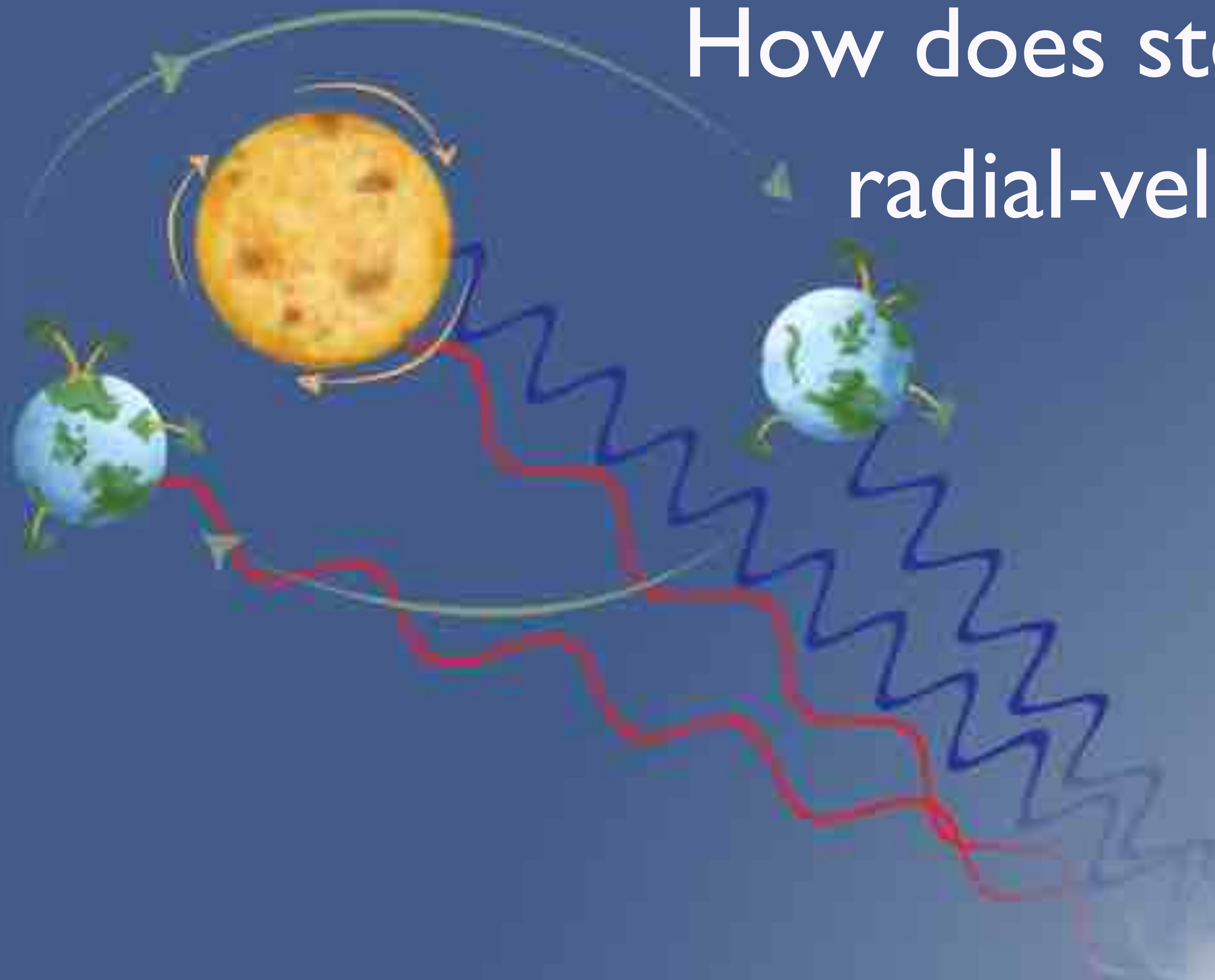
How does stellar activity impact radial-velocity observations?



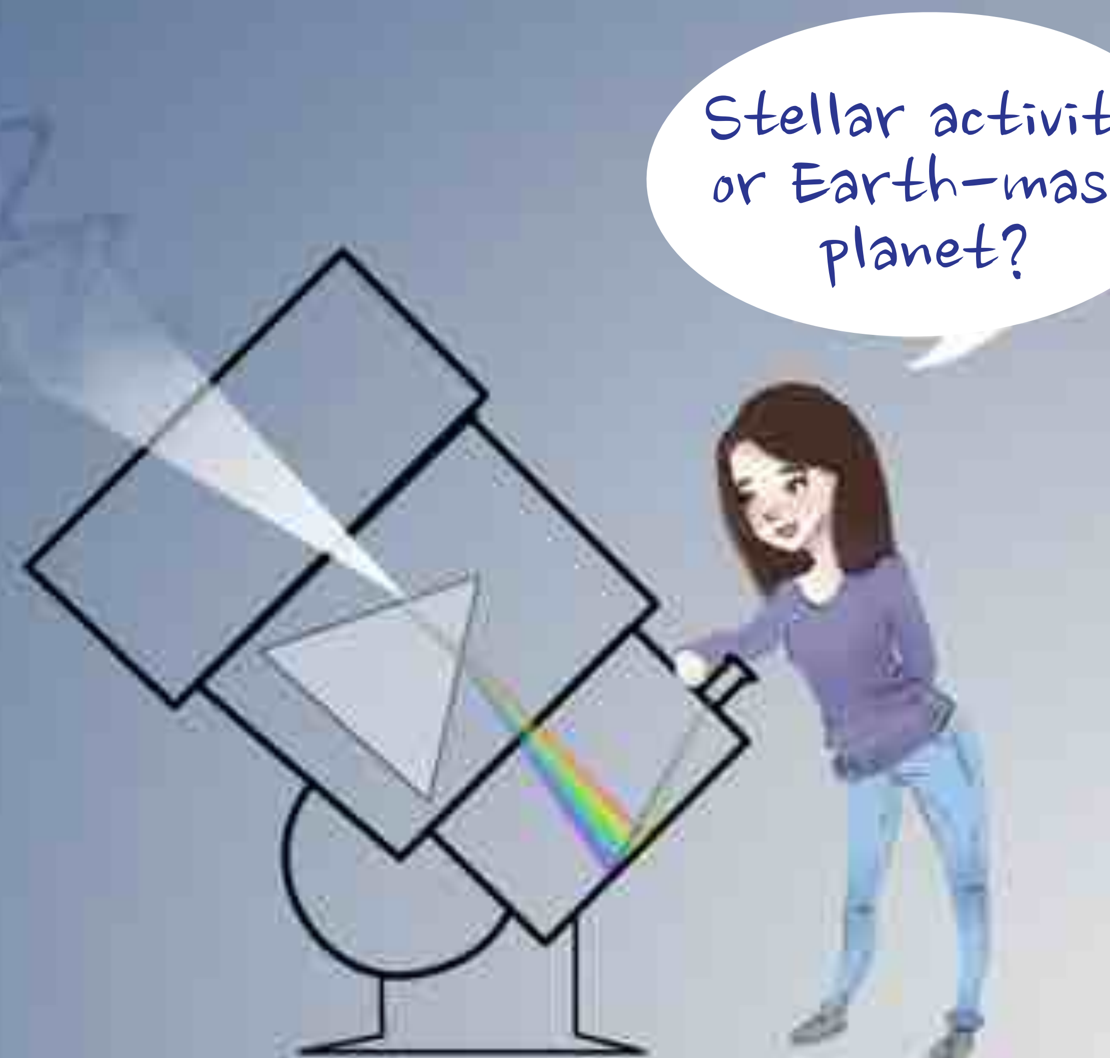


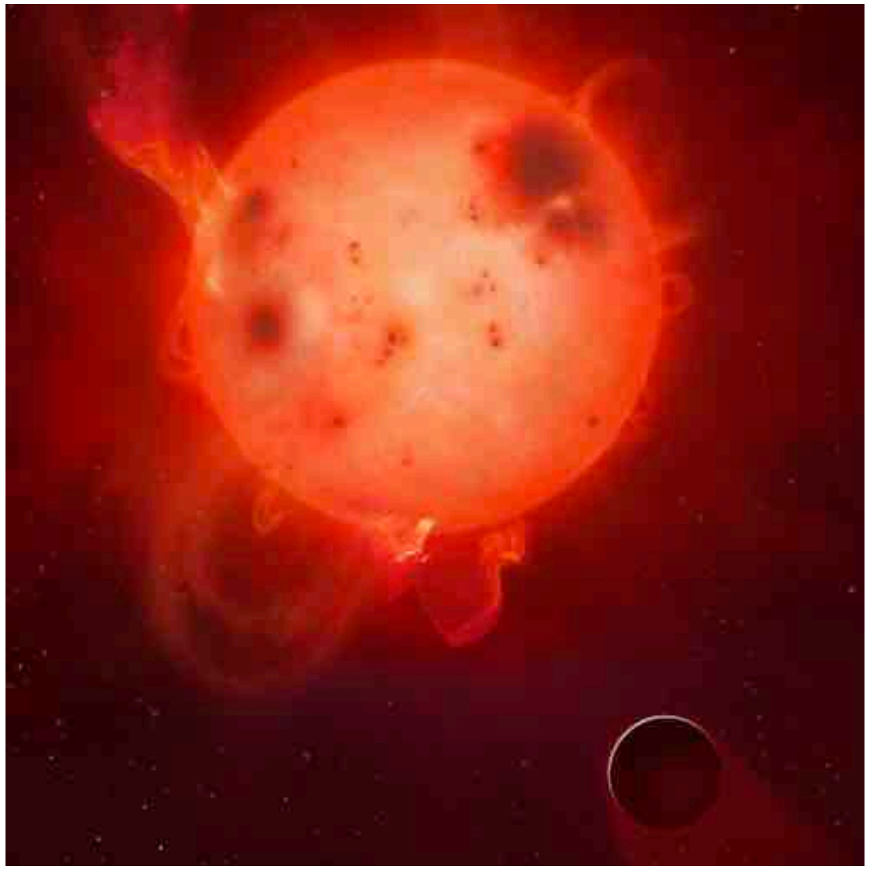
Image credit: Natalie Cameron

Raphaëlle D. Haywood

Sagan Fellow, Harvard Observatory

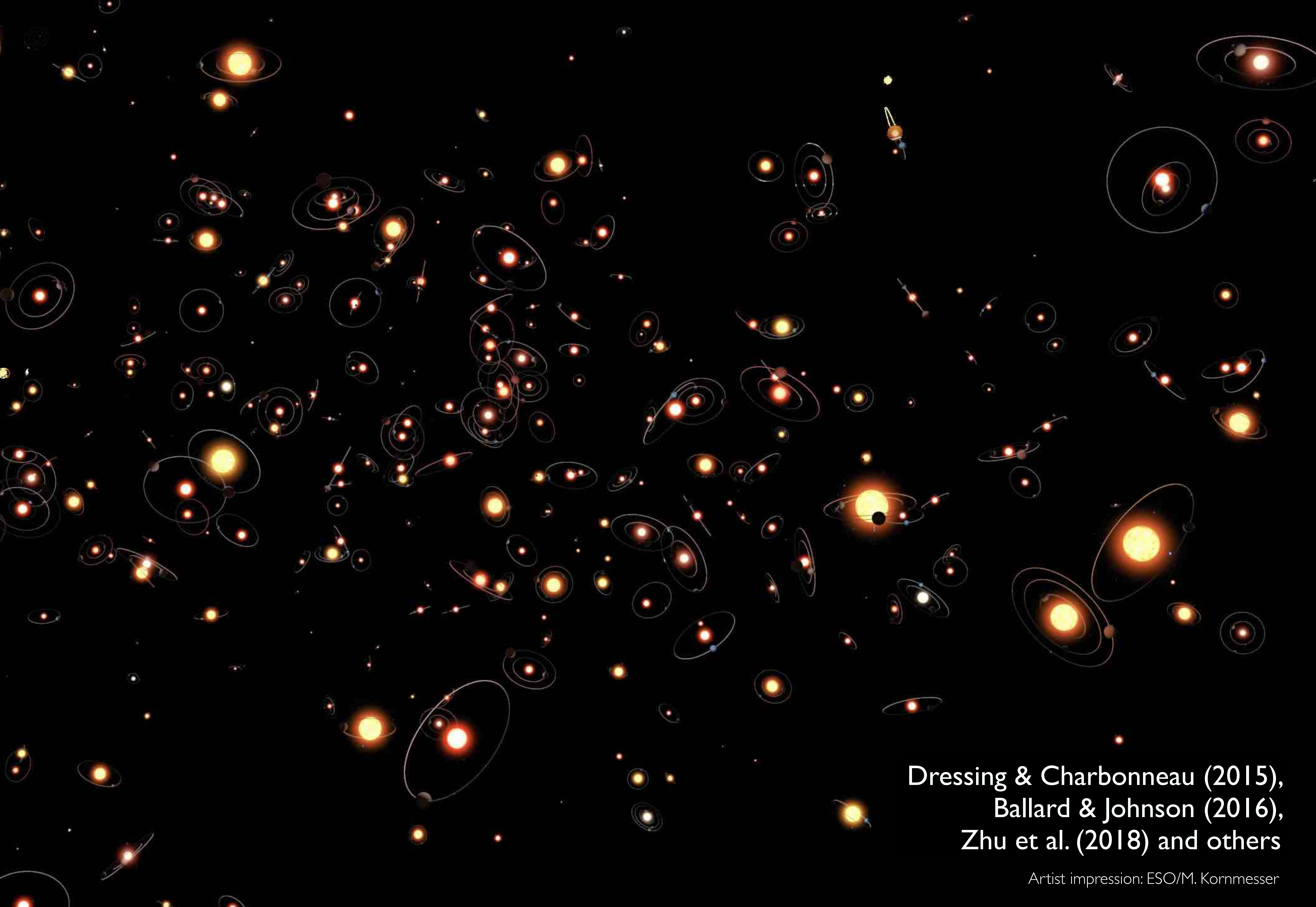
Outline

- Stellar activity is the main obstacle to characterising small exoplanets.
- How does stellar activity impact radial-velocity (RV) observations?
- How can we correct for activity to better characterise small exoplanets?



Artist impression: M. Garlick

We now know that there are more planets than stars in our galaxy



Dressing & Charbonneau (2015),
Ballard & Johnson (2016),
Zhu et al. (2018) and others

Artist impression: ESO/M. Kornmesser

Discovering and characterising nearby small planets, and examining their atmospheres to assess their potential for hosting life

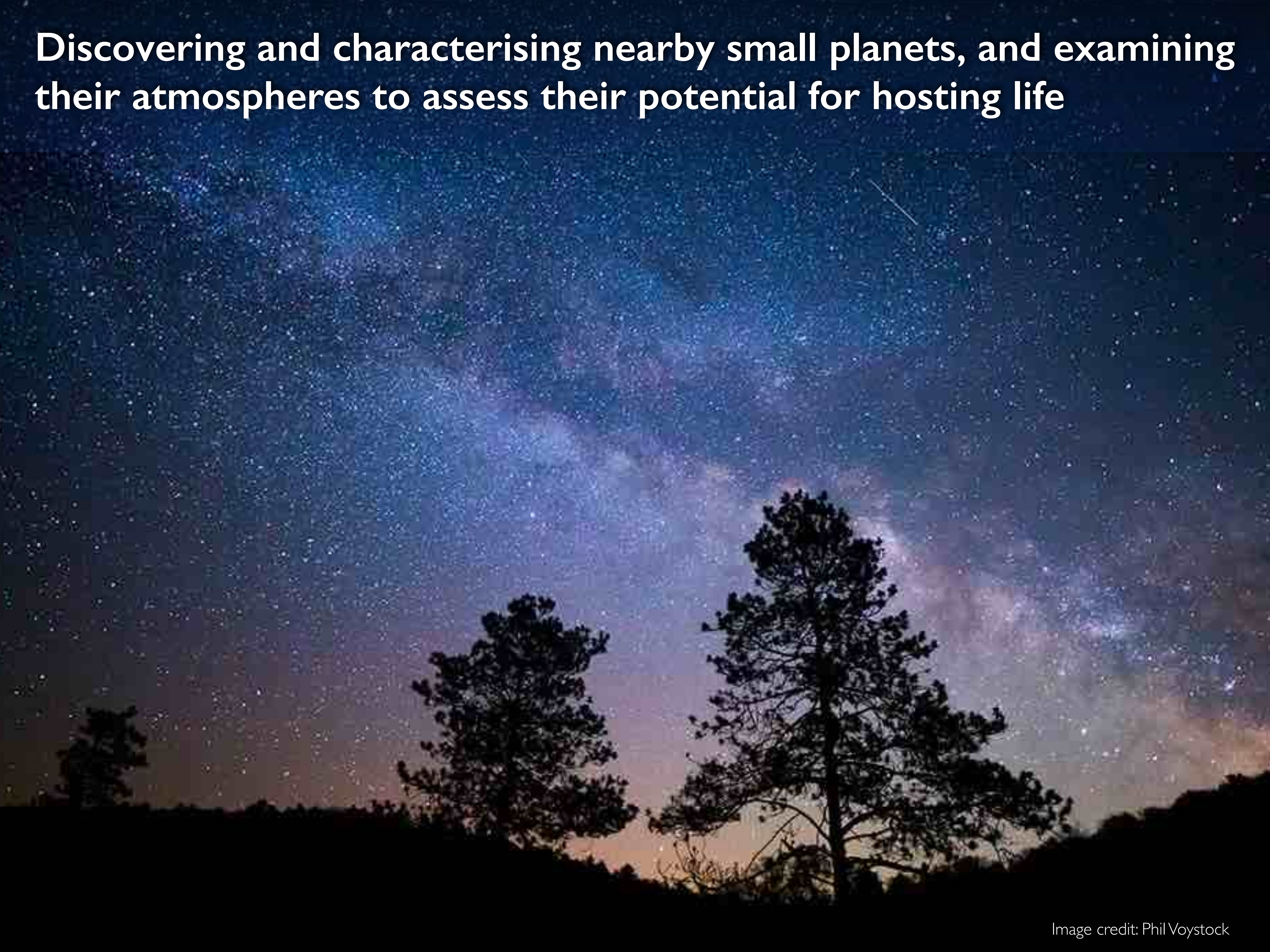


Image credit: Phil Voystock

Discovering and characterising nearby small planets, and examining their atmospheres to assess their potential for hosting life

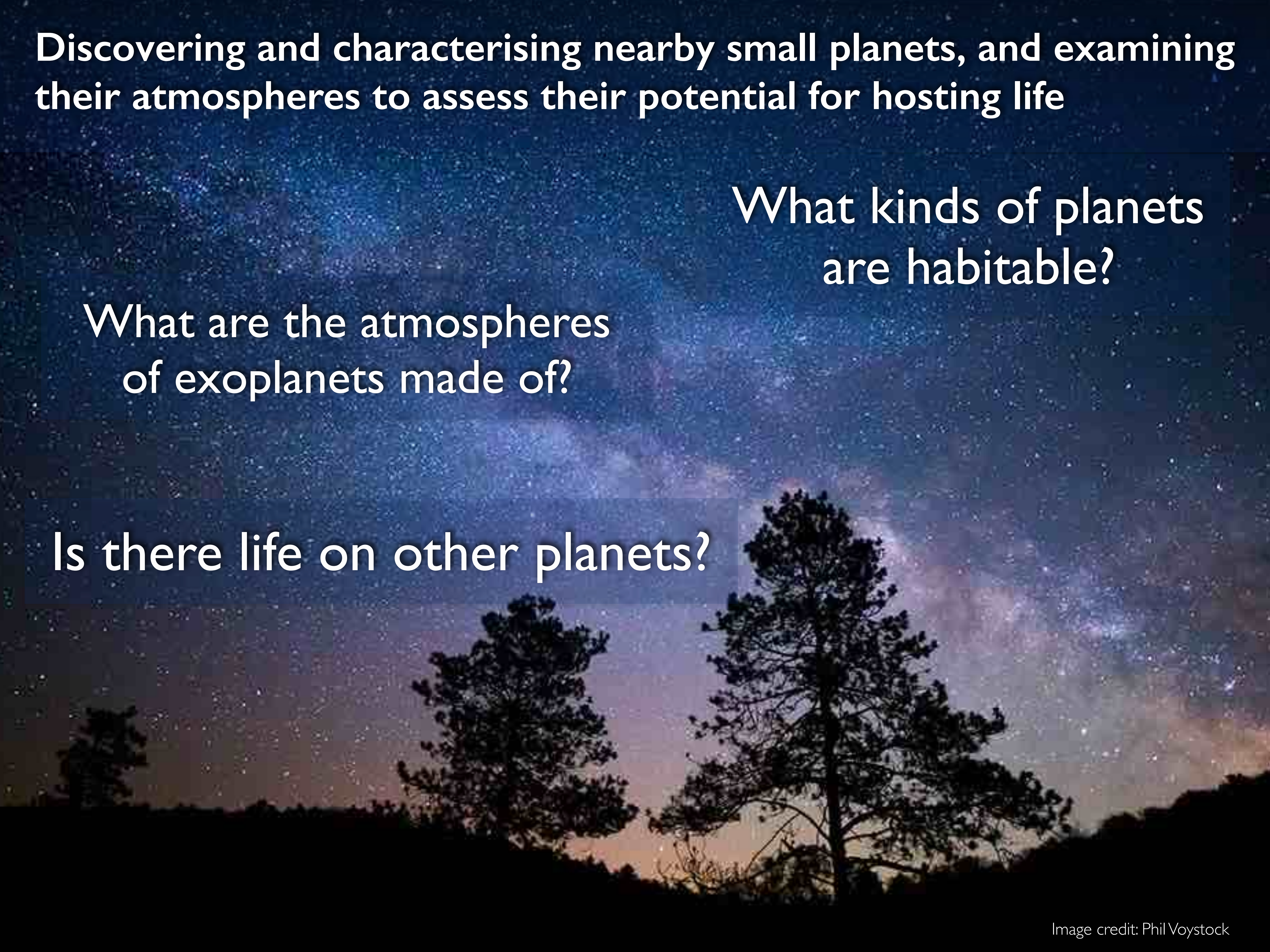
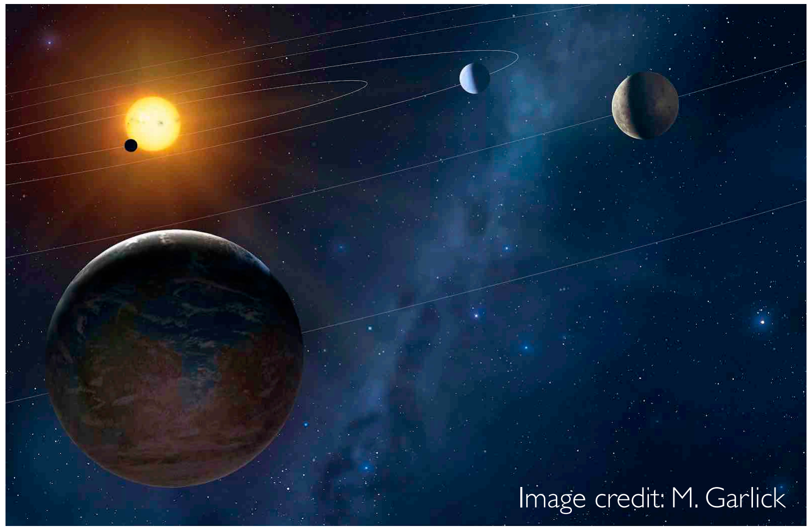


Image credit: Phil Voystock

Discovering and characterising nearby small planets, and examining their atmospheres to assess their potential for hosting life

Step 1:

Discover the nearest
Earth- to Neptune-size exoplanets
in our celestial neighbourhood

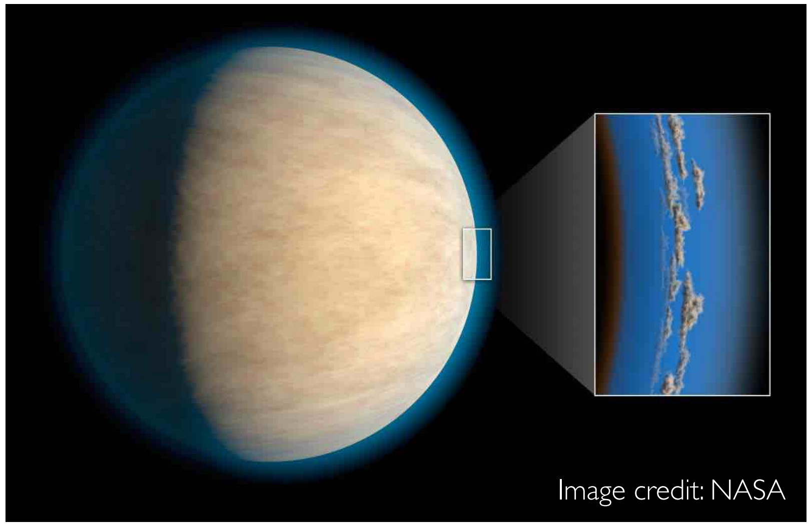


Step 2:

Confirm and characterise
these exoplanets

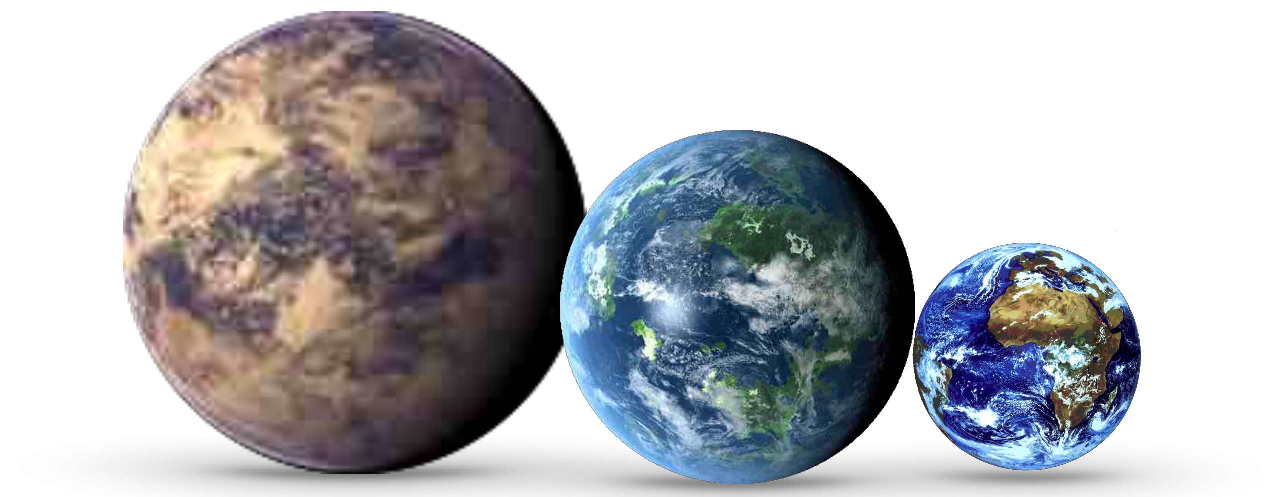
Step 3:

Carry out and interpret
observations of their
atmospheres



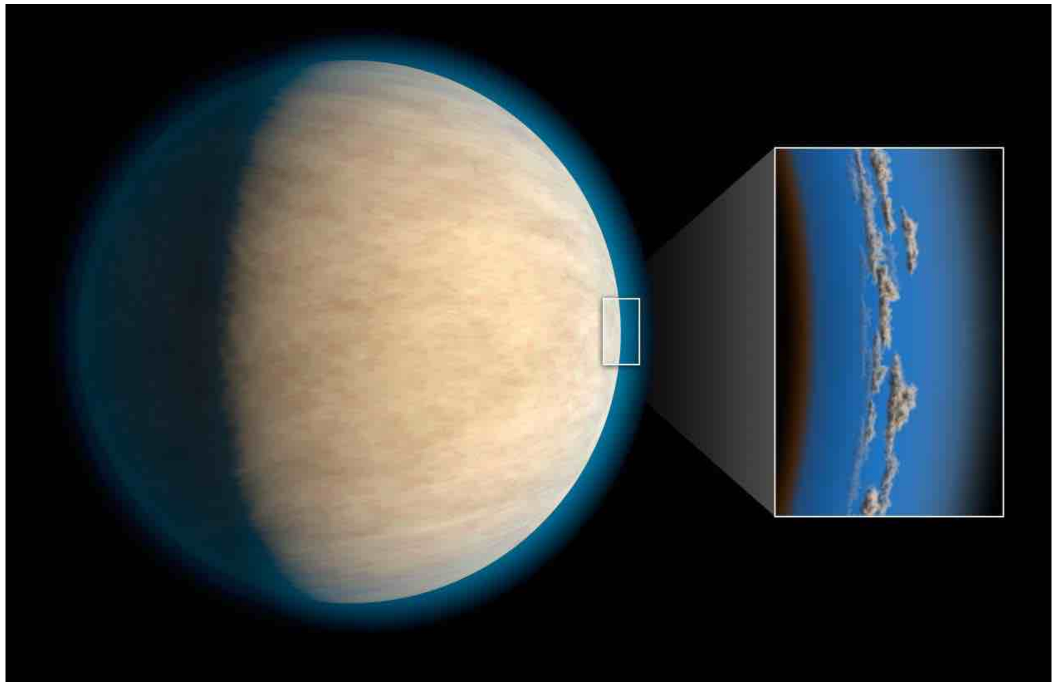
Mass and radius are the most fundamental parameters of a planet

Main inputs for models of interior composition/structure



Zeng & Sasselov (2013)

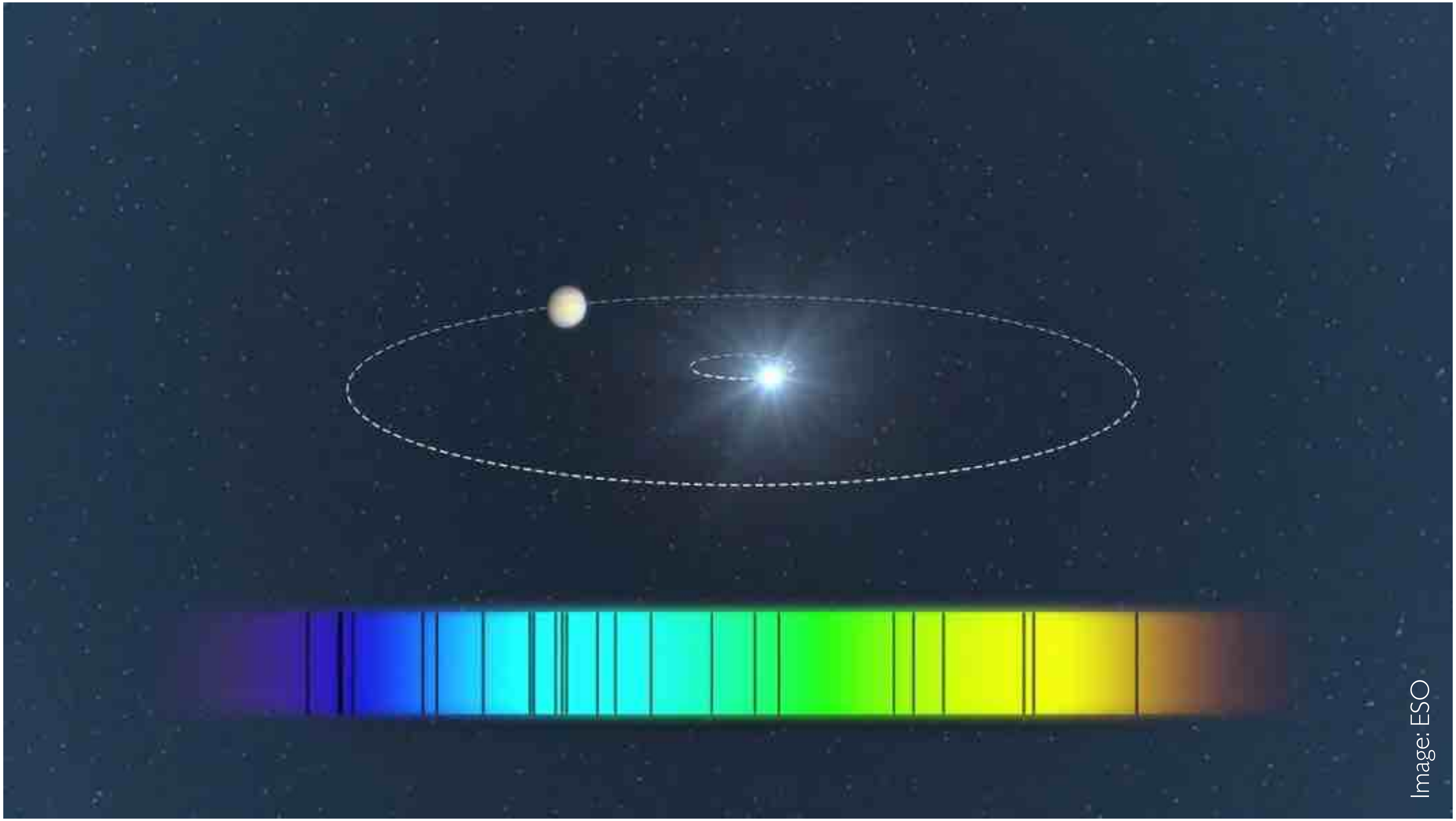
Mass is essential to interpreting observations of atmospheres



Morley et al. (2017)
Winn (2010)

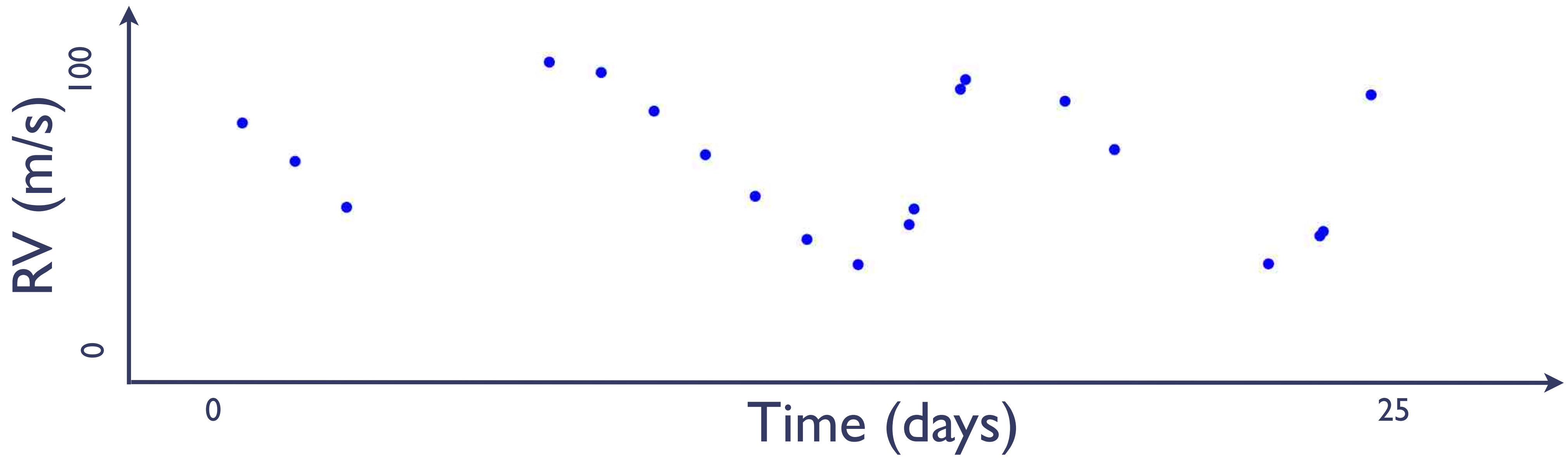
Image credits: NASA

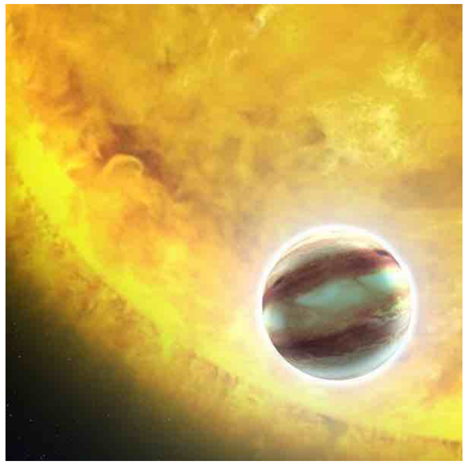
How do we determine planet masses?



We use highly precise and stable spectrographs to monitor the star's radial-velocity (RV) variations over time

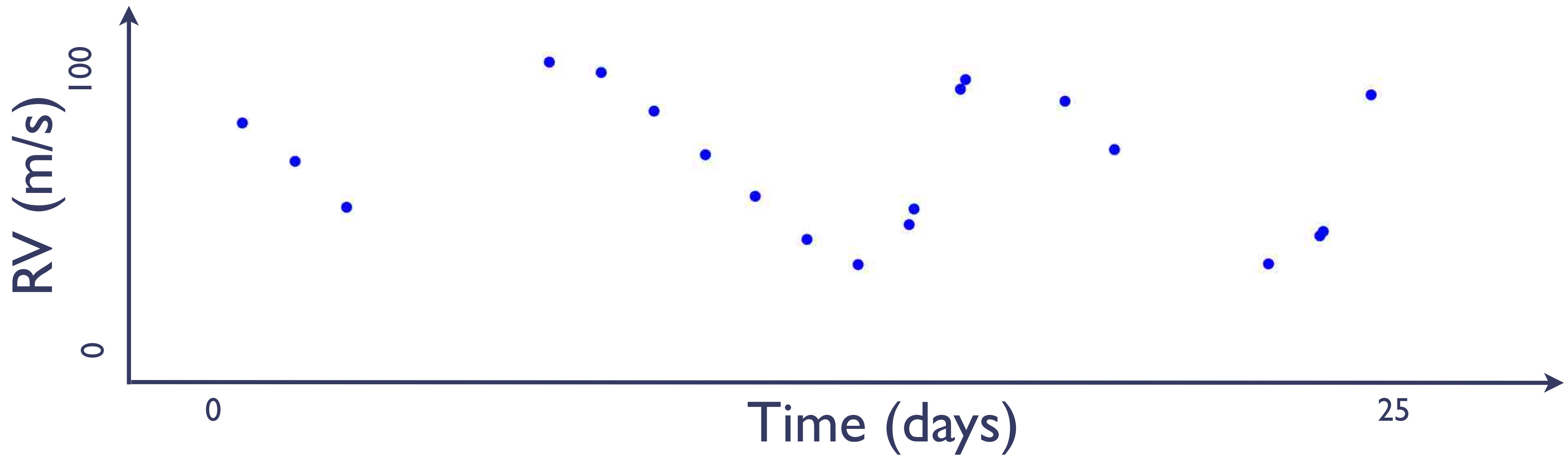
The radial-velocity (RV) amplitude is proportional to the planet's mass

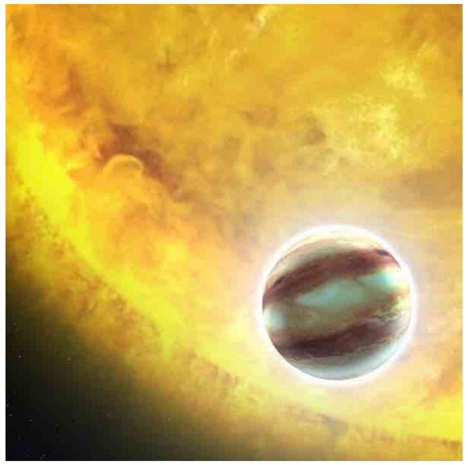




WASP-8, a hot Jupiter system

The radial-velocity (RV) amplitude is proportional to the planet's mass

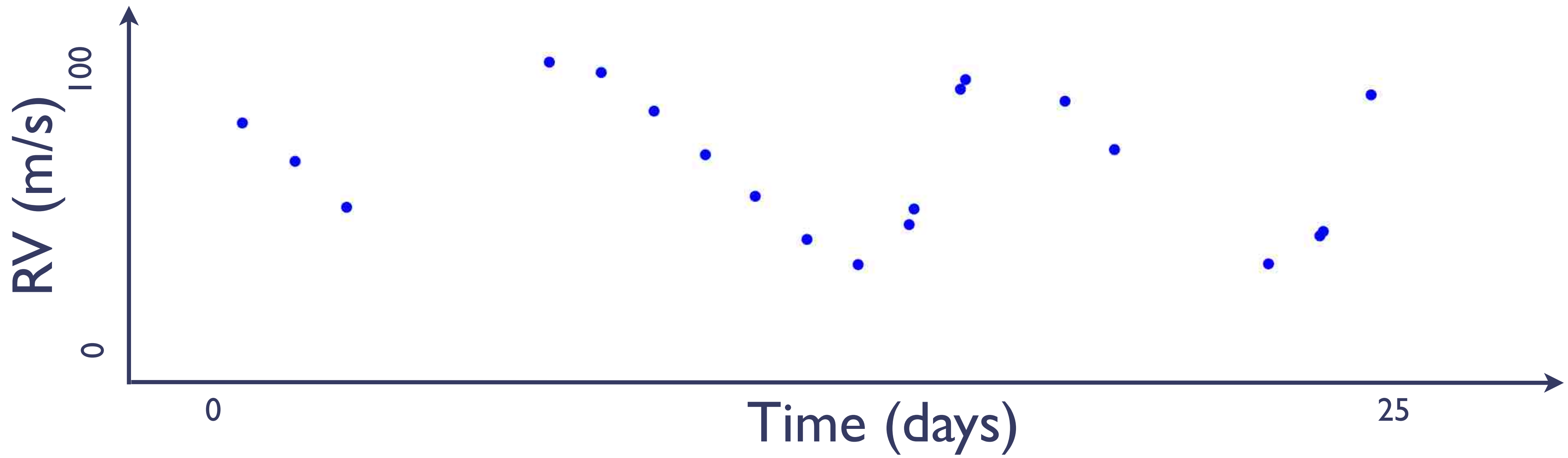


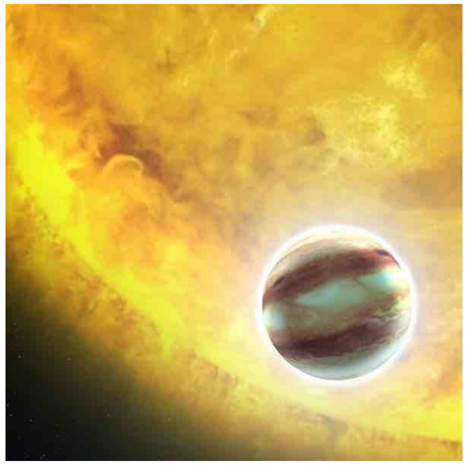


WASP-8, a hot Jupiter system

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

The radial-velocity (RV) amplitude is proportional to the planet's mass



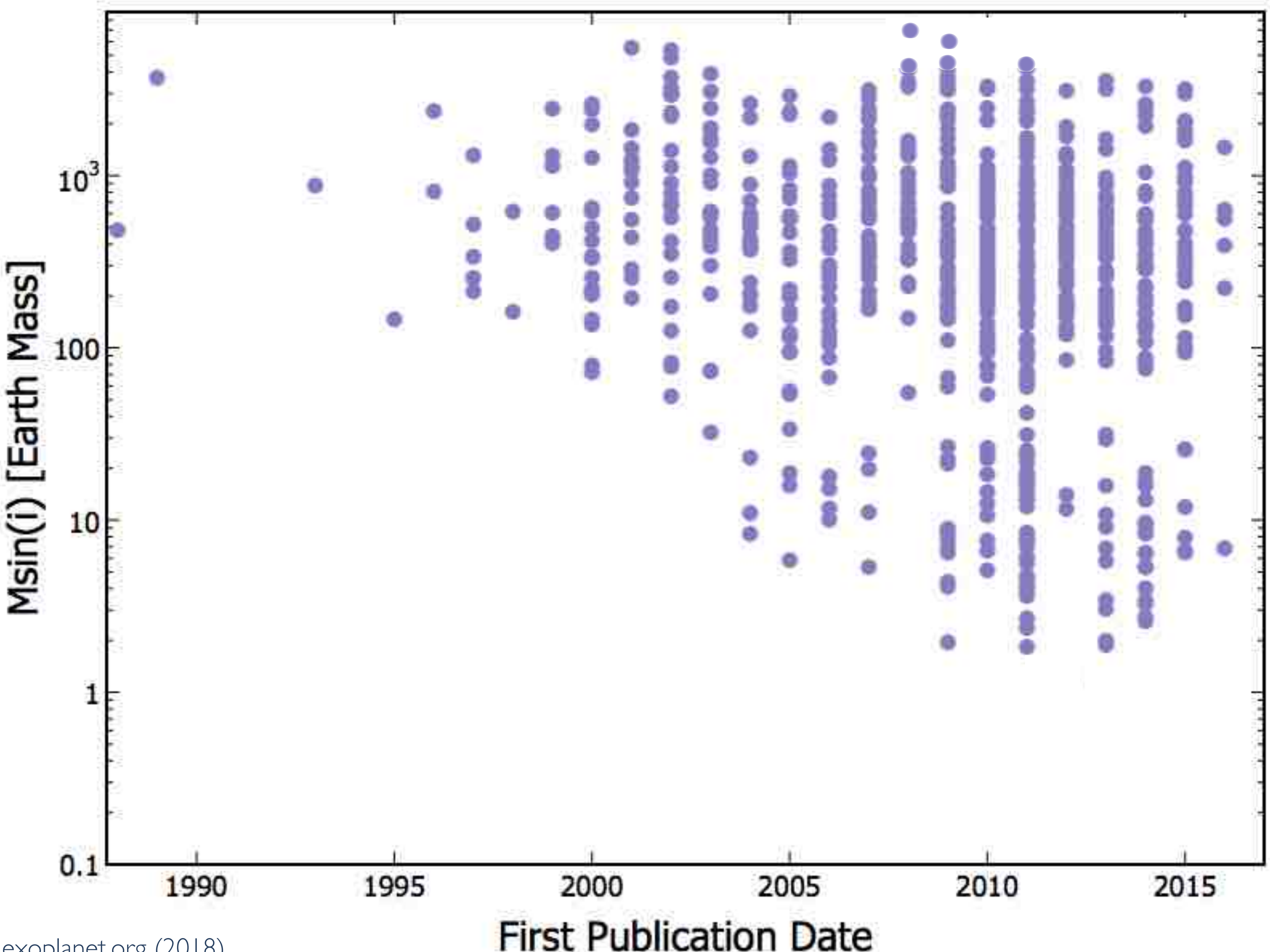


WASP-8, a hot Jupiter system

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

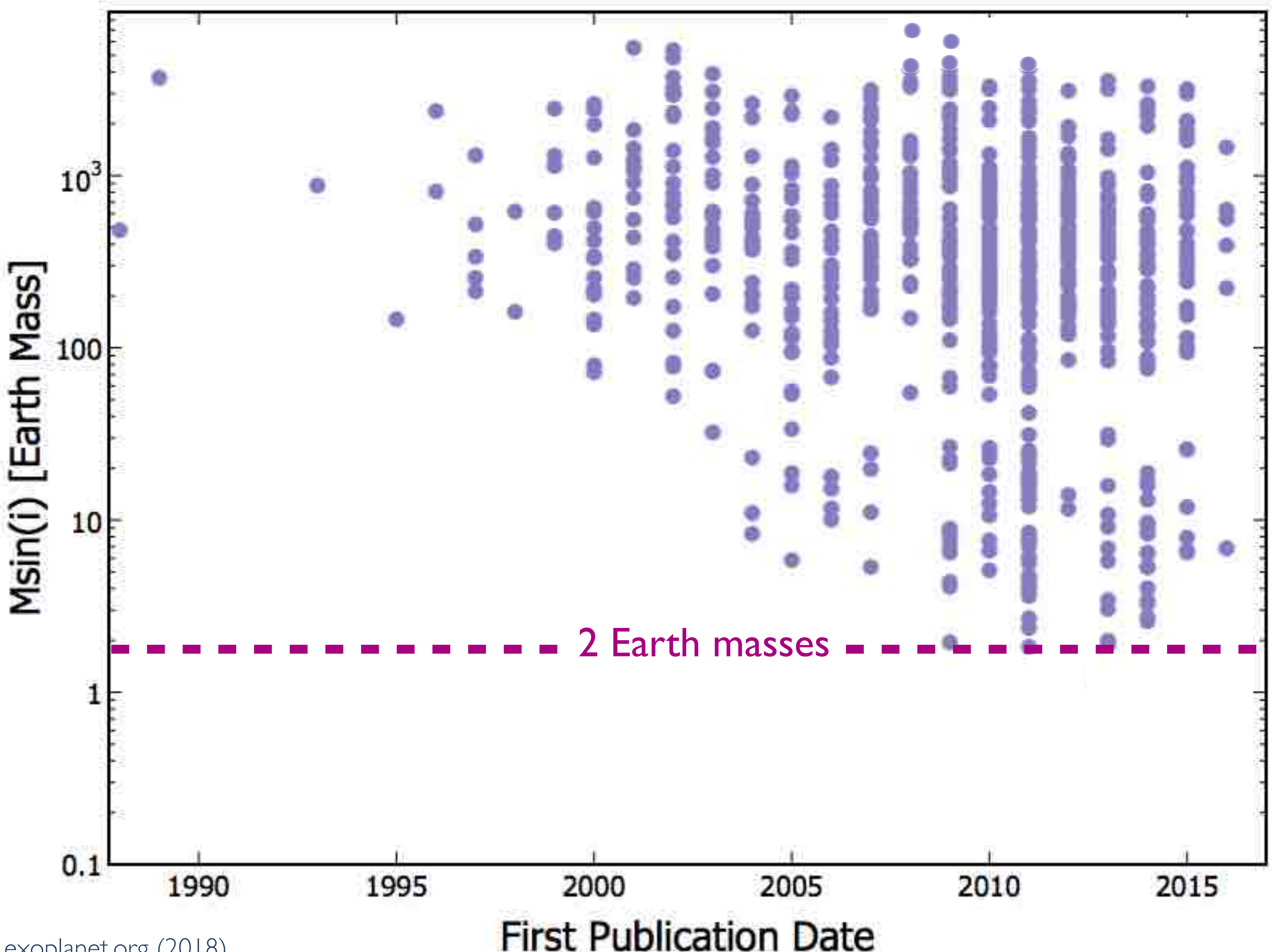
Earth orbit around Sun: 0.09 m/s!

We cannot yet measure reliable masses of small, rocky planets



Plotted at exoplanet.org (2018)

We cannot yet measure reliable masses of small, rocky planets



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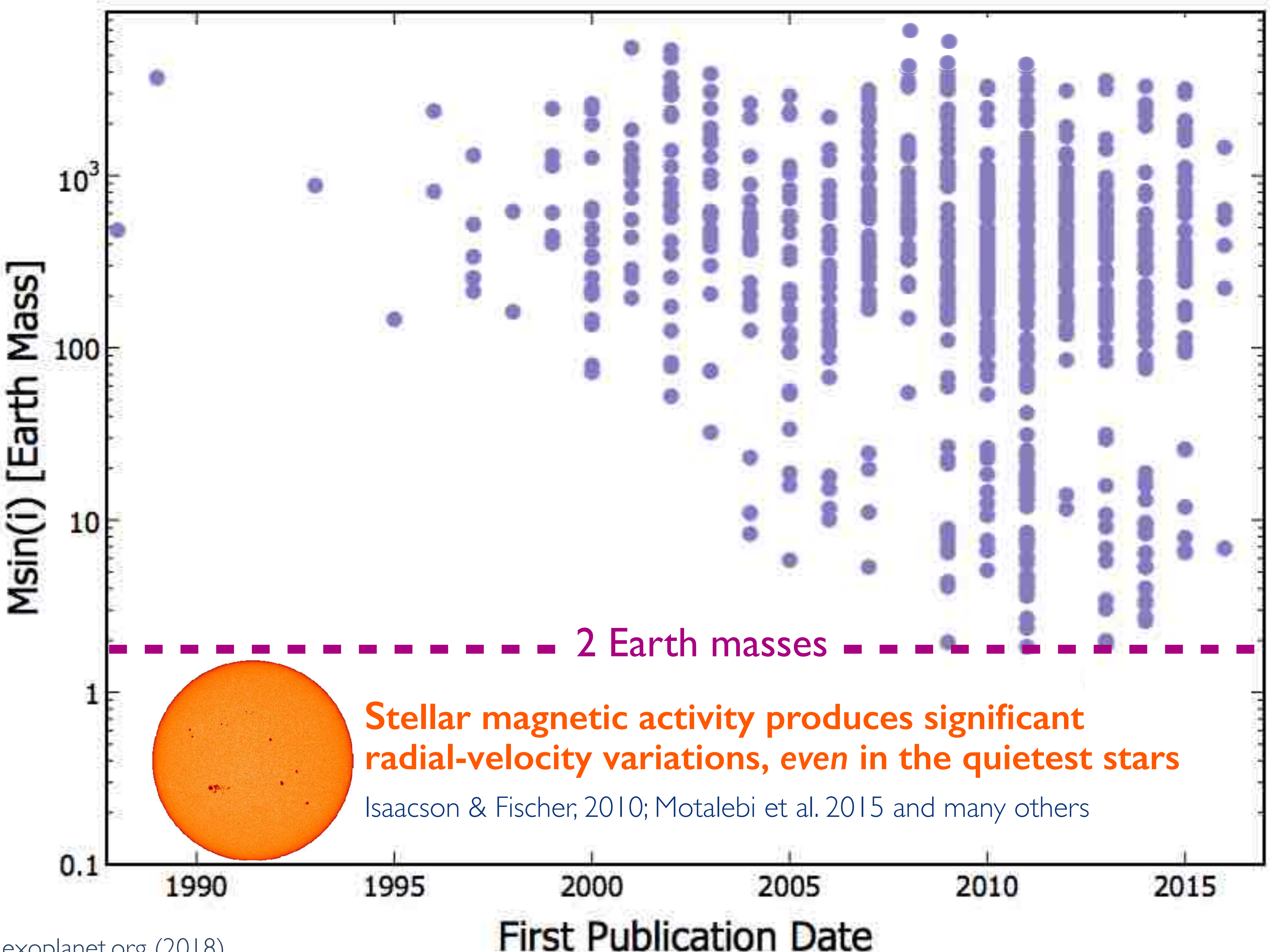
We cannot yet measure reliable masses of small, rocky planets



Plotted at exoplanet.org (2018)

To determine precise masses of small, rocky planets, we need to understand the physical processes at play on the surfaces of the host stars

See Fischer et al. (2016), Dumusque et al. (2017) and others

Timescales of stellar activity

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

Pressure-mode oscillations 5-10 min

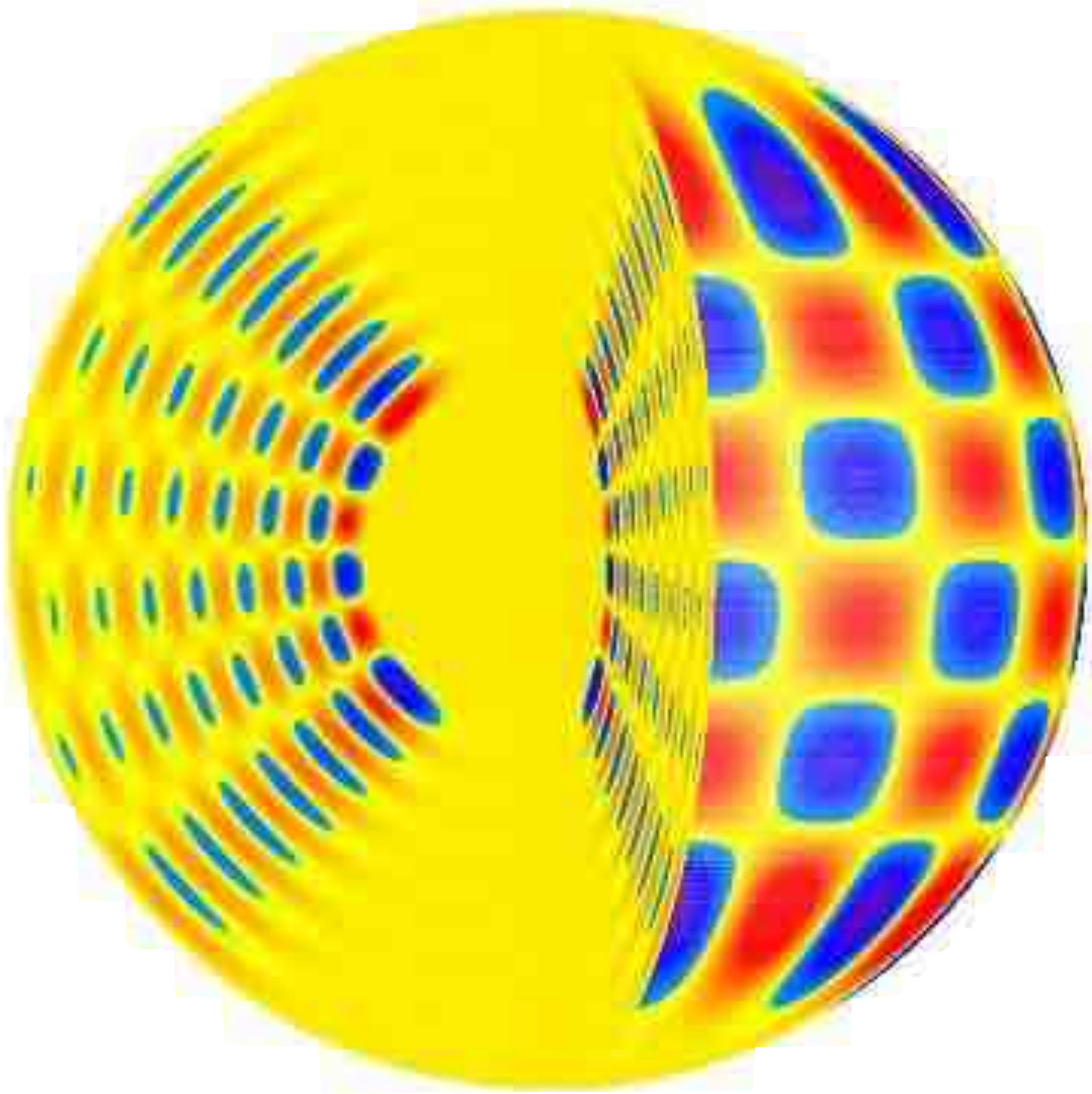
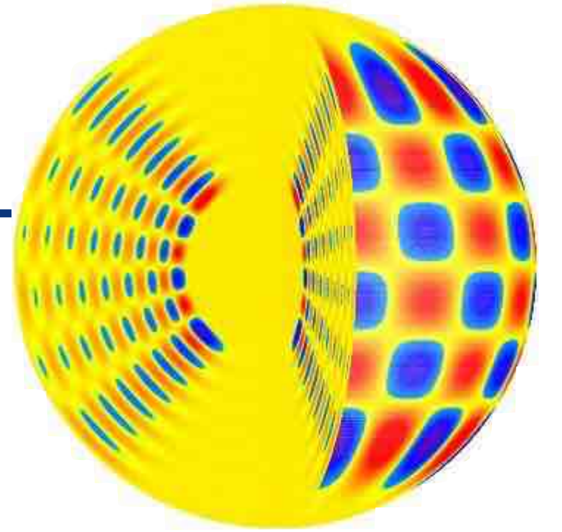
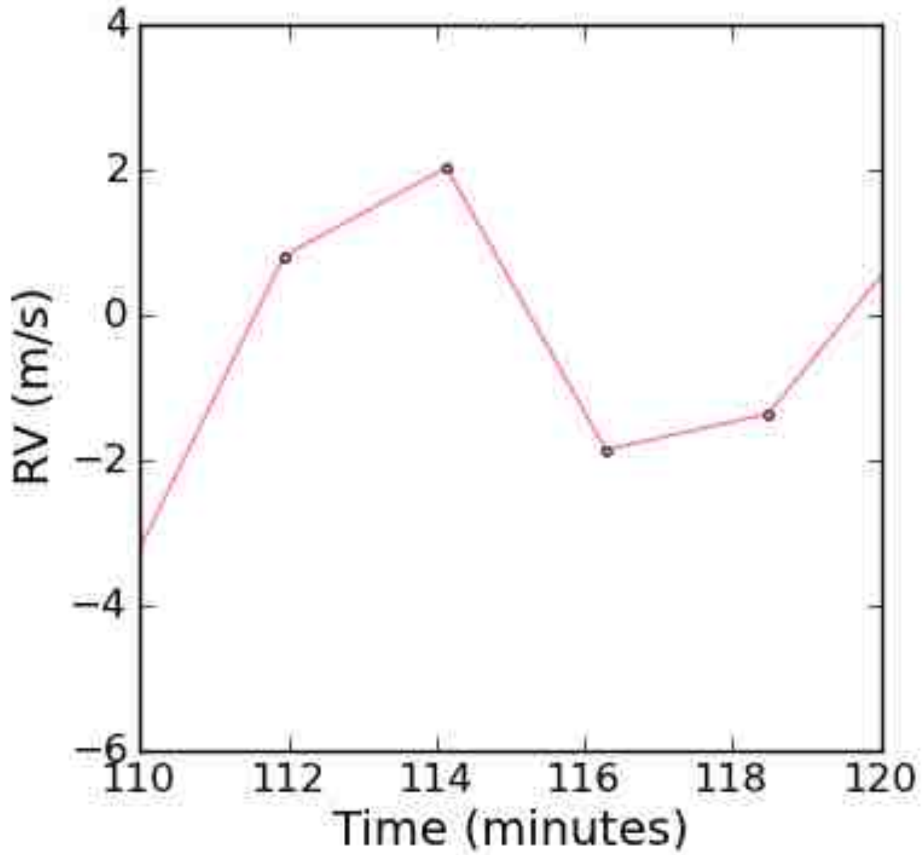


Image: Kiepenheuer Institute for Solar Physics

Pressure-mode oscillations

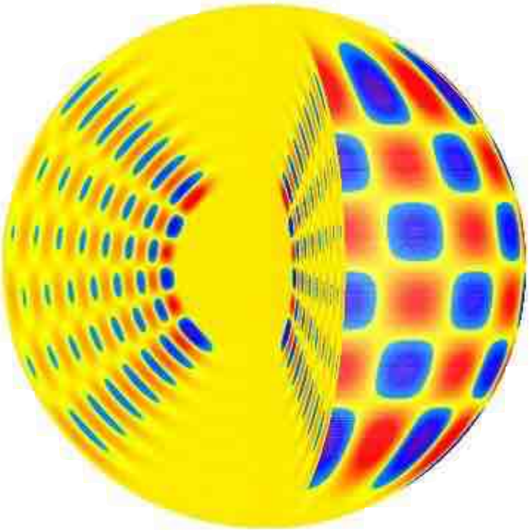


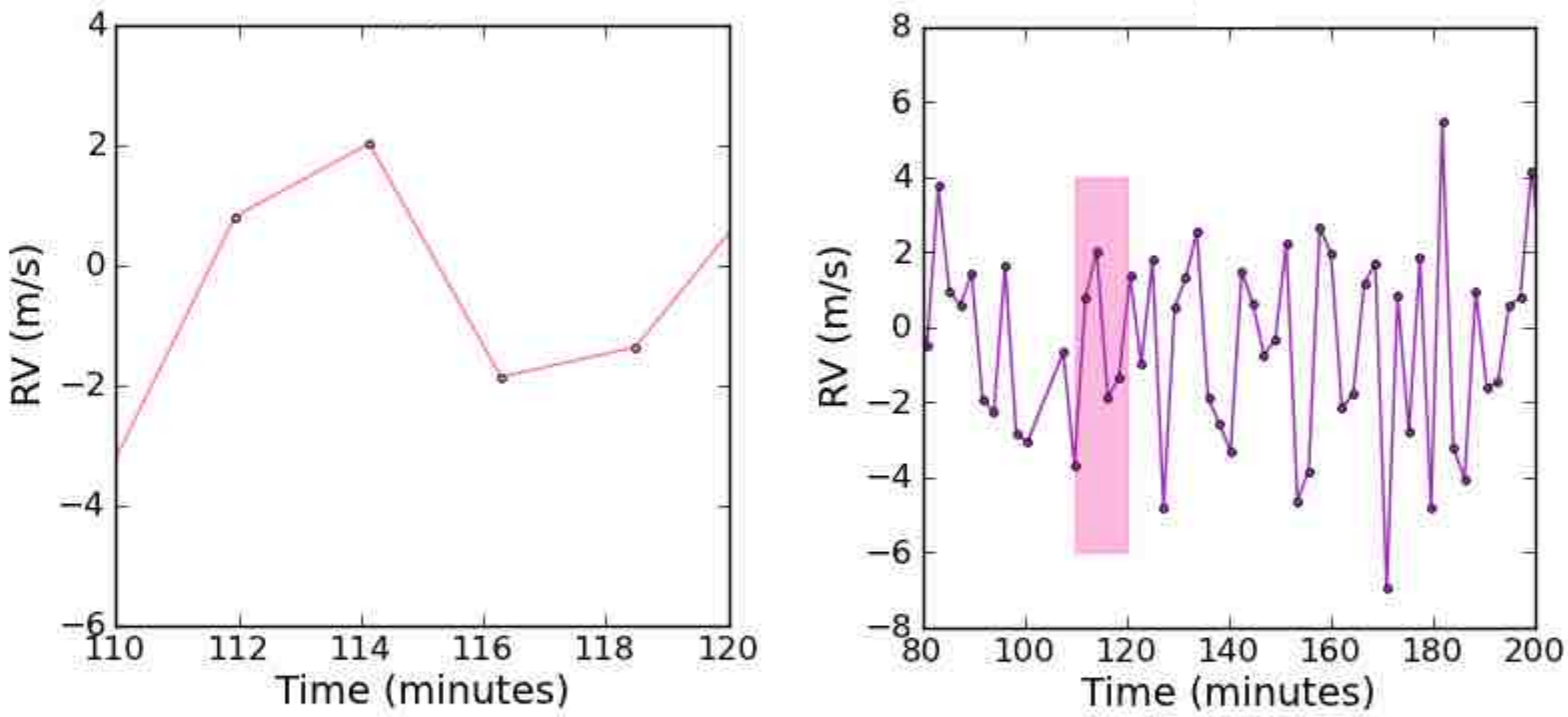


μ Arae, RV data from Bouchy et al. (2005)

Image: Kiepenheuer Institute for Solar Physics

Pressure-mode oscillations





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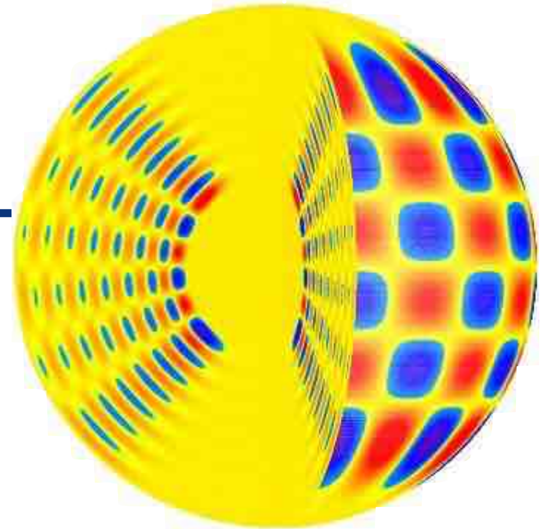
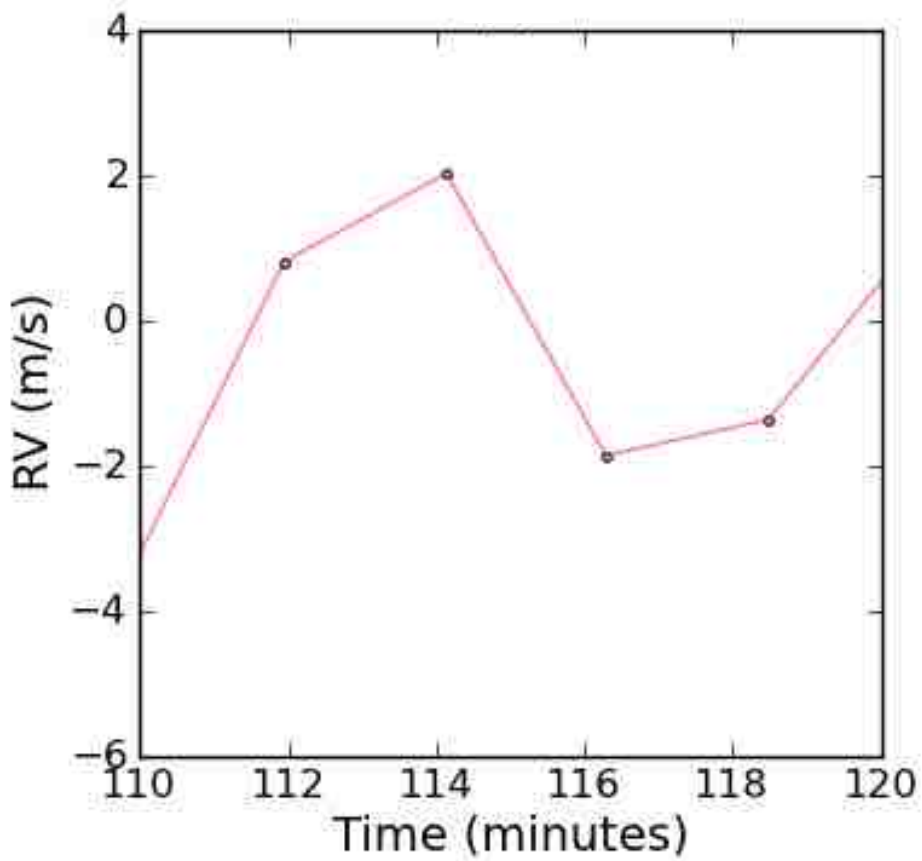
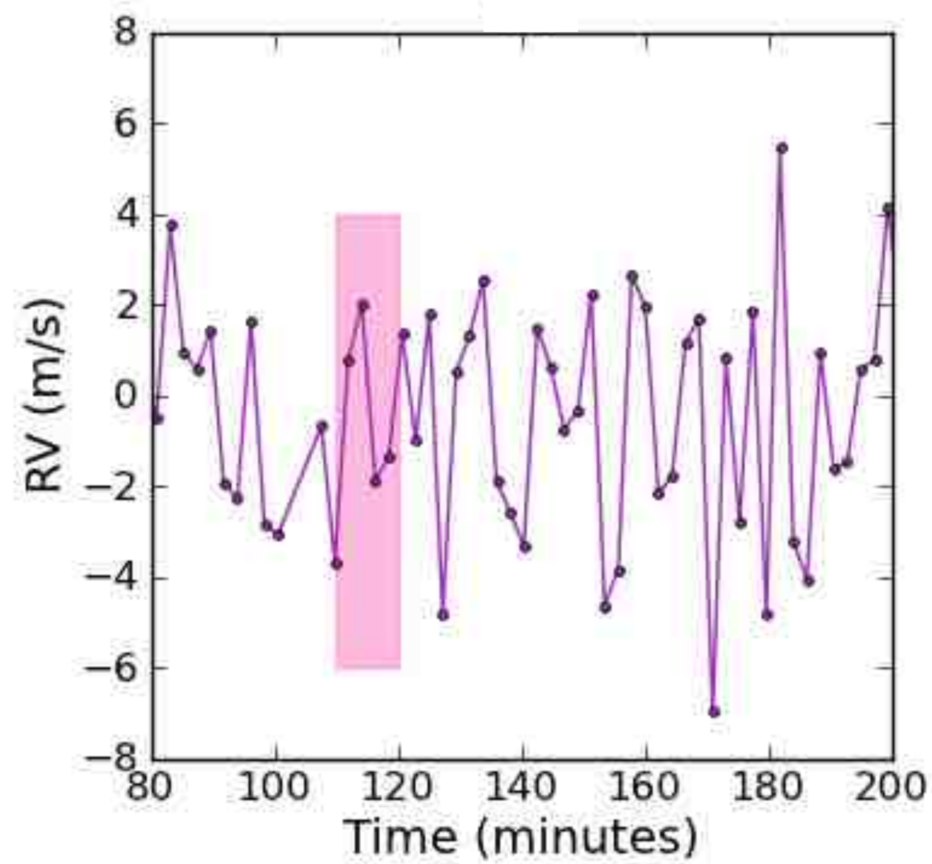
Pressure-mode oscillations



Stellar oscillations can be averaged out to < 10cm/s by choosing the right exposure time

Chaplin, Cegla et al. (2019)





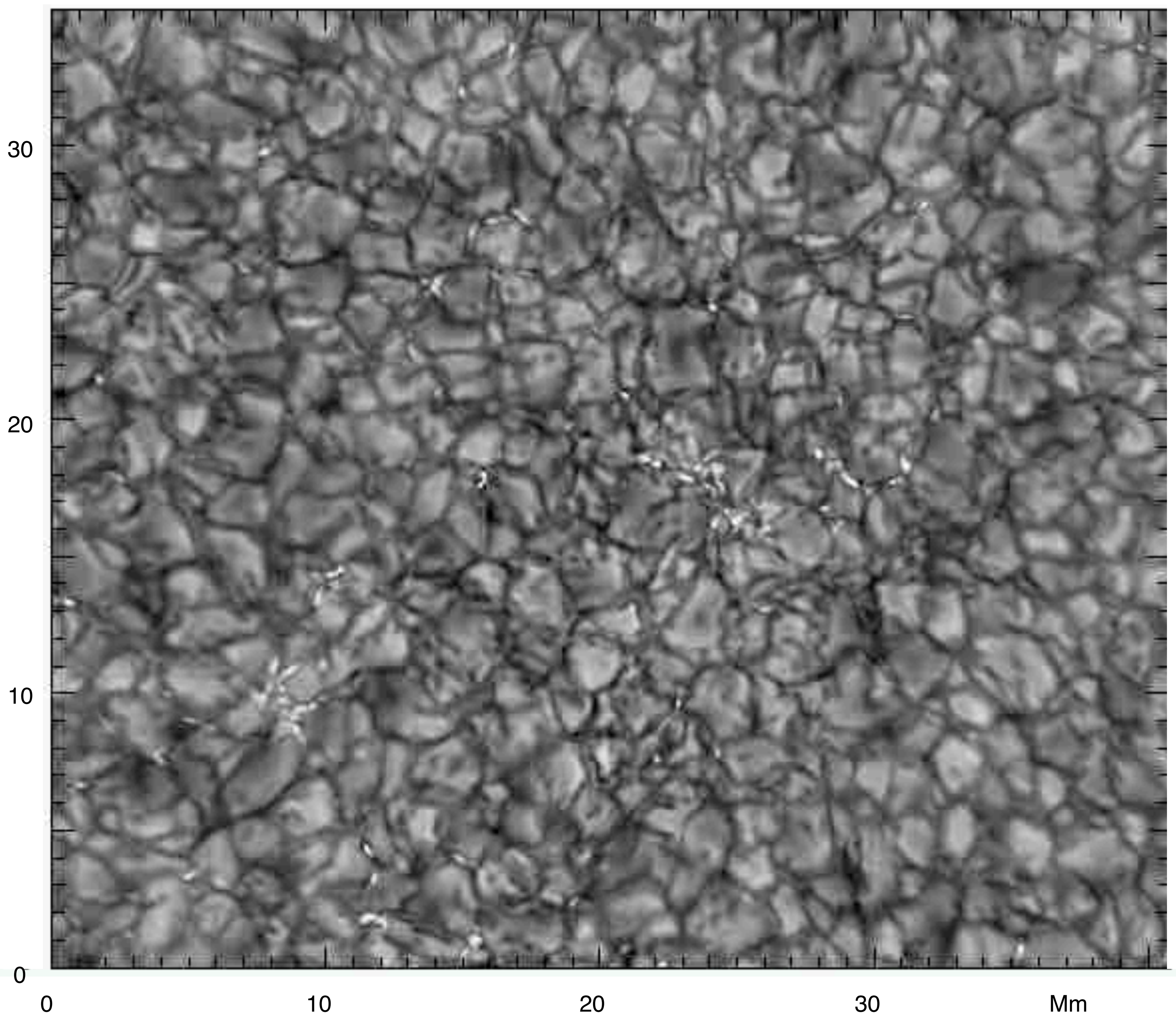
μ Arae, RV data from Bouchy et al. (2005)

Image: Kiepenheuer Institute for Solar Physics

Code: https://github.com/grd349/ChaplinFilter

See supplementary slides in this talk

Magnetoconvection (granulation, supergranulation)



On the Sun:

- granulation: 0.8 m/s
- supergranulation: up to 1.1 m/s

Meunier et al. (2015)

Figure: H. Cegla, Dunn Solar Telescope

Meunier et al. (2015); Dumusque et al. (2011)

Magnetoconvection (granulation, supergranulation)

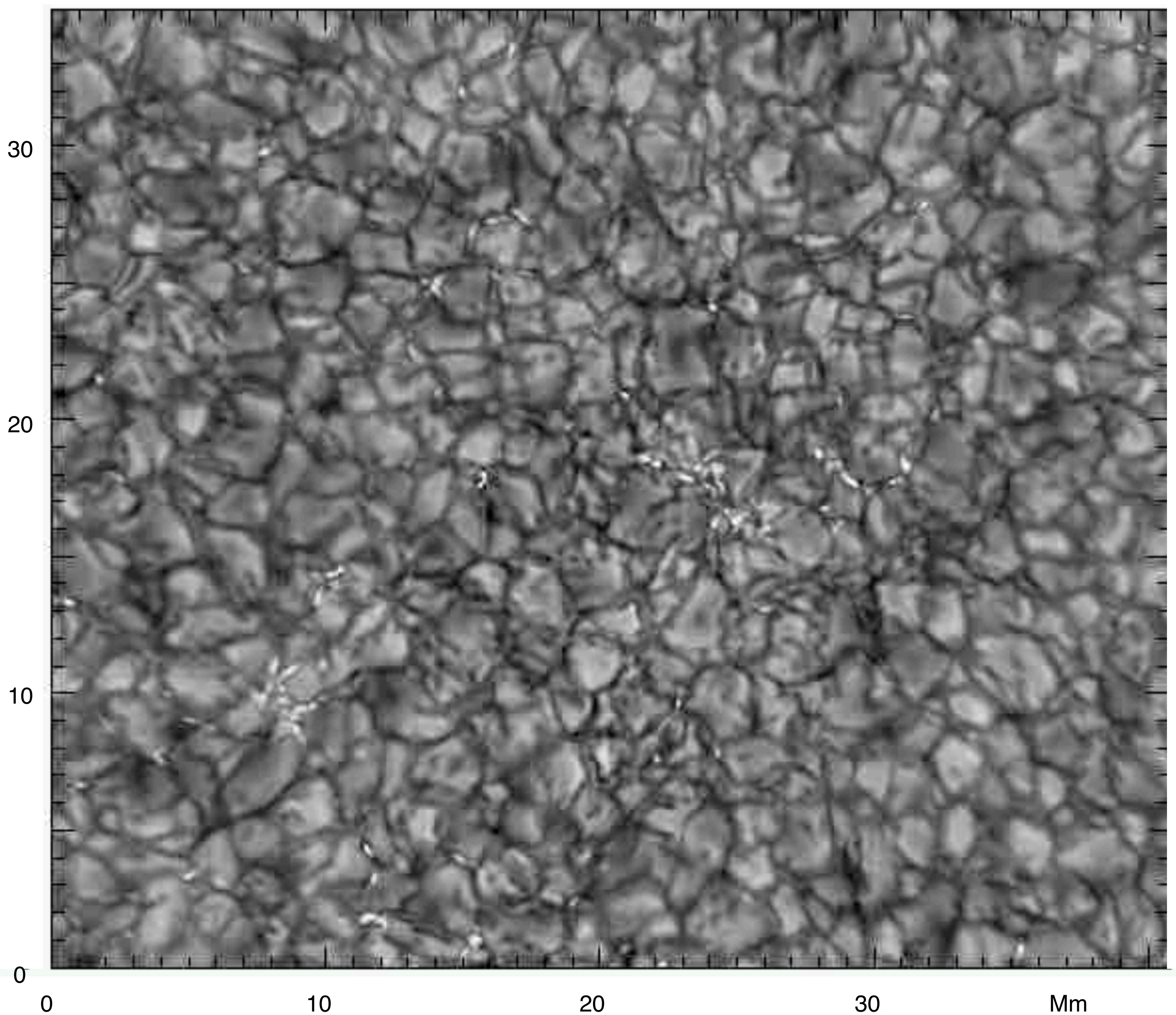


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Figure: H. Cegla, Dunn Solar Telescope

Meunier et al. (2015); Dumusque et al. (2011)

Magnetoconvection (granulation, supergranulation)

"Averaging out" with multiple exposures/night will not get you <≈ 0.5 m/s

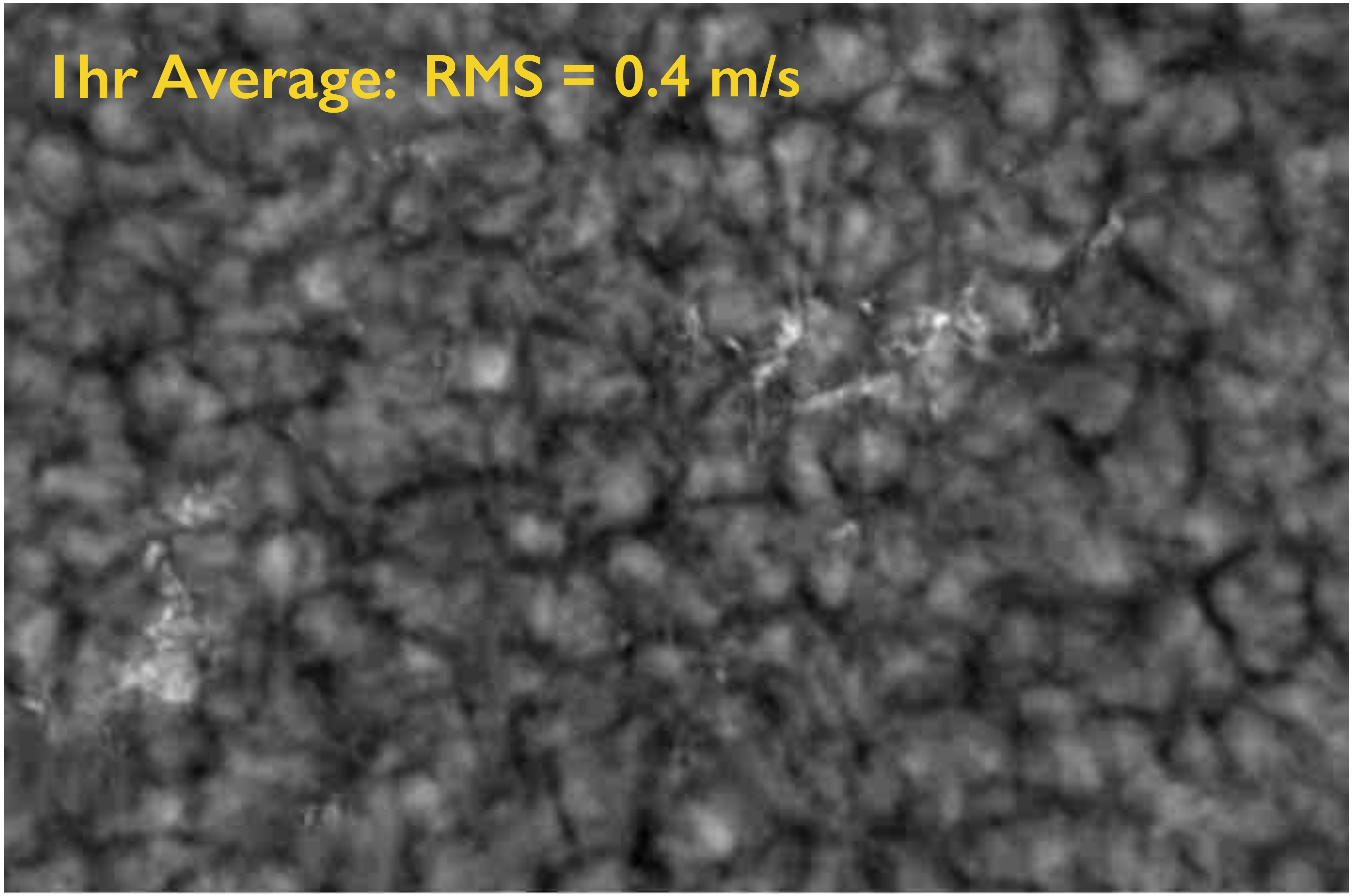


Figure: H. Cegla, Dunn Solar Telescope (G-band)

Meunier et al. (2015)

Magnetoconvection (granulation, supergranulation)

"Averaging out" with multiple exposures/night will not get you <≈ 0.5 m/s

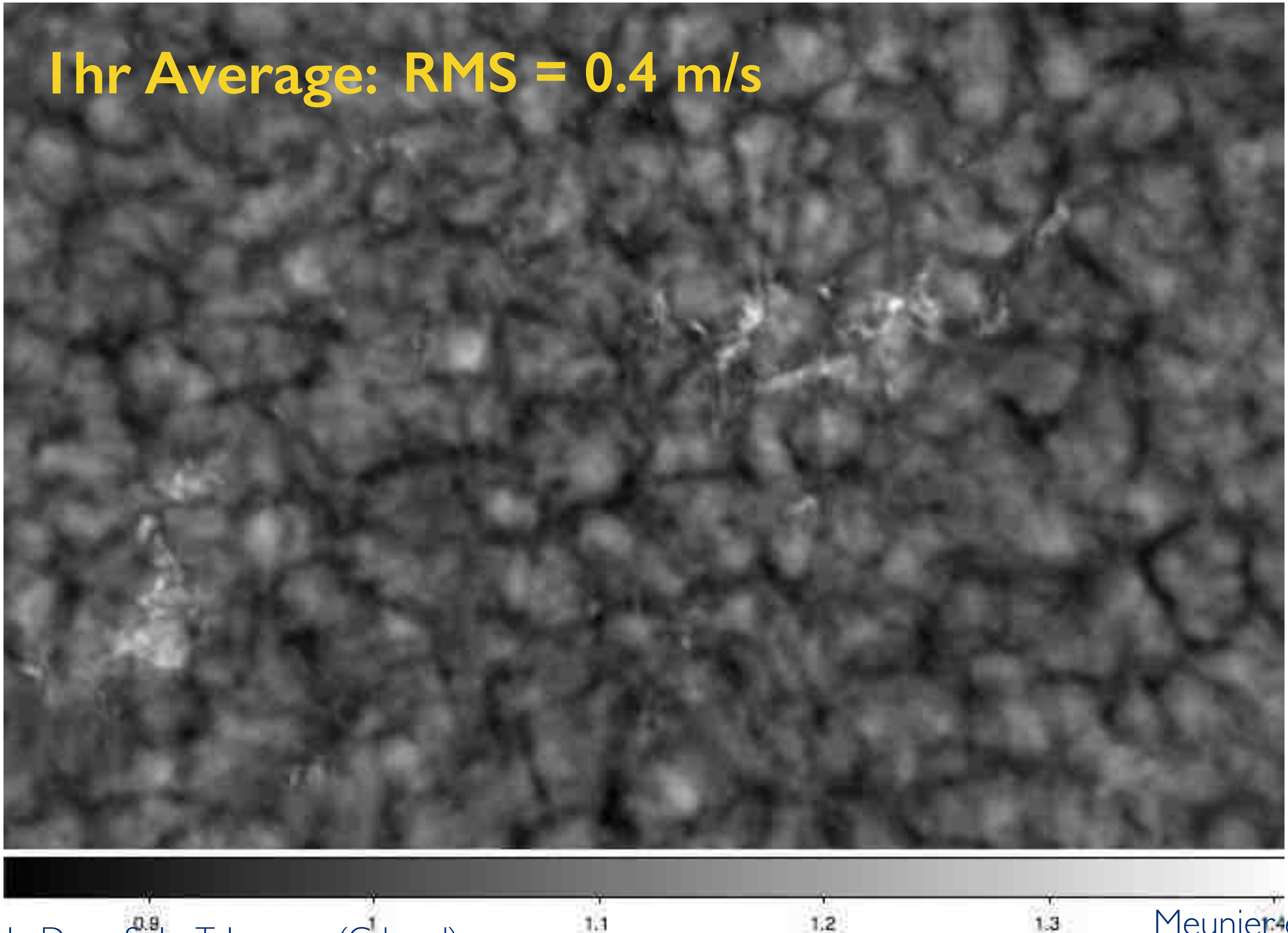
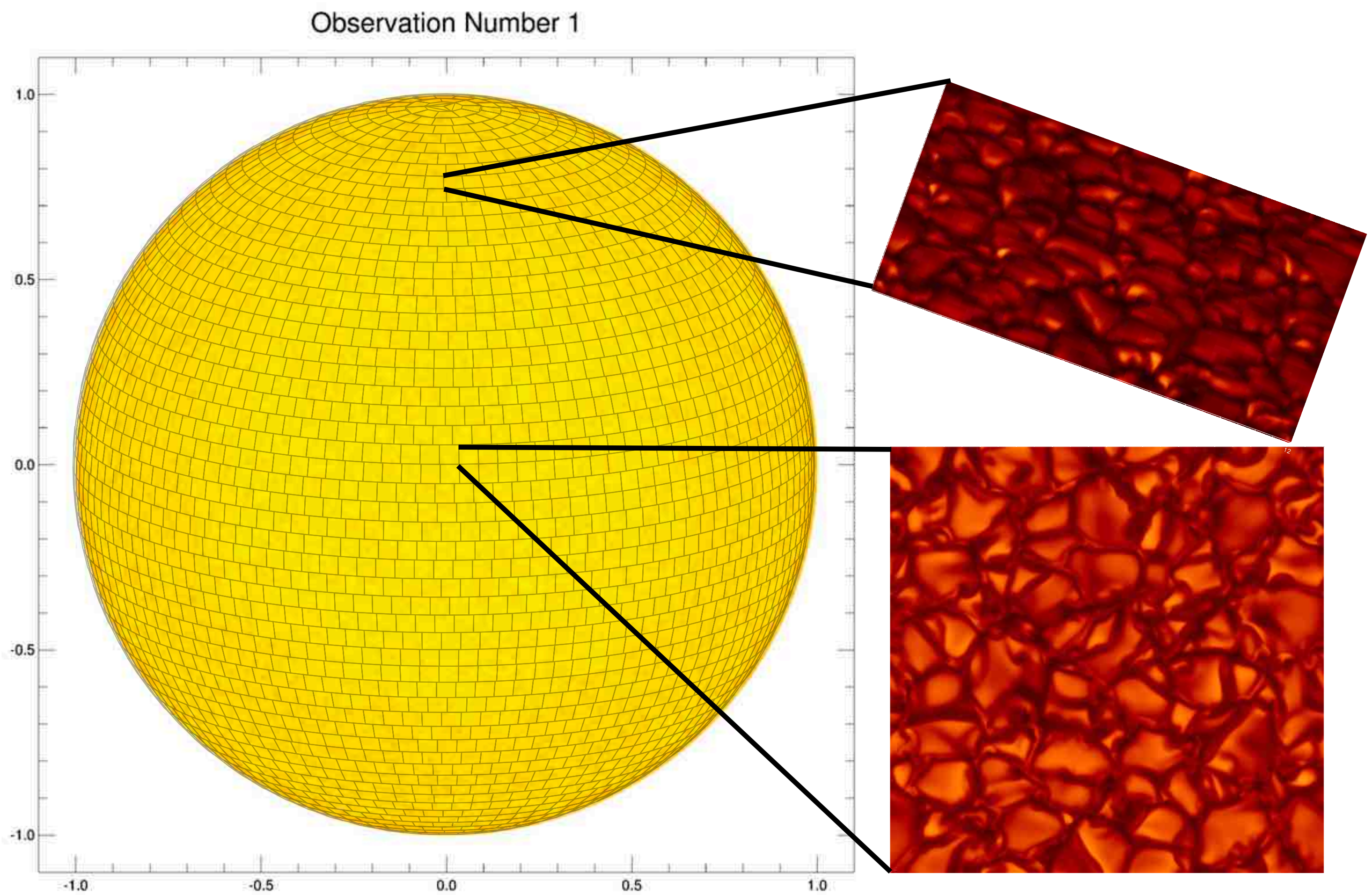


Figure: H. Cegla, Dunn Solar Telescope (G-band)

Meunier et al. (2015)

Using 3D magneto-hydrodynamical (MHD) simulations

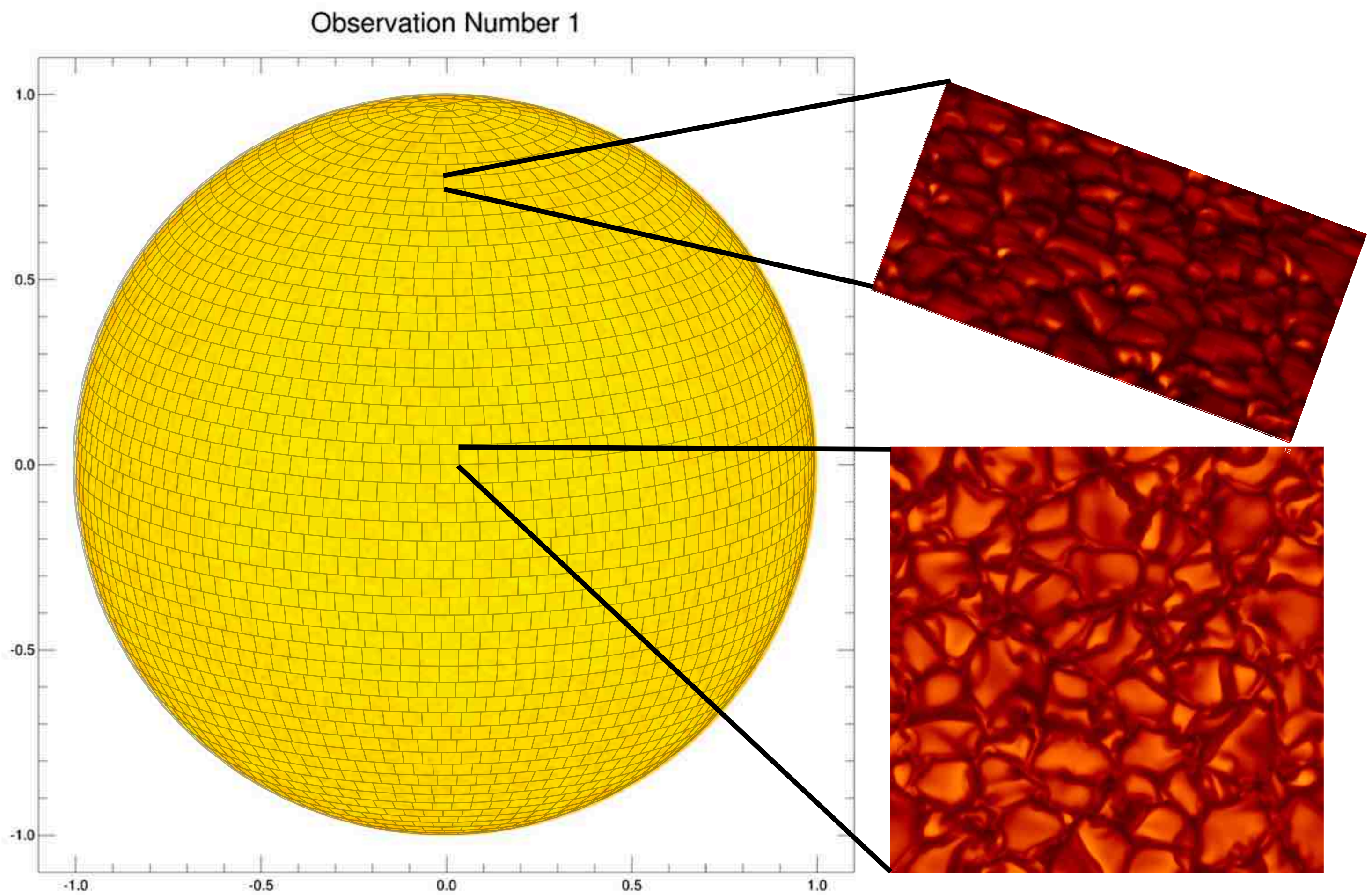


- Understand the effect of granulation on the shapes of spectral lines
- Identify proxies that will allow us to fit and subtract granulation RV signal

Figure: H. Cegla

Cegla et al. (2013, 2018, 2019)

Using 3D magneto-hydrodynamical (MHD) simulations



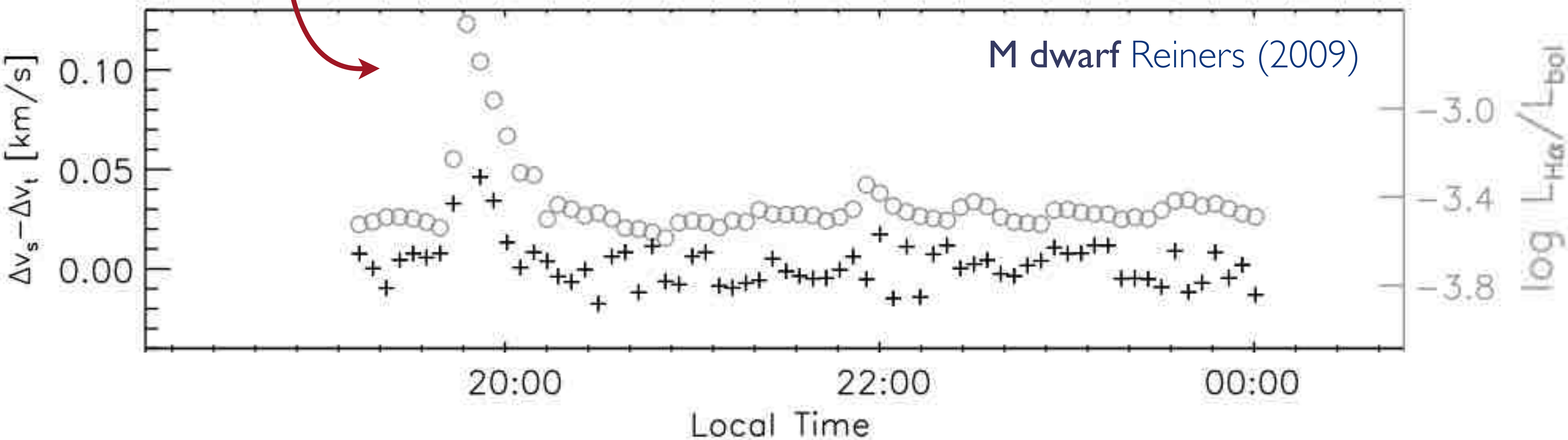
- Understand the effect of granulation on the shapes of spectral lines
- Identify proxies that will allow us to fit and subtract granulation RV signal

Figure: H. Cegla

Cegla et al. (2013, 2018, 2019)

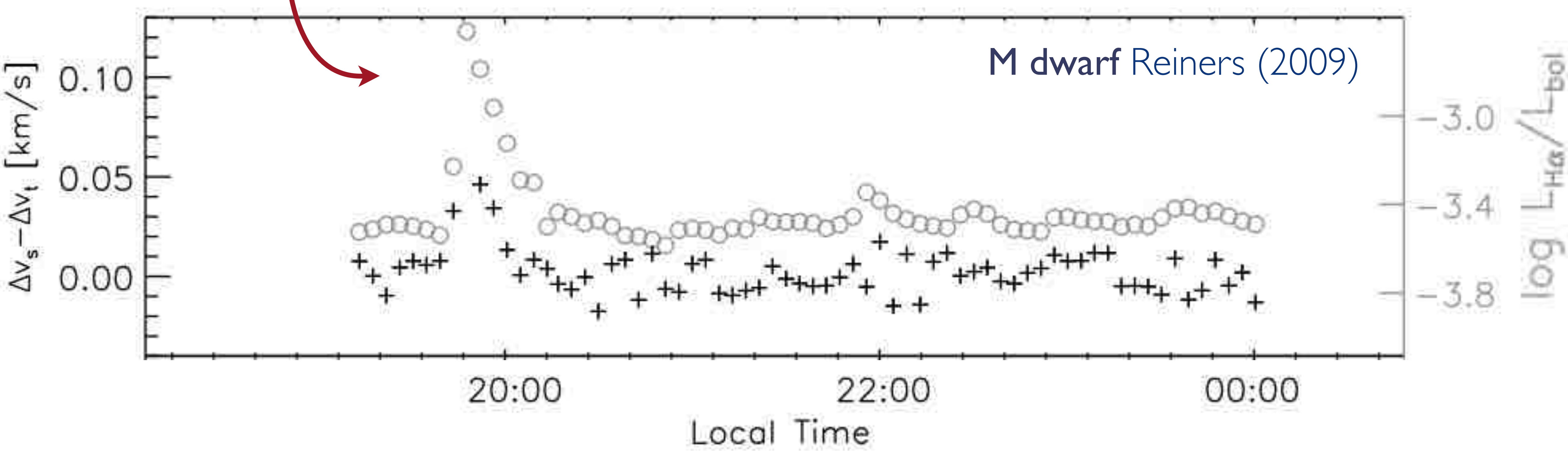
Minutes to hours: flares

Few min: flares/coronal mass ejections



Minutes to hours: flares

Few min: flares/coronal mass ejections



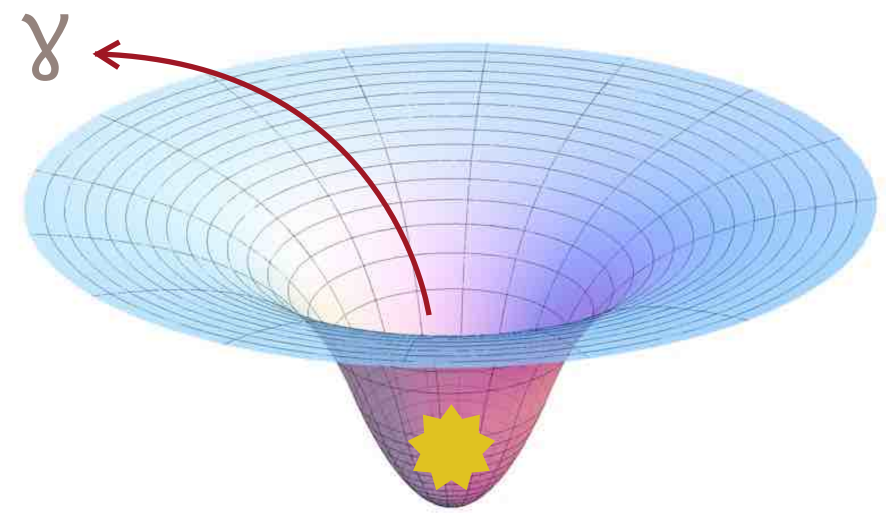
Rare events in Sun-like stars

Strong signatures in Hα emission profile

But very frequent in some M dwarfs!

Reiners (2009), see also Anglada-Escudé et al., (2016) and others

Gravitational redshift



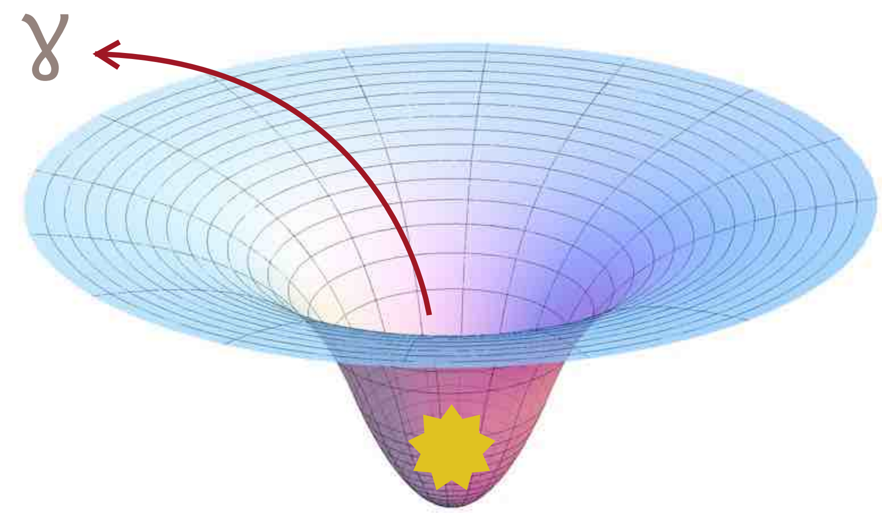
Change in stellar radius 0.01% can induce RV shift of 0.06 m/sec

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

Cegla et al. (2012)

Days

Gravitational redshift



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

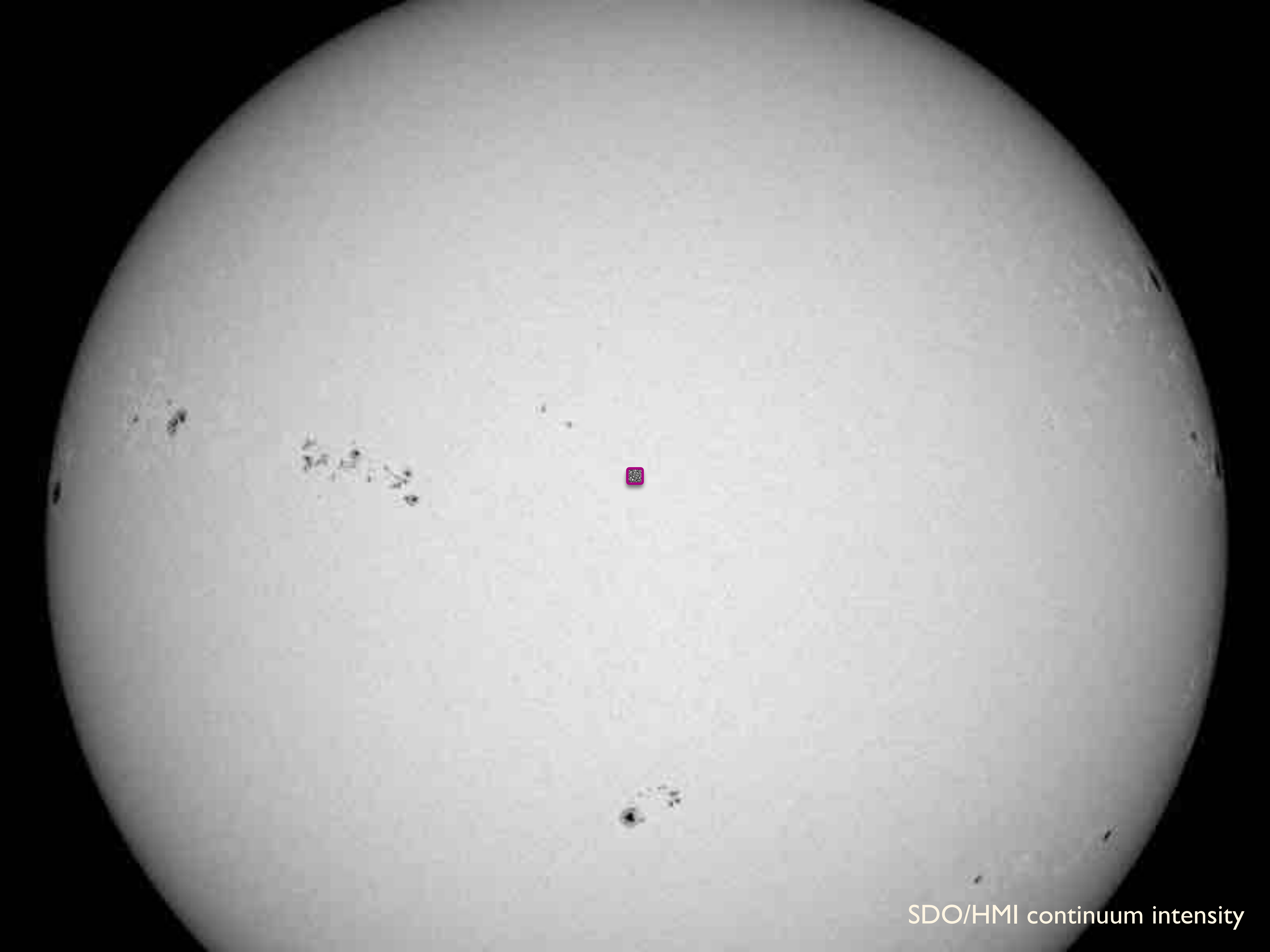
Slow changes, eg. from granulation or Wilson depression can have such effect

Cegla et al. (2012)

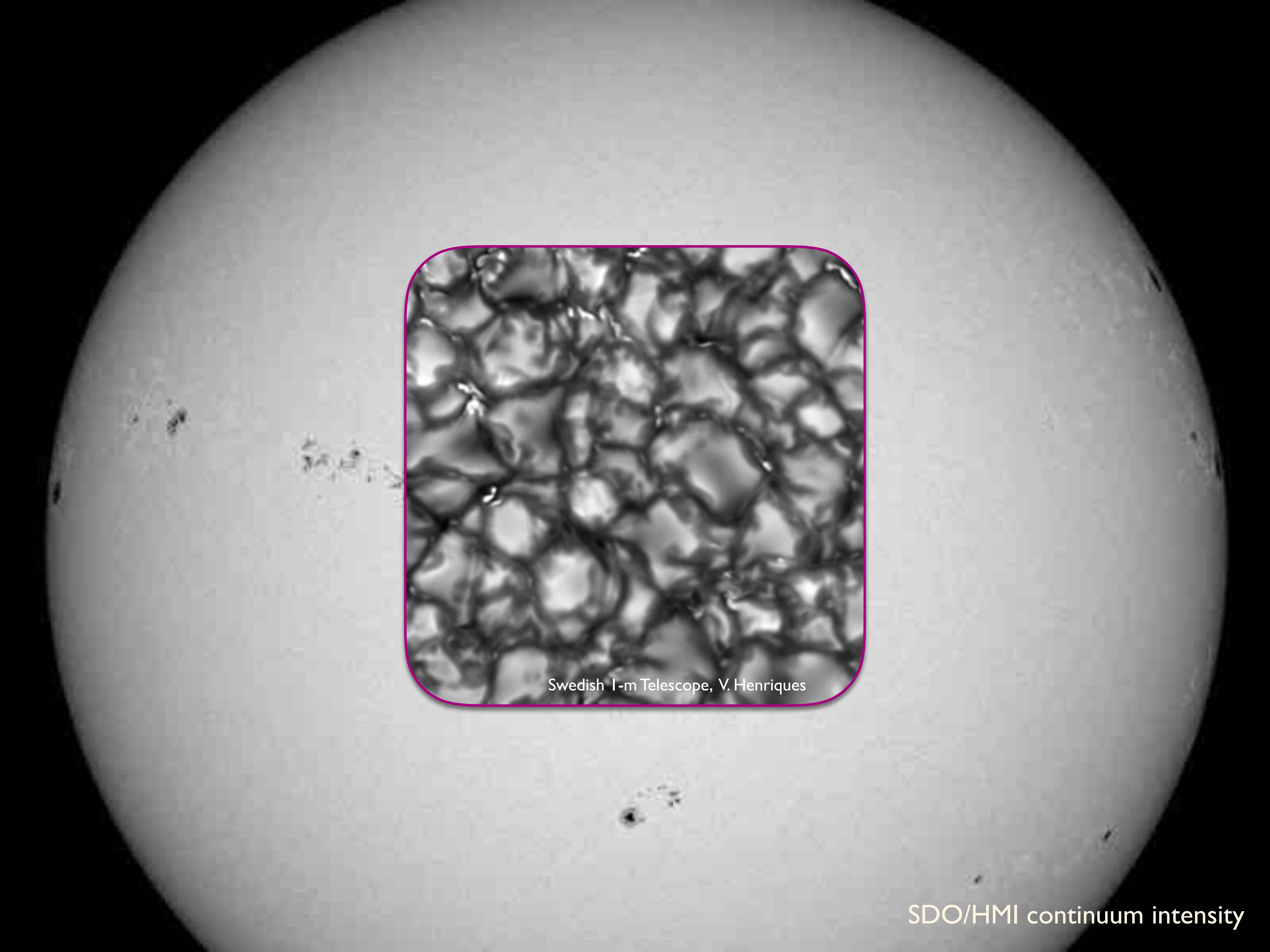
Not currently the main problem in RV surveys
Will become an issue as we get to Earth-like planets

Cegla et al. (2012)

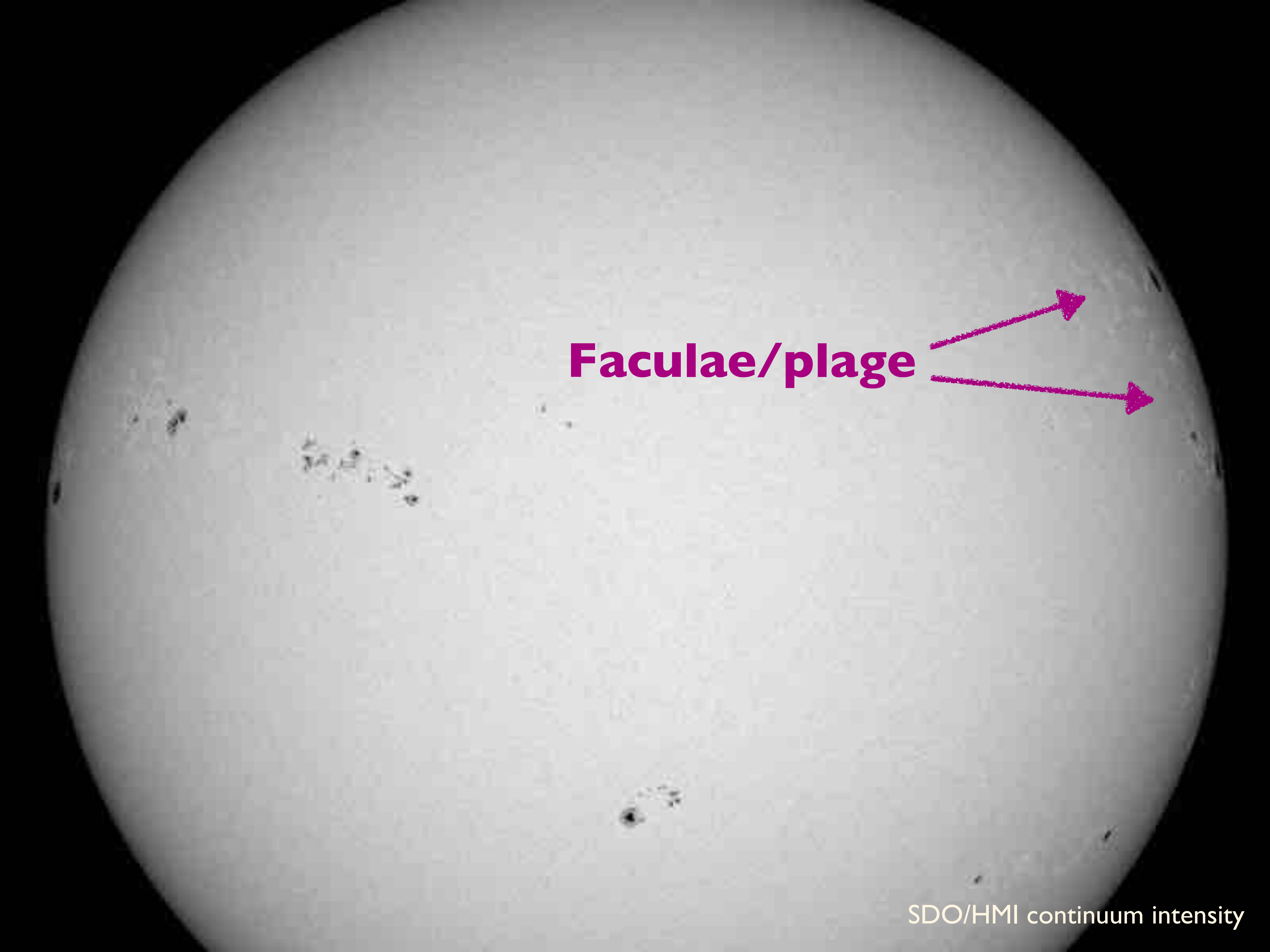
Stellar rotation period (15-40 days in Sun-like stars)

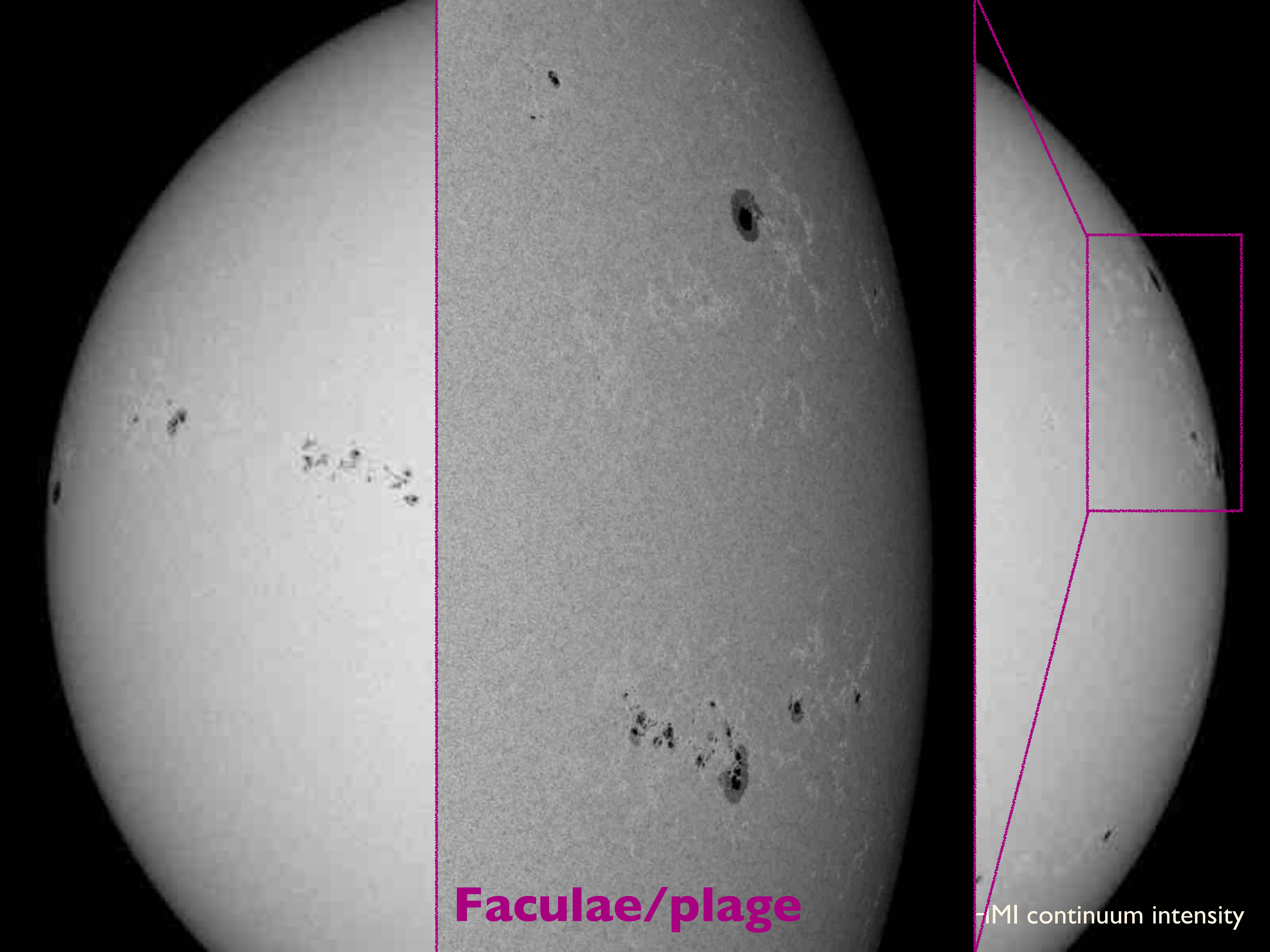


SDO/HMI continuum intensity


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


Sunspots
SDO/HMI continuum intensity

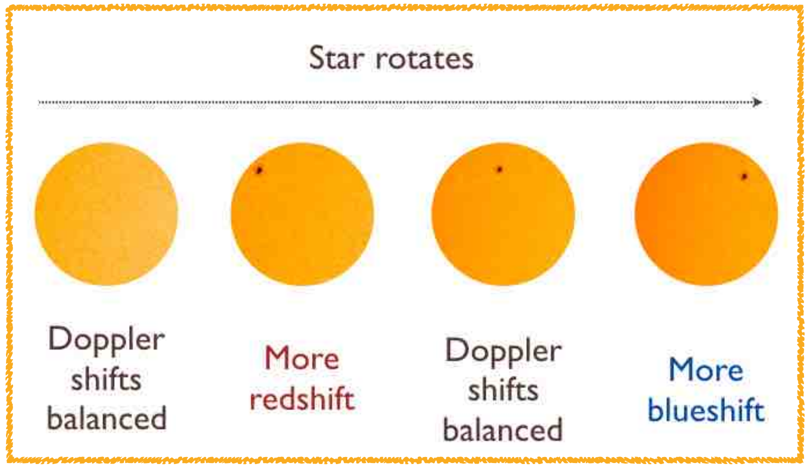

Faculae/plage
SDO/HMI continuum intensity


Faculae/plage
HMI continuum intensity

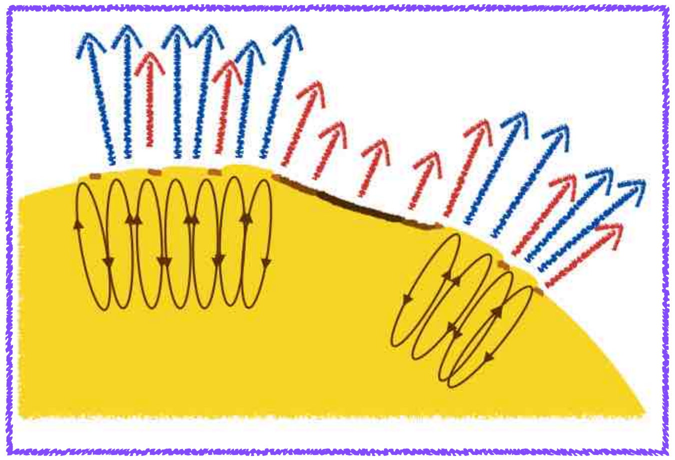
Stellar rotation period (15-40 days in Sun-like stars)

$$\Delta RV_{activity} = \Delta RV_{rot} + \Delta RV_{conv} + \Delta RV_{other?}$$

Rotational imbalance due to brightness inhomogeneities

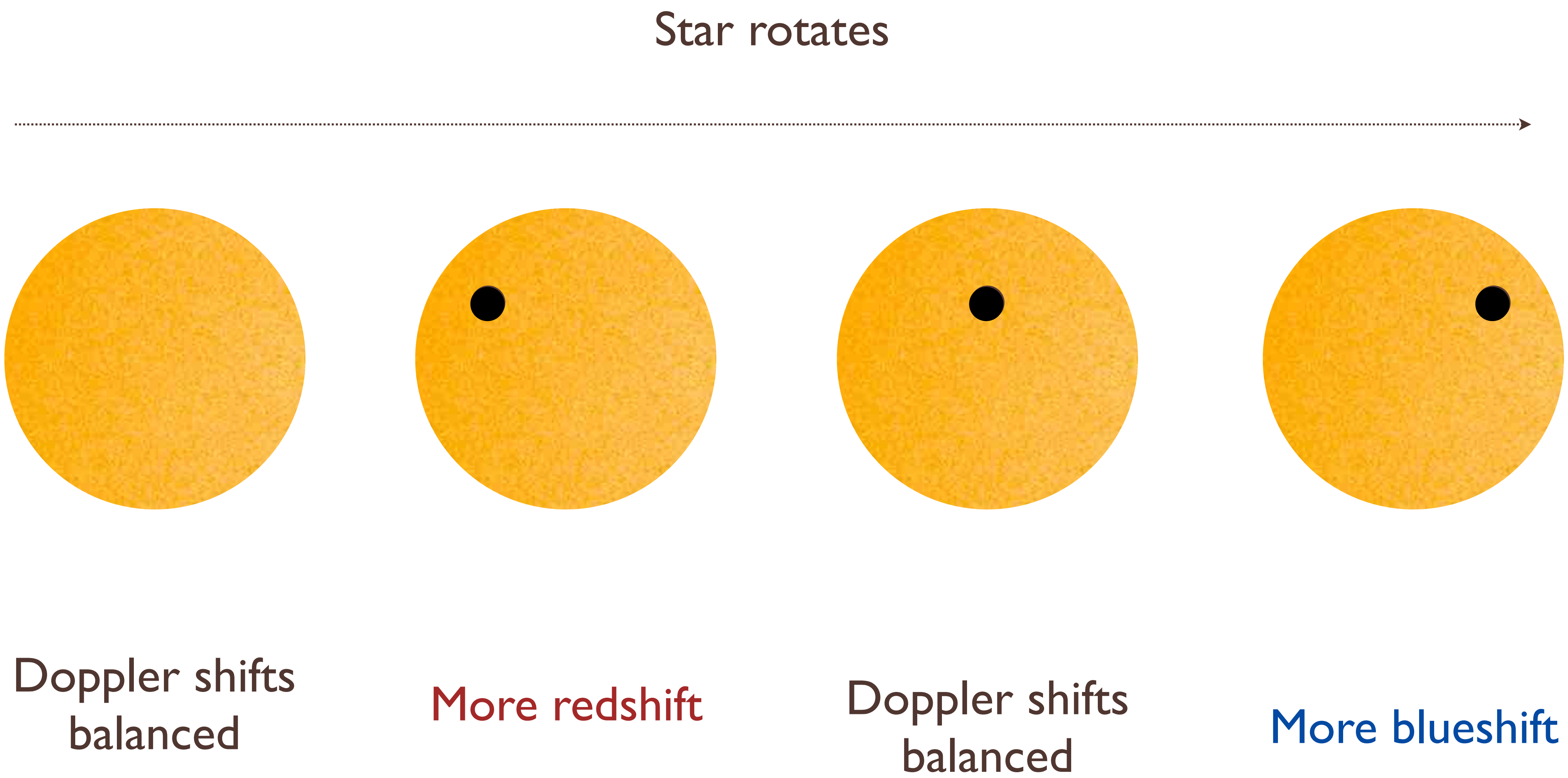


Suppression of convective blueshift



ΔRV_{rot}: Rotational imbalance due to brightness inhomogeneities

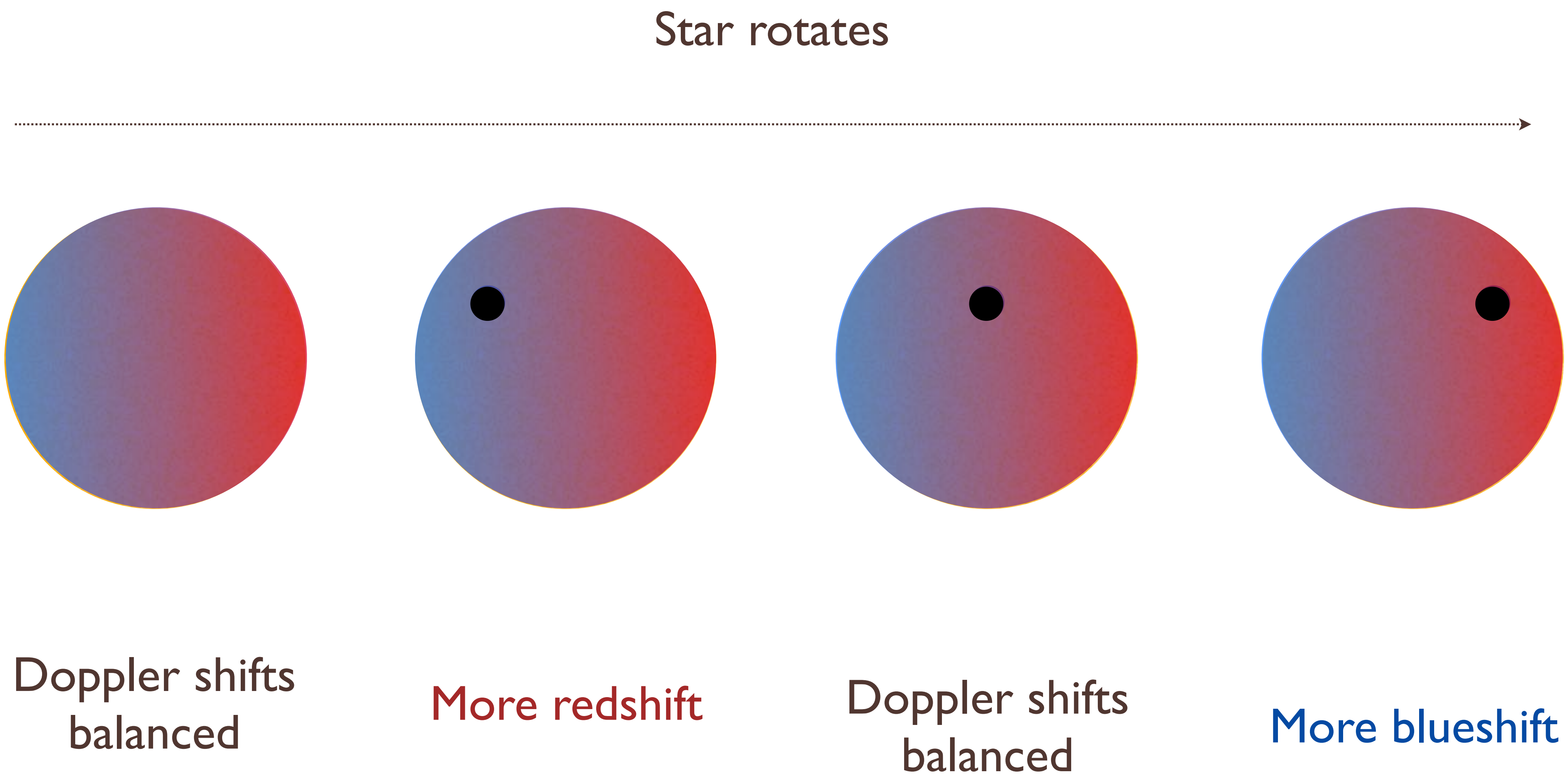
RMS: 0.1-0.5 m/s



Lagrange et al. (2010)
Meunier et al. (2010a,b)

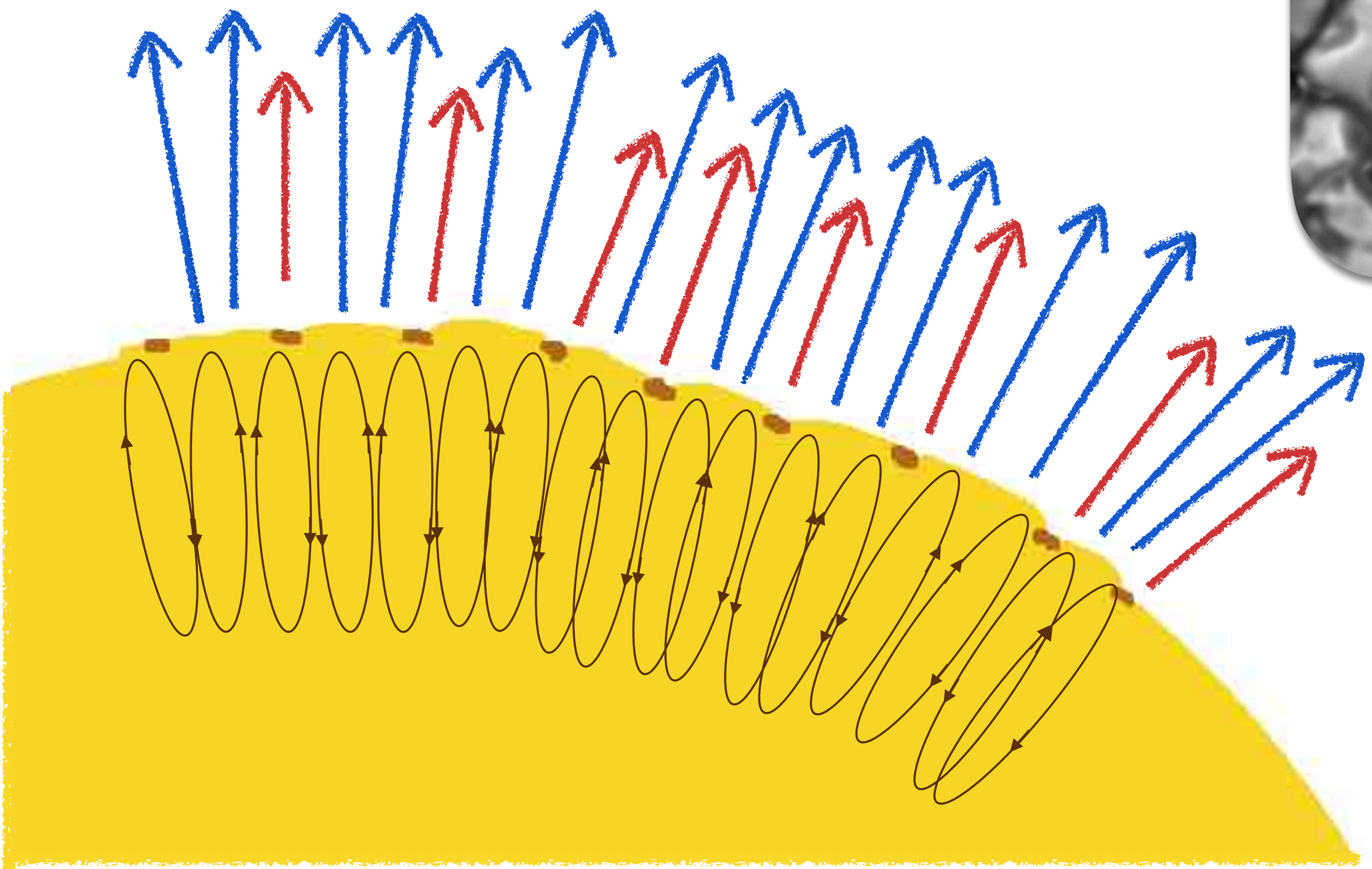
ΔRV_{rot}: Rotational imbalance due to brightness inhomogeneities

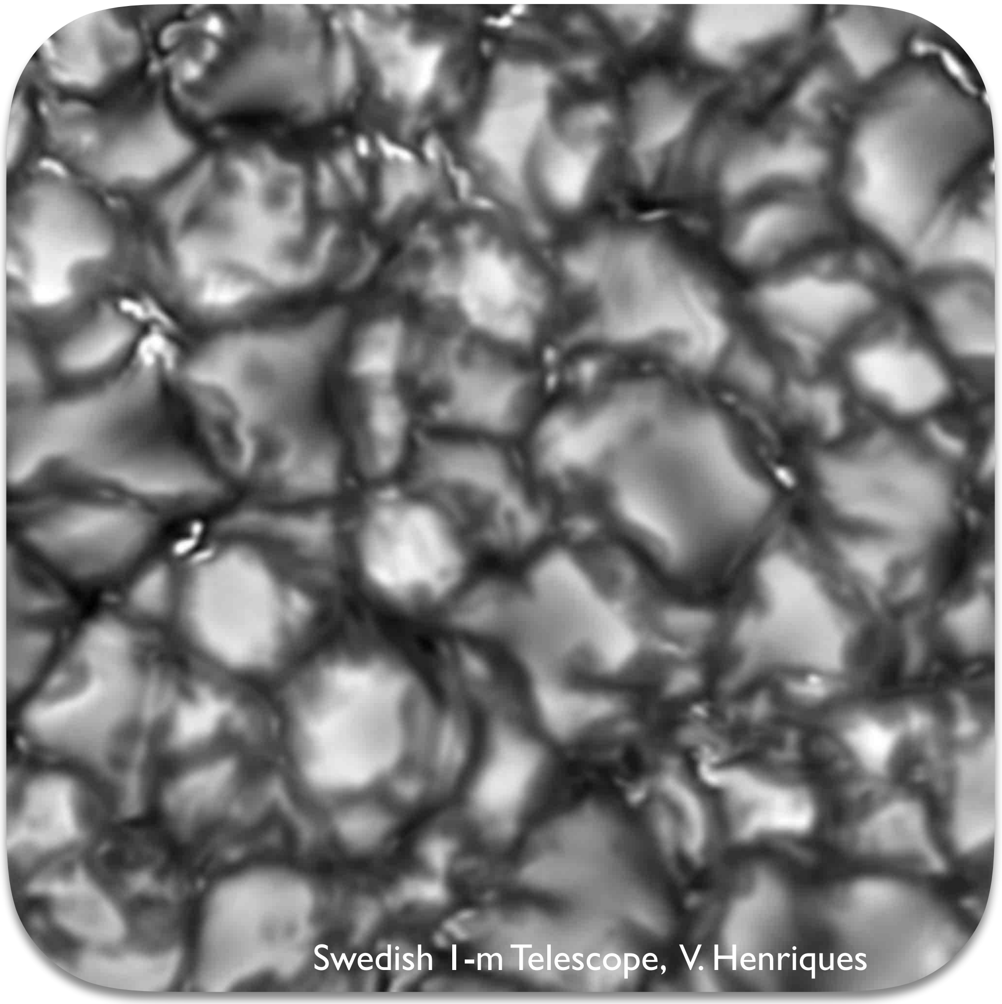
RMS: 0.1-0.5 m/s



Lagrange et al. (2010)
Meunier et al. (2010a,b)

ΔRV_{conv}: Suppression of convective blueshift

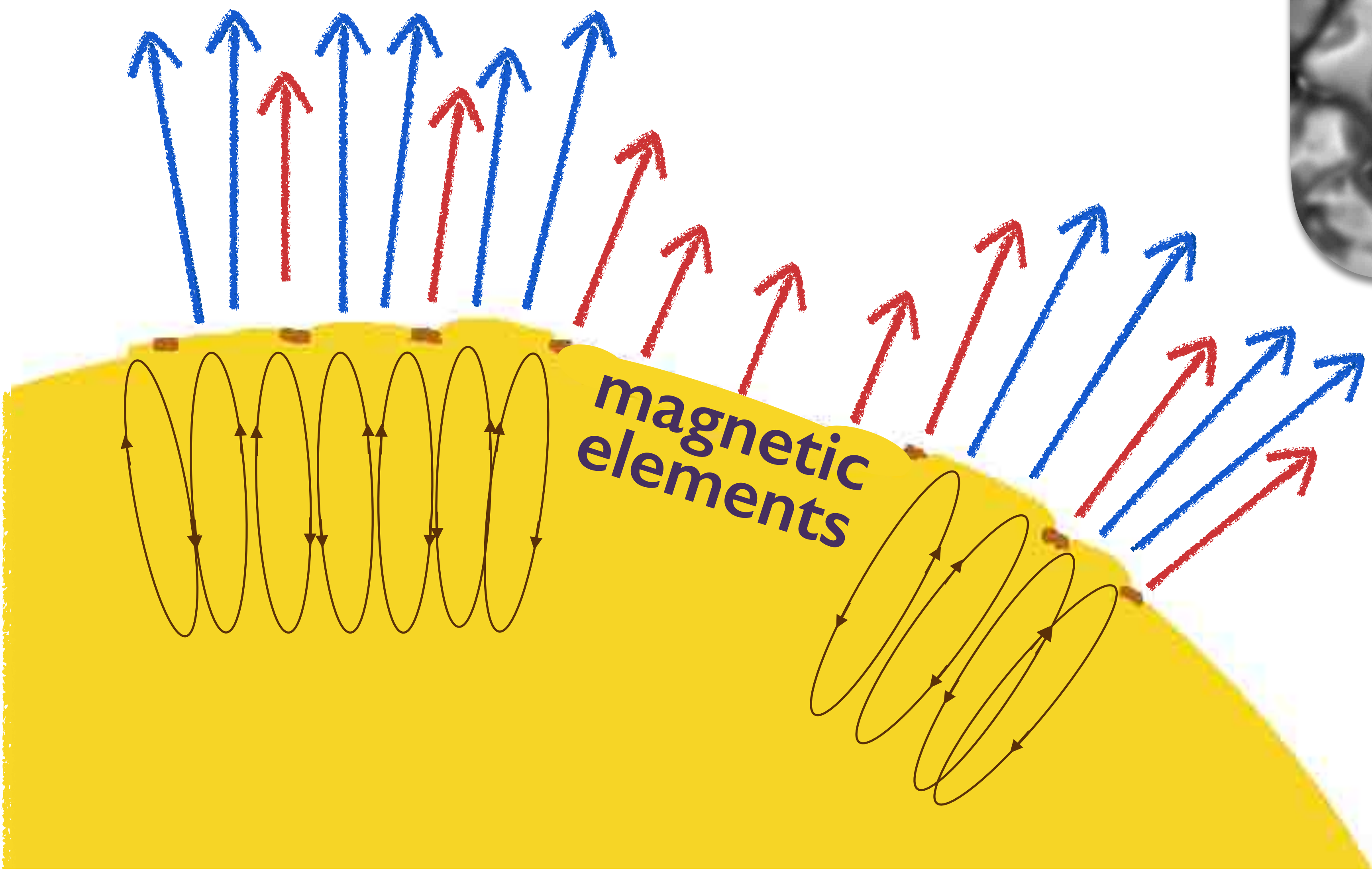


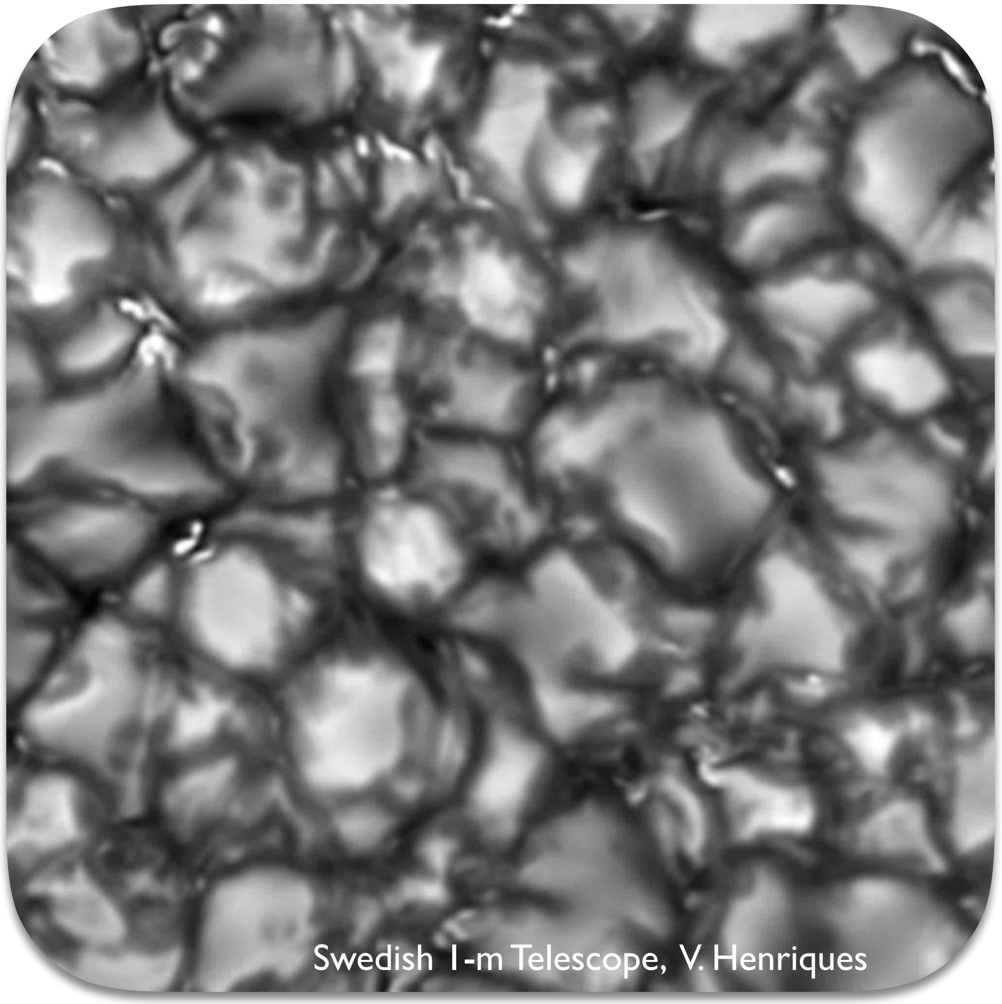


Haywood et al. (2016)
Meunier et al. (2010a,b)
Dumusque et al. (2014)

ΔRV_{conv}: Suppression of convective blueshift

RMS: several m/s!



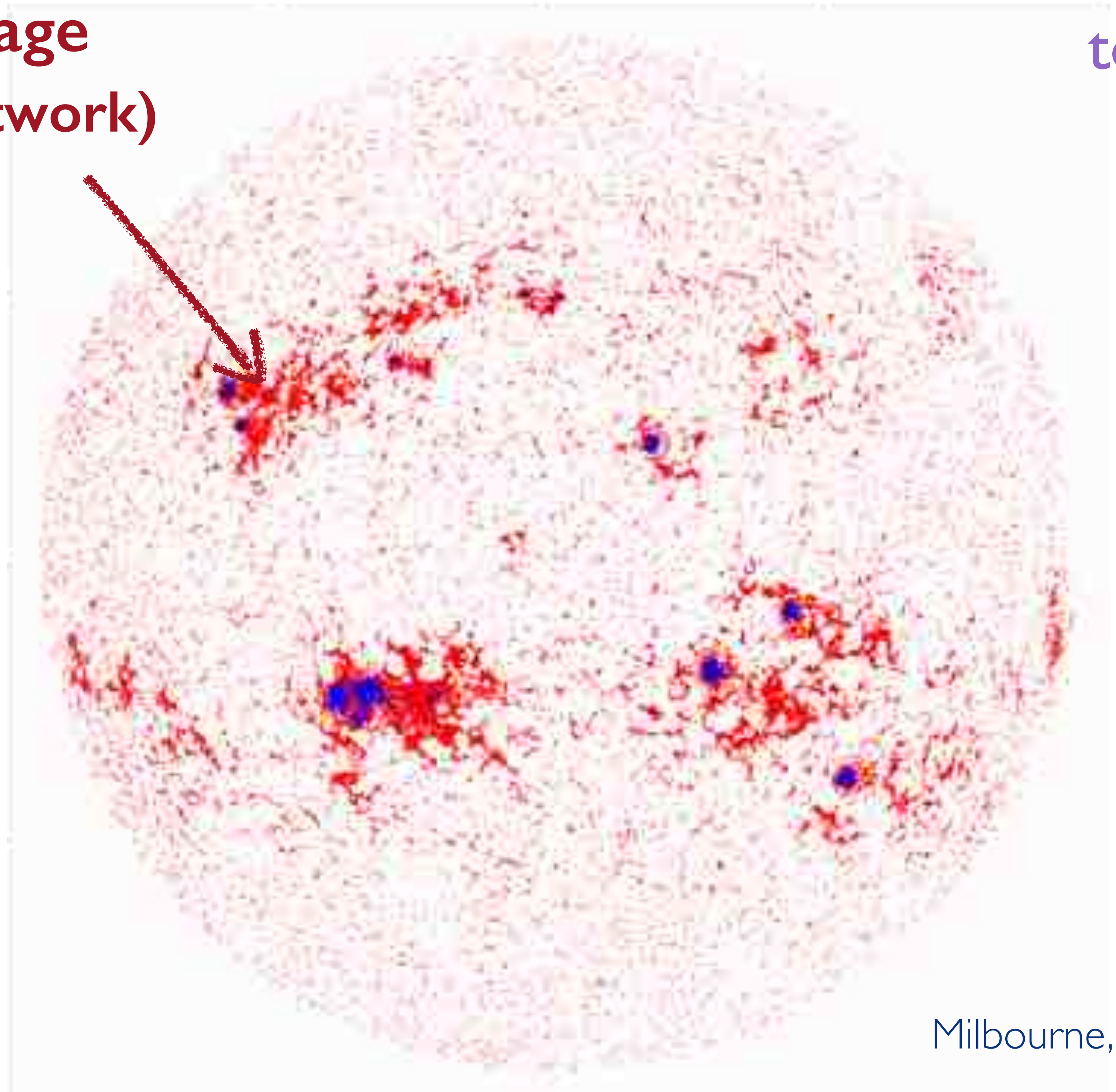


Haywood et al. (2016)
Meunier et al. (2010a,b)
Dumusque et al. (2014)

Faculae *in plage* are the dominant features at play

See my next talk tomorrow!

Faculae in plage
(not in the network)

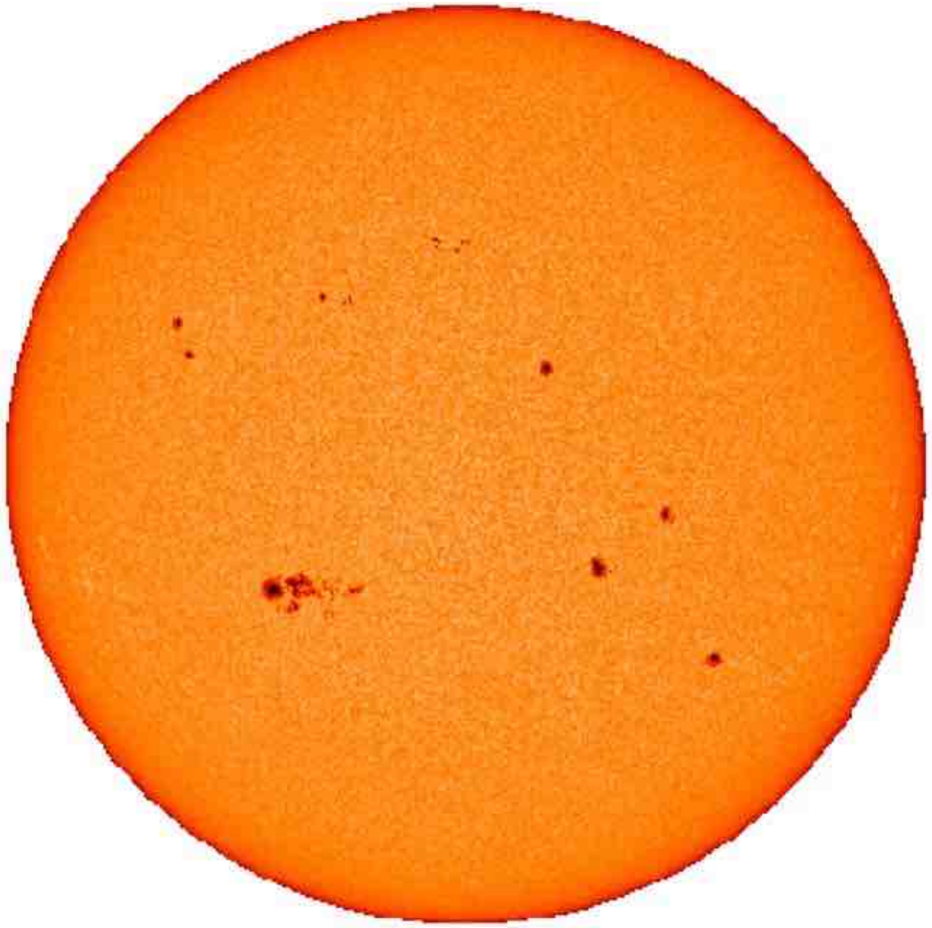


Milbourne, Haywood et al. (2019)
Haywood et al. (2016)
Meunier et al. (2010a,b)

SDO/HMI continuum image

Other (as yet unknown) physical processes are likely at play

- **Mesoscale flows?** Meunier et al. (2015)
- **Horizontal velocity flows around active regions?** Gizon (2010); summer project by Anthony Iampietro, 2019
- **Other features/processes?**



SDO/HMI continuum intensity

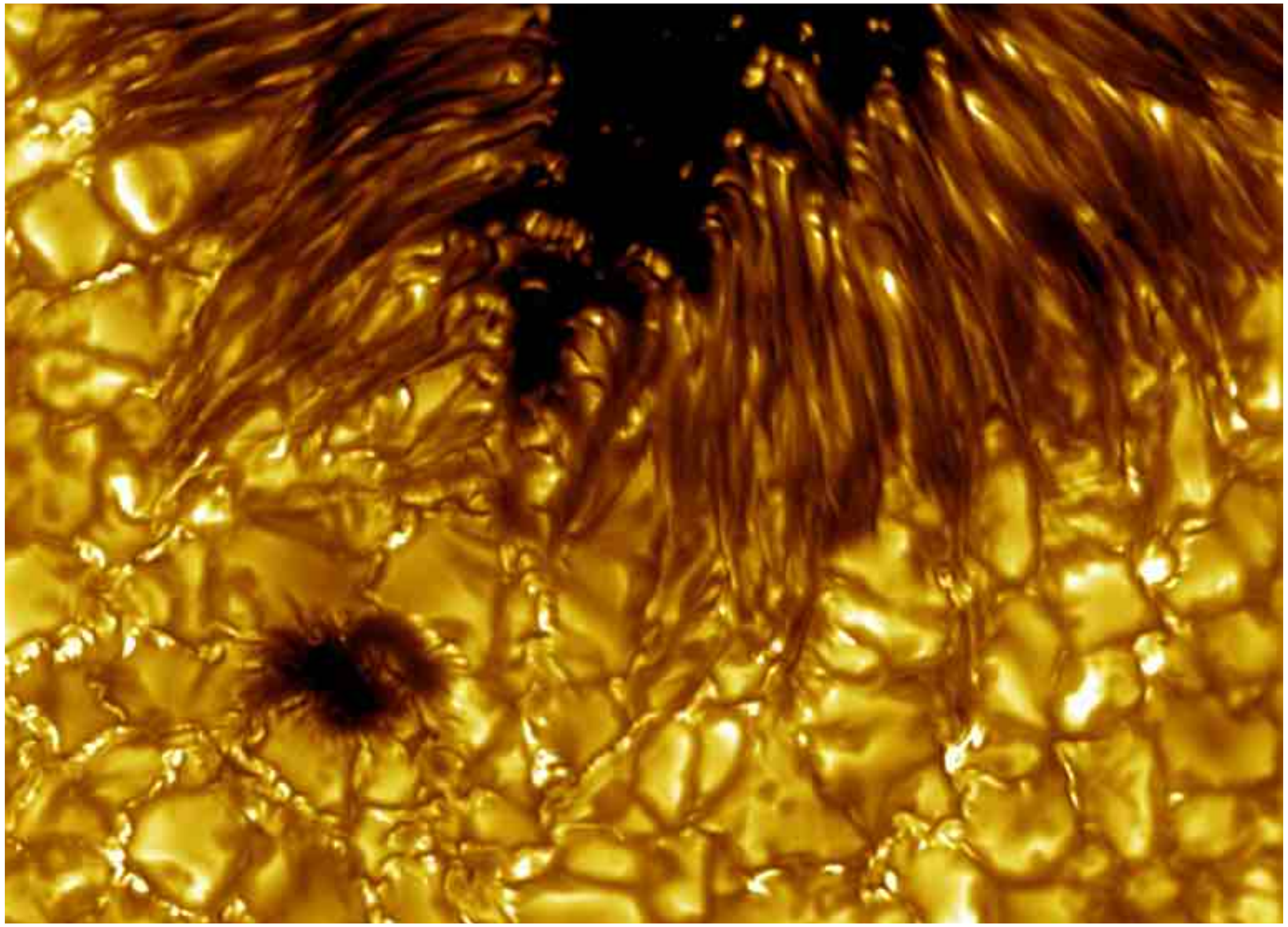


Photo: Swedish 1-m Telescope, V. Henriques

Various tools to model rotationally modulated activity

Model RV variations using simultaneous photometry:

***FF'* method (**Aigrain et al., 2011**)**

Build your stellar surface:

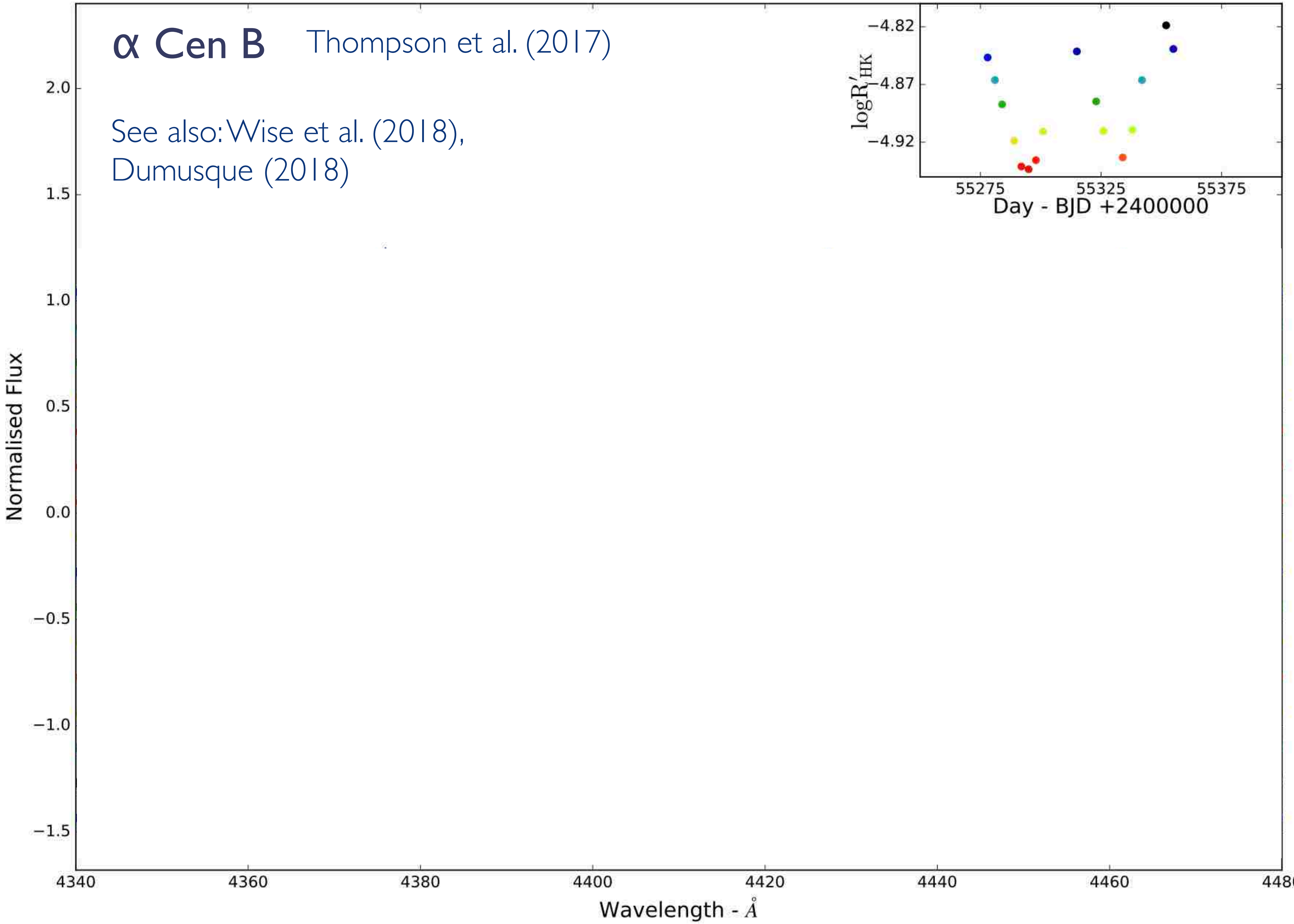
SOAP 2.0 (Boisse et al., 2011, Dumusque et al., 2014**), StarSim (**Herrero et al., 2016**) — beware of degeneracies (eg.** Jeffers & Keller, 2009, **see supplementary slides)**

Treat activity as correlated noise/data-driven methods:

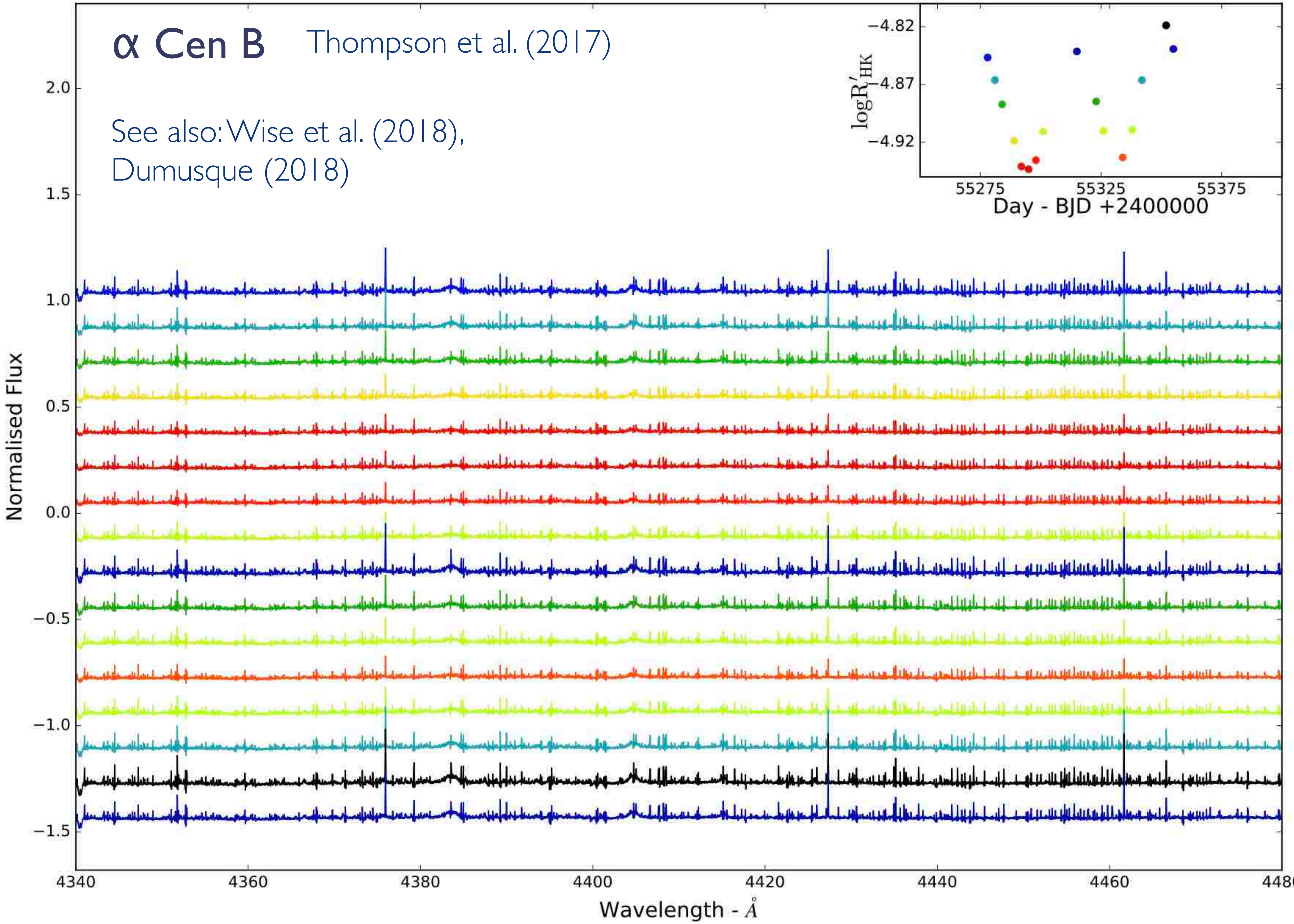
Gaussian process regeression (eg. Haywood et al. 2014, Rajpaul et al. 2015, Jones et al. 2017**), *wobble* (**Bedell et al., 2019**)**

(This is not a comprehensive list)

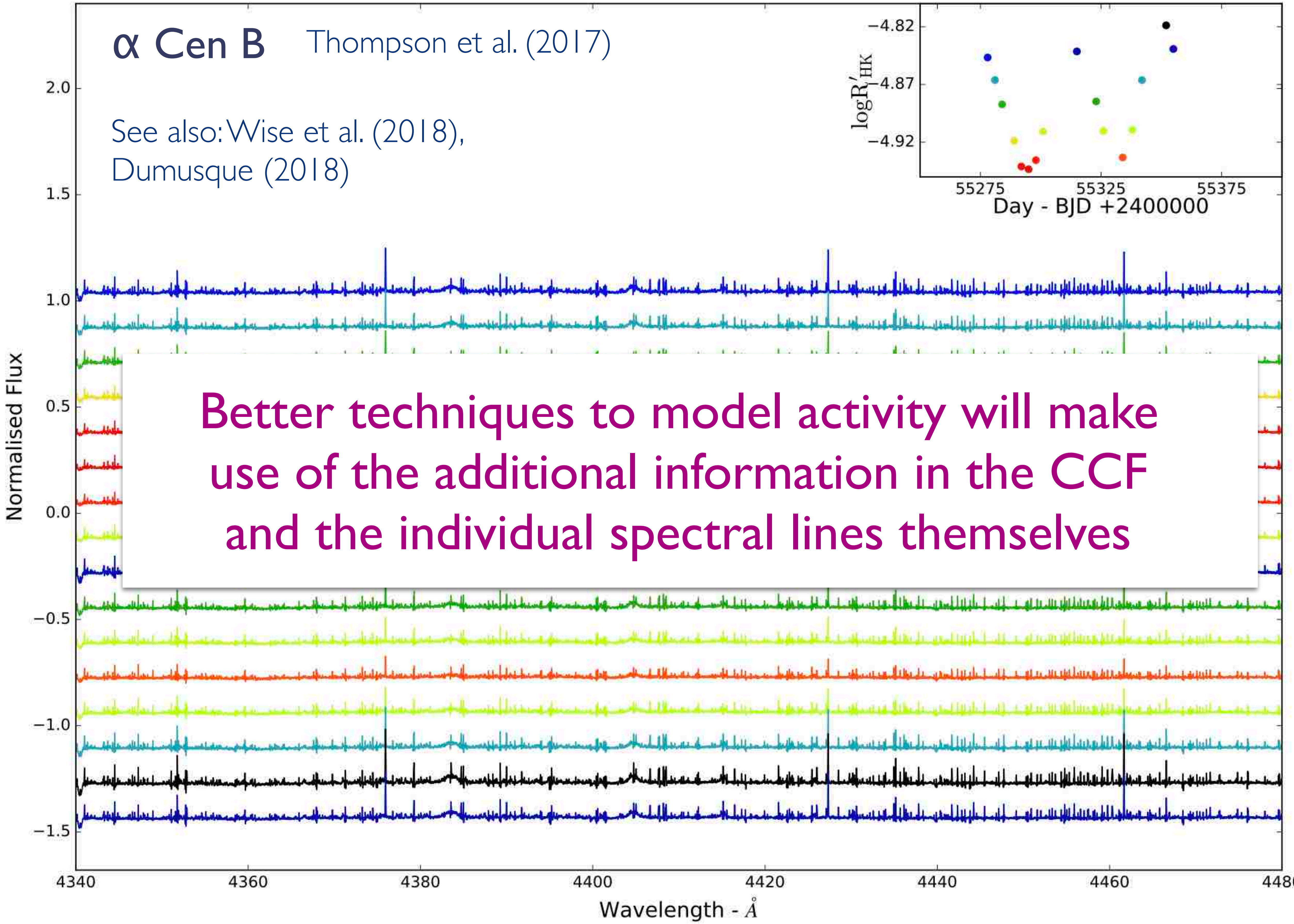
Spectral lines change over rotation timescales



Spectral lines change over rotation timescales

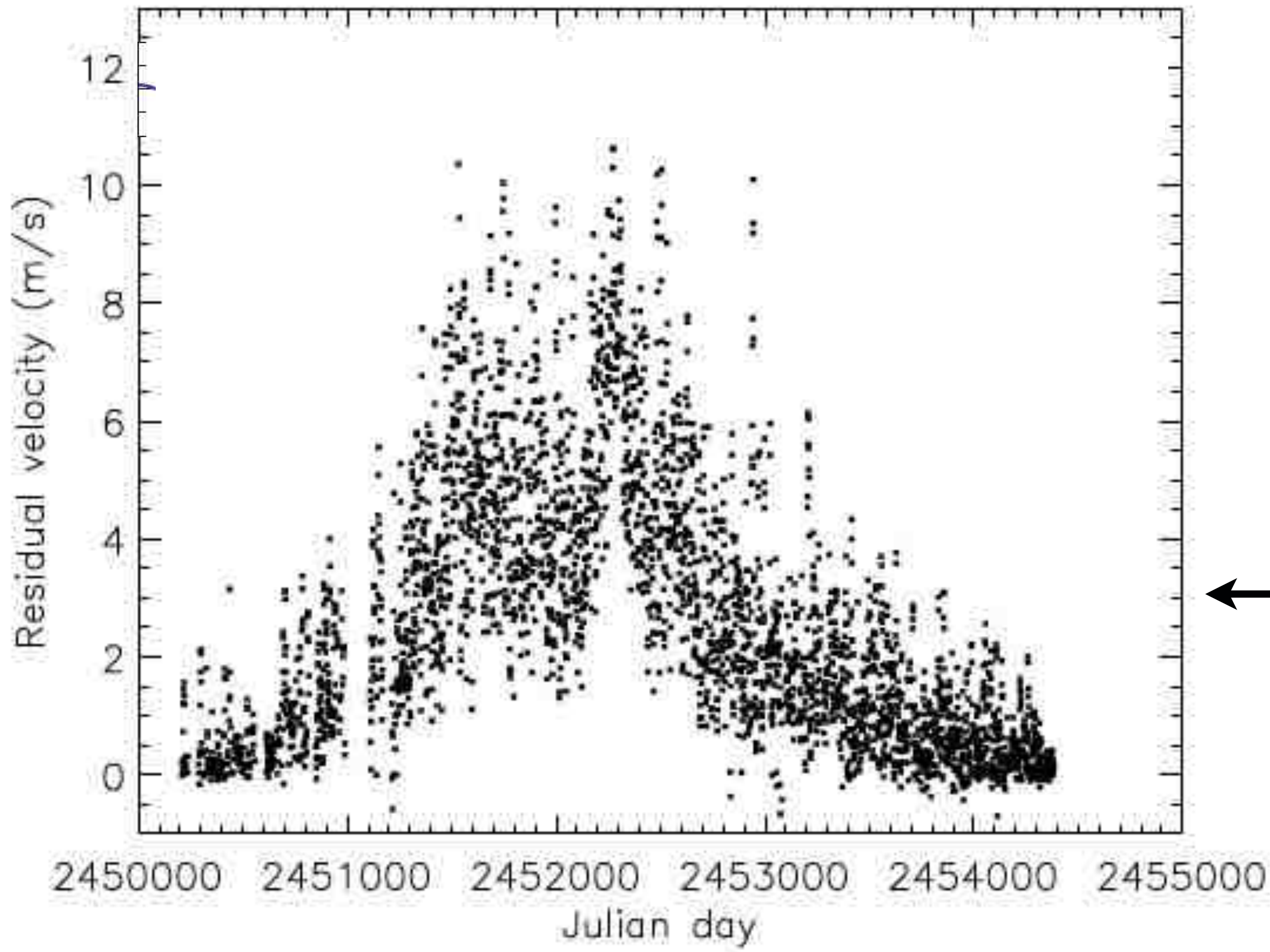


Spectral lines change over rotation timescales



Better techniques to model activity will make use of the additional information in the CCF and the individual spectral lines themselves

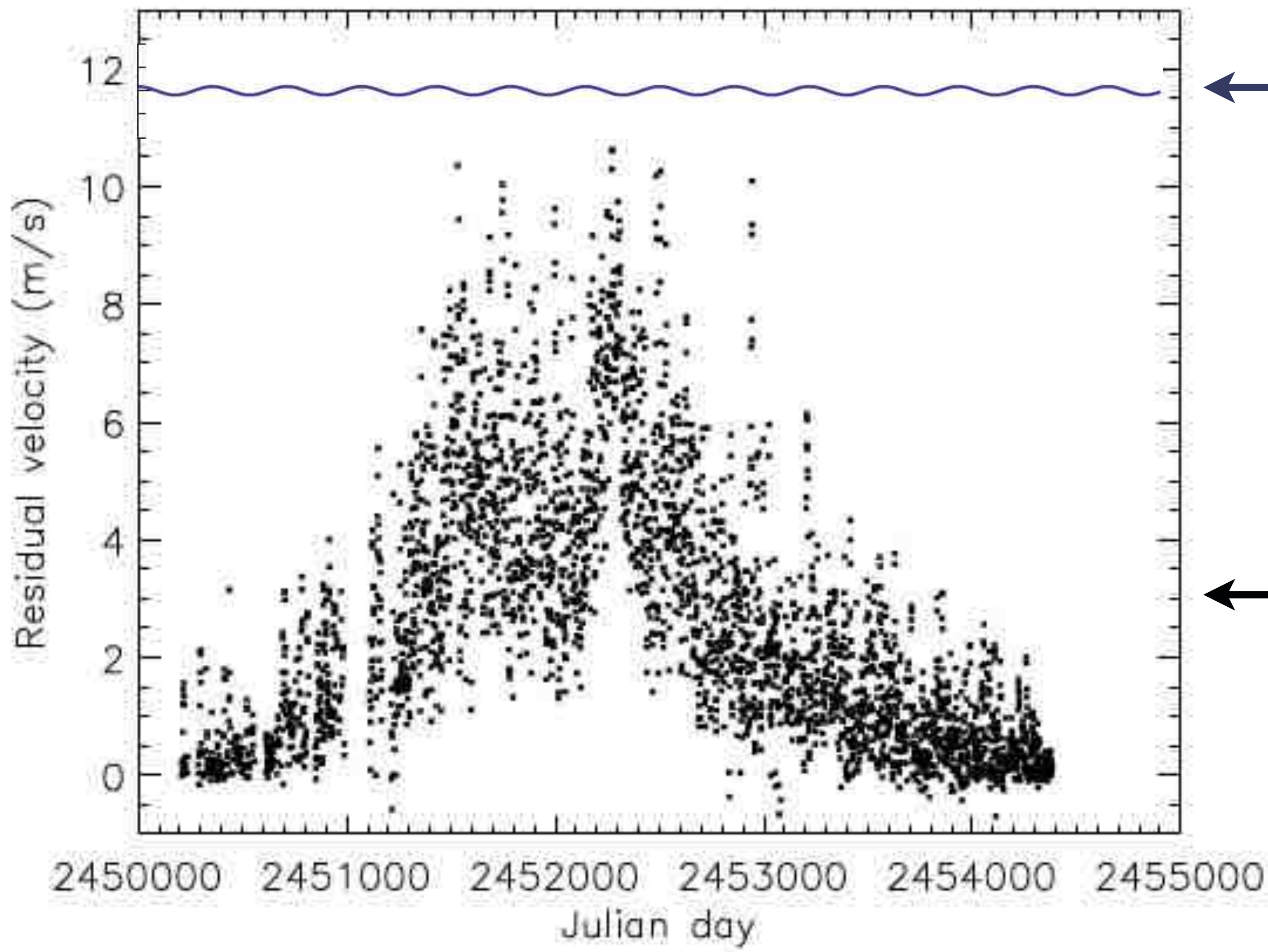
Magnetic cycles (decades)



Solar activity-induced RV variations

Meunier et al. (2010a,b)

Magnetic cycles (decades)

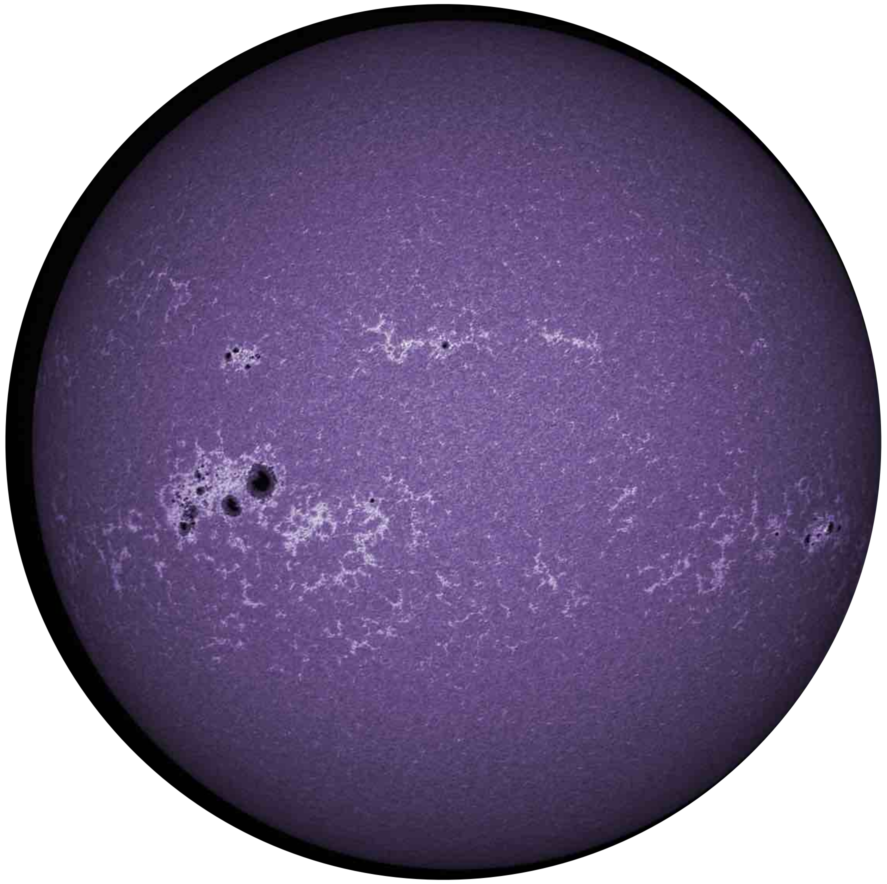


9 cm/s solar reflex orbital motion for 1 $M_\oplus$ planet at 1 AU

Solar activity-induced RV variations

Meunier et al. (2010a,b)

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



S-index: Vaughan et al. (1978)
log R'HK: Noyes et al. (1984)

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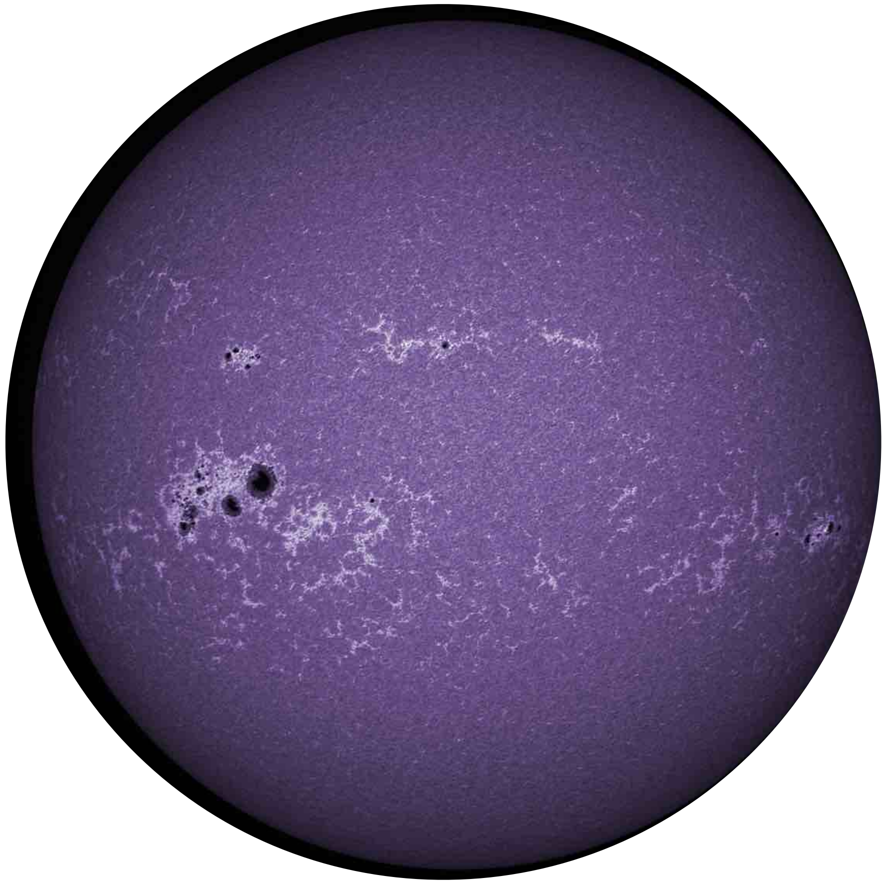

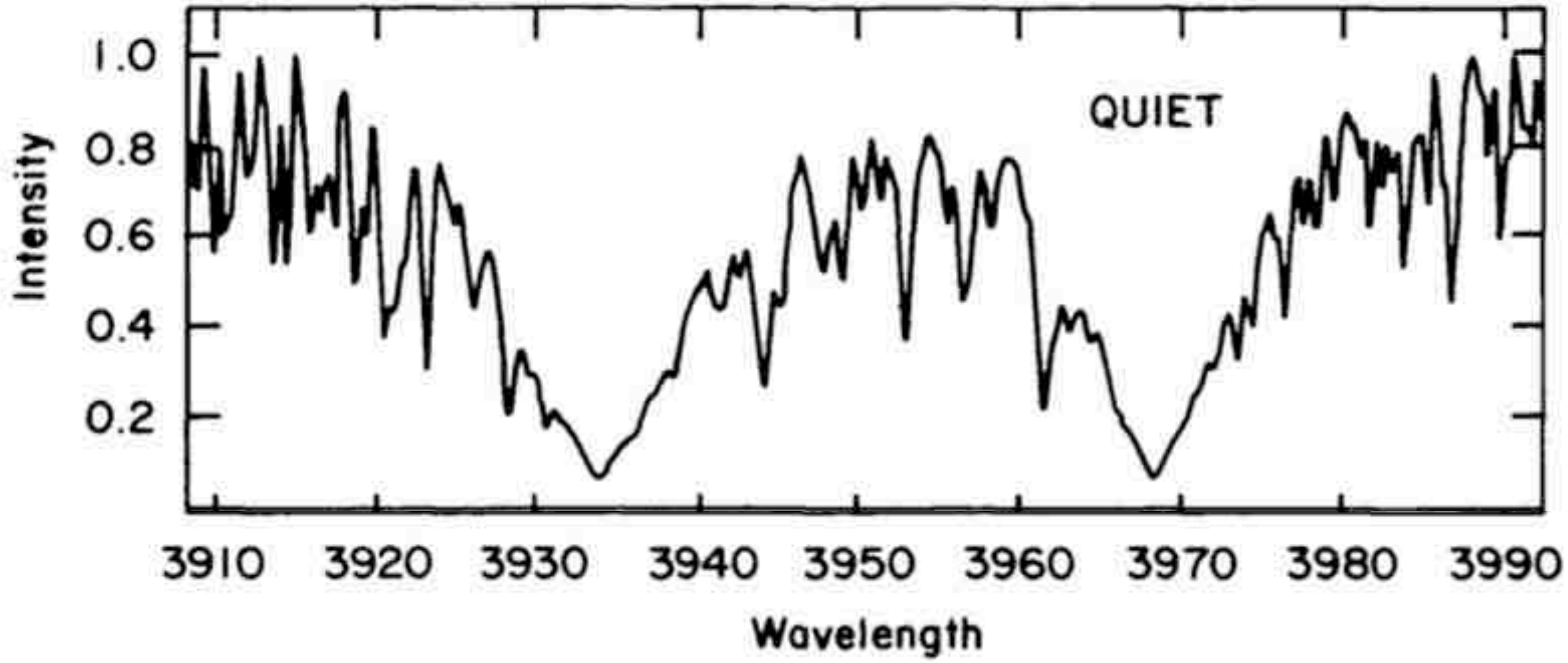

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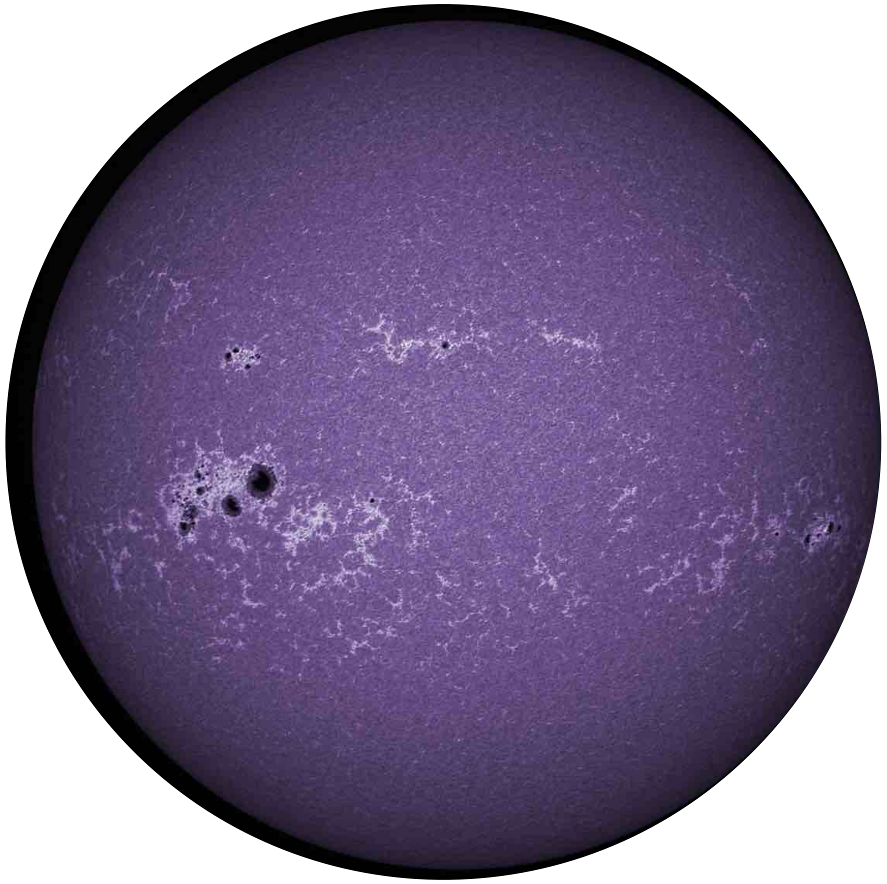

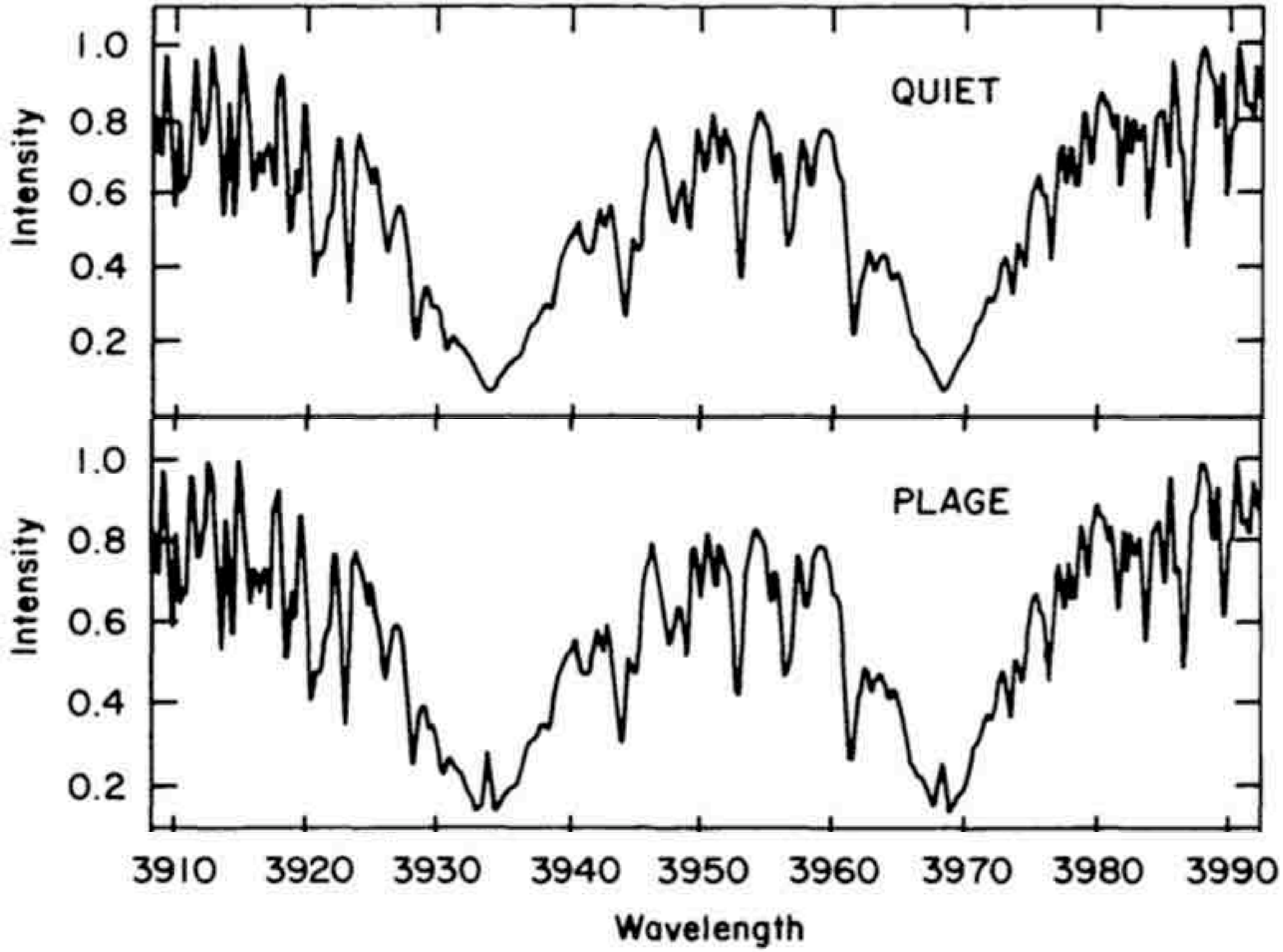

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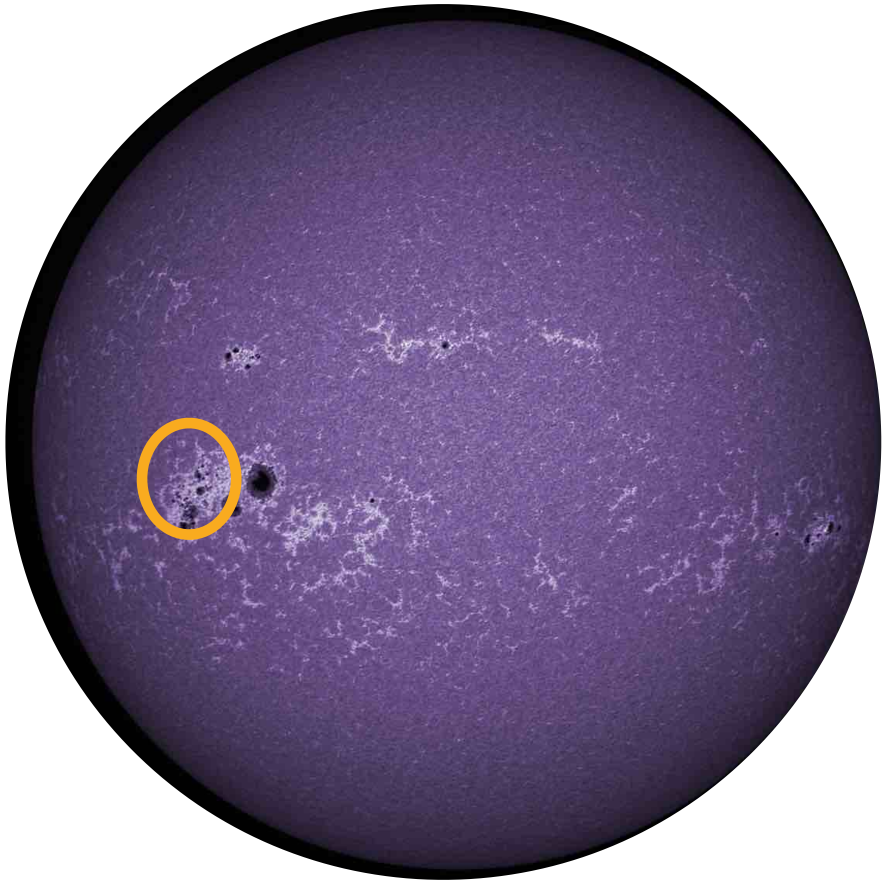

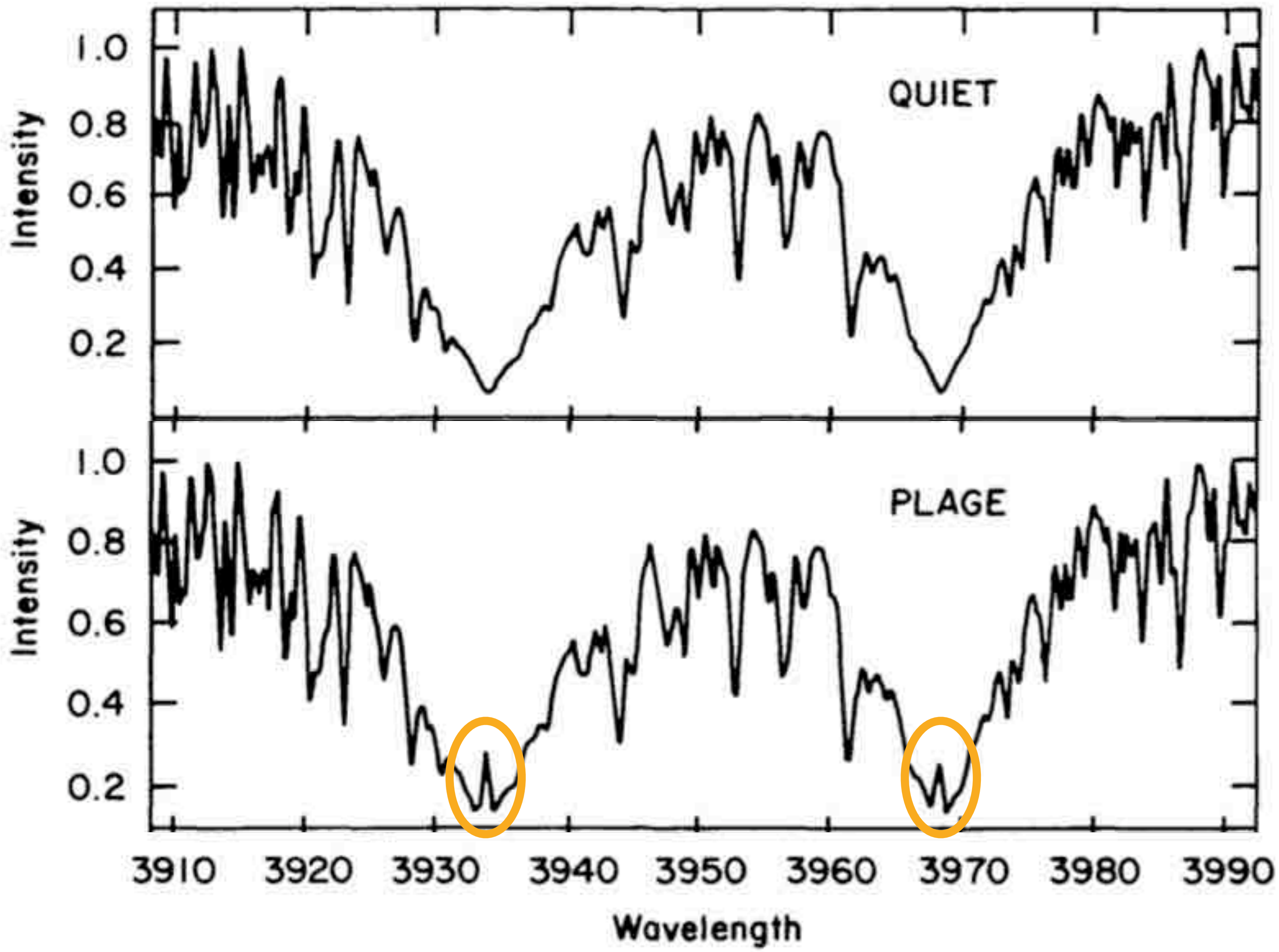

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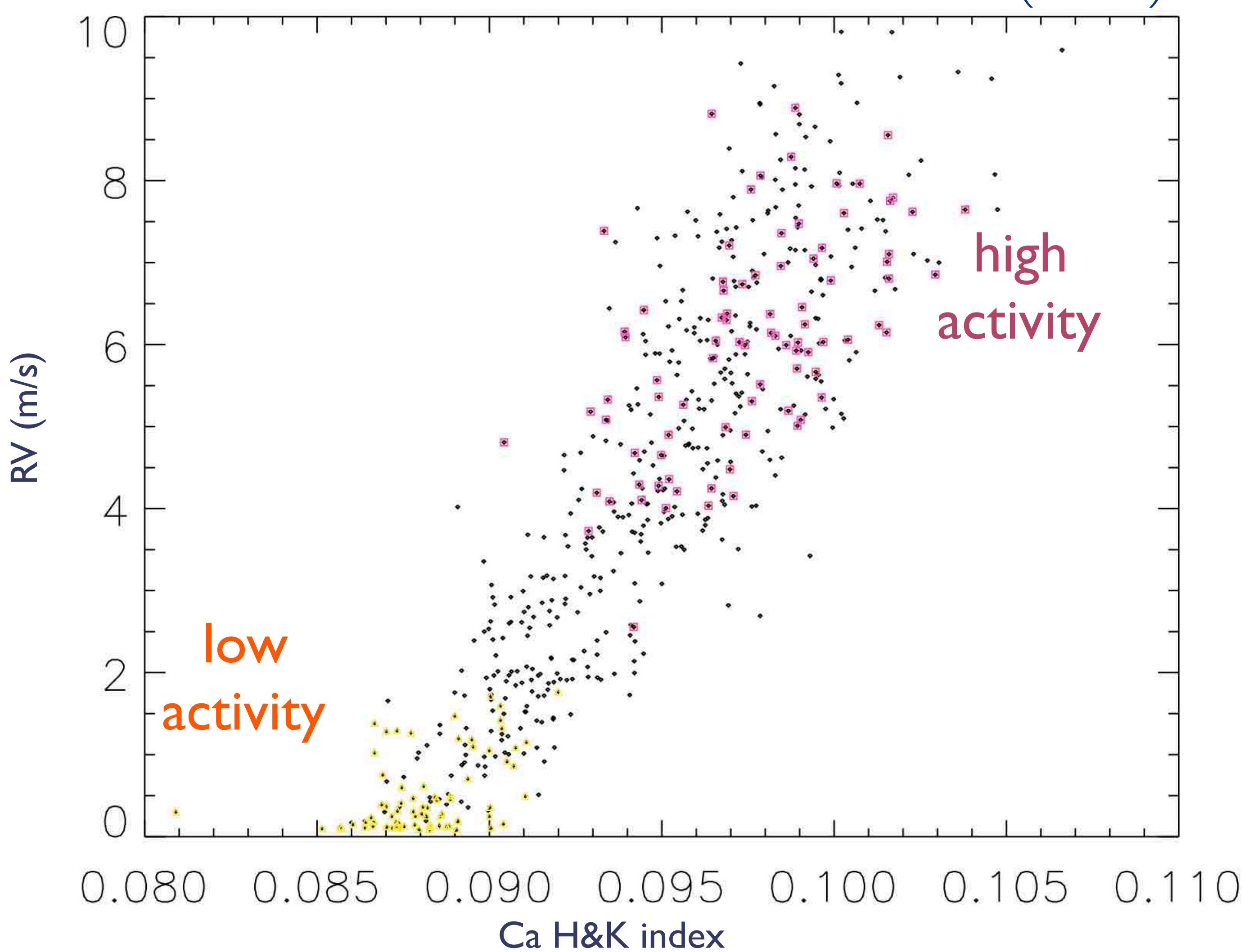
On the magnetic cycle timescale, Ca II H&K tends to correlate well with RV variations

The Sun

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



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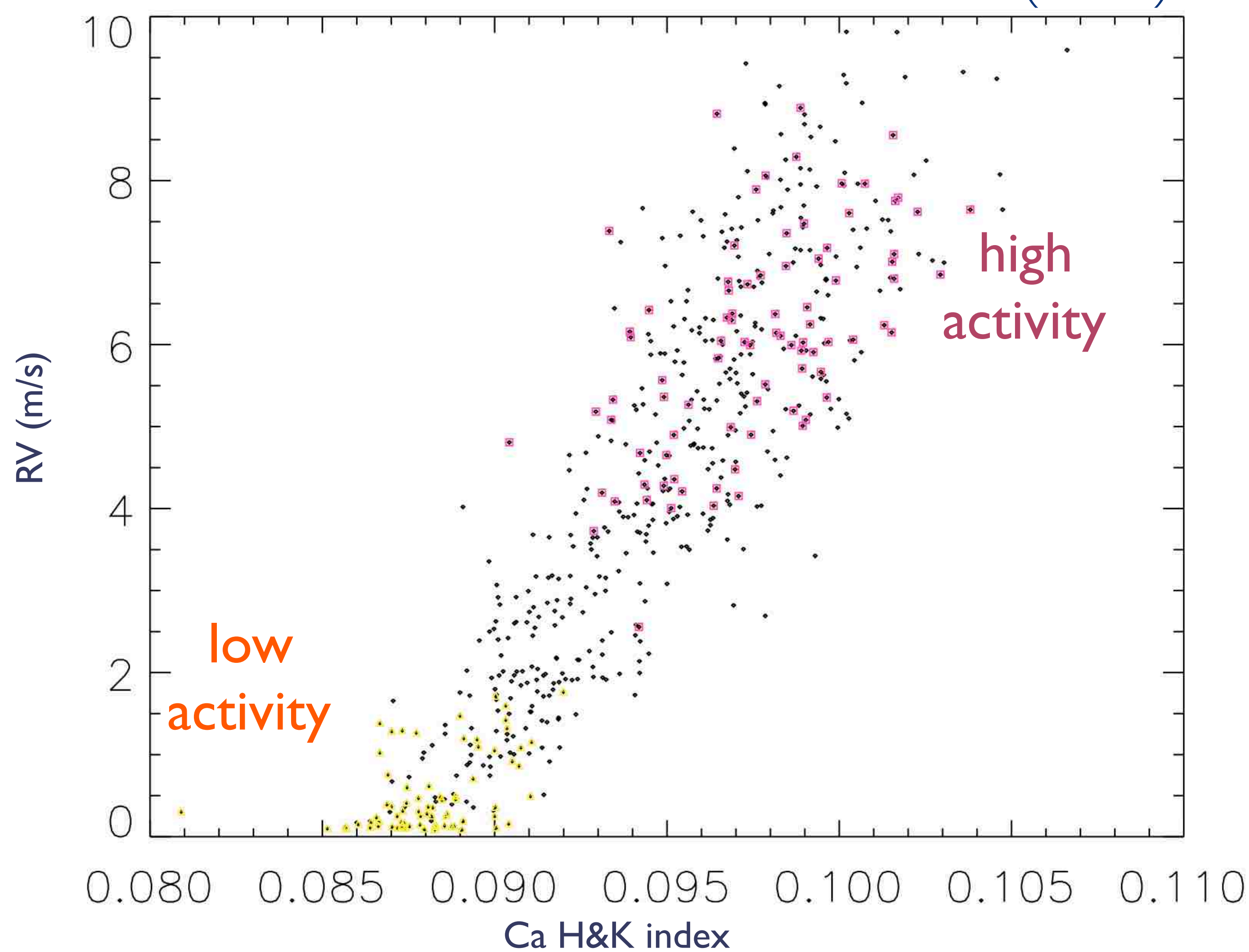
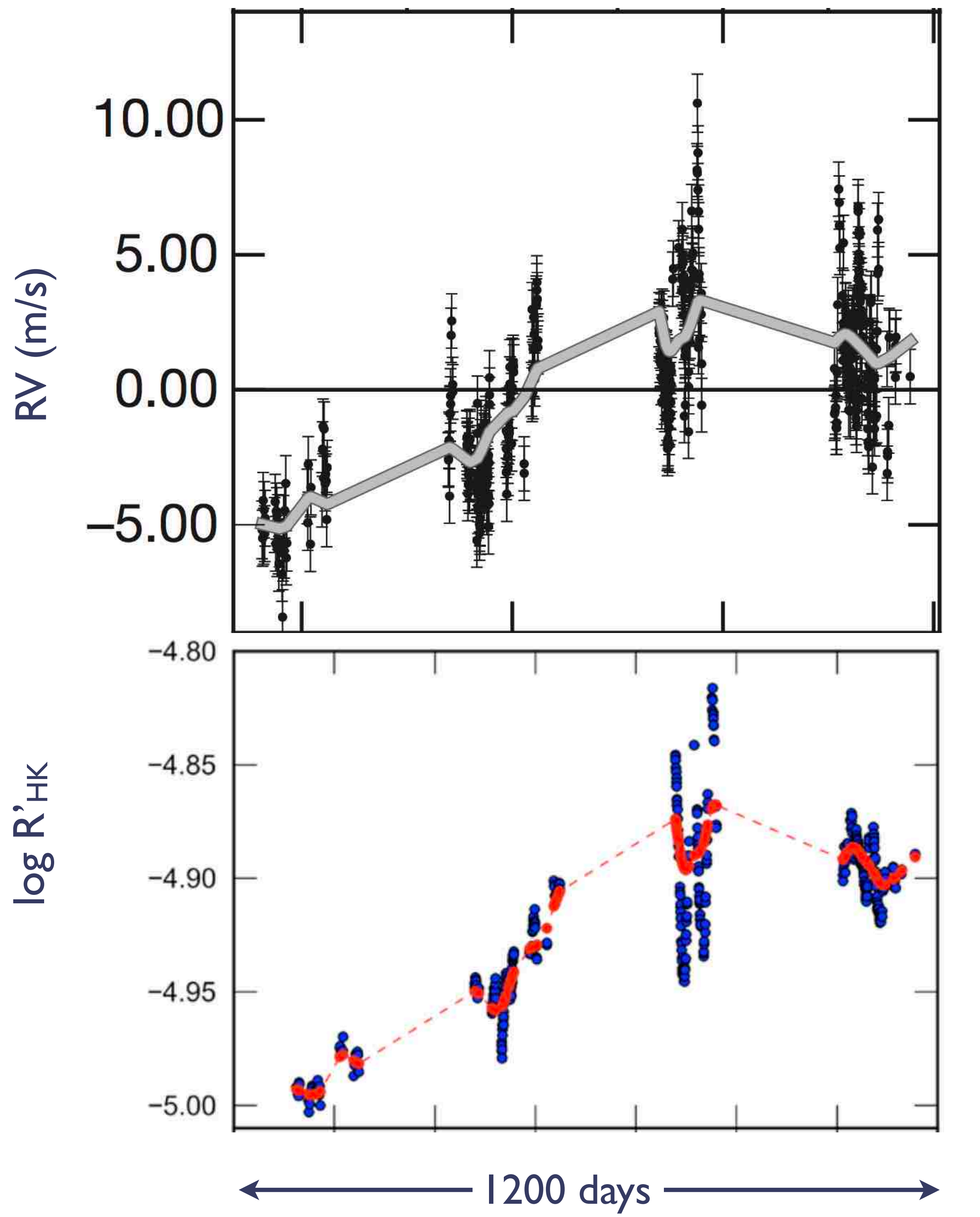


Alpha Cen B

Dumusque et al. (2012)



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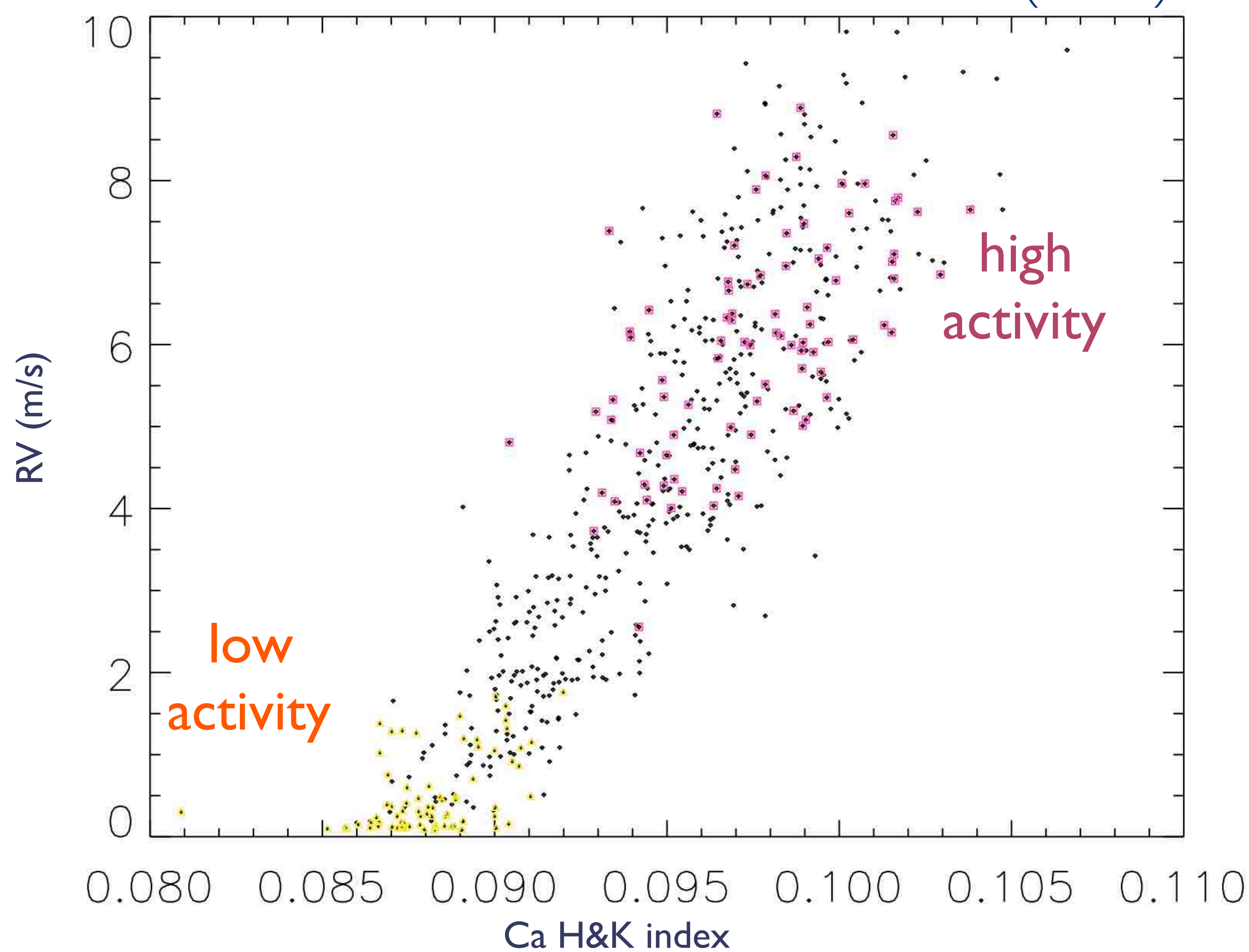

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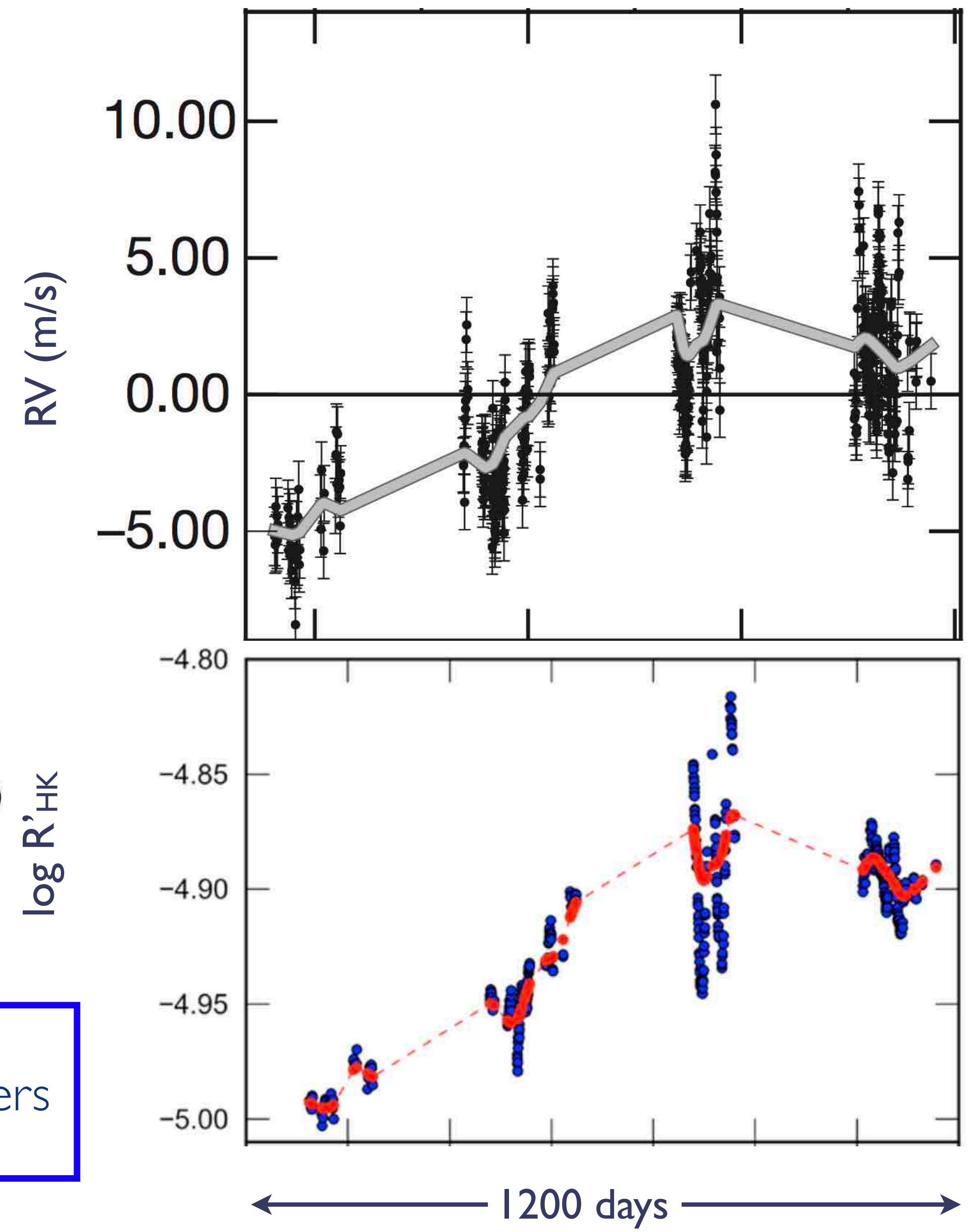
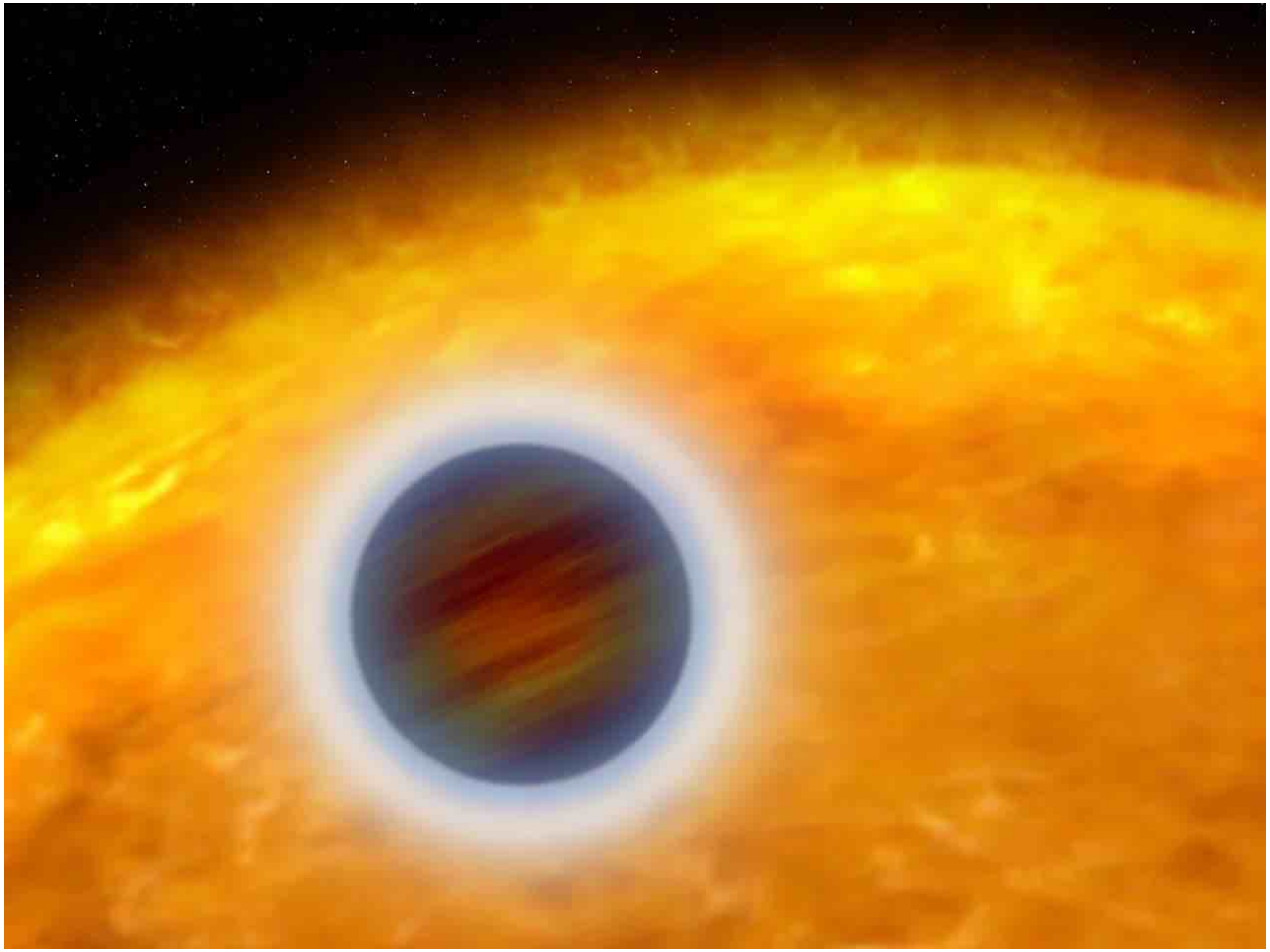
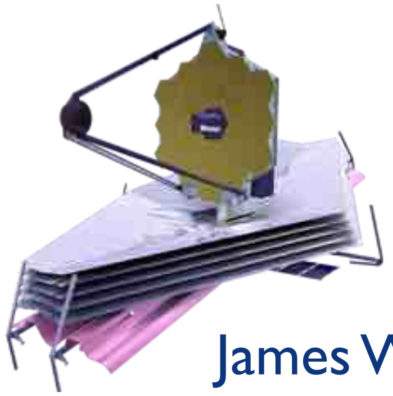


$\Delta RV \propto \log R'_{HK}$ Lovis et al. (2011) and others

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

Final remarks

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Look out for NASA/NSF Roadmap to EPRV in March 2020!

Know thy star, know thy planet!

Supplementary slides

Summary: stellar surface processes that produce RV variations

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

Summary: stellar surface processes that produce RV variations

- Minutes to hours:
  - oscillations
  - surface granulation
  - flares and coronal mass ejections

We can deal with it reasonably well by adapting (RV) exposure times.

Will become a problem when we determine (RV) masses of Earth-mass planets. We are using 3D MHD simulations to find observational proxies so that we can model it out.

Currently a big problem for (RV) masses and atmopsheric characterisation of planets around M dwarfs!

- Days-weeks (stellar rotation period):
  - spots
  - faculae

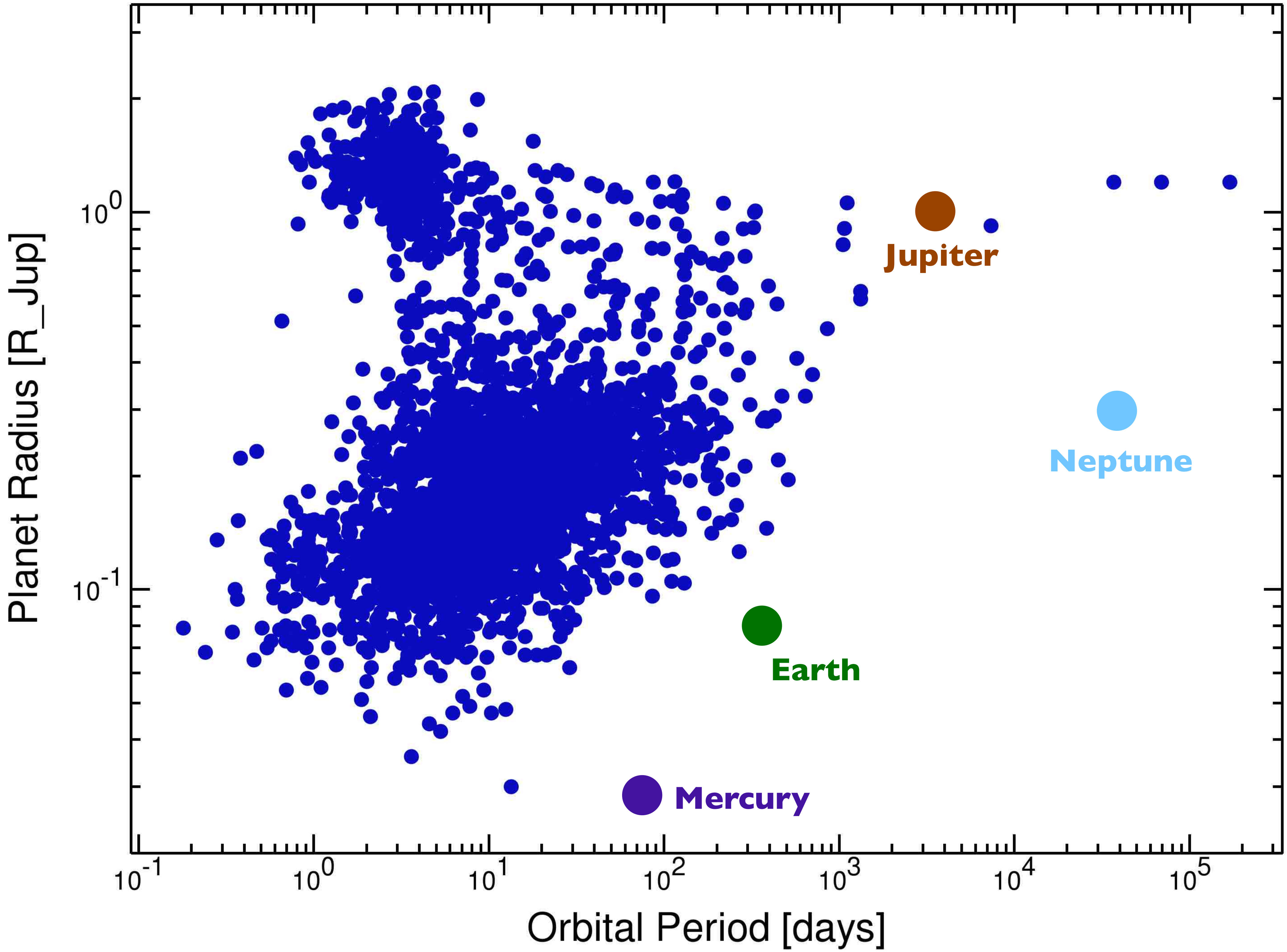
Could be problematic at (RV) Earth-mass level, and for atmospheric characterisation. But on slowly rotating, old stars like the Sun they are harmless compared to faculae…

Currently the main obstacle to determining (RV) masses of Neptunes & super-Earths. Will also be a major obstacle for atmospheric characterisation of these planets

- Decades:
  - magnetic cycles

Looks just like a Jupiter in an RV survey — beware! Not an issue when considering orbital periods < a few months

Over 4000 exoplanets confirmed to date, and many more planet candidates



Plotted at the NASA Exoplanet Archive (2018)

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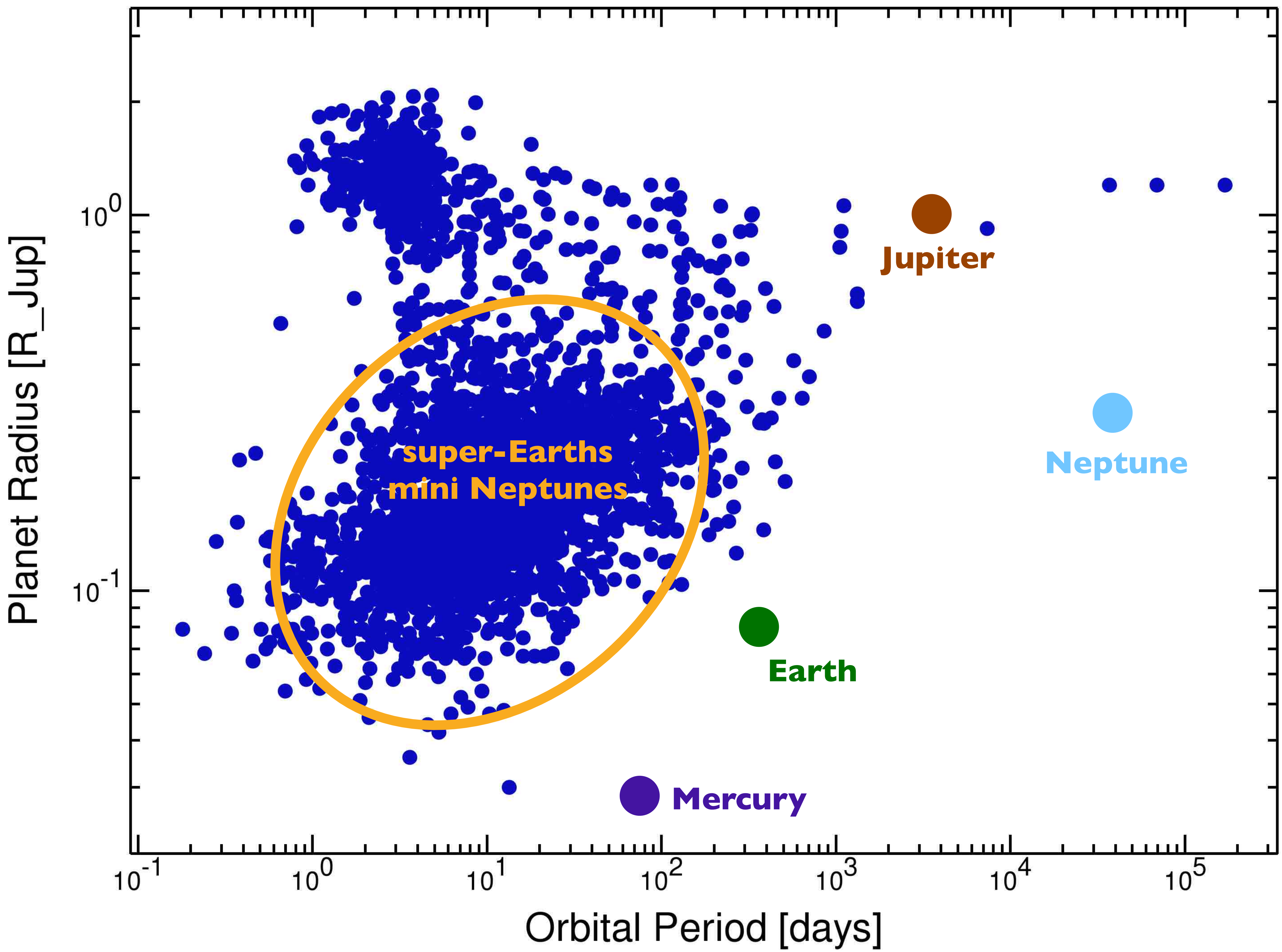

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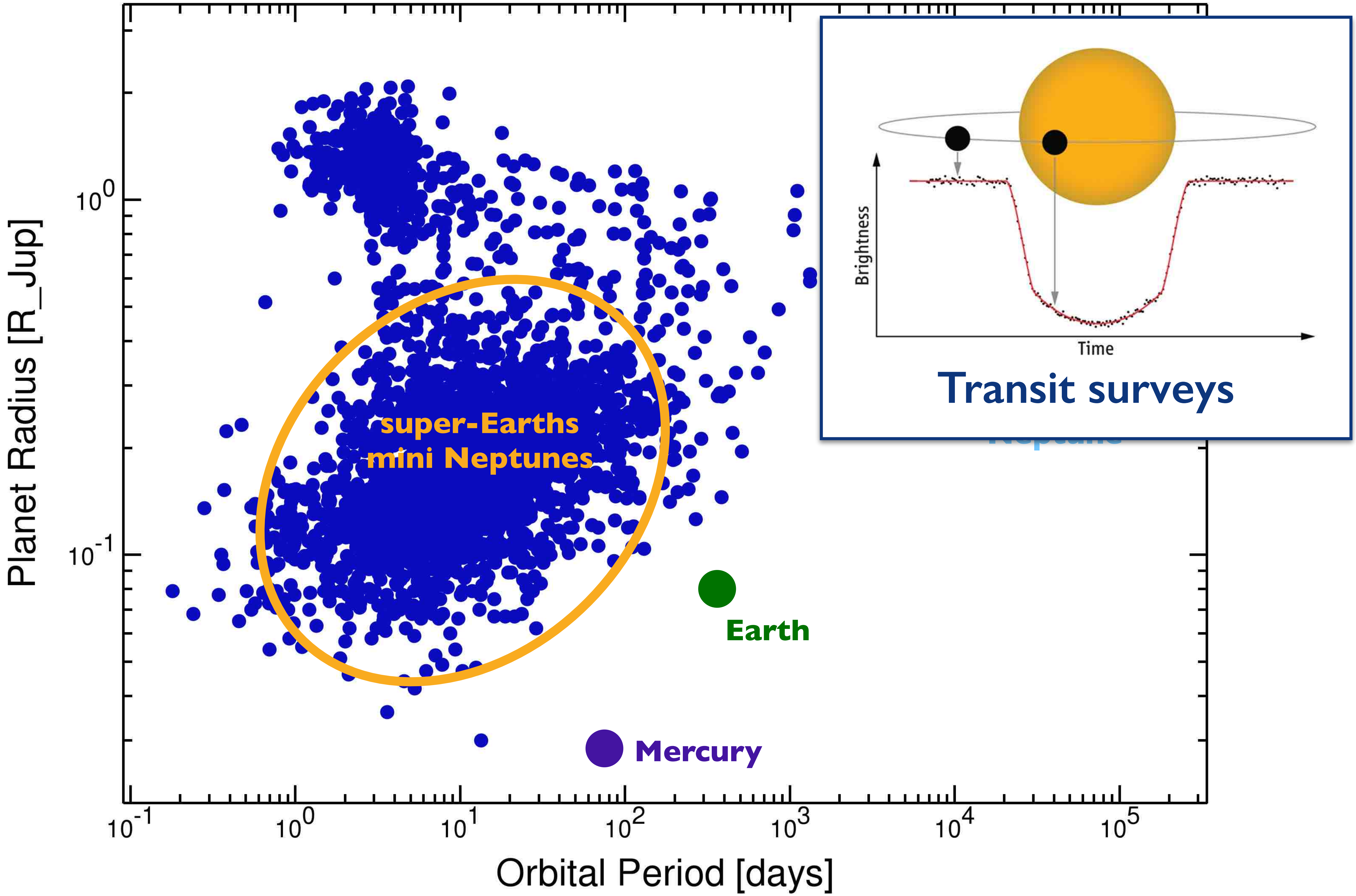

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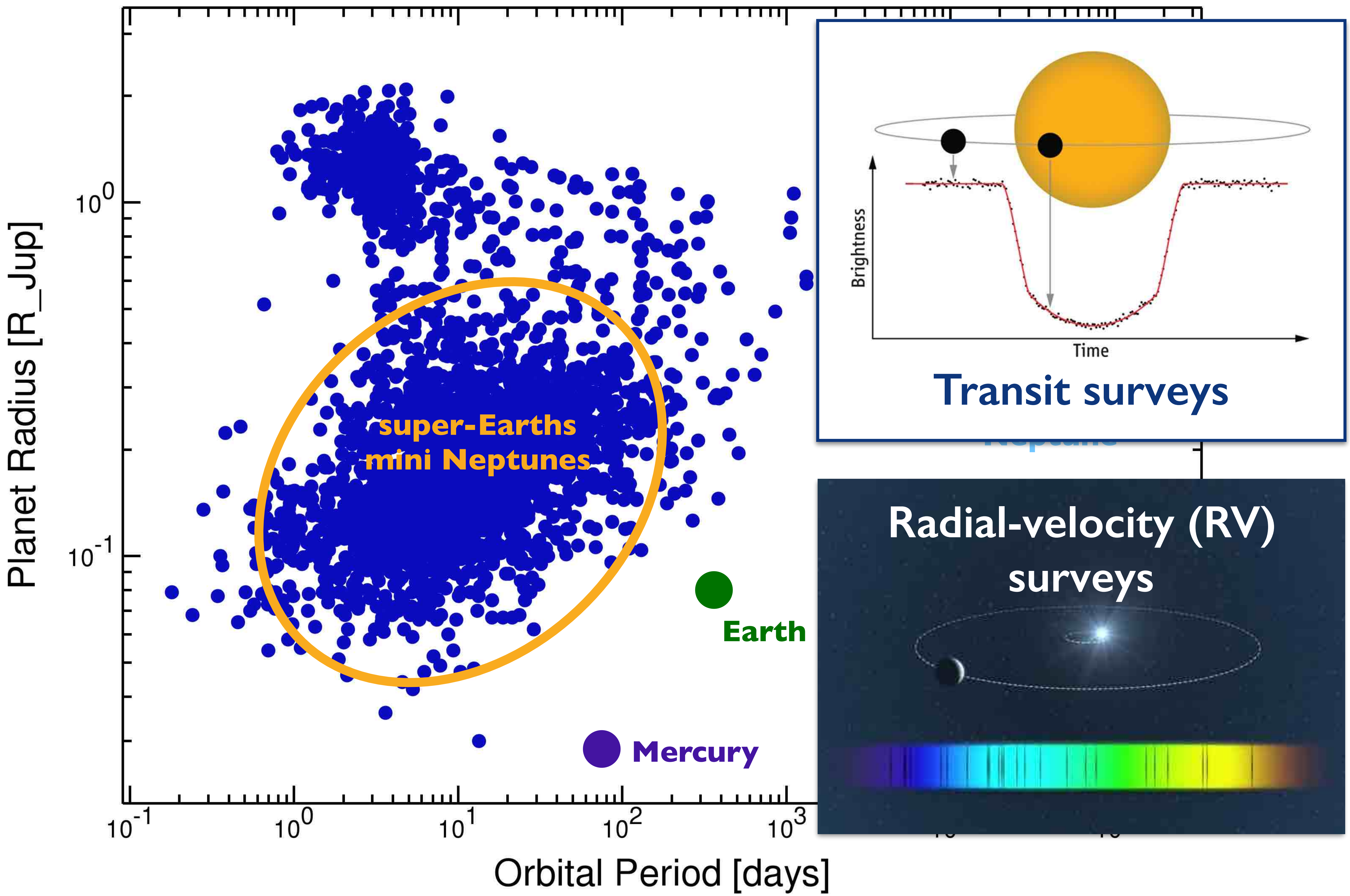
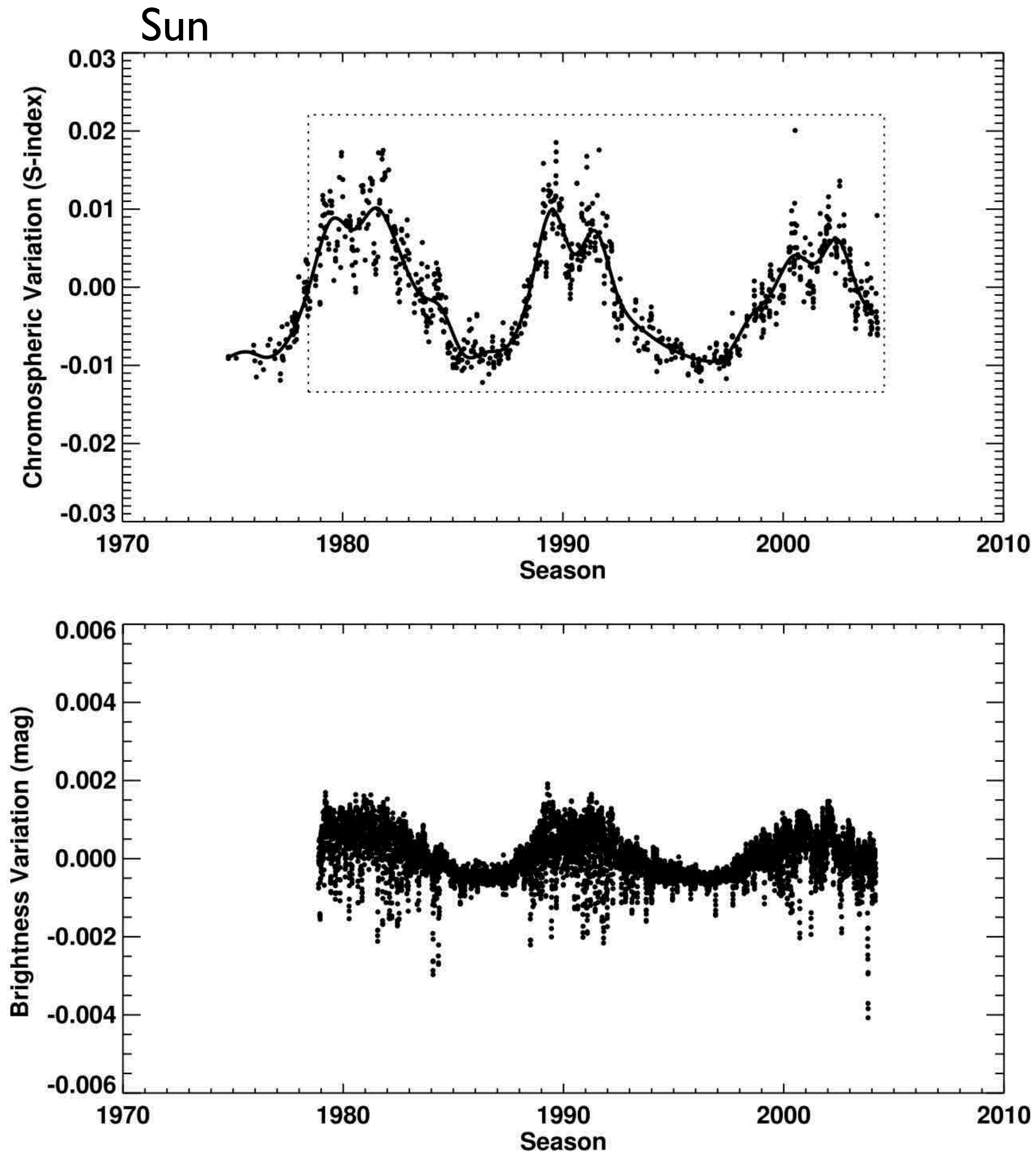


Plotted at the NASA Exoplanet Archive (2018)

Old, slowly rotating stars like the Sun are faculae-dominated

Ca H&K emission

Optical photometry

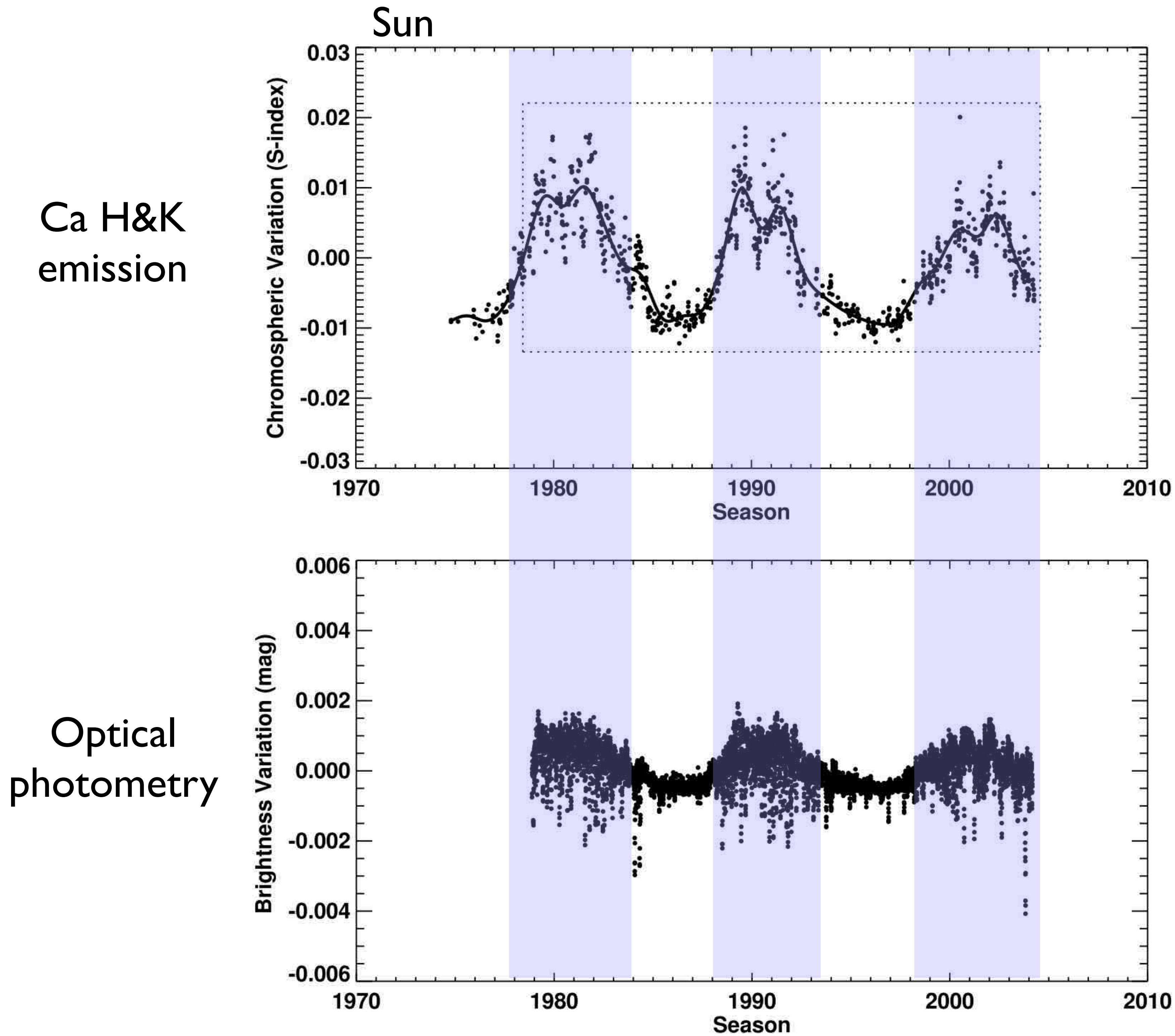


Mount Wilson HK Project (Mt Wilson Observatory, Lowell Observatory)

Radick et al. (1988), Lockwood et al. (2007), Radick et al. (2018)

Figure from Lockwood et al. (2007)

Old, slowly rotating stars like the Sun are faculae-dominated



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Solar pressure-mode oscillations

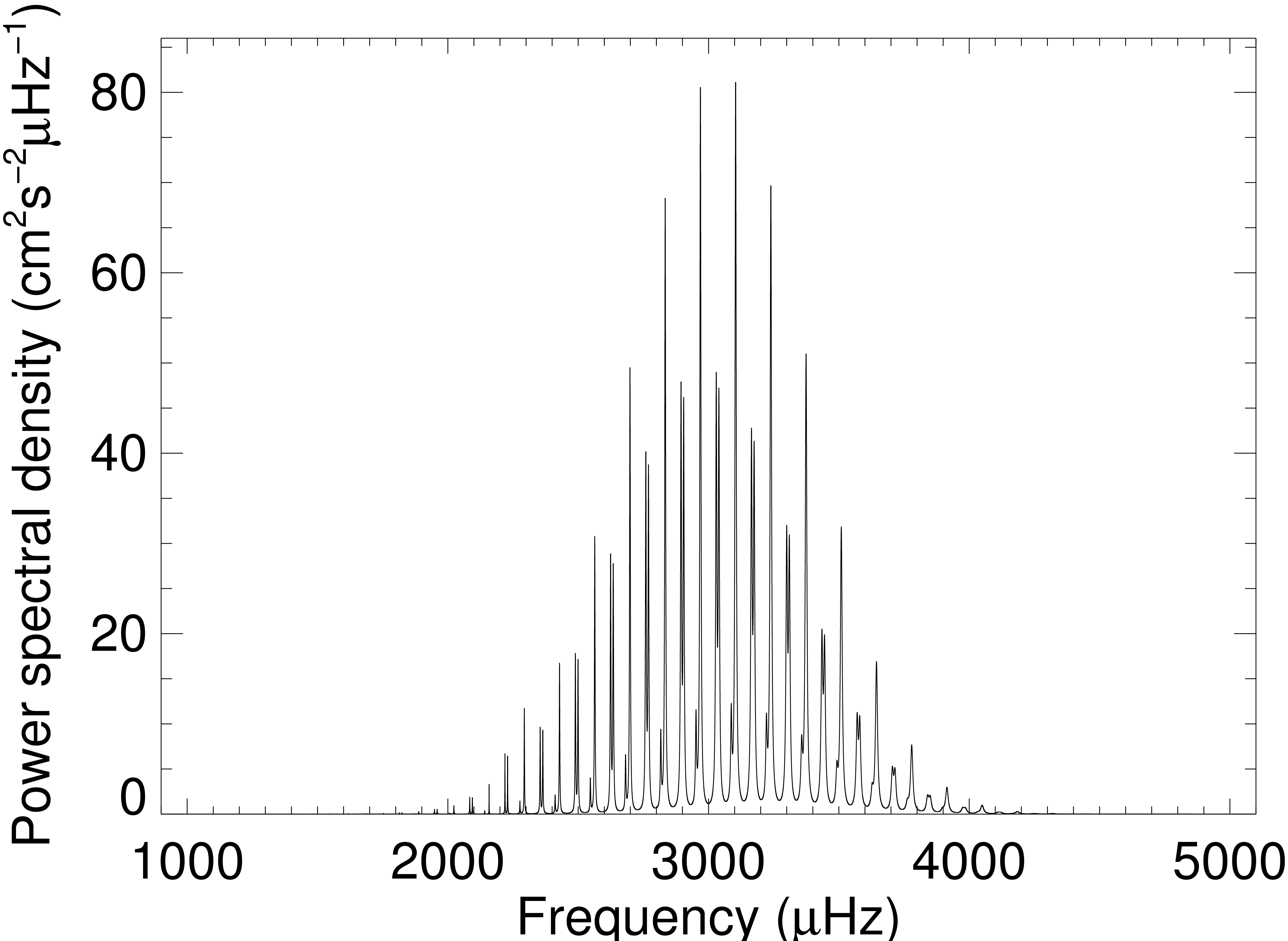

Figure: H. Cegla

Chaplin, Cegla et al. (2019)

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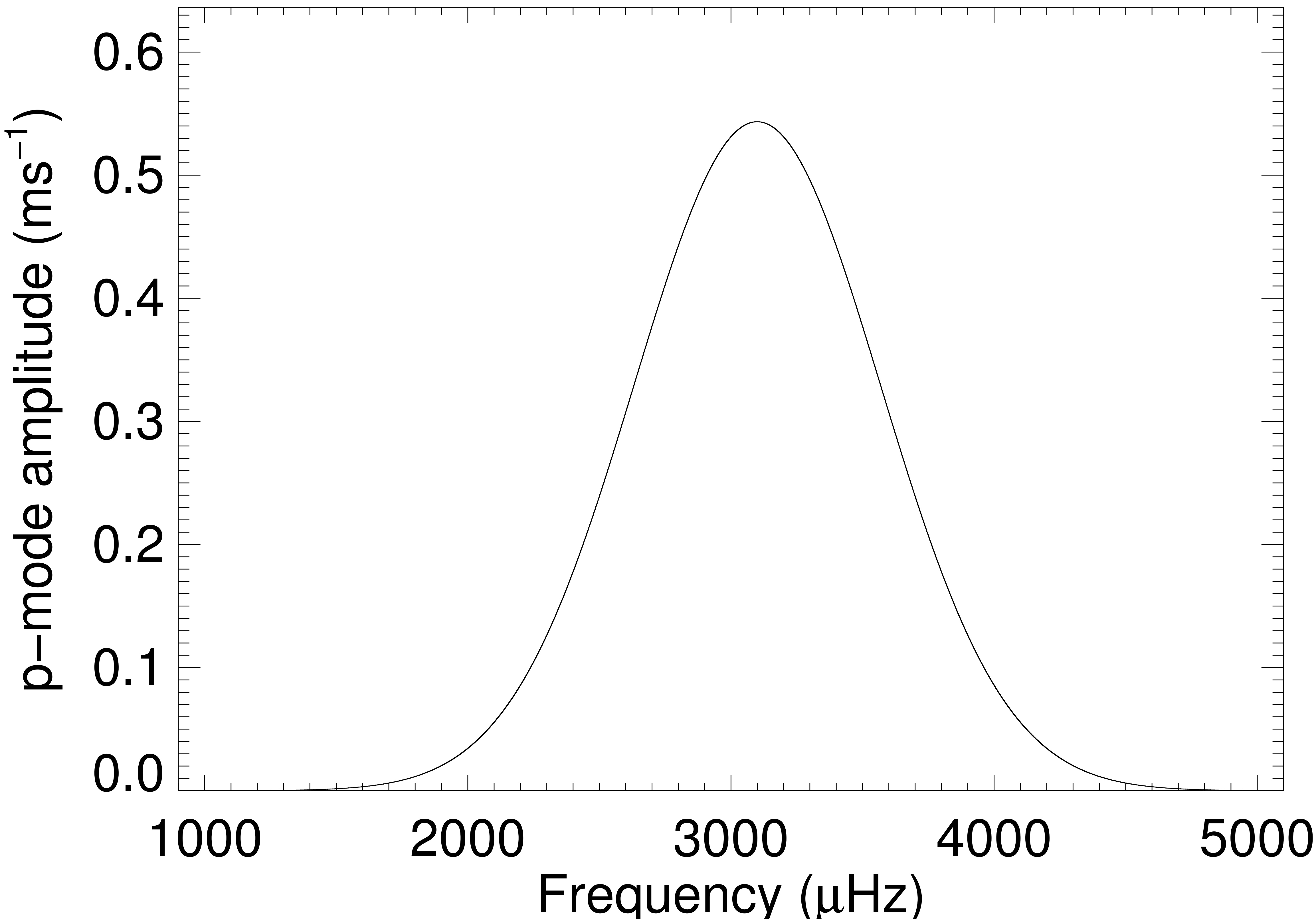

Figure: H. Cegla

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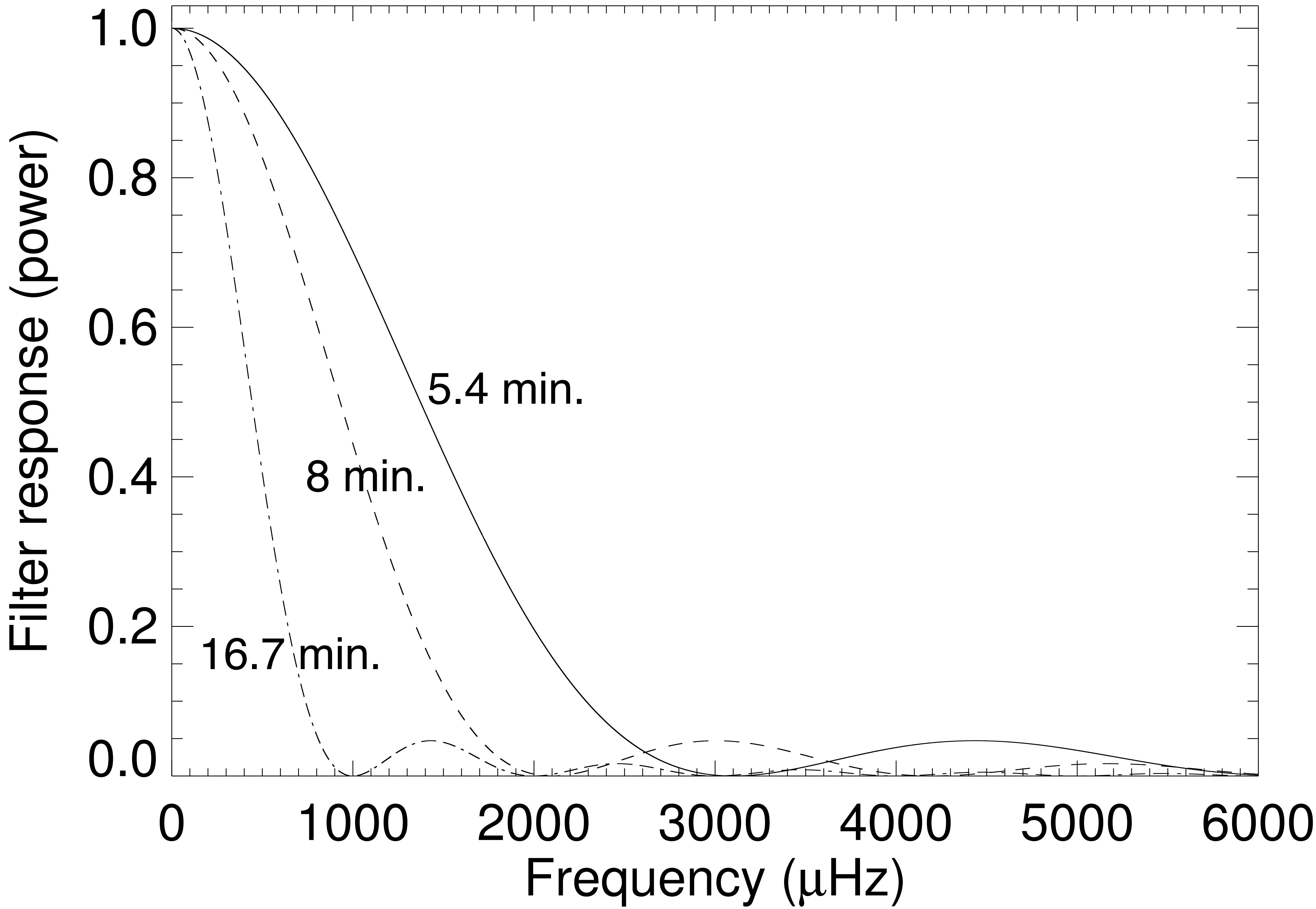
Finite exposure times = boxcar filter



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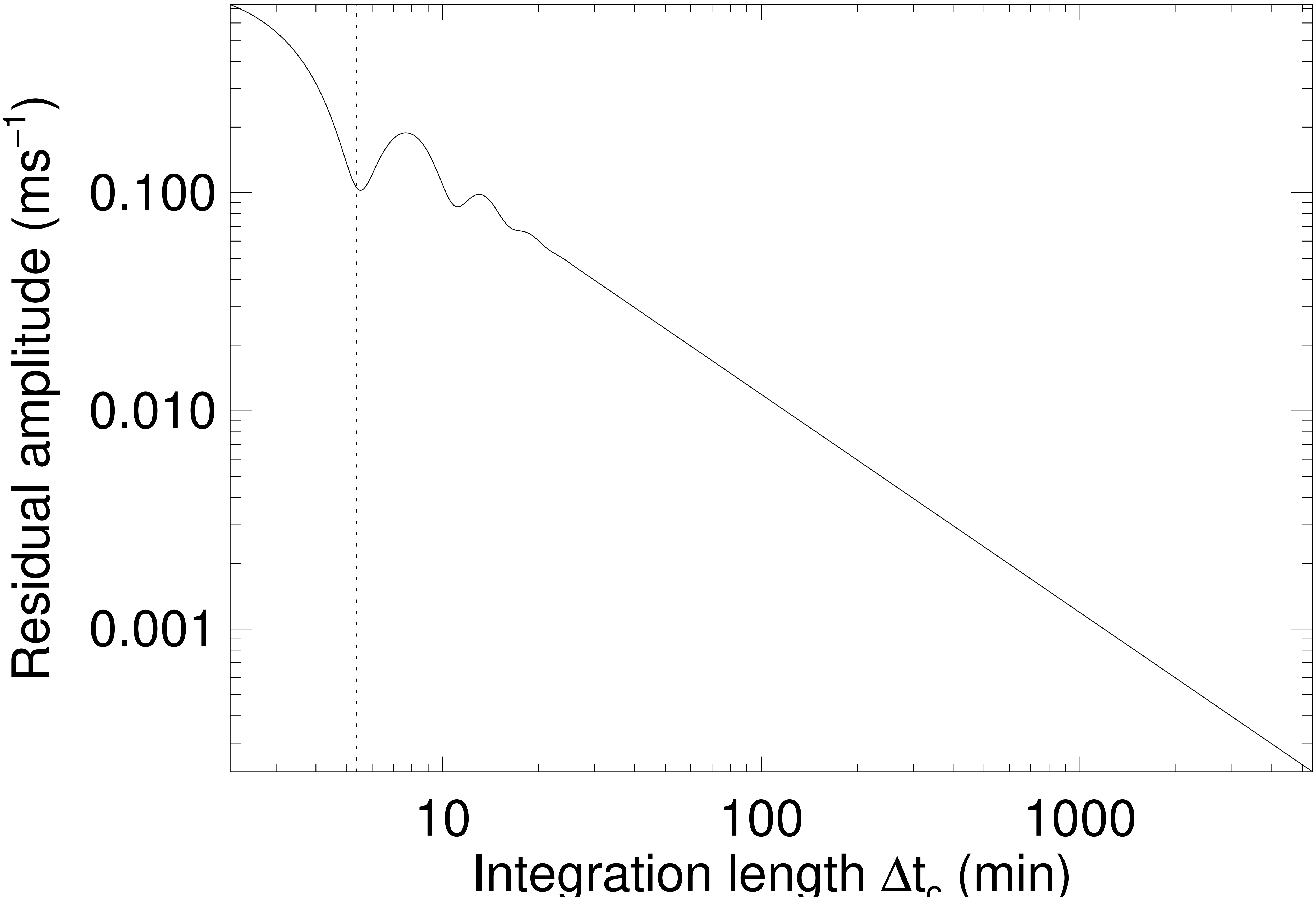
Impact of various exposure lengths



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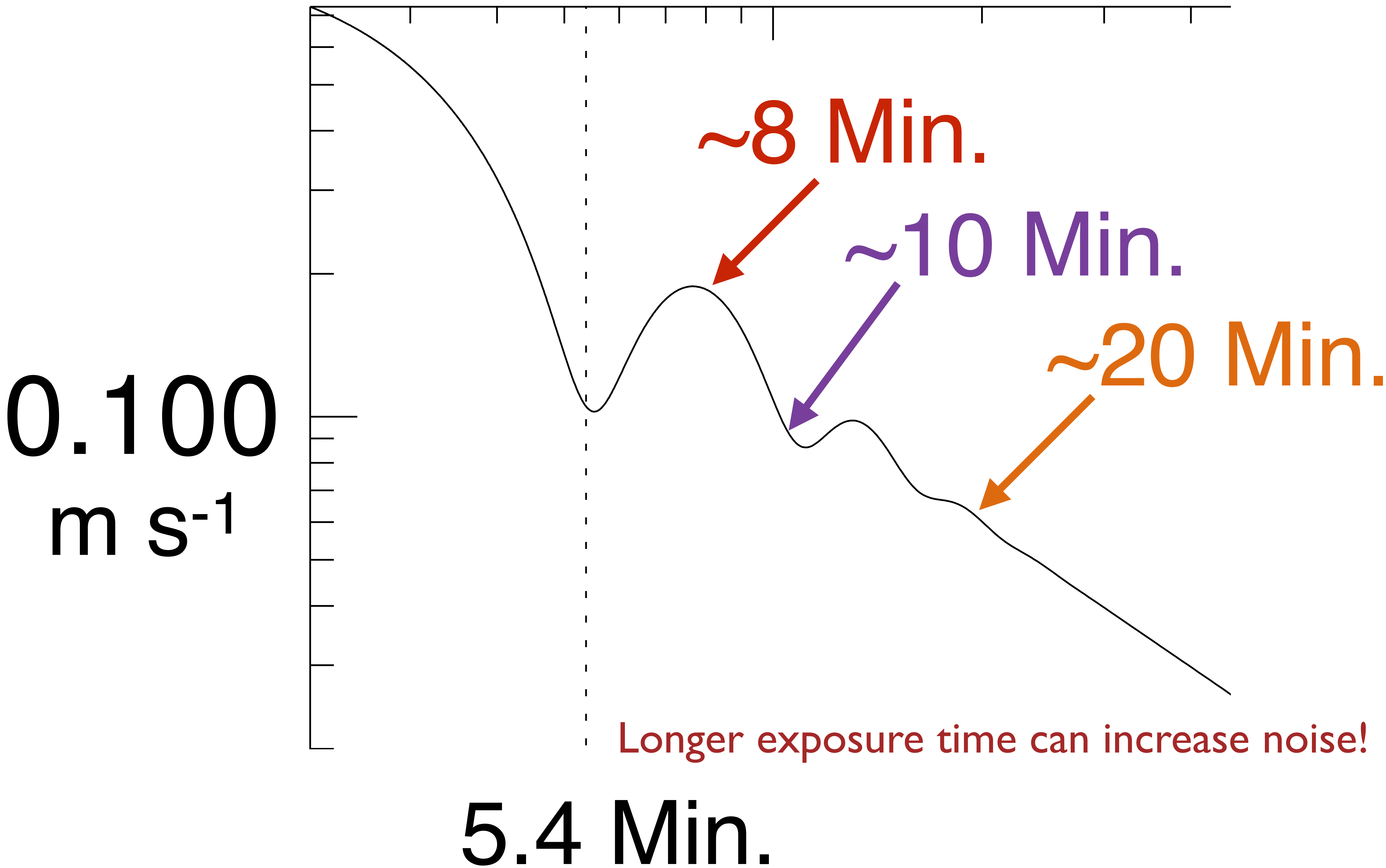

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Chaplin, Cegla et al. (2019)

Calculating the best exposure time for any star

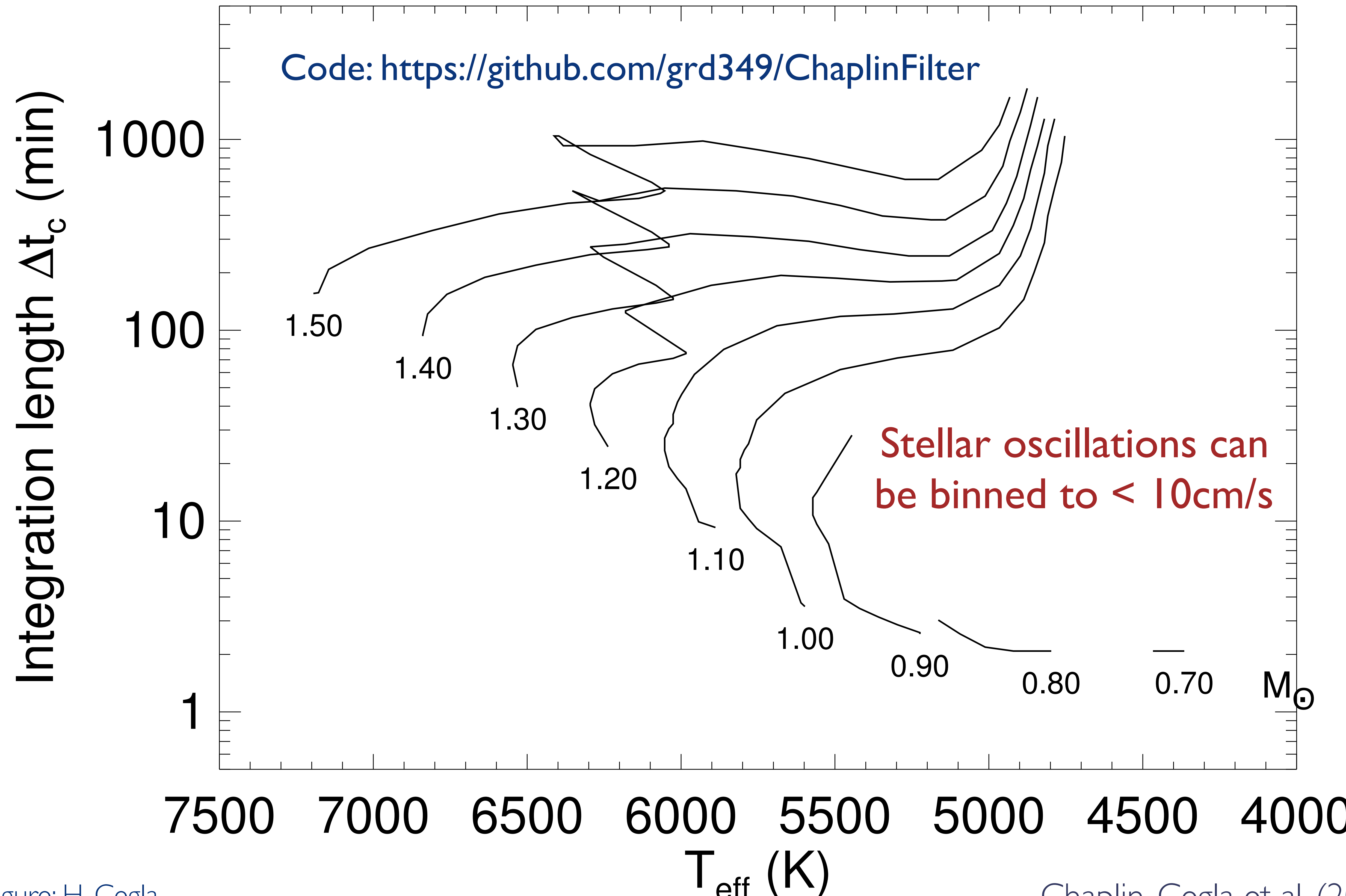


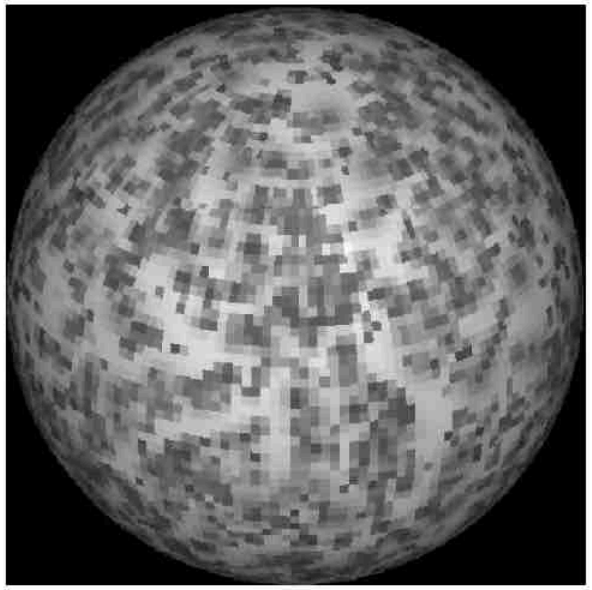
Figure: H. Cegla

Chaplin, Cegla et al. (2019)

Beware of degeneracies!

Jeffers & Keller (2009)

Synthetic stellar surface



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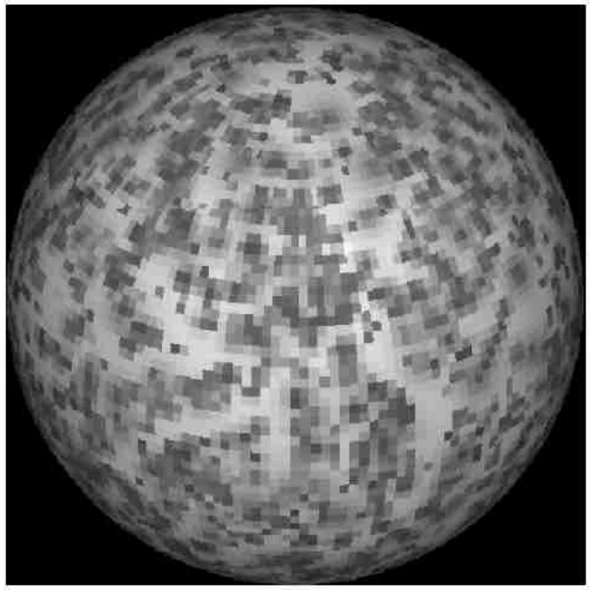
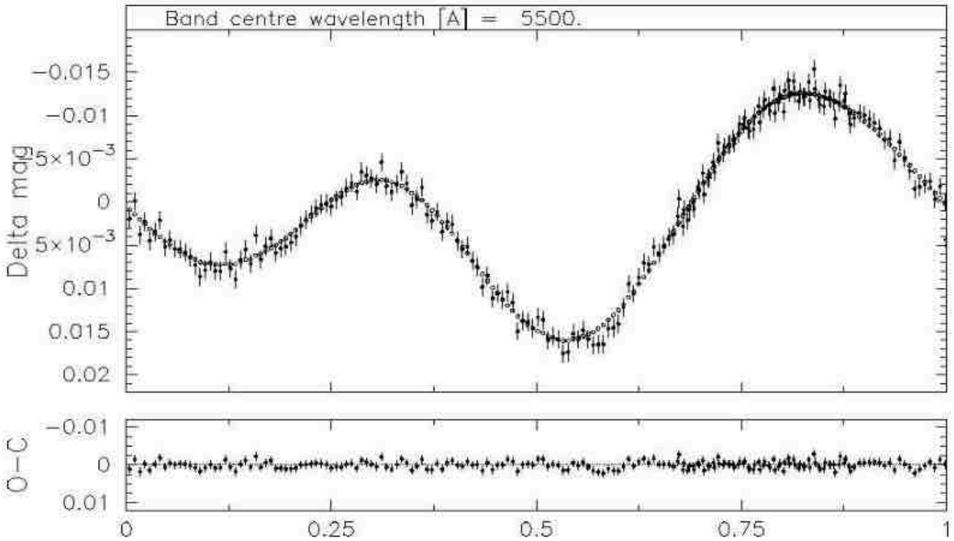


Reconstructed lightcurve



One rotation period

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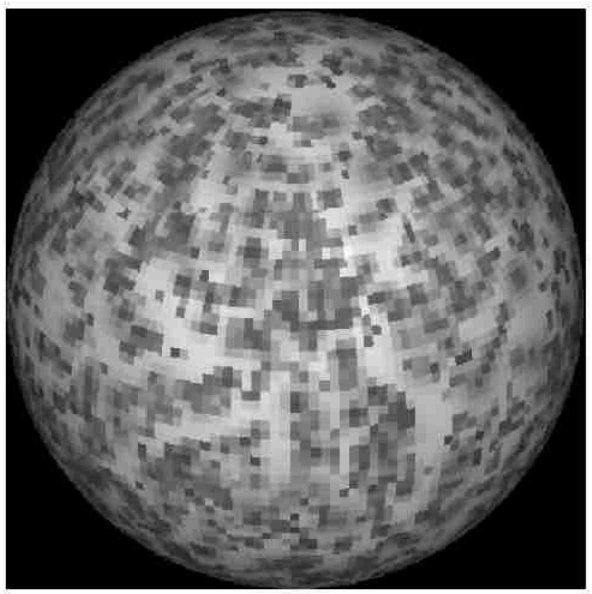

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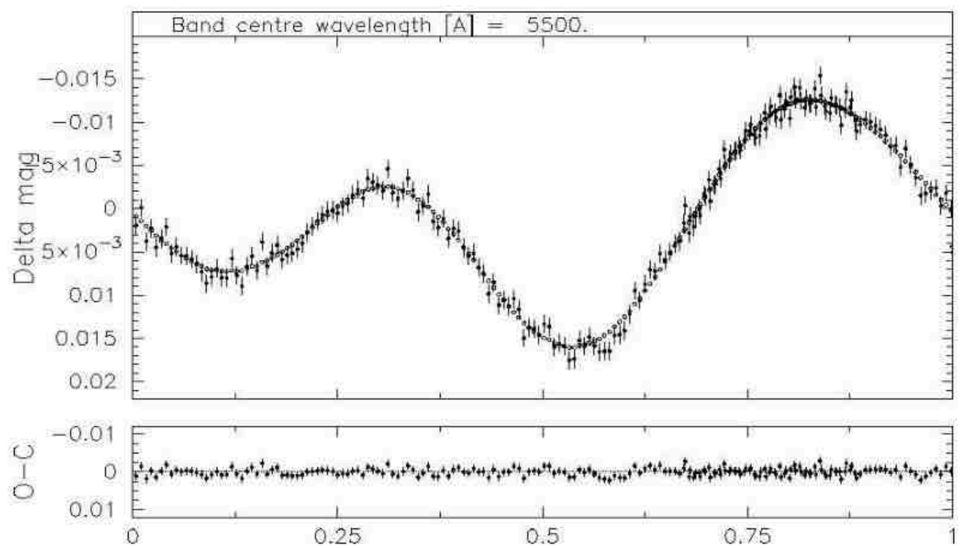
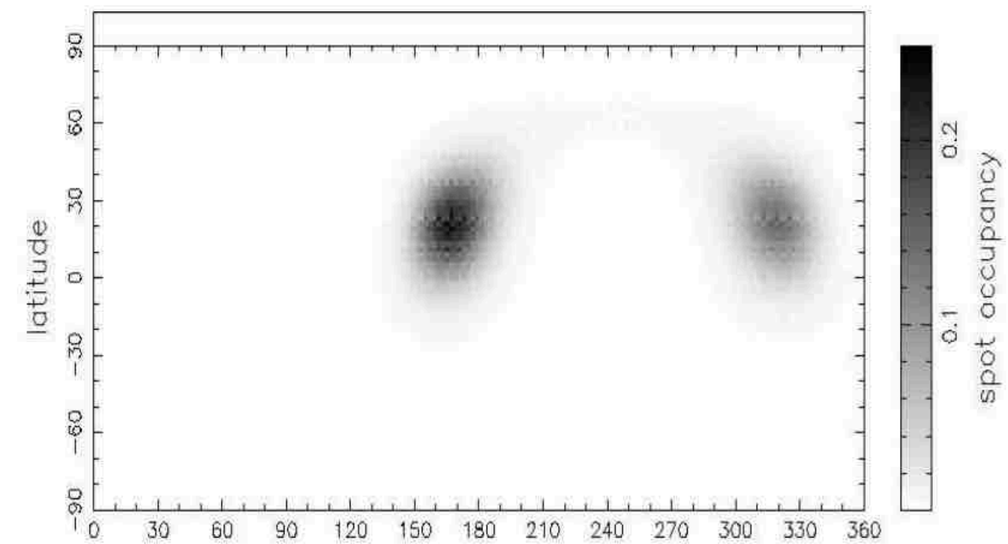


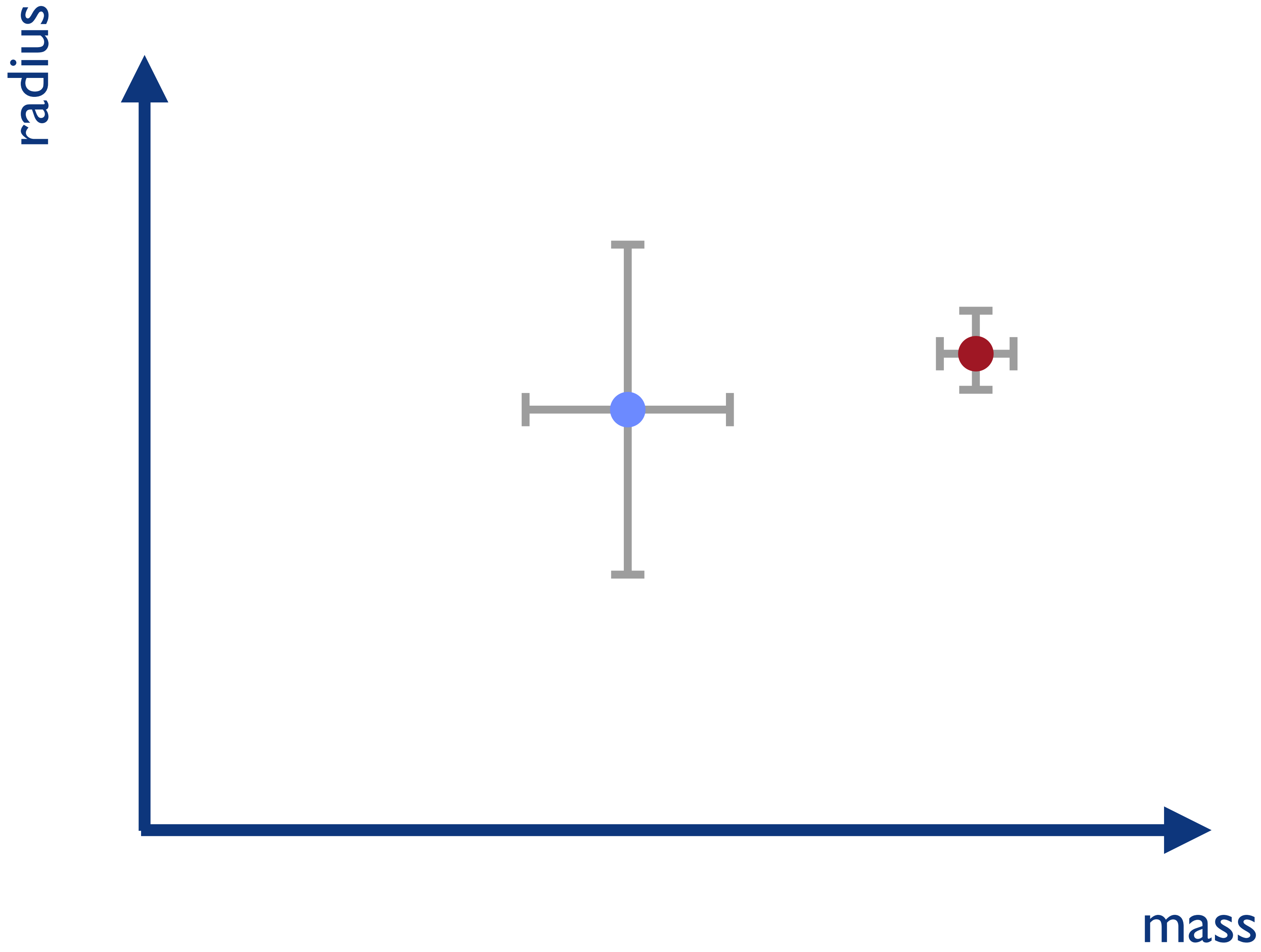
One rotation period

Reconstructed surface map



Longitude

Accuracy and precision of a parameter estimate



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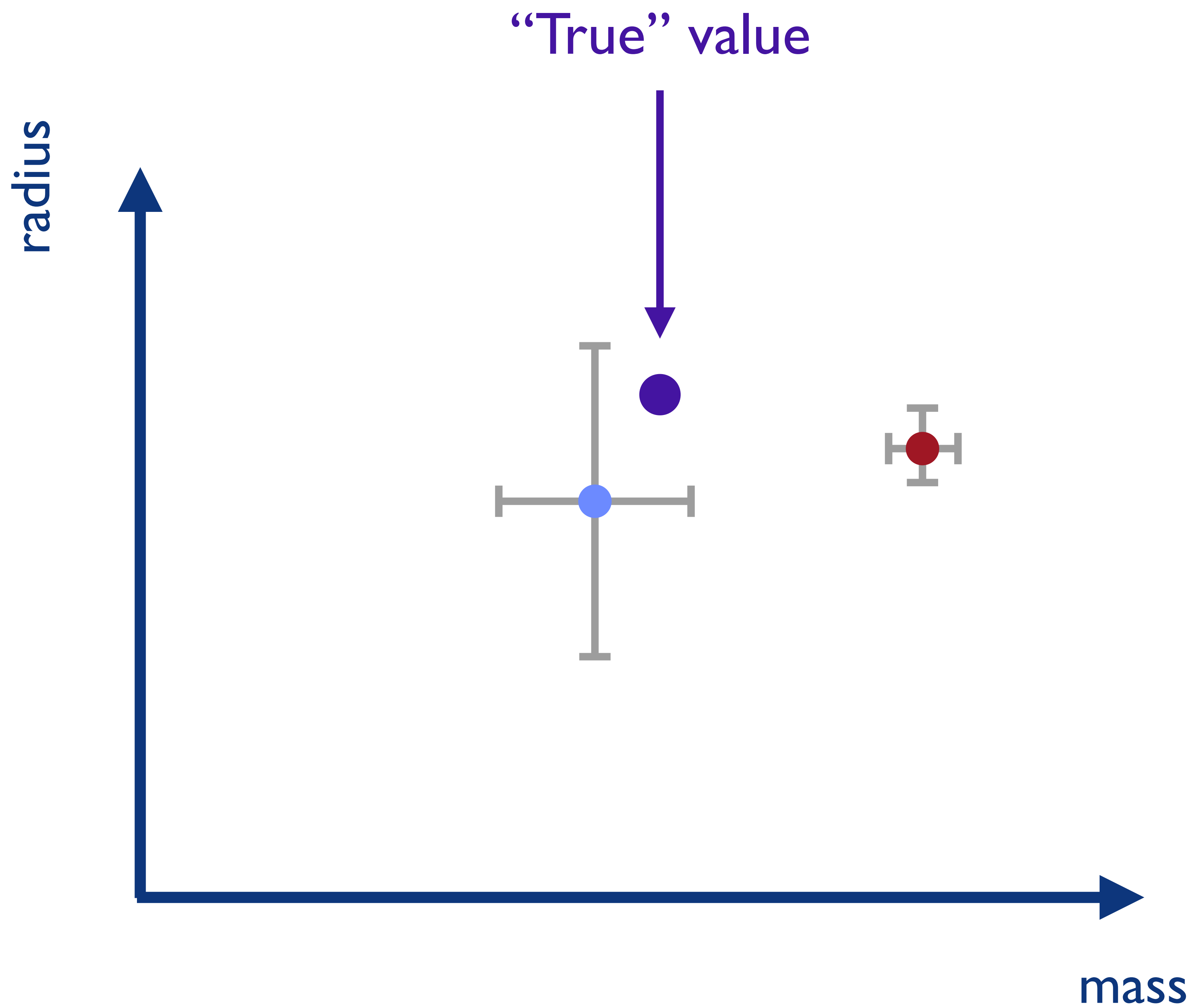

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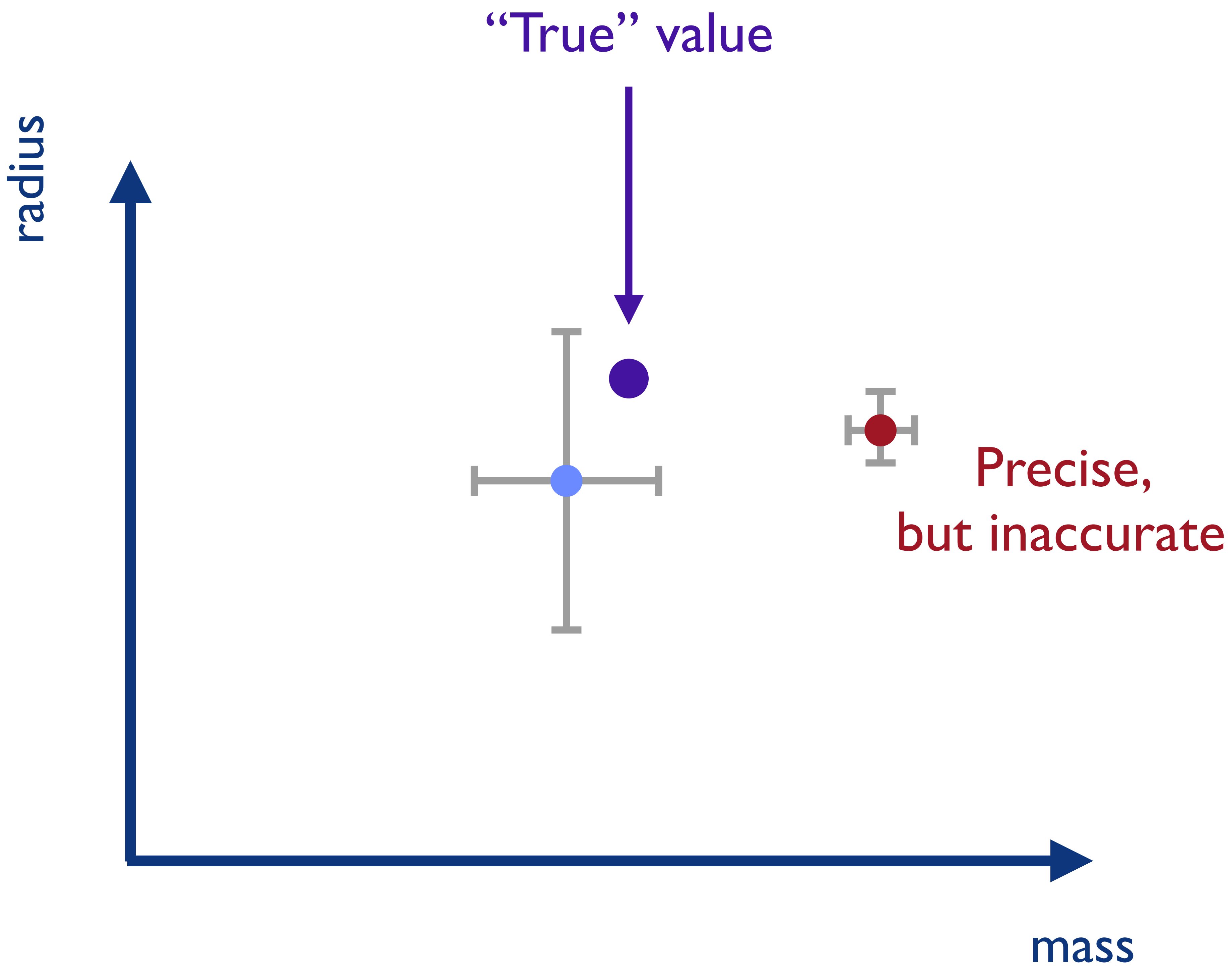

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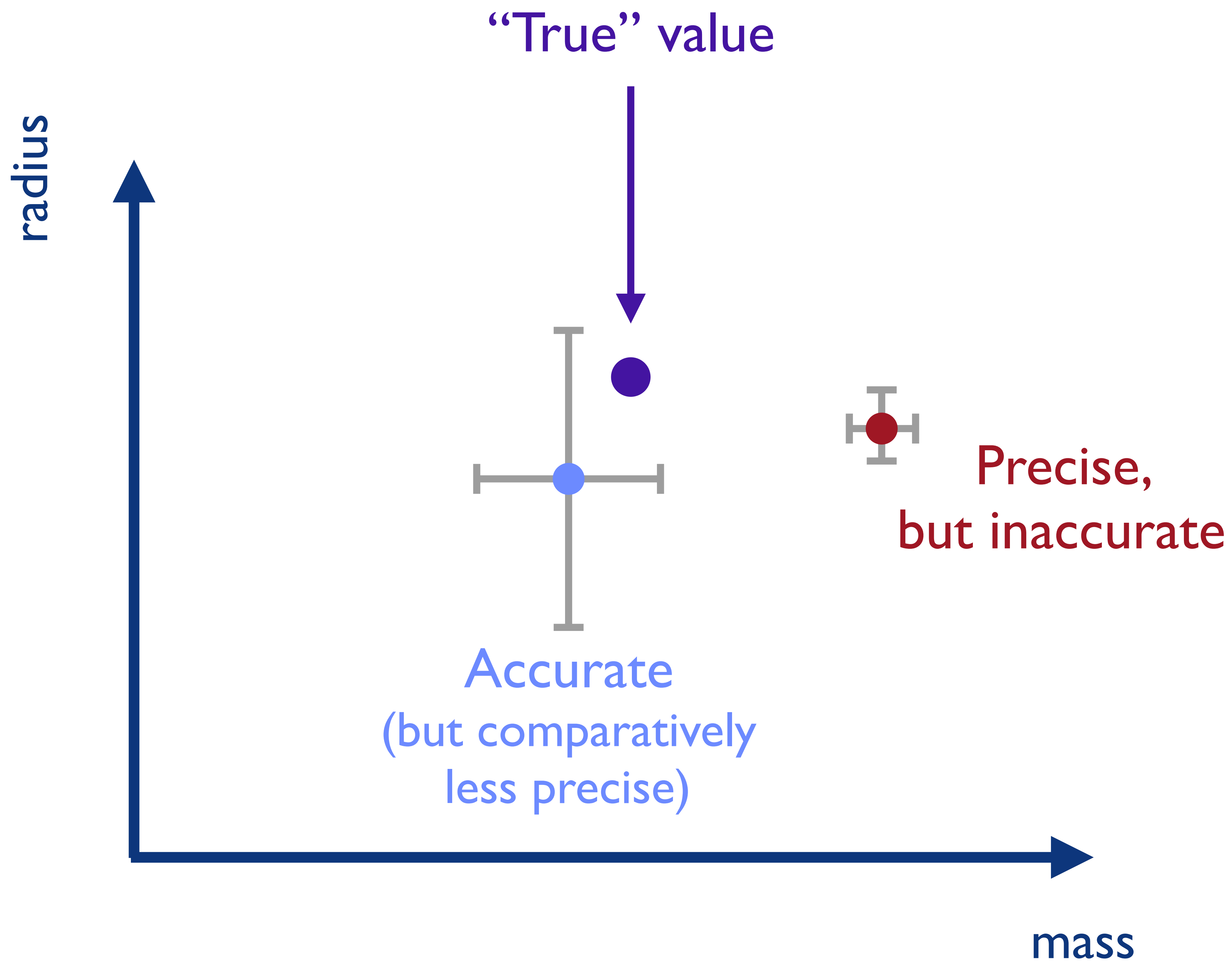

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