Young(?) and (Metal)-Rich: The Puzzling RR Lyrae Stars in the Galactic Disk

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About me…

PhD: 2018 — 2019 — 10/2024

Expertise & Interests: Dynamics and kinematics of galaxies, Galactic archaeology, stellar and binary evolution, astrophysical interpretation of GW

GaiaUB group

Transients group
(PI. Nadia Blagorodnova)

Virgo group

Stellar dynamics group
Mark Gieles
Sara Rastello

Collaborations @ ICCUB

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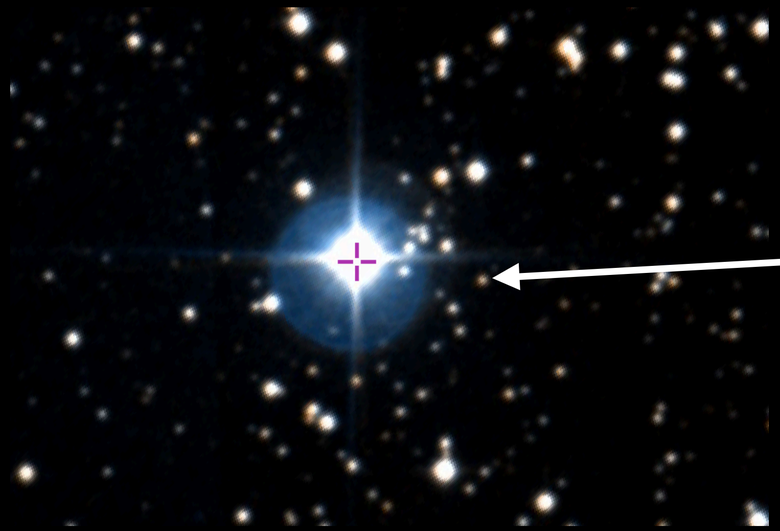
Main Project:

Fundación "la Caixa"

Formation channels and characterisation of metal-rich RR Lyrae stars

The RR Lyrae stars



RR Lyrae

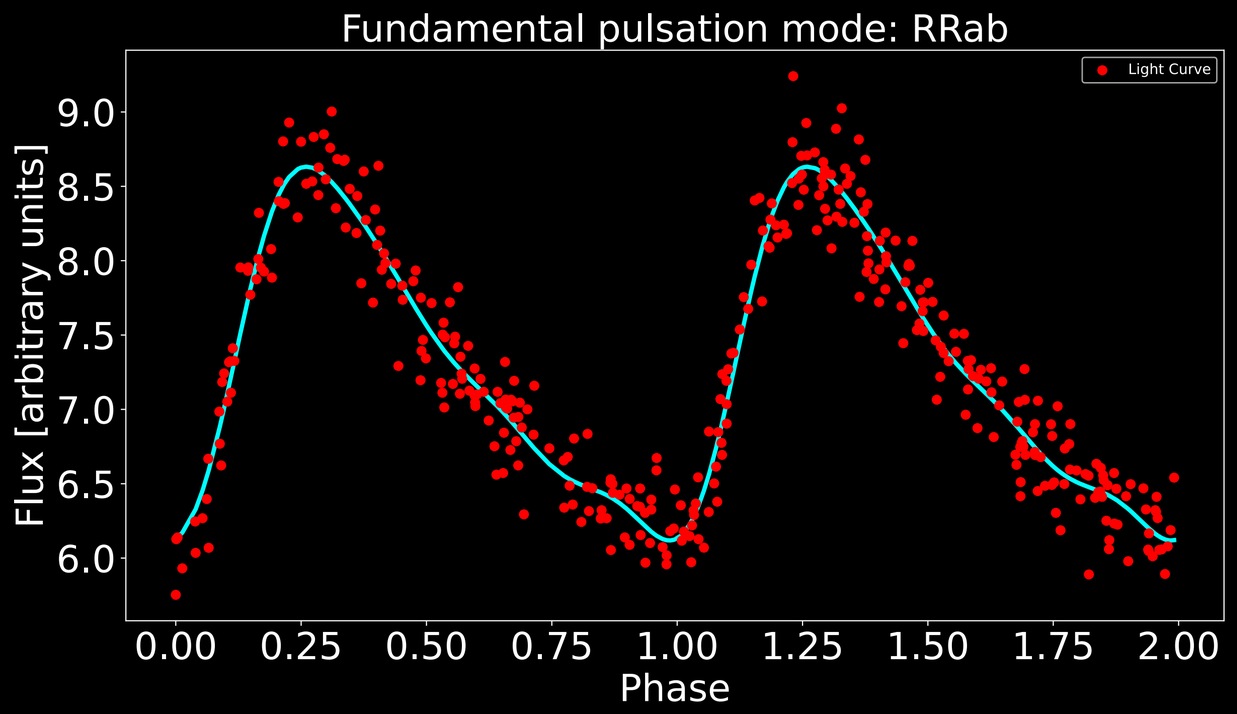
Discovered by Williamina Fleming (1901)

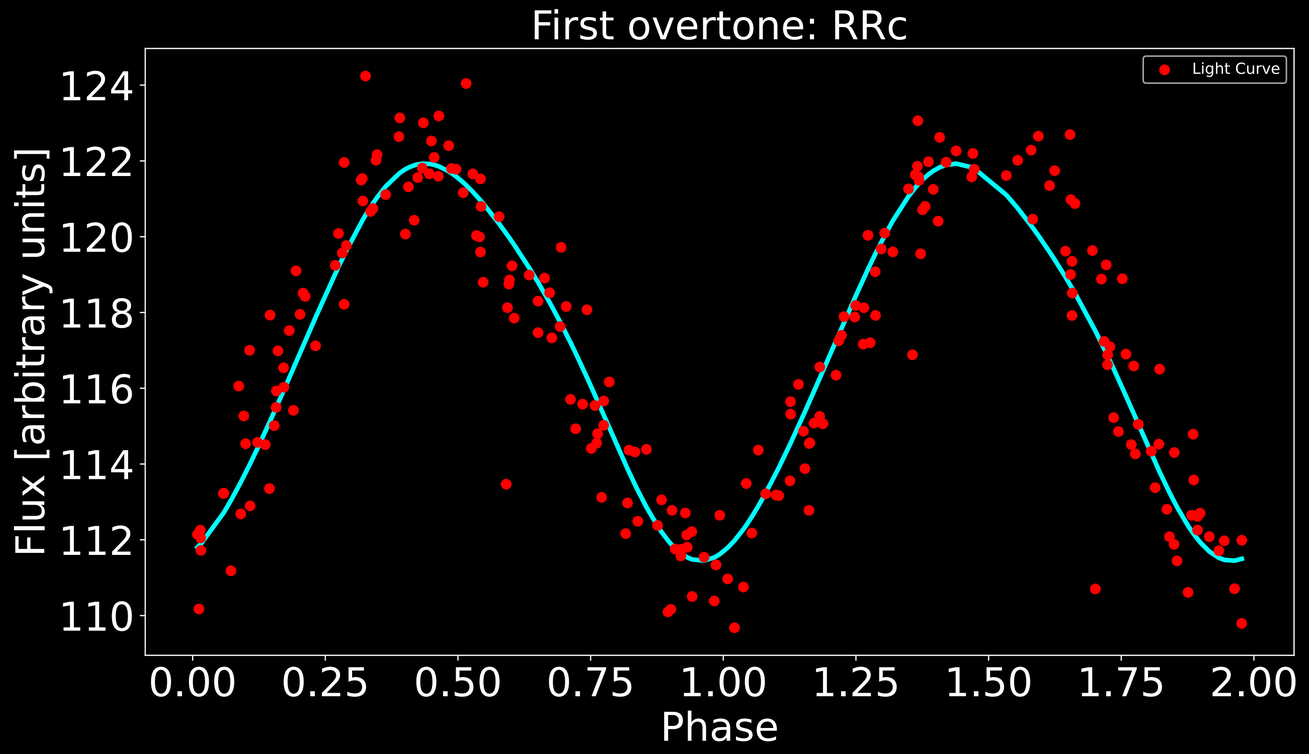
The star’s luminosity varies regularly with a period of 0.5 days

Vega

Lyra constellation

The RR Lyrae stars

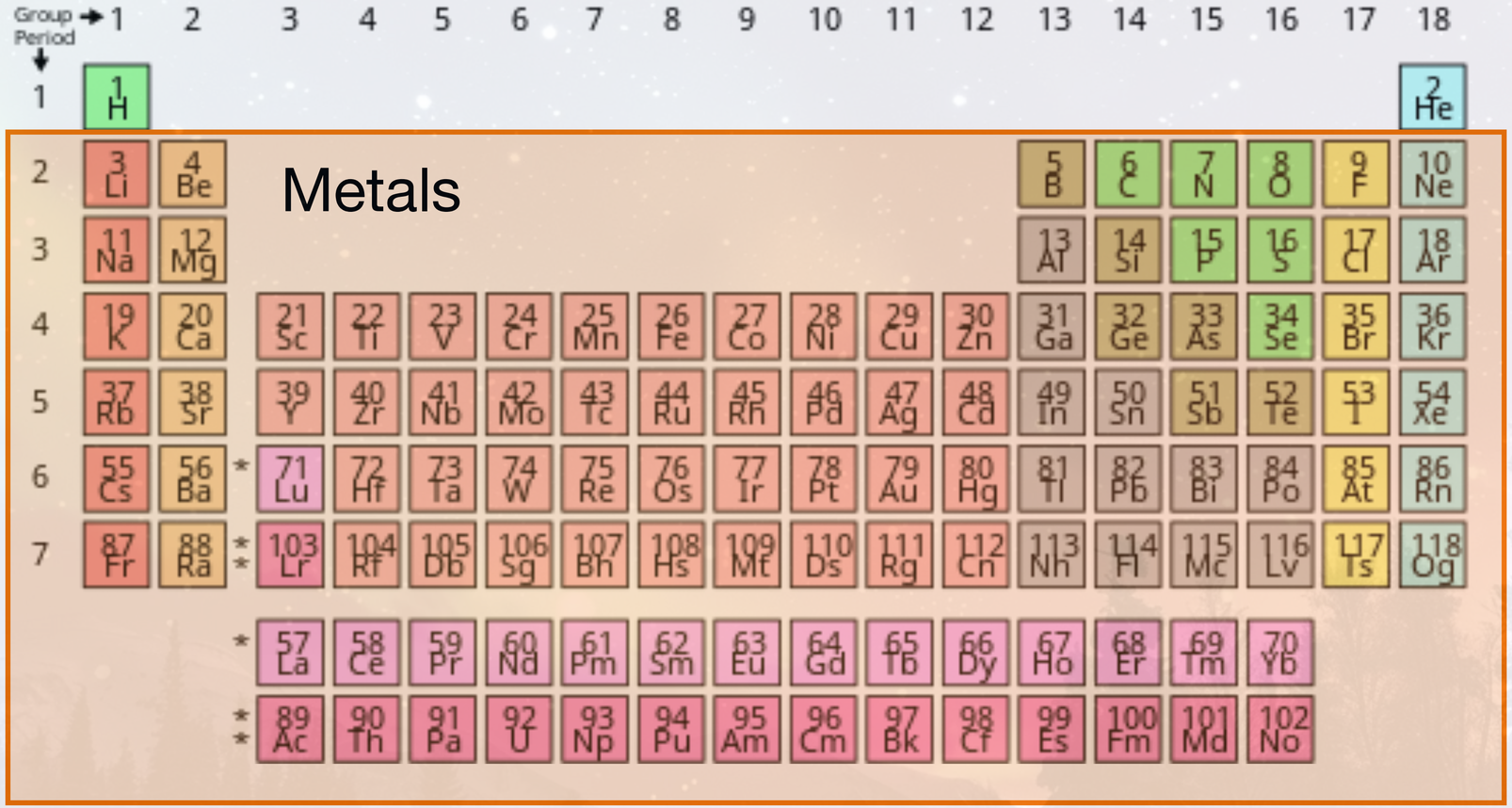




- **Short period variables: 0.2 -1 day**
- **Radial pulsators**
- **<u>Period-Luminosity-Metallicity relations</u>**

Interlude: Metallicity in Astrophysics

Metals in astrophysics: all the elements heavier than He



Metallicity proxy in stars:

$$[\mathrm{Fe/H}] = \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{\mathrm{star}} - \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{\mathrm{Sun}}$$

$[\mathrm{Fe/H}] = 0$ Sun-like

$[\mathrm{Fe/H}] < -1$ Metal poor

$[\mathrm{Fe/H}] > -0.5$ Metal rich

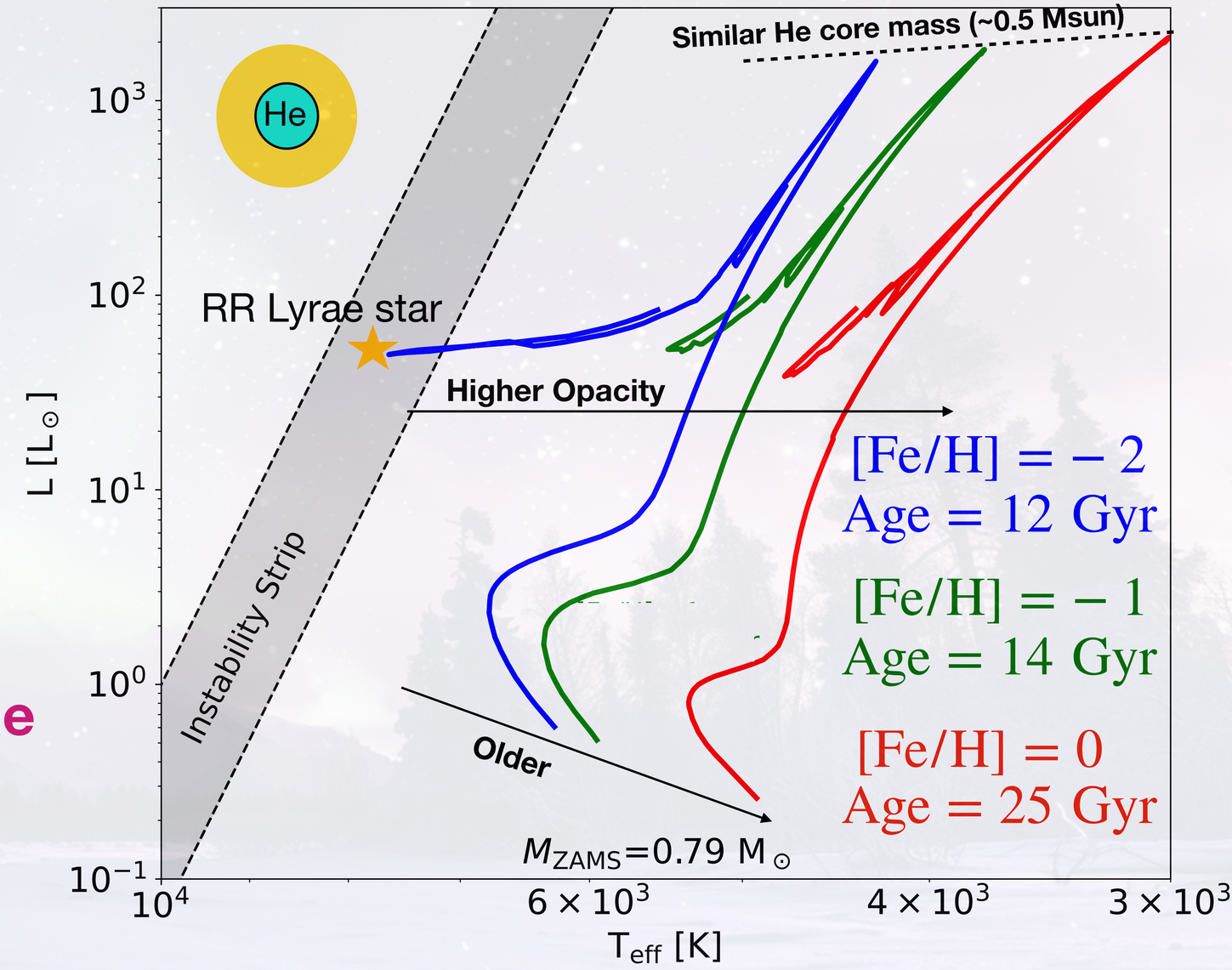
The “Classical” textbook definition

(e.g. Catelan09, Smith04)

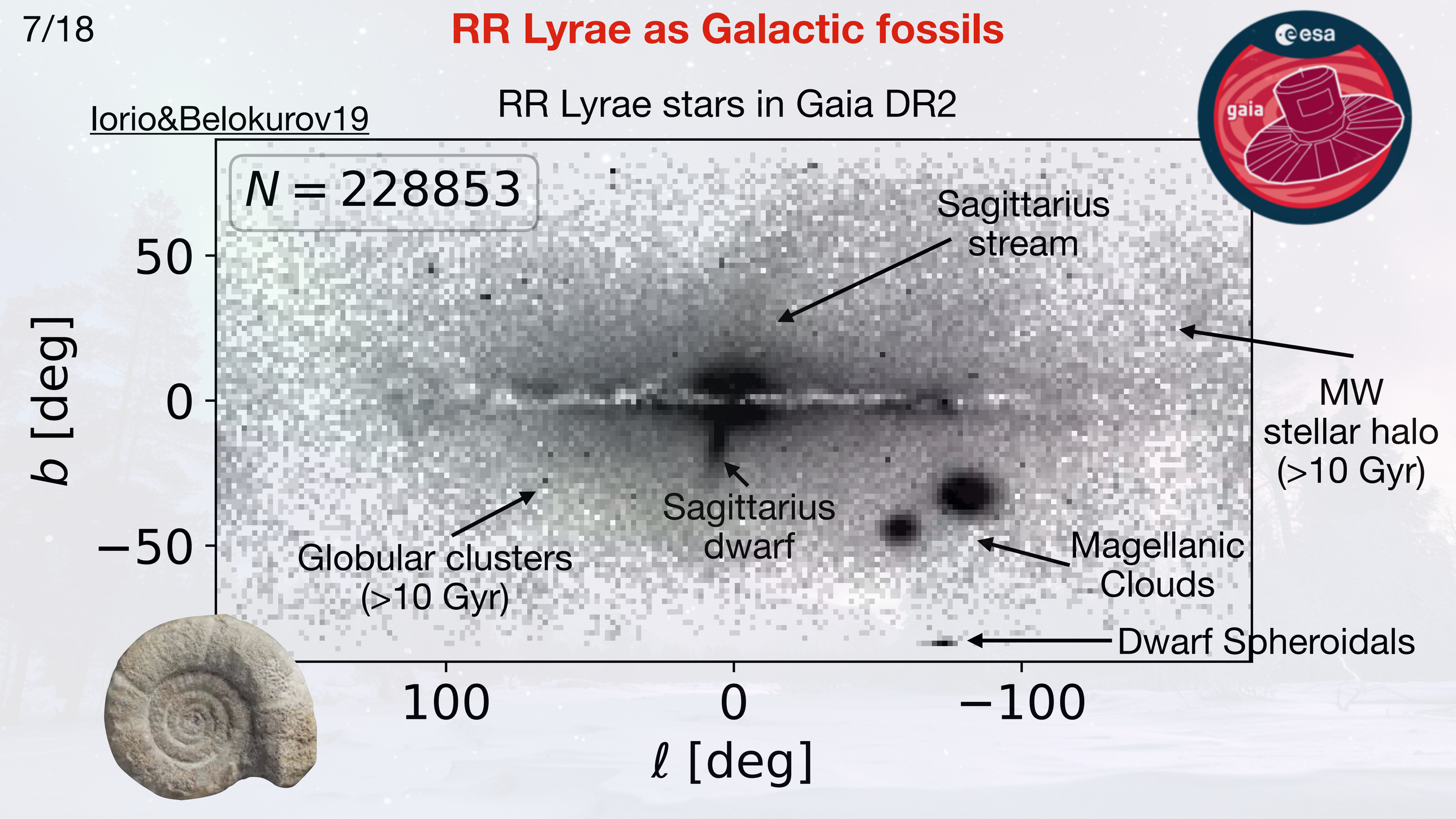
Core Helium burning star

- **Low-mass** (<1 Msun)
- **Old** (>10 Gyr)
- **metal-poor** ([Fe/H]<-1)

- **Tracers of old populations** (Halo, Globular clusters, Streams)
- **Metal-rich and/or young RR Lyrae stars should not exist**

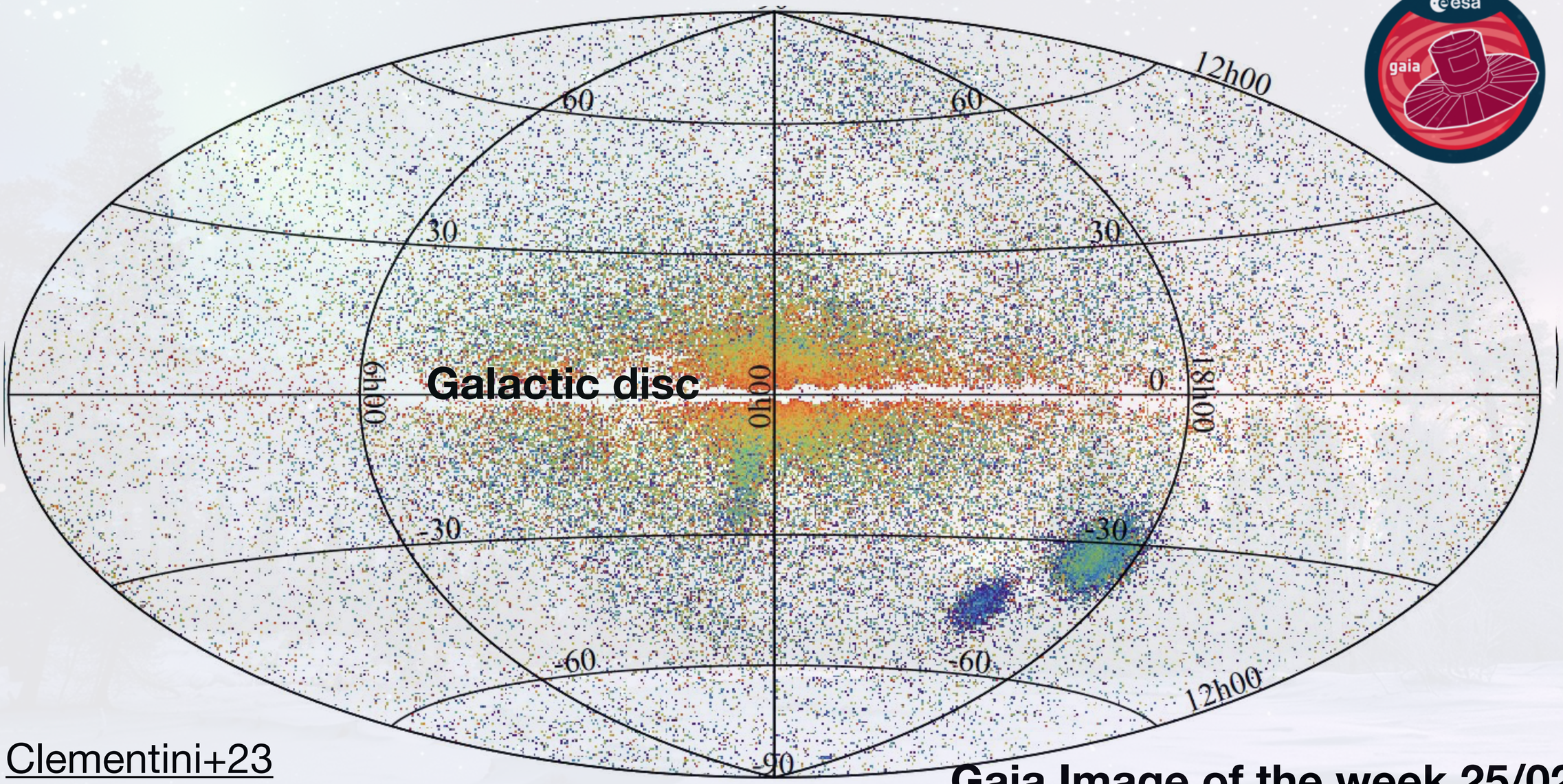


RR Lyrae as Galactic fossils



SURPRISE!

Metal-rich (up to solar) RR Lyrae stars exist all over the Galactic disc



Clementini+23

Gaia Image of the week 25/02/2022

Metal-rich RR Lyrae in the Galactic disc

- **Thin-disc like spatial distribution**

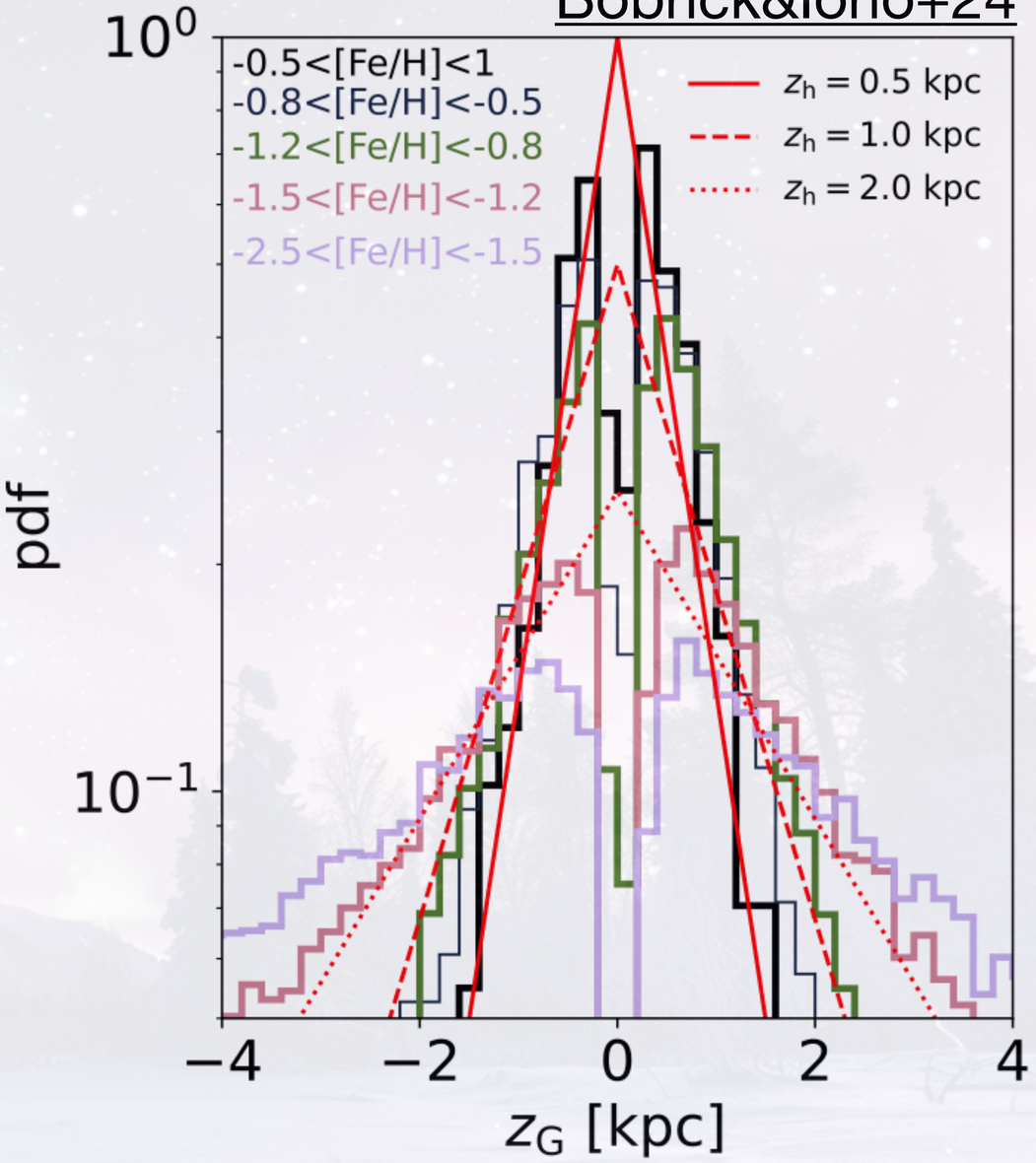
$$h_z < 500 \text{ pc}$$

(Ages of typical stars in the thin disc < 10 Gys)
Yesterday Matthew's talk

- **Follows the disc structures as the intermediate-young populations (<5 Gyrs)**

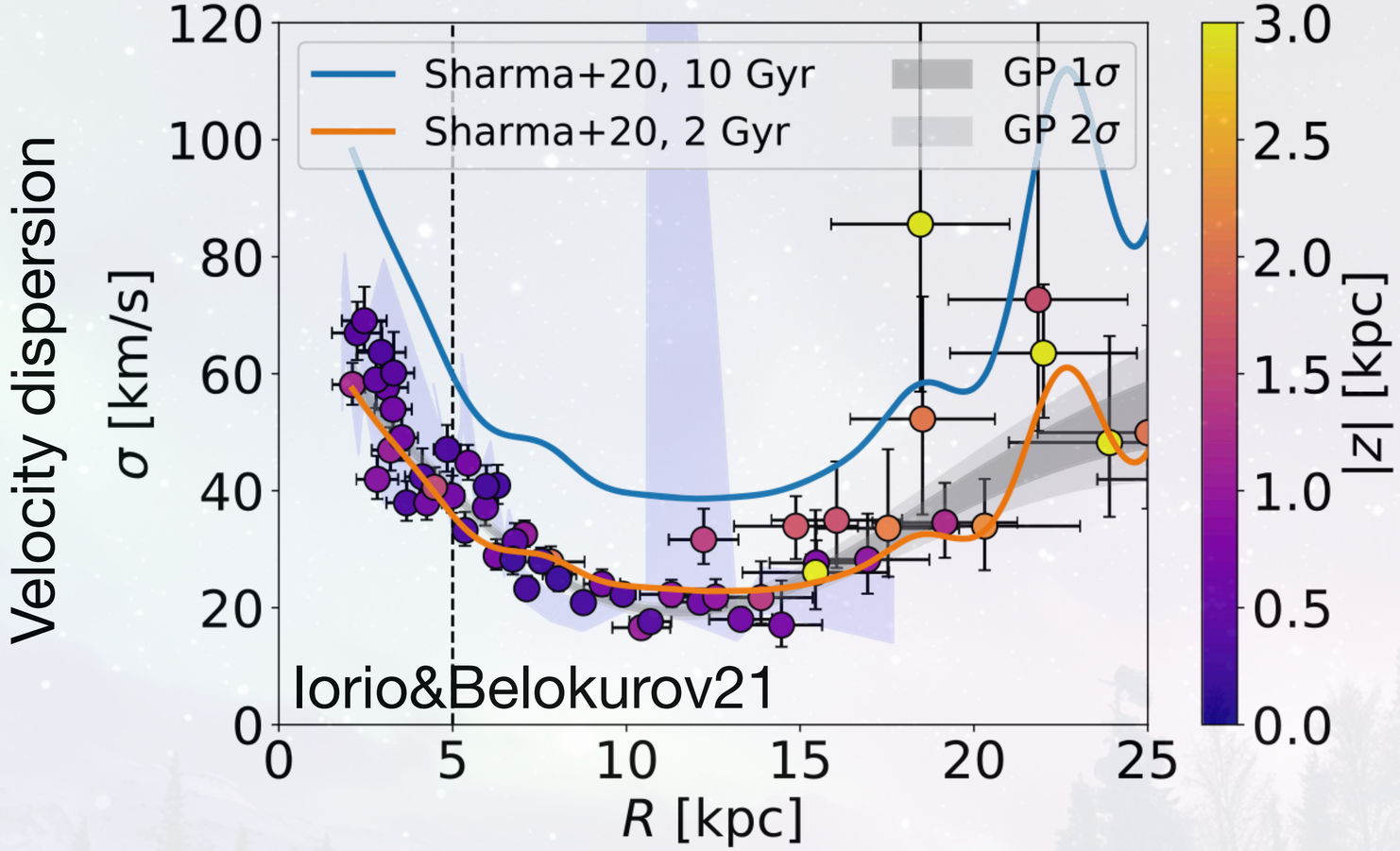
  Cabrera-Gadea+24

Bobrick&Iorio+24



They "share" a similar spatial distribution with intermediate-young disc stars.

Metal-rich RR Lyrae in the Galactic disc



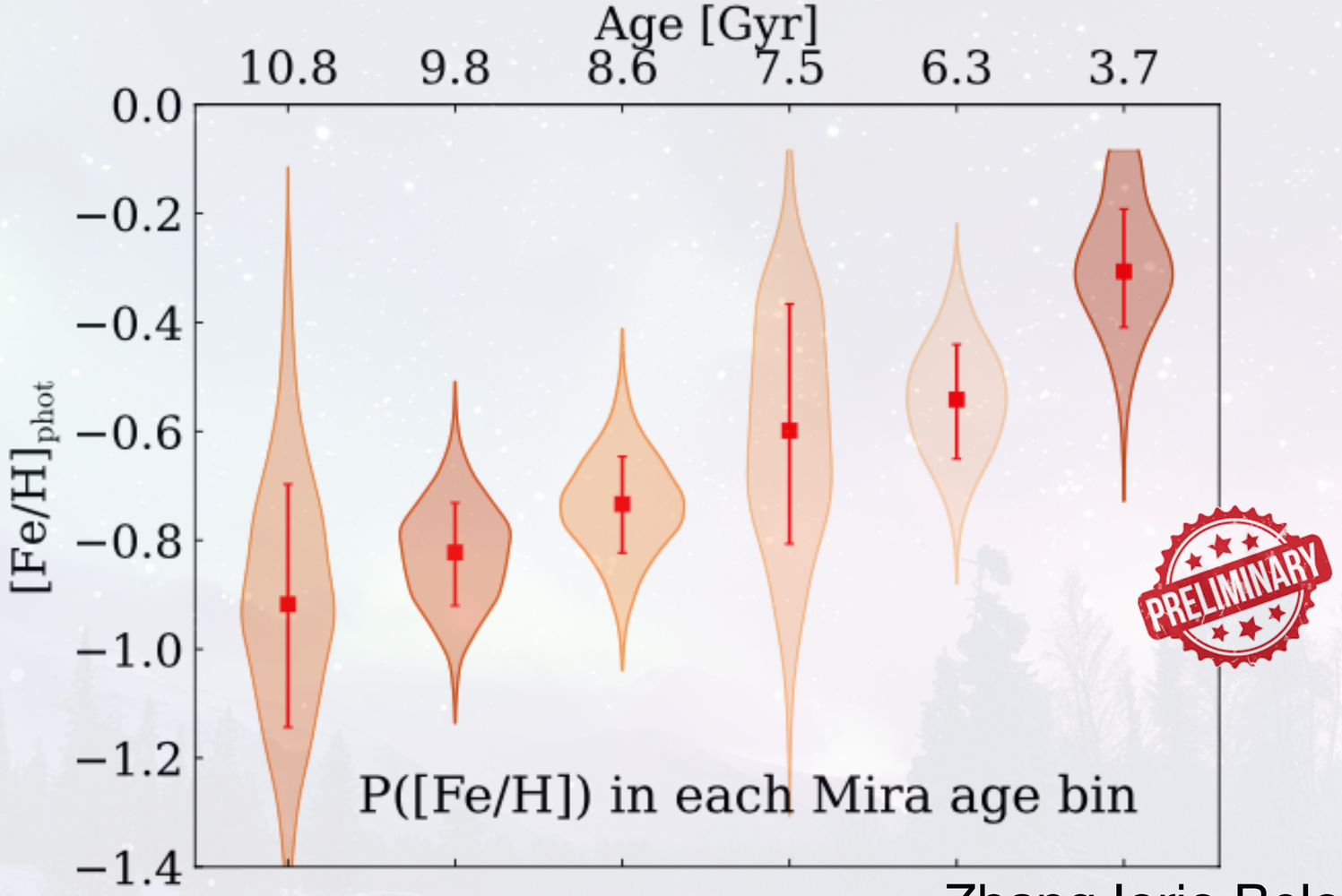
Rotations and dispersion consistent with young-intermediate populations

(also Zinn+20, Prudil+20)

They “move” similarly to intermediate-young disc populations

Metal-rich RR Lyrae in the Galactic disc

Comparing Phase space distribution RR Lyrae with stars in the disc with known ages:

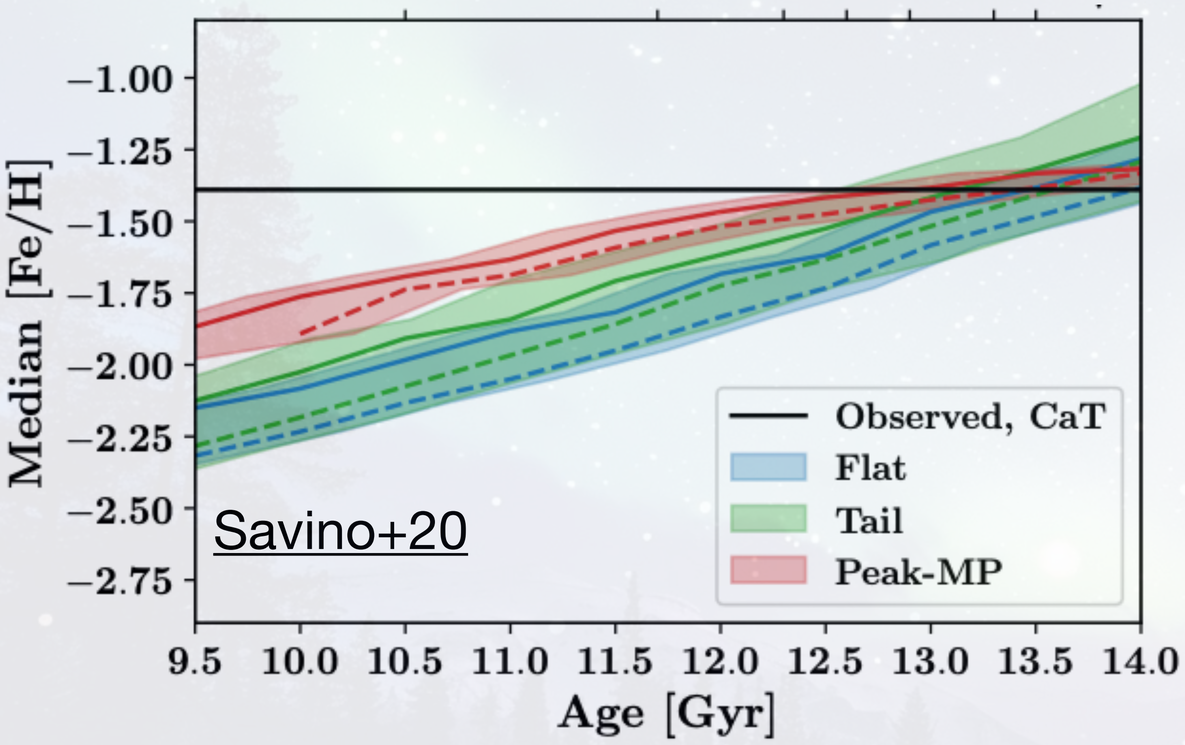


Zhang,Iorio,Belokurov in prep.

Age-metallicity trend opposite to the theoretical prediction!

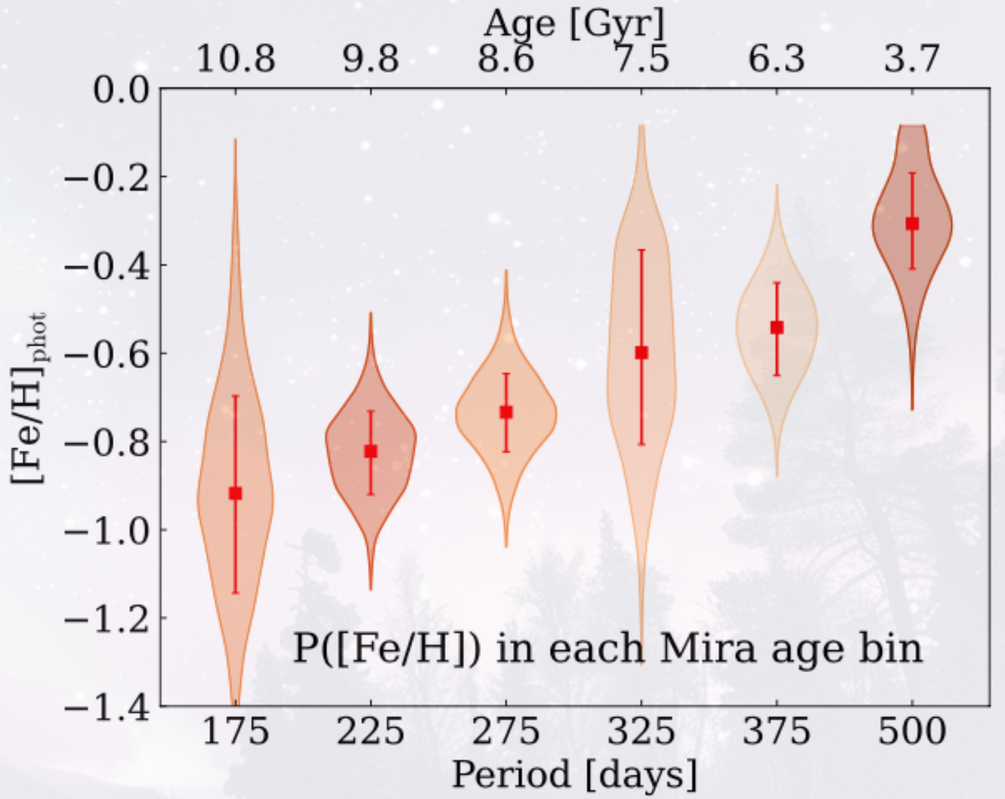
A Mystery of Galactic proportion

Theory



- **Higher** the metallicity, **older** the RR Lyrae
- Metal-rich RR Lyrae should not exist

Evidences



- **Higher** the metallicity, **younger** the RR Lyrae
- Metal-rich RR Lyrae up to Solar metallicities

A Mystery of Galactic proportion

What are the astrophysical implications?

Are they young?

- **Paradigm shift:** RR Lyrae may also trace intermediate-young populations
- **Impact on stellar evolution:** revision or new formation channel(s) needed

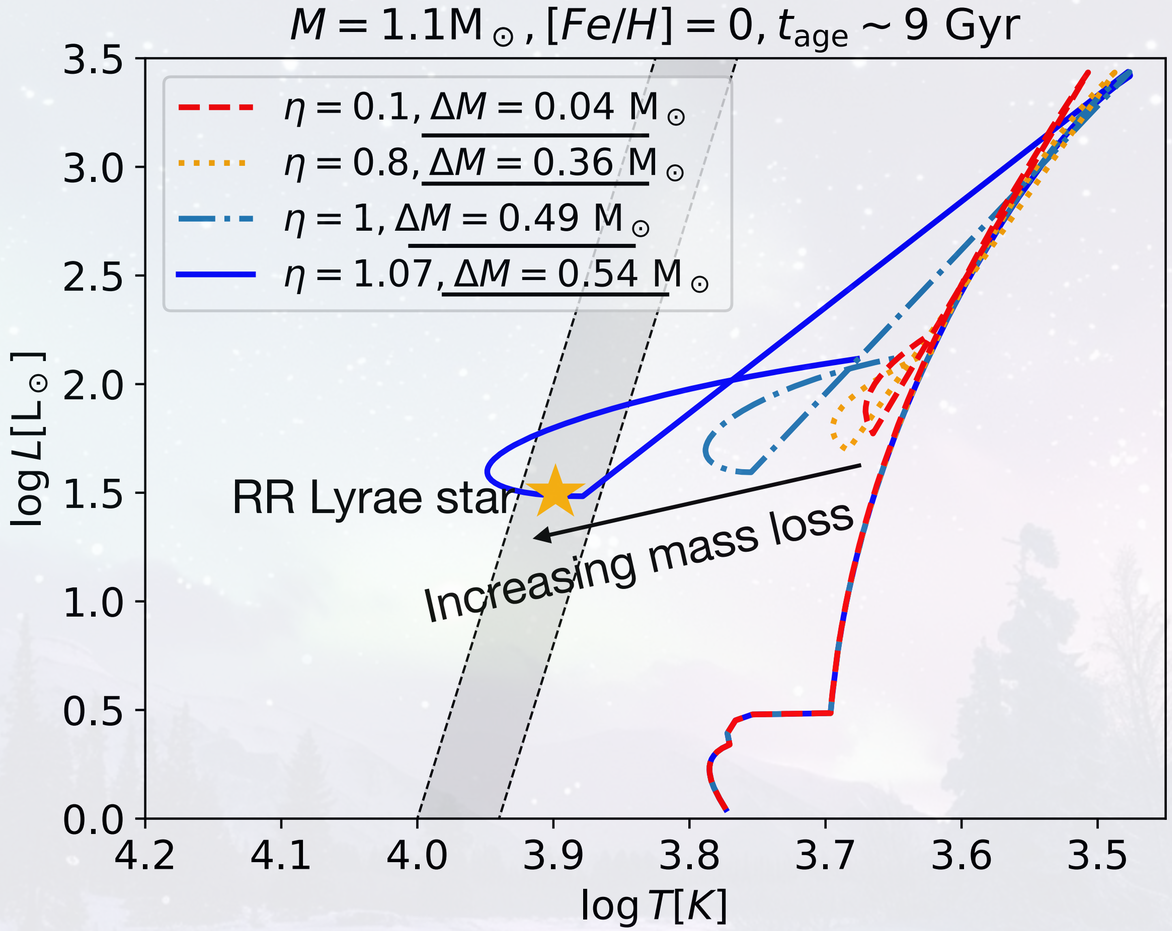
Are they old?

- **Challenge for models of Milky Way formation and evolution:**
  - Why do they resemble younger populations?

I focus on exploring alternative formation channels

Recipes to produce a metal-rich RR Lyrae star

Metal-rich RR Lyrae require less massive envelopes to balance higher opacity (see e.g. Bono+98).



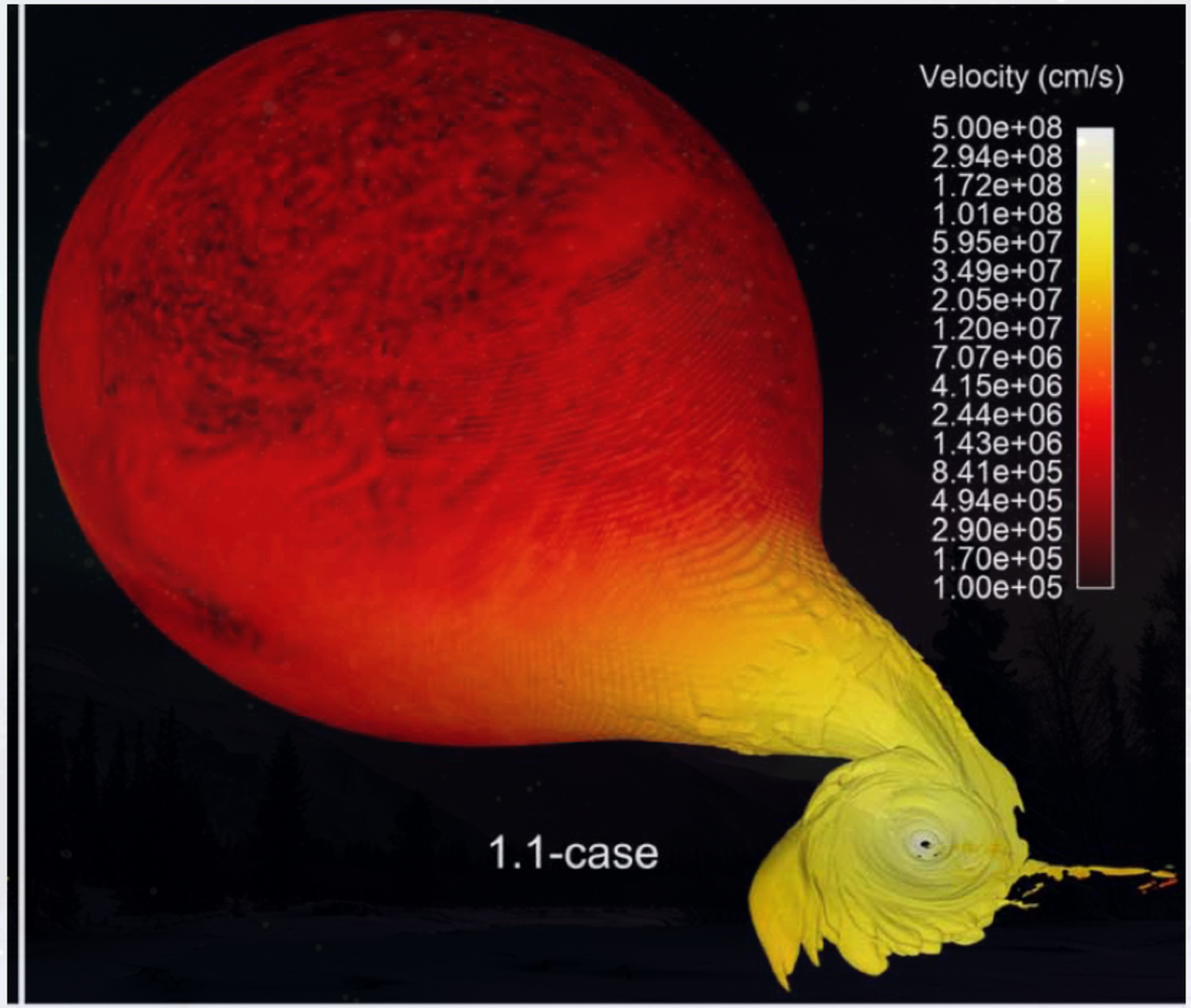
Stars lose mass through **stellar winds**, but..

Required mass-loss through winds is not supported by observations

(<0.3 Msun, see e.g. Salaris+13, Origlia+14, Savino+19, Tailo+22)

Alternative formation channel: binary mass transfer

~20-50% of low-mass stars are in a Binary (Offner+22, Moe+19)



Dickson24

Mass-transfer in binary much more efficient than Stellar Winds

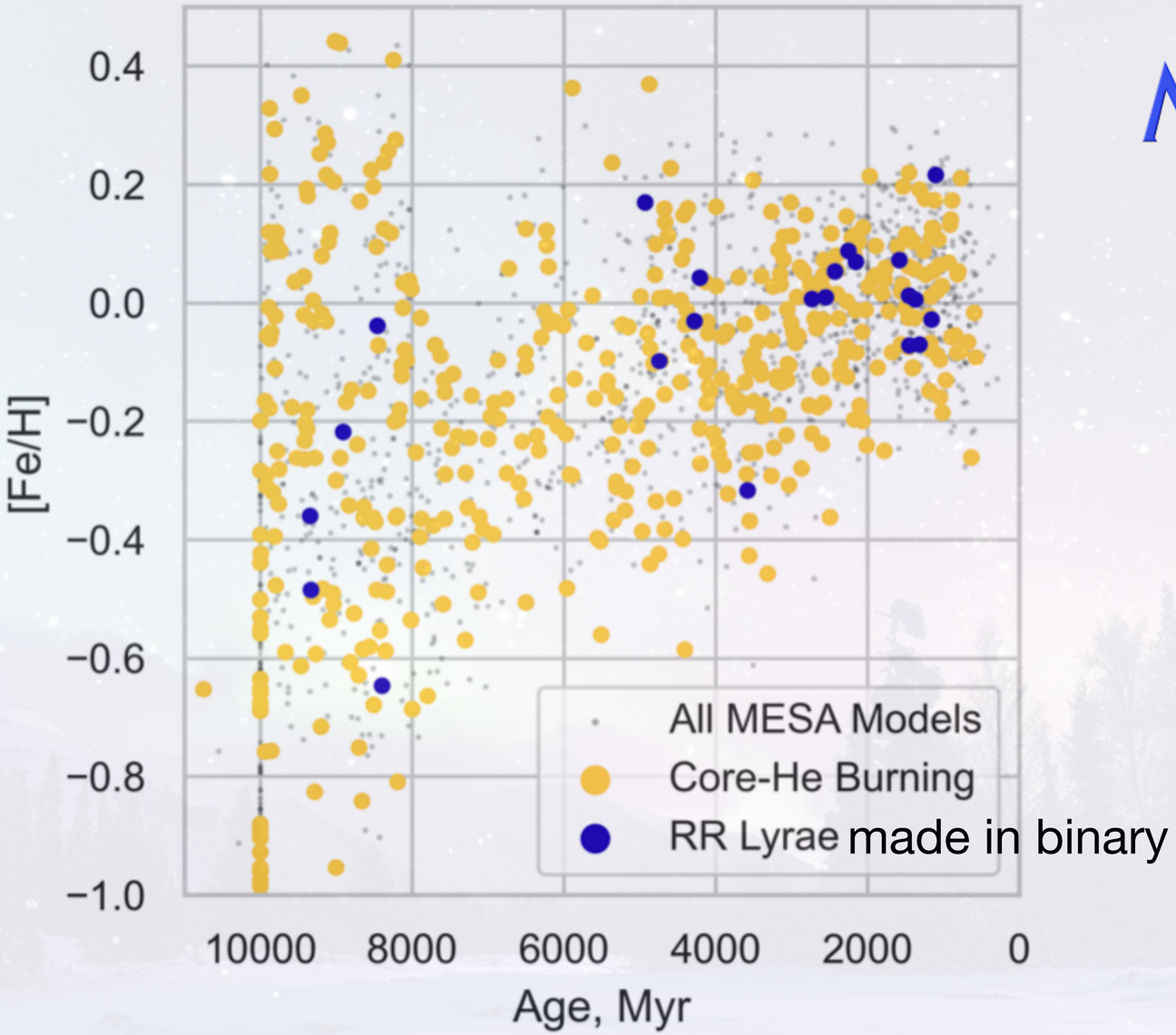
Alternative formation channel: binary mass transfer

Bobrick&Iorio+24

Binary stellar evolution simulations

+

Galactic population models



MESA

Paxton+19

Initial investigations indicate a good match with data

(Bobrick&Iorio+24, Karczmarek+17), but evidence of RR Lyrae in binary is still lacking.

A Mystery of Galactic proportion

What are the astrophysical implication?

RR Lyrae from binary evolution is a prediction

Are they young?

- **Paradigma shift:** RR Lyrae are also tracers of intermediate-young populations
- **Impact on stellar evolution:** Exploration of new formation channels required
- **Impact on binary evolution:** Probes for studying the mass transfer

Are they old?

- **Challenge for MW formation models and evolution:**
  - why are they similar to the younger populations?
- **Impact on binary evolution:** should we revise our models?

Conclusions

- Metal-rich RR Lyrae in the Galactic disc represent an intriguing populations that **challenges current models of stellar evolution**

- **Their existence and formation channels have many implications** on stellar and binary evolution theories and on the formation and evolution of our Galaxy

- **Binary formation channel is a promising solution**, but direct observational evidence is still lacking

My project

- Investigate the formation channels through **stellar and binary evolution simulations** covering a wide parameter space

- **Improve the characterisation of this population** by using current and forthcoming datasets and state-of-the-art machine learning methods

Recipes to produce a young metal-rich RR Lyrae

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)

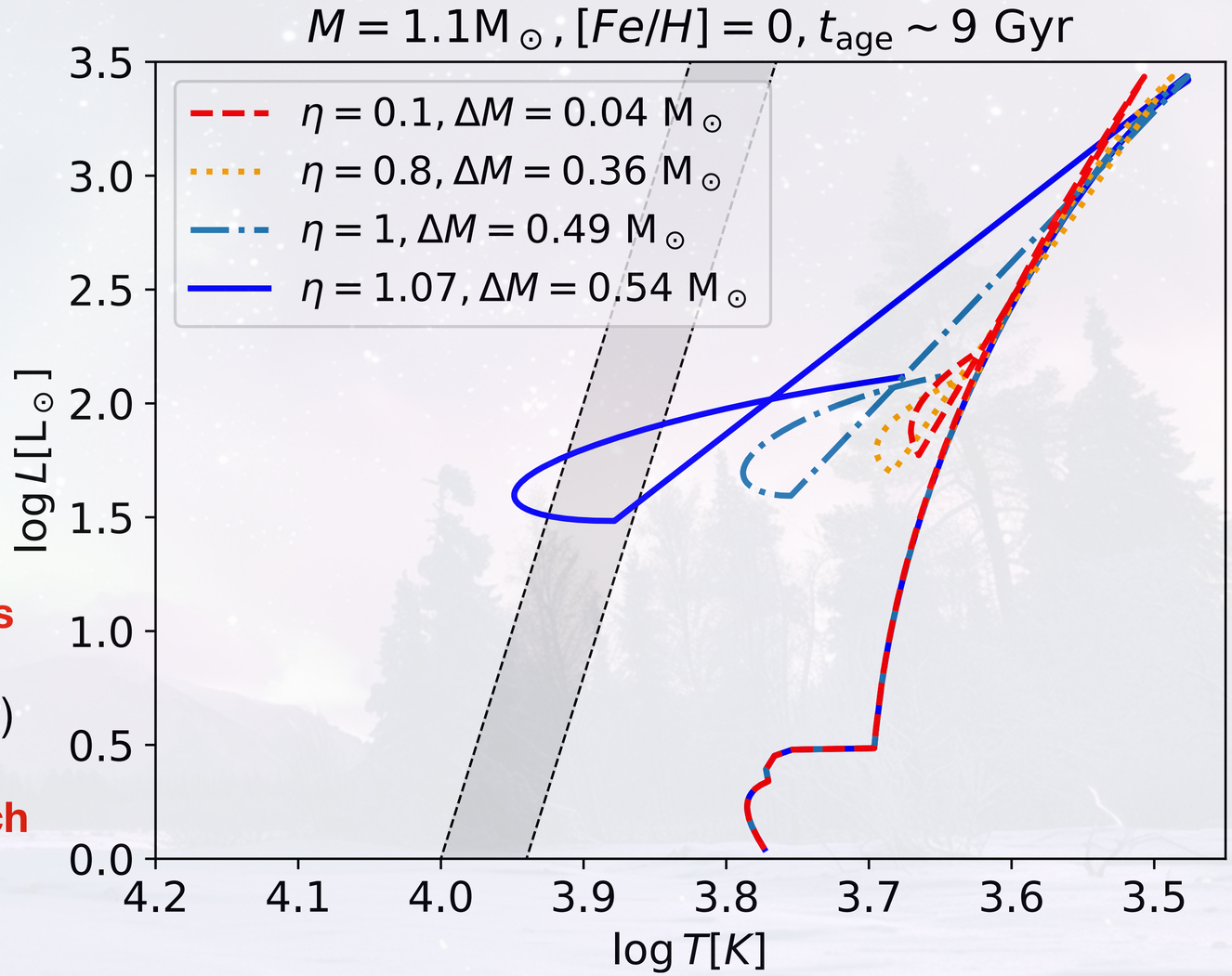
Higher wind mass loss during RGB (>0.4-0.5 Msun)

↓

Hotter core He burning stars

Challenges:

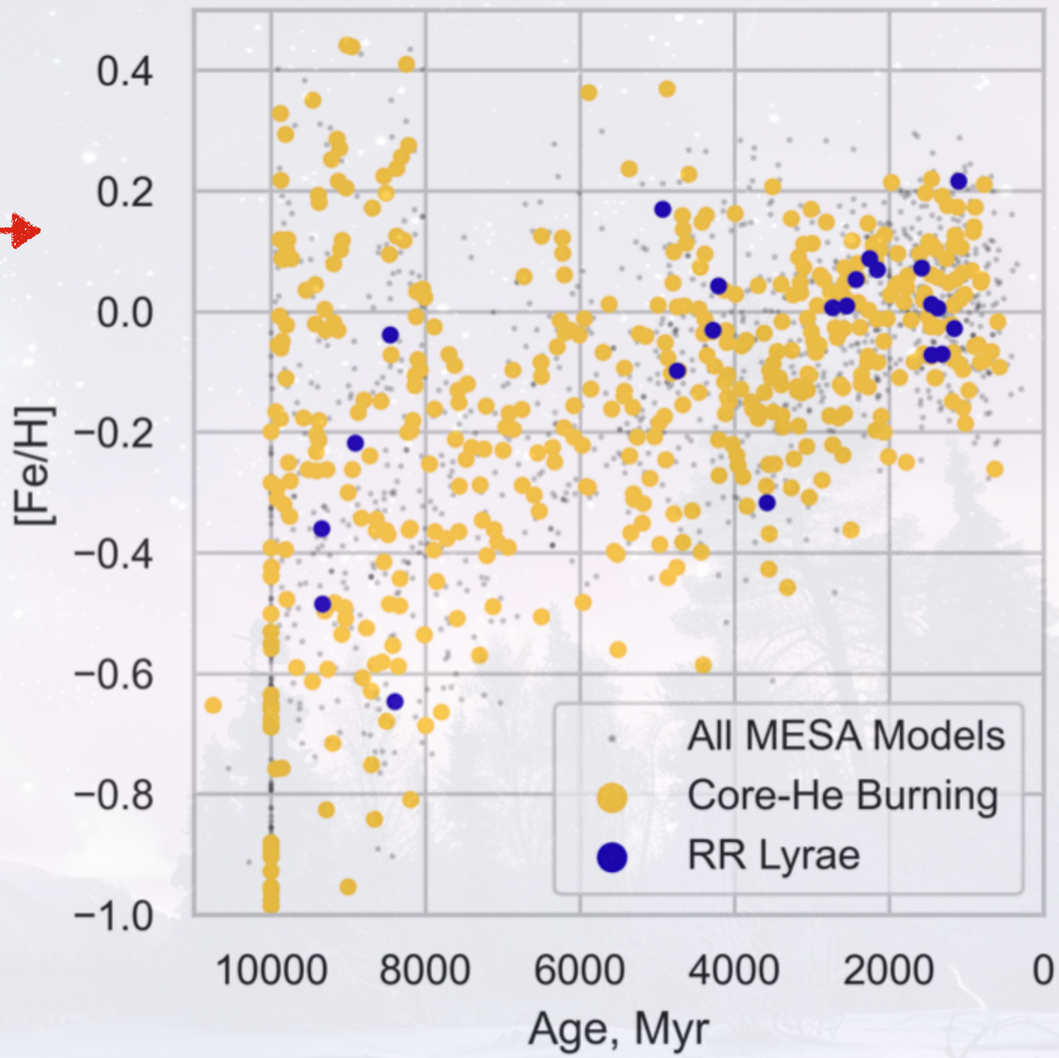
- **High RGB mass loss not supported by observations (<0.3 Msun,eta<0.6)**
  (See e.g. Salaris+13, Origlia+14, Savino+19, Tailo+22)
- **Most of the RR Lyrae in the MW should be metal-rich**



Predicted RR Lyrae population

Considering the Besançon MW model:

- **Consistent with the RRL Metal-rich population**
- **Consistent with intermediate-young populations**



1 Binary made metal-rich RRL each 1E6 Msun

Expected fraction of binary-made RR Lyrae:

- ~ 30% in the thin disc region
- ~ 5-6% in the inner Galaxy
- ~ 0% in the stellar halo

Consistent with the fraction of observed metal-rich and/or kinematically young RR Lyrae
(e.g. Iorio&Belokurov+21, Savino+20)

Do metal-rich RR Lyrae have a companion?

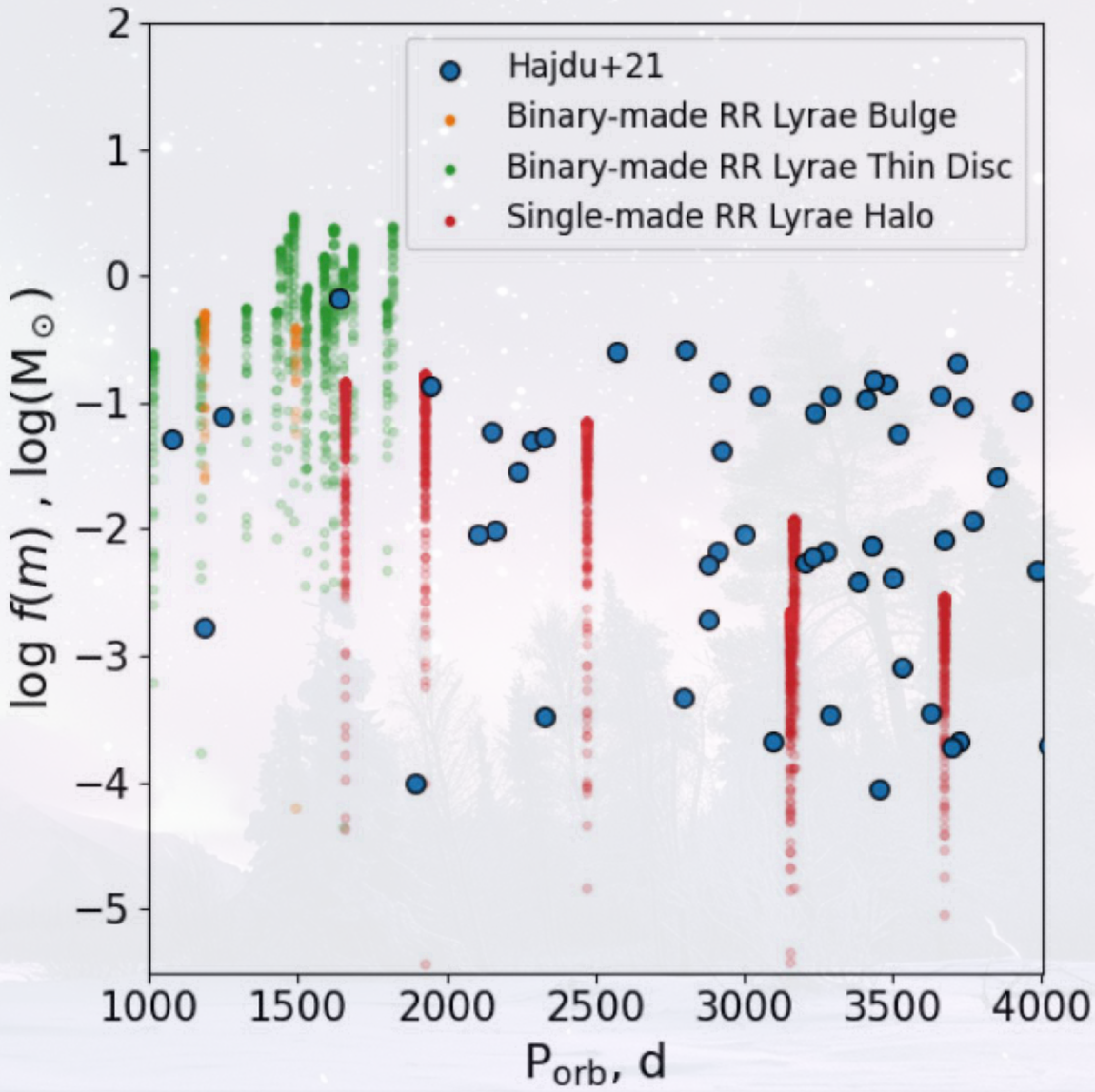
If formed through binary mass transfer Metal-rich RR Lyrae must have a companion

- ~1 order of magnitude fainter
- P ~1000-2000 days
  (Most of Gaia DR3 binaries < 1000 days)
- Low orbital velocity (< 10 km/s)
  (RRL pulsations ~50 km/s)

Challenging to observe!

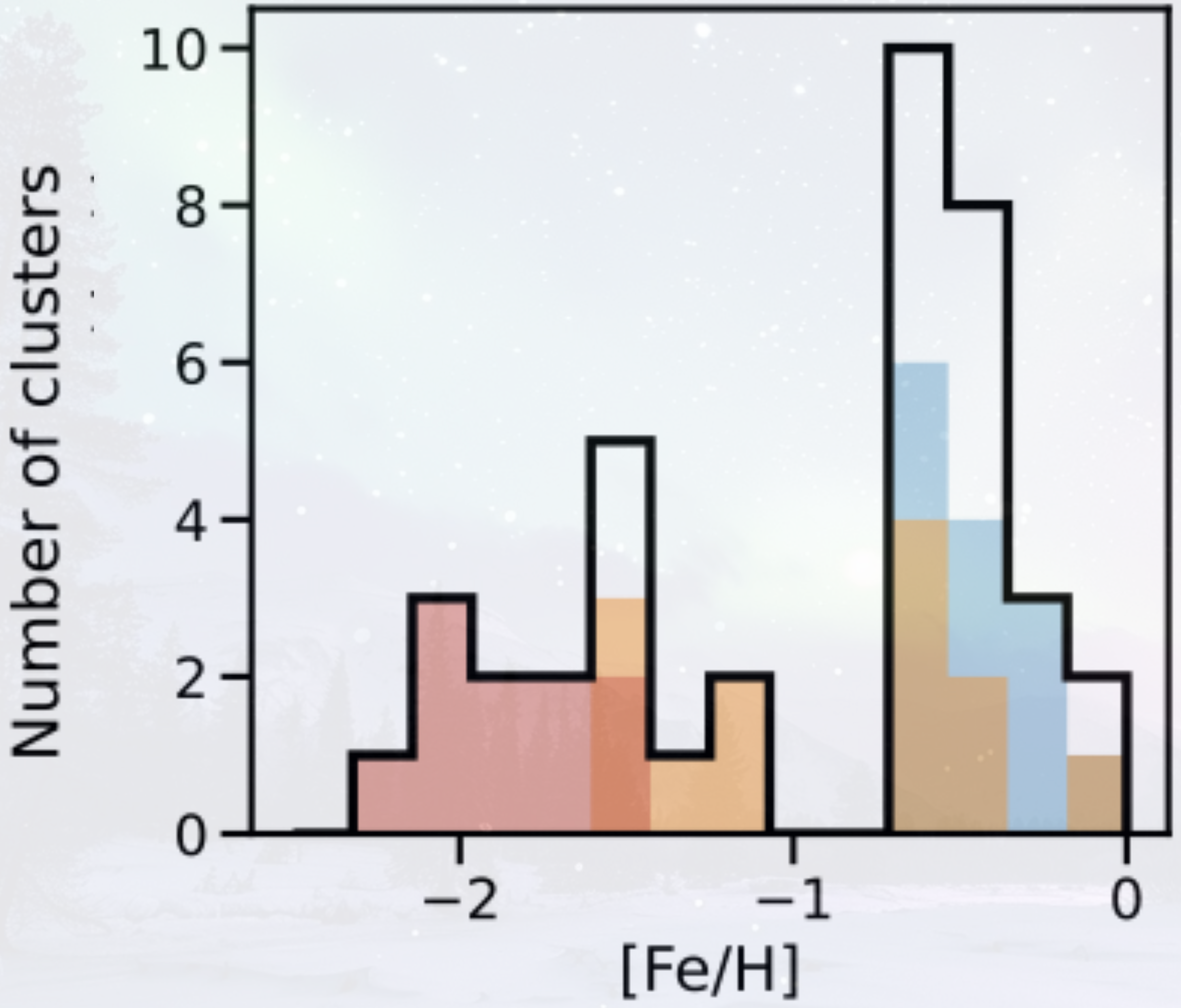
There are candidates!
(Liska+16,Kervella+19,Hajdu+21)

No tensions at the moment!



Metal-rich RR Lyrae in the LMC

RR Lyrae stars associated to LMC stellar clusters
(Cuevas-Otahola+24)



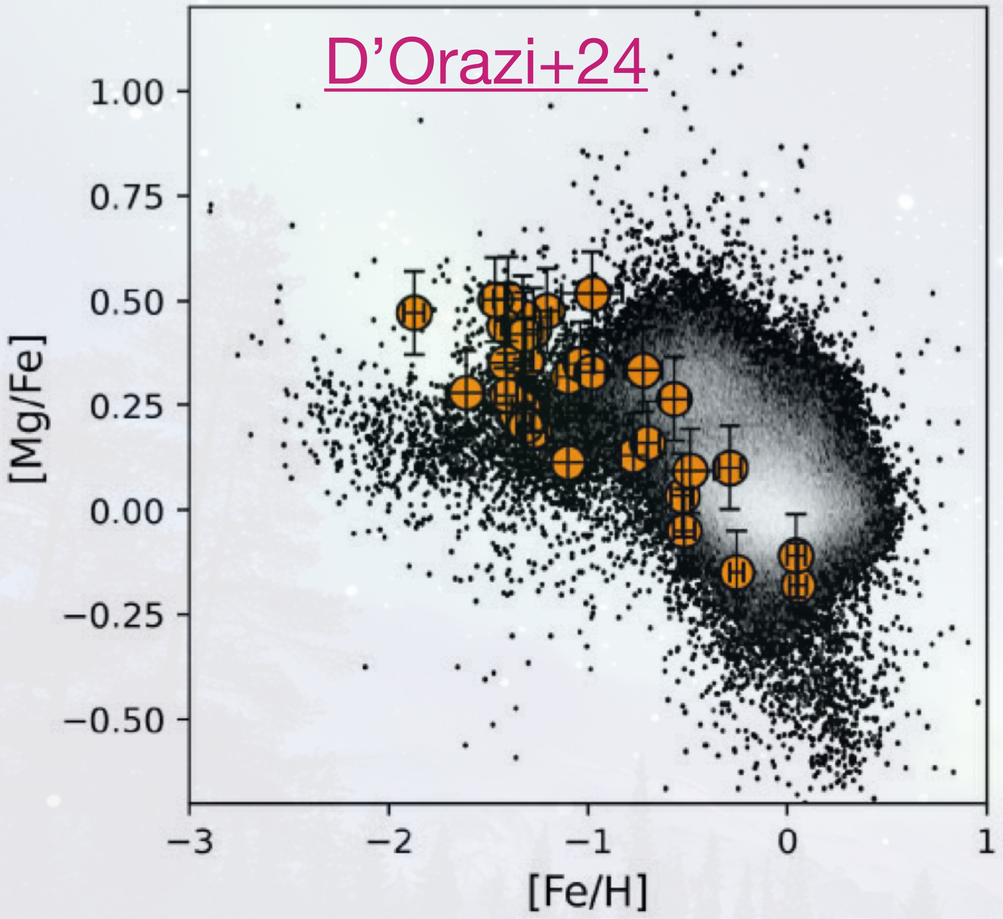
$N_{\mathrm{RRL}} = 15$

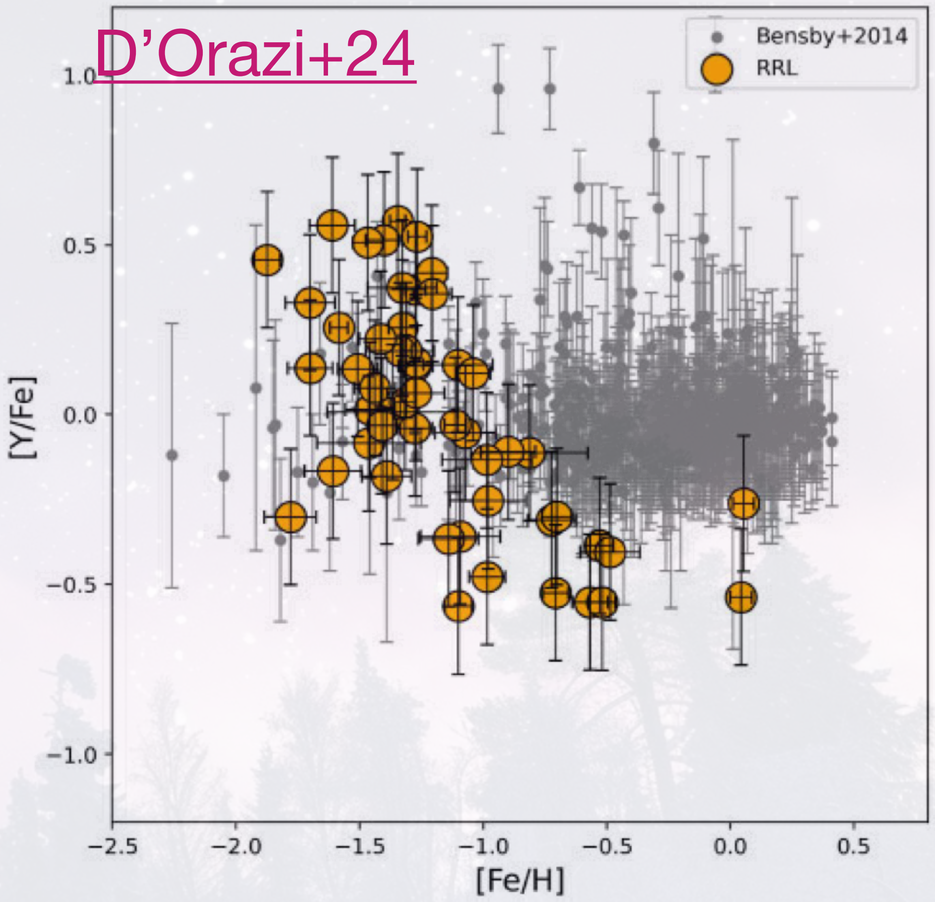
$N_{\mathrm{RRL}} = 9$

$N_{\mathrm{RRL}} = 160$

Evidences of young and meta-rich RR Lyrae stars in the LMC stellar clusters

About detailed chemical composition



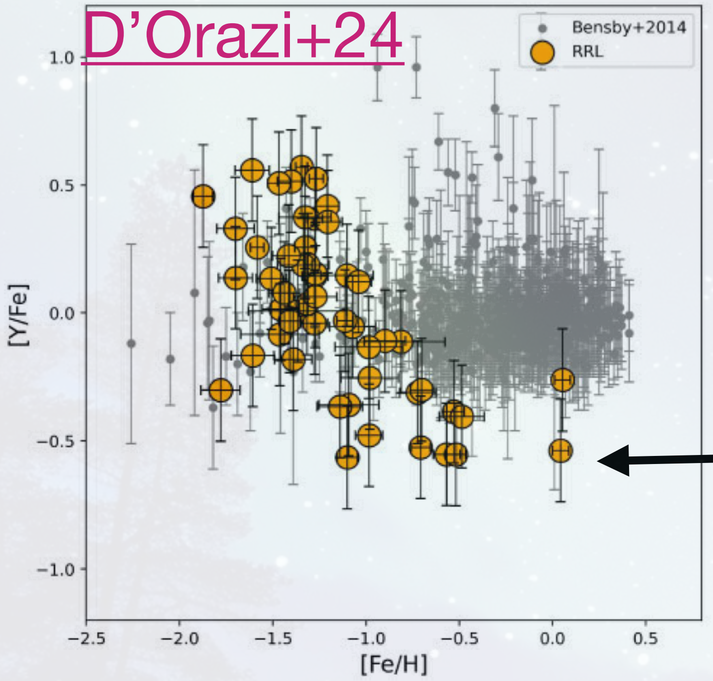


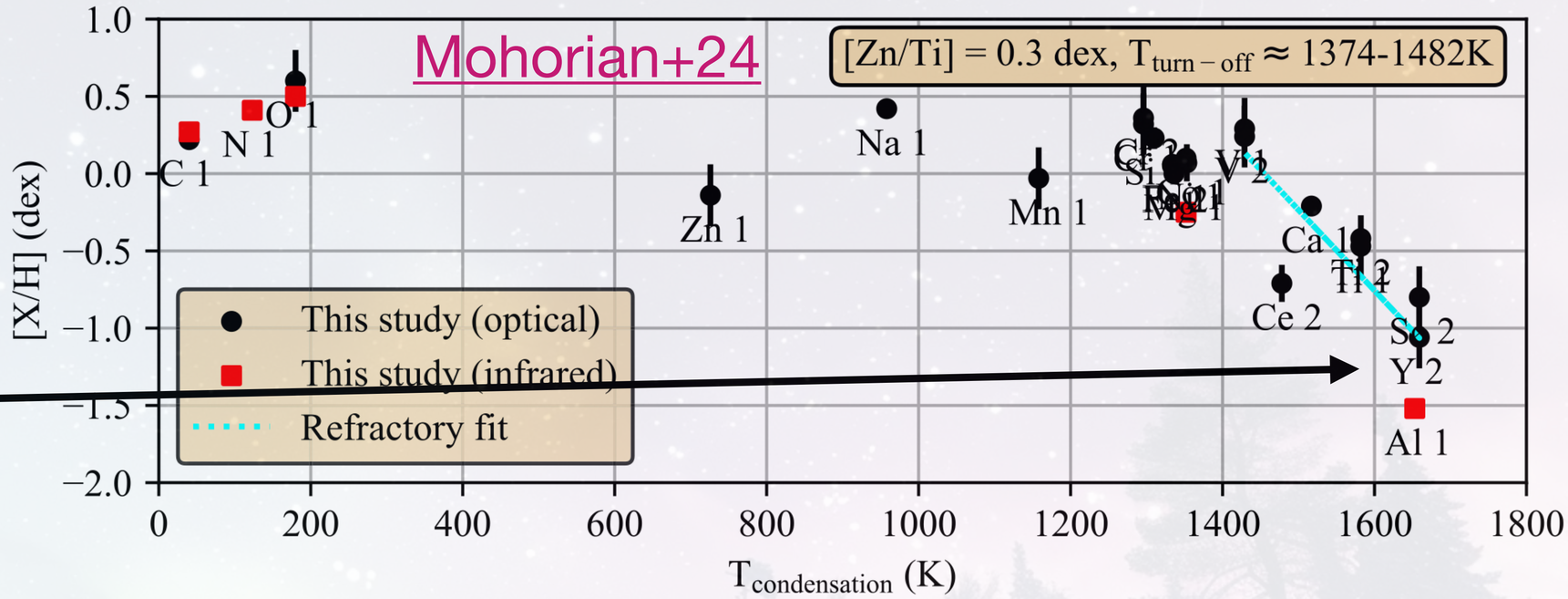
α-poor typical of thin-disc stars…. but peculiar under abundance for some elements (Y, Ba,Ca)

Signature of an accreted old population in the disc?
(D'Orazi+24, Feuillet+22)

or additional evidences of past binary interactions?

About detailed chemical composition



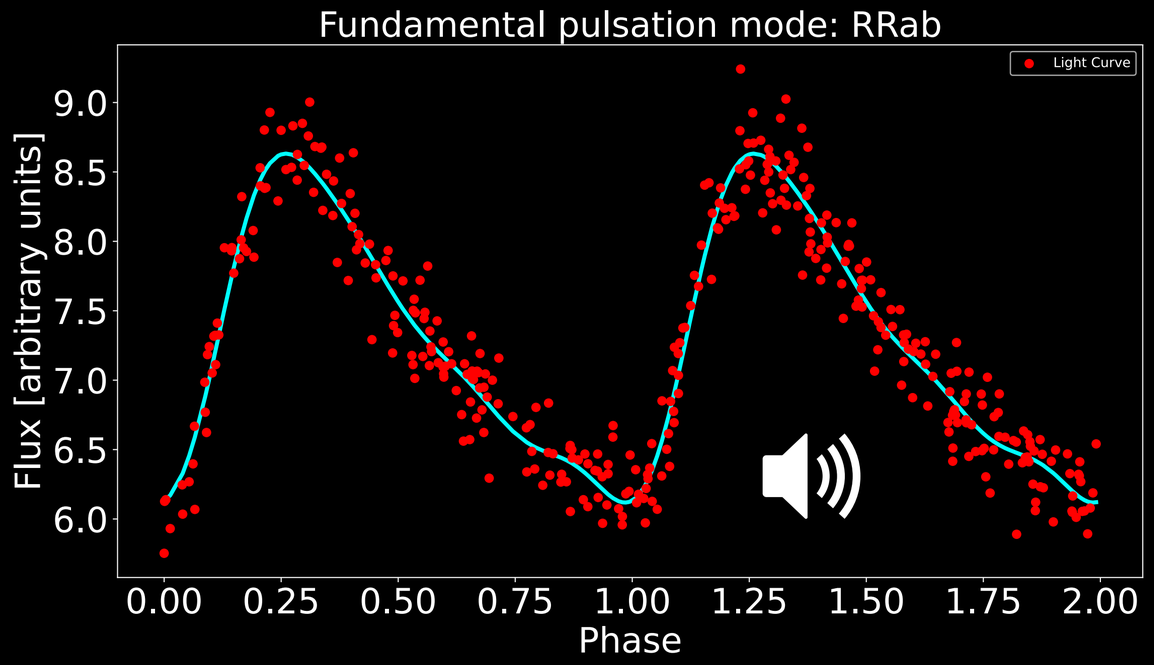


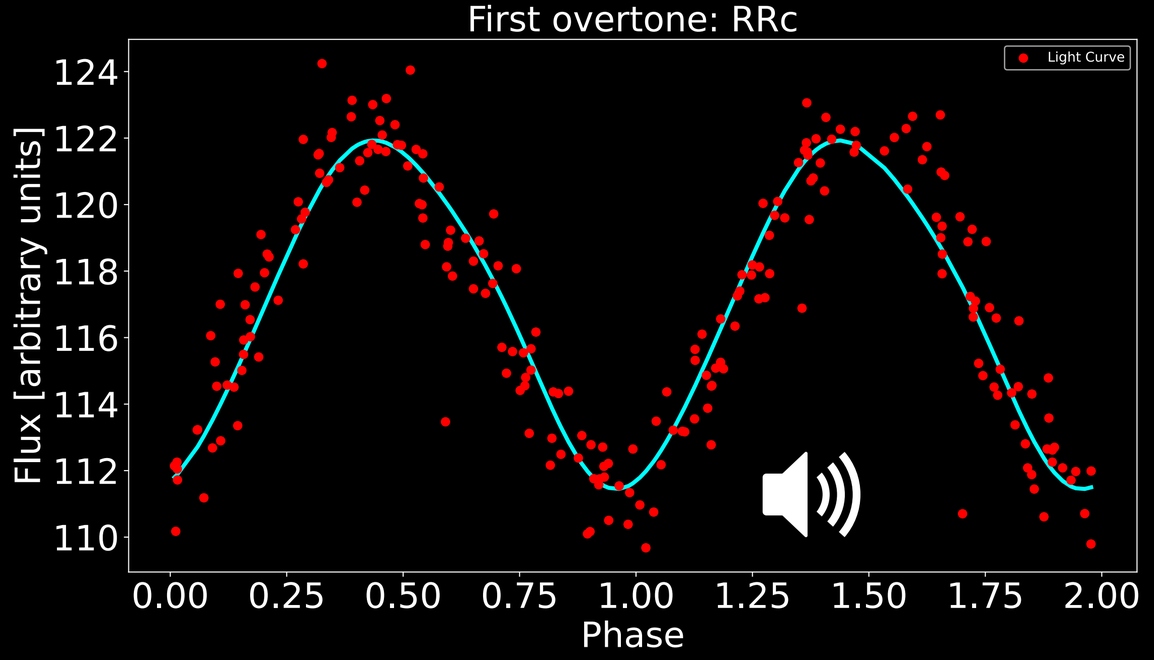
Peculiar abundances as signature of re-accreted circumbinary material?

(Molina+25, in prep)

This a peculiar signature of post-RGB, post-AGB stars,
stars evolved off the RGB or AGB due to exceptional mass loss
(Kamat+15, Mohorian+24)

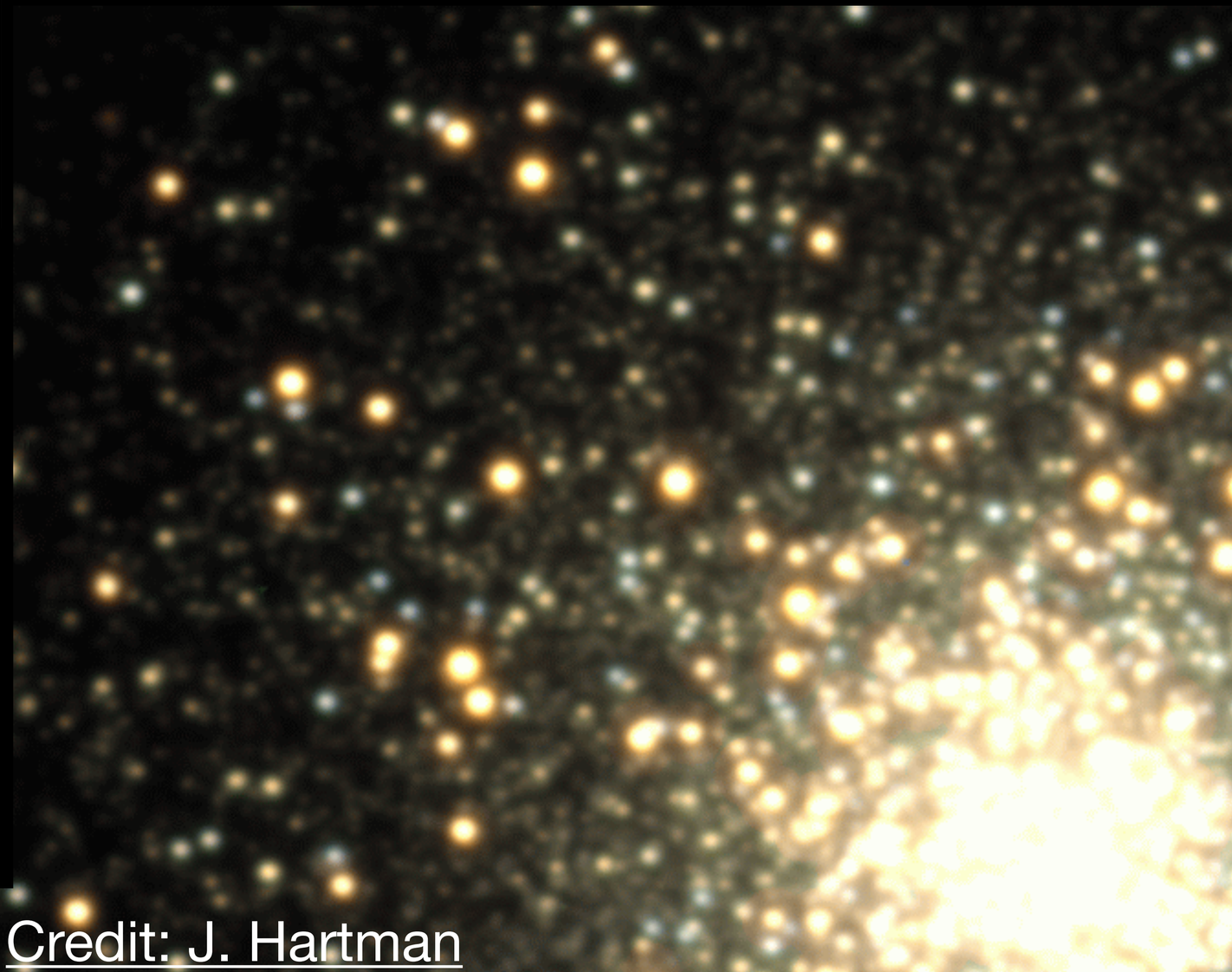
Are we tracing a similar population?



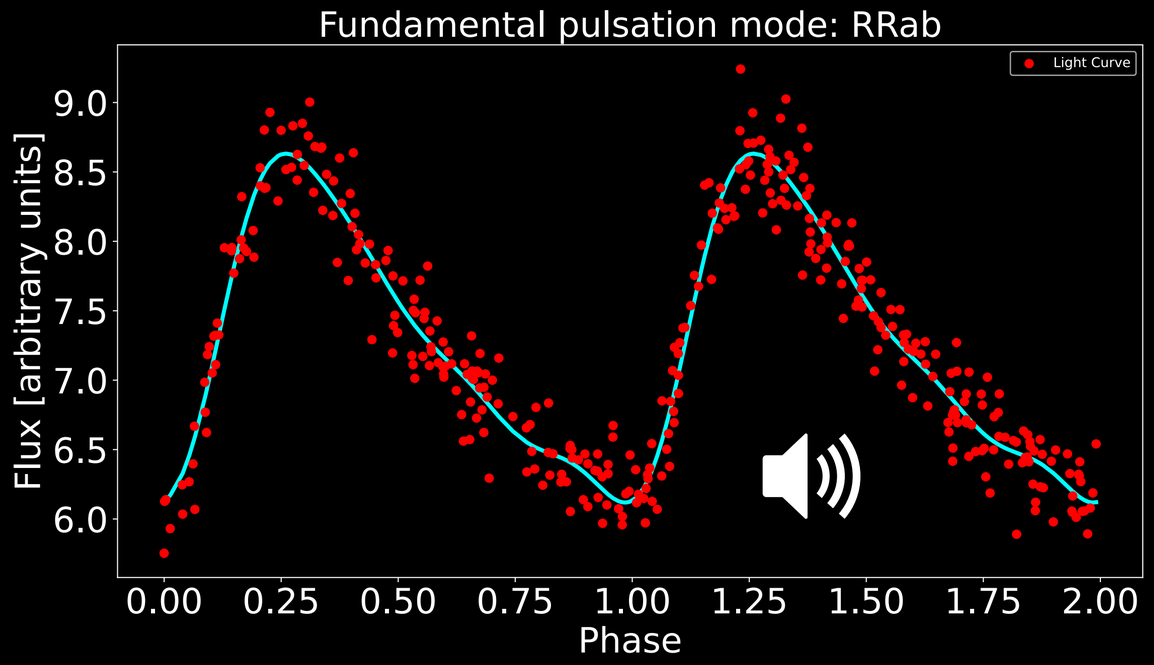


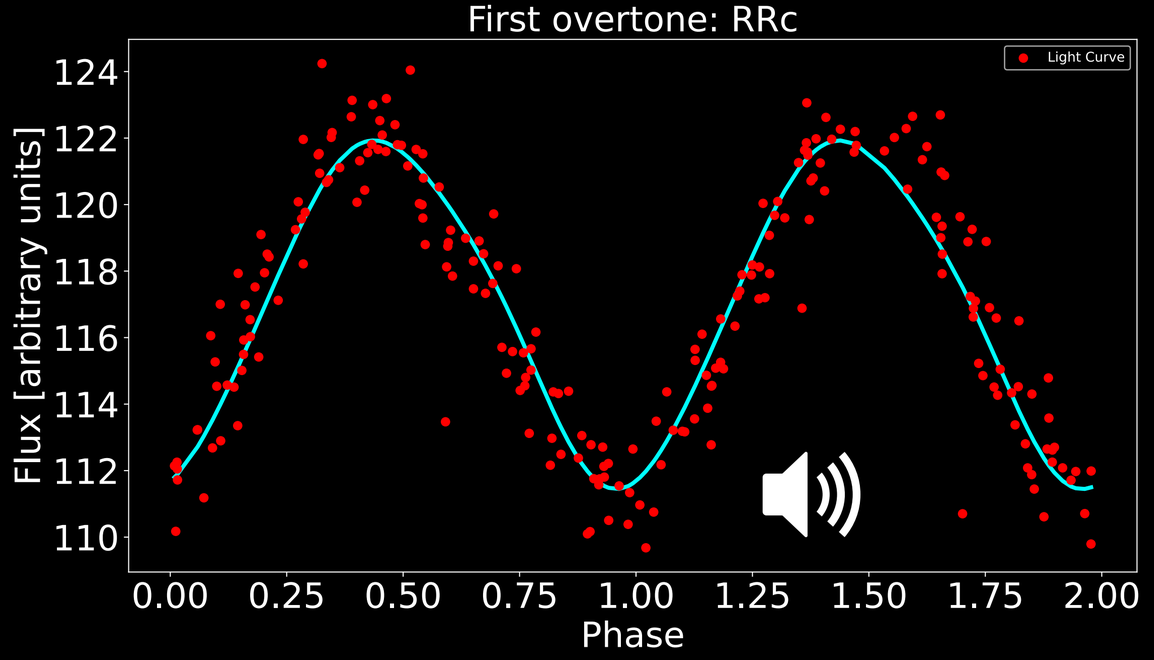
Fundamental+first overtone: RRd

RR Lyrae in the Globular cluster M3



Credit: J. Hartman





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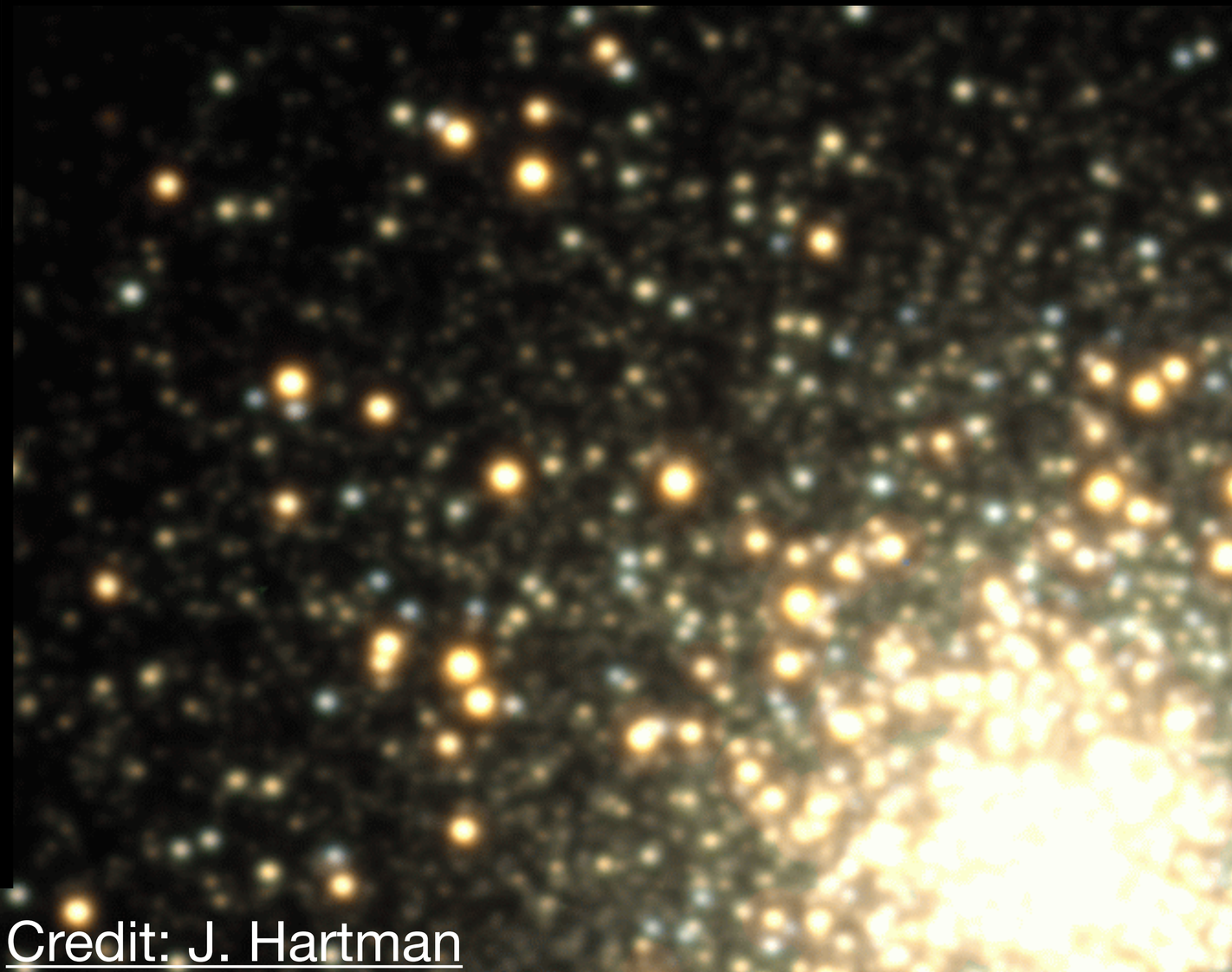

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