Hi! My name is Carmen, and I am a 2nd year PhD student at IA involved with the PoET telescope, working on stellar activity and its impact on the detection of Earth twins using the RV method.

If you have any questions I will be around during the conference, or you can contact me at Carmen.SanNicolas@astro.up.pt

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Scan this QR code to access my web page, where I talk about the work I do, LBL RVs and more!

A NOVEL LINE-BY-LINE RV CODE: PAVING THE WAY FOR EARTH-LIKE PLANET DISCOVERY

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Background

Achieving the 10 cm/s radial velocity (RV) precision required to detect Earth-like planets orbiting Sun-like stars remains a significant challenge, largely due to stellar "noise", variability caused by magnetic activity, granulation, and oscillations that can mimic and/or mask planetary signals [1].

Even with state-of-the-art instruments like ESPRESSO [2] and refined RV extraction methods, current techniques still struggle to fully mitigate these effects [3]. Gaining a deeper understanding of how individual spectral lines react to stellar variability is key to advancing RV precision. This project aims to address that by leveraging high-resolution solar observations from PoET [4], enabling an unprecedented exploration of the origins and dynamics of stellar noise.

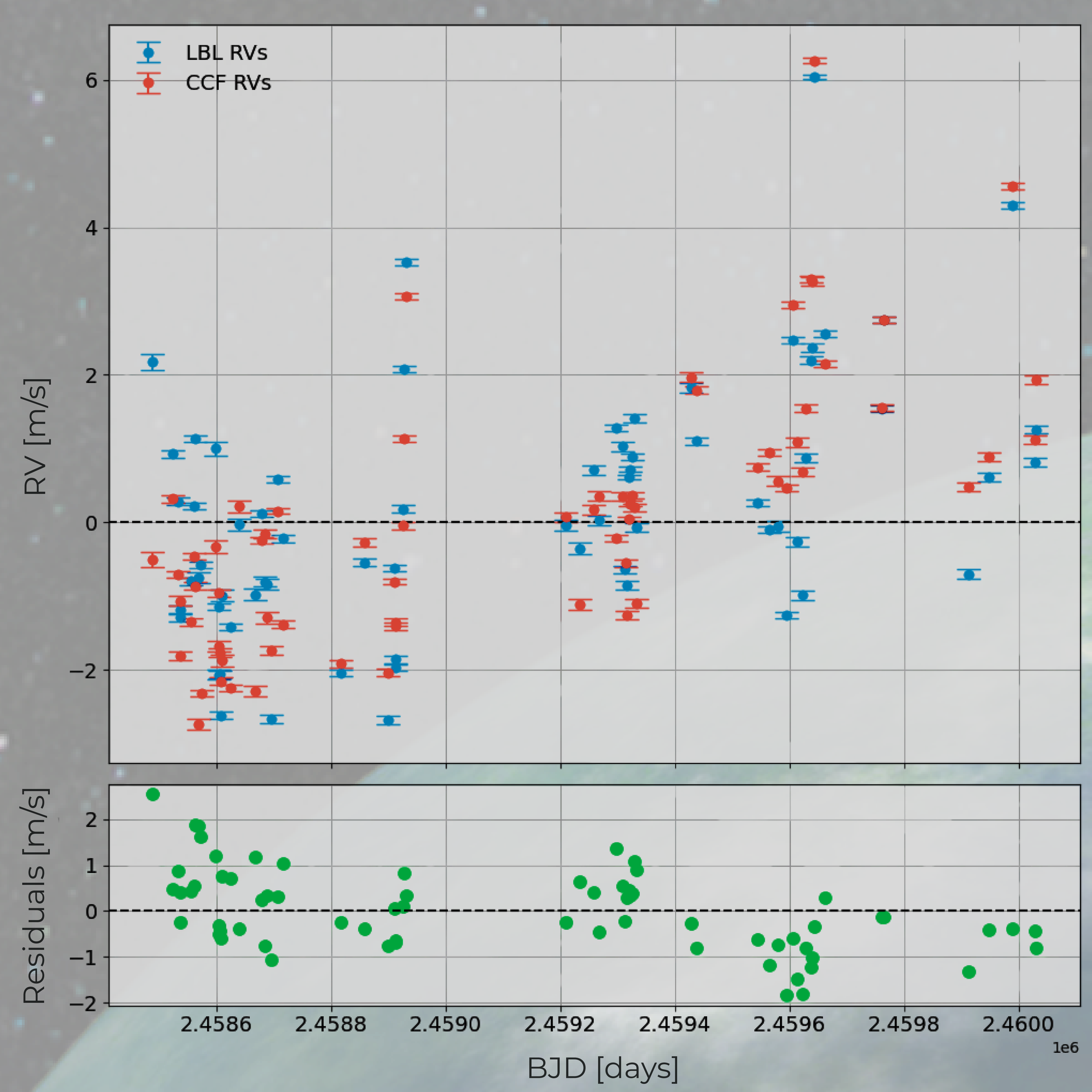
Results: Application to HD102365

The code has so far been tested on the nearby Sun-like star HD 102365 (G2V) [7], known to host a Neptune-mass planet [8].

For this analysis, we used 527 ESPRESSO observations collected between January 2019 and March 2023, with a median signal-to-noise ratio of 267. We computed the RV time series using our template-free LBL method and compared the results with those produced by the official ESPRESSO pipeline, which relies on the CCF technique.

Our weighted values (binned by night):
Standard deviation of RVs: 1.637 m/s
Average RV error bar: 5.453 cm/s

CCF values (binned by night):
Standard deviation of RVs: 1.734 m/s
Average RV error bar: 5.445 cm/s



Upper panel: Weighted RV time-series of star HD 102365 compared with the RVs from the CCF (all binned by nights).
Lower panel: Residuals of the RVs binned by nights.

[1] Santos N., et al., 2014, Astronomy & Astrophysics, 566, A35
[2] Pepe F., et al., 2021, Astronomy & Astrophysics, 645, A96
[3] Haywood R., et al., 2022, The Astrophysical Journal, 935, 6
[4] Santos N. C., et al., 2025, arXiv preprint arXiv:2505.08540
[5] Sousa S. G., Santos N. C., Israelian G., Mayor M., Monteiro M., 2007, Astronomy & Astrophysics, 469, 783
[6] Bouchy F., Pepe F., Queloz D., 2001, Astronomy & Astrophysics, 374, 733
[7] Gray R. O., Corbally C., Garrison R., McFadden M., Bubar E., McGahee C., O'Donoghue A., Knox E., 2006, The Astronomical Journal, 132, 161
[8] Tinney C., Butler R. P., Jones H. R., Wittenmyer R. A., O'Toole S., Bailey J., Carter B. D., 2011, The Astrophysical Journal, 727, 103

Line-by-line code

To measure precise velocities and their variability in PoET solar observations, we are developing a novel line-by-line (LBL) code that adopts a template-free strategy, setting it apart from other methods.
The code integrates with ARES [5] to perform Gaussian fits and determine the centers of spectral lines, using a fixed list of approximately 4400 well-characterized solar lines that we previously identified. RVs are then derived using the classical Doppler formula, ensuring a consistent and high-precision approach to RV extraction:

$$RV = \frac{\lambda_{obs} - \lambda_{ref}}{\lambda_{ref}} . c$$

The RV errors per line were computed based on the flux errors [6]:

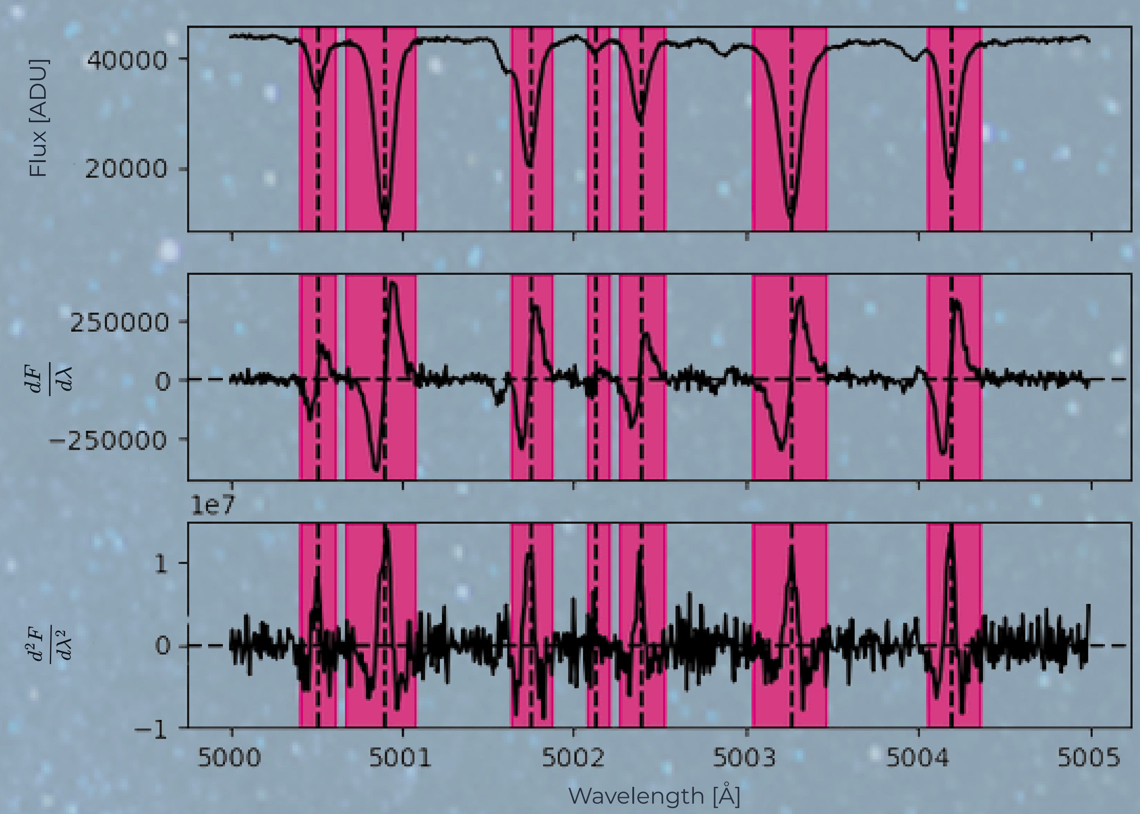
$$\sigma_{RV} = (\sum \frac{1}{\sigma^2_{\nu_i}})^{-1/2} \quad ; \quad \sigma_{\nu_i} = |\frac{dF}{d\lambda}|^{-1} . \frac{c}{\lambda_i} . \sigma_{Fi}$$

Where $dF/d\lambda$ is the error of the velocity in every point of the line, σ_{Fi} is the derivative of the flux respect to the wavelength and σ_{ν_i} is the error of the flux at a given point i.

Using the first and second derivatives of the flux, we defined windows around the line centers to estimate the uncertainties.

Next, a 2-sigma iterative clipping is applied to both the radial velocities and their associated errors to discard outliers. Finally, each line is weighted according to its sensitivity to stellar activity, allowing the code to combine them into a single, optimized RV measurement per observation.

This approach enables the generation of ultra-precise RV time series, which are crucial for identifying Earth-like exoplanets.

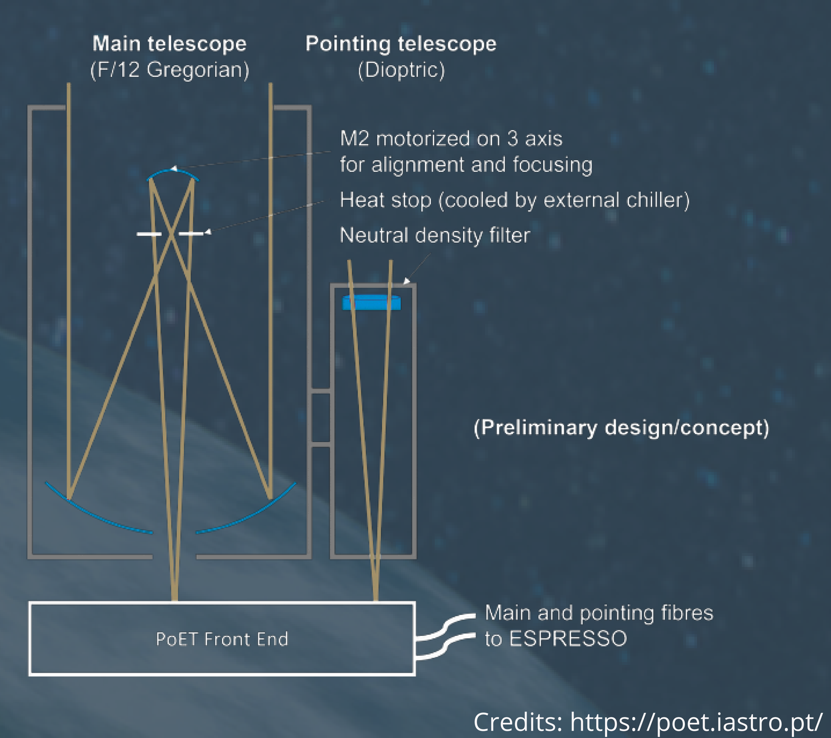


1st panel: Spectra of one observation with the center of the spectral lines marked in dashed lines, and the window limiting the region of the spectral line in purple.
2nd panel: First derivative of the flux respect to the wavelength to determine the extremes of the window of the spectral lines based on .
3rd panel: Second derivative of the flux respect to the wavelength, to confirm the extremes of the line based on

PoET

The Paranal solar ESPRESSO Telescope will be linked to the ESPRESSO spectrograph (ESO) and allow to acquire simultaneously disk-integrated (sun-as-a-star) and arcsecond level disk-resolved observations of the Sun at a spectral resolution R~200000.

With PoET, we will be able to obtain disk-resolved observations of different solar activity phenomena, granulation, center-to-disk, etc. These observations will be processed with our LBL code to study which lines are more and less sensitive to the different stellar phenomena.



Credits: https://poet.iastro.pt/

Take-home messages

- We developed a template-free LBL code to retrieve precise RVs.
- The code will be applied to PoET observations in order to study different solar activity phenomena.
- So far it has been tested with the Sun-like star HD102365. The standard deviation and average error bar obtained with the LBL RVs were similar to or better than the CCF.
- Our methodology will now be applied to other Sun-like stars.
- The paper accompanying the LBL code is in preparation. Stay tuned!

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