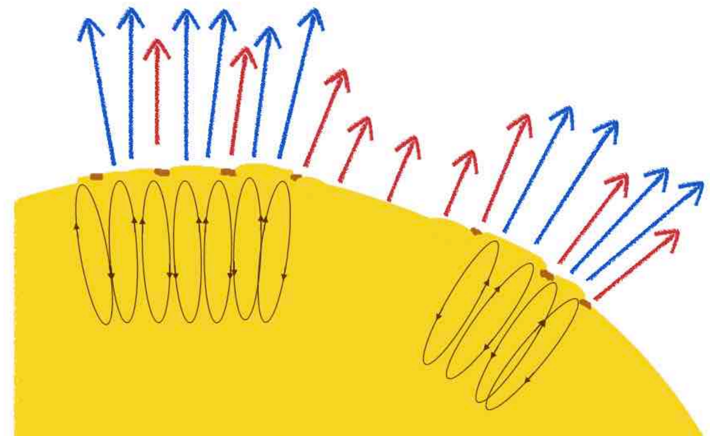
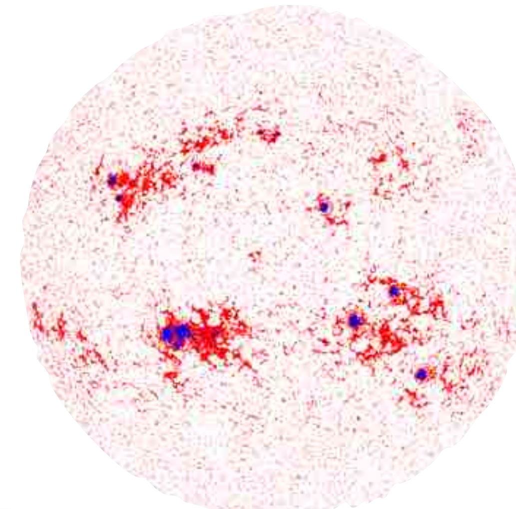
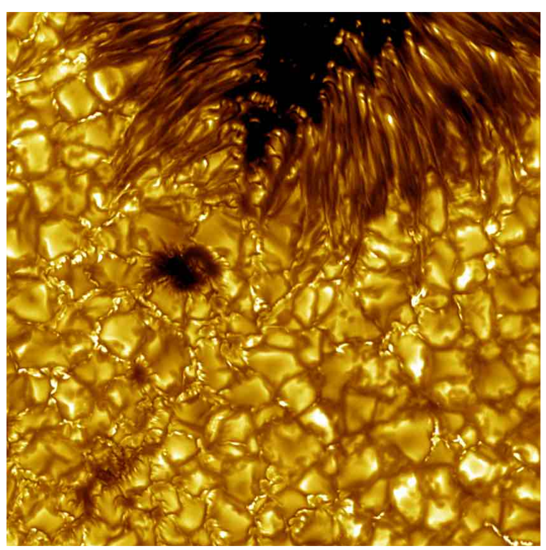
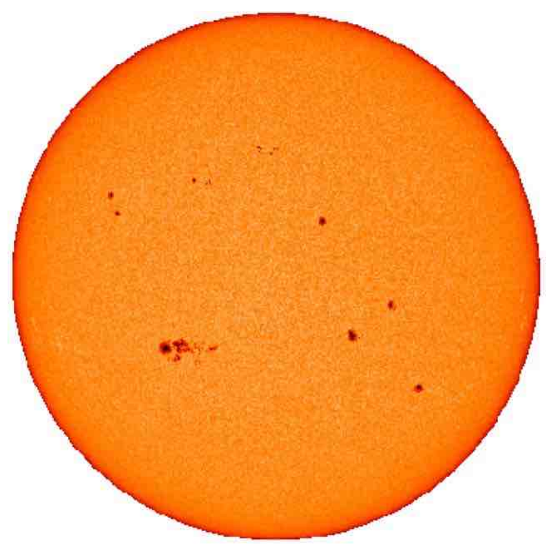
What are we learning from observing the Sun as a star?









Raphaëlle D. Haywood

NASA Sagan Fellow, Harvard College Observatory

Images: Solar Telescope at HARPS-N (D. Phillips), suppression of convective blueshift (R. Haywood), solar faculae and spots (R. Haywood), solar granulation (Swedish 1-m Telescope, V. Henriques), Sun (HMI/SDO), Solar Dynamics Observatory (NASA).

Outline

Why does exoplanet science need solar science?

How can we estimate the Sun's radial-velocity (RV) variations from spatially resolved images?

What do we learn from comparing them to the Sun observed "as a star"?

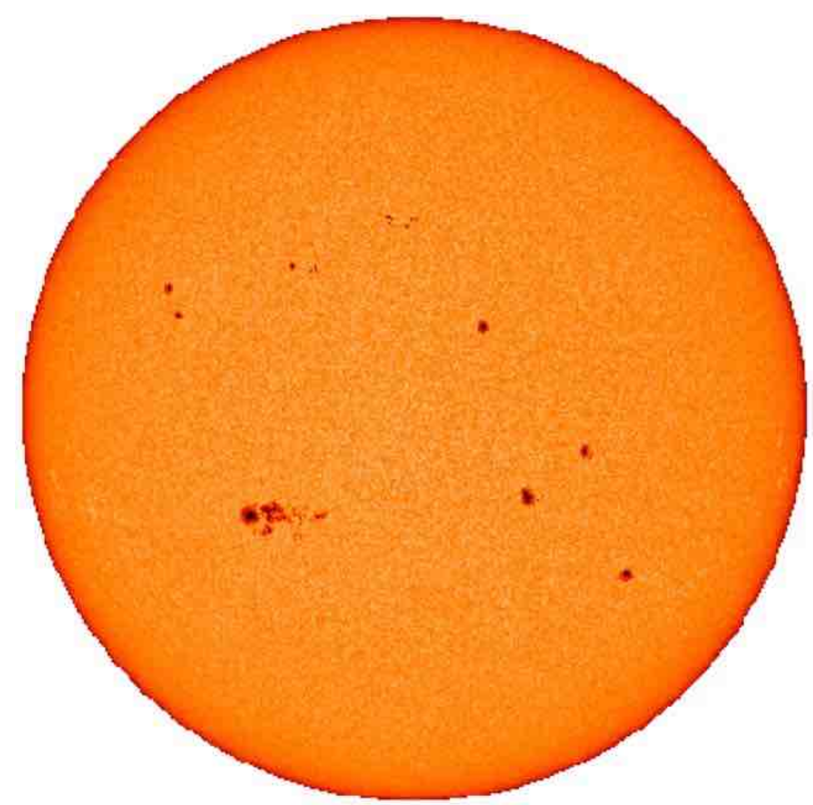
How can we apply this solar knowledge to other stars?

Looking to the future: exoplanet atmospheres

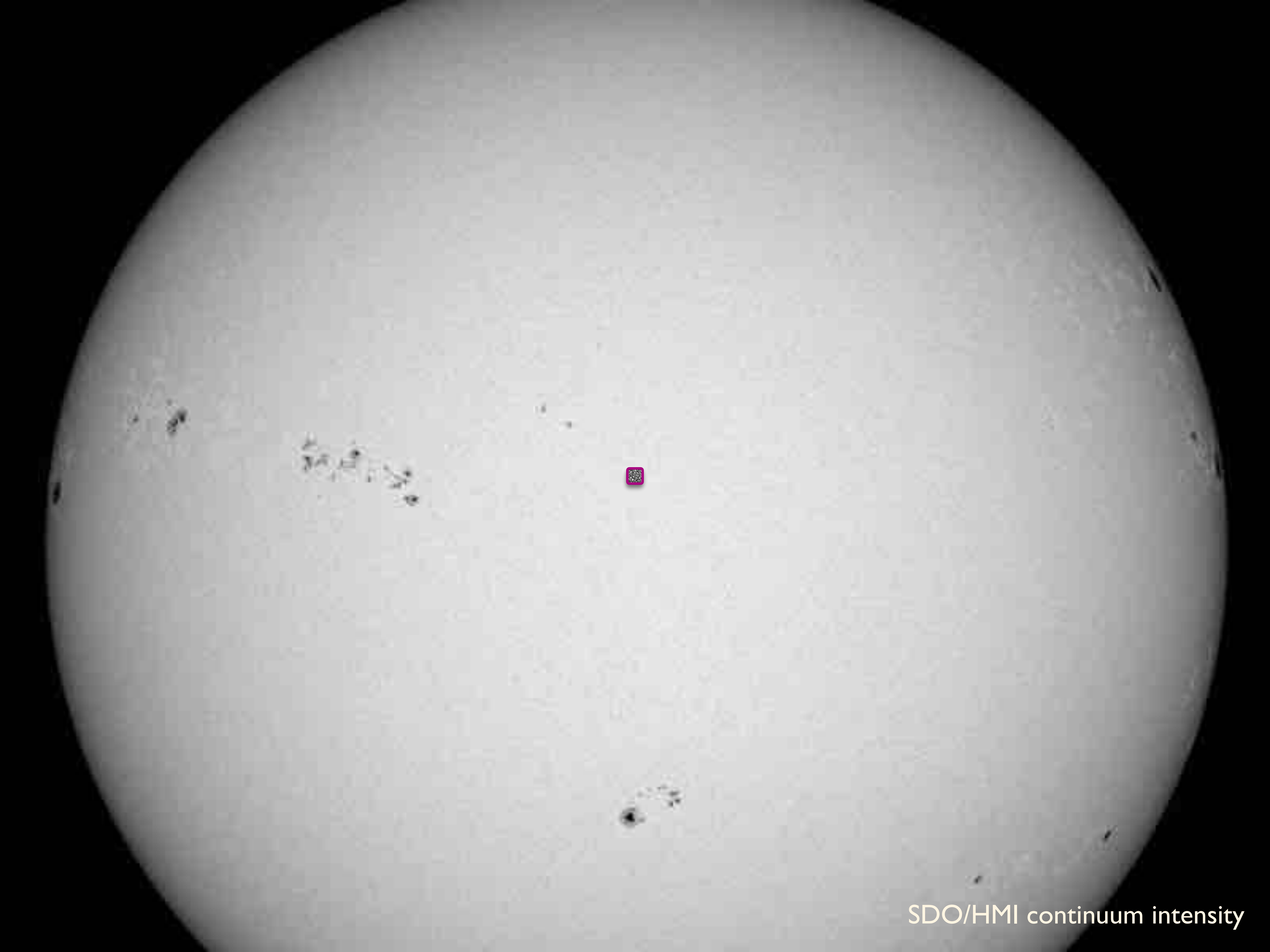
What makes the Sun special?

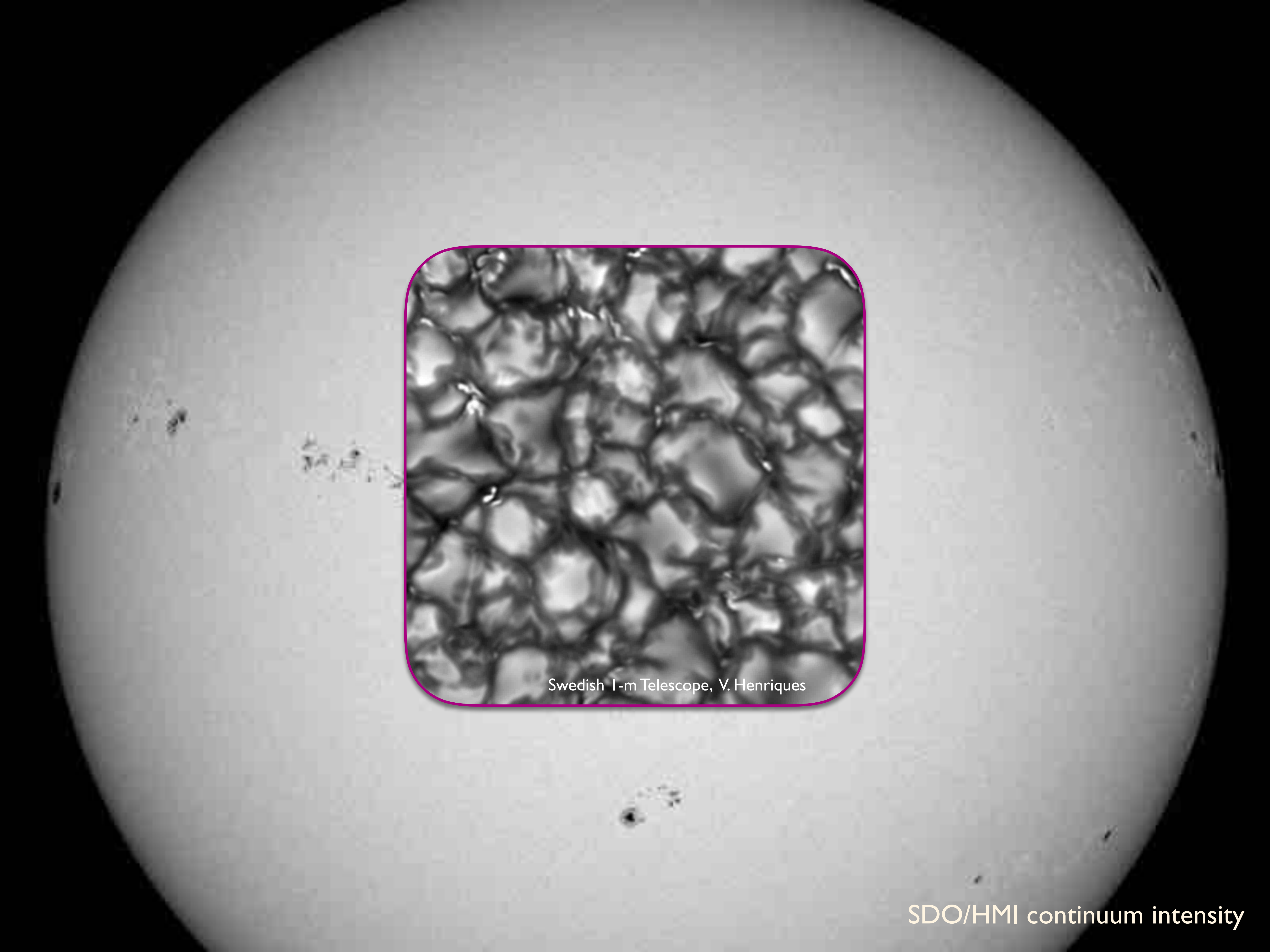
We can observe the Sun as if it were a distant, point-like star

… and use spatially resolved observations of the Sun to identify RV contribution from magnetic activity features



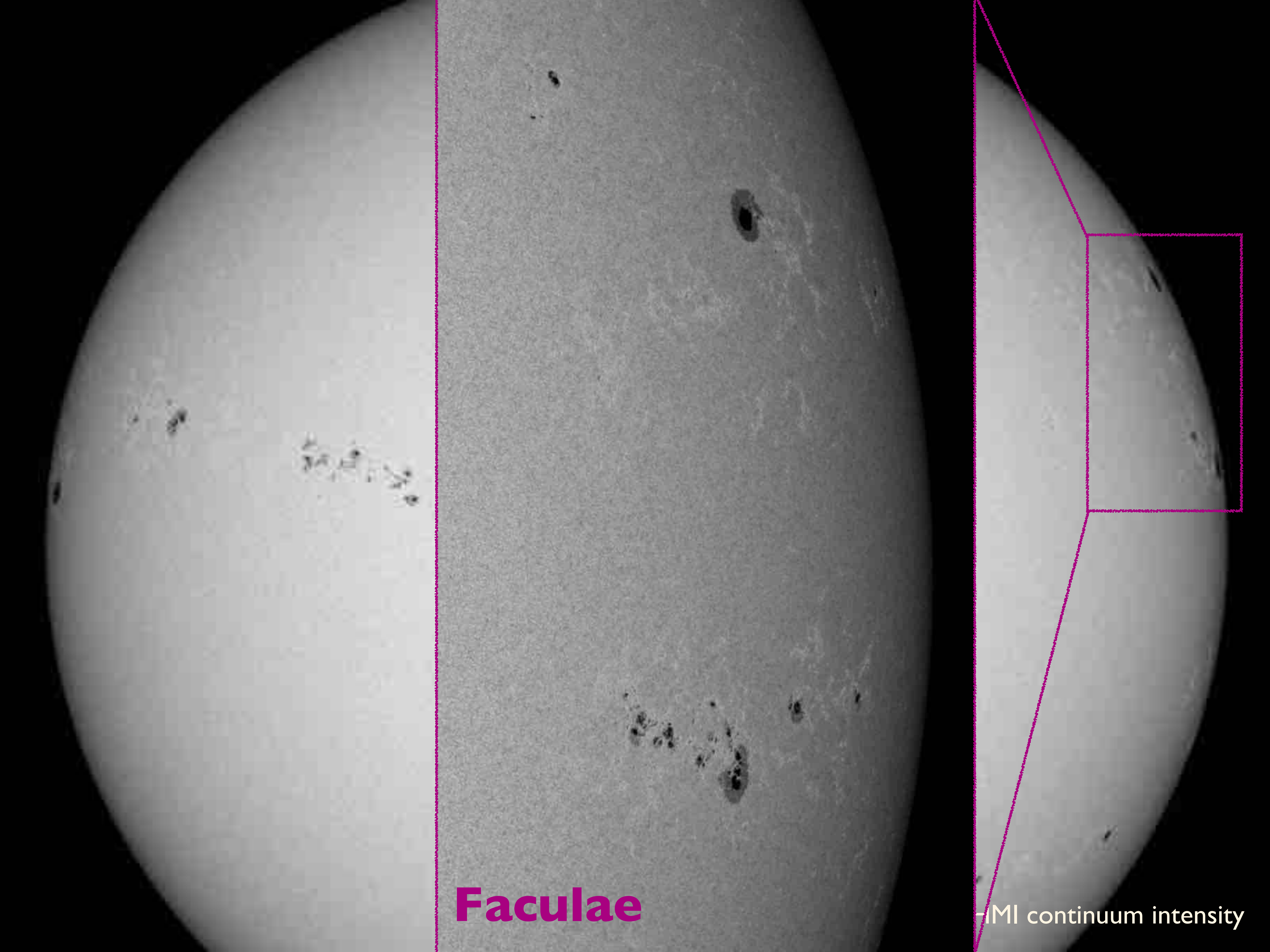

SDO/HMI continuum intensity


SDO/HMI continuum intensity


Swedish 1-m Telescope, V. Henriques
SDO/HMI continuum intensity

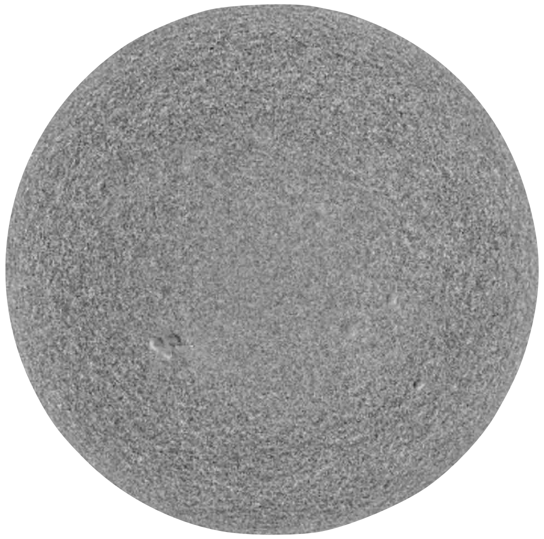

Sunspots
SDO/HMI continuum intensity


Faculae
SDO/HMI continuum intensity

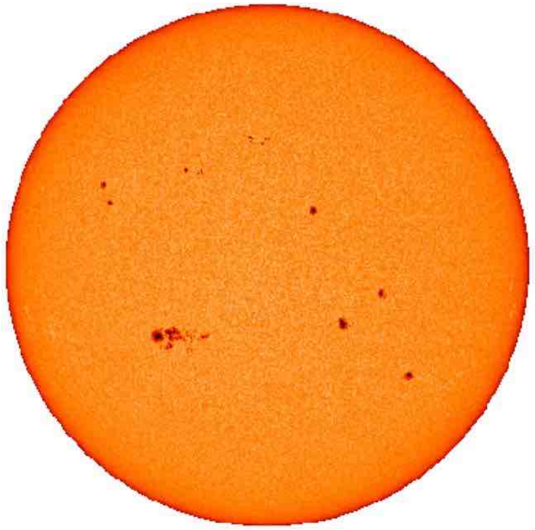

Faculae
continuum intensity

Estimating the radial-velocity variations of the Sun using spatially resolved images

Helioseismic & Magnetic Imager onboard the Solar Dynamics Observatory (SDO/HMI)



Doppler image



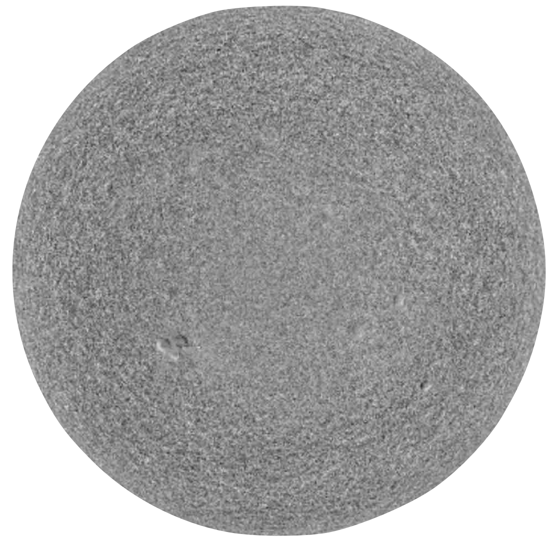
Continuum intensity

Magnetic field

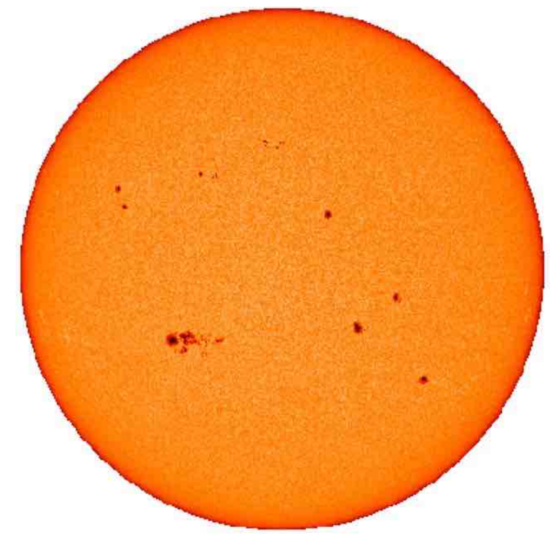
Technique developed by Meunier, Lagrange & Desort (2010) for SoHO/MDI images

Estimating the radial-velocity variations of the Sun using spatially resolved images

Helioseismic & Magnetic Imager onboard the Solar Dynamics Observatory (SDO/HMI)



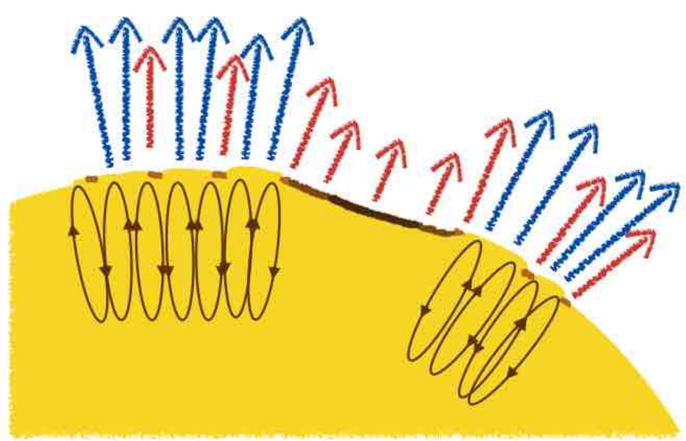
Doppler image



Continuum intensity

Magnetic field

Model:



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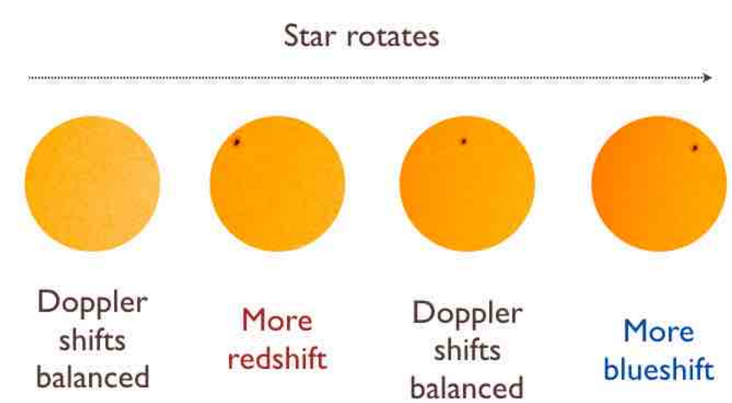
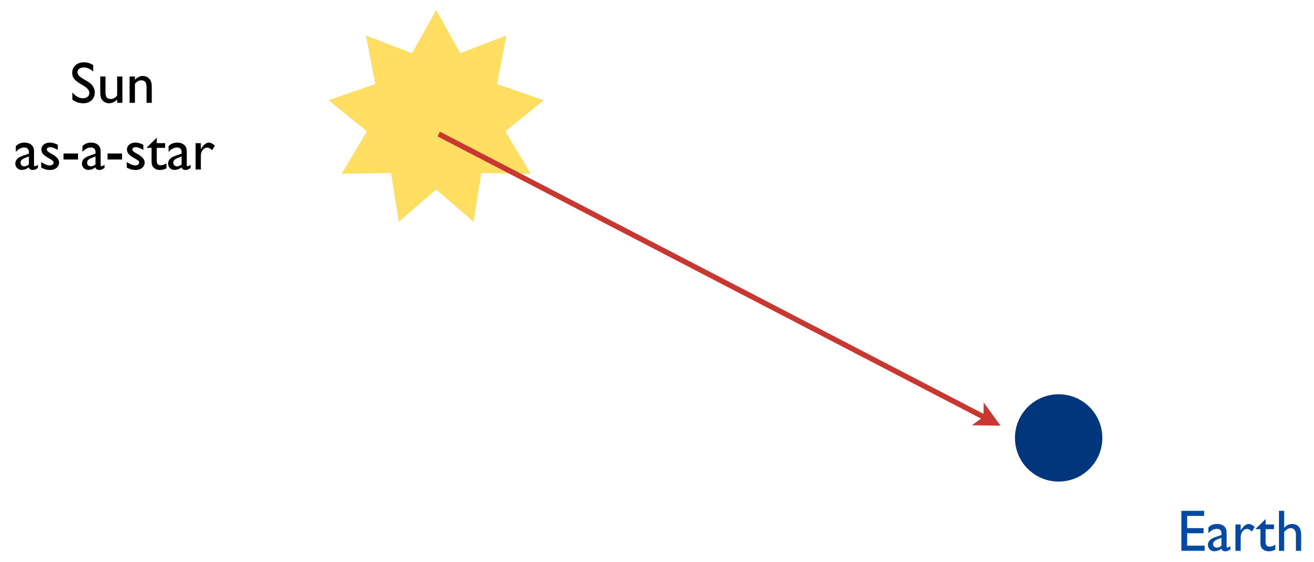


Technique developed by Meunier, Lagrange & Desort (2010) for SoHO/MDI images

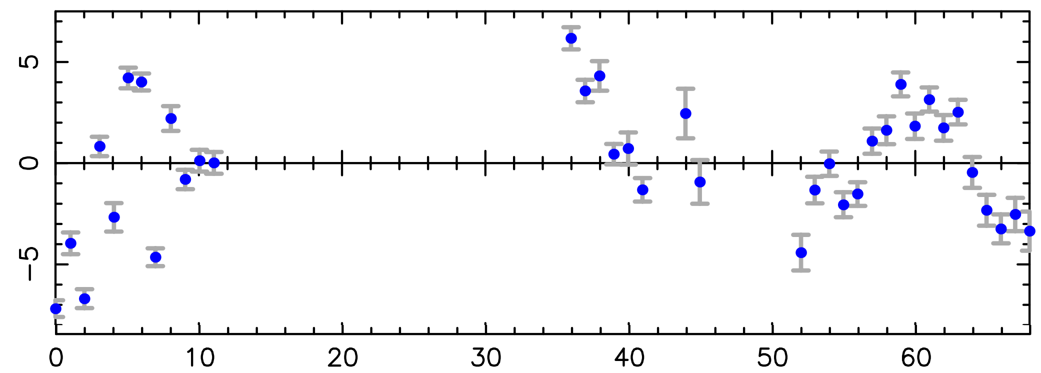
Comparing to the ground truth: the Sun



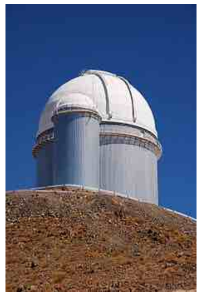
Ground truth 1: sunlight reflected off Vesta

HARPS
Sun as-a-star
RVs

[m/s]

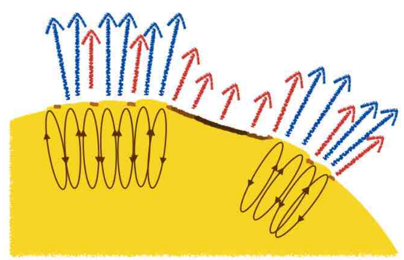


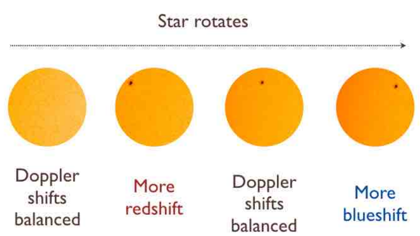
Time [days]

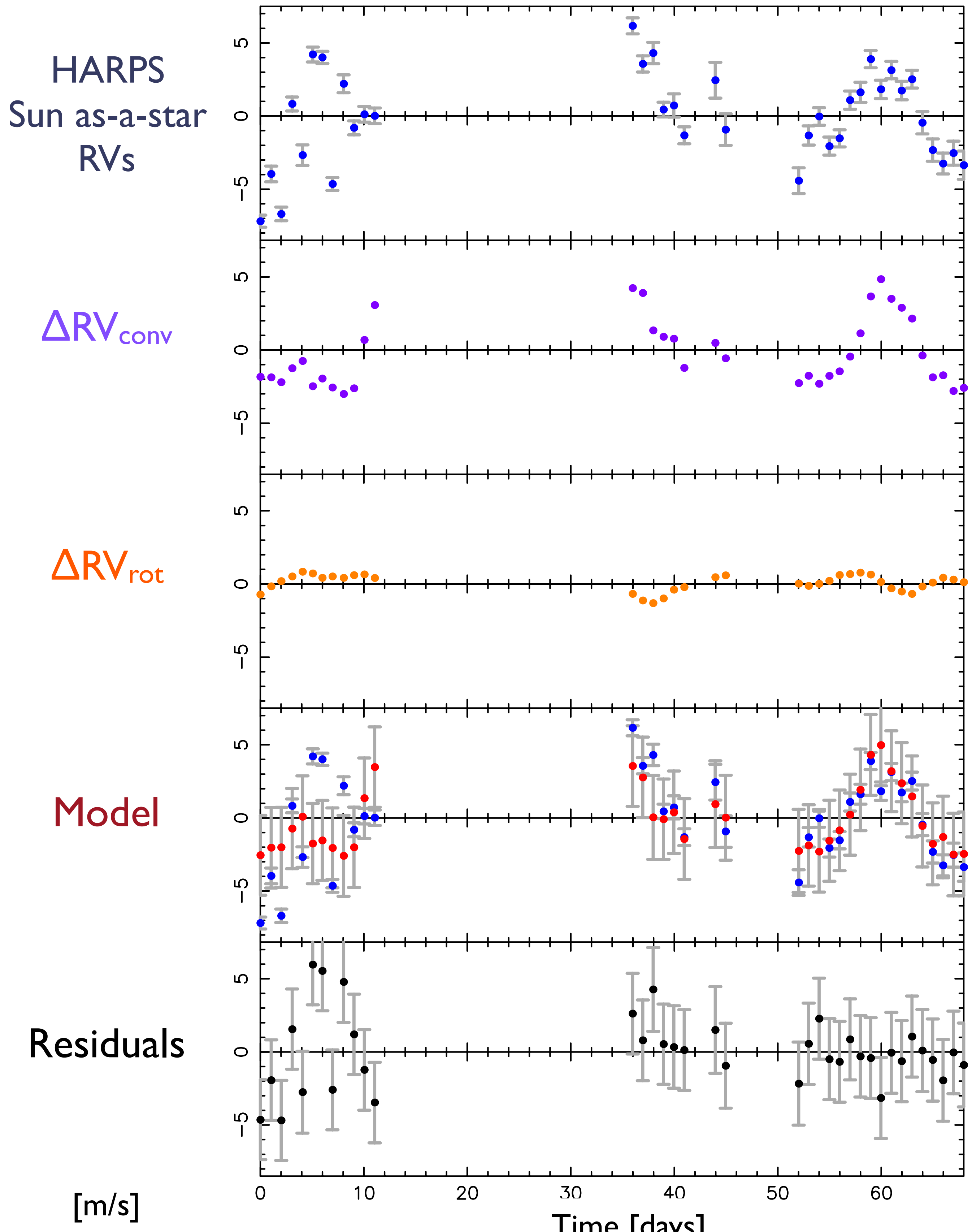


Haywood et al. (2016)

Ground truth 1: sunlight reflected off Vesta

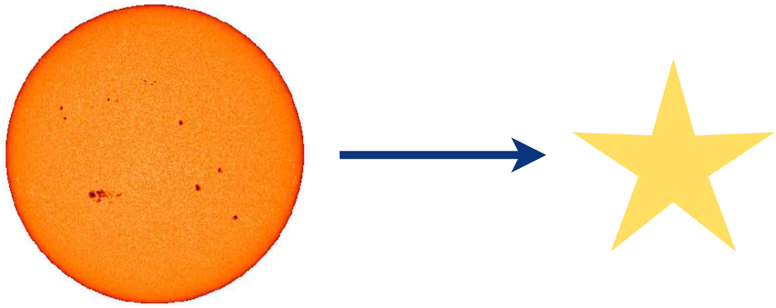






Haywood et al. (2016)

Ground truth II:
We are observing the Sun with the exoplanet hunter HARPS-N



Solar/HARPS-N Project:
Glenday, Phillips et al. (2012), Dumusque et al. (2016), Phillips et al. (2016)

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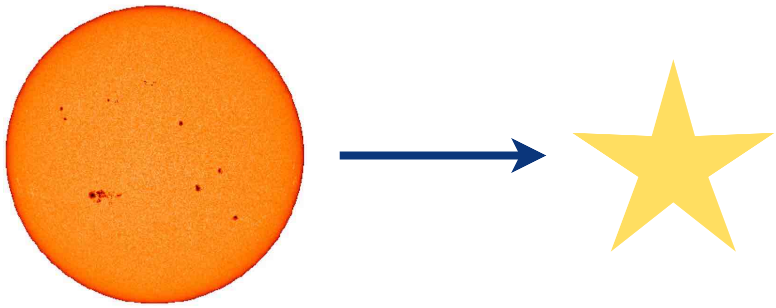

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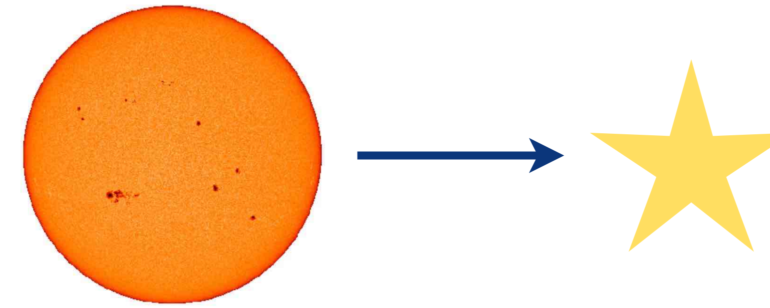
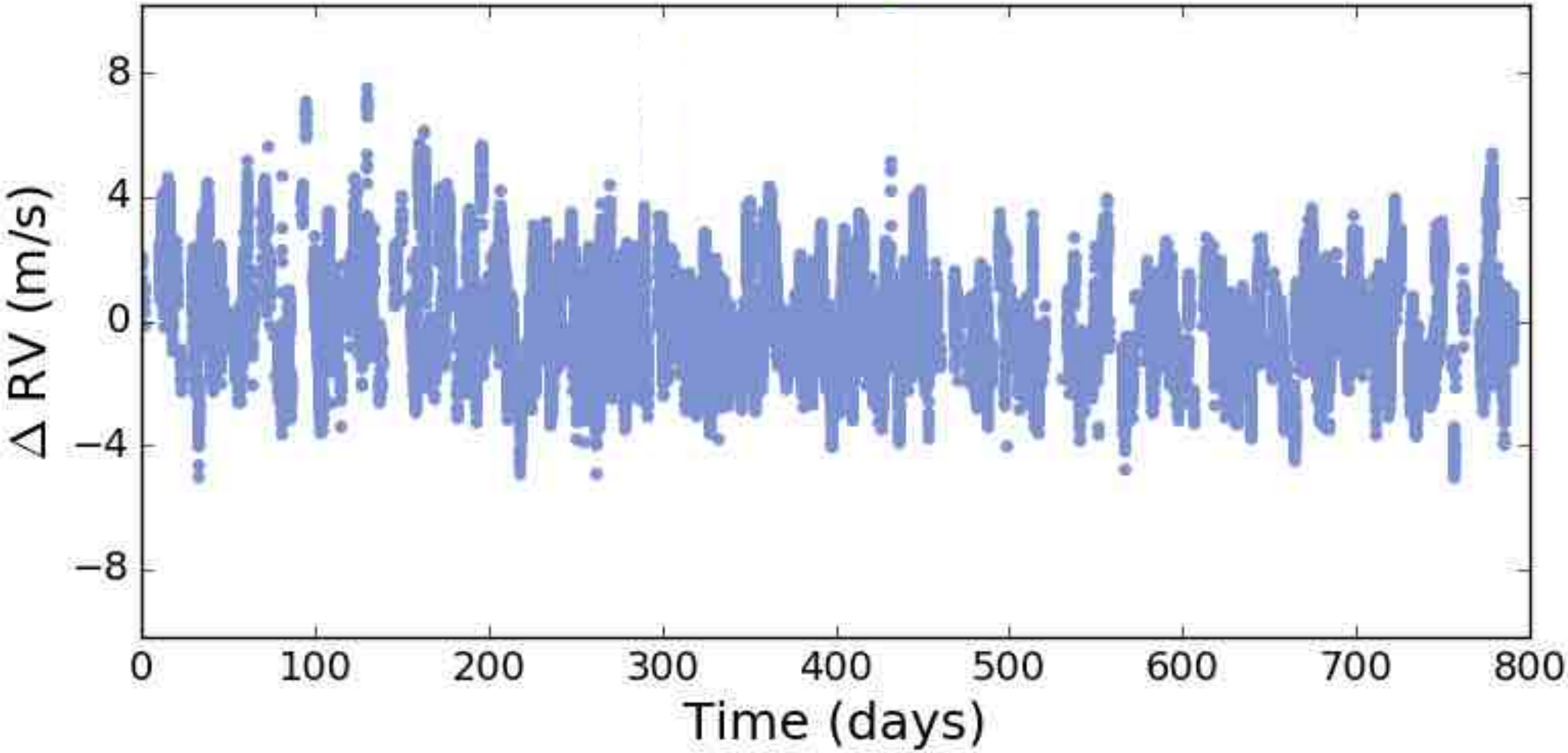


Solar/HARPS-N Project:
Glenday, Phillips et al. (2012), Dumusque et al. (2016), Phillips et al. (2016)

RV variations of the Sun as a distant, point-like star, with no planets orbiting it!

>26000 observations, 5-min exposures, photon noise rms scatter: 40-50 cm/s



Solar/HARPS-N Project:
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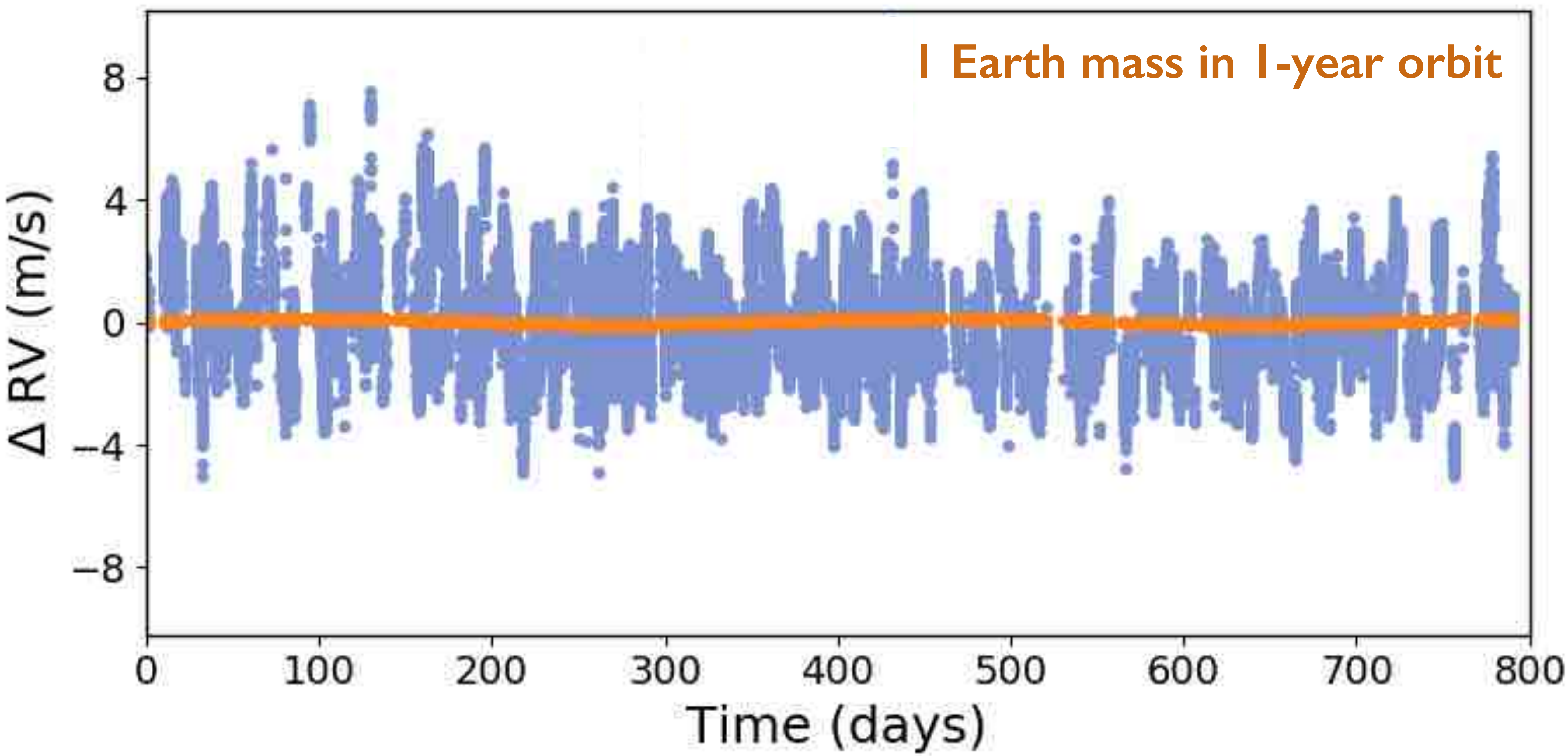

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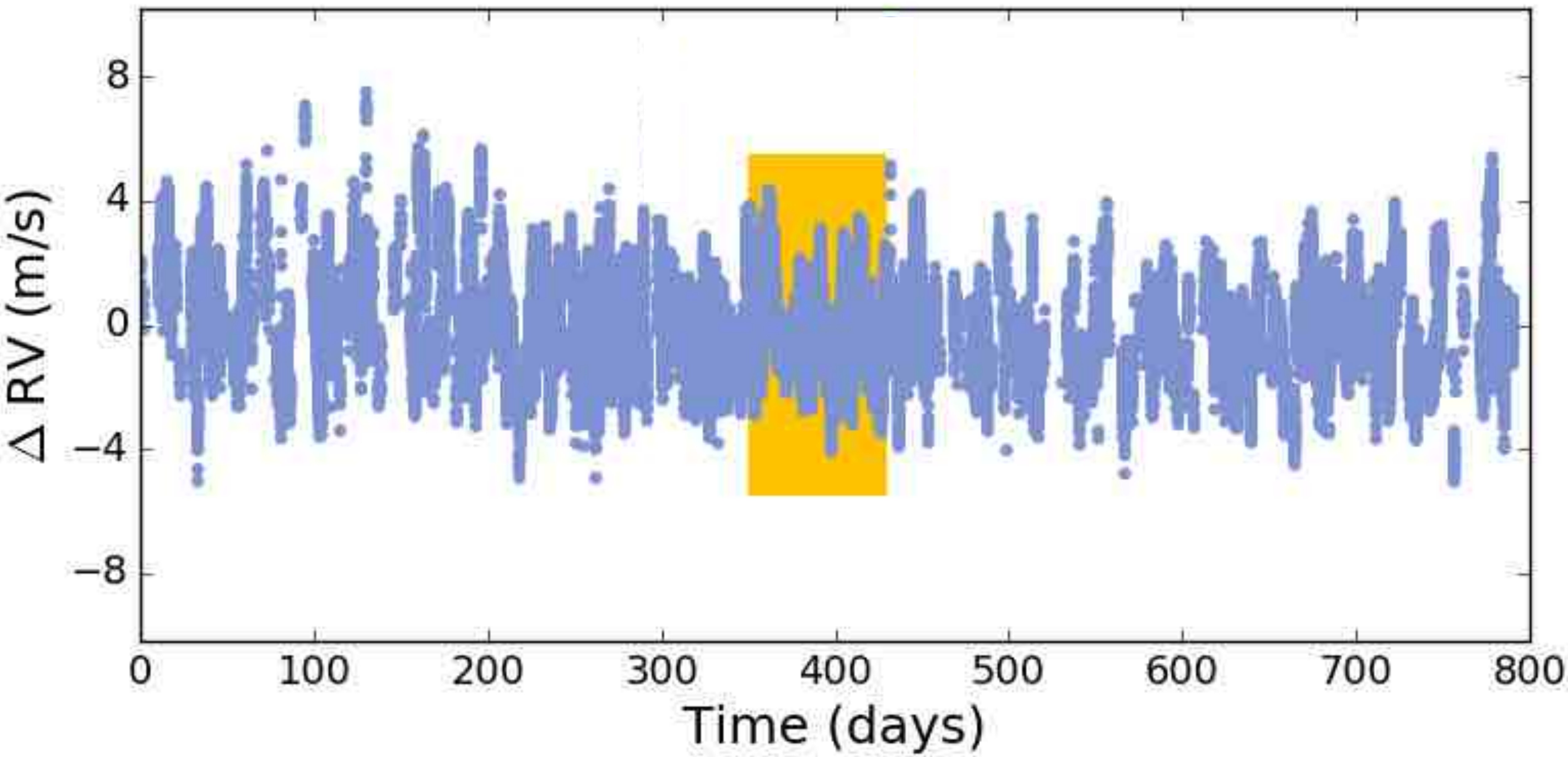

Solar/HARPS-N Project:
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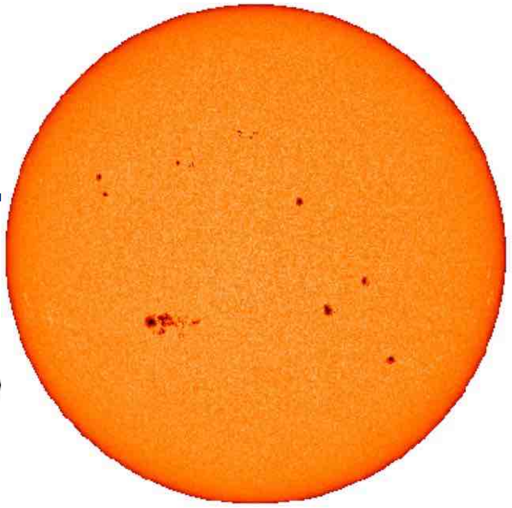
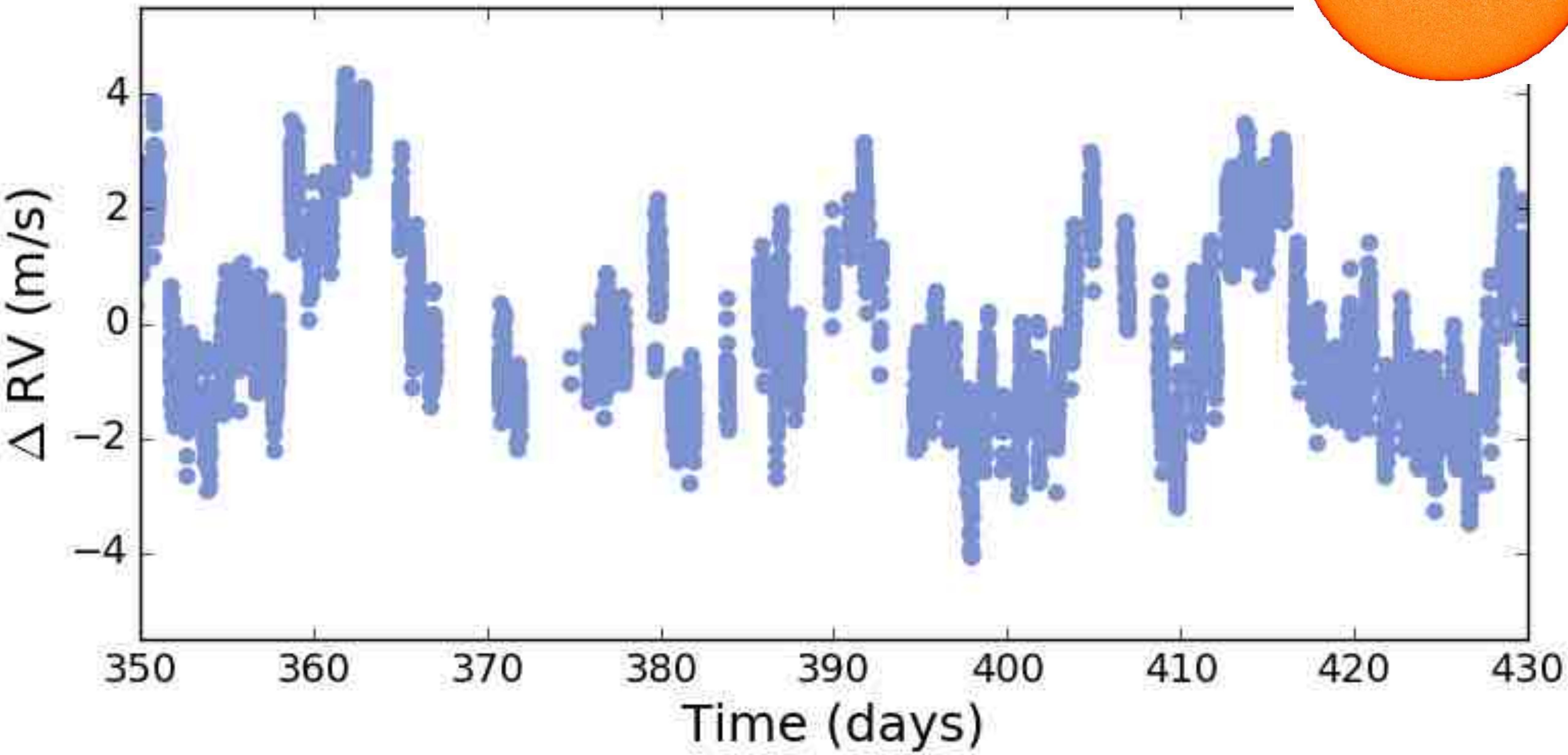
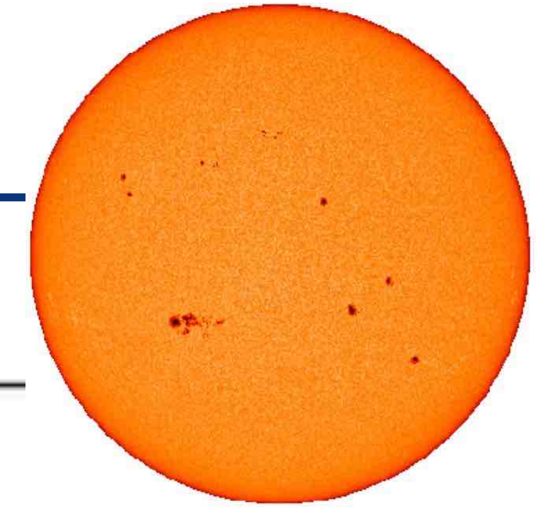
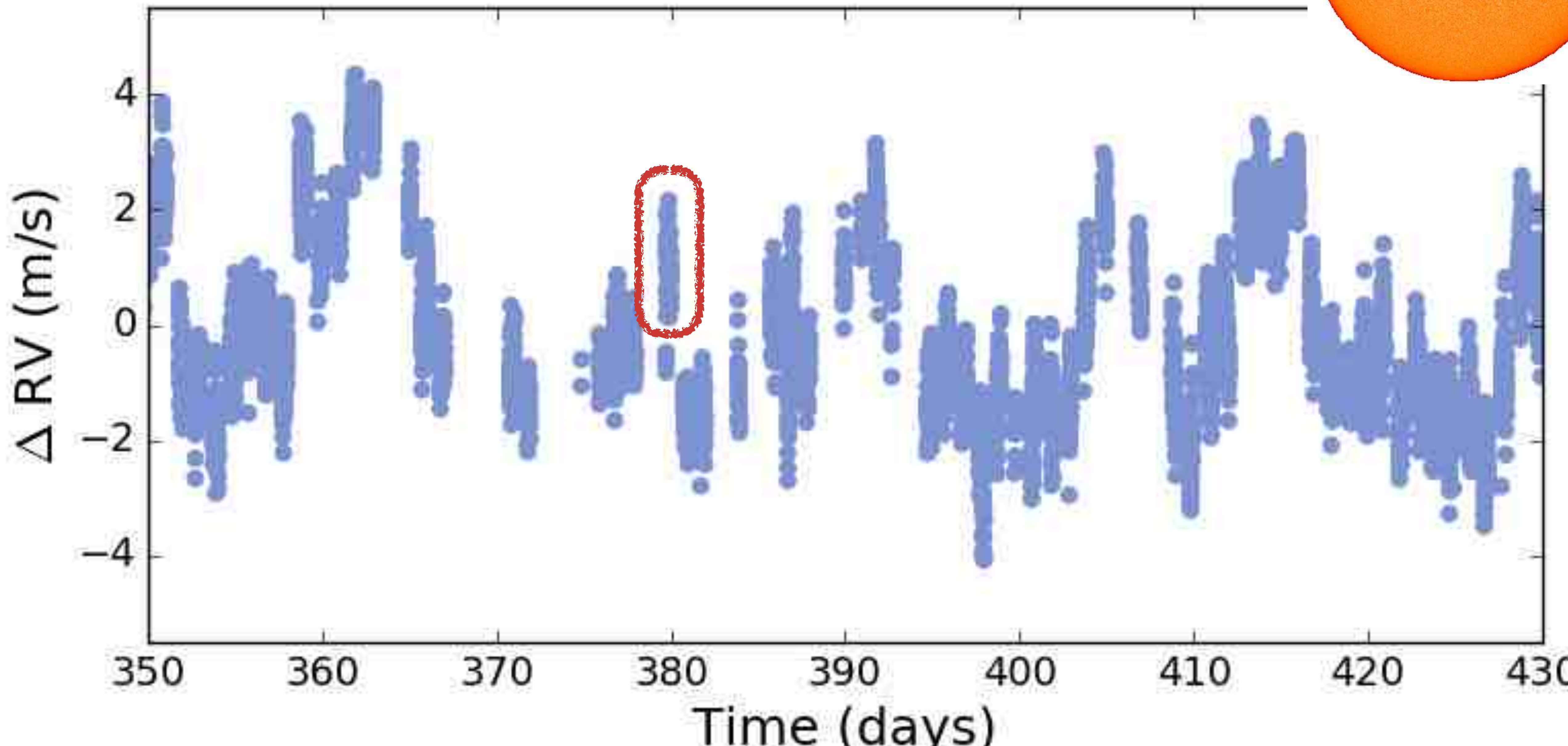
RV variations of the Sun over a few solar rotations



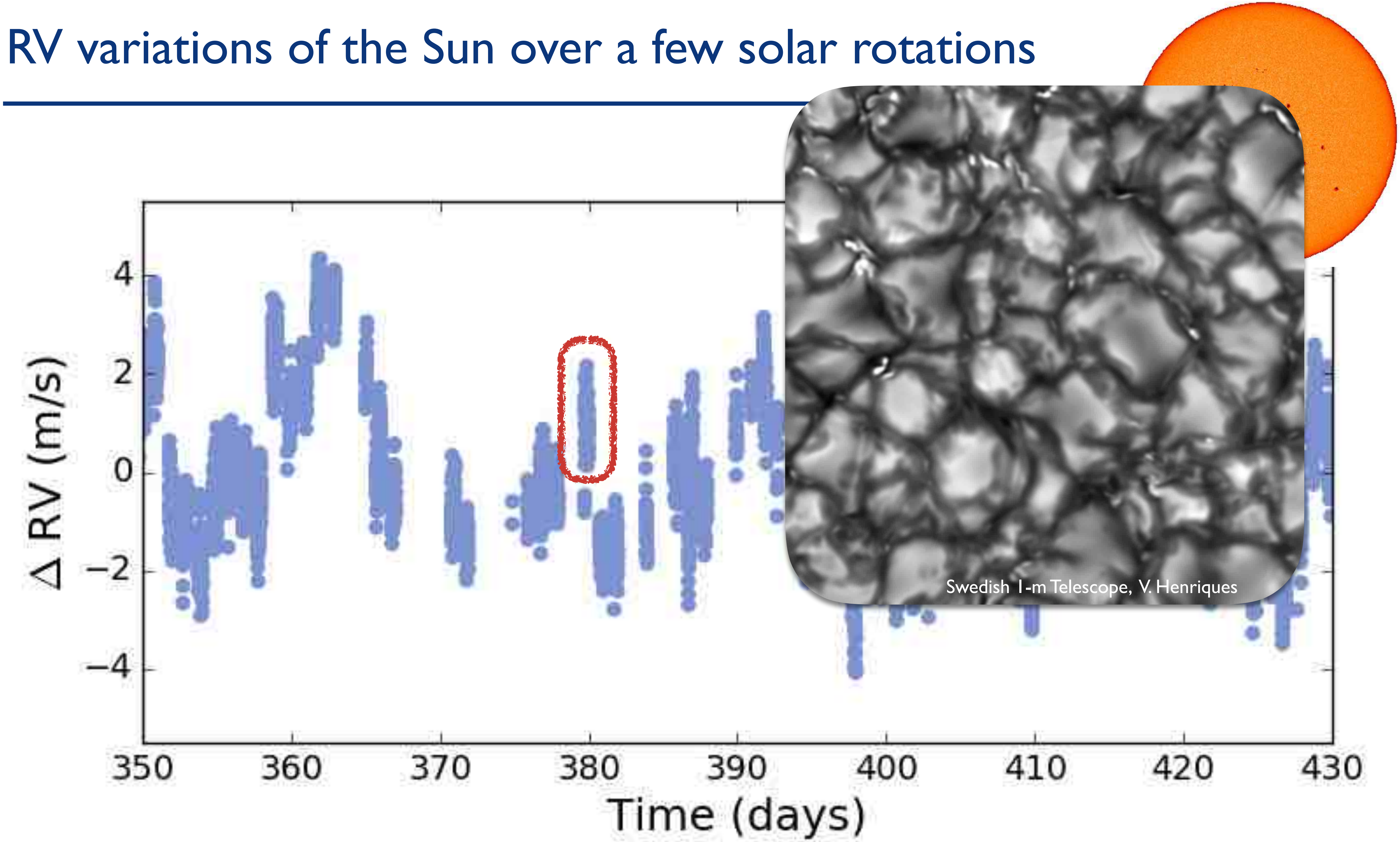


RV variations of the Sun over a few solar rotations

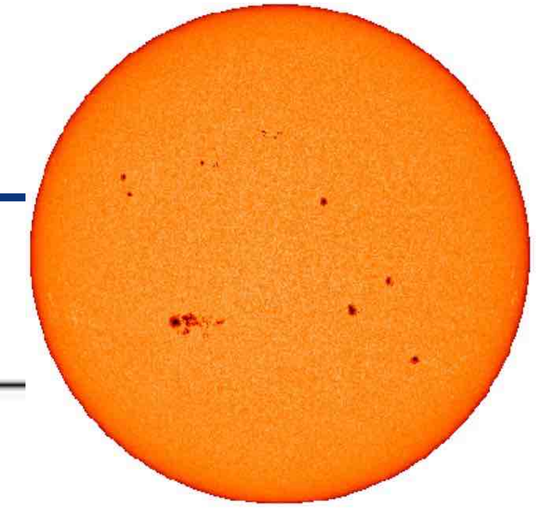


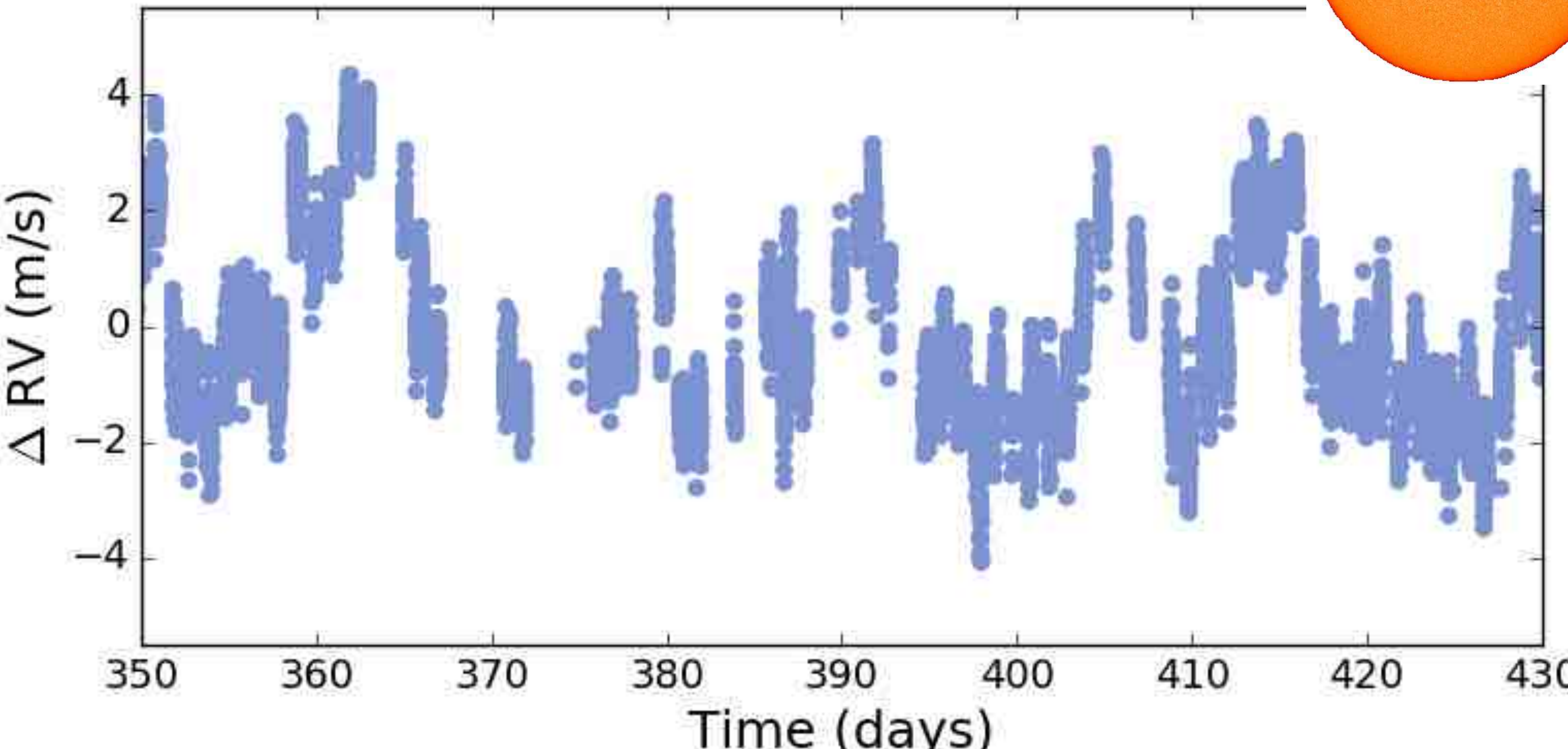


RV variations of the Sun over a few solar rotations



RV variations of the Sun over a few solar rotations





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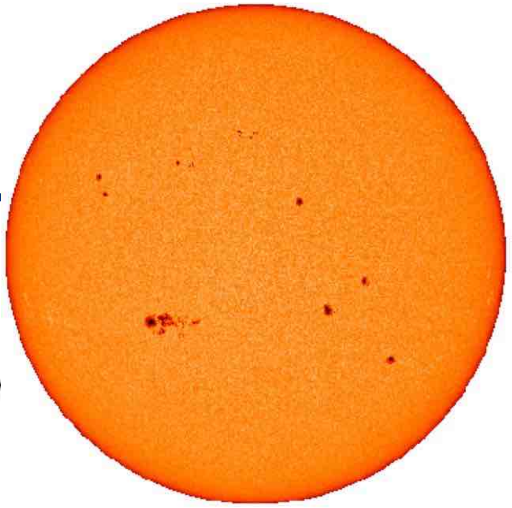
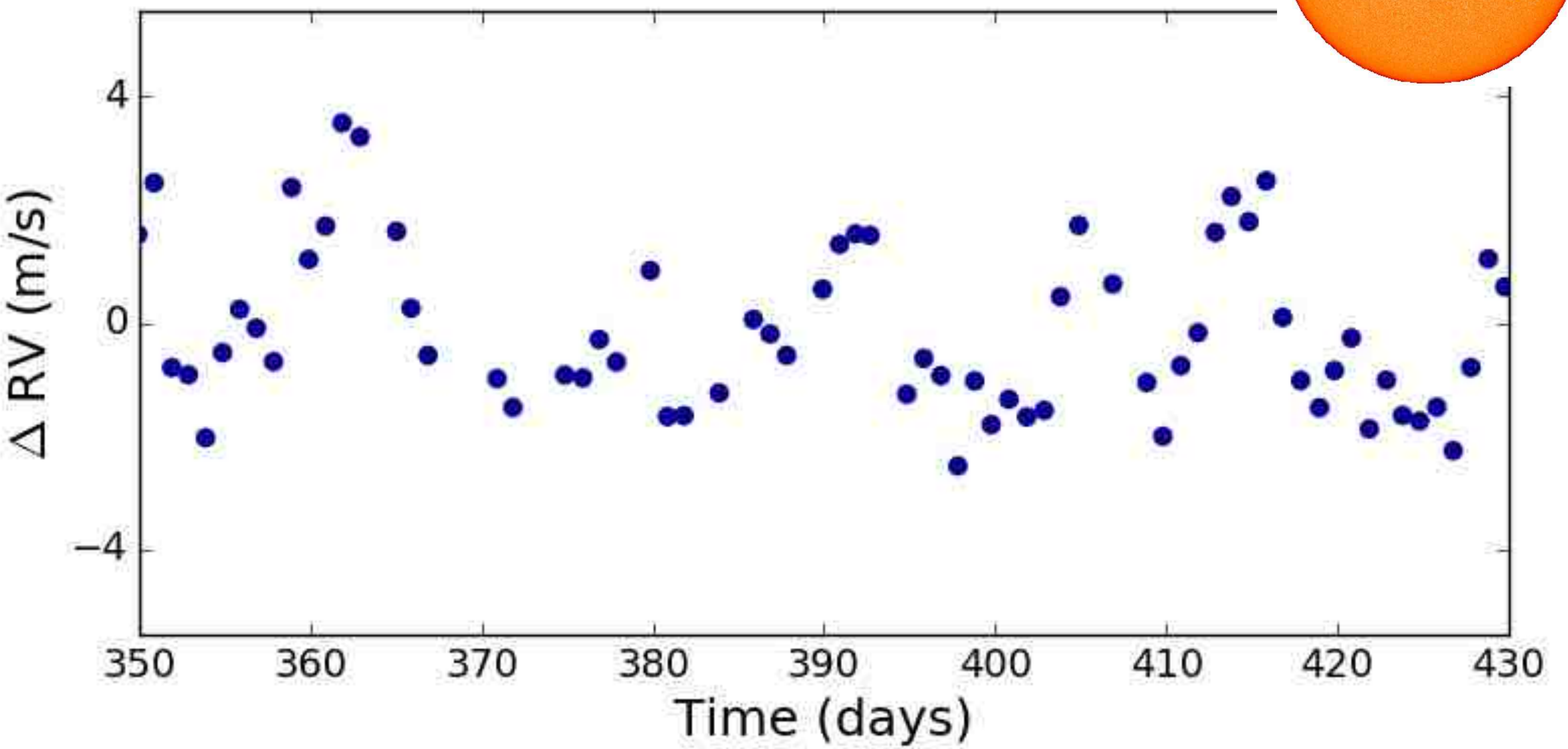


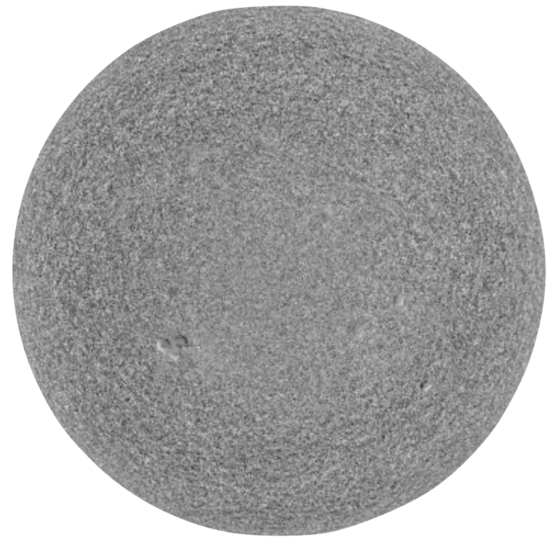
Daily averages



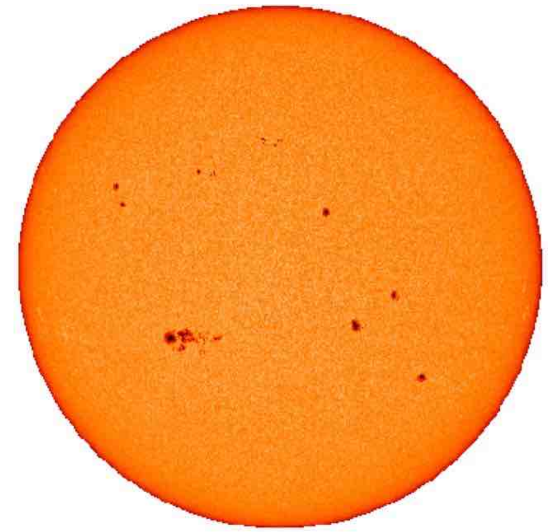
Milbourne, Haywood et al. (2019)

Estimating the radial-velocity variations of the Sun using spatially resolved images

Helioseismic & Magnetic Imager onboard the Solar Dynamics Observatory (SDO/HMI)



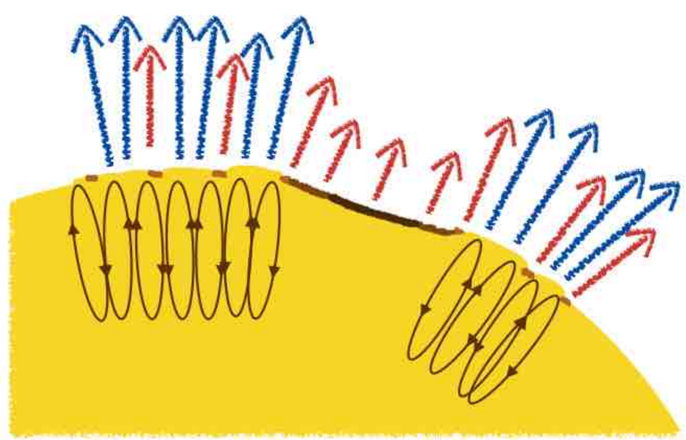
Doppler image



Continuum intensity

Magnetic field

Model:



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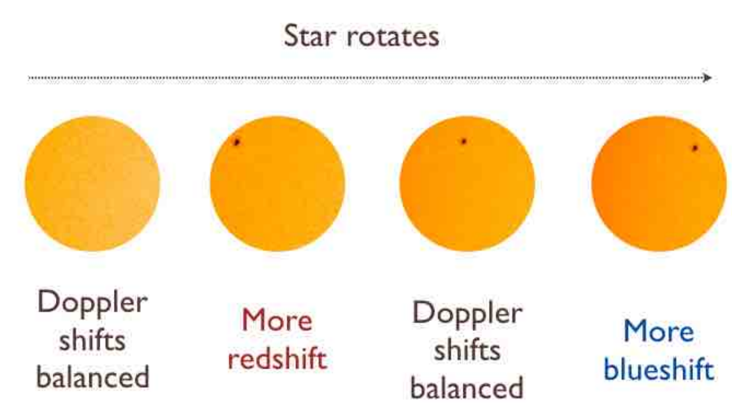
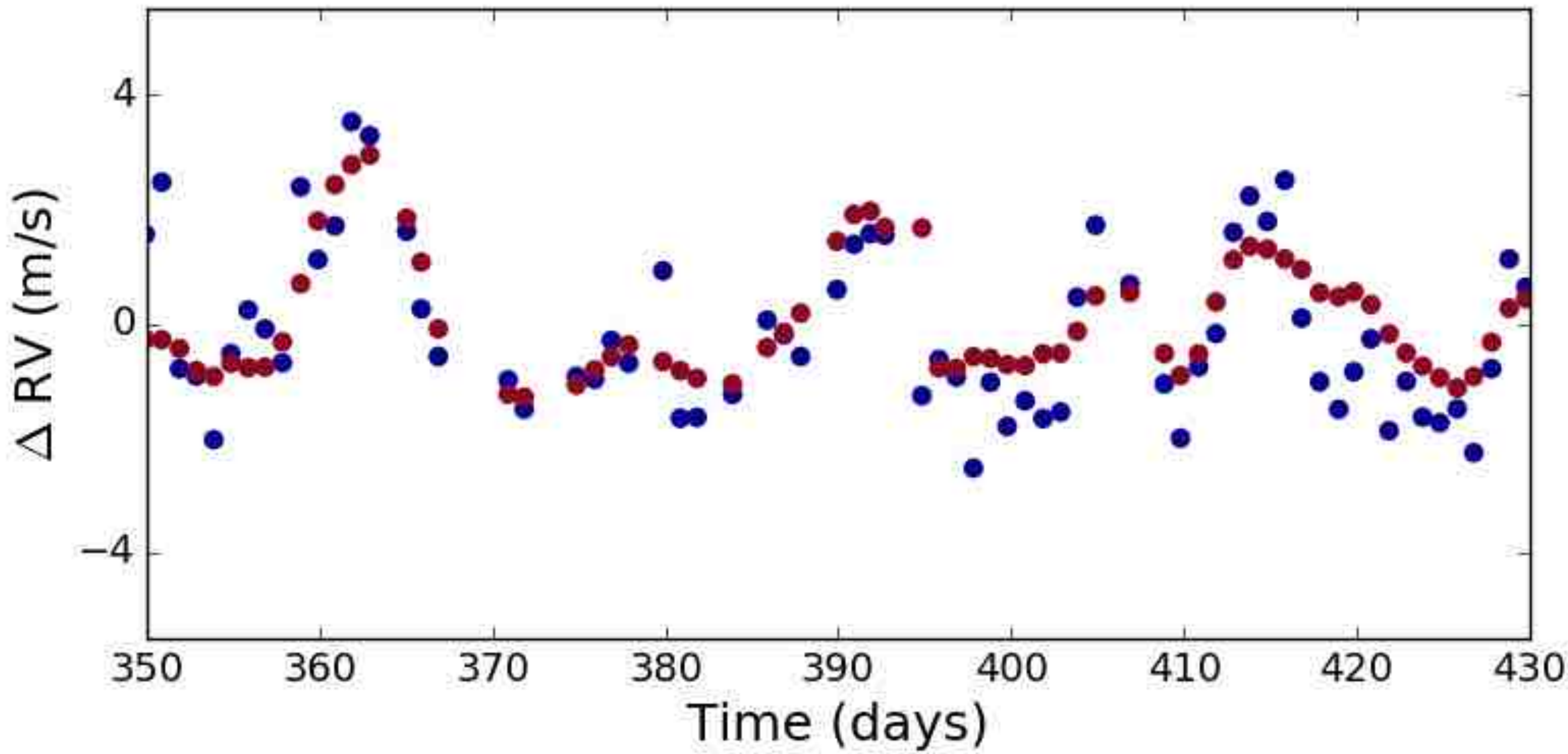


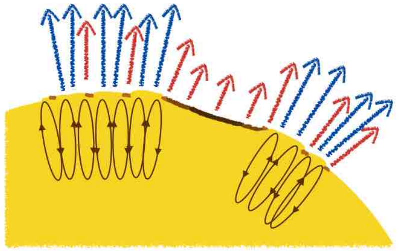
Technique developed by Meunier, Lagrange & Desort (2010) for SoHO/MDI images

RV variations of the Sun over a few solar rotations

Daily averages



Model:



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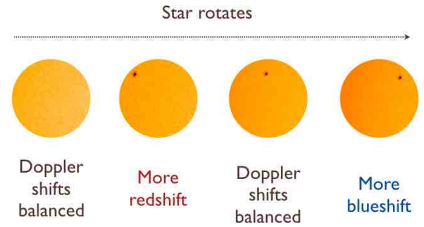
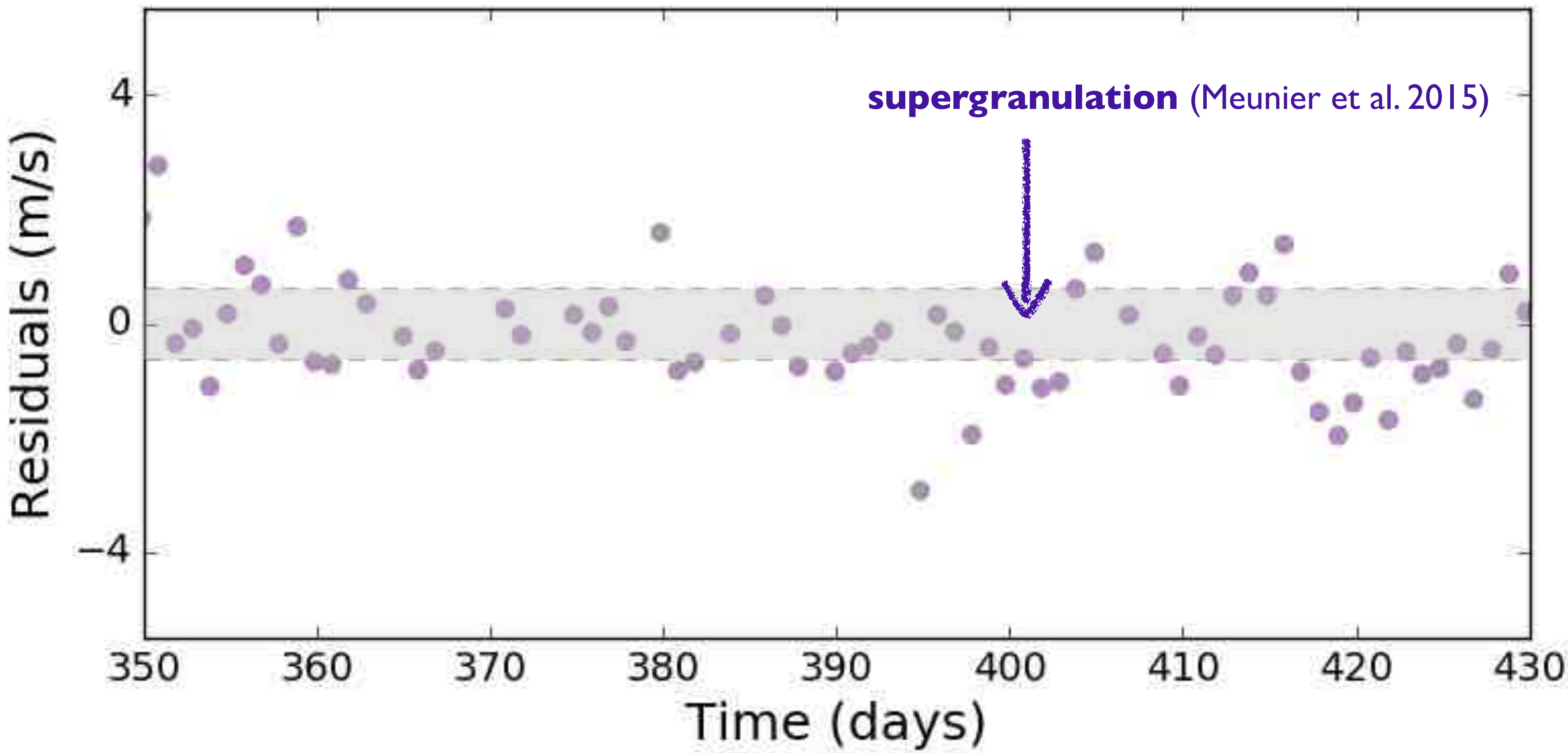


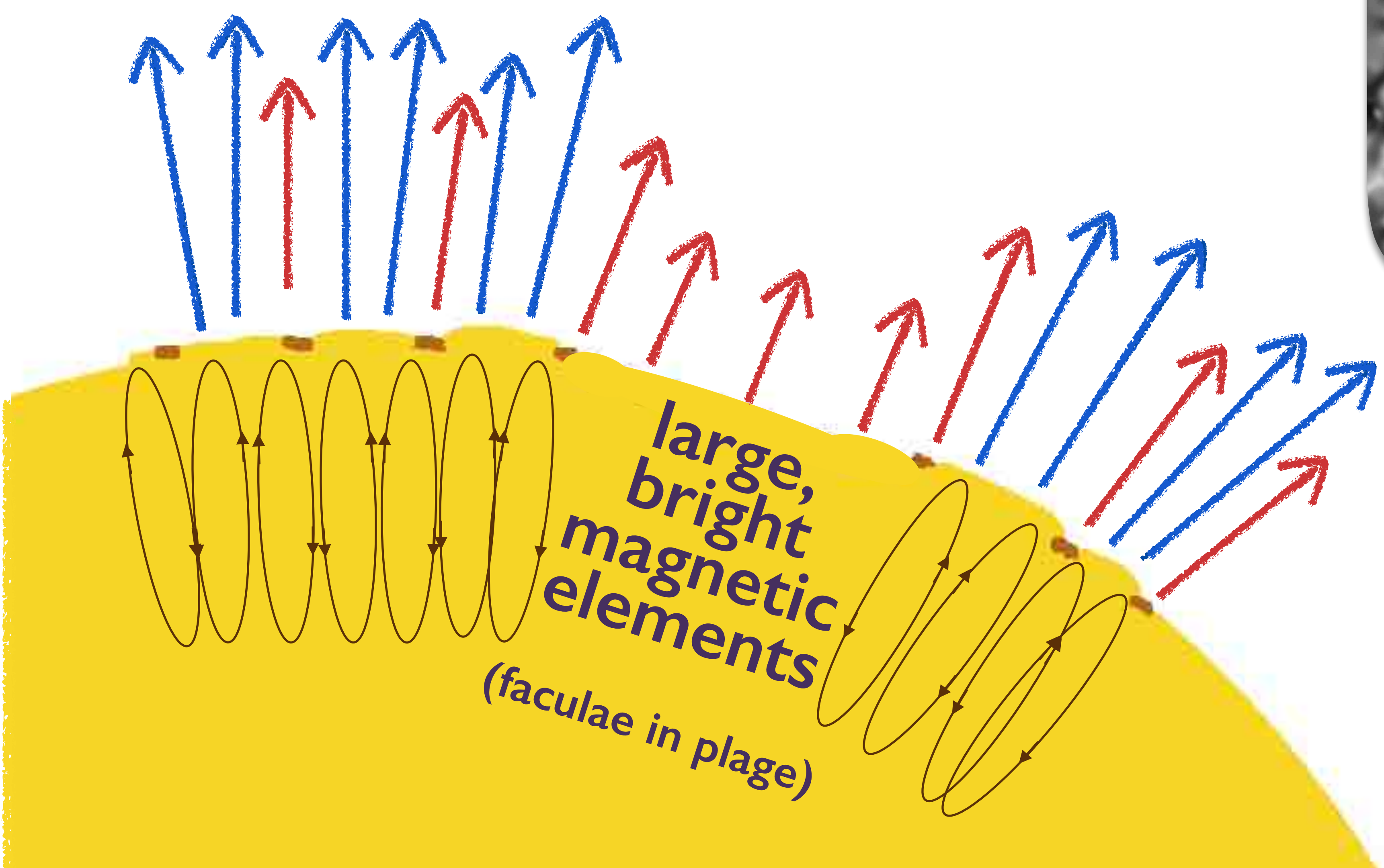
Milbourne, Haywood et al. (2019)

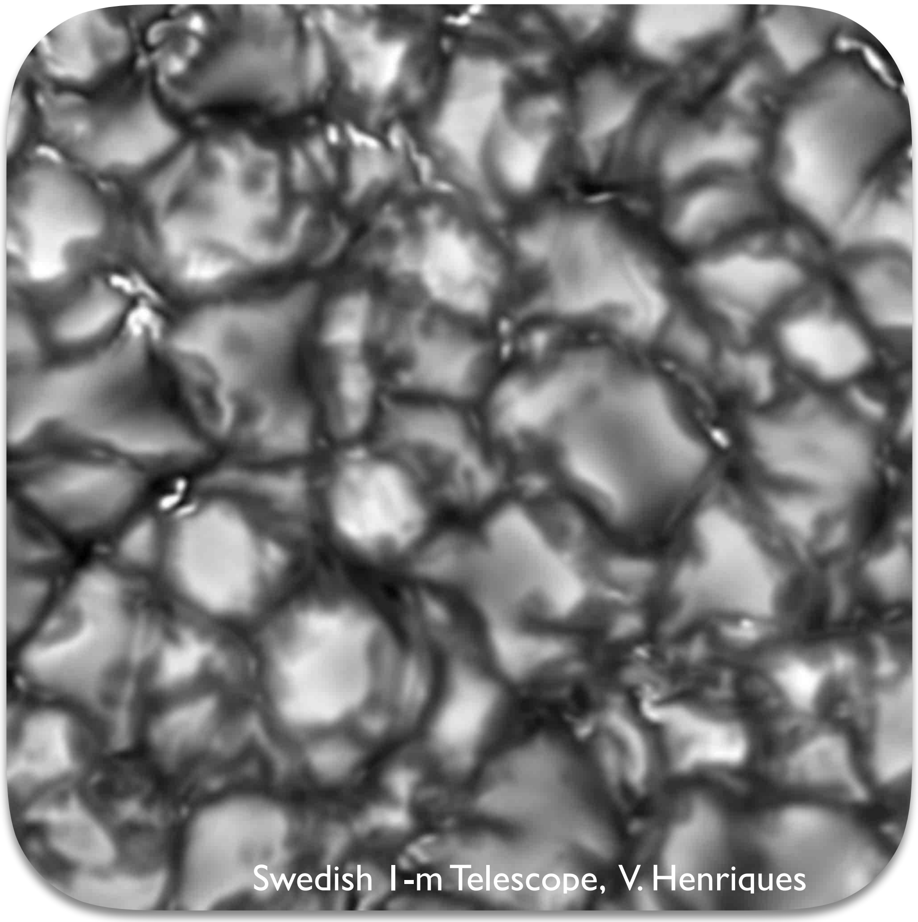
Our model accounts well for rotationally modulated solar activity



Milbourne, Haywood et al. (2019)

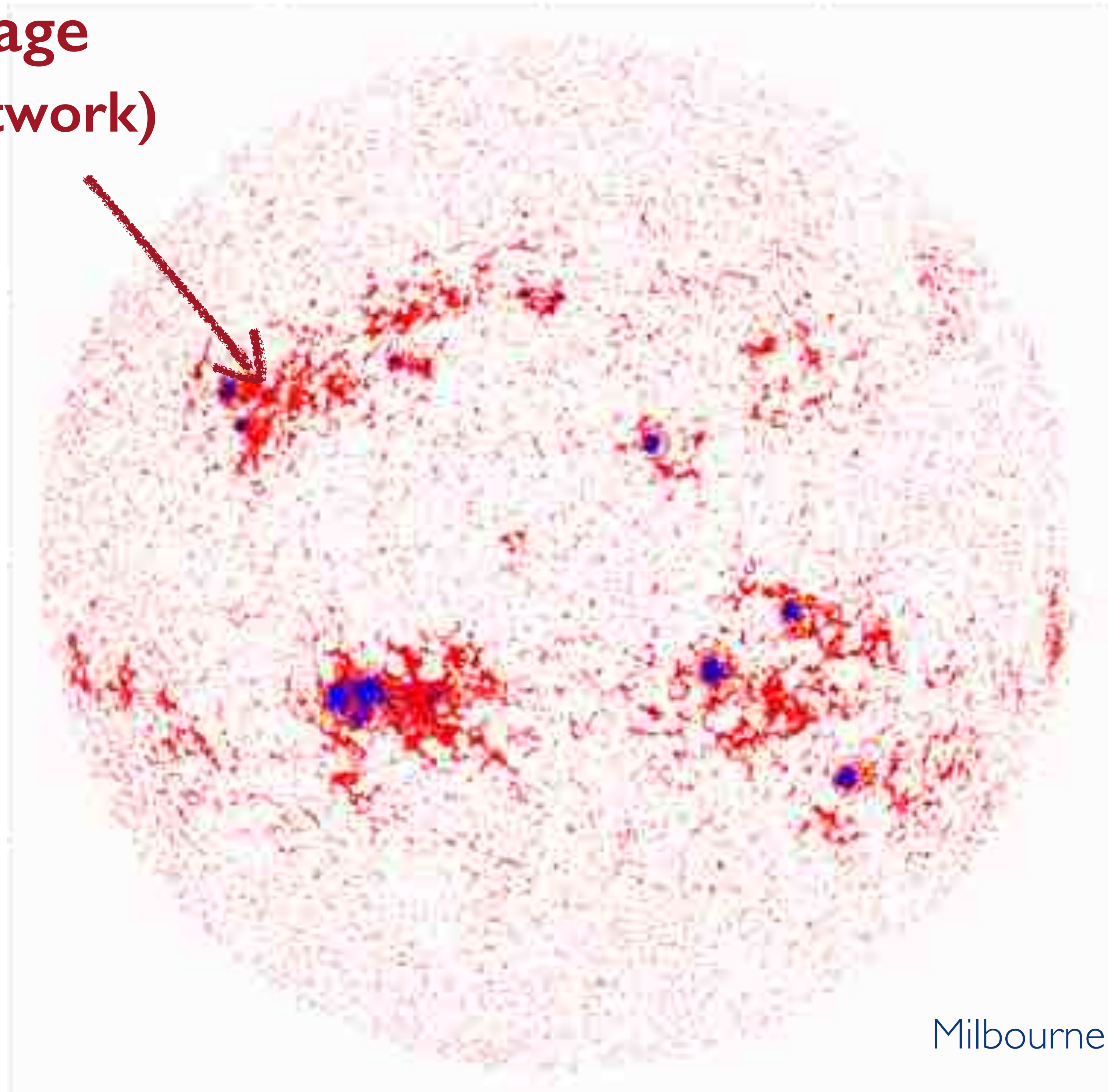
The Sun's RV variations are dominated by the suppression of convective blueshift





Milbourne, Haywood et al. (2019)
Haywood et al. (2016)
Meunier et al. (2010a,b)

Faculae *in plage* are the dominant features at play



Milbourne, Haywood et al. (2019)
Haywood et al. (2016)
Meunier et al. (2010a,b)

SDO/HMI continuum image

Characterising center-to-limb variations in RV

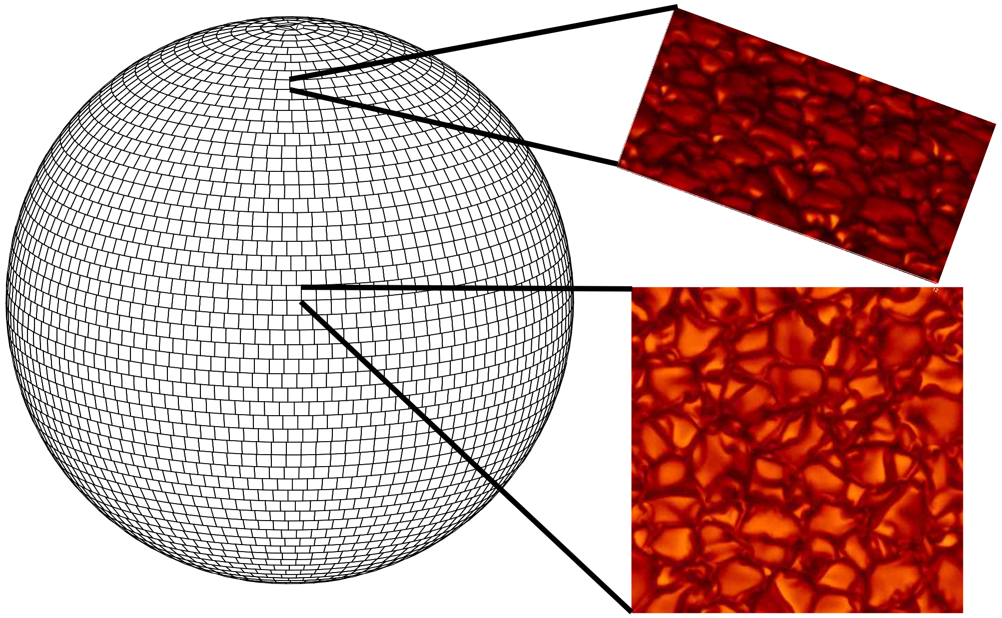
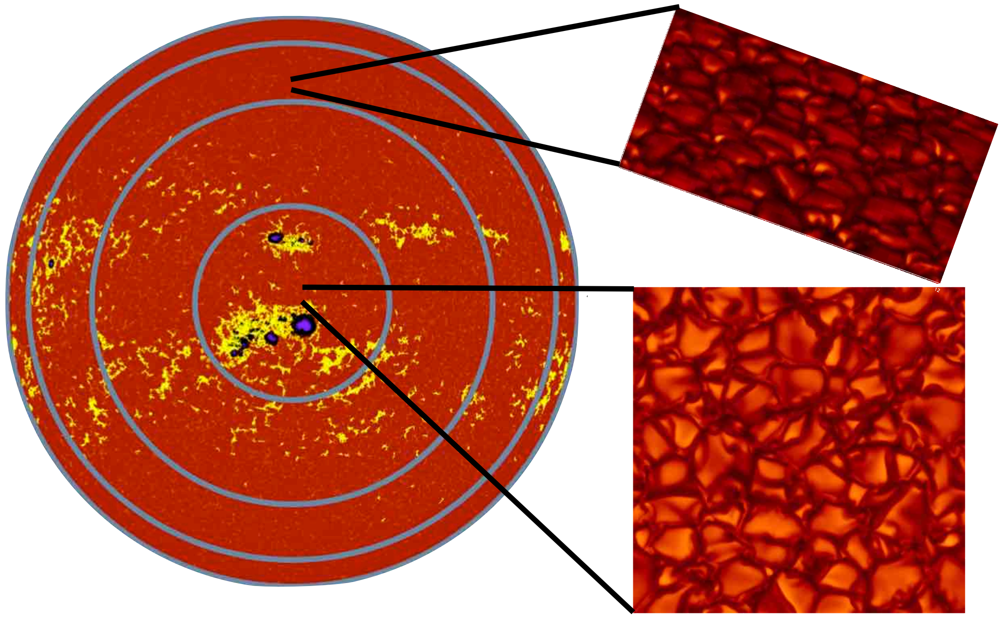


Image credit: H. Cegla, M. Palumbo

Characterising center-to-limb variations in RV



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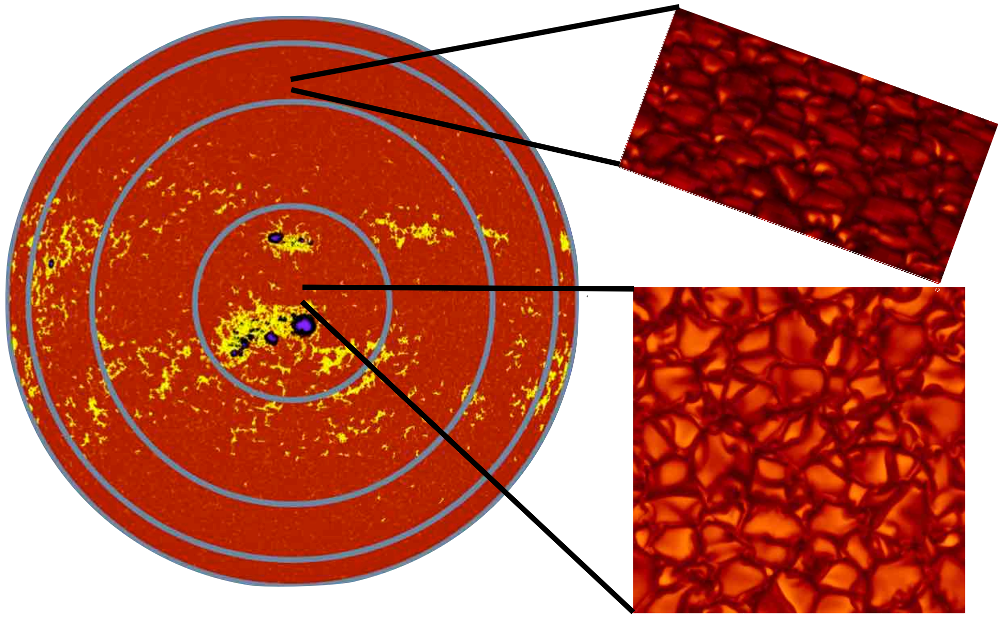
Characterising center-to-limb variations in RV



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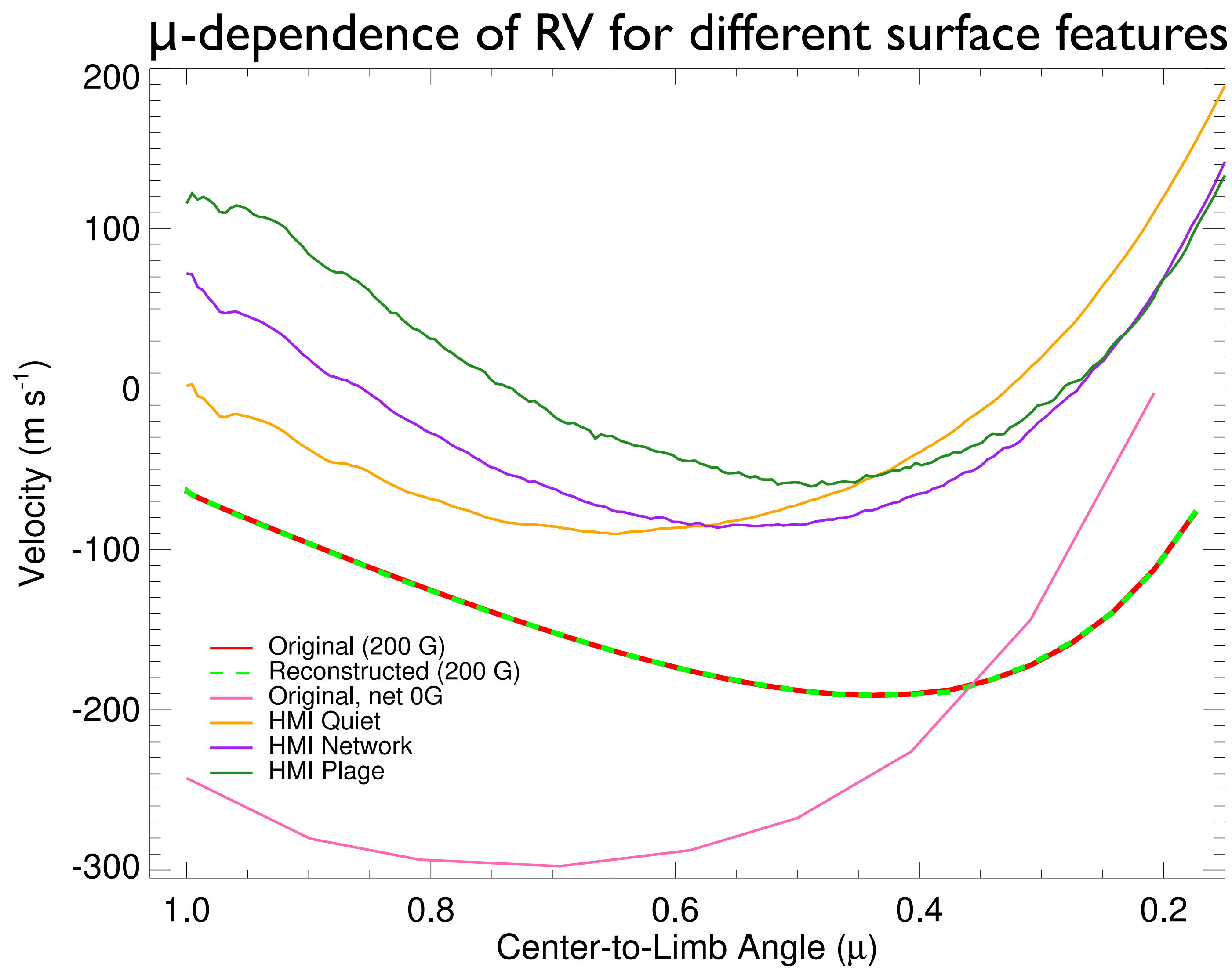
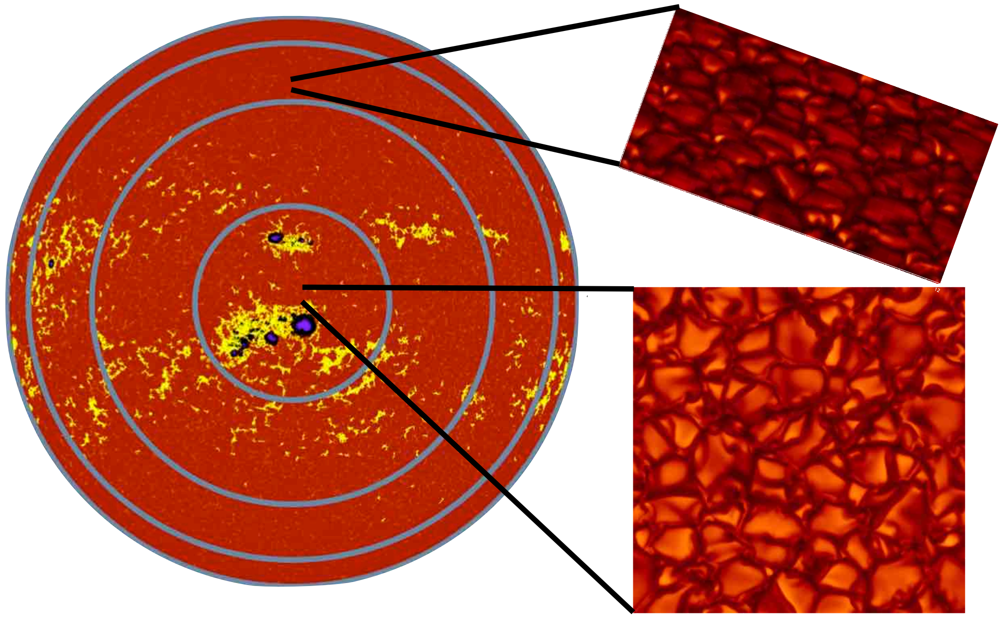


Cegla et al. (2019)

See also Löhner-Böttcher et al. (2018)

Characterising center-to-limb variations in RV



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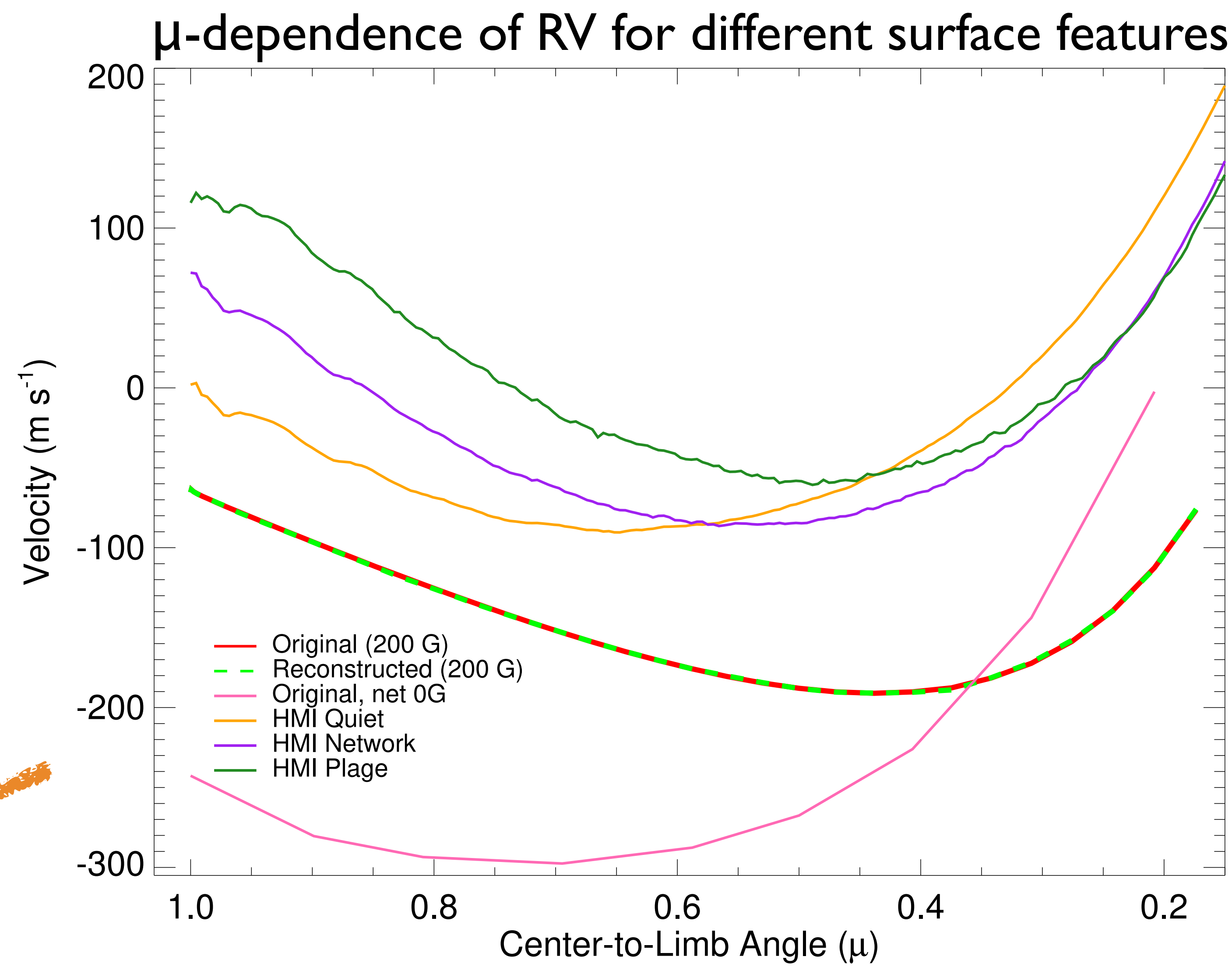

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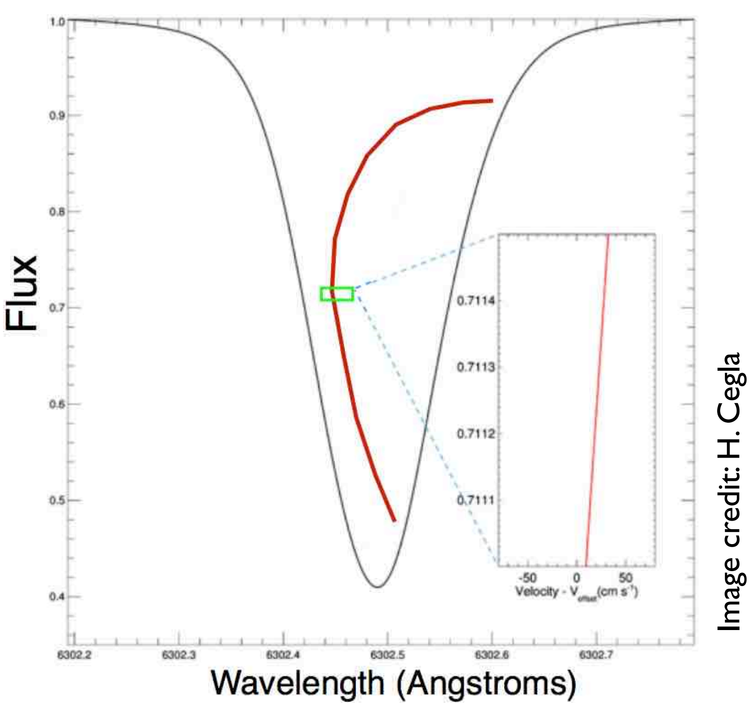
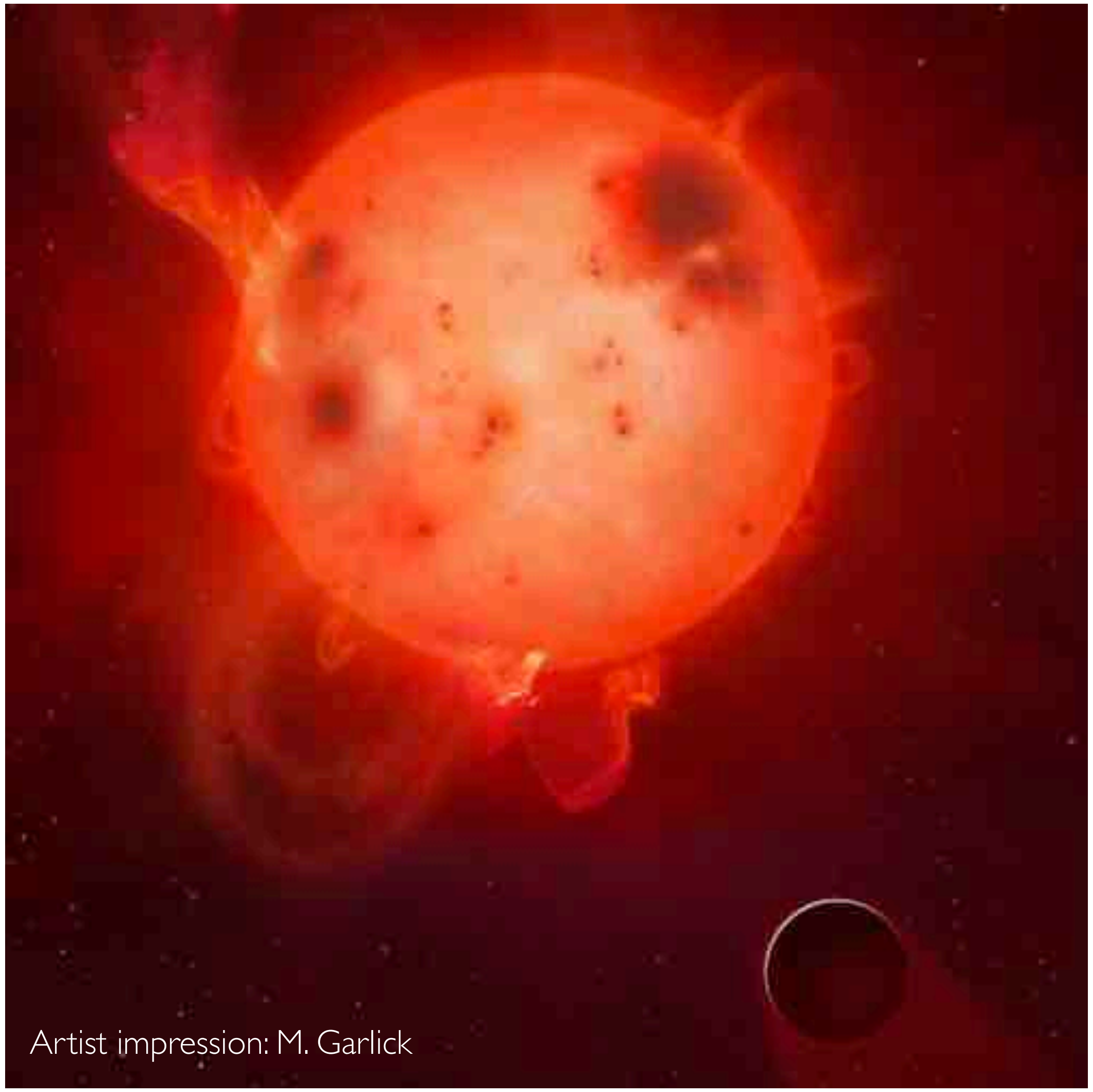


Image credit: H. Cegla

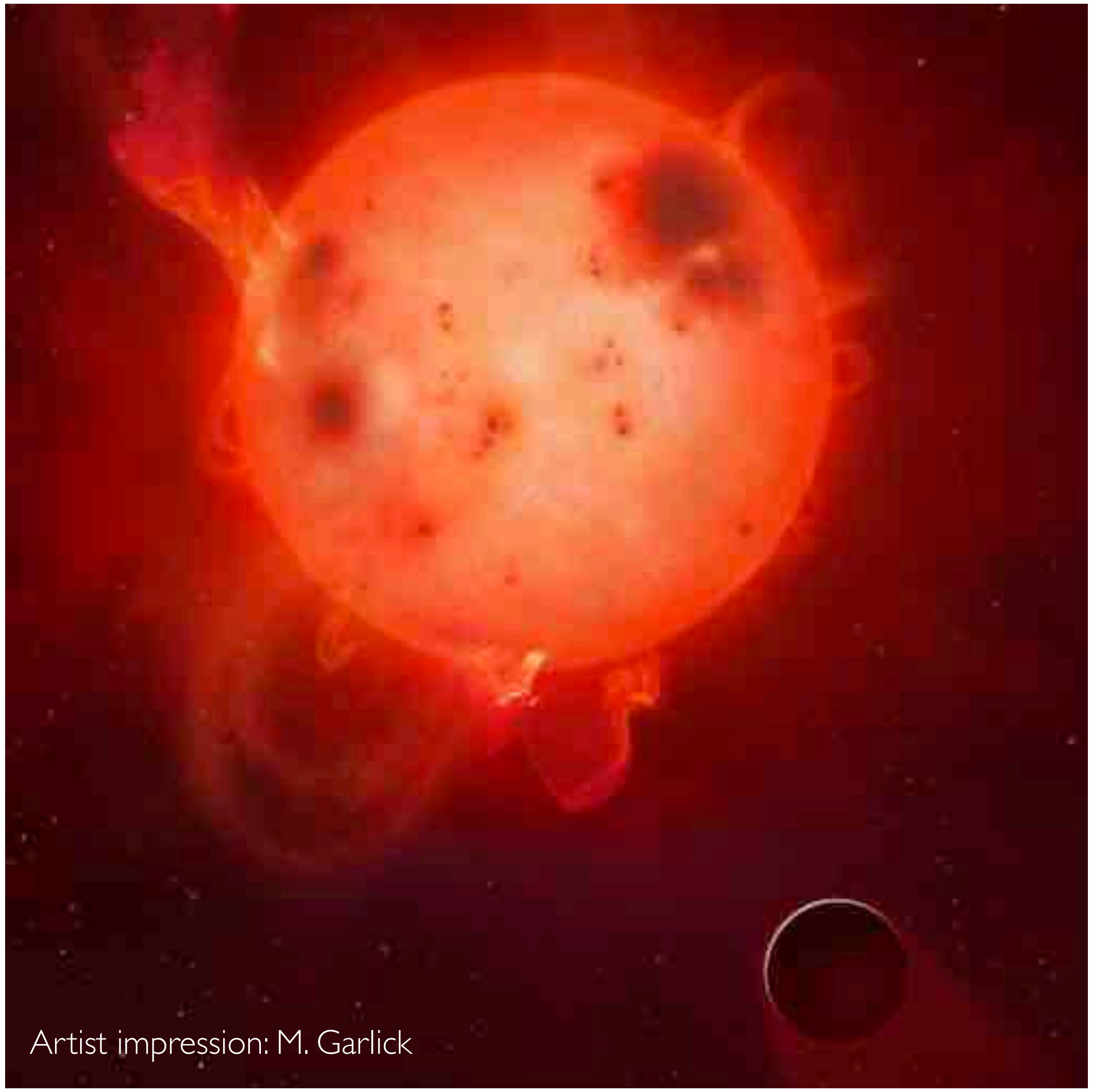
Essential input to parametrisations to recreate line profile shapes and RV shifts (eg., MHD simulations)

How can we use this solar knowledge to "correct" RV observations of other stars?



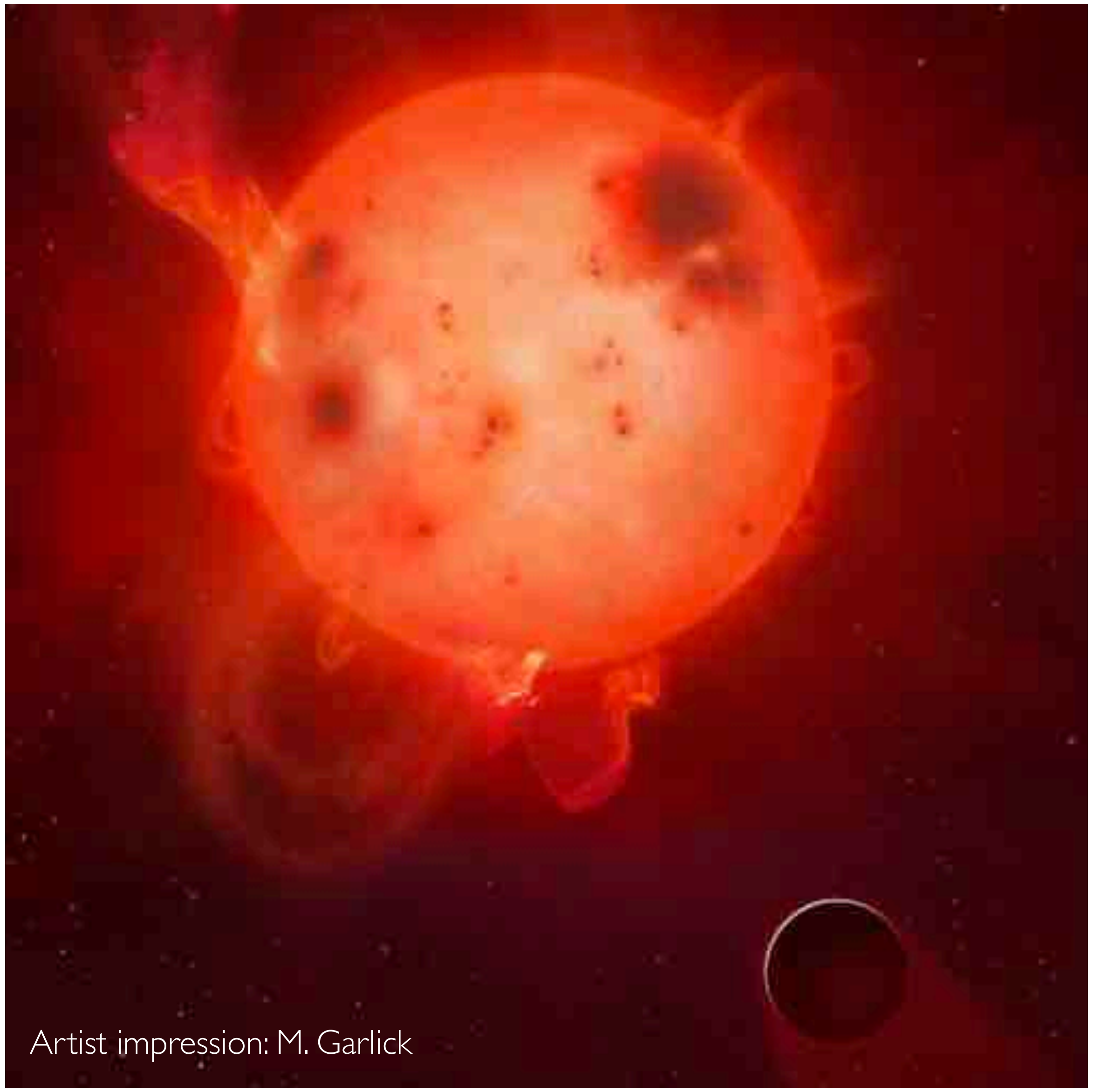
How can we use this solar knowledge to "correct" RV observations of other stars?

- Build physically motivated models

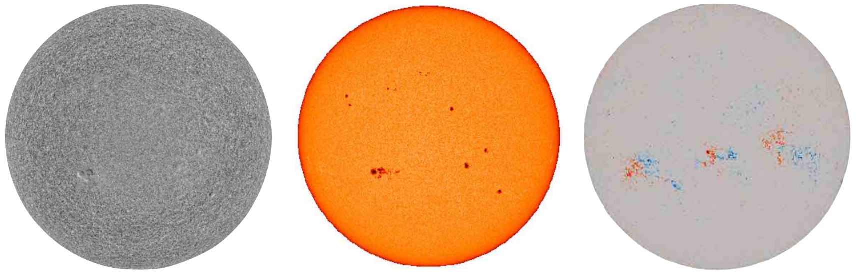


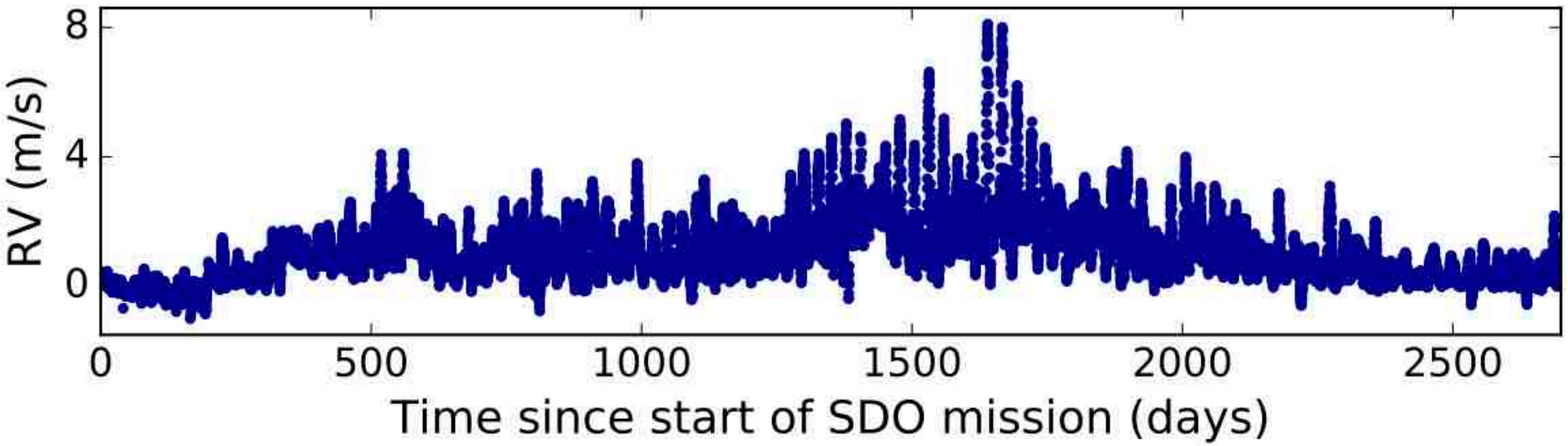
How can we use this solar knowledge to “correct” RV observations of other stars?

- Build physically motivated models
- Identify observable proxies for activity RV variations



RV variations of the Sun estimated from SDO/HMI images





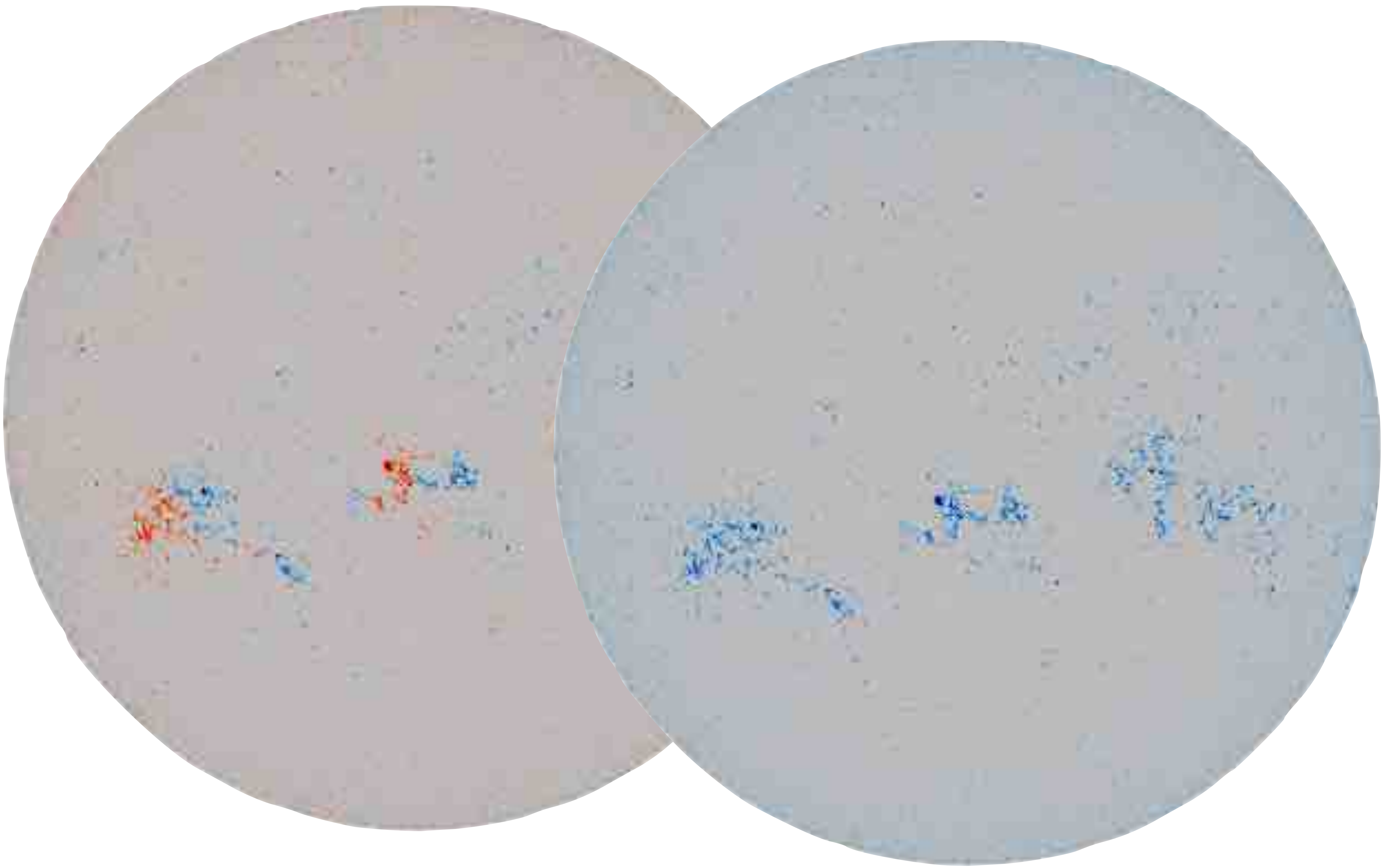
Haywood et al. (in prep.)

Full-disc, unsigned magnetic flux from SDO/HMI magnetograms

Haywood et al. (2016)
See also Robinson (1980), Saar (1988, 1986)

SDO/HMI magnetograms

Full-disc, unsigned magnetic flux from SDO/HMI magnetograms



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SDO/HMI magnetograms

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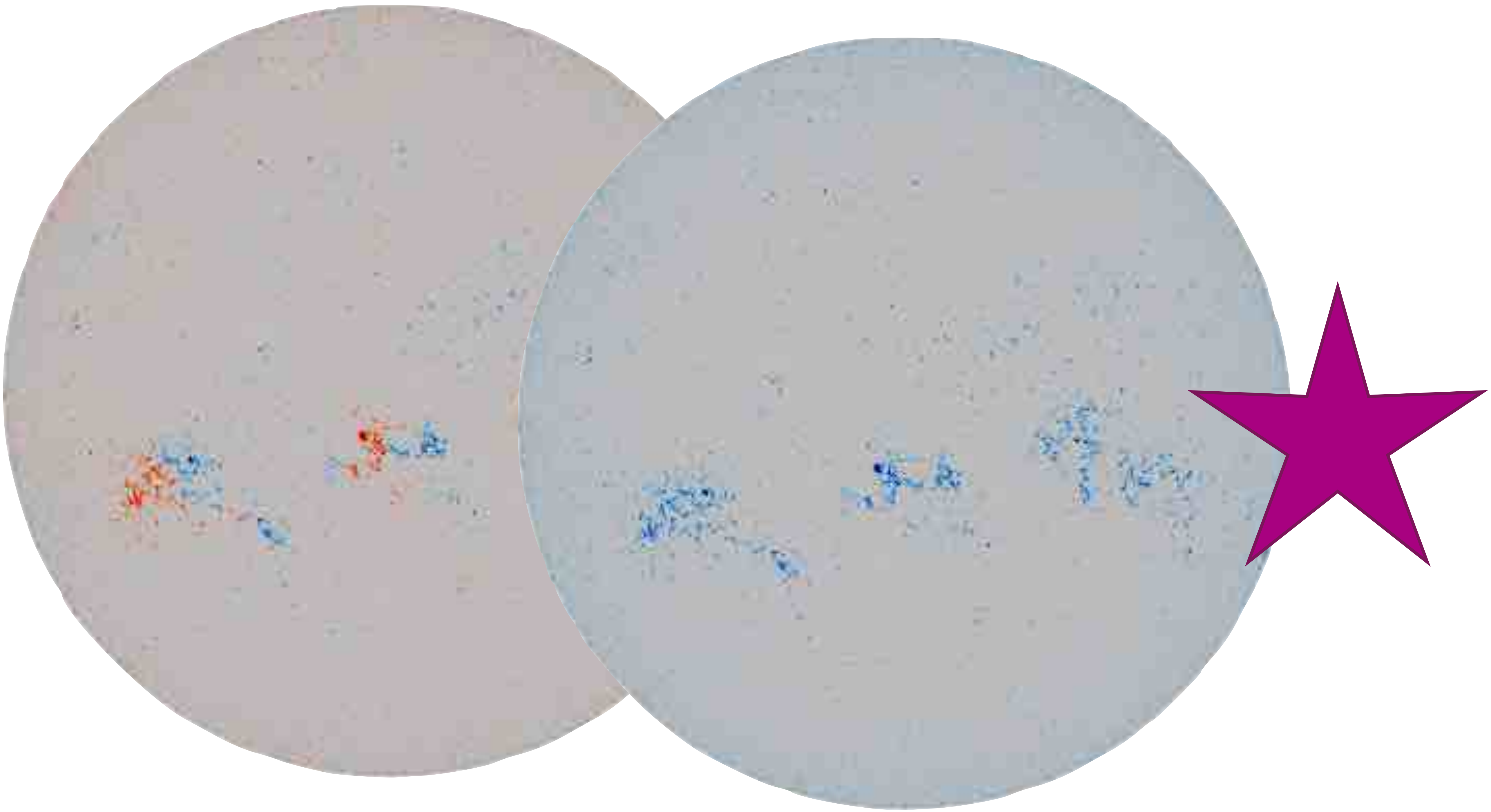

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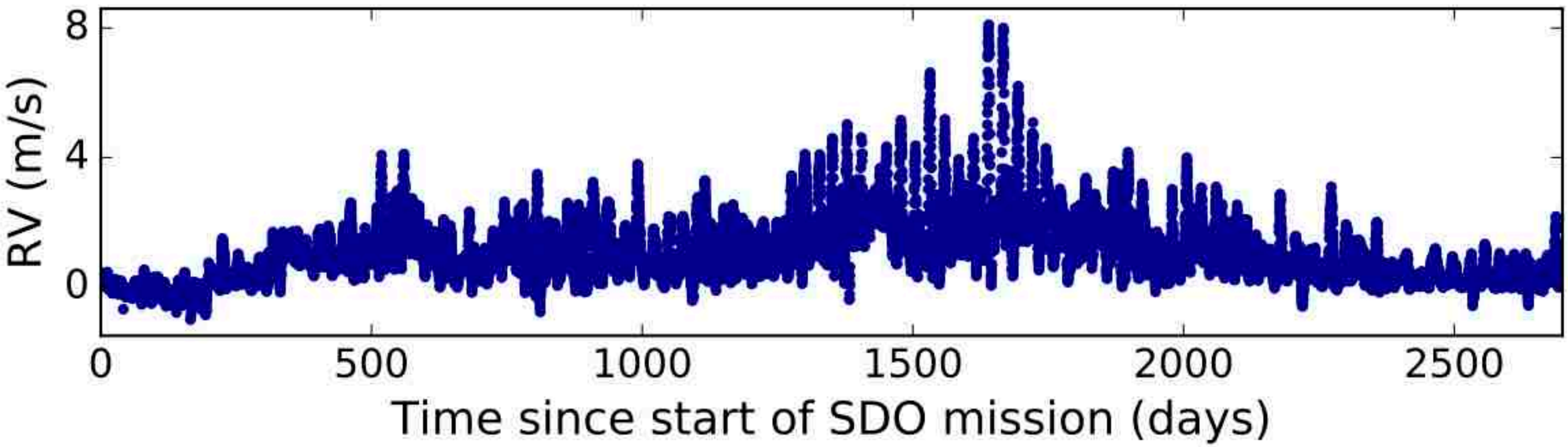
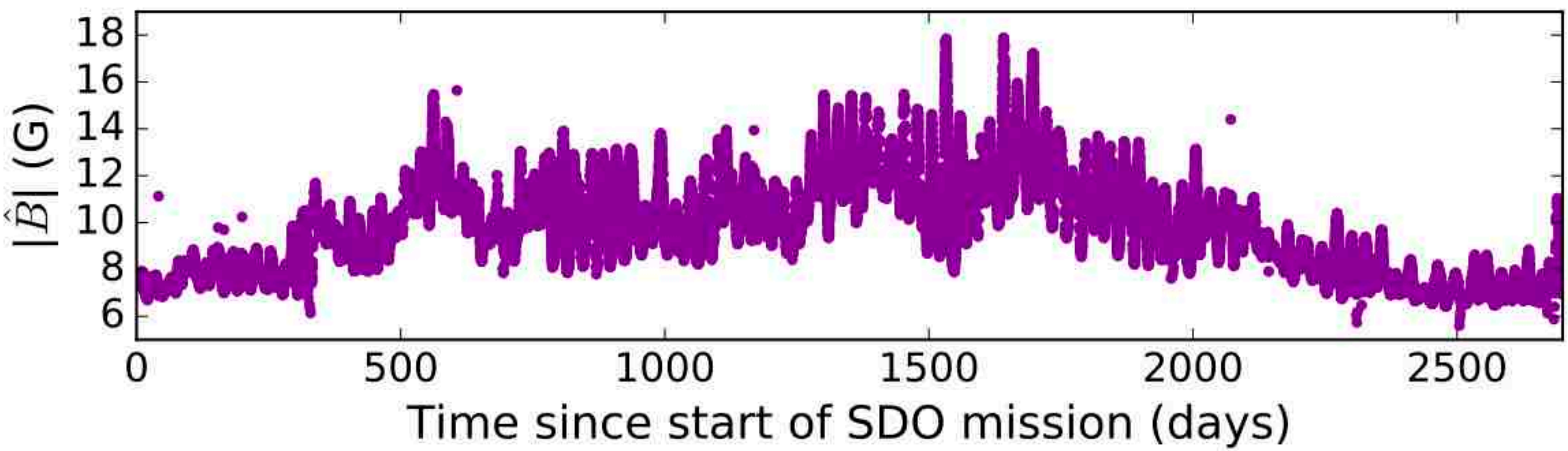
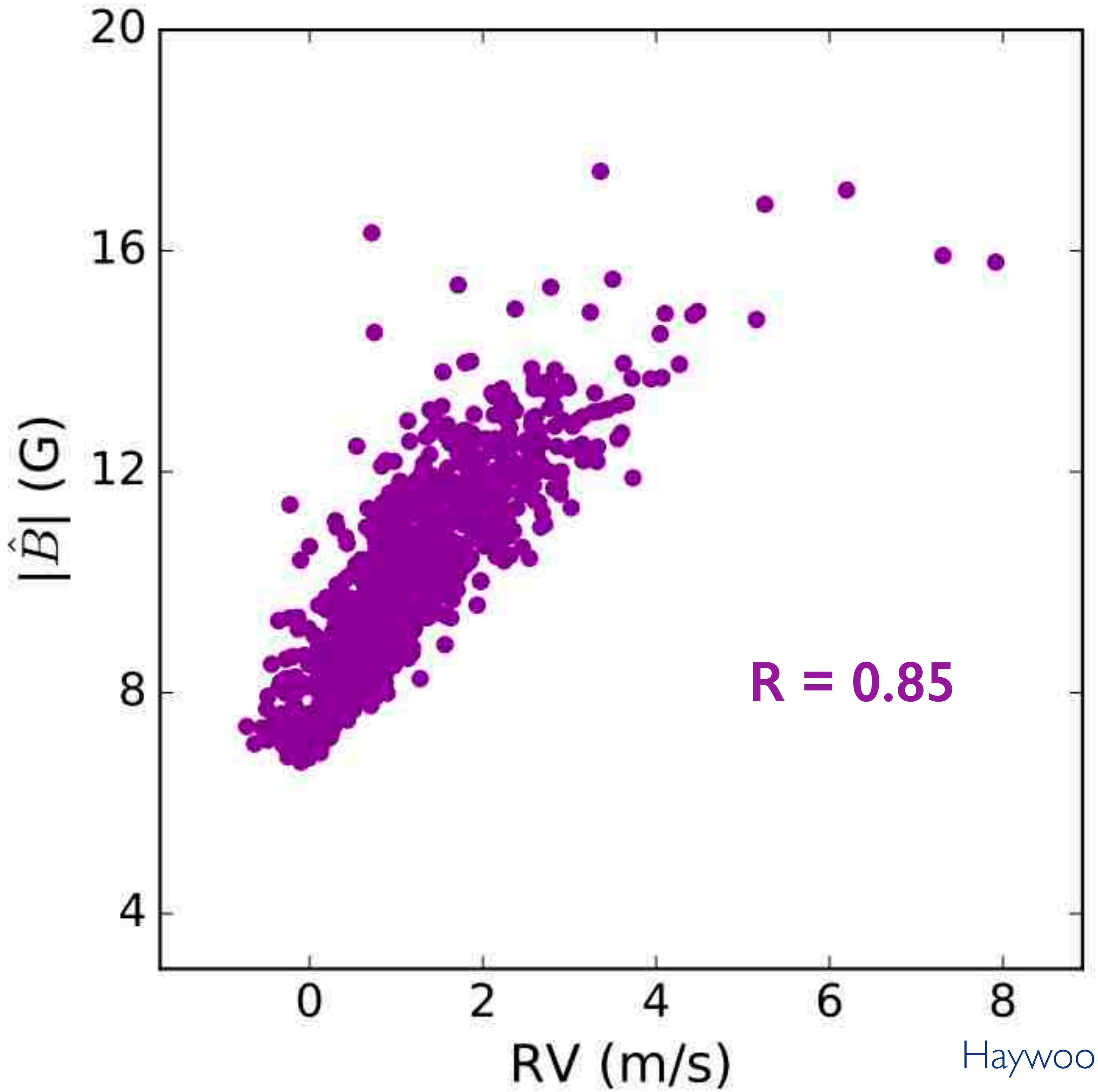
Full-disc, unsigned magnetic flux from SDO/HMI magnetograms





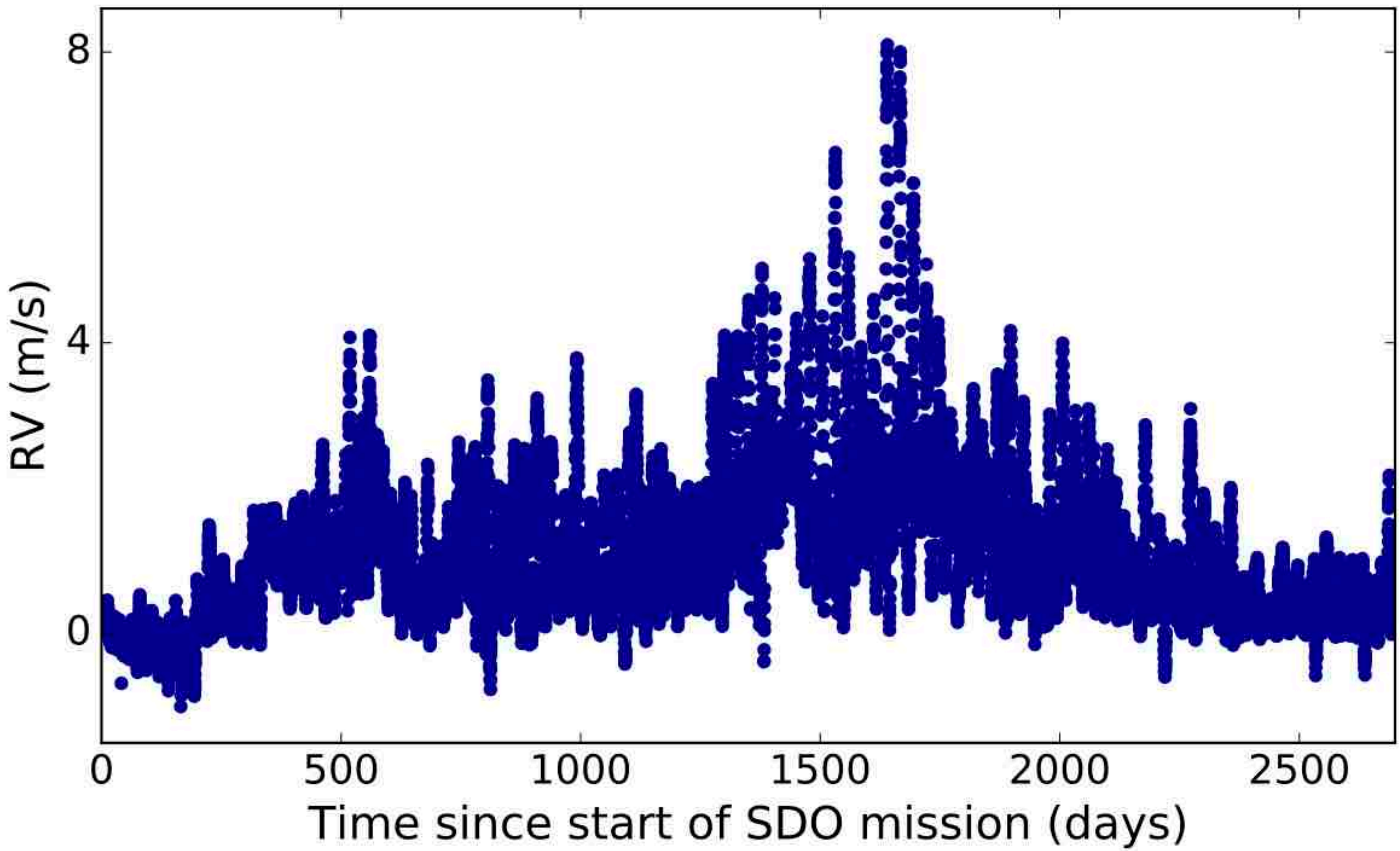
Haywood et al. (in prep.)

The unsigned magnetic flux as a proxy for RV variations



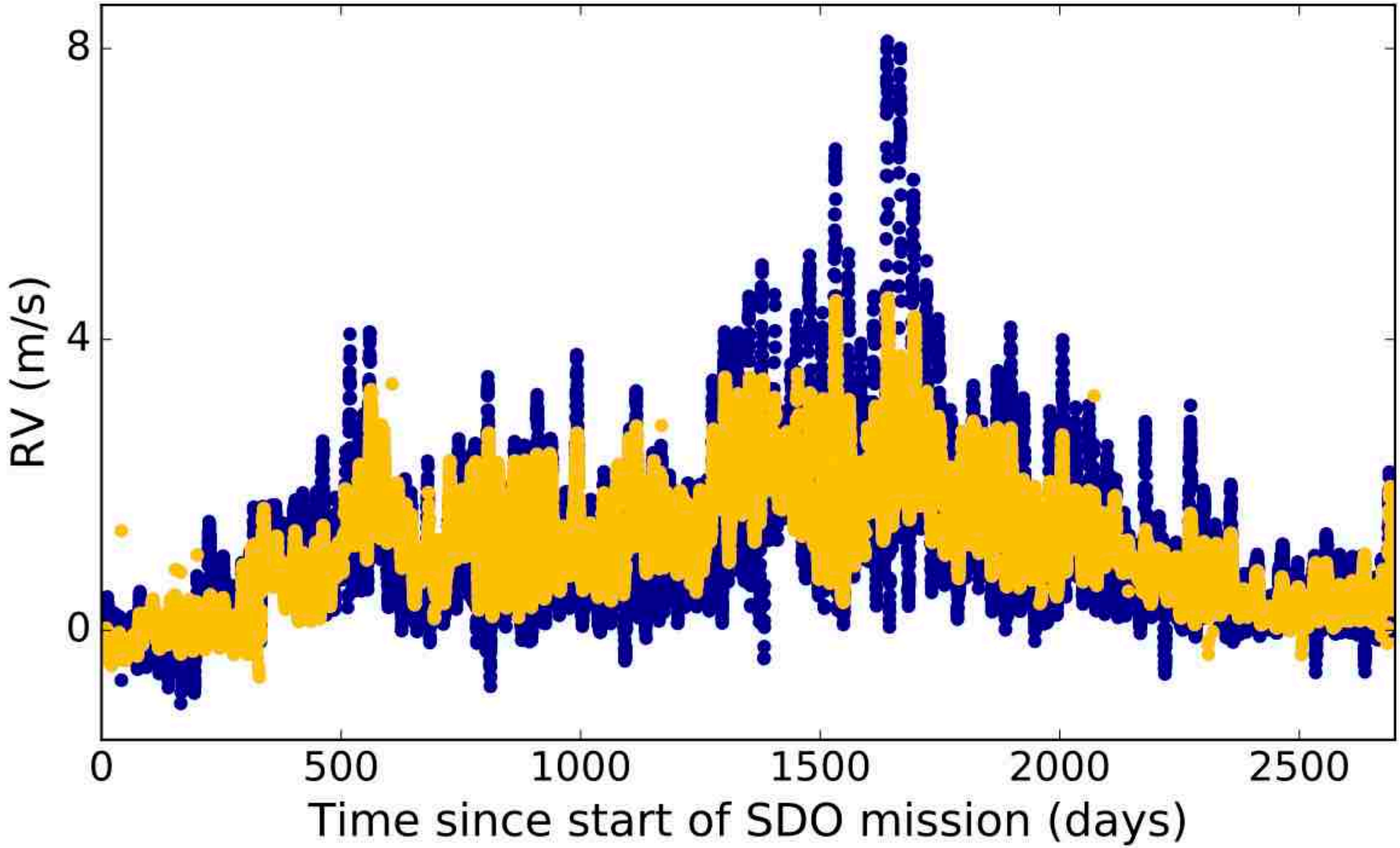
Haywood et al. (in prep.)

The unsigned magnetic flux *B* as a proxy for RV variations



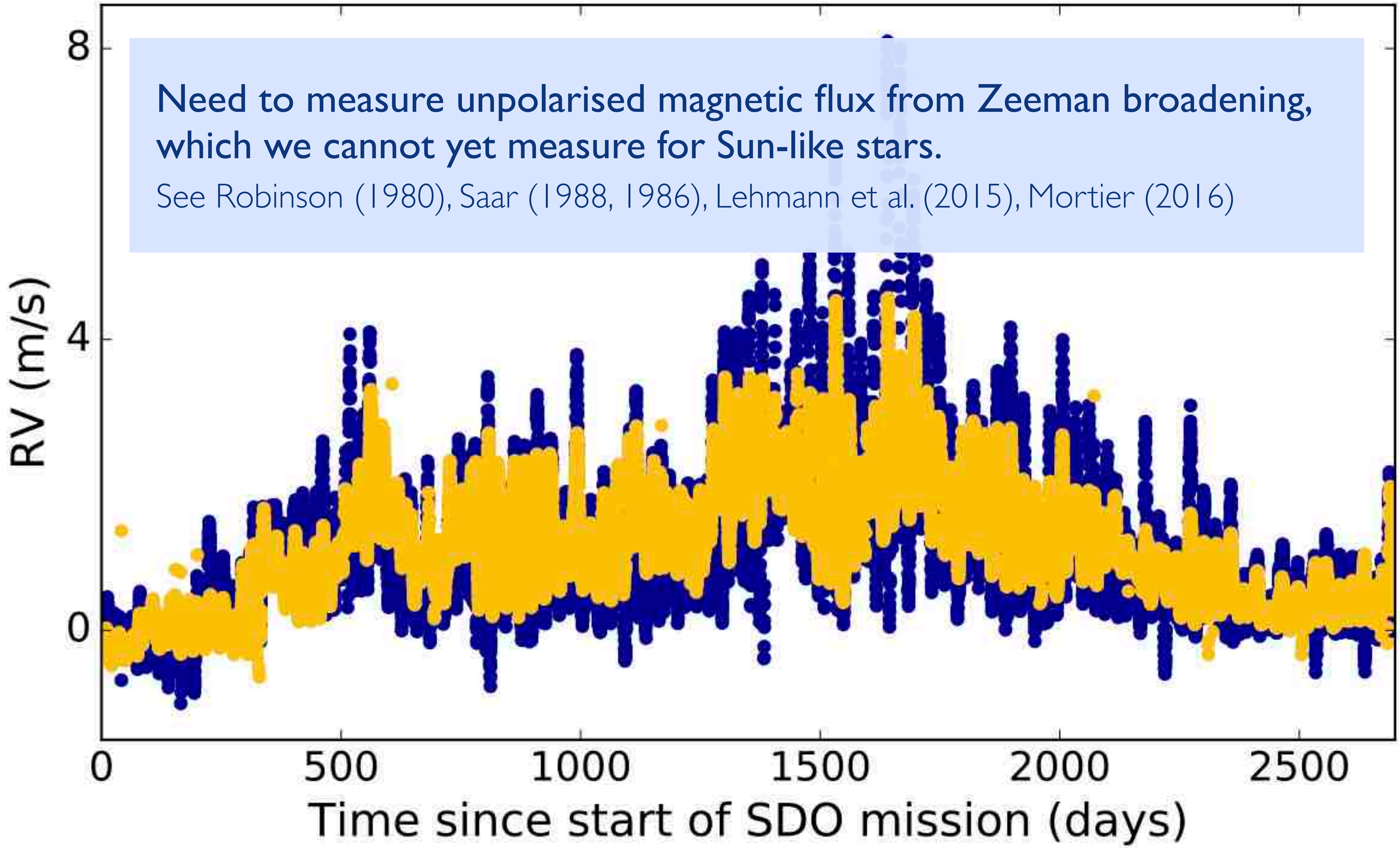
Haywood et al. (in prep.)

A simple fit with *B* reduces RV variations by 46% down to 55 cm/s



Haywood et al. (in prep.)

A simple fit with *B* reduces RV variations by 46% down to 55 cm/s

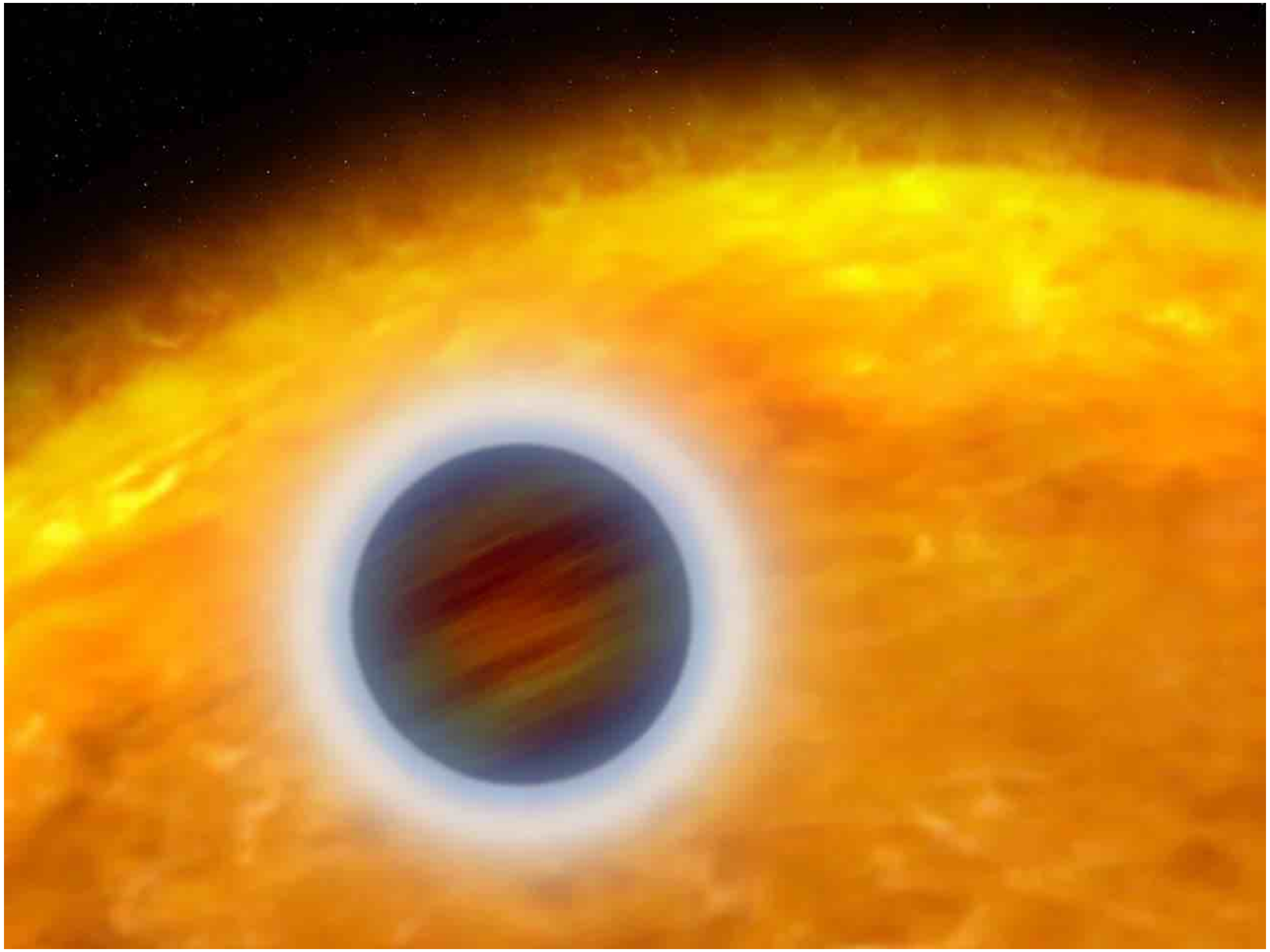


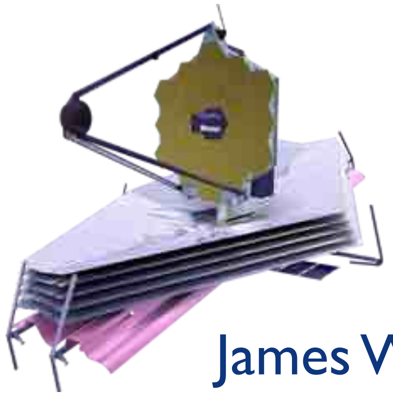
Need to measure unpolarised magnetic flux from Zeeman broadening, which we cannot yet measure for Sun-like stars.

See Robinson (1980), Saar (1988, 1986), Lehmann et al. (2015), Mortier (2016)

Haywood et al. (in prep.)

Observations of atmospheres via transmission spectroscopy will be strongly affected by stellar activity!



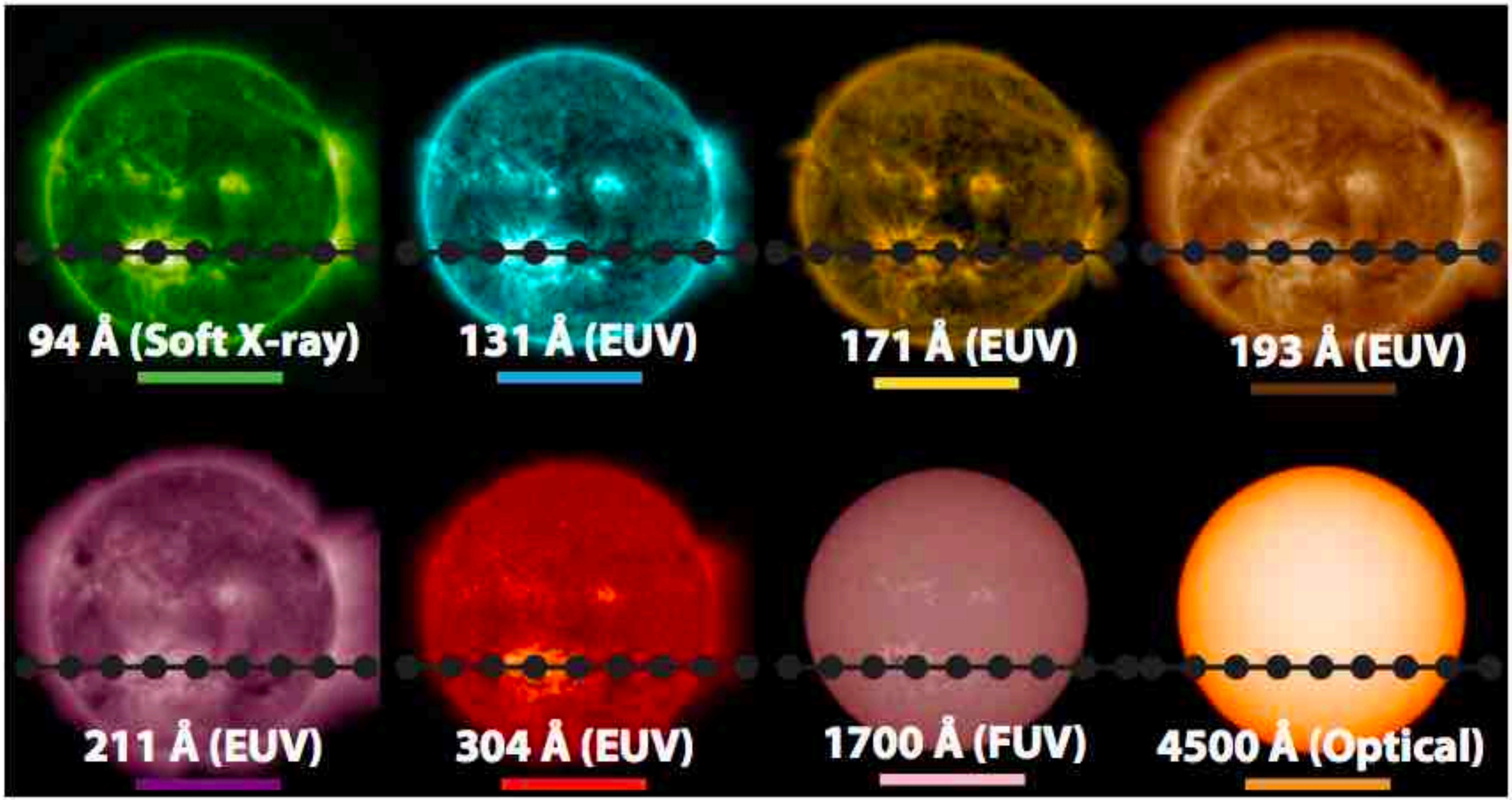


James Webb Space Telescope
launch planned 2020

See Rackham et al. (2017, 2018), Cauley et al. (2018), Mallonn et al. (2018), Oshagh et al. (2014), McCullough et al. (2014) among others

Artist impression: NASA, ESA & G. Bacon (STScI)
JWST cartoon: NASA

Stellar activity is wavelength dependent



SDO images in the EUV, UV and optical

Llama & Shkolnik (2015)

See also Rackham et al. (2017, 2018), Cauley et al. (2018), Mallonn et al. (2018), Oshagh et al. (2014), McCullough et al. (2014)

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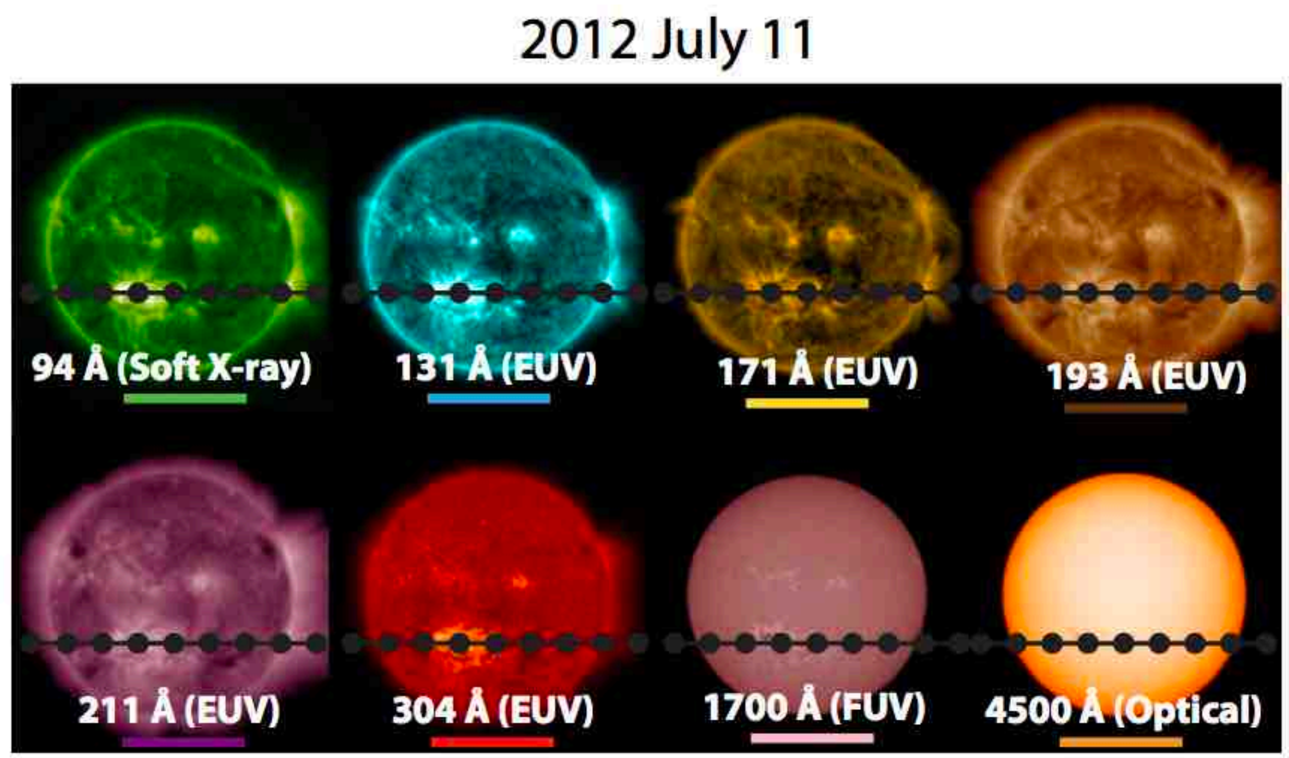
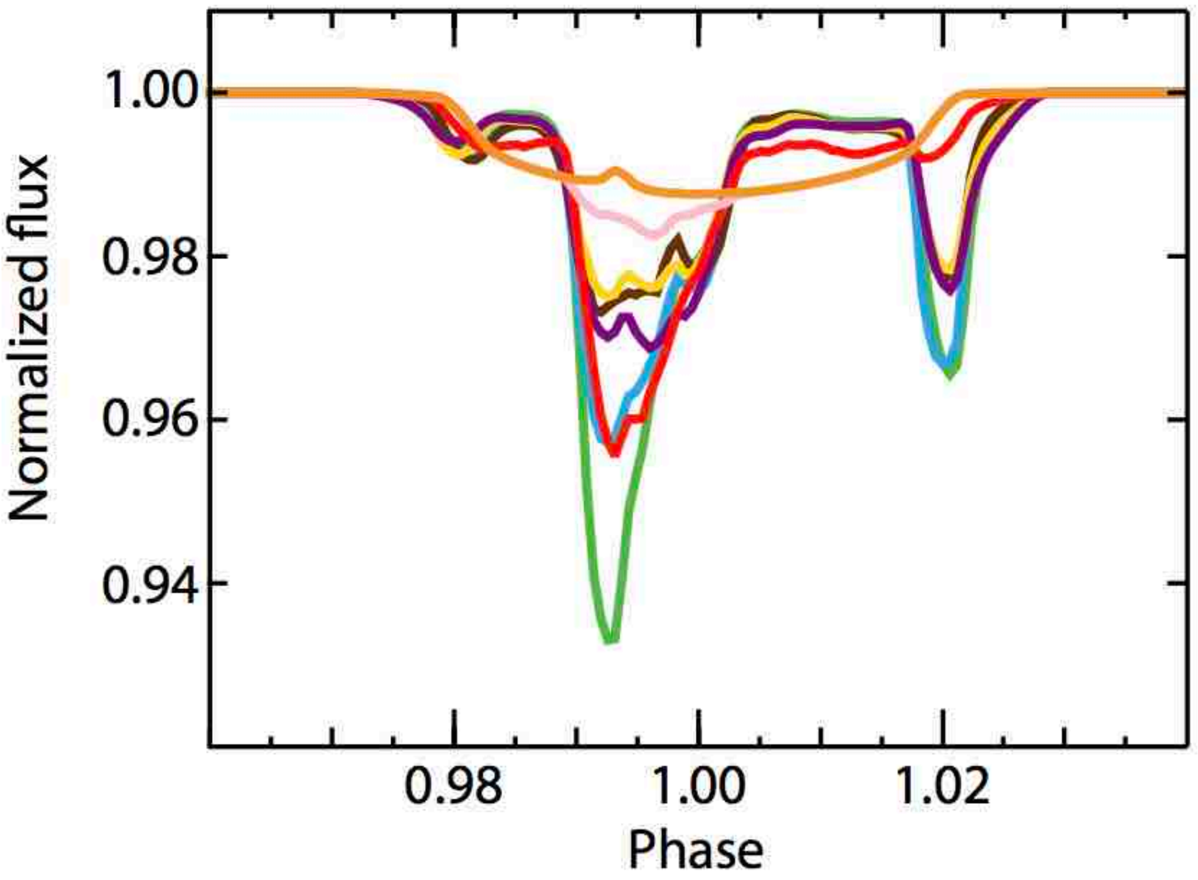


SDO images in the EUV, UV and optical



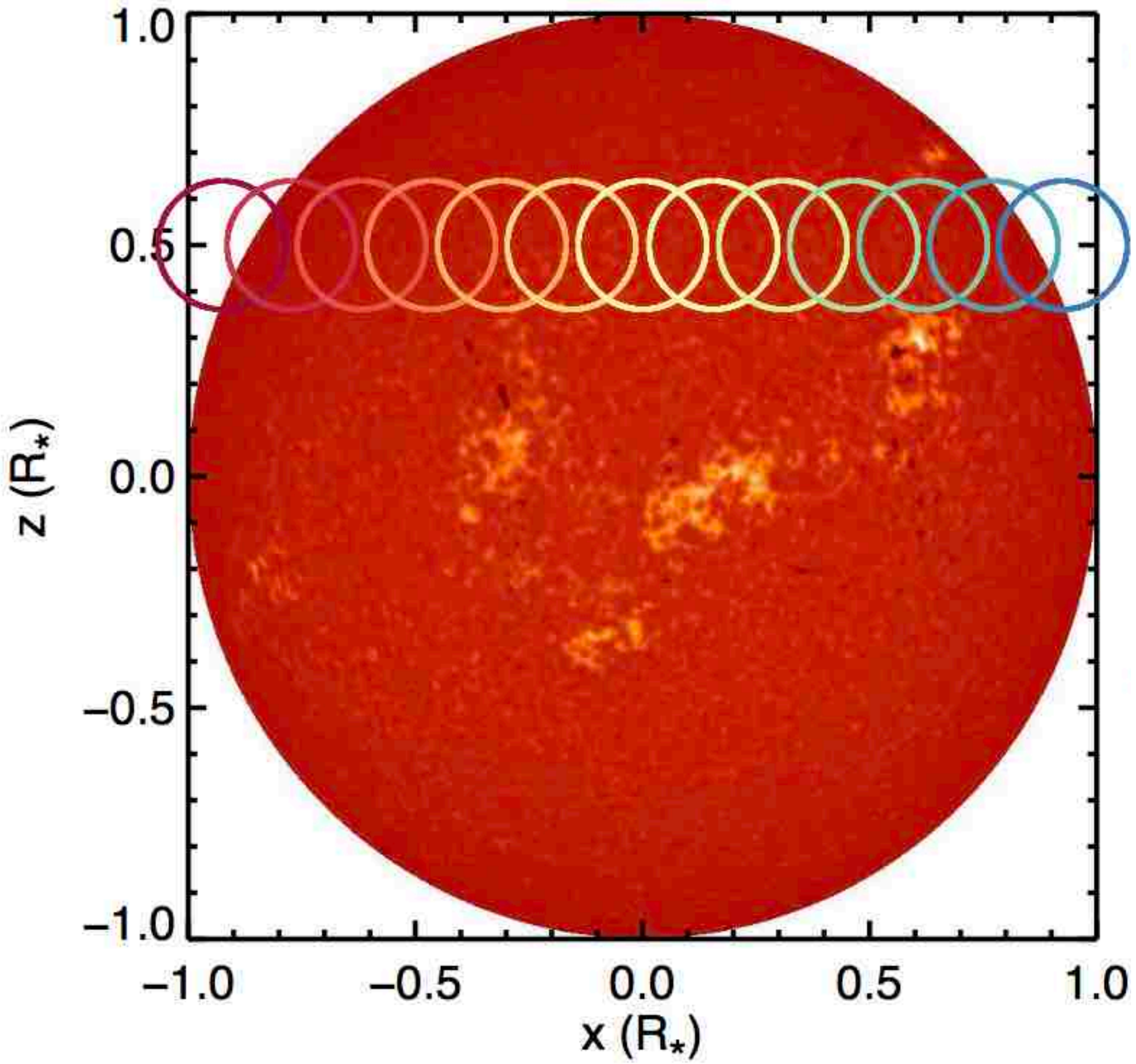
Hot Jupiter radii can be over- or under- estimated by 20 to 70%

Llama & Shkolnik (2015)

See also Rackham et al. (2017, 2018), Cauley et al. (2018), Mallonn et al. (2018), Oshagh et al. (2014), McCullough et al. (2014)

Using solar observations to quantity activity impact on transits

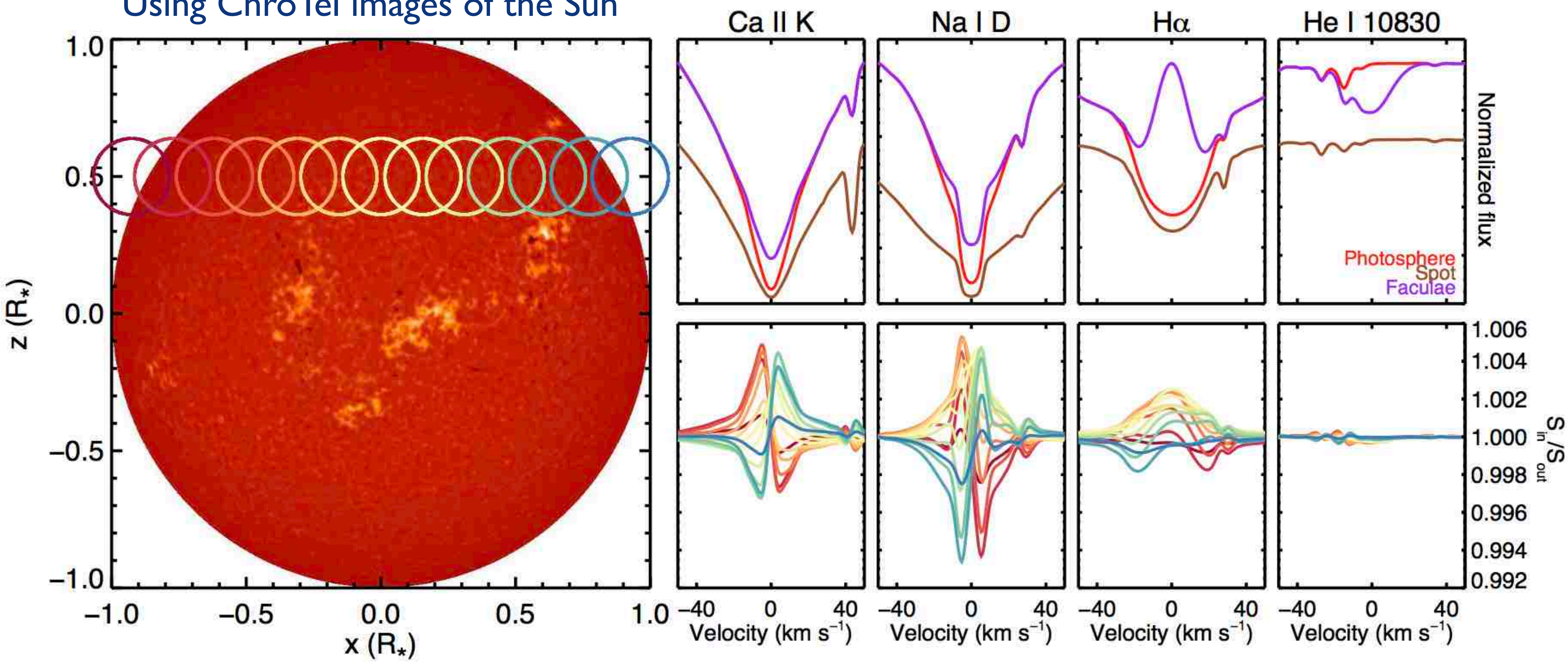
Using ChroTel images of the Sun



Cauley et al. (2018)

Faculae have more impact than spots in transmission spectroscopy

Using ChroTel images of the Sun



Mean absorption signatures in Na I D and Hα can reach 0.2-0.3%

Cauley et al. (2018)

Final remarks

In the Sun, RV variations are dominated by suppression of convective blueshift from faculae in plage (large, bright magnetic regions)

We can use spatially resolved images of the Sun to test models of spectral line profiles

Activity indicators (eg. Ca II H&K emission, magnetic flux) can allow us to identify activity-induced RV variations on other stars

This solar knowledge will be key to interpreting measurements of exoplanet atmospheres