

Towards precise and accurate
exoplanet mass determinations

HARPS-N
observes
the Sun

Raphaëlle D. Haywood (CfA)
and the HARPS-N science team



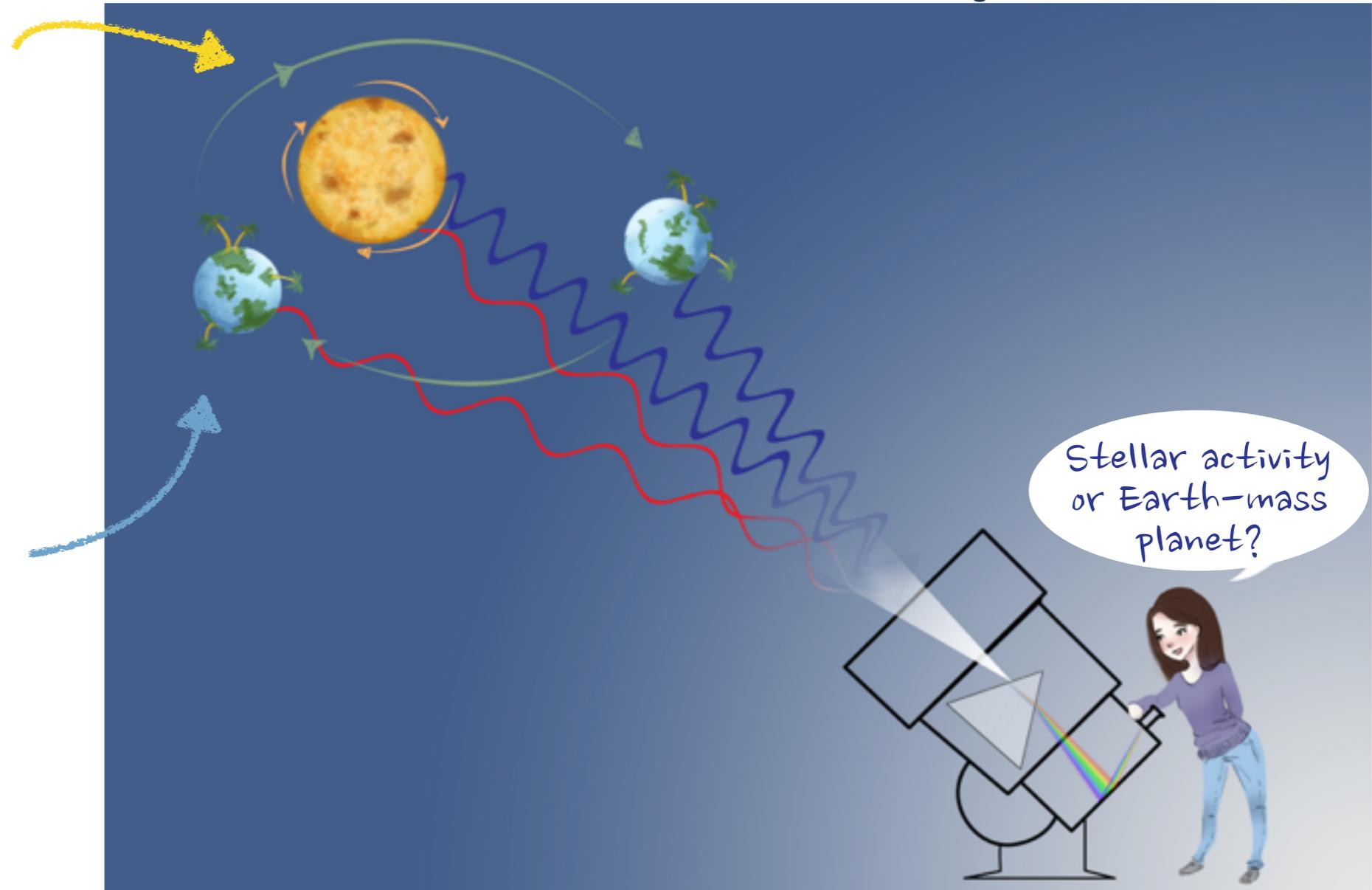
Why get radial-velocity observations of the Sun?

Image credit: Natalie Cameron

Even “quiet” stars have
 $\Delta RV_{\text{activity}} \approx 1\text{-}2 \text{ m/sec}$

Isaacson & Fischer 2010

Super-Earth ($5 M_{\oplus}$) at 0.1 AU:
 $\Delta RV \approx 1.4 \text{ m/sec}$

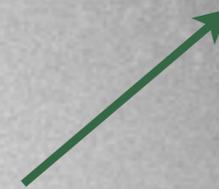


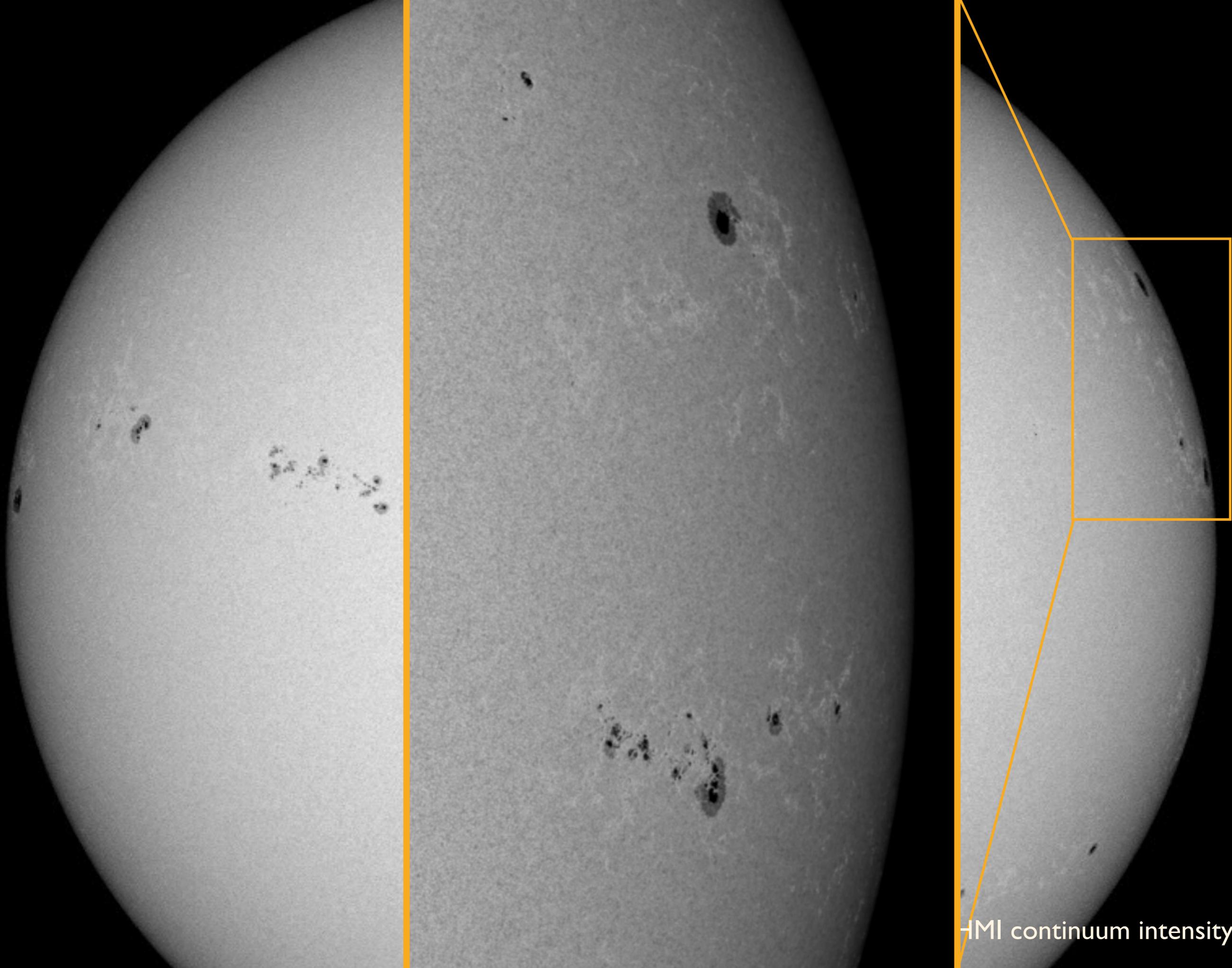
A deeper understanding of the physics behind activity-driven RV variability is key to determining precise and accurate masses of exoplanets

spots



faculae/plage

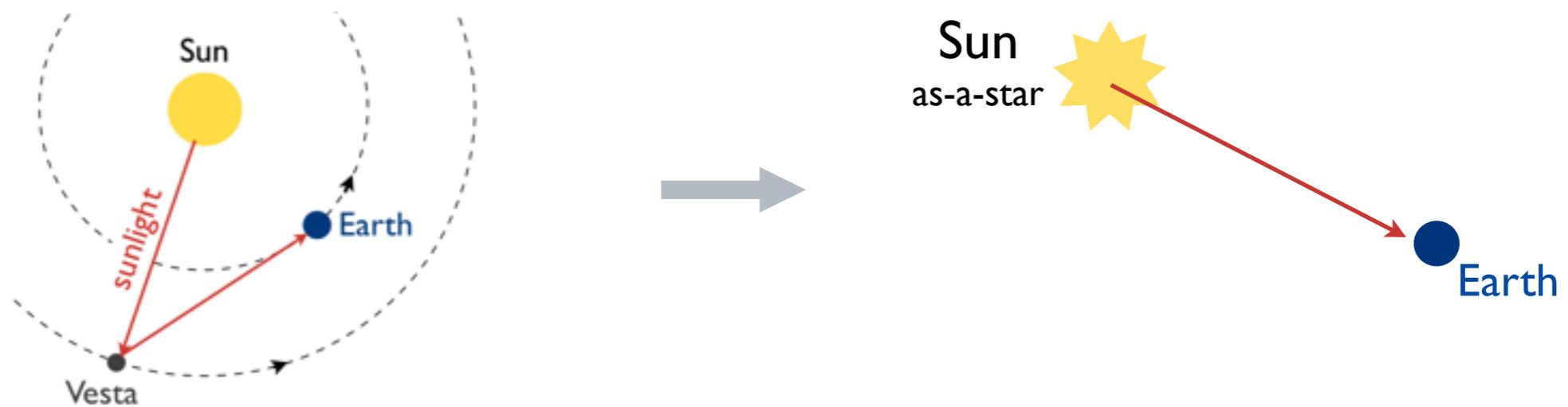




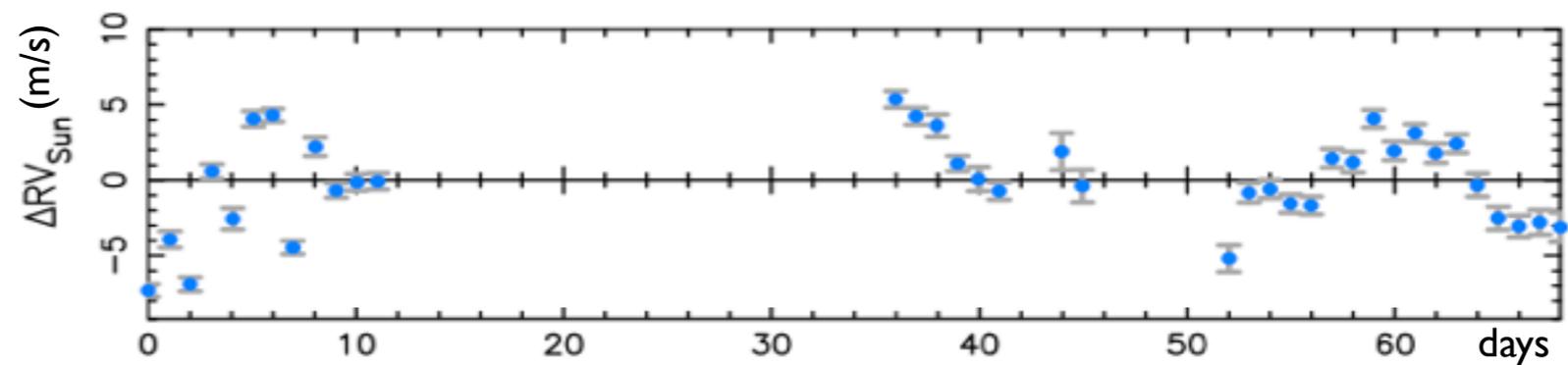
HMI continuum intensity

HARPS RVs of sunlight scattered off Vesta

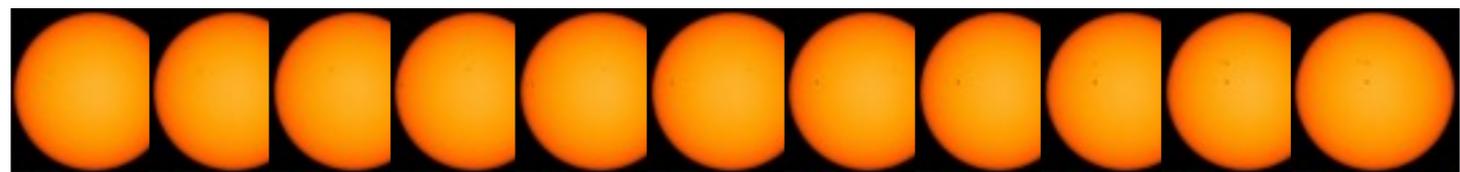
Haywood et al. (2016)



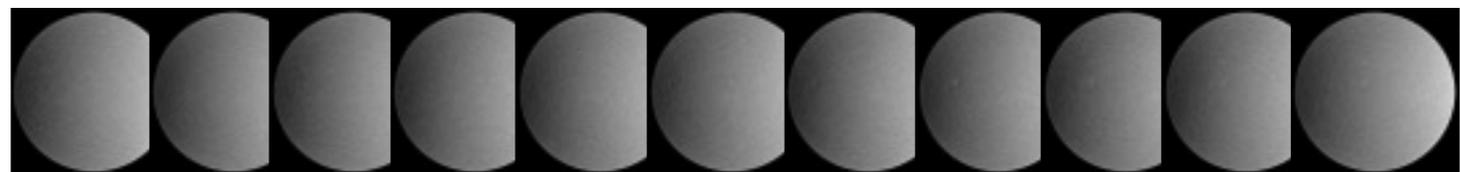
HARPS Sun as-a-star
RV variations



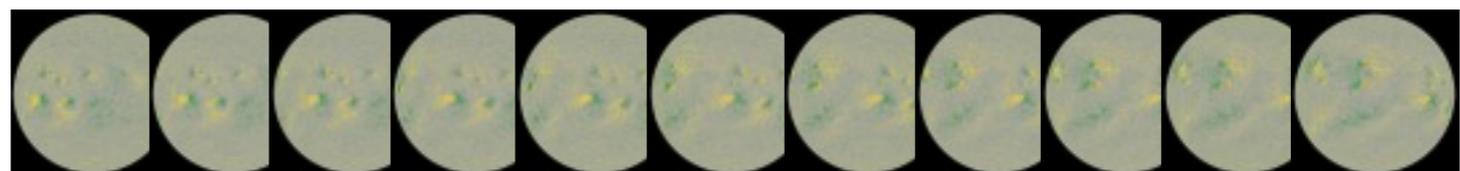
SDO/HMI continuum



Dopplergrams



magnetograms



Scale SDO/HMI-derived RV contributions to HARPS observations

HARPS observations of sunlight reflected off Vesta:
 $RV_{\text{harps}} = RV_0 + \Delta RV_{\text{vesta}} + A \Delta RV_{\text{phot}} + B \Delta RV_{\text{conv}}$

- Observed activity-driven RV variations well reproduced by this model
- Suppression of convective blueshift is dominant contribution

HARPS
Sun as-a-star
RVs

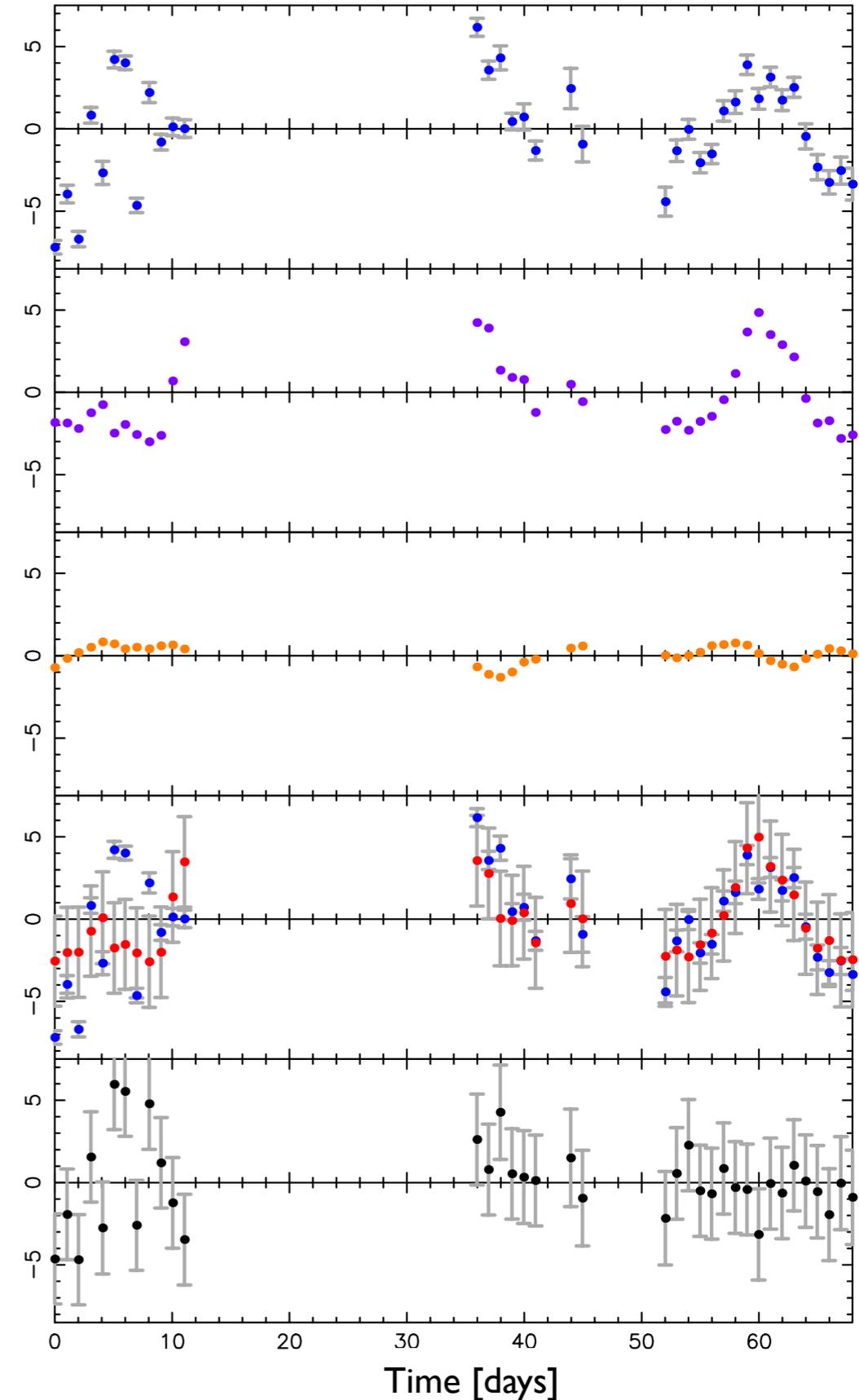
ΔRV_{conv}

ΔRV_{phot}

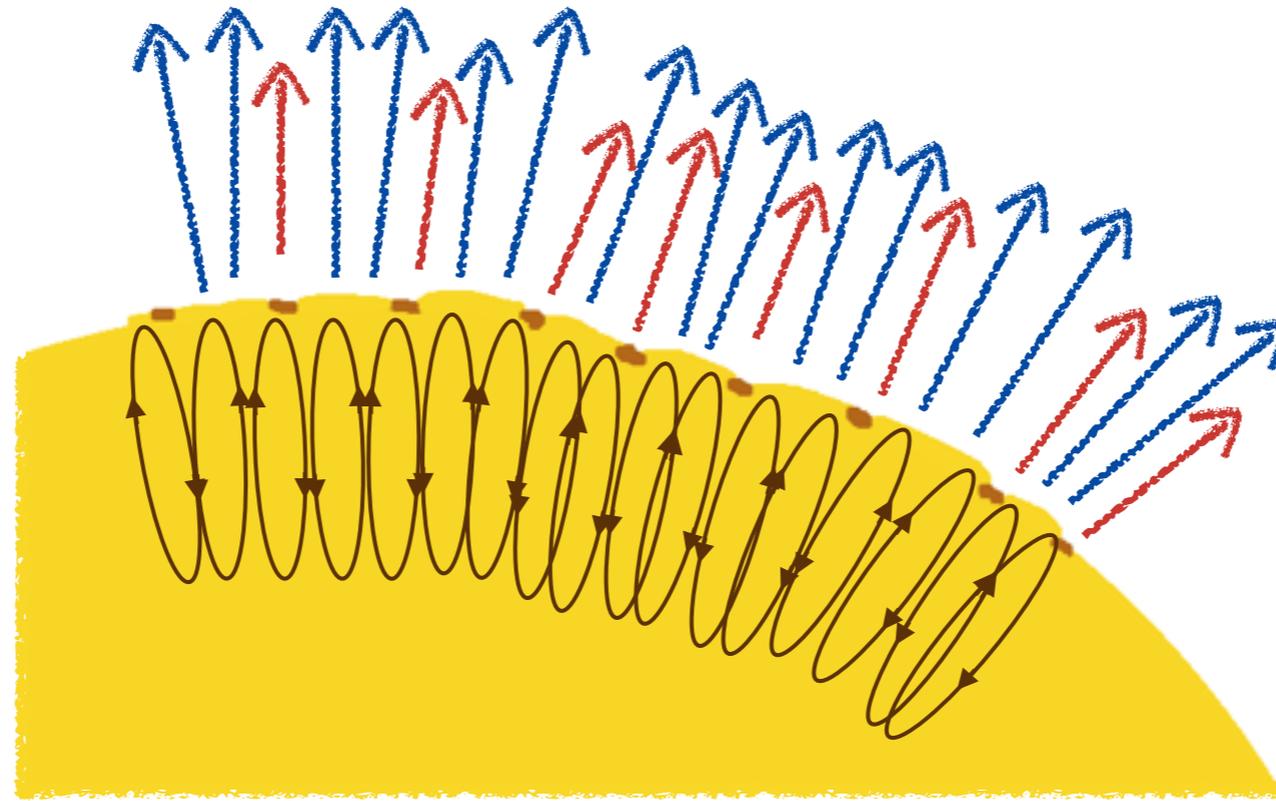
Model

Residuals

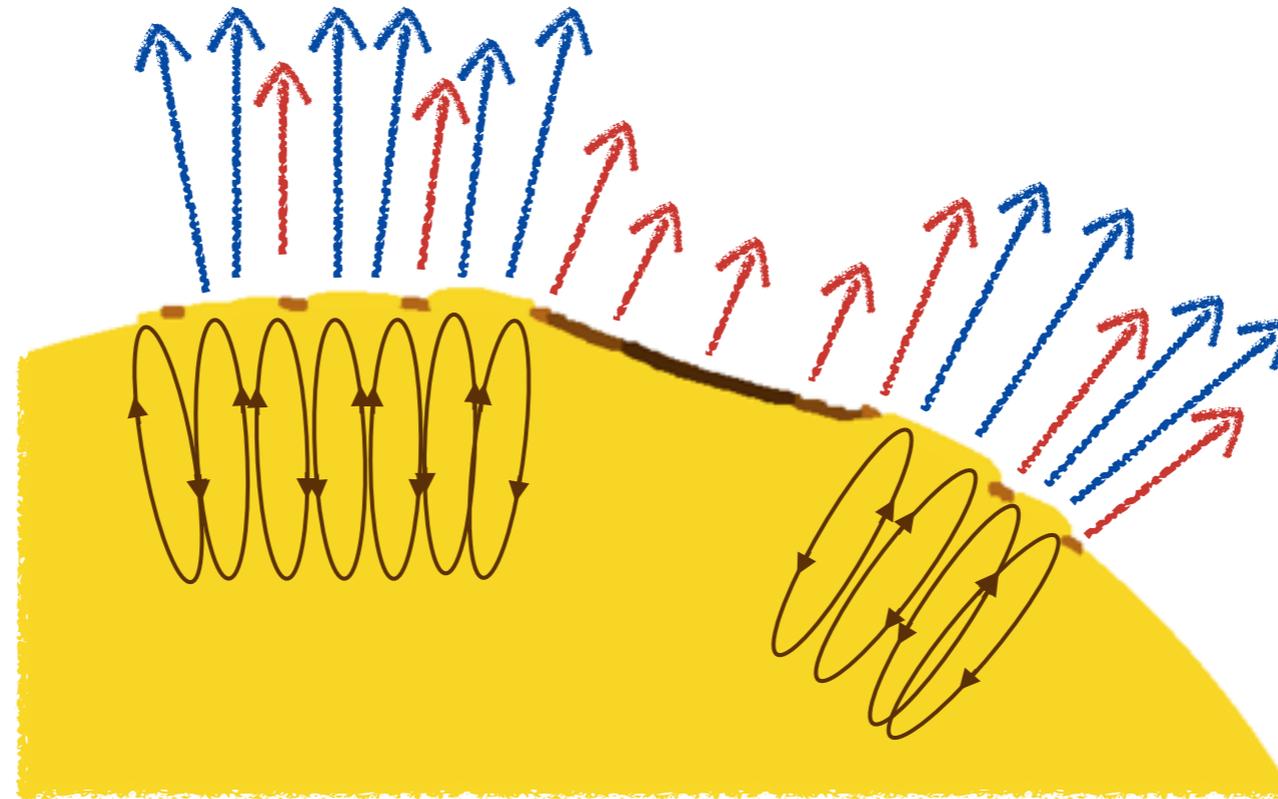
[m/s]



The dominant process at play is the suppression of convective blueshift from magnetic regions



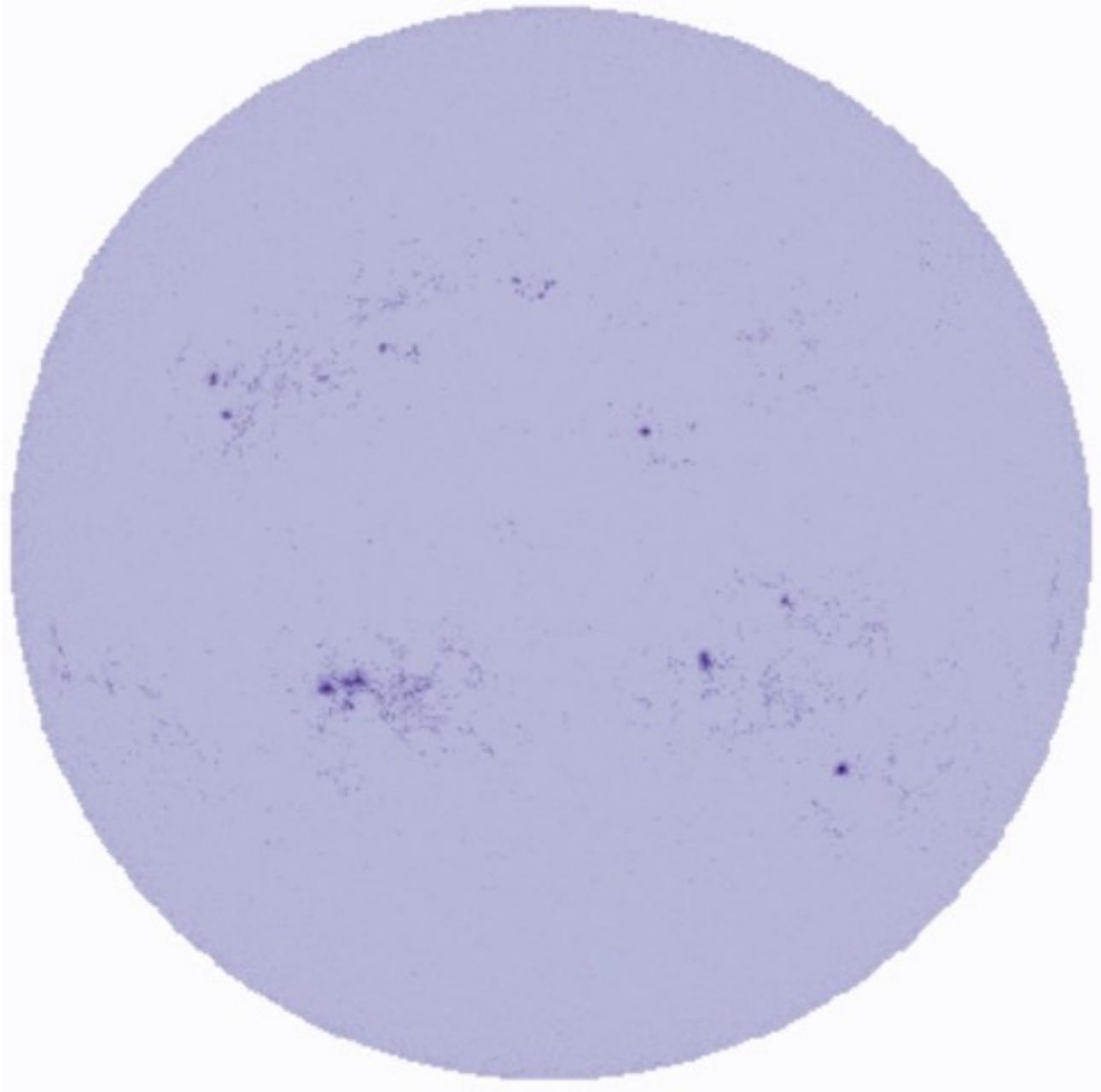
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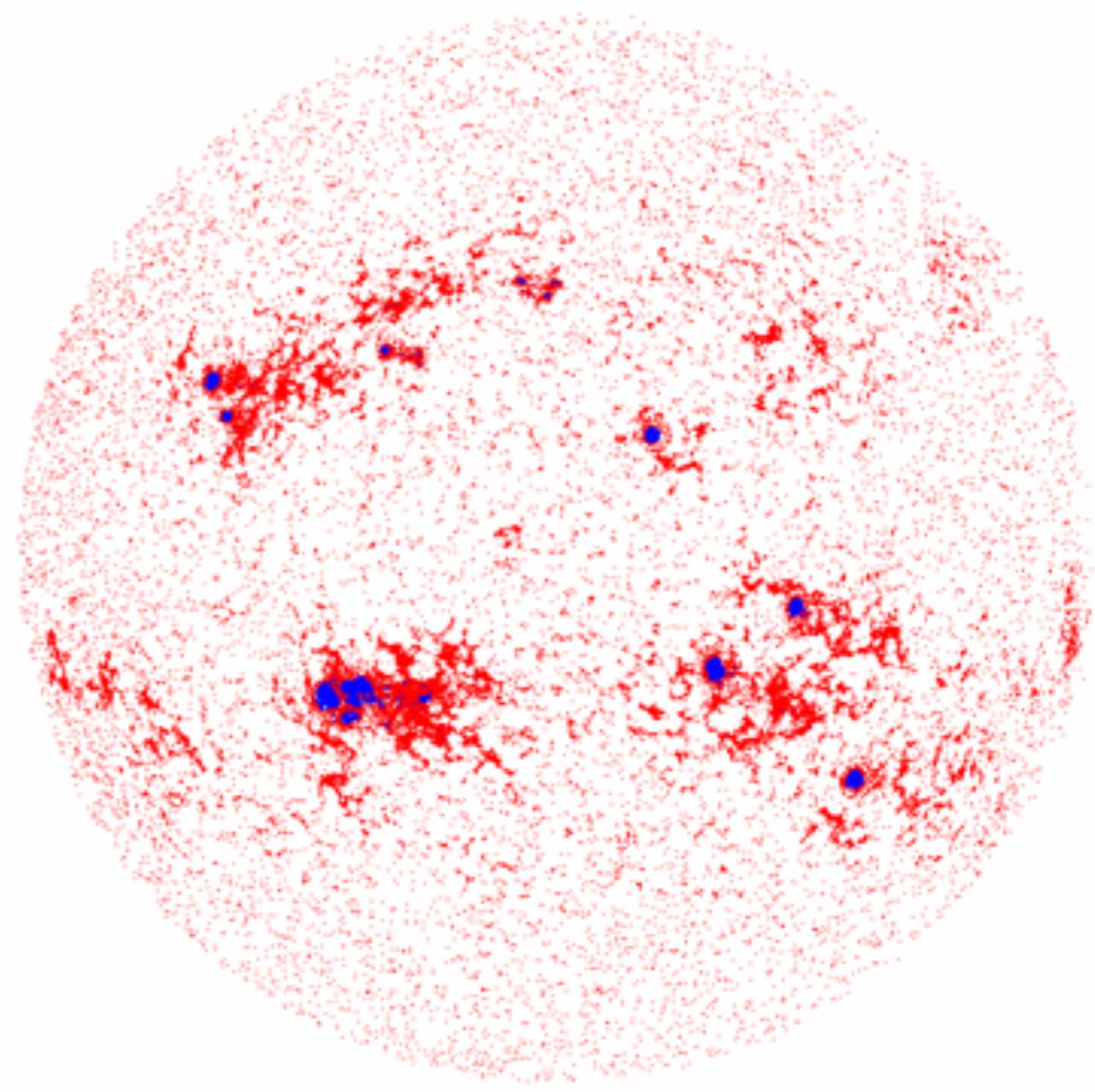
- Evolution of active regions induces quasi-periodic rotational modulation of several m/s
- Dominant activity contribution

Meunier et al. 2010, Haywood et al. 2014, Dumusque et al. 2014, Haywood et al. 2016

Faculae are the main source of suppression of convective blueshift

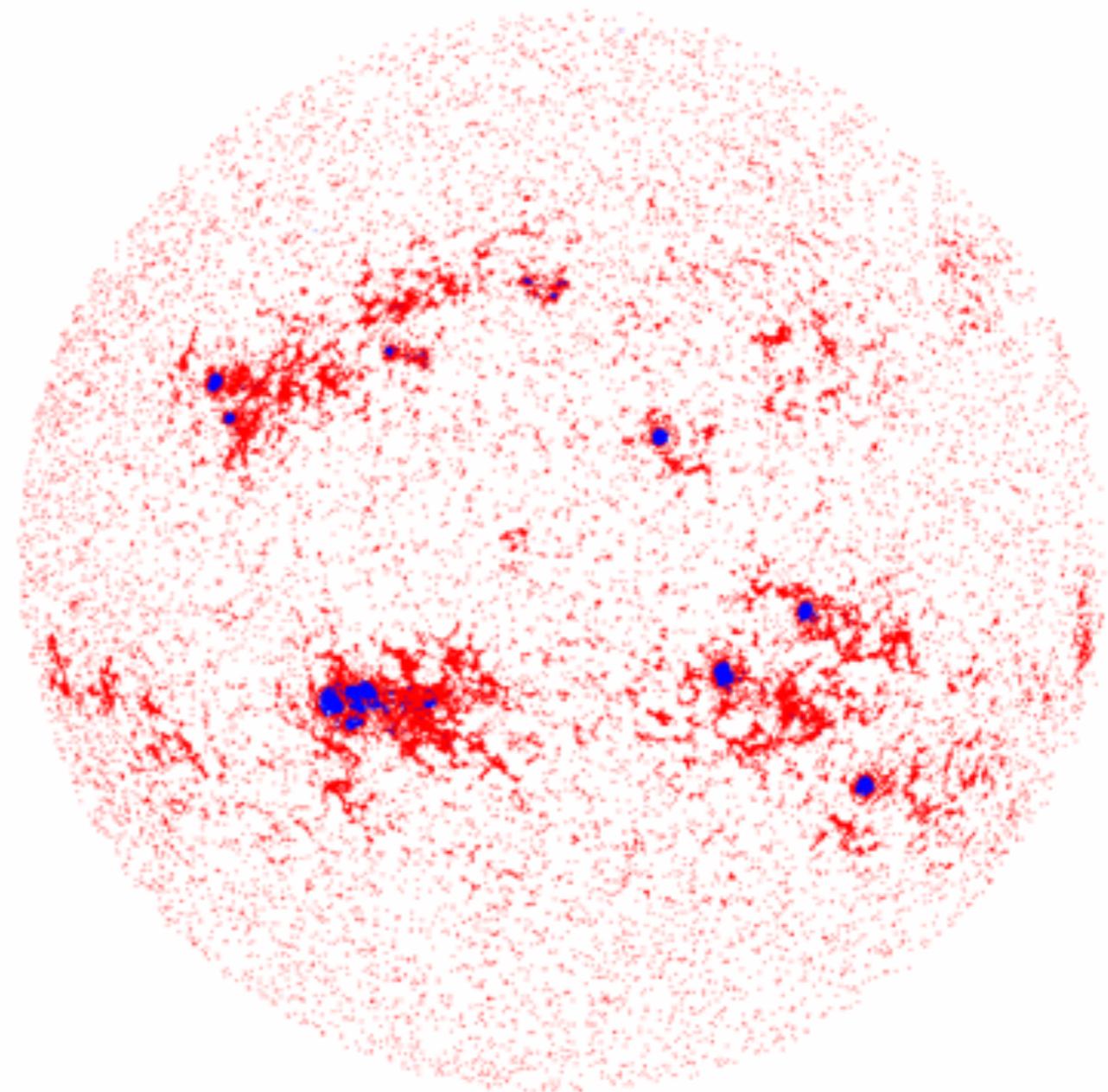
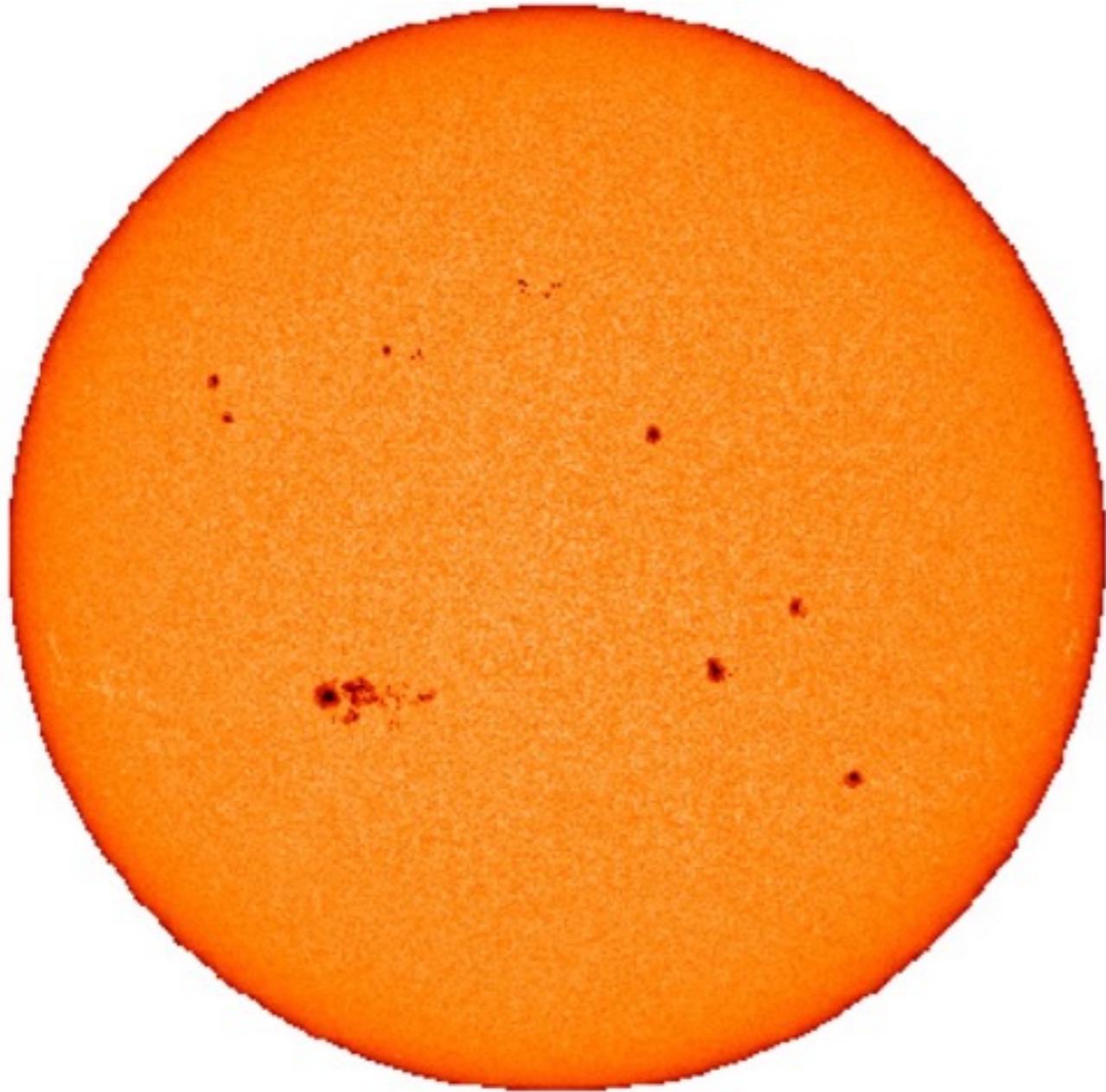


SDO/HMI magnetogram



Faculae pixels
Sunspot pixels

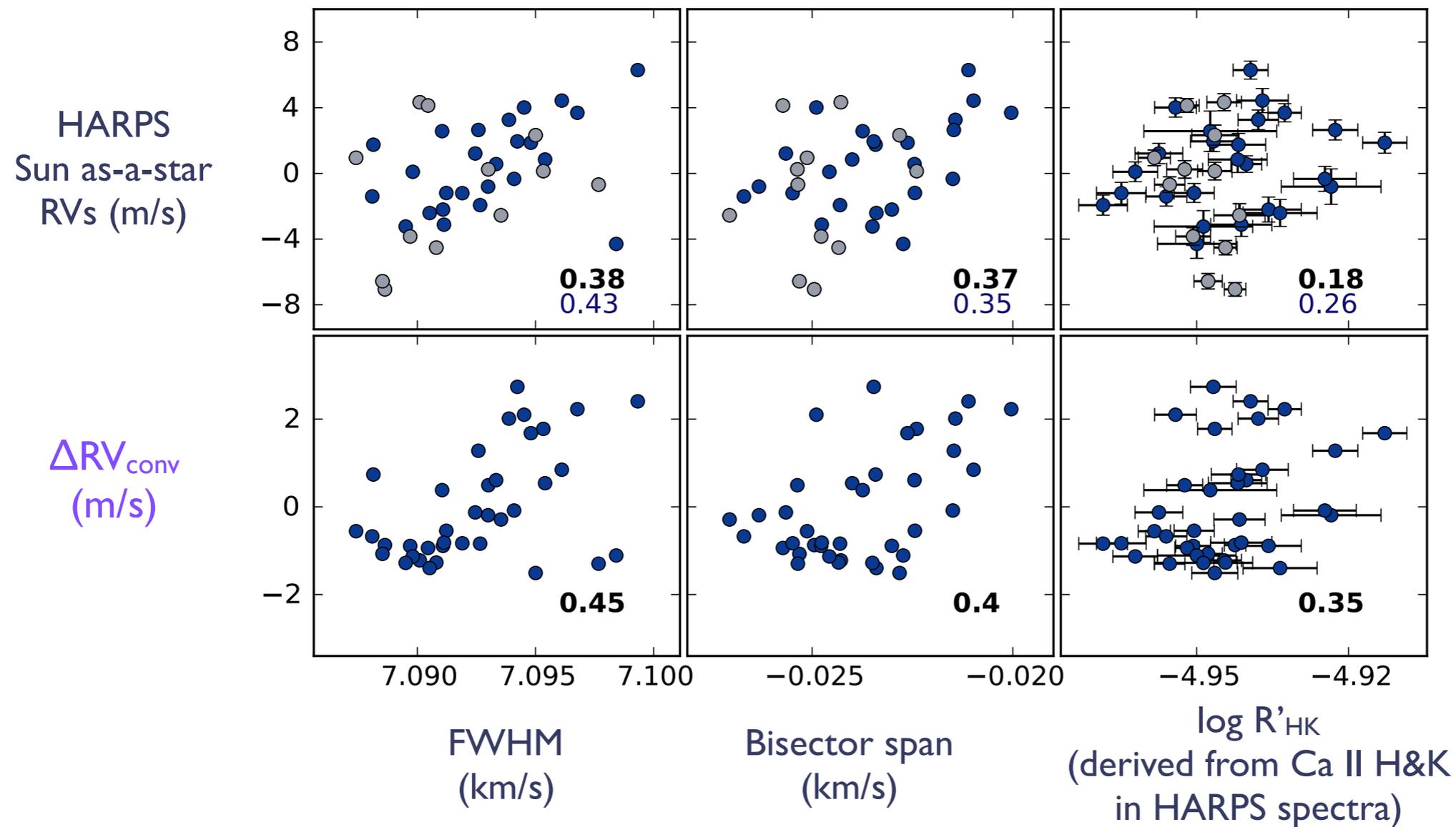
Optical lightcurves can only give incomplete prediction of RV variations



Because sunspots and faculae are not completely co-spatial

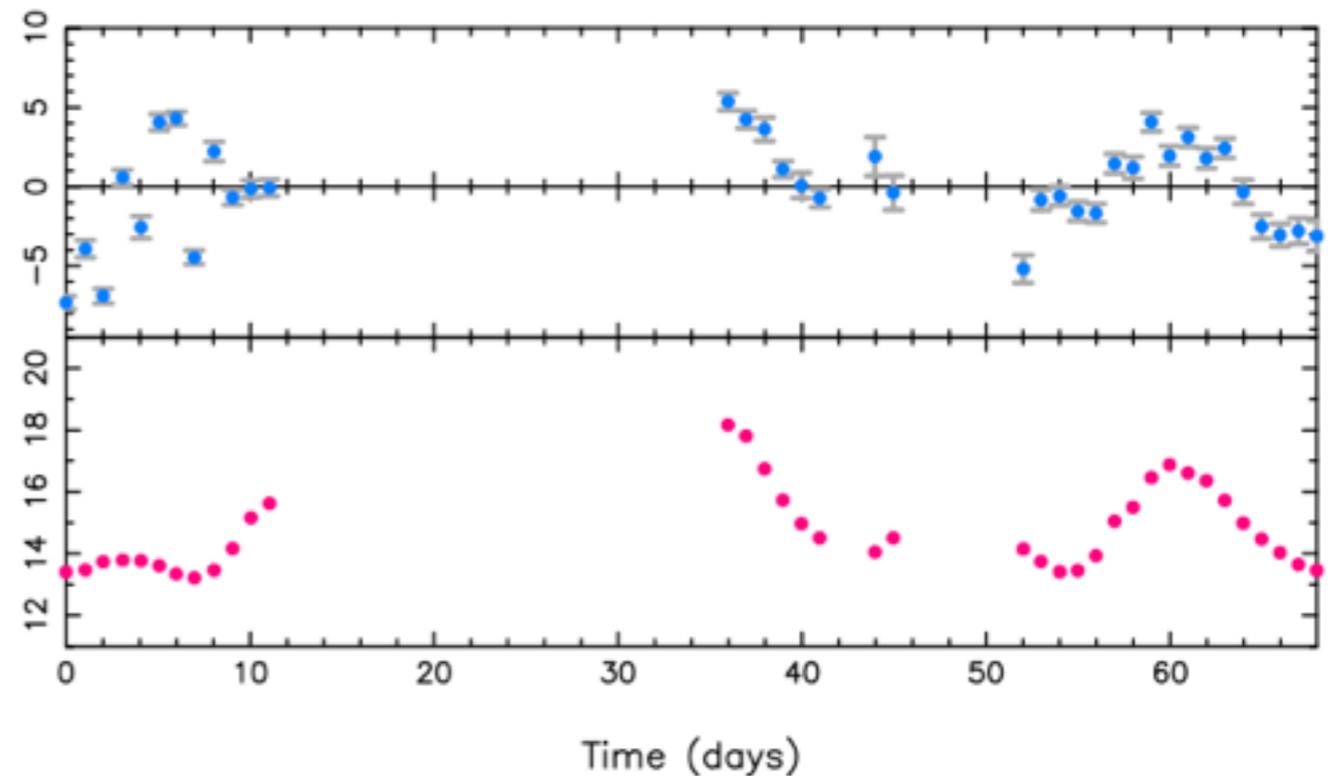
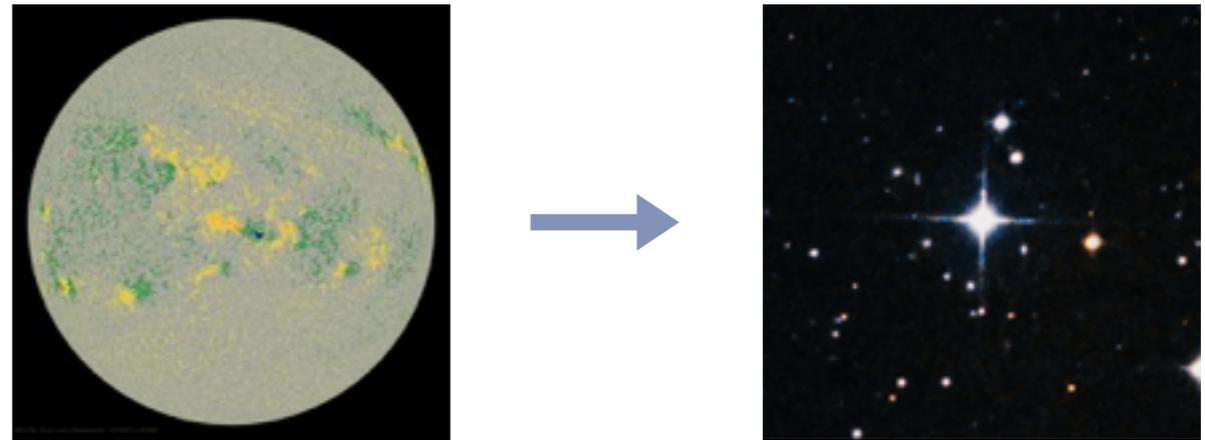
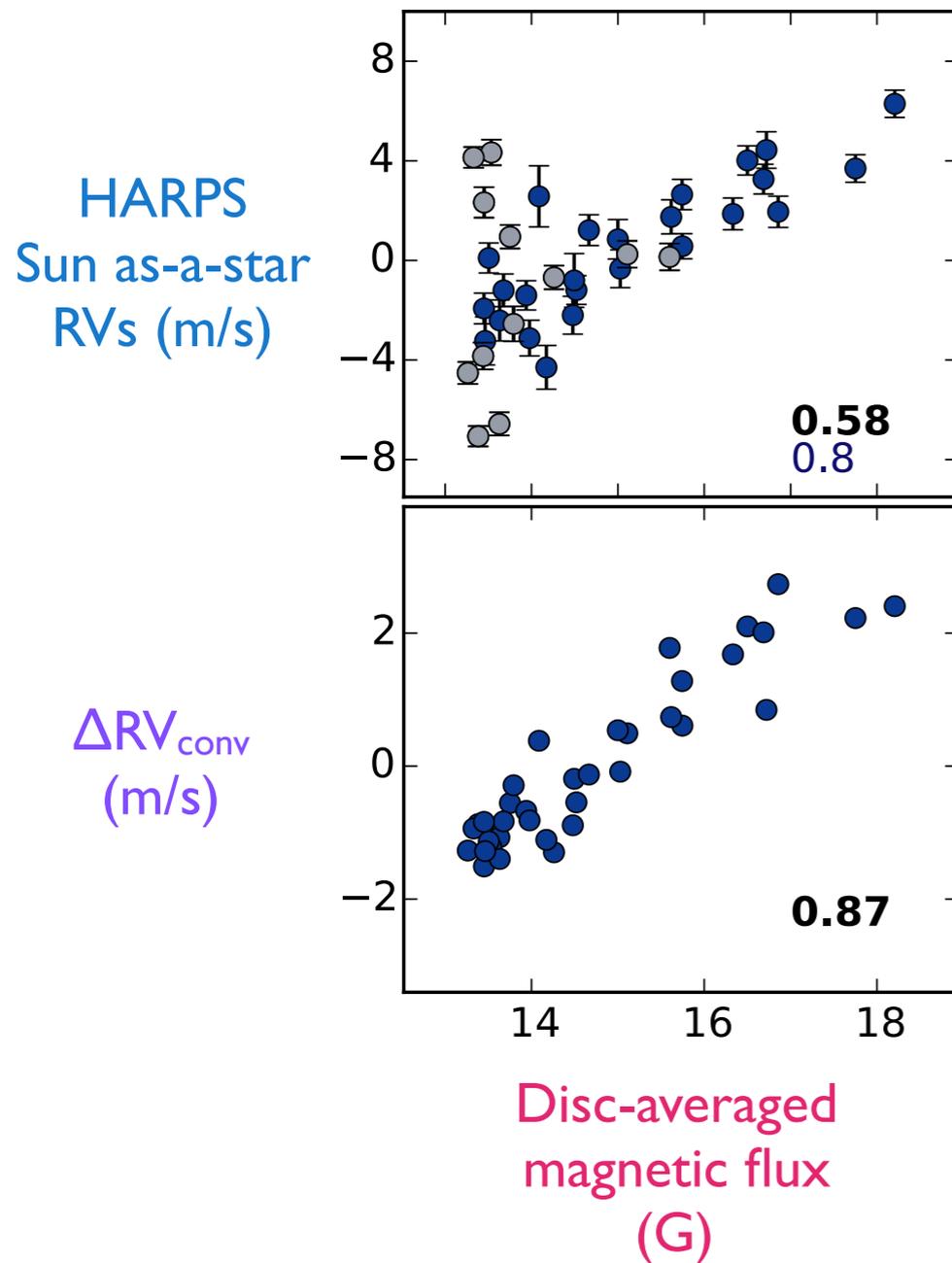
Correlations between RV and traditional spectroscopic indicators

Haywood et al. (2016)



- Ca II H&K index better indicator for longer timescales \sim years [Lanza et al. 2016](#)
- Further investigations currently under way (J. Maldonado, G. Micela at INAF, Palermo)

Full-disc magnetic flux as an activity indicator



- Cannot yet measure in distant Sun-like stars
- But could become useful in the future!

Further investigations are now possible with the new solar telescope at HARPS-N

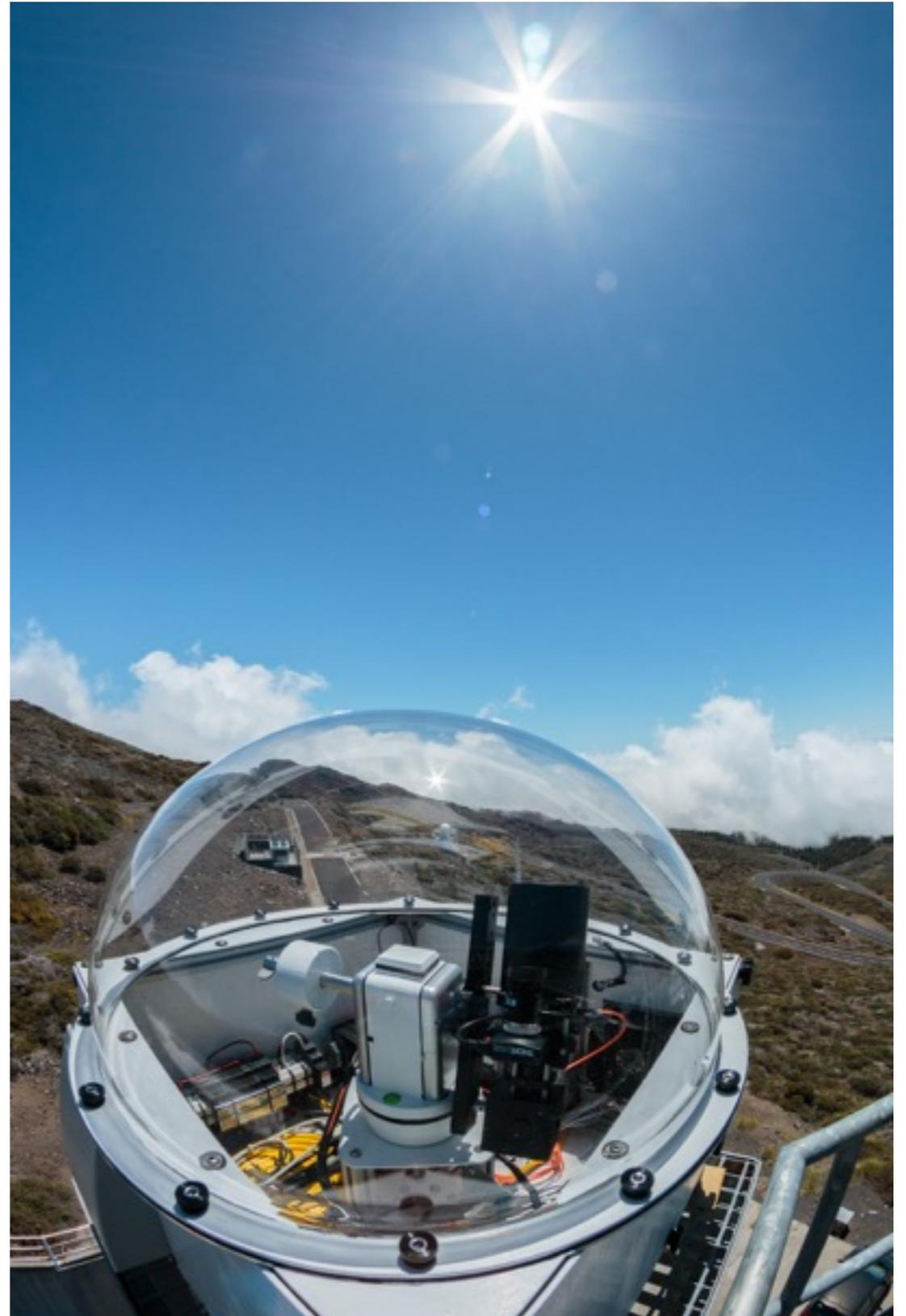
- 3-inch automated telescope feeding an integrating sphere
- Integrated sunlight then fed into HARPS-N spectrograph
- Operational since July 2015
- Photon noise rms scatter: 40-50 cm/s in 5-min exposures

See:

Dumusque et al., *ApJL* 2015

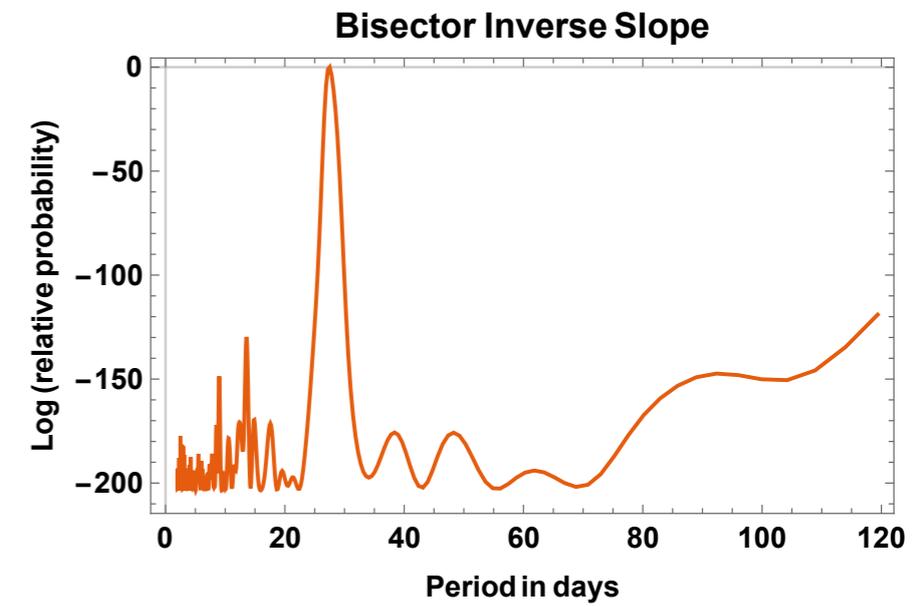
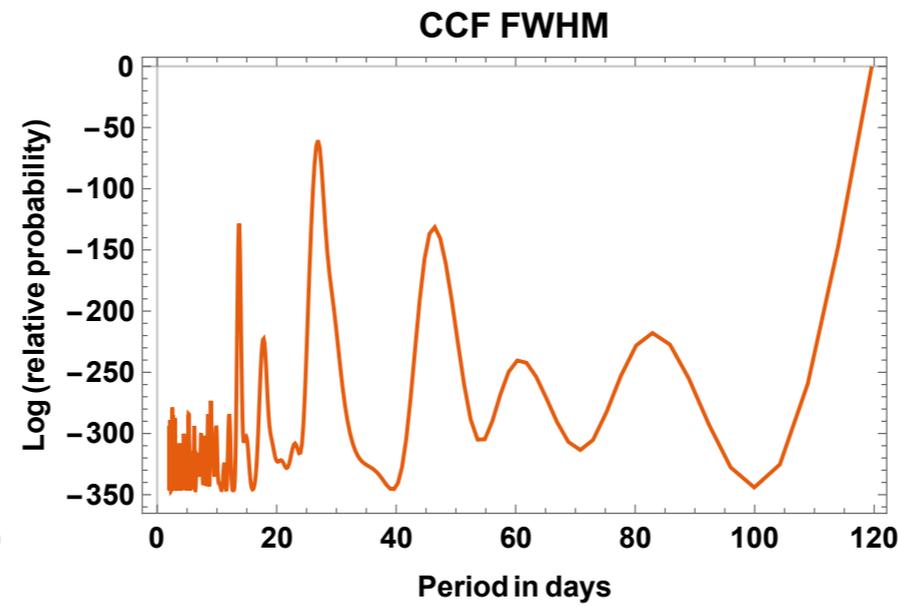
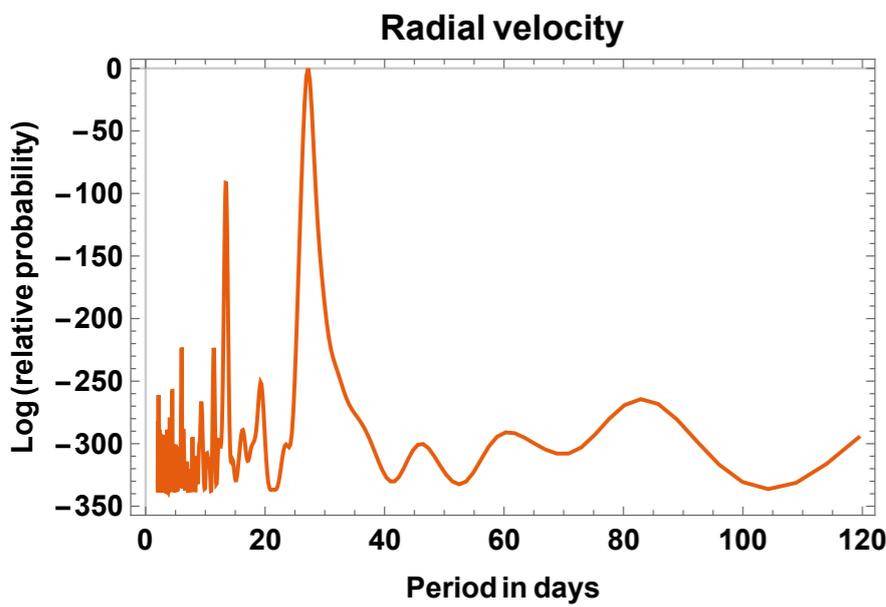
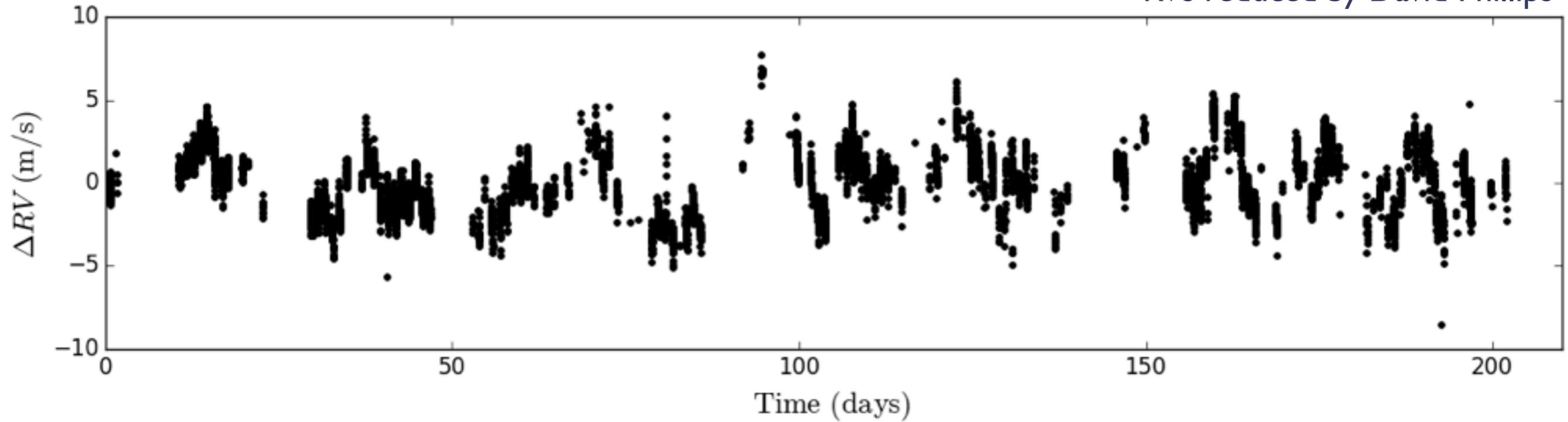
Glenday A., Phillips D. F. et al., in prep.

Photos by David Phillips



HARPS-N Sun as-a-star RV observations

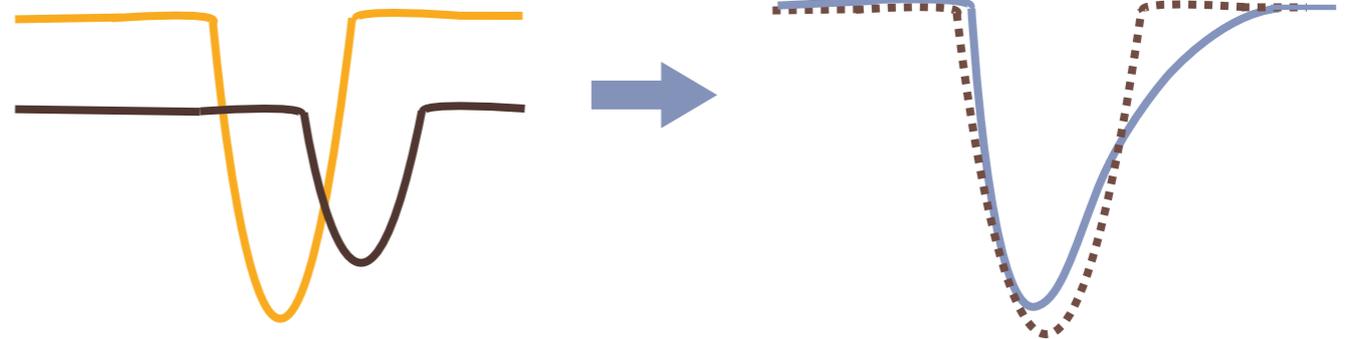
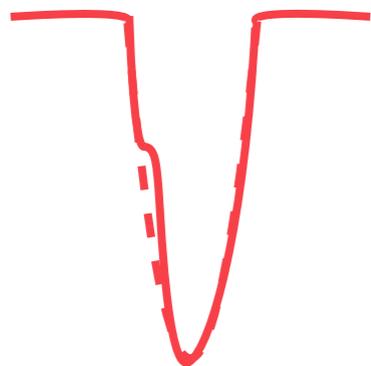
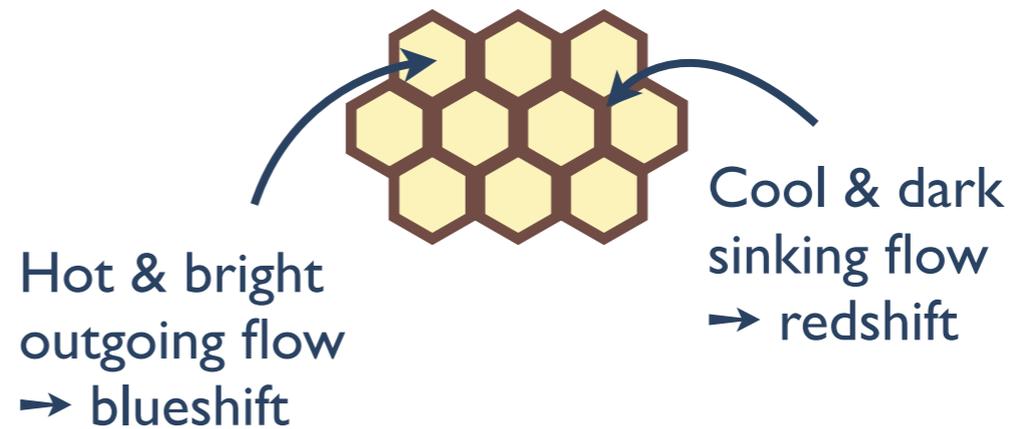
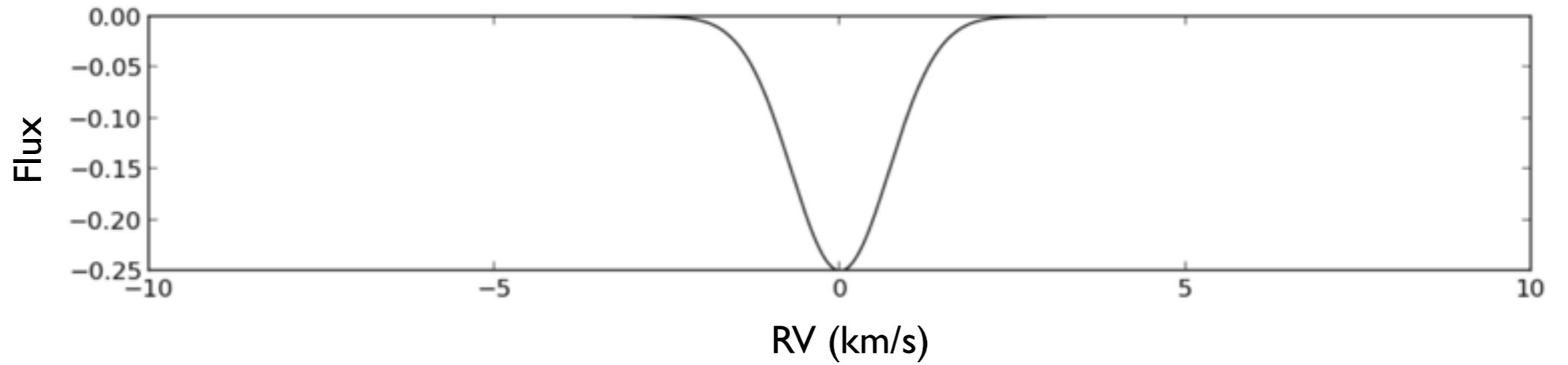
RVs reduced by David Phillips



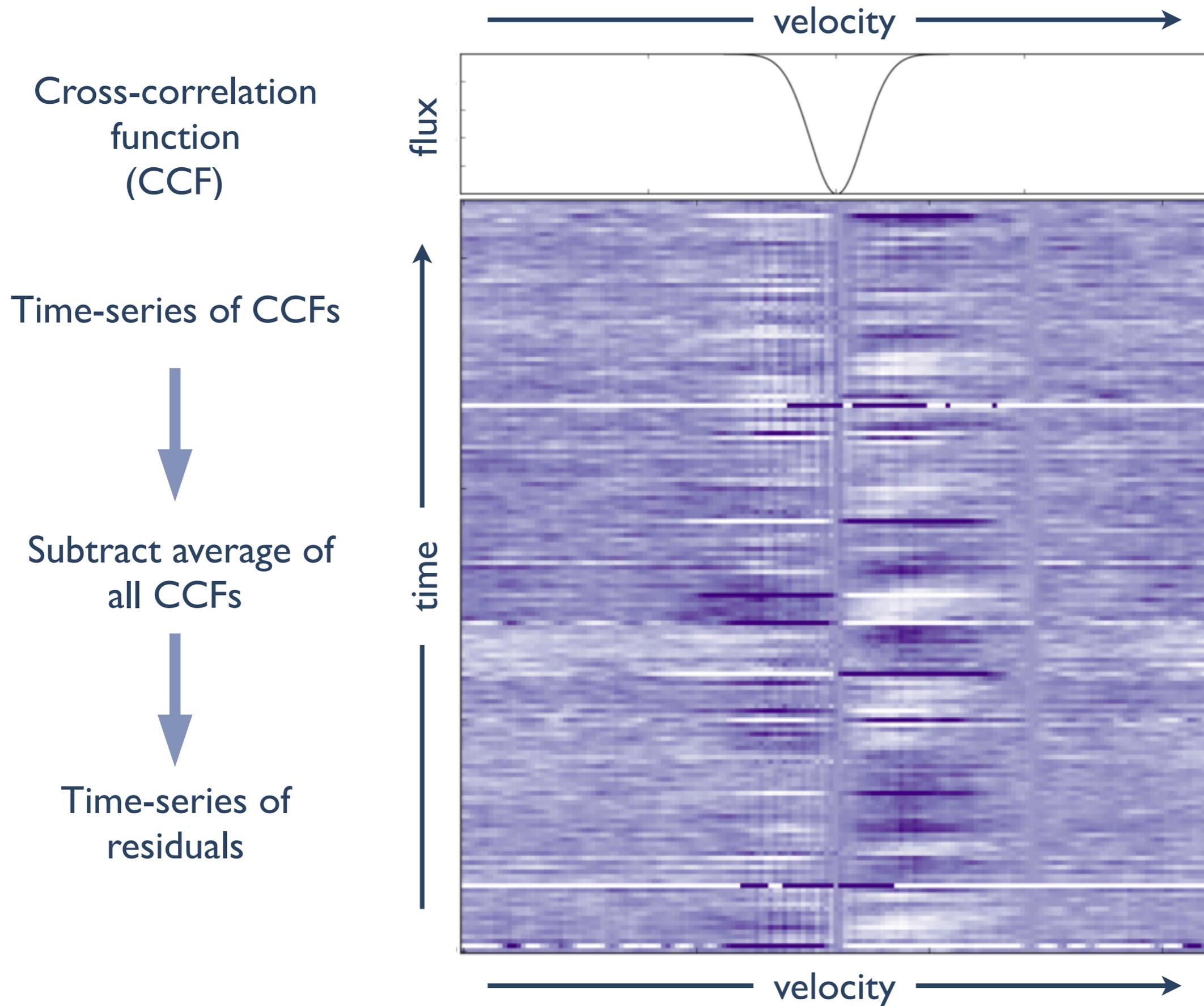
Periodograms by Andrew Collier Cameron

Spots, faculae, granulation distort the shape of spectral lines

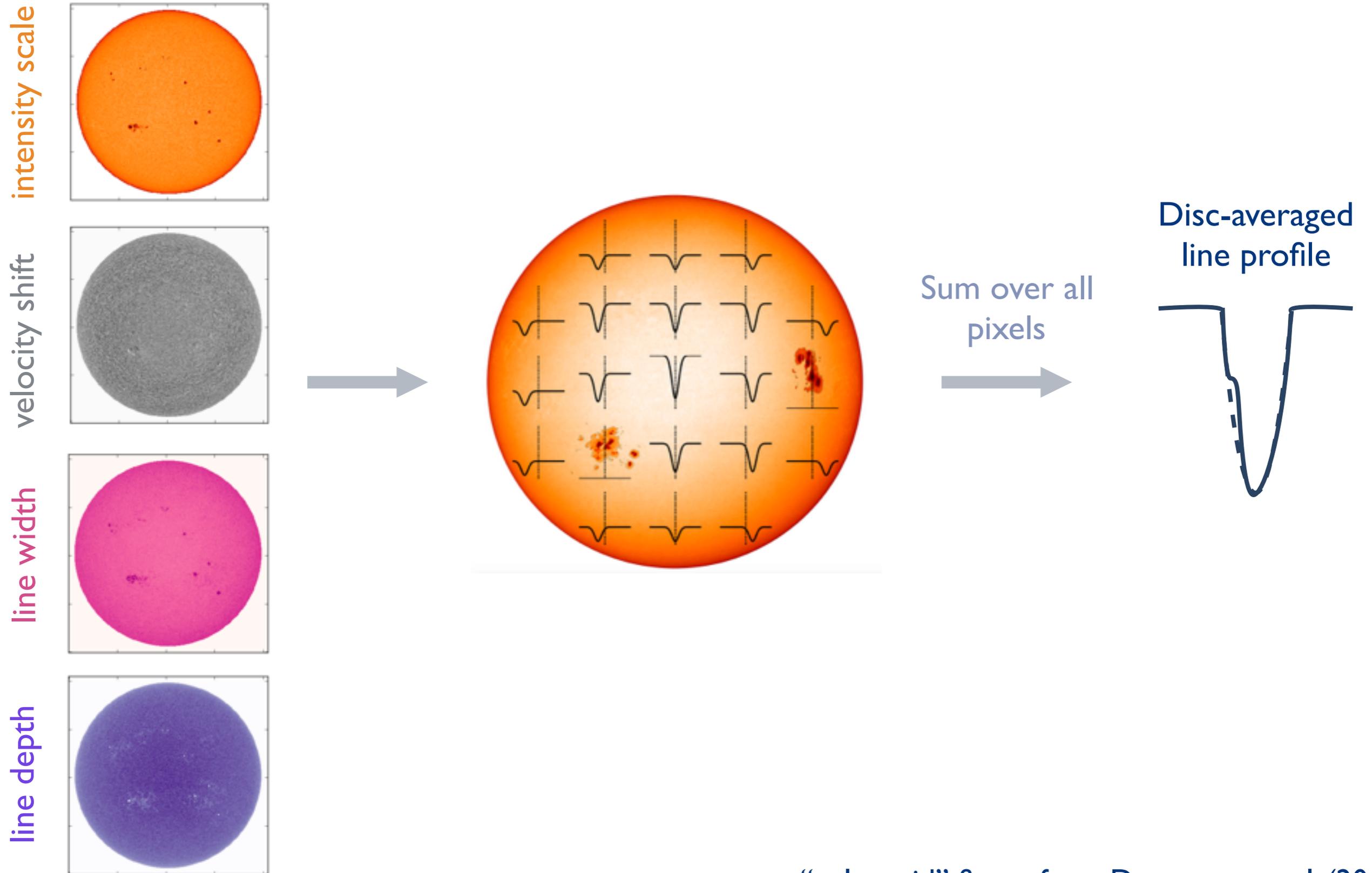
Cross-correlation function (CCF)



Time-series of line profile distortions seen by HARPS-N

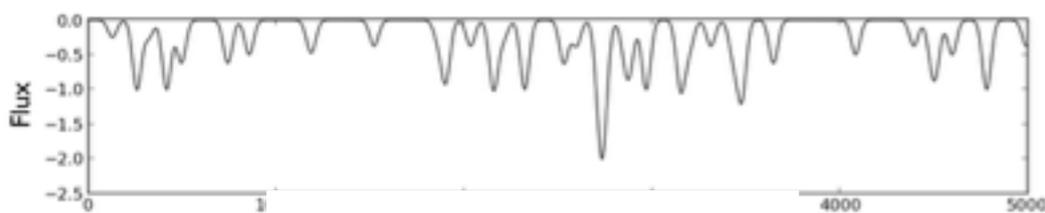
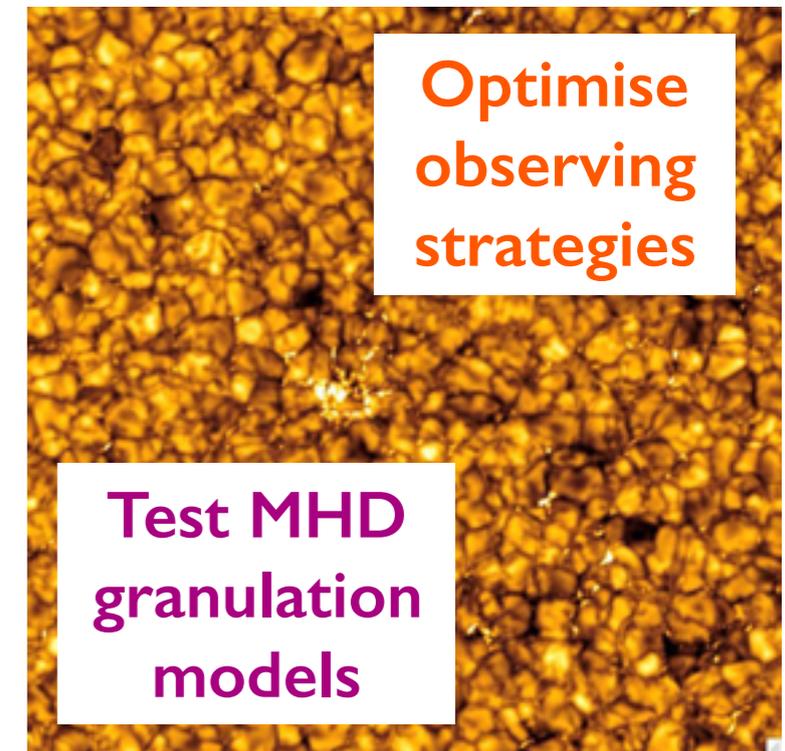
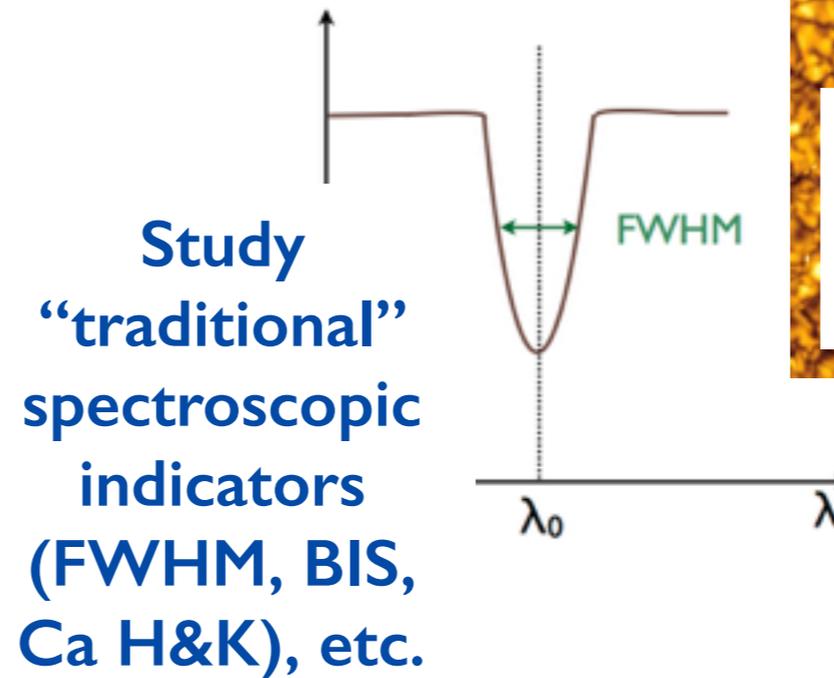
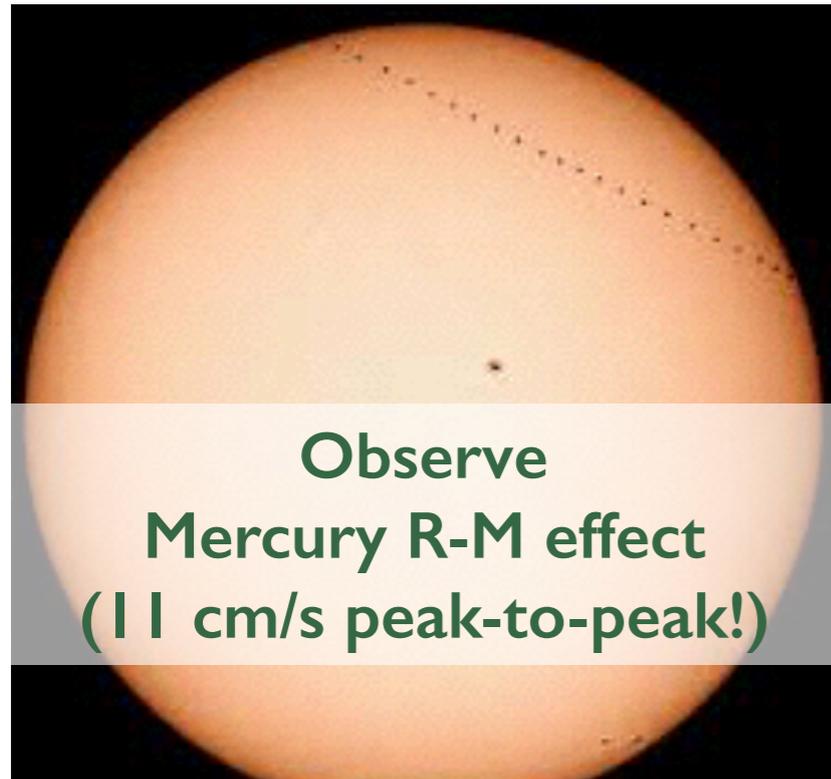


Next: synthesize full-disc line profiles using SDO/HMI images



“solar grid” figure from Dumusque et al. (2014)

A small selection of our many ongoing HARPS-N solar projects!



Apply LSD to extract unpolarised Zeeman broadening

