Classical pulsators: beyond radial modes - observations and theory

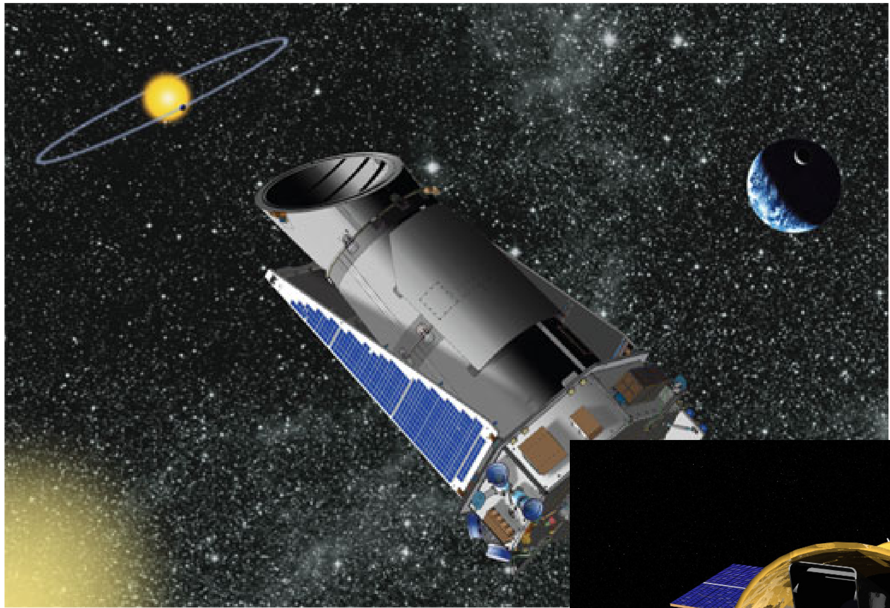
Radek Smolec

Nicolaus Copernicus Astronomical Center, Warsaw

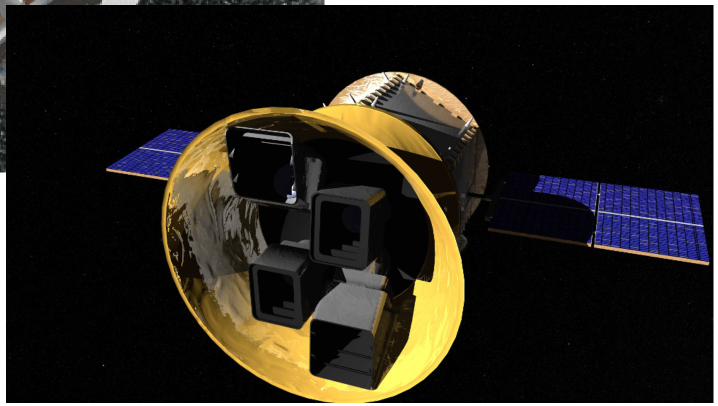
Beyond radial modes

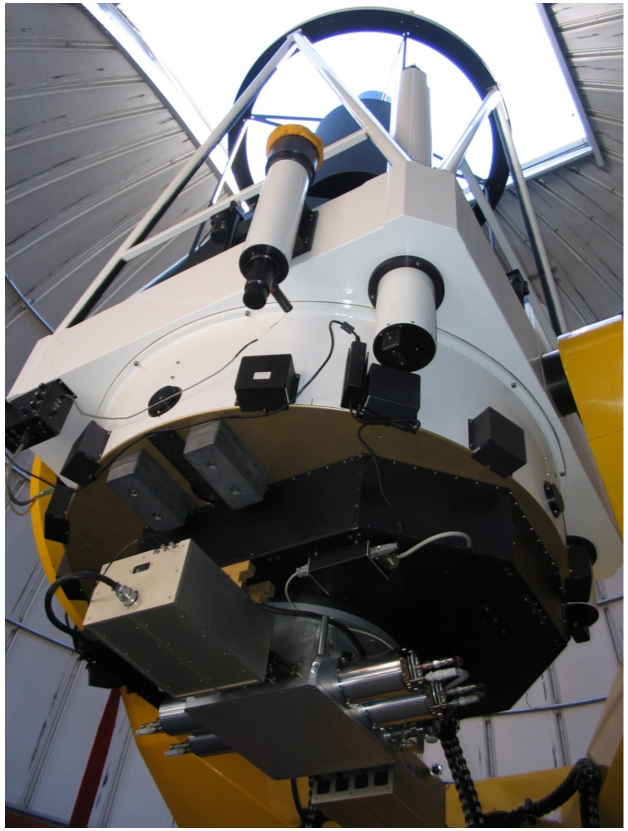
- additional low-amplitude periodicities
- all flavours of periodic modulation
- back to radial modes

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 largely thanks to **ground-based projects**
- **long-term, precise** photometry for **tens of thousands** of classical pulsators

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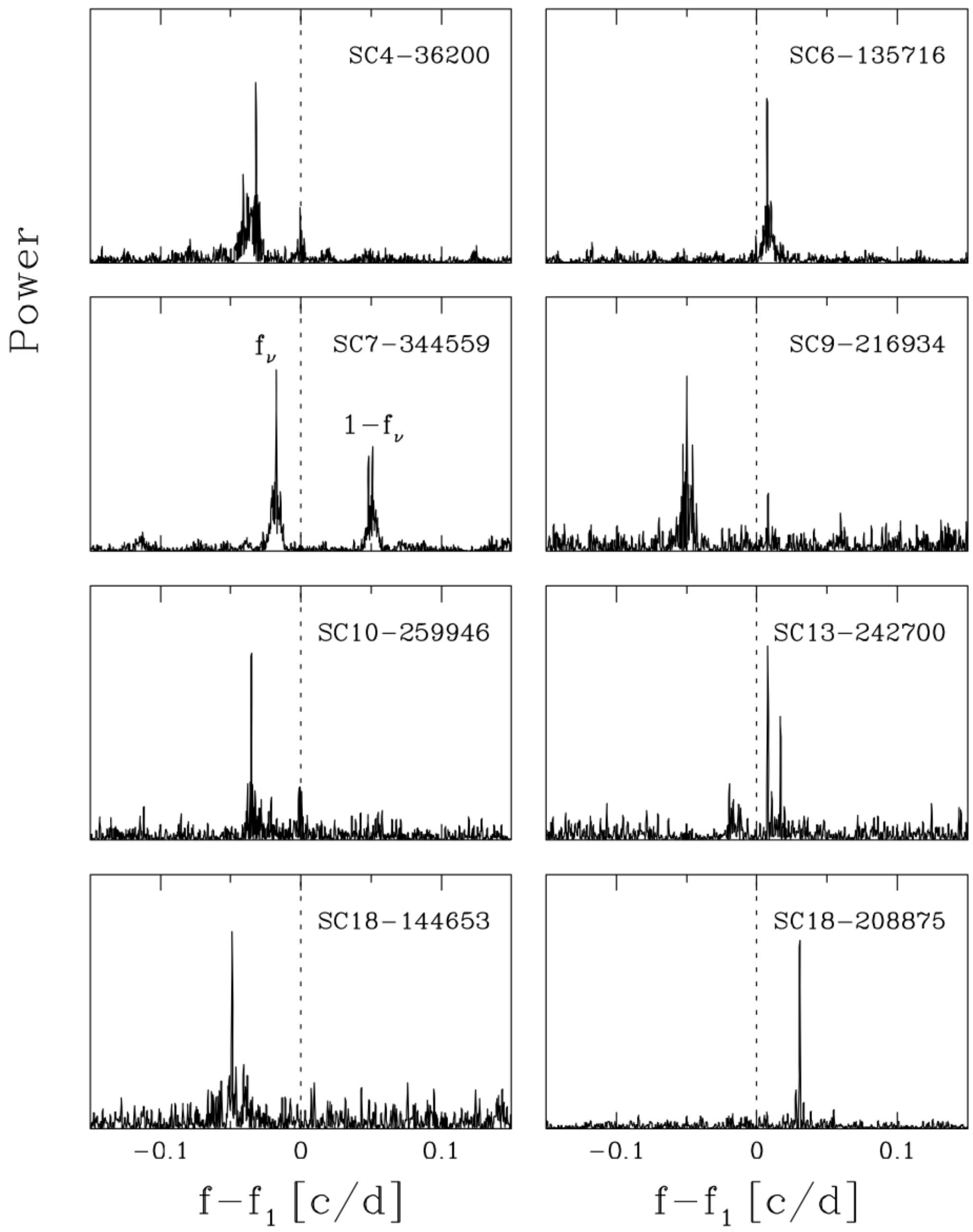
Low-amplitude periodicities

- 1O Cepheids: ∼close frequencies
- 1O Cepheids: 0.6–0.65 period ratios
- RRc: 0.6–0.65 period ratios
- RRc: ∼0.68 period ratio
- RR Lyrae: other puzzling classes



Moskalik & Kołaczkowski (2009), *MNRAS*

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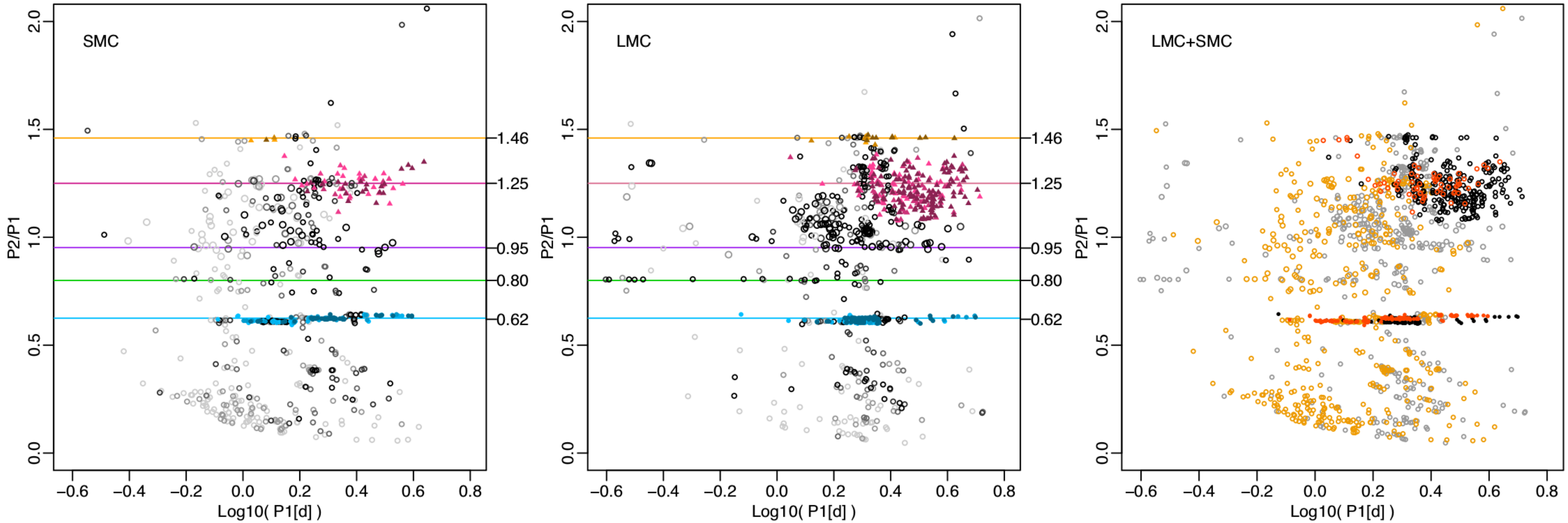
A few classes of additional periodicities



Süveges & Anderson (2018), *MNRAS*

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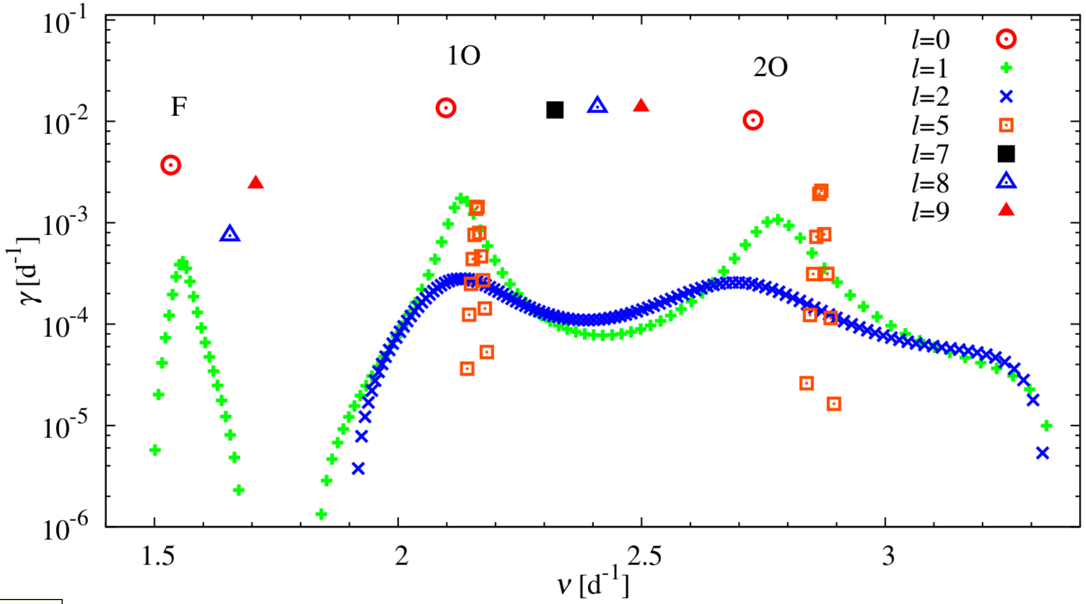

Modulation with strongly asymmetric sidepeaks?

- only in one out of 37 stars from the Moskalik & Kołaczkowski sample we could detect trace of modulation with newer data (Kotysz & Smolec, 2018)

Non-radial modes?

- which? what is the mode selection mechanism?

Dziembowski (2016), *CoKon*

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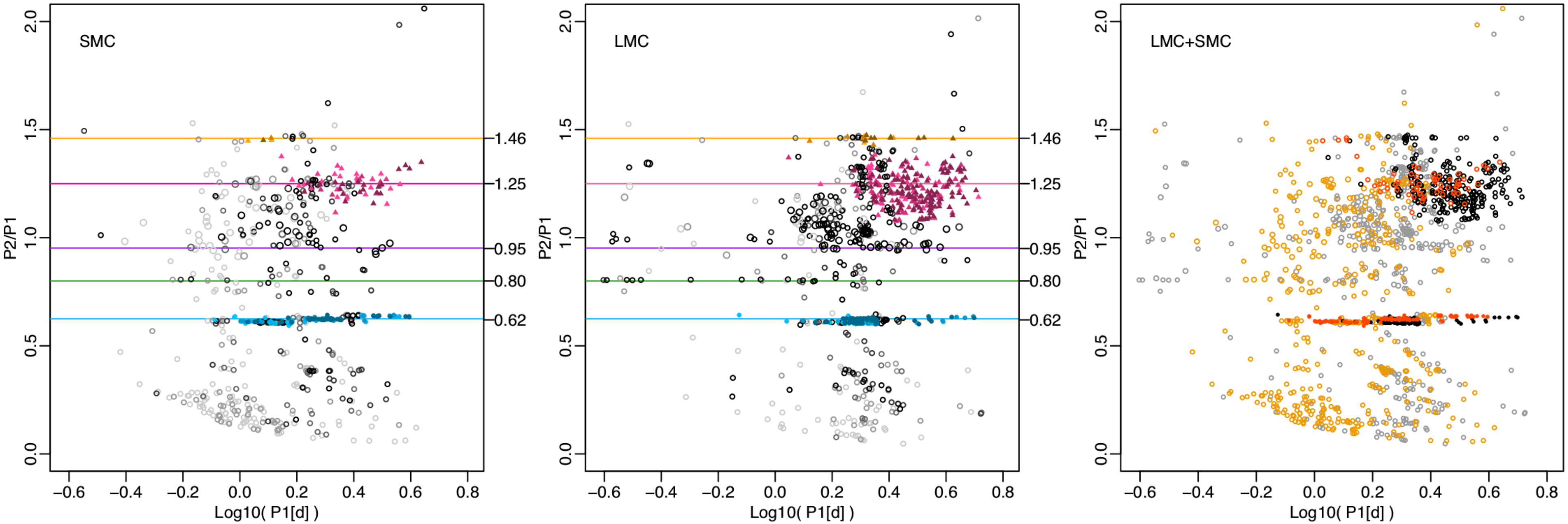

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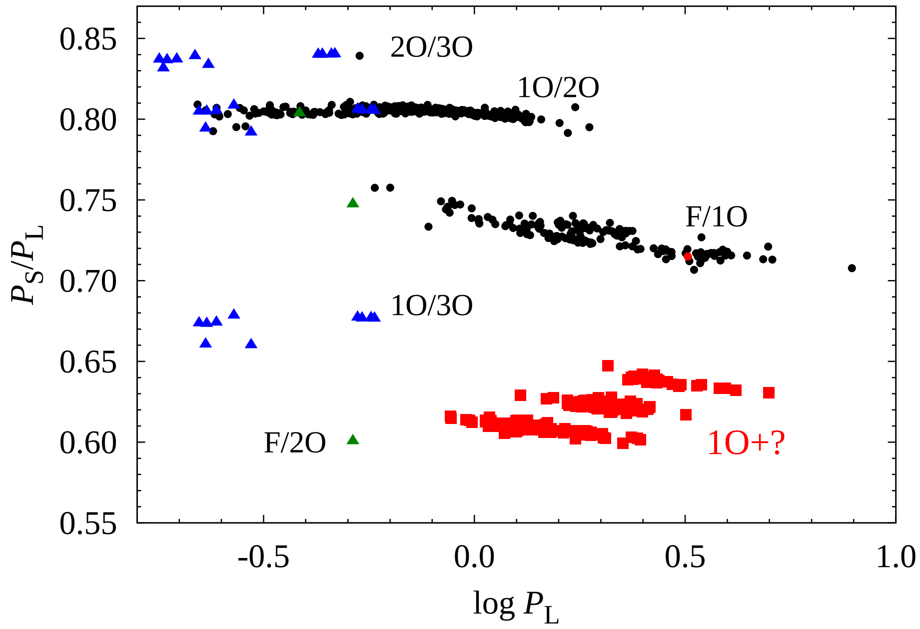

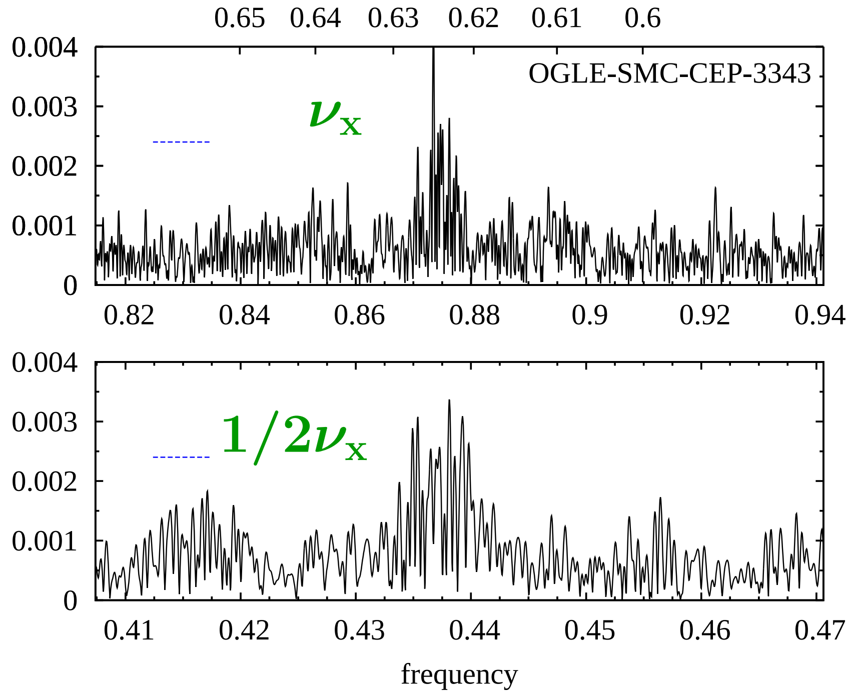

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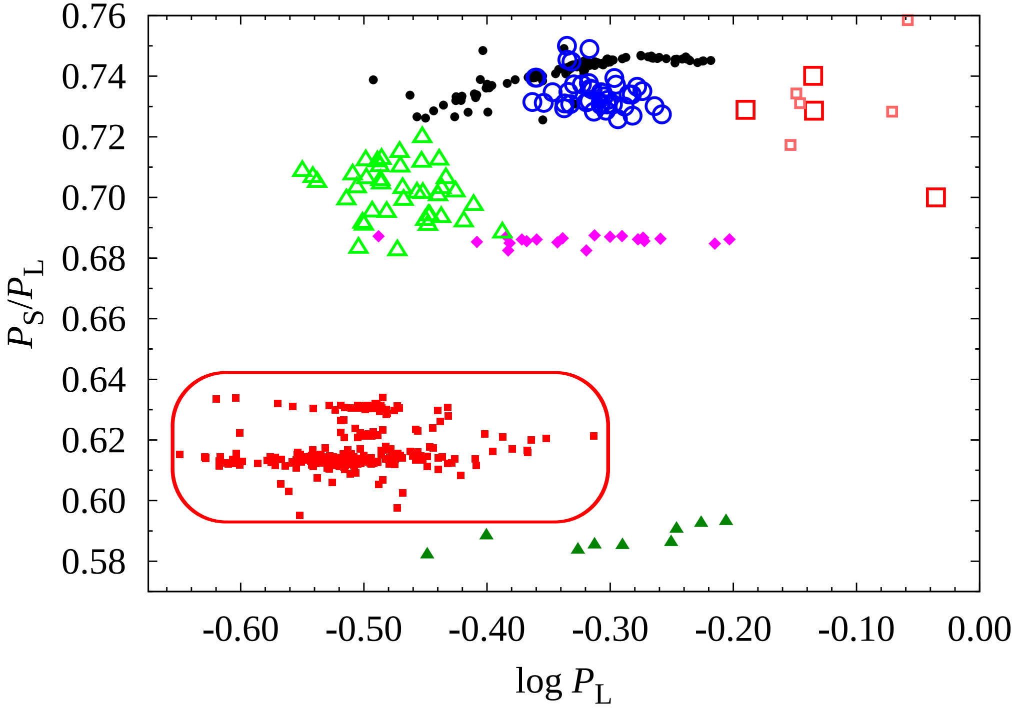

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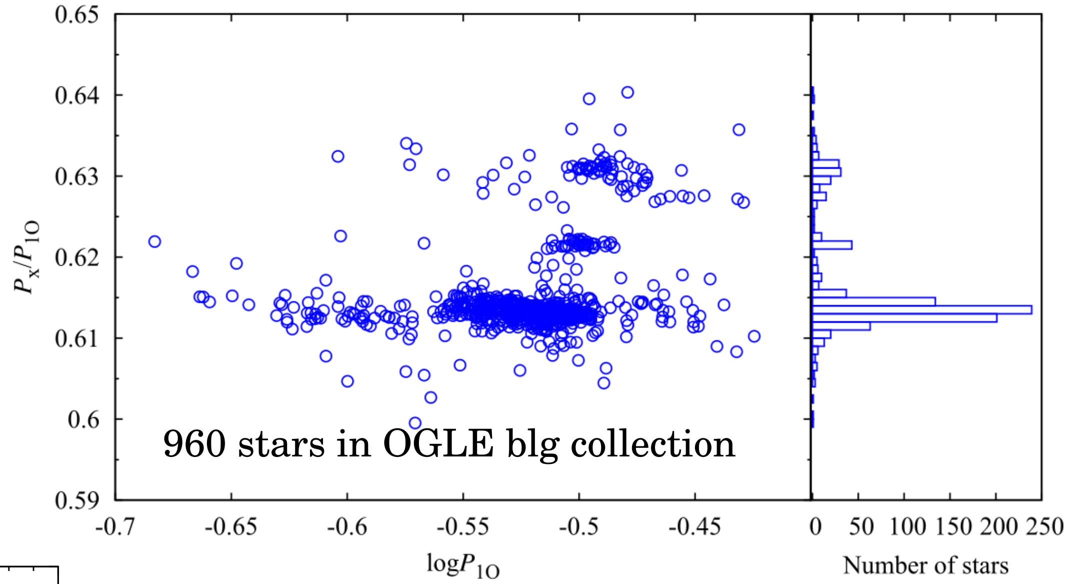

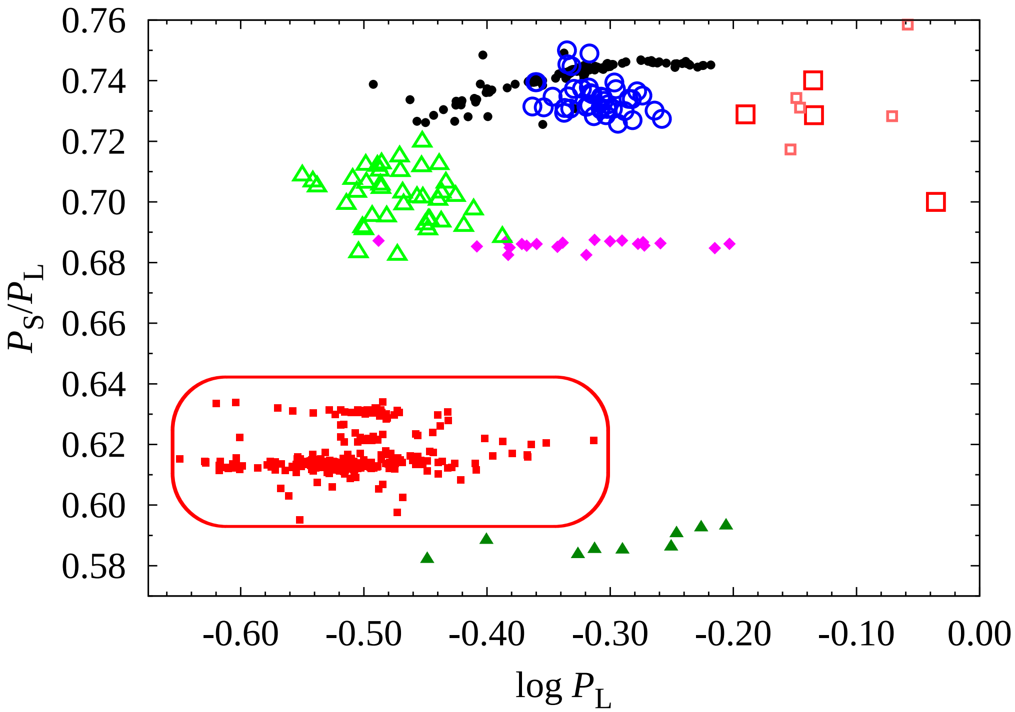

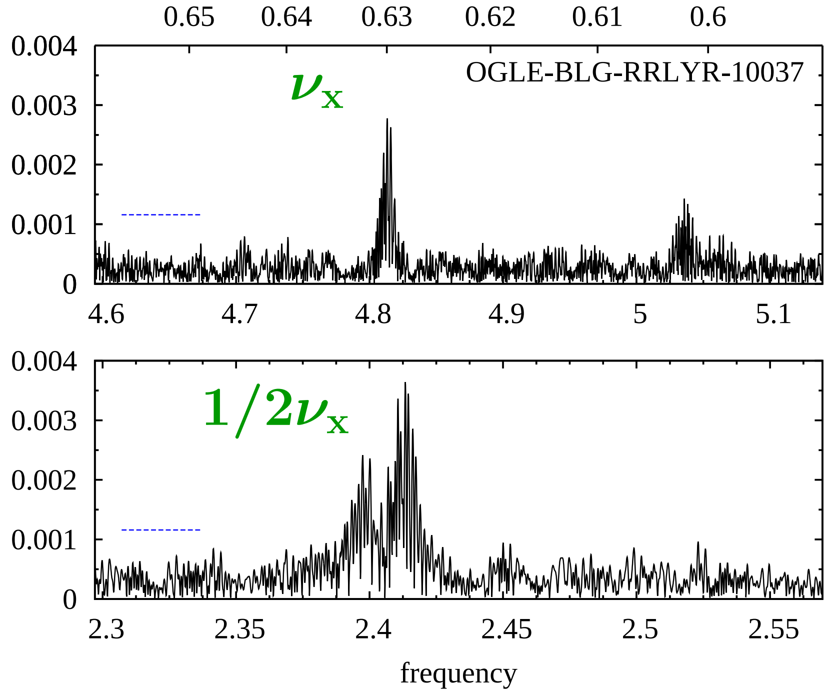

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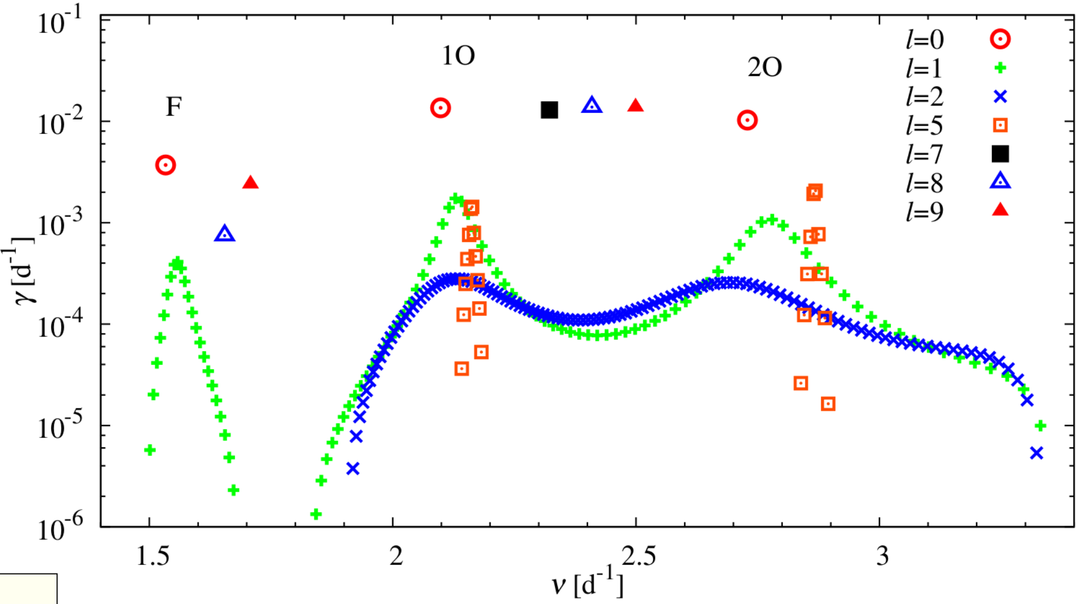
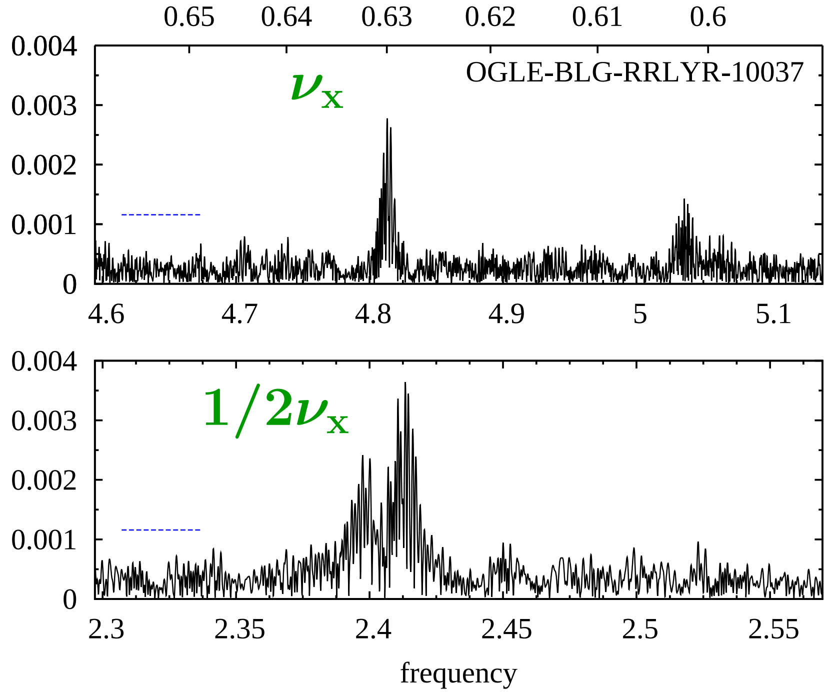


Strongly Trapped Unstable modes?

- $\ell = 8, 9$ (RRL) and $\ell = 7, 8, 9$ (Cep) match the frequencies at $1/2\nu_x$
- ν_x is a harmonic then: better visible due to nonlinear and geometric effects



Dziembowski (2016), *CoKon*

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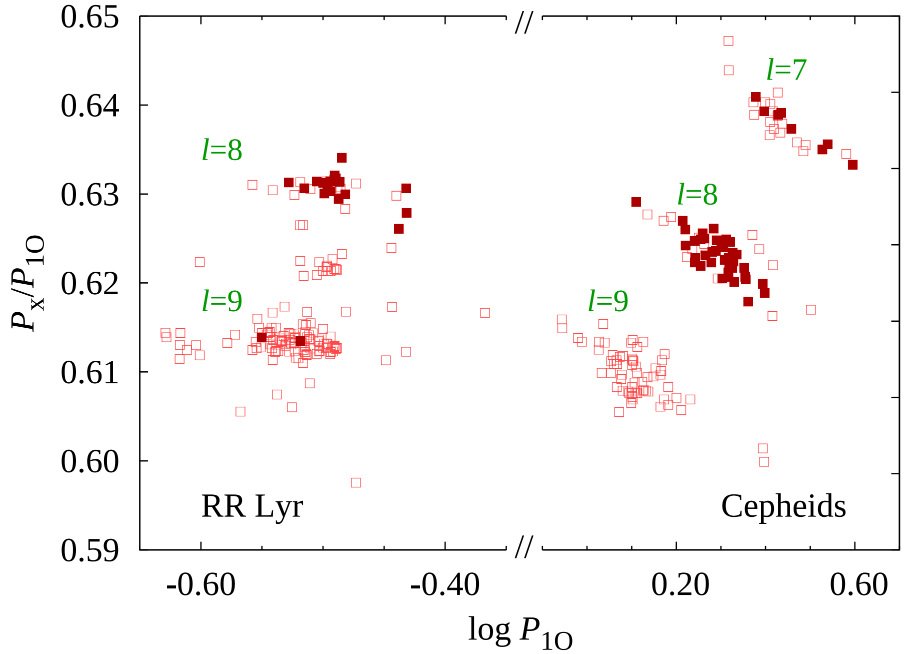

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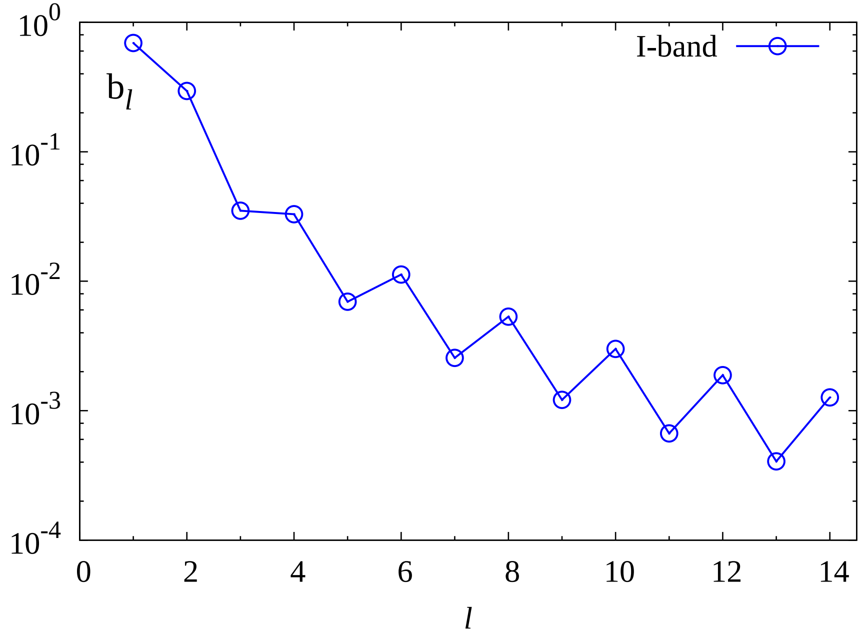

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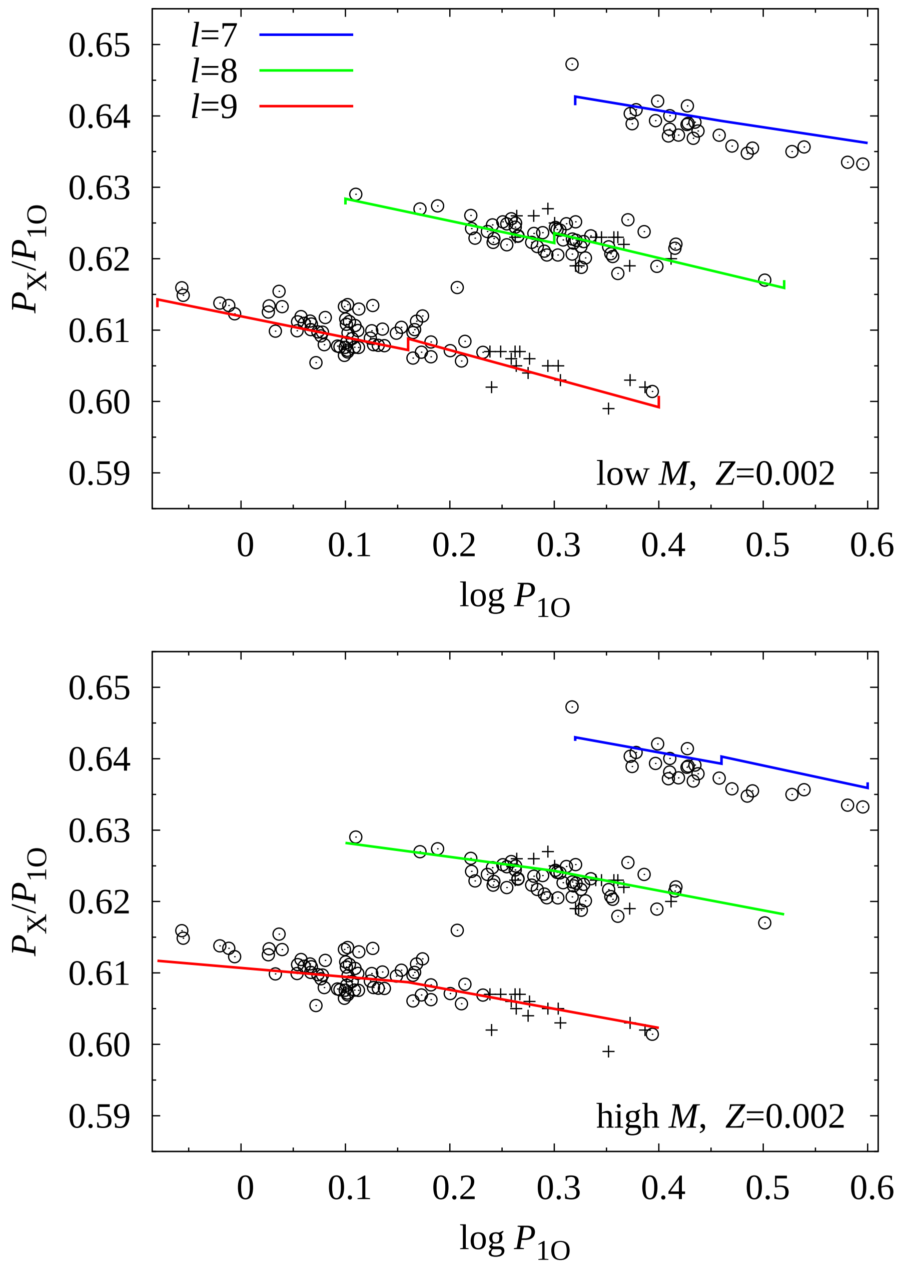

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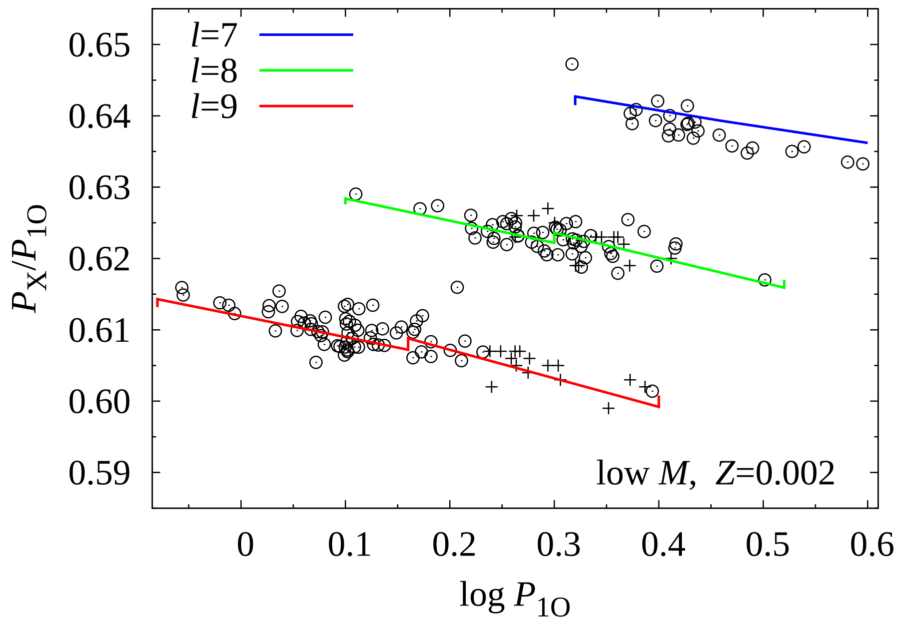

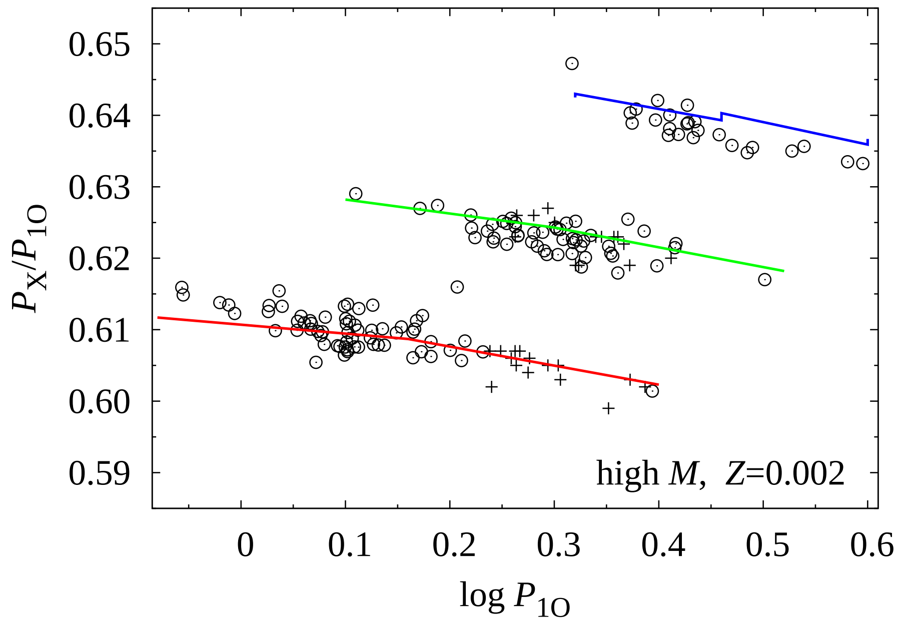

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⋆ obs. mode identification needed (H.Netzel talk)

⋆ signals at $3/2\nu_x$ difficult to explain

⋆ LMC picture is not that clear

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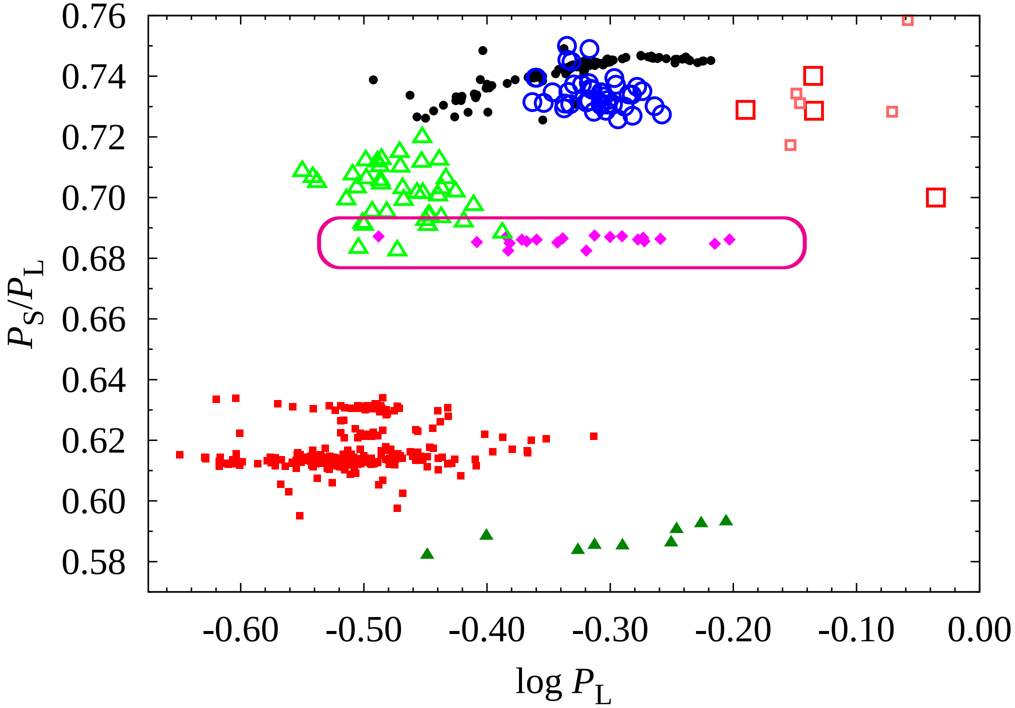

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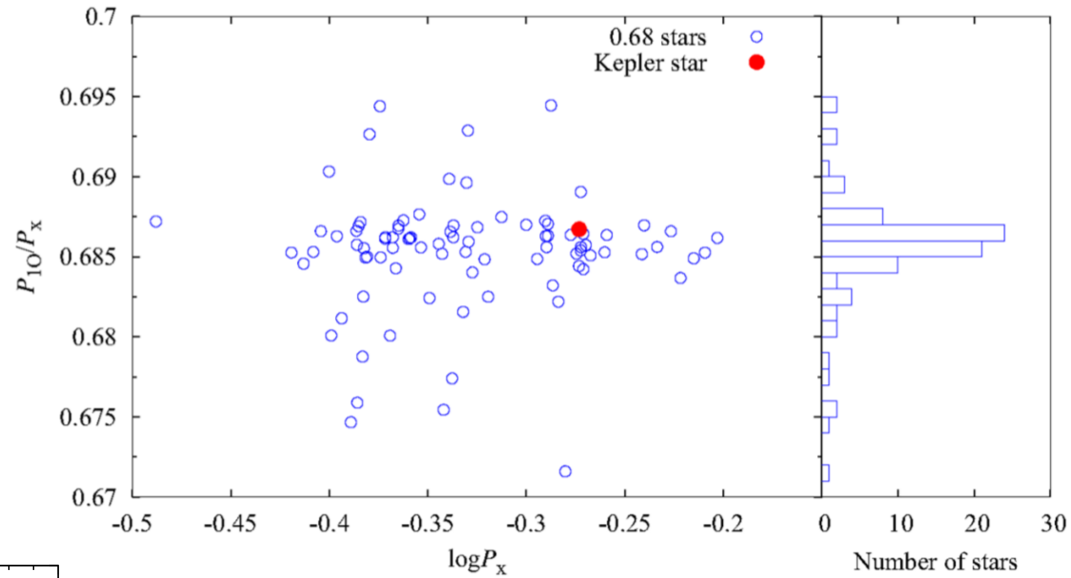

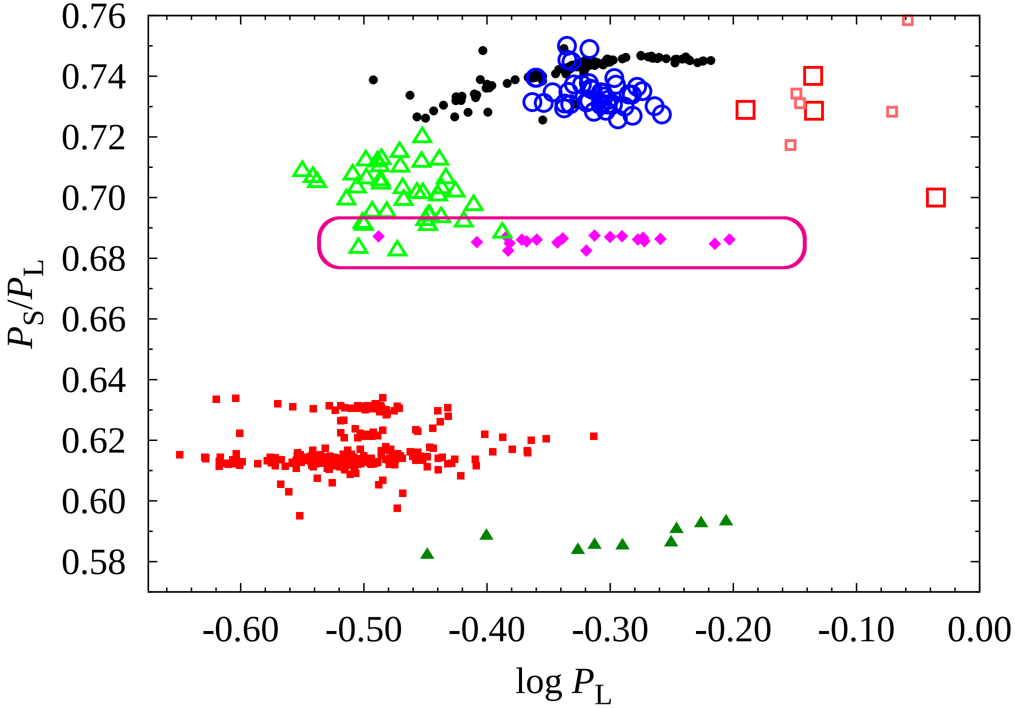

- 147 stars in OGLE blg collection
- frequency below radial F mode
- strongly coherent variability

Netzel & Smolec (2019), *MNRAS*

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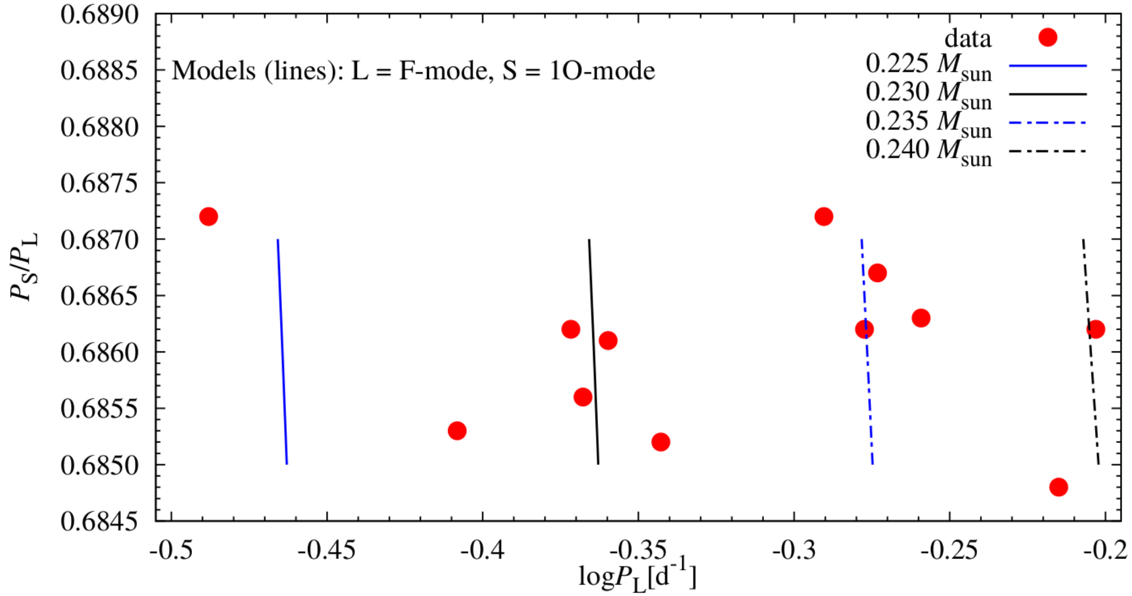

Stripped red giants?

- F+1O period ratio OK, but
- in conflict with 0.61-mode solution

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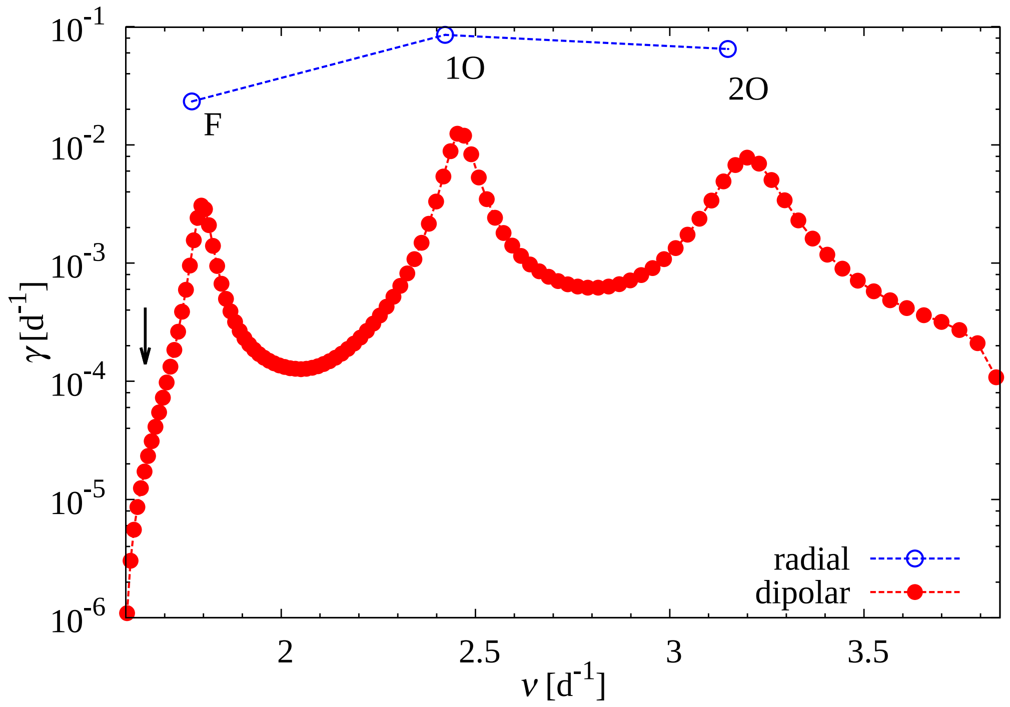

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Non-radial mode?

- what is the mode selection?

Any explanation must account for coherent nature of additional periodicity

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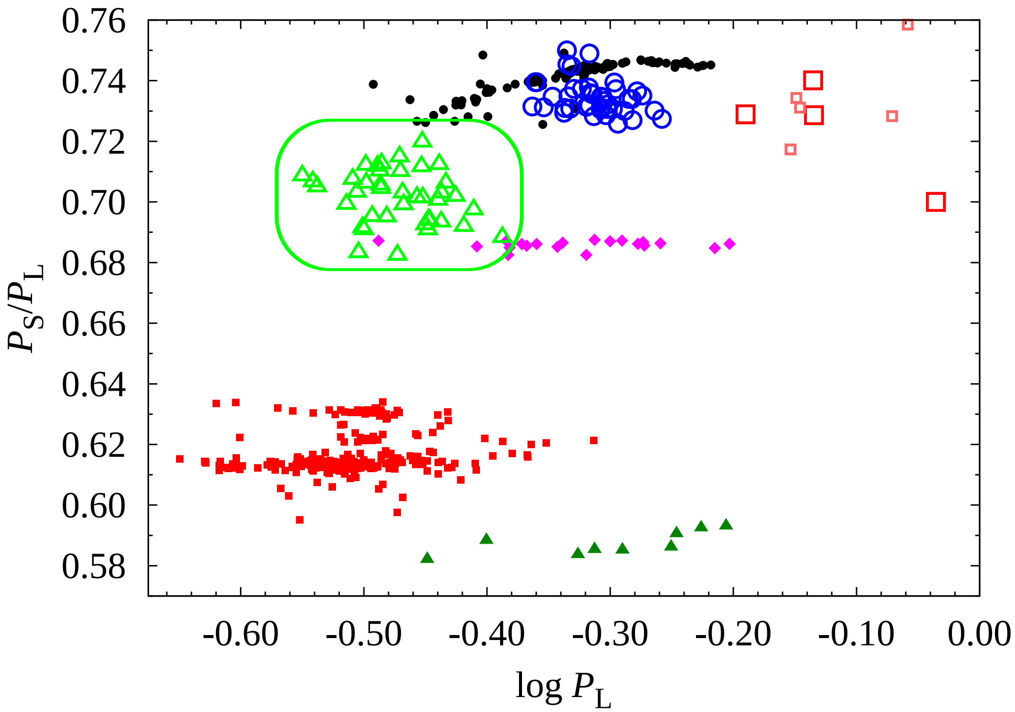

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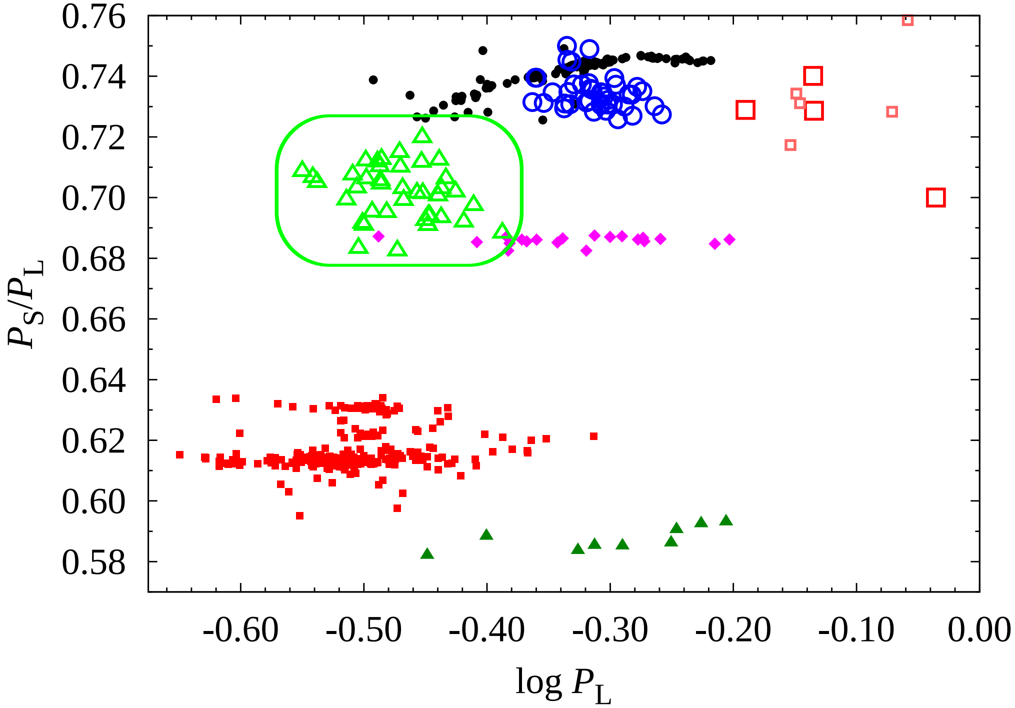

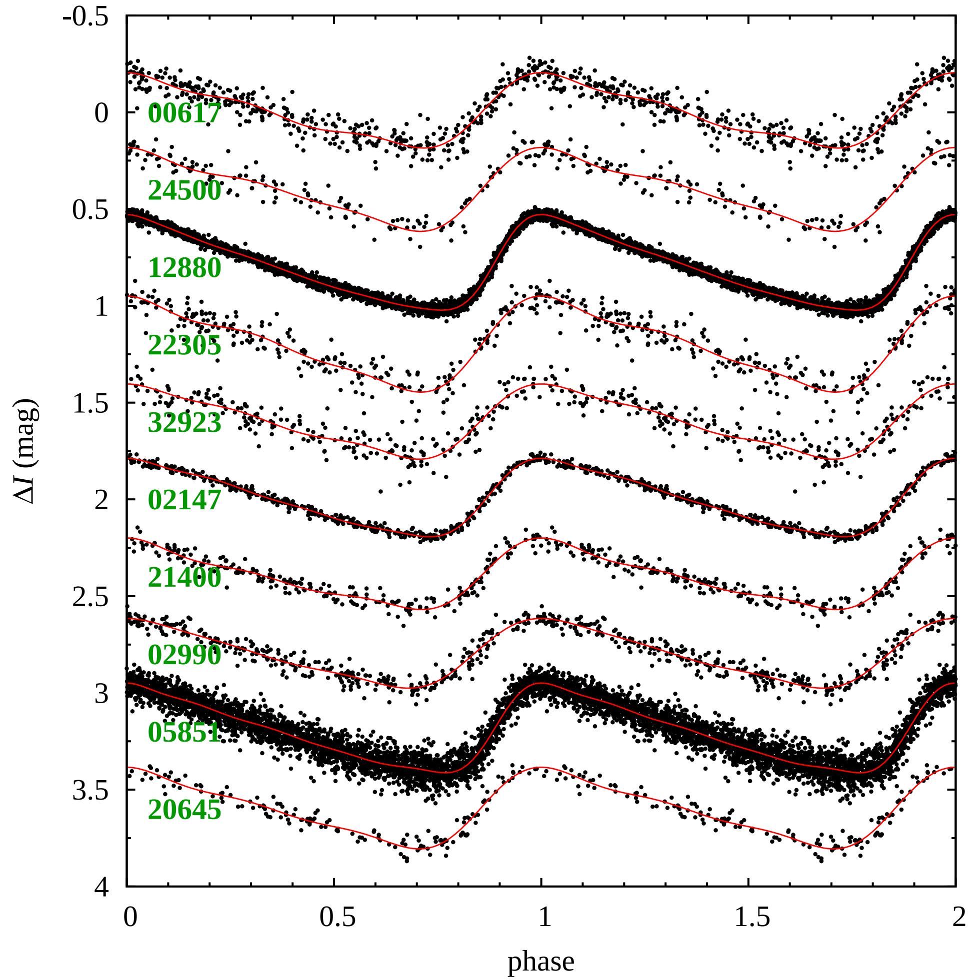

$$m = A_0 + \sum_k A_k \sin(k\omega_0 t + \phi_k)$$

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

Prudil et al. (2017), *MNRAS*

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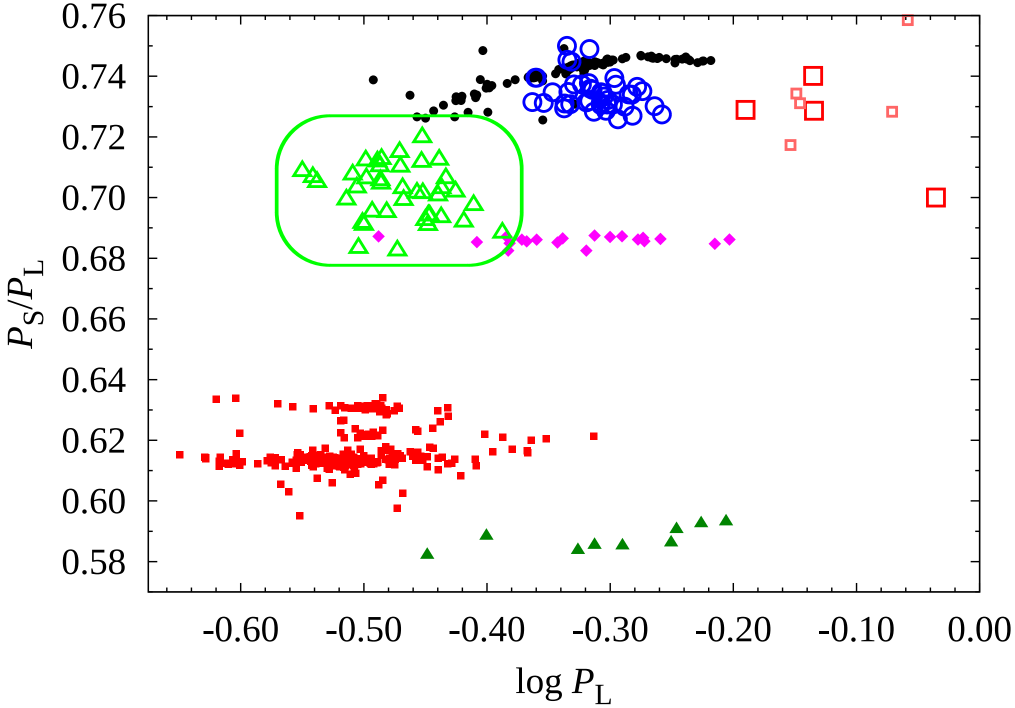

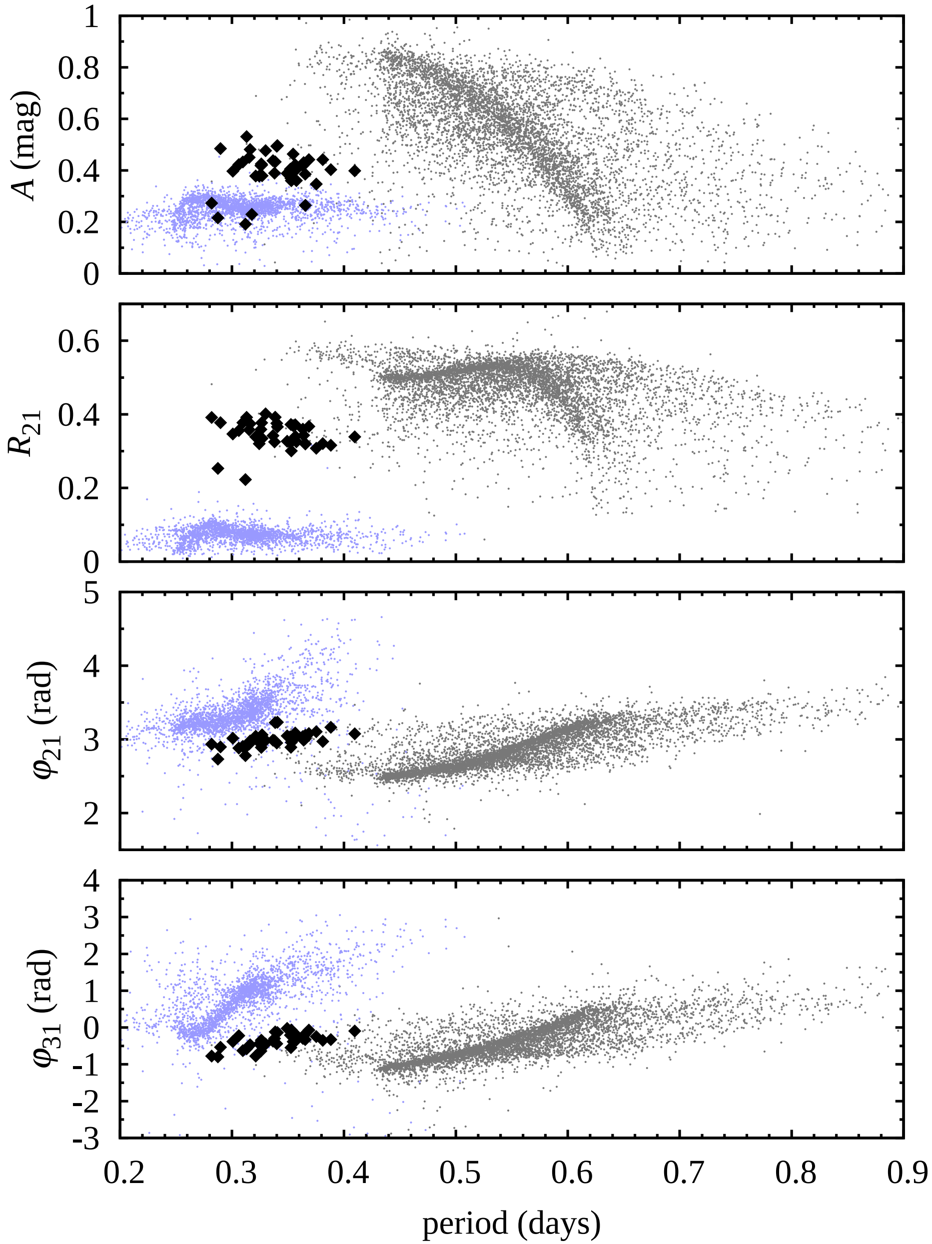

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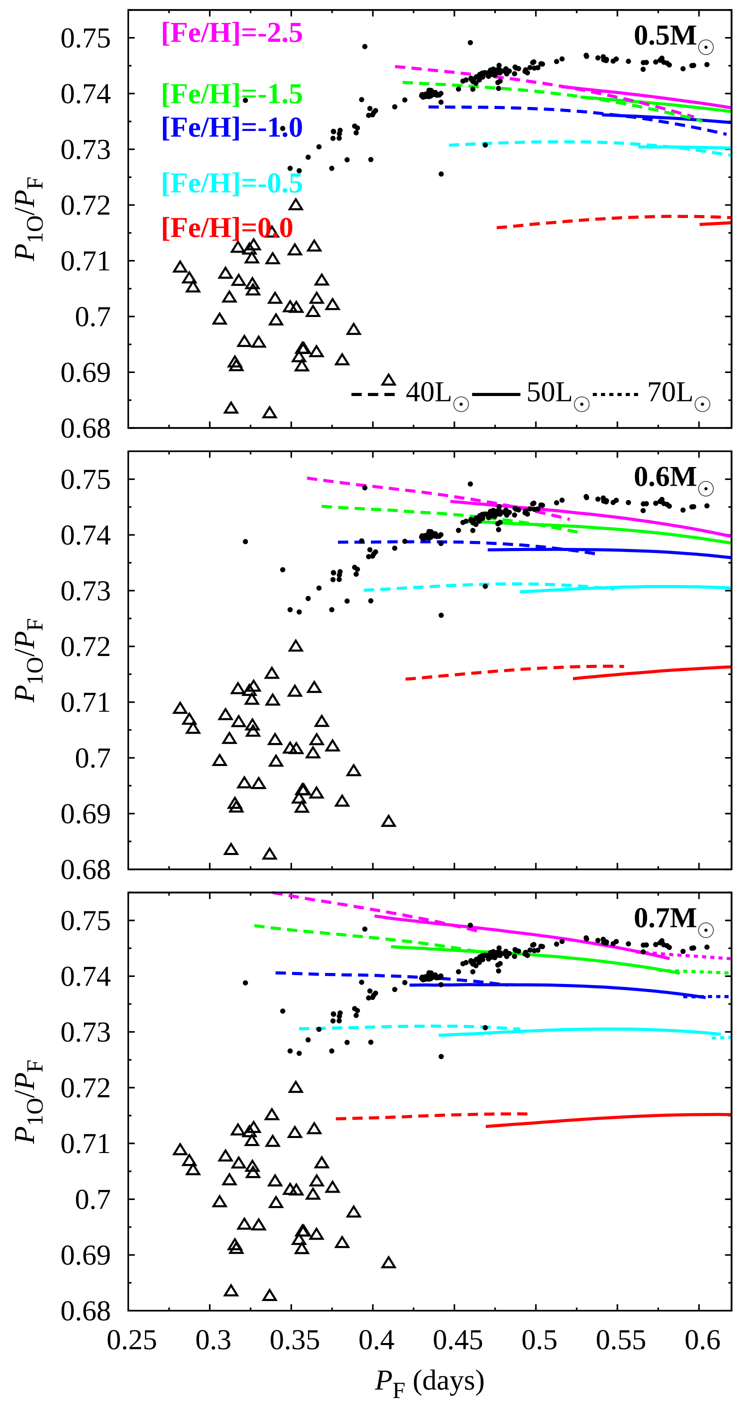
F+1O RR Lyrae or striped giant?

- Period ratios do not fit!

Is dominant periodicity F-mode?
Are these RR Lyrae?

Prudil et al. (2017), *MNRAS*



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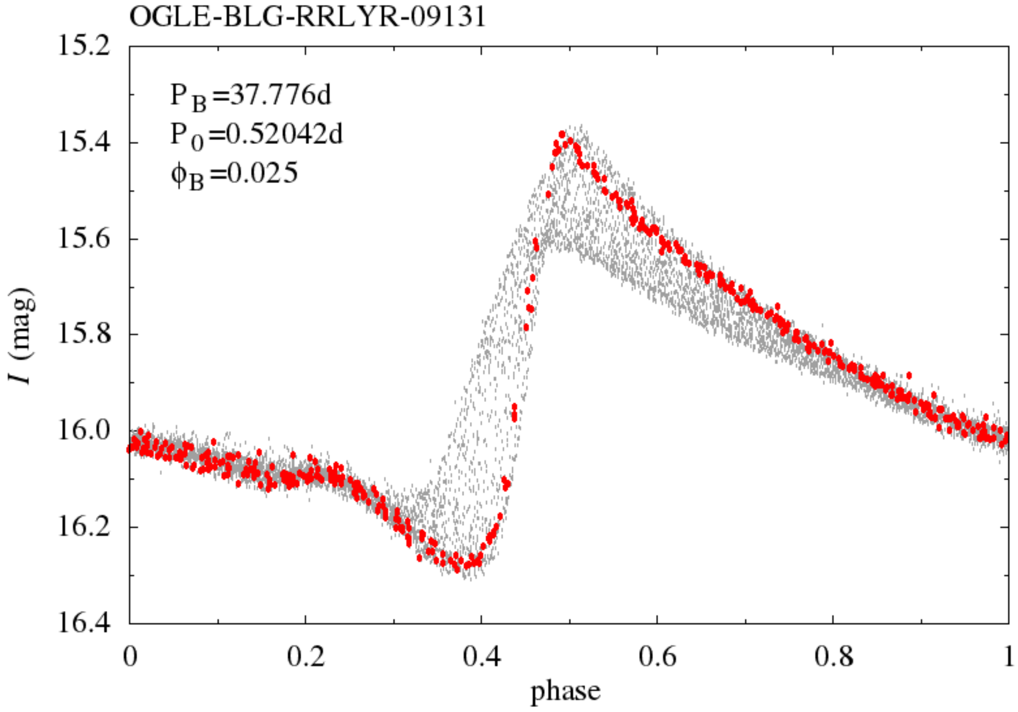
Periodic modulations

- RR Lyrae stars: Blazhko effect
- classical Cepheids: 1O+2O
- classical Cepheids: F-mode
- type-II Cepheids



animation: OGLE-IV data / R. Smolec

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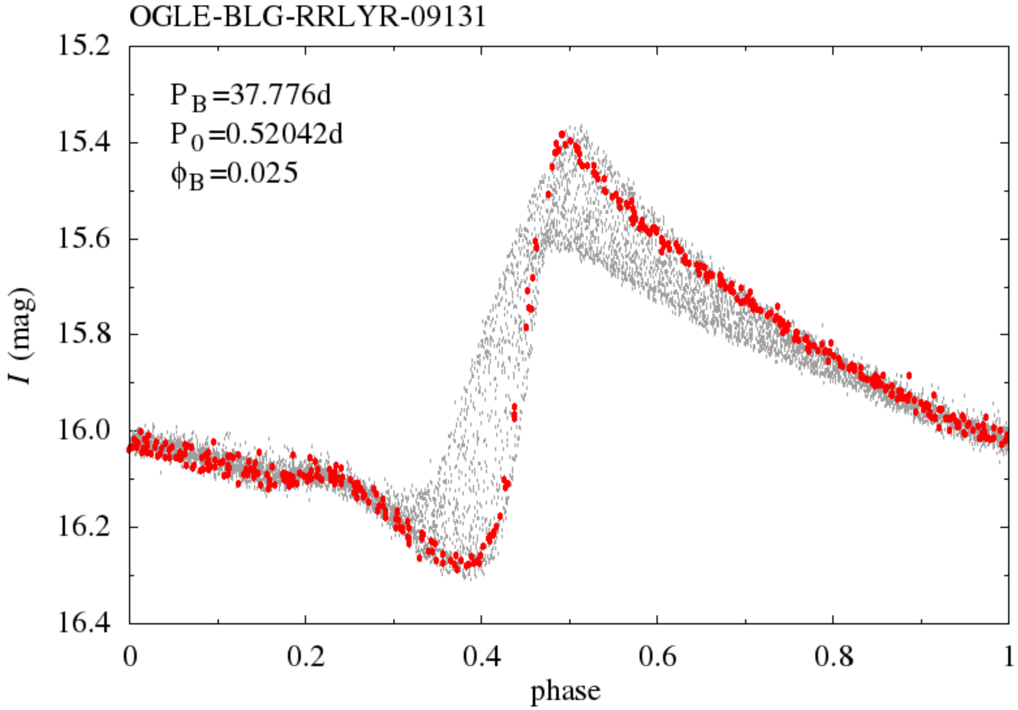
Possible explanations: Zoltan Kollath talk,
9:2 resonance with 9O
What about **RRc**?

My comment on 1D models:
The models are indeed simple and clearly lack some physics. But I believe the correct way to proceed is to put the best available physics we have at hand into it. Using unphysical assumption, that violates essential physics for convection and pulsation, because the models better match the observations, is risky.



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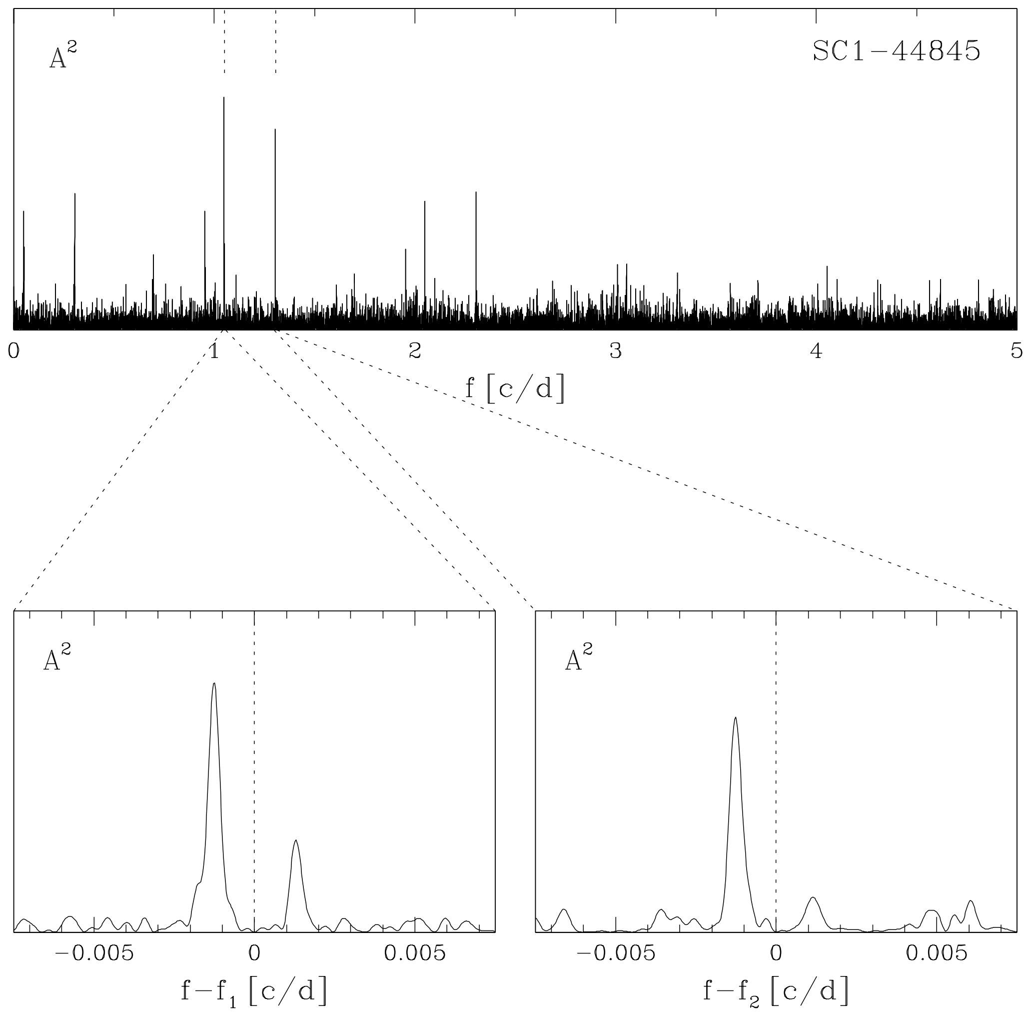

⋆ long-period modulation in 1O+2O Cepheids

⋆ both 1O and 2O are modulated

⋆ anticorrelated amplitudes

Moskalik & Kołaczkowski (2009), *MNRAS*

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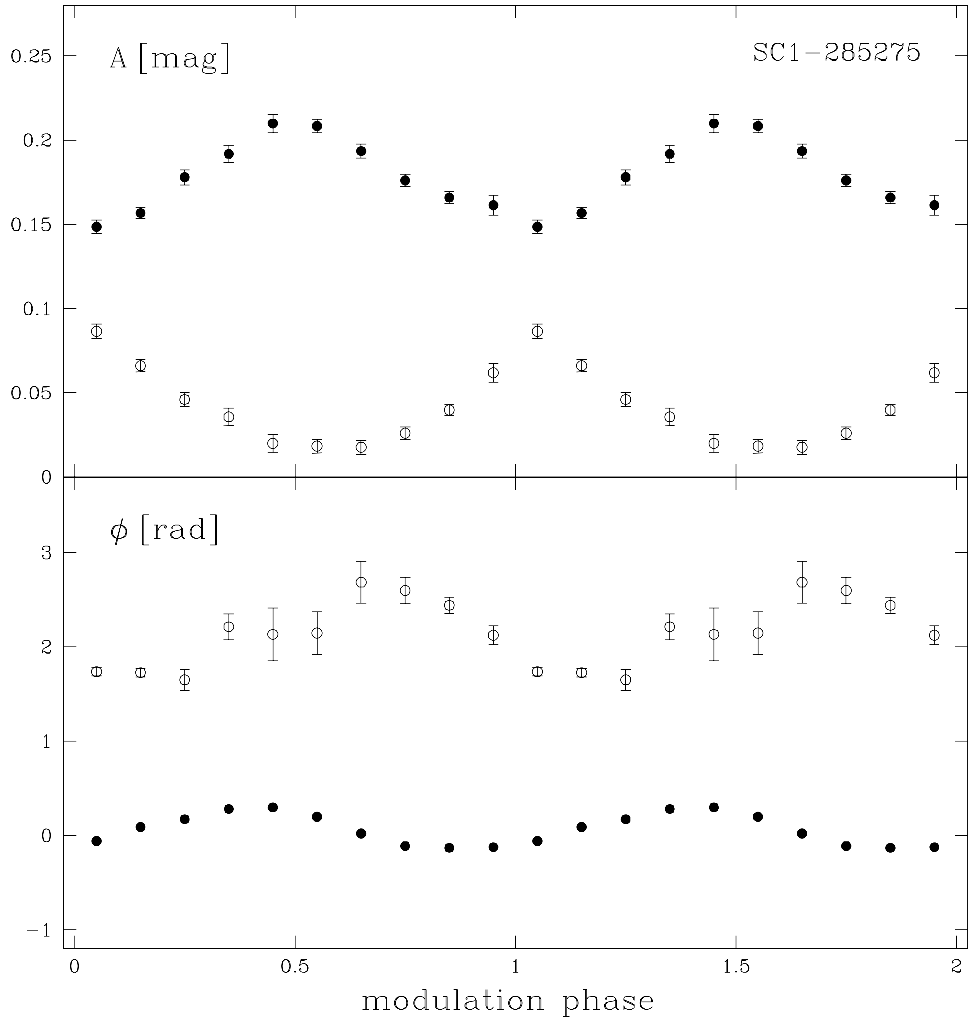

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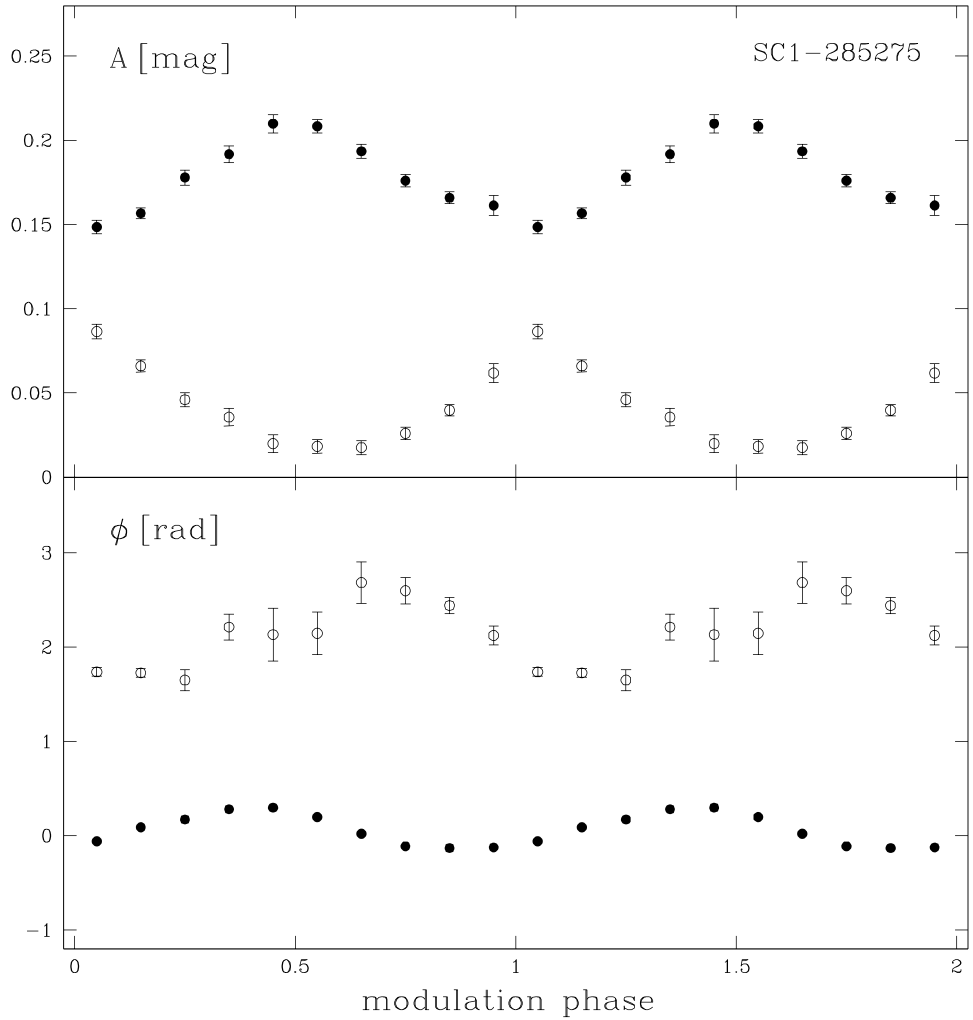

Moskalik & Kołaczkowski (2009) concluded that mode interaction must take place. Likely one of the 1O/2O modes in resonance with other radial/non-radial mode, the other affected by crosssaturation.

No detailed scenario proposed, no further investigation.

Moskalik & Kołaczkowski (2009), *MNRAS*

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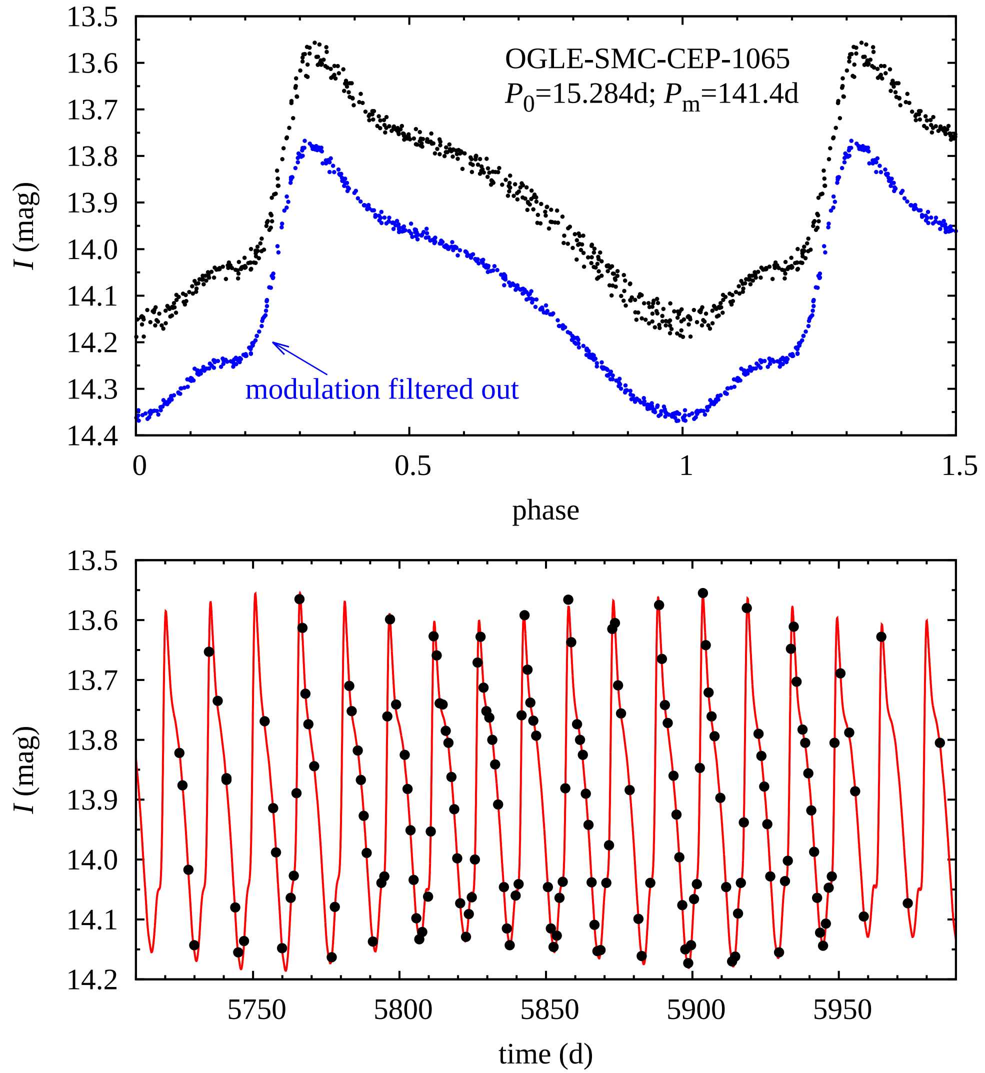

- ⋆ up to 10 mmag effect
- ⋆ modulation period $\sim 10 \times P_0$
- ⋆ the effect may be common
- ⋆ mean brightness modulation

Smolec (2017), *MNRAS*

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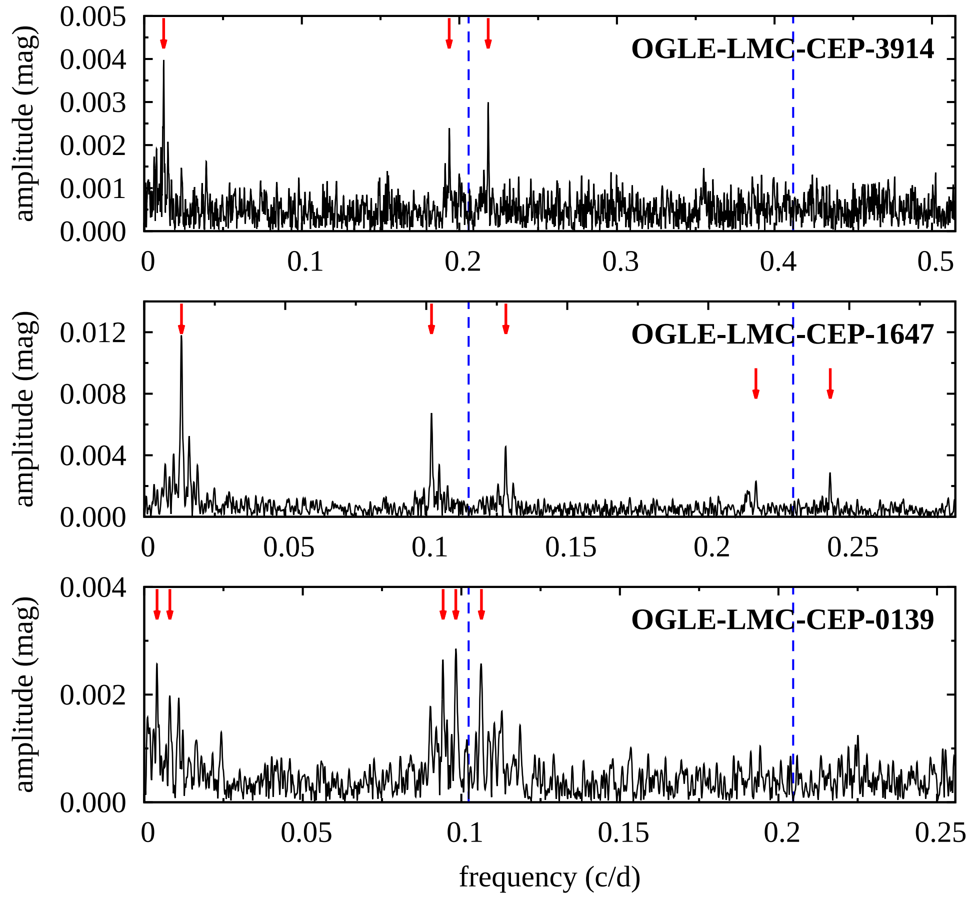

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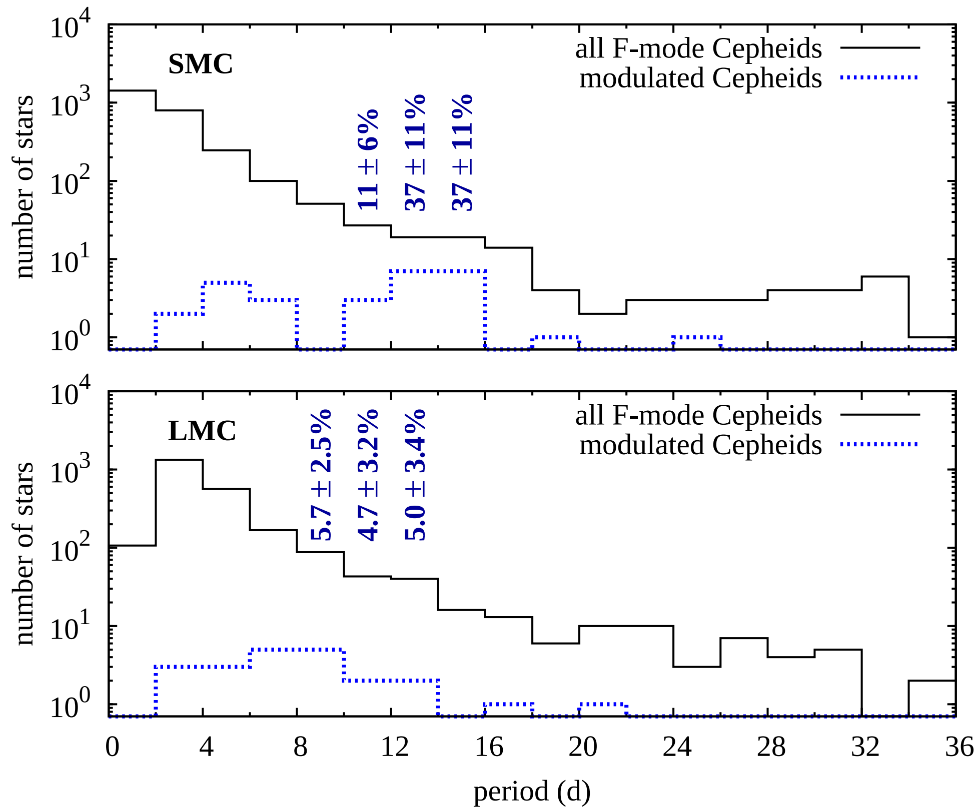

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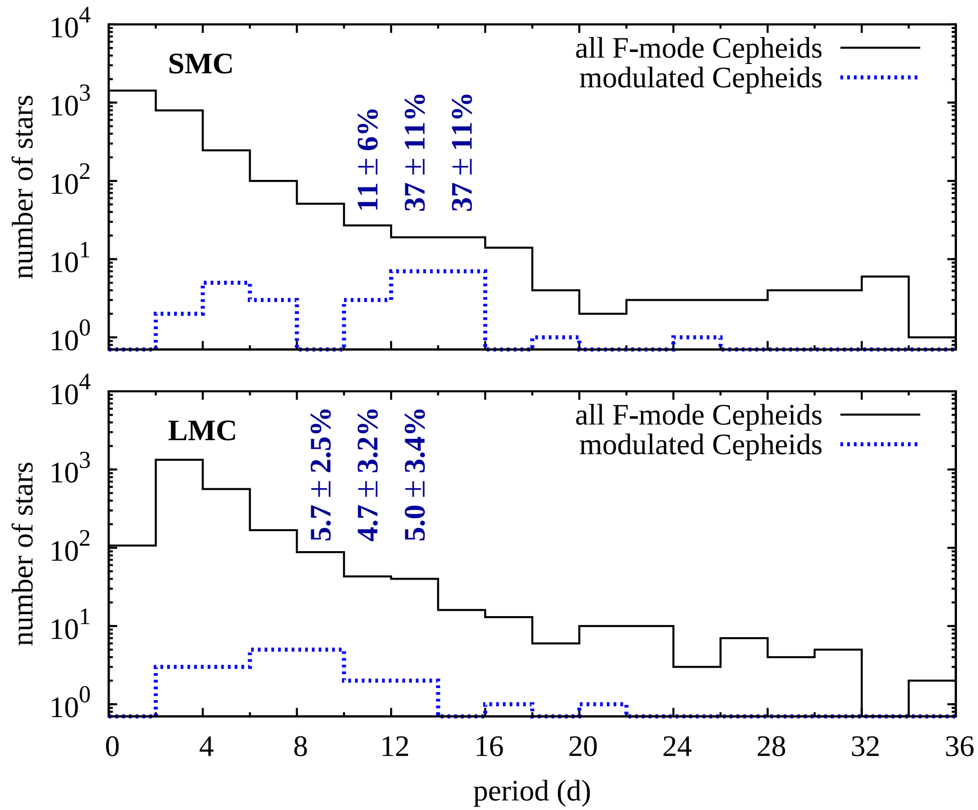

In Smolec (2016), I speculate that 2:1 resonance that shapes the Hertzsprung bump progression may play a role. The 2:1 resonance in the context of Blazhko effect was discussed wit AEs by Moskalik (1986)

No detailed scenario proposed, no further investigation.

Smolec (2017), *MNRAS*

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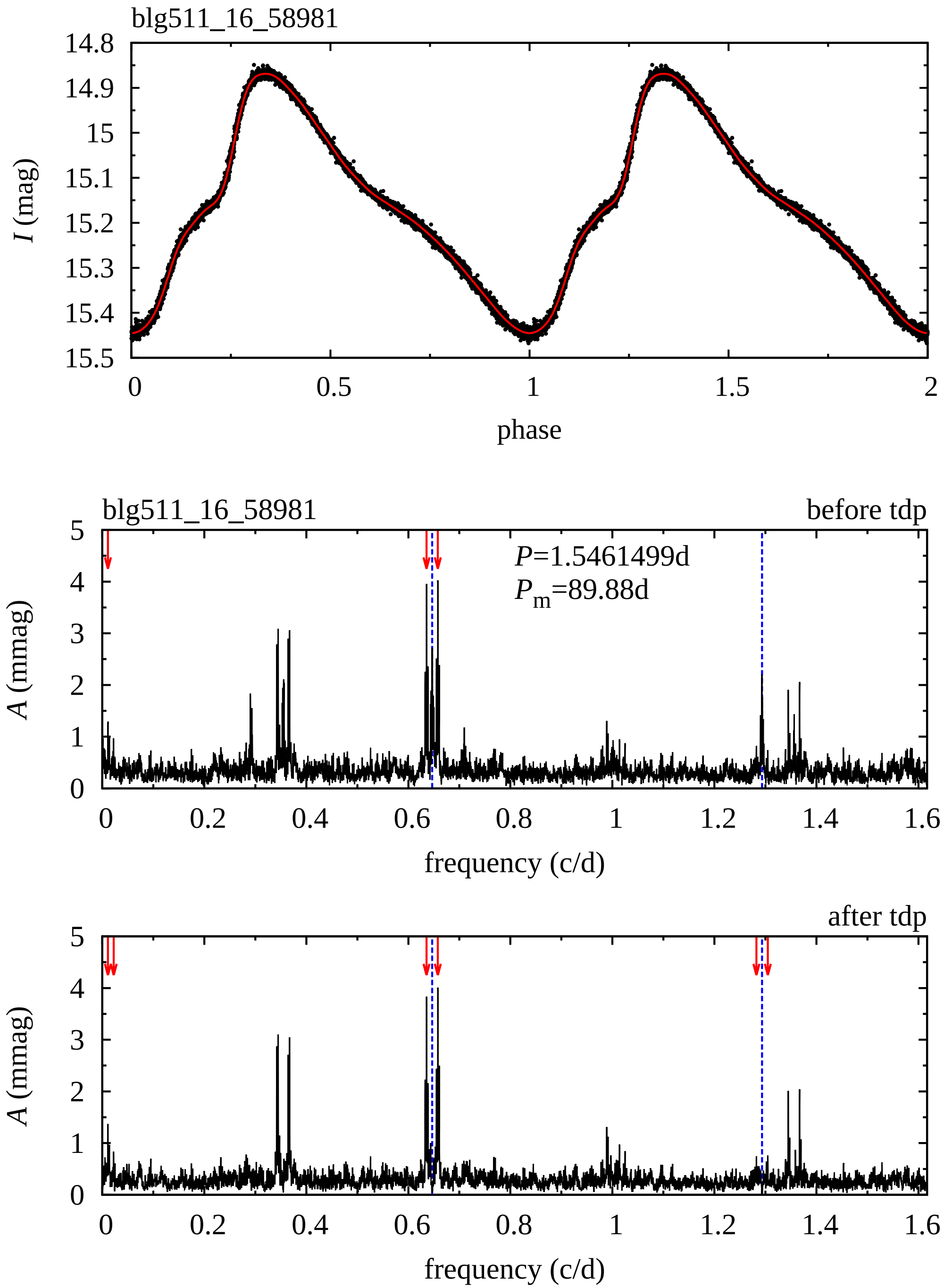

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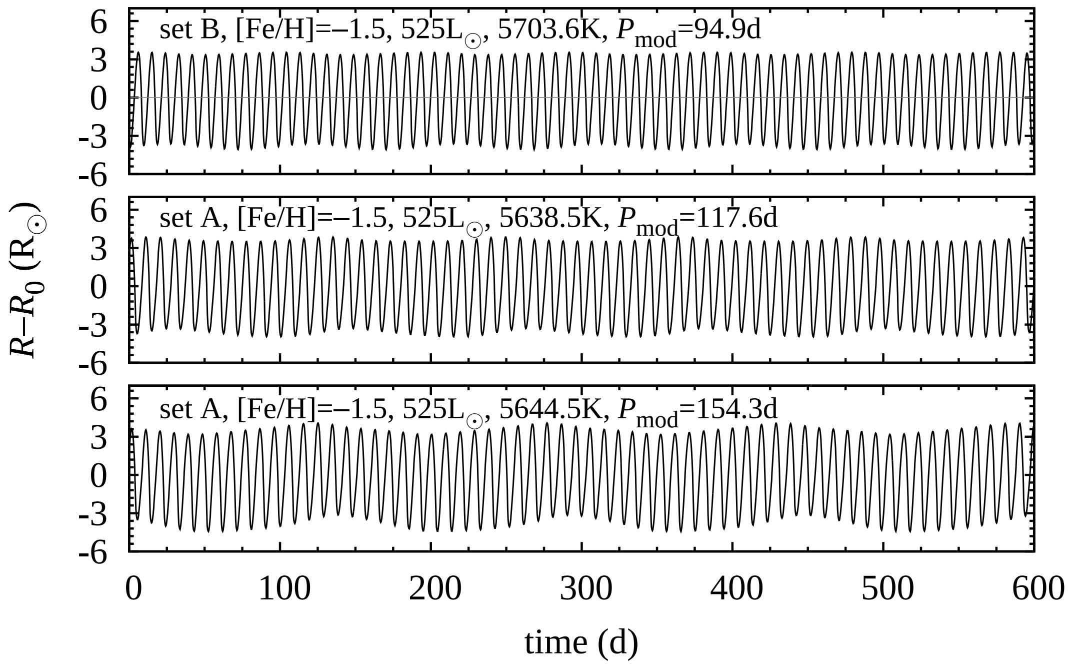
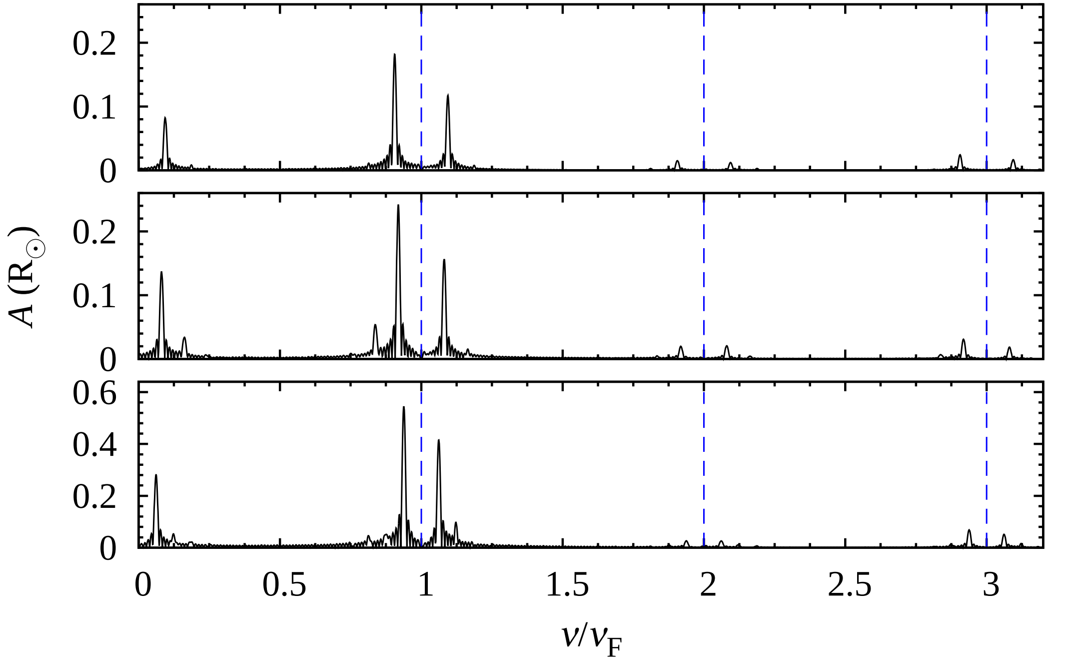




Modulated nonlinear convective models of type-II Cepheids were reported in Smolec & Moskalik (2012) and Smolec (2016). In some of the models modulation is on top of PD and **may be due to half integer resonances**.

In some models modulation was detected only, no PD. Origin may be resonant.

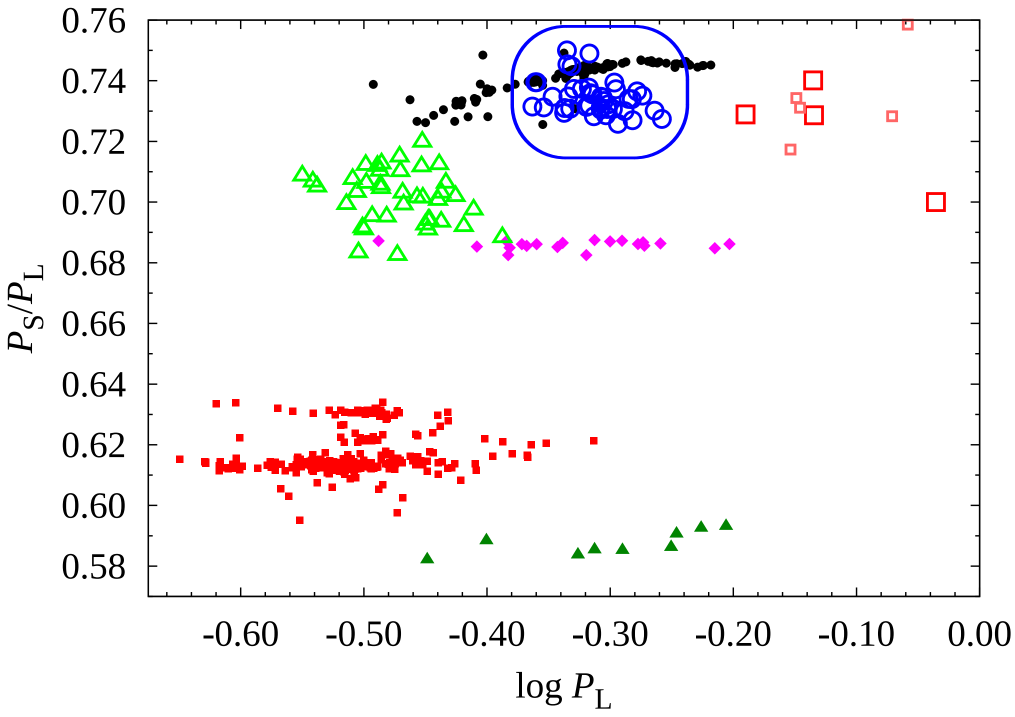
Smolec (2016), *MNRAS*

Beyond radial modes

- additional low-amplitude periodicities
- all flavours of periodic modulation
- back to radial modes

Radial modes

- RR Lyrae: anRRd, eRRd
- BL Her: F+1O
- BL Her: 1O
- BL Her: PD effect
- W Vir: PD effect



Radial modes

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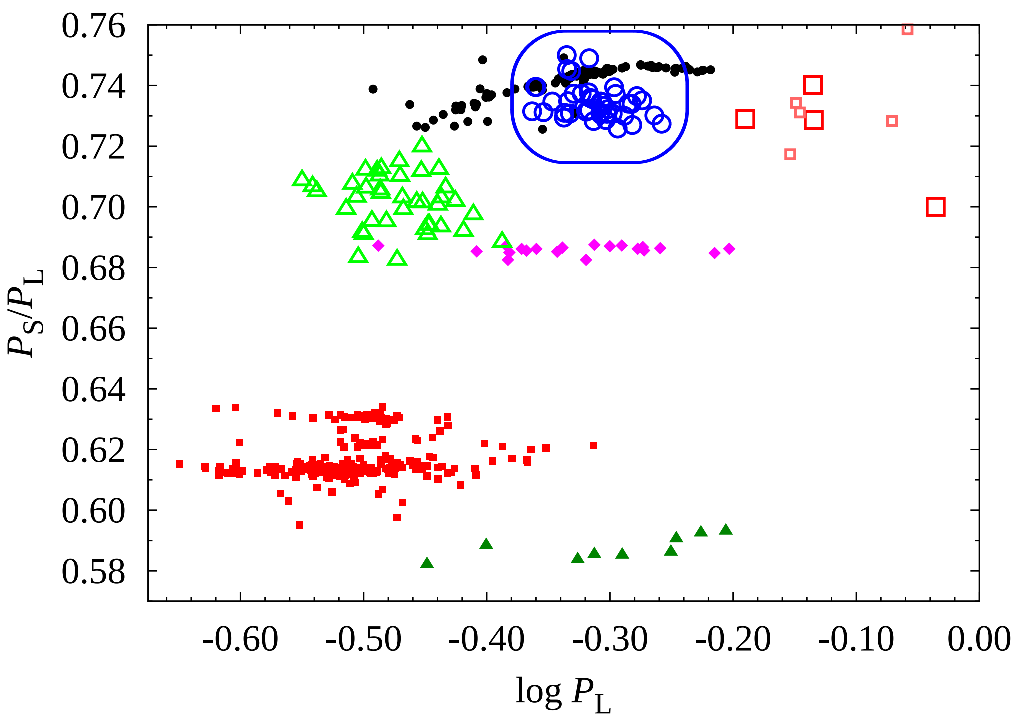

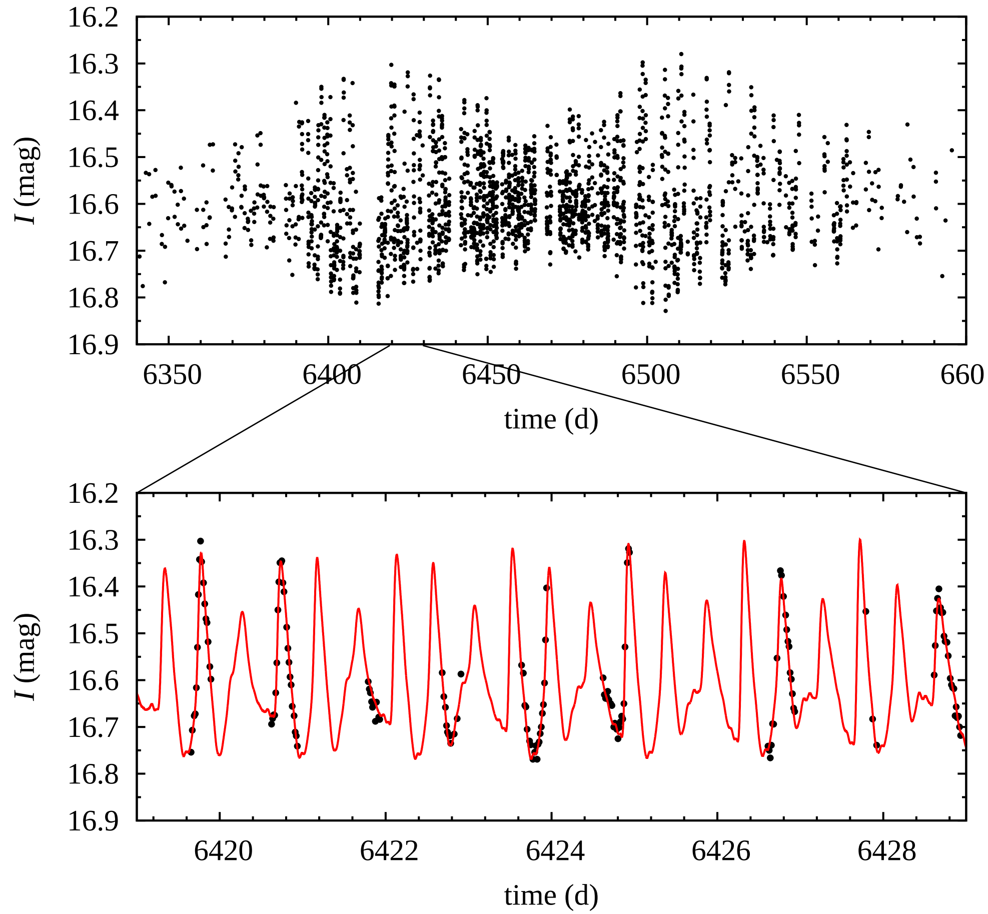

Anomalous RRd stars

- ⋆ with modulation
- ⋆ with anomalous period and amplitude ratios

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

Radial modes

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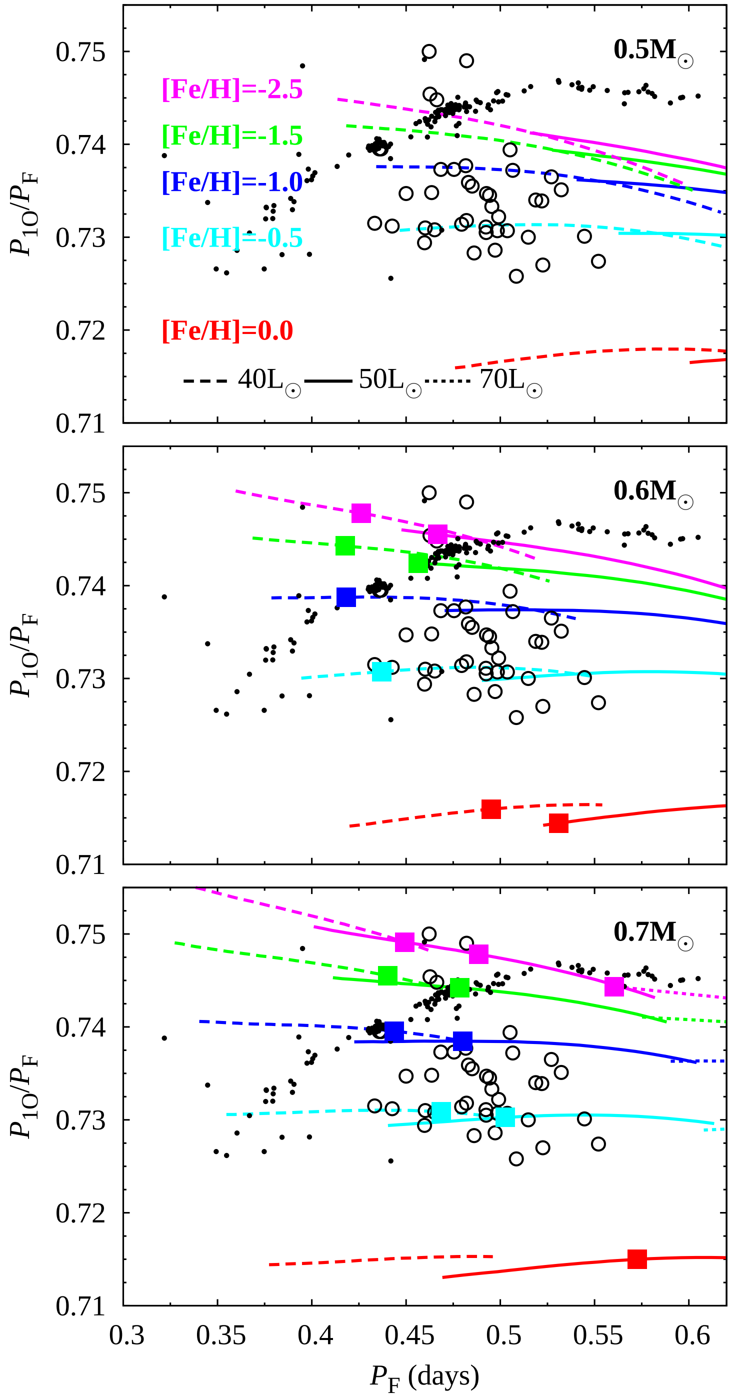

Is F+1O indeed plausible explanation?

- Period ratios do fit!

What is the cause of anomalies?

- $2\nu_{1O} = \nu_F + \nu_{2O}$ resonance?

Needs verification; but how? AEs?

Smolec et al. (2015)

Radial modes

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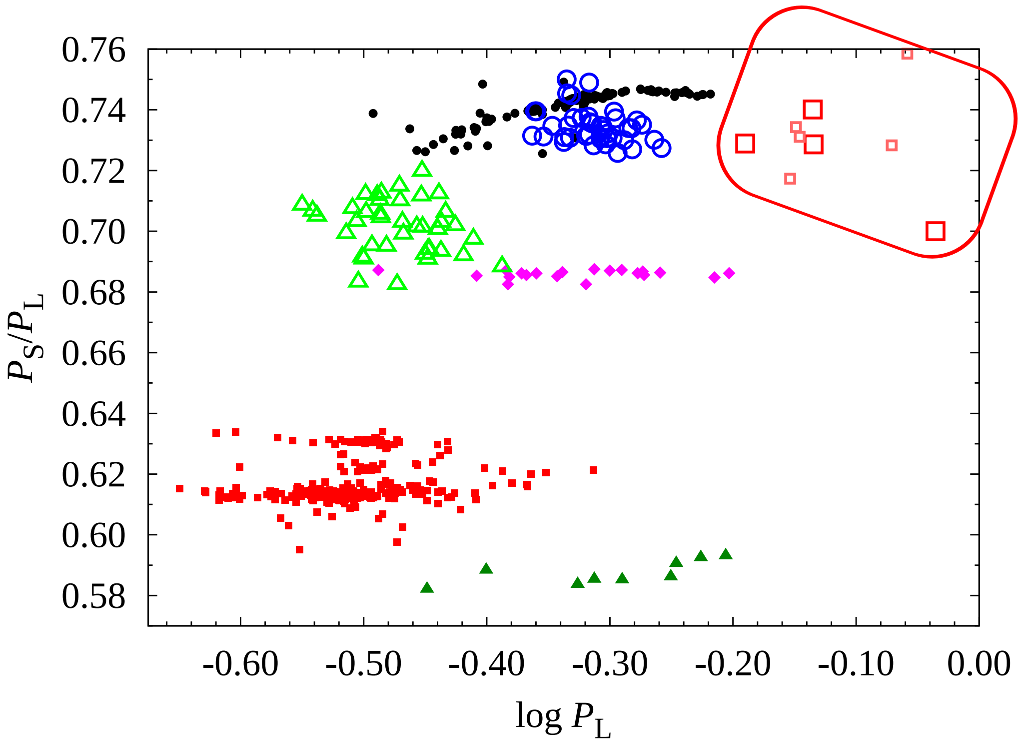

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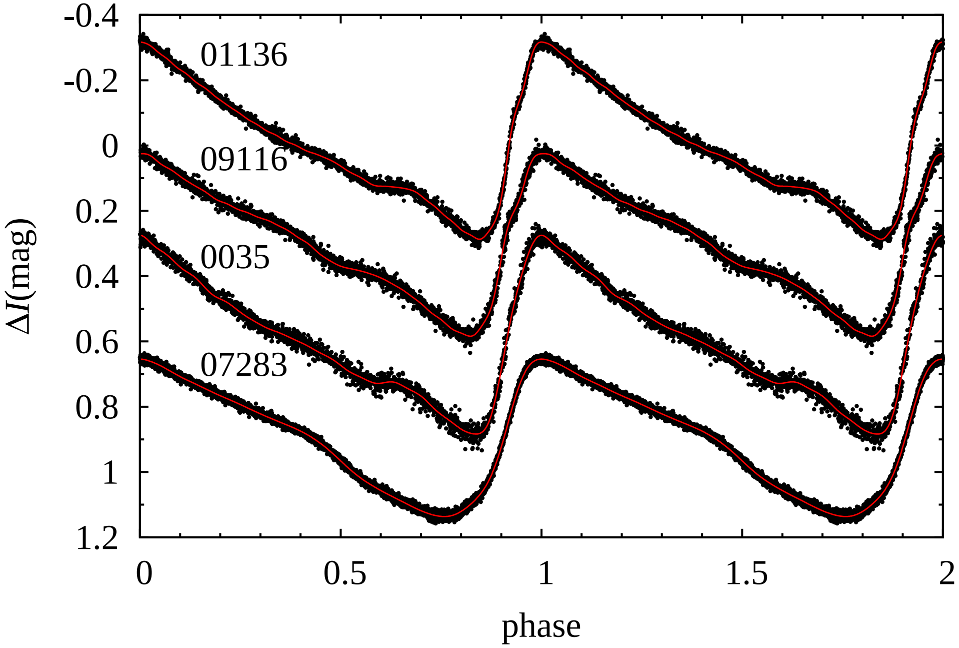

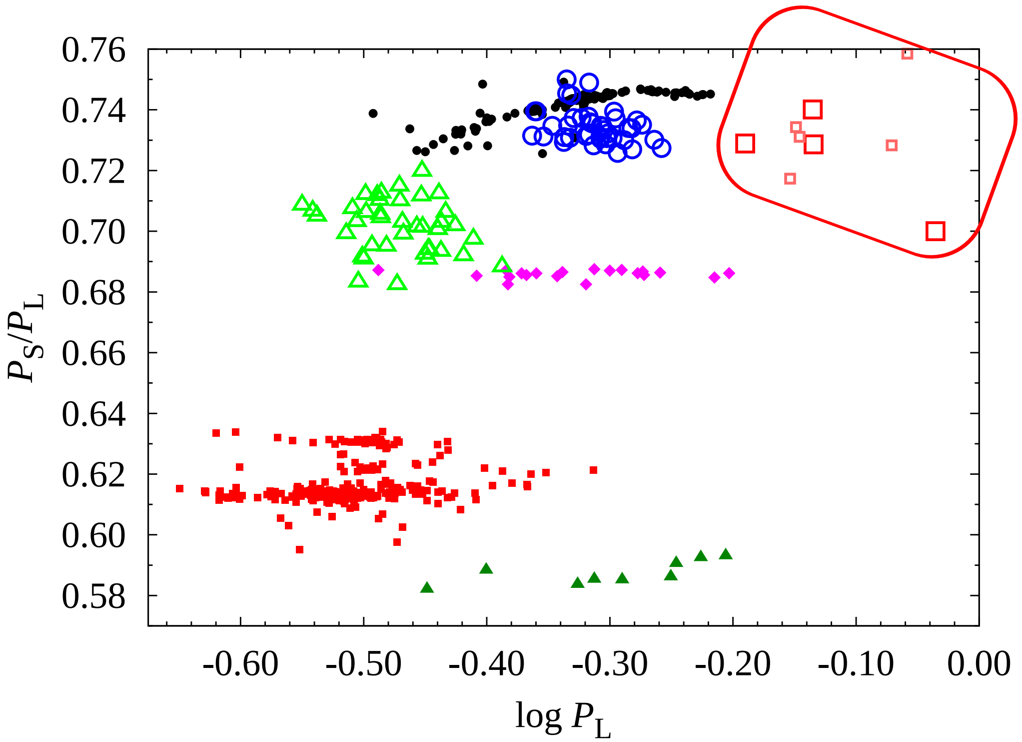

⋆ extreme RRd stars, with dominant F

Smolec et al. (2016)

Radial modes

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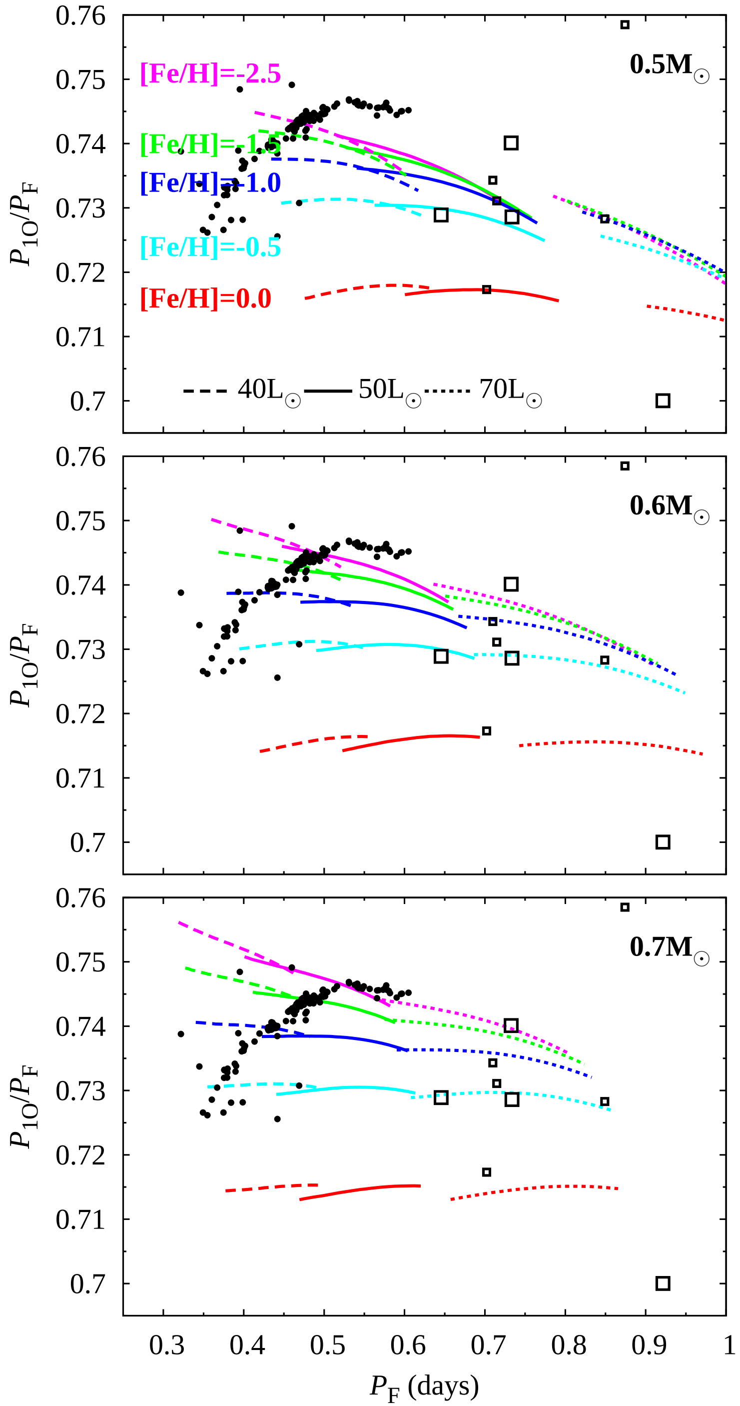

Is F+1O indeed plausible explanation?

- ▶ Period ratios do fit!

Why RRd at such long periods?

Smolec et al. (2016)

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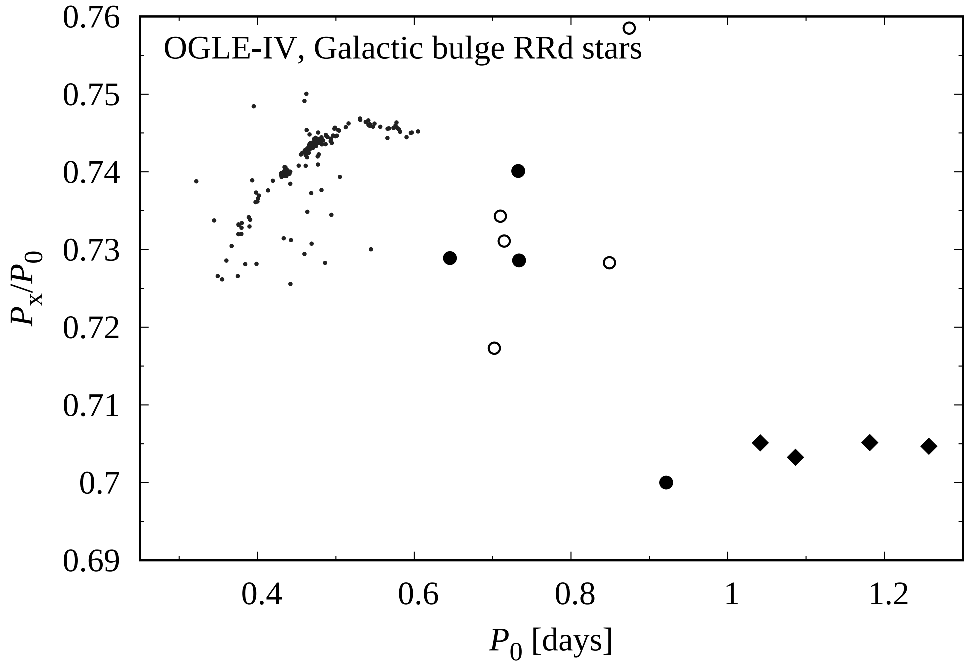

Smolec et al. (2018), *MNRAS*; Udalski et al. (2019), *AcA*

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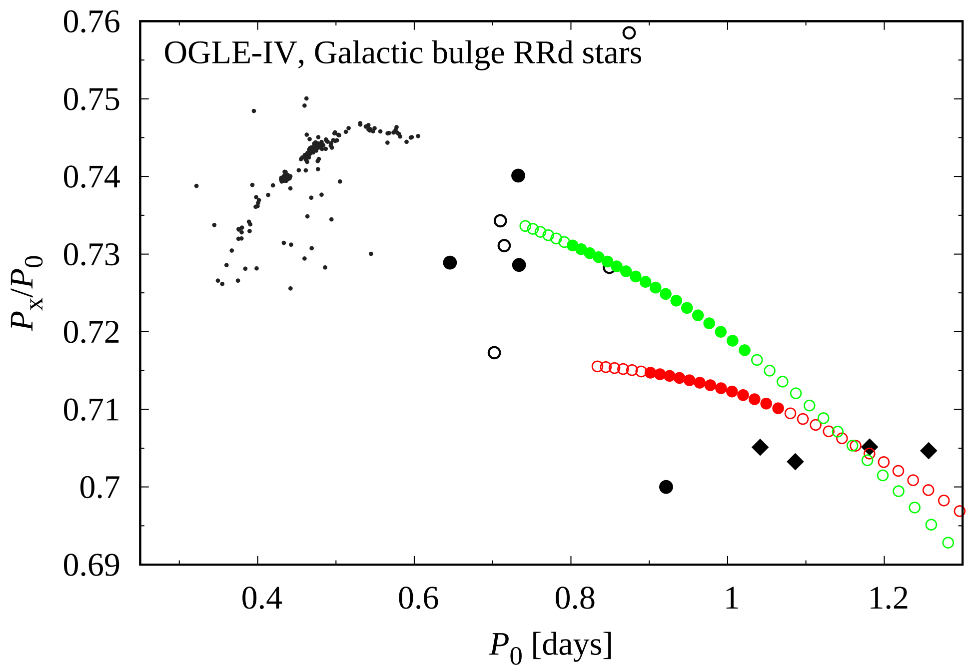

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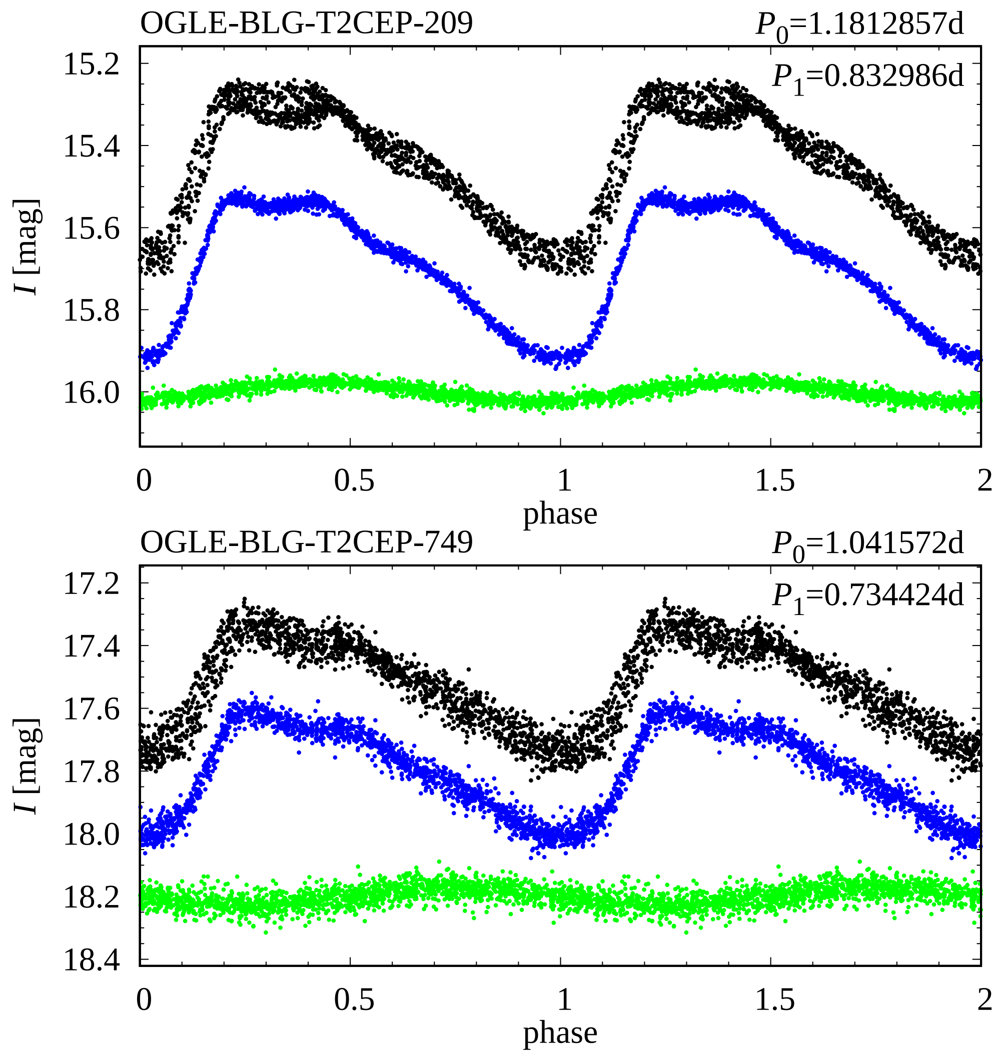

Smolec et al. (2018), *MNRAS*

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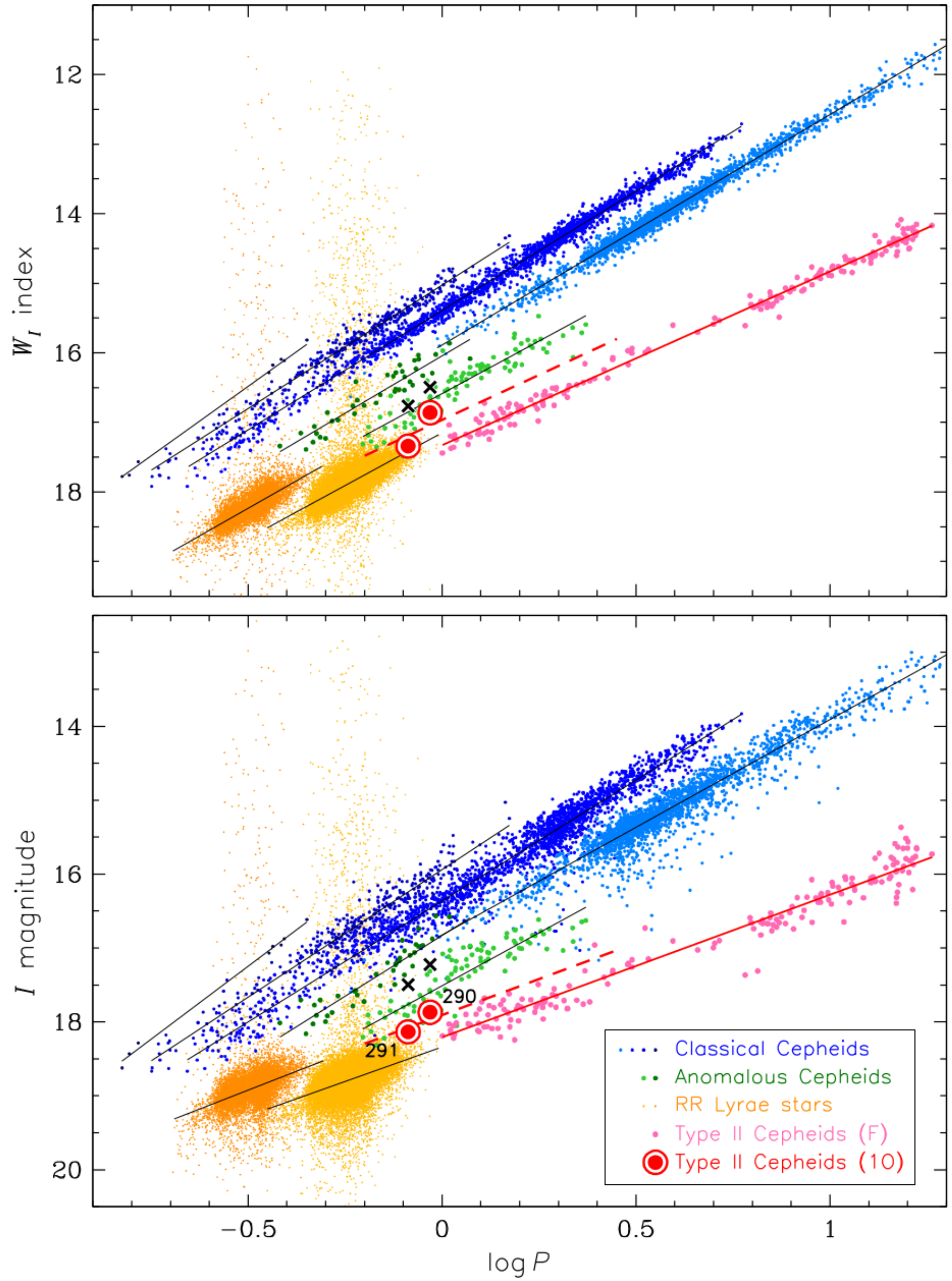

Soszyński et al. (2019), *ApJ*

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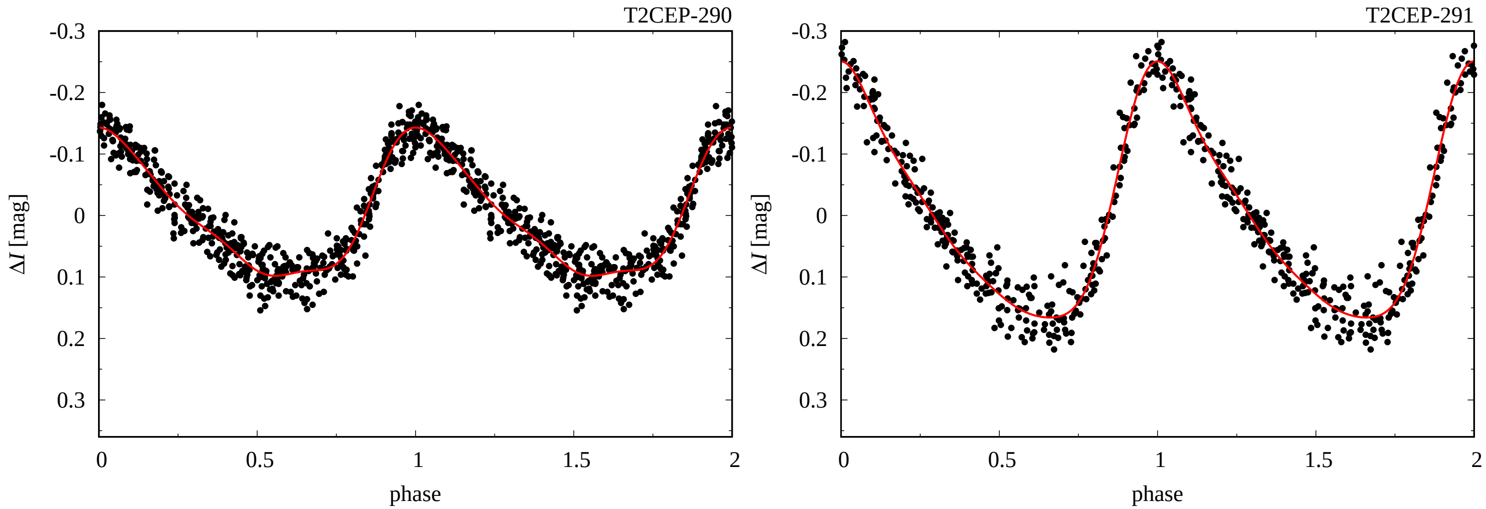

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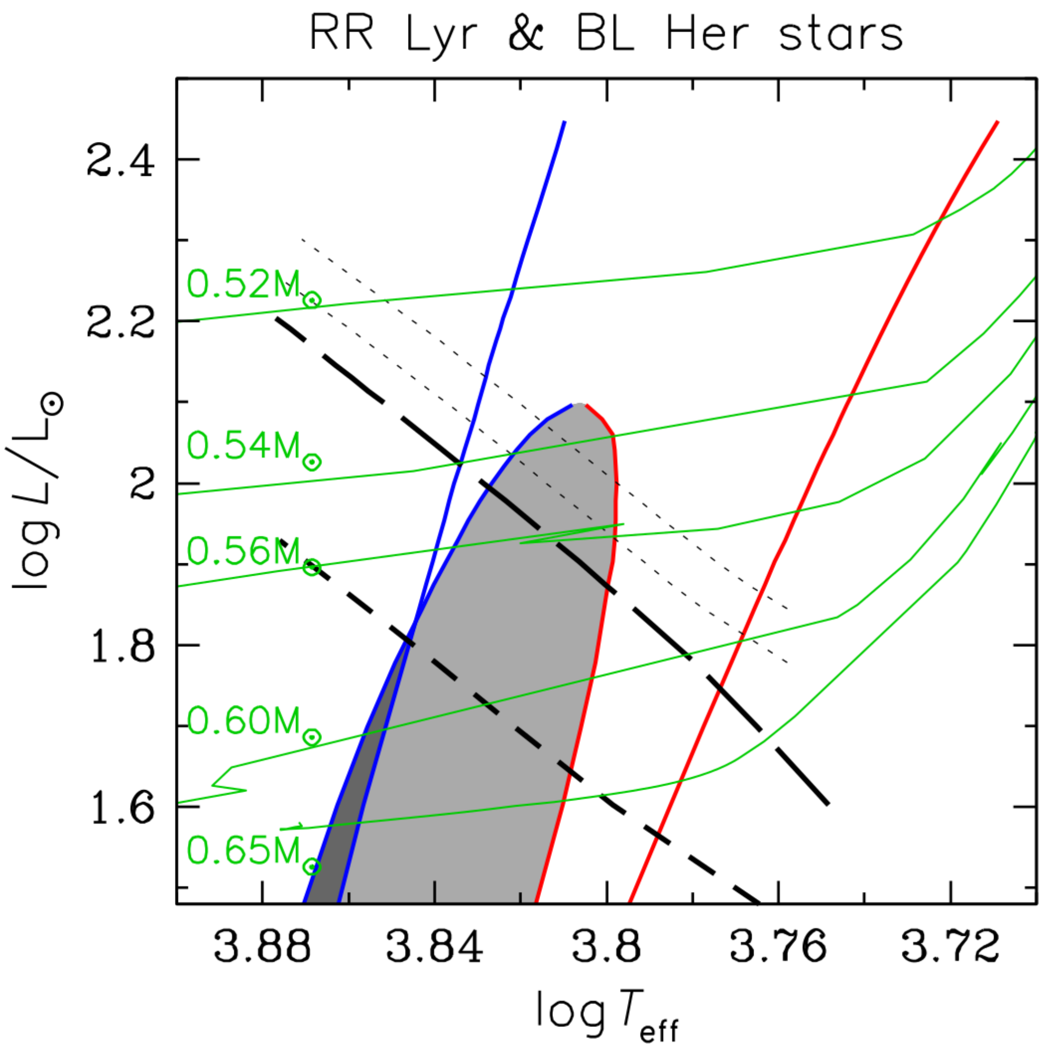

Is 1O pulsation plausible for BL Her stars?

- Instability strip: OK!
- Mode selection is a challenge!

Soszyński et al. (2019), *ApJ*

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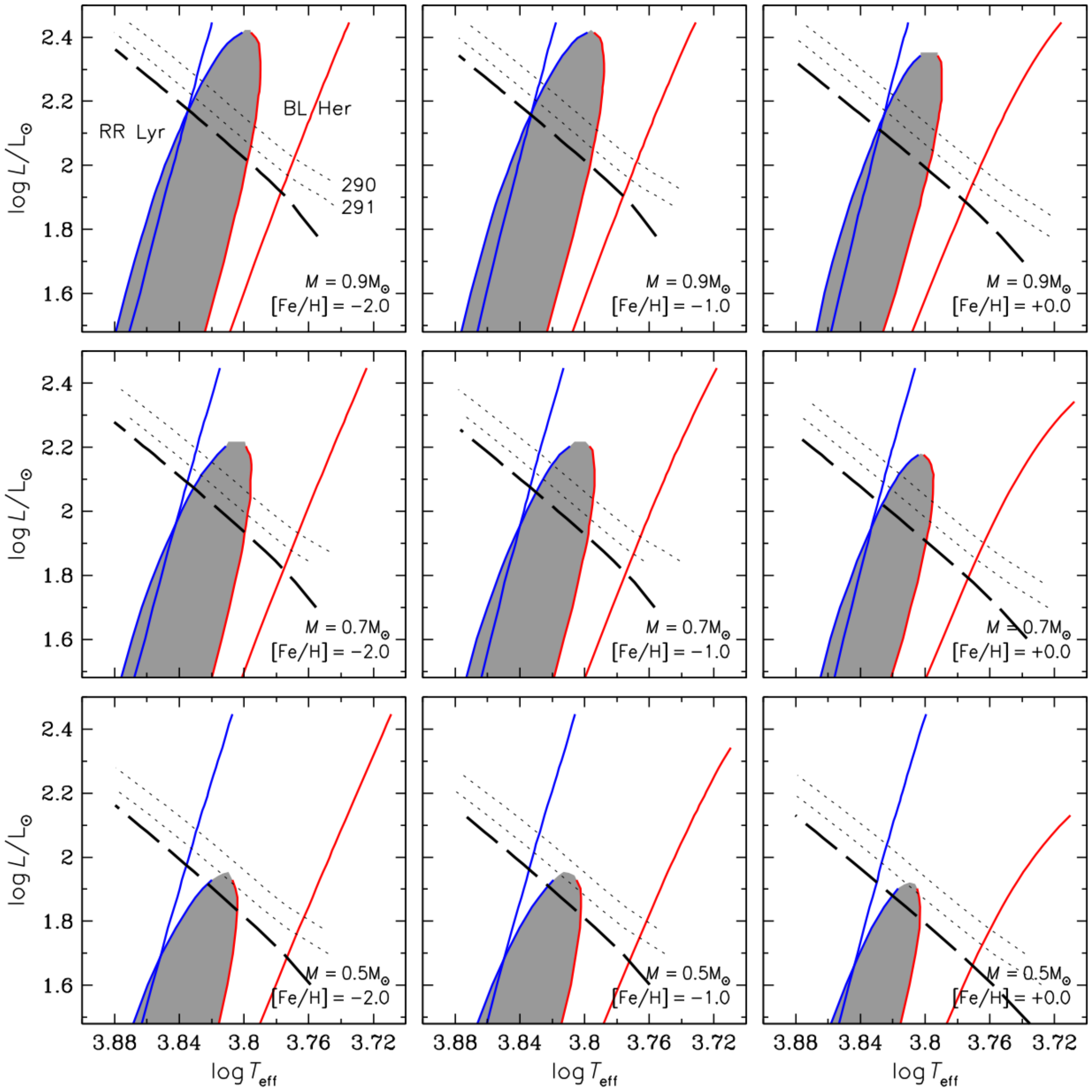

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Soszyński et al. (2019), *ApJ*

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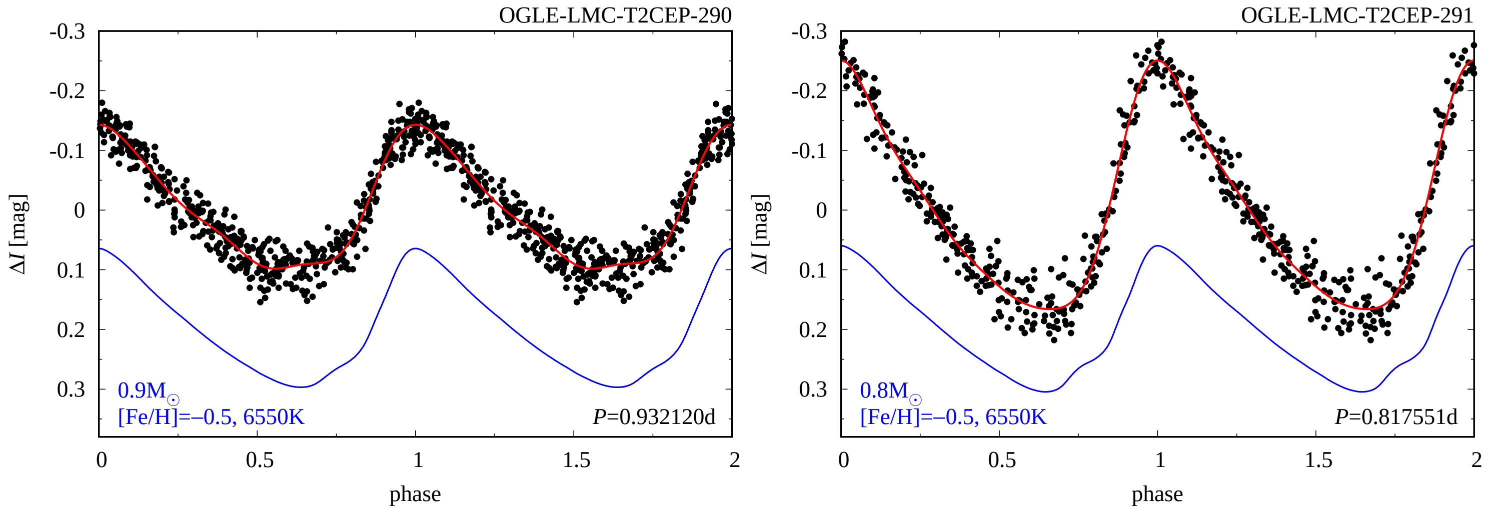

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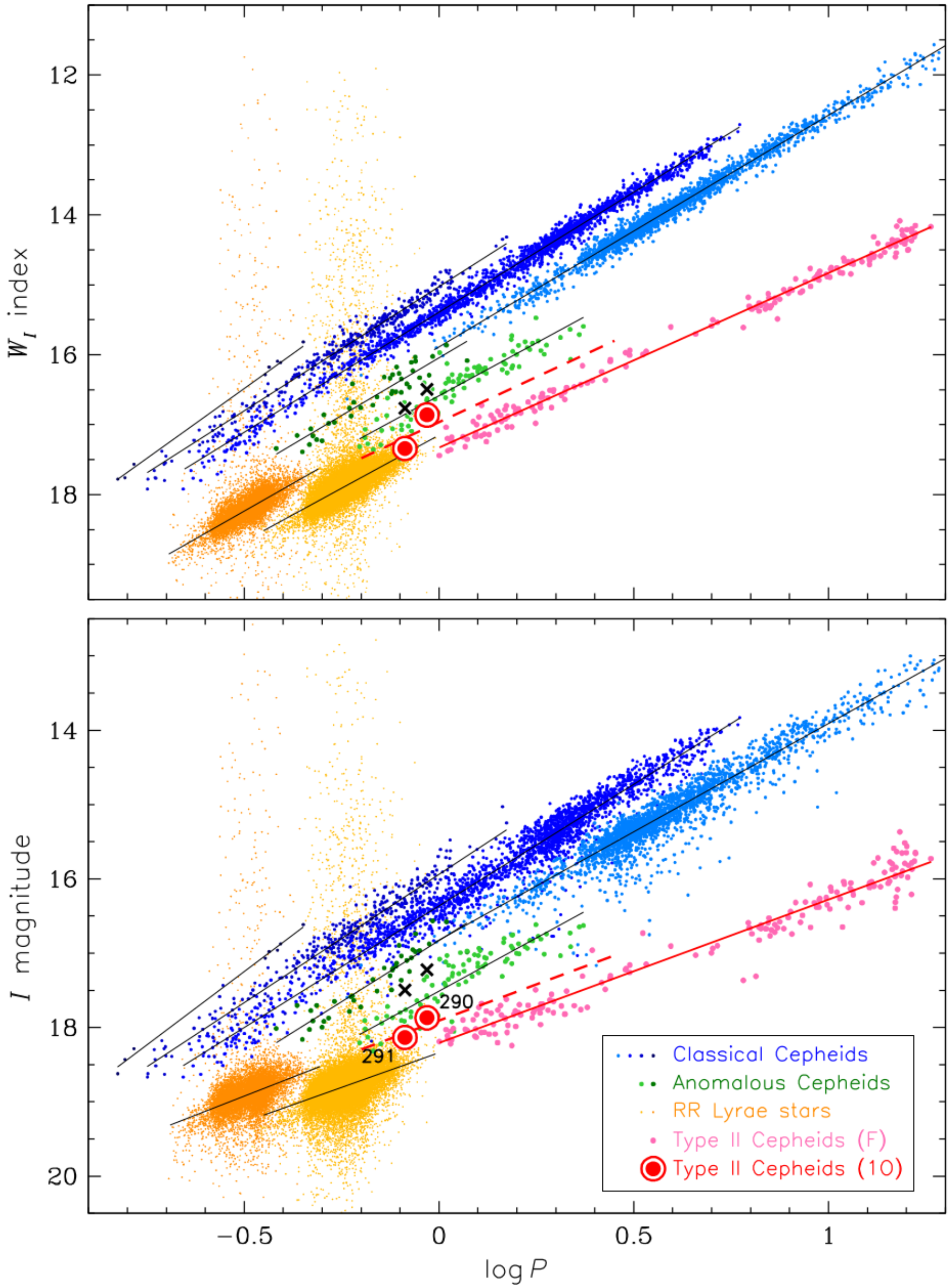

Is 1O pulsation plausible for BL Her stars?

- Instability strip: OK!
- Mode selection is a challenge!
- ⇒Constraint on phys. params.
- Models are overluminous!

Soszyński et al. (2019), *ApJ*

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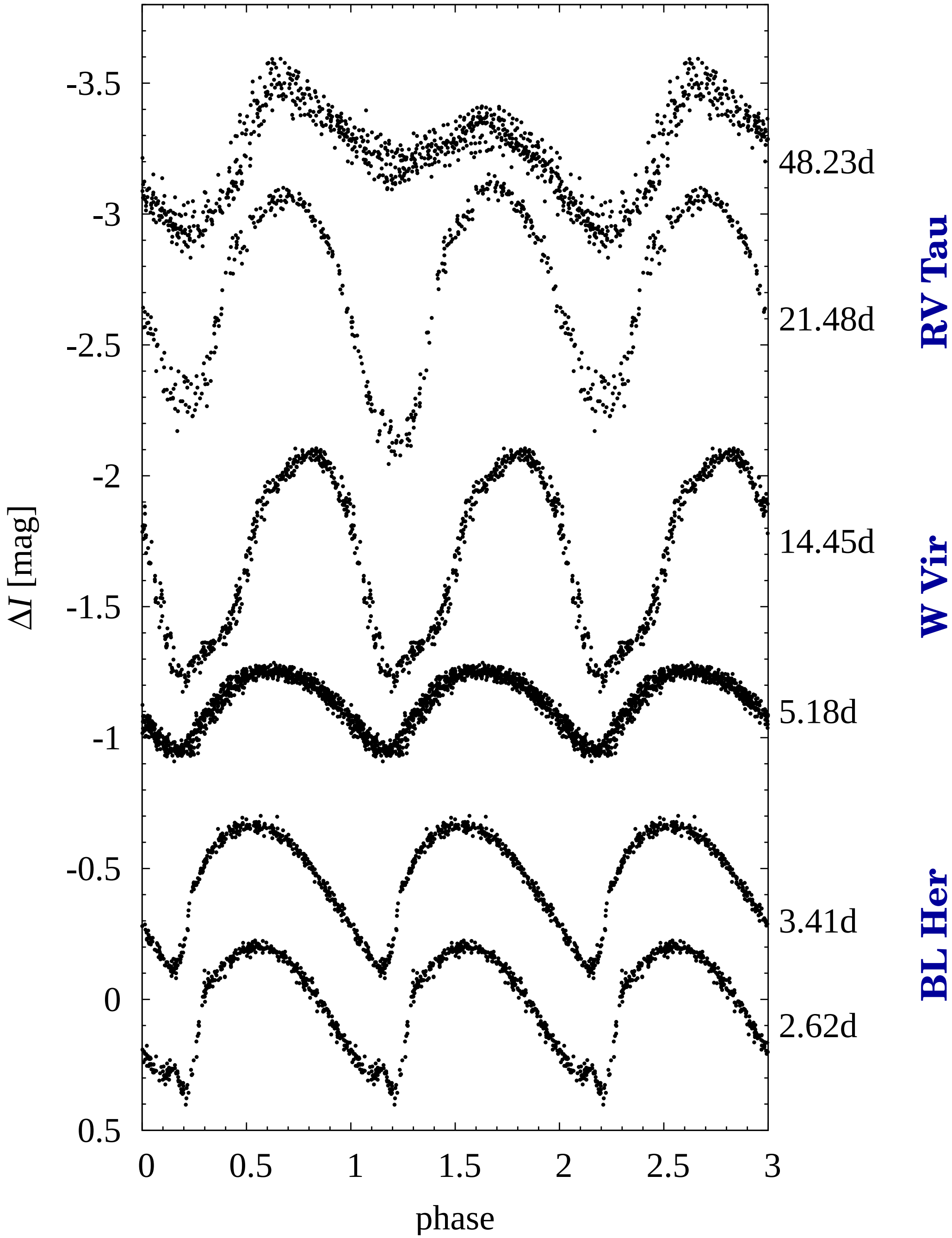

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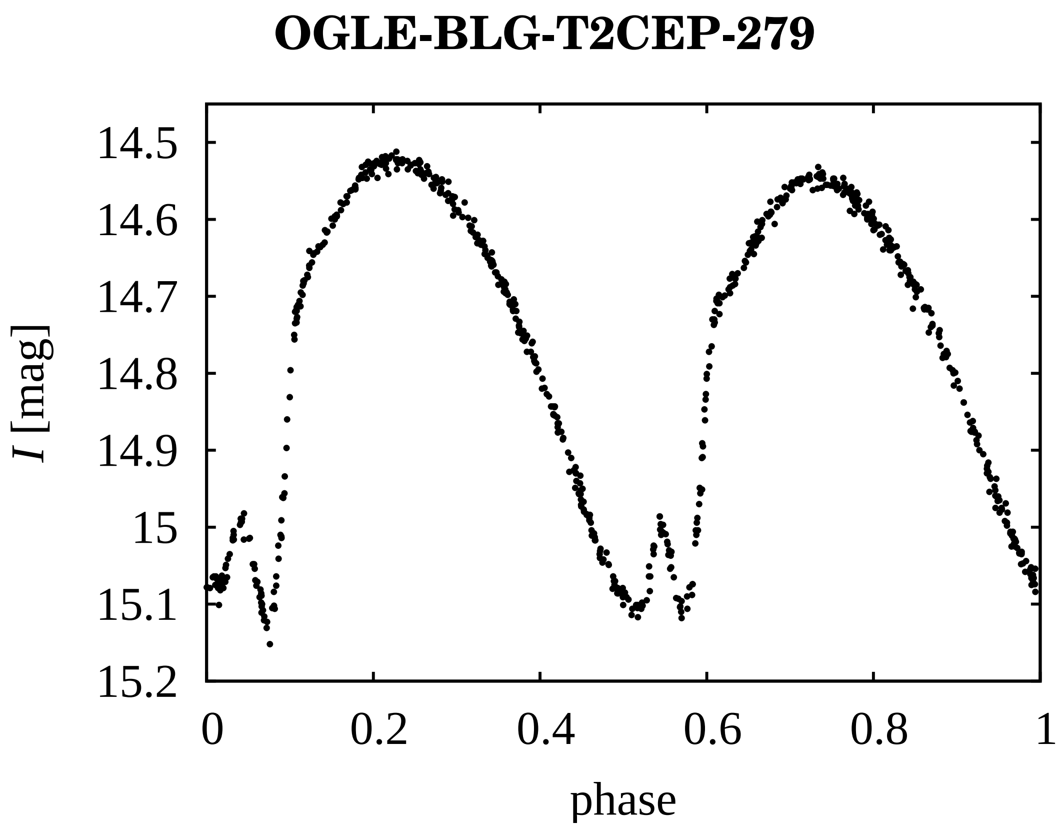

Smolec et al. (2012), *MNRAS*

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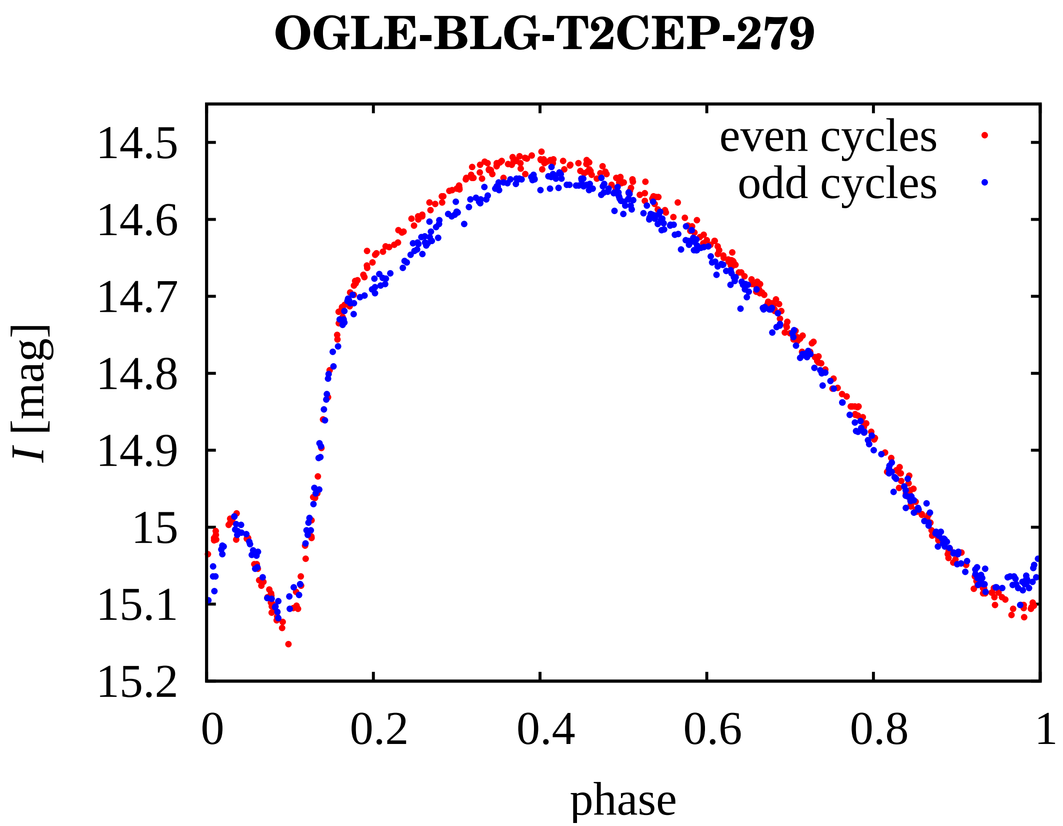

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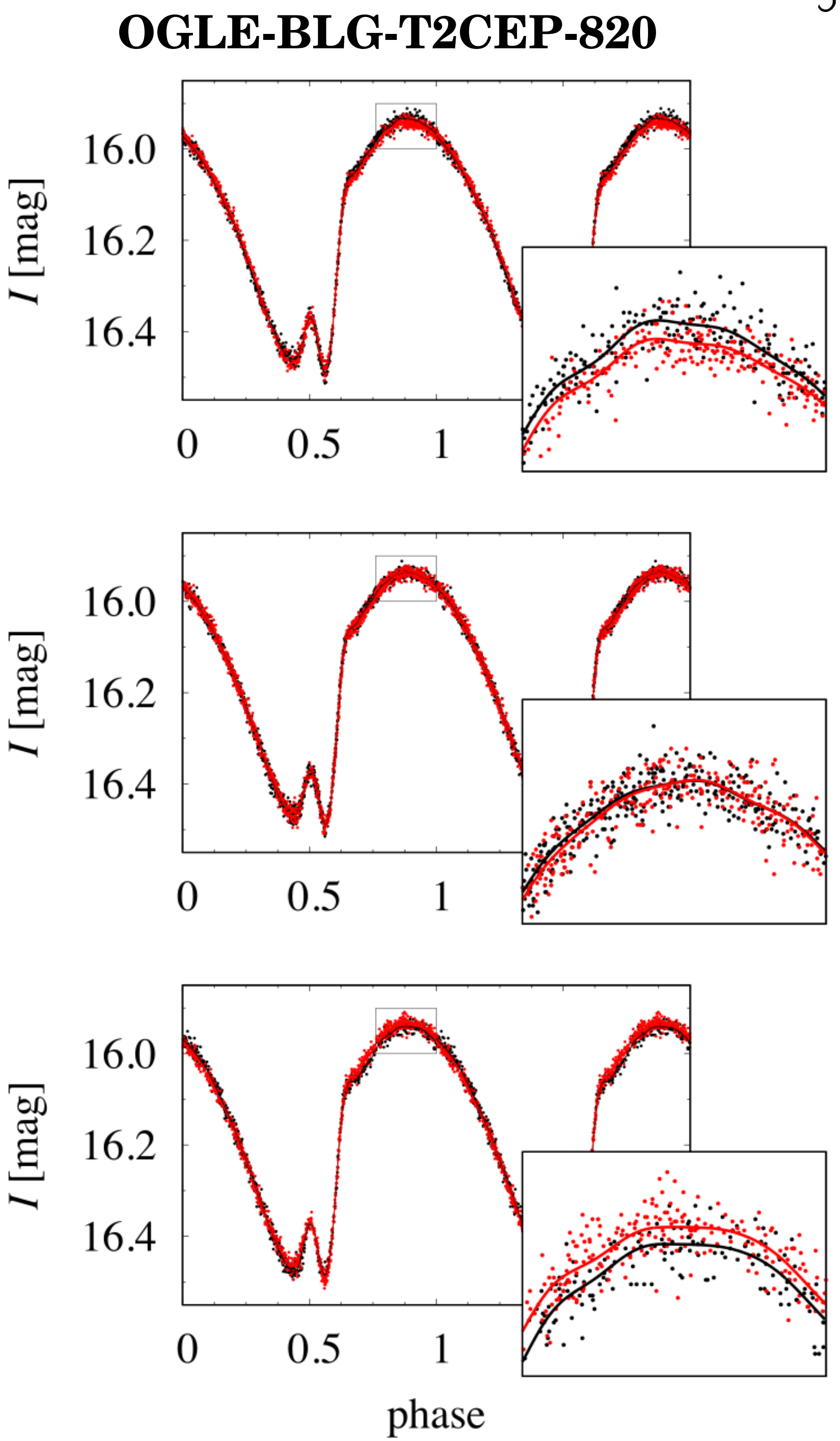

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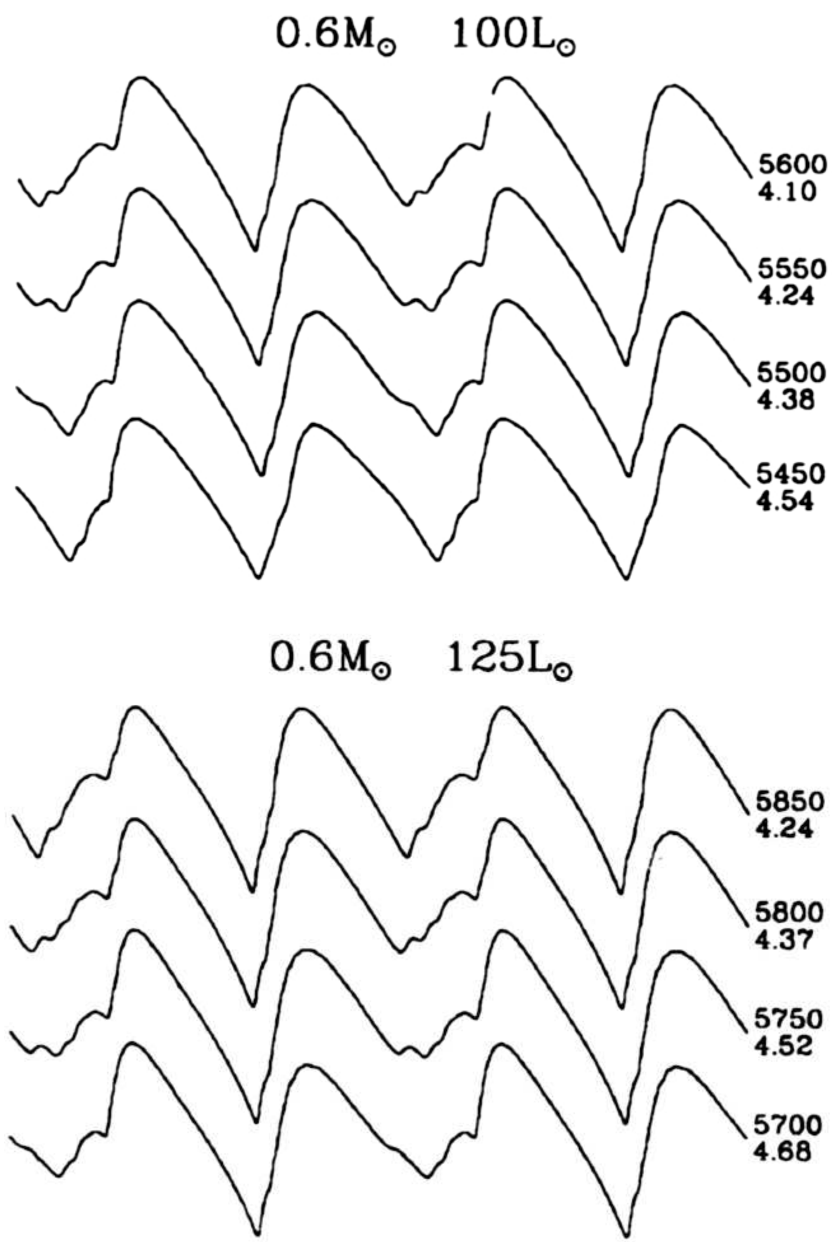

Moskalik & Buchler (1990) traced the origin of PD phenomenon to half-integer resonances:
$(2n+1)\omega_0 = 2\omega_k$.
Buchler & Moskalik (1992) predicted, based on nonlinear model calculations, that PD should occur in BL Her stars due to 3:2 resonance between F and 1O.

Buchler & Moskalik (1992), *ApJ*

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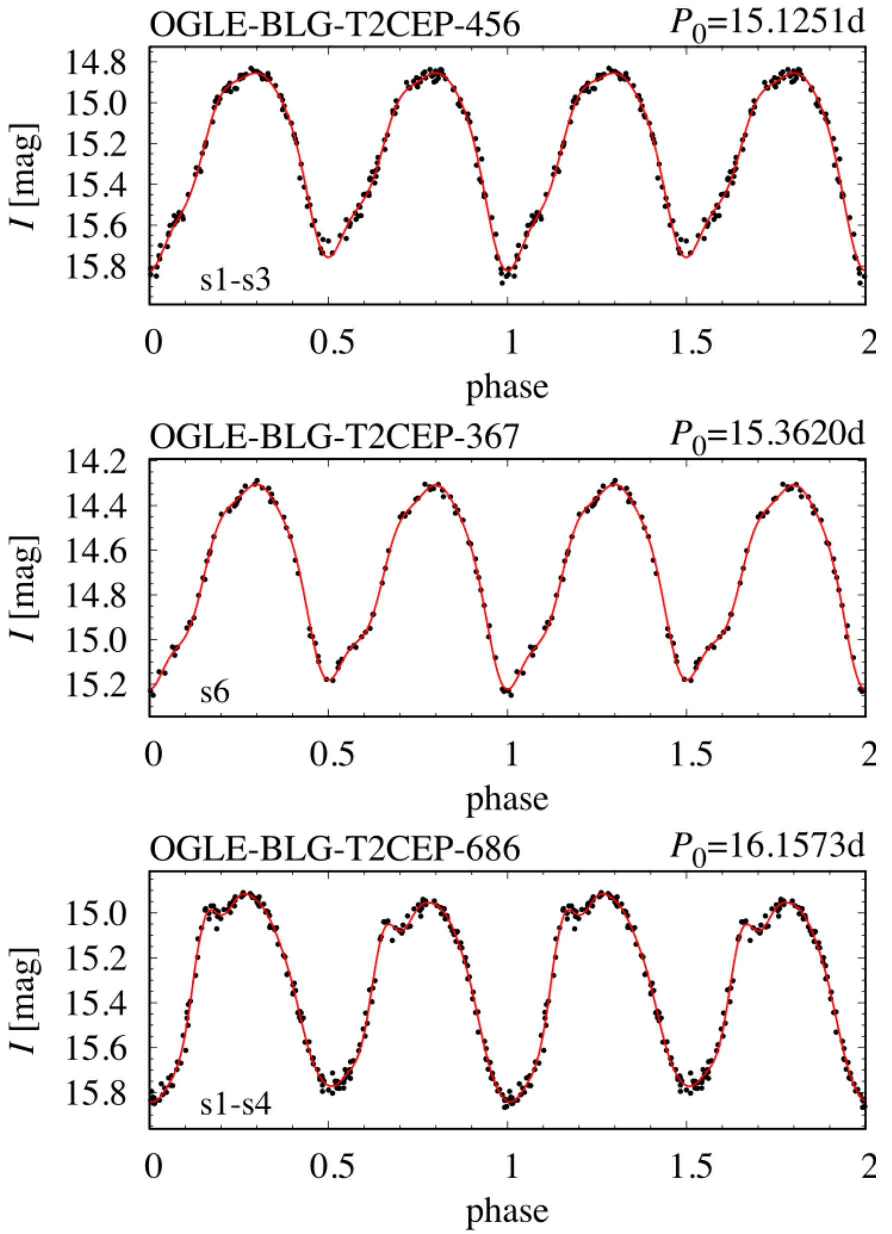

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P	N_{PD}	N	N_{PD}/N
15–16 d	4	33	0.12 ± 0.06
16–17 d	5	23	0.22 ± 0.09
17–18 d	7	14	0.50 ± 0.13
18–19 d	4	9	0.44 ± 0.17
19–20 d	5	7	0.71 ± 0.17

Moskalik & Buchler (1990) traced the origin of PD phenomenon in RV Tau-type models to 5:2 resonance between F and 2O

Transition between W Vir and RV Tau class is smooth.

Smolec et al. (2018), *MNRAS*

Some uncovered topics

- non-periodic changes and modulations
- period jitter
- mode-switching
- period-4, chaotic dynamics

For the majority of dynamical phenomena discovered recently we lack theoretical explanation.