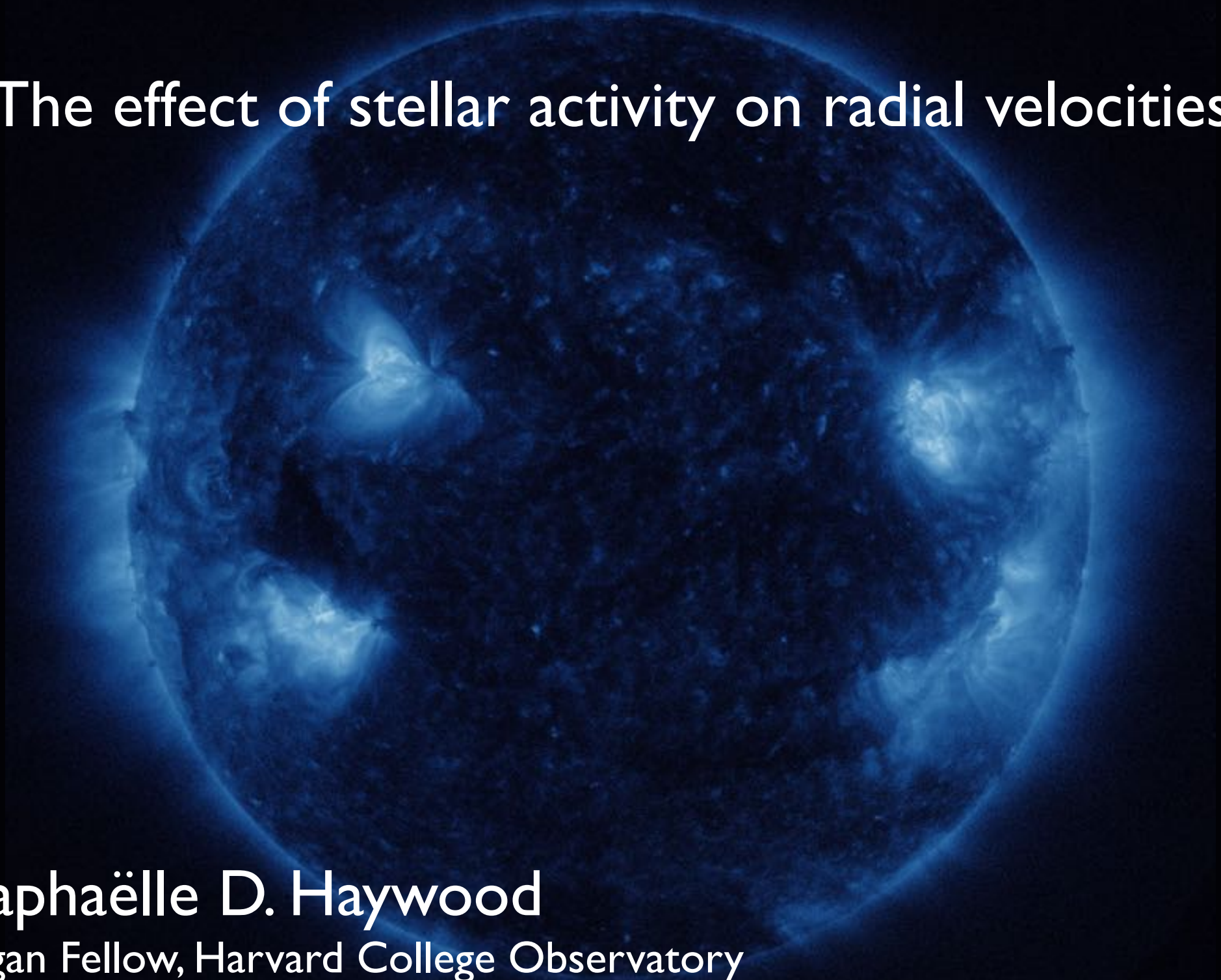
The effect of stellar activity on radial velocities

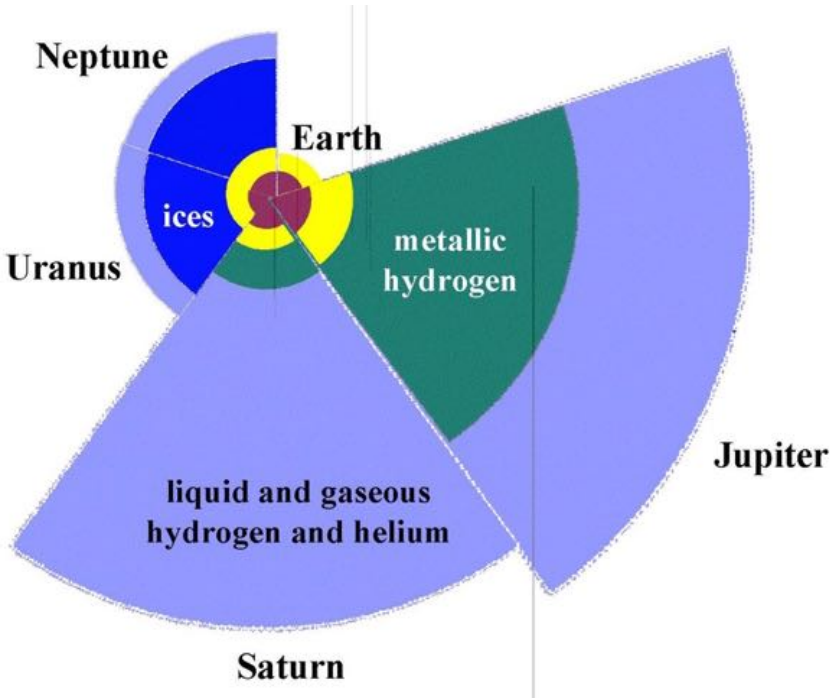


Raphaëlle D. Haywood
Sagan Fellow, Harvard College Observatory

Mass and radius are the most fundamental parameters of a planet

Main inputs for models of interior composition/structure

(eg. see Zeng & Sasselov 2013)



Essential to interpreting observations of atmospheres

(eg. see Winn 2010)

Mass and radius are the most fundamental parameters of a planet

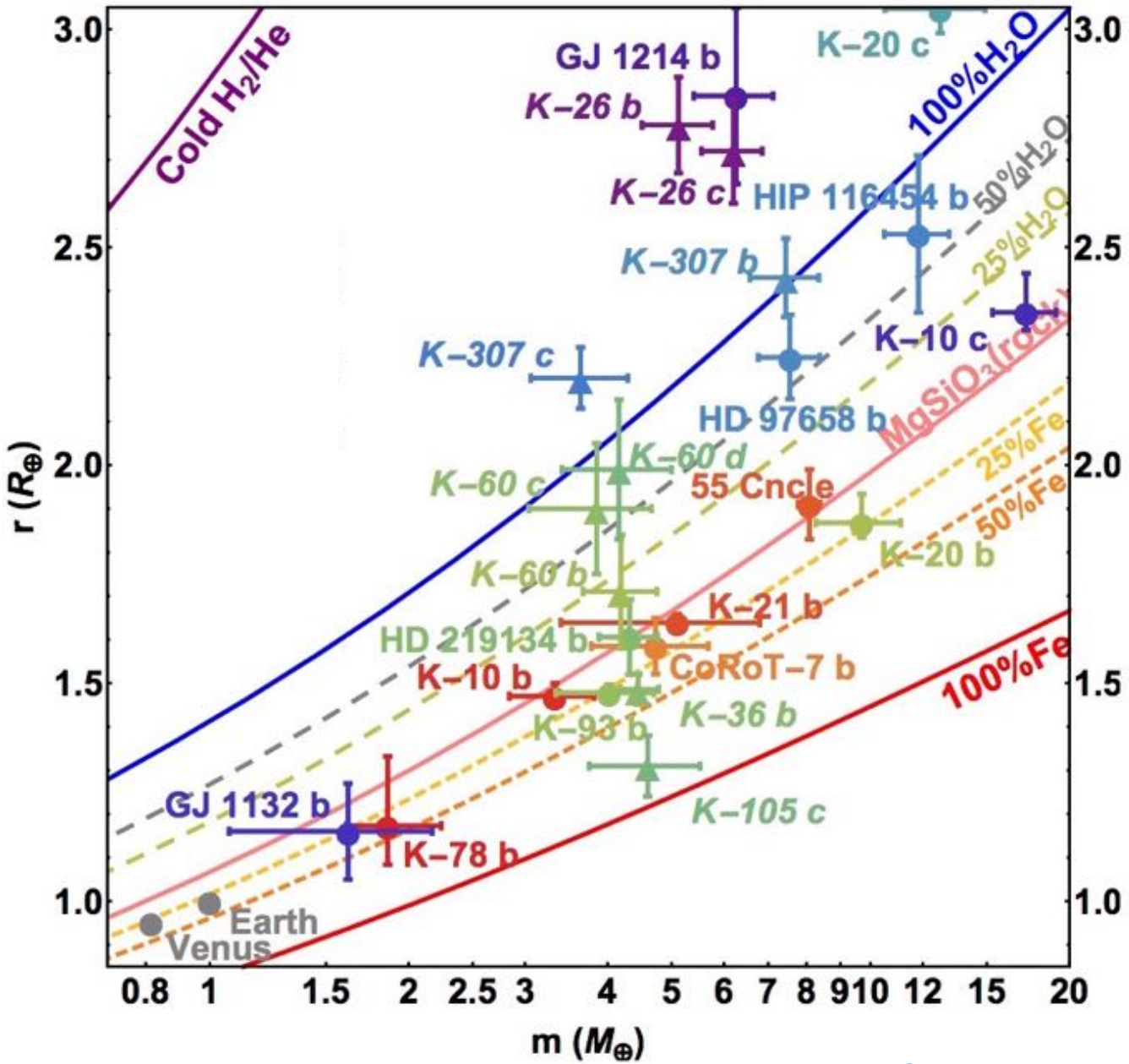
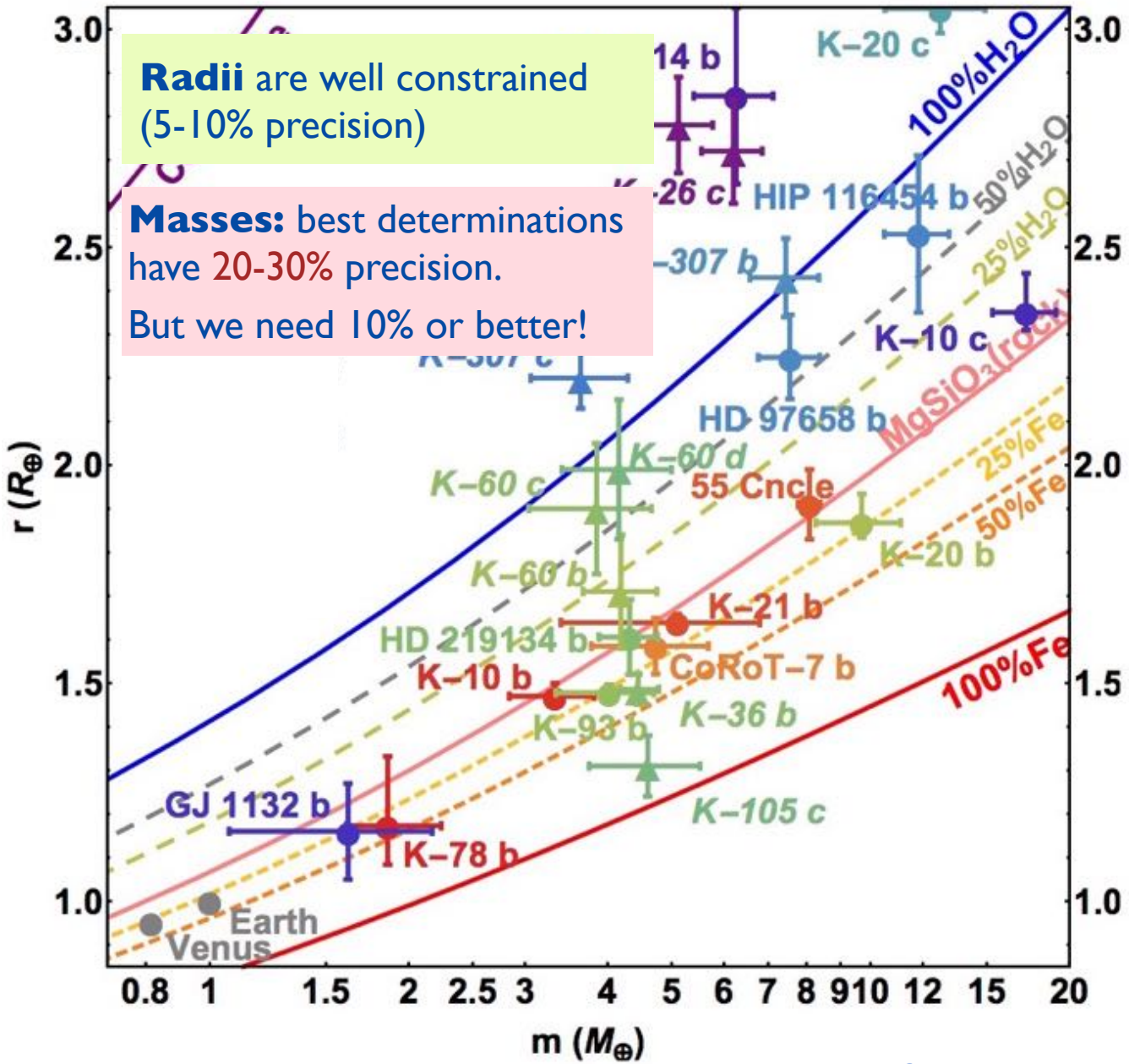


Figure from López-Morales et al. (2016)

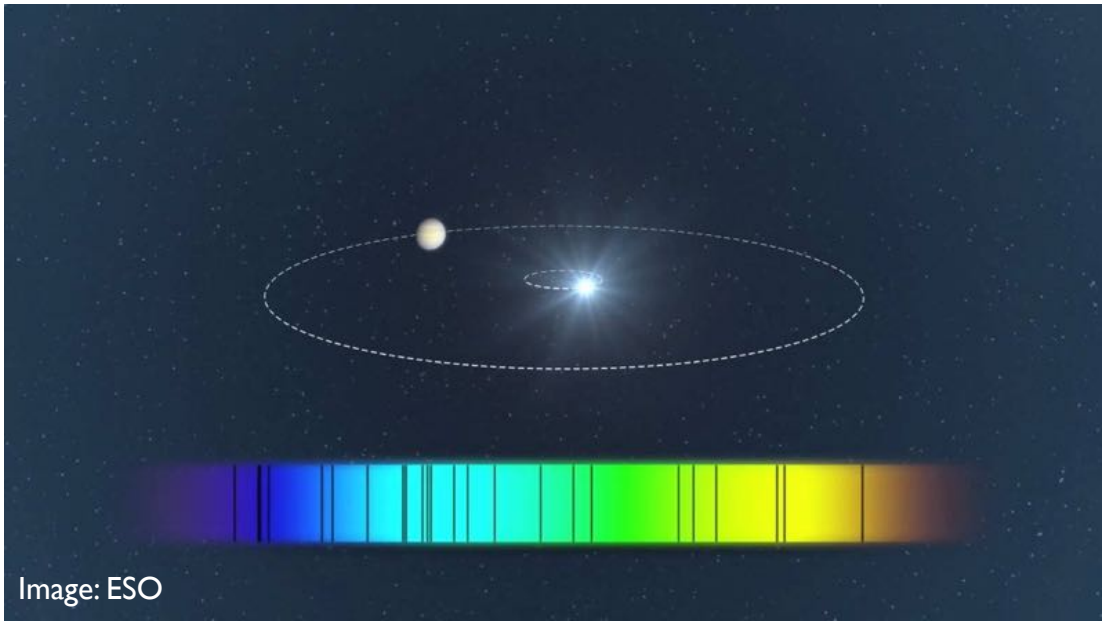
Mass and radius are the most fundamental parameters of a planet



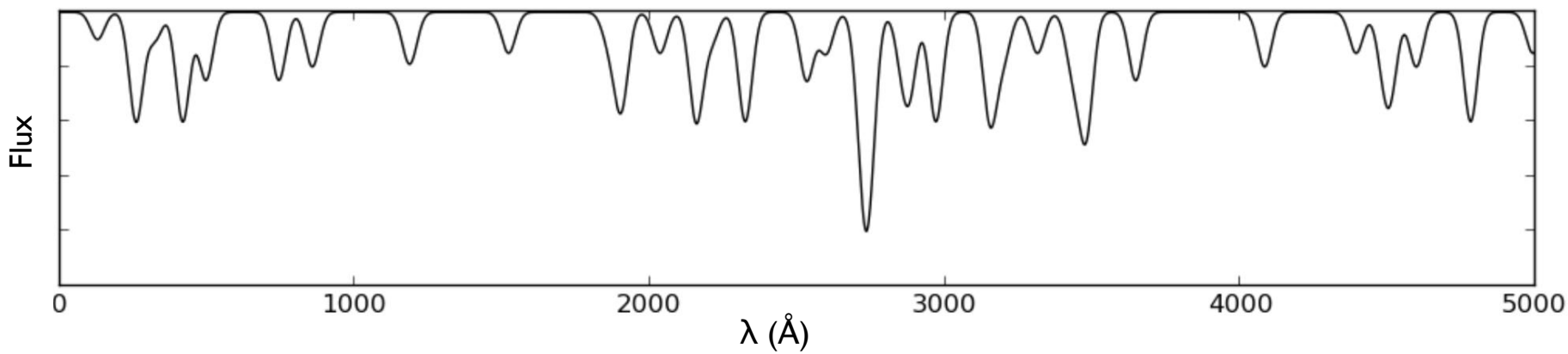
Zeng & Sasselov (2013)

Figure from López-Morales et al. (2016)

How are planet masses determined?

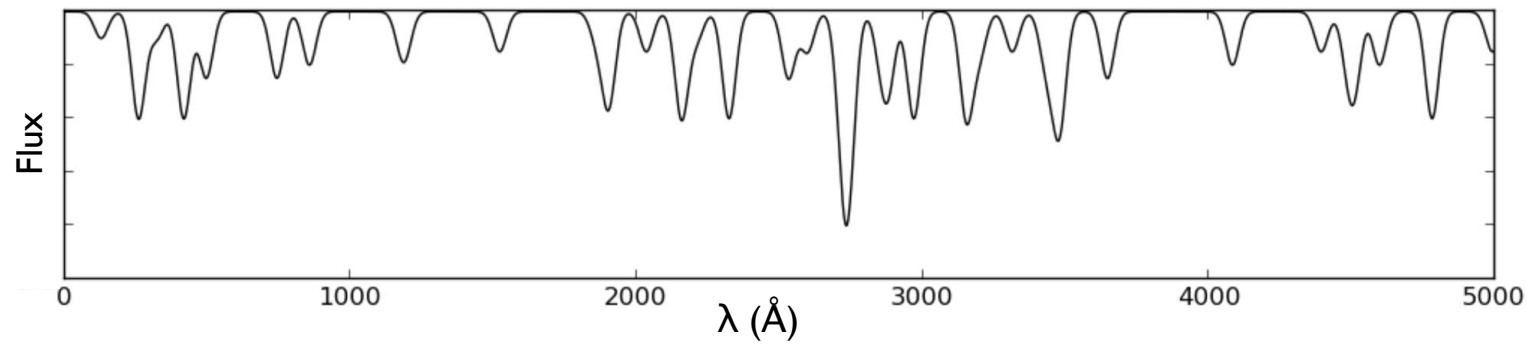


Stellar spectrum



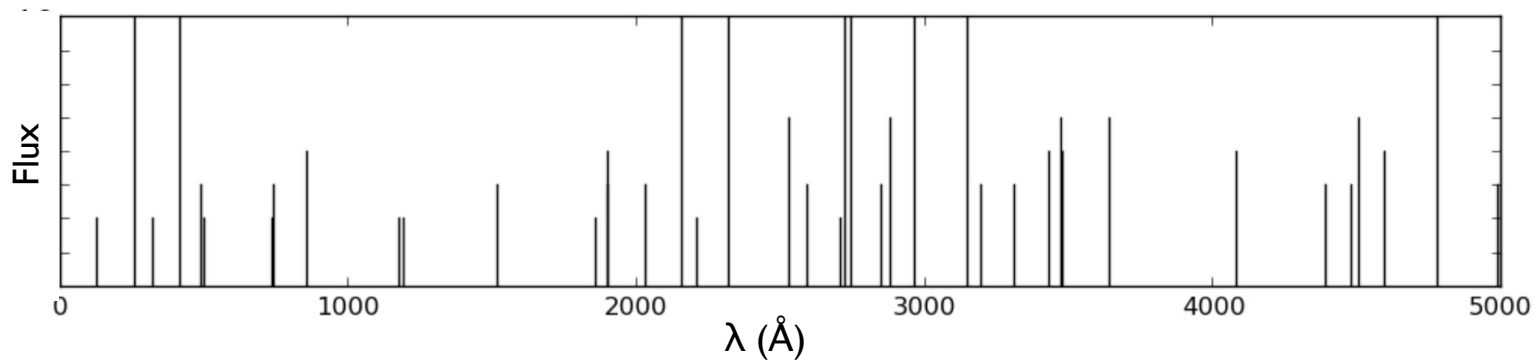
From a stellar spectrum to a radial-velocity (RV) measurement

Stellar spectrum



*

Line mask



=

Cross-correlation function (CCF)

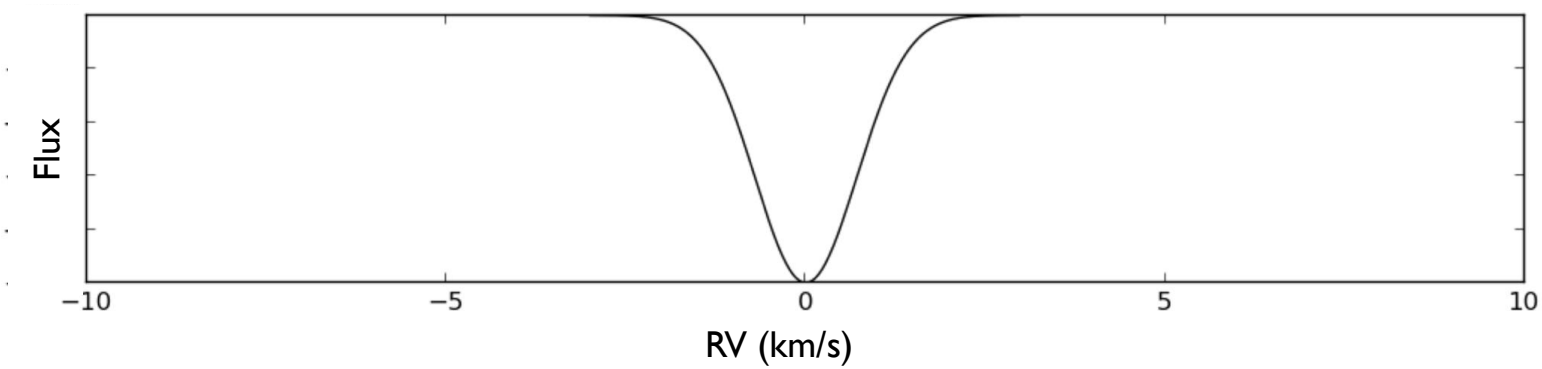
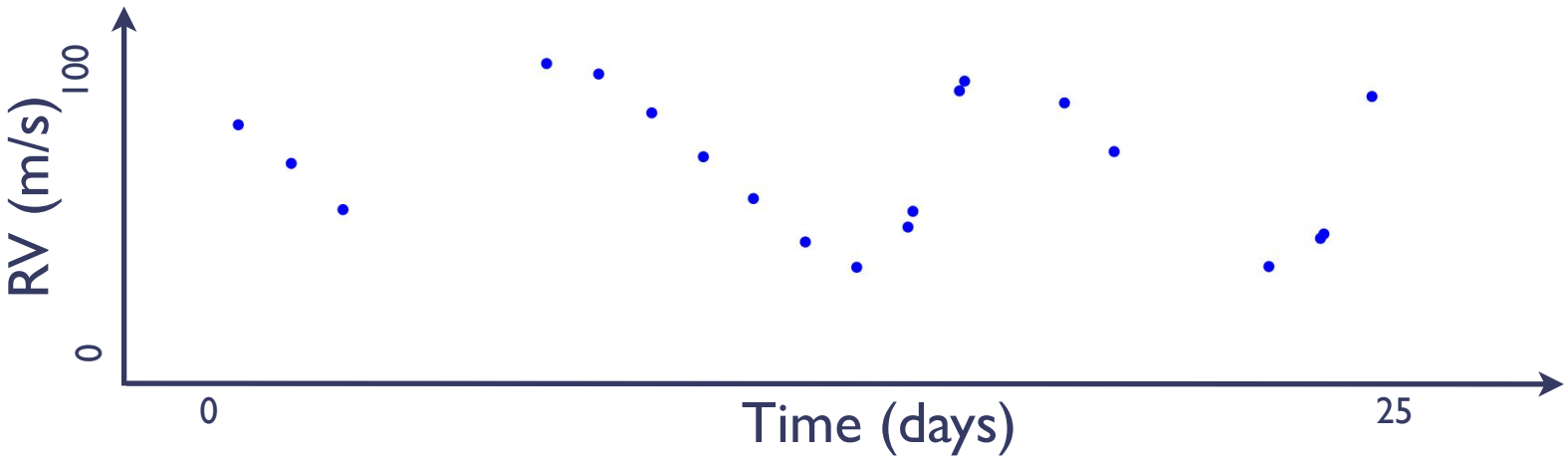
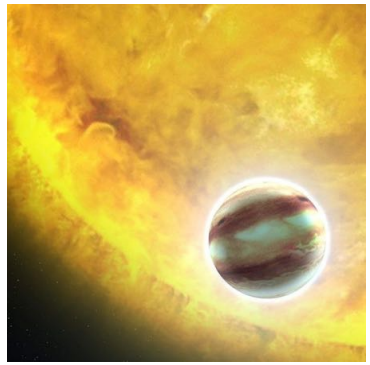


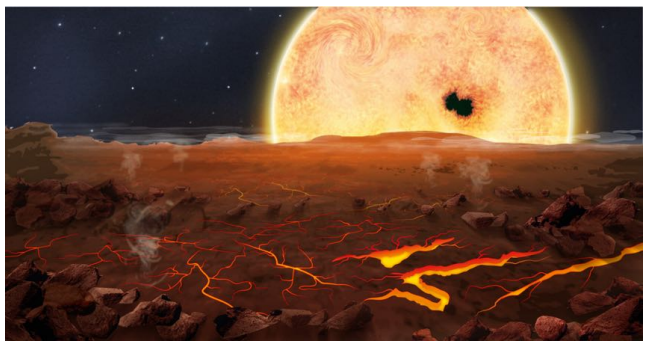
Image credit: Annelies Mortier

Planet mass is proportional to radial-velocity (RV) amplitude





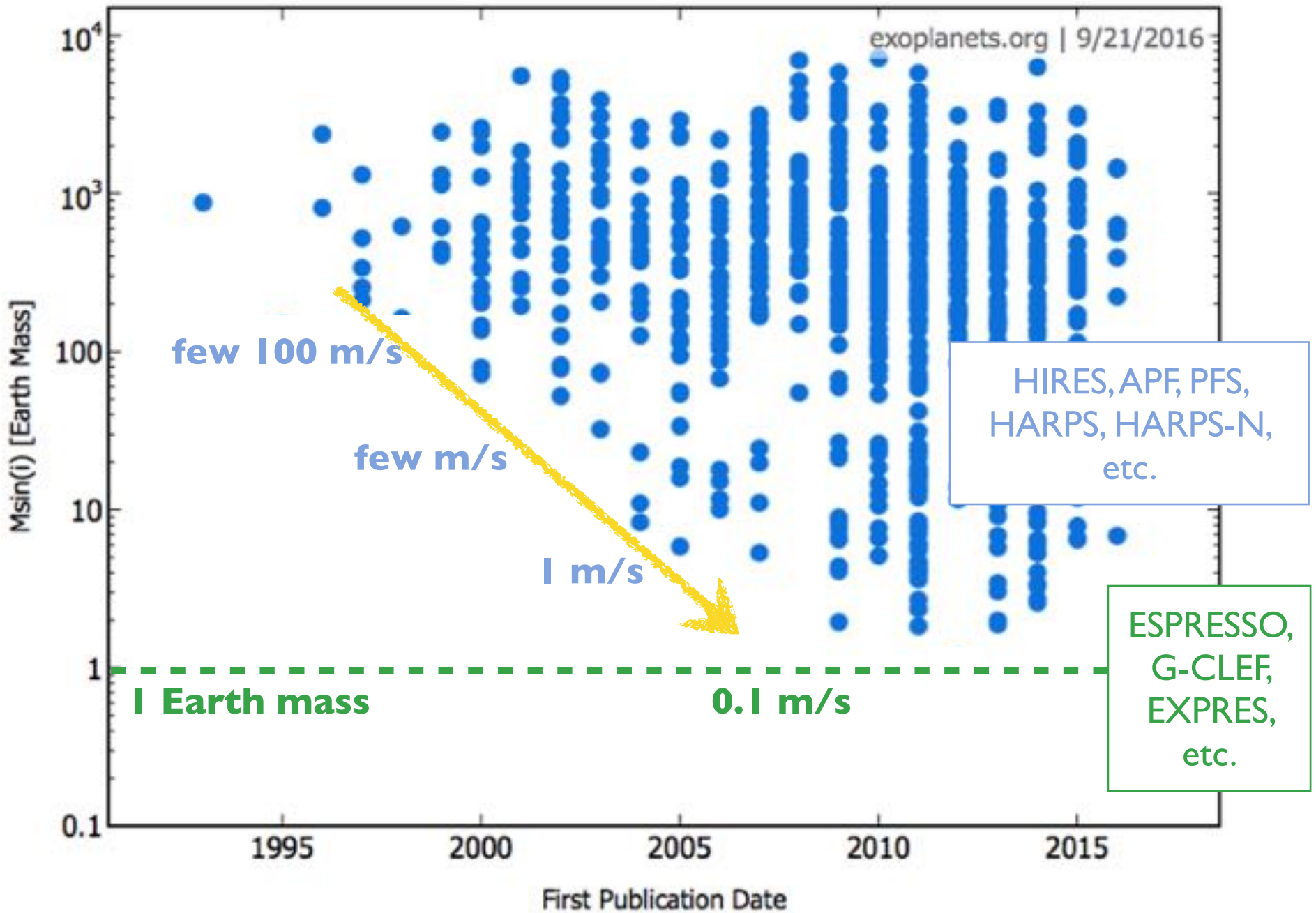
WASP-8, a hot Jupiter system



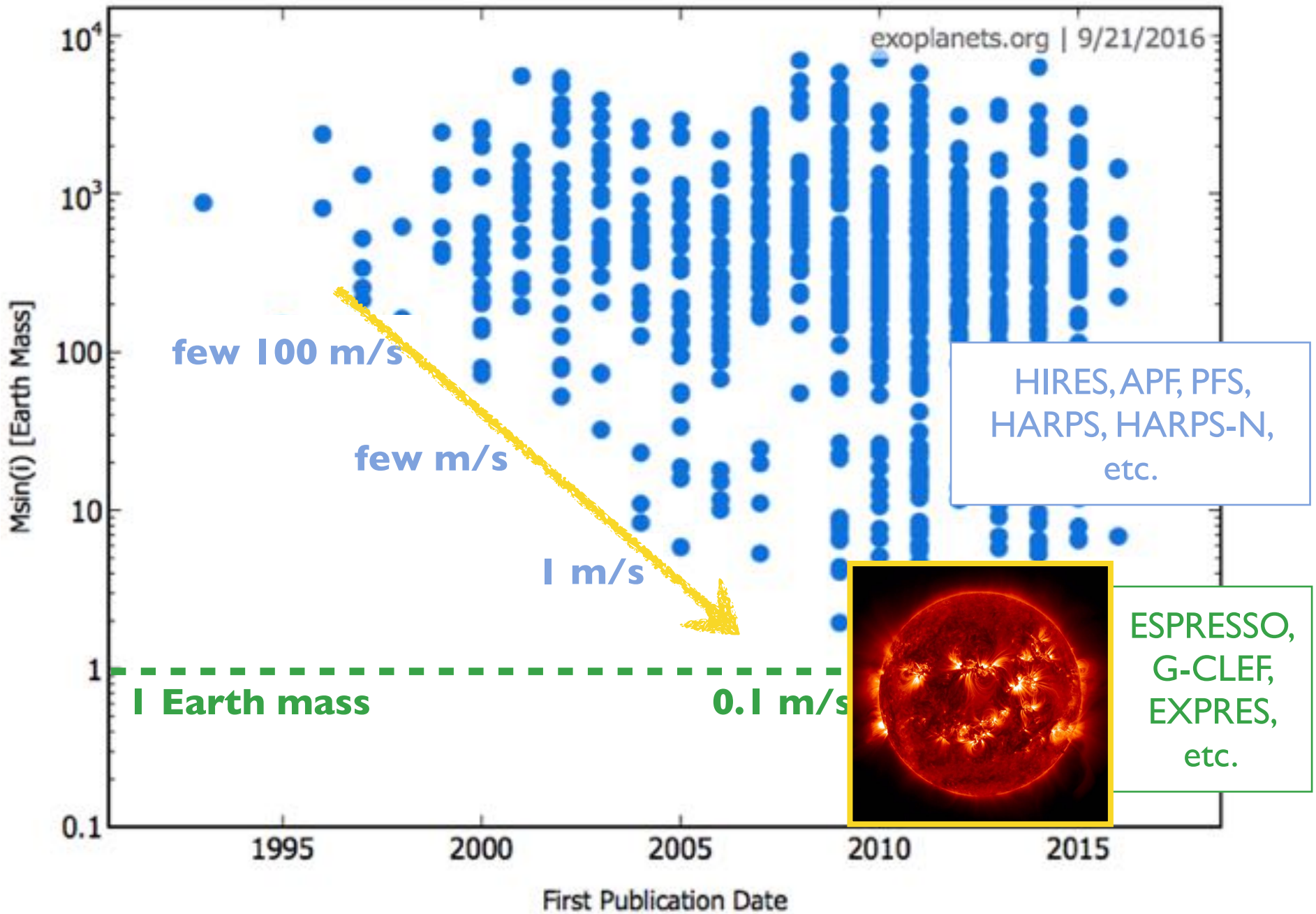
Super-Earth ($\approx 5M_{earth}$) in orbit of a few days: $\approx$ 3-5 m/s

Earth orbit around Sun: 0.09 m/s!

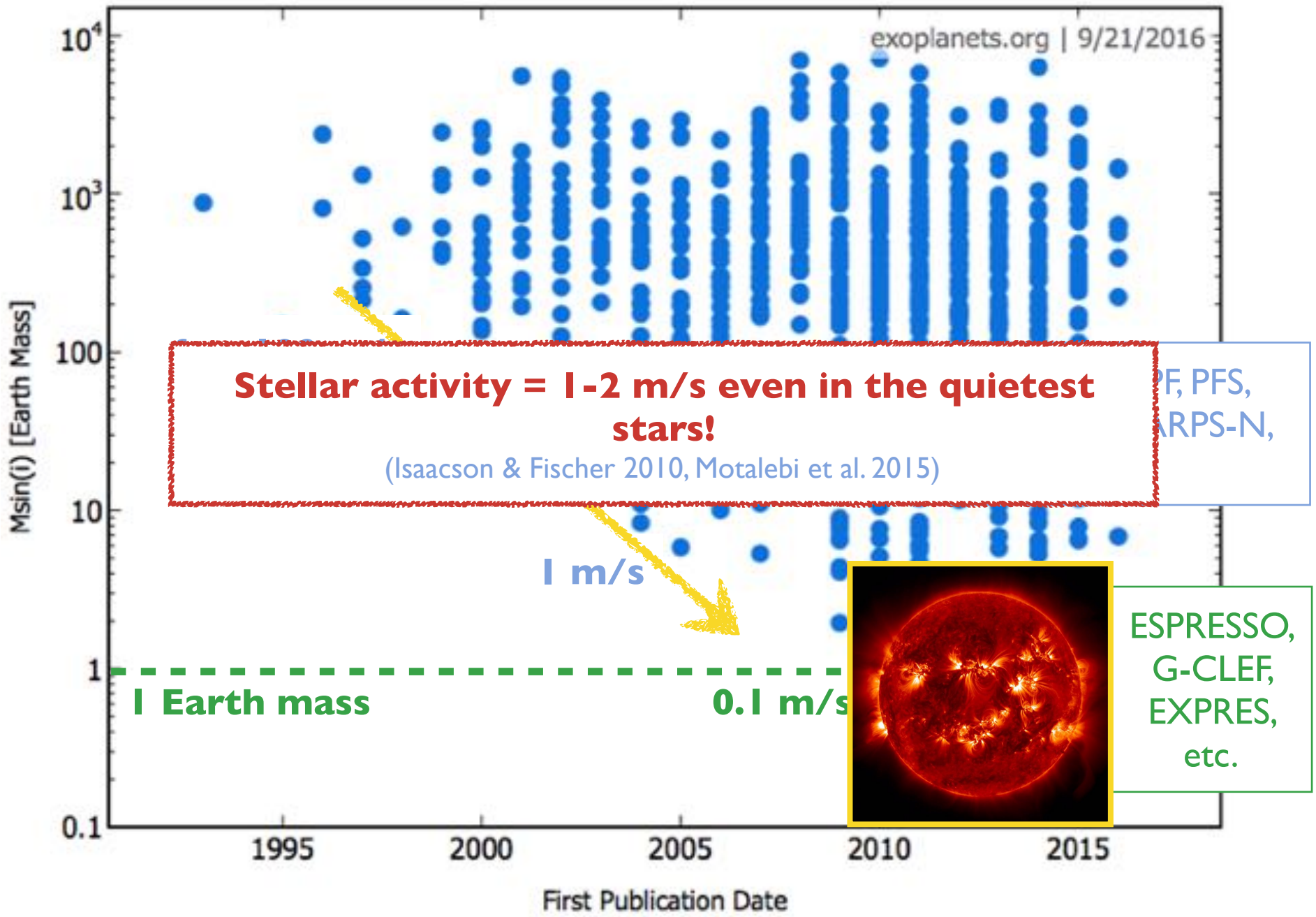
Exoplanets detected or confirmed via radial-velocity monitoring



Exoplanets detected or confirmed via radial-velocity monitoring



Exoplanets detected or confirmed via radial-velocity monitoring

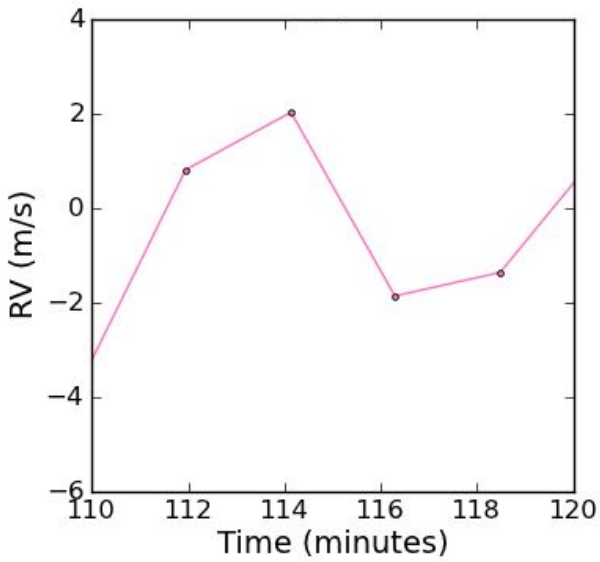


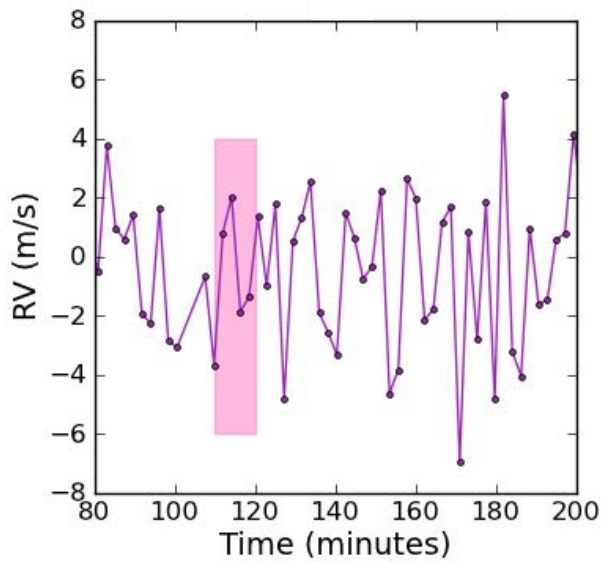
Timescales of stellar activity

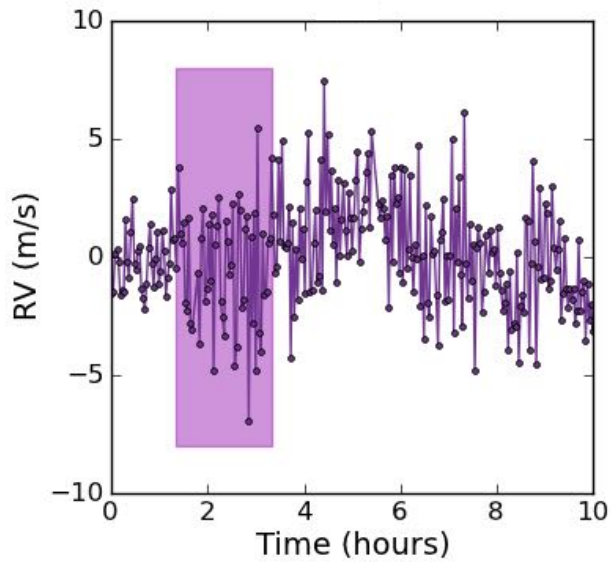
- Minutes to hours
- Days
- Days-weeks (stellar rotation period)
- Decades

Minutes to hours

μ Arae, RV data from Bouchy et al. (2005)

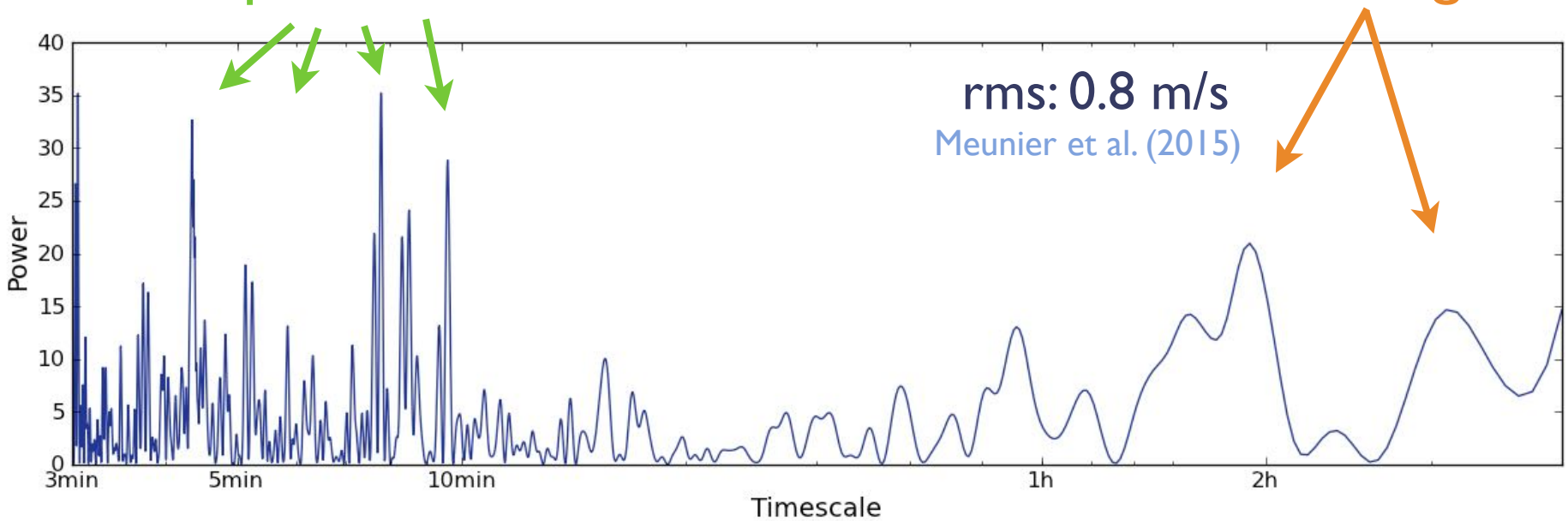






5-10 min: p-mode oscillations

30 min - few hours: granulation

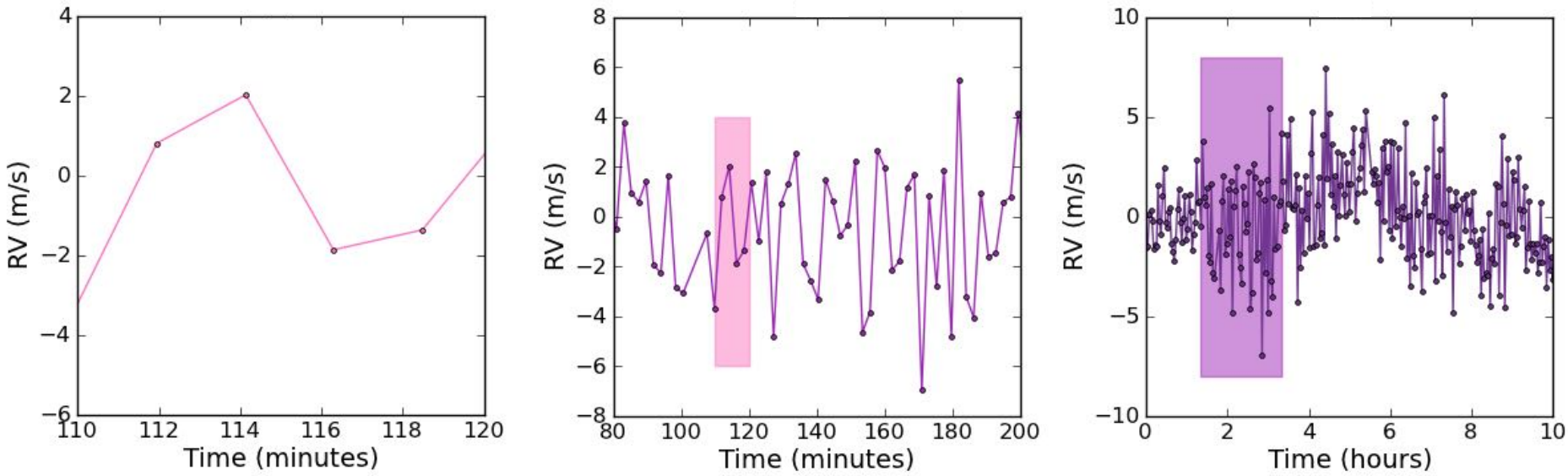


rms: 0.8 m/s

Meunier et al. (2015)

Minutes to hours

μ Arae, RV data from Bouchy et al. (2005)



5-10 min: p-mode oscillations

30 min - few hours: granulation

Adapt observing strategy:

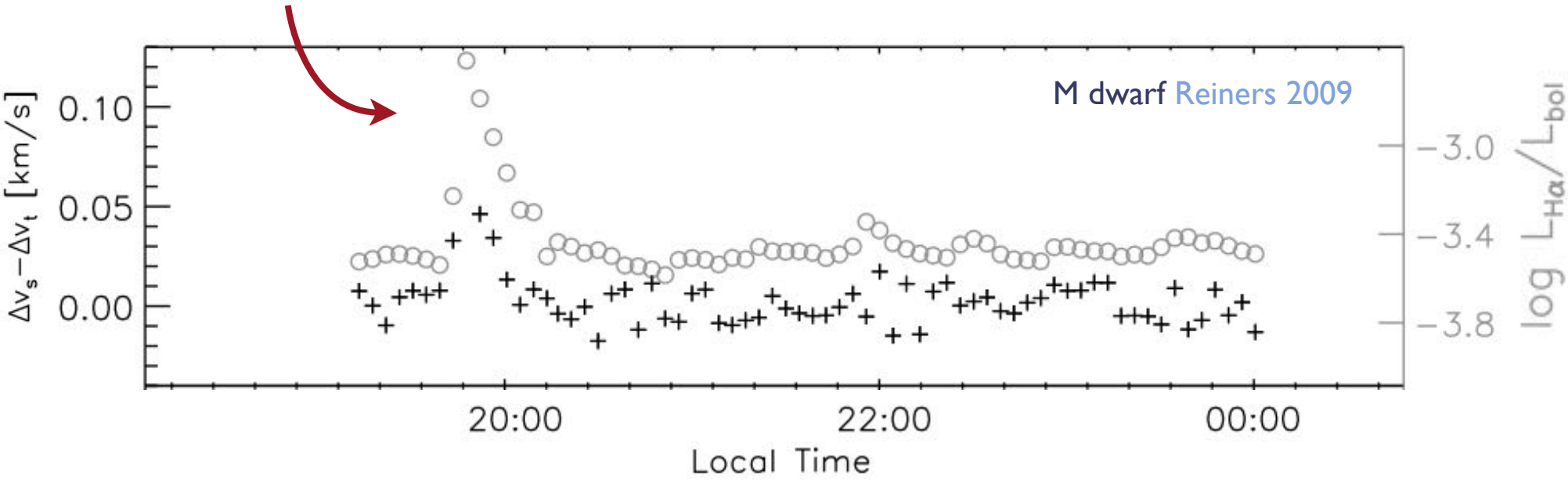
15 min exposures

2 or 3 observations per night

Dumusque et al. (2010)

Minutes

Few min: flares/coronal mass ejections



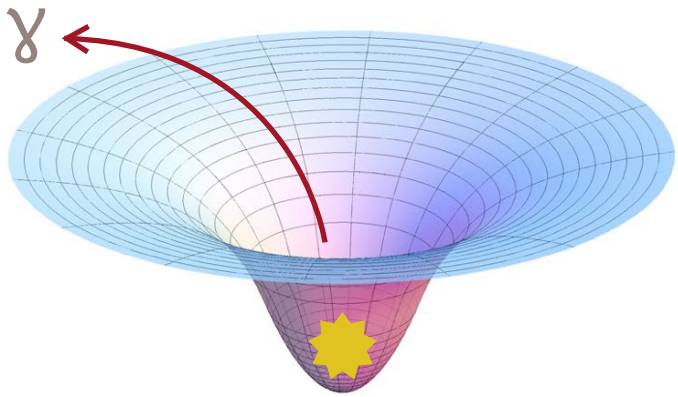
Rare events in Sun-like stars

Strong signatures in Hα emission profile

Reiners 2009

Days

Gravitational redshift



Change in stellar radius 0.01% can induce RV shift of 0.06 m/sec

Slow changes, eg. from granulation or Wilson depression can have such effect

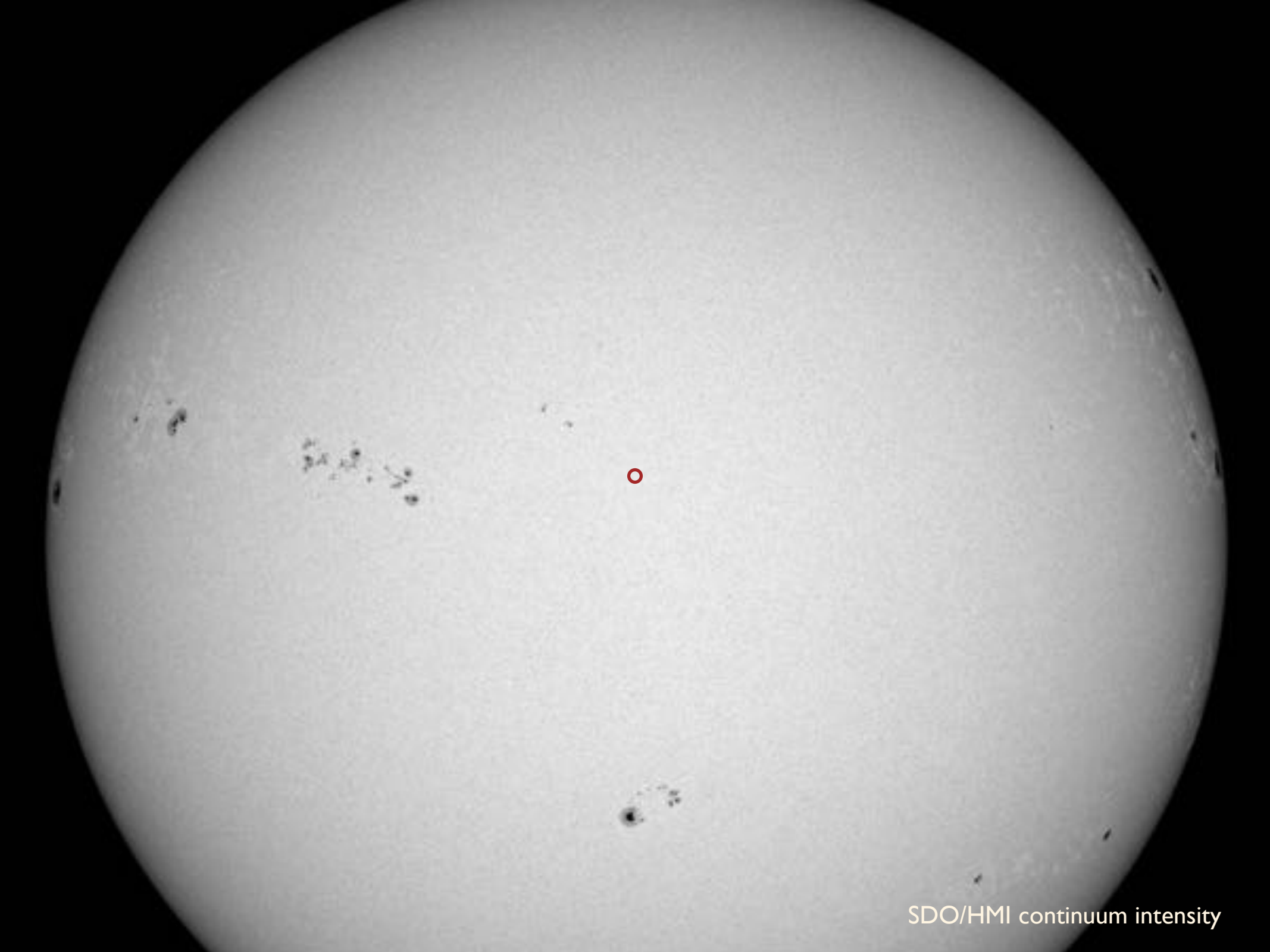
Cegla et al. (2012)

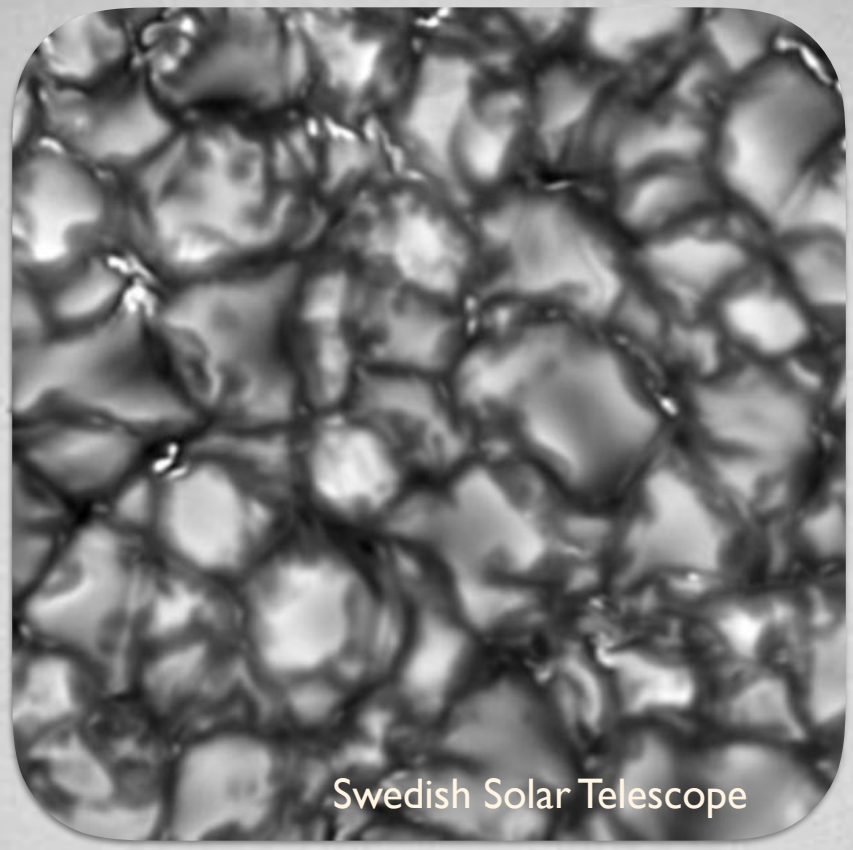
Not currently the main problem in RV surveys
Will become an issue as we get to Earth-like planets

Cegla et al. (2012)

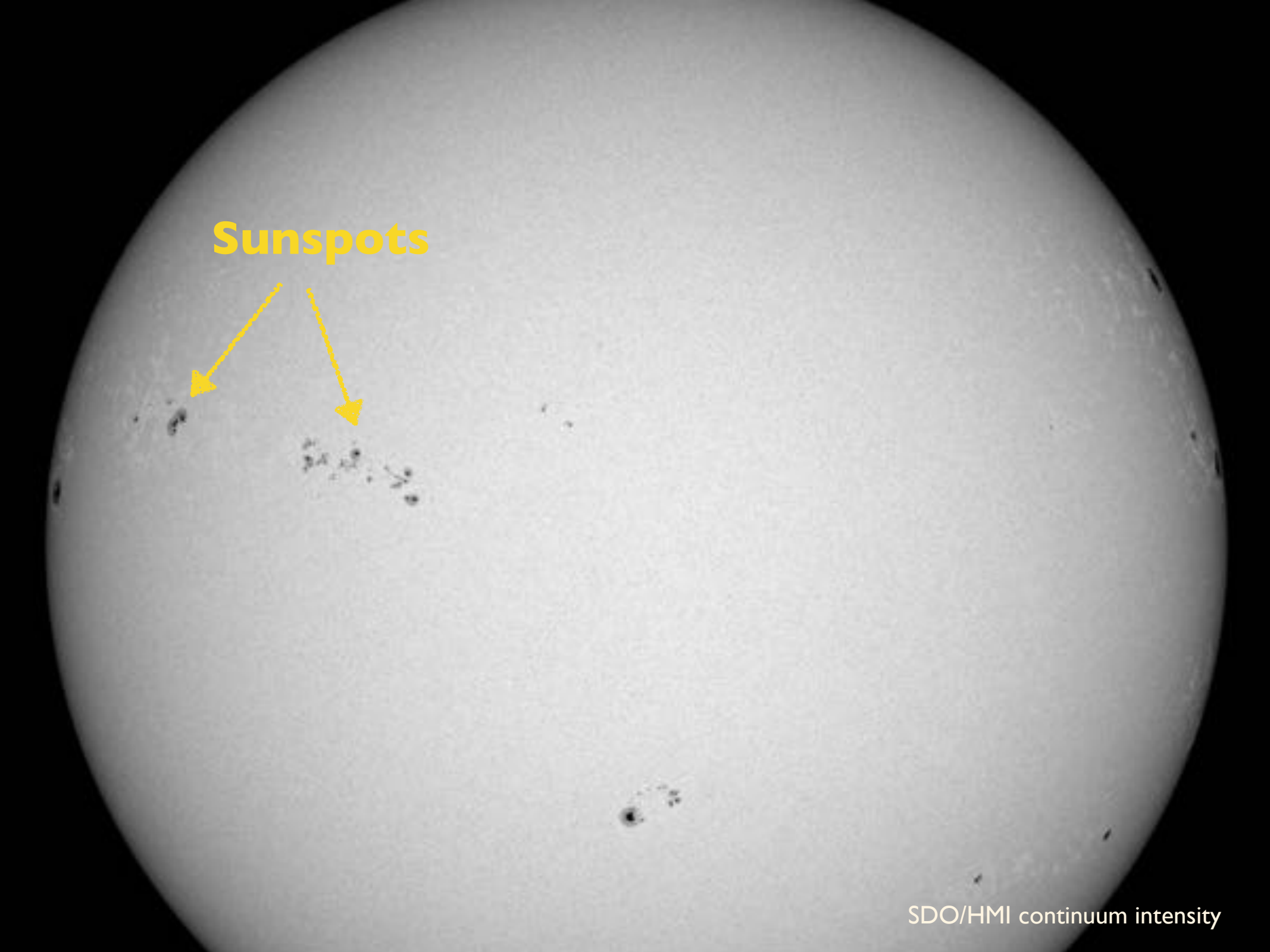
Stellar rotation period (15-40 days in Sun-like stars)

SDO/HMI continuum intensity

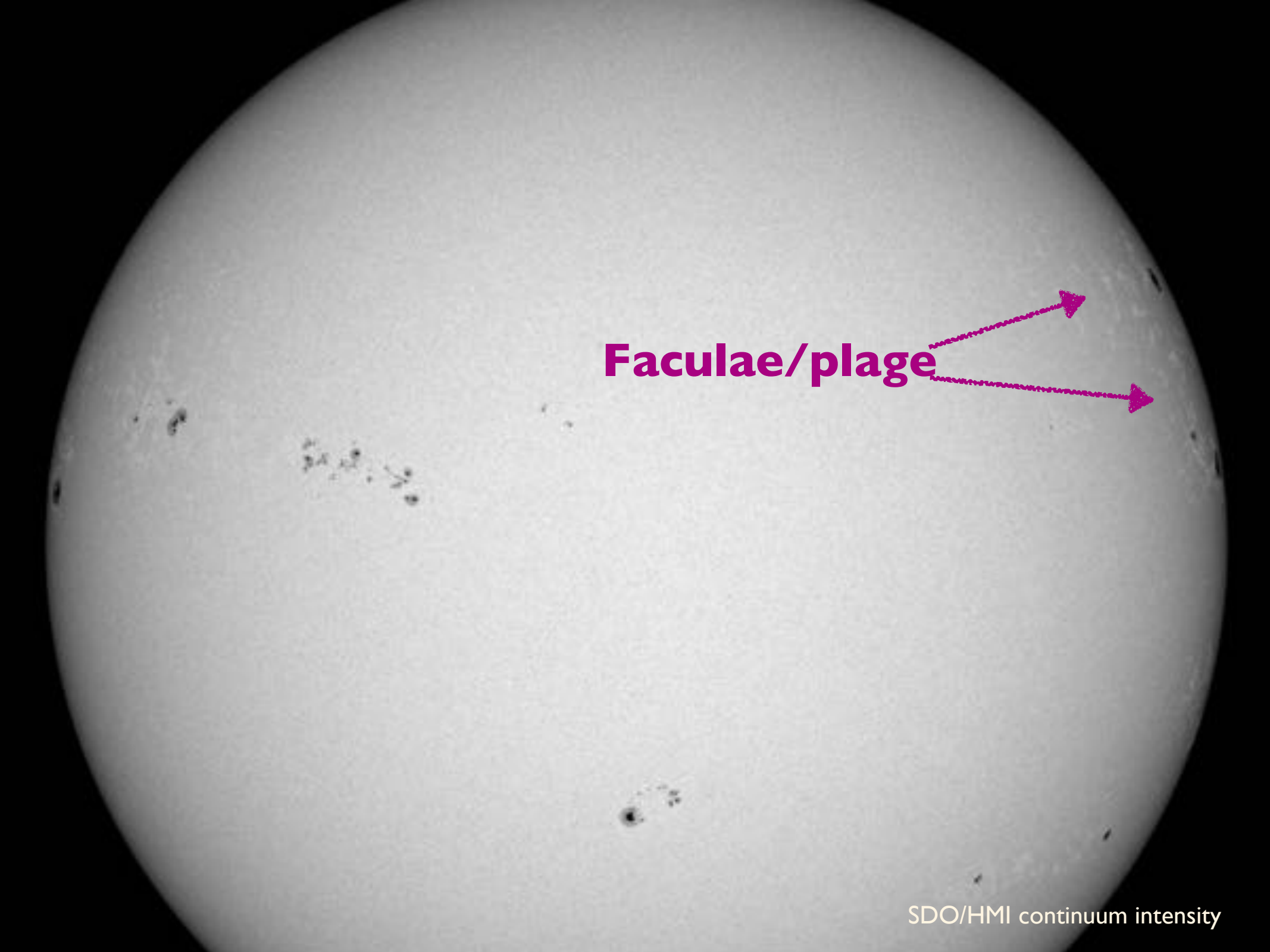

SDO/HMI continuum intensity



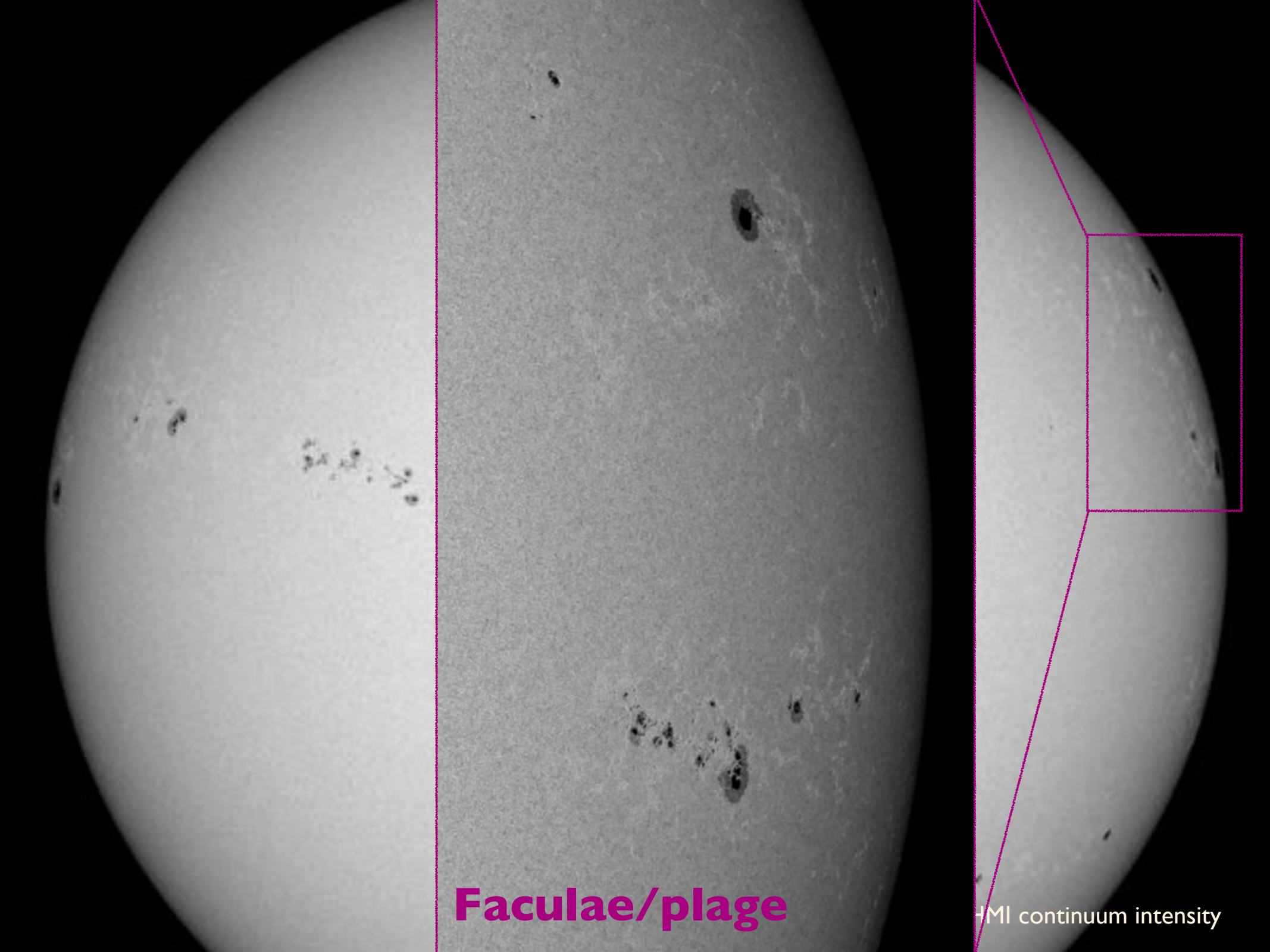
SDO/HMI continuum intensity



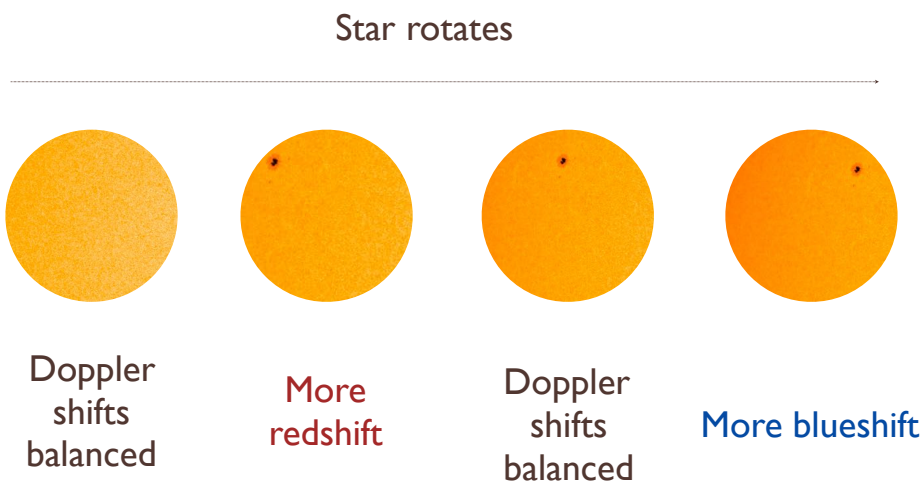
SDO/HMI continuum intensity



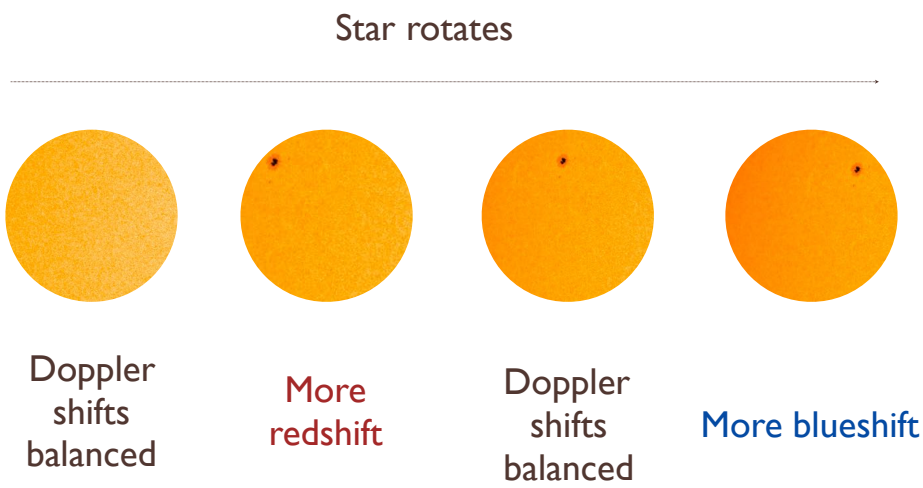
SDO/HMI continuum intensity


Faculae/plage
HMI continuum intensity

Magnetically-active regions on the stellar surface induce RV variations



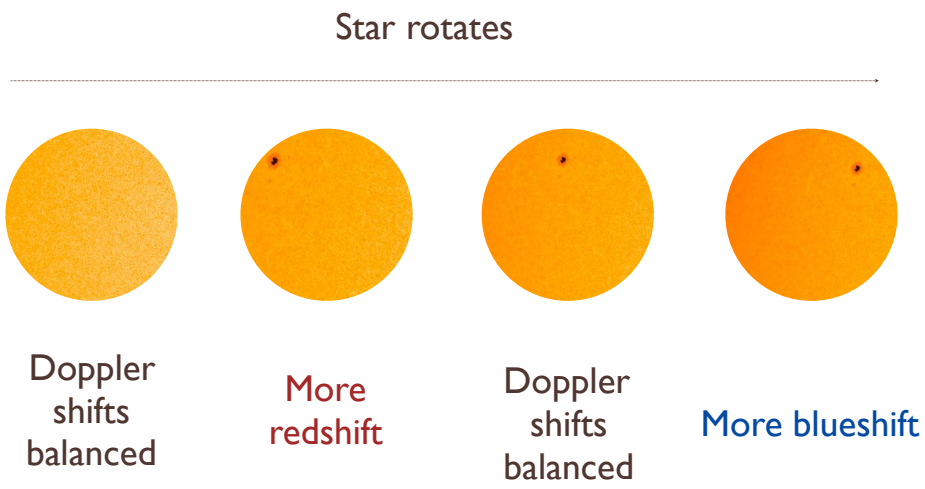
Magnetically-active regions on the stellar surface induce RV variations

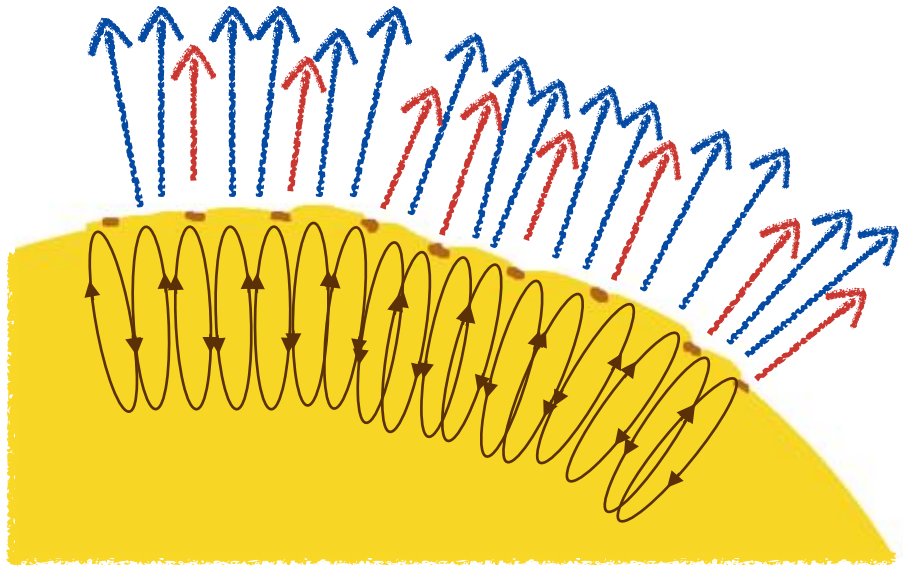


Rotational imbalance due to brightness inhomogeneities (~0.1 m/s)

Lagrange et al. (2010), Haywood et al. (2016)

Magnetically-active regions on the stellar surface induce RV variations





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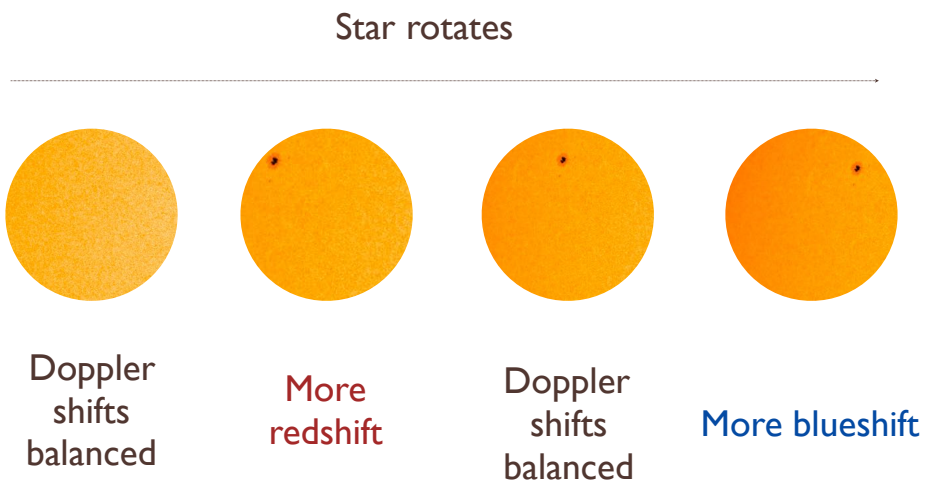

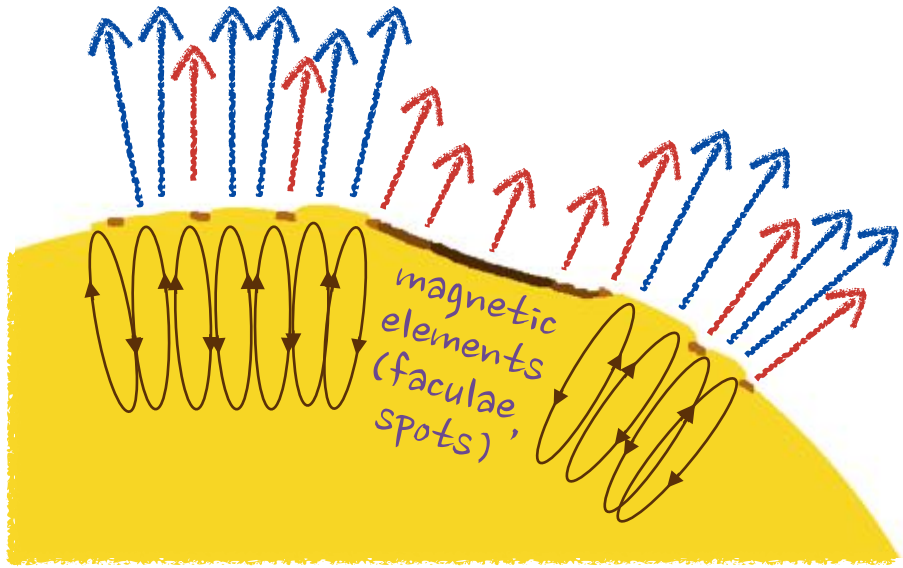

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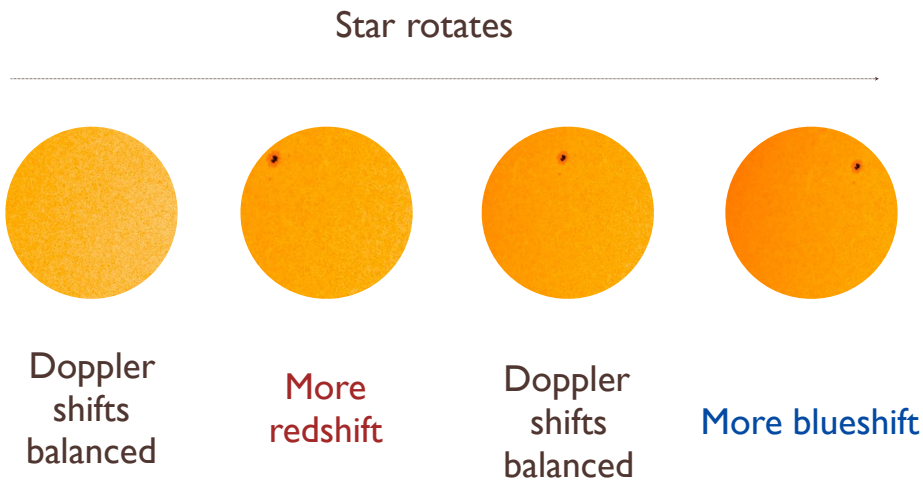
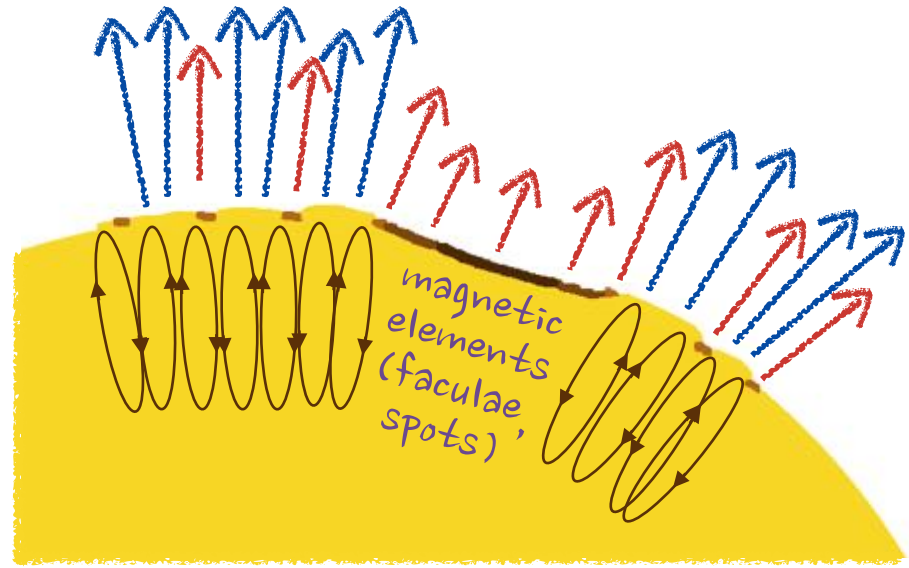
Magnetically-active regions on the stellar surface induce RV variations





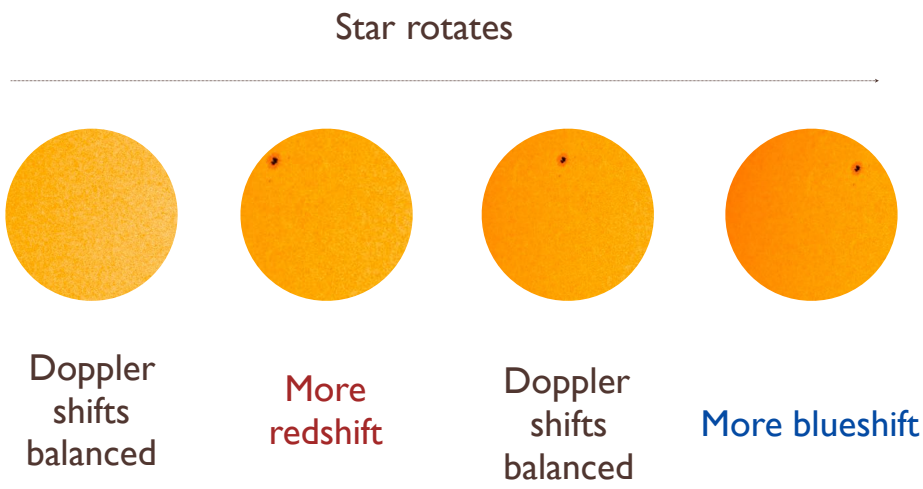
Rotational imbalance due to brightness inhomogeneities
(~0.1 m/s)

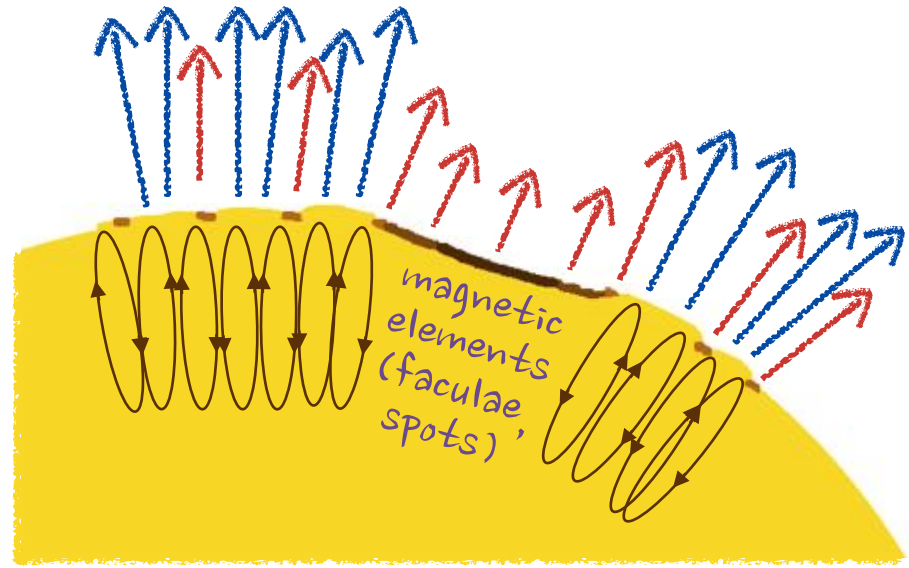
Lagrange et al. (2010), Haywood et al. (2016)

Suppression of convective blueshift by magnetic regions
(~few m/s)

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

Magnetically-active regions on the stellar surface induce RV variations





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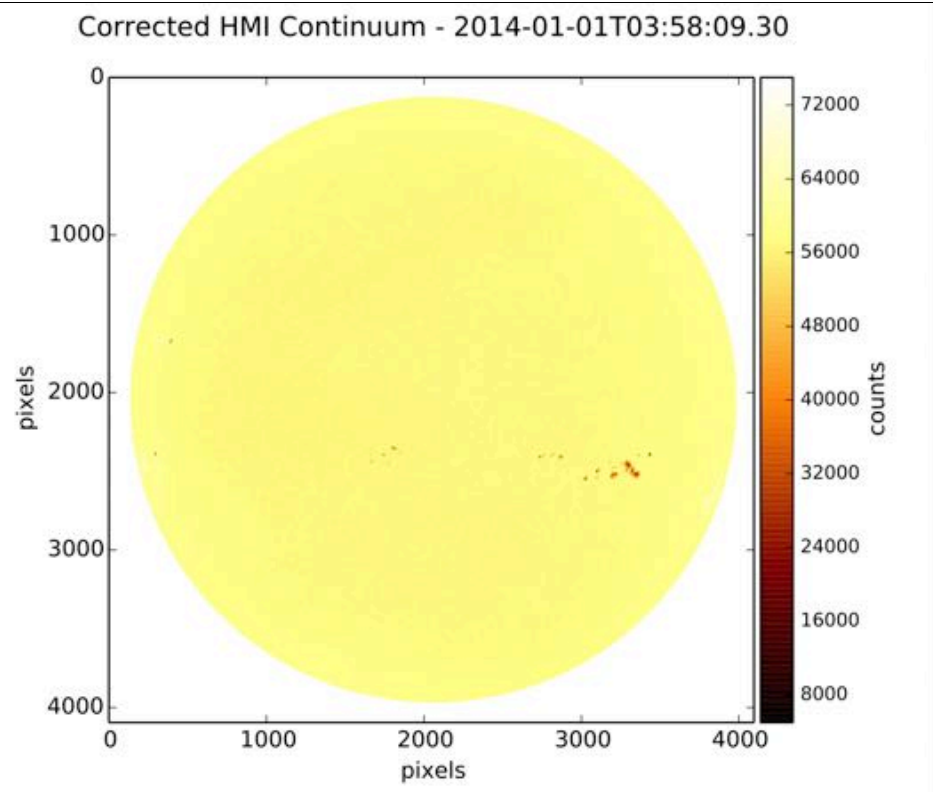
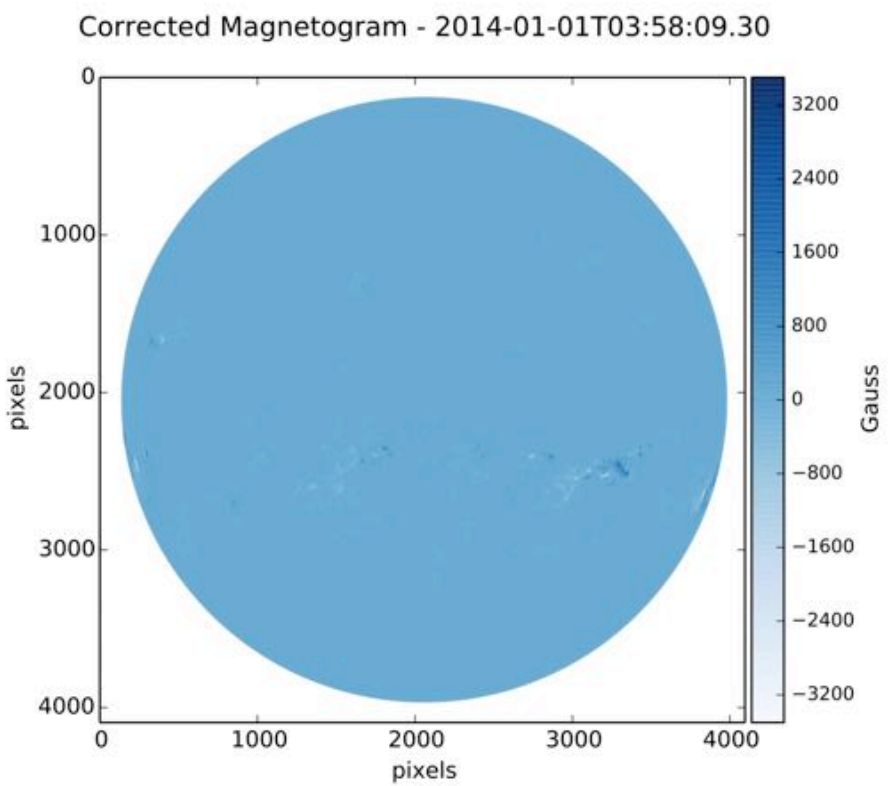
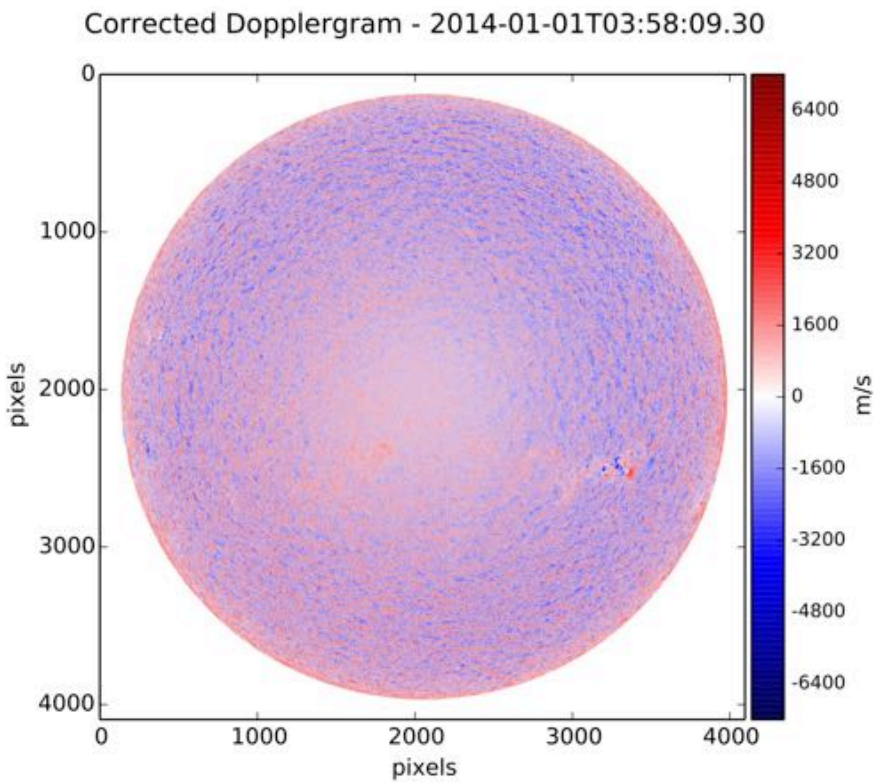
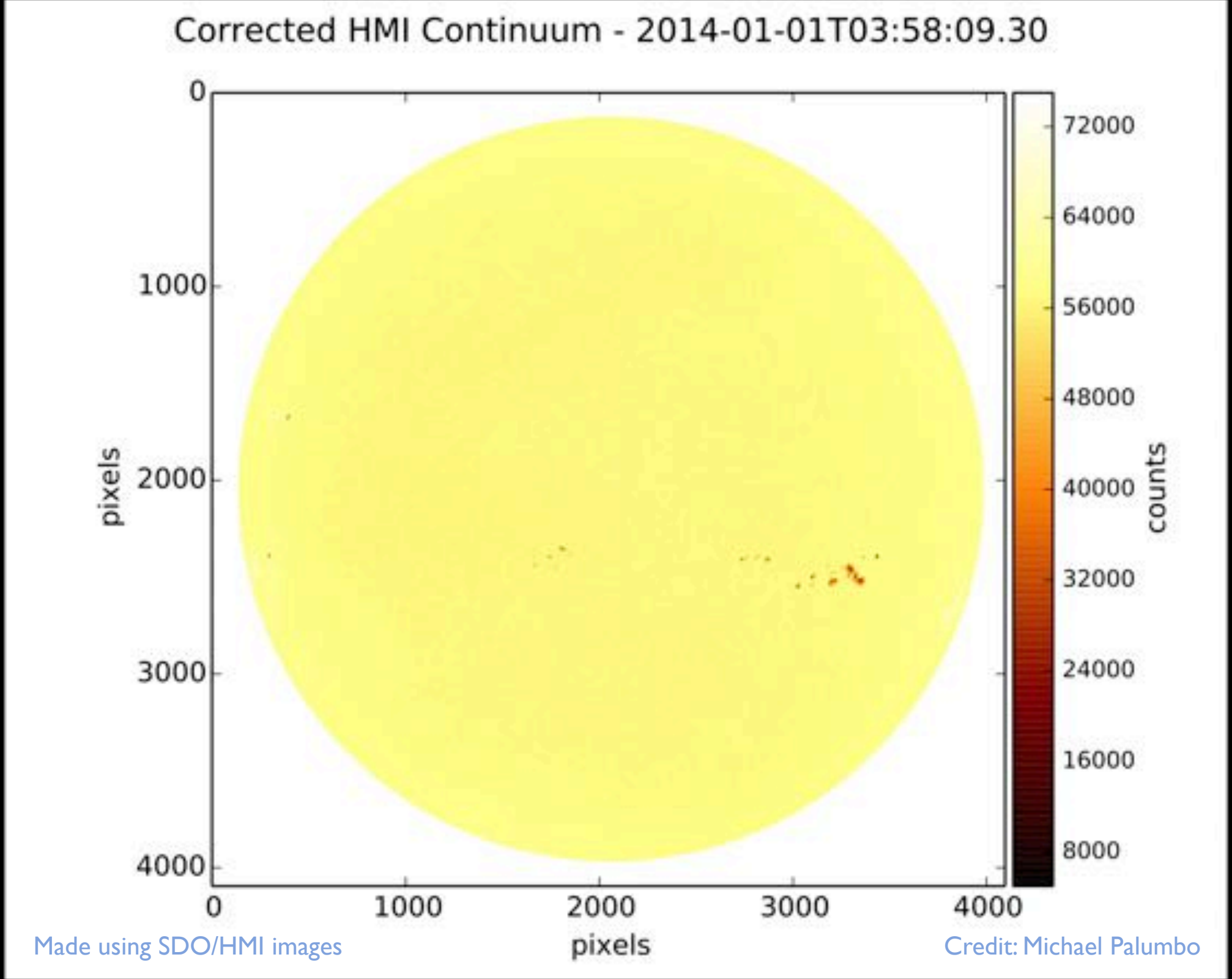




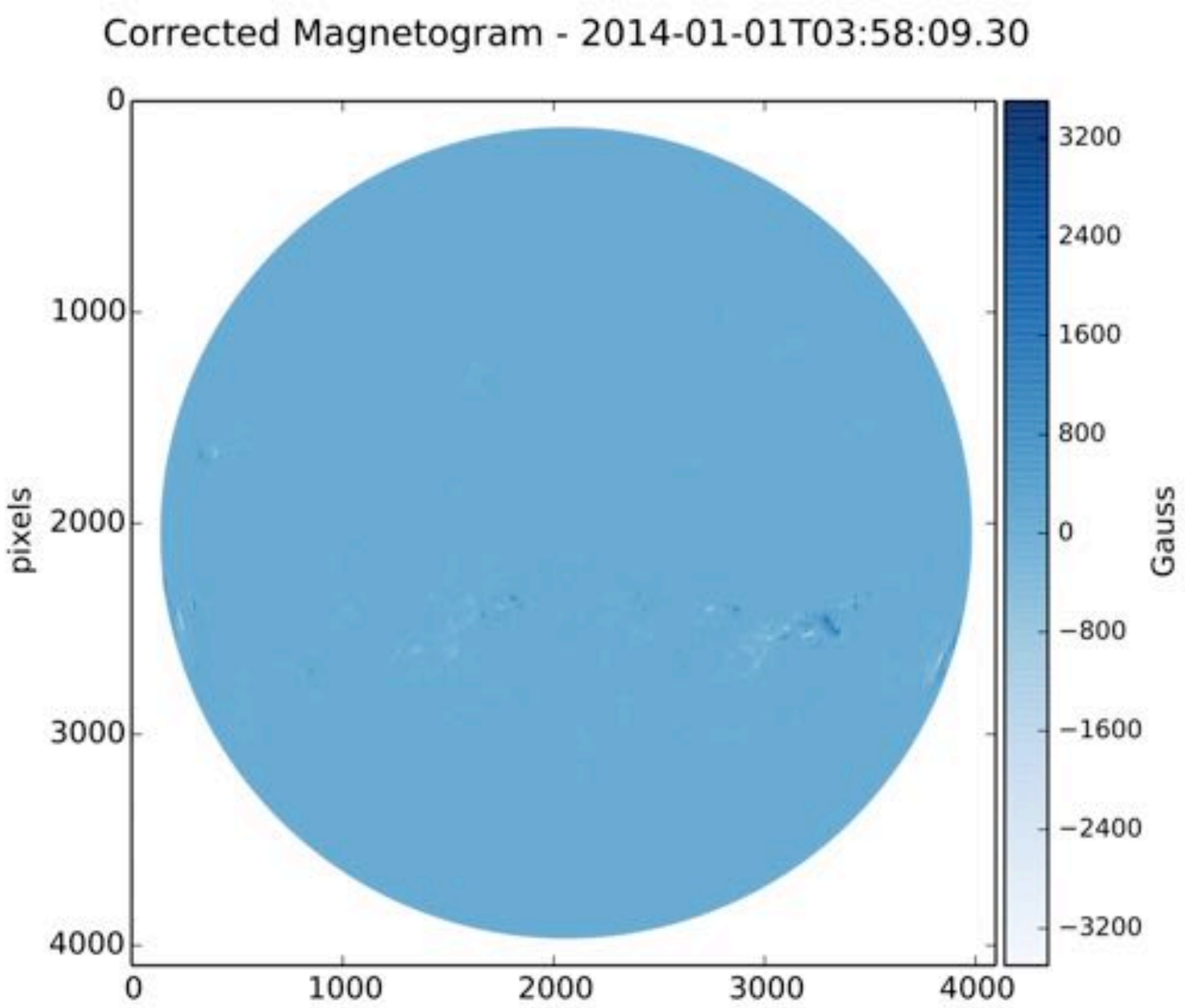


Movies made by Michael Palumbo using SDO/HMI images



Made using SDO/HMI images

Credit: Michael Palumbo



Made using SDO/HMI images

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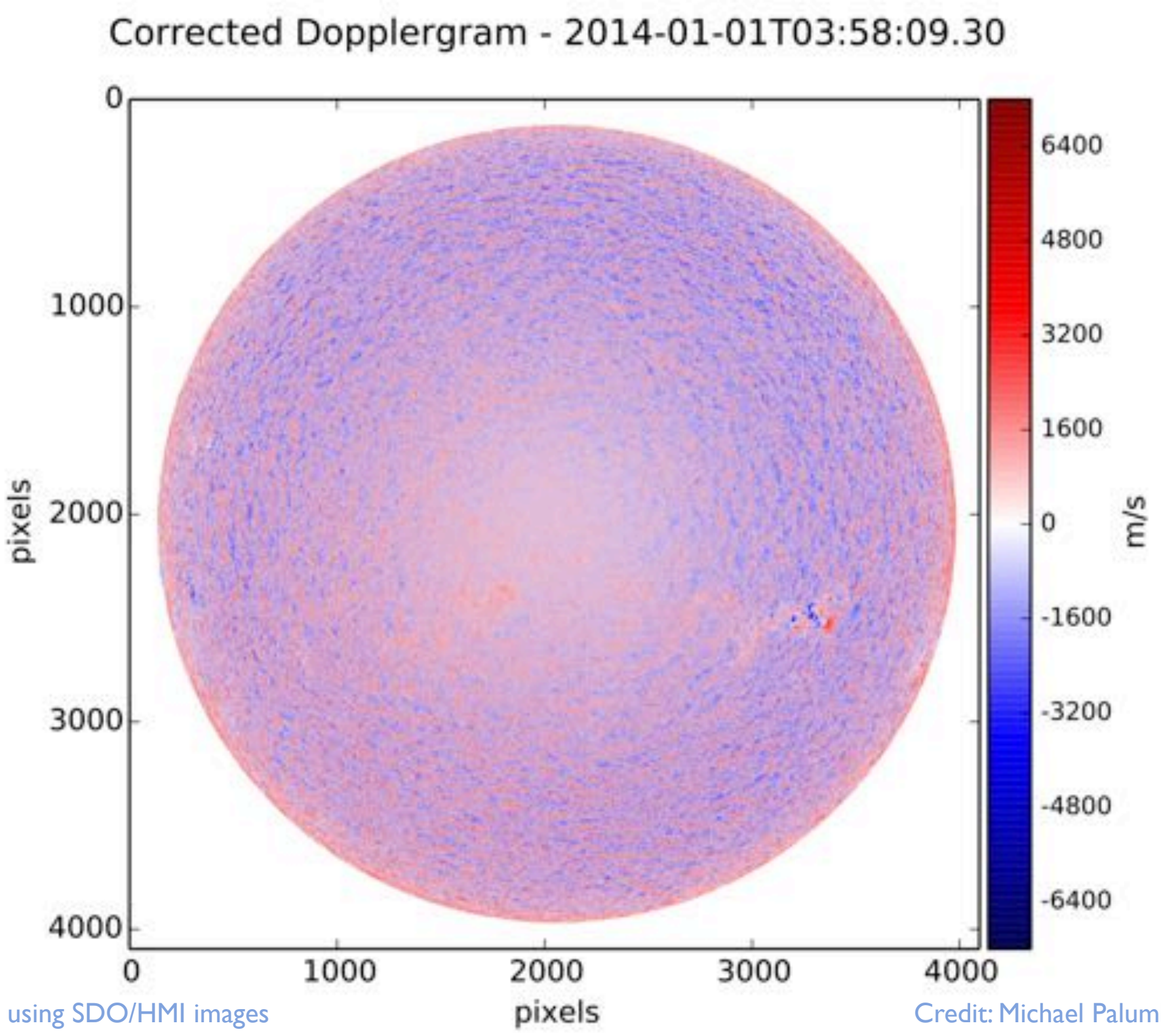

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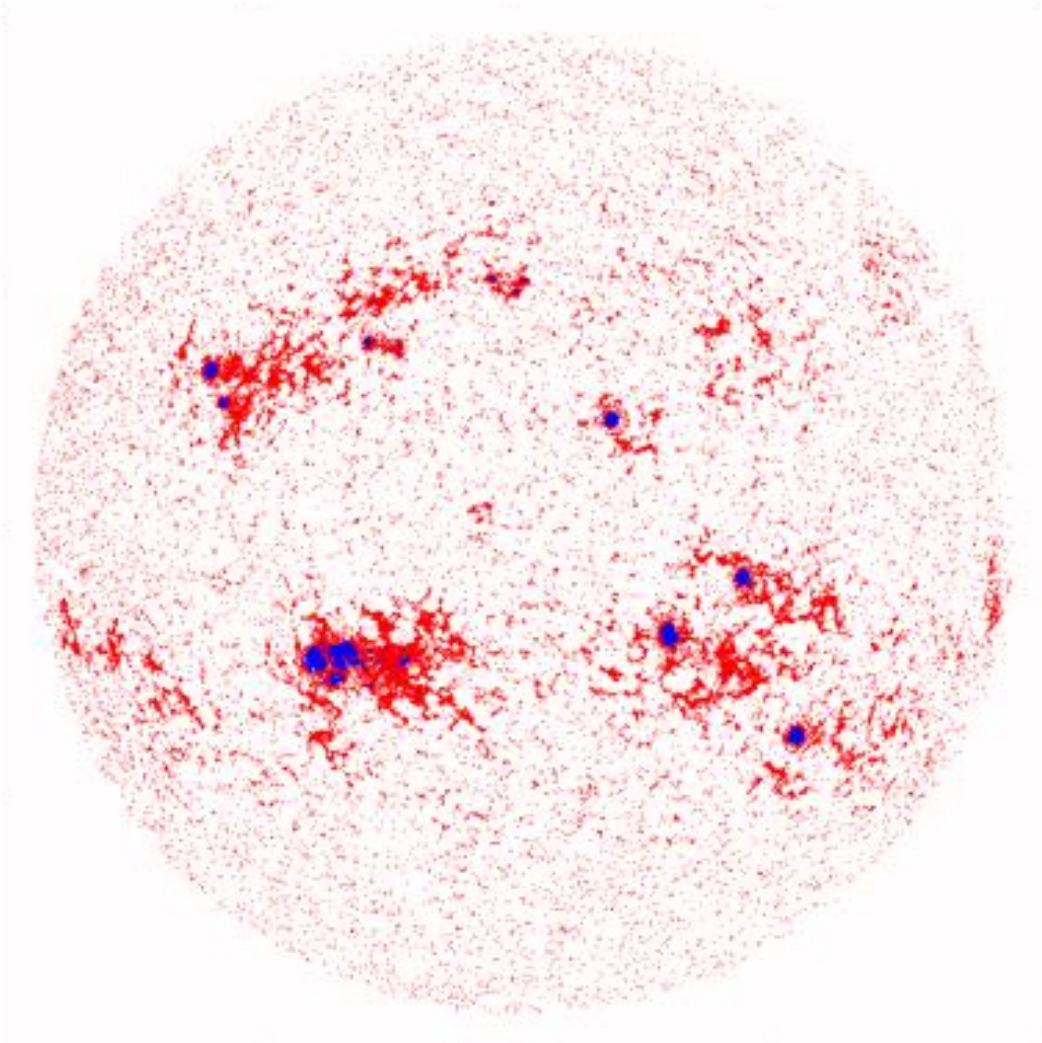
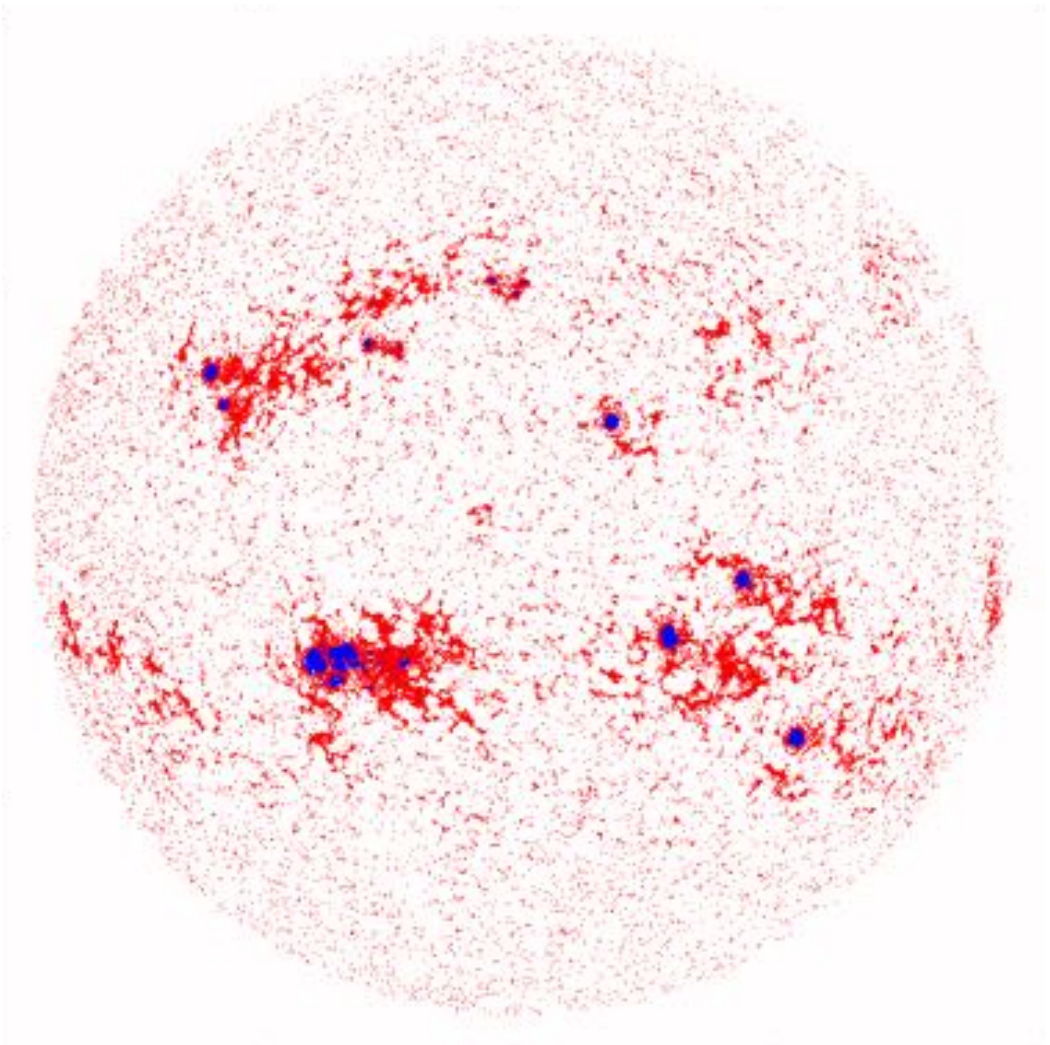


Faculae pixels
Sunspot pixels

Faculae
are the main source
of suppression of
convective blueshift

Meunier et al. (2010), Haywood et al. (2016)

Optical lightcurves can only give incomplete prediction of RV variations



Faculae pixels
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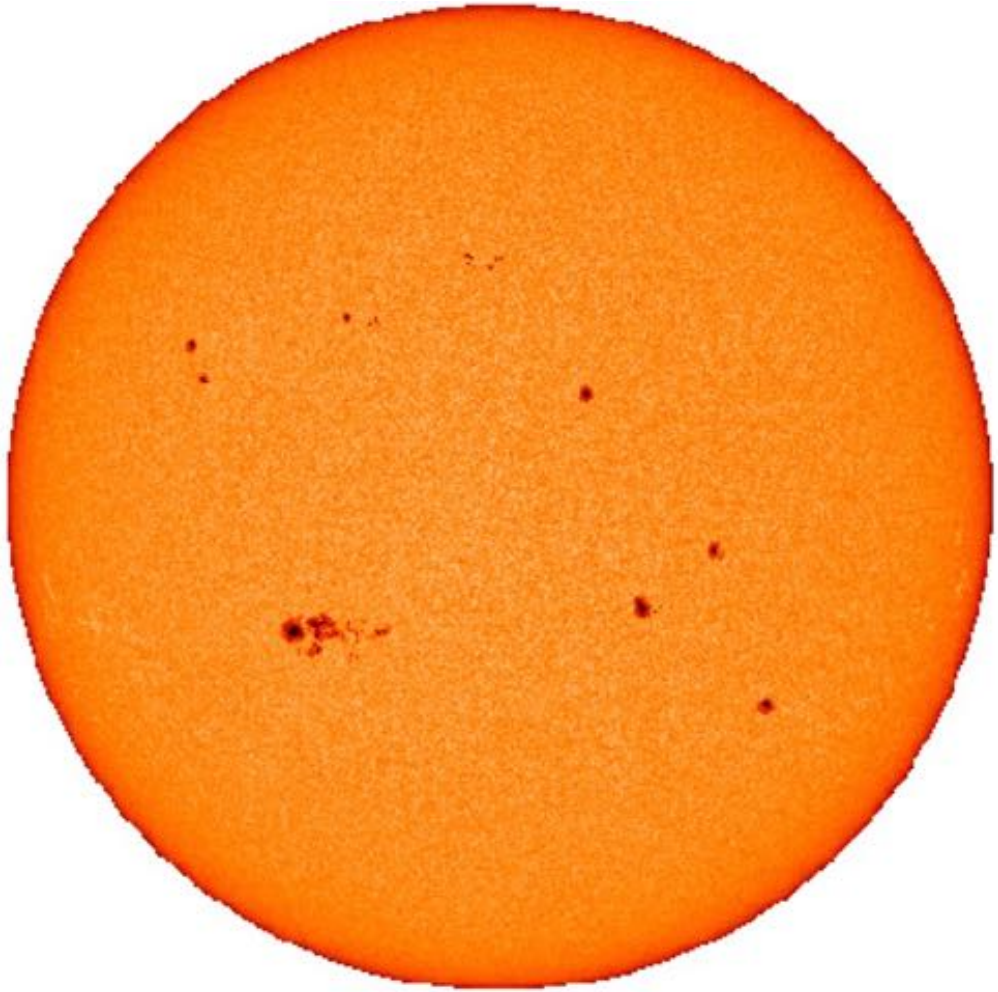
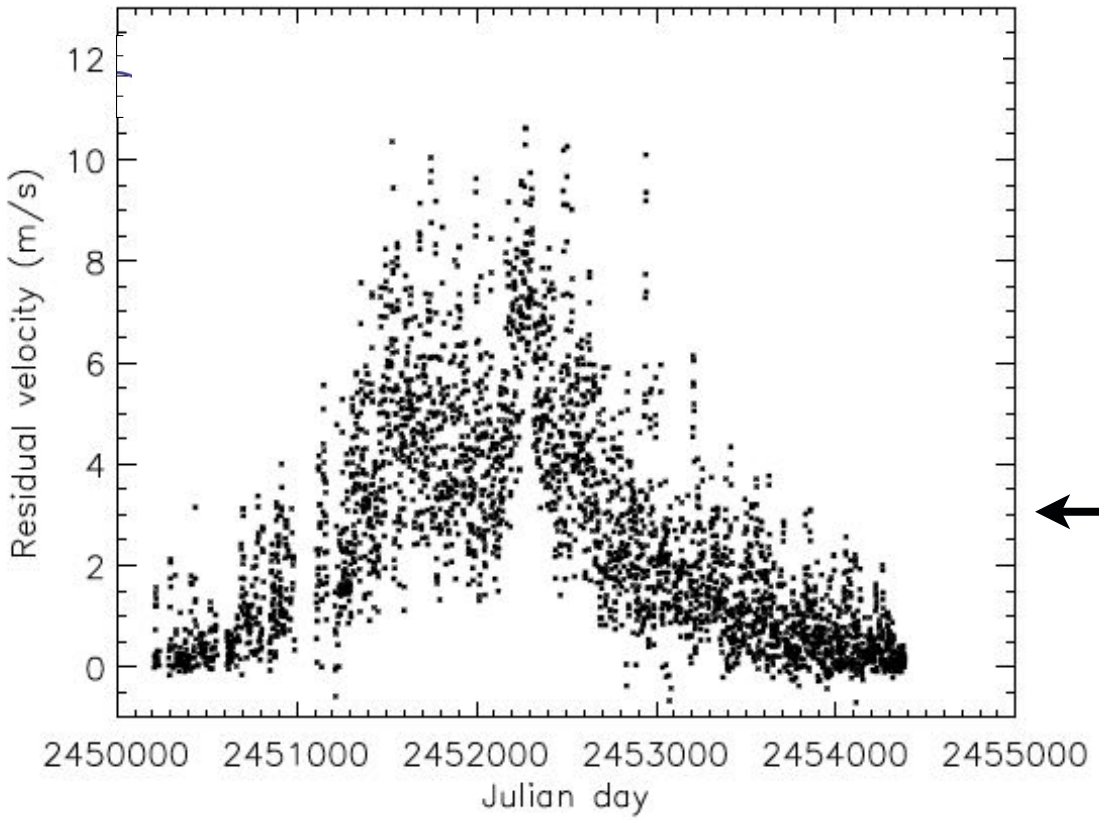


Haywood et al. (2016)

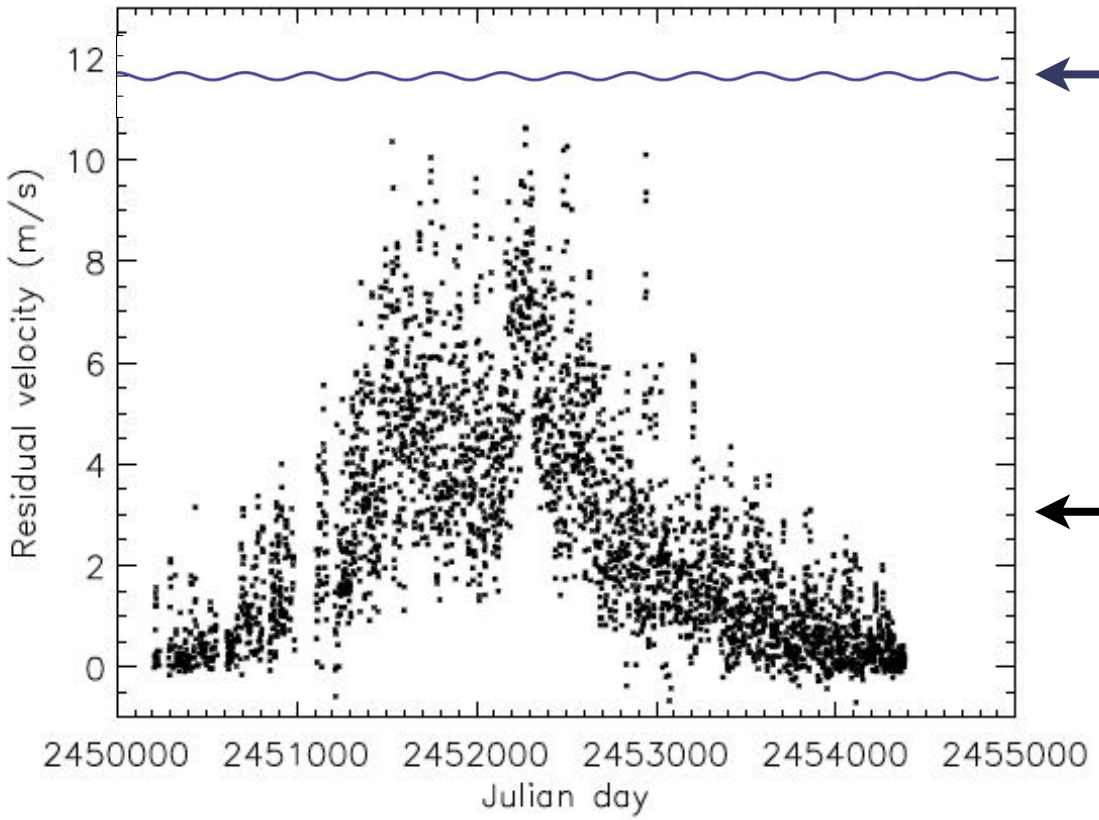
Decades: magnetic cycles



Full-disc convective blueshift suppression in facular areas from SOHO/MDI images

Meunier et al. (2010a,b)

Decades: magnetic cycles



9 cm/s solar reflex orbital motion for 1 $M_\oplus$ planet at 1 AU

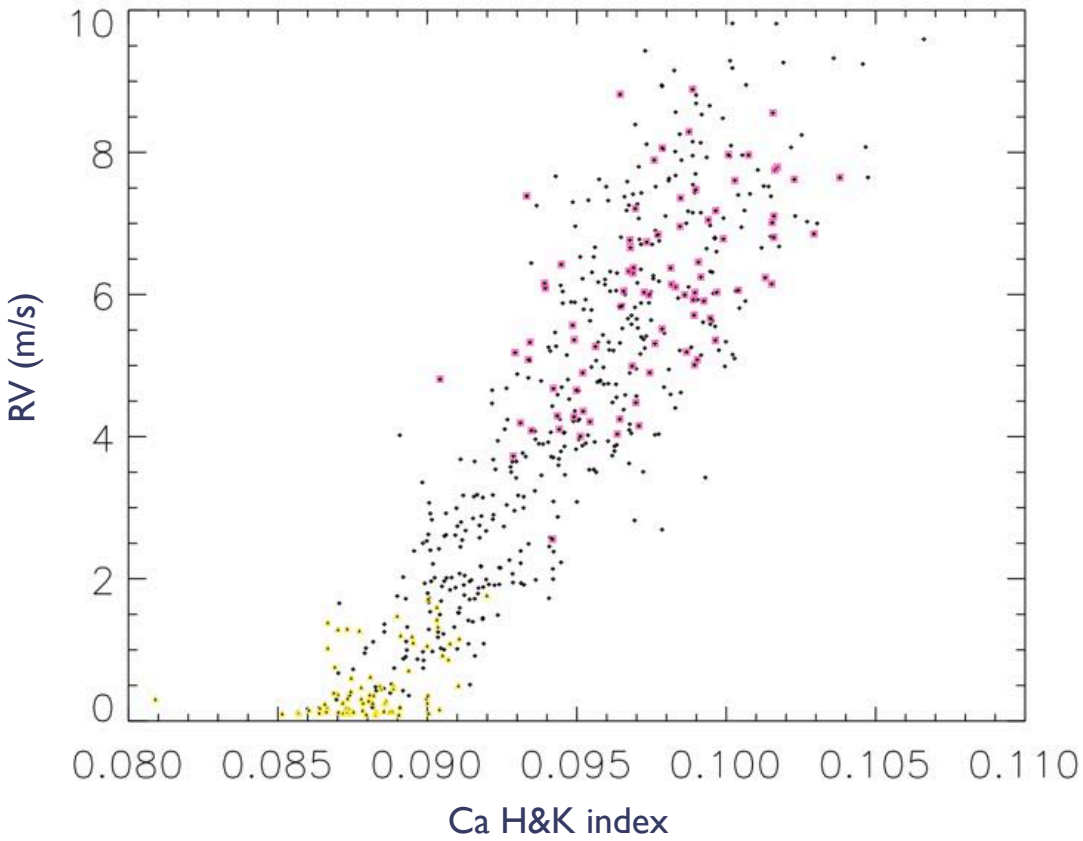
Full-disc convective blueshift suppression in facular areas from SOHO/MDI images

Meunier et al. (2010a,b)

On magnetic cycle timescale, Ca II H&K tends to correlate well with RV variations

The Sun

Meunier et al. (2010a)
See also Lanza et al. (2016)



On magnetic cycle timescale, Ca II H&K tends to correlate well with RV variations

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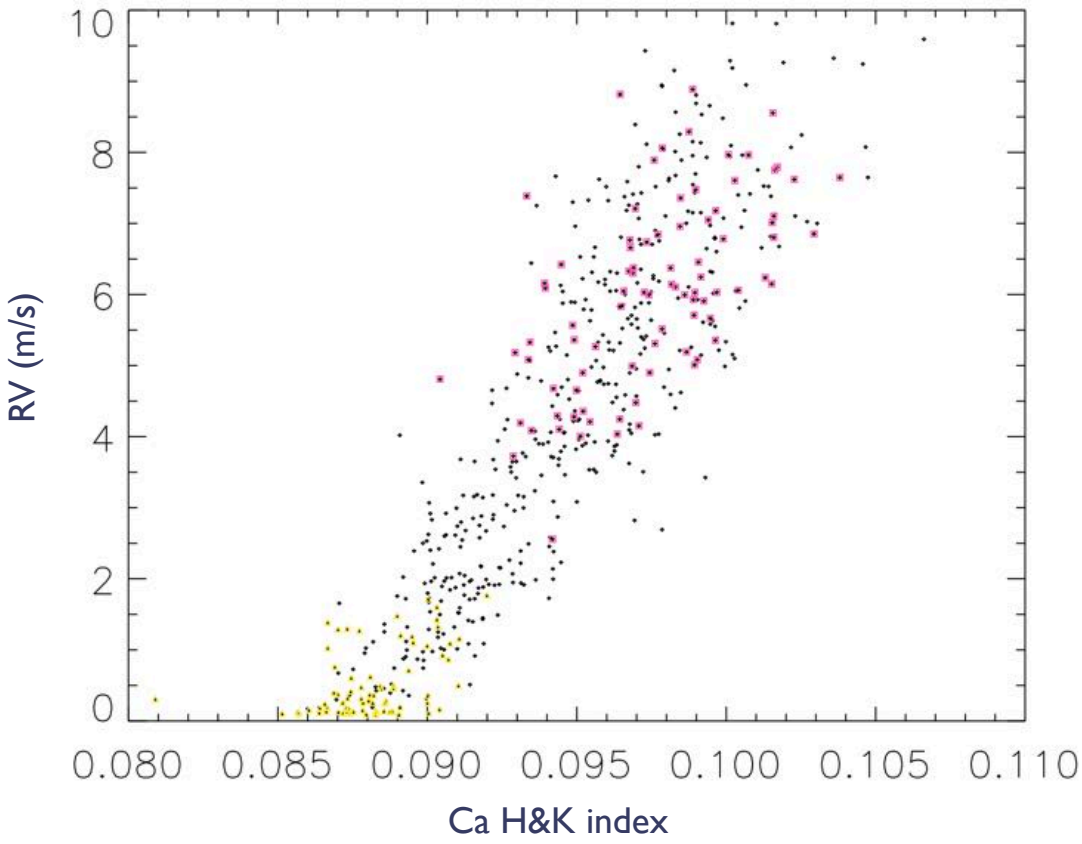
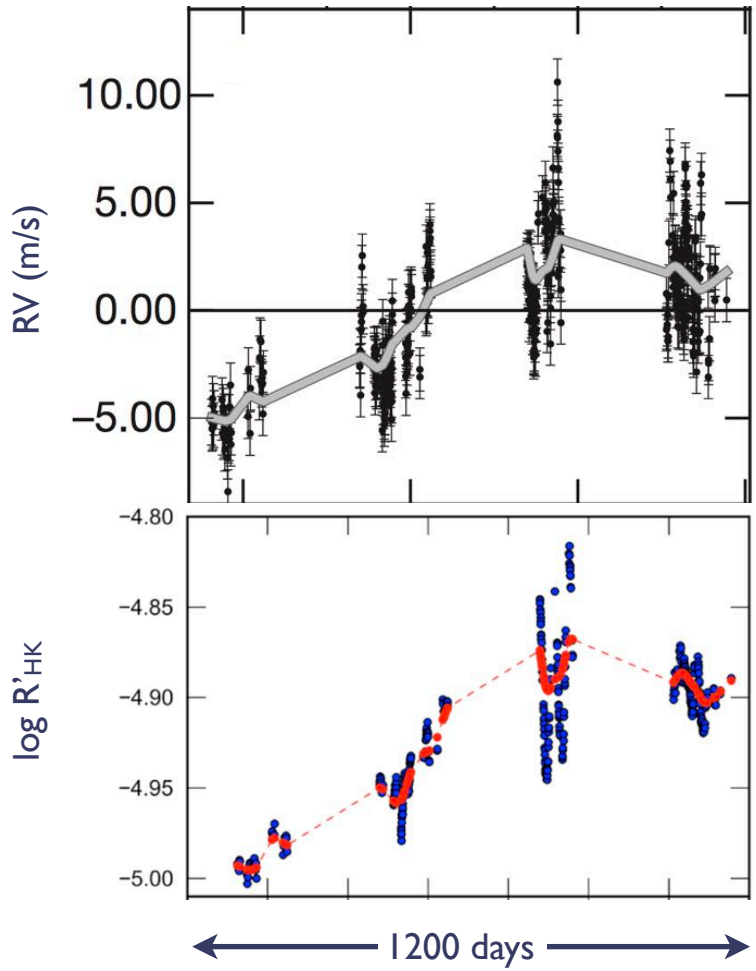


Alpha Cen B

Dumusque et al. (2012)



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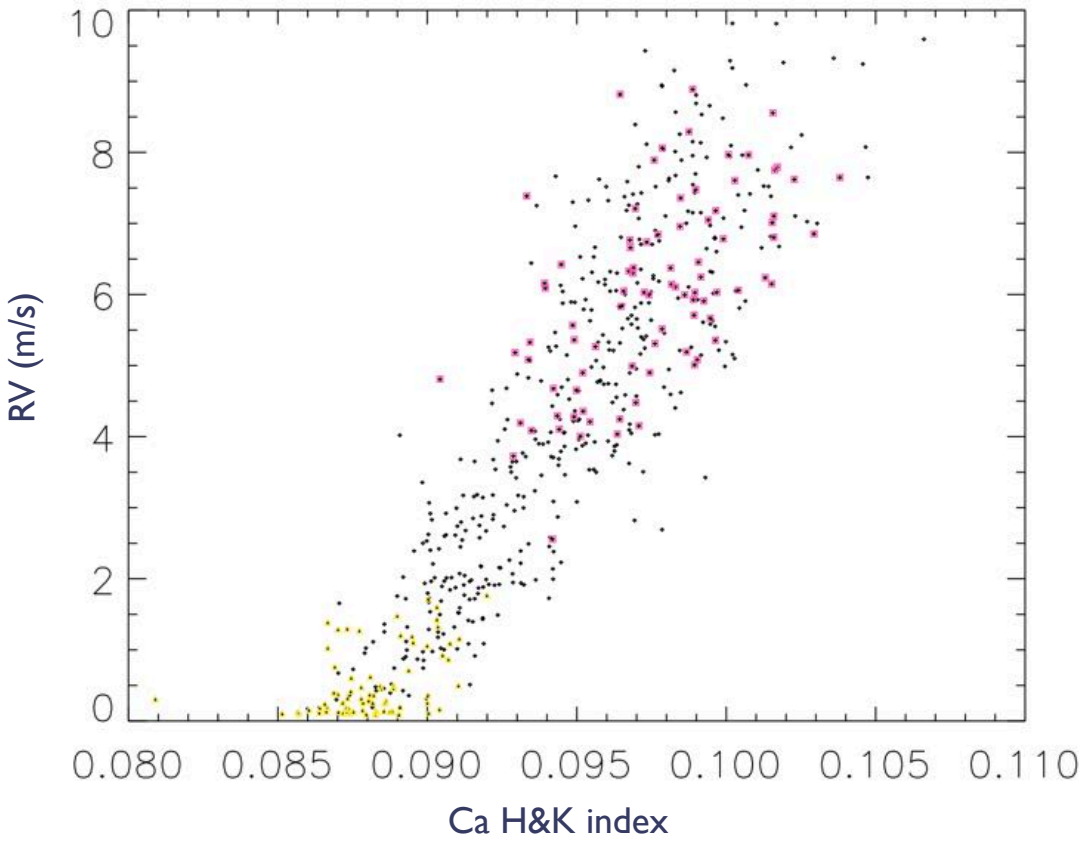
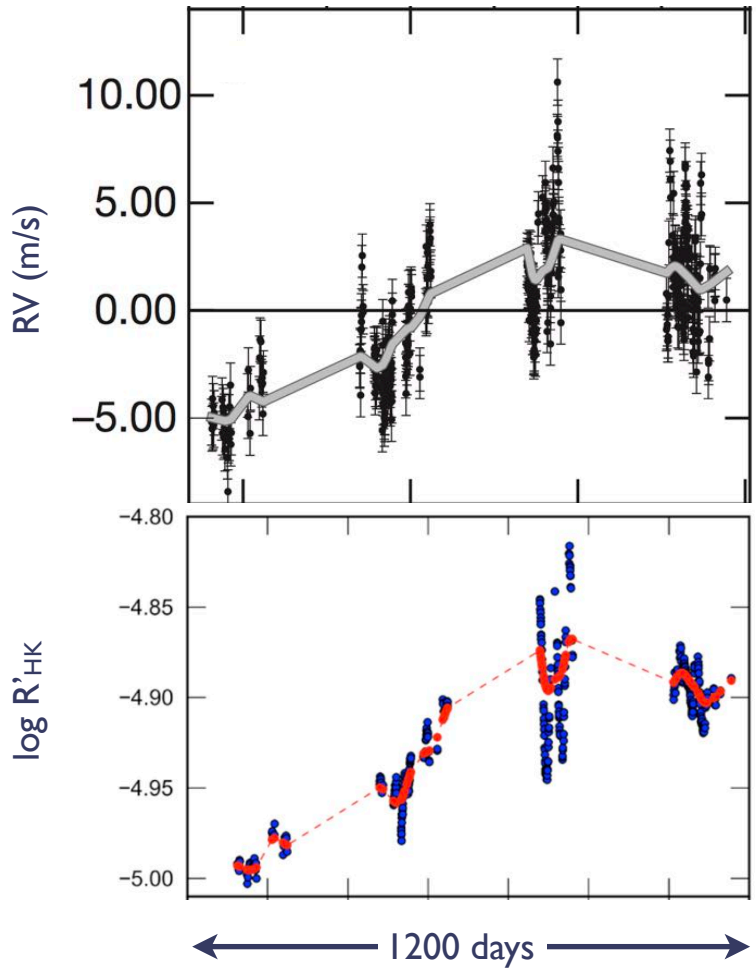
Meunier et al. (2010a)
See also Lanza et al. (2016)



$\Delta RV \propto \log R'_{HK}$ Lovis et al. (2011) and others

Alpha Cen B

Dumusque et al. (2012)



Activity-induced RV variations

- Minutes to hours:
  - oscillations
  - surface granulation
  - flares and coronal mass ejections
- Days:
  - gravitational redshift
- Days-weeks (stellar rotation period):
  - spots
  - faculae
- Decades:
  - magnetic cycles

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Young stars are dominated by spots
Old stars (like the Sun) are dominated by faculae

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What can we do to minimise/account for rotation-modulated activity?

I will talk about it…

Before observations: Pick the right stars

After observations: Include uncorrelated and correlated noise terms in RV analysis

tomorrow

In general: Learn about the physical processes at play to develop tailored, sophisticated, physically-motived models

Thursday

During observations: Sample planet orbit *and* stellar rotation strategically

Friday