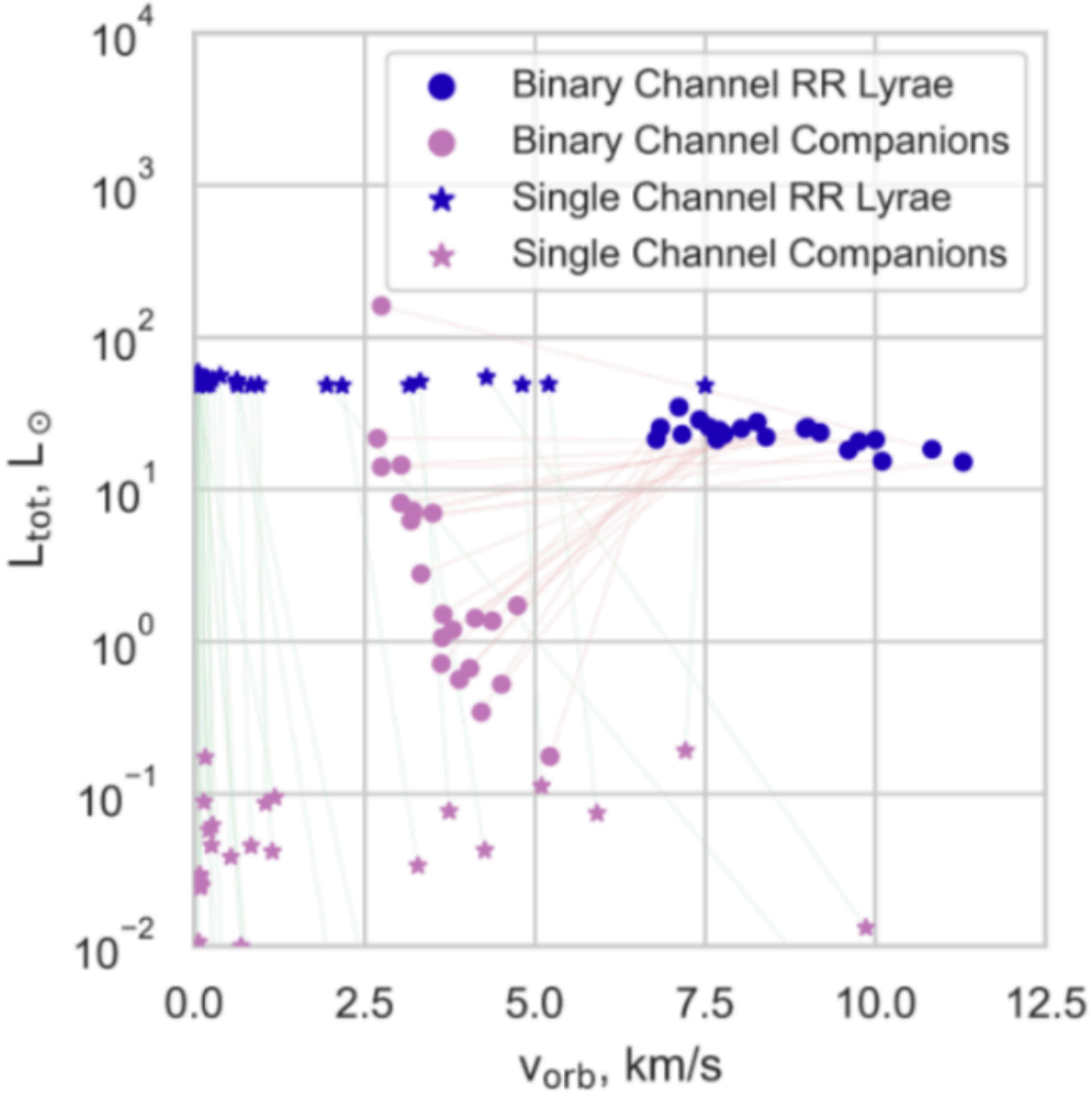
Young and metal-rich?

Binary-made RR Lyrae





Binary-made RR Lyrae

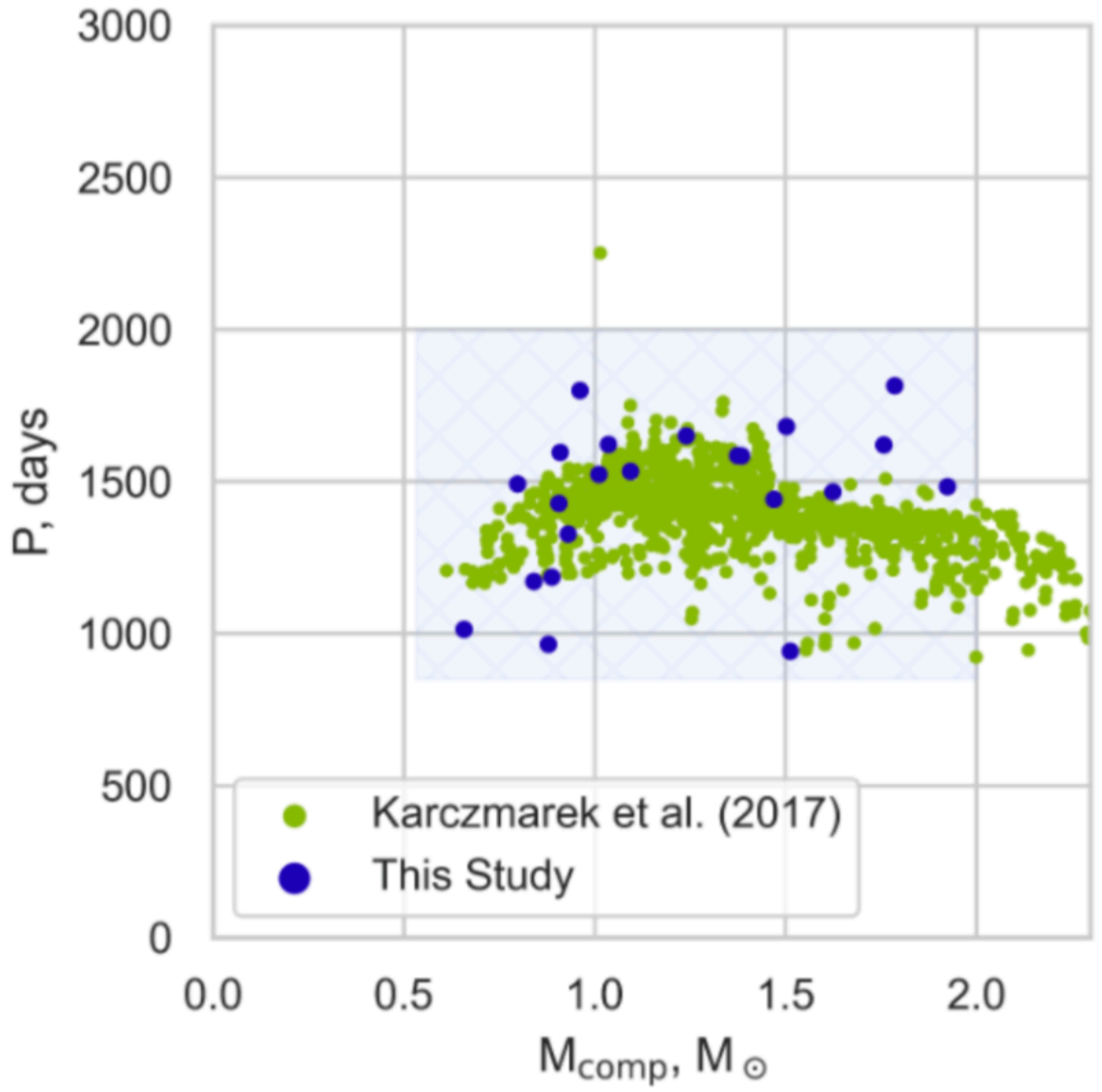


Binary-made RR Lyrae: comparison with Karczmarek+17

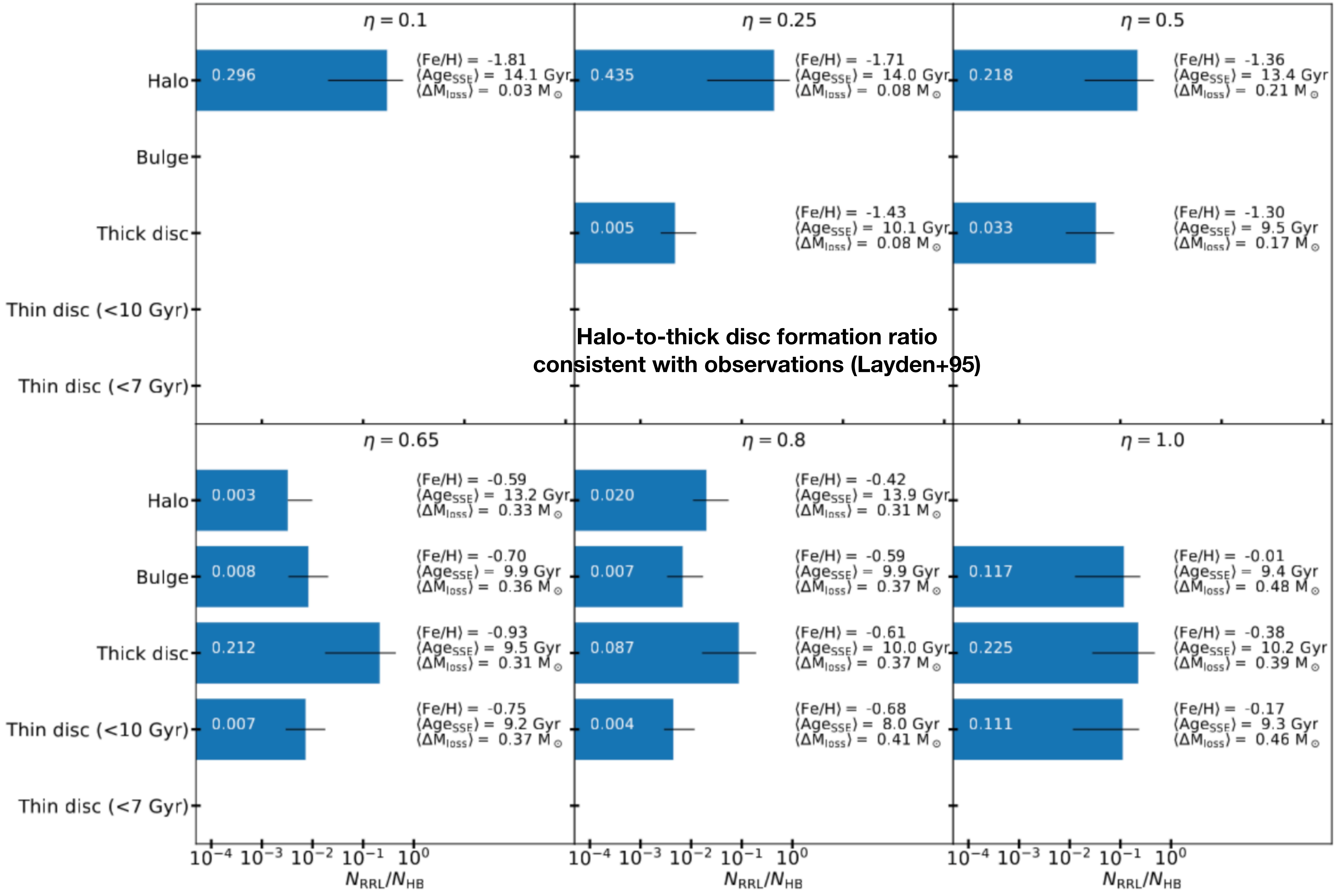
Their conclusion:
Only 0.8% of RR Lyrae are binary made

However:
- They consider that 20% of stars between 0.8-0.9 produce a single made RRL independently of the metallicity

Correcting for the effect of metallicity:
- Their and our results agree within 30%



Uncertainty from Wind-mass loss



Binary candidates

Catalogue	N_{match}	N_{clean}	$f_{disc/halo}$	$f_{rich/poor}$	$f_{disc/halo,control}$	$f_{rich/poor,control}$
RR Lyrae yrBinCan (Liška et al. 2016a)	68	22	0.24 (4:17)	0.50 (10:20)	**0.19 (10:53)**	**0.20 (40:200)**
Hajdu et al. (2021)†	**52**	**0**	**-**	**0 (0:3)**	**0.34 (14:41)**	**0.52 (59:114)**
Kervella et al. (2019a)	139	73	**0.51 (23:45)**	0.27 (18:67)	**0.34 (25:73)**	**0.16 (22:133)**
Kervella et al. (2019b)	7	3	2 (2:1)	2 (2:1)	**0.8 (8:10)**	**0.17 (16:95)**
Prudil et al. (2019)†	8	1	0 (0:1)	0 (0:1)	**0.63 (5:8)**	**0.43 (17:40)**

Simulation setup

Property	Functional Form	Parameter Range	Comments and references
IMF	$\mathrm{d}N/\mathrm{d}M_\star \propto M_\star^{-\alpha}$	$\alpha = \begin{cases} 1.3 & \text{for } 0.09\,\mathrm{M}_\odot < M_\star < 0.5\,\mathrm{M}_\odot \\ 1.8 & \text{for } 0.5\,\mathrm{M}_\odot < M_\star < 1.53\,\mathrm{M}_\odot \\ 3.2 & \text{for } 1.53\,\mathrm{M}_\odot < M_\star < 150\,\mathrm{M}_\odot \end{cases}$	Kroupa & Haywood v6 model Continuous, normalised (Czekaj et al. 2014) (Kroupa 2008; Haywood et al. 1997)
$M_{\mathrm{primary,simulated}}$	—	$0.7 - 2.1\,\mathrm{M}_\odot$	All degenerately-igniting primaries
$q_{\mathrm{init}} \equiv \frac{M_{\mathrm{primary}}}{M_{\mathrm{secondary}}}$	$\mathrm{d}N_{\mathrm{binary}}/\mathrm{d}q_{\mathrm{init}}^{-1} \propto 1$	$0 < q_{\mathrm{init}}^{-1} < 1$	(Raghavan et al. 2010)
$q_{\mathrm{init,binary-made}}$	—	$1 < q_{\mathrm{init}} < 3$	All stably transferring binaries
P_{orb}	$\frac{\mathrm{d}P_{\mathrm{orb}}}{\mathrm{d}\log P_{\mathrm{orb}}} \propto 1$	$1 < P_{\mathrm{orb}} < 10^4\,\mathrm{d}$	Close binaries (Abt 1983)
$P_{\mathrm{orb,binary-made}}$	—	$100\,\mathrm{d} < P_{\mathrm{orb}} < 700\,\mathrm{d}$	All degenerately-igniting interacting primaries
$a_{\mathrm{orb,single-made}}$	—	$1.2\,a_{\mathrm{RLO,max,RGB}} < a_{\mathrm{orb}} < 2 \cdot 10^4\,\mathrm{AU}$	All non-interacting primaries (Abt 1983)
Metallicity	$[\mathrm{Fe/H}] \propto \mathcal{N}([\mathrm{Fe/H}]_i, \sigma_{[\mathrm{Fe/H}],i})$	—	Galactic metallicity distribution, Table 1
Binary prob-ty	0.45	—	Galactic binary fraction (Abt 1983)
Close binary prob-ty	0.25, 0.40	—	Close binary fraction at $[\mathrm{Fe/H}] \approx -0.2$ and halo metallicity, respectively (Moe et al. 2019)
Age cut	—	$-300\,\mathrm{Myr} < t_{\mathrm{RGBtip}} - t_{\mathrm{now}} < 700\,\mathrm{Myr}$	All present-day core-He burning stars
Mass loss parameters	$\dot{M}_{\mathrm{accretor}} = (1 - \alpha - \beta - \delta)\lvert\dot{M}_{\mathrm{lost}}\rvert$†	$\begin{cases} \beta = 1 \text{ if over-spinning or } \tau_{\mathrm{acc}} < \tau_{\mathrm{K-H}} \\ \beta = 0 \text{ otherwise} \\ \alpha = \gamma = \delta = 0 \text{ always} \end{cases}$	Effectively fully non-conservative When $\dot{M} \gtrsim 10^{-5} - 10^{-6}\,\mathrm{M}_\odot/\mathrm{yr}$ Mass loss with J_z of accretor (Tauris & van den Heuvel 2006)

Besancon Model

Galactic bin	Age Gyr	Mass fraction	[Fe/H]
Thin Disc - Bin 1	0 – 0.15	0.030	0.01 ± 0.12
Thin Disc - Bin 2	0.15 – 1	0.069	0.03 ± 0.12
Thin Disc - Bin 3	1 – 2	0.076	0.03 ± 0.10
Thin Disc - Bin 4	2 – 3	0.072	0.01 ± 0.11
Thin Disc - Bin 5	3 – 5	0.132	-0.07 ± 0.18
Thin Disc - Bin 6	5 – 7	0.126	-0.14 ± 0.17
Thin Disc - Bin 7	7 – 10	0.171	-0.37 ± 0.20
Bulge	8 – 10	0.192	0.00 ± 0.40
Thick Disc	10	0.123	-0.78 ± 0.30
Halo	14	0.008	-1.78 ± 0.50