Lessons from "Sun-as-a-star" observations

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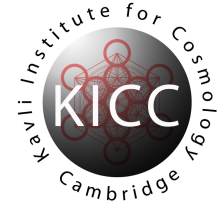
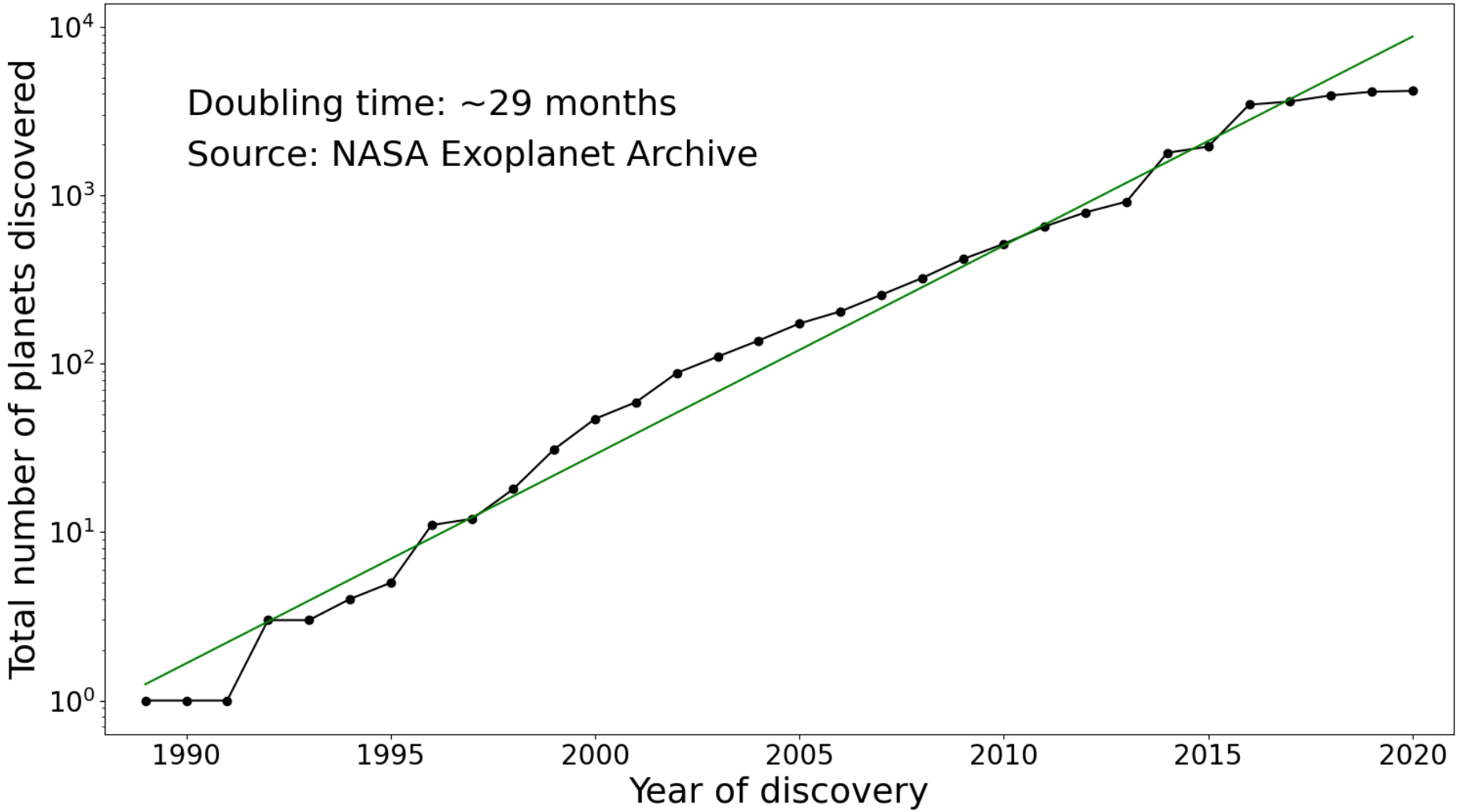
Sagan Exoplanet Workshop, July 2020

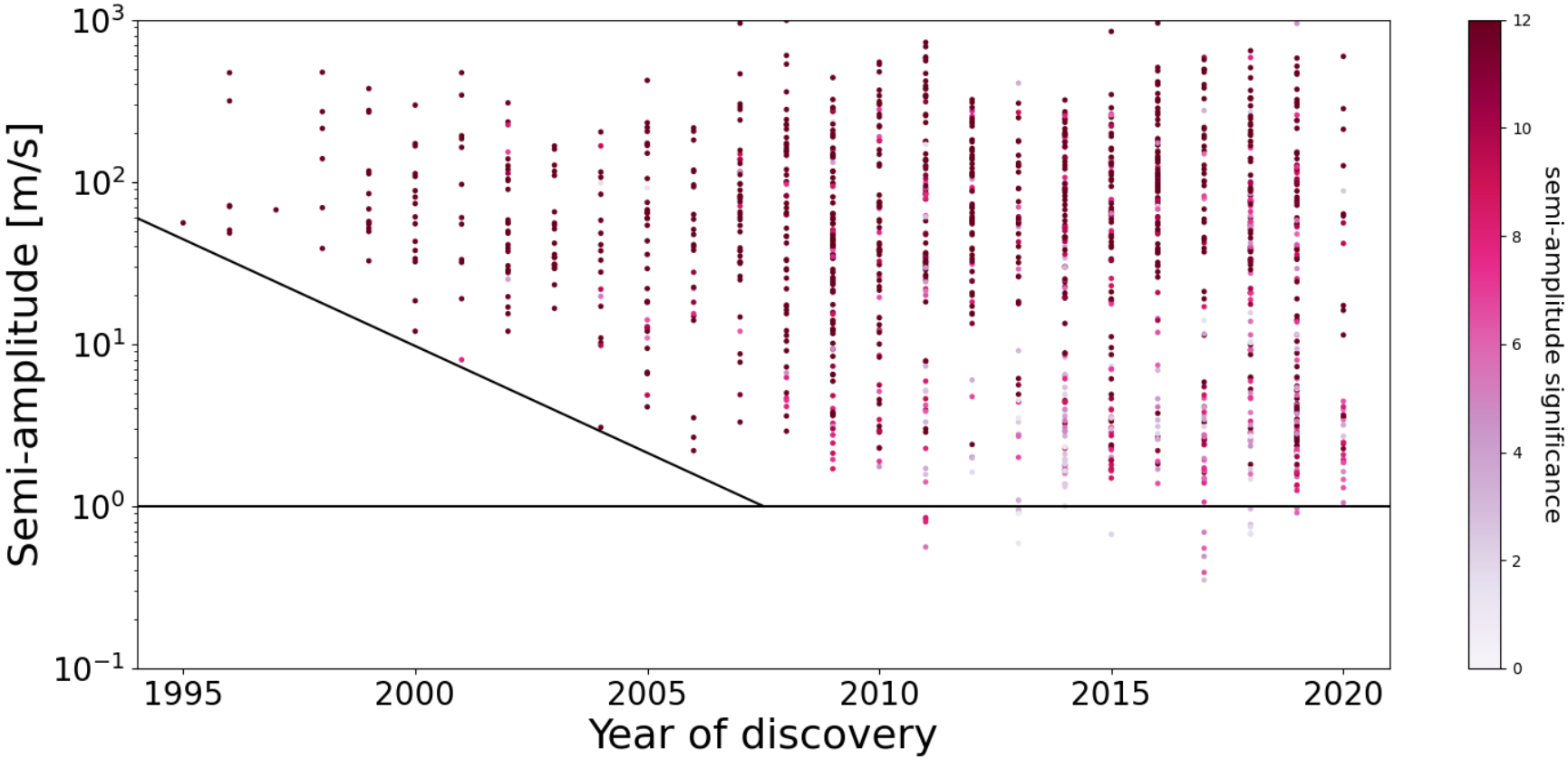
UNIVERSITY OF CAMBRIDGE



Exoplanet discoveries have risen exponentially



Have we hit an RV barrier?



Better instruments and better modeling techniques have pushed towards the smallest signals.

Source: NASA Exoplanet archive

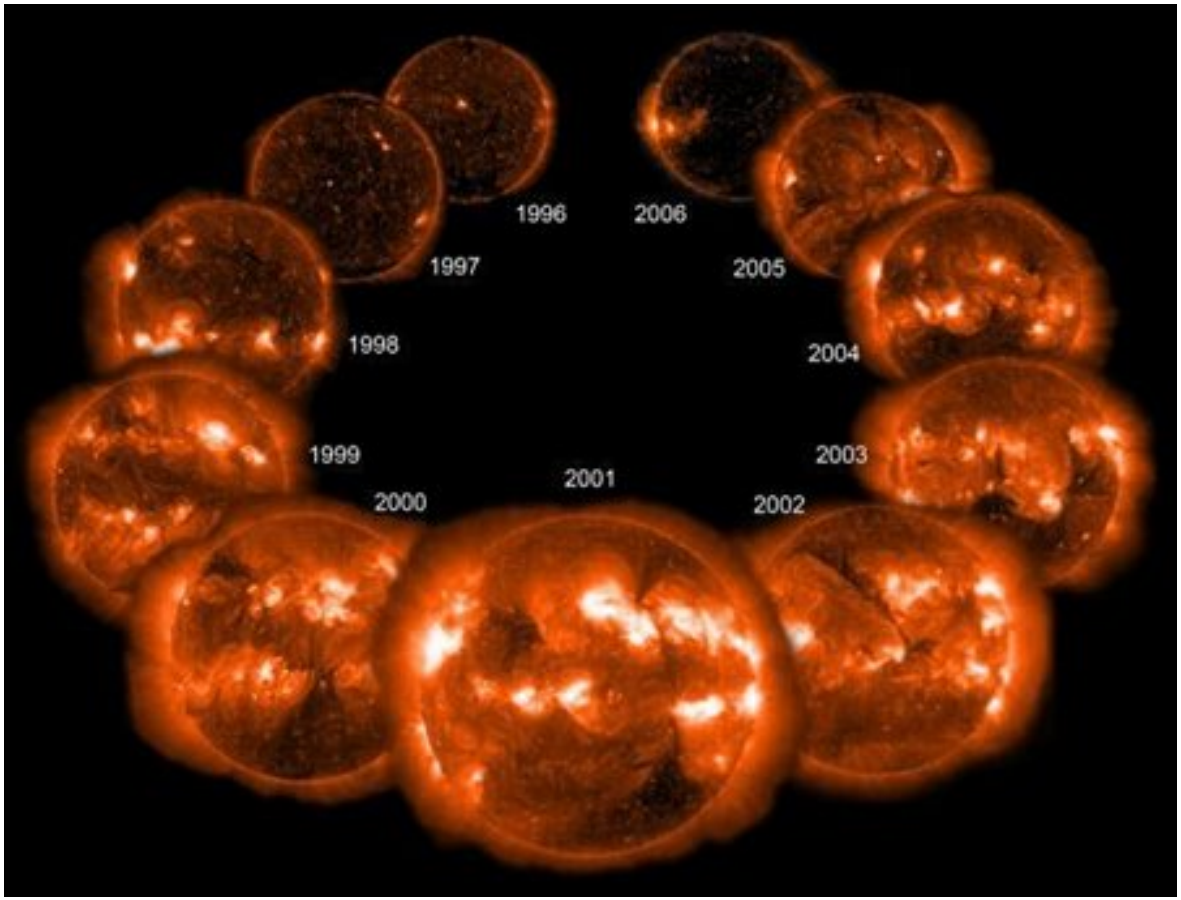
Know the star, know the planet

You can only know
an exoplanet
if you know
its host star!

Know the star, find the planet

You can only ~~know~~ find
an exoplanet
if you know
its host star!

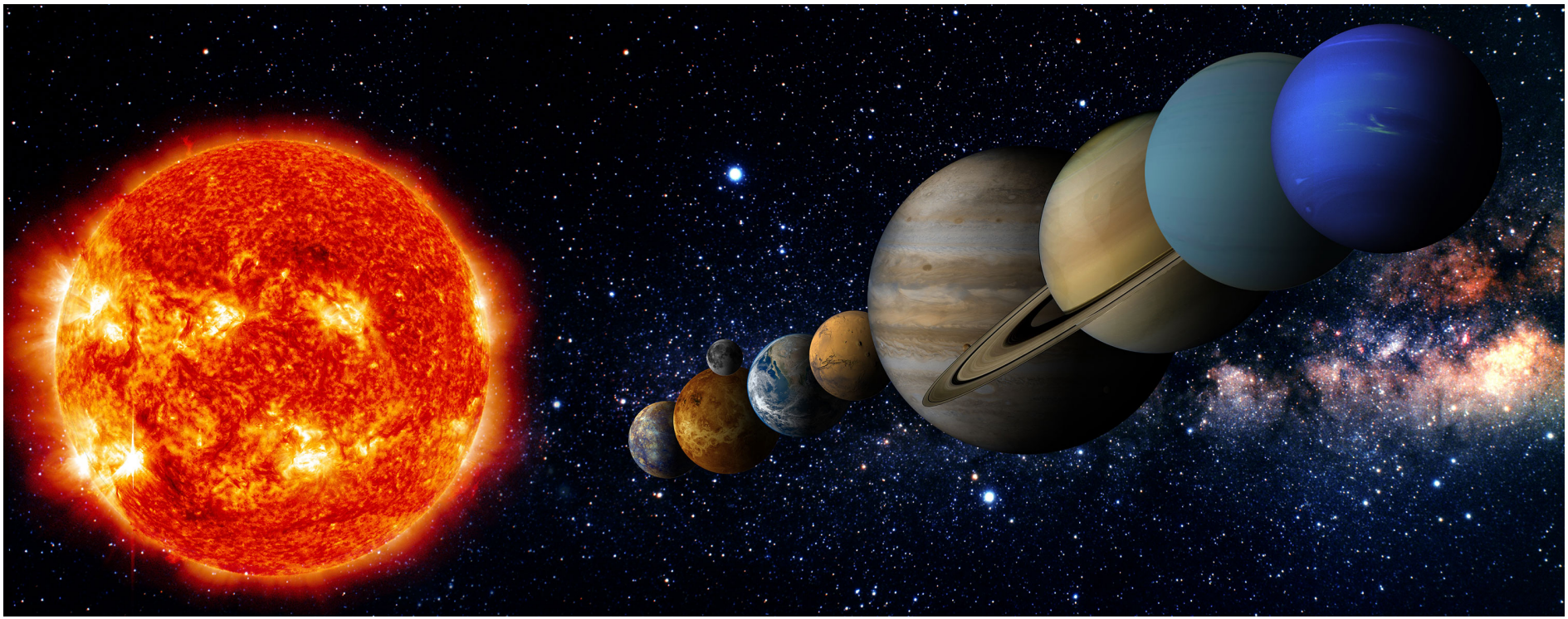
The most problematic 'noise' in RV data: the star



(Source: NASA/ESA. See also recently released SDO's timelapse video!)

Stars are not static; like the Sun, they go through activity cycles.
To find an Earth twin, we will need to understand stellar variability.

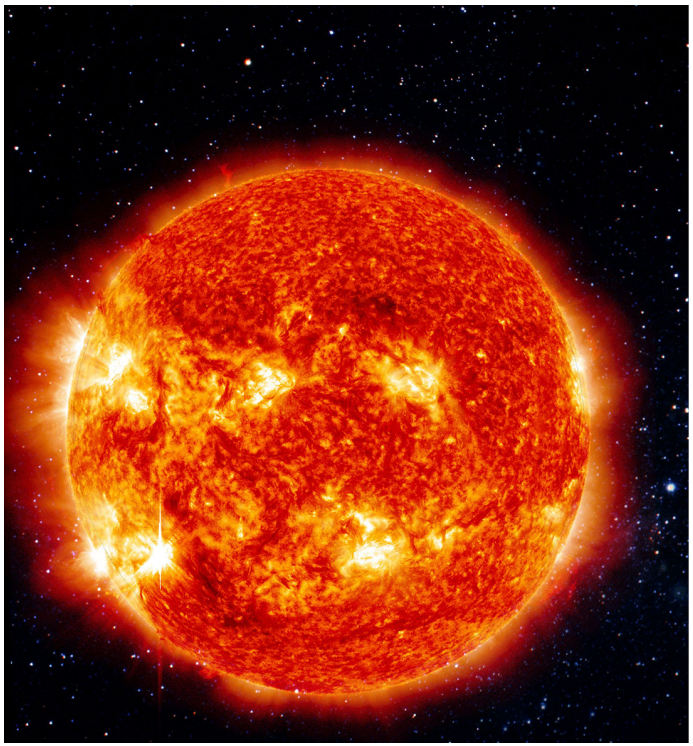
Benefits from "Sun-as-a-star" observations



(Source: www.britannica.com)

The Sun is the only star we know that has no orbiting planets...

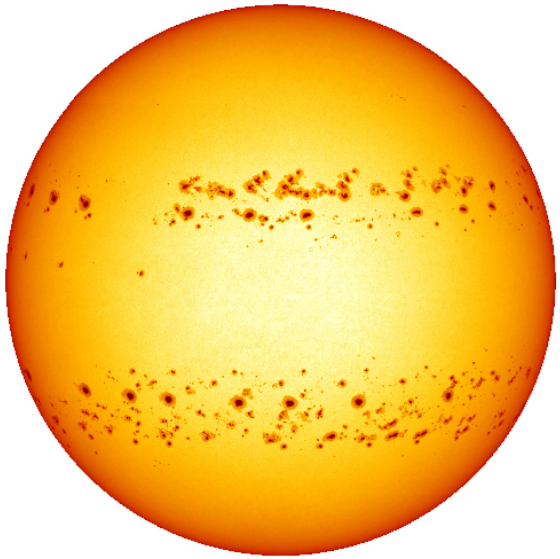
Benefits from "Sun-as-a-star" observations

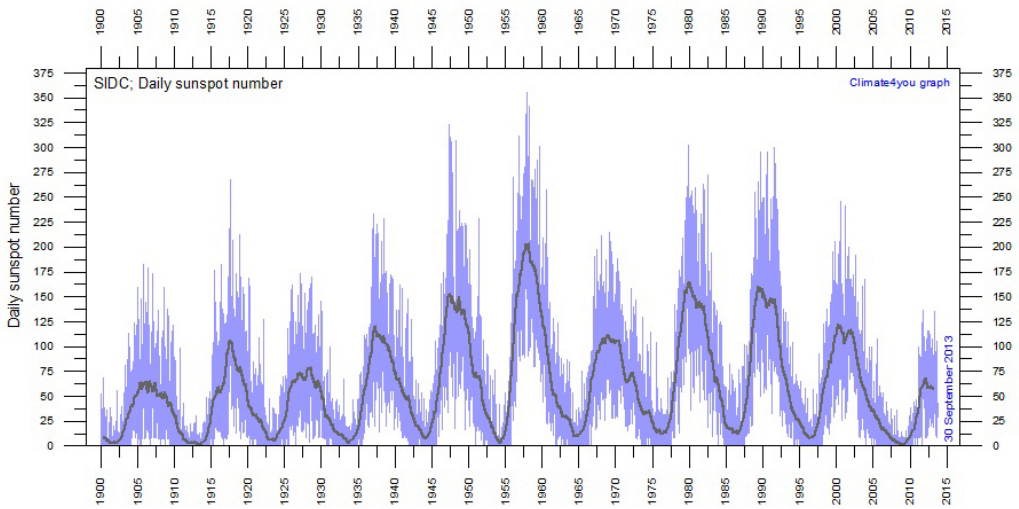


(Source: www.britannica.com)

The Sun is the only star we know that has no orbiting planets...
Because we can remove them from the data.

Stellar activity happens on multiple timescales





(Source: Cesar - ESA)

Solar magnetic cycle is roughly 11 years.
Solar rotational effects are seen on 25-30d timescales.
Then there's granulation, oscillations, flows, ...
happening on timescales from minutes to hours to days.

See also talk by Heather Cegla.

Sun-as-a-star observations for EPRV work

- Simulations
  - Using full simulated spectra: e.g. Desort+ 2007,Lagrange+ 2010, Meunier+ 2010, Gilbertson+ 2020
  - Using simulated cross-correlation functions: SOAP/SOAP2.0 - Boisse+ 2012, Dumusque+ 2014
- Indirect observations
  - Via Moon/asteroids: Lanza+ 16, Haywood+ 16
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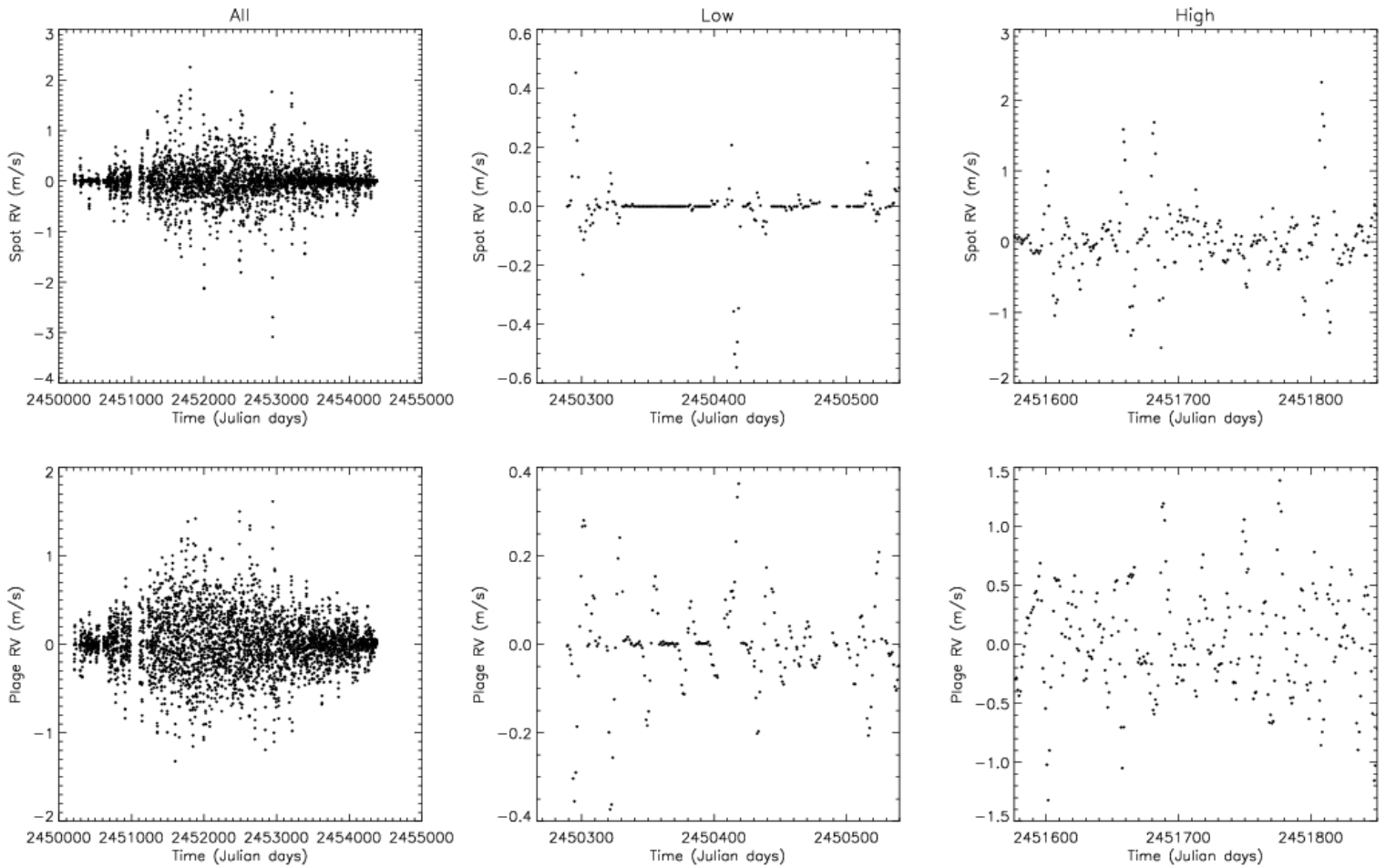
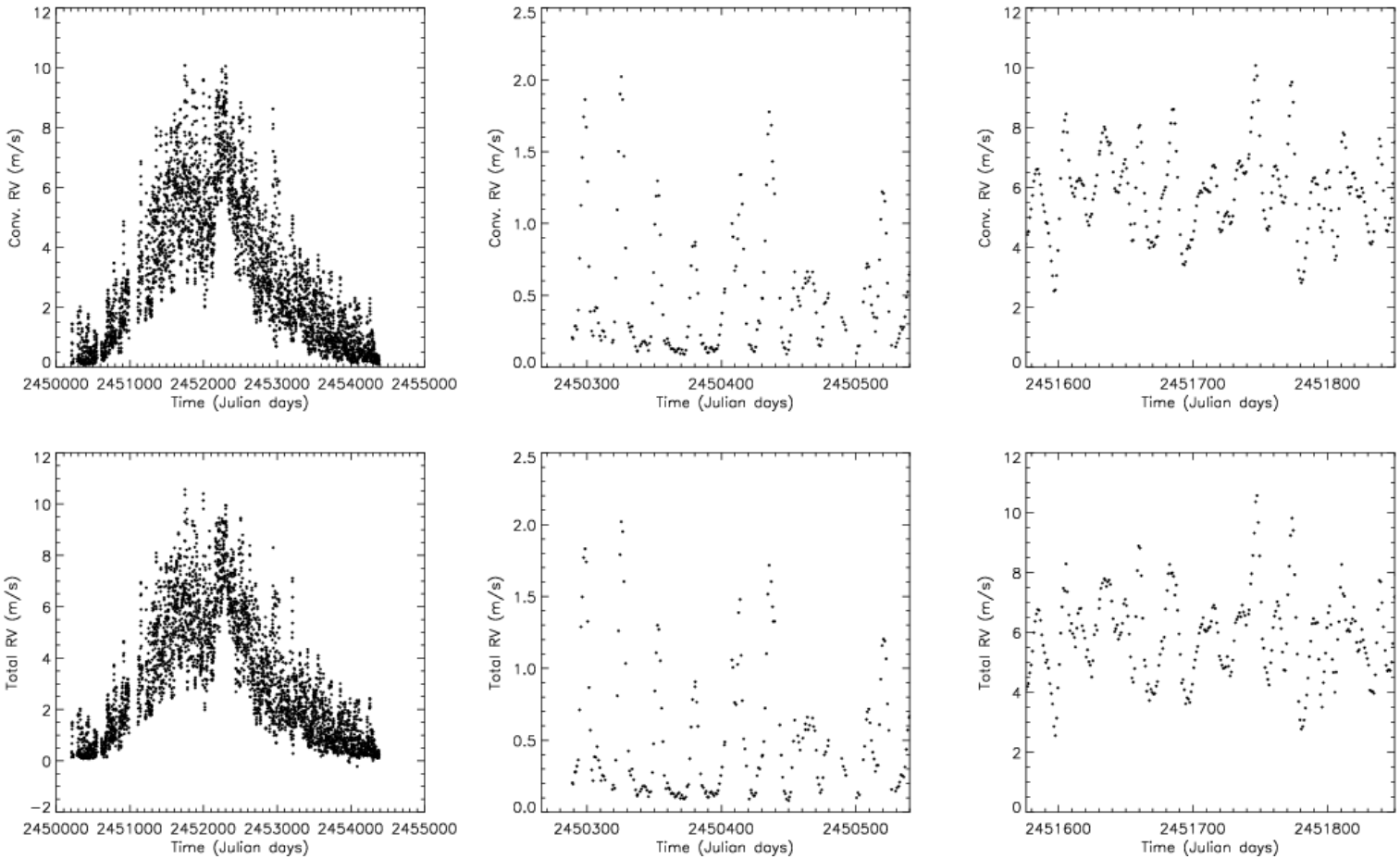
RVs from simulated spectra: spots and plages



(Meunier, Desort, Lagrange 2010)

RVs from spots and plages: generally the amplitude stays below 2m/s.

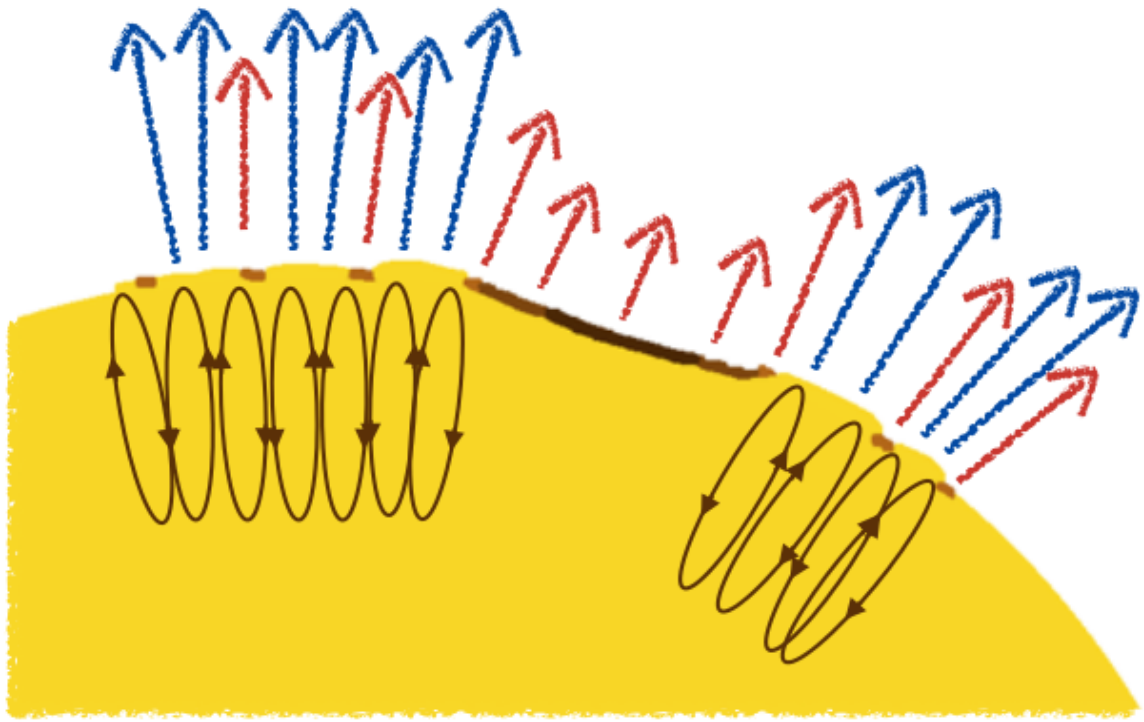
RVs from simulated spectra: convective blueshift



(Meunier, Desort, Lagrange 2010)

Suppression of convective blueshift is main source of solar RV variation.

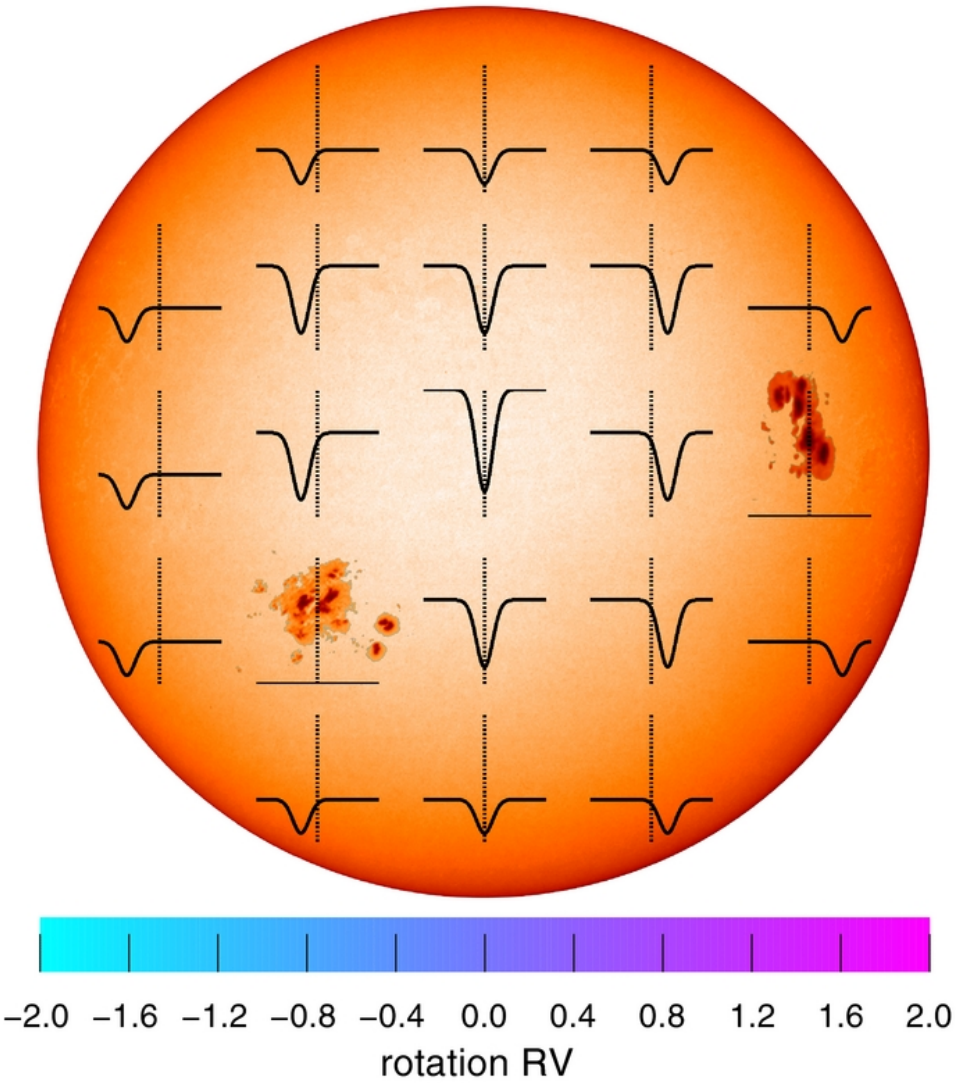
Suppression of convective blueshift



(courtesy R. Haywood)

Suppression of convective blueshift makes RV vary with several m/s.
Faculae are main source of this suppression.
Time scales related both to magnetic cycle and rotation period.
See talk by Heather Cegla.

Simulated CCFs with SOAP/SOAP2.0



(Dumusque et al. 2014)

Spot Oscillation And Planet (SOAP) simulates CCFs across a stellar disc.

Sun-as-a-star observations for EPRV work

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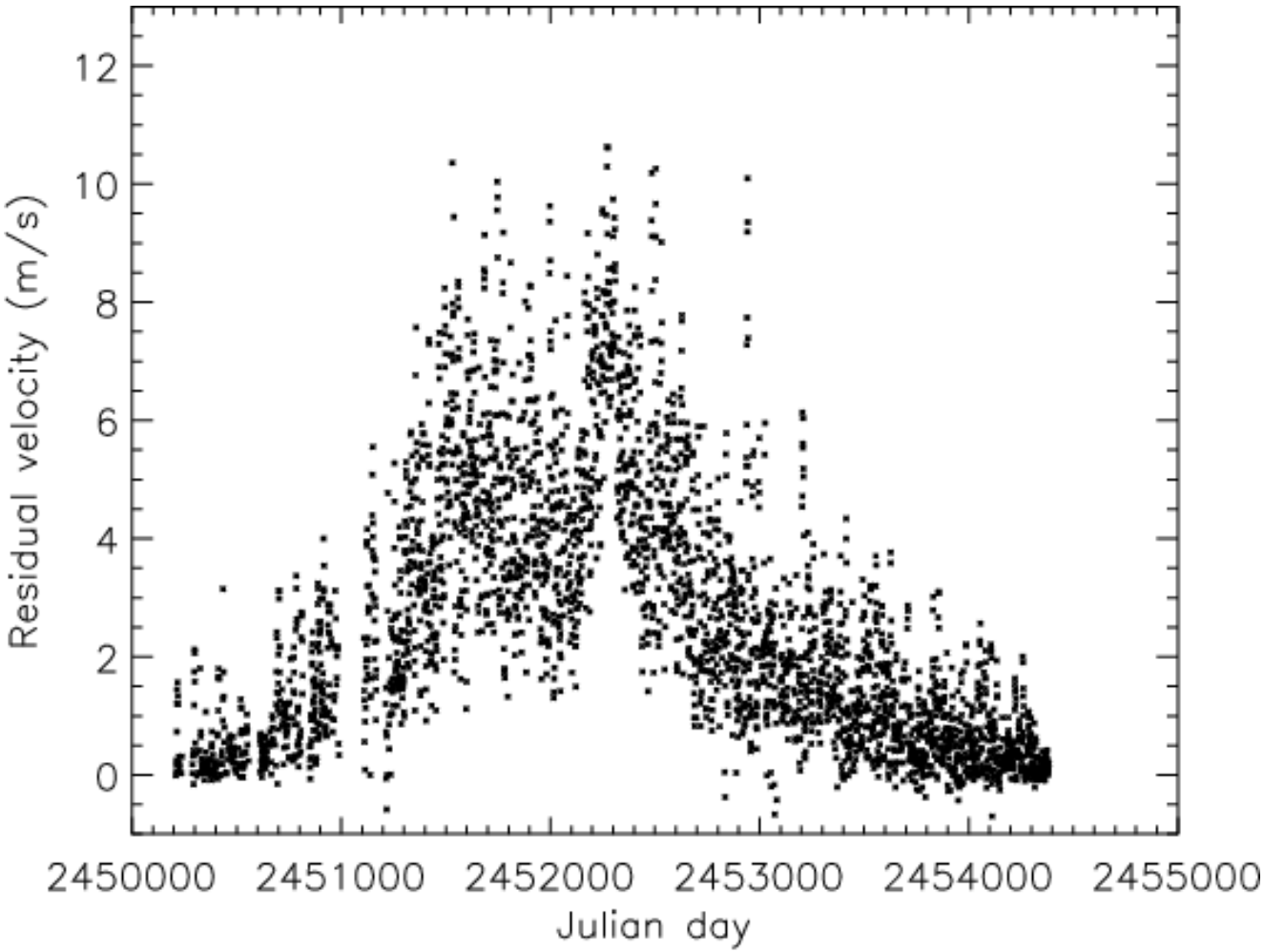
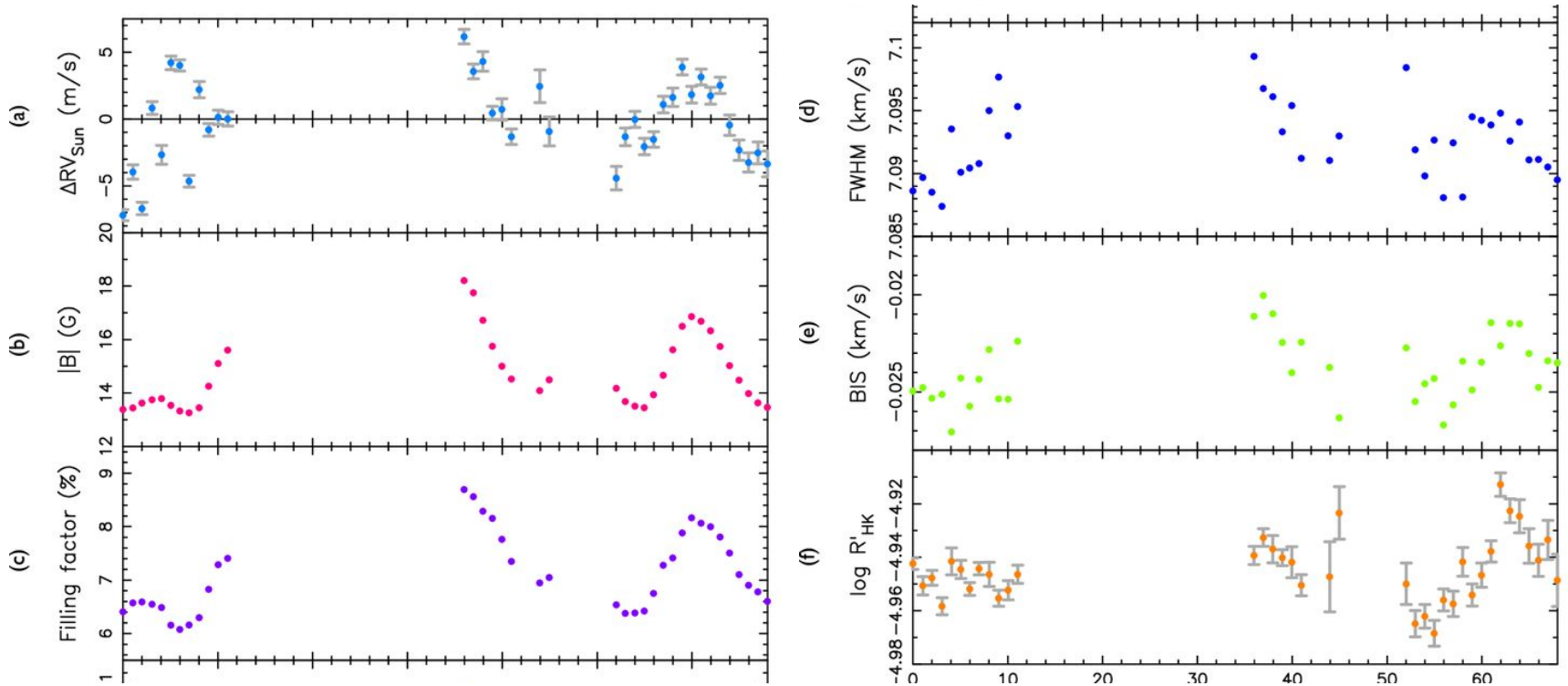
Indirect observations: Reconstructing from MDI/SOHO



(Meunier, Lagrange, Desort 2010)

RVs from disc-resolved observations confirm the simulations.

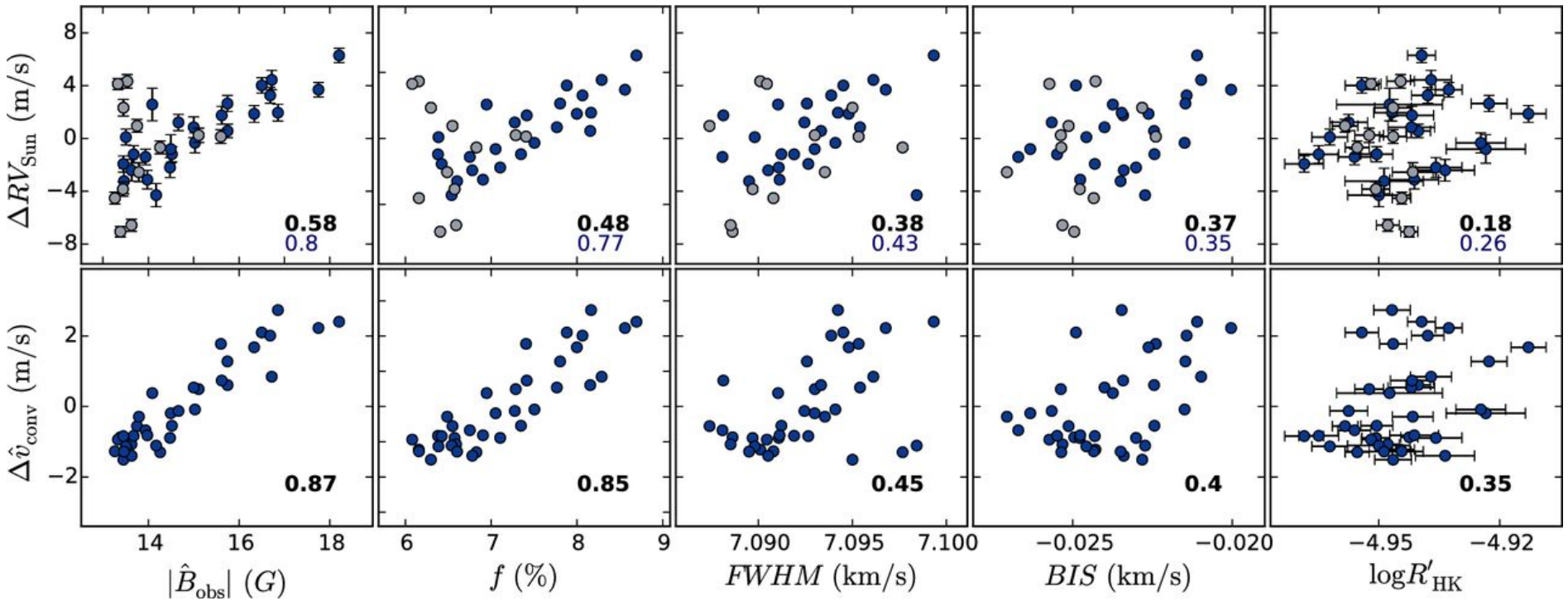
Indirect observations: Using the asteroid Vesta



(Haywood et al. 2016)

Hemispherically-averaged line-of-sight magnetic flux density, B, correlates well with RV.

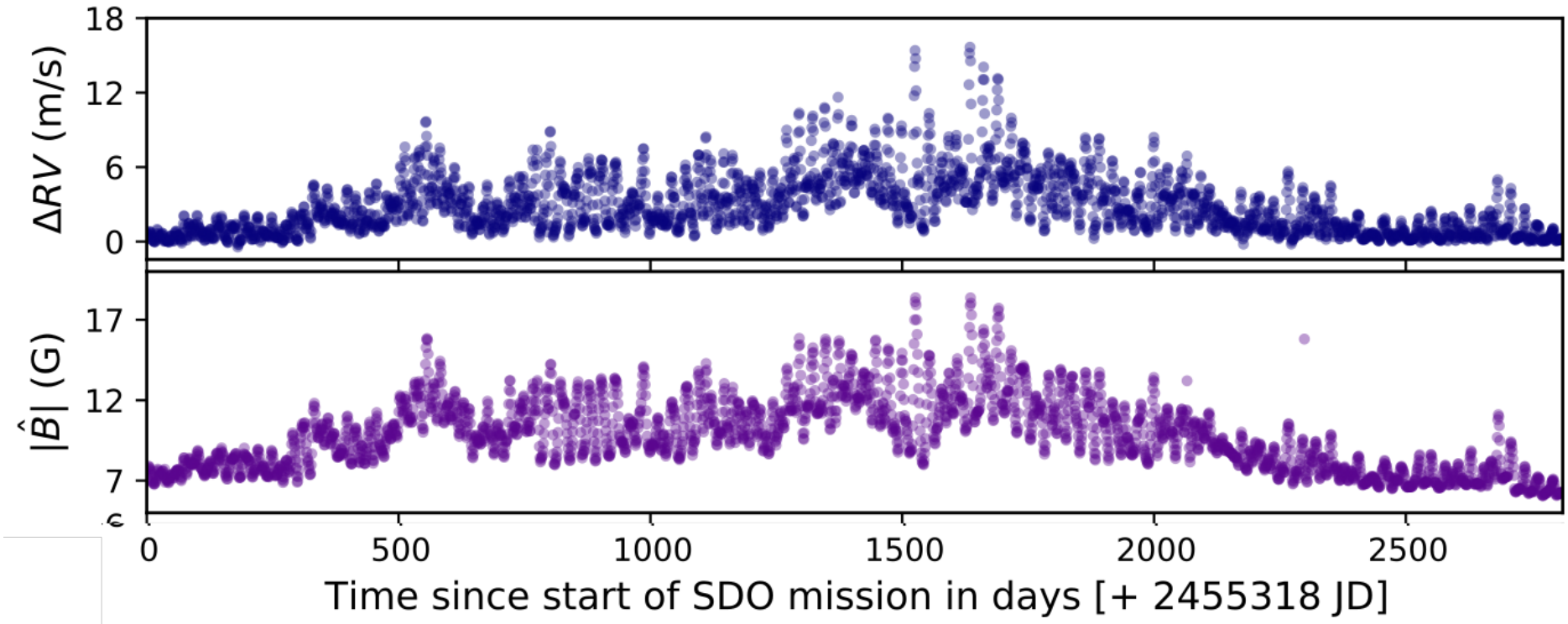
Indirect observations: Using the asteroid Vesta



(Haywood et al. 2016)

Hemispherically-averaged line-of-sight magnetic flux density, B, correlates well with RV.
It outperforms other standard activity indicators (see also Jenn Burt's talk).

Indirect observations: Reconstructing from SDO



(Haywood et al. 2020)

A simple linear fit with the unsigned magnetic flux reduces the rms of solar RV variations by 62% (factor of 2.6).

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The solar telescope feeding into HARPS-N

Courtesy: A. Glenday

The solar telescope feeding into HARPS-N

Operational since July 2015.
Daily 5-minute exposures from 9am till ∼4pm.

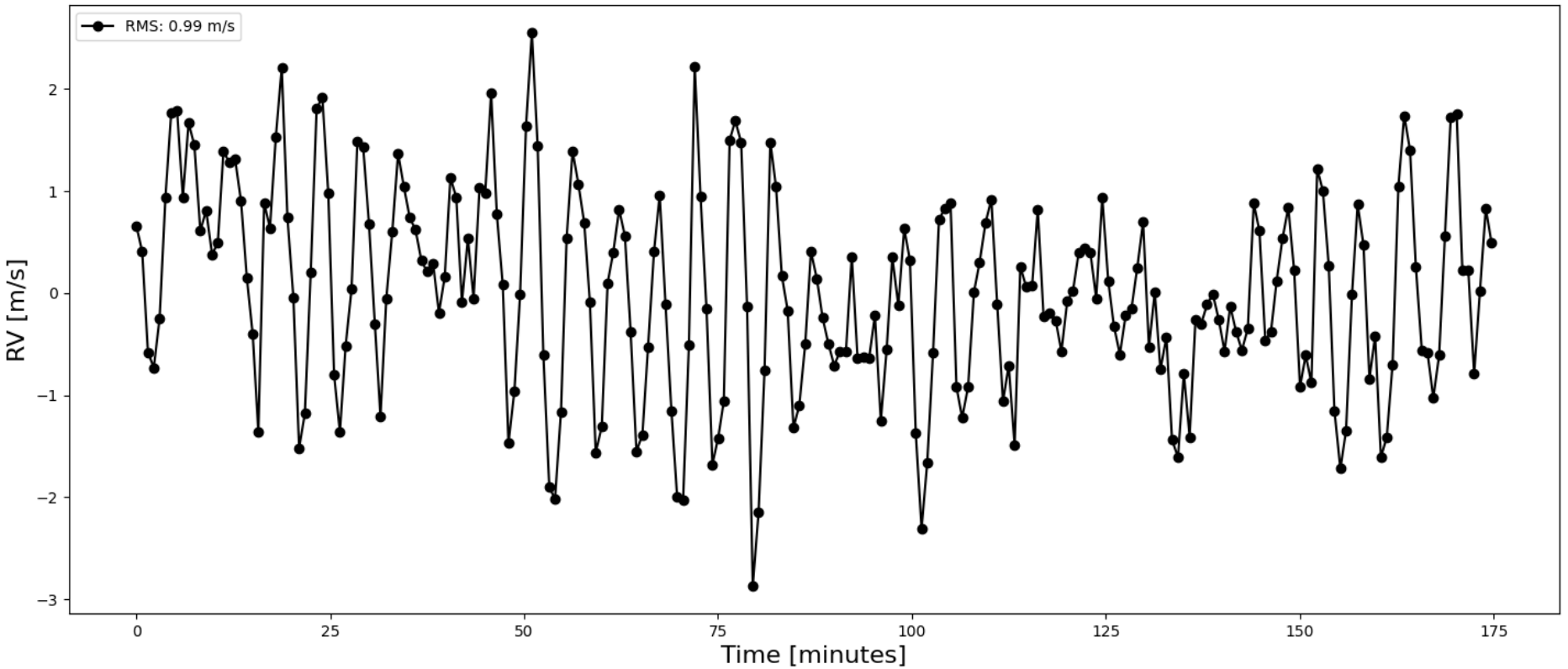
Courtesy: A. Glenday

HELIOS: The solar telescope feeding into HARPS

Courtesy: X. Dumusque

Operational since October 2018. Daily 5-minute exposures.
PIs: X. Dumusque & P. Figueira

Why take 5-min exposures?



(using HARPS-N solar data)

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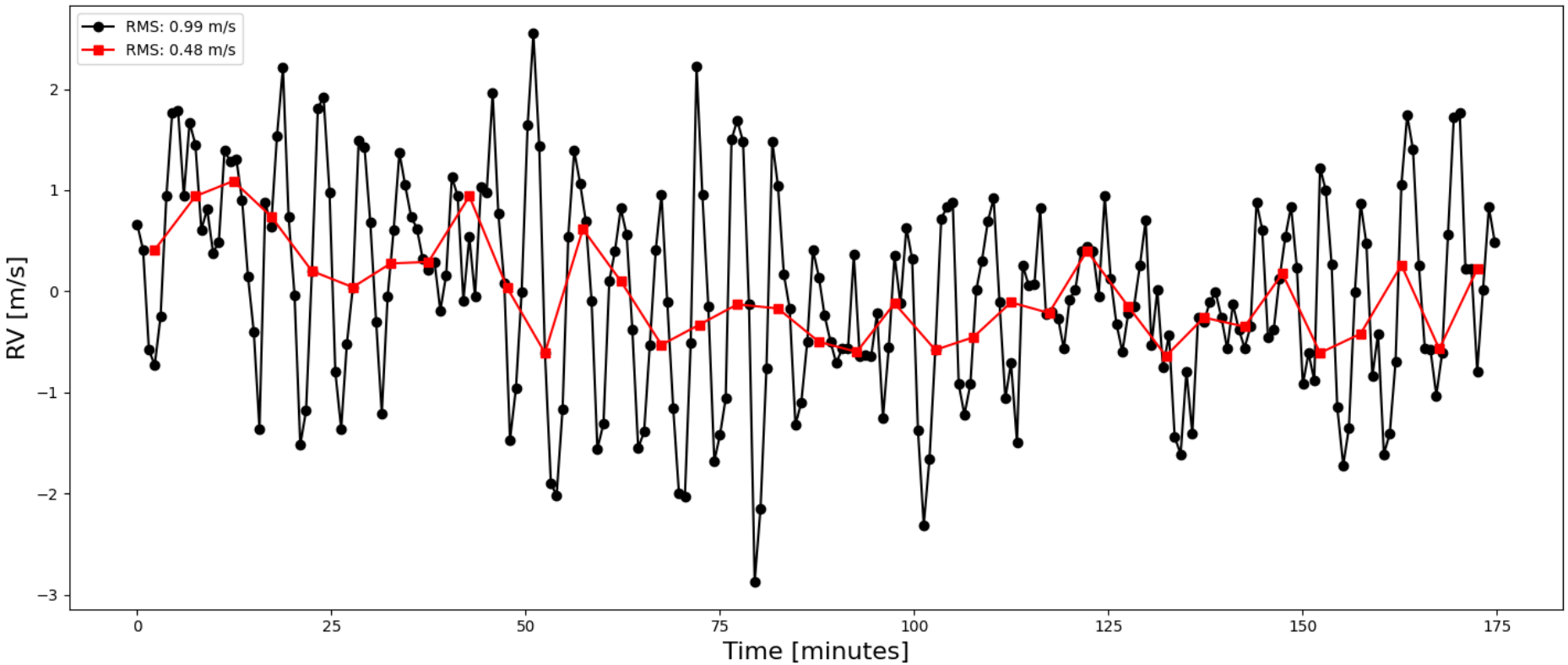
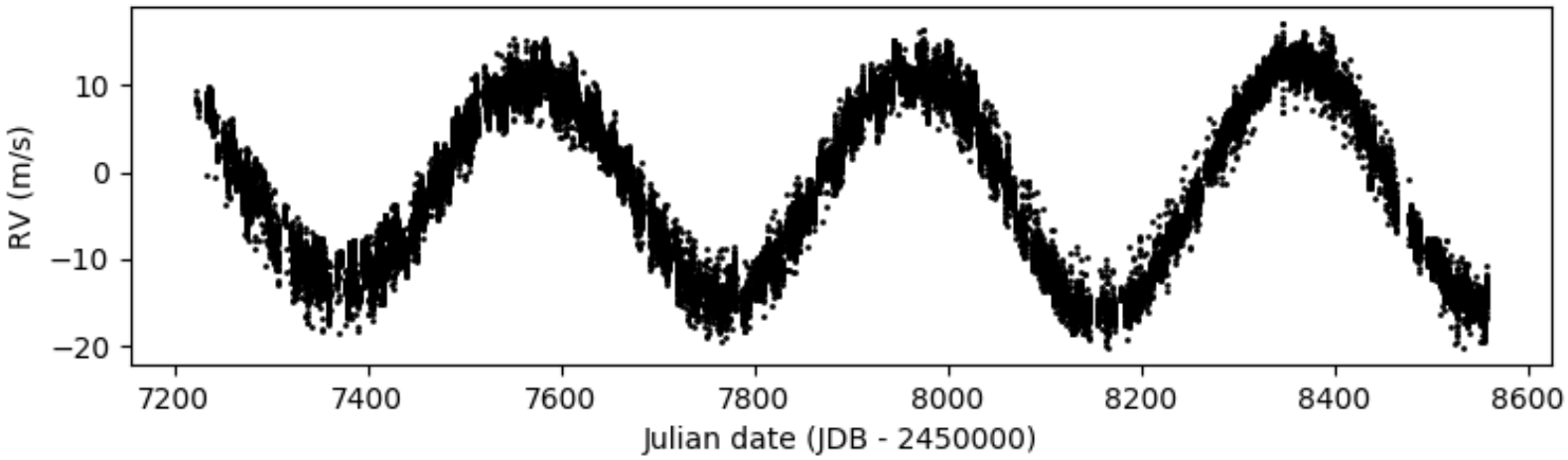


(using HARPS-N solar data)

5-minute exposures average over the oscillation variations.
Carefully tailored stellar exposure times are worth it.
See also Dumusque+ 2011, Chaplin+ 2019.

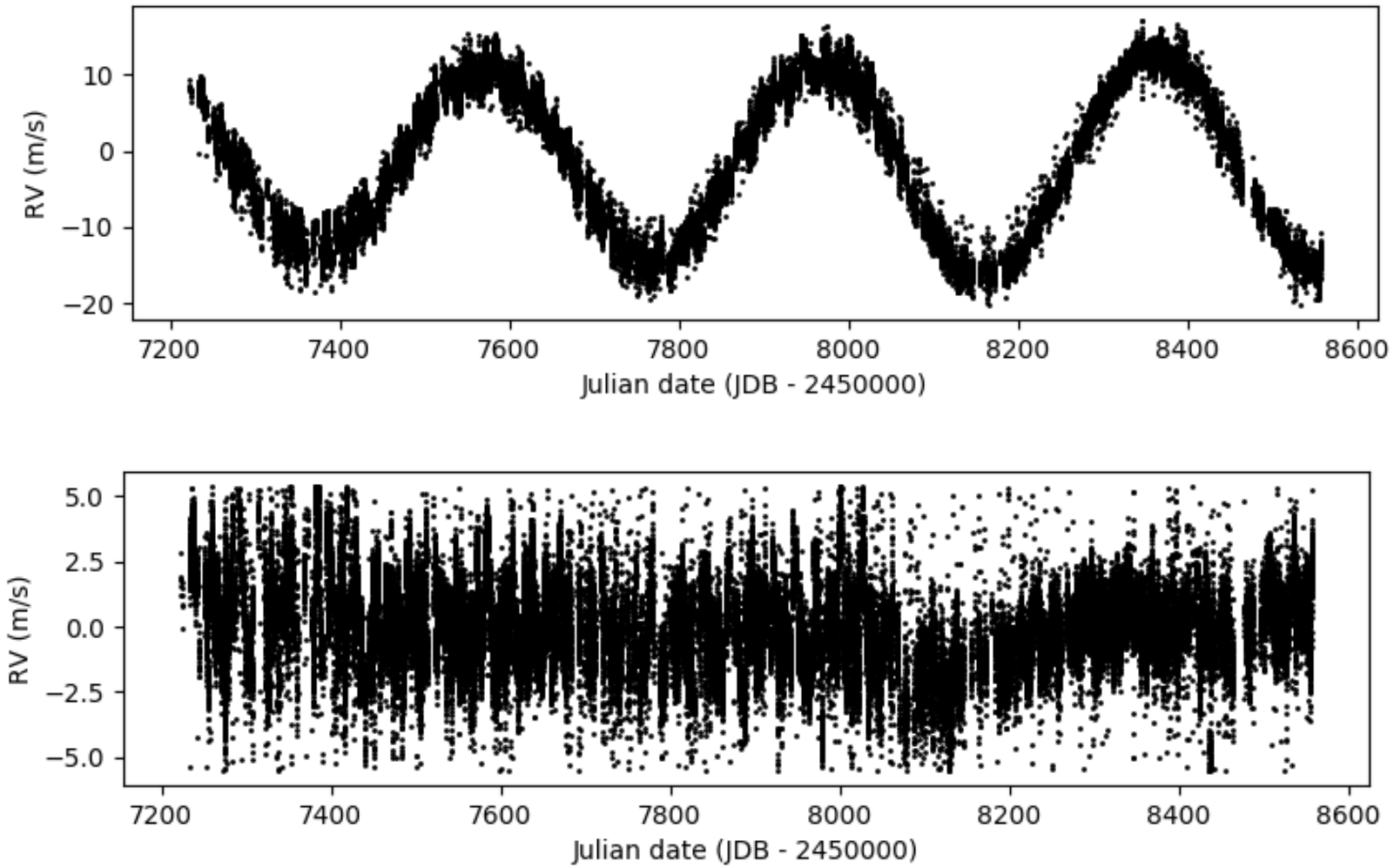
Let's look at the data

Jupiter clearly detected



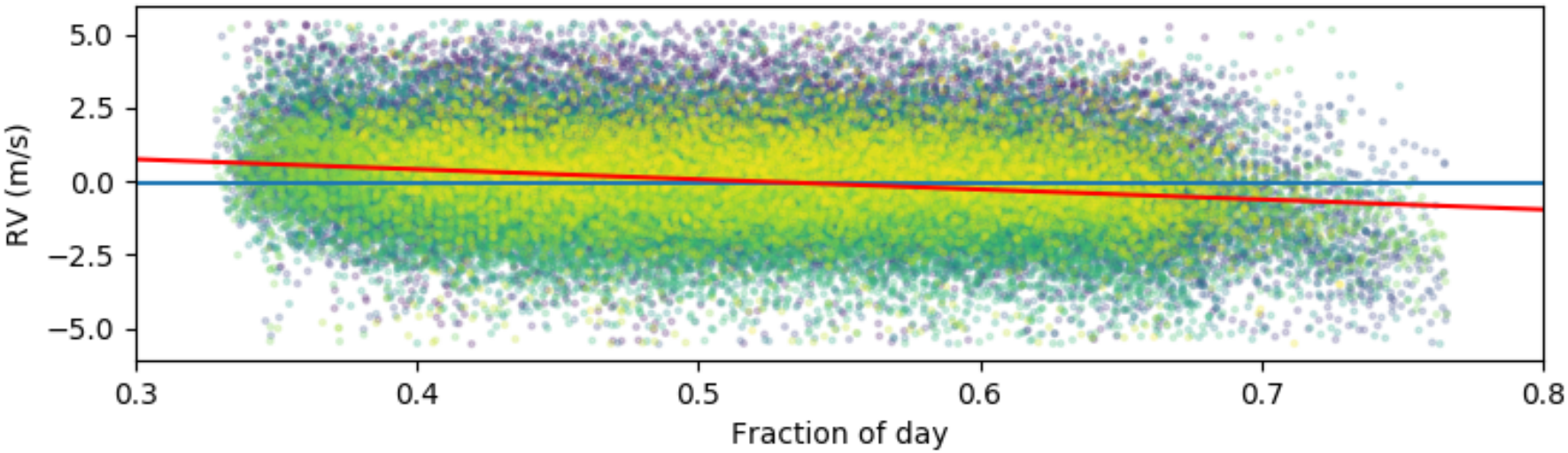
(Adapted from Collier Cameron, Mortier et al. 2019)

Jupiter clearly detected - corrected using JPL Horizons



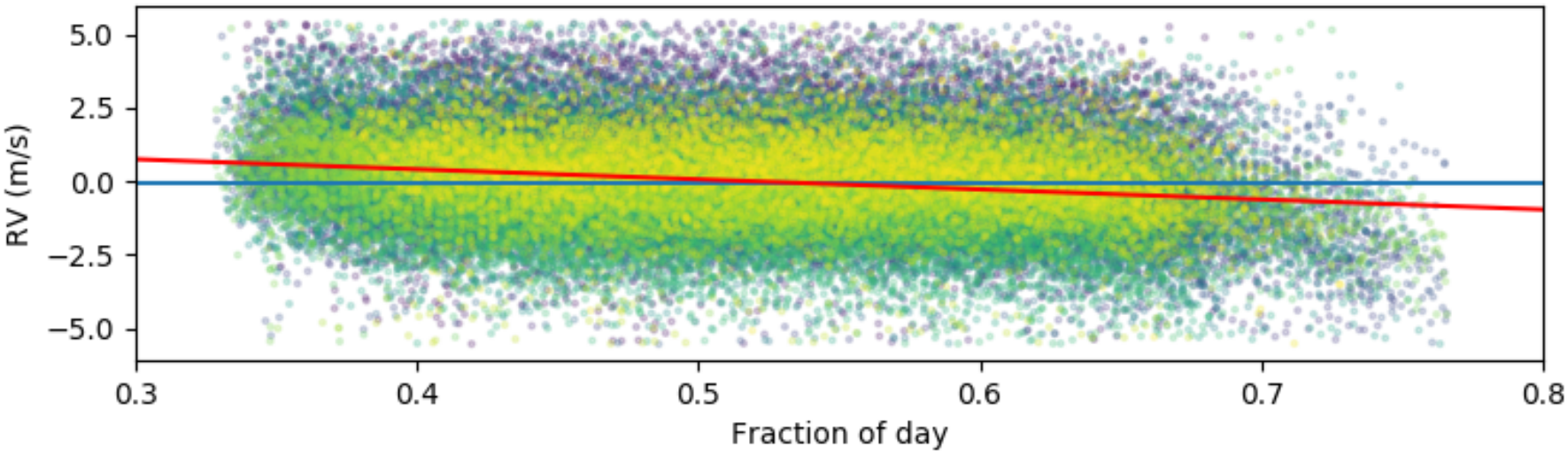
(Adapted from Collier Cameron, Mortier et al. 2019)

Daily downwards trend



(Adapted from Collier Cameron, Mortier et al. 2019)

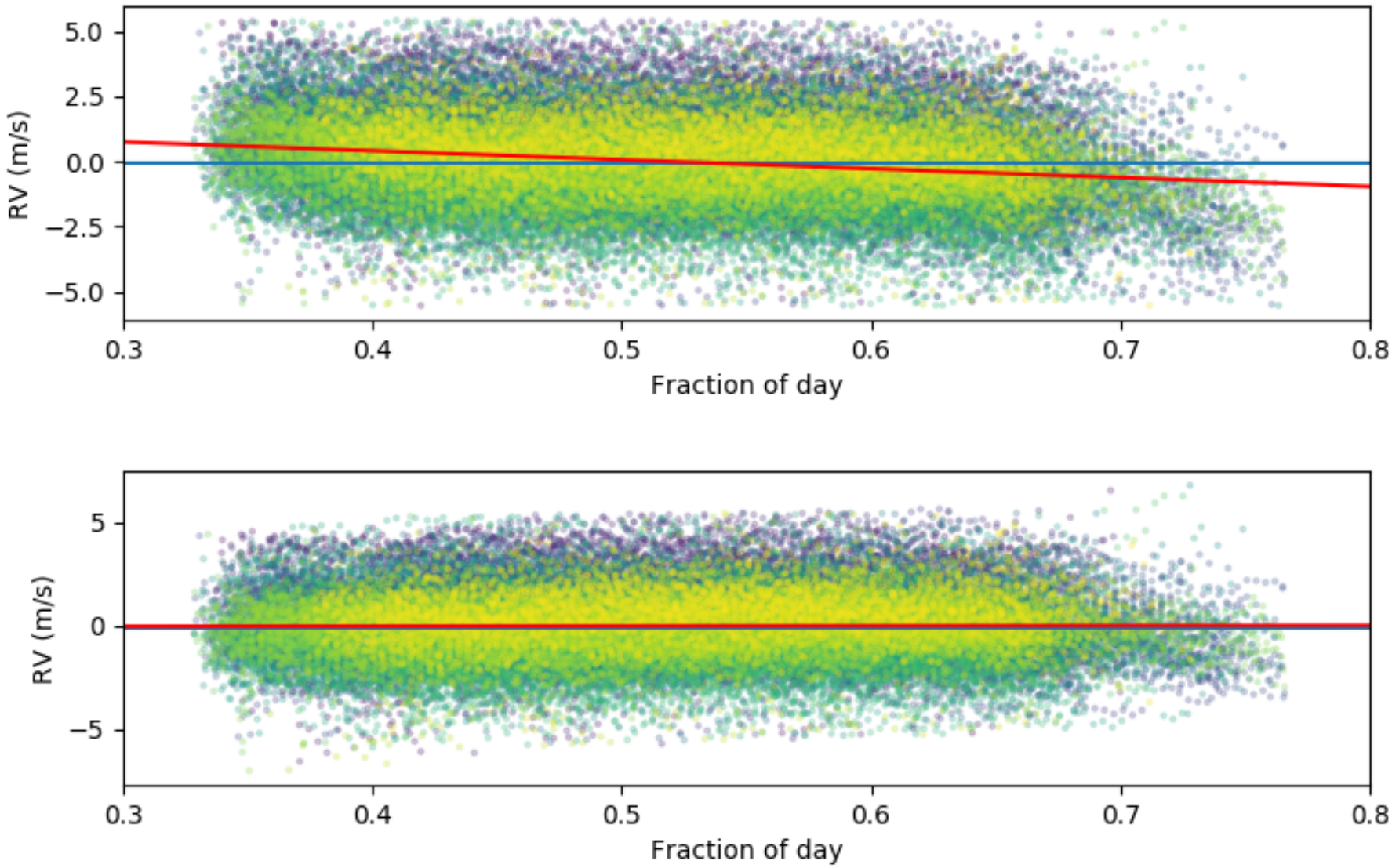
Daily downwards trend - due to differential extinction?



(Adapted from Collier Cameron, Mortier et al. 2019)

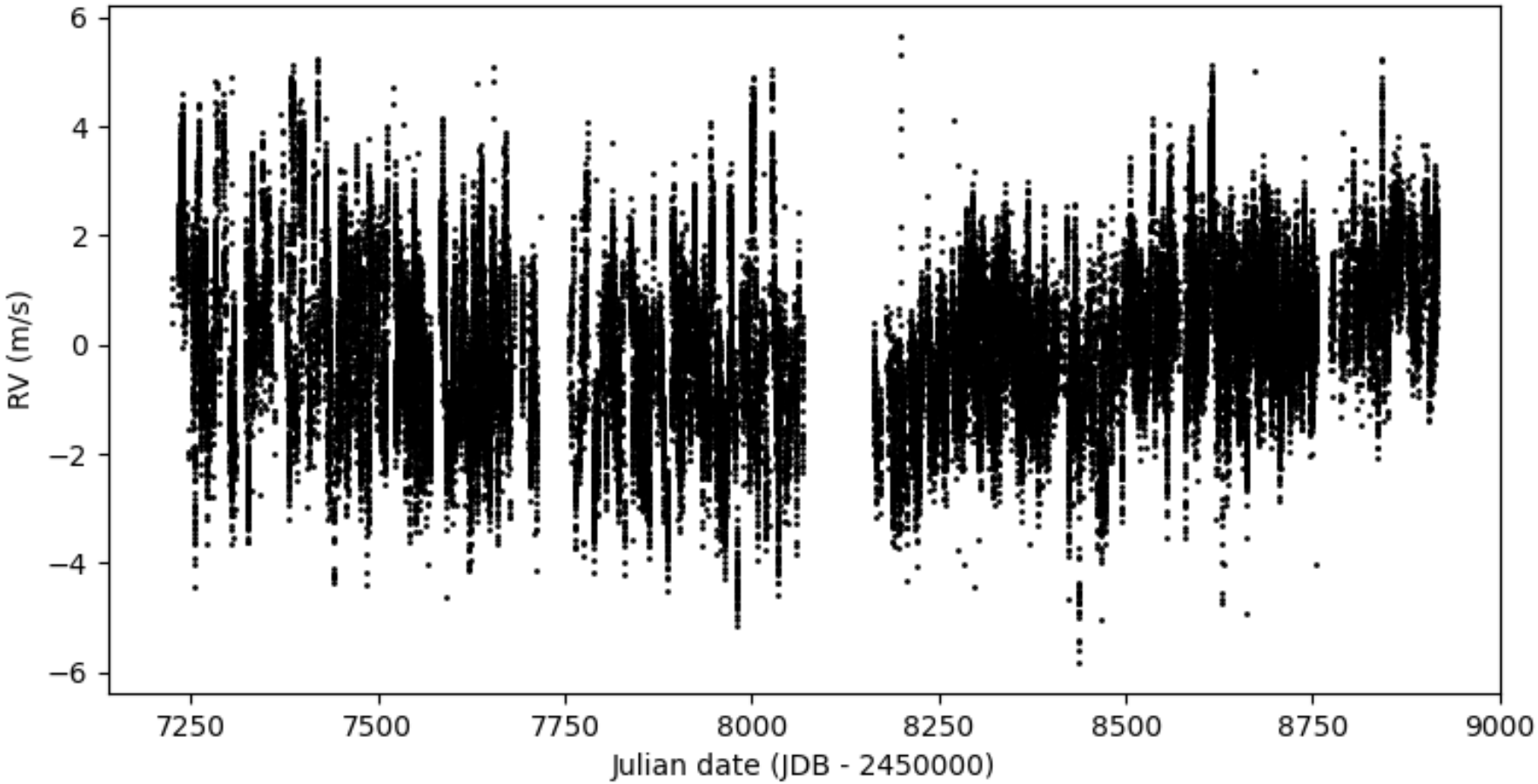
Unlike stars, the Sun is resolved in the sky, creating additional issues in treating it as a star.

Correct for differential extinction - rms still 1.6 m/s!



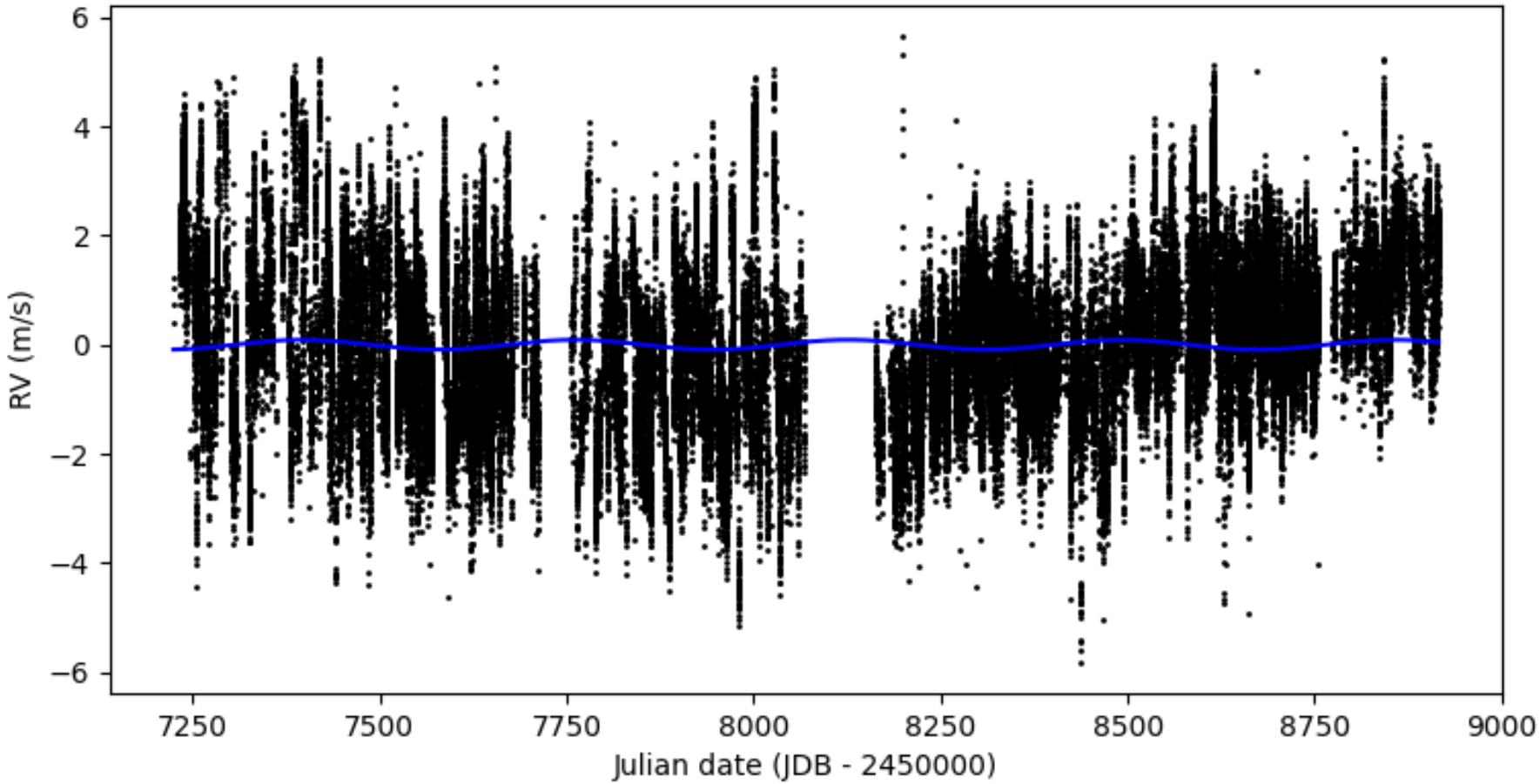
(Adapted from Collier Cameron, Mortier et al. 2019)

HARPS-N now has 5 full years of data



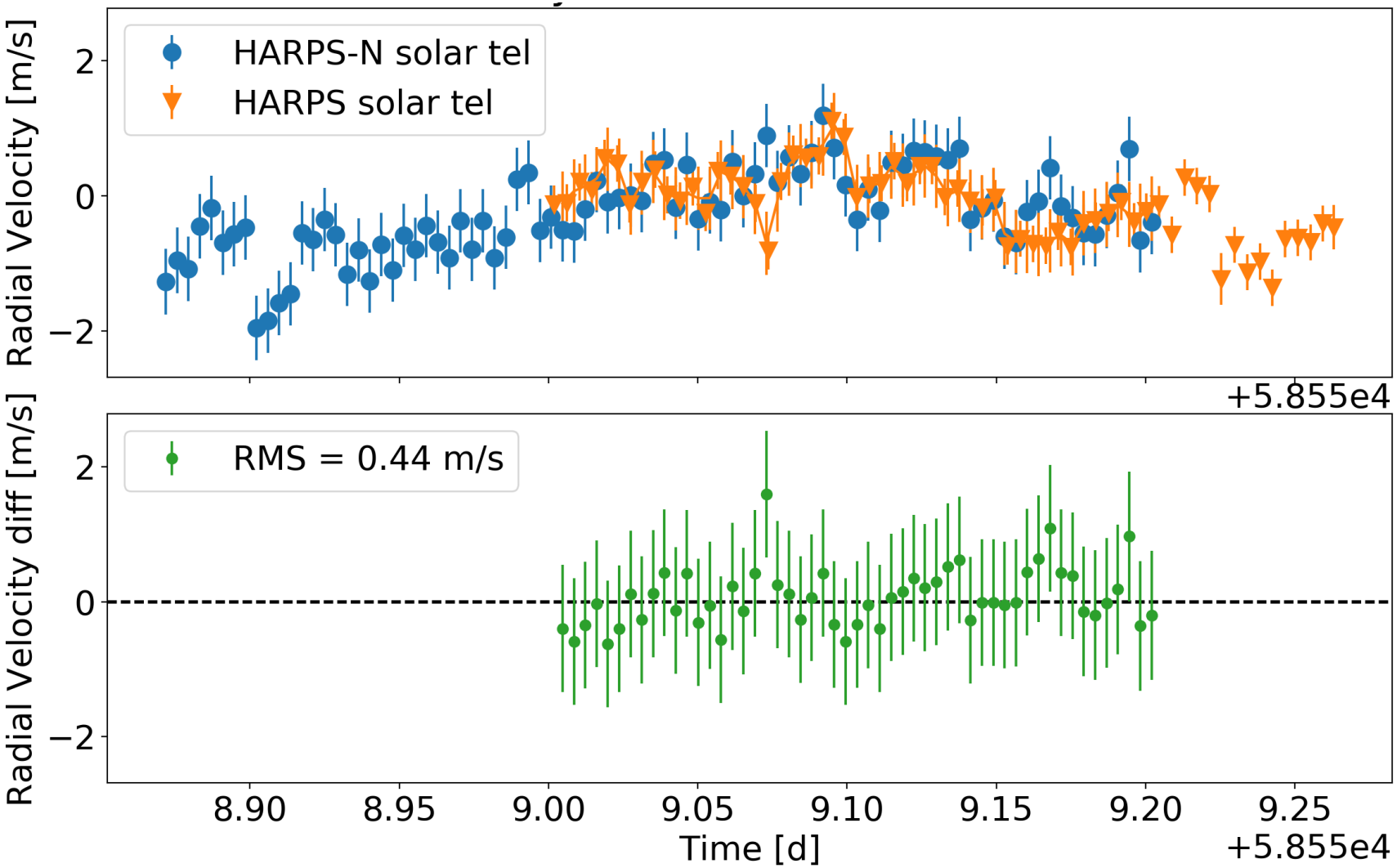
First three years of spectra, CCFs (homogeneously reduced) will be released 1st September 2020 through DACE.

Let's remind ourselves again what we're looking for



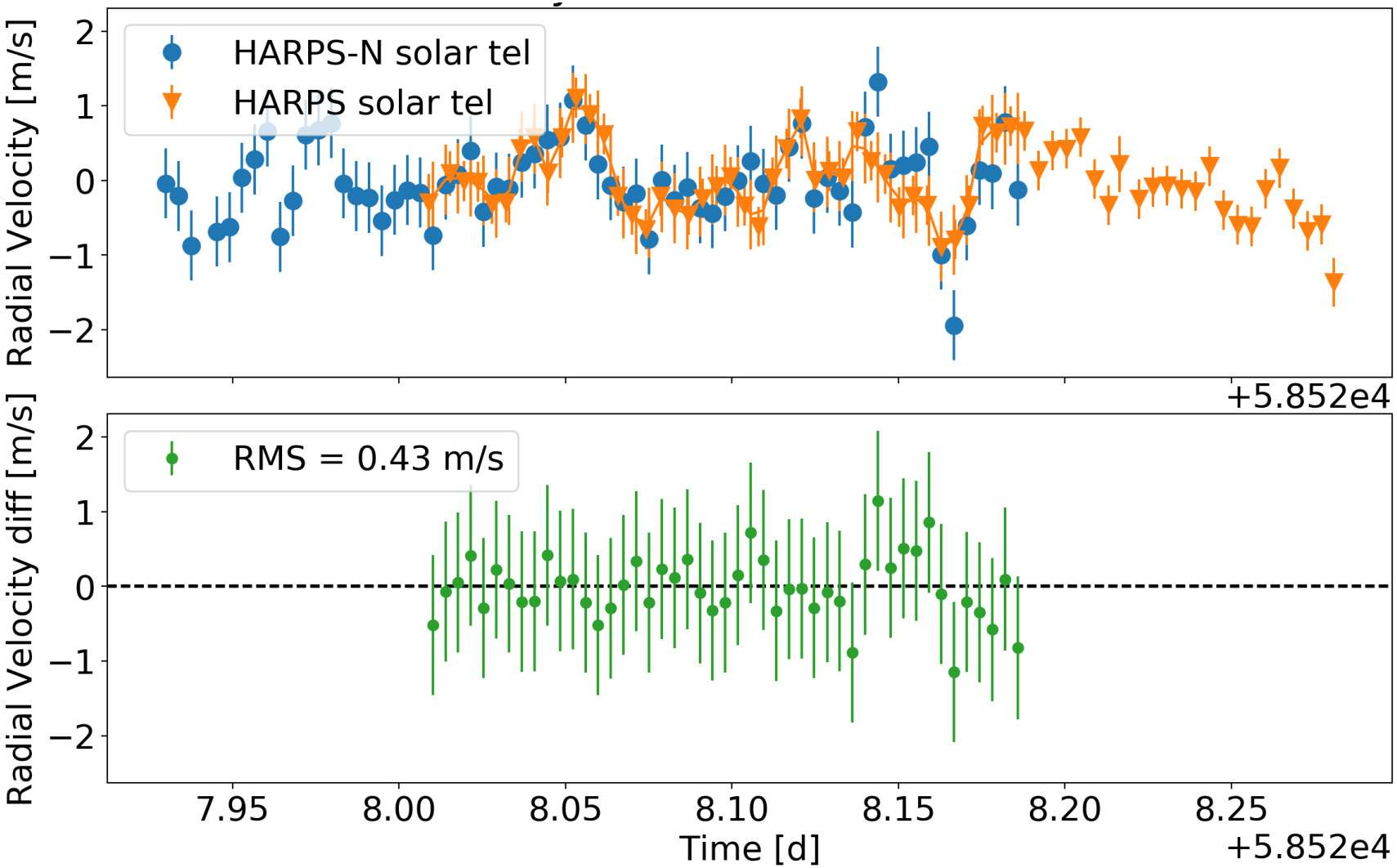
Finding an Earth twin remains a non-straightforward challenge, even for quiet stars (Sun is at solar minimum).

The power of the HARPS-N – HELIOS combo



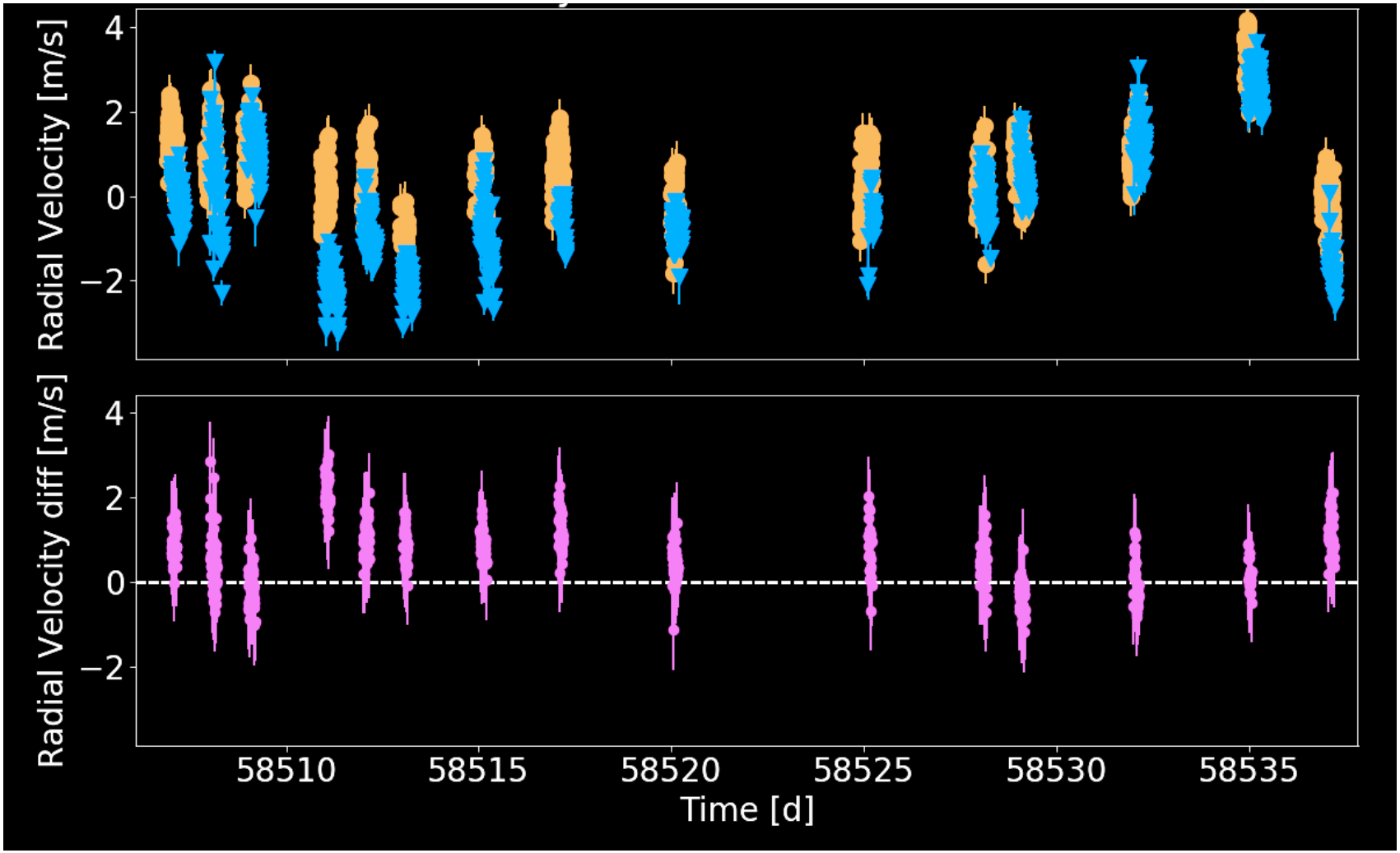
Courtesy X. Dumusque

Activity-induced RV variations are unpredictable



Courtesy X. Dumusque

Issues revealed with daily calibration jumps

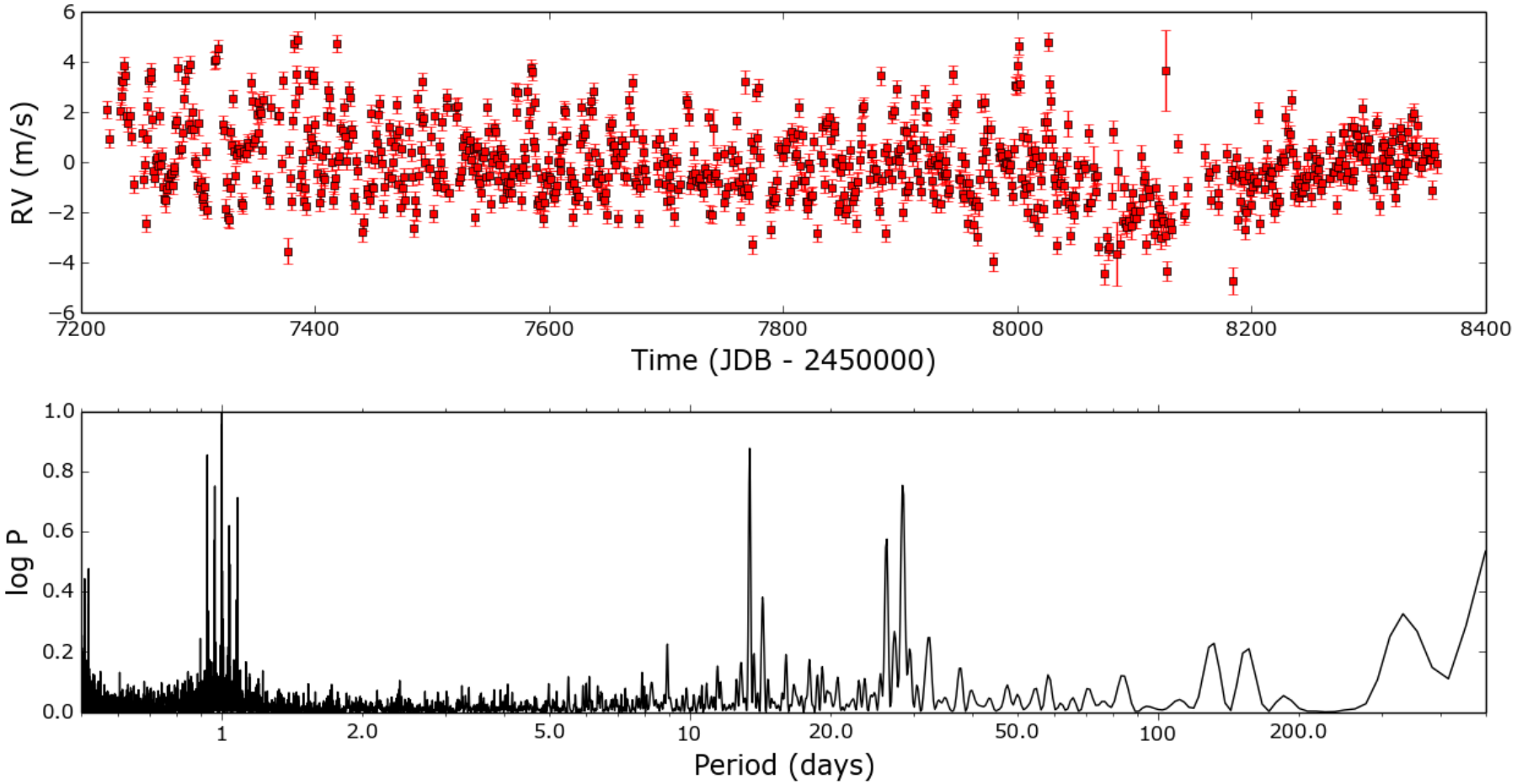


(Courtesy: X. Dumusque)

New pipeline resolves this. Data releases will be under new pipeline.

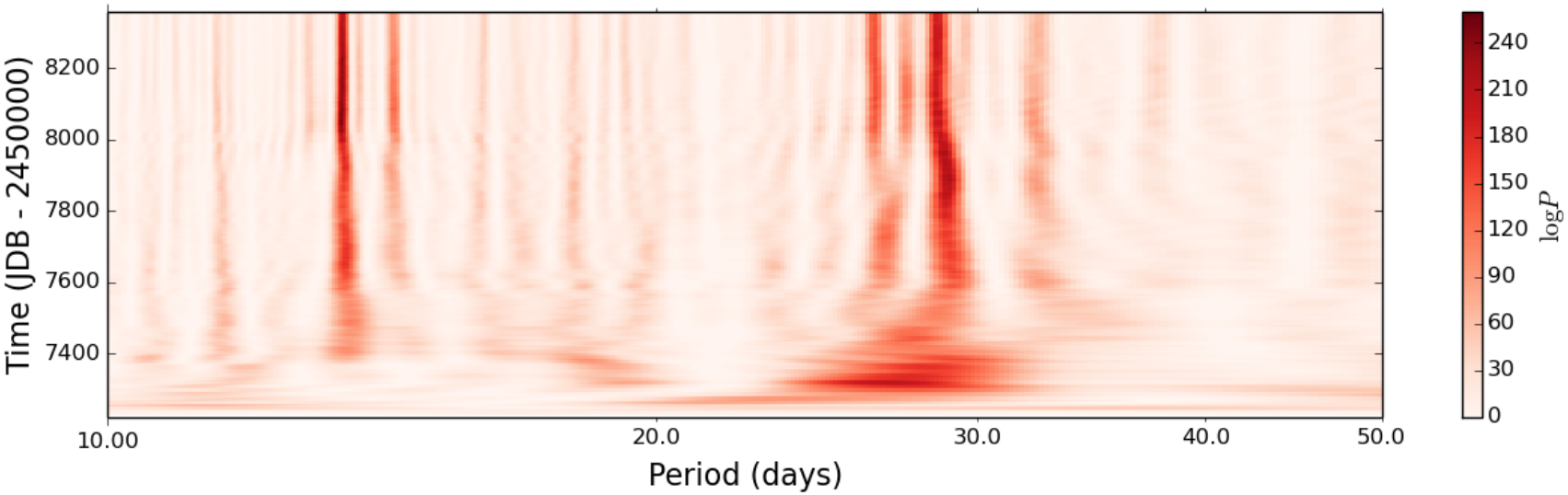
Does the data contain a solar rotational signal?

Solar RVs for $\sim$ 3 years - binned per day



(Data: Collier Cameron, Mortier et al. 2019. BGLS periodogram: Mortier et al. 2015)

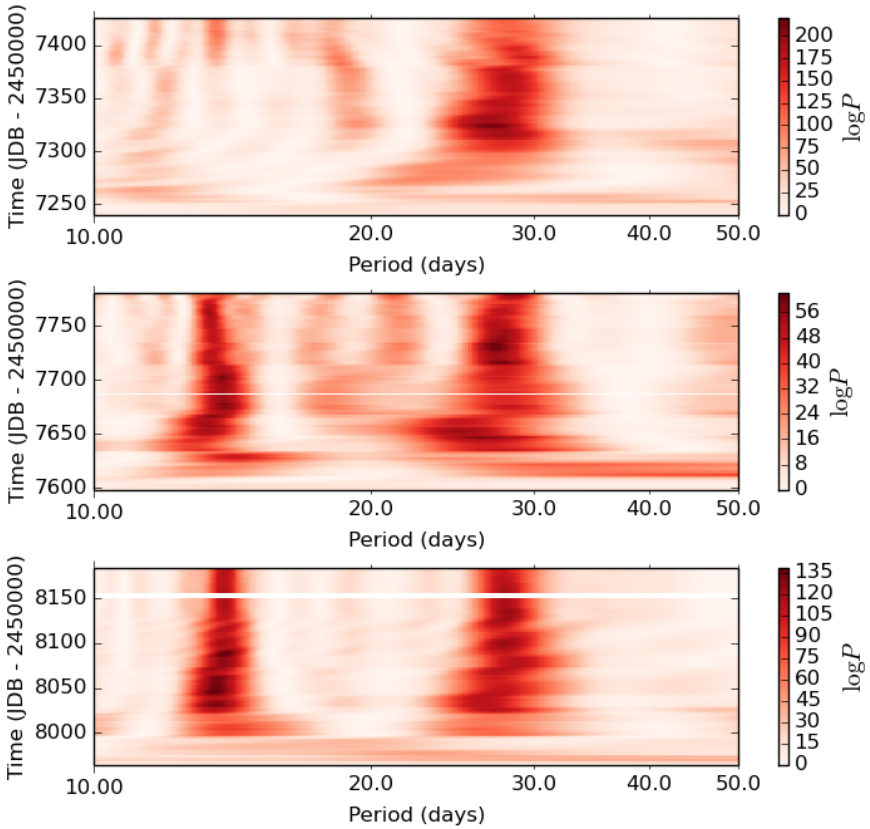
Solar rotation

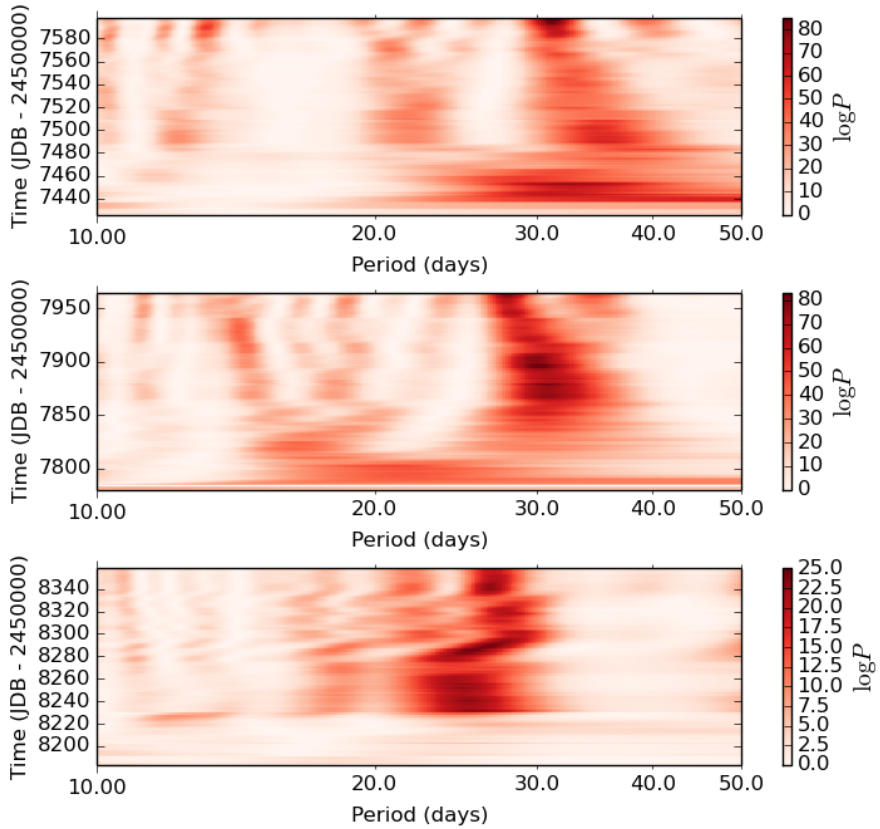


Solar rotation at ~ 28 days
and its harmonic at ~ 13 days
clearly visible and unstable over time.

(Data: Collier Cameron, Mortier et al. 2019. Stacking periodograms: Mortier et al. 2015, 2017)

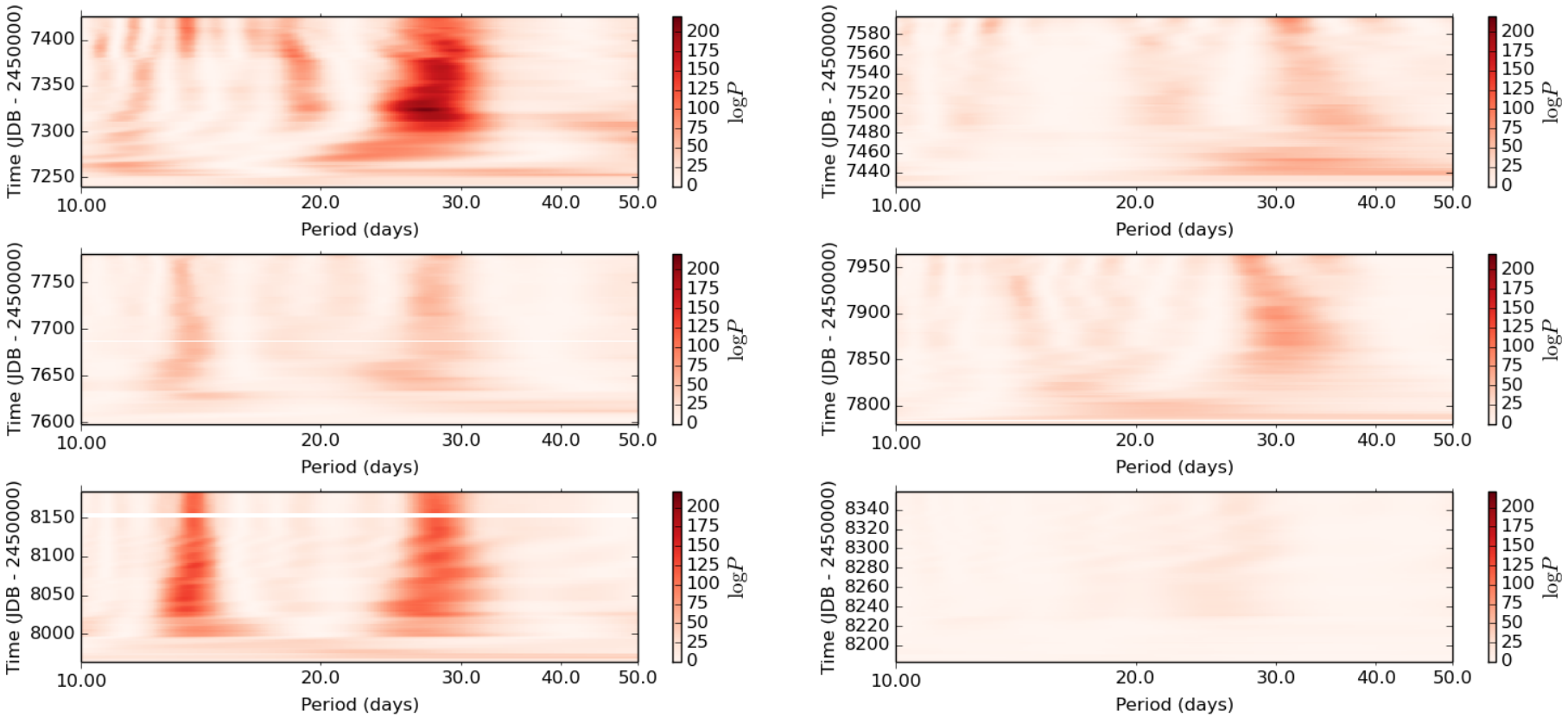
Data split in semesters





Strongest periodicity and its strength highly variable.

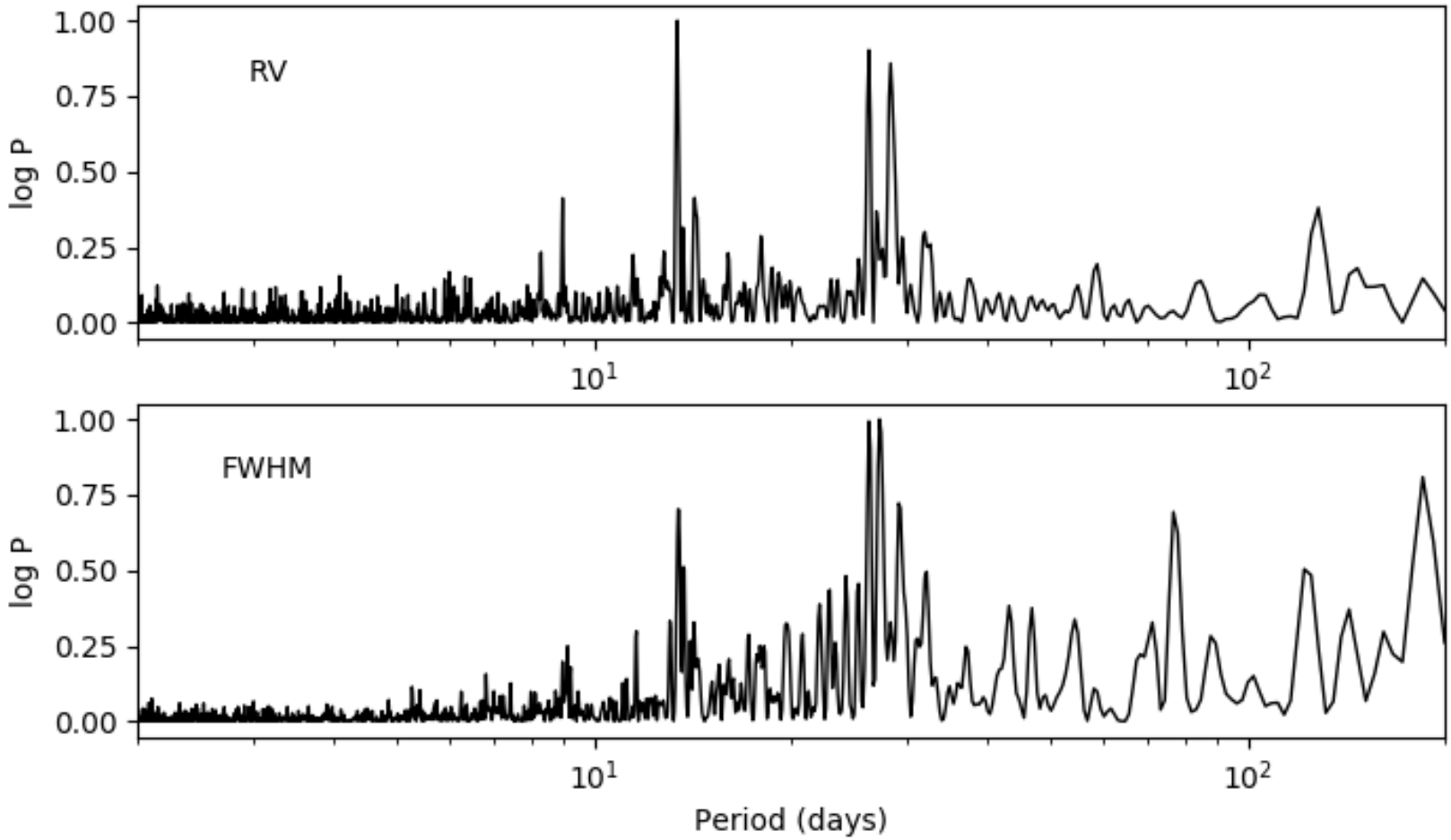
Data split in semesters



Strongest periodicity and its strength highly variable.

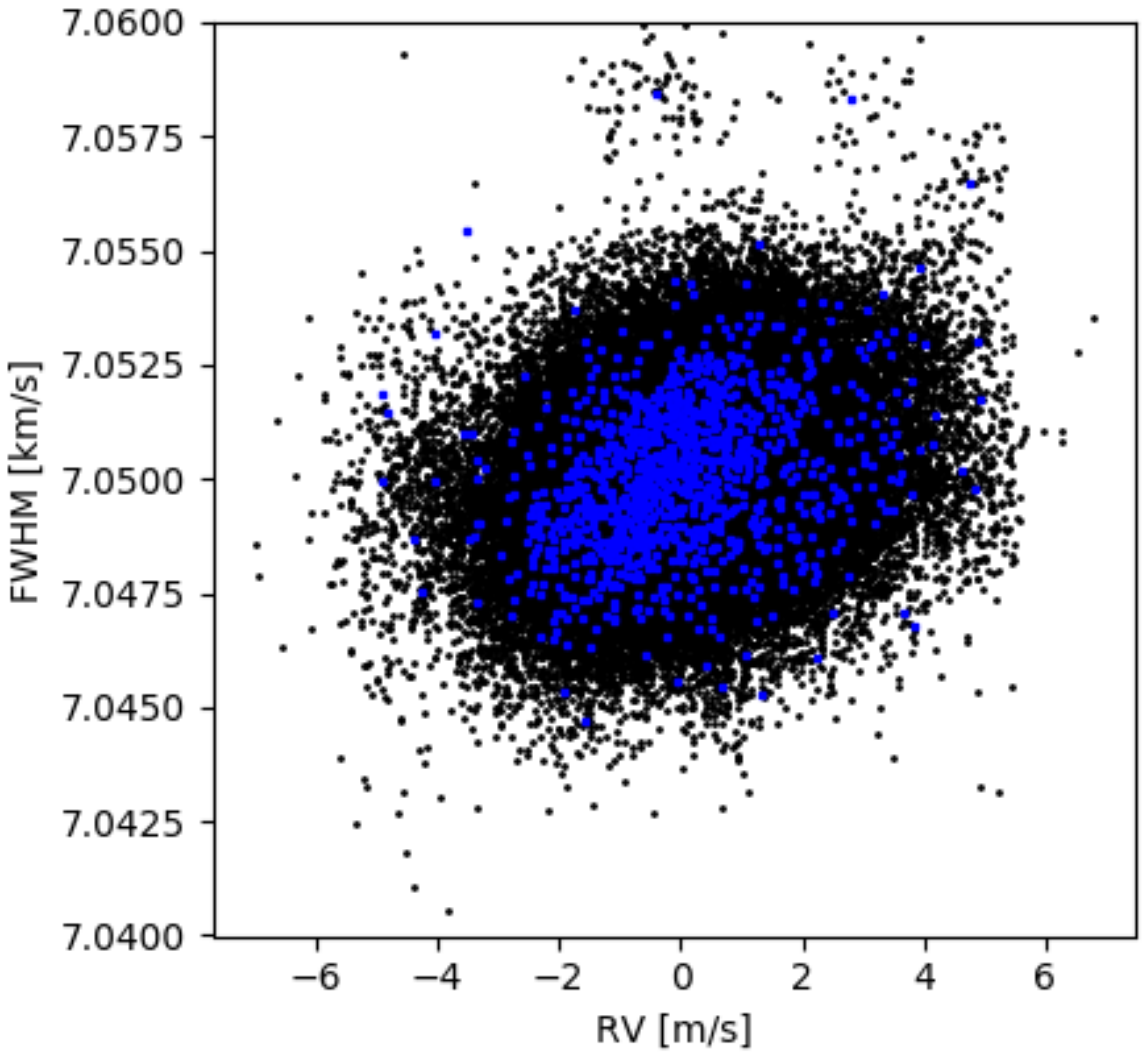
What about our activity indicators?

RV and FWHM show similar periodicity behaviour



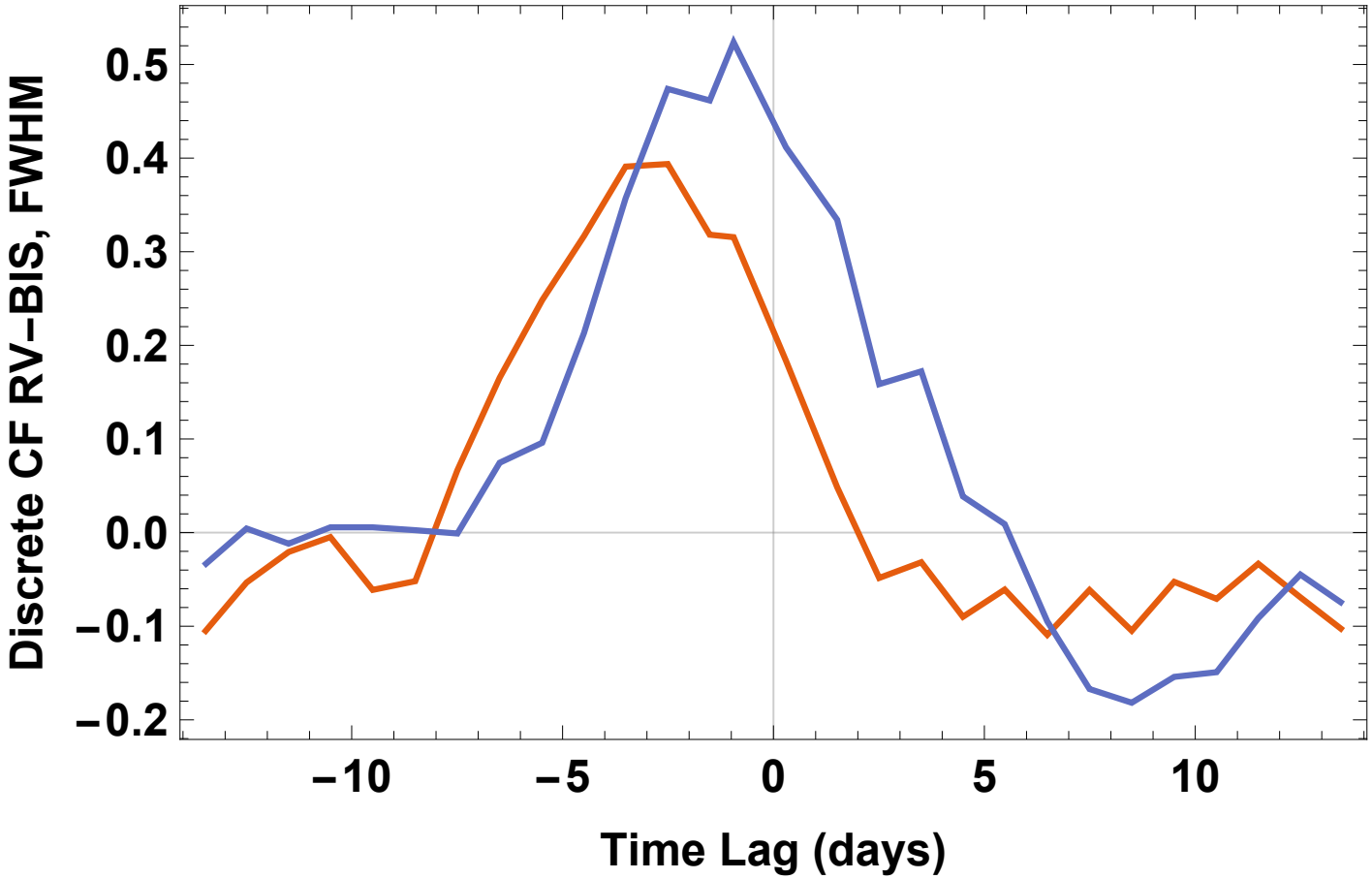
(using data from Collier Cameron, Mortier et al. 2019)

Similar periodicity behaviour - no correlation?



(using data from Collier Cameron, Mortier et al. 2019)

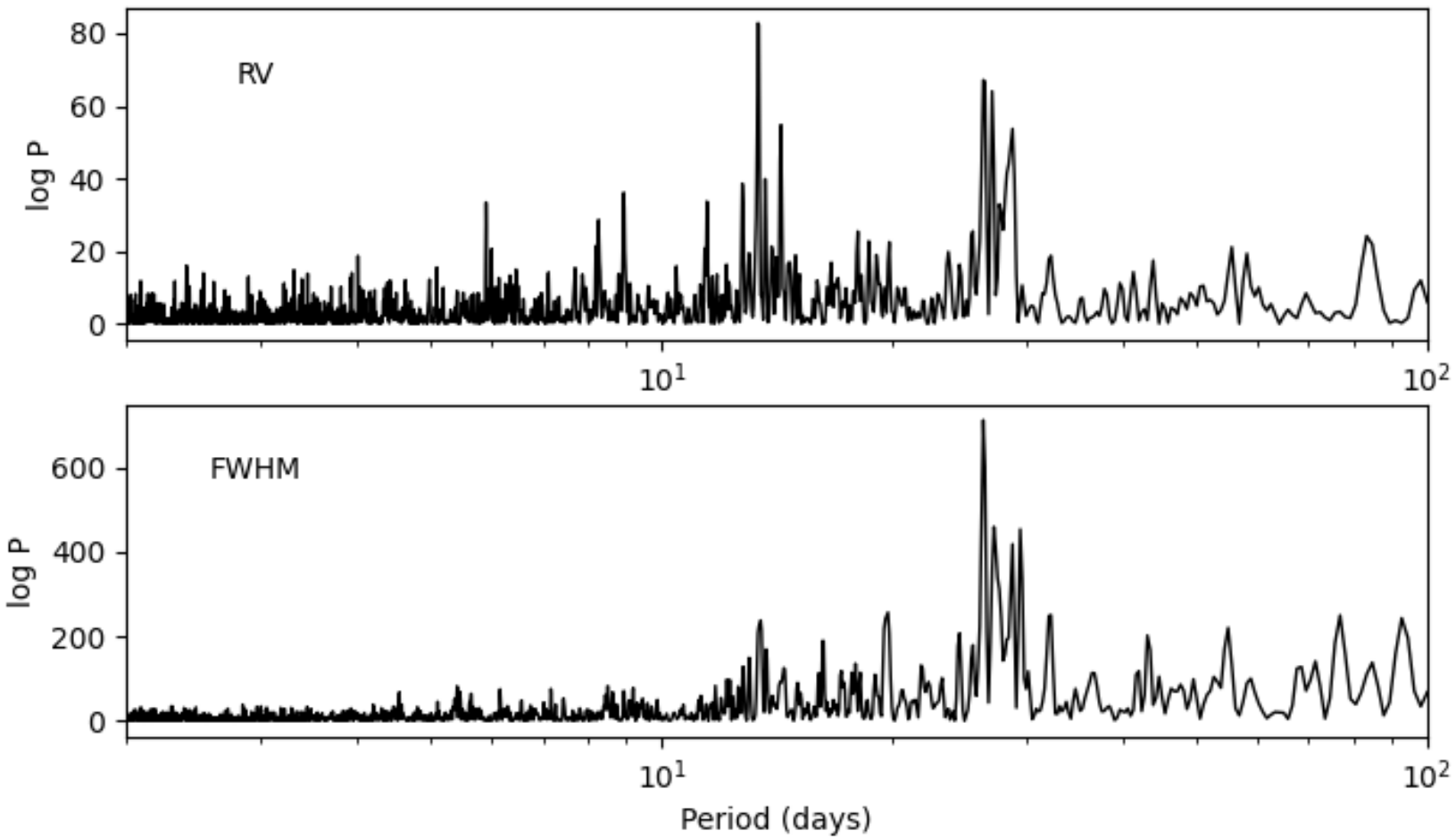
Time lag between RV, FWHM, BIS, ...



(Collier Cameron, Mortier et al. 2019)

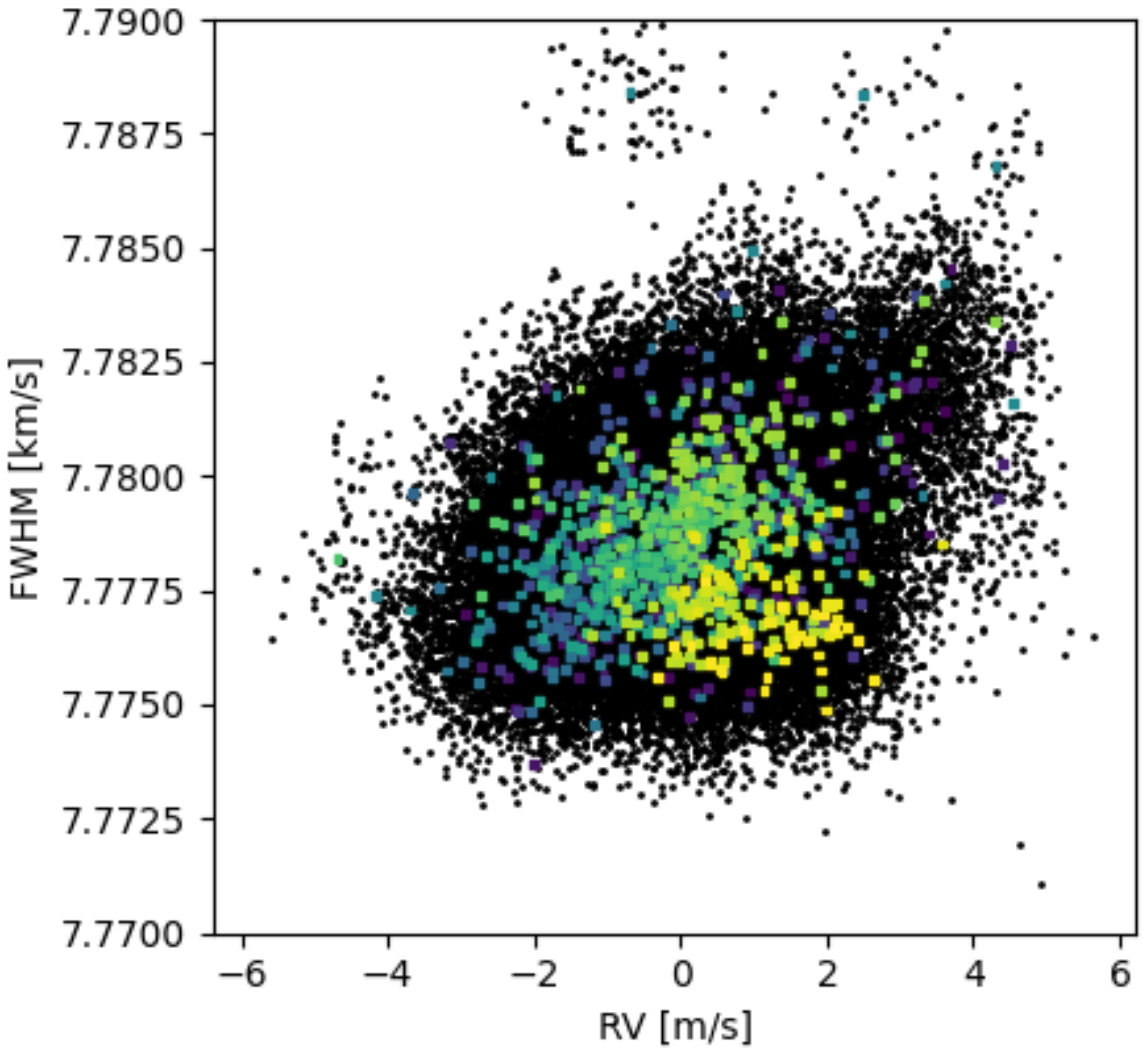
Temporal offset between RV, FWHM, BIS weakens their correlation.

Let's use all the data - including solar minimum



(using the full 5 years of HARPS-N solar data)

Is there an additional time dependence?



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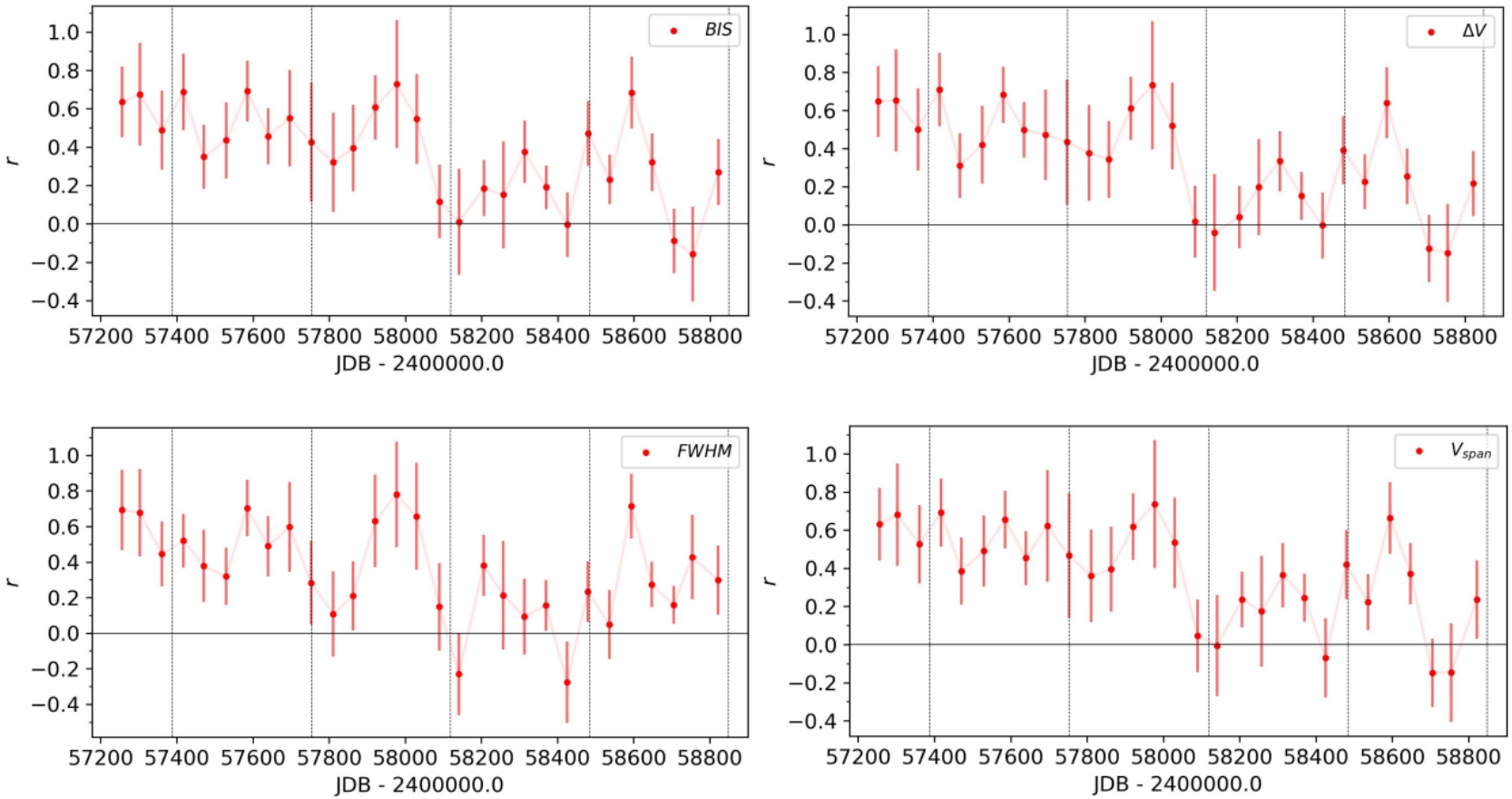
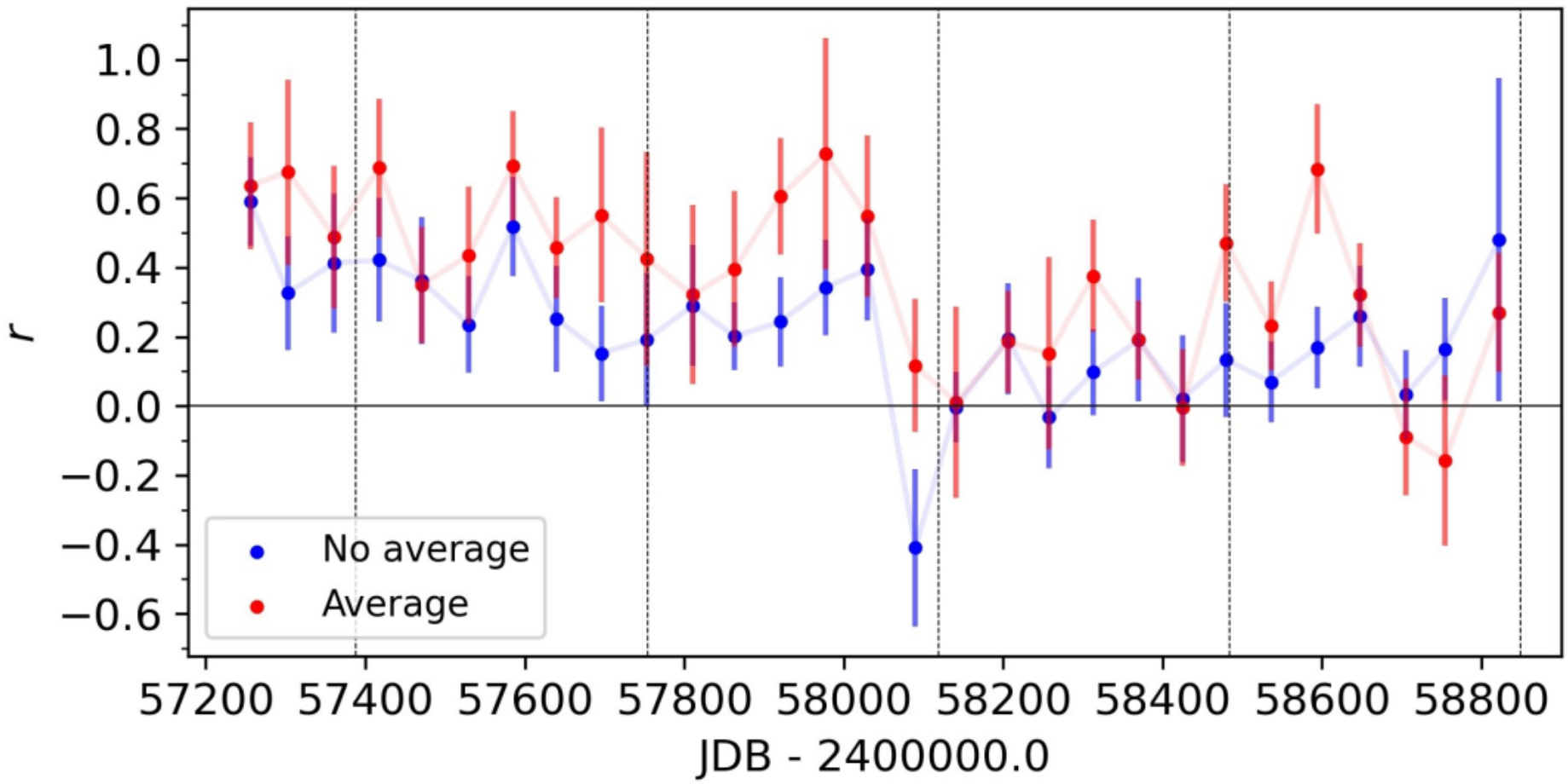
Correlation gets weaker with Sun going in Solar minimum



(done by James Hazzard - using 4.5yr of HARPS-N solar data)

With Sun going firmly into solar minimum, correlations get weaker or even disappear.

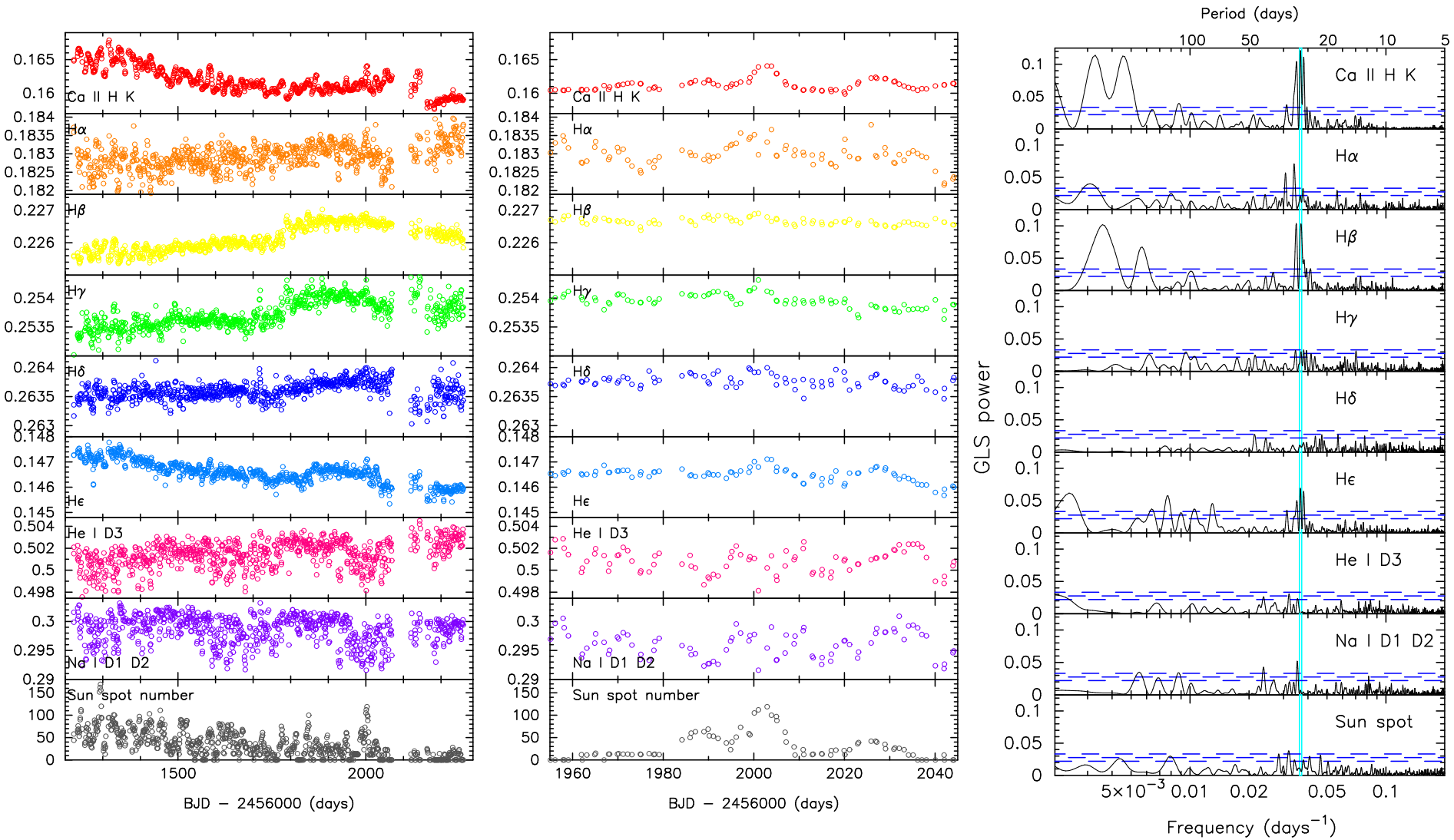
Daily binning to control granulation



(done by James Hazzard - using 4.5yr of HARPS-N solar data)

Binning densely sampled data, helps to strengthen rotationally-modulated correlations. Caveat: can we get this sampling for stars?

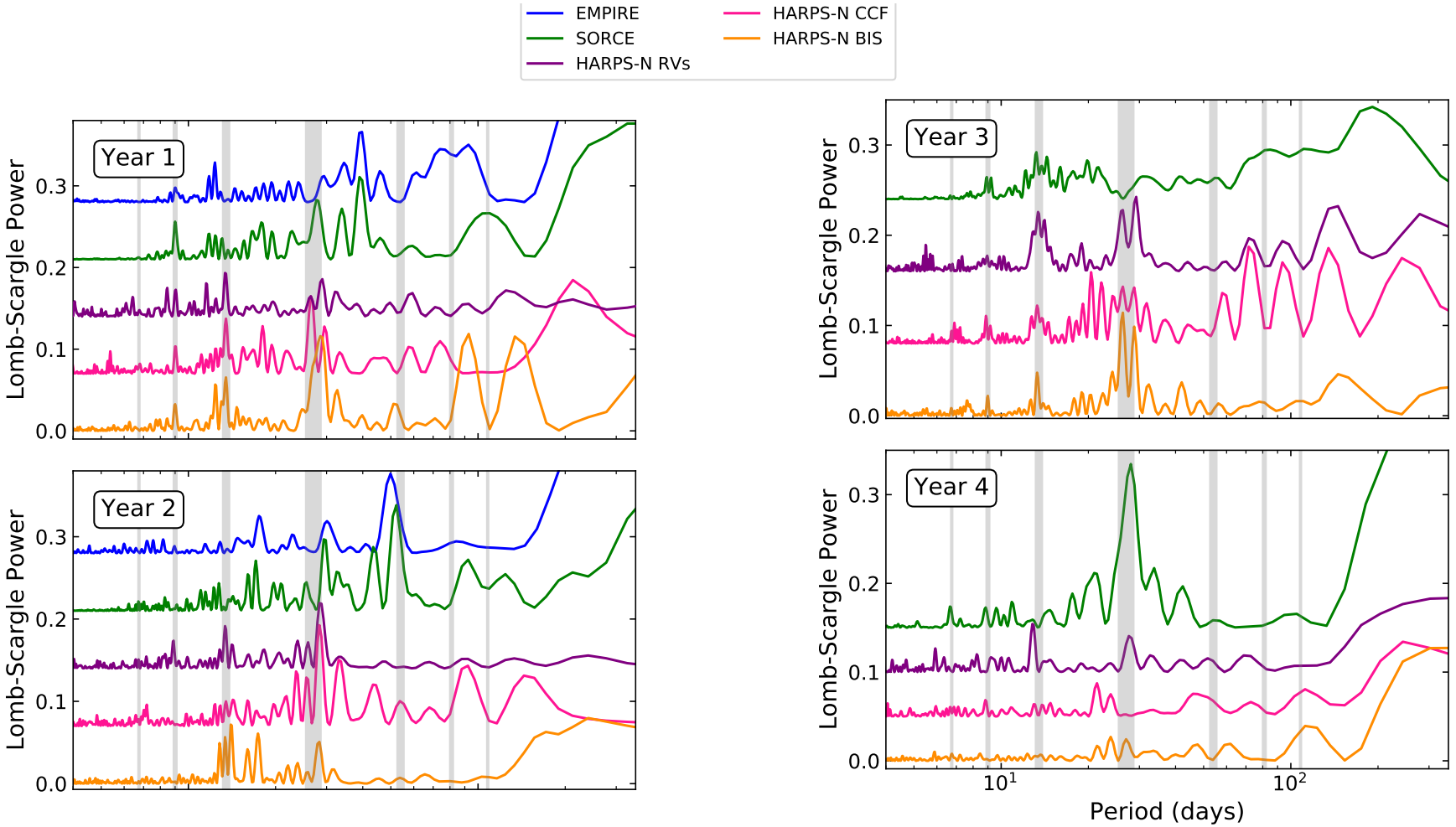
No known optical activity indicators are perfect



(Maldonado et al. 2019)

What about photometry?

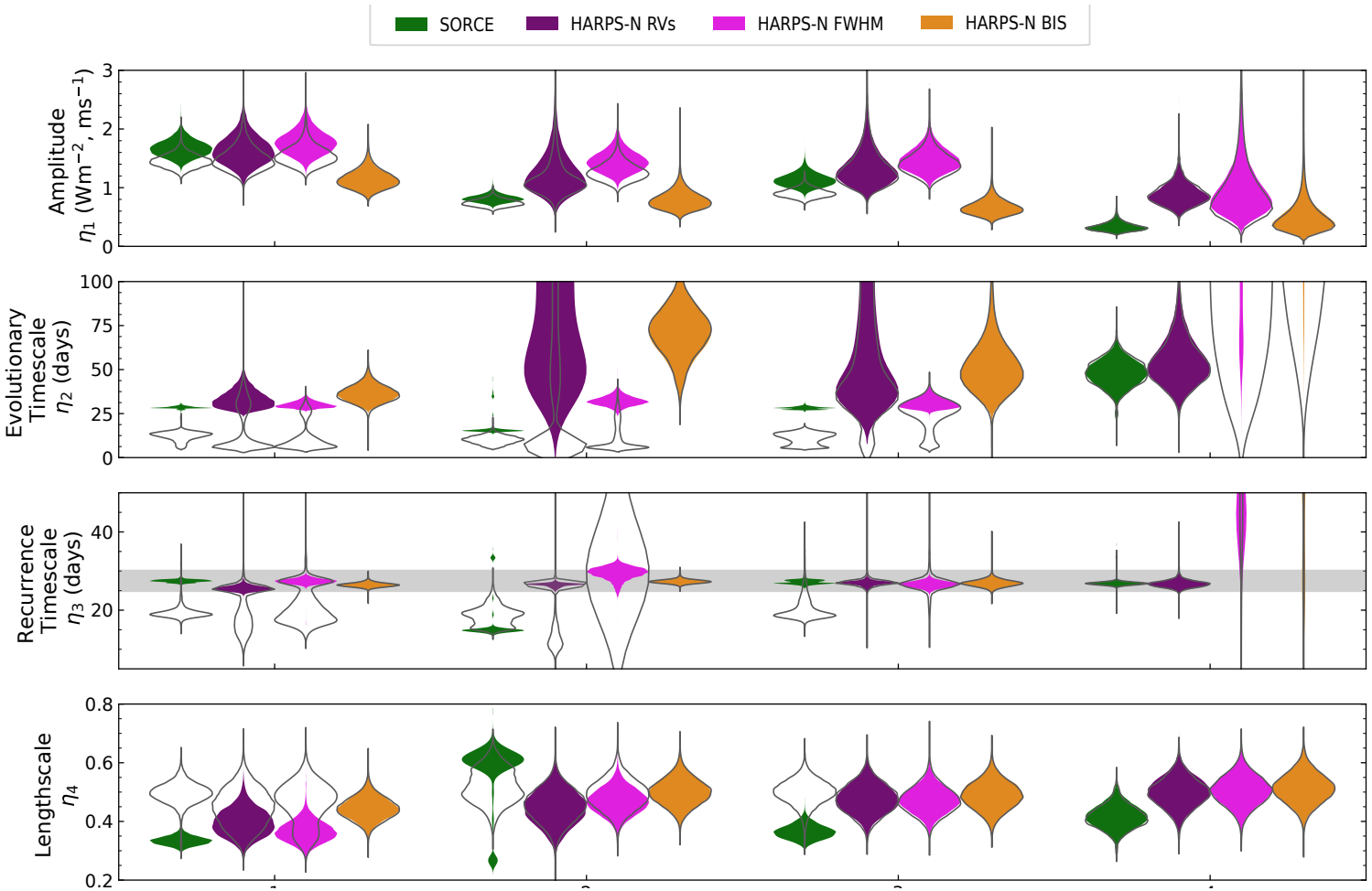
Periodograms often do not determine rotation period



(Kosiarek & Crossfield 2020)

Quasiperiodic nature of stellar variability and sparse sampling cause trouble for periodogram or ACF approach. See also Nava et al. 2020.

Using GPs much better, still not optimal (see also talk Vinesh Rajpaul)



(Kosiarek & Crossfield 2020)

Photometry can be helpful, but does not always trace the same variability.

Smallest active regions do not matter for RVs

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HARPS-N Solar RVs Are Dominated by Large, Bright Magnetic Regions

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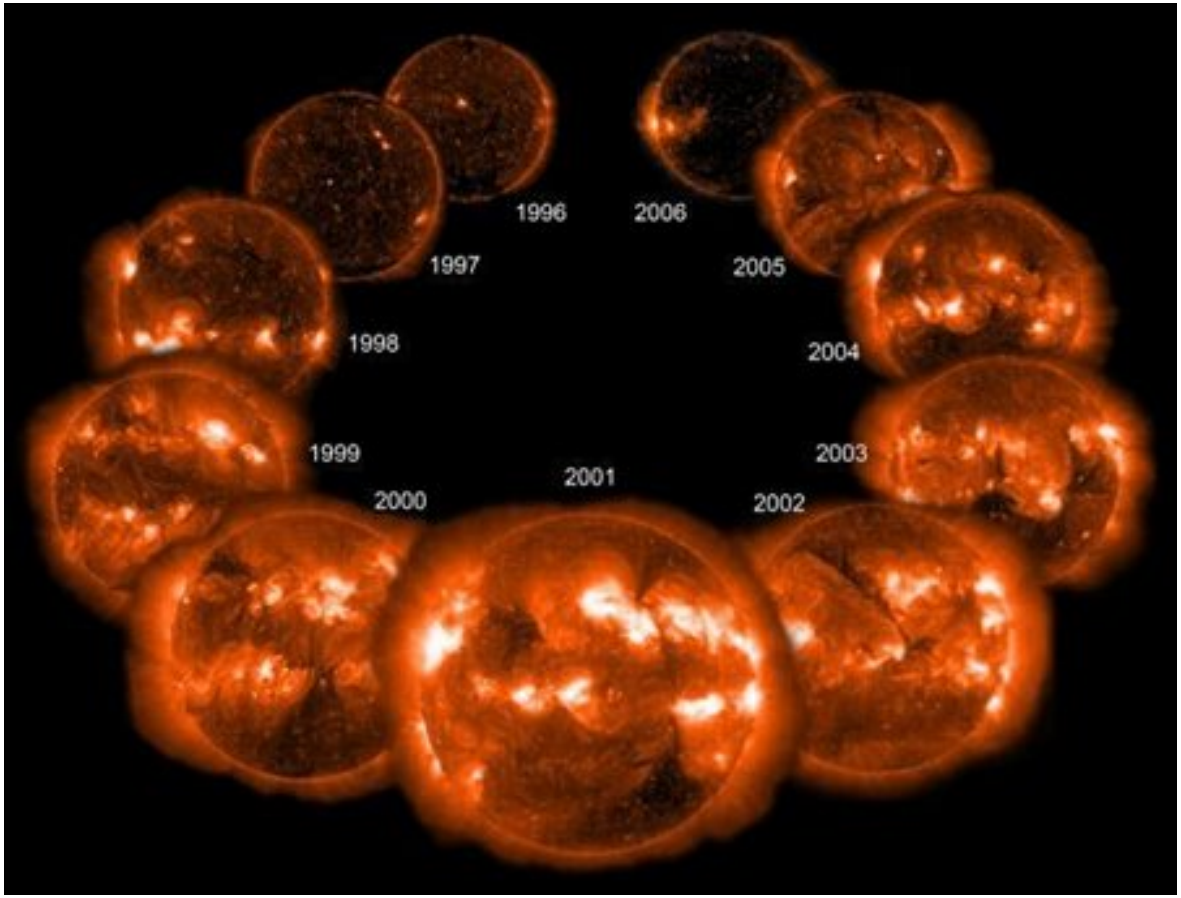
Abstract

State-of-the-art radial-velocity (RV) exoplanet searches are currently limited by RV signals arising from stellar magnetic activity. We analyze solar observations acquired over a 3 yr period during the decline of Carrington Cycle 24 to test models of RV variation of Sun-like stars. A purpose-built solar telescope at the High Accuracy Radial-velocity Planet Searcher for the Northern hemisphere (HARPS-N) provides disk-integrated solar spectra, from which we extract RVs and $\log R'_{\rm HK}$. The *Solar Dynamics Observatory* (*SDO*) provides disk-resolved images of magnetic activity. The Solar Radiation and Climate Experiment (SORCE) provides near-continuous solar photometry, analogous to a *Kepler* light curve. We verify that the SORCE photometry and HARPS-N $\log R'_{\rm HK}$ correlate strongly with the *SDO*-derived magnetic filling factor, while the HARPS-N RV variations do not. To explain this discrepancy, we test existing models of RV variations. We estimate the contributions of the suppression of convective blueshift and the rotational imbalance due to brightness inhomogeneities to the observed HARPS-N RVs. We investigate the time variation of these contributions over several rotation periods, and how these contributions depend on the area of active regions. We find that magnetic active regions smaller than 60 $\rm Mm^2$ do not significantly suppress convective blueshift. Our area-dependent model reduces the amplitude of activity-induced RV variations by a factor of two. The present study highlights the need to identify a proxy that correlates specifically with large, bright magnetic regions on the surfaces of exoplanet-hosting stars.

Lessons learned from Sun-as-a-star observations

- The Sun is the only star we'll ever be sure has no planets "in the data"
- Observing the Sun-as-a-star requires more careful data processing, but it can also help to improve the instrument and pipeline
- Suppression of convective blueshift is the main source of RV variations
- Even in solar minimum, variations extend 1m/s
- Magnetic flux density traces RV variations best
- Traditional activity indicators show weakened correlation with RV
- No known simultaneous activity indicator trace the RV variations well
- Binning densely sampled data improves correlations
  $\rightarrow$ granulation not traced by indicators?
- Simultaneous photometry can help, when analysed carefully with GPs
- Large bright magnetic regions dominate RV variations

To know/find the planet is to know its star



Studying the Sun-as-a-star helps us understand activity-induced RV variations, allows us to test models, theories, and algorithms.
It is the way forward to detecting a true Earth twin.