

Uncovering Planetary Radial Velocity Signals with Spectral Activity Indicators

Link to Google slides (working animations!)

https://docs.google.com/presentation/d/1lBivfRvllLhCjEFAptlt1cR2E_h8yf_pri7LOxNo6pc/edit?usp=sharing

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with:

S. Aigrain, B. Klein, H. Yu, M. Cretignier, N. Zicher, and more!

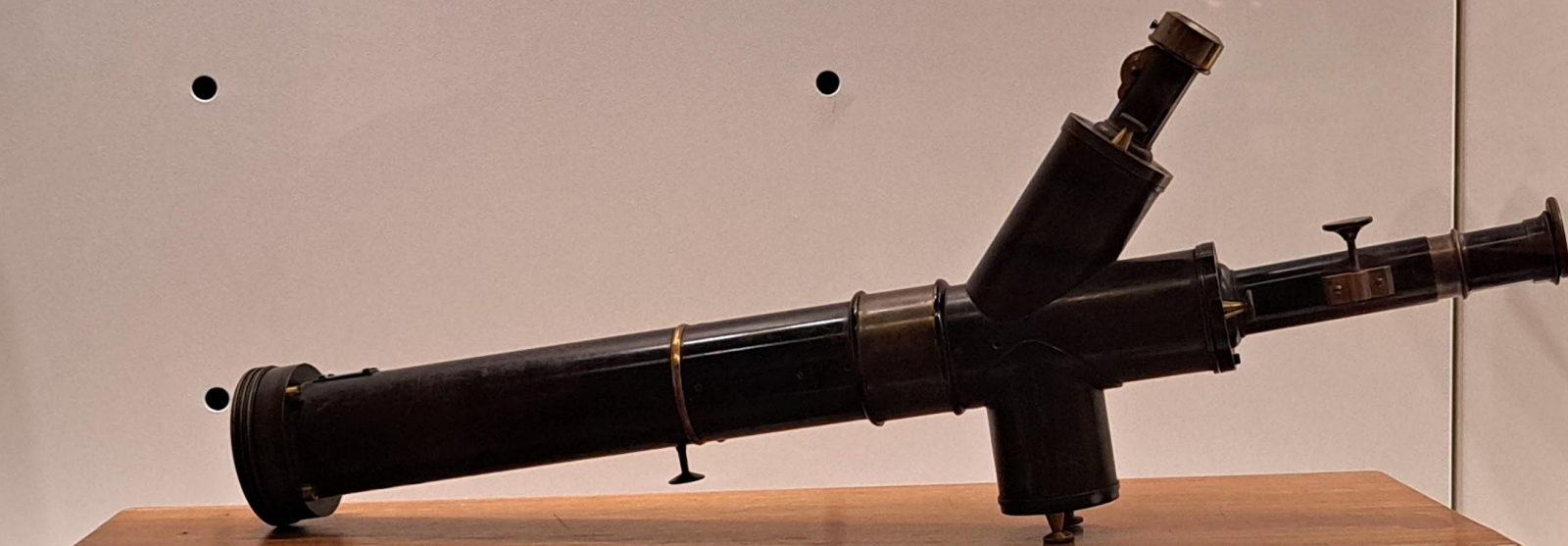


European Research Council
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Department of Physics
University of Oxford

with
Suzanne Aigrain
(University of Oxford)

Spectral Fidelity
Firenze ♥, Italia
September 04, 2023

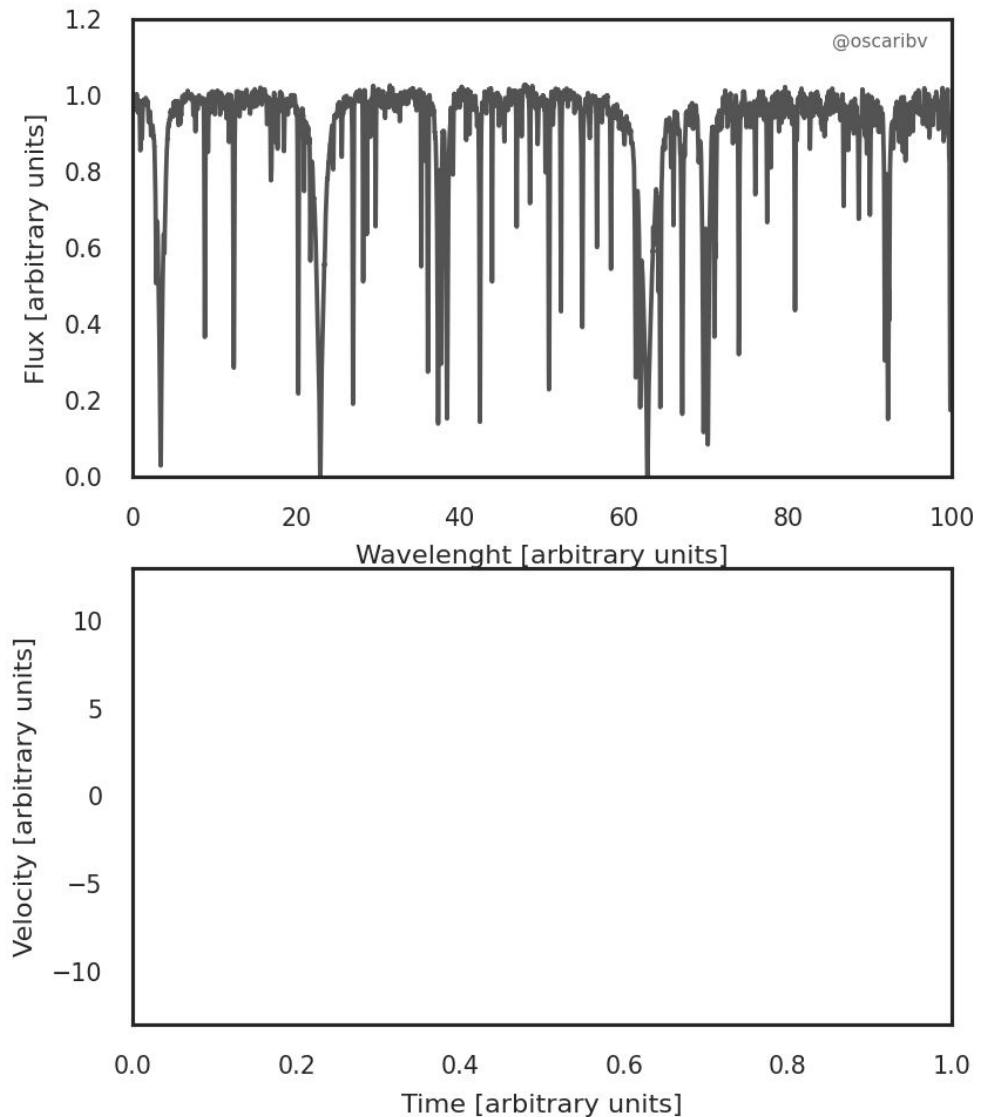


2

**A few
centuries
after**

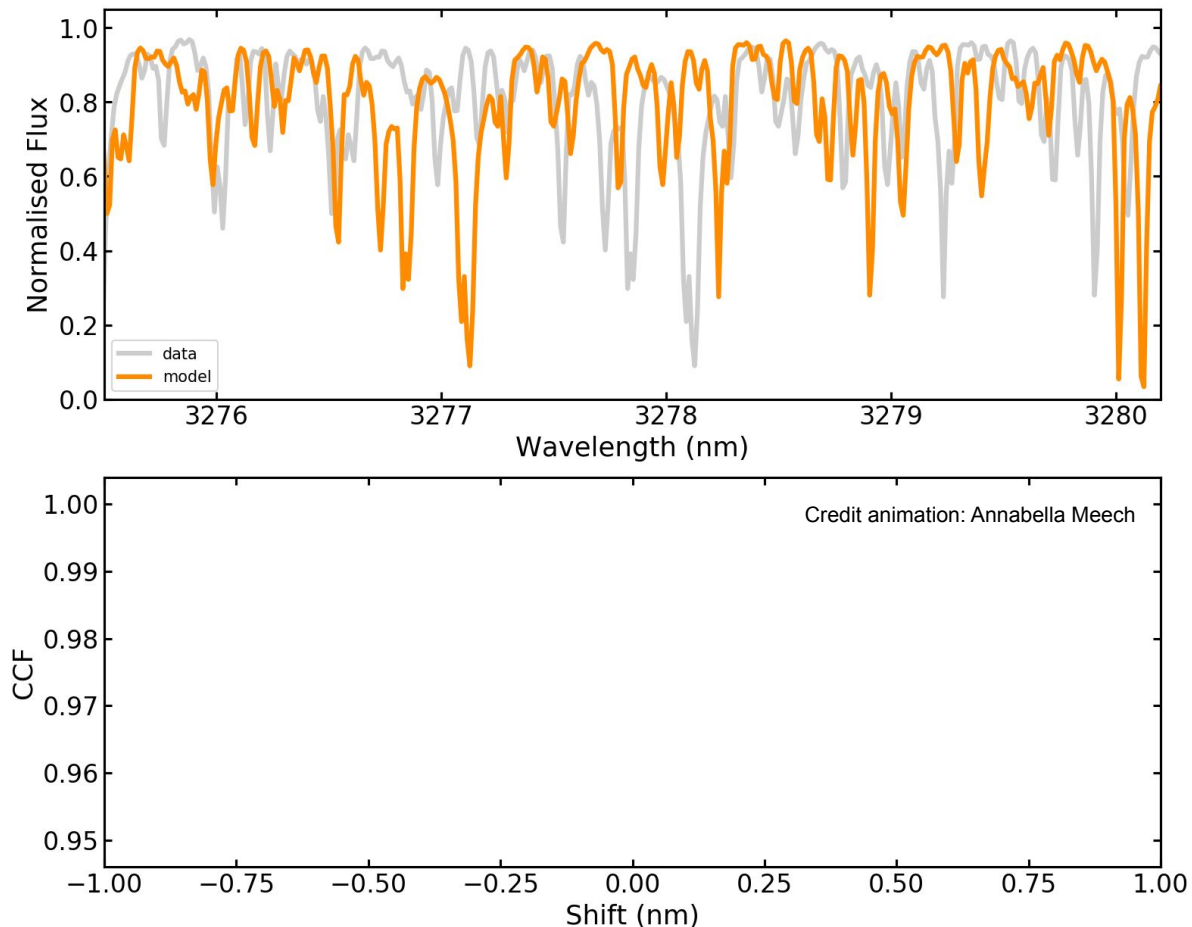
Radial Velocity (RV) method

If a planet orbits
a star,
the star spectrum
oscillates
between blue
and red

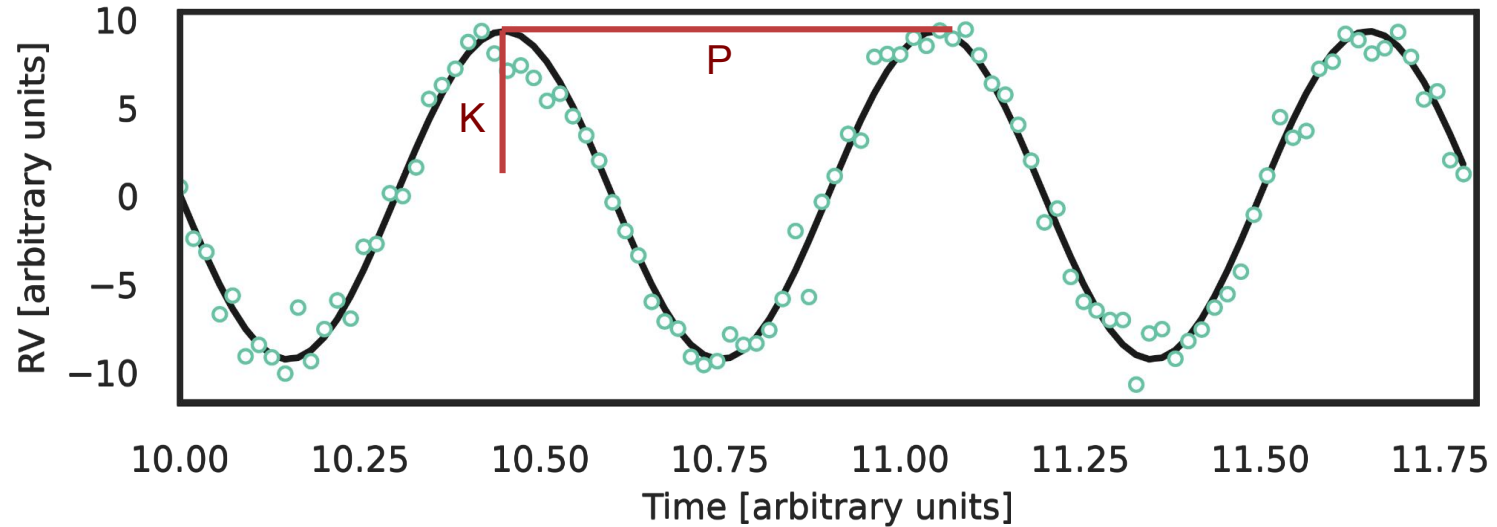


Radial Velocity (RV) method

Cross Correlation Function (CCF)

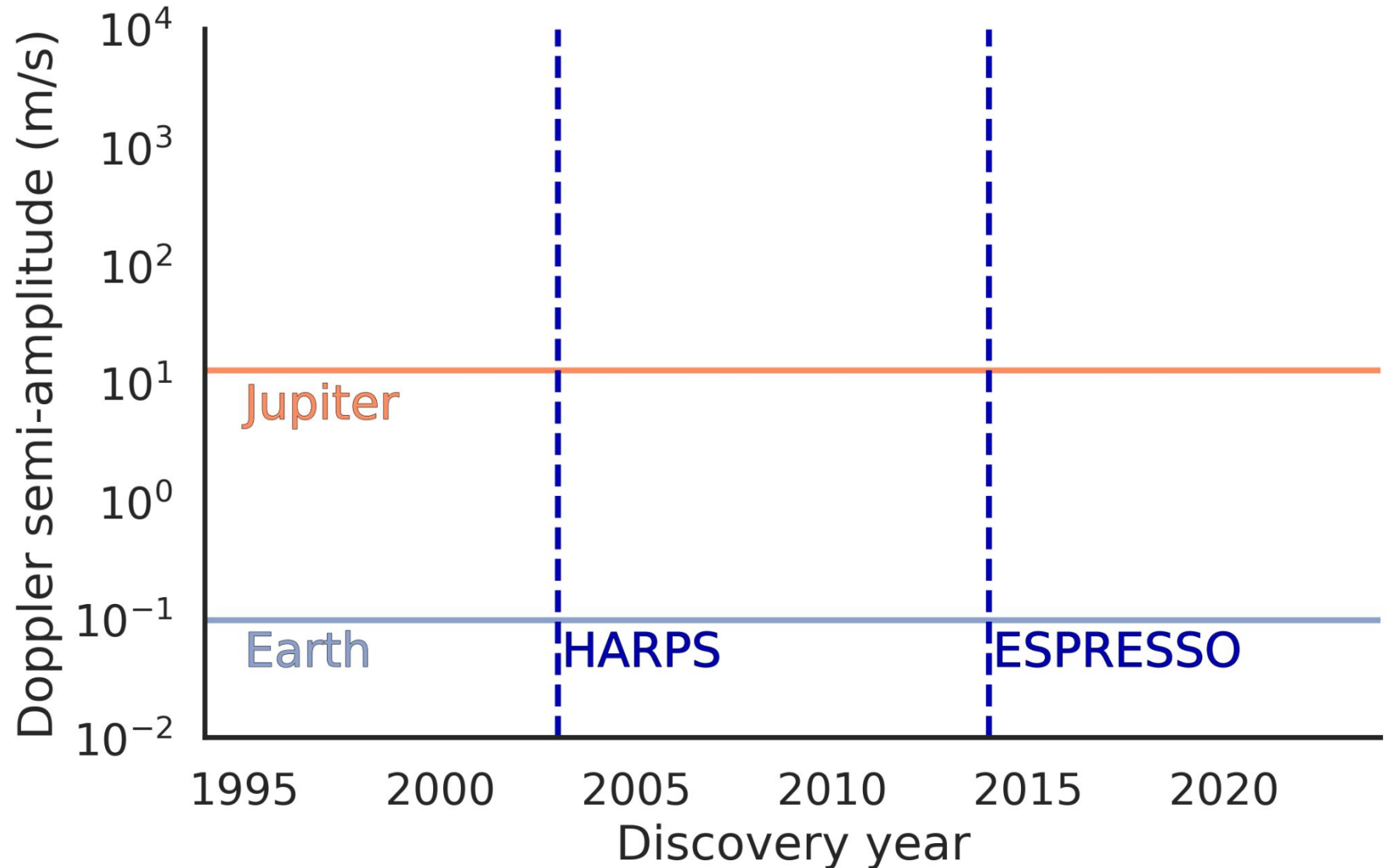


Radial Velocity (RV) method

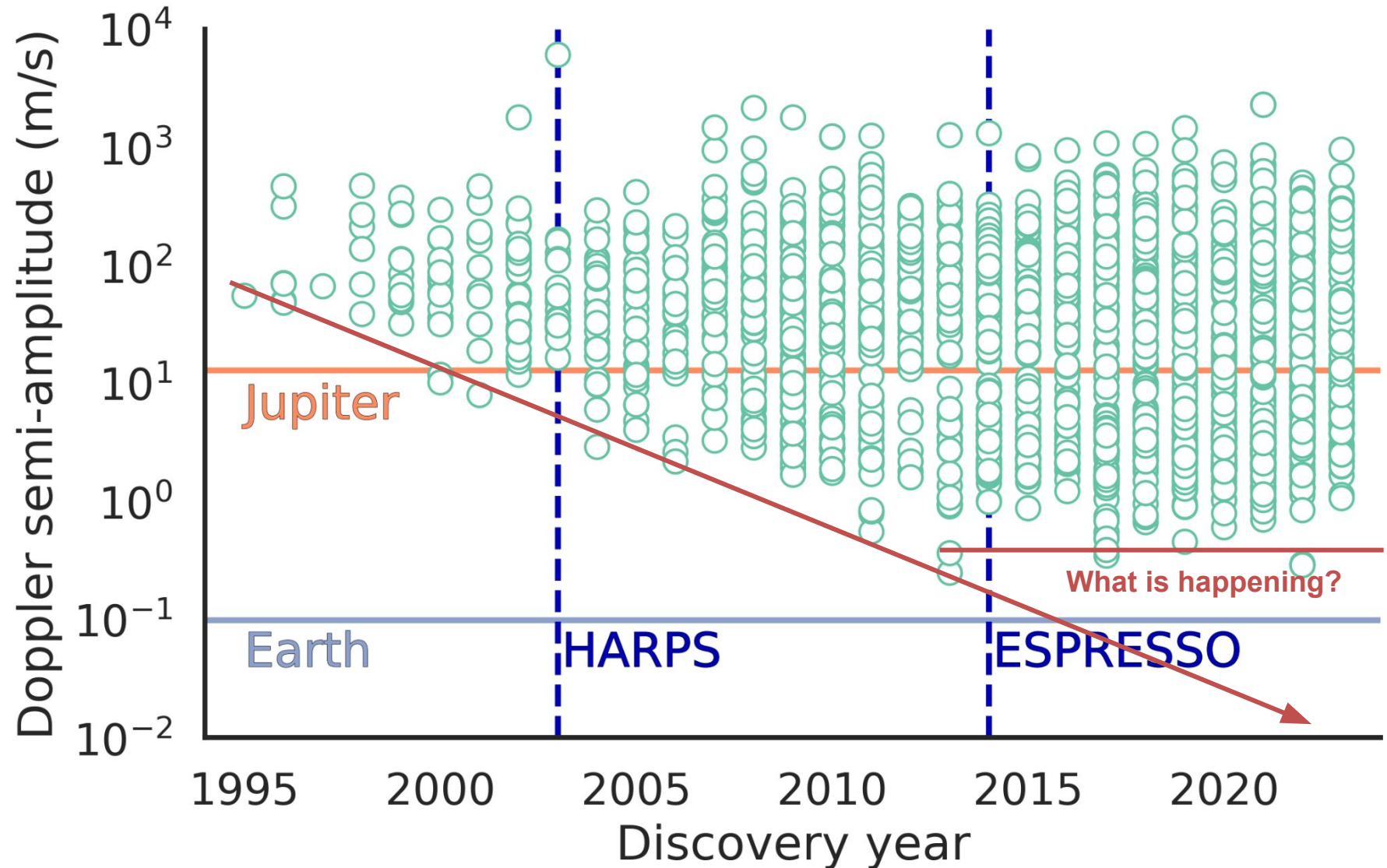


$$K \propto P^{-1/3} \frac{M_p}{M_\star^{2/3}} \sin i$$

RV detections



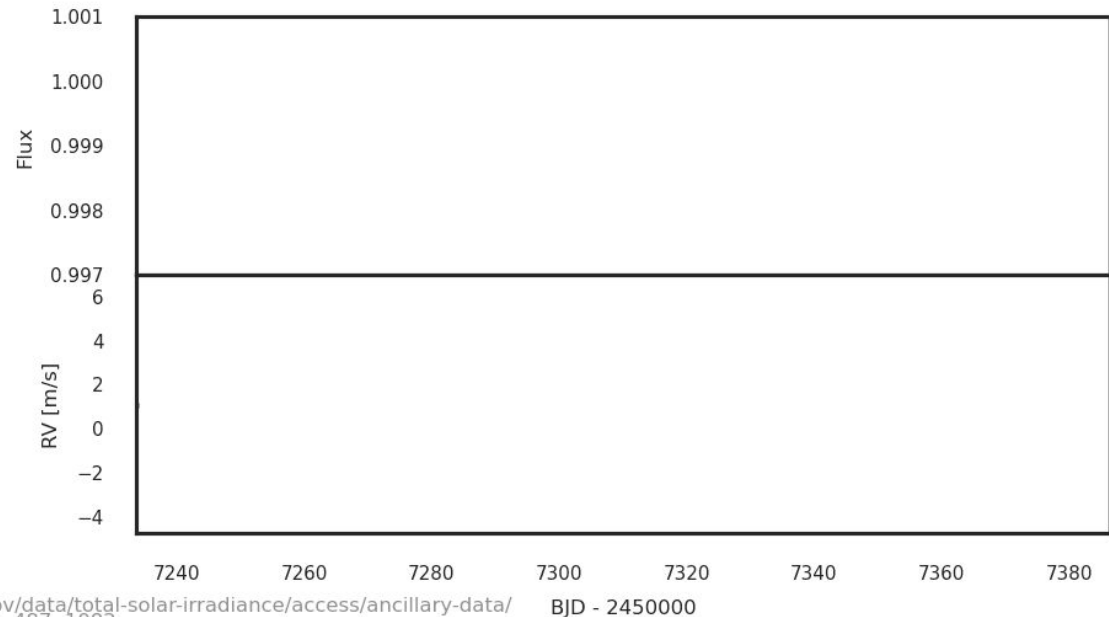
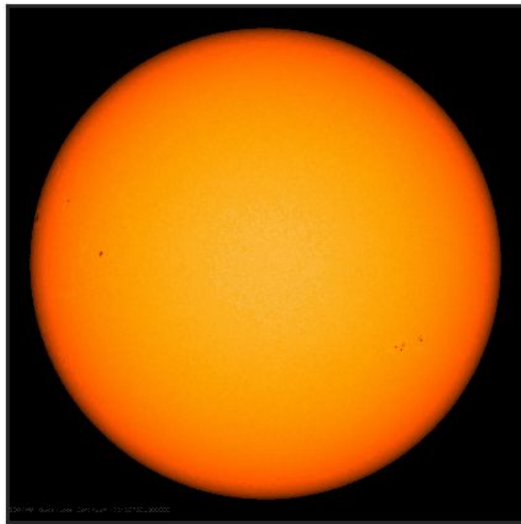
RV detections



Stars are not uniform discs of light

“Not even stars escape from the ruin of life”

Gabriel García Márquez, *El general en su laberinto*.



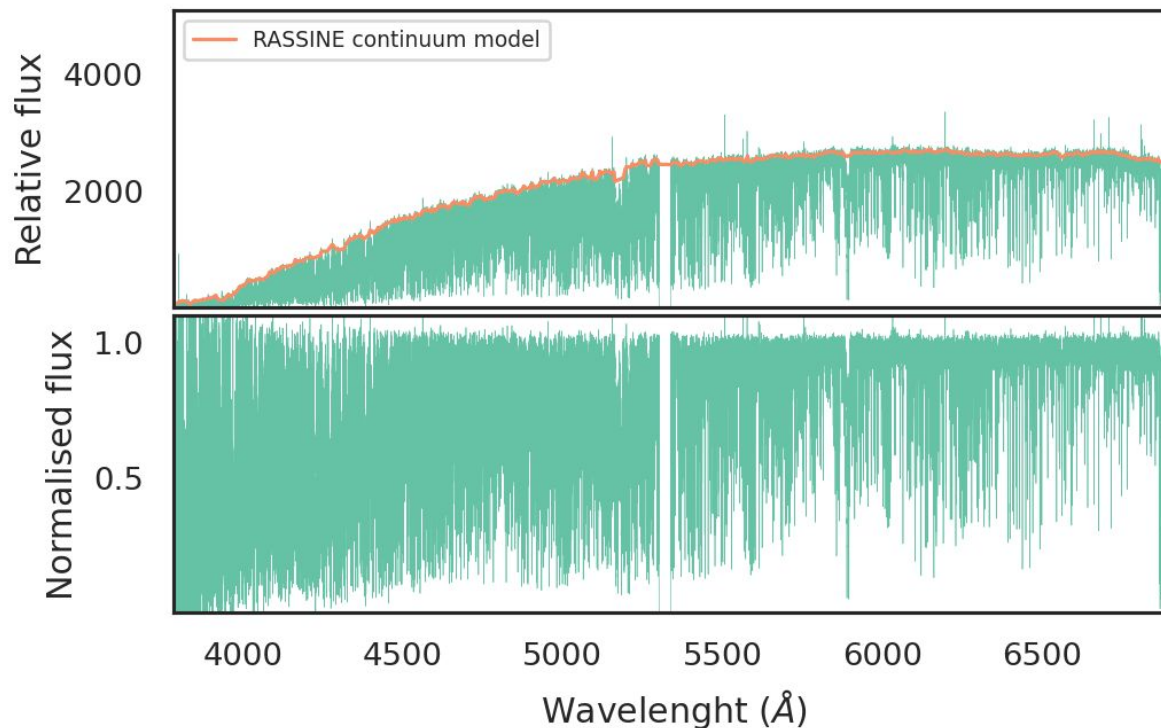
Oscar Barragán (@oscaribv)
Sun images downloaded from <https://sdo.gsfc.nasa.gov/>
Irradiance data downloaded from <https://www.ncei.noaa.gov/data/total-solar-irradiance/access/ancillary-data/>
Time-series data from Collier-Cameron et al., 2019, MNRAS, 487, 1082

Intrinsic stellar signals jeopardise
exoplanet detections



**How can we
deal with this?**

Spectra are more than RVs

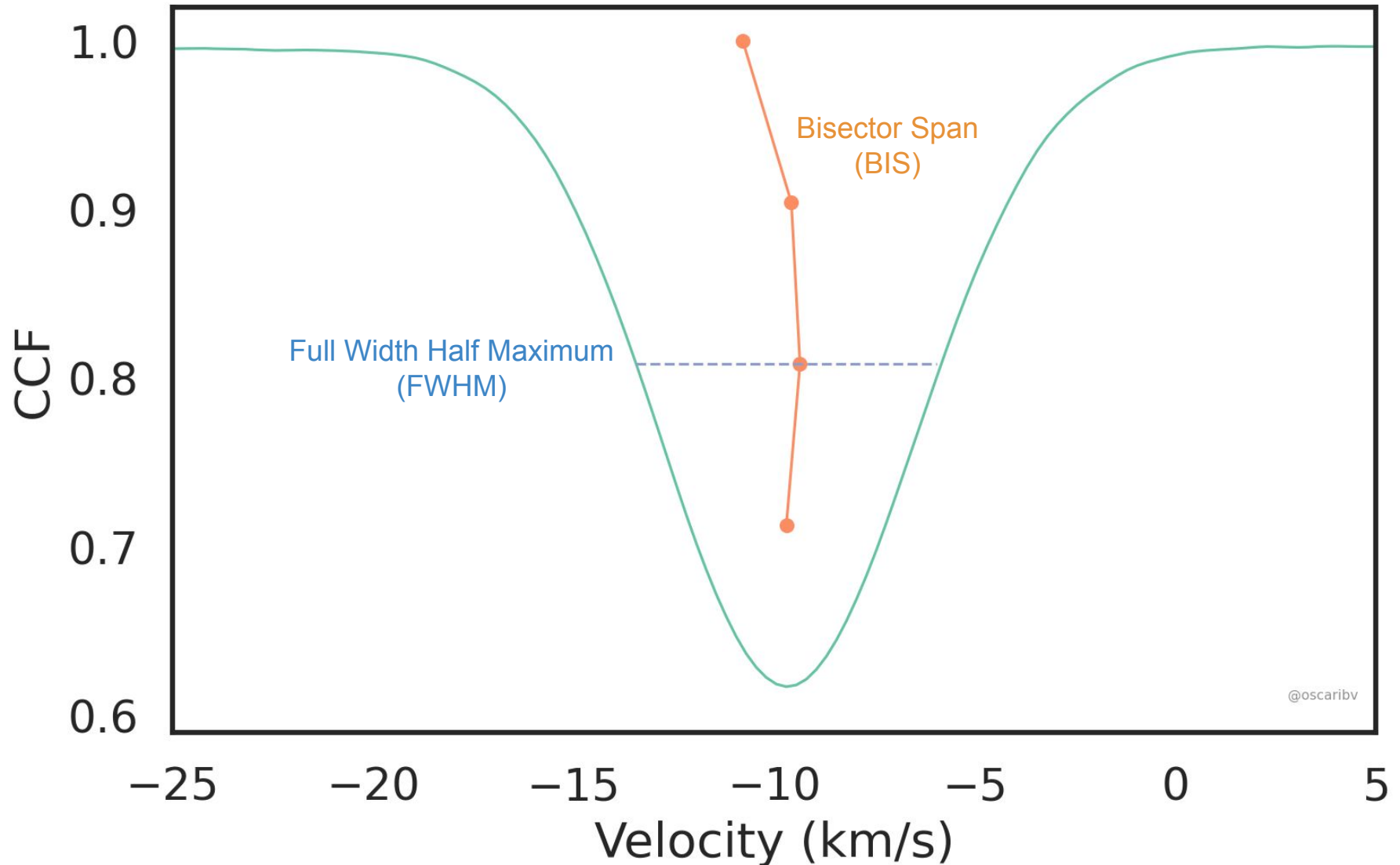


Stellar activity also manifests in other observables that come from spectra

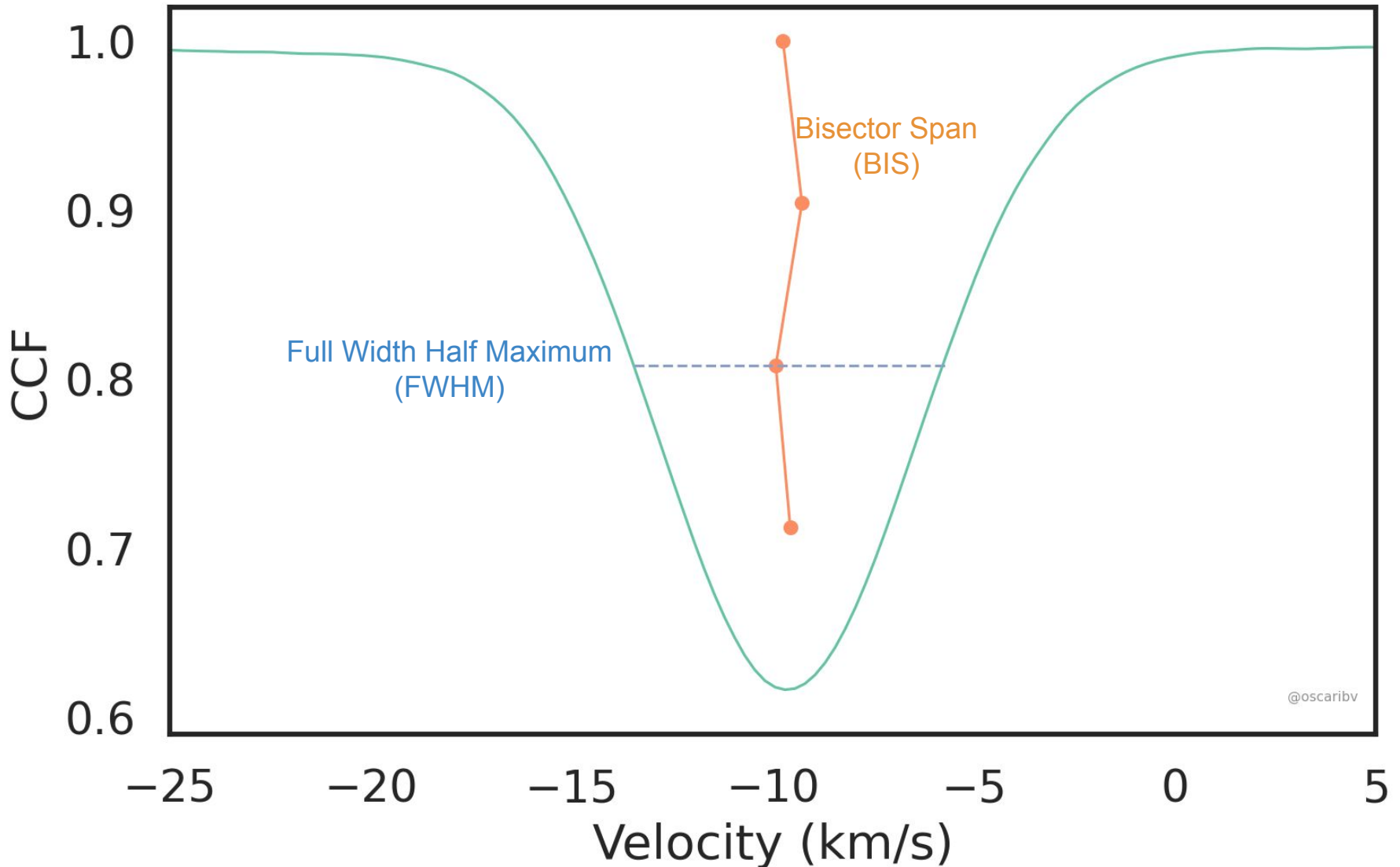
These measurements of intrinsic stellar signals are called **Activity Indicators**

They can be obtained from deformations of the lines,
intensity of the lines, CCFs, etc.

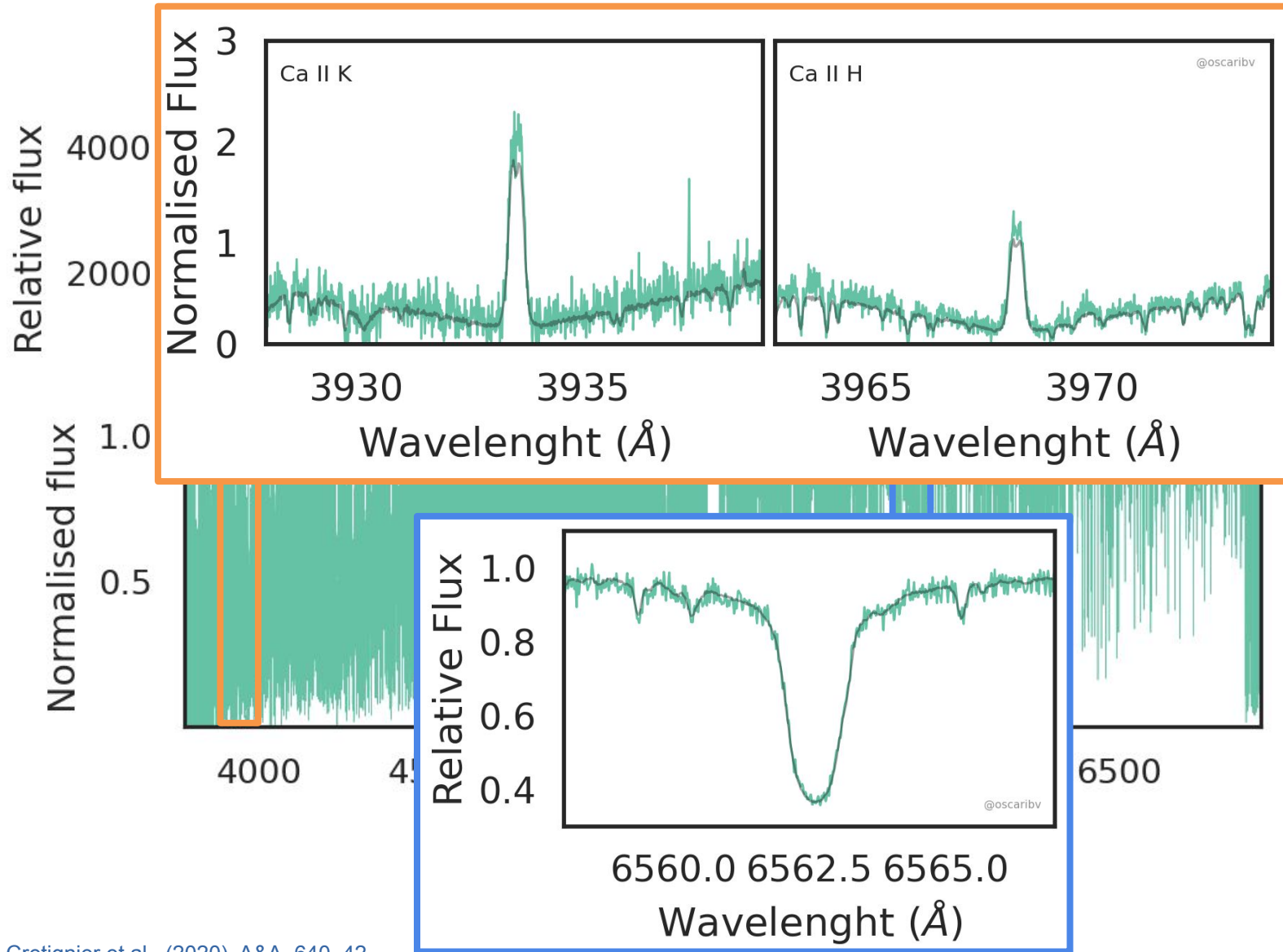
CCF activity indicators



CCF activity indicators

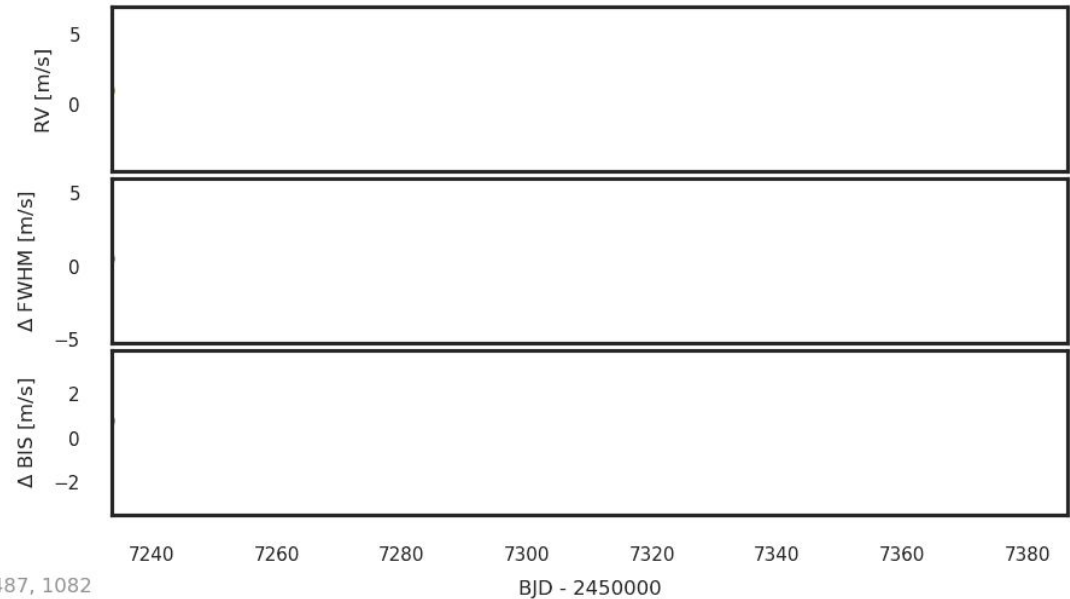
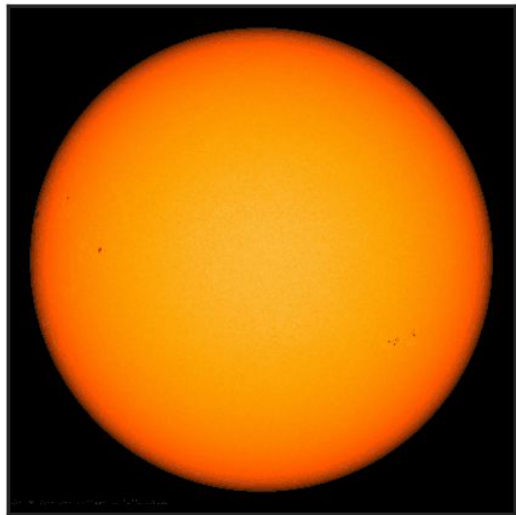


Chromospheric activity indicators



Activity indicators time-series

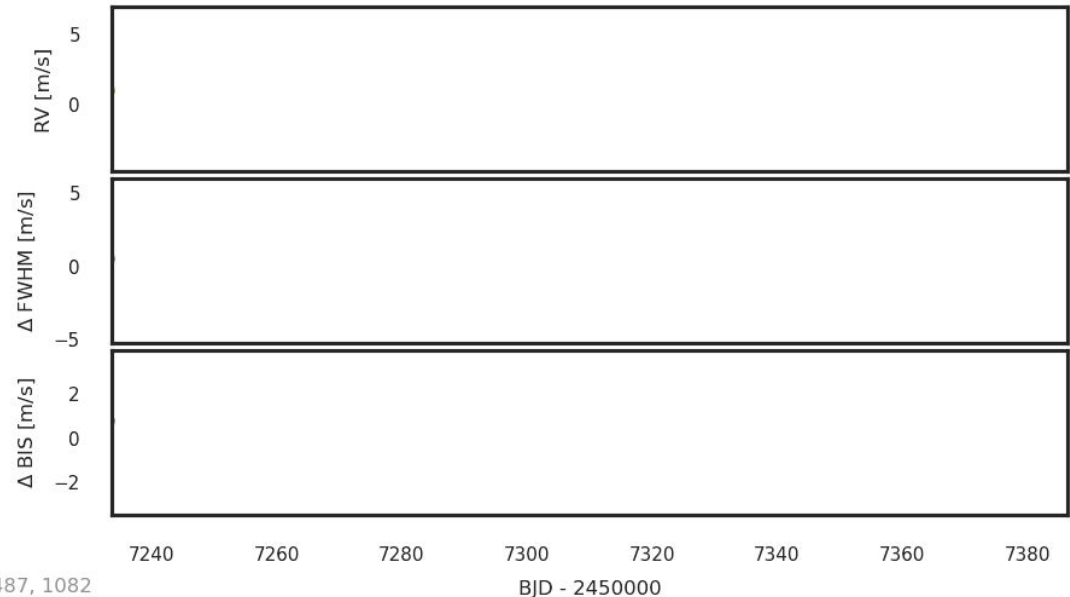
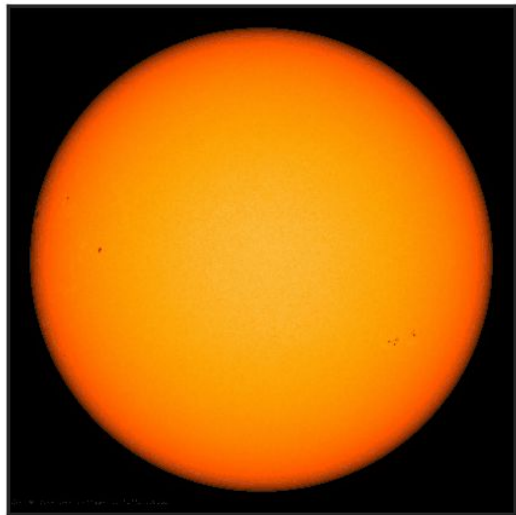
We can quantify activity indicators to generate time-series that contain only information about the star, not about the planets



Oscar Barragán (@oscaribv)
Sun images downloaded from <https://sdo.gsfc.nasa.gov/>
Time-series data from Collier-Cameron et al., 2019, MNRAS, 487, 1082

Activity indicators time-series

How can we use activity indicators to learn the shape of the stellar activity in the RV time-series?



Oscar Barragán (@oscaribv)
Sun images downloaded from <https://sdo.gsfc.nasa.gov/>
Time-series data from Collier-Cameron et al., 2019, MNRAS, 487, 1082

Multi-GP framework

[Rajpaul et al., \(2015\)](#) created a **Multidimensional Gaussian Process** (multi-GP) framework to model stellar signals in RV and activity indicators taking into account derivatives

$$\Delta RV = V_c G(t) + V_r \dot{G}(t)$$

$$\log R'_{\text{HK}} = L_c G(t)$$

$$BIS = B_c G(t) + B_r \dot{G}(t)$$

One Gaussian Process to rule them all!

Pyaneti II: Multi-GP approach

Barragán et al., 2022, MNRAS, 509, 866

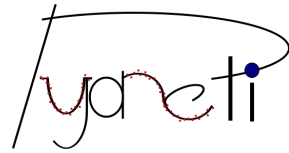
This approach can easily be generalised to an arbitrary combination of time-series

A stylized logo for 'pyaneti' in a red, cursive font, with a blue dot above the 'i' and a black arc above the letters.

$$\mathcal{A}_1 = A_1 G(t) + B_1 \dot{G}(t)$$

\vdots

$$\mathcal{A}_N = A_N G(t) + B_N \dot{G}(t),$$

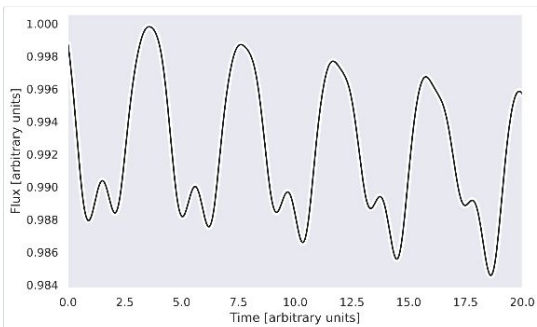
A stylized logo for 'pyaneti' in a red, cursive font, with a blue dot above the 'i' and a black arc above the letters.

See the **pyaneti II** paper

See also the works by [Jones et al. \(2017\)](#), [Gilbertson et al. \(2020\)](#), and [Delisle et al., \(2022\)](#)

Multi-GPs in one slide

Spot coverage
(not observed)

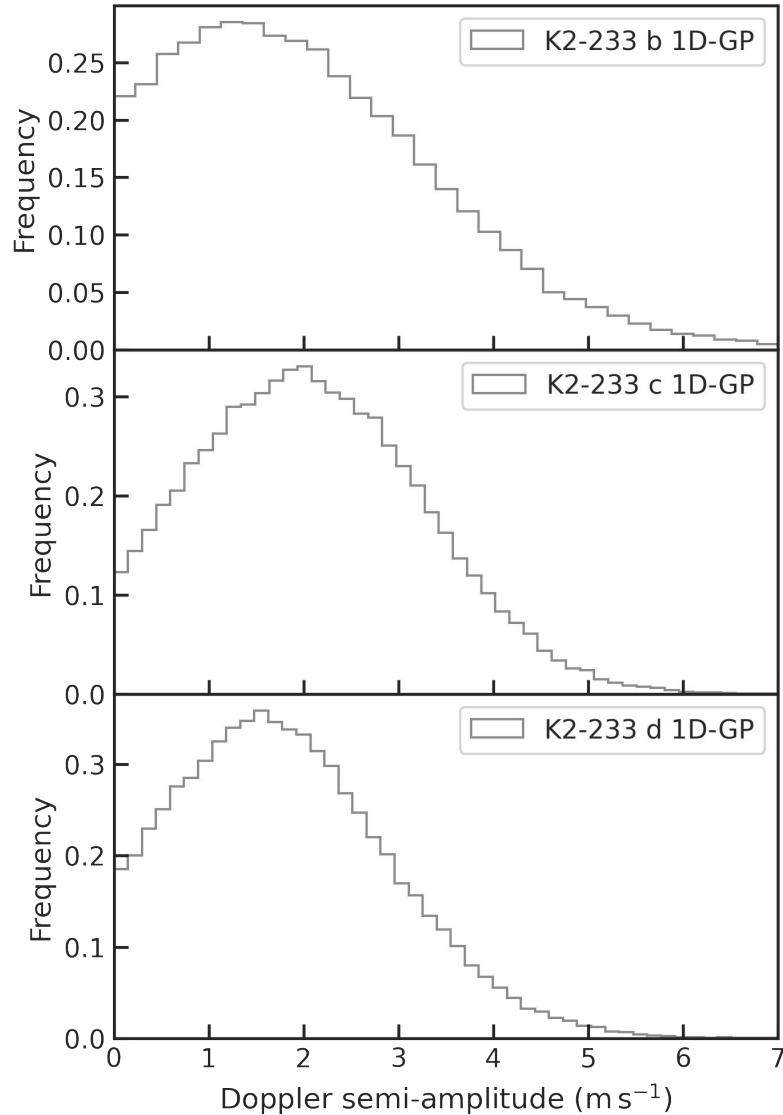




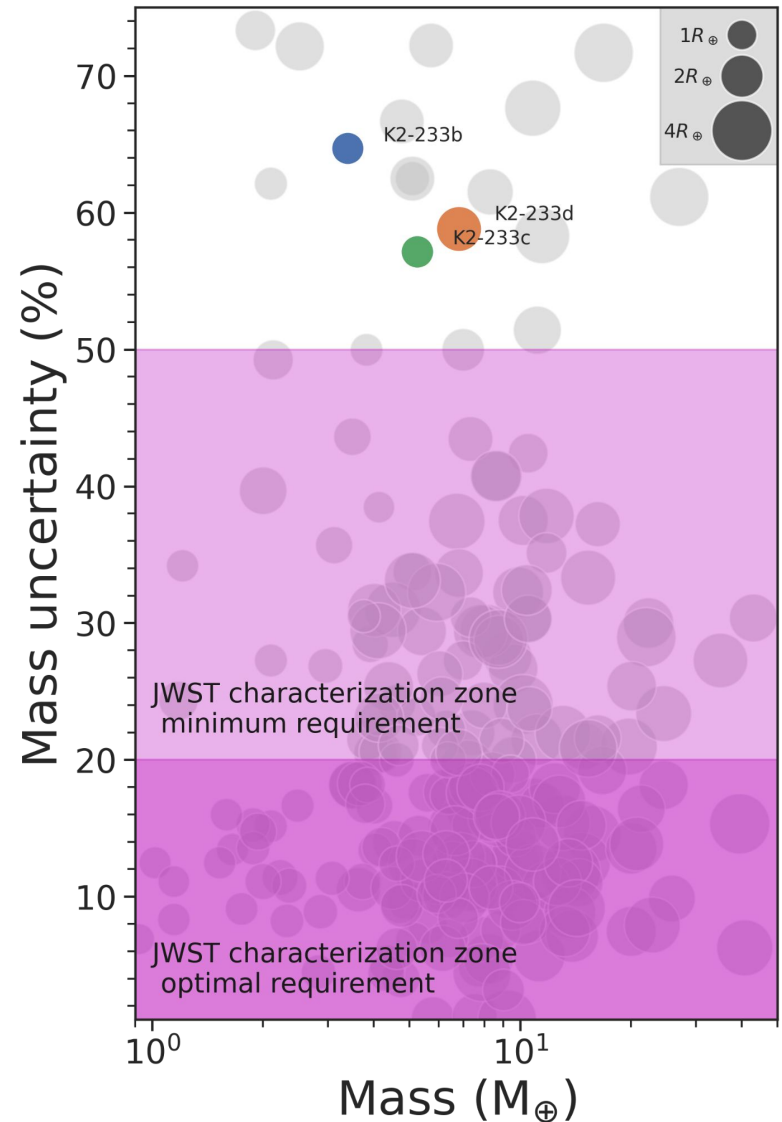
Examples

Multi-GP for K2-233

Barragán et al., 2023, MNRAS, 522, 3458

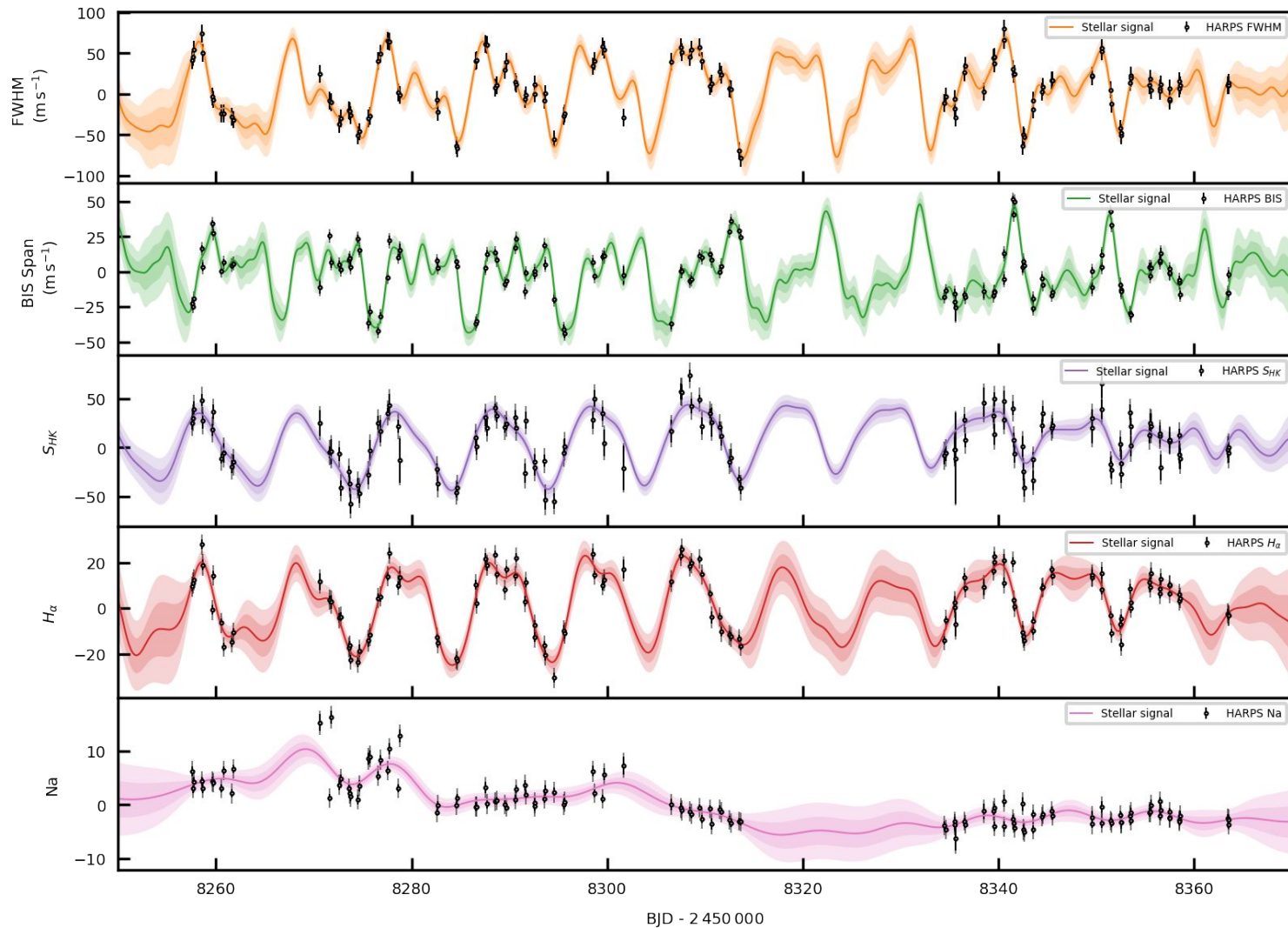


Data from Lillo-Box J. et al. , 2020.



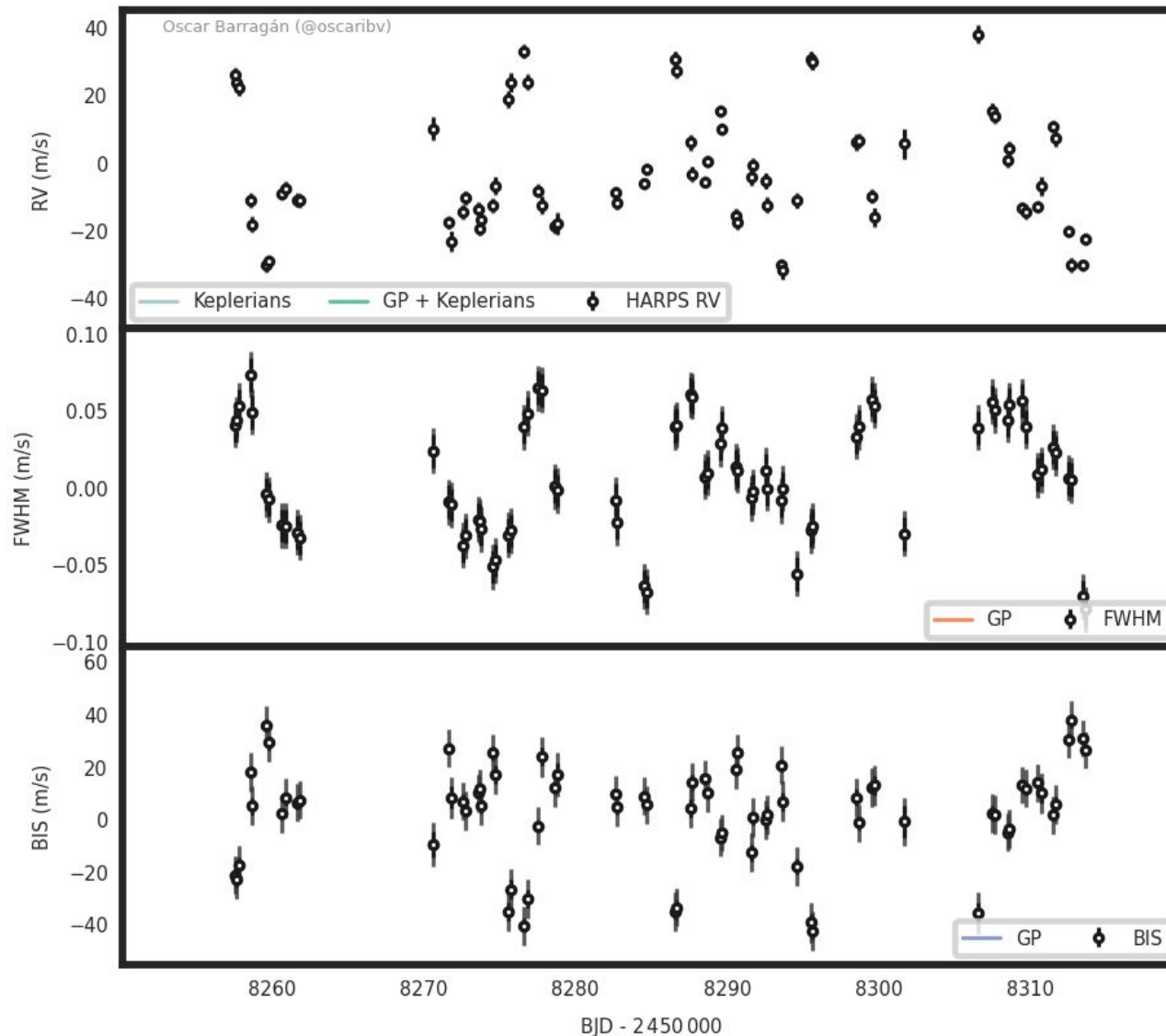
Multi-GP for K2-233

Barragán et al., 2023, MNRAS, 522, 3458



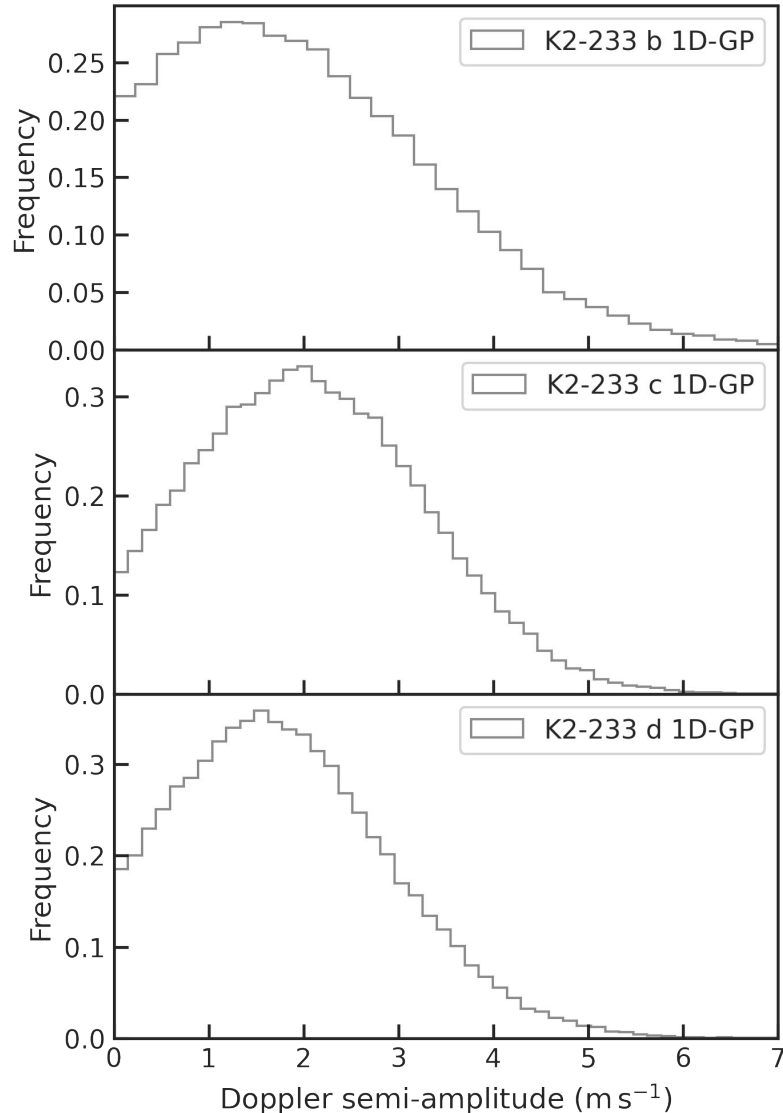
Multi-GP for K2-233

Barragán et al., 2023, MNRAS, 522, 3458

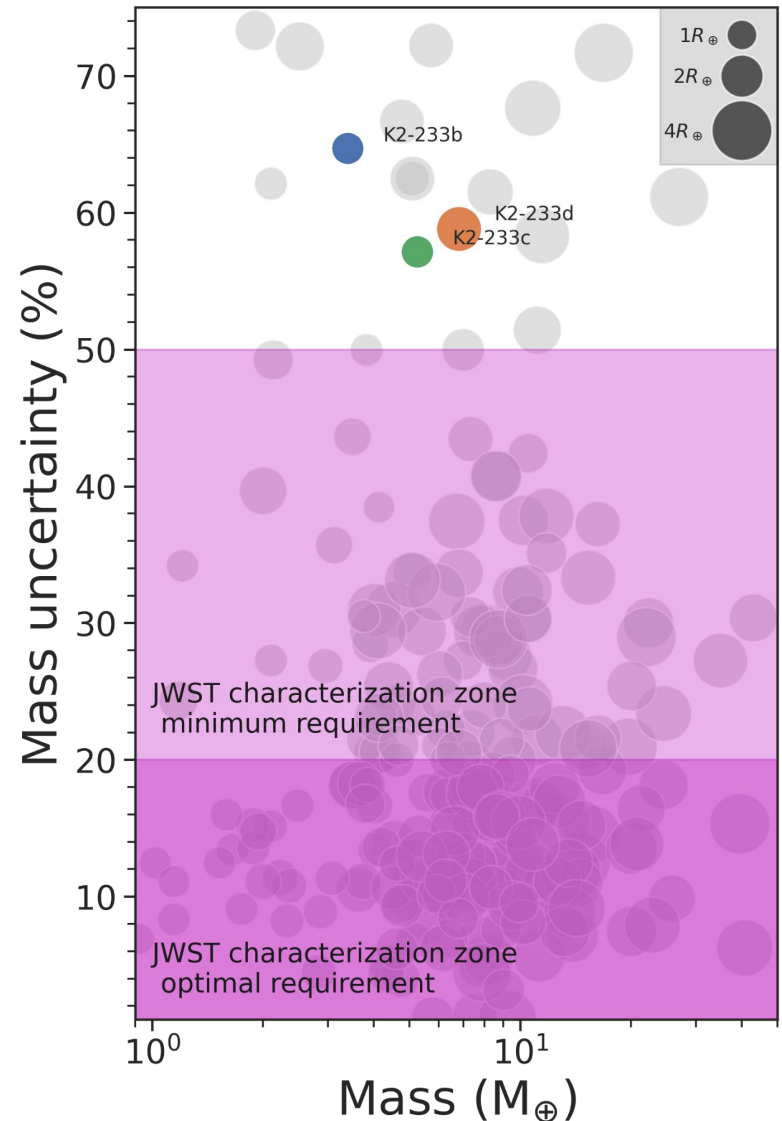


Multi-GP for K2-233

Barragán et al., 2023, MNRAS, 522, 3458

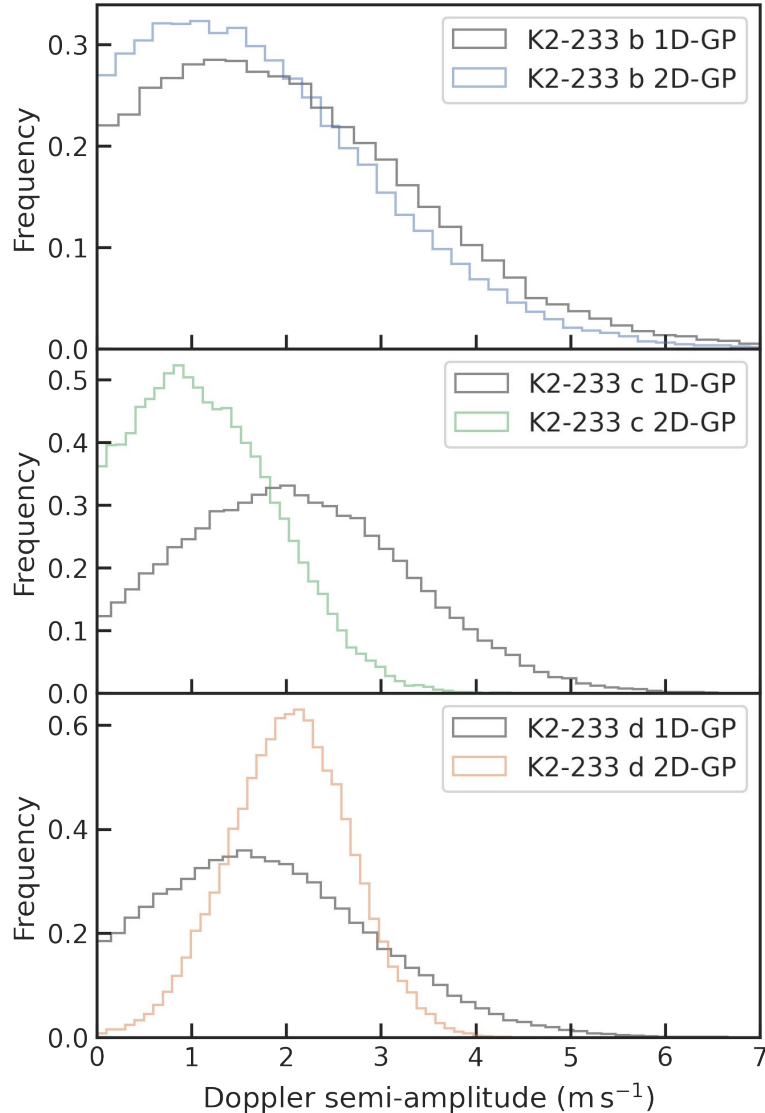


Data from Lillo-Box J. et al. , 2020.

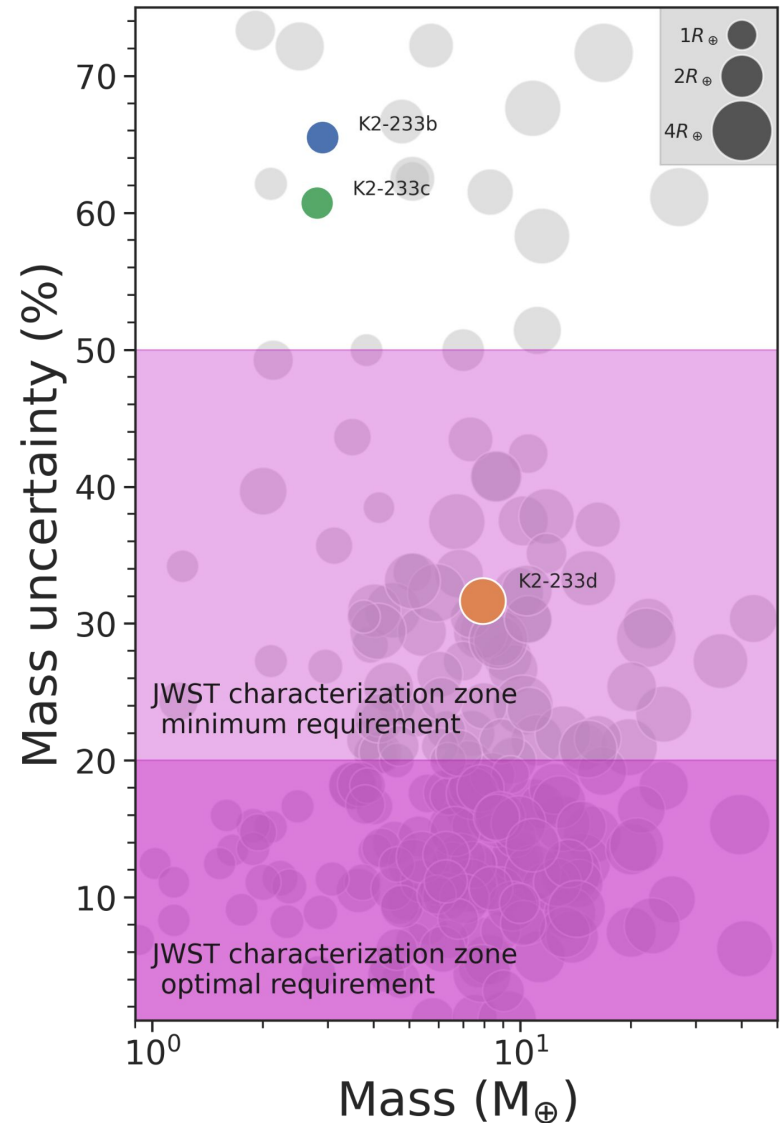


Multi-GP for K2-233

Barragán et al., 2023, MNRAS, 522, 3458

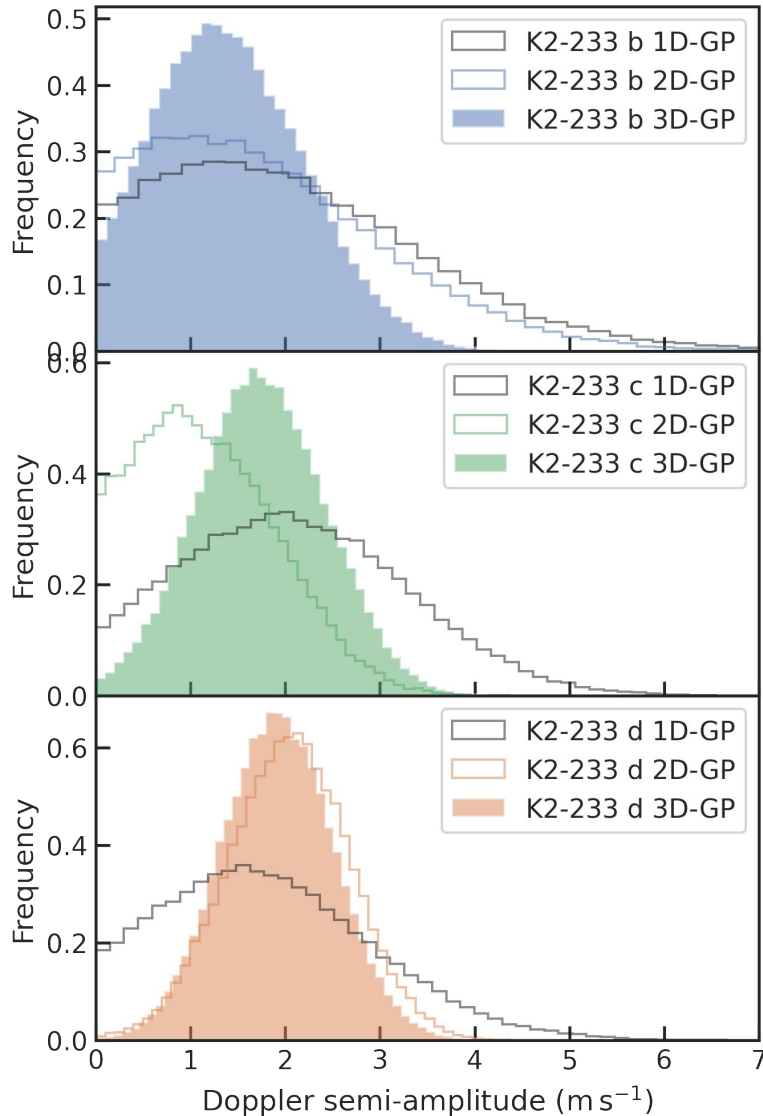


Data from Lillo-Box J. et al. , 2020.

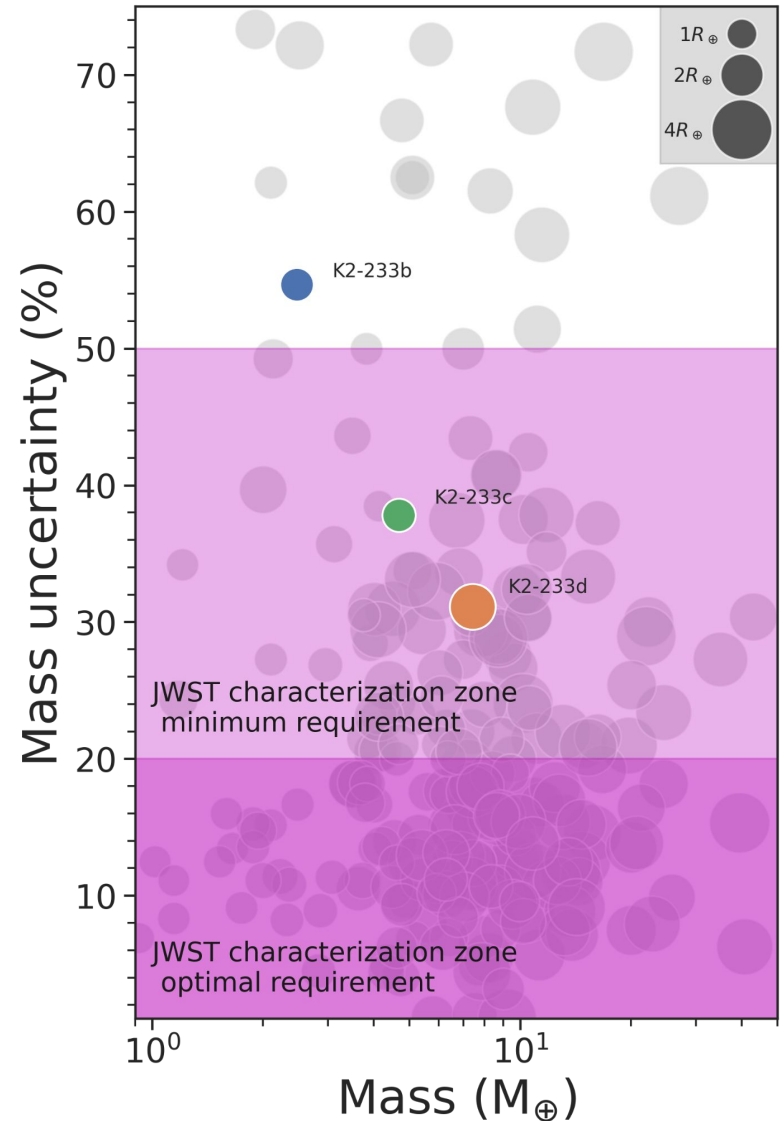


Multi-GP for K2-233

Barragán et al., 2023, MNRAS, 522, 3458



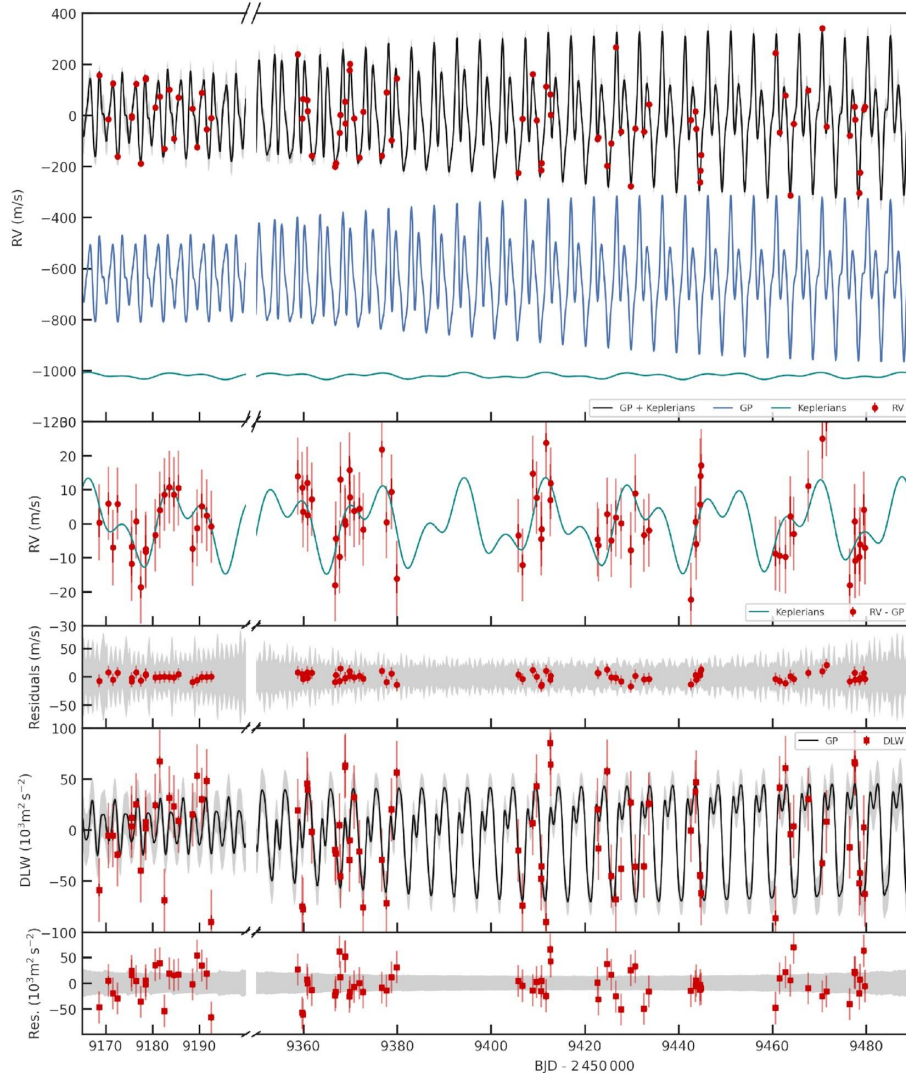
Data from Lillo-Box J. et al. , 2020.



Multi-GP applications: Young planets

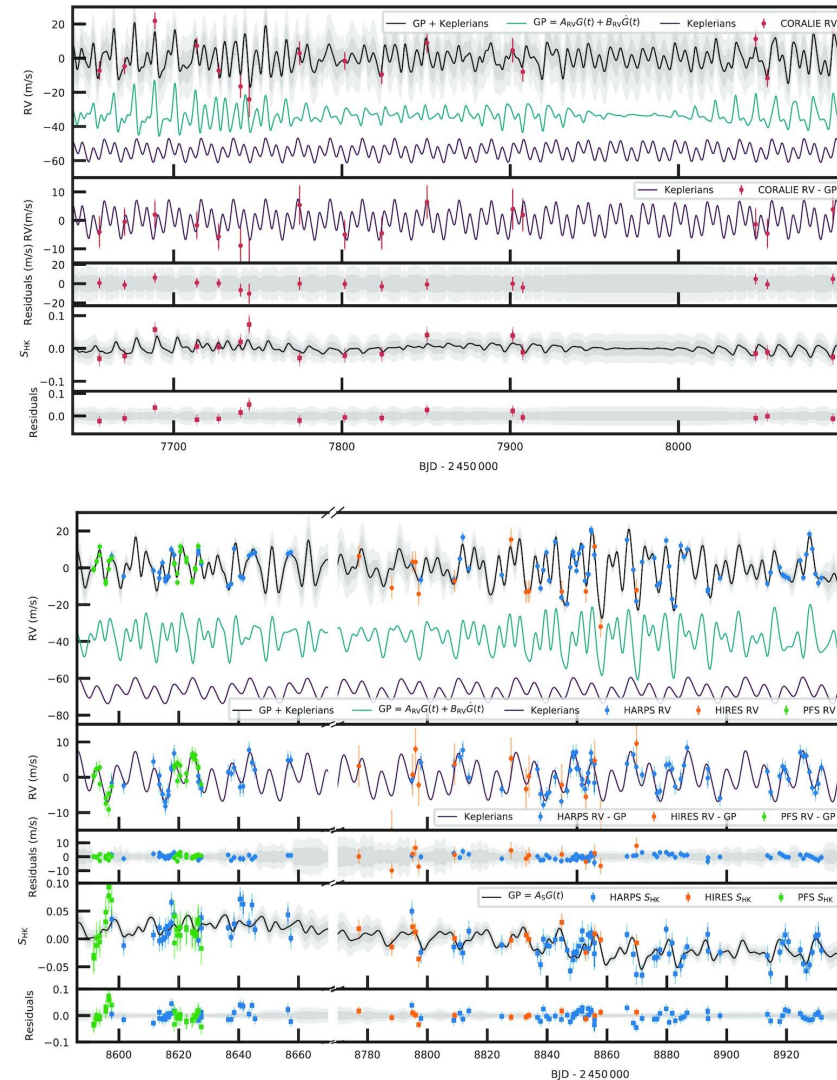
AU-Mic

Zicher, Barragán, et al., 2022, MNRAS, 512, 3060



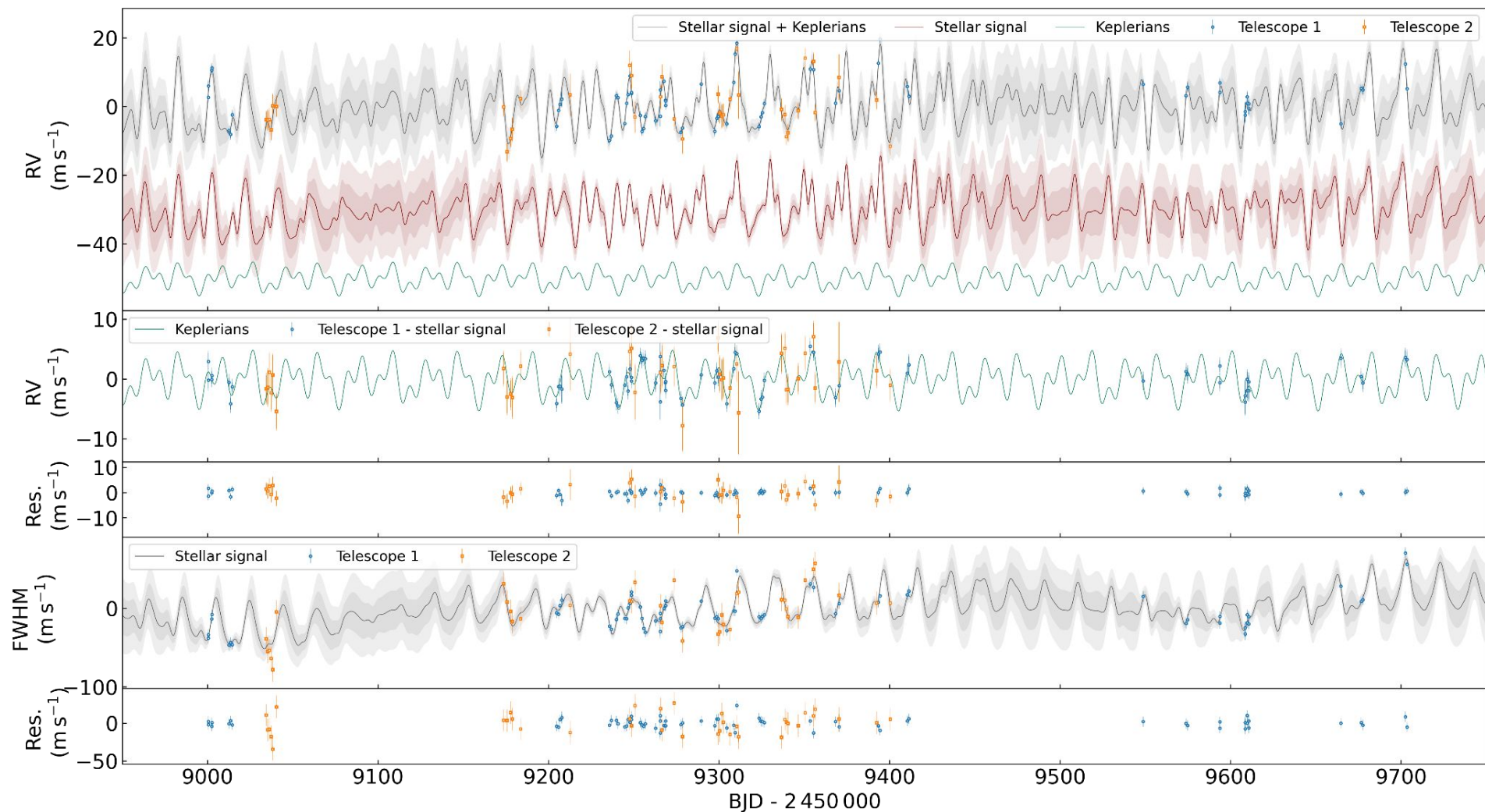
TOI-560

Barragán et al., 2022, MNRAS, 514, 1606



This also works for older stars

HD 110067 (Luque et al., Nature, submitted)



Take home

1. **Stellar spectra** contain precious information about what is happening on the stellar surface as **activity indicators**.
2. **Multi-GPs** are useful to find planetary signals using activity indicators to set constraints on the RV stellar signal.
3. We need to find more **activity indicators** and how they are related to the **RVs**.