Seeing Double:

RVs Lagging Behind Magnetic Activity Indicators in HD 26965

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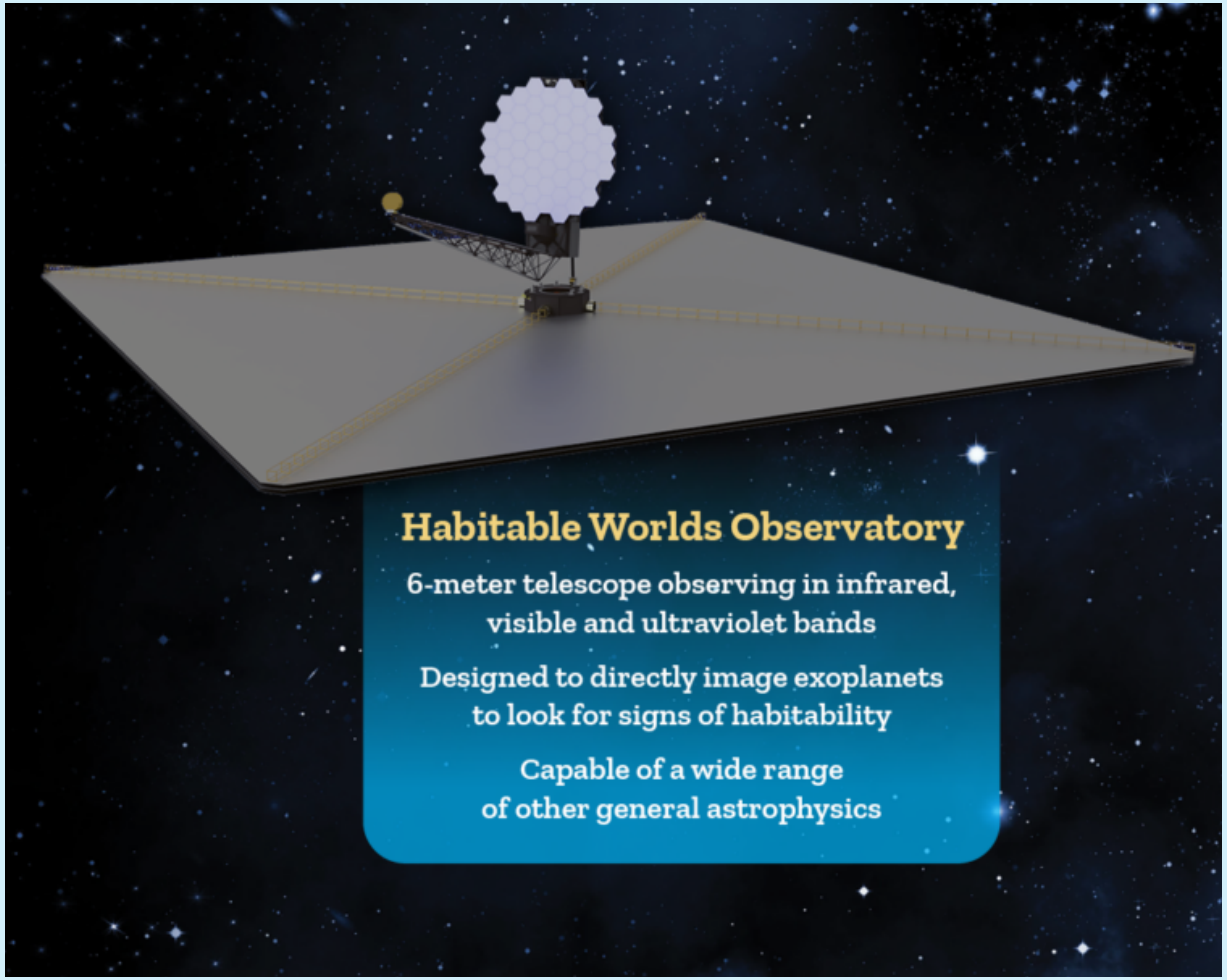
In collaboration with: Lily Zhao, Jared Siegel, Christian Gilbertson, Sam Halverson, Paul Robertson, the NEID science team, the EXPRES team

The Need for Extreme Precision Radial Velocities (EPRV)



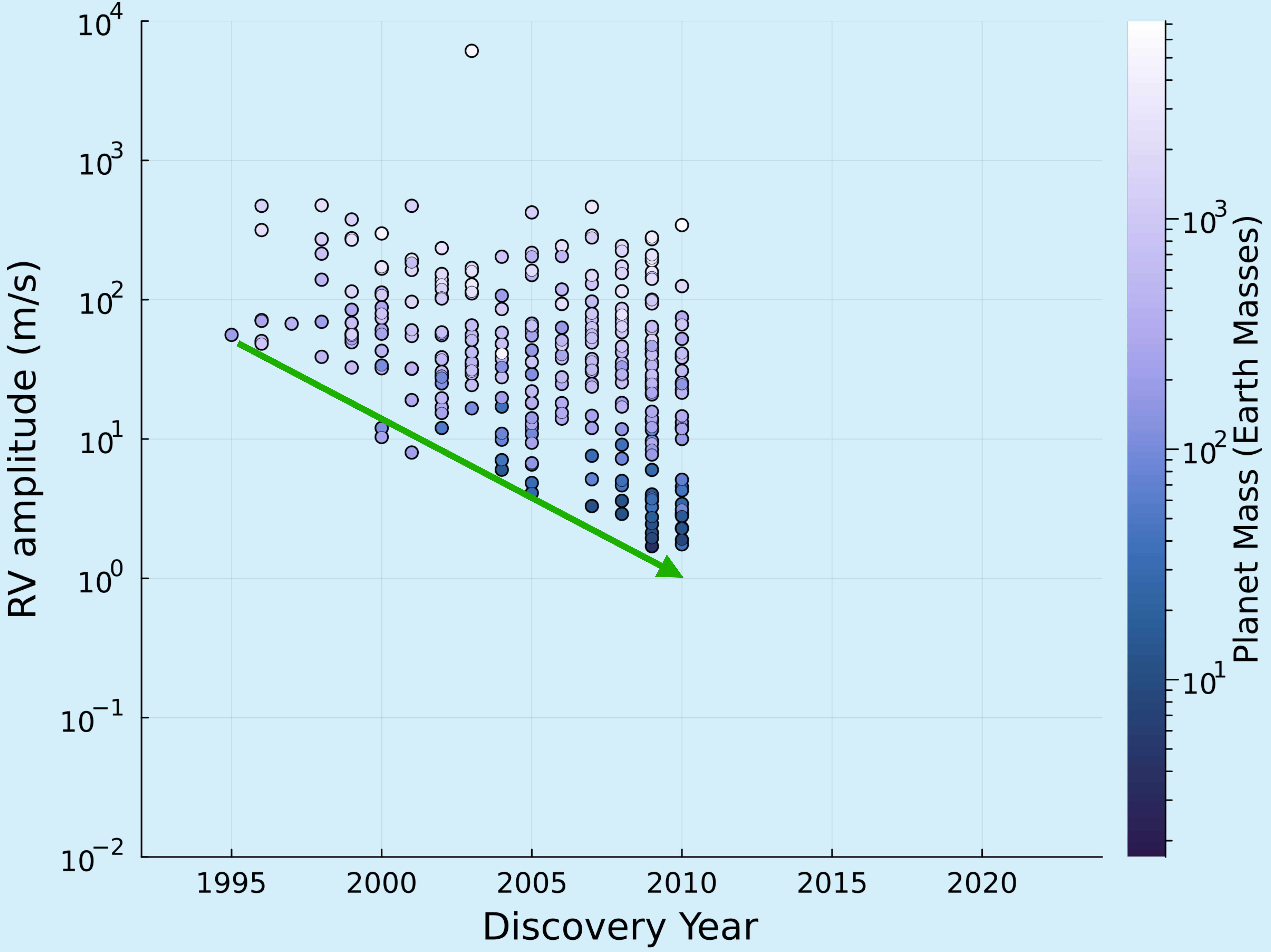
A vetted list of well-characterized planets will be critical for HWO success:

1. Improved efficiency over a blind direct imaging search

2. Precise masses are essential for distinguishing between **atmospheric models** (< 20%) & determining **planet composition** (<10%)

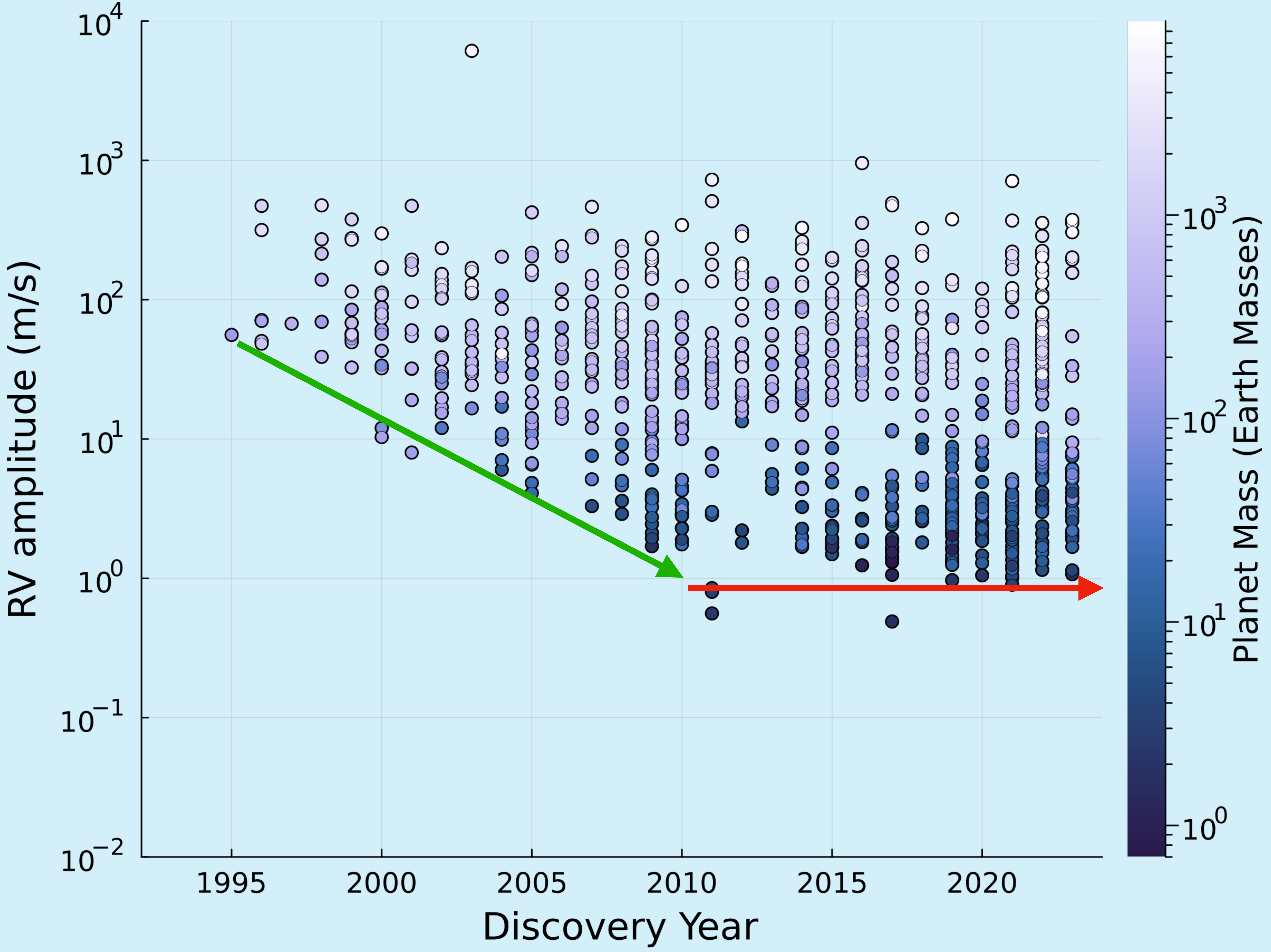
Batalha et al. (2019), Valencia et al. (2007)

Radial Velocity Detections



Adapted from Anna John et al. (2023)

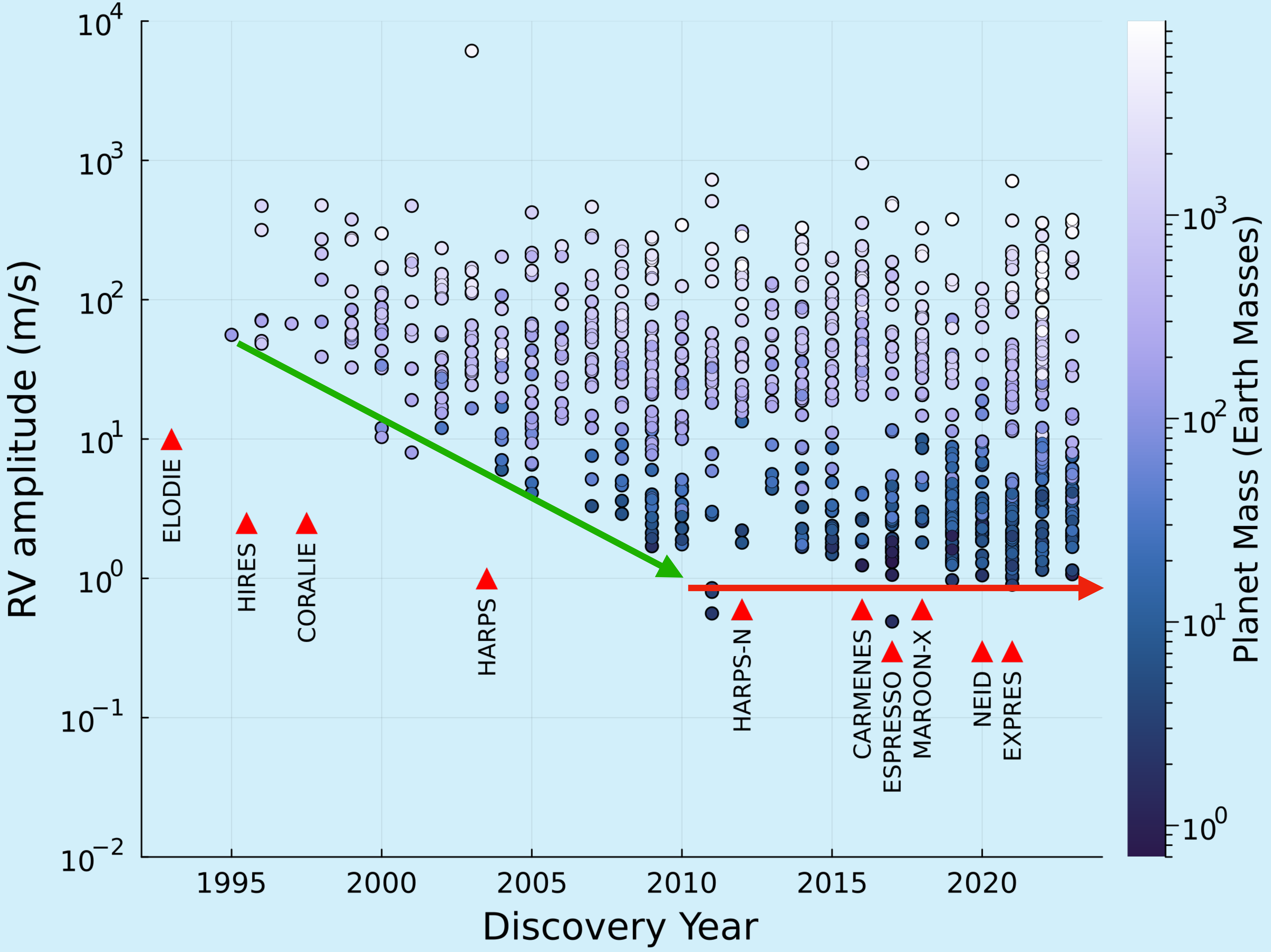
Radial Velocity Detections



RV discoveries at the
sub-m/s level remain elusive

Adapted from Anna John et al. (2023)

Radial Velocity Detections

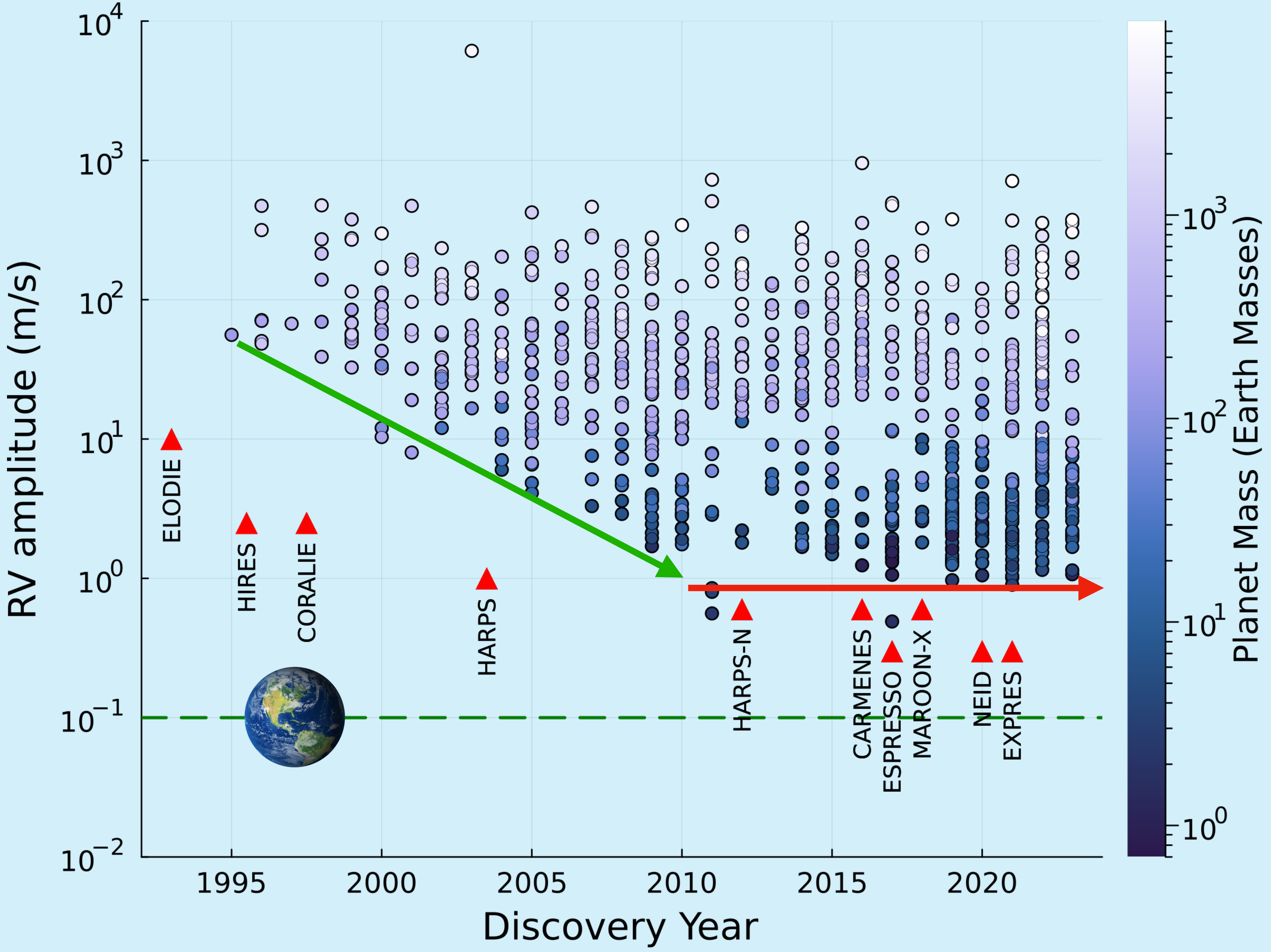


RV discoveries at the sub-m/s level remain elusive

…even in the EPRV era

Adapted from Anna John et al. (2023)

Radial Velocity Detections



RV discoveries at the sub-m/s level remain elusive

…even in the EPRV era

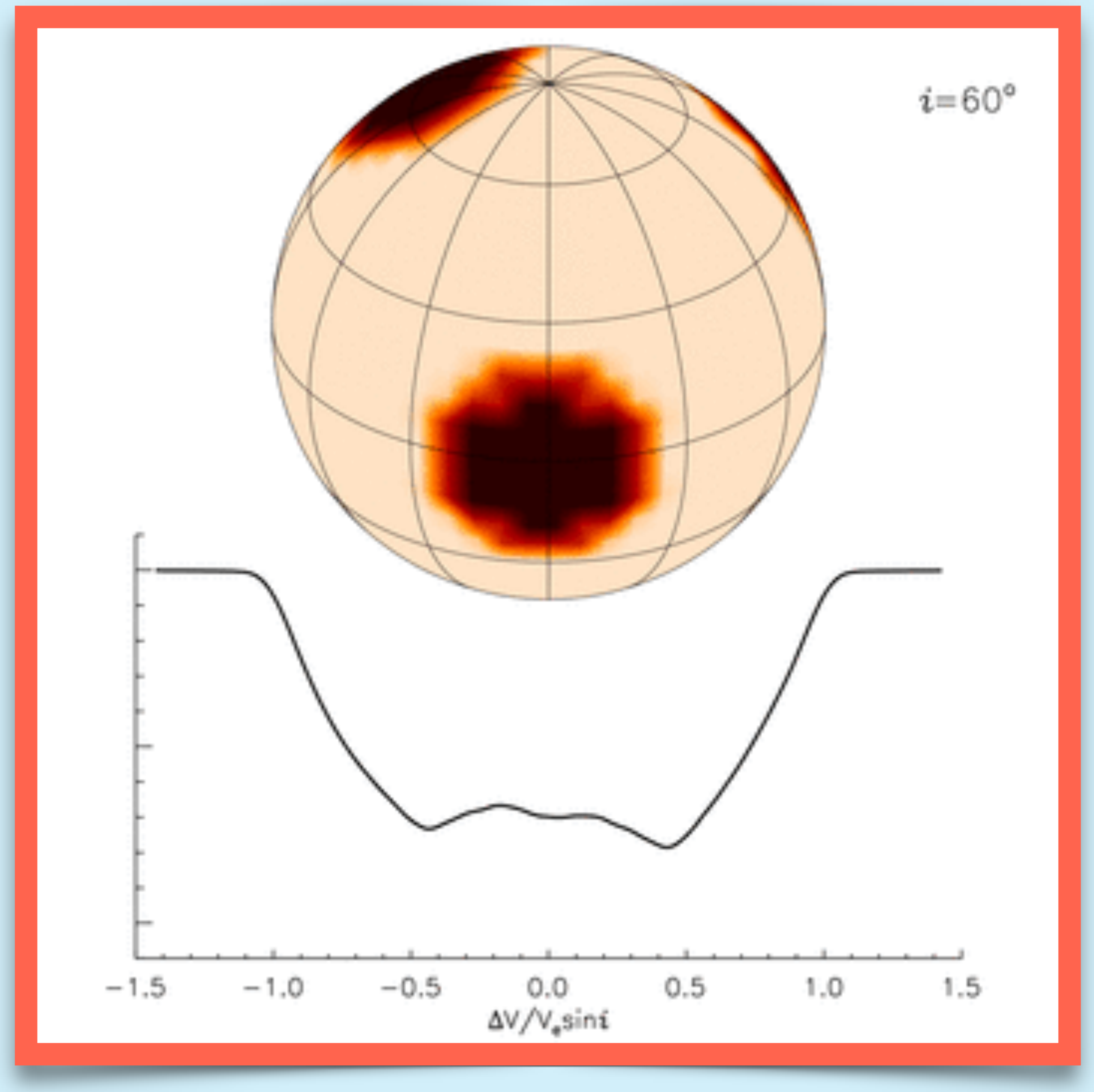
Adapted from Anna John et al. (2023)

Earth-analog detections are no longer limited by instrumental precision, but instead by **intrinsic stellar variability**

A finding of the EPRV Working Group Report (Crass et al. 2021), echoed in Luhn et al. (2023)

The Challenge of Stellar Variability

Magnetic activity

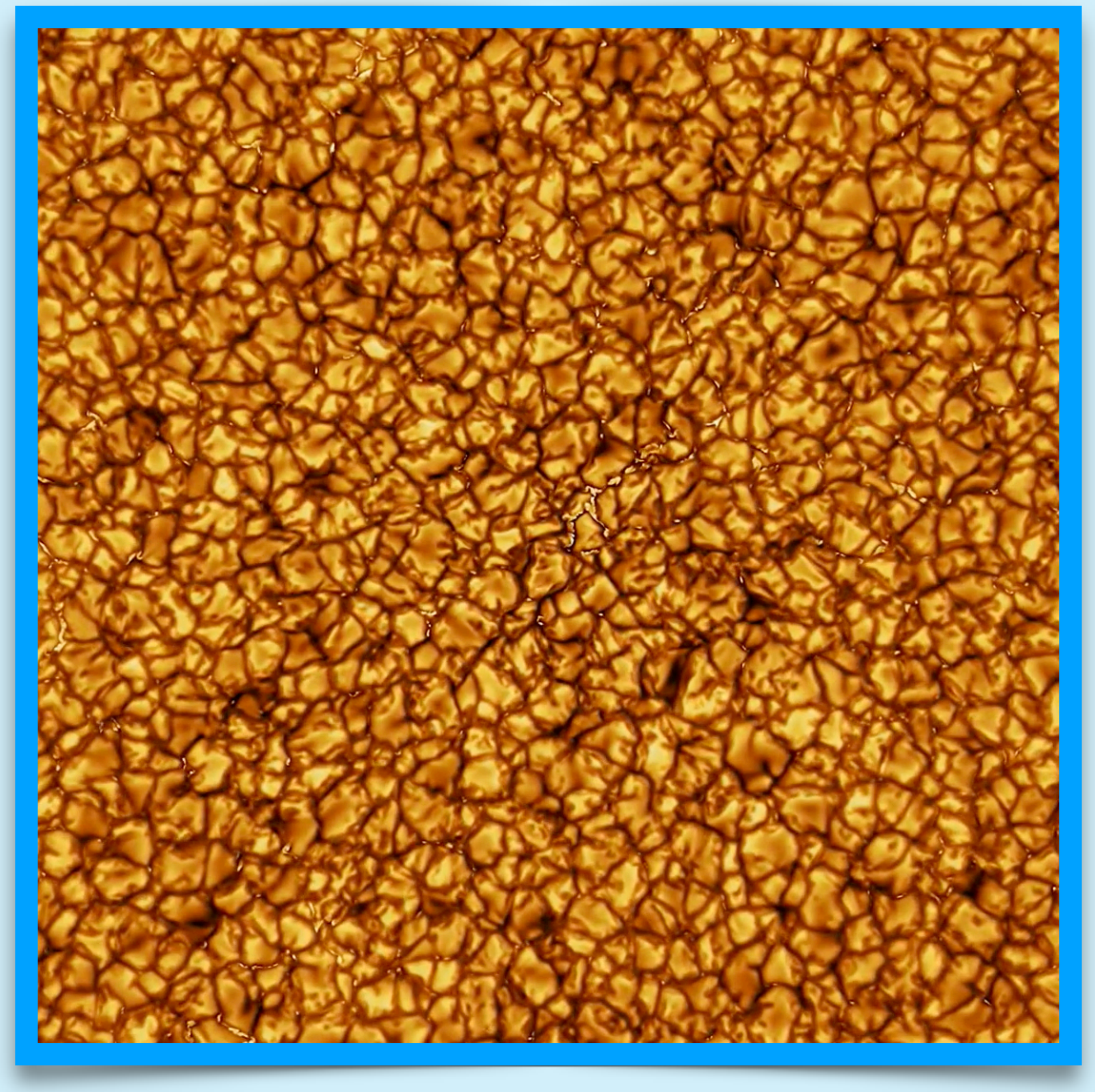


https://www.physics.uu.se

days/months/years

1–10+ m/s

Granulation

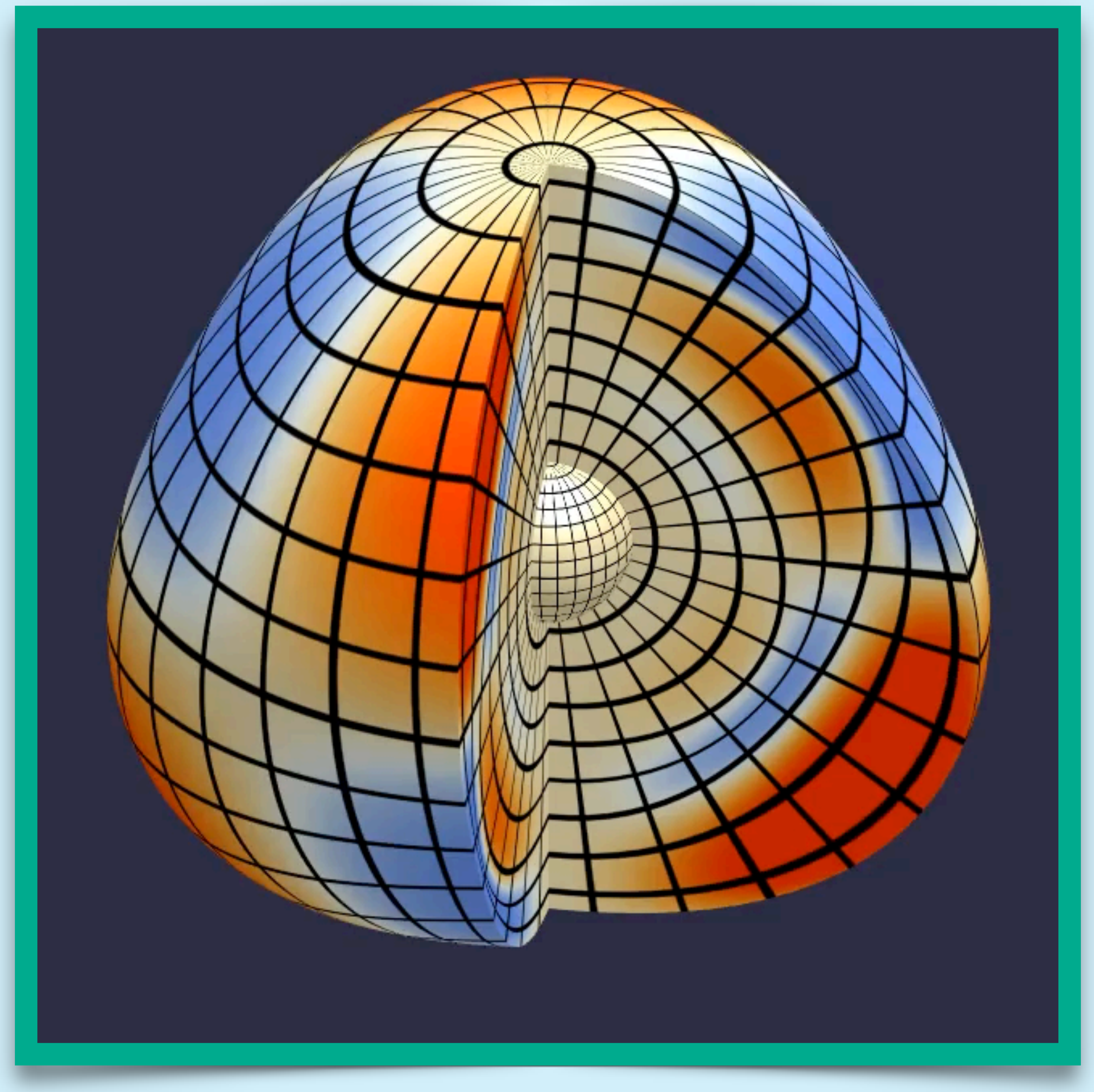


DKIST, NSO/NSF/AURA

minutes–hours

0.3–1+ m/s

Oscillations

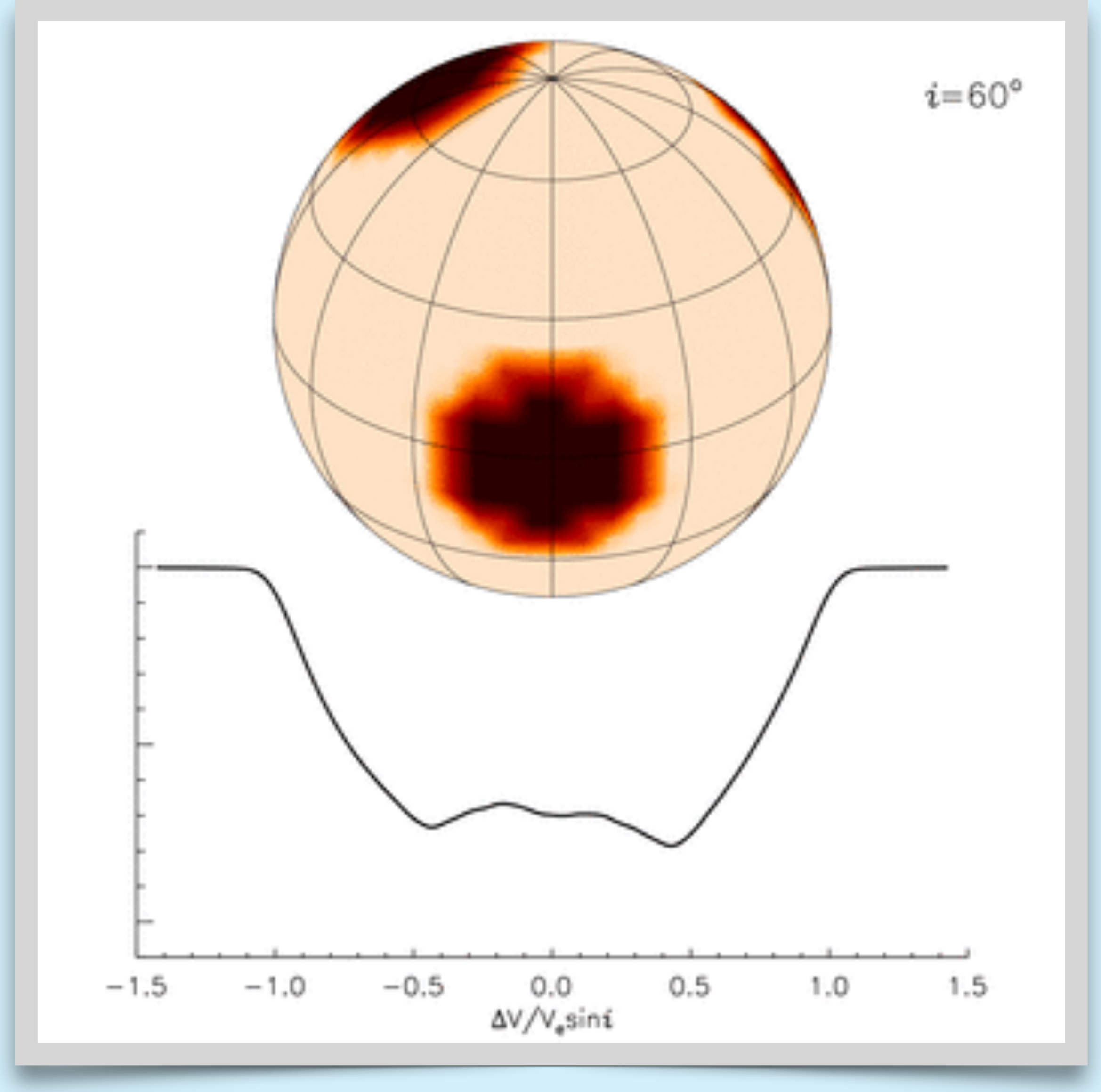
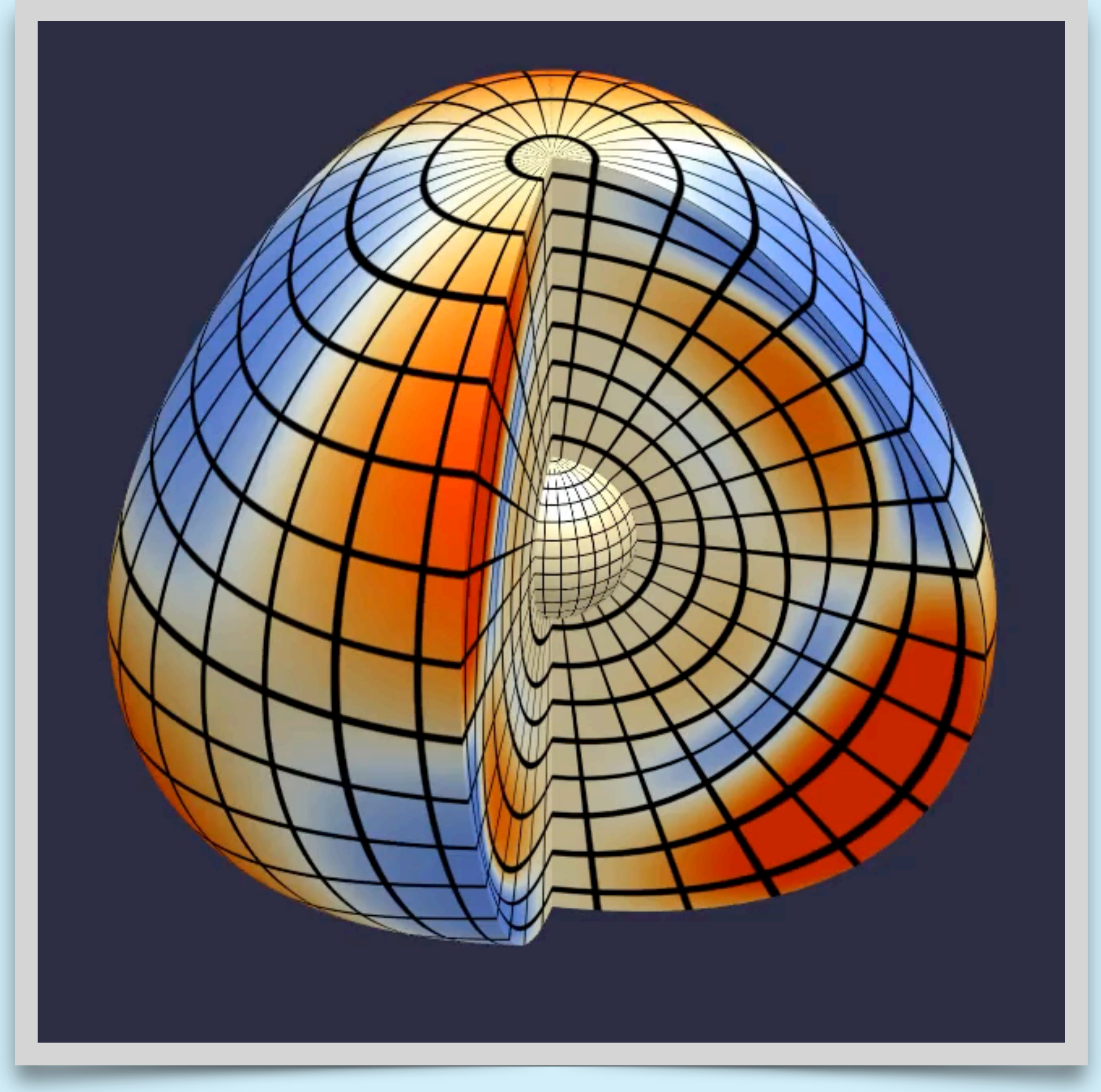


Victoria Antoci, asteroSTEP

minutes

< 1 m/s

Overcoming Stellar Variability

Magnetic activity	Granulation	Oscillations
		

Magnetic activity

Activity indicators
Bonfils+ (2007), Robertson+ (2014)

Gaussian processes
Haywood+ (2014), Rajpaul+ (2015), Jones+ (2017)

Line morphology
Collier Cameron+ (2021), Gilbertson+ (2023)

Line-by-line RVs
Dumusque (2018), Cretignier+ (2020), Wise+ (2022)

Granulation

Binning observations
Dumusque+ (2011)

Line morphology
Collier Cameron+ (2021), Gilbertson+ (2023)

Oscillations

Exposure time averaging
Chaplin+ (2019)

see de Beurs+ (2023) for a good summary

The EXPRES Stellar Signals Project

Zhao et al. (2022)

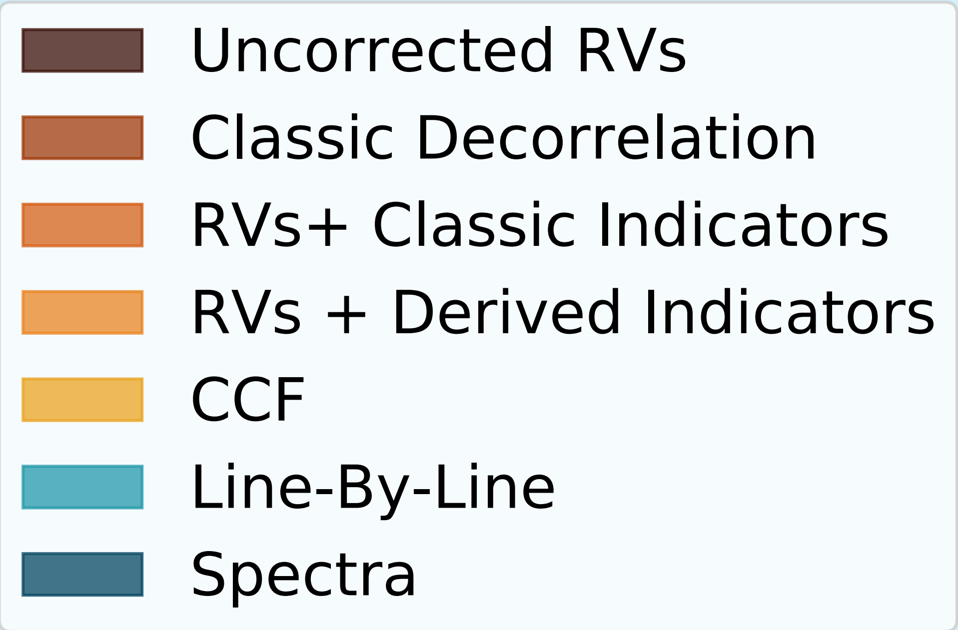
A community data challenge to assess techniques for mitigating stellar variability

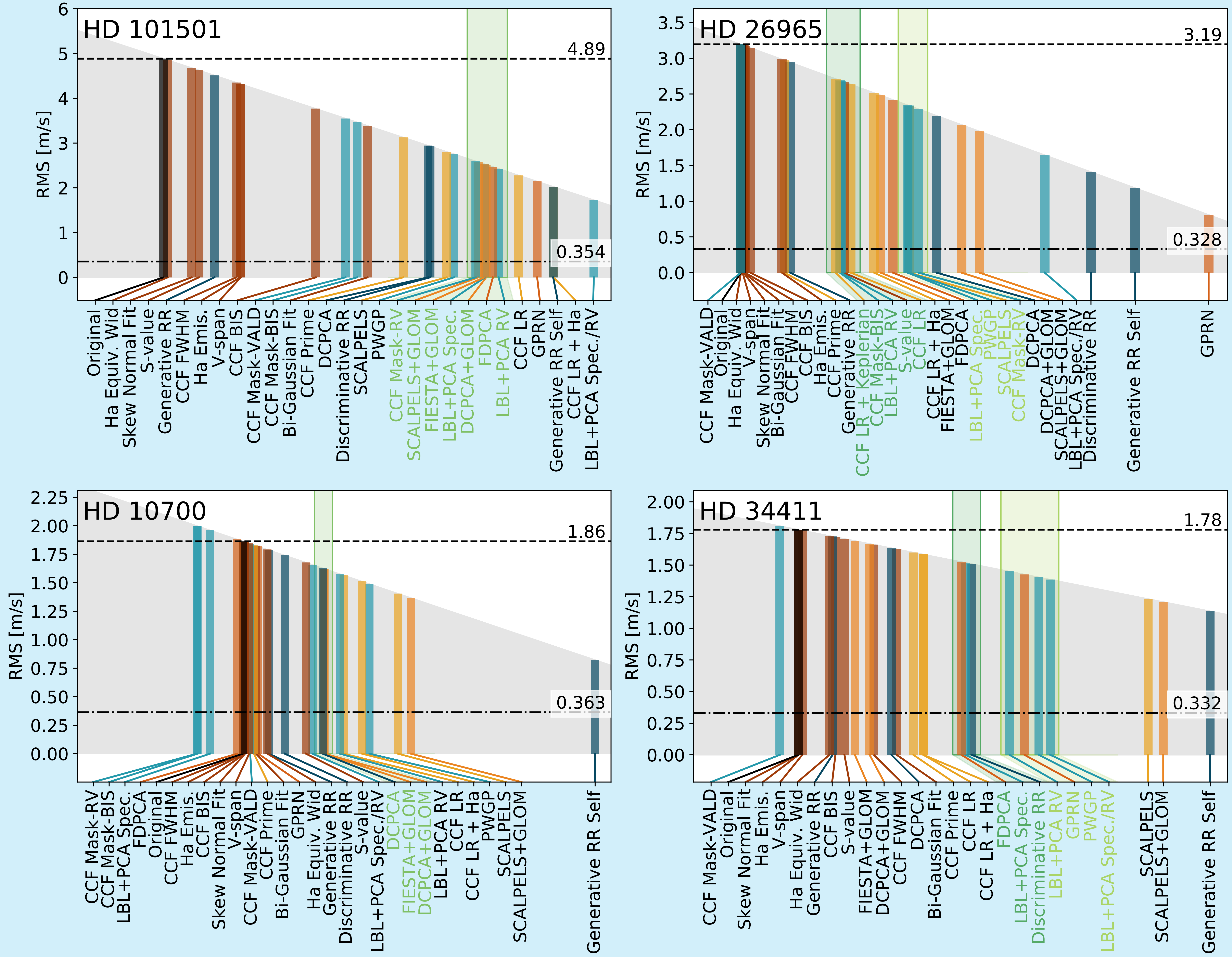
4 EXPRES targets

20+ mitigation techniques

The EXPRES Stellar Signals Project

Zhao et al. (2022)





Methods disagree on amplitude/ timescales associated with variability for each star

Performance of methods is inconsistent from star to star

The Case for High-fidelity Variability Data Sets

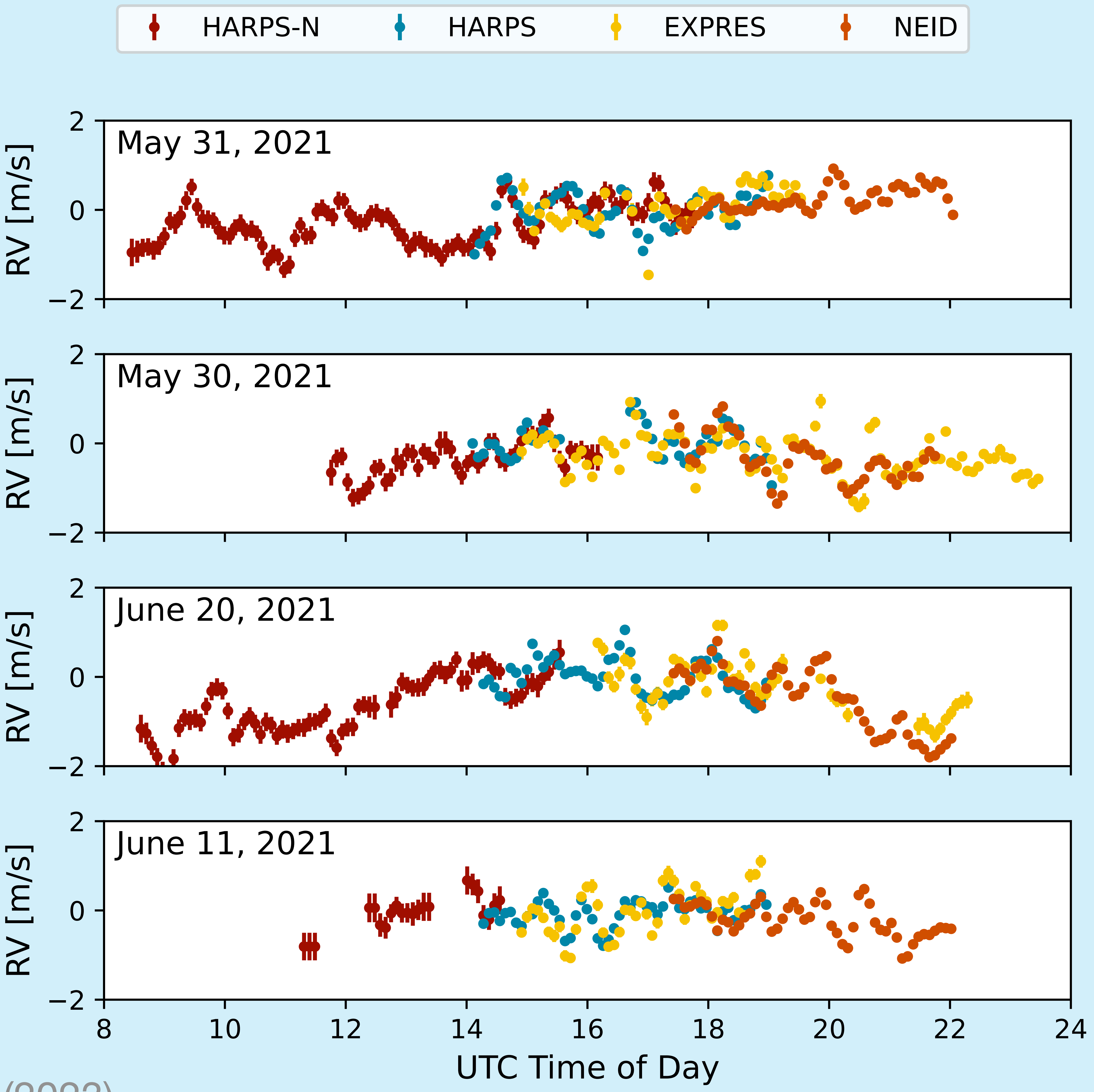
In the EPRV era, we have:

Requisite precision & stability to resolve sub-m/s variability

New probes of stellar variability (CCF morphology, LBL diagnostics)

Ultimately allow unprecedented views of how stellar variability affect spectra

The Case for High-fidelity Variability Data Sets



Zhao et al. (2023)

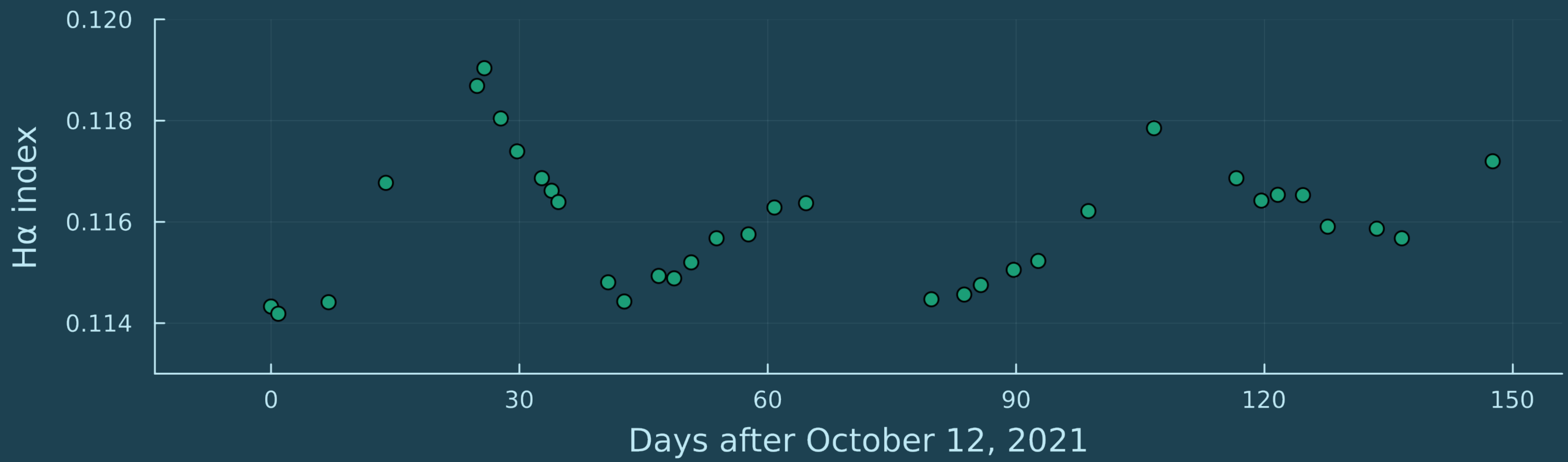
...beyond the Sun

Solar data have set the stage for these detailed analyses

We will want similar data sets for testing on other stars

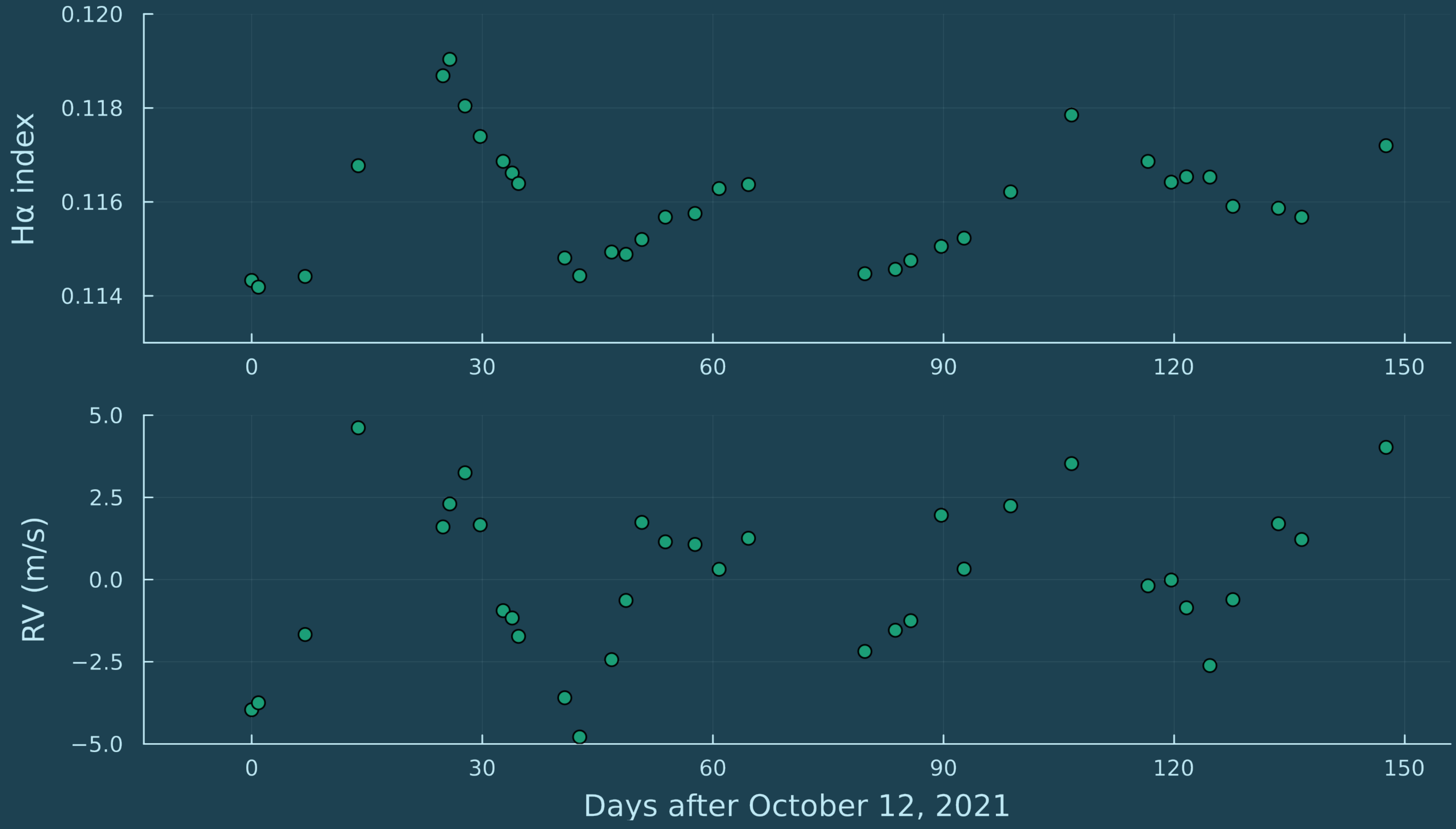
Magnetic activity on rotation timescales in HD 26965

A very active time series



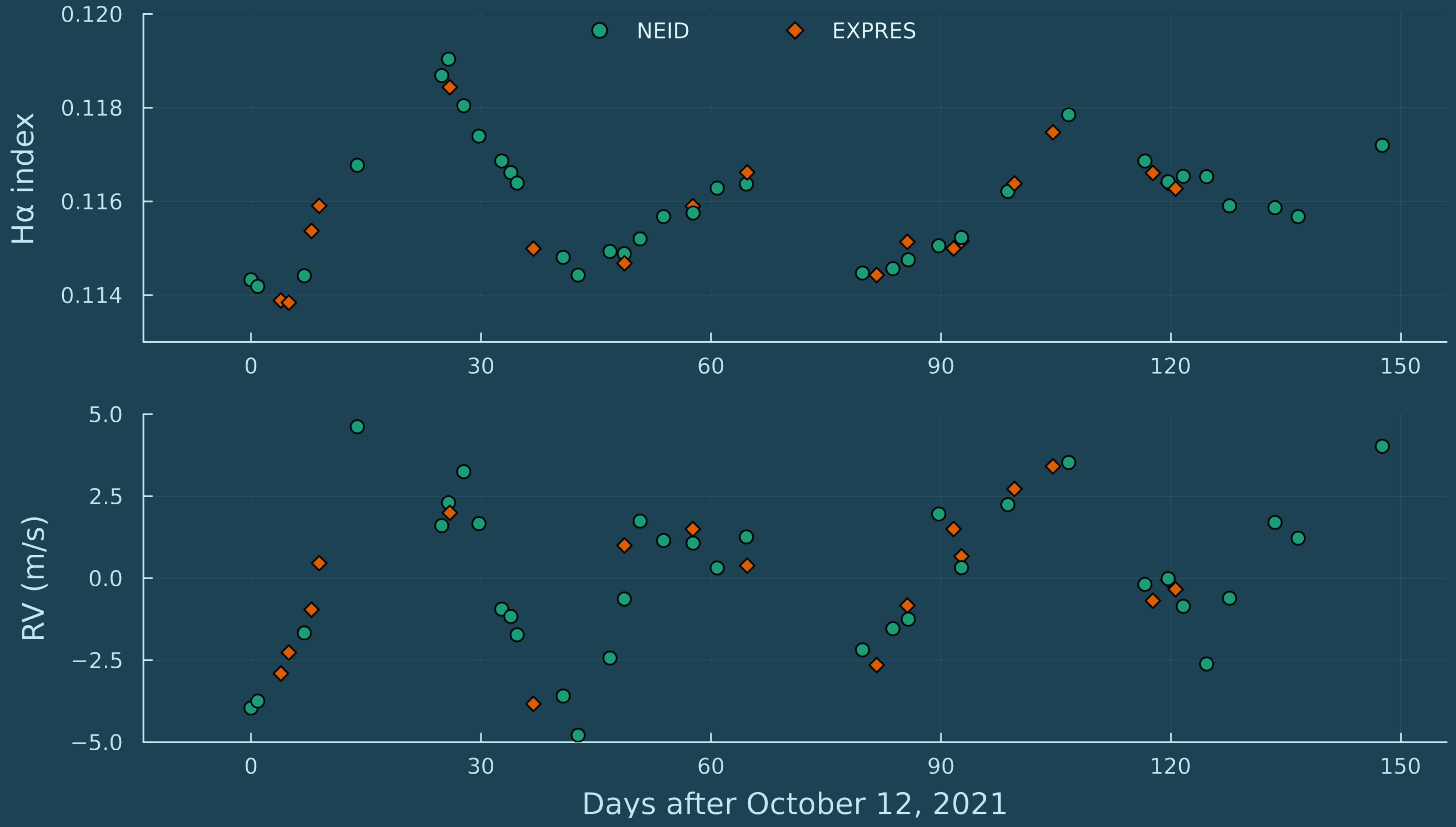
NEID observations show clean activity signal…

A very active time series



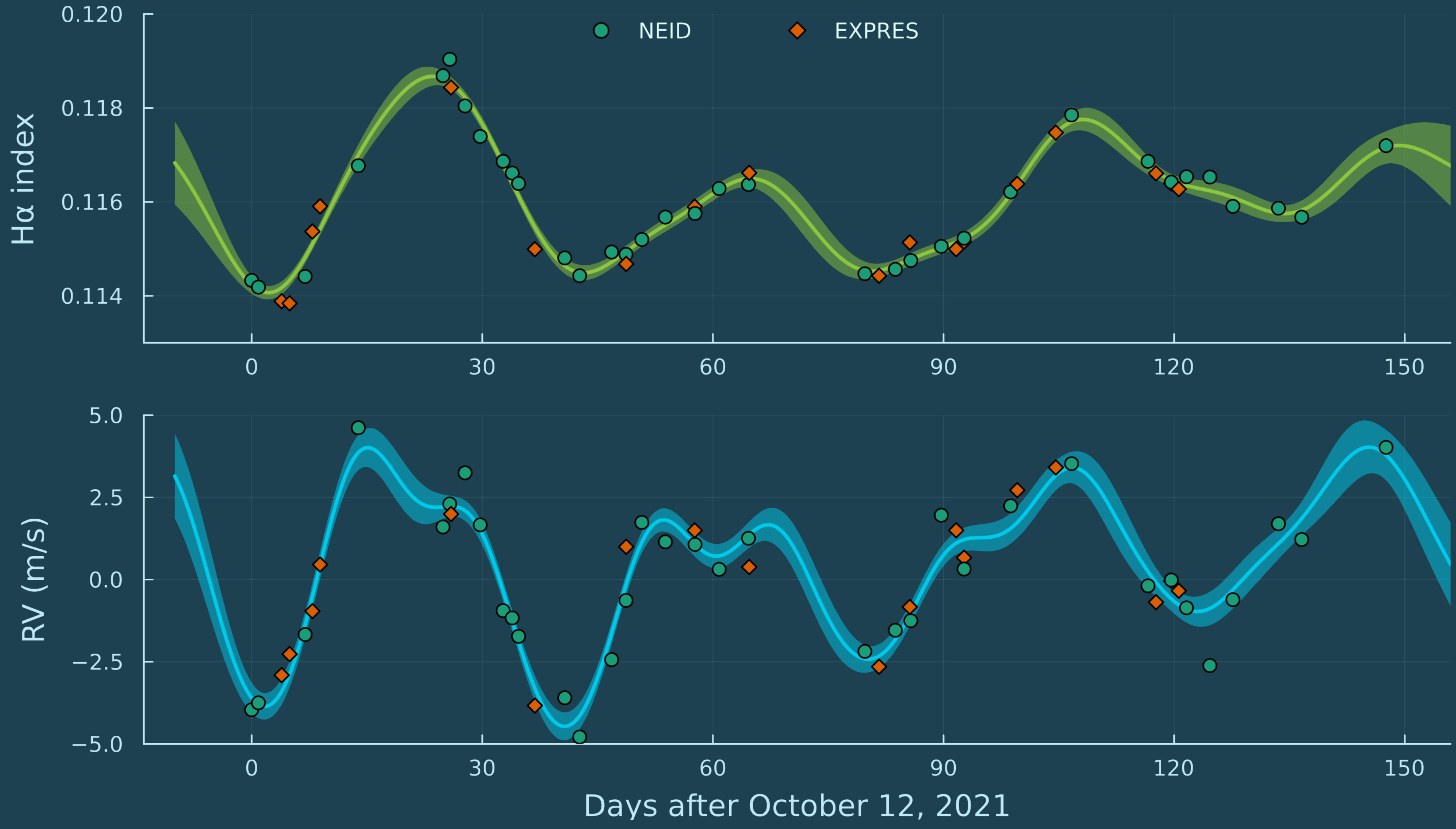
NEID observations show clean activity signal…also seen in the RVs…

A very active time series



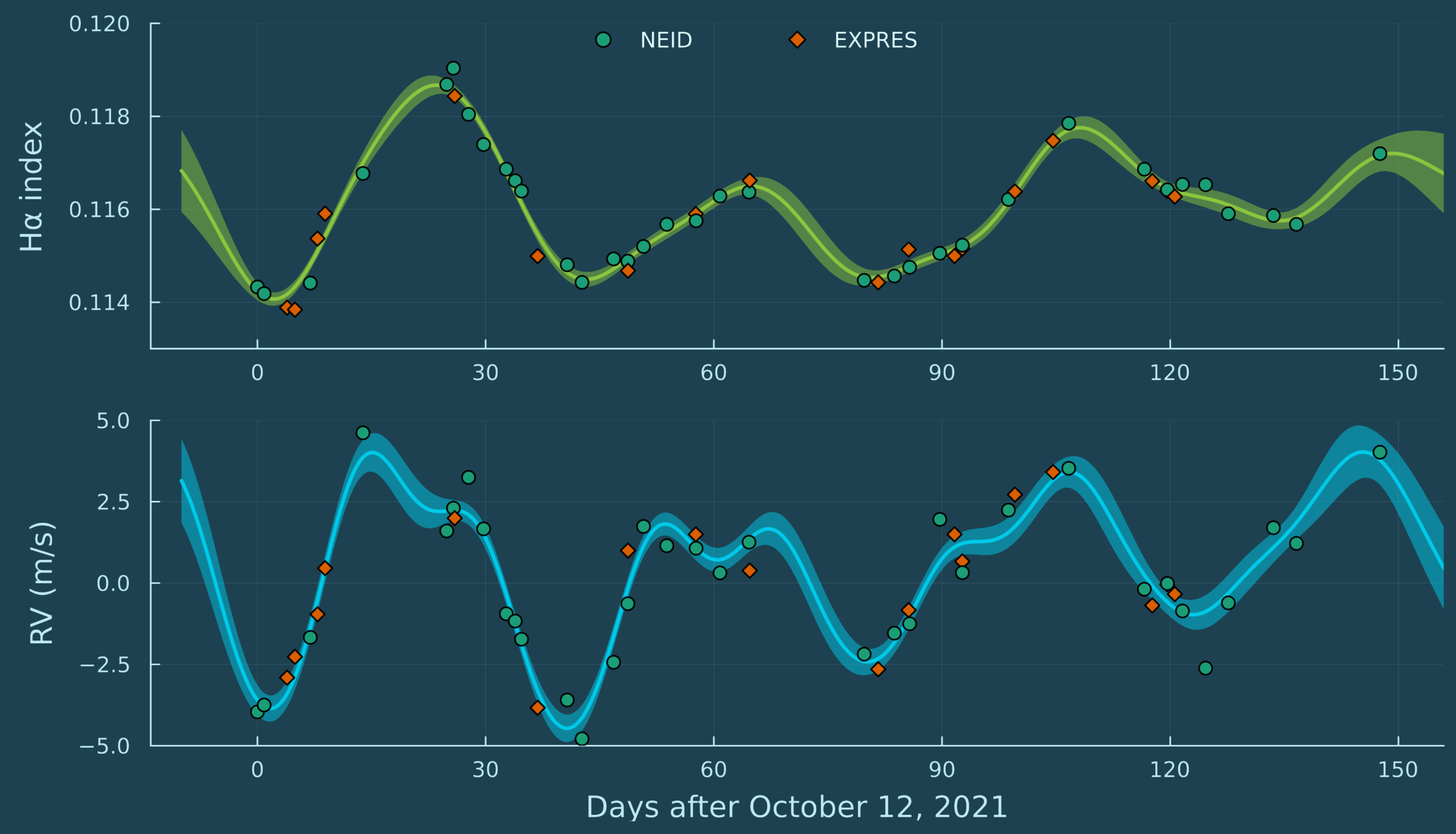
NEID observations show clean activity signal…also seen in the RVs…and matched by EXPRES!

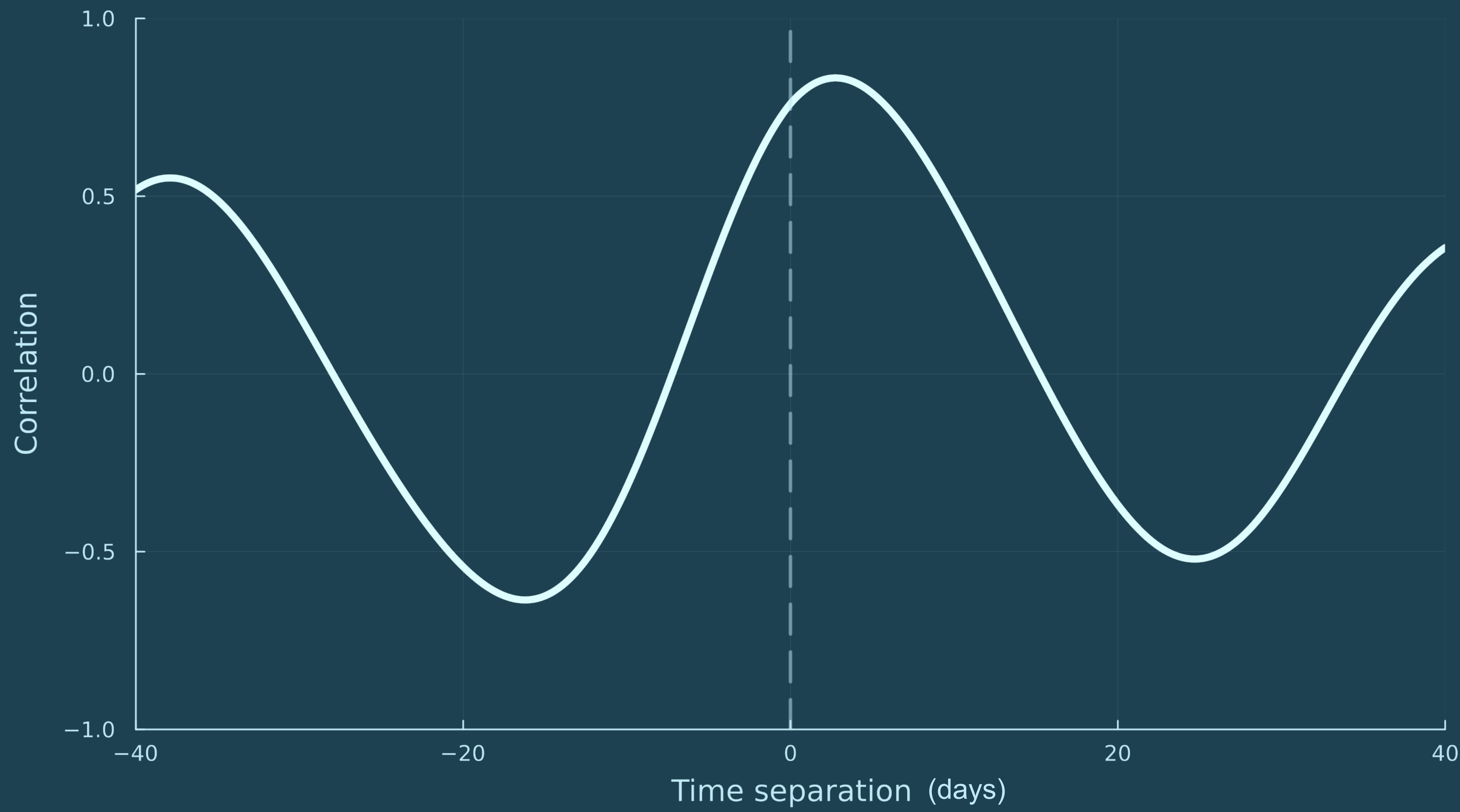
A very active time series



NEID observations show clean activity signal…also seen in the RVs…and matched by EXPRES!

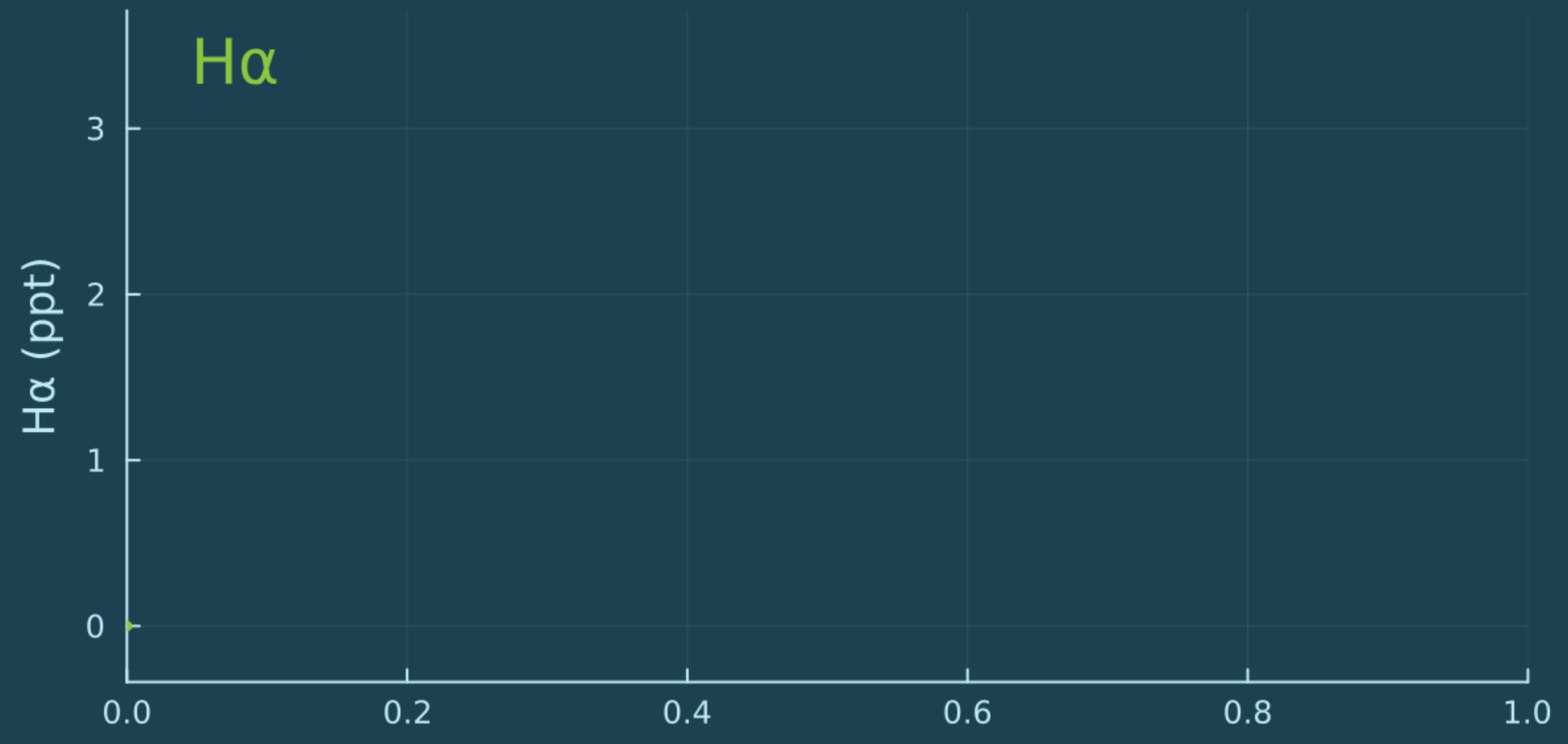
A correlated signal





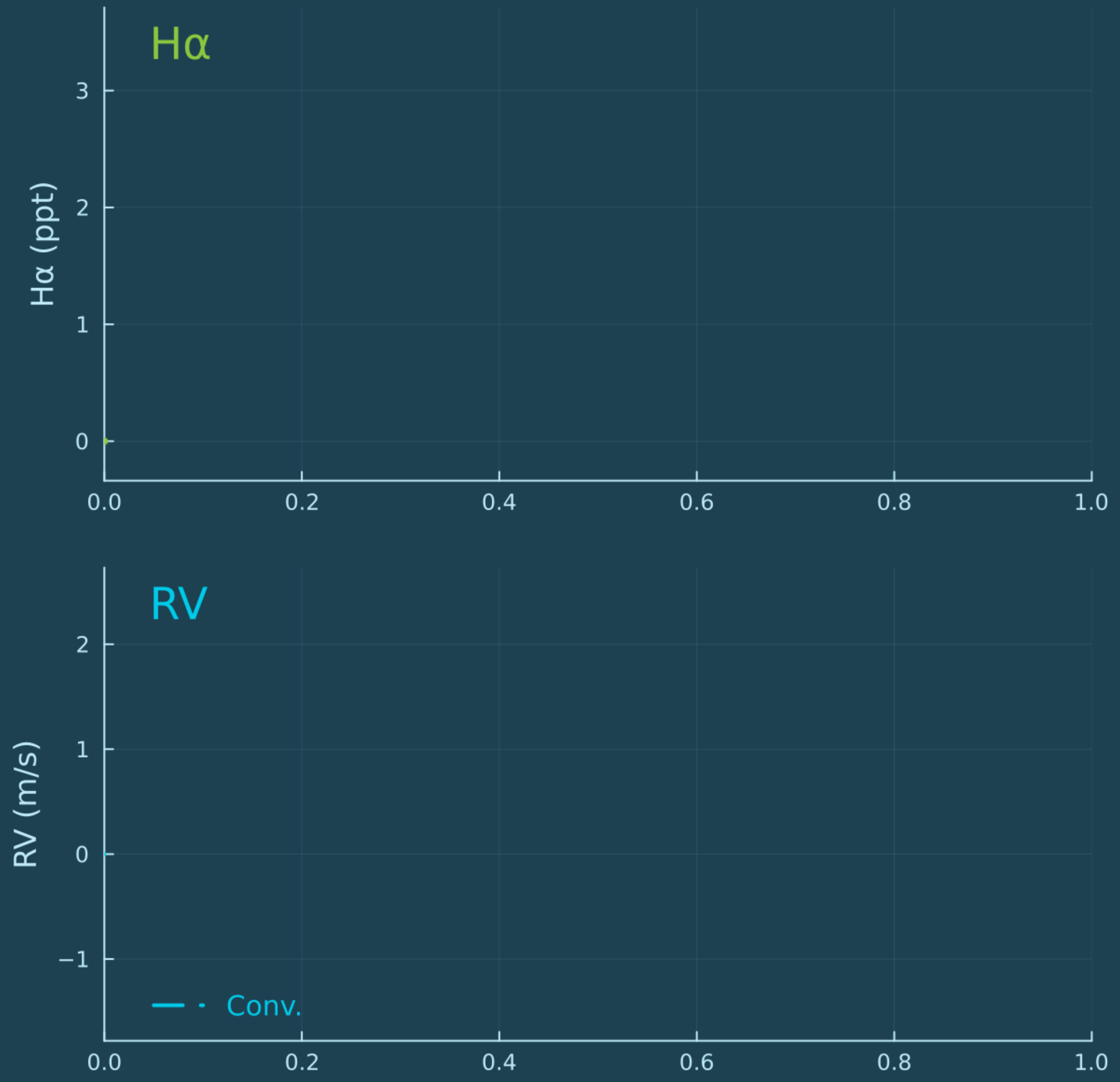
RVs are correlated, but indicate a several day time lag

A simple spot model



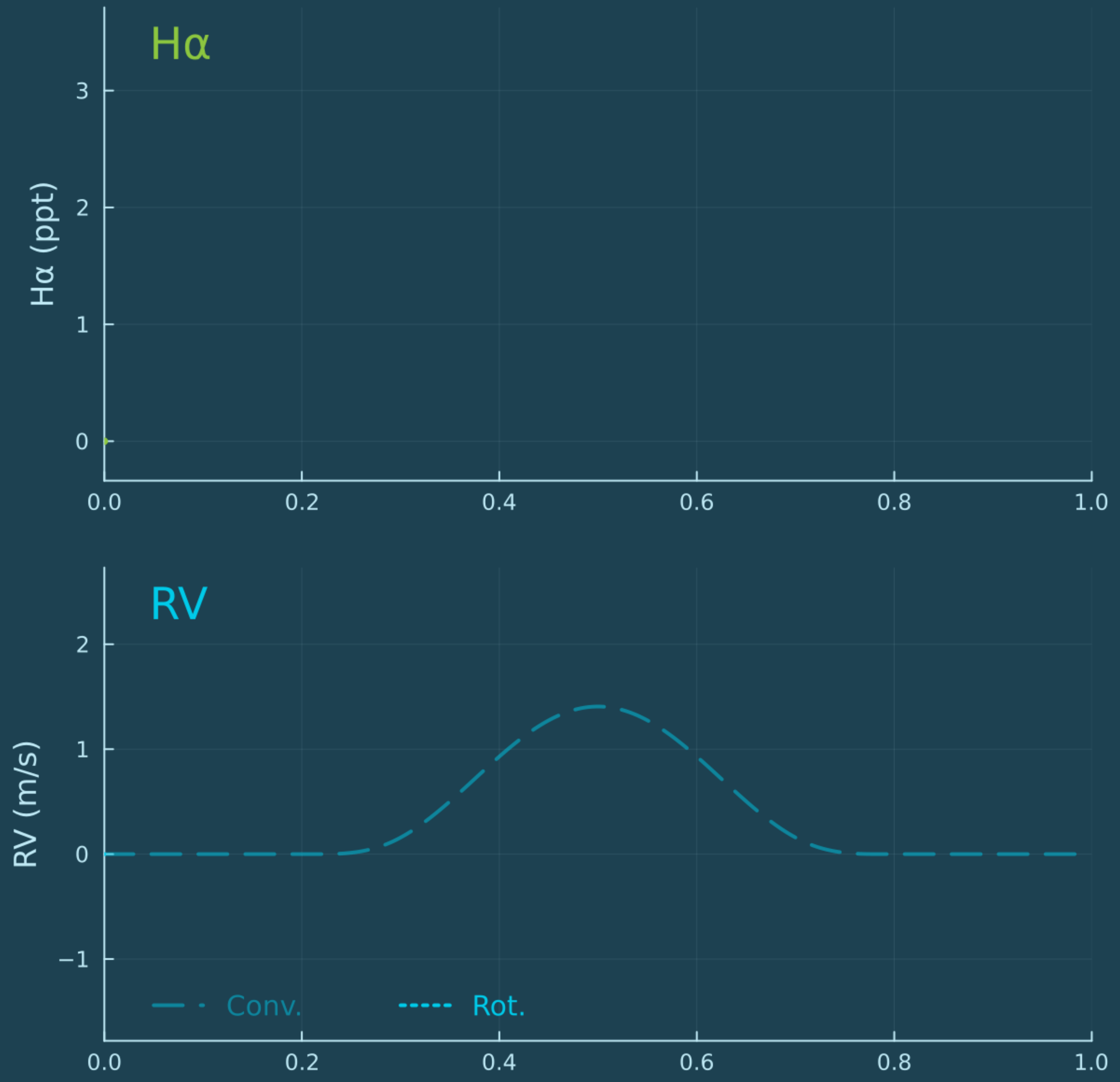
Traditional activity indicators trace global magnetic fields

A simple spot model



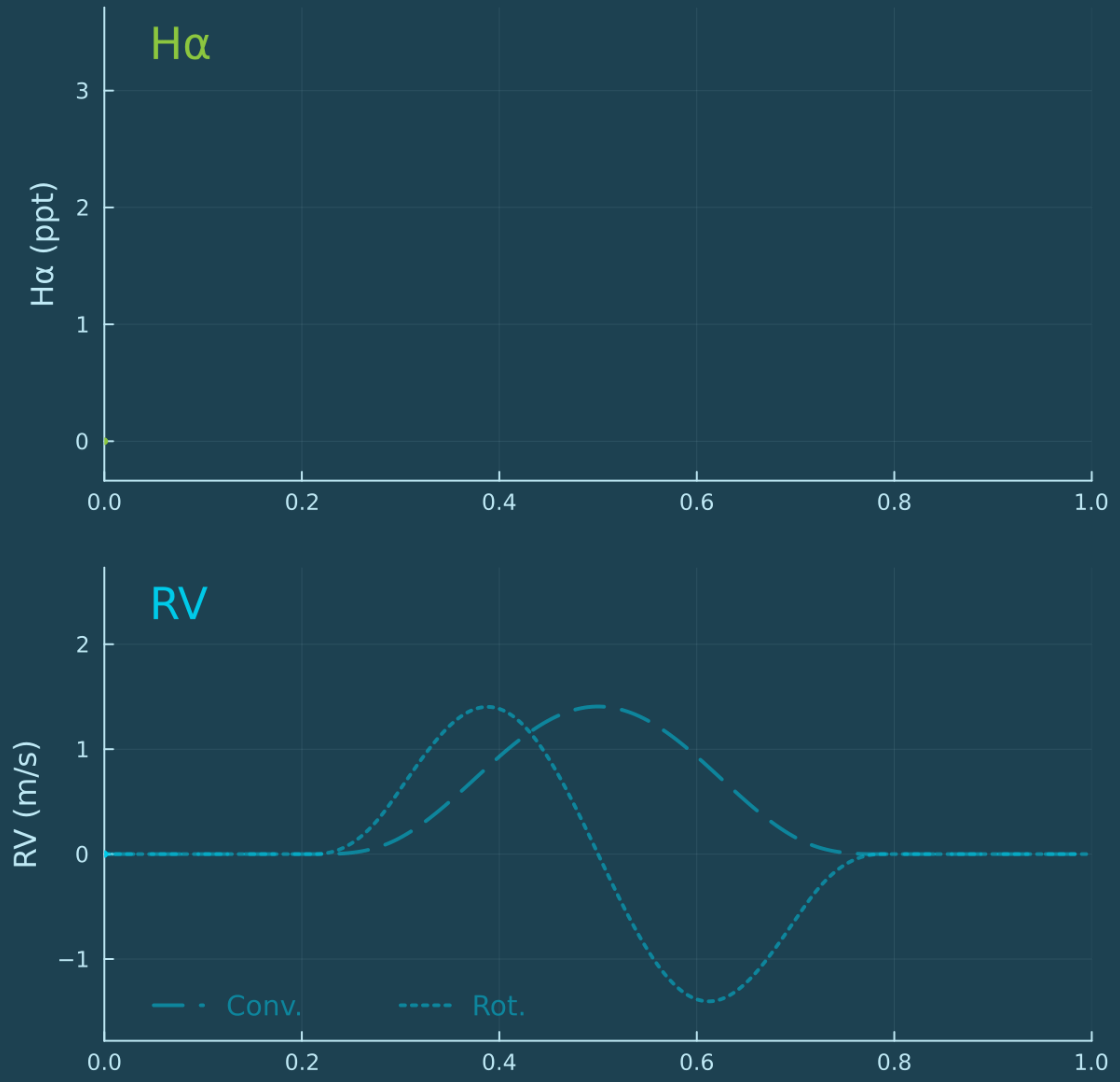
Magnetic fields inhibit local convection & reduce the net convective blue-shift

A simple spot model



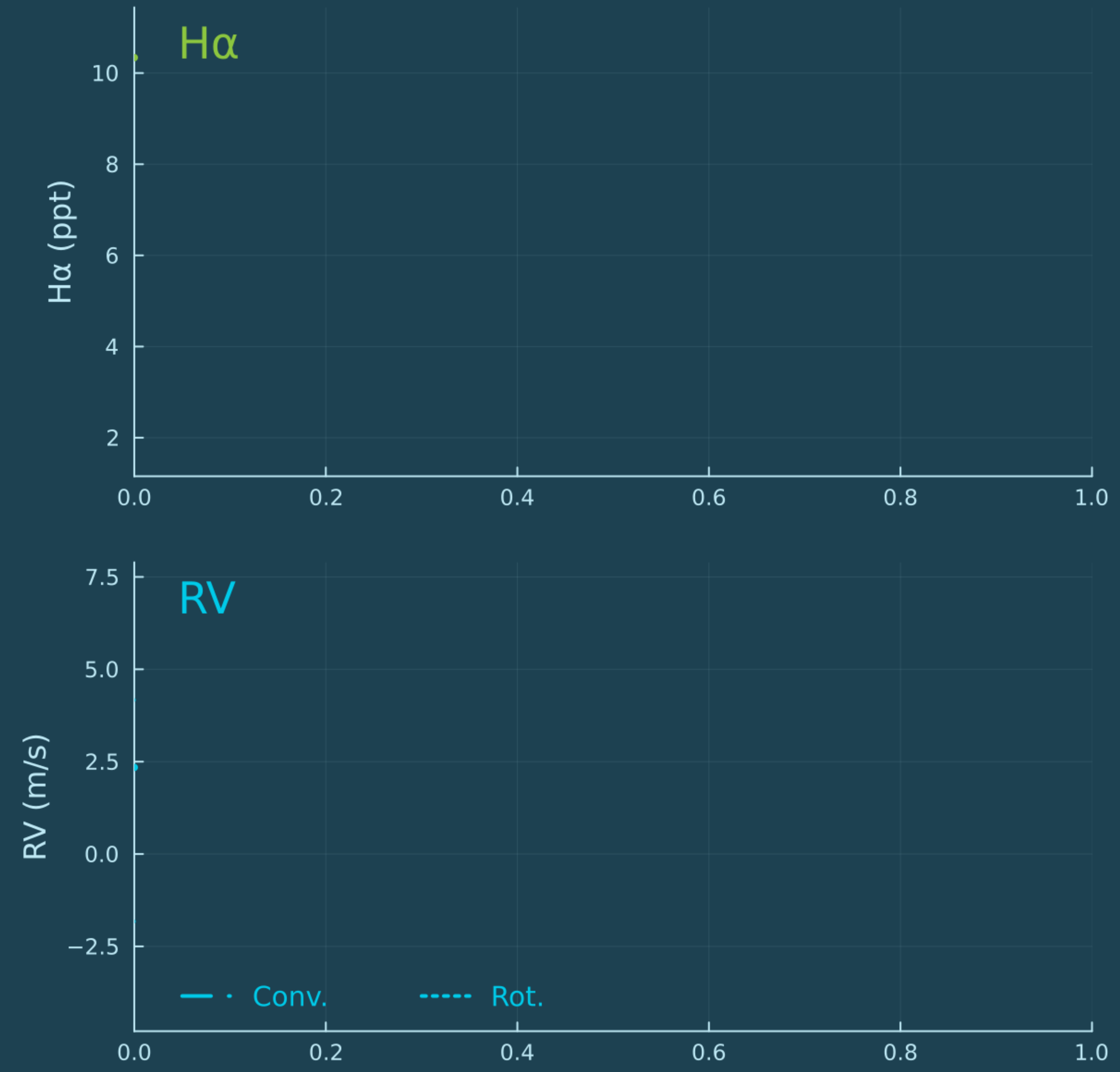
Spots perturb rotational symmetry of disk, à la Rossiter-McLaughlin for transiting planets

A simple spot model



RV_c is proportional to activity, and RV_{rot} proportional to its derivative

A simple spot model — multiple spots



More complex spot geometries lead to quasi-periodic behavior

A simple spot model — A GP approach

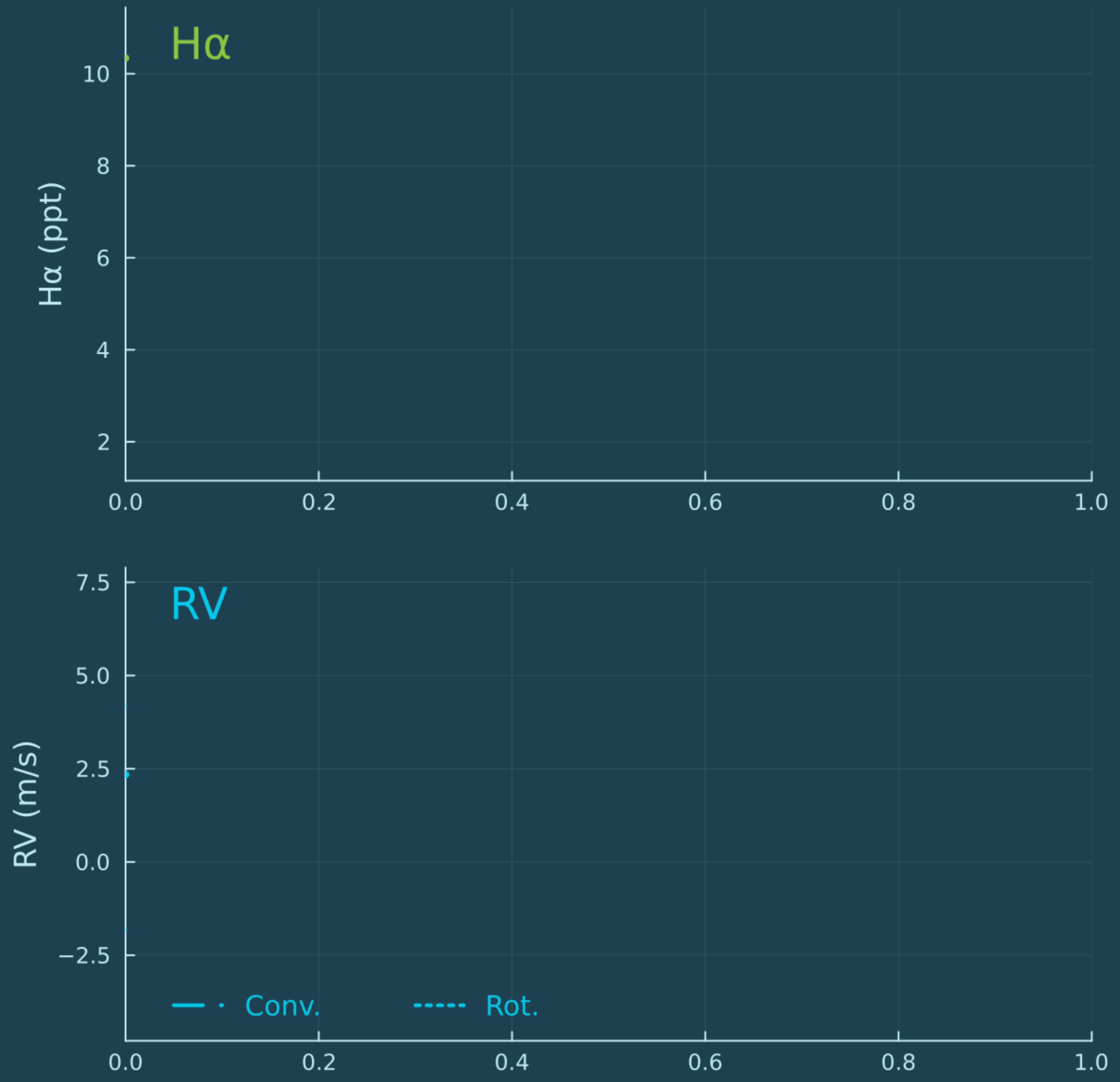
e.g., Rajpaul et al. (2015)

$$H\alpha = a_{10} G(t)$$

$$RV = \underbrace{a_{00} G(t)}_{RV_c} + \underbrace{a_{01} G'(t)}_{RV_{rot}}$$

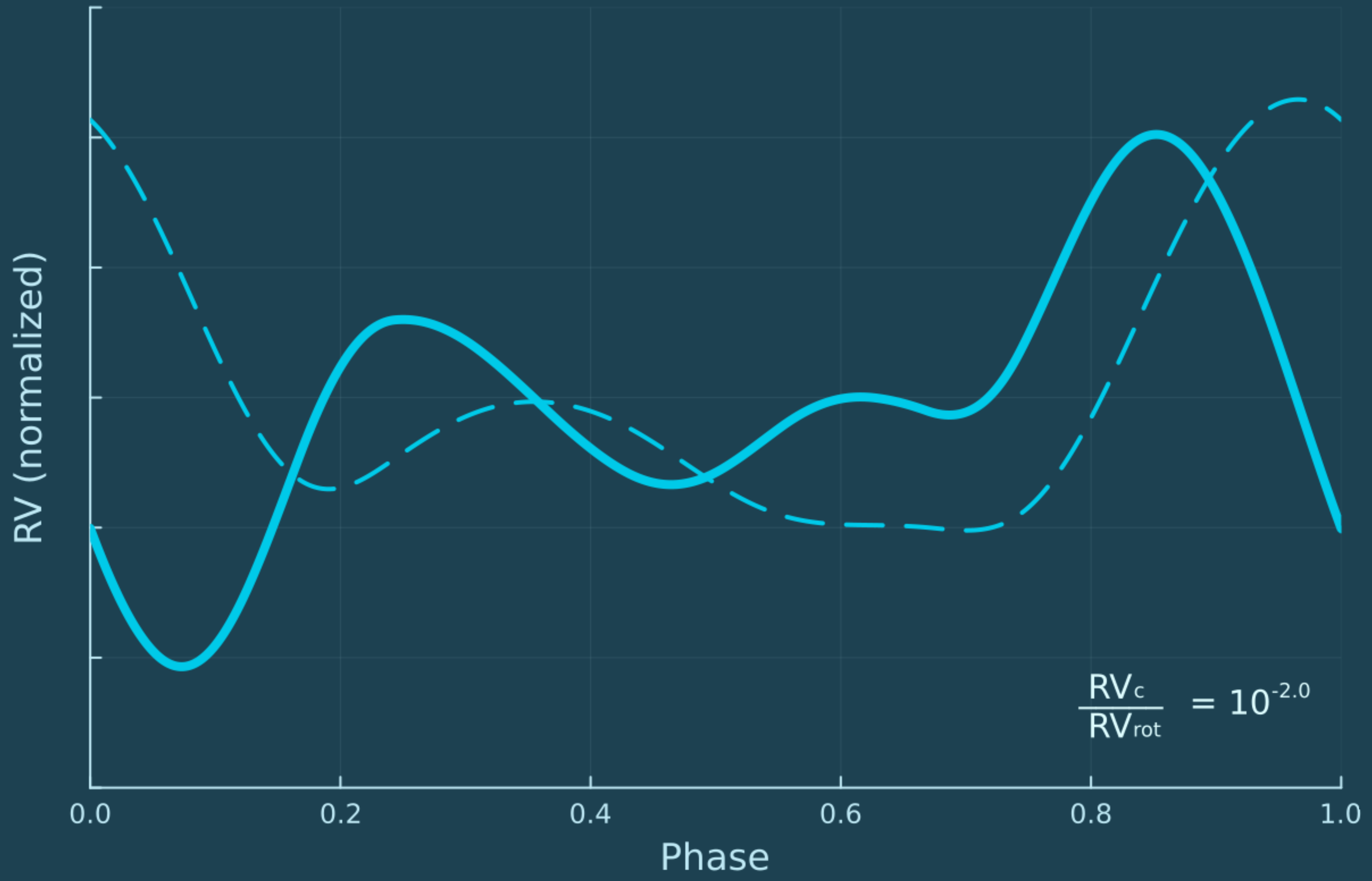
G(t) often chosen as a quasi-periodic GP kernel

A simple spot model — multiple spots



The relative contributions of RV_c and RV_{rot} introduce *apparent time lags*

A simple spot model — apparent time lags



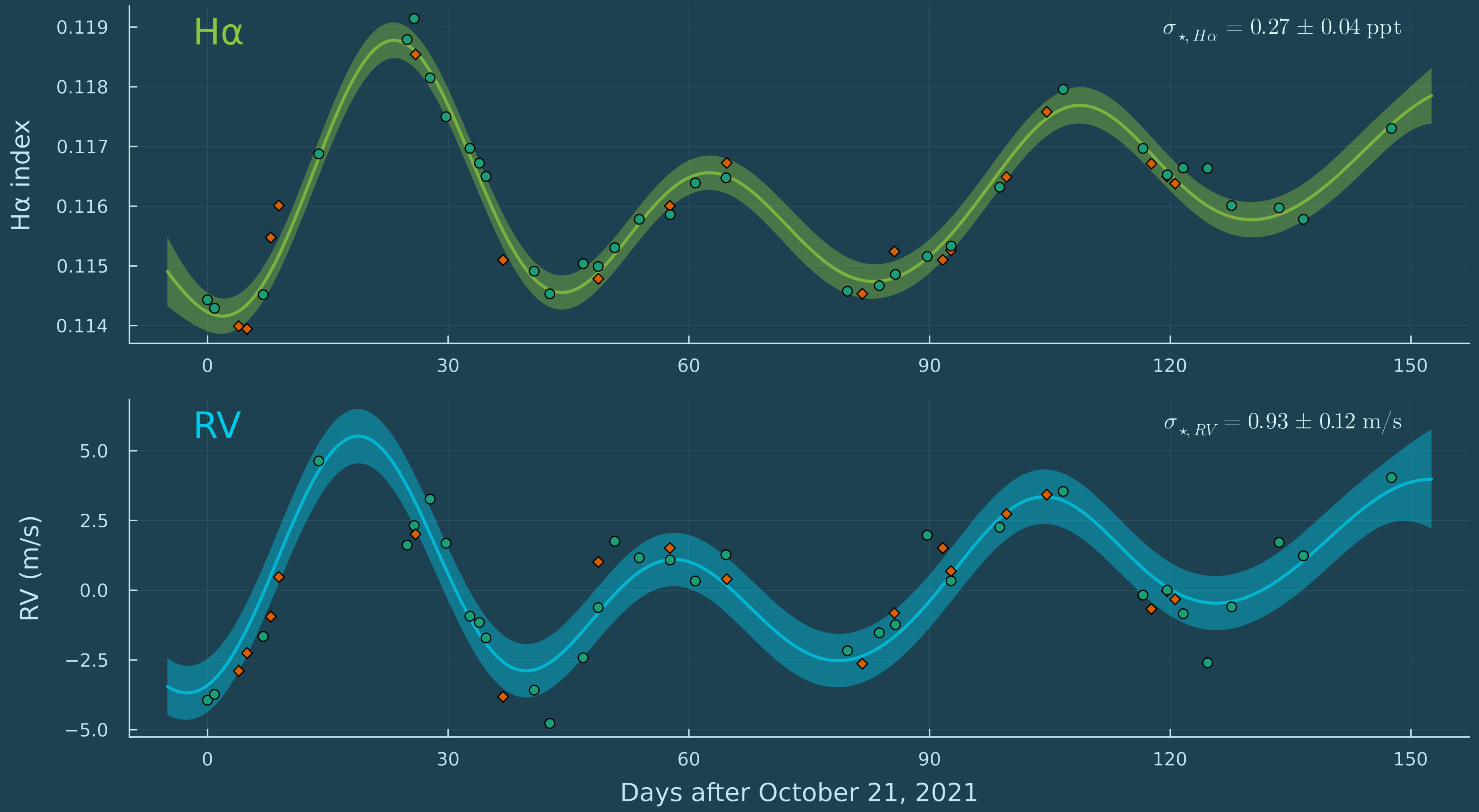
The relative contributions of RV_c and RV_{rot} introduce *apparent time lags*

Fitting apparent time lags

see Burrows et al. (submitted)

$$H\alpha = a_{10} G(t) \qquad RV = a_{00} G(t + \Delta t)$$

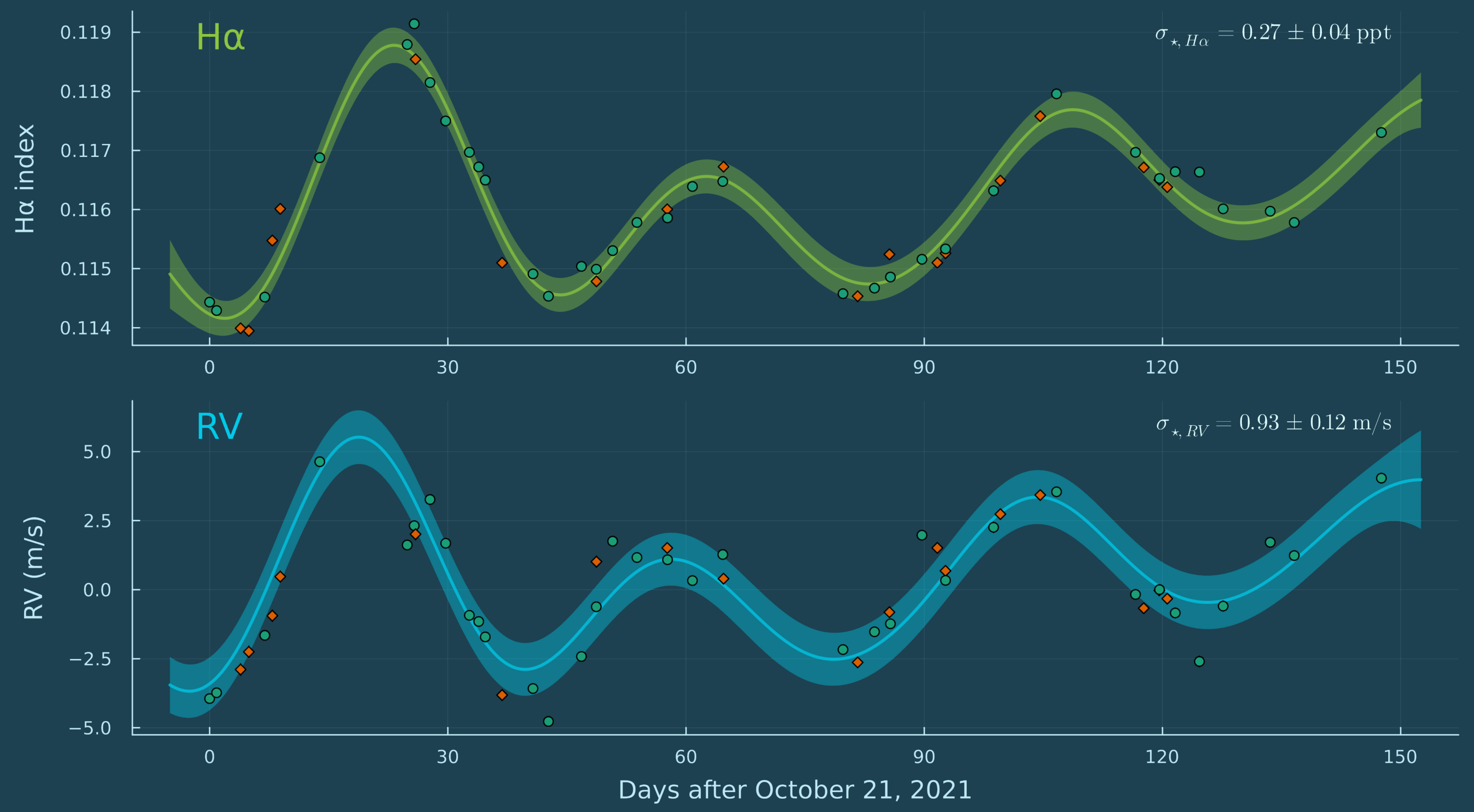
Lagged GP model includes a time lag hyperparameter, as well as "jitter" terms for RV and activity



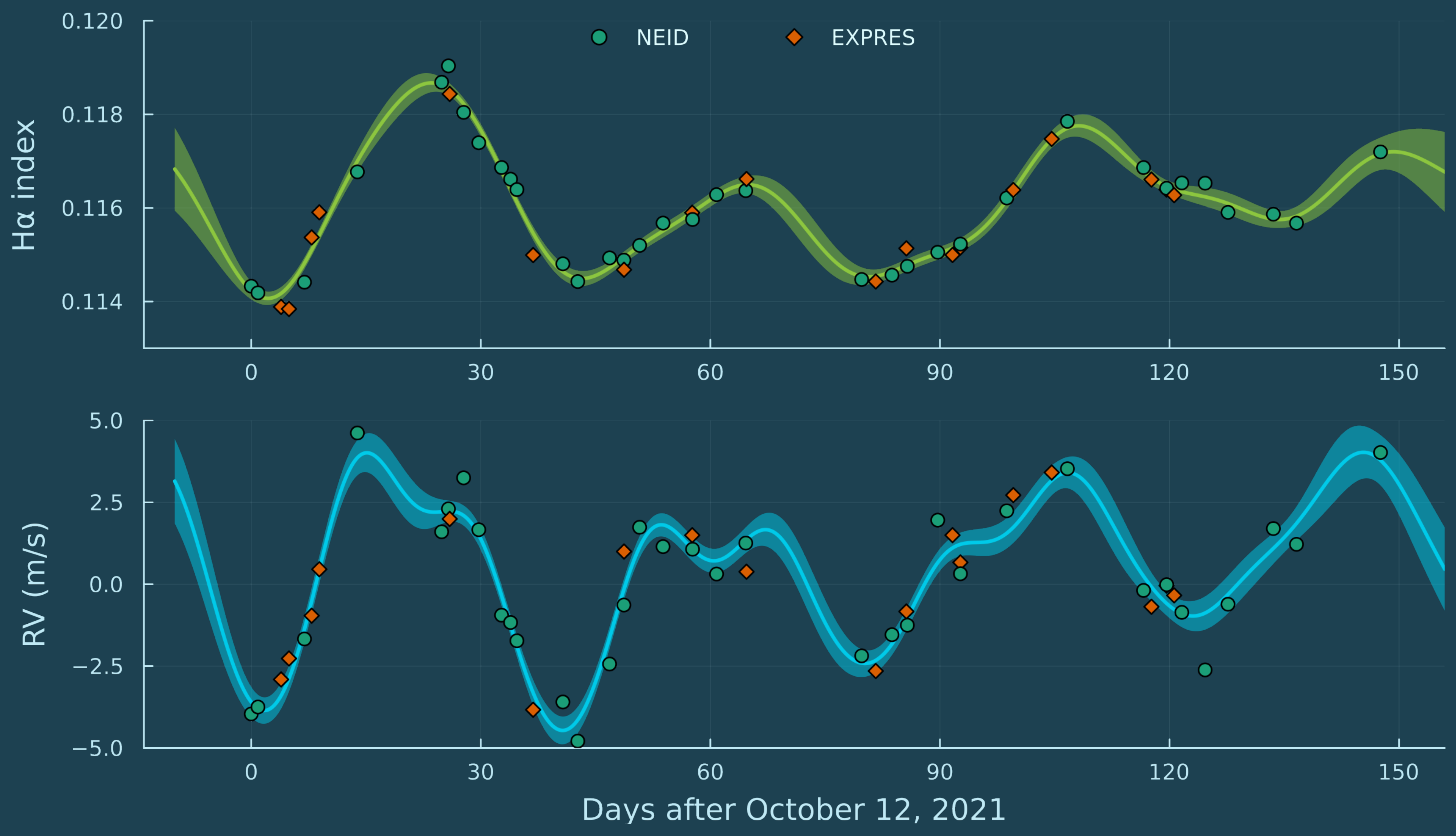
GP time lag:

$$\Delta t = 4.44 \text{ days}$$

Fitting apparent time lags



Lagged GP model



Independent GPs

The lagged GP model appears to not capture the full story

A simple spot model — A GP approach

e.g., Rajpaul et al. (2015)

$$H\alpha = a_{10}G(t)$$

$$RV = a_{00}G(t) + a_{01}G'(t)$$

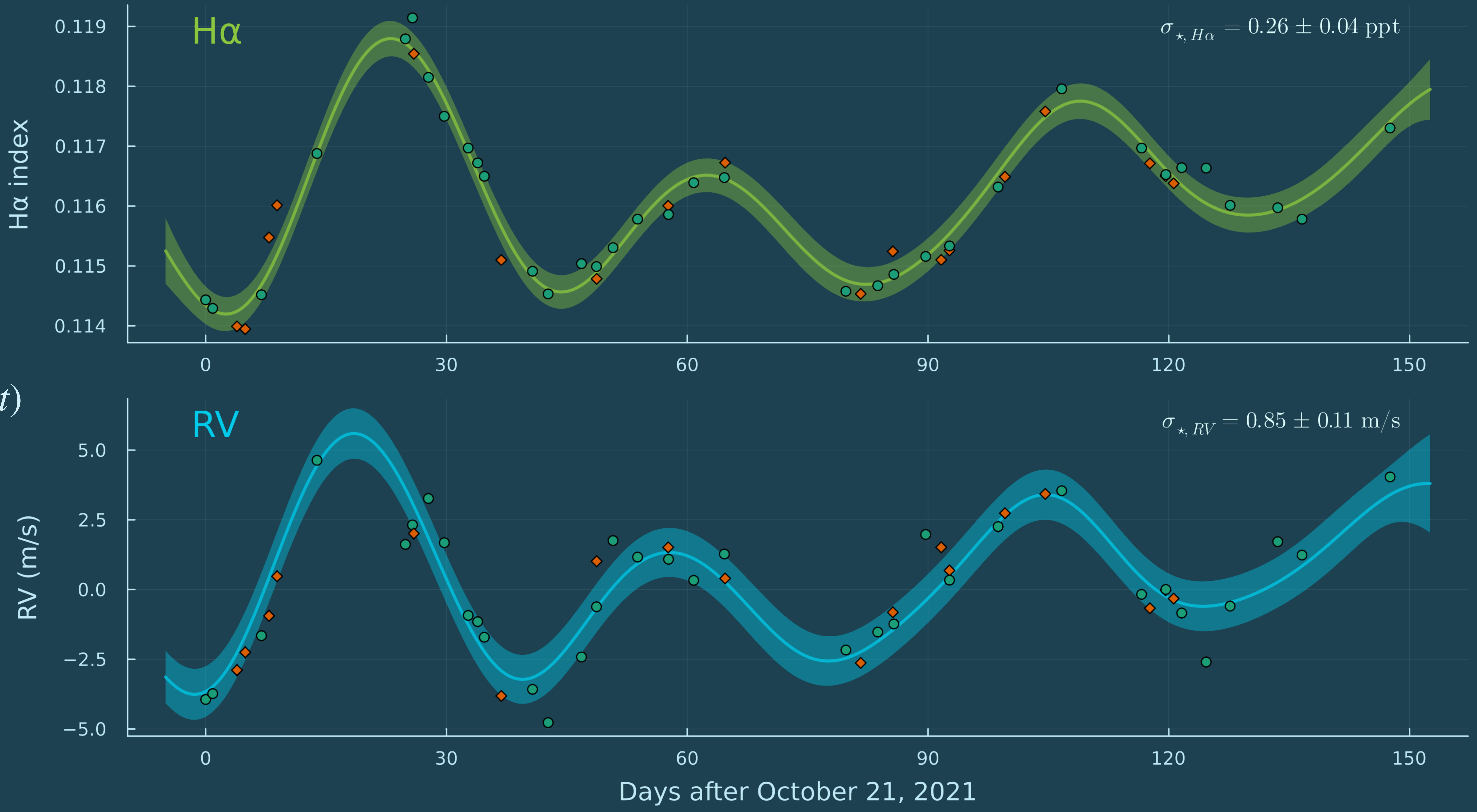
RV_c $\quad$ RV_{rot}

A simple spot model — A GP approach

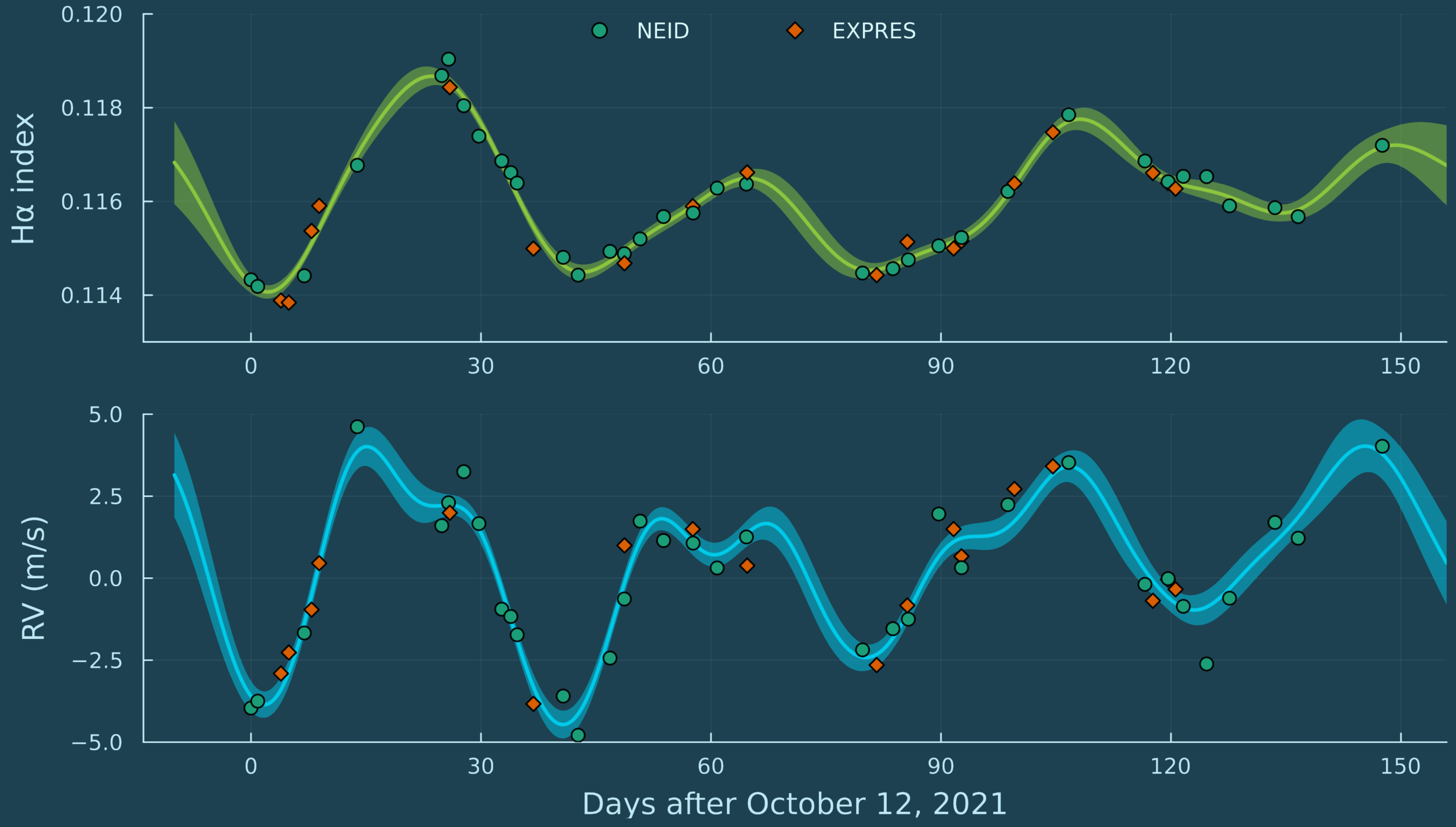
e.g., Rajpaul et al. (2015)

$$H\alpha = a_{10}G(t)$$

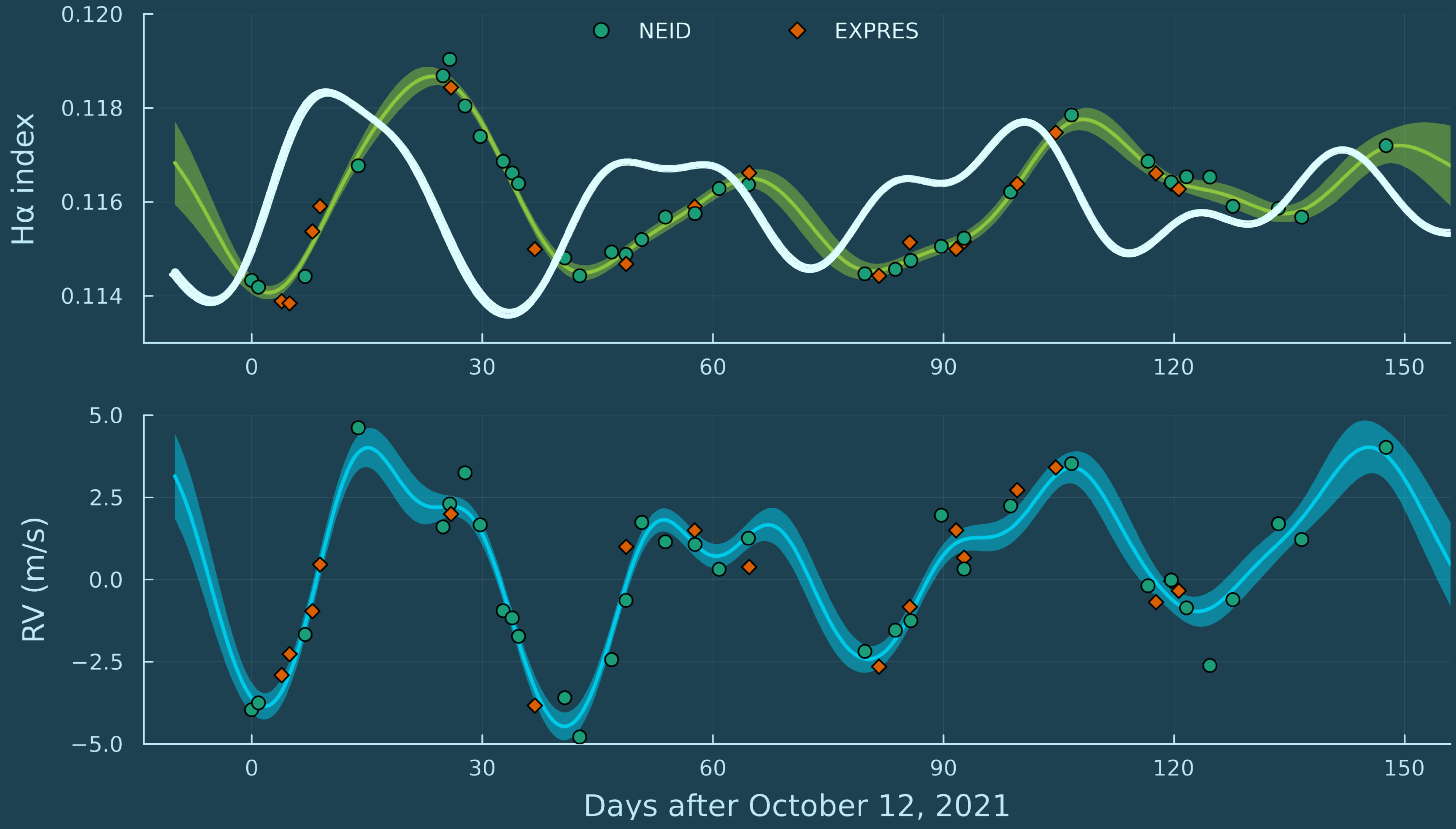
$$RV = a_{00}G(t) + a_{01}G'(t)$$



The simple spot model performs similar to lag model, leaving 85 cm/s of stellar “jitter”

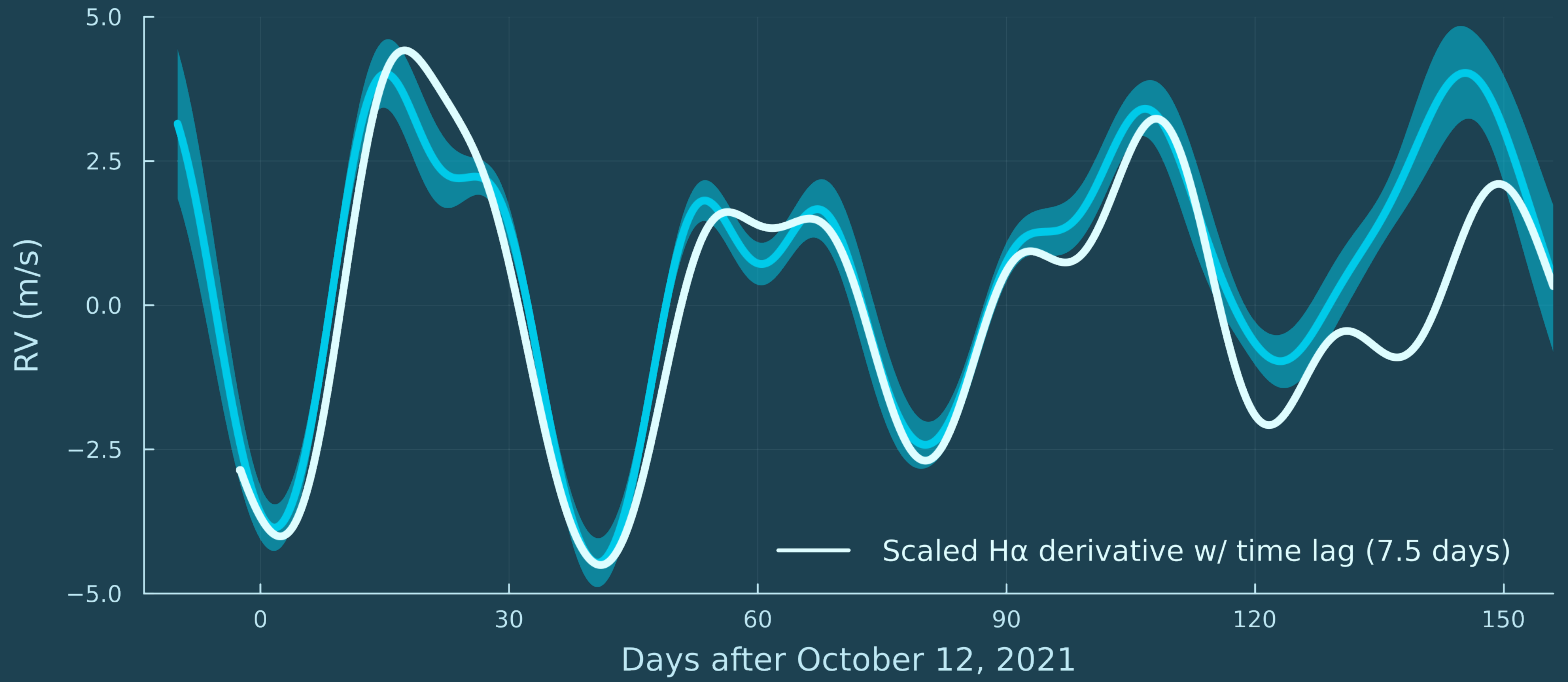


NEID
EXPRES
Hα index
0.120
0.118
0.116
0.114
0
30
60
90
120
150
RV (m/s)
5.0
2.5
0.0
−2.5
−5.0
Days after October 12, 2021



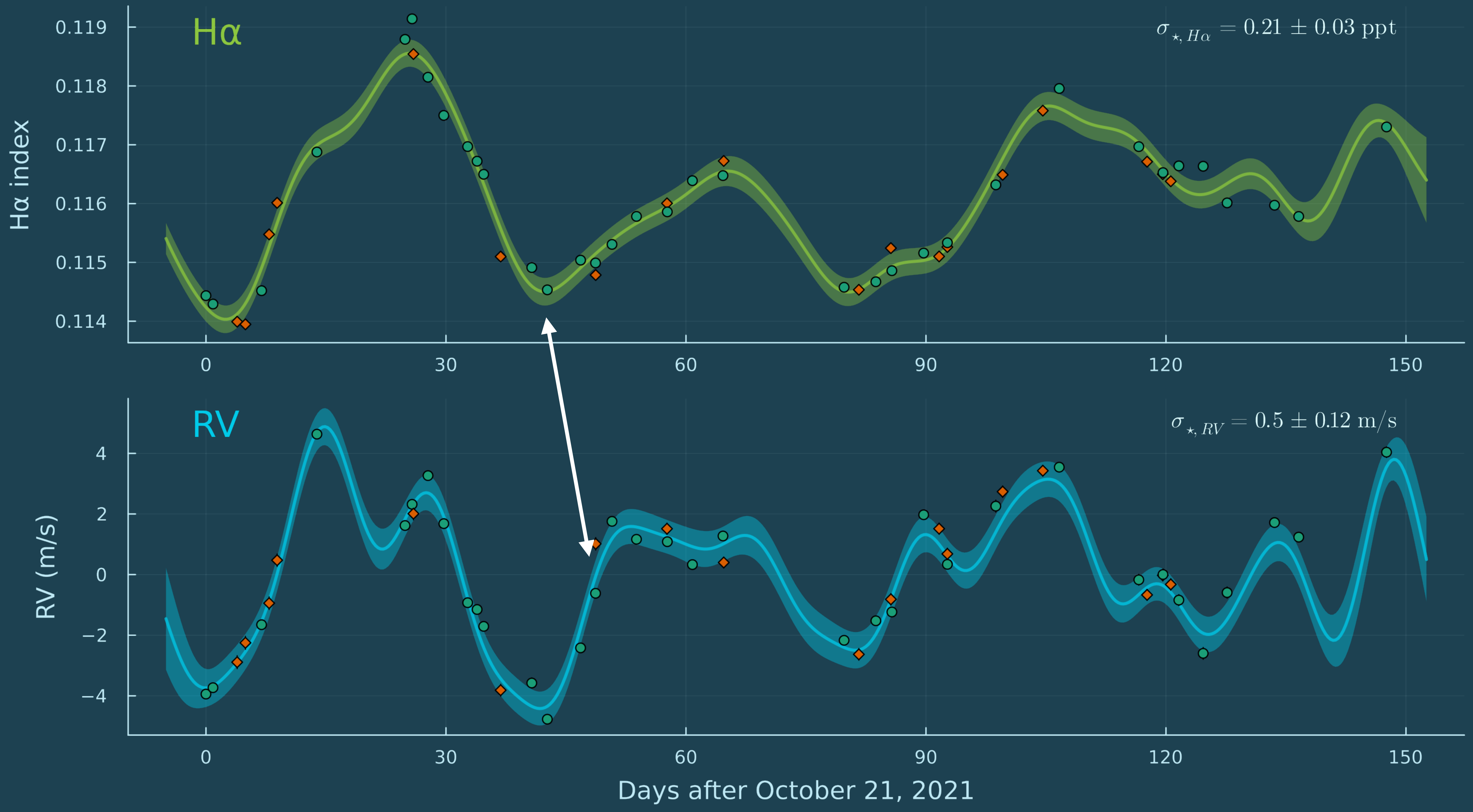
Can the RVs be explained by a lagged derivative model?

A time-lagged derivative?



Can the RVs be explained by a lagged derivative model?

$\Delta t = -6.4$ days



What are the implications?

Instantaneous derivative of activity time series predicts RV behavior 6.5 days later!

An opportunity for PRV instruments?

Can complex spot geometries/configurations be at play?

Possibly, we are *spinning up* STARRY, SOAP2.0

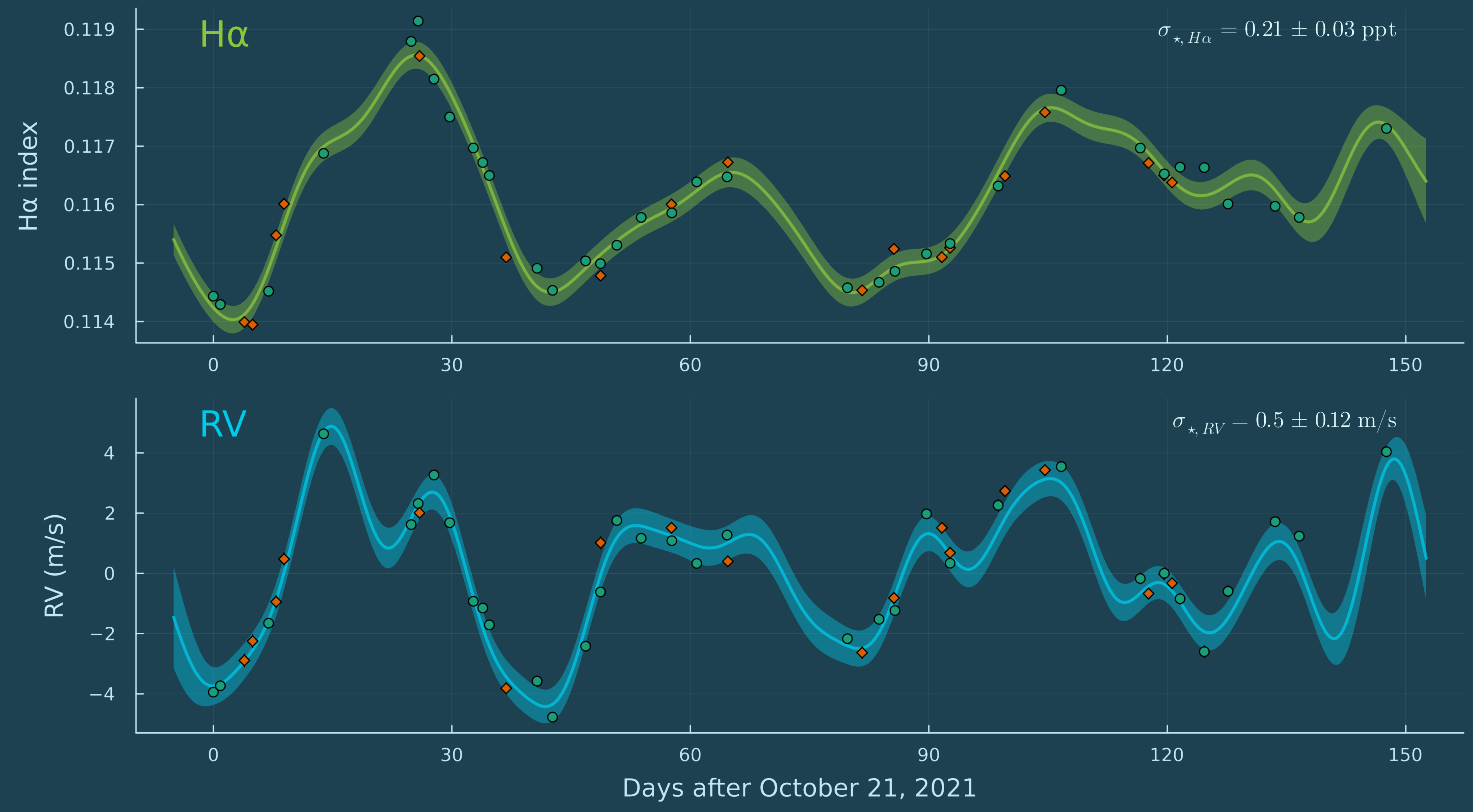
An astrophysical lag?

Simple spot model assumes flux effect, magnetic effect, and RV are coupled

Magnetically bright (but photometrically quiet) features that precede dark spots?

Summary

Activity–RV connections highlight need for high cadence & tricks beyond simple correlation metrics



Time lags between activity and RVs suggest a more complex spot configuration or an astrophysical lag not accounted for in current models