*

*I acknowledge the support of the INAF OAS-BO through the grant Obiettivo Funzione — 1.05.12.04.02, PI: Tatiana Muraveva

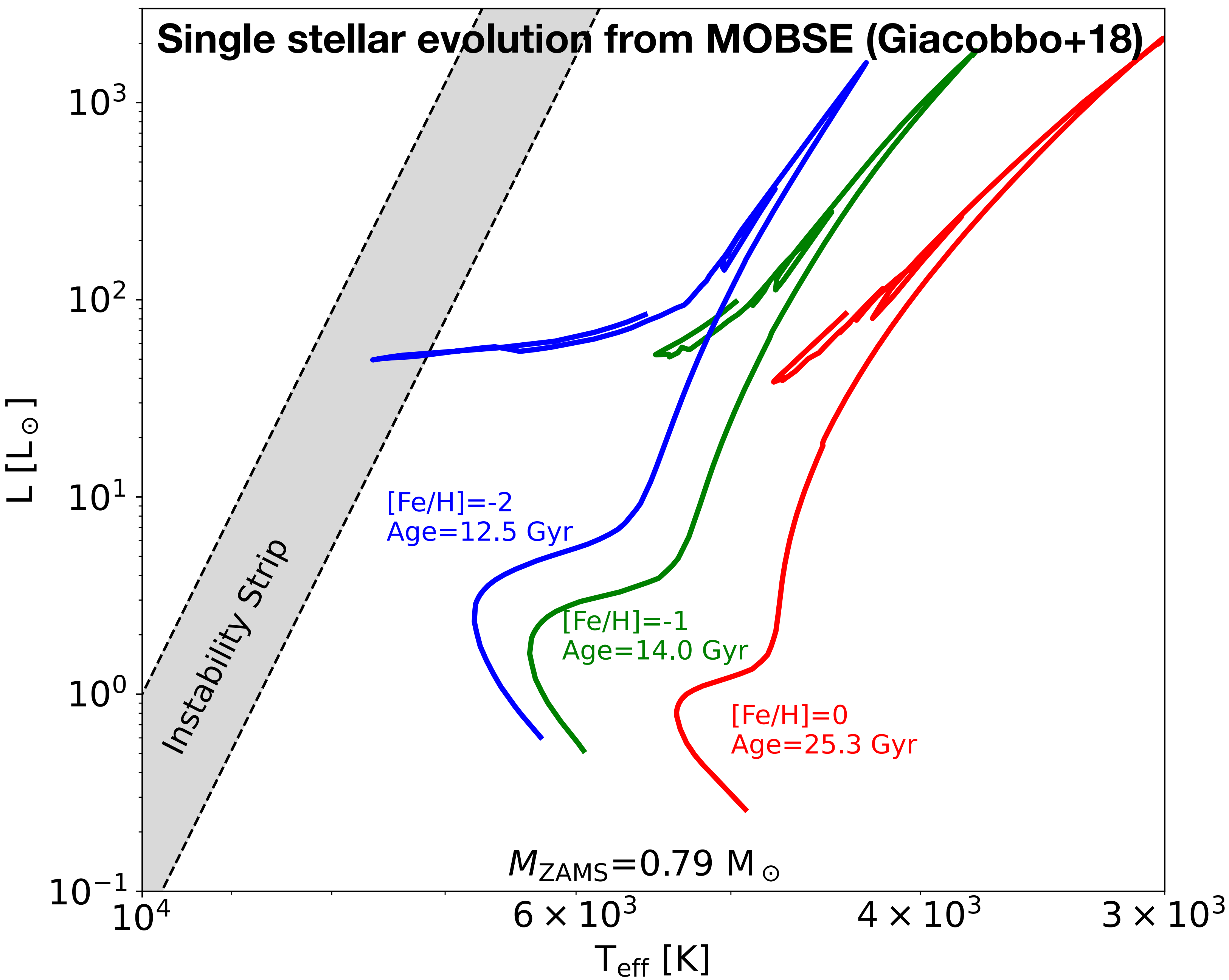
The RR Lyrae in the disc as an interesting GaiaNIR scientific case

Giuliano Iorio
University of Padova

Gaia-NIR: next generation astrometric mission.
Gathering the interest of the Italian Community

17-18 Jan 2024, Bologna

The RR Lyrae stars (RRLs) in the Milky Way

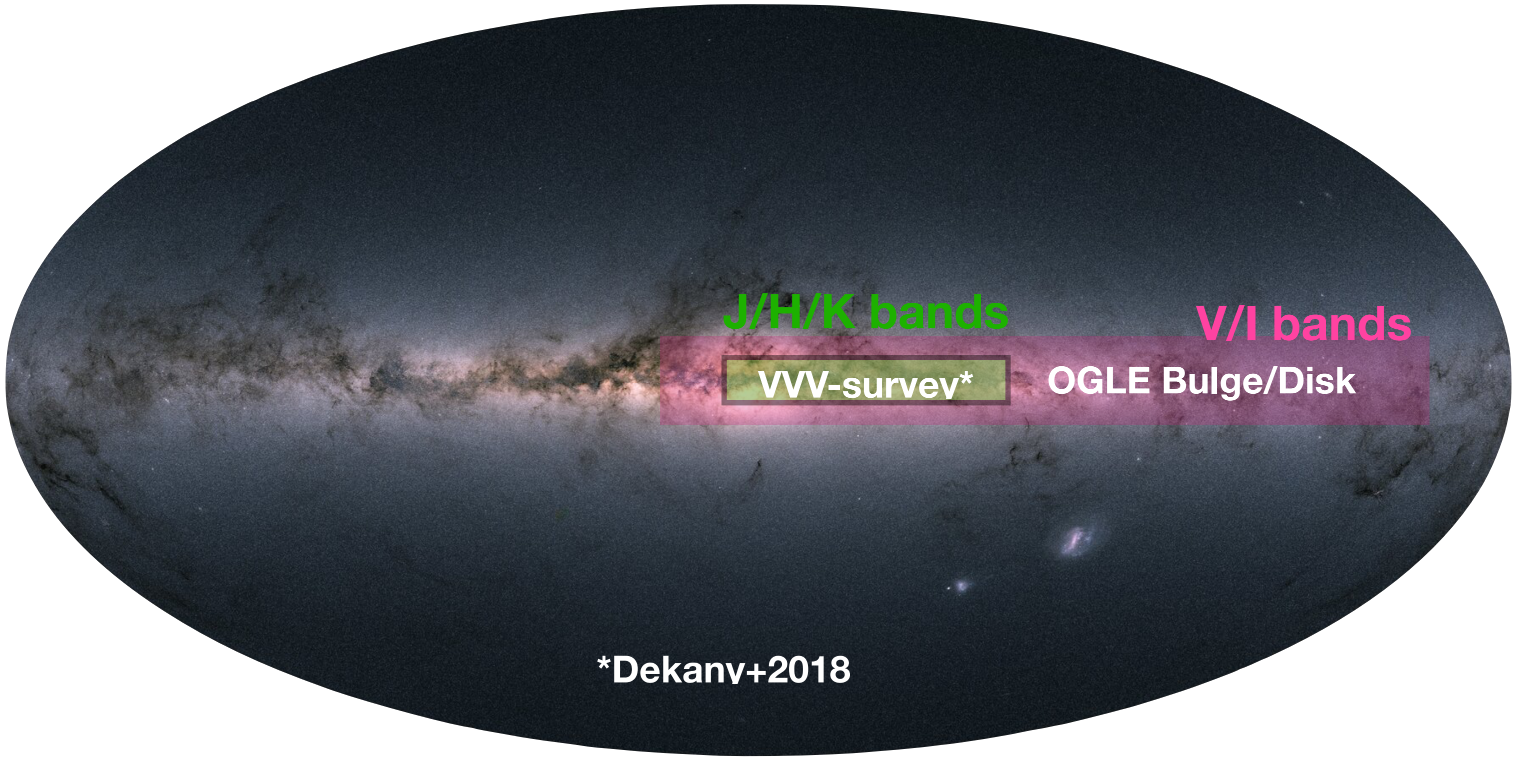


The "Classical textbook definition"

(e.g. Catelan09, Smith04)

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

RRLs in the disc: a science case for GaiaNIR?



- **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**

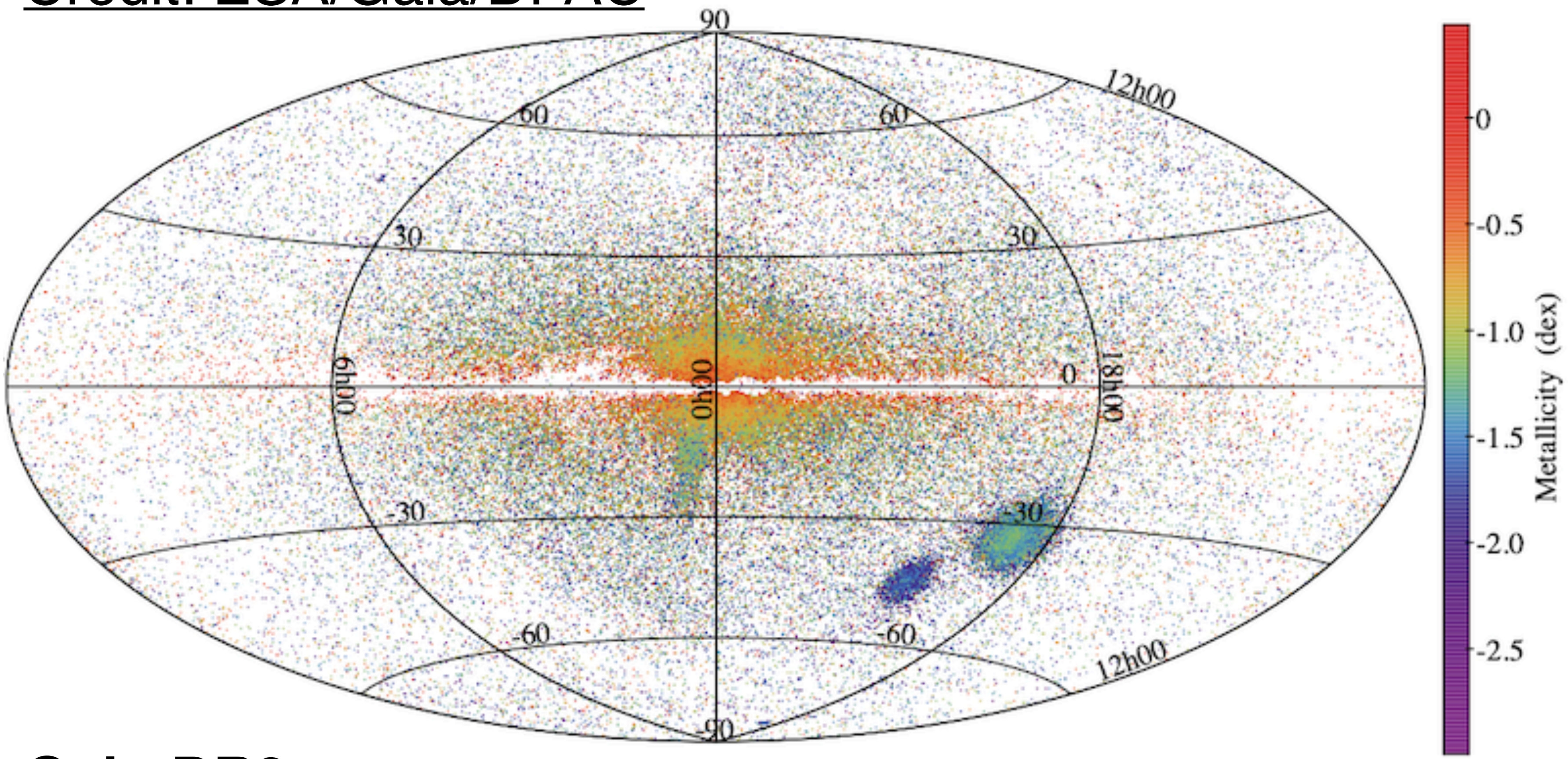
GaiaNIR could produce an unprecedented astrometric survey of RRLs in the disc

Do they represent an interesting scientific case?

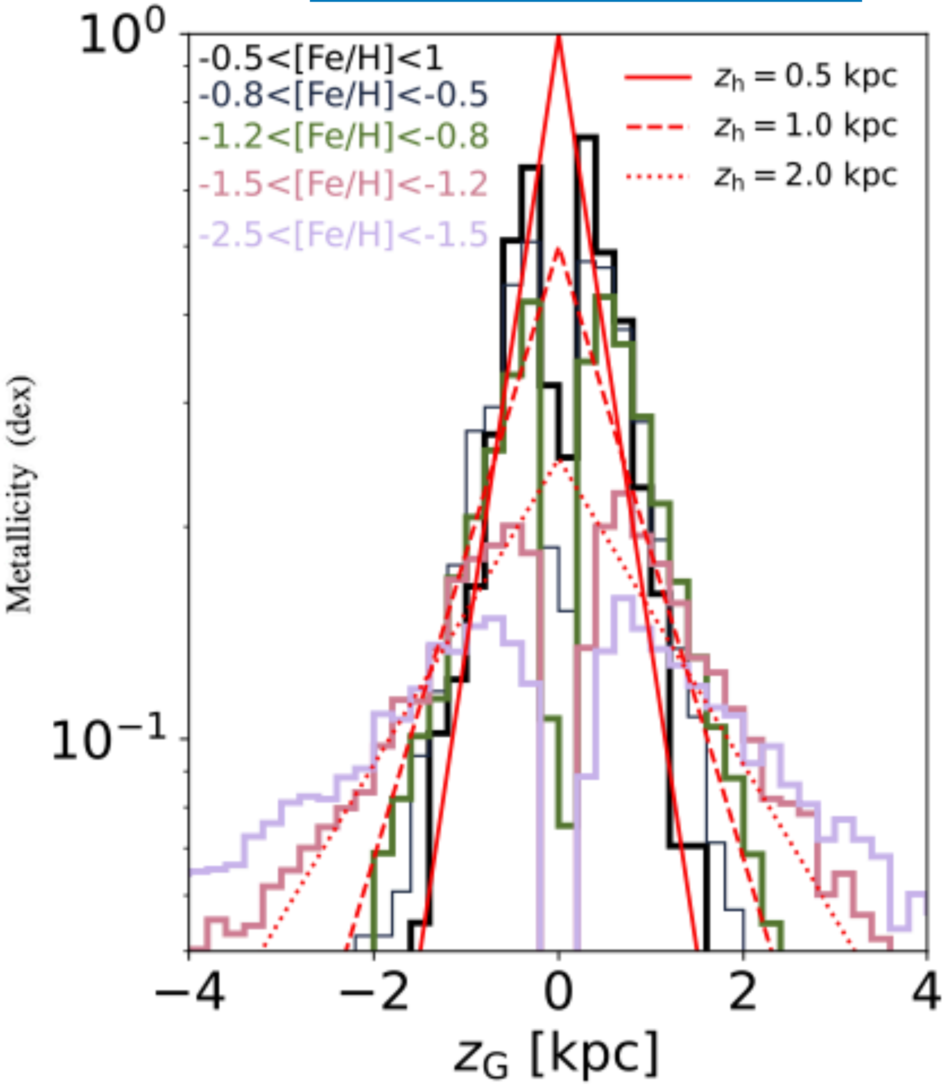
RRLs in the disc: properties

Bobrick&Iorio+24

Credit: ESA/Gaia/DPAC



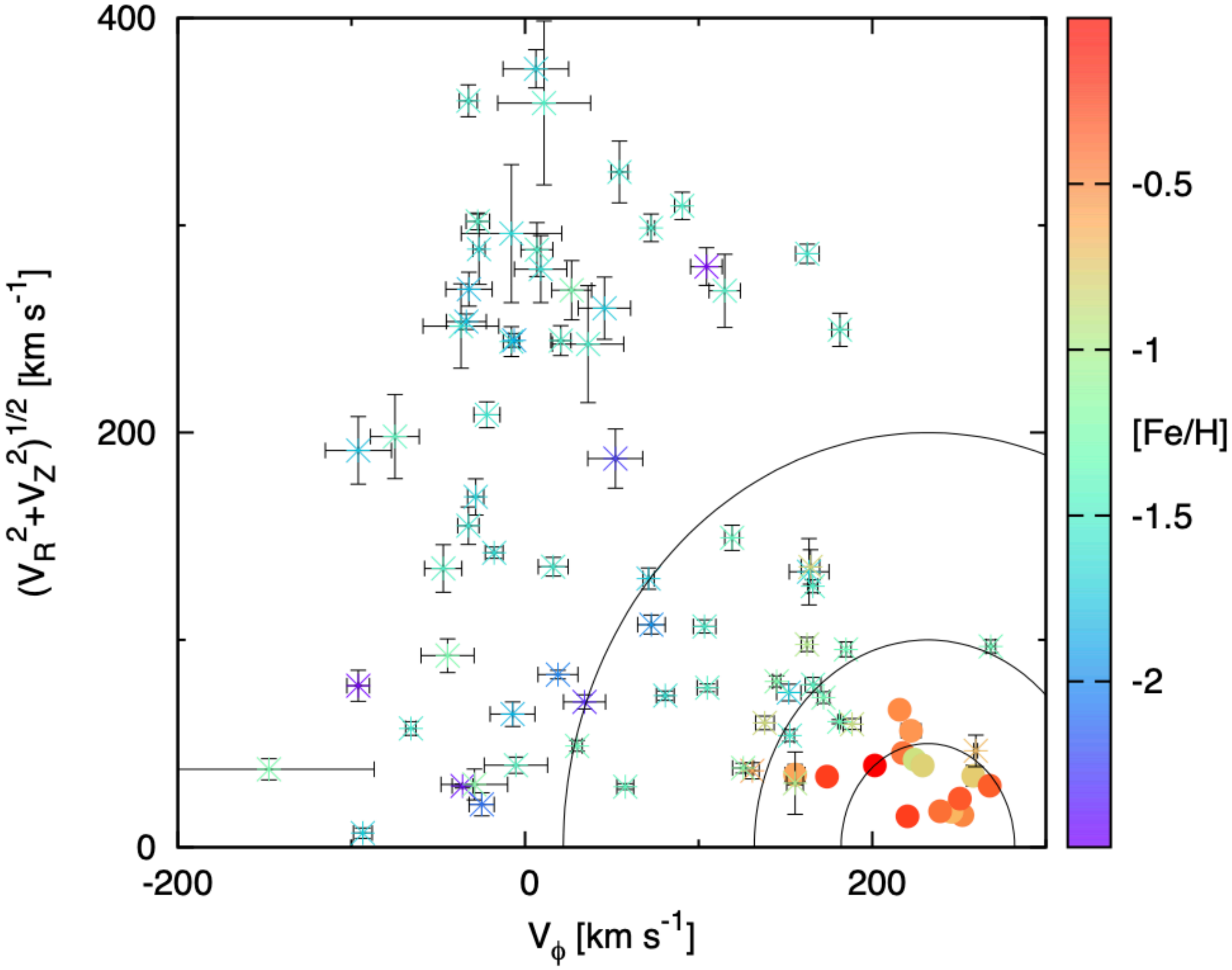
Gaia-DR3



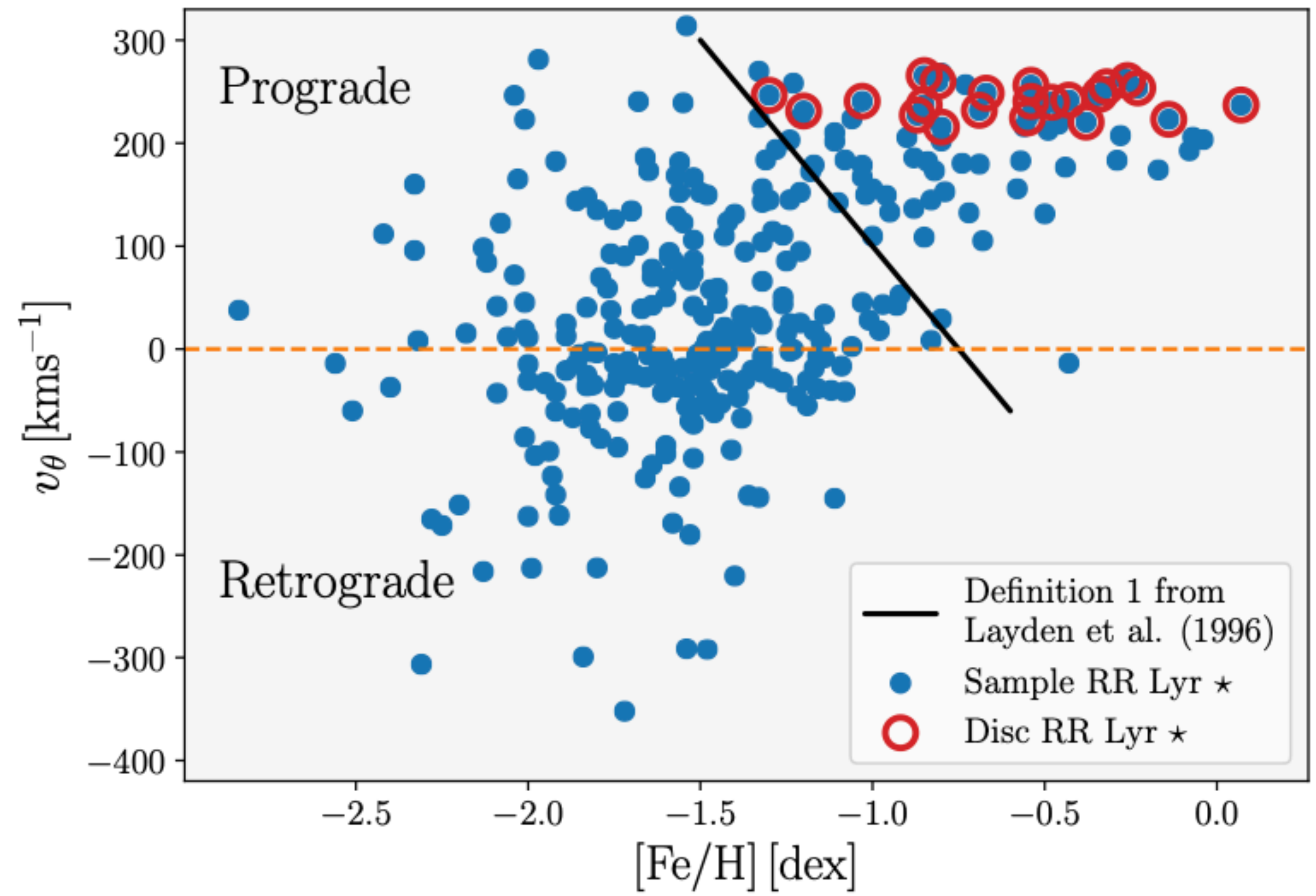
- **More metal-rich than the halo counterpart ([Fe/H]>-1)**
- **Settled in an exponential thin-disc like vertical structure**

RRLs in the disc: properties

Zinn+20



Prudil+20

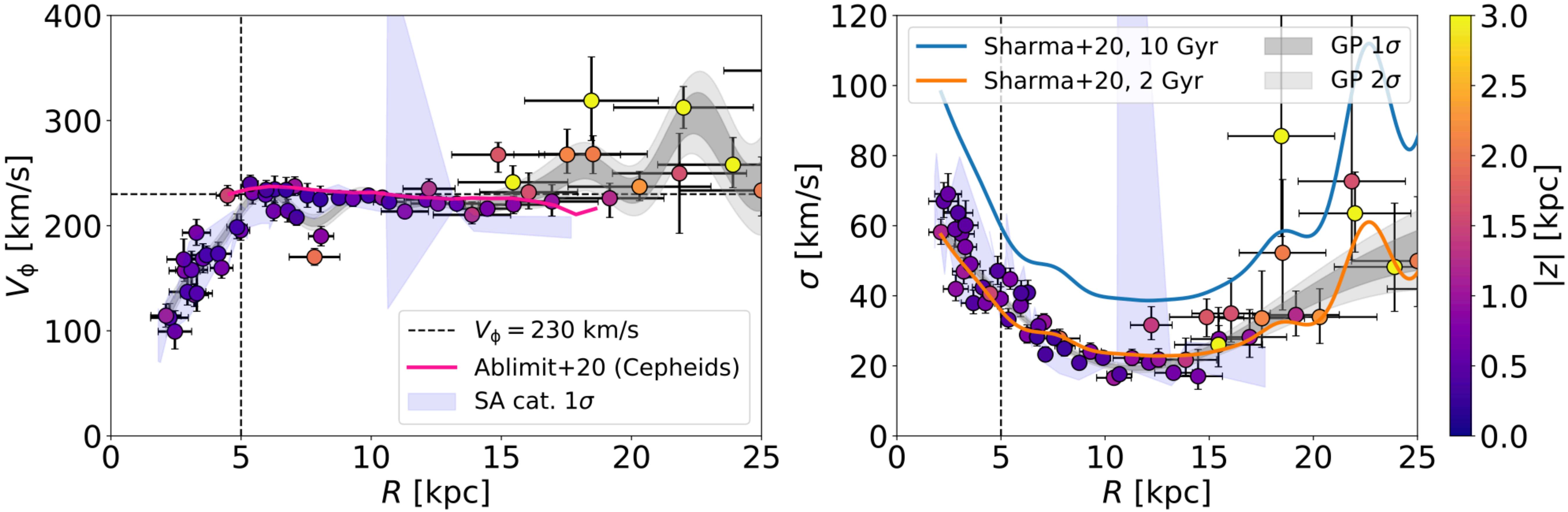


In the Solar neighbourhood:

- **Solar like rotation**
- **Low velocity dispersion (< 40 km/s typical <10 Gyr old pop)**

RRLs in the disc: properties

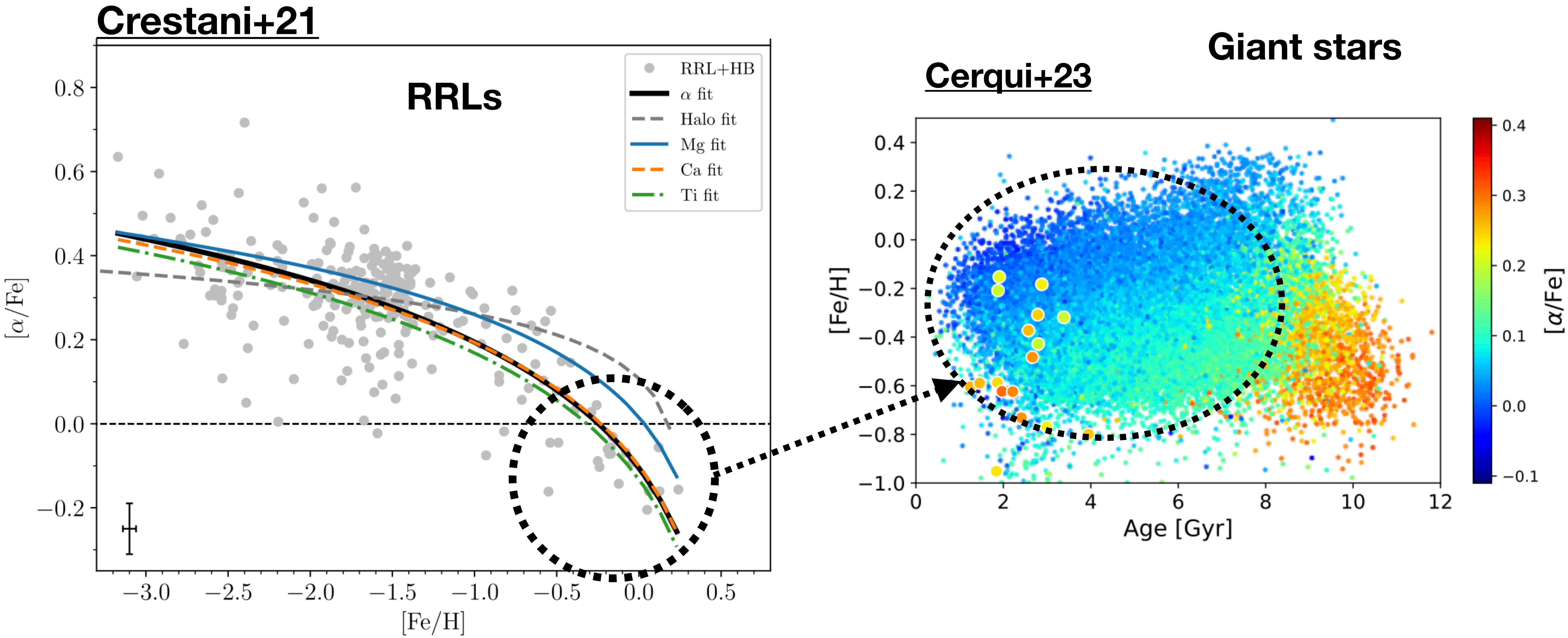
Iorio&Belokurov, 20



Everywhere:

- **Thin-disc like rotation curve**
- **Velocity dispersion typical of <10 Gyr old populations**

RRLs in the disc: properties



- **Lower alpha abundances wrt RRLs in the halo**
- **Clearly a different population wrt to the halo**
- **Typical of <10 Gyr old field populations?**

RRLs in the disc: summary

- **A Thin-disc like population of RRLs exists**
- **Properties consistent with an intermediate-young population**

RRLs in the disc: summary

- **A Thin-disc like population of RRLs exists**
- **Properties consistent with an intermediate-young population**

Mass loss is capable to produce young metal-rich RRLs (e.g. Bono+98)

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

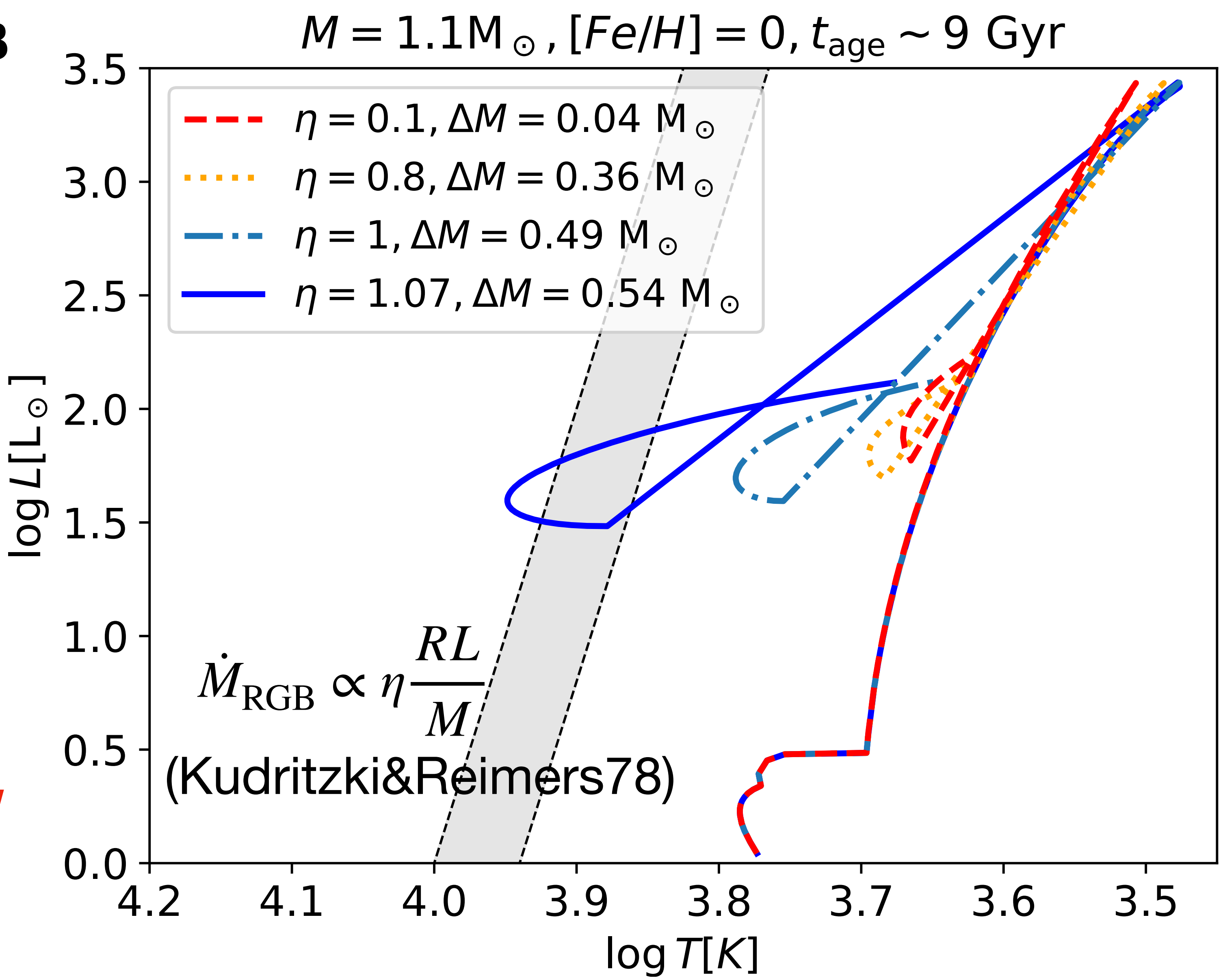
↓

Hotter core He burning stars

- **Very 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**



RRLs in the disc: alternative formation channel
Binary-made RRLs

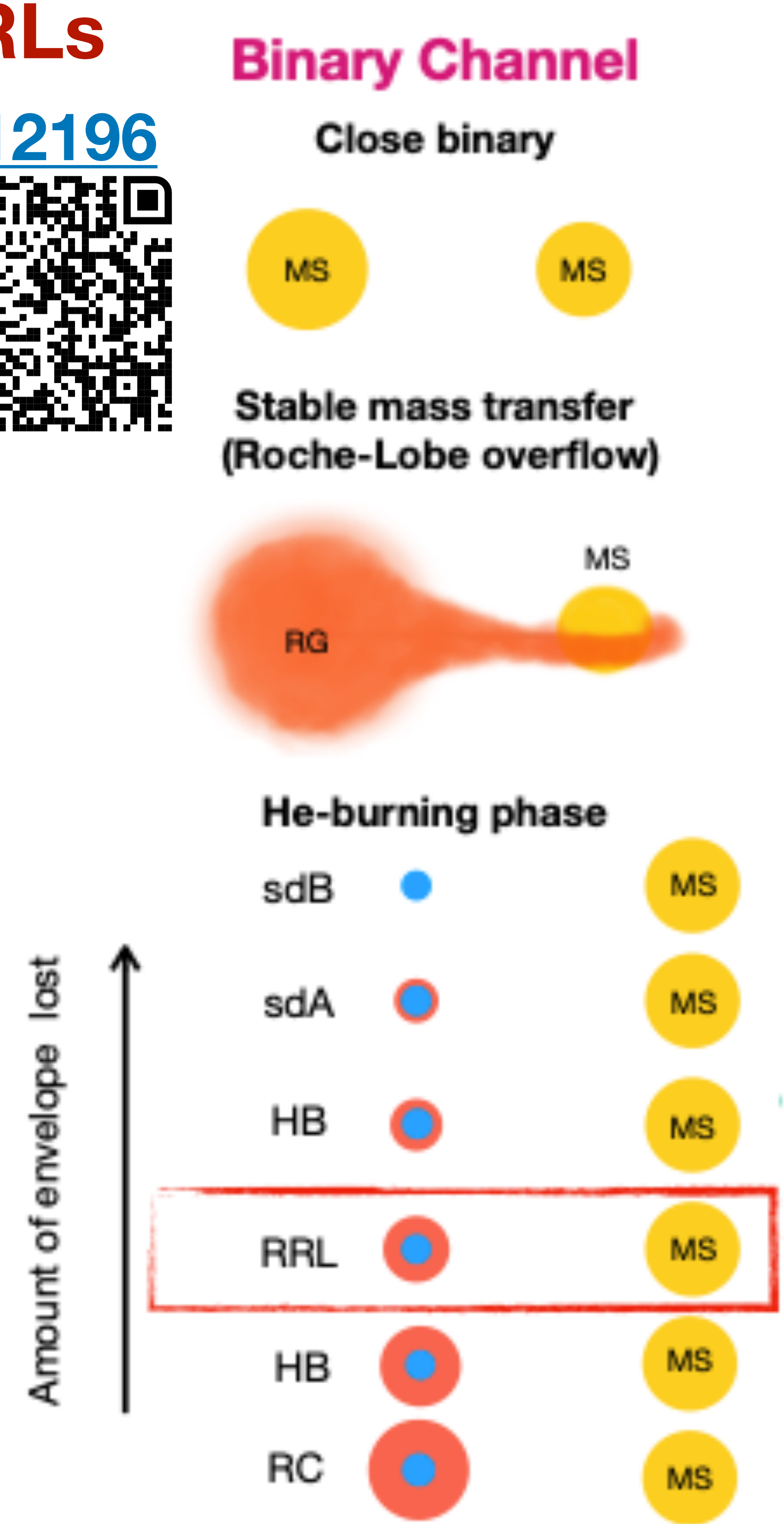
[Bobrick&Iorio et al., 2024, MNRAS, 527, 12196](#)

(Open access)

(See also Karczmarek+17)

Simulation setup (Vos+20): 2060 binaries

- **Detailed stellar evolution models by MESA (Paxton+13-19)**
- **Besançon Galactic population (Robin+03)**
  Close binary fraction 25% (Moe+19)
- Standard RLO mass transfer model
- Close binary (100<P/days<700)
- Solar like stars (0.7<M/Msun<2)



RRLs in the disc: alternative formation channel
Binary-made RRLs

Considering the Besancon model:

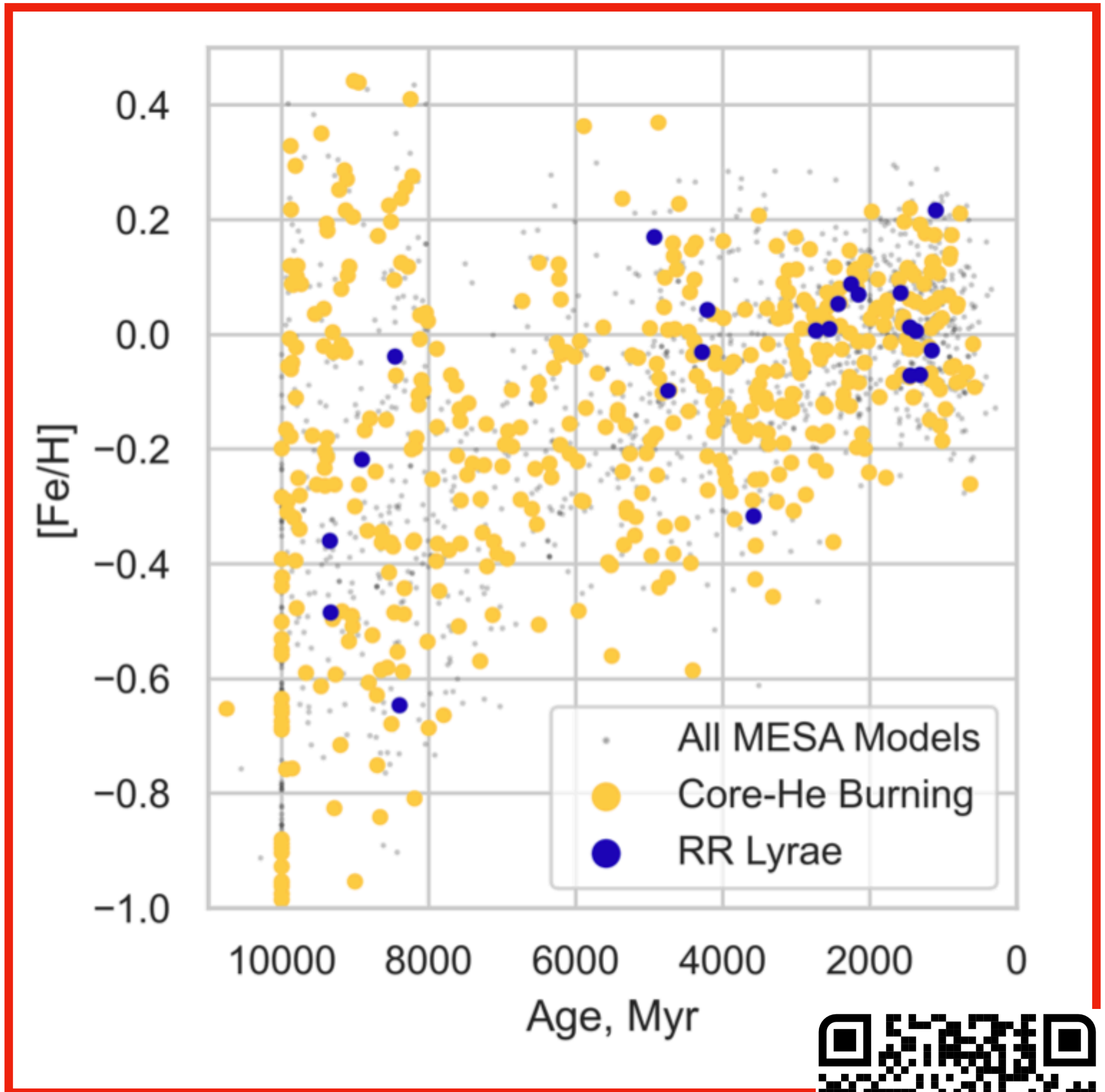
- **~ 50,000 in the Thin-Disc** (10% MW RRLs population)

- 0 in the Halo and Thick-Disc

- ~12,000 in the Bulge (but very simplified bulge model)

- **Consistent with the RRL disc population (metallicity, magnitude)**

- **Consistent with intermediate-young populations**



RRLs in the disc: alternative formation channel
Binary-made RRLs

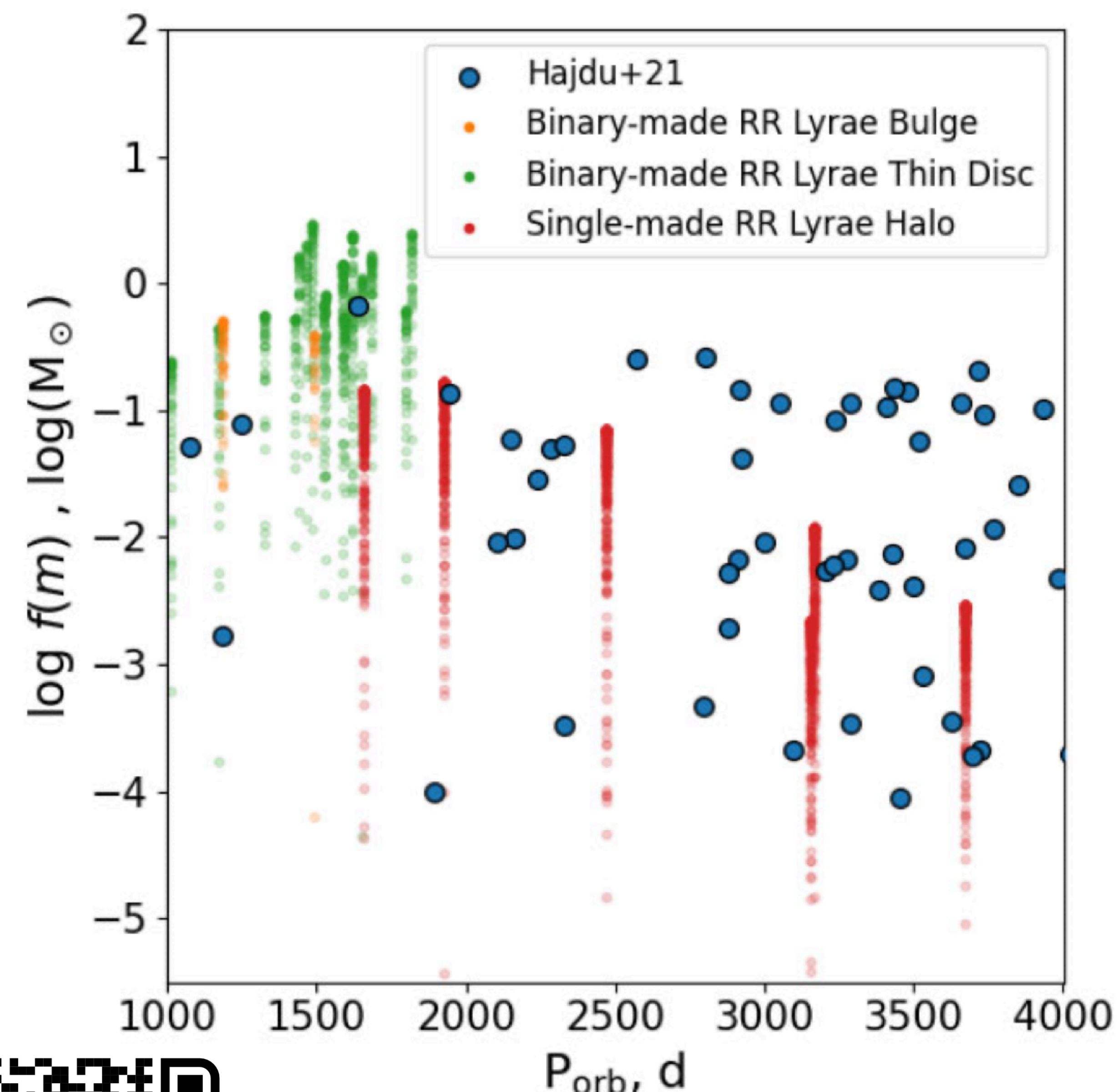
Have we seen binary RR Lyrae?

Not really

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)



But there are candidates

(e.g. Hajdu+21)

Still not enough to confirm of discard this formation channel

Mass function

$$f(m) = \frac{M_{\rm comp}^3 \sin^3 i}{M_{\rm binary}^2}$$

RRLs in the disc: why GAIA-NIR

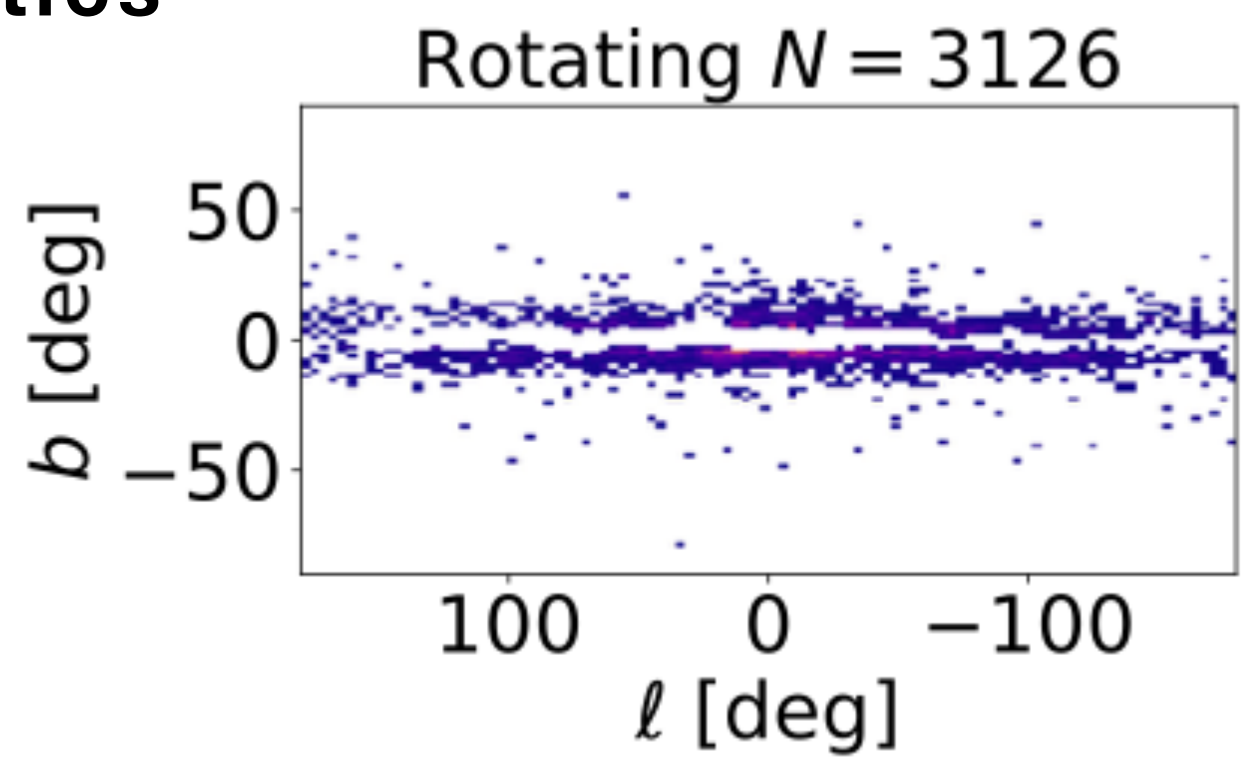
GaiaNIR can surely help in investigating the nature of RRLs in the disc

- **Increase the sample** (looks deeper in the disc)

- **Improved distance/proper motions estimates** (infrared PLZ relations, lower reddening)

- **Precise and direct kinematics estimate** (if RVs available)

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



RRLs in the disc: scientific implications

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

- Exploration of **new formation channels** (He-enrichment, rotation, revised stellar evolution)

- Cold and metal-rich old population: **challenge for MW formation models** (radial migration?)

- **No RRLs in binary? Do we need to revise mass transfer in binaries?**

RRLs in the disc: scientific implications

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

- Exploration of **new formation channels** (He-enrichment, rotation, revised stellar evolution)

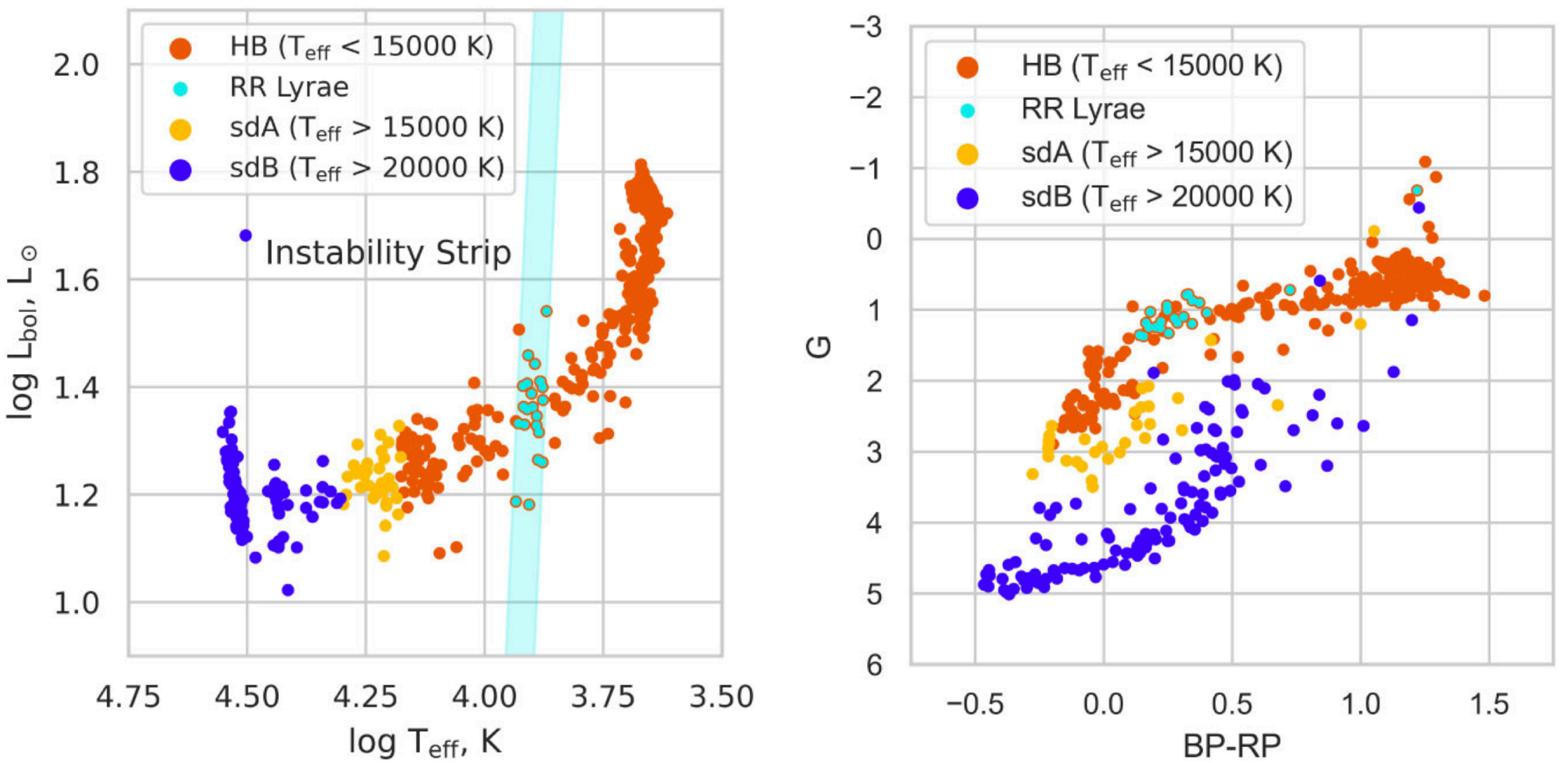
- Cold and metal-rich old population: **challenge for MW formation models** (radial migration?)

- **No RRLs in binary? Do we need to revise mass transfer in binaries?**

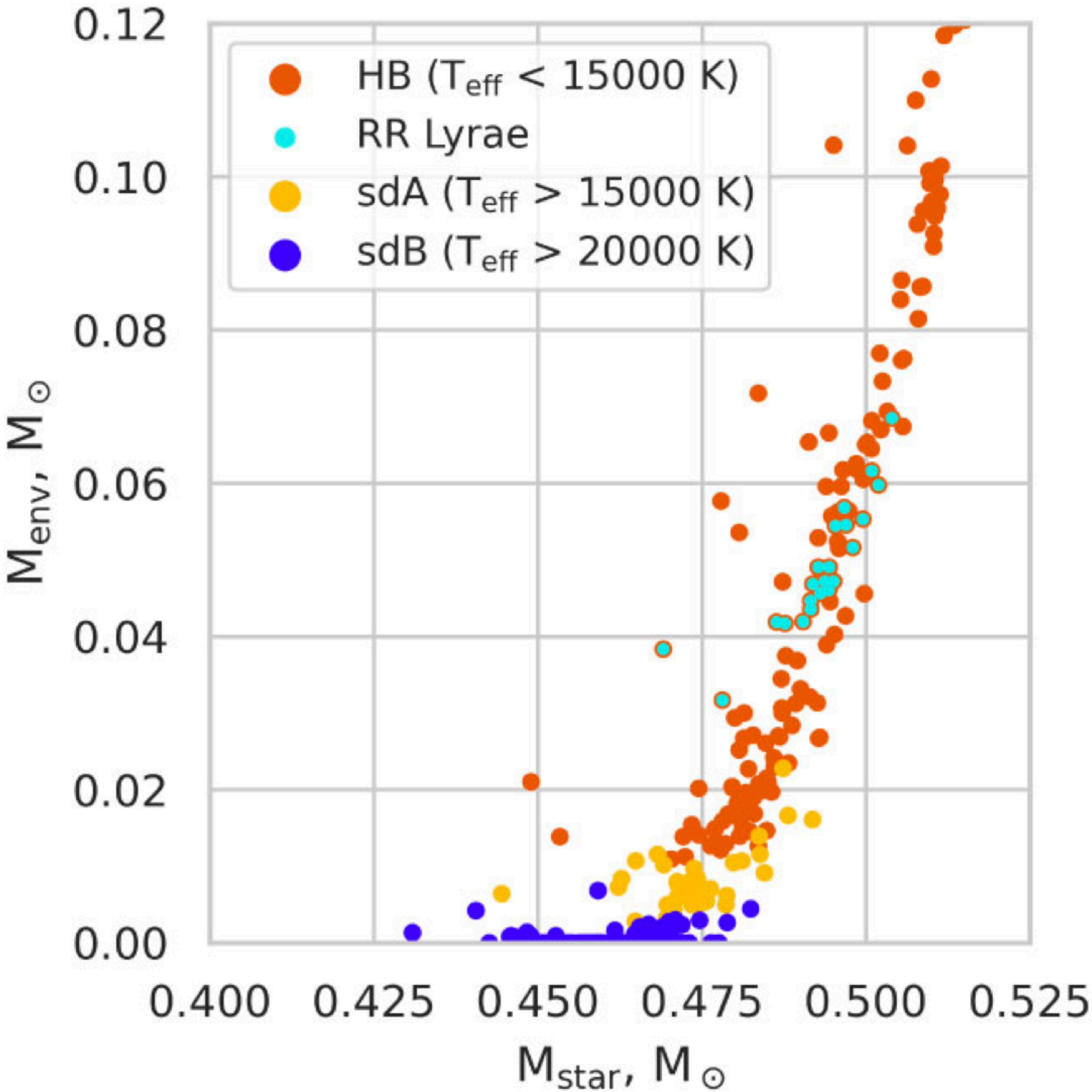
Thank You!

Backup

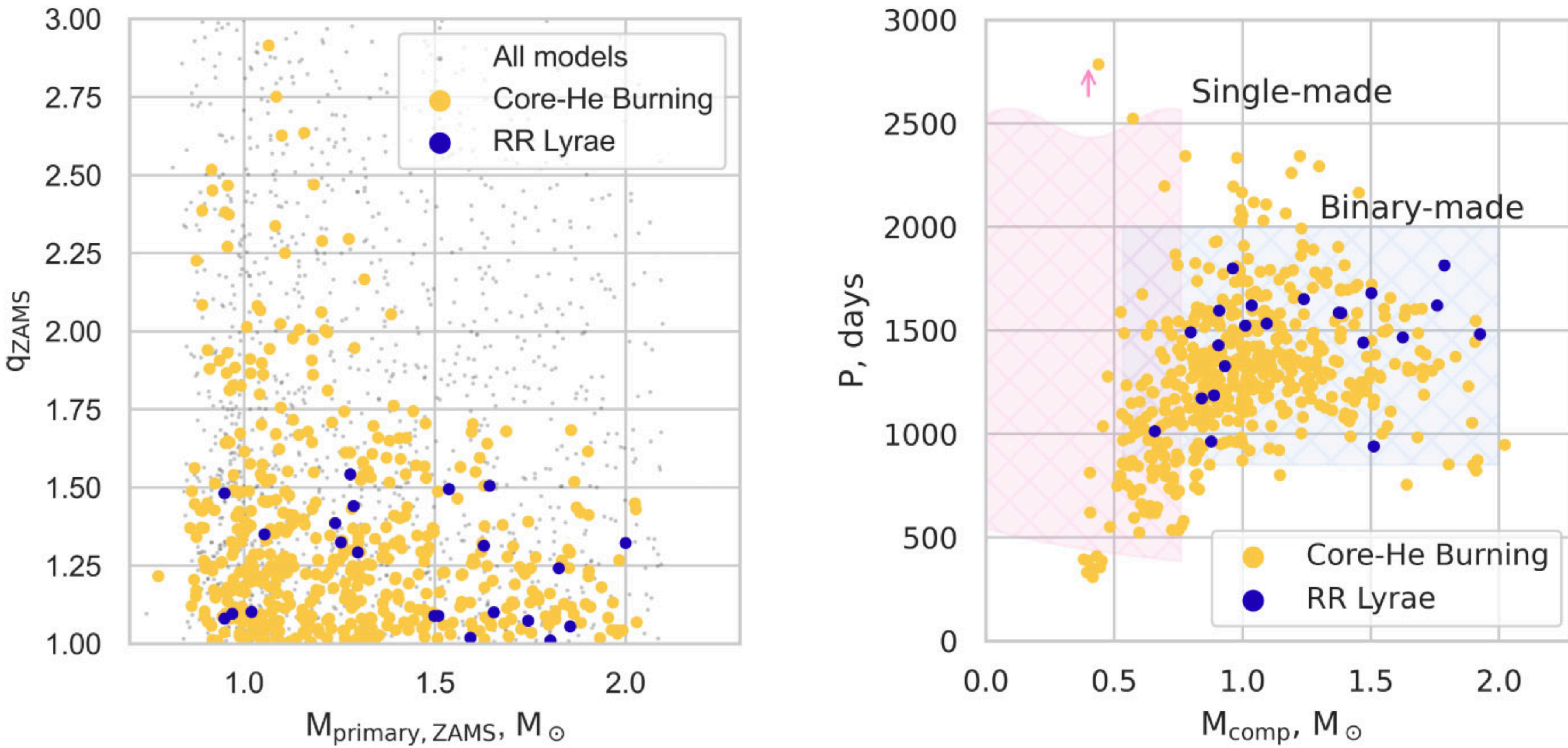
Binary made RRLs



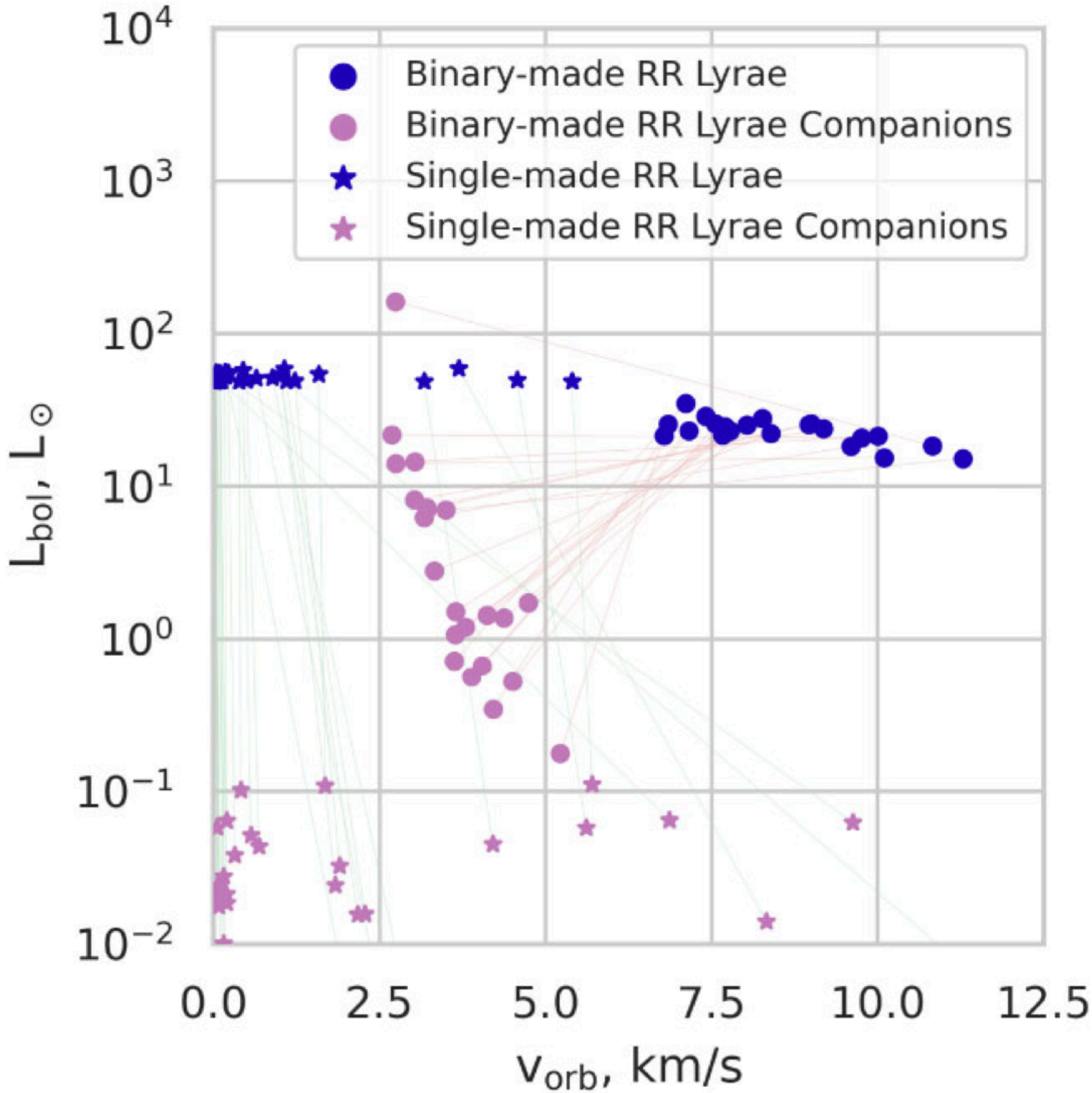
Binary made RRLs



Binary made RRLs



Binary made RRLs



Metal-rich RRLs in GCs and GCs

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

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 Msun, 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 peculiar He-enriched clusters (but see Bhardwaj+06).

- **Total mass in observable open clusters is ~1E5 Msun** (100-1000 Msun per cluster, Piskunov+08, ~1000 open clusters, Castro-Ginard+22, 10% of them older than 1 Gyr, Bossini+19)**, we expect no RRLs, consistent with the observations**

Expected single and binary made RRLs

Type	Thin disc	Thick disc	Bulge	Halo	Total
R_{tot}, kyr^{-1}	$0 : 0.51 \pm 0.11$	$0 : <0.06$	$0 : 0.13 \pm 0.09$	$9.46 \pm 1.67 : 0$	$9.46 \pm 1.67 : 0.63 \pm 0.13$
F_{tot}, $M_{\odot}^{-1}$	$0 : (1.1 \pm 0.3) \times 10^{-6}$	$0 : <1.3 \times 10^{-7}$	$0 : (8.6 \pm 6.1) \times 10^{-7}$	$(1.0 \pm 0.2) \times 10^{-3} : 0$	$(1.0 \pm 0.2) \times 10^{-3} : (1.0 \pm 0.2) \times 10^{-6}$
N_{tot}	$0 : 48\,000 \pm 11\,000$	$0 : <5300$	$0 : 10\,500 \pm 7400$	$523\,400 \pm 92500 : 0$	$523\,400 \pm 92500 : 58\,500 \pm 12500$
n_{loc}, kpc^{-3}	$0 : 43.6 \pm 9.7$	$0 : <0.9$	$0 : 0$	$9.2 \pm 1.6 : 0$	$9.2 \pm 1.6 : 43.6 \pm 9.3$
$N_{500\,pc}$	$0 : 13.2 \pm 3.0$	$0 : <0.4$	$0 : 0$	$4.8 \pm 0.8 : 0$	$4.8 \pm 0.8 : 13.2 \pm 2.8$
$N_{1\,kpc}$	$0 : 70.5 \pm 15.8$	$0 : <2.6$	$0 : 0$	$38.4 \pm 6.8 : 0$	$38.4 \pm 6.8 : 70.5 \pm 15.0$

Based on our model and simulations:

- **Binary made RRLs represents the 10% of the whole RRL population, but the 100% of the metal-rich population**
- **5-6% of binary made RRLs in the Galactic center (within 3 kpc). Consistent with the number of metal-rich RRLs in the bulge area (Savino+20, <10%).**
- **20-30% of binary made RRLs in the thin-disc area (within 3 kpc from the plane). Consistent with the number of thin-disc like metal-rich RRLs found in Iorio&Belokurov 20 (27%).**

Comparison with RRLs 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)

Low statistics, but in the sample with largest number of matches (Kervella+ 2019 a) we found a larger number of binary candidates in the metal-rich thin-disc like RR Lyrae

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	$[\mathrm{Fe/H}] \propto \mathcal{N}([\mathrm{Fe/H}]_i, \sigma_{[\mathrm{Fe/H}],i})$	—	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	$\dot{M}_{\mathrm{accretor}} = (1-\alpha-\beta-\delta)\lvert\dot{M}_{\mathrm{lost}}\rvert\dagger$	$\begin{cases} \beta = 1 \text{ if over-spinning or } \tau_{\mathrm{acc}} < \tau_{\mathrm{K-H}} \\ \beta = 0 \text{ otherwise} \\ \alpha = \gamma = \delta = 0 \text{ always} \end{cases}$	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)

For the purpose of this work, we define the instability strip boundaries following Karczmarek et al. (2017):

$$\log\left(\frac{T_{\mathrm{red}}}{\mathrm{K}}\right) = -0.05\log\left(\frac{L}{\mathrm{L}_\odot}\right) + 3.94$$

$$\log\left(\frac{T_{\mathrm{blue}}}{\mathrm{K}}\right) = -0.05\log\left(\frac{L}{\mathrm{L}_\odot}\right) + 4.00. \qquad (1)$$

Besançon 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

Binary-made RR Lyrae: comparison with Karczamarek+17

Their conclusion:

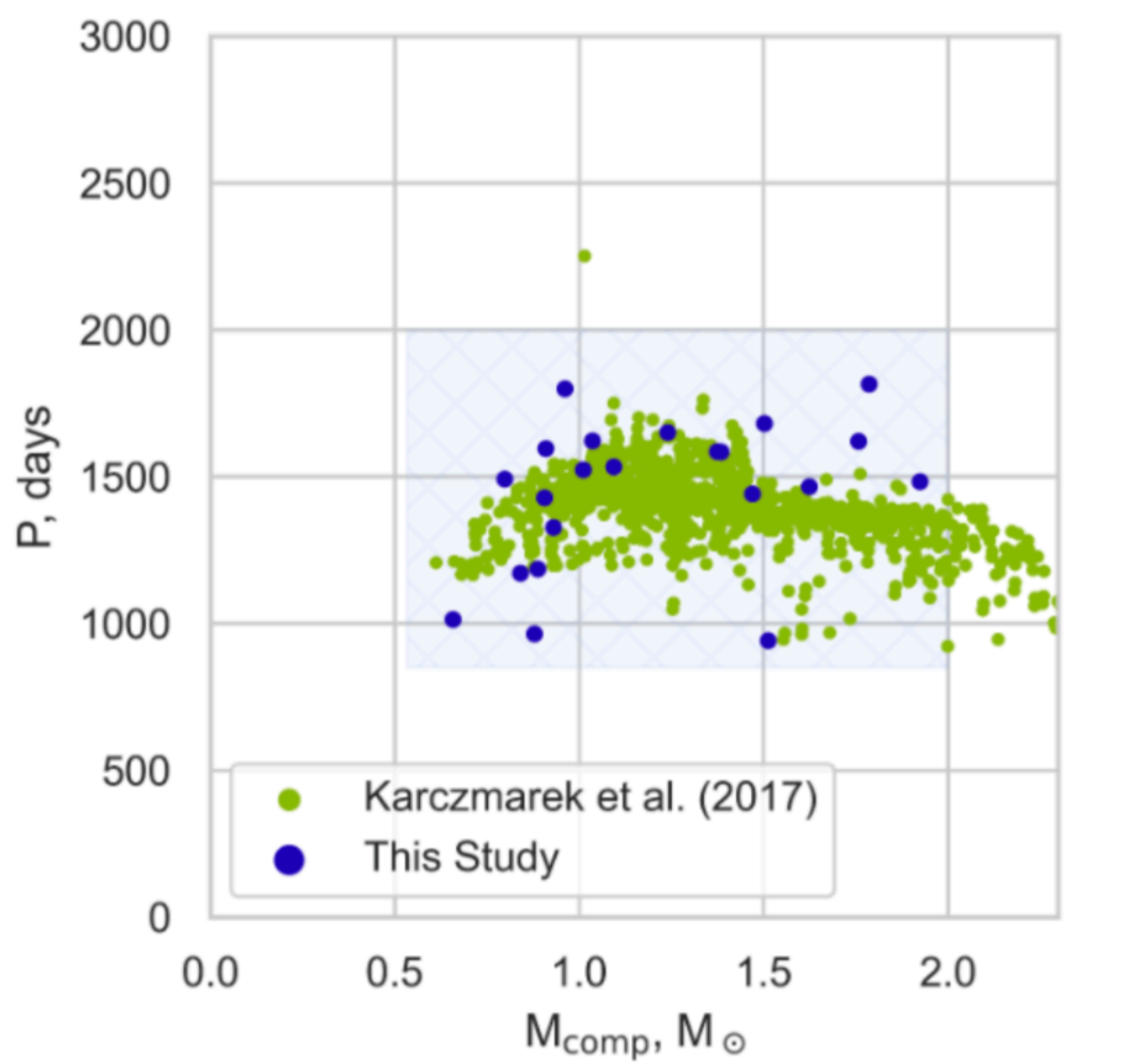
Only 0.8% of RR Lyrae are binary made

However:

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

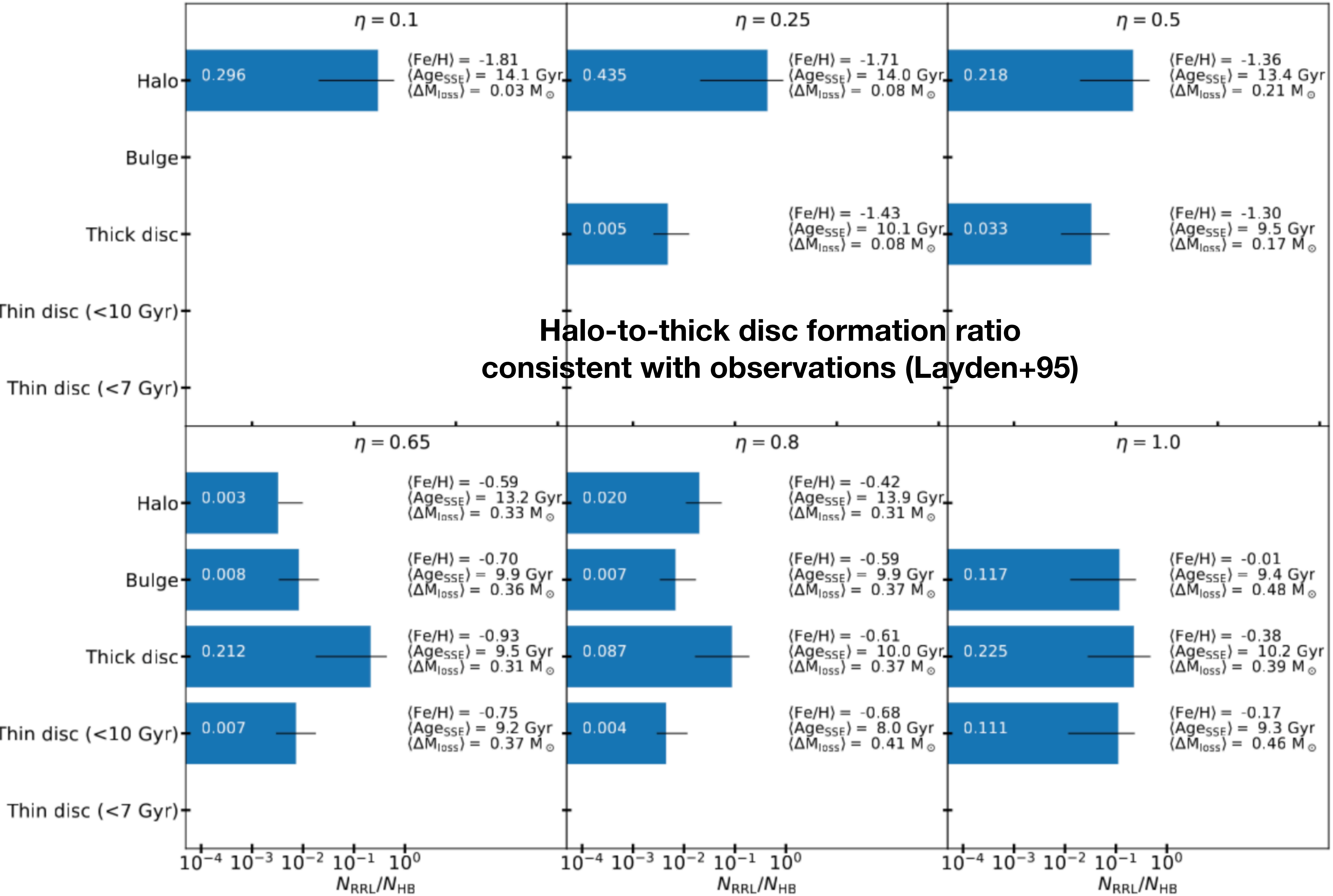
Correcting for the effect of metallicity:

- Their and our results agree within 30%



Wind mass loss: varying eta

N_RRL/N core He burning stars



Halo-to-thick disc formation ratio consistent with observations (Layden+95)

Wind mass loss: observations