First detection of period doubling in a BL Herculis type star. Observations and theoretical models.

Radosław Smolec[1], Igor Soszyński[2], Paweł Moskalik[3]

A. Udalski[2], M.K. Szymański[2], M. Kubiak[2], G. Pietrzyński[2,4], Ł. Wyrzykowski[2,5],

K. Ulaczyk[2], R. Poleski[2], S. Kozłowski[2], P. Pietrukowicz[2]

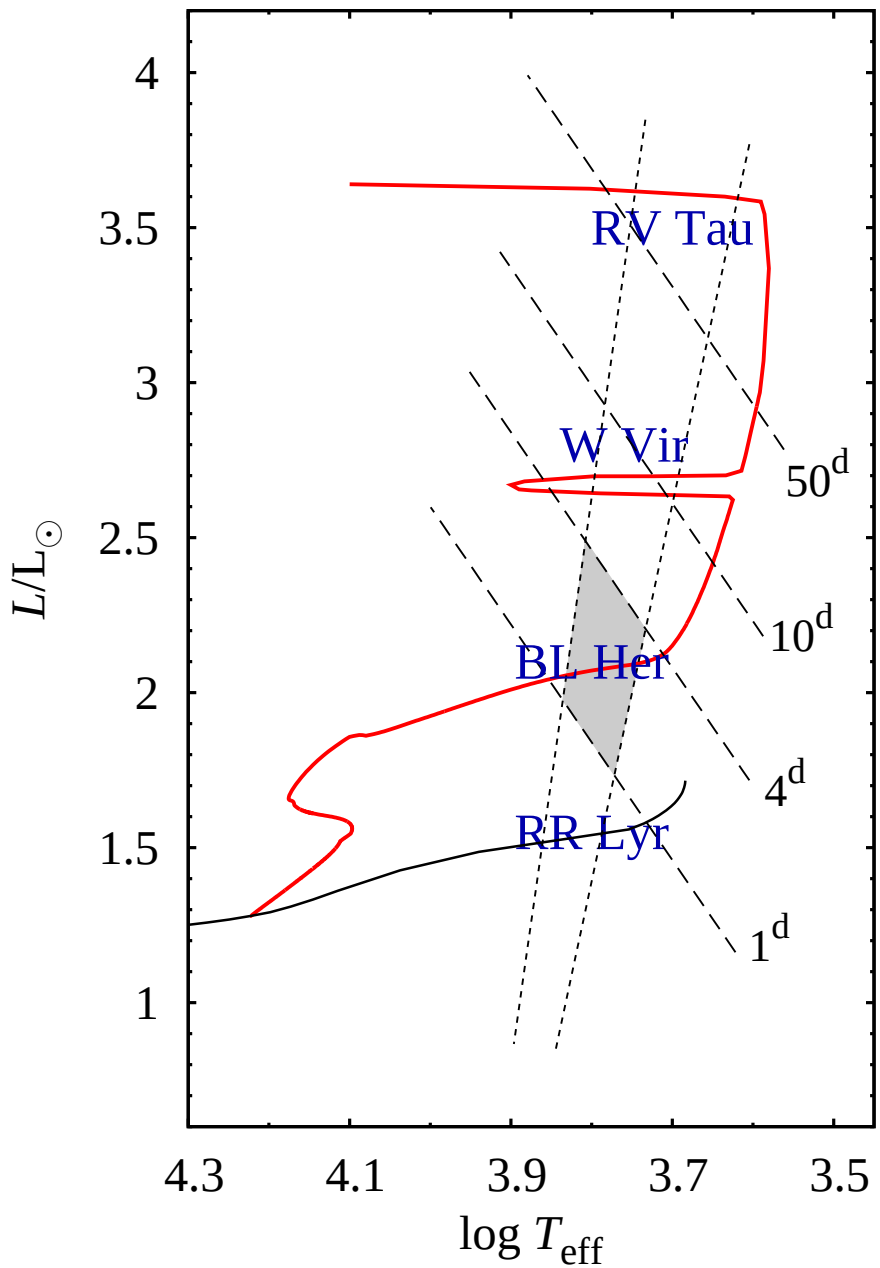
[1]Institute of Astronomy, University of Vienna
[2]Warsaw University Observatory, Warsaw, Poland
[3]Nicolaus Copernicus Astronomical Center, Warsaw, Poland
[4]Universidad de Concepción, Departamento de Astronomia, Concepción, Chile
[5]Institute of Astronomy, University of Cambridge, Cambridge, UK

institut für astronomie
UNIVERSITÄTSSTERNWARTE WIEN

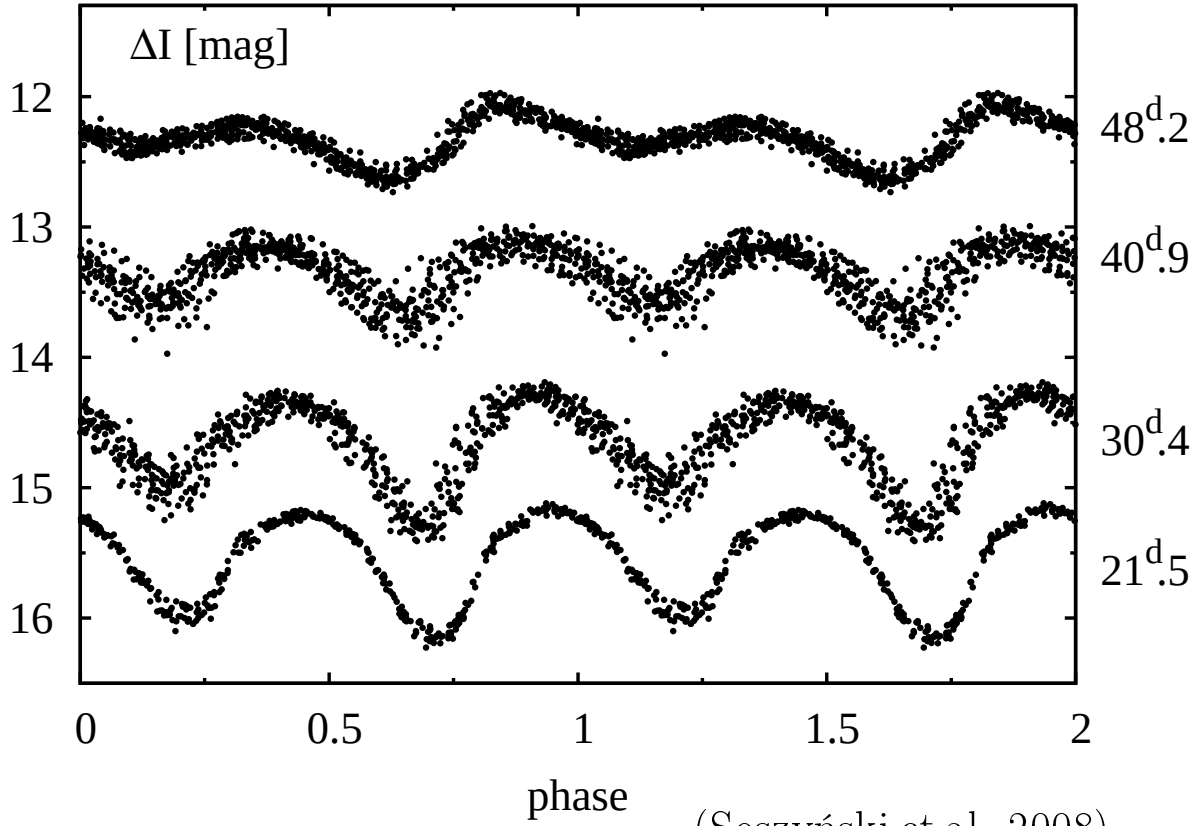
Polish Academy of Sciences
Nicolaus Copernicus
Astronomical Center

Type-II Cepheids:

- **BL Her stars**
  - ▸ periods of $\sim 1 - 4\,\mathrm{d}$
  - ▸ evolve from ZAHB toward AGB
- **W Vir stars**
  - ▸ periods of $\sim 4 - 20\,\mathrm{d}$
  - ▸ loop into the instability strip during the helium-shell flashes
- **RV Tau stars**
  - ▸ periods longer than $\sim 20\,\mathrm{d}$
  - ▸ evolve away from the AGB toward a white dwarf domain
  - ▸ period doubling behaviour



Period doubling effect in RV Tau stars:



(Soszyński et al. 2008)

- period doubling detected also in *Kepler* RR Lyrae data (Kolenberg et al. 2010, Szabó et al. 2010)

Period doubling effect

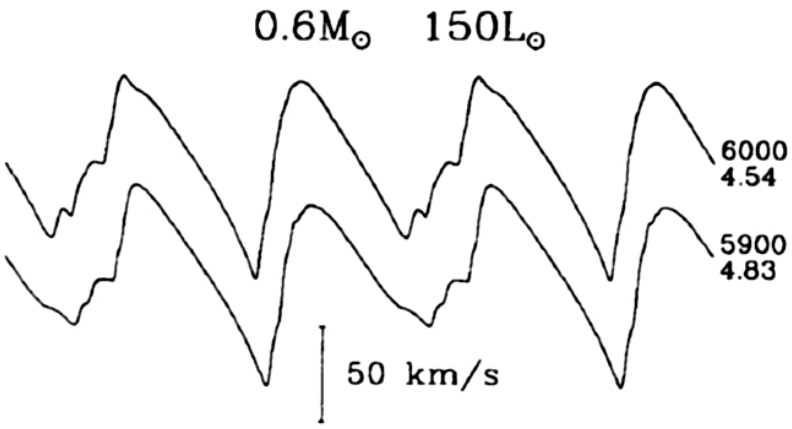
- present in early nonlinear models of W Vir and RV Tau stars (Buchler & Kovács 1987; Kovács & Buchler 1988)
- the origin of the period doubling in hydrodynamic models was traced by Moskalik & Buchler (1990) to the destabilising role of the half-integer resonances:

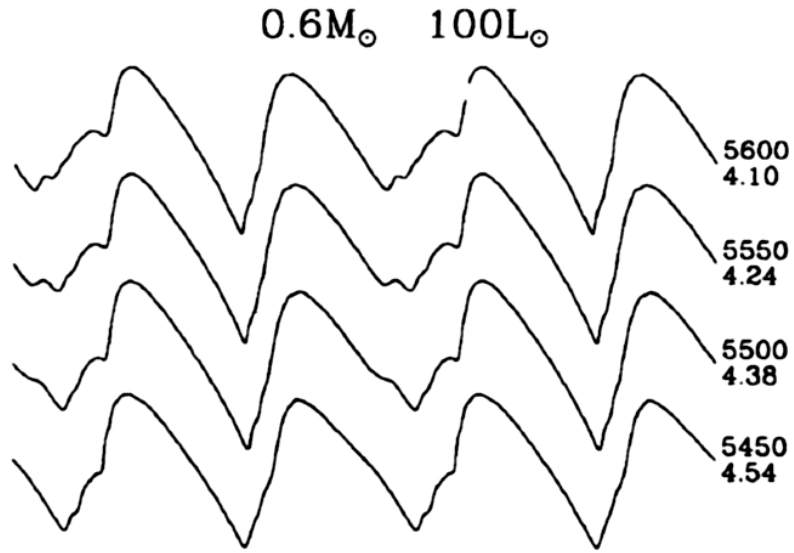
$$(2n+1)\omega_0 = 2\omega_k \,,$$

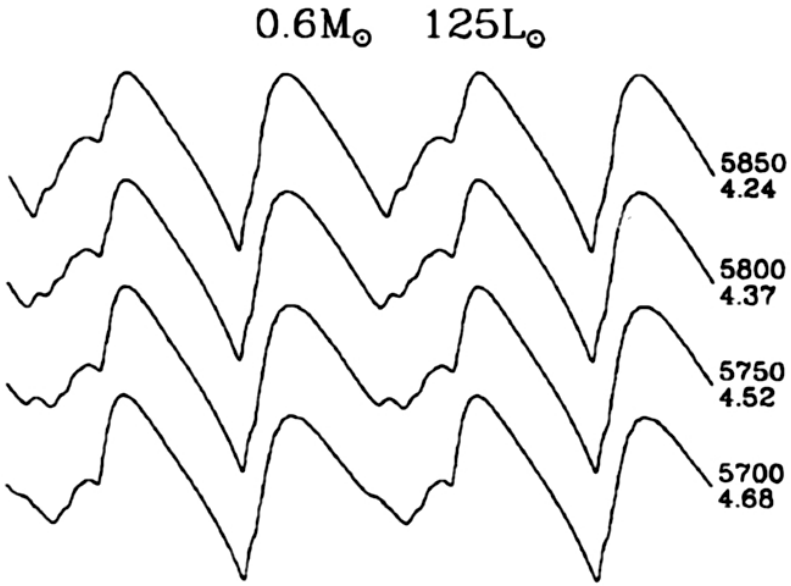
  between the fundamental mode and the higher order overtones
- close to the resonance centre period-doubling bifurcation can occur: the fundamental mode limit cycle becomes unstable, and period-two solution, with alternating shape of the light and radial velocity curves can emerge

Nonlinear radiative models of BL Her stars (Buchler & Moskalik 1992):

- period doubling computed in several model sequences with periods in a range $2.0\,\mathrm{d} < P_\mathrm{F} < 2.6\,\mathrm{d}$
- period doubling caused by the 3:2 resonance between the fundamental mode and the first overtone, $3\omega_0 = 2\omega_1$
- robust and large amplitude alternations $\Rightarrow$ the phenomenon should be observed







OGLE Observations:

Optical Gravitational Lensing Experiment, OGLE-III

1.3 m Warsaw telescope, Las Campanas, Chile

Type II Cepheids

- **LMC & SMC:** 240 stars (including 81 BL Her, no period doubling)

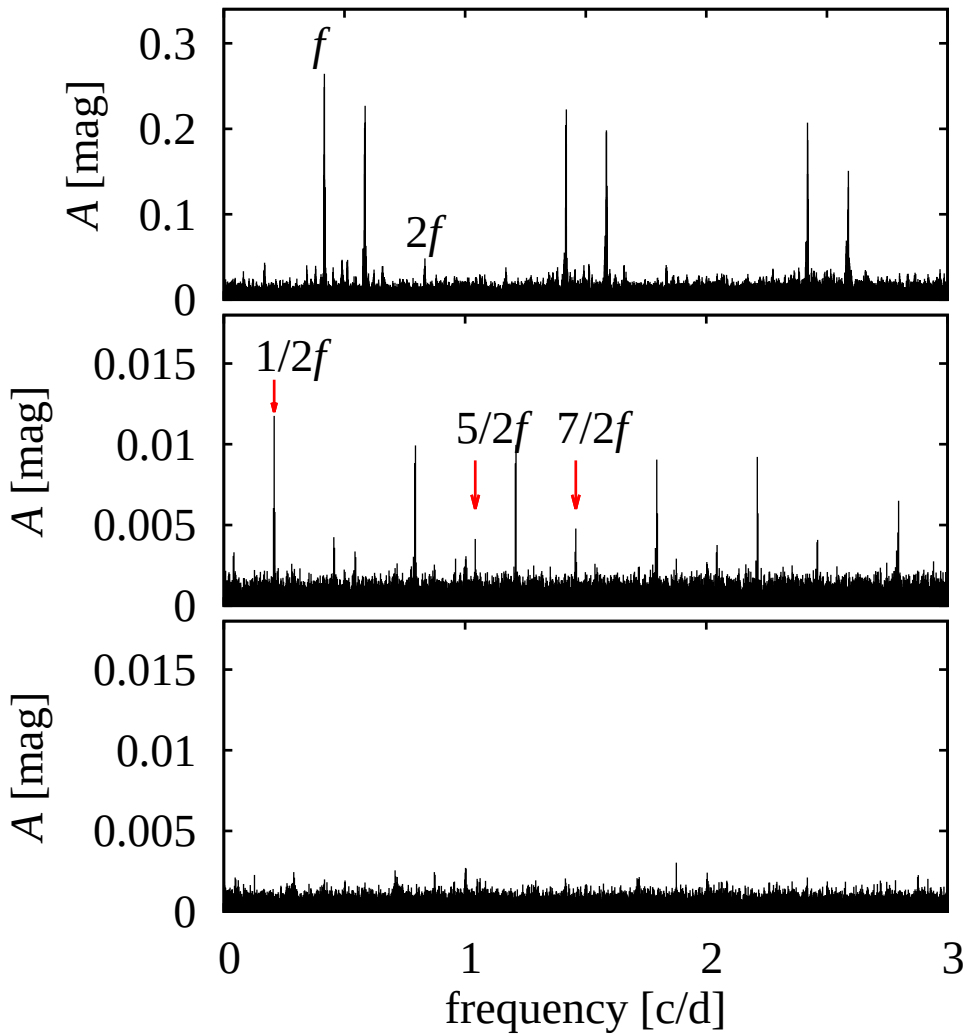
  (Soszyński et al. 2008, 2010)

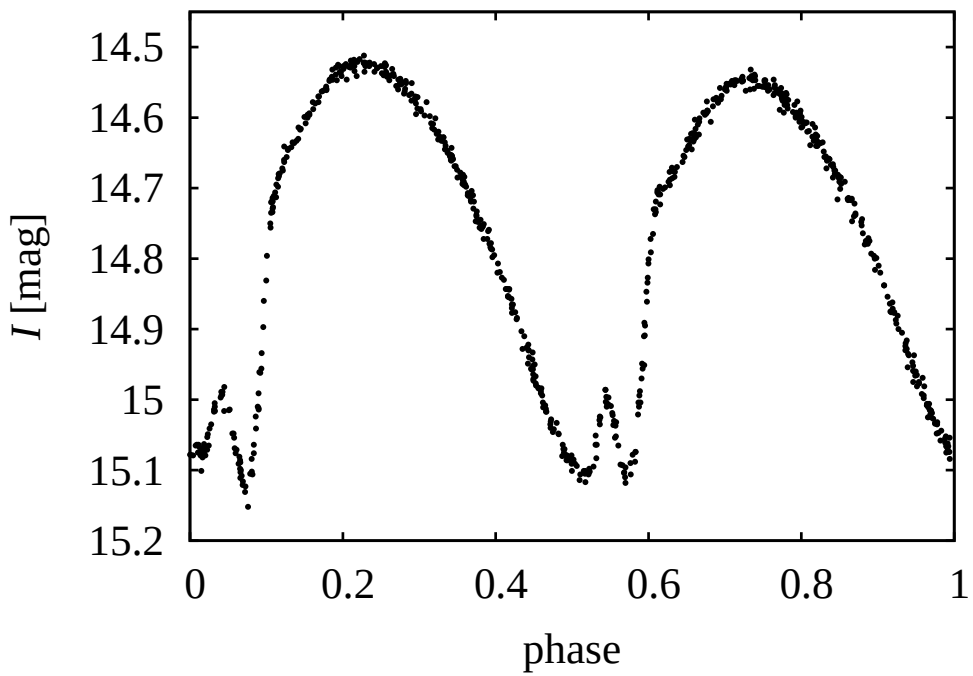
- **Galactic bulge** – catalog in preparation

  Two period doubling candidates:

- BLG184.7 133264, $P_0 = 2.40\,\mathrm{d}$
- BLG189.6 137529, $P_0 = 2.25\,\mathrm{d}$

BLG184.7 133264: Data analysis:





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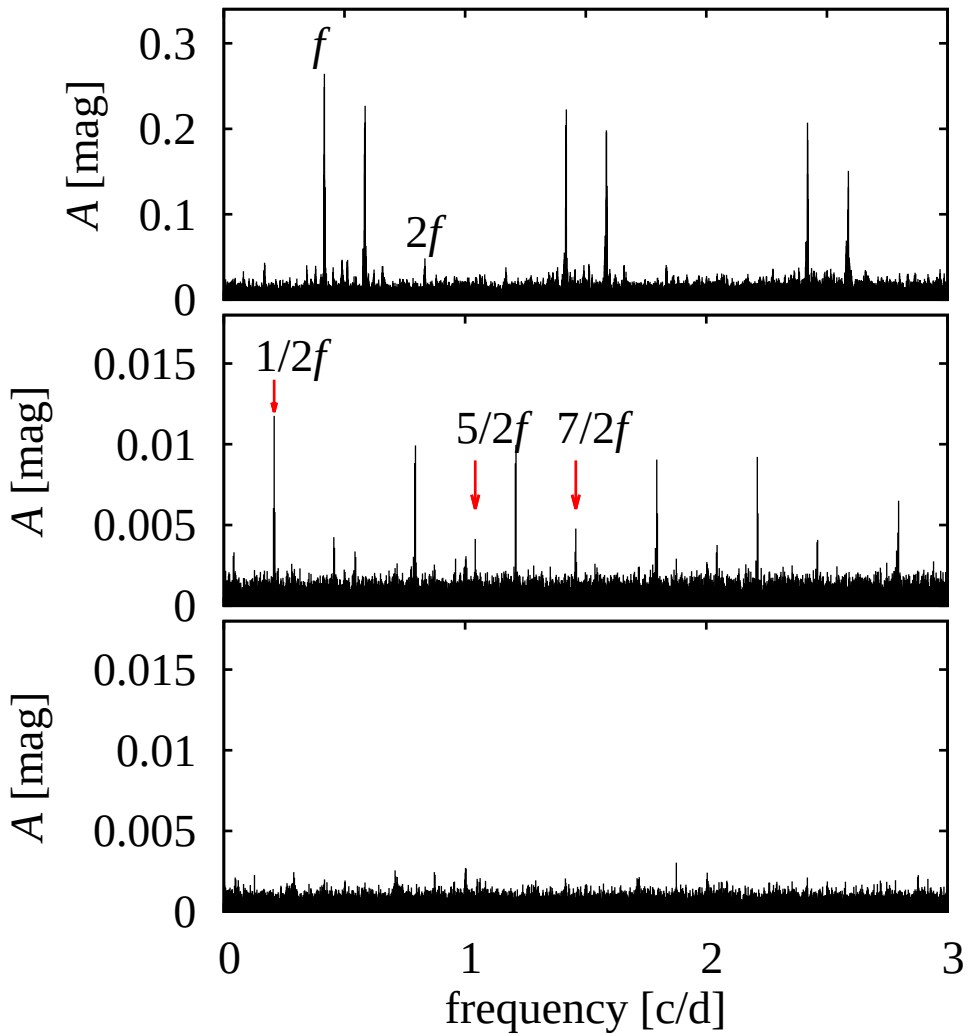
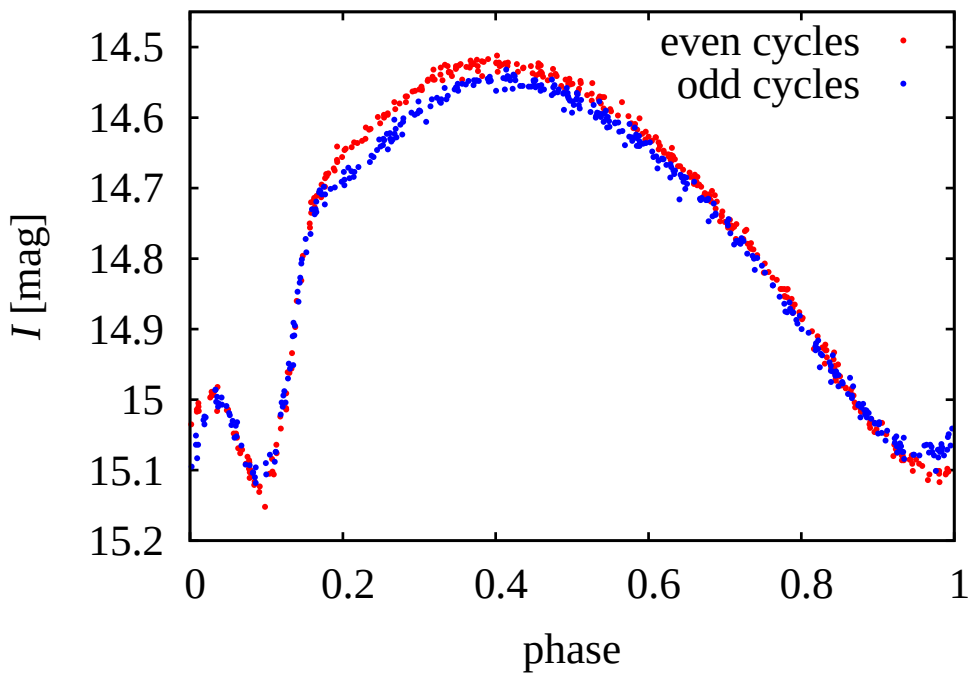
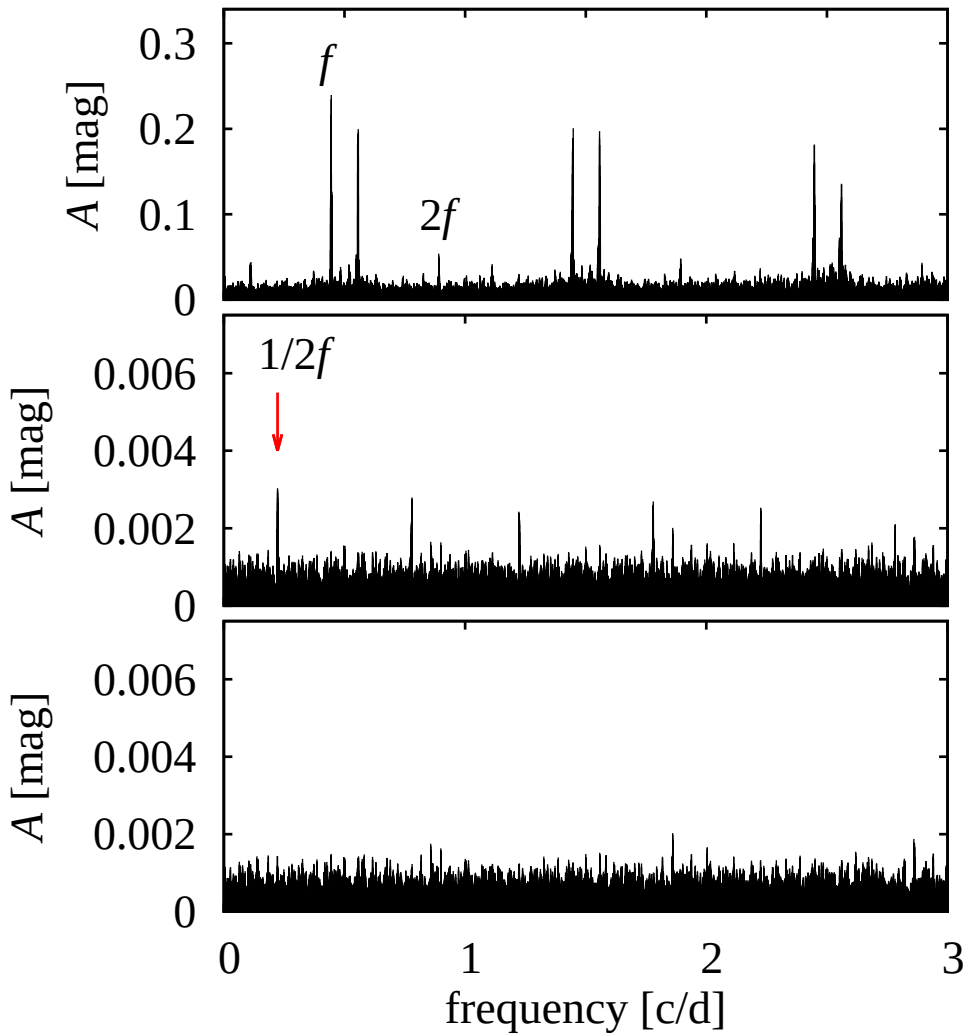
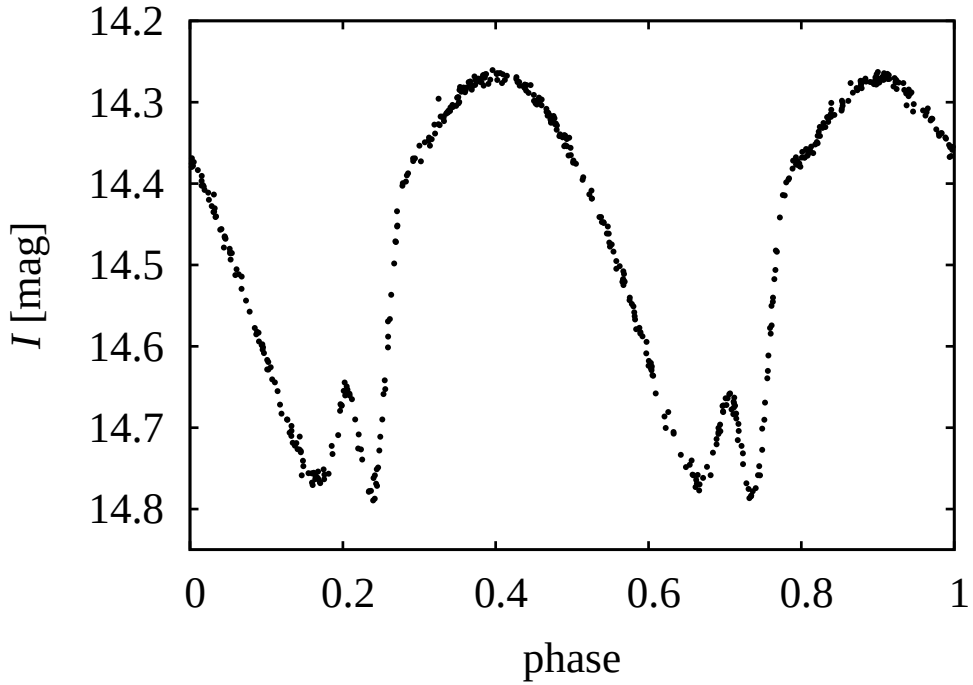




BLG189.6 137529: Data analysis:





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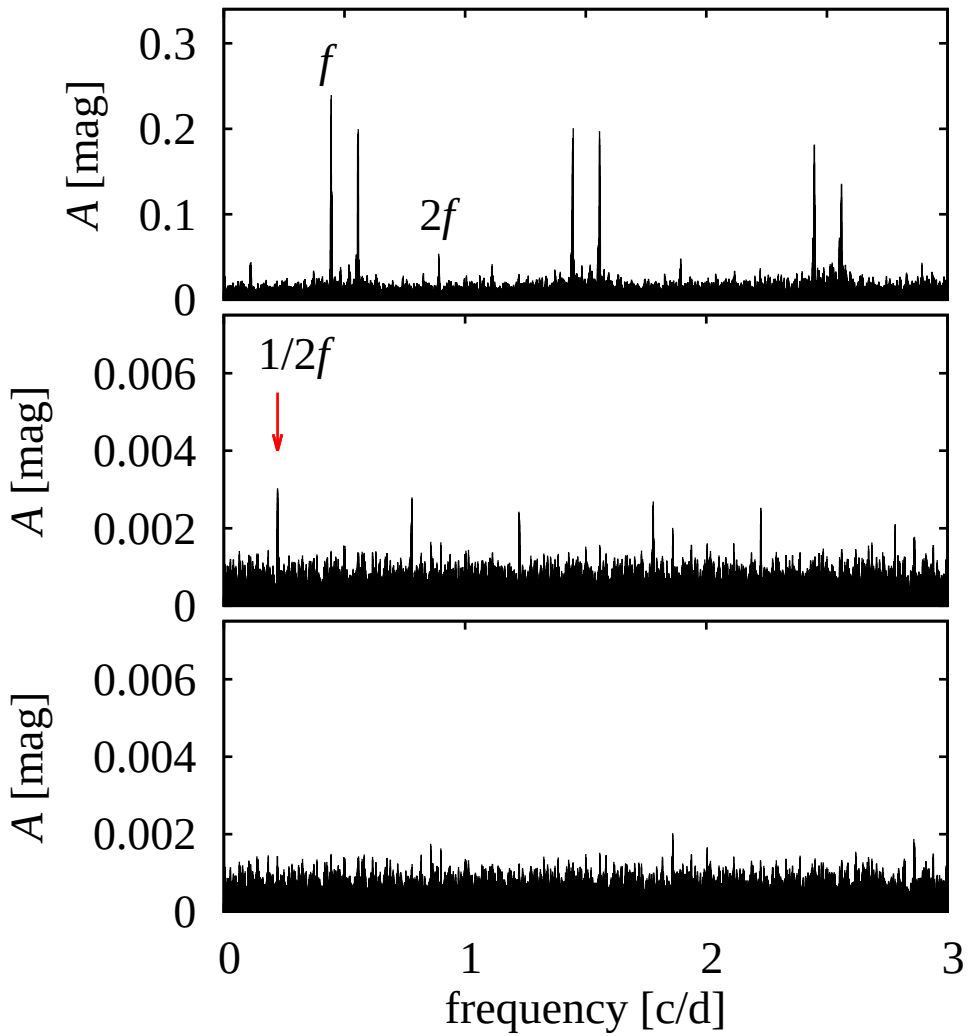

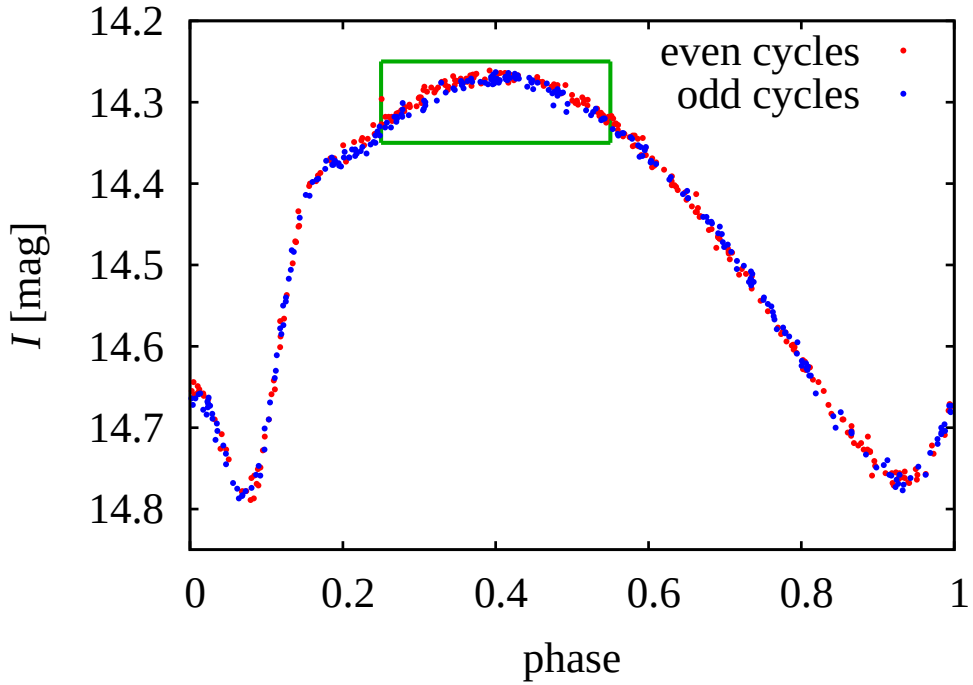

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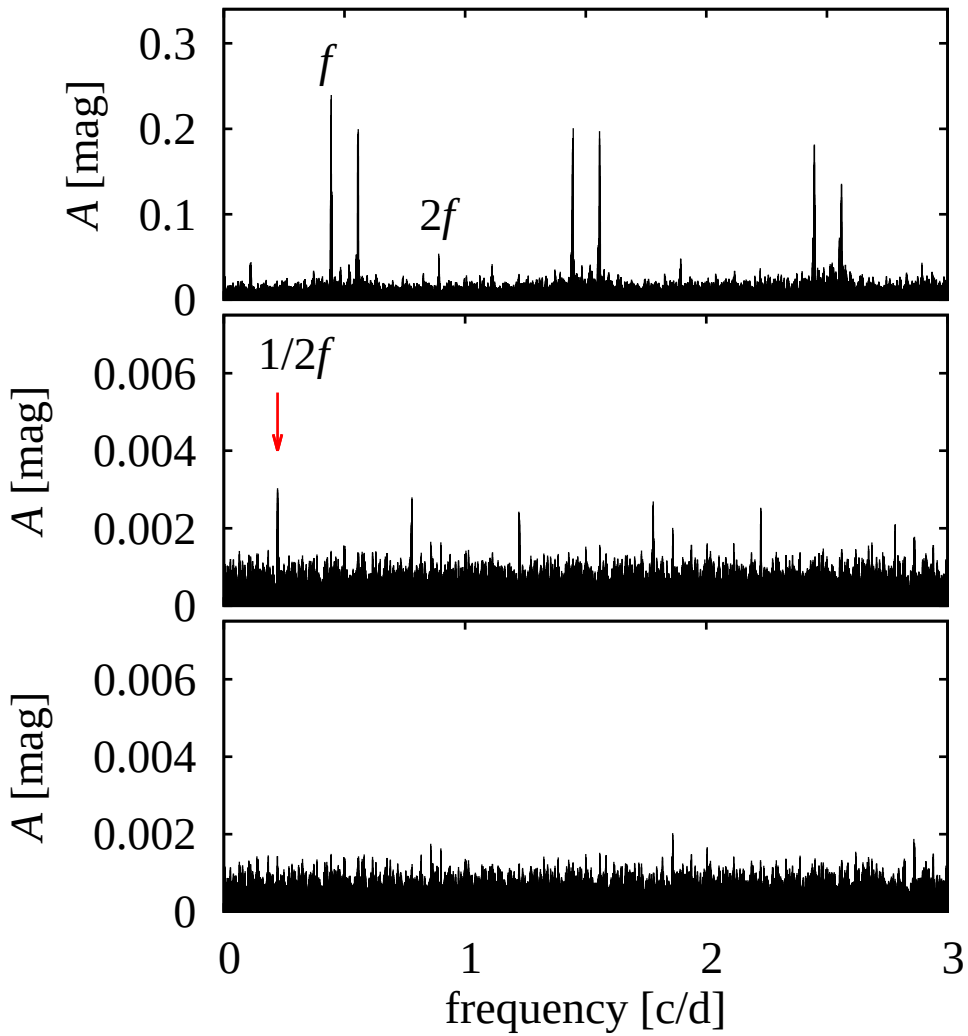
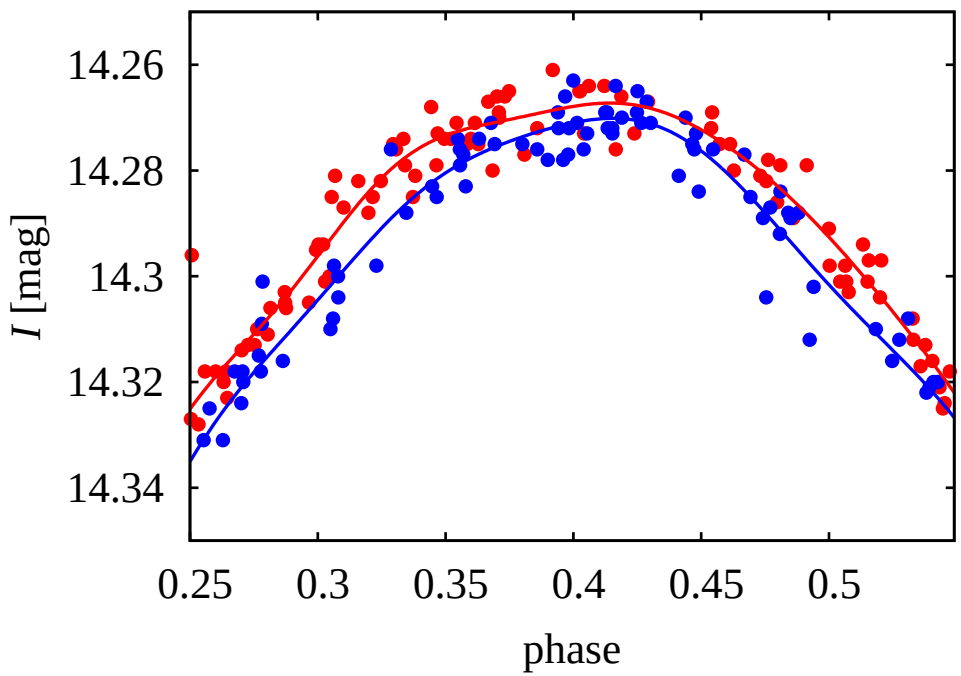


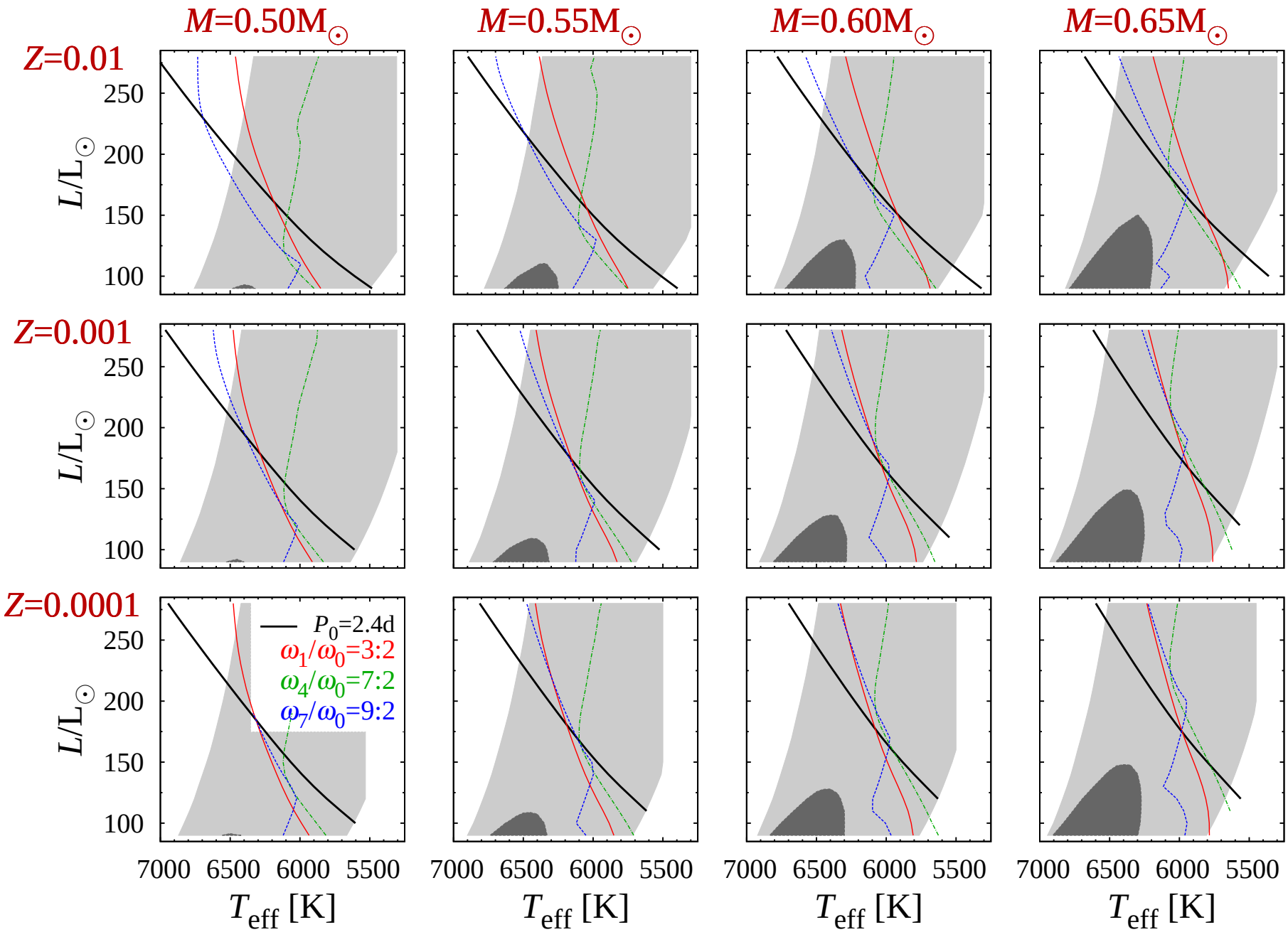


Theoretical models:

- Models computed with Warsaw convective pulsation hydrocodes (Smolec & Moskalik 2008a)
- linear non-adiabatic code and nonlinear direct time integration hydrocode
- one-equation turbulent convection model (Kuhfuß 1986)
- three different sets of convective parameters

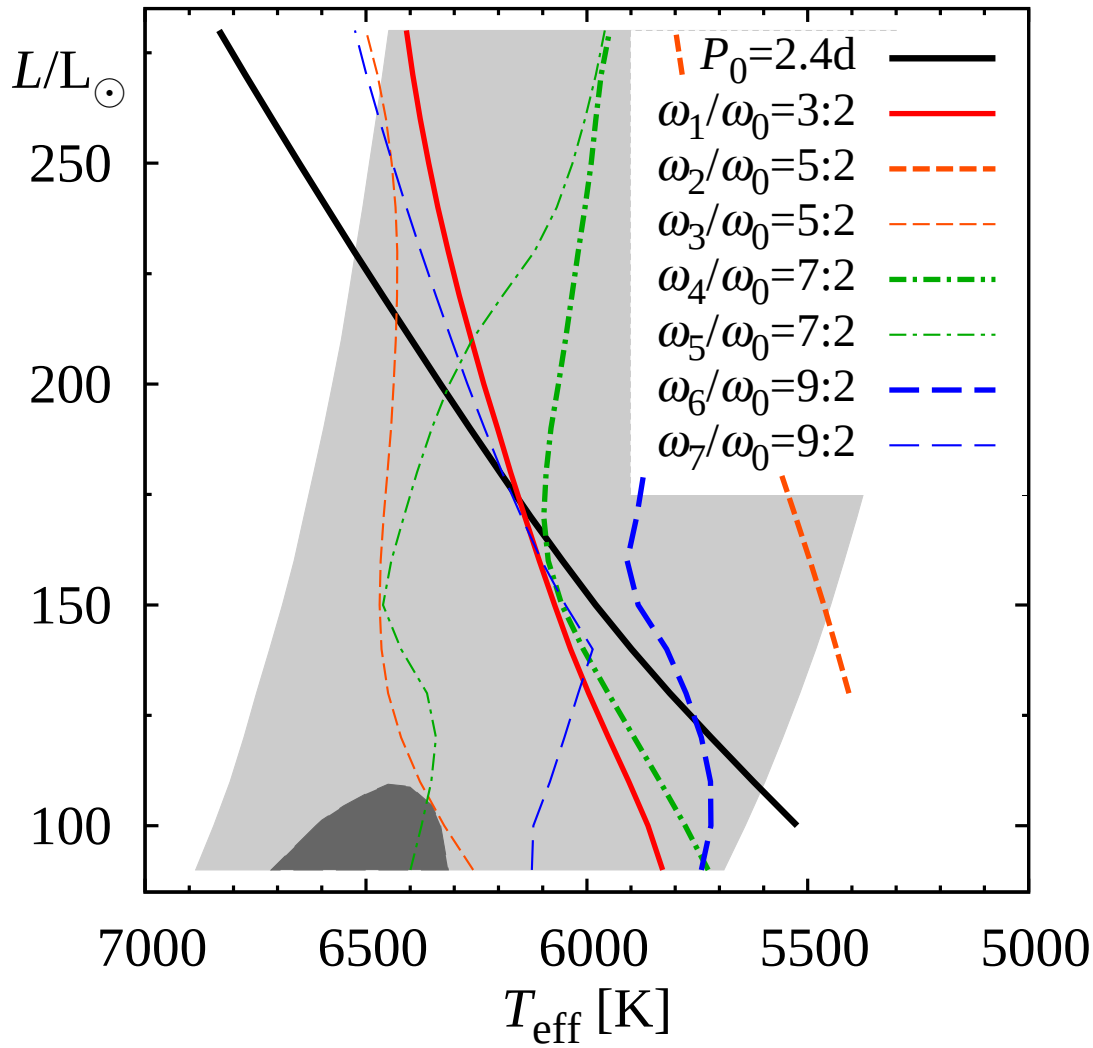
Initial model survey with several goals

- is period doubling possible in the convective BL Her models with $P_0 = 2.4\,\mathrm{d}$?
- what is the origin of period doubling (3:2 resonance, $3\omega_0 = 2\omega_1$)?
- model the light curve of the only firm BL Her star showing the period doubling
- constrain its physical parameters (mass, luminosity, metallicity)


M=0.50M⊙
M=0.55M⊙
M=0.60M⊙
M=0.65M⊙
Z=0.01
Z=0.001
Z=0.0001
L/L⊙
250
200
150
100
P0=2.4d
ω1/ω0=3:2
ω4/ω0=7:2
ω7/ω0=9:2
7000 6500 6000 5500
Teff [K]

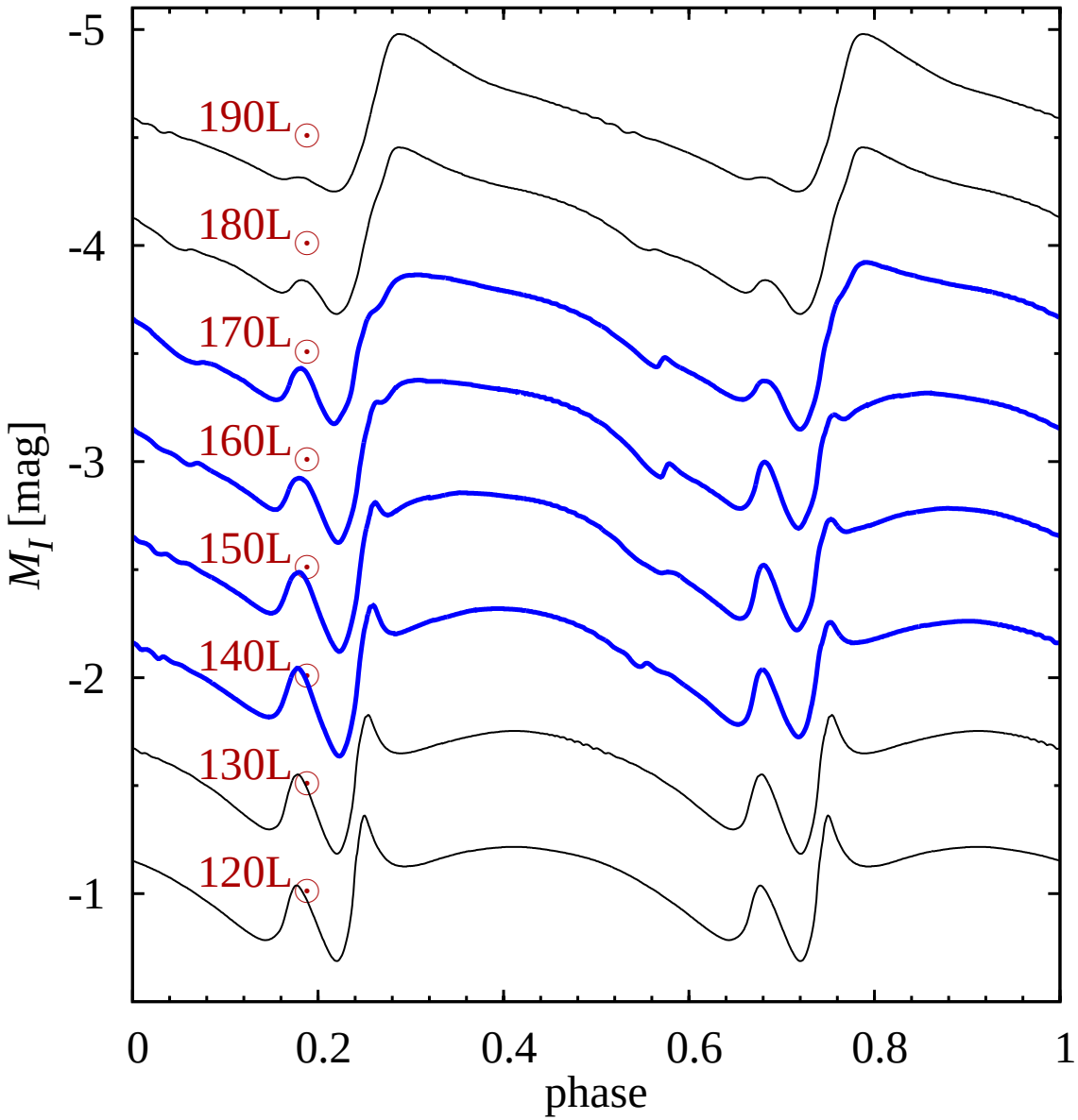
Linear model survey:

- several half-integer resonances crossing the instability strip and $P_0 = 2.4\,\mathrm{day}$



Nonlinear models:

- all nonlinear models have $P_0 = 2.4\,\mathrm{d}$
- period doubling easily found in nearly all model sequences over a wide range of luminosities

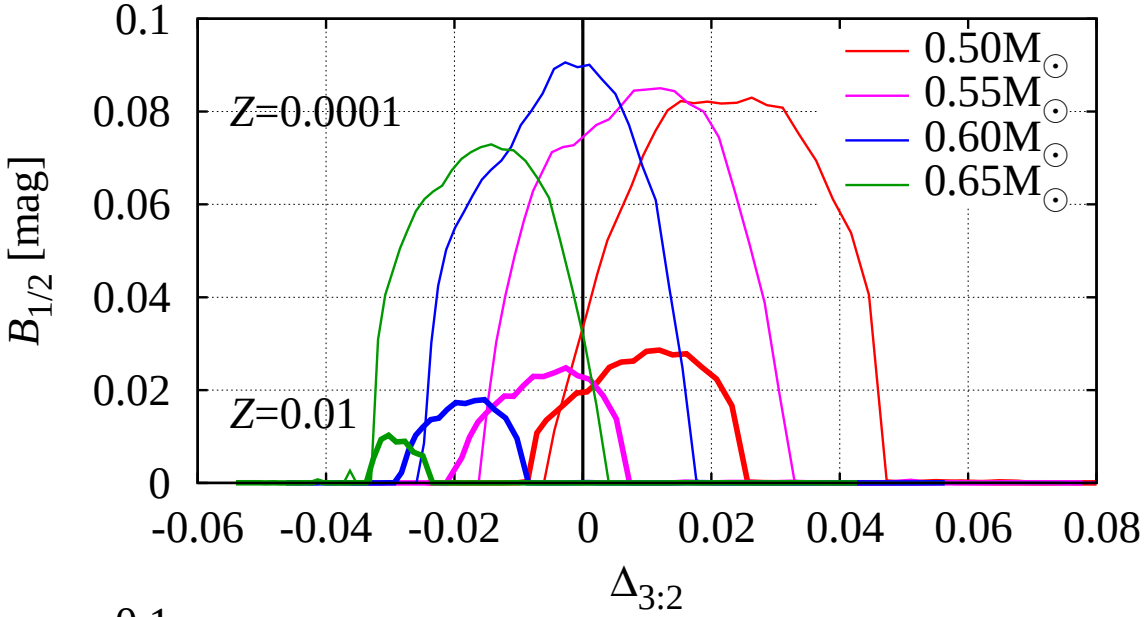


Origin of the period doubling:

- 3:2 resonance with 1O

$$\Delta_{3:2} = \omega_1/\omega_0 - 1.5$$

always very close: $\Delta_{3:2} < 0.05$

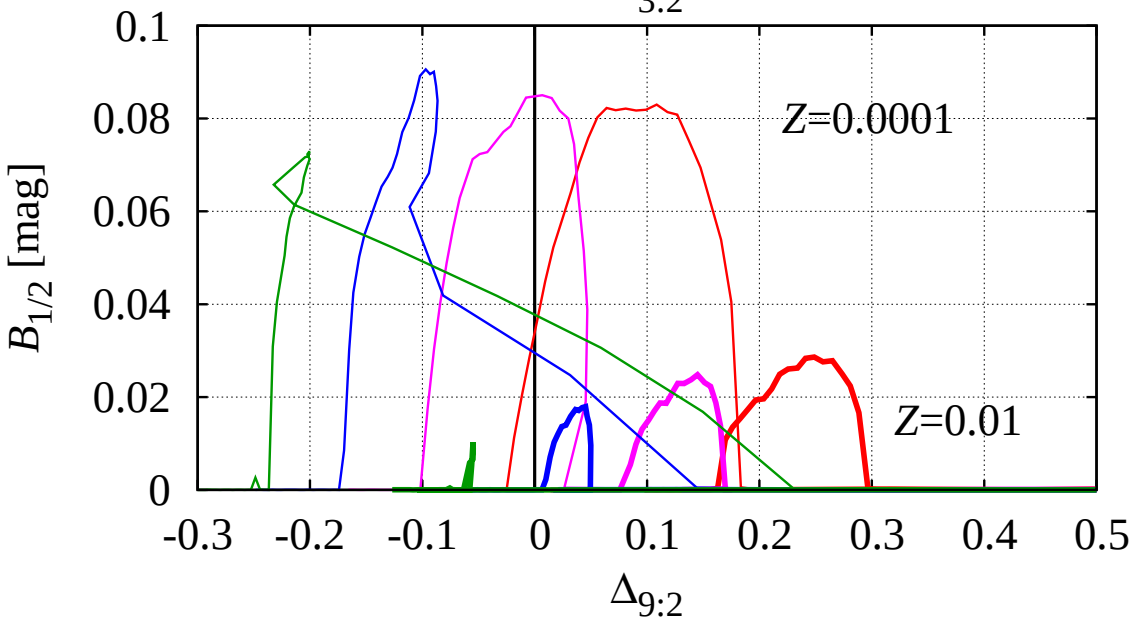


- 9:2 resonance with 7O

$$\Delta_{9:2} = \omega_7/\omega_0 - 4.5$$

sometimes as far as

$\Delta_{9:2} > 0.2$



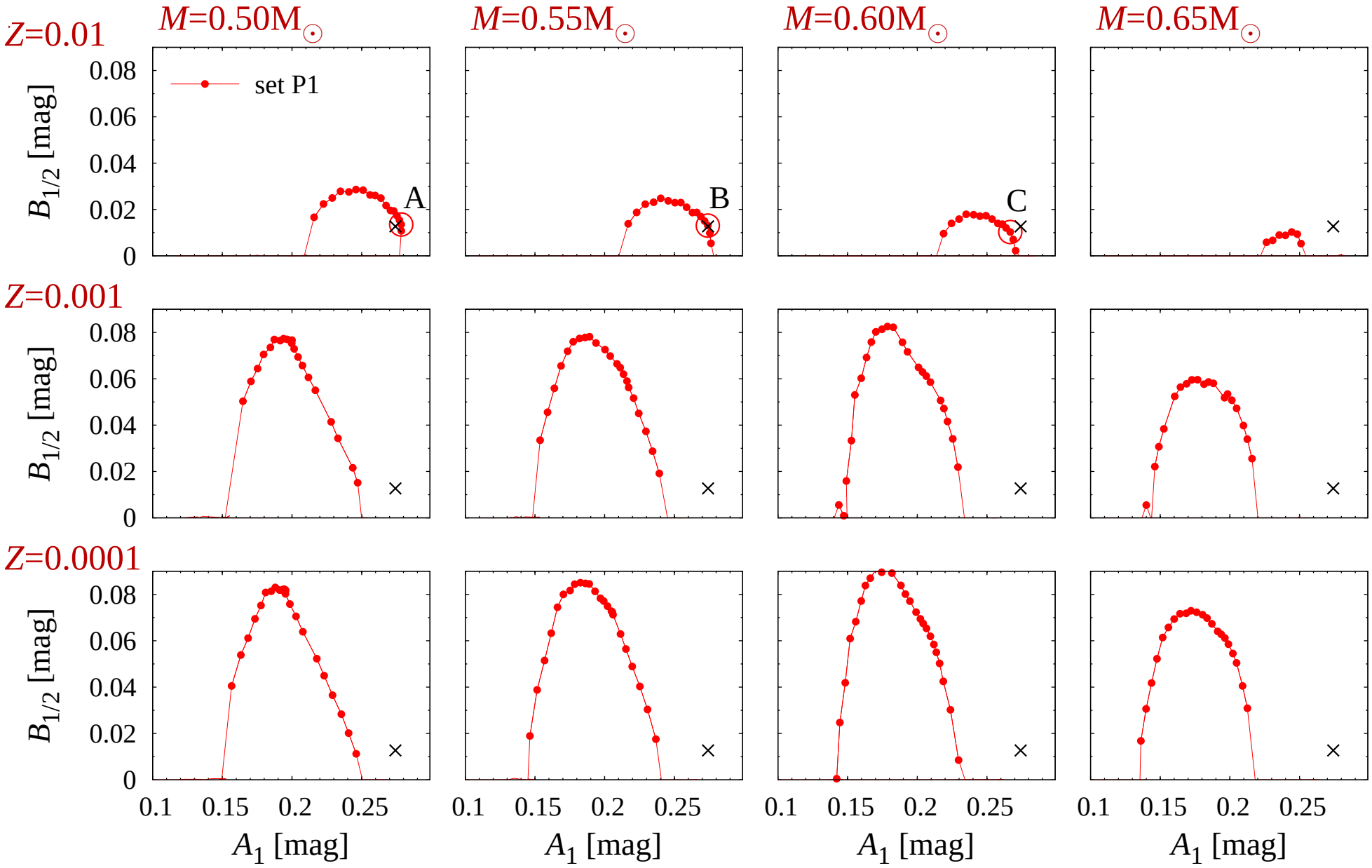
the crucial role of the 3:2 resonance with 1O confirmed

The best model for BLG184.7 133264:

- comparison of the model and observed light curve through comparison of Fourier decomposition parameters, amplitudes, amplitude ratios, and phase differences

$$I(t) = I_0 + \sum_k A_k \cos\left(2\pi k f_0 t + \phi_k\right) + \\ + \sum_n B_{n+1/2} \cos\left[2\pi(n+1/2) f_0 t + \psi_{n+1/2}\right]. \quad (1)$$

- with current hydrocodes Fourier phases of high-amplitude pulsators cannot be modelled satisfactorily: they differ systematically from the observed ones
- therefore, we focus on the amplitudes: A_1 and $B_{1/2}$


Z=0.01
M=0.50M⊙
M=0.55M⊙
M=0.60M⊙
M=0.65M⊙
set P1
A
B
C
Z=0.001
Z=0.0001
B1/2 [mag]
0.08
0.06
0.04
0.02
0
0.1
0.15
0.2
0.25
A1 [mag]

Best matching models:

- all have $Z = 0.01$
- all have $P \approx 2.4\,\mathrm{d}$
- all match the amplitudes

Light curves

- **model A:**

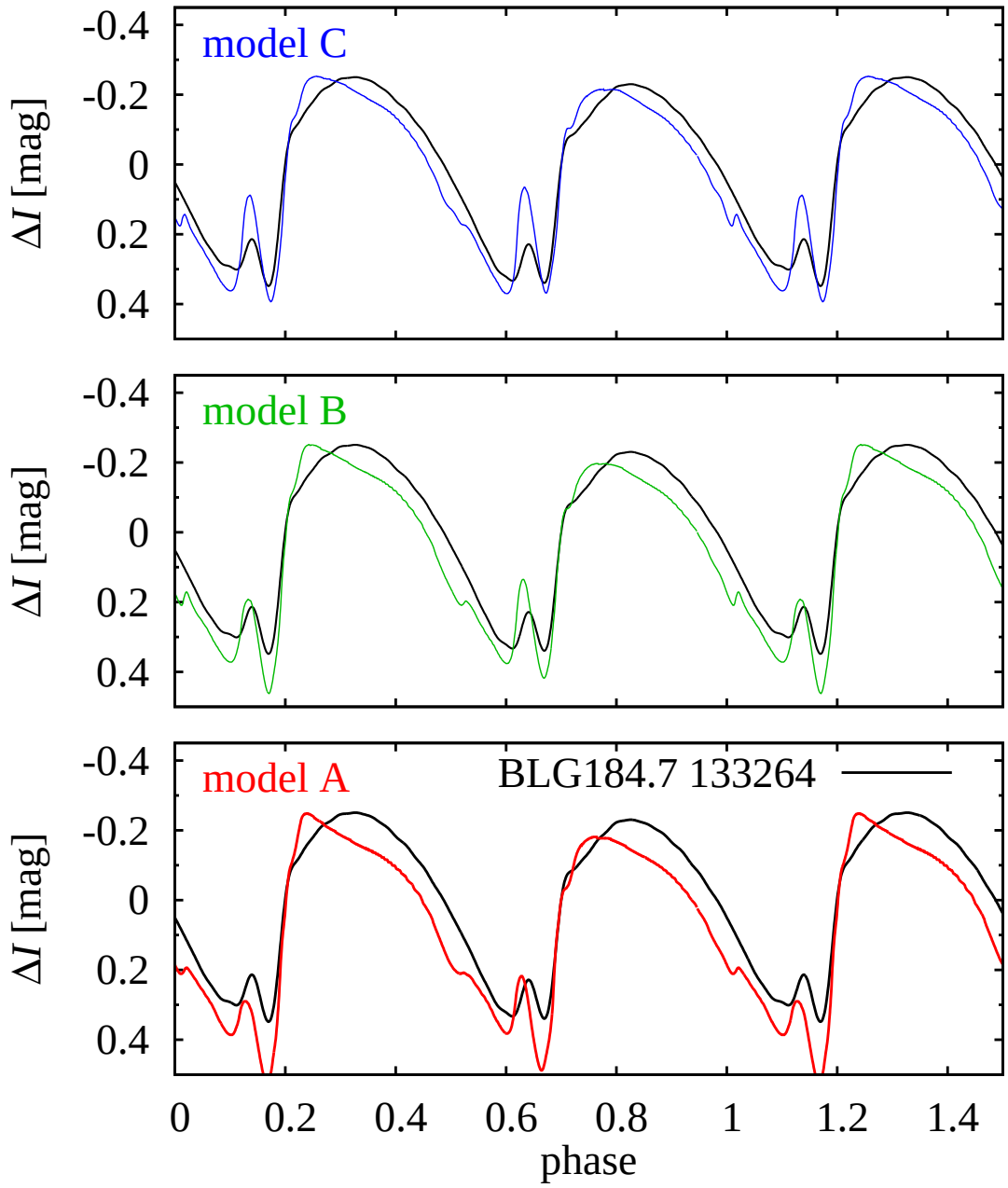
  $M = 0.50\mathrm{M}_\odot,\ L = 168\mathrm{L}_\odot$

- **model B:**

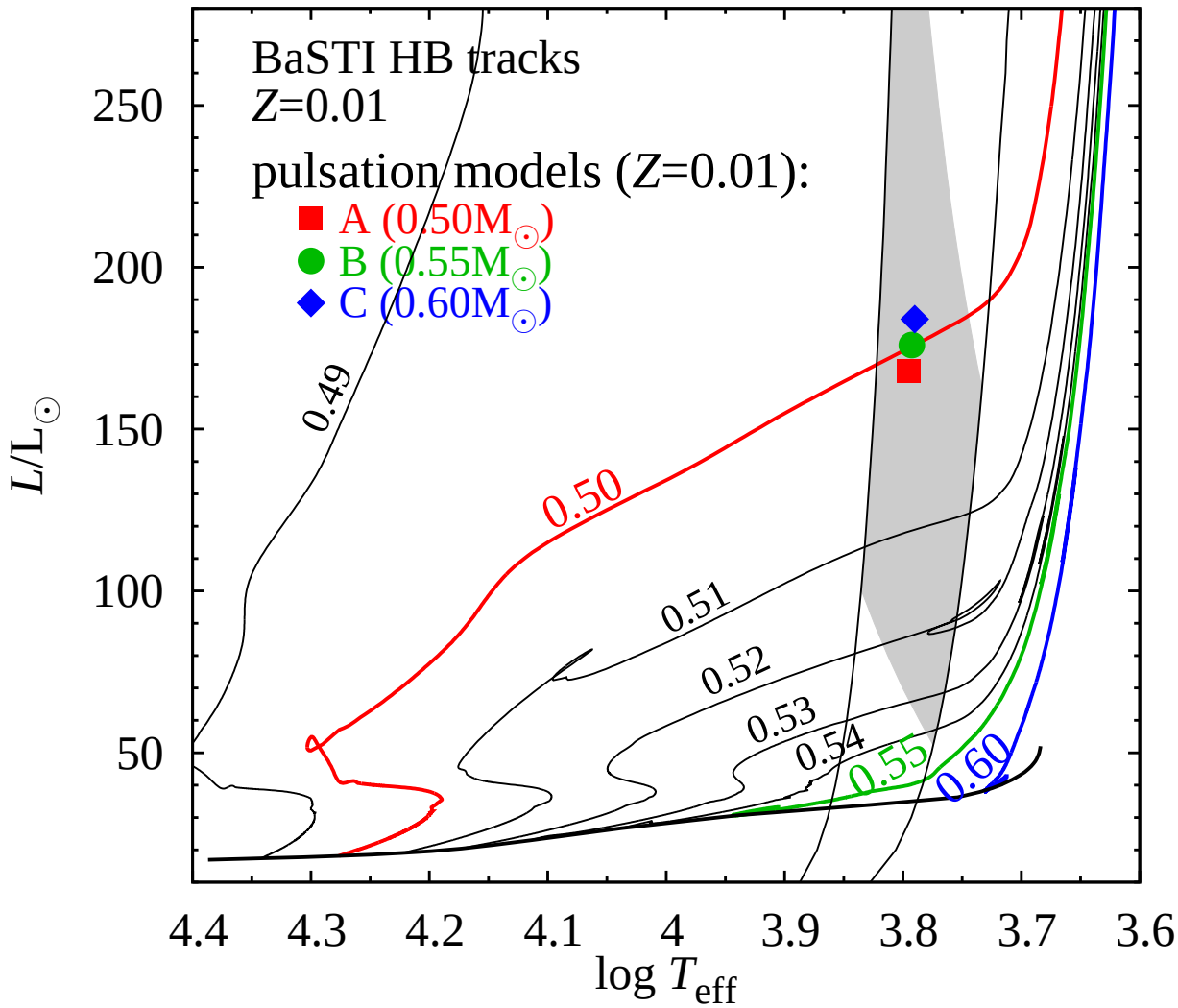
  $M = 0.55\mathrm{M}_\odot,\ L = 176\mathrm{L}_\odot$

- **model C:**

  $M = 0.60\mathrm{M}_\odot,\ L = 184\mathrm{L}_\odot$



Comparison with BaSTI evolutionary tracks: (Pietrinferni et al. 2006)



Comparison with evolutionary tracks:

- Only low mass model (A, $M = 0.50\mathrm{M}_\odot$) consistent with evolutionary tracks
- The same conclusion from analysis of other tracks: Dartmouth, Padova, Y^2

Summary & conclusions

- We have discovered the first BL Herculis star showing the period doubling effect, predicted by theoretical models of Buchler & Moskalik (1992)
- Other star is a strong period doubling candidate
- We confirm the earlier result of Buchler & Moskalik (1992) that the 3:2 resonance with the 1O is responsible for the period doubling behaviour
- We were able to model the light curve of the only BL Her star showing the period doubling satisfactorily
- We have estimated the parameters of the star: $M \approx 0.50\mathrm{M}_{\odot}$ and $Z = 0.01$

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