Understanding stellar activity in the exoplanetary field

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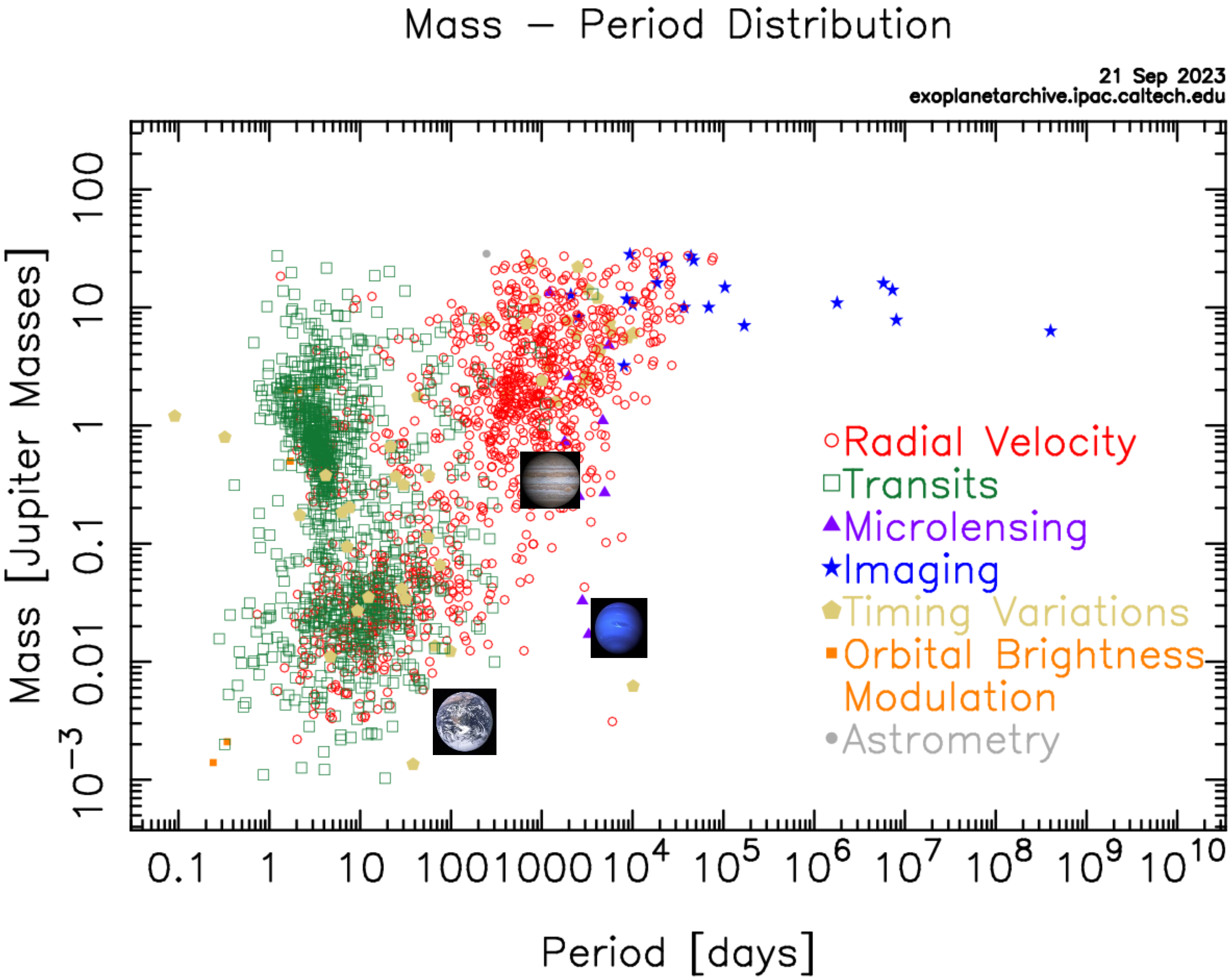
Outline

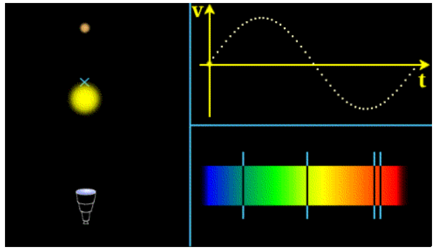
- Introduction: context and challenge
- Part 1: Stellar variability, overview, origin, what do we know from the Sun and for other stars
  - Magnetic activity
  - Flows
- Part 2: Methods to evaluate the impact and tools
  - Methods
  - Tools
- Part 3: Impact and approaches to mitigate the impact of stellar activity
  - RV
  - Photometric transits
  - Atmosphere characterisation (transmission spectroscopy)
  - Astrometry
- Conclusion

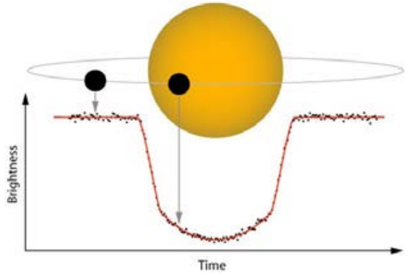
Won’t talk about…

- Direct imaging
  - *=> lecture A. Boccaletti*
- Direct impact of the star on the planetary properties (atmosphere, habitability…)
  - *=> lectures Rim Fares, Ekaterina Ilin, Julián Alvarado Gómez, Sudeshna Boro Sakia*
- Importance of knowledge of the star on different aspects such as
  - Fundamental parameters, including age, radius (strong impact on transits), mass
  - Center-to-limb darkening
  - Distance
- Other effects affecting the search for exoplanets
  - Instrumental systematics
  - Tellurics
  - Presence of other planets (in RVs), known or unknown

Introduction: context and challenge







Radial velocity (projected) mass

Transits Radius

Indirect technique
Stellar photons

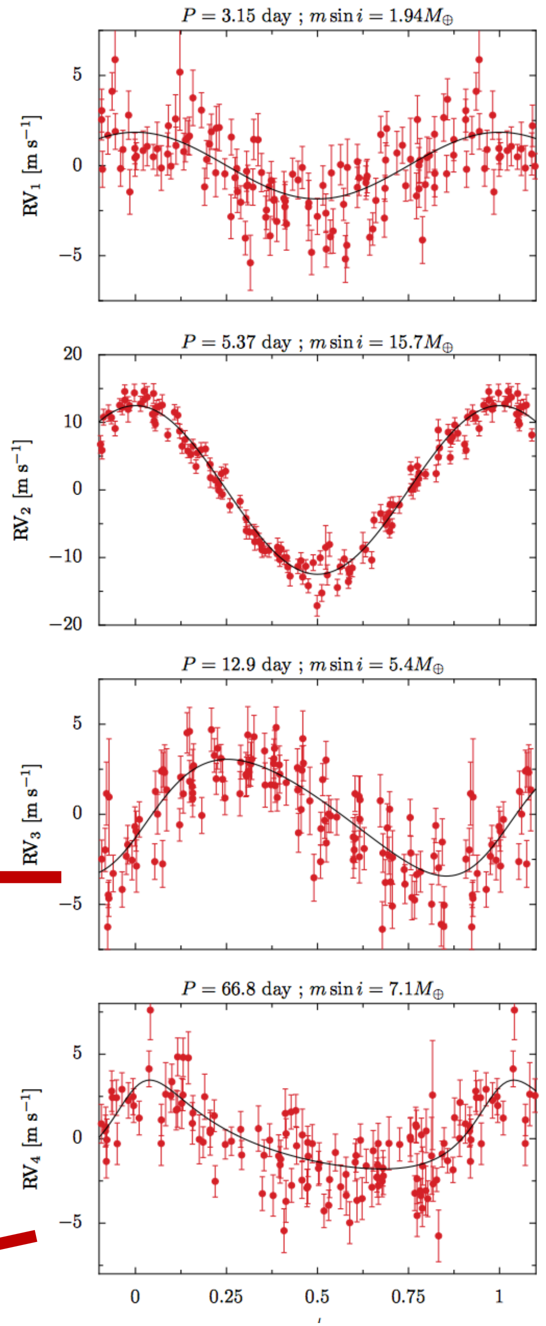
Indirect detection methods

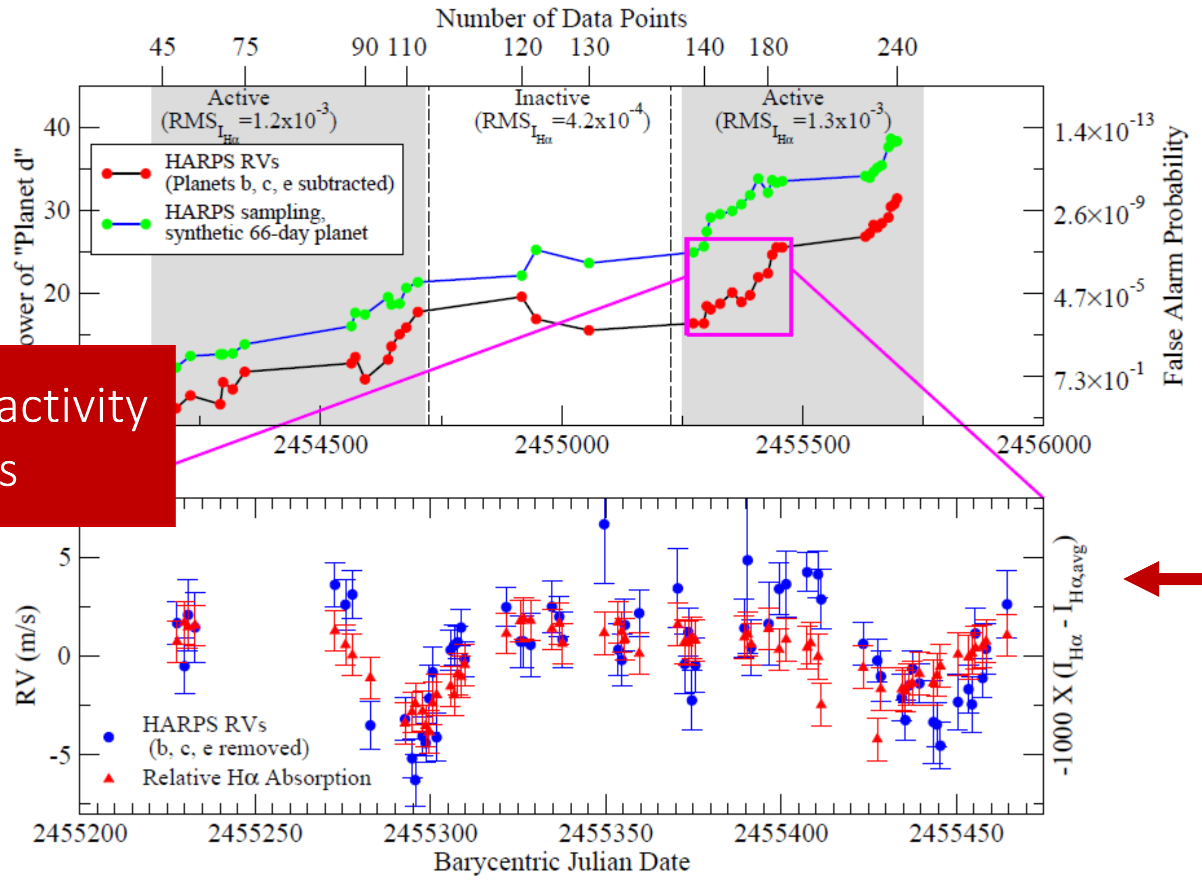
Stellar variability can

- *Mimic* the planetary signal (RV, atmospheric features)
- *Hide* the planetary signal
- *Affect* the determination of planetary parameters (mass, radius, atmosphere caracterisation) / uncertainties, biases

Gl581 (M3)

Mayor+ 09
4 planets !!!





Importance of activity indicators

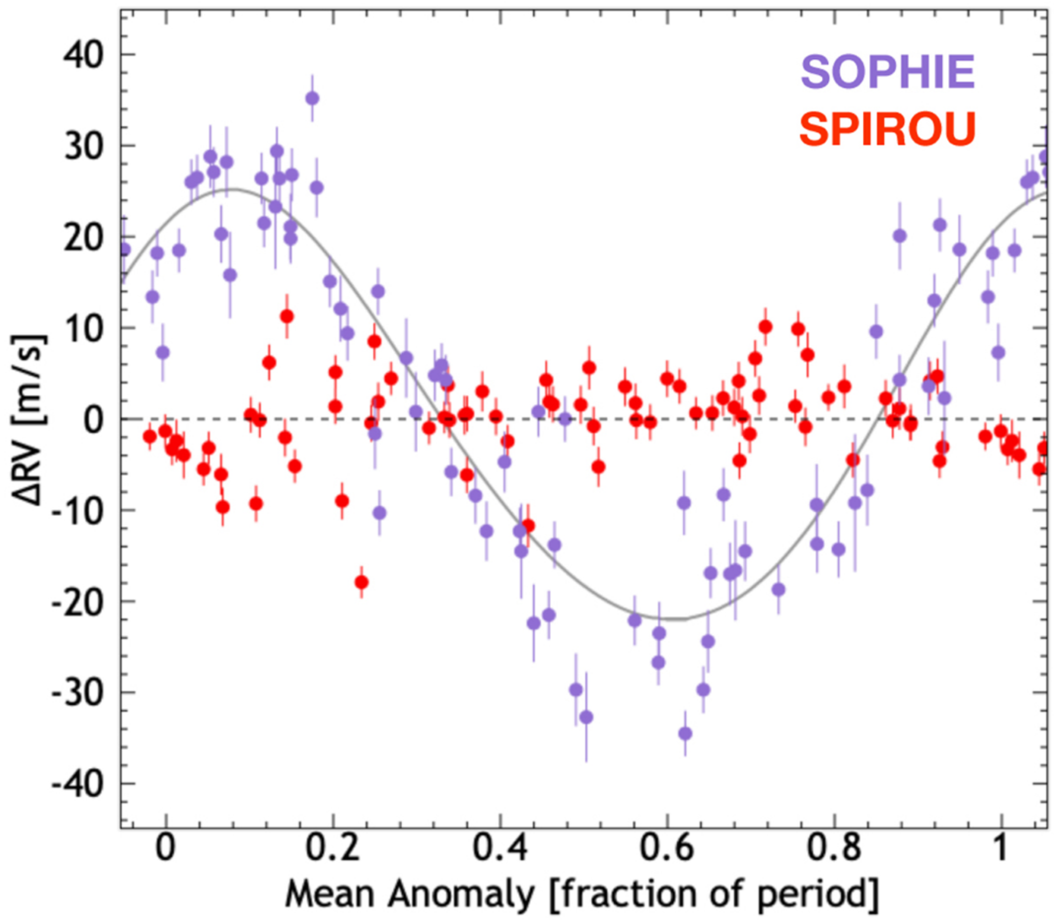
Robertson+ 14
Re-analysis

Still controversial

AD Leo (M3)

Tuomi+18 claimed a planet based on VIS observations
Kossakowski+22 found link with various activity indicators
Carmona+23 rejected the planet based on IR observations

Importance of wavelength coverage



Indirect detection methods

Stellar variability can

- *Mimic* the planetary signal (RV, atmospheric features)
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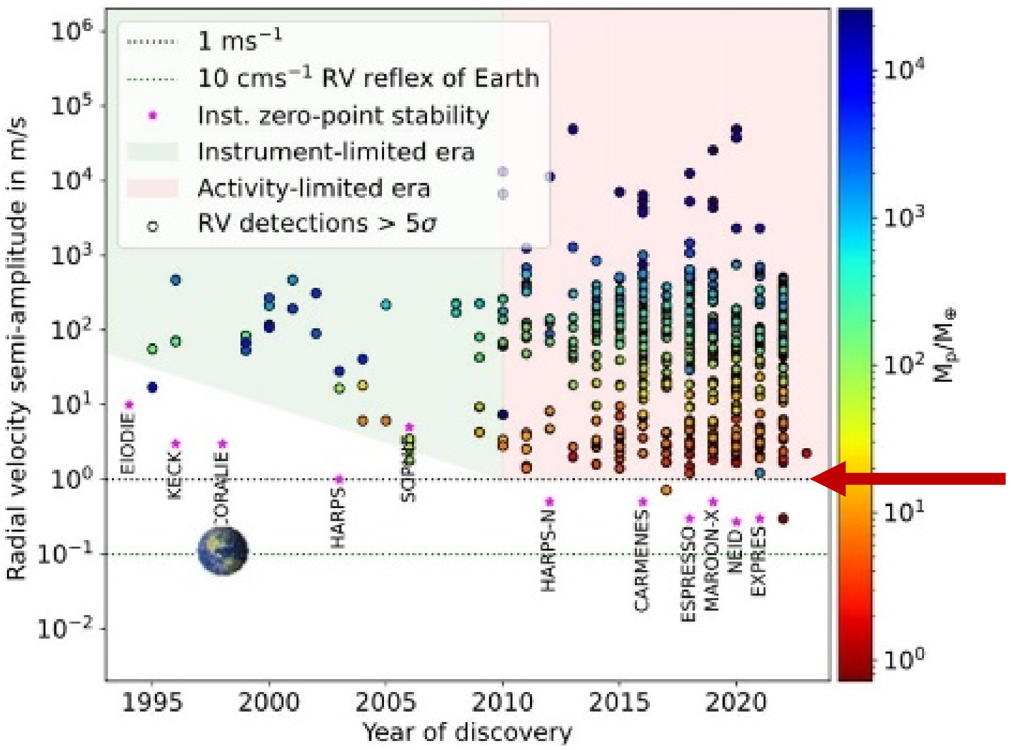
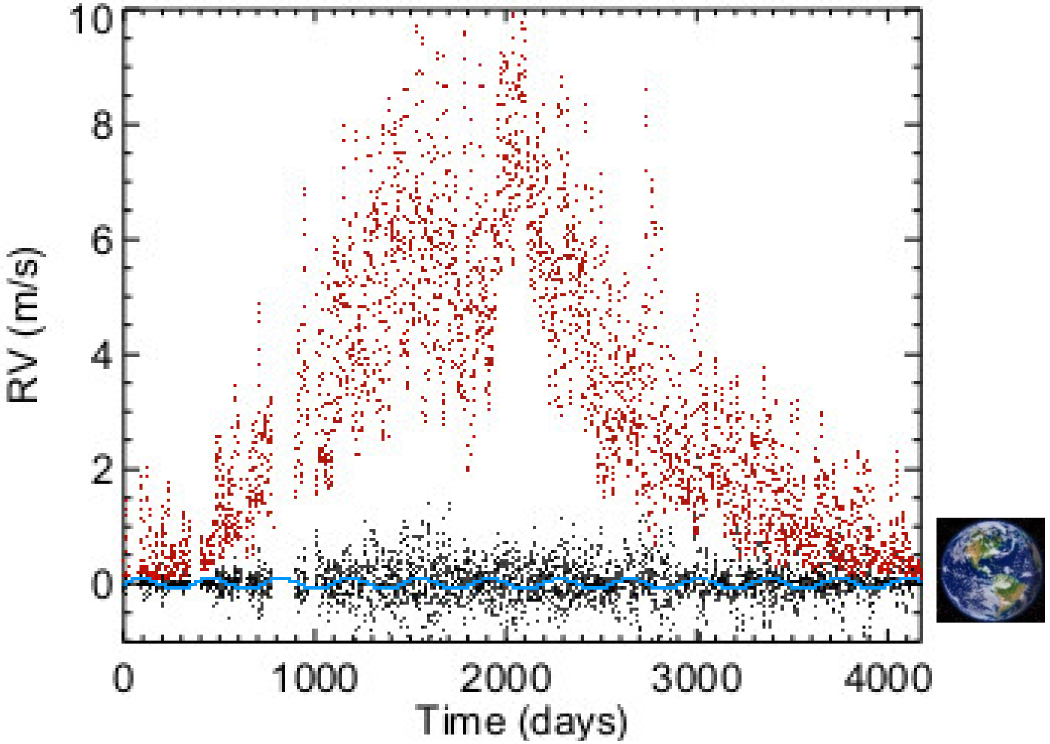
- *Affect* the determination of planetary parameters (mass, radius, atmosphere caracterisation) / uncertainties, biases

Main limitation to detect low mass planets

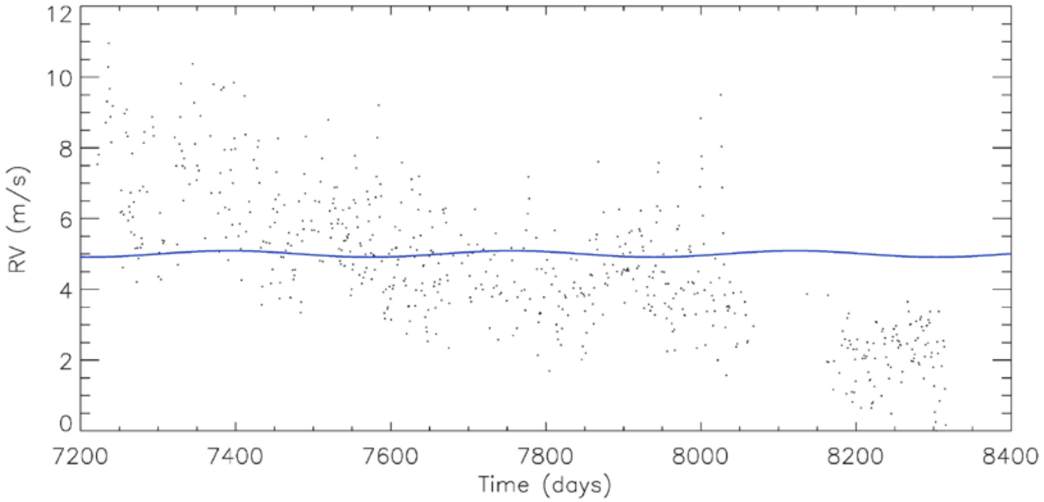


John+23

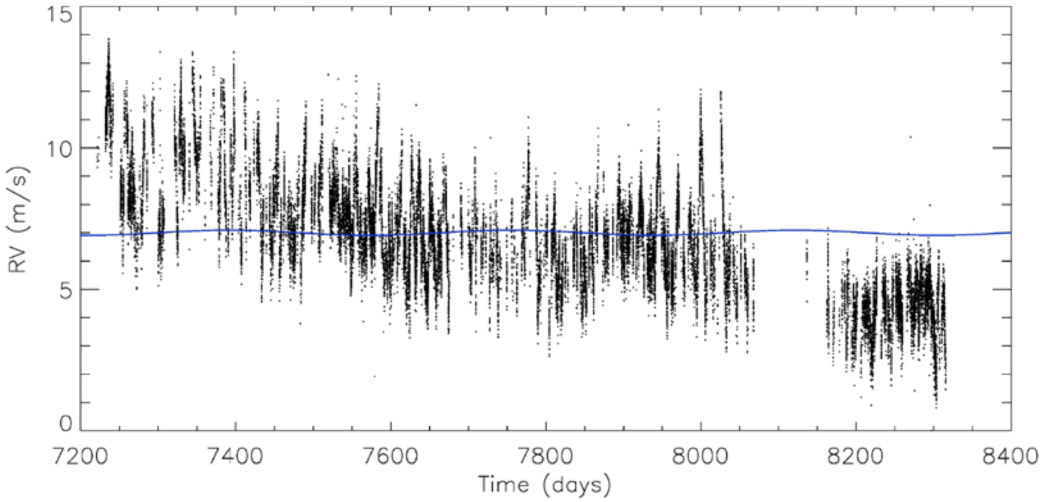


Meunier+10

Solar HARPS-N data Dumusque+21



Daily averages



All individual observations (5 min averages)

Indirect detection methods

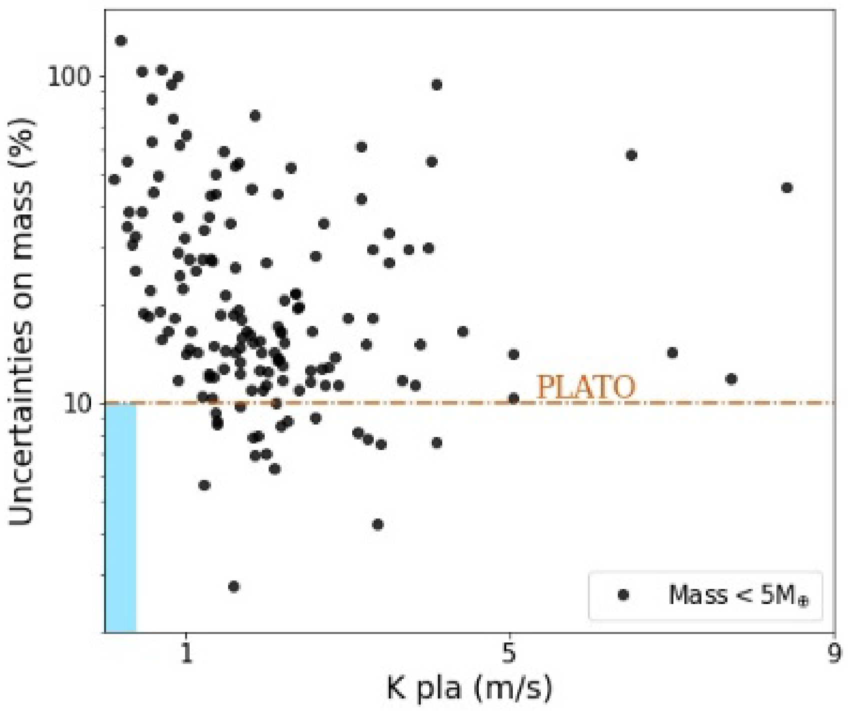
Stellar variability can

- *Mimic* the planetary signal (RV, atmospheric features)
- *Hide* the planetary signal
- *Affect* the determination of planetary parameters (mass, radius, atmosphere caracterisation) => uncertainties, biases

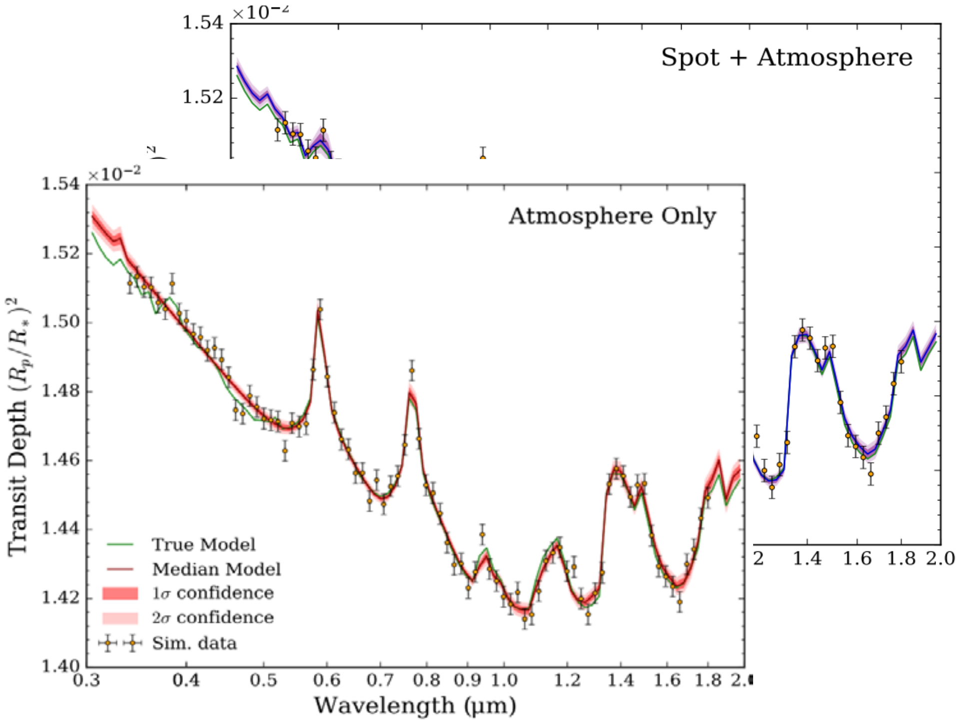
Impact on exoplanet characterisation

On mass estimation

M<5Mearth
From https://exoplanet.eu/



On atmosphere characterisation



Rackham+22

Part 1: Stellar variability

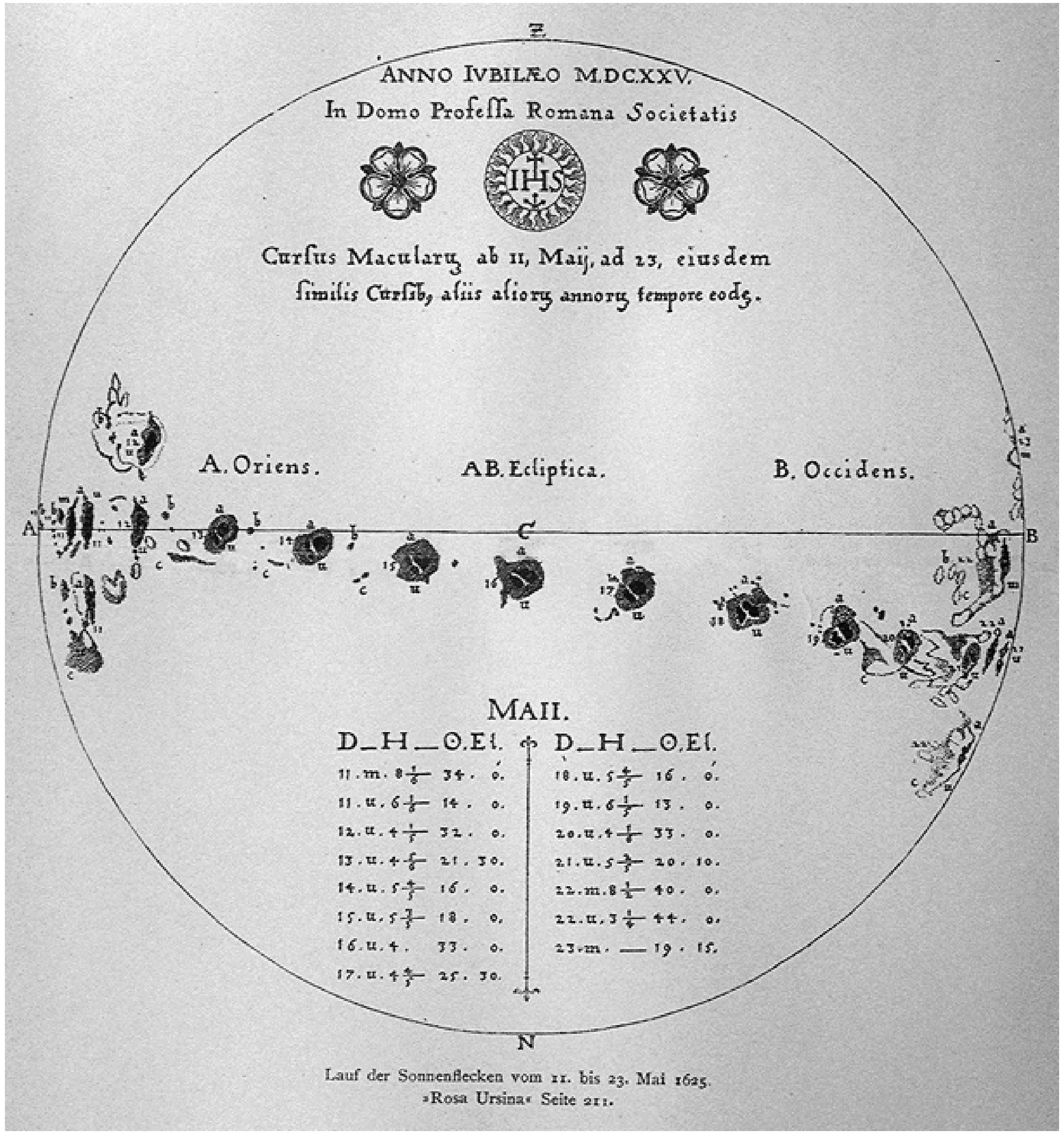
Magnetic activity

- Intensity observations
- Chromospheric emission
- Dynamo and magnetic fields : spots, faculae, flares

Flows

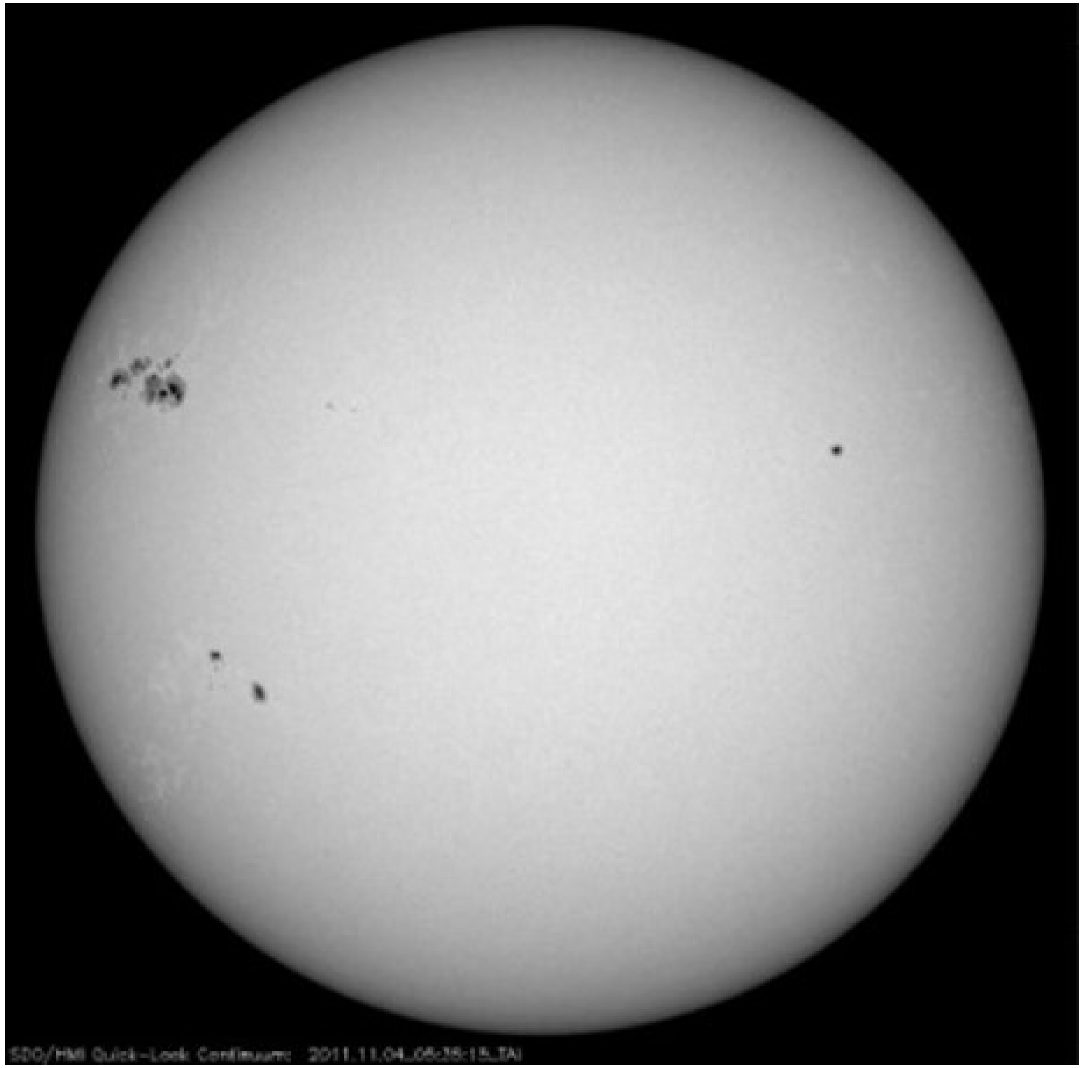
- Differential rotation
- Oscillations/pulsations
- Granulation
- Supergranulation, meridional circulation, convective blueshift inhibition

Lot’s of information from the Sun
Focus on interesting properties for exoplanet searches and characterisation

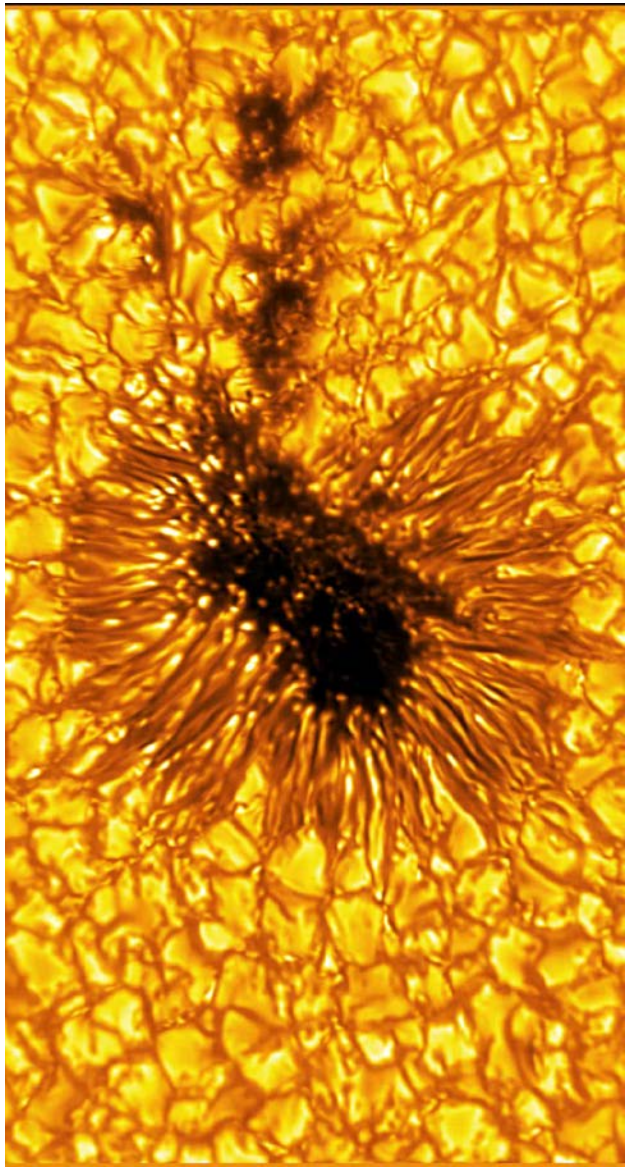


Scheiner 1625

Spots and faculae

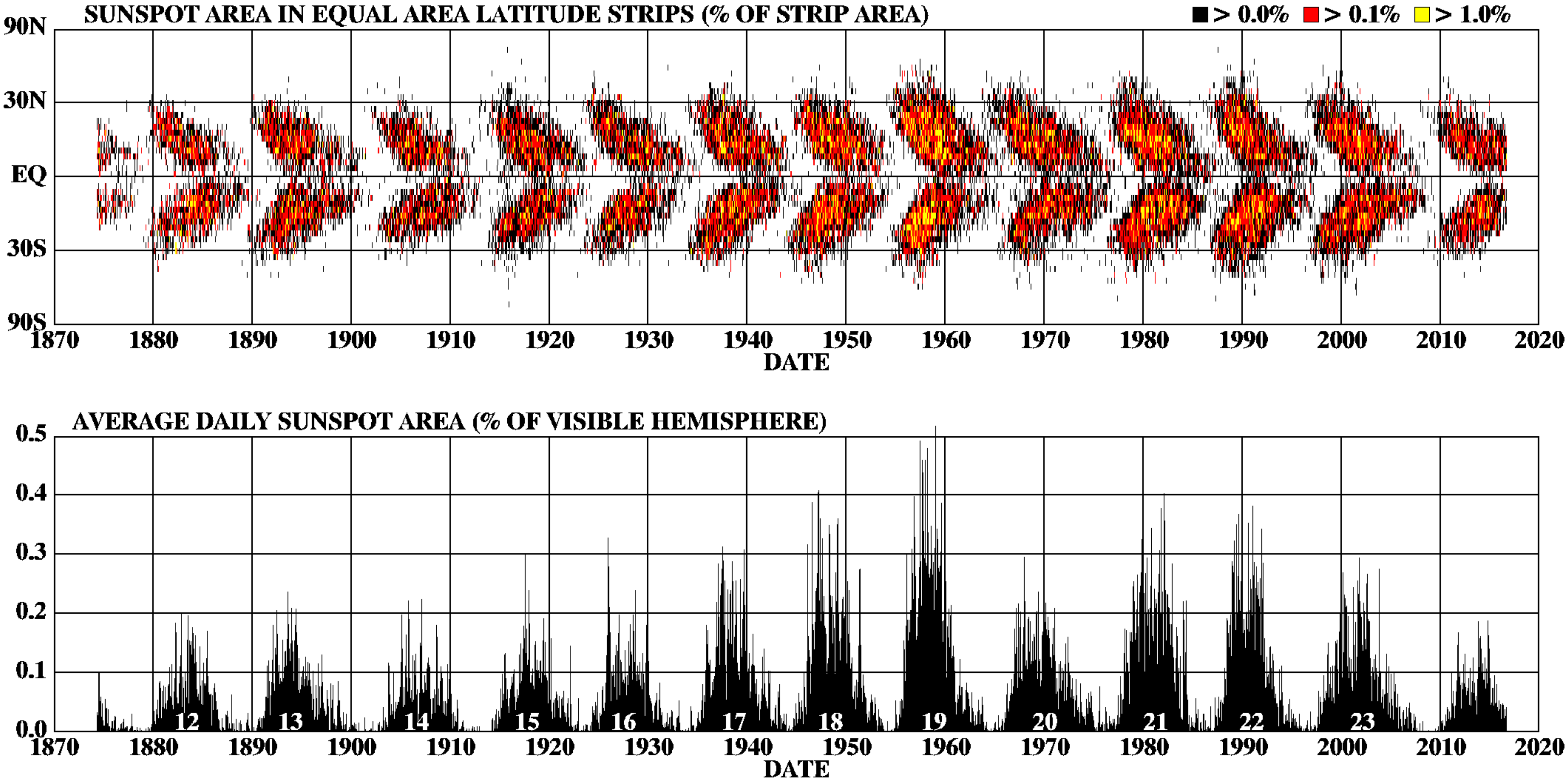


SDO/HMI



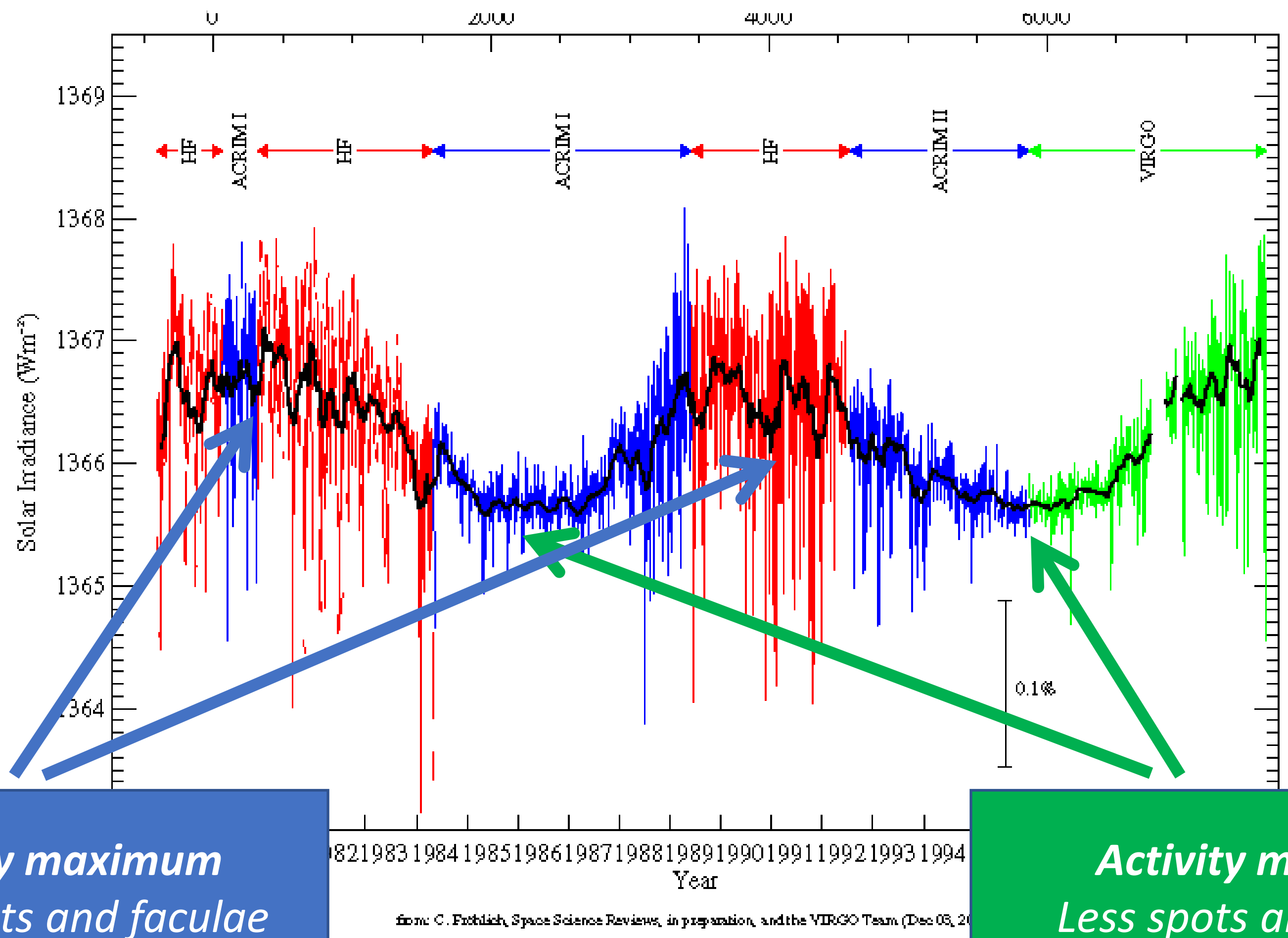
D.K.Inouye telescope, Maui
photosphere

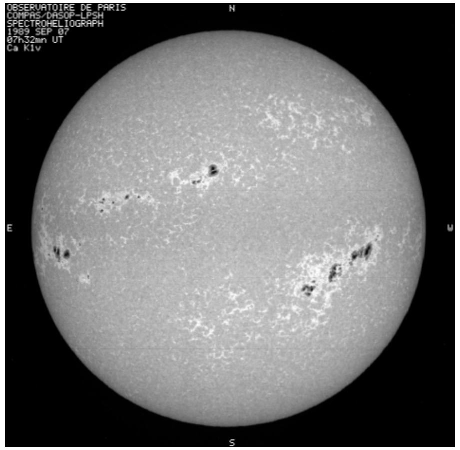
DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS



http://solarscience.msfc.nasa.gov/ HATHAWAY NASA/ARC 2016/10

Solar irradiance variability

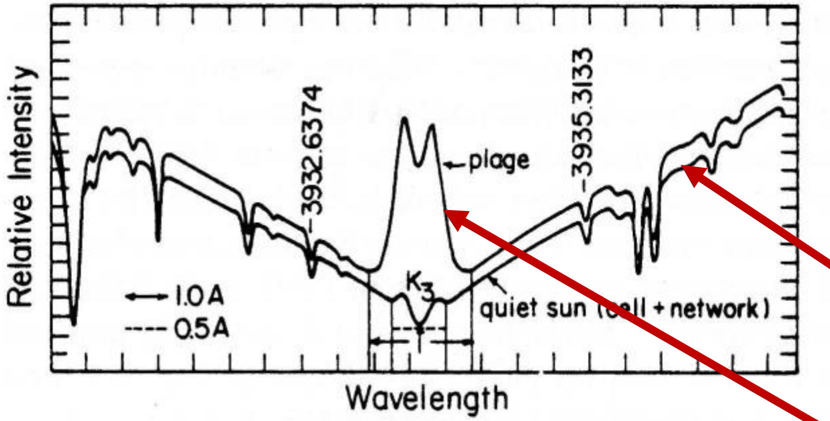




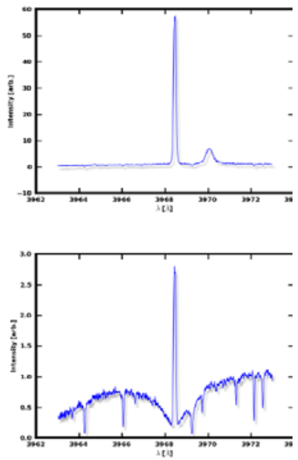
Activity maximum
More spots and faculae

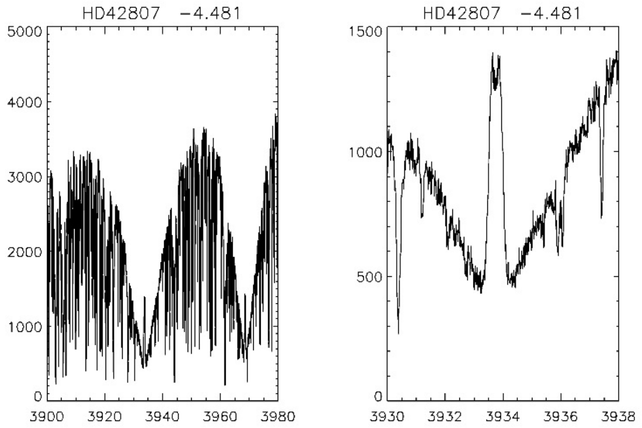
Activity minimum
Less spots and faculae

The Ca II H&K lines at ≈3933 and 3968 Å



Ca II H&K

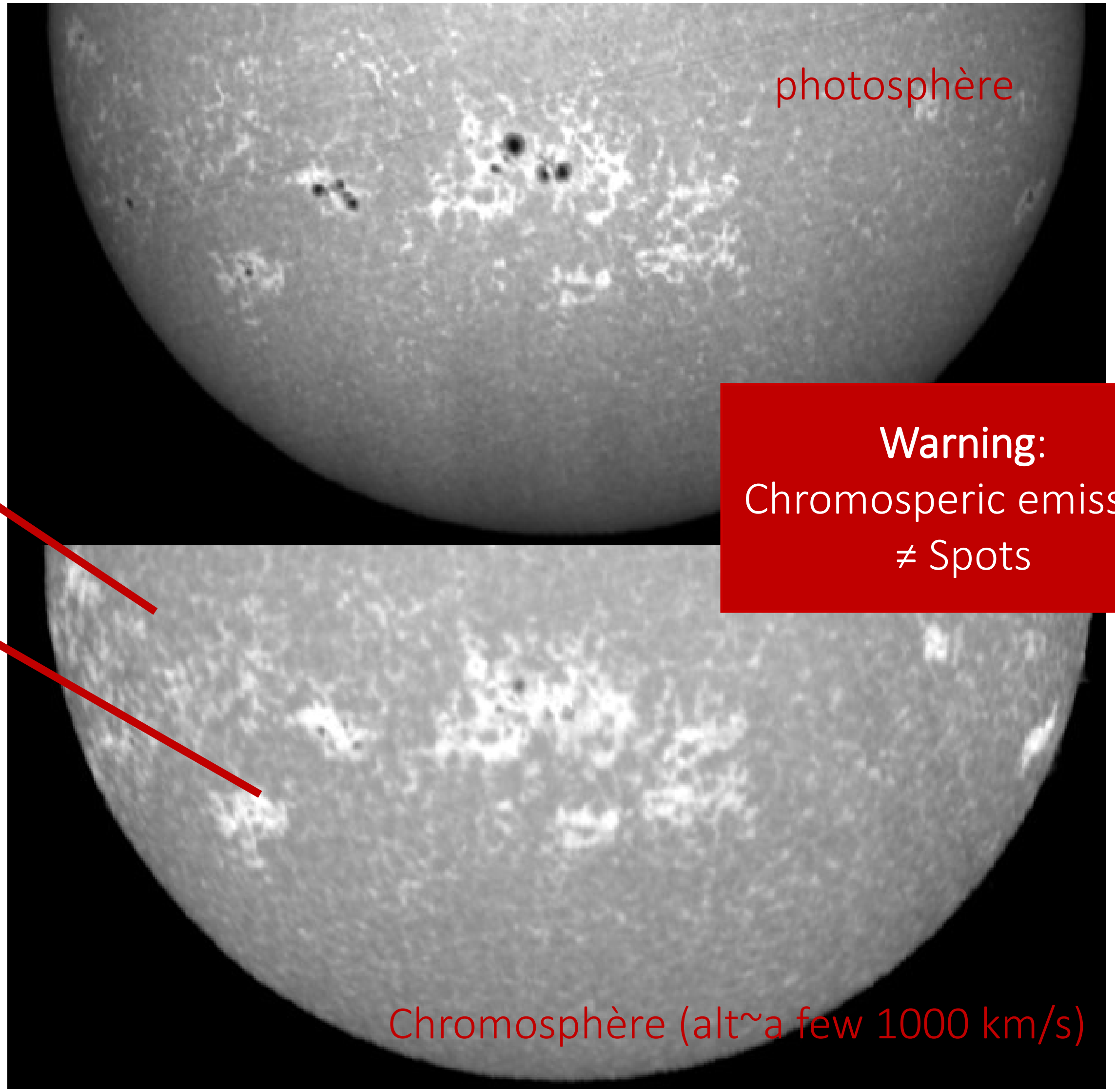




Active M dwarf

G dwarf

HARPS data



Warning:
Chromosperic emission
≠ Spots

Meudon/BASS2000

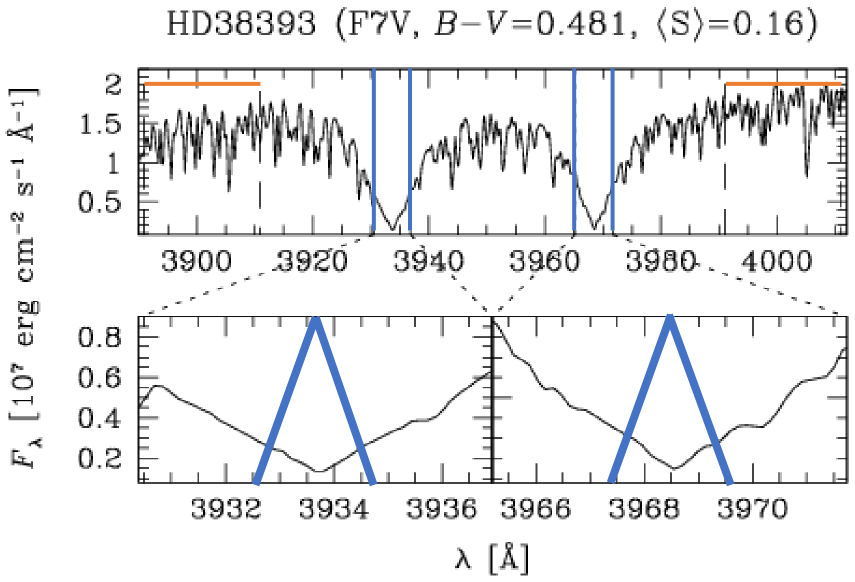
The LogR’$_{HK}$ indicator

S-index = integrated line core emission of Ca II H et K relative to average continuum

- Usually with a calibration factor depending on instrument
- Color-dependent

Two calibration steps => for comparison between stars

- **Photospheric contribution** (calibration vs B-V, Noyes 84 **FGK stars** ; Astudillo-Defru+16 **M stars**) → flux R_{HK}
- **Bolometric flux** (calibration vs B-V Noyes 84) → R'_{HK} → LogR’$_{HK}$



Cincunegui+ 07
Based on Mount Wilson survey e.g. Baliunas+95

Recent complementary approach

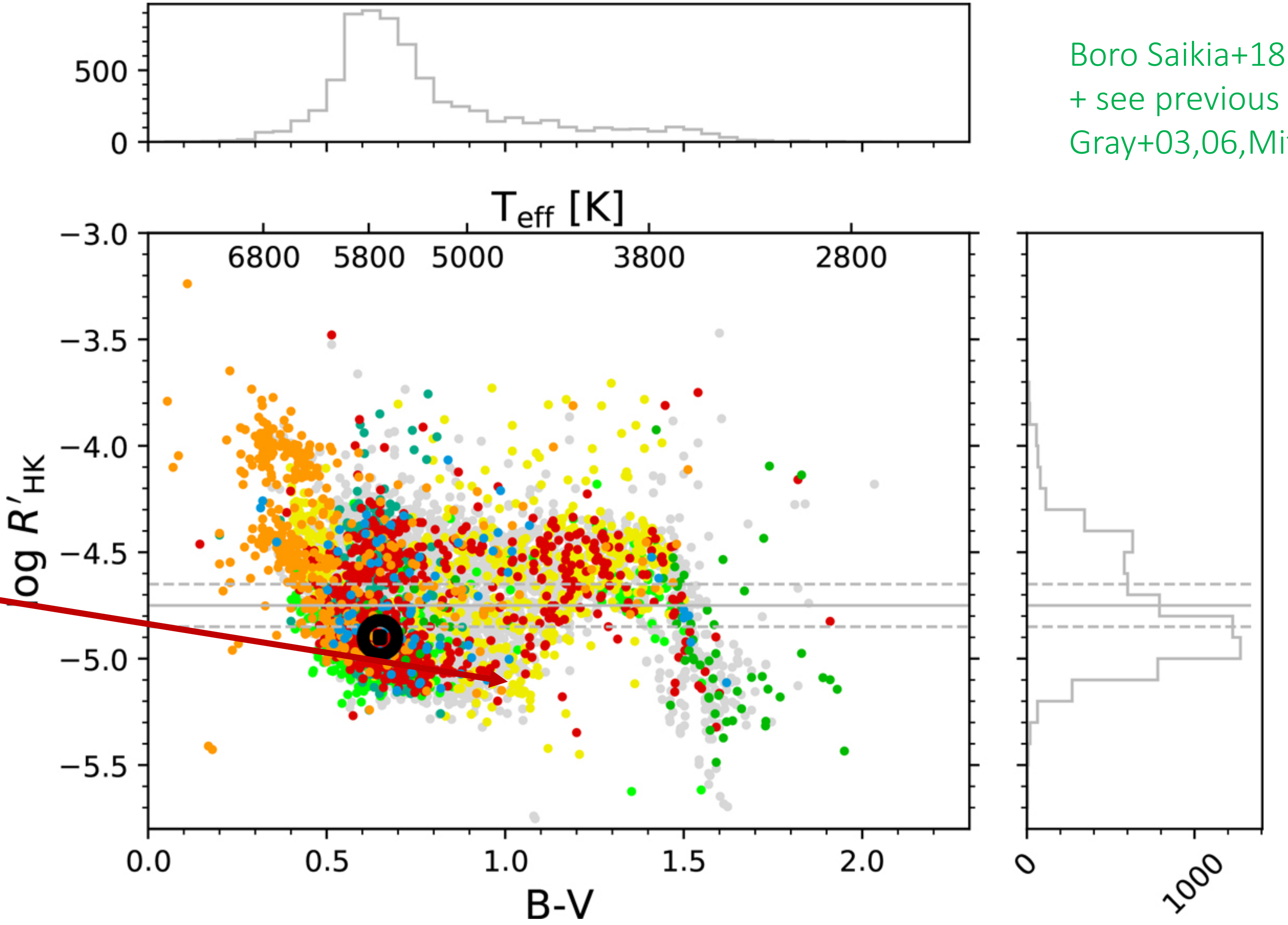
- Use of more information from the whole line cores Crétignier+23

Other chromospheric indices

- Hα, Na doublet, Ca IR triplet, He I 10830, UV lines…

Warning: not always equivalent, especially with Hα (Cincunegui+07,Meunier+22,24, Gomes da Silva+14,22)

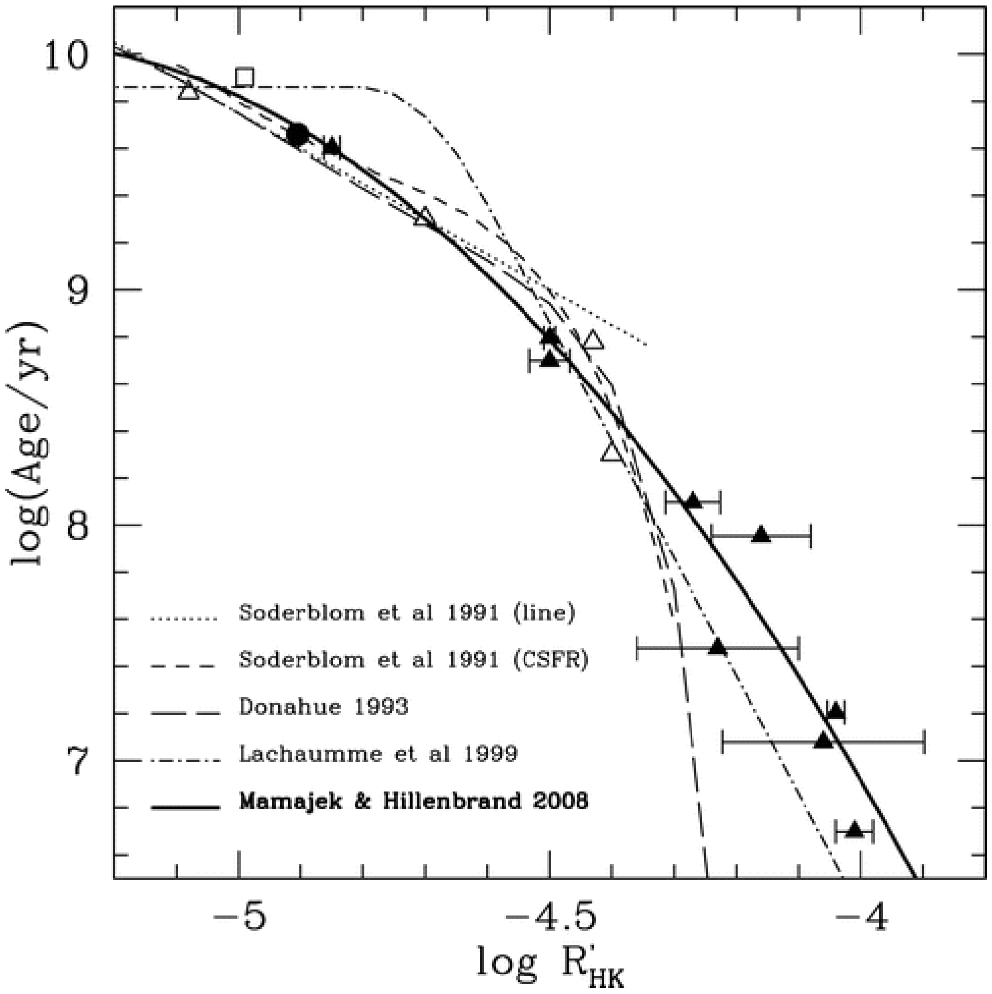
Average activity levels

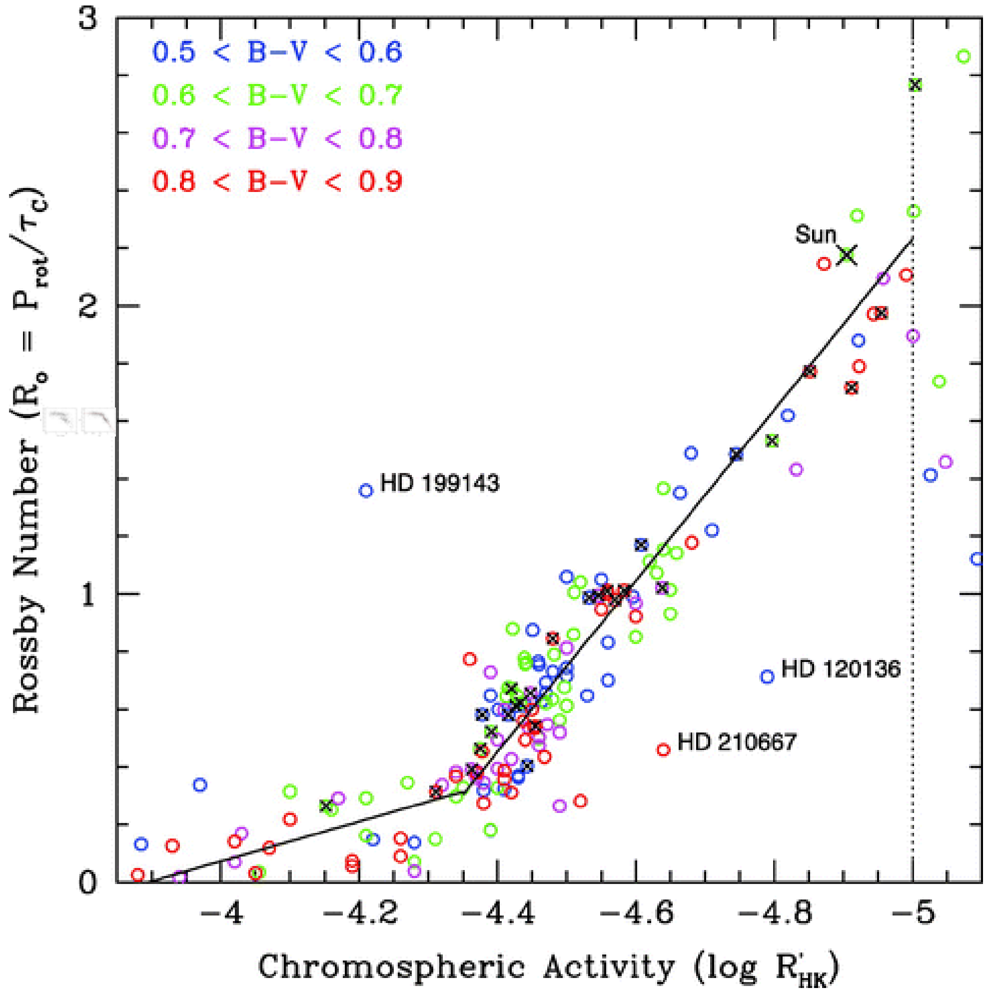


Boro Saikia+18
+ see previous works
Gray+03,06,Mittag+13…

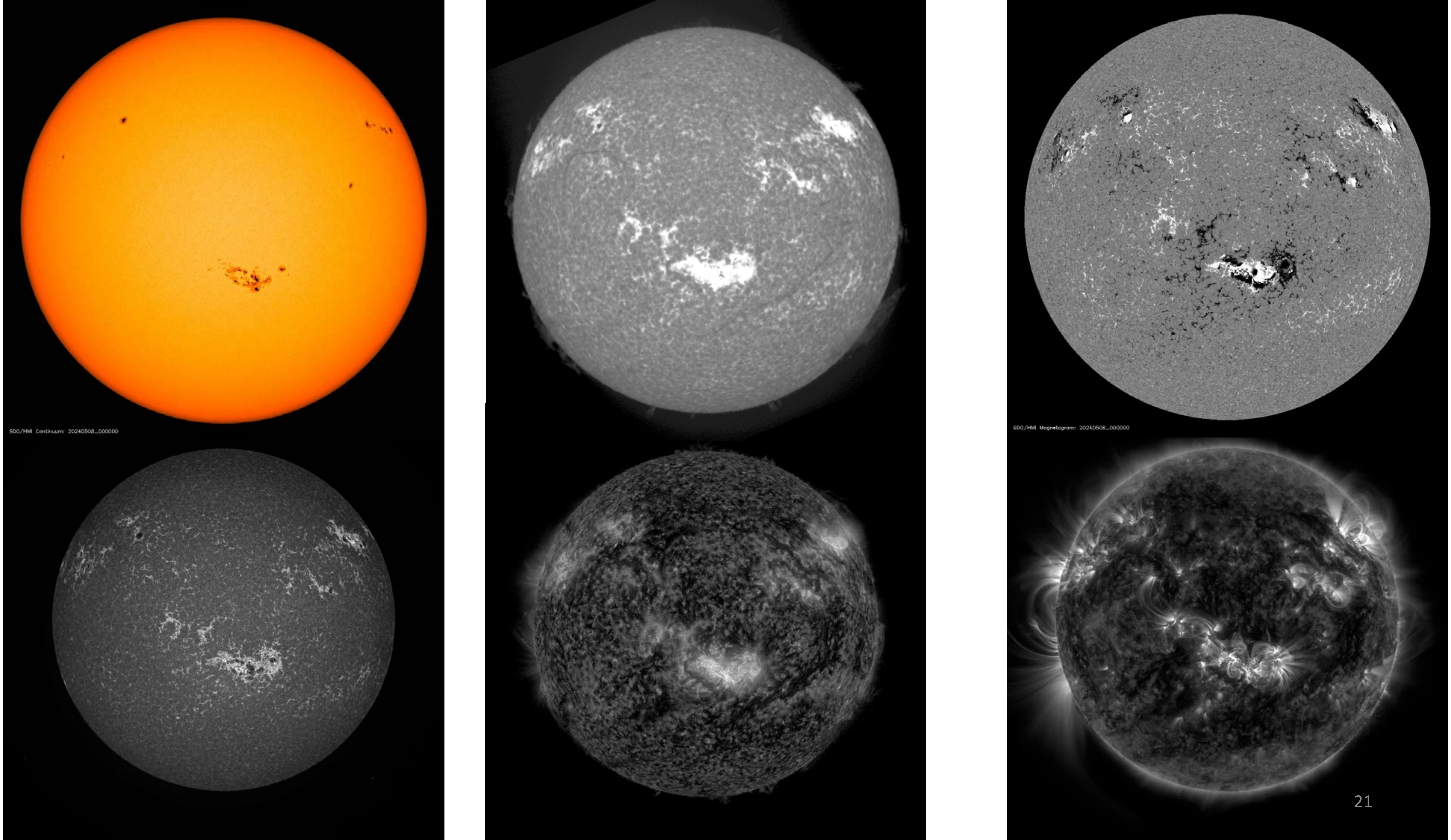
Warning: 2 definitions of « basal » flux

Age-Activity-Rotation relationship

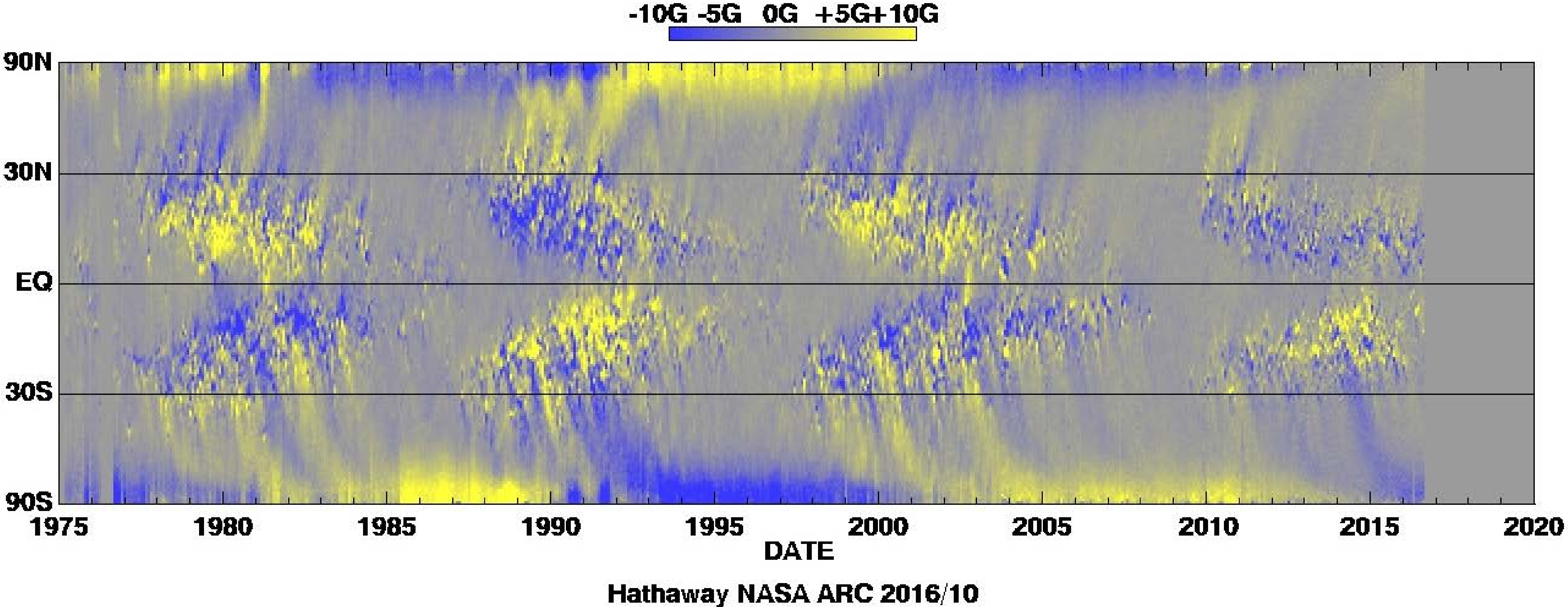




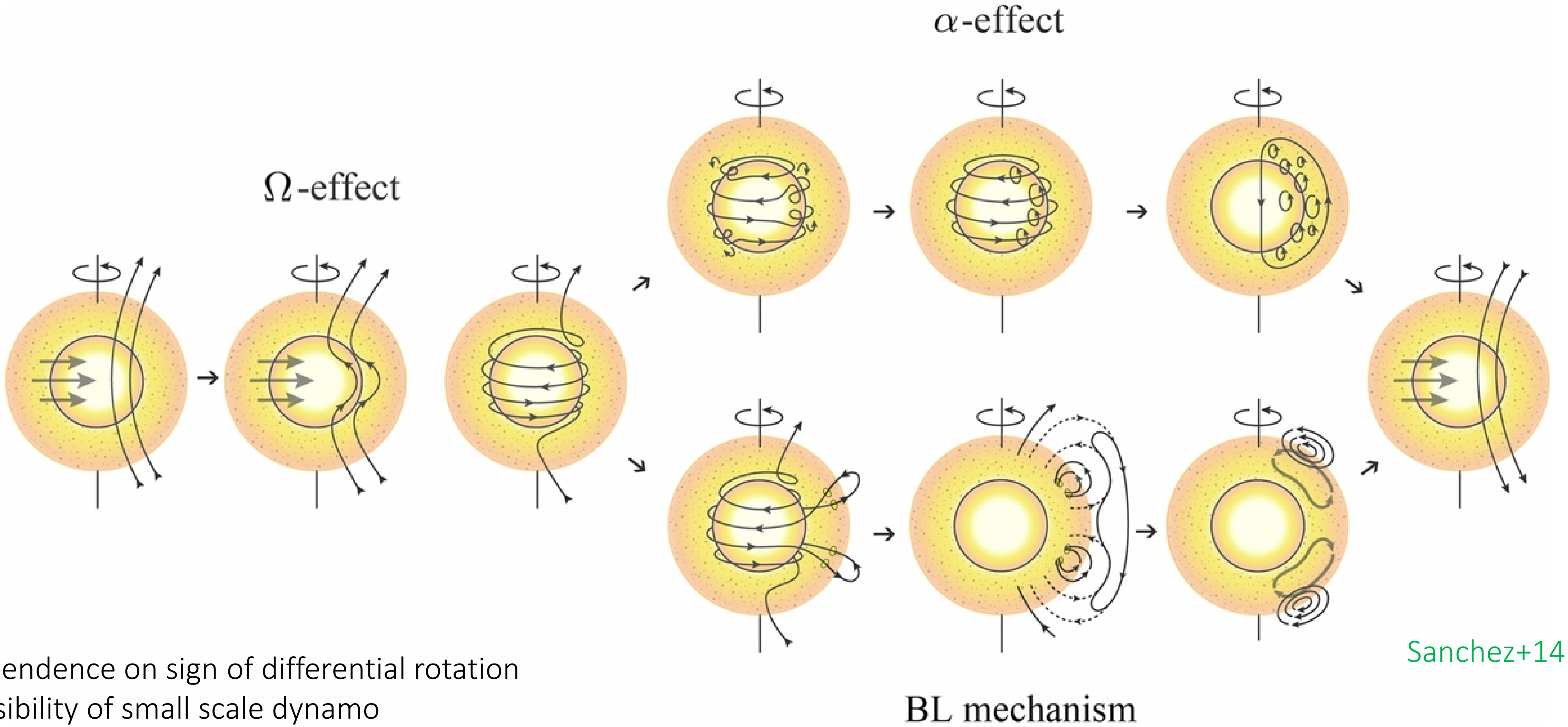
Mamajek&Hillebrand 08


SDO/HMI Continuum: 20240508_000000
SDO/HMI Magnetogram: 20240508_000000

Magnetic butterfly diagram



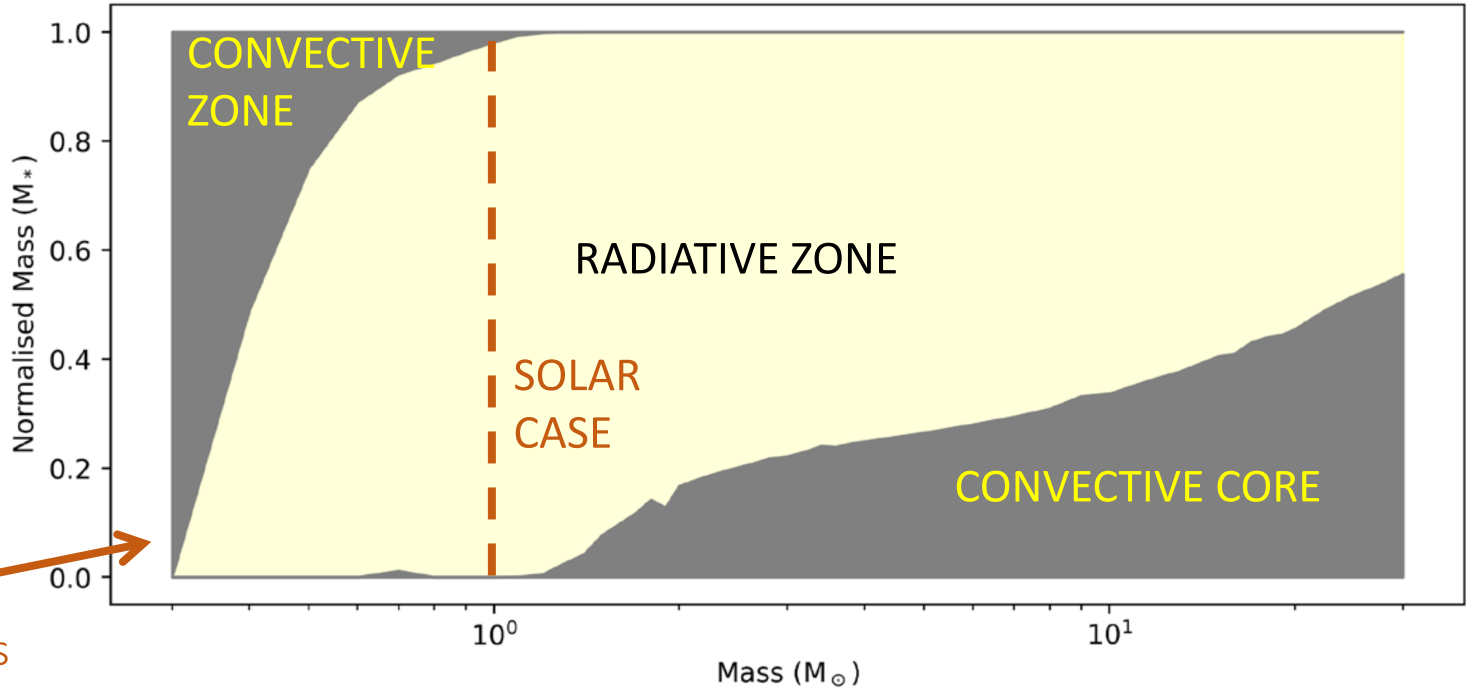
Solar large-scale dynamo



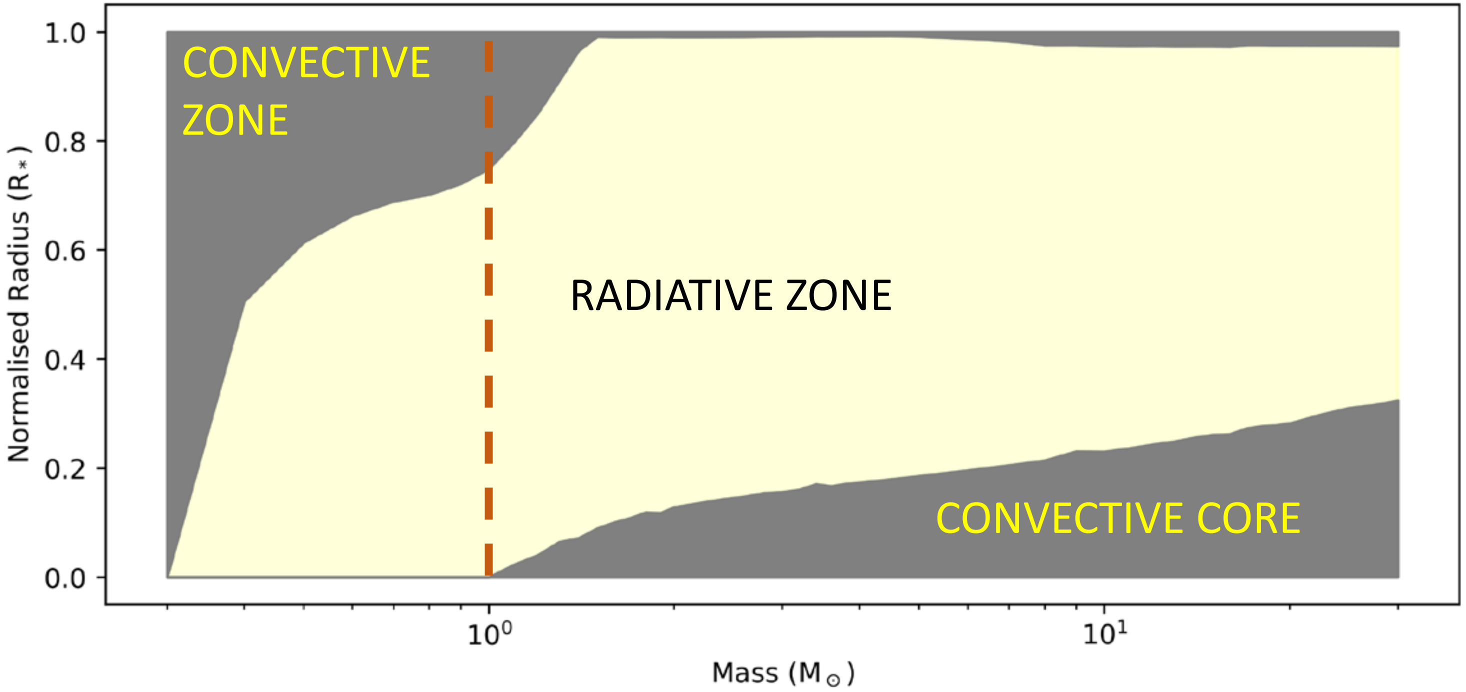
Sanchez+14

Dependence on sign of differential rotation
Possibility of small scale dynamo
See for example Brun+17

• Mettre fig



Fully convective M dwarfs
Masses<~0.35MʘO

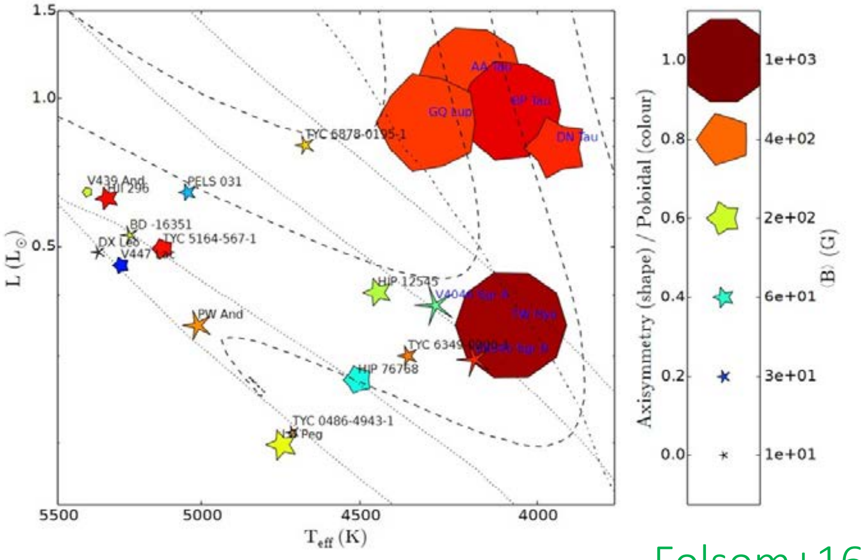


Adapted from Amard+19
Brun et al 24

Some trends but strong diversity

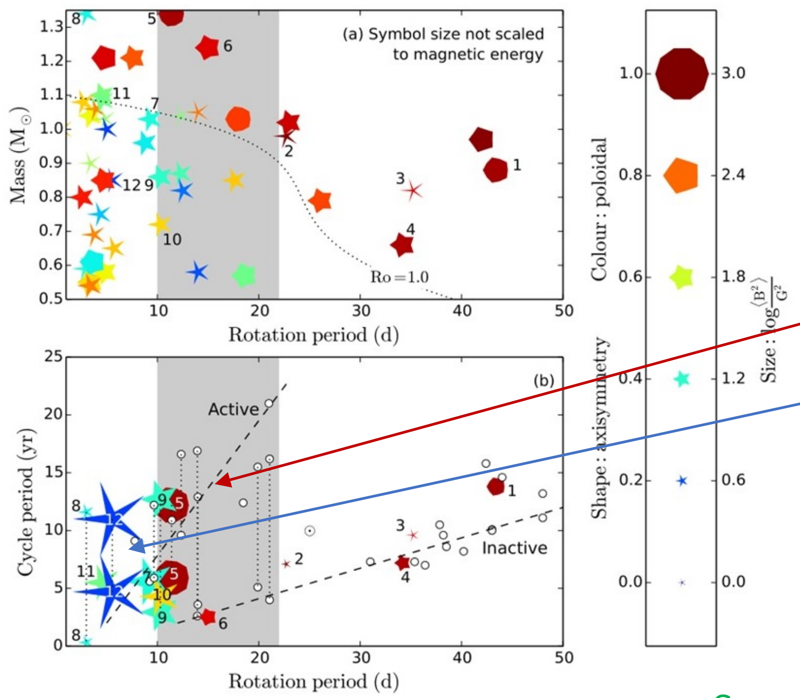
- Zeeman-Doppler Imaging => large-scale fields (cancellation of opposite polarities)
- Zeeman broadening => small-scale fields ($B > B_{ZDI}$)

Young stars



Folsom+16

Size: B strength
Color: red/poloïdal, blue/toroïdal
Shape: B topology (circular = axisymmetric)

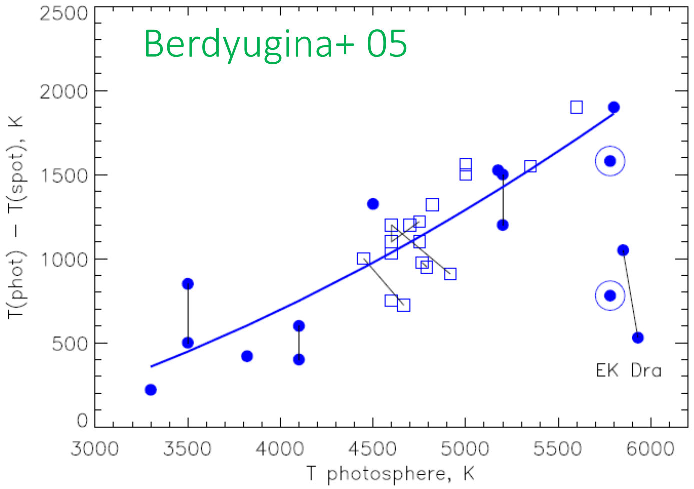


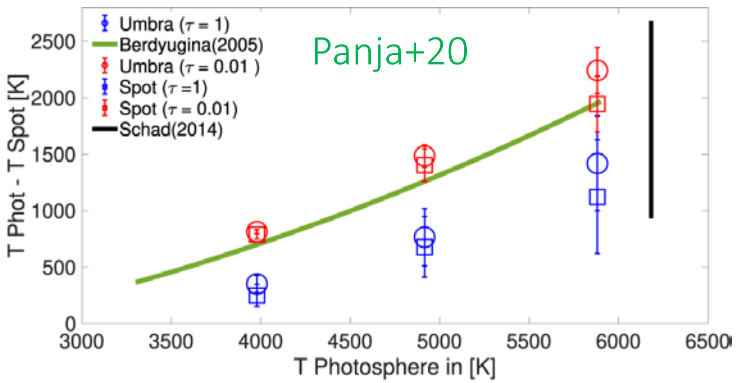
Red/poloïdal
Blue/toroïdal

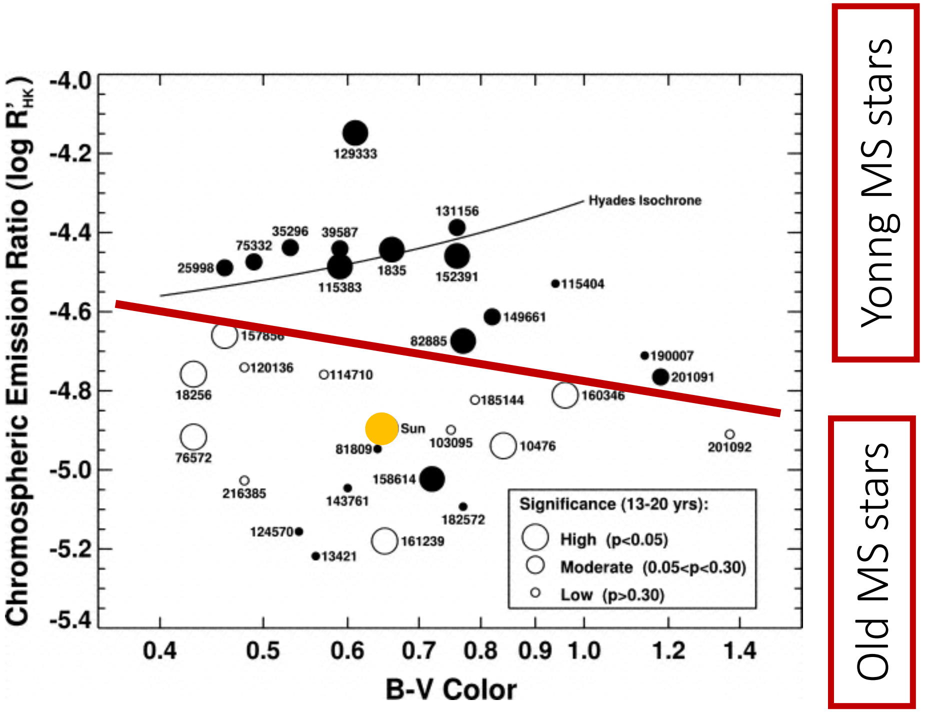
See+16

Shape: B topology (circular = axisymmetric)

Spots & faculae: contrasts







Lockwood+ 07 (Radick+98,18)

Inclination may bias the correlations Meunier+19

Spots

- **Contrast increases with Teff**
- From observations
- From models: Panja+20
- Low T => impact on molecules

Plages

- **Contrast depends on spectral type**
- **Strong B, μ dependence** (~15% at the limb, dark in IR)

Norris+16,23, Witzke+22

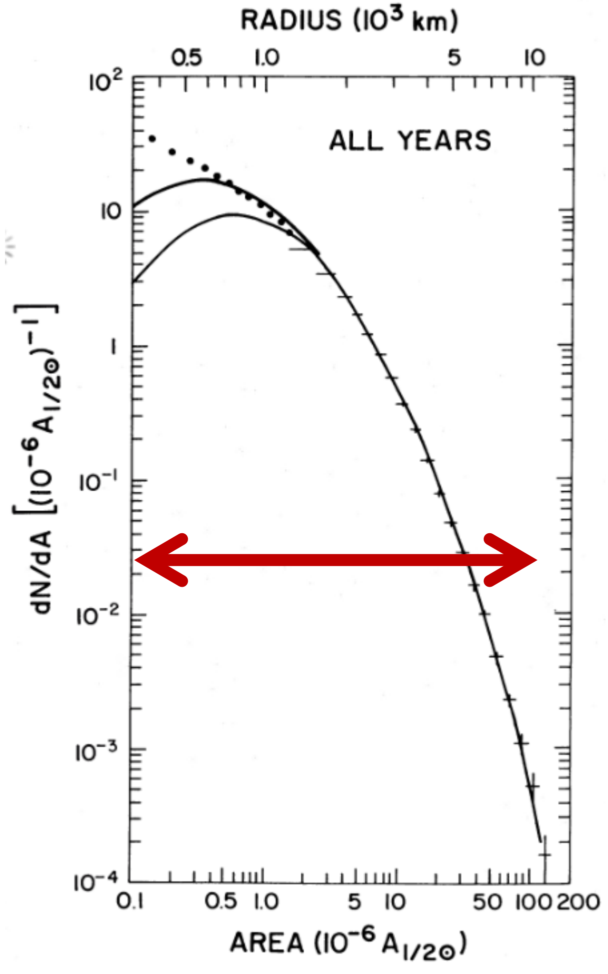
Spots & faculae: sizes & lifetimes

Size ?

- ~log-normal distribution for the Sun
- A few publications for other stars but do not take into account the degeneracies (size/contrast/number, spot/plage)
  - Walkowicz+13, Basri+18, Luger+21 about intrinsic degeneracies
- Never clear if large spot or pack of small spots
- Umbra/Penumbra ratio for other stars?

Lifetime ?

- Larger solar structures last longer
- Expected to be longer for low Teff
  - Smaller convection level → slower decay
  - Hint of agreement with theory for F-K stars ? Giles+16
- M stars: large diversity, but some cases with very stable pattern >1-2 y compatible with low granulation level
- Observed light curves: Strong degeneracies as well (Basri+22)



Bogdan+88

Warning: finite lifetime impact peaks at Prot in periodograms

A few reviews of interest for the Sun

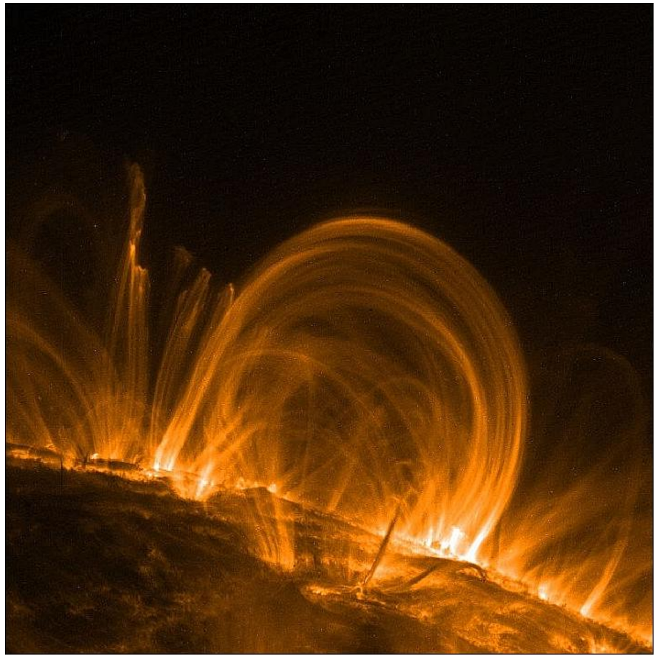
- Solanki03
- Berdyugina05
- Solanki+06
- van Driel-Gesztelyi +14
- Brun+17

Flares

Energetic events

- Usually associated to active regions
- Due to magnetic reconnexion
- Strong release of energy => electromagnetic radiation at all wavelengths and high energy particules (proton, electrons)

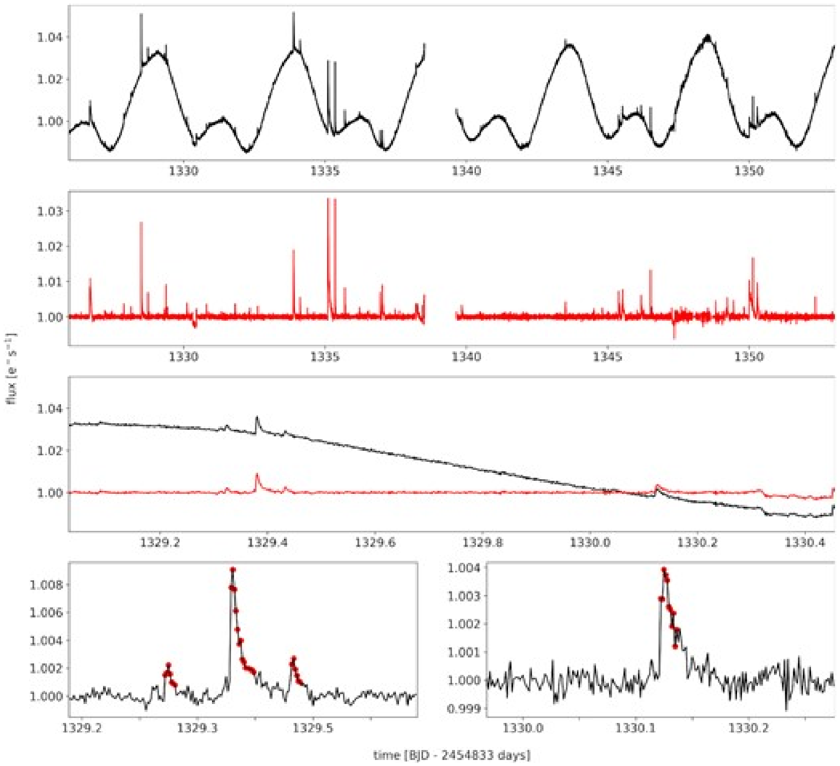
Sometimes associated to coronal mass ejections



Many observations of (energetic) stellar flares

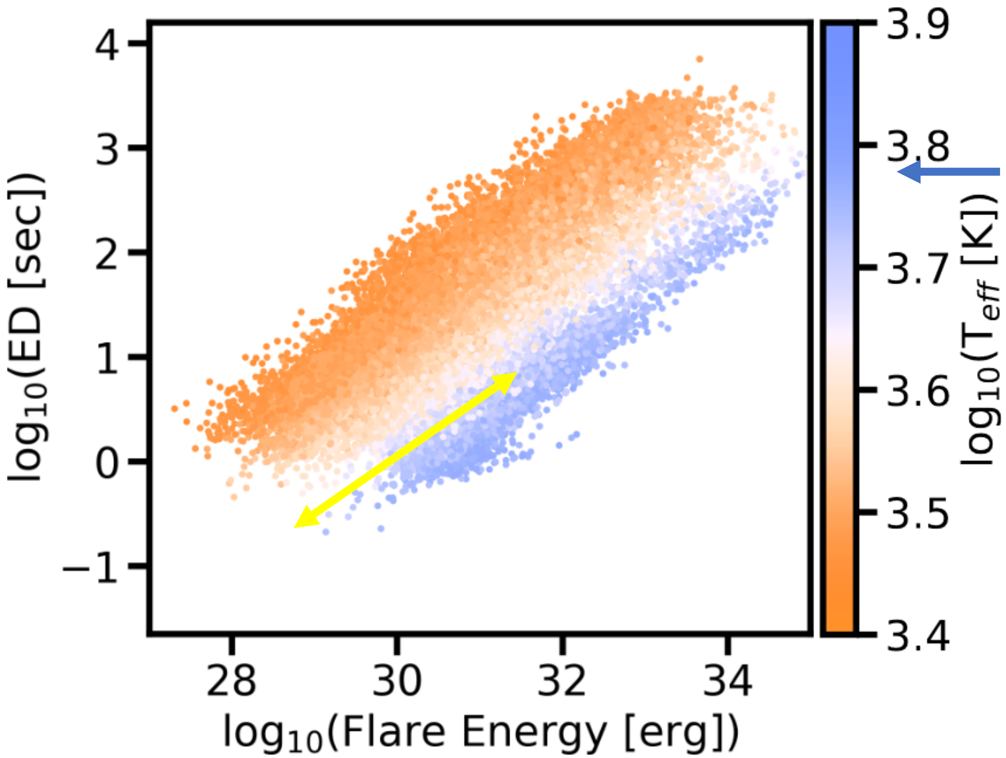
Example of AU Mic (TESS)

Ilin & Poppenhaeger 2021



Statistics TESS, GKM stars age < 300 Myr

Feinstein et al 2024



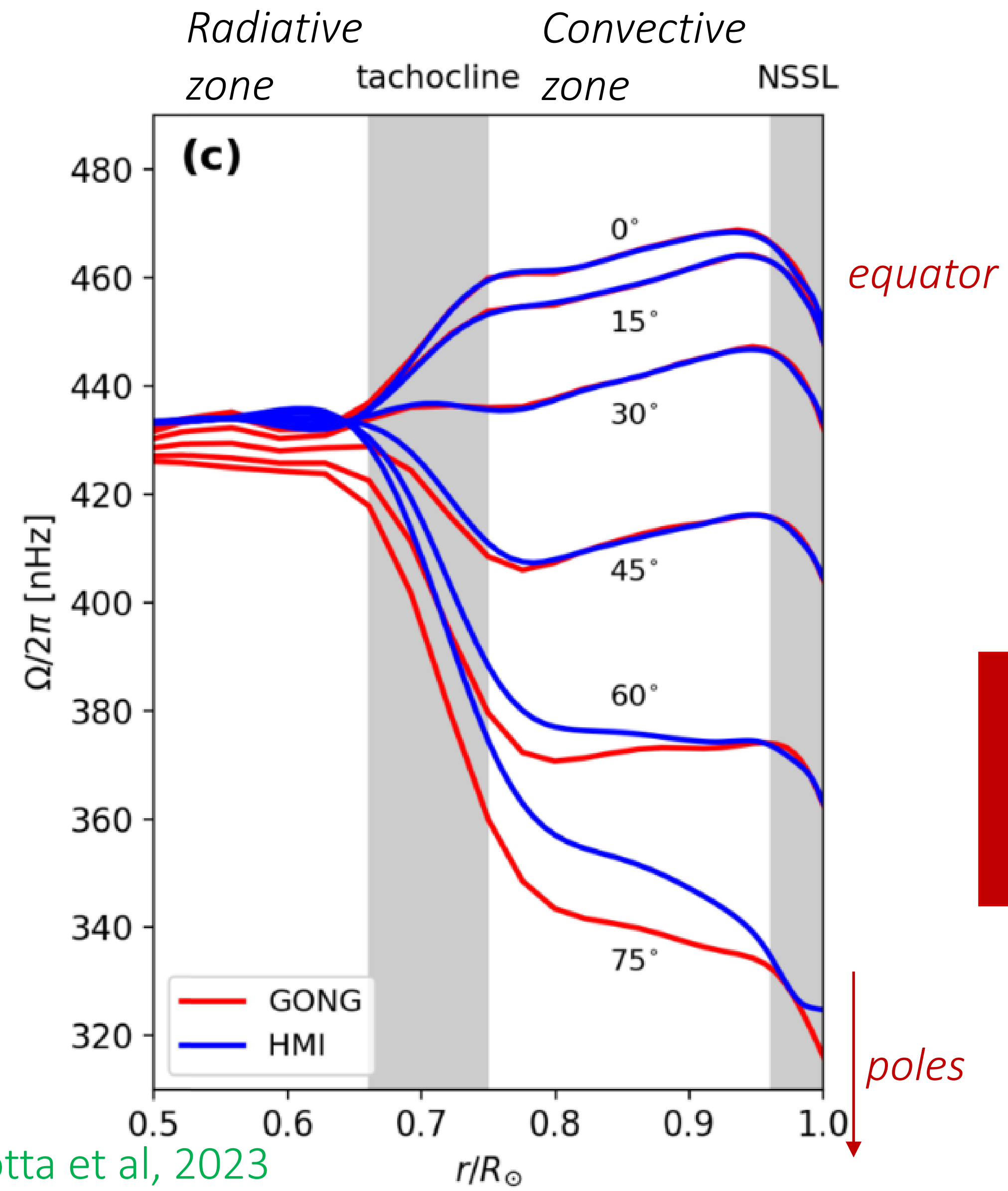
Magnetic activity

- Intensity observations
- Chromospheric emission
- Dynamo and magnetic fields : spots, faculae, flares

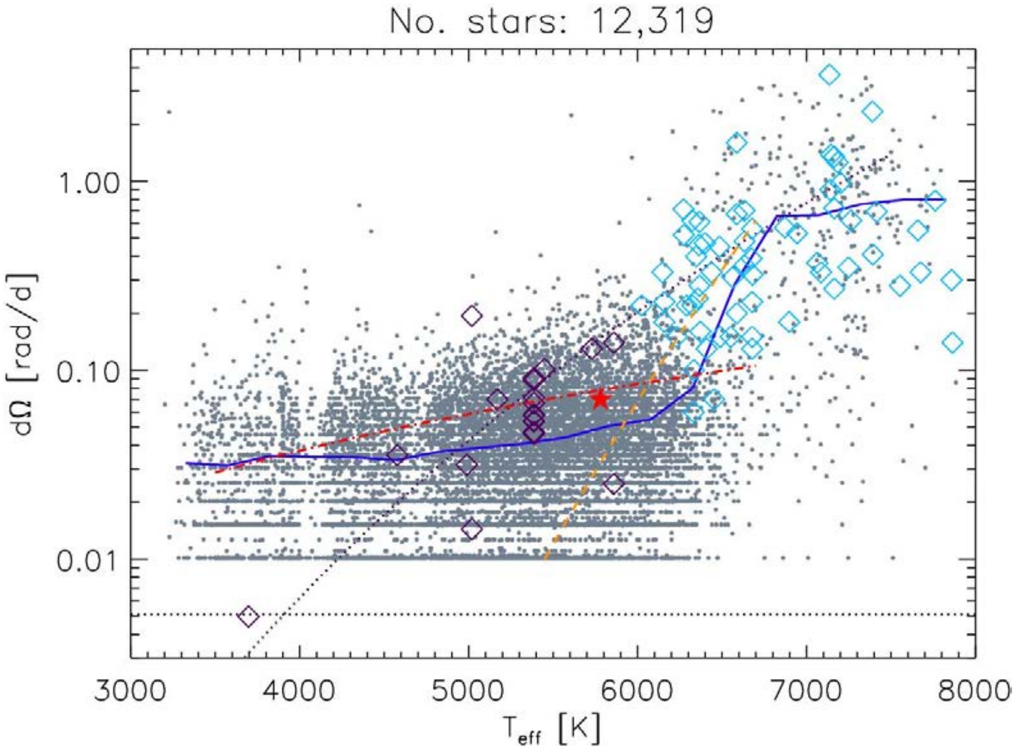
Flows

- Differential rotation
- Oscillations/pulsations
- Granulation
- Supergranulation, meridional circulation, convective blueshift inhibition

Differential rotation



Hotta et al, 2023



Reinhold & Gizon 2015

Kepler data

absolute shear ΔΩ

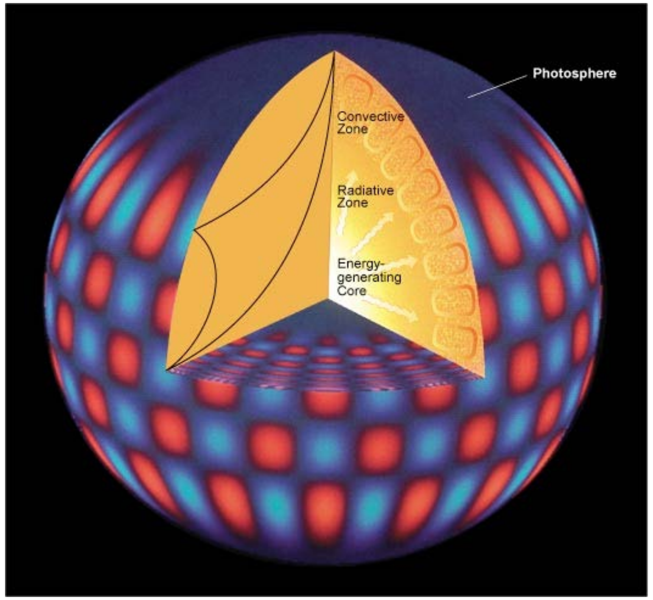
Leads to multiple peaks in periodograms

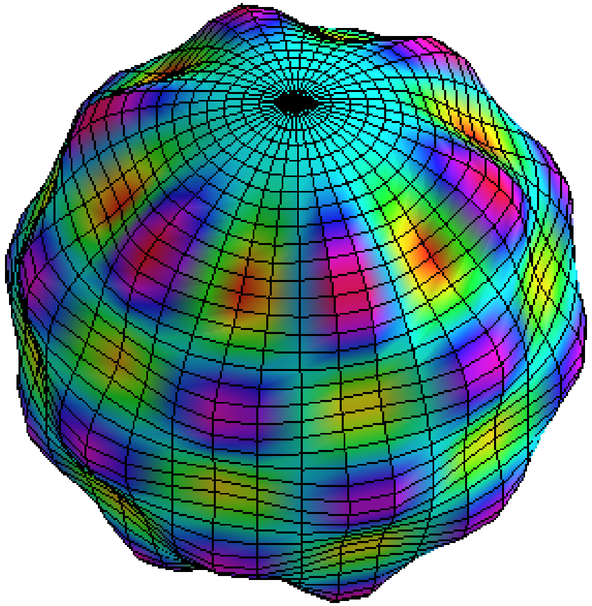
Warning: Usually from activity proxies related to spots $\Delta\Omega = \Omega_{max} - \Omega_{min}$

➔ unknown latitude range!!!

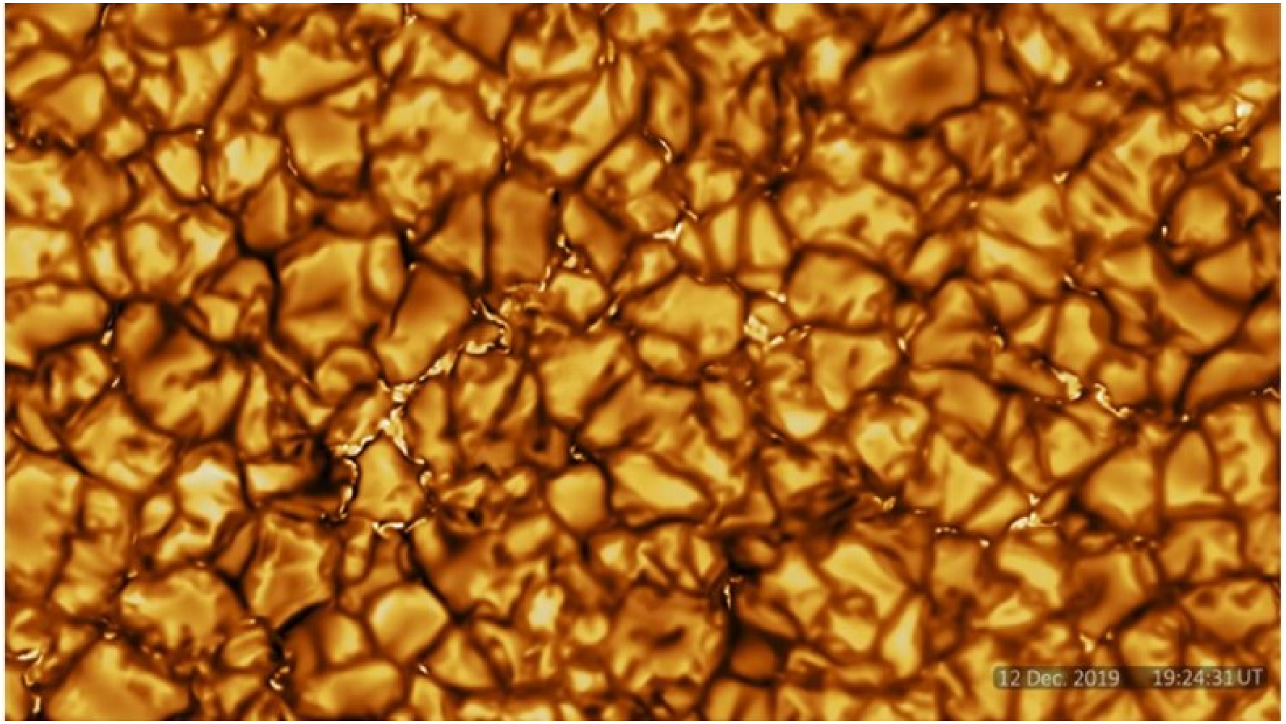
Oscillations and pulsations

- Solar-type p-modes (accoustic waves)
  - For the Sun: forest of peaks, ~5 minutes
  - Weak brightness variations (solar VIRGO/SOHO ~15 ppm Fröhlich+97)
  - Scaling laws e.g. Kjeldsen&Bedding11
- Young massive stars exhibit strong pulsations (δScuti: Kappa mechanism related to He, γDor: gravity wave)





Granulation



D.K.Inouye telescope, Maui

Convection pattern

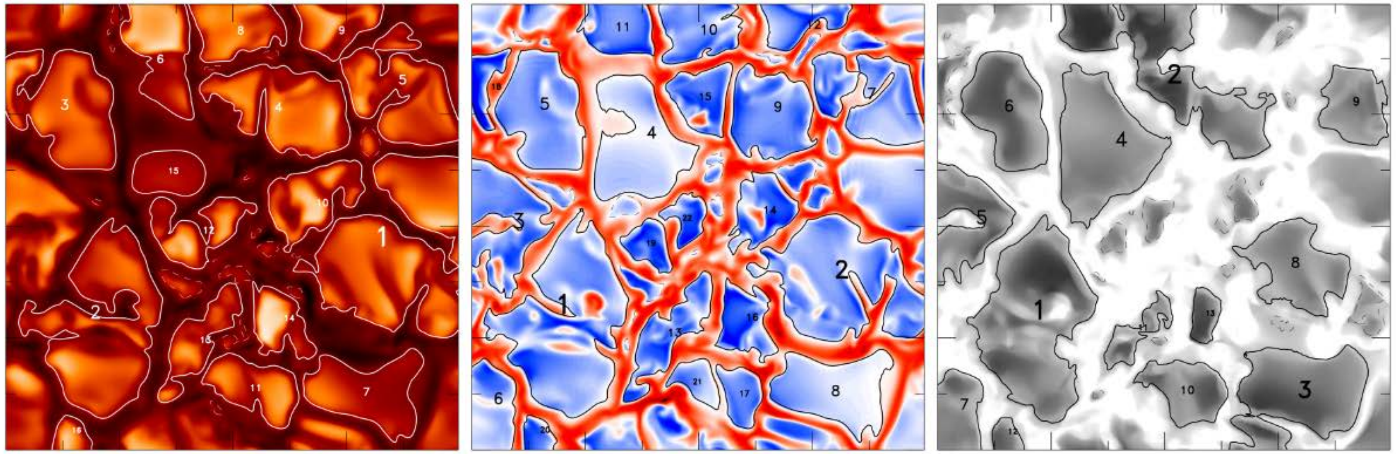
Typical scales for the Sun

- Lifetime **~10 minutes** (large distribution)
- Size **~1000 km**
- Flows **~km/s**

Contrasts

- Contrast increasing from blue to IR
- Up to ~26% in the blue
- Warning: estimation depends on spatial resolution

Lead to convective blueshift



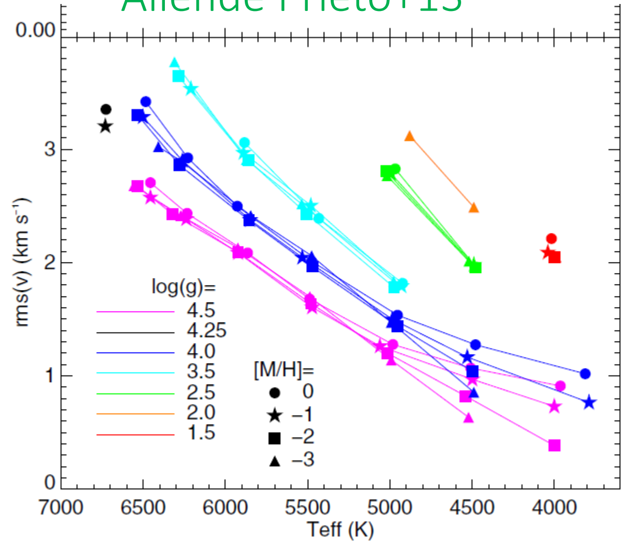
Magic & Asplund 14

Convection level in other stars

Velocities and contrasts increase with Teff

- Numerical simulations: CO5BOLD (Freytag+12, Allende Prieto+13, Tremblay+13), STAGGER (Magic+13,14, Chiavassa+18, Rodriguez Diaz+22,24), MURaM (Beeck+13,15), Trampedach+13 [not exhaustive]
- Observations : Gray 09, Meunier+17,18, Liebing+21 (through convective blueshift) Dumusque+11

Allende Prieto+13



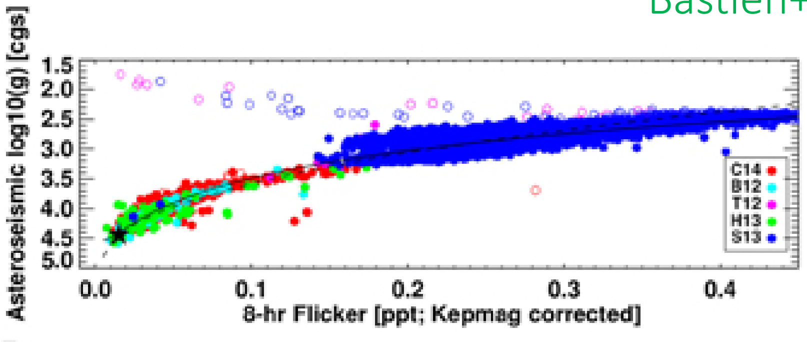
Contrast increases with decreasing metallicity

- E.g. Magic+13, Tremblay+13, Witzke+23

Contrast increases with decreasing log g

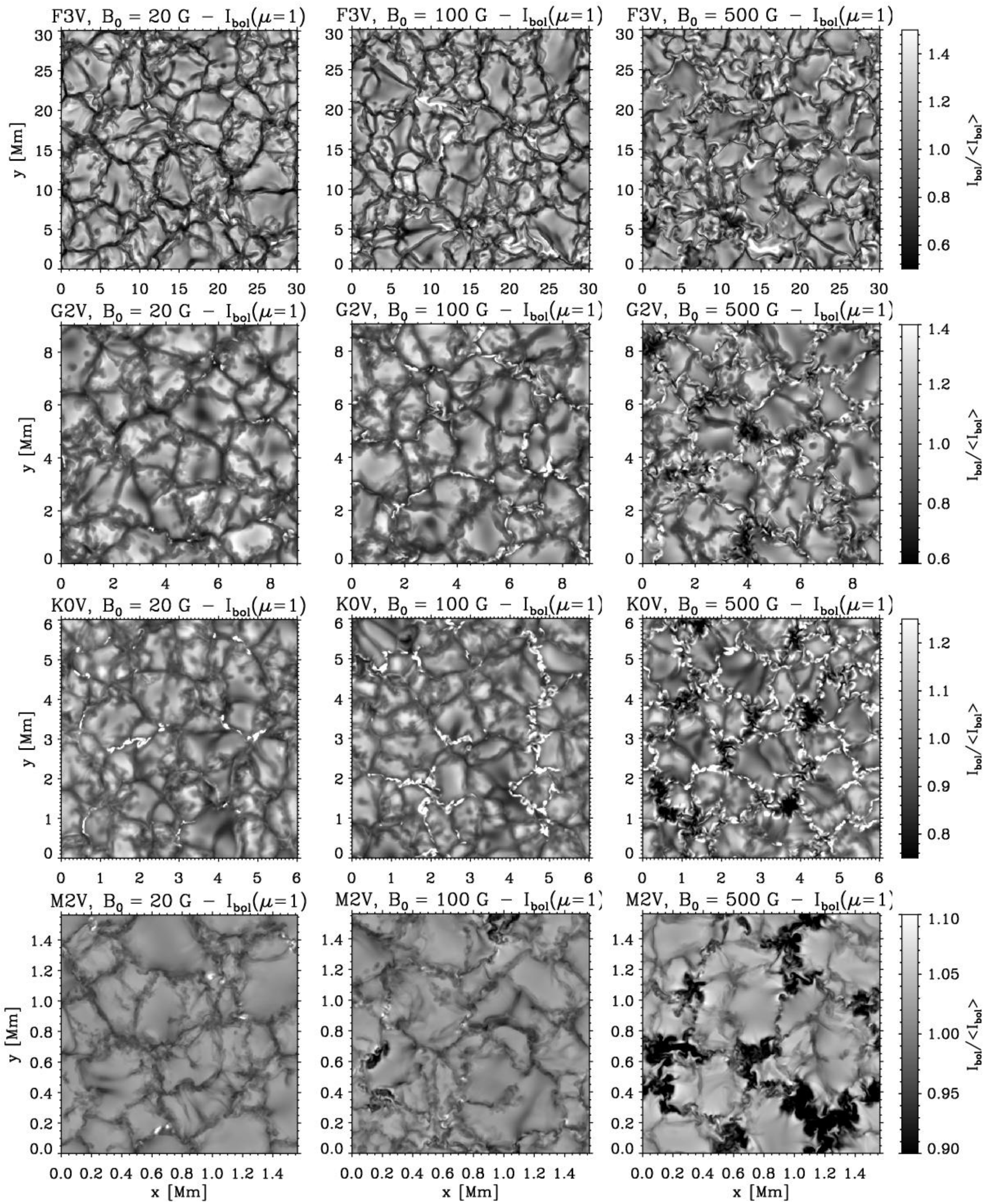
- E.g. Bastien+16

Bastien+16



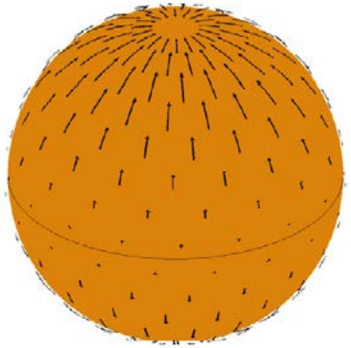
Some include magnetic fields

- Plage simulation
- B = almost no dependence on Teff or initial injected B
- Expected impact of metallicity (Witzke+18,20)
- Change in behavior for M ?

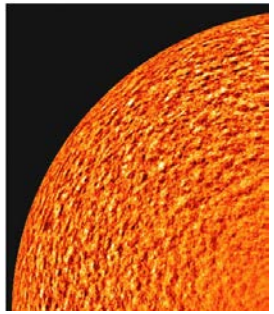


Beeck+15

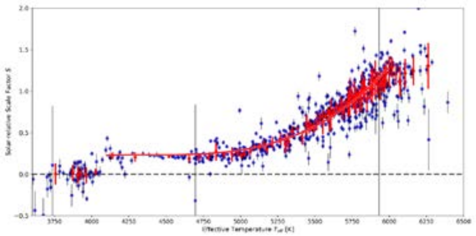
Only for RVs



- Meridional circulation
- Supergranulation
- Granulation+magnetism => convective blueshift inhibition



➔ Details later in RV section



Summary

Process	RV	Photometric transit	Transit spectroscopy	Astrometry
Spots & faculae	X (contrast, Zeeman)	X (contrast)	X (contrast, spectral features)	X (contrast)
Oscillations/pulsations	X	X	X	
Granulation	X	X	X	
Supergranulation	X			
Meridional circulation	X			
Convective blueshift inhibition	X			
Flares	X	X	X	

Part 2: Methods to evaluate the impact and tools

- Methods to evaluate the impact on observables
- Data and tools

Methods to estimate the impact on observables

Solar observations

Solar and stellar simulations (forward modeling)

Solar observations combined with models
Test of models on stellar observations

⇒To estimate the amplitude of different processes

⇒To test mitigation techniques (blind tests)

Not exhaustive: some mitigation techniques may help to characterise certain processes

Stellar observations

Solar observations

- **Reconstruction** of the **solar** integrated RV from observed velocity maps (dopplergrams)
  - Meunier+10,Haywood+16,21,Milbourne+19
- **Indirect** observations of the integrated **solar** light
  - Asteroids, Moon, Jupiter satellites Lanza+16
- **Direct** observations of the integrated **solar** light
  - SOHO/Virgo (photometry), SOHO/GOLF (RV) Sulis+20a,b
  - HARPS-N (RV)+ other on-going/future projects similar to HARPS-N (VIS and IR) Dumusque+15,21,Collier-Cameron+19, Zhao+23, ...

RV, active regions

RV, active regions

RV, photometry, spectroscopy
Active regions, supergranulation

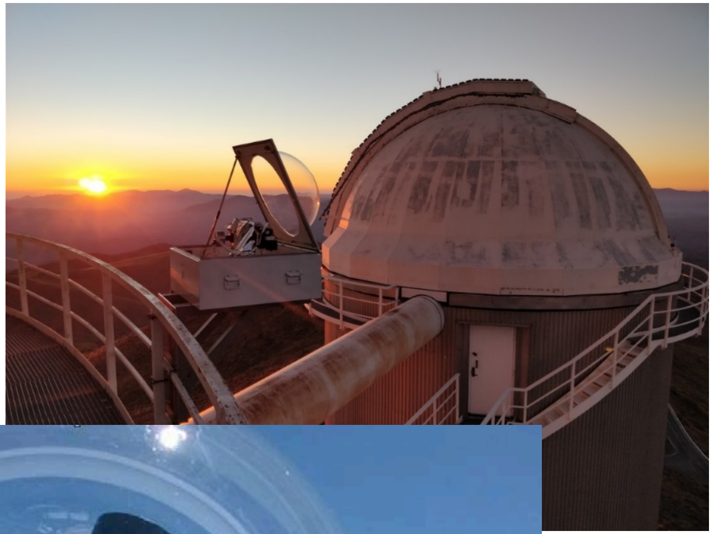
Allow comparison with actual known surface features

Take all/most processes into account (including unidentified ones!!!)

But also include instrumental effects (Meunier+24)

Direct solar observations using stellar spectrographs

Dumusque+15
Phillips+16
Collier Cameron+19
Dumusque+21 => *last version*



Adaptation needed to feed the solar light to stellar spectrograph

- Coelostat + sphere to integrate the light
- HARPS-N@La Palma → ~6h/d, 5 min cadence ≈ 8 years (3 years public data)

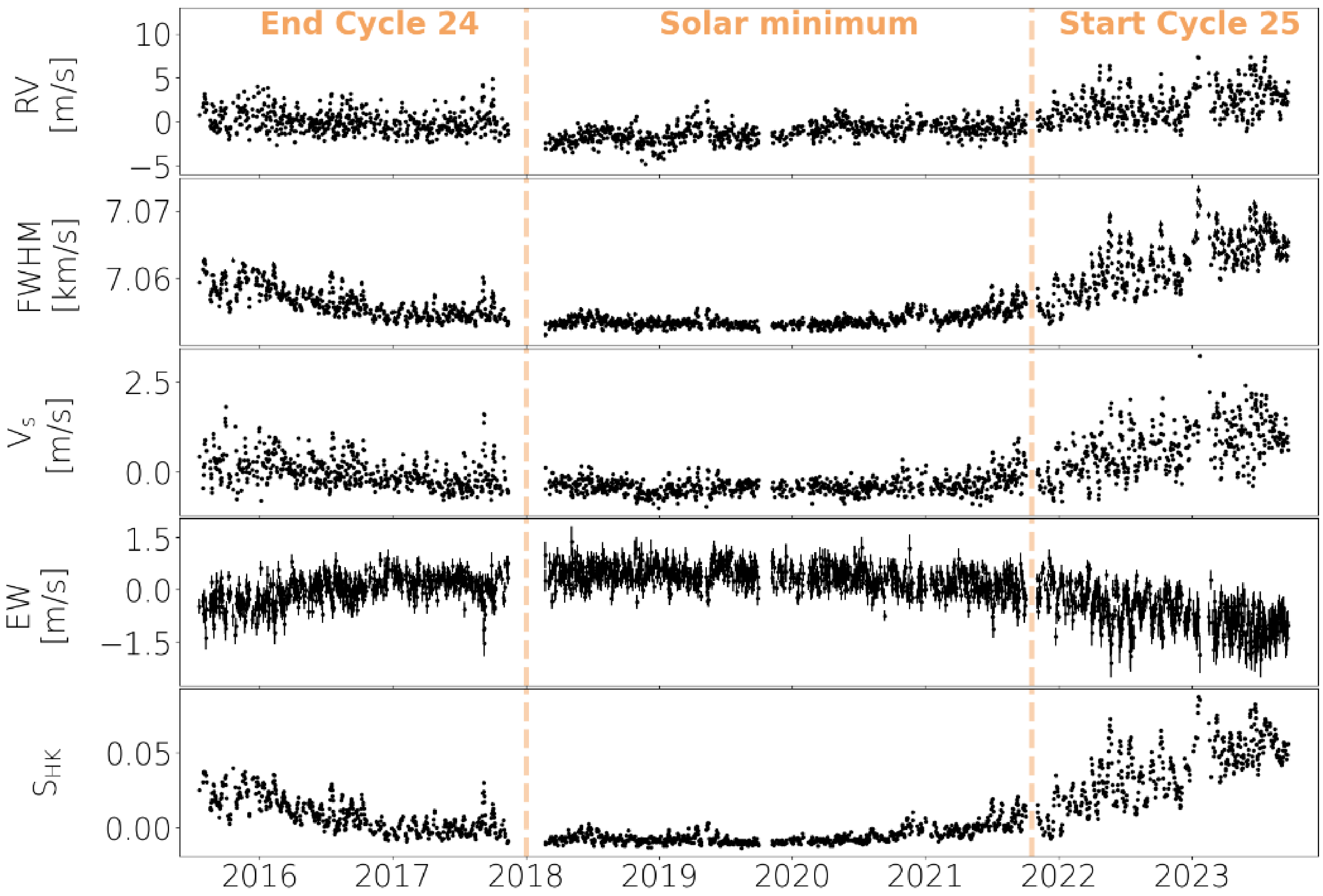
Adaptation needed / data processing

- Finite solar size+rotation+atmosphere
- Precise removal of known planets

Many on-going projects

- HARPS (south) @ La Silla + IR
- Expres @ Lowell obs.
- NEID @ WIYN
- Poet project @ Espresso/VLT (N. Santos)
- …

Klein+24



End Cycle 24
Solar minimum
Start Cycle 25
RV [m/s]
10
5
0
−5
FWHM [km/s]
7.07
7.06
V_s [m/s]
2.5
0.0
EW [m/s]
1.5
0.0
−1.5
S_{HK}
0.05
0.00
2016
2017
2018
2019
2020
2021
2022
2023

Solar and stellar observations combined with models

- Reconstruction based on observed **solar** structures + models = forward modelling *RV, active regions*
  - Makarov+10, Meunier+10,24
- Adjustment of models on well-sampled **stellar** observations *RV, active regions*
  - Dumusque+14

Robustness of the results

Make the link between observations and simulations

Adjustment not often done in RVs because of the temporal sampling

Solar & stellar simulations (forward modeling)

- **Simulations** of integrated RV from **synthetic spots and faculae**, representative of **solar** & **stellar** configurations
  - Simple activity configuration Desort+07, Boisse+12, Dumusque+14…
  - Complex activity patterns Borgniet+15, Herrero+16, Dumusque+16, Meunier+19 …
- **Flow simulations** based on **empirical laws** Meunier+19,20
- **MHD simulations** of the **solar** and **stellar** surface Meunier+15, Cegla+18,19, Sulis+20,22 (+ many others for different purposes)

RV, photometry, active regions, granulation/SG

RV, granulation/SG

RV, photometry, granulation

Extend the models to other stars

Study processes separately to understand their behavior

Allow blind tests

Activity simulations
(spots,faculae,inhibition convective blueshift)

One/few spots

Objectives

- To derive typical RV amplitudes and shapes for simple activity configuration
- To study fine effects
- To model observations

A few results

- Dependence on spectral resolution, v sini, latitude, center-to-limb variation
- Desort+07 Boisse+12 Dumusque 14

Complex & realistic activity pattern of spots and plages

Objectives

- To derive (predict) detection limits
- To test temporal samplings / observing strategies
- To test correction methods / bind tests
- To identify properties that could be used in new methods
- May include granulation, supergranulation…

A few approaches

- List of structures => analytical time series
- List of structures => integrated spectra => analysis similar to stellar observations
- Borgniet+15, Herrero+16,Dumusque+16,Meunier+19 …

See more details in appendix

+ Many stellar observations performed in stellar physics context

- Photometry: spot modeling, rotation period determination, attempt to search for cycles, …
- Chromospheric emission: rotation period, search for cycles, …
- Spectropolarimetry: large scale and small scale magnetic fields
- Spectroscopy: fondamental parameters, v sini, …
- Interferometry: stellar radius, …
- …

Open source codes
(see list in Rackham+22)

- SOAP (Boisse+12, Dumusque+14) => RV (and line shape), photometry, spot and faculae + SOAP-T (Oshagh+13) => transit, spot-occultation (2D map)
- STarsim2 (Rosich+20) => RV (and line shape, CCF), photometry, spot and faculae
- ECLIPSE (Silva+13)=> transit, spot-occulation (2D map)
- PRISM (Tregloan-Reed+13) => transit (2D map)
- SPOTROD (Béky+14) => transit, spot occultation (semi-analytic)
- STSP (Davenport15,Morris+17,Schutte+22) => transit, spot-occulation
- ellc (Maxted16) => transit, spot-occulation (semi analytical, semi numerical)
- Probably others…

Part 3: Impact on observables and tools to mitigate stellar variability

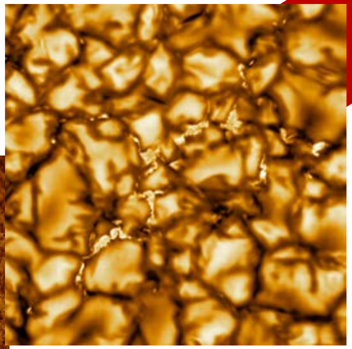
- RV
- Photometric transits
- Atmosphere characterisation (transit spectroscopy)
- High precision astrometry

Summary

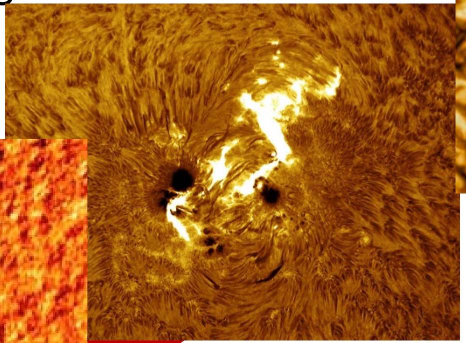
Process	RV	Photometric transit	Transit spectroscopy	Astrometry
Spots & faculae	X (contrast, Zeeman)	X (contrast)	X (contrast, spectral features)	X (contrast)
Oscillations/pulsations	X	X	X	
Granulation	X	X	X	
Supergranulation	X			
Meridional circulation	X			
Convective blueshift inhibition	X			
Flares	X	X	X	

Processes affecting RVs and time scales

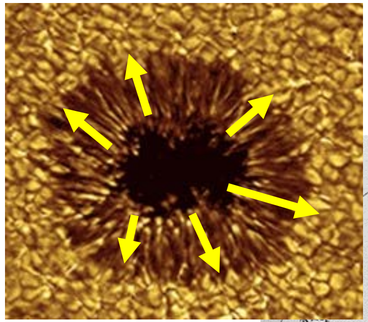
Minutes



Hours

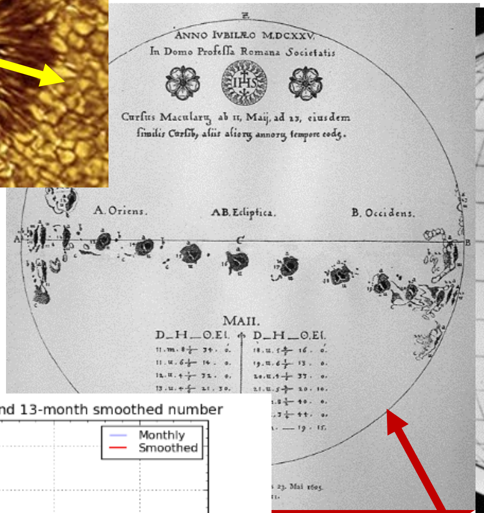


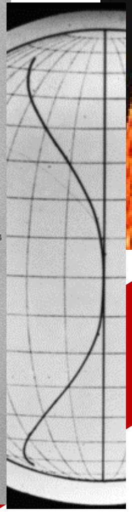
Evershed flows

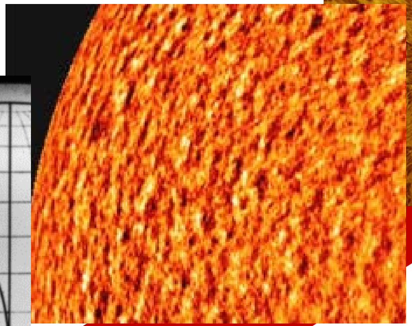


Days

Month



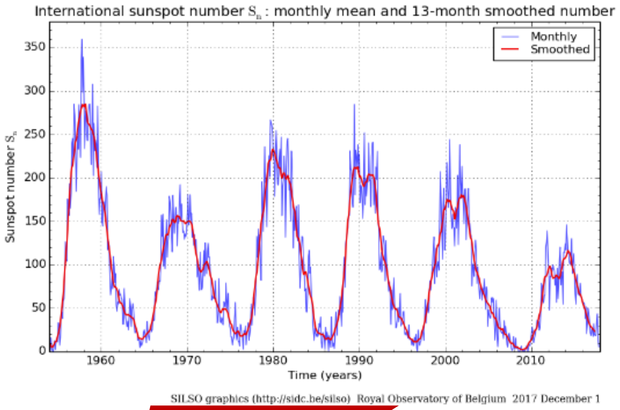




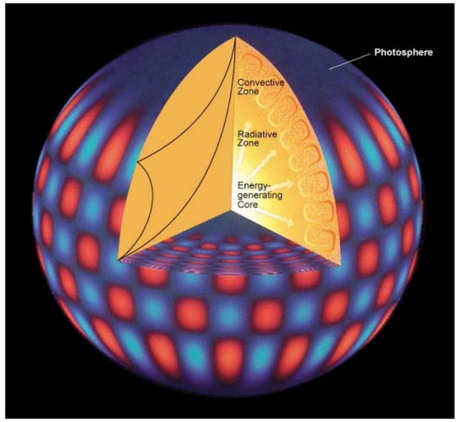
Flares

Supergranulation

Years
Decades+



Granulation
Pulsations



Convection
inhibition

Spots, plages

Rotation period, cycle
Evolution of structures / lifetime
Large scale flows
Gravitational redshifts (Cegla+12)

See reviews Meunier+21,24

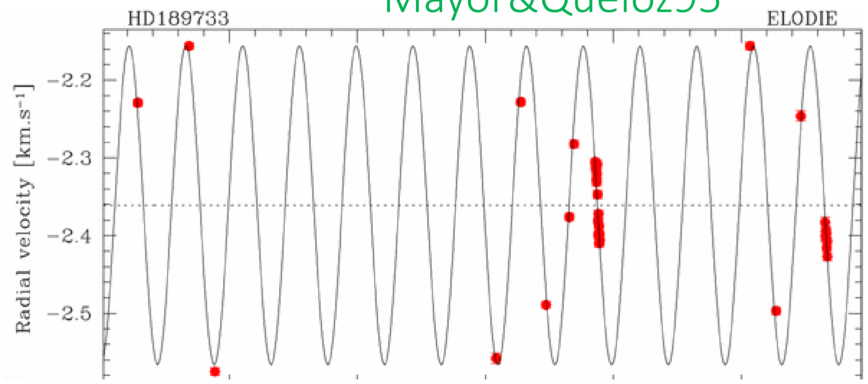
Temporal sampling issue

Radial velocities

Planet: Research of long term signal (depending on orbital period), *all points affected by planet*
Star: Signal at all time scales

Very irregular and sparse sampling, bad phase covering (planet & star)

Mayor&Queloz95

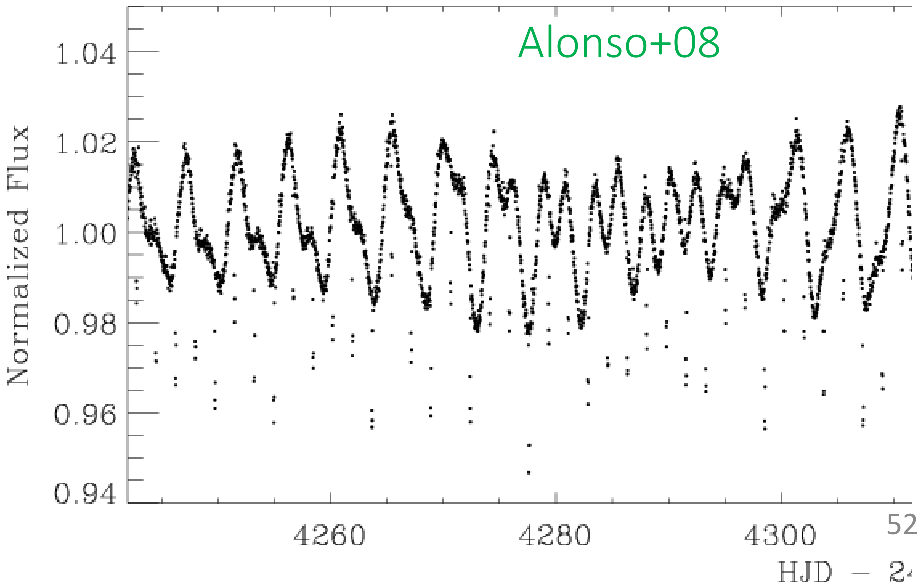


Photometric transit

Planet: Search for short-term signal, *small fraction of the time series impacted by the planetary signal*
Star: signal at all time scales

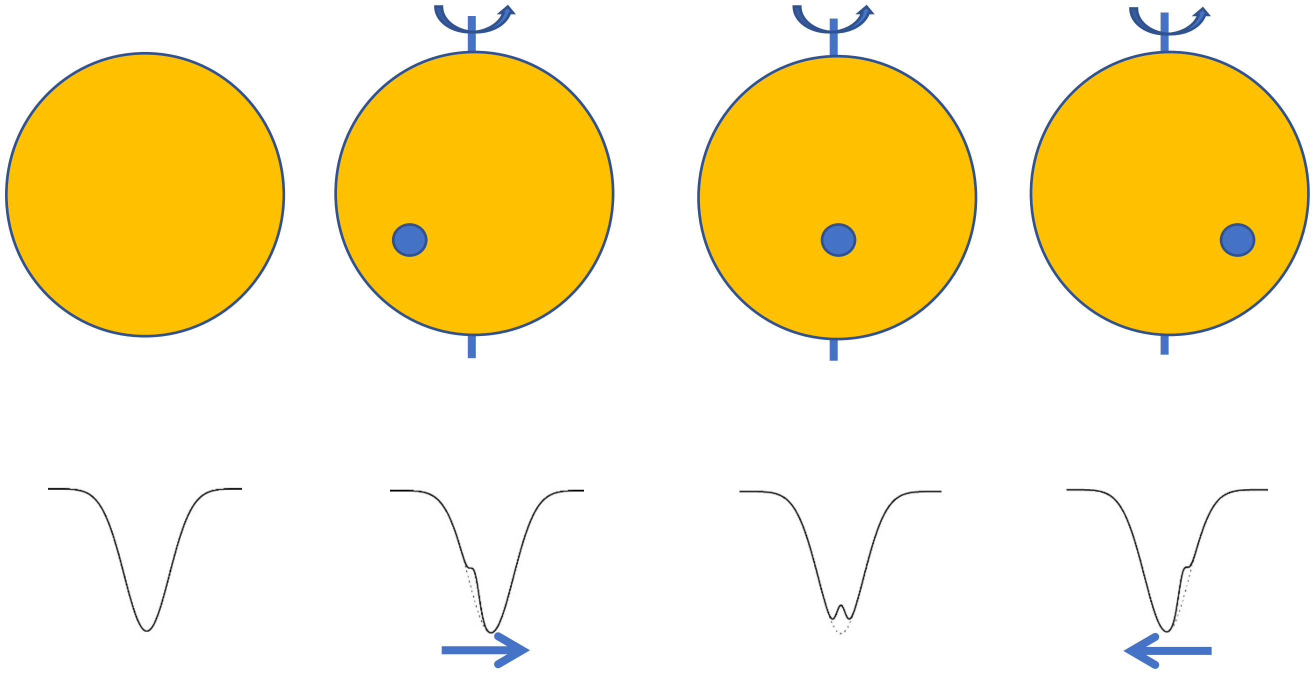
Regular and dense sampling, limited time span

Alonso+08



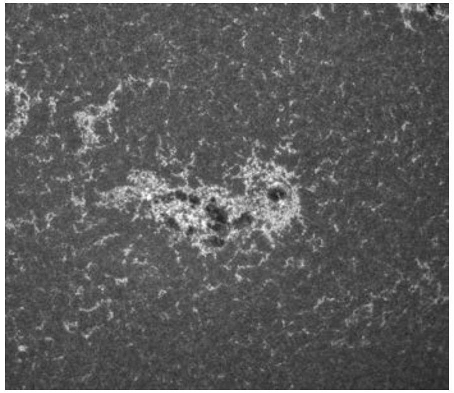
52

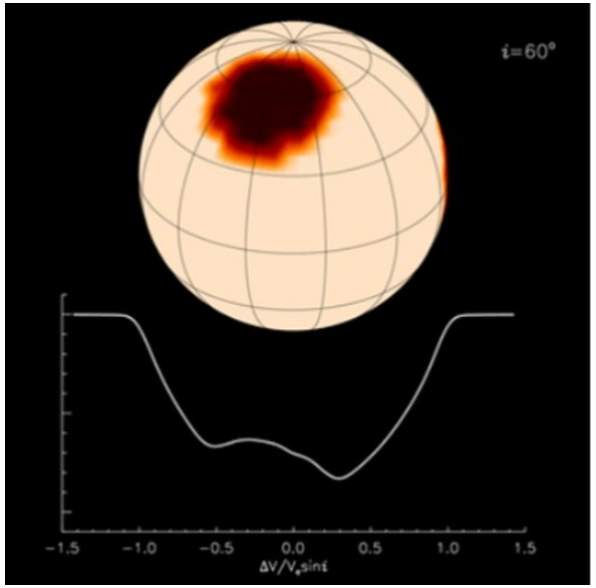
Spots and faculae/plages



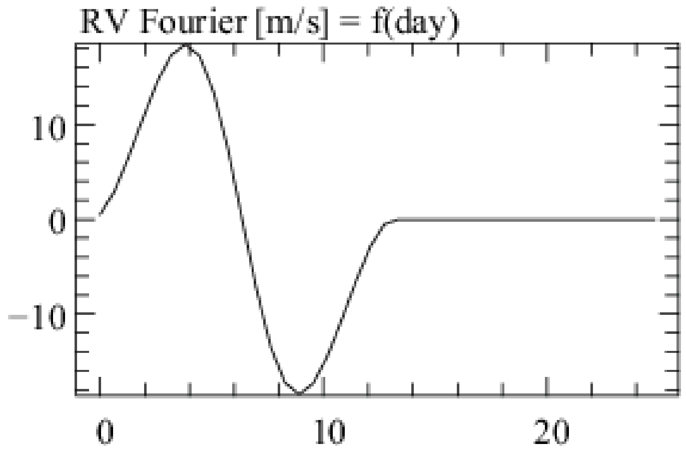
RV meas.
biased >0

RV meas.
biased <0





O. Kochukhov (movie)
http://www.astro.uu.se/~oleg/



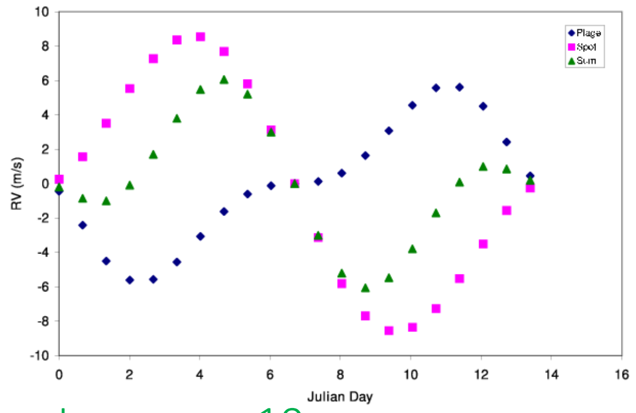
+ déformation des raies
Desort+07

RV signal due to line distortion

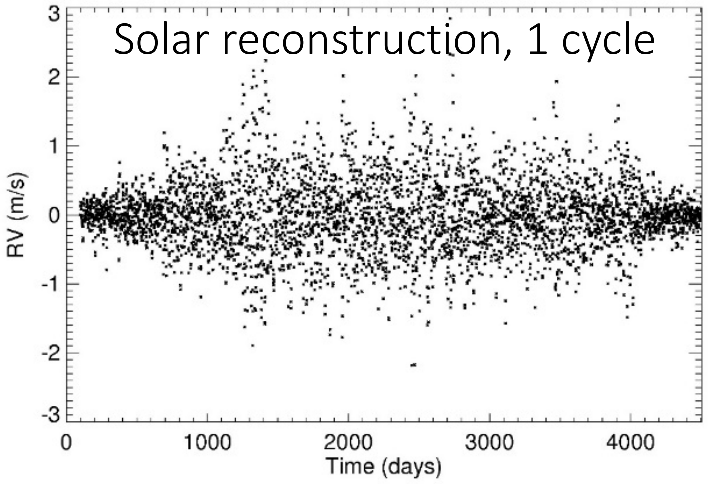
Saar&Donahue97, Hatzes02, Saar+03, Wright05

Typical RV properties due to spots and plages

- Typical time scales: week-months (-years)
  - *Rotationnal modulation* + harmonics (incl. active longitudes) + differential rotation
  - *Finite lifetime* + structure evolution
- Amplitude in RV
  - RV dispersion 0.1 up to >1 m/s for solar-type stars
- Effect of
  - Stellar inclination
  - Wavelength
  - Degeneracy spots/plages
  - Magnetic fields → Zeeman effect Reiners 13, more important in IR



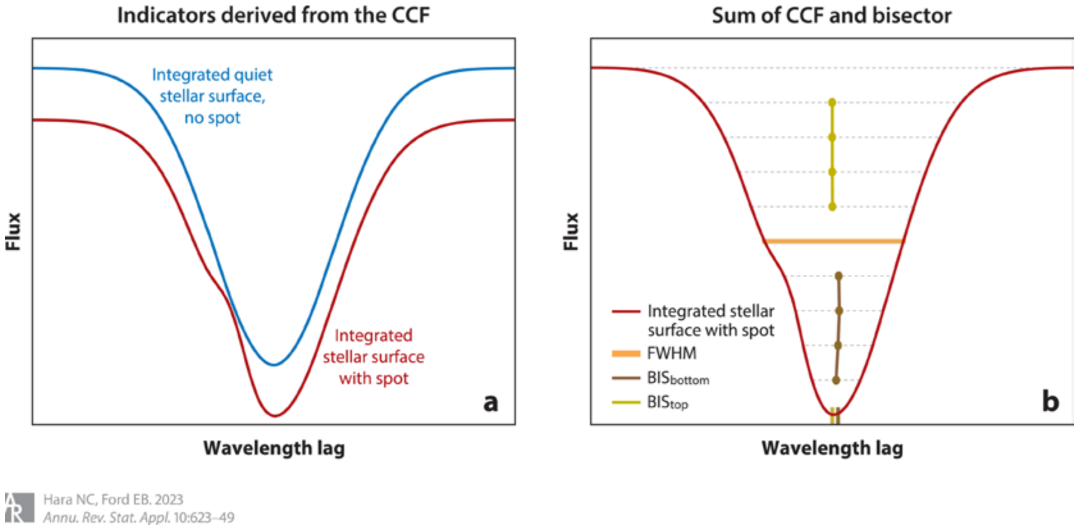
Lagrange+10



Meunier+10

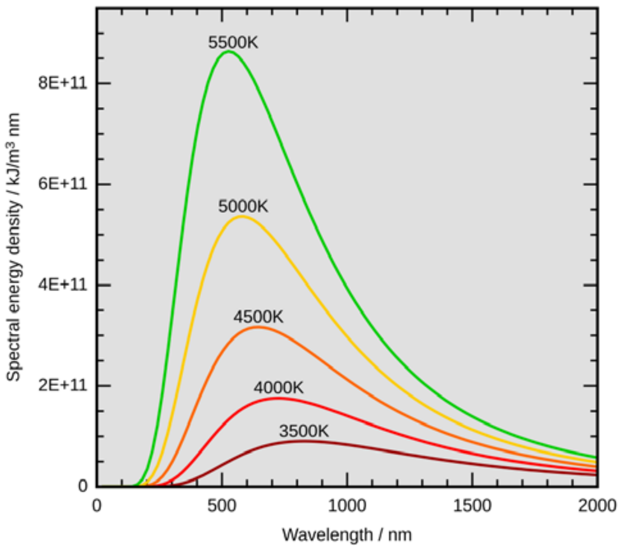
Important properties for correction purposes

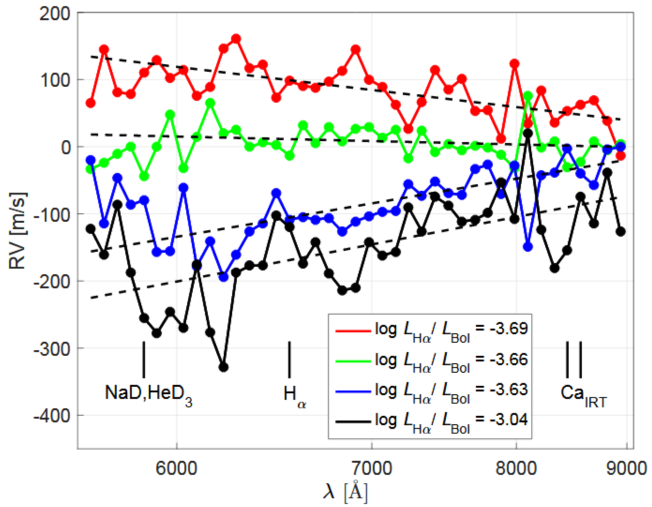
Line distortion
identified for a long time
⇒ bisector shape (BIS) often
used as activity indicator
⇒ FWHM



Hara&Ford23

Chromatic dependence of the contrast due to black body
Much remains to be understood to understand the observed differences between VIS and IR



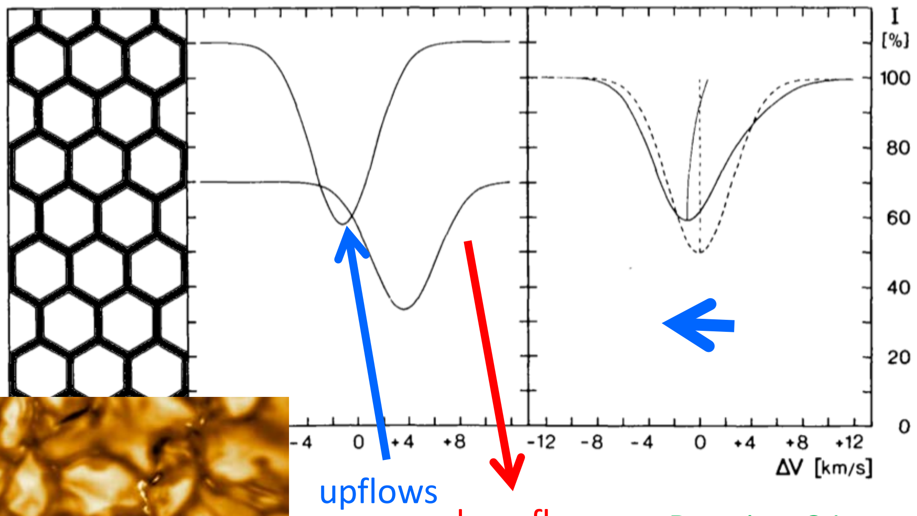


Tal-Or+18 CARMENES/VIS

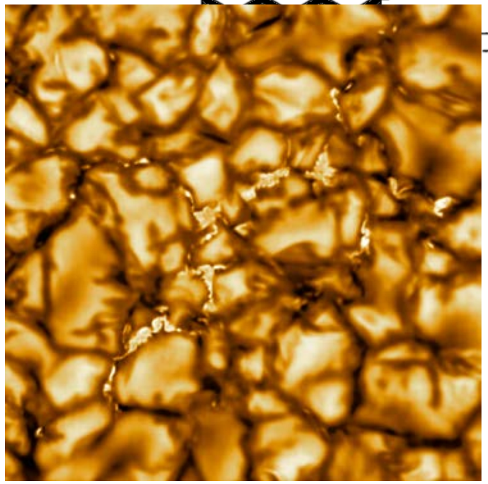
Inhibition of the convective blueshift in plages

Stellar convective blueshift

Sun ≈ 300-400 m/s



Dravins 81, …



Attenuation in plages

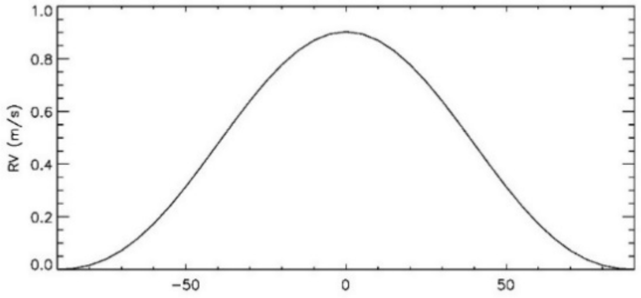
Magnetic field →Inhibition of the flows (anomalous granulation)

Weaker in network structures

RV = Net redshift

Maximal RV when plage on central meridian

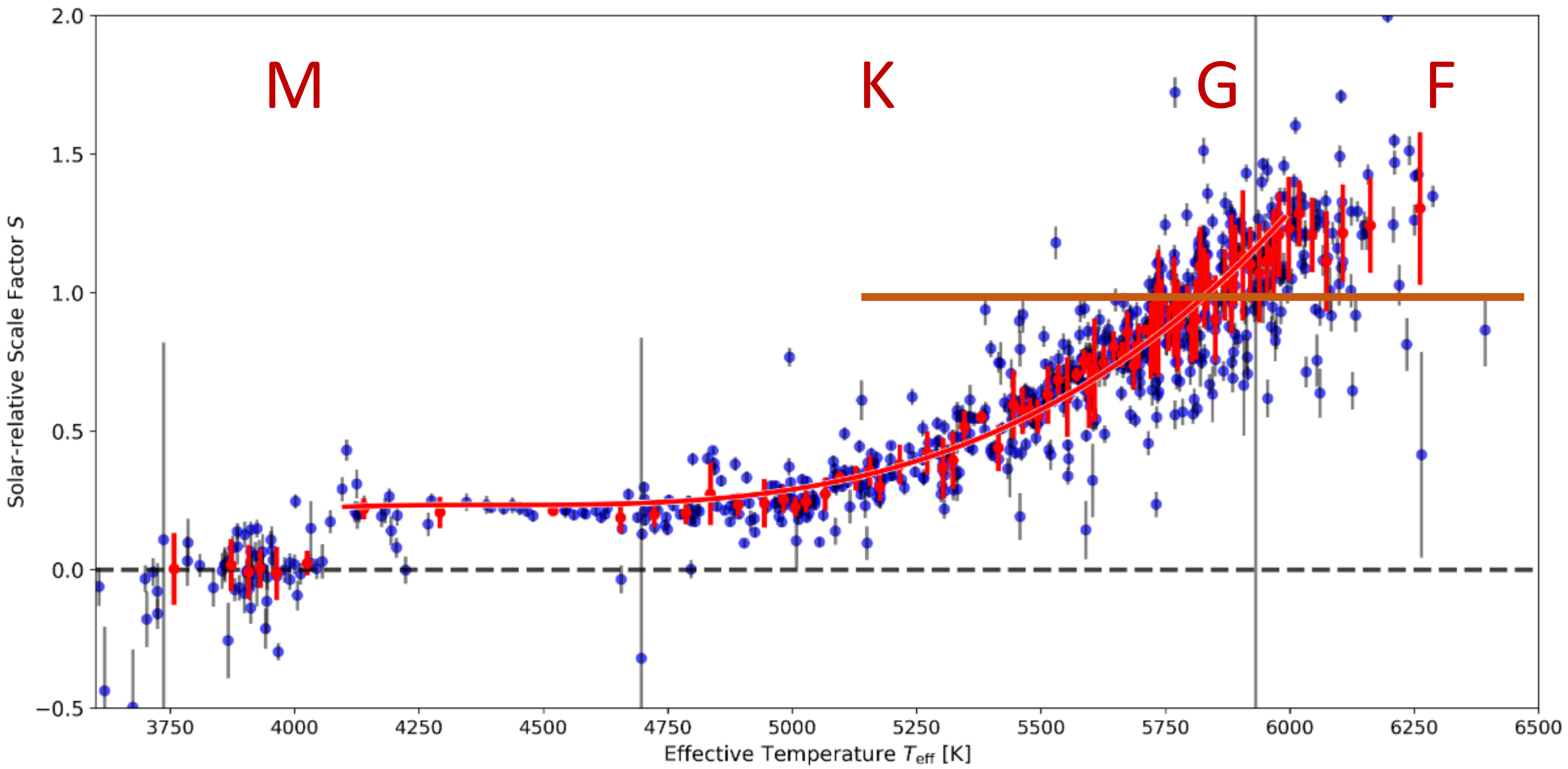
~ correlation with logR'$_{HK}$ (filling factor)

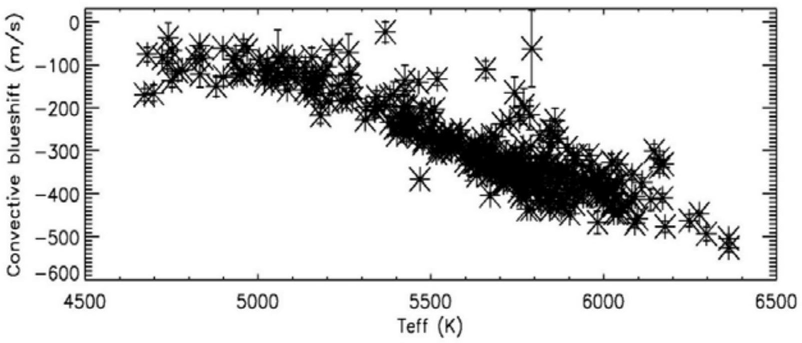


Flows + Magnetic activity

Convective blueshift versus Teff

Liebing+21





Meunier+17

Several applications to other stars: eg. Dravins 1987, 1989, Allende Prieto et al 1999, Landstreet 2007 …

Variability of the inhibition factor versus spectral type Meunier+17a,b

Temporal variability for the Sun Meunier+24

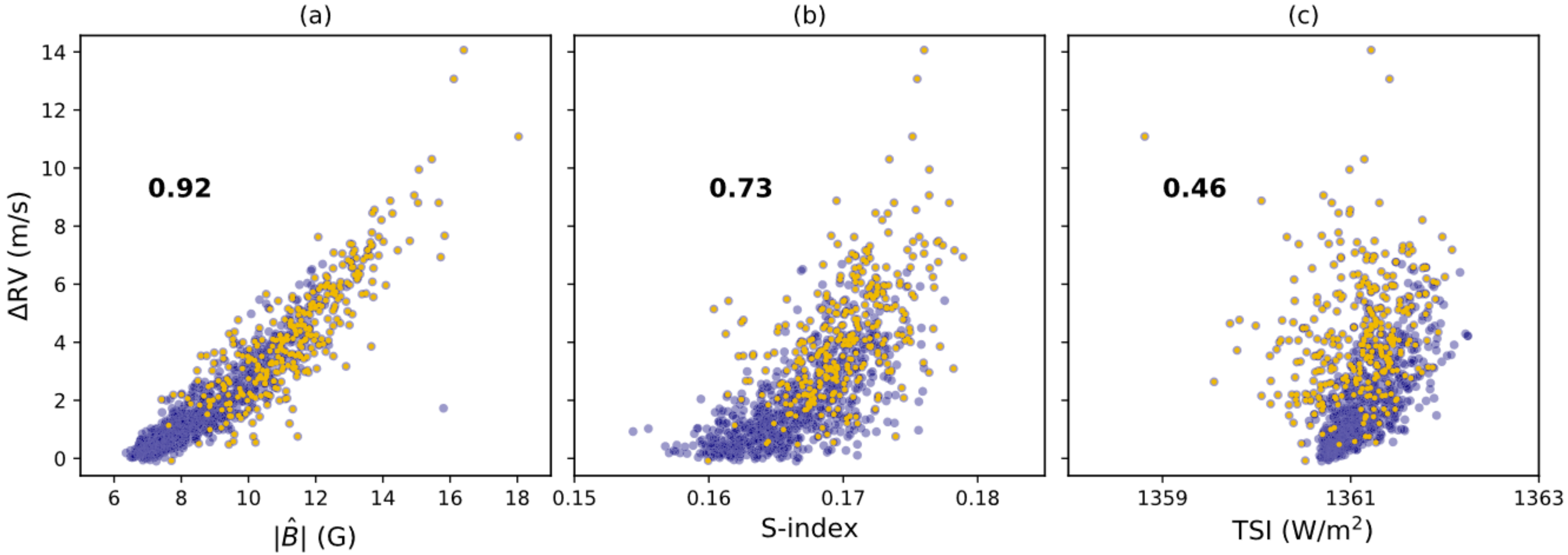
Important properties for correction purposes

Correlation with ff faculae => logR'$_{HK}$ often used

- but see departure due to projection effects+butterfly diagram Meunier+19

Average |B| (Haywood+22) correlates better with RV

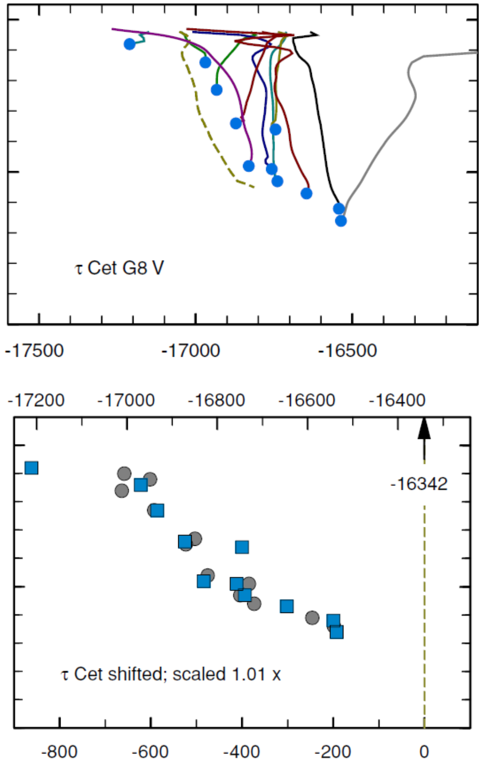
- see Lienhard+23 for tests on the Sun



Important properties for correction purposes

Depth dependence

Flux

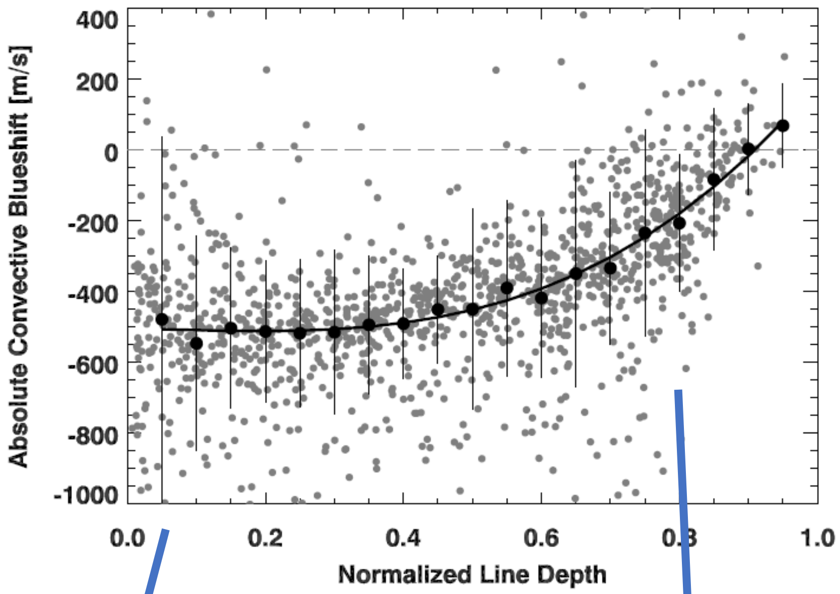


Velocity (m/s)

Gray 09

→ Universal signature

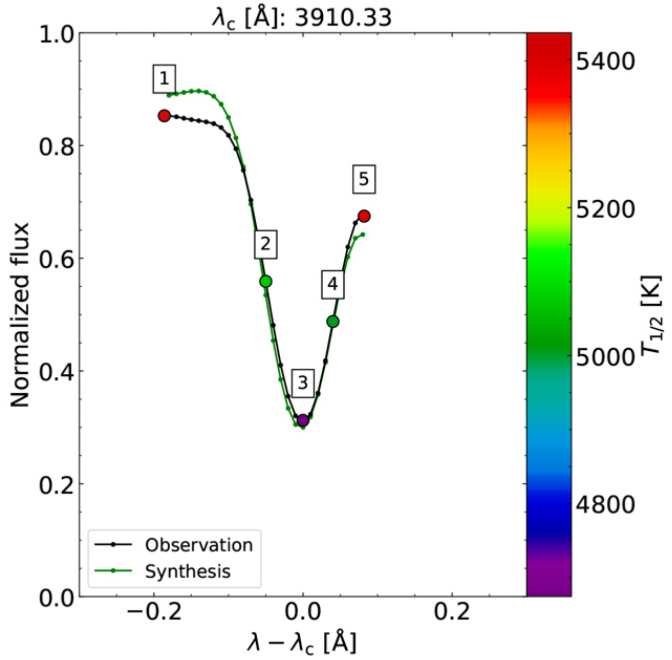
Reiners+16



Weak lines Formed lower

Deep lines Formed higher

Al Moulla+22,23

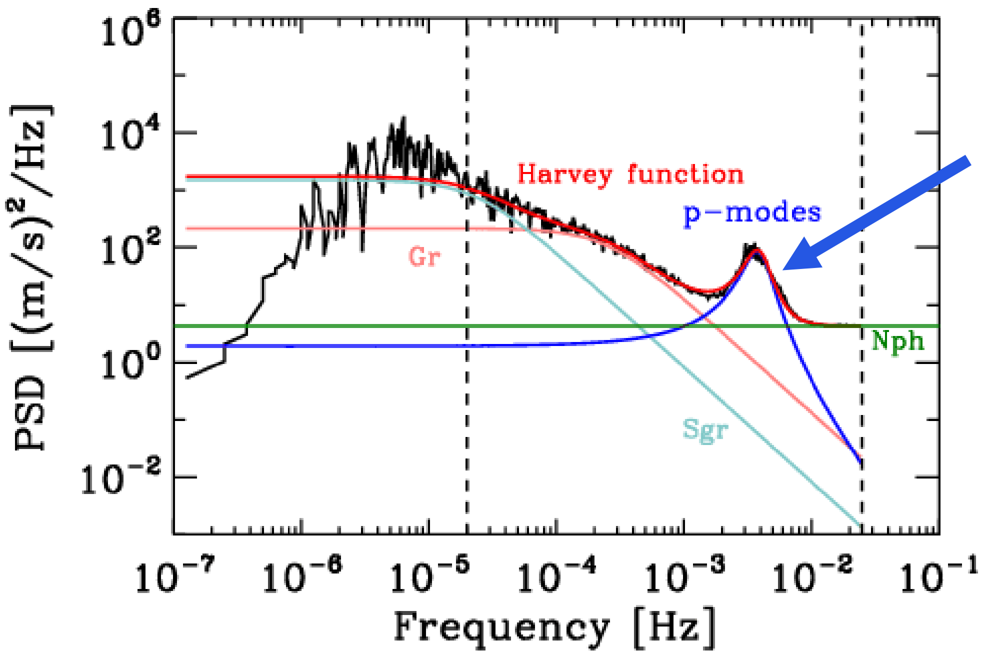


Warning: signal visible mostly with line core (Gray09) ; selection of lines of different depths=> no strong variability of the RV amplitude (Meunier+24)

Oscillations and pulsations

Typically ~ a few min for solar type stars (p-modes), ~1 m/s

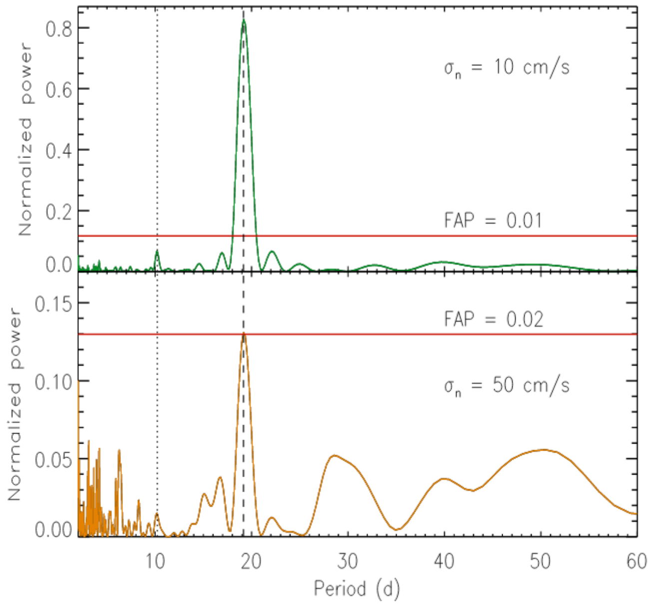
- Many peaks in the power spectrum with well-defined envelope (Kjeldsen95, …)
- → Helioseismology / asteroseismology
- Easily averaged Dumusque+11, Chaplin+19



Lefebvre+08
+ many other papers
Based on laws from Harvey85

- Impact of sectoral r-modes
  - Global scale equatorial Rossby wave
  - Main mode for the Sun = 0.44 m/s @ 19.16d

Lanza+19

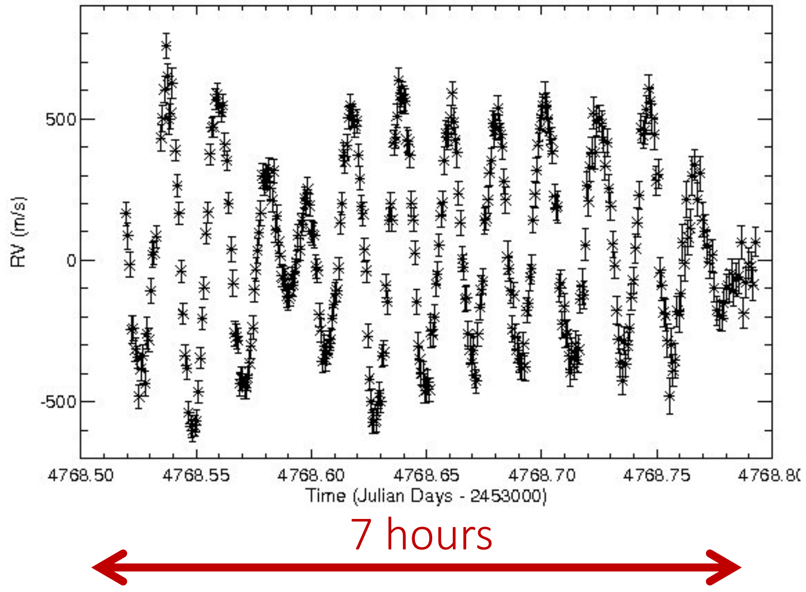


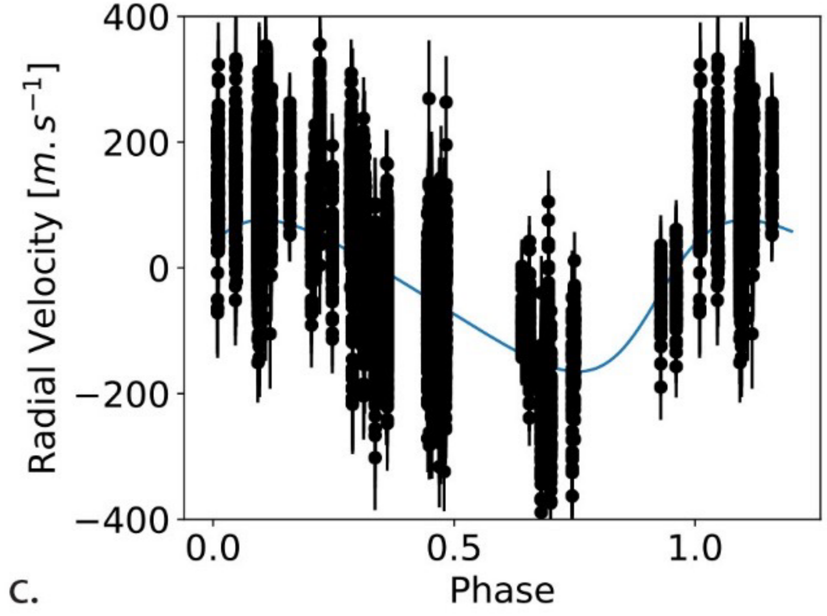
Pulsations δ Scuti, γDor

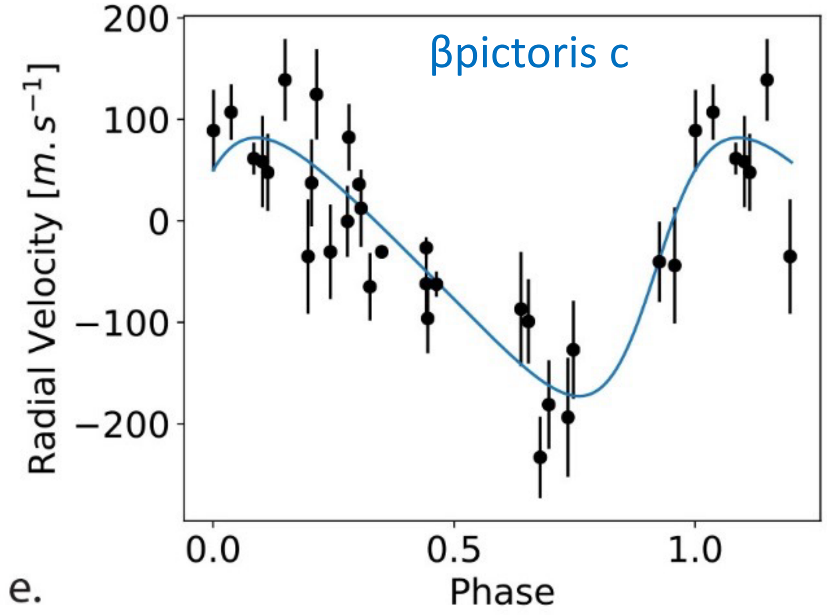
Different time scales depending on the star (minutes - hours)

Can be of very high amplitude, for ex. δ Scuti → critical to detect planets

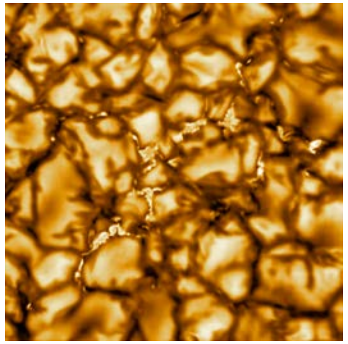
Example: βPictoris (A star, δScuti), Lagrange+19, 20



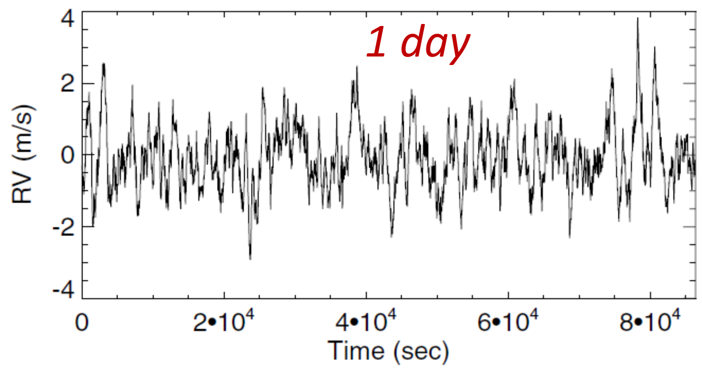


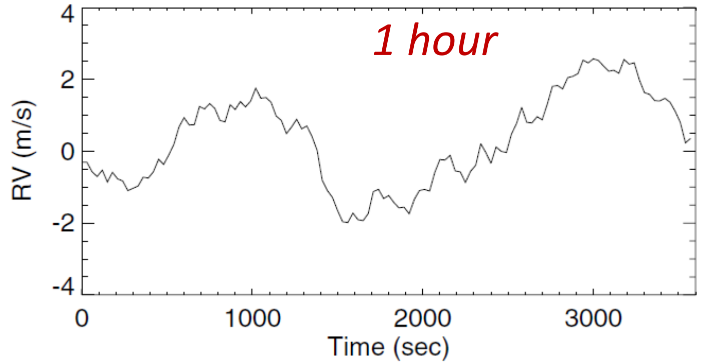


Granulation



DKIST





Different realisations of the 10^6 granules over time

→RV(t)

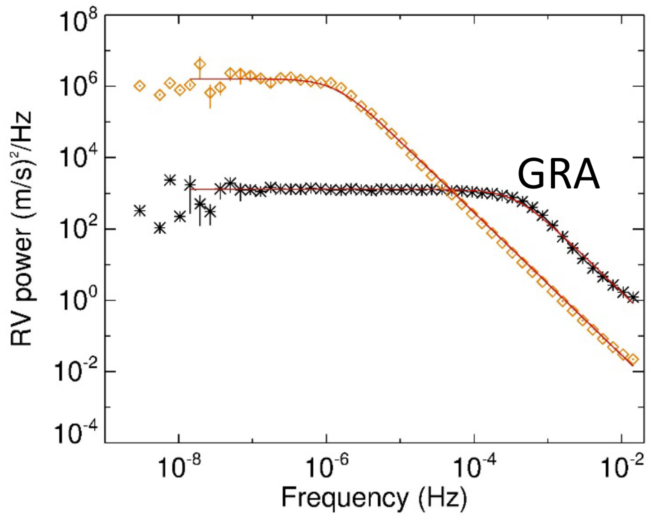
Solar observations

- Elsworth+94, Pallé+99 ~0.4 m/s from specific lines

Solar simulation of ~10^6 granules based on properties from HD simulations

- Meunier+15 ~0.8 m/s
- Power spectrum compatible with proposition from Harvey 84,85
- For a large number of simulations : use of the Harvey power spectrum
- Makes it difficult to average (1h => /~2)

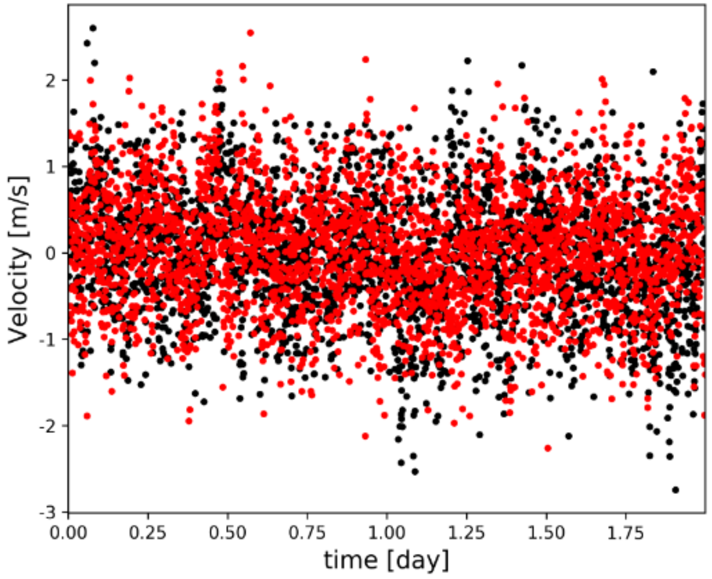
Meunier+ 15

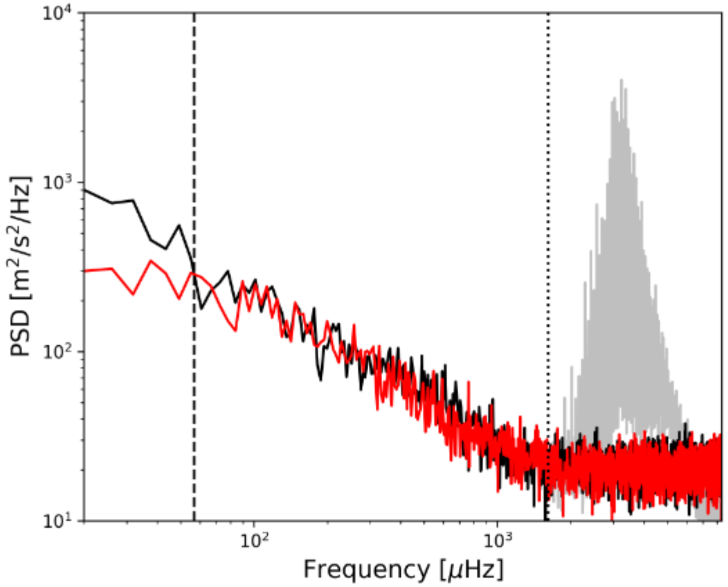


RV due to granulation in 3D HD simulations

Direct MHD simulation in small boxes

- Cegla+19 : low amplitude of the signal
- Sulis+20 comparison with observed solar RVs SOHO/GOLF in the Na doublet => ~0.4 m/s
- Importance of the shape of the power spectrum

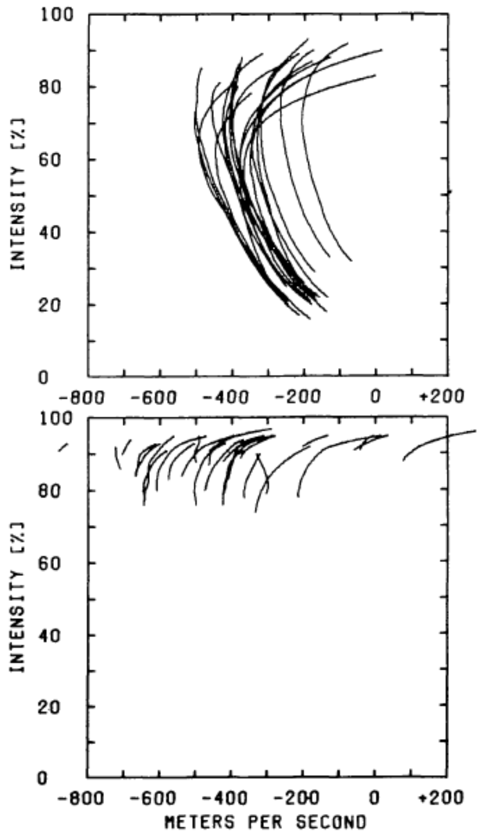




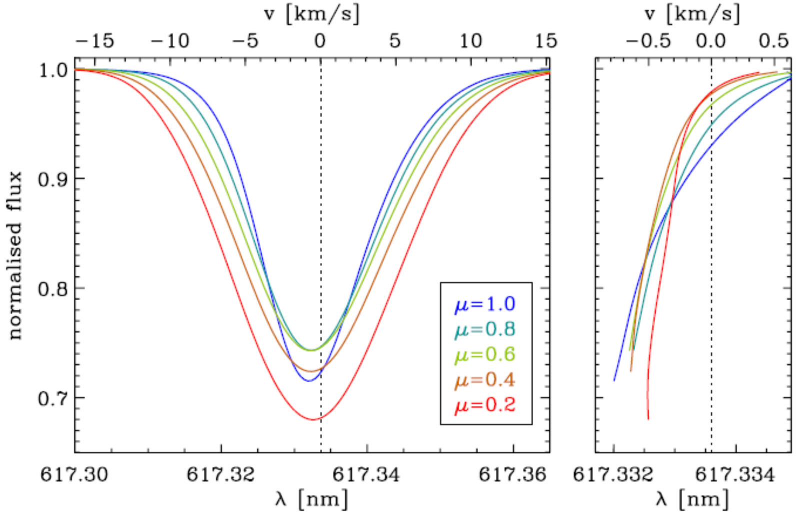
GOLF/SOHO observations
MHD simulations
Sulis+ 20

Important properties: line shape

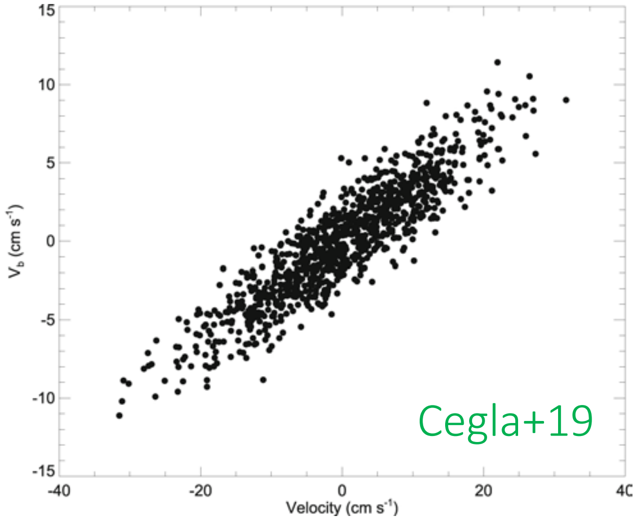
Strong distorsions of the line shapes



Dravins+81
Observed
See also Dravins+21…



Beeck+13



Cegla+19

Line-shape effect superposed on those due to other processes

Impact of spectral resolution

Supergranulation

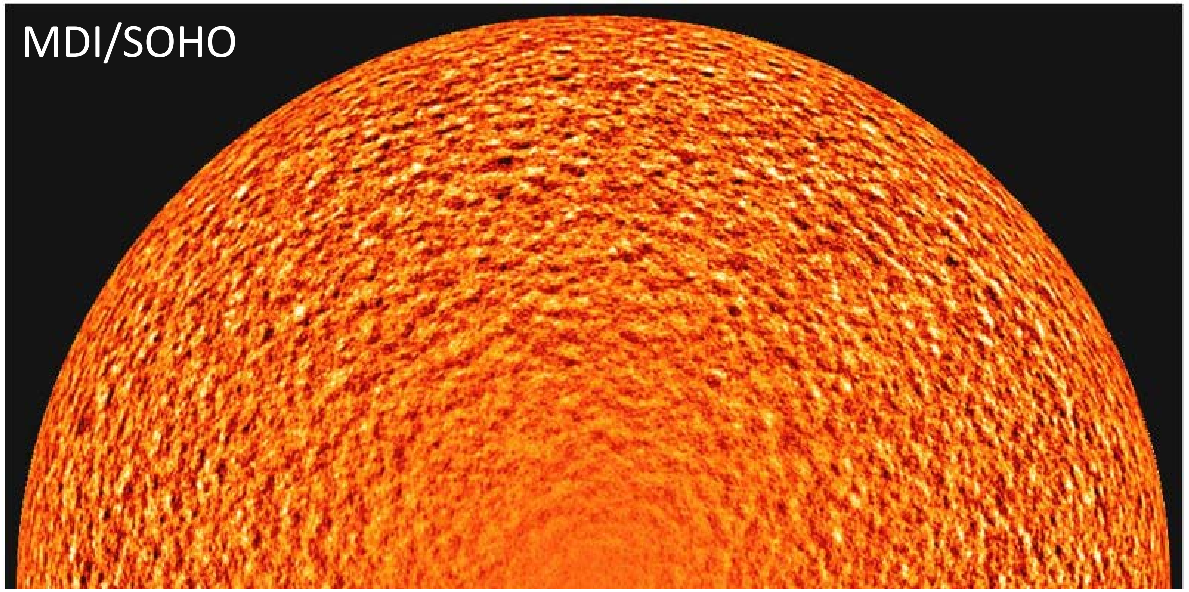
Large cells outlined by the magnetic network

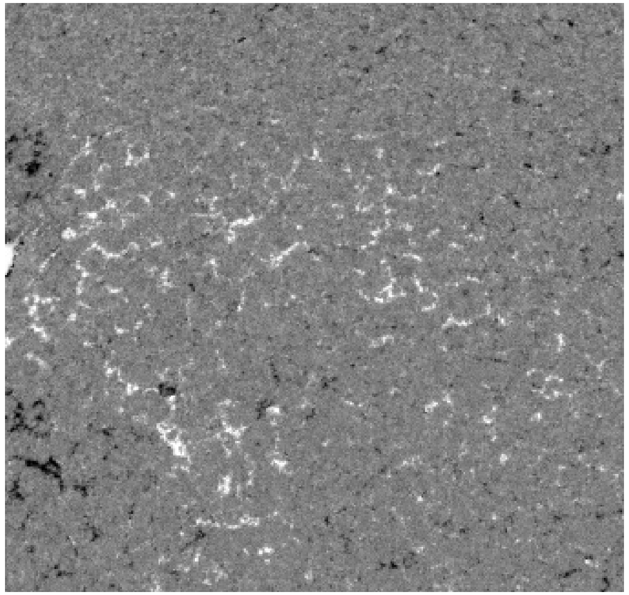
- Leighton+1962
- Solar lifetimes **~24-48h**
- Size **~20000 km**
- Horizontal flows **~200-300 m/s**
- No intensity contrast
- Origin unknown, perhaps due to explosive granules
- Many work related to cycle variations (due to magnetic field inside the cells)

Not characterised for other stars

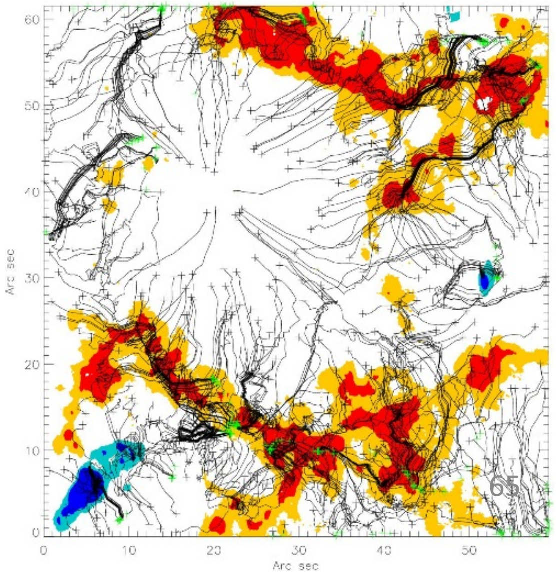
- Likely scaled to granules

See reviews
Rieutord+10
Rincon+18





Roudier+16



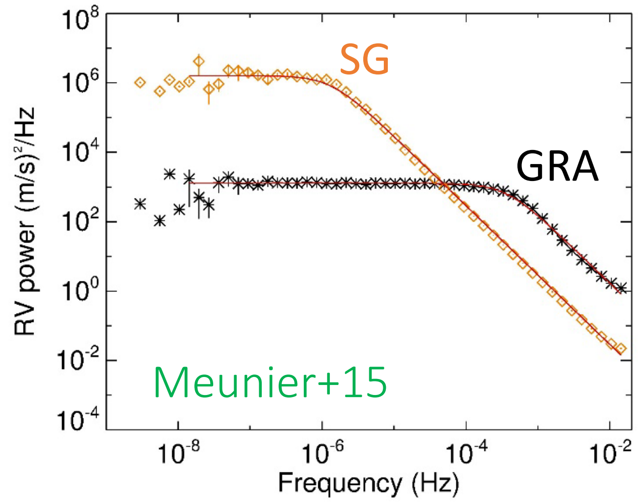
Supergranulation

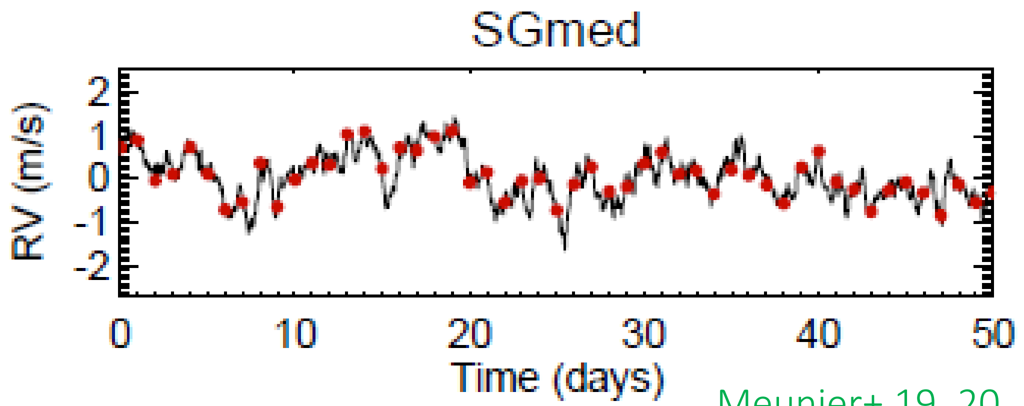
RV jitter not well constrained

- Slower flows than granulation but less cells on the surface → Jitter remains strong !
- Solar observations Palle+99 **0.78 m/s**
- Solar estimation from simulations: median value **0.7 m/s** (low estimate 0.3 m/s Meunier+15)
- Medium value compatible with day-to-day from HARPS-N **1.02 m/s** Dumusque+21
- Recent results on HARPS-N solar data :
  - **~0.7 m/s** Al Moulla+22
  - **~0.9m/s** Lakeland+24

More difficult to average

No link with usual indicators





Meunier+ 19, 20

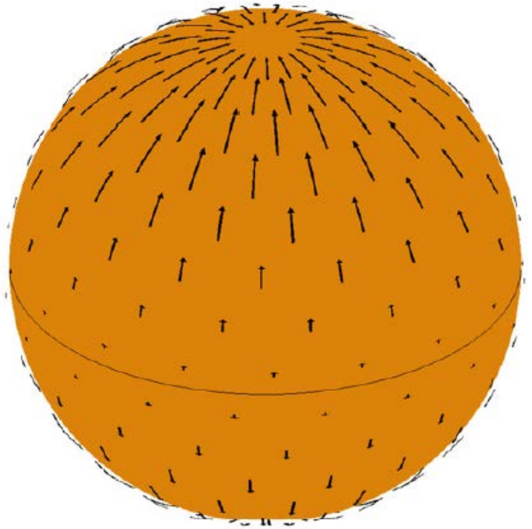
Meridional circulation

Solar case

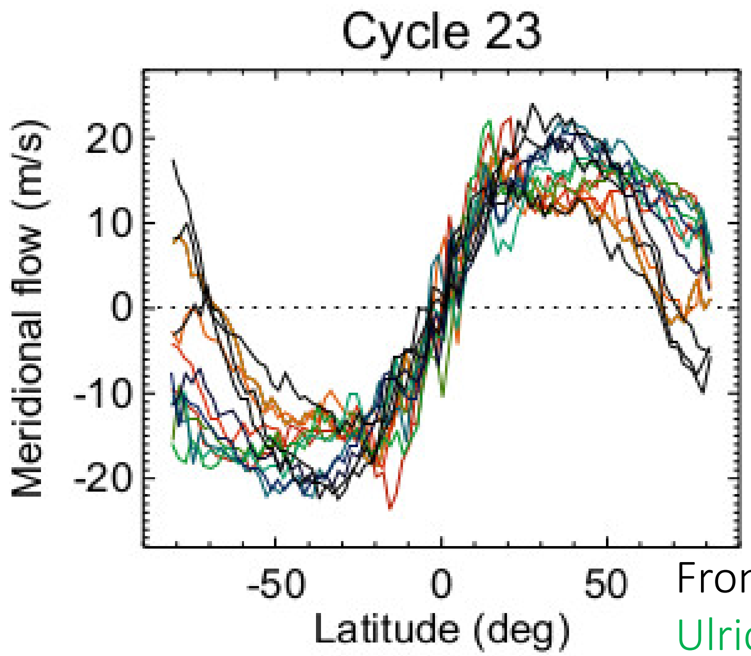
- Large scale flow
- Poleward
- Amplitude max **~10-20 m/s**
- Related to differential rotation and transport of angular momentum
- Variability over the cycle Komm+93, Meunier+99 + many other references

Stellar case

- No observational constrain
- Theoretical predictions
  - Smaller for fast rotators Ballot+07, Brun+17
  - Smaller for low masses Matt+11, Brun+17
  - May be multicells Matt+11, Guerrero 13,16



Makarov+10



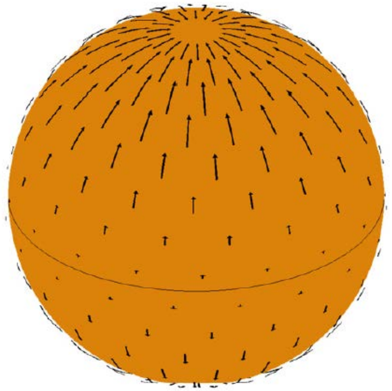
From Ulrich10

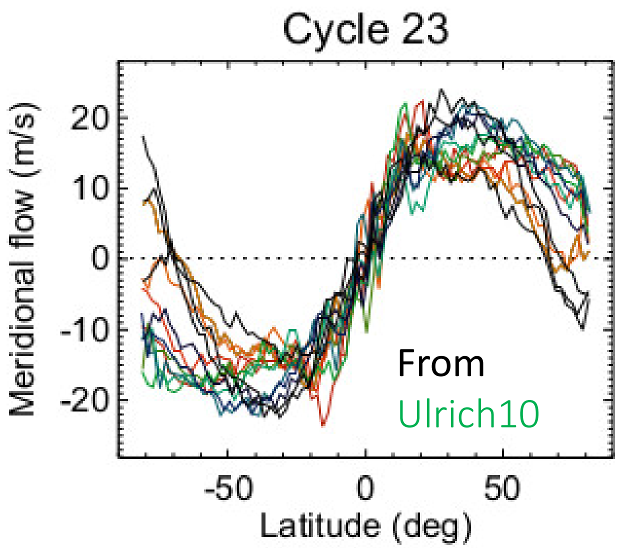
Meridional circulation

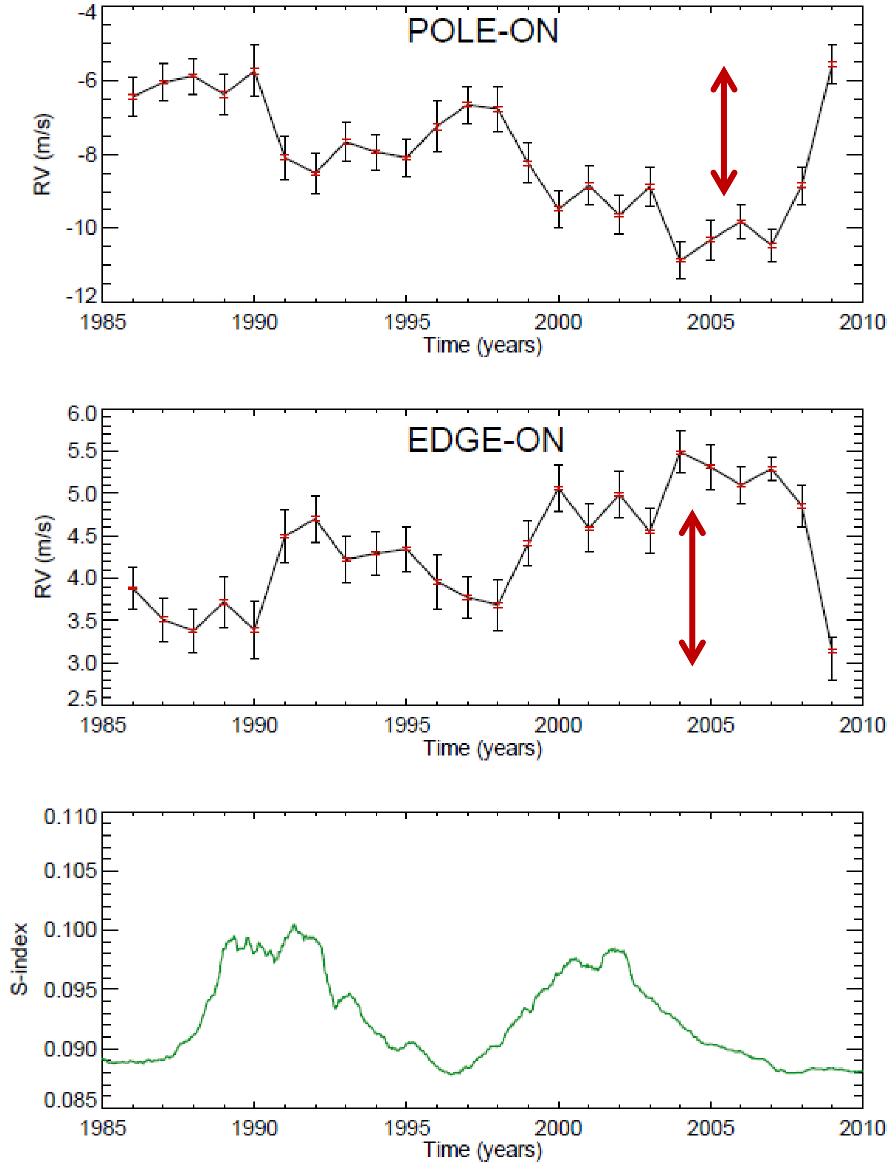
Variable solar meridional circulation

Impact of meridional circulation on RV

- Solar, edge-on: Makarov 10 (mixed with other processes)
- Inclination →reversal in sign
- New reconstruction :
  - ~1m/s edge-on
  - ~2 m/s pole-on rms (Meunier+20)

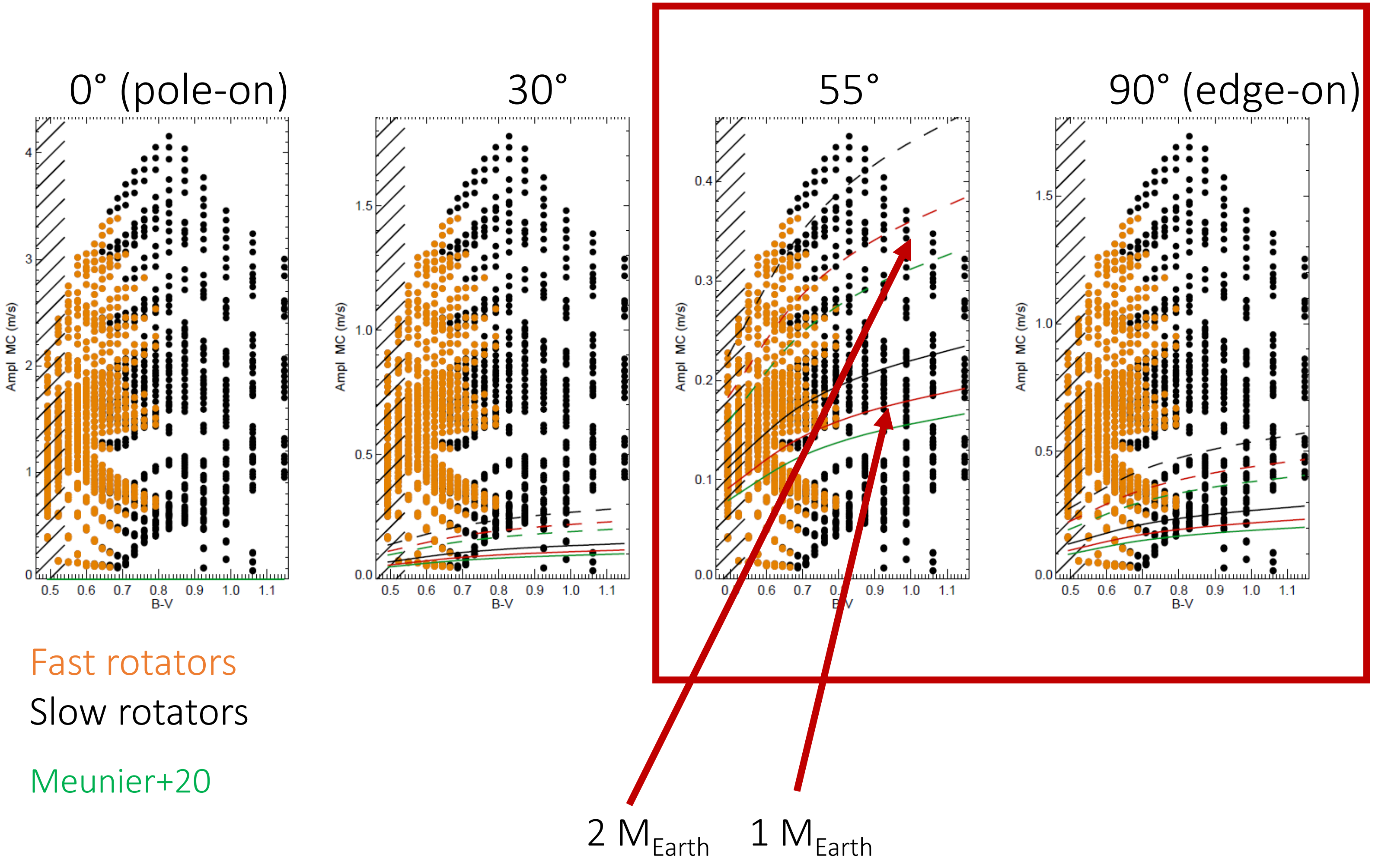






Meunier+20a

Expected stellar amplitudes



Fast rotators
Slow rotators

Meunier+20

Smaller for fast rotators Ballot+07, Brun+17 & multicells Matt+11, Guerrero 13,16

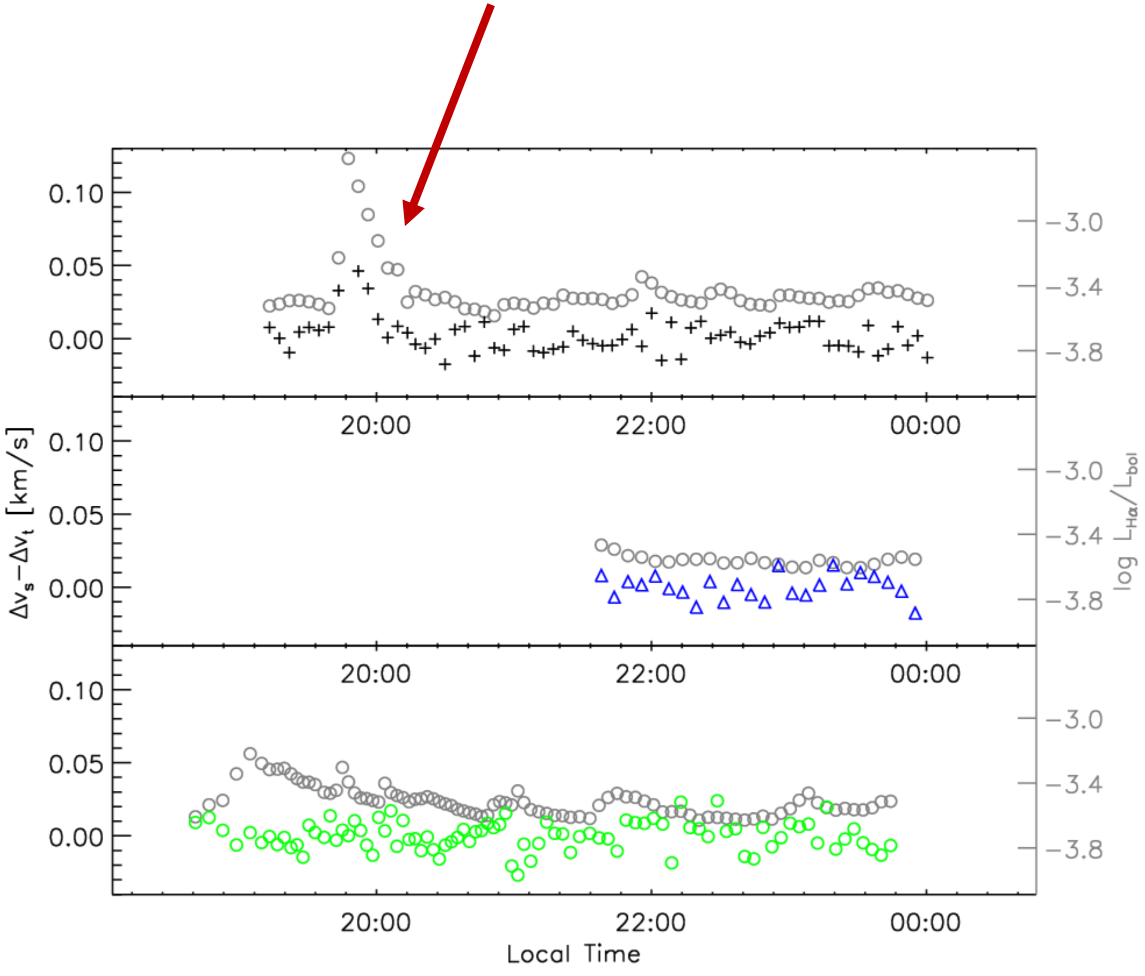
Smaller for low masses Matt+11, Brun+17

Scaling on cycle amplitude
→ ~ 0.1-4 m/s

Flares

Need to be major to impact RV

- Negligible for G stars (Saar+18)
- Impact a large fraction of M stars, major flares exist
- Often appears as outliers given the temporal sampling



Reiners+09

RV summary

Many sources, at various scales

- Several contributions in the 0.3-1 m/s range
- Complex for solar-type stars
- May be more stable for young stars or some M stars

Complexity

- Activity pattern
- Differential rotation
- Finite lifetime of spots/faculae + evolution of structures
- Sum of different individual contributions → strong degeneracies
- Large range of sizes and timescales

Importance of the temporal sampling

Correction methods: RV

See also Zhao+22,Hara&Ford+24

Based on RV time series

SPOTS/PLAGES
Fits of sinusoids / harmonics Boisse+11
Prewhitening at Prot Queloz 09, Hatzes+ 10
Spot modeling Moulds+ 13 Dumusque+14 Herrero+16

OSCILLATIONS/GRANULATION
Averaging (for oscillation/granulation) Dumusque+ 11 Meunier+15
Periodogram standardization (MHD sim. granulation) & error propagation Sulis+17,20,22

Using different sets of RVs (spectral level)

Using selected sets of lines (depths) Meunier+ 17
Combining different line properties Dumusque+18, Crétignier+20
Using different parts of the lines (Teff) Al Moulla+22
Selection of lines minimisation RV signal Belotti+22
Wavelength dependence/chromatic index e.g. Tal-Or+ 18

Using other indicators from the spectra

⇒ *cross-correlation function (CCF, ~average line) or full spectra [not exhaustive]*
⇒ *Associated to search for new activity indicators (lines, IR)*

Correlation with line bisector span(+) Desort+ 07, Boisse+ 09
Chromospheric emission Boisse+09, Pont+10, Dumusque+12, Meunier+ 13, Robertson+14, Rajpaul+15, Lanza+16, Borgniet+17 incl. Non-linear relationship Meunier+19,24
Gaussian processes (simple, multivariate…) Rajpaul+ 15,20, Dumusque+17, Damasso+17, Barragan+19,22 …
PCA Davis+17, Crétignier+23 (YARARA)
Doppler imaging Hebrard+16 …
Shift&Shape SCALPELS Collier-Cameron+21 FIESTA Zhao&Ford22
ML (linear regression, NN) DeBeurs+22,Perger+23… => *next lecture*
…

Using other indicators

FF' method using photometry Aigrain+12 + multi-GPs

Focus on gaussian processes (GPs)

Non parametric method Rasmussen & Williams 2006

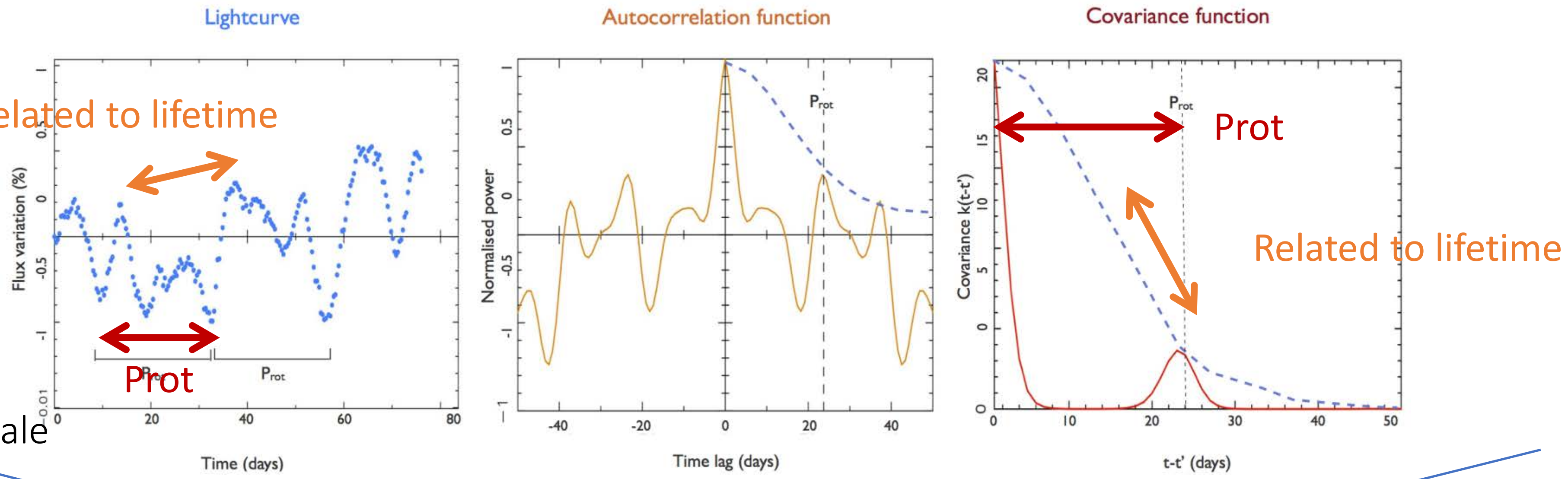
Replacing a parametric function => flexibility given the stochastic nature of stellar activity (can usually not be fitted with strictly periodic function for example)

General principle of a GP

- *Describe how two values (RV,…) at t and t' are **correlated*** (i.e. value at t => most probable value at t'?) => relation described by a **covariance function**
- Parameters of the covariance function= hyperparameters
- Adjustment of the hyperparameters on the time series => Can be used to compute **covariance matrix**
- Allow to derive most probable value + uncertainty (including for interpolation)

See Haywood 2014 (PhD) chapter 2 for very clear description

Main implementation: rotational modulation



Evolution timescale

Amplitude

Recurrence timescale ~Prot

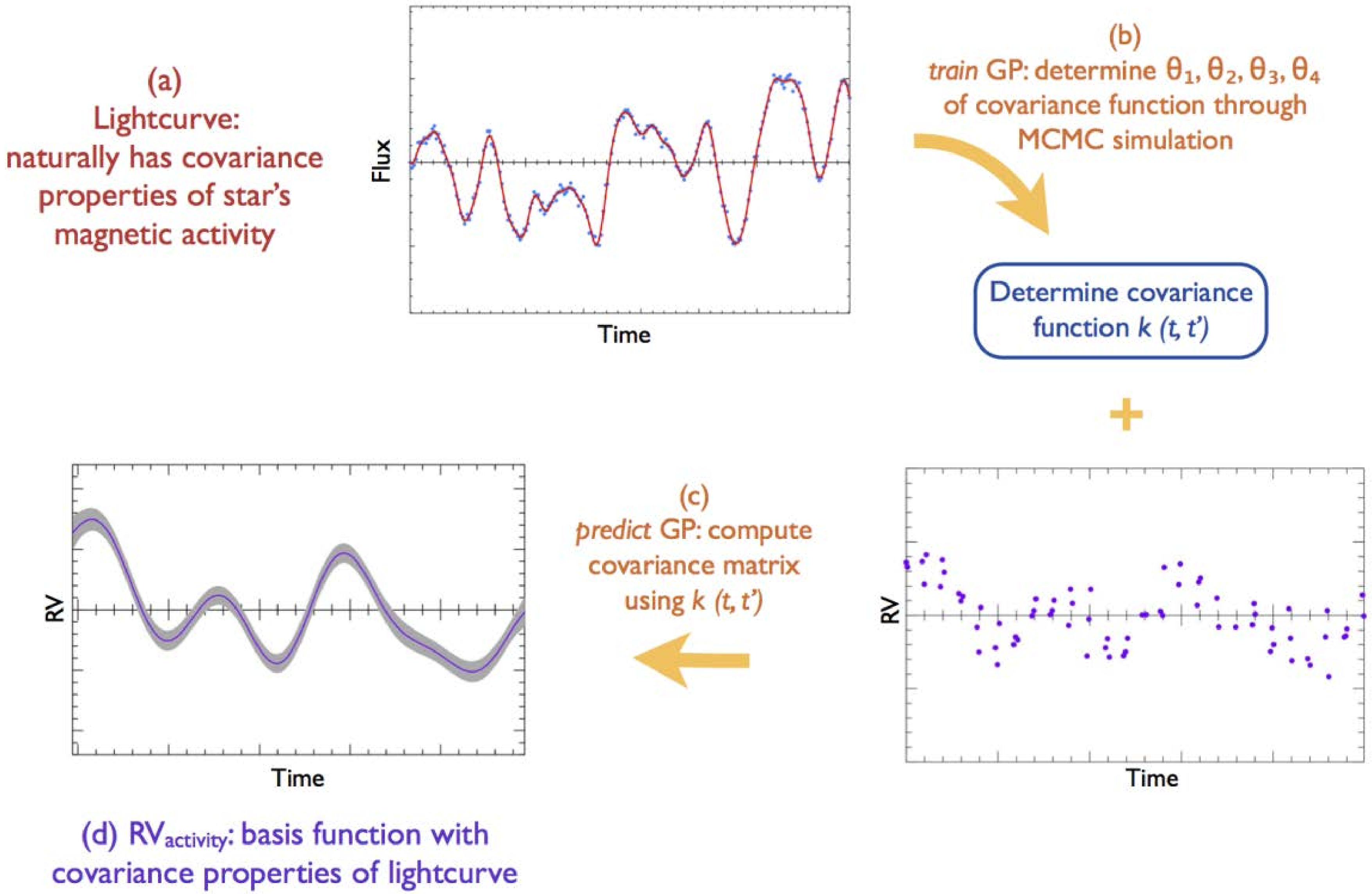
Relative importance of evolution vs. periodicity

$$k(t,t') = \theta_1^2 \cdot \exp\left[-\frac{(t-t')^2}{\theta_2^2} - \frac{\sin^2\left(\frac{\pi(t-t')}{\theta_3}\right)}{\theta_4^2}\right] + \sigma_i^2 \cdot \delta_{tt'}$$

Quasi-periodic function (variants exists)

Usually include a white noise term

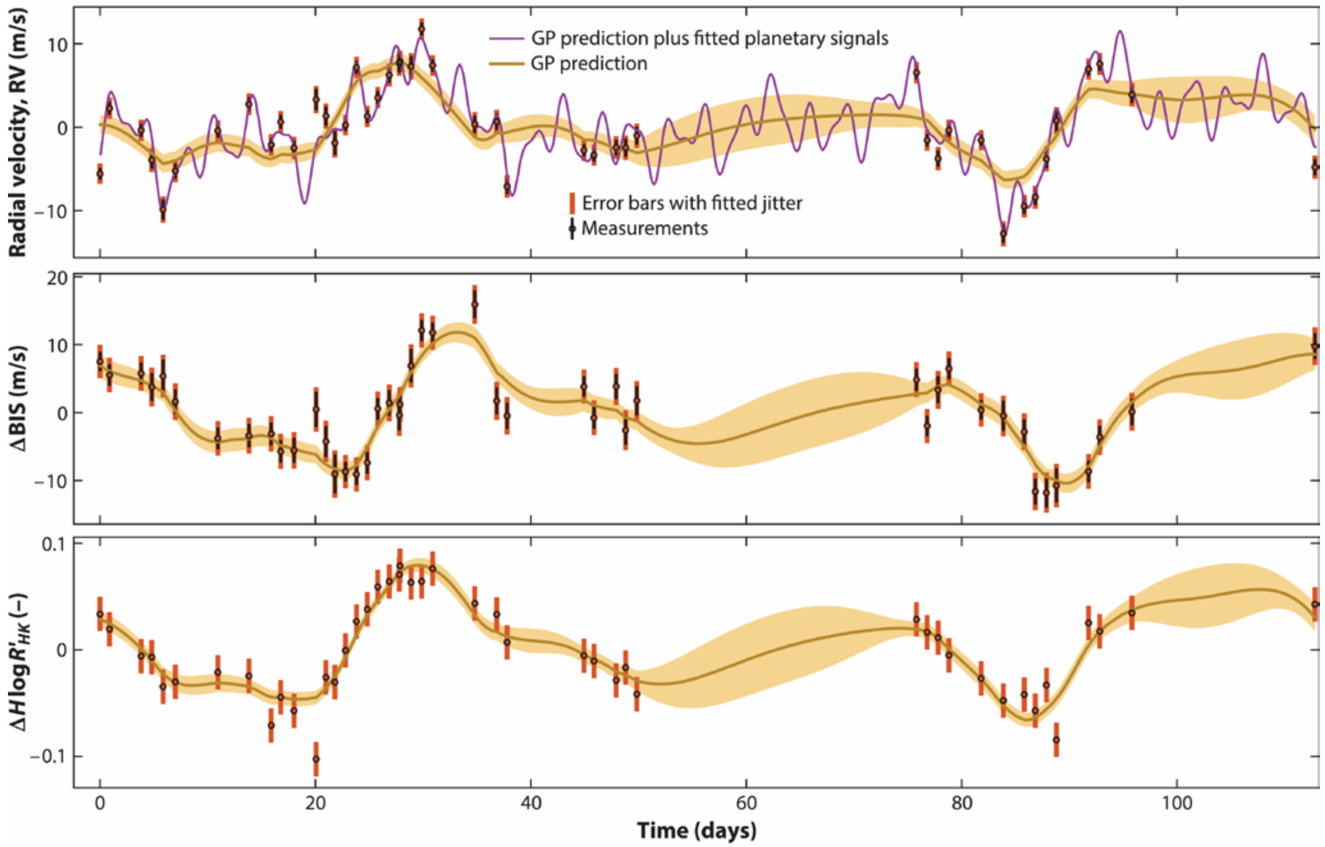
Haywood14



Training on observables which does not include any planetary signal: (out-of-transit) LC, $\log R'_{HK}$, BIS …

Assume have same covariance function

Haywood14



Hara NC, Ford EB. 2023
Annu. Rev. Stat. Appl. 10:623–49

Hara&Ford23

Current status

Evolution over the last decade

- Used in many studies, see methods in Rajpaul+ 15,20, Dumusque+17, Damasso+17, Jones+17, Barragan+19,22 …
- On RVs: need to apply GP+Keplerian at the same time (otherwise flexibility leads to planetary absorption in the GP)
- Development of more sophisticated tools, including multi-variate GPs = fit on RV + indicators simultaneously
- Openings to include other contributions than rotational modulation, with different covariance functions (but not always analytical form possible)

Open source codes [not exhaustive]

- package george (Ambikasaran et al. 2015)
- RadVel package (Fulton et al. 2018)
- Pyaneti (Barragan+19,22)
- …

- Question:
  - Can the flexibility absorb the planetary signal? (in particular at Porb>Prot)

Many methods, but some limitations

All reduce the RV jitter due to the stellar signal to some level

Importance of blind tests (see appendix for details), e.g.:

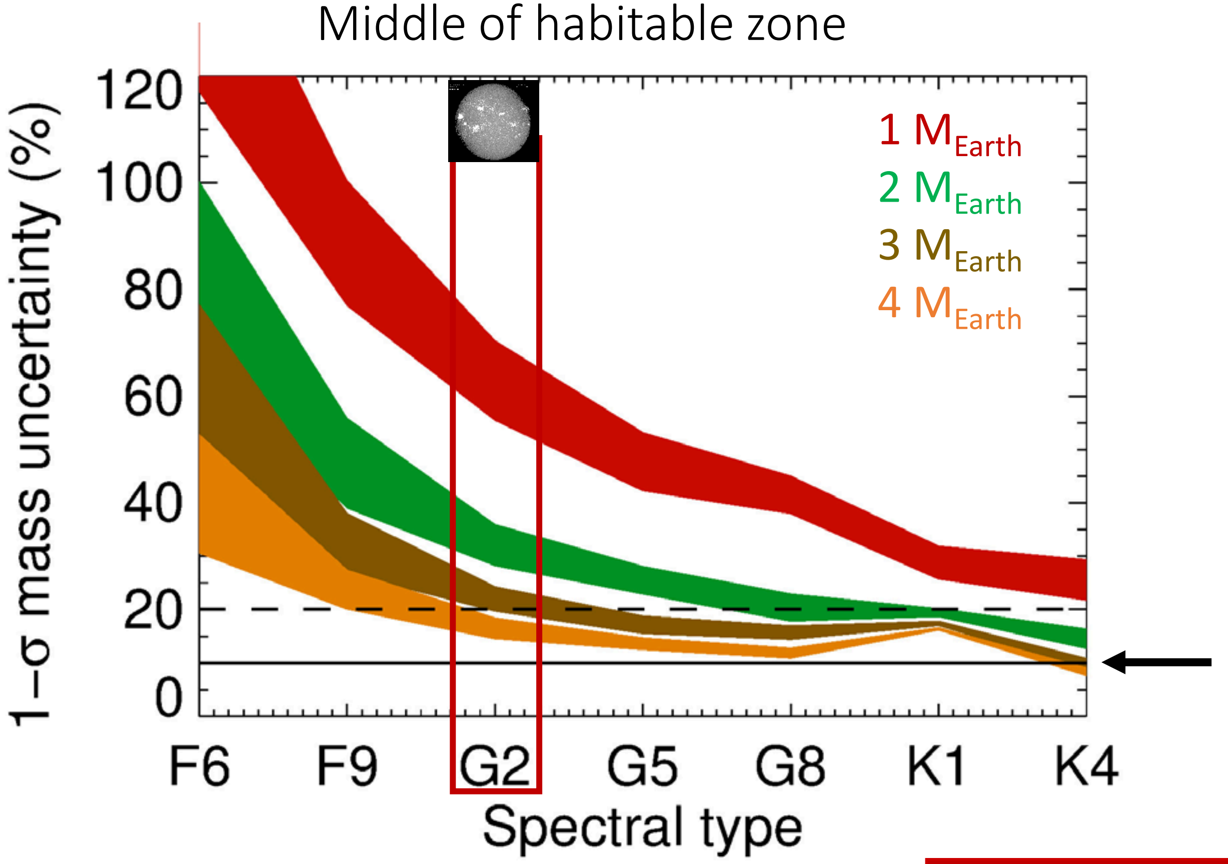
- Dumusque+16,17: data challenge on a few time series, 8 teams (blind search)
- Meunier+19,21: large scale, on flows only (granulation, supergranulation) => two types of blind tests (RV follow-up and blind search)
- Meunier+24: large scale, magnetic activity+flows (RV follow-up and blind search)

Residual jitter still too high **to allow the detection of a one Mearth planet in the habitable zone** of a solar type star

What is the reliability of the residuals?
Do we introduce spurious « planetary » signal?
Do we remove part of the planetary signal?
Do we propagate properly the errors and control the false alarm probabilities (see Sulis+20,22, Hara+20)

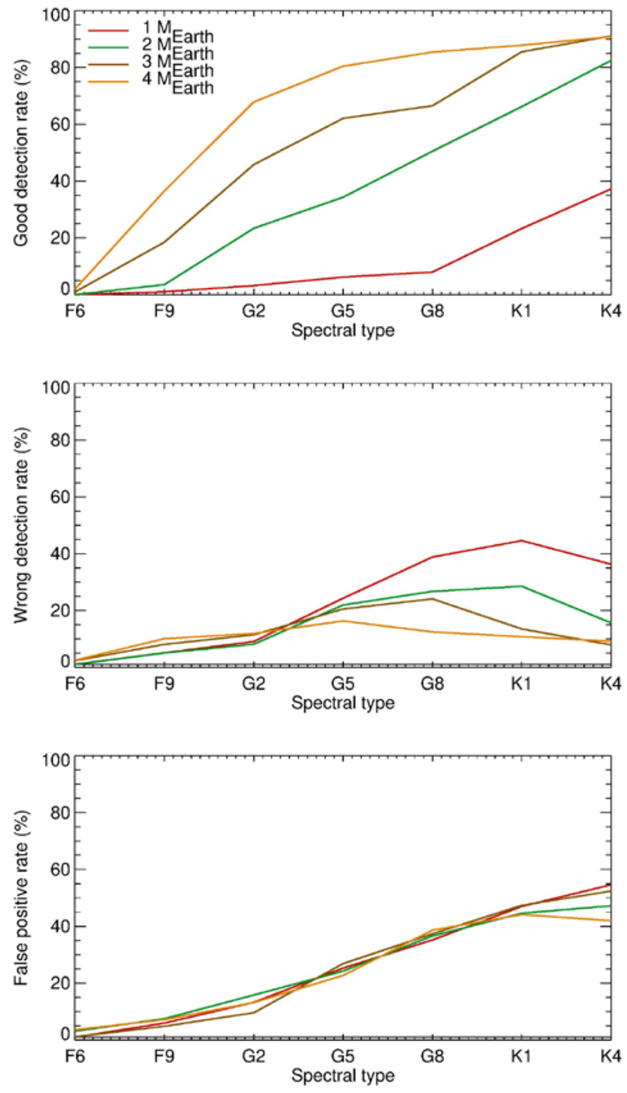
Follow-up of a transit detection

Search for planets



Meunier+23

Rms of residuals and fap not reliable



Effect on (broad-band) photometric transits

3 main sources

- Unocculted spots and faculae during the transit
- Occulted spots and faculae during the transit
- Stellar granulation

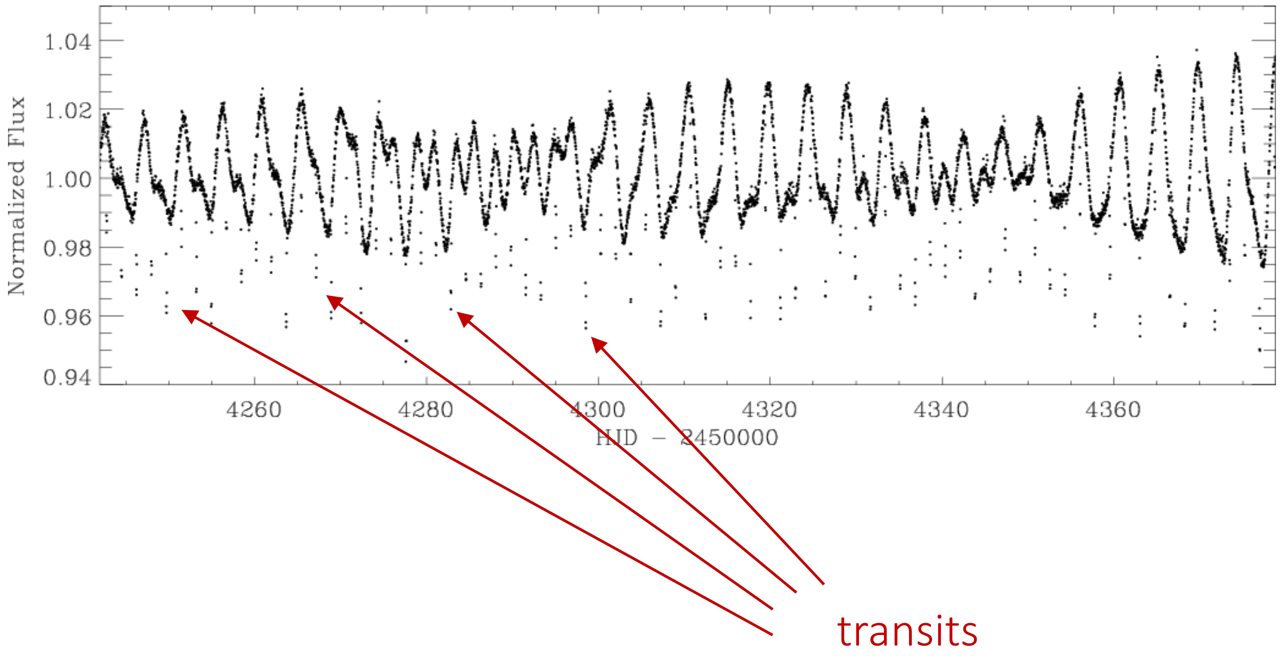
Not forgetting

- Flares => often removed before searching for transits, but small residuals may remain
- Issues with stellar properties not directly related to variability (limb-darkening law, including impact of spot)

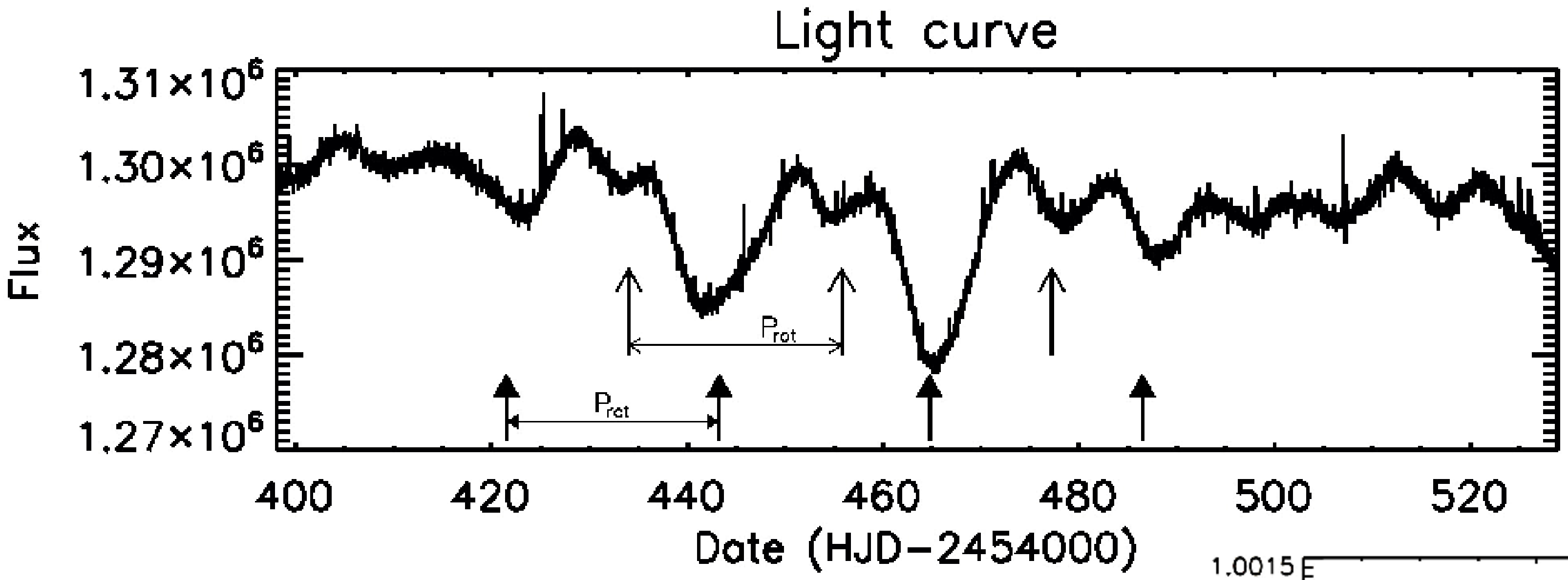
Impact on

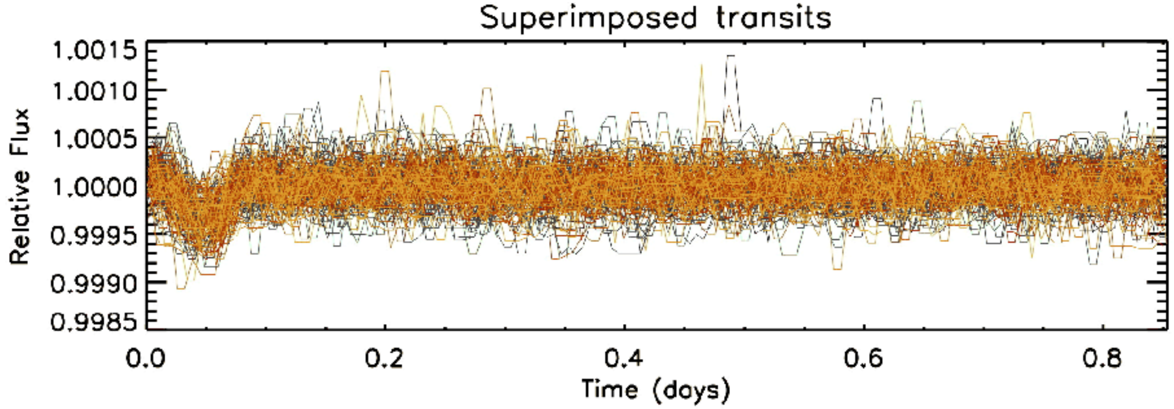
- **Detection**
- **Transit depth**
- Mid-transit time, certain orbital parameters (Barros+13)

Corot 2b Alonso et al 2009



See Bruno&Deleuil 21 for a review

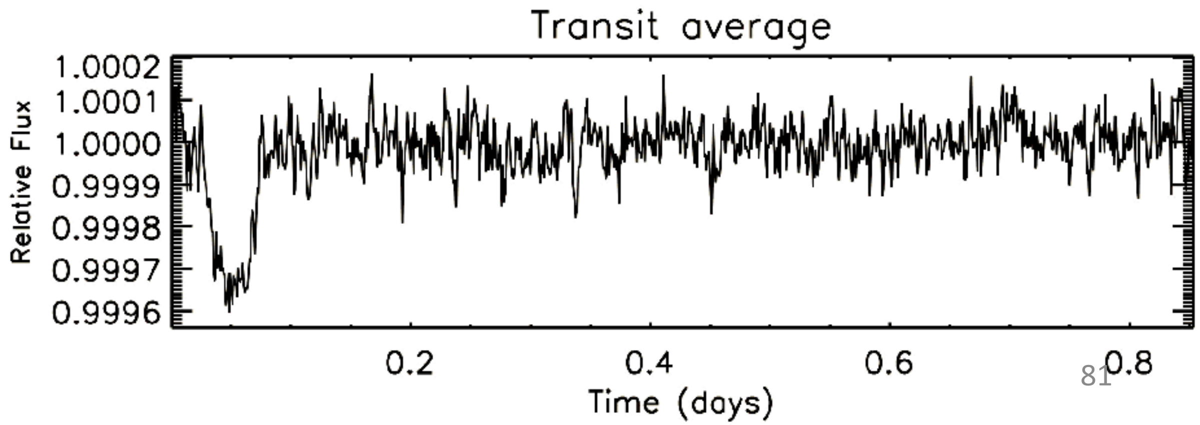




Corot 7-b

Léger et al 2009

Several low-pass and high-pass filtering



Un-occulted spots and faculae

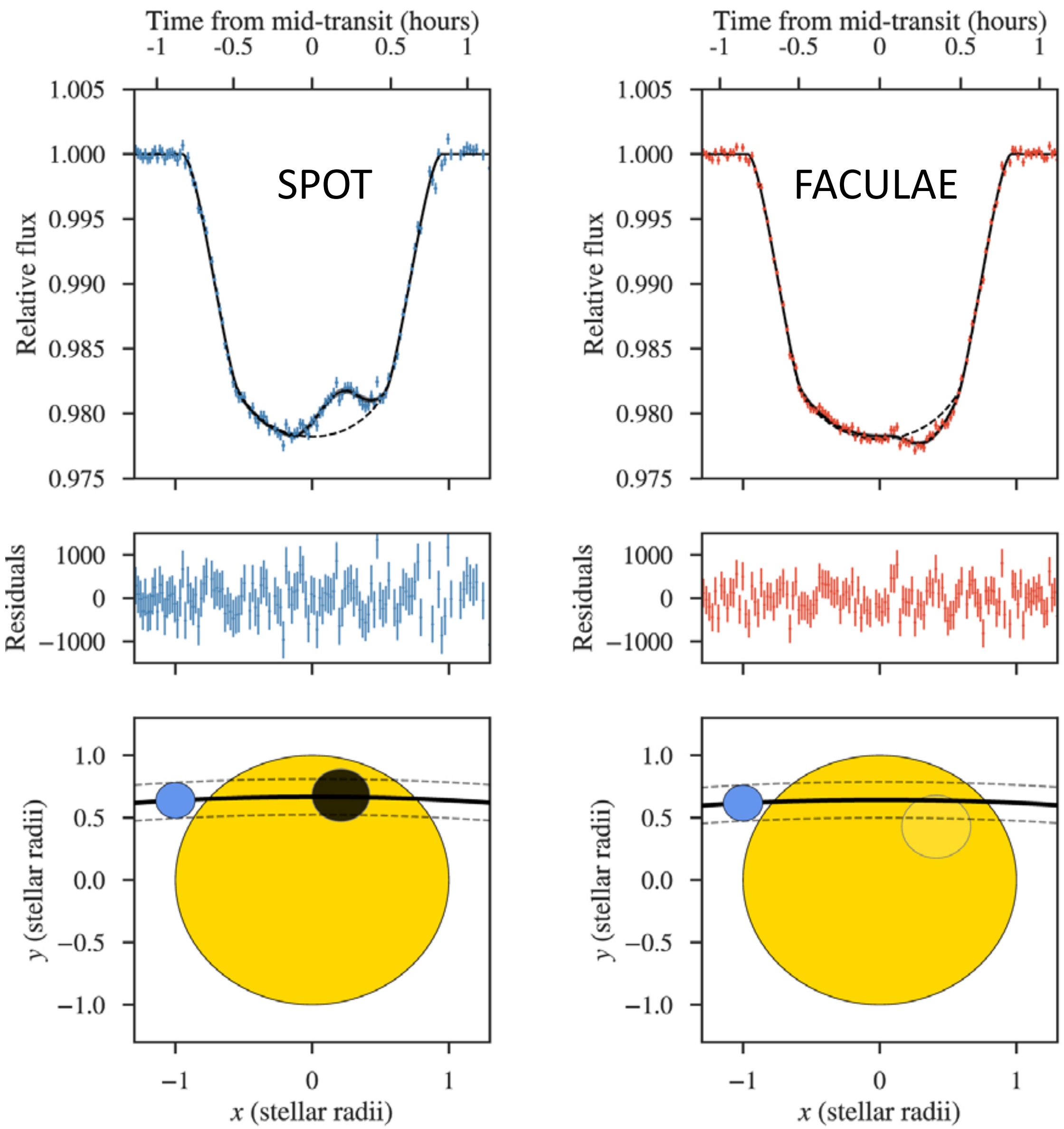
$$Transit\ depth = \frac{F_{out} - F_{in}}{F_{out}} = \left(\frac{r_{pla}}{R_{star}}\right)^2$$

- F_{out} = reference, supposed to be the star with no spot of facula / different level + variability during transit => strong impact on transit depth
- Photometric variation ~ a few 100 ppm - a few %
- Suggestion to use unaffected F_{out} but level unknown

Occulted spots and faculae

- Produce bumps in the transit LCs
  - If many structures + noise => distortions in the LCs that may be difficult to identify (Ballerini+12,Czesla+09,Silva-Valio+10)

- Ex of Corot2b: if assume only dark spots, radius may be overestimated by up to 3% (but less if faculae present, Bruno+16)
- Very interesting for stellar physics: can lift degeneracies
  - Latitude
  - Longitude
  - size & temperature



Espinoza+19
WASP-19b

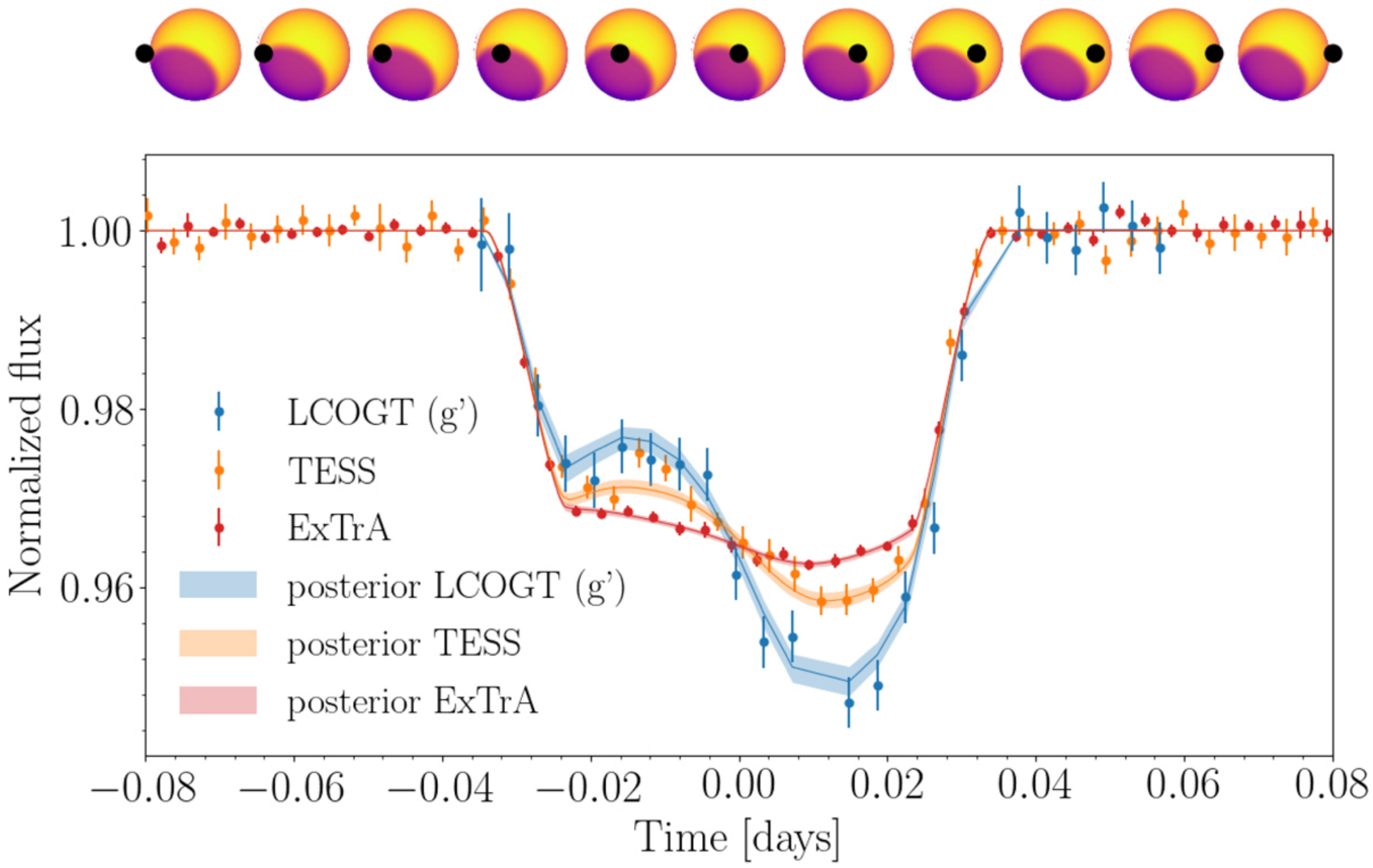
Another example with a very large polar spot

Almenara+22
TOI-3884b

5-min binned LCs

Strong chromatic effects

- TESS 0.6-1 µm
- ExTrA 0.88-1.55 µm
- LCOGT ~0.464 µm (*g*′)



Correction methods: photometric transits

Un-occulted spots and faculae

- Spot/faculae modelling (without the transit) => subtraction (fast)
- GP modelling (kernel rotational modulation) => subtraction (Haywood+14 and later works) (more time consuming)
- Simultaneous modelling of spot/faculae+transit (Bruno+16)

Occulted spots and faculae

- Need specific in-transit spot modelling (e.g. Silva-Valio+08 and more recent works)

=> + stellar results on sizes and contrasts

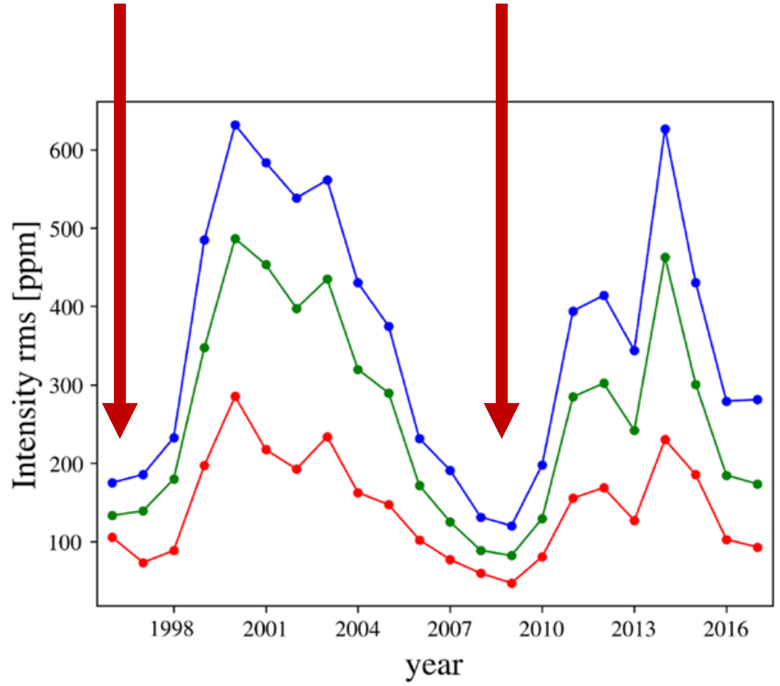
Warning about spot modelling = strong degeneracie, unspotted level can not be determined

Walkowicz+13, Basri+18, Lüger+21

Granulation

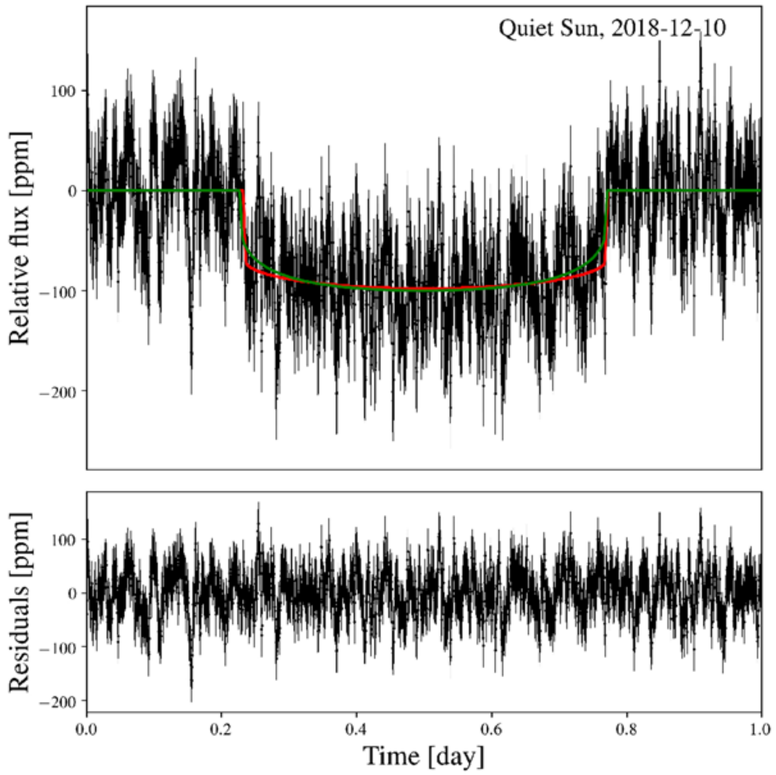
- First estimation led to small impact Chiavassa+17
  - MHD simulation of granulation + paving of the surface
  - Hot Jupiter, Hot Neptune, terrestrial planet
  - Photometric variability 1-16 ppm a bit low compared to the Sun
  - Larger impact on radius for G compared to K : 0.9% and 0.45%
  - Larger in the visible
- Sulis+20 => stronger impact, up to 10%
  - Based on solar observation + MHD simulations
- => included in error budget (CHEOPS, PLATO…)

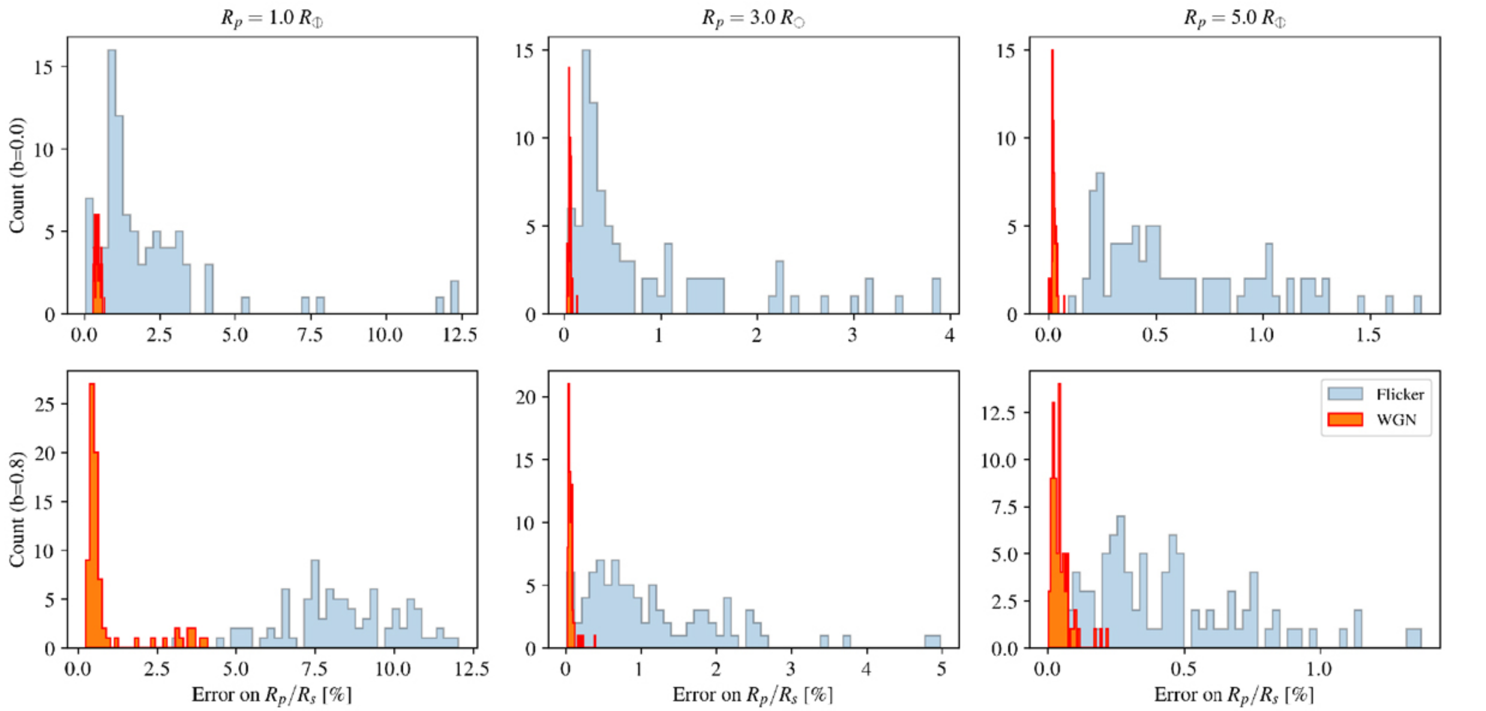
Solar minima



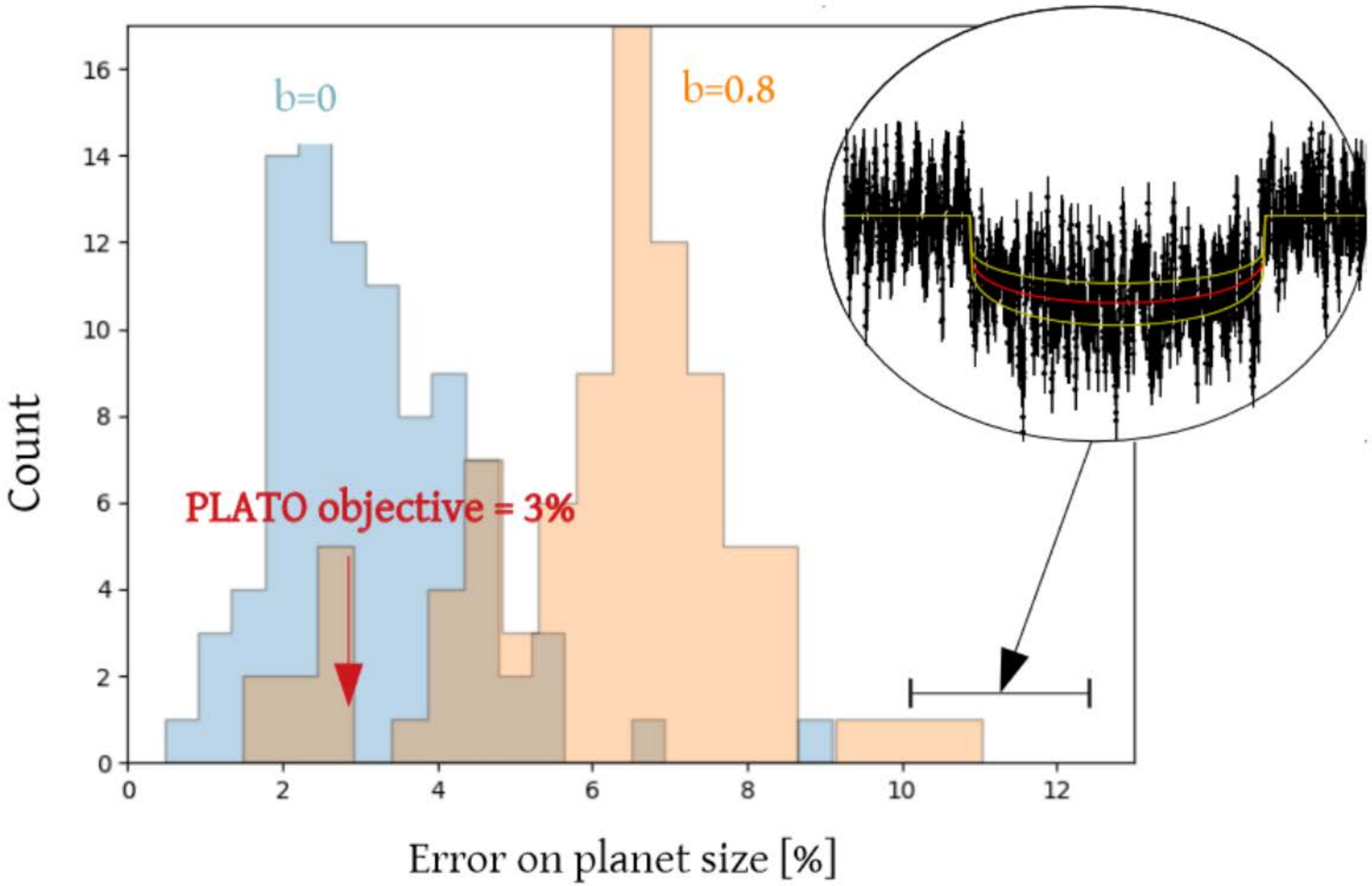
Sulis+20
VIRGO/SOHO: red, green and blue channels

Eart-like transit





Sulis+20



b=0
b=0.8
PLATO objective = 3%
Count
Error on planet size [%]
0
2
4
6
8
10
12
14
16

Sulis+20

Effect on atmosphere characterisation: transmission spectroscopy

Extension of the photometric transit => function of wavelength (+time)
- Like detection: can hide or mimic planetary signal
- Can dominate over planetary absorption features for terrestrial planets

Wide range of wavelengths
- HST, Spitzer, various ground-based telescopes, JWST (ARIEL)
- Mostly for giant planets => towards rocky planets

Main processes
- Spots, faculae
- Granulation
- Flares

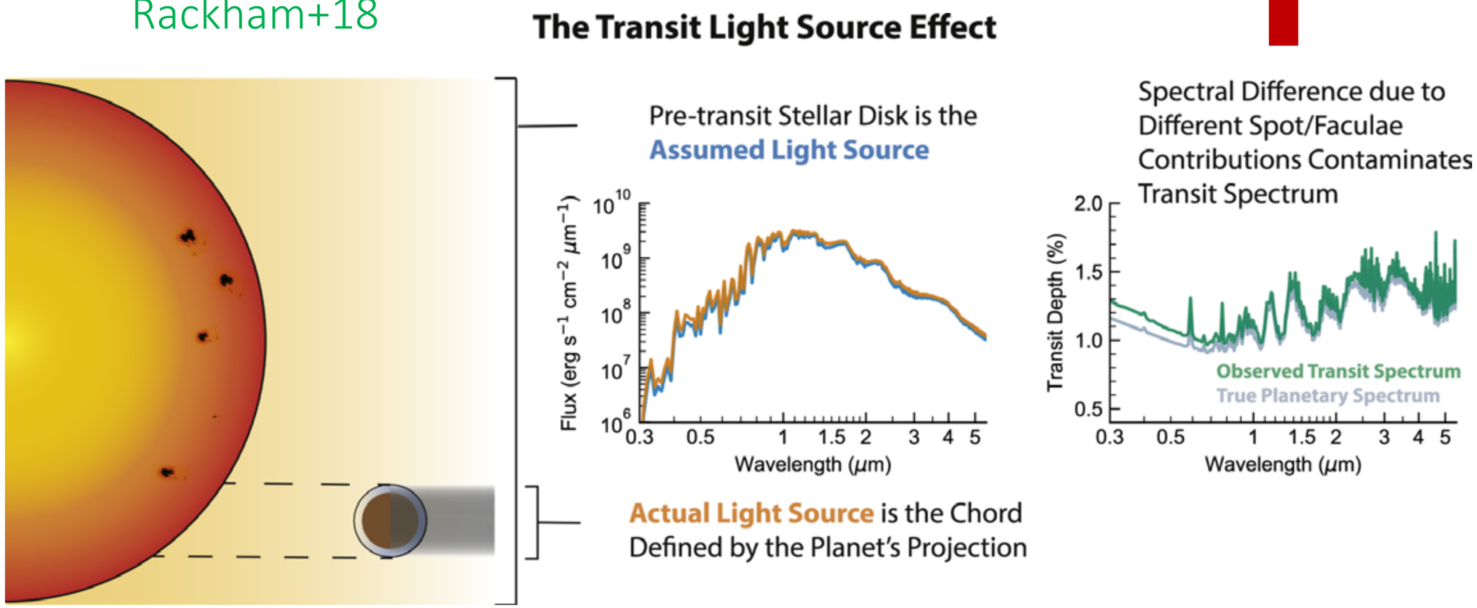
Rackam+18 (M dwarfs) and Rackham+19 (FGK) for thorough analysis; Pont+08, Sing+11

Rackham+23 : Study Analysis Group 21 (SAG21) of NASA's Exoplanet Exploration Program Analysis Group (ExoPAG)

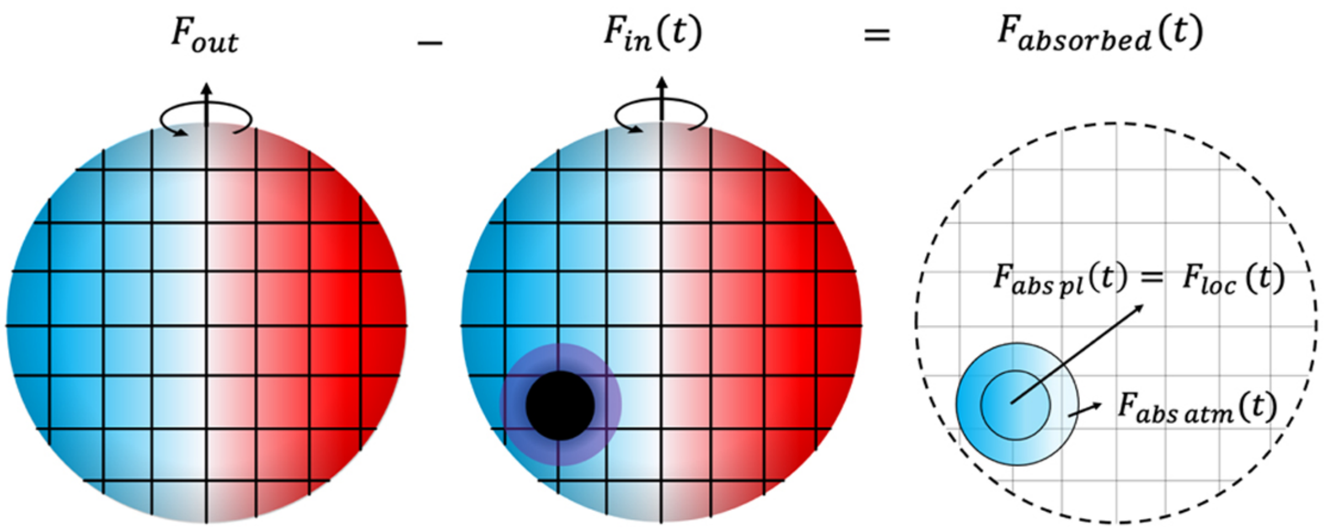
Contrast vs λ
Spectral features

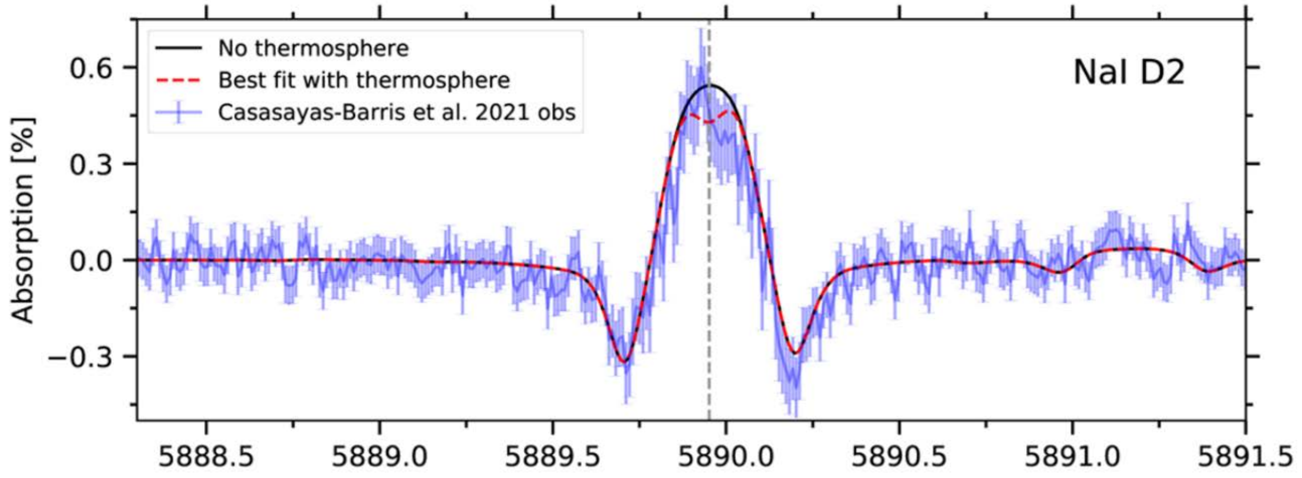
$$D_{\lambda,\mathrm{obs}} = \frac{D_\lambda}{1 - f_{\mathrm{het}}\left(1 - \frac{F_{\lambda,\mathrm{het}}}{F_{\lambda,\mathrm{phot}}}\right)},$$

Rackham+18



Even with no structures: potential impact of rotation (fast rotators) + CLV (slow rotators)





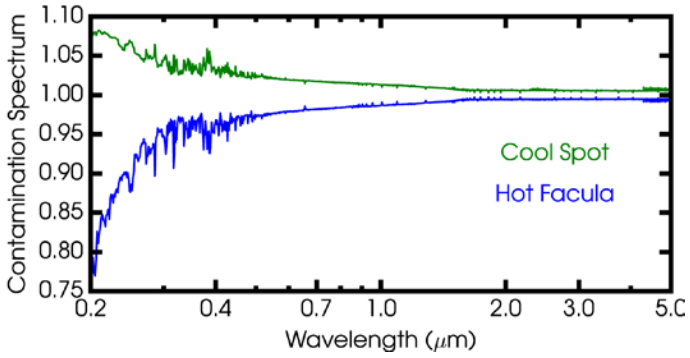
Dethier&Bourrier22
ESPRESSO

HD 209458 b computed with the out-of-transit spectrum as a function of the wavelength in the planetary rest frame with and without sodium atmosphere

Unocculted features

Pinhas+18
T contrast 300K, f=10%
unocculted

- Contrast depends on λ
- Unocculted spots
  - positive features in transmission spectra that may be mistaken for evidence of absorption or scattering in the exoplanet atmosphere.
- Unocculted faculae
  - negative features, which can mask genuine spectral features originating in the exoplanet atmosphere
- Flare => also bumps as occulted features (Lim+23 on TRAPPIST-1)
- Granulation:
  - Adds noise to the light curves
  - Different granulation realisations between full disk and occulted area



Spectral features, ex. H_2O present in sunspots at T<3000K (Wallace+95, Wöhl71), can mimic water absorption at ~1.4 m and 2.3 m (Wakeford+19)
See also TiO (Neff+95) and other molecules metal hybrides, oxides, CNO-based molecules (Berdyugina05,11 ; Cauley+18, Saba+24)

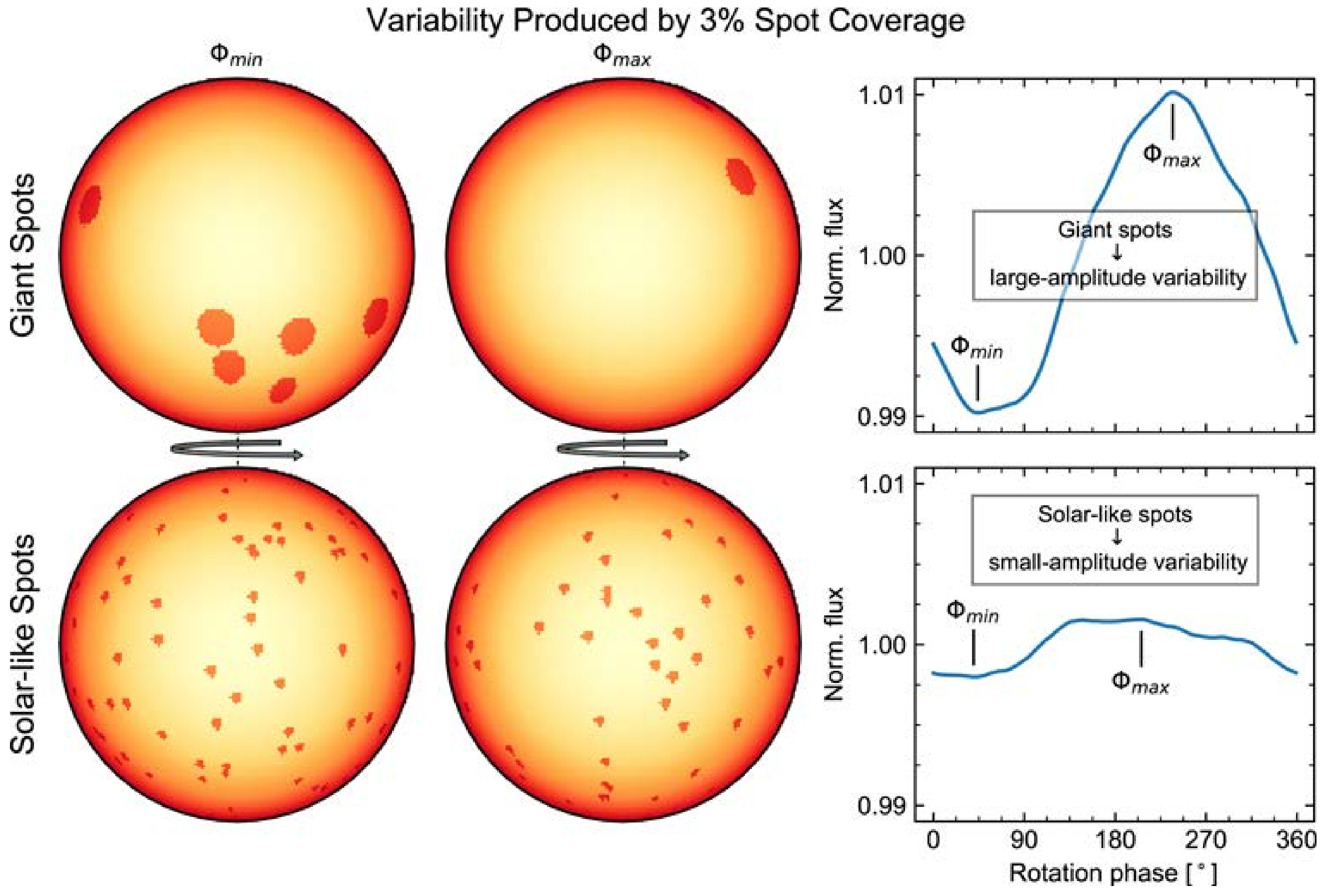
Forward modelling for M dwarfs

Rackham+18

Model with giant spot or multiple small spots for a given flux variability
Without or with faculae (ratio~10)
Based on PHOENIX models, neglecting impact of magnetic field or limb distance

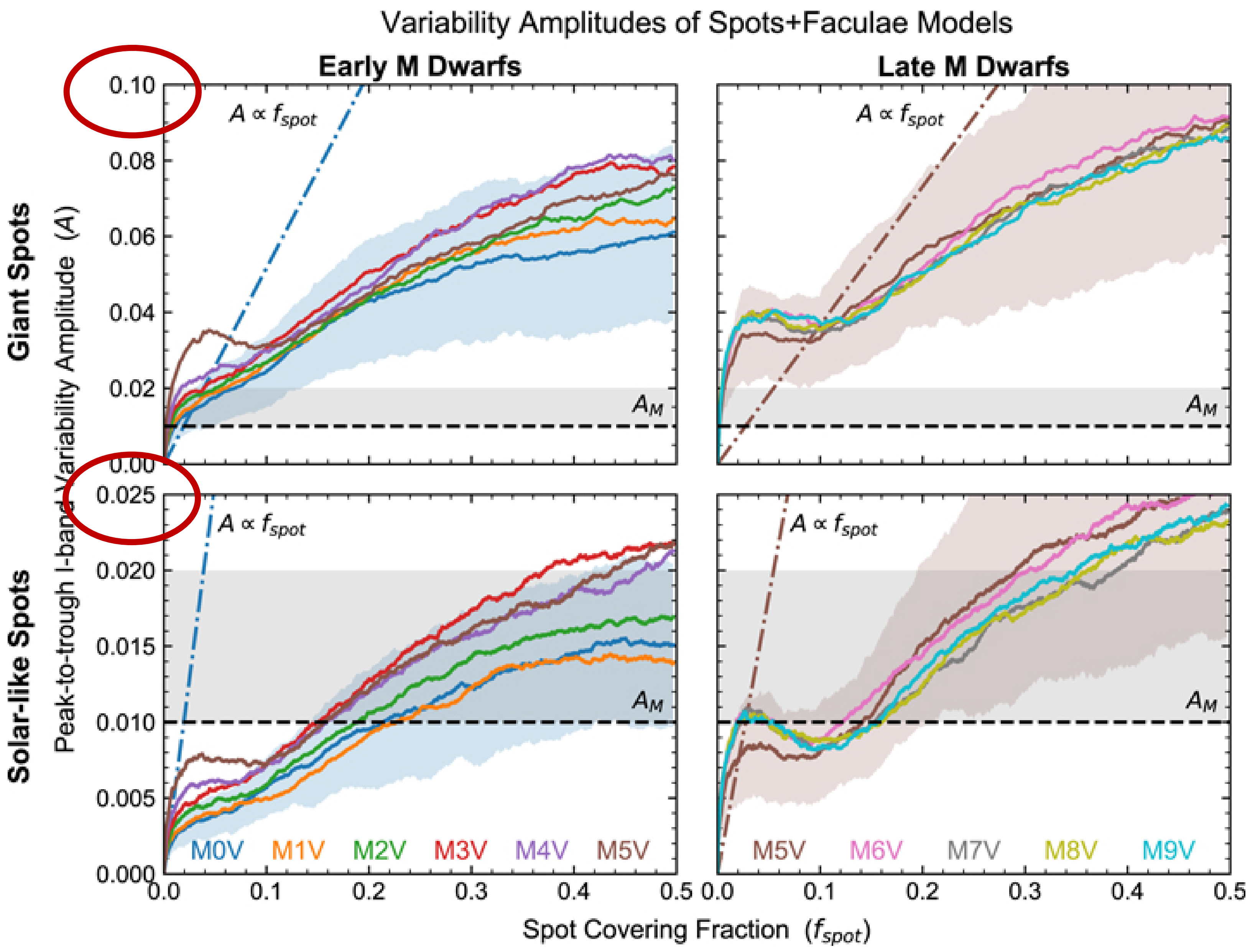
For the same fspot

- variability depends on size
- variability not affected by constant level of structures spread everywhere (axisymetric component does not affect variability but will affect spectra!)



Assuming linear relation between coverage and amplitude of variability = poor approximation

Strong dispersion (not a one-to-one relation)



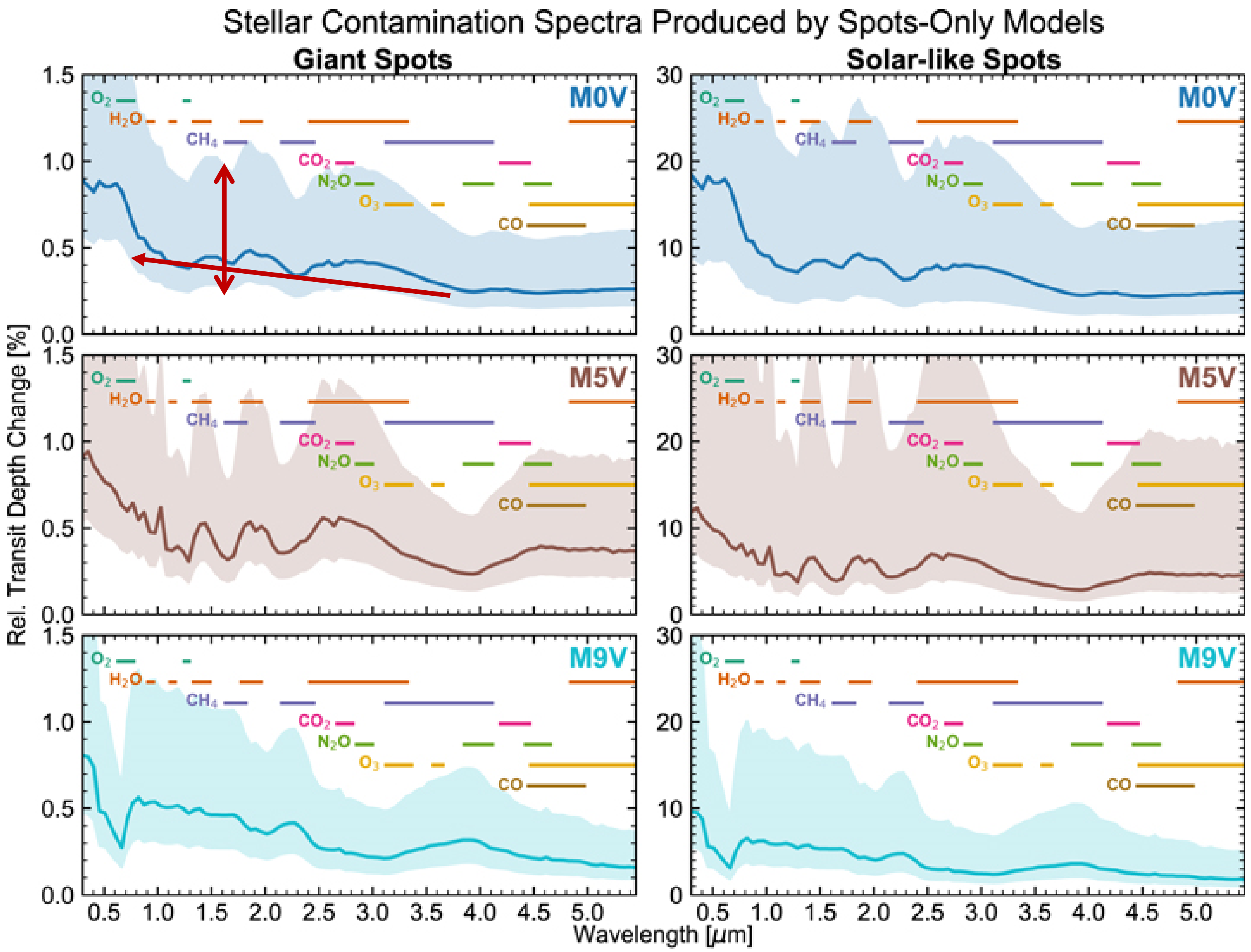
Rackham+18

Impact of plage addition: small plateau at low fspot

Rackham+18

Increase in transit depth largest at low λ
Impact molecular bands

Spot size (for a given observed variability amplitude) has a strong impact: below <% for giant spots, up to 30% for small (more numerous) spots
Solar-like spots => increase of transit depth > expected for exoplanet features



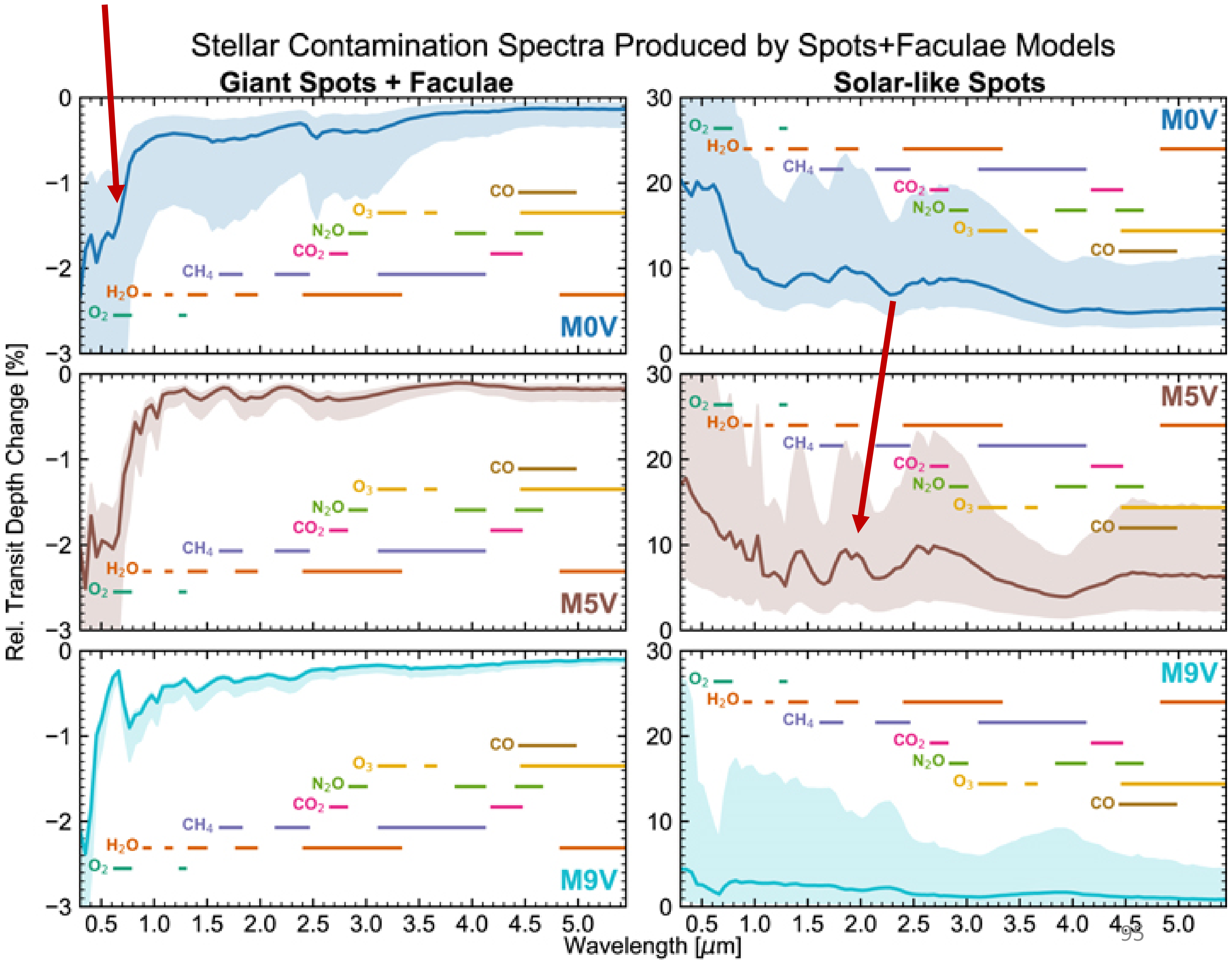
Rackham+18

Faculae not well constrain => large range of possibility expected
For a given variability amplitude, adding faculae means larger fspot

Large faculae coverage => limit on the assumptions, and prevent masking crossing

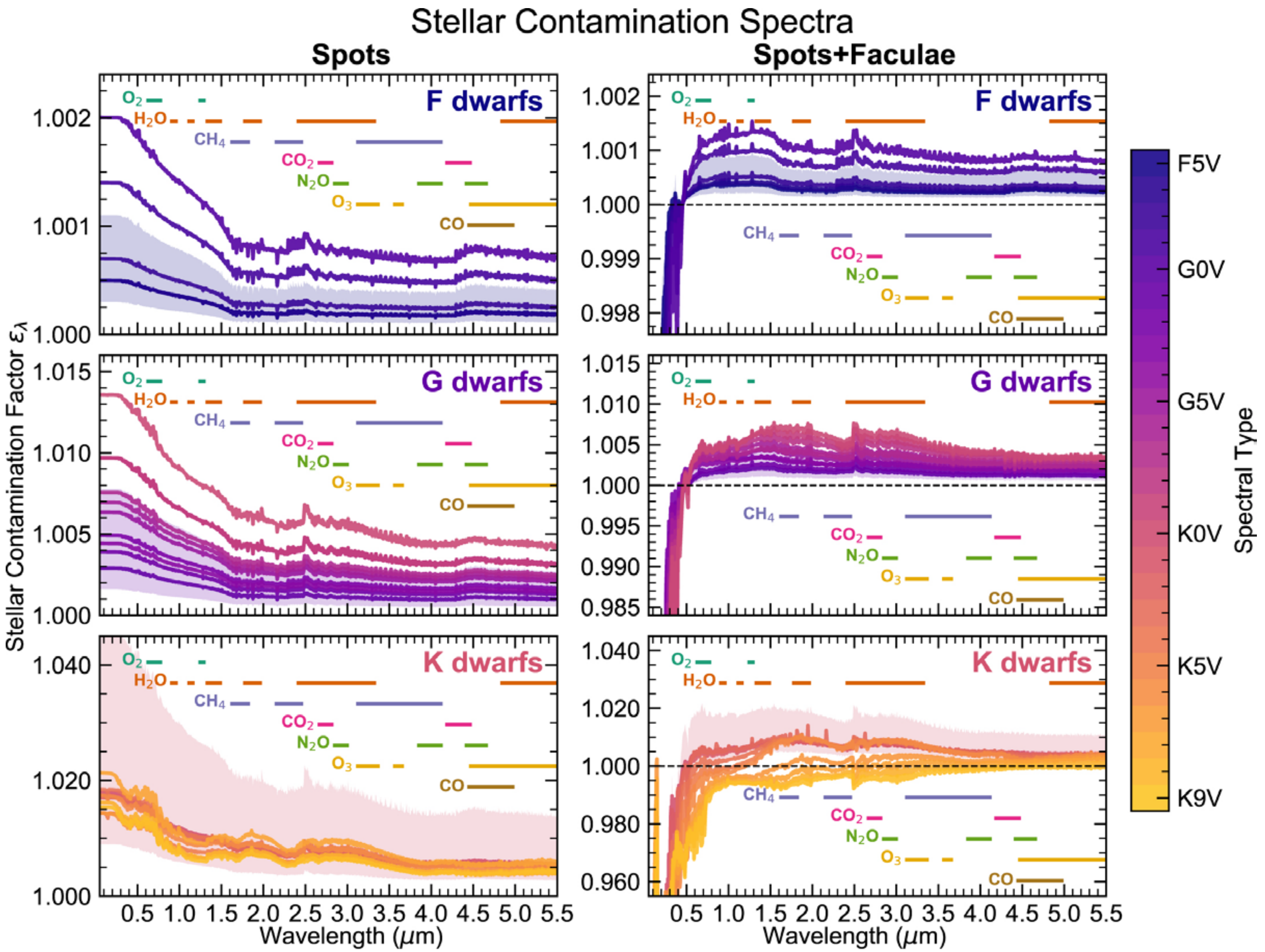
Can mask planetary signal

Can mimic planetary signal



FGK stars

Rackham+19



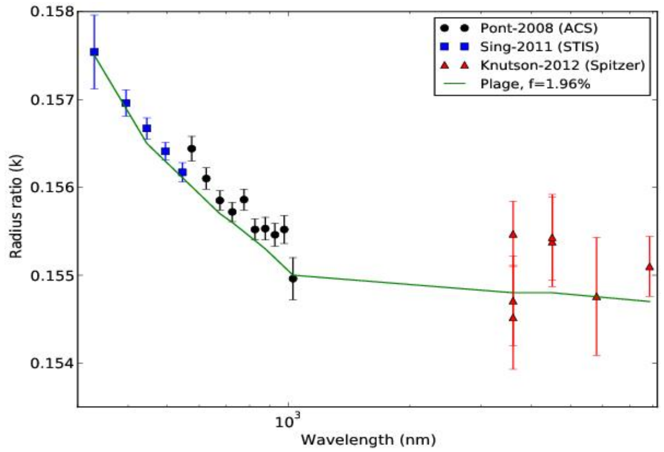
Occultation

Wavelength dependence of the contrast

- Can mimic broadband characteristics of planetary atmospheres
- Risk of interpreting slope versus λ as Rayleigh scattering

Some difficulties

- More complicated if multiple transits (e.g., Czesla et al. 2009; Désert et al. 2011a; Morris et al. 2017)
- Interplay with limb-darkening
- Faculae have low contrast => more difficult to extract from the noise
- Degeneracies spots/faculae
- Presence of multiple structures
- Many unknown properties (umbra/penumbra ratio for ex.)



Oshagh+14

Mitigating solutions

Removing of affected points (occulted features) => not satisfactory

« Direct » correction of LCs (Sing+11, Berta+11)

- Warning: assume max(LC)=unspotted level=> wrong assumption

Use of out of transit spectra

Toward retrieval done simultaneously with spot/facula contribution = 3 additional parameters (filling factor, Tphot, Tstructures) e.g. Pinhas+18, Bruno+20, Rathcke+21, Fournier-Tondreau+24, Thompson+24, ...

Combination of removing+Gpfit+detrending with activity indicators to remove flare signal (Lim+23)

See list of codes slide 57

Limitations:

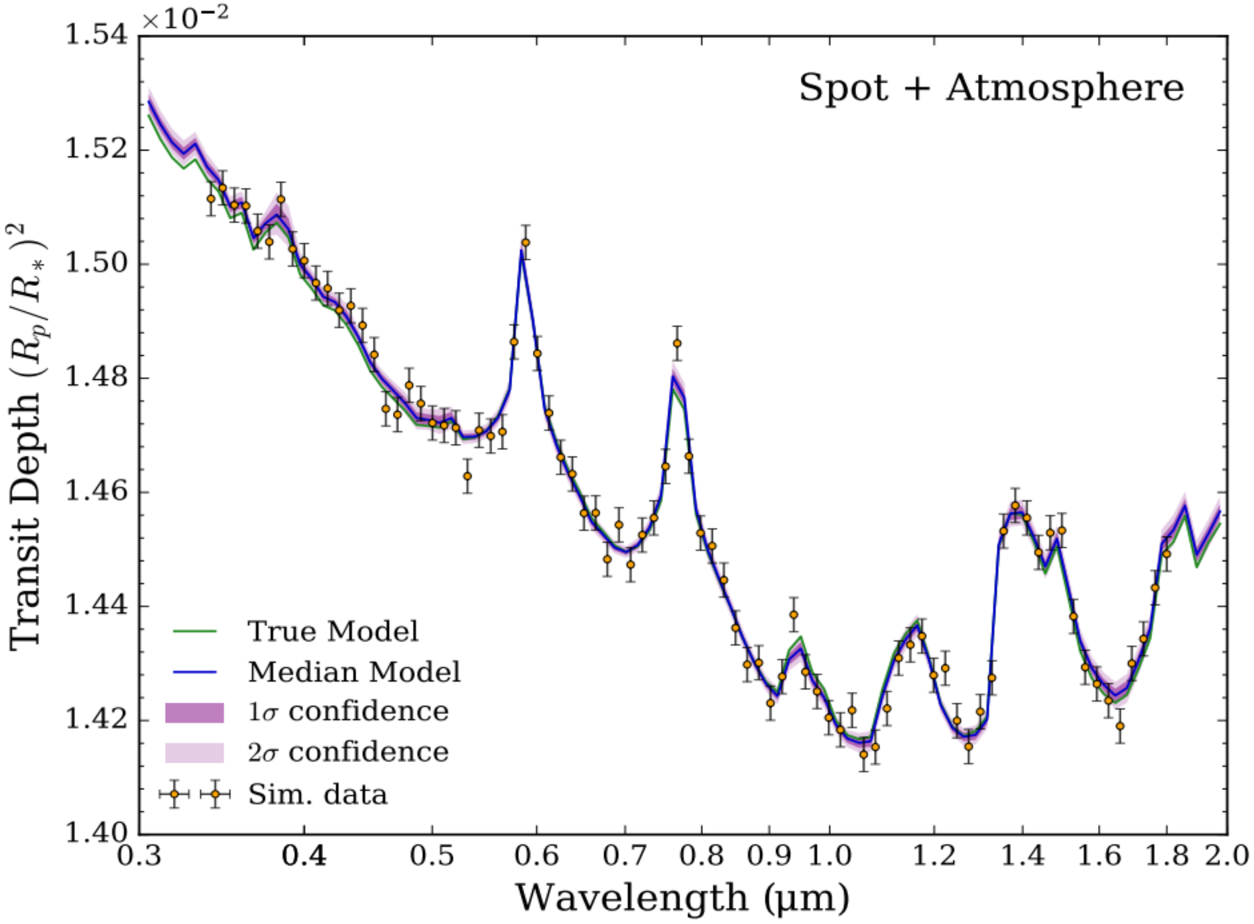
- strong degeneracies on the distribution of the features on the surface
- knowledge of stellar and spot/facula models

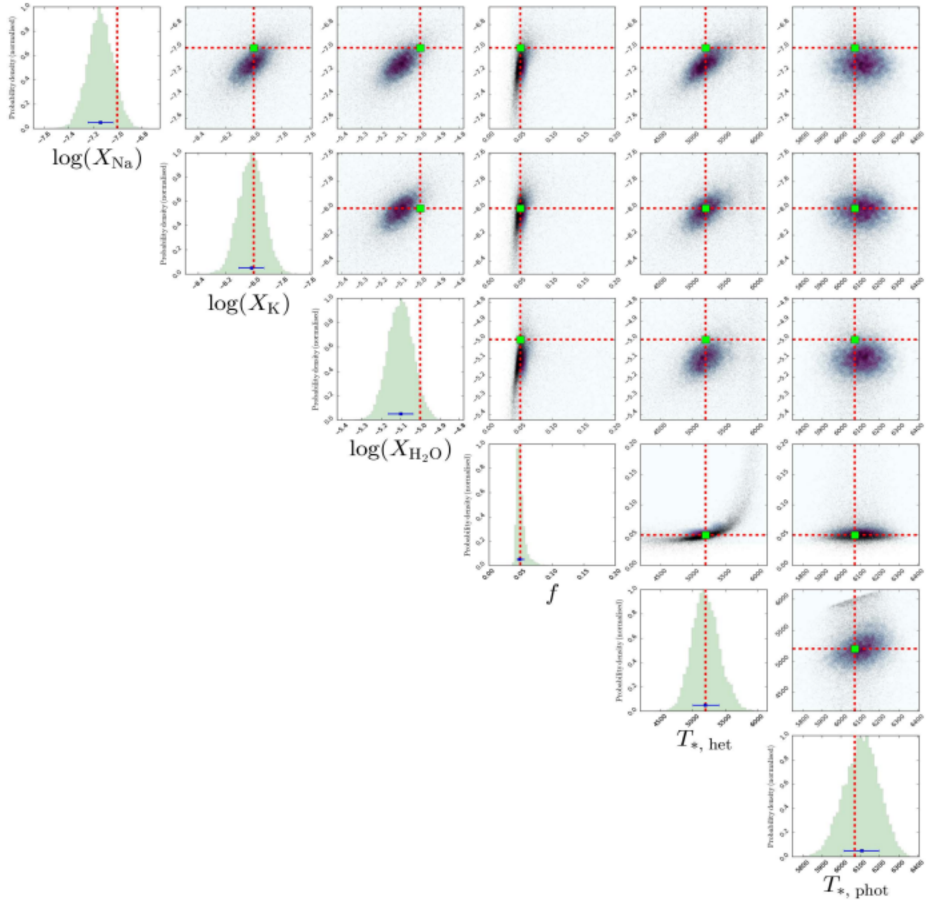
Rackham+18

Het=heterogeneaous, spots and/or faculae

Rackham+22

Simulated data with spot ; fit with atmosphere+spot => good retrieval of the parameters

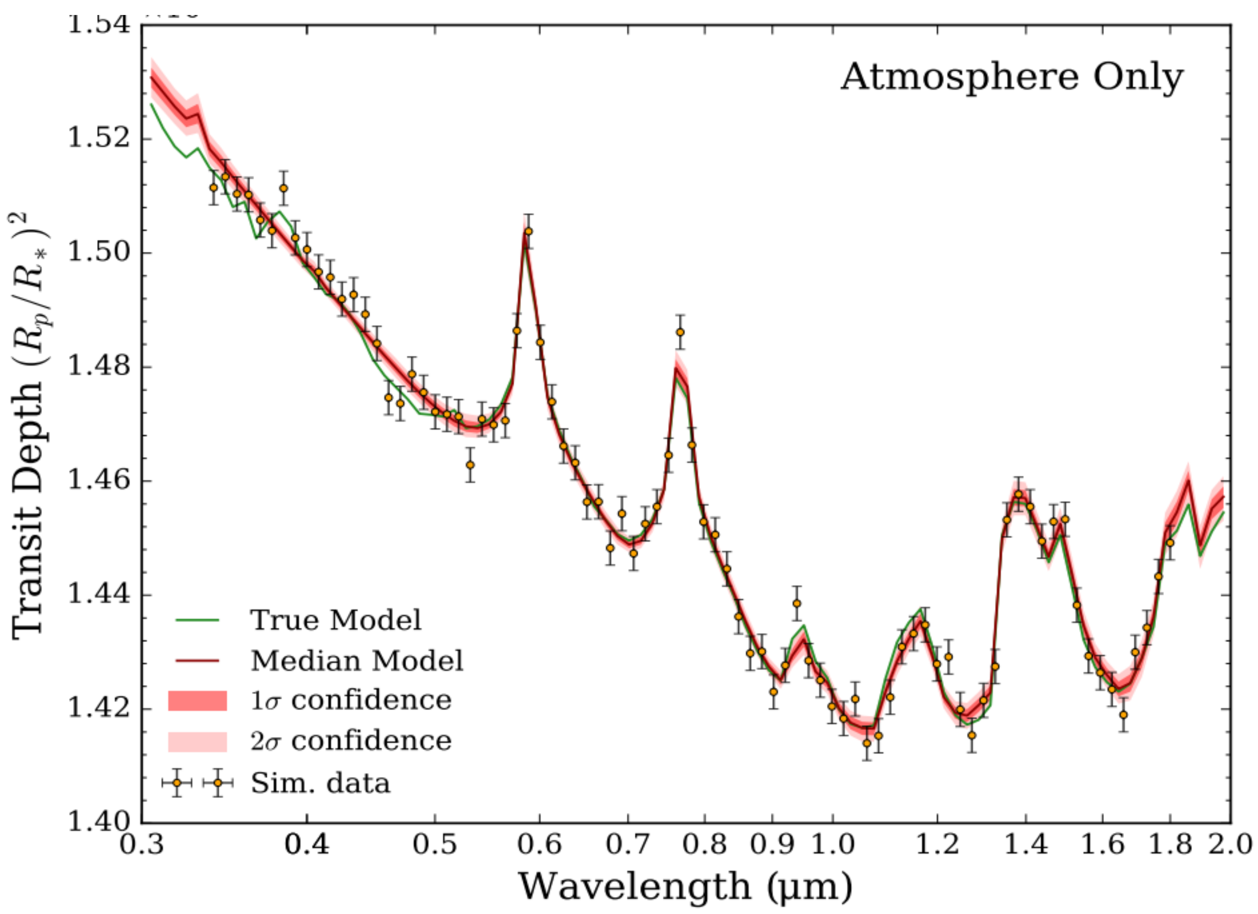


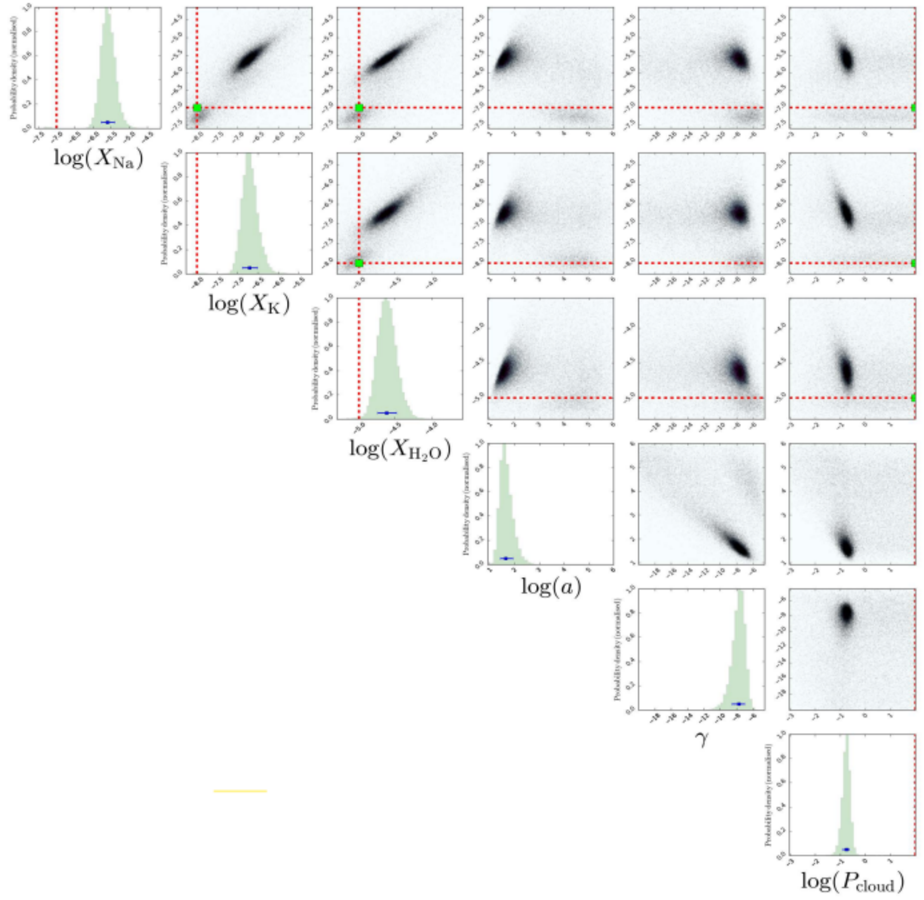


Rackham+22

fit with atmosphere only => equally good fit, wrong parameters, add haze+cloud deck to compensate

Biased on abundances by 3-5 sigma+spot (Na, K, H2O)





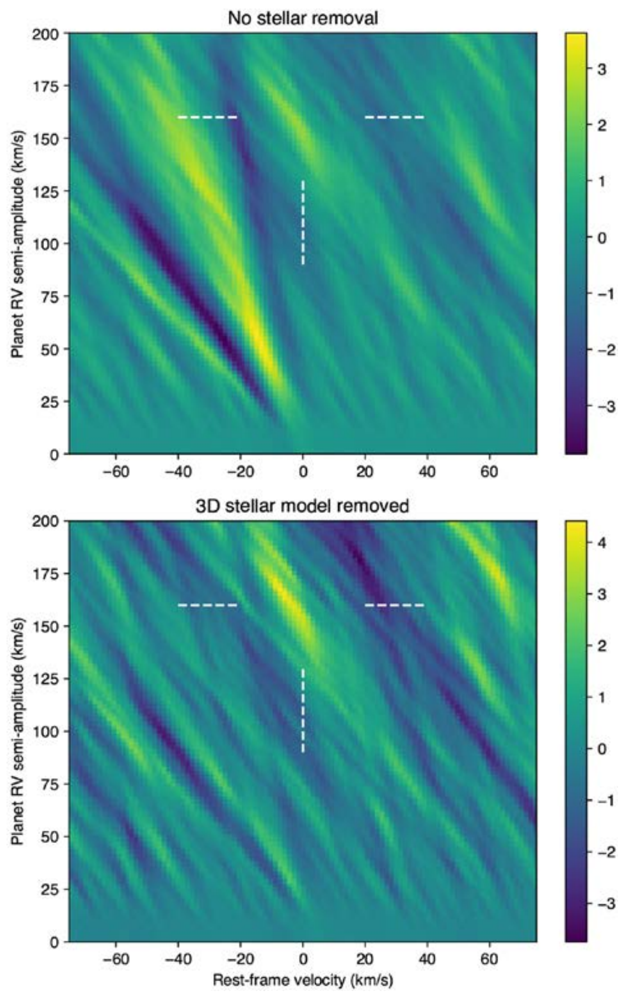
Impact of granulation

High resolution spectra => resolved lines => cross-correlation techniques for transmission and emission spectroscopy

Chiavassa&Brogi19

- Use of 3D HD simulation of stellar granulation + IR transfer
- Temporally and averaged intensity realistic stellar spectrum (+ version to model changes during transit)
- Removal of the stellar spectrum
- => Improvment of the SNR on the detection

- See also Maimone+22



Chiavassa&Brogi19
HD189733b, CO detection

Effect on high precision astrometry

To consider mostly for future missions (e.g. THEIA)

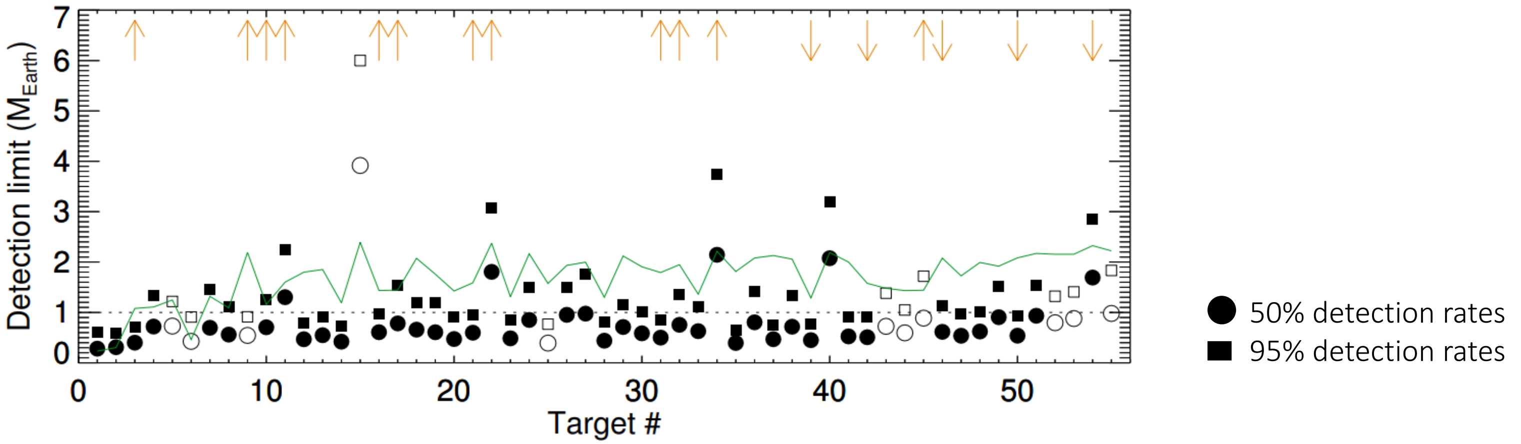
- Not a concern for very massive planets (Gaia)

Dominated by impact of spot and faculae contrasts

- Displacement of the photocenter

Simulations

- Earlier works on a few spots only
- Solar case as a reference => Makarov+10, Lagrange+11
- Recent extension to other stars, with realistic complex activity patterns: blind tests for large grid of parameters for stars@10pc (Meunier&Lagrange 20), new detection limits for the THEIA targets (Meunier&Lagrange 22) => not problematic to detect Earth-like planet



Conclusion: a few messages

Impact on RV

- Many complex processes, highly stochastic, always present, all time scales
- Strong diversity, poorly constrained => need better knowledge of the stellar physics for best use of a variety of activity indicators
- Usually sparse sampling in RV & bad phase coverage => need good coverage
- Superposed on other contributions: other planets - known or unknown, instrumental… (sophisticated methods need very good SNR)
- Still lot’s to do => stellar physics, methods, control of the residuals

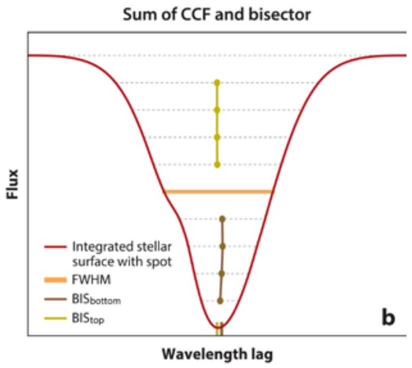
Impact on photometry (transit, atmospheres)

- Link with RVs (PLATO follow-up)
- Warning about fine effects not often considered (granulation) for very low mass planets
- Strong augmentation of this issue in exoplanet atmosphere studies

Impact on high precision astrometry

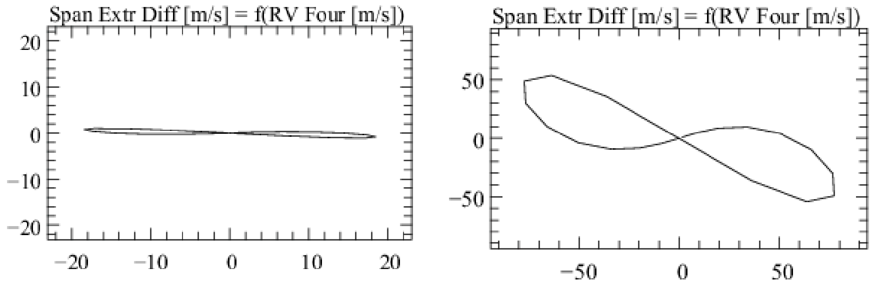
- Stellar physics not a limitation

Simple spot simulations



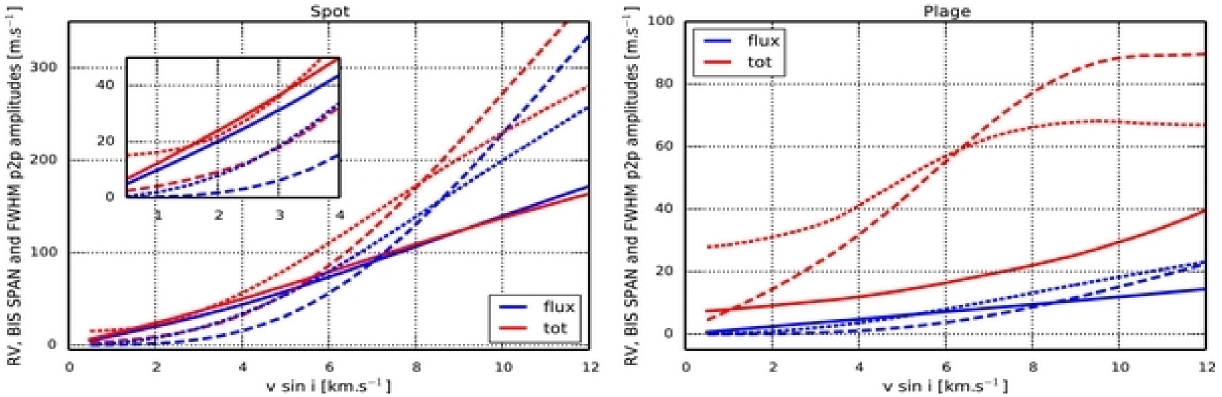
Hara&Ford23

- Desort+07
  - BIS not changed if *v* sin i < spectral resolution
  - Regimes where RV significant, BIS not significant
  - Scaling laws depends on instrument & spectral type
  - Strong impact of latitude and inclination
  - Possibility to use chromatic effects
- Boisse+12
  - Similar conclusions /Desort+07 (v sin i, ff)
  - + impact latitude, center-to-limb darkening
  - Comparison with observations
- Dumusque+14
  - Addition plages & convective blueshift inhibition, more realistic limb-darkening
  - Impact of spectral resolution
  - Use of spot and quiet Sun spectra as inputs

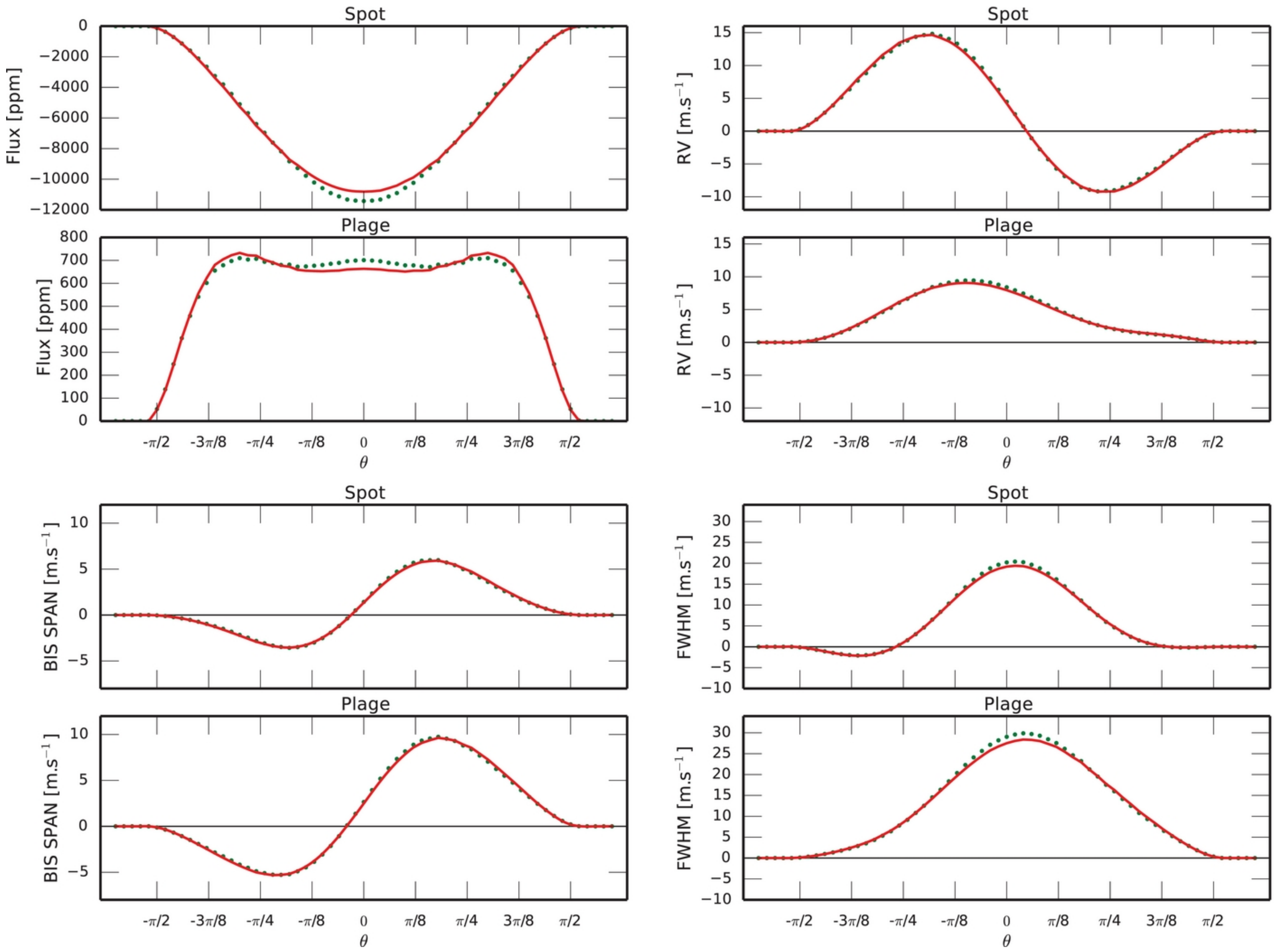


v sini = 2 & 7 km/s

Desort+07



Dumusque+14


Spot
Plage
Flux [ppm]
RV [m.s^{-1}]
BIS SPAN [m.s^{-1}]
FWHM [m.s^{-1}]
-π/2 -3π/8 -π/4 -π/8 0 π/8 π/4 3π/8 π/2
θ

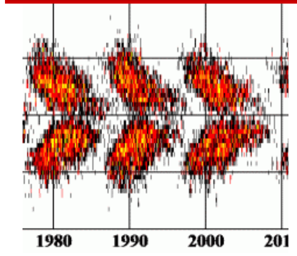
Dumusque+14

Simulation parameters from empirical laws

List of structures vs. t

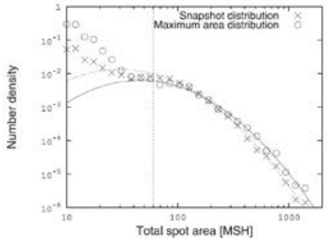
Consistent description *spots+plages+ network*

Spatio-temporal distribution



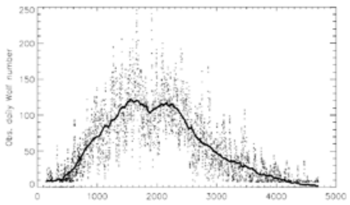
Butterfly diagram & maximum latitude, active longitudes

Size distributions …



Size, decay, Spot/plage size ratio, Plage to network ratio

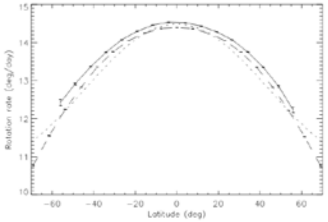
Long-term variability



Cycle length, Amplitude, shape

Dynamics

Prot, differential rotation, meridional circulation, diffusion



Time series

RV, Photometry, Astrometry, $\log R'_{HK}$

Contrasts
(Photometry, RV, astrometry)
Spots, plages

Convective blueshift in plages (RV)
Amplitude, attenuation factor

Borgniet+ 15

Simulations structures → RV, photometry

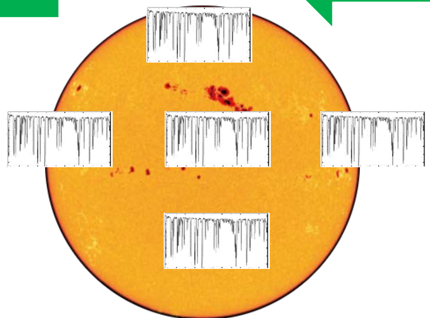
Production of spots → Faculae associated to each spot → (*Decay*) Production of the magnetic betwork

Evolution | *Evolution* | *Evolution*

List of structures (date, latitude, longitude,size)

Version 1 (analytical) :
Filling factor, RV, photometry, astrometry, logR'HK

Mapping



Version 2 (pixels/map)
Filling factor, spectra (=>RV and indicators), photometry, astrometry

Ex. Borgniet+15,Meunier+19

Fitting challenge : Dumusque+16,17

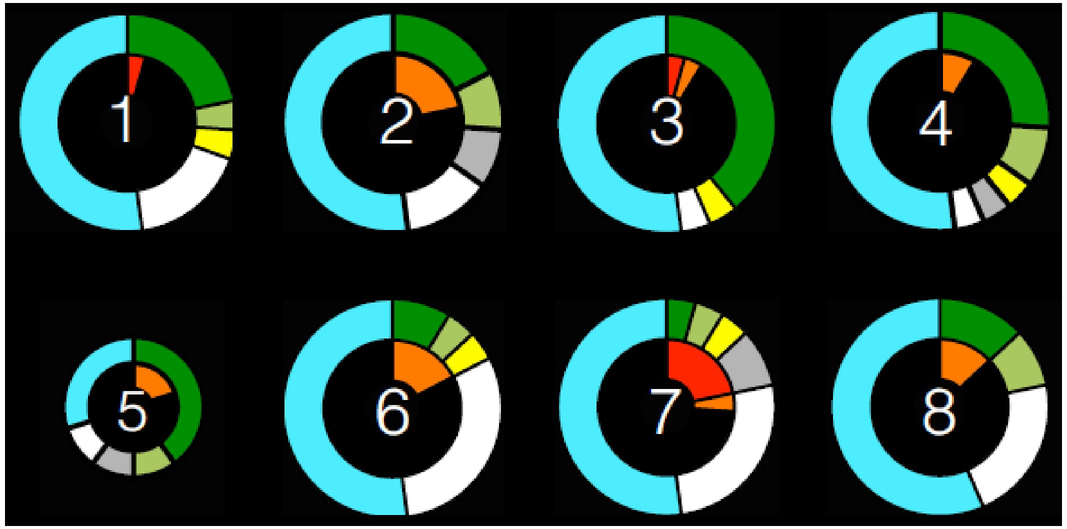
- Use of complex synthetic time series
- Add planet (or not)
- Blind test → analysis by 8 teams
- Focus on exoplanet detectability

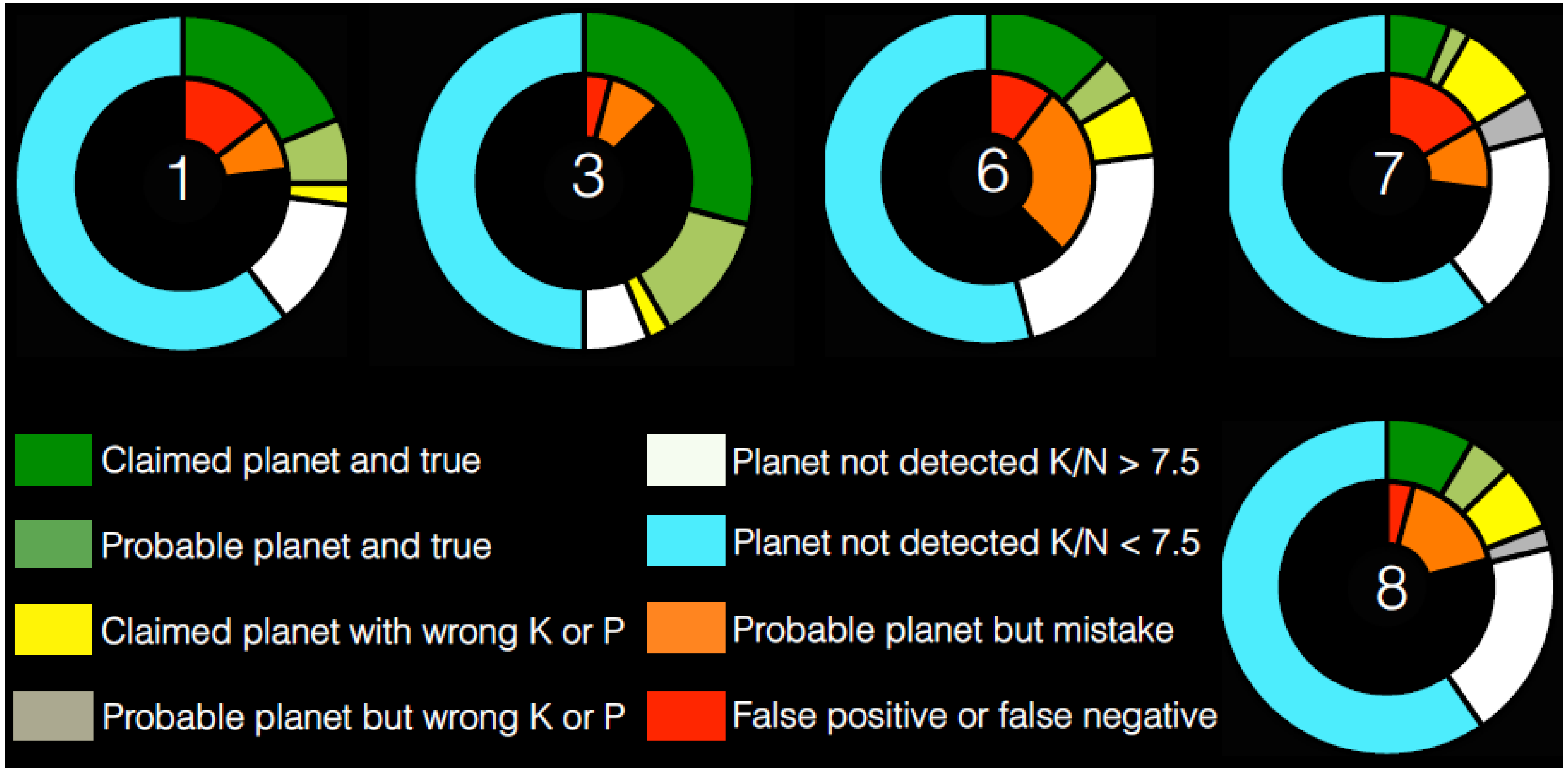
Table 2. Recovery rate of planetary signals detected (dark green, light green, yellow and gray color flags), of publishable planets with correct orbital parameters (dark green and yellow color flags) and of false positives and false negatives (red color flag) for each team.

	Bayesian framework + red-noise models					Other techniques		
	1: Torino	2: Oxford	3: Tuomi	4: Gregory	5: Geneva	6: Hatzes	7: Brera	8: IMCCE
Detected planetary signals $K/N > 7.5$								
5 first systems (total 10)	80% (8)	70% (7)	90% (9)	90% (9)	83% (5/6)	30% (3)	40% (4)	50% (5)
all systems (total 18)	68% (12)	–	83% (15)	–	–	39% (7)	50% (9)	50% (9)
Publishable planetary signals $K/N > 7.5$								
5 first systems (total 10)	50% (5)	40% (4)	90% (9)	70% (7)	67% (4/6)	20% (2)	20% (2)	30% (3)
all systems (total 18)	50% (9)	–	61% (11)	–	–	28% (5)	39% (7)	39% (7)
Detected planetary signals $K/N \leq 7.5$								
5 first systems (total 13)	8% (1)	8% (1)	8% (1)	8% (1)	25% (1/4)	8% (1)	15% (2)	0%
all systems (total 30)	3% (1)	–	20% (6)	–	–	13% (4)	7% (2)	3% (1)
Publishable planetary signals $K/N \leq 7.5$								
5 first systems (total 13)	0%	0%	8% (1)	0%	0%	8% (1)	8% (1)	0%
all systems (total 30)	3% (1)	–	13% (4)	–	–	13% (4)	3% (1)	0%

Notes. Recovery rates between 0 and 33, 33 and 66, and 66 and 100% are highligthed in red, yellow and green, respectively.

Dumusque+17

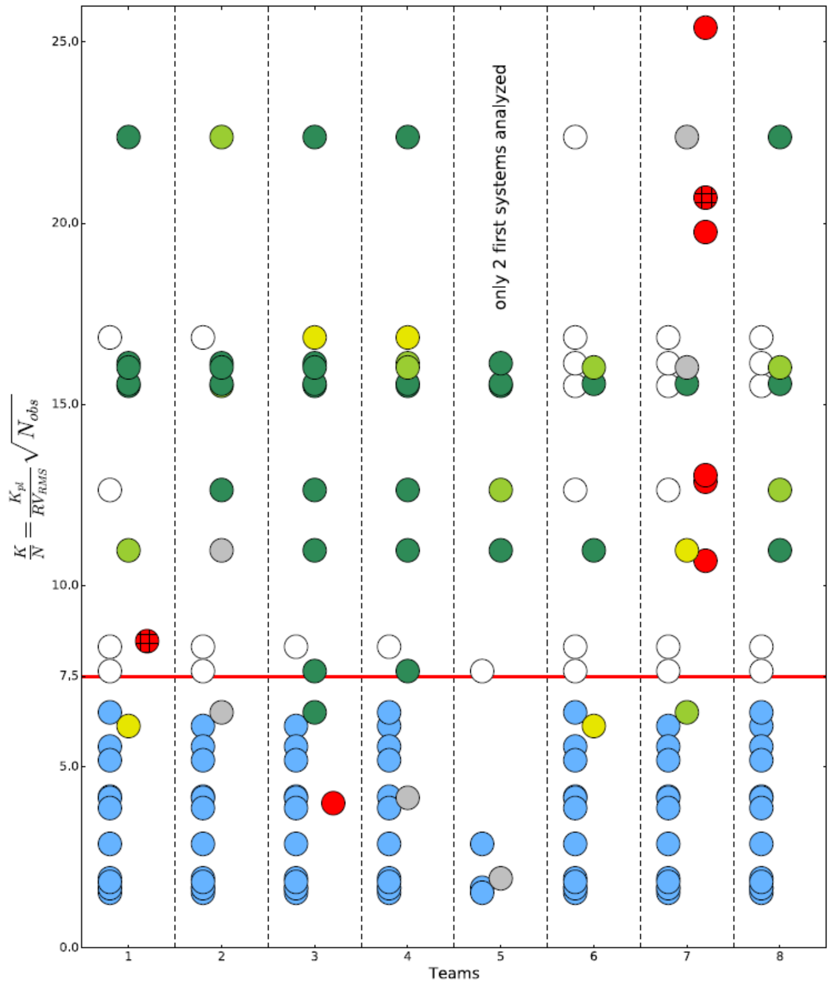

1
2
3
4
5
6
7
8


1
3
6
7
8
Claimed planet and true
Probable planet and true
Claimed planet with wrong K or P
Probable planet but wrong K or P
Planet not detected K/N > 7.5
Planet not detected K/N < 7.5
Probable planet but mistake
False positive or false negative

Fitting challenge : Dumusque+16,17

- Use of complex synthetic time series
- Add planet (or not), several time series
- Blind test → analysis by 8 teams
- Focus on exoplanet detectability
- GPs performed best

- Criterion C=Kpla x $\sqrt{Nobs}$ / RVjitter



Large-scale RV blind tests

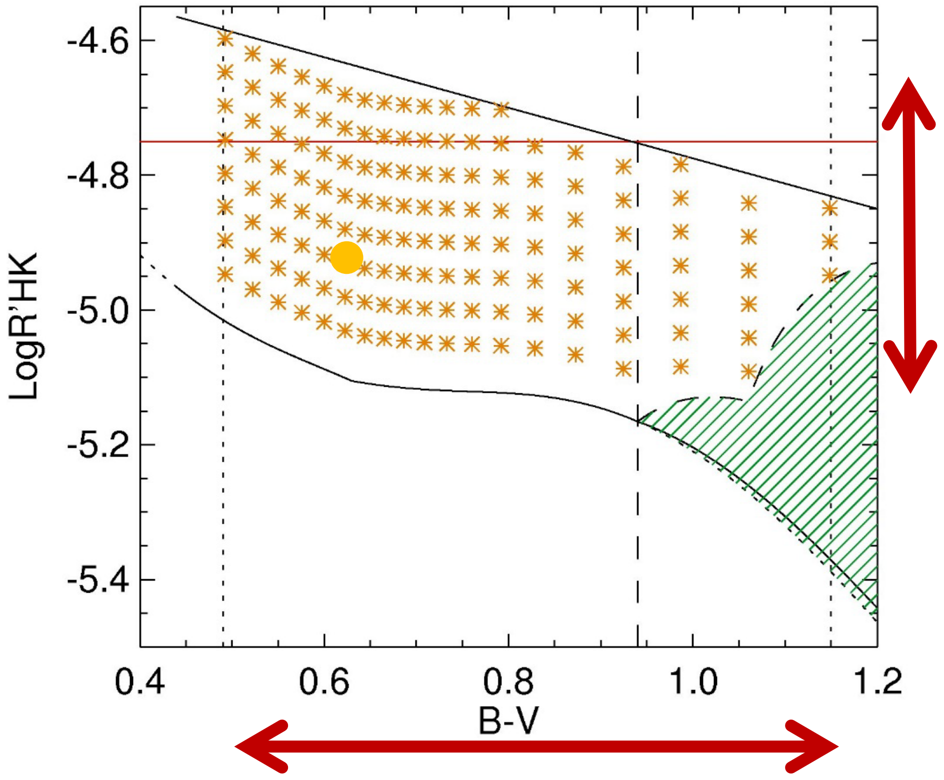
Based on

- Very good knowledge of the Sun
- Scaling based on stellar observations and simulations

Large sets of realistic synthetic time series

- Complex solar-like activity patterns, structure evolution
- All time scales
- **All processes (except meridional circulation)**
- Covering range in spectral types & activity levels
- >11000 synthetic time series x 10 inclinations
- Production of $\log R'_{HK}$, photometry & astrometry

Show the importance of blind tests + need to improve mitigation techniques



F6-K4

Based on published laws
Details in Meunier+ 19

Two types of blind tests

Set-up

- Planet-free synthetic stellar RV time series + photon noise + **planet**
- Temporal sampling
- Model to correct for stellar activity (non-linear function of $\log R'_{HK}$ and cycle phase Meunier+19) → RV only

10 year time series
1000 nights
4 month gap / year
1h average
HARPS-like / VIS

Follow-up of a transit detection

Mass estimation
Uncertainty

Search for planets

Good detection rates
Wrong detection rates
False positive rates