Theoretical efforts in the modelling of Cepheid and RR Lyrae properties in the Gaia bands

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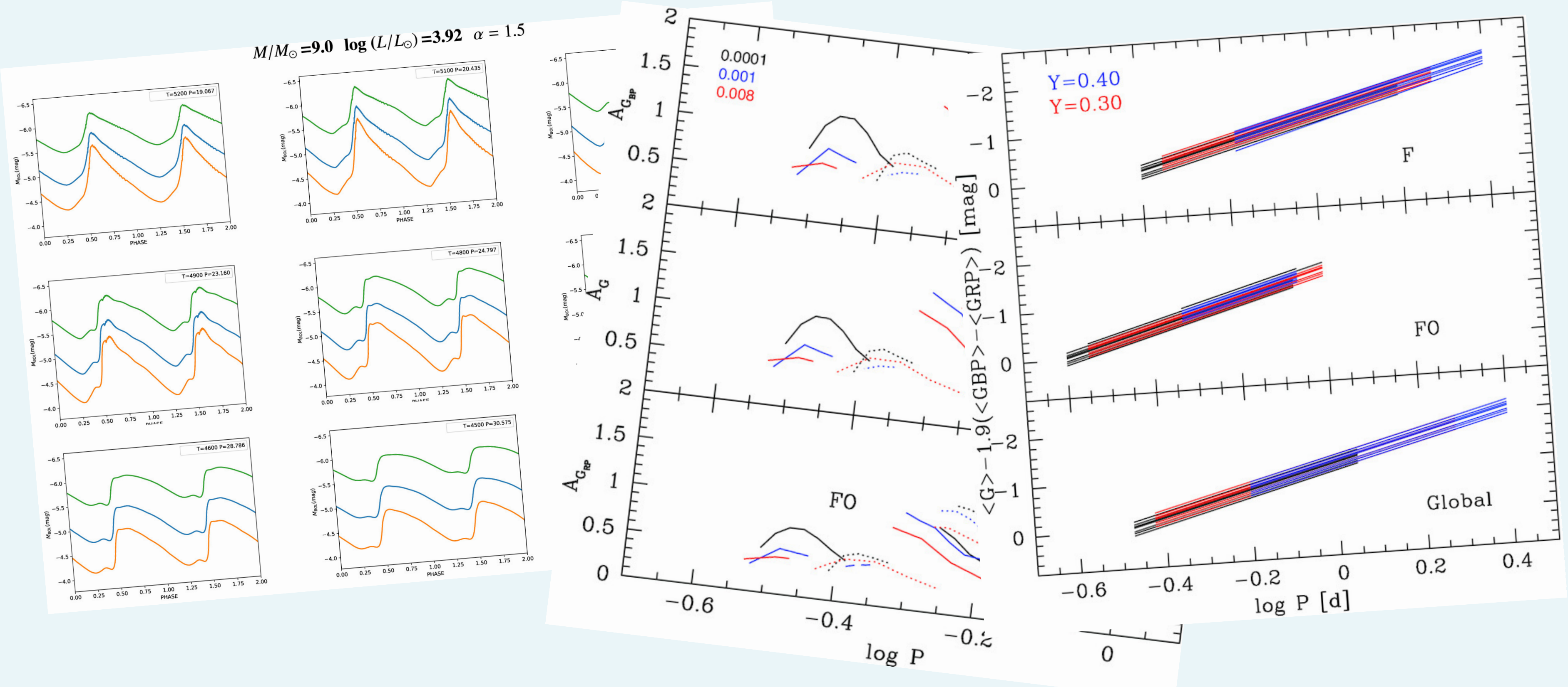


“Stellar variability, stellar multiplicity: periodicity in time & motion” June 6-8, 2023, Sofia, Bulgaria

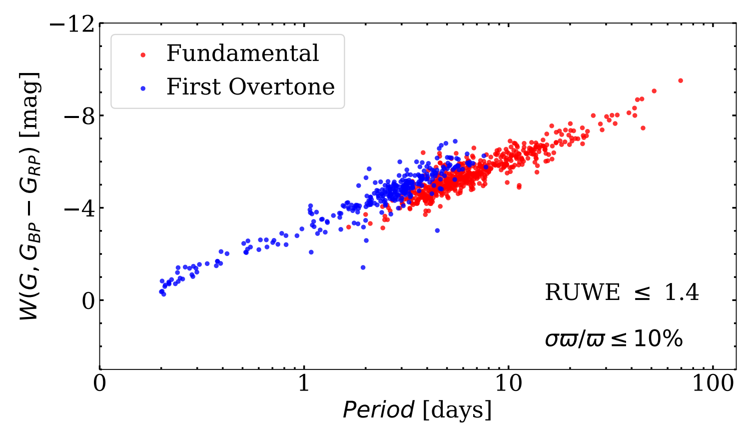
Outline

- Relevance of Cepheids and RR Lyrae in the Gaia era
- Nonlinear convective pulsation modeling
- The theoretical scenario in the Gaia filters
- Recent results for Cepheids and RR Lyrae
- Next steps and open issues

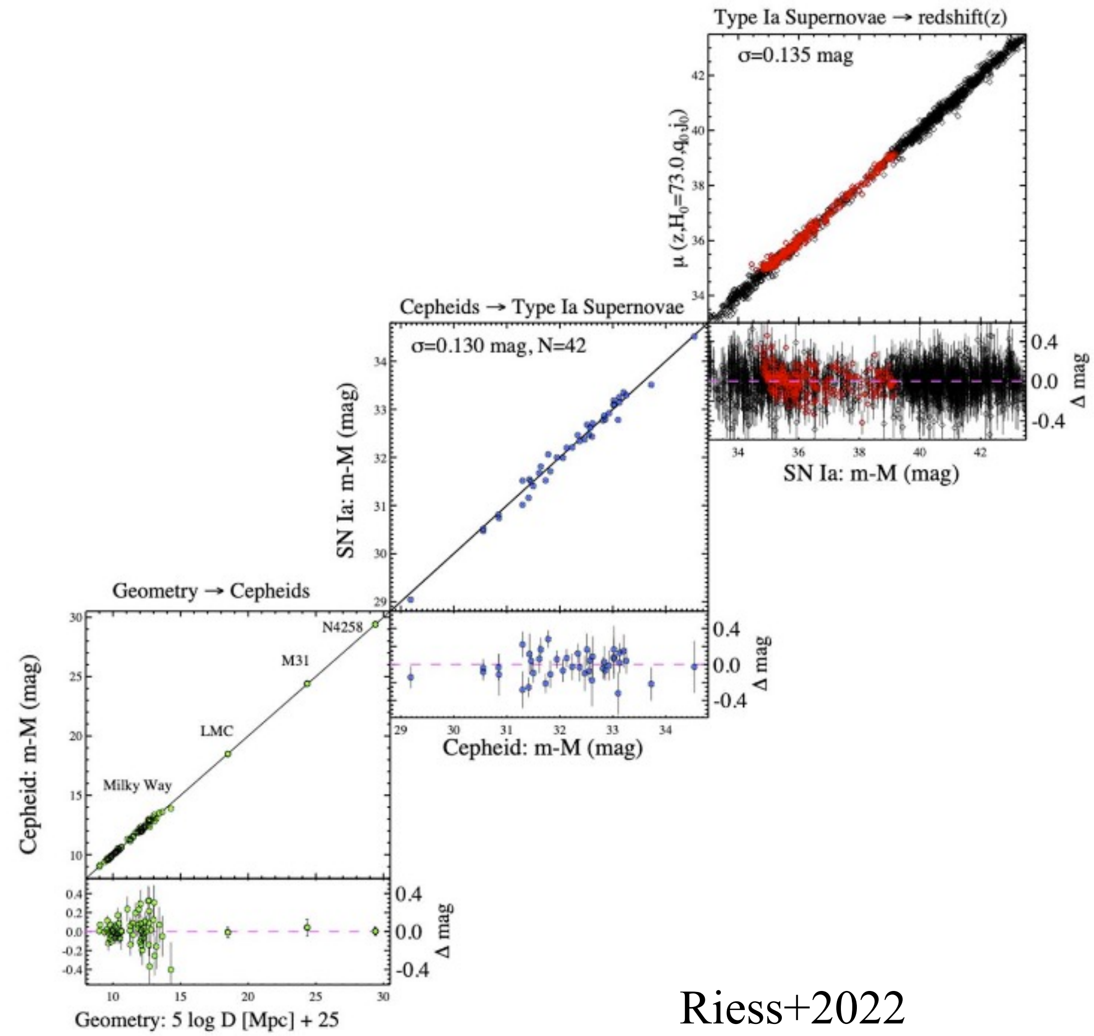
Relevance of Cepheids in the Gaia era

3,434 MW **Classical Cepheids** in Gaia DR3 → largest homogeneous dataset published so far.

~1060 Cepheids in Gaia DR3 with high-precision parallaxes (distances, see talk by V. Ripepi)



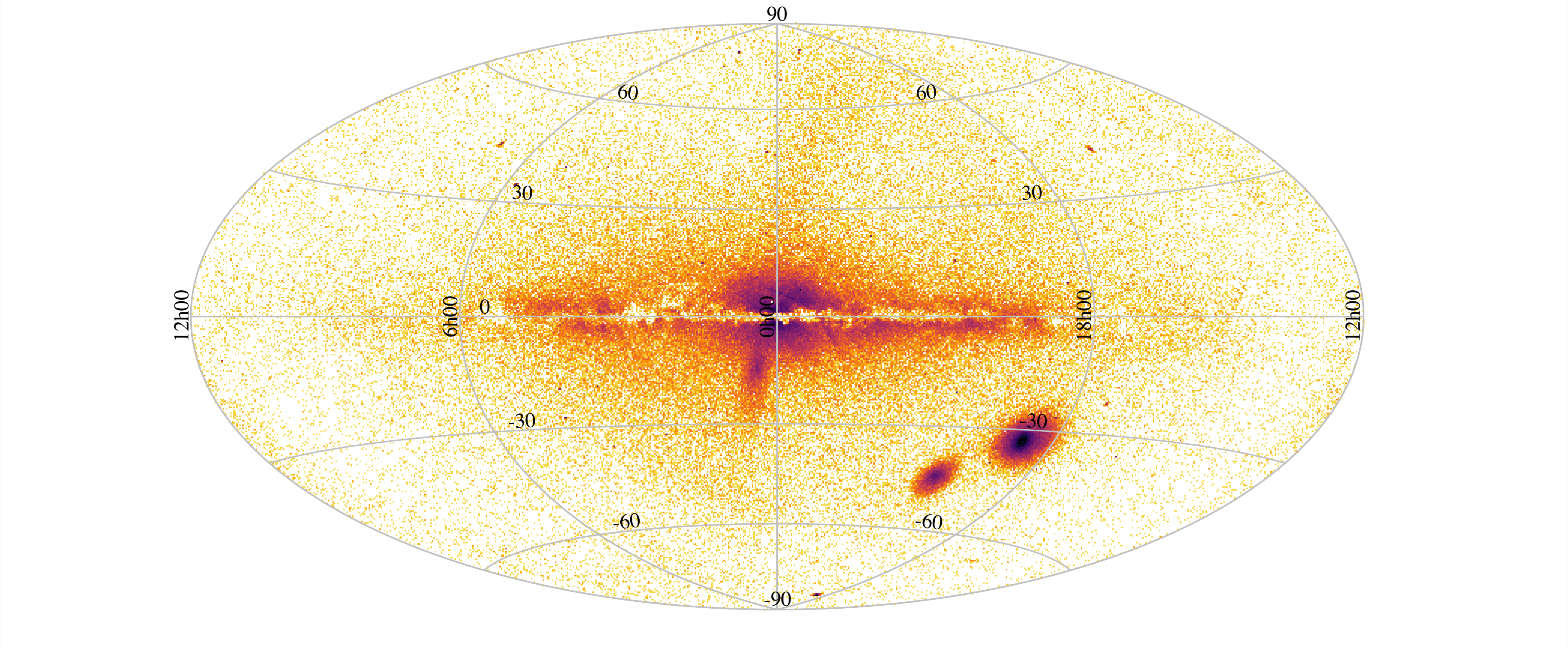
Gaia measurements (photometry and parallaxes) → **calibrate with unprecedented accuracy the extragalactic distance scale**



Riess+2022

Relevance of RR Lyrae in the Gaia era

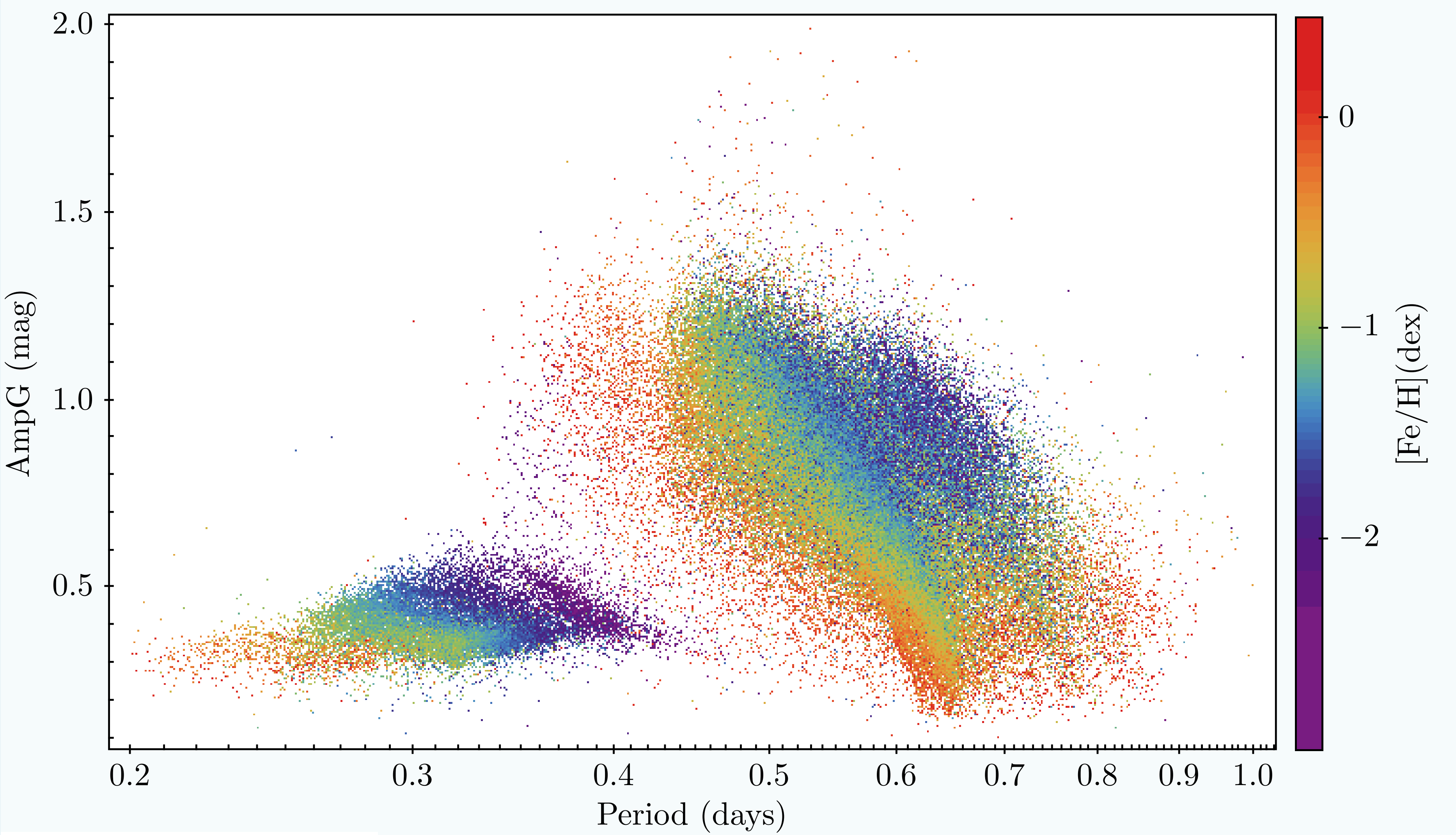
Distribution on sky, in galactic coordinates, of the clean sample of 270 905 DR3 RR Lyrae stars ← 200,294 known RR Lyrae stars and 70,611 new discoveries by Gaia.



Clementini et al. 2023 in press

RR Lyrae Period-Amplitude diagram

Metallicities derived from the Fourier parameters of the light curves (for 133 559 RR Lyrae stars)



Clementini et al. 2023 in press

Nonlinear convective pulsation models

Nonlinear convective hydrodynamical 1D models means that the hydrodynamic equations describing the pulsation phenomenon are NOT linearized and that not only the periods and the instability strip edges can be estimated but also the pulsation amplitudes (full amplitude variation of all the relevant quantities along the pulsation cycle)

$\Rightarrow$ Periods, amplitudes, lightcurves, blue and red edges

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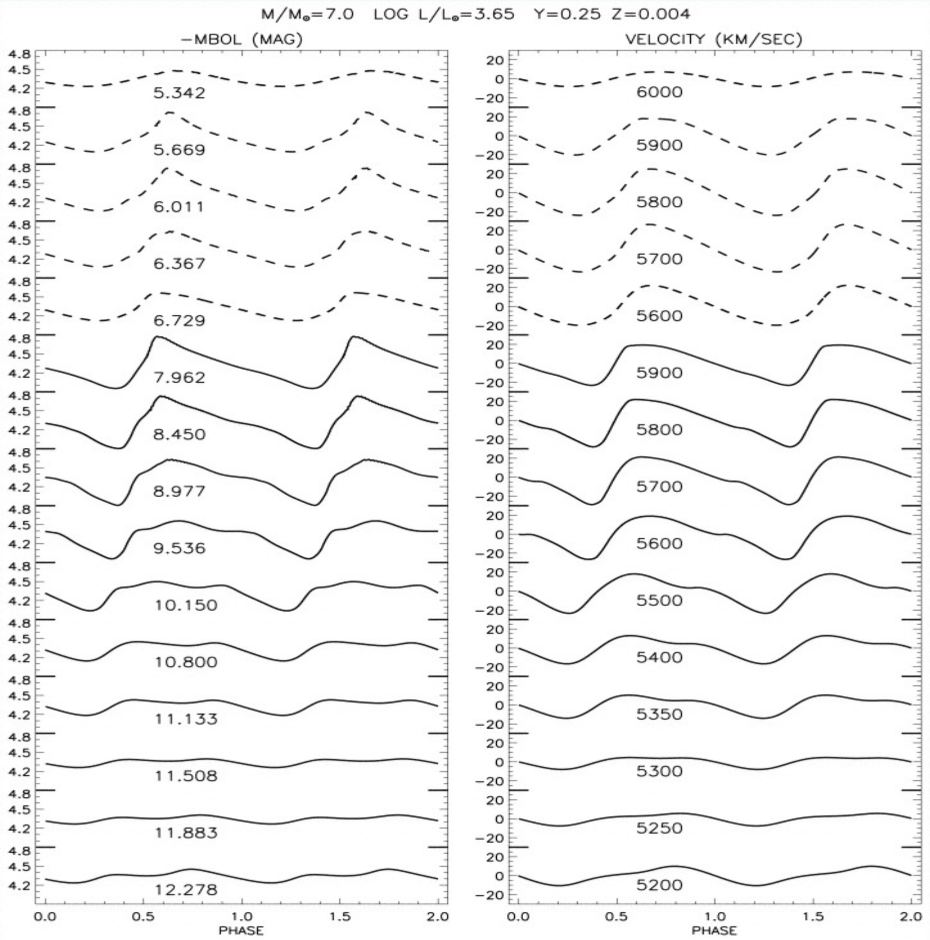
⇒ Periods, amplitudes, lightcurves, blue and red edges

Several authors developed nonlinear convective pulsation models of Cepheids and RR Lyrae (e.g. ***Gehmeyr et al. 1990, Bono & Stelingwerf 1994, Yecko et al. 1998; Kolláth et al. 2002; Bono, Marconi Stellingwerf 1999, Szabo et al. 2000, 2004, Smolec & Moskalik 2008, Paxton et al.2019*****)**

Nonlinear convective pulsation models

Light curves

Radial velocity curves



First Overtone

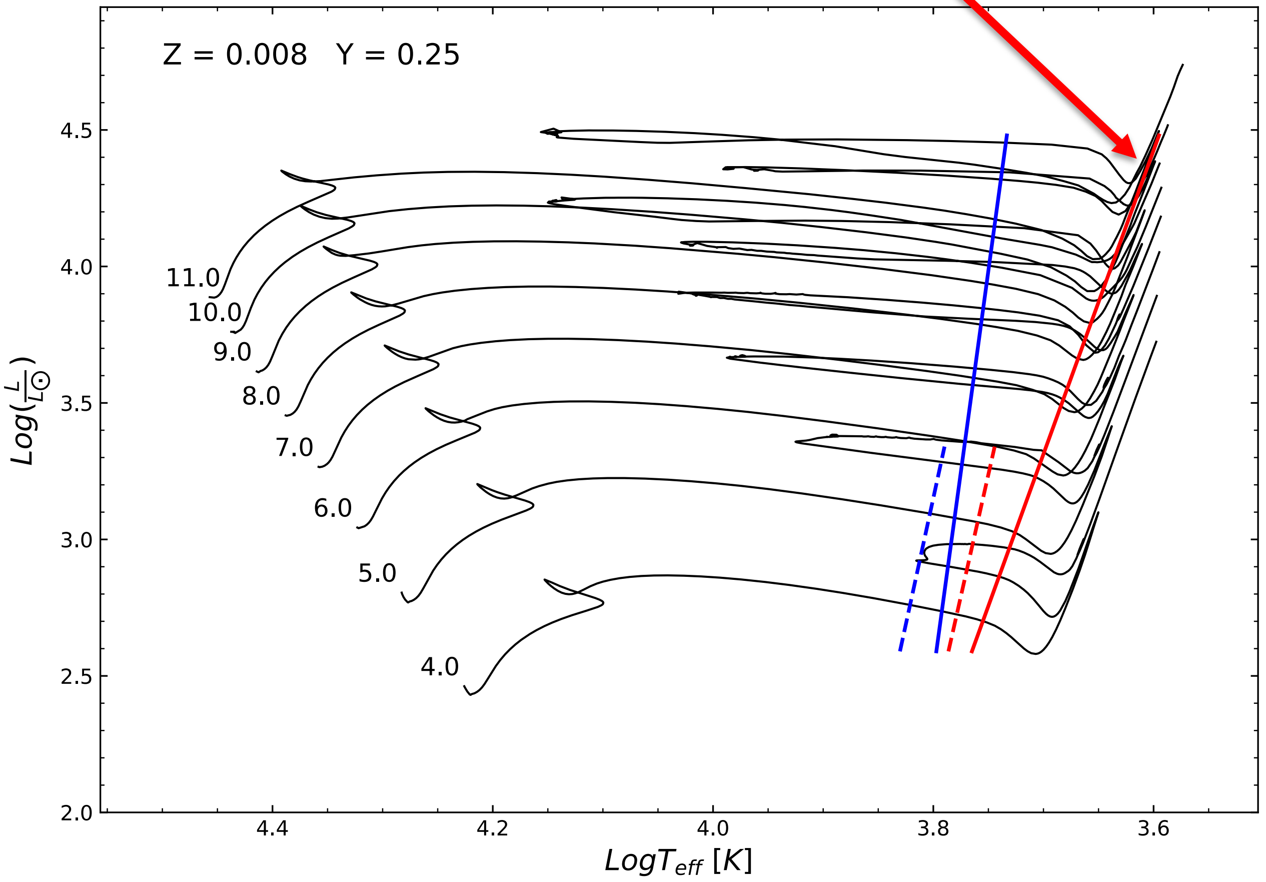
Classical Cepheid model light curves updated Stellingwerf's code

Fundamental

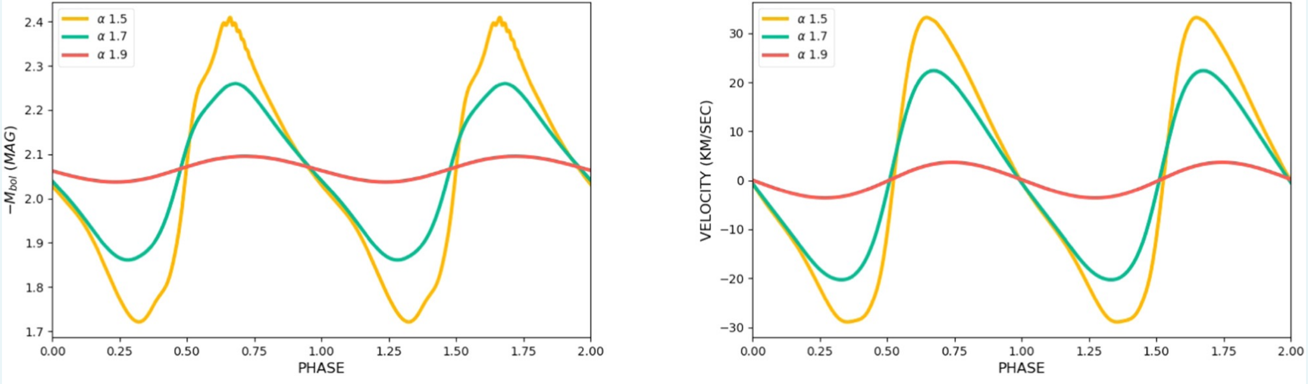
Bono, Marconi & Stellingwerf 2000 ApJ

Nonlinear convective pulsation models

De Somma et al. 2021 MNRAS

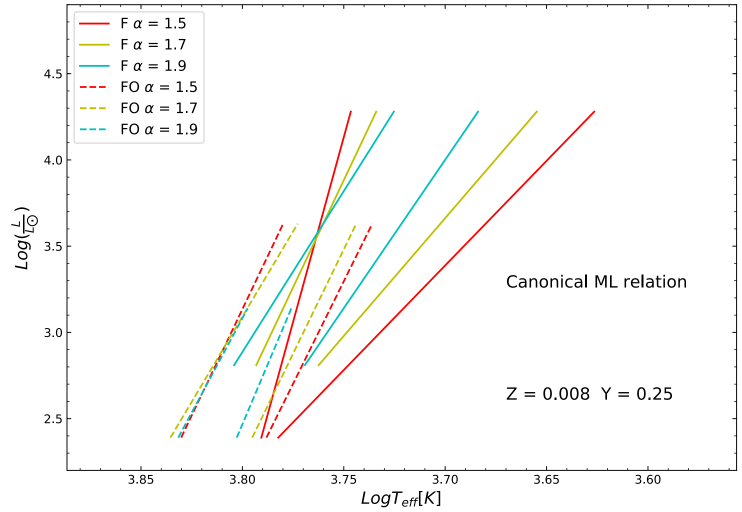


De Somma et al. 2020, 2022 ApJS computed nonlinear convective pulsation models for various assumptions about the efficiency of super-adiabatic convection



(a) (b)

Cepheid updated Stellingwerf's code model predictions: the effects of convective efficiency



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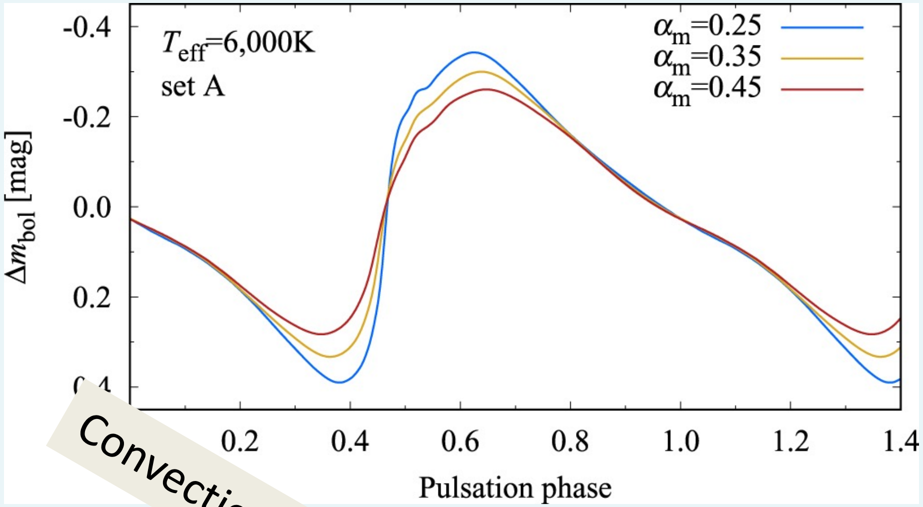
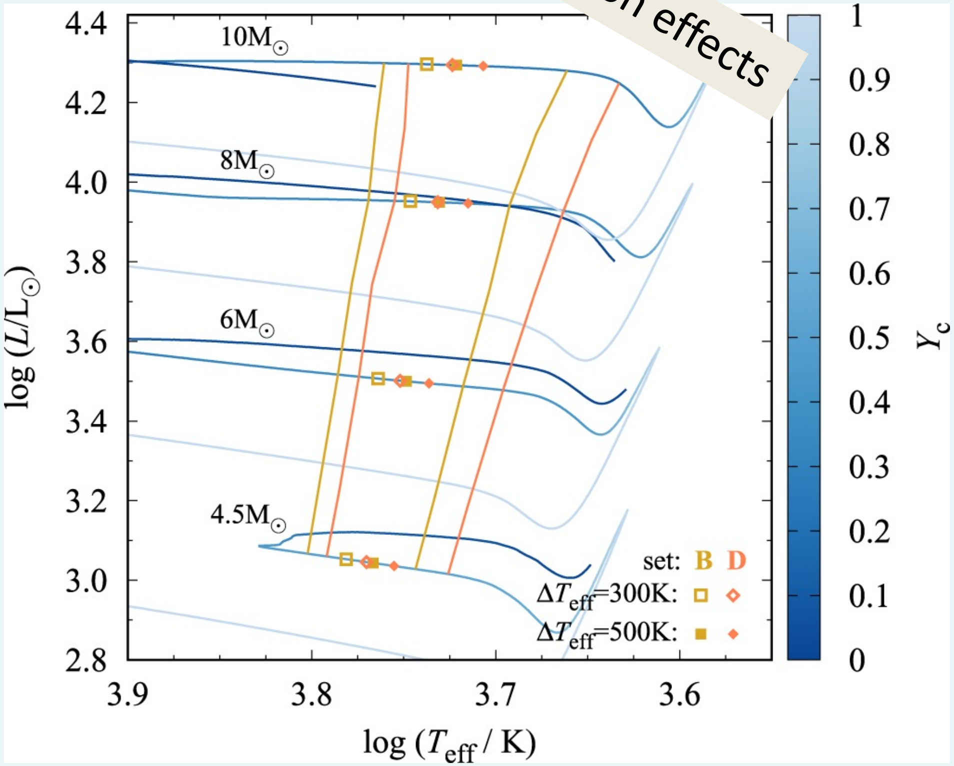
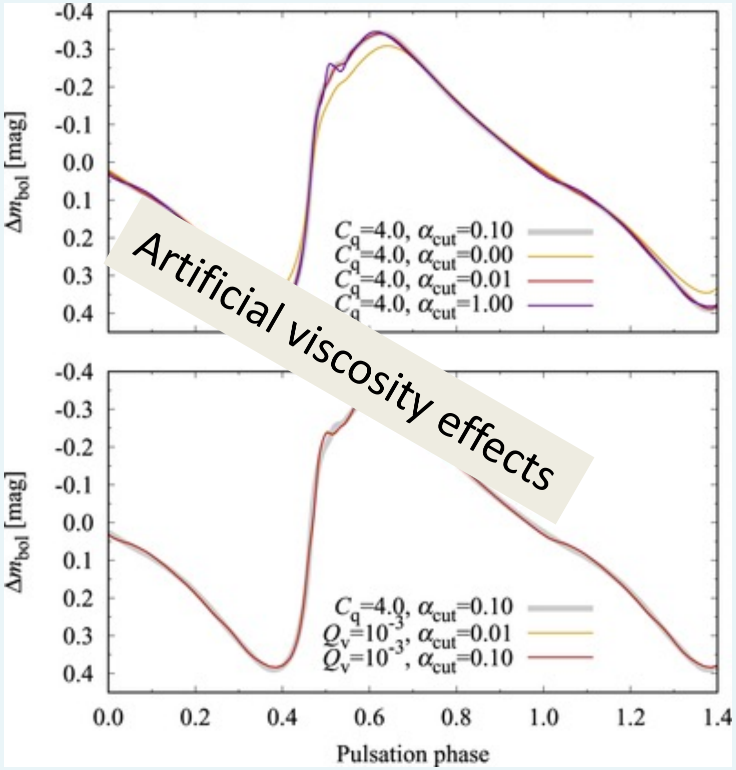
Cepheid MESA RSP model predictions: the effects of model assumptions



Convection effects

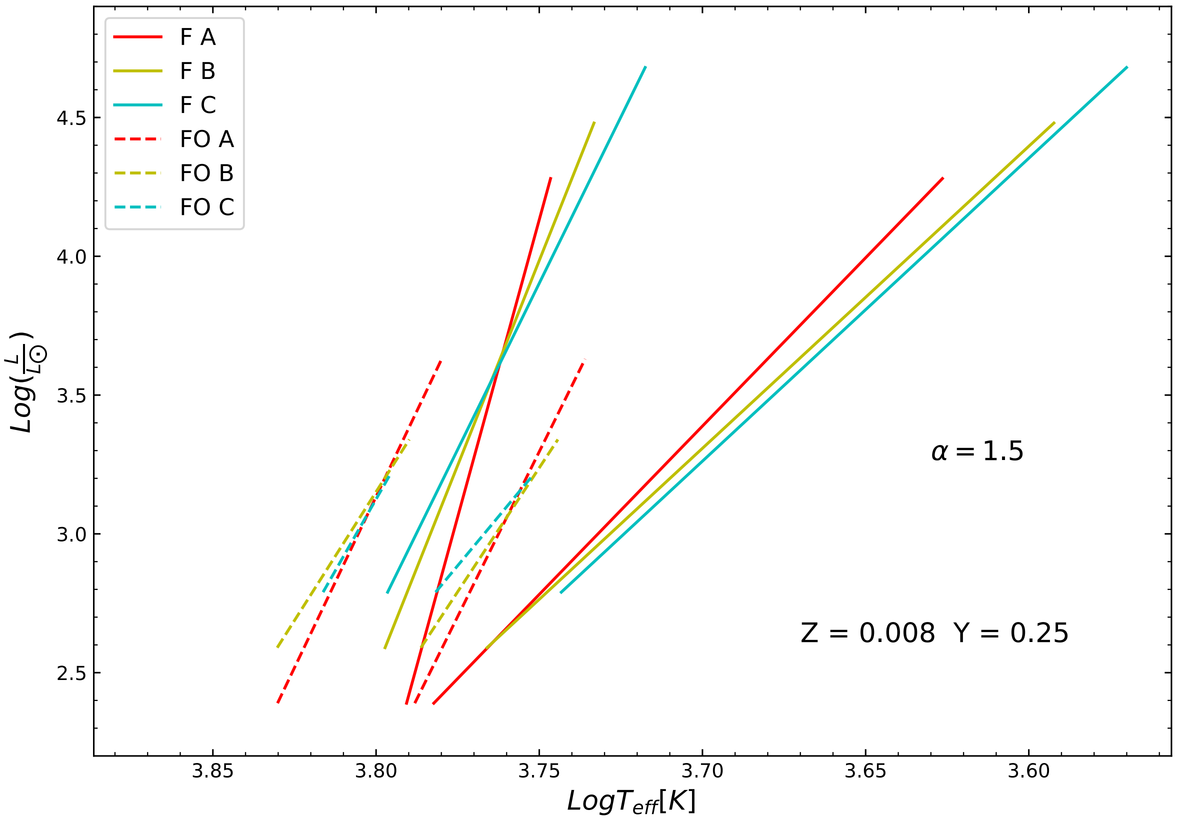


Artificial viscosity effects



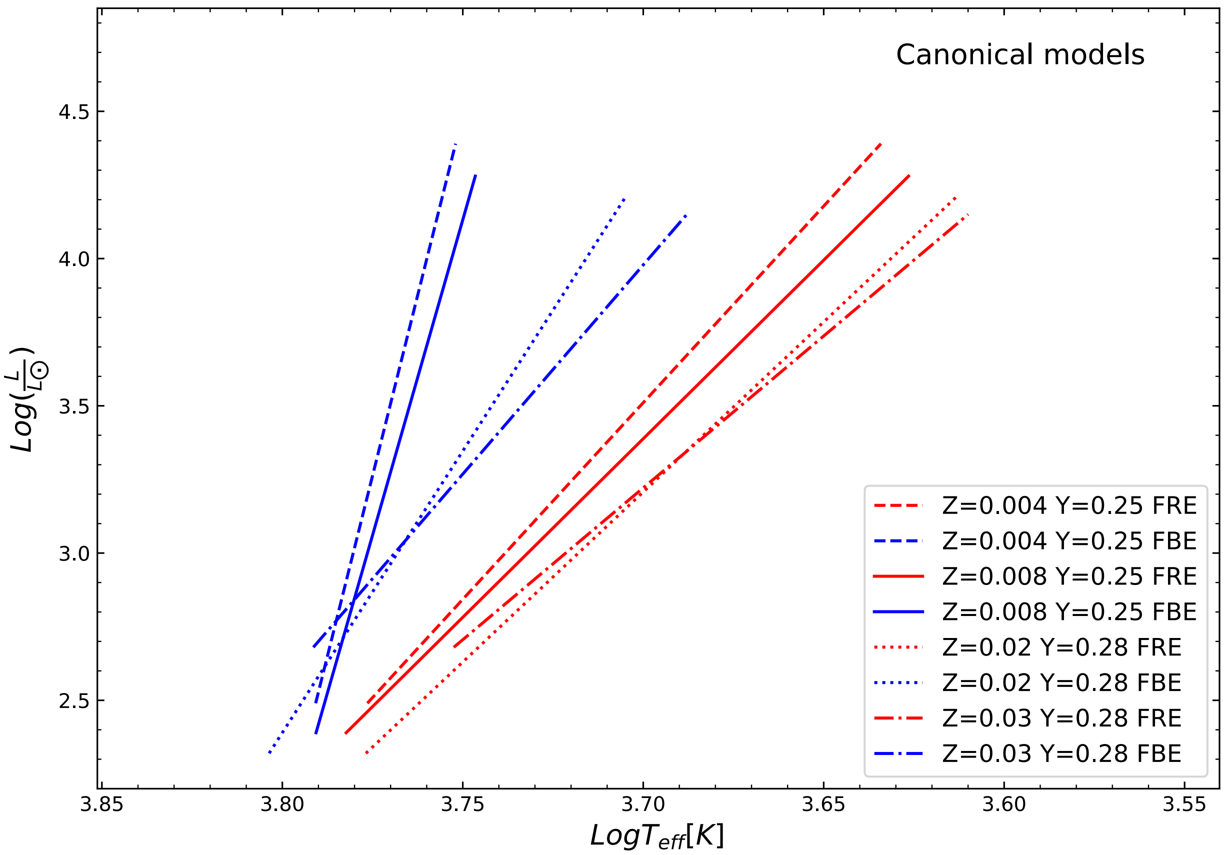
Paxton et al. 2019 ApJS

Cepheid updated Stellingwerf's code model predictions: the effects of the Mass-Luminosity (ML) relation



De Somma et al. 2022 ApJS

Cepheid updated Stellingwerf's code model predictions: the effects of metallicity



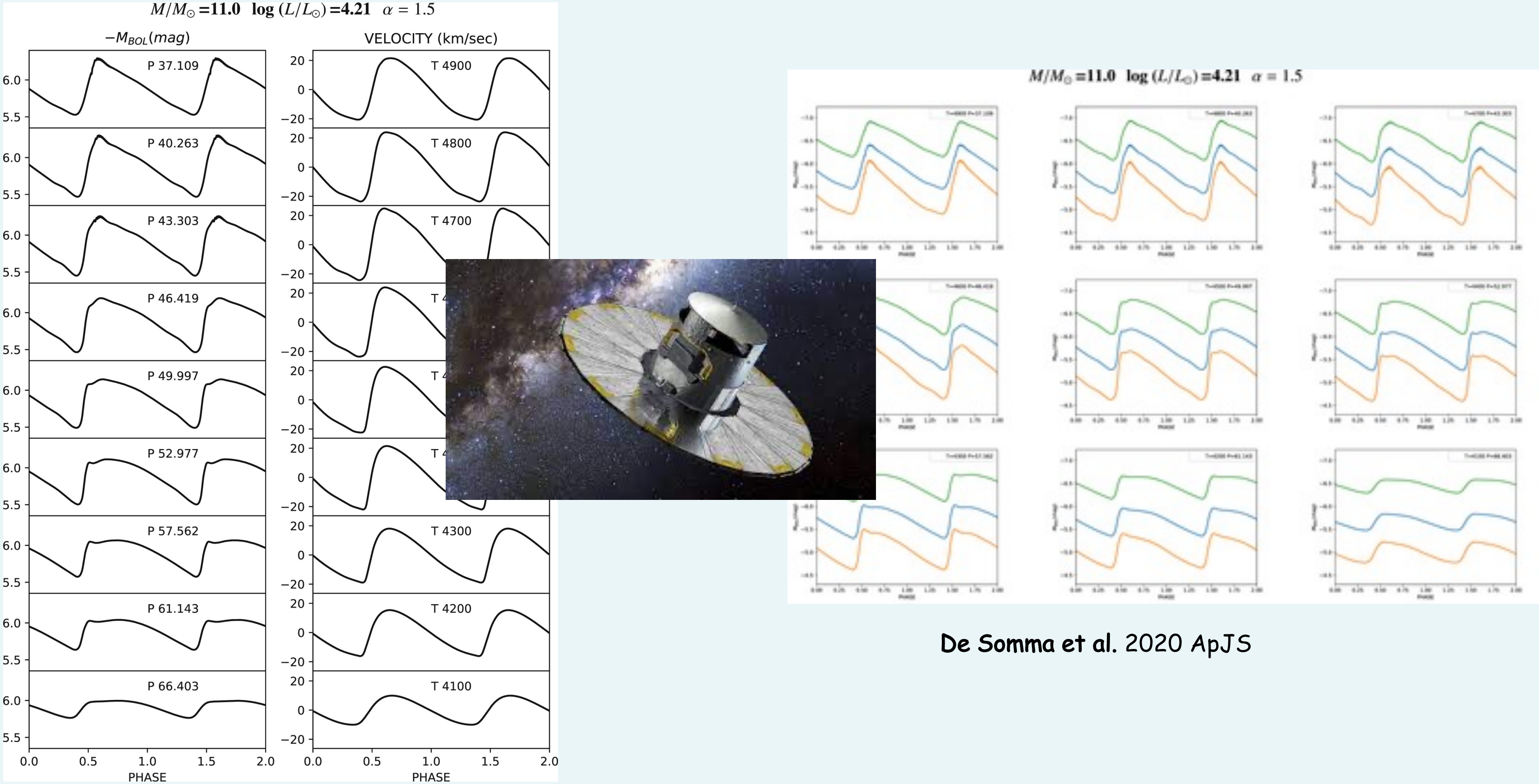
De Somma et al. 2022 ApJS

Bolometric light curves are transformed into various photometric filters

mean magnitudes and colors

Predicted PL, PLC, PW relations

Cepheid predicted properties in the Gaia filters



De Somma et al. 2020 ApJS

Cepheid predicted properties in the Gaia filters

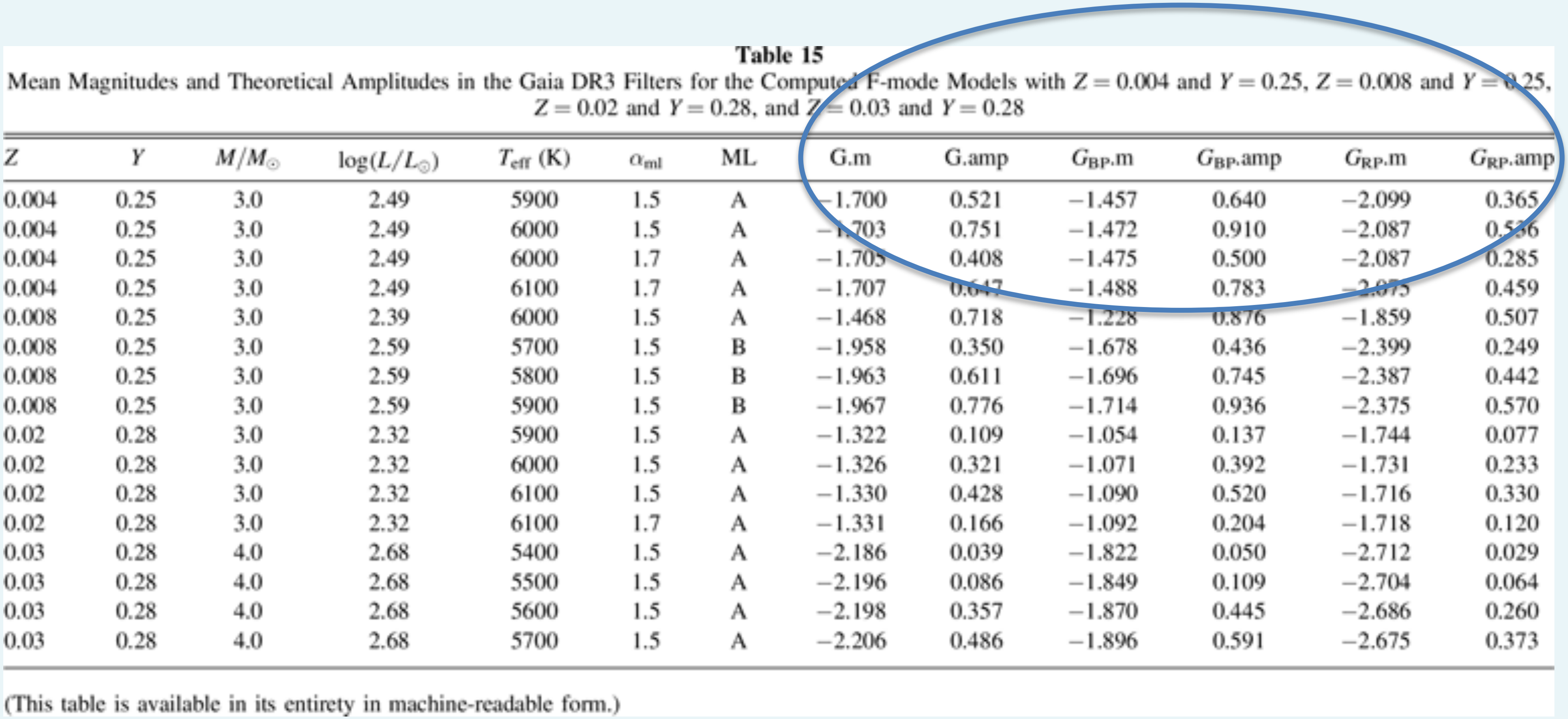


Table 15

Mean Magnitudes and Theoretical Amplitudes in the Gaia DR3 Filters for the Computed F-mode Models with $Z = 0.004$ and $Y = 0.25$, $Z = 0.008$ and $Y = 0.25$, $Z = 0.02$ and $Y = 0.28$, and $Z = 0.03$ and $Y = 0.28$

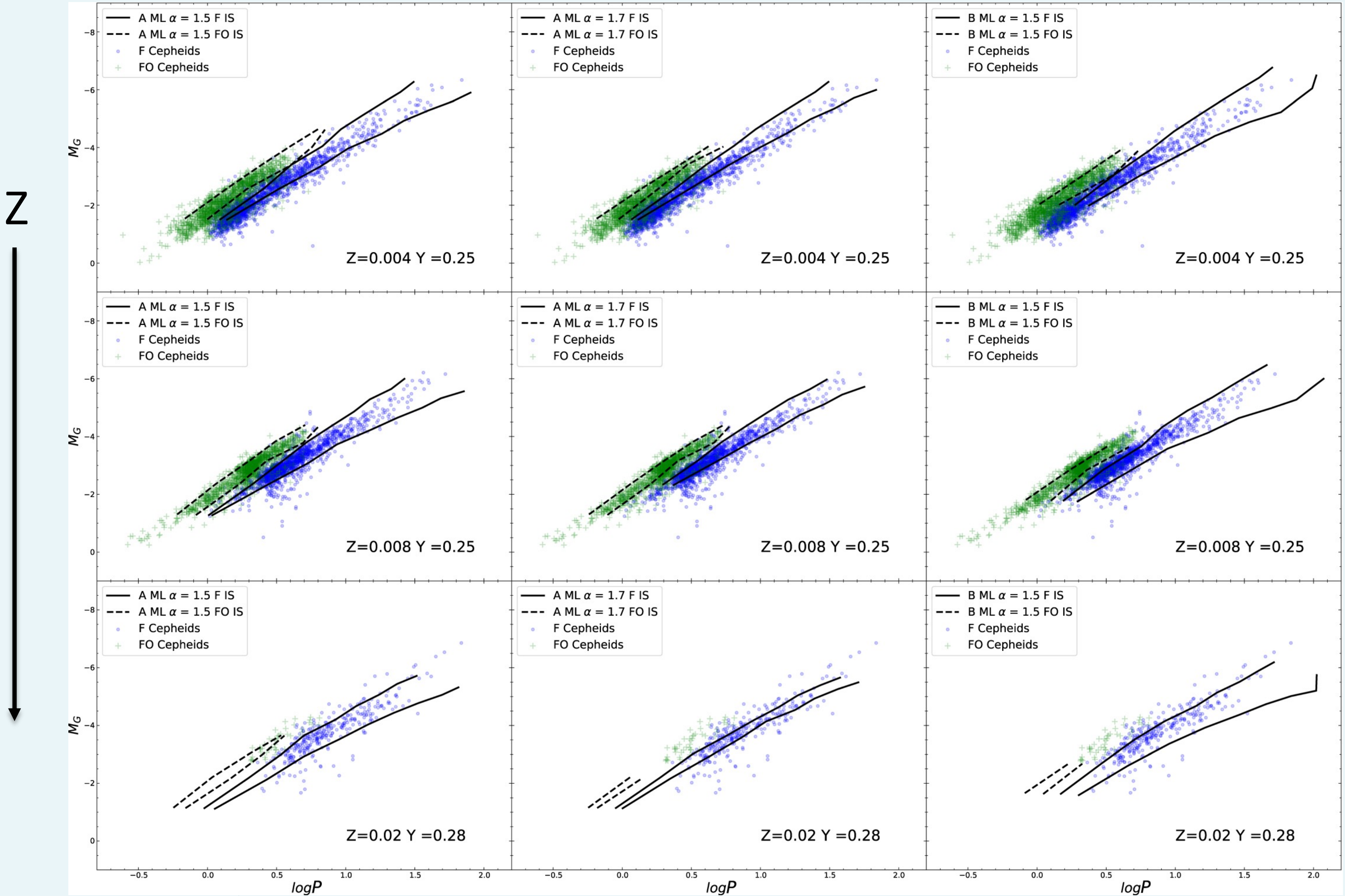
Z	Y	$M/M_\odot$	$\log(L/L_\odot)$	$T_{\rm eff}$ (K)	$\alpha_{\rm ml}$	ML	G.m	G.amp	$G_{\rm BP}$.m	$G_{\rm BP}$.amp	$G_{\rm RP}$.m	$G_{\rm RP}$.amp
0.004	0.25	3.0	2.49	5900	1.5	A	−1.700	0.521	−1.457	0.640	−2.099	0.365
0.004	0.25	3.0	2.49	6000	1.5	A	−1.703	0.751	−1.472	0.910	−2.087	0.536
0.004	0.25	3.0	2.49	6000	1.7	A	−1.705	0.408	−1.475	0.500	−2.087	0.285
0.004	0.25	3.0	2.49	6100	1.7	A	−1.707	0.647	−1.488	0.783	−2.075	0.459
0.008	0.25	3.0	2.39	6000	1.5	A	−1.468	0.718	−1.228	0.876	−1.859	0.507
0.008	0.25	3.0	2.59	5700	1.5	B	−1.958	0.350	−1.678	0.436	−2.399	0.249
0.008	0.25	3.0	2.59	5800	1.5	B	−1.963	0.611	−1.696	0.745	−2.387	0.442
0.008	0.25	3.0	2.59	5900	1.5	B	−1.967	0.776	−1.714	0.936	−2.375	0.570
0.02	0.28	3.0	2.32	5900	1.5	A	−1.322	0.109	−1.054	0.137	−1.744	0.077
0.02	0.28	3.0	2.32	6000	1.5	A	−1.326	0.321	−1.071	0.392	−1.731	0.233
0.02	0.28	3.0	2.32	6100	1.5	A	−1.330	0.428	−1.090	0.520	−1.716	0.330
0.02	0.28	3.0	2.32	6100	1.7	A	−1.331	0.166	−1.092	0.204	−1.718	0.120
0.03	0.28	4.0	2.68	5400	1.5	A	−2.186	0.039	−1.822	0.050	−2.712	0.029
0.03	0.28	4.0	2.68	5500	1.5	A	−2.196	0.086	−1.849	0.109	−2.704	0.064
0.03	0.28	4.0	2.68	5600	1.5	A	−2.198	0.357	−1.870	0.445	−2.686	0.260
0.03	0.28	4.0	2.68	5700	1.5	A	−2.206	0.486	−1.896	0.591	−2.675	0.373

(This table is available in its entirety in machine-readable form.)

De Somma et al. 2020, 2022. ApJS

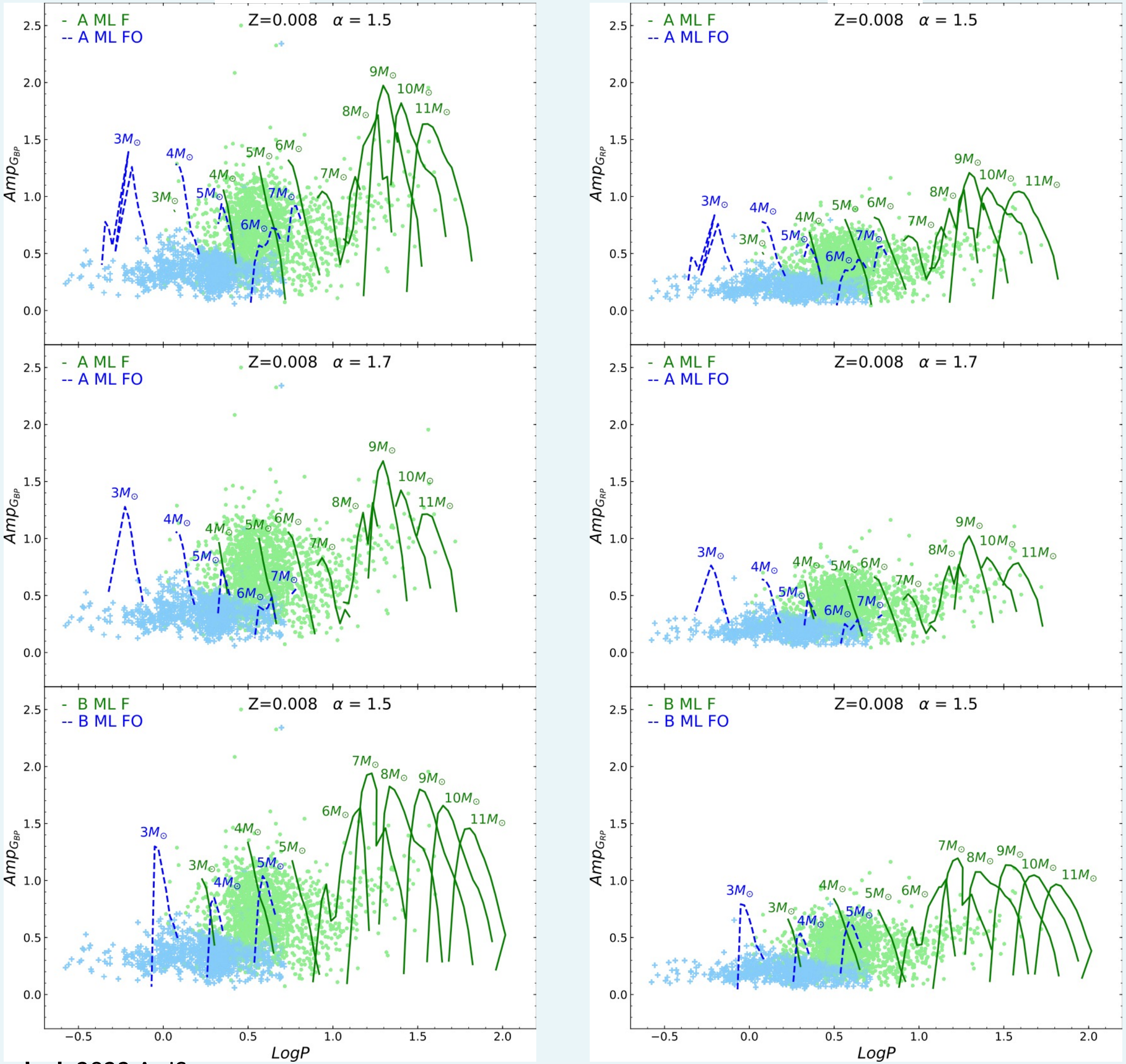
Predicted versus observed instability strip in the Period-Gaia magnitude planes

Canonical l/Hp = 1.5 Canonical l/Hp = 1.7 Non Canonical l/Hp = 1.5



De Somma et al. 2022 ApJS

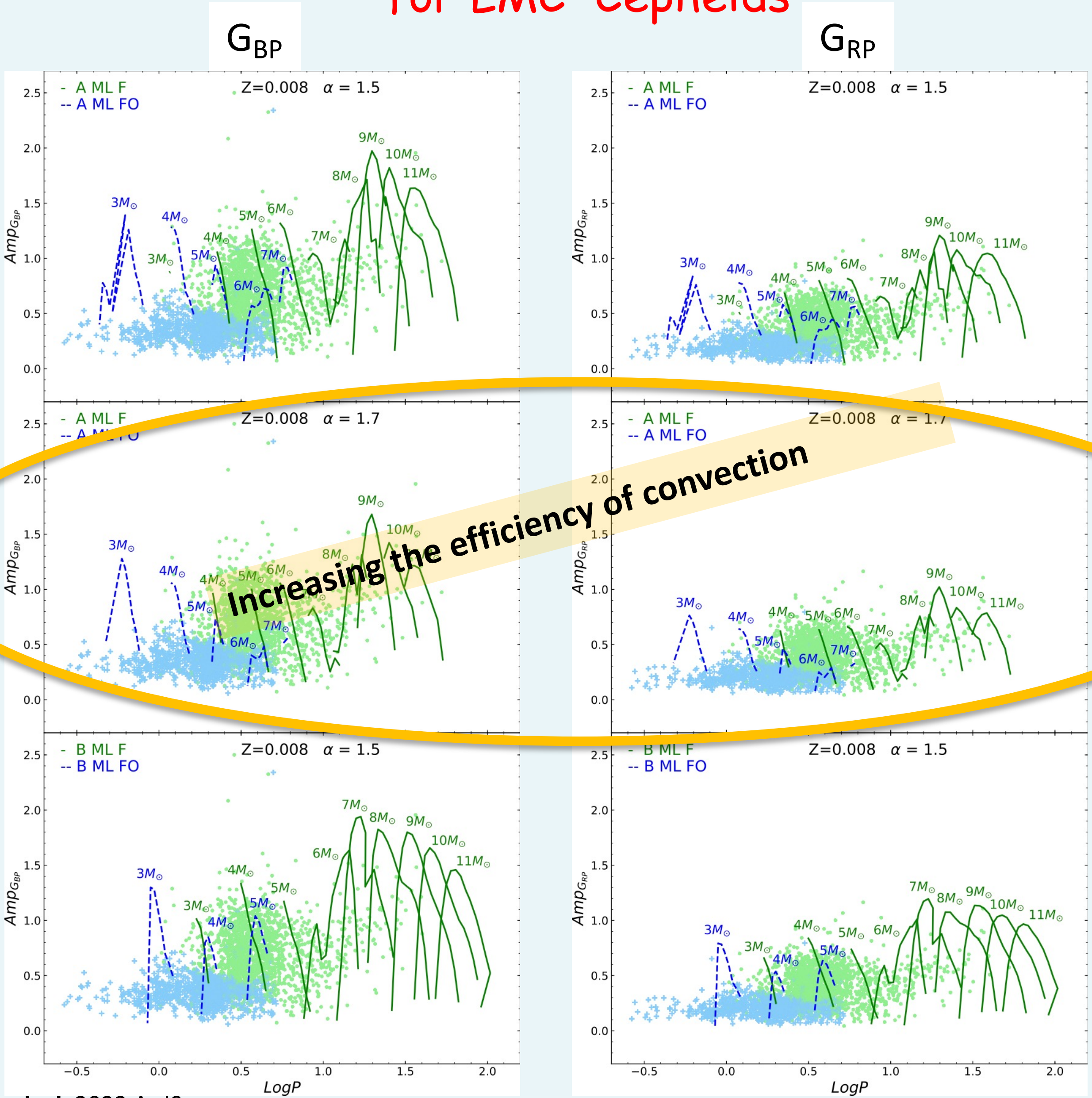
Predicted versus observed Period-Amplitude planes for LMC Cepheids


G_{BP} G_{RP}

De Somma et al. 2022 ApJS

“Stellar variability, stellar multiplicity: periodicity in time & motion” June 6-8, 2023, Sofia, Bulgaria

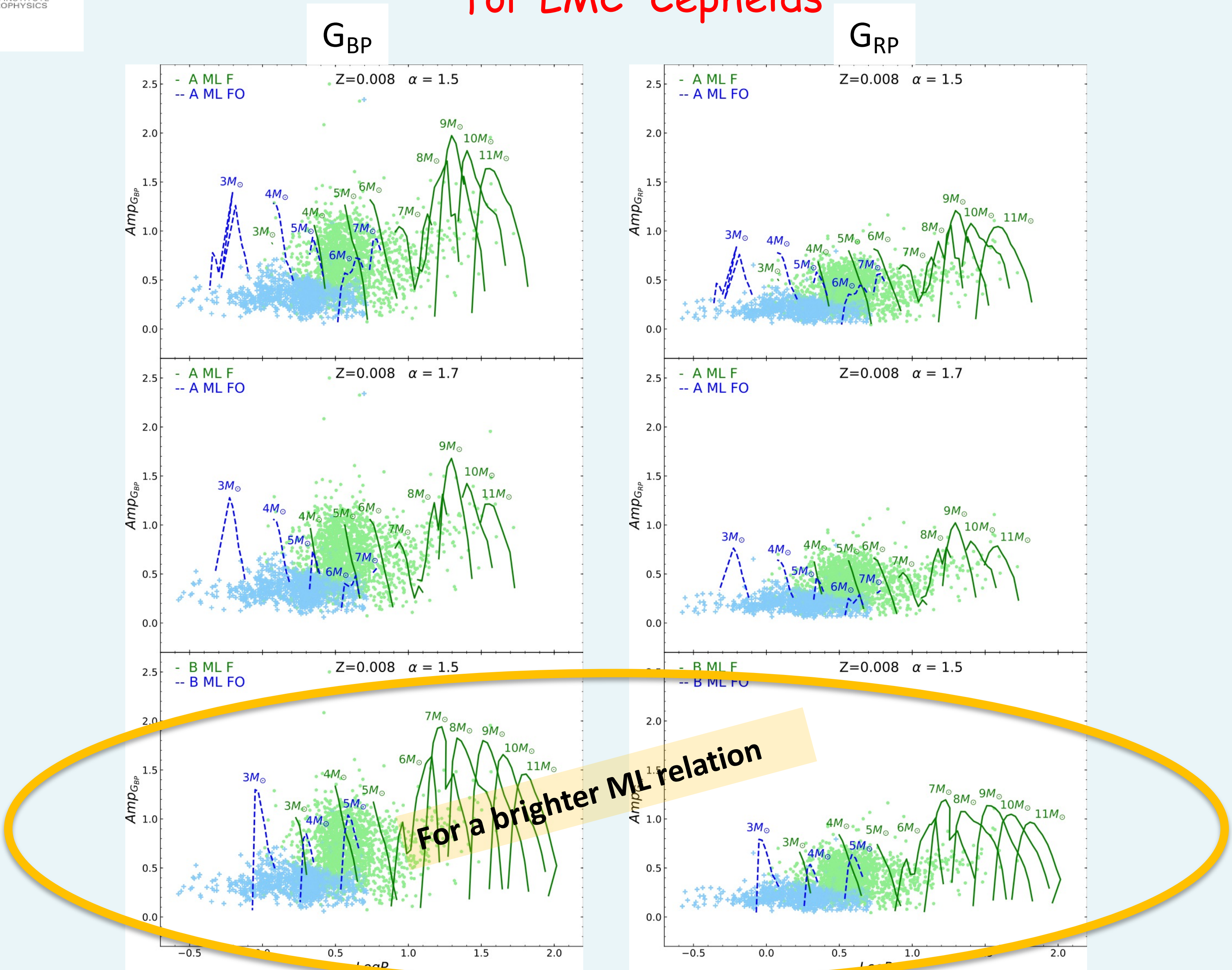
Predicted versus observed Period-Amplitude planes for LMC Cepheids



Increasing the efficiency of convection

De Somma et al. 2022 ApJS

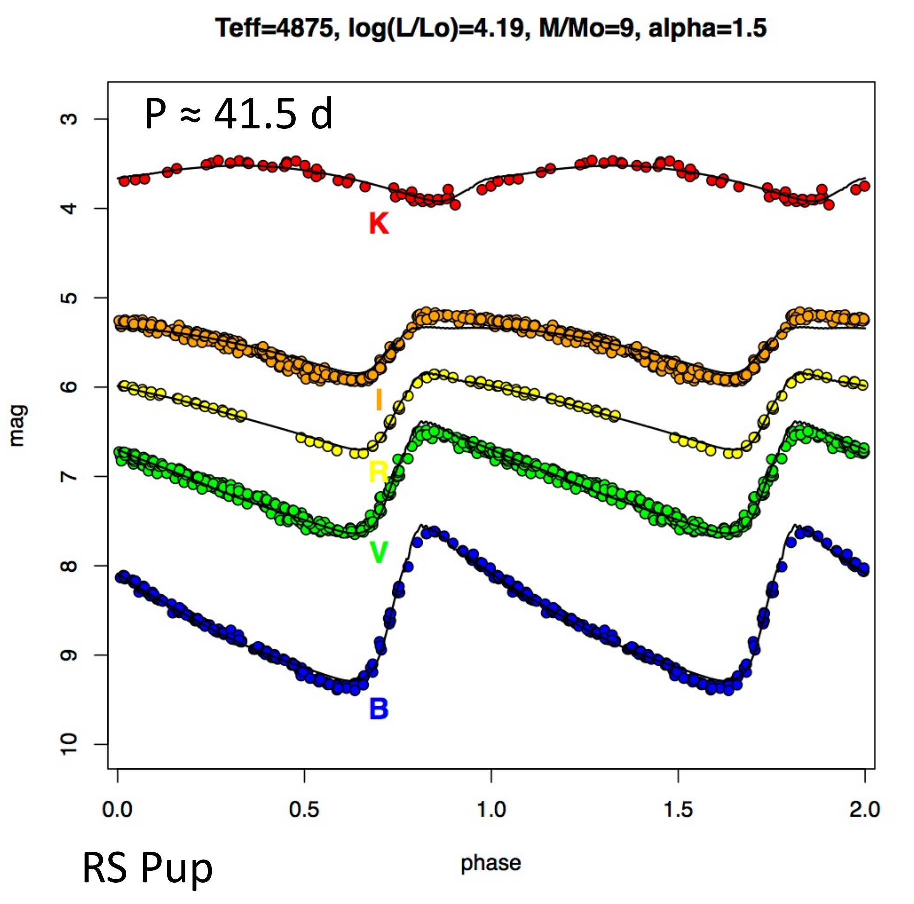
Predicted versus observed Period-Amplitude planes for LMC Cepheids

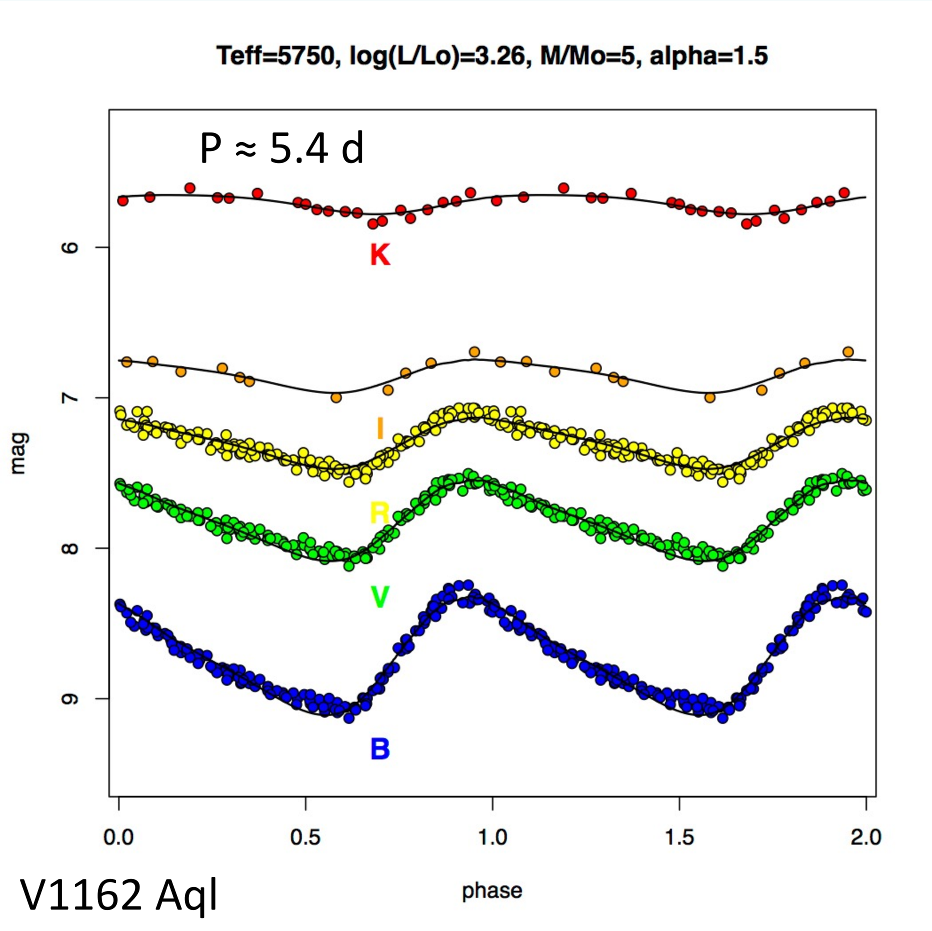


For a brighter ML relation

De Somma et al. 2022 ApJS

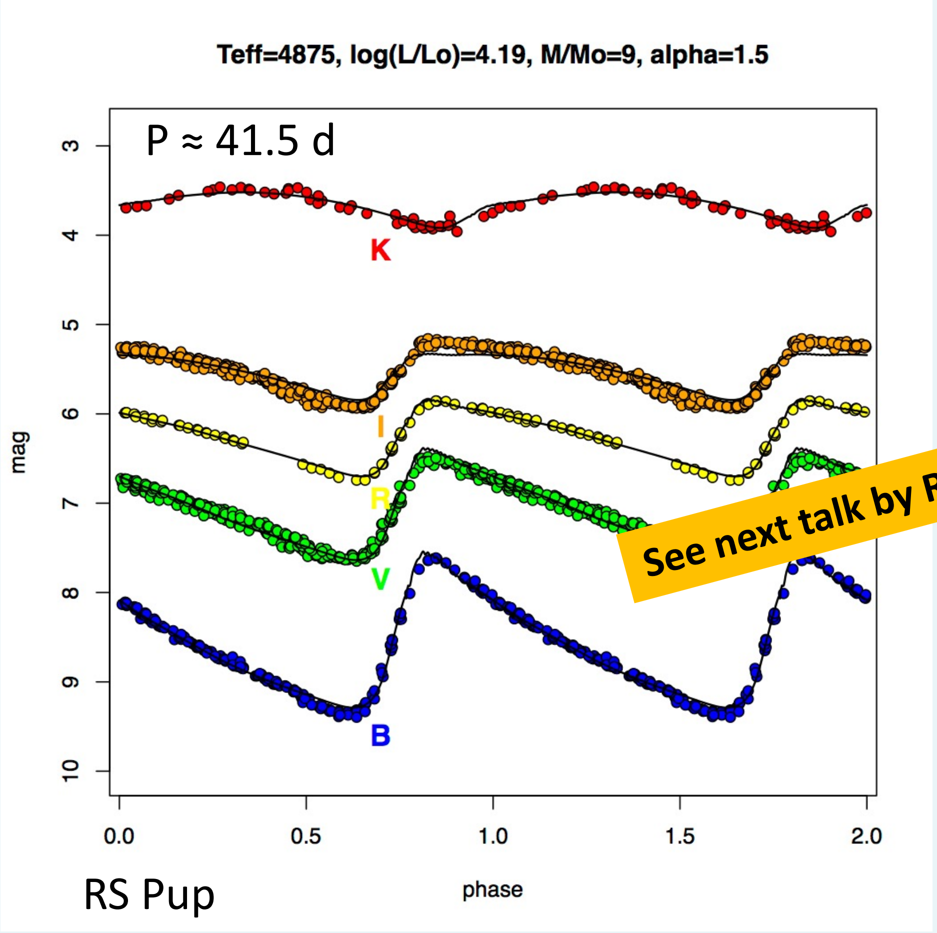
Predicted versus observed light curves

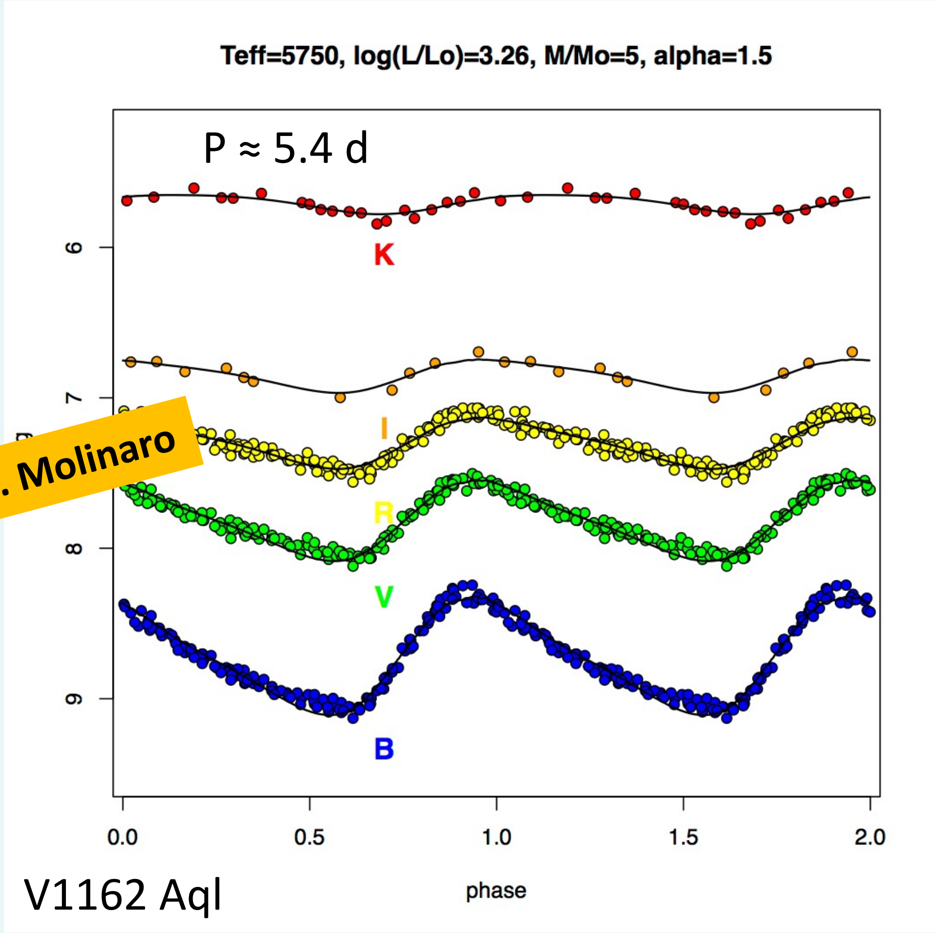




Gaia Collaboration, Clementini et al. 2017 A&A

Predicted versus observed light curves





See next talk by R. Molinaro

Gaia Collaboration, Clementini et al. 2017 A&A

The multi-filter Period-Luminosity-Color and Period-Wesenheit relations

For each chemical composition, mean magnitude and colors are adopted together with the periods to infer PLC and PW relations in different filter combinations, including the Gaia bands

PLC → $\langle G\rangle = a + b\log P + c\langle G_{BP}\rangle - \langle G_{RP}\rangle$

PW → $\langle W\rangle = \langle G\rangle - 1.9\langle G_{BP}\rangle - \langle G_{RP}\rangle = a + b\log P$

The metal-dependent Period-Wesenheit relations

$W = a + b \log P + c\,[Fe/H]$

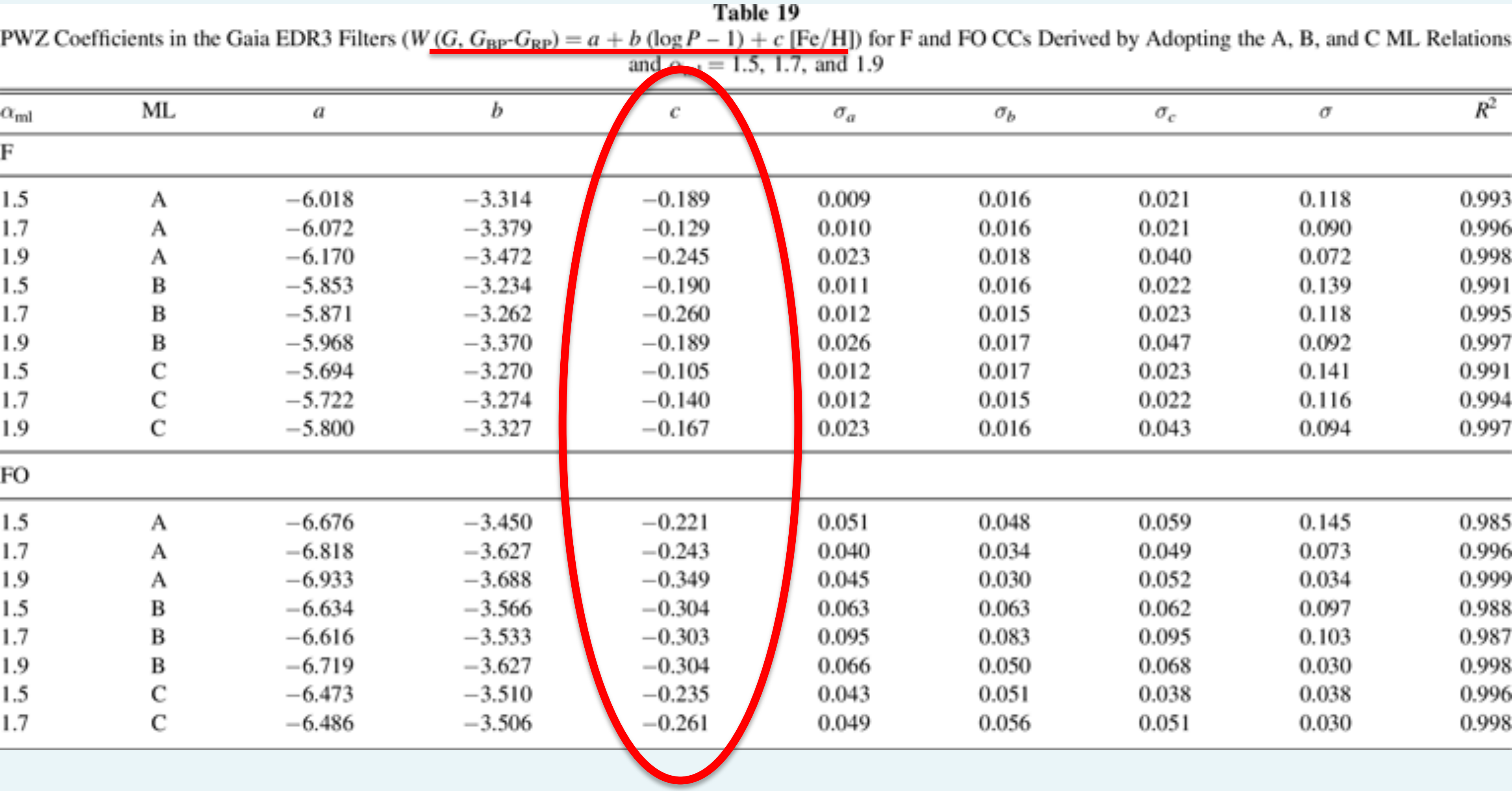


Table 19

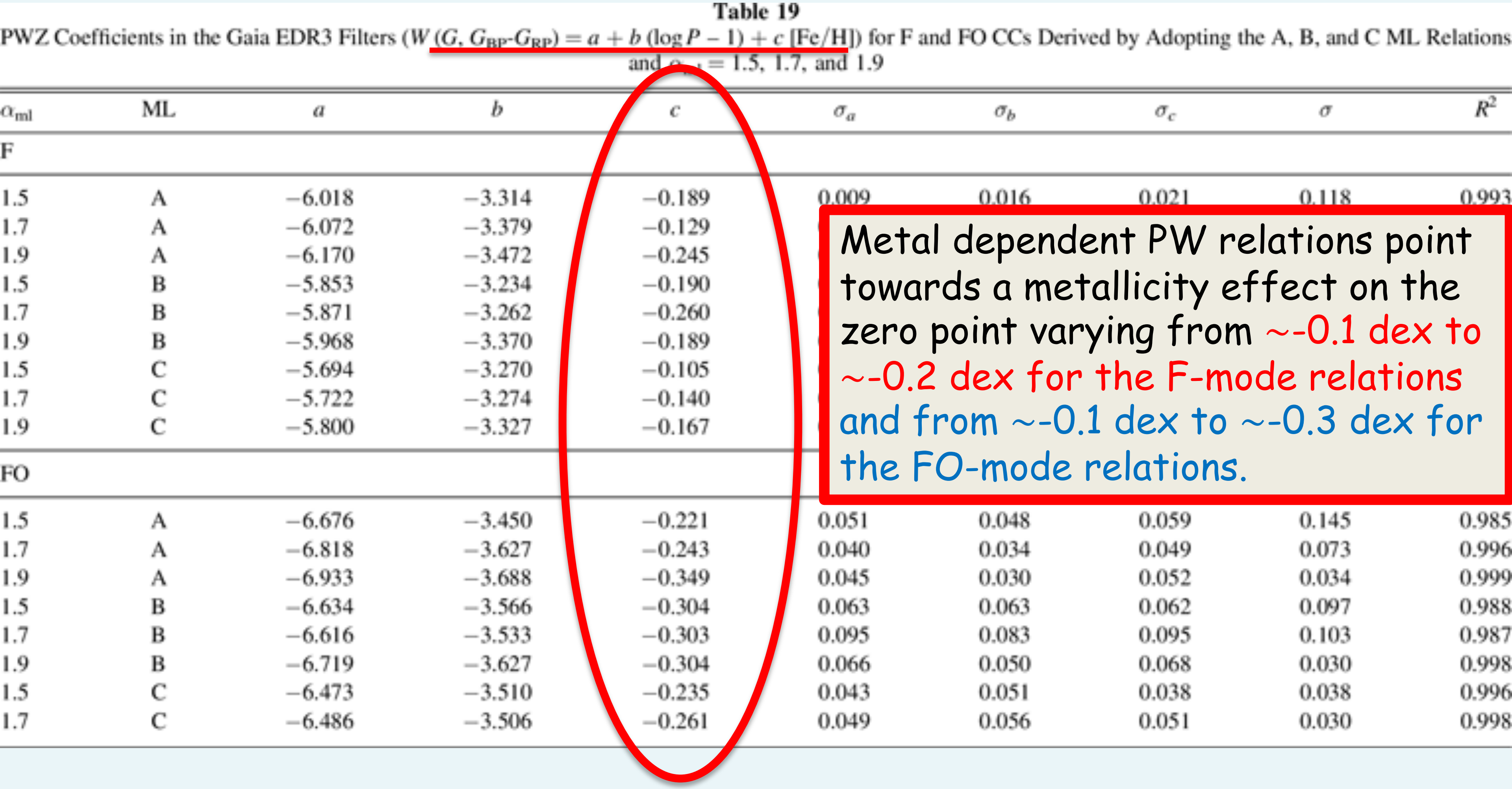
PWZ Coefficients in the Gaia EDR3 Filters ($W(G, G_{BP}-G_{RP}) = a + b(\log P - 1) + c\,[Fe/H]$) for F and FO CCs Derived by Adopting the A, B, and C ML Relations and α_{ml} = 1.5, 1.7, and 1.9

α_{ml}	ML	a	b	c	σ_a	σ_b	σ_c	σ	R^2
F									
1.5	A	−6.018	−3.314	−0.189	0.009	0.016	0.021	0.118	0.993
1.7	A	−6.072	−3.379	−0.129	0.010	0.016	0.021	0.090	0.996
1.9	A	−6.170	−3.472	−0.245	0.023	0.018	0.040	0.072	0.998
1.5	B	−5.853	−3.234	−0.190	0.011	0.016	0.022	0.139	0.991
1.7	B	−5.871	−3.262	−0.260	0.012	0.015	0.023	0.118	0.995
1.9	B	−5.968	−3.370	−0.189	0.026	0.017	0.047	0.092	0.997
1.5	C	−5.694	−3.270	−0.105	0.012	0.017	0.023	0.141	0.991
1.7	C	−5.722	−3.274	−0.140	0.012	0.015	0.022	0.116	0.994
1.9	C	−5.800	−3.327	−0.167	0.023	0.016	0.043	0.094	0.997
FO									
1.5	A	−6.676	−3.450	−0.221	0.051	0.048	0.059	0.145	0.985
1.7	A	−6.818	−3.627	−0.243	0.040	0.034	0.049	0.073	0.996
1.9	A	−6.933	−3.688	−0.349	0.045	0.030	0.052	0.034	0.999
1.5	B	−6.634	−3.566	−0.304	0.063	0.063	0.062	0.097	0.988
1.7	B	−6.616	−3.533	−0.303	0.095	0.083	0.095	0.103	0.987
1.9	B	−6.719	−3.627	−0.304	0.066	0.050	0.068	0.030	0.998
1.5	C	−6.473	−3.510	−0.235	0.043	0.051	0.038	0.038	0.996
1.7	C	−6.486	−3.506	−0.261	0.049	0.056	0.051	0.030	0.998

De Somma et al. 2022 ApJS

The metal-dependent Period-Wesenheit relations

$W = a + b \log P + c\,[Fe/H]$



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1.5	B	−5.853	−3.234	−0.190	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1.7	B	−5.871	−3.262	−0.260	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1.9	B	−5.968	−3.370	−0.189	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1.5	C	−5.694	−3.270	−0.105	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1.7	C	−5.722	−3.274	−0.140	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1.9	C	−5.800	−3.327	−0.167	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
FO									
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1.7	C	−6.486	−3.506	−0.261	0.049	0.056	0.051	0.030	0.998

Metal dependent PW relations point towards a metallicity effect on the zero point varying from ~-0.1 dex to ~-0.2 dex for the F-mode relations and from ~-0.1 dex to ~-0.3 dex for the FO-mode relations.

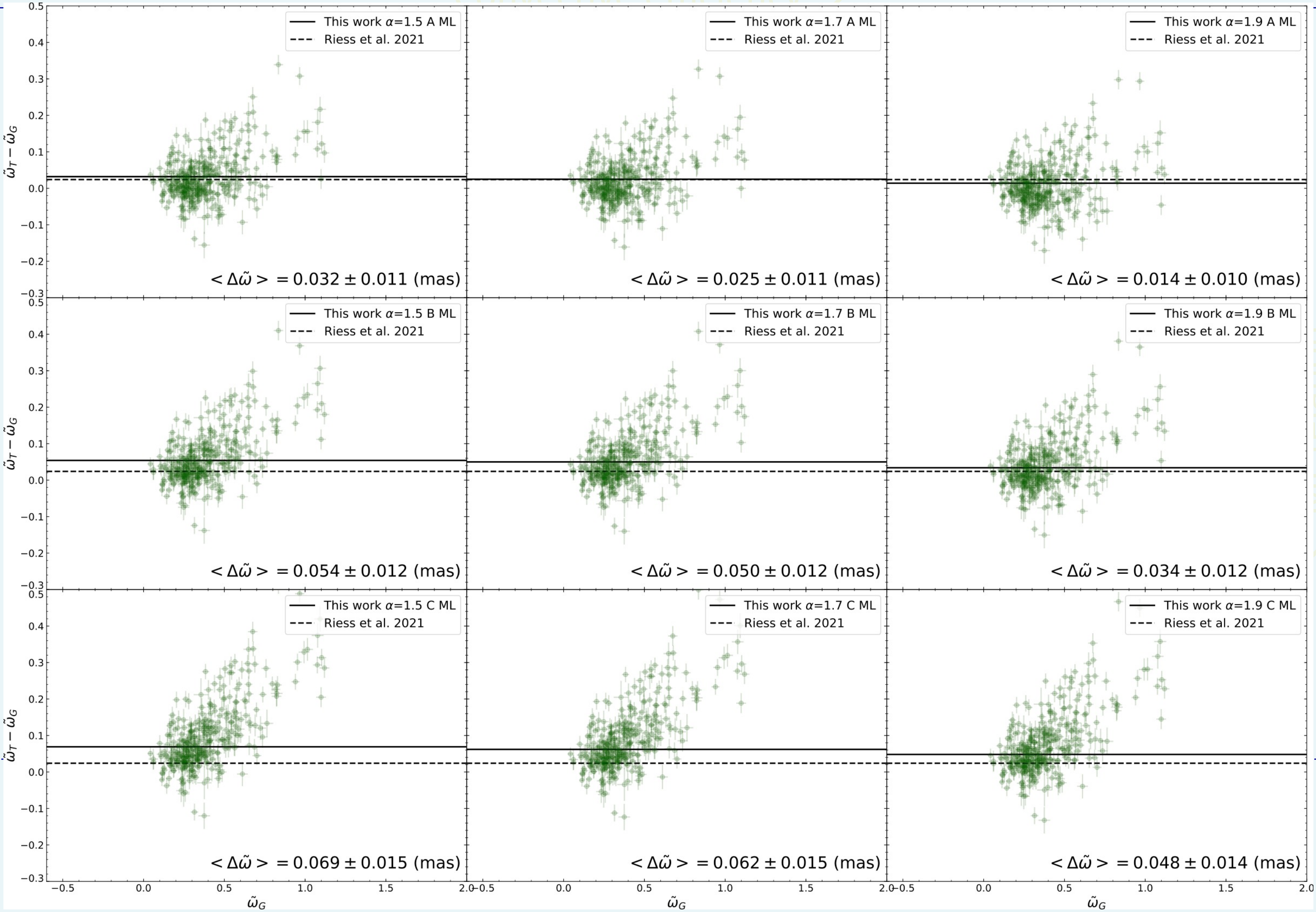
De Somma et al. 2022 ApJS

Theoretical versus Gaia parallaxes for Galactic Cepheids

With theoretical parallax obtained by applying the PWZ: W= a + b logP + c [Fe/H]

Convective efficiency →

Theoretical - Gaia parallax

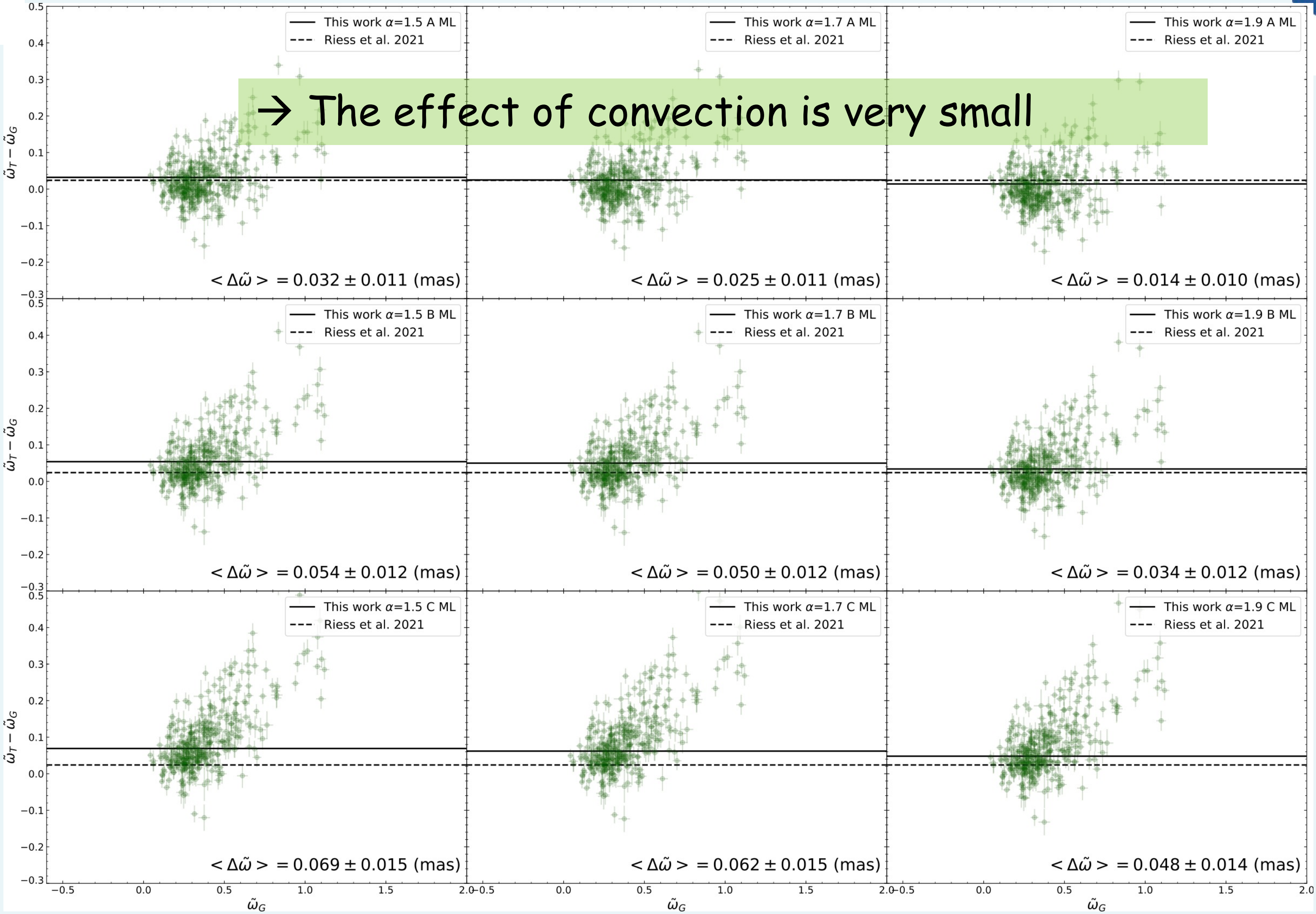


← ML relation

Gaia parallax

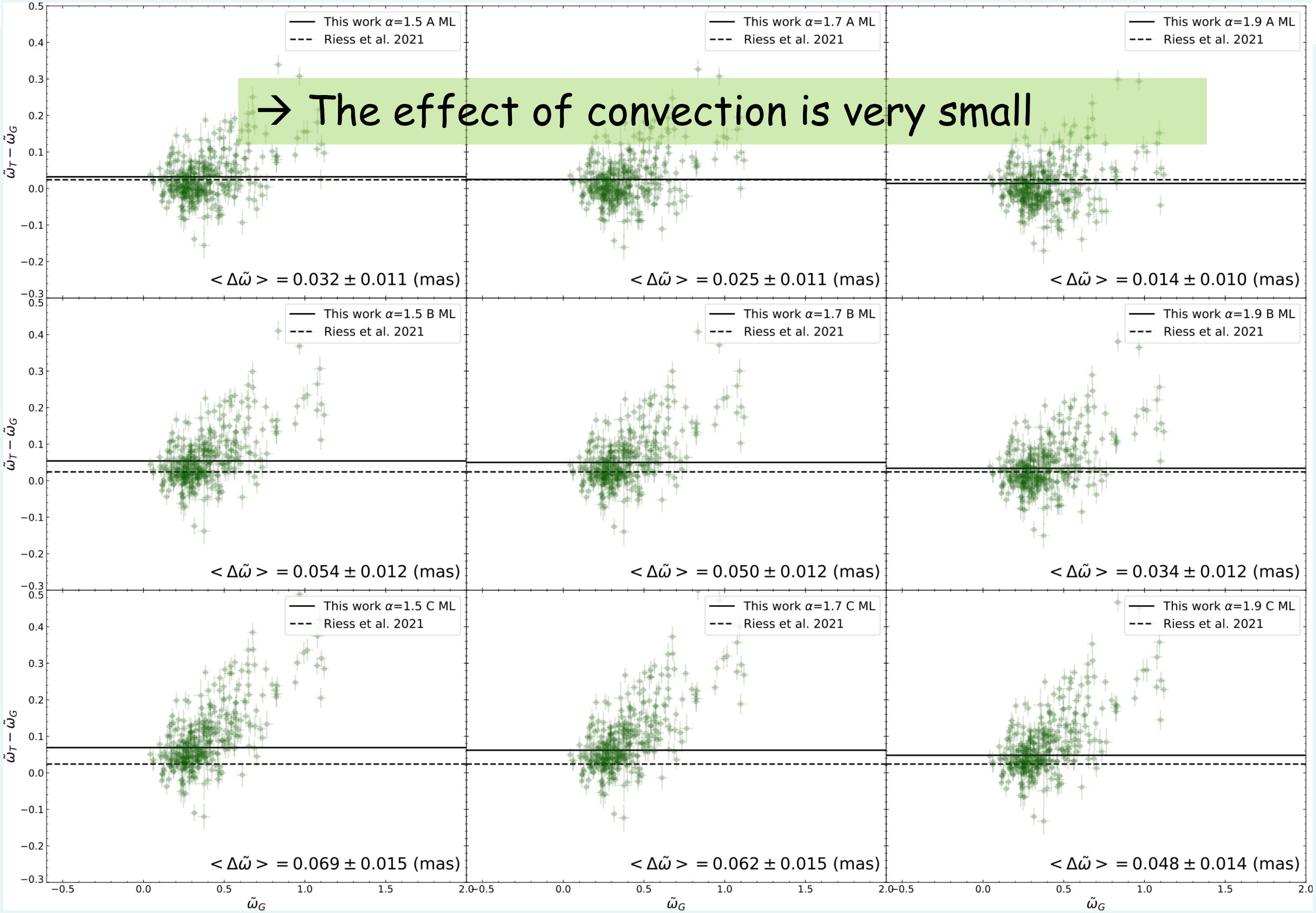
De Somma et al. 2022 ApJS

Effect of the ML relations



→ The effect of convection is very small

Effect of the ML relations



→ The effect of convection is very small

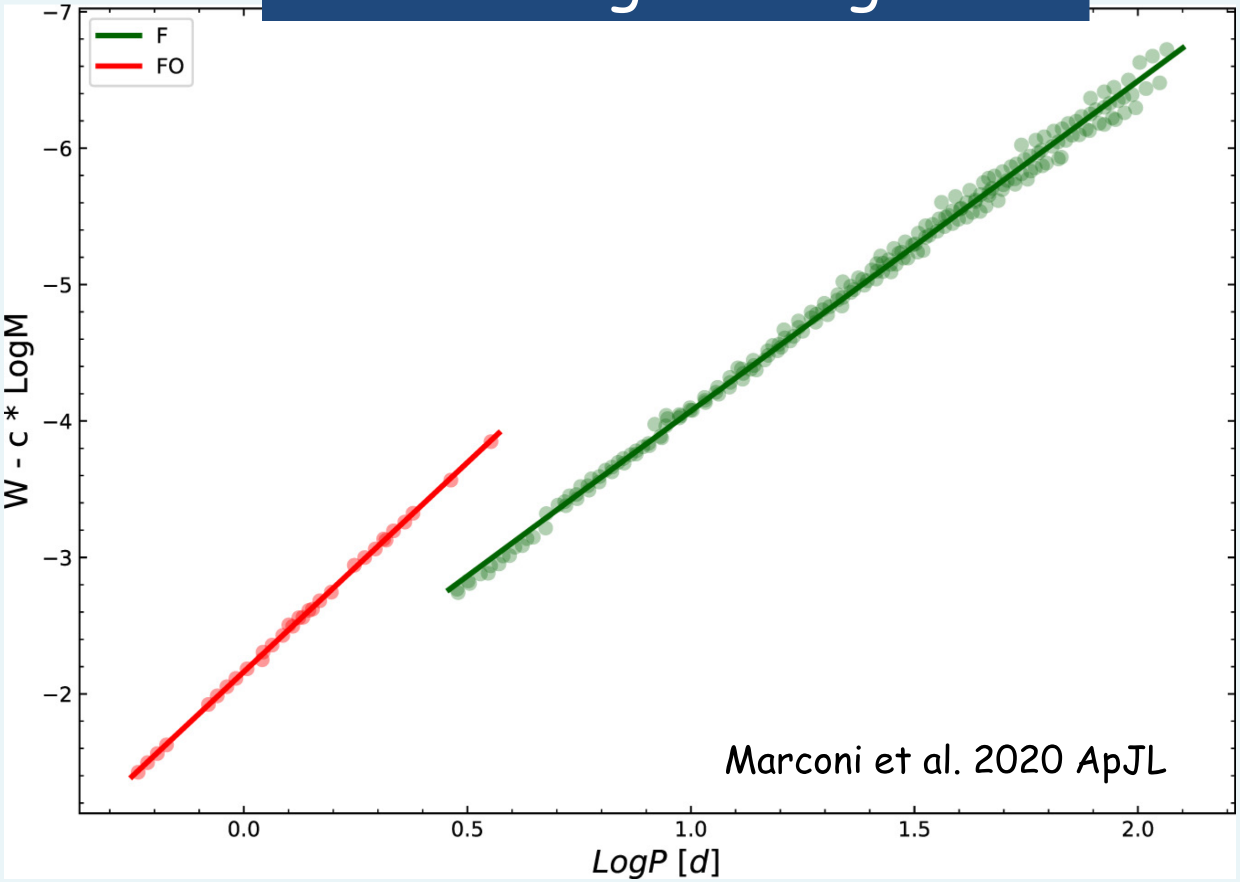
→ The effect of ML is more important

Brighter/fainter ML relation implies a shorter/longer distance scale
→ increase/decrease of H_0

Mass determinations based on Gaia parallaxes and PWM relations

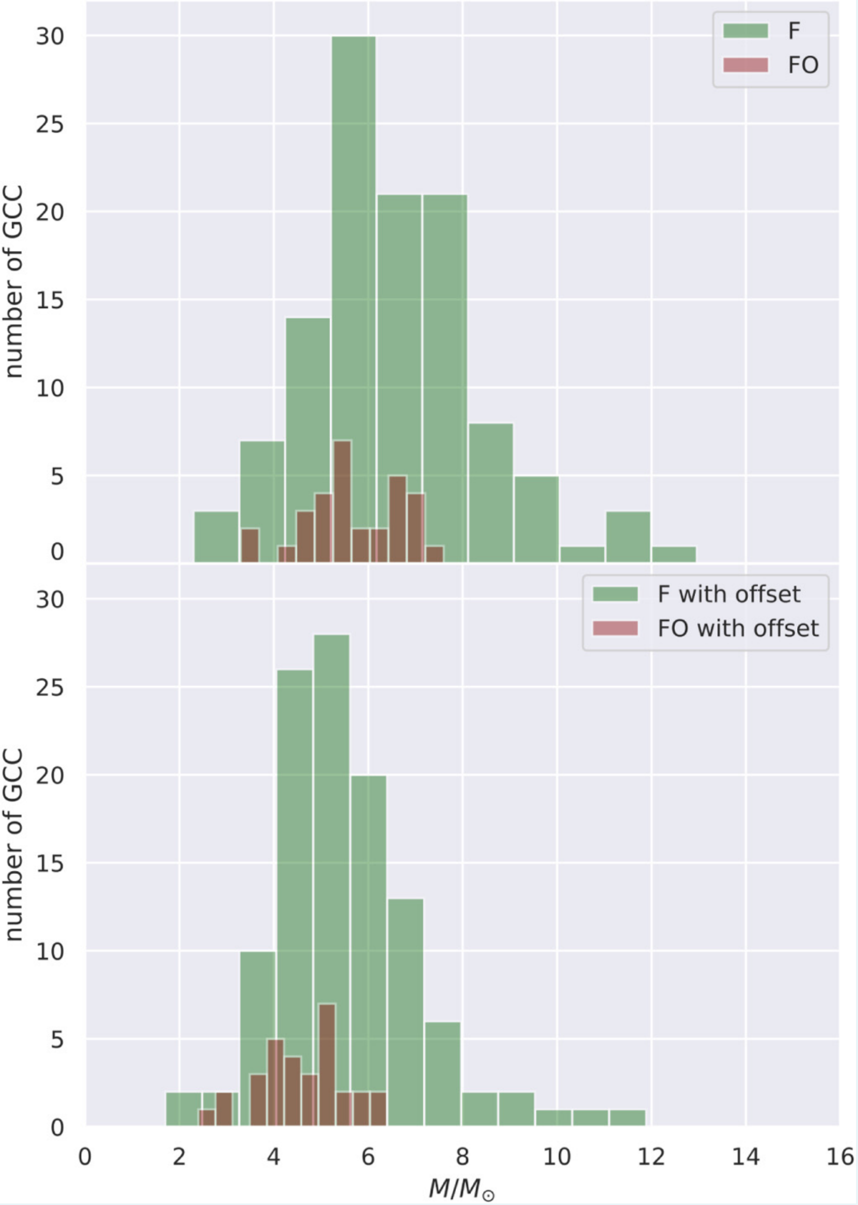
At fixed solar metallicity, including models with different ML relation, mass-dependent Period-Wesenheit (PWM) relations were derived.

$$W = a + b \log P + c \log M/M_o$$



Marconi et al. 2020 ApJL

Mass determinations based on Gaia parallaxes and PWM relations

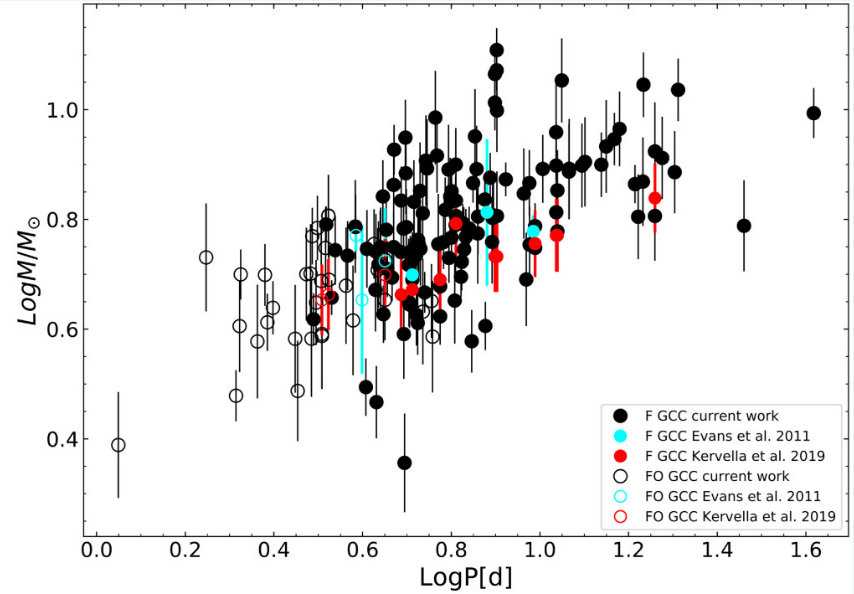


The predicted mass distribution of the F (green bars) and FO (red bars) mode pulsators.

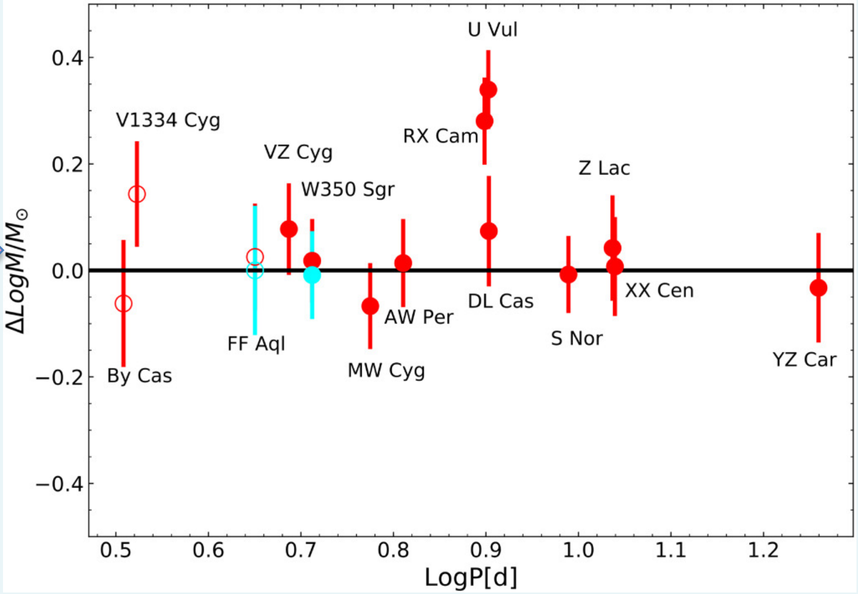
The same distribution as in the top panel, but obtained including the Gaia Cepheid parallax offset. (Marconi et al. 2021 ApJL)

Mass determinations based on Gaia parallaxes and PWM relations

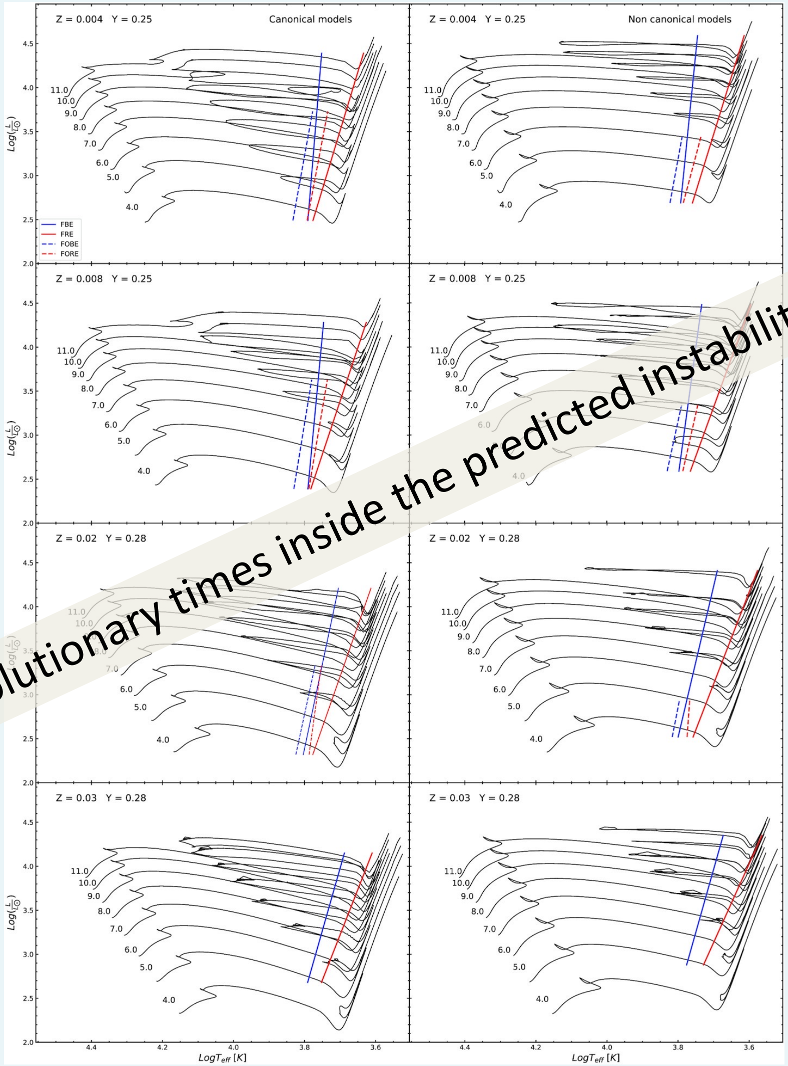
The predicted mass distribution of the F (filled circles) and FO (open circles) pulsators as a function of the pulsation period.



The difference between these results and the ones based on binary system dynamical analysis by Kervella et al. (2019, red symbols) and Evans et al. (2011, cyan symbols) for common Cepheids



The metal-dependent Period-Age-Color (PAC) relations in the Gaia filters



Evolutionary times inside the predicted instability strip

\+ Theoretical PLMT relation

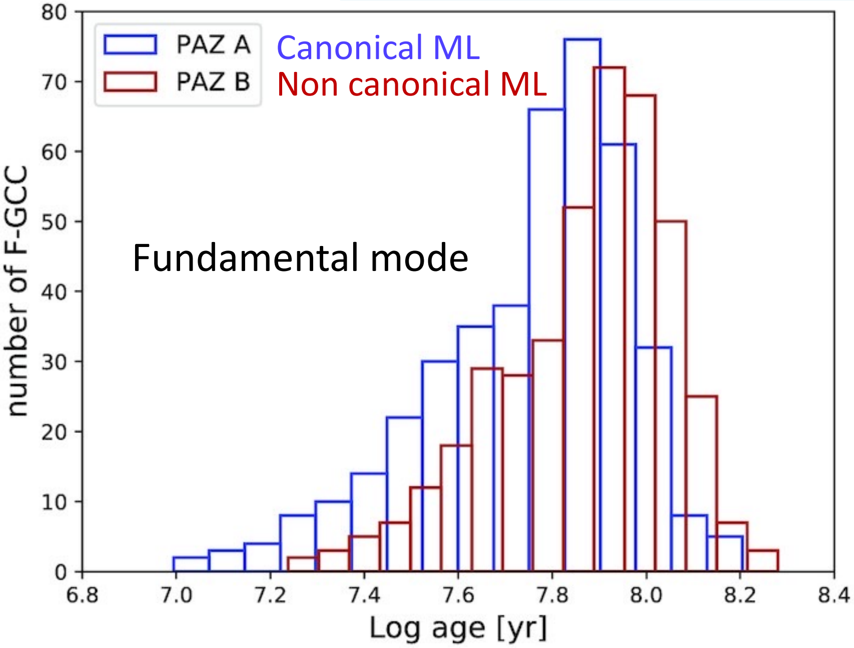
Period-Age and Period-Age-Color relations, for each Z, Y

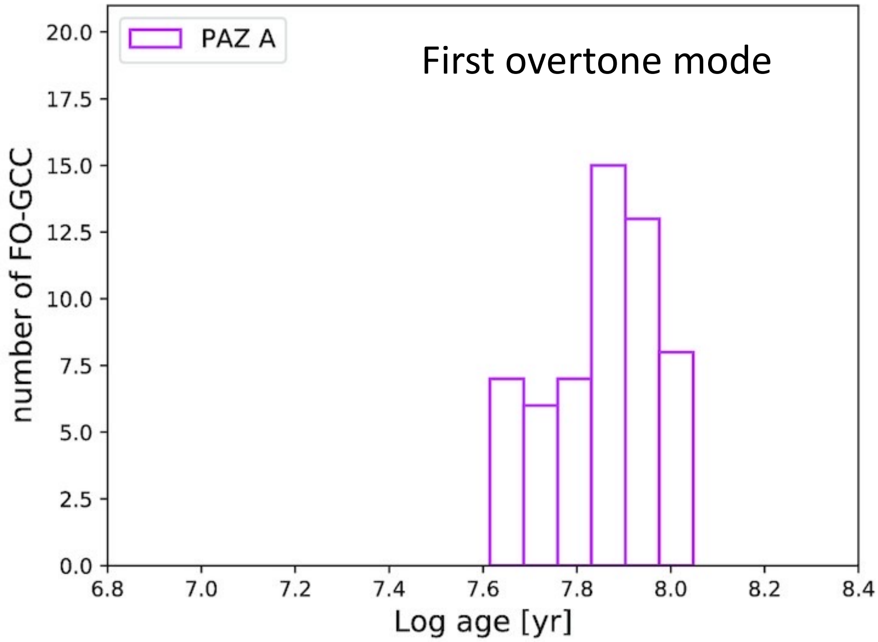
Period-Age-[Fe/H] and Period-Age-Color-[Fe/H] relations

De Somma et al. 2021 MNRAS

Age distribution of Gaia Galactic Cepheids

De Somma et al. 2021 MNRAS





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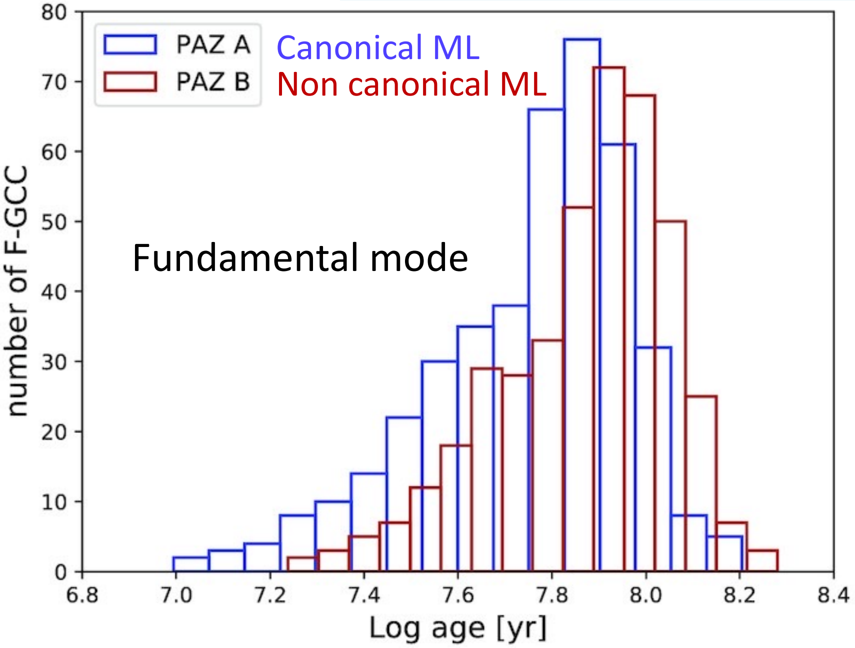
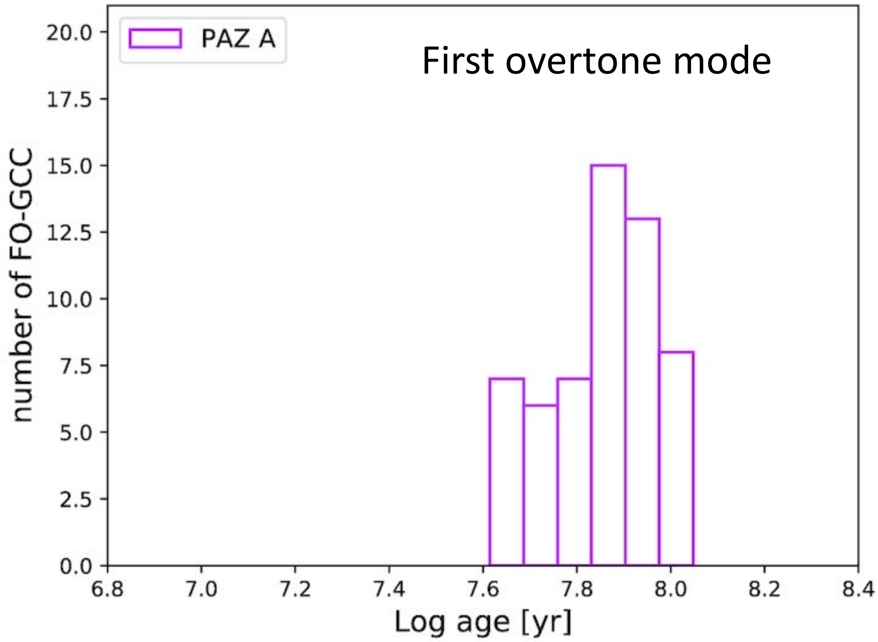
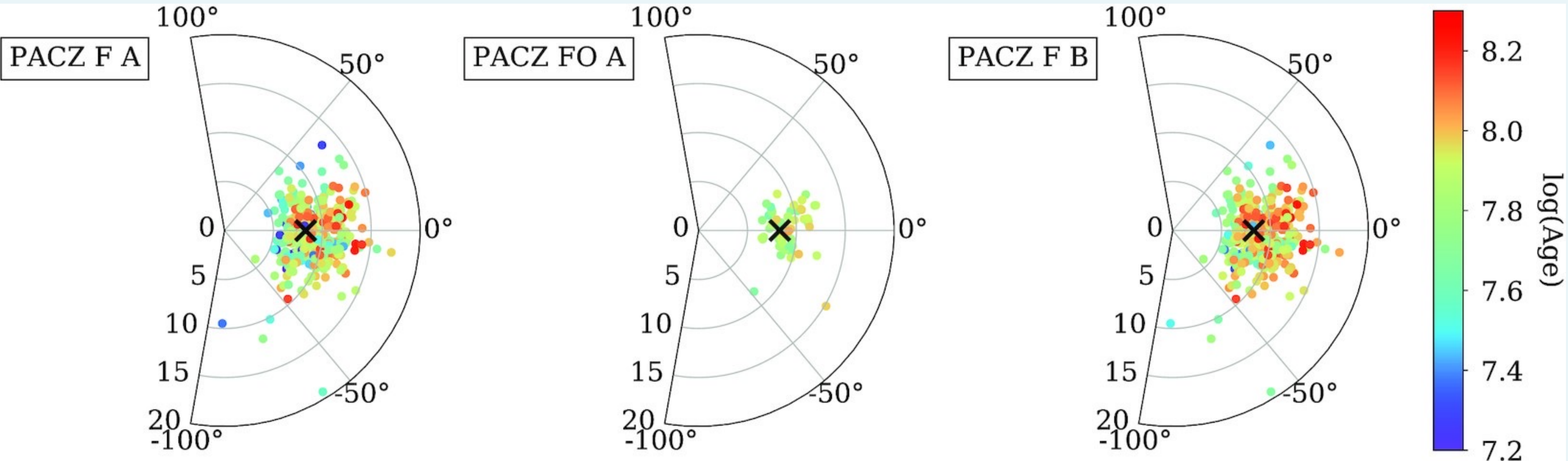
De Somma et al. 2021 MNRAS

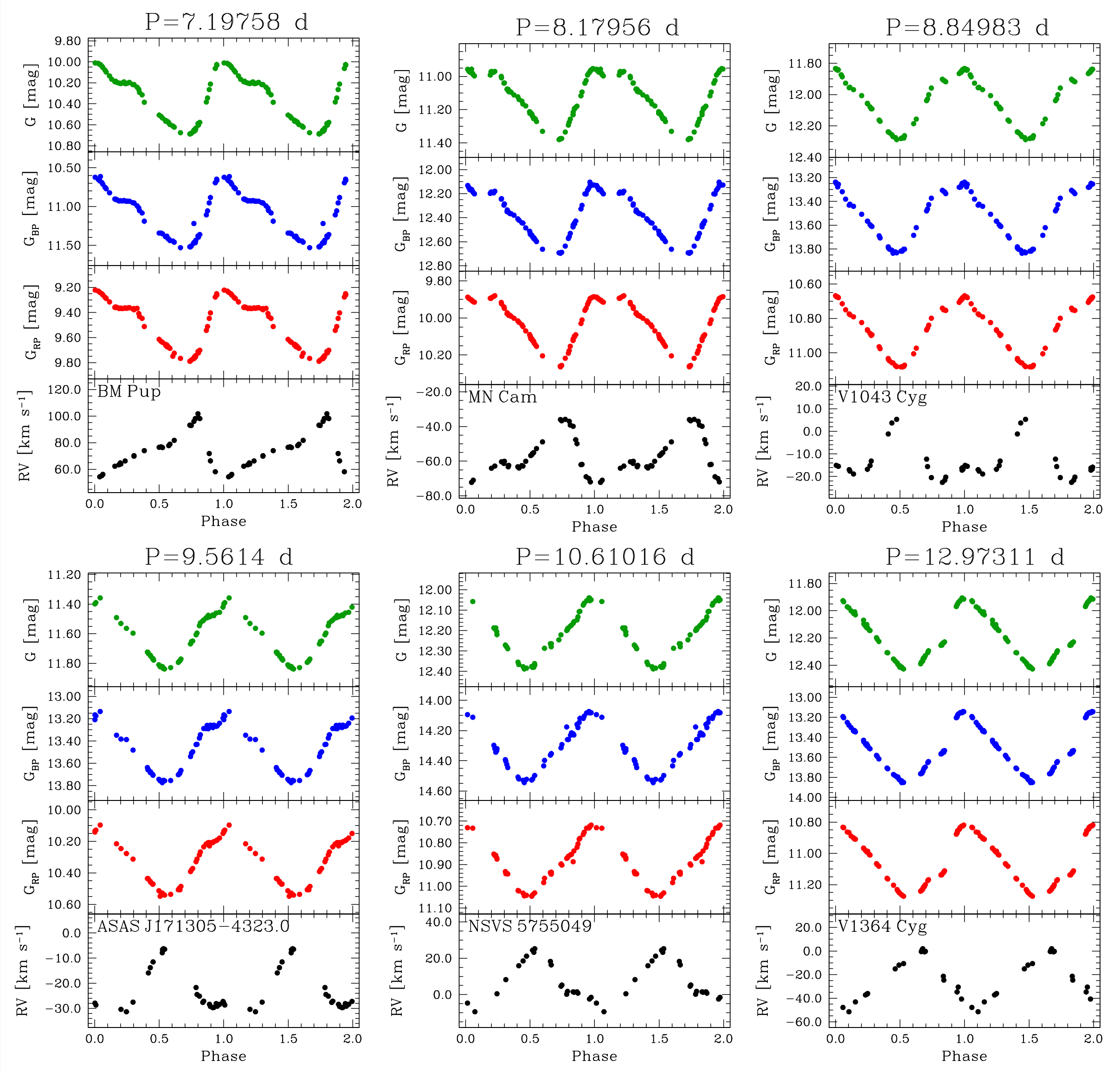






On the Hertzprung progression of Classical Cepheids

ESA Gaia Image of the week 27/05/2022



On the Hertzprung progression of Classical Cepheids

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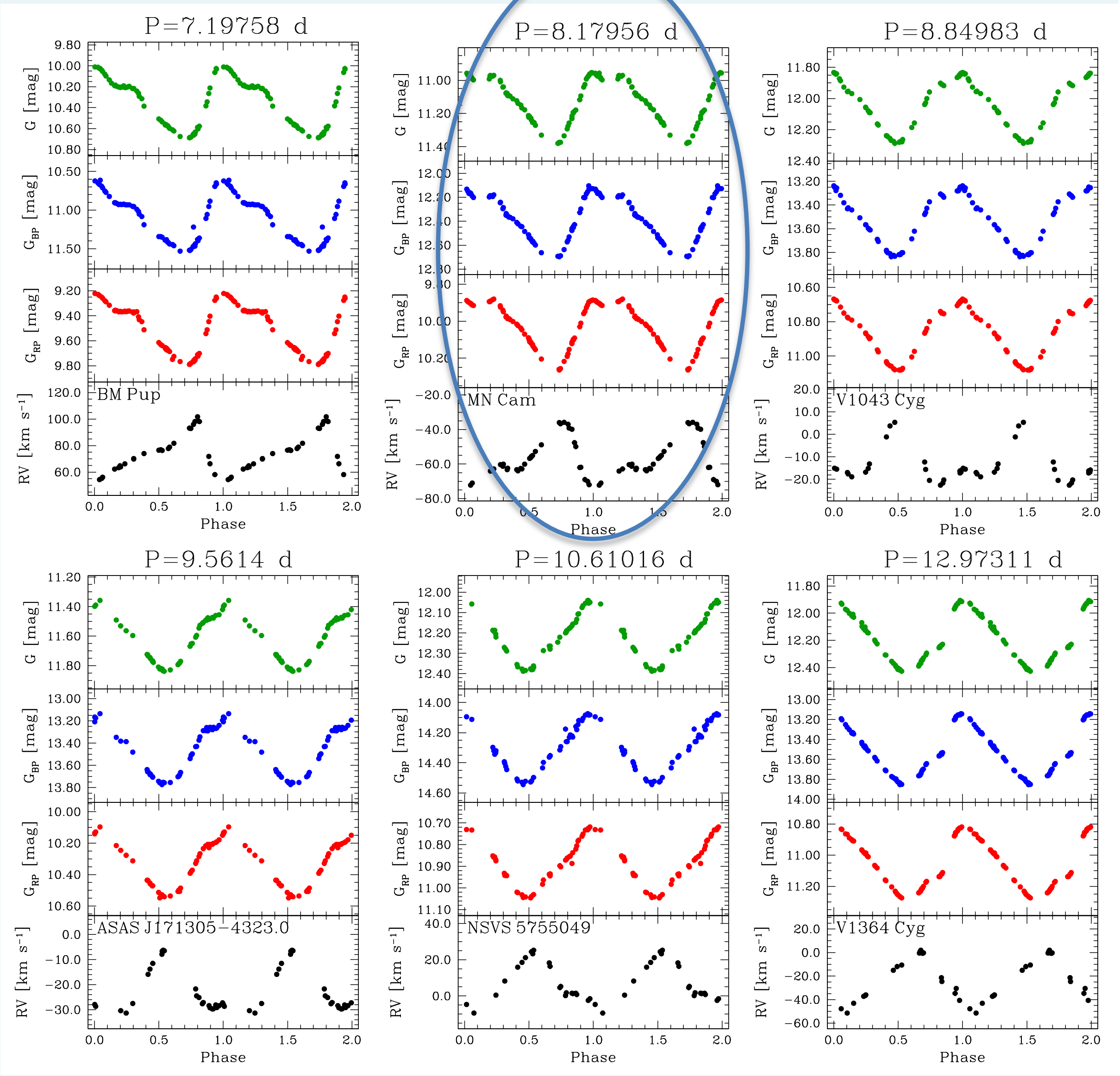
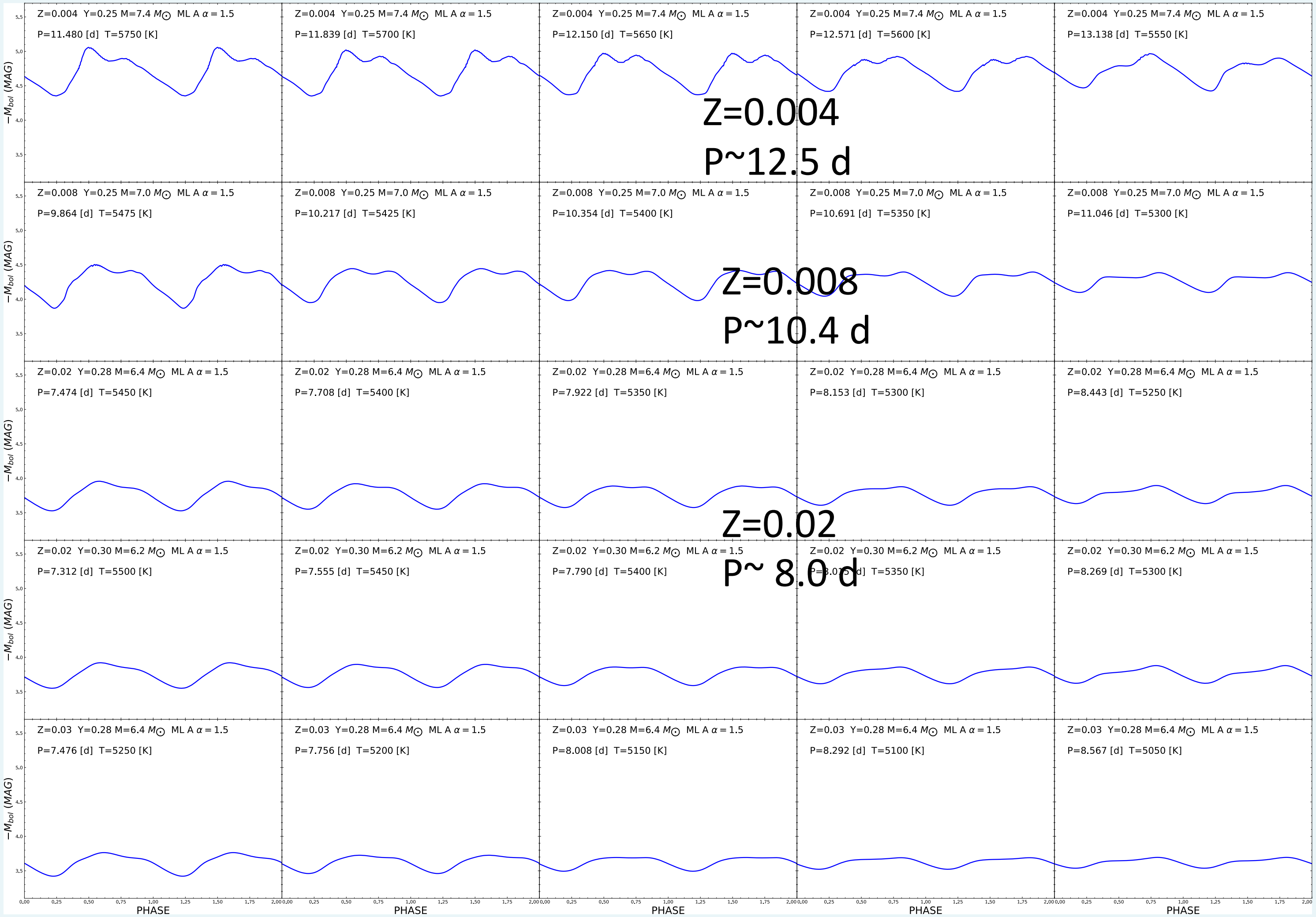


“Stellar variability, stellar multiplicity: periodicity in time & motion” June 6-8, 2023, Sofia, Bulgaria

On the Hertzprung progression of Classical Cepheids

Model predictions: the effect of Z→



Z=0.004
P~12.5 d

Z=0.008
P~10.4 d

Z=0.02
P~ 8.0 d

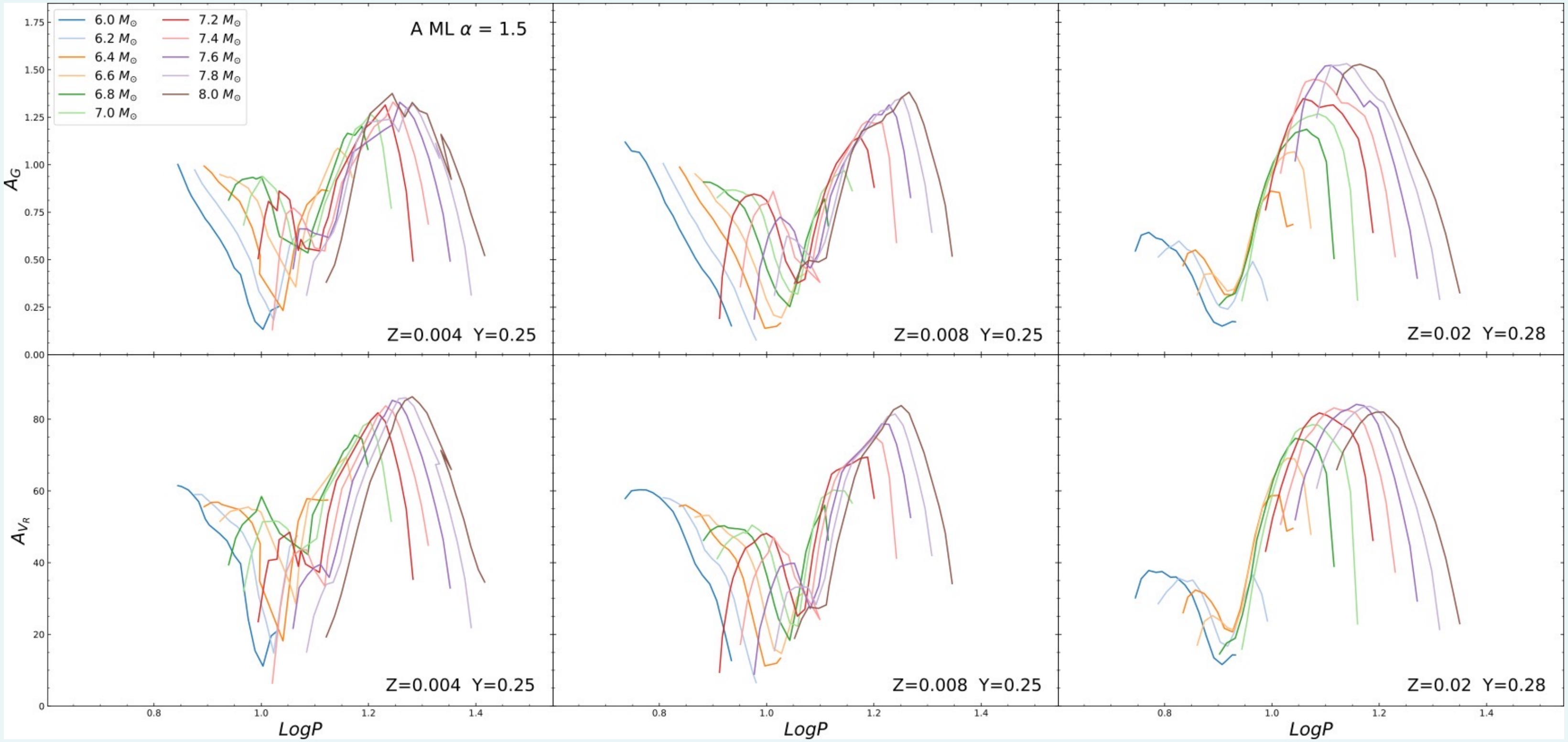
Marconi et al. in prep

On the Hertzprung progression of Classical Cepheids: the metallicity effect

Z=0.004 Z=0.008 Z=0.02

G amplitude (mag)

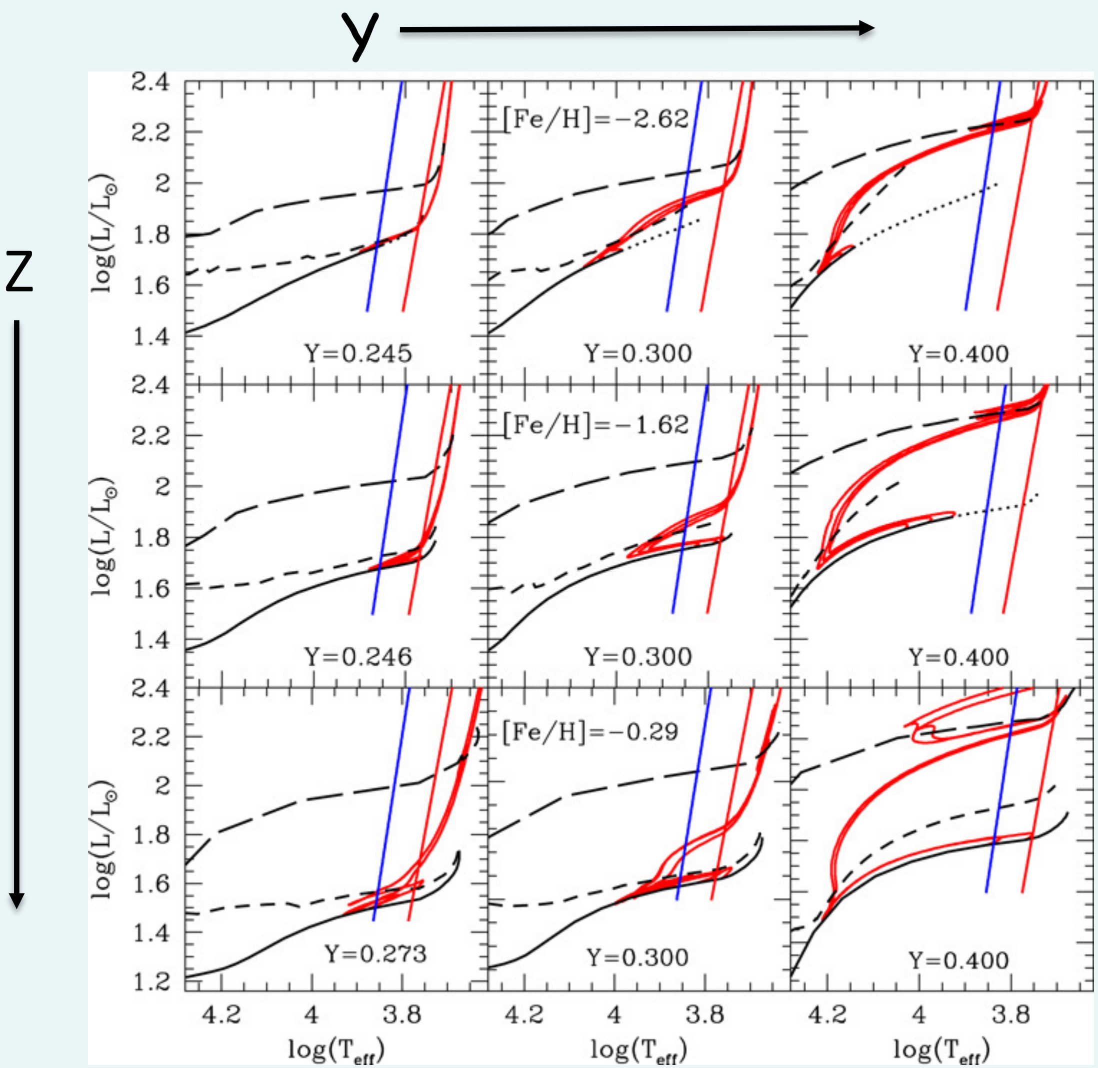
V_{puls} amplitude (Km/s)



Marconi et al. in prep

Recent RR Lyrae pulsation models

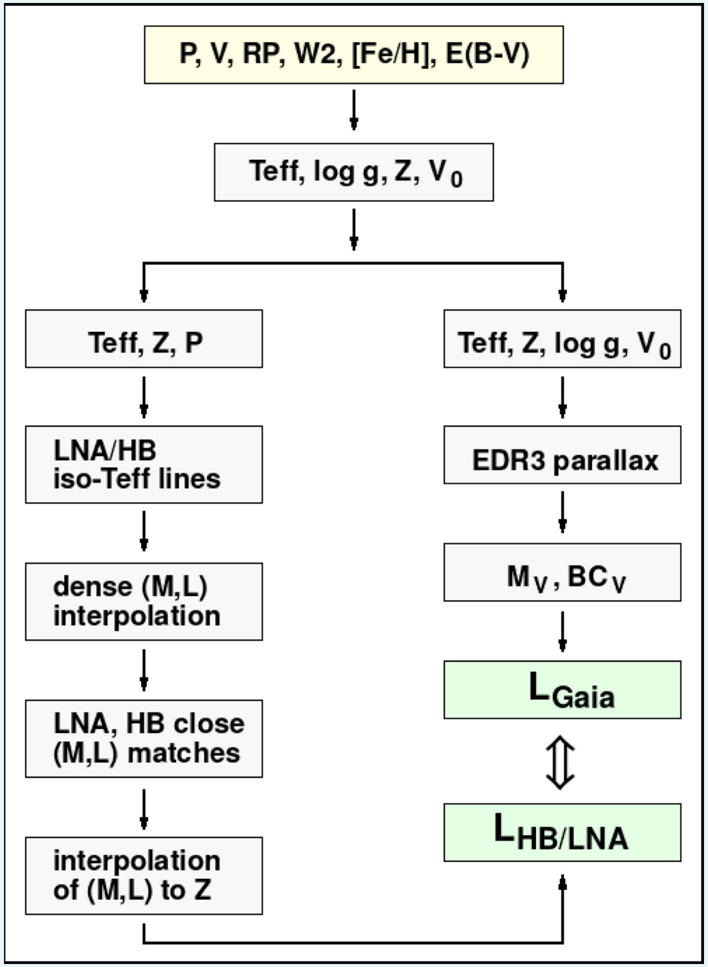
A combination of Horizontal Branch evolutionary predictions and pulsation modelling for central He burning stars



Marconi+2018 ApJL

A theoretical approach based on stellar evolution and linear non adiabatic pulsation models to match Gaia luminosities for RR Lyrae

Kovacs & Karamiqucham 2021 A&A Letter



P, V, RP, W2, [Fe/H], E(B-V)

Teff, log g, Z, V_0

Teff, Z, P

LNA/HB iso-Teff lines

dense (M,L) interpolation

LNA, HB close (M,L) matches

interpolation of (M,L) to Z

Teff, Z, log g, V_0

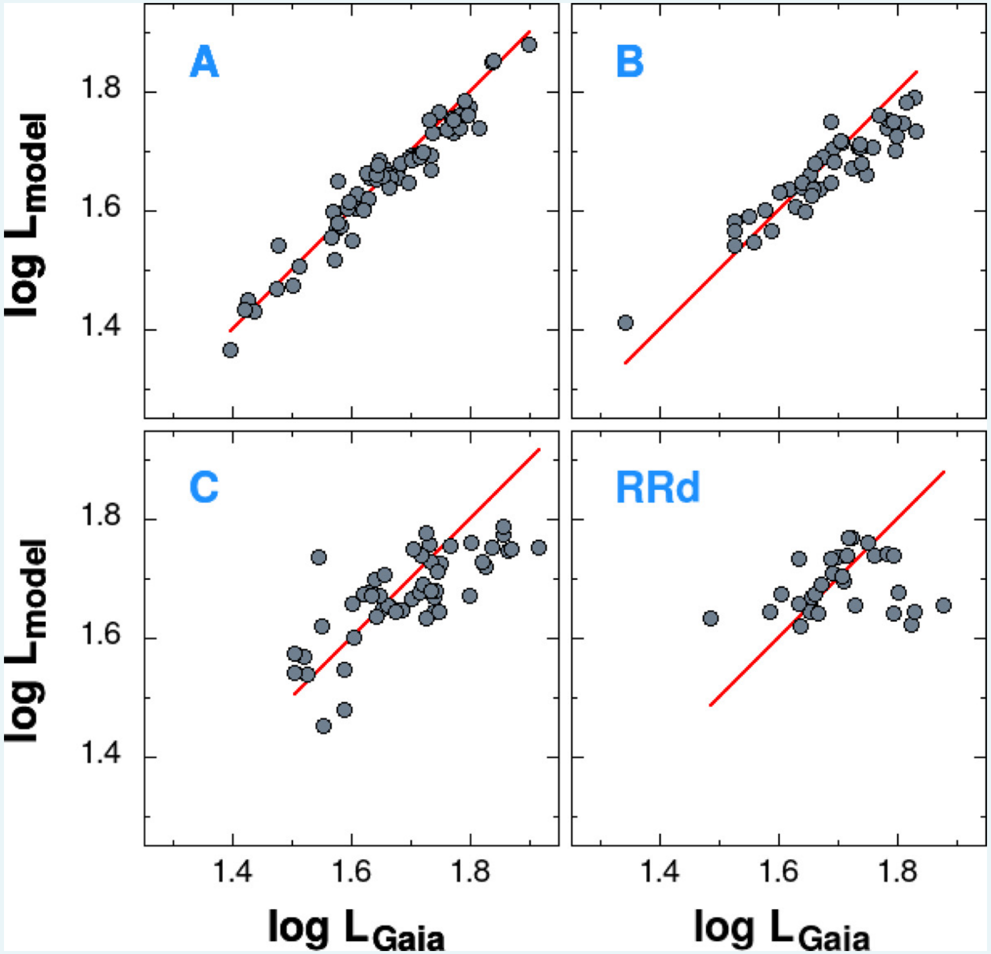
EDR3 parallax

M_V, BC_V

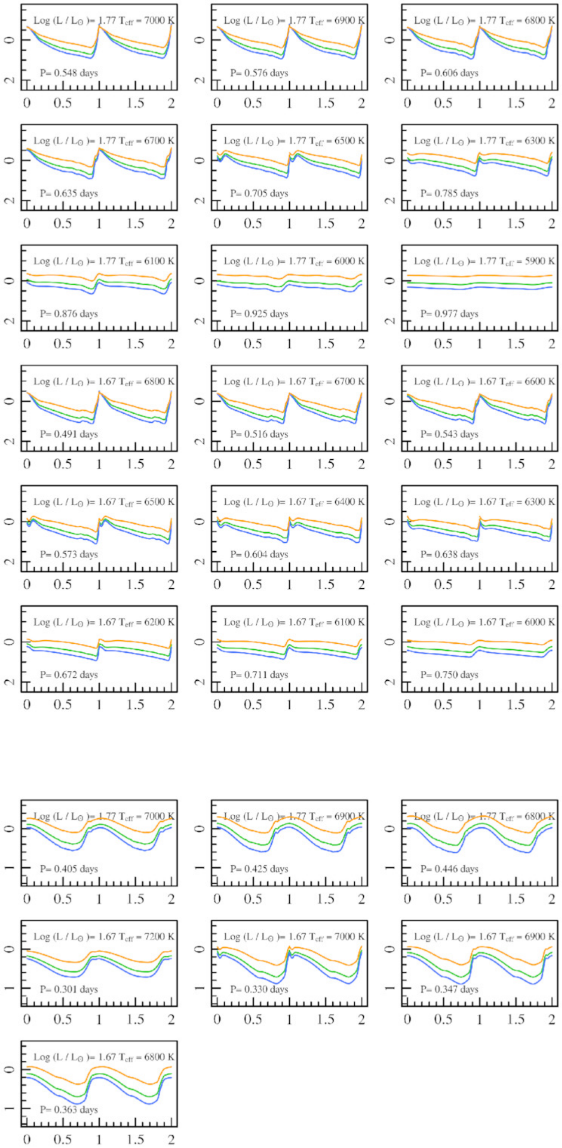
L_{Gaia}

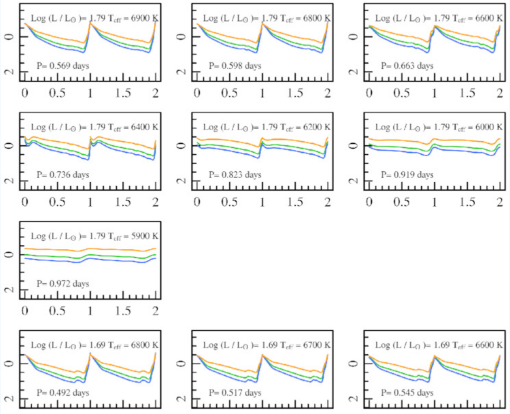
⇕

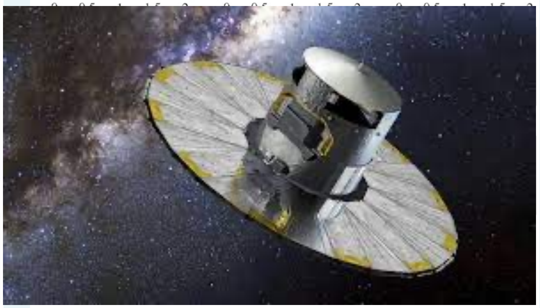
$L_{HB/LNA}$

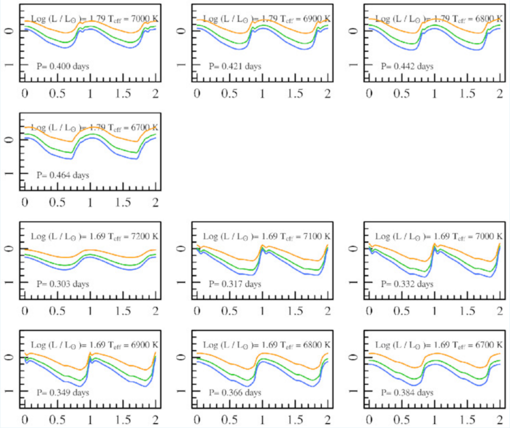


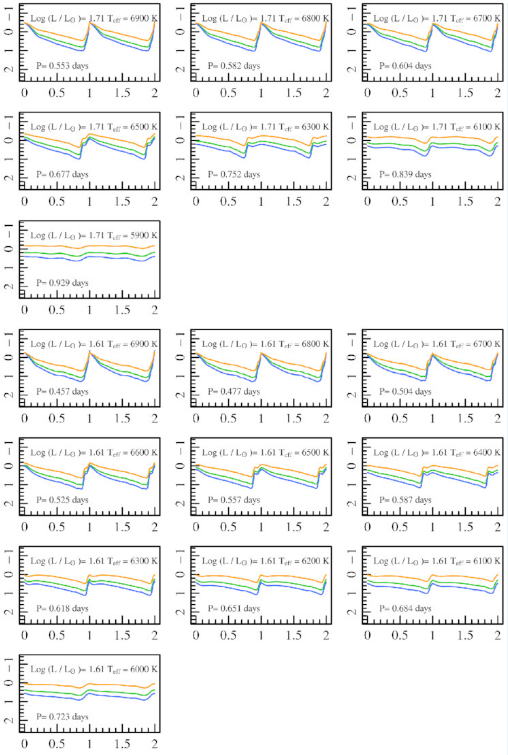
Bolometric light curves based on non linear Convective pulsation models were transformed into the Gaia filters



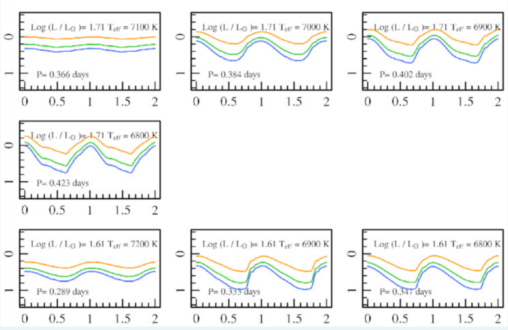








Marconi et al. 2021 MNRAS



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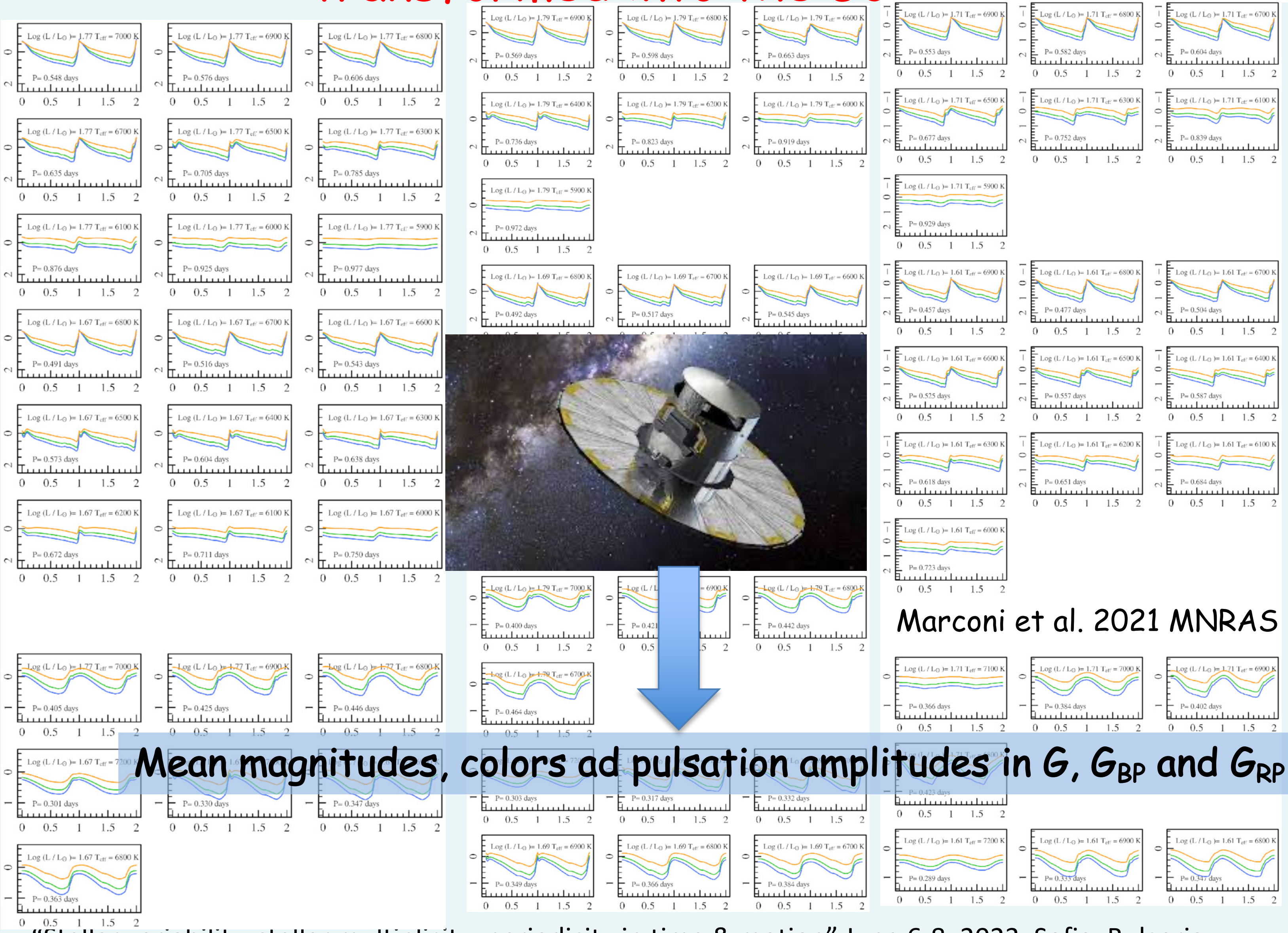
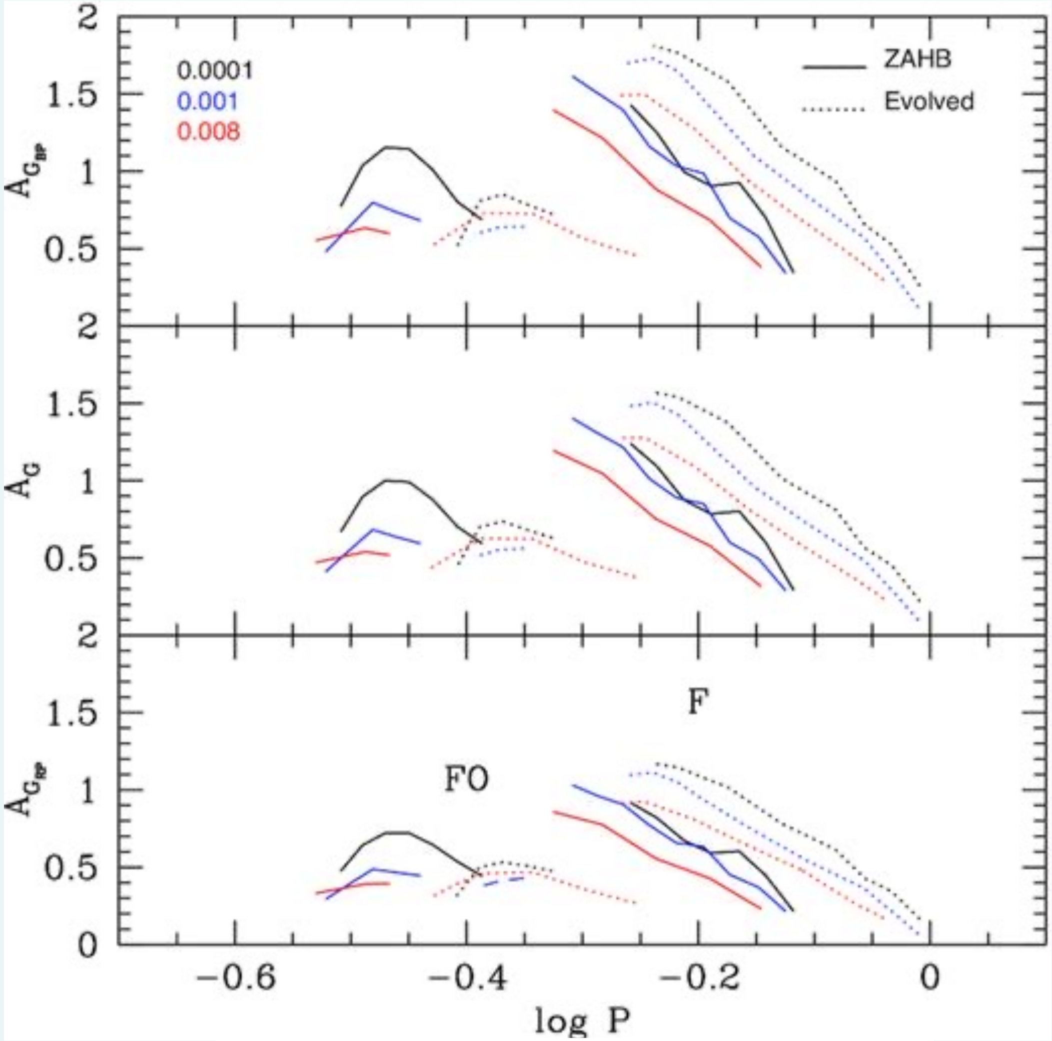


Marconi et al. 2021 MNRAS

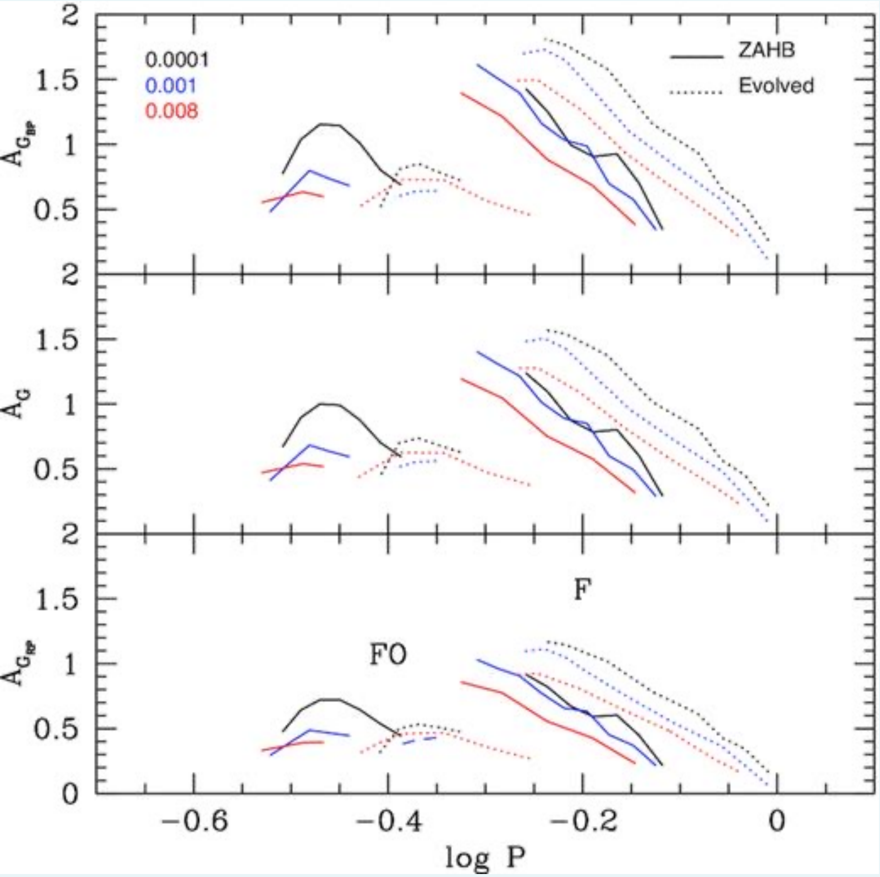
Mean magnitudes, colors ad pulsation amplitudes in G, G_{BP} and G_{RP}

The first theoretical Bailey diagram in the Gaia filters

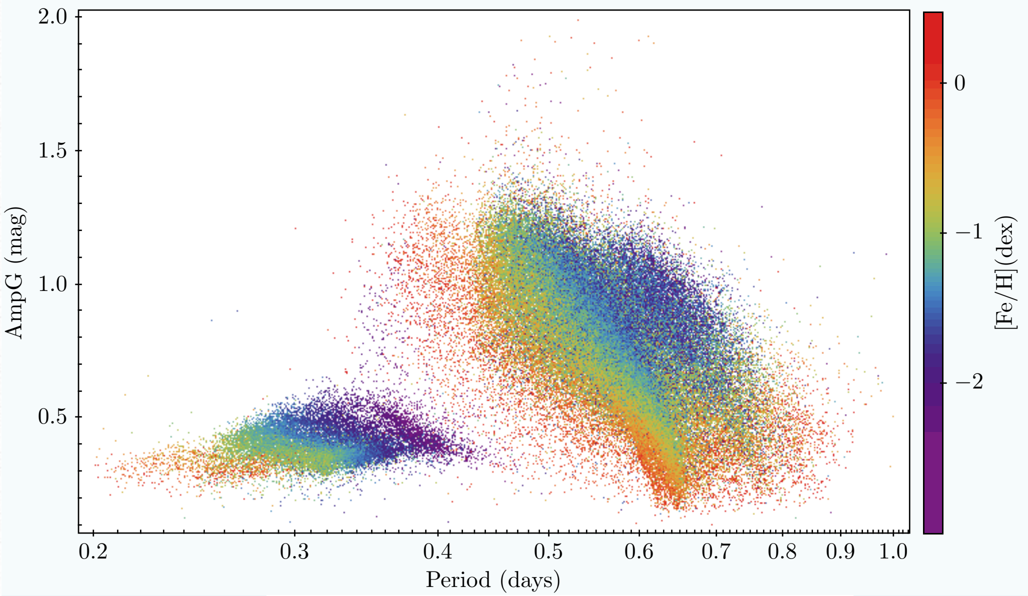


Marconi et al. 2021 MNRAS

The metal abundance effect:Theory versus Observations

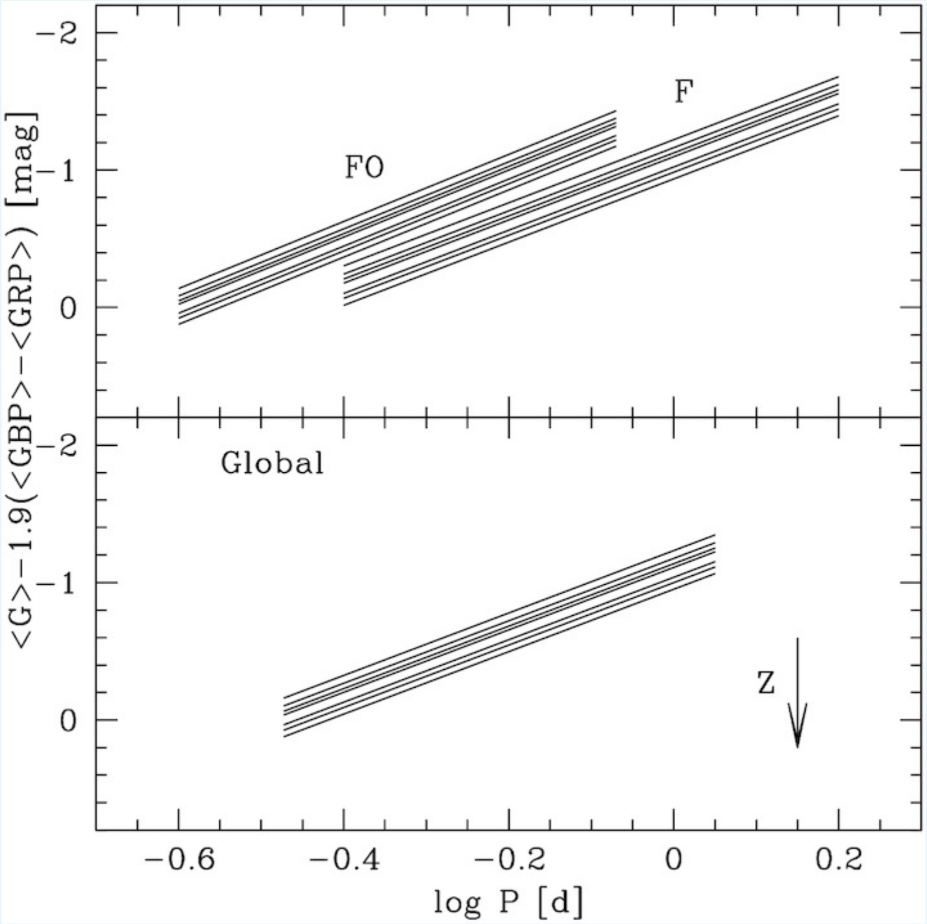


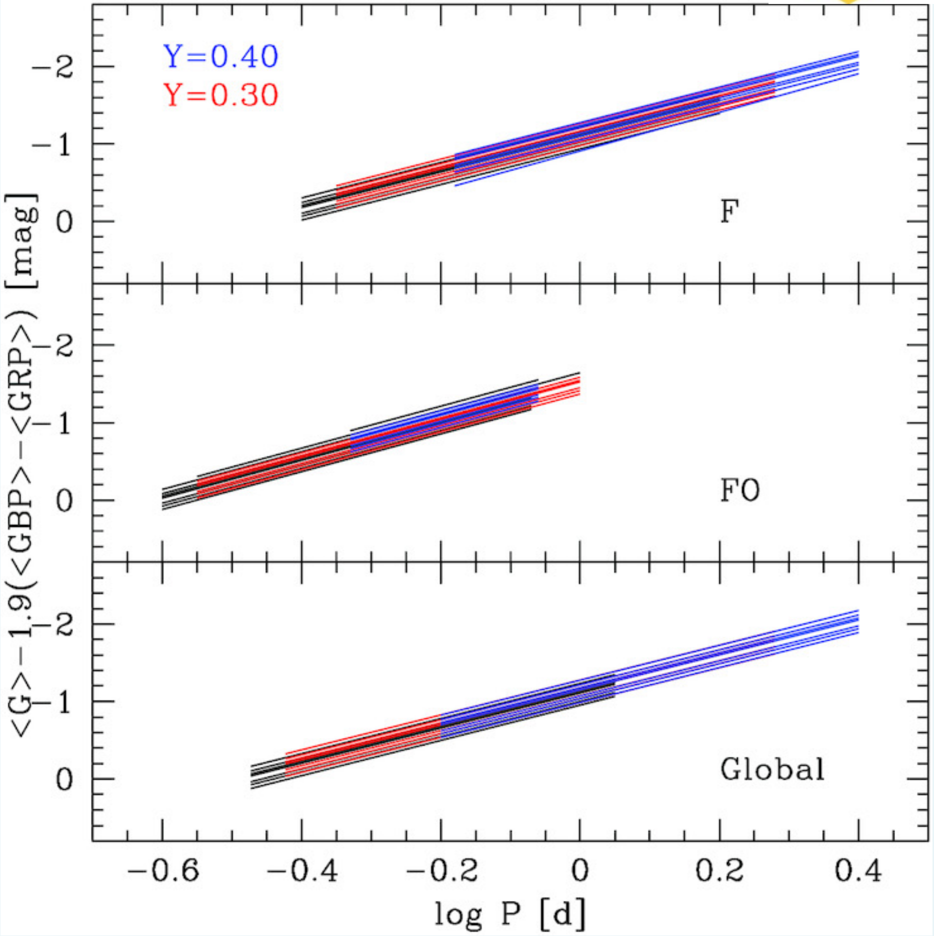
Marconi et al. 2021 MNRAS



Clementini et al. 2022 A&A

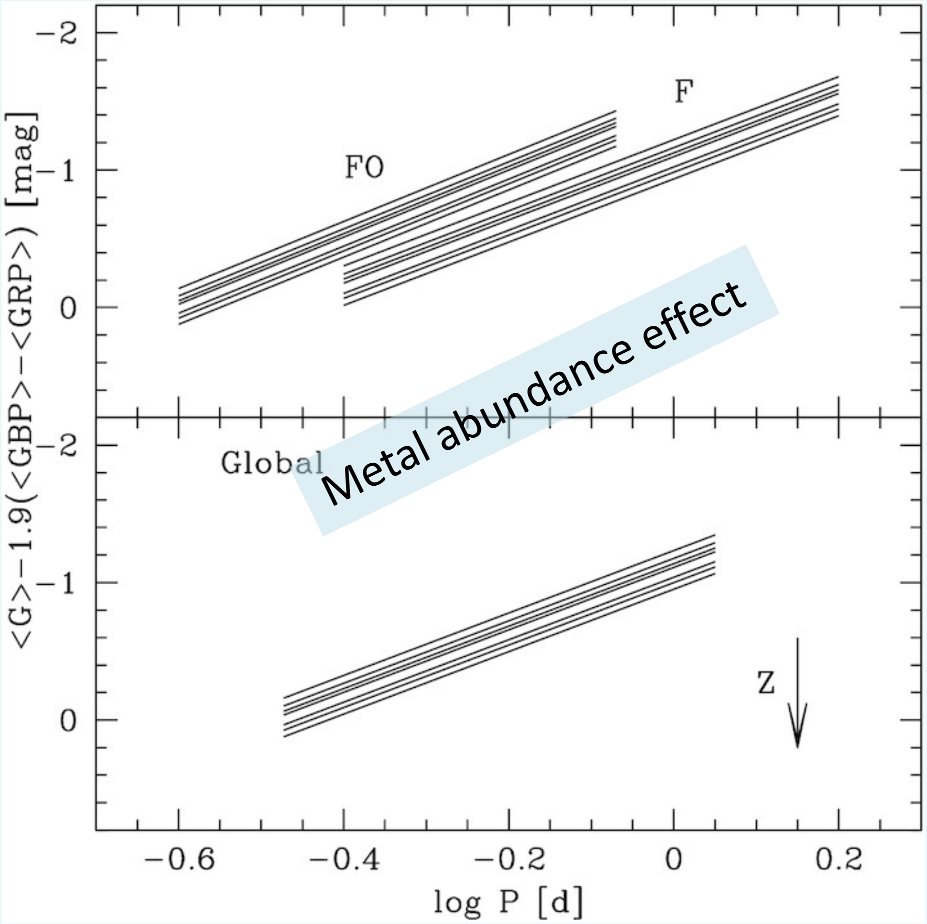
The Period-Wesenheit relations in the Gaia filters



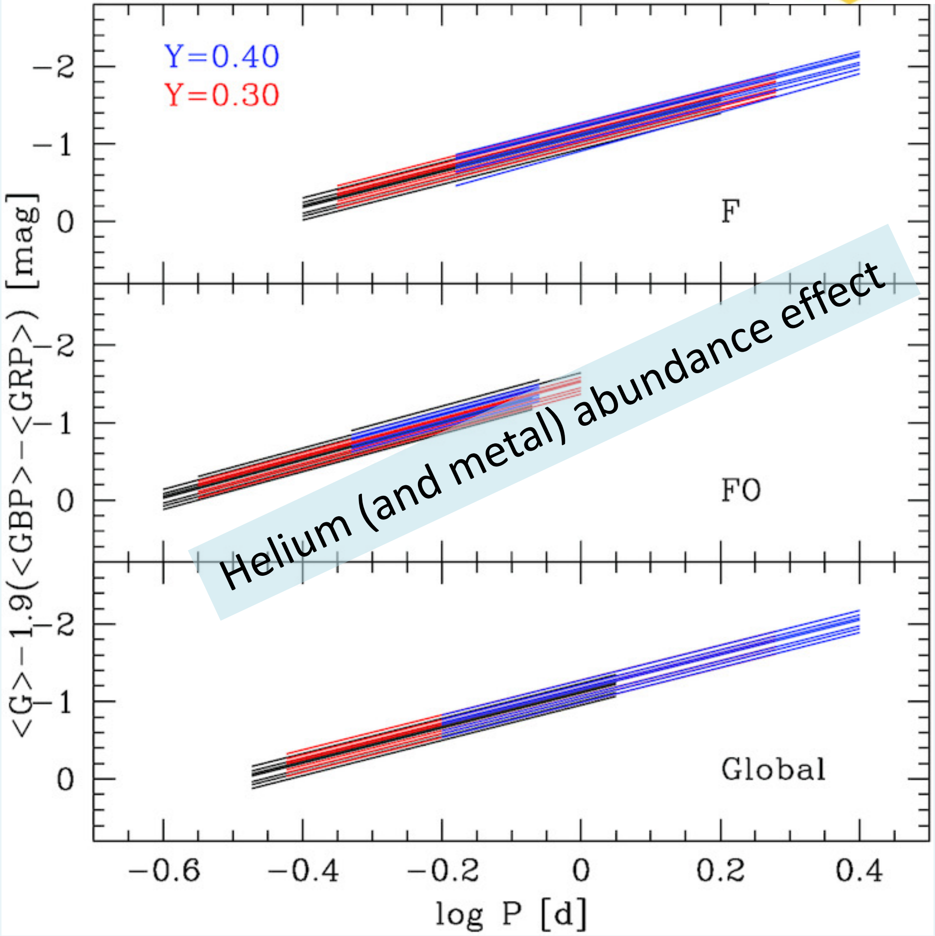


Marconi+ 2021 MNRAS

The Period-Wesenheit relations in the Gaia filters



Metal abundance effect

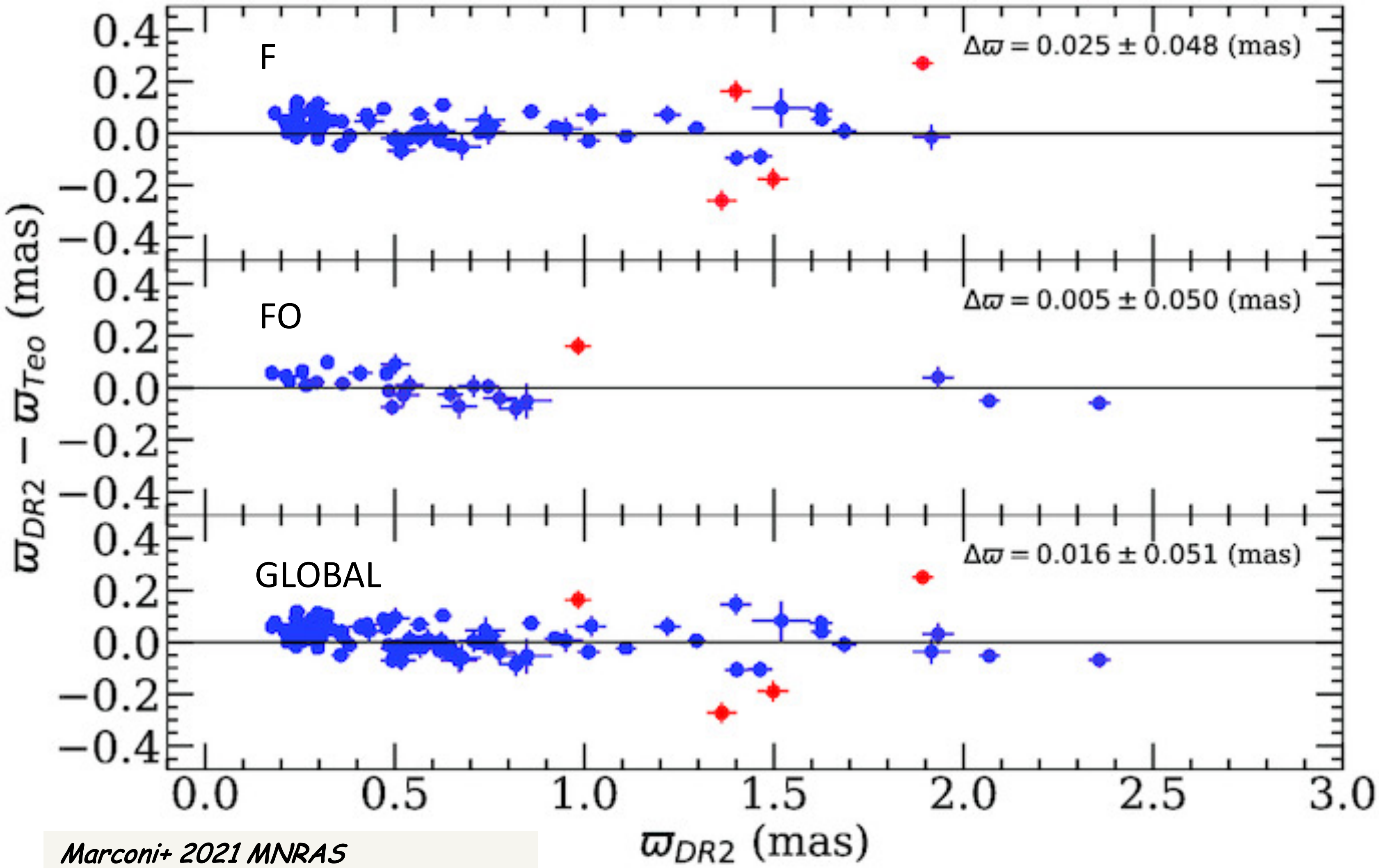


Helium (and metal) abundance effect

Marconi+ 2021 MNRAS

Predicted parallaxes based on Period-Wesenheit-[Fe/H] relations versus Gaia DR2 values (mean magnitudes from Gaia DR2, HRS [Fe/H] from Magurno et al. + Crestani et al.)

blue and red symbols correspond to accepted and discarded objects by a 2.5 σ−clipping

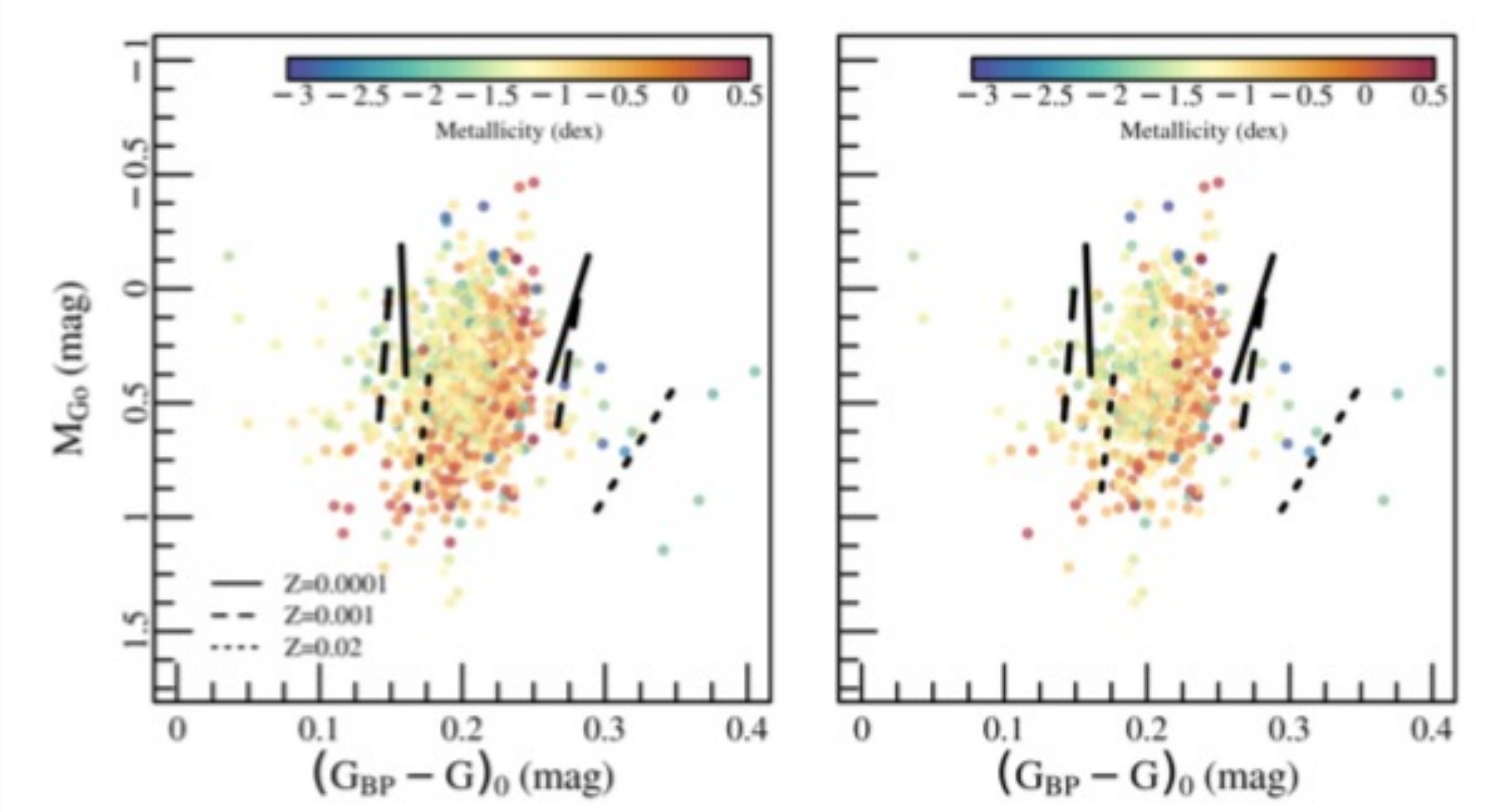


Marconi+ 2021 MNRAS

Comparison between predicted and obsrved IS

915 Gaia DR3 RRab stars with A(G) < 0.2 mag

620 Gaia DR3 RRab stars with A(G) < 0.1 mag

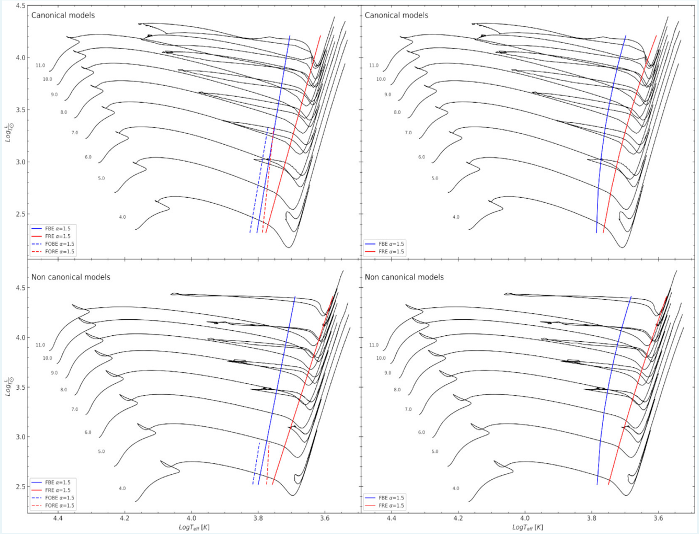


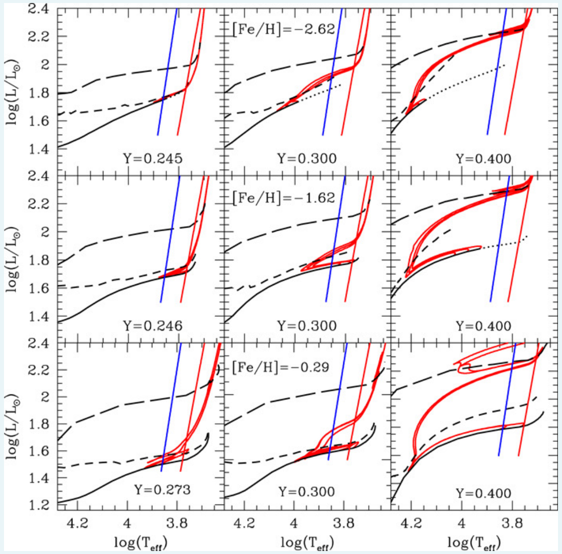
Clementini et al. 2023 in press

Next steps

- Improve the nonlinear convective pulsation models waiting for next Gaia releases.

→ Self-consistently update the physical inputs in stellar evolution and pulsation models (→ML relation, HB properties)

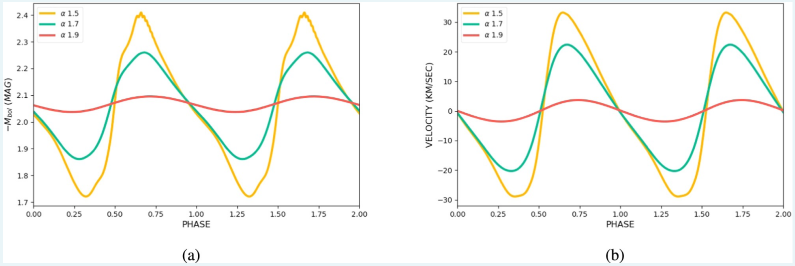




Next steps

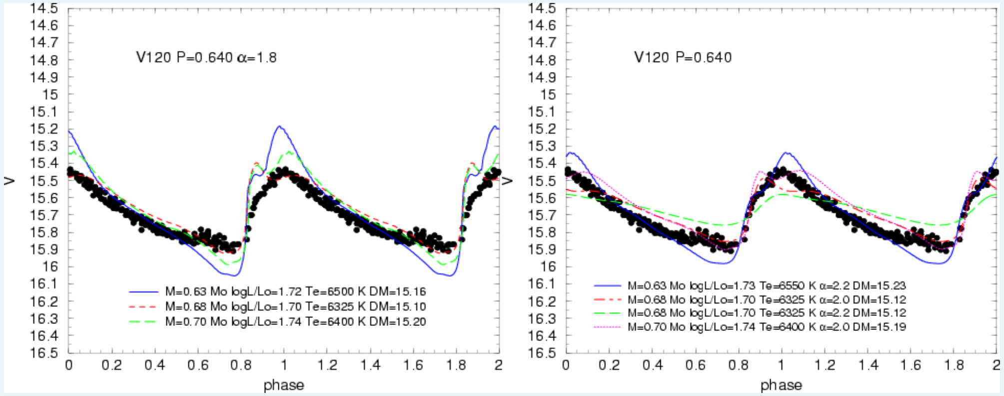
- Improve the nonlinear convective pulsation models waiting for next Gaia releases.

→ Improve the treatment of super-adiabatic convection



(a)

(b)



- Difficult to reproduce peculiar features of light curves close to the red edge ← limitations of the convective treatment

Next steps

- Improve the nonlinear convective pulsation models waiting for next Gaia releases.

→ Merge stellar evolution and pulsation codes to compute pulsation along evolution (partially following MESA RSP module idea, see Paxton et al. 2019)

See e.g.

SPECTRUM

Stellar Pulsation and Evolution: a Combined Theoretical physical Renewal and Updated Models

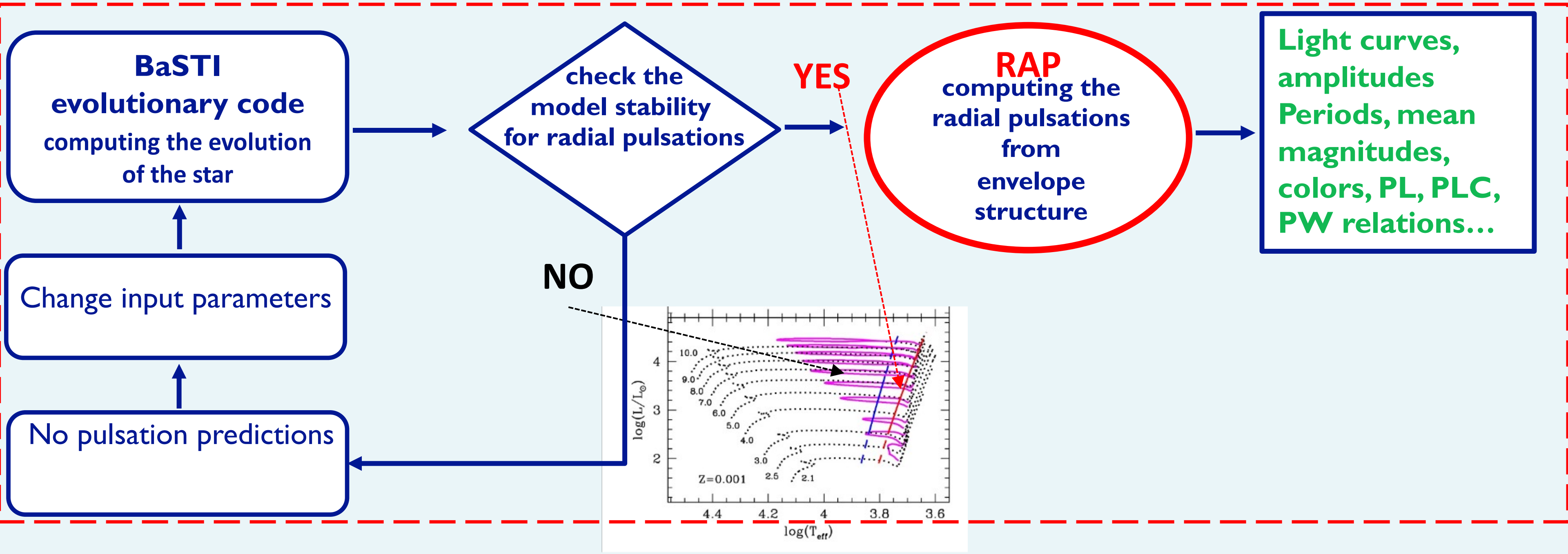
Project just funded by INAF and led by Giulia De Somma (INAF-OACN)
Supervisors: Santi Cassisi (INAF-OAAb) Marcella Marconi (INAF-OACN)

INAF
ISTITUTO NAZIONALE DI ASTROFISICA
NATIONAL INSTITUTE FOR ASTROPHYSICS

SPECTRUM

MW Gaia

To link the pulsational and evolutionary model computations: the **RA**dial **P**ulsating star (**RAP**) tool.



BaSTI evolutionary code
computing the evolution of the star

check the model stability for radial pulsations

YES

RAP
computing the radial pulsations from envelope structure

Light curves, amplitudes Periods, mean magnitudes, colors, PL, PLC, PW relations…

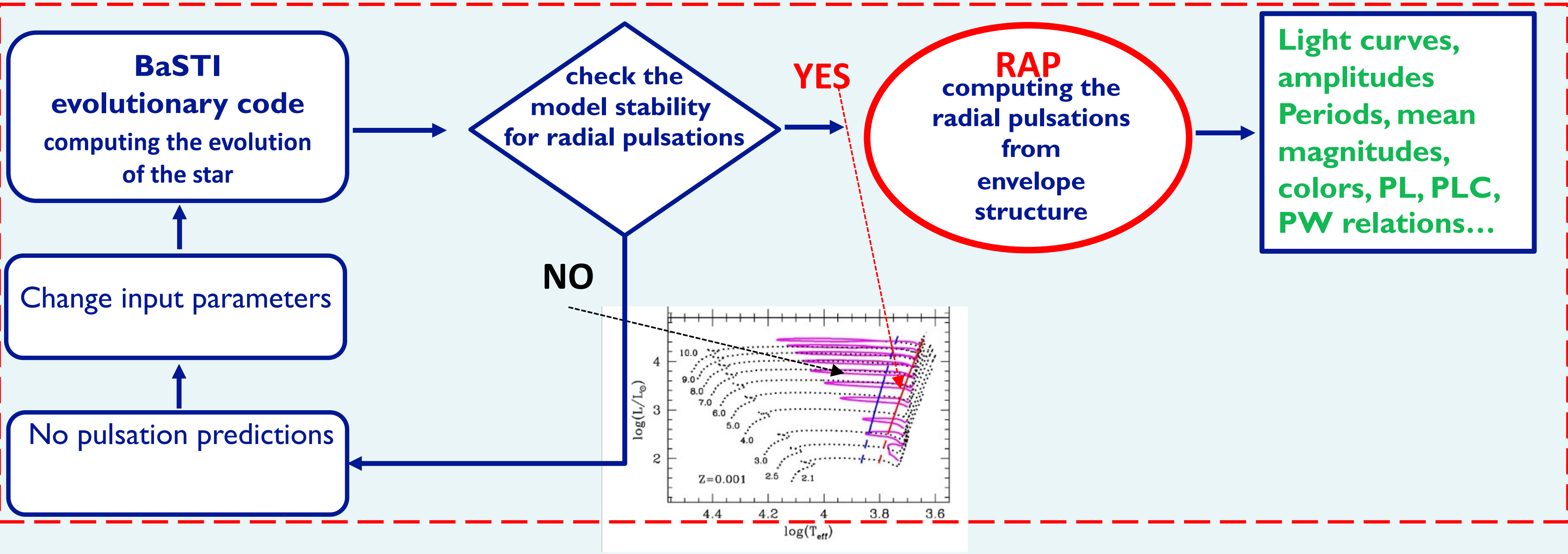
NO

No pulsation predictions

Change input parameters

SPECTRUM

To link the pulsational and evolutionary model computations: the **RA**dial **P**ulsating star (**RAP**) tool.



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Light curves, amplitudes Periods, mean magnitudes, colors, PL, PLC, PW relations…

NO

Change input parameters

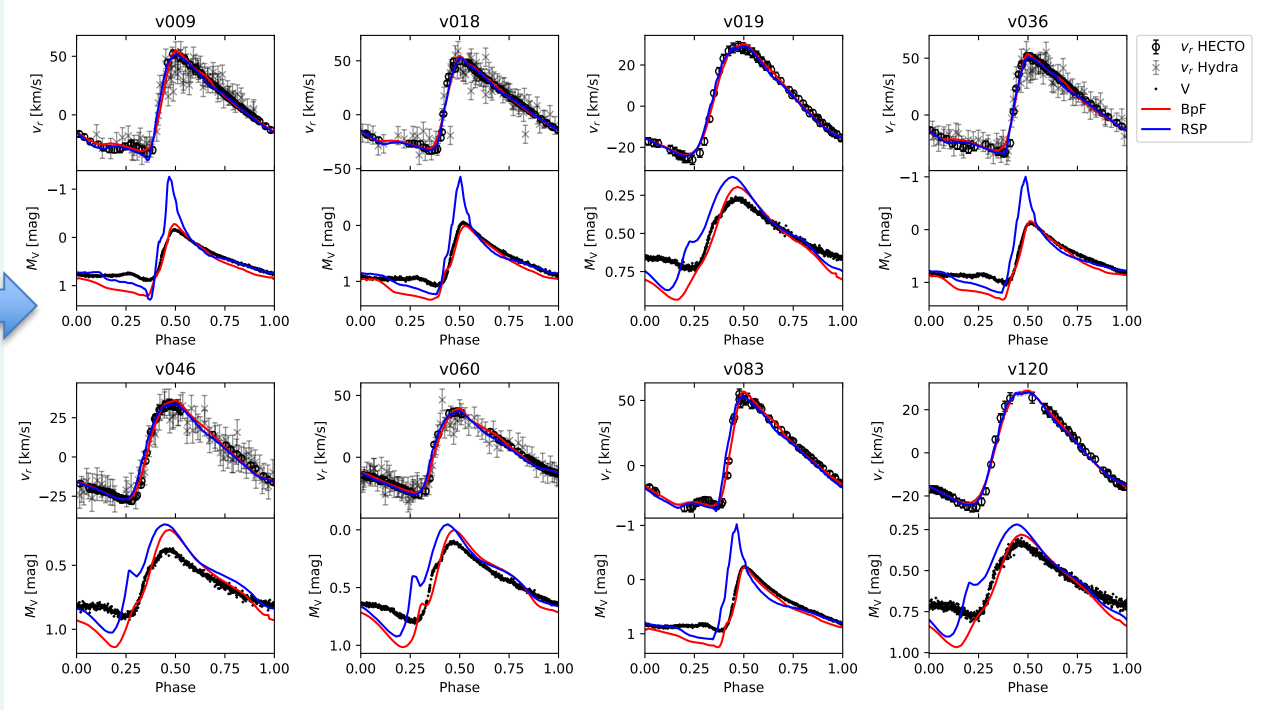
No pulsation predictions

Stay tuned !

Next steps

→ comparison and inter-calibration among different hydrocodes (see e.g. Smolec & Moskalik 2008, Kovàcs, G.B., Nuspl, J., Szabò, R. 2023)

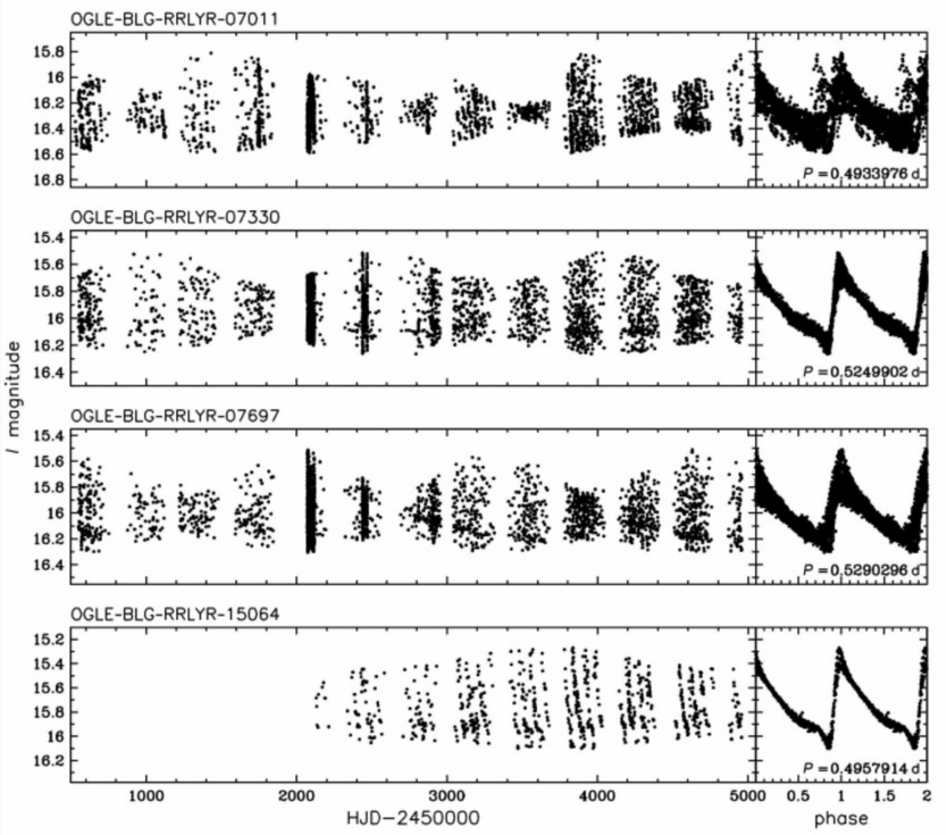
The case of the Budapest-Florida code versus the MESA RSPs module (Kovàcs, G.B., Nuspl, J., Szabò, R. 2023)



To afford open issues such as…

- Blazhko effect in RR Lyrae stars

The Blazhko phenomenon, still remains a puzzle
(see Kolenberg+ 2011, Netzel+ 2018)



To afford open issues such as…

- Blazhko effect in RR Lyrae stars
- Double mode pulsators among classical Cepheids are difficult to reproduce by most of current hydrocodes

As nicely discussed by Smolec & Moskalik 2008 AcA

Conclusions

- The theoretical scenario for Cepheids and RR Lyrae based on nonlinear convective pulsation models has been converted into the Gaia filters.

- Successful comparisons between theory and Gaia observations have been obtained for what concerns the instability strip, the light curves, the period-amplitude diagrams and distances based on Period-Wesenheit-Metallicity relations.

- The residual limitations in the adopted pulsation models are mainly related to the incomplete treatment of convection and it is important to test new input physics and/or model atmospheres but also to develop new self-consistent approaches while waiting for the next Gaia data releases.

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Thanks!