The Star Is the Signal: Taming Stellar Activity to Reveal Sun-Earth Analogues

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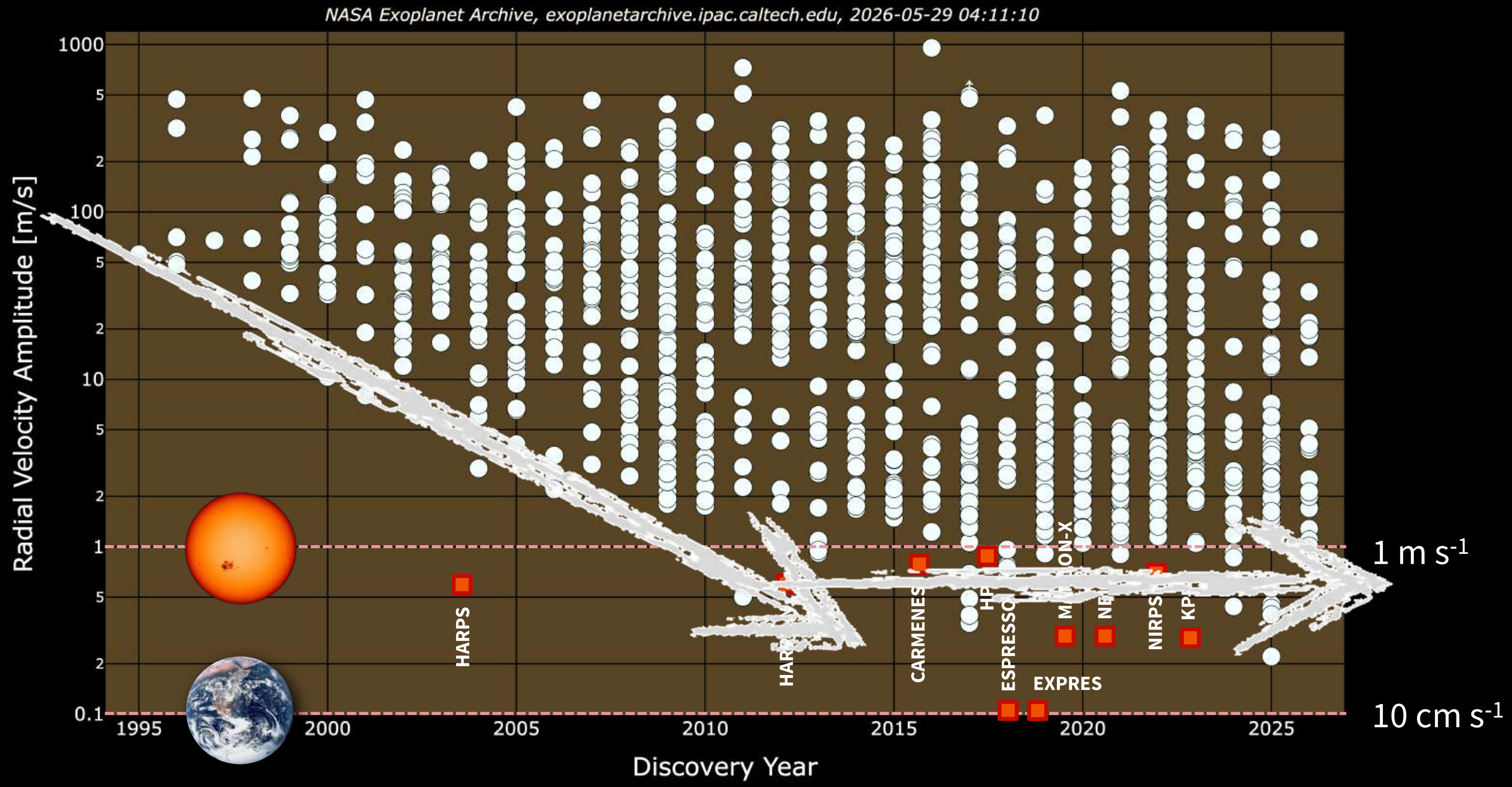
Cool Stars 23, Tokyo, June 2026

Precise radial velocities: exoplanet discoveries

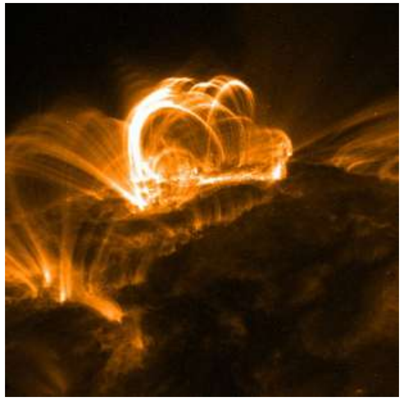
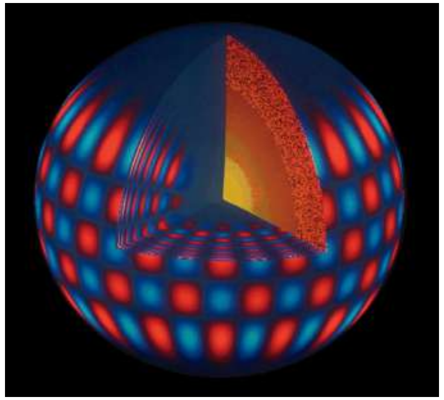
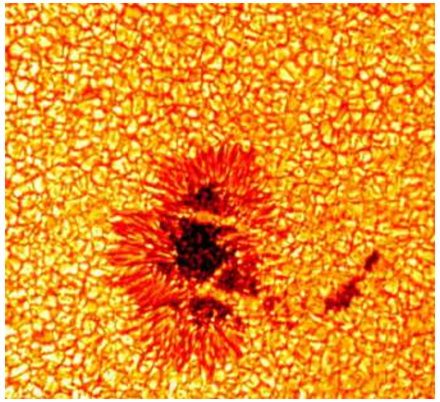
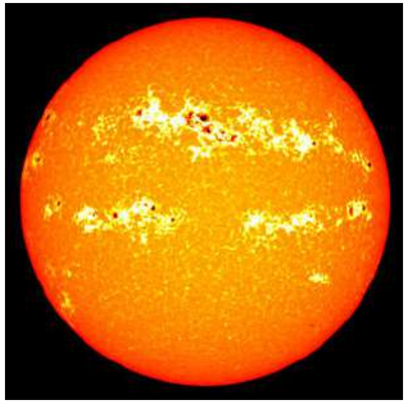
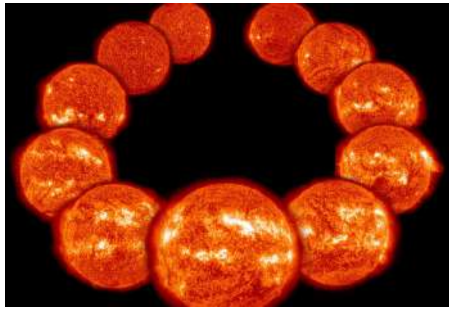


The fundamental limit is no longer instrumental but astrophysical

→ **essential to model and correct out stellar effects**

Stars are not quiet, homogeneous gas spheres...

- Minutes to hours: p-mode oscillations, granulation, flares
- Hours to days: (meso-) supergranulation
- Days to rotation period: active region evolution, differential rotation, spot modulation
- Rotation period to activity cycle: emergence and decay of active regions, meridional flows
- Decades-centuries: activity cycle

Stellar variability is often just seen as a source of "noise"

Solar global RV variability

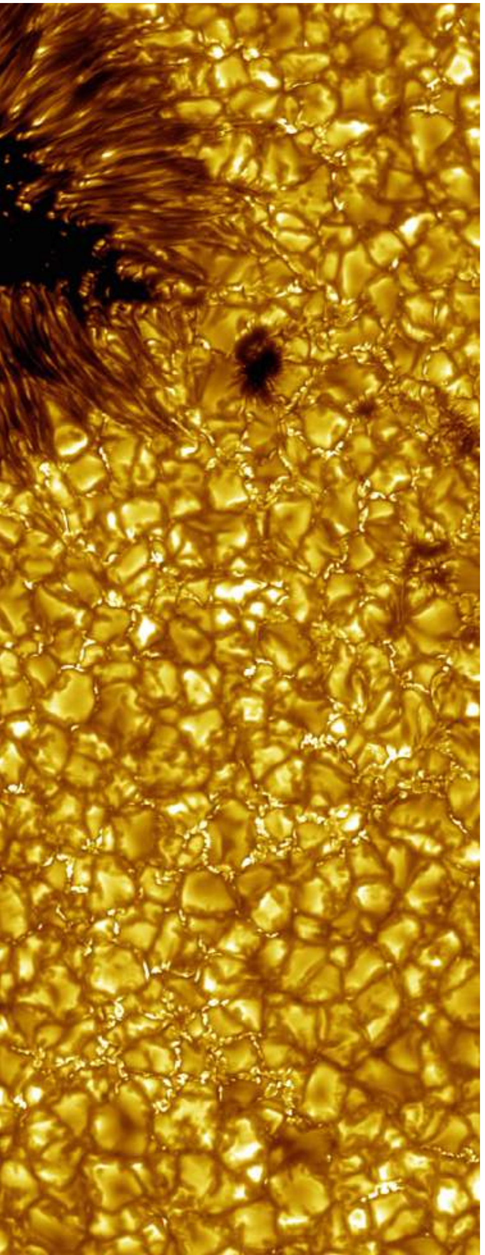
Process	Timescale	Velocity scale	Global RV scatter
p-mode oscillations[1]	5 min	0.1 – 1 km s^{-1}	~0.2 – 0.5 m s^{-1}
Granulation[1]	5 – 15 min	1 – 5 km s^{-1}	~0.3 – 0.5 m s^{-1}
Supergranulation[1]	1 – 2 days	0.3 – 0.5 km s^{-1}	~0.6 – 0.8 m s^{-1}
Magnetic regions[2]	Days – months	Rotation	1 – 5 m s^{-1}
Meridional flows[1]	Years	10 – 20 m s^{-1}	~0.5 – 0.7 m s^{-1}
Activity cycle[2]	11 years	Rotation	2 – 10 m s^{-1}

[1] For flows, the global attenuation factor ➔ time coherence & number of surface elements averaged (AF up to 10^3 – 10^4!)

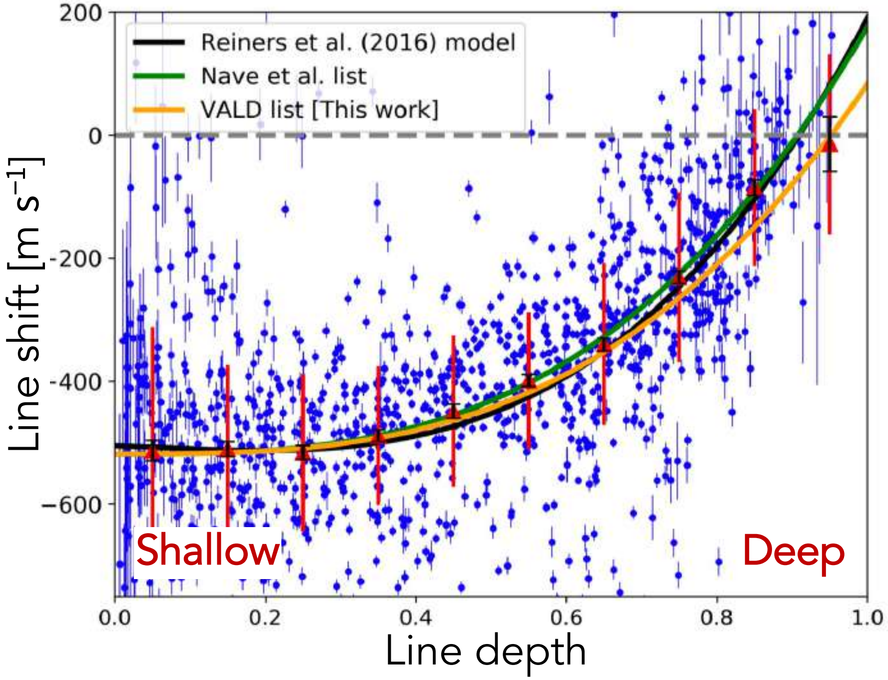
[2] Scales the surface rotation velocity with filling factor

The dominant effect is magnetic activity, followed by surface flows

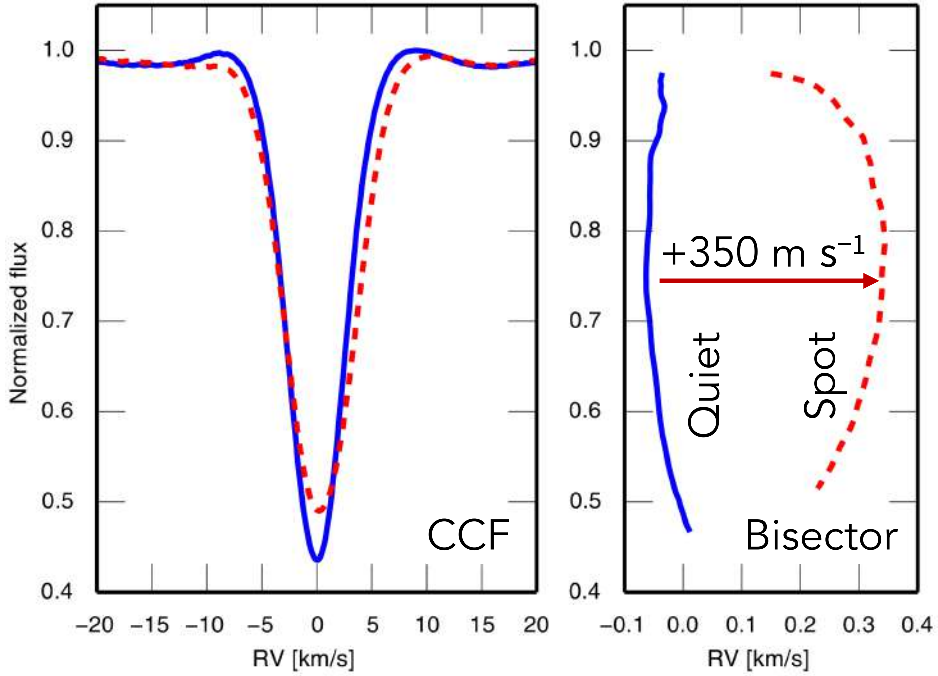
Solar global RV variability



Convection ➔ net line shift: 0 to −500 m s^{-1} (line depth ∝ 1/formation depth)



Liebing et al. (2021, A&A)

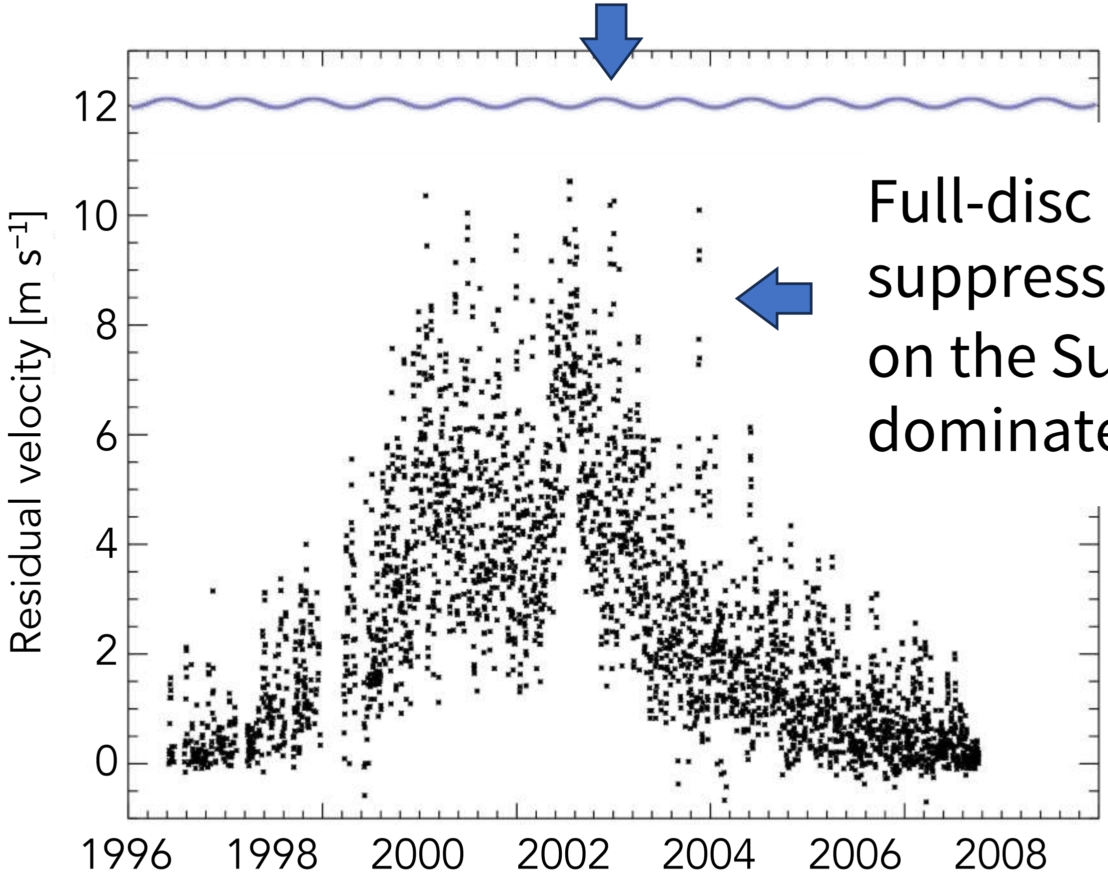


Dumusque et al. (2014, A&A)

- Quiet photosphere: Dynamic nature of convection ➔ RV residuals (sub-m s^{-1})
- Active regions ➔ Two effects:
  1. Light suppression of approaching or receding stellar face (line distortion)
  2. Magnetic fields inhibit convective motions (& blueshift)

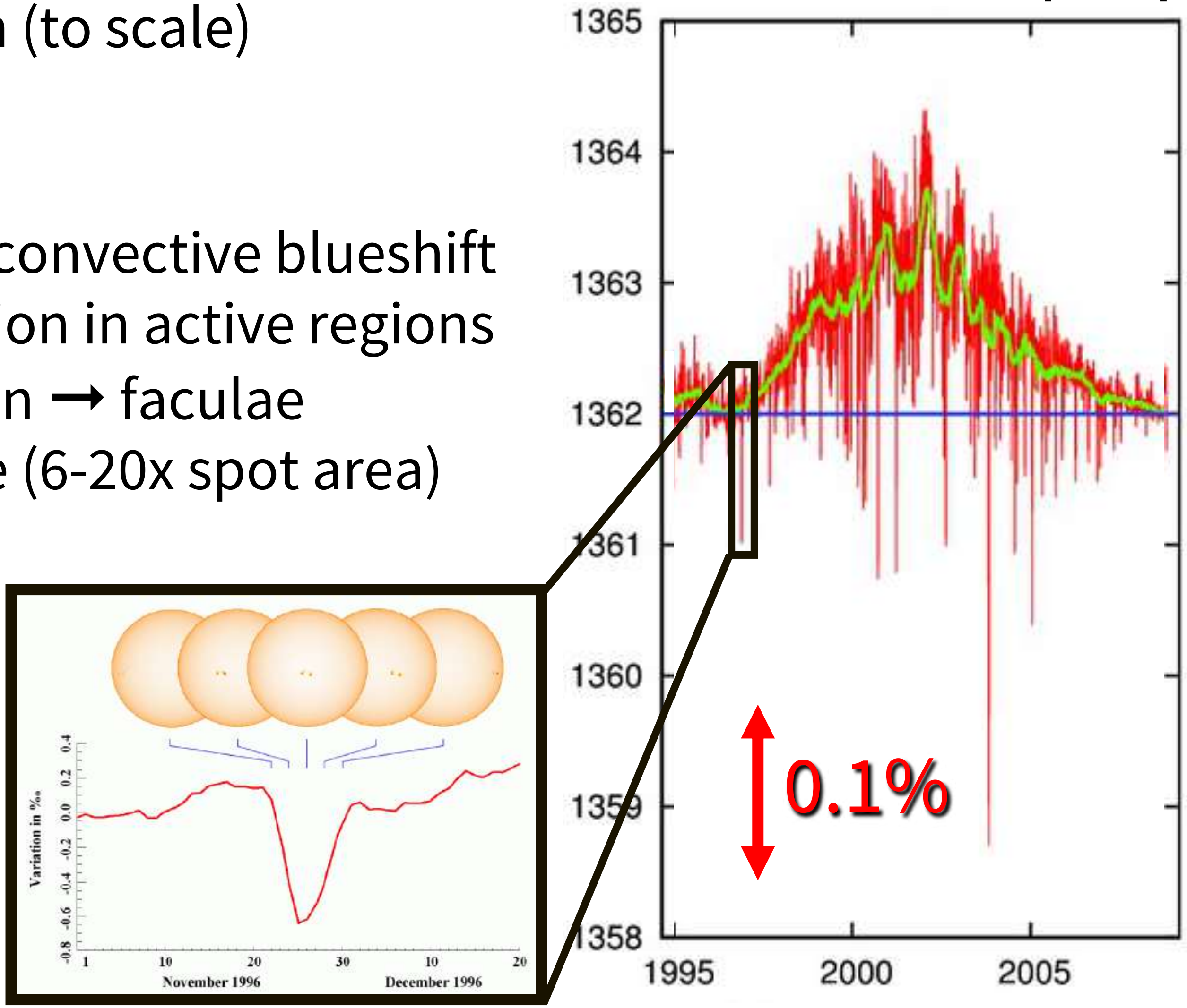
The stellar activity challenge

9 cm s^{-1} solar reflex orbital motion of Earth (to scale)



Full-disc convective blueshift suppression in active regions on the Sun → faculae dominate (6-20x spot area)

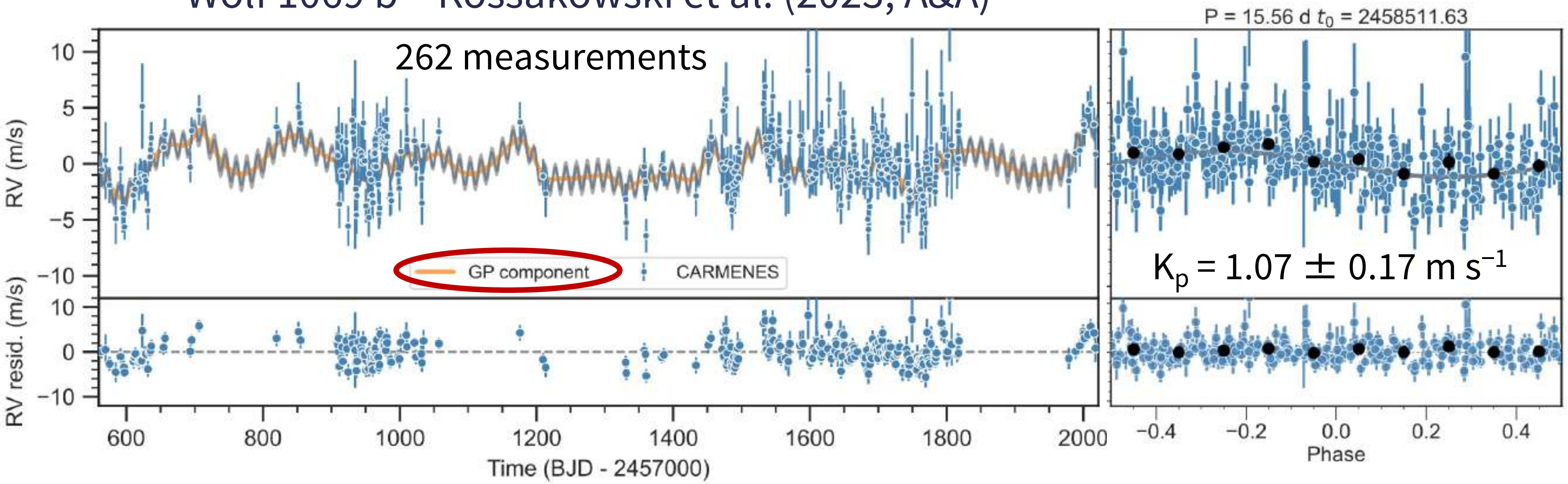
Meunier et al. (2010, A&A)
See also Jeffers et al. (2014, MNRAS)



Dewitte & Clerbaux (2017, Rem. Sens.)

Data-driven: GPs & others

Wolf 1069 b – Kossakowski et al. (2023, A&A)



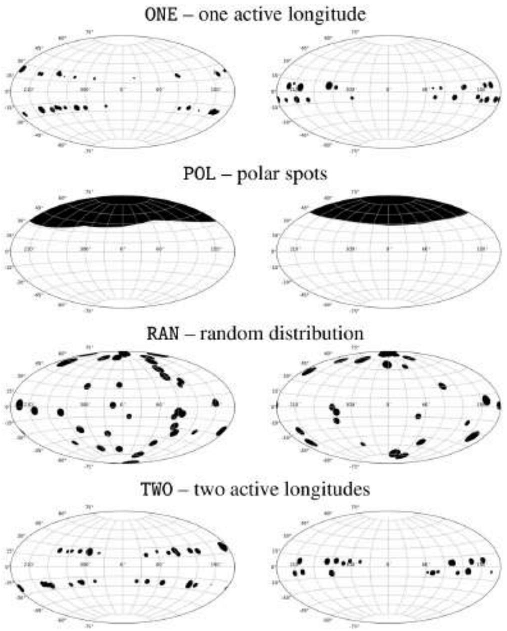
$$\mathcal{L} = \frac{1}{(2\pi)^{N/2}} |C|^{-1/2} \exp\left(-\frac{1}{2} \sum_{i=1}^{N} \sum_{j=1}^{N} r_i r_j C_{ij}^{-1}\right),$$

$$r_i = v_{\mathrm{obs}}(t_i) - v_{\mathrm{mod}}(t_i),$$

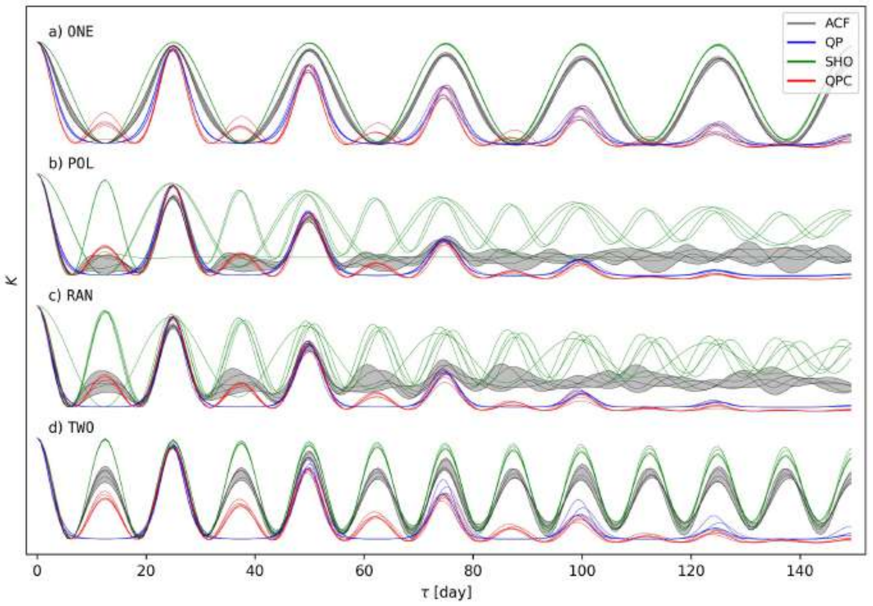
$$C_{ij} = (\sigma^2 + \epsilon_i^2)\,\delta_{ij} + K(t_i - t_j)$$

Gaussian Processes framework – Kernel function

Choice of kernel ➞ physics motivated



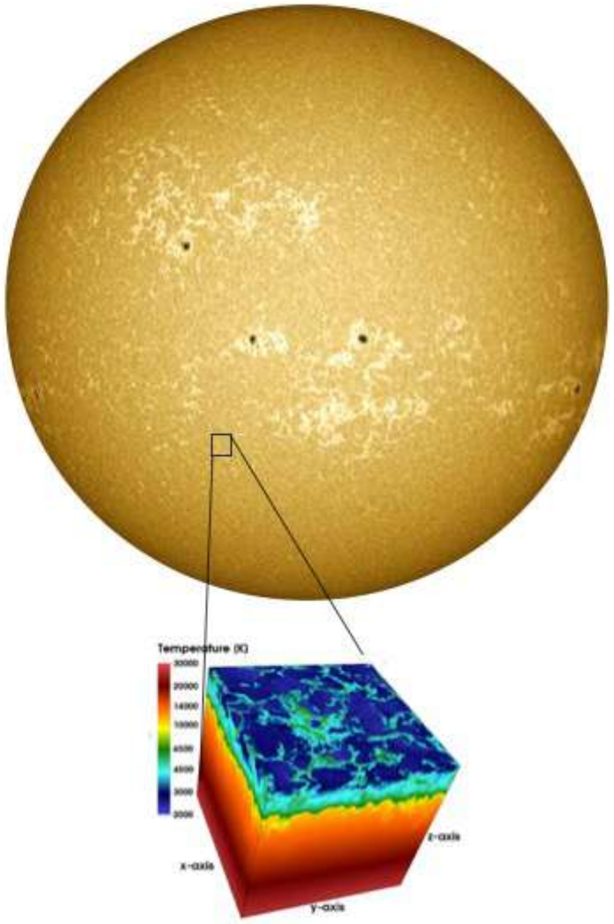
Perger et al. (2021, A&A)



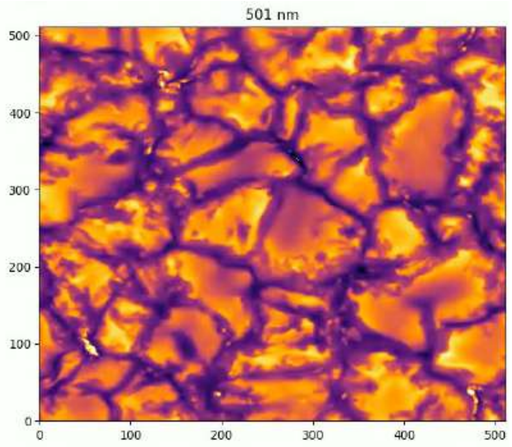
- GPs & multivariate GPs:
  - Haywood et al. (2014, MNRAS)
  - Rajpaul et al. (2015, MNRAS)
  - Foreman-Mackey et al. (2017, AJ)
- PCA:
  - Collier Cameron et al. (2021, MNRAS)
- Line-by-line:
  - Dumusque (2018, A&A)
- Machine Learning:
  - de Beurs et al. (2022, AJ)
  - Perger et al. (2023, A&A)

Physics-driven: Stellar models

Significant improvements from 1D (e.g., Phoenix) to 3D MHD (e.g., MURaM) models

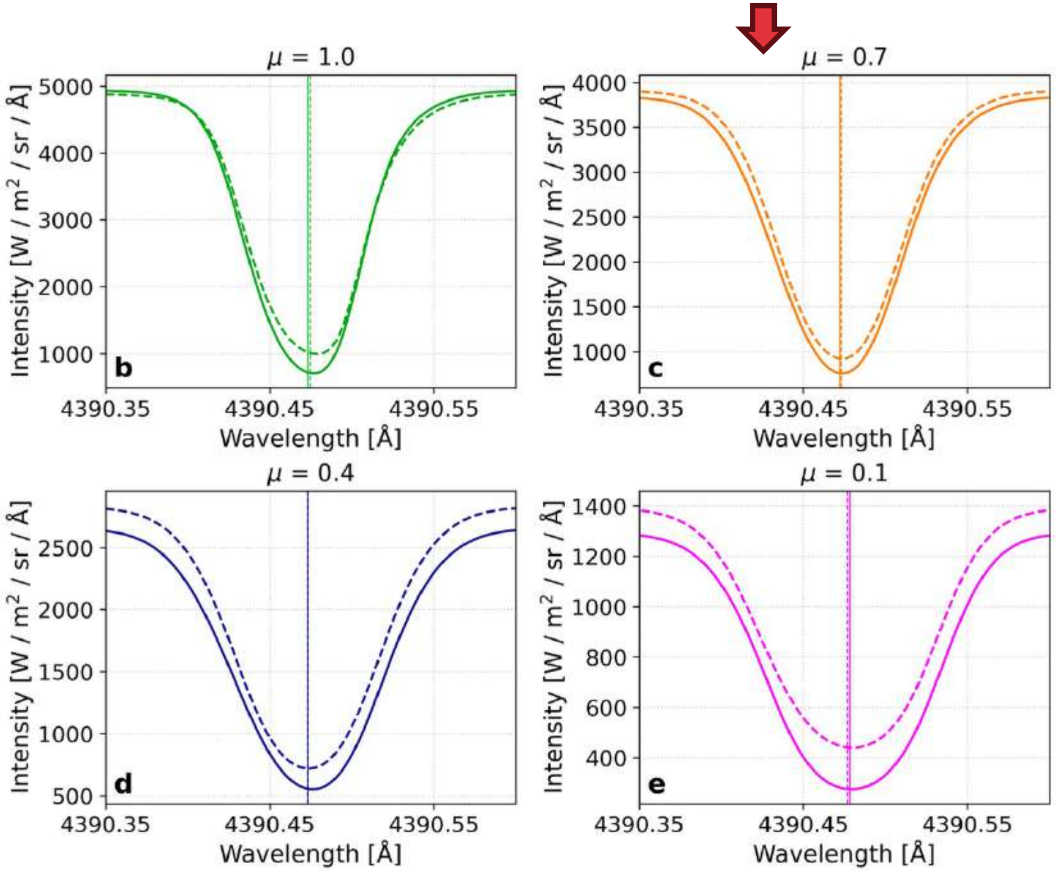


Box-in-a-star approach to simulate near-surface layers and atmospheres



MURaM (Vögler et al. 2005, A&A)

Quiet photosphere, spot and facula spectra!



Kröll et al. (2026, ApJ Lett.)

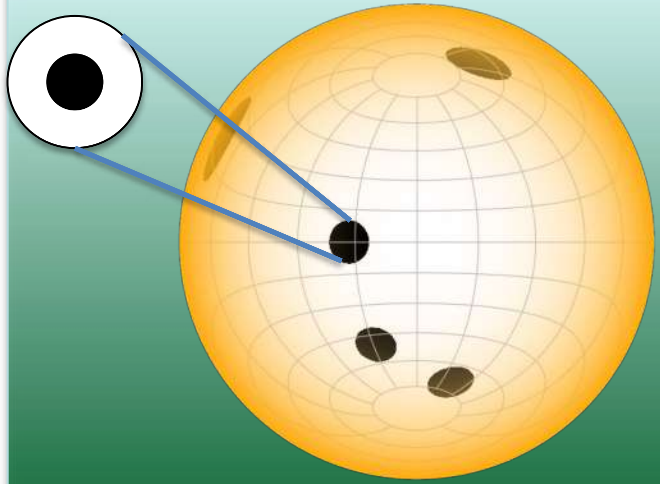
Poster P1065!

Physical simulation of stellar activity

Spotted photosphere

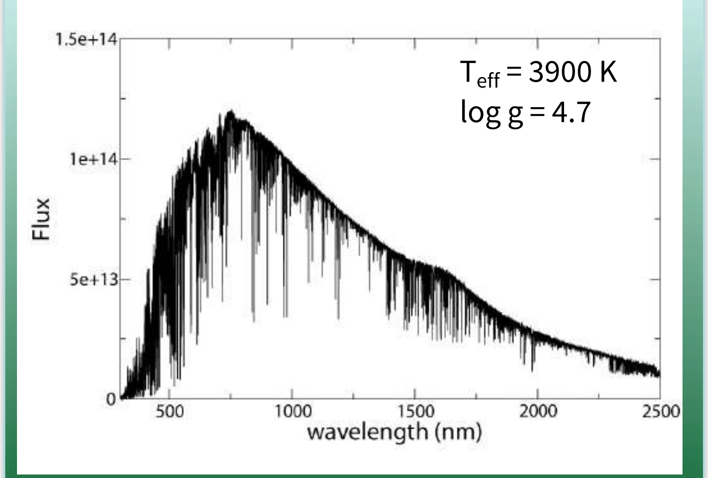
Σ (spectrum of each surface element):

- Quiet, spot or facula
- Spot map + ΔT_{eff} + Q
- Limb darkening (I_μ)
- Doppler shift



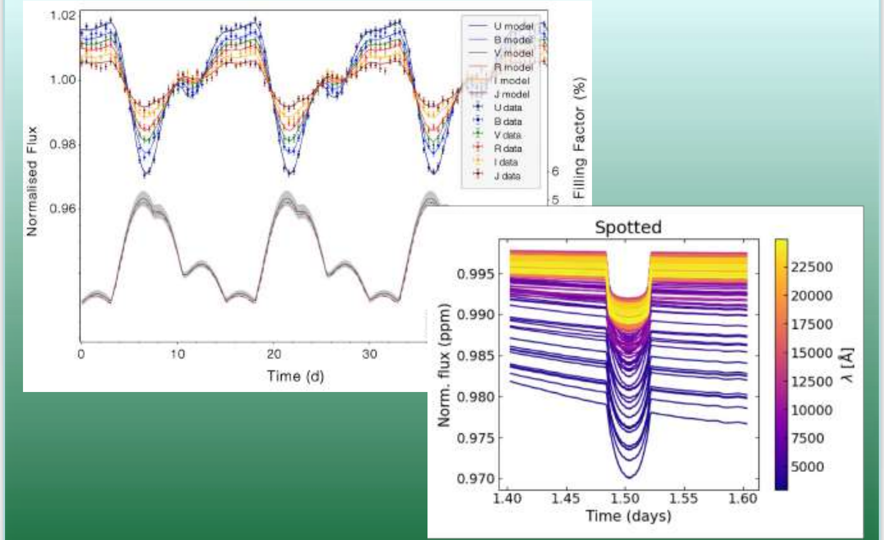
Stellar models (Phoenix, MURaM/MPS-ATLAS)

- T_{eff}, log g, [m/H]
- Rotation period
- Differential rotation
- Rotation axis inclination
- Active region evolution



Time-series forward model & transits

- Photometry using filters
- RVs & indices using CCFs
- Chromatic transits
- Spot crossings & TLS effect



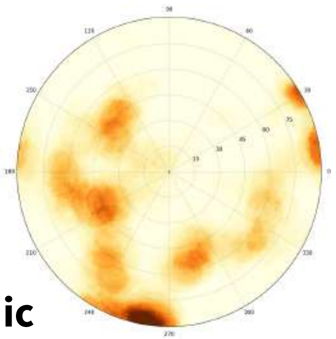
StarSim: Herrero et al. (2016, A&A); Rosich et al. (2020, A&A); Gomes et al. (in prep.)
SOAP: Boisse et al. (2012, A&A); Dumusque et al. (2014, A&A); Cristo et al. (2025, A&A)

Physical simulation of stellar activity: StarSim

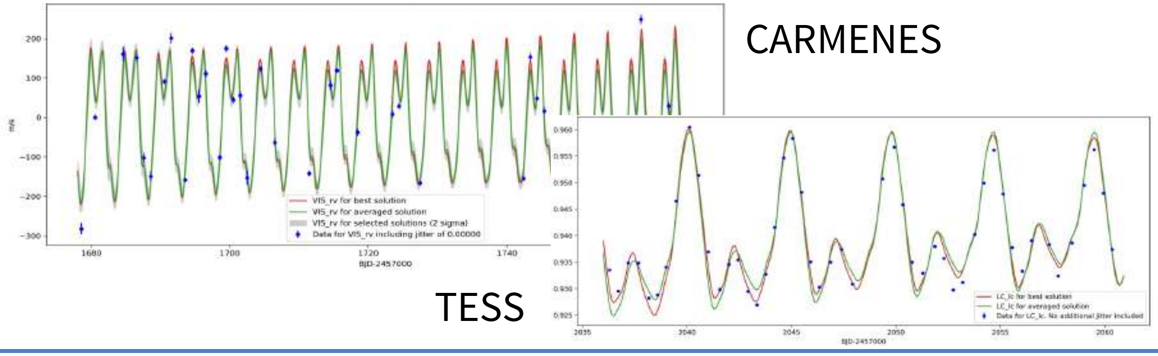
Rigorous physical model → **STAR'S DIGITAL TWIN**

(work by postdoc N.R.C. Gomes & PhD student E. Fernandez-Puig)

Direct inversion (derive surface map from time-series data) – Work by PhD student C. Blázquez



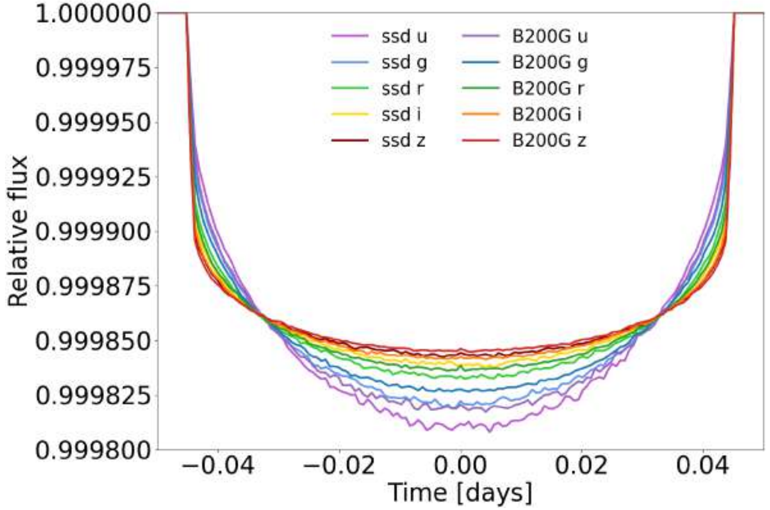
AU Mic

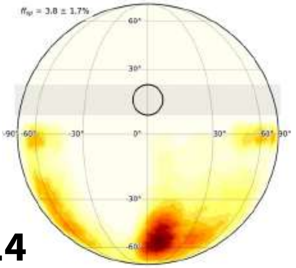


Massive forward simulations (training of ML-based schemes) – Talk by M. Perger (work by PhD student J. Blanco-Pozo)

Activity effects on exoplanet transits (chromaticity, spot crossing, TLS effect, faculae) – Poster by MSCA fellow N.E. Nèmec + work by PhD student O. Porqueras-León

Nèmec et al. – **poster P1075**





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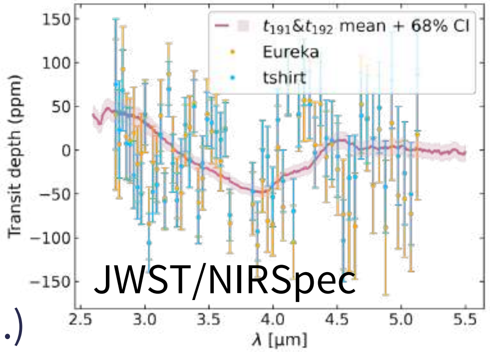


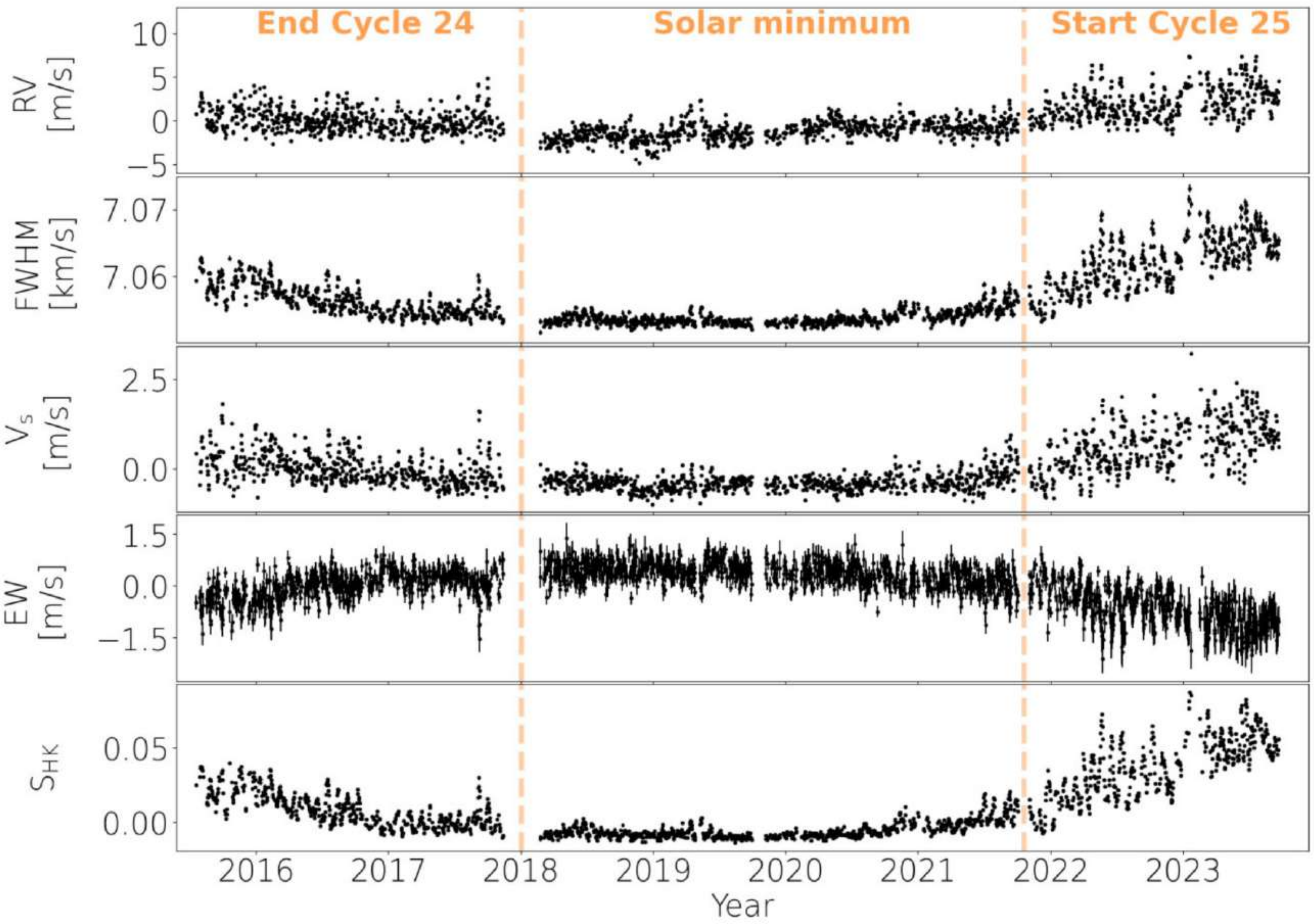
Porqueras-León et al. (A&A, subm.)

Sun-as-a-star precise radial velocity data

Several solar telescopes feeding precise RV instruments:

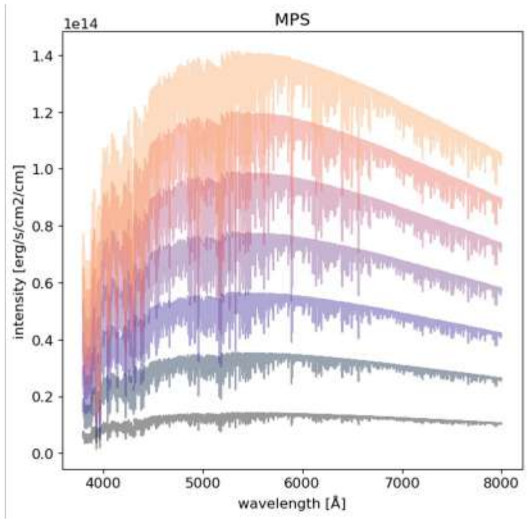
- ➢ HARPS-N (LCST – 2016)
- ➢ HARPS (HELIOS – 2018)
- ➢ EXPRES (LOST – 2019)
- ➢ NEID (2020)
- ➢ NIRPS (HELIOS – 2023; **P1063 Al Moulla**)
- ➢ ESPRESSO (PoET – 2026; **P1052 San Nicolás Martínez**)

PoET

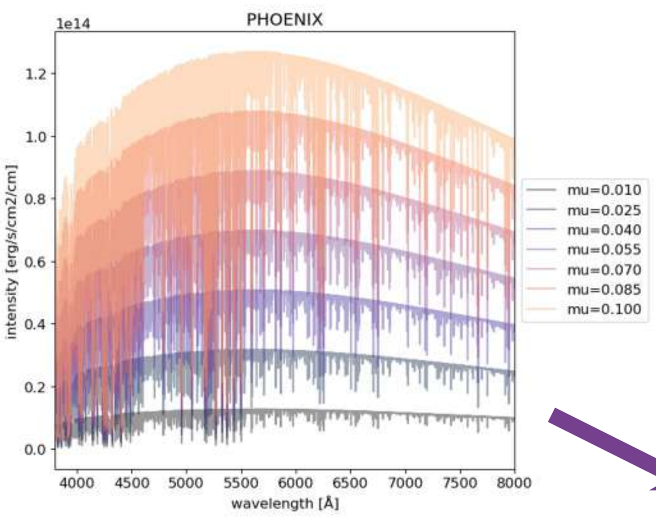


Klein et al. (2024, A&A)
See also Zhao et al. (2023, AJ)

Testing against ground truth: the Sun (SunSim)



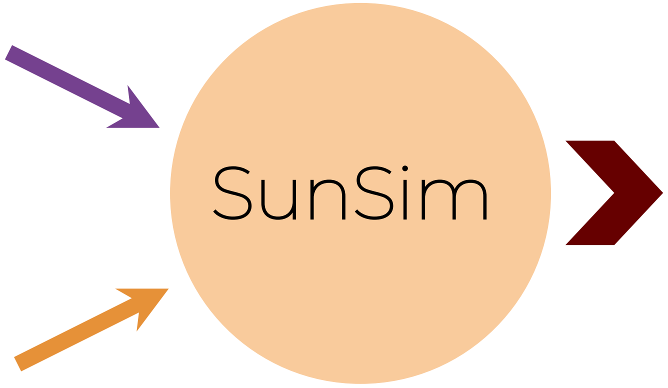
MURaM/MPS-ATLAS 3D MHD

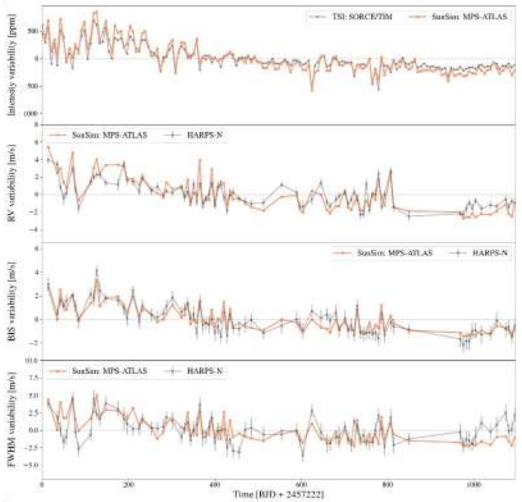


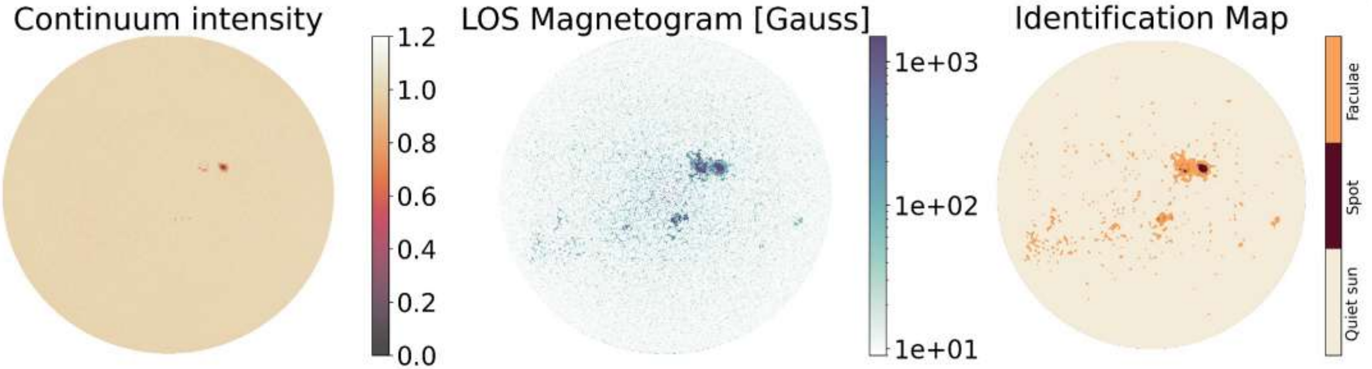
PHOENIX 1D

Work by PhD student Sophie Stucki

Stucki et al. (A&A, to be subm.)



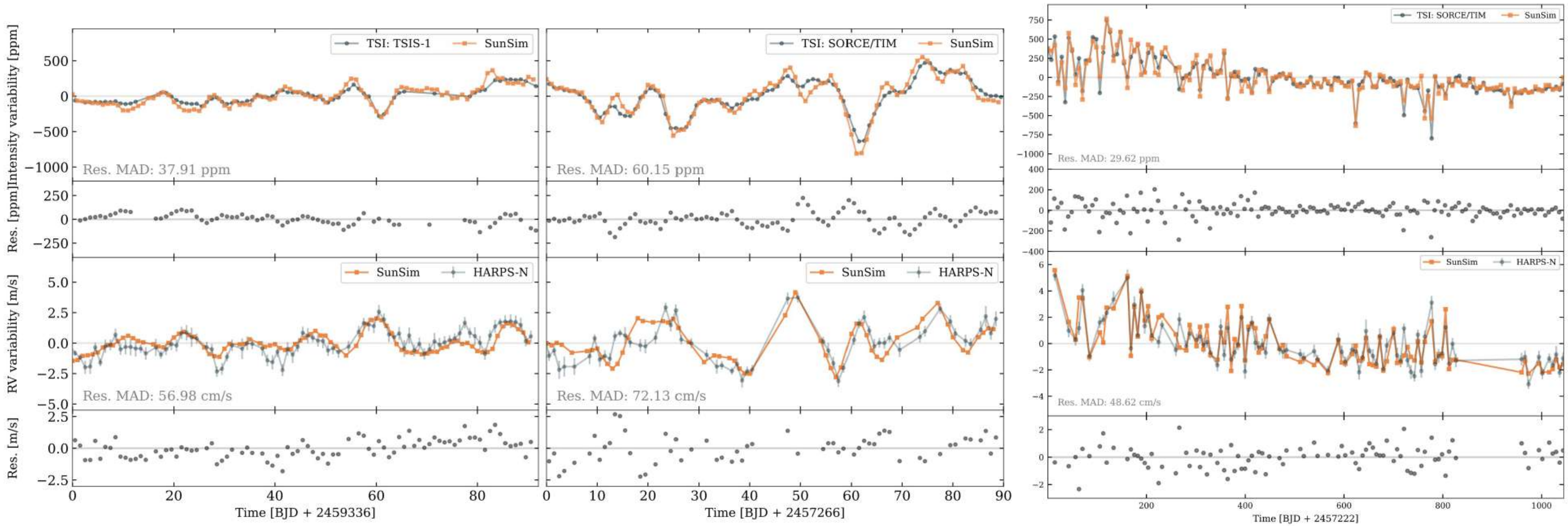




- We use data from SDO/SORCE & HARPS-N
- Forward model only to predict (no free parameters except for facula threshold!):
  - Intensity
  - RV
  - BIS
  - FWHM

Testing against ground truth: the Sun (SunSim)

	Low activity		High activity		3 years	
	MAD data	MAD residuals	MAD data	MAD residuals	MAD data	MAD residuals
Phot [ppm]	78.3	37.9	139.0	60.1	125.5	29.6
RV [m s^{-1}]	0.62	0.57	1.05	0.72	**1.04**	**0.49**



Testing against ground truth: the Sun

Where we are with HARPS-N data:

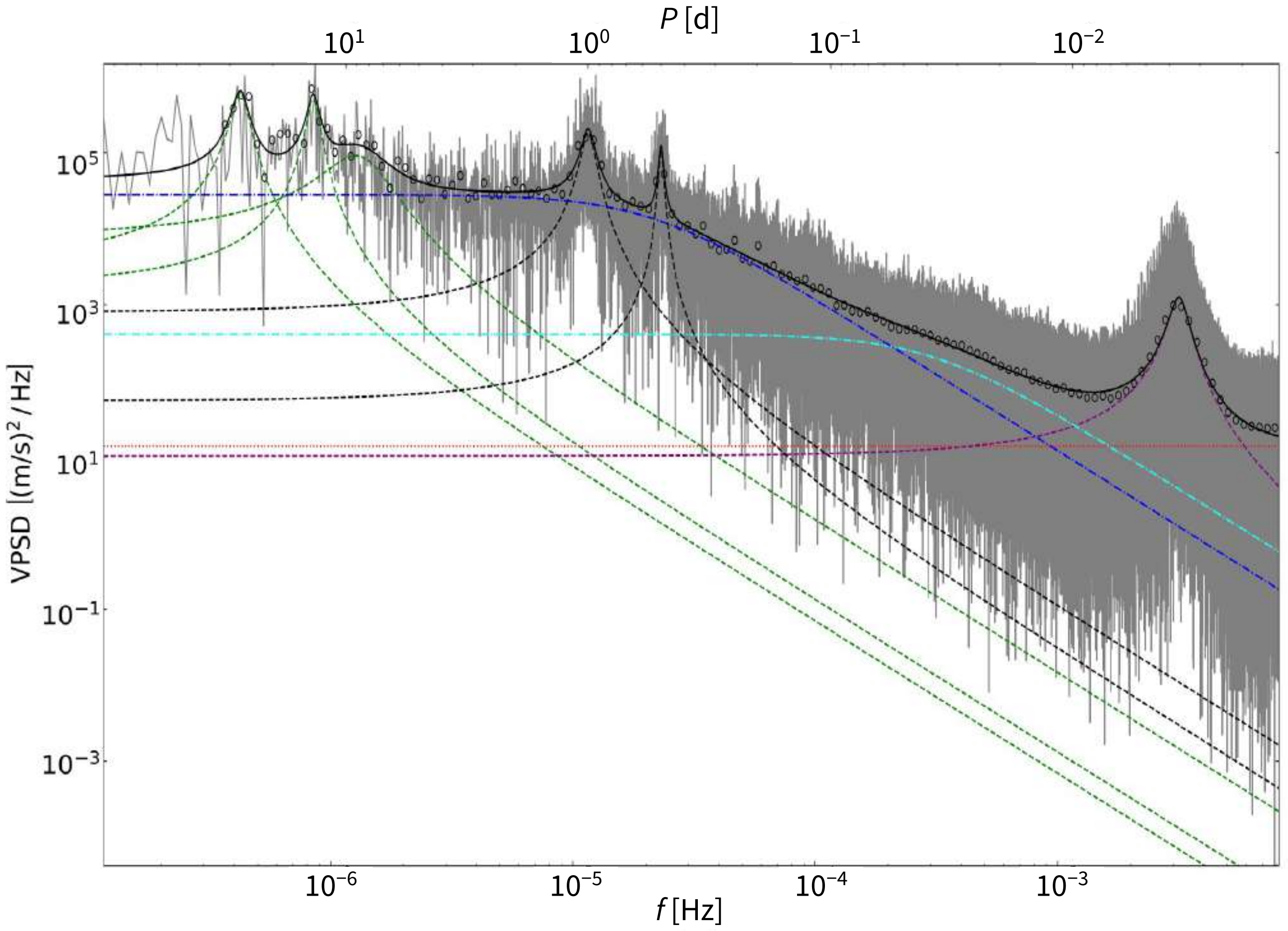
Category	Reference	Method	Timespan	# chunks	RMS [m s^{-1}]
Instrument stability	Dumusque et al. (2026)	None	10 yr	-	2.95
		Intraday	10 yr	-	0.49 (median)
		Daily average + fit to Mg2 index + 30-day moving average	10 yr	-	0.41 (median)
Physics-based / forward	**Stucki et al.**	**3D MHD + SunSim**	**3 yr**	**-**	**0.80**
	Barka et al. (2026)	1D + SOAPv4	3 yr	2	0.91
	Zhao et al. (2025)	1D + SOAP-GPU	8.5 yr	3	0.79-0.91
Data-driven[1]	McWilliam et al. (2026)	CNNs	6 yr	-	0.93
	Klein et al. (2024)	PCA	8 yr	-	1.06
	Cameron et al. (2021)	ACF	5 yr	-	1.25

[1] GPs applied to residuals of model yield RMS of ~0.6-0.8 m s^{-1} depending on seasons

See additional results in some of the upcoming talks & P1076 Rescigno; P1082 Palumbo; P1095 Luhn; P1175 Rubenzahl; P1179 Hobbs; P2026 Flagg; P2104 Goods; P2132 Llama; P2179 Gavankar; P2188 Lakeland

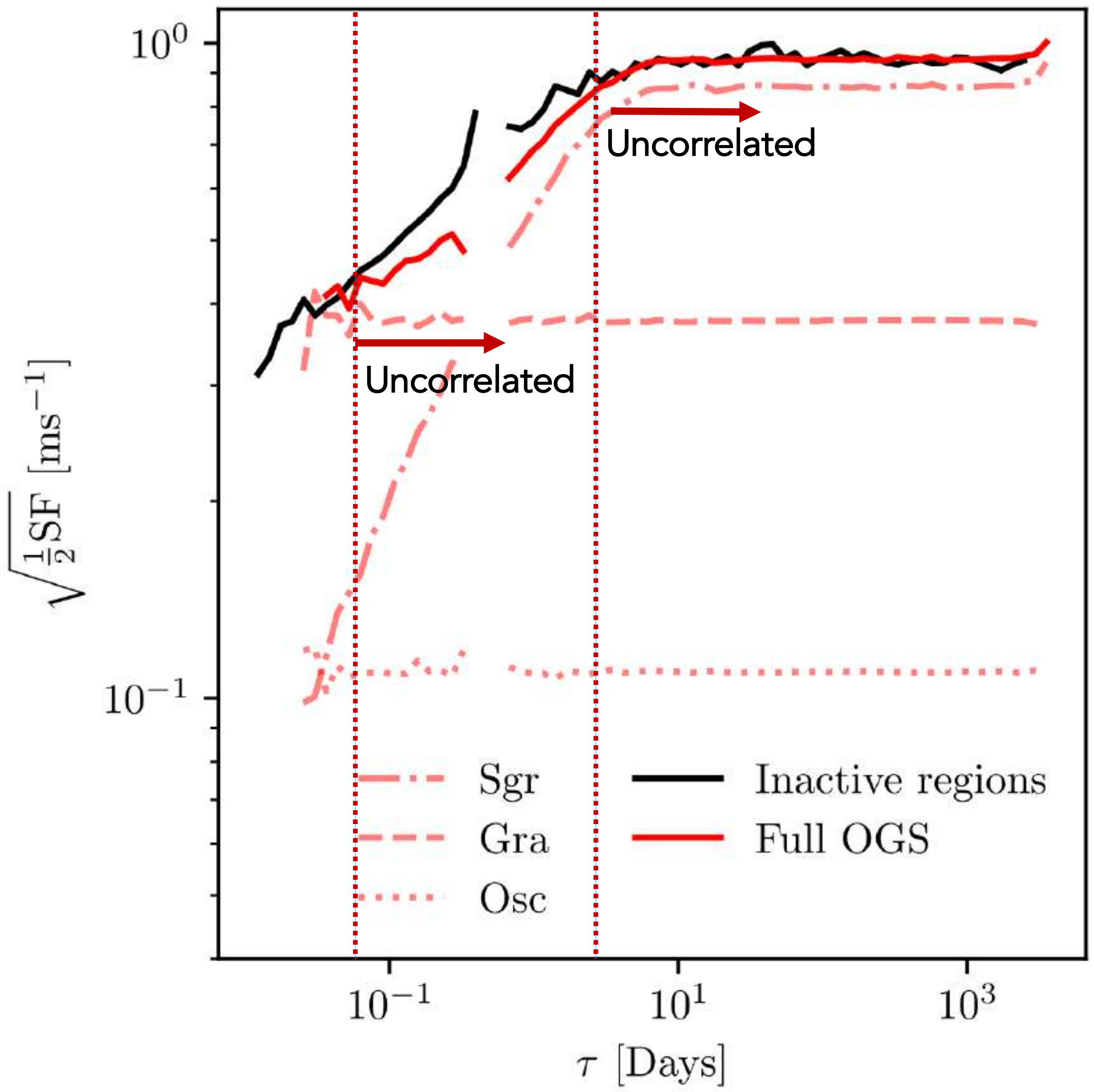
Solar global RV variability

Global Sun



Al Moulla et al. (2023, A&A)

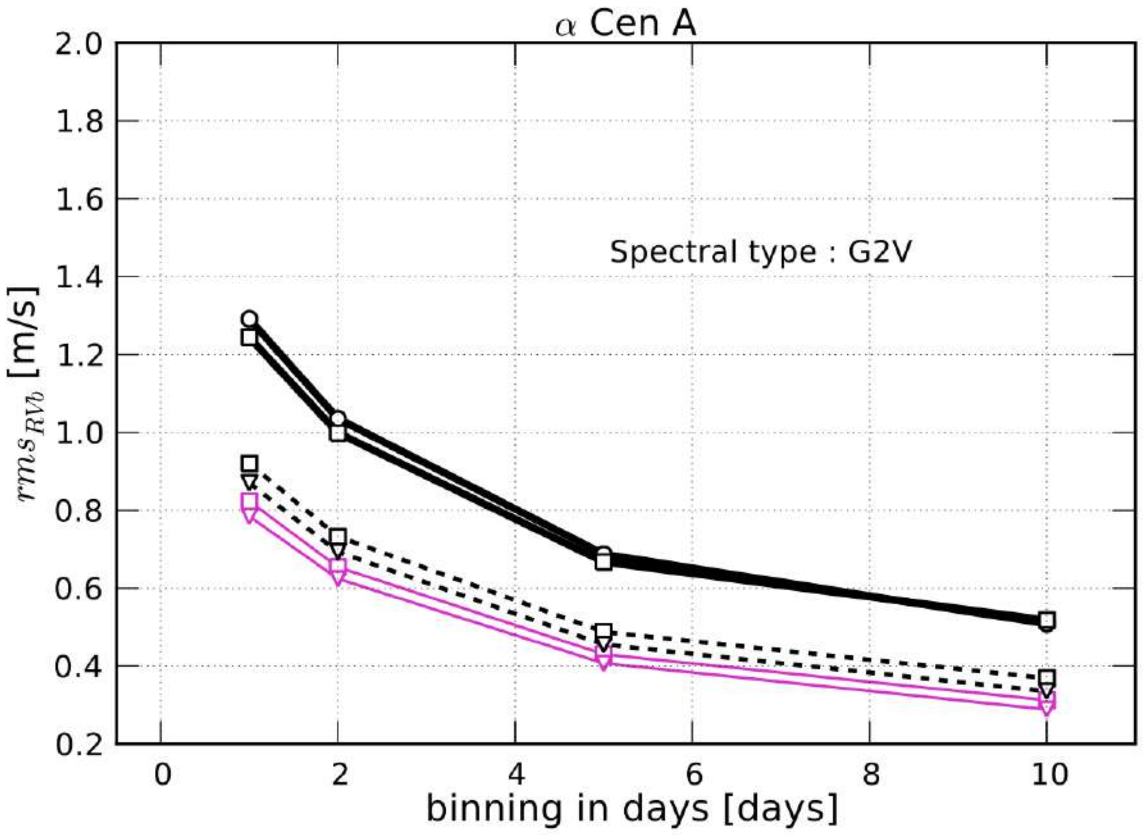
Inactive solar regions – network



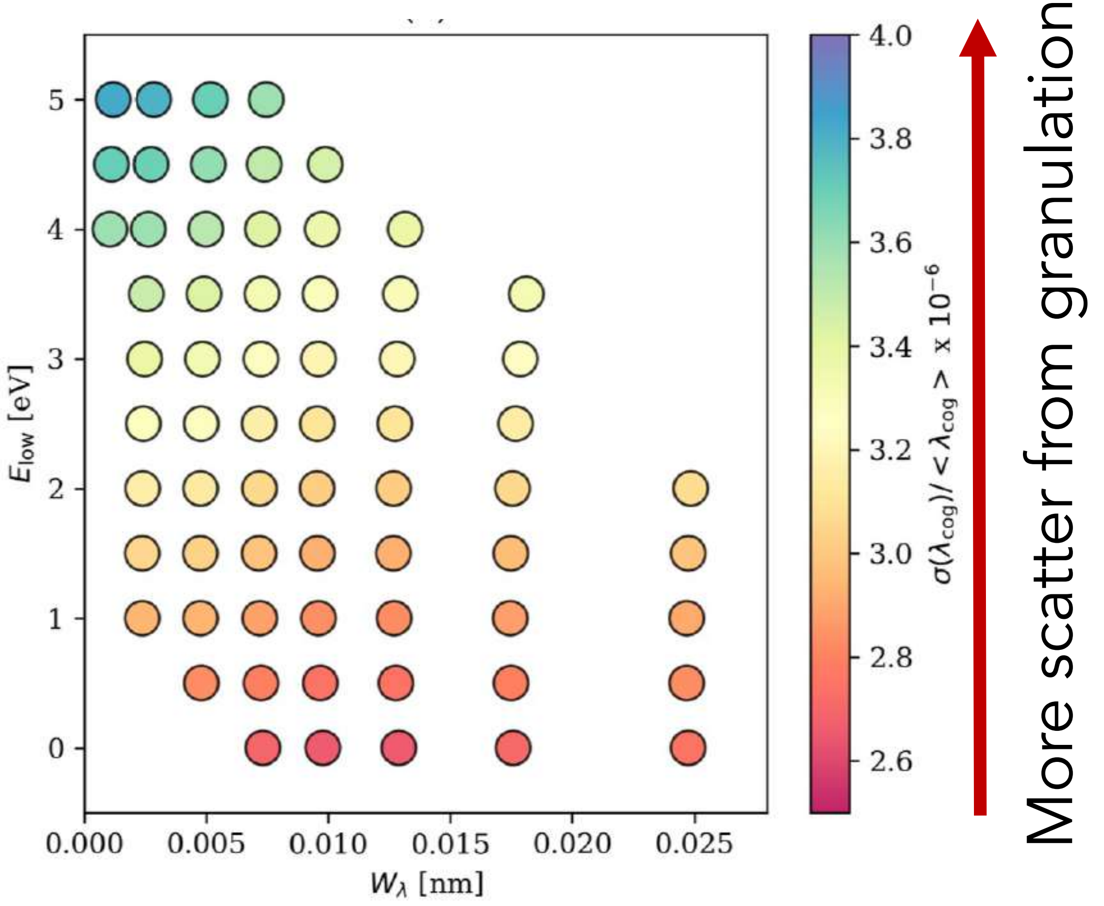
Lakeland et al. (2023, MNRAS)

General mitigation strategies for flows

- ➢ Averaging strategies (uncorrelated) ➔ expensive!
- ➢ Sensitivity of different lines



Dumusque et al. (2011, A&A)
See also Meunier et al. (2015, A&A)



Sowmya et al. (2011, ApJ)

Solar global RV variability correction

Process	Global RV scatter	Timescale	Method	Path to correction
p-mode oscillations	~0.2 – 0.5 m s^{-1}	5 min	Average of a few exposures	✅
Granulation	~0.3 – 0.5 m s^{-1}	5 – 15 min	Daily averages, line selection	~
Supergranulation	~0.6 – 0.8 m s^{-1}	1 – 2 days	Averages, physical, GPs, line sel. (?)	❌
Magnetic regions	1 – 5 m s^{-1}	Days – months	Physical, GPs, line sel.	~
Meridional flows	~0.5 – 0.7 m s^{-1}	Years	Physical (?)	❓
Activity cycle	2 – 10 m s^{-1}	11 years	Physical, GPs	~

Main takeaways

- Essential to gain deeper understanding of stars and the Sun to reach the exoEarth domain ➞ move away from stellar "noise" mindset ➞ **THE STAR IS THE SIGNAL**
- Major improvements in stellar atmosphere models allow for physics-based approach to correct stellar activity effects ➞ **DIGITAL TWIN**
- Excellent results for the Sun (**RMS $\lesssim$ 80 cm s^{-1} for 3 yr**) and other stars (talk by M. Perger), reaching the level of residual flow scatter
- Potential to improve with line-by-line analyses to enhance/decrease sensitivity (velocity fields, granulation, magnetic fields) + develop optimal GP kernels
- Strategy to deal with variability from flows (supergranulation, meridional circulation) is still an issue

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