Astrophysical problems crossing the Gaia path

G. Bono, (Univ. of Rome TOV, INAF-OAR), + **many others**

Roman road system

AASS, Roma, December 6 2021

Astrophysical problems crossing the Gaia path

OUTLINE OF THE TALK

→ Gaia tidbits

→ RR Lyrae & Galactic Halo

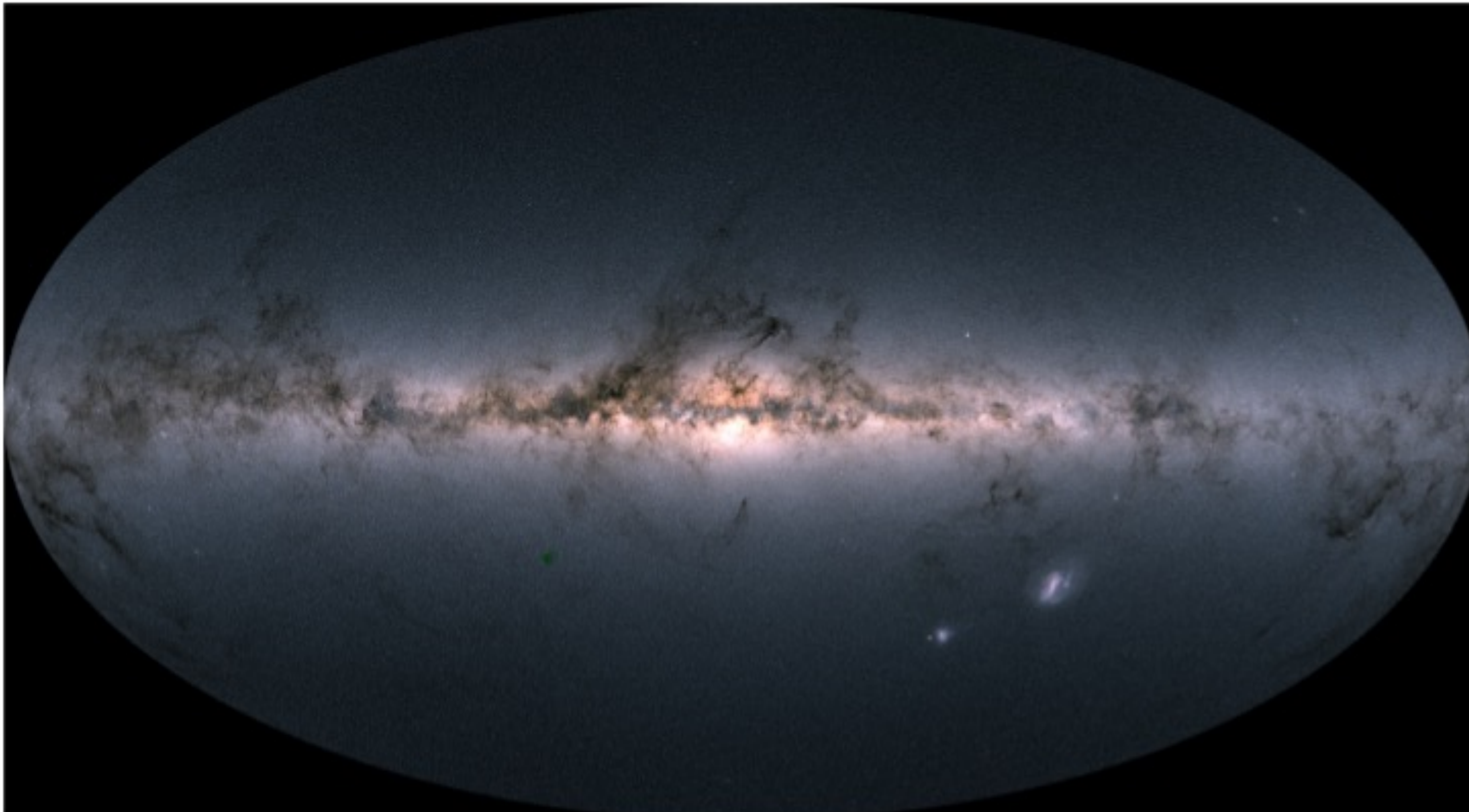
→ Classical Cepheids and thin disk

→ Ho et similia

→ The Magellanic Clouds

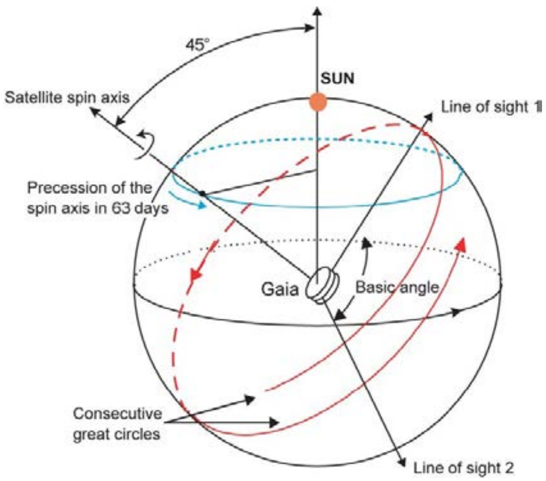
→ Conclusions

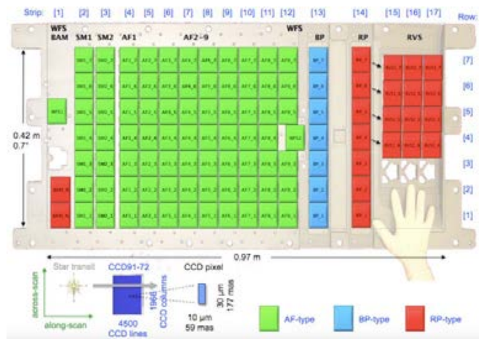
Gaia view of the nearby Universe

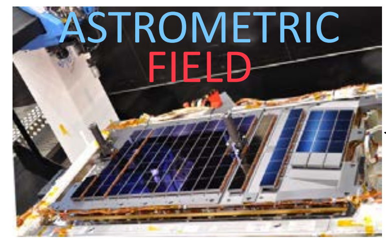


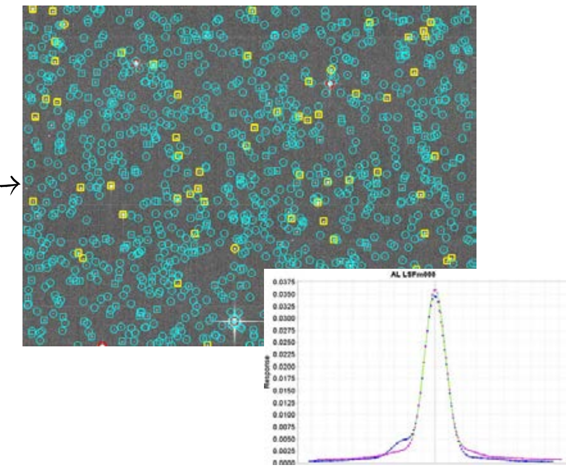
AASS, Roma, December 6 2021

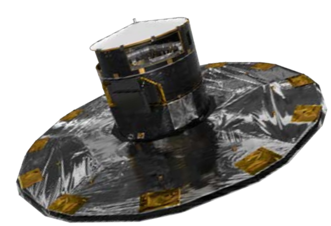
Gaia instruments and measurements



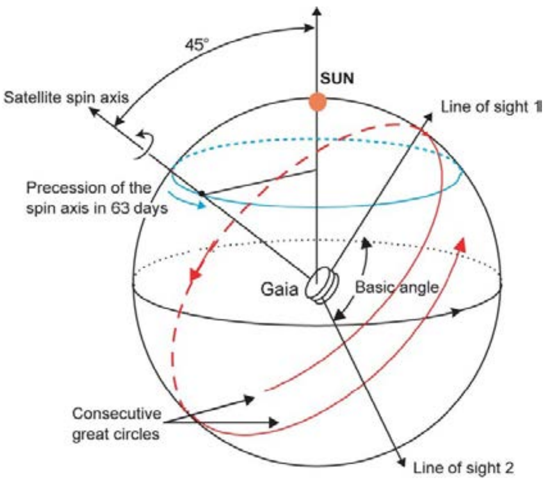


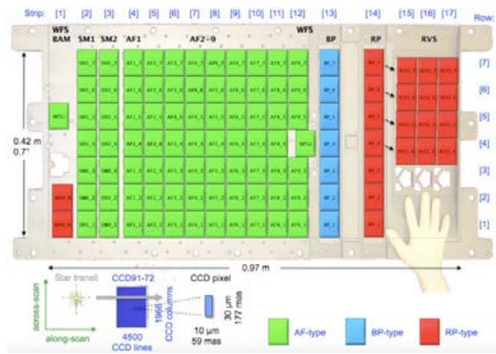


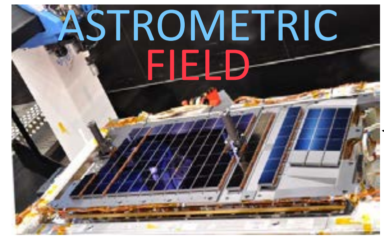


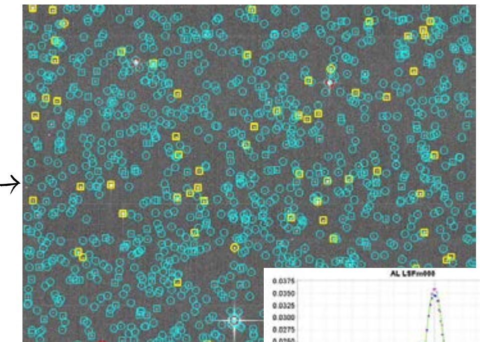


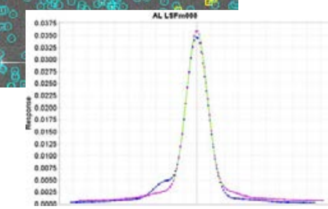
Gaia instruments and measurements

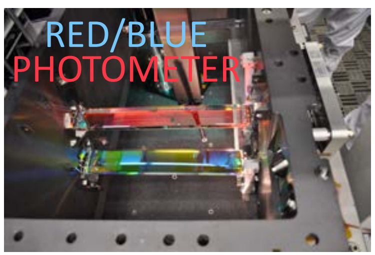


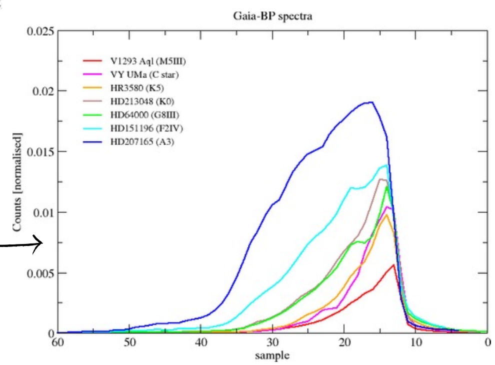


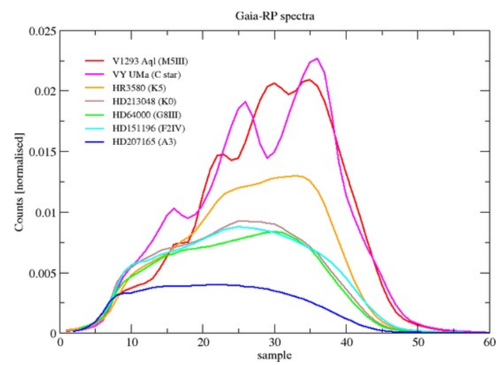


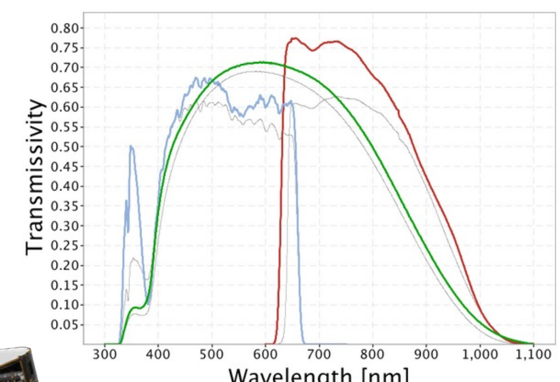


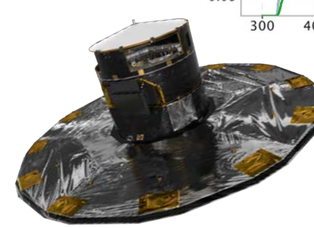




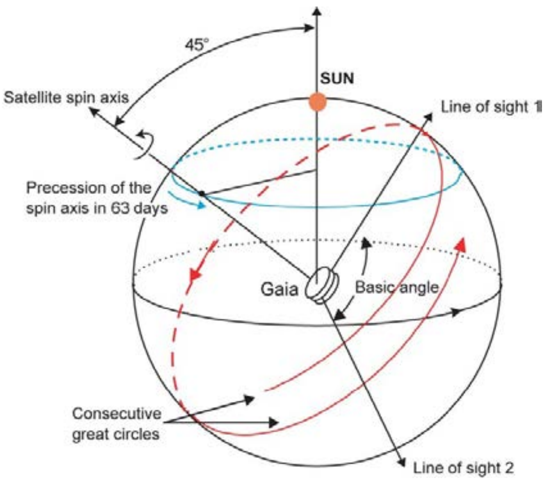


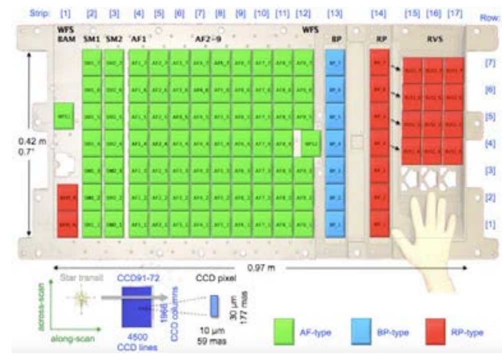


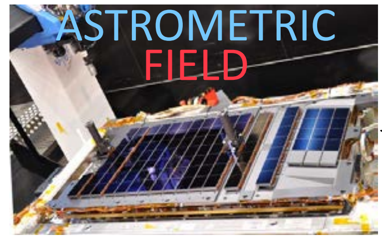


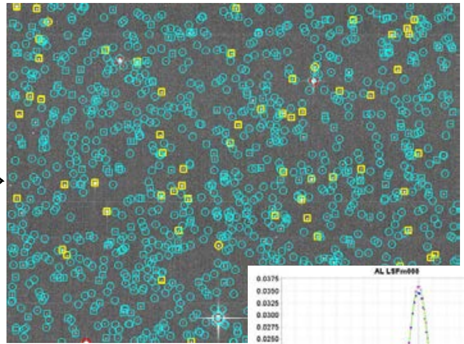


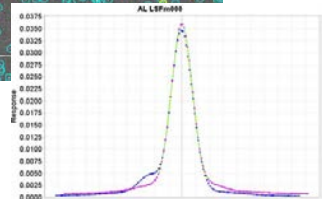
Gaia instruments and measurements

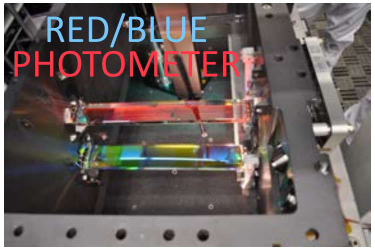


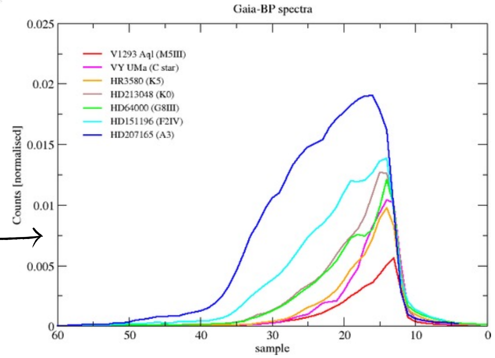


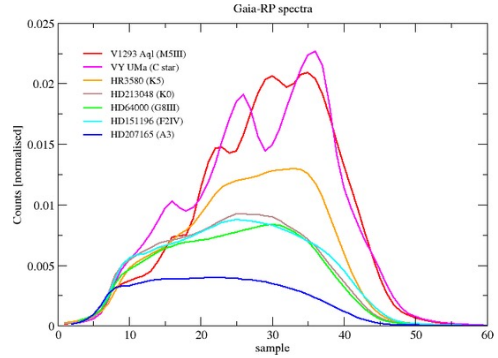


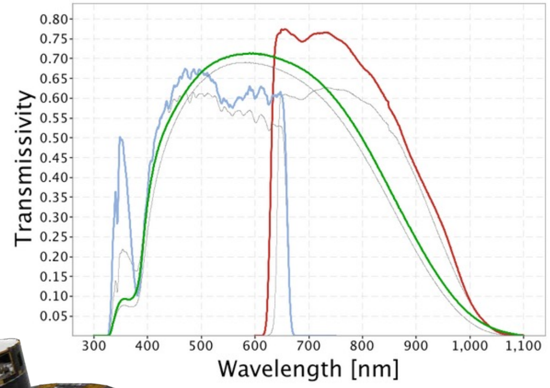


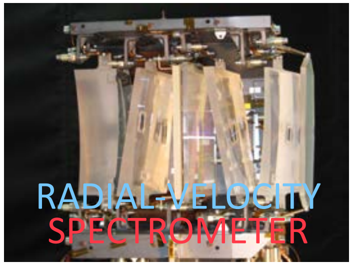


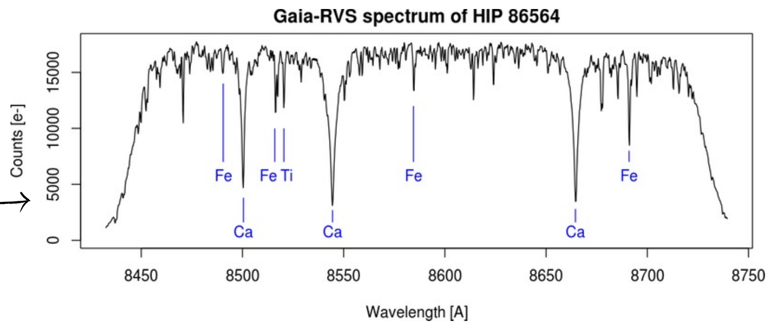


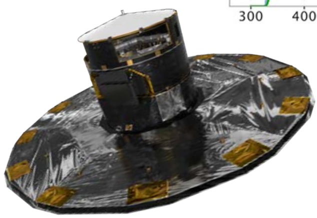










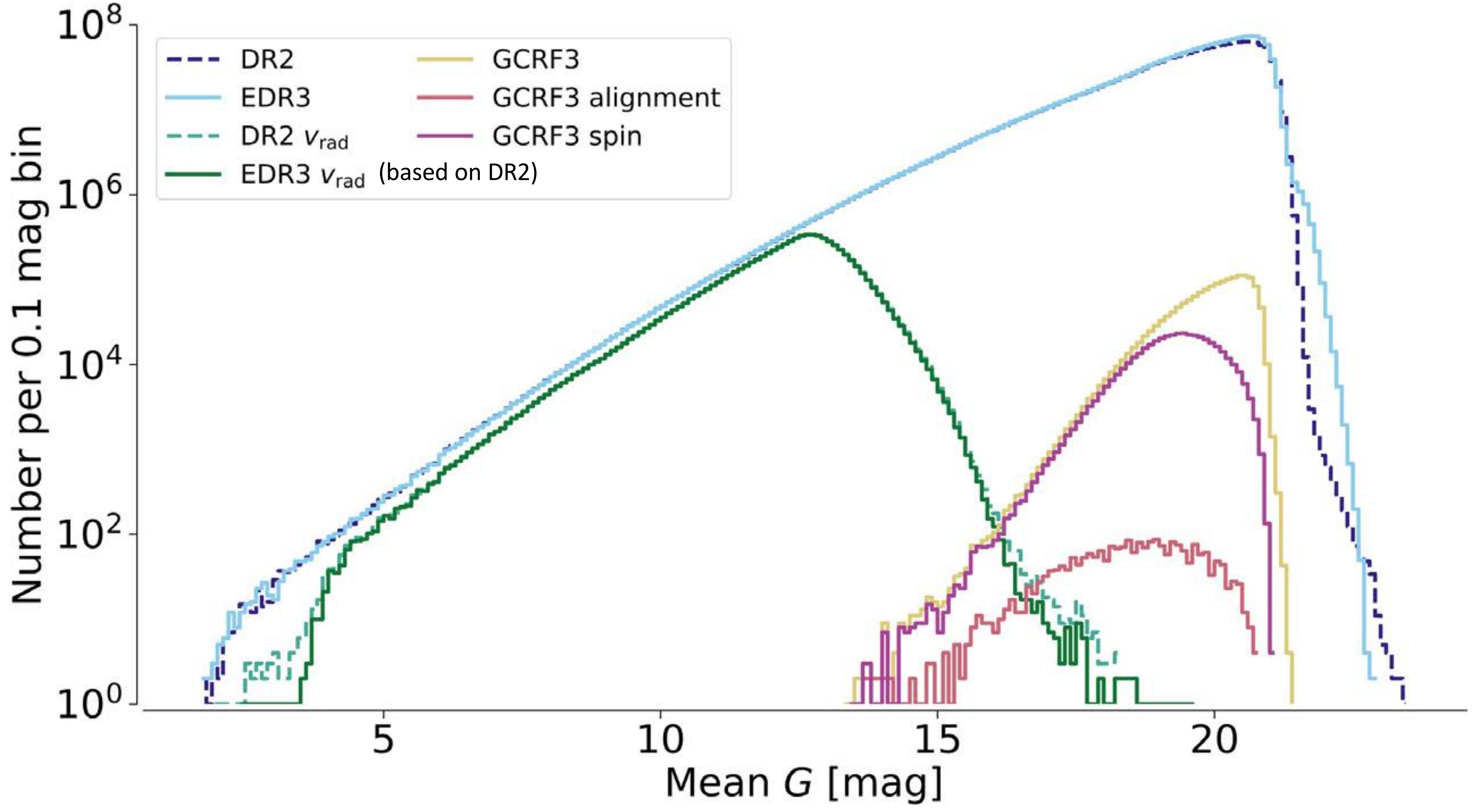


Gaia Early Data Release 3 - Content

Data collected between 25 July 2014 (10:30 UTC) and 28 May 2017 (08:44 UTC) => 34 months.

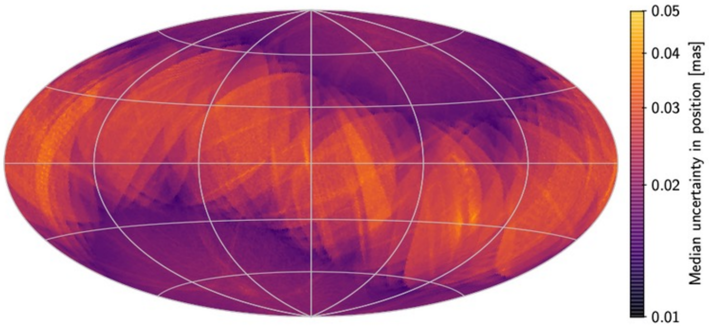
	# sources in Gaia EDR3	# sources in Gaia DR2	# sources in Gaia DR1
Total number of sources	1,811,709,771	1,692,919,135	1,142,679,769
Number of 5-parameter sources	585,416,709	1,331,909,727	2,057,050
Number of 6-parameter sources	882,328,109		
Number of 2-parameter sources	343,964,953	361,009,408	1,140,622,719
Sources with mean G magnitude	1,806,254,432	1,692,919,135	1,142,679,769
Sources with mean G_{BP}-band photometry	1,542,033,472	1,381,964,755	-
Sources with mean G_{RP}-band photometry	1,554,997,939	1,383,551,713	-
Gaia-CRF sources	1,614,173	556,869	2,191
Sources with radial velocities	7,209,831 (Gaia DR2)	7,224,631	-
Variable sources	*expected with Gaia DR3 / see DR2*	550,737	3,194
Known asteroids with epoch data	*expected with Gaia DR3 / see DR2*	14,099	-
Effective temperatures (T_{eff})	*expected with Gaia DR3 / see DR2*	161,497,595	-
Extinction (A_G) and reddening ($E(G_{BP}-G_{RP})$)	*expected with Gaia DR3 / see DR2*	87,733,672	-
Sources with radius and luminosity	*expected with Gaia DR3 / see DR2*	76,956,778	-
and more…	*expected with Gaia DR3*	-	-

Source counts

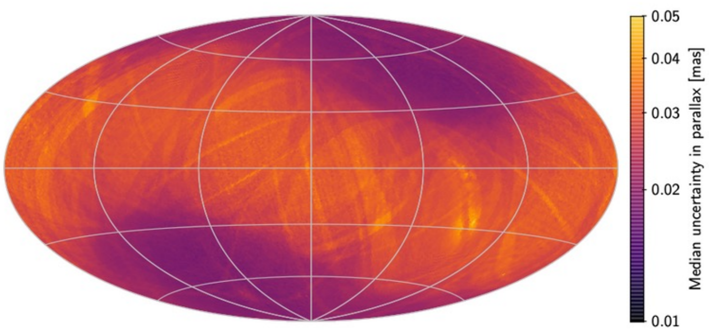


Gaia Collaboration, Brown et al. 2020

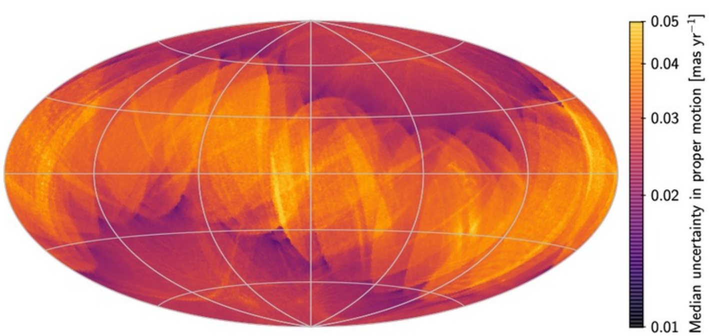
Astrometric performance



Position uncertainties:
- G<15 0.01-0.02 mas
- G=17 0.05 mas
- G=20 0.4 mas
- G=21 1.0 mas



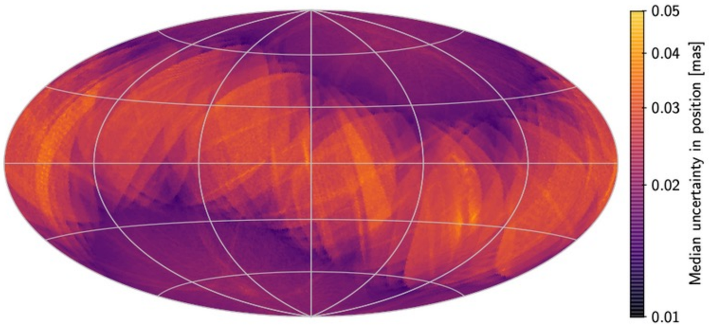
Parallax uncertainties:
- G<15 0.02-0.03 mas
- G=17 0.07 mas
- G=20 0.5 mas
- G=21 1.3 mas



Proper motion uncertainties:
- G<15 0.02-0.03 mas/yr
- G=17 0.07 mas/yr
- G=20 0.5 mas/yr
- G=21 1.4 mas/yr

Lindegren et al. 2020, Fabricius et al. 2020

Astrometric performance



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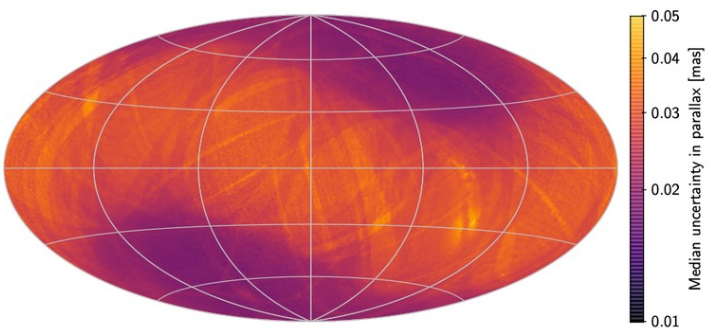
Precision +30%
Systematics -40%



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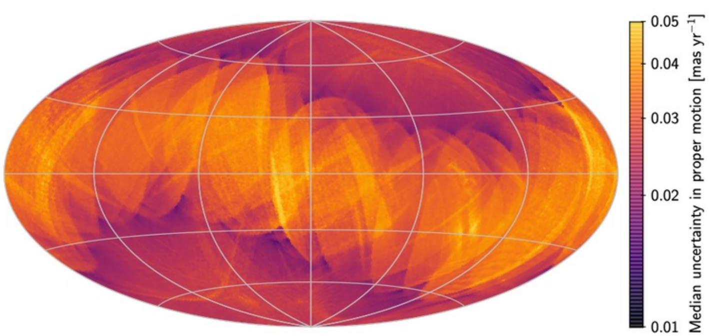

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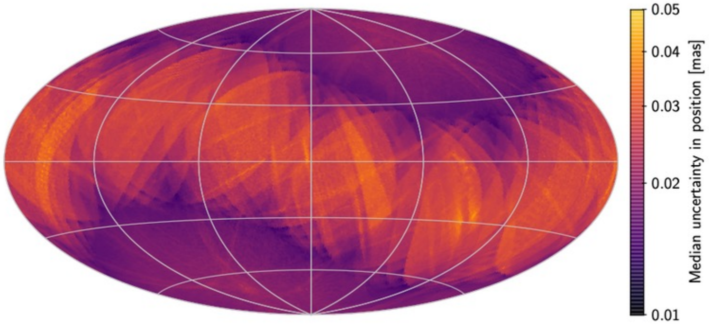
Precision x2
Systematics ÷2.5

Lindegren et al. 2020, Fabricius et al. 2020

Astrometric performance



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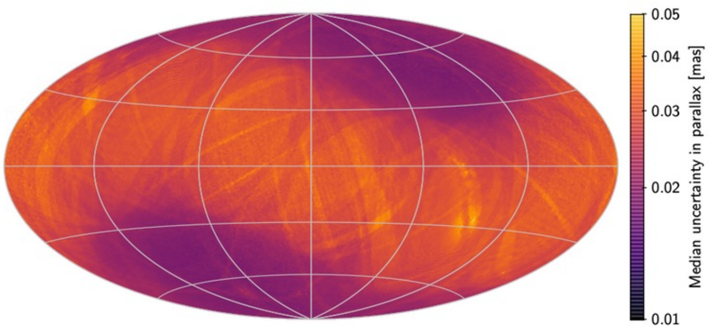

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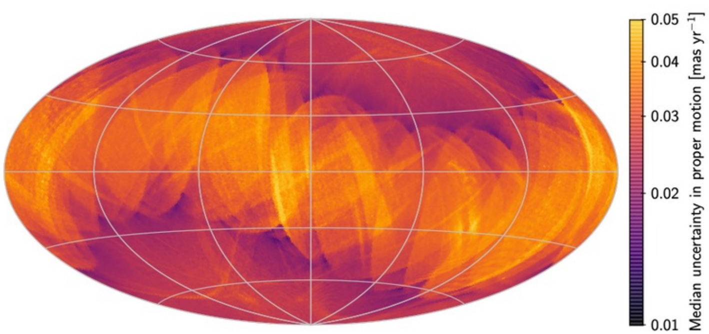

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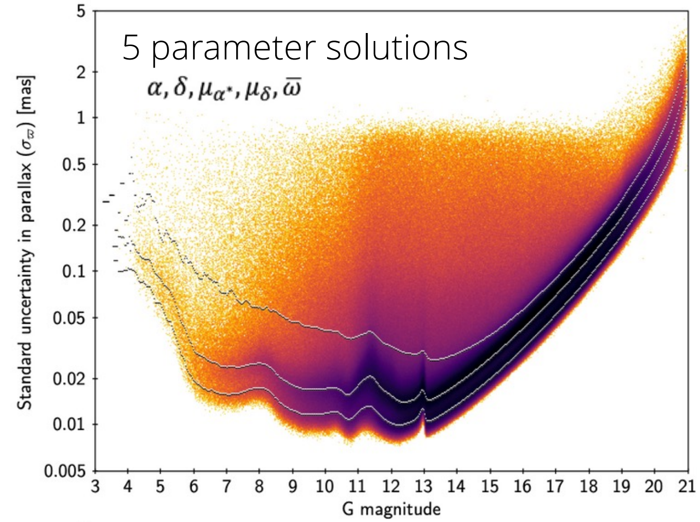
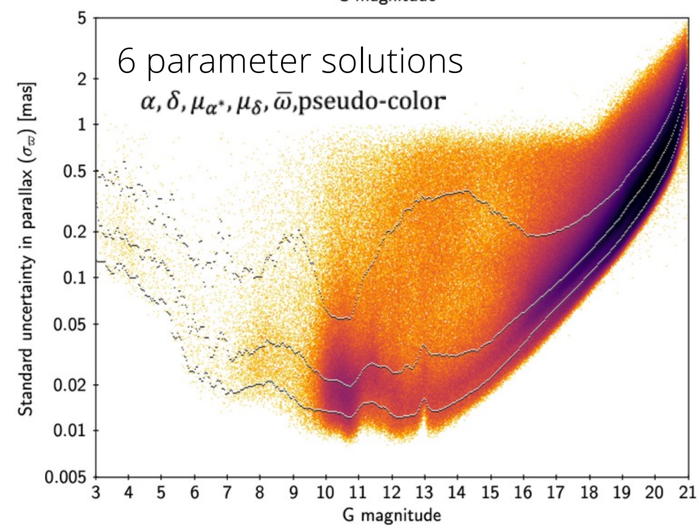
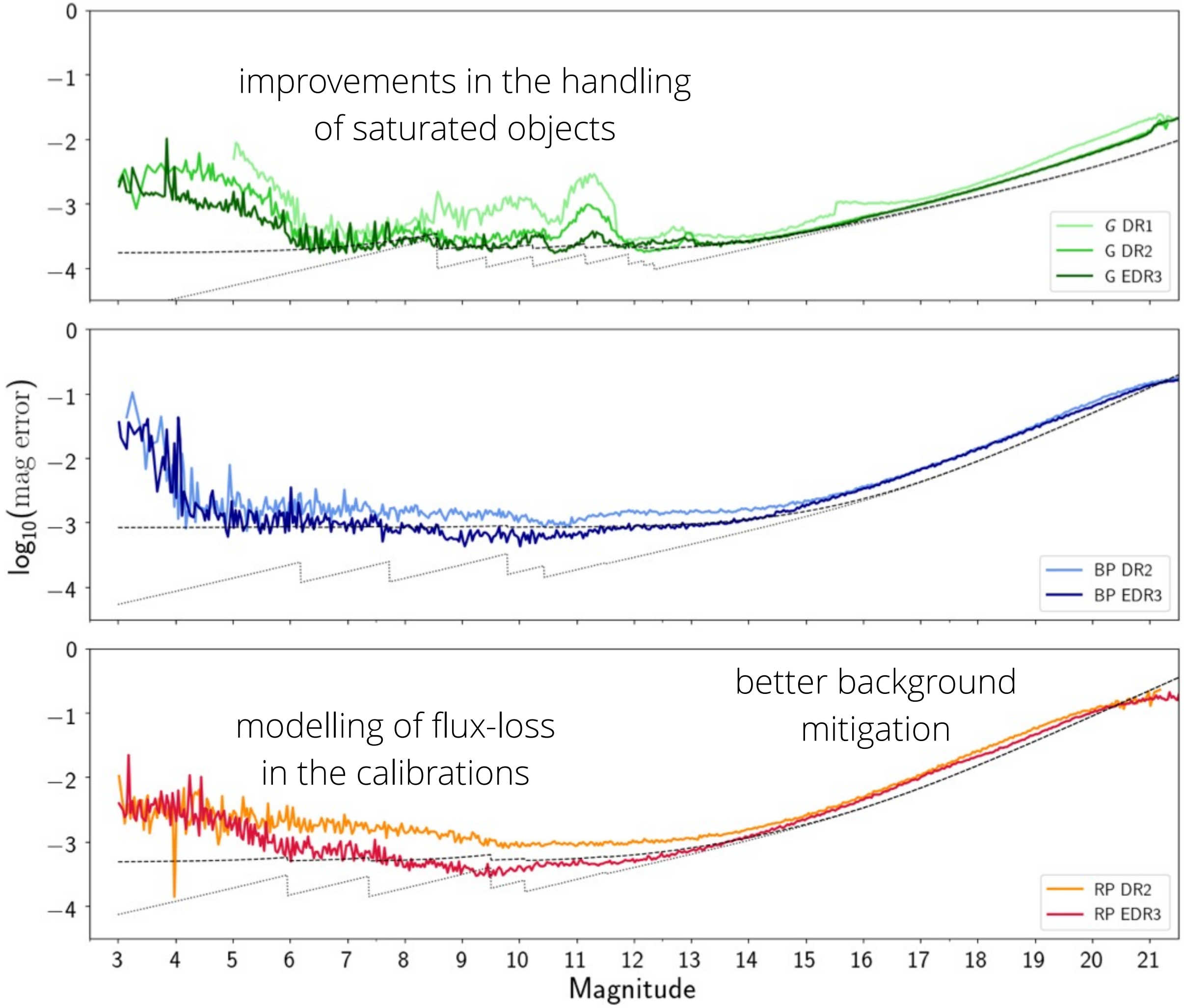




Lindegren et al. 2020, Fabricius et al. 2020

Photometric performance



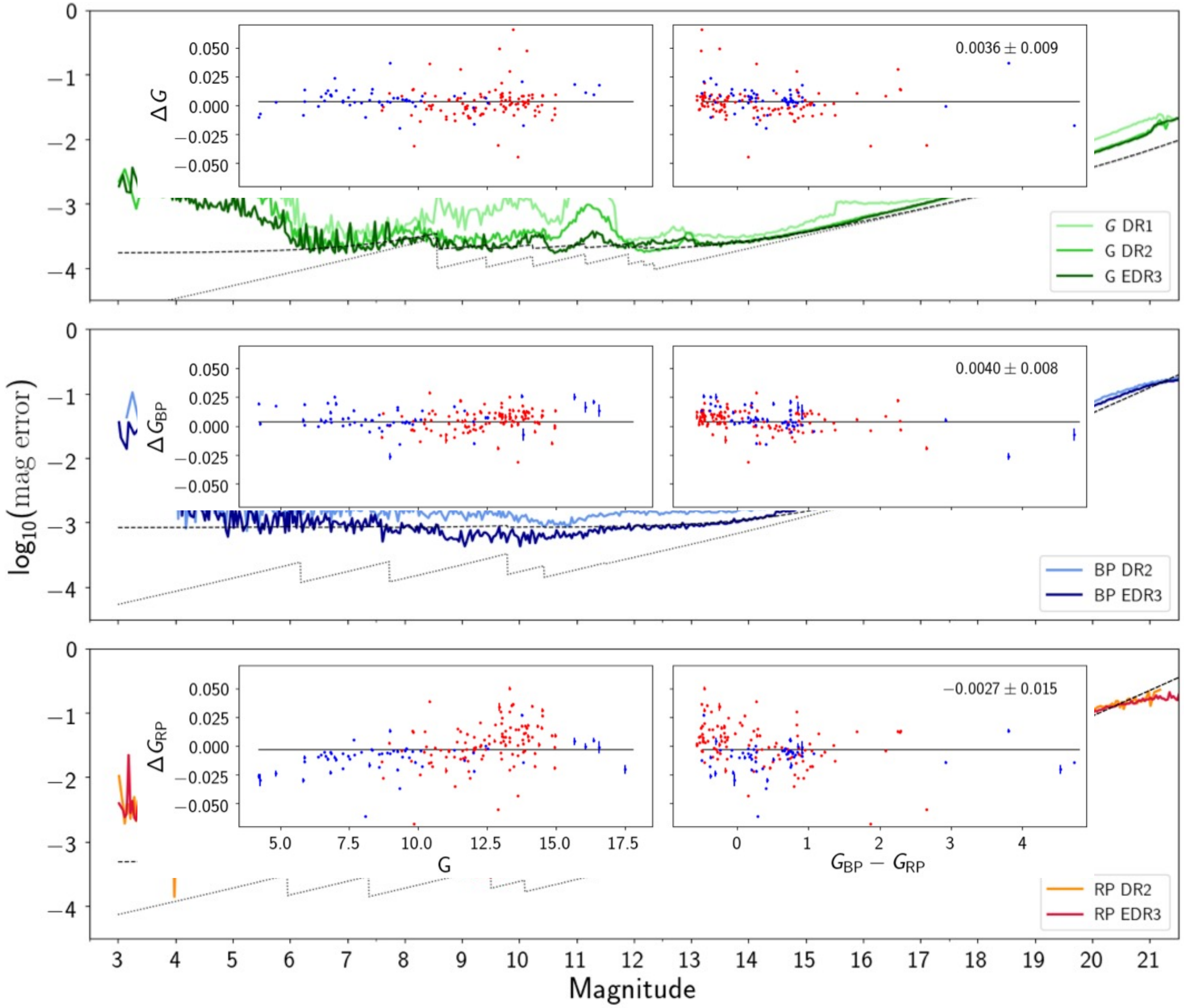
G-band uncertainties:
- G<13 0.3 mmag
- G=17 1 mmag
- G=20 6 mmag

BP-band uncertainties:
- BP<13 0.9 mmag
- BP=17 12 mmag
- BP=20 108 mmag

RP-band uncertainties:
- RP<13 0.6 mmag
- RP=17 6 mmag
- RP=20 52 mmag

Riello et al. 2020

Photometric performance



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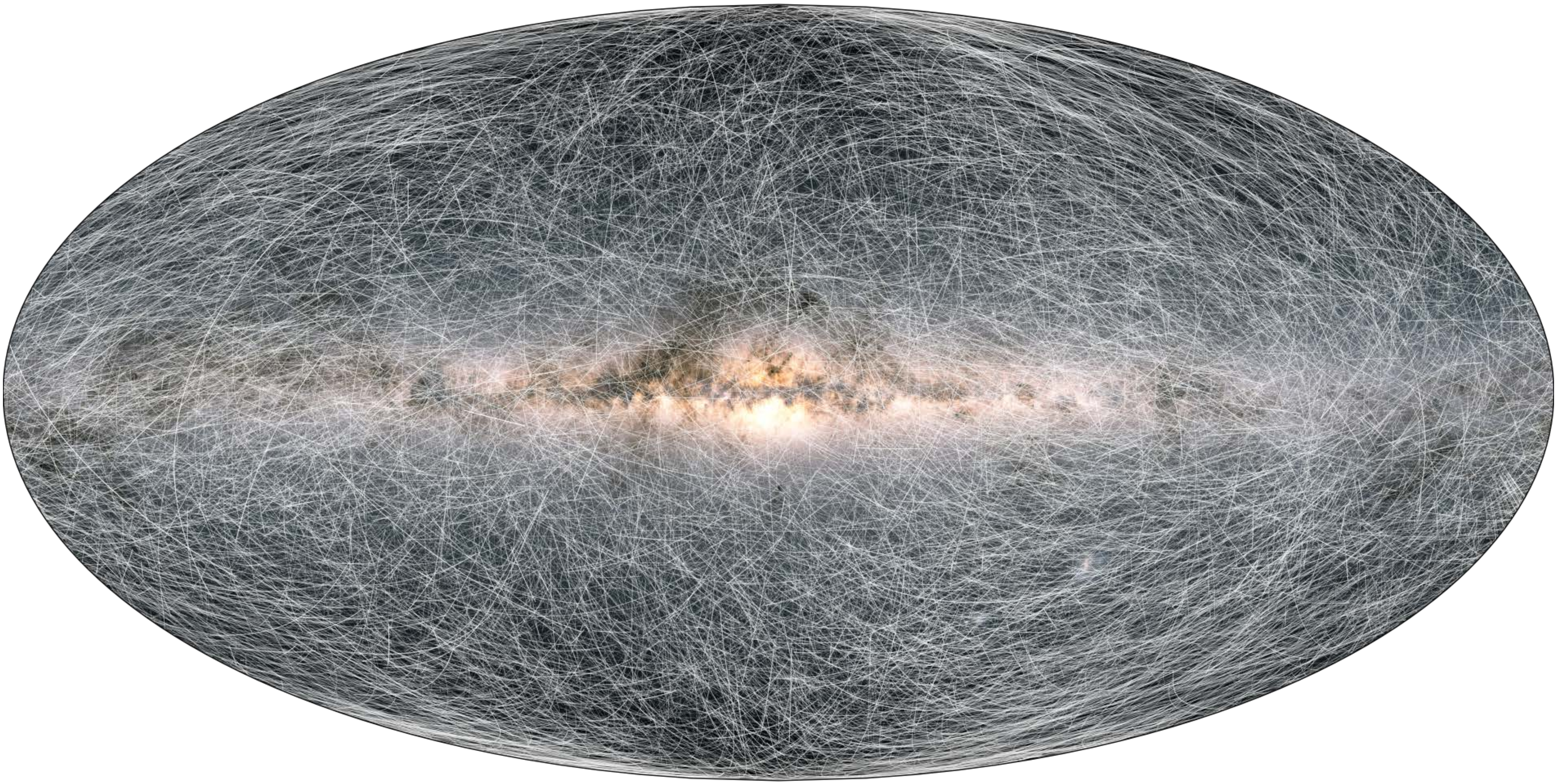
Riello et al. 2020

How 40.000 stars within 100 parsec from the sun move across the sky over 400 thousand years



Eyer et al.: *Gaia* DR2 – The CaMD of Variable Stars

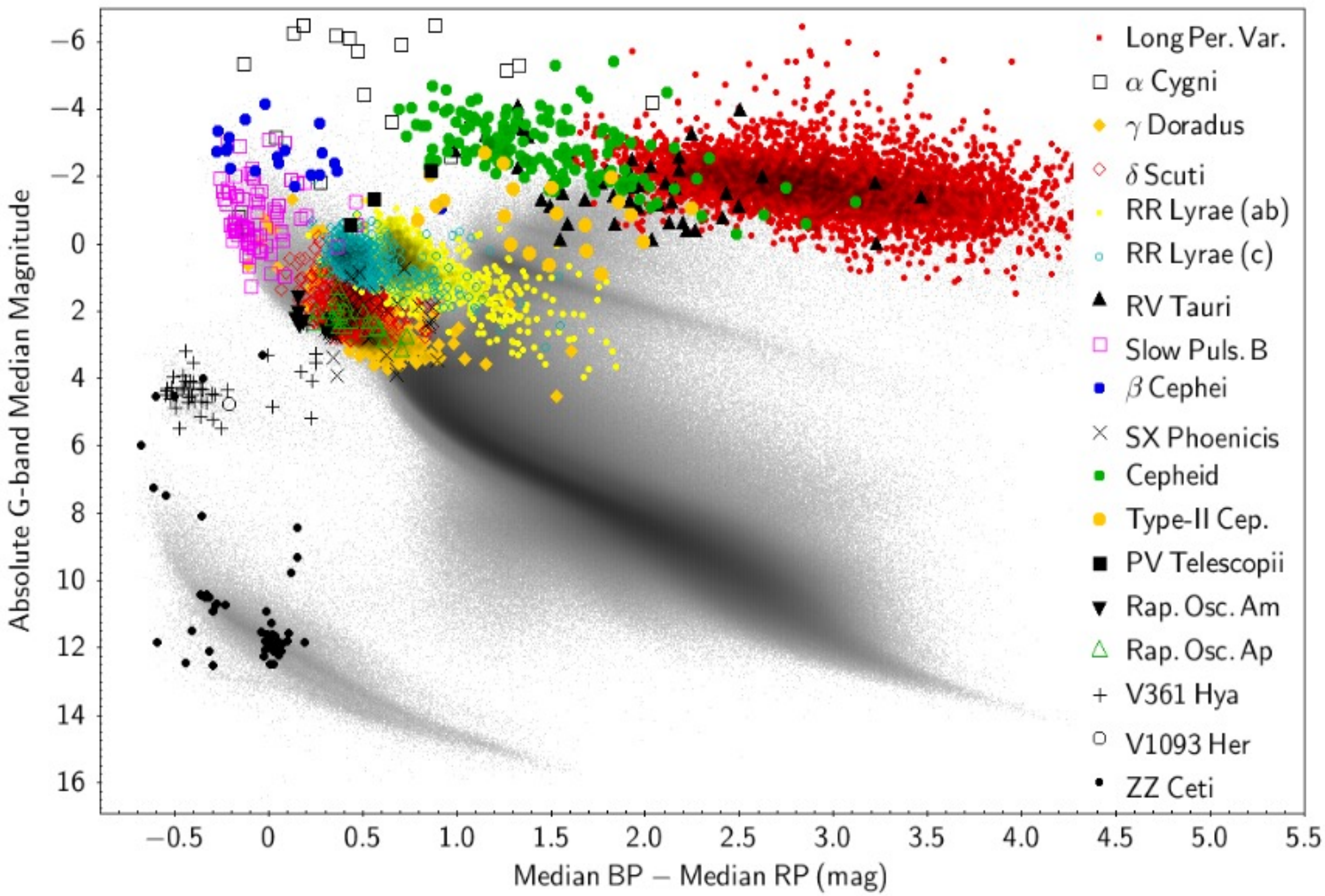


Fig. 2. Known pulsating variable stars retrieved from pubished catalogues are placed in the observational CaMD, with symbols and colours representing types as shown in the legend (see A.1 for the references from literature per type). All stars satisfy the selection criteria described in Appendix B. The background points in grey denote a reference subset of objects with a stricter constraint on parallax ($\varpi > 1$ mas), which limits the sample size, extinction, and reddening. The effects of interstellar matter and other phenomena (see text) are not corrected for. The condition on the relative precision of G_{BP} measurements introduces artificial cuts in the distributions of low-mass main sequence stars and red (super)giants.

Why Variables?
(RRLs, Cepheids, Mira)

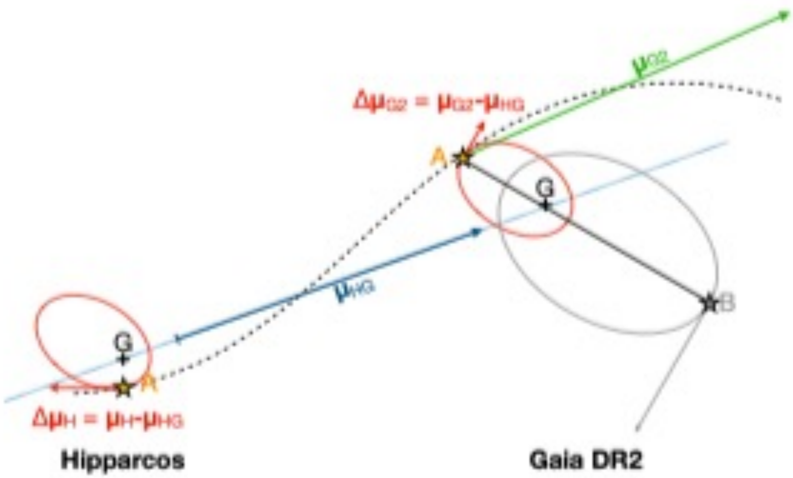
Individual distance, age, reddening

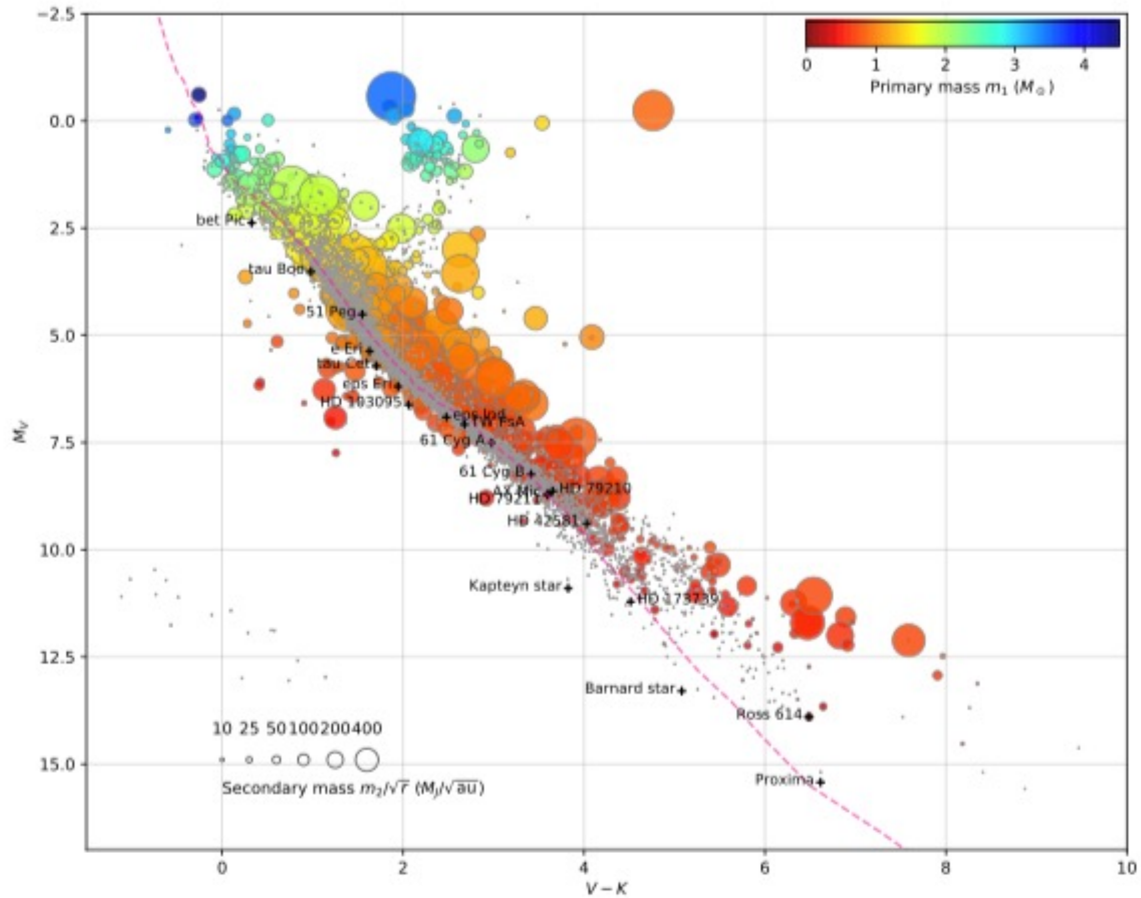
Gaia DR2 → systematics introduced by satellite scanning law

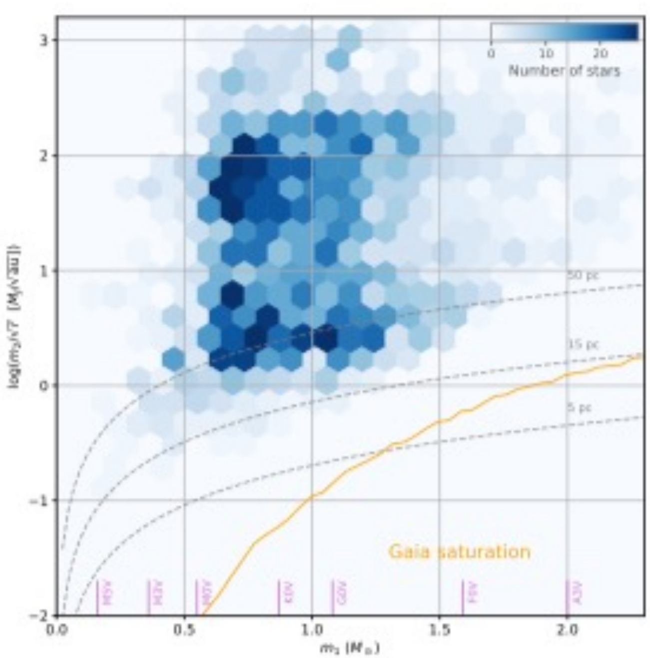
Plus automatic classifications, Plus selection effects

Lemasle + 2018

Stellar & substellar companions of nearby stars from Gaia DR2
Binarity from proper motion anomaly (Kervella + 2019)



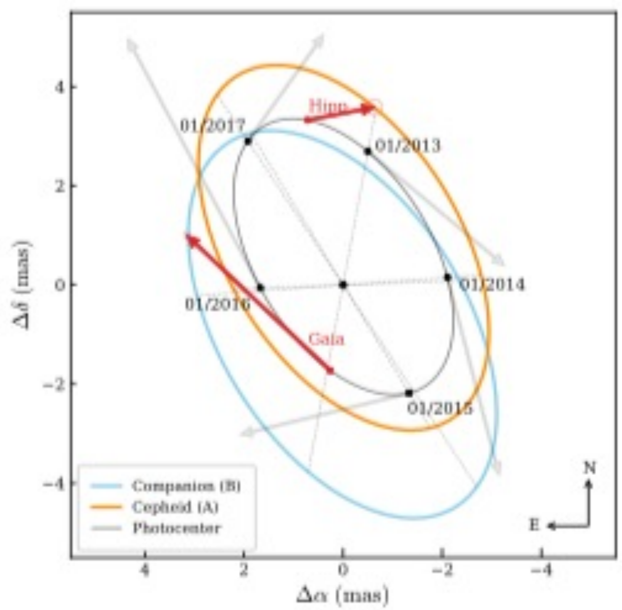


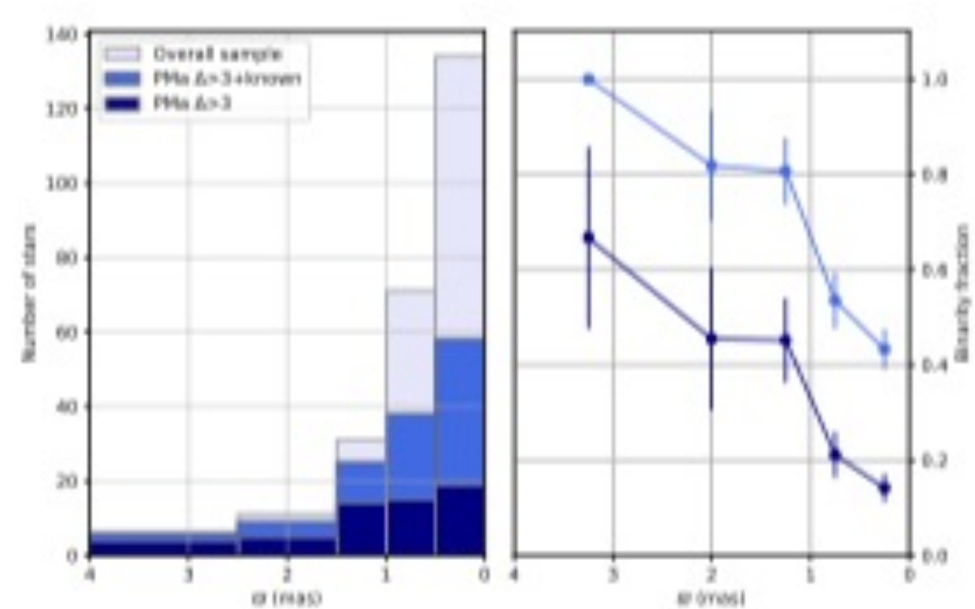


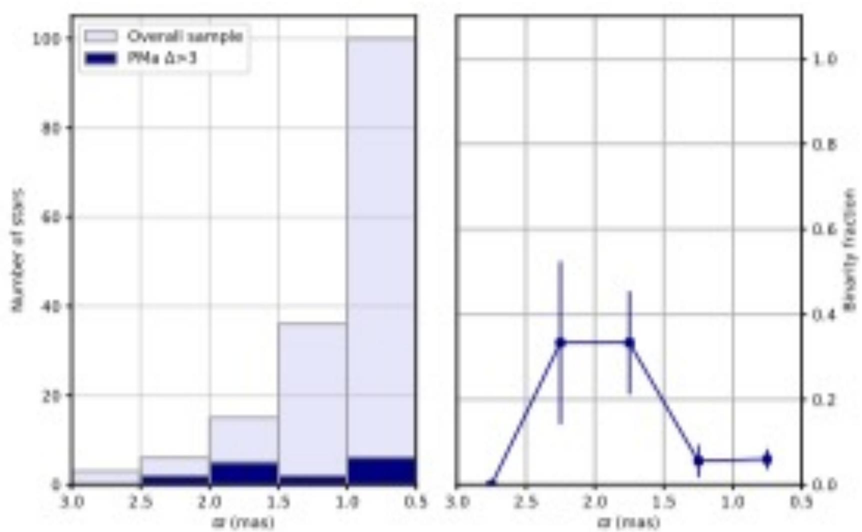
6741 nearby (d< 50 pc) stars

Brown dwarf desert

Multiplicity of Galactic Cepheids & RR Lyrae from Gaia DR2
Binarity from proper motion anomaly (Kervella + 2019)







~350 nearby Cepheids
binary fraction ~80%

~200 RR Lyrae
binary fraction ~7%

Multiplicity of Galactic Cepheids & RR Lyrae from Gaia DR2
Resolved common proper motion pairs (Kervella + 2019)

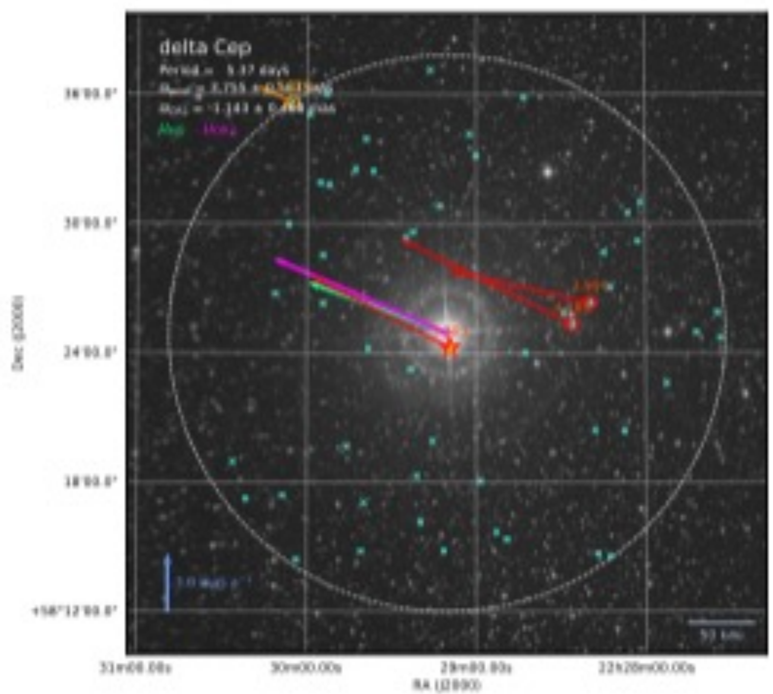


Table 3. Absolute and relative motion of δ Cep A and δ Cep B (HD 213307).

	δ Cep A		δ Cep B	
	α	δ	α	δ
μ_{HG}	$+14.069_{0.009}$	$+2.703_{0.016}$	$+14.134_{0.009}$	$+3.548_{0.015}$
dv_{tan}			$+0.089_{0.013}$	$+1.181_{0.021}$
μ_{H}	$+15.35_{0.22}$	$+3.52_{0.18}$	$+16.19_{0.59}$	$+4.28_{0.50}$
$\Delta\mu_{H}$	$+1.28_{0.23}$	$+0.82_{0.19}$	$+2.06_{0.59}$	$+0.73_{0.51}$
Δ_{H}	7.0		3.8	
μ_{G2}	$+17.64_{0.81}$	$+3.98_{0.73}$	$+14.09_{0.09}$	$+3.79_{0.09}$
$\Delta\mu_{G2}$	$+3.57_{0.82}$	$+1.27_{0.72}$	$-0.04_{0.11}$	$+0.24_{0.12}$
Δ_{G2}	4.7		2.1	

Notes. The absolute and linear proper motions (μ and $\Delta\mu$) are expressed in mas a^{-1} and the differential tangential velocity of B relative to A (dv_{tan}) in km s^{-1}. The angular proper motion was converted to velocity using the GDR2 parallax of component B ($\varpi_{G2,B} = 3.393 \pm 0.049$ mas).

Trigonometric parallaxes of companion stars are more accurate than Cepheid parallaxes:

a) Static stars no variation in photometric barycenter

b) Systematically fainter

Galactic Formation

Eggen 62: monolithic collapse of a gas cloud.

Searle & Zinn 78: hierarchical merging of protogalaxies.

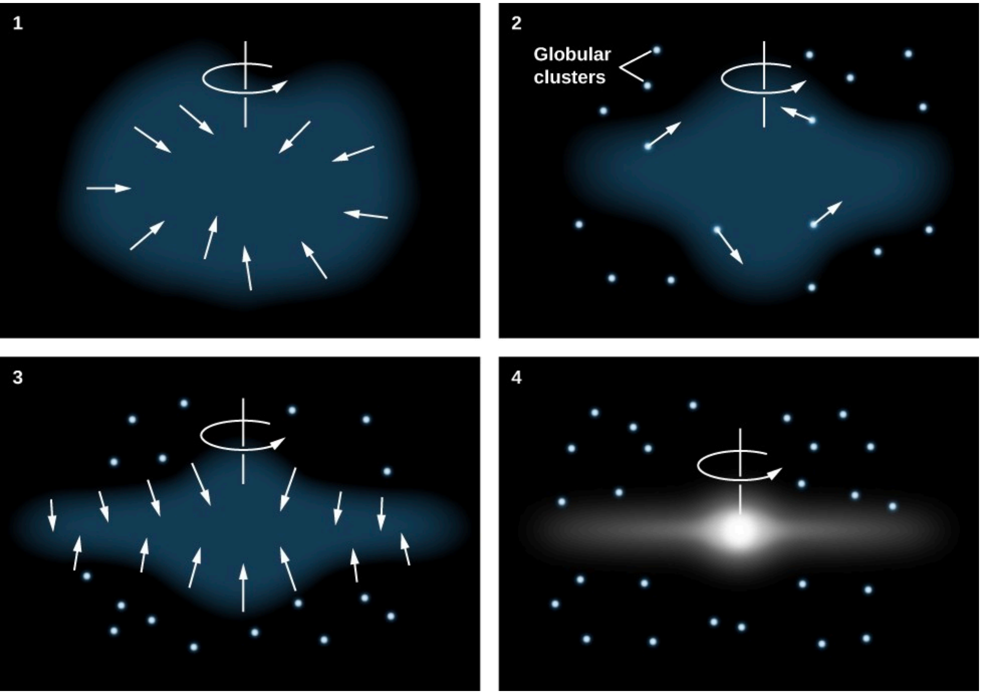


Image by LumenLearning

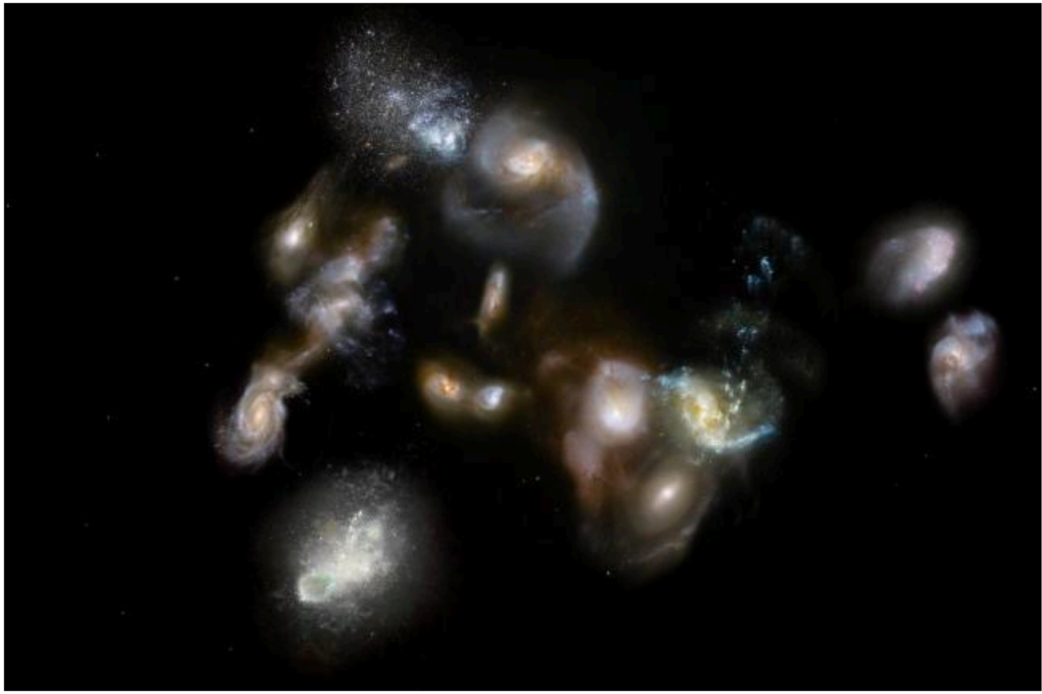
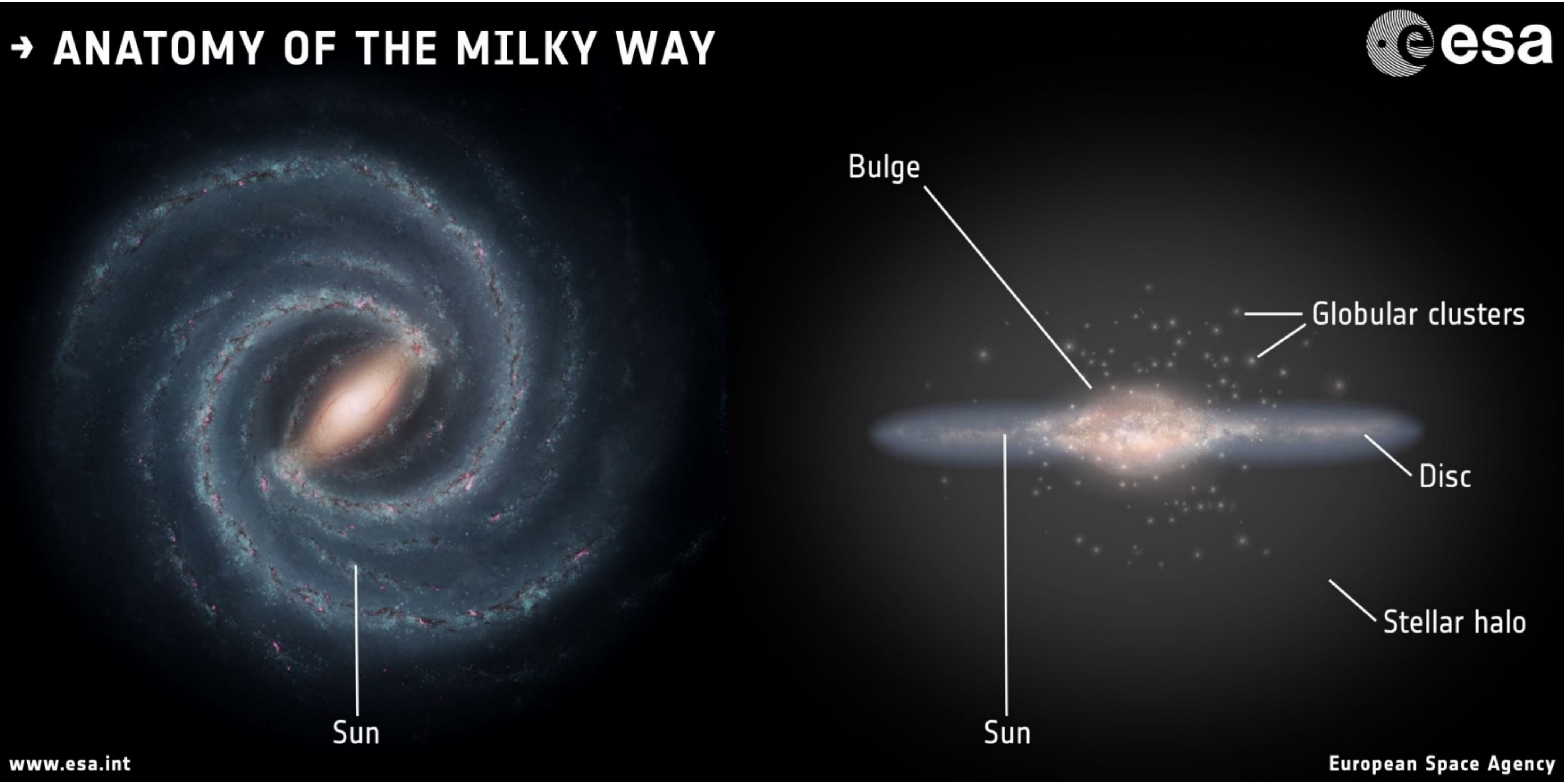


Image by ESO/M. Kornmesser

The Milky Way

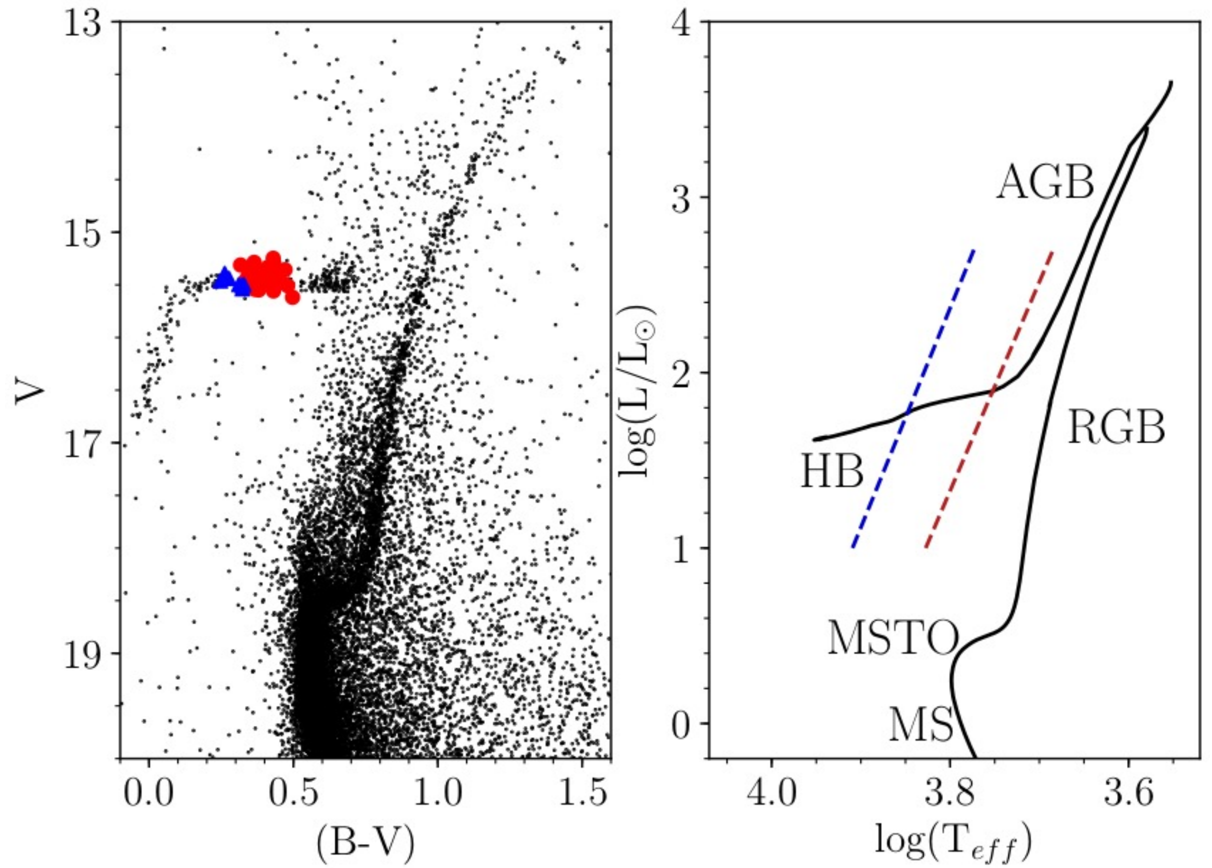


The RR Lyrae Stars

Bright, **old** low mass stars that burn He in their cores and H in a shell.

They are found in a wide range of metallicities ([Fe/H] ≈ −2.5 dex to slightly super-solar). Yes, metal-rich too!

Short period radial pulsators (periods under around 1 day) with very characteristic light curves.

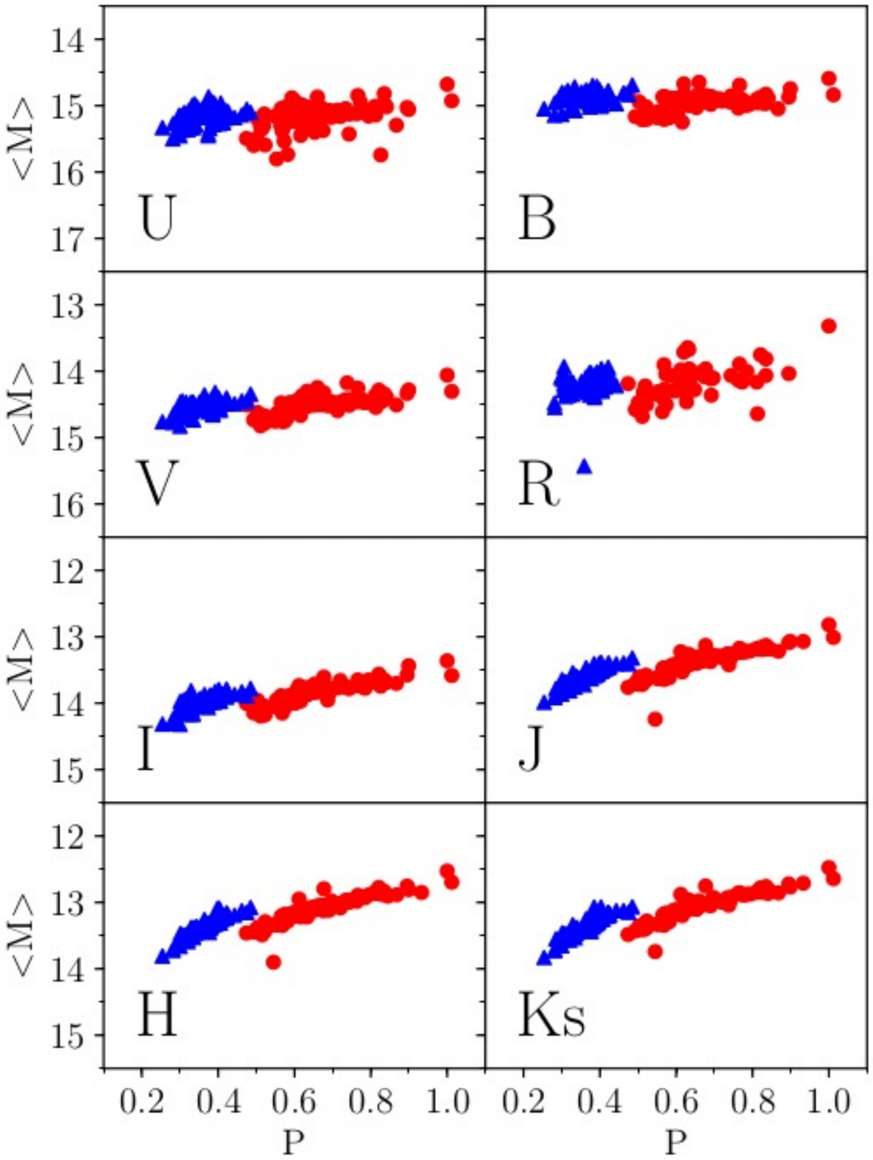


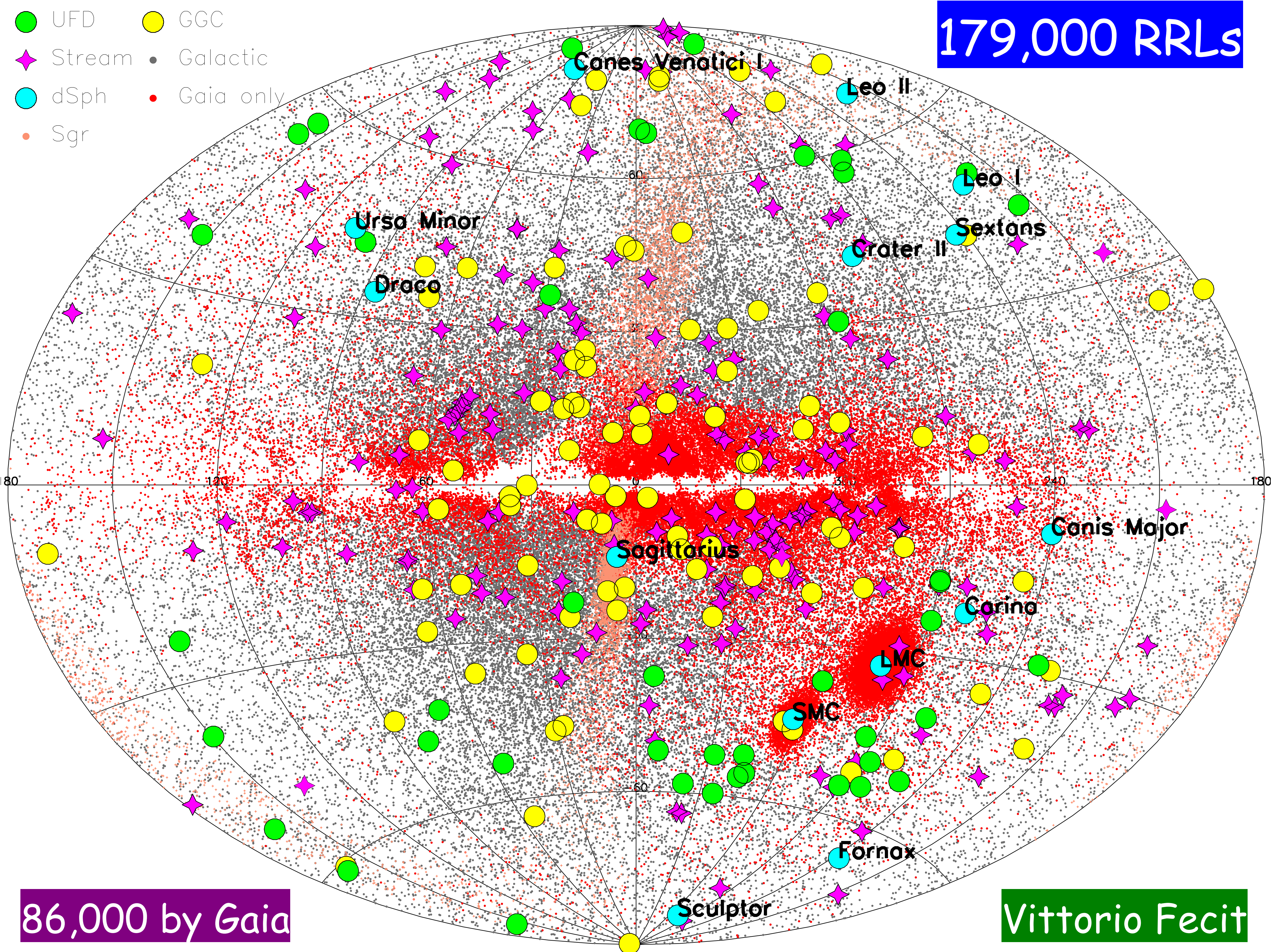
The RR Lyrae Stars

Period-luminosity relations in the near-infrared.

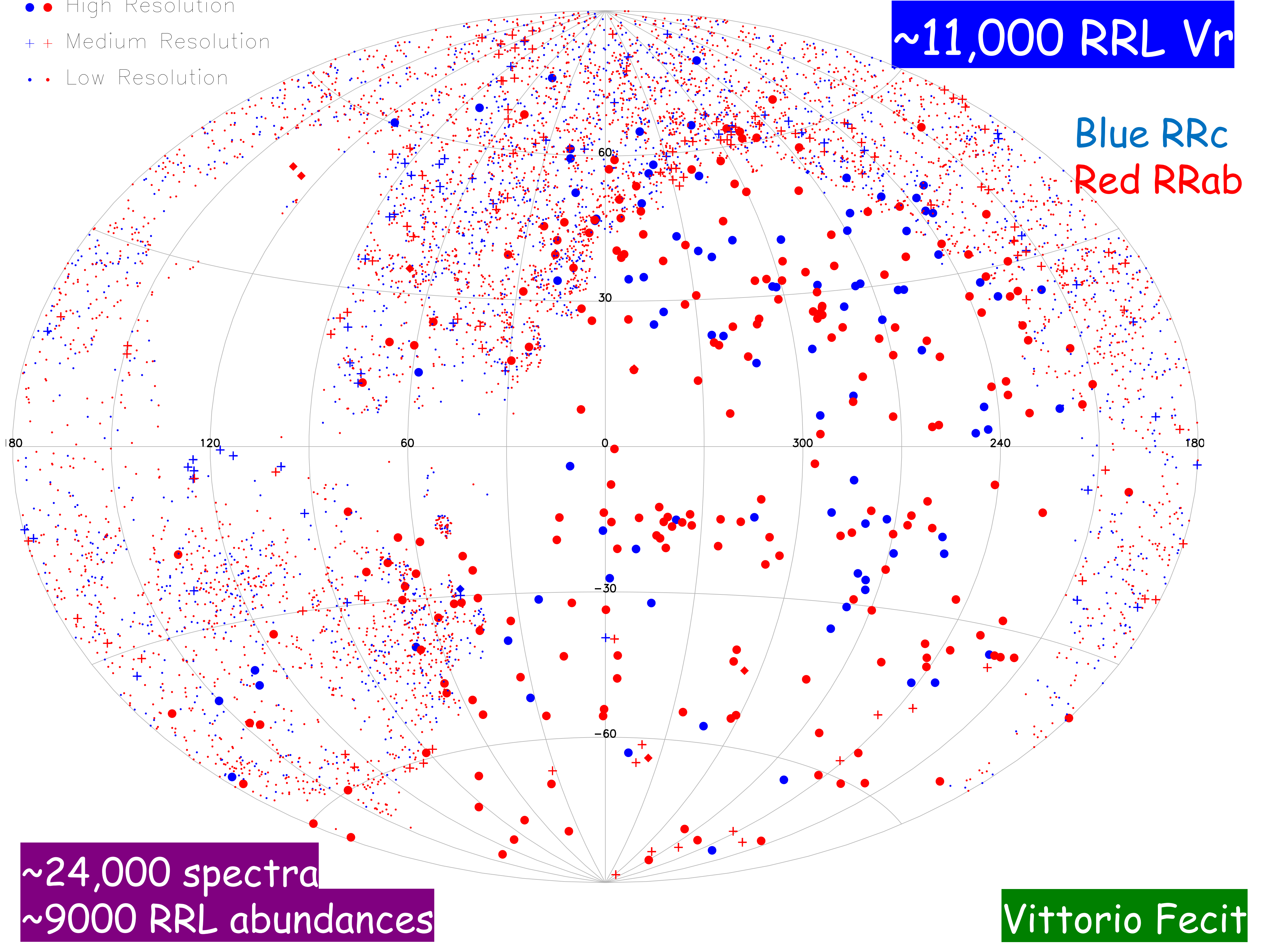
They can be placed in 3D!

Ideal old tracers: bright, well constrained ages, precise positions, wide range of chemical enrichment histories.





UFD
GGC
Stream
Galactic
dSph
Gaia only
Sgr
179,000 RRLs
Canes Venatici I
Leo II
Leo I
Sextans
Ursa Minor
Crater II
Draco
Canis Major
Sagittarius
Carina
LMC
SMC
Fornax
Sculptor
86,000 by Gaia
Vittorio Fecit


High Resolution
Medium Resolution
Low Resolution
~11,000 RRL Vr
Blue RRc
Red RRab
60
30
0
−30
−60
180
120
60
0
300
240
180
~24,000 spectra
~9000 RRL abundances
Vittorio Fecit

High resolution sample (6300 spectra, 143 RRLs)

Feros

Harps

Du Pont

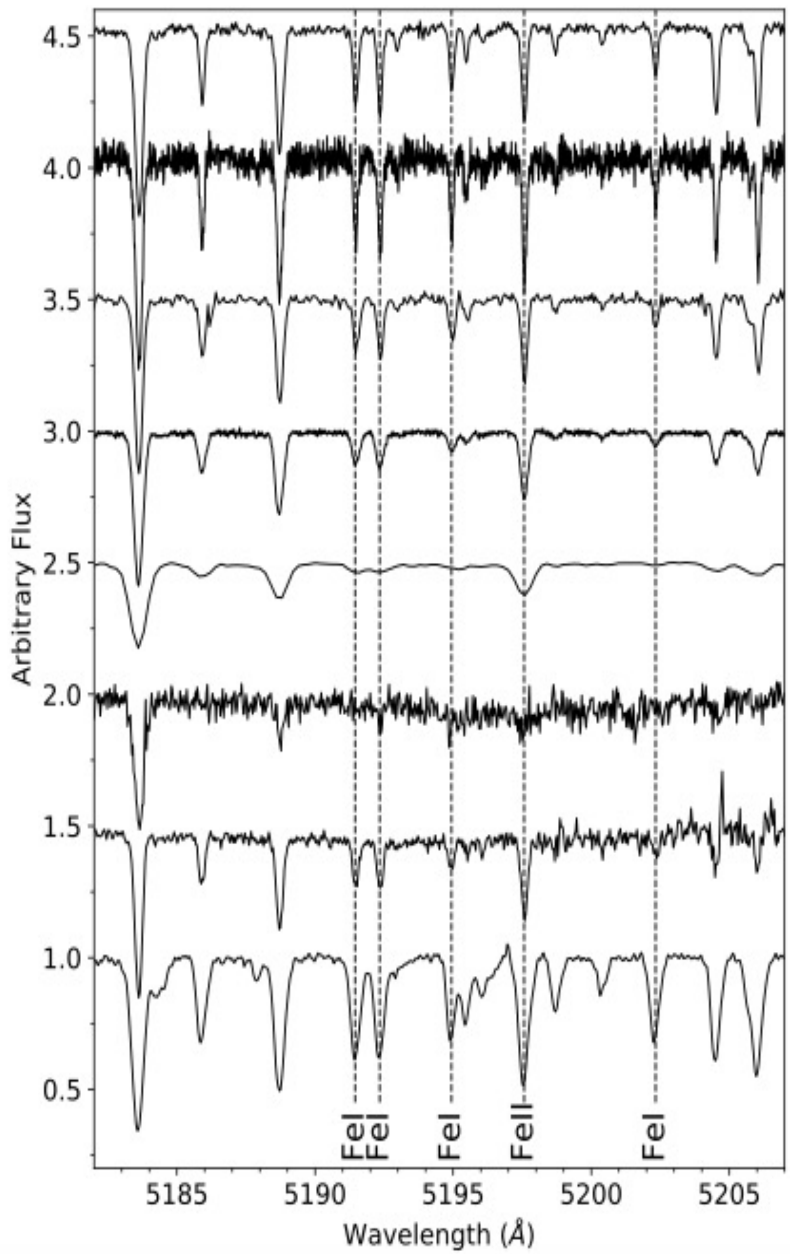
UVES

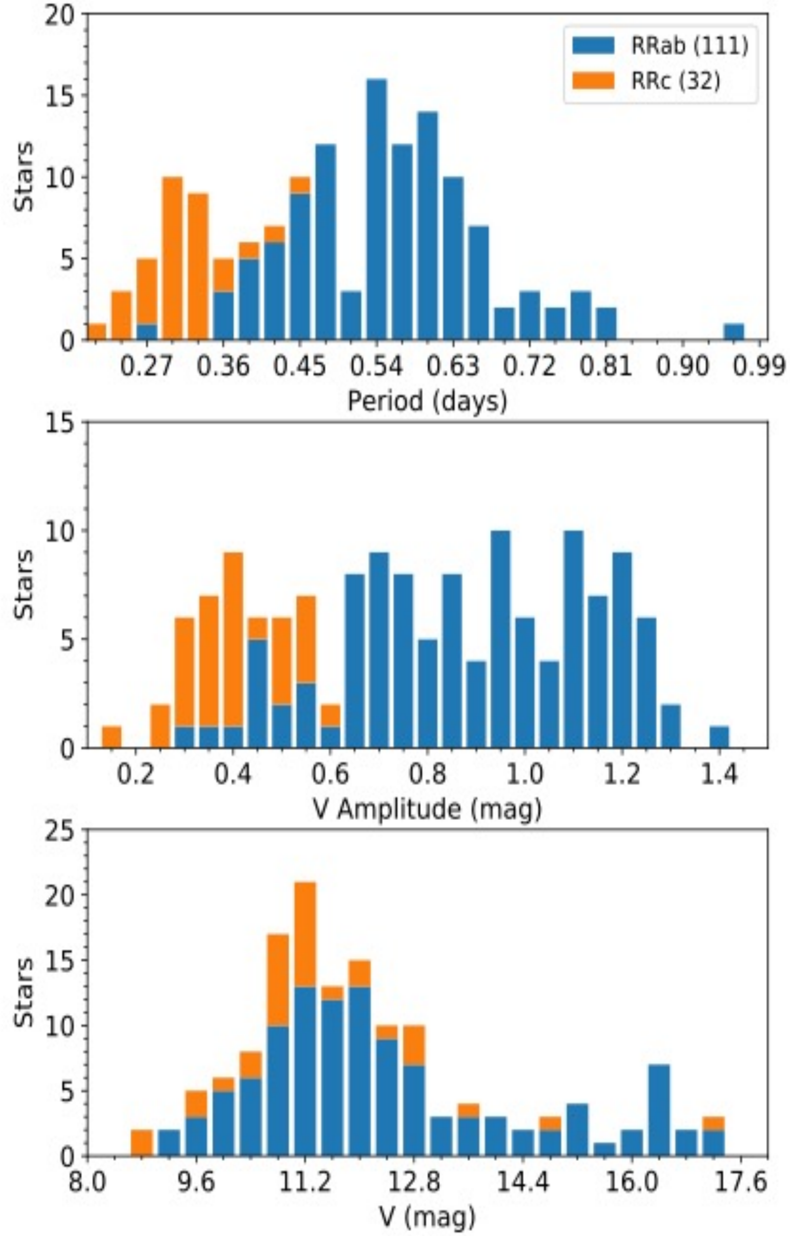
X-shooter

Subaru

Stella

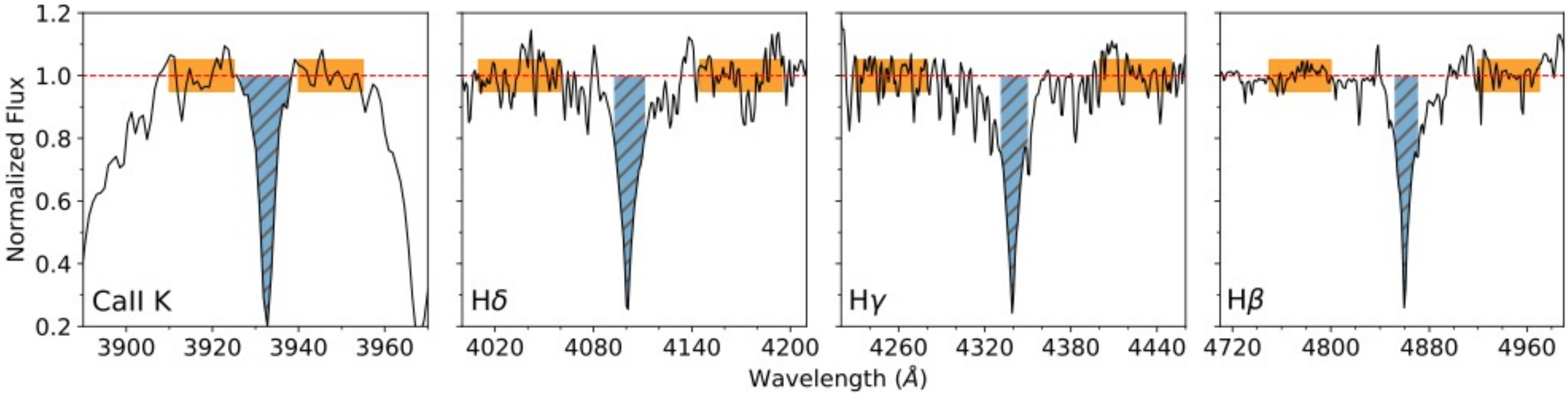
Salt





Crestani + 2021a

Low resolution sample (6450 spectra, 5000 RRLs)

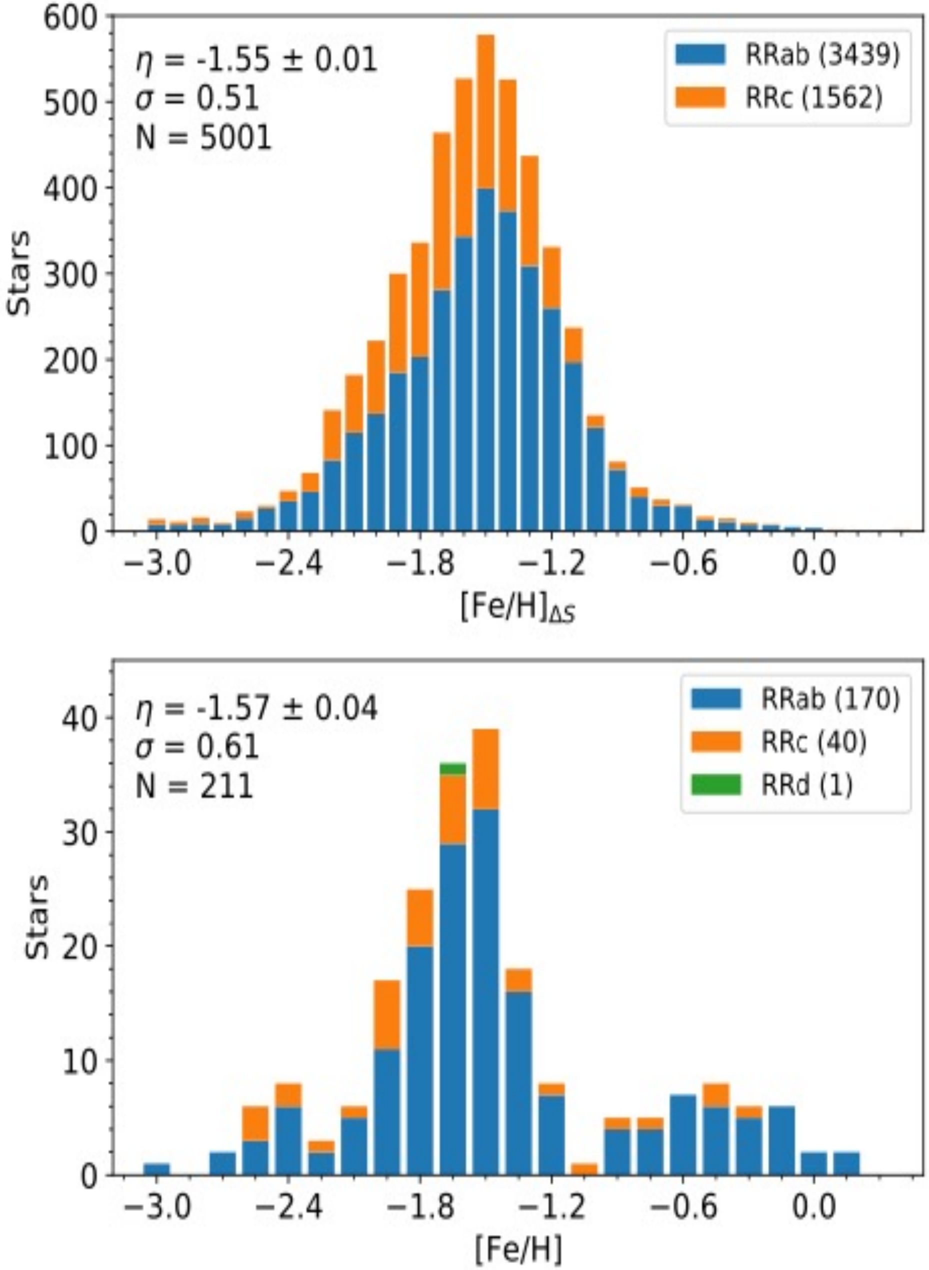


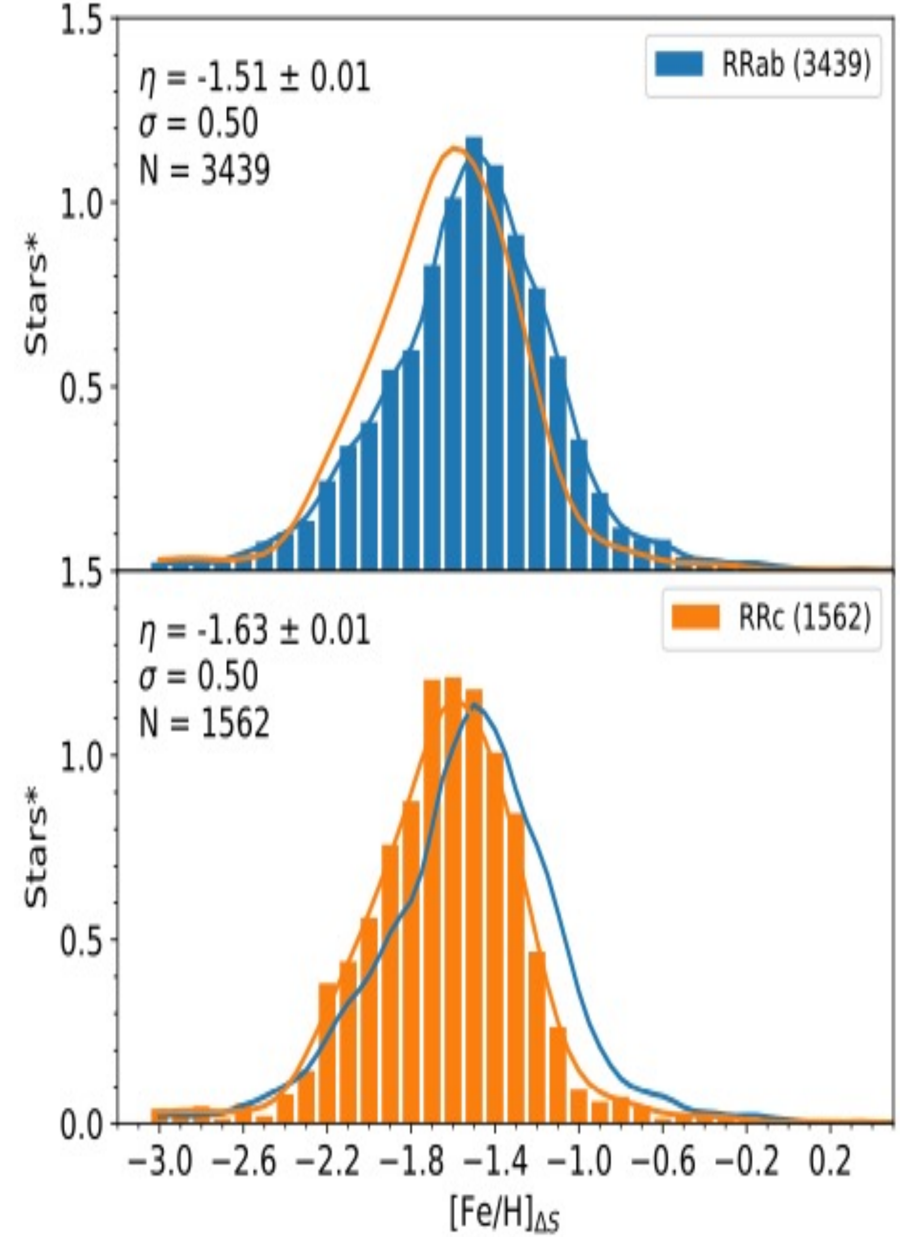
A new calibration of the DeltaS method introduced more than 60 years ago by Preston (1959) testing everything Wavel. range, pulsation cycle, linearity over 3 dex in metallicity and for the first time including first overtone RRLs.

SDSS-SEGUE

Crestani + 2021a

High & Low resolution sample

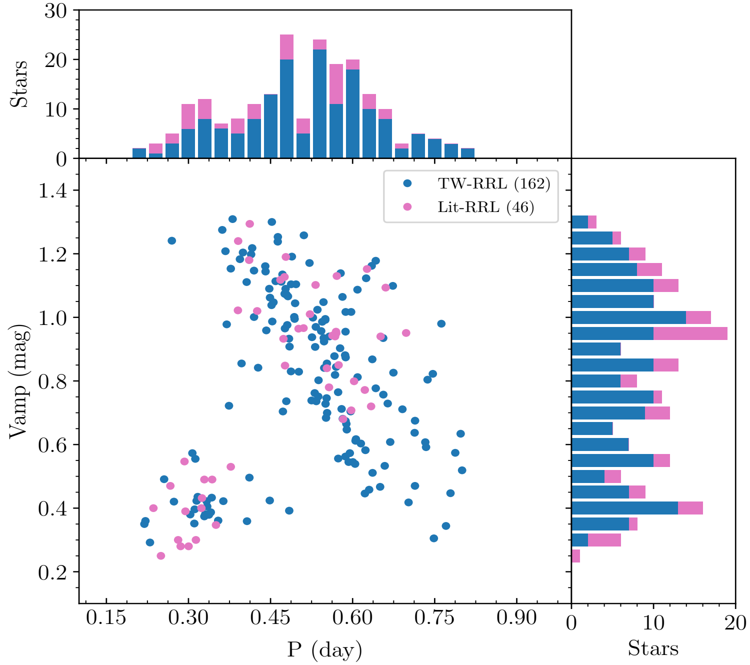


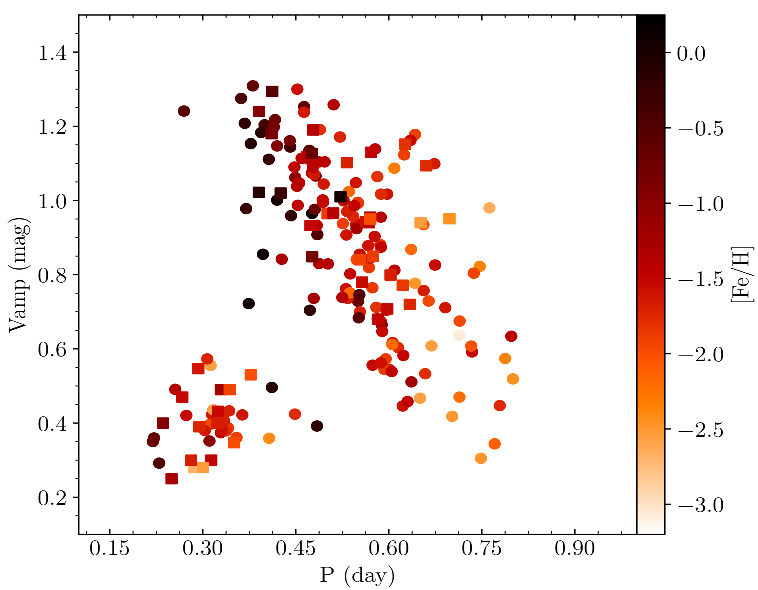


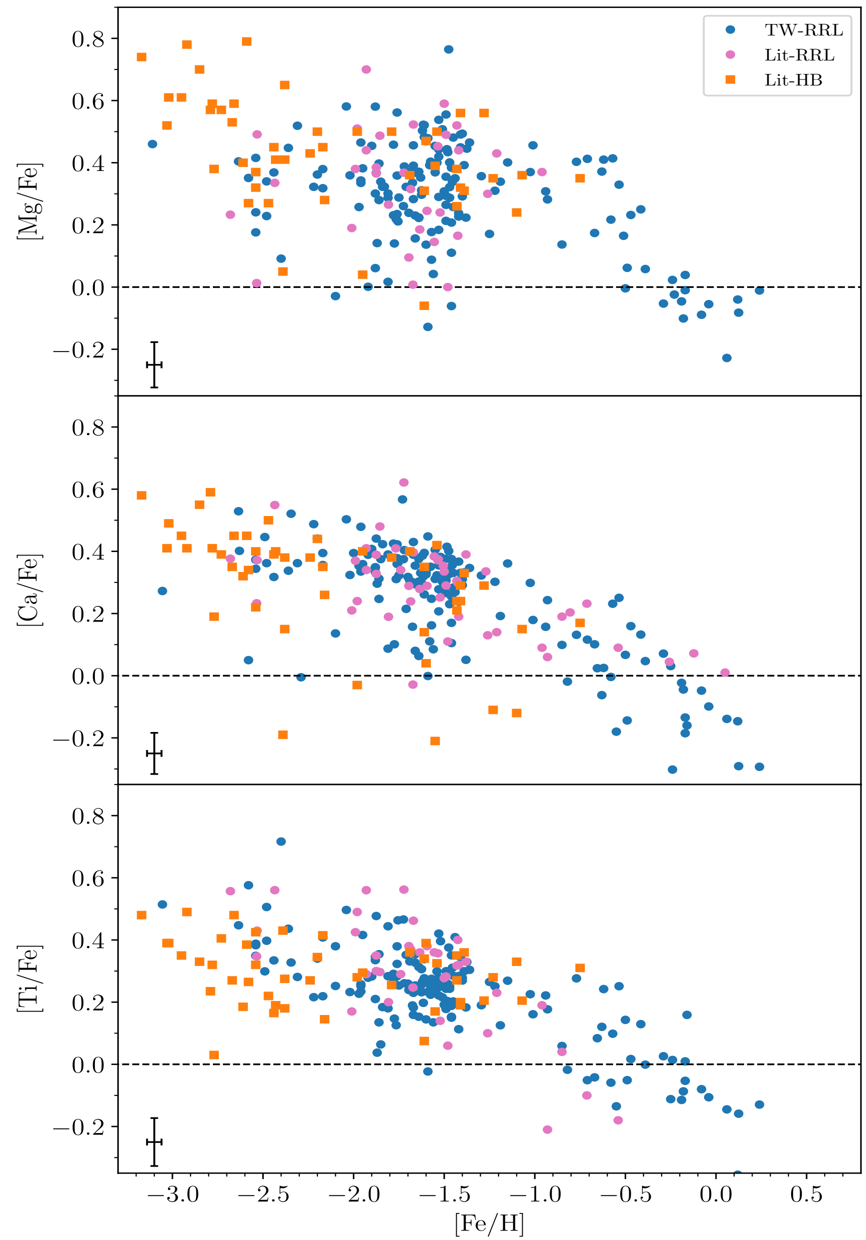
Solid evidence of metal-rich RRLs

Crestani + 2021a

The more you get the more you want!!



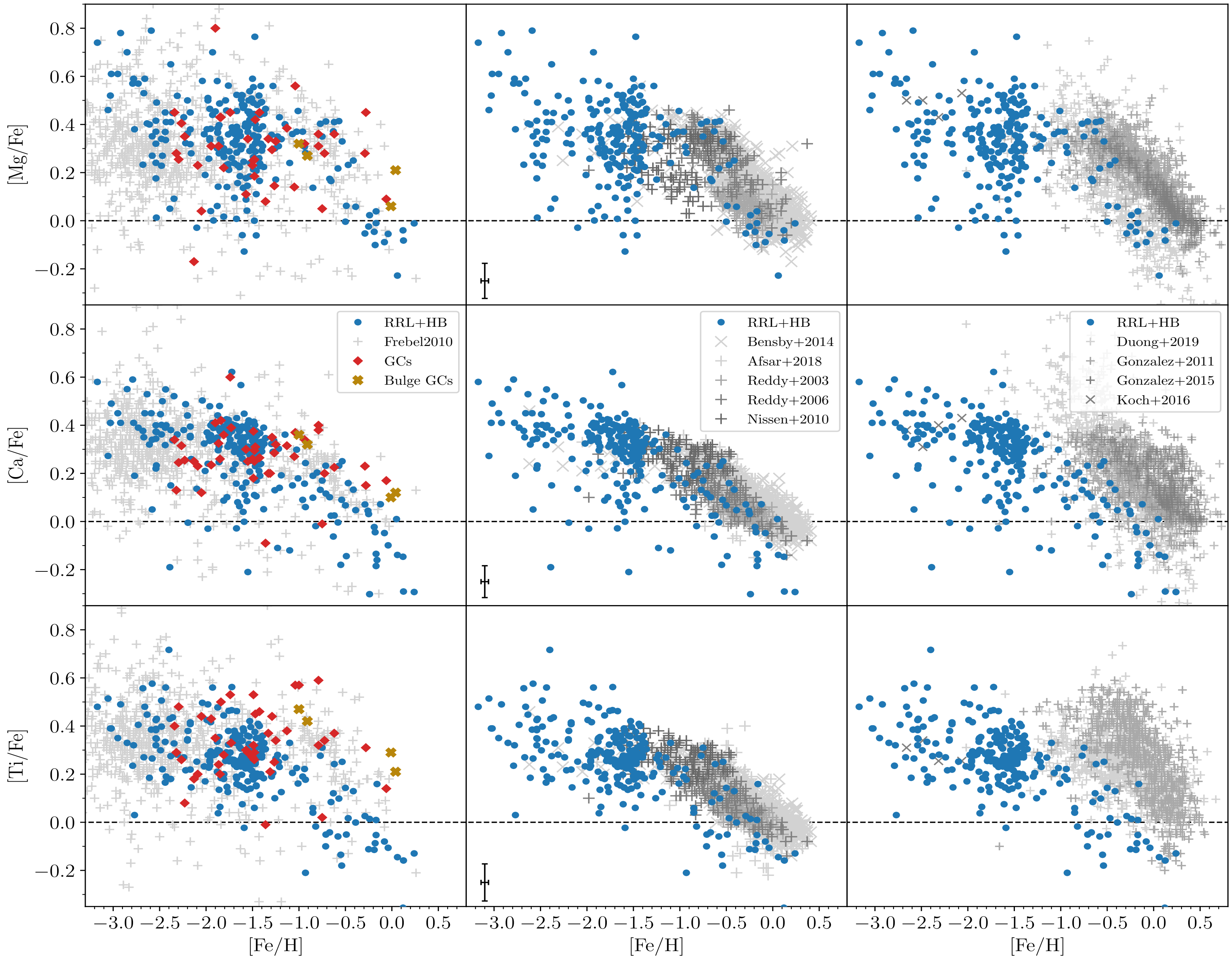




Larger HR sample (>200) abundances for Mg, Ca, Ti

Crestani + 2021b

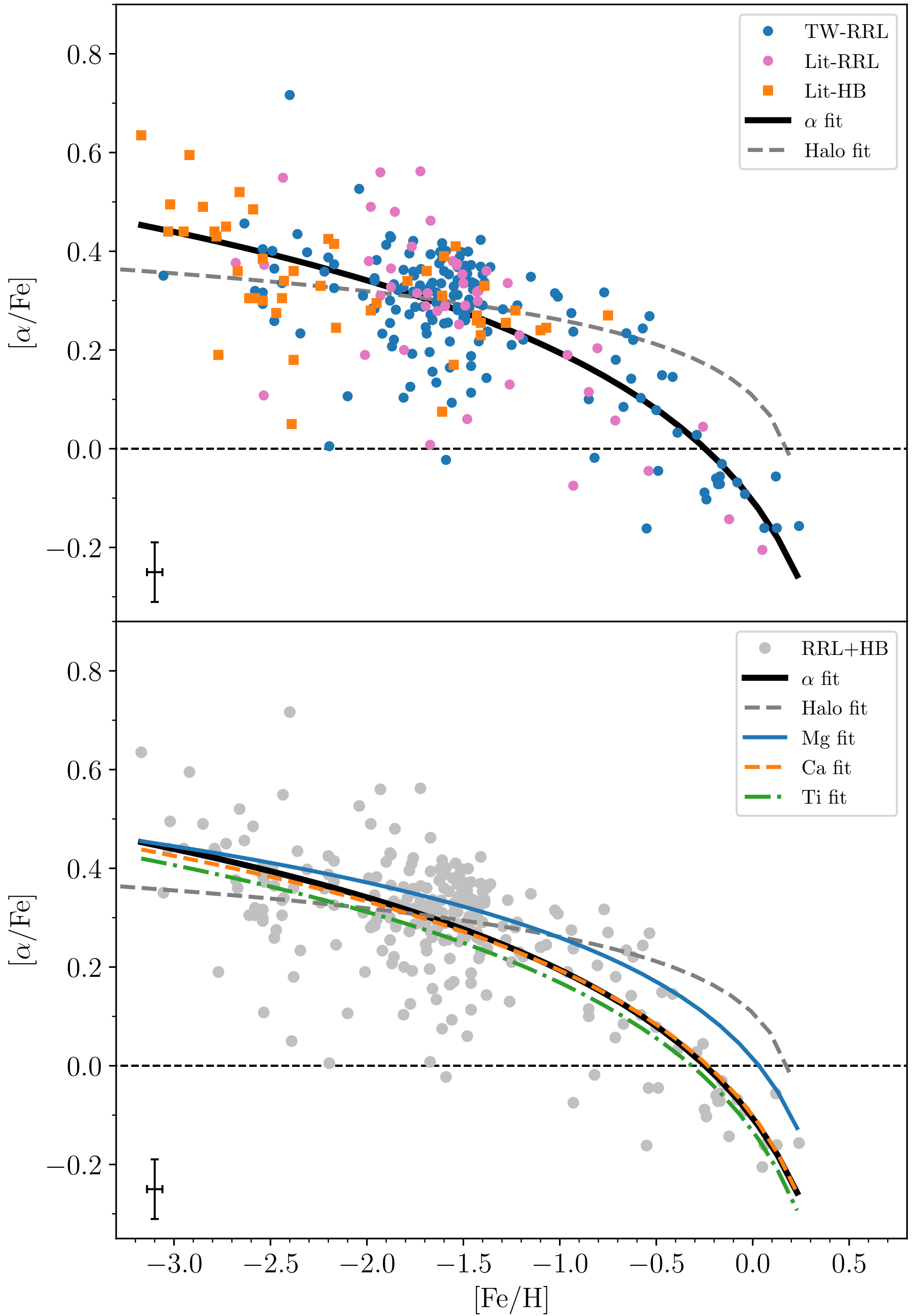
The more you get the more you want!!



GCs marginally cover the metal-rich regime

Crestani + 2021b

The more you get the more you want!!



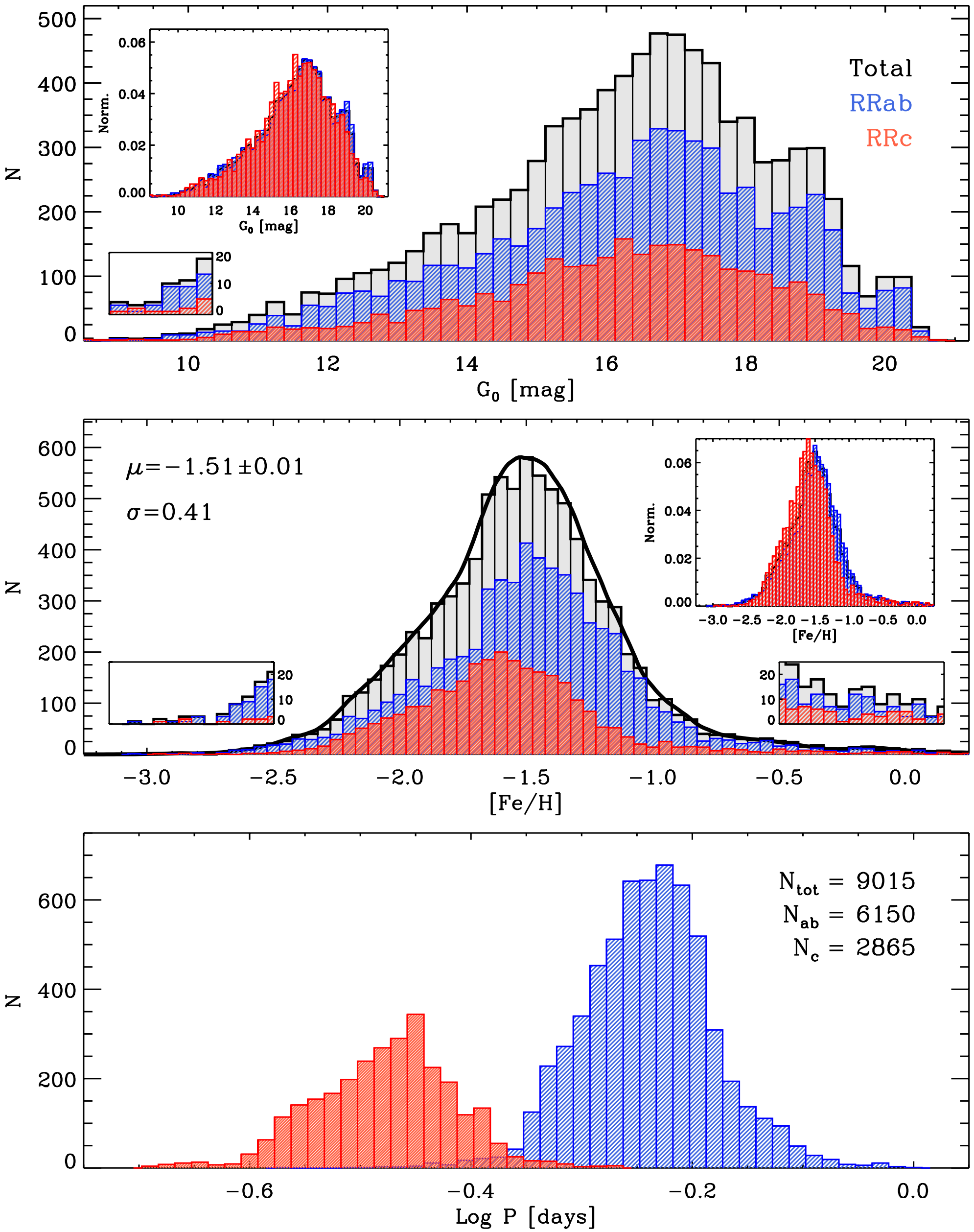
Solid evidence of metal-rich alpha-poor RRLs

The trend is clear in Ca & Ti
Milder in Mg

If supported by independent investigations → implications on the early SNIa enrichment

Crestani + 2021b

A new spin on the Oosterhoff dichotomy



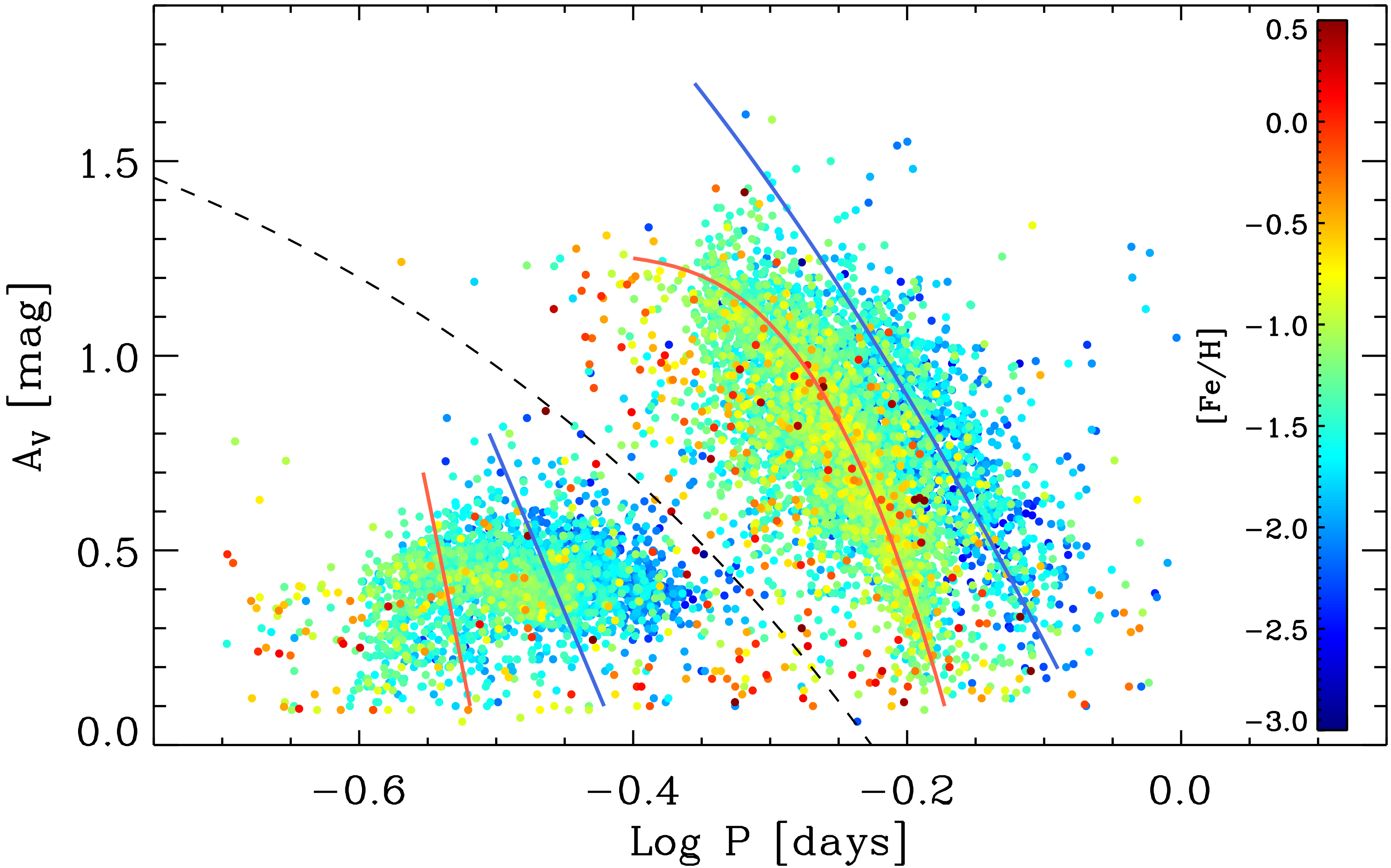
Largest spectroscopic catalog for field RRLs ever collected (more than 9000)

mean metallicity and spread agree with previous estimates,

RRc are on average more metal-poor

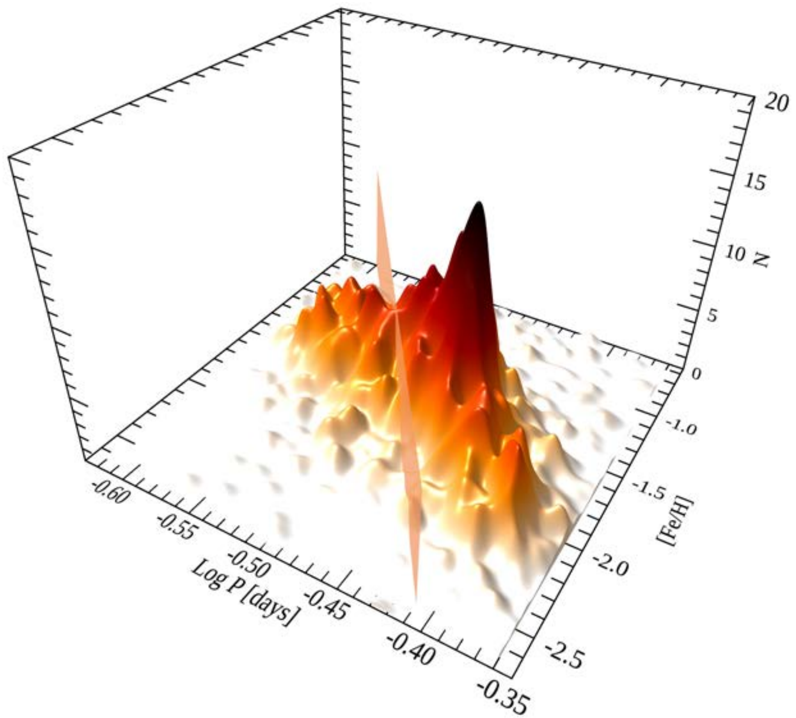
Fabrizio + 2021

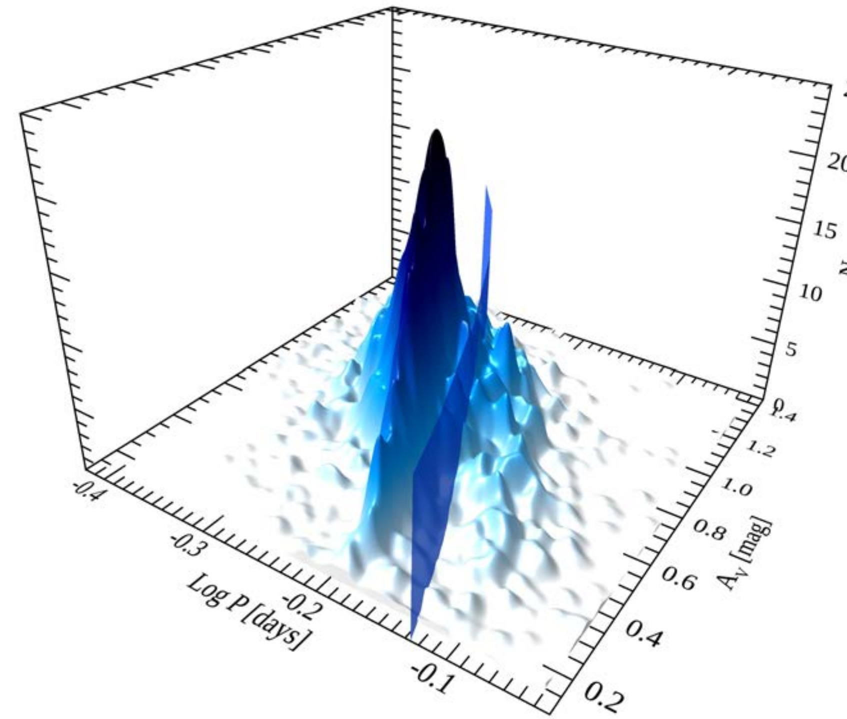
A new spin on the Oosterhoff dichotomy

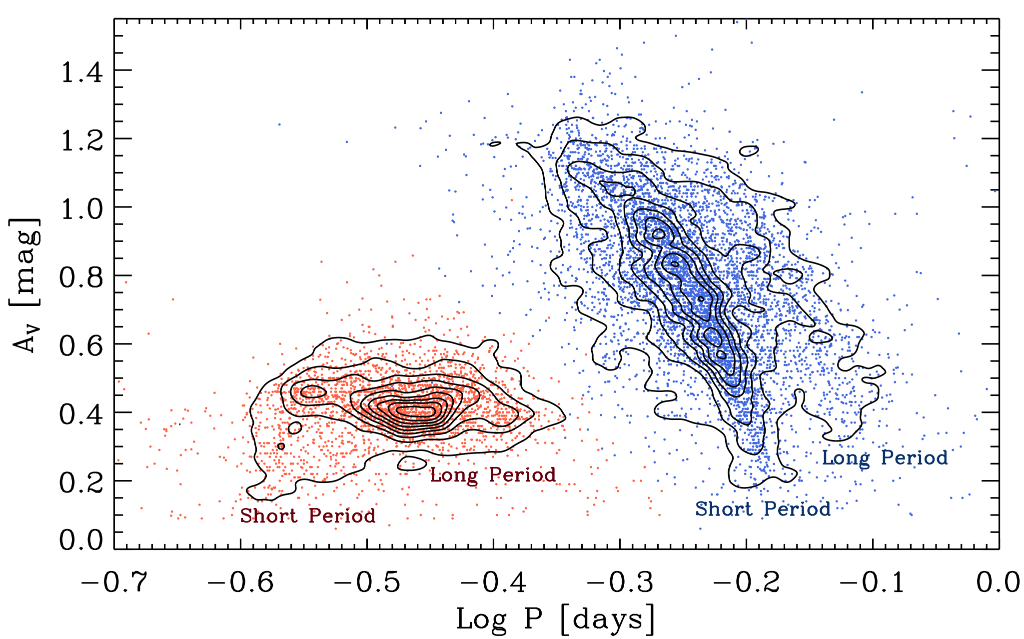


Fabrizio + 2021

A new spin on the Oosterhoff dichotomy

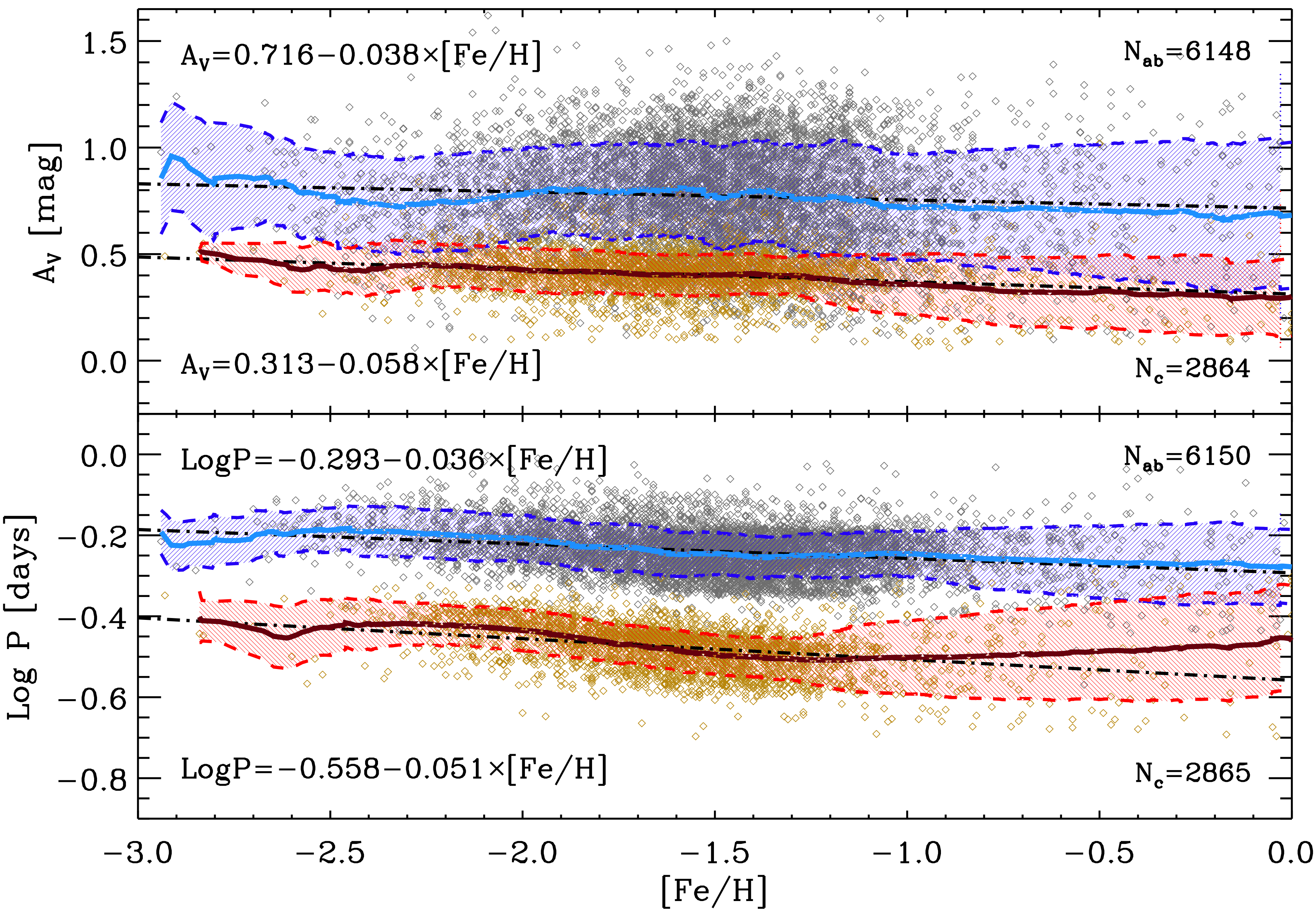




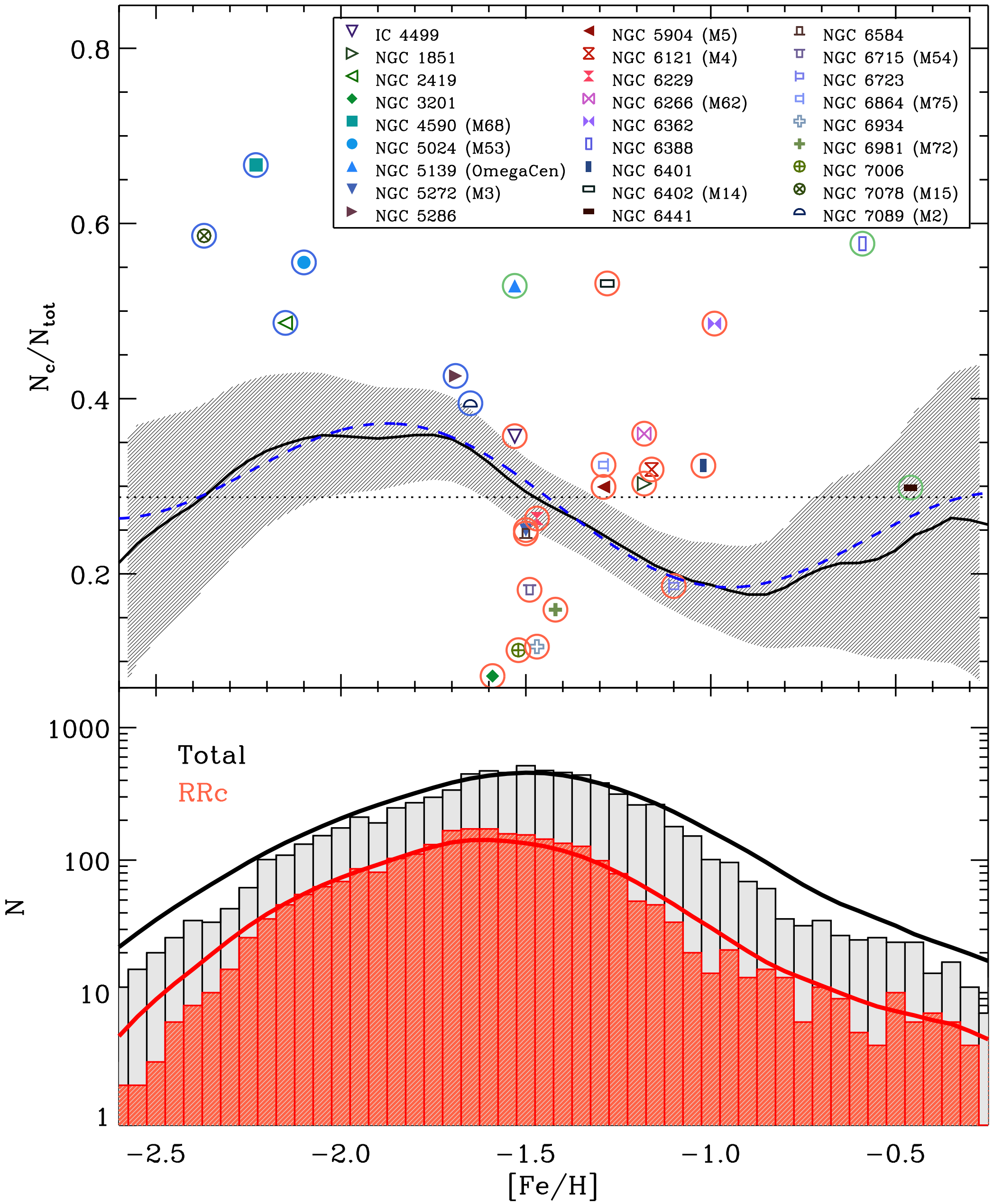


Fabrizio + 2021

The transition from discrete to continuous distributions!!!



The transition from discrete to continuous distributions!!!



Galactic globulars played a minor role in building up the Halo

The increase in the population ratio is not supported by canonical HB morphology

Fabrizio + 2021

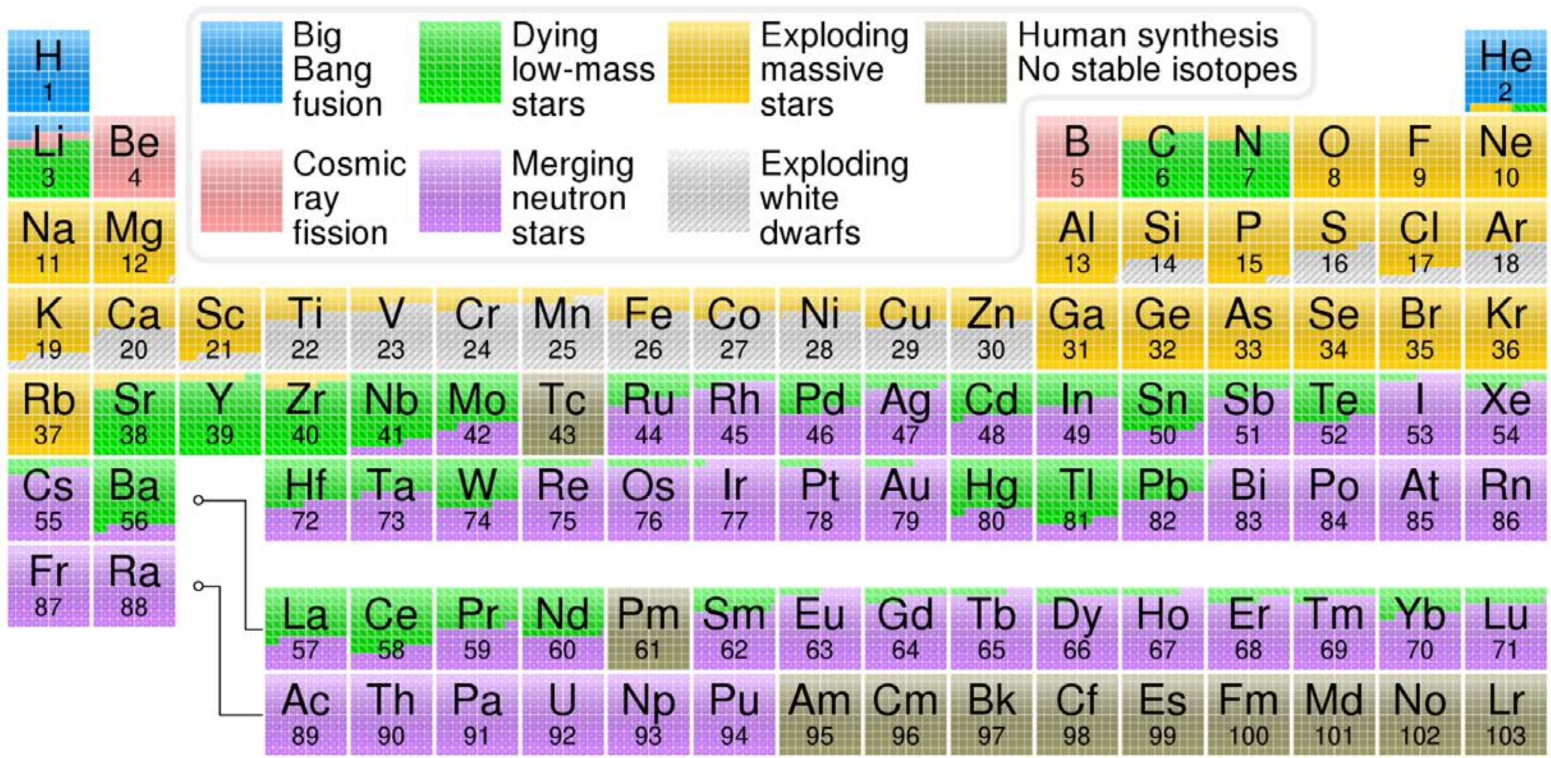
Elements of all major chemical families → CHEMICAL TAGGING

Light odd-Z elements: Na and Al

α-elements: Mg, Si, S, Ca, and Ti.

Fe-peak elements: Sc, V, Cr, Mn, Fe, Co, Ni, Cu, and Zn.

n-capture elements: Sr, Y, Zr, Ba, La, Ce, Pr, Nd, and Eu.

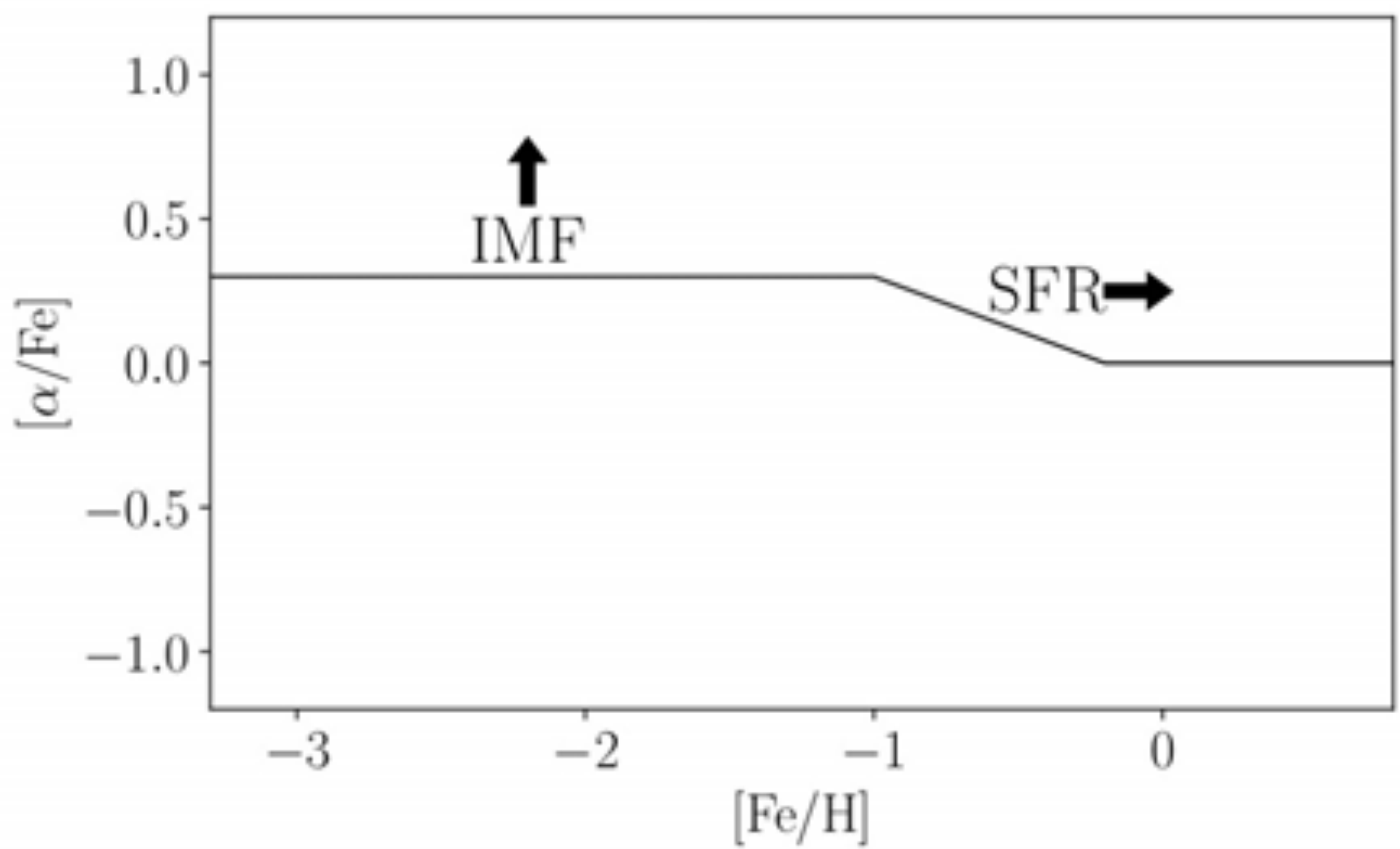


(Elements by astrophysical site, roughly speaking. Image by Cmglee at Wikipedia)

The α-elements

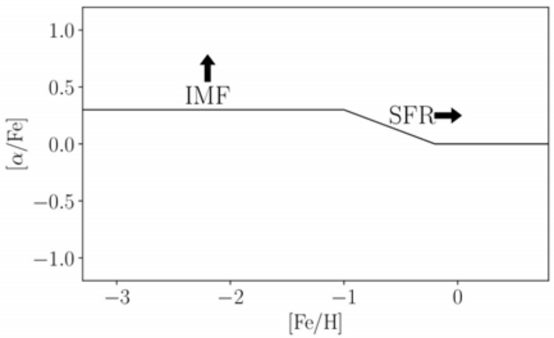
Bona fide tracers of SNe II and the onset of SNe Ia.

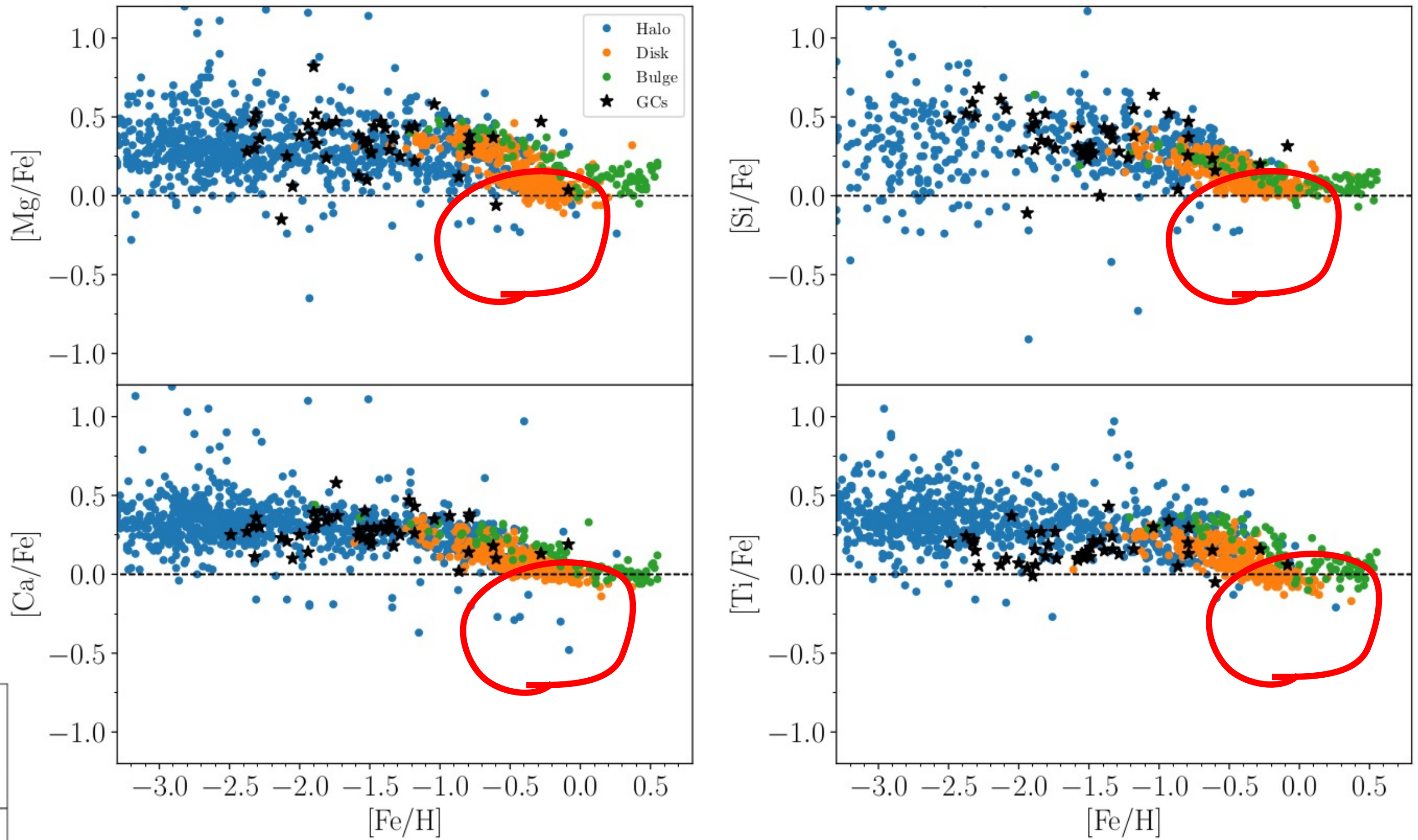
A very interesting plateau and “knee” in the [α/Fe] vs [Fe/H] (metallicity) plane.



The α-elements

Field stars from the literature (not RRLs!) in the three Galactic components.

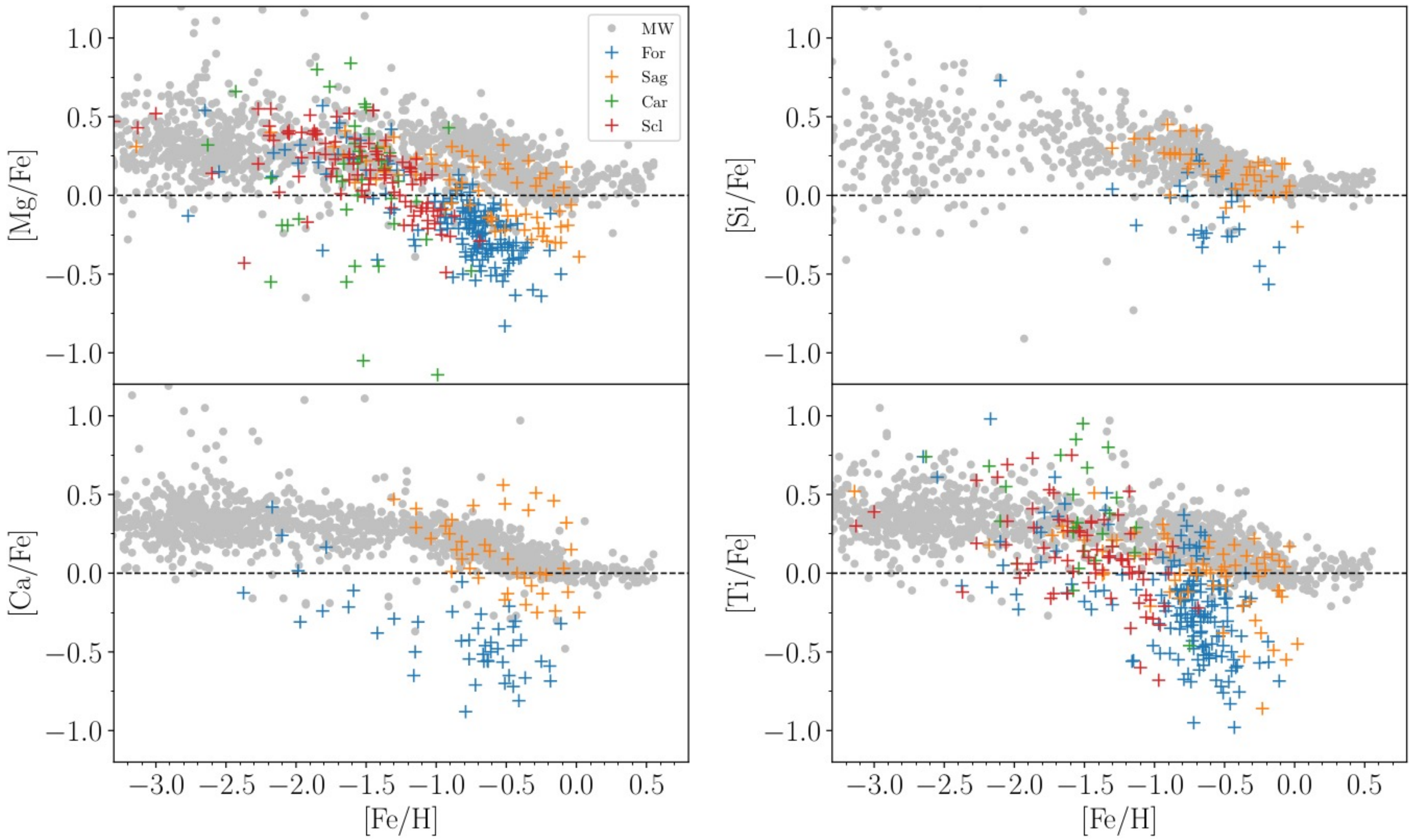




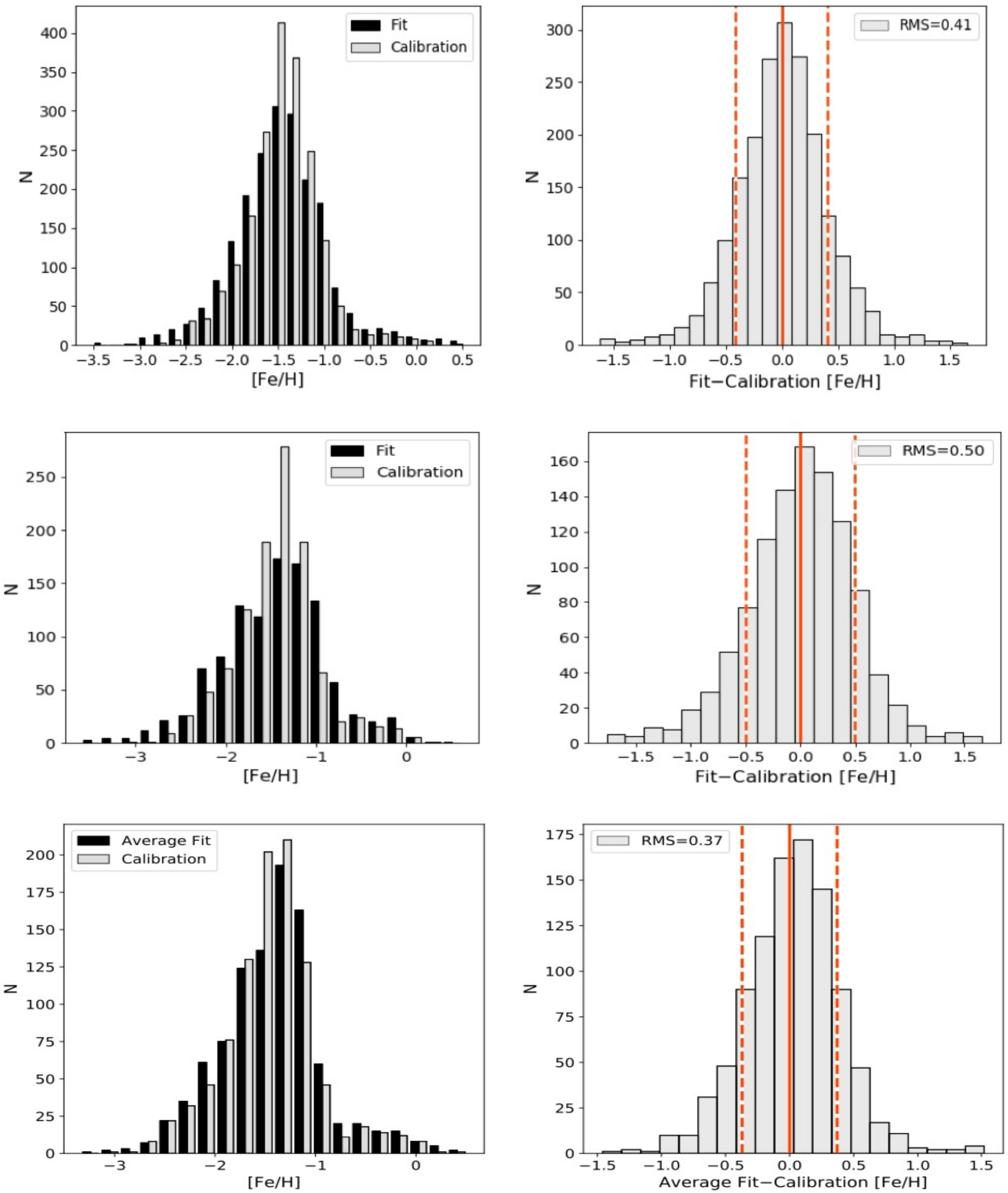
The α-elements

The metal-rich regime is crucial!

Here we see the MW (grey) and nearby dwarf galaxies (colored).



Light curve Fourier Metallicities



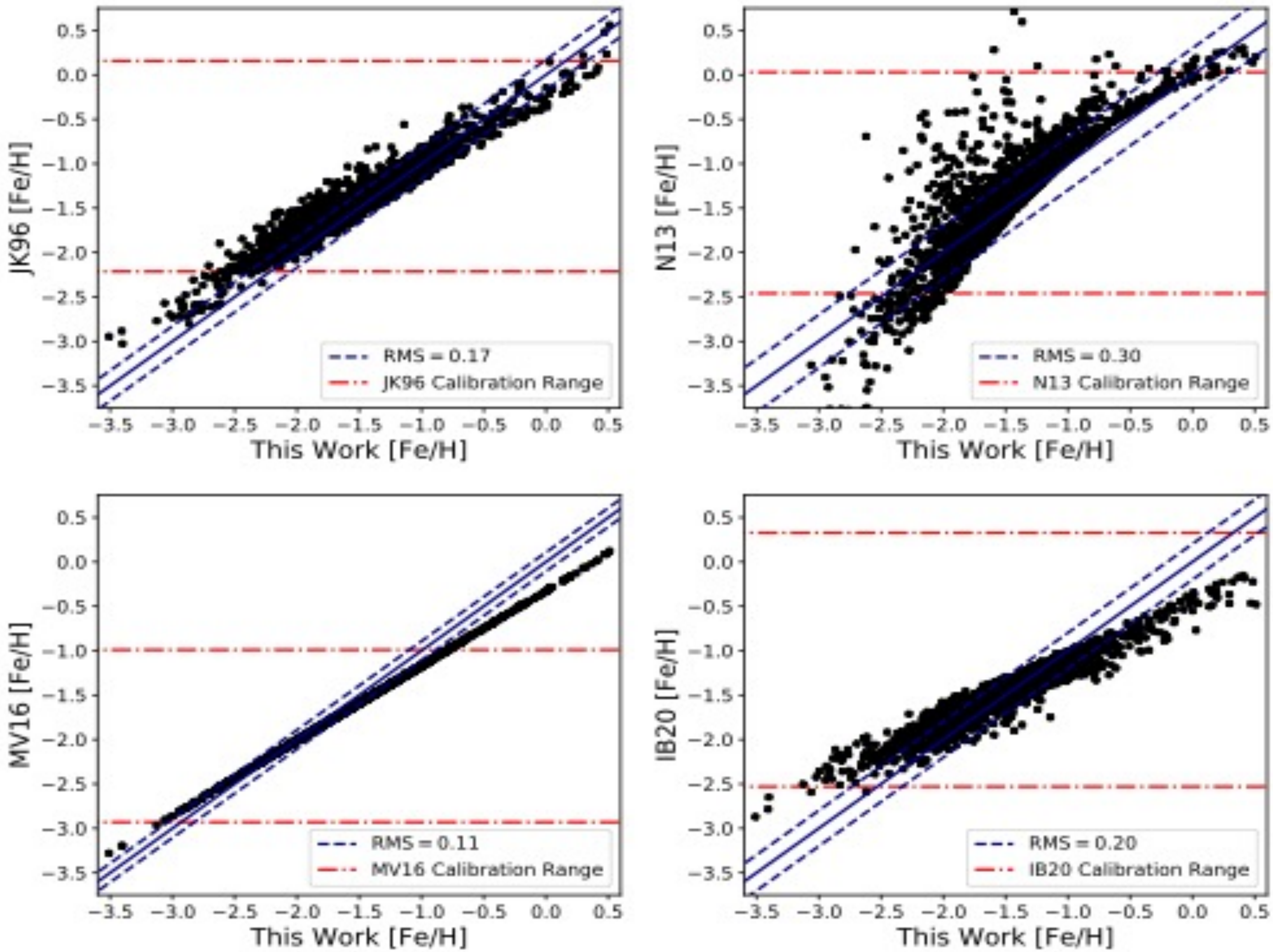
ASAS-SN light curves

Neo-Wise light curves

Neo-Wise + ASAS-SN
Standard deviation ~0.35 dex

Mullen + 2021

Light curve Fourier Metallicities



Systematics in previous empirical relations in the metal-poor and in the metal-rich regime

Mullen + 2021

A new spin on radial velocity templates

barycentric velocities require demanding spectroscopic observations
To overcome the limitation → use of radial velocity template

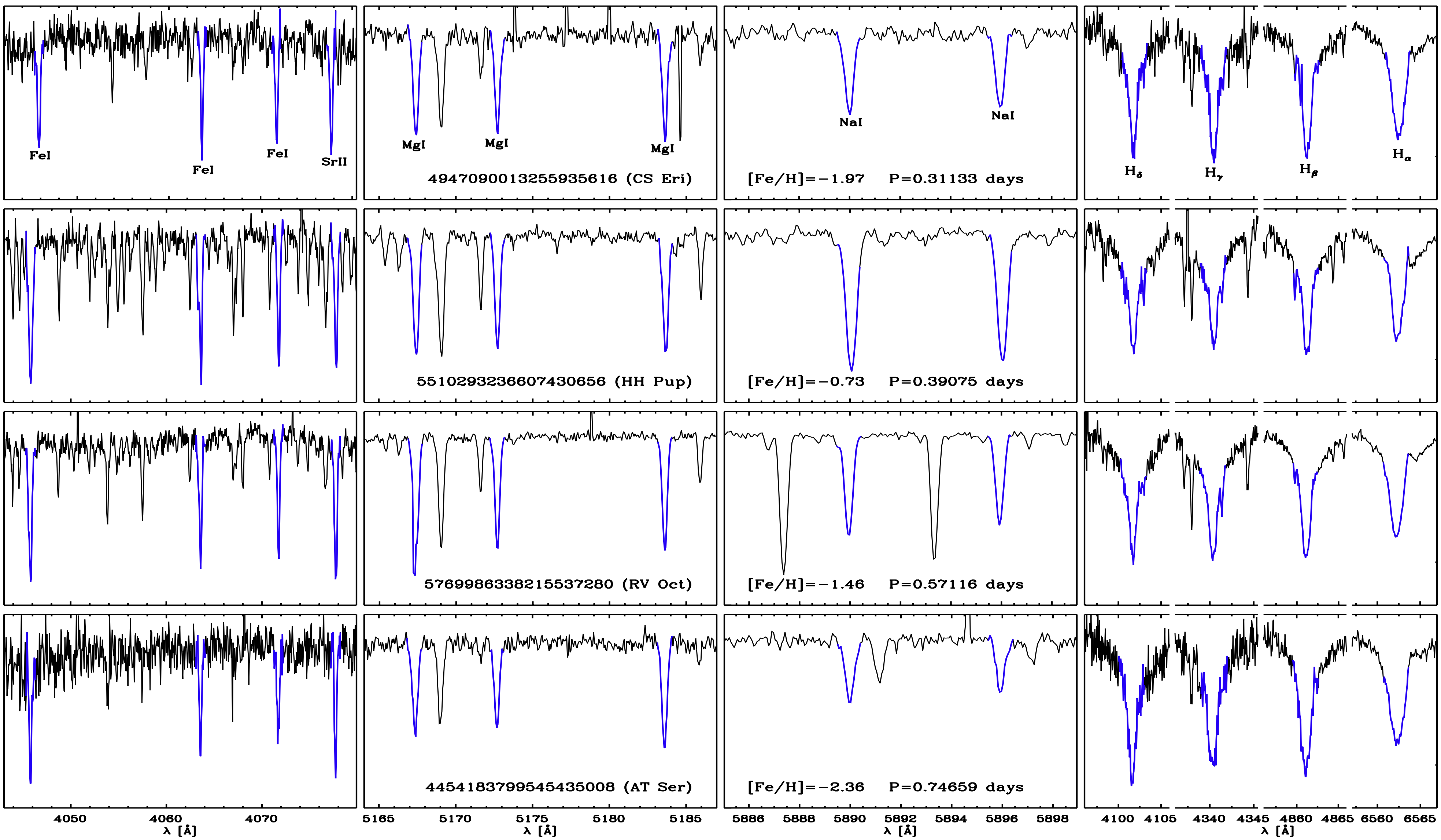
Once period, luminosity amplitude & reference epoch are known
barycentric velocity can be estimated with a single measurement

- → Phase difference between radial & luminosity cuyrve
- → Phase difference among metallic & Balmer lines
- → Phase to anchor the template(s)
- → Occurrence of sencondary features (nonlinear phenomena)
- → Amplitude (luminosity over radial velocity) ratio

All of them have been addressed in detail and solved

Braga + 2021

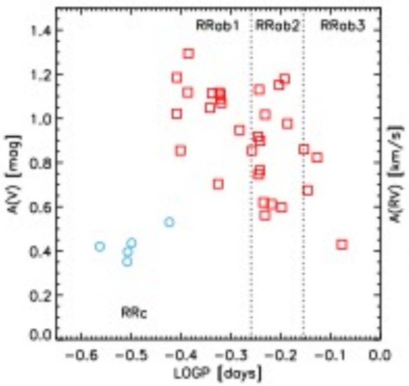
A new spin on radial velocity templates

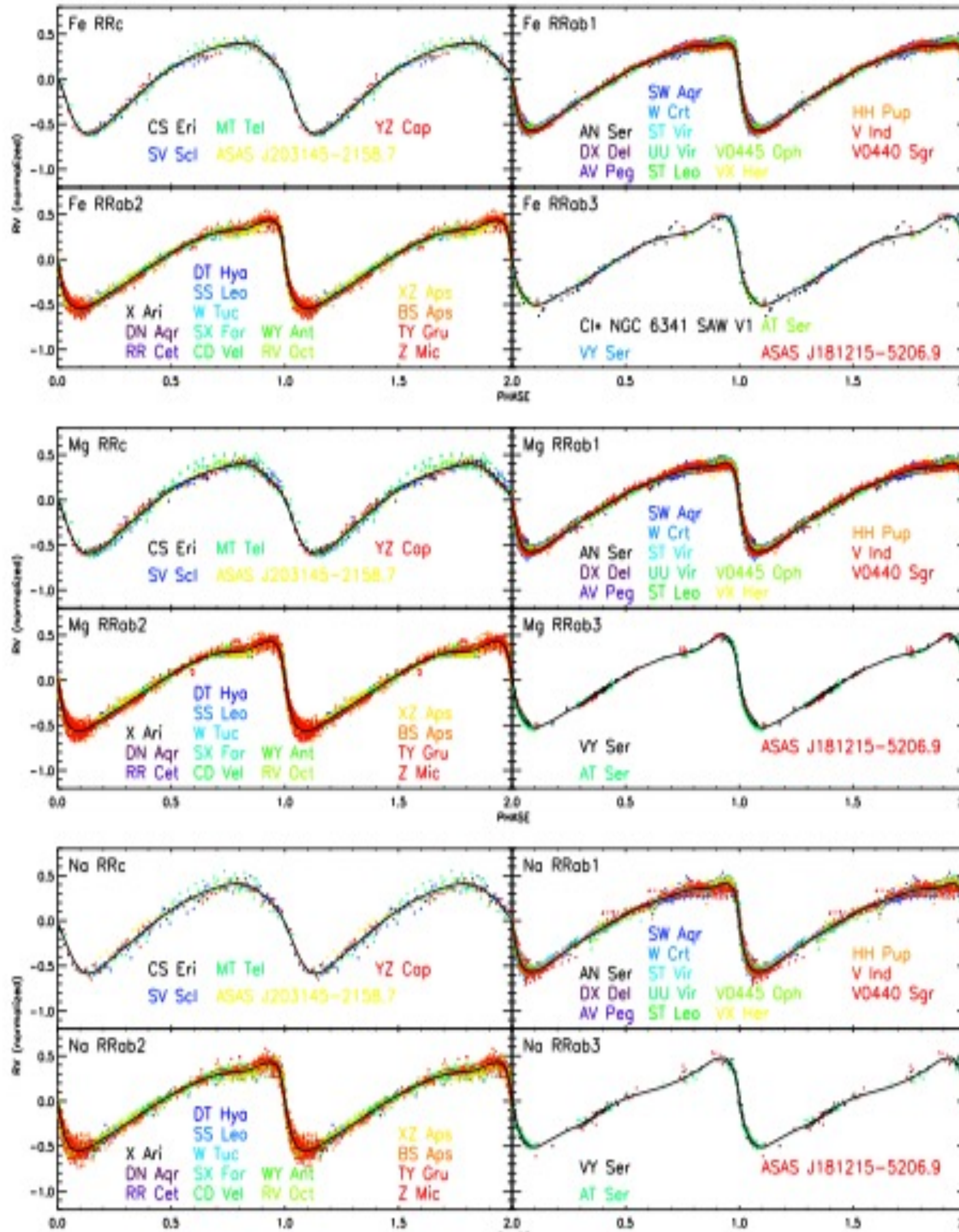


metallic lines Mg triplet Na doublet 4 Balmer lines

Seven diagnostics based on the very same spectra

A new spin on radial velocity templates

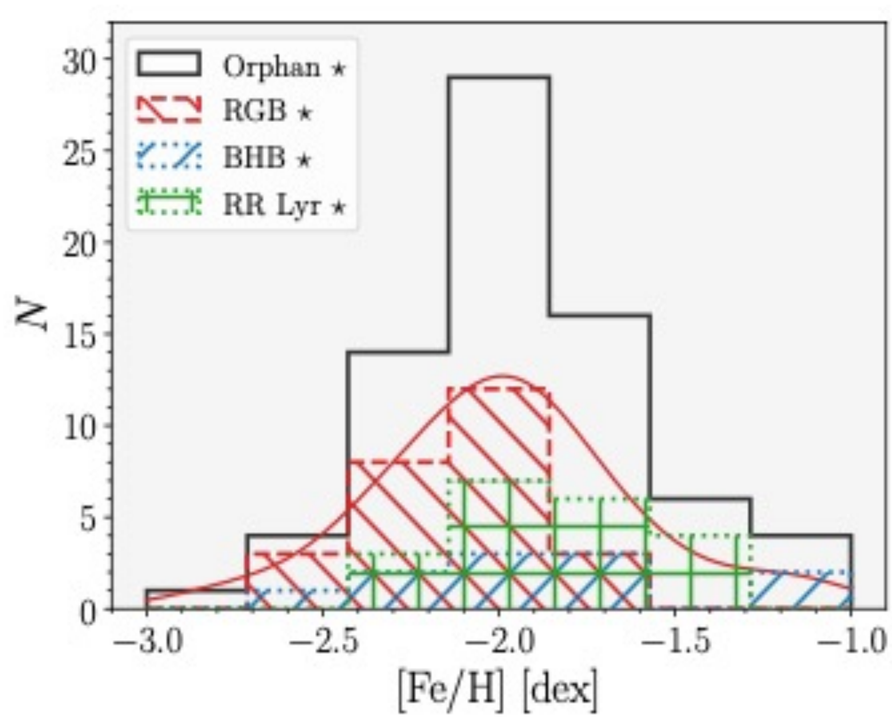




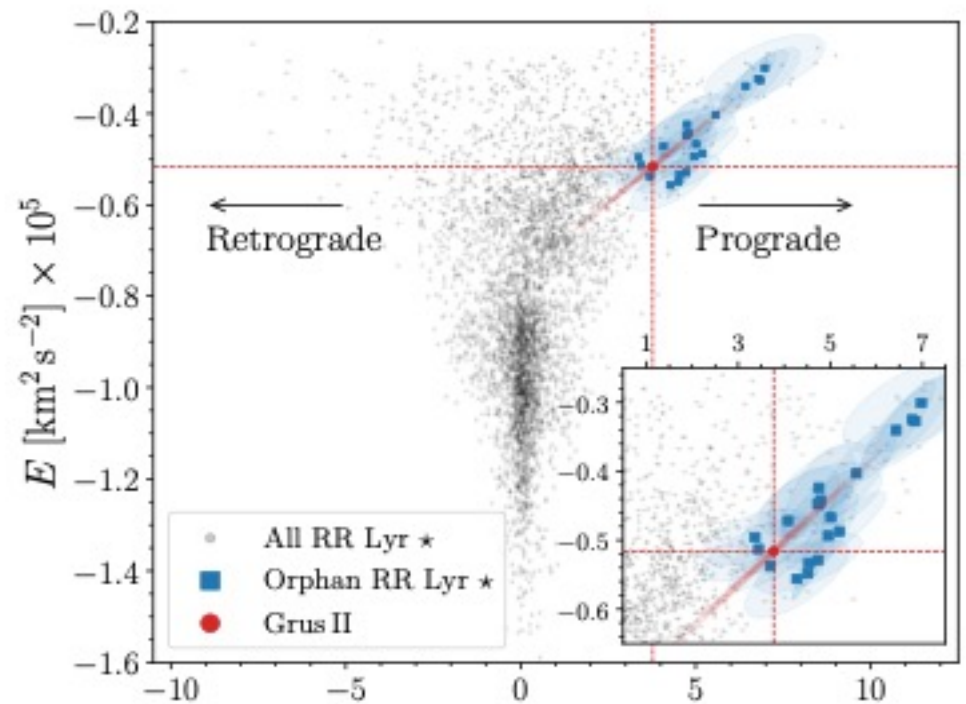
Three dozen calibrating RRLs full coverage of the pulsation cycle thousands of spectra

Mean accuracy of RVC templates 2/3 km/sec

An application of RVC templates & DeltaS



Metallicity based on new Delta S



Rad. vel. based on RVC temp

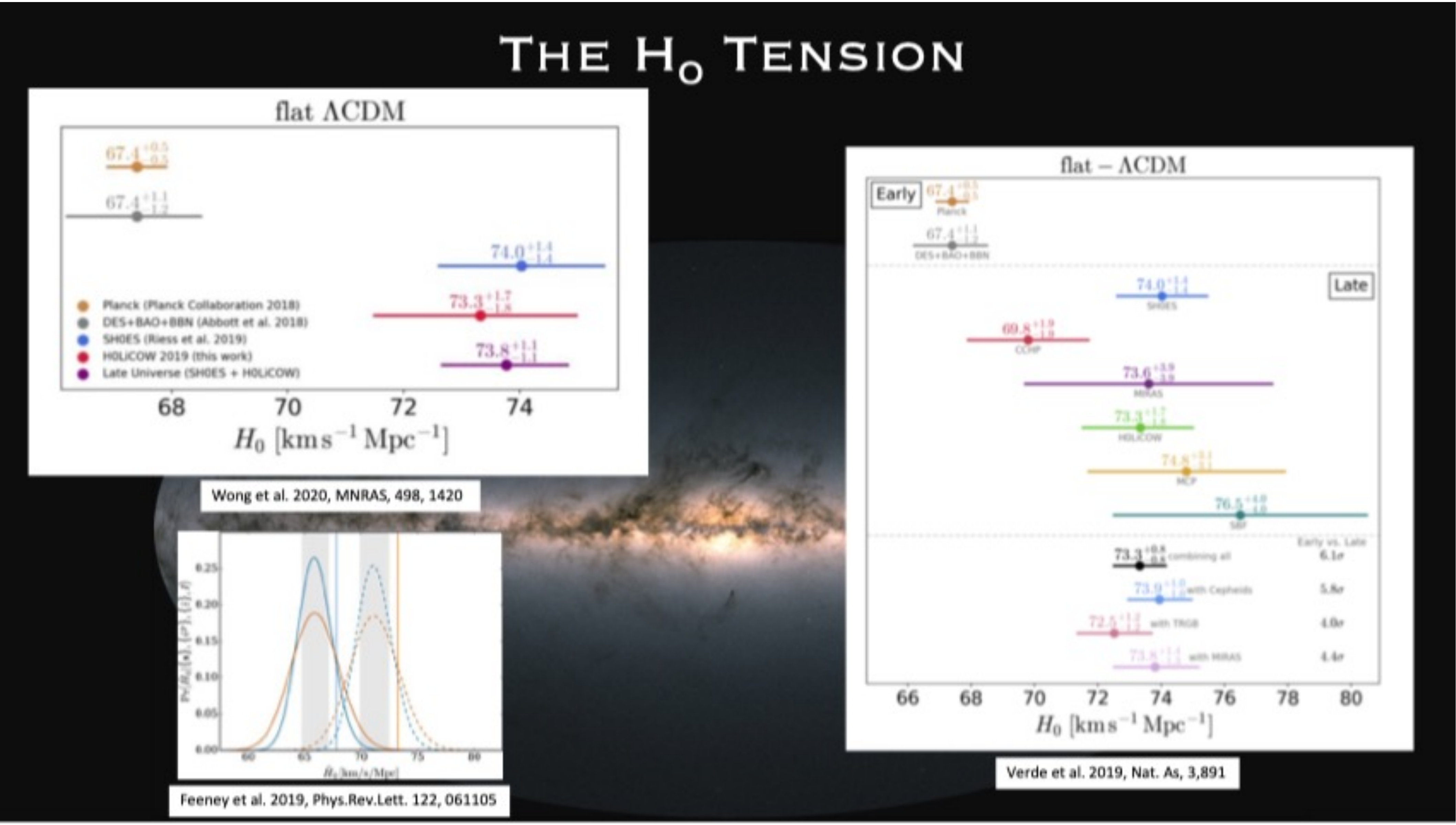
Orphan Stream -- the kinematics of both stream RR Lyrae & Grus II are on a prograde orbit with similar orbital properties ….

However, uncertainties affecting dynamical & chemical properties make the connection difficult → more statistics

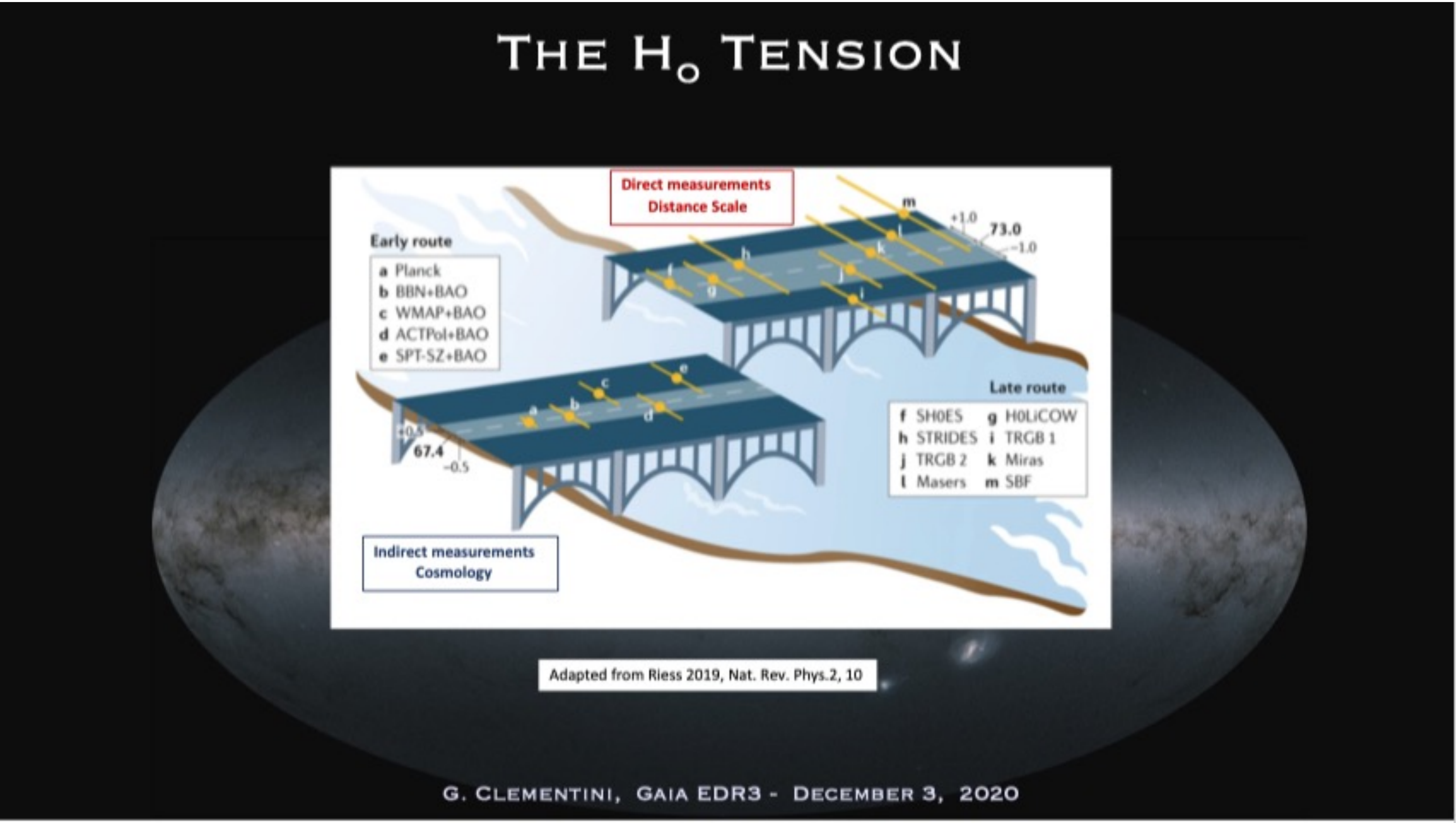
Prudil + 2021

Cosmic distance scale & Ho

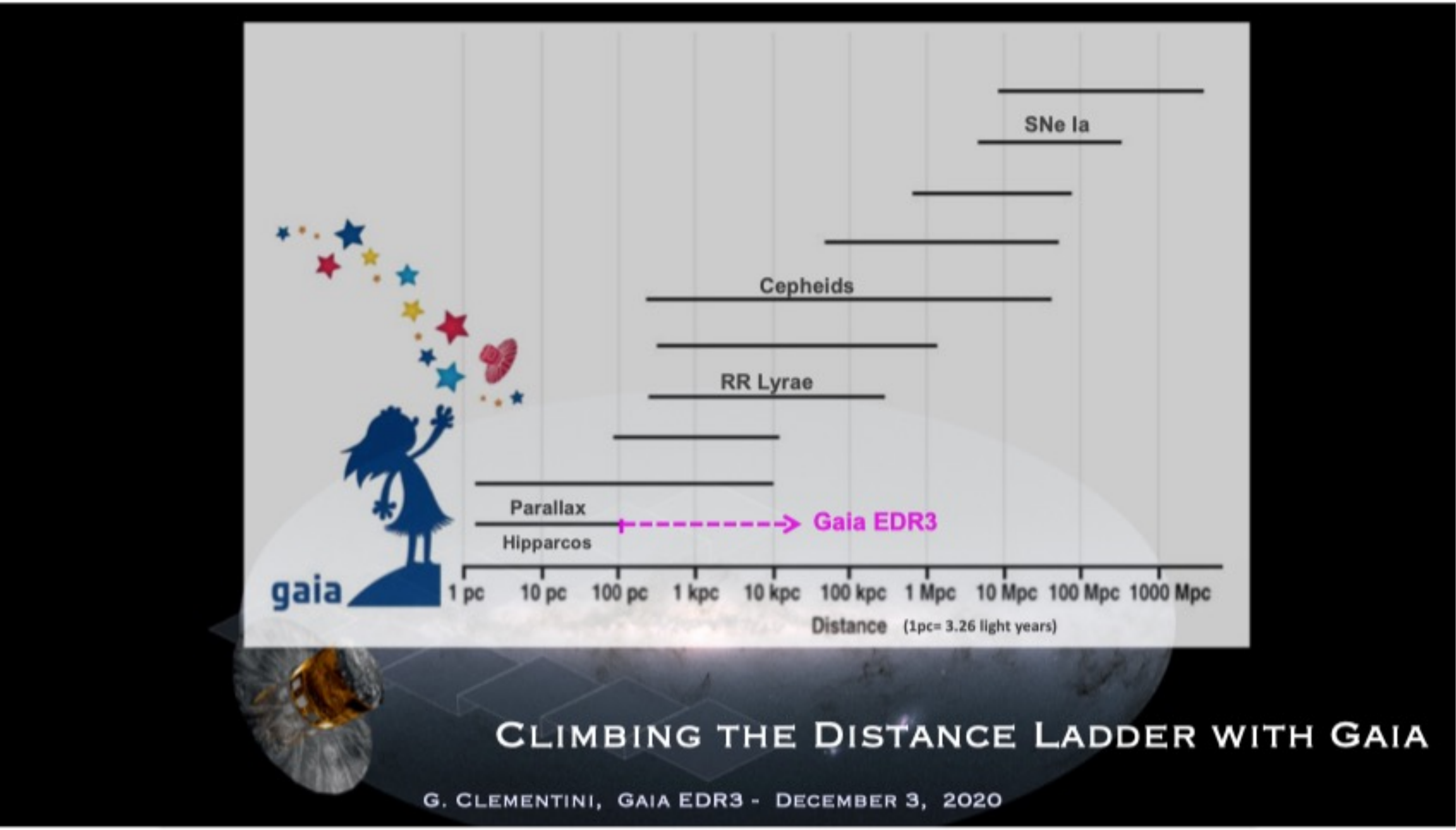
Cosmic distance scale & Ho



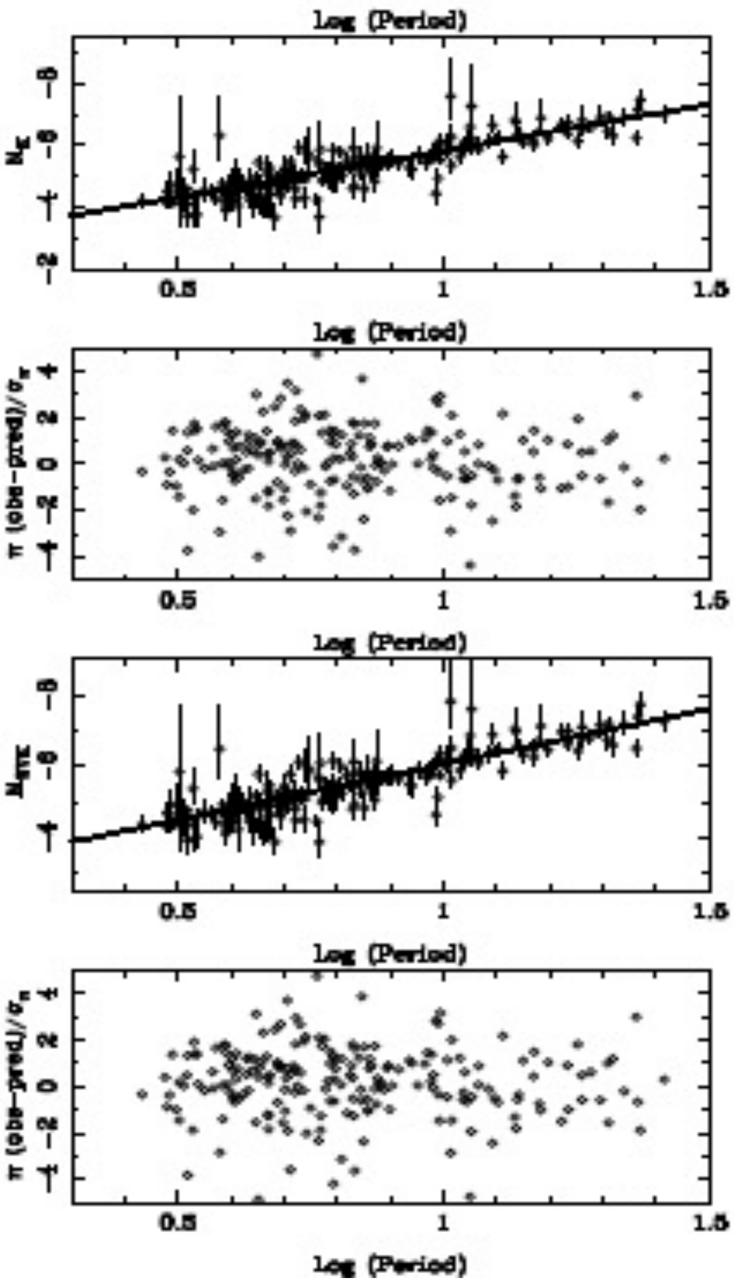
Cosmic distance scale & Ho



Cosmic distance scale & Ho



Gaia DR2 Parallaxes being systematically smaller



Groenewegen 2018

~450 Cepheids with
Spectroscopic abundances

Goodness of the fit <8
~200 Cepheids

Zero-point offset of -0.049±1.8 mas

Galactic & LMC slope differ at 3σ

The use of the LMC slope →
A zero-point offset of -0.1 mas

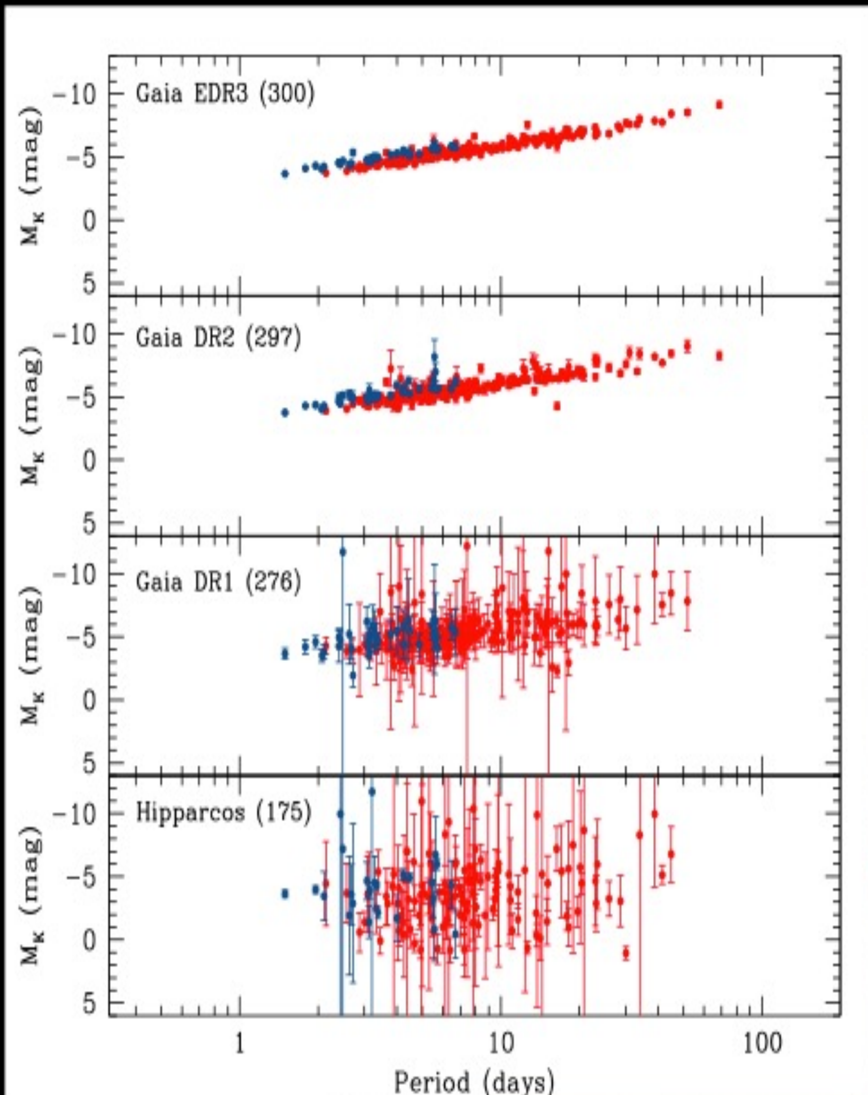
Strong correlation between ZP, period and [Fe/H]

a ZP offset of ~0.055mas → a change in DM=0.2 at 1 kpc, DM=1.1 mag at 7 kpc

The required accuracy is 0.003 mas!!!!

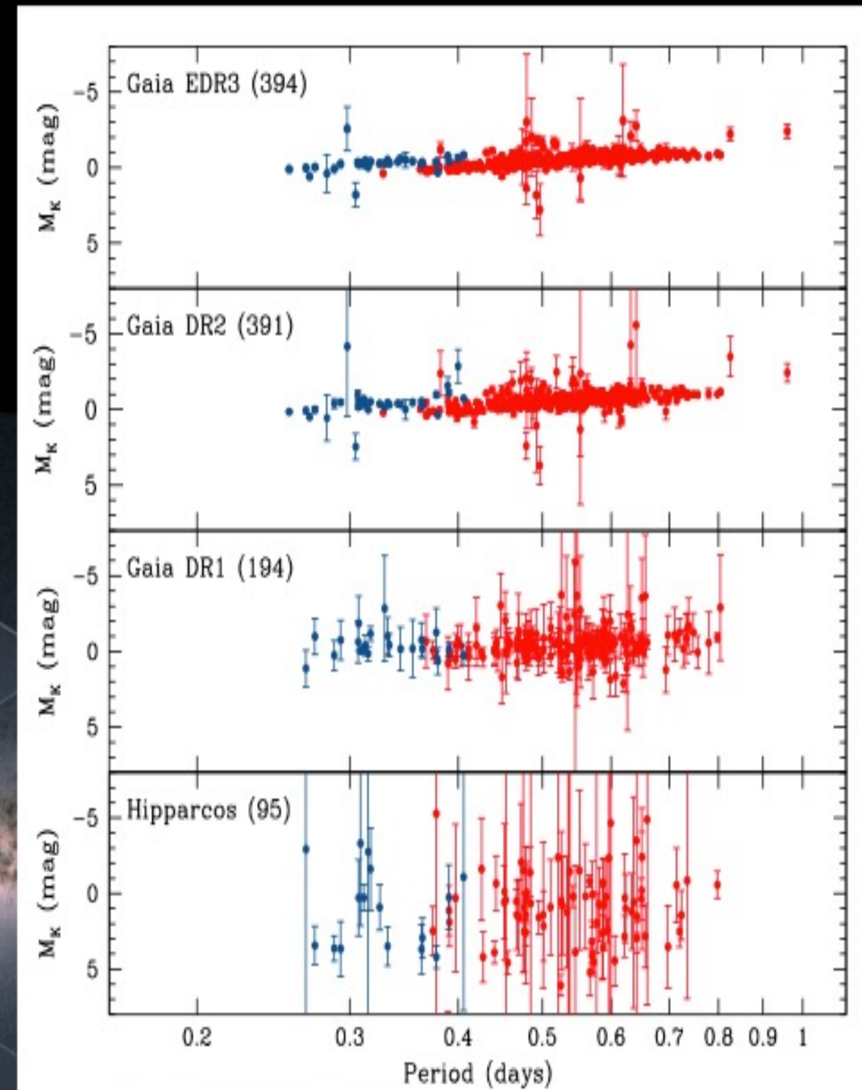
Cepheids and RR Lyrae as Standard Candles
From Hipparcos to DR1 to DR2 To Gaia EDR3

Cepheids



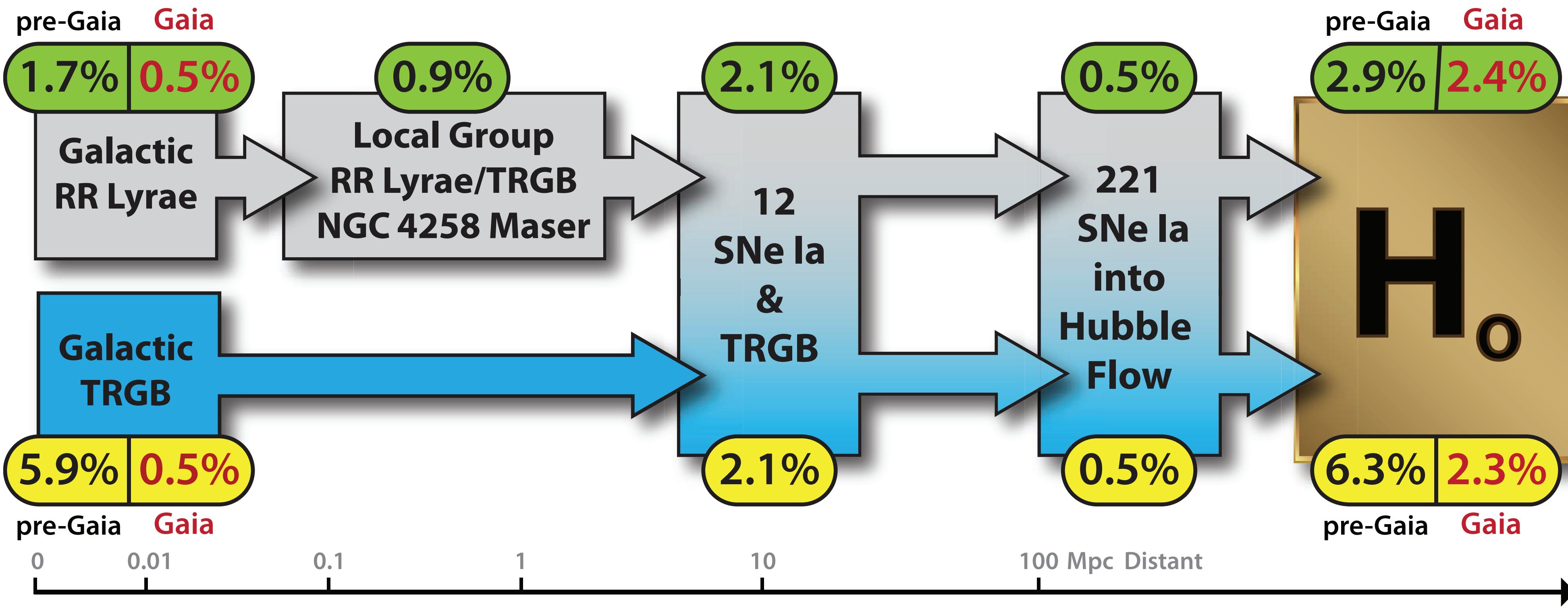
Credit: ESA/Gaia/DPAC, created by: V. Ripepi

RR Lyrae



Credit: ESA/Gaia/DPAC, created by: T. Muraveva & A. Garofalo

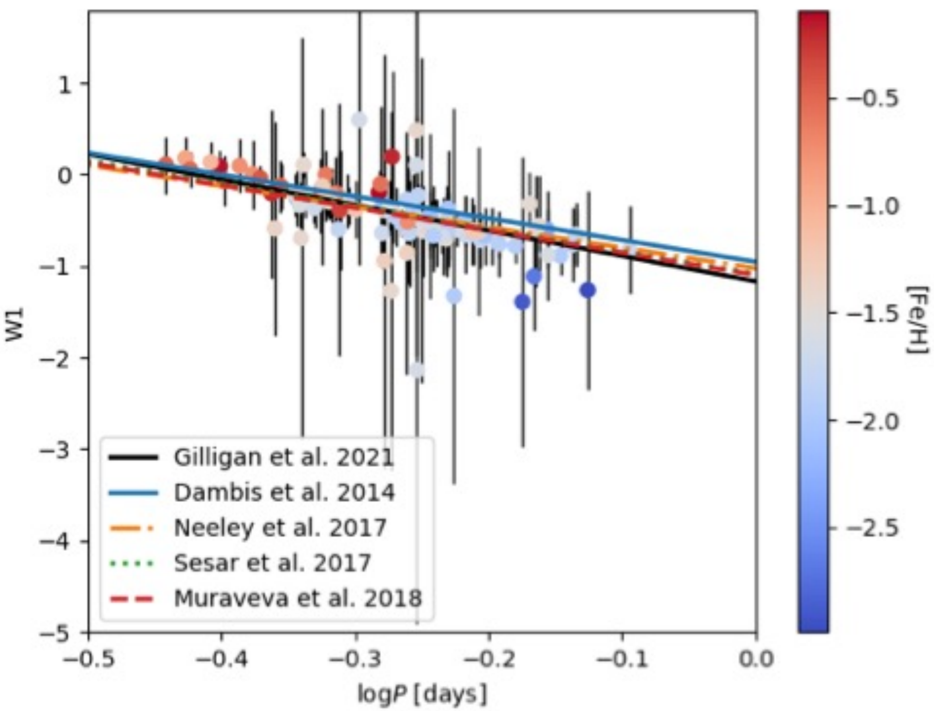
The CCHP Pathways to a 3% Determination of the Hubble Constant

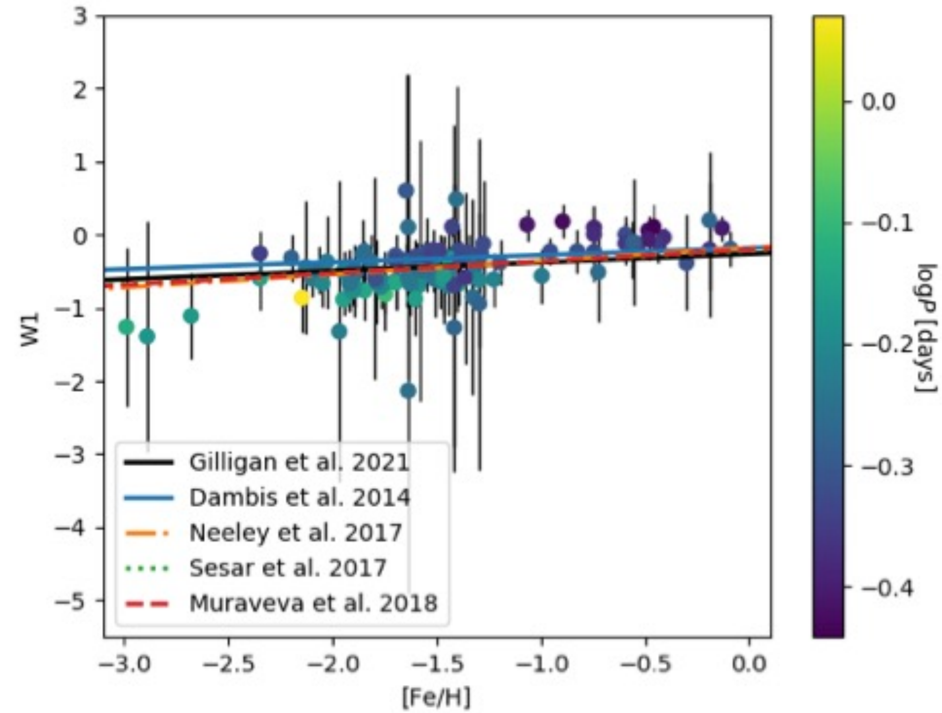


Population II route to Ho

Beaton + 2018, Breuval + 2020 + many others

RR Lyrae distance scale



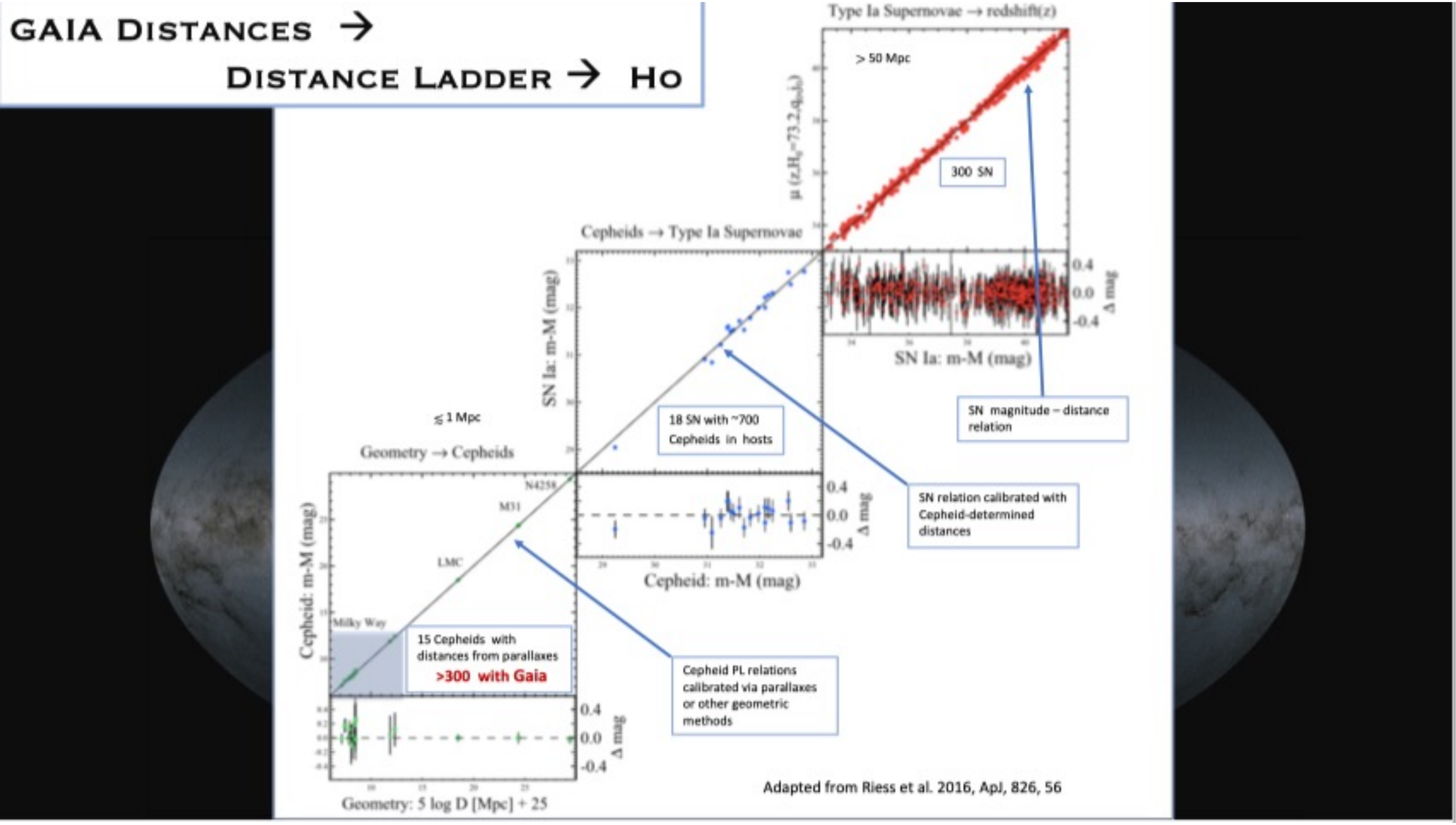


PLZ (W1, W2, neo-Wise) and relative Period-Wesenheit-metallicity relations + spectroscopic (HR sample) abundances (~100 RRLs).

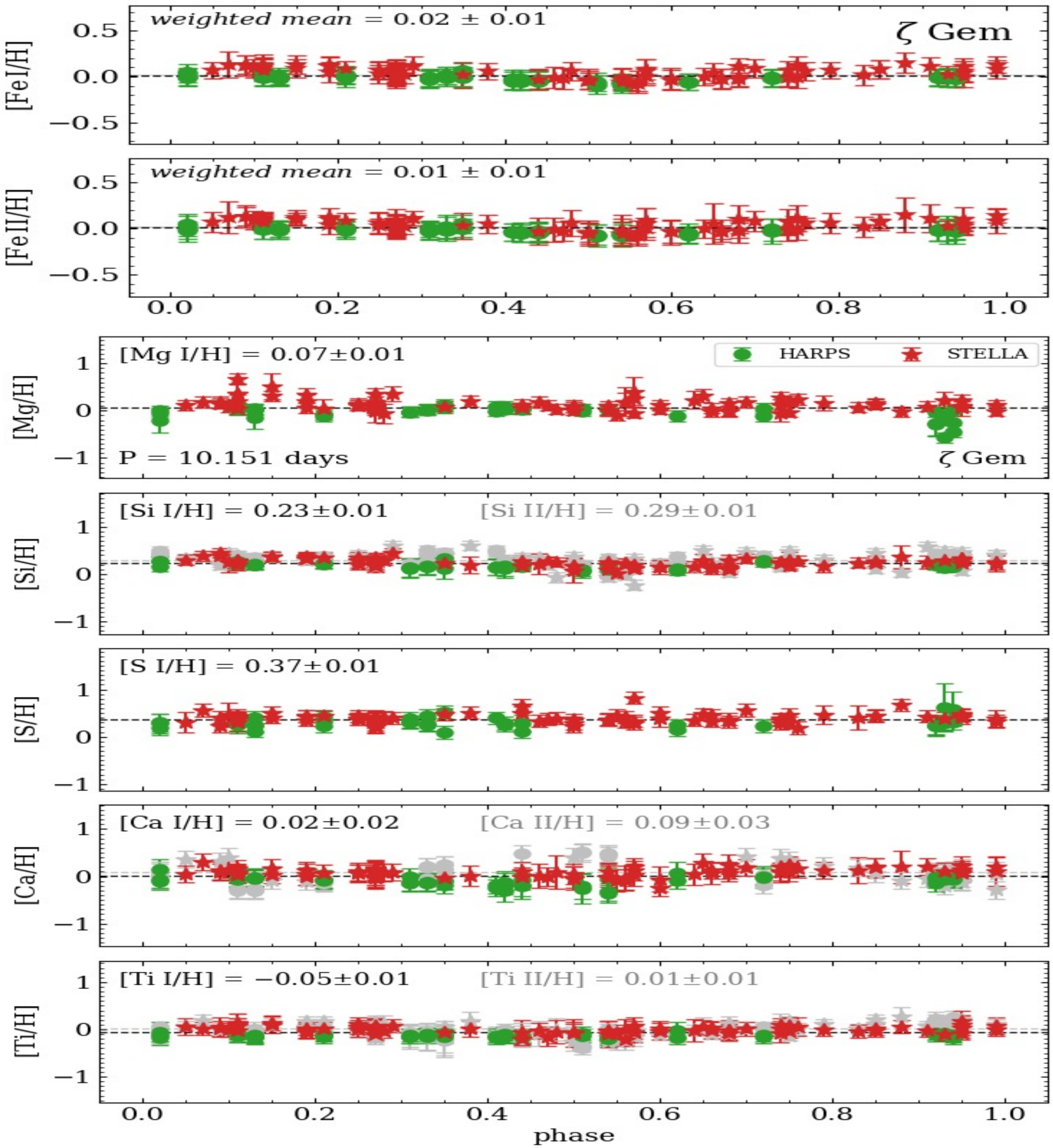
They agree, within the errors, with literature values.

Gilligan + 2021

Cosmic distance scale & Ho



Classical Cepheids: abundance Variations

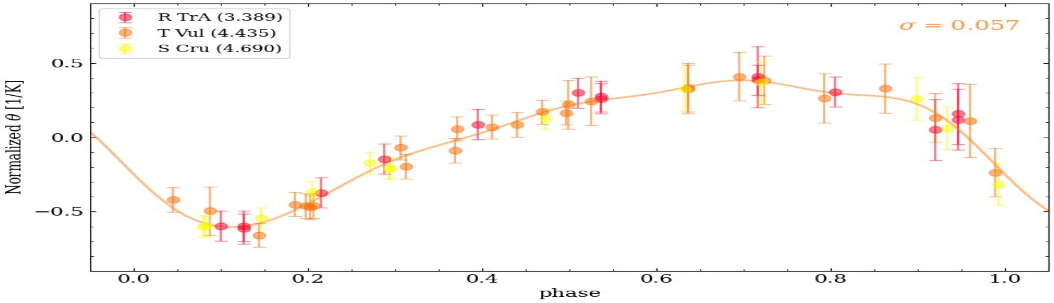


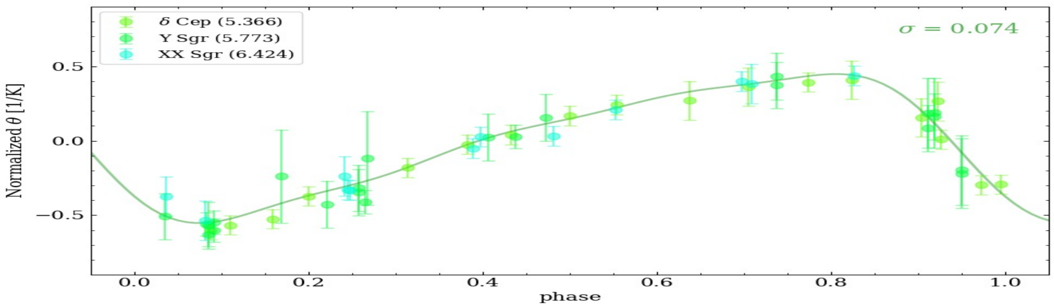
Two dozen calibrating Galactic Cepheids

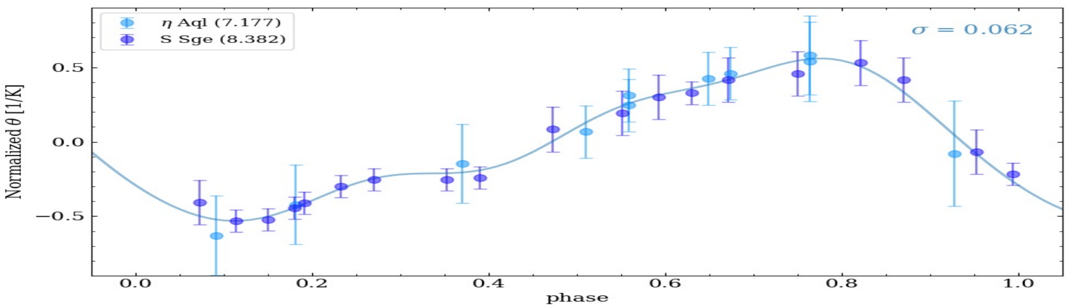
Huge prepratory work for selecting good lines

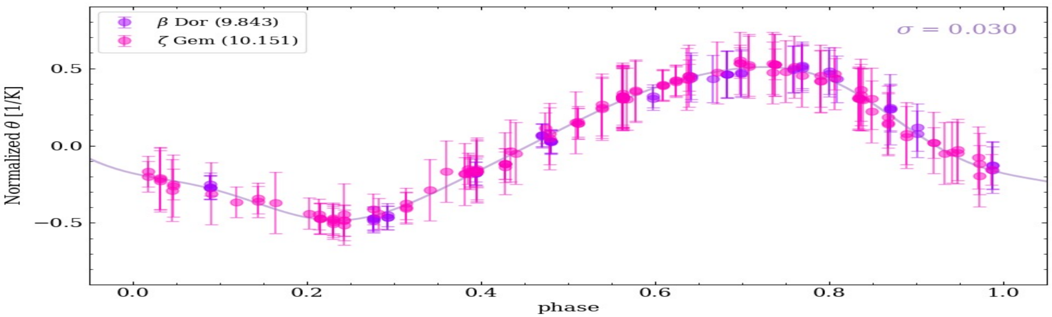
Ronaldo Fecit

Classical Cepheids: temperature variations







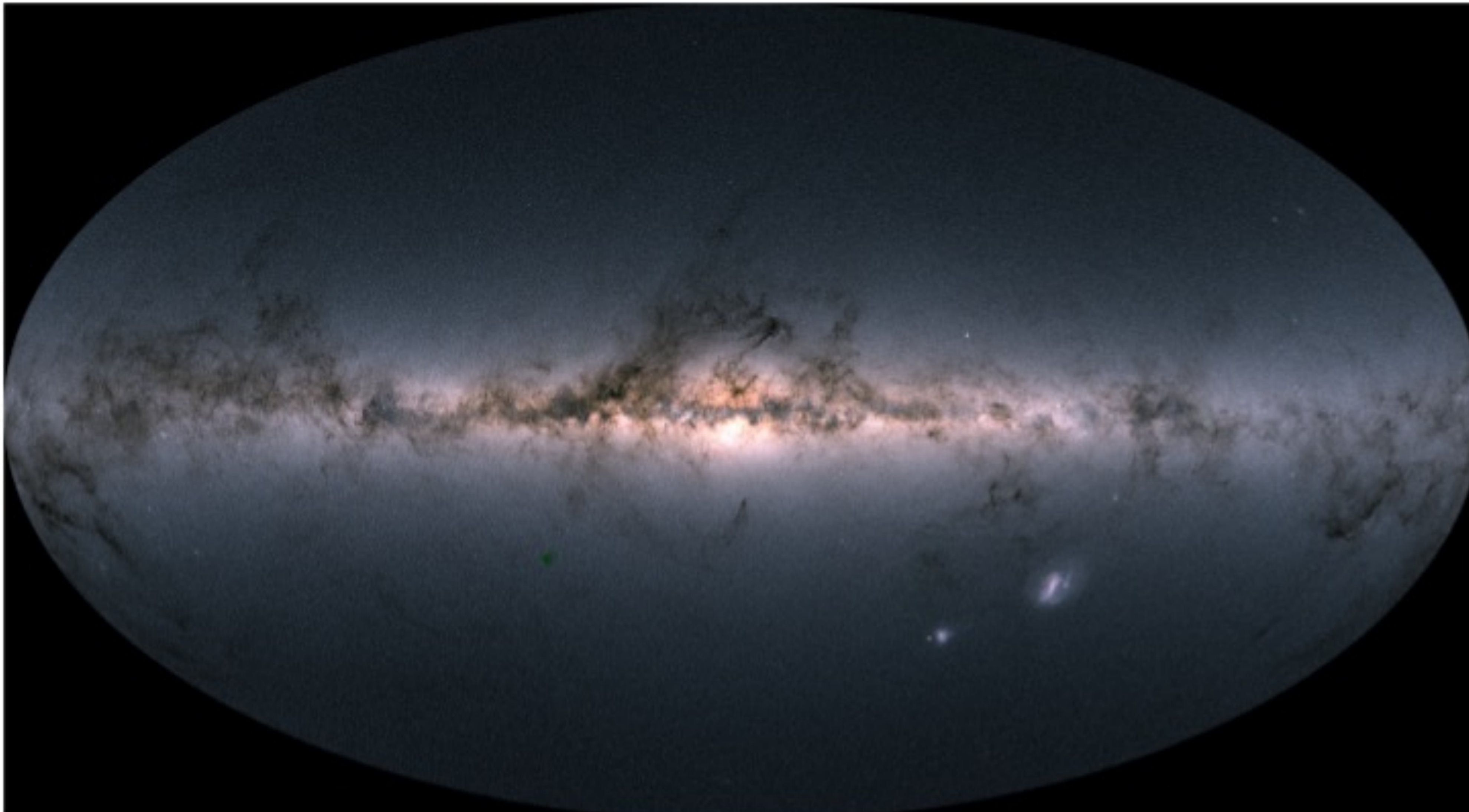


First attempt for an effective temperature template

Very good preliminary news for NIR spectroscopy In the metal-poor regime ..

Ronaldo Fecit

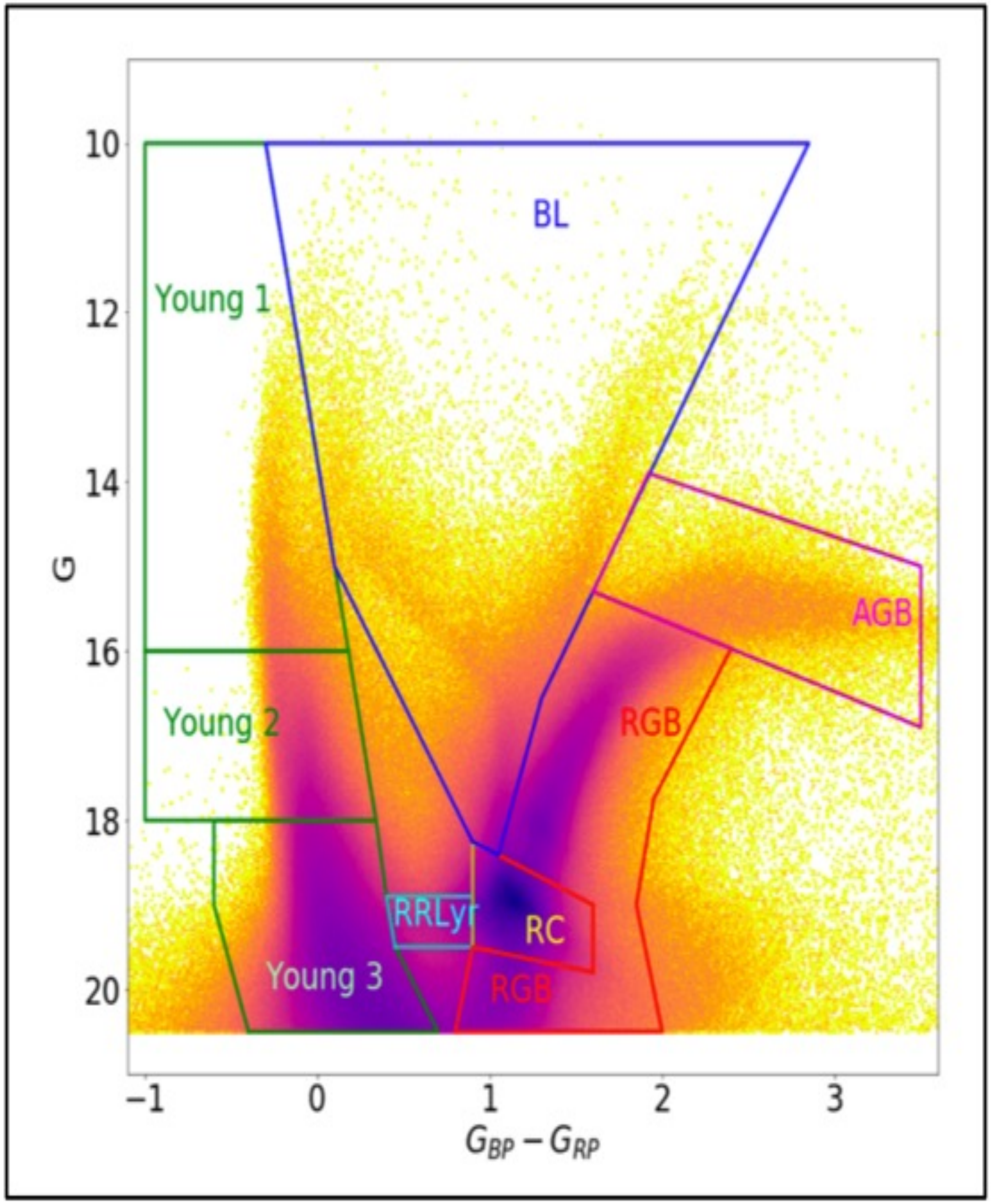
Gaia view of the nearby Universe: MCs

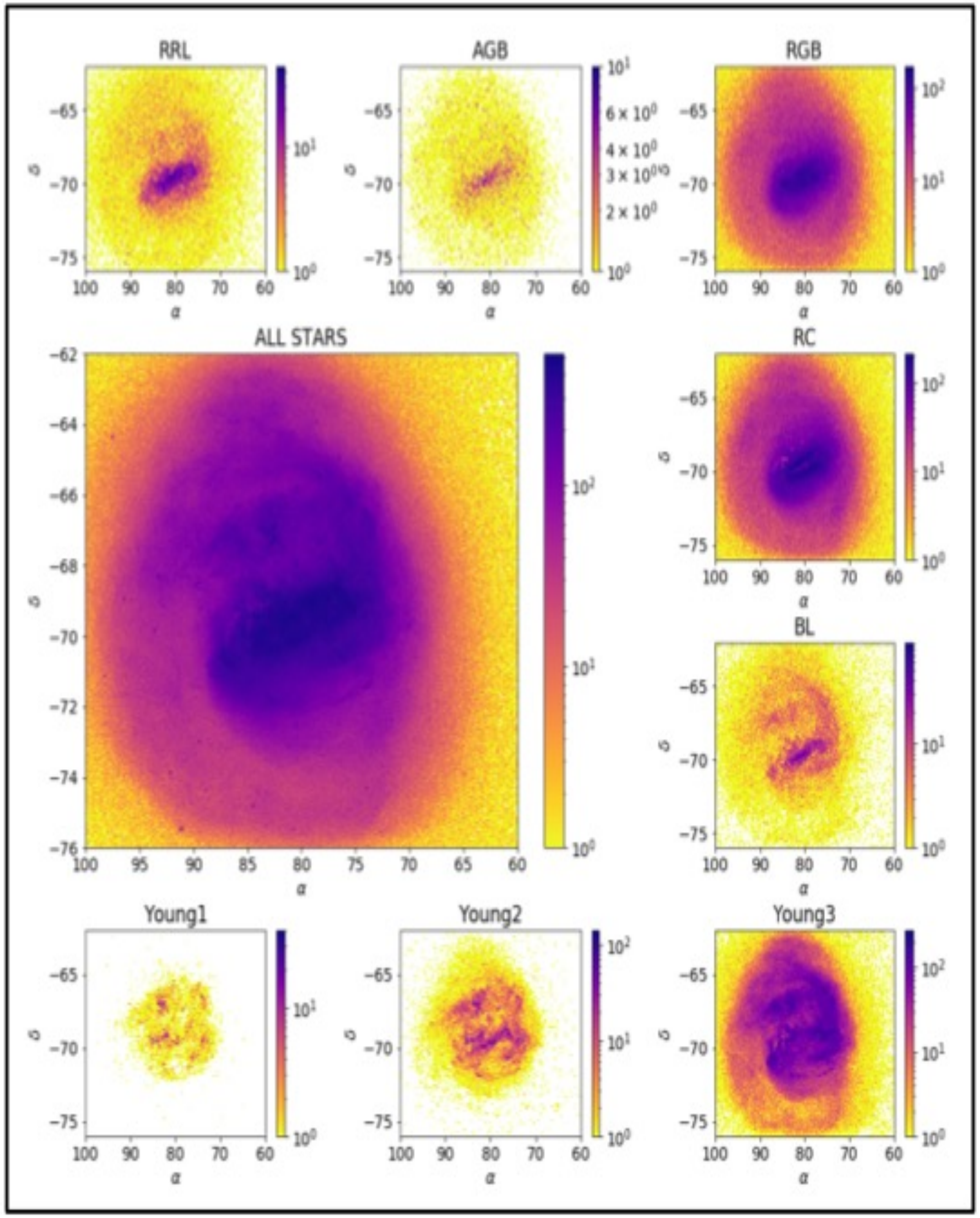


AASS, Roma, December 6 2021

Le Nubi viste con stelle di differenti età

Grande Nube

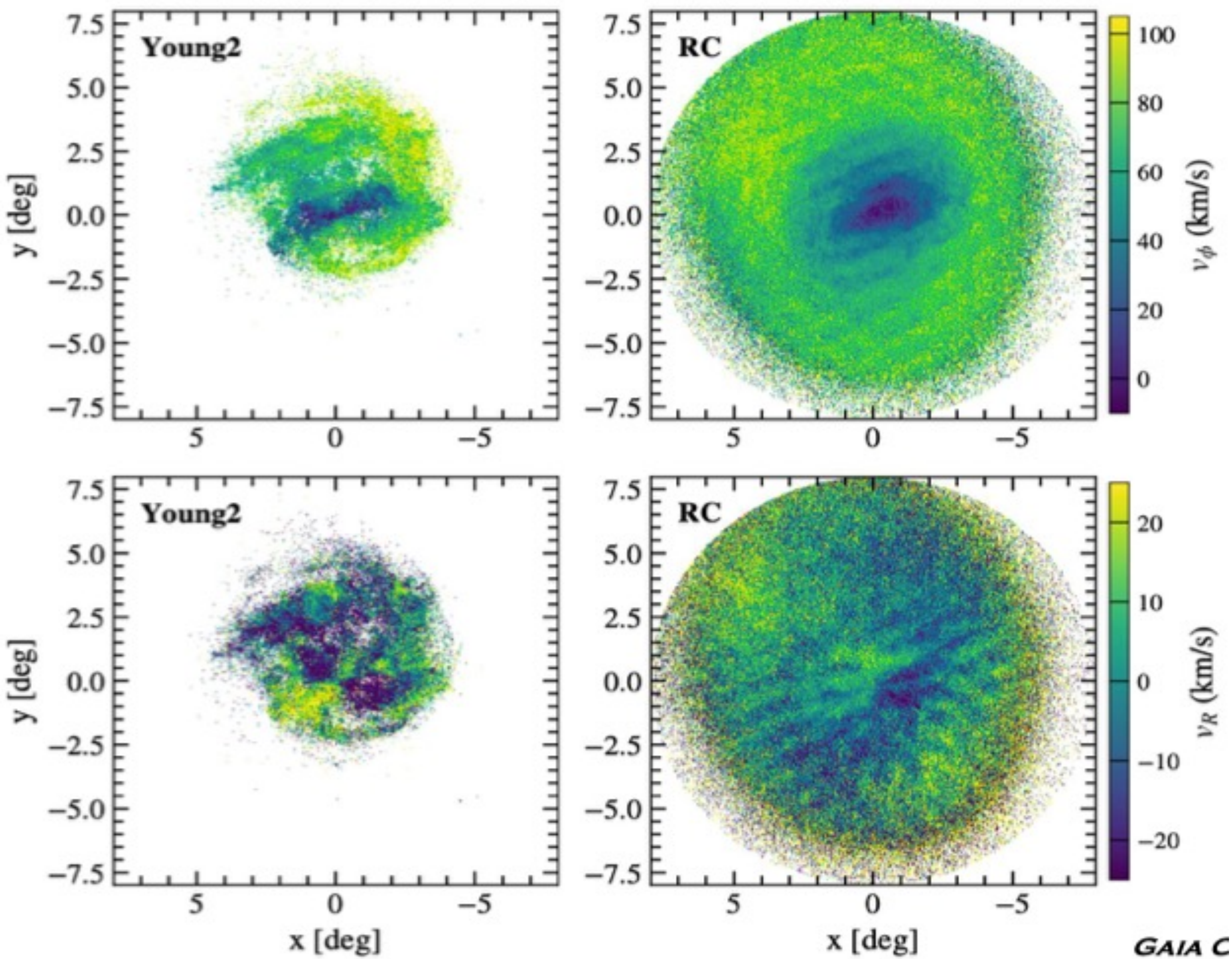




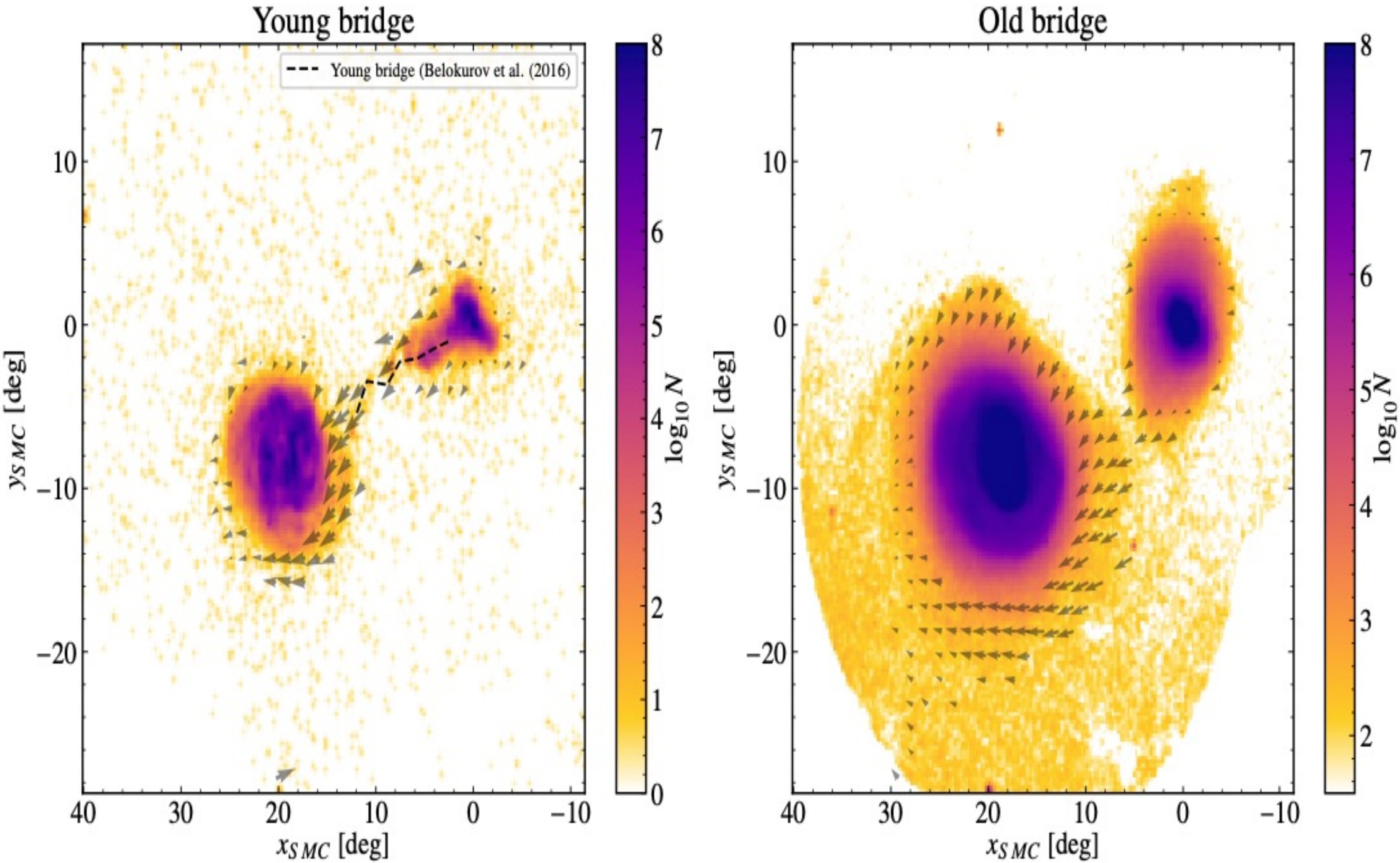
Gaia Collaboration, X. Luri, et al. 2020 A&A

By Ripepi Gaia EDR3, 2020

Radial velocity structures



GAIA C



By Ripepi Gaia EDR3, 2020

CONCLUSIONS

→ (Almost) All stellar roads (will) lead to Gaia

→ Golden age for resolved stellar populations

→ Ground-based follow up spectroscopy:
MUSE + MOONS + 4MOST
But in particular MAVIS → Halo outskirts

→ Ground-based multi-band photometry: LSST
from 20-21 to 25-26 mag → where is the edge?

→ ELT(s) see talk by E. Valenti

Thank you for your attention

Credits

To young, differently young & senior colleagues with whom I have the pleasure to share this wonderful adventure

THANKS!!!