New Perspectives on Classical Pulsators

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- ⋆ Henryka Netzel (CAMK)
- ⋆ Marzena Śniegowska (UW)
- ⋆ Zdenek Prudil (Heidelberg)
- ⋆ Igor Soszyński & OGLE Team (UW)
- ⋆ Paweł Moskalik (CAMK)
- ⋆ Emese Plachy (Konkoly)
- ⋆ Wojtek Dziembowski (CAMK, UW)
- ⋆ Marek Skarka (Konkoly/Brno)

Cepheids & RR Lyrae stars

- located within classical instability strip; pulsations driven by the κ mechanism
- textbook examples of simple, radial, typically single-periodic pulsators
- well understood, except some connoisseur topics: excitation of double-mode pulsation or origin of the Blazhko modulation

⋆ excellent standard candles of crucial importance for cosmology and astrophysics

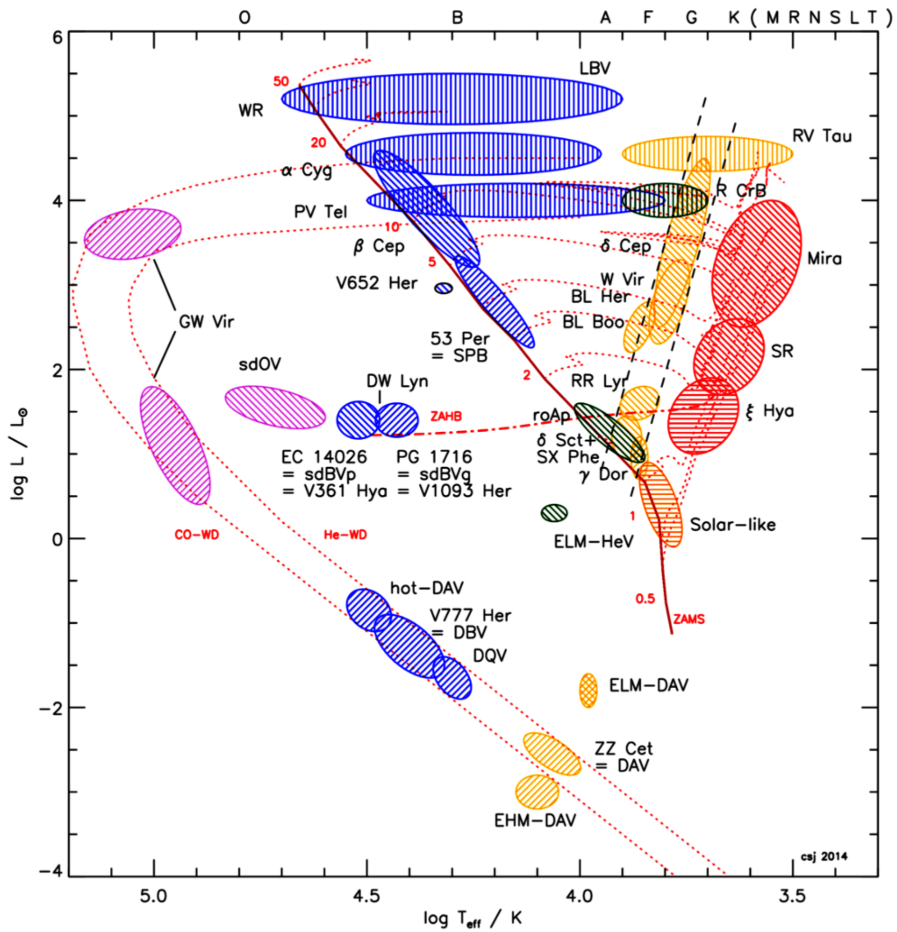

fig.: Jeffery & Saio (2016)

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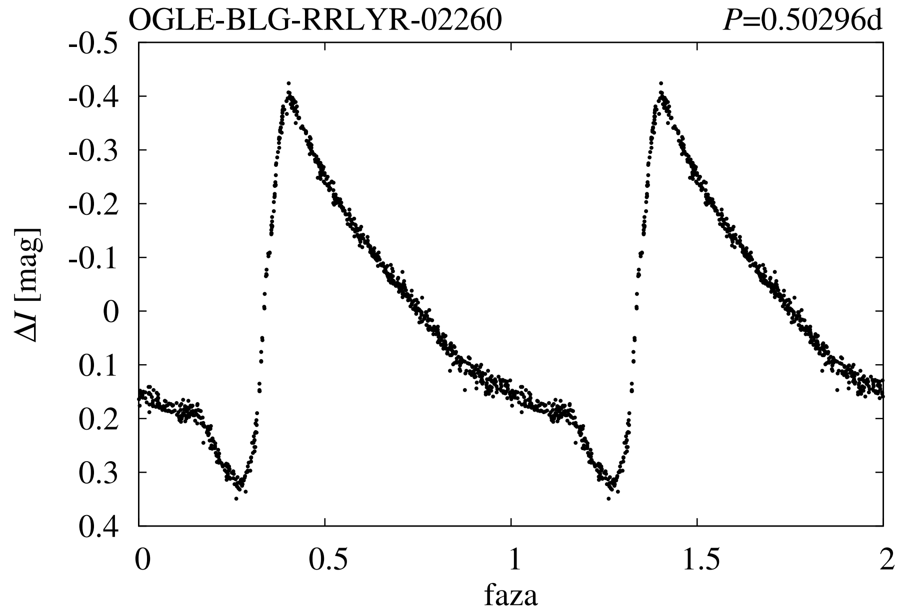

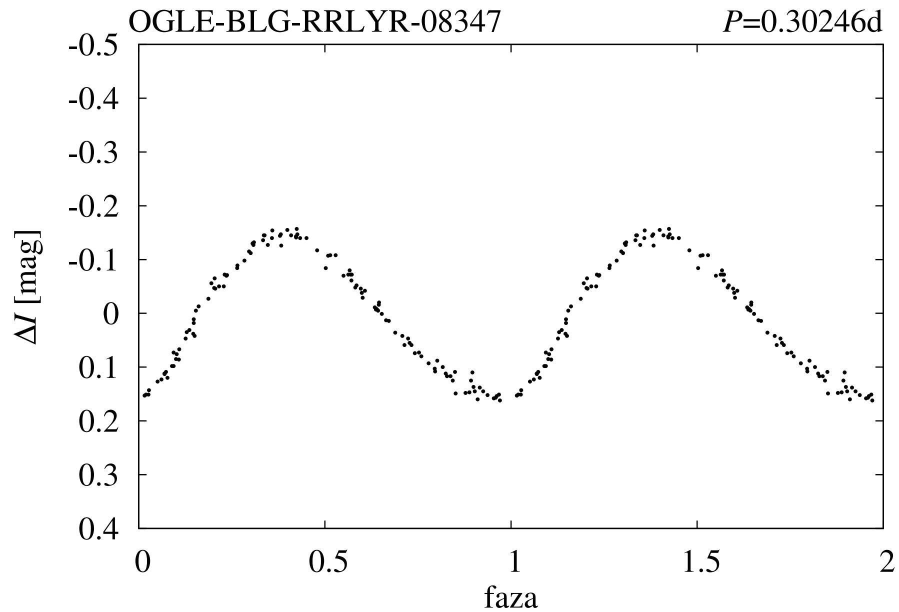

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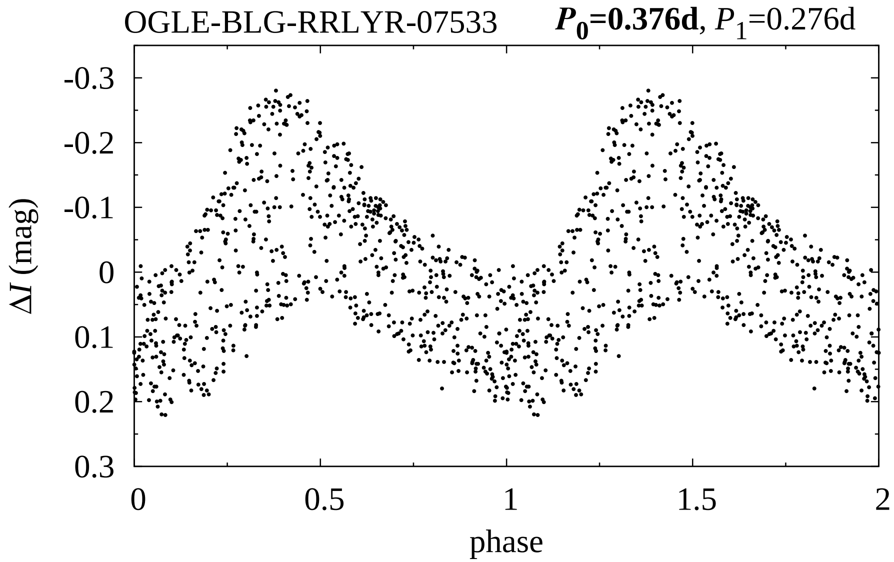

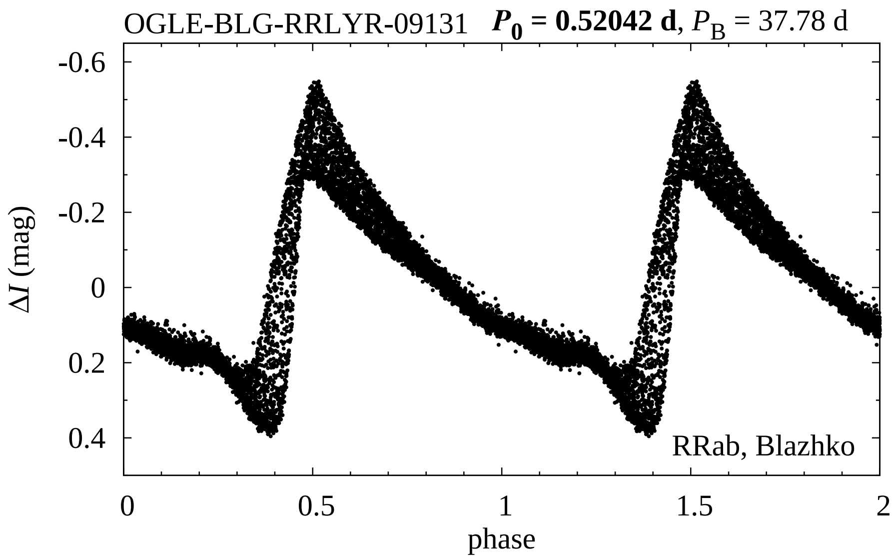

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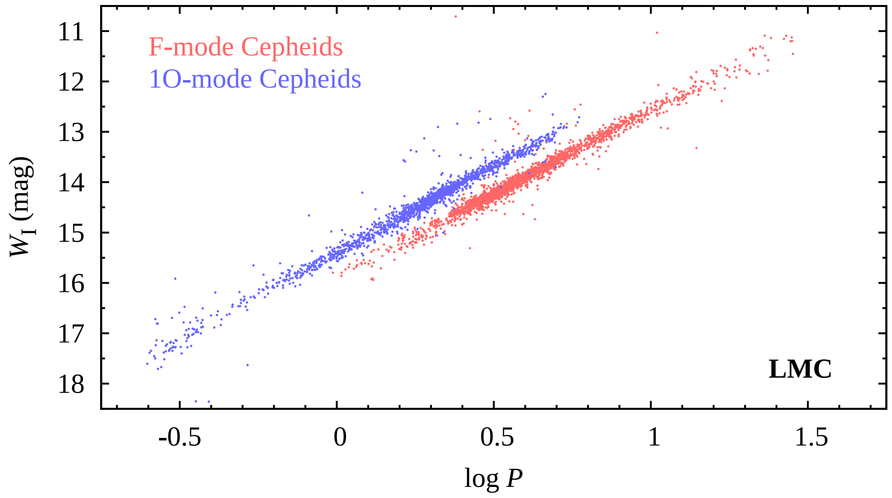
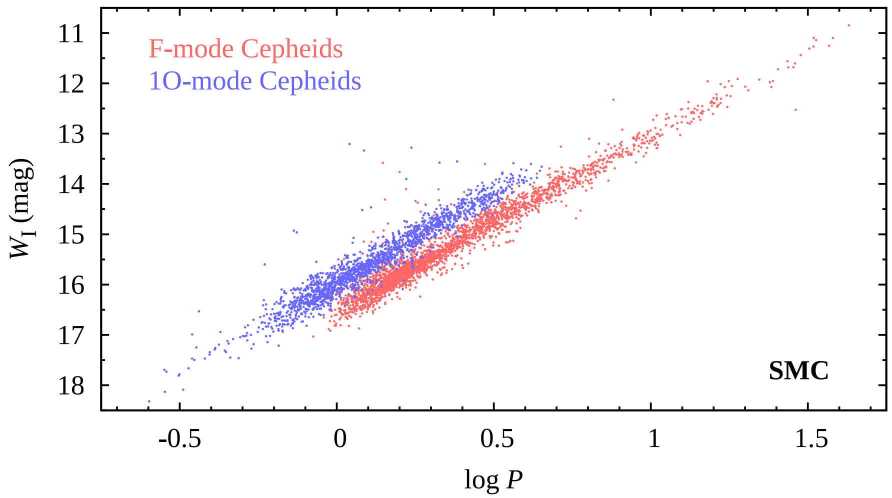


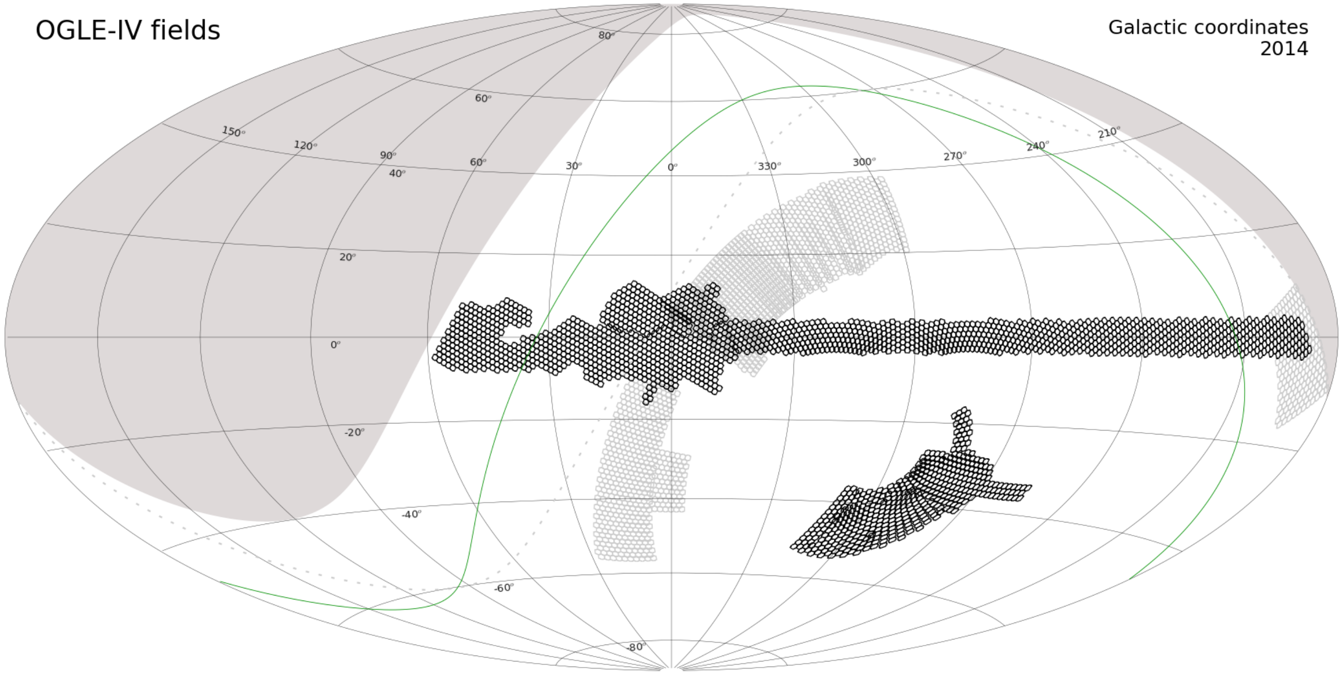


New perspectives on classical pulsators:

- **common** presence of additional, small-amplitude periodicities
- low-amplitude modulations **might be common** in all groups of classical pulsators

⋆ these results are not only thanks to space observations, but mostly thanks to photometric sky surveys

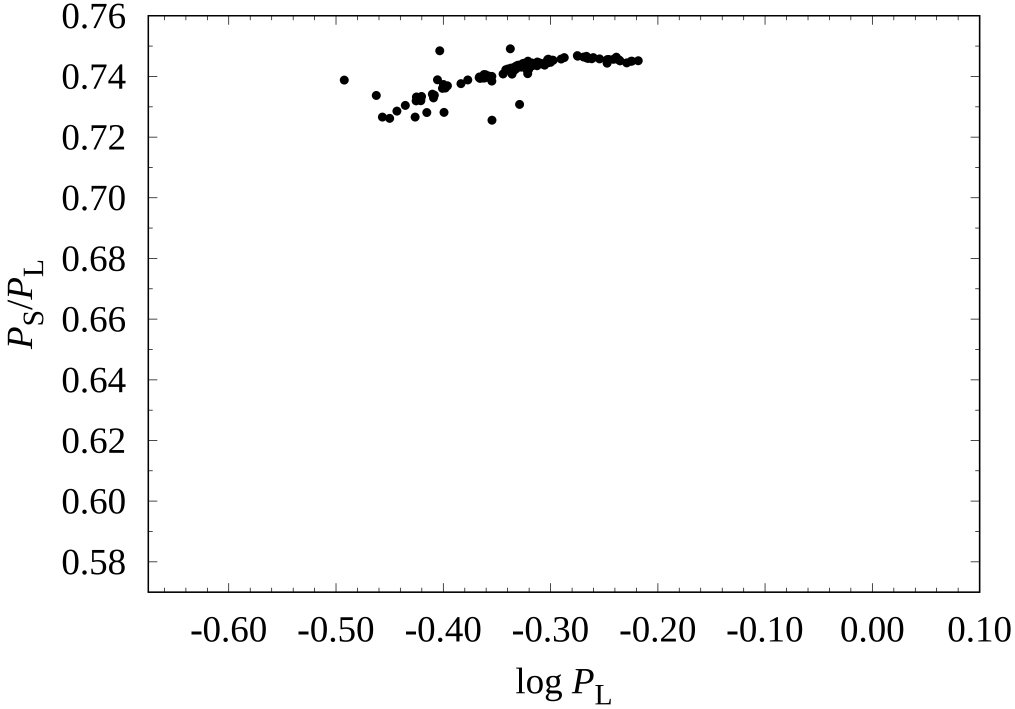
Classical pulsators in the OGLE collection



	Cepheids		RR Lyr	
	F	1O	F	1O
Bulge	34	34	27 480	11 415
LMC	2 476	1 775	28 193	9 663
SMC	2 753	1 793	5 105	801

fig.: http://ogle.astrouw.edu.pl/

Multi-periodic RR Lyr stars



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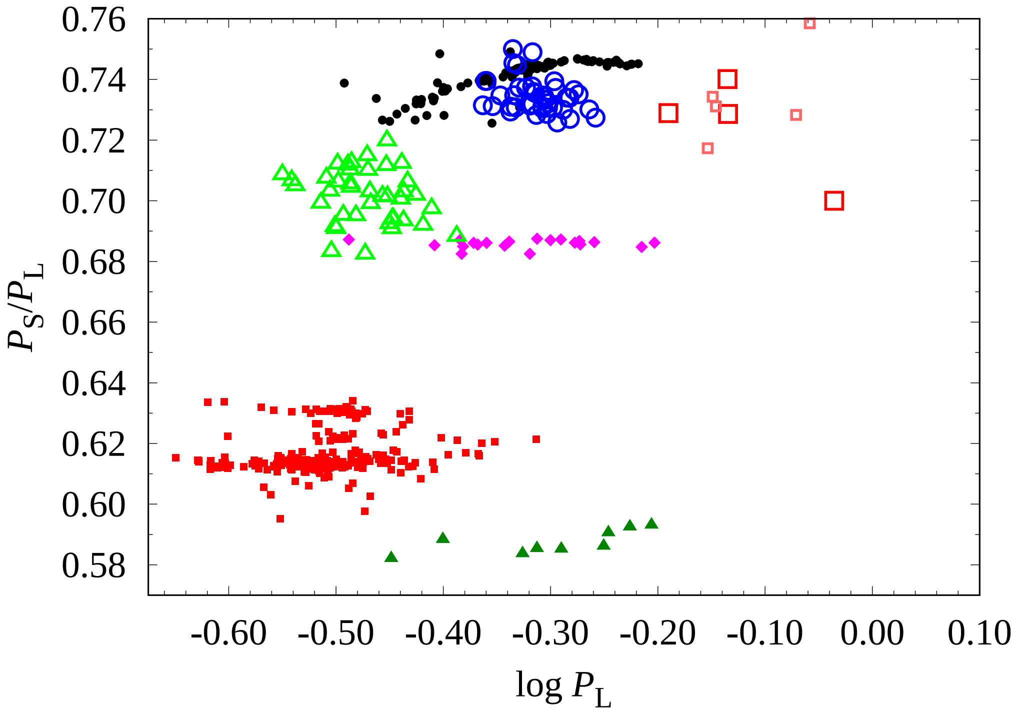

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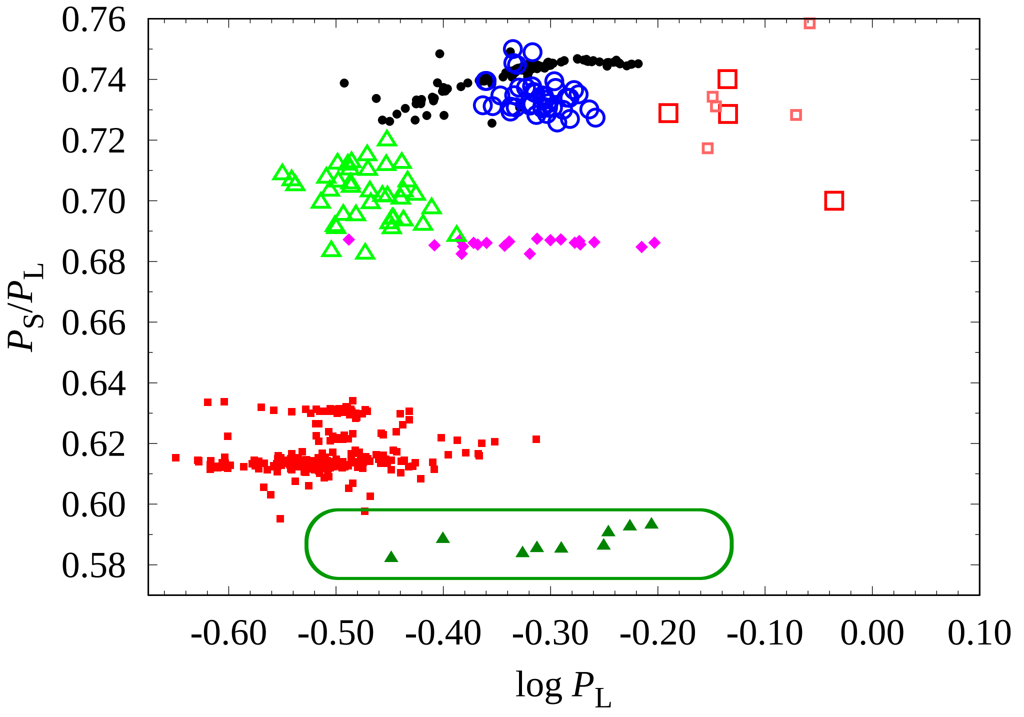
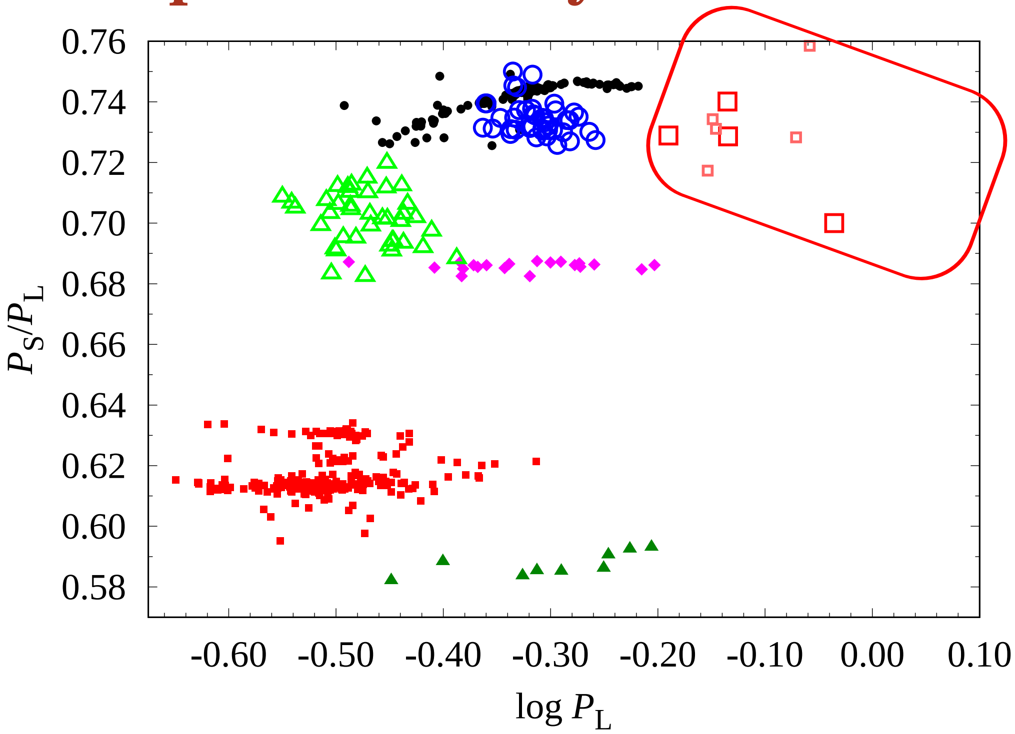
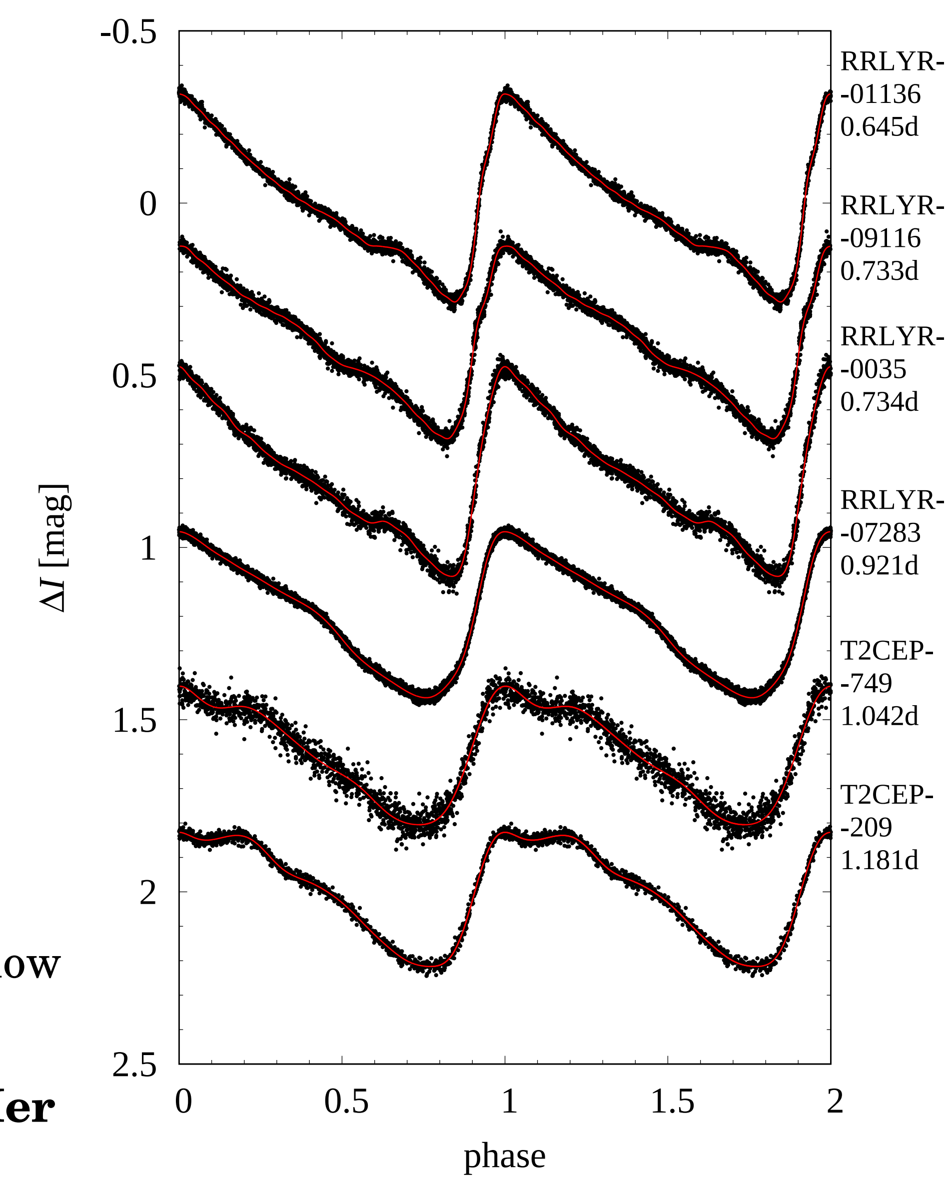


- F+2O, double-mode, radial; a few stars with Blazhko effect, low-amplitude and non-coherent 2O signal (e.g. Benkő et al. 2014)

Multi-periodic RR Lyr stars

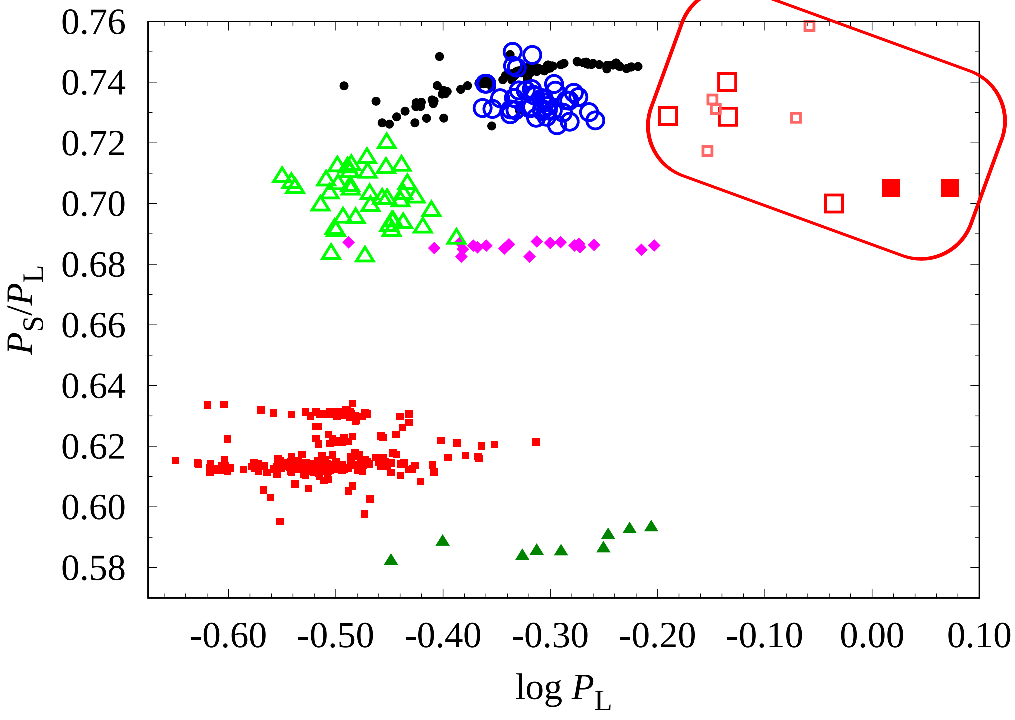


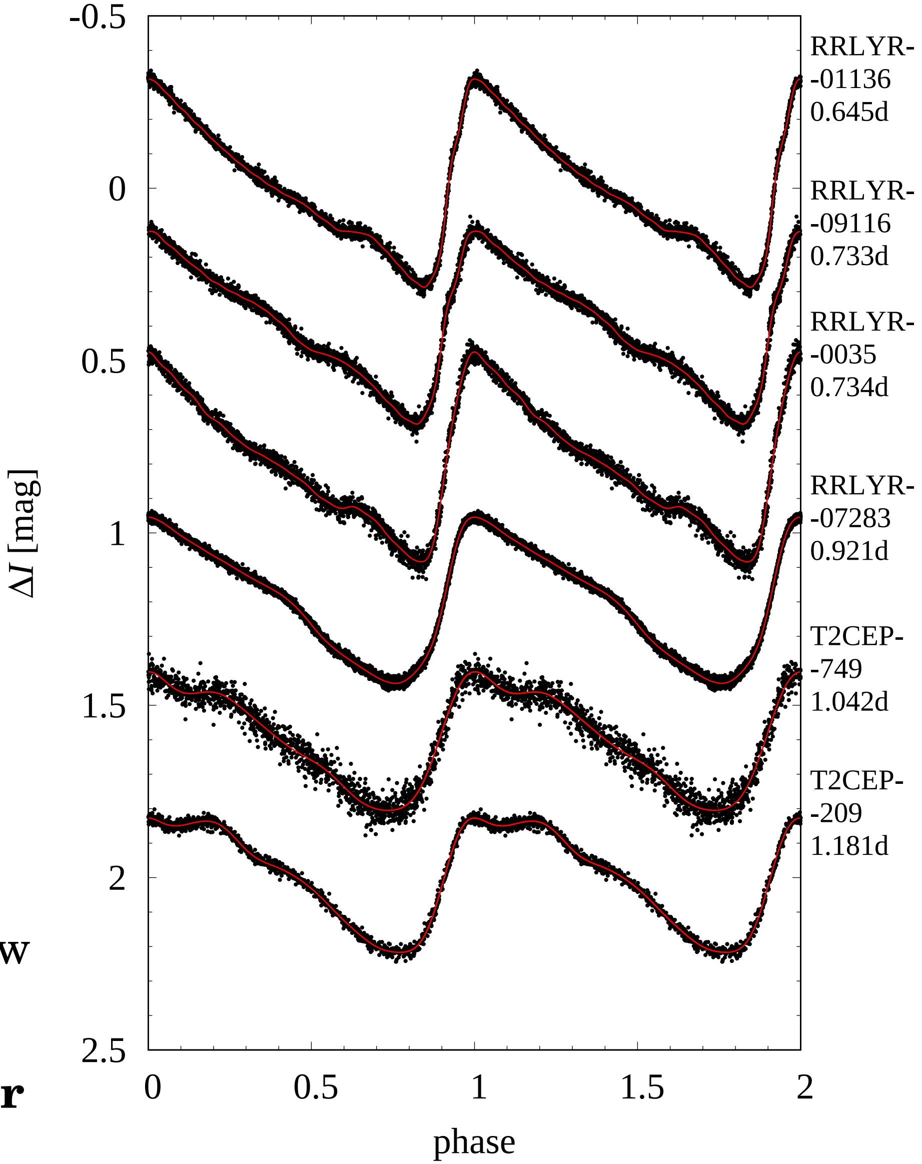


- ⋆ dominant variability: F mode
- ⋆ characteristic light-curve shape
- ⋆ additional variability of shorter period and of low amplitude
- ▶ origin: **extreme, longest-period RRd + BL Her**

Smolec, Prudil, Skarka, Bąkowska (2016), *MNRAS*; Smolec et al. (2018), submitted

Multi-periodic RR Lyr stars





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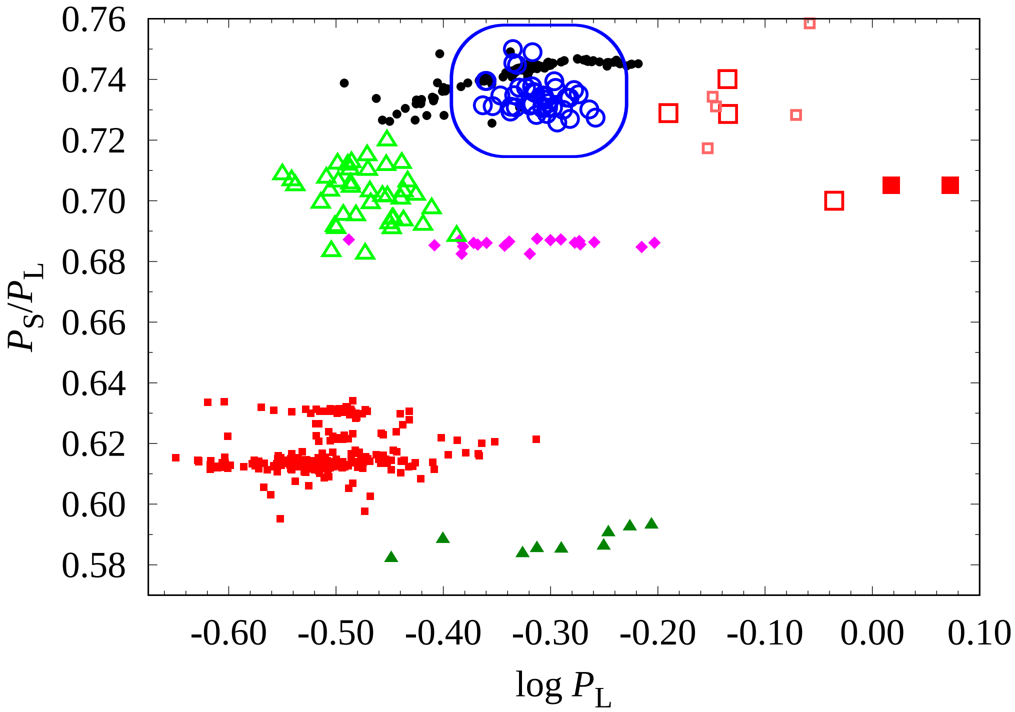
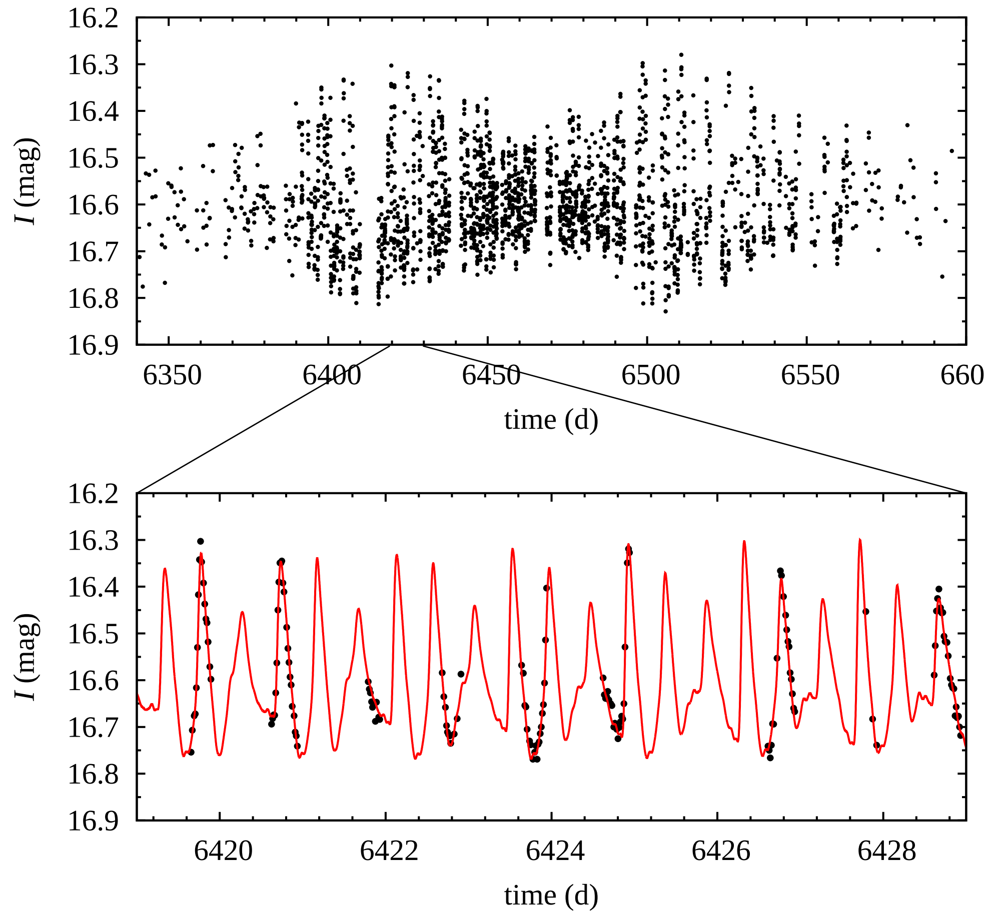
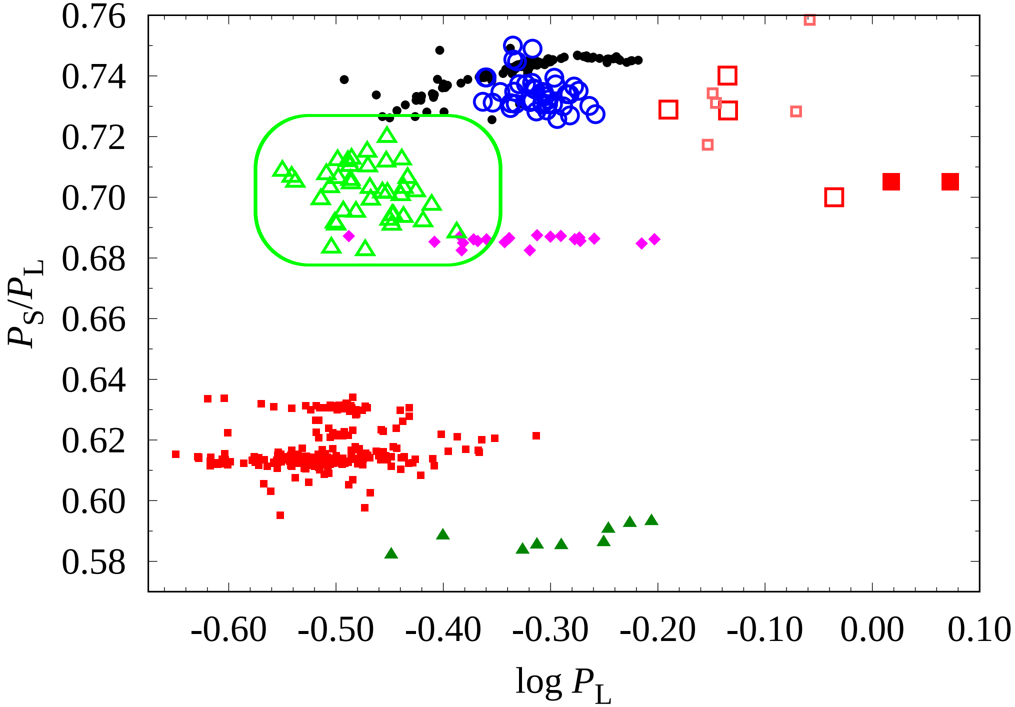


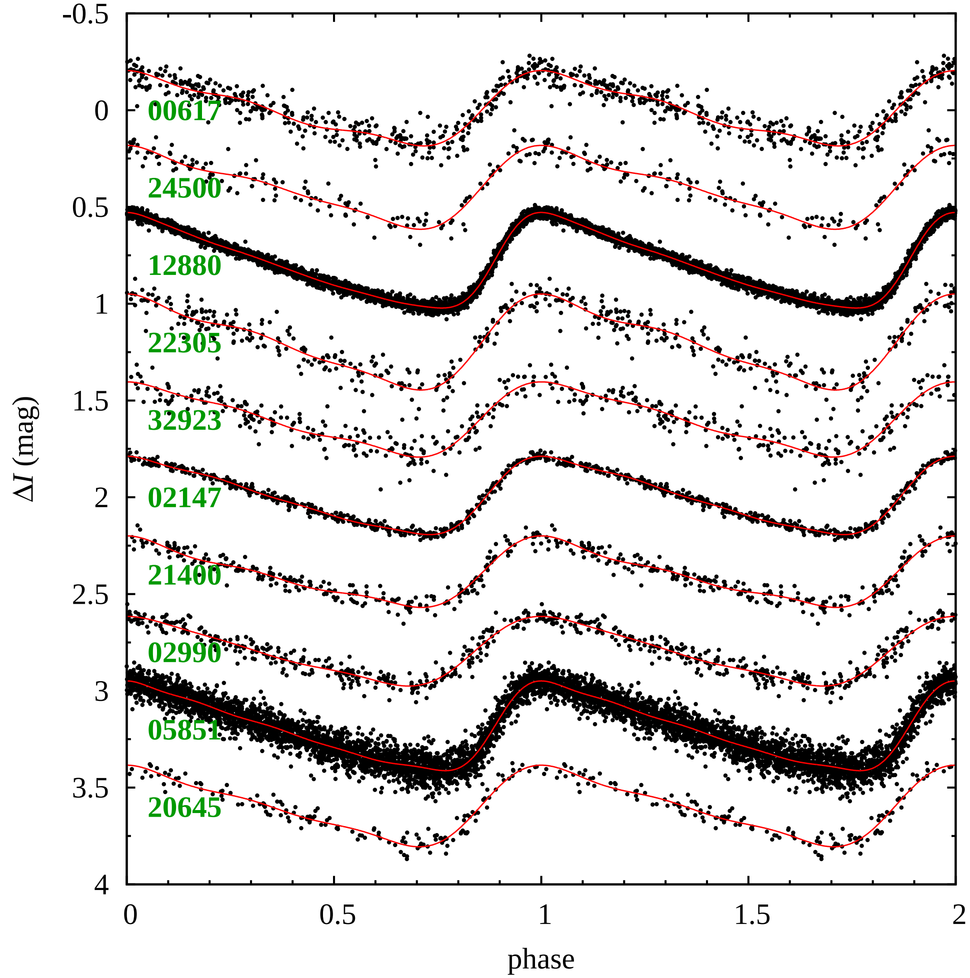


- ⋆ anomalous RRd stars (bulge, M3, MC)
- ⋆ modulation (Blazhko) observed in most cases
- ⋆ anomalous period ratios
- ⋆ anomalous amplitude ratio (F dominates)
- ▸ origin: **RRd (F+1O), resonant?**

Soszyński et al. (2014); Smolec et al. (2015); Jurcsik et al. (2014); **Soszyński et al. (2016)**

Multi-periodic RR Lyr stars





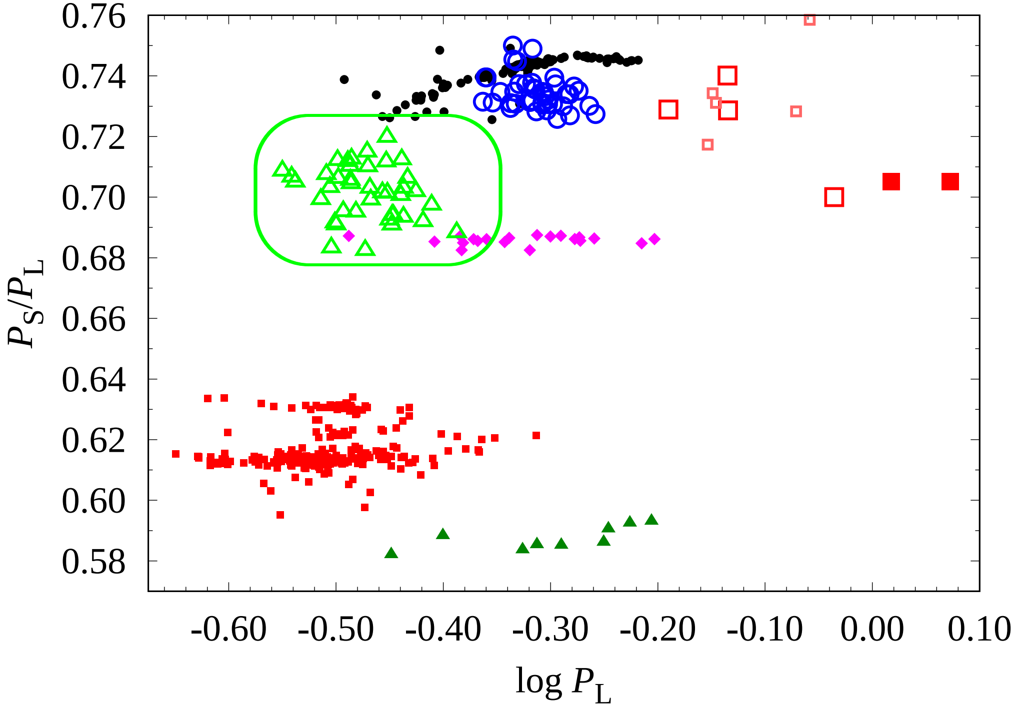
- ⋆ 42 stars, F-mode dominates
- ⋆ secondary variability of shorter period and of relatively large amplitude
- ⋆ Blazhko-like modulation is frequent
- ⋆ characteristic triangular light curve
- ⋆ Fourier parameters *in between* RRab and RRc
- ▸ origin: **unknown, F-mode? RR Lyrae?**

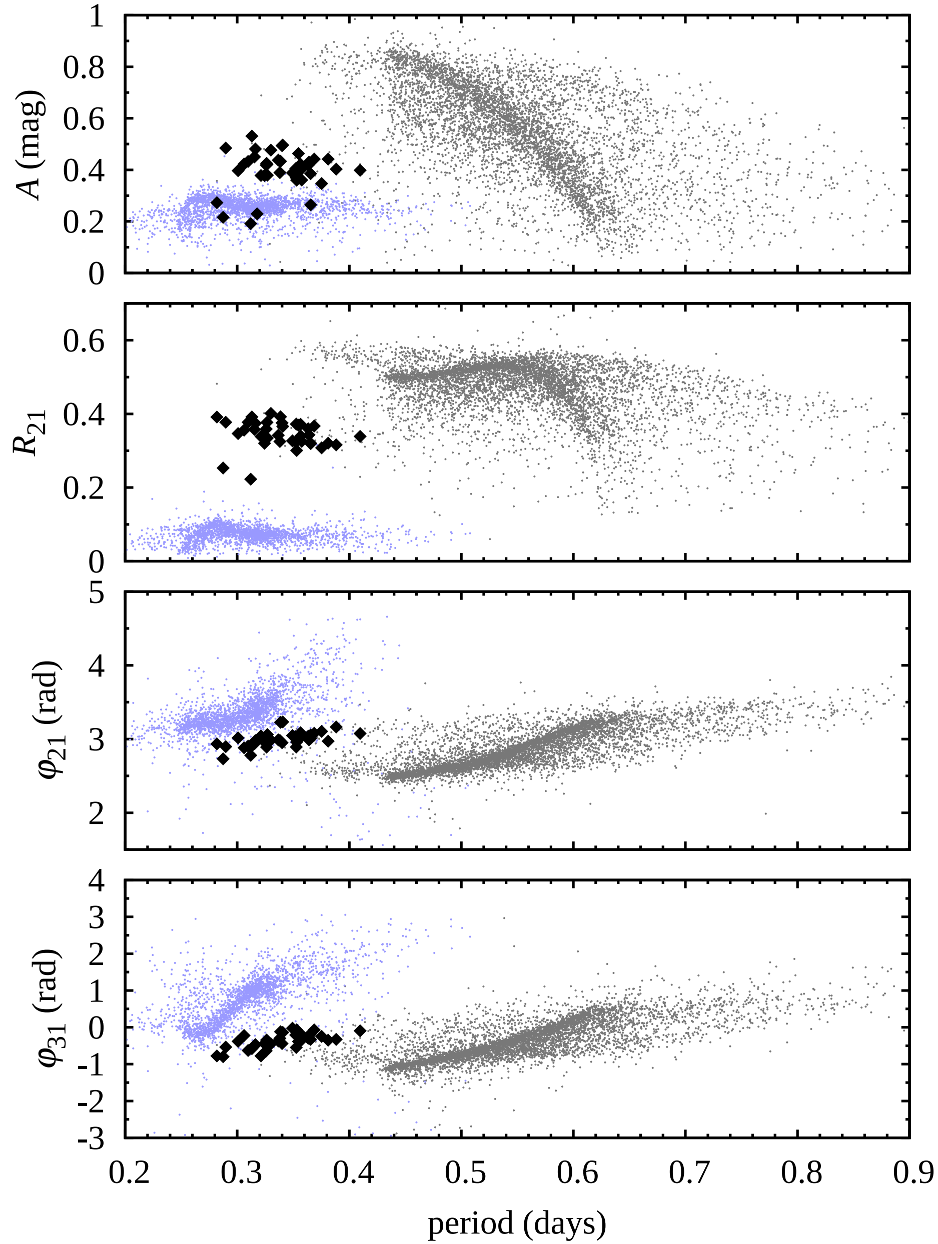
$$m = A_0 + \sum_k A_k \sin(k\omega_0 t + \phi_k)$$

$$R_{k1} = \frac{A_k}{A_1}, \quad \varphi_{k1} = \phi_k - k\phi_1$$

Prudil, Smolec, Skarka, Netzel (2017), *MNRAS*

Multi-periodic RR Lyr stars





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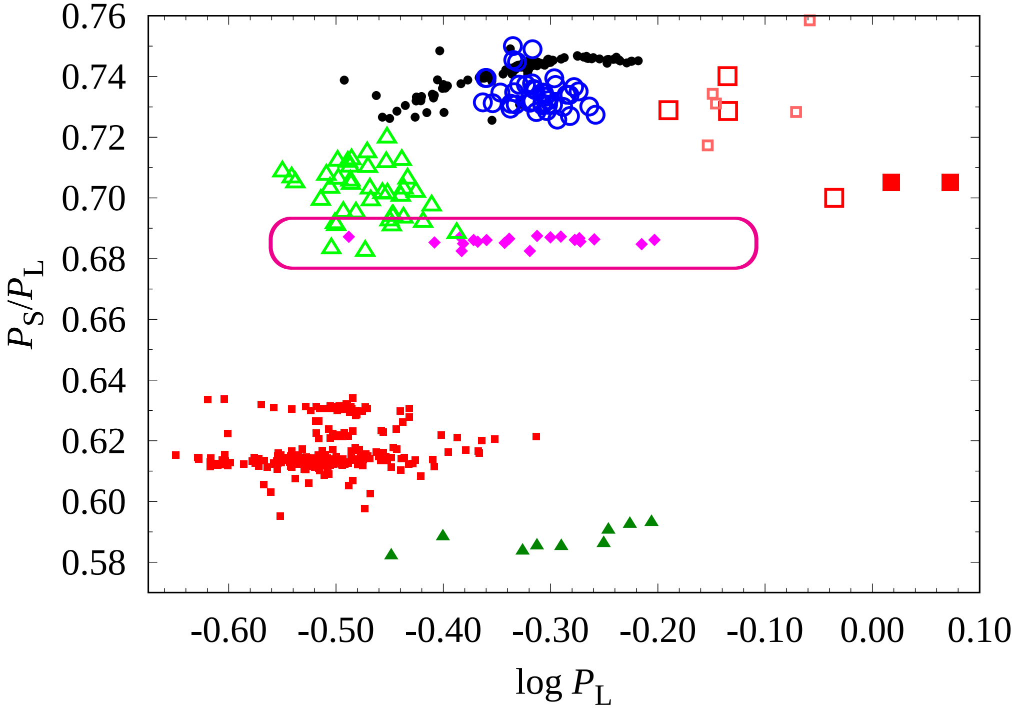
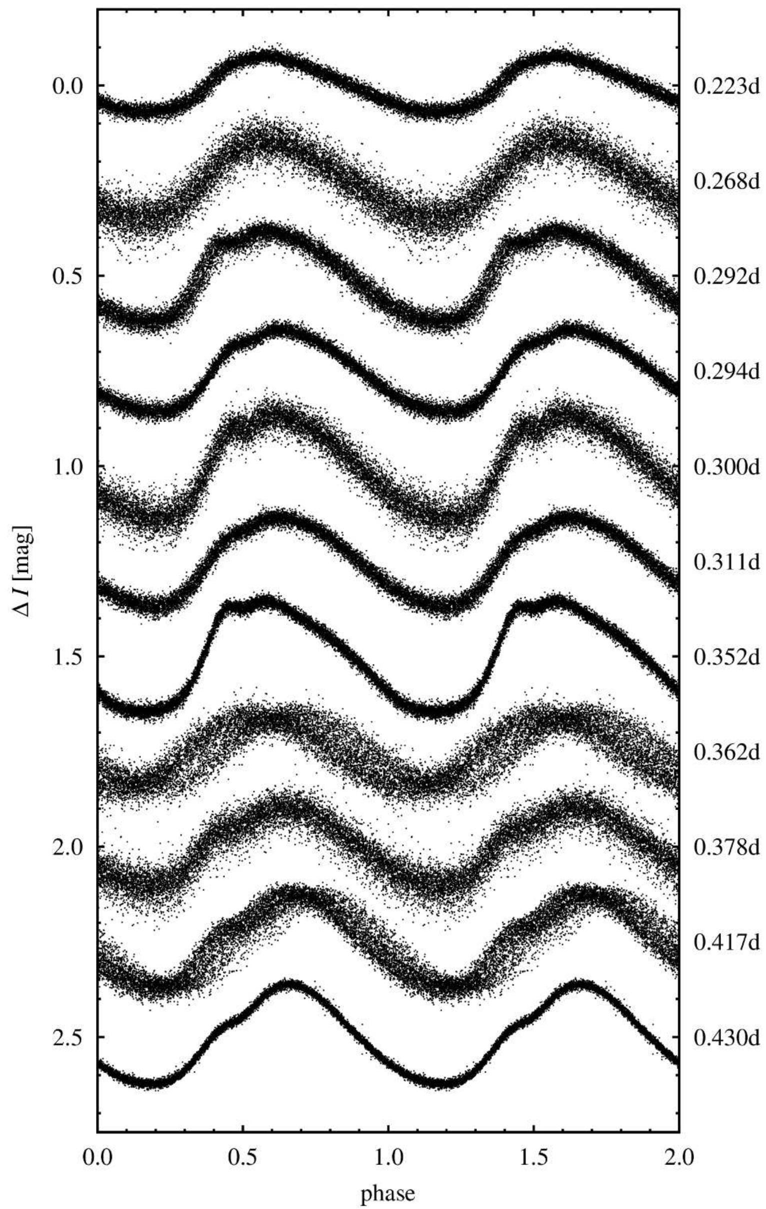
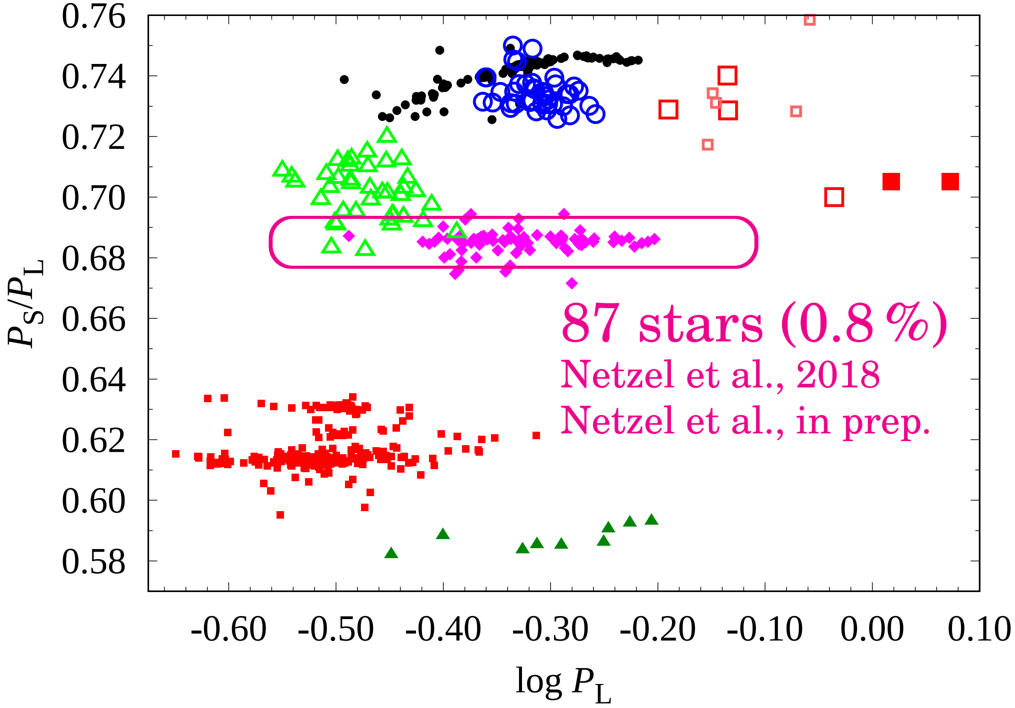


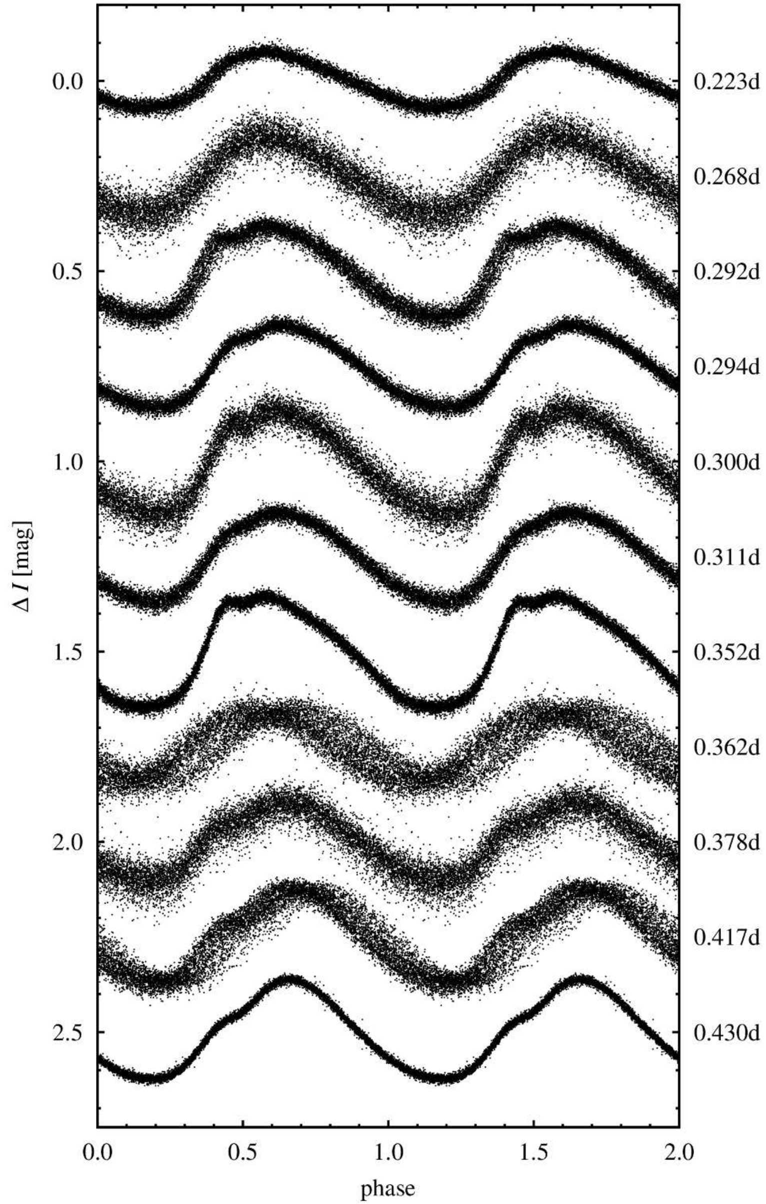


- ⋆ tight period ratios, $P_{1O}/P_X \approx 0.686$
- ⋆ additional variability of long period...
- ⋆ ...too long to be radial fundamental mode
- ⋆ additional variability is of low A and coherent
- ⋆ perfectly normal RRc light curve
- ⋆ origin: **?**

Netzel, Smolec, Dziembowski (2015), *MNRAS Lett.*; Netzel & Smolec (2016), *Proc. PAS*

Multi-periodic RR Lyr stars





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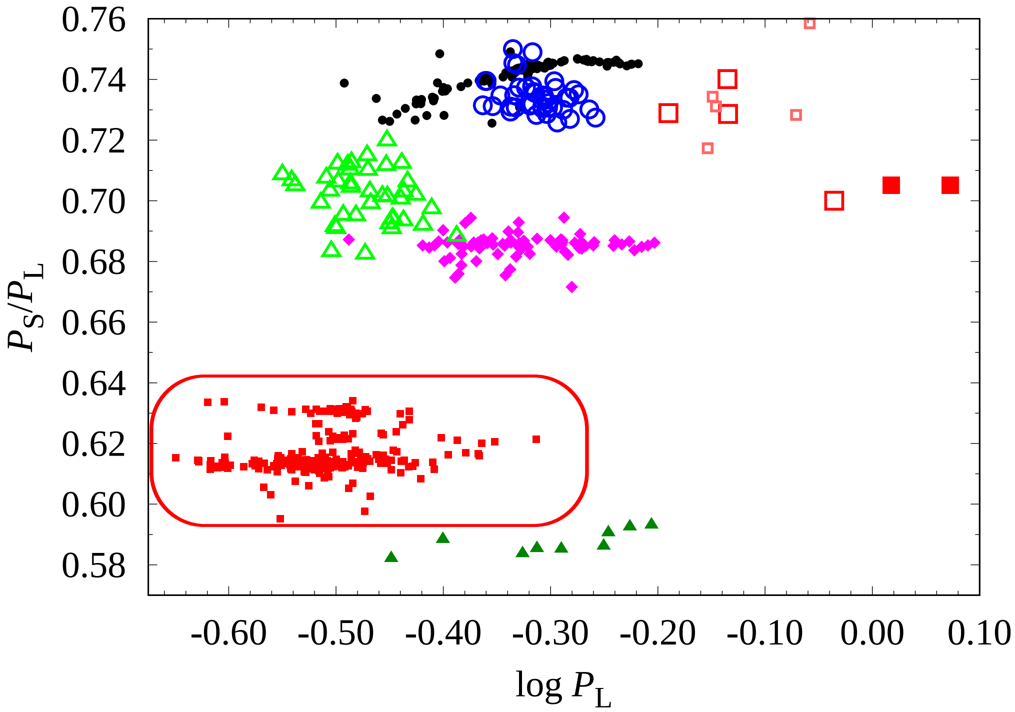

1O+?: > 300 stars

Gruberbauer i in. (2007)
Olech & Moskalik (2009)
Soszyński i in. (2009)
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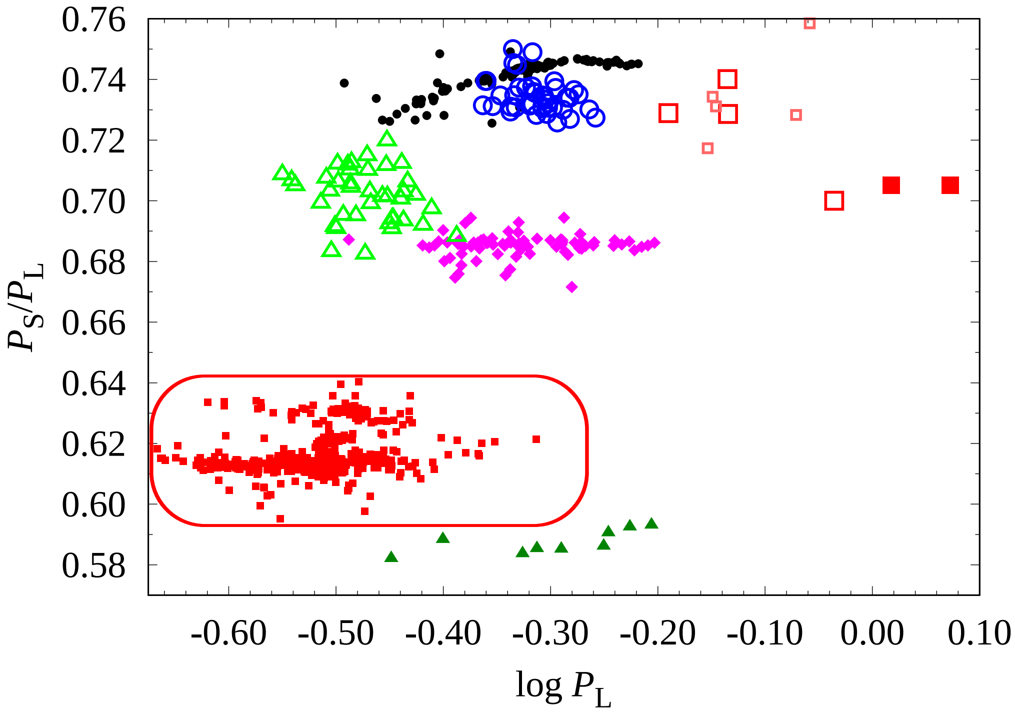
Chadid (2012), Szabo i in. (2014)
Molnar i in. (2015)
Netzel, Smolec & Moskalik (2015a)
Smolec i in. (2015, Bl-RRd)
Jurcsik i in. (2015)
Netzel, Smolec & Moskalik (2015b)
Kurtz et al. (2016)

14/15 RRc/RRd observed from space

>260 in OGLE data!

Multi-periodic RR Lyr stars



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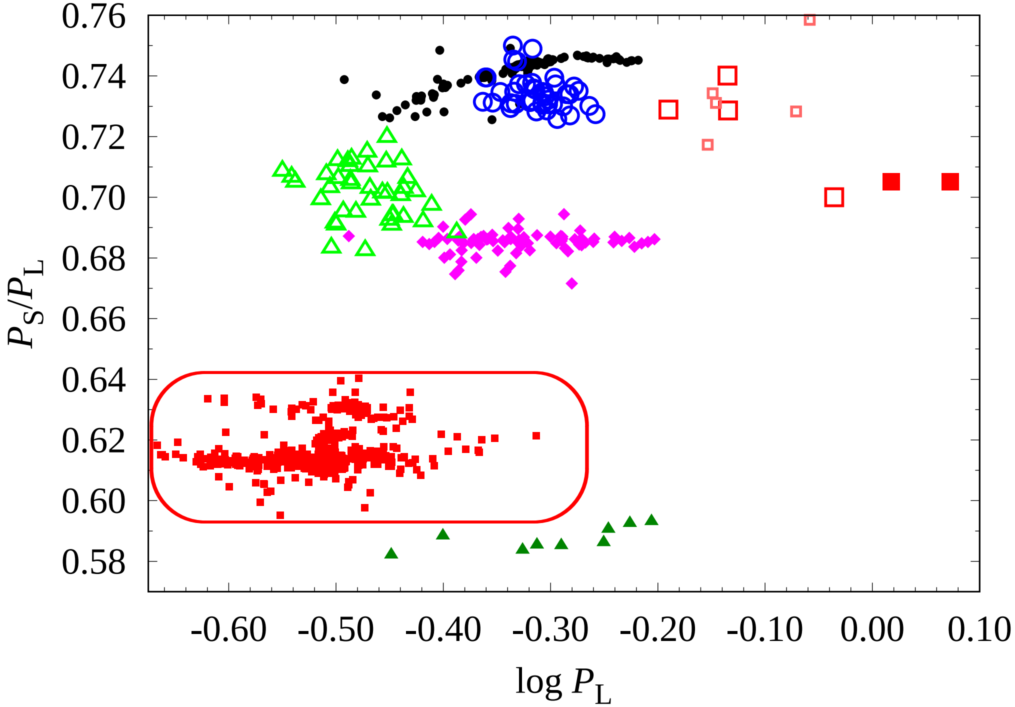
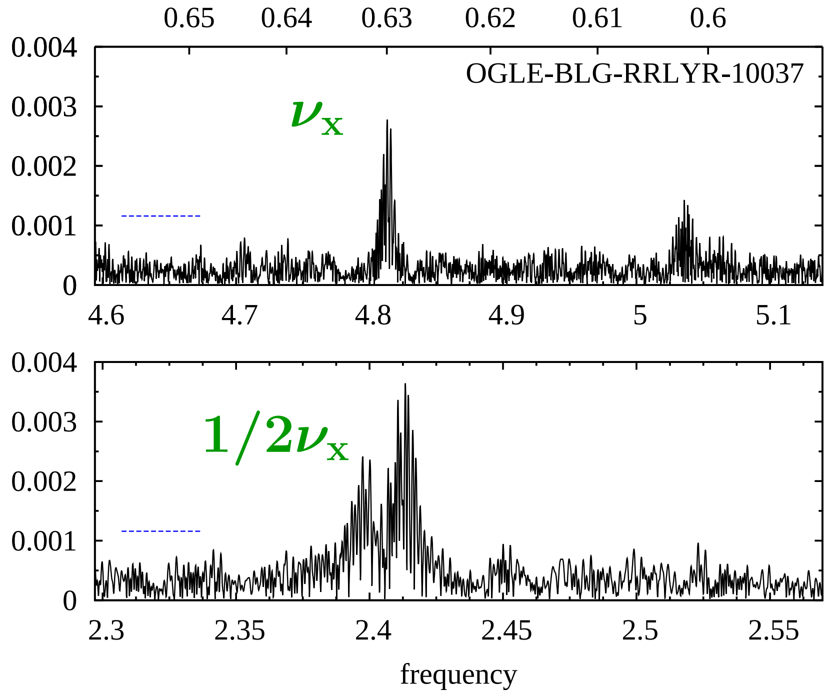
754 in OGLE data (6.6%)!
Netzel et al., 2018, PPAS
Netzel et al., in prep.

Multi-periodic RR Lyr stars

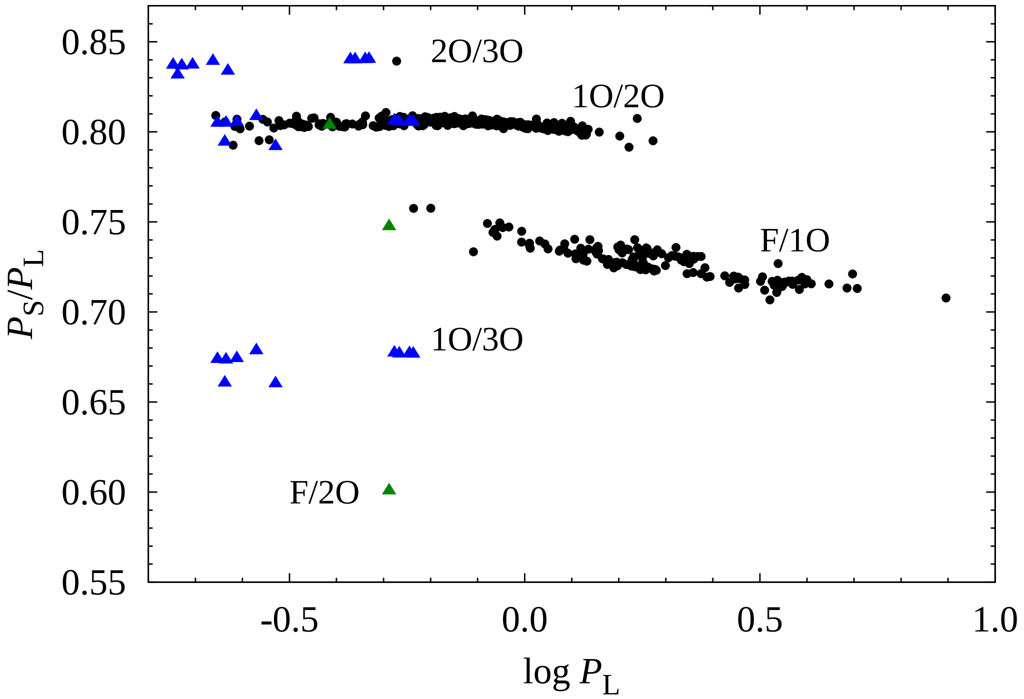




- ⋆ three sequences in the Petersen diagram
- ⋆ signals centered at $1/2\nu_x$ are often detected
- ⋆ signals are of low amplitude and noncoherent
- ⋆ origin: **radial modes do not fit**

Netzel, Smolec & Moskalik (2015a,b), *MNRAS*

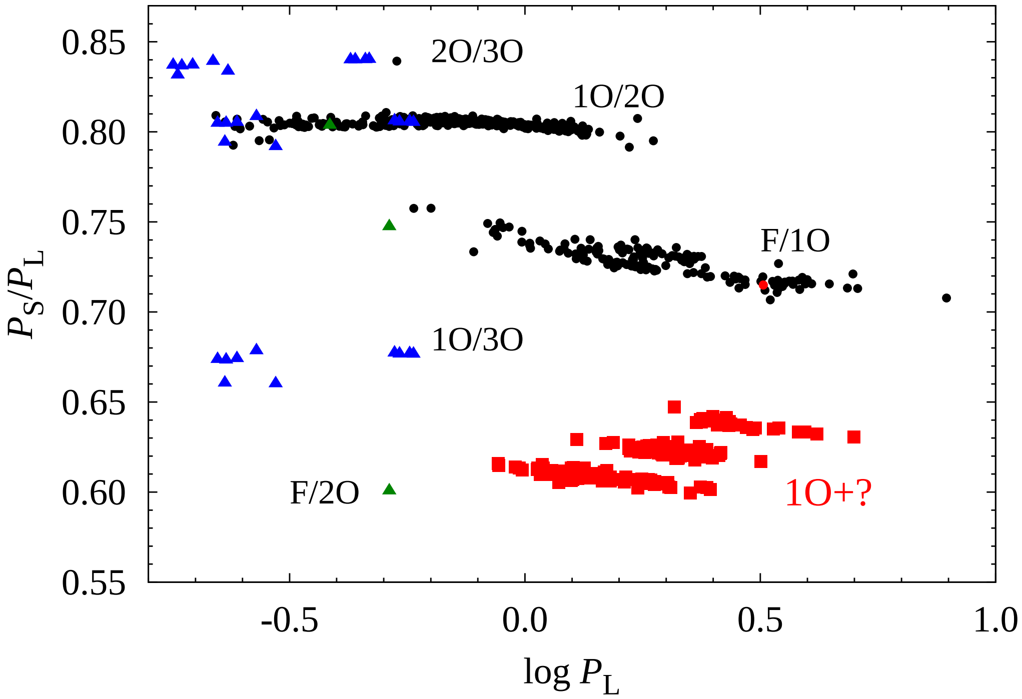
Multi-periodic Cepheids



⋆ *radial mode inventory (OGLE):*

- double-mode: F+1O, 1O+2O (hundreds)
- double-mode, *unique*: 1O+3O (1); 2O+3O (1)
- triple-mode: F+1O+2O (1), 1O+2O+3O (9)
- quadruple-mode: F+1O+2O+3O (1)

Multi-periodic Cepheids



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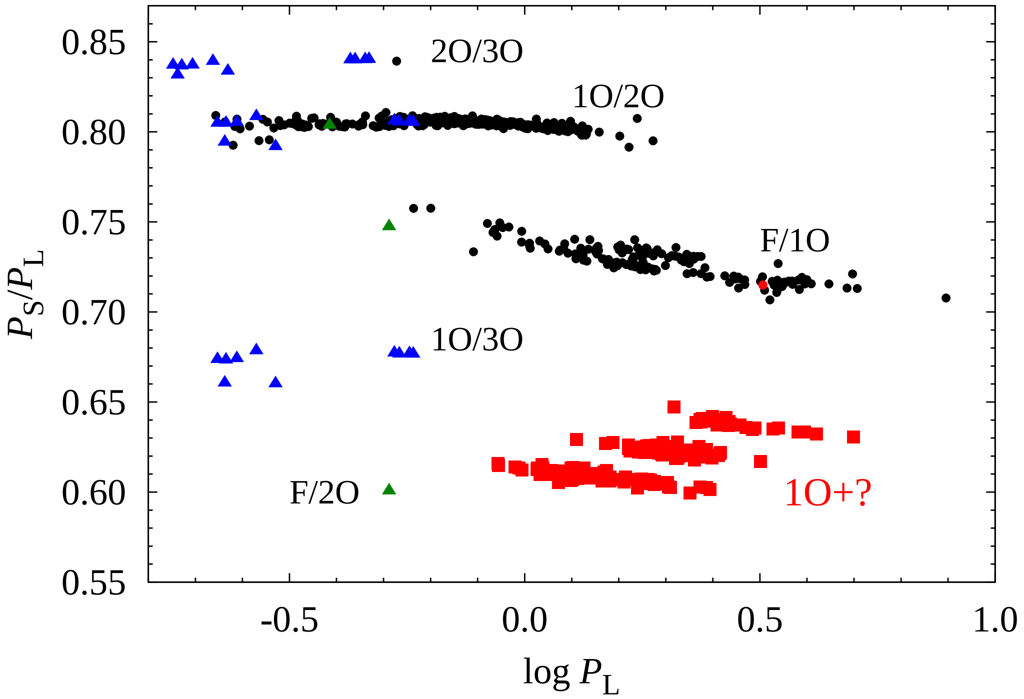
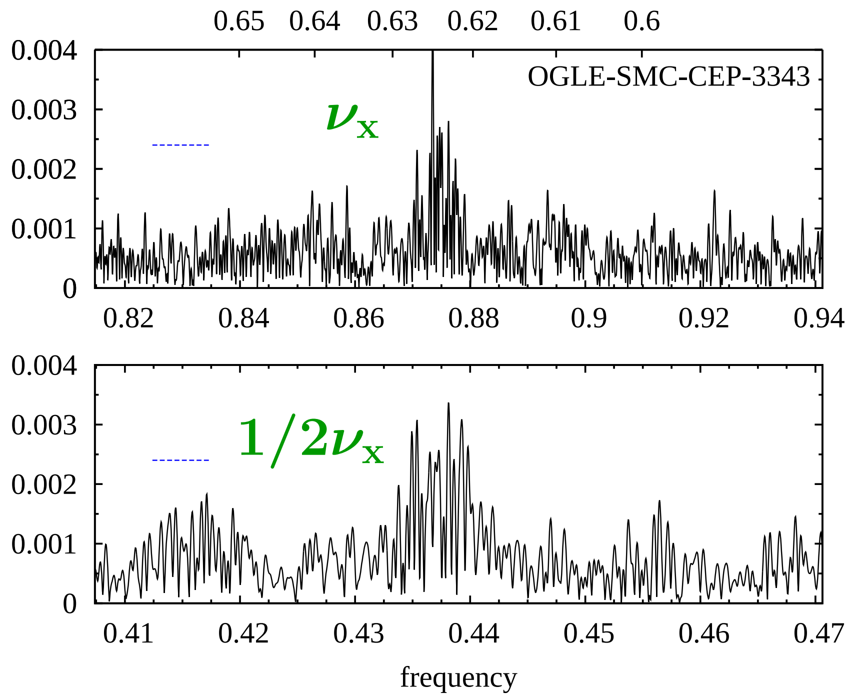
1O+?: > 300 stars

Moskalik & Kołaczkowski (2009)
Soszyński et al. (2008,-10,-15)
Pietrukowicz et al. (2009)

detailed analysis in
Smolec & Śniegowska (2016)
138 SMC stars

Multi-periodic Cepheids





⋆ three sequences in the Petersen diagram

⋆ typical colors, luminosities, light curves

⋆ amplitudes are low, $\sim 2-4\%$ of 1O amplitude

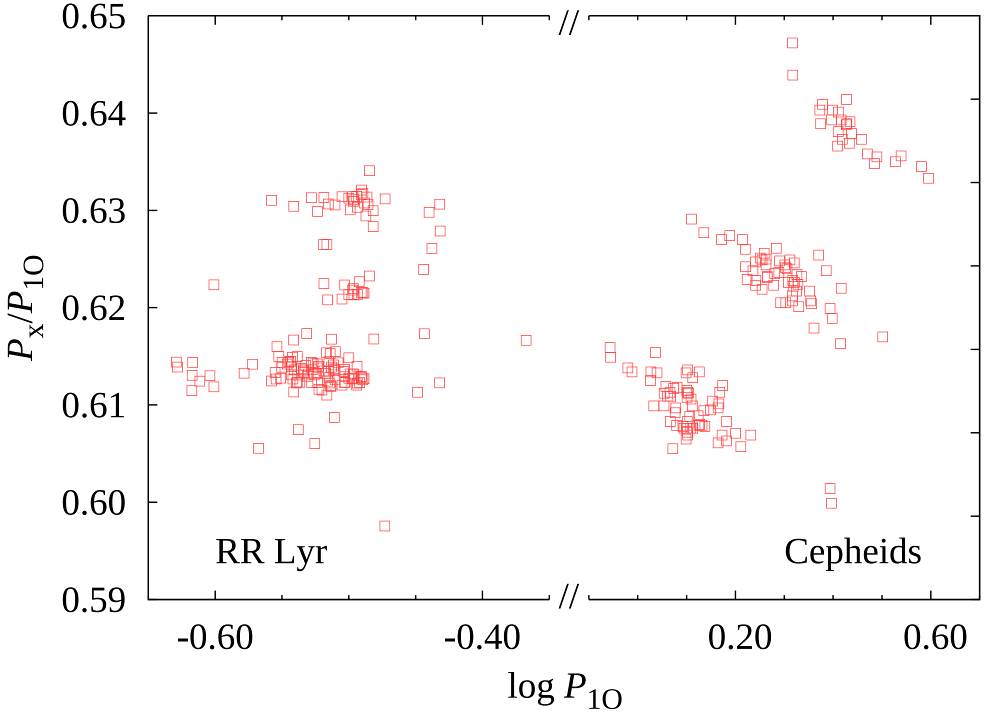
⋆ signal at $1/2\nu_{\rm x}$ is often detected

⋆ signals at $\nu_{\rm x}$ and $1/2\nu_{\rm x}$ are noncoherent

⋆ see also Süveges & Anderson, 2018, *MNRAS*

Smolec & Śniegowska (2016), *MNRAS*

Common explanation for RR Lyr/Cepheids: Dziembowski's model



Dziembowski (2016), Dziembowski & Smolec, in prep.

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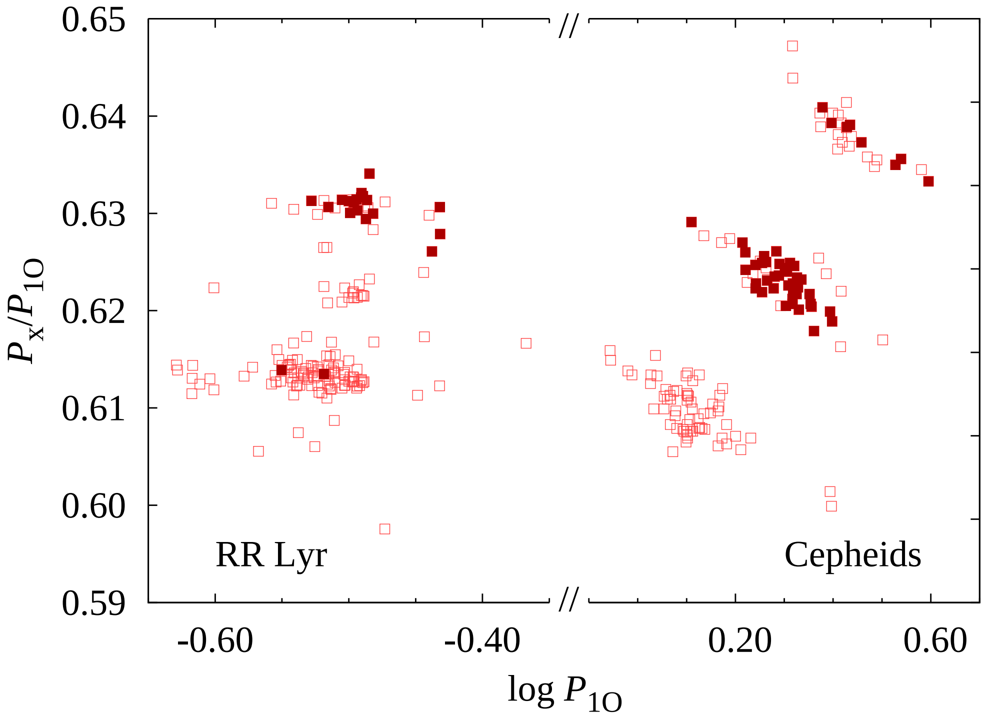

⋆ stars with signals centered at $1/2\nu_x$ are not distributed randomly; signals at $1/2\nu_x$...

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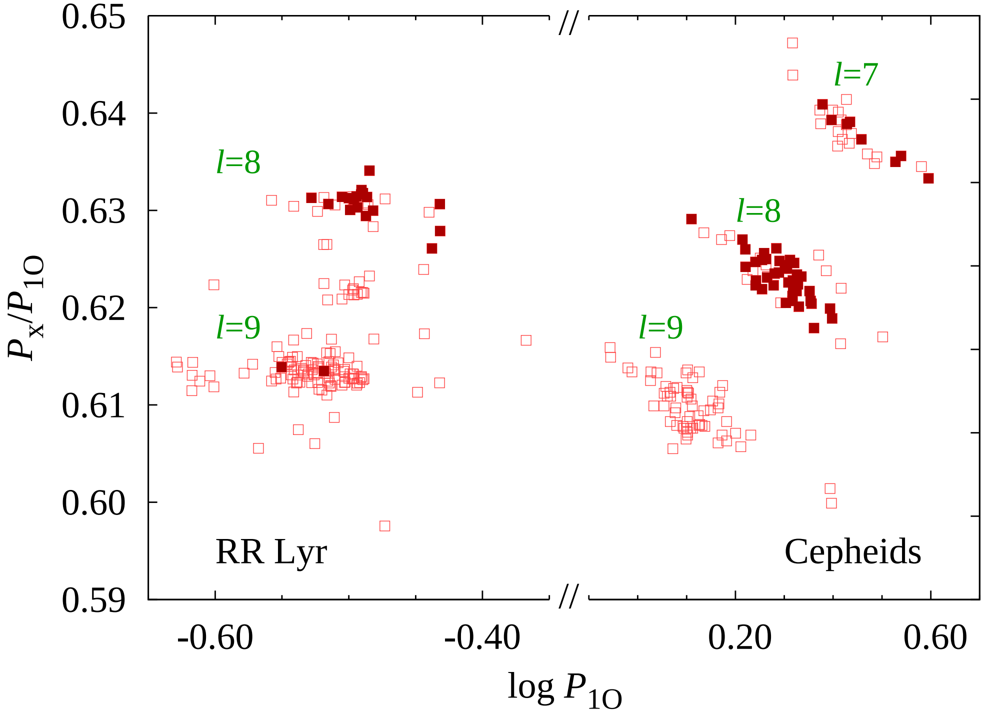

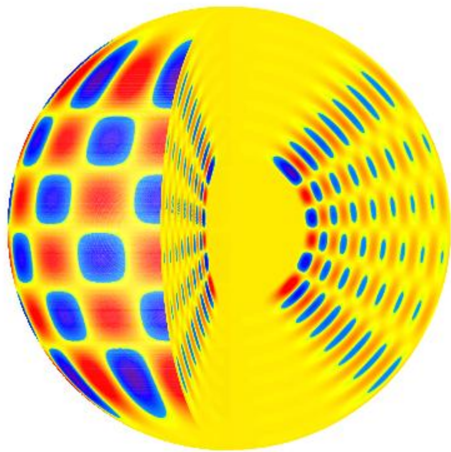

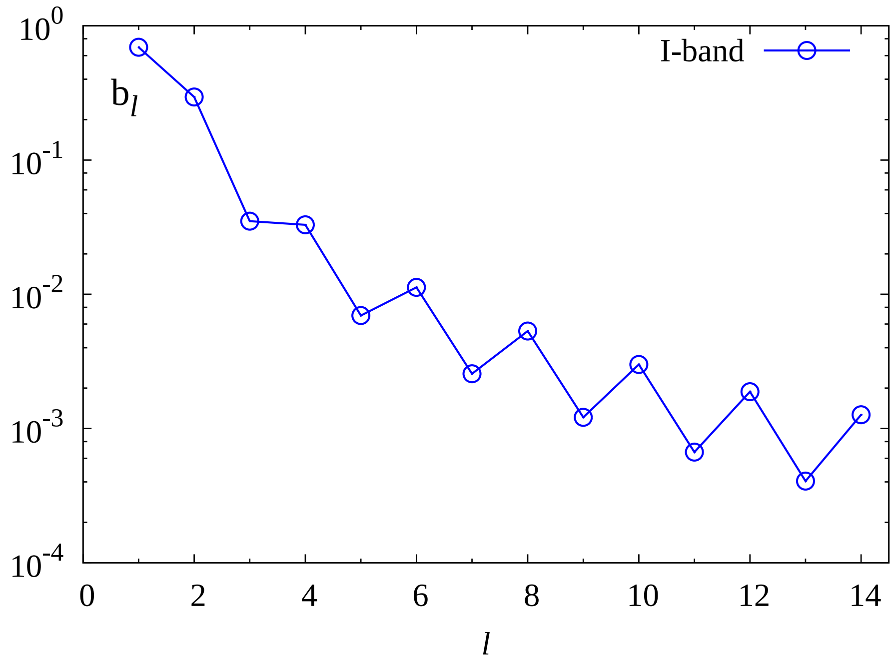

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- ⋆ ...correspond to nonrad modes of $\ell = 7, 8, 9$, but only $\ell = 8$ is commonly detected (cancellation)...

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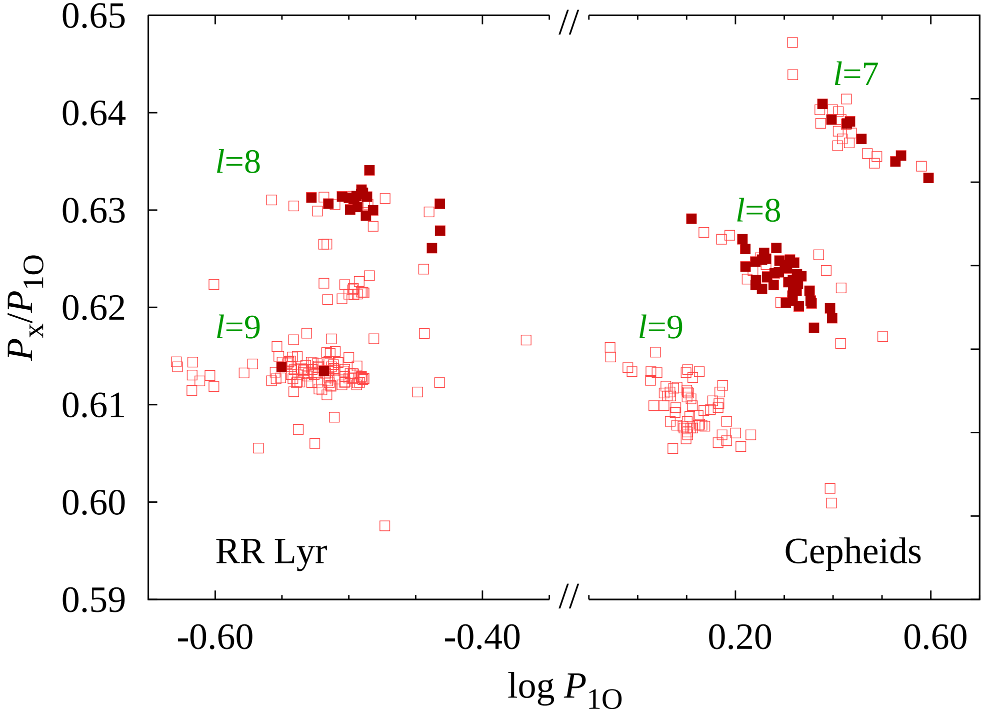

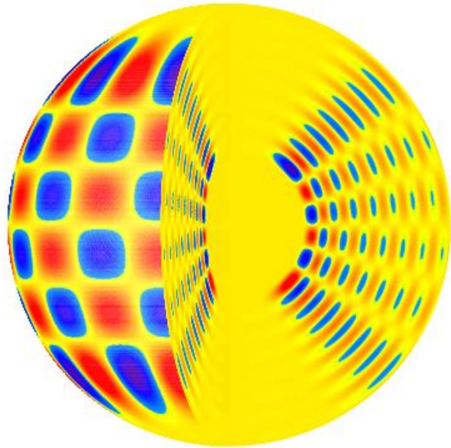

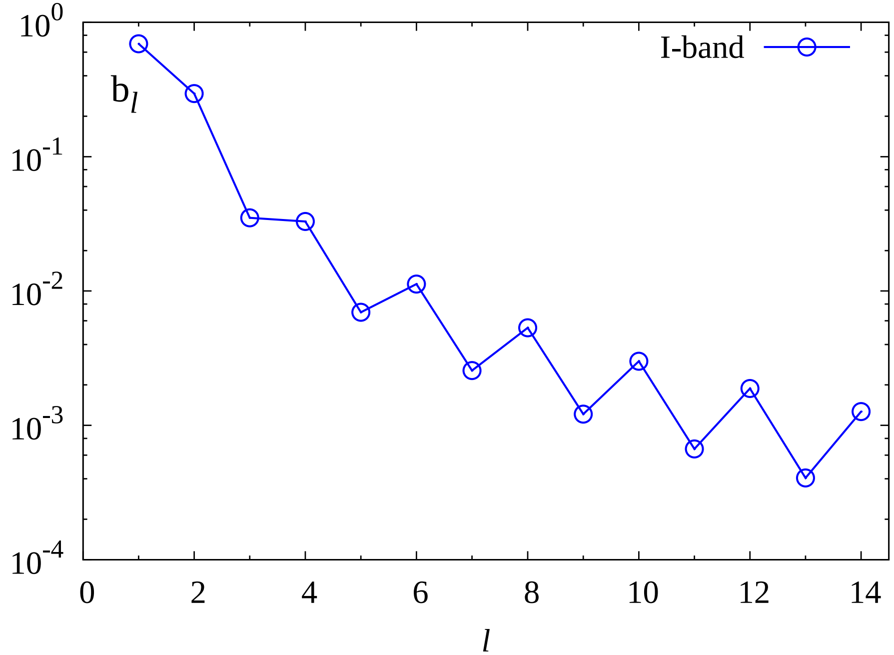

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- ⋆ ...other manifest through harmonic, i.e. signal at $\nu_{\rm x}$

Dziembowski (2016), Dziembowski & Smolec, in prep.

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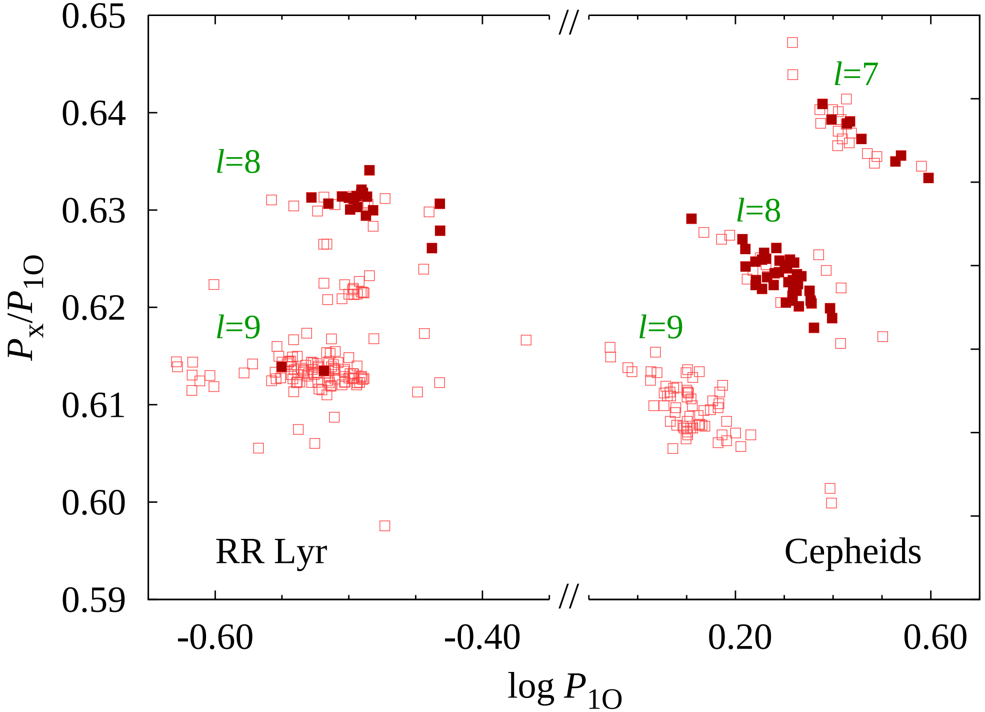

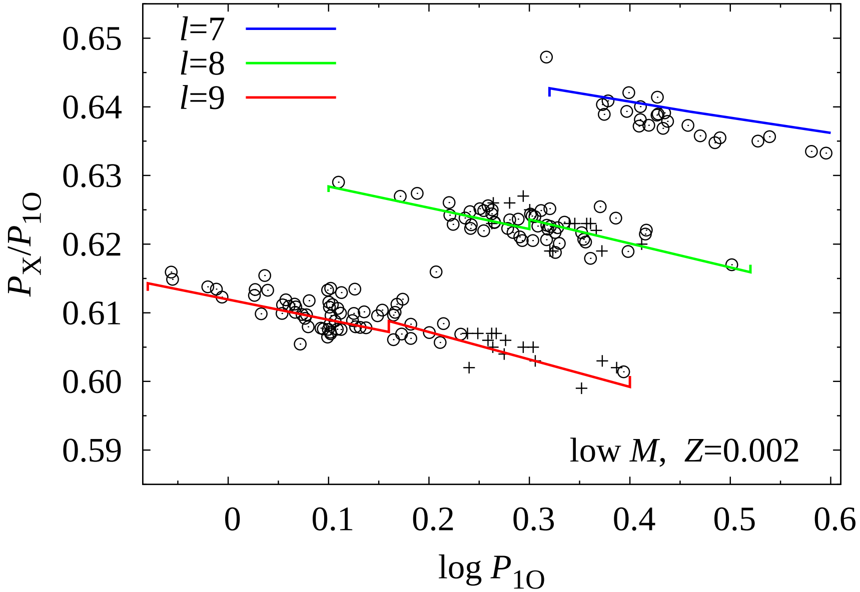

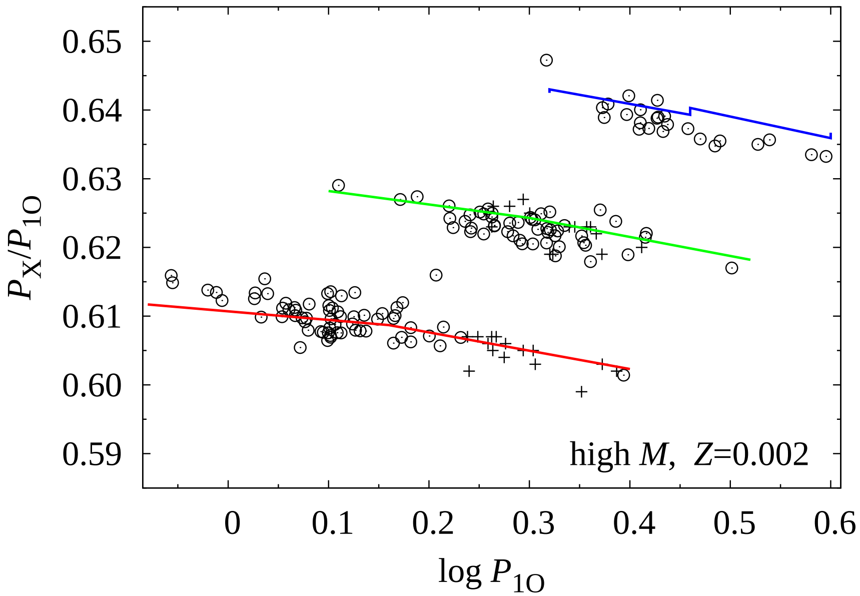

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- ⋆ ...other manifest through harmonic, i.e. signal at $\nu_{\rm x}$
- ⋆ very good match with the models

Dziembowski (2016), Dziembowski & Smolec, in prep.

Periodic modulations in classical pulsators

⋆ RR Lyr stars

- Blazhko effect in RRab stars (up to 50%), RRc and RRd stars
- RRc stars: OGLE Galactic bulge sample: Netzel et al. (2018) MNRAS

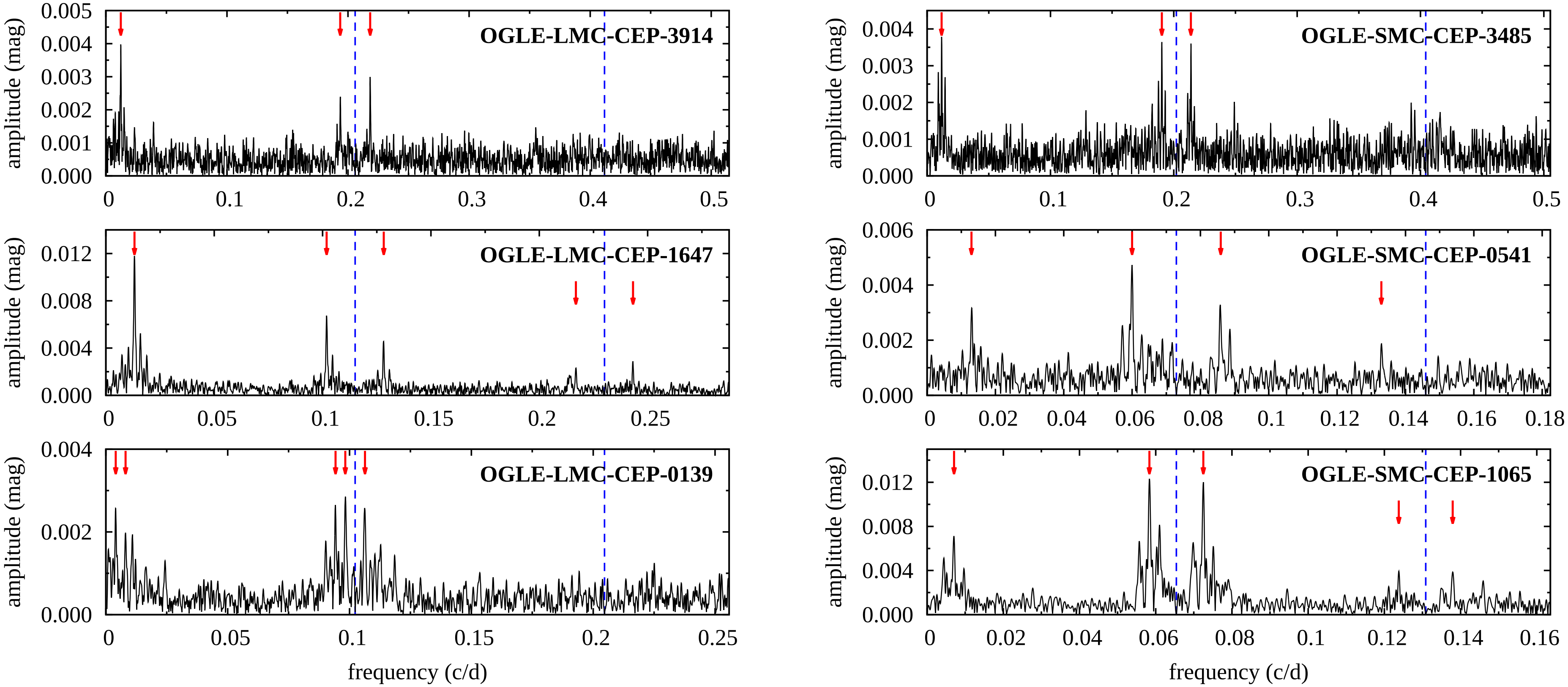
⋆ classical Cepheids

- V473 Lyr – unique 2O, modulated star (e.g. Molnar & Szabados, 2014)
- double overtone, 1O+2O Cepheids (Moskalik & Kołaczkowski, 2009)
- V1154 Cyg, the only Cepheid in the original *Kepler* field (Derekas et al. 2012, 2017)
- F-mode Cepheids form the OGLE collection (Smolec, 2017)

⋆ type-II Cepheids

- BL Her, W Vir and RV Tau form the OGLE collection (Smolec et al., 2018, submitted to MNRAS)

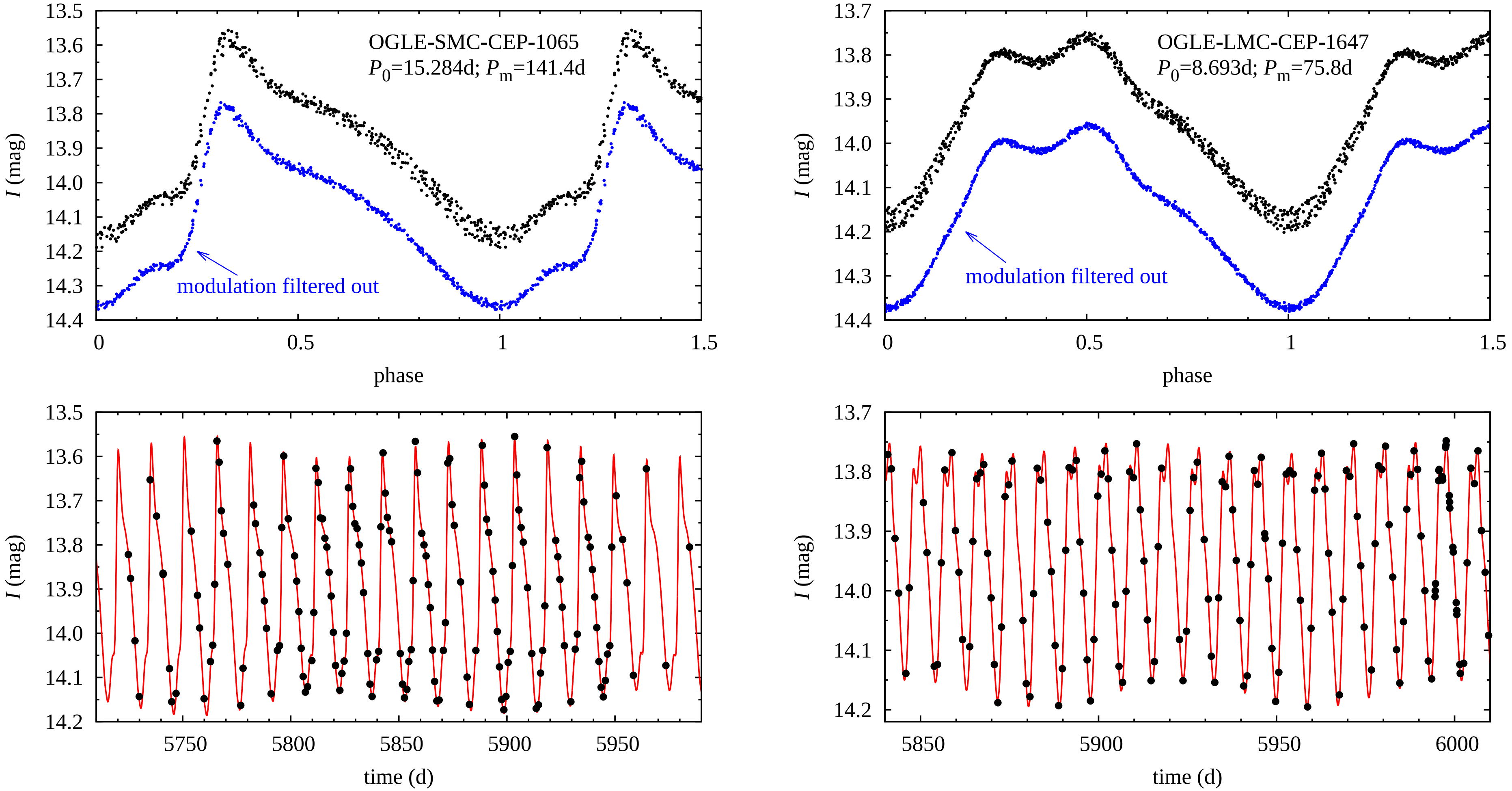
Modulation in classical, F-mode Cepheids



Smolec (2017), *MNRAS*

- in the majority of cases, modulation detected thanks to analysis of frequency spectra only

Modulation in classical, F-mode Cepheids



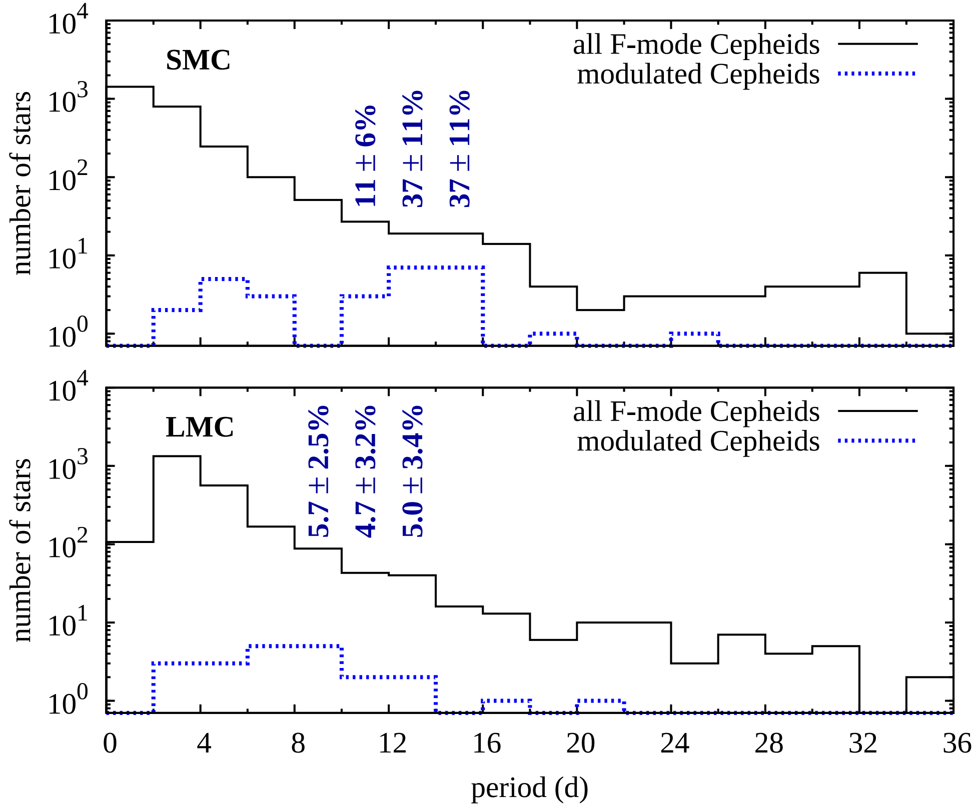
Smolec (2017), *MNRAS*

- in the majority of cases, modulation detected thanks to analysis of frequency spectra only
- in a few cases modulation is well visible directly in the light curve

Modulation in classical, F-mode Cepheids

⋆ 29 stars in SMC, 22 in LMC ($\sim 1\%$)

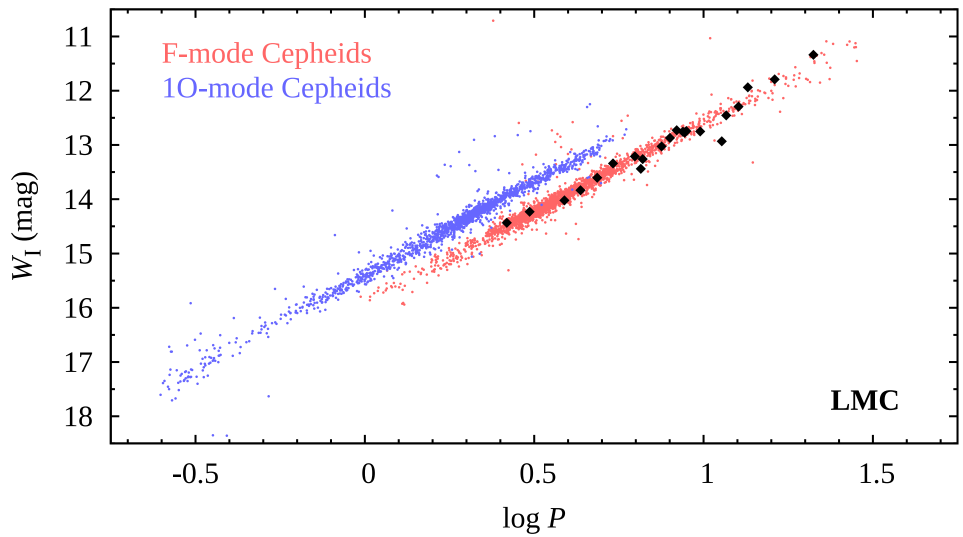
⋆ in SMC for $12\,\mathrm{d} < P_\mathrm{F} < 16\,\mathrm{d}$ the effect is very frequent ($\sim 40\%$)

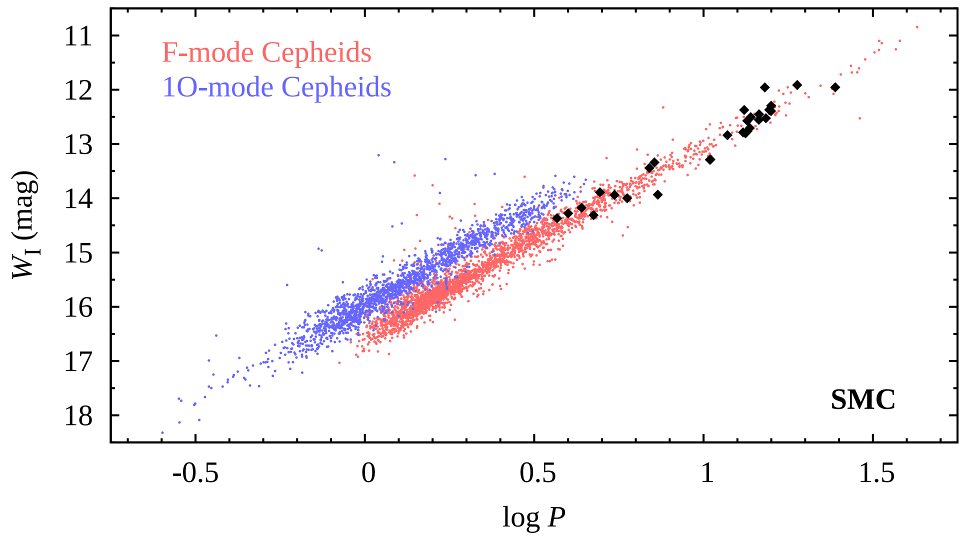


Smolec (2017), *MNRAS*

Modulation in classical, F-mode Cepheids

- ⋆ 29 stars in SMC, 22 in LMC ($\sim 1\%$)
- ⋆ in SMC for $12\,\mathrm{d} < P_{\mathrm{F}} < 16\,\mathrm{d}$ the effect is very frequent ($\sim 40\%$)
- ⋆ typical light curves
- ⋆ typical brightnesses
- ⋆ no modulation in SMC for $P_{\mathrm{F}} < 3.6\,\mathrm{d}$ (the effect is real)
- ⋆ typical modulation period is $10 \times P_{\mathrm{F}}$

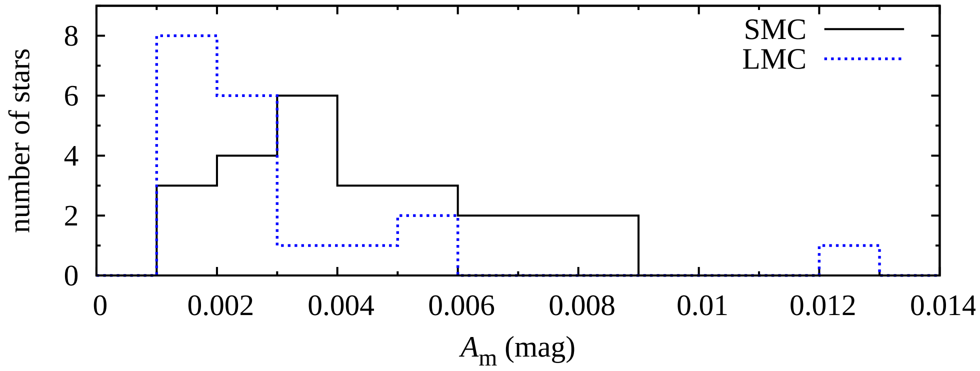


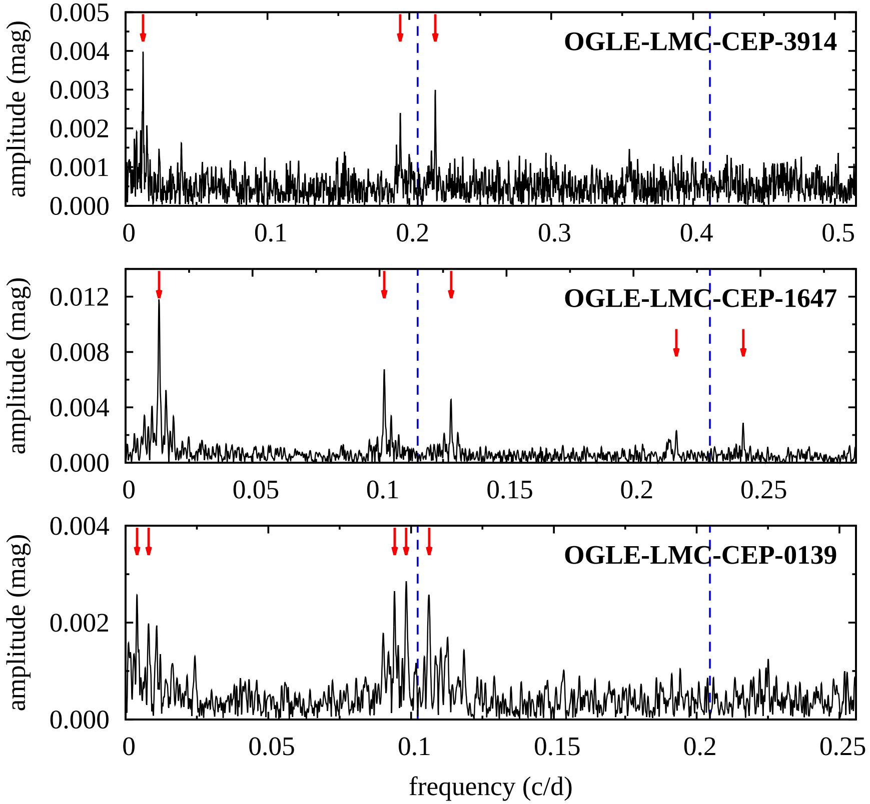


Smolec (2017), *MNRAS*

Modulation in classical, F-mode Cepheids

- ⋆ 29 stars in SMC, 22 in LMC ($\sim 1\%$)
- ⋆ in SMC for $12\,\mathrm{d} < P_\mathrm{F} < 16\,\mathrm{d}$ the effect is very frequent ($\sim 40\%$)
- ⋆ typical light curves
- ⋆ typical brightnesses
- ⋆ no modulation in SMC for $P_\mathrm{F} < 3.6\,$d (the effect is real)
- ⋆ typical modulation period is $10 \times P_\mathrm{F}$
- ⋆ mean brightness modulation typically below $0.01\,$mag
- ⋆ relative modulation amplitude $< 6\,\%$

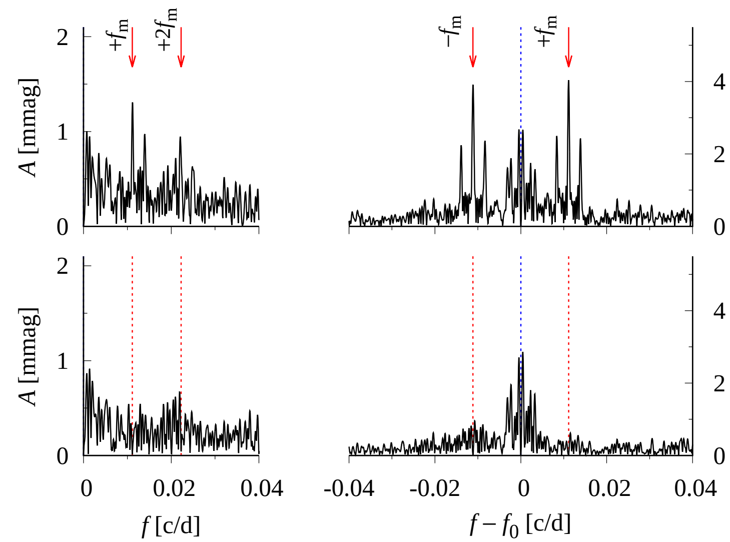


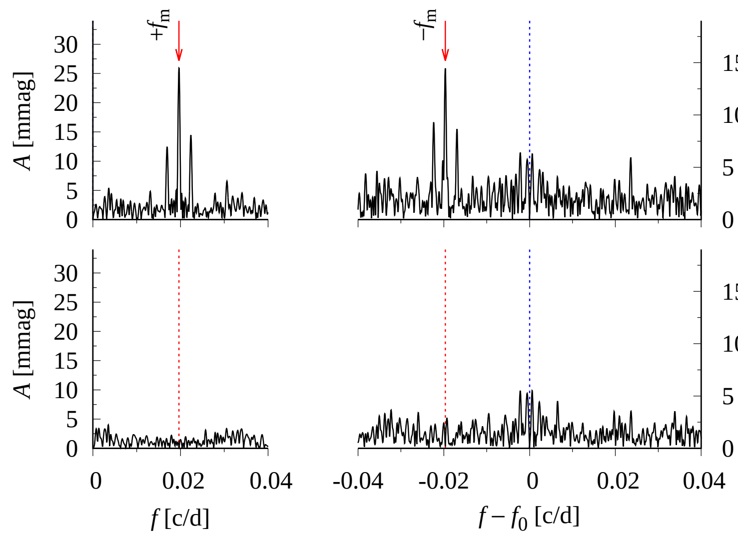


Smolec (2017), *MNRAS*

Modulation in type II Cepheids

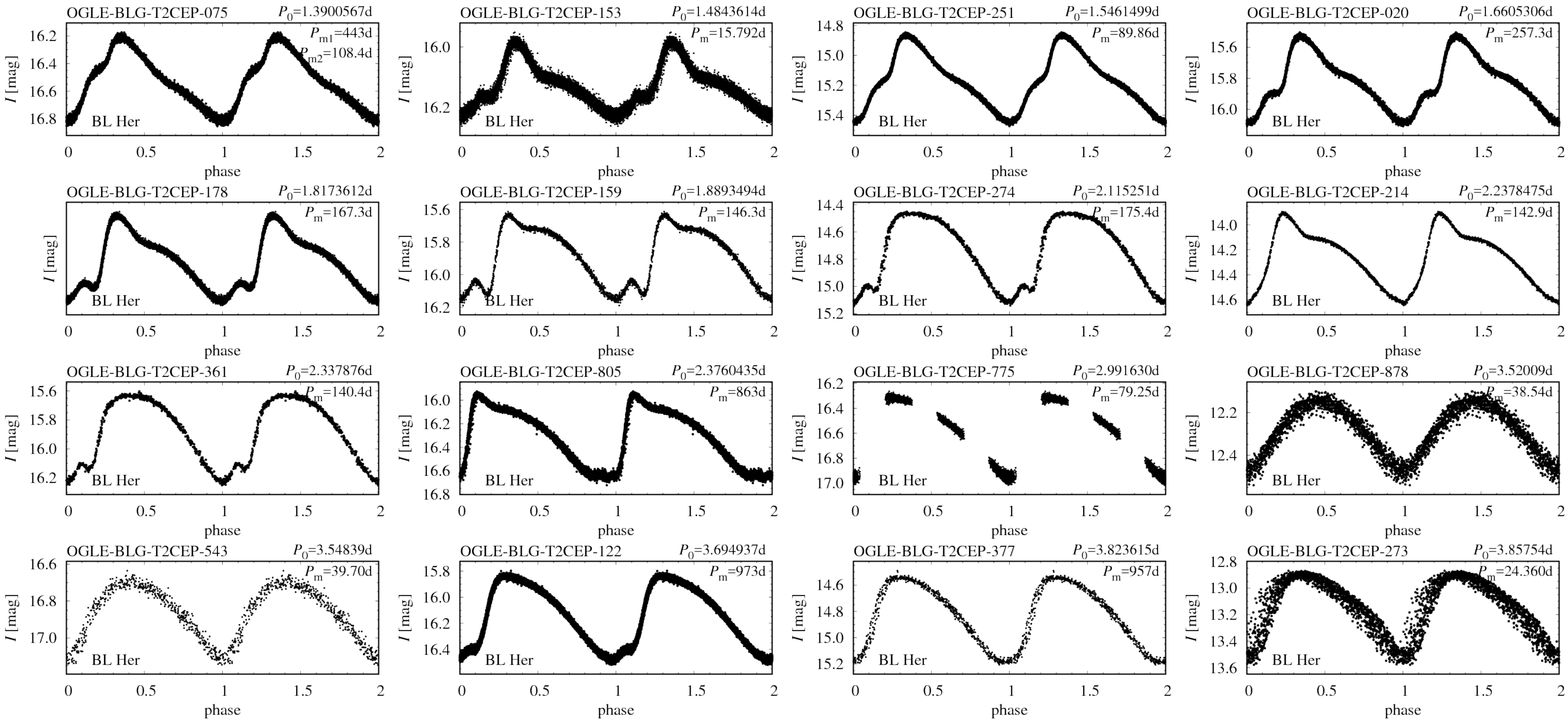
- ⋆ low-amplitude modulations detected based on analysis of the frequency spectra
- ⋆ modulation in 16 BL Her (4 %), 9 W Vir (2.5 %) and in 7 RV Tau stars (5 %)
- ⋆ mean brightness modulation is common





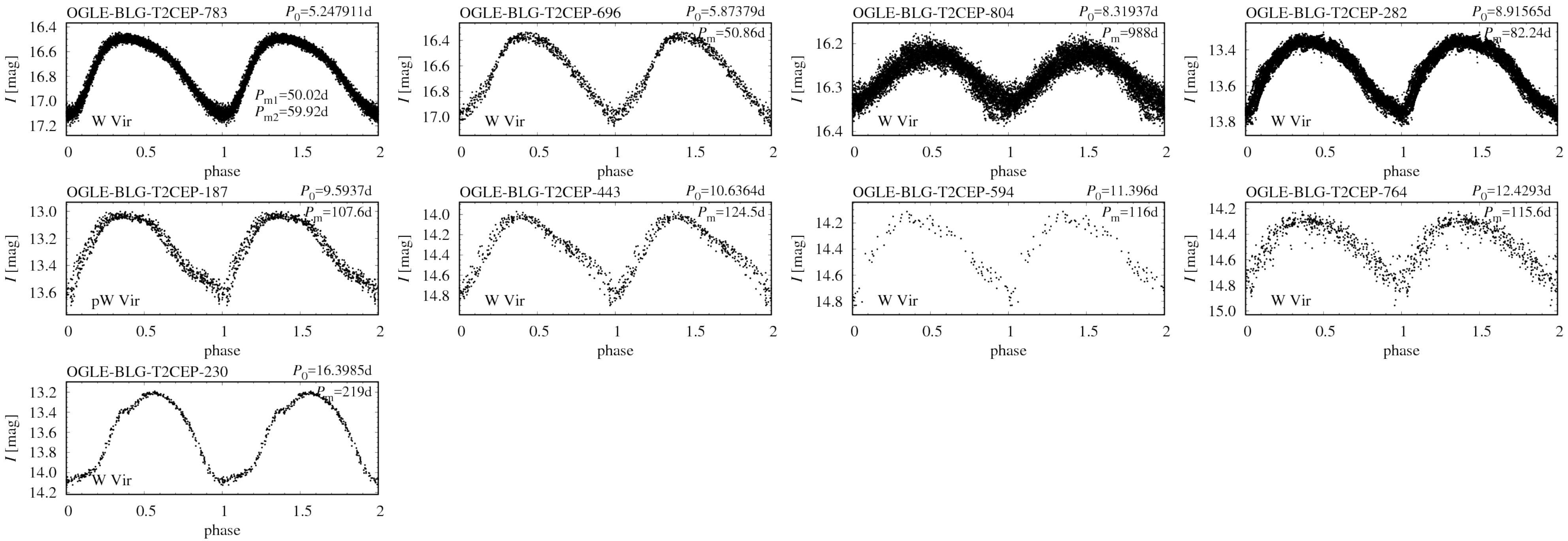
Smolec et al. (2018), *MNRAS*, submitted

Modulation in type II Cepheids: BL Her stars



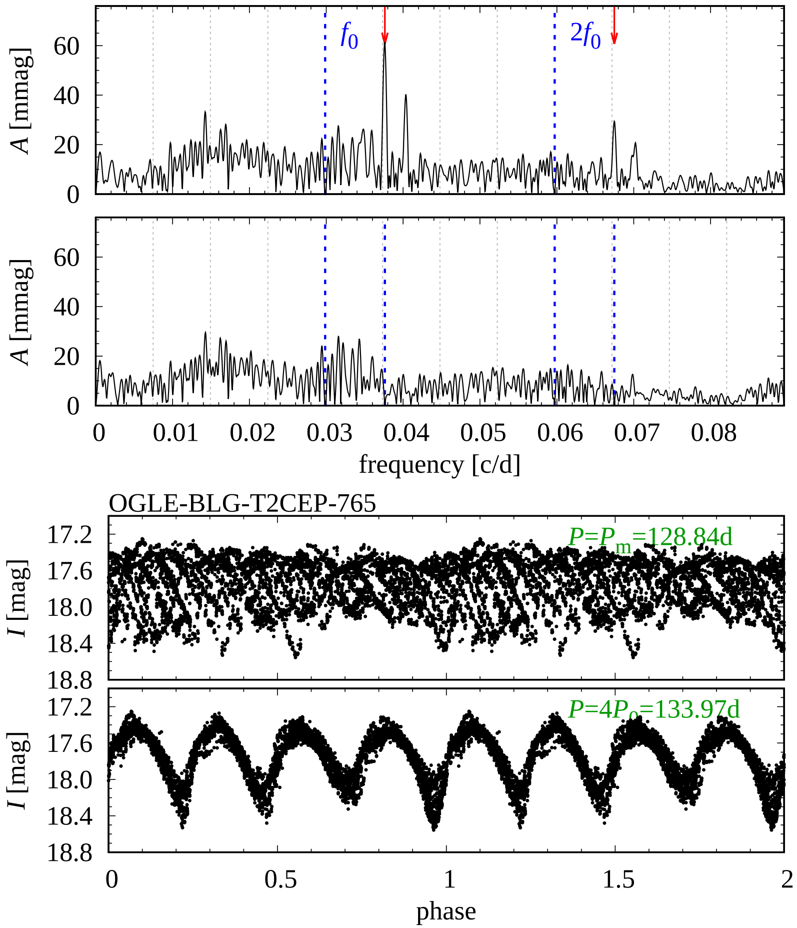
Smolec et al. (2018), *MNRAS*, submitted

Modulation in type II Cepheids: W Vir stars



Smolec et al. (2018), *MNRAS*, submitted

Modulation in type II Cepheids: RV Tau stars

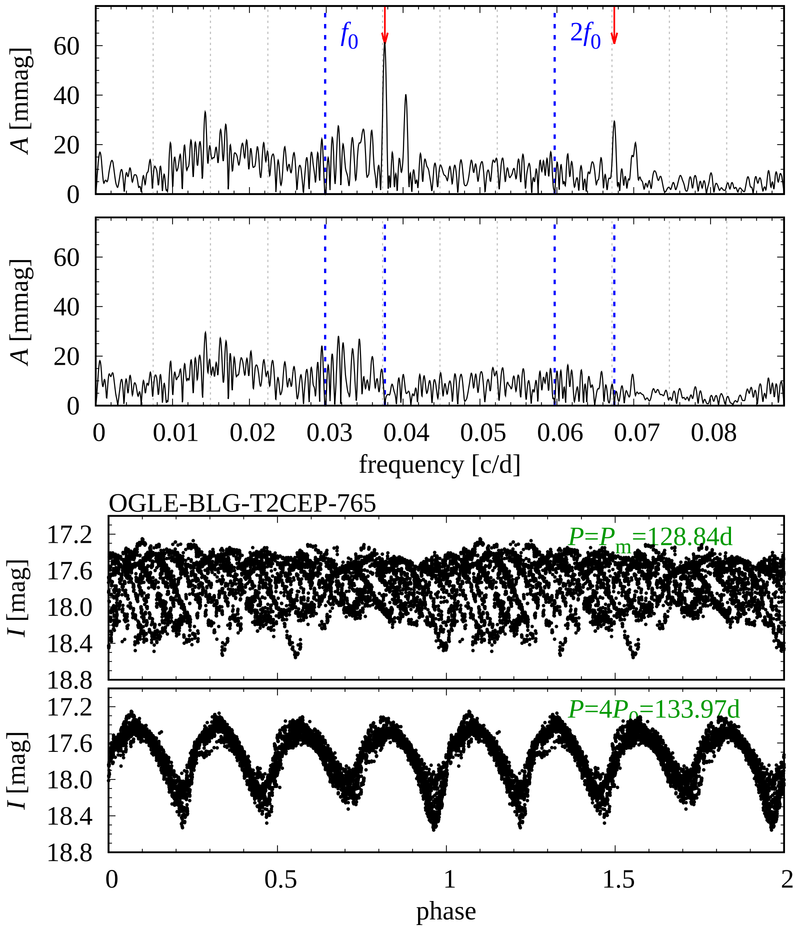


Smolec et al. (2018), *MNRAS*, submitted

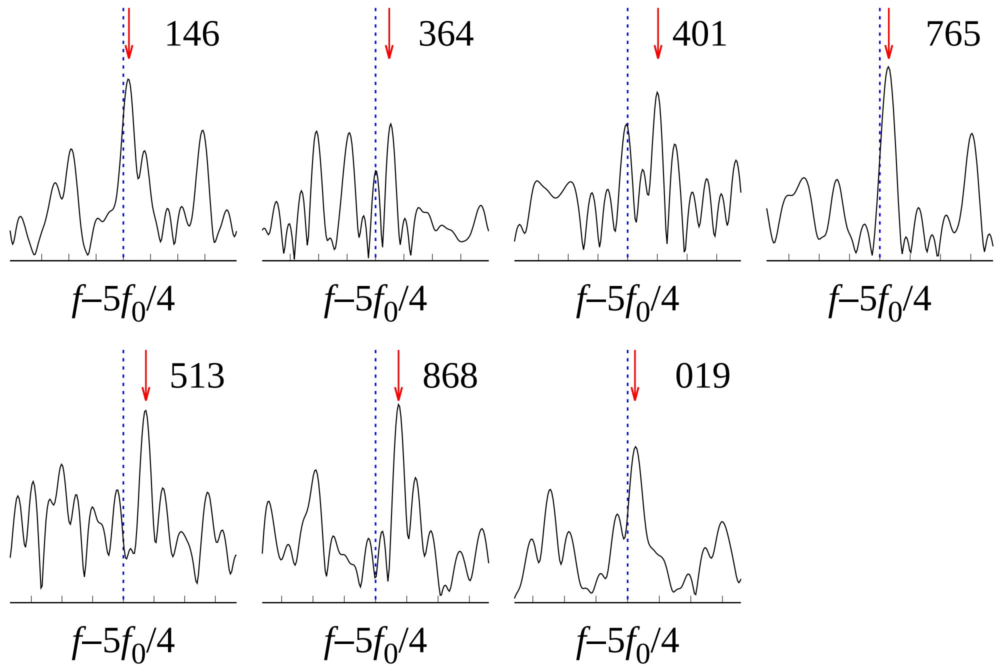
⋆ a family of modulation peaks close to harmonics of $f_0/4$

⋆ the highest modulation peak at a frequency slightly larger than $5f_0/4$

Modulation in type II Cepheids: RV Tau stars

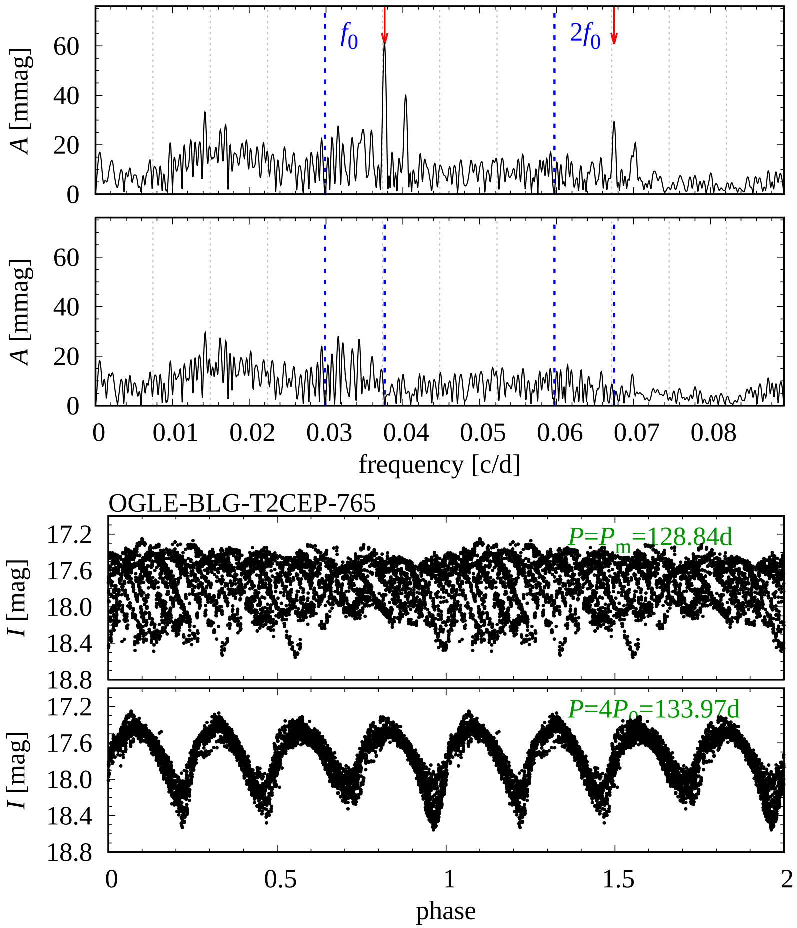


- ⋆ a family of modulation peaks close to harmonics of $f_0/4$
- ⋆ the highest modulation peak at a frequency slightly larger than $5f_0/4$
- ⋆ in all seven stars



Smolec et al. (2018), *MNRAS*, submitted

Modulation in type II Cepheids: RV Tau stars

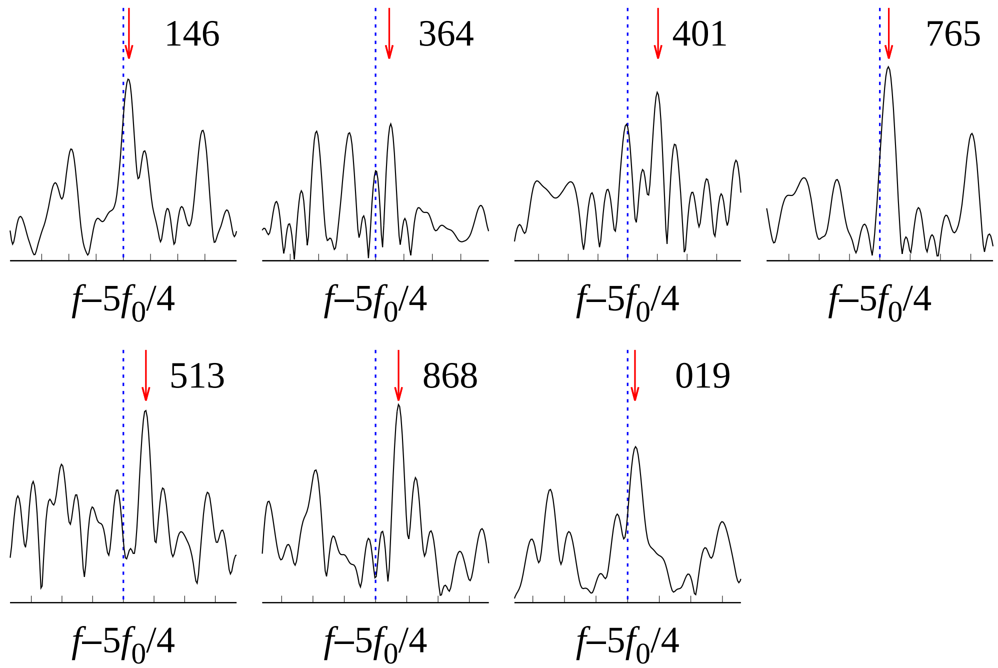


- ▸ modulation is most likely
- ▸ period-4 and non-radial modes are less likely

⋆ a family of modulation peaks close to harmonics of $f_0/4$

⋆ the highest modulation peak at a frequency slightly larger than $5f_0/4$

⋆ in all seven stars



Smolec et al. (2018), *MNRAS*, submitted

New perspectives on classical pulsators

- no longer purely radial
- non-radial pulsation might be common, at least in 1O stars
- low-amplitude additional periodicities are frequent in all groups of classical pulsators
- low-amplitude periodic modulations are frequent in all groups of classical pulsators
- most of the above phenomena lack satisfactory theoretical explanation