PLATO Ground-based Observation Program (GOP)
Workshop 2022

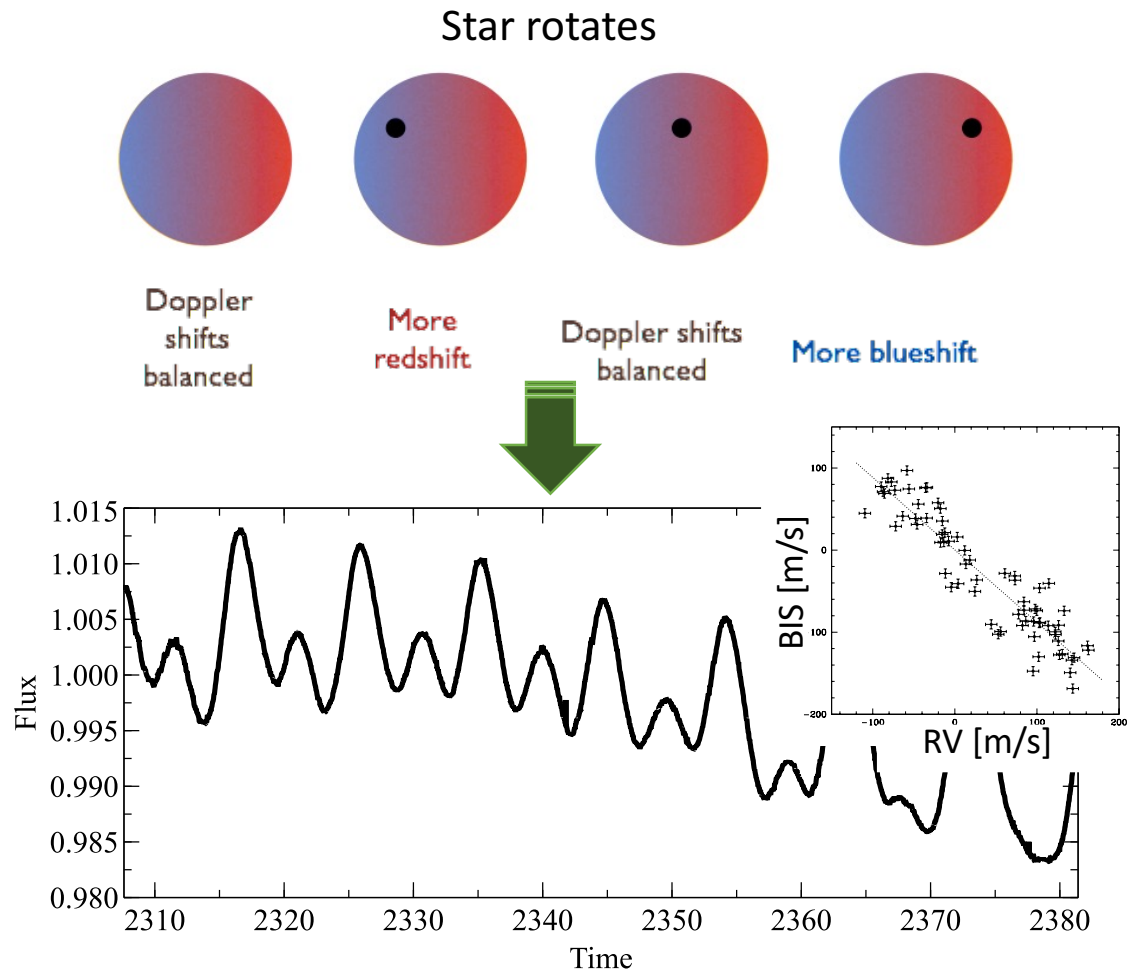
Luca Malavolta

Modelling or mitigating stellar noise

Stellar activity

Rotational imbalance due to brightness inhomogeneity
(~0.1 ms^{-1} for a *quiet* star)

Lagrange et al. (2010), Haywood et al. (2016)



Stellar activity

Rotational imbalance due to brightness inhomogeneity
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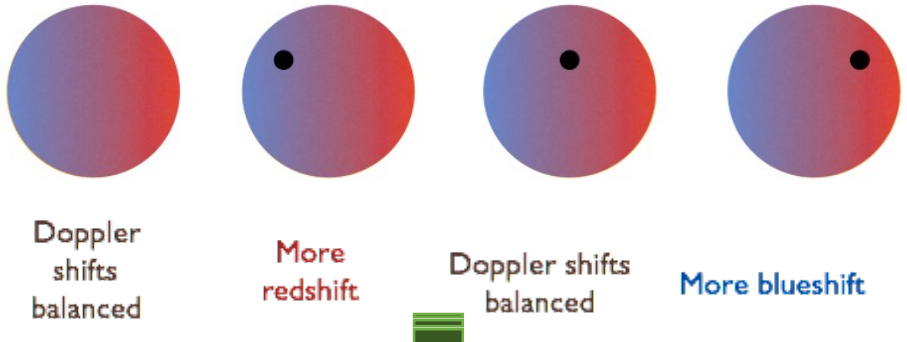
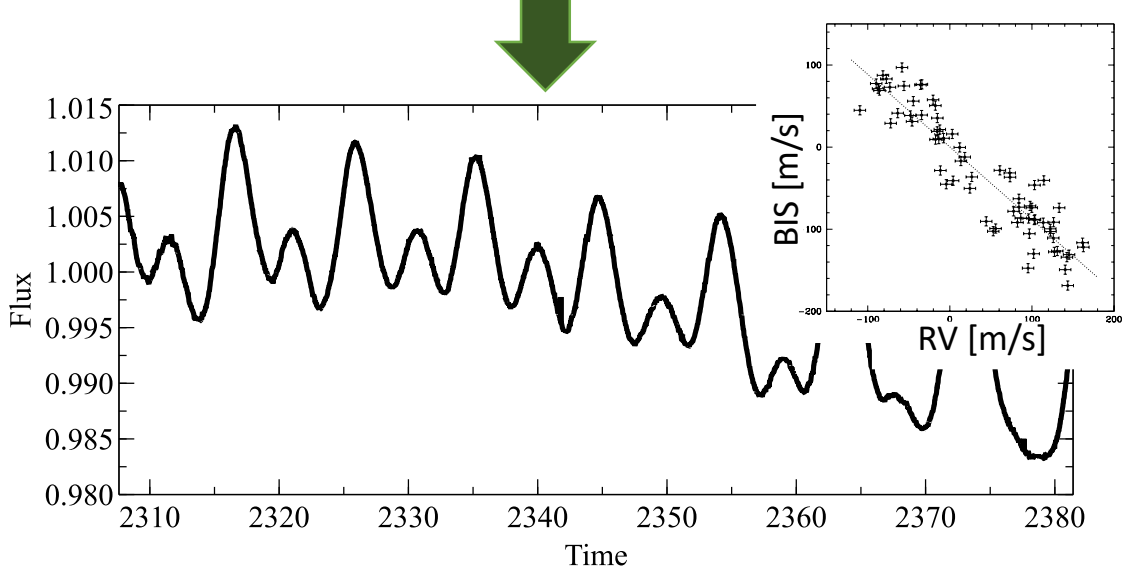
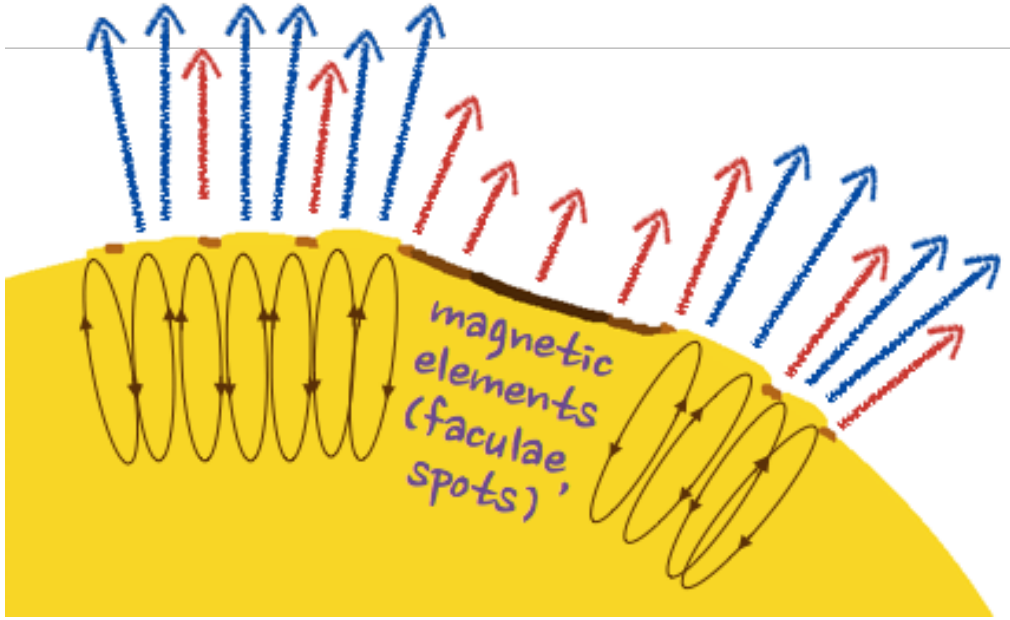
Star rotates





Suppression of convective blueshift by magnetic regions
(a few ms^{-1} for a *quiet* star)
Meunier (2010a, b), Haywood et al. (2016)
Cegla et al. (2013)

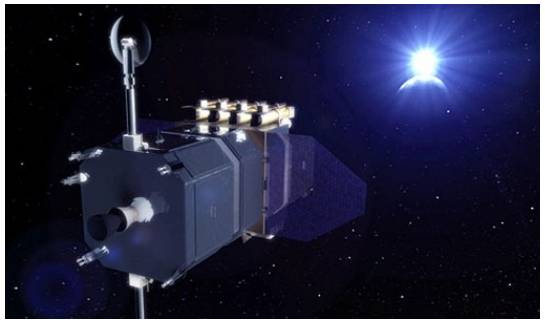


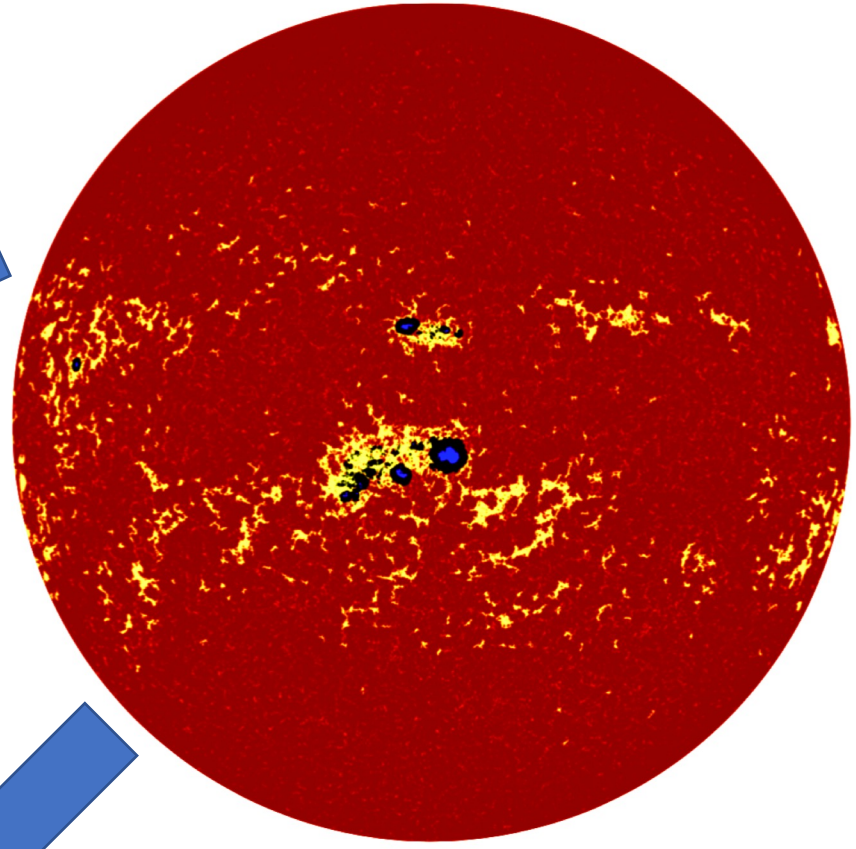
????????

Credits: R. Haywood

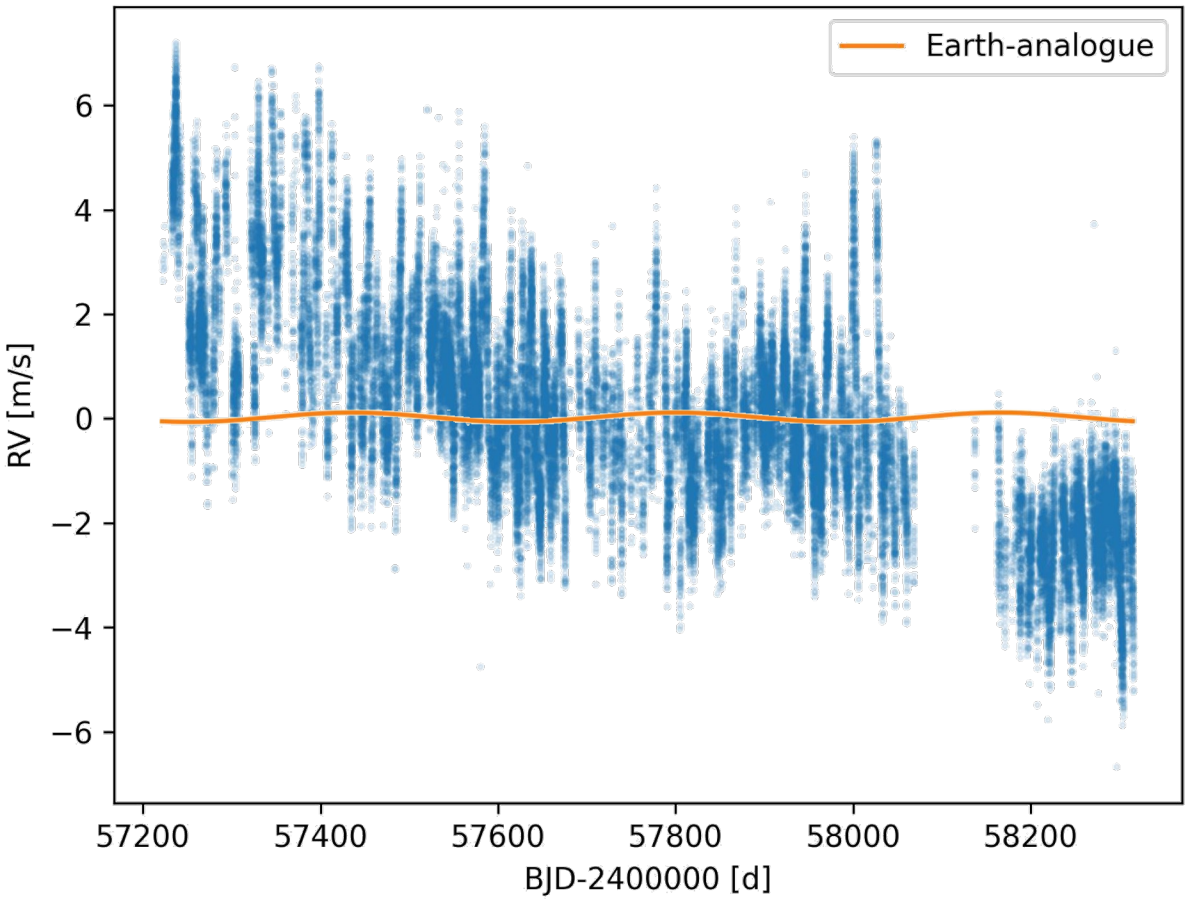
The Sun: a «quiet» star

Solar Dynamics Observatory (NASA)





Credit: M. Palumbo



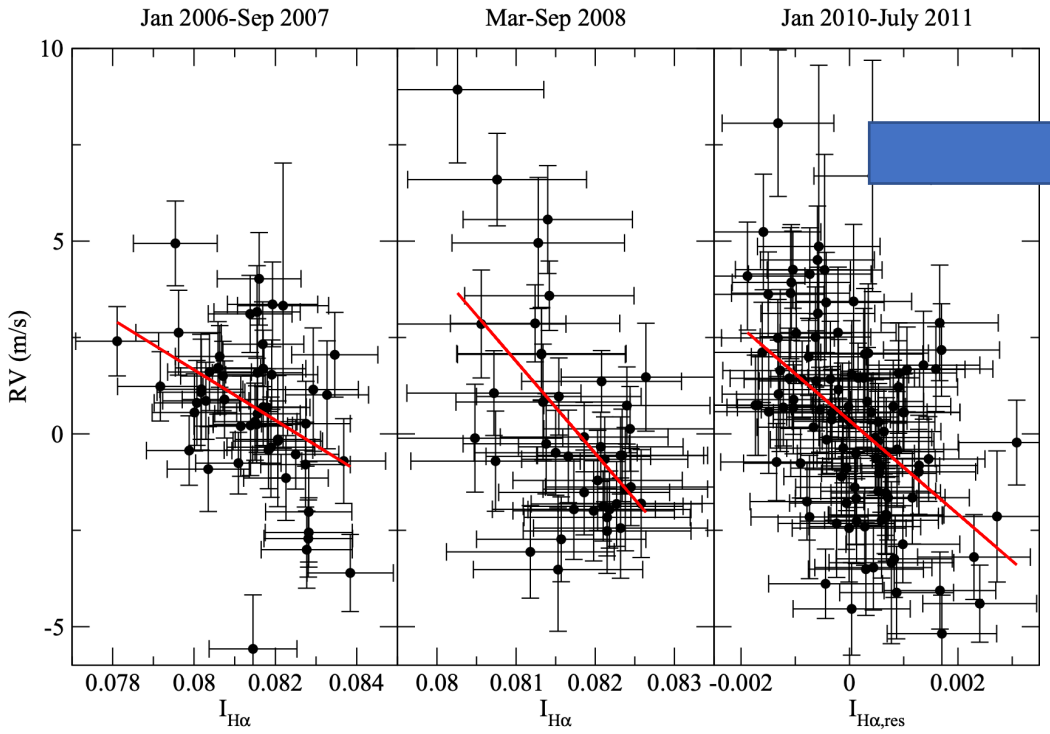
The Sun observed as a star with HARPS-N Solar Telescope

- several m/s signals even during the solar minimum
- daily meter-per-second variability from super granulation
- stellar granulation and oscillations not fully averaged out

(Dumusque+2015 +2022 , Collier-Cameron+2021, Phillips+2017)

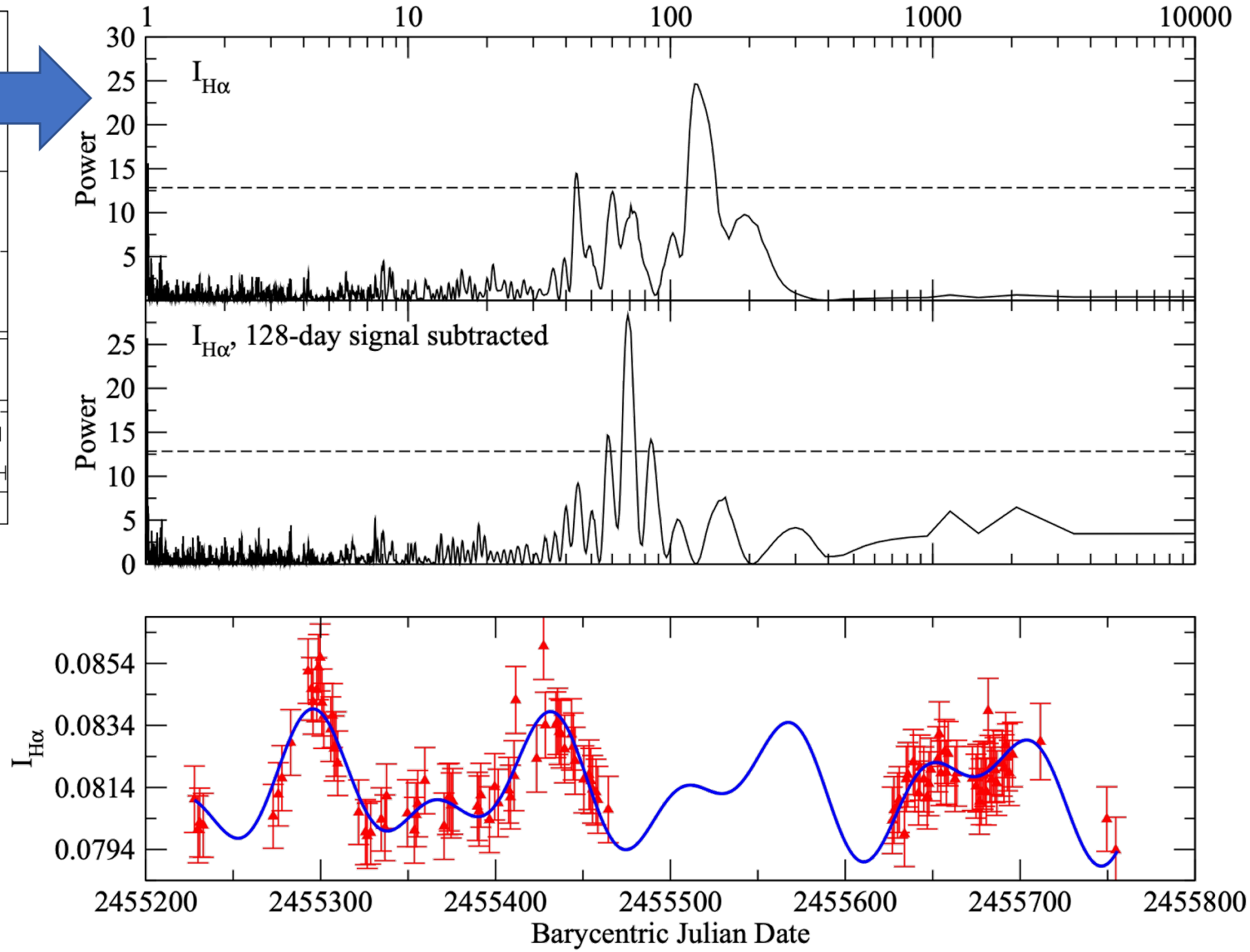
Ways to deal with stellar activity

Decorrelation with activity indexes



However:
Simola+2022: Accounting for stellar activity signals in radial-velocity data by using change point detection techniques

Robertson +2014: Stellar Activity Masquerading as Planets in the Habitable Zone of the M dwarf Gliese 581



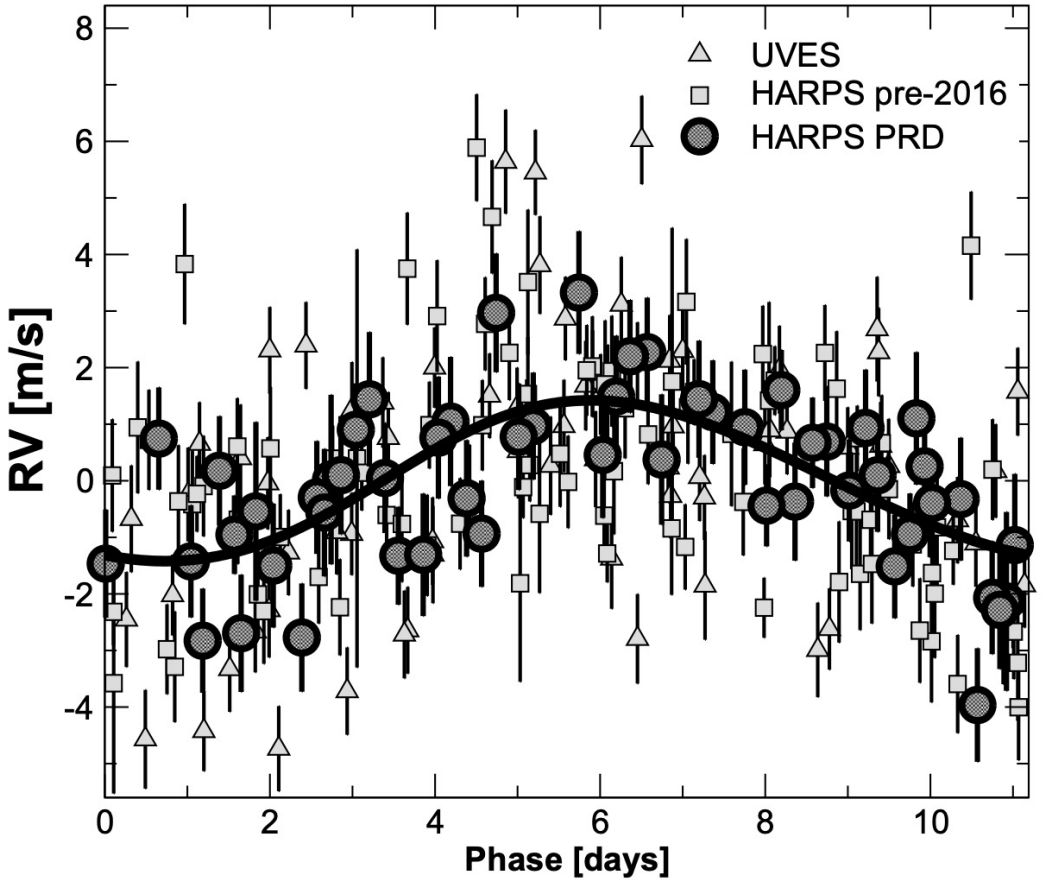
Ways to deal with stellar activity

Moving Average MA: a simple parameterization of correlated noise that depends on the residual of the previous measurement $\epsilon_{i-1,INS}$.

$$\mathrm{MA}_{i,\mathrm{INS}} = \phi_{\mathrm{INS}} \exp\left\{\frac{t_{i-1} - t_i}{\tau_{\mathrm{INS}}}\right\} \epsilon_{i-1,\mathrm{INS}}$$

A decorrelation with activity indexes is often introduced:

$$\mathrm{A}_{i,\mathrm{INS}} = \sum_{\xi} C_{\xi,\mathrm{INS}}\ \xi_{i,\mathrm{INS}}$$

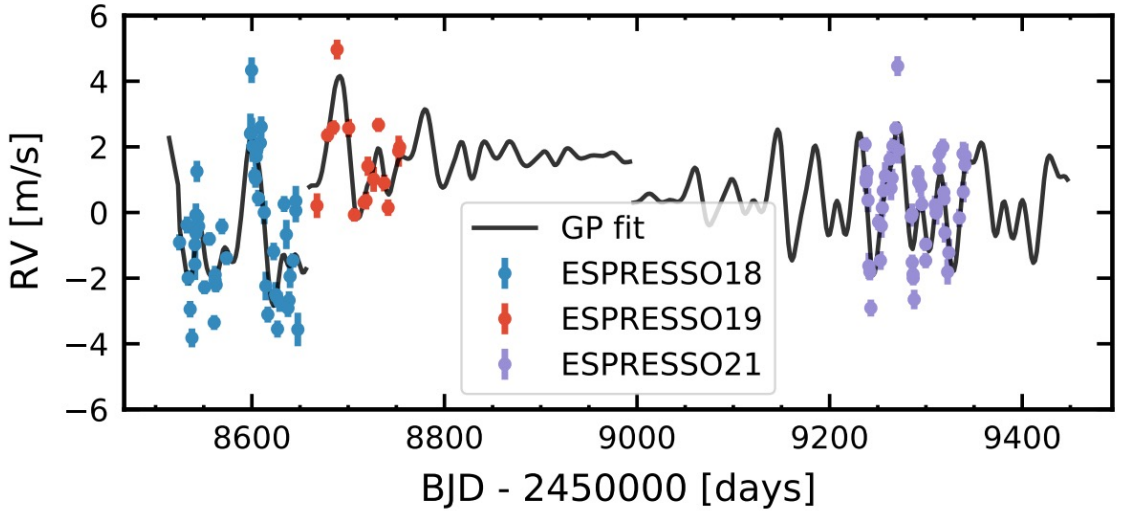


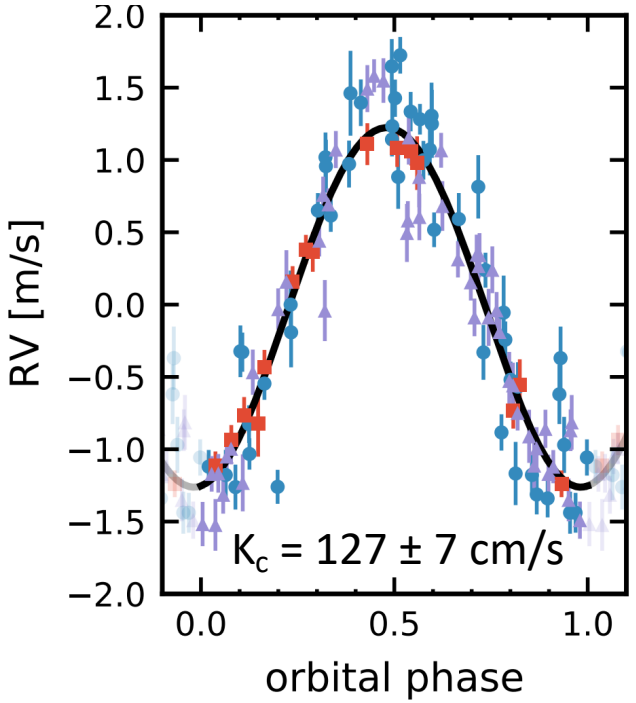
Full model may include an offset, a linear trend, and several Keplerians

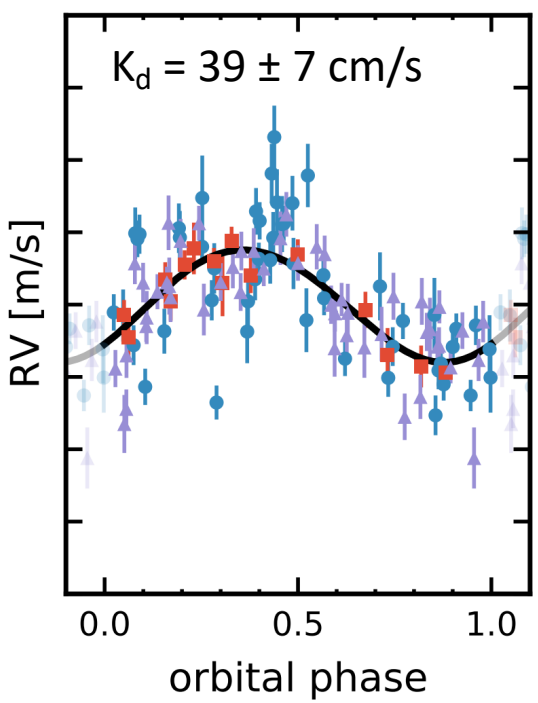
$$\epsilon_{i,\mathrm{INS}} = m_{i,\mathrm{INS}} - \left\{\gamma_{\mathrm{INS}} + \dot{\gamma}\Delta t_i + \kappa(\Delta t_i) + \mathrm{MA}_{i,\mathrm{INS}} + \mathrm{A}_{i,\mathrm{INS}}\right\},$$

Gaussian processes

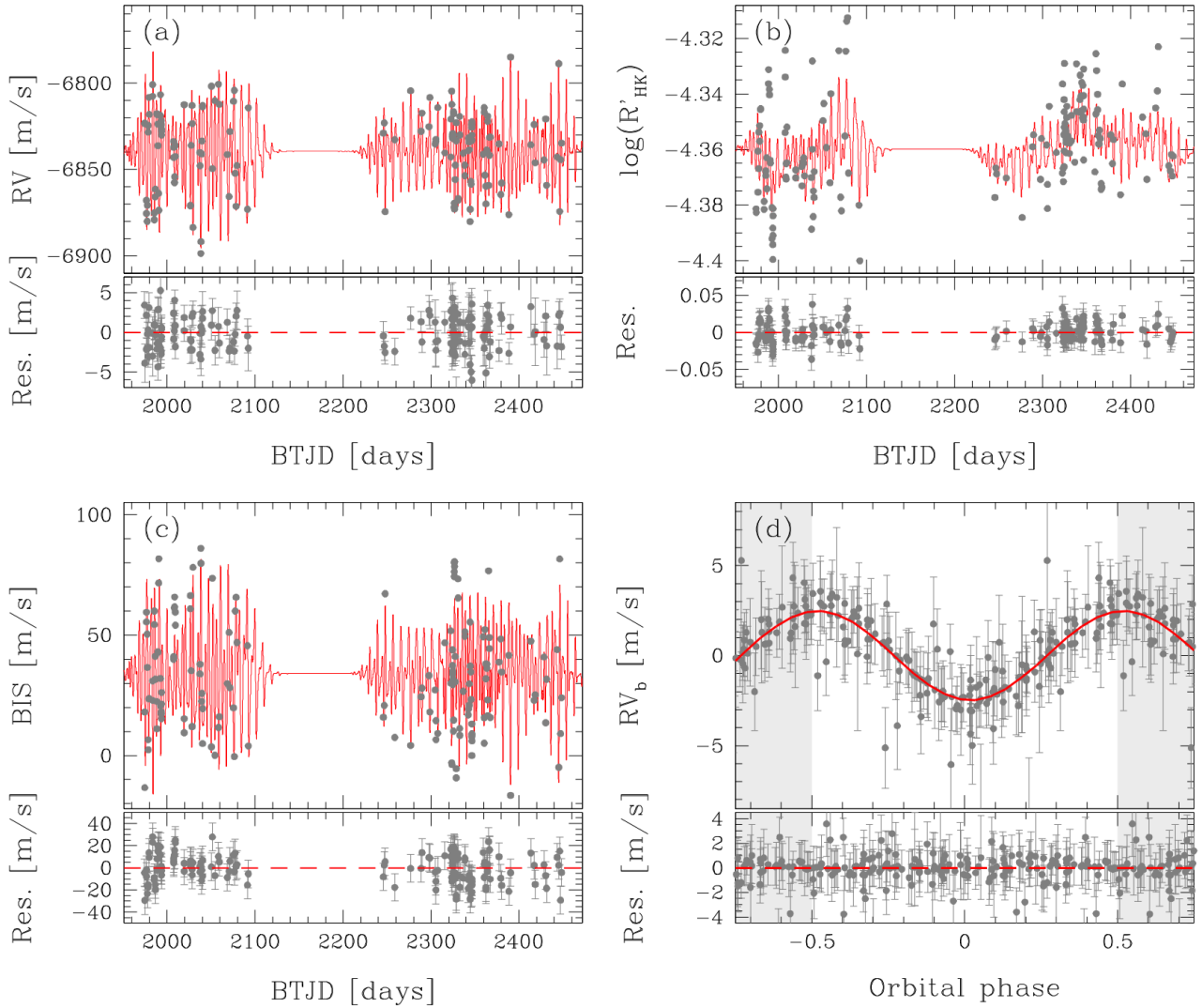
Proxima Centauri b & d, Faria+2022 with ESPRESSO







TOI-1807, Nardiello+2022, young star with HARPS-N



«Standard» GPs

Multidimensional GPs

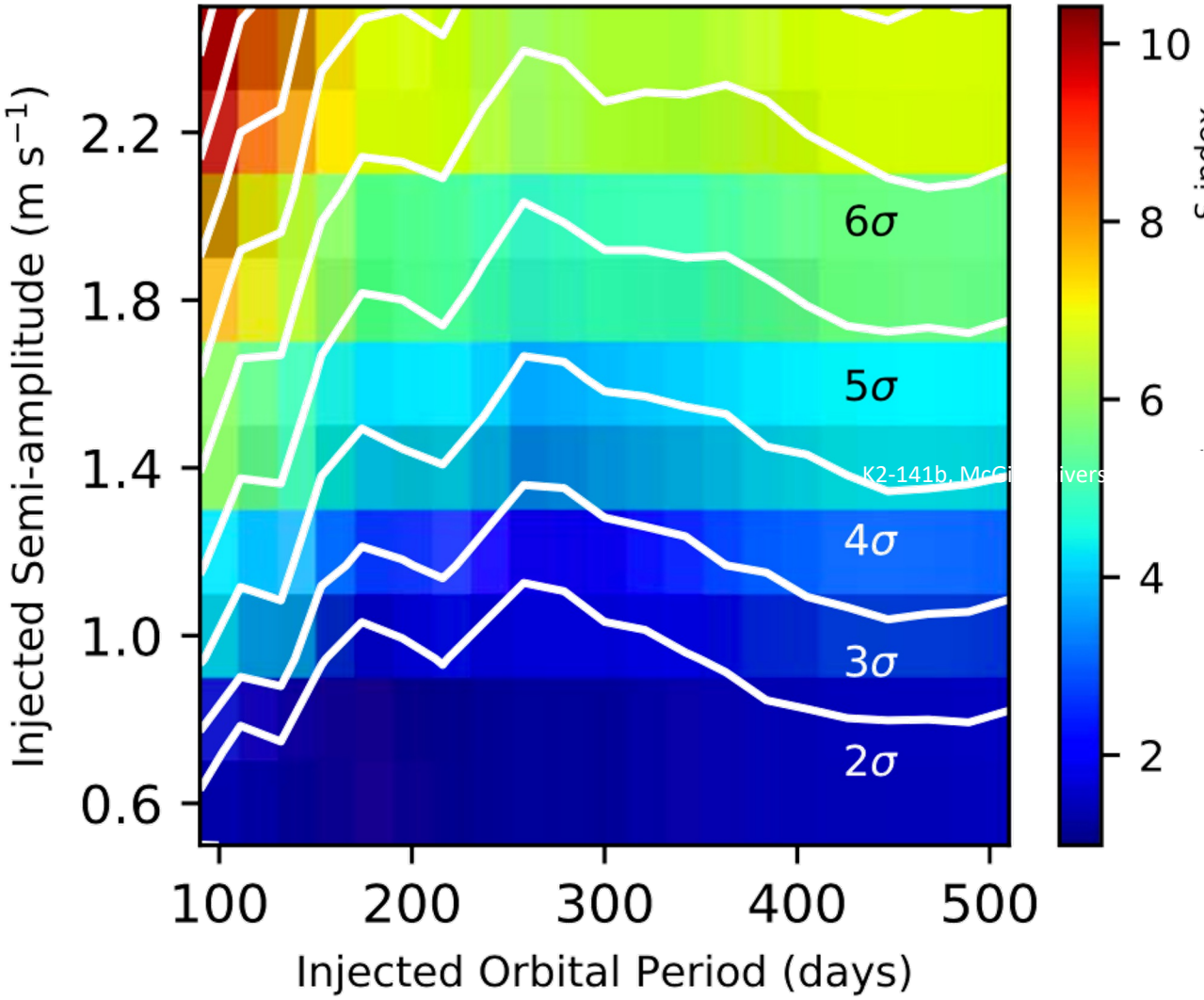
K_b = 2.39 ± 0.46 m/s

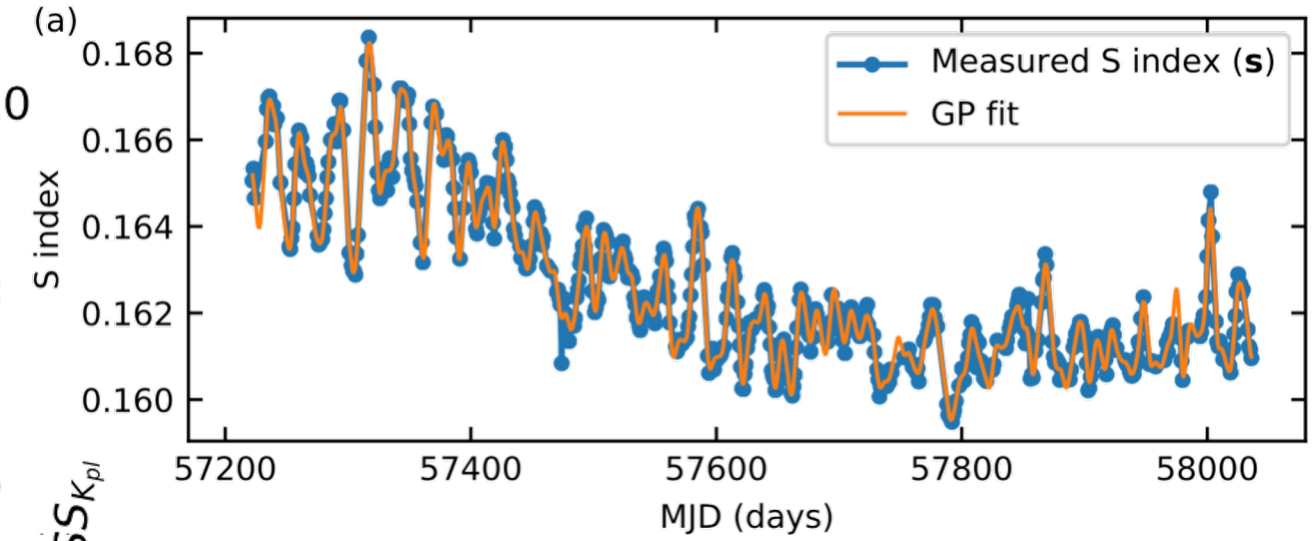
K_b = 2.48 ± 0.39 m/s

Gaussian processes

Langellier+2021: discovering massive Earth-analogues using current-generation spectrographs and GP regression will require > 10 yr of densely sampled RV observations

800 days of solar RVs.



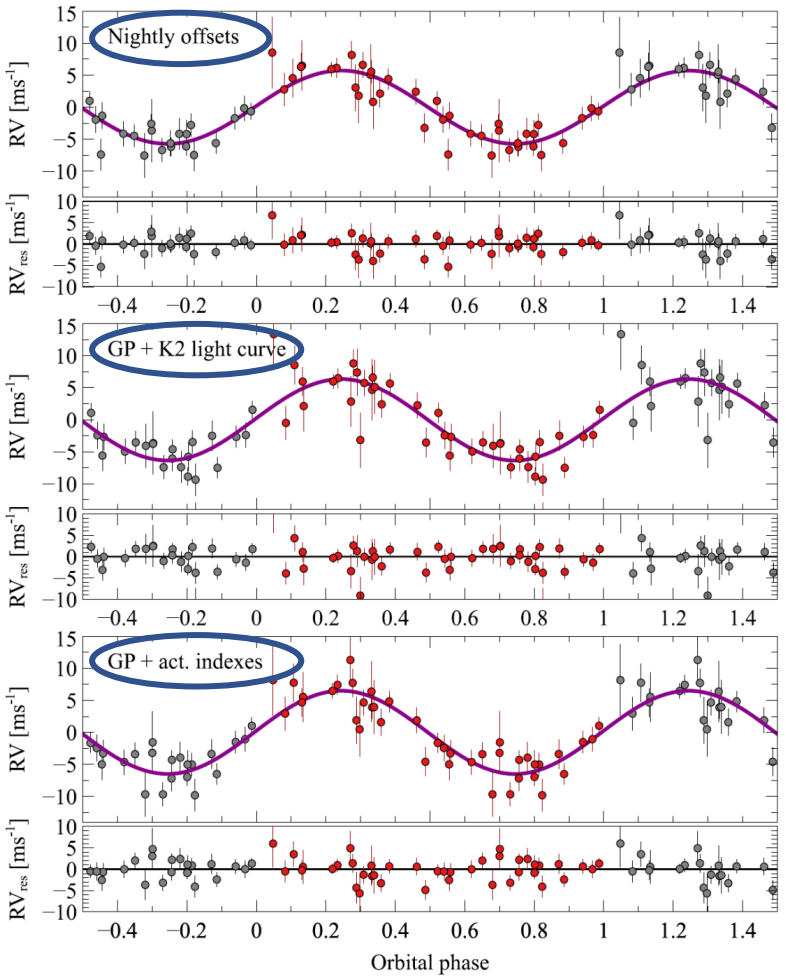


Caveat: sub-optimal RV extraction

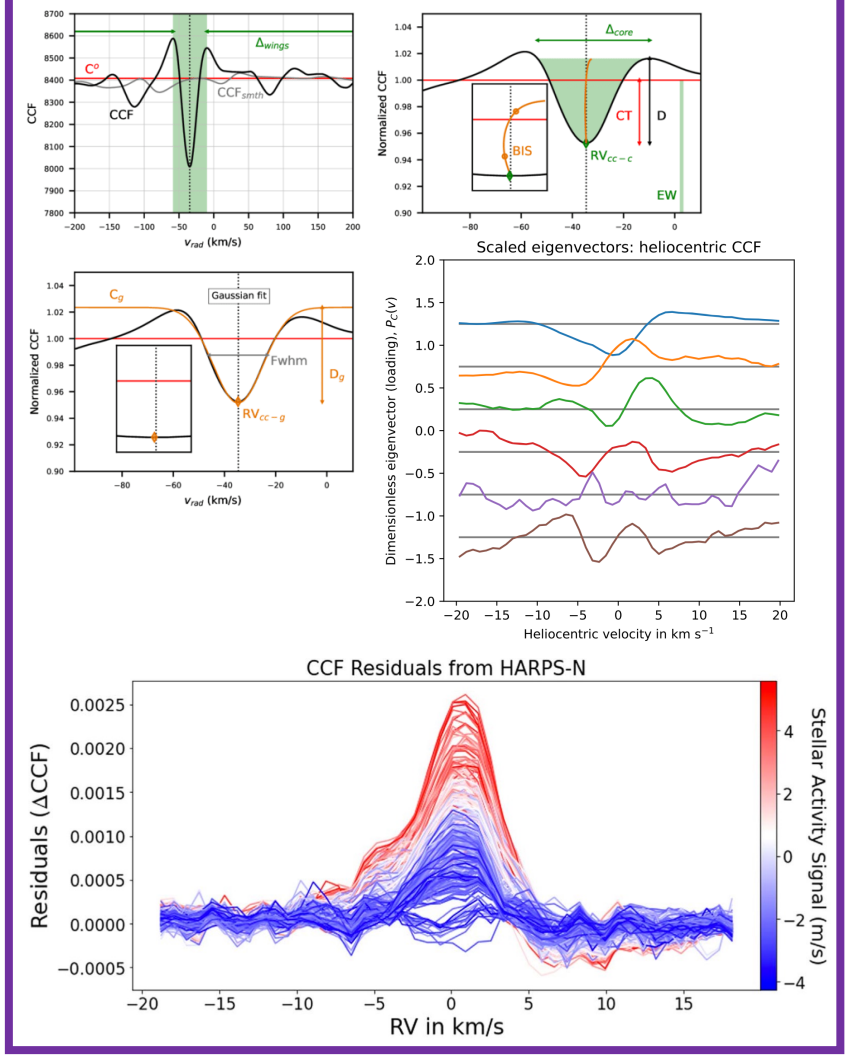
Orbital period of the planet much greater than rotational period of the star!

Recent developments

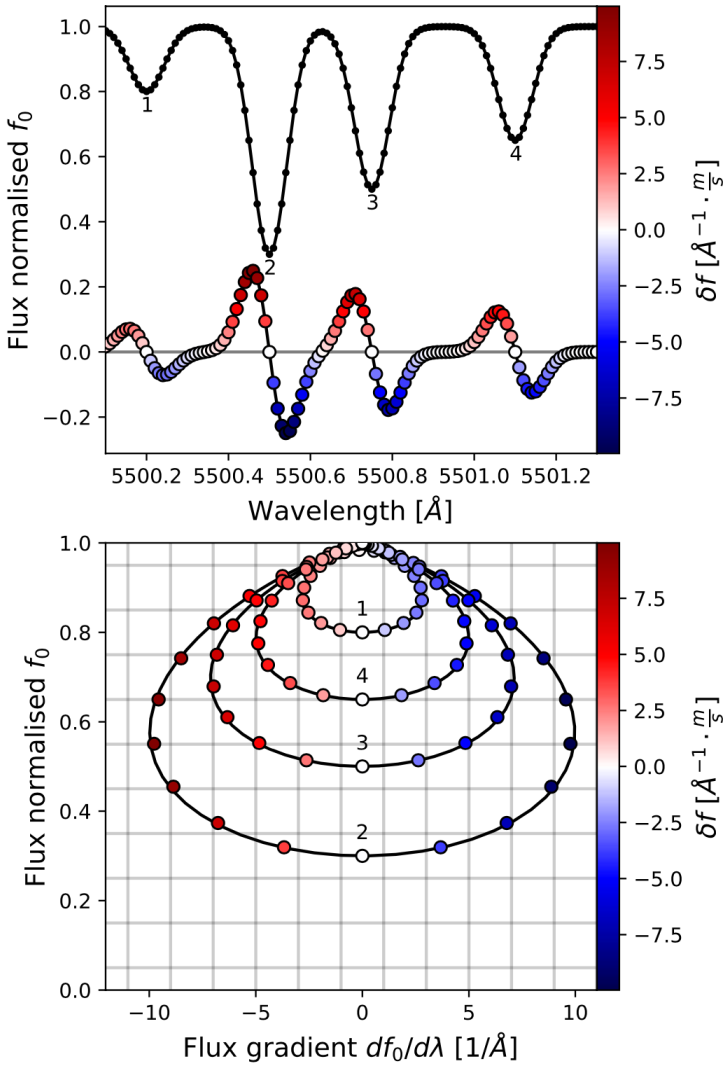
RV + activity indexes (more or less) simultaneous modelling



Activity removal at the level of Cross-Correlation Function



Activity removal at the spectral level



All the due references in the next slides….

Recent developments

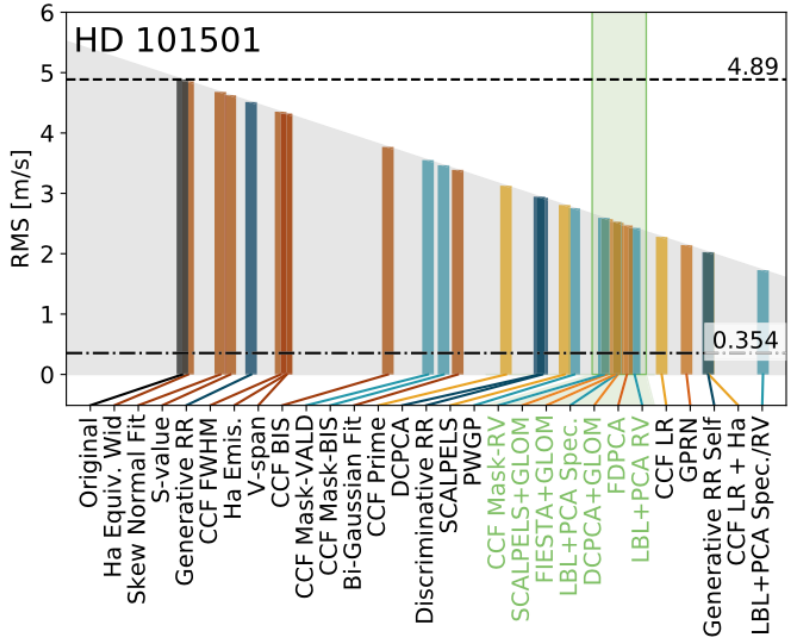
Method	Metric	Mitigation	Separation	Reference
GP Framework		Multidimensional GP Modeling		Rajpaul+2015, Barragan+2022
GLOM		Multidimensional GP Modeling		Gilbertson+2022
FDPCA		Commonalities in Fourier Space		Ramirez Delgado+2022
GPRN		GP Neutral Net Modeling		Camacho +2022
SCALPELS	PCA Amplitudes (CCF)		Shape/Shift-driven RVs	Collier Cameron+2021
CCF Prime	GP Model Coefficients		Shape/Shift-driven RVs	Baptiste Klein tbs
FIESTA+GLOM	Fourier Model Coefficients			Zhao & Ford 2022
CCF Linear Regression			Shape/Shift-driven RVs	de Beurs+2020
CCF Masks			Variable/Stable Lines	Alex Wise, Lafarga+2020
LBL+PCA spectr			Variable/Stable Lines	Dumusque 2018, Cretignier+2022
LBL+PCA rv	PCA Amplitudes (LBL RVs)			Cretignier+2021, +2022
PWGP			Variable/Stable Lines	Rajpaul +2020
DCPCA	PCA Amplitude (Spectra)			Jones+2017
Generative RR		Regression w/ Spectral Residuals		Zhao+2022
Discriminative RR				Zhao+2022

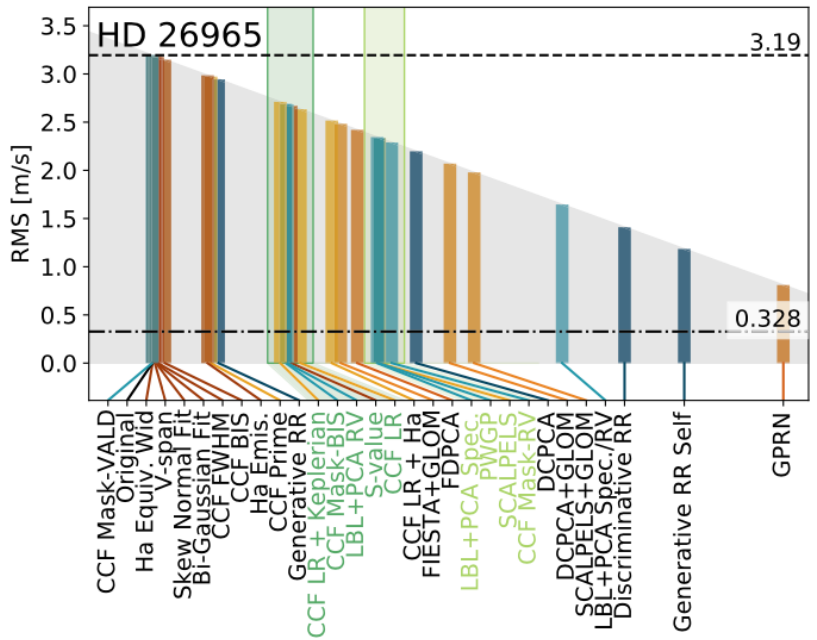
Gaussian Process Linear Ordinary Differential Equation (ODE) Maker (GLOM)
Fourier Domain Principal Component Analysis (FDPCA),
Gaussian Process Regression Network (GPRN)
Self-correlation Analysis of Line Profiles for Extraction of Low-amplitude Shifts (SCALPELS)

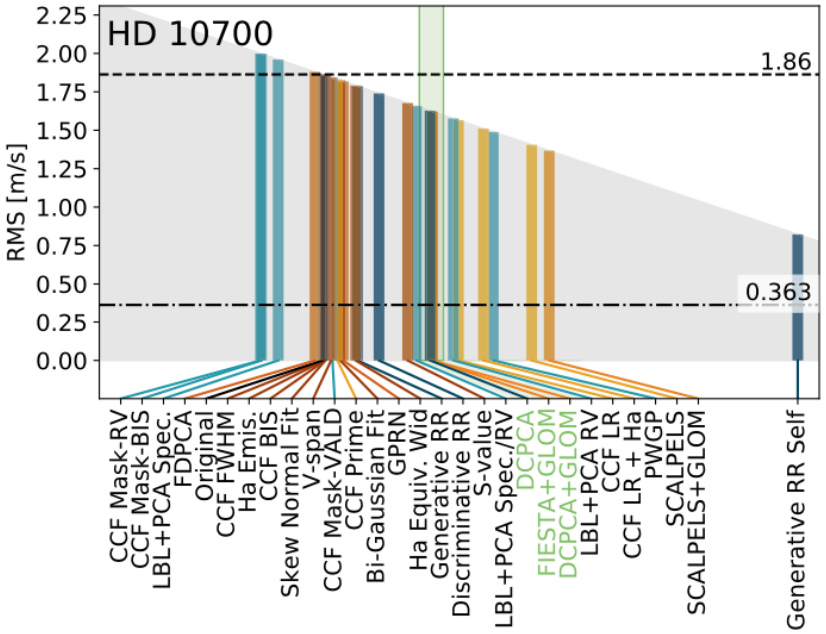
Fourier Phase Spectrum Analysis (FIESTA)
Line By Line (LBL)
Pairwise GP (PWGP) RV extraction
Doppler-constrained PCA (DCPCA)

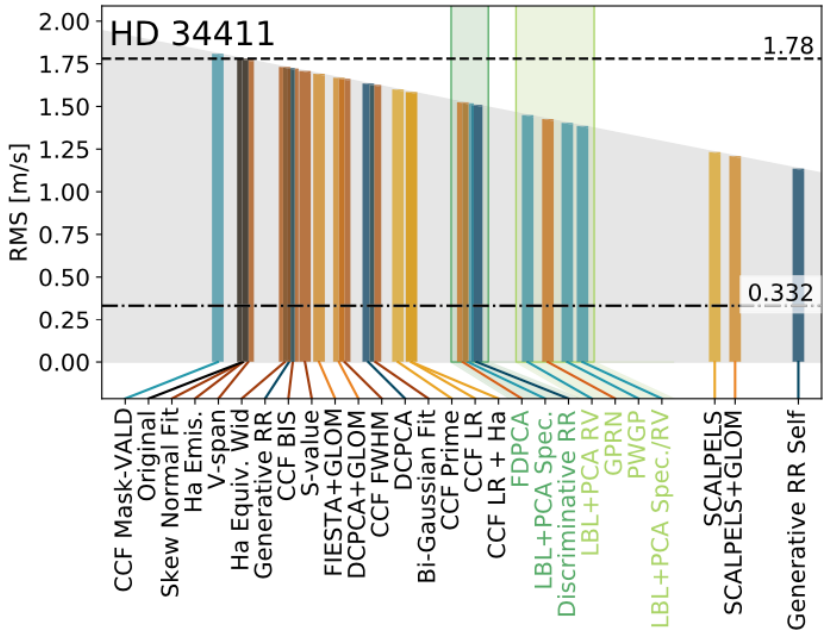
Adapted from Zhao+2022

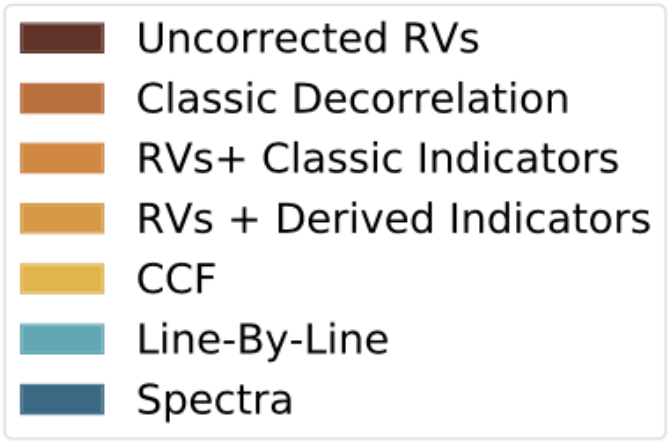
The EXPRES Stellar Signals Project









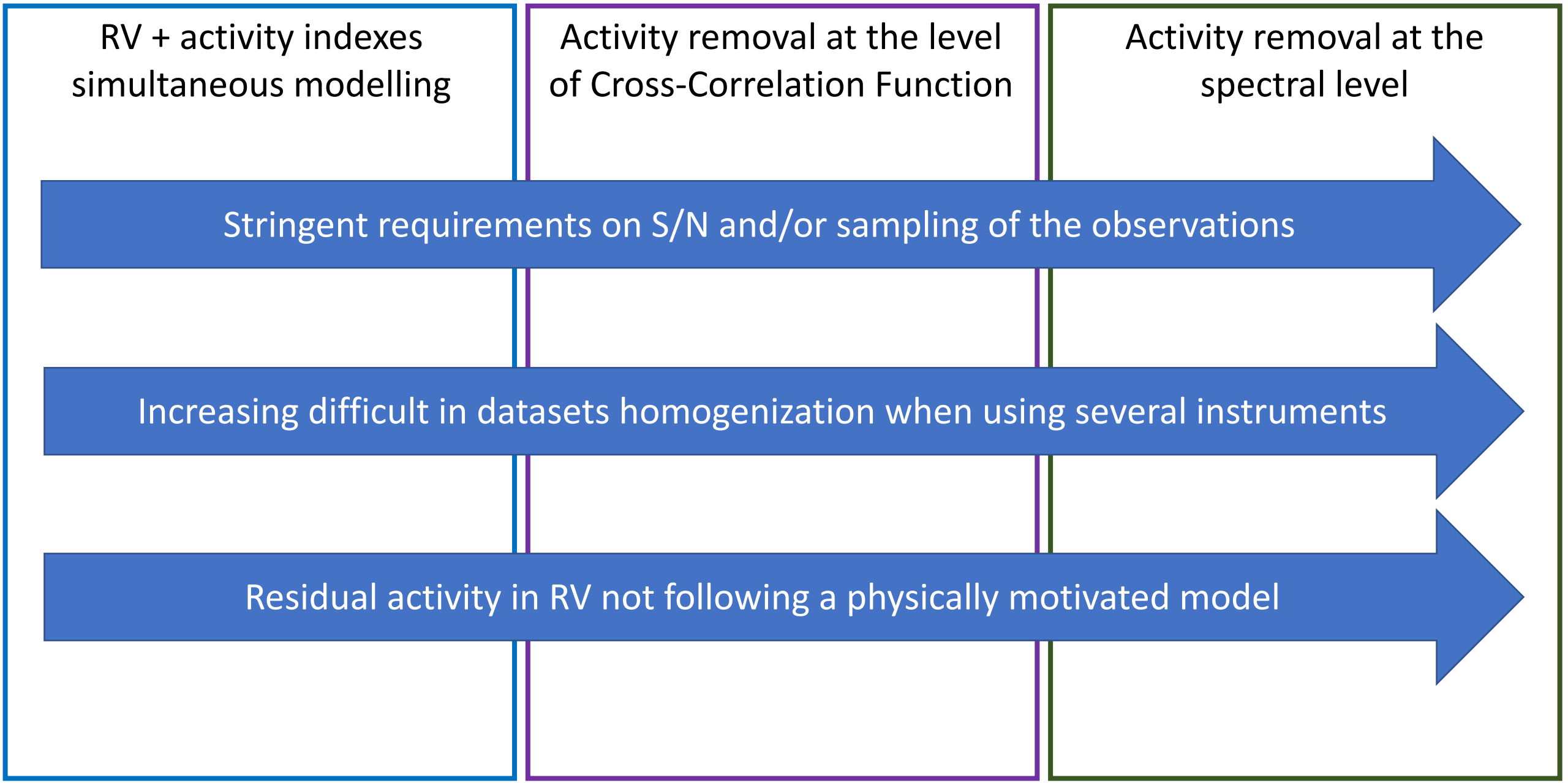


ESSP II. State of the Field in Disentangling Photospheric Velocities (Zhao+2022)

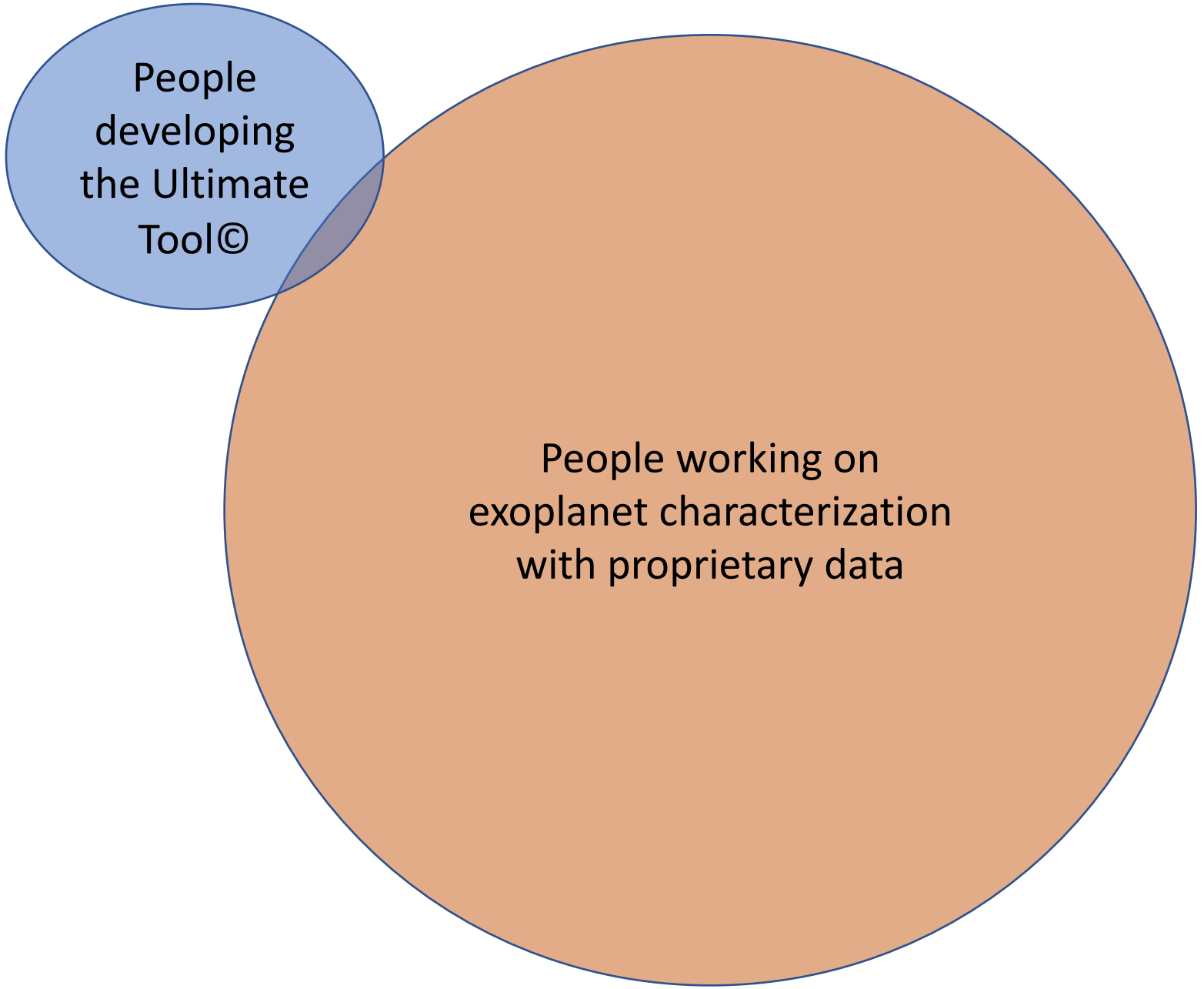
No method is yet consistently reducing the RV rms to sub-m/s levels

Concerning lack of agreement between the RVs returned by different methods

How about using several instruments?



The hard truth



You have developed the Most Wonderful Tool© for RVs, but

- You do not release the code
- There are open-source alternatives

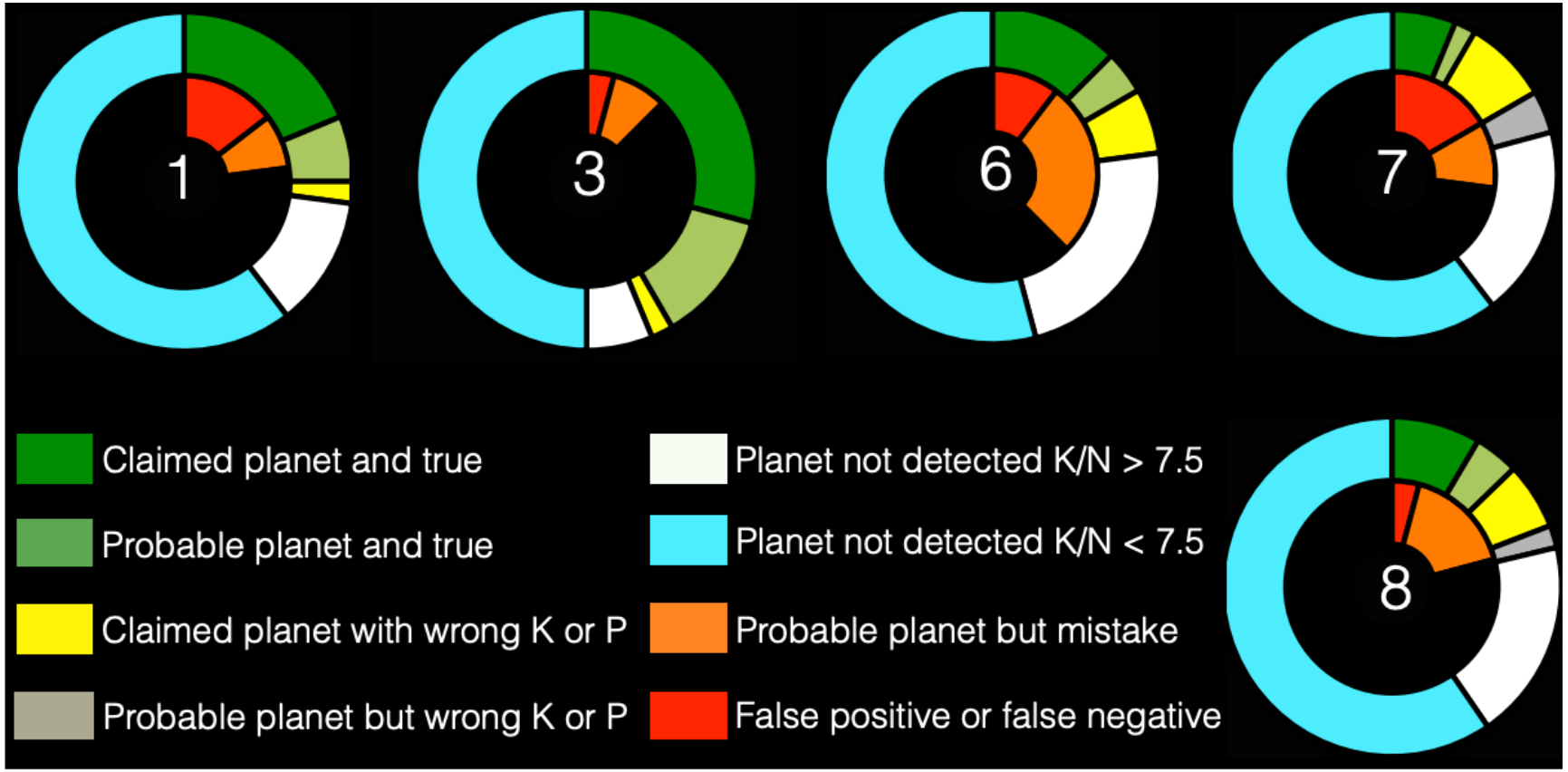
Then people may (or may not) ask your help only if the tools that they already have totally fail.

«But all the mathematical steps are described in the paper»

- Not ALL technical details will be reported in the paper…
- Implementing somebody else's idea is never easy
- People simply may not have time to redo your job

A practical example

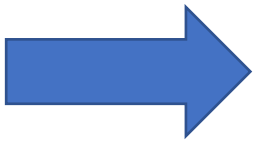
Results of the Radial-velocity fitting challenge (Dumusque+2017)



1) GP regression

3) Moving Average with decorrelation

Packages like *george, celerite* made GPs accessible, contributing to their success and finally becoming a standard



The most popular tool may not be the best one….

Conclusions

- Detection of a 0.10 m/s signal on a Solar-type star is difficult but work in progress
- Future comparisons should make use of various well-characterized data sets—such as solar data or data with known injected planetary and/or stellar signals—to better understand method performance and whether planetary signals are preserved.
- We can fully understand how well a technique works only if it is applied blindly to a large number of cases. It will happen only if usable code is released.
- Dataset homogenization increasingly difficult as the techniques move from RV modelling to spectral analysis
- Activity-tools «developers» are ignoring photometry – will they change their mind with the *exquisite* PLATO light curves?