Predicting radial-velocity dispersion due to granulation in FGK stars

Dr Shweta Dalal

with Raphaëlle Haywood, Annelies Mortier, William Chaplin and Nadége Meunier

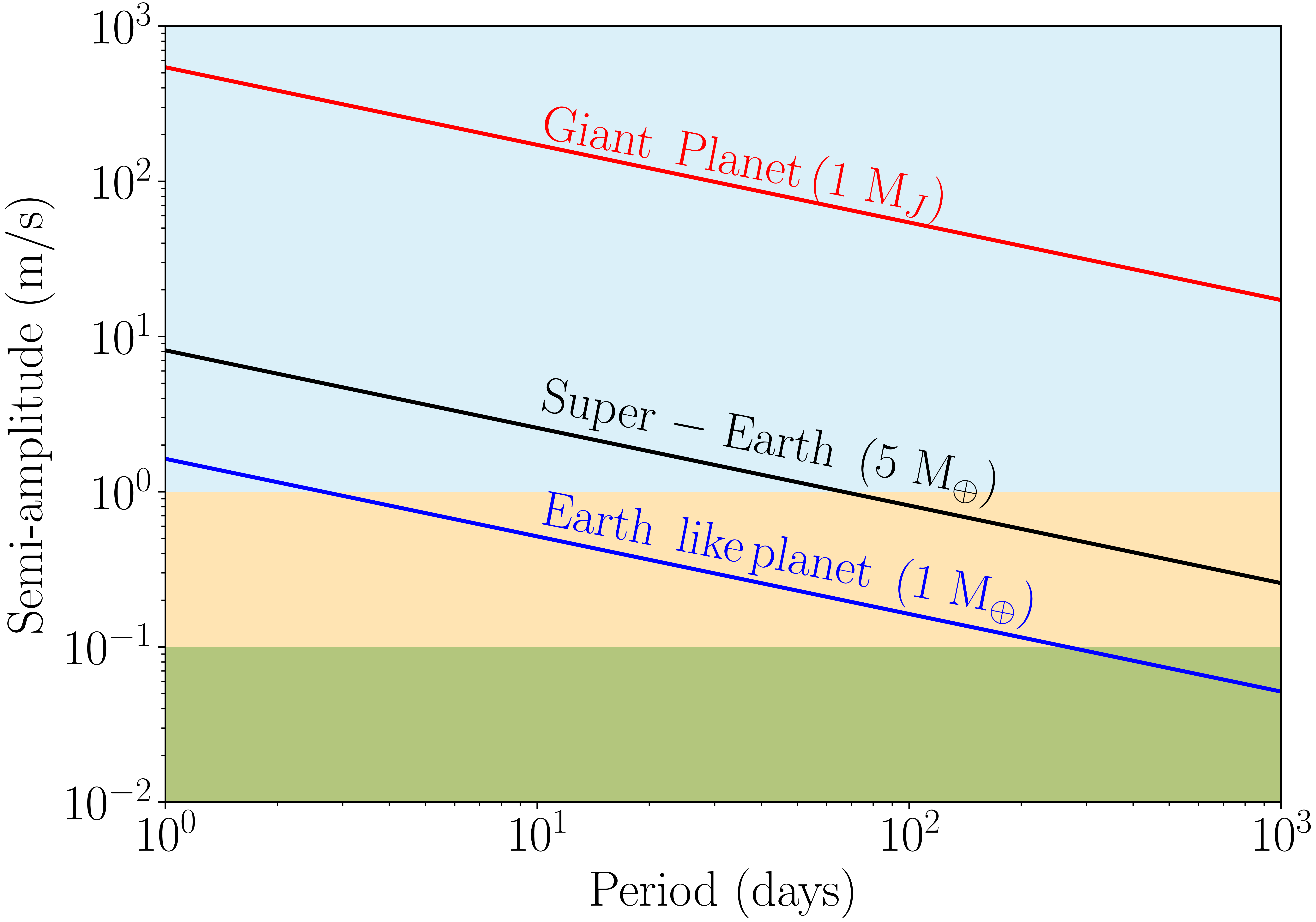
University of Exeter

PLATO

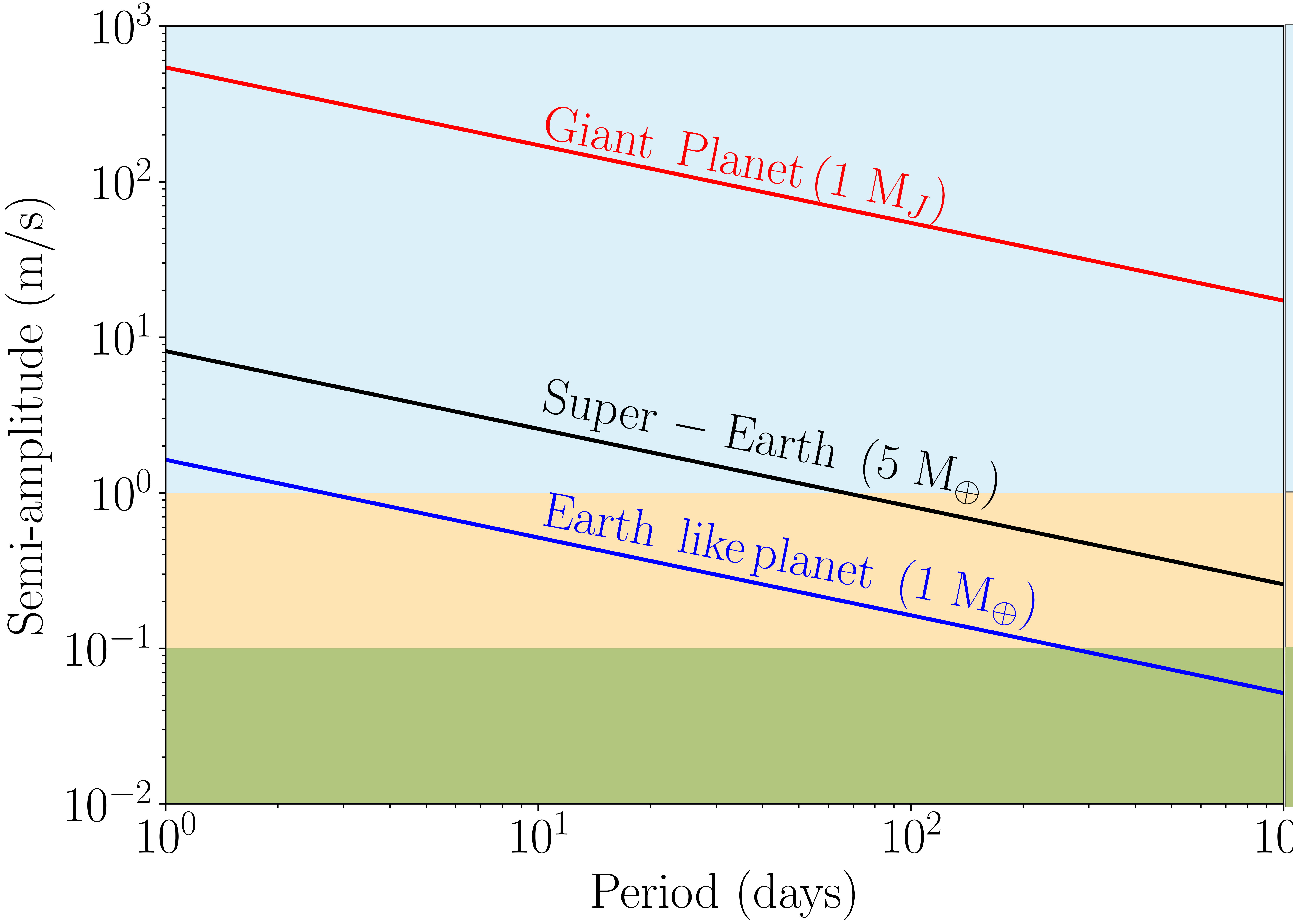
1. planet detection and radii determination from photometric transits of planets in orbit around bright stars ($V < 11$)
2. **determination of planet masses from ground-based radial velocity follow-up**,
3. determination of accurate stellar masses, radii, and ages from asteroseismology, and
4. identification of bright targets for atmospheric spectroscopy.

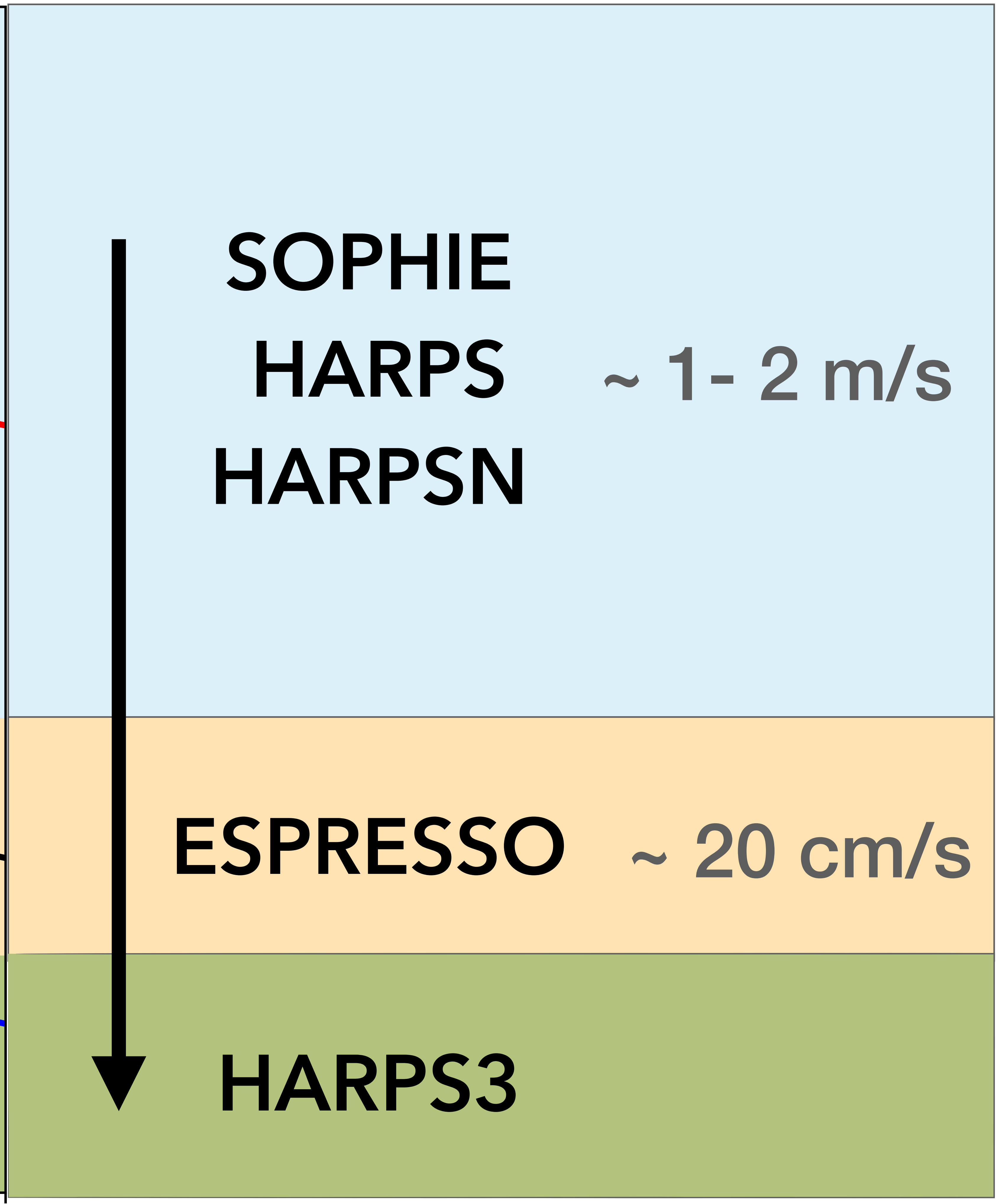
https://www.cosmos.esa.int/web/plato/

Where We Stand



Where We Stand : A Look at Instrument Advancements





SOPHIE
HARPS
HARPSN

~ 1- 2 m/s

ESPRESSO ~ 20 cm/s

HARPS3

Stellar Variability: An Obstacle in the Hunt for Other Earths

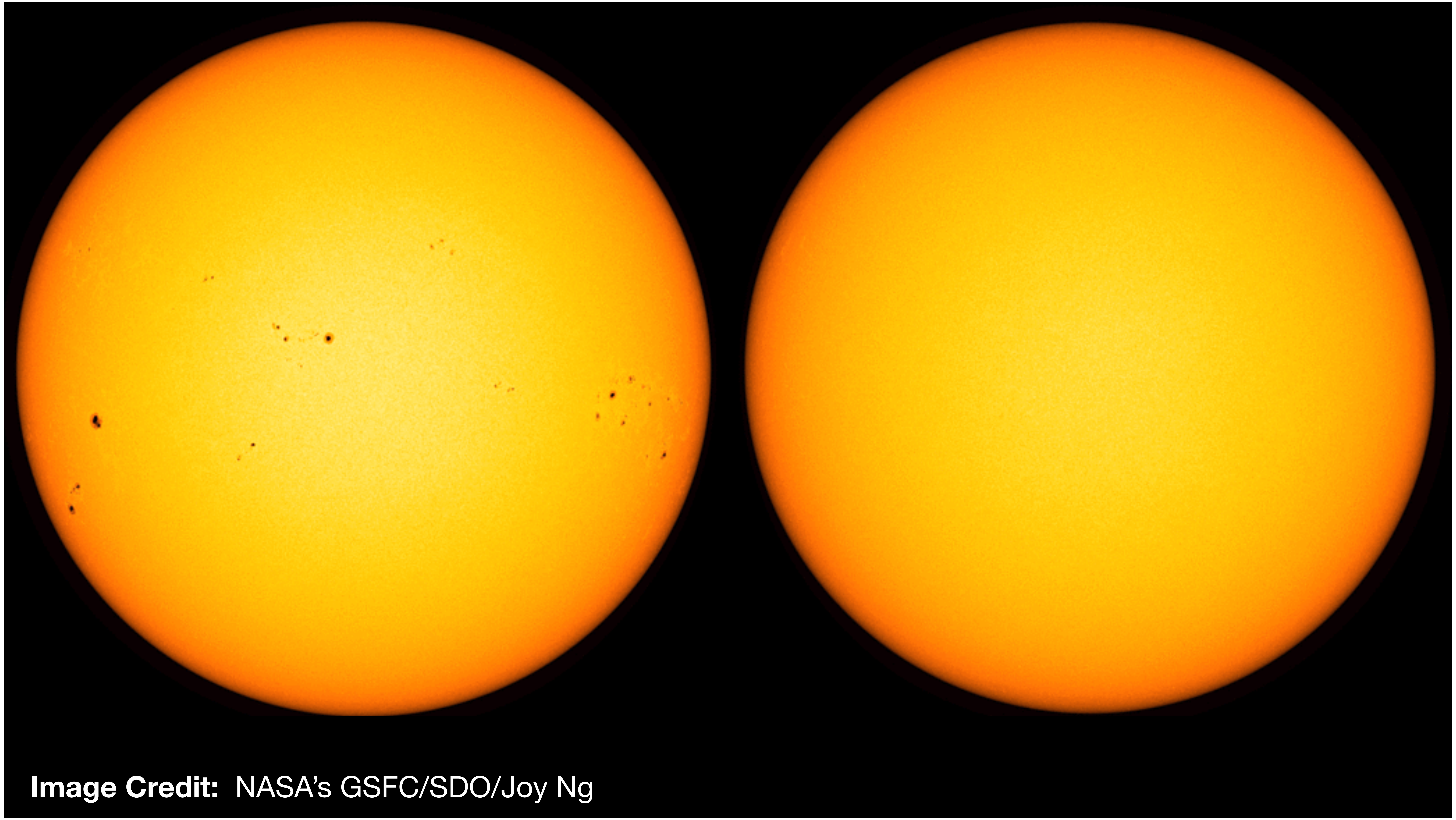


Image Credit: NASA's GSFC/SDO/Joy Ng

Stellar Variability: An Obstacle in the Hunt for Other Earths

Data Credit - https://dace.unige.ch/dashboard/

Stellar Variability: An Obstacle in the Hunt for Other Earths

Data Credit - https://dace.unige.ch/dashboard/

Overcoming the stellar variability

- **Observational strategies** that average out oscillations over time
  (Dumusque et al. 2011; Chaplin et al. 2019)

- **De-trending the stellar activity signal using activity indicators**
  (Boisse et al. 2009; Tuomi et al. 2014)

- **Building simple models of stellar surface features**
  (Lanza et al. 2010; Boisse et al. 2012)

- **Gaussian Processes** to account for correlated stellar noise
  (Haywood et al. 2014; Rajpaul et al. 2015; Barragán et al. 2019)

Understanding the stellar variability

Insights into the **Characteristic Amplitudes and Timescales** of active regions (**Saar et al. 1998**, **Bastien et al. 2014**, **Rodríguez Díaz et al. 2022**)

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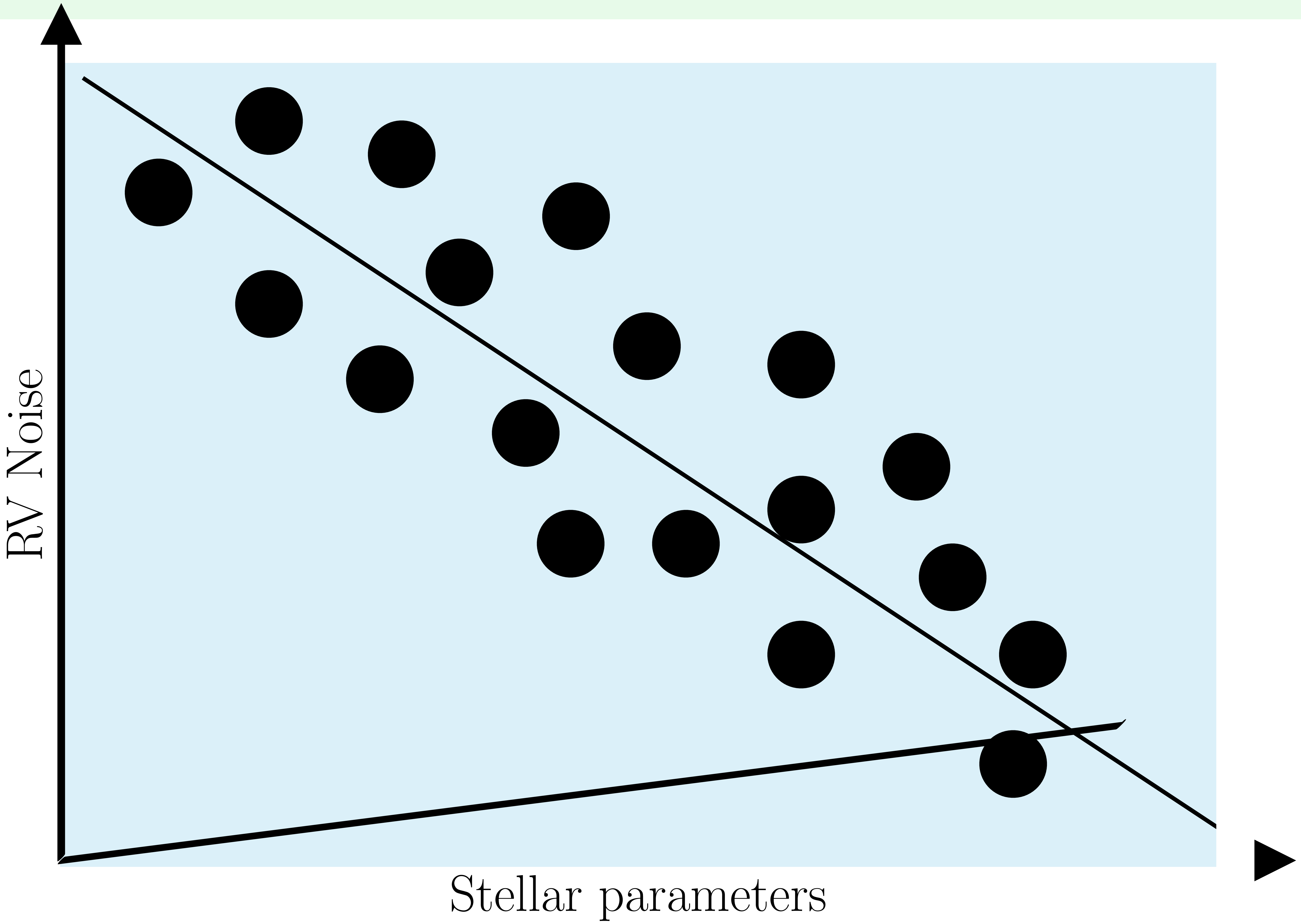
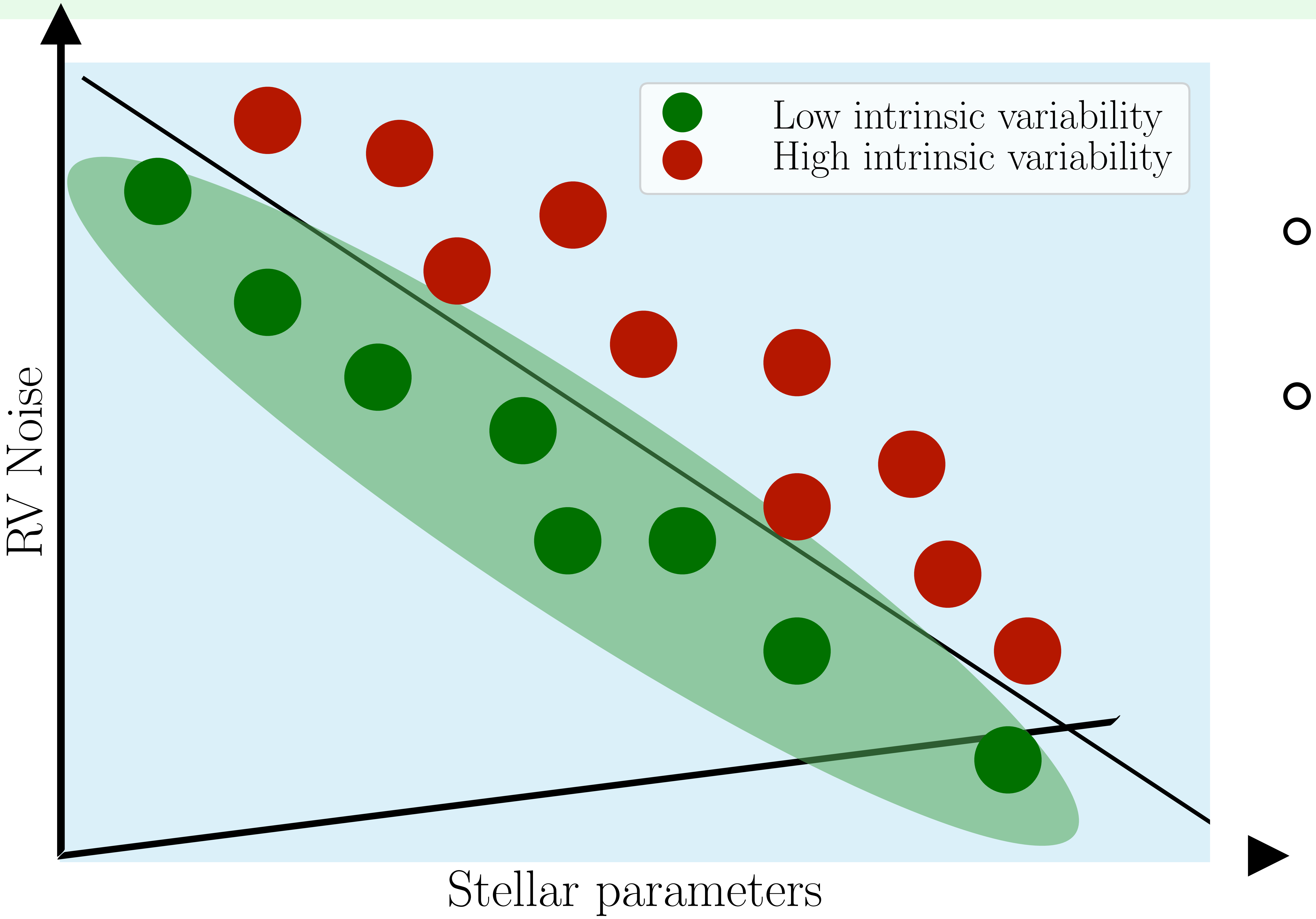


Understanding the stellar variability

Insights into the **Characteristic Amplitudes and Timescales** of active regions (**Saar et al. 1998**, **Bastien et al. 2014**, **Rodríguez Díaz et al. 2022**)



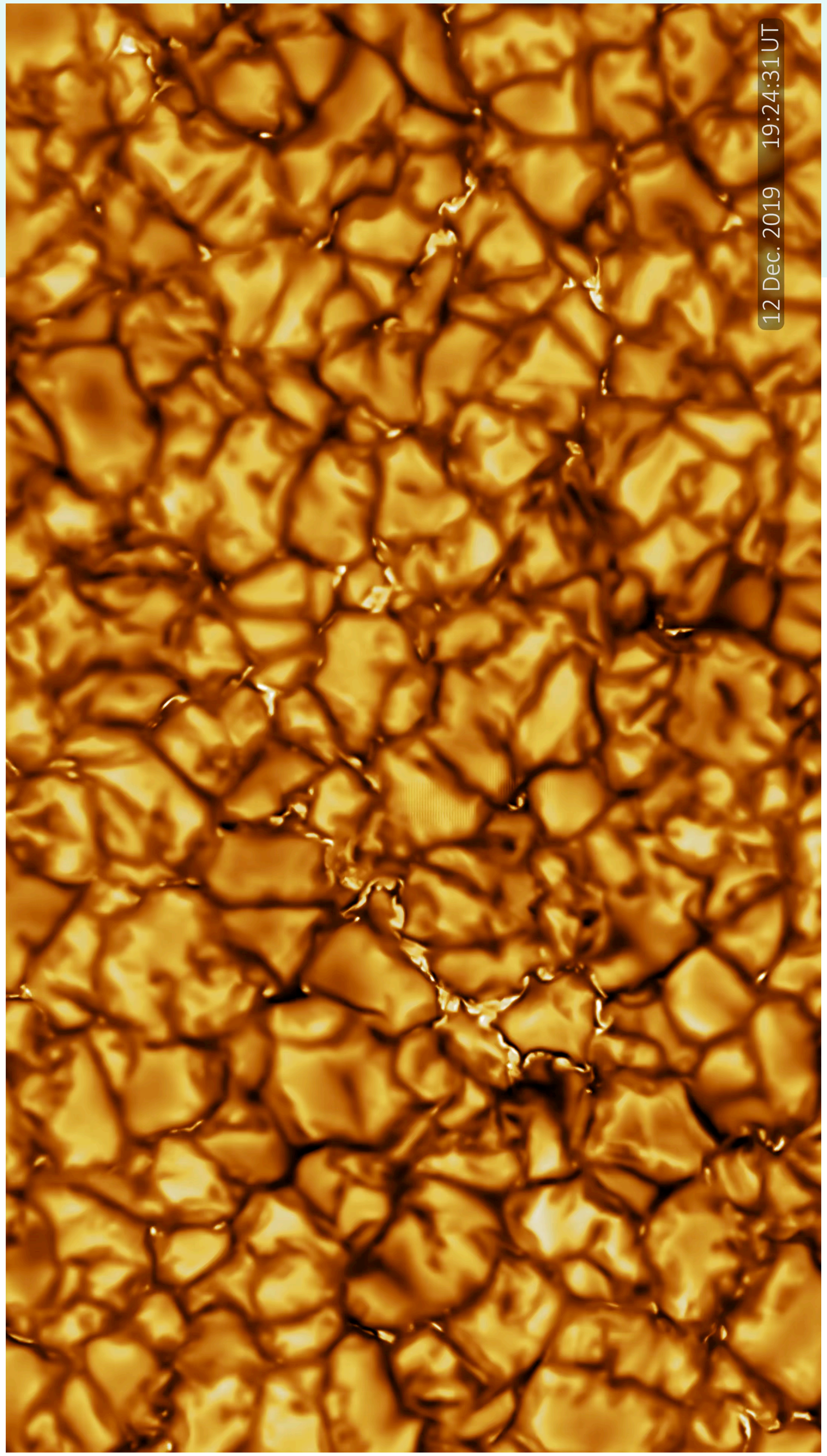
- Select most amenable targets for future missions such as PLATO.
- Step closer to modeling the radial velocity variability for stellar activity signals -> perform MHD for detailed analysis.

GRANULATION ON THE SURFACE OF STAR

- Granulation is the **visible signature of convective cells** at the surface of stars, which have a convective envelope in their outer layer.

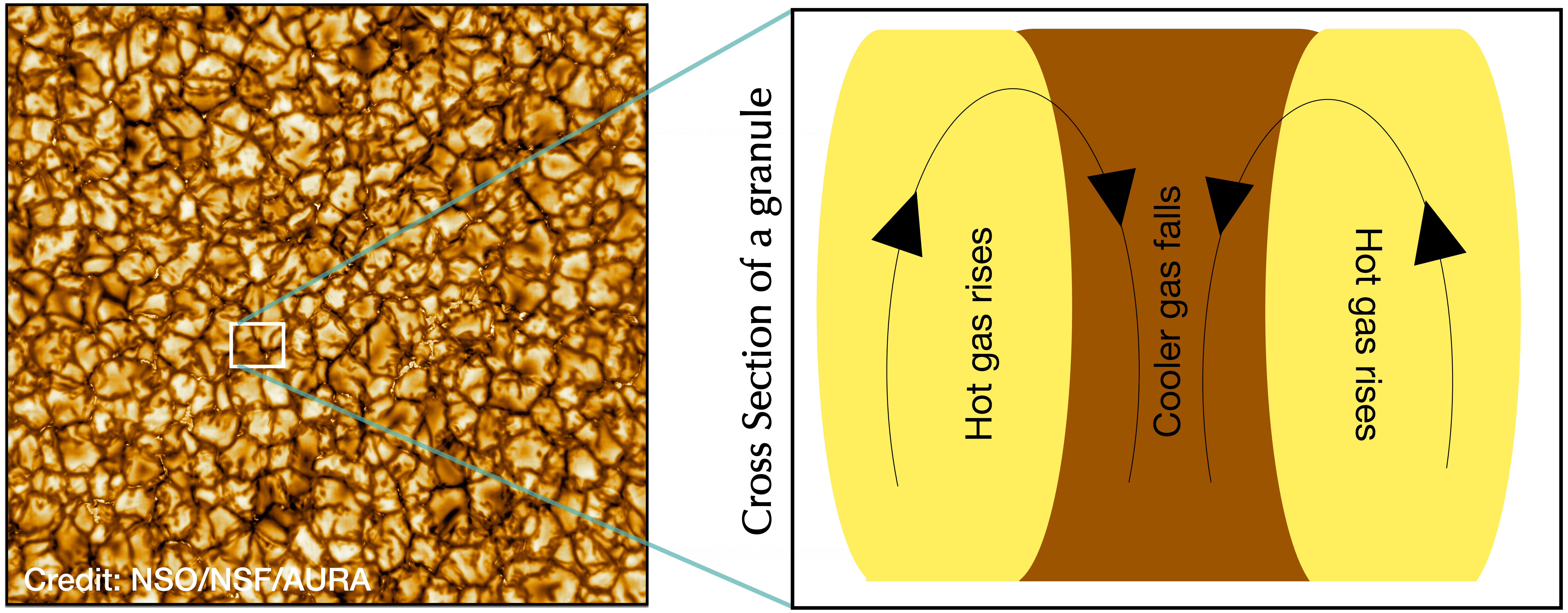
- Granules are small, bright areas of hot rising gas, while intergranular lanes are dark, thin areas between granules where cooler gas sinks.

- Typical granule has a diameter of **30 -1500 kilometres with characteristic lifetimes of ~ 10 minutes.**



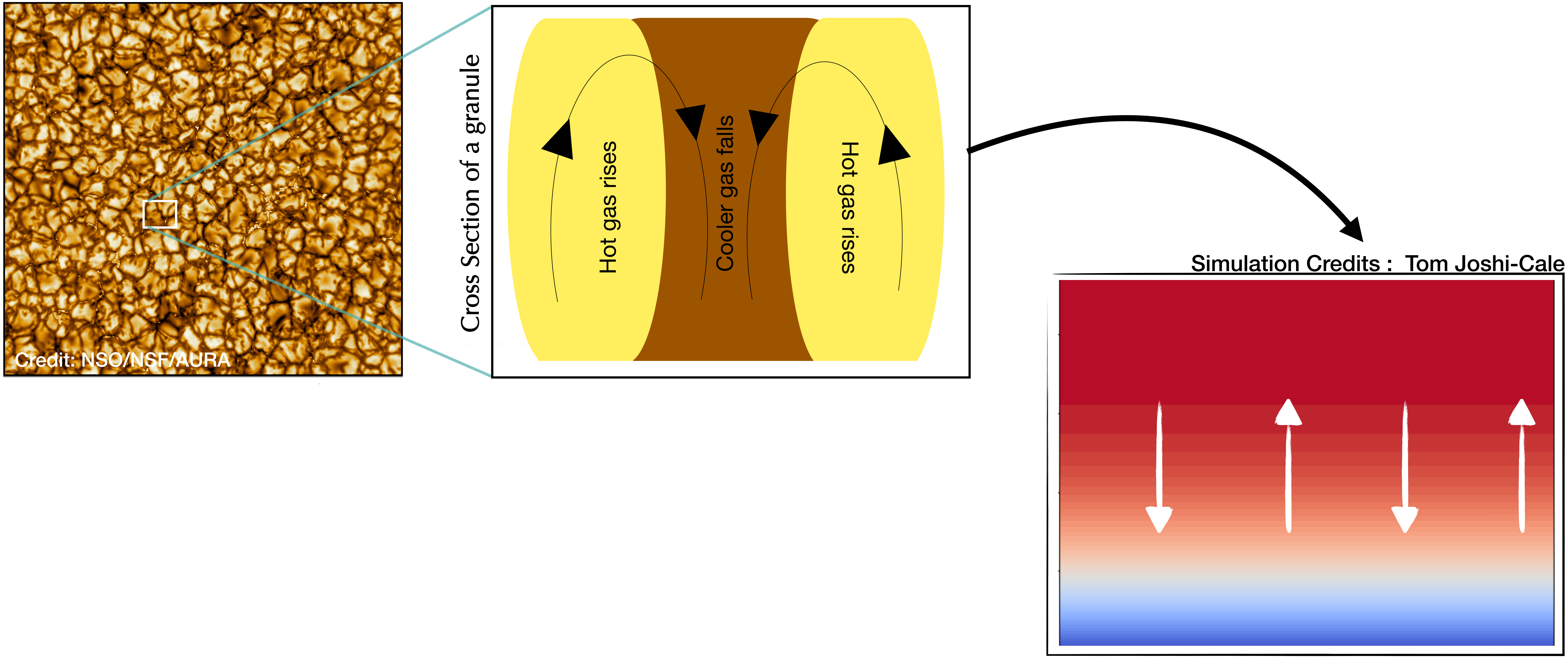
Credit: NSO/NSF/AURA

Stellar Granulation



Credit: NSO/NSF/AURA

Stellar Granulation to Convective Blueshift



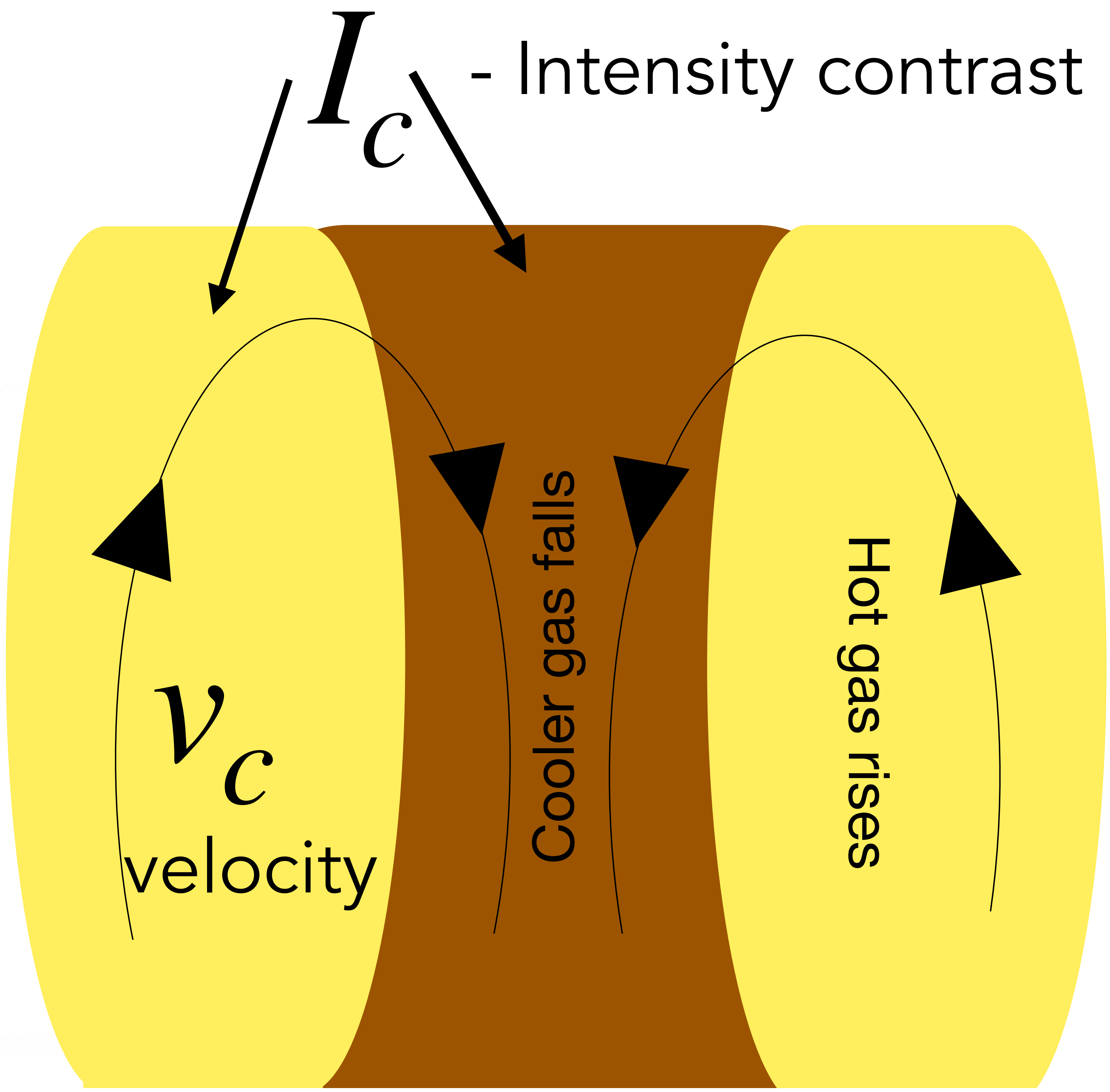
Credit: NSO/NSF/AURA

Simulation Credits : Tom Joshi-Cale

Model : To predict Convective Blueshift of FGK stars

Our model for Convective Blueshift $(\mathscr{V})$

$$\mathscr{V} = f_c v_c$$



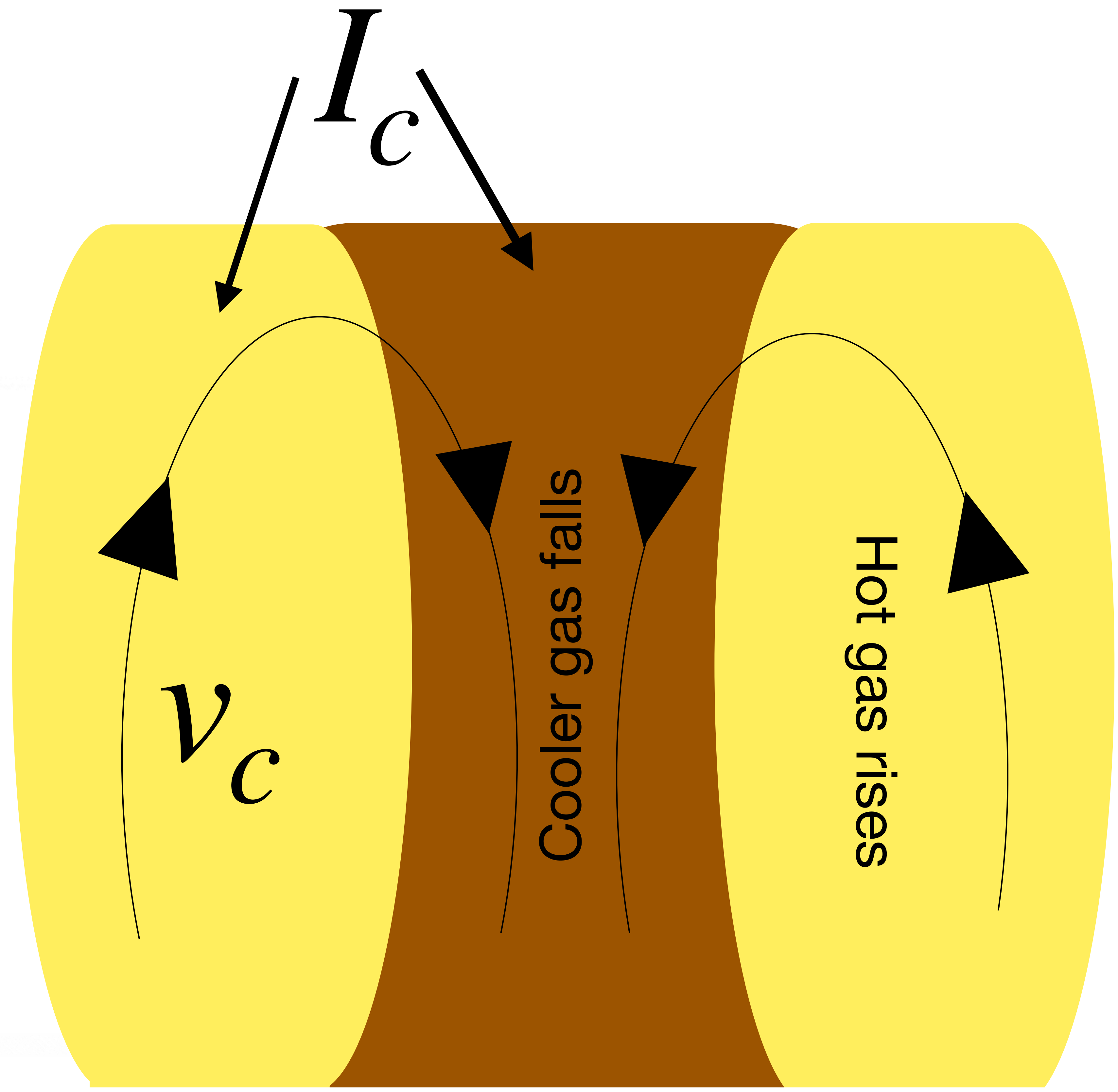
Cross Section of Granule

Our model for Convective Blueshift $(\mathscr{V})$

$$\mathscr{V} = f_c v_c$$

Convection factor

Convection velocity



Cross Section of Granule

Our model for Convective Blueshift $(\mathscr{V})$

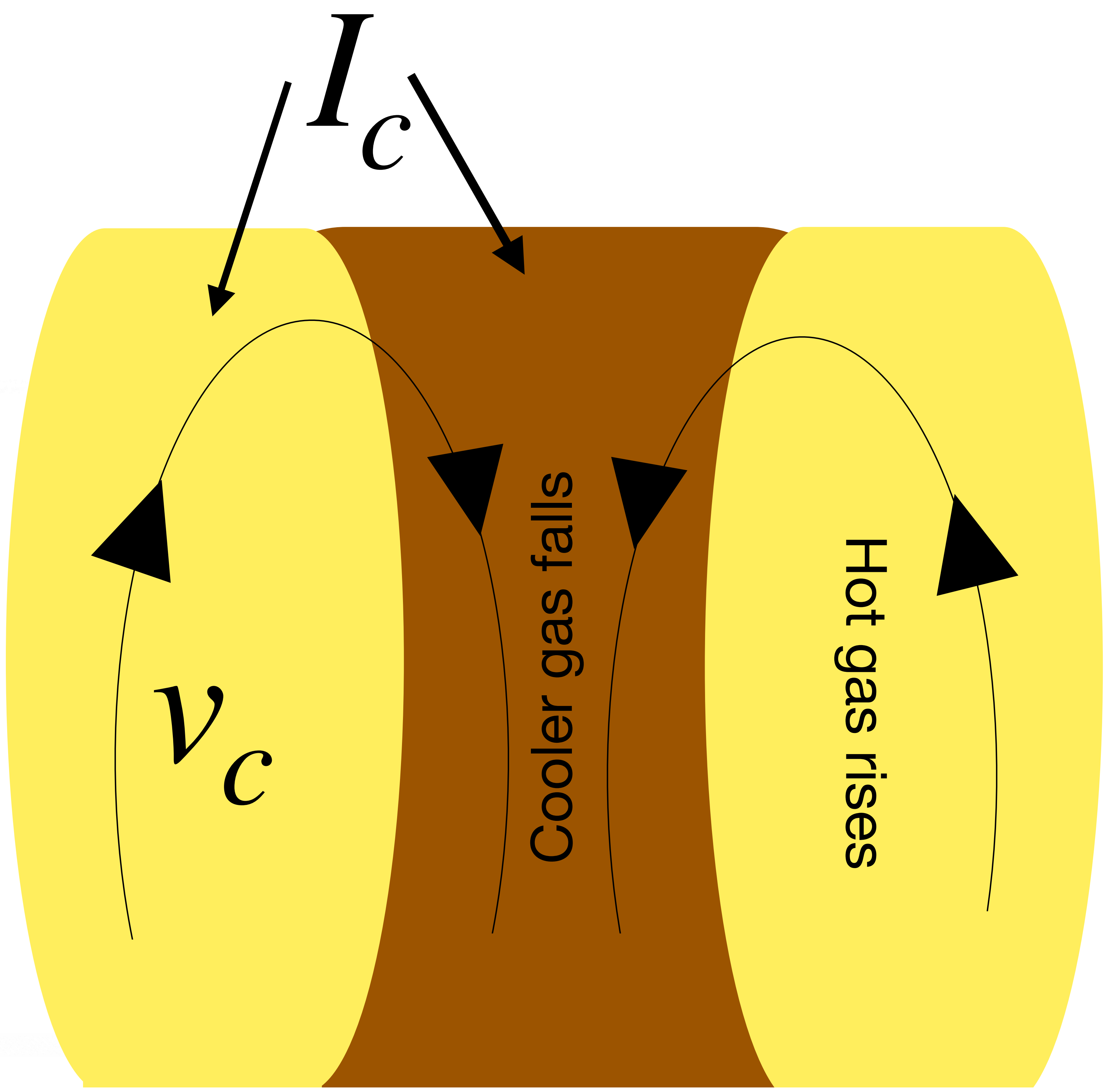
$$\mathscr{V} = f_c \, v_c$$

Convection factor

Convection velocity

$$v_c \propto T_{\rm eff}^{32/9} \, g^{-2/9}$$

Basu & Chaplin 2017



Cross Section of Granule

Our model for Convective Blueshift $(\mathscr{V})$

$$\mathscr{V} = f_c \, v_c$$

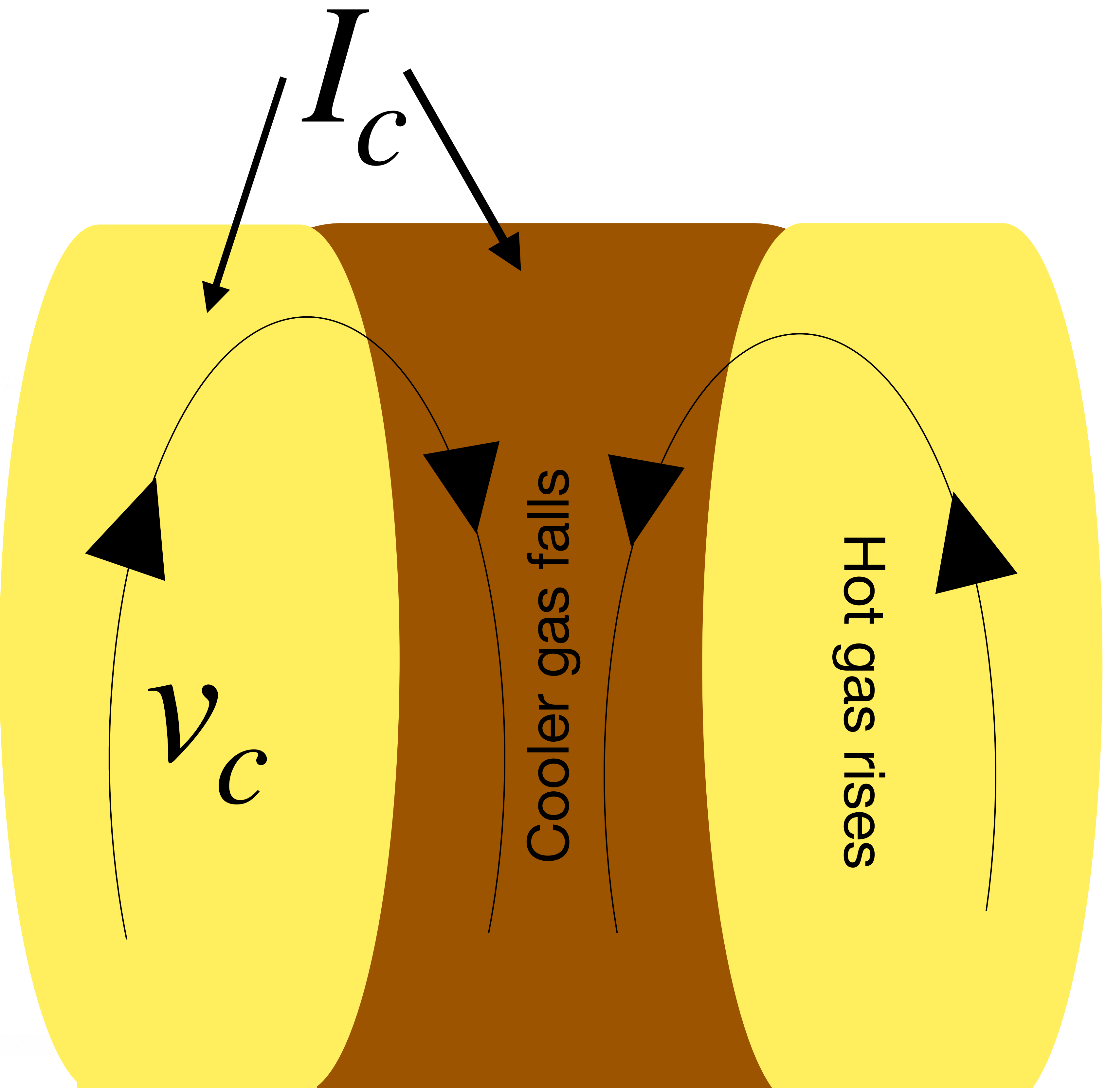
Convection factor

Convection velocity

$$f_c \sim I_c^2$$

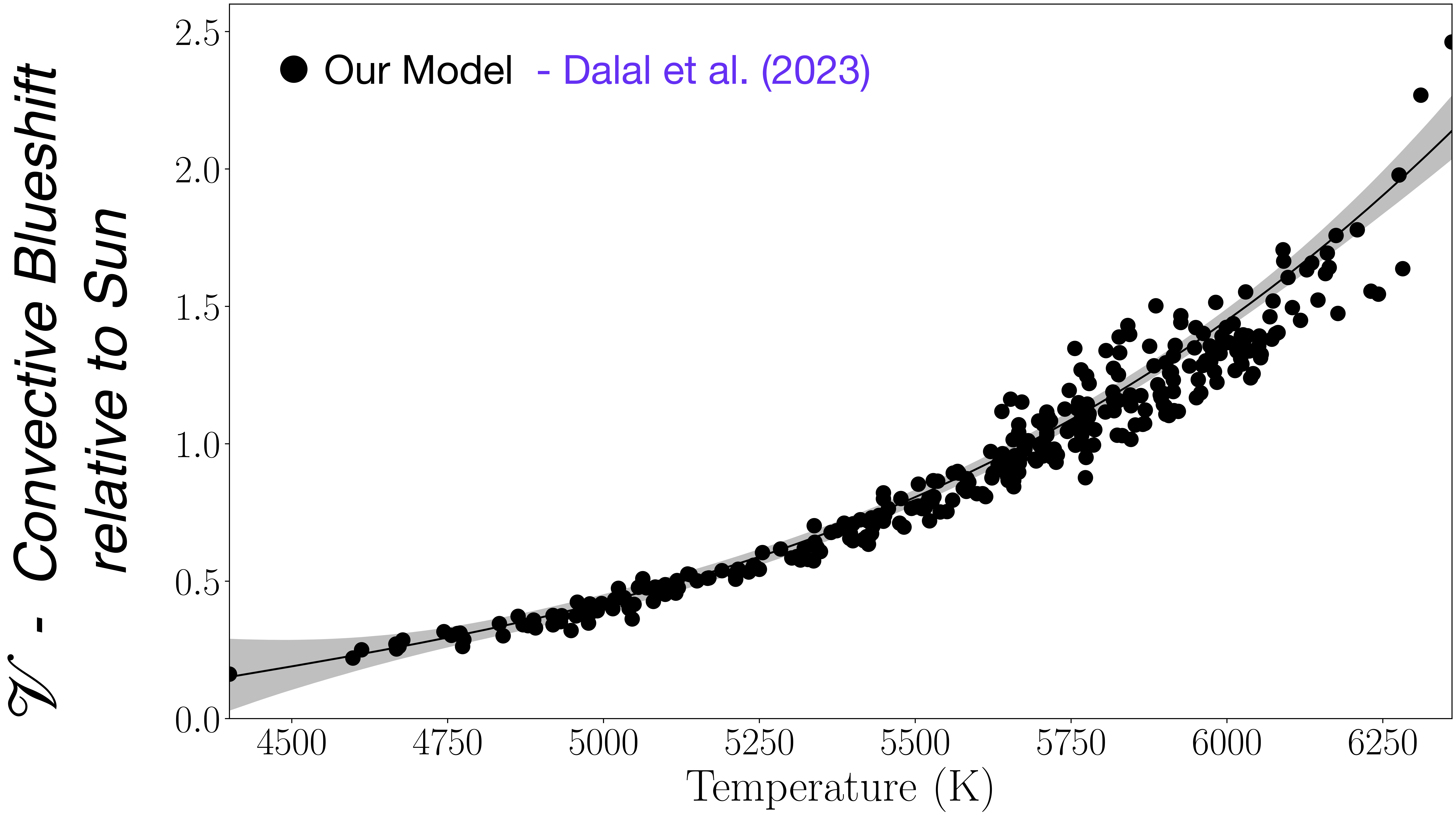
$$v_c \propto T_{\text{eff}}^{32/9} \, g^{-2/9}$$

Basu & Chaplin 2017

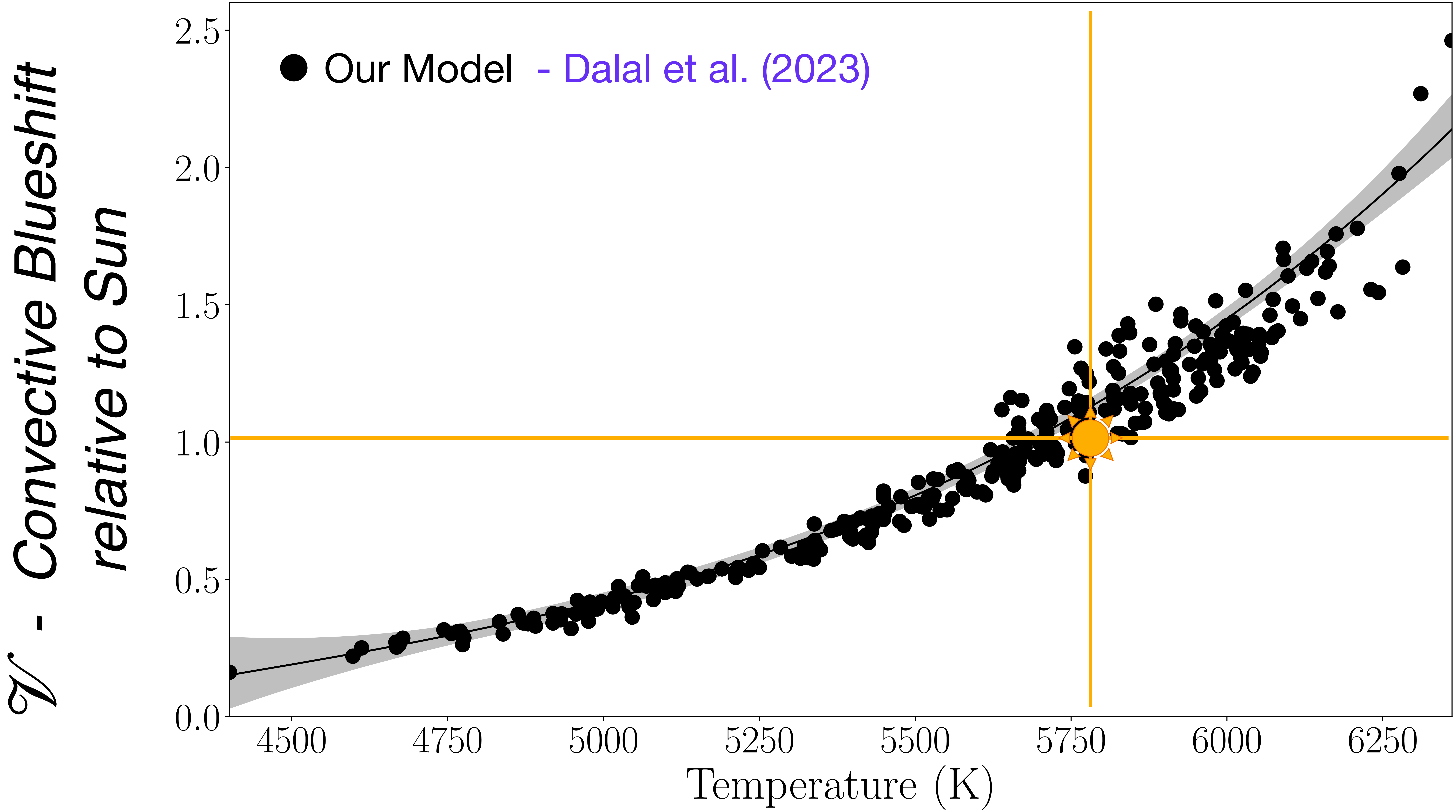


Cross Section of Granule

Convective Blueshift ($\mathscr{V}$) - Temperature

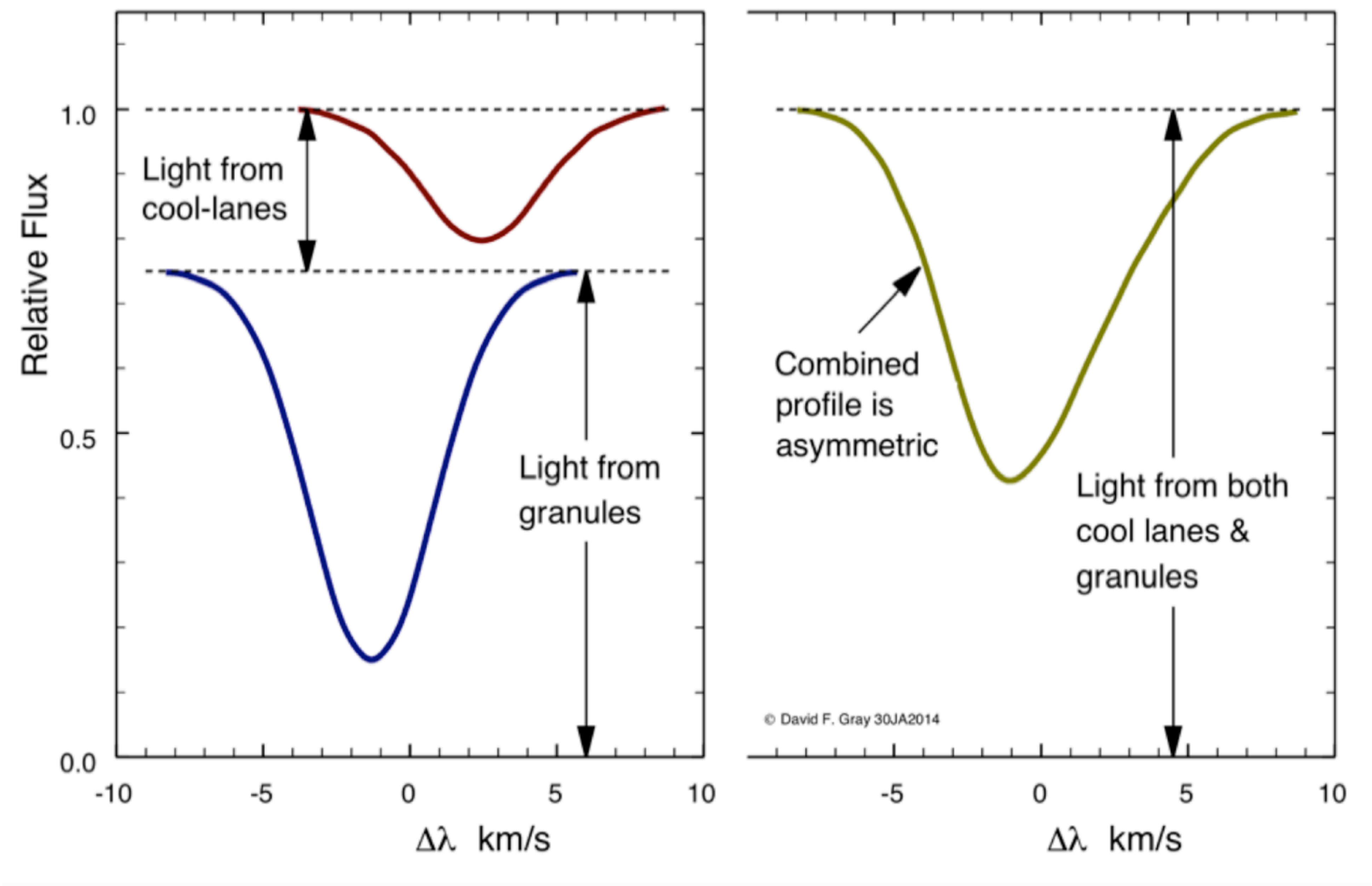


Convective Blueshift ($\mathscr{V}$) - Temperature



Comparison with *Observed* Convective Blueshift

Convective Blueshift ($\mathscr{V}$) - Observed



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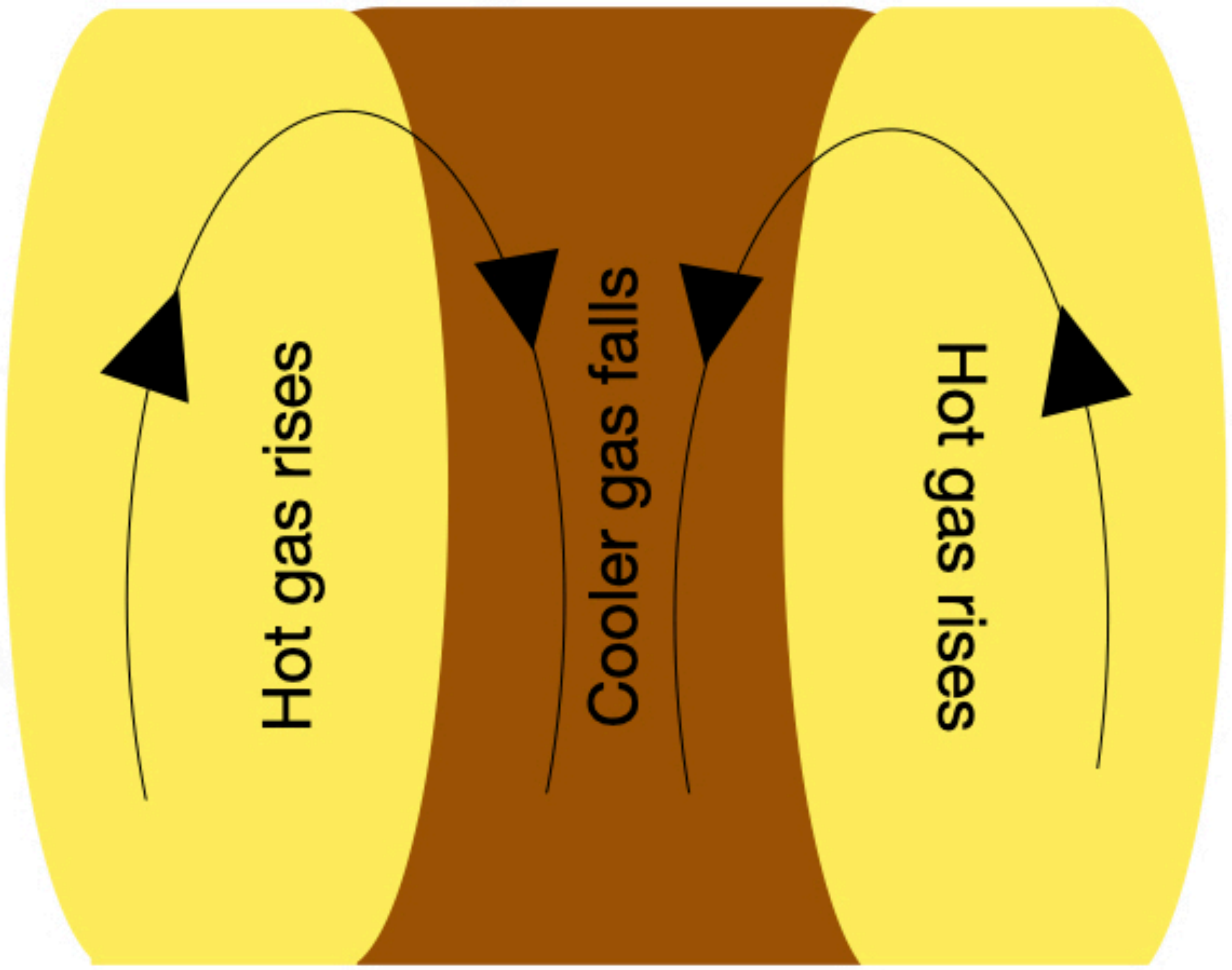
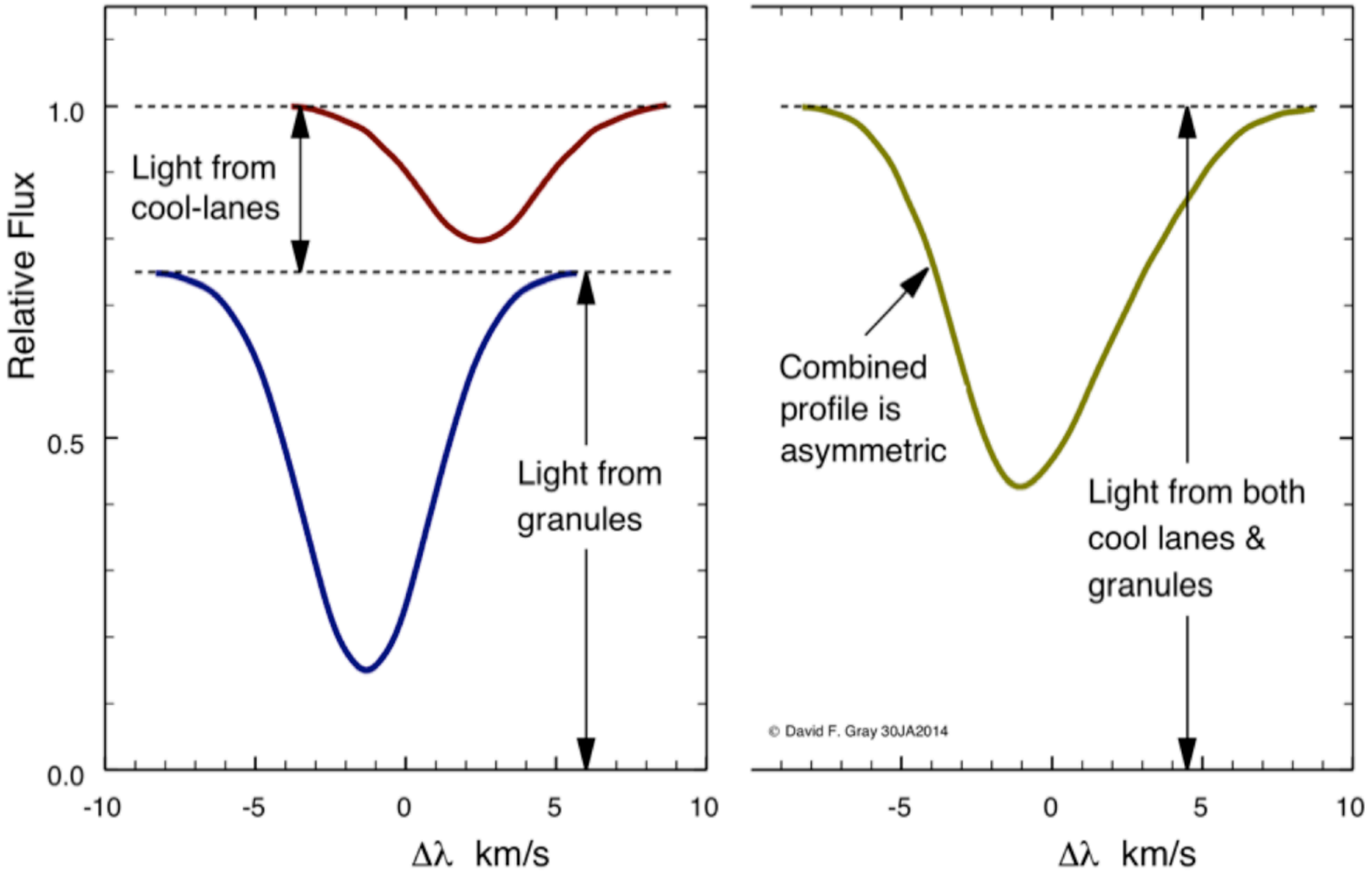
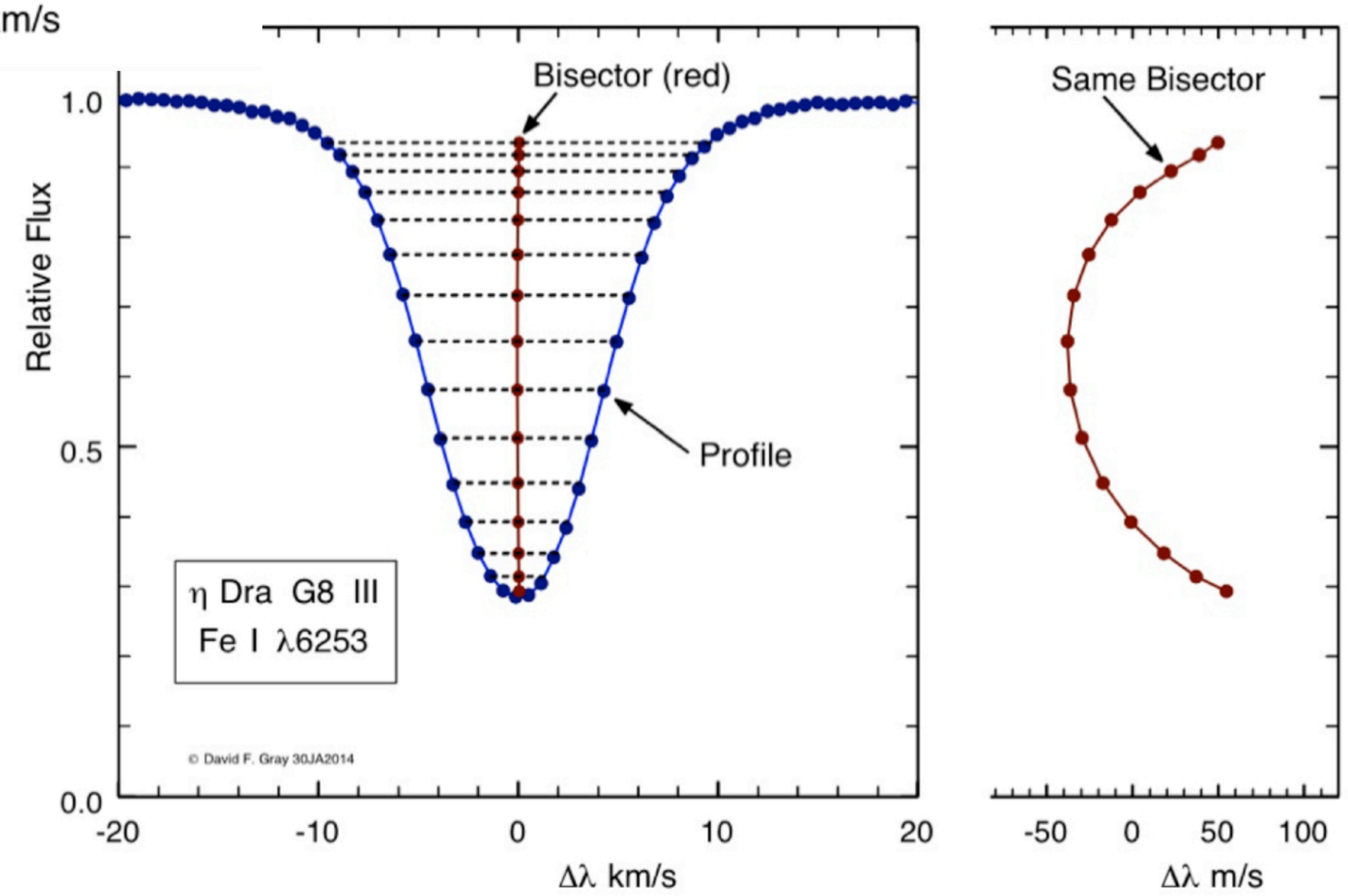
Cross- Section of granules

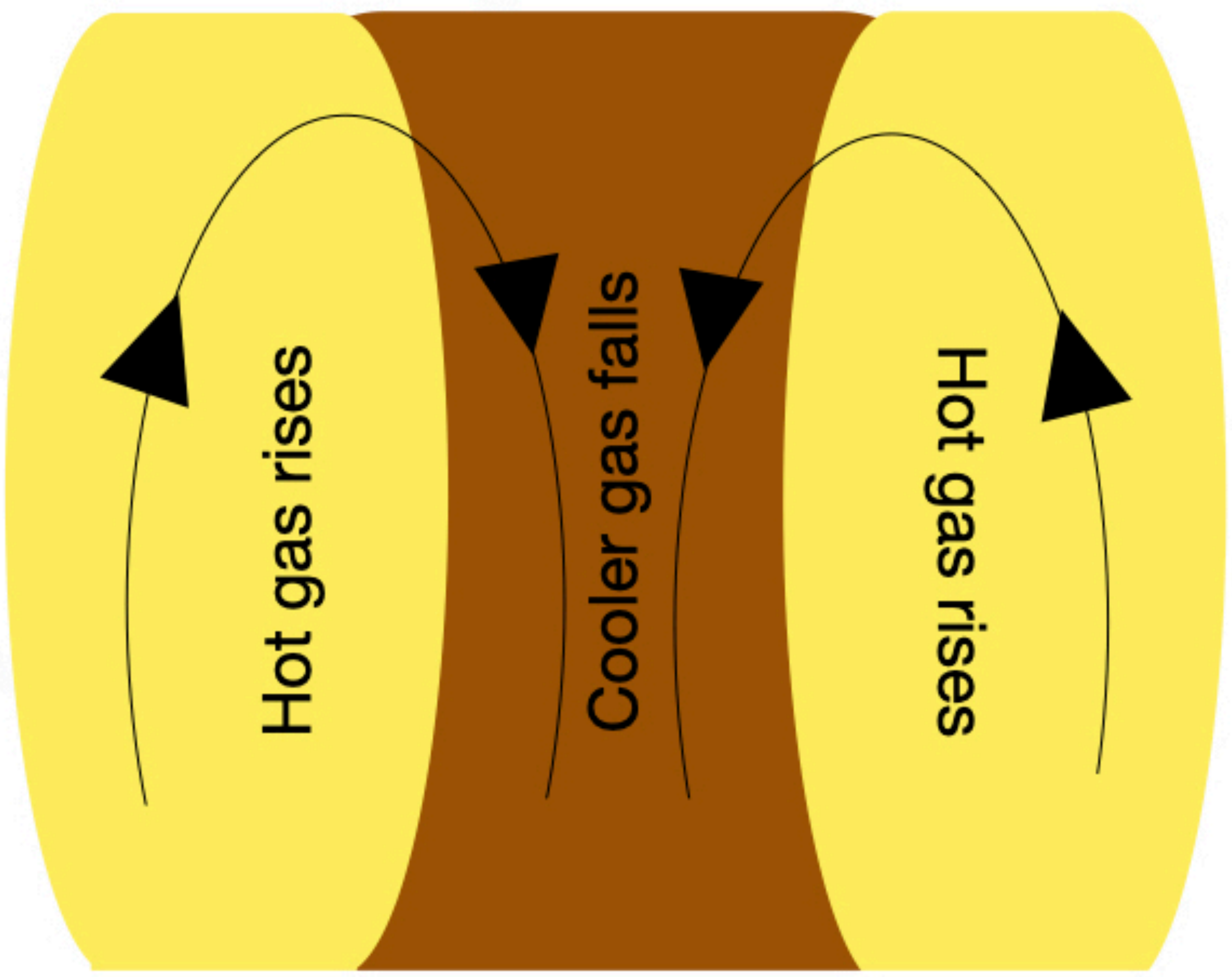


Convective Blueshift ($\mathscr{V}$) - Observed





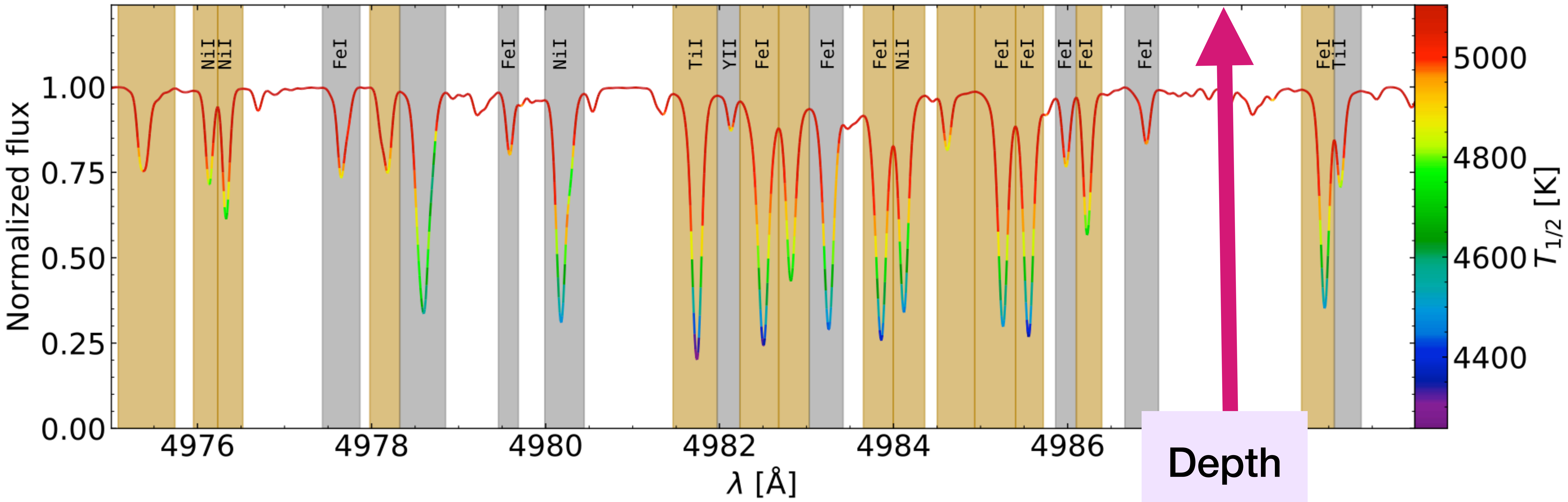
Cross- Section of granules



Convective Blueshift ($\mathscr{V}$) - Observed

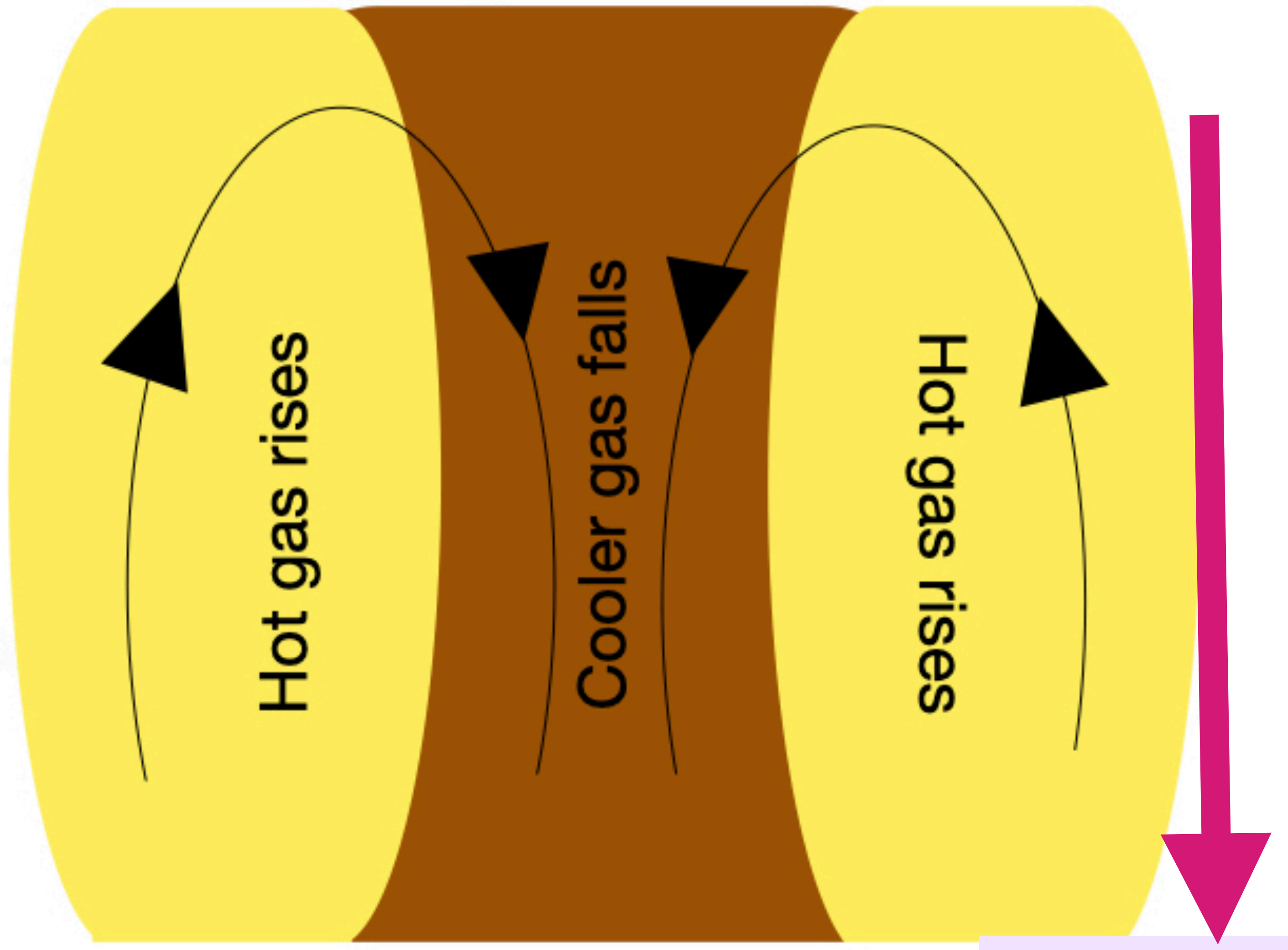
THIRD SIGNATURE OF GRANULATION

Al Moulla et al. (2022)



Depth

Cross- Section of granules

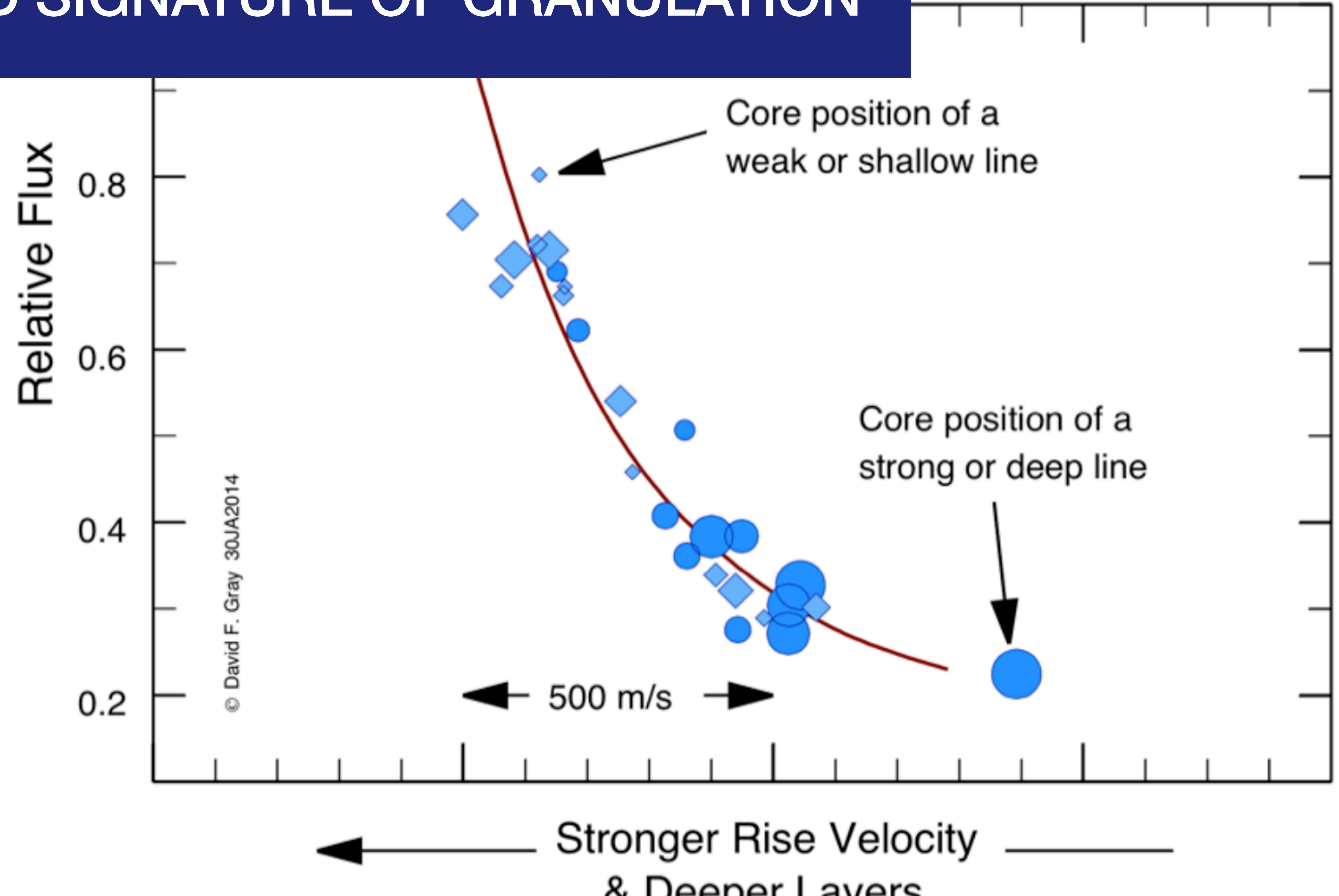


Depth

& Velocity

Convective Blueshift ($\mathscr{V}$) - Observed

THIRD SIGNATURE OF GRANULATION



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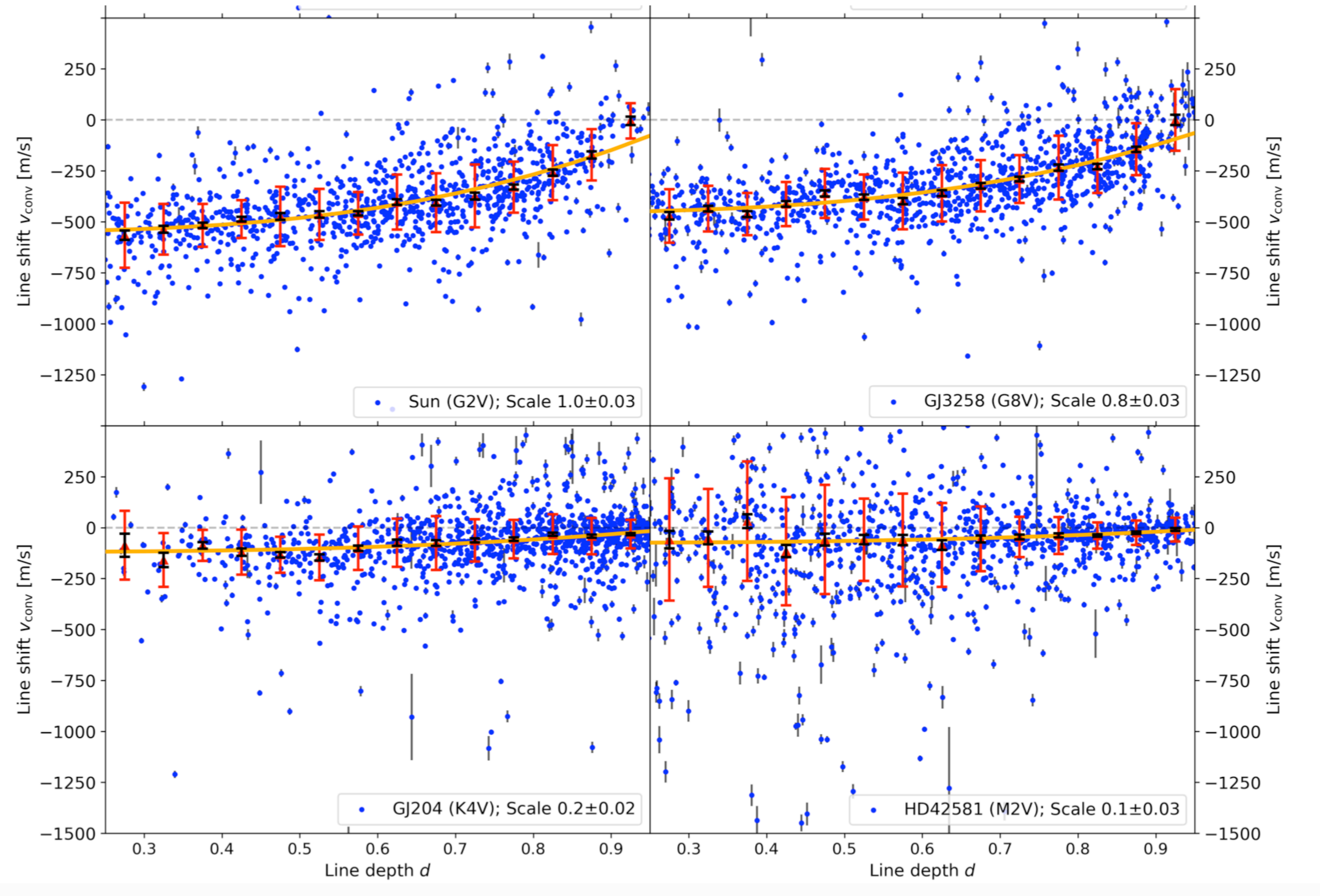
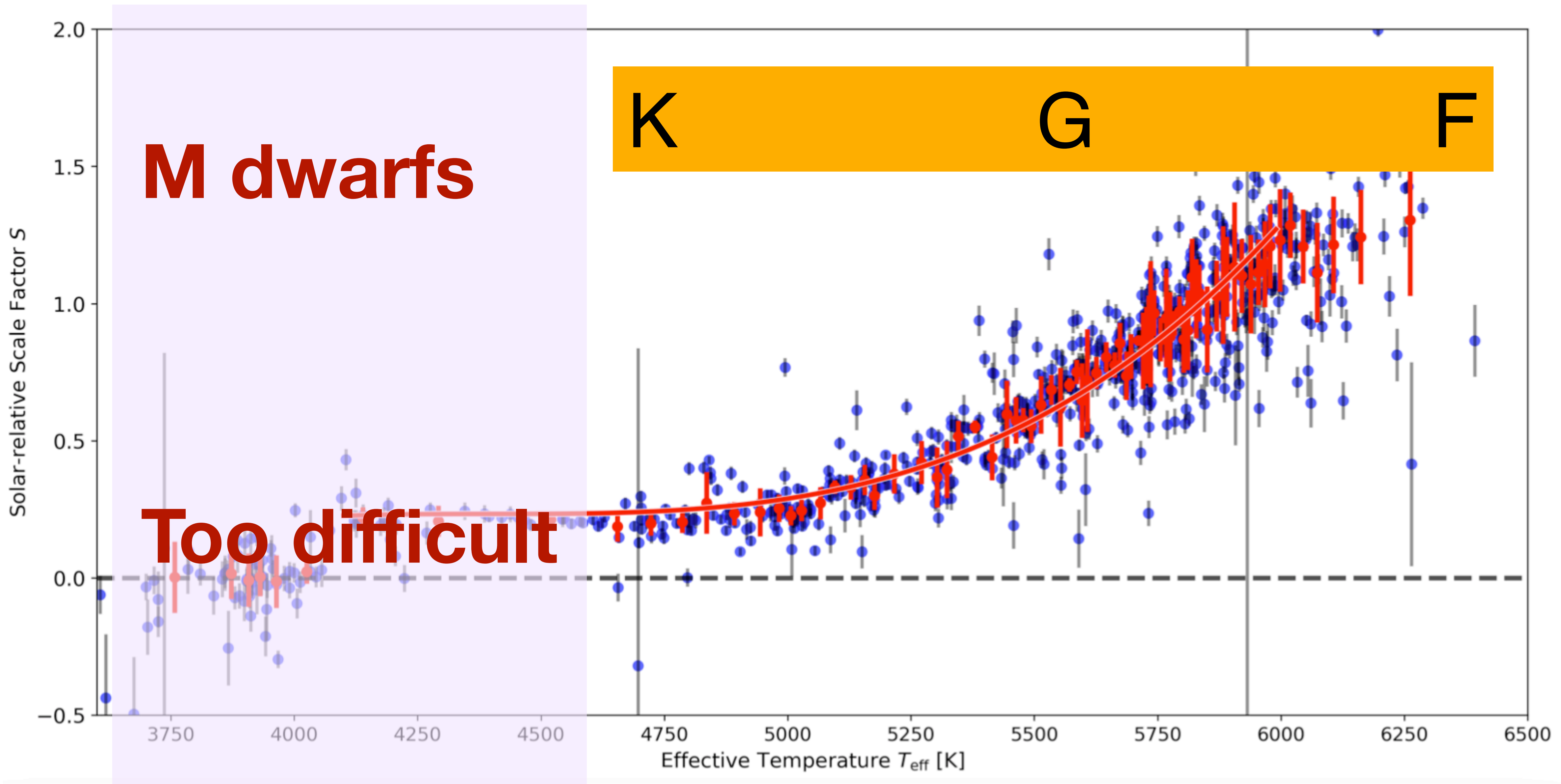
Convective Blueshift ($\mathscr{V}$) - Observed

Liebing et al. 2021





M dwarfs

Too difficult

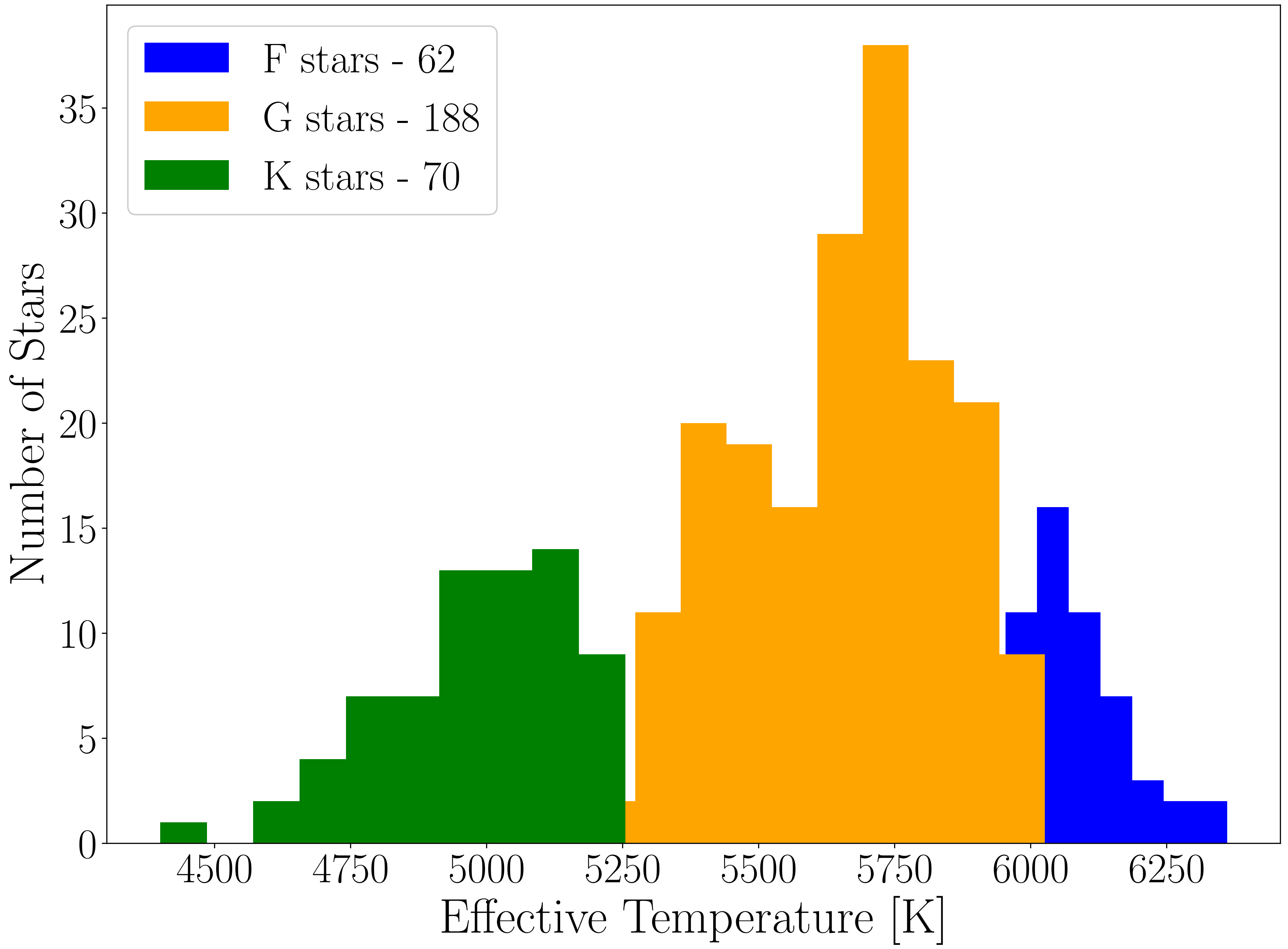
Sample & Stellar Parameters

1. Liebing et al. (2021) sample : HARPS database

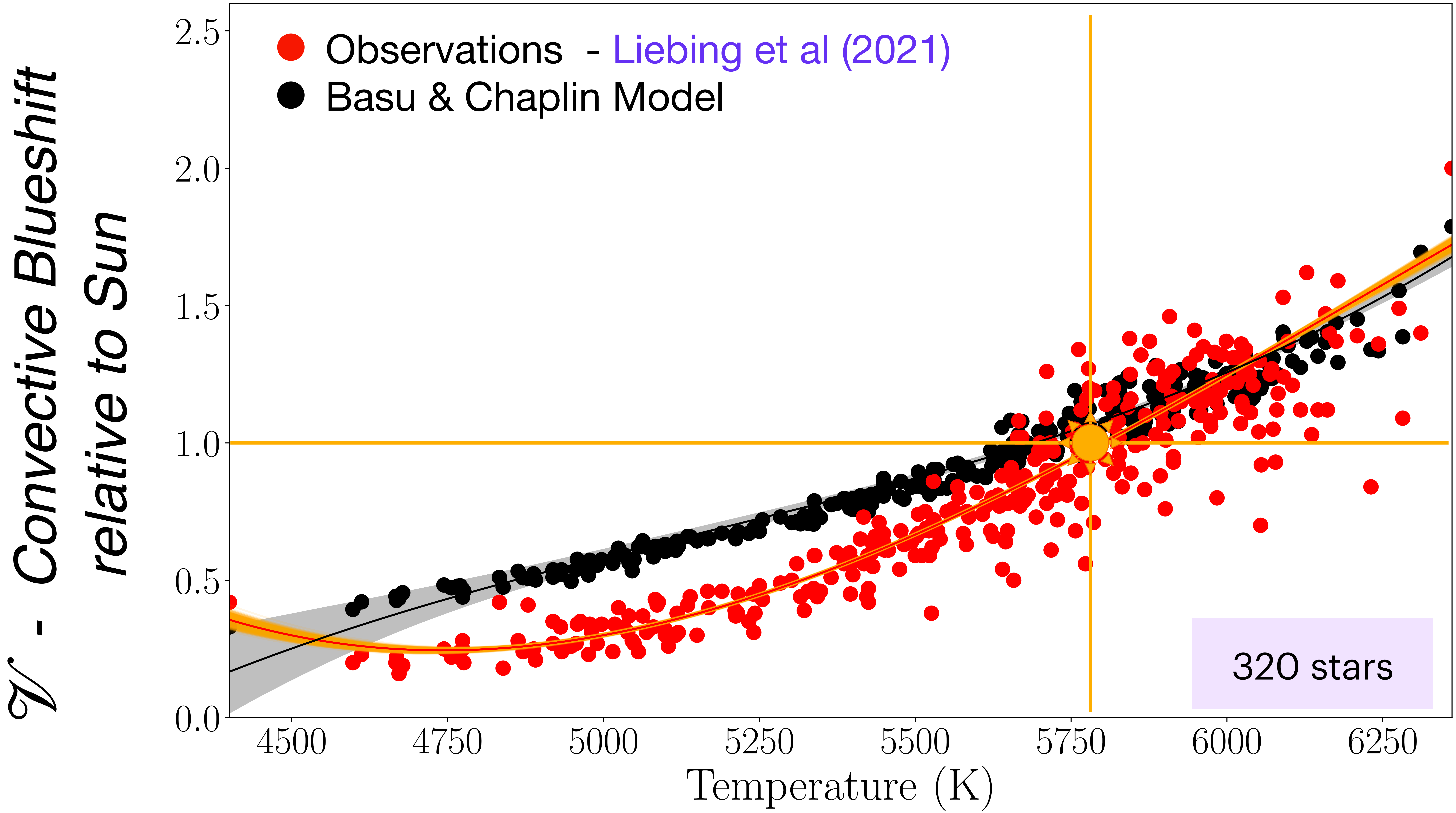
2. Removed M-dwarfs

3. SWEET-Cat stellar parameters - Delgado Mena et al. (2017).

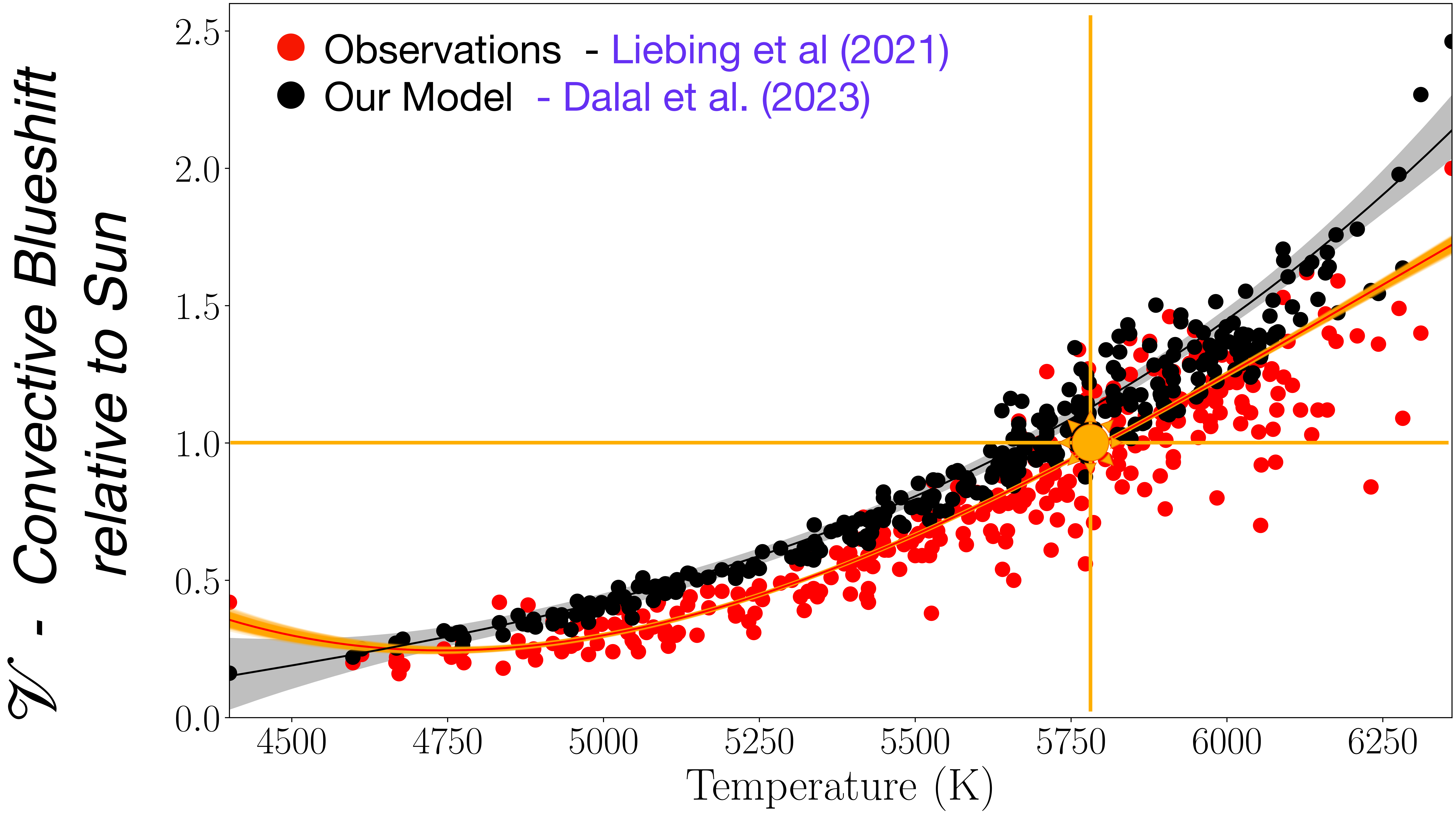
320 stars



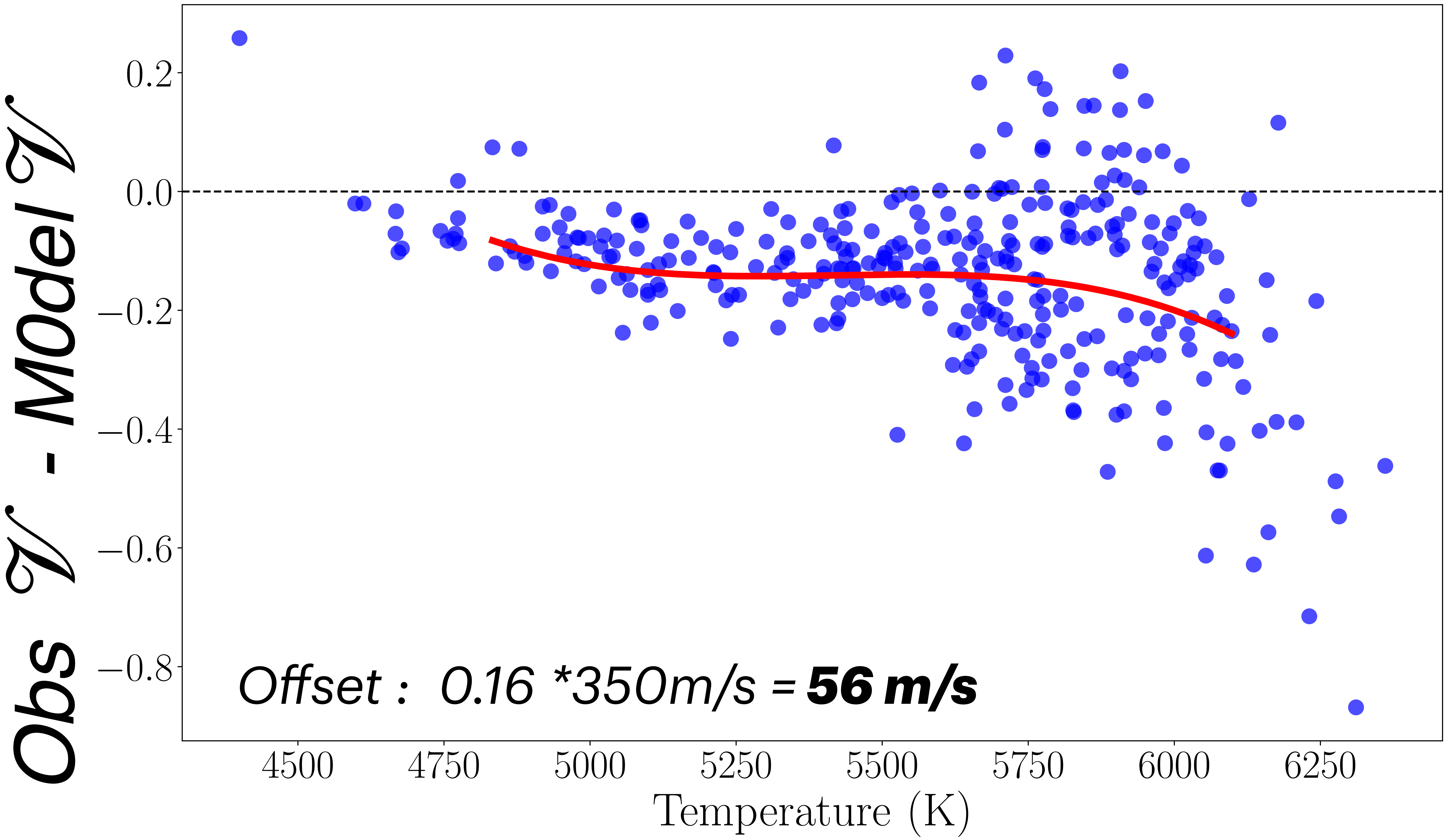
Convective Blueshift ($\mathscr{V}$) - Temperature



Convective Blueshift ($\mathscr{V}$) - Temperature

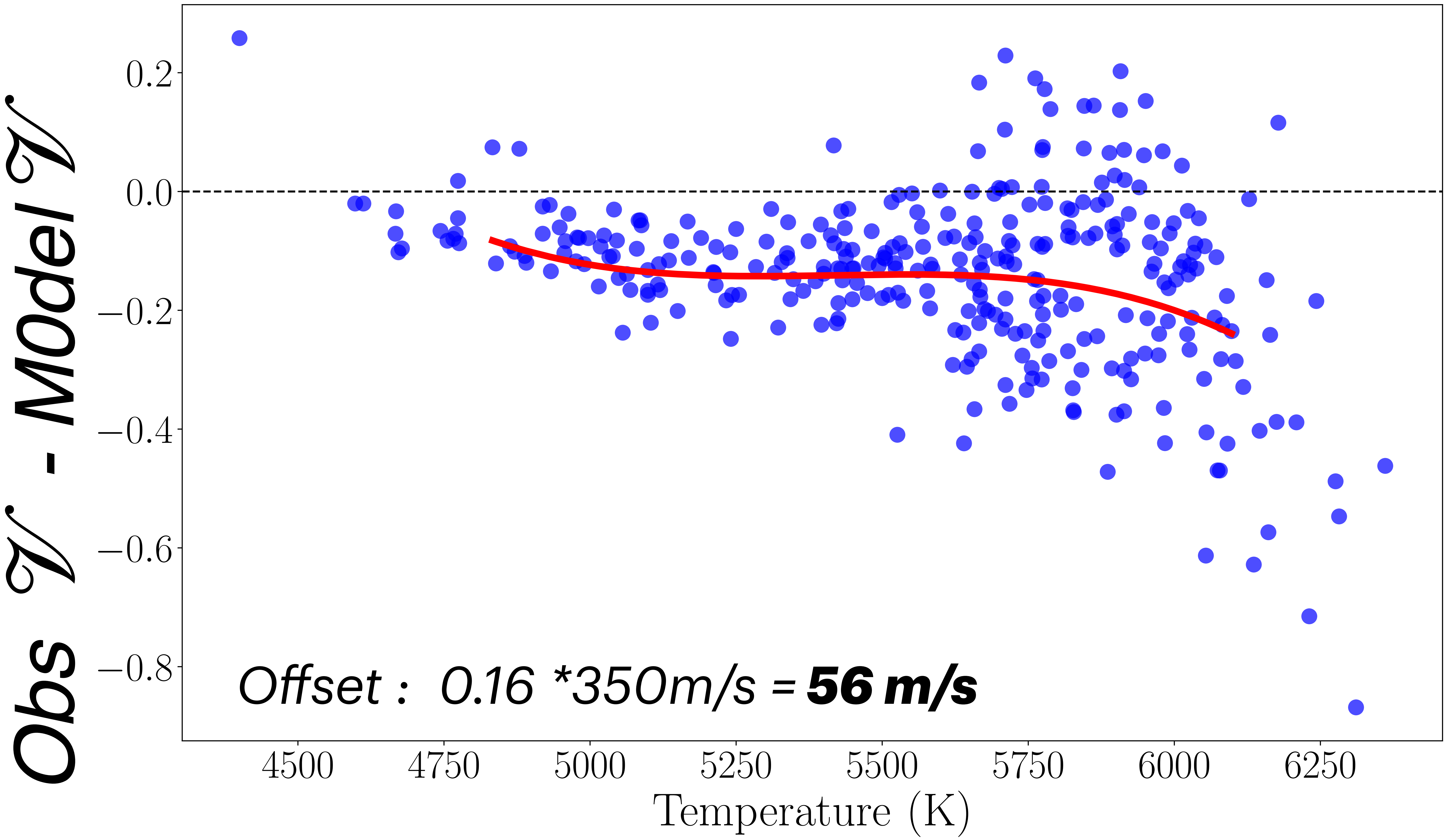


Offset between observations & model



*Offset : 0.16 *350m/s =* ***56 m/s***

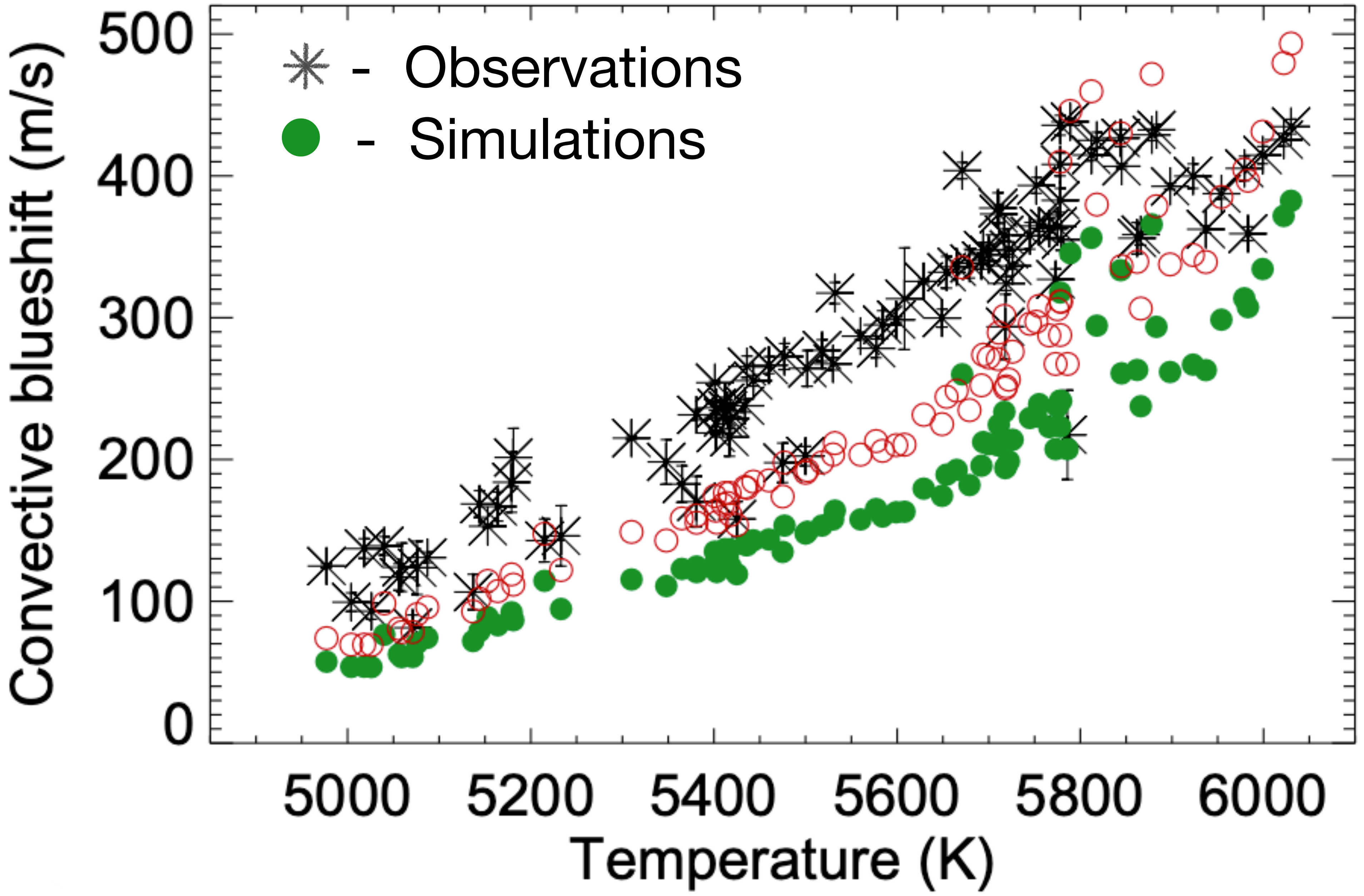
Offset between observations & model



*Offset : 0.16 *350m/s =* ***56 m/s***

Simulations Vs Observations

Meunier et al. 2017

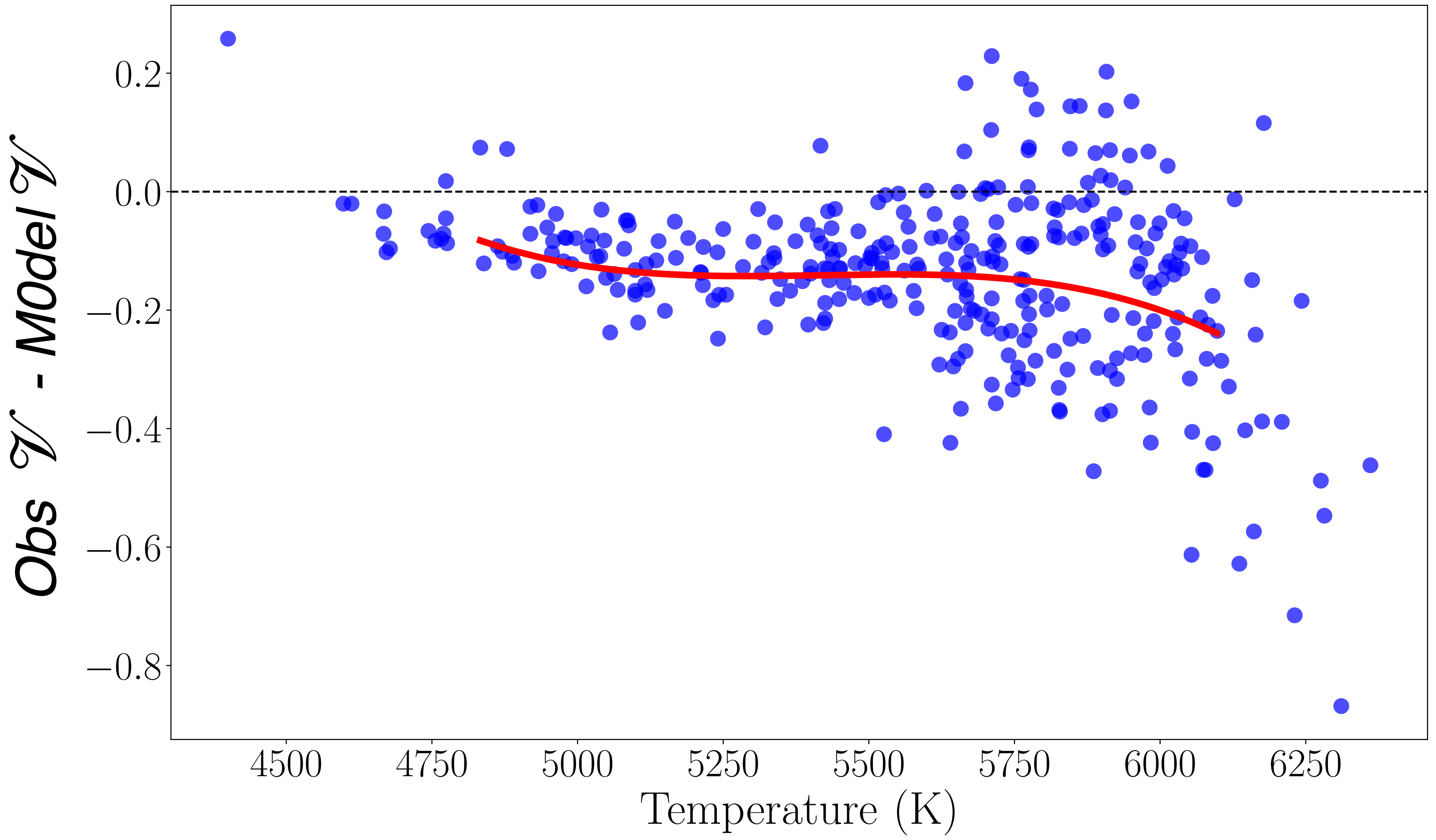


Offset : ***70 m/s***

Offset between observations & model

Reasons for this offset :

- Using the Sun as a reference when retrieving the observed convective blueshift may lead to an offset.



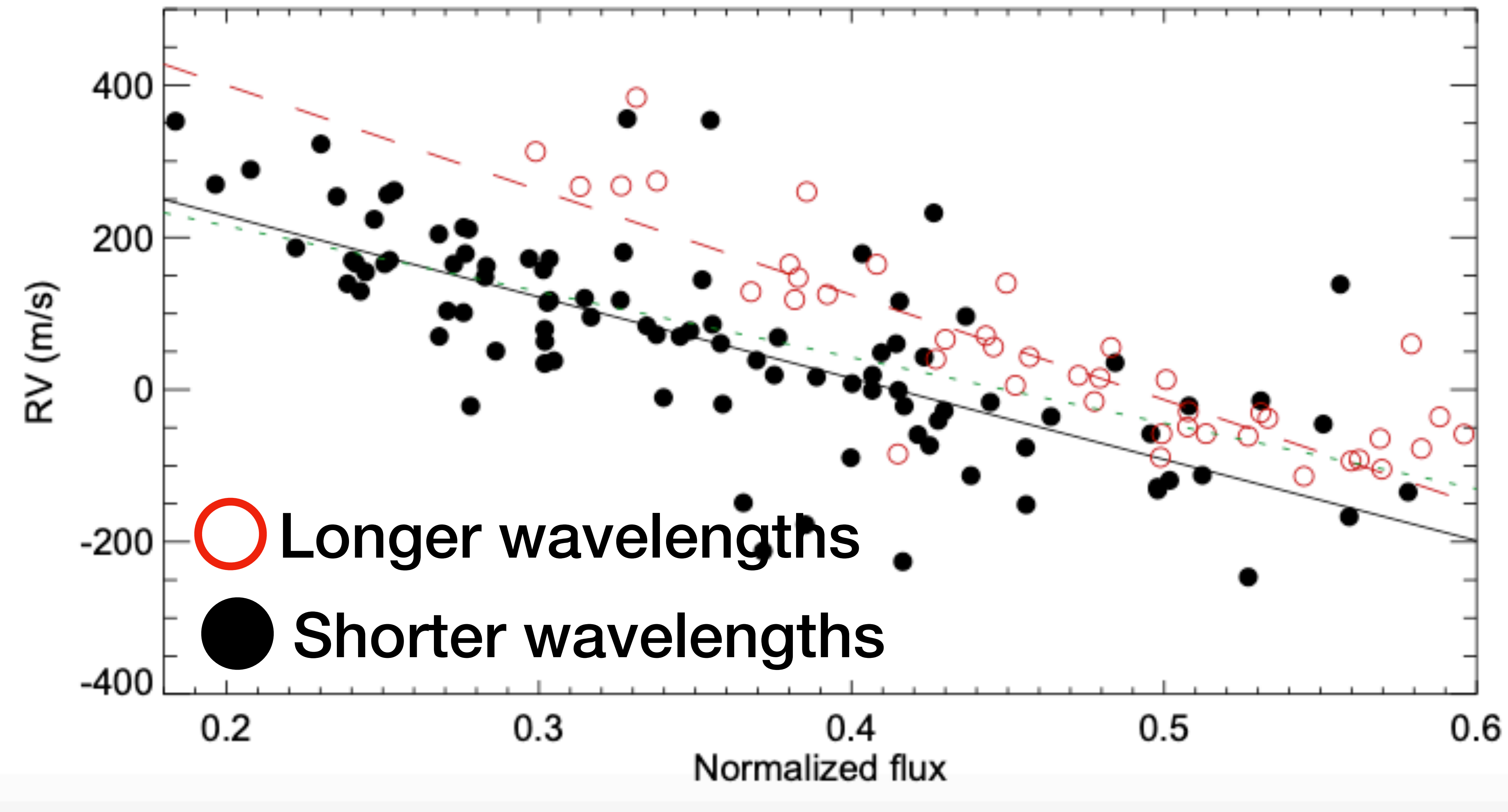
*Offset : 0.16 *350m/s =* ***56 m/s***

Offset between observations & model

Reasons for this offset :

- Using the Sun as a reference when retrieving the observed convective blueshift may lead to an offset.
- We do not consider any wavelength dependence on the velocity and intensity contrast of the granules.

Meunier et al. 2017



Offset between observations & model

Reasons for this offset :

- Using the Sun as a reference when retrieving the observed convective blueshift may lead to an offset.
- We do not consider any wavelength dependence on the velocity and intensity contrast of the granules.
- Our model doesn't include foreshortening effects.

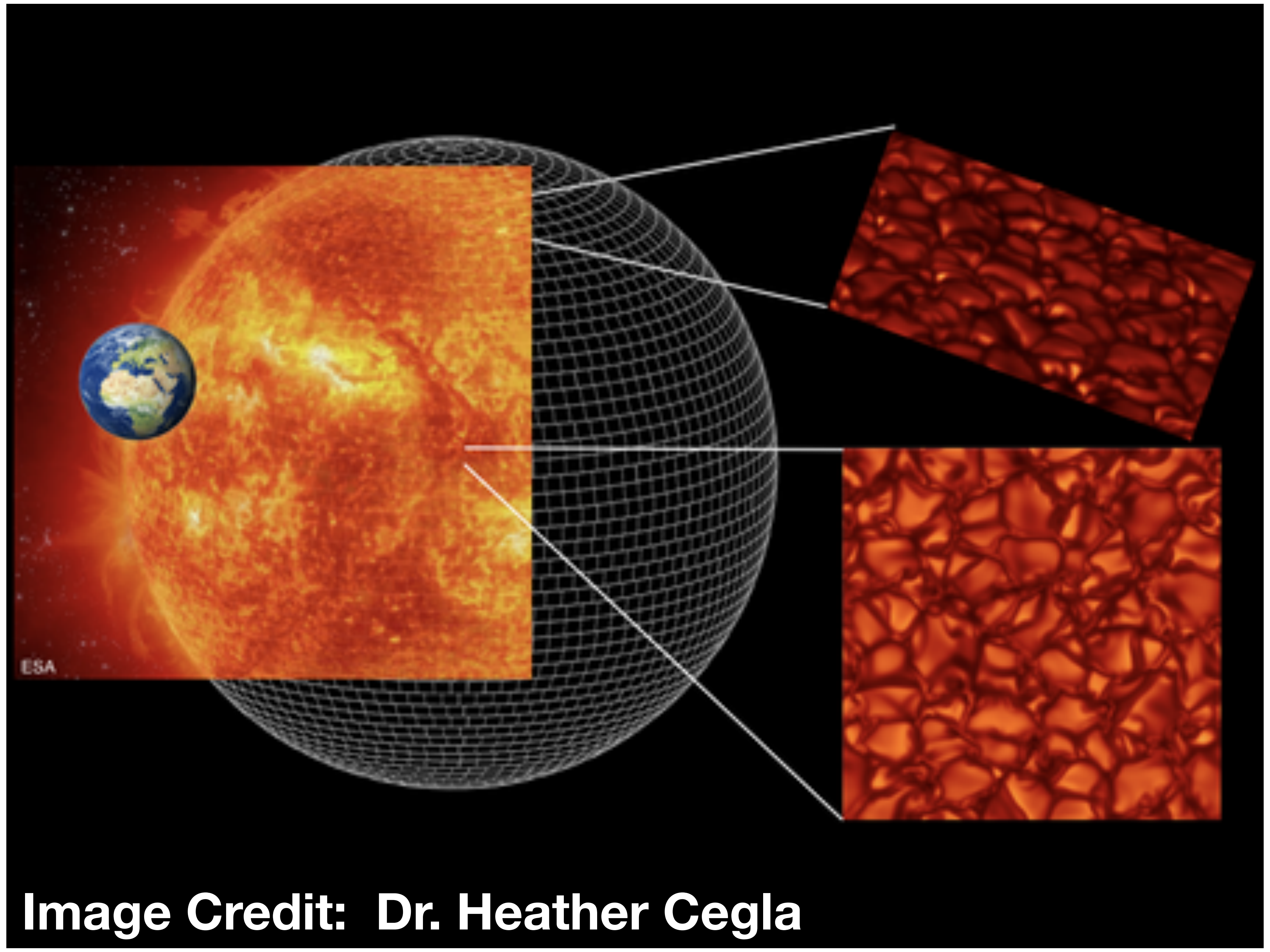


Image Credit: Dr. Heather Cegla

Radial-velocity dispersion due to stellar granulation

Granulation Noise ($\sigma_{\mathscr{G}}$)

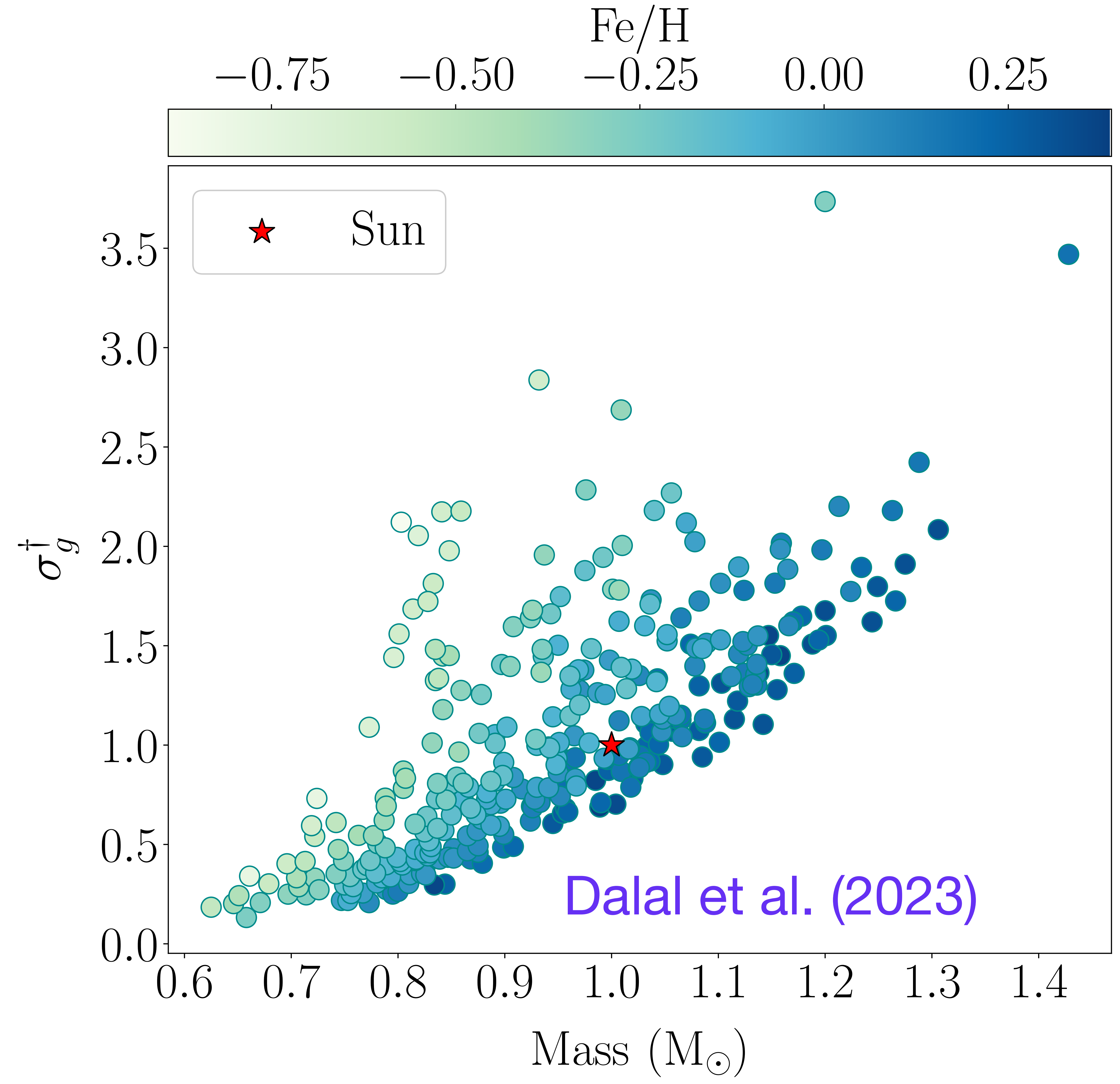
Divide the visible hemisphere of the star in N granules. Ignoring foreshortening, number of granules :

$$N_g \sim \left(\frac{R}{r_g}\right)^2$$

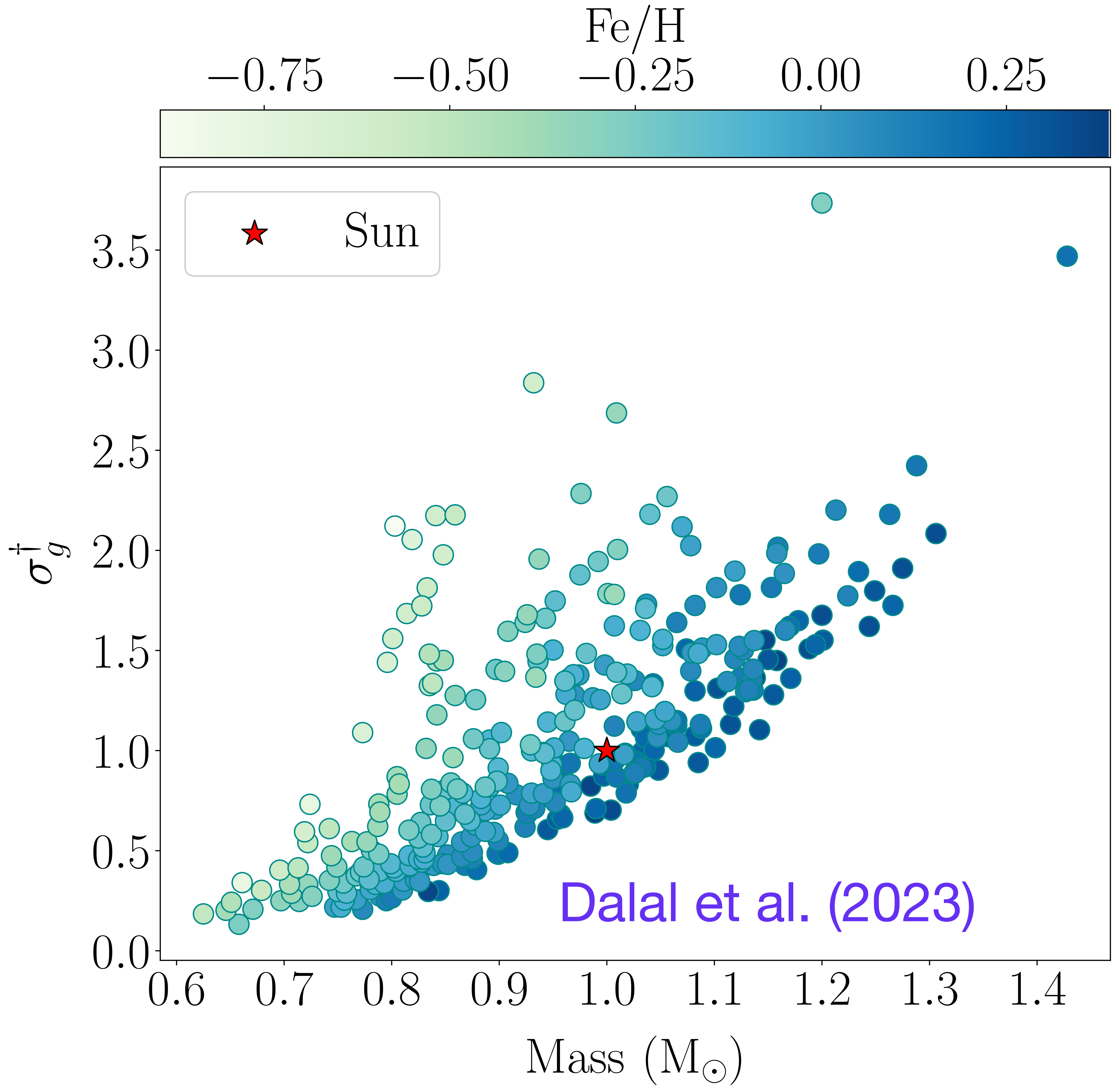
We assume that all granules behave in as statistically independent manner **and their velocity dispersion scales as their velocity** (Basu & Chaplin 2017):

$$\sigma_{\mathscr{G}} \sim \frac{\mathscr{V}}{\sqrt{N_g}}$$

Granulation Noise ($\sigma_{\mathscr{G}}$)



Granulation Noise ($\sigma_{\mathscr{G}}$)



Dalal et al. (2023)

SUN

Number of granules ~ 2 million

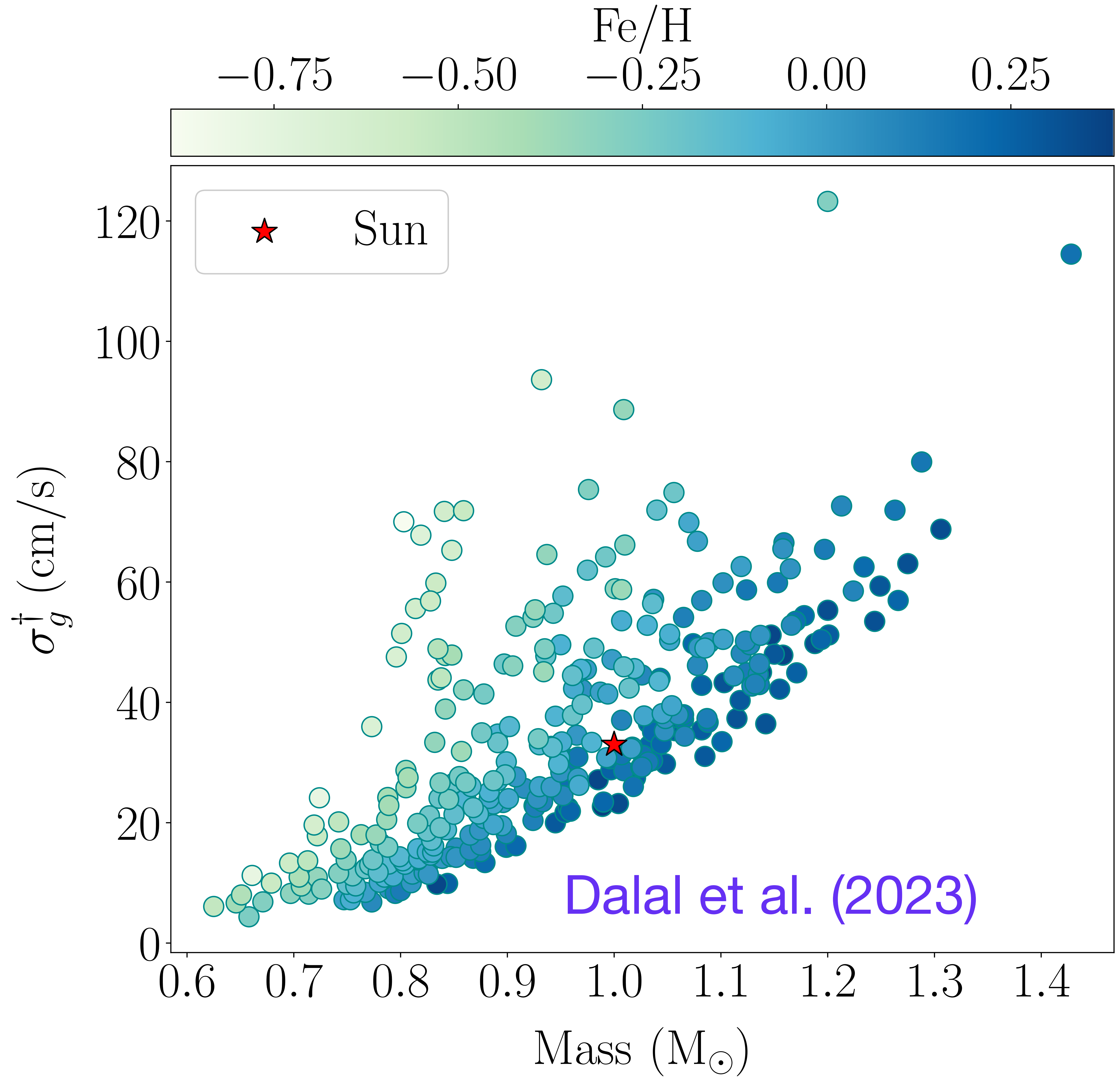
Convection Blueshift ~ 350 m/s

$$\sigma_{\mathscr{G}} \sim \frac{\mathscr{V}}{\sqrt{N_g}}$$

Granulation Noise ~ 0.33 m/s

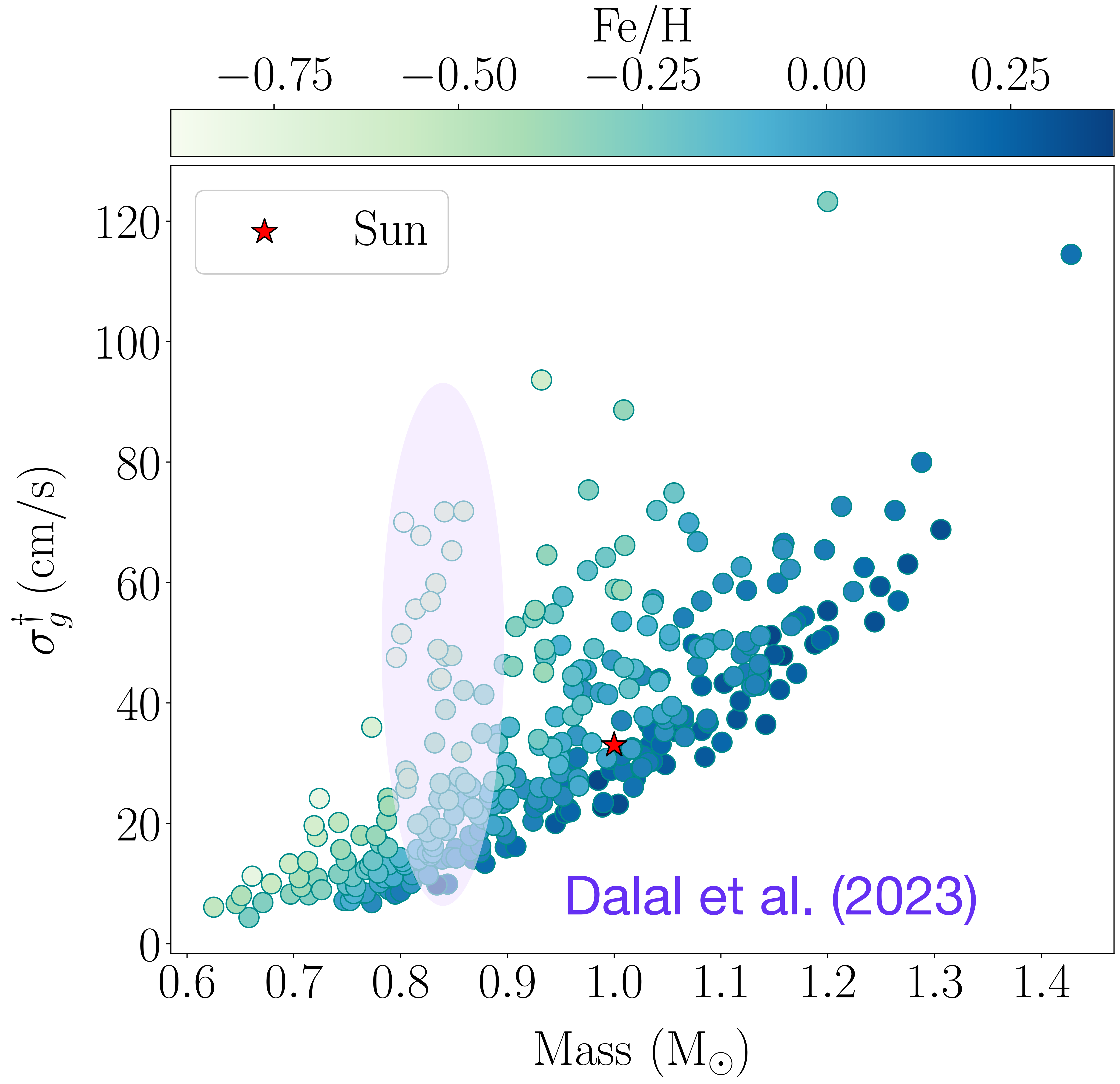
(e.g., Pallé et al. 1999; Collier Cameron et al. 2019; Sulis et al. 2020; Al Moulla et al. 2023)

Granulation Noise ($\sigma_{\mathscr{G}}$)



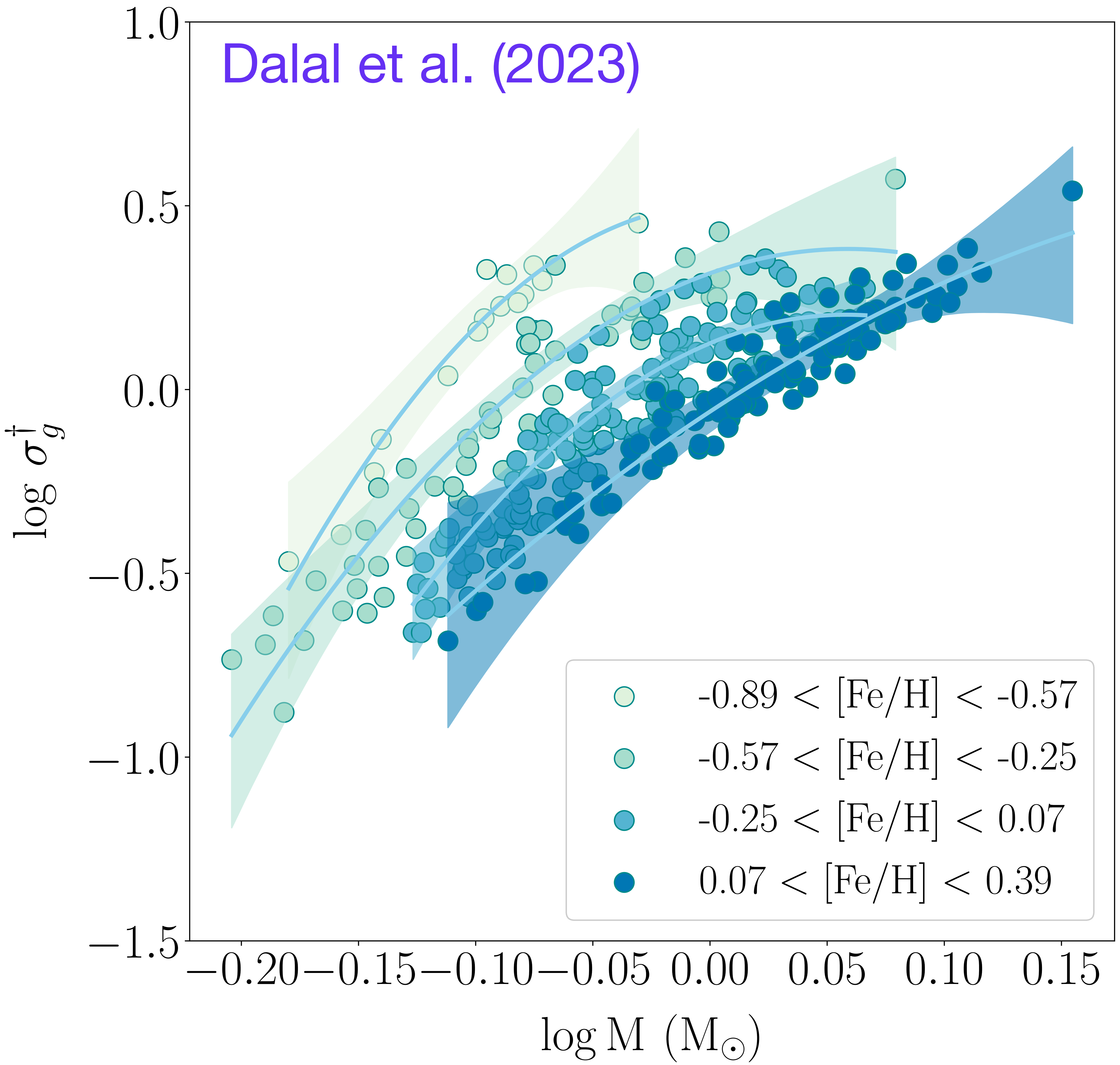
Dalal et al. (2023)

Granulation Noise ($\sigma_{\mathscr{G}}$)



- The granulation noise increase with stellar mass.
- Lower metallicity stars have higher granulation noise.
- K stars (~ 5 cm/s) are the most suitable targets for monitoring when searching for other Earths.

Granulation Noise ($\sigma_{\mathscr{G}}$)



Predict granulation noise using the following relation:

$$\sigma_g = f(\mathrm{M}, \mathrm{Fe/H})$$

Summary

- *Our model accurately predicts the convective blueshift of FGK stars.*
- *We also provide equations to predict the granulation noise to inform exoplanet surveys for selecting the most amenable targets.*
- *K stars (and high metallicity stars) are the most suitable targets for monitoring when searching for other Earths.*