A special thanks to
MW-Gaia Cost action

Explore the population of disc metal-rich RR Lyrae stars with GaiaNIR

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&
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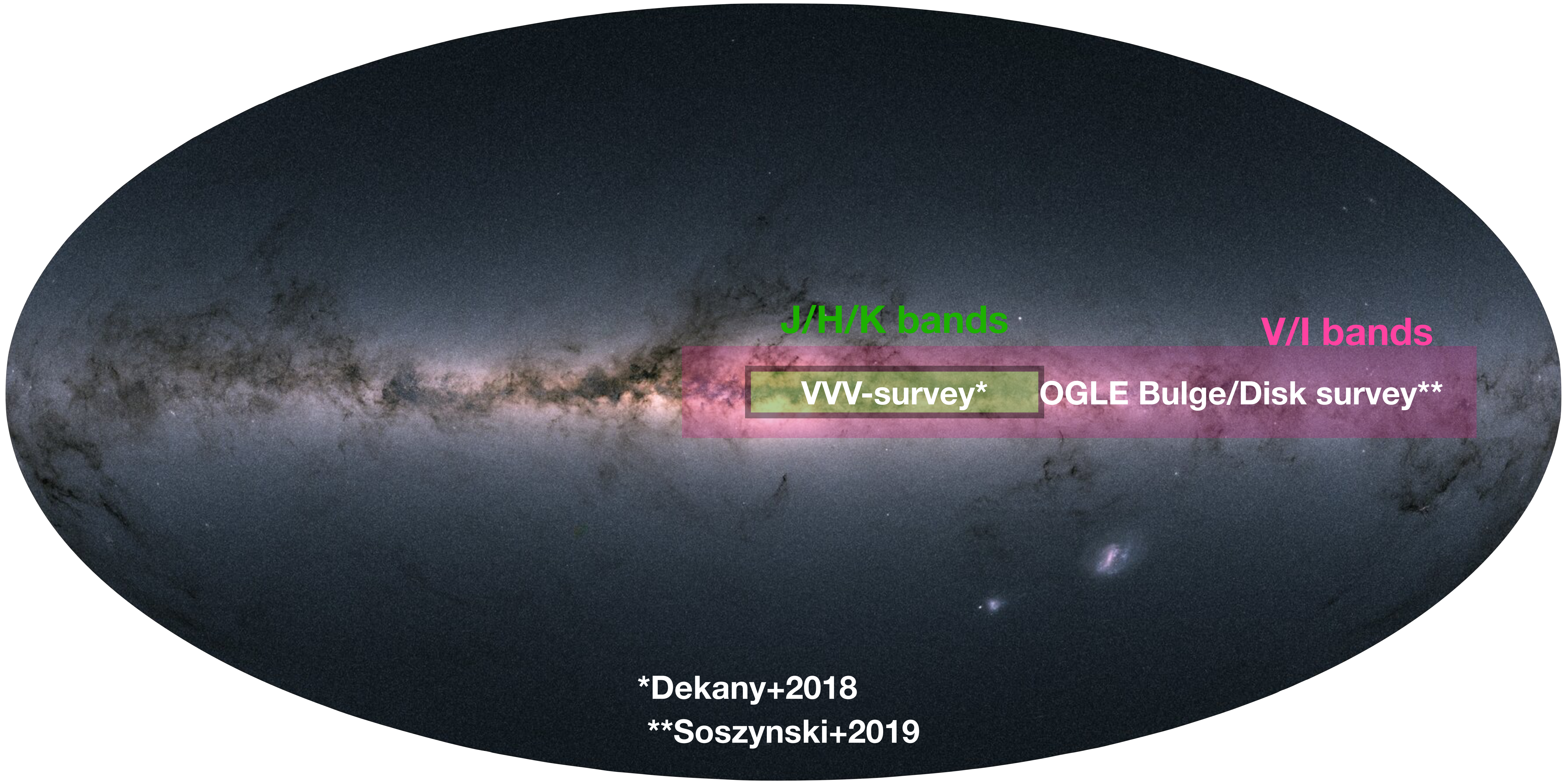
Based on:

- 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)

Science and technology roadmap for μas studies of the Milky Way: 18-20 Jul 2023, Lund

RR Lyrae stars (RRLs) in the disc: a science case for Gaia NIR?



- RRL studies focused mostly in the Bulge/Halo regions
- RRL in the disc challenging to observe and not an “hot topic” (so far)
- Only RRL astrometric information in the NIR from VVV (VIRAC, Smith+18) and OGLE (Sumi+18), but mostly in the Bulge

GaiaNIR could produce an unprecedented astrometric survey of RRLs in the disc

Do they represent an interesting scientific case?

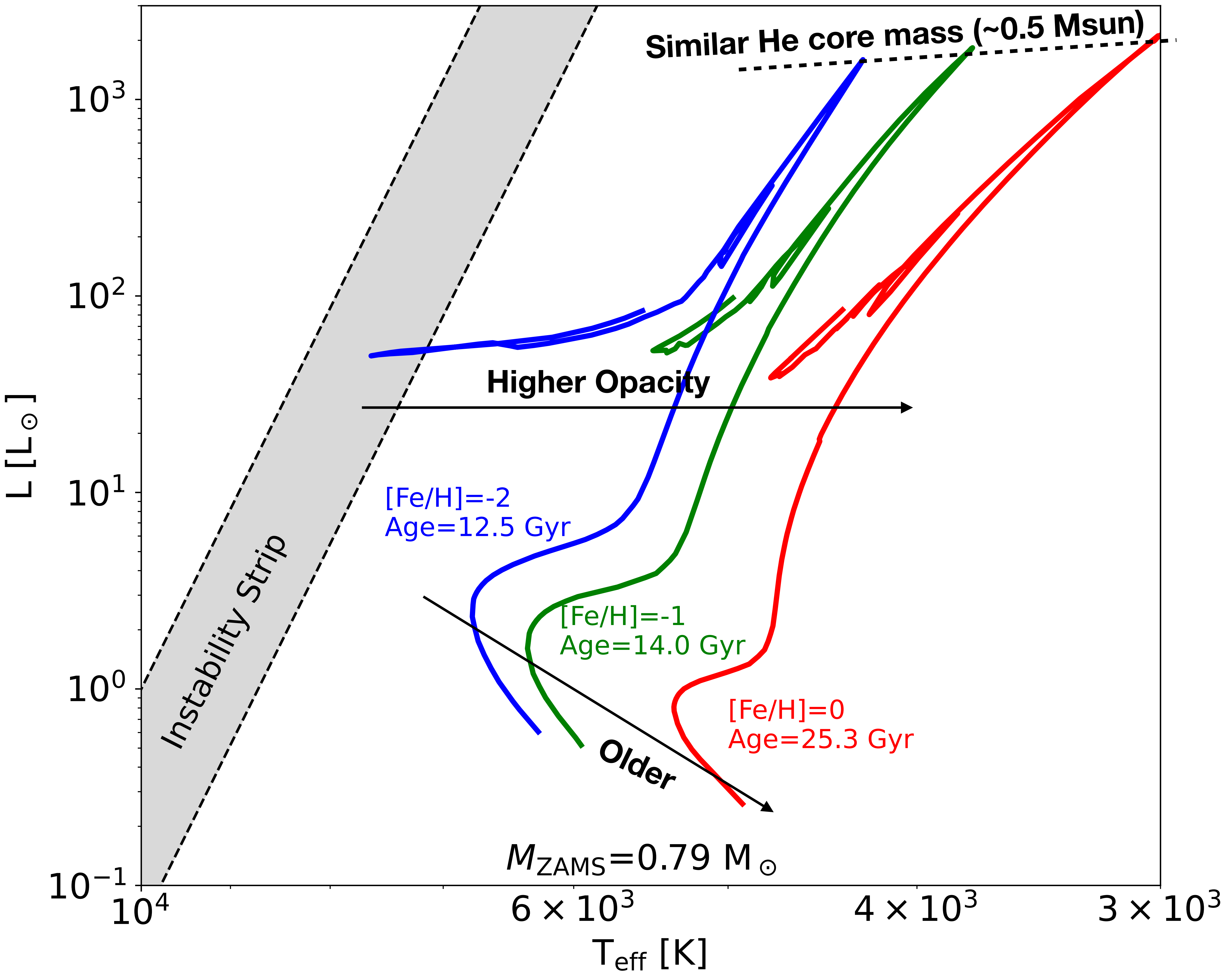
The RR Lyrae in the Milky Way

The "Classical textbook definition"

(e.g. Catelan09, Smith04)

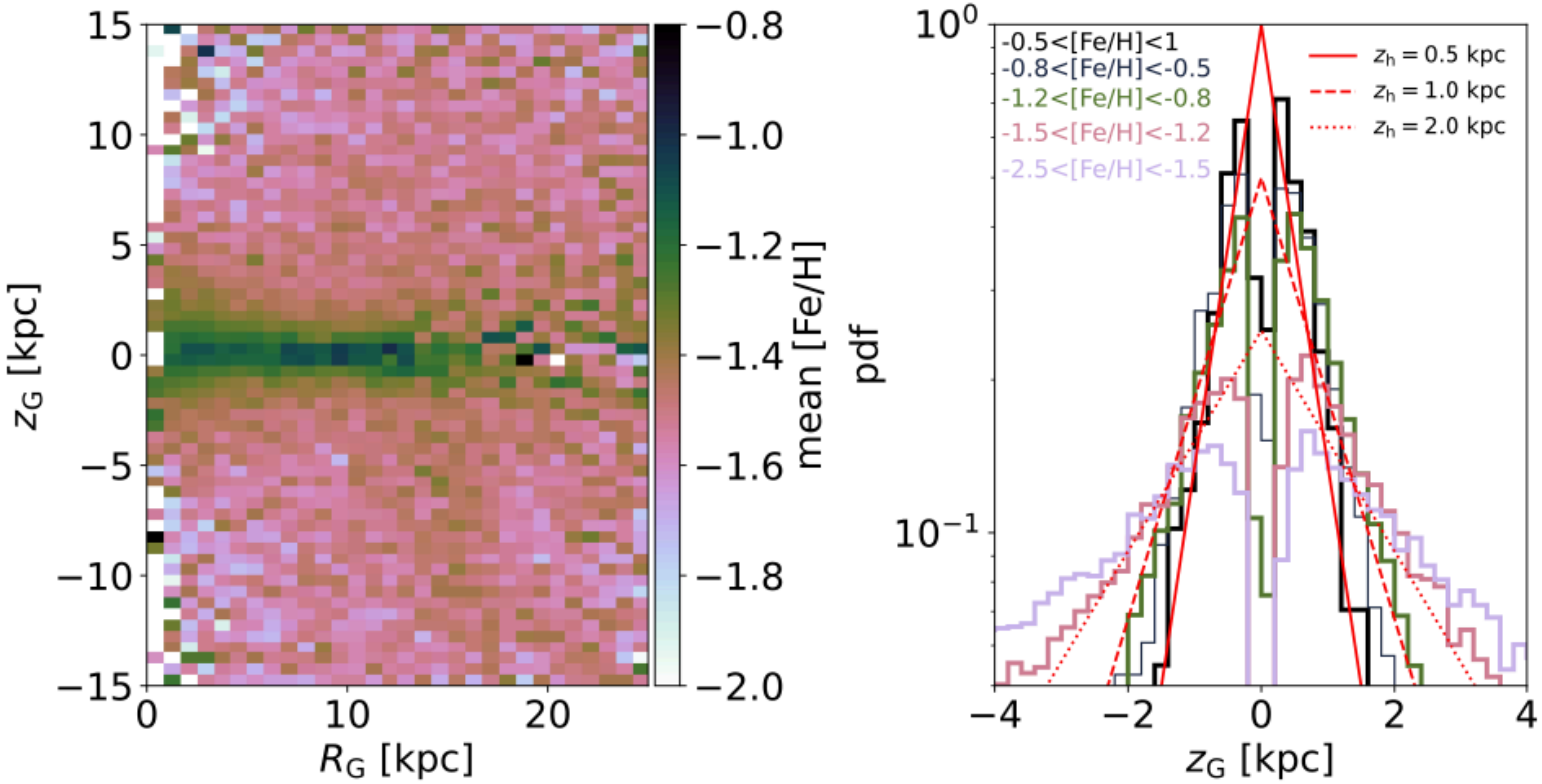
- **Low-mass** (<1 Msun) core He burning stars
- **Old** (>10 Gyr) and **metal-poor** ([Fe/H]<-1) **popII** stars
- **Tracers of old populations** (Halo, Globular clusters, Thick disc, Streams)

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

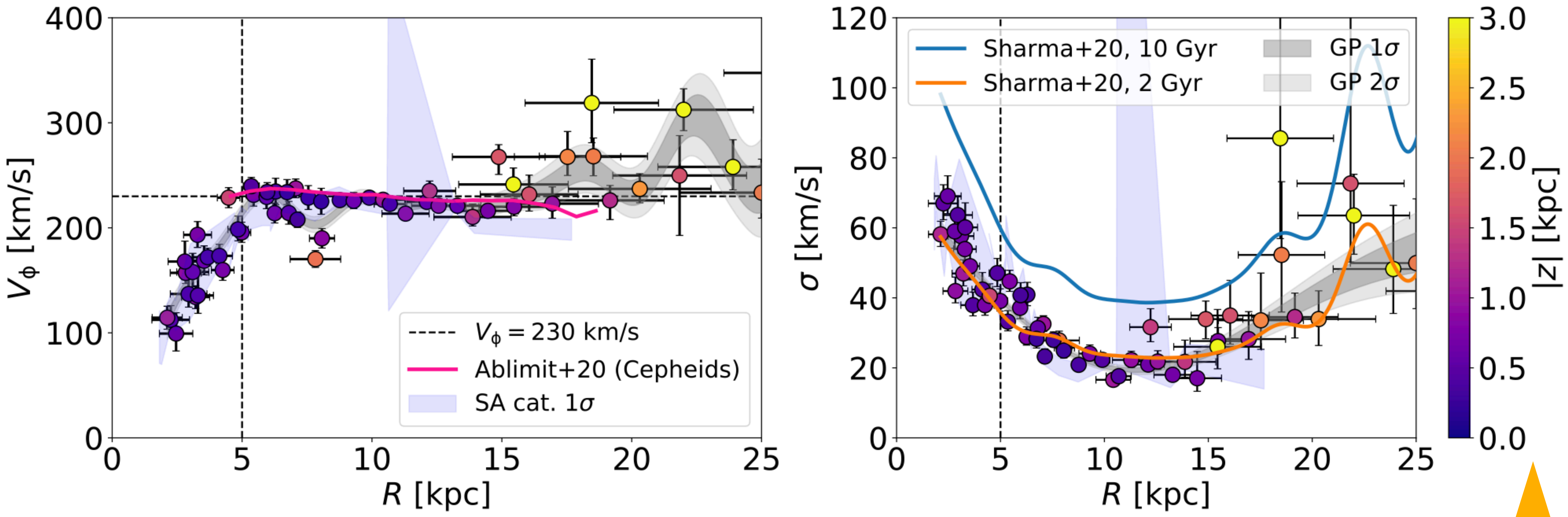
They have a flattened (thin?) disc-like distribution

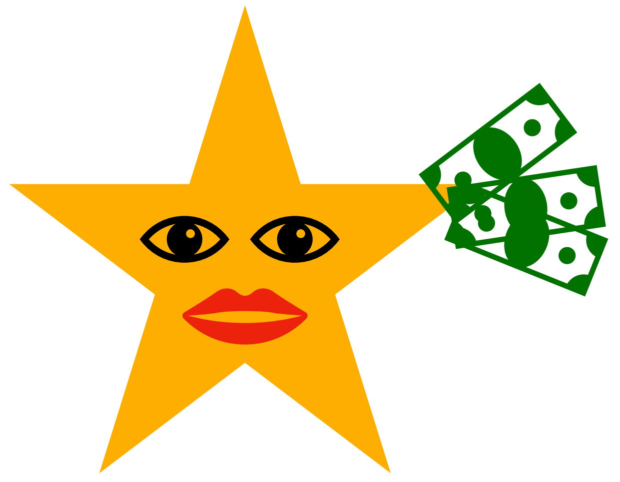
(See also Layden+95,Muraveva+18,Prudil+20,Zinn+20,Crestani+21,Garofalo+22)

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 rotating kinematical model for RRLs 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 neighborhood
(e.g. Layden+94, Pietrukowicz+20, 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).

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

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

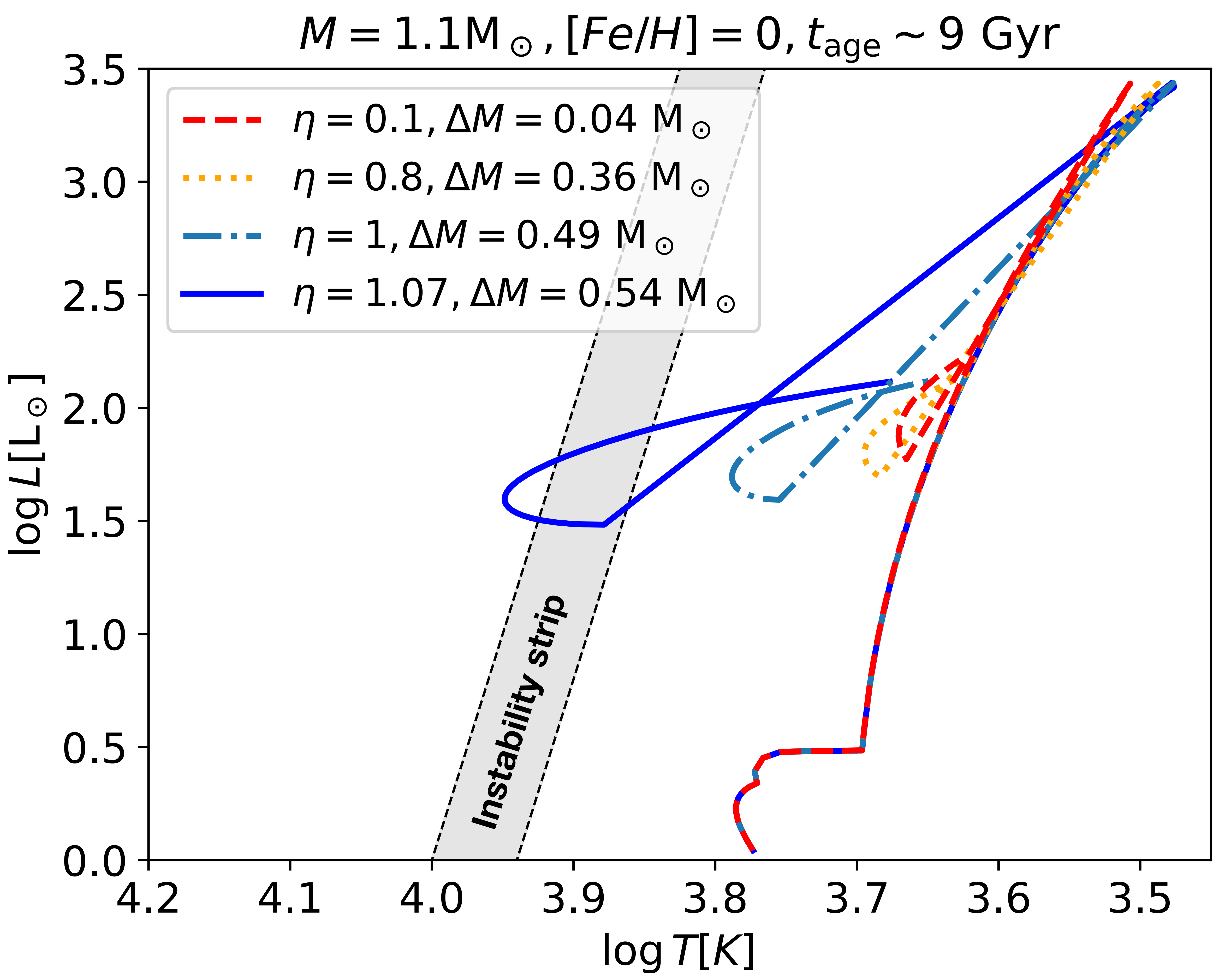
↓

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**

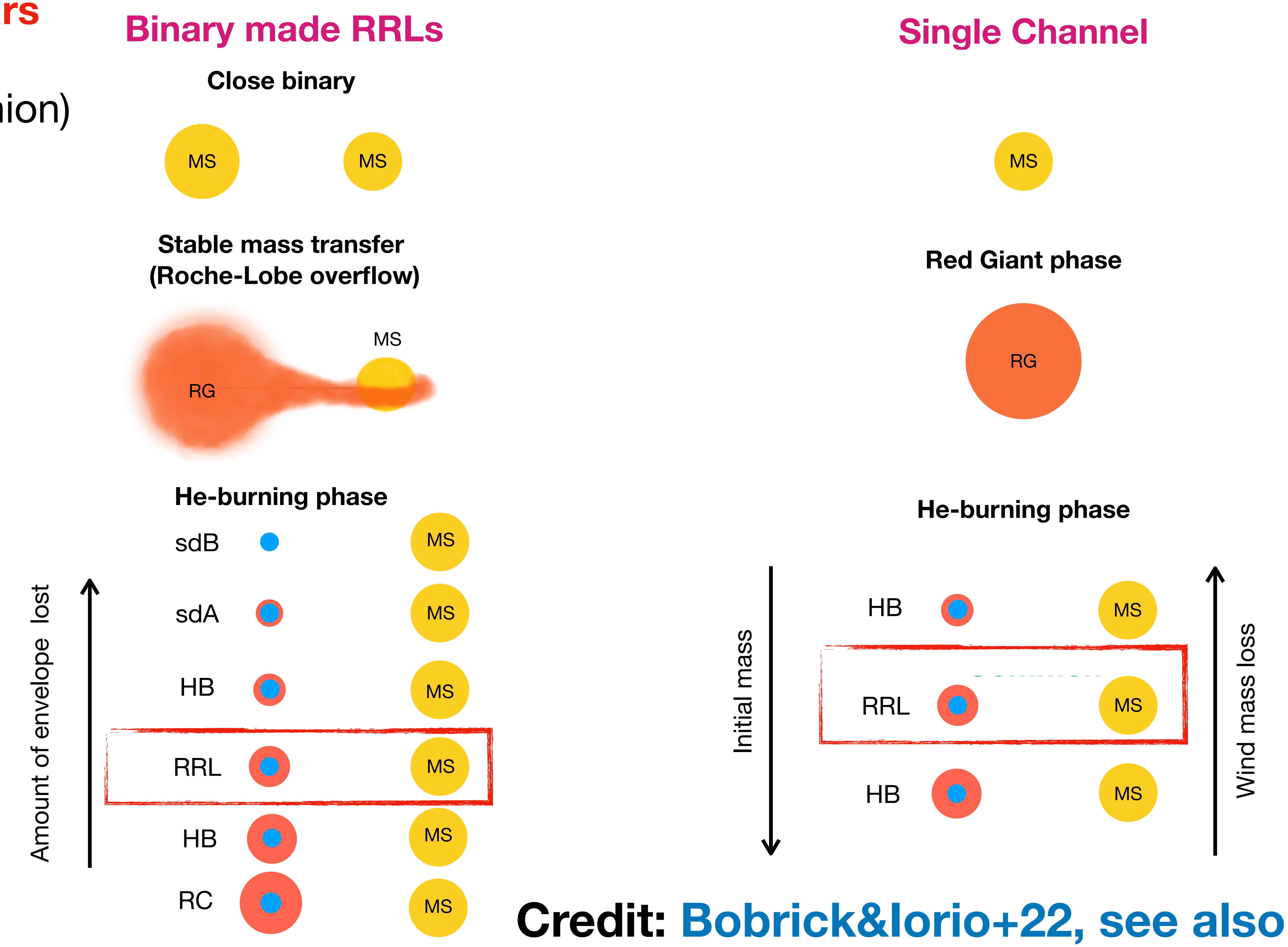


Single stellar evolution from MOBSE (Giacobbo+18)

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).

~10-30% of Sun-like stars are in a binary system
(with a lower mass companion)
Offner+22,Moe+18, Moe&Distefano17



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

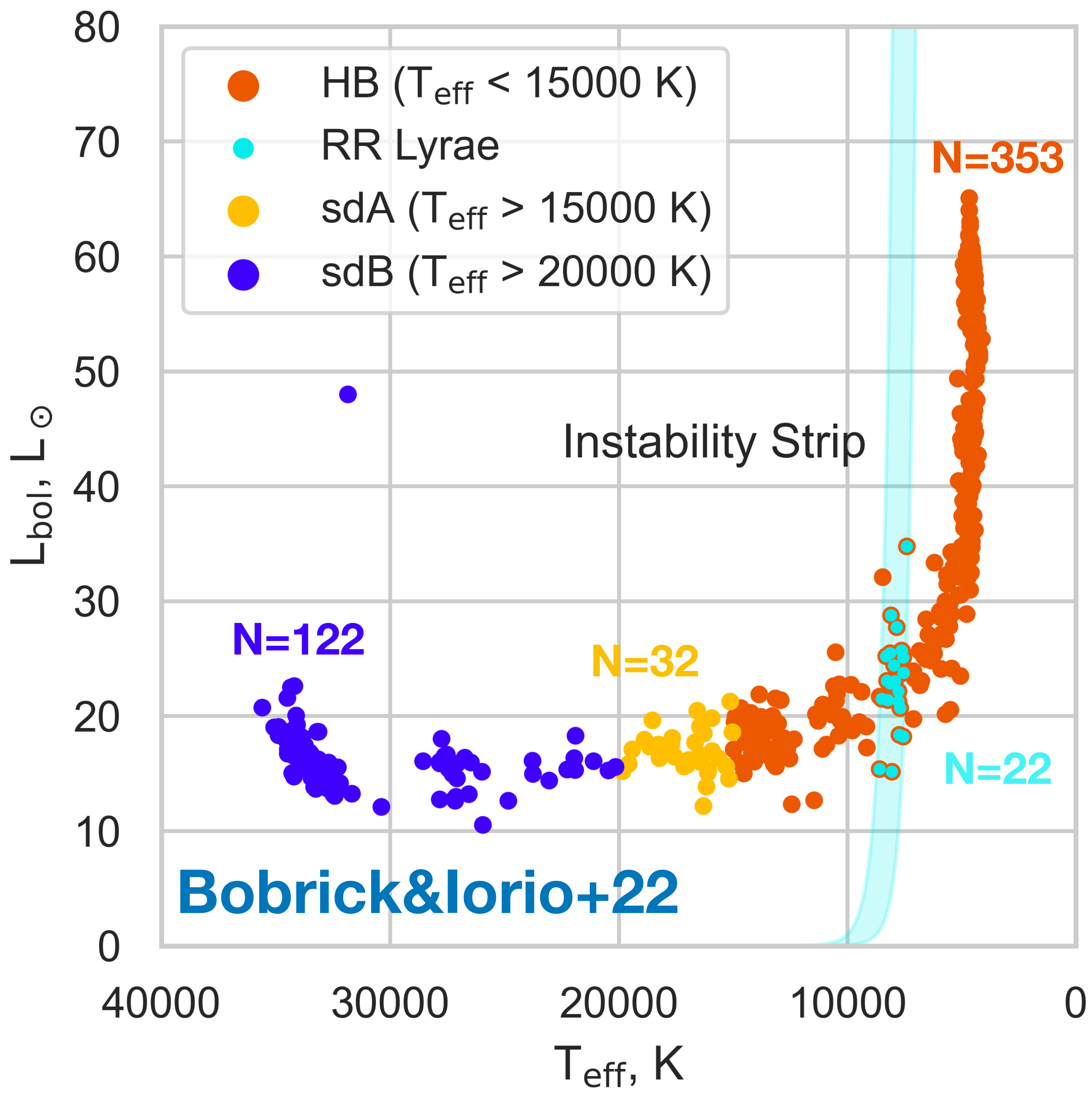
An alternative formation channel: Binary mass loss

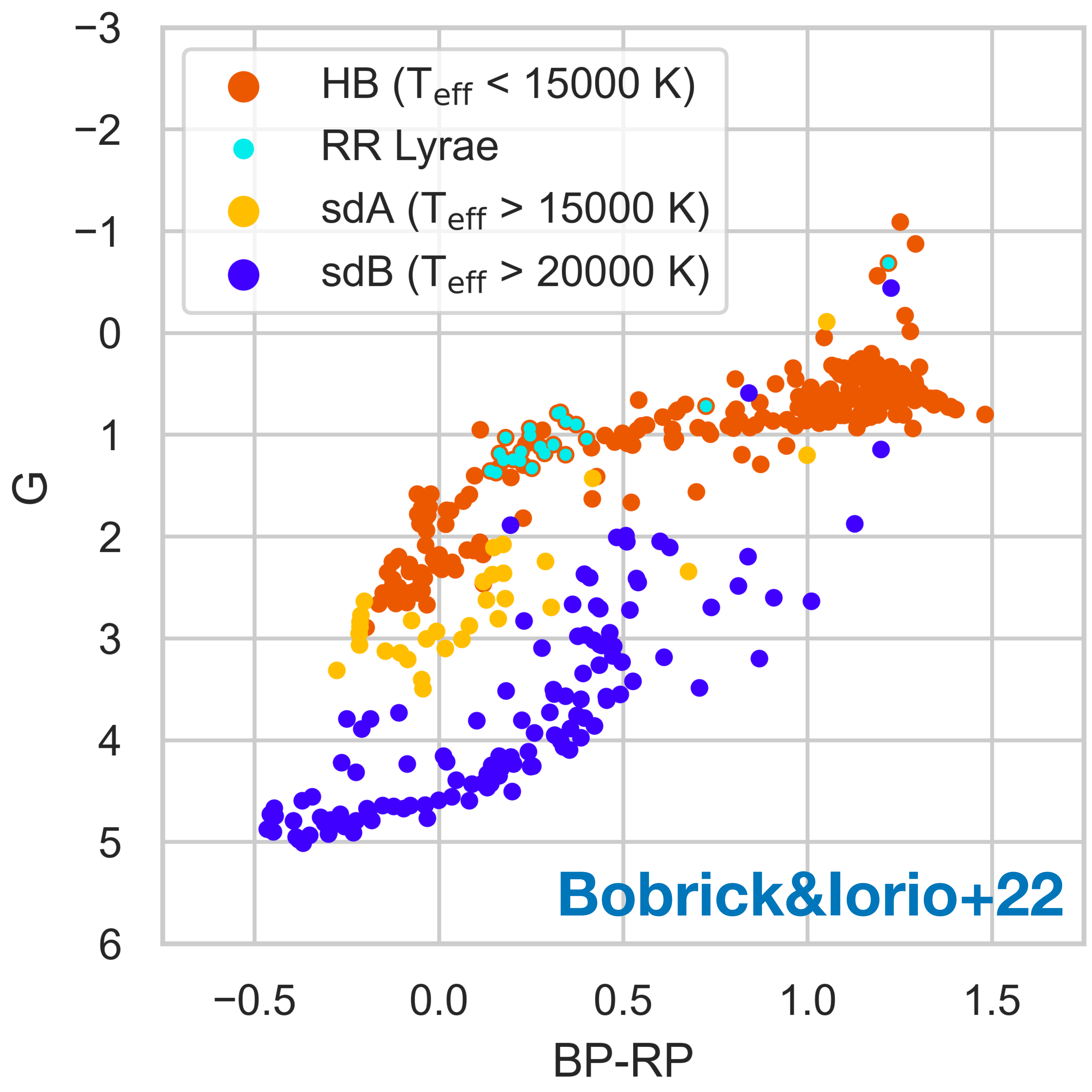
Simulation setup (Vos+20): 2060 binaries

- 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)
- Besançon Galactic population (Robin+03) Close binary fraction 25% (Moe+19)

Binary made RRLs

Binary made RR Lyrae stars





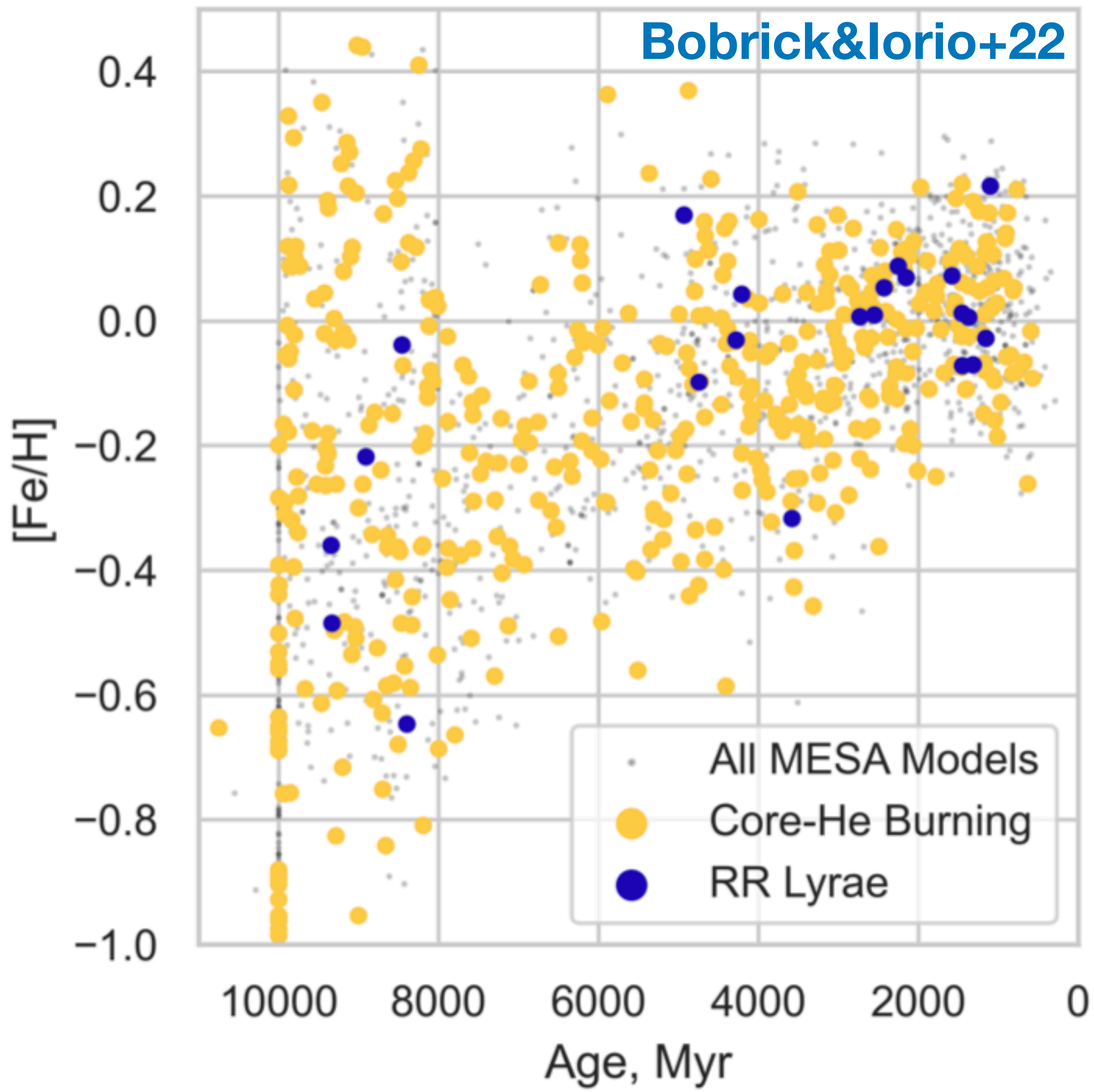
Consistent with Luminosity-metallicity relation of RRLs:
Binary made RRLs are fainter than metal-poor ones

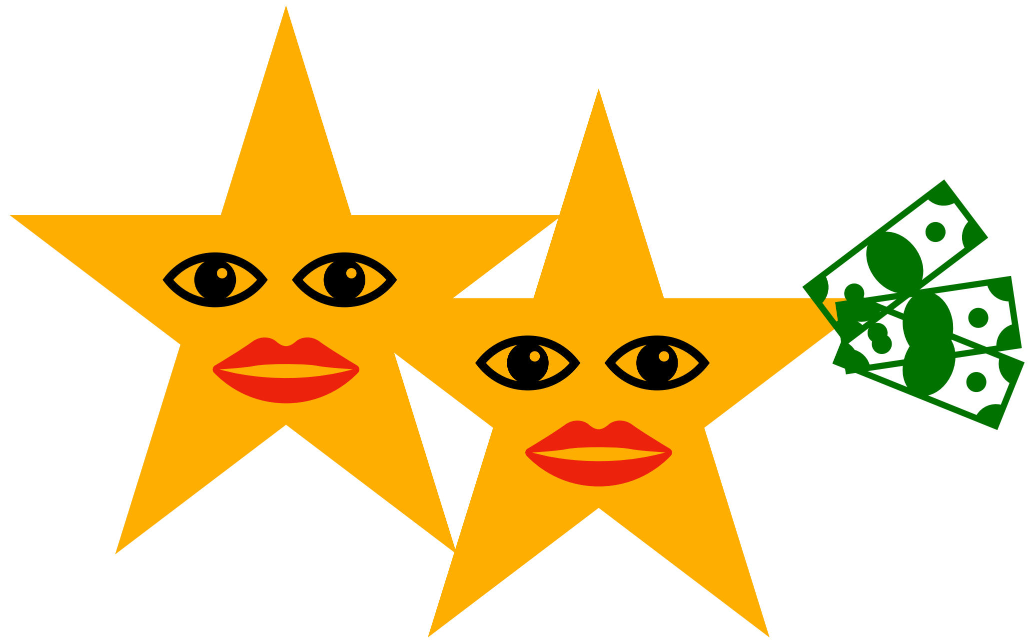
(See e.g. Muraveva+20, Garofalo+22)

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**





Model prediction: Metal-rich RRLs have a binary 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)

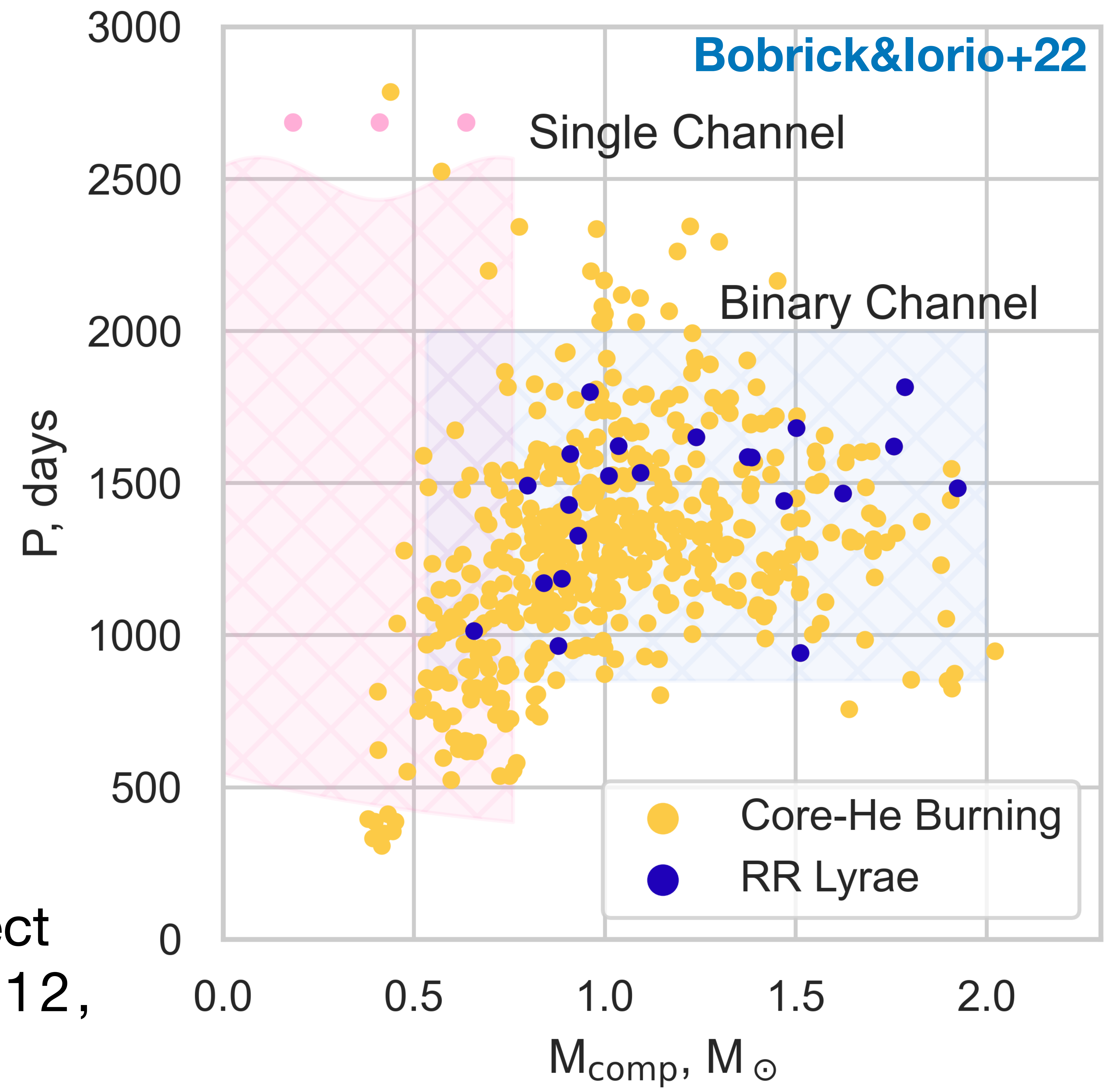
Challenging to observe!

Only two confirmed RRLs in binary systems:

- Tu Uma (halo RRL, wide orbit P~8000 days)
  (see e.g. Liska+16)

- BEP (Binary Evolution Pulsator), peculiar object (see e.g. Soszynski+09, Pietrzynski+12, Smolec+13)

+ candidates (Liska+16,Kervella+19,Hajdu+21)



Why GaiaNIR

GaiaNIR could produce an unprecedented astrometric survey of RRLs in the disc

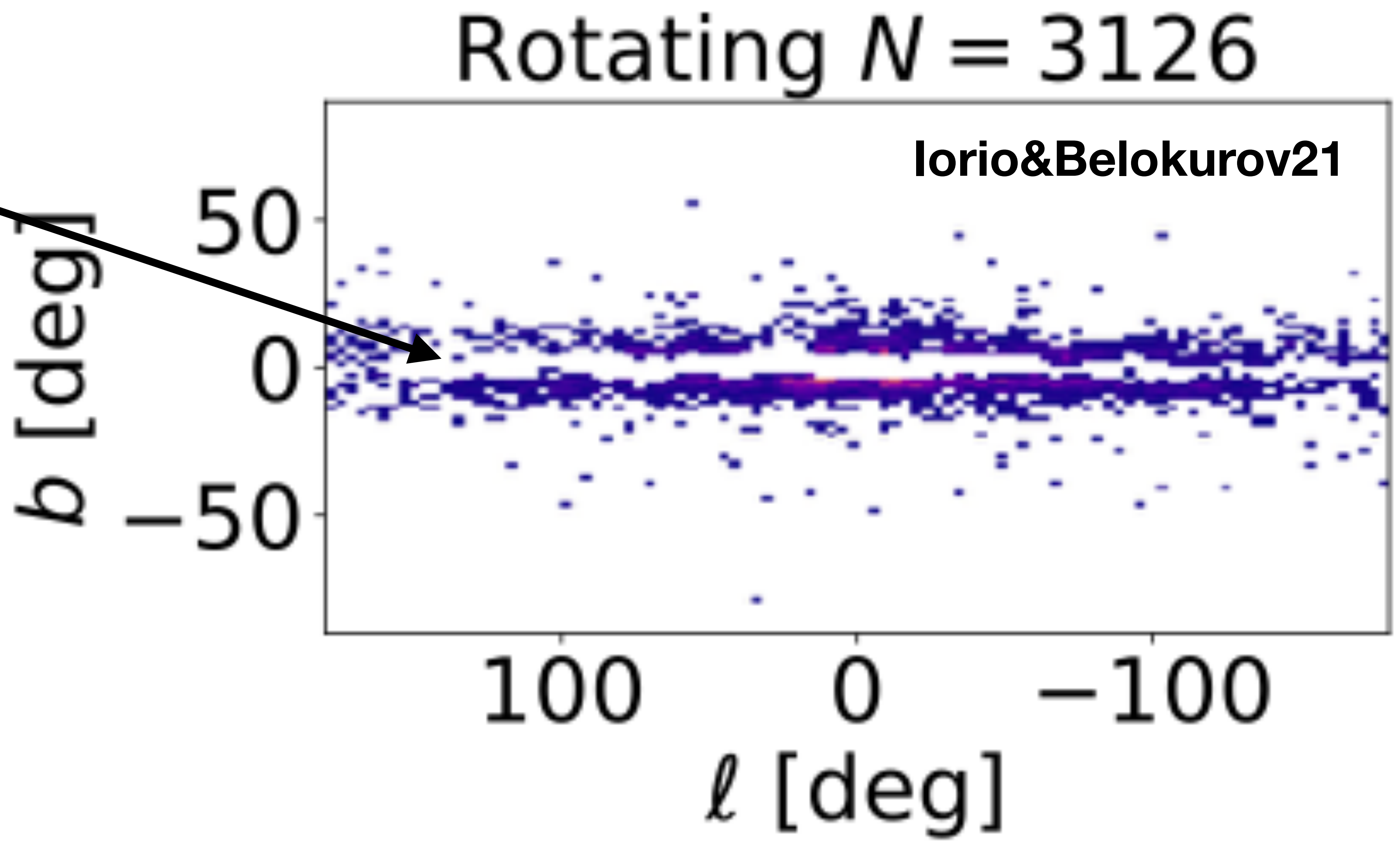
- **Increase the sample:**
  - Observe variable stars very close to the Galactic plane, where we expect to find most of the metal-rich RRLs.

- **Improve the distance/proper motion estimates (Muraveva talk)**
  - Period-Luminosity relation in the K-band
  - Less dependence on the reddening correction

- **If billions of RVs will be available:**
  - Precise and direct kinematics estimate

GaiaNIR can surely help in investigating the nature of metal-rich RRLs in the disc

Sample of RRLs with high likelihood to belong to the rotating component



Is this a interesting scientific case? What we can learn?

Win/Win scenario

If the young-population/binary formation channel are confirmed:

- Paradigma shift: RRLs are not only pop. II stars.
  Tracers of intermediate-young populations

- Exceptional probes to study the details of the mass transfer in binary systems

If the young-population/binary formation channel is/are not confirmed:

- (If confirmed young) Exploration of new formation channels (He-enrichment, rotation, revised stellar evolution)

- (If confirmed old) Why a very old population is kinematically consistent with the young thin-disc? Why it is enriched in metals? Challenge for MW formation models. (Radial migration from the inner bulge? Cristina Chiappini talk)

- Why no RRLs in binary? Do we need to revise mass transfer in binaries?

Takeaway messages

- Metal-rich RRLs in the disc are ubiquitous

- Their existence and kinematics represent a challenge for the classical RRL formation scenario.

- The solution of this conundrum will have significant implications in the understanding of the stellar and binary evolution and on the formation of the MW.

- GaiaNIR is the perfect instrument to solve this mystery

Backup Slides

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**

He-enriched RRL

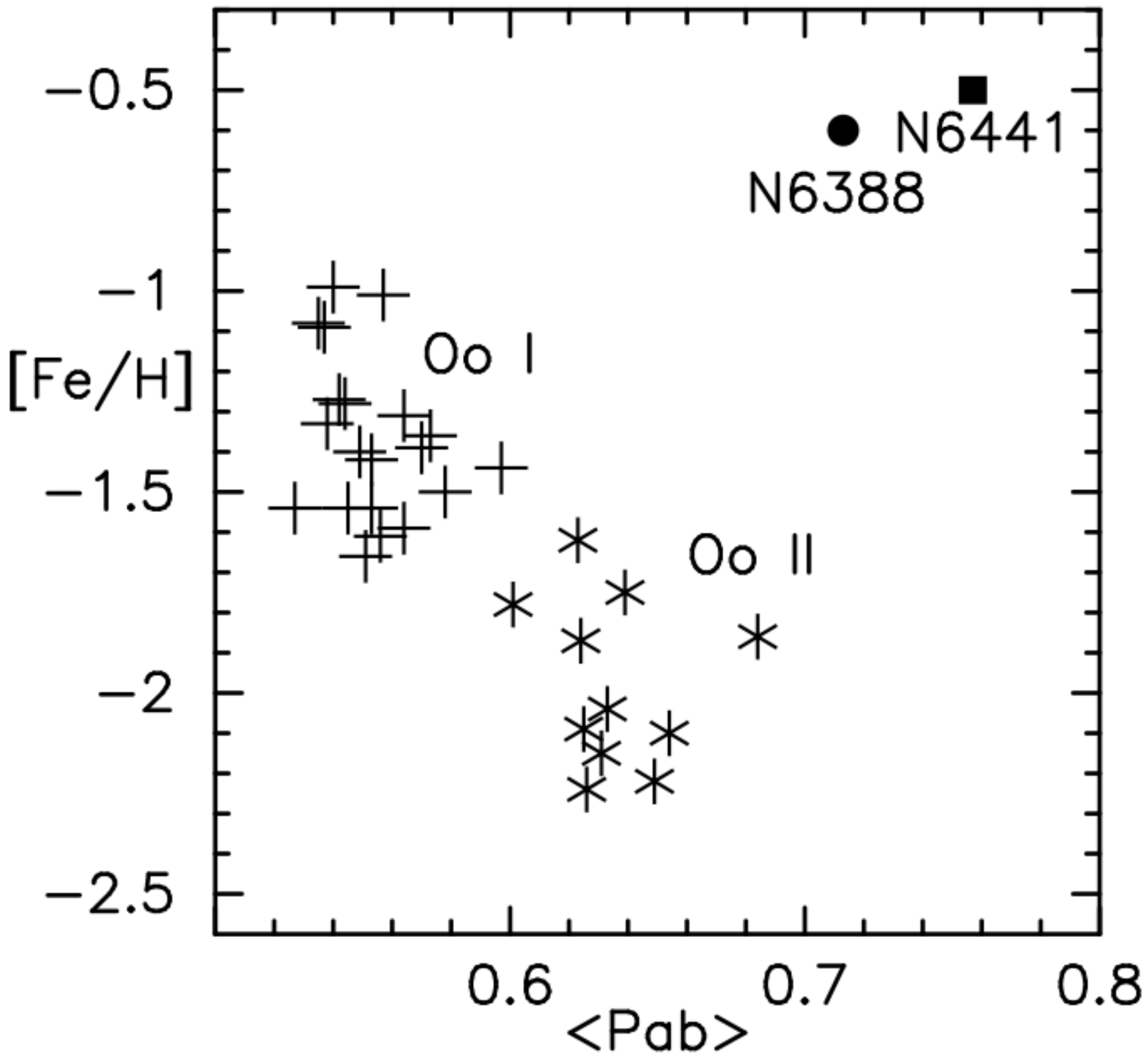
He-enriched envelopes produce hotter stars and can help (in combination with stellar winds) metal-rich star to enter in the IS.

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

Challenge:

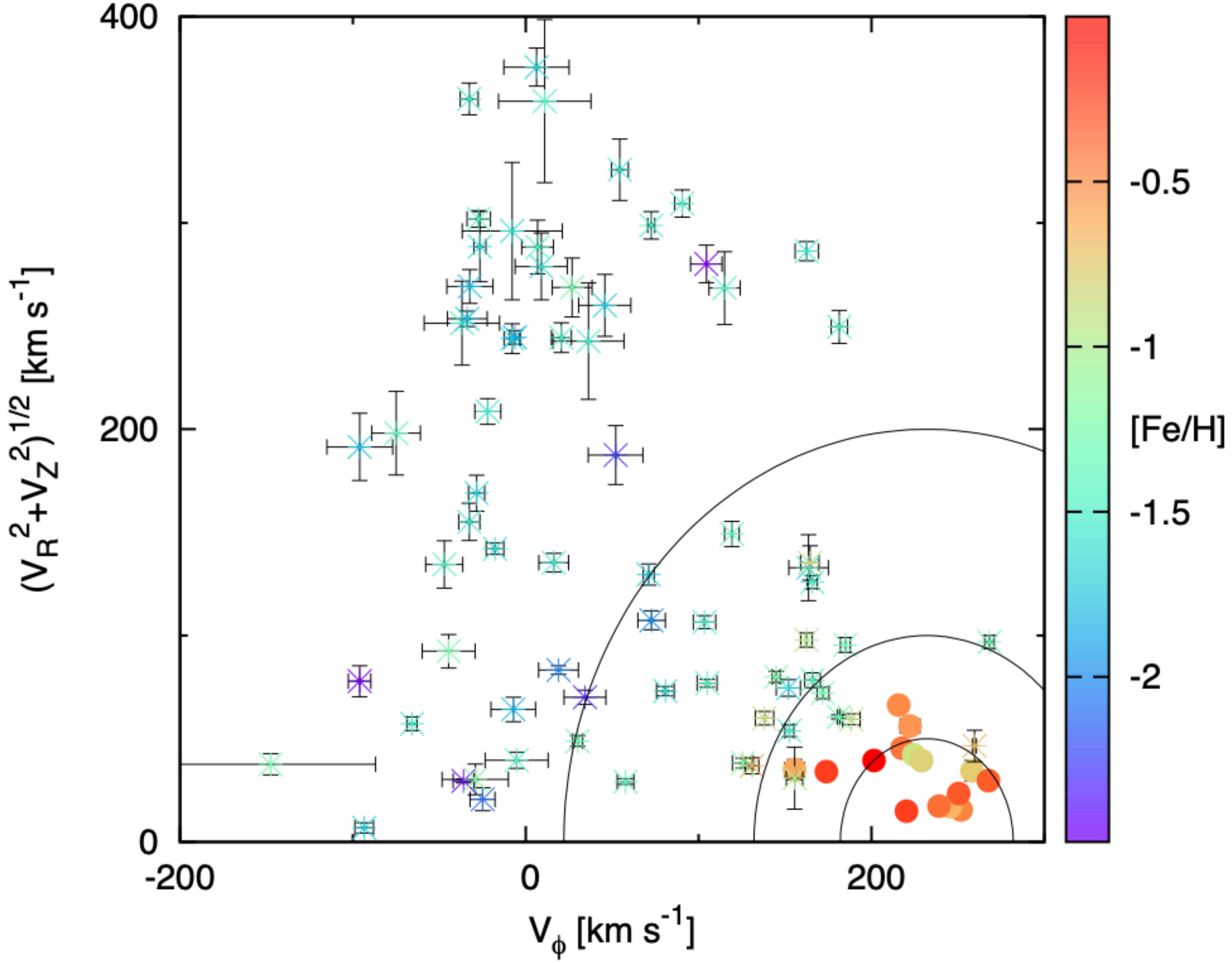
- RR Lyrae Period not consistent with metal-rich RRL in the field

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



*recent works claim that there are no signatures of He-enrichment in the RRLs of NGC6441 (see e.g. Bhardwaj+22)

Metal-rich RRLs in the solar neighborhood

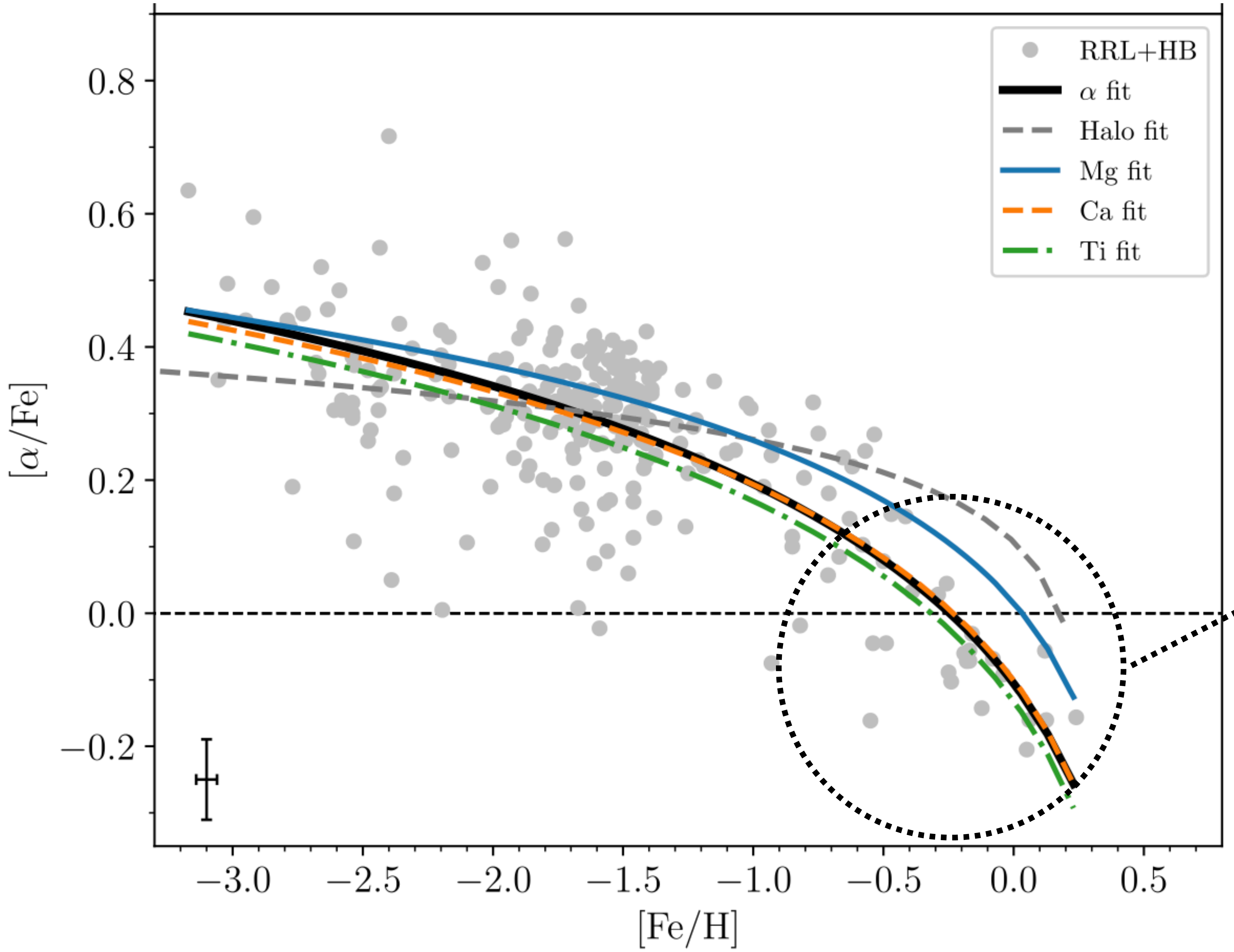


Zinn+20

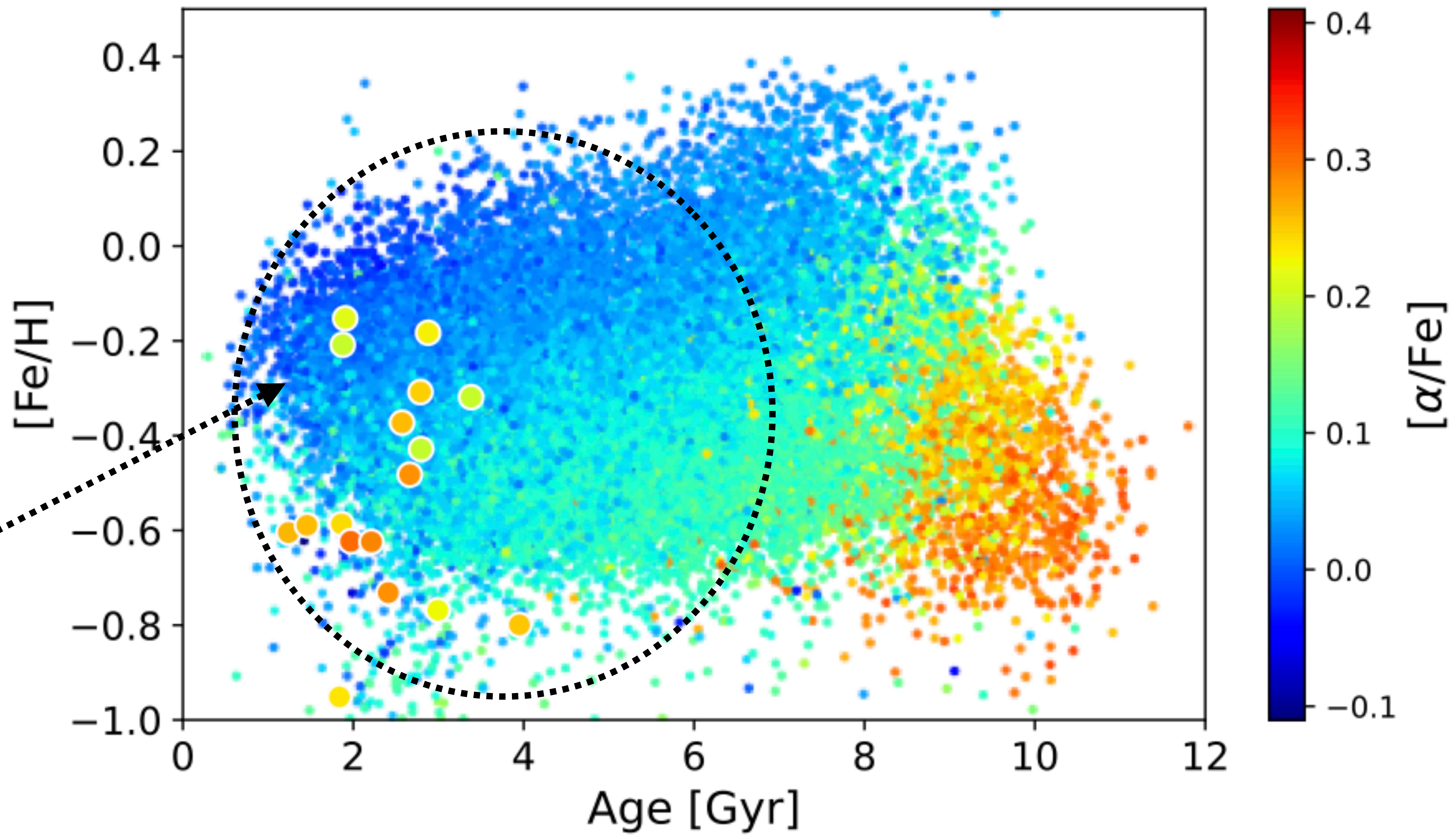
Circle: alpha-poor
Asterisk: alpha-rich

Metal-rich RRLs alpha elements

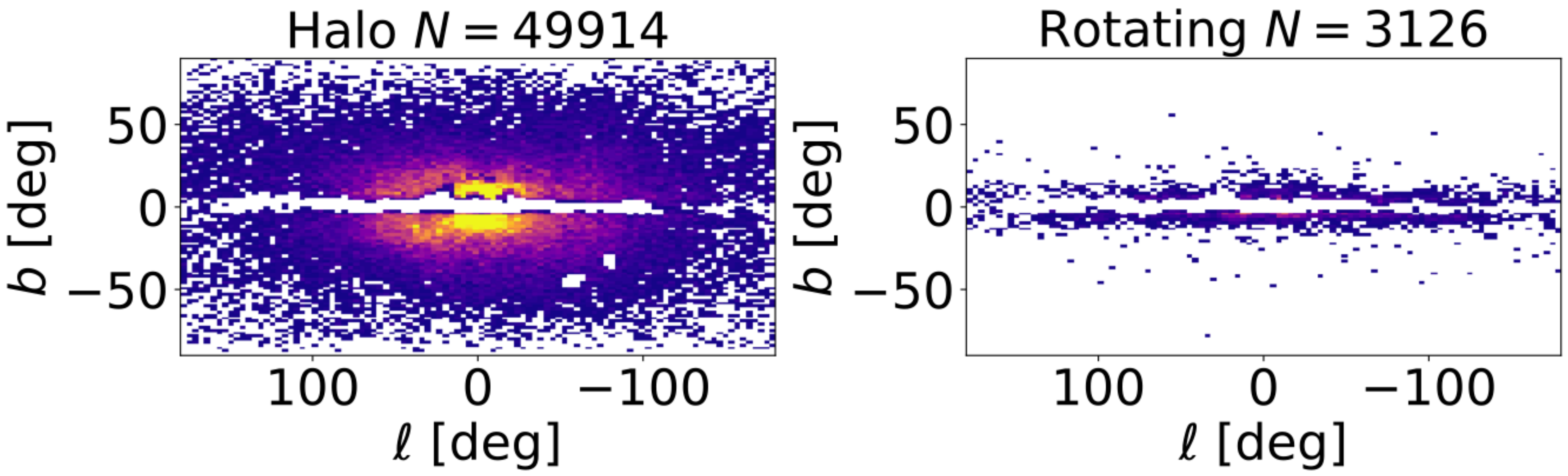
Crestani+21

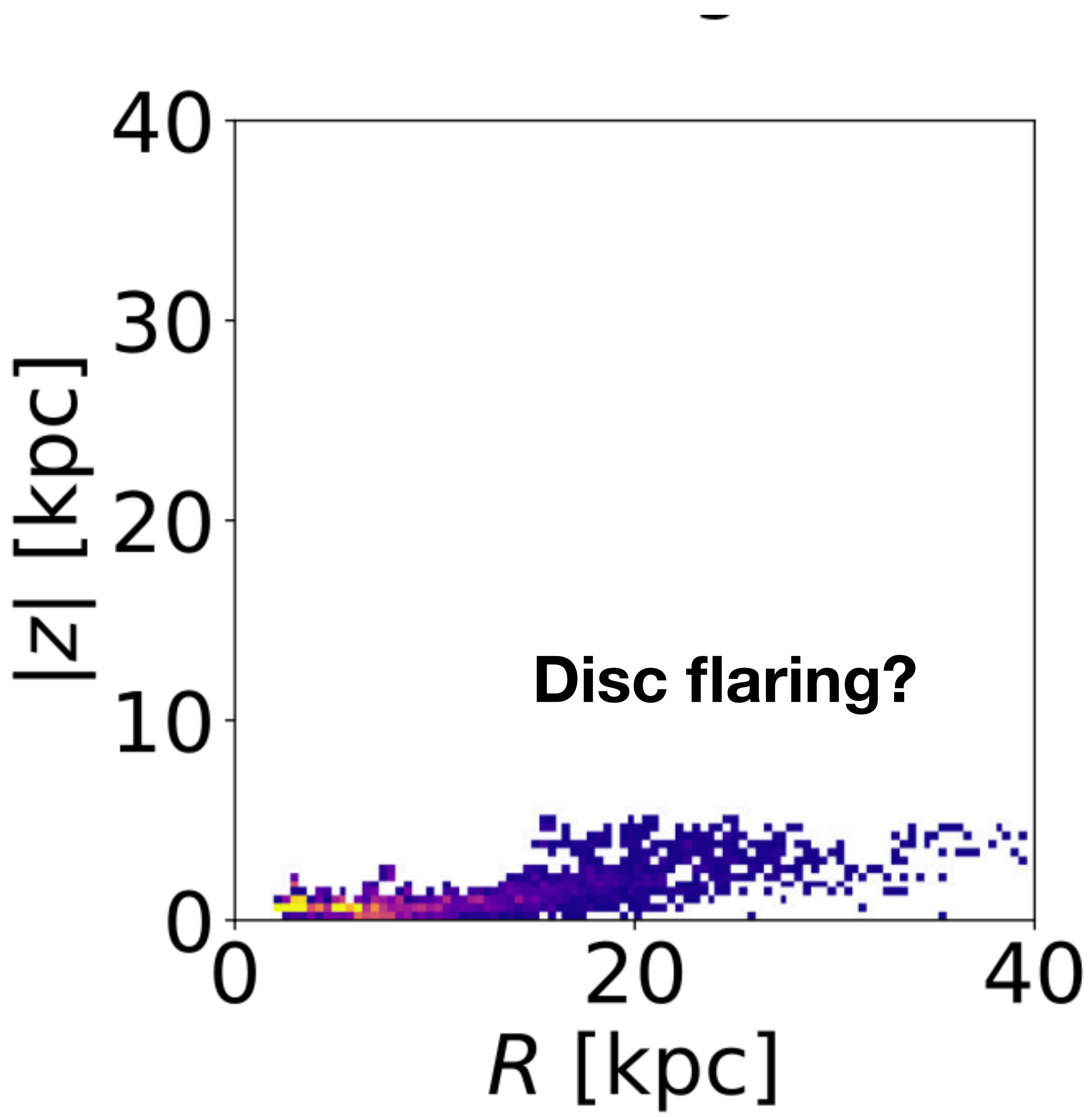


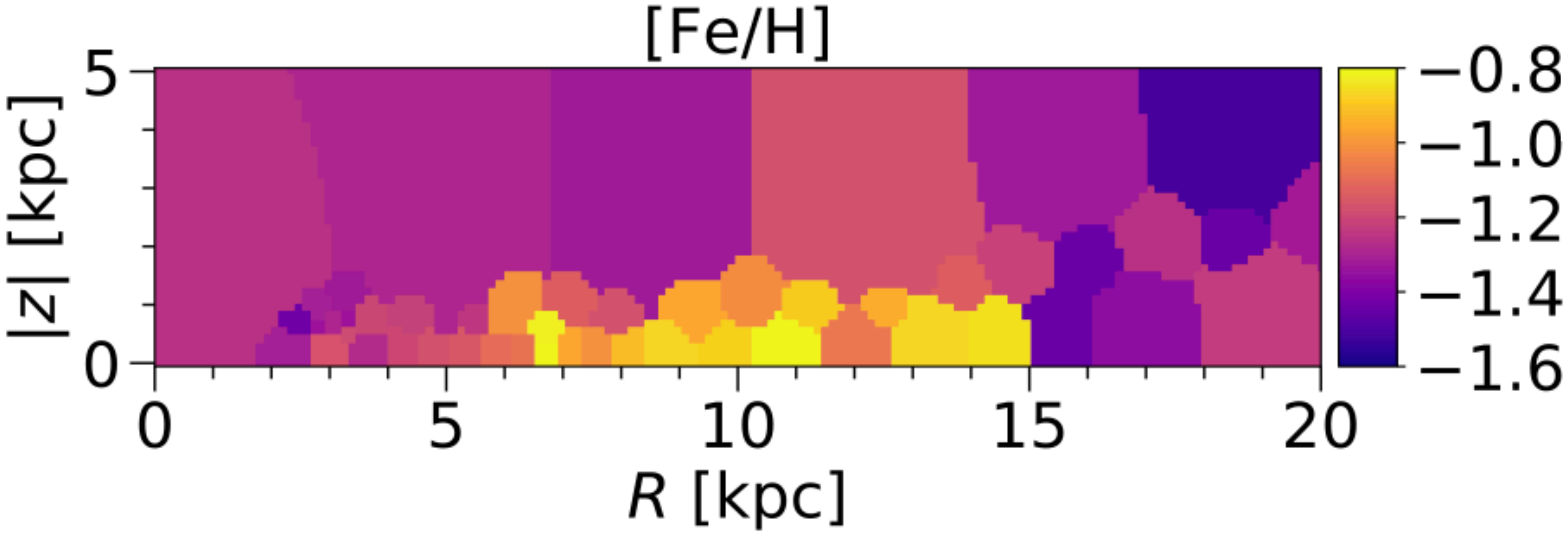
Cerqui+23 **Giant stars**



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



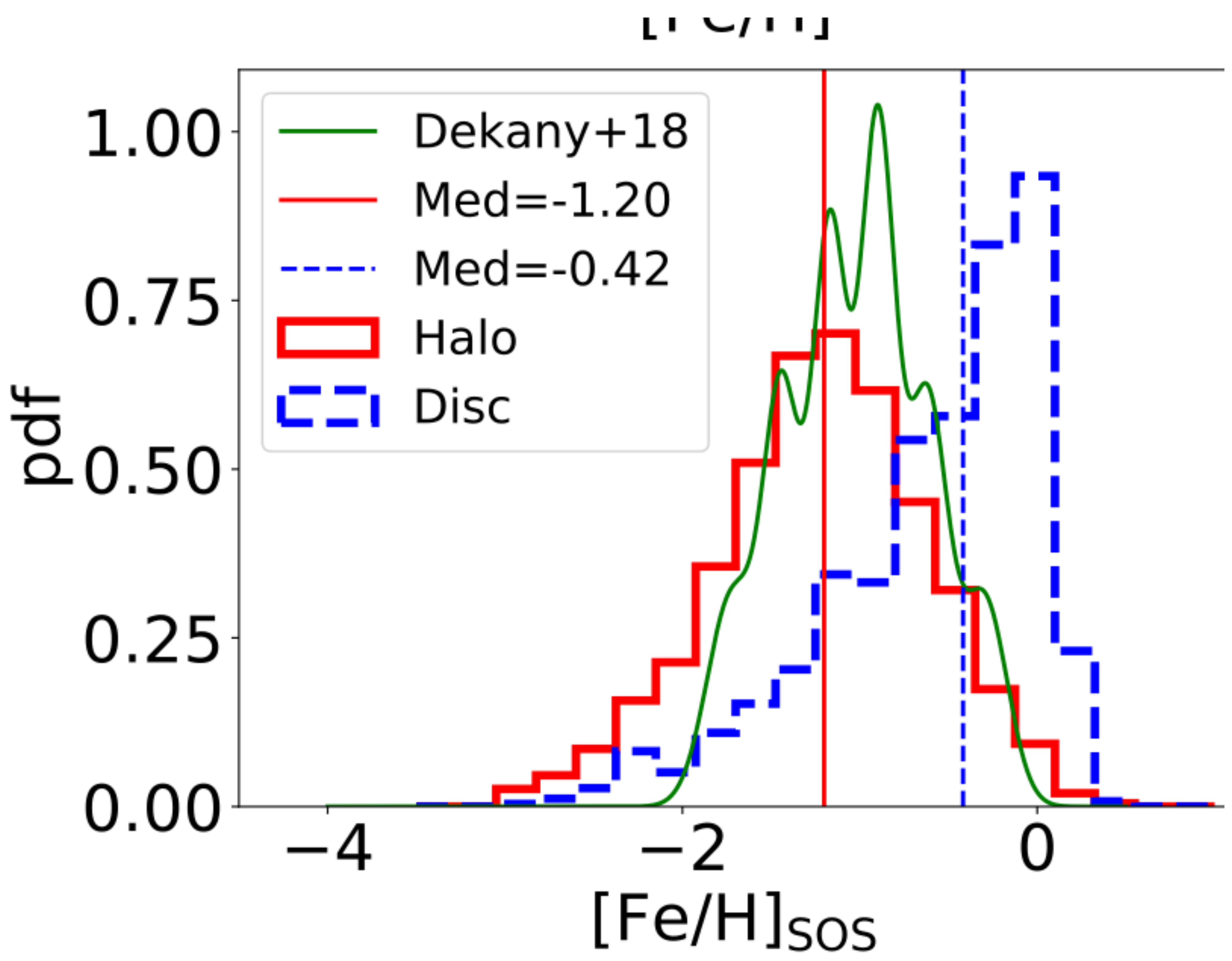


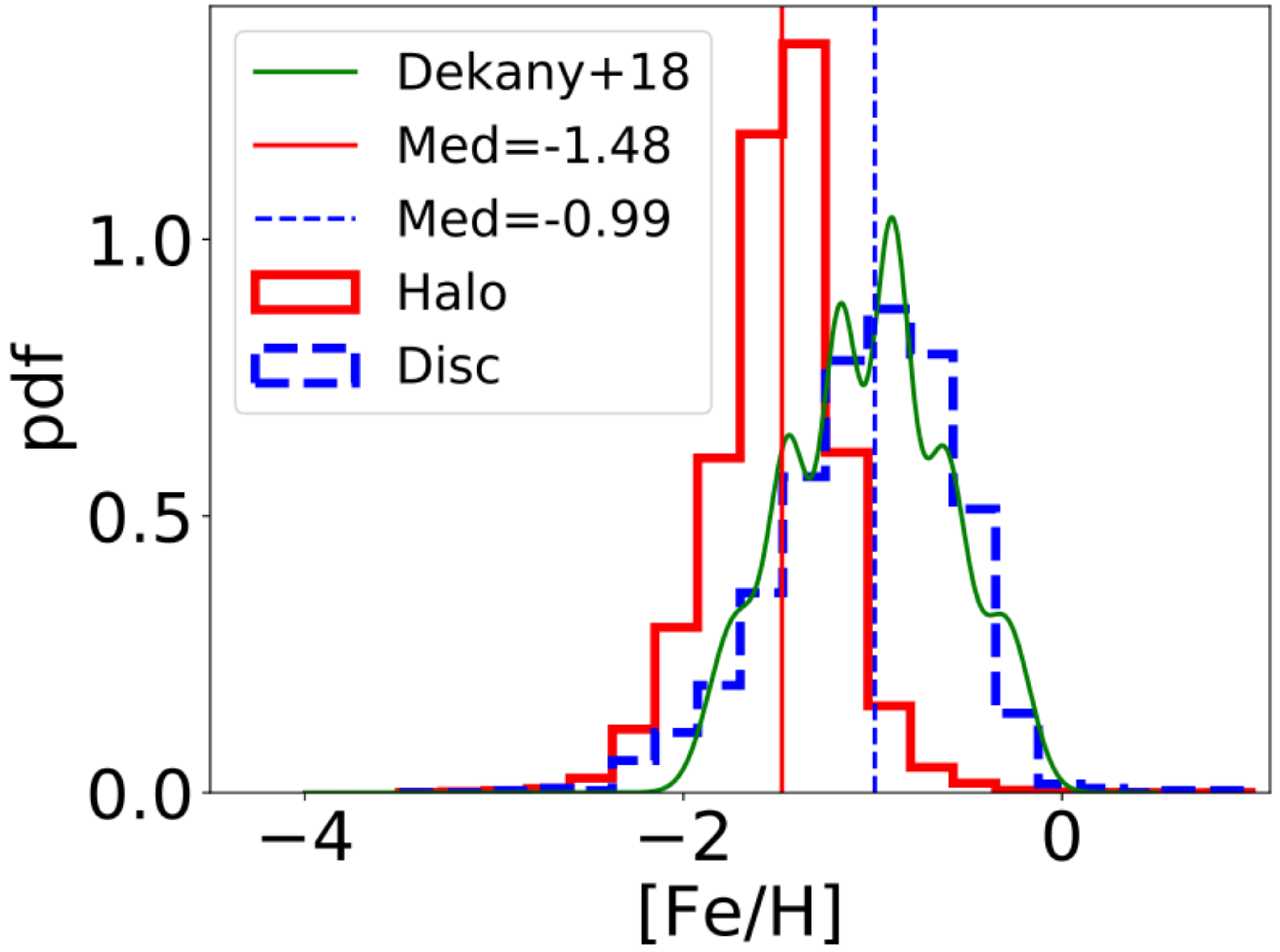


Iorio&Belokurov21

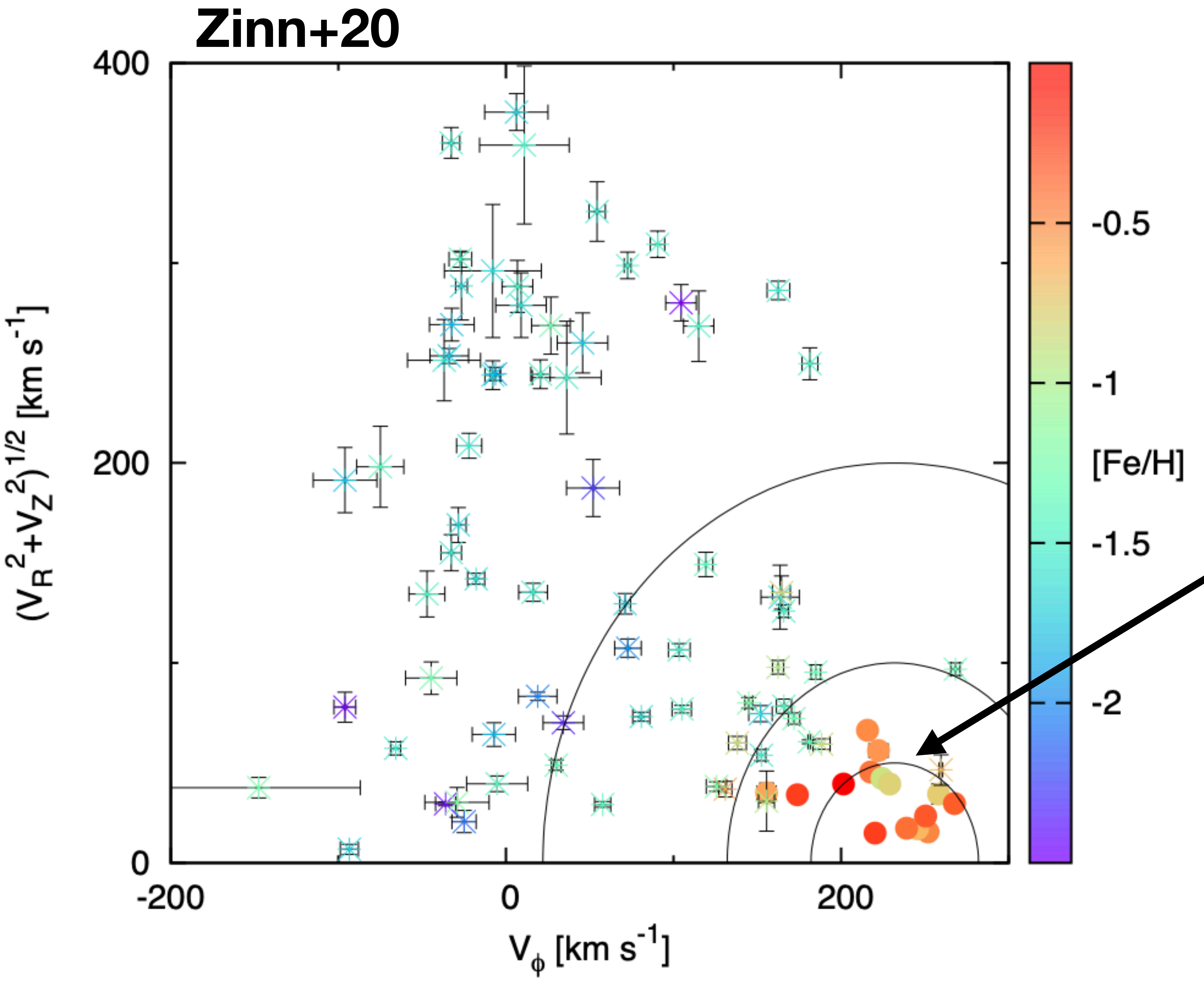
Disc-lile RRLs in the stellar disc from Gaia (DR2)

Iorio&Belokurov21





The RR Lyrae in the Milky Way



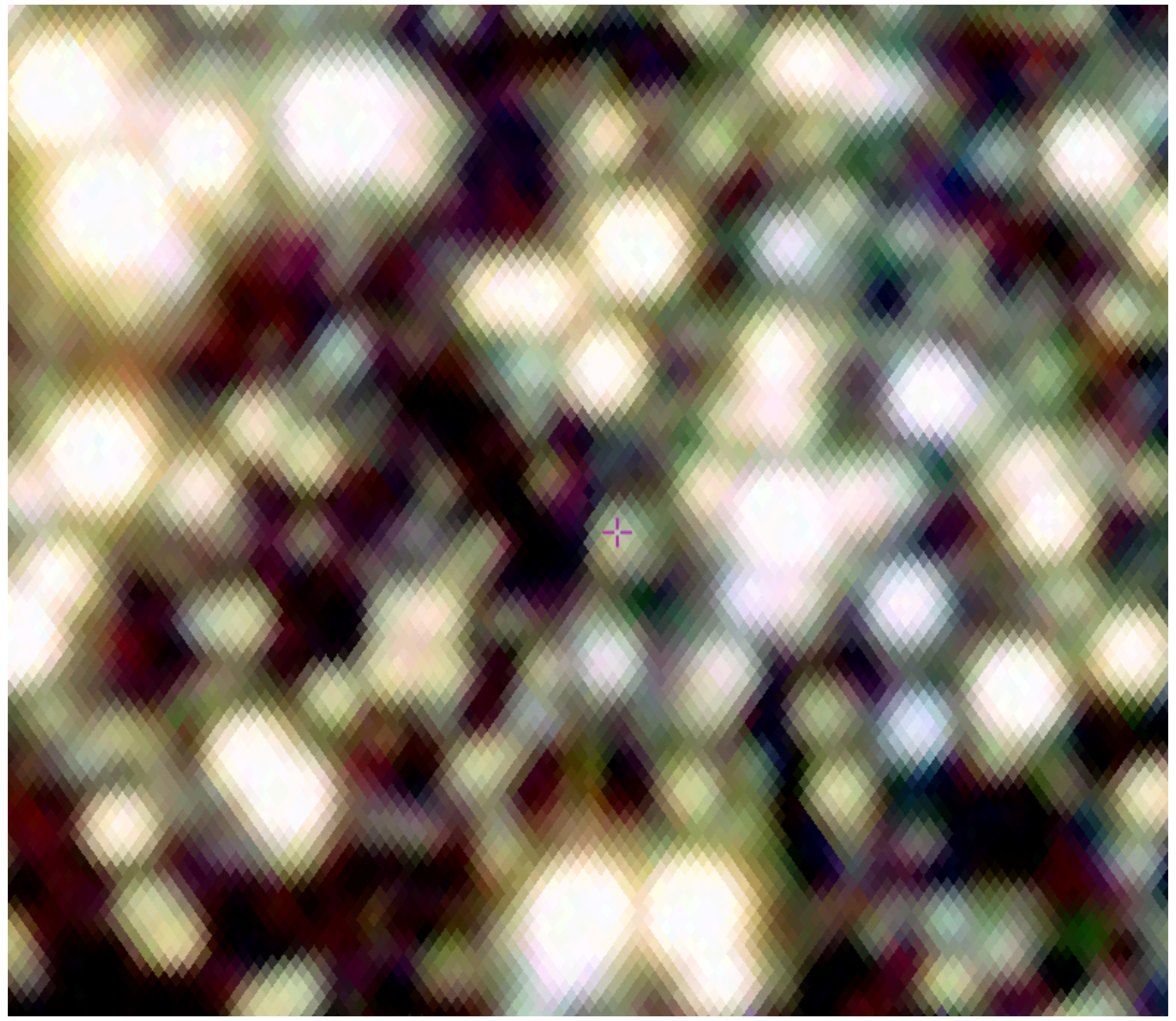
Metal-rich RR Lyrae should not exist!

But we observed few of them in the disc in the solar neighbourhood

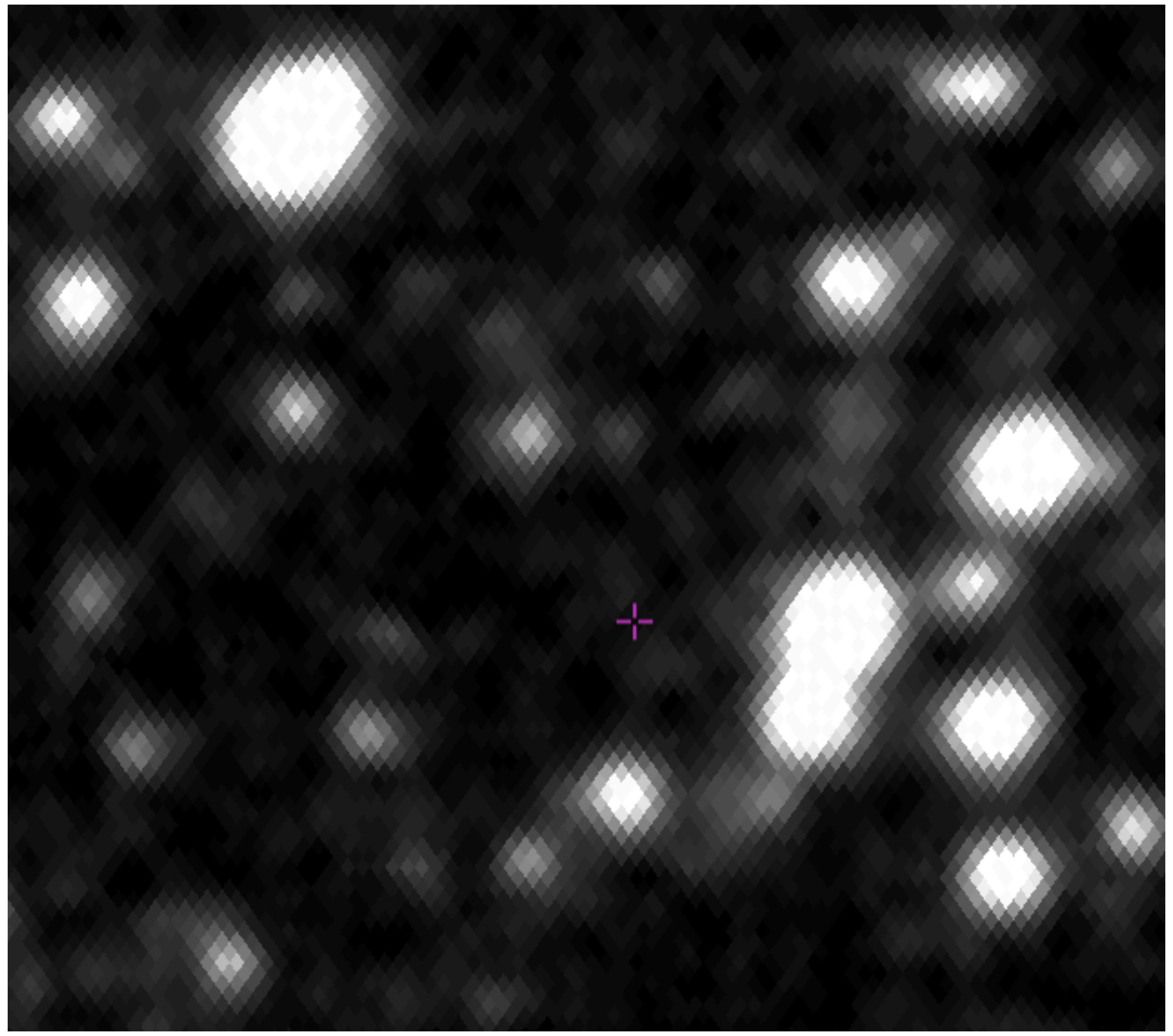
(Layden+95,Prudil+20,Zinn+20,Crestani+21)

NIR vs Visual

VVV J172028.52-393602.4

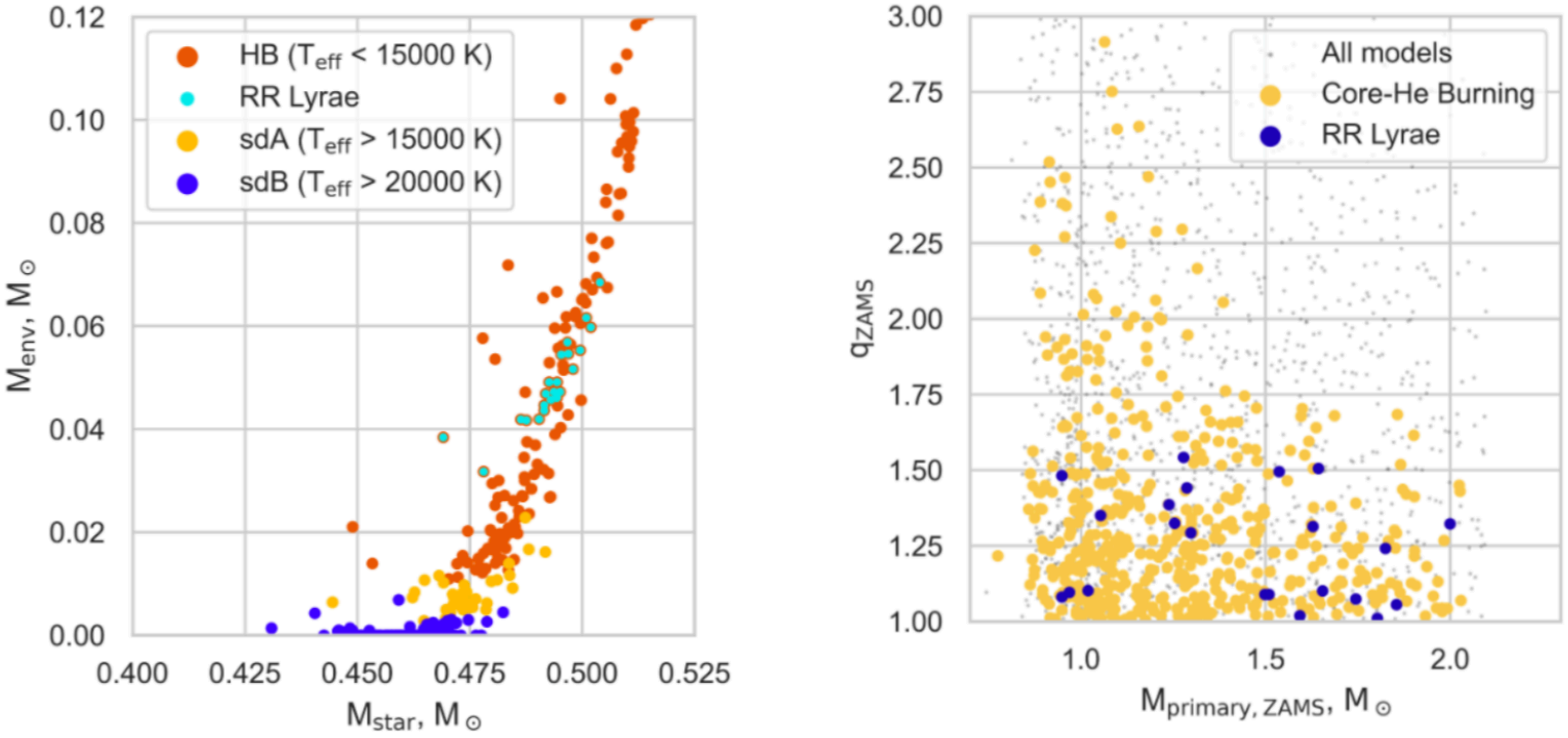


J band mag: 15.5

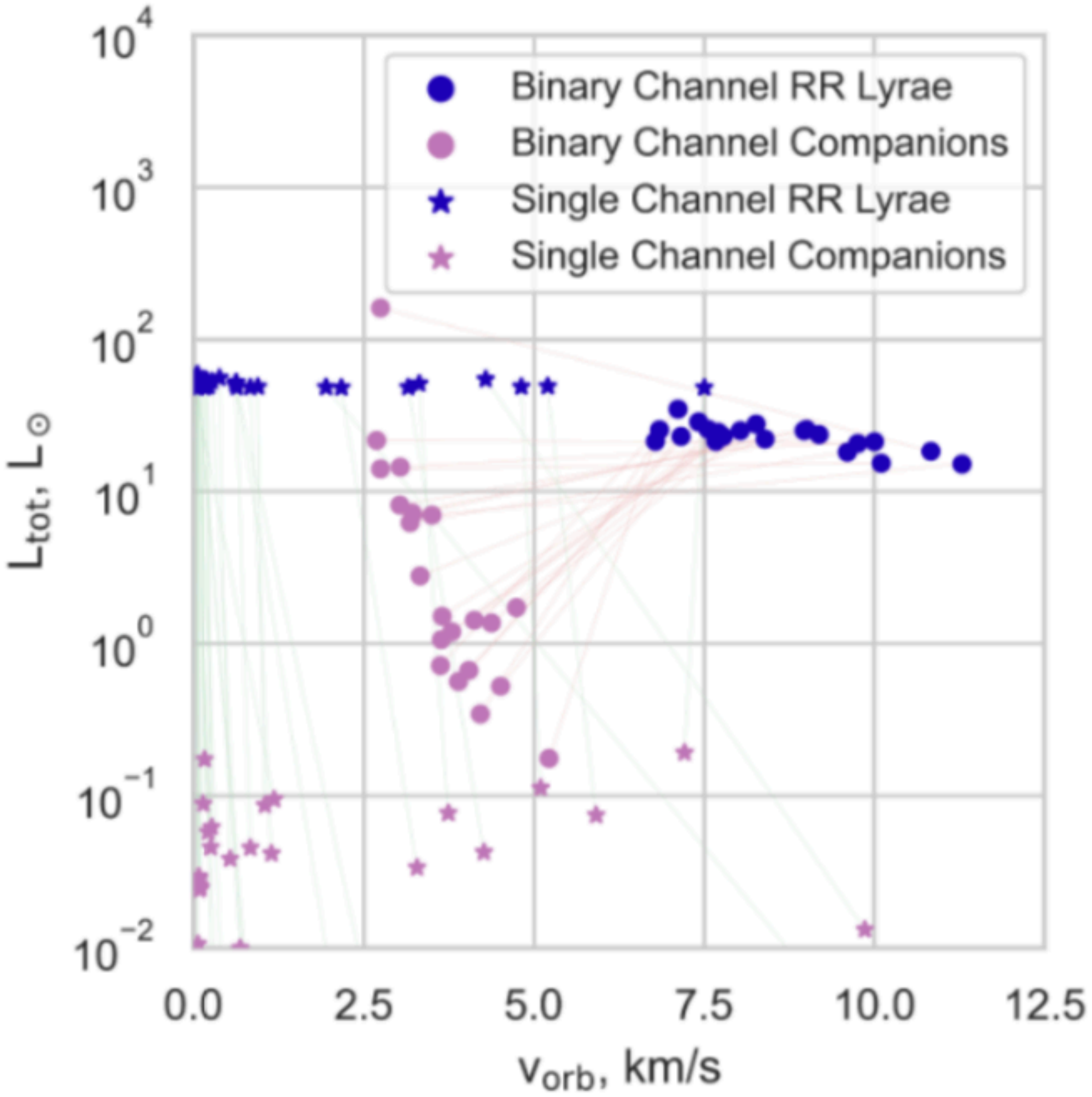


G band mag: 20.0

Binary-made RR Lyrae



Binary-made RR Lyrae companion

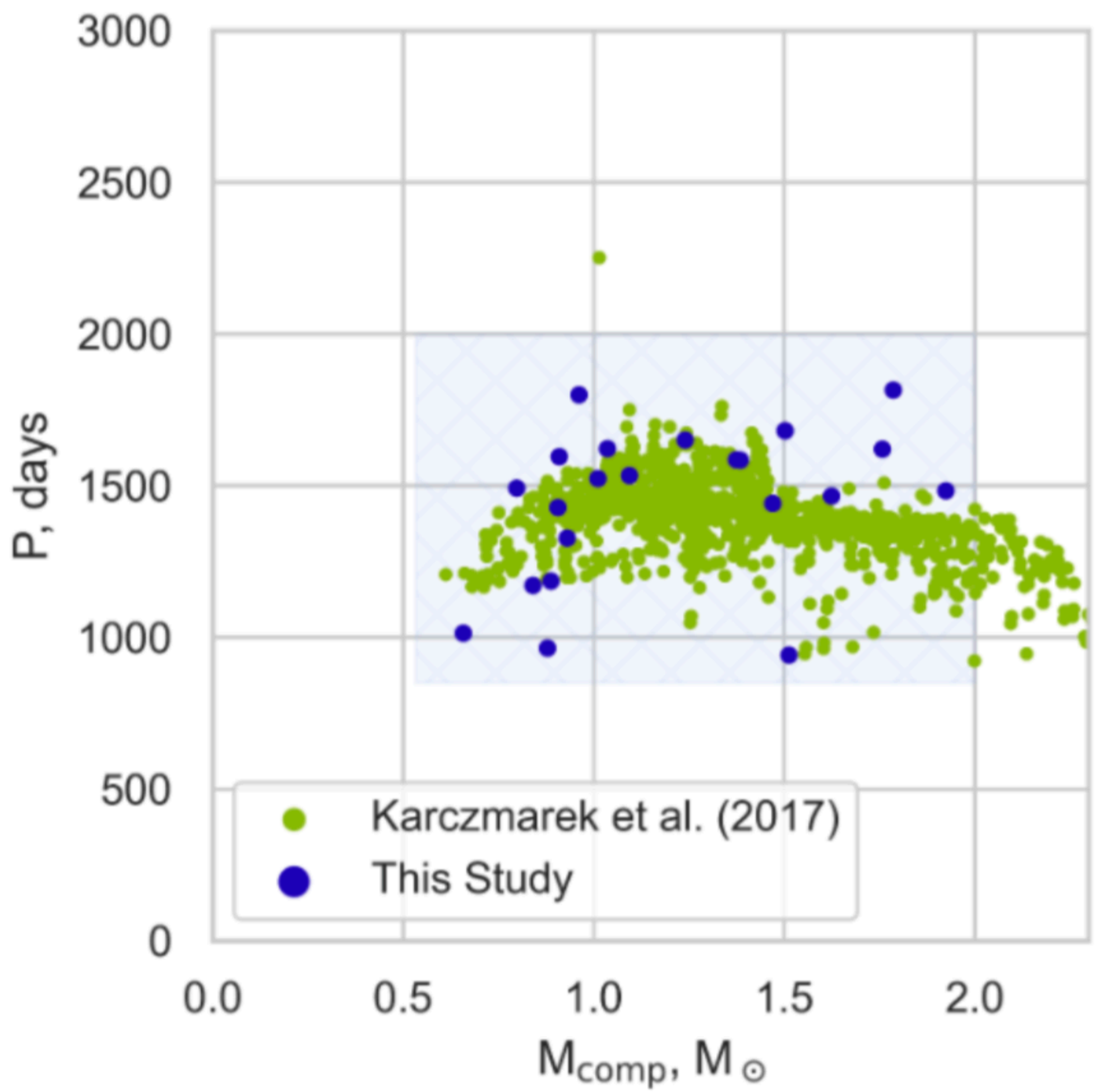


Binary-made RR Lyrae: comparison with Karczamarek+17

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

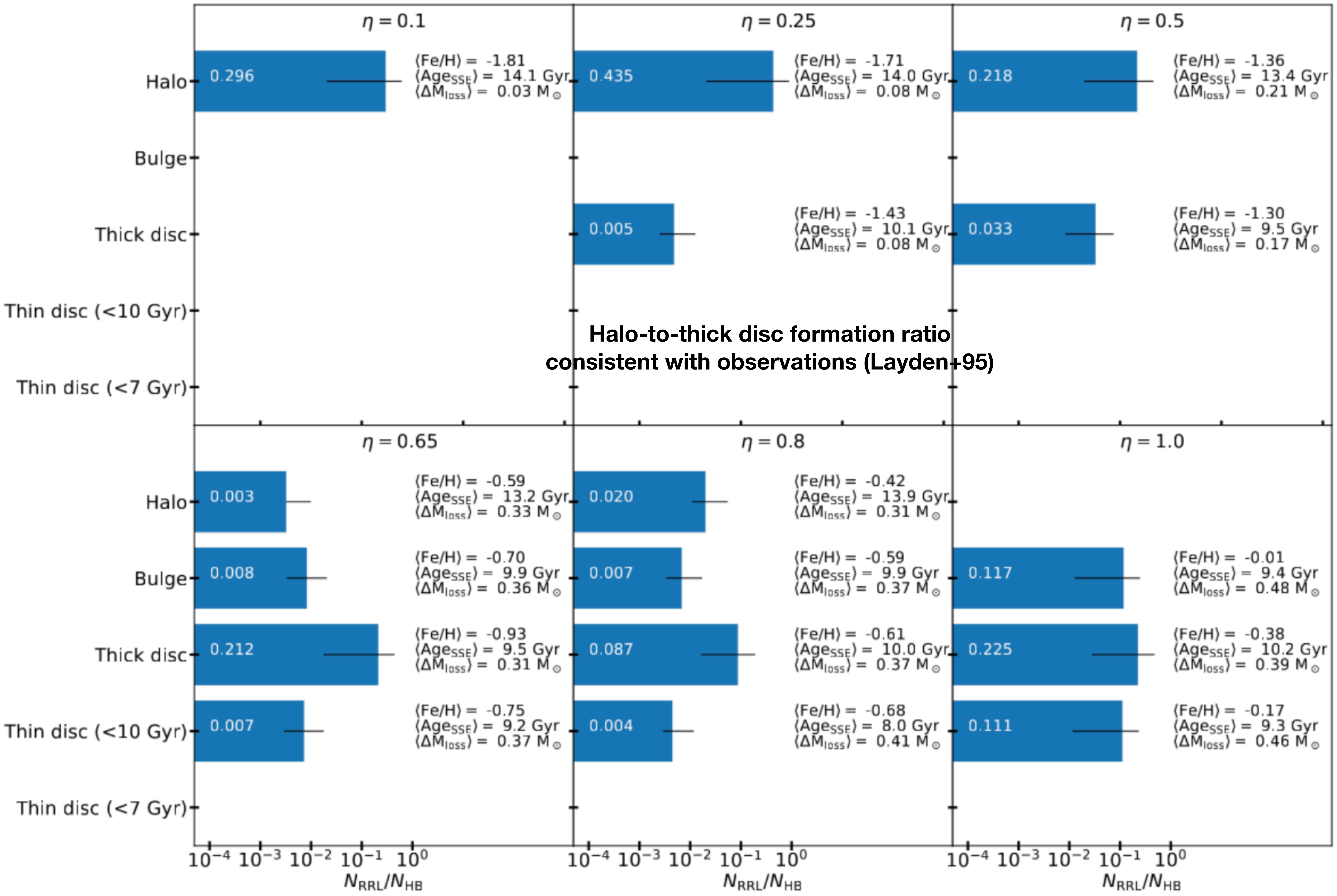
However:
- They consider that 20% of stars between 0.8-0.9 produce a single made RRL independently of the metallicity

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

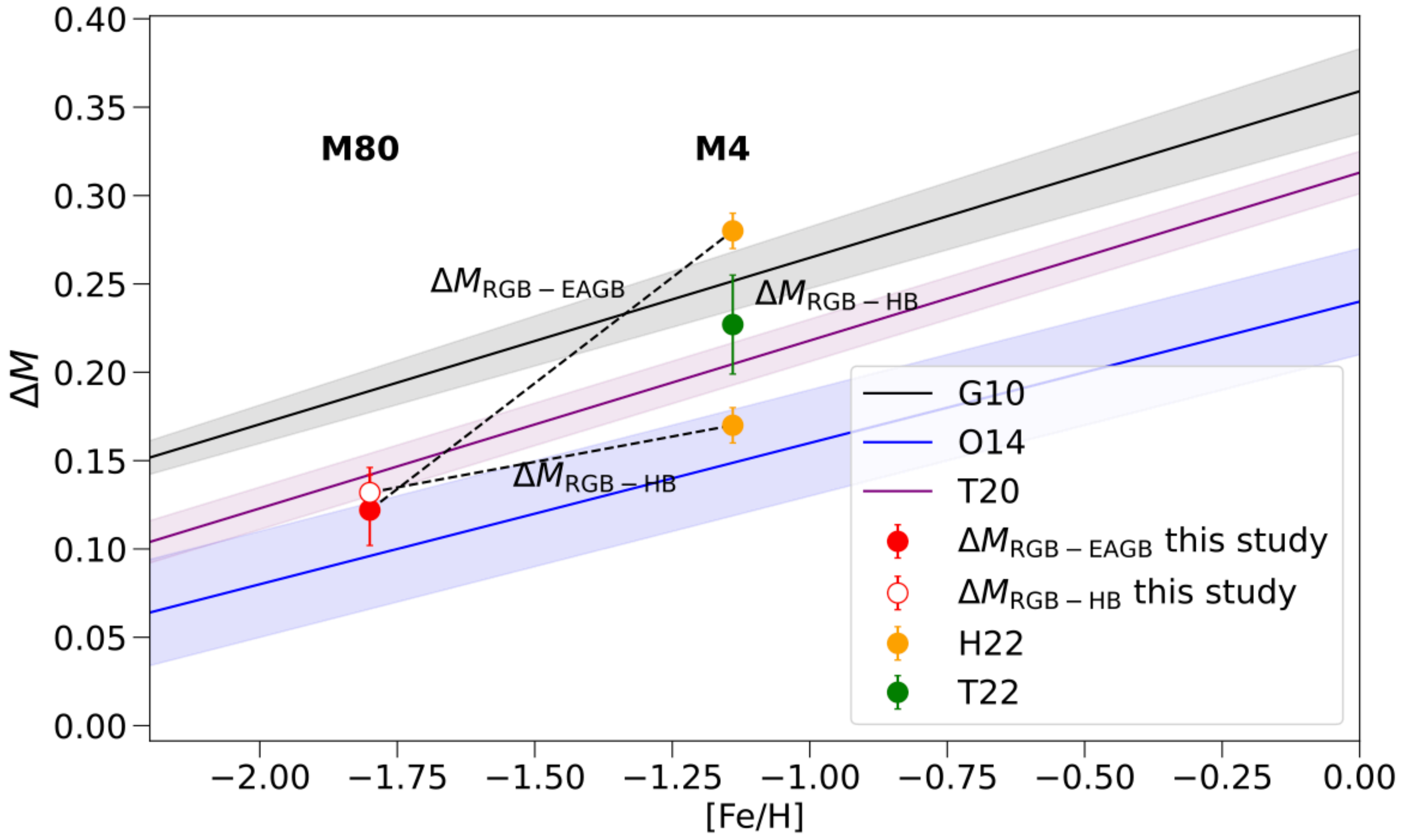


Varying wind mass-loss

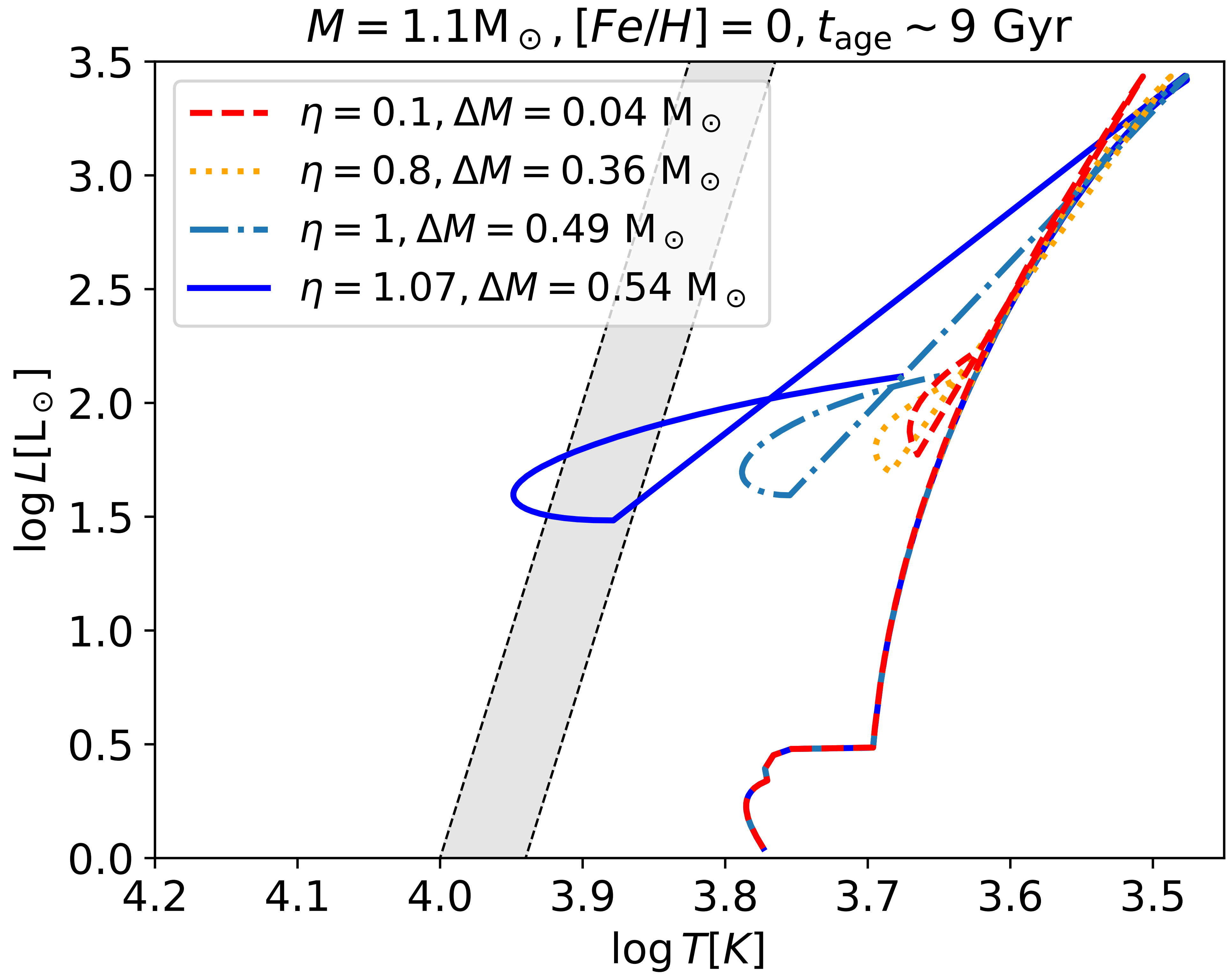
$$\dot{M}_{\mathrm{RGB}} \propto \eta \frac{RL}{M}$$



Wind mass-loss from observations



Howell+23



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)

Simulations setup

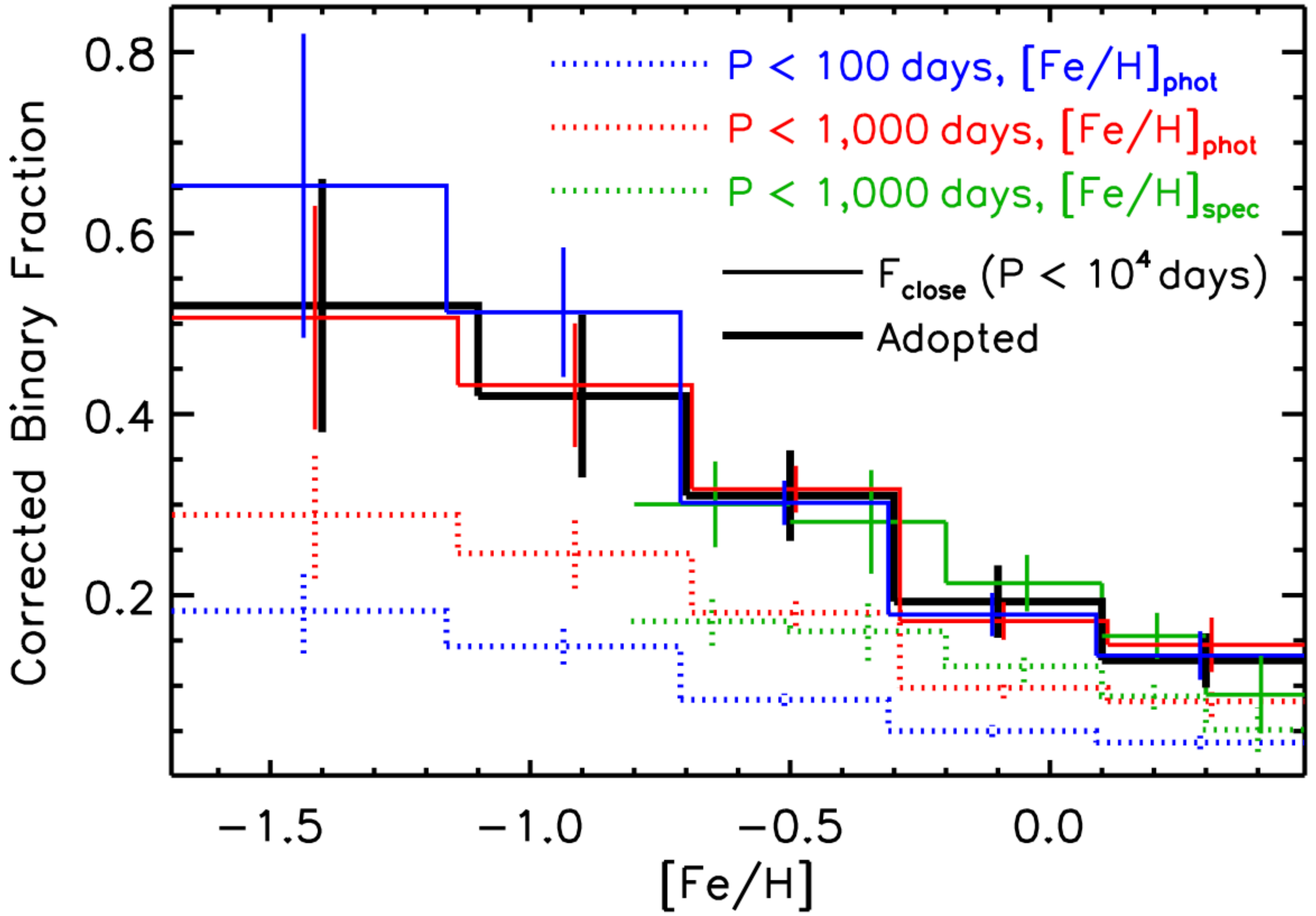
Property	Functional Form	Parameter Range	Comments and references
IMF	$\mathrm{d}N/\mathrm{d}M_\star \propto M_\star^{-\alpha}$	$\alpha = \begin{cases} 1.3 & \text{for } 0.09\,\mathrm{M_\odot} < M_\star < 0.5\,\mathrm{M_\odot} \\ 1.8 & \text{for } 0.5\,\mathrm{M_\odot} < M_\star < 1.53\,\mathrm{M_\odot} \\ 3.2 & \text{for } 1.53\,\mathrm{M_\odot} < M_\star < 150\,\mathrm{M_\odot} \end{cases}$	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	$[\mathrm{Fe/H}] \propto \mathcal{N}([\mathrm{Fe/H}]_i, \sigma_{[\mathrm{Fe/H}],\mathrm{i}})$	—	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 $\dot{M} \gtrsim 10^{-5} - 10^{-6}\,\mathrm{M_\odot/yr}$ Mass loss with J_z of accretor (Tauris & van den Heuvel 2006)

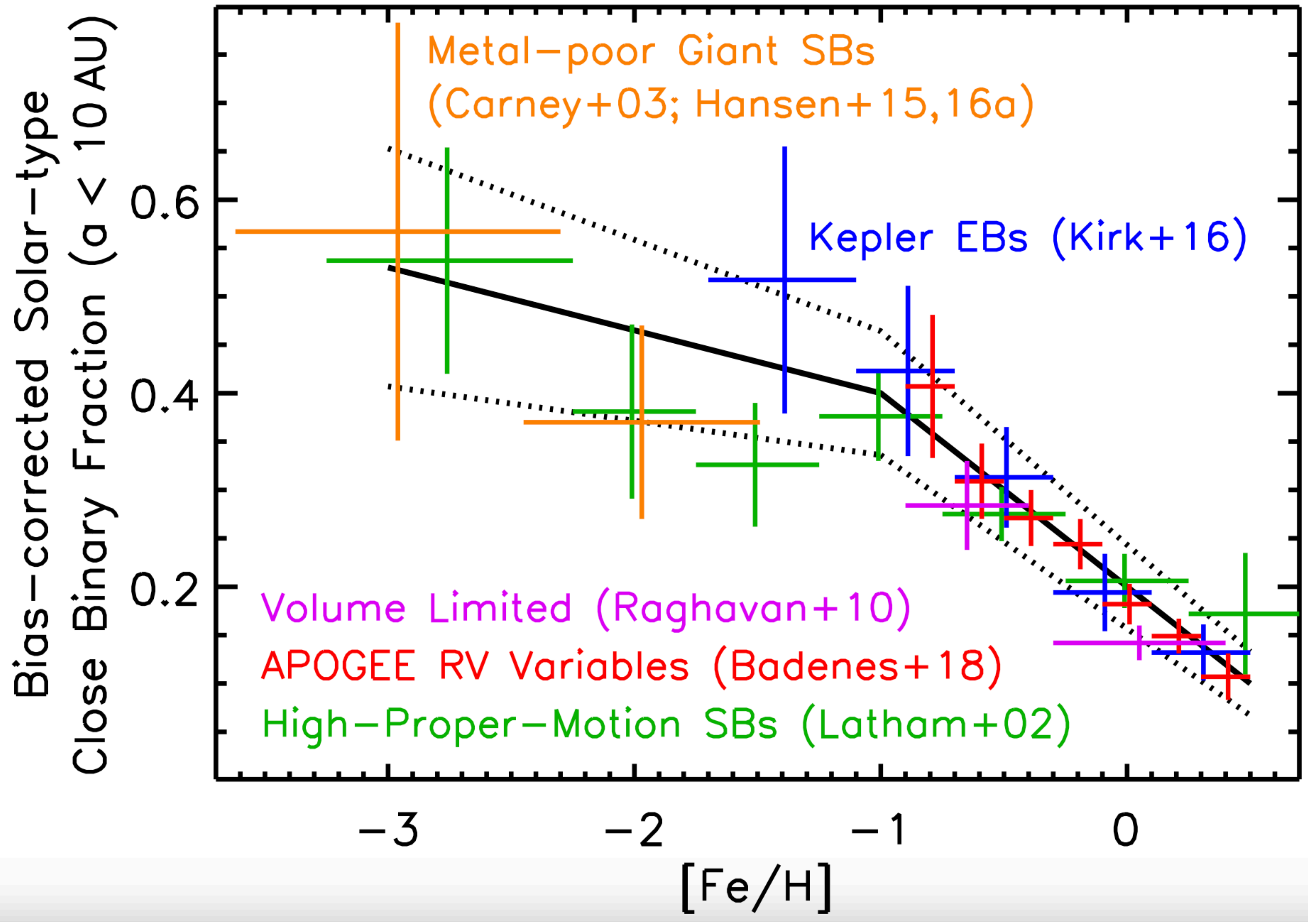
Besançon model - predictions

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

Type	Thin disc	Thick disc	Bulge	Halo	Total
R_{tot}, kyr^{-1}	0 : 0.51	0 : 0	0 : 0.13	9.46 : 0	9.46 : 0.63
N_{tot}	0 : 48 000	0 : 0	0 : 10 500	523 400 : 0	523 400 : 58 500
n_{loc}, kpc^{-3}	0 : 43.6	0 : 0	0 : 0	9.2 : 0	9.2 : 43.6
$N_{500\,pc}$	0 : 13.2	0 : 0	0 : 0	4.8 : 0	4.8 : 13.2
$N_{1\,kpc}$	0 : 70.5	0 : 0	0 : 0	38.4 : 0	38.4 : 70.5

Binary fraction





Moe+19