The complex temporal and chromatic jitter signal of the M-dwarf EV Lac with multi-wavelength PRVs

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Context for our work and main takeaways

- **Context:** Stellar activity is the greatest roadblock to measuring precision planet masses
  - Jitter decreases with wavelength, but exact relation is unknown[1,2,3], and temporal evolution is complex
  - Activity models are phenomenological, need to be tied to stellar conditions: B-field, surface features[4,5]
- **Main takeaway:** EV Lac is a highly active M-dwarf with a complex activity signal
  - There is clear periodicity in both photometry and RVs at the same period, with multipole behavior
  - Signal evolves over ~month to years, to different extents in photometry vs. RVs vs. activity indicators
  - NIR jitter is always smaller, but visible and NIR jitter decrease by different relative amounts over time

EV Lac: properties and description

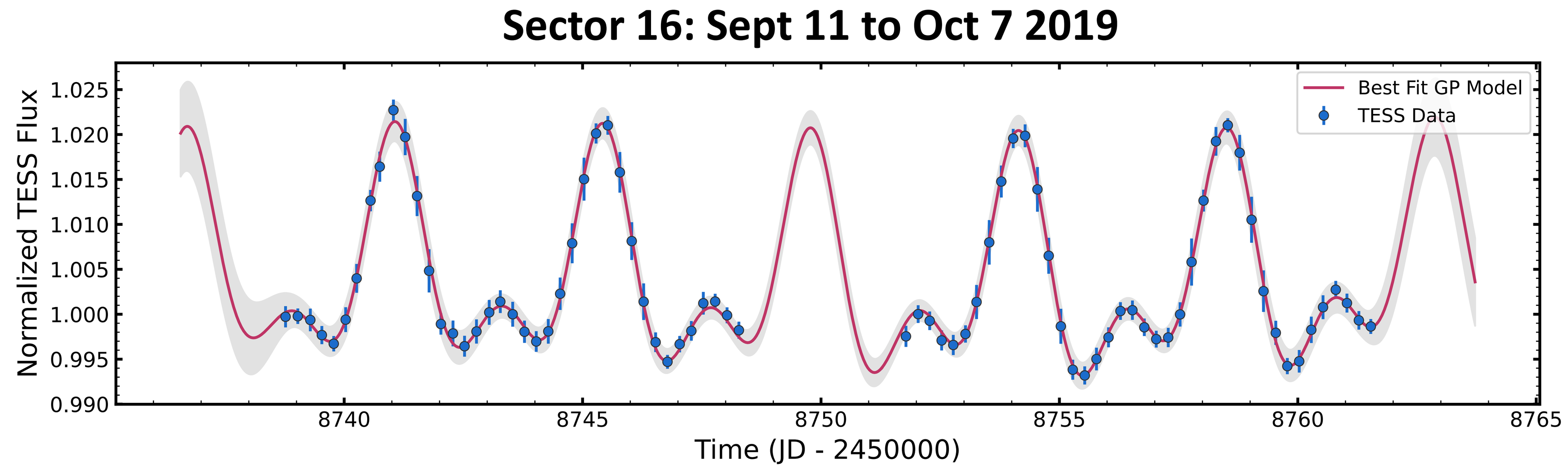
- A young, active M3 dwarf with a rotation period of ~4.3 days[6,7,8]
- CARMENES finds activity RV signal with multiple periodicities[9]
- EV Lac is known to flare frequently[10,11,12]

Observations and data sets

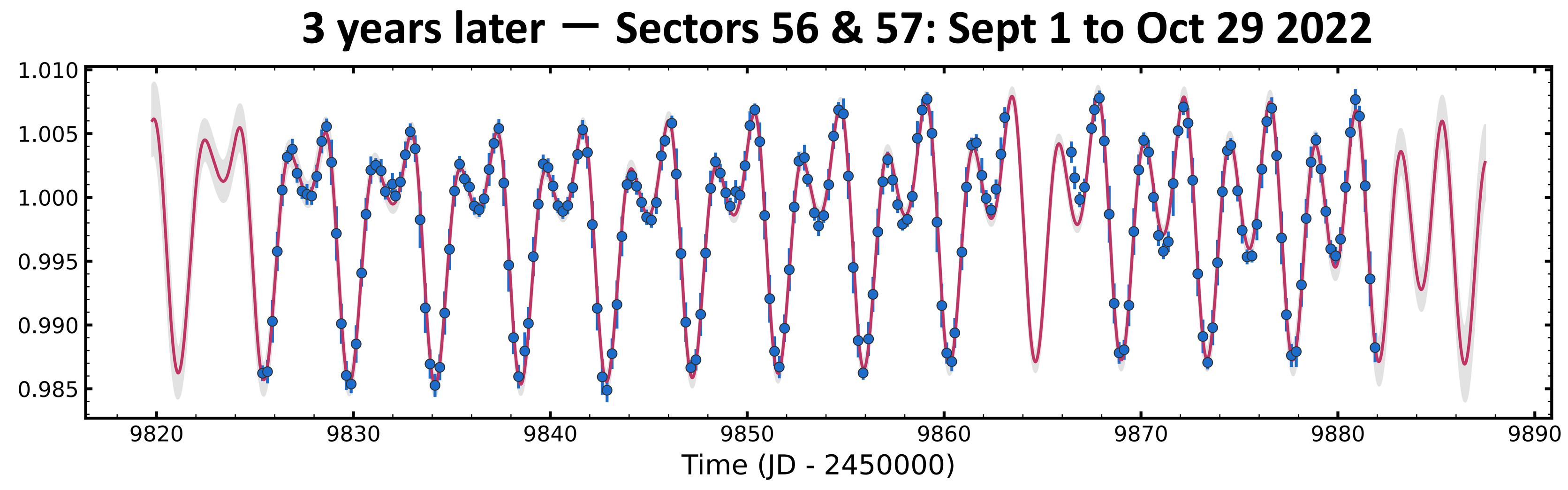
- Precision RVs with the APF[13] (visible) and HPF[14] (NIR) over 1.5 years
- Two "seasons" of TESS data: Sep-Oct 2019 & Sep-Nov 2022
- The Fall 2022 APF, HPF, and TESS data is contemporaneous

TESS Photometry: there is rotational modulation in multiple sectors

Sector 16: Sept 11 to Oct 7 2019



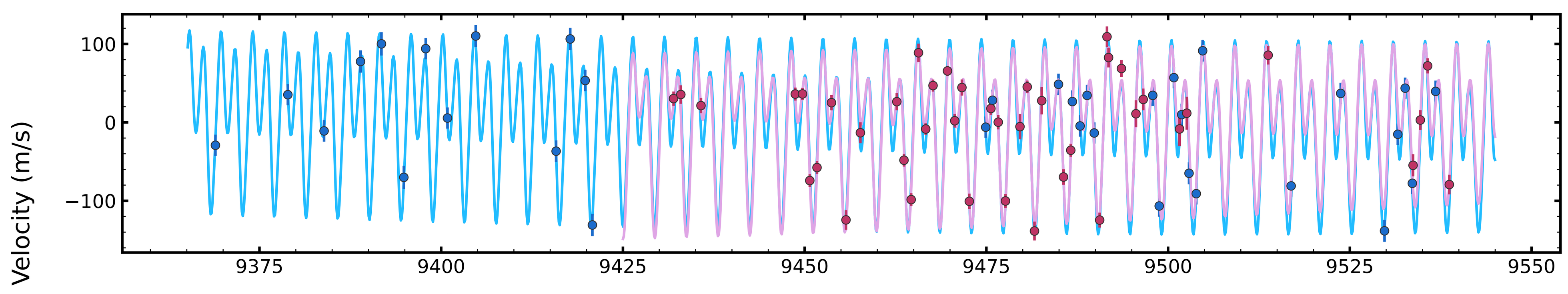
3 years later — Sectors 56 & 57: Sept 1 to Oct 29 2022



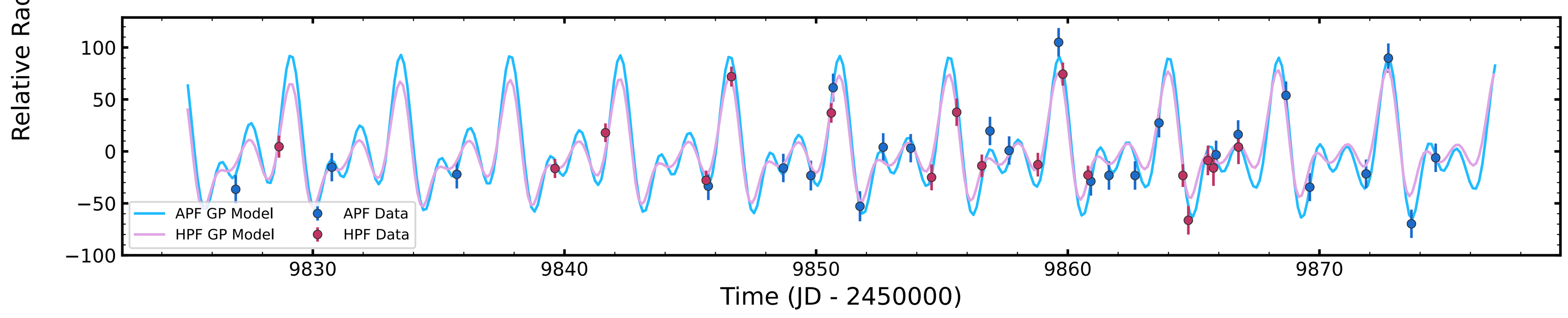
- There is clear periodicity in the light curve at P_{rot} = 4.36 days and its first harmonic
- There is constant flaring of small to large amplitude (removed in this work)
- Modulation amplitude is similar across seasons, but shape evolves significantly
- The signal is "inverted" in 2022 vs 2019: change in spot distribution and size

Multi-wavelength precision RVs: A complex jitter signal

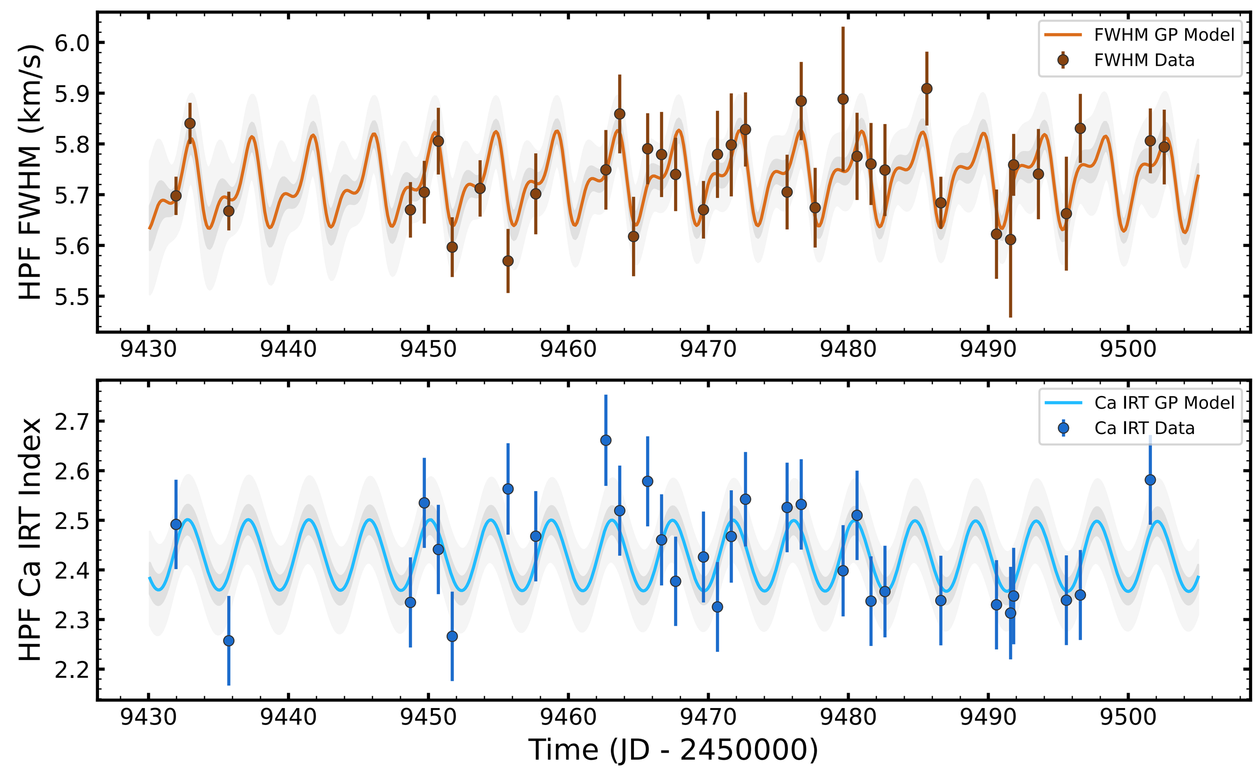
Season 1: June to December 2021



Season 2: September to November 2022



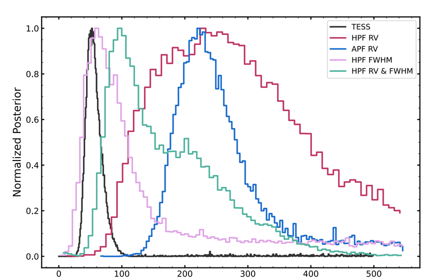
- **Multi-periodicity** at rotation and harmonic is seen in **RVs**, as in the TESS photometry
- Fit the APF and HPF time series with a **quasi-periodic Gaussian process**[15,16] with pyaneti[17]
- Prediction from the light curve (FF' method[16,18]) describes RV variation well but not exactly
- **Evolution in the signal between observing seasons** – comparable to light curve shape changes



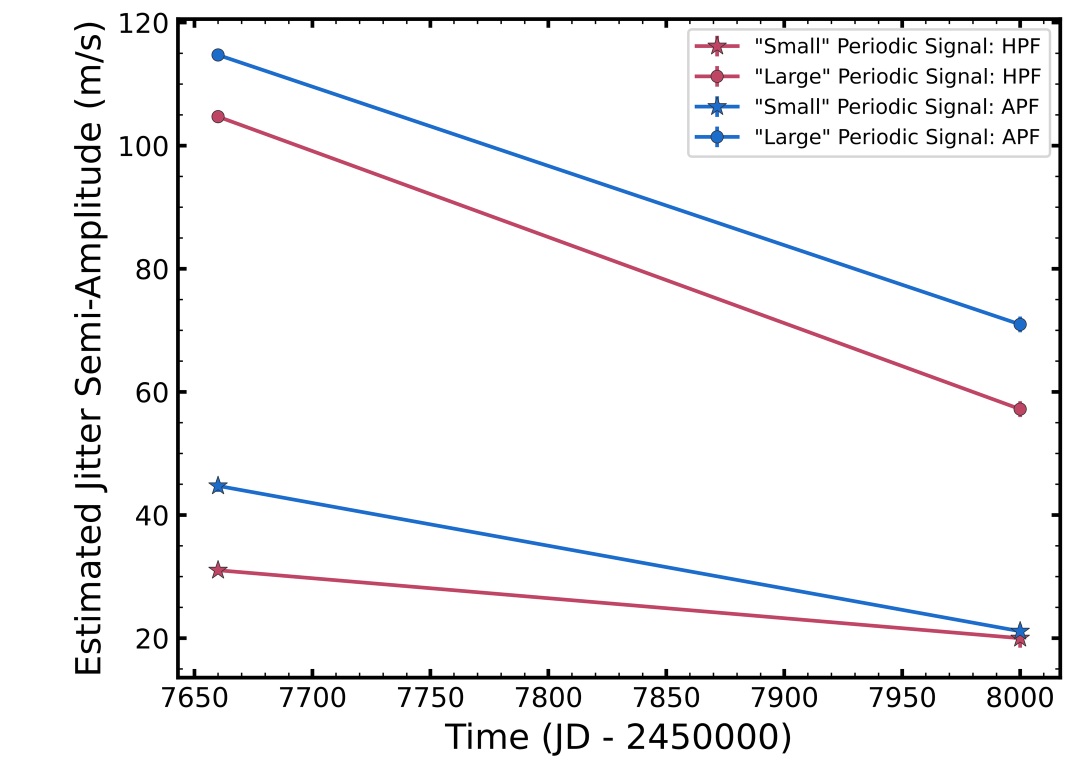
- **HPF activity indicators**: **FWHM** from RV method and **Ca IRT**, both should track spot filling factor[19,20]
- Both have a 4.3 d periodicity
- **FWHM** has stronger and more **consistent periodic signal**
- **Ca IRT** has weaker periodicity and GP fit finds large jitter – **less useful?**

Gaussian process fit hyperparameter comparison

- The GP period (~P_{rot}) agrees across datasets
- GP evolutionary timescale (spot evolution[16,20]) differs: TESS and HPF FWHM favor shorter, while RVs favor longer (*right*).
- From cadence? Or different response to surface changes?



Jitter's temporal and chromatic evolution



- Above: estimated jitter semi-amplitude for each rotation harmonic signal
- **Jitter in both signals is: smaller in NIR & decreases between seasons**
- Visible jitter decreases a lot at both periods, while NIR decreases more so for the "larger" signal than the "smaller" signal
- CARMENES jitter from years prior falls in the middle of above curves[21]

Future work and open questions

- Additional data to include: APF Ca H & K for activity indicator in visible
  - Search archival data (including CARMENES DR1[21])
- Think about: multidimensional GP fit with instruments of different wavelengths and activity indicators that are related but not equal
  - Happy to discuss! (e.g. chromatic GP kernel[22])
- Analyze other targets: we have APF/HPF data for a handful of other active stars. Other significant campaigns: M-dwarfs AD Leo and OT Ser

References

[1] Reiners+ 2010, [2] Robertson+ 2020, [3] Tran+ 2021, [4] Lagrange+ 2010, [5] Shapiro+ 2014, [6] Shkolnik+ 2009, [7] Díez Alonso+ 2019, [8] Schöfer+ 2022, [9] Jeffers+ 2022, [10] Roques 1955, [11] Schmitt 1994, [12] Paudel+ 2021, [13] Vogt+ 2014, [14] Mahadevan+ 2014, [15] Roberts+ 2012, [16] Haywood+ 2014, [17] Barragán+ 2022, [18] Aigrain+ 2012, [19] Isaacson & Fischer 2010, [20] Rajpaul+ 2015, [221] Ribas+ 2023, [22] Cale+ 2021