Stellar activity and exoplanet observations

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About me

- Reseacher at INAF – Catania Astrophysical Observatory, Italy (2018-)

- Postdoc at Space Telescope Science Institute, Baltimore, MD, USA (2016-2018)

- PhD at Aix-Marseille University/Astrophysics Laboratory of Marseille, France (2012-2015)

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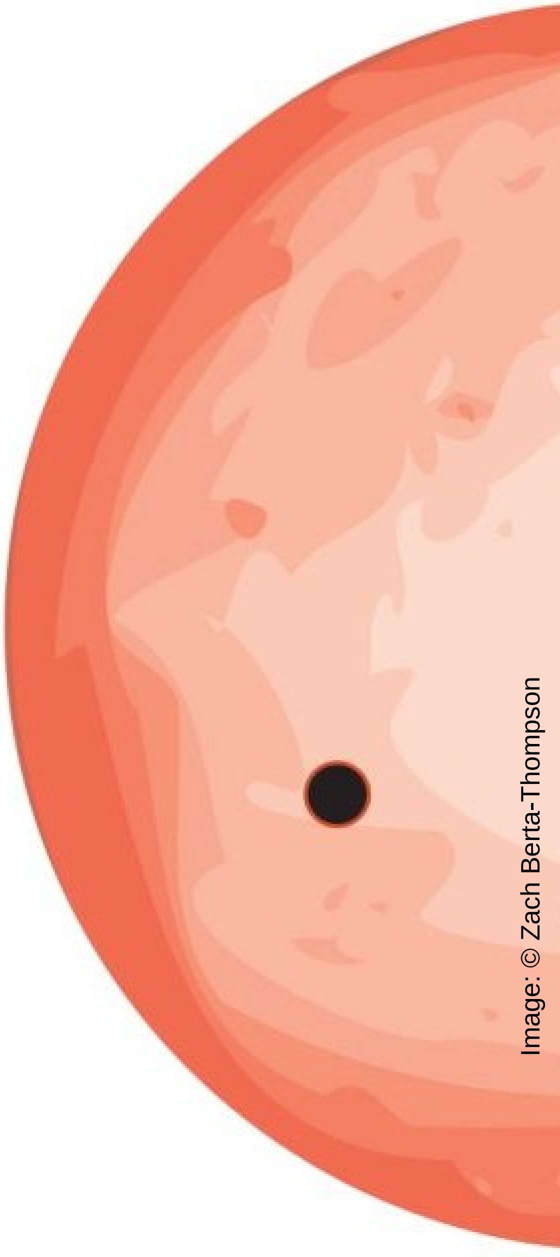


Image: © Zach Berta-Thompson

Outline

Starspots and faculae

- Observational highlights
- Main effects on exoplanet observations, current mitigation strategies
  - Transits
  - Radial velocity

Stellar granulation

Perspectives on upcoming space missions

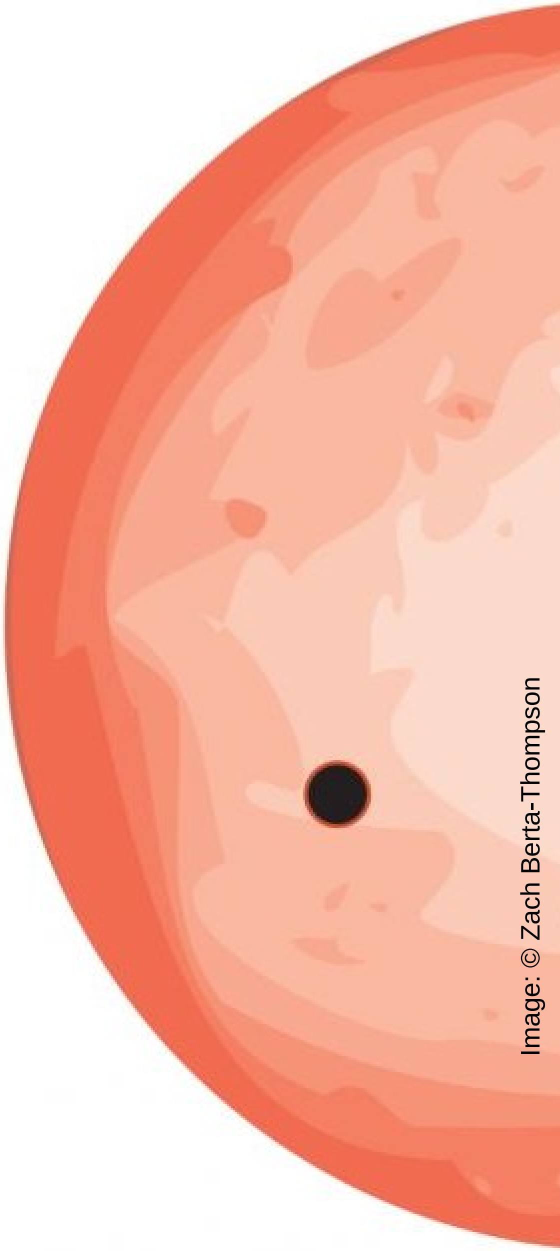
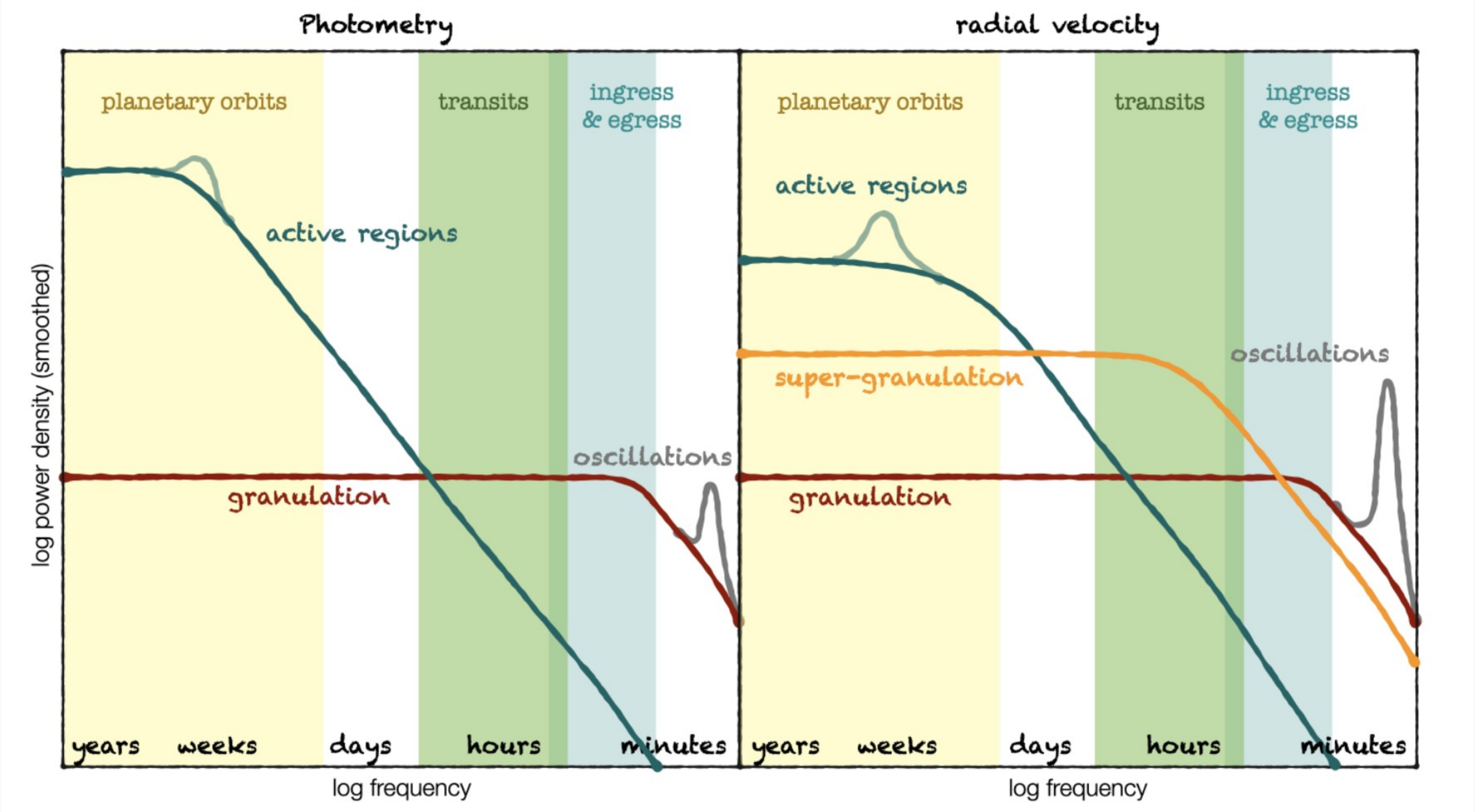


Image: © Zach Berta-Thompson

Timescales involved

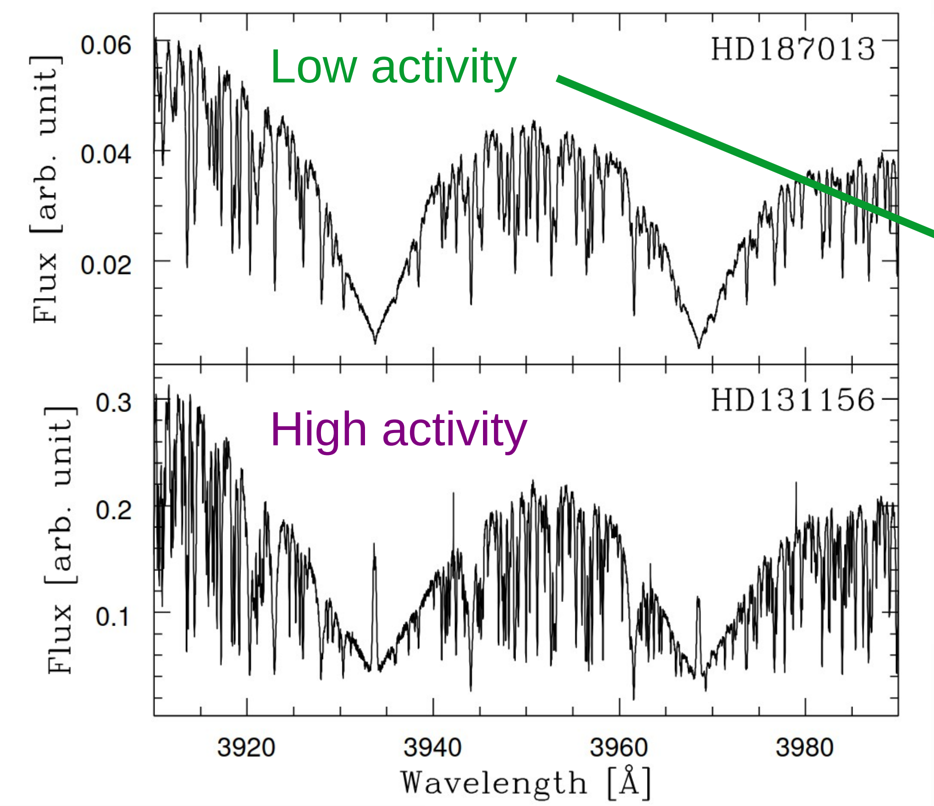


Courtesy of S. Aigrain

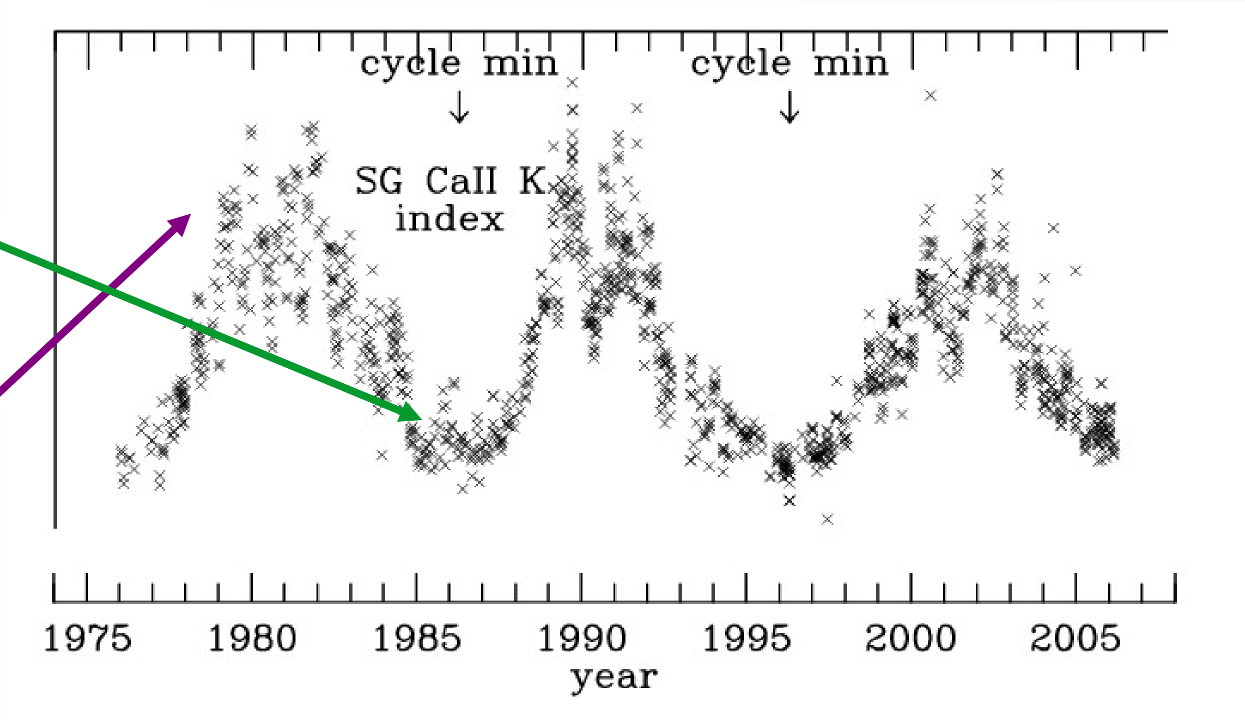
Spectroscopic stellar activity indicators

Mount-Wilson S-index

Boisse+2010



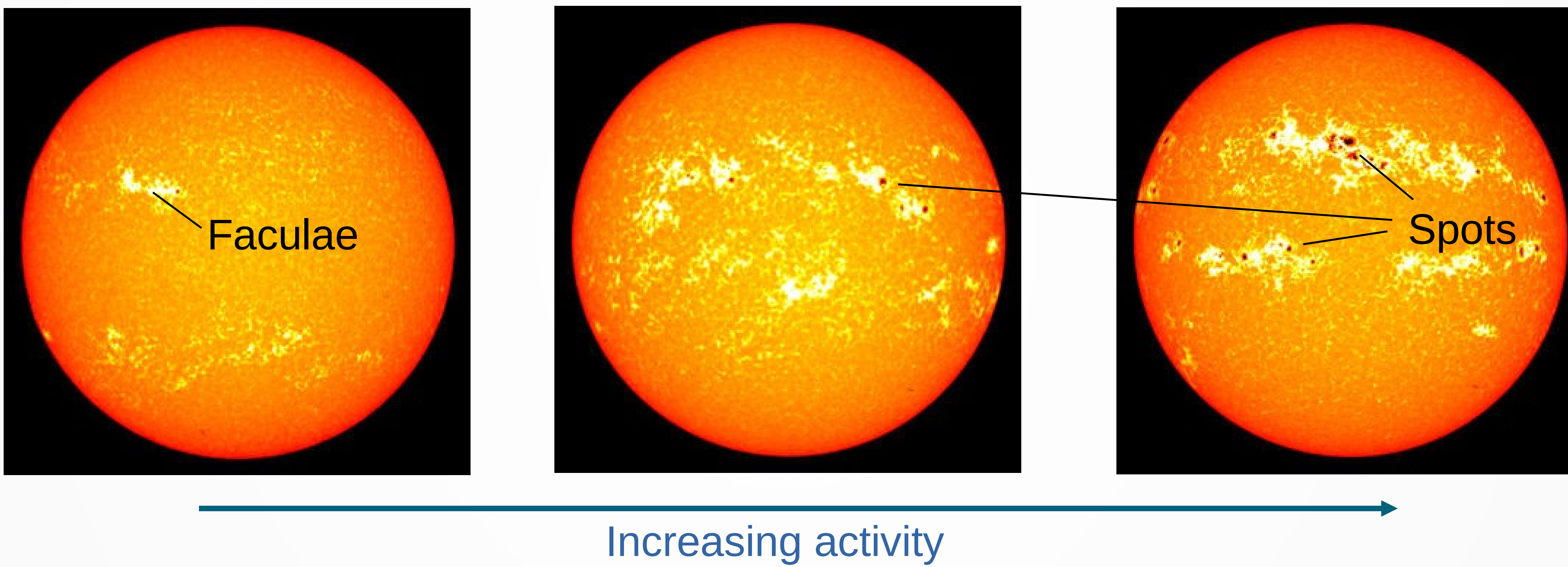
Sun-as-a-star



Livingston et al. (2007)

Wilson (1968)
Vaughan et al. (1978)
Noyes et al. (1984)
Lyra et al. (2005)
...

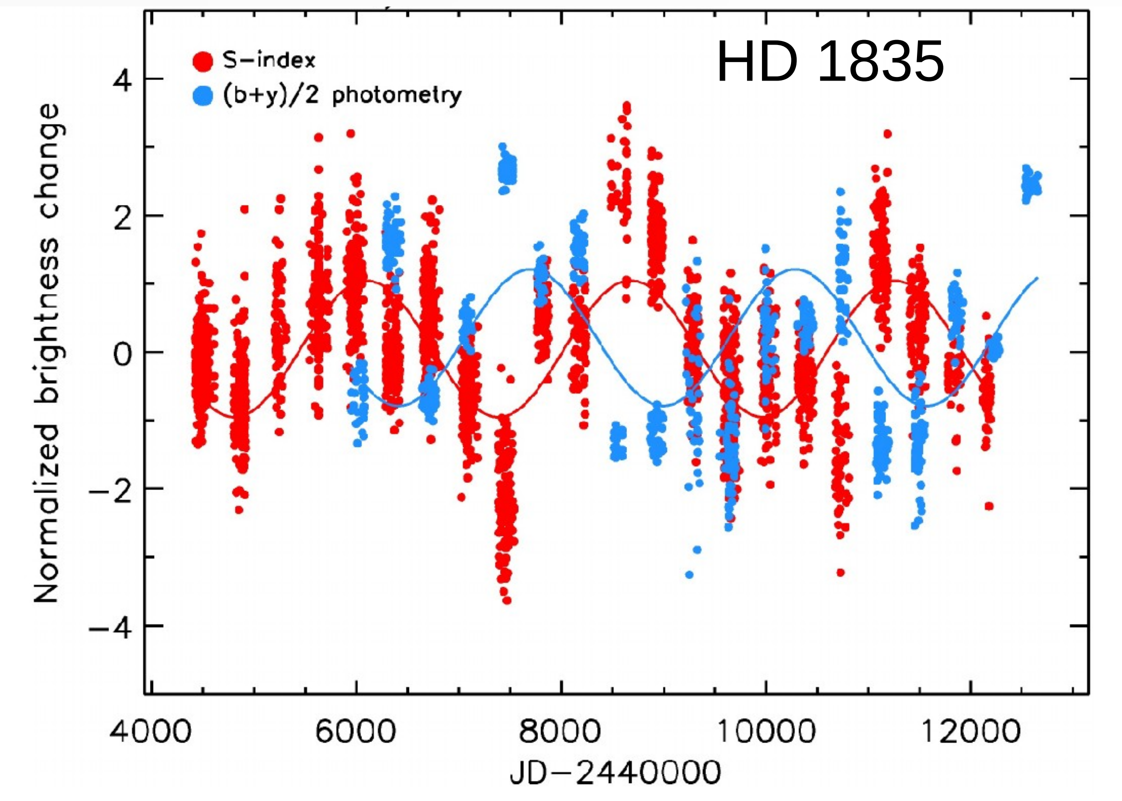
Photospheric active regions

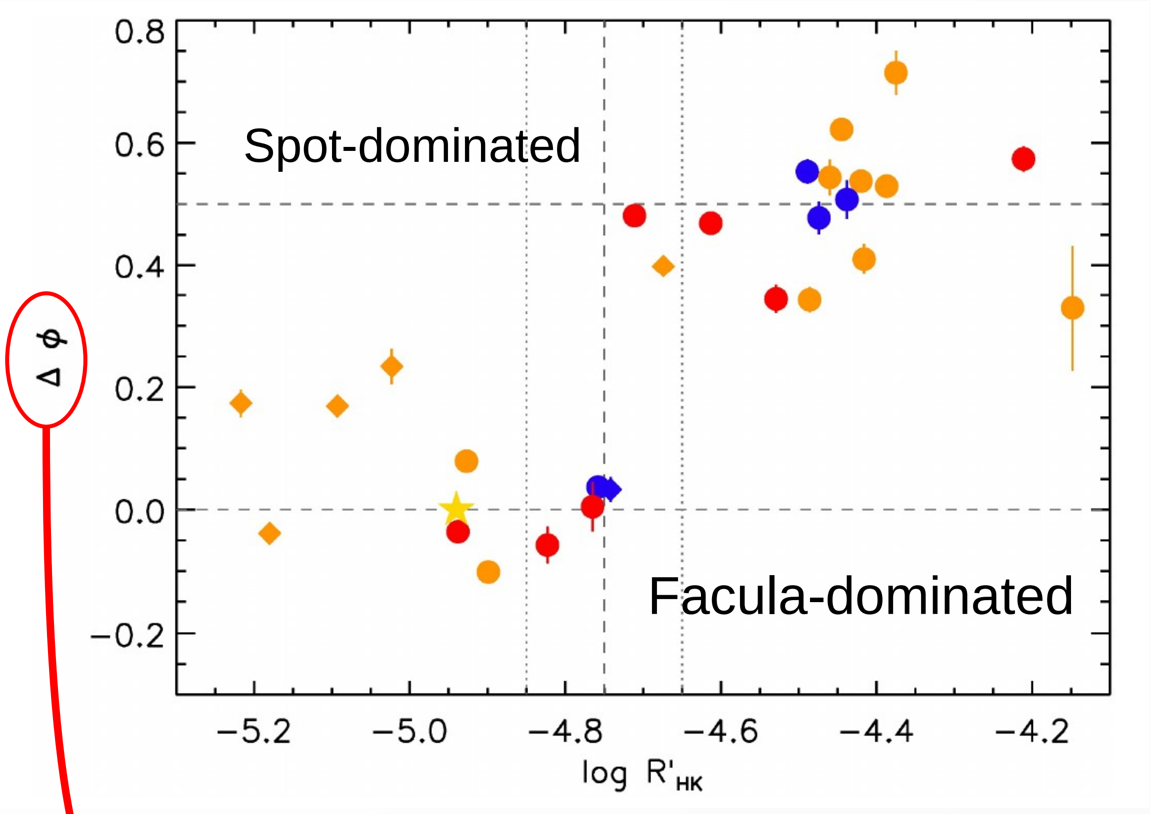


NASA/Goddard Space Flight Center

Scientific Visualization Studio. Source data courtesy of HAO & NSO PSPT project team. HAO is a division of the National Center for Atmospheric Research which is supported by the National Science Foundation.Special thanks to Vanessa George (University of Colorado/LASP) and Randy Meisner(Michigan State University)

More active stars are spot-dominated
Less active stars are facula-dominated

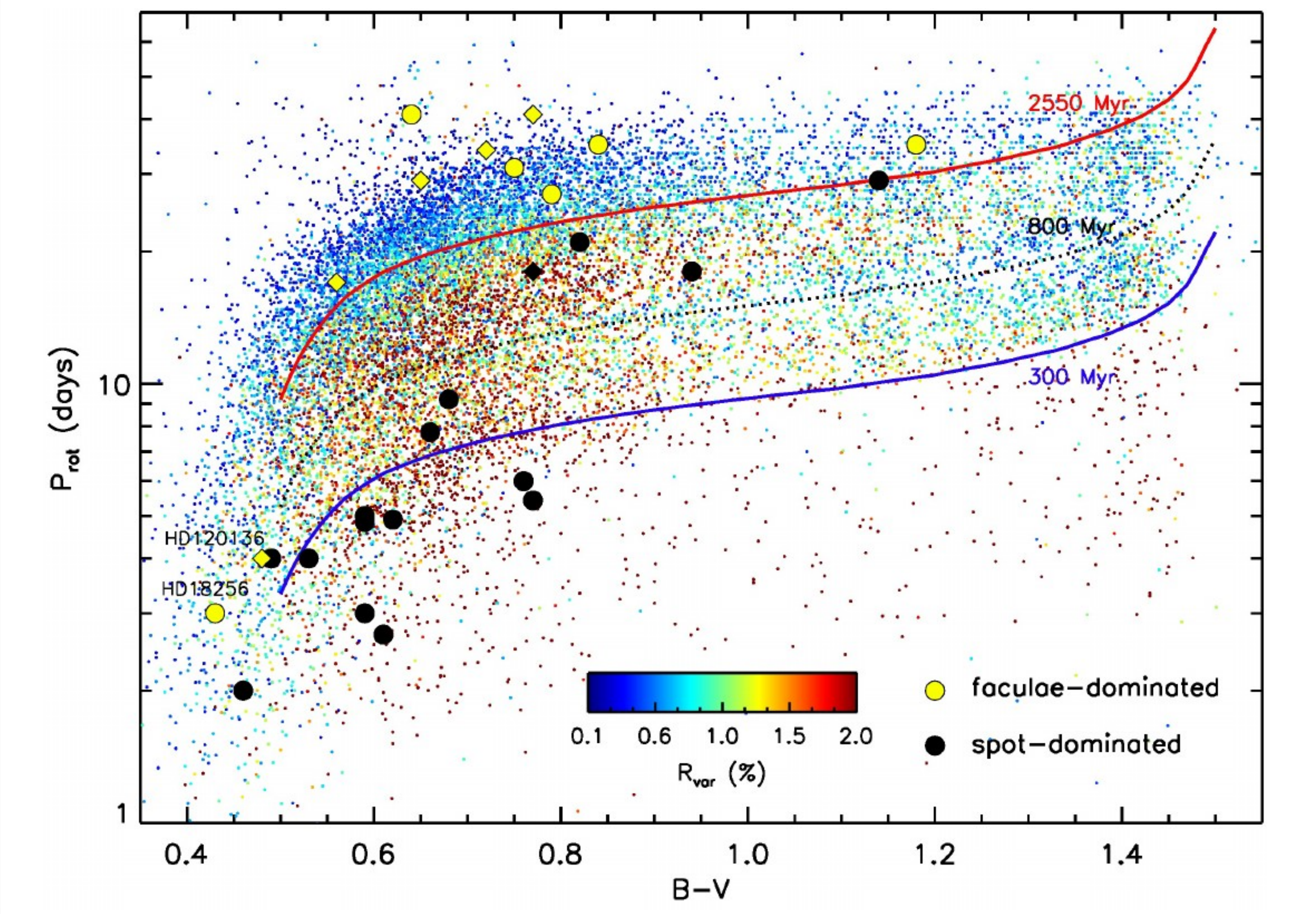




Photospheric vs. chromospheric phase difference

Reinhold+2019

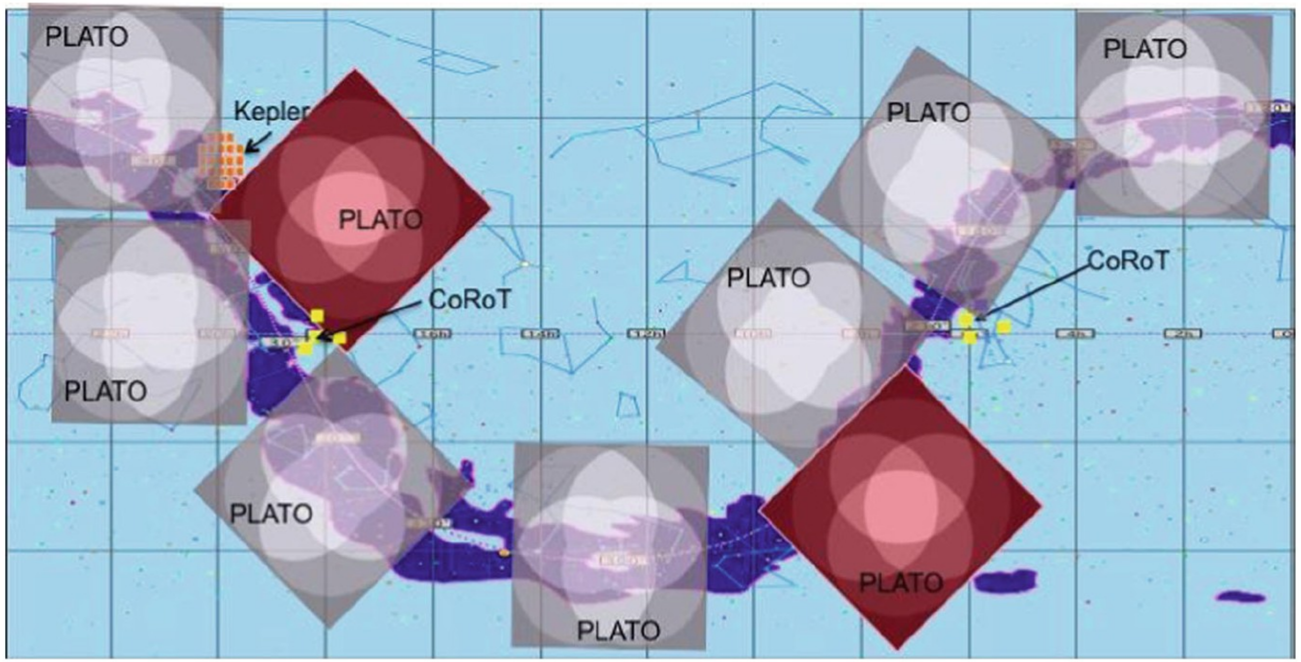
More active stars are spot-dominated
Less active stars are facula-dominated

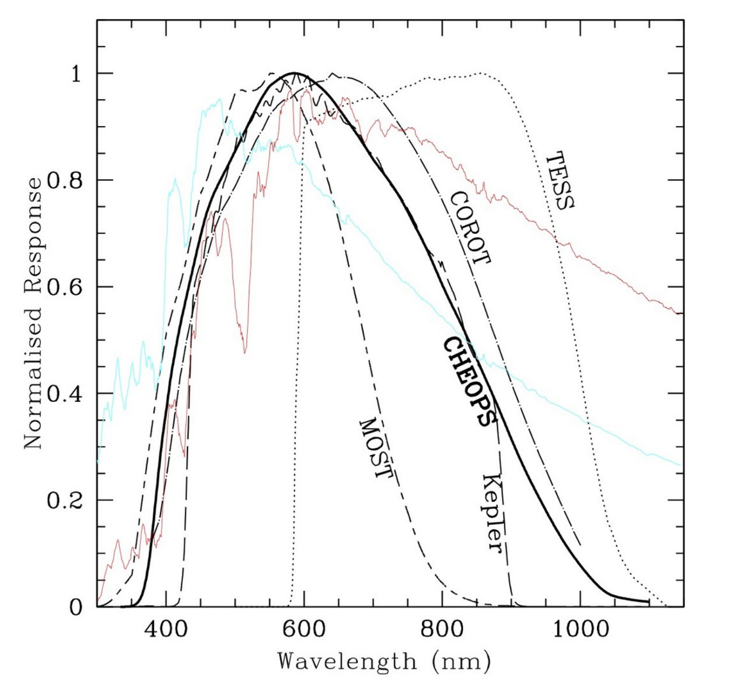


T_{eff}

Reinhold+2019

Space surveys with long baselines

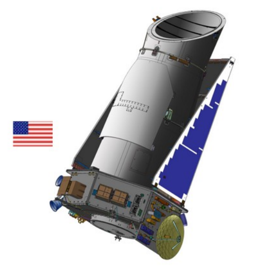




CoRoT(2007-2012)

Precision: 700 ppm/hr
Time sampling: 512 or 32 s
11.5 ≤ mV ≤ 16
~170 000 target stars
(12000 exoplanet)

Kepler/K2 (2009-2018)



Precision: 80 ppm/hr
Time sampling: 32 or 1 min
7 ≤ Kp-mag ≤ 17
170 000 target stars

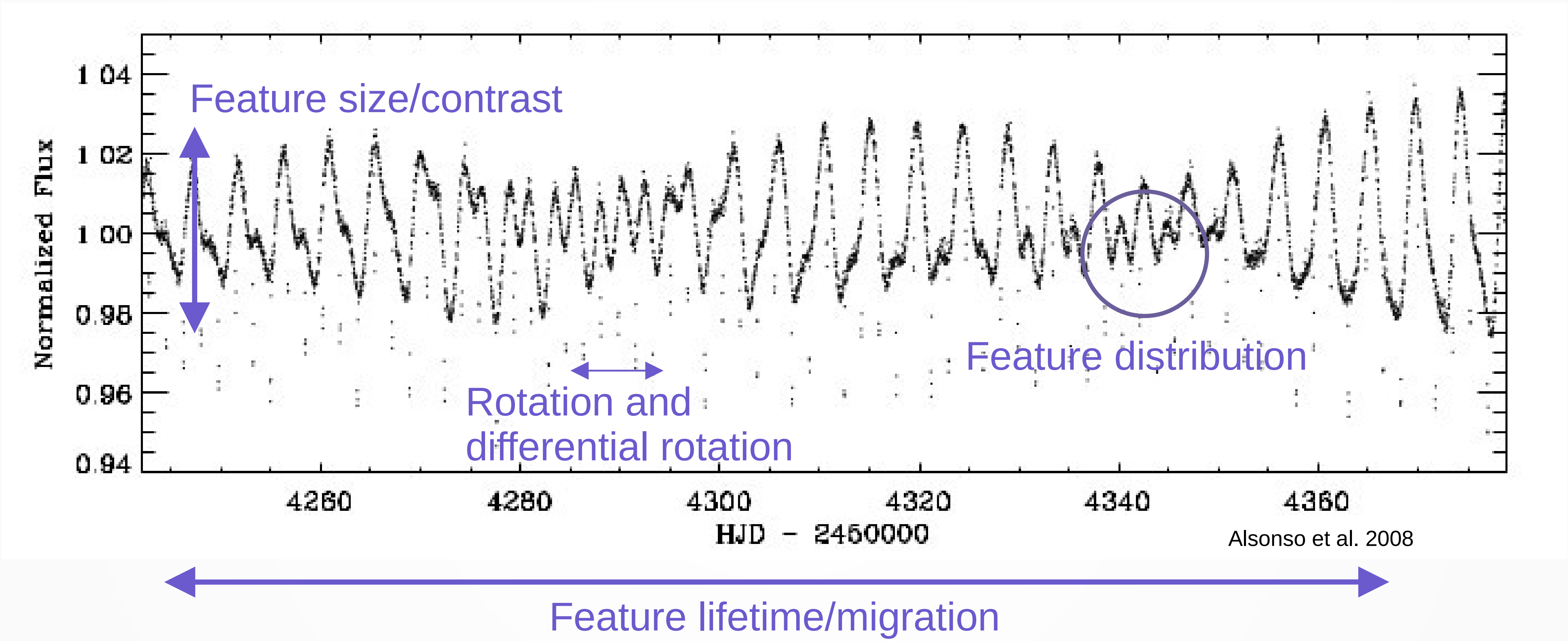
TESS (2018-)

Precision: 60 ppm/hr
Time sampling: 30 or 2 min
6 ≤ I_c ≤ 18
> 200000 FGKM stars

PLATO (2026-2029+)

Precision: 30 ppm/hr until ~11 magV
Time sampling: 25 or 2.5 s
8 ≤ magV ≤ 16
>1 million tragets
(85 000 magV < 11)

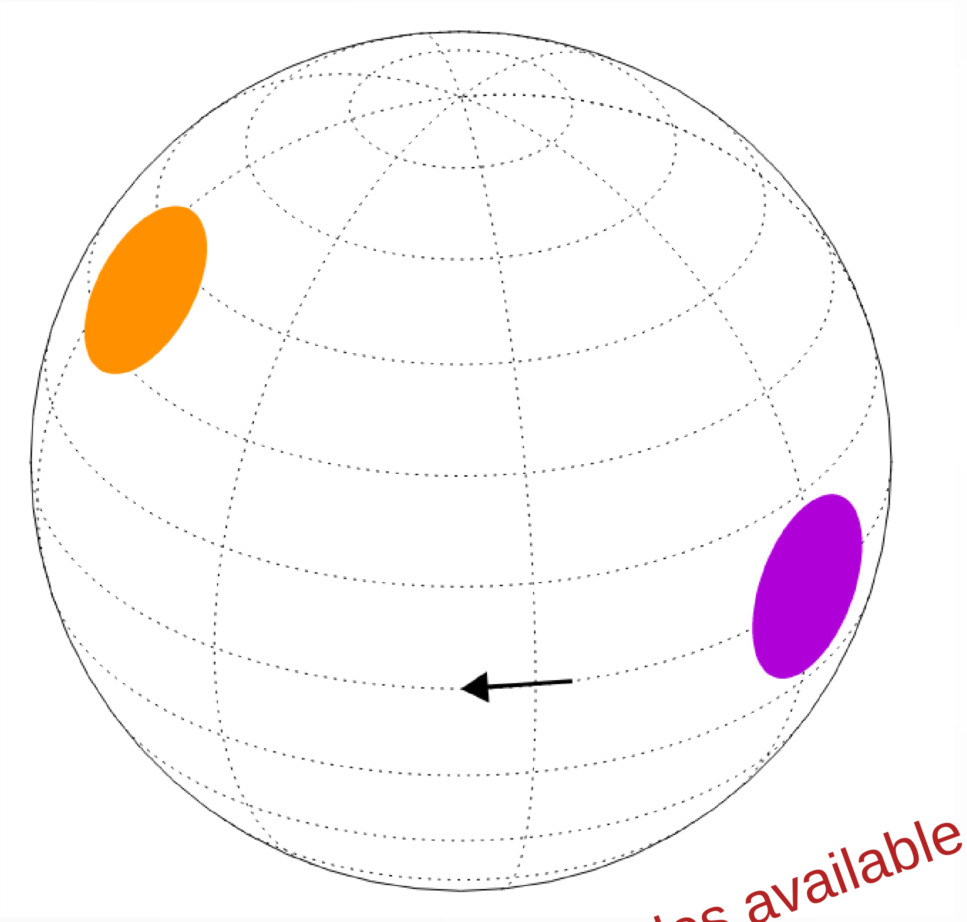
Young G7V star, school case: CoRoT-2



Amplitude variation: ~20x solar max

P_{rot}: ~4.5 days (Sun: 24-38 days)

Light curve modelling



Davenport+2015

Several codes available

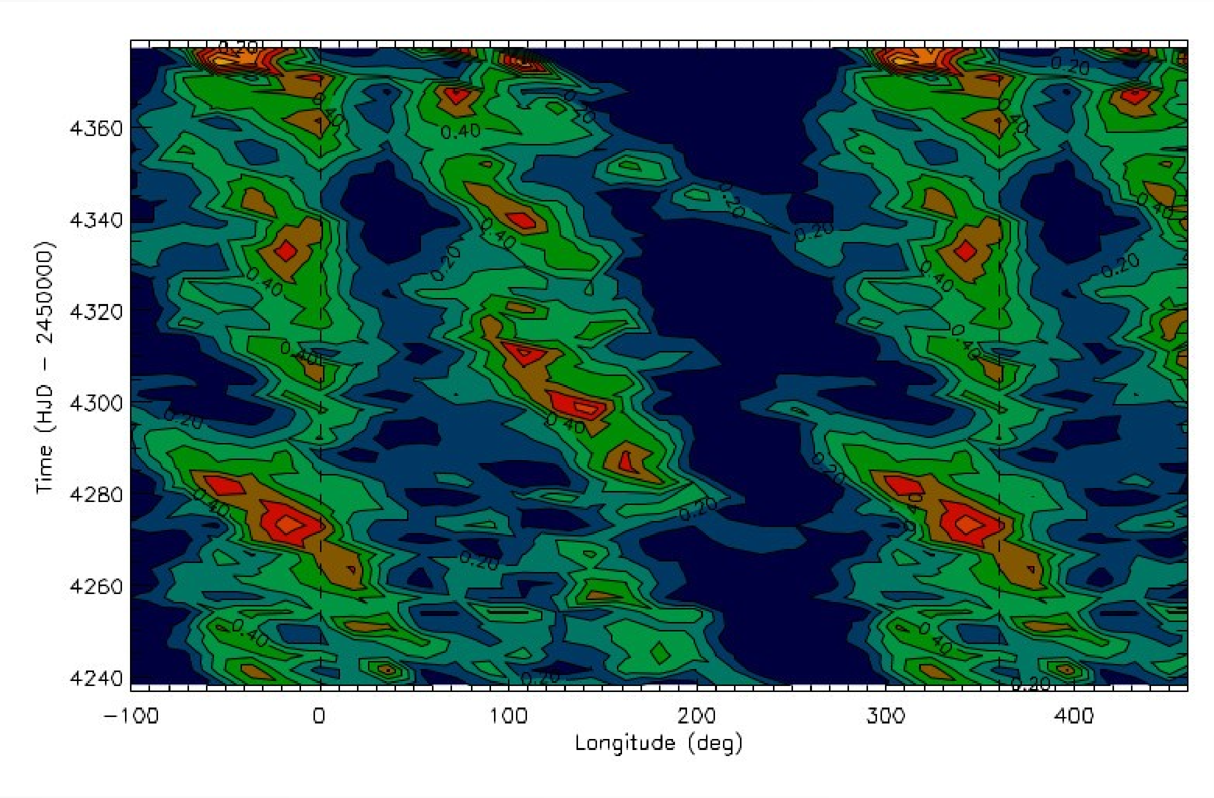
<u>Flexible, can be put in Bayesian framework, but degenerate solutions</u>

Longitude
Latitude (no constraint without occultation)
Contrast
Size
Stellar obliquity
Rotation period

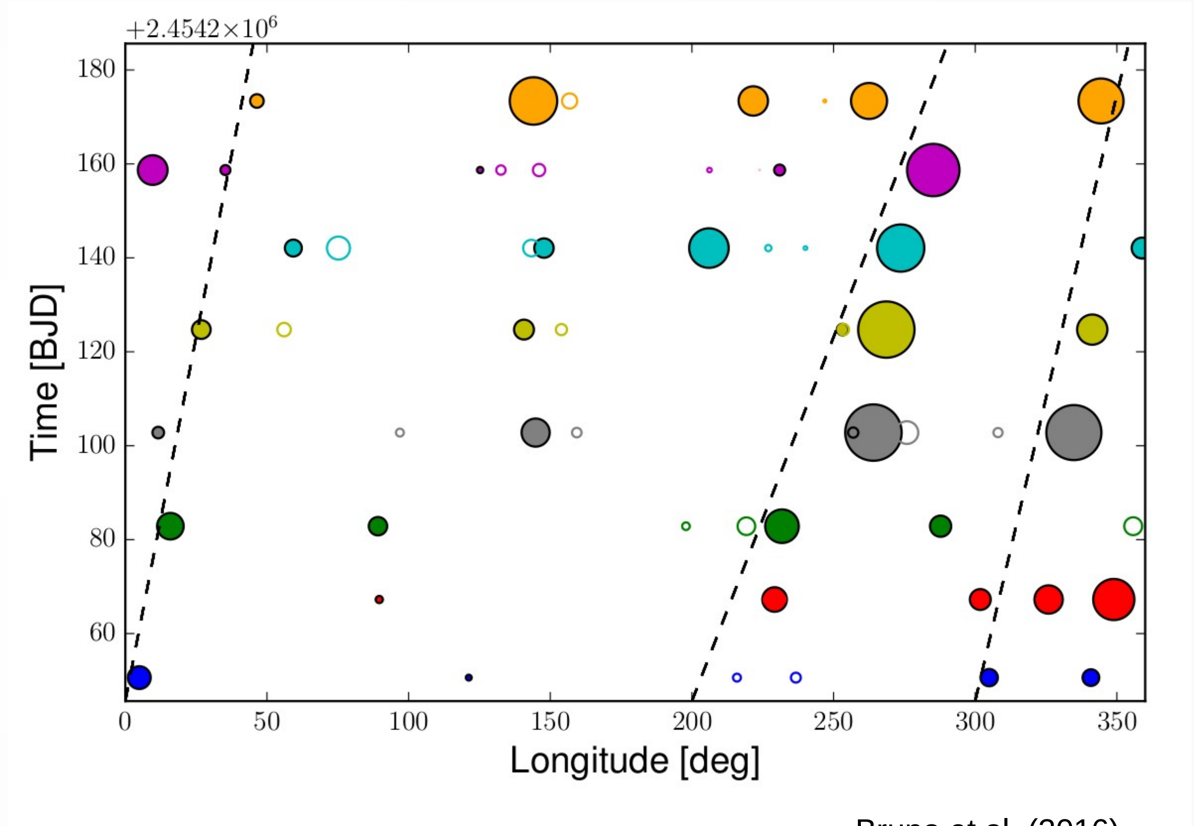
Starspot limb darkening
Faculae limb brightening (currently not characterised)

Starspot/faculae number
Starspot/faculae size evolution

Light curve modelling



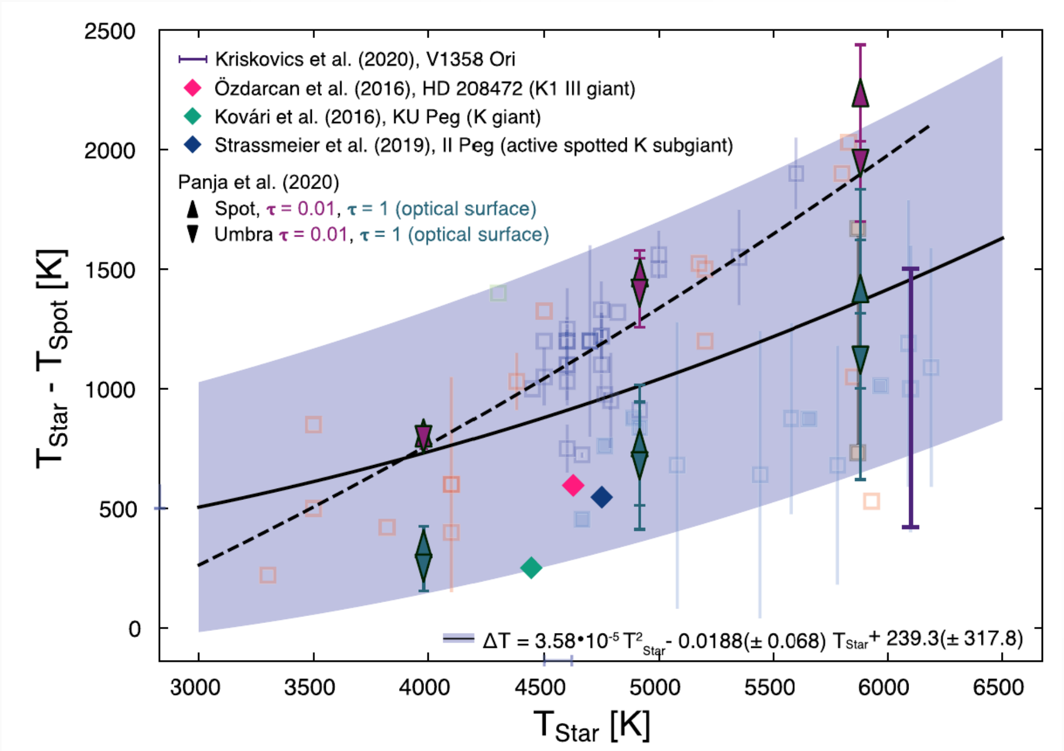
Lanza et al. (2009)



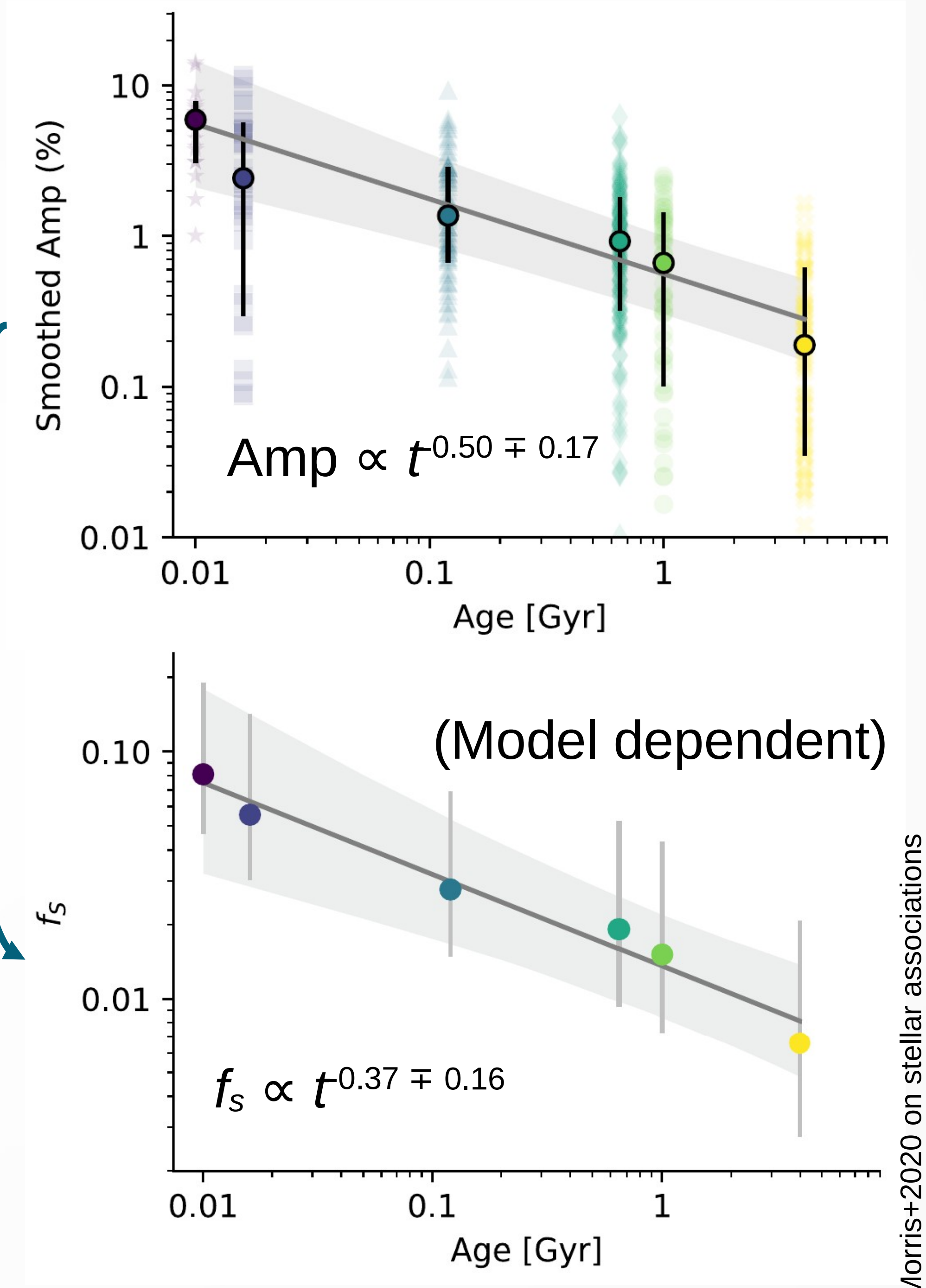
Bruno et al. (2016)

Starspot trends

Techniques (e.g. Berdyugina 2005)
- Photometry
- Spectroscopy
- Polarimetry
- Interferometry
- Microlensing



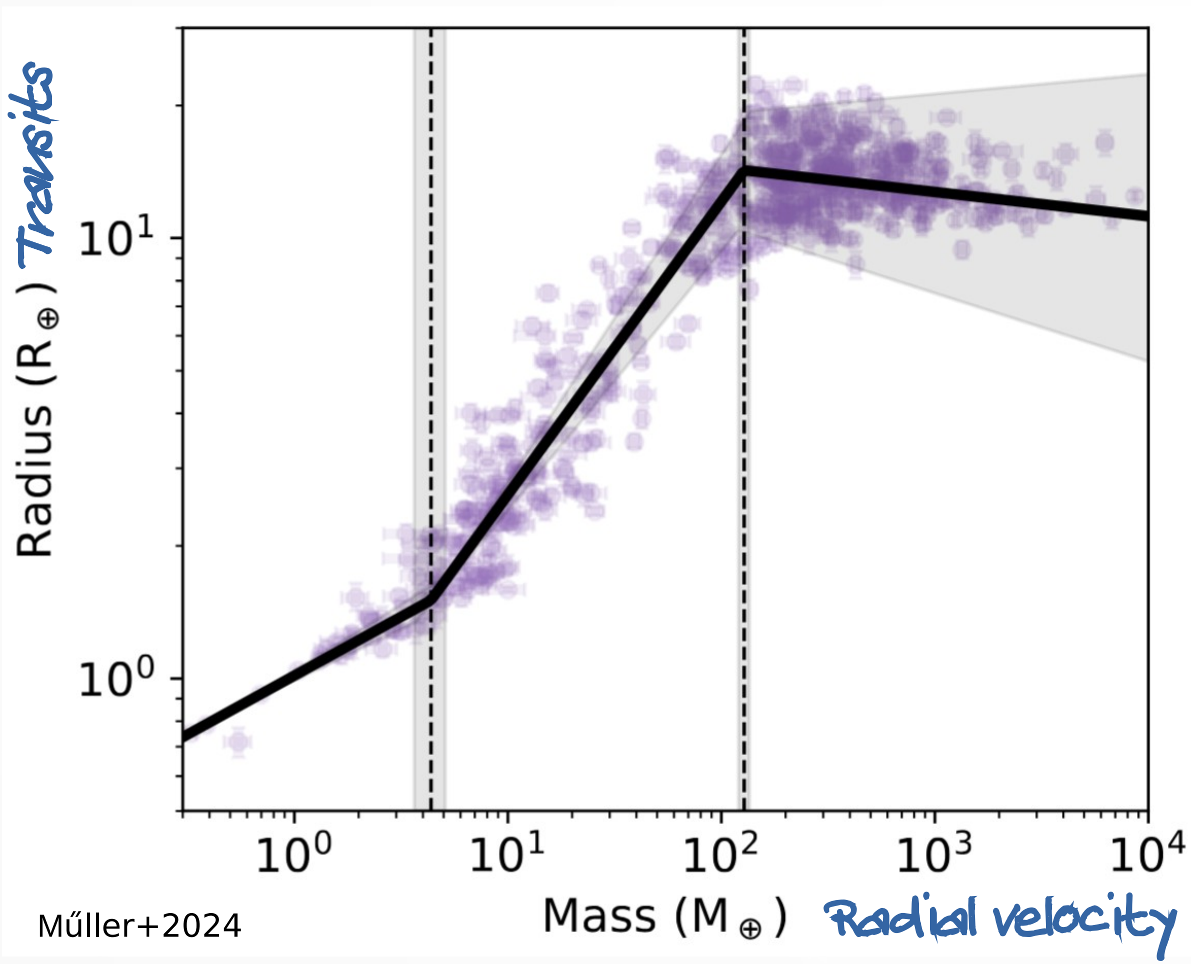
Herbst+2021
Berdyugina (2005)

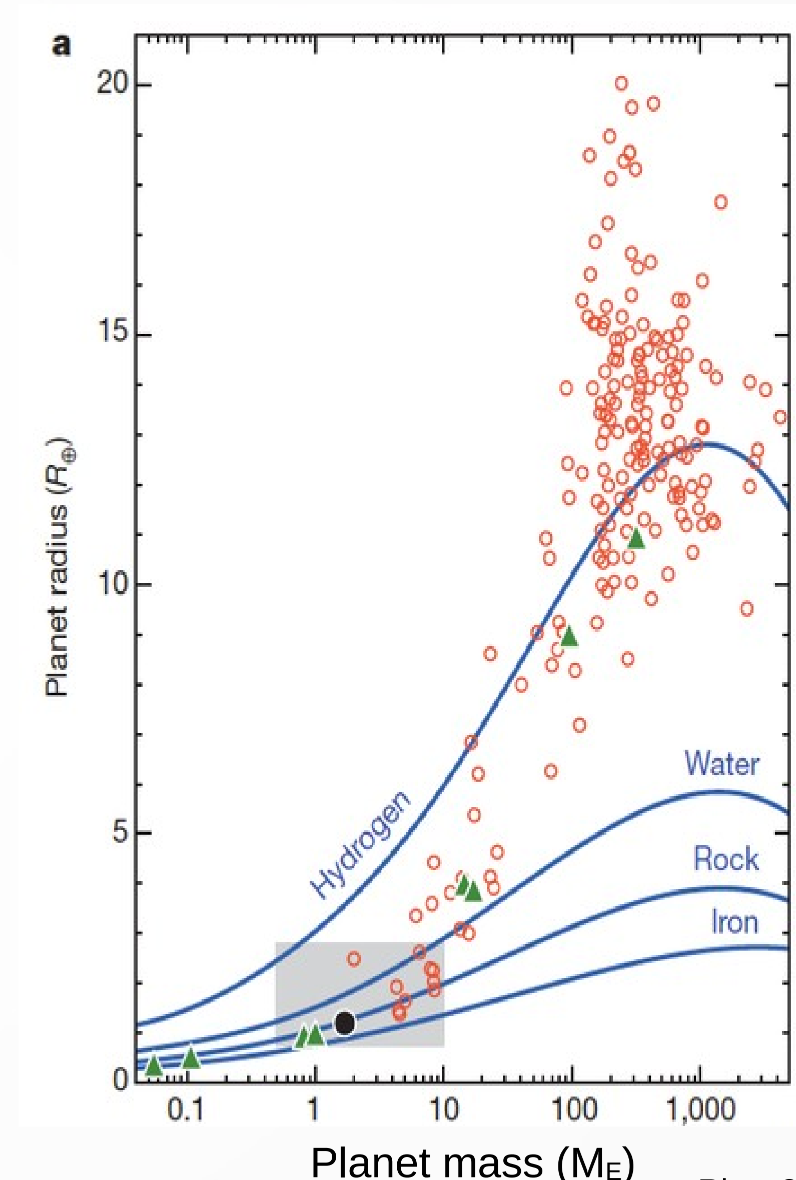


Morris+2020 on stellar associations

What’s the matter with planets?

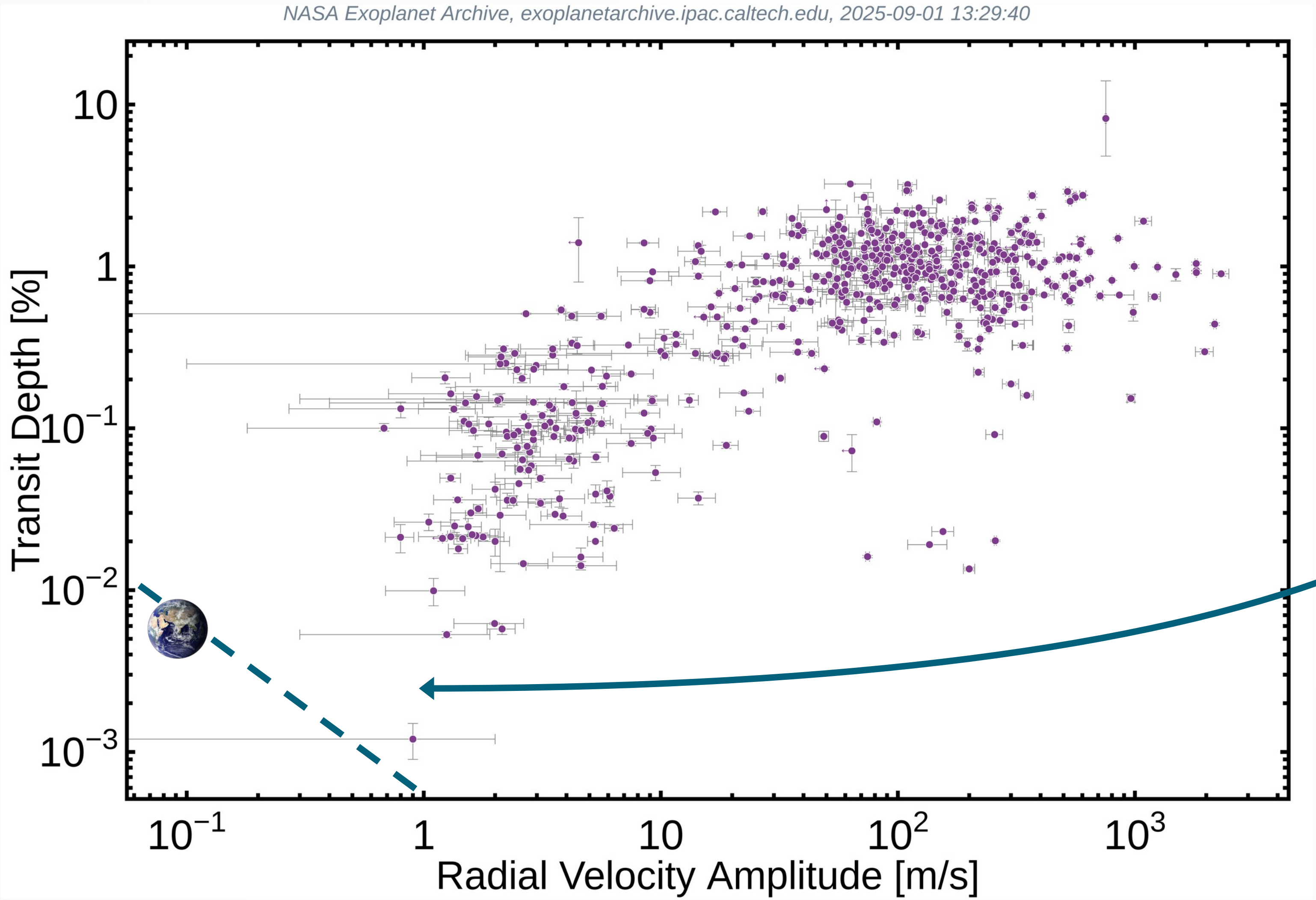
Measured masses, radii and inferred internal/atmospheric composition are affected by stellar activity





Rice+2014

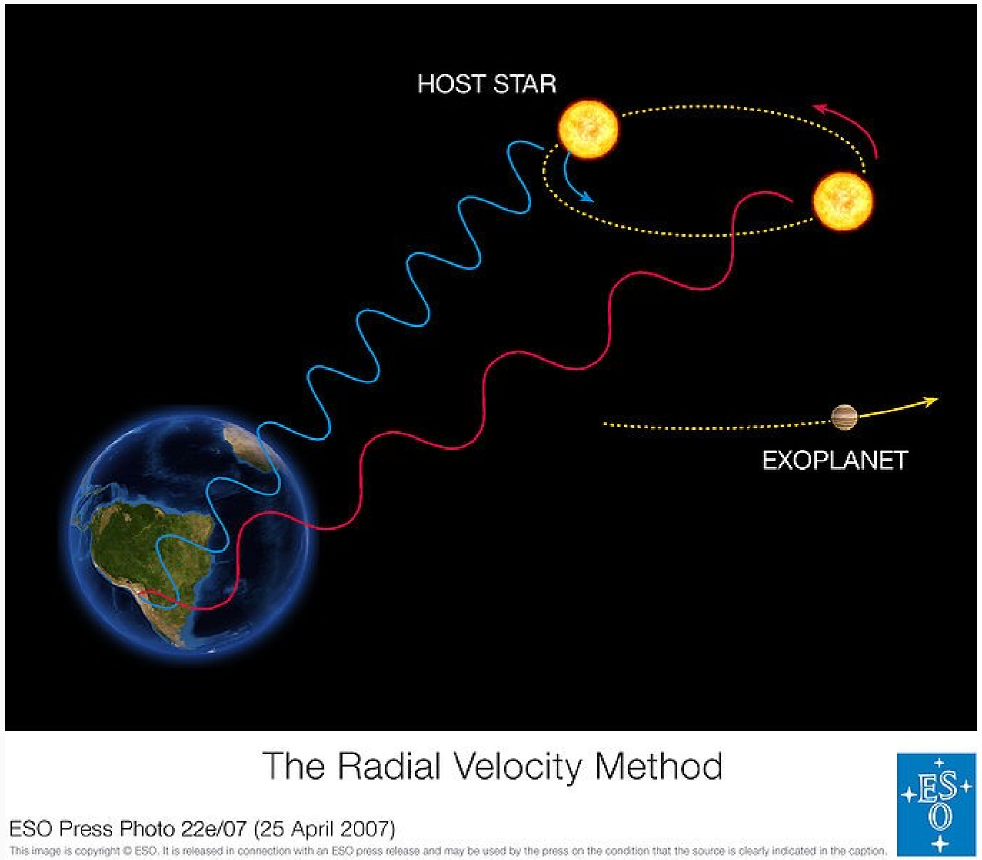
What's the matter with planets?

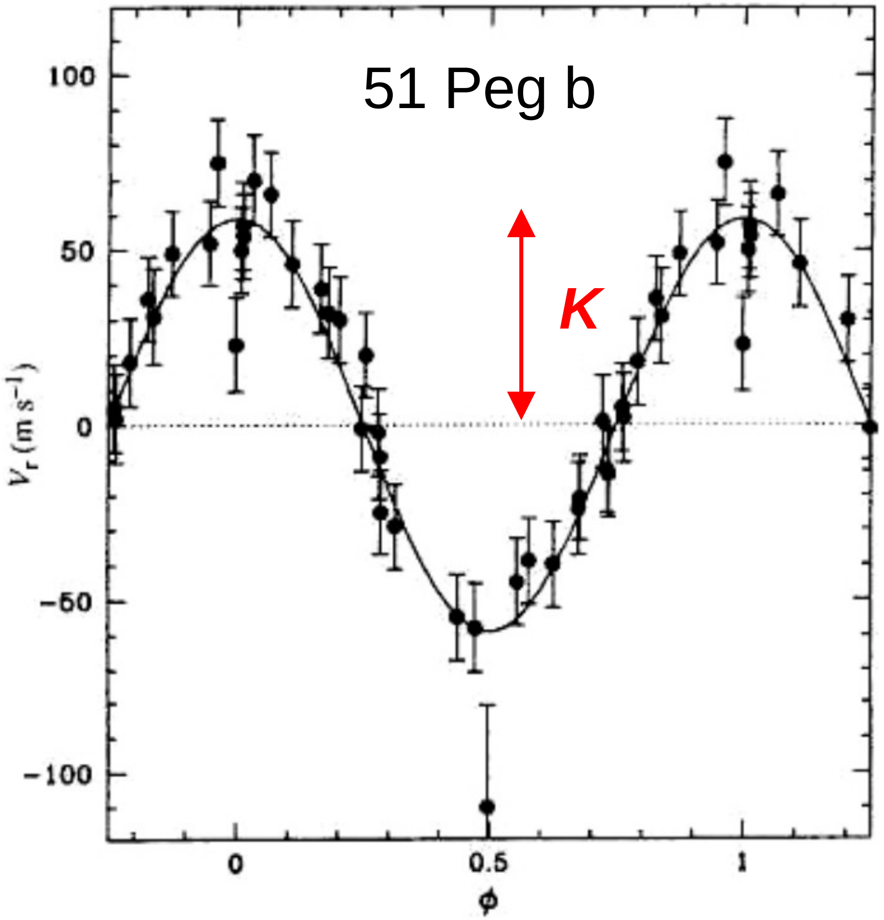


Detections here are challenged by stellar noise

Part of the uncertainties is due to stellar activity, and must be properly estimated

Radial velocity exoplanet observations

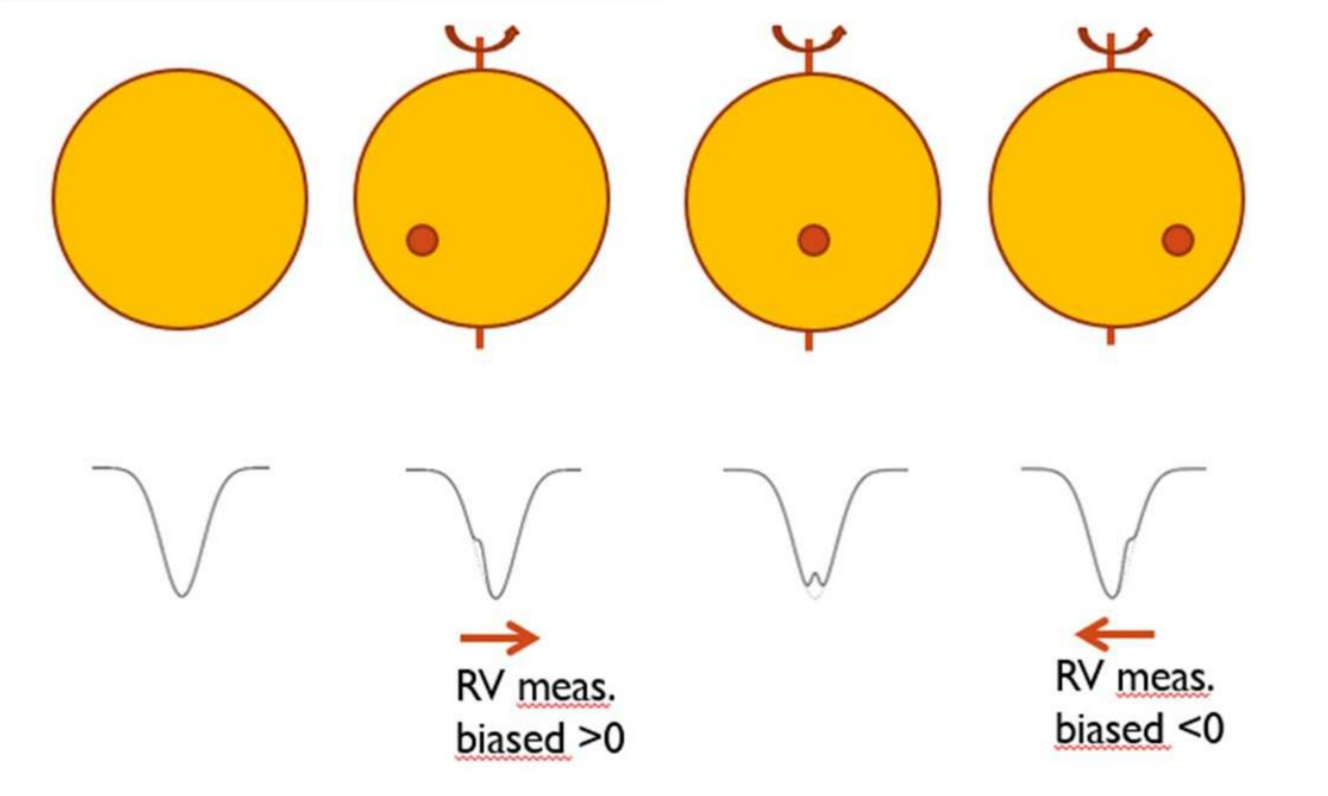




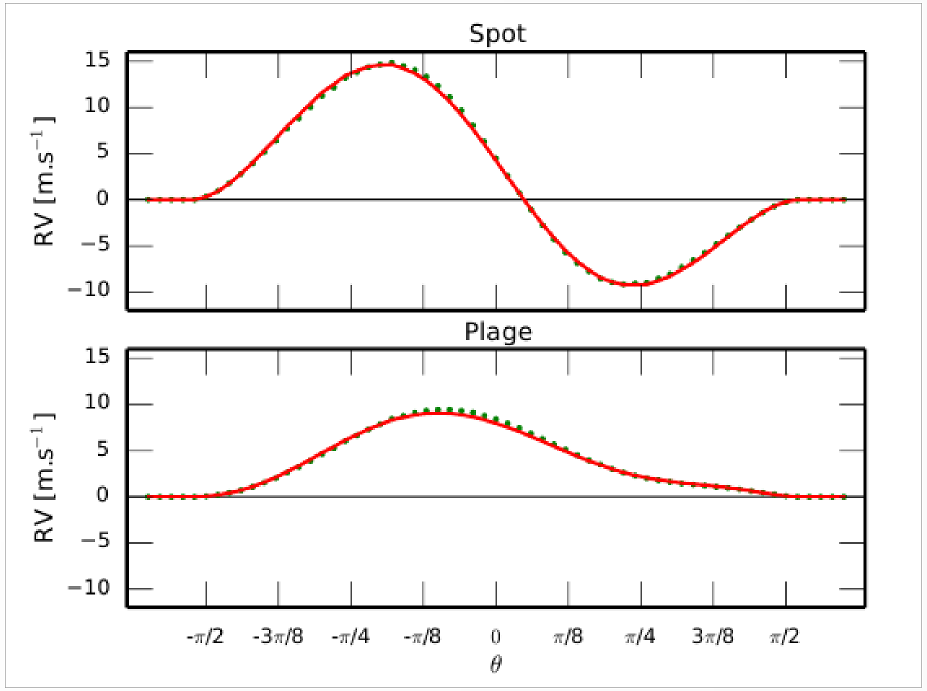
$$K = \frac{8.95\mathrm{cm\,s^{-1}}}{\sqrt{1-e^2}} \frac{m_p \sin i}{M_\oplus} \left(\frac{M_\star + m_p}{M_\odot}\right)^{-2/3} \left(\frac{P}{\mathrm{yr}}\right)^{-1/3}$$

Mayor & Queloz (1995)

Impact of active regions in radial velocity

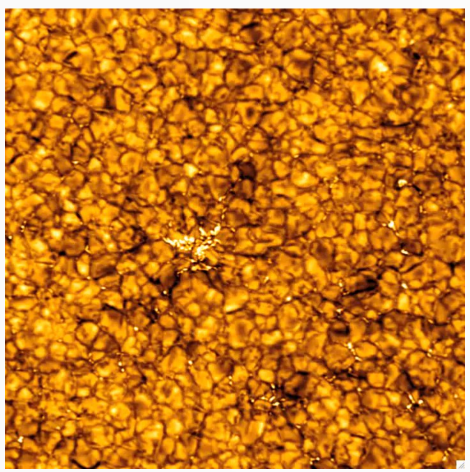


Meunier (2021)

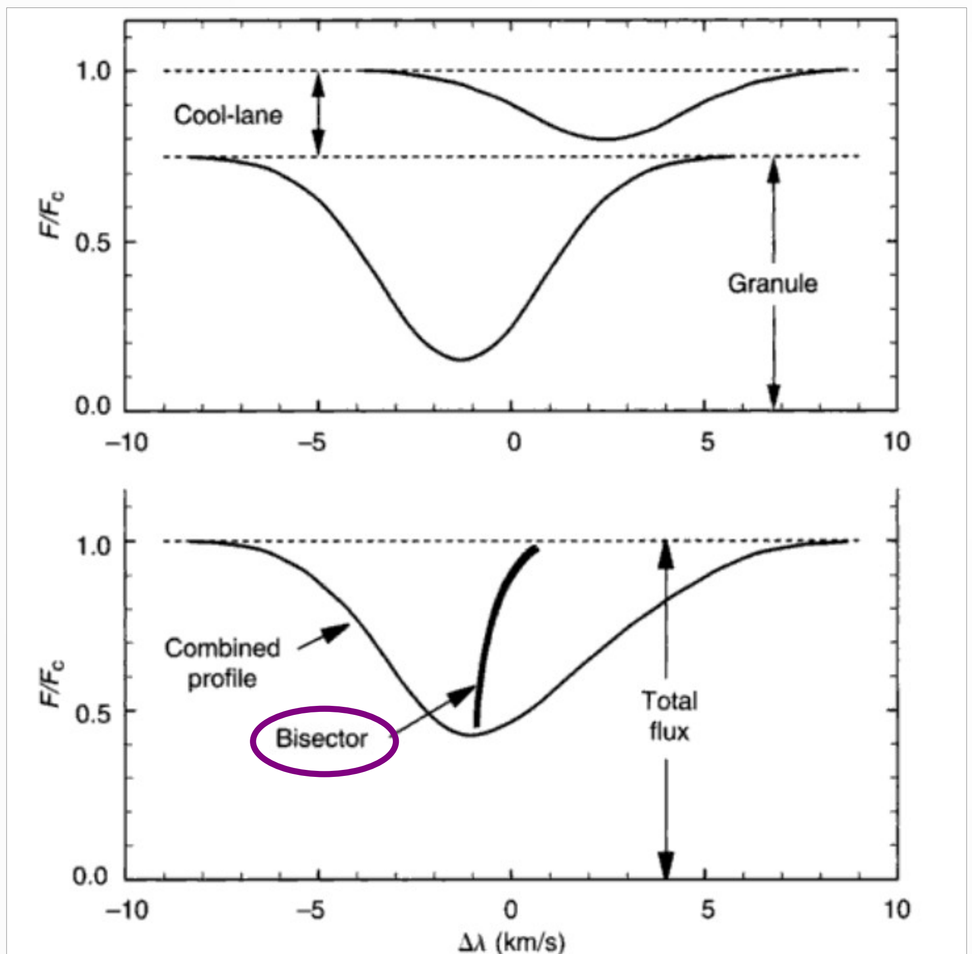


1. Contrast effect
→ blueshift/redshift
because of stellar rotation

Impact of active regions in radial velocity



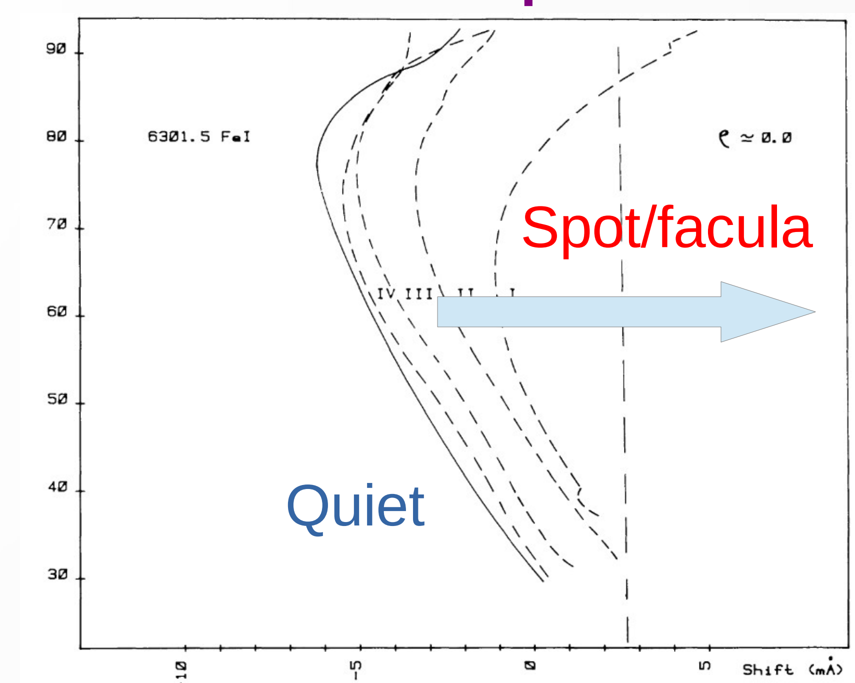
Credit: Bob Trembley



Gray (2005)

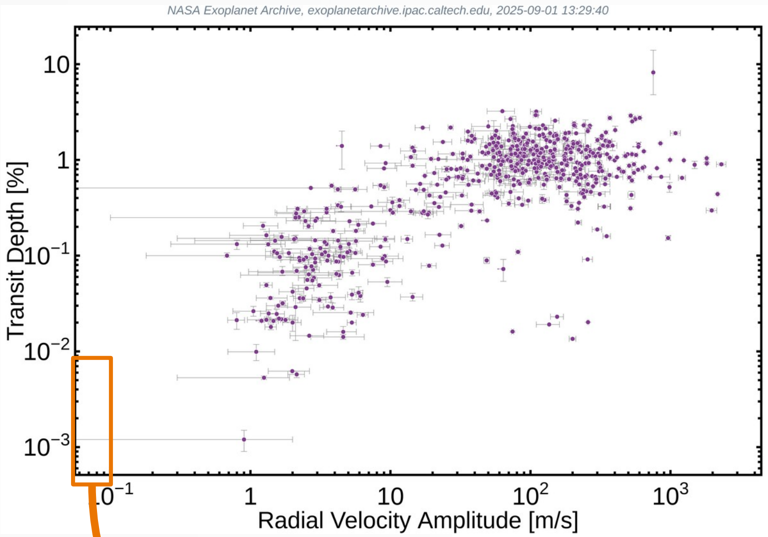
2. Suppression of convective blueshift inside active regions
(e.g. Cavallini 1985, Dravins 1981)
→ Redshift induced (~300 m/s for the Sun)

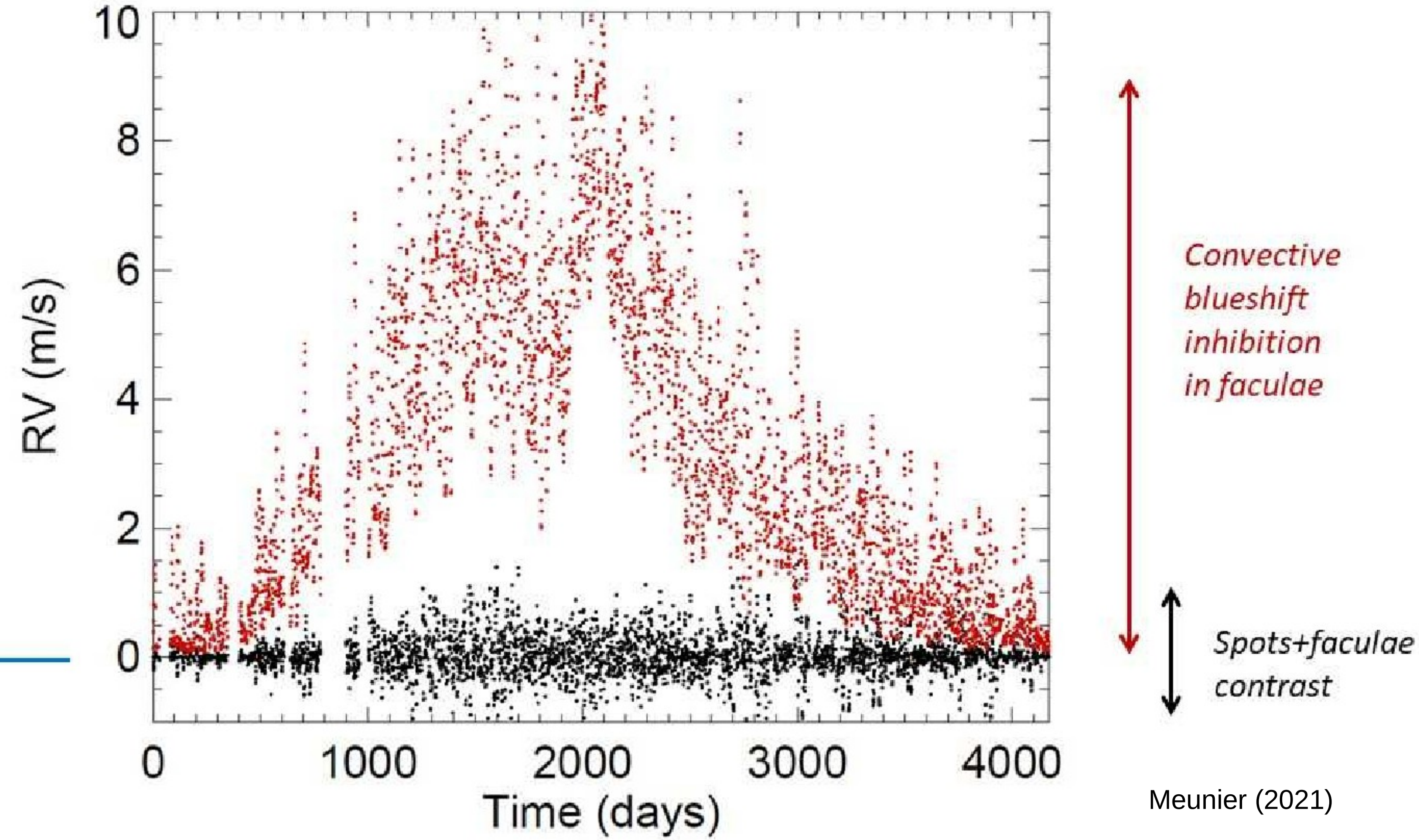
Bisector span



Cavallini+1985
Dumusque+2014

Adding the planet (the most difficult case)

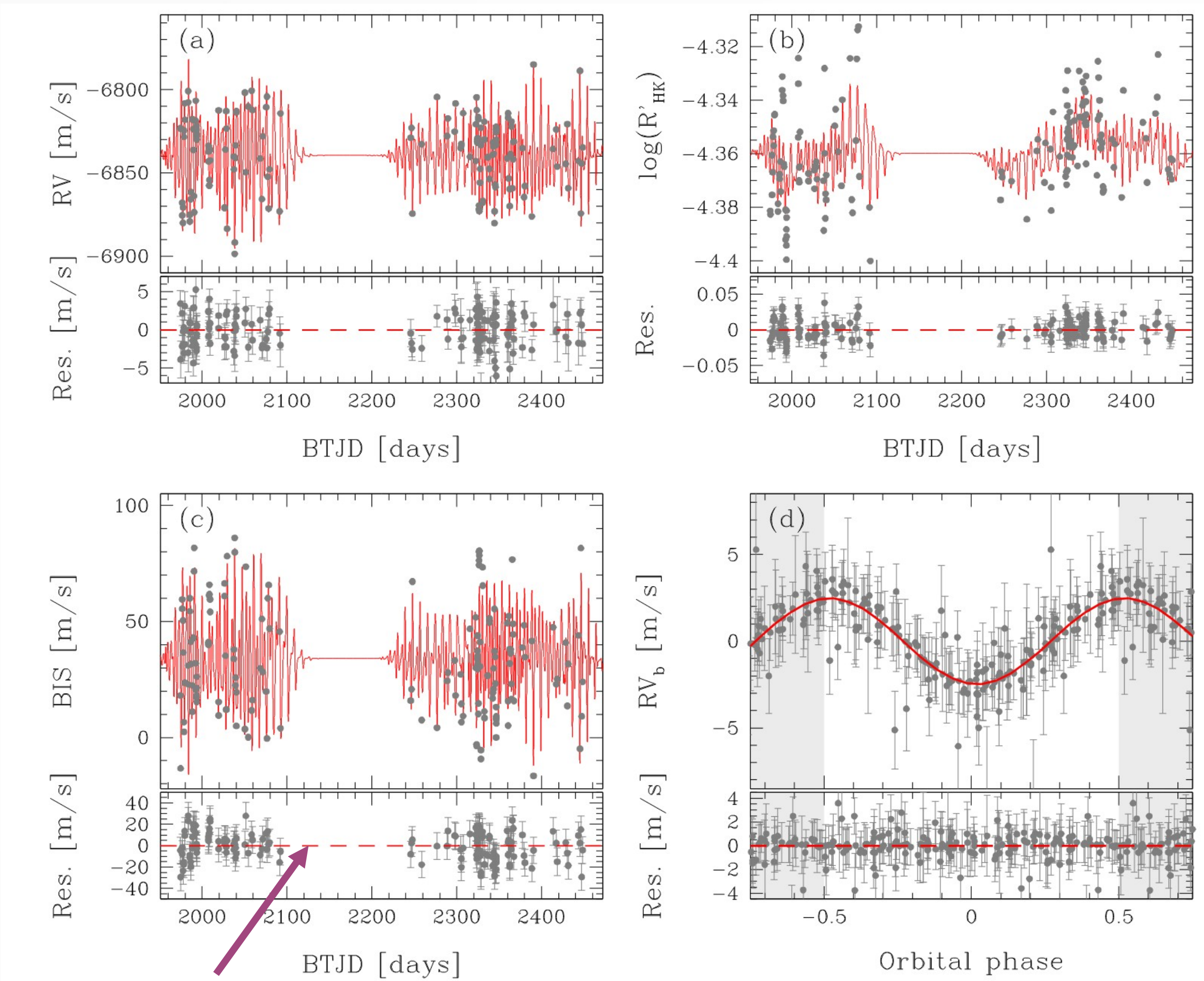


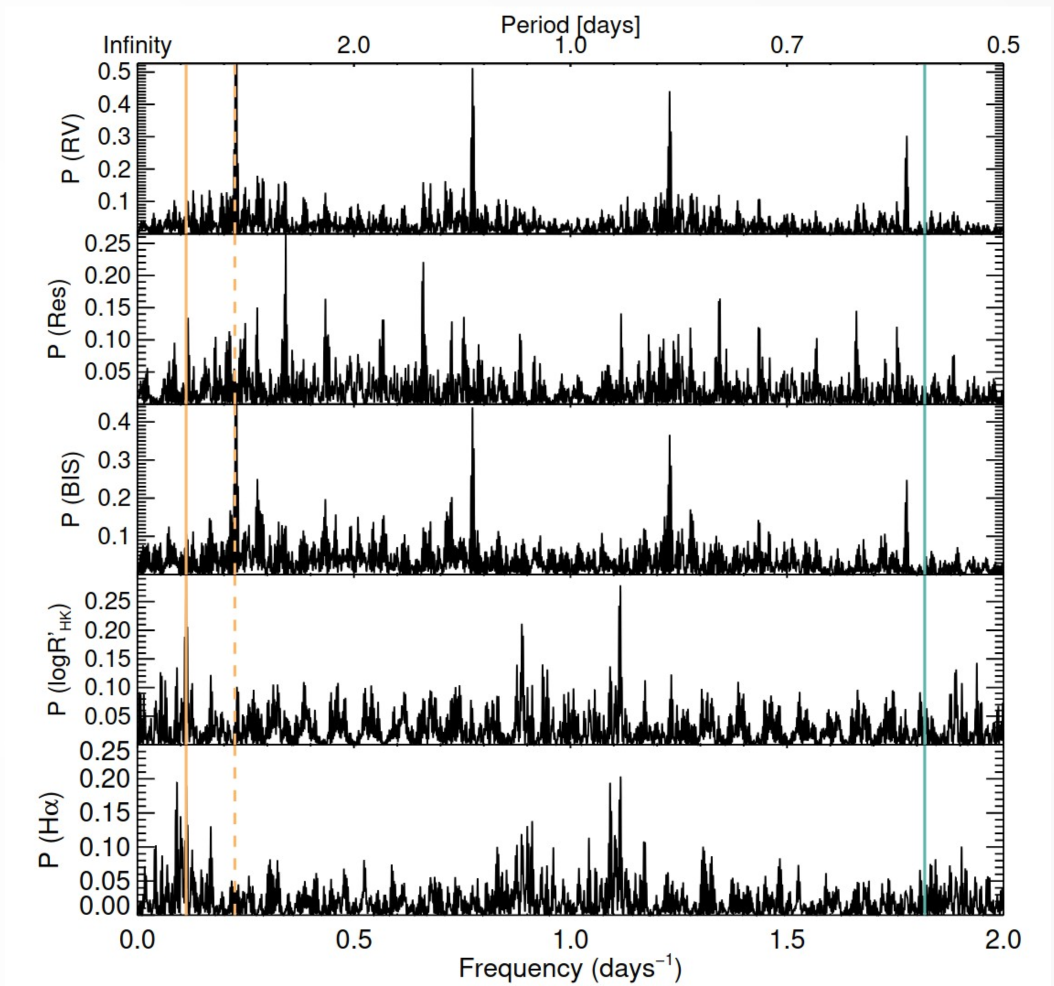


Meunier (2021)

An easier case: TOI-1807 b

Multi-dimensional GP (better if photometry is added)





Peaks due to active regions are identified

Must not be correlated with RV
(Queloz+2001)

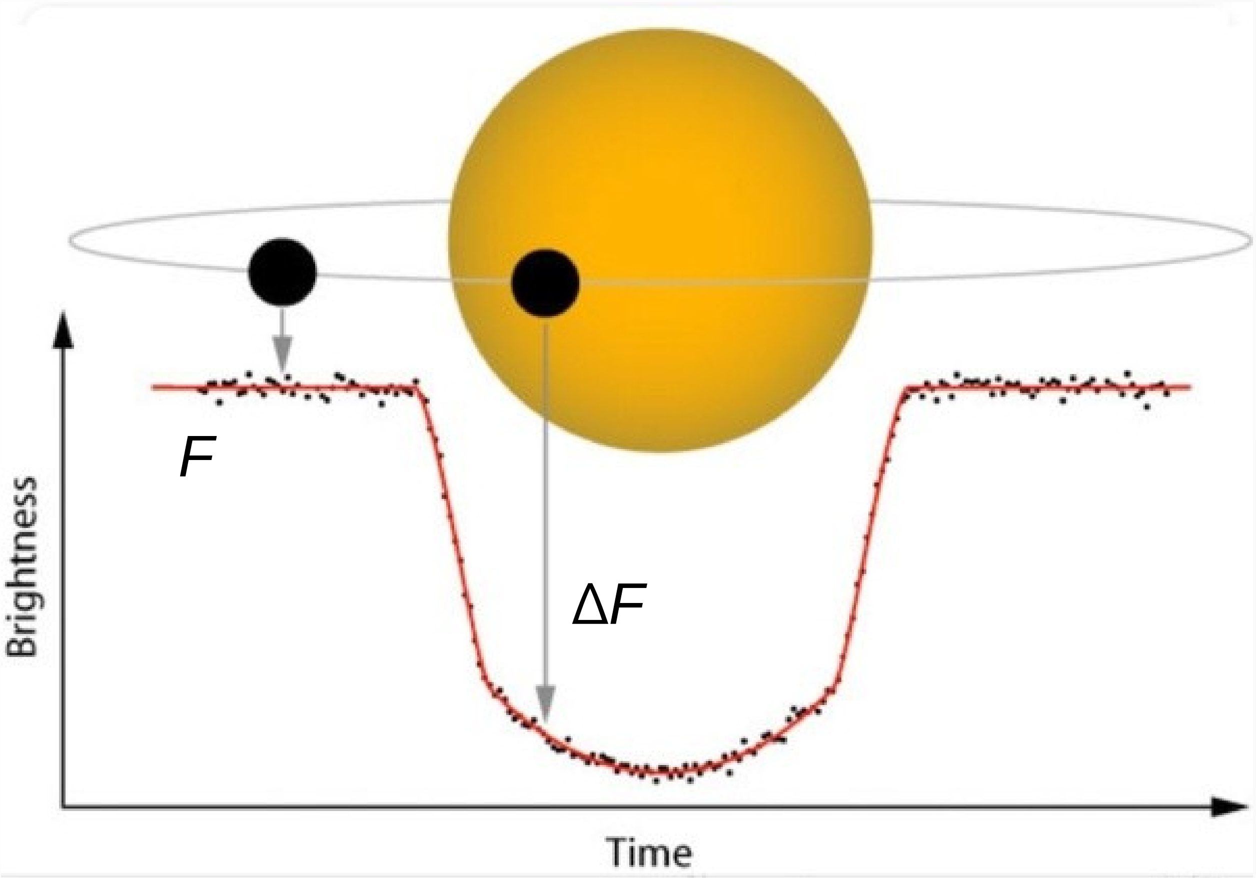
Activity signal removed

Questions?

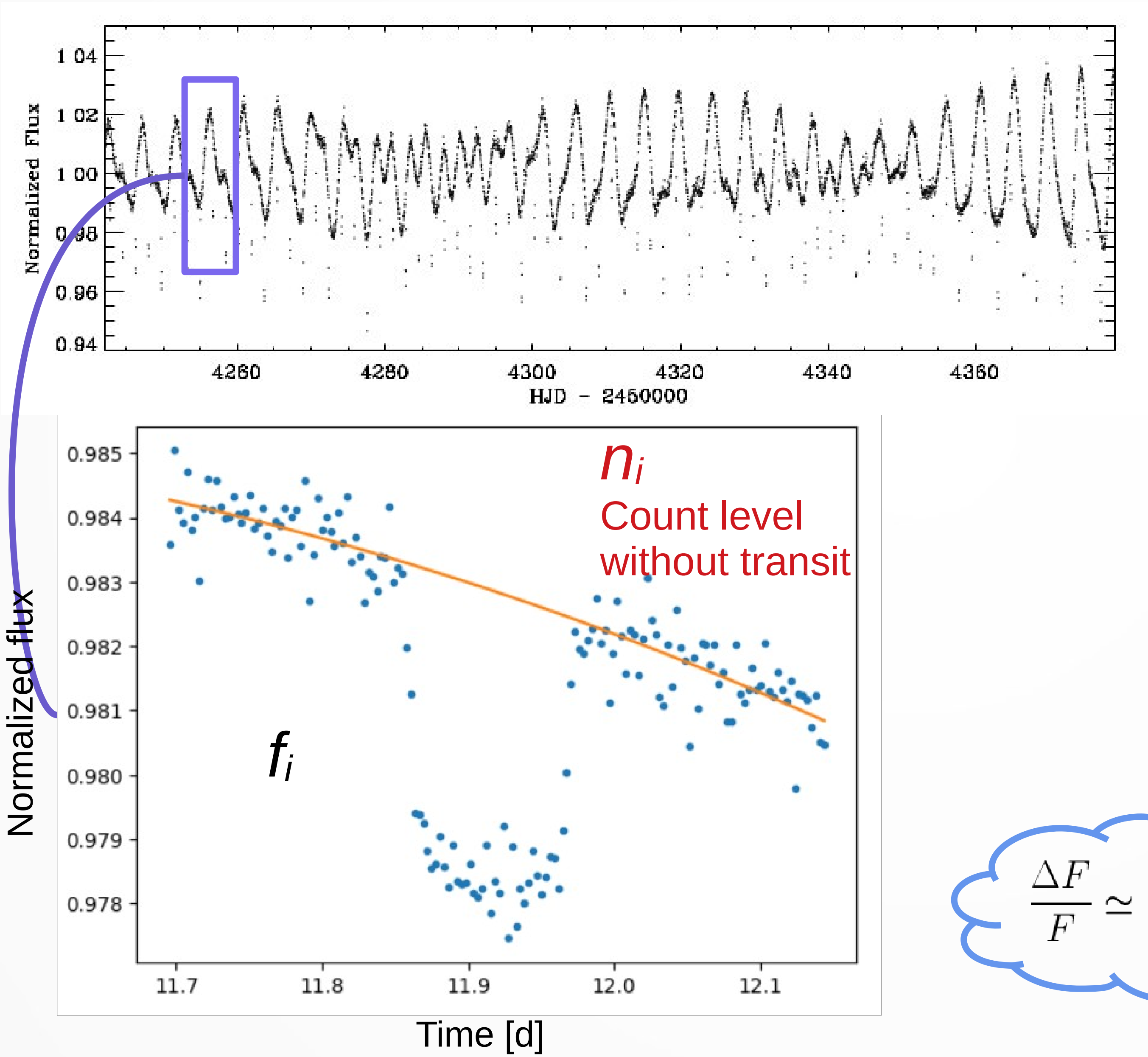
https://www.pngkit.com/

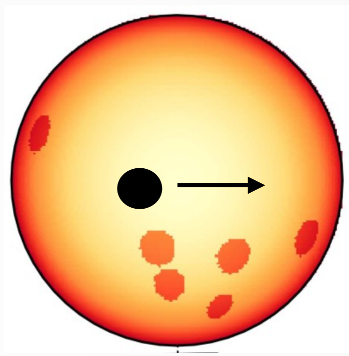
Transit photometry

$$\frac{\Delta F}{F} = 8.41 \cdot 10^{-5} \left(\frac{r_p}{R_\oplus}\right)^2 \left(\frac{R_\star}{R_\odot}\right)^{-2}$$



Non-occulted starspots effect on transit depth





Rackham+2018

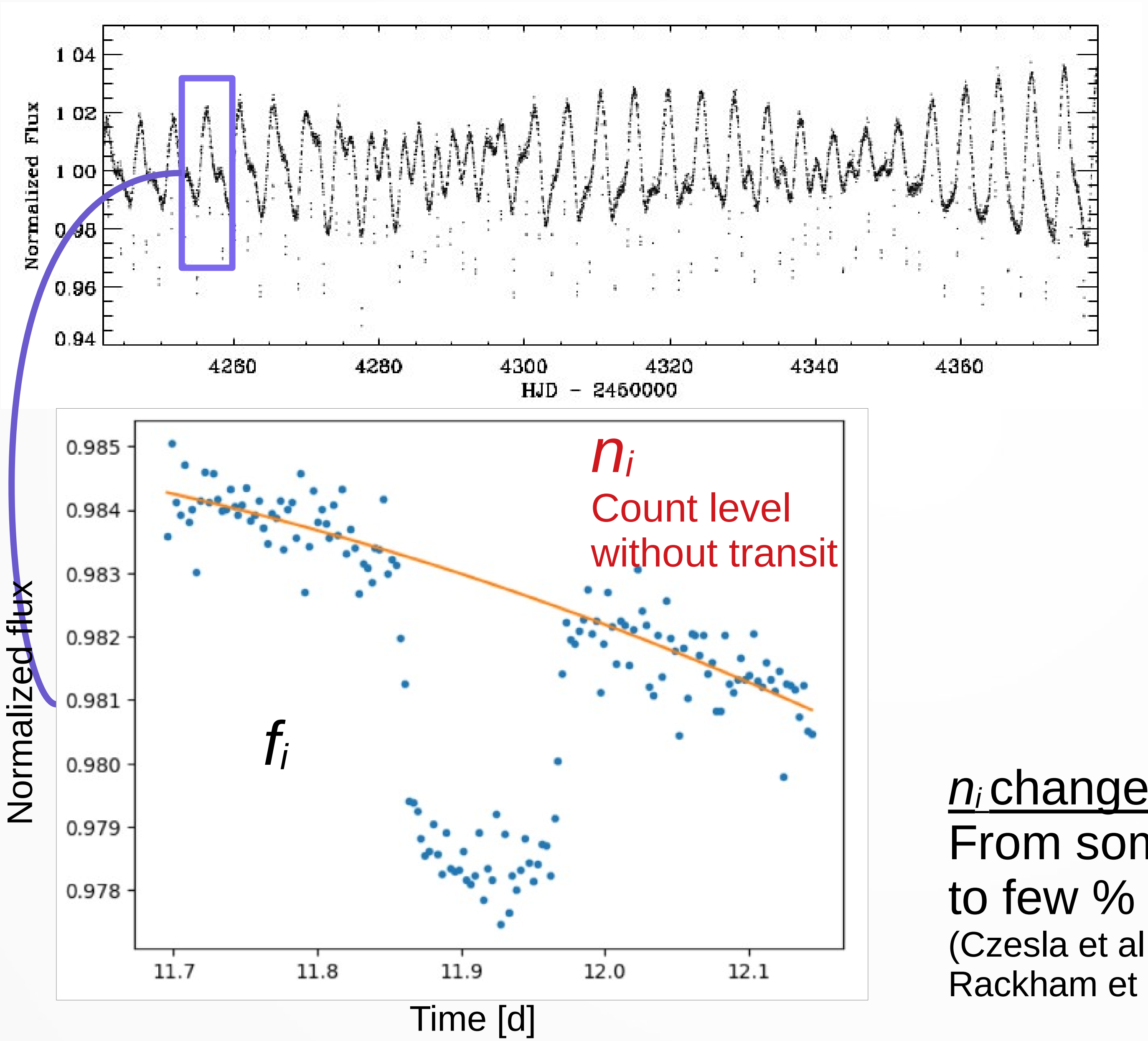
Normalized flux:

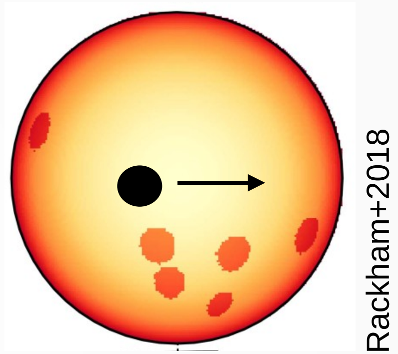
$$y_i = \frac{f_i}{n_i}$$

For every bin *i*

$$\frac{\Delta F}{F} \simeq \left(\frac{r_{\rm planet}}{R_\star}\right)^2$$

Non-occulted starspots effect on transit depth





Normalized flux:

$$y_i = \frac{f_i}{n_i}$$

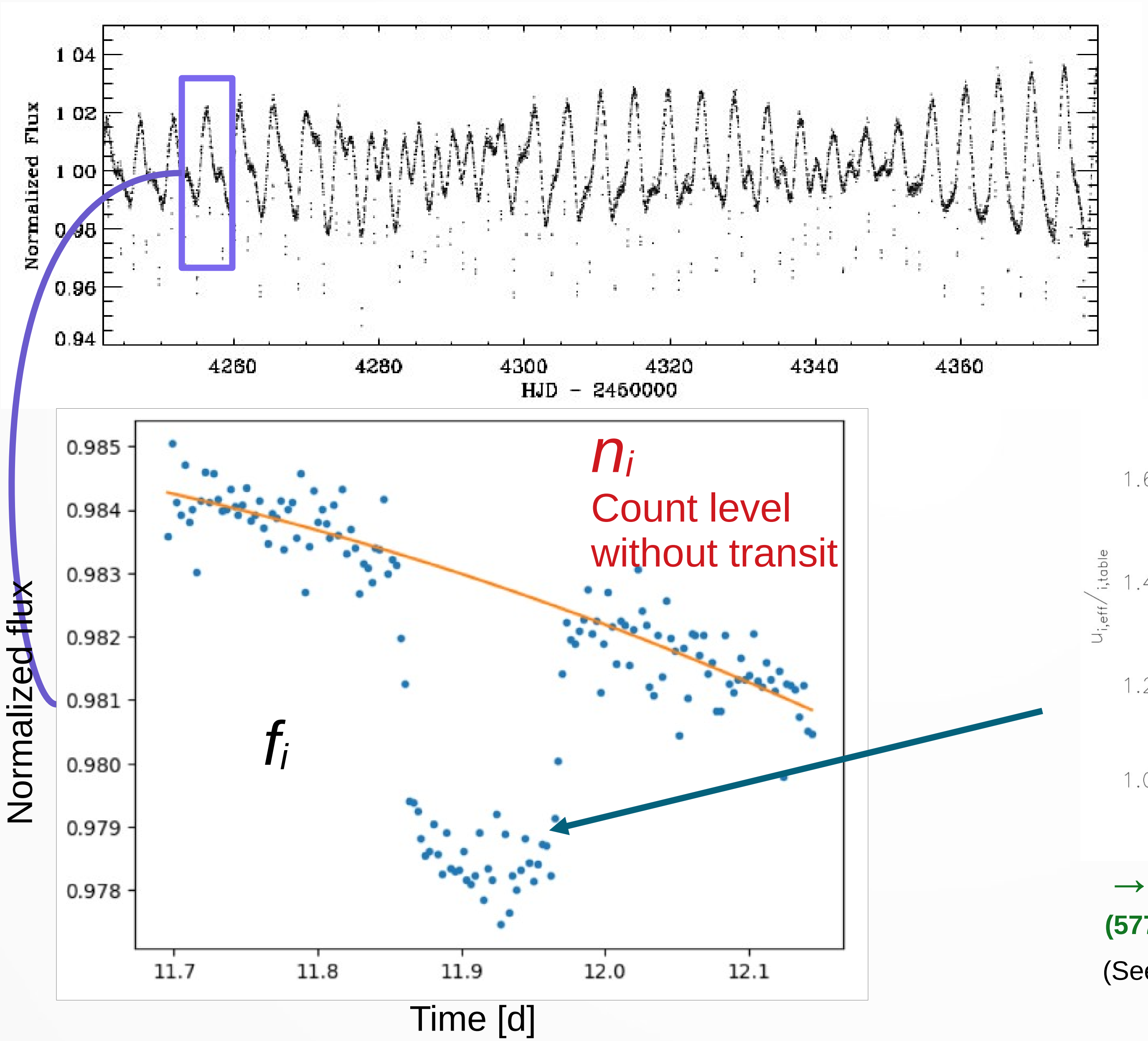
For every bin *i*

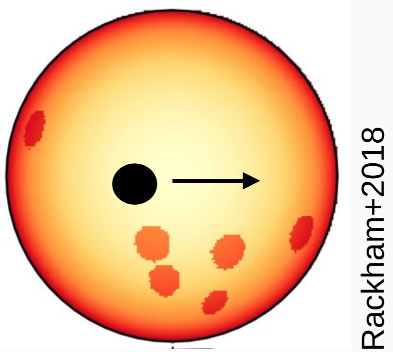
<u>n_i changes with time</u>

From some 100 ppm to few % variations

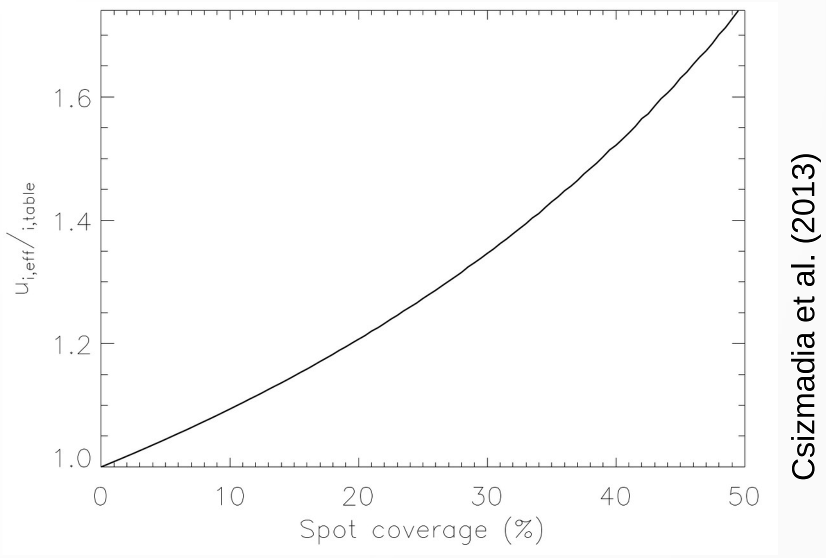
(Czesla et al. 2009, Rackham et al. 2018)

Non-occulted starspots effect on transit depth





Limb darkening coefficients variations

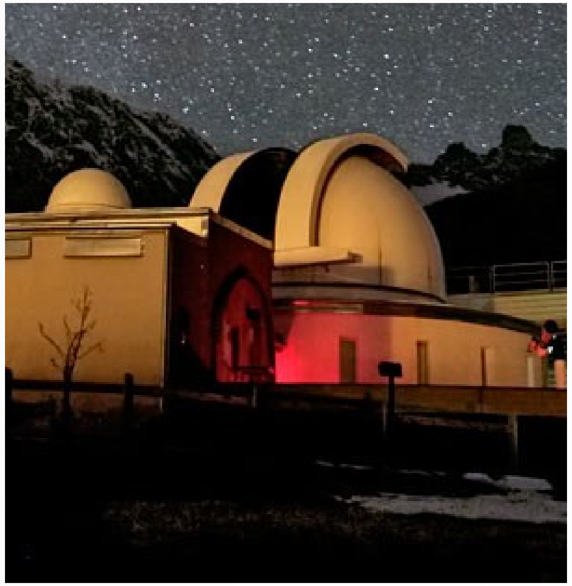


→ 5-10% radius ratio variation

(5775 K star, 3775 K starspot)

(See also Sing (2010) vs Claret & Bloement (2011)

How to deal with non-occulted starspots

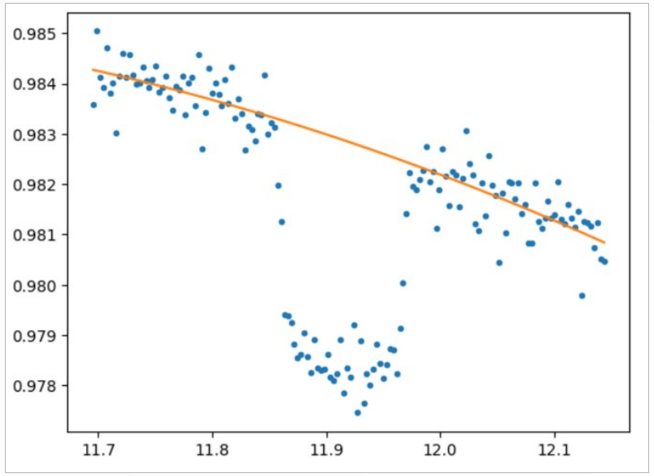


Credit: P. Calcidese–Fondazione C. Fillietroz, ONLUS/ESO

0) Get to know your star with a monitoring at least a few stellar rotations worth

How to deal with non-occulted starspots

1) Using polynomials



How to deal with non-occulted starspots

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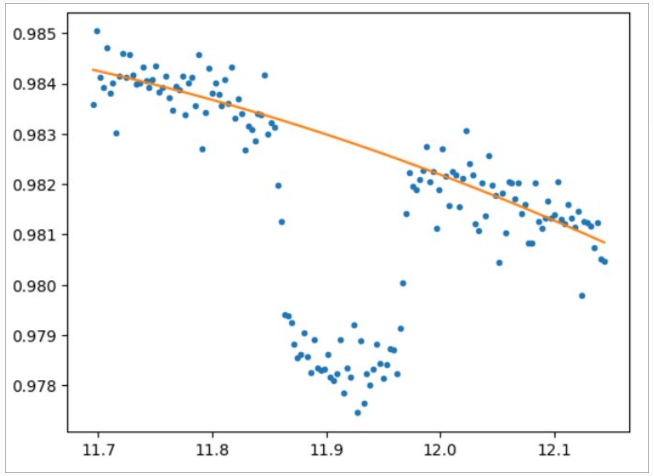
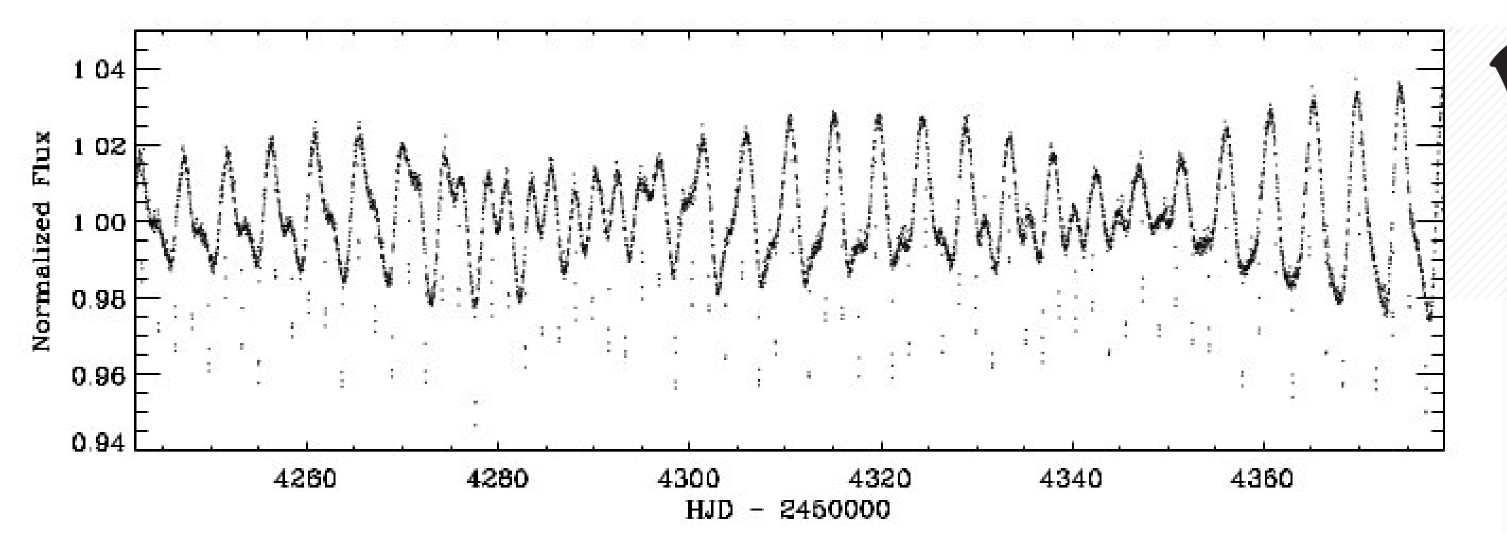


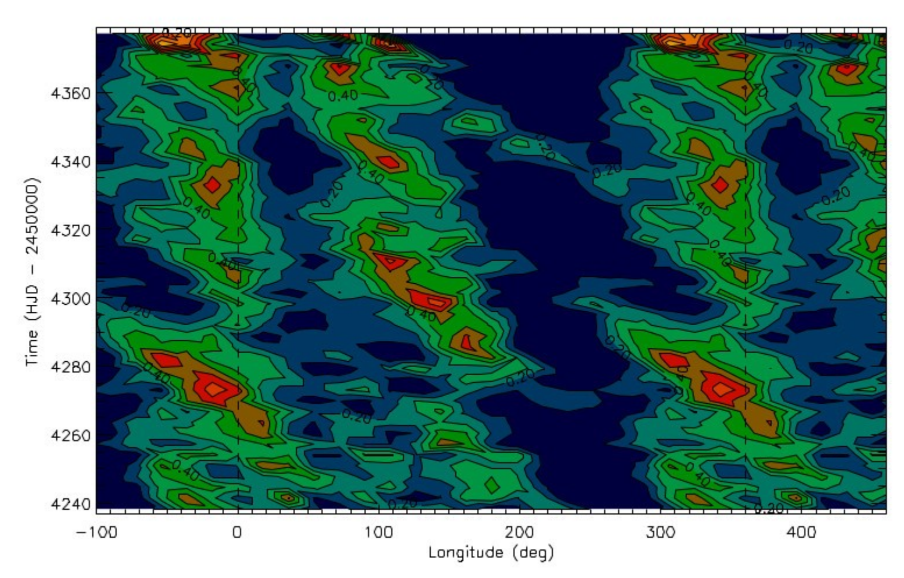
But where are we in the activity cycle?



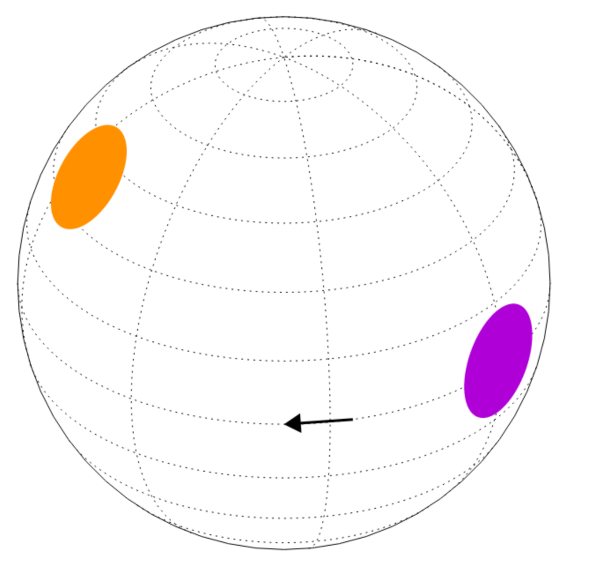
Starspot/facula ratio
→ spot modeling

How to deal with non-occulted starspots

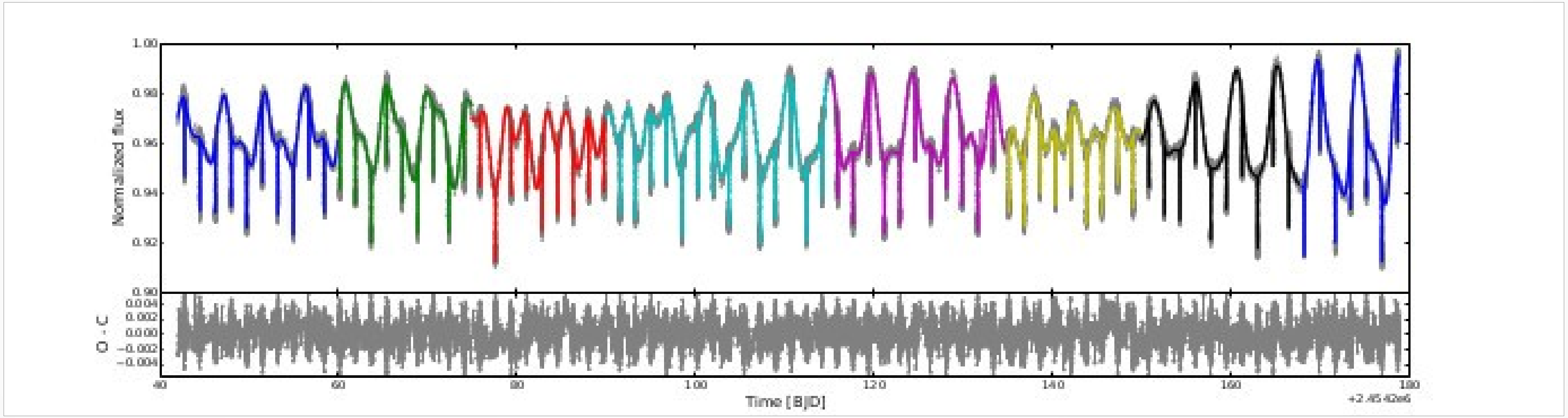
2) Performing spot modeling (ideally including transits)
→ Degenerate problem, high computational cost



Lanza et al. (2009)



Davenport et al. (2015)



Bruno et al. (2016)

How to deal with non-occulted starspots

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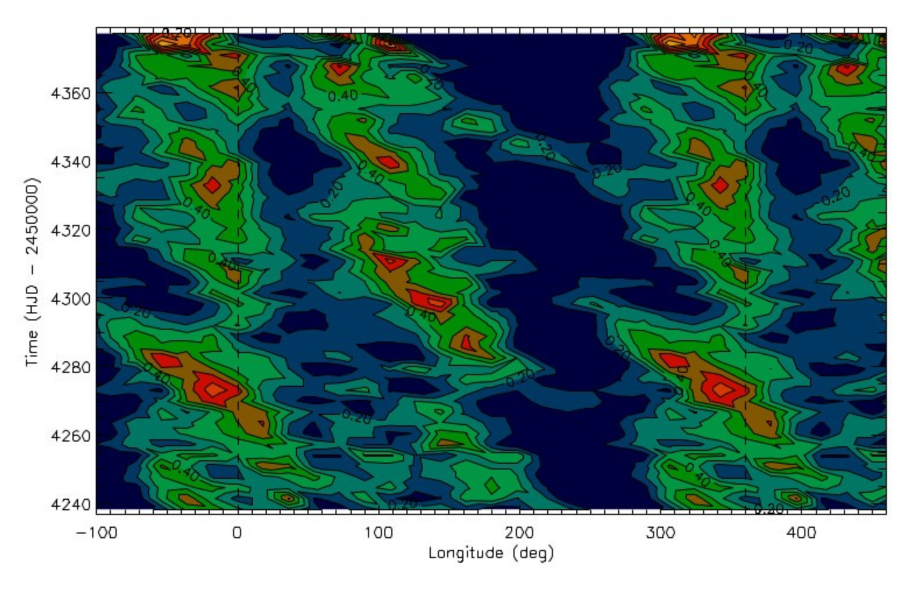
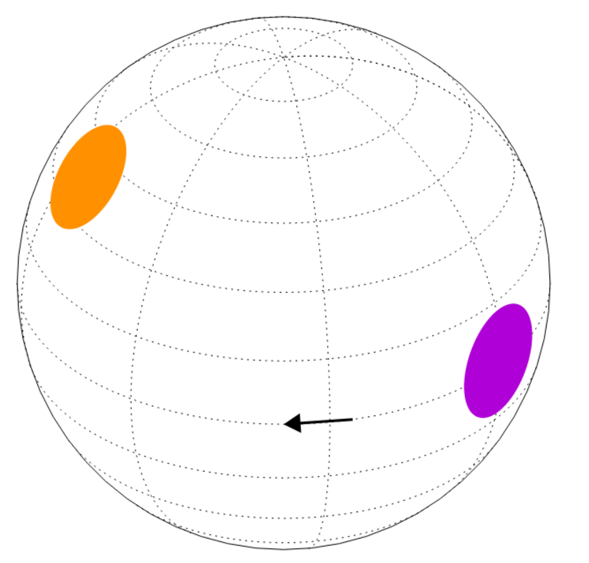


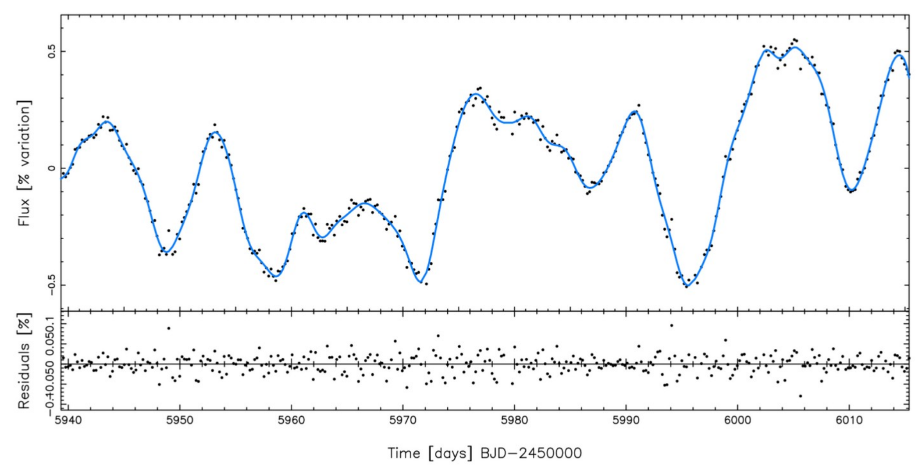
Lanza et al. (2009)



Davenport et al. (2015)

3) With Gaussian processes or wavelets
(ideally including transits - high computational cost)

Hyperparameters ↔ Starspot properties (e.g. Barros et al. 2020)



Haywood et al. (2014)

How to deal with non-occulted starspots

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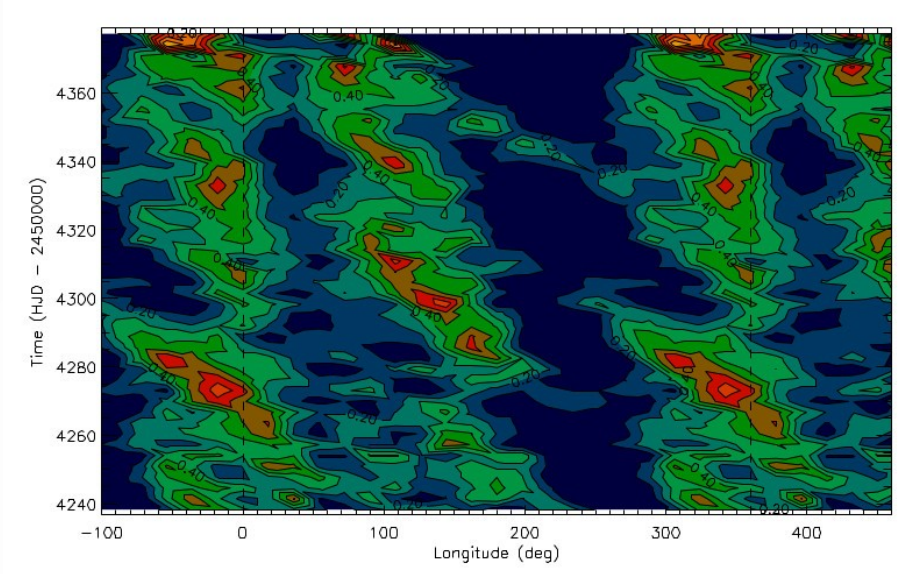
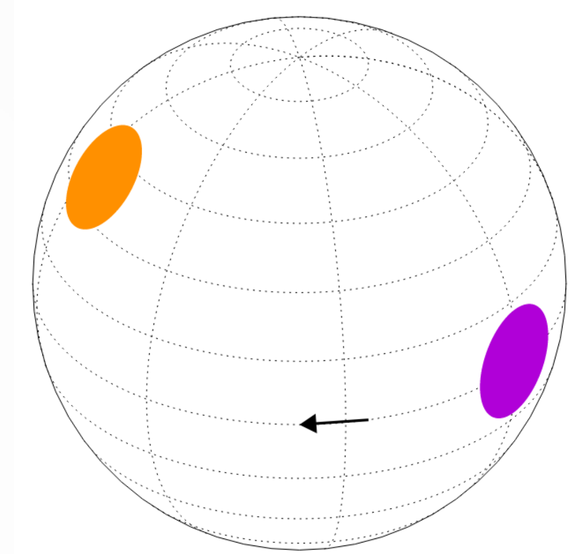
→ Degenerate problem, high computational cost



Lanza et al. (2009)

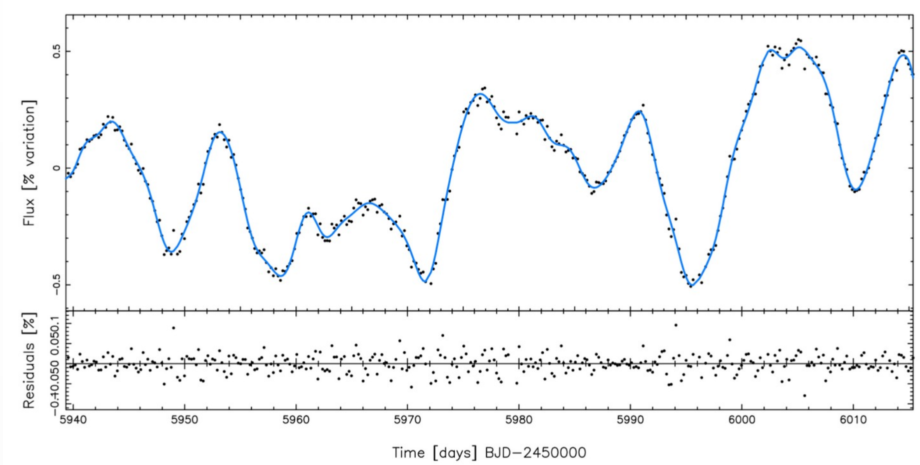


Davenport et al. (2015)

3) With Gaussian processes or wavelets
(ideally including transits - high computational cost)

Hyperparameters ↔ Starspot properties (e.g. Barros et al. 2020)

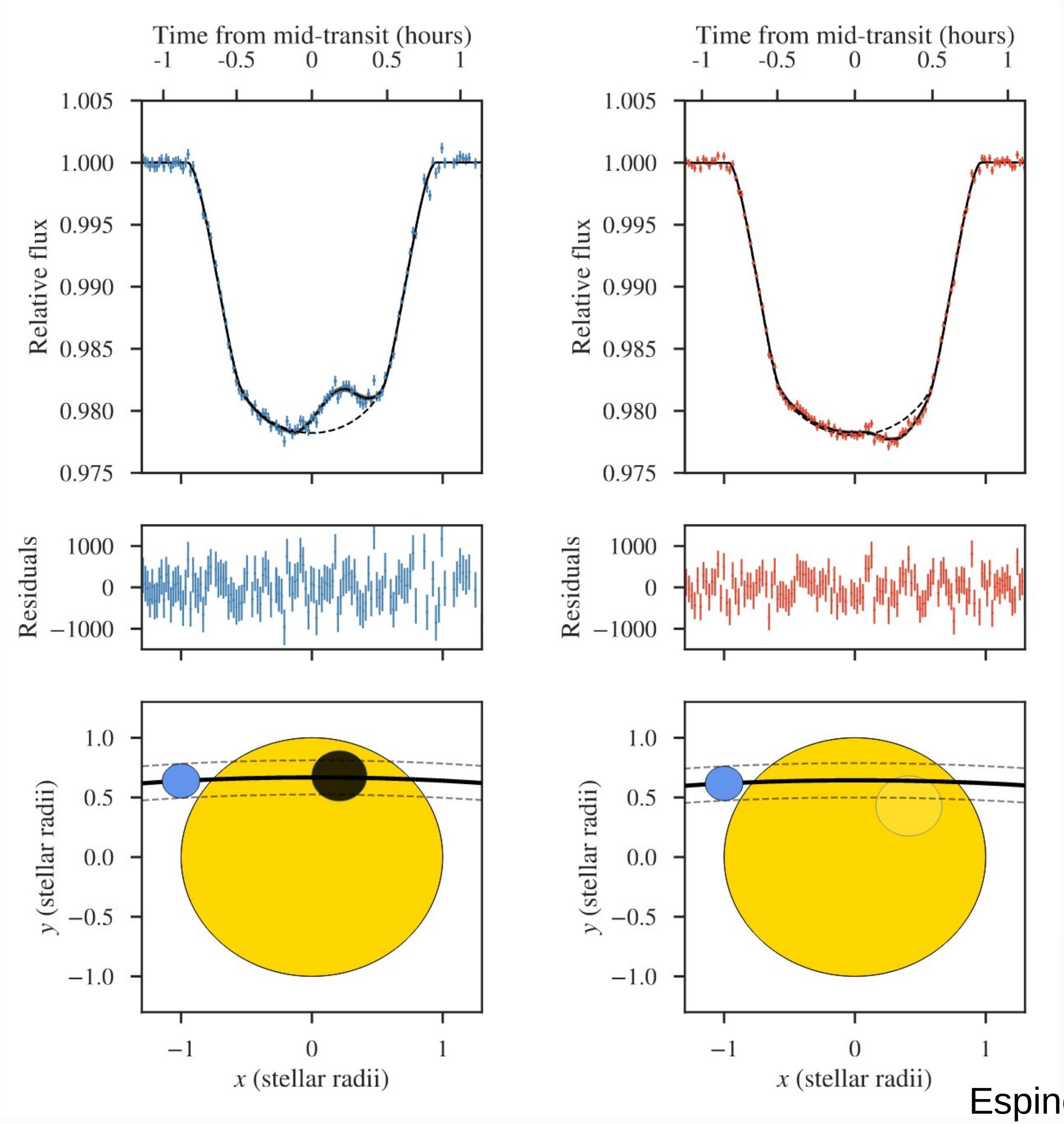
4) Fit for limb darkening coefficients and use 4-coefficients law if possible (Czismadia 2013)



Haywood et al. (2014)

Occulted activity features: effect on transit depth

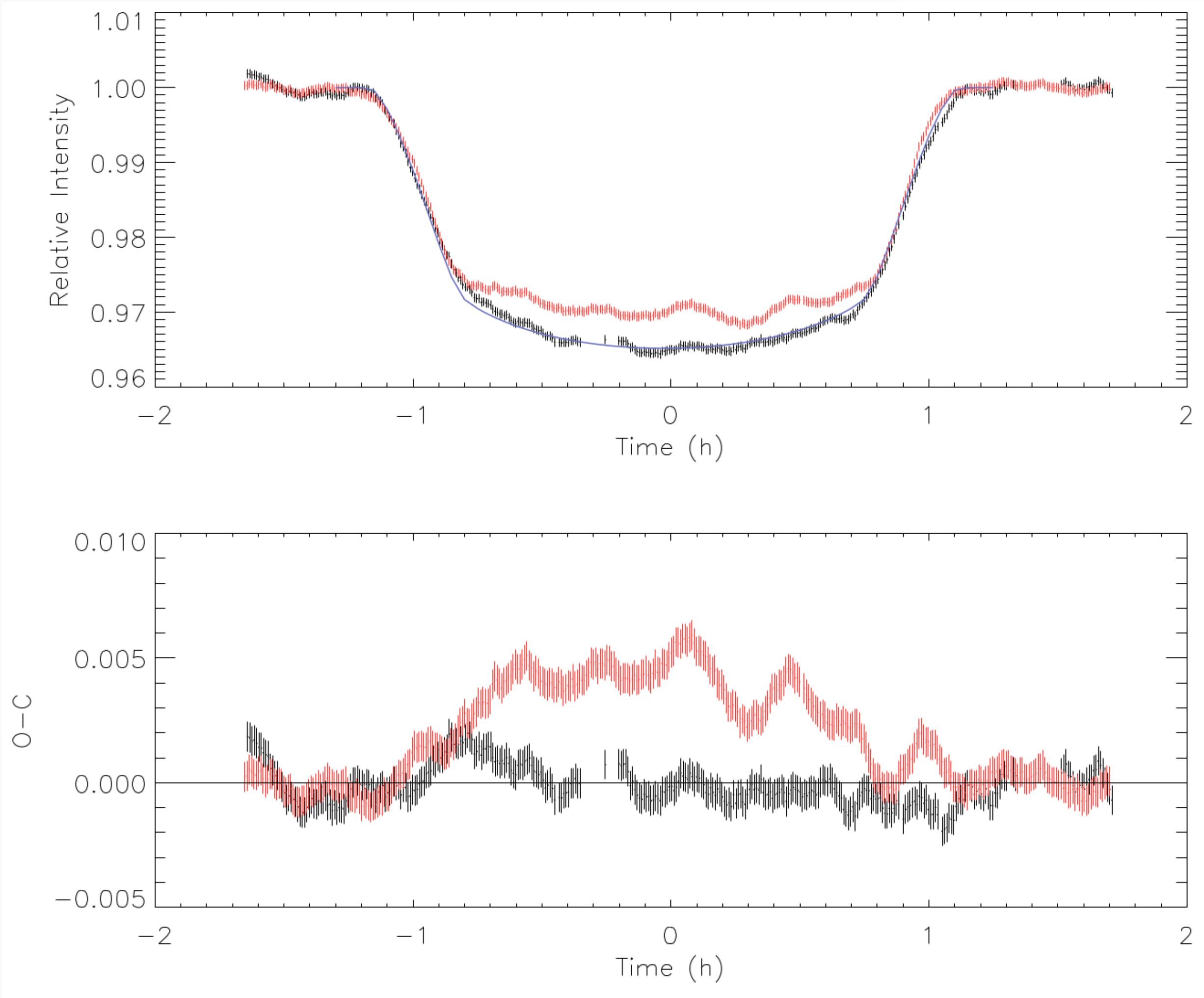
Dark starspot: decreased transit depth

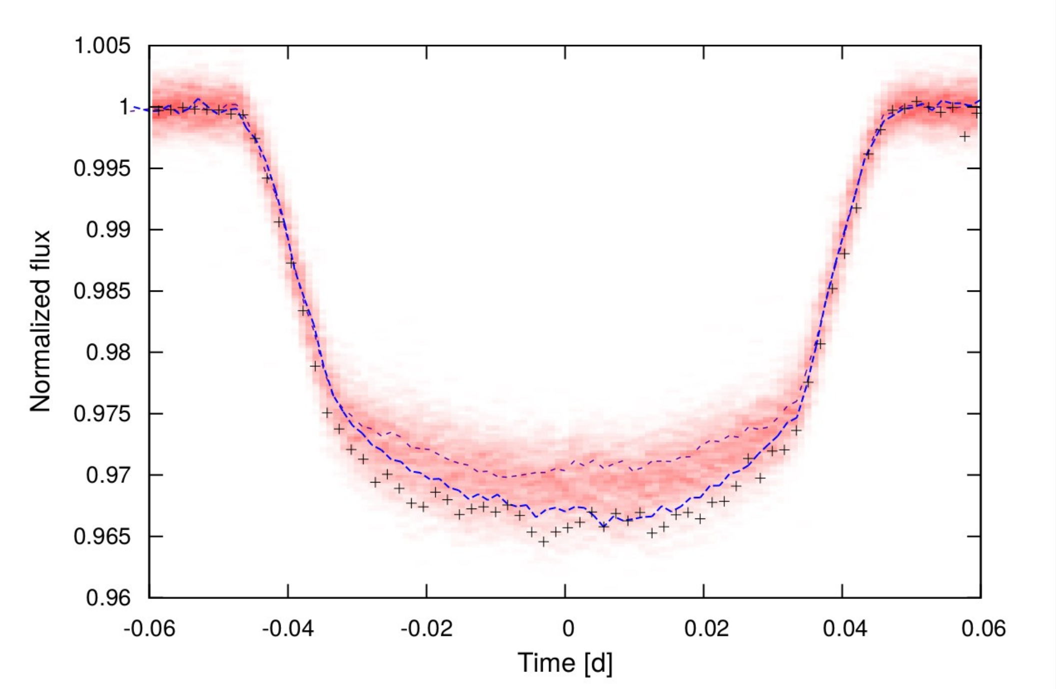


Bright starspot (facula/plage): increased transit depth

Espinoza+2018

Occulted activity features: effect on transit depth

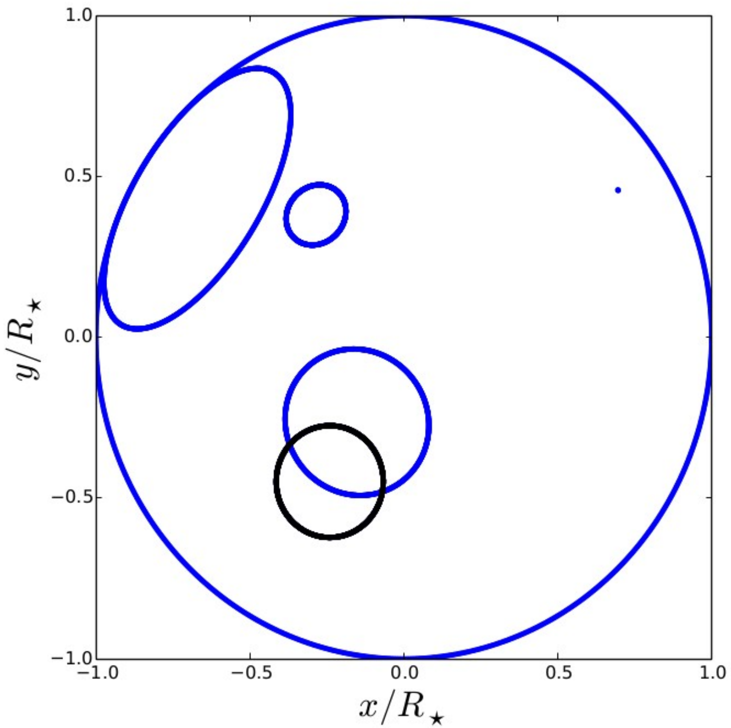




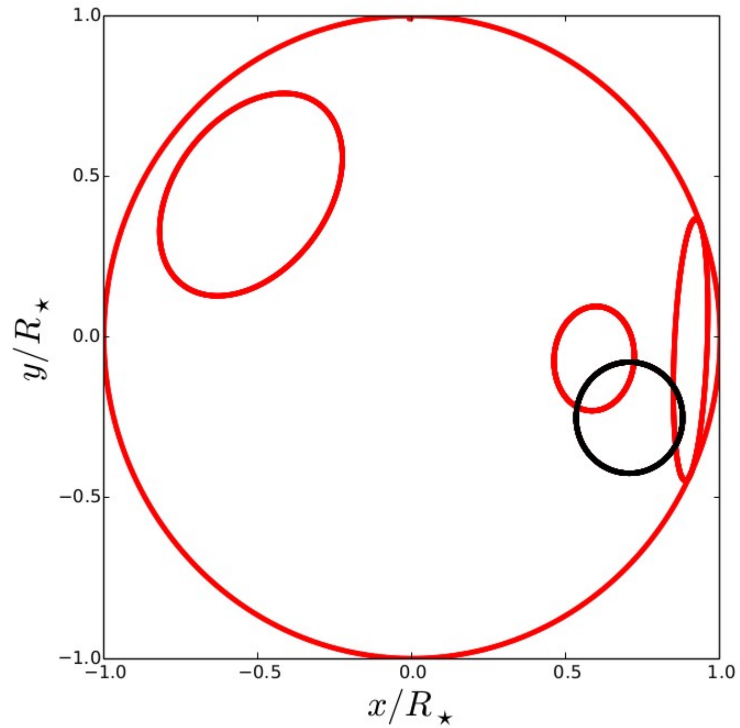
3% variation in the radius of CoRoT-2 b
(Czesla et al. 2009)

Can be hard to mask out in the case of many, small-size spots and few transits
(Silva-Valio et al. 2010)

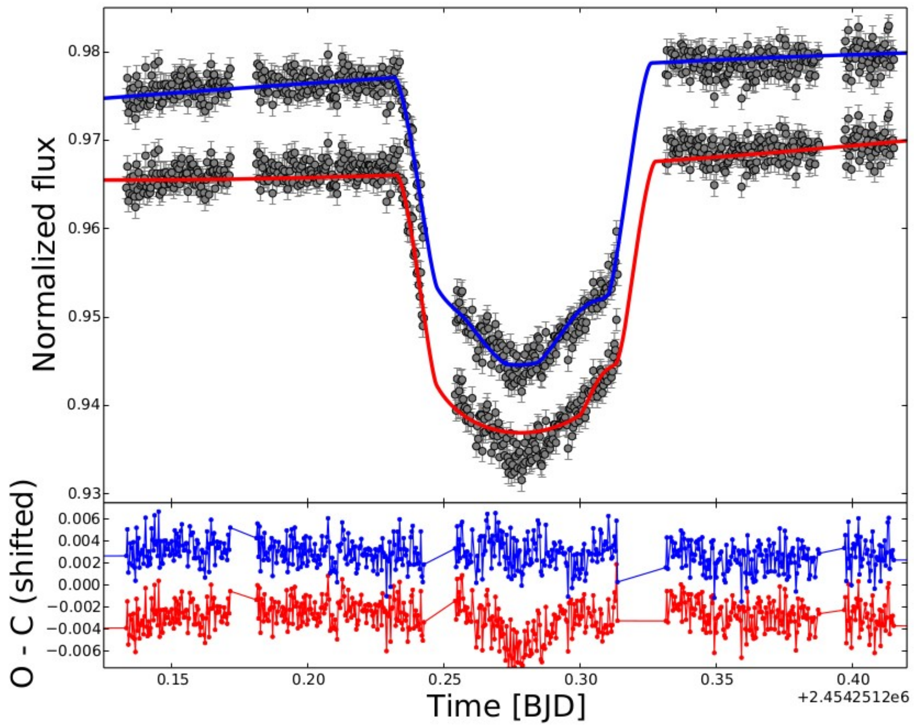
A spot + transit model can help interpretation



Starspots + facula



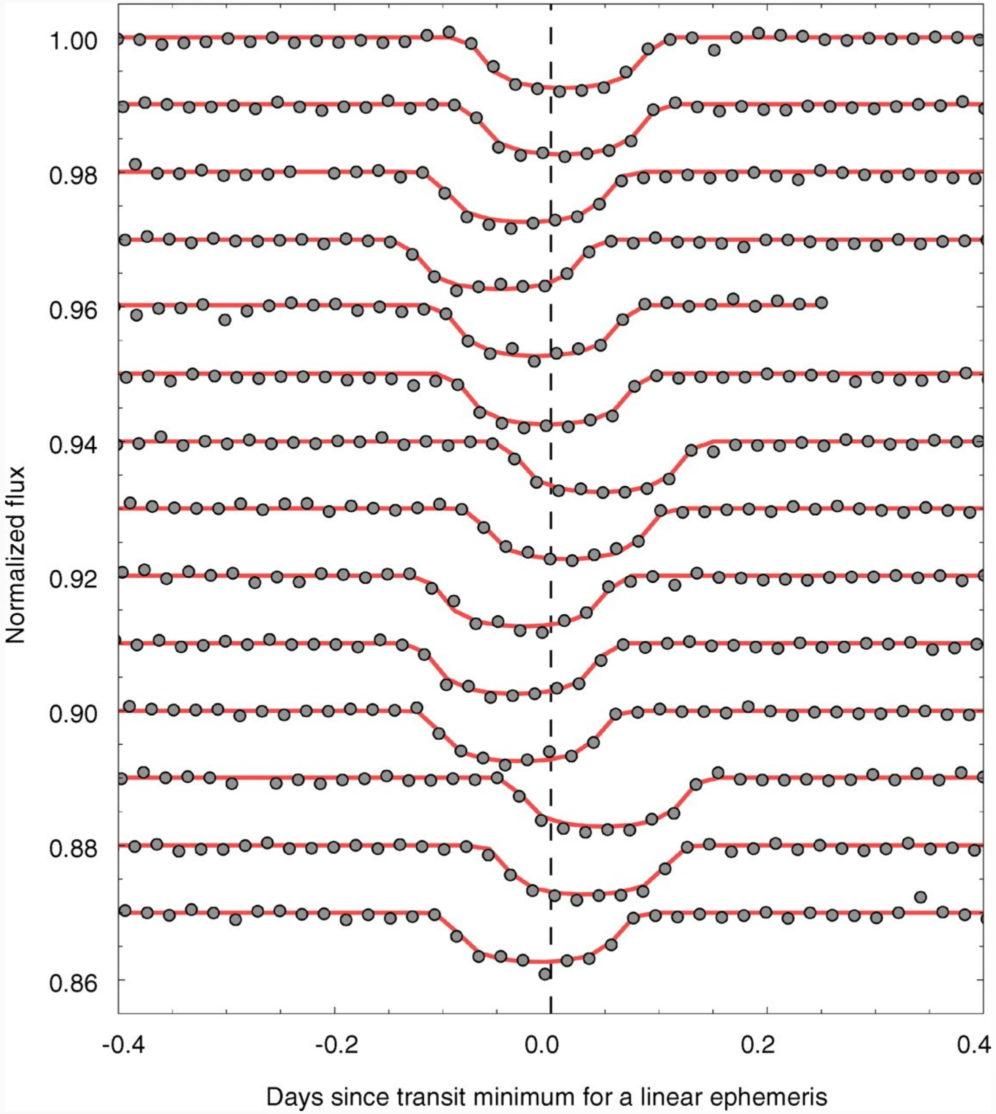
Only starspots



Bruno et al. (2016)

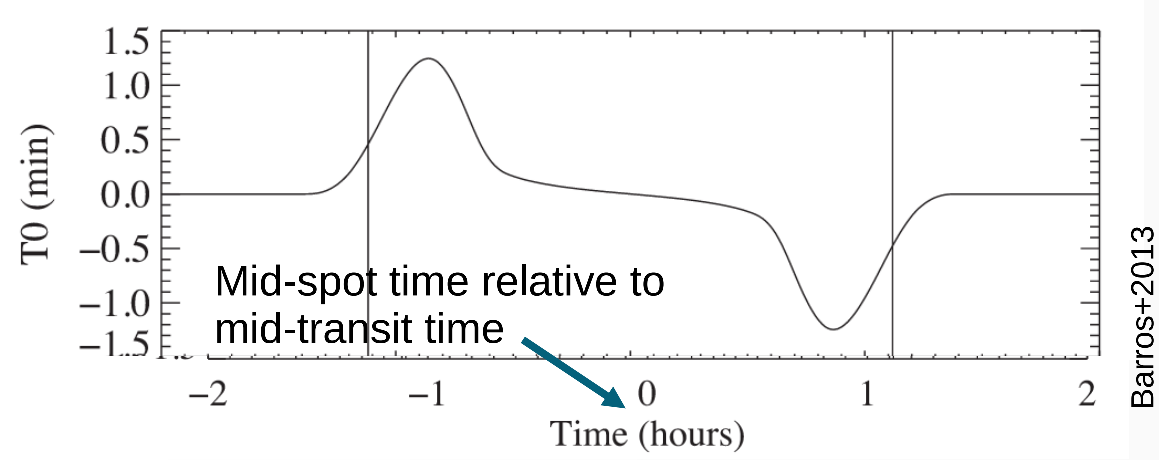
Facula model preferred by BIC

Occulted activity features: false planet detections

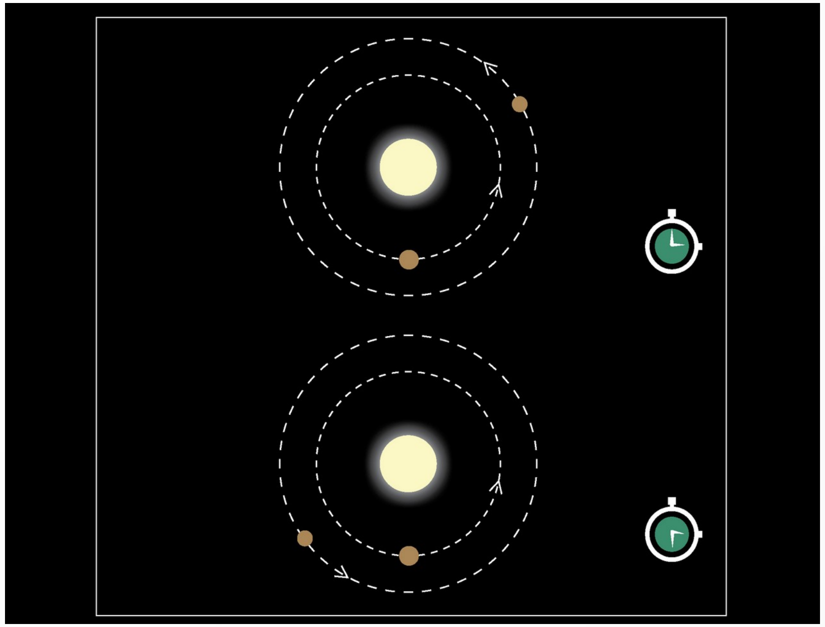


Nesvorny+2012
Agol+2005

False transit timing variations
(e.g. WASP-10 b)

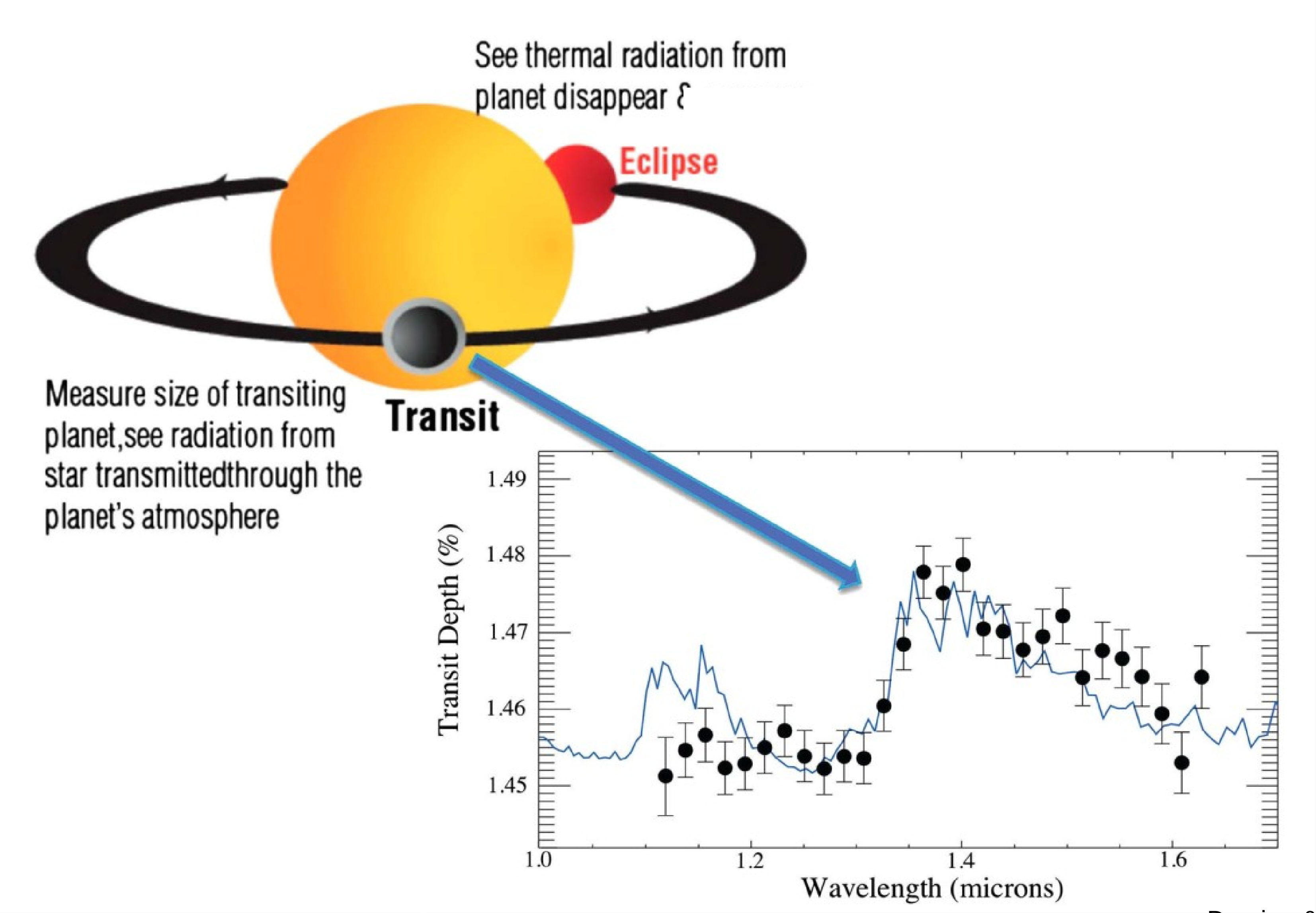


Barros+2013



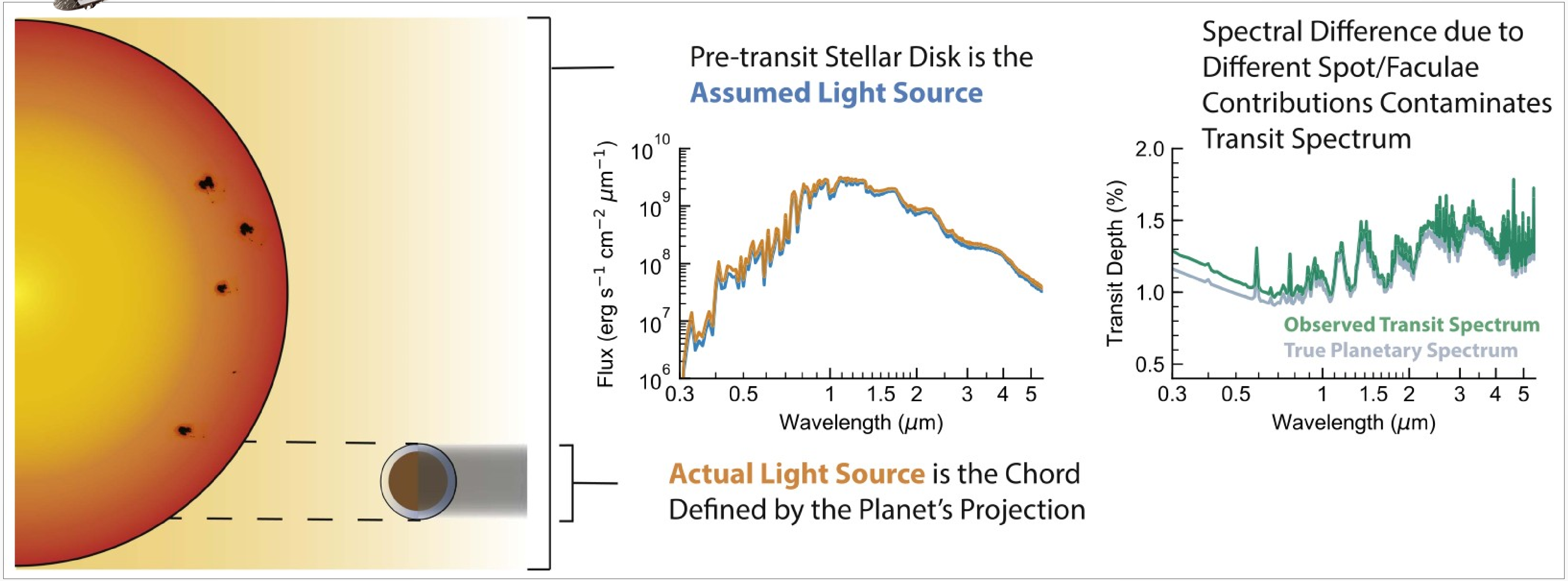
Credit: ESA

Non-occulted starspots effect on transit depth (spectroscopy)



Deming & Seager (2017)

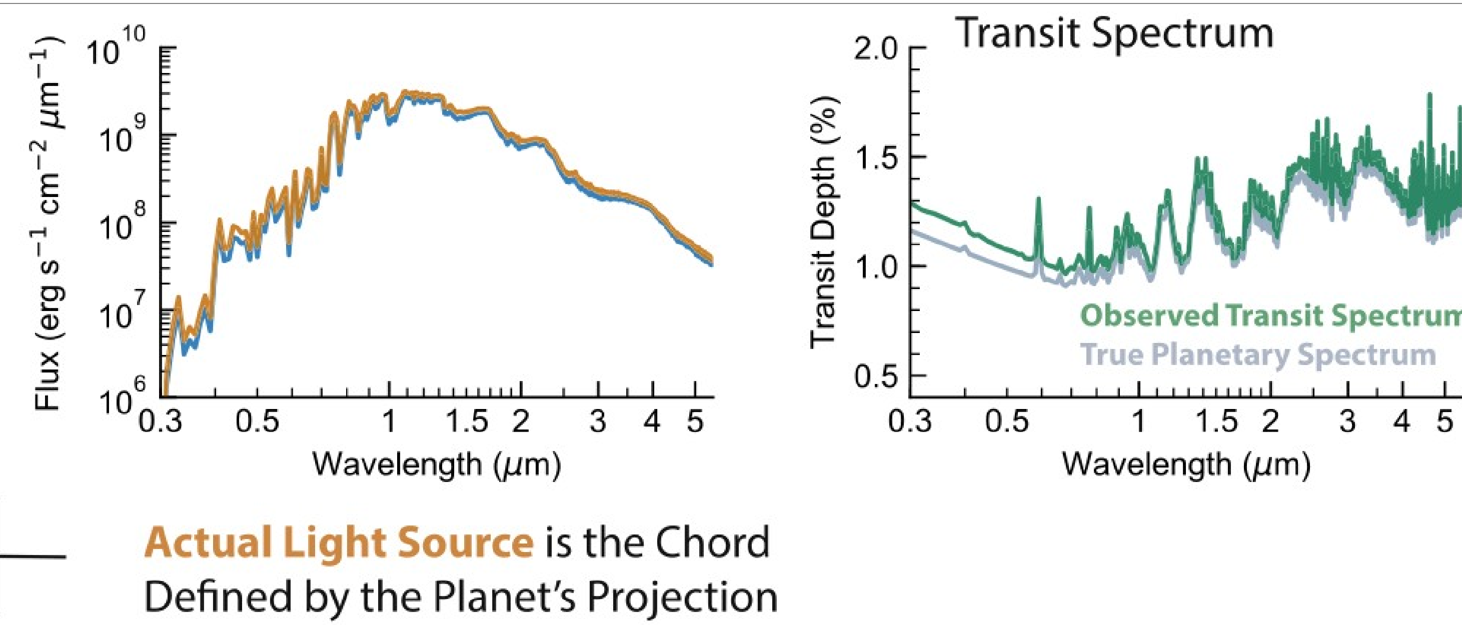
Non-occulted starspots effect on transit depth (spectroscopy)



Rackham et al. 2018

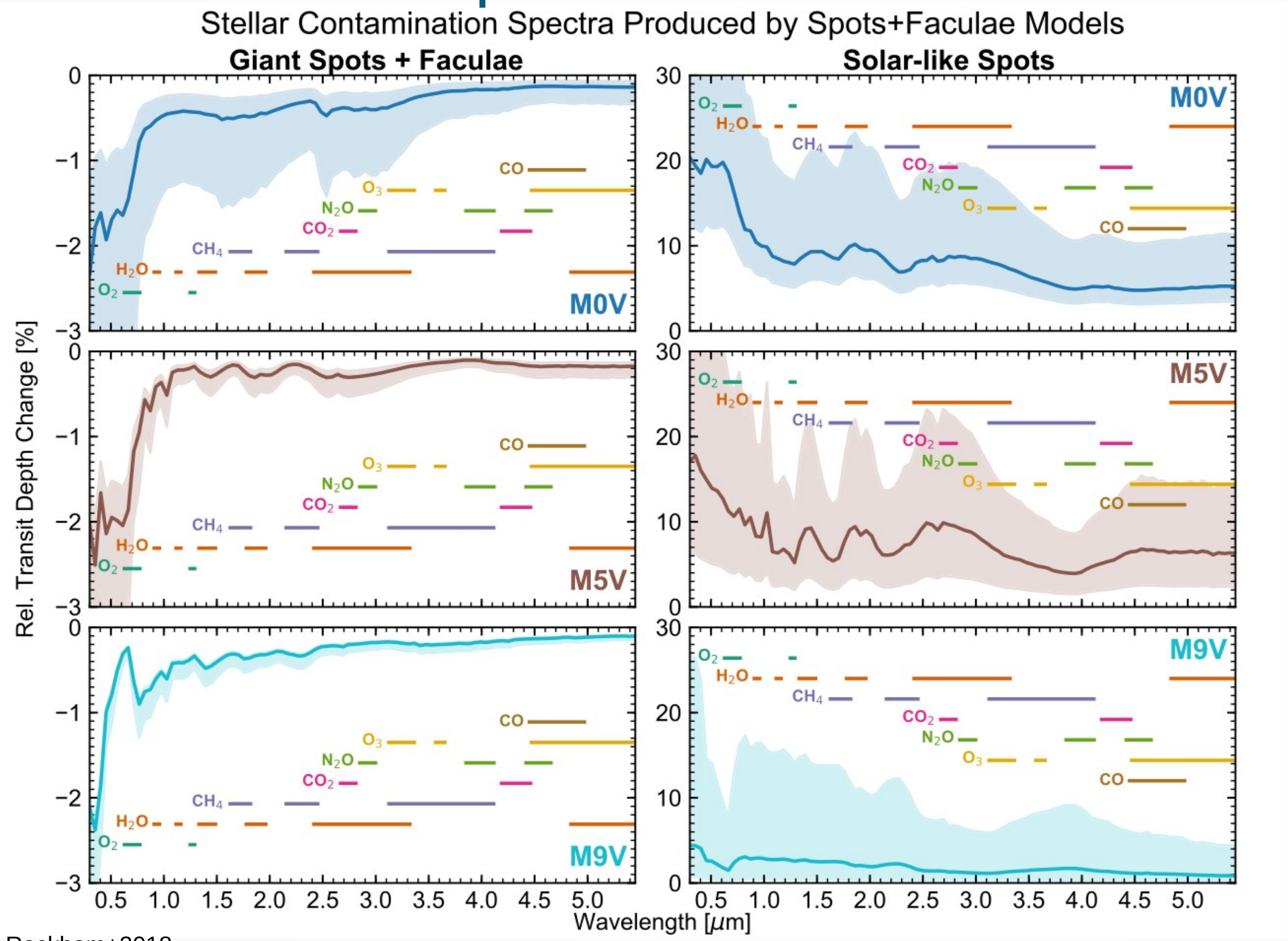
Non-occulted starspots effect on transit depth (spectroscopy)

- Mimics Rayleigh scattering in the visible (e.g. McCullough+2014, Oshagh+2014)
- Bias in planet density affects inferred volatiles (Rackham+2018)
- Water lines contamination in the IR (Wakeford+2018)
- Contamination changes across observing epochs (Barstow+2015)



Rackham et al. 2018

Spectral lines contamination



Rackham+2018

Follow-up needed

→ filling factor
(Huitson+2013)

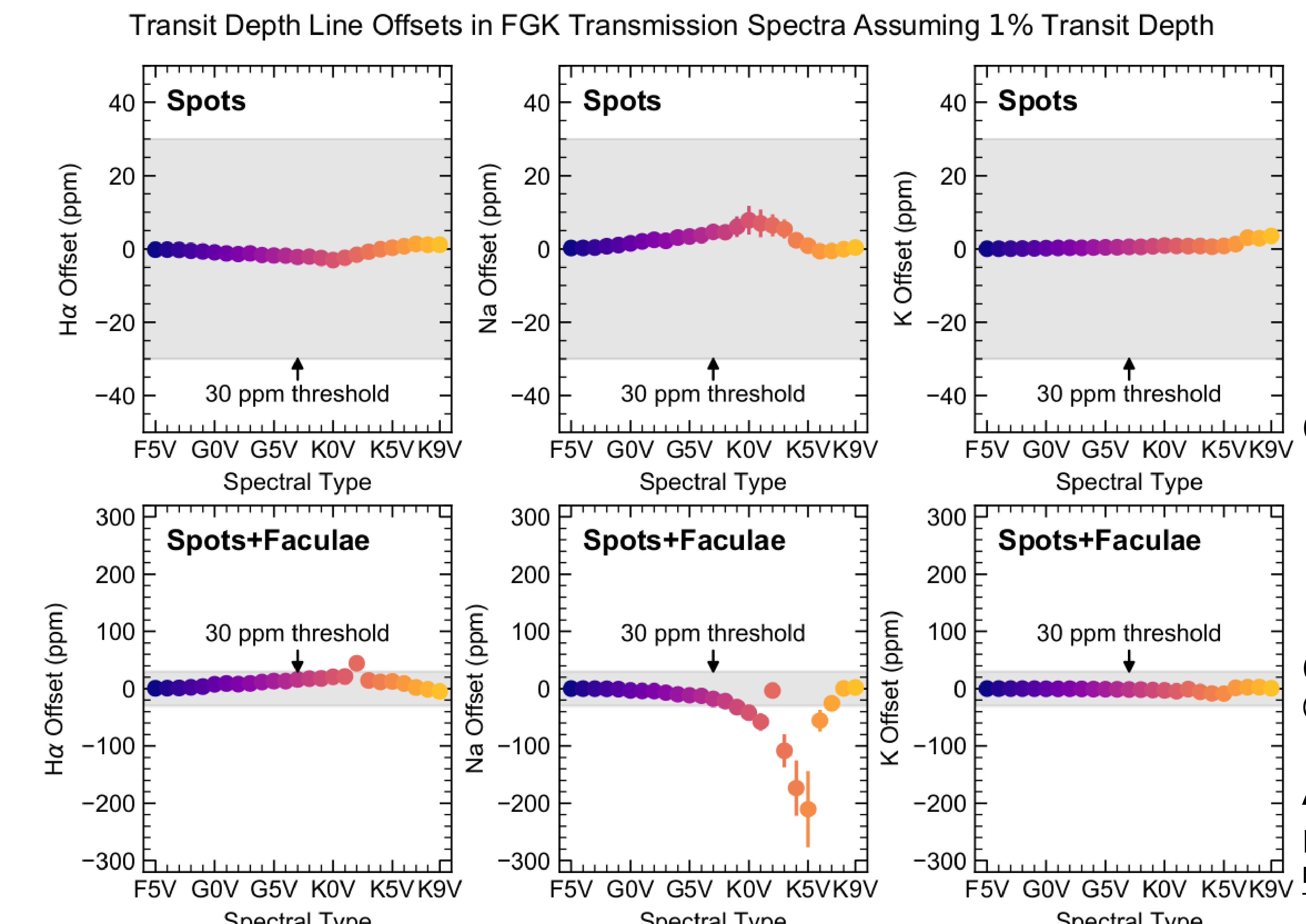
Correction factor for every λ

Or at least

Out-of-transit flux
(Cracchiolo+2021, Wakeford+2019)

Adding starspots to retrievals (Barstow+2015, Bruno+2020, Fournier-Trondeau+2025)

Smaller effect for FGK stars



Rackham+2019

Follow-up needed

→ filling factor
(Huitson+2013)

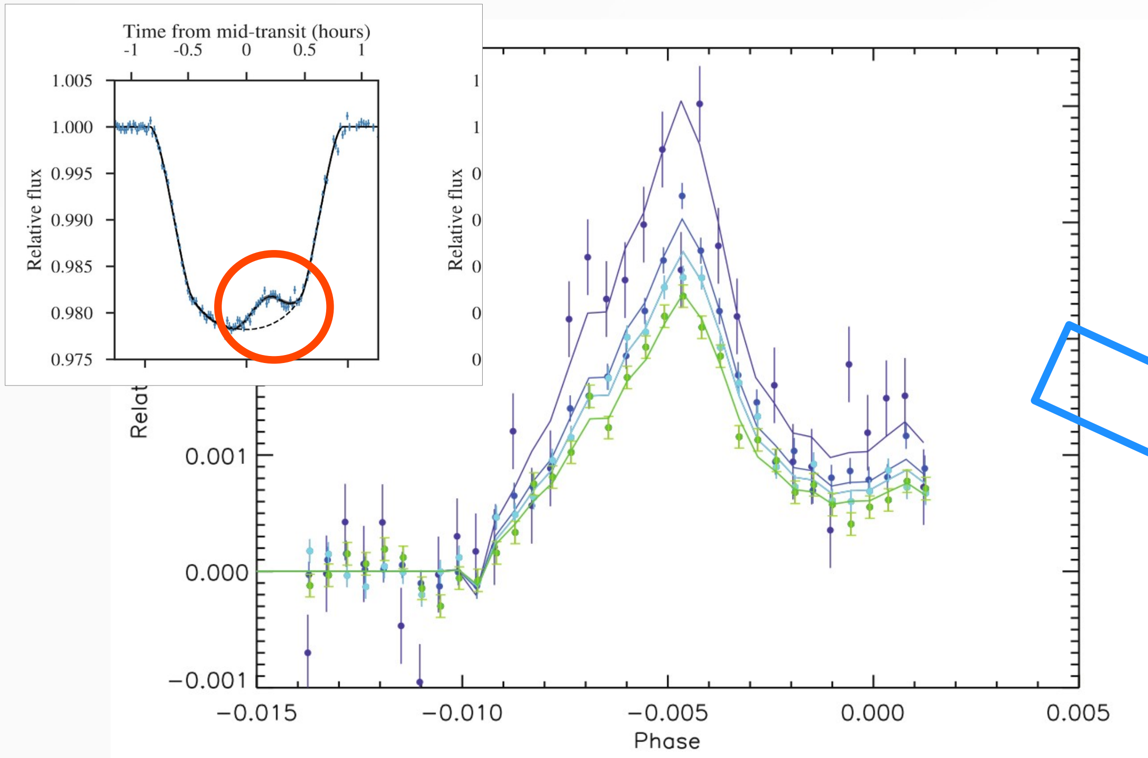
Correction factor for every λ

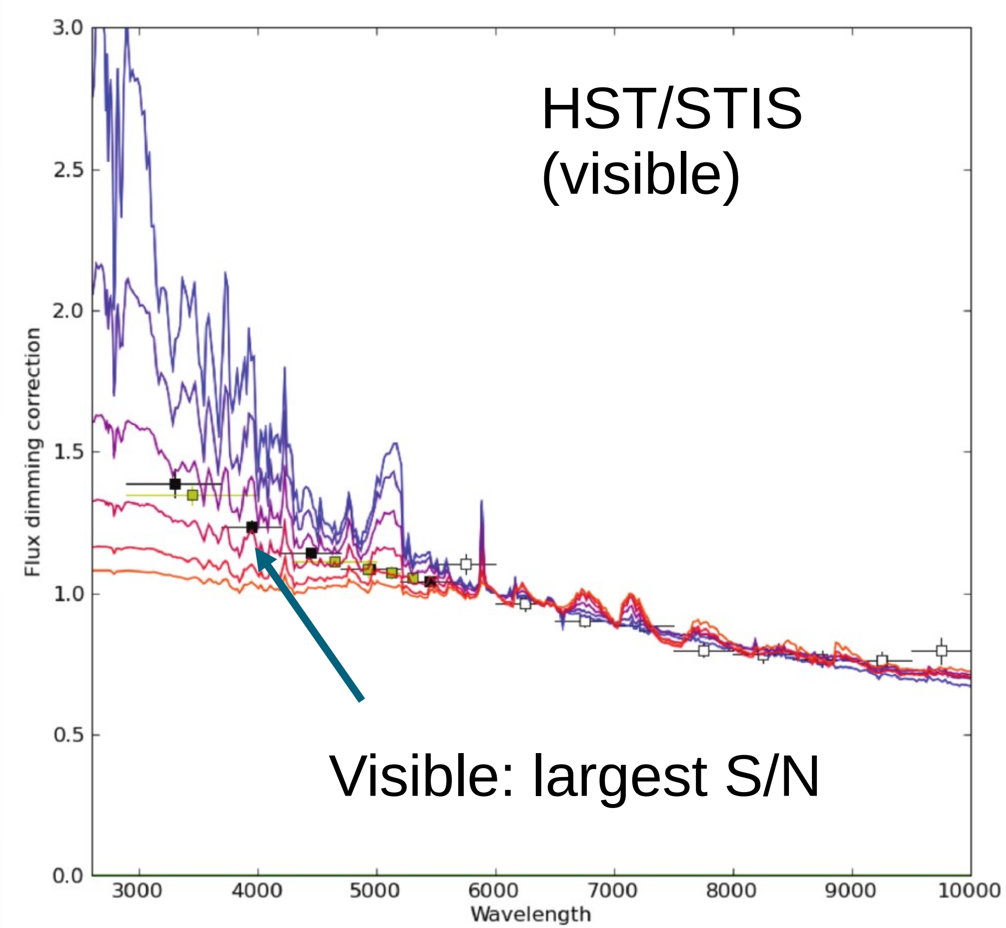
Or at least

Out-of-transit flux
(Cracchiolo+2021, Wakeford+2019)

Adding starspots to retrievals (Barstow+2015, Bruno+2020, Fournier-Trondeau+2025)

Occulted active regions: spot temperature



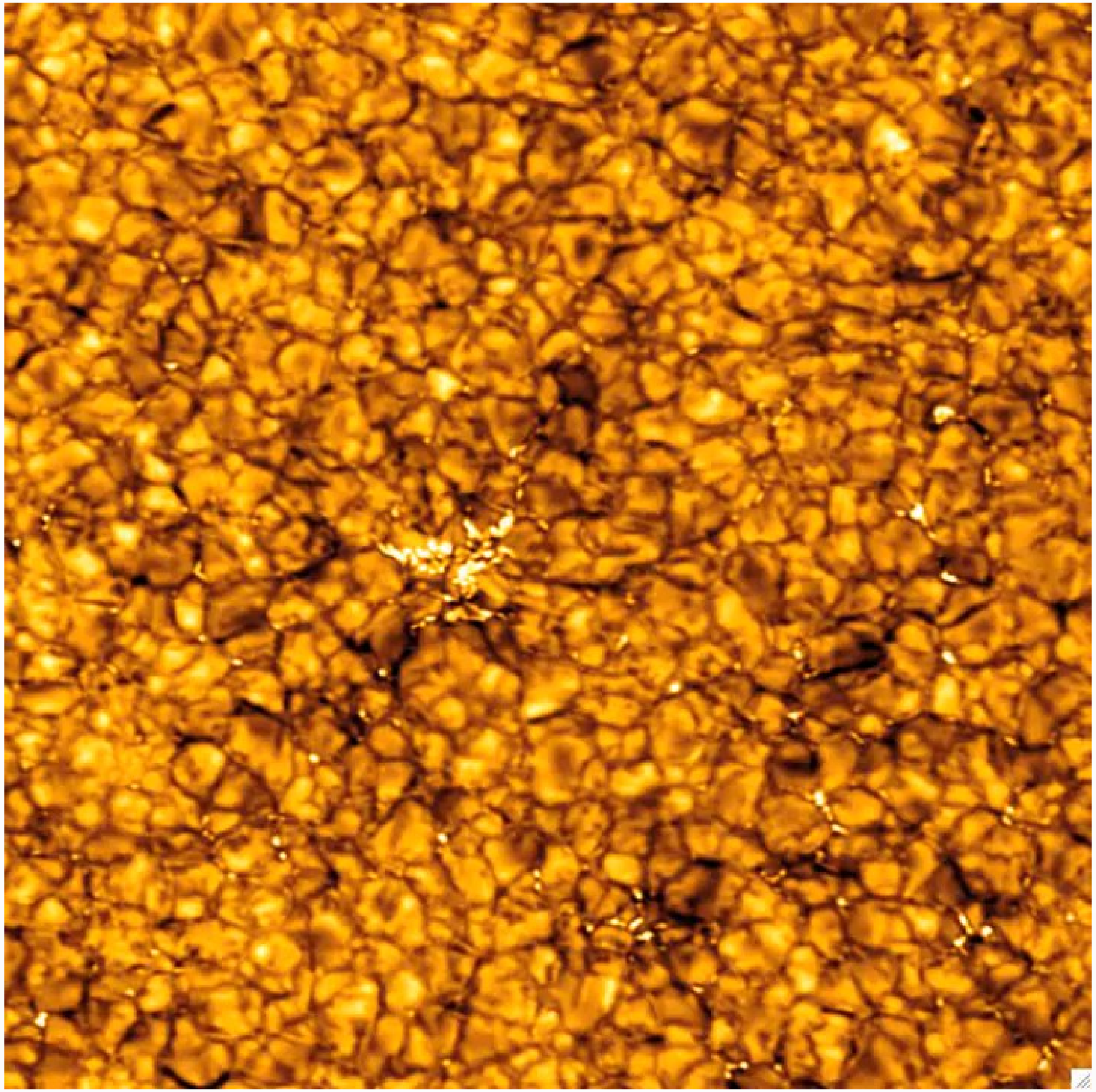


Wavelength variation of starspot “bump”
→ fit starspot temperature with stellar models
(e.g. Sing et al. 2011, Espinoza+2018, Bruno+2022)

$$\Delta f_\lambda / \Delta f_{\lambda_0} = \left(1 - \frac{F_\lambda^{T_\mathrm{spot}}}{F_\lambda^{T_\mathrm{star}}}\right) \Big/ \left(1 - \frac{F_{\lambda_0}^{T_\mathrm{spot}}}{F_{\lambda_0}^{T_\mathrm{star}}}\right)$$

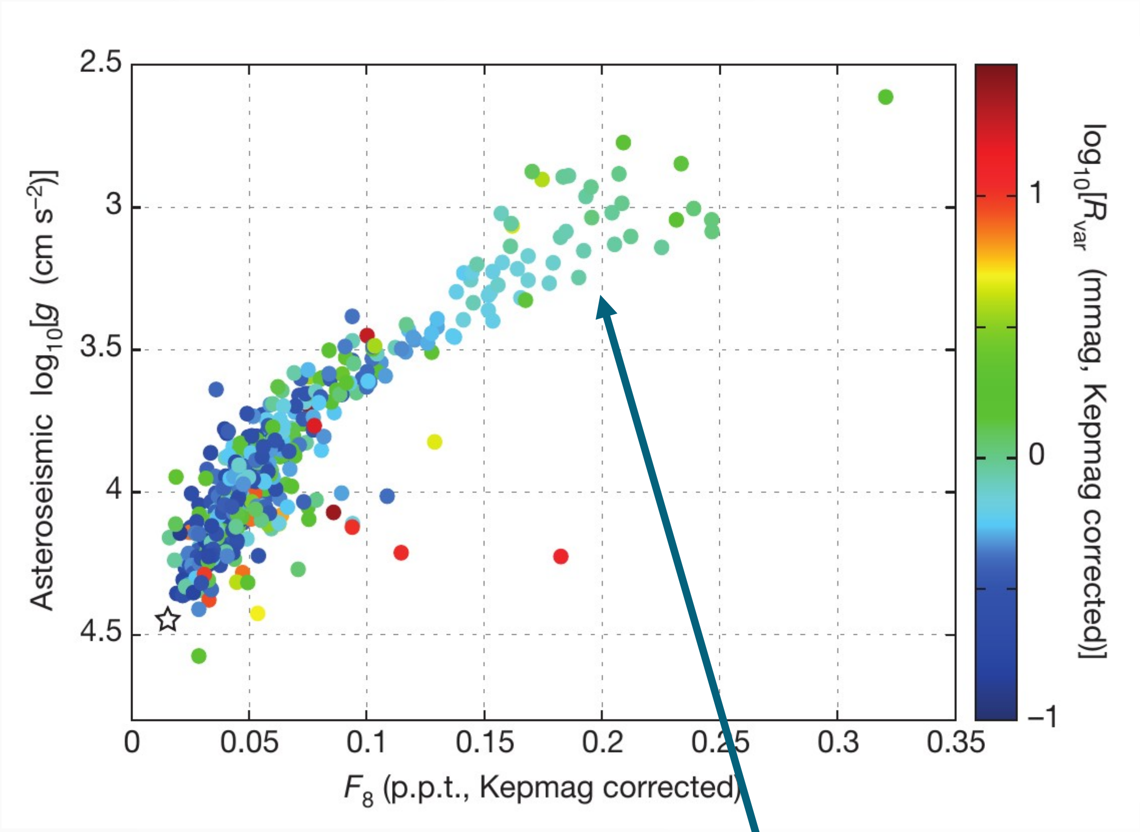
Stellar granulation

10^6 m
(Sun)

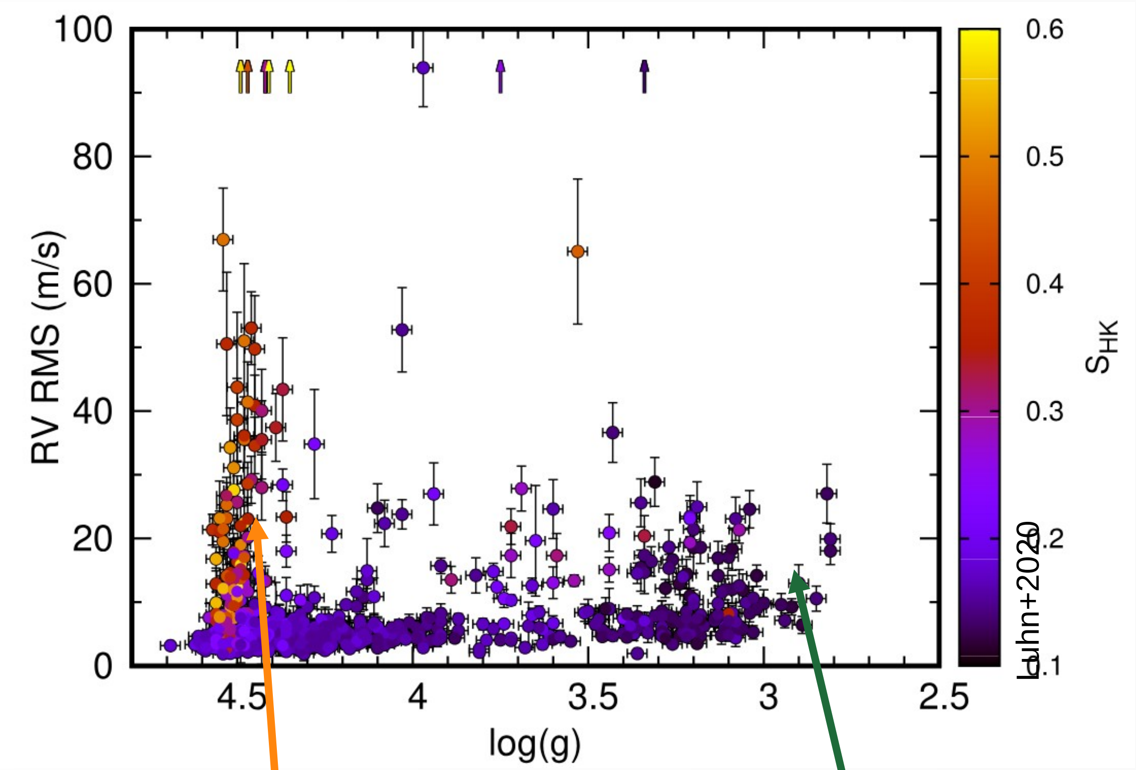


Credit: Bob Trembley

Dominating source of noise for evolved stars



Bastien+2013

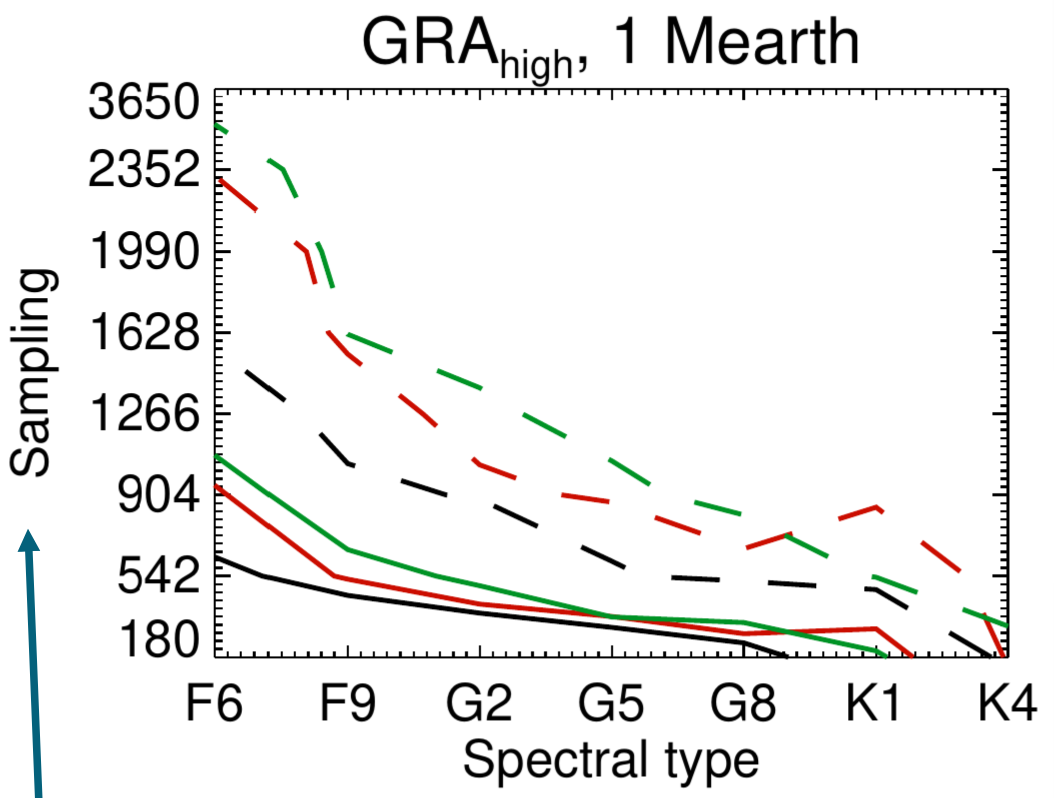


Subgiants and giants

Younger and more active
(S index meas.)
> active regions

More evolved and less active
(> granulation)

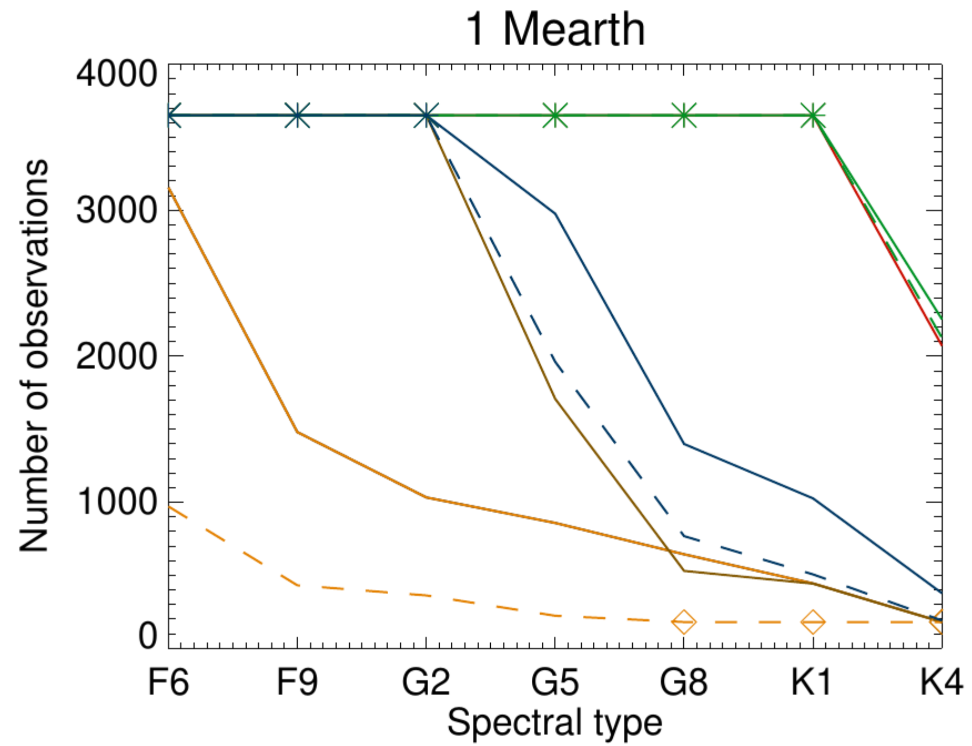
Effect on exoplanet observations (RV)



Meunier & Lagrange (2020)

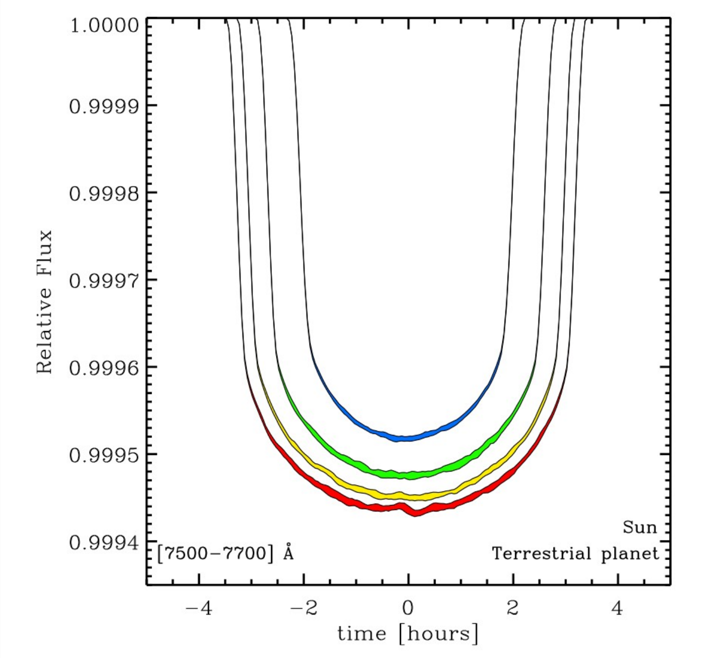
Number of observations needed to reach 50 (-) and 95 (--) detection rates

Simulated Earth-mass planets in habitable zone of F6 to K4 star



To reach 20% uncertainties on M_p

Effect on exoplanet observations (Transits)

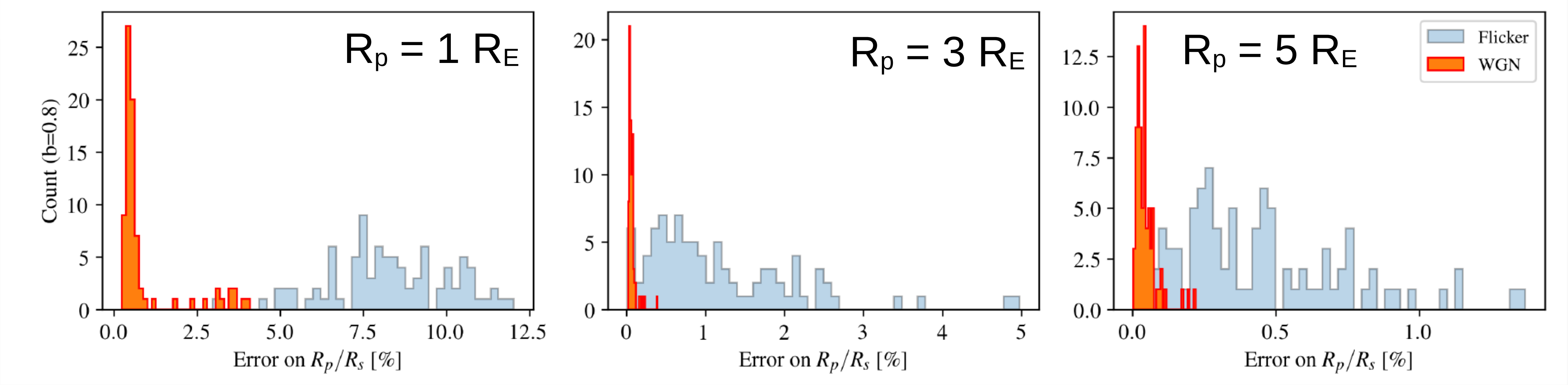


Chiavassa+2017

3D RHD simulations + solar images

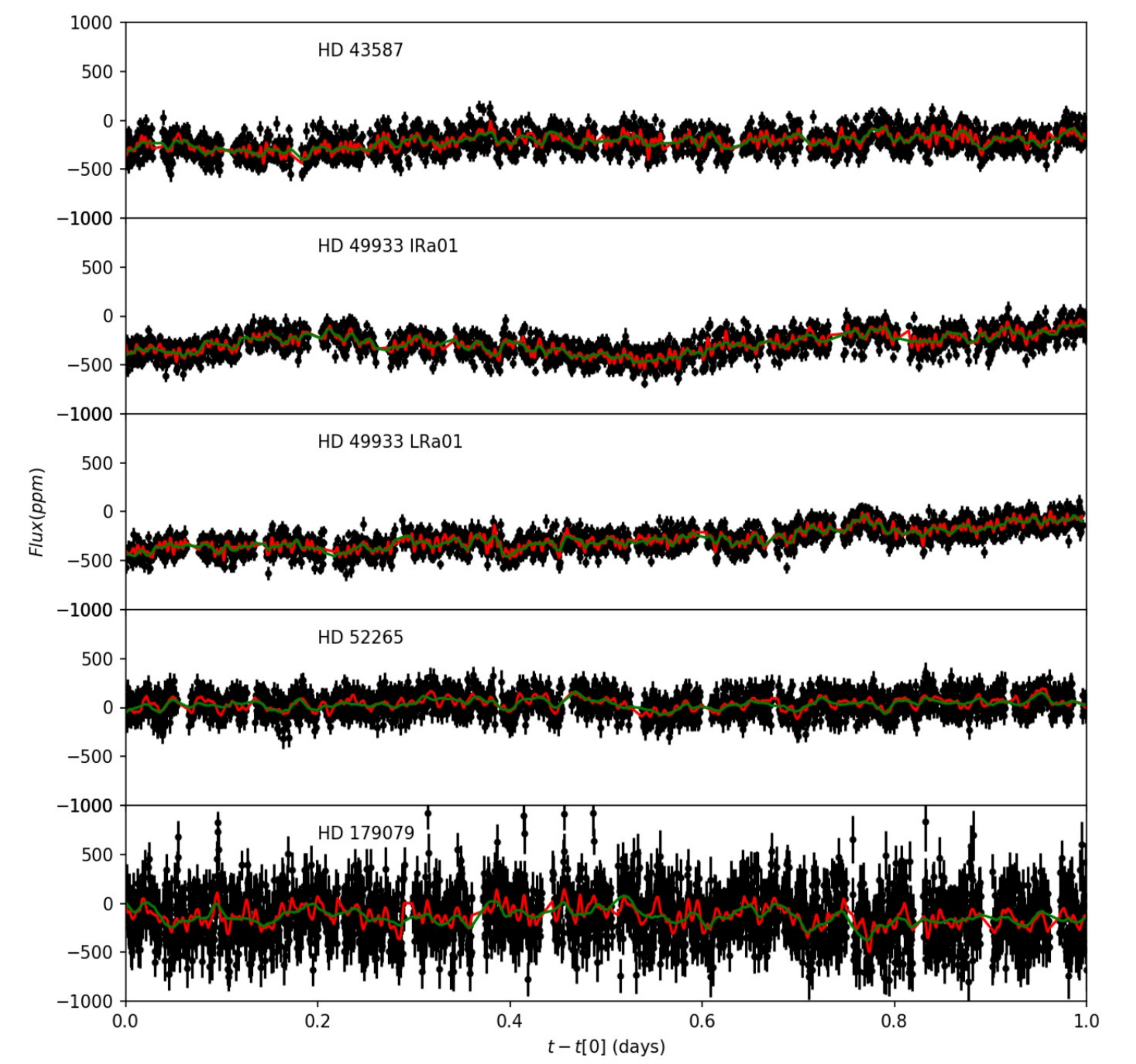
Wavelength-dependent effect to be explored

Solar-like granulation and simulated transits

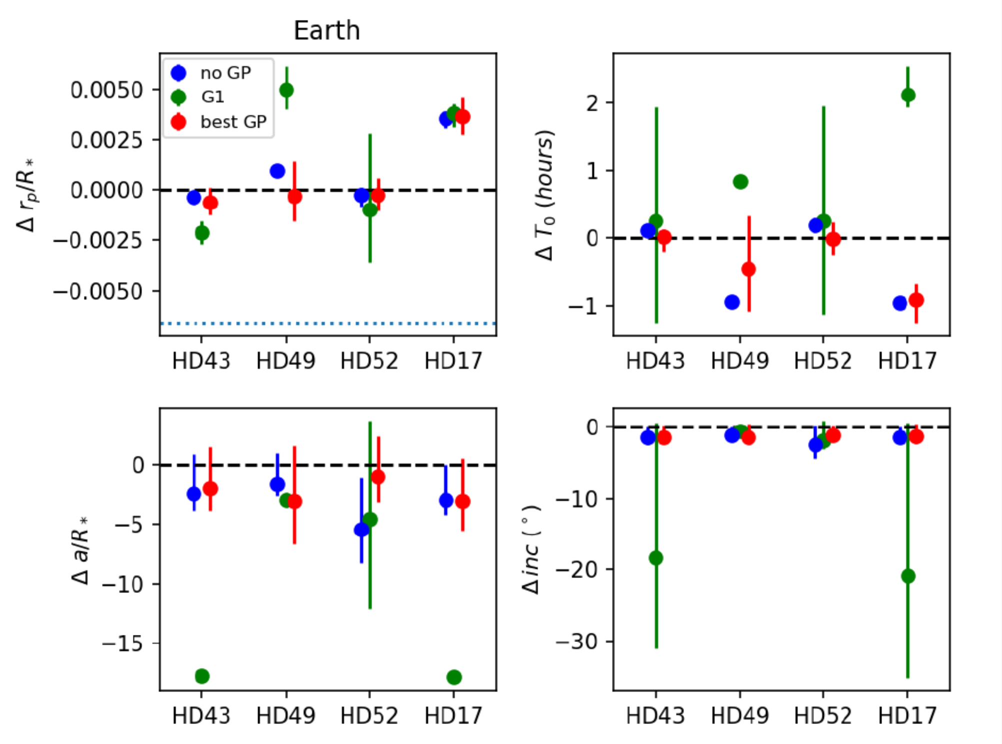


Sulis+2020

How to deal with granulation



GPs/wavelets are currently our best weapon, but improvements are needed
(e.g. Barros+2020, Maxted+2022)



Strategies for current and near-future surveys

Search and study terrestrial exoplanets in the habitable zone of solar-like stars

Analyse the atmosphere of a thousand exoplanets

- Preliminary, homogeneous study of stellar companions
- Selection of most convenient targets
- Hare-and-hound tests to understand pros and limitations of each technique
- Data challenges

Take-home messages

- Stellar activity is a challenge for exoplanet science

  - Planet radius

  - Transit parameters

  - Atmospheric composition

  but **there is hope**

- Exoplanet observations give us plenty of opportunities to study stellar activity

  - Photospheric brightness maps, stellar obliquity

  - Starspot distribution and lifetimes

  - Stellar rotation and differential rotation

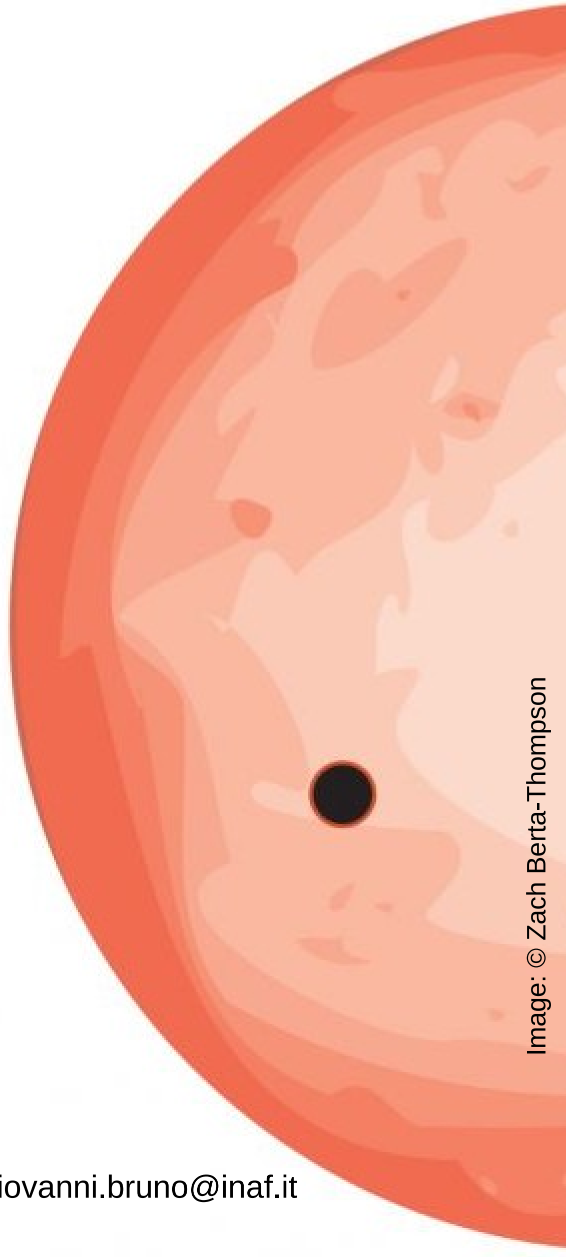


Image: © Zach Berta-Thompson

giovanni.bruno@inaf.it