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STELLAR ACTIVITY OR A PLANET?

Revisiting dubious planetary signals in M-dwarf system

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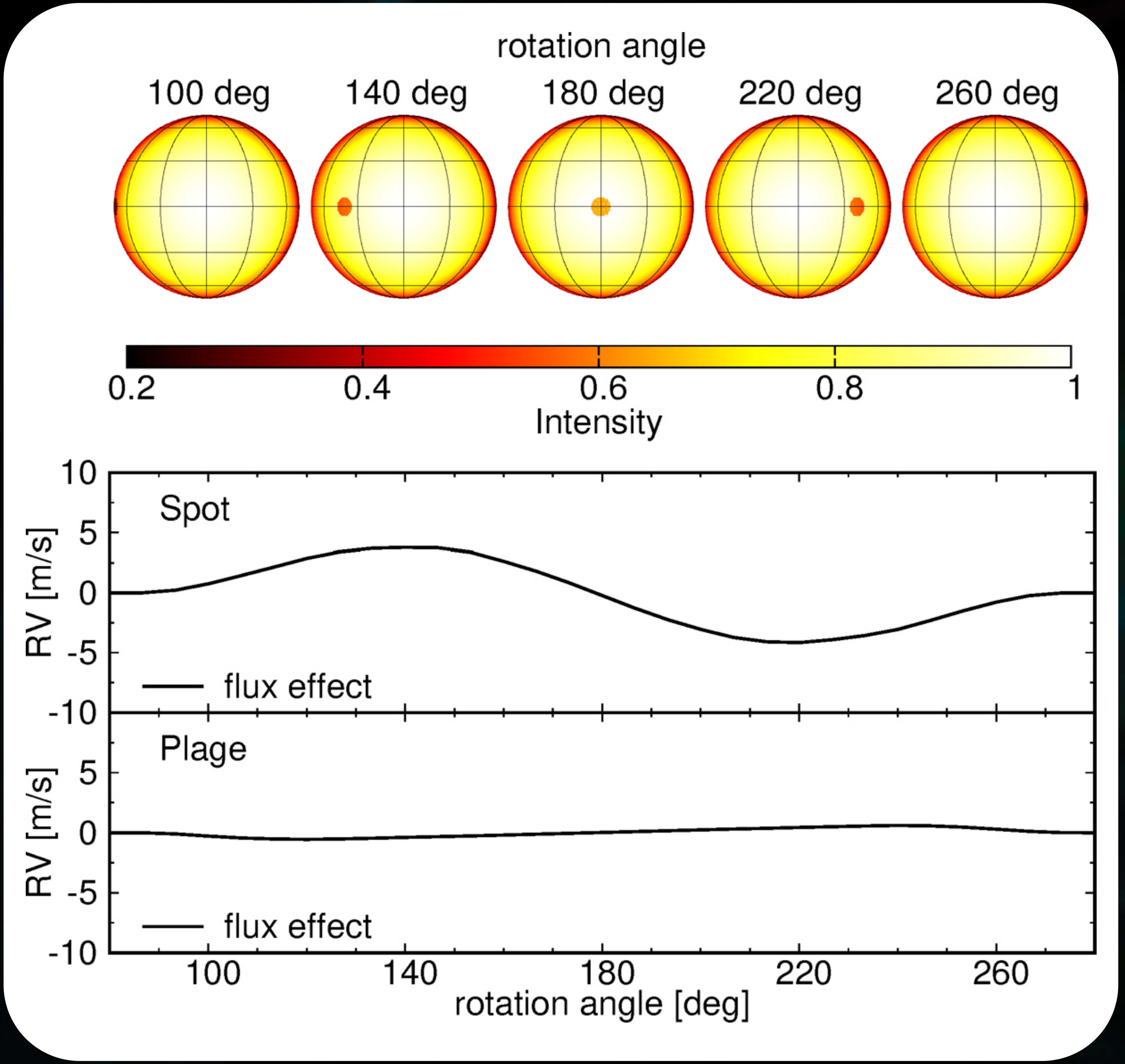
Context

- M dwarfs are known to be magnetically active (Reiners, 2012; Jeffers et al., 2018; Kochukhov, 2021)
- The presence of magnetic activity can affect the RV measurements inducing signals
- When these signals are periodic, they can be missinterpreted as planetary signature (Hébrard et al., 2014; Meunier et al., 2017; Dumusque et al., 2015; Costes et al., 2021).



Upper panel: Schematic view of a G2 simulated star (T= 5780K) with a dark spot rotating across the projected stellar disk. *Middle panel:* RV curve produced by the flux effect of a dark spot. *Lower panel:* RV curve produced by the flux effect of a bright plage. (Credits: F. Bauer et al. 2017)

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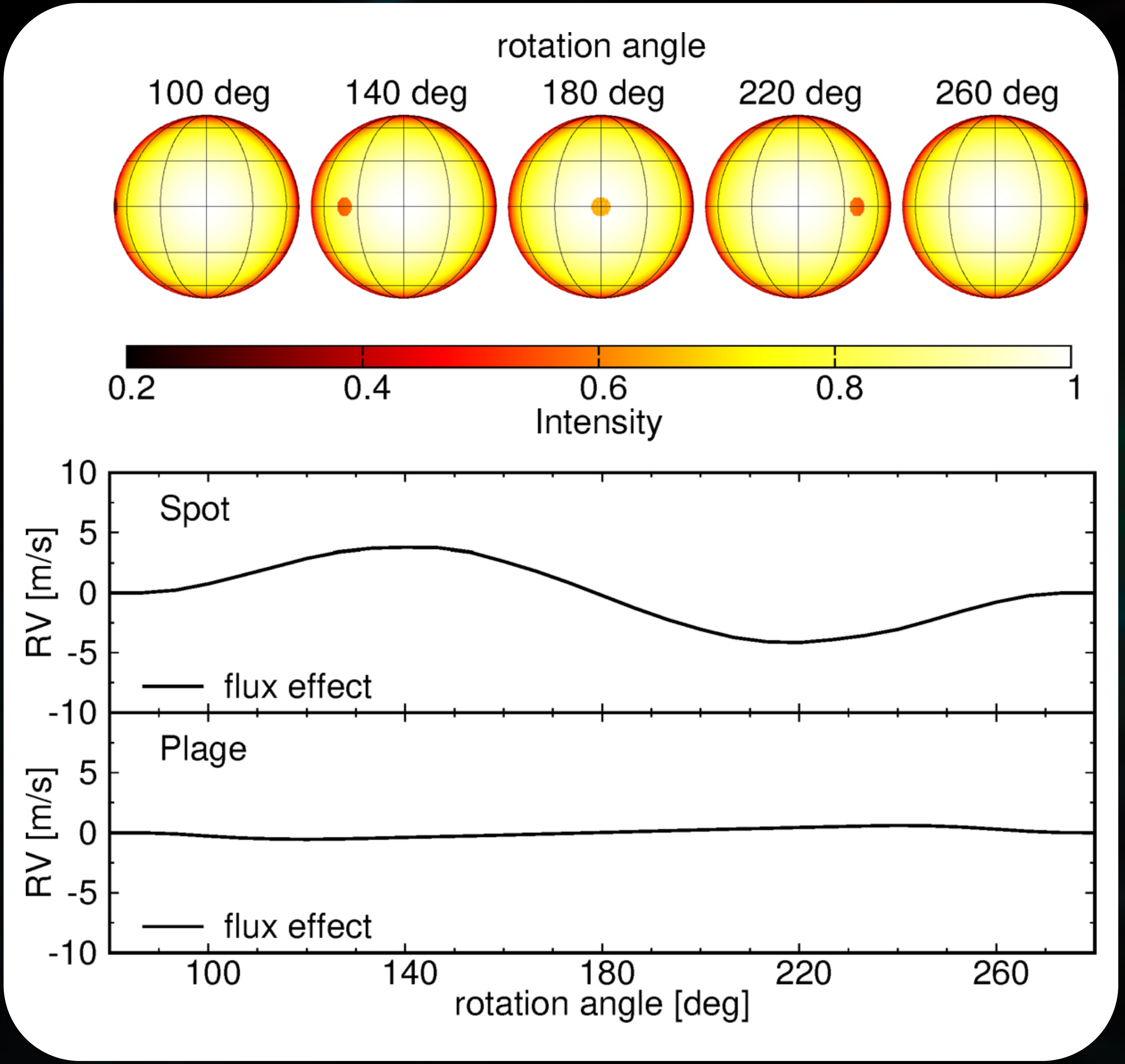
- When these signals are periodic, they can be misinterpreted as planetary signatures (Hébrard et al., 2014; Meunier et al., 2017; Dumusque et al., 2015; Costes et al., 2021).
- Boisse et al., 2009 have shown that stellar spots induce RV variations at the star's rotational period P_{rot} and it's two first harmonics.



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GJ581 - The controversial system

Stellar Rotation Period (days): **132 ± 6.3**						
Parameter	GJ581 b	GJ581 c	GJ 581 d	GJ581 e	GJ581 f	GJ581 g
Orbital Period (days)	$5.368^{+0.001}_{-0.001}$	$12.9^{+0.003}_{-0.002}$	$\mathbf{66.80}\pm0.08$	$3.15^{+0.001}_{-0.006}$	433 ± 13	$\mathbf{36.56}\ \pm0.05$
K (m/s)	12.35	3.28	2.63	1.55	1.30	1.29
Reference	Bonfils et al.(2005)	Udry et al.(2007)	Mayor et al.(2009)	Mayor et al.(2009)	Vogt et al. (2010)	Vogt et al. (2010)

Principal orbital parameters of the multiplanetary system GJ581 based on literature. In bold, we present the stellar rotation period alongside the orbital periods of planets d and g for comparison. Notably, the stellar rotation period is about twice and four times orbital period of planets d and g, respectively, which raises questions about the existence of the planetary signatures

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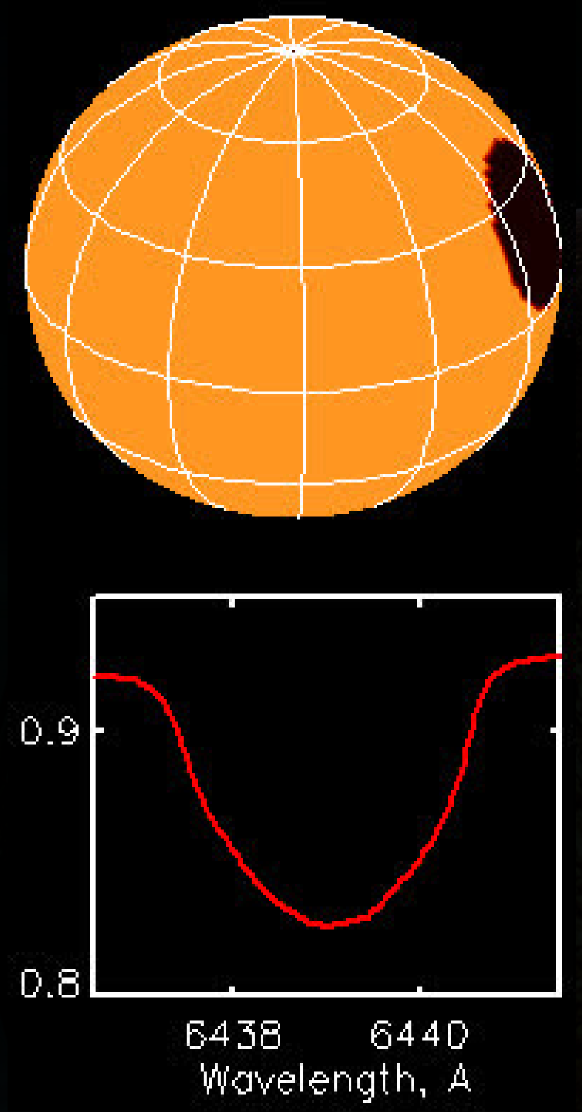
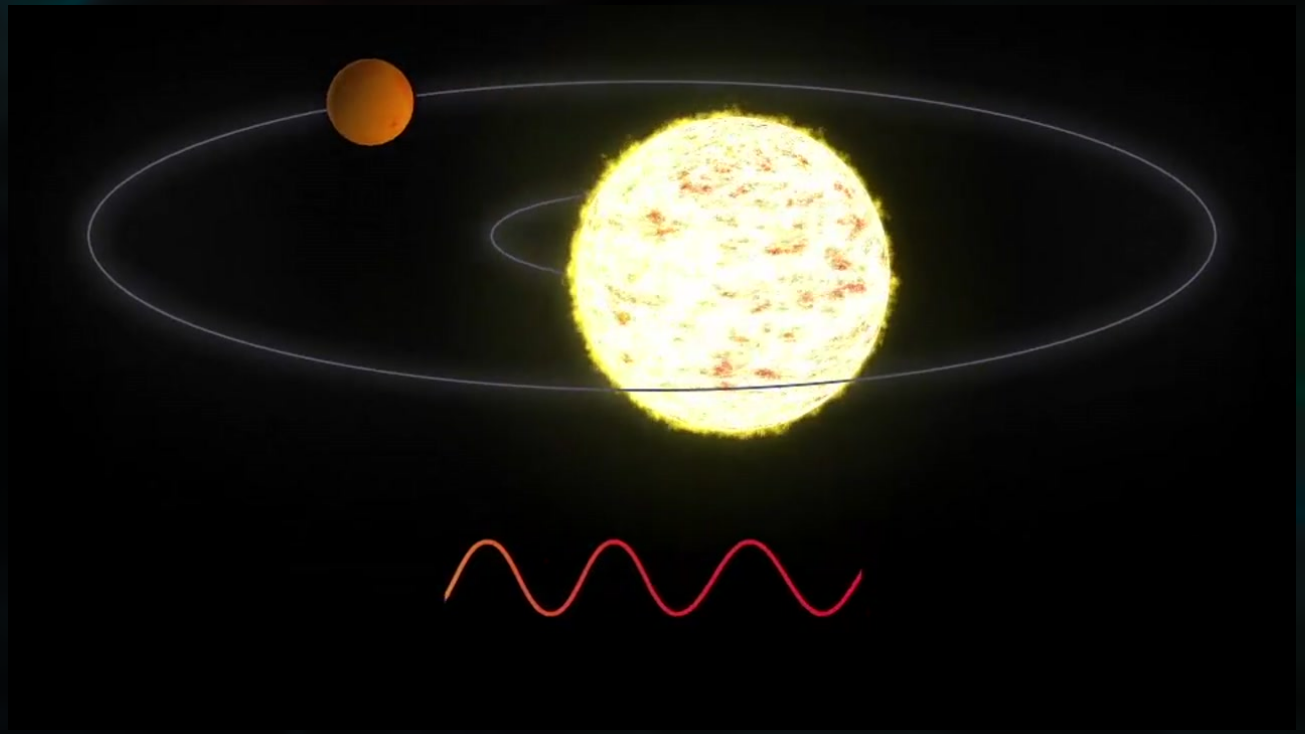
- Robertson et al., 2014, attributted the signals to an artifact of stellar activity.
- Anglada-Escudé & Tuomi. 2015, pointed out that the analysis done by Robertson et al., 2014, is incorrect and that GJ581d is the first planet candidate reported in the habitable zone.
- Robertson et al. 2015 maintain that activity on GJ581 induces RV shifts.

My work



Then... What is the origin of the 66-d signal?



Data

Radial Velocities

Spectrograph	Number of RV datapoints	Mean error (m/s)	Spectral Resolution R
HARPS* (Mayor et al.2003)	**252**	**1.32**	**115000**
HIRES (Butler et al.2017)	**412**	**1.78**	**85000**
CARMENES (Ribas et al. 2023)	**54**	**0.99**	**94600**

* **NAIRA** (New Algorithm to InferRAdial-velocities, Astudillo Defru et al 2017b)

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Spectroscopic Activity Tracers

1. **The S-index (Ca II H&K):** was computed following Astudillo-Defru et al. (2017a).
2. **Hα index:** the method described in Gomes da Silva et al. (2011) was used.
3. **Na I D index (D1: 5895.92 Å; D2: 5889.95 Å):** was computed following Astudillo-Defru et al. (2017b).

- Butler et al.2017 provides S-index and Hα.
- SERVAL (SpEctrum Radial Velocity AnaLyser, Zechmeister et al. 2017) pipeline provides the indices.

Analysis:

Stellar rotation period estimation

The Ca II H&K and Hα lines have proved to be good indicators in the search for rotational modulation (Gomes da Silva et al. 2011; Robertson et al. 2015; Rajpaul et al. 2015; Suárez-Mascareño et al. 2016).

By modeling these activity indicators with a **Gaussian Process** (GP) Regression with a **Quasi-Periodic Kernel** we can derive the stellar rotation period.

$$k_{\mathcal{GP}}(t,t') = \eta_1^2 \exp\left[-\frac{(t-t')^2}{2\eta_2^2} - \frac{2}{\eta_4^2}\sin^2\left(\frac{\pi(t-t')}{\eta_3}\right)\right]$$

J. D. Camacho et al. 2022

Stellar rotation period estimation

We use the GP modeling capability of `RadVel` (Fulton et al. 2018). The optimal kernel hyperparameters for the model are determined through the MCMC method.

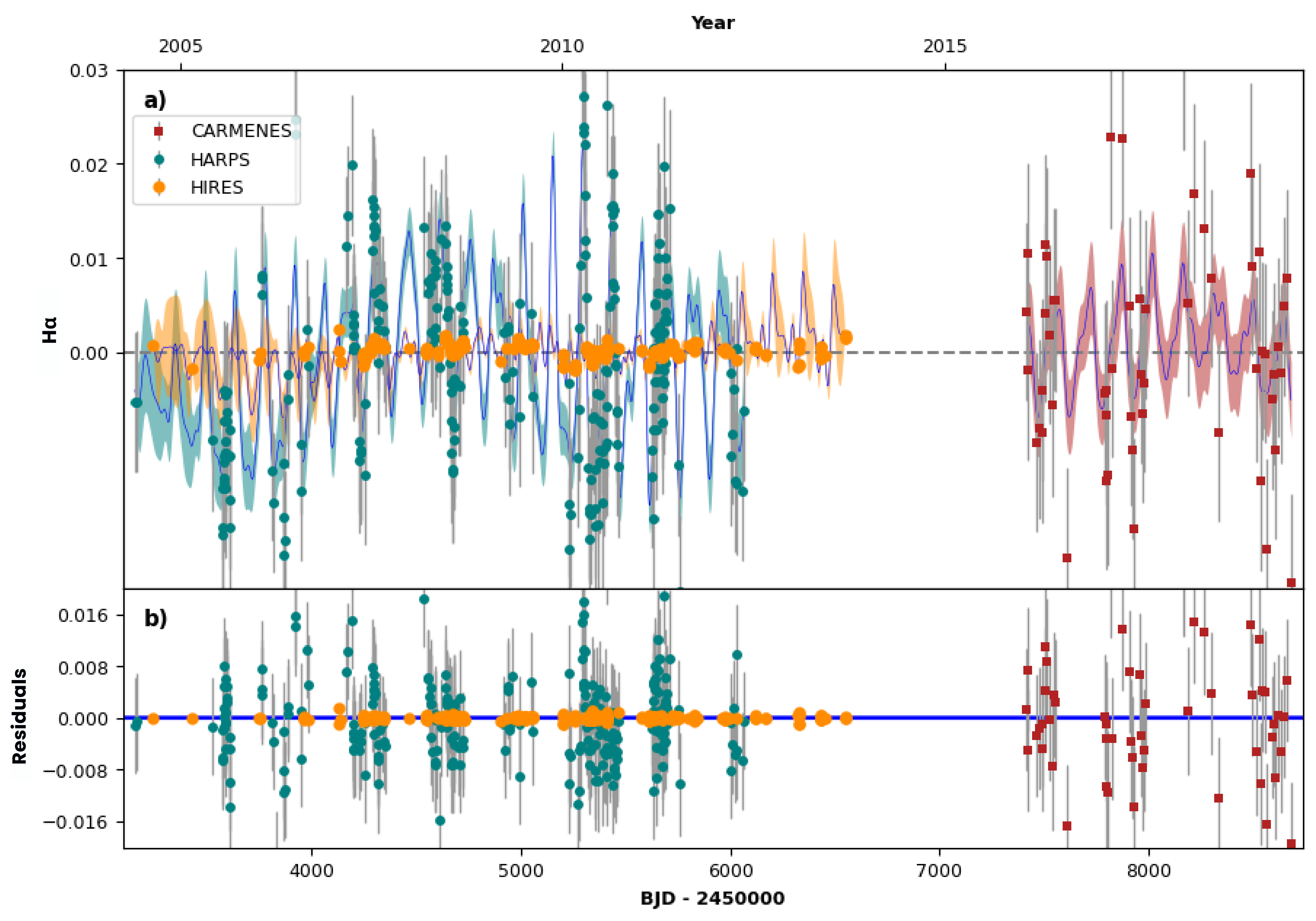


Fig. 1 Hα time series modelled with a GP using a quasi-periodic kernel. a) Model showing the GP resulting from the median of the hyper-parameters' posteriors (blue curve). The coloured zone depicts the model 1-σ confidence. b) Residual of the fit.

We obtained a stellar rotation period value of:

$$P_{rot} = 132.24^{+1.82}_{-1.71}\ [d]$$

**improving the measurement reported in Suárez Mascareño et al. (2015)*

Analysis:
Identifying periodic signals

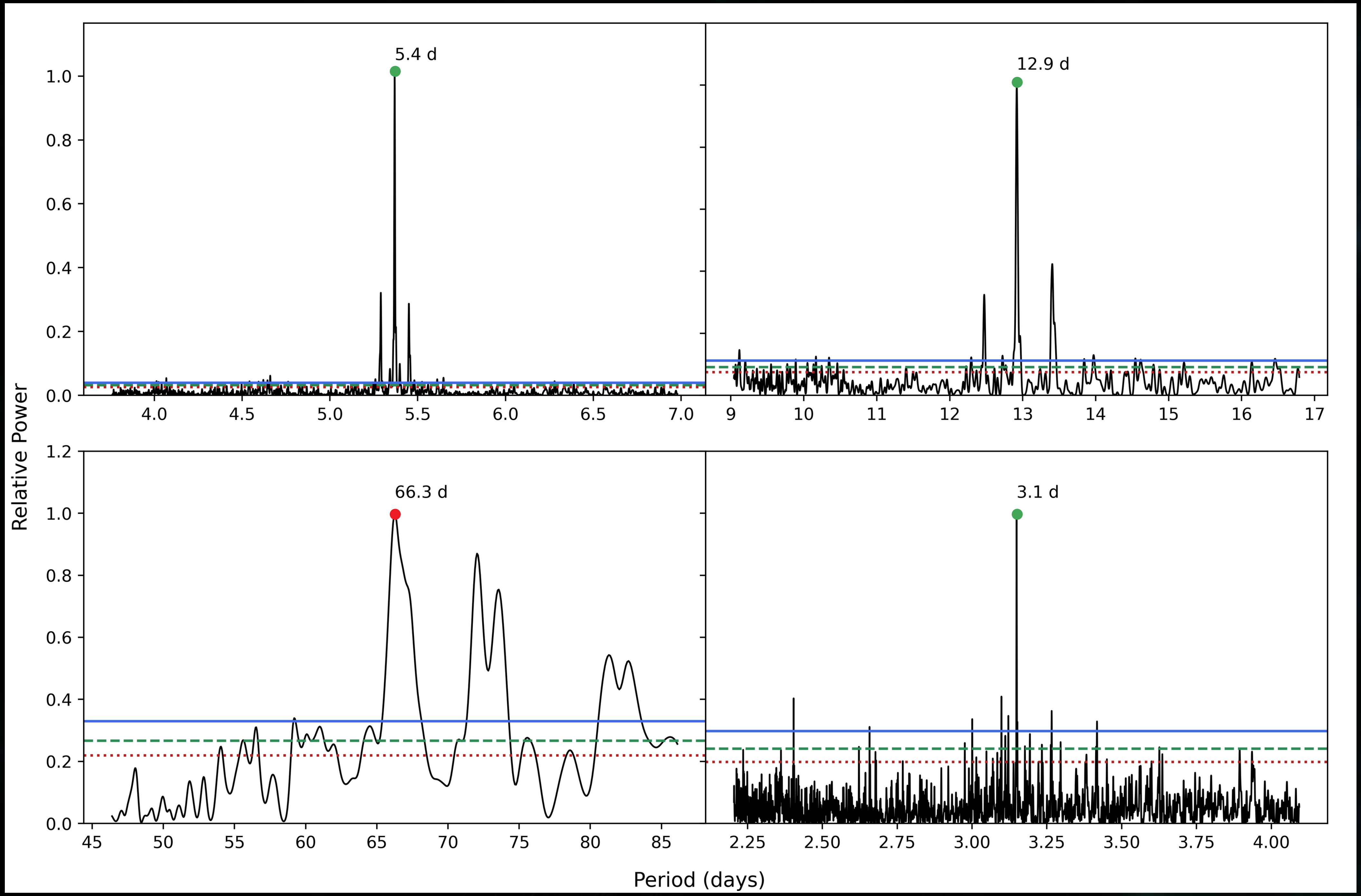


Fig. 2: **GLS periodograms of GJ581 from the RVs' time series.** The solid, dashed and dotted horizontal lines represent the 0.3%, 4.6%, and 31.7% FAP levels corresponding to a 3σ, 2σ, and 1σ detection threshold, respectively

We computed the Generalized Lomb-Scargle **(GLS)** periodogram (Zechmeister & Kürster, 2009) of the RVs and the residuals.

We have detected and confirmed periodic signals corresponding to planets **b**, **c** and **e**, with orbital periods of 5.37, 12.9 and 3.1 days, respectively. This finding aligns with previous studies by Bonfils et al. 2015; Udry et al. 2007 & Mayor et al. 2009.

Analysis:

Temporal stability analysis

based on the principle that stellar activity signals are variable and incoherent.

We computed the Stacked Bayesian GLS (sBGLS) periodogram (Mortier & Collier Cameron, 2017) of the RVs and residuals.

- Activity-induced signals: If there is a quasi-periodic signal, the power can either **increase or decrease** at different epochs as more data are added (Mortier et al. 2015).
- Planetary signal: The power of this signal should increase with the addition of more observations (Howard et al. 2011; Hatzes 2013; Suárez Mascareño et al. 2016).

Temporal stability analysis

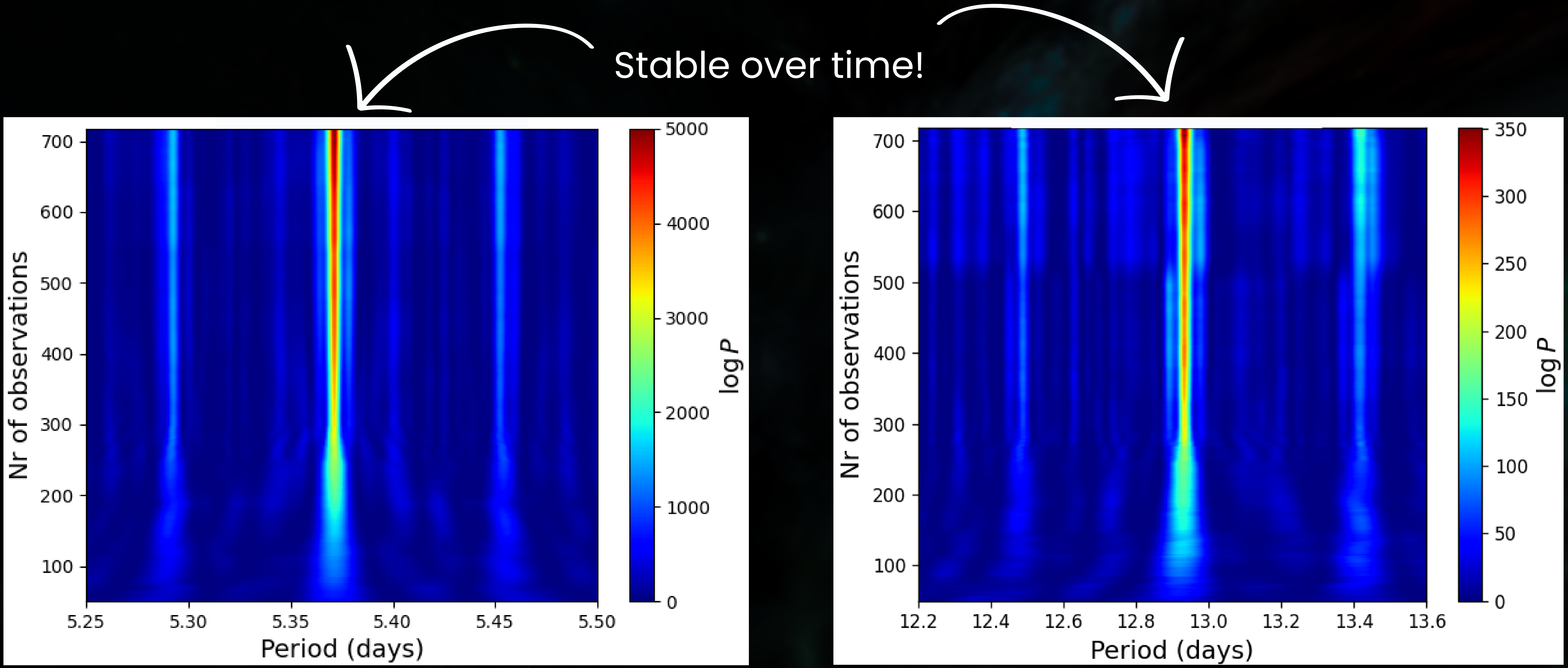
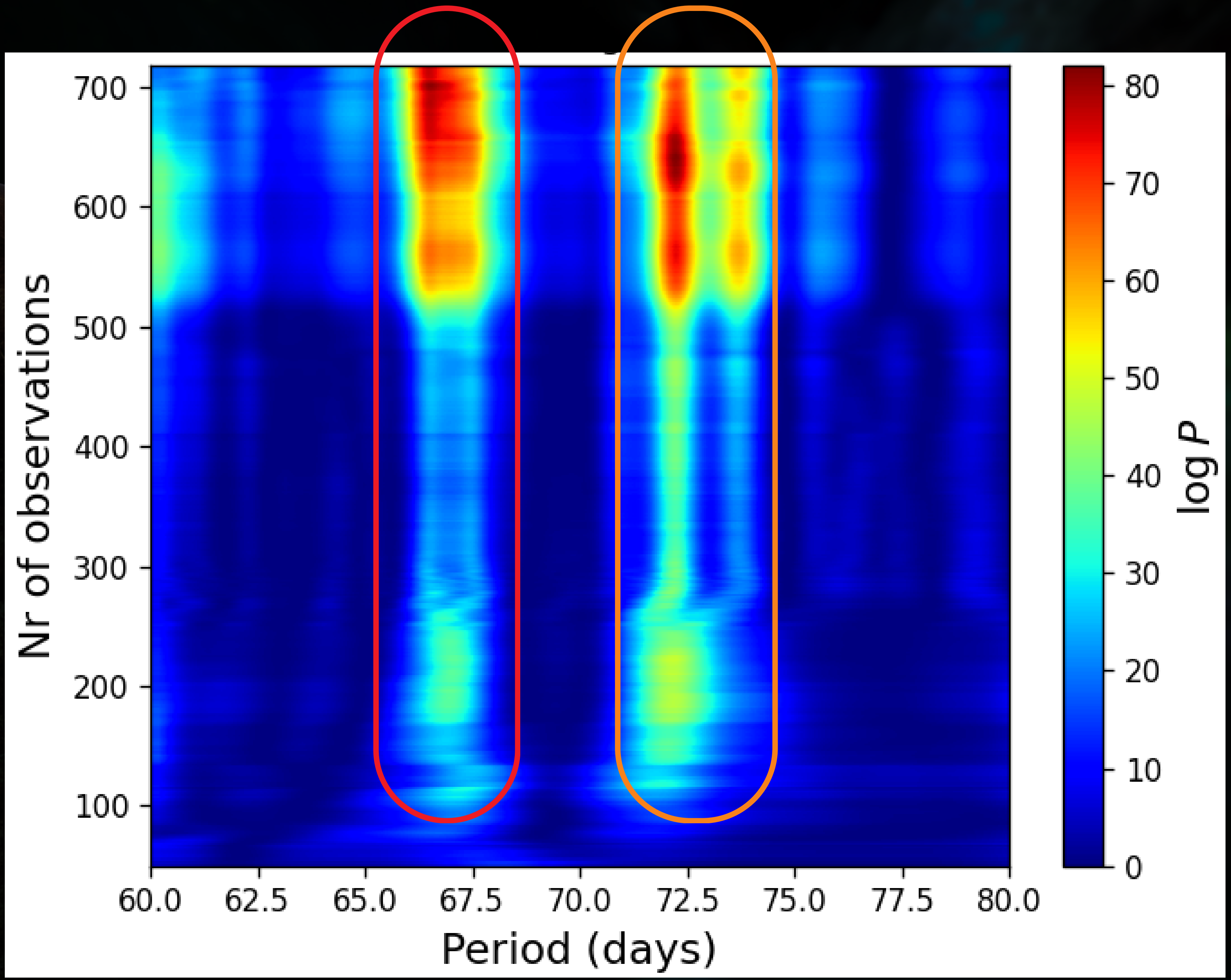


Fig 3: Stacked BGLS periodogram of GJ581 RVs data, zoomed around 5.37 days (left) and 12.9 days (right). Amount of observations is plotted against period, with the colour scale indicating the logarithm of the probability, where redder is more likely.

Temporal stability analysis

Not stable over time!

*Signal planet d



*Another signal around ~72 days

Fig 4: sBGLS periodogram of the residuals, zoomed around 66-days signal.

Analysis:

Keplerian Models

We modelled the RVs using `Pyaneti` (Barragán et al. 2022).

If a star is orbited by N_p planets, the general expression for the radial velocity of the star is:

Barragán et al. 2018

$$M_{\mathrm{RV}}(\vec{\phi};t) = \gamma_i + \sum_{j=1}^{N_\mathrm{p}} K_j \left[\cos(\theta_j + \omega_{\star,j}) + e_j \cos\omega_{\star,j}\right].$$

- γ_i Depends on the spectrograph i to account for possible instrumental offsets
- θ True anomaly
- e eccentricity
- $\omega_\star$ angle of periastron of the star
- $K_\star$ radial velocity semi-amplitude variation

$$M_{\mathrm{RV}}(\vec{\phi};t) = f(\{T_0, P, e, w_\star, K\}_j, \gamma_i; t),$$

Set of parameters that we provide as input priors, which need to be repeated for each planet j.

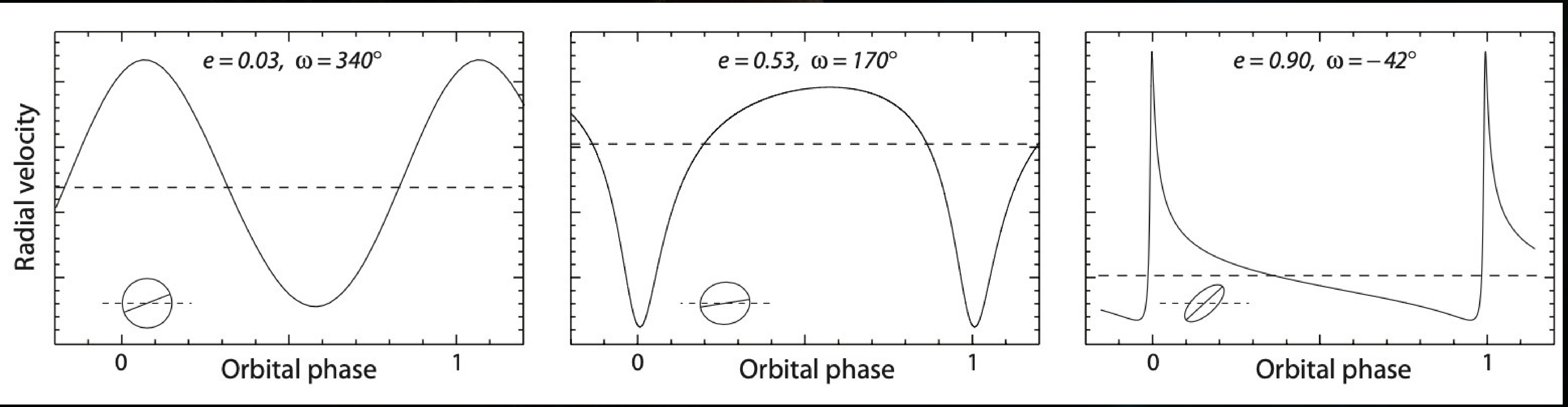


Fig. 5: Example stellar radial velocity curves, illustrating their dependence on e and ω. Image credits: The exoplanet handbook

1-Keplerian Model

Fitted Parameters	Value
P [days]	5.3686
K [m/s]	12.314
M_p [$M_\oplus$]	15.437
e	0.0323
ω [deg]	78.07

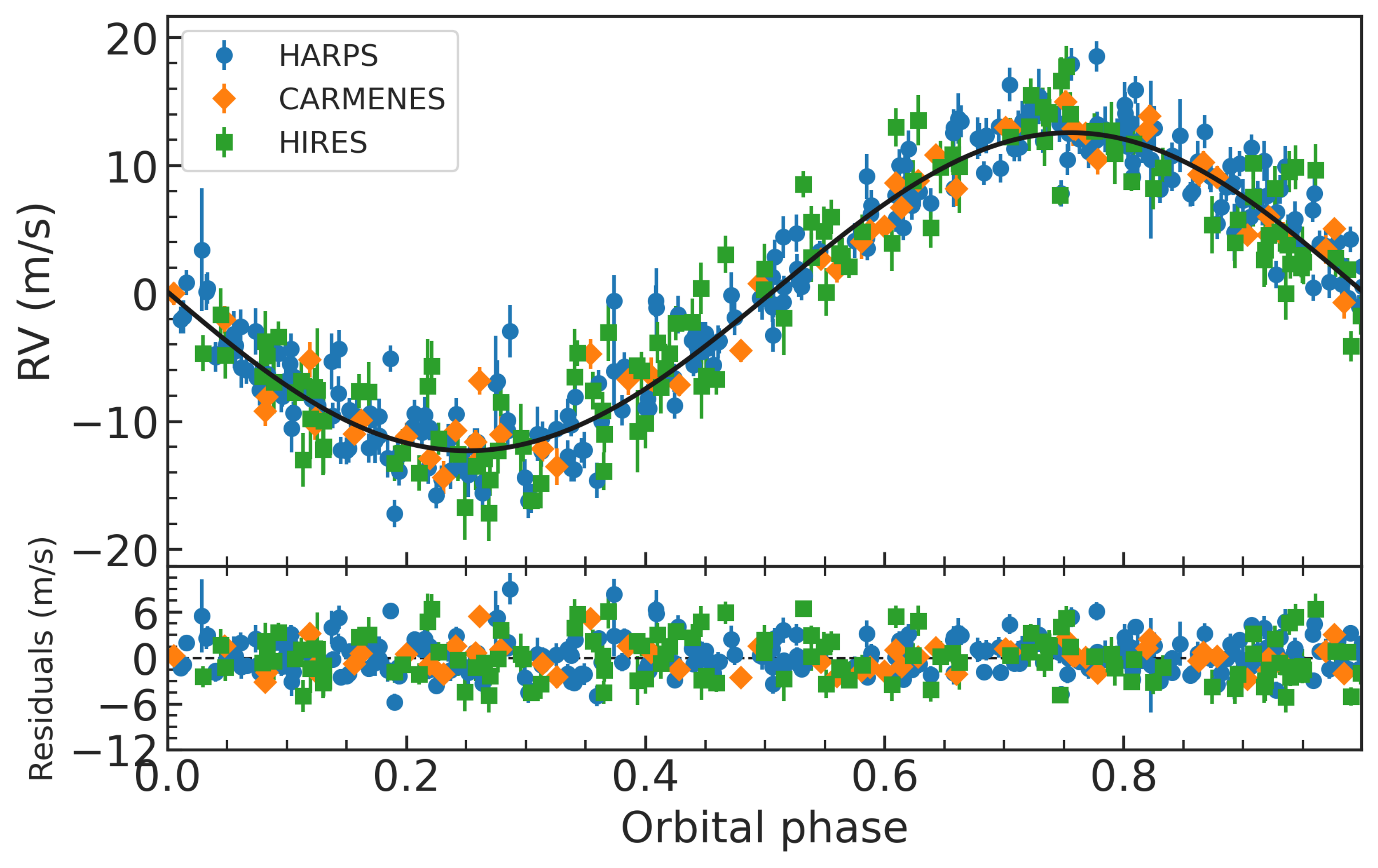
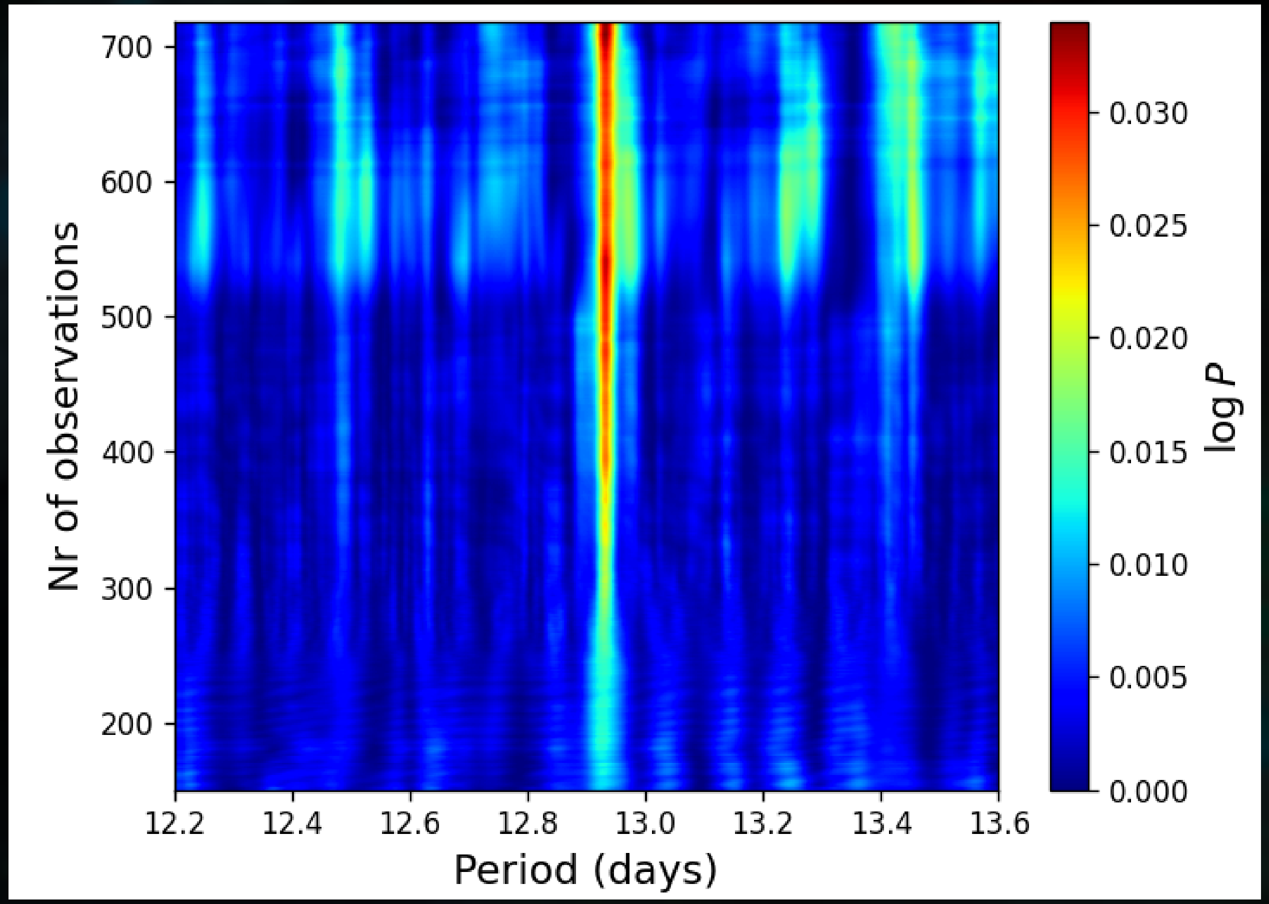


Fig. 6: 1-Keplerian model and the residual.

*Signal planet c = 12.9 days



sBGLS of the residual.
A signal still persist

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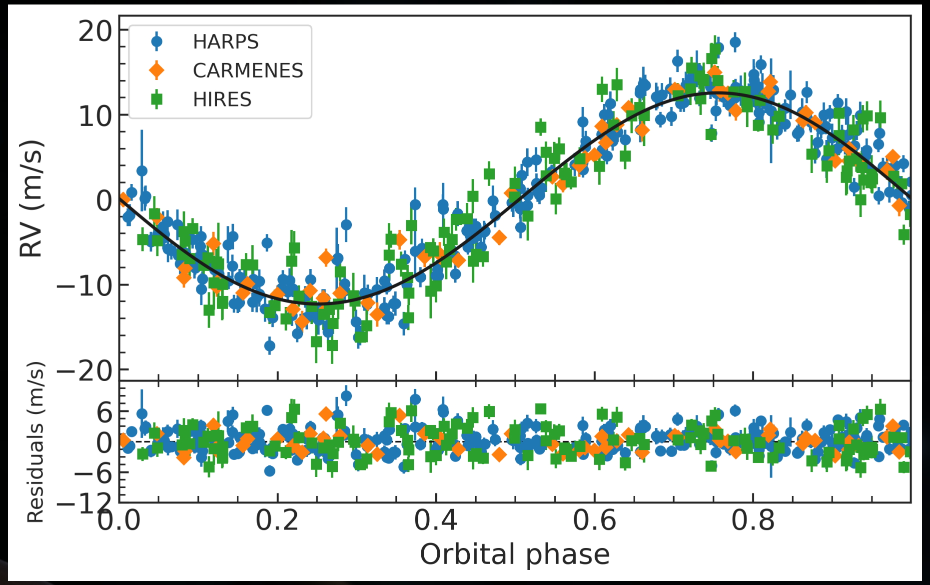
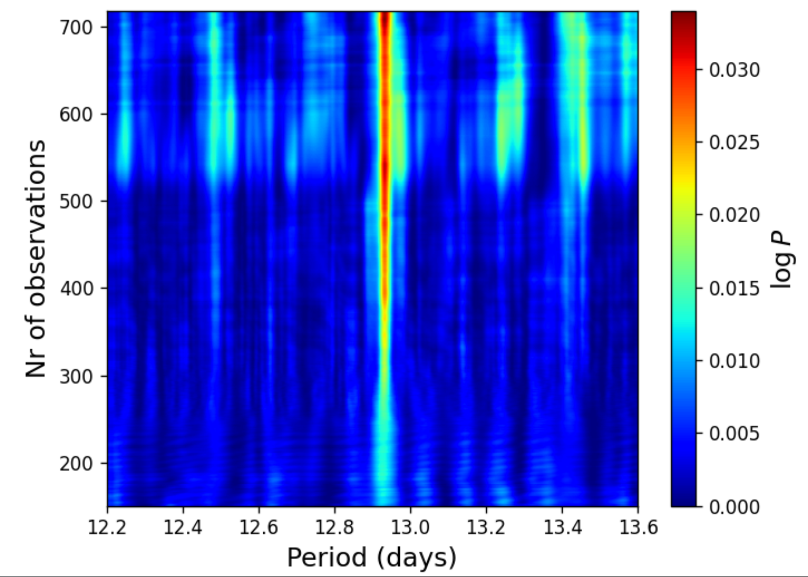




sBGLS of the residual.

2-Keplerian Model

Fitted Parameters	Value
P [days]	12.918
K [m/s]	3.444
M_p [$M_\oplus$]	5.772
e	0.05
ω [deg]	140.69

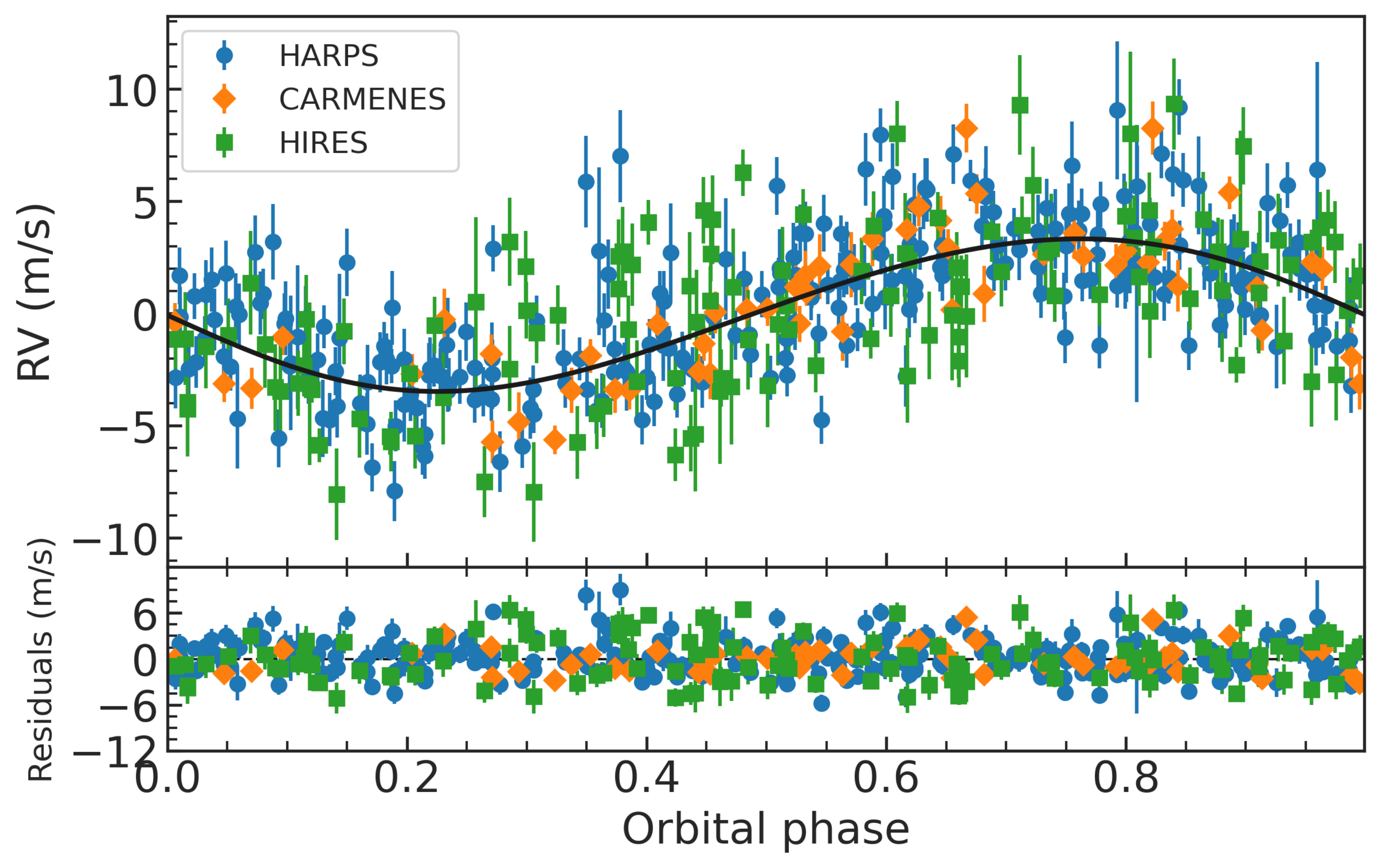
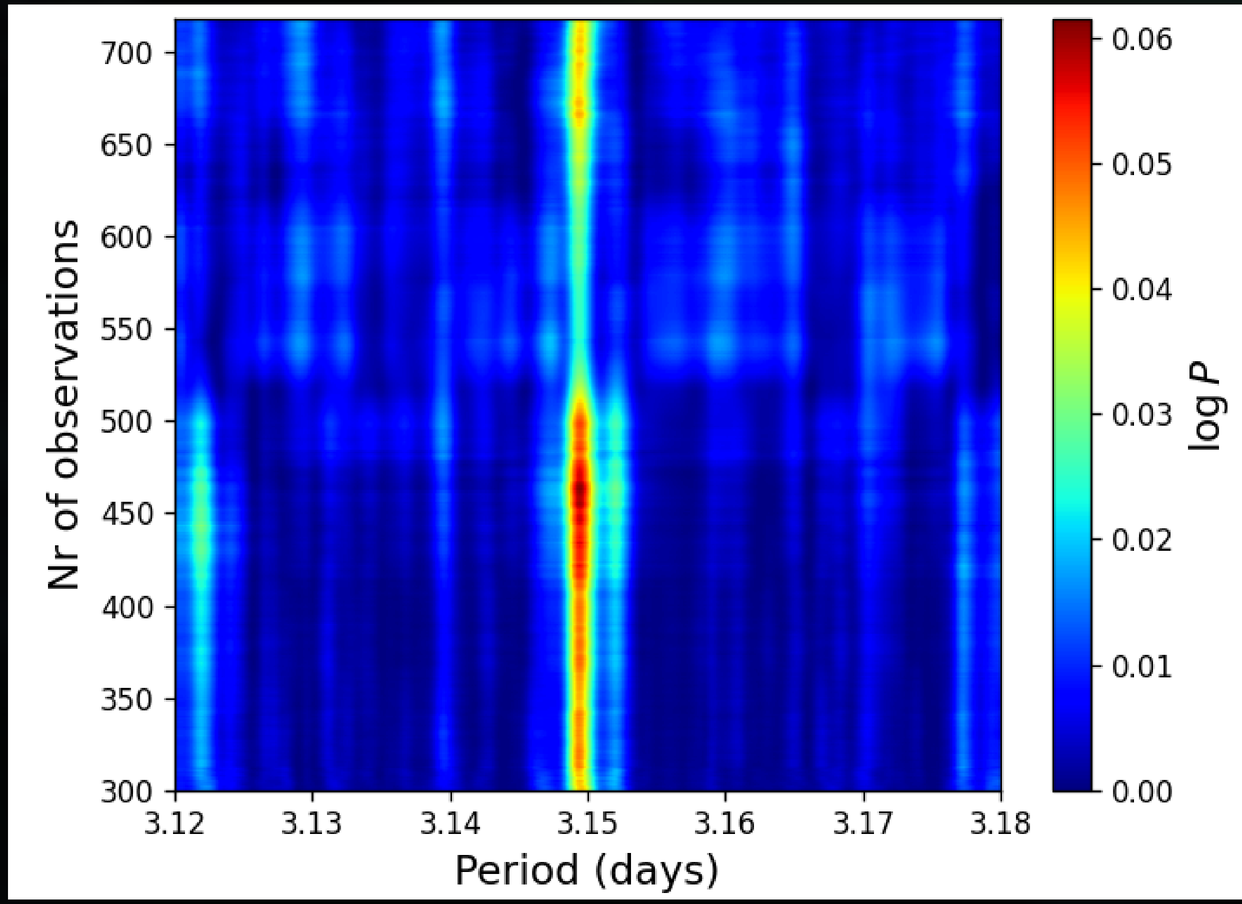


Fig. 7: 2-Keplerian model and the residual.



sBGLS of the residual.
A signal still persist

3-Keplerian Model

Fitted Parameters	Value
P [days]	3.148
K [m/s]	1.569
M_p [$M_\oplus$]	1.534
e	0.307
ω [deg]	65.931

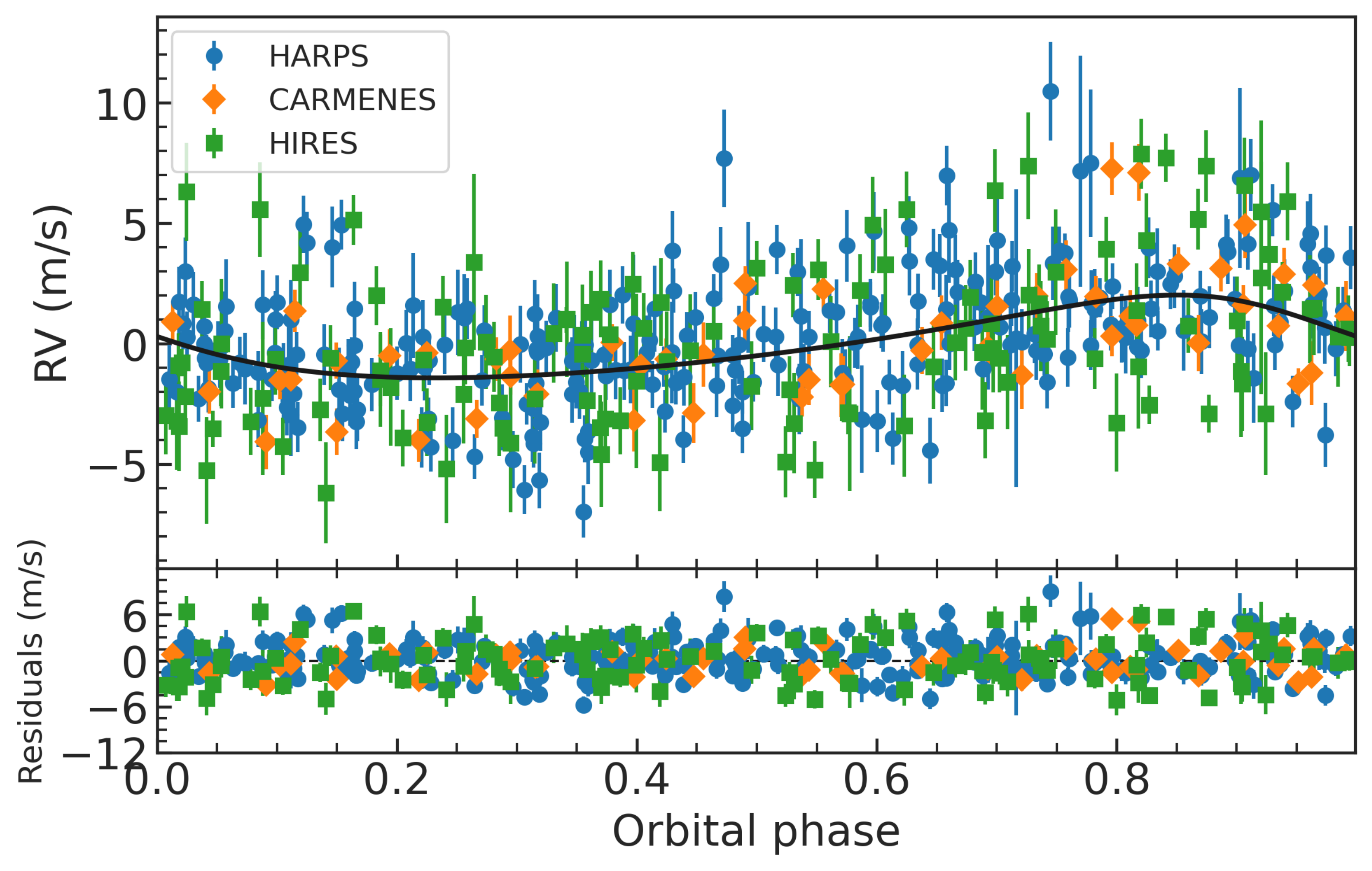
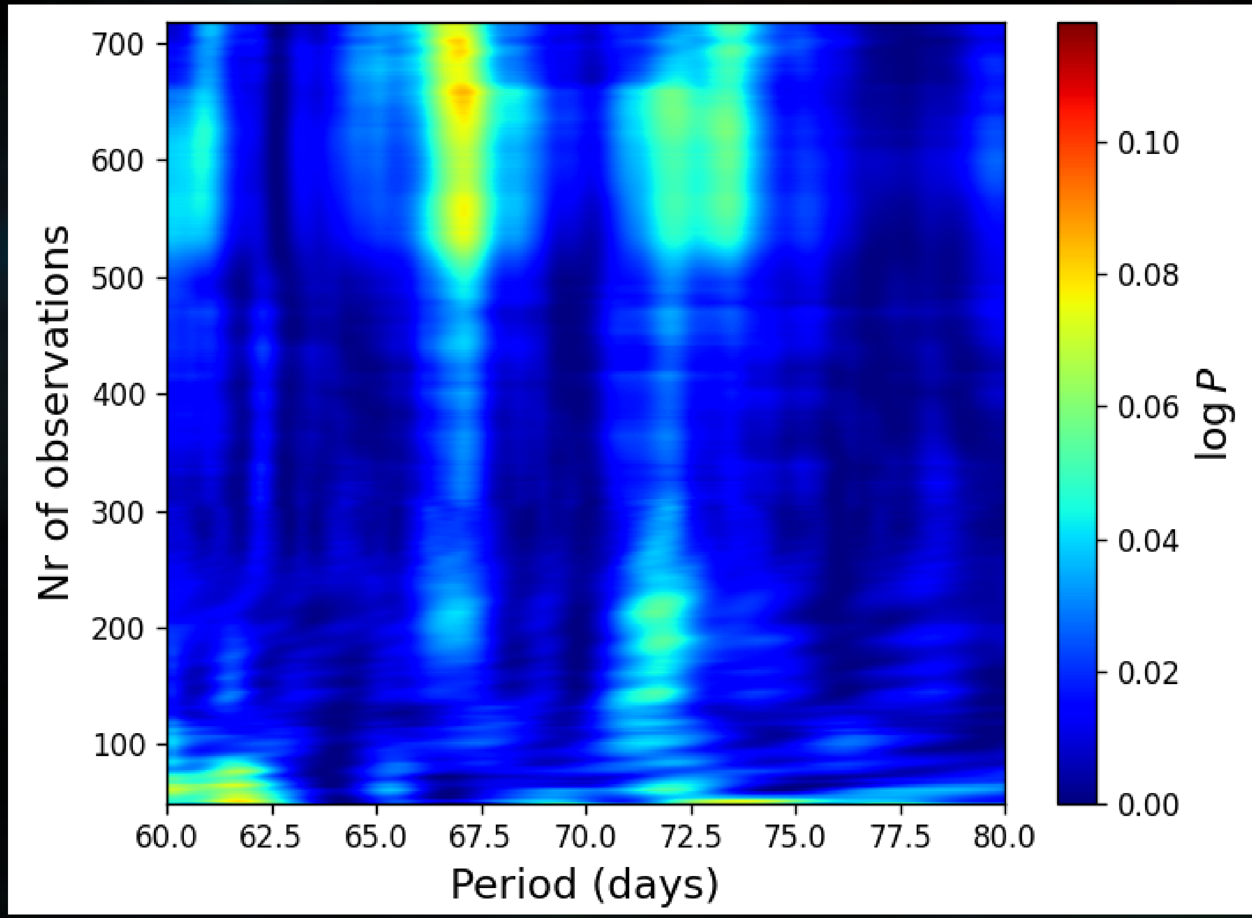


Fig. 8: 3-Keplerian model and the residual.

sBGLS of the residual.



*The signal lacks significance and is not constant over time.

What's next?

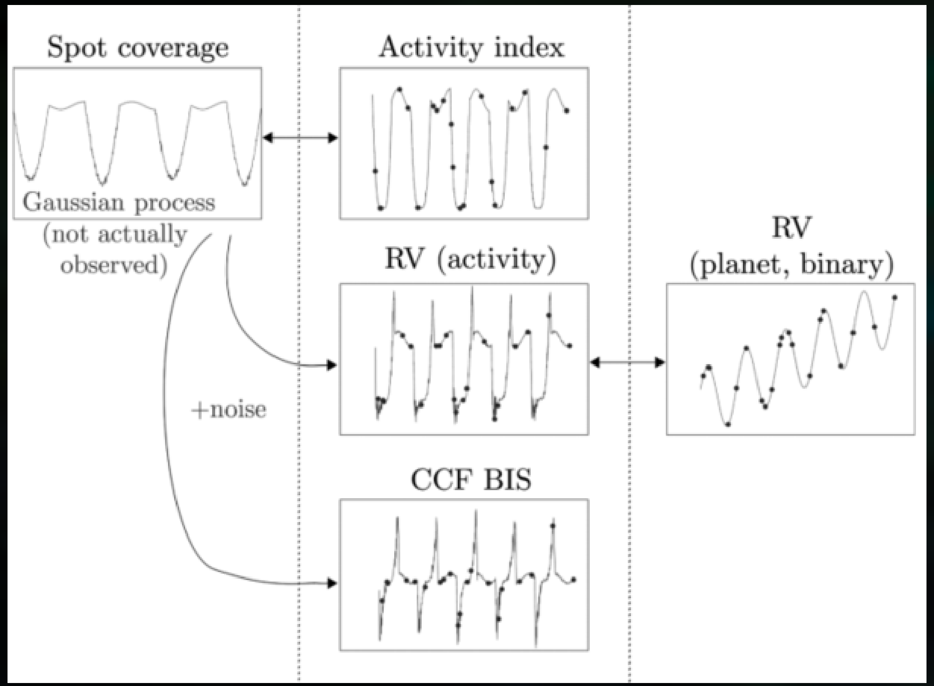
RVs and Activity Tracers model

We will analyze the RVs alongside the stellar activity tracers: Hα, Na D I and the S-index, independently.

Index	Model
$H\alpha$	3-Keplerian
	4-Keplerian
S-Index	3-Keplerian
	4-Keplerian
Na I D	3-Keplerian
	4-Keplerian

Table showing the simultaneous RV and activity index models that we will perfom

The underlying stochastic process givin rise to activity signals in RV timeseries can be described by a GP, with suitable chosen covariance function, such as the **quasi-periodic kernel.**



Simplified, schematic sketch of the GP-based scheme for the joint modelling of an RV time series with ancillary activity diagnostics

Take-home message

- Stellar activity is one of the main causes of false alarm signals when analyzing high-precision radial velocity (RV) time series

- It's crucial to account stellar activity in RV models especially when the orbital periods of the candidate planets is similar to the stellar rotation period.

- Our investigation suggests that the 66.3 days signal is predominantly attributed to stellar activity. Further analysis is essential to validate and confirm this observation.

Forget about planets, ***Know your star***

- Suárez Mascareño

Want to ask/discuss something?

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