

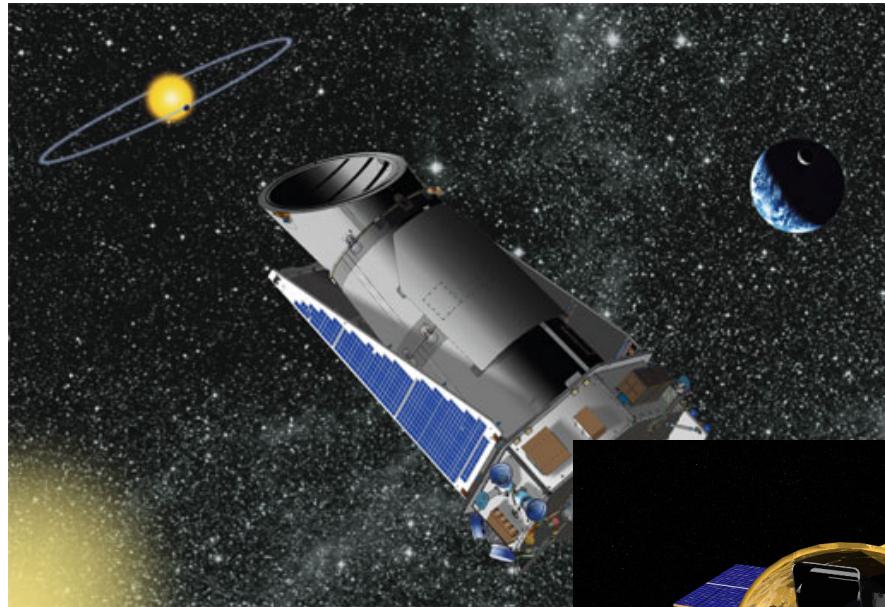
OGLE view on pulsating stars

Radek Smolec

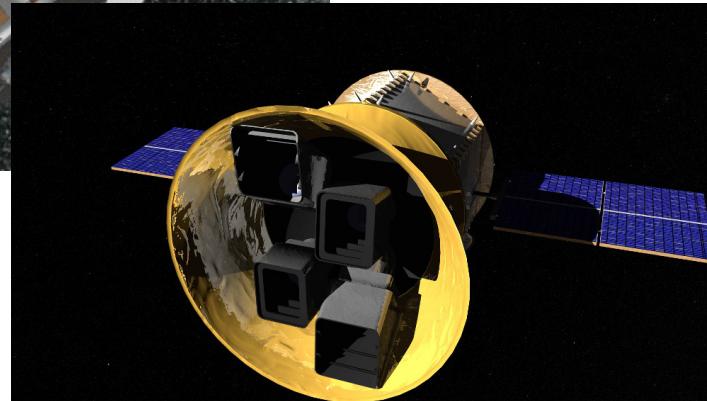
Nicolaus Copernicus Astronomical Center, Warsaw



Pulsating stars: space revolution?



$\sim 10^2 - 10^3$
classical pulsators

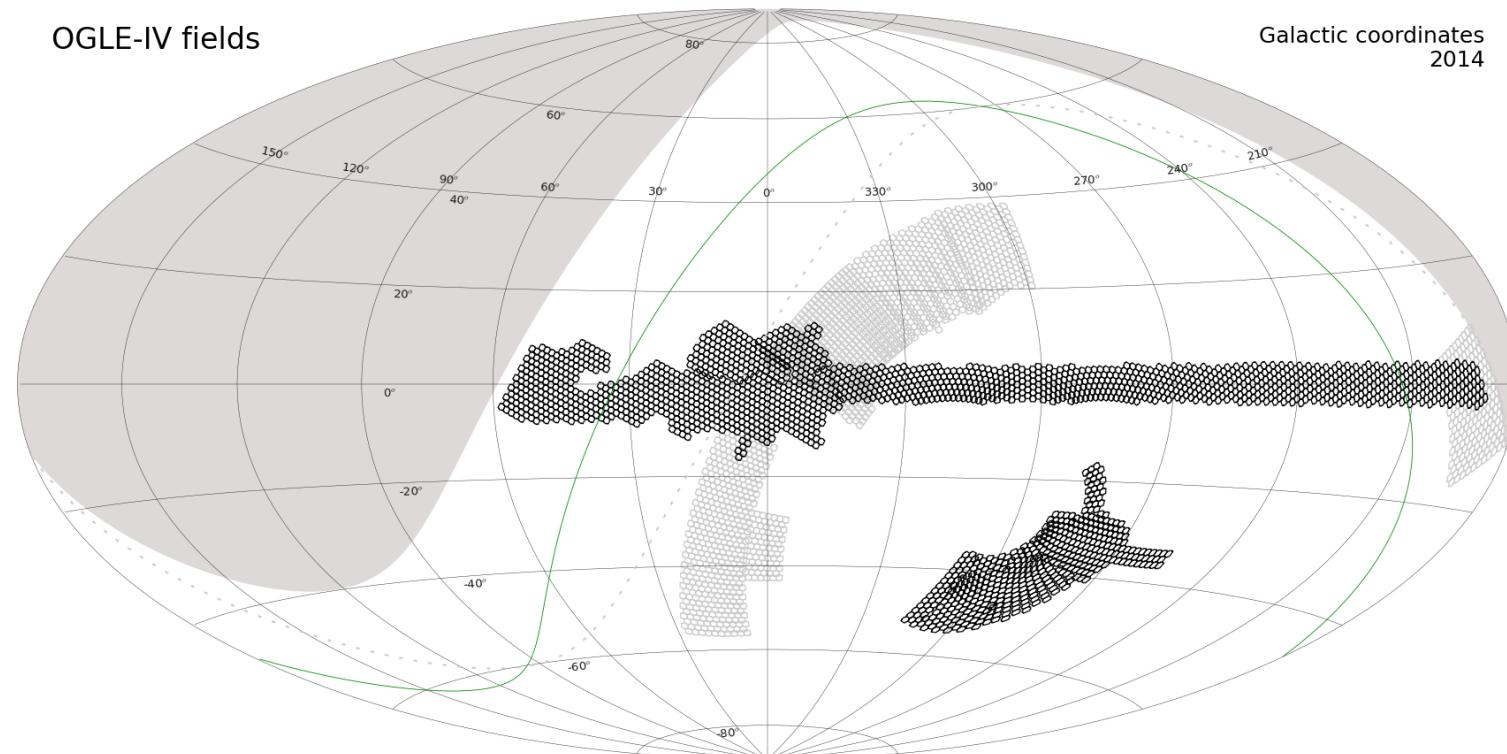


$\sim 10^5$ classical pulsators

- ▶ **Space telescopes** revolutionised asteroseismology, except for...
- ▶ ...classical pulsators, where revolution is thanks to **ground-based OGLE project**
- ▶ **long-term, precise photometry** for **tens of thousands** of classical pulsators



Classical pulsators in the OGLE collection



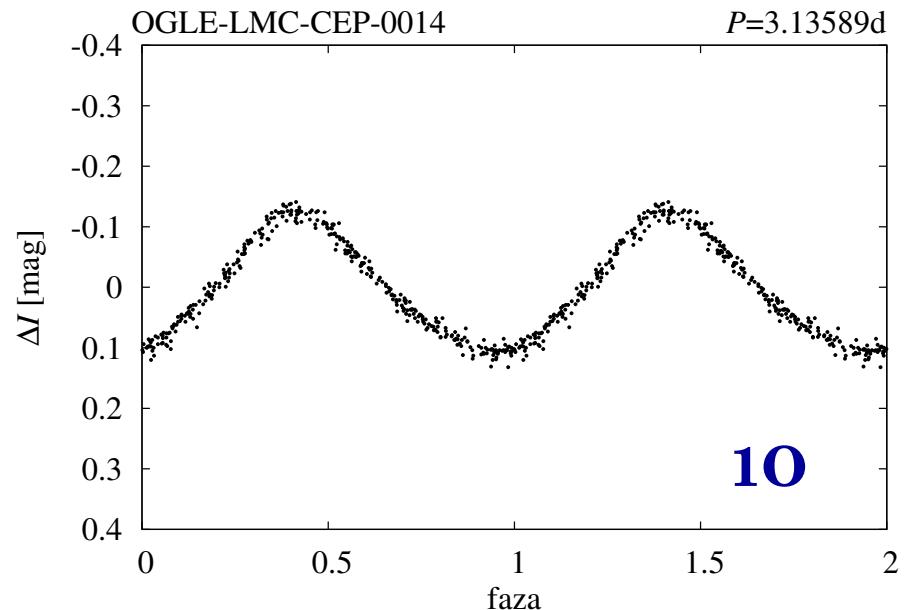
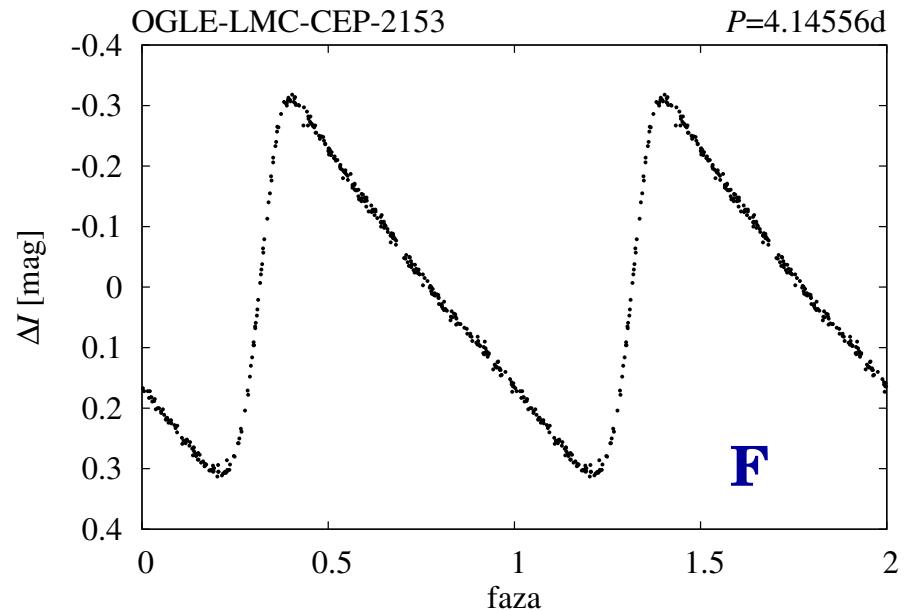
	Cep	RR Lyr	t2Cep
LMC	4 706	41 116	290
SMC	4 944	6 712	53
blg	155	39 074	1 068
gd	1 359		170

fig.: <http://ogle.astrow.u.edu.pl/>



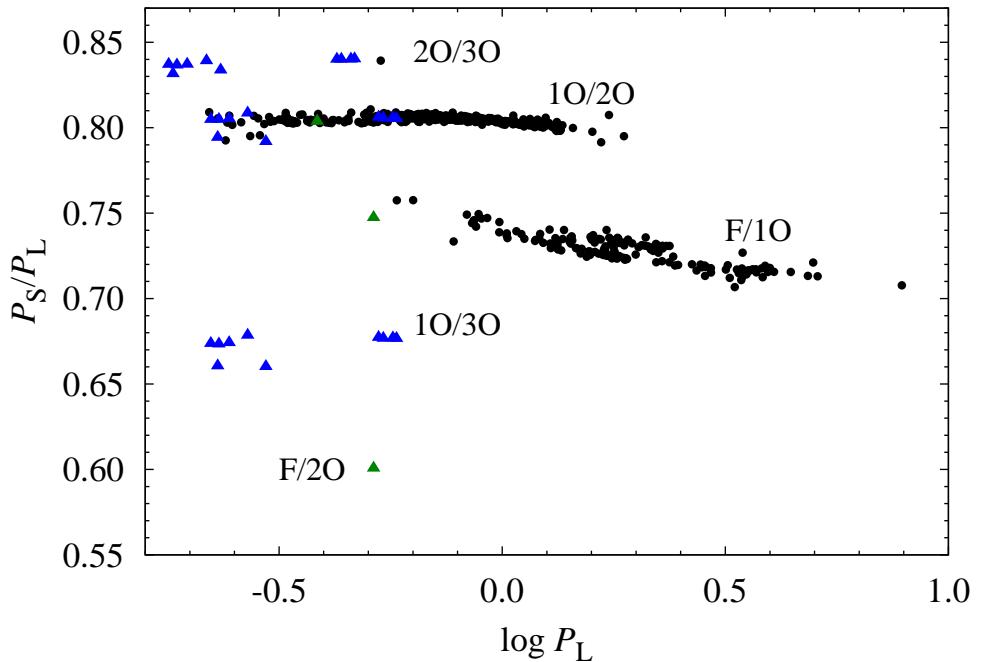
Classical Cepheids

- ▶ radial pulsation modes
- ▶ non-radial pulsation modes
- ▶ modulations: 1O+2O
- ▶ modulations: F-mode
- ▶ physical parameters



Classical Cepheids

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* *radial mode inventory (OGLE):*

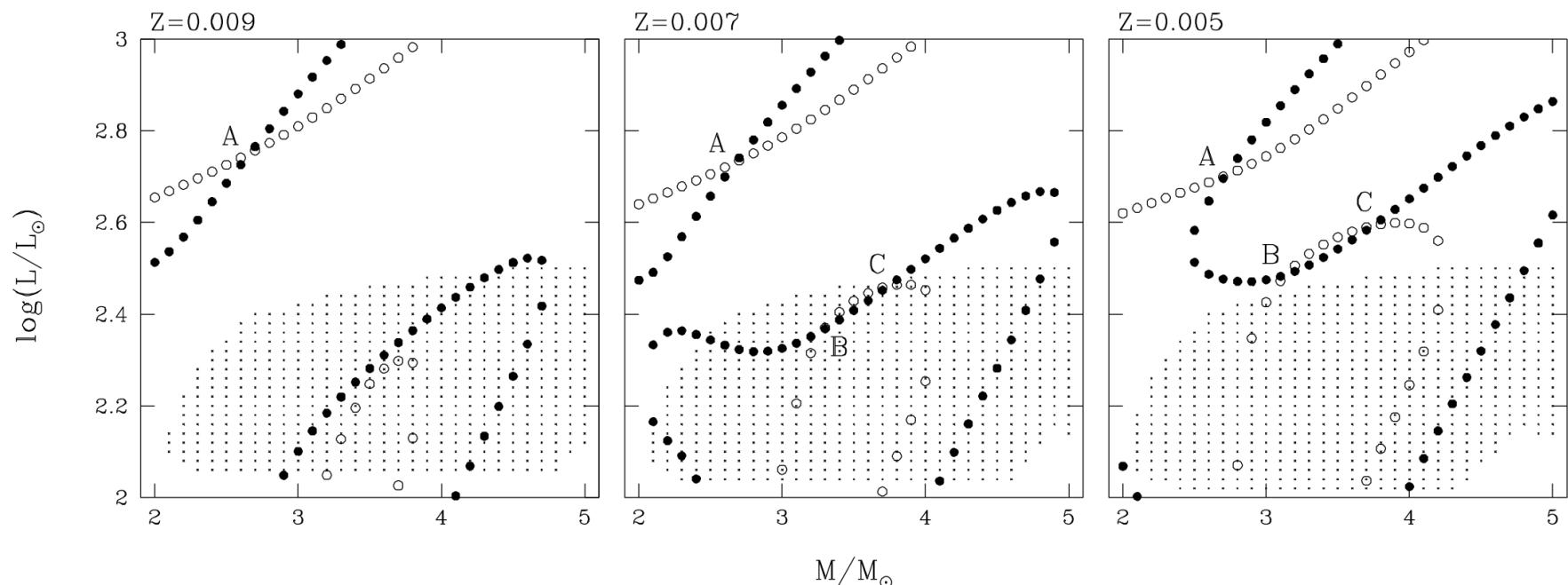
- ▶ double-mode: F+1O, 1O+2O (hundreds)
- ▶ double-mode, *unique*: 1O+3O (1); 2O+3O (1)
- ▶ triple-mode: F+1O+2O (1), 1O+2O+3O (9)
- ▶ quadruple-mode: F+1O+2O+3O (1)



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Three-mode asteroseismology



Moskalik & Dziembowski (2005), *A&A*



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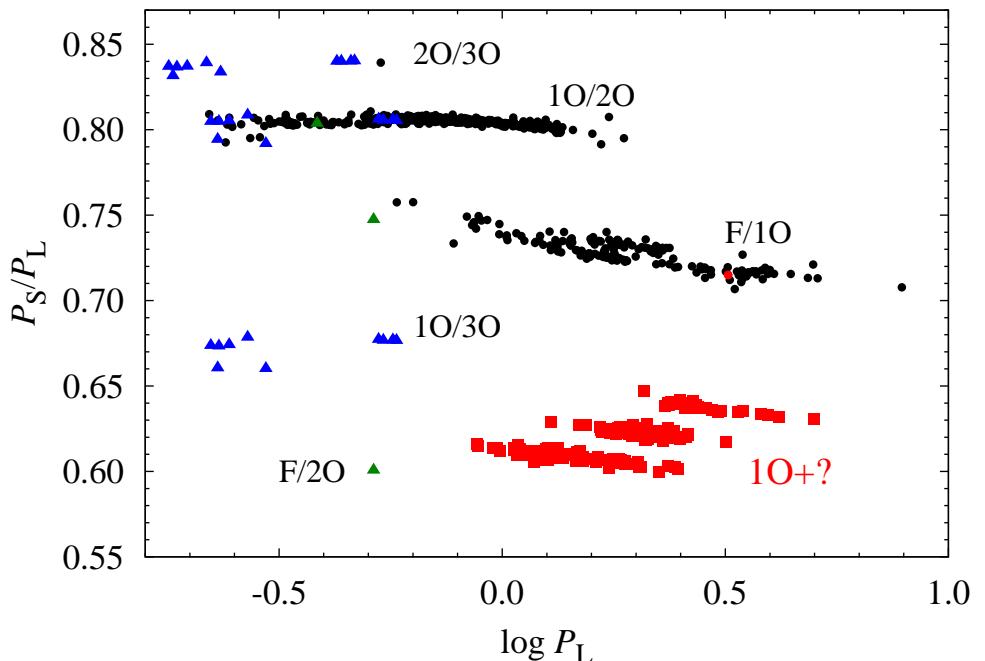
1O+?: > 300 stars

Soszyński et al. (2008,-10,-15)

Moskalik & Kołaczkowski (2009)

Pietrukowicz et al. (2009)

detailed analysis in
Smolec & Śniegowska (2016)

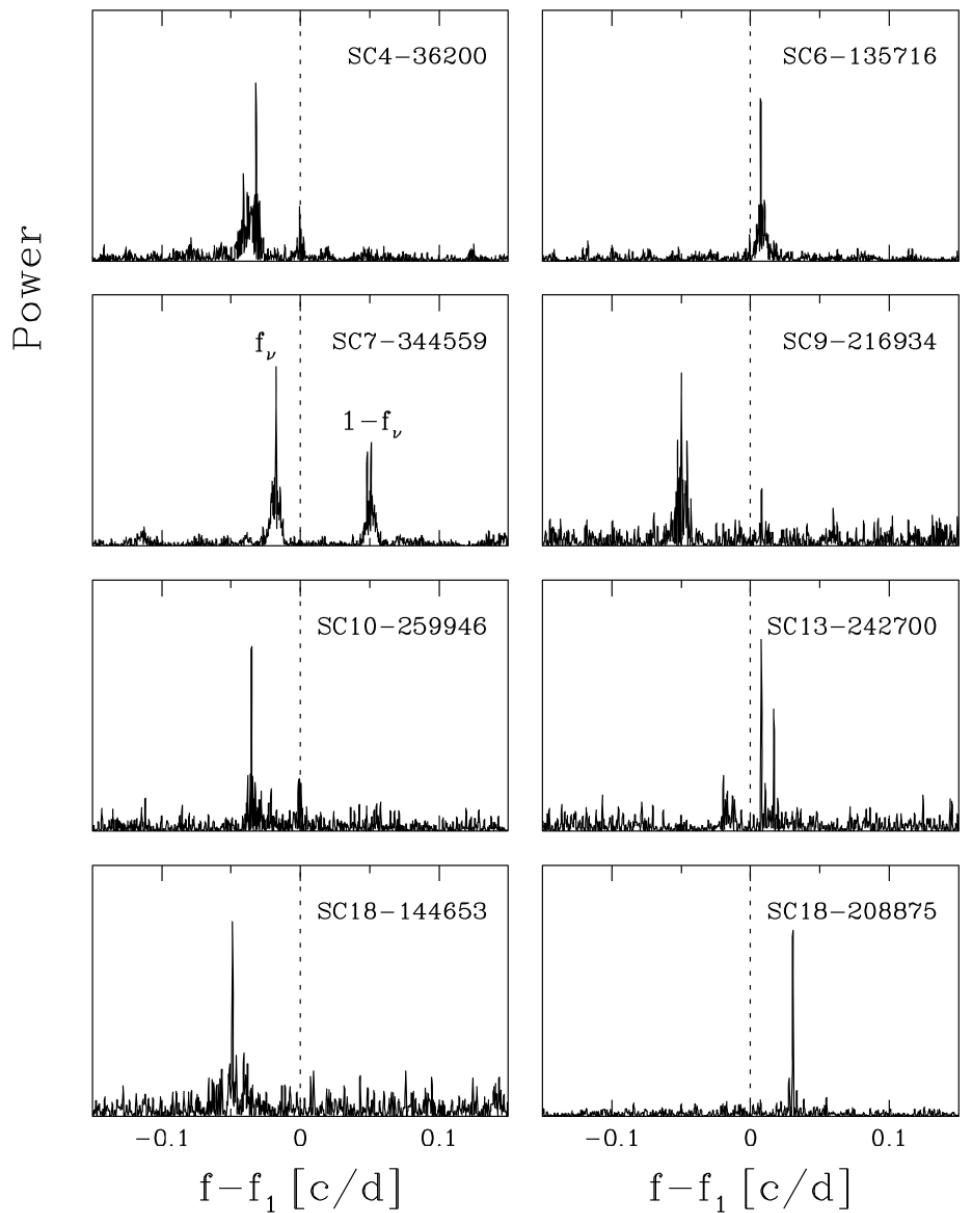


Classical Cepheids

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Additional periodicities close to 1O frequency

⇒ most likely non-radial modes



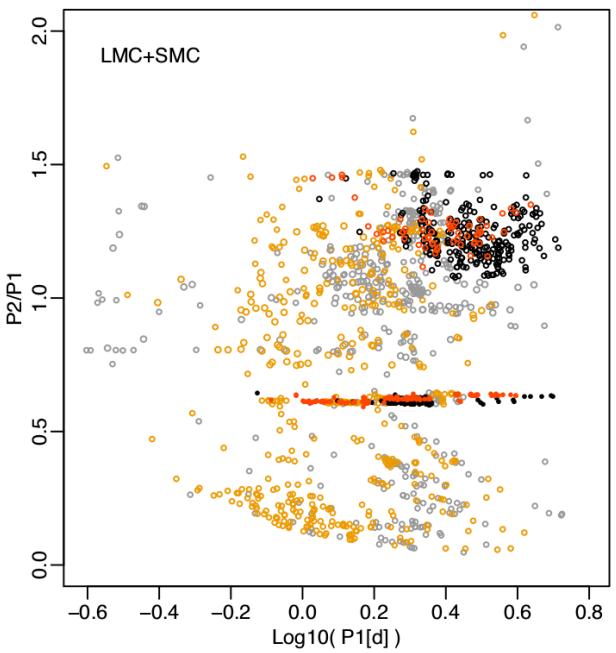
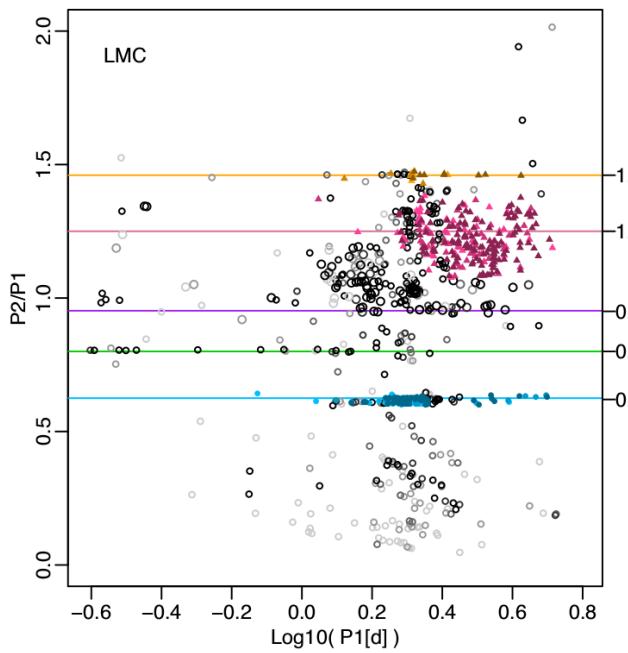
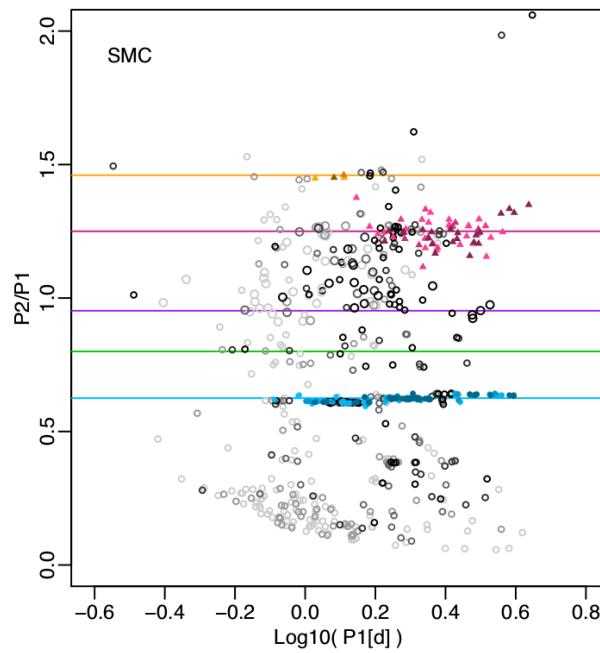
Moskalik & Kołaczkowski (2009), MNRAS



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A few classes of additional periodicities



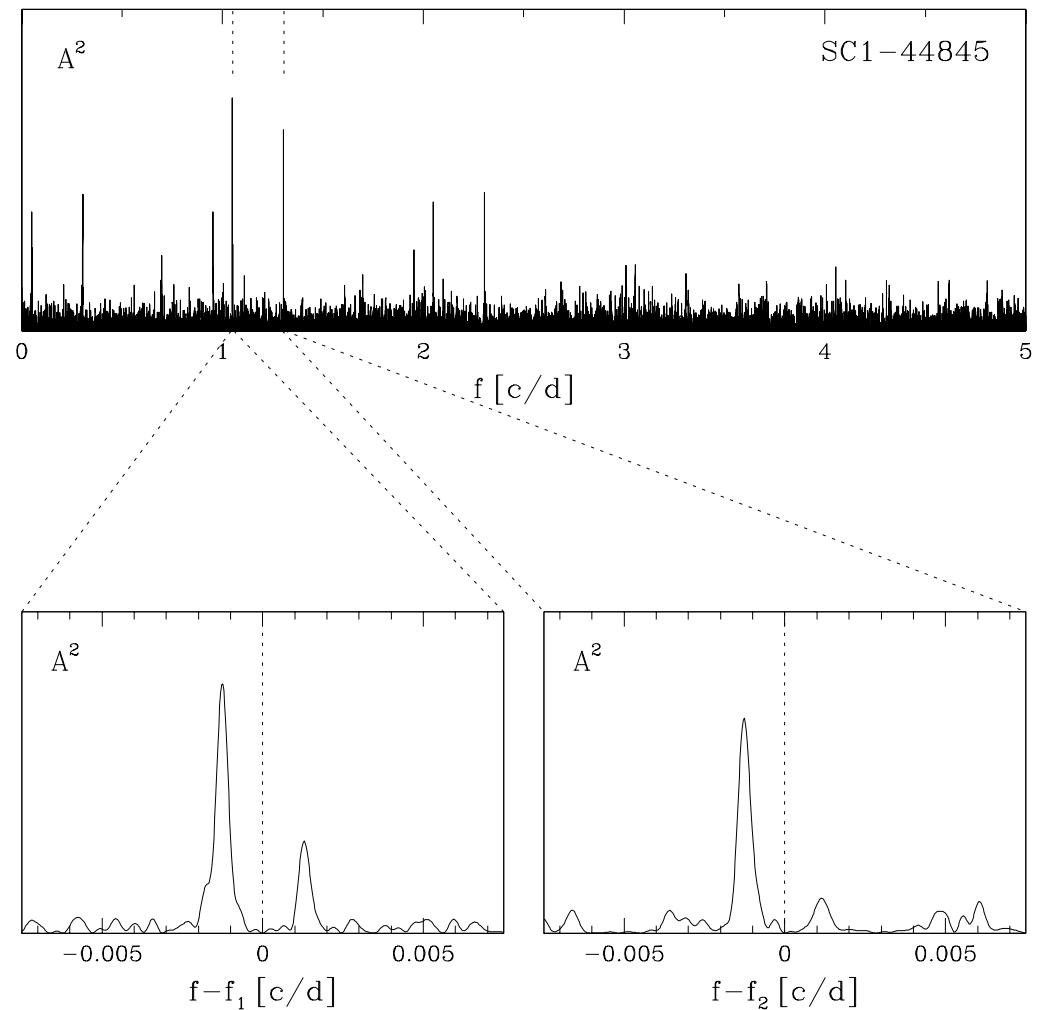
Süveges & Anderson (2018), MNRAS



Classical Cepheids

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- ★ long-period modulation in 1O+2O Cepheids
- ★ both 1O and 2O are modulated
- ★ anticorrelated amplitudes



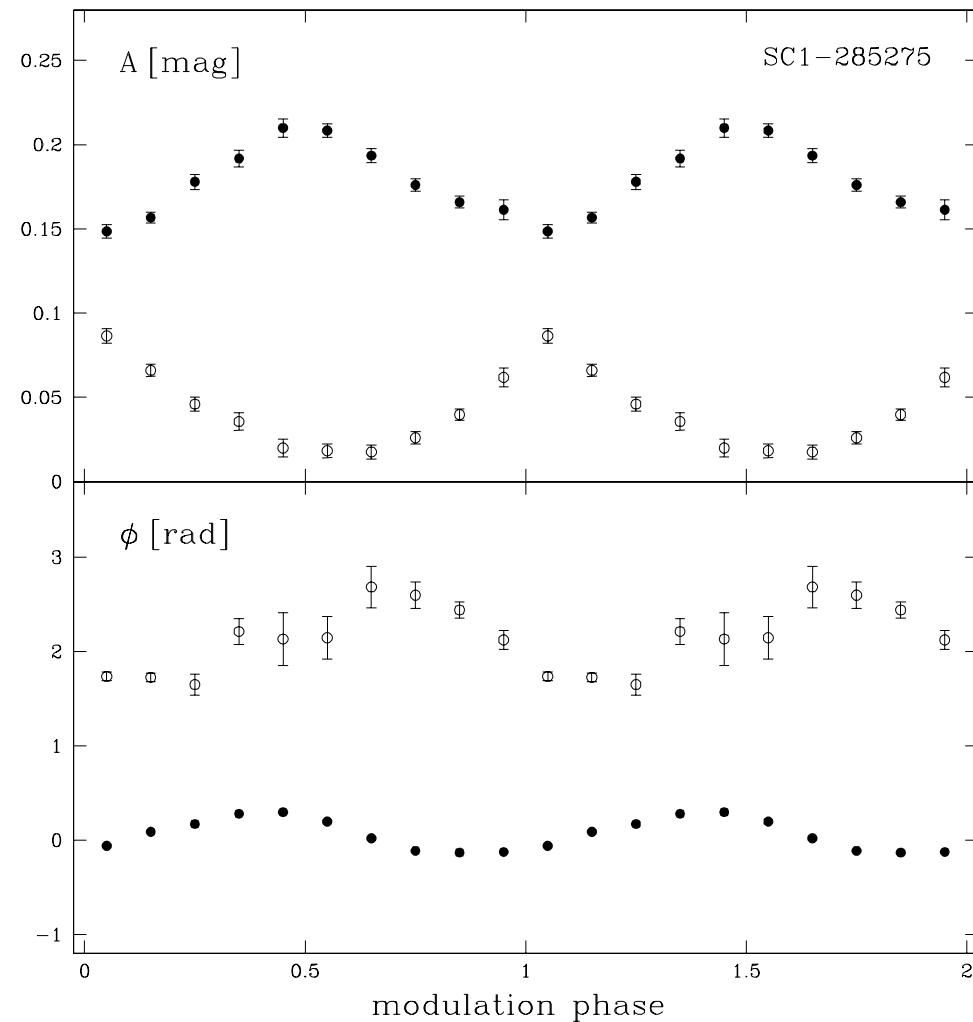
Moskalik & Kołaczkowski (2009), MNRAS



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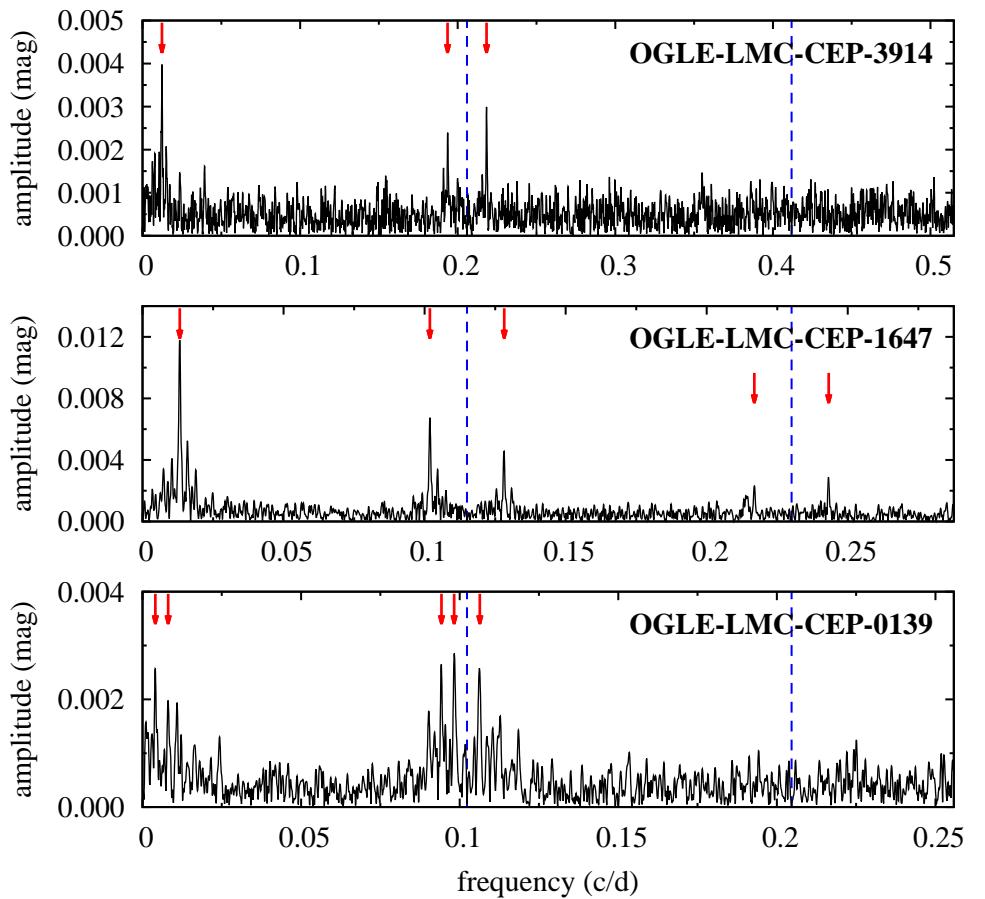


Moskalik & Kołaczkowski (2009), MNRAS



Classical Cepheids

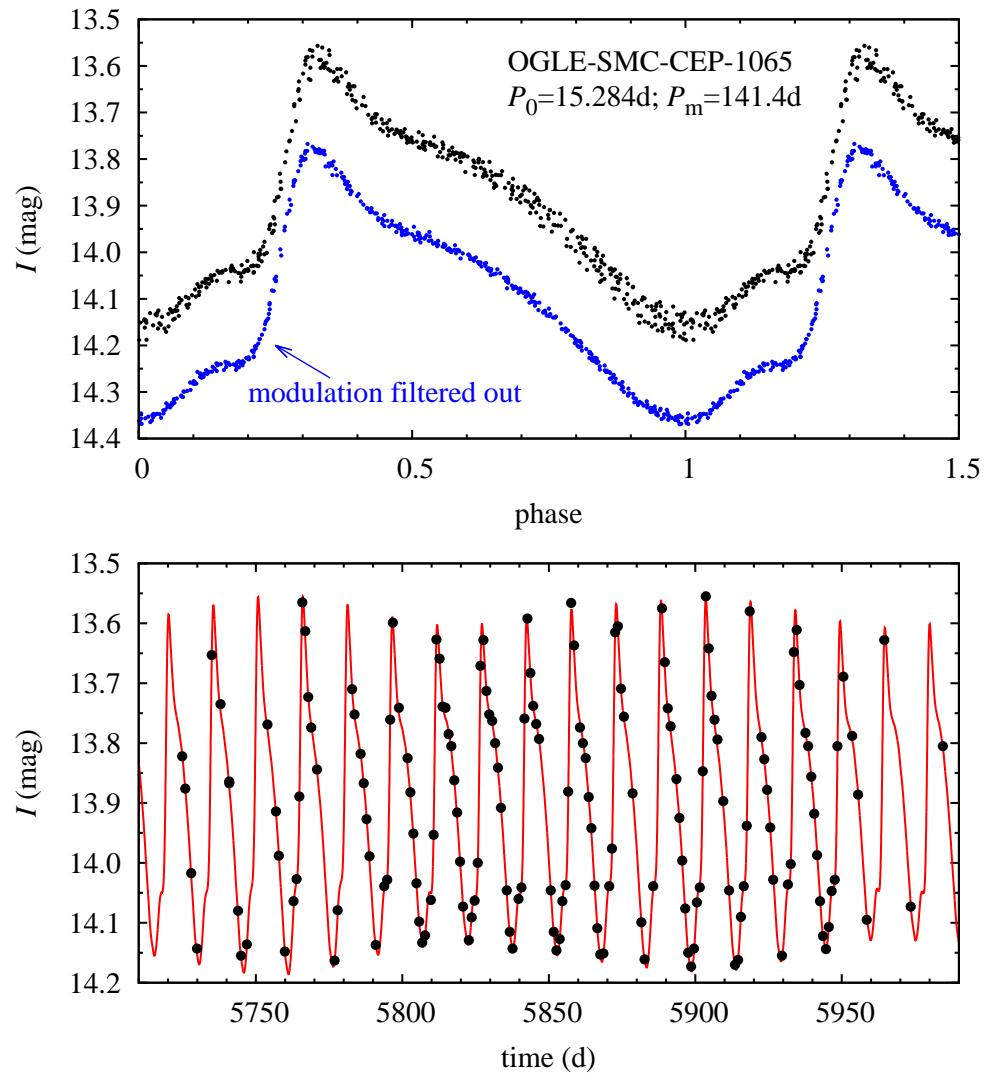
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 - ▶ physical parameters
- ★ up to 10 mmag effect
- ★ modulation period $\sim 10 \times P_0$
- ★ the effect may be common
- ★ mean brightness modulation



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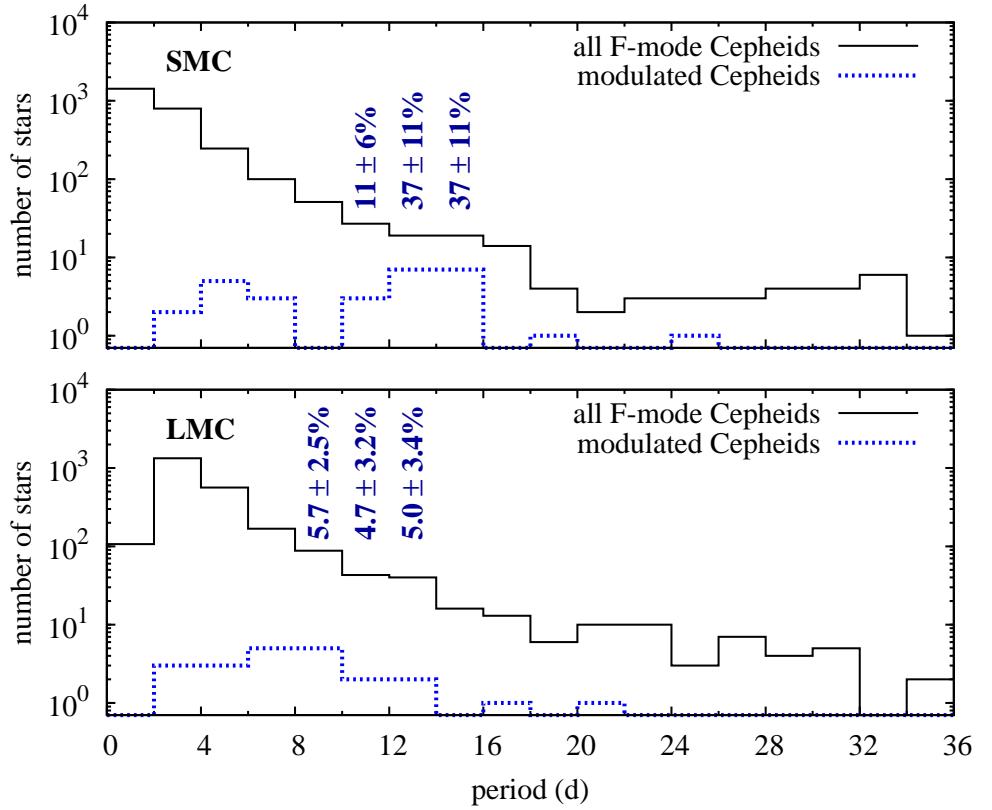
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Classical Cepheids

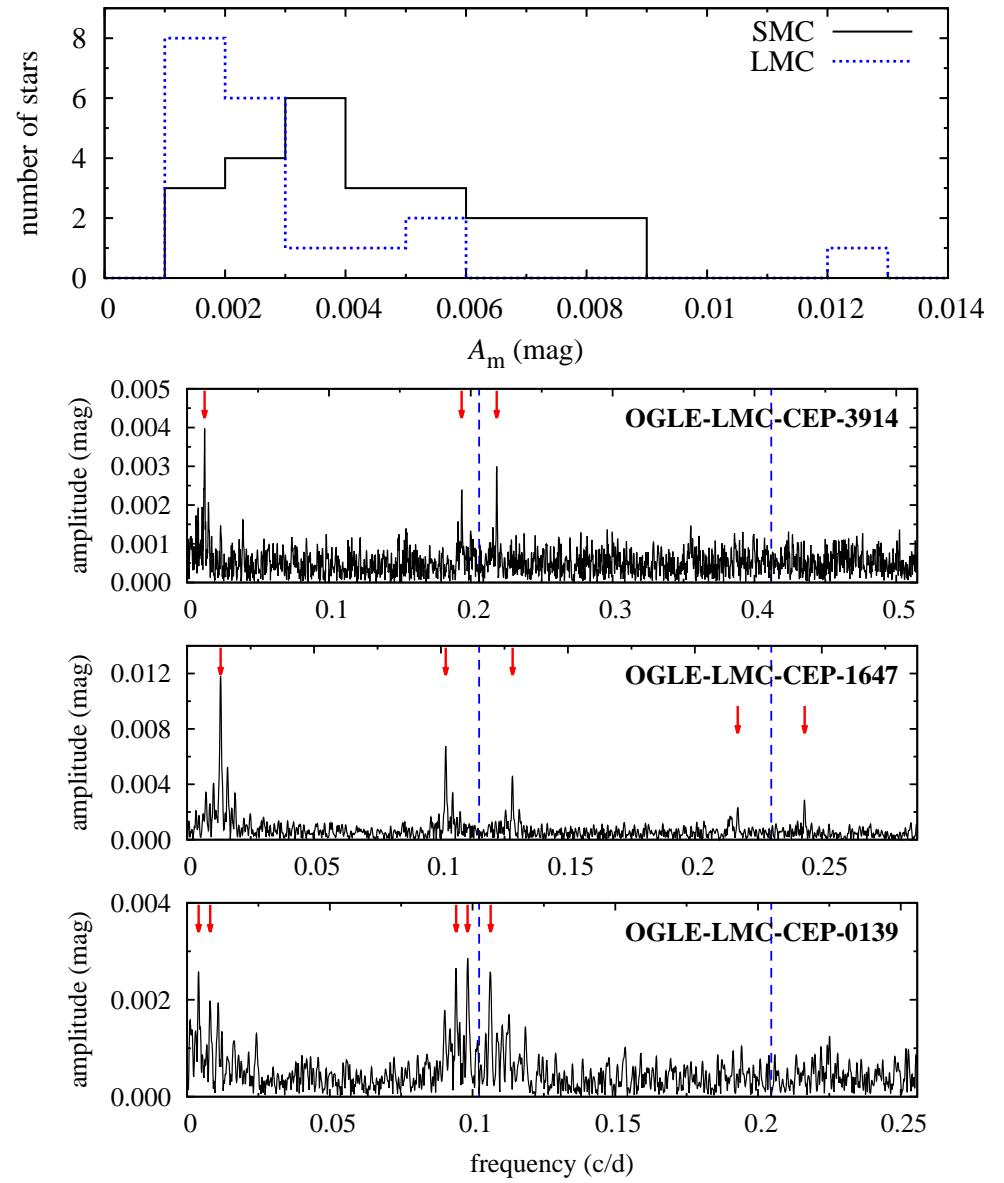
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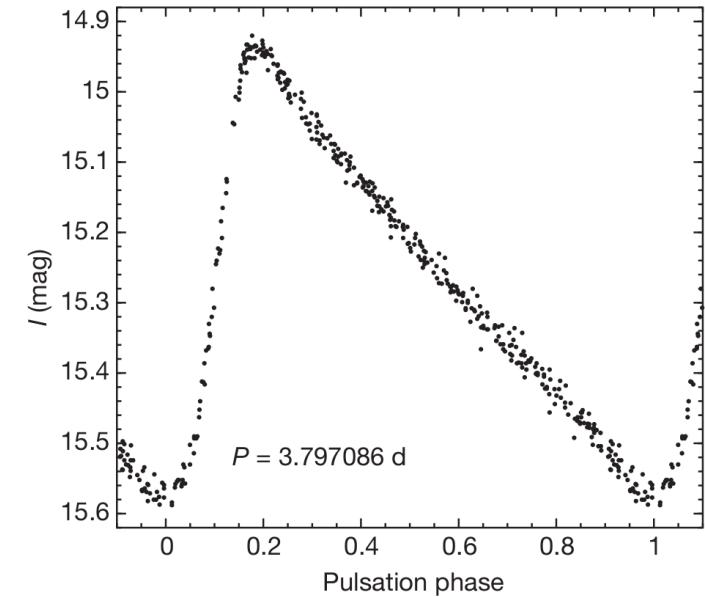
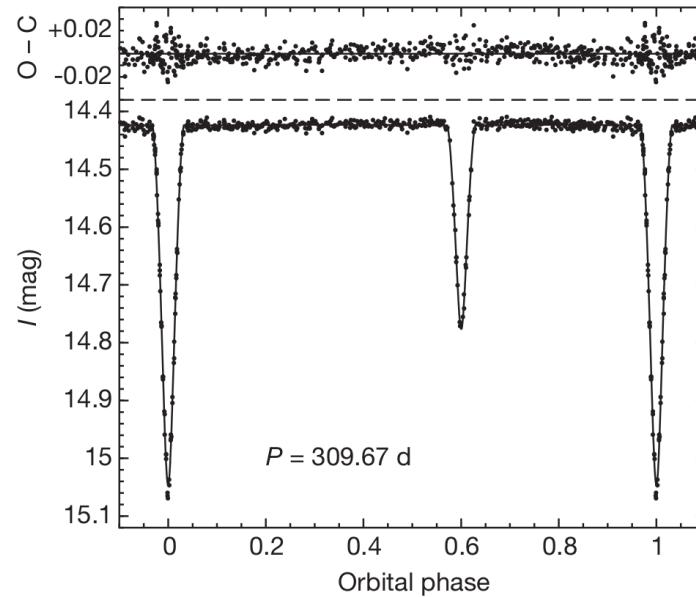
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OGLE-LMC-CEP-227 – first dynamical mass
pulsation theory is correct

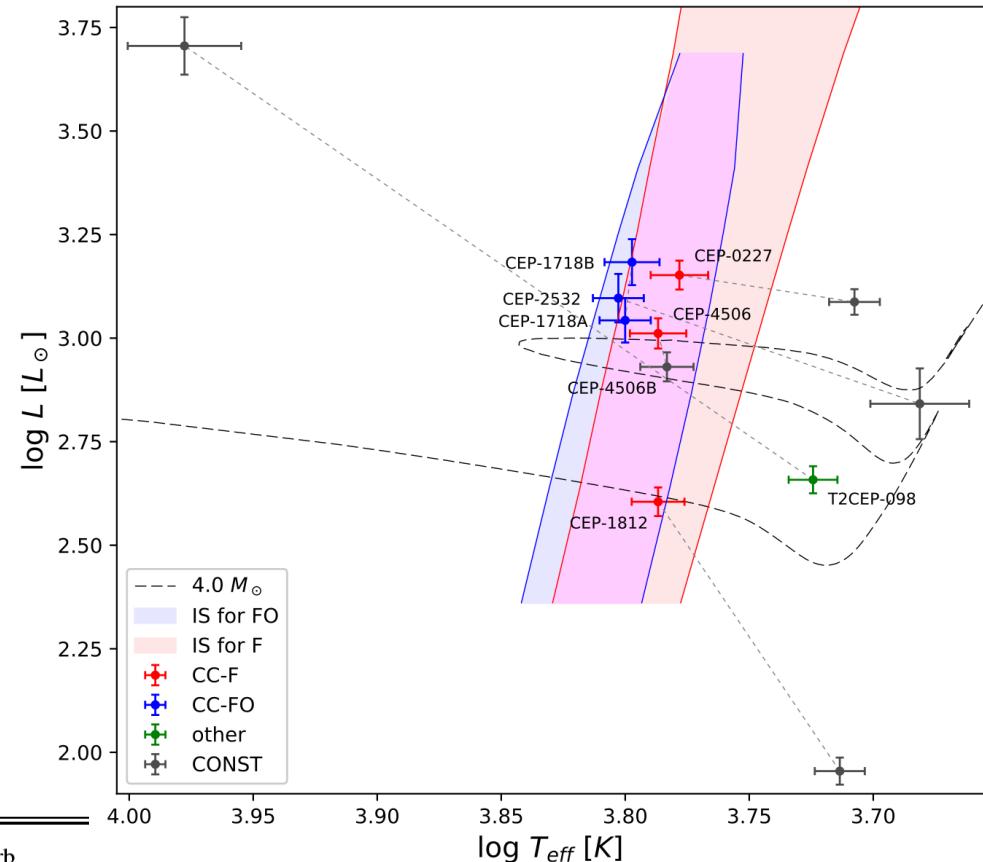


Pietrzynski et al. (2010), *Nature*



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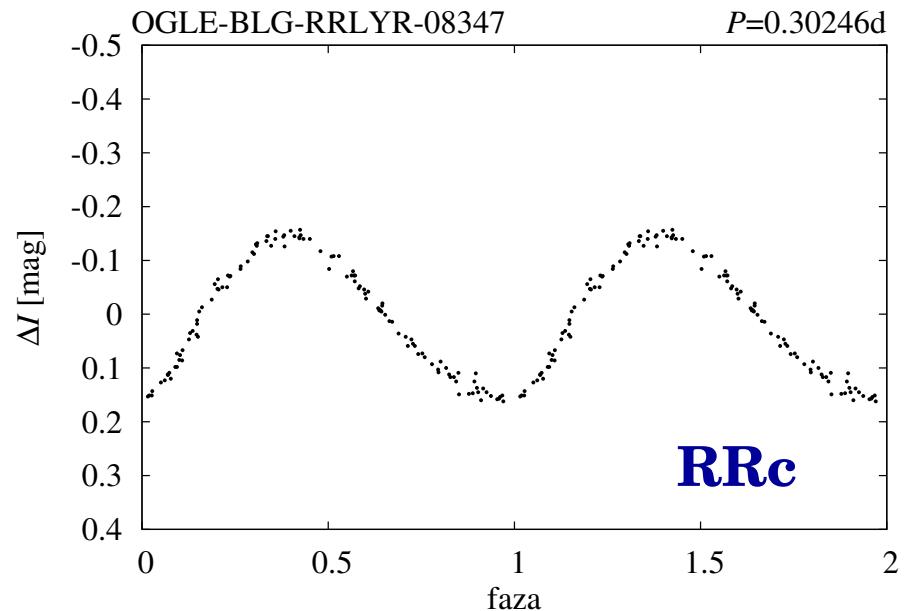
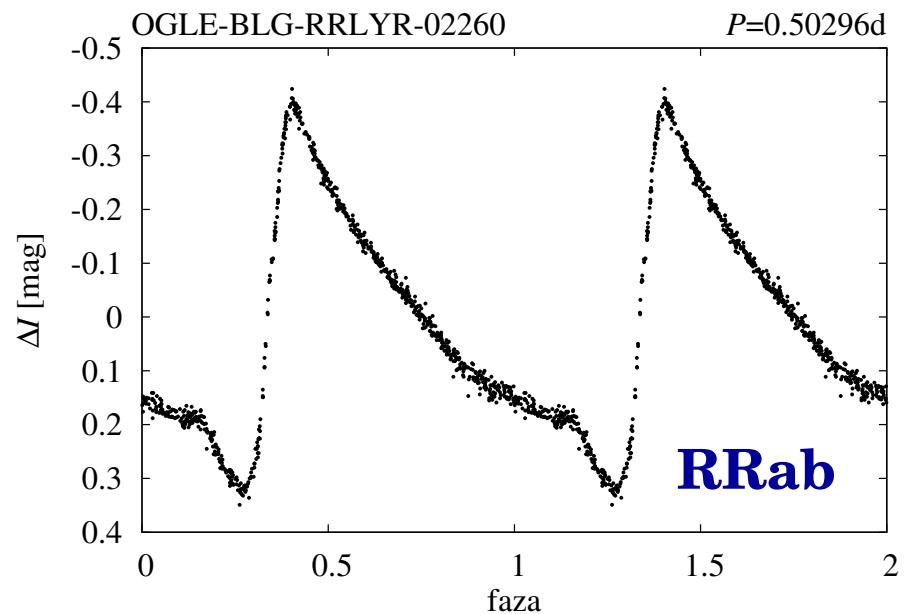
Object	Mode	P_{puls}	P_{orb}
OGLE ID		(days)	(days)
LMC-CEP-1718 ^a	FO+FO	1.964+2.481	412.8
LMC-CEP-1812	F	1.313	551.8
LMC-CEP-0227	F	3.797	309.7
LMC-CEP-2532	FO	2.035	800.4
LMC-CEP-4506 ^b	F	2.988	1550
LMC-T2CEP-098 ^c	F	4.973	397.2

Pilecki et al. (2018), *ApJ*



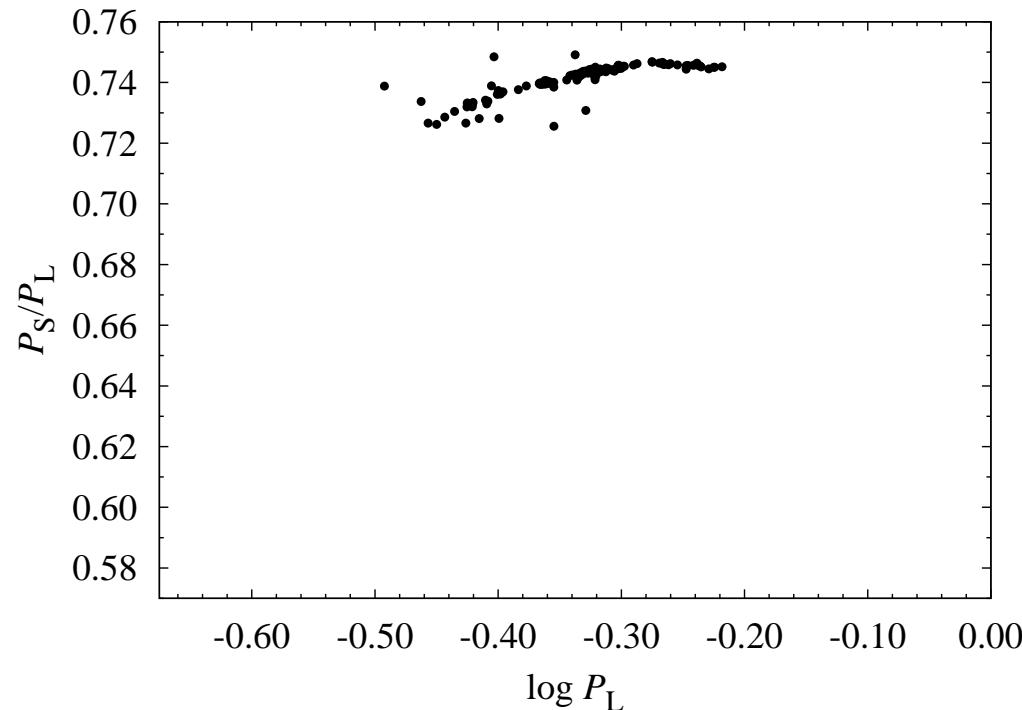
RR Lyrae stars

- ▶ radial pulsation modes
- ▶ non-radial pulsation modes
- ▶ additional periodicities
- ▶ mode switching
- ▶ modulations



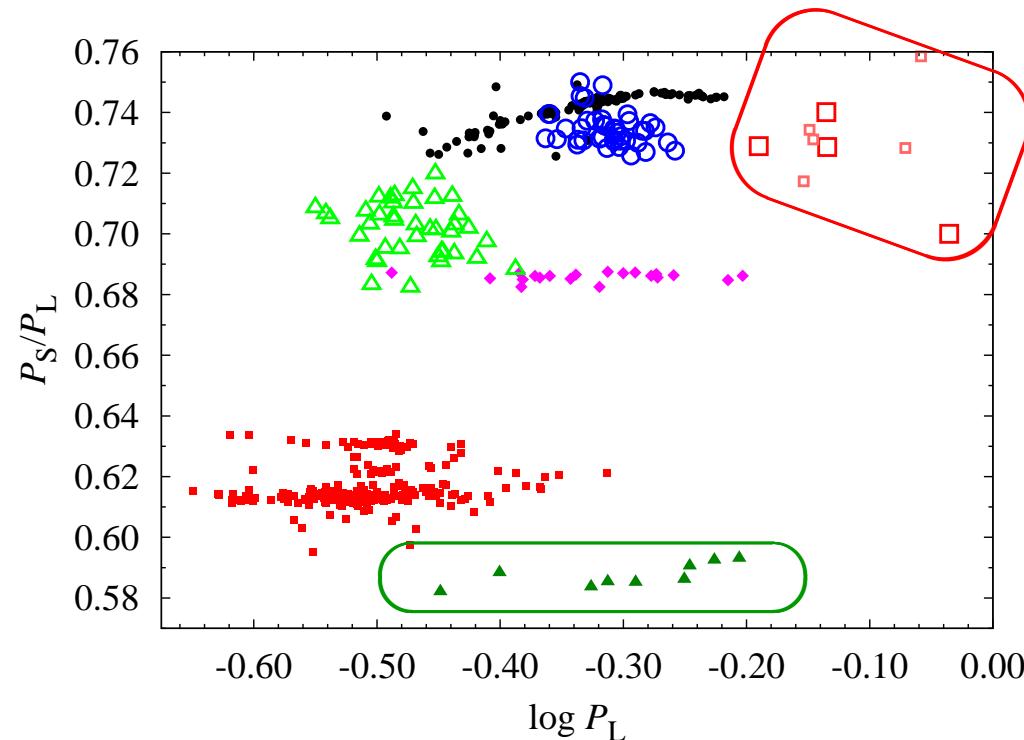
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RR Lyrae stars

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 - ▶ modulations
- * F+2O stars (mostly *Kepler*)
 - * extreme RRd stars, with dominant F

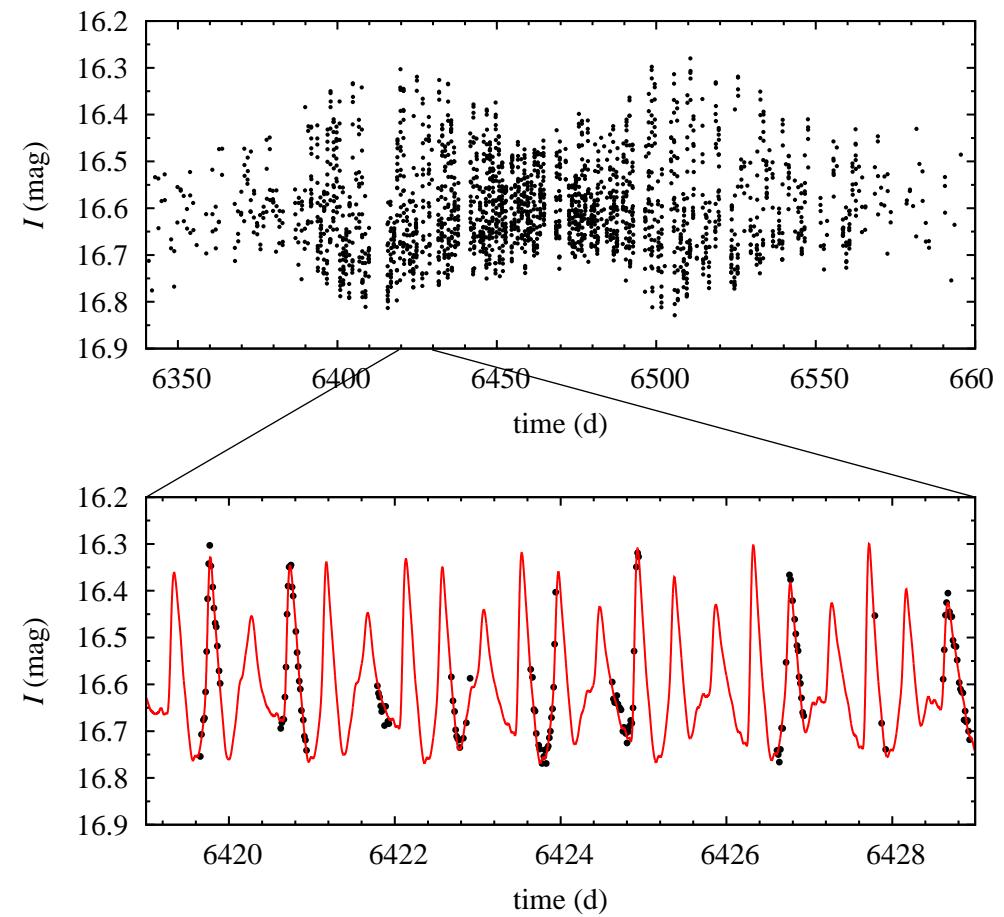
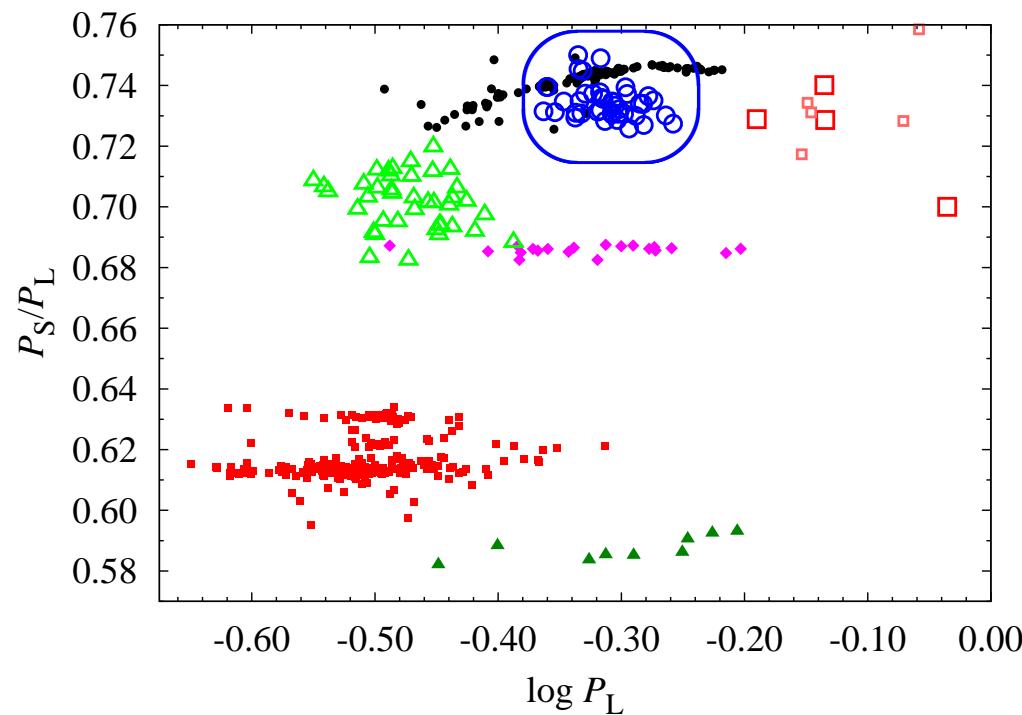


eg., Benkő et al (2010, 2014); Smolec et al. (2016)



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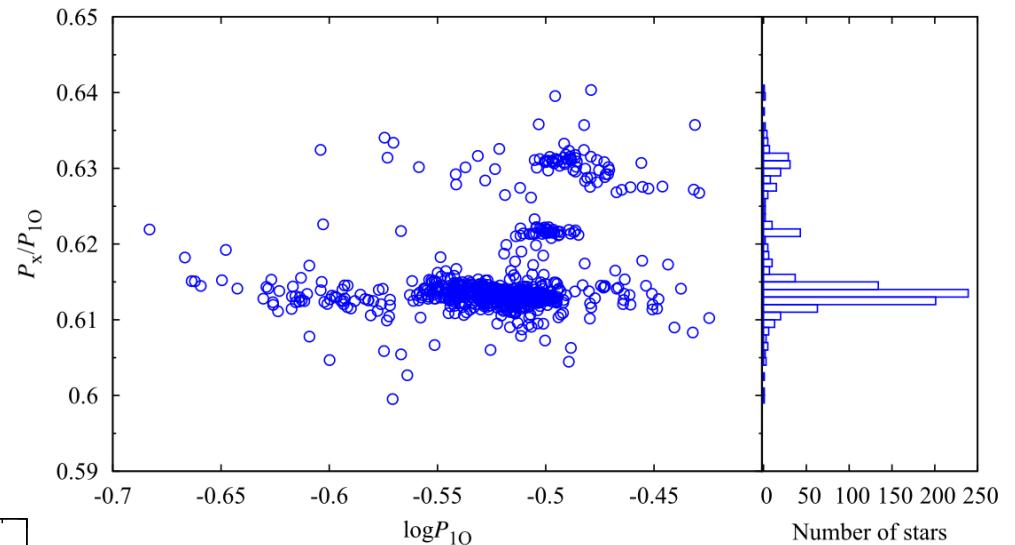
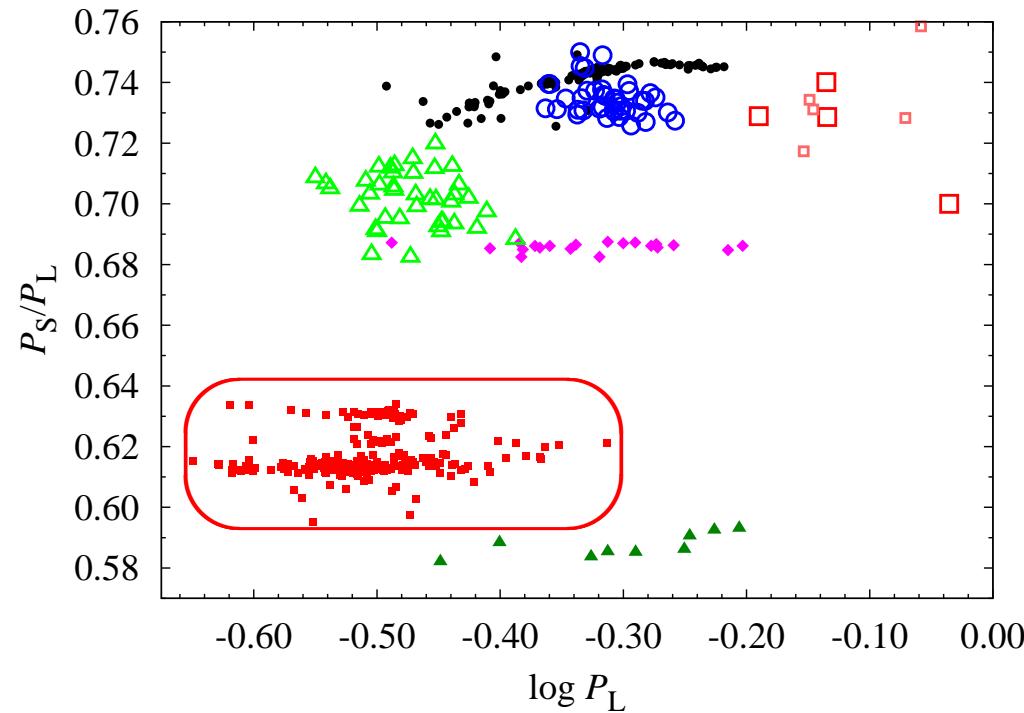
Anomalous RRd stars, with modulation

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



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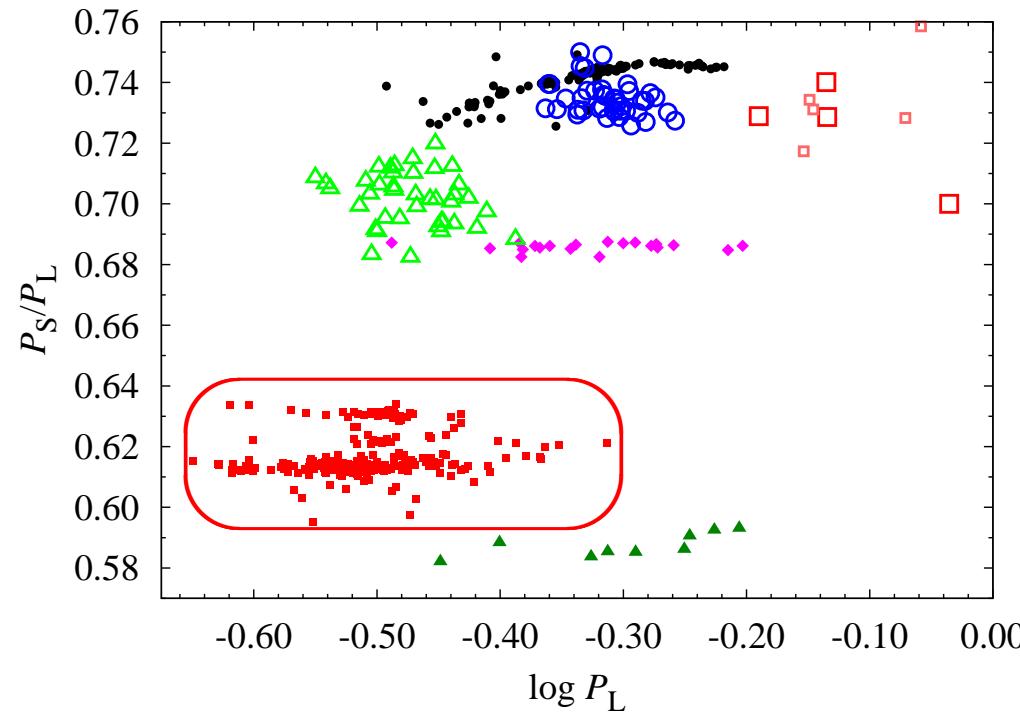
- ▶ 960 stars in OGLE blg collection
- ▶ the phenomenon must be common
- ▶ observed both in RRL and Cepheids

Netzel & Smolec (2019), MNRAS

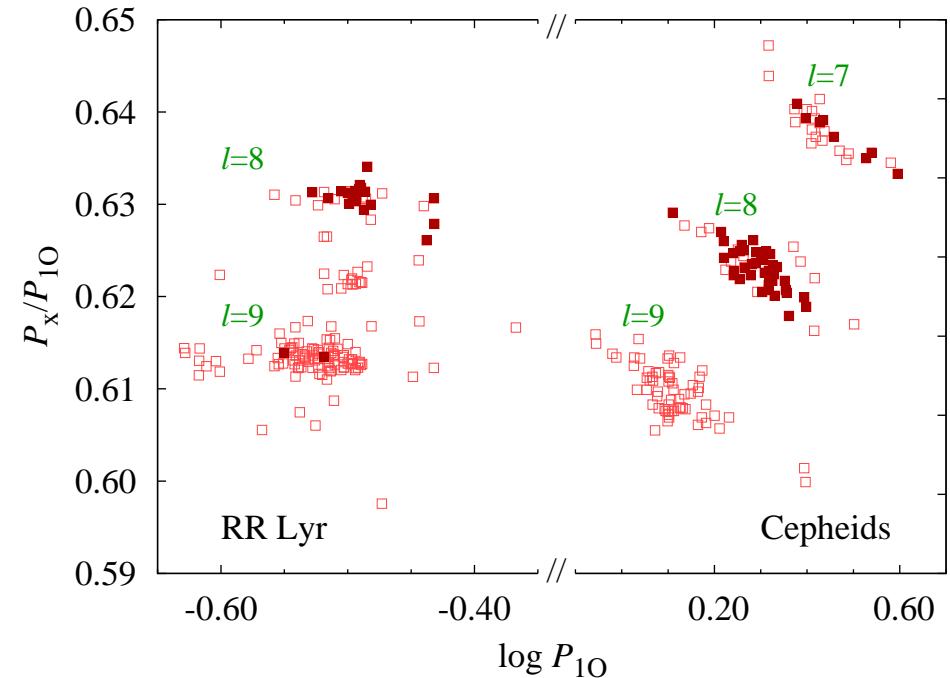


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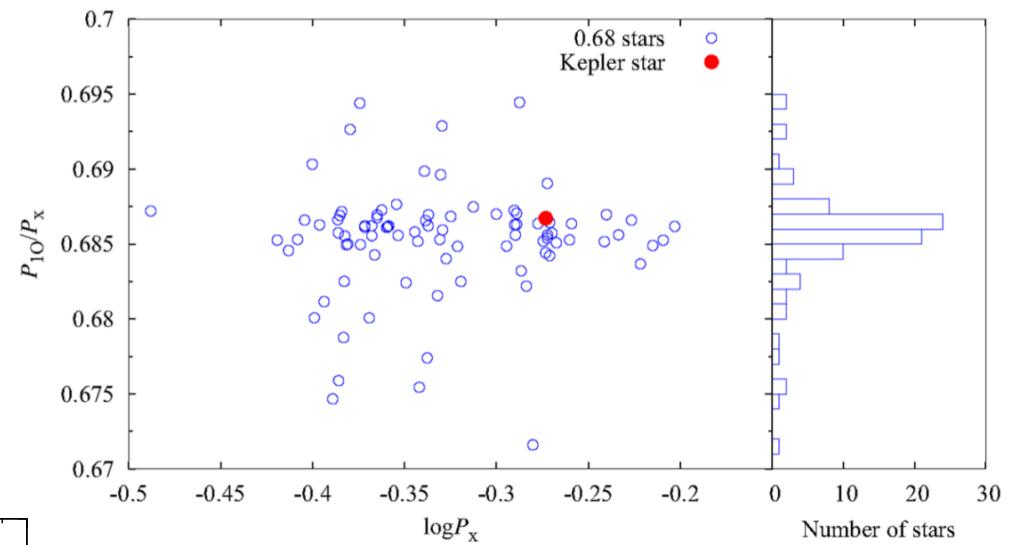
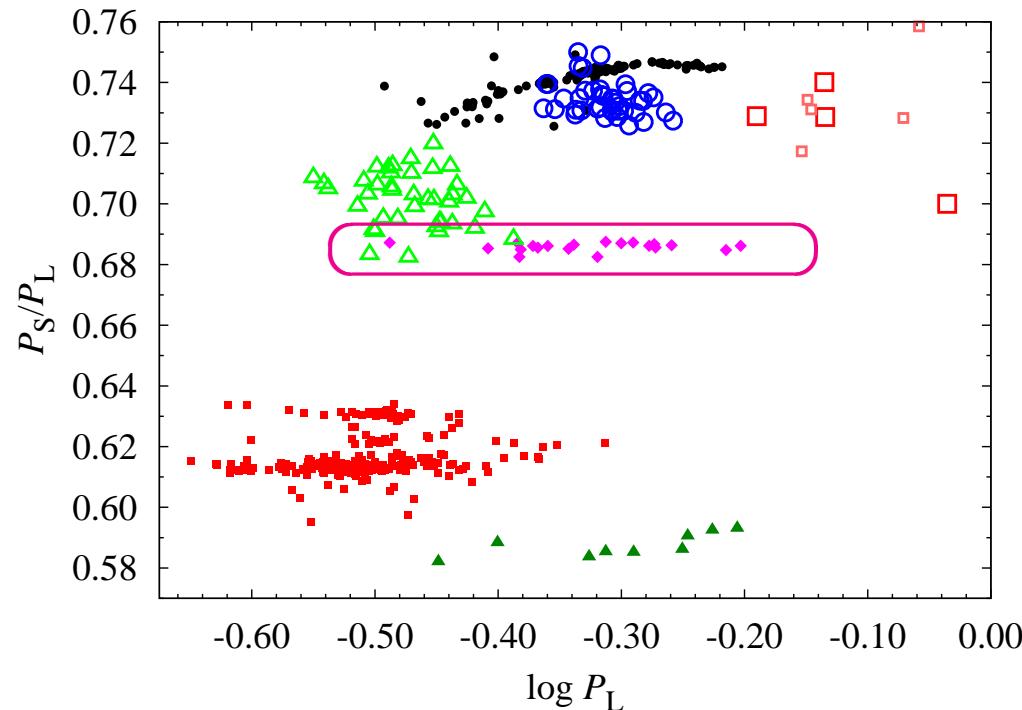
Dziembowski (2016), *CoKon*



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RR Lyrae stars

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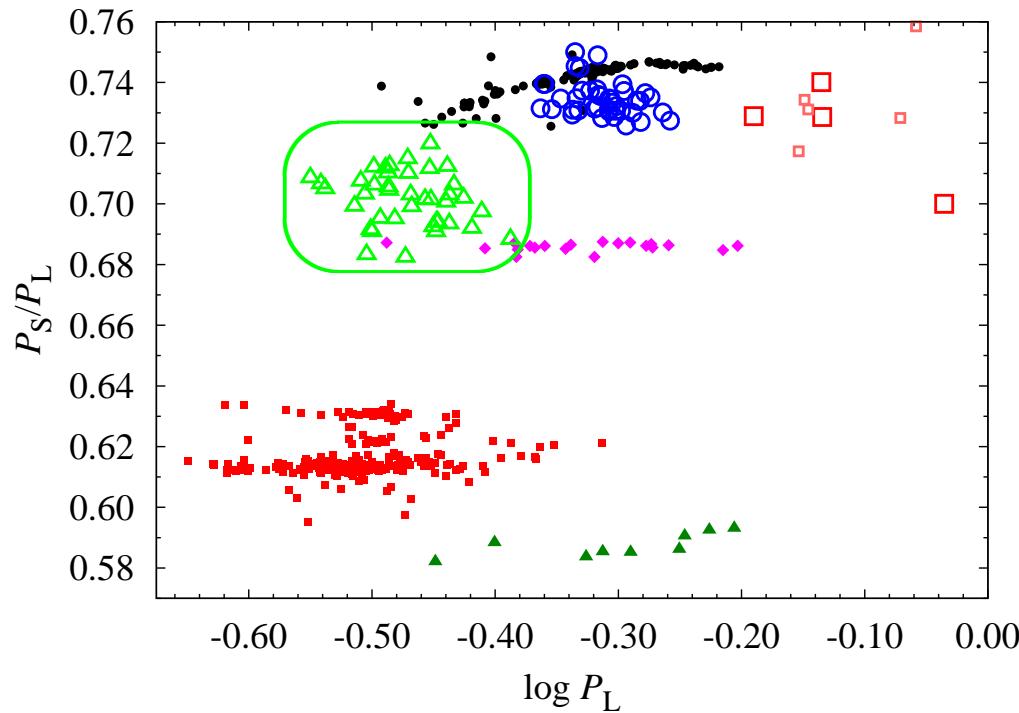
- ▶ 147 stars in OGLE blg collection
- ▶ frequency below radial F mode
- ▶ strongly coherent variability

Netzel & Smolec (2019), MNRAS

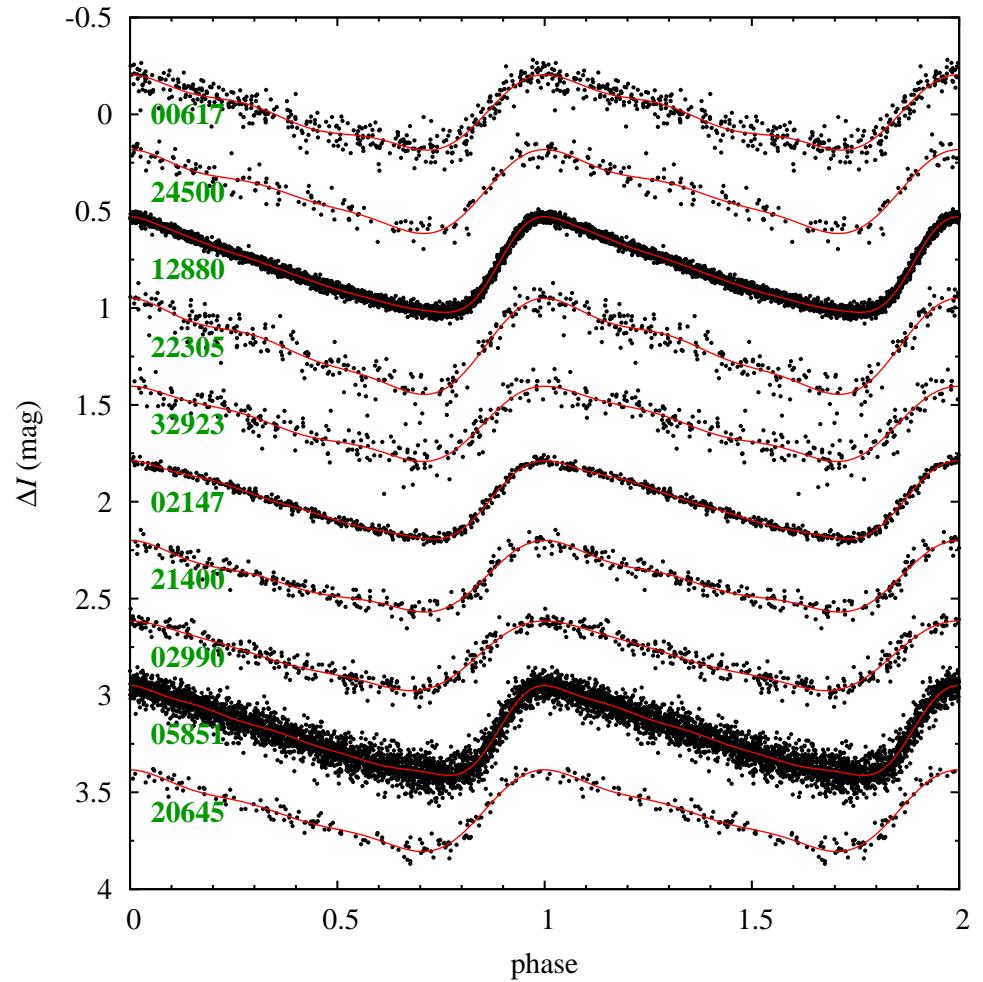


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Prudil et al. (2017), MNRAS



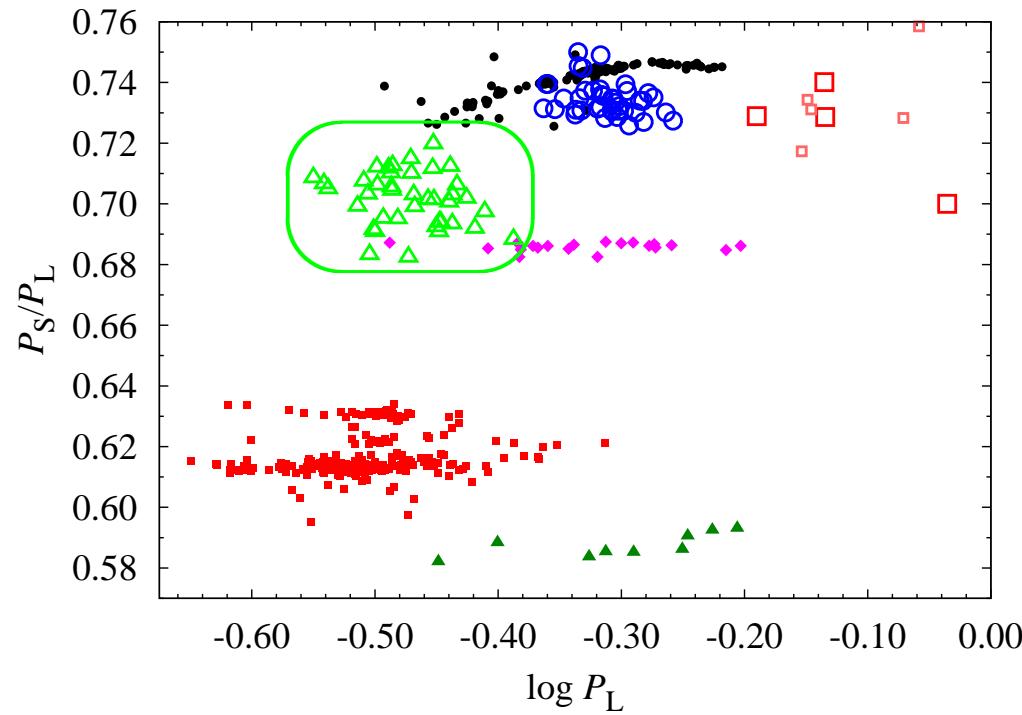
$$m = A_0 + \sum_k A_k \sin(k\omega_0 t + \phi_k)$$

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

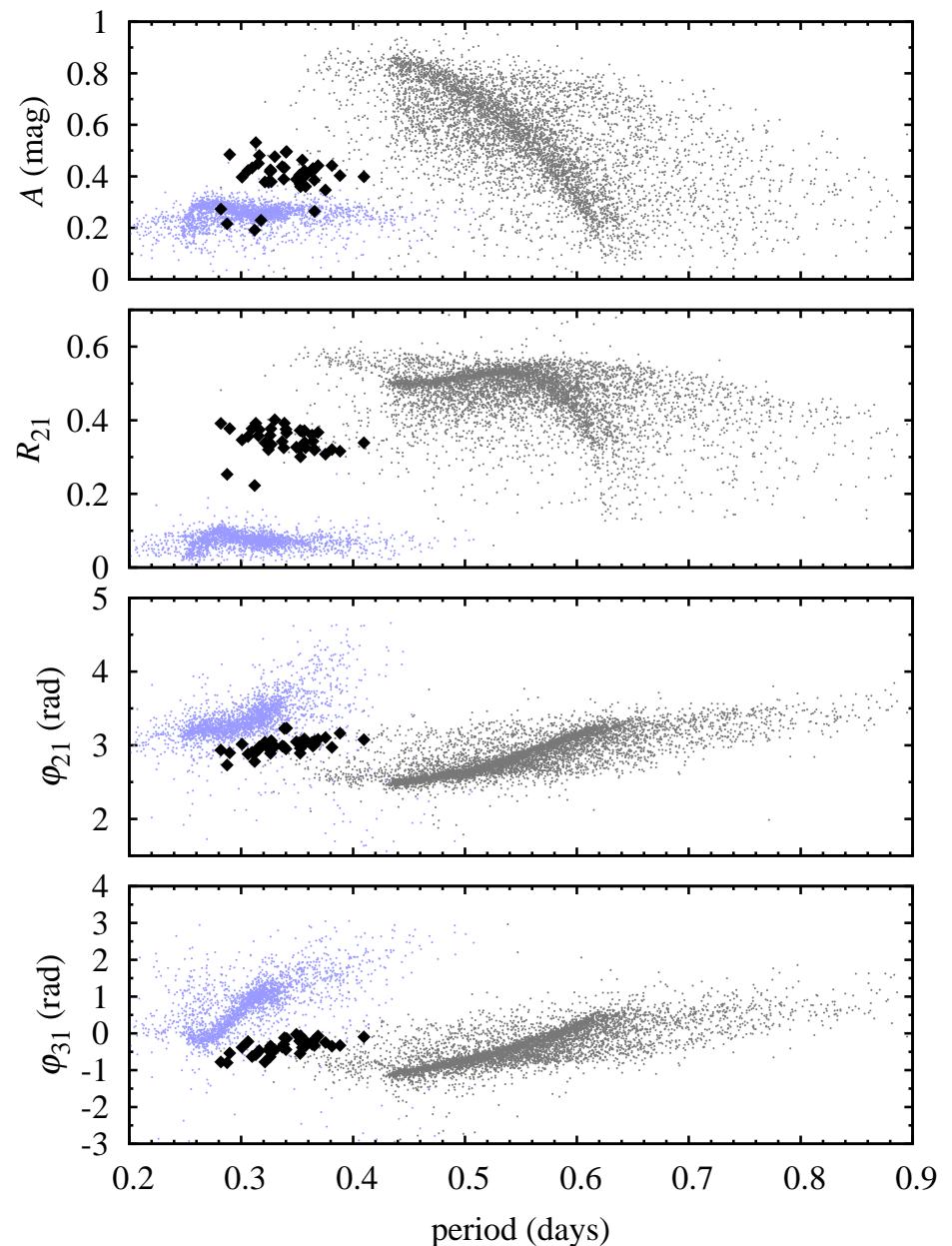


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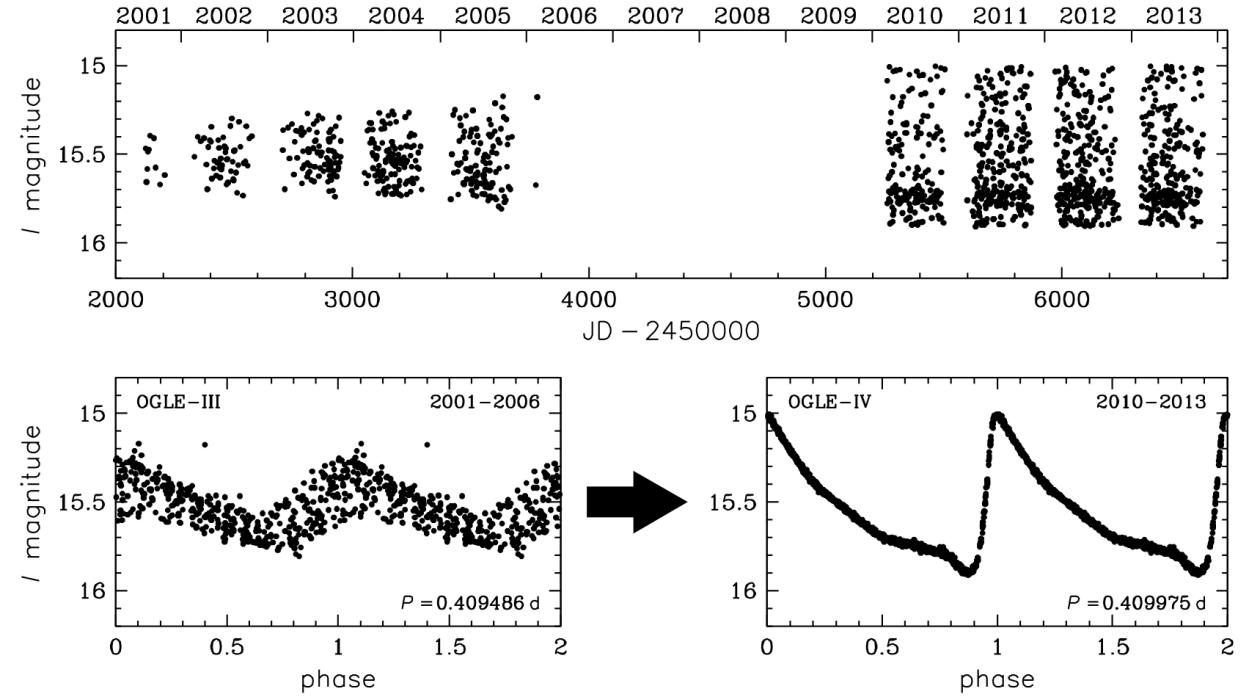


Prudil et al. (2017), MNRAS



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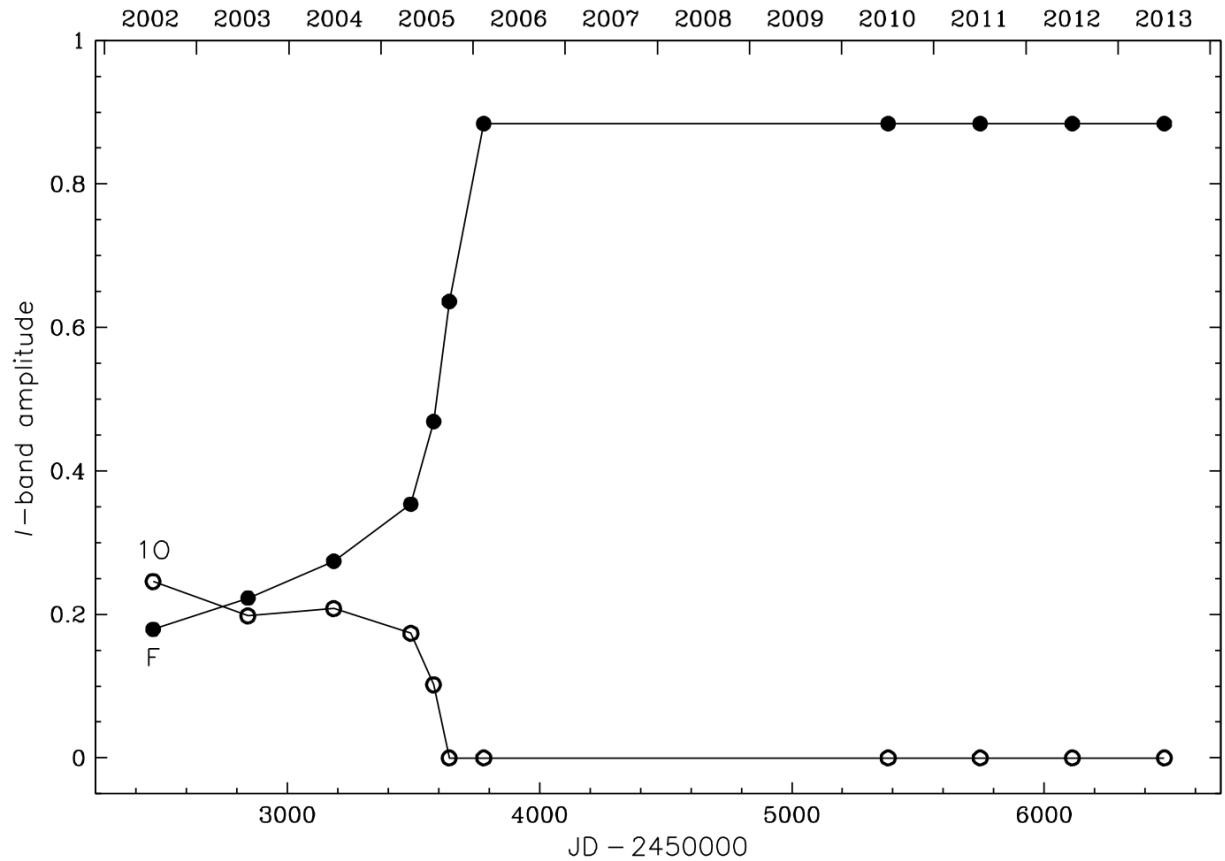


Soszyński et al. (2014), *AcA*



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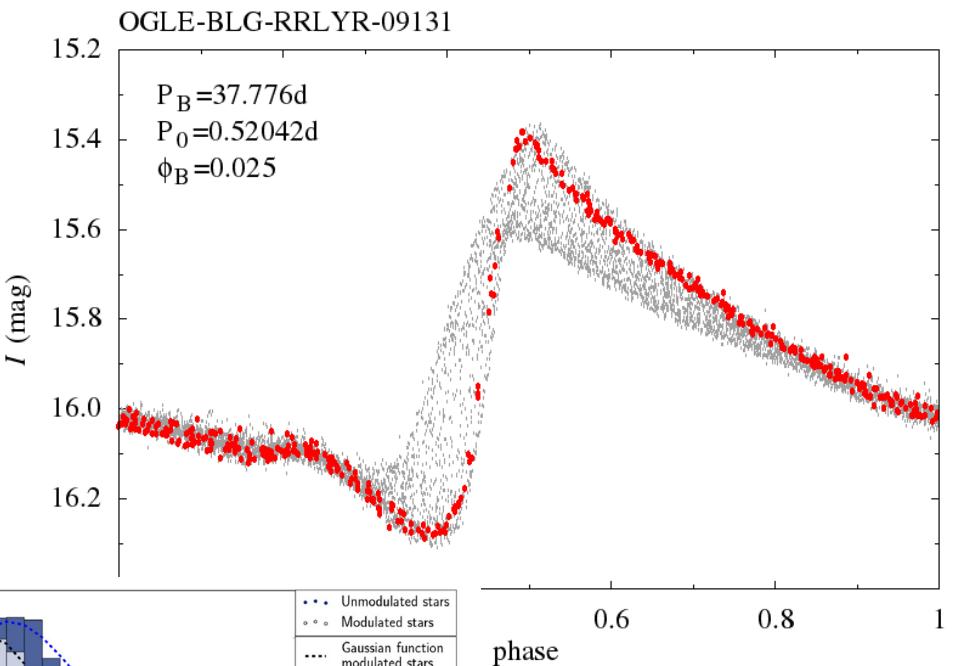
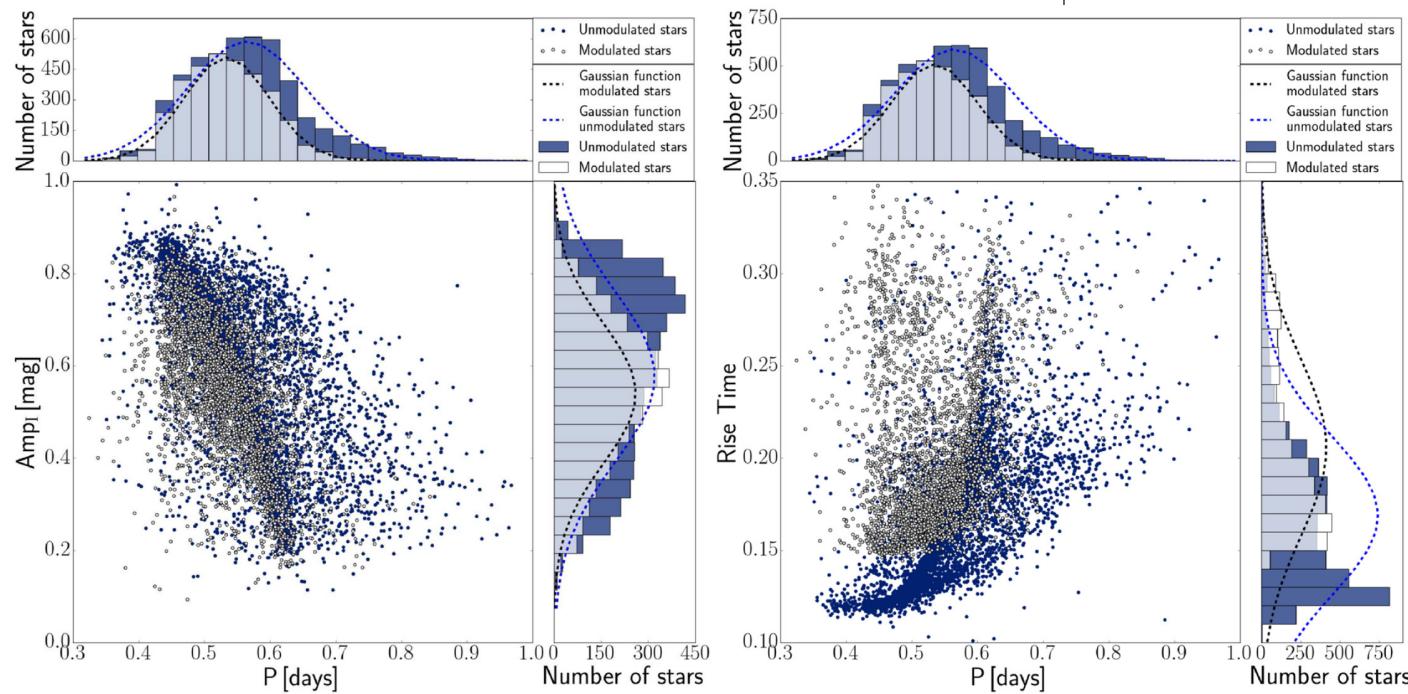


Soszyński et al. (2014), *AcA*



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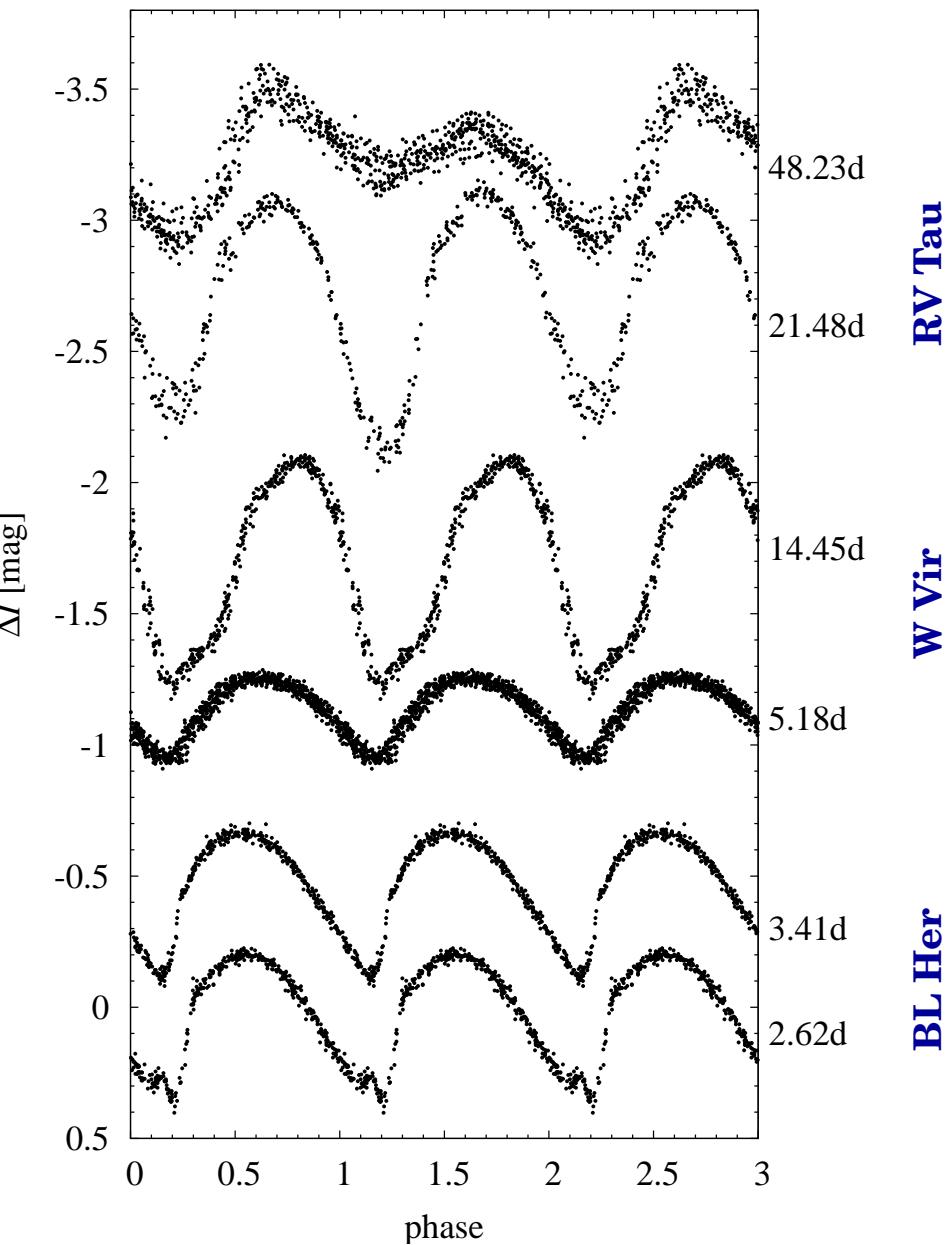


Prudil & Skarka (2019), MNRAS



Type-II Cepheids

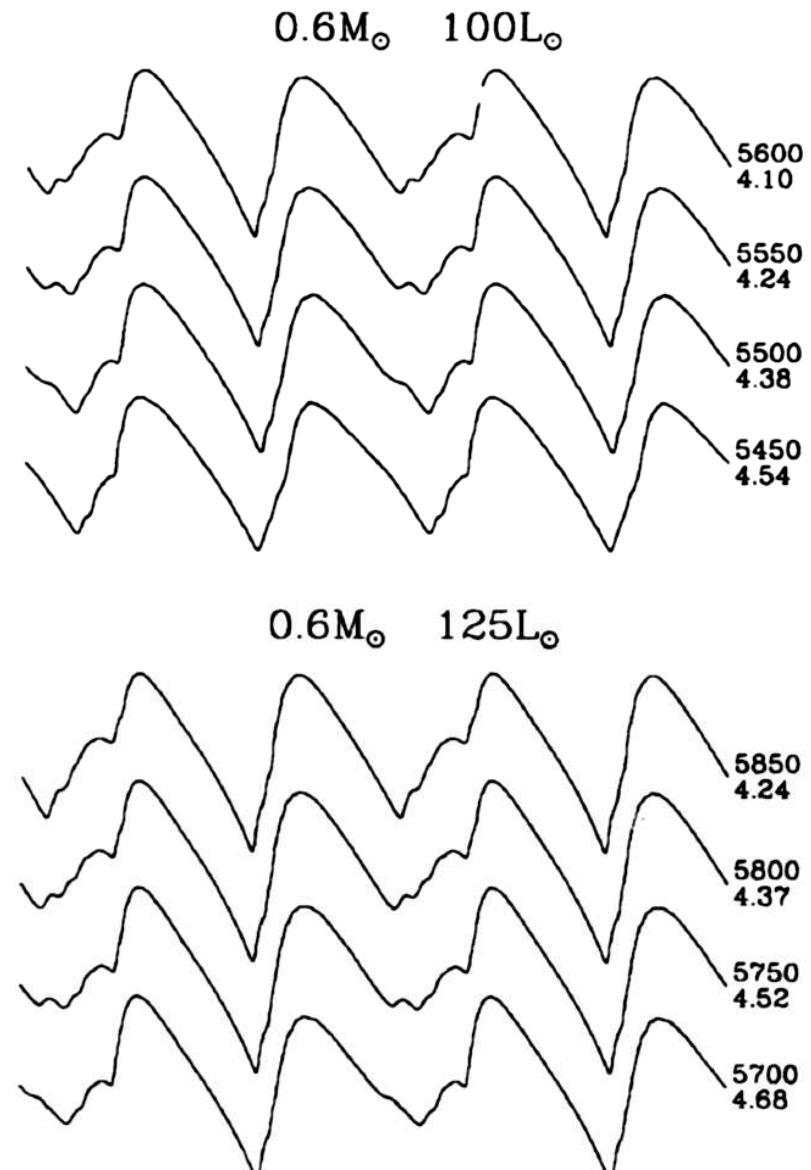
- ▶ period doubling in BL Her stars
- ▶ period doubling in W Vir stars
- ▶ periodic modulations of pulsation
- ▶ double-mode BL Her stars
- ▶ first overtone BL Her stars



Type-II Cepheids

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from 1992 theoretical prediction...



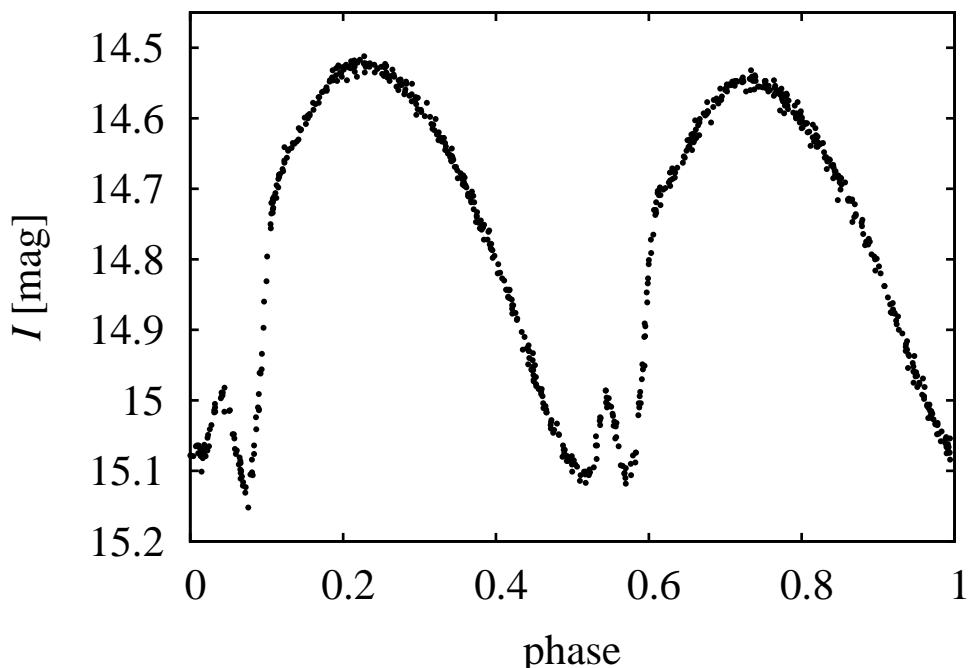
Buchler & Moskalik (1992), *ApJ*



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OGLE-BLG-T2CEP-279



from 1992 theoretical prediction...

...to 2012 OGLE discovery

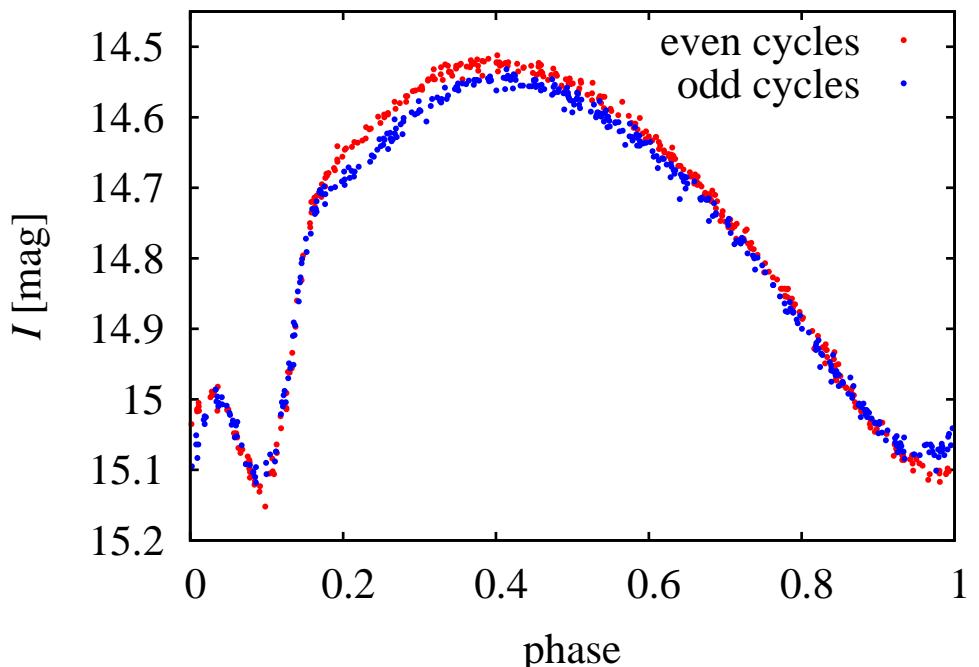
Smolec et al. (2012), MNRAS



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OGLE-BLG-T2CEP-279



from 1992 theoretical prediction...

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Smolec et al. (2012), MNRAS



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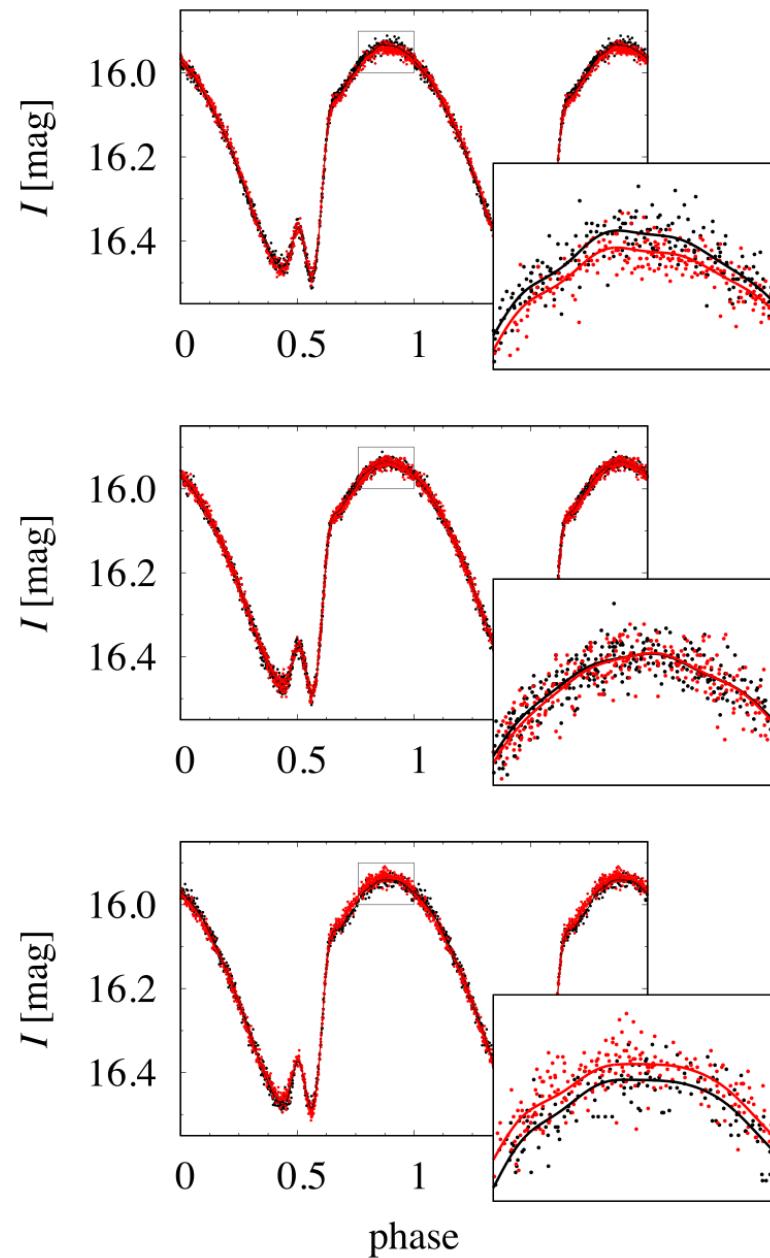
from 1992 theoretical prediction...

...to 2012 OGLE discovery

Smolec et al. (2018), MNRAS

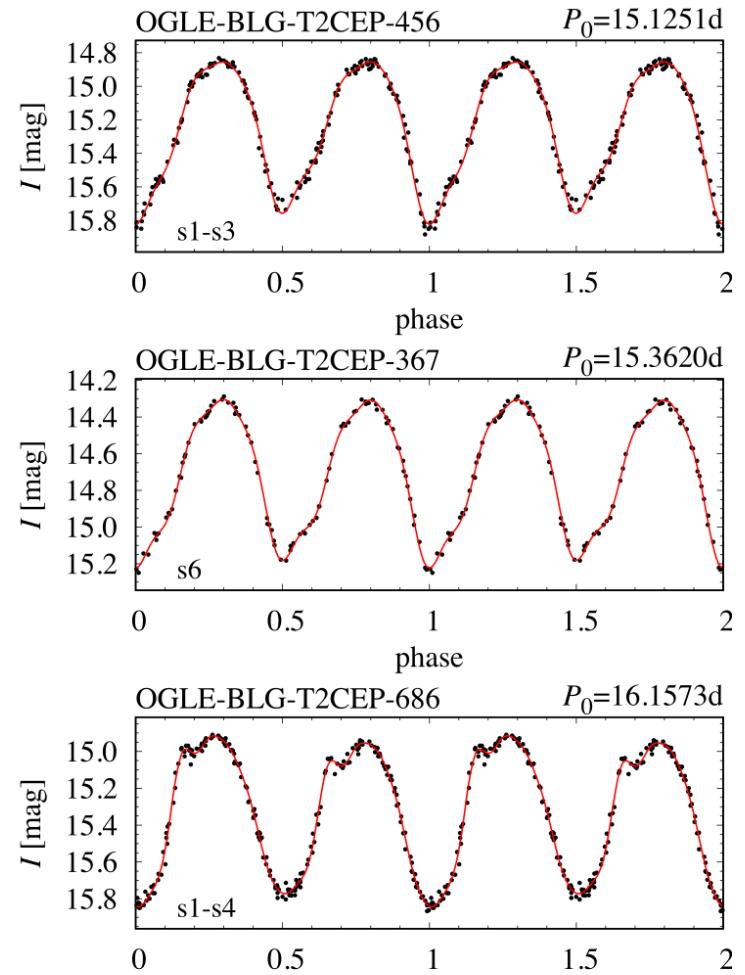


OGLE-BLG-T2CEP-820



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- ▶ double-mode BL Her stars
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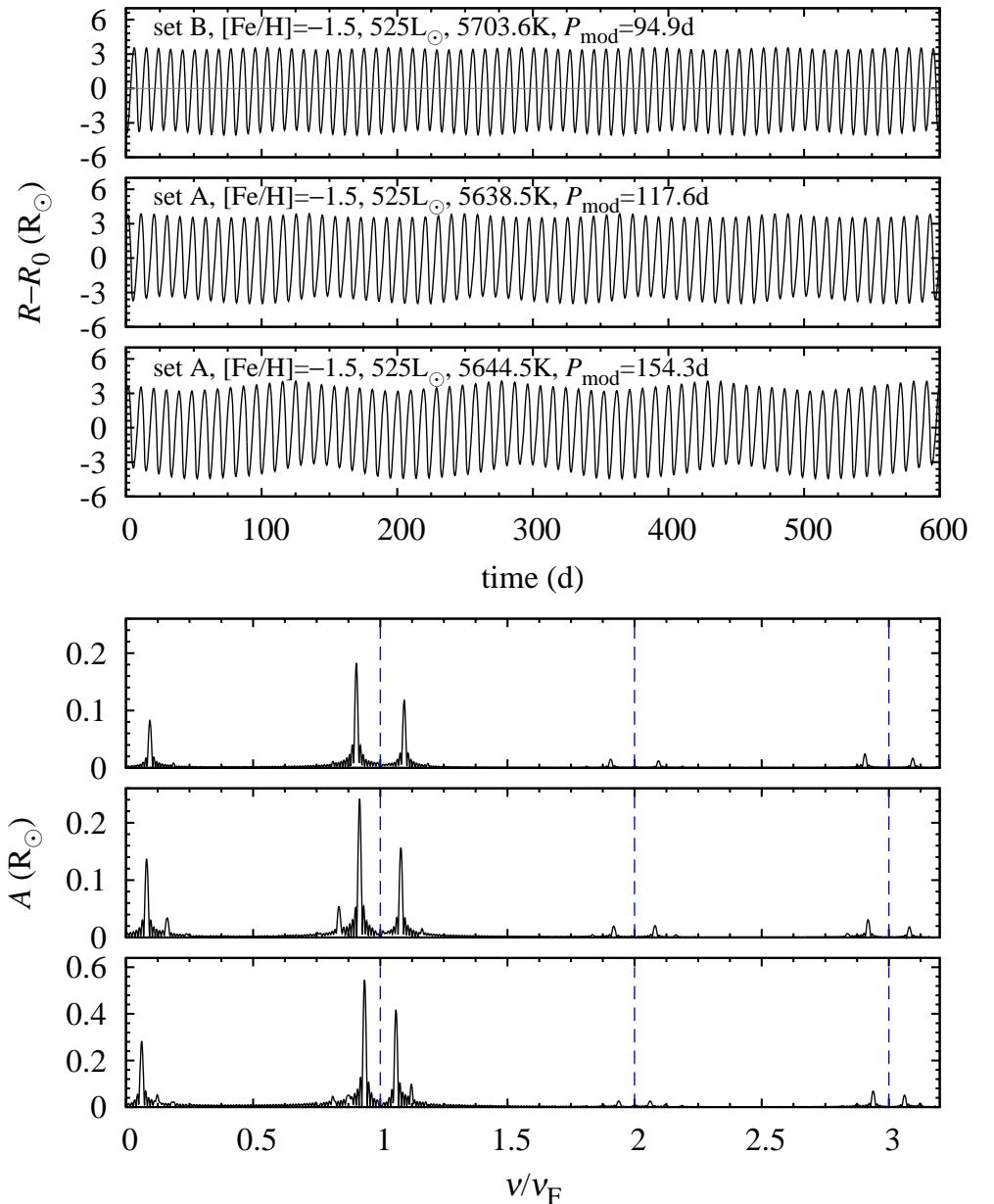


P	N_{PD}	N	N_{PD}/N
15–16 d	4	33	0.12 ± 0.06
16–17 d	5	23	0.22 ± 0.09
17–18 d	7	14	0.50 ± 0.13
18–19 d	4	9	0.44 ± 0.17
19–20 d	5	7	0.71 ± 0.17



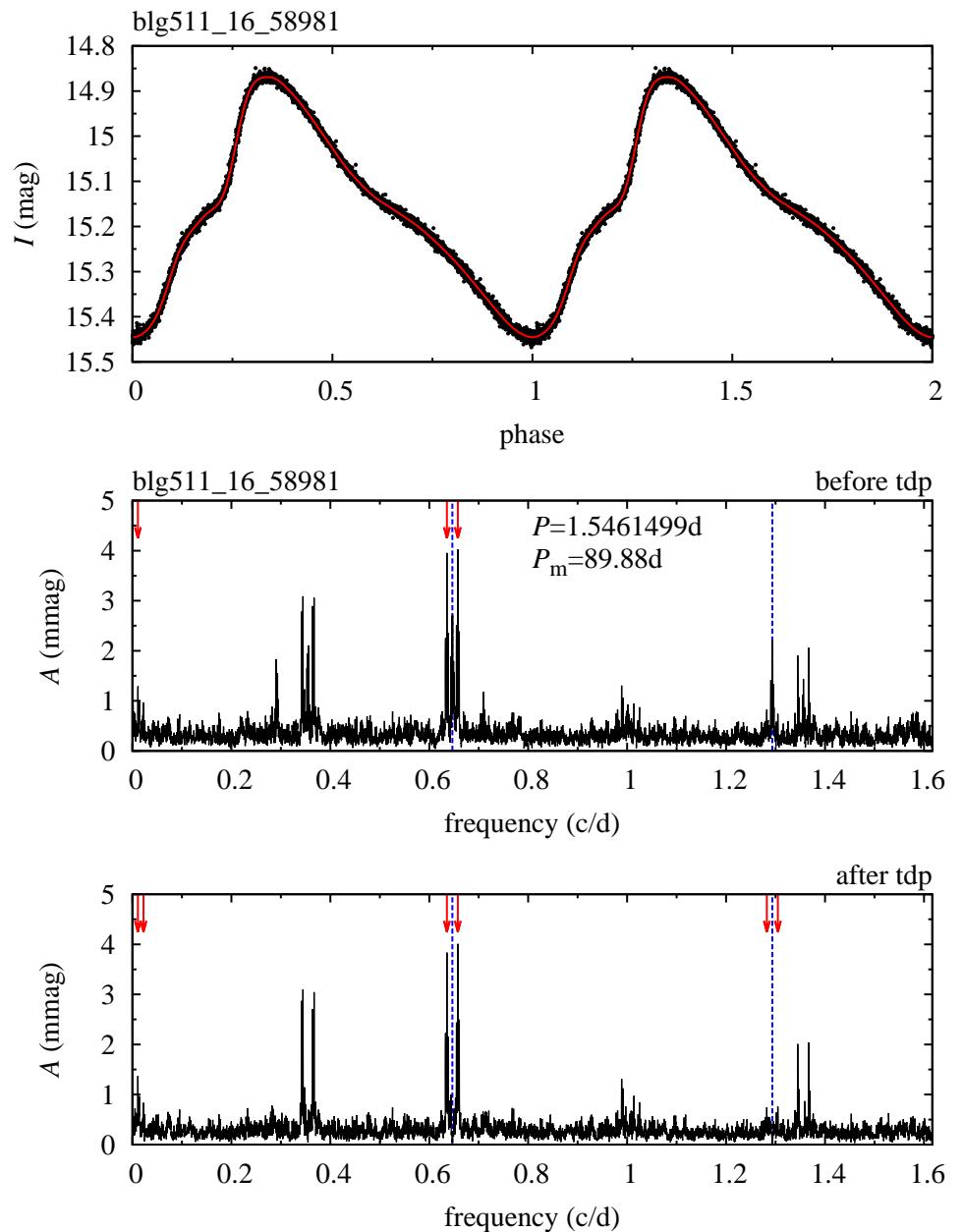
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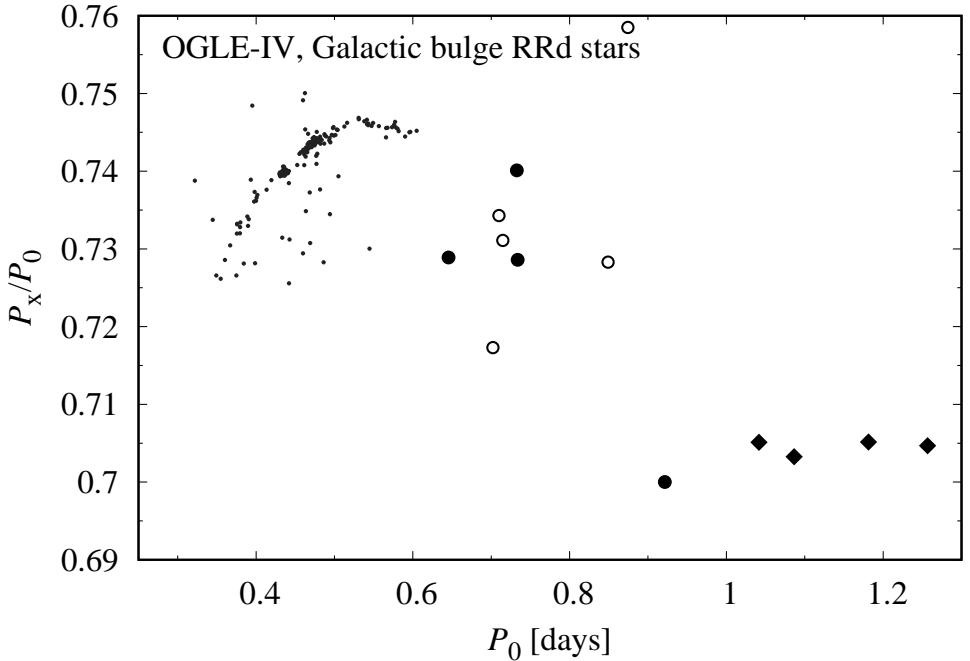
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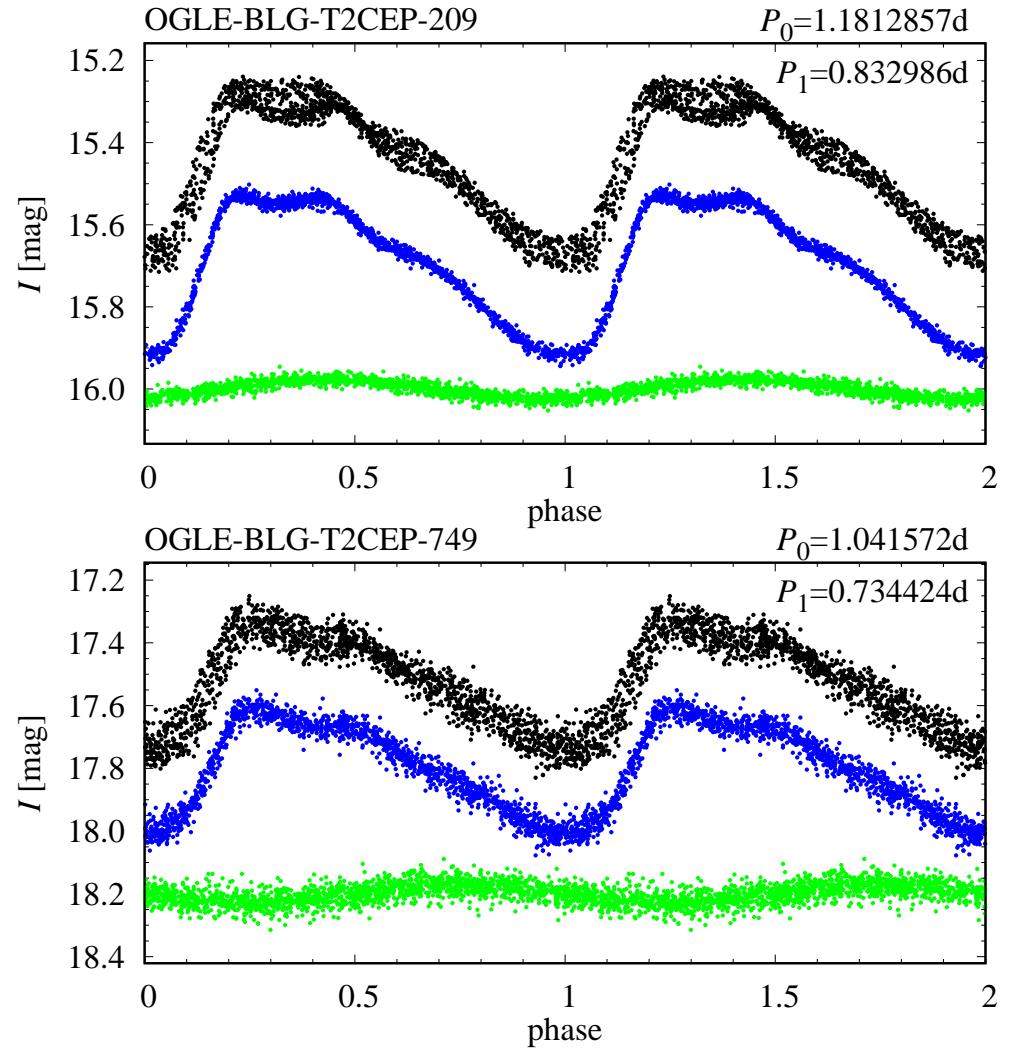


Smolec et al. (2018), *MNRAS*; Udalski et al. (2019), *A&A*



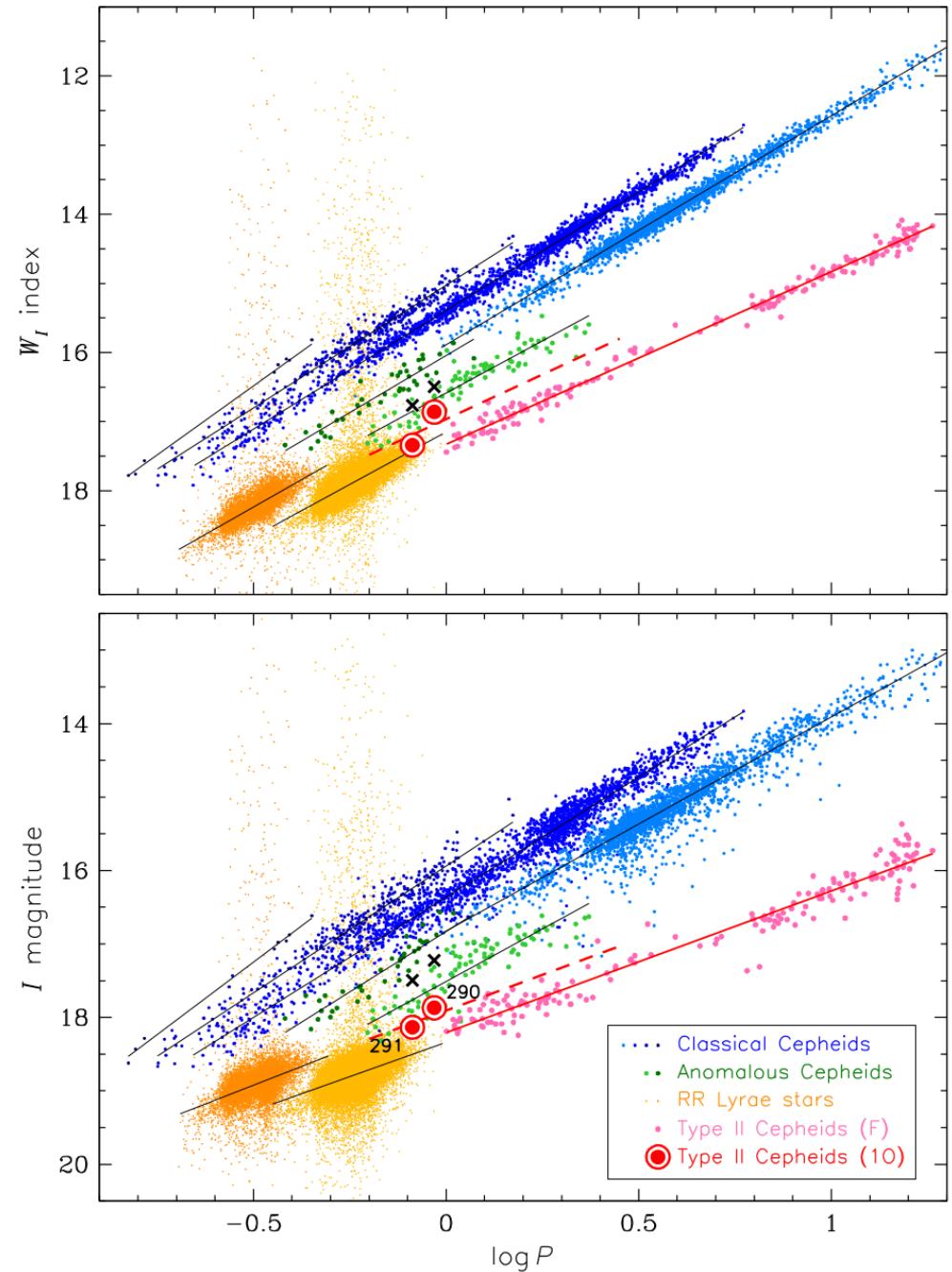
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- ▶ period doubling in W Vir stars
- ▶ periodic modulations of pulsation
- ▶ double-mode BL Her stars
- ▶ first overtone BL Her stars

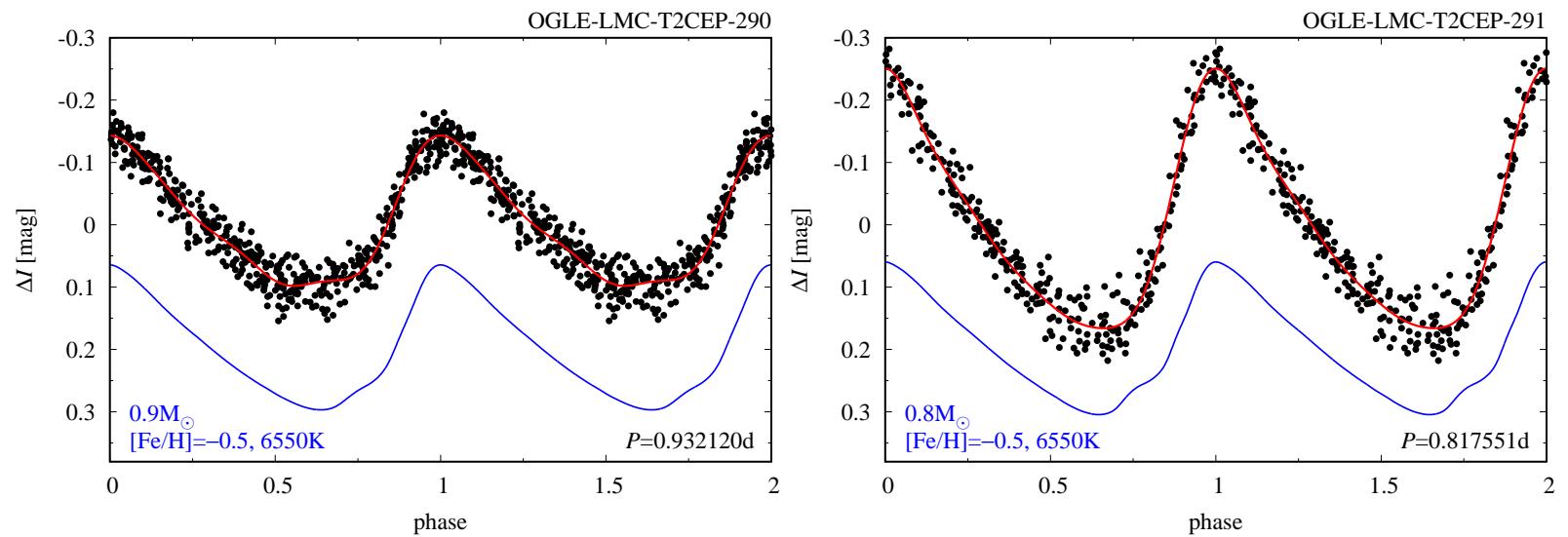


Soszyński et al. (2019), *ApJ*



Type-II Cepheids

- ▶ period doubling in BL Her stars
- ▶ period doubling in W Vir stars
- ▶ periodic modulations of pulsation
- ▶ double-mode BL Her stars
- ▶ first overtone BL Her stars

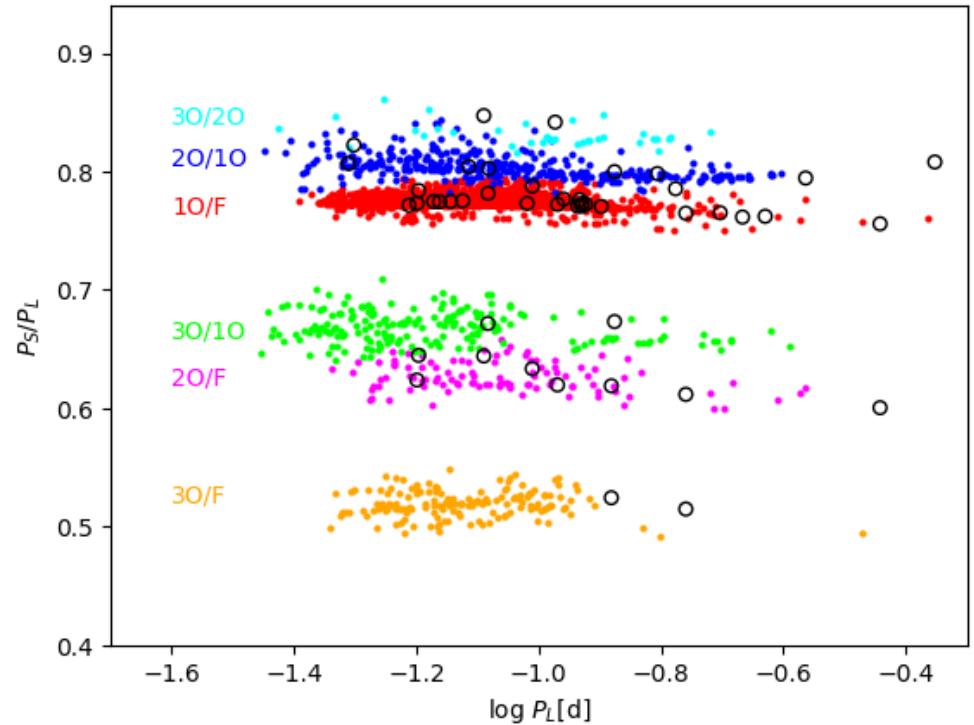


Soszyński et al. (2019), *ApJ*



Delta Sct stars

- ▶ multiperiodic radial δ Sct stars
- ▶ excellent targets for asteroseismology

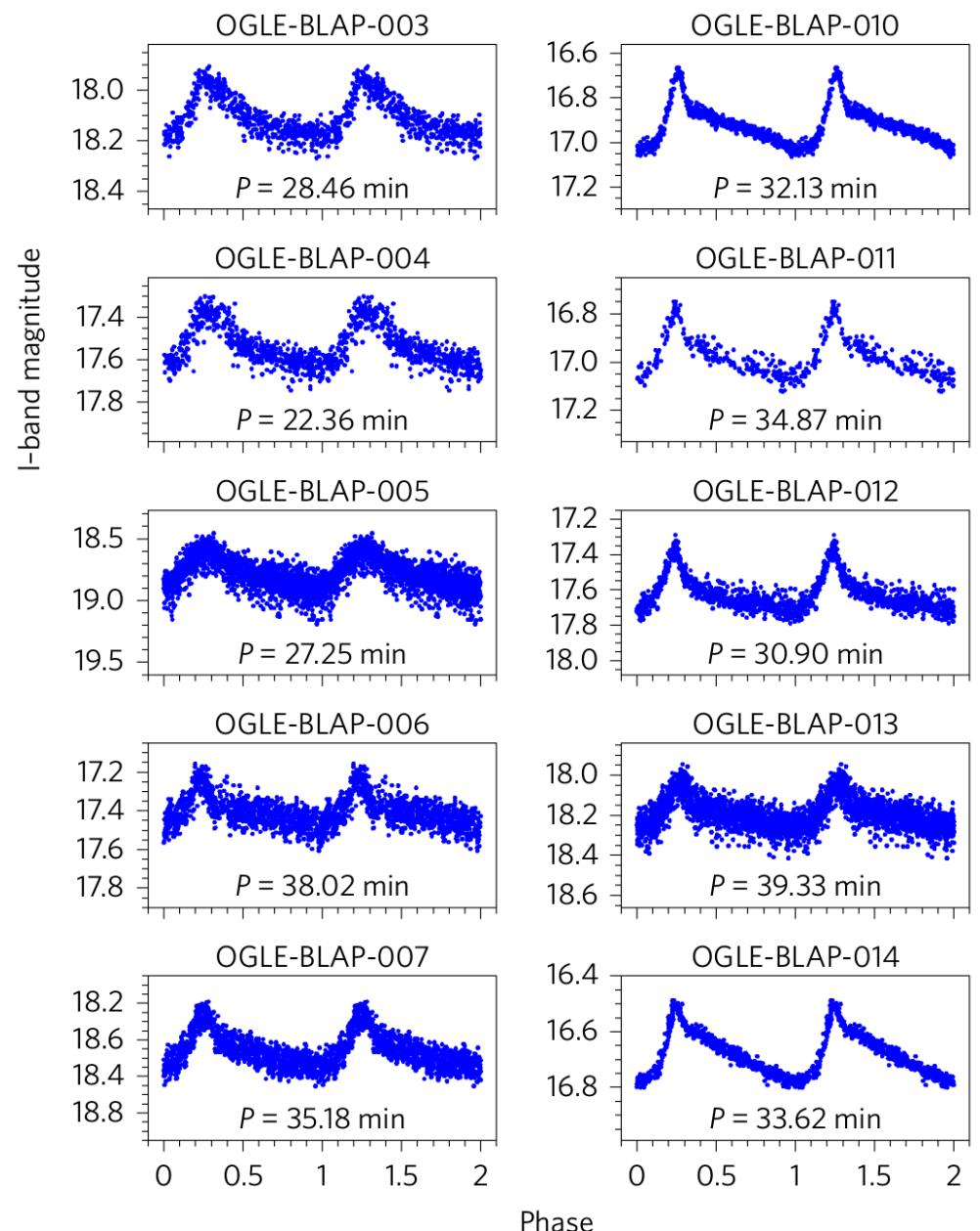


Netzel et al., *in prep.*



Blue Large Amplitude Pulsators

- BLAPs

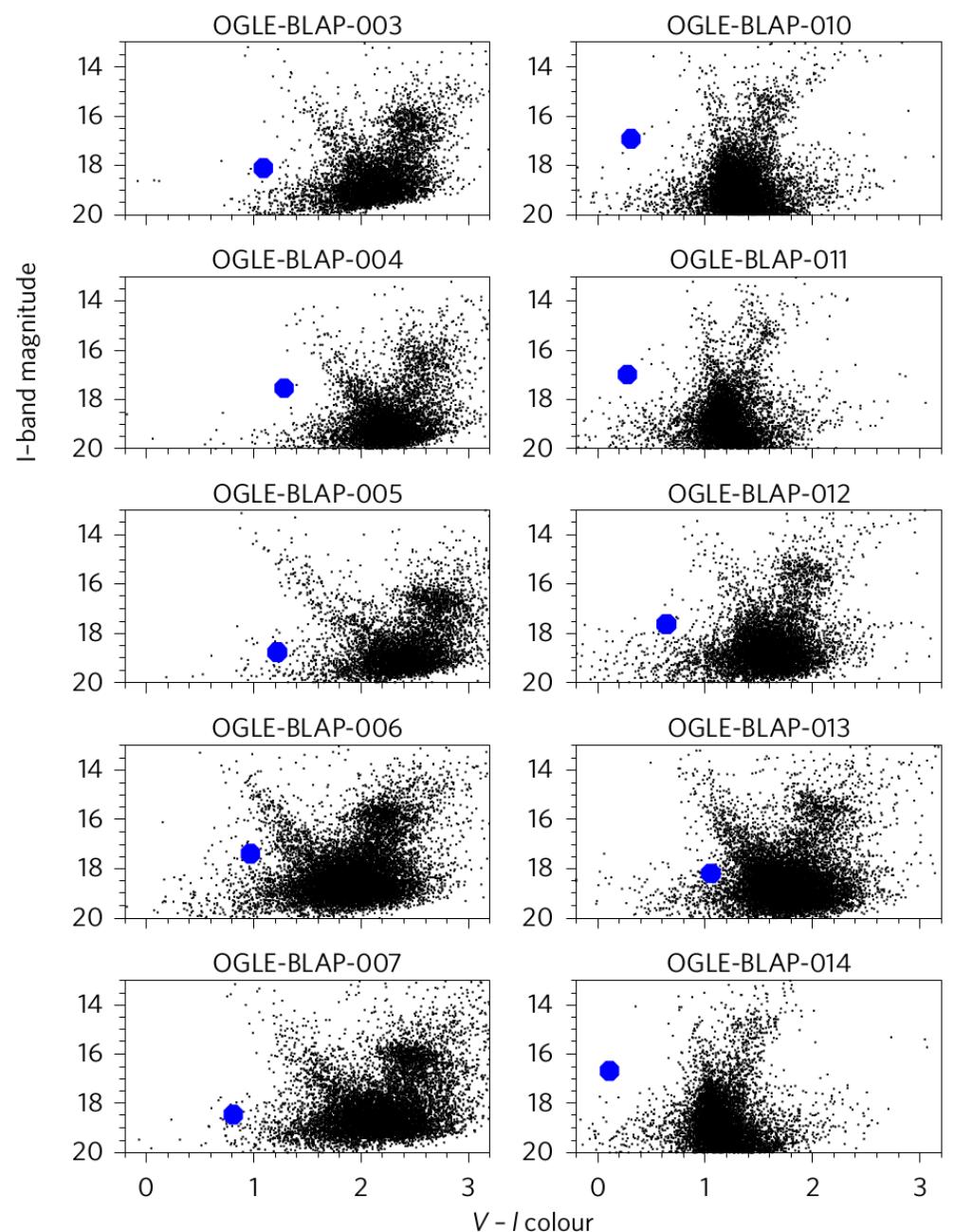


Pietrukowicz et al. (2017), *Nature Ast.*



Blue Large Amplitude Pulsators

- BLAPs

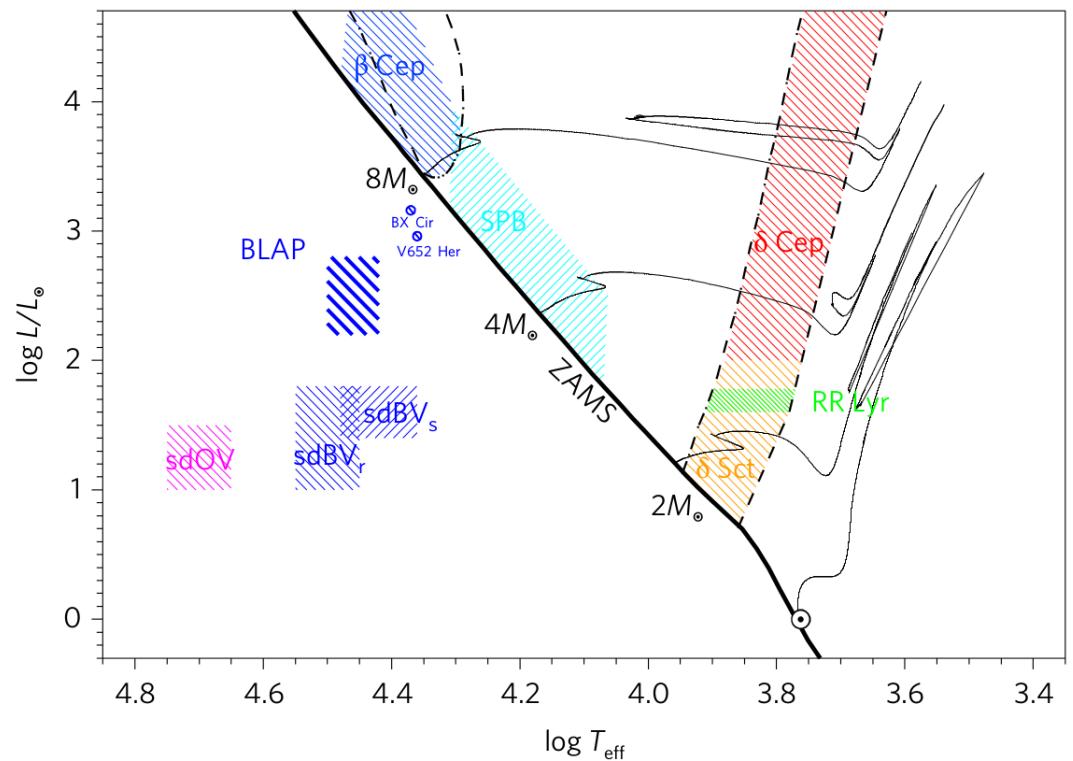


Pietrukowicz et al. (2017), *Nature Ast.*



Blue Large Amplitude Pulsators

- BLAPs



Pietrukowicz et al. (2017), *Nature Ast.*



OGLE view on classical pulsators

- ▶ no longer purely radial
- ▶ non-radial pulsation might be common, at least in 10 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 lacks satisfactory theoretical explanation

