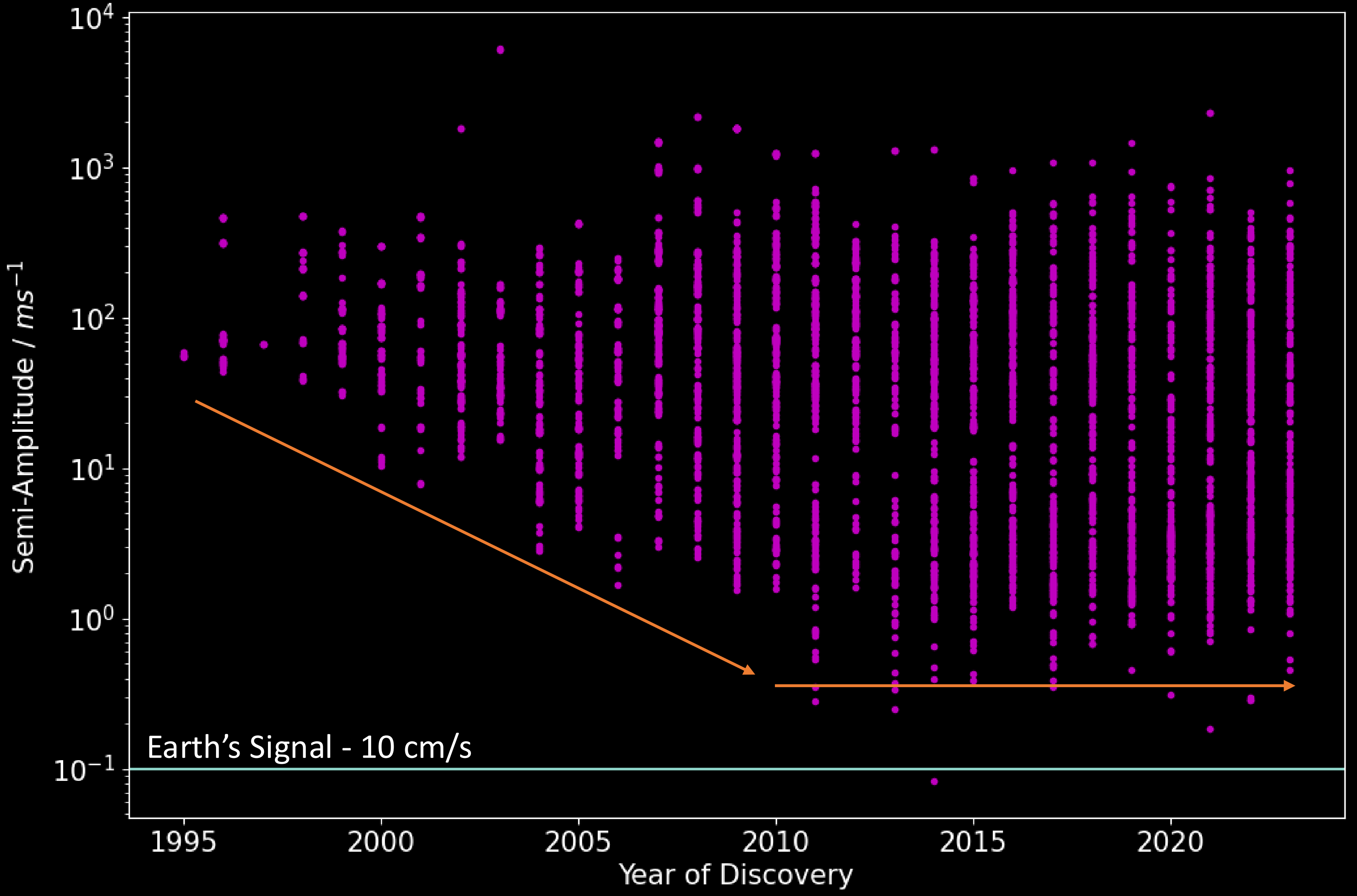
Image credit: NASA

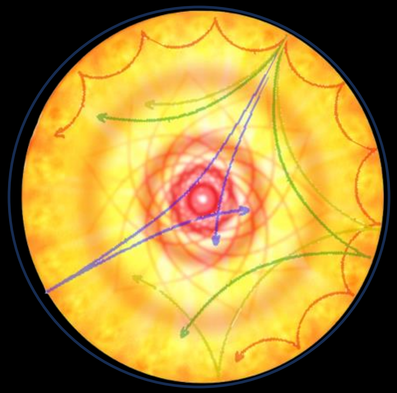
Tackling Supergranulation in Earth-Twin Surveys using the HARPS-N Solar Data

Niamh K. O’Sullivan
Suzanne Aigrain, Michael Cretignier,
Ben Lakeland
University of Oxford

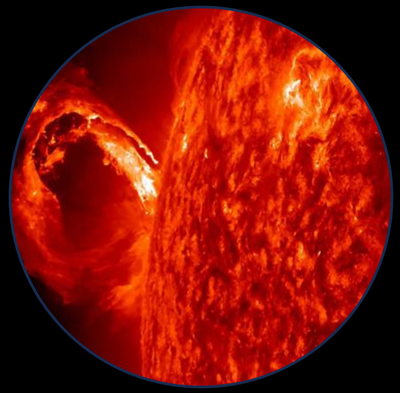


Earth's Signal - 10 cm/s
Semi-Amplitude / ms^{-1}
10^4
10^3
10^2
10^1
10^0
10^{-1}
1995
2000
2005
2010
2015
2020
Year of Discovery

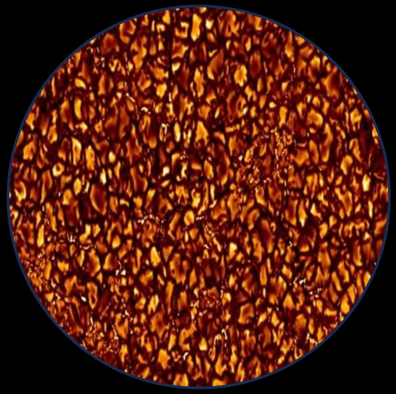
Stellar Variability of Sun-Like Stars in EPRV



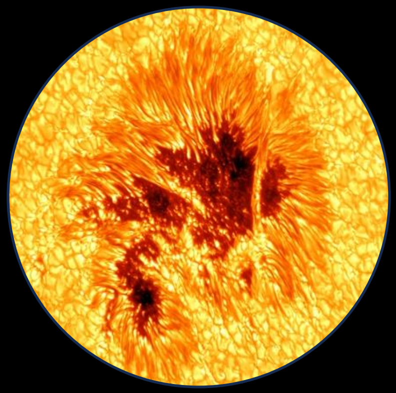
Oscillations



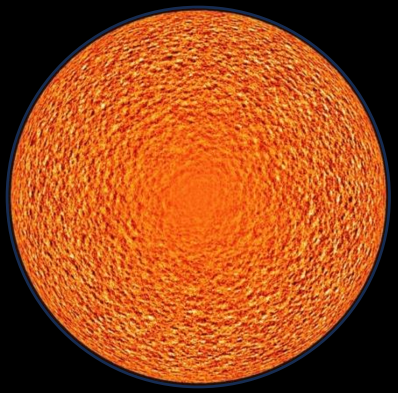
Flares



Granulation



Activity



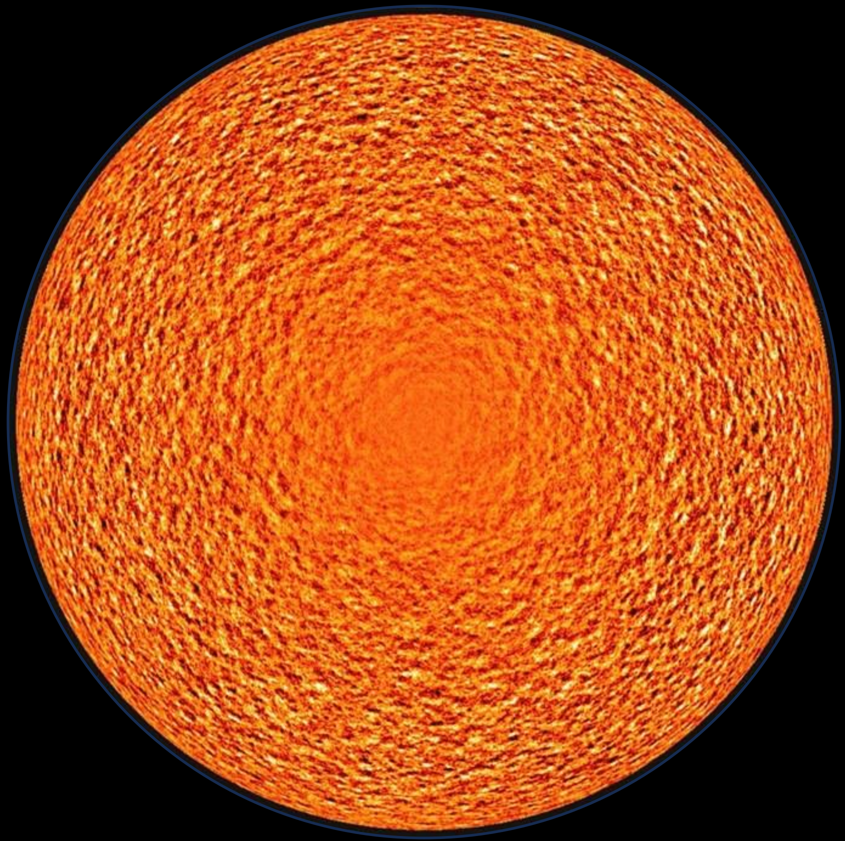
Supergranulation

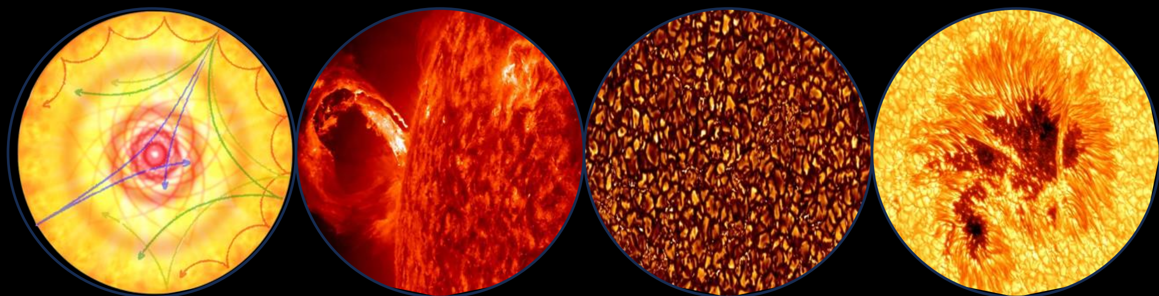
Image credits: IAC/NASA/NSO/AURA/NSF/SDO/HMI

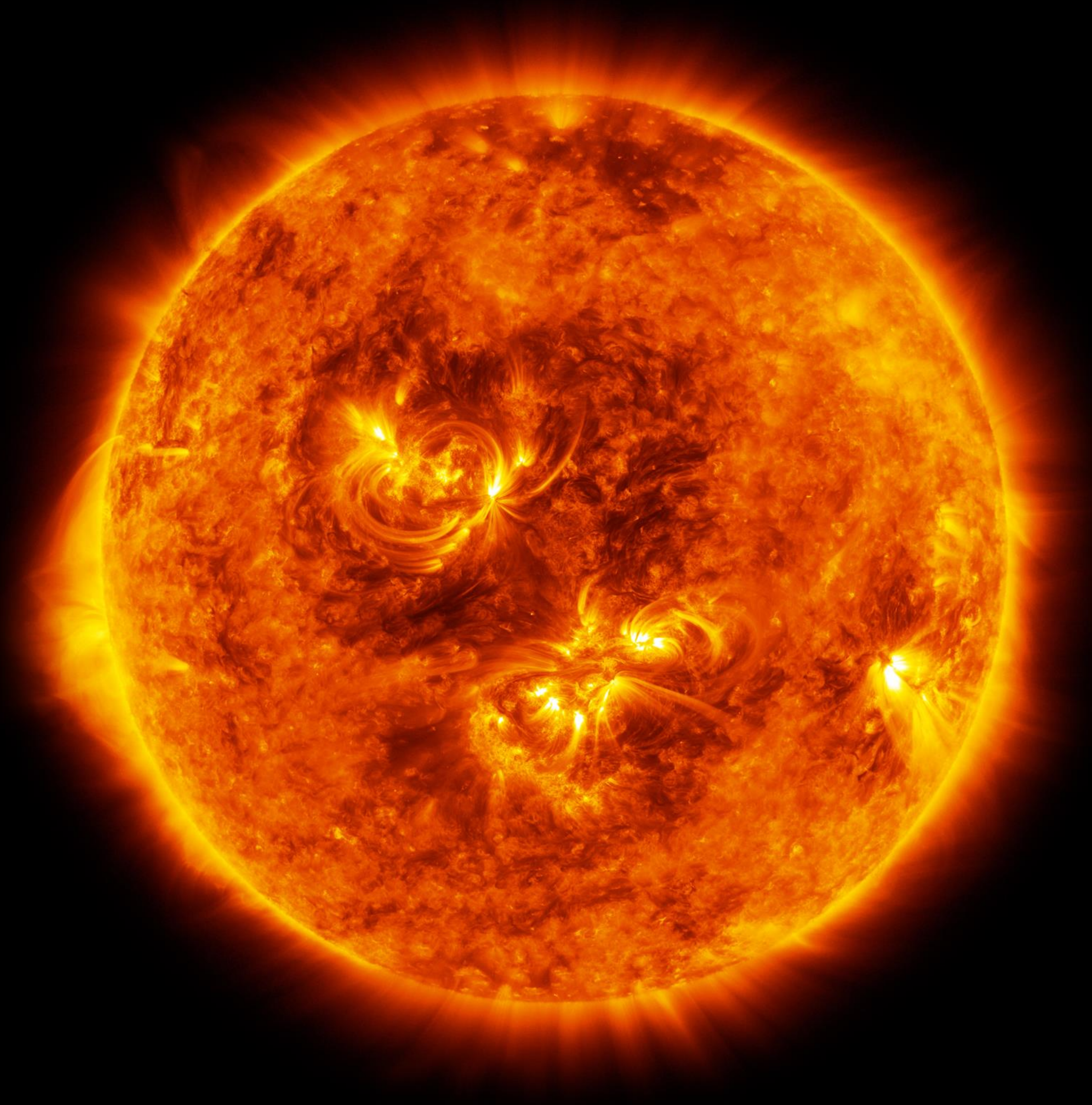
Supergranulation

- First discovered through Doppler imaging of the Sun
- Horizontal flow of 200 – 300 m/s
- (Vertical flow of 20 - 30 m/s)
- Horizontal scale of 30-35 Mm
- Convective origin
- Timescale of 1-3 days
- 0.5-1 m/s RV scatter

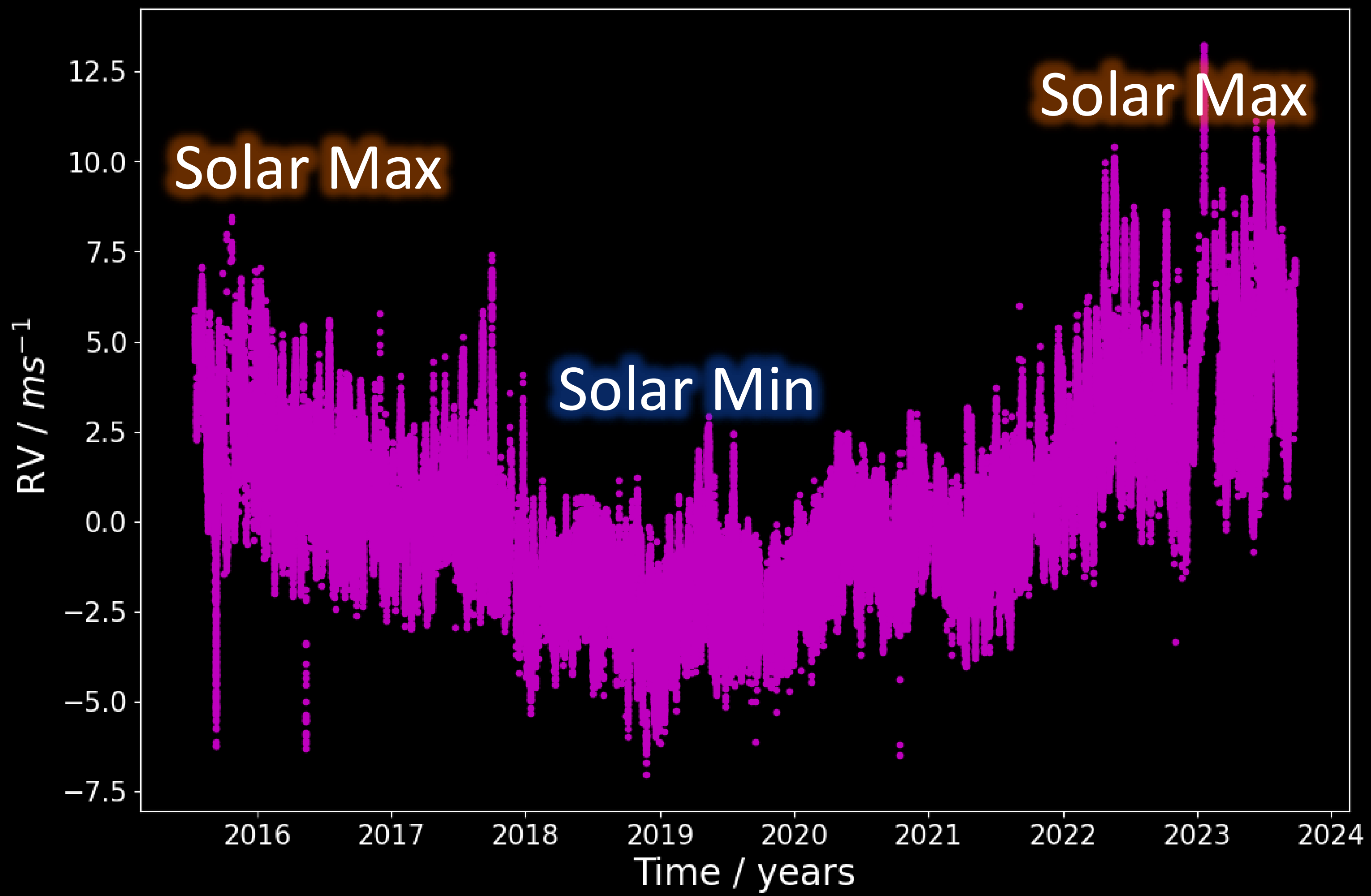
- **Review by Rincon & Rieutord 2018**

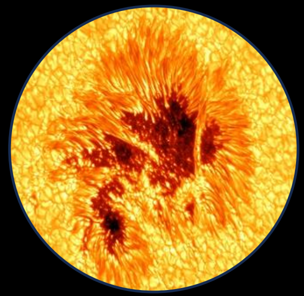


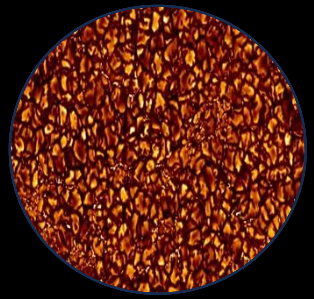


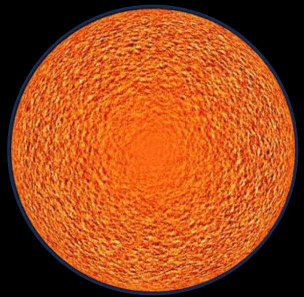


HARPS-N Solar Data



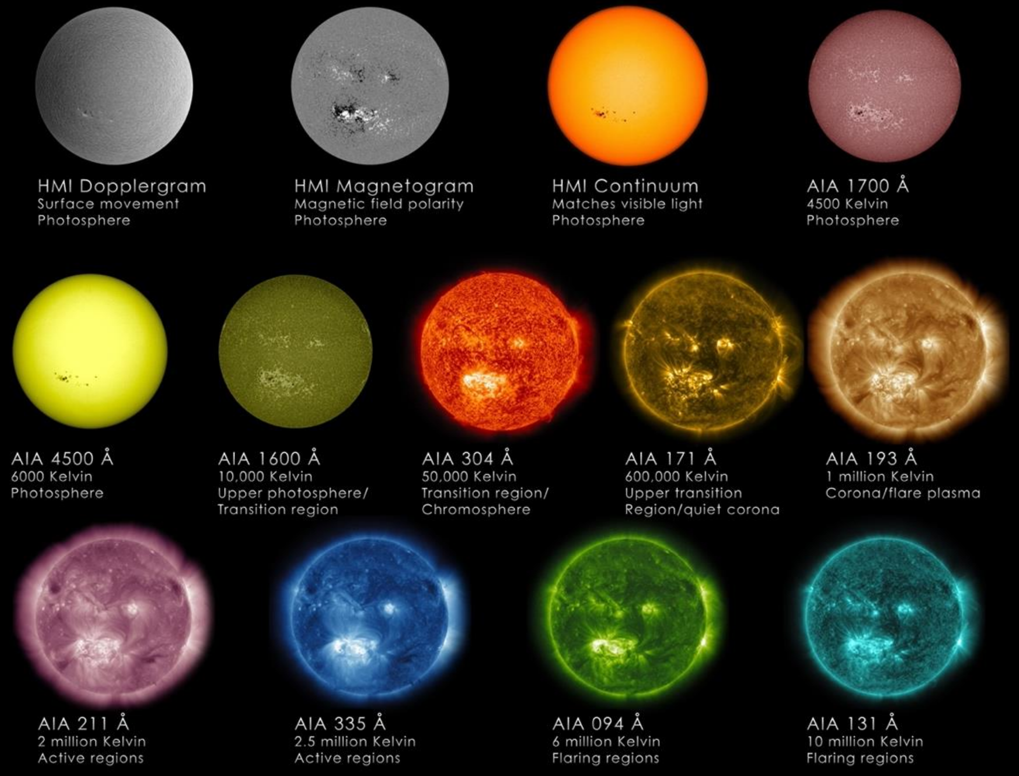






Collier Cameron et al. (2019), Dumusque et al. (2021), Dumusque et al. (in prep)

Evaluating Activity Induced RV Variation: SDO vs YARARA



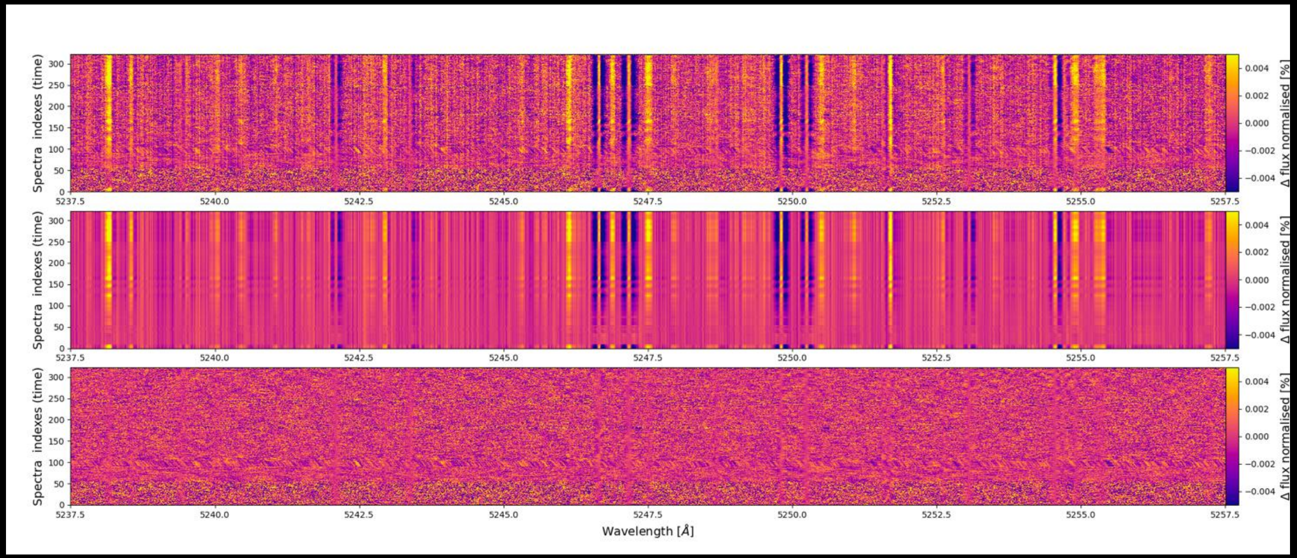


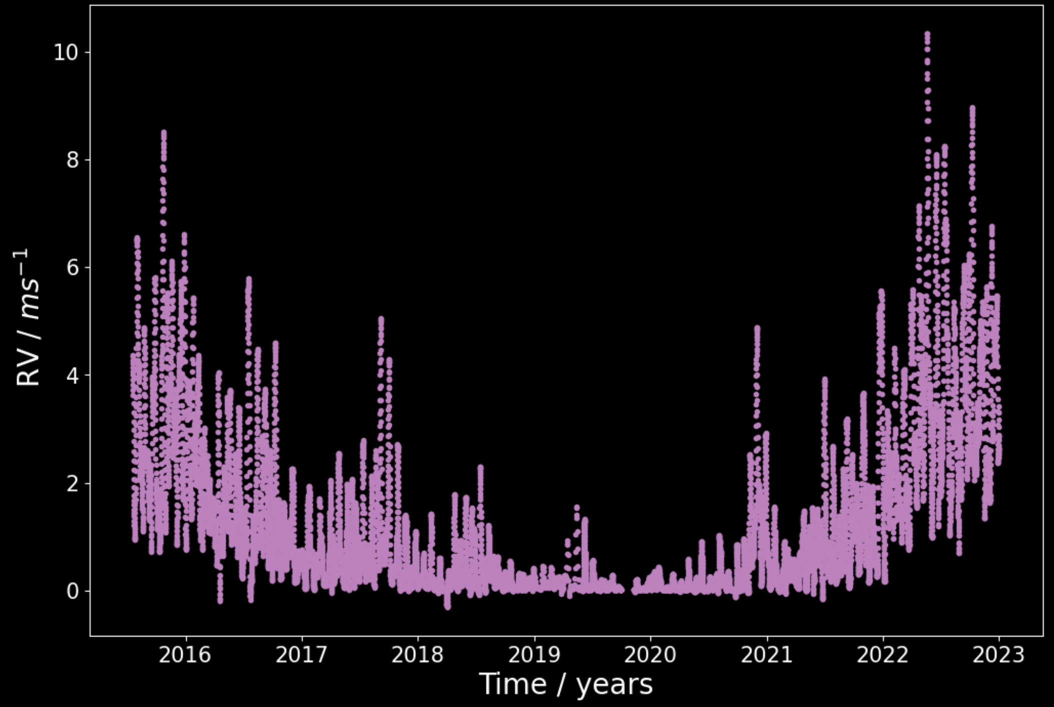
Image credit: SDO/HMI

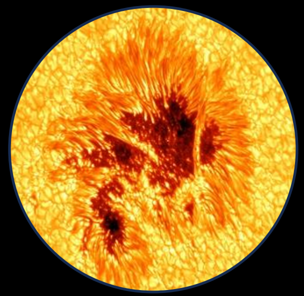
Haywood et al (2016), Milbourne et al (2019) ,
Haywood et al (2022), Lakeland et al (2024)

Image credit: Cretignier courtesy

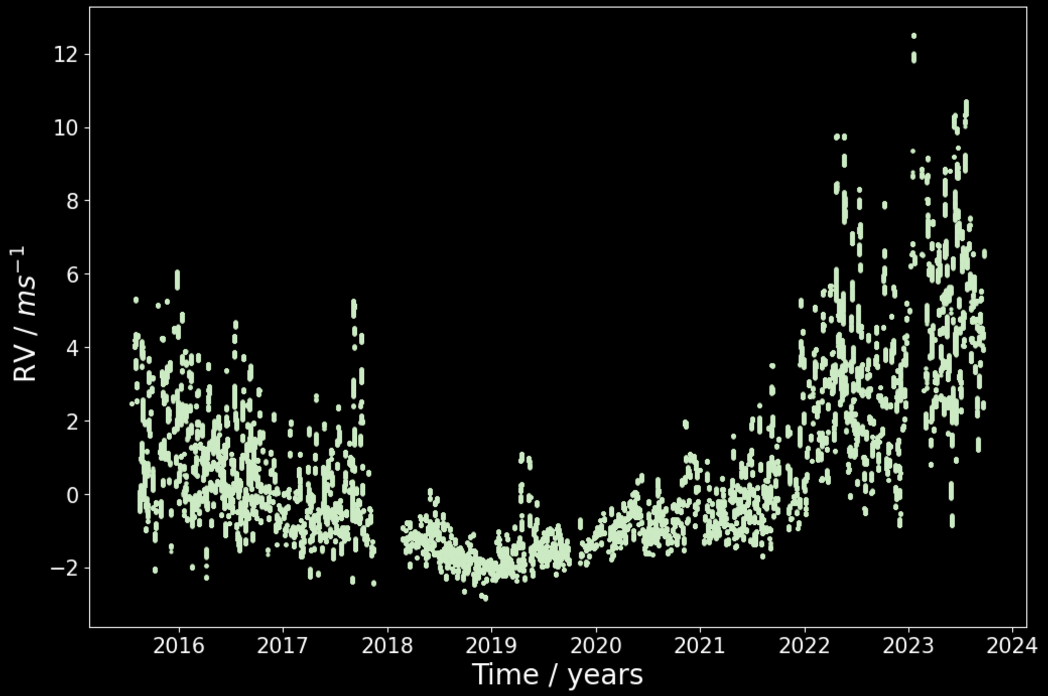
Magnetically Active Solar RVs

SDO





YARARA



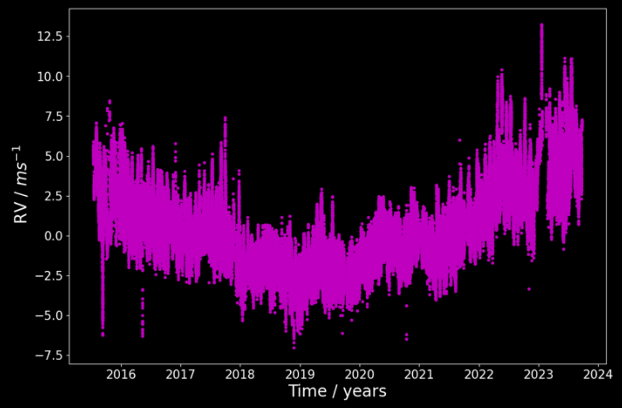
Haywood et al (2016), Milbourne et al (2019) ,
Haywood et al (2022), Lakeland et al (2024)

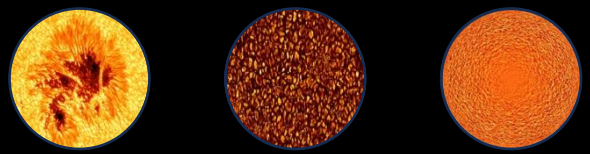
Cretignier et al (2021)

Quiet Sun RVs

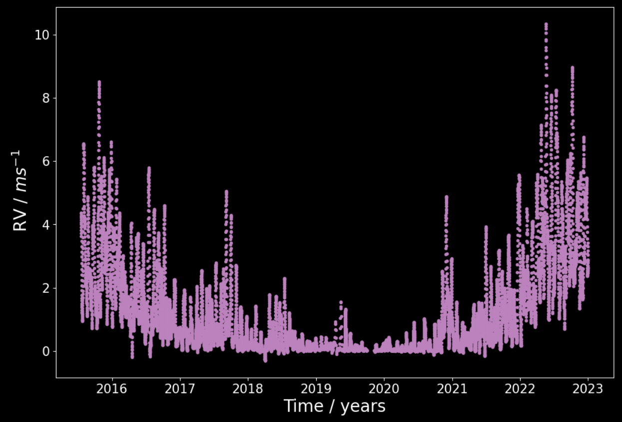
Poster 2:03 by Ben Lakeland
The RV variability of the magnetically quiet Sun

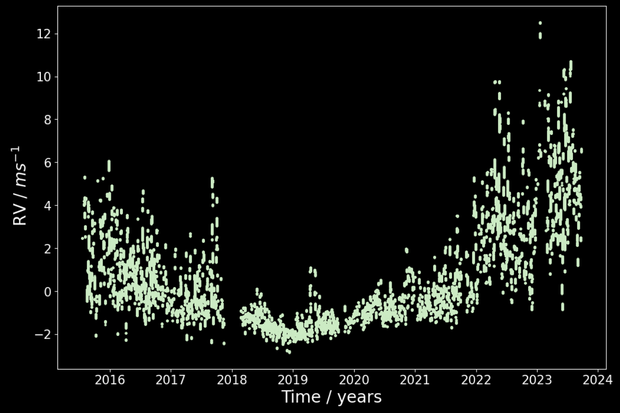
HARPS-N Solar RVs

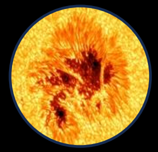




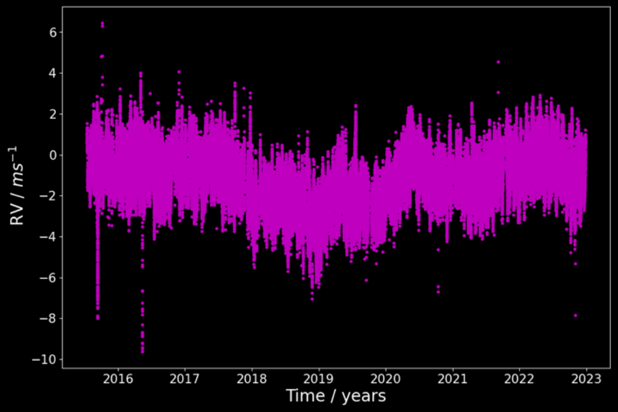
Magnetically Active Solar RVs





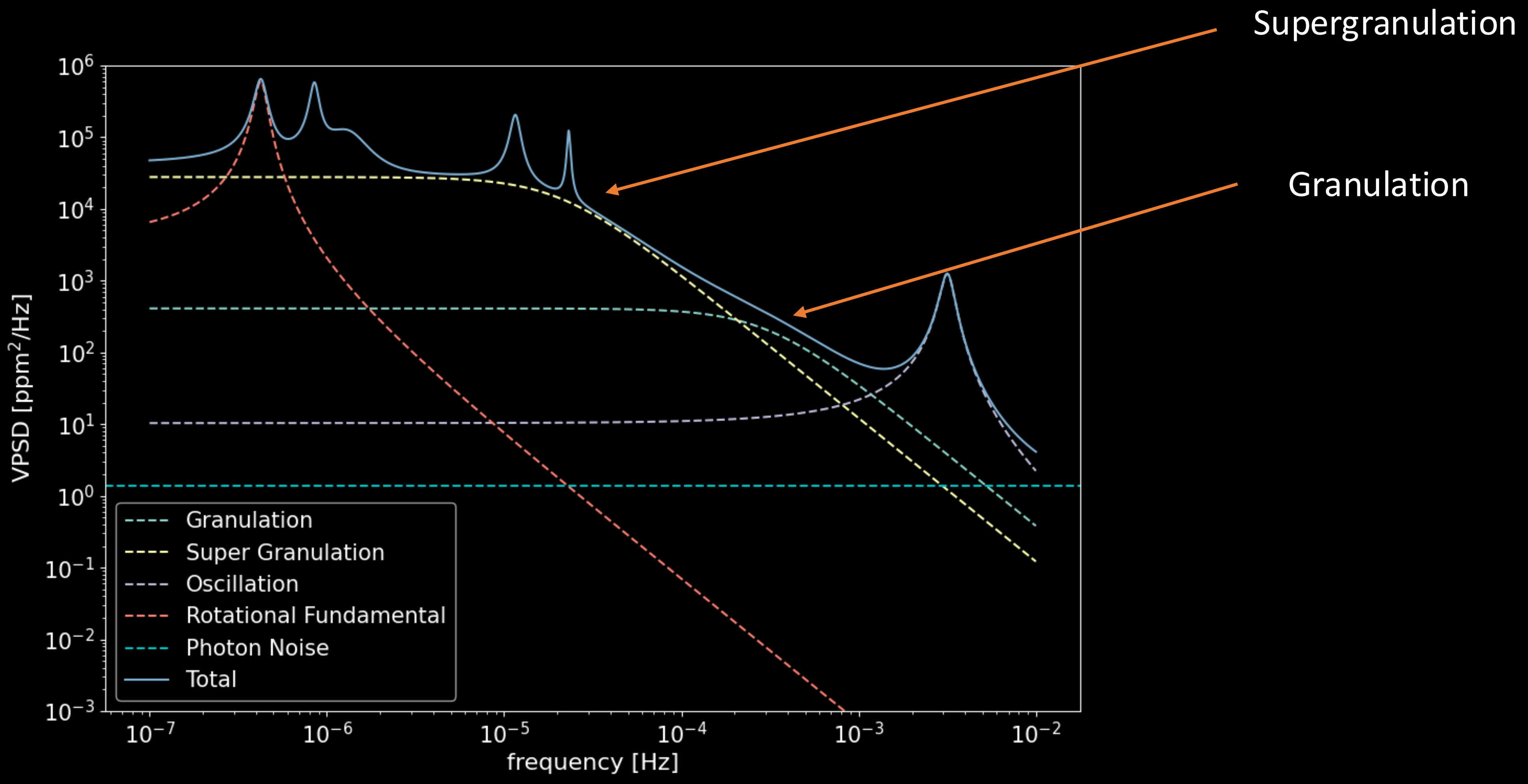


Quiet Solar RVs



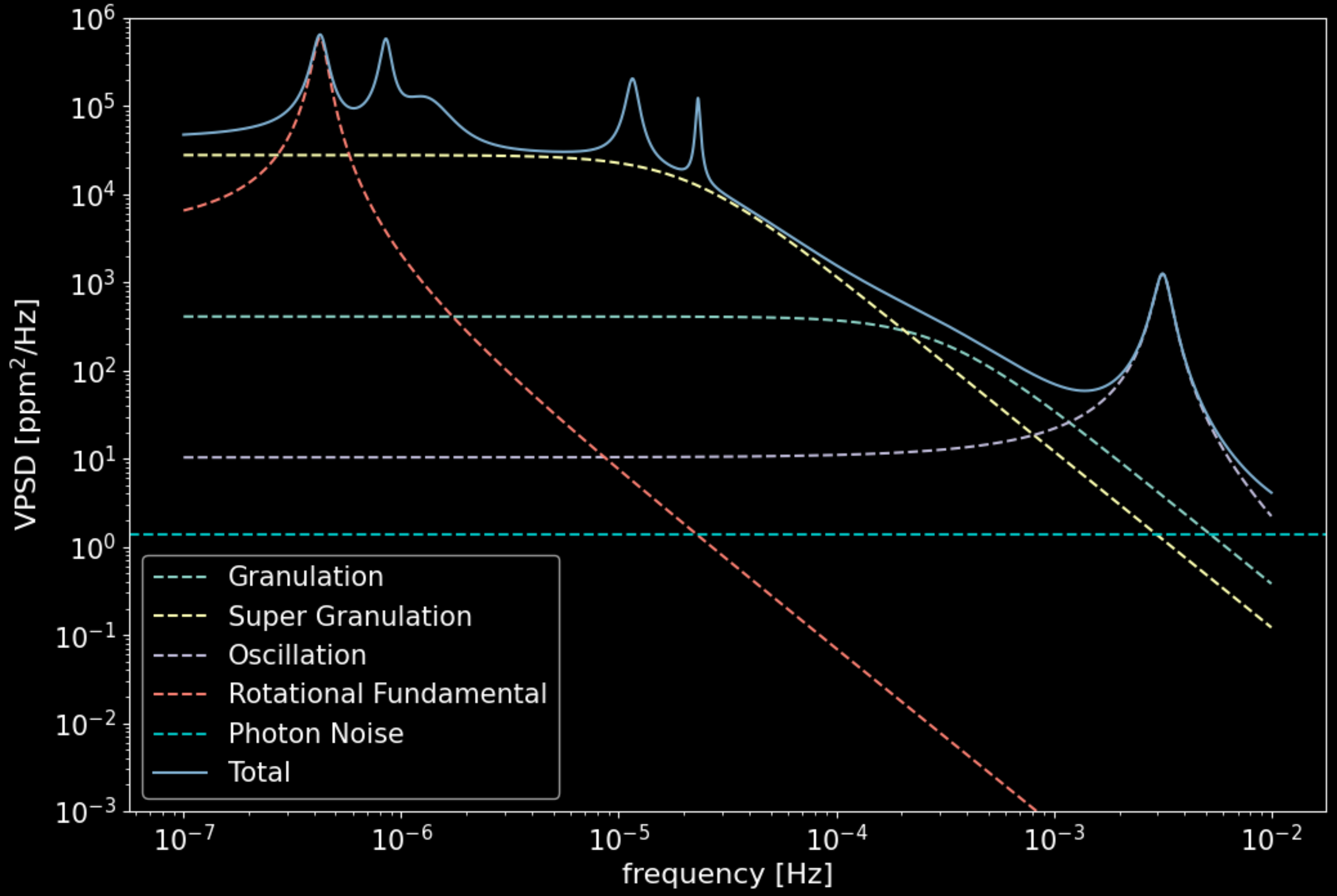
Lakeland et al (2024)

Characterising Stellar Signals with Gaussian Processes (GPs)



Al Moulla et al (2023)

Characterising Stellar Signals with Gaussian Processes (GPs)



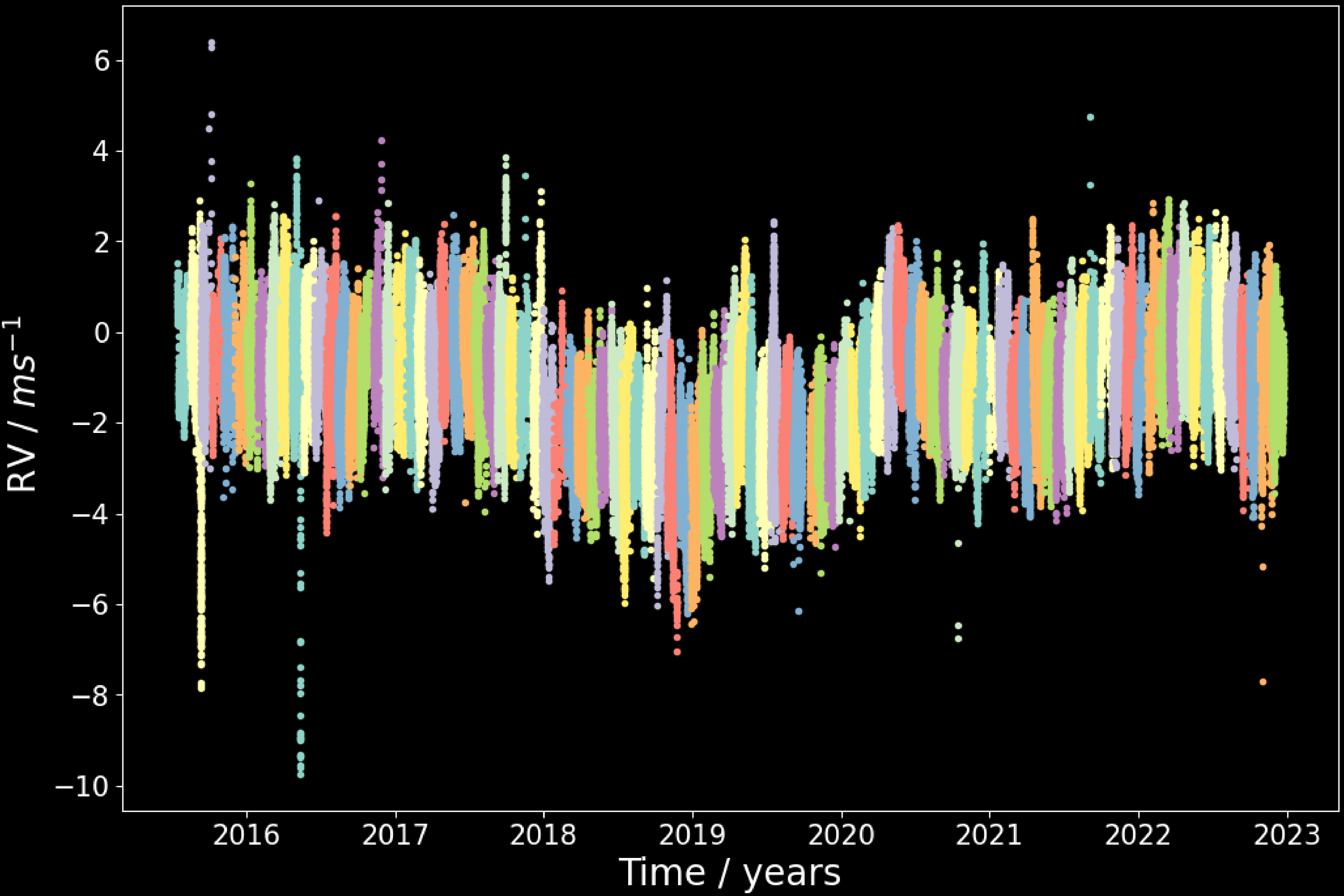
Define the data set as a multivariant Gaussian, and fit the correlation between data points

$$C(\tau) = S_0 \omega_0 e^{-\frac{\omega_0 \tau}{\sqrt{2}}} \cos\left(\frac{\omega_0 \tau}{\sqrt{2}} - \frac{\pi}{4}\right)$$

$$P_{SHO,Q=1/\sqrt{2}}(\nu) = \frac{2S_0}{1 + \left(\frac{\nu}{\nu_0}\right)^4}$$

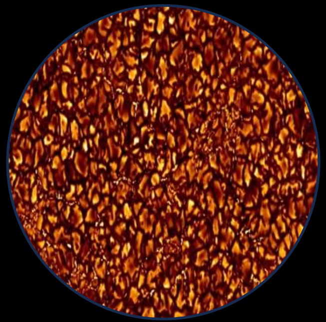
$$\tau = \frac{2\pi}{\omega_0} \qquad \sigma = \sqrt{\frac{S_0 \omega_0}{\sqrt{2}}}$$

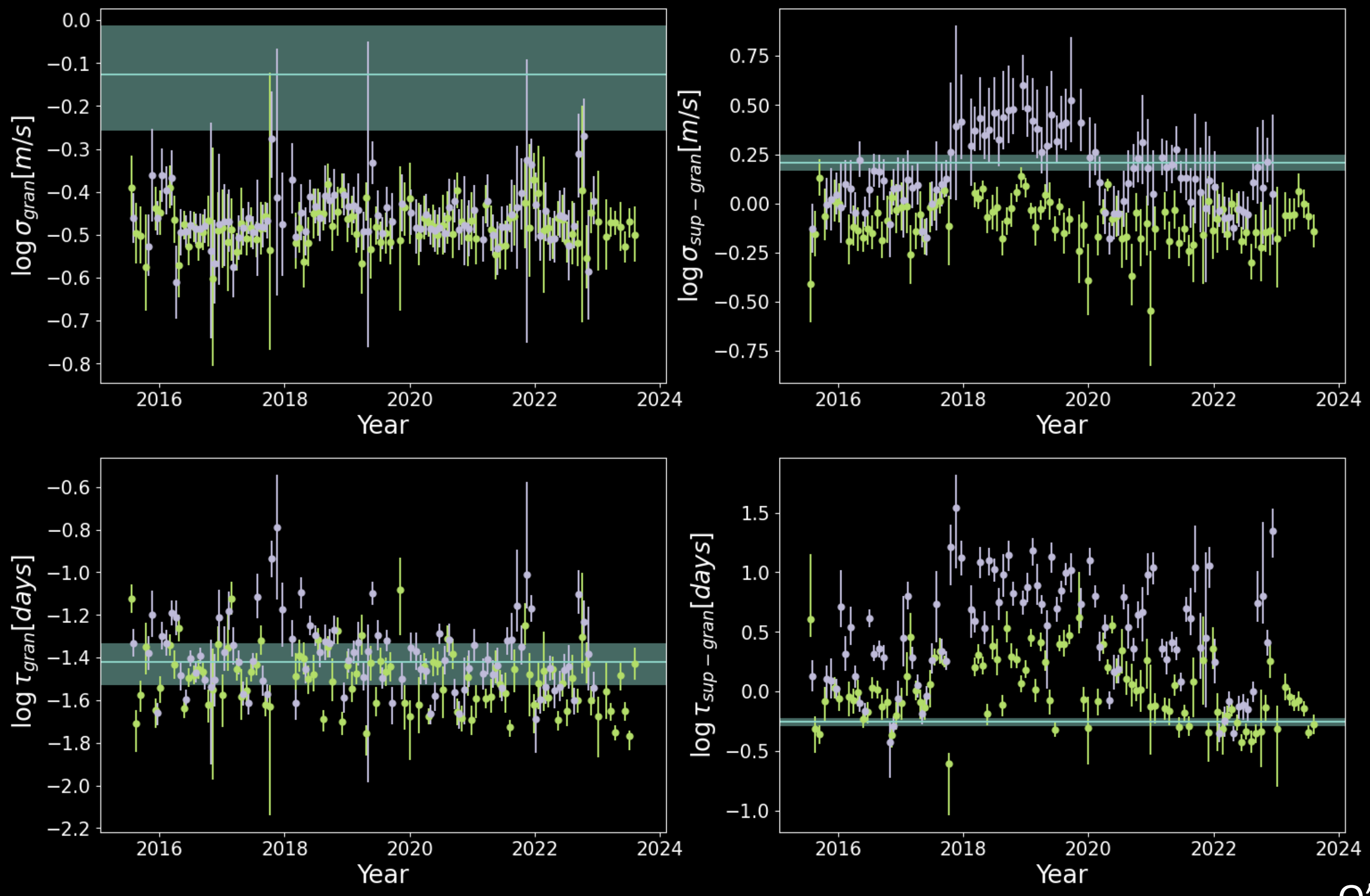
O'Sullivan & Aigrain (2024)

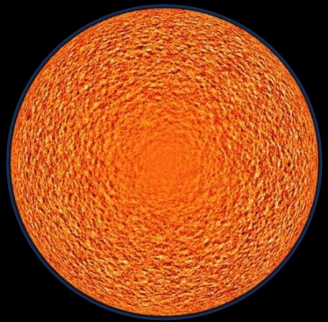


6
4
2
0
−2
−4
−6
−8
−10
RV / ms^{-1}
2016
2017
2018
2019
2020
2021
2022
2023
Time / years

(Super)Granulation Characteristics

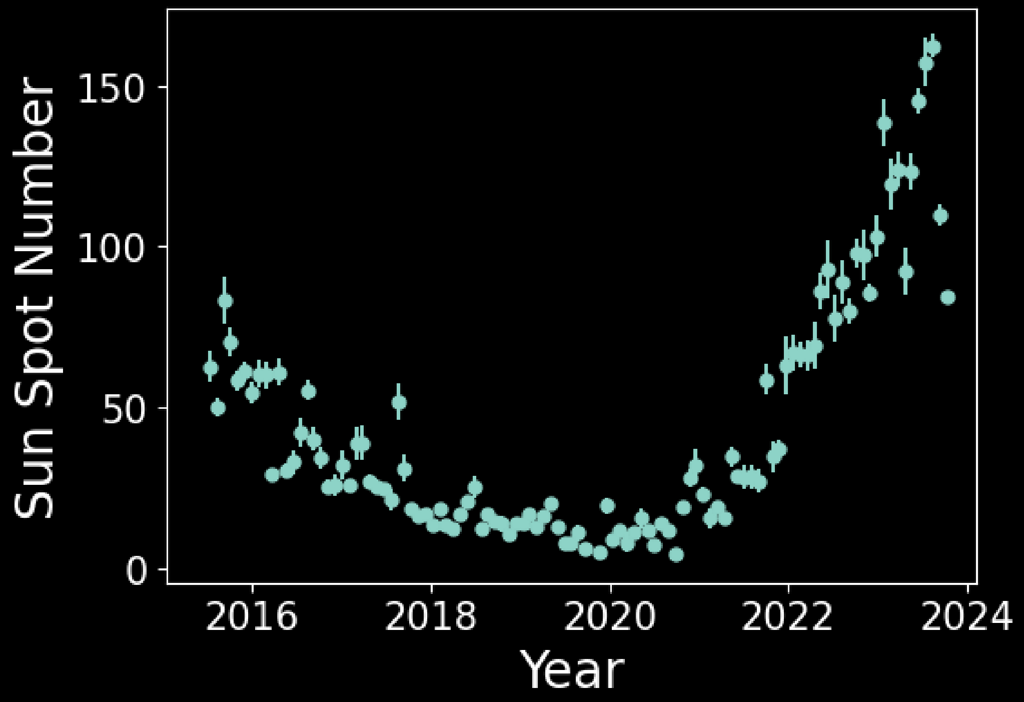


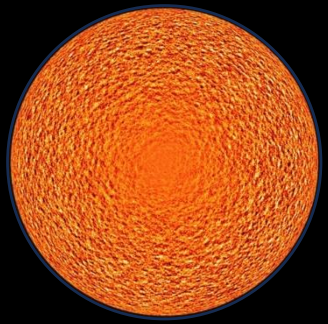


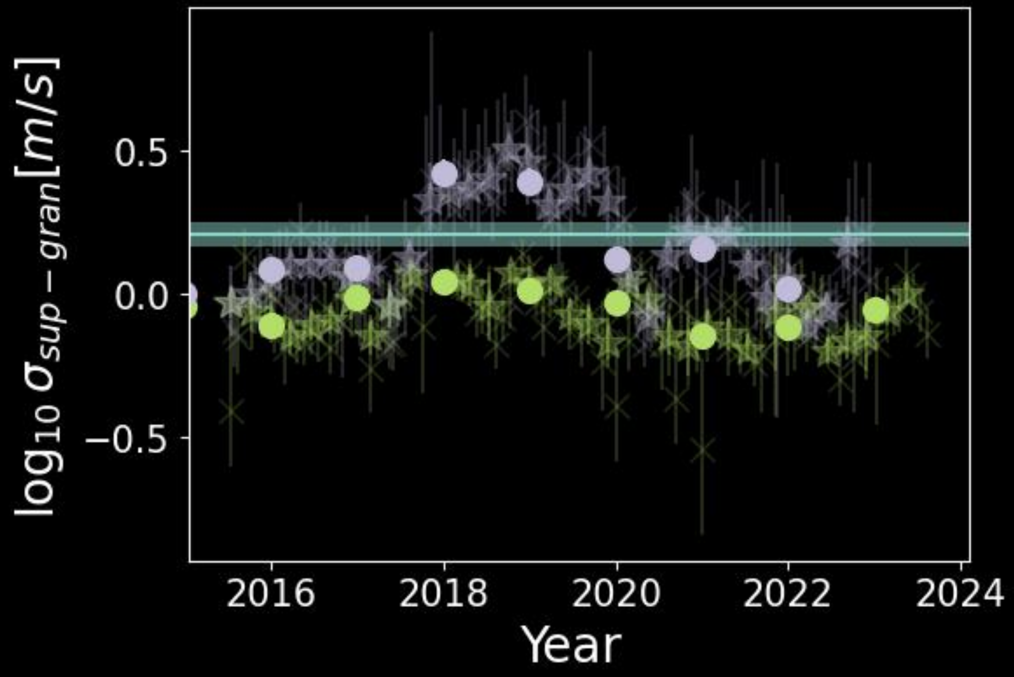


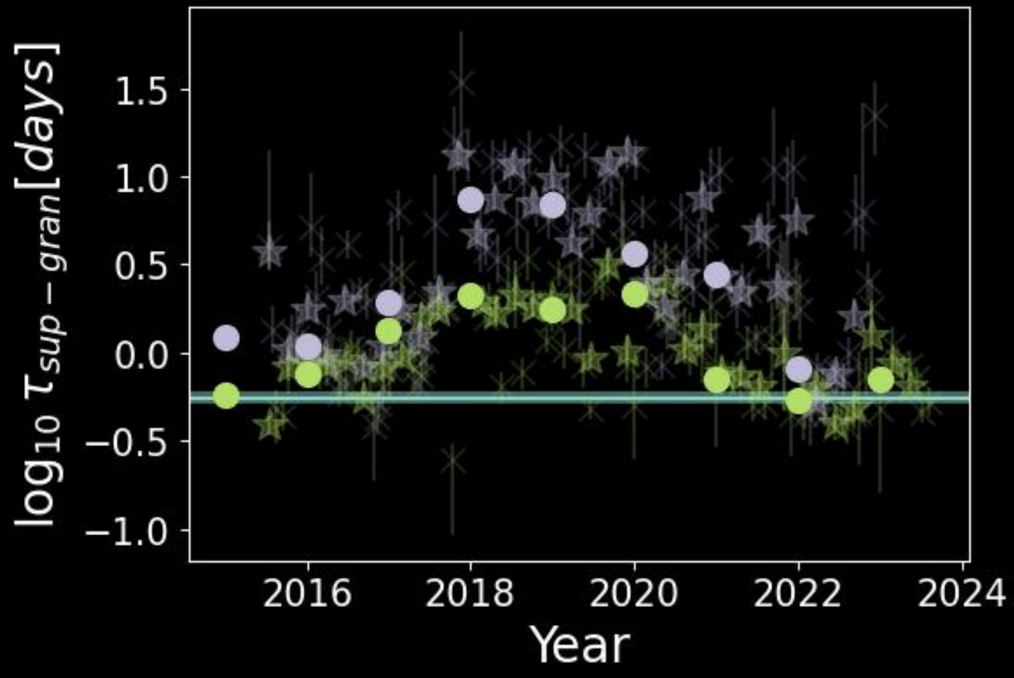
O'Sullivan et al (In Prep)

Supergranulation Cycle?









O'Sullivan et al (In Prep)

Table 1. List of variations of supergranual sizes and lifetimes with magnetic field from the literature. Updated from Meunier et al. (2007). The first 6 references concern studies at a given time (spatial variations), while the last 6 reference studies covering the solar cycle or part of it. FT means Fourier Transform. A plus sign (+) means an increase in cell size with increasing activity levels, while a minus sign (-) means the opposite. An equal sign (=) means no variation was found.

Reference	Data	Method	Size	Time	Comments
Sýkora (1970)	Ca II images	autocorrelation	+		
Wang (1988)	magnetograms	autocorrelation	+	-	large errorbars
Wang et al. (1996)	magnetograms	autocorreltation	+		
Hagenaar et al. (1997)	Ca II K images	segmentation	=		
Raju & Singh (2002)	Ca II K images	autocorrelation	-		
Meunier et al. (2007)	magnetograms	segmentation	-		
Singh & Bappu (1981)	Ca II K images	autocorrelation	-		Via latitude variations
Muenzer et al. (1989)	Ca II K images	2D TF	+		
Kariyappa & Sivaraman (1994)	Ca II K images	segmentation	-		Via brightness intensity
Komm et al. (1995)	magnetograms	autocorrelation	+		FWHM of the autocorrelation curves
Berrilli et al. (1999)	Ca II K images	segmentation	-		Over 1 year only
De Rosa & Toomre (2004)	Doppler	segmentation	-	+	2 time series
Gizon & Duvall (2003, 2004)	Doppler	helioseismology	=	-	week dependance
Meunier et al. (2008)	magnetograms	velocity field divergences	-		1σ detection
McIntosh et al. (2011)	magnetograms & Ca II K images	segmentation	+		
Chatterjee et al. (2017)	Ca II K images	watershed	+		
Mandal et al. (2017)	Ca II K images	watershed	+		
Rajani et al. (2022)	Ca II K images	segmentation	-		
Sowmya et al. (2023)	Ca II K images	segmentation		+	

How much do we need to observe?

Use the Fisher information content which allows us to quantify the fractional uncertainty of a parameter as a function of the observational strategy used.

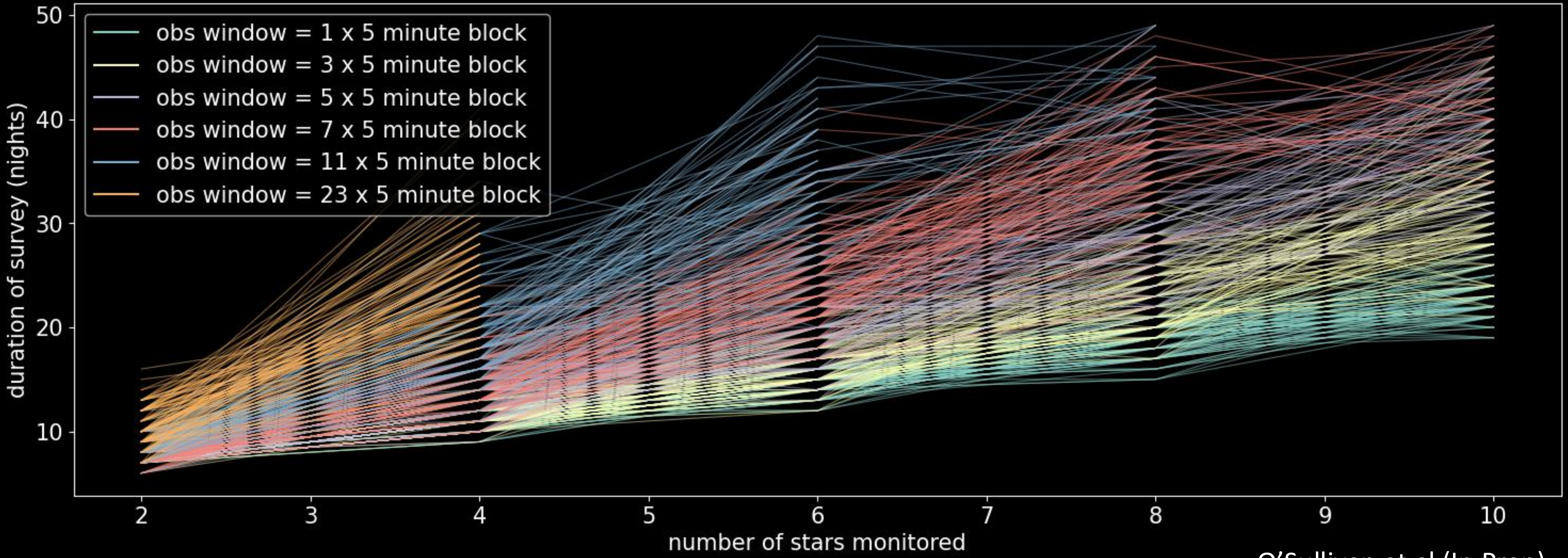
$$\mathbf{B}_{ij} = \left(\frac{\partial\mu}{\partial\theta_i}\right)^T C^{-1}\left(\frac{\partial\mu}{\partial\theta_i}\right) + \frac{1}{2}\,\mathbf{tr}\left(C^{-1}\frac{\partial C}{\partial\theta_i}C^{-1}\frac{\partial C}{\partial\theta_i}\right)$$

$$\sigma^2_{\theta_i} = \boldsymbol{B}^{-1}_{i,j}$$

Gupta + Bedell (2024)

How much do we need to observe?

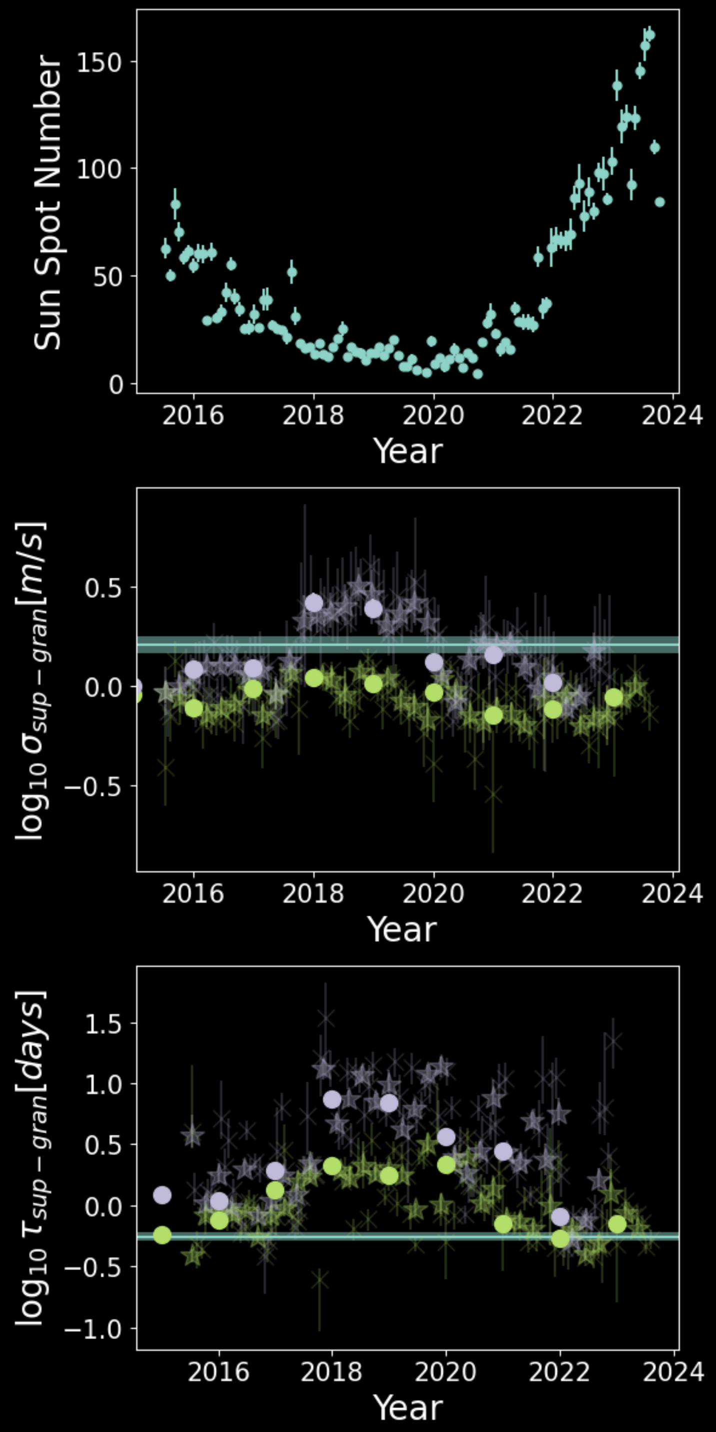
Talk tomorrow by Arvind Gupta on the EPRV Standard Star Survey



O'Sullivan et al (In Prep)

Summary

- Best to characterise granulation and supergranulation in the time domain
- The characteristic time-scale of supergranulation appears to vary over the Sun's magnetic cycle
- 10 stars can be characterised in 20 nights of observations



Email: niamh.osullivan@physics.ox.ac.uk
Bluesky: @niamhk12.bsky.social

Injection Recovery Tests
One Earth Planet

- Green = -50 > Log FAP
- Blue = -10 > Log FAP > - 50
- Yellow = -5 > Log FAP > -10
- Pink = -1.5 > Log FAP > -5
- Red = -1.5 < Log FAP
- White =Not Detected