The Yale Radial Velocity Challenge: results and application for testing tools to detect low-mass planets

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The challenge

Intrinsic stellar variability represents a major limiting factor for planet searches in radial velocity (RV) data.
New spectrographs (e.g. ESPRESSO) will improve RV precision by a factor of ~100.
This will stress the challenge of distinguishing planetary signals from stellar activity-induced RV signals.

Good progress has been made in simulating stellar activity signals (e.g. Dumusque et al. 2011A, 2011b).
At the Porto 2014 meeting “Towards Other Earths II” X. Dumusque (CfA/Obs. Geneva) challenged the community to a large scale blind test using the simulated RV data at the 1 m/s level of precision, to understand the limitations of present solutions to deal with stellar signals and to select the best approach.

15 planetary systems were simulated for solar-type stars (GK dwarfs)
Observables: RV, BIS, FWHM and log(R'_{HK})

https://rv-challenge.wikispaces.com/

The challenge

24 groups expressed their interest.
8 of them participated, and 5 analyzed all the 15 tests:

- Francesco Borsa, Giuseppe Frustagli, Monica Rainer, Ennio Poretti (INAF Brera)
- Mario Damasso, Aldo Bonomo, Paolo Giacobbe, Raphaëlle Haywood, Matteo Pinamonti, Alessandro Sozzetti (INAF Torino)
- Phil Gregory
- Artie Hatzes
- Vinesh Rajpaul, Suzanne Aigrain (Oxford)
- Mikko Tuomi, Anglada Escude
- Rodrigo Diaz, Damien Ségransan (Geneva Observatory)
- Nathan Hara, Frédéric Dauvergne, Gwenaël Boué, Jacques Laskar (Paris Observatory)

We analyzed all the exercises working in a Gaussian Process framework, while the study of the method and the development of the necessary software tools were in progress.
→ limited results, necessarily!

We participated to the Yale Workshop in July, where the challenge was discussed (http://exoplanets.astro.yale.edu).

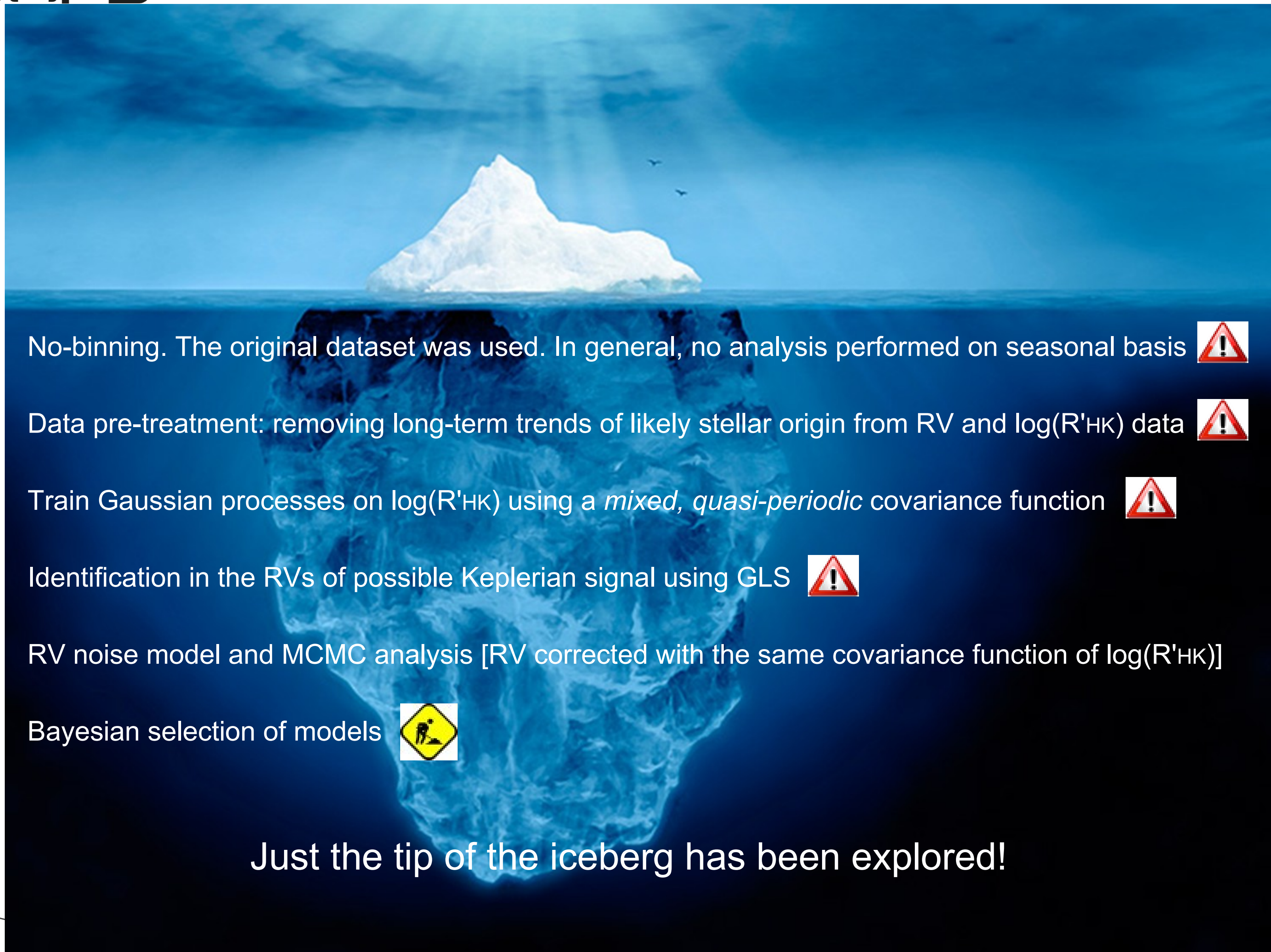
1st draft of a paper foreseen for the end of November (X. Dumusque, priv. comm.)

The simulated datasets

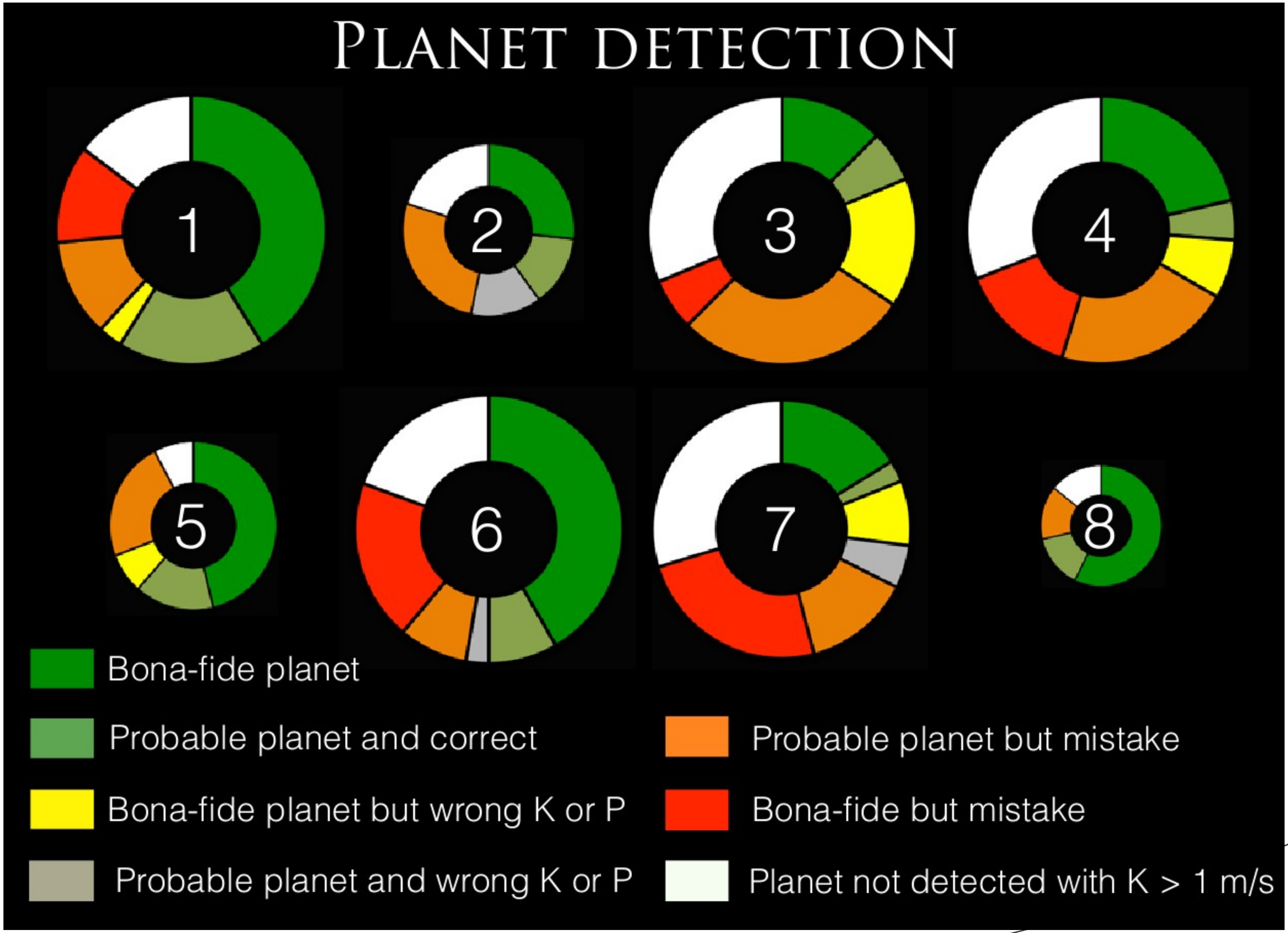
#	Calendar	Prot	Planetary systems
1	Tau Ceti	25.05	Kepler-11 (b,d,e,g) + 1 HZ
2	Tau Ceti	25.05	Kepler-20 (5 pl)
3	Tau Ceti	25.05	HD10180 (b,d,e,g,h) + 26.3d + 1 HZ
4	Tau Ceti	25.05	None
5	HD192310	40.00	HD10700 (b,c,e,f) + 26.2 + 1 HZ
6	HD192310	~40.00 (real)	HD192310 (2 pl) + 36.8d + 105.2d + 1 HZ
7	HD192310	40.00	HD192310 (2 pl) + 36.8d + 105.2d + 1 HZ
8	HD192310	40.00	None
9	Alpha Cen B	36-40 (real)	Alpha Cen Bb ?
10	Alpha Cen B	36-40 (real)	Bb ? + HD85512 (1p) + 0.82d + 1 ZH
11	Alpha Cen B	36-40 (real)	Bb (sim) + HD10700 (b,c,d) + 1 ZH + 3200d
12	Alpha Cen B	40.00	Bb (sim) + HD10700 (b,c,d) + 1 ZH + 3200d
13	Alpha Cen B	40.00	None
14	Corot 7	~22.32 (real)	None
15	Corot 7	22.32	Corot 7 published planets

57 planets, 22 with K>1m/s and 35 with K<1m/s

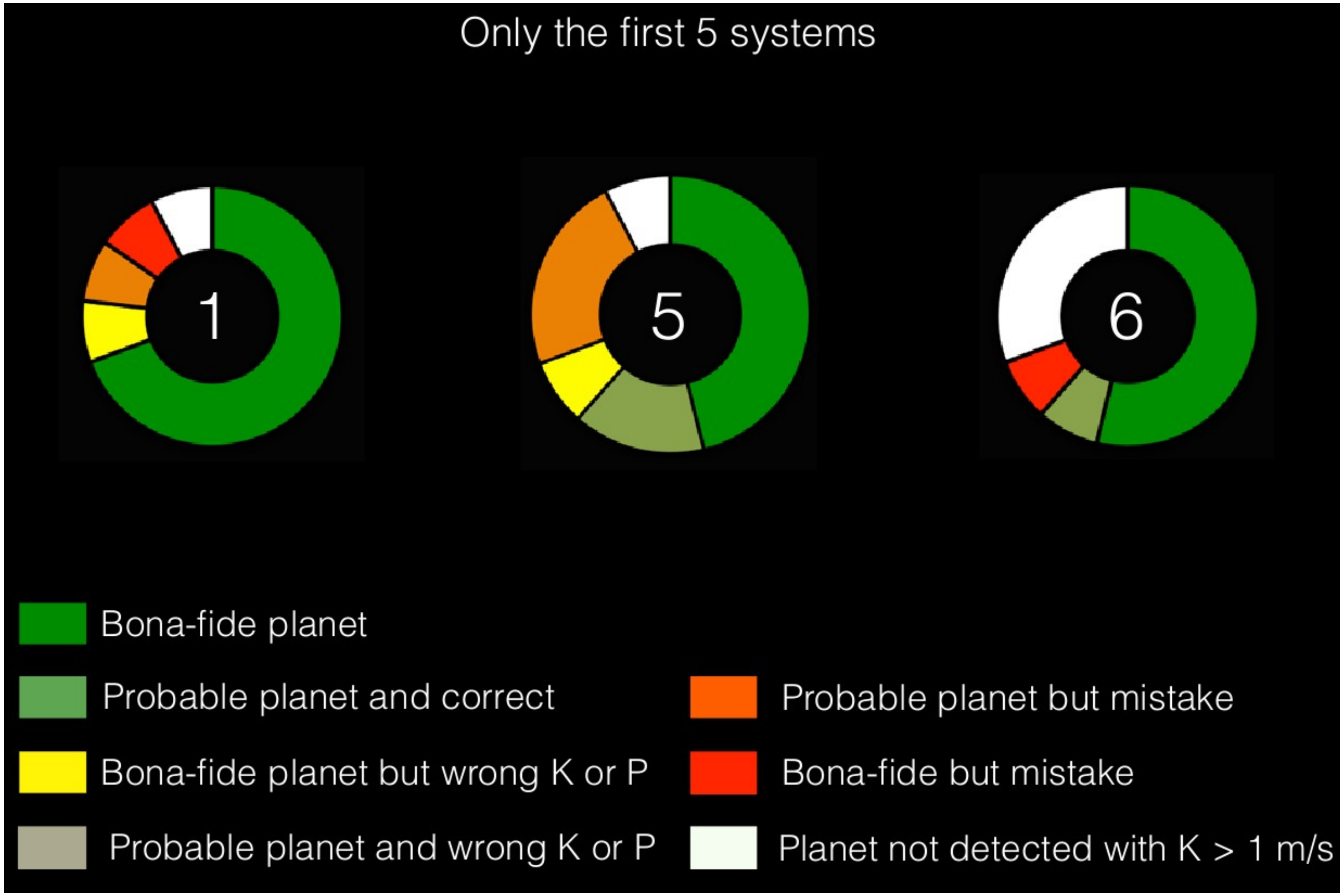
Our general approach



Results
(over the total declared detections)



Results
(over the total declared detections)



Our results

PLANET DETECTION

bona fine planet	15
Probable planet	3
bona fine planet but wrong P or K	0
Probable planet and wrong P or K	1
mistake but flaged as probable	3
mistake and flagged as bona fide	7
non detected , with K > 1m/s	7
not detected, with K < 1m/s	32

ROTATIONAL PERIOD DETECTION

good Prot	9
harmonic of Prot	4
wrong Prot	2

False positives: 2 P_{rot} and 1 $P_{rot}/2$ (wrong P_{rot}), 2 ~P_{rot} (correct P_{rot}), 1 had p-value ~1%
→ they could be avoided!

We reported correctly about the 3 systems without planets

2nd placement!

The challenge datasets are high-level simulations,

and now that we know solutions

they represent a valuable test bench for further analysis,

to explore/develop different detection techniques

Post-challenge analysis
test#1

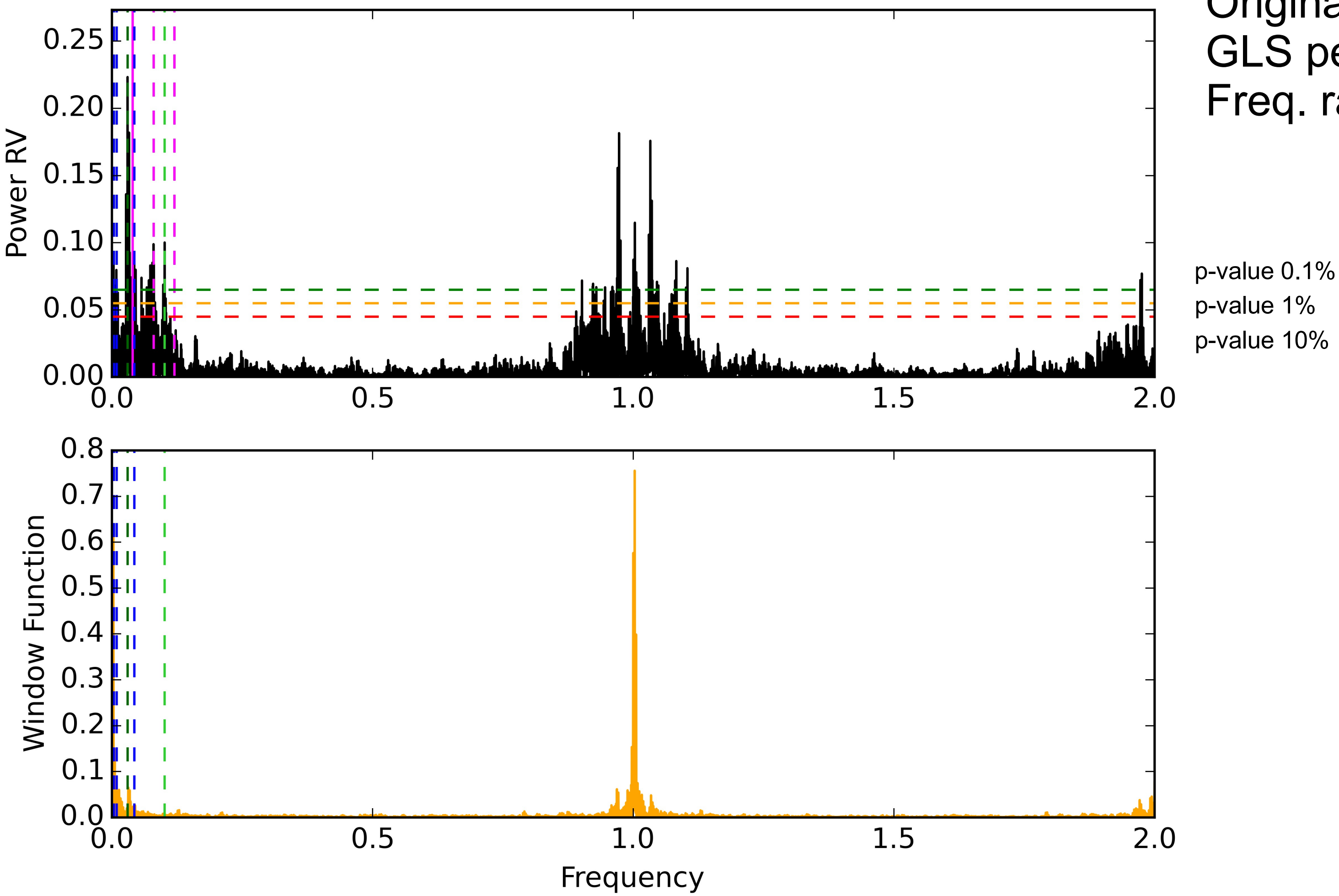
Planetary system 1	Prot	25			
calendar	PL system				25.03
Tau Ceti synth (recent 5 years)	Kepler-11 - 2 pl + 1 hz				
planets	period used	mass used	ecc used	K	
b	9.89	4.128	0.096	1.45	K = 1.65 +/- 0.18
d	23.37	6.283	0.1236	1.67	
e	33.28	8.736	0.0832	2.05	K = 2.15 +/- 0.24
g	112.46	2.375	0.209	0.38	
fake	273.20	1.9	0.16	0.22	

Stellar mass M=0.78 Ms
Three planets with K>1 m/s
No false detections
P_{rot} OK

Planet b doubtful because P ~P_{rot}/2 (but not so close!)
Planet d detected but ignored because P~P_{rot} (very close) → Quite easy to avoid

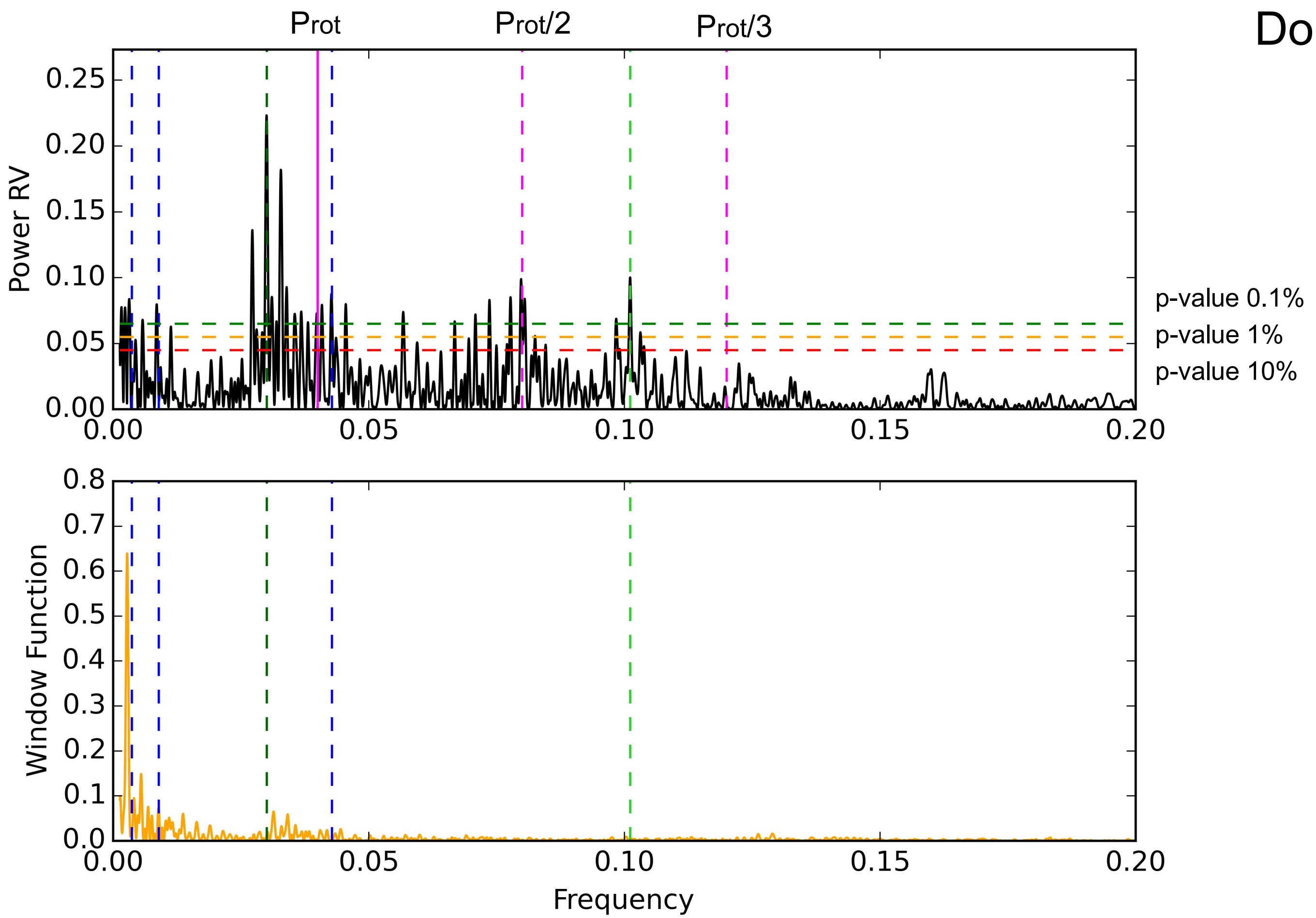
Post-challenge analysis
test#1

Original RVs
GLS periodogram
Freq. range=[0.0013-2]

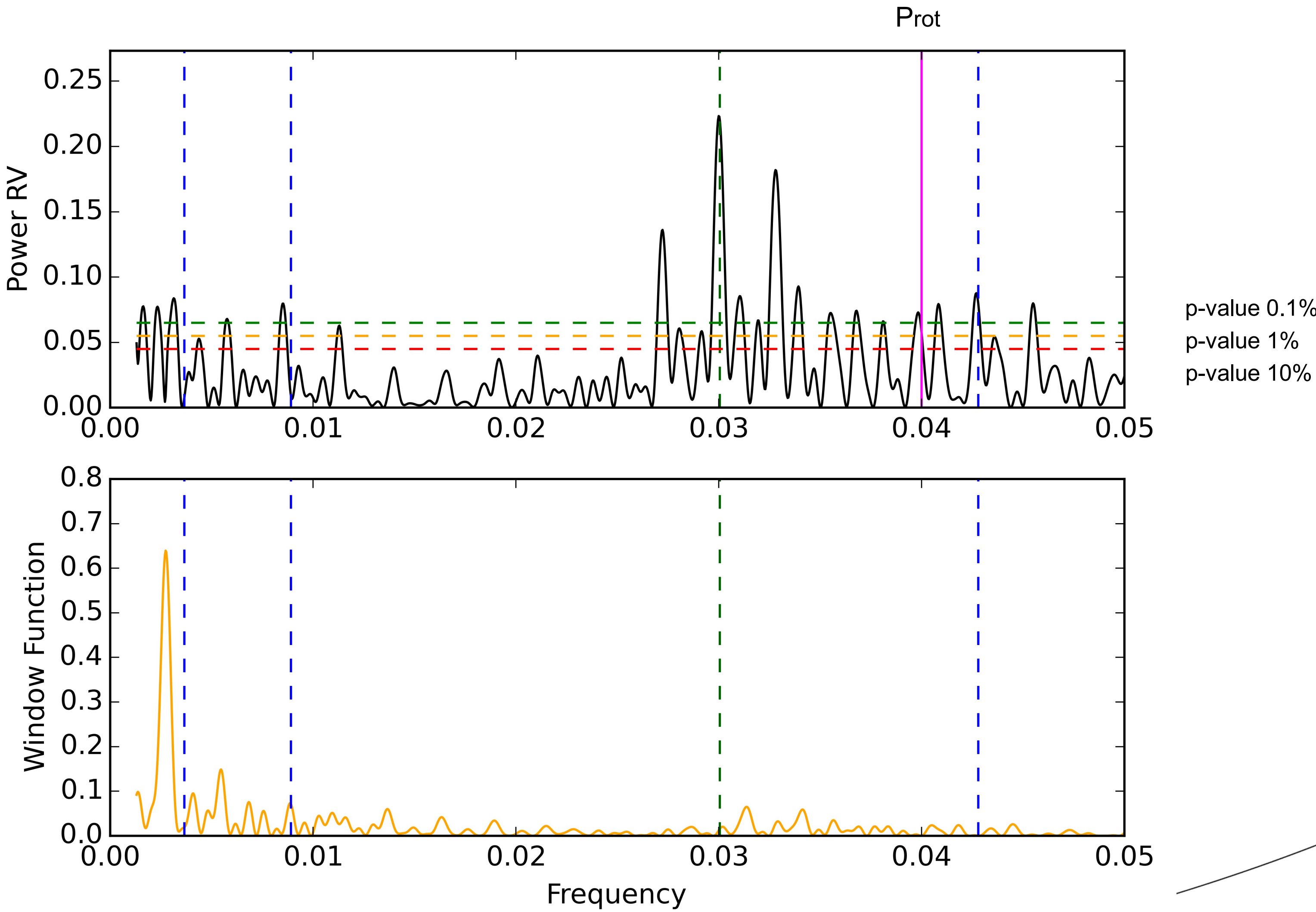


Post-challenge analysis
test#1

Dominant noise @ $P_{rot}/2$



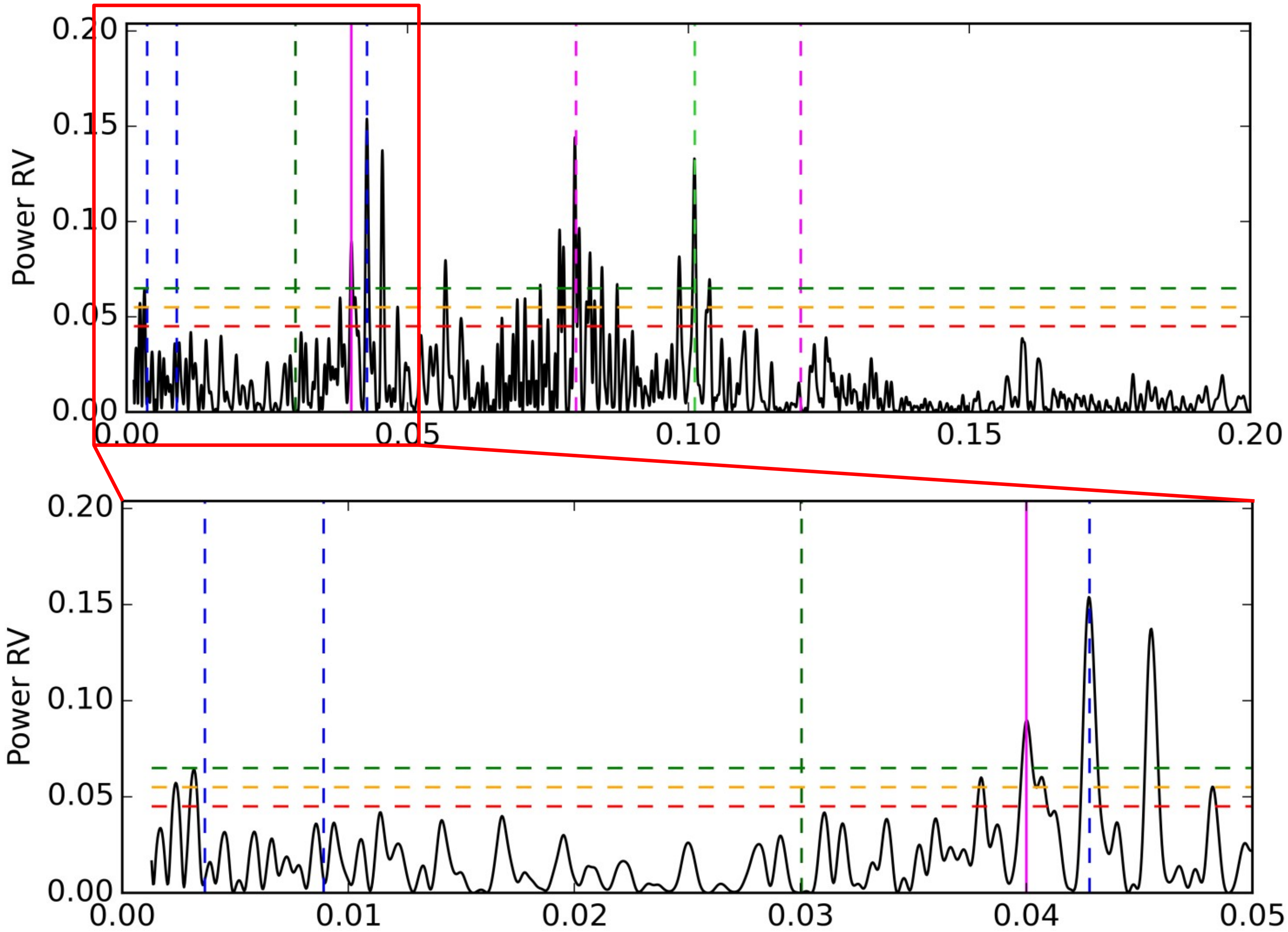
Post-challenge analysis
test#1



Post-challenge analysis

test#1

GLS periodogram of the residuals

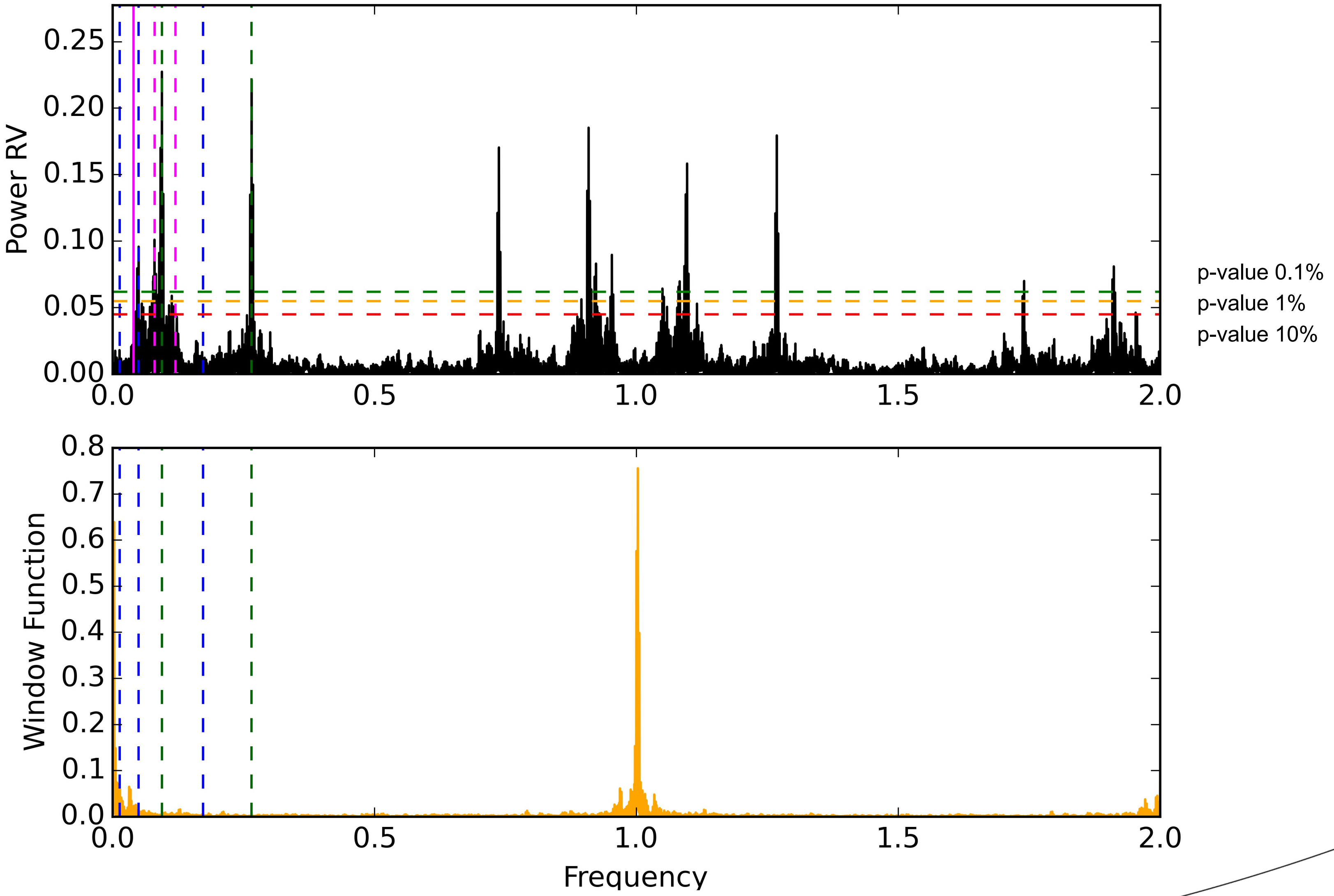


Post-challenge analysis
test#2

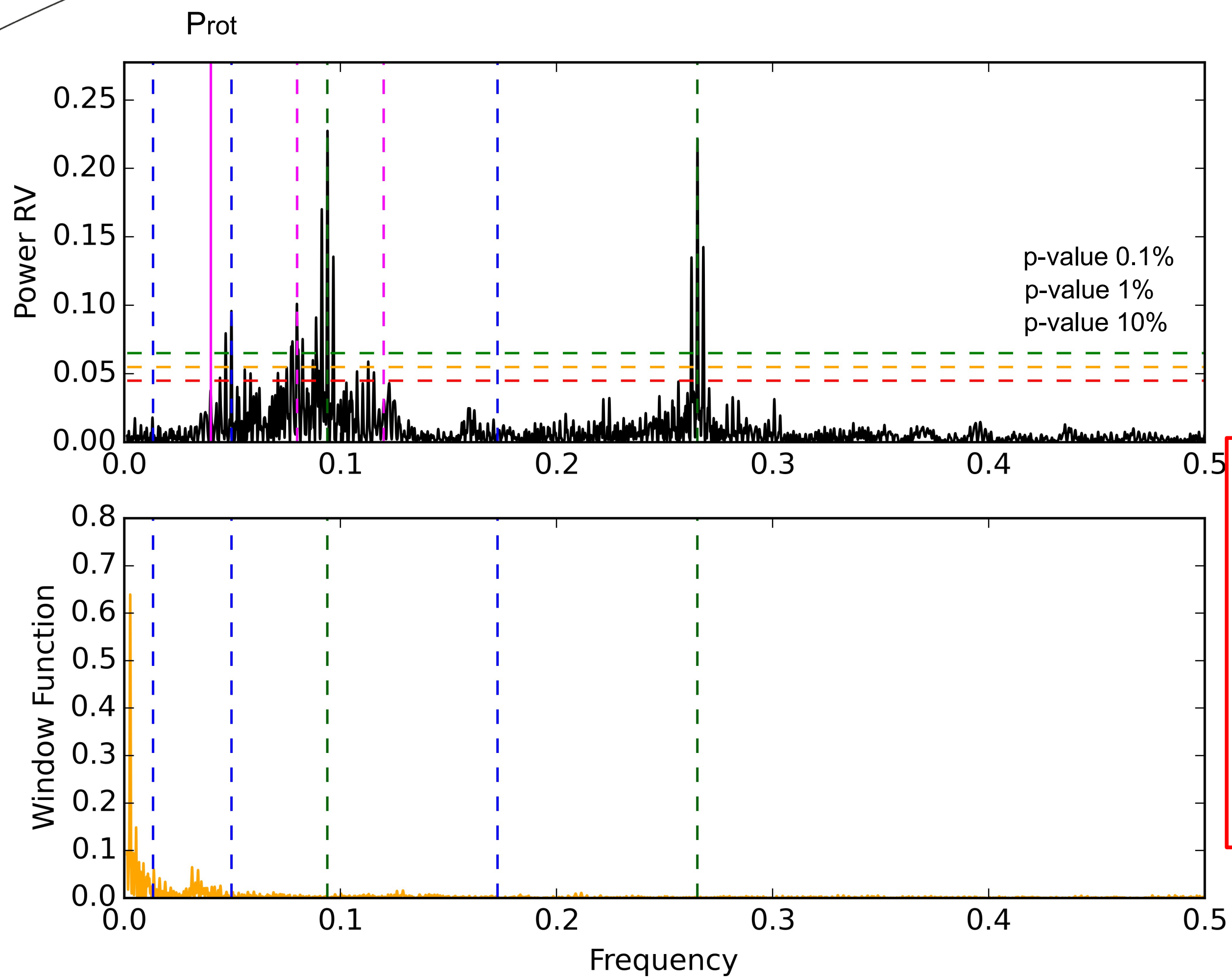
Planetary system 2	Prot	25			25.04
calendar	PL system				
Tau Ceti synth (recent 5 years)	Kepler-20				
planets	period used	mass used	ecc used		
b	3.77	5.677517264	0.051	2.75	K =2.7 +/- 0.15
e	5.79	0.629564763	0.114	0.27	
c	10.64	8.243197866	0.1372	2.85	K = 2.7 +/- 0.2
f	20.16	1.23182611	0.0824	0.34	
d	75.28	7.413963441	0.194	1.35	

Stellar mass M=0.78 Ms
Three planets with K>1 m/s
No false detections
P_{rot} OK

Post-challenge analysis
test#2



Post-challenge analysis
test#2



Planet f (P=20d, K=0.34 m/s, circular): significant peak,and best signal after 2 iterations on the residuals, with p-value=0.01% and K=1.1 m/s. Excluded because close to P_{rot} (which does not show power!)

Planet e (P=5.79d, K=0.27 m/s, e=0.1): best peak after 13 iterations on the res., with p-value=23% and K=0.54 m/s

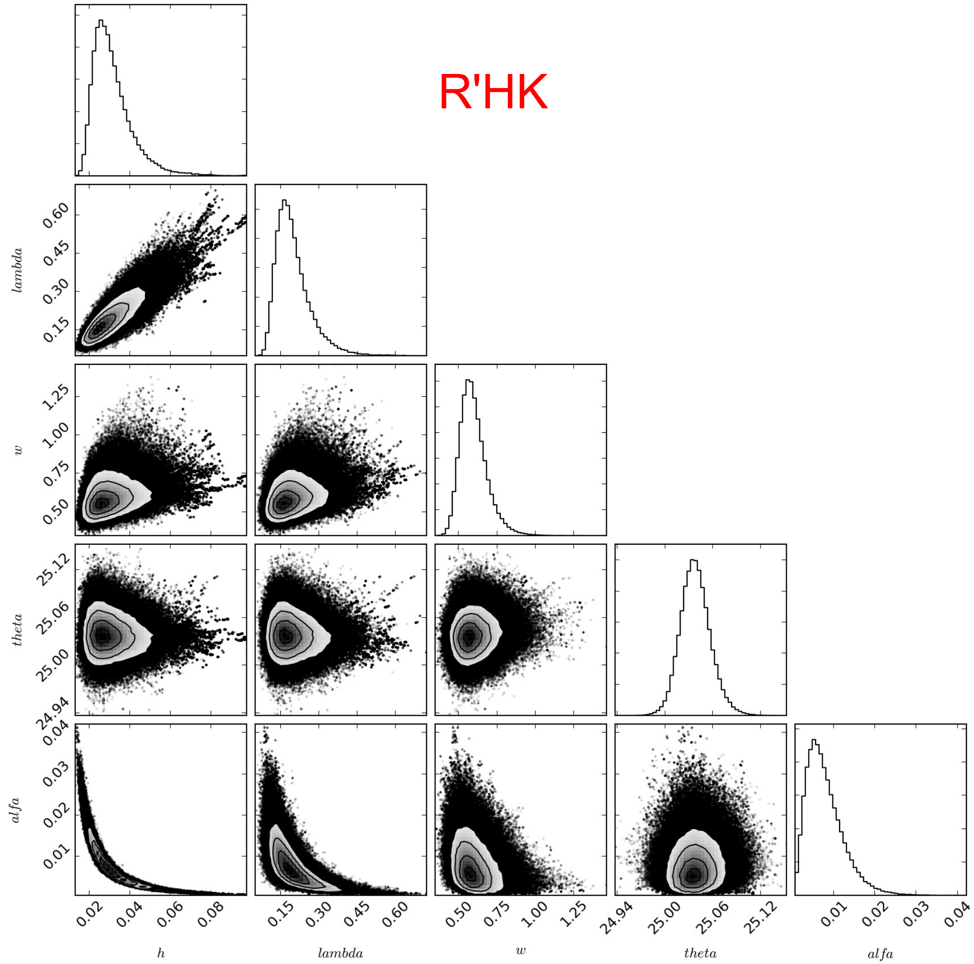
Planet d (P=75d, K=1.35 m/s, e=0.19): best peak after 14 iterations on the res., with p-value=30% and K=0.53 m/s

No power in the periodogram!

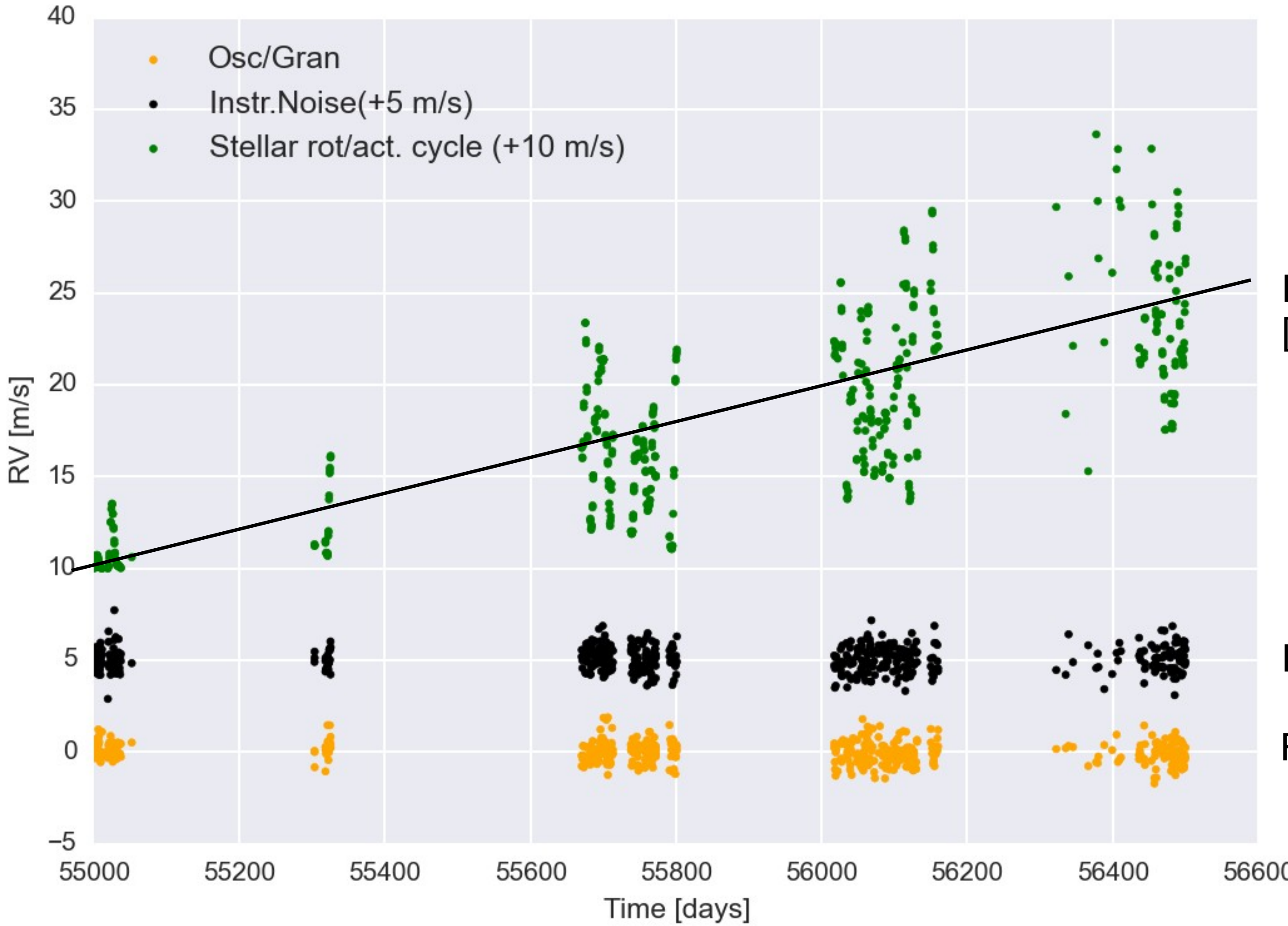
Post-challenge analysis
test#1

Question: how well does the GP trained on the R'HK index reproduce the stellar+instrumental noise in the RV data?

First answer: Modeling the residuals (original RVs *minus* the 5 injected planets); same GP covariance function and non-informative priors based on the hyperparameter posterior distributions obtained for R'HK.



Post-challenge analysis
test#1



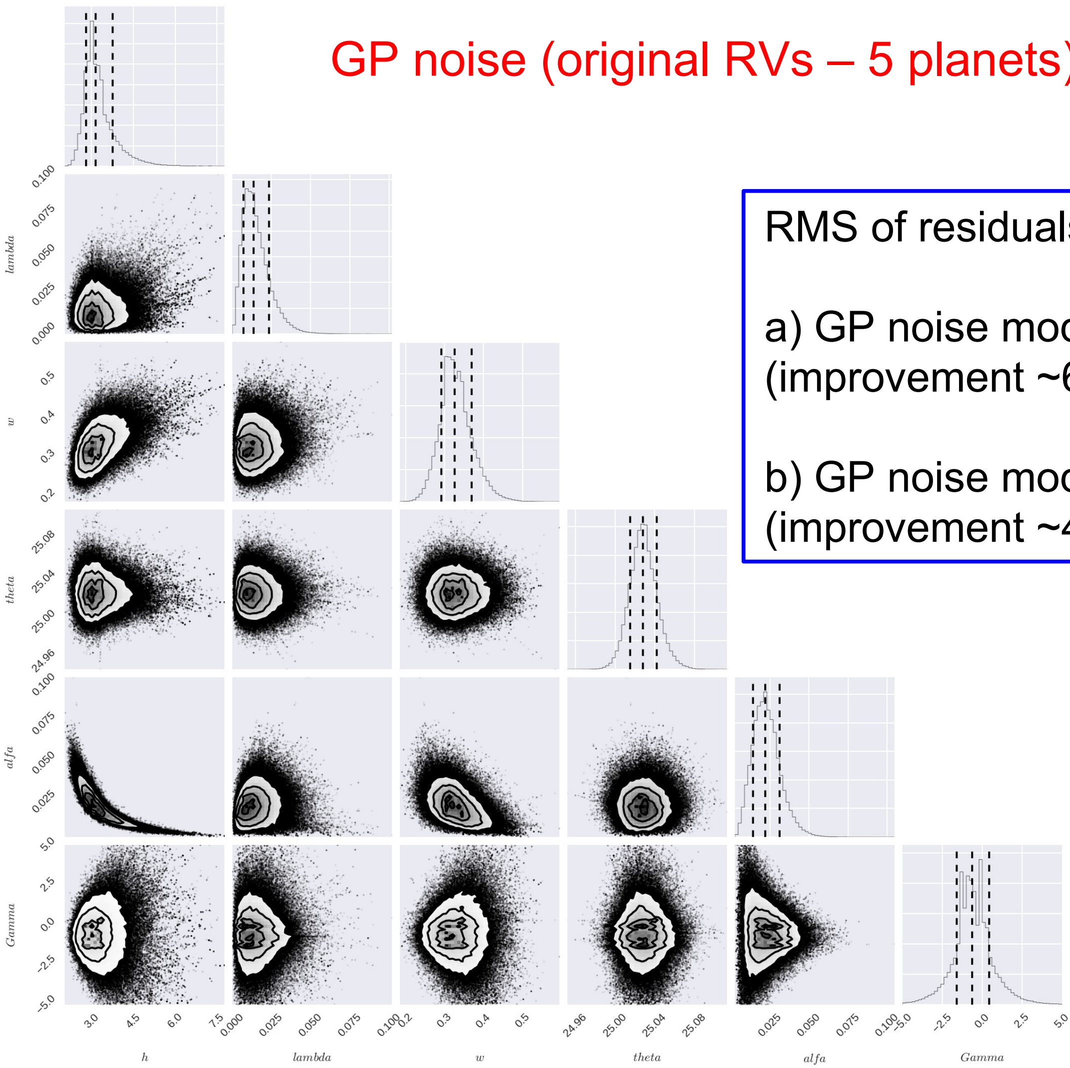
RMS = 2.06 m/s
[de-trended with R'HK]

RMS = 0.68 m/s

RMS = 0.57 m/s

Post-challenge analysis
test#1

GP noise (original RVs – 5 planets)



RMS of residuals :

a) GP noise model - Σ(noise sources) = 0.88 [m/s] (improvement ~60%)

b) GP noise model - Stellar rot/act. cycle = 1.19 [m/s] (improvement ~43%)

Possible next steps: new approaches to be explored

1) Bayesian analysis with **MultiNest**, including correlated noise to mitigate the stellar noise. A possible approach is described in **Feroz & Hobson (2013)**.
MultiNest provide an efficient calculation of the Bayesian evidence *Z*, then should allow for a statistically robust model selection.

→ software is implemented; computationally expensive for N>3 signals (w/o GP);
A physically motivated noise model needs to be included, e.g. GP trained on $\log(R'_{HK})$

2) Bayesian inference with **Diffusive Nested Sampling**, including correlated noise to take into account the stellar noise. A first approach (w/o stellar noise model included) is described in **Brewer & Donovan (2015)**.
The posterior distribution probability of the number of Keplerians *N* can be obtained.

→ basic software to be tested; inclusion into a GP framework (work in progress by others)

Possible next steps: explore approaches used in the challenge

Geneva Observatory (Diaz et al. 2015, http://arxiv.org/abs/1510.06446)

- Correlation with log(R'_{HK})
- Noise jitter dependent on activity level
- Bayesian model comparison

→ new ways of calculating the Bayes' factor; testing their outcomes

Phil Gregory (http://www.exostats.org/wp-content/talks/gregory.pdf)

- Apodized Keplerian
- De-trended FWHM with log(R'_{HK}) and looked for signals

Let's wait for the forthcoming paper!

Collaboration and ideas are very welcome!

More independent techniques we handle, better it is!