Sensitivity of spectral lines to granulation: from the Sun to K-type stars

Valeriy Vasilyev

Max Planck Institute for Solar System Research

Collaborators:
K. Sowmya, A. I. Shapiro, N. Kostogryz, D. Vukadinovic, V. Witzke, T. Bhatia, A. Collier Cameron, L. Gizon, S. K. Solanki

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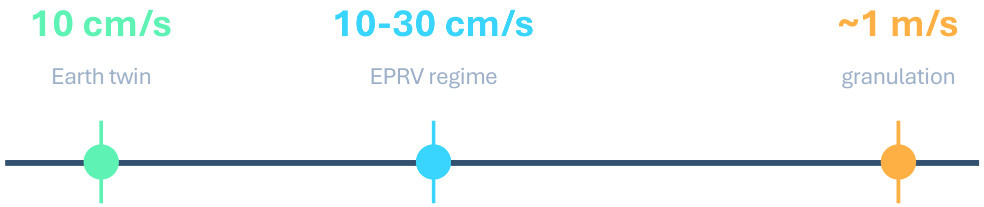
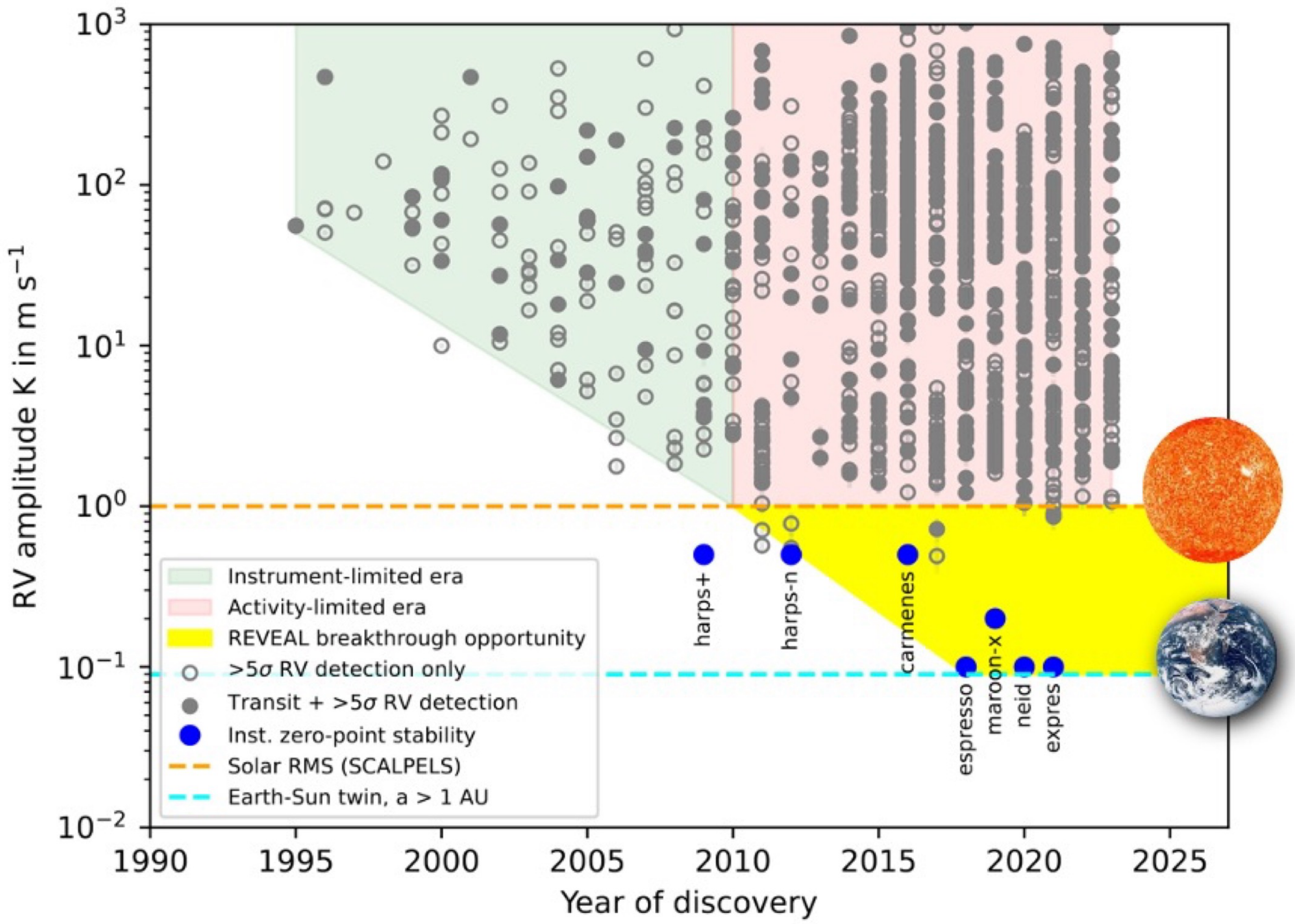
The RV bottleneck is astrophysical, not instrumental

- Precision of modern spectrographs reaches ~10-30 cm/s (Fisher et al 2016)
- **Even for relative quiet star like the Sun only granulation produces RV signal in a level of 1 m/s (Lakeland et al 2024)**
- Eath-mass planet creates RV semiamplitude of ~10 cm/s

RV semi-amplitude / jitter scale



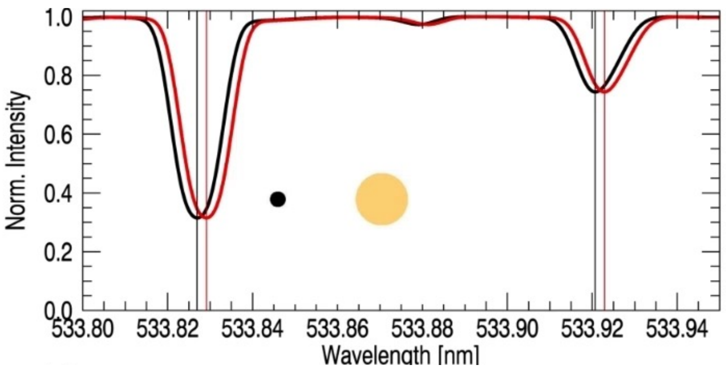


Credits: Andrew Collier Cameron

Planet vs Star

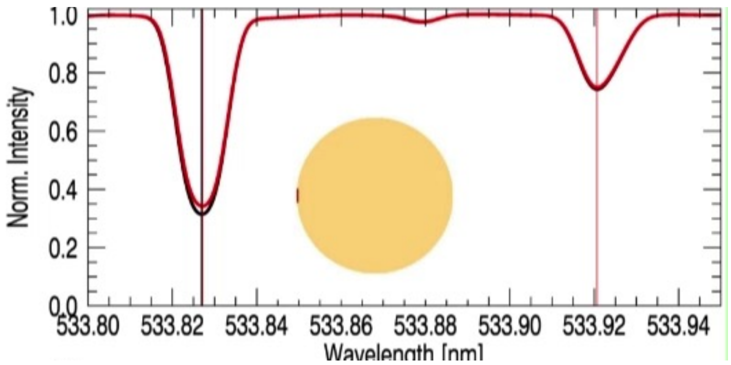
Sasha Shapiro

For illustration, the effect on lines is increased by a factor of 1000



Planet induced Doppler motion is common shift for all lines

+



Granulation (and magnetic activity) induced RV signals are line-dependent

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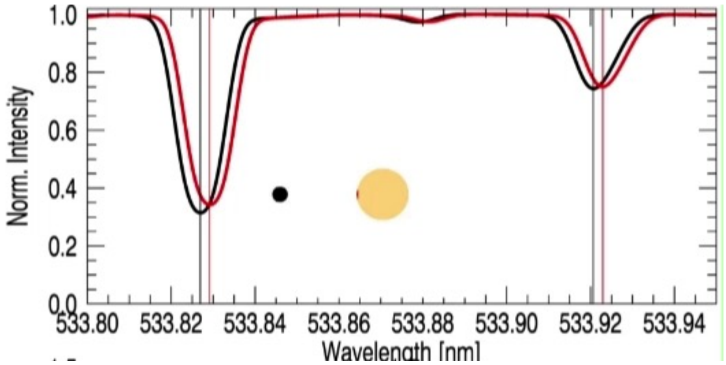


Observations show a combination of these effects

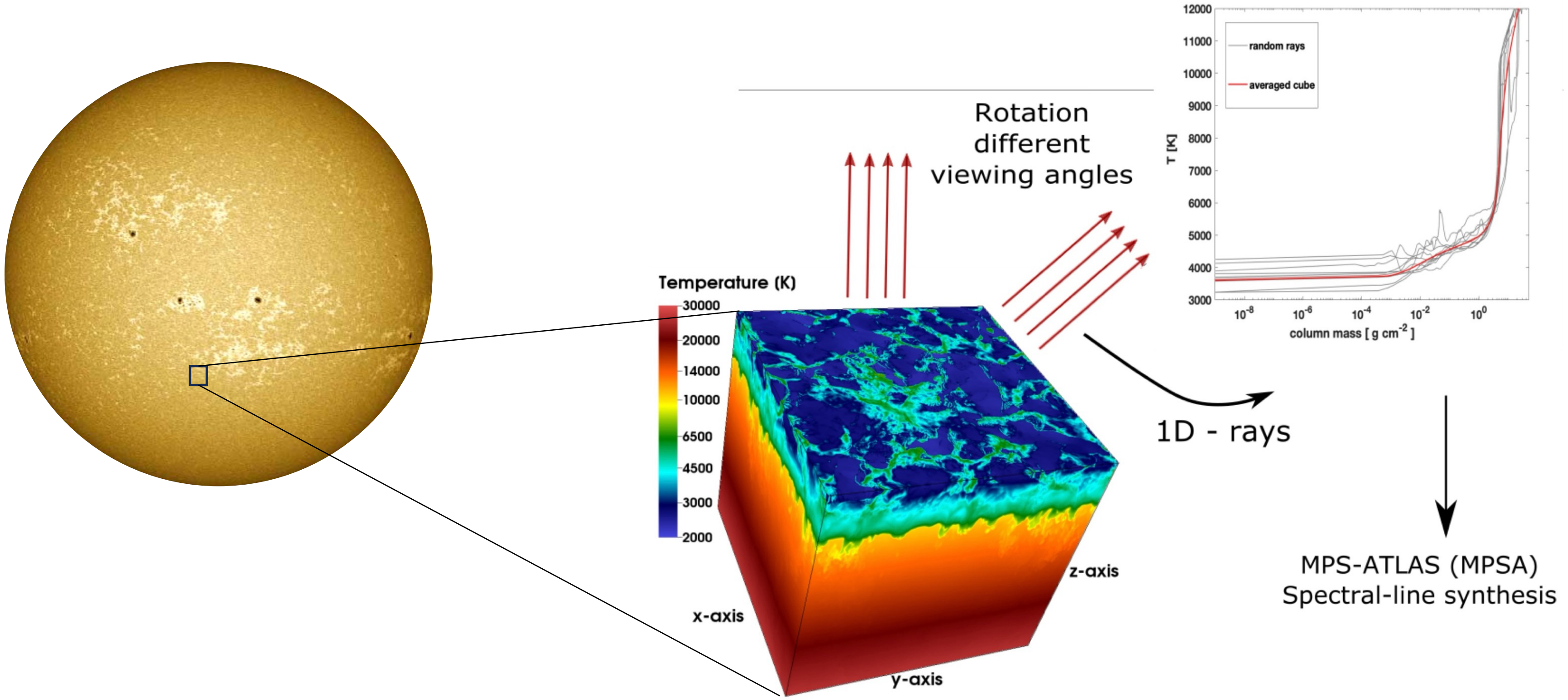
RV measurements generally use a line profile averaged over thousands of lines.

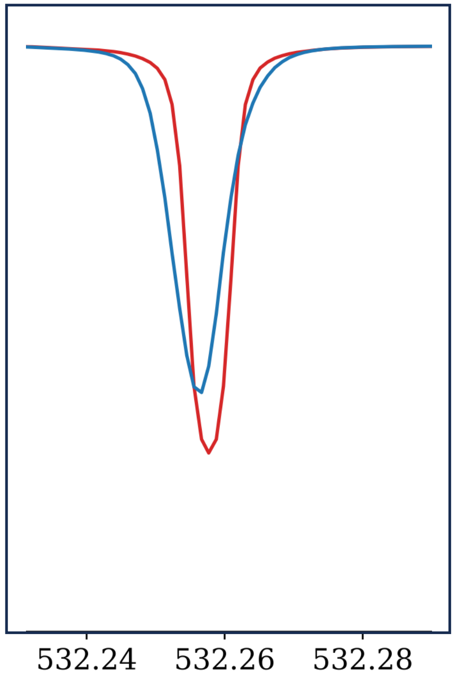
Differential sensitivity of lines to granulation in the averaging is still missing

To push the threshold due to stellar variability down to 10 cm/s and discover Earth-like planets, we need to model the differential effects from stars and incorporate them into algorithms for stellar RV

Approach: MURaM simulations + MPS-ATLAS

Veronika
Witzke





MURaM: 3D convective velocity and thermal structure

- 3D MHD code MURaM (Vögler et al. 2004, 2005)
- Box-in-a-star approach to simulate near-surface layers and atmospheres
- MHD equations in Cartesian geometry, 3D non-grey multigroup RT
- Magnetic fields are generated by the Small-Scale Dynamo (SSD)

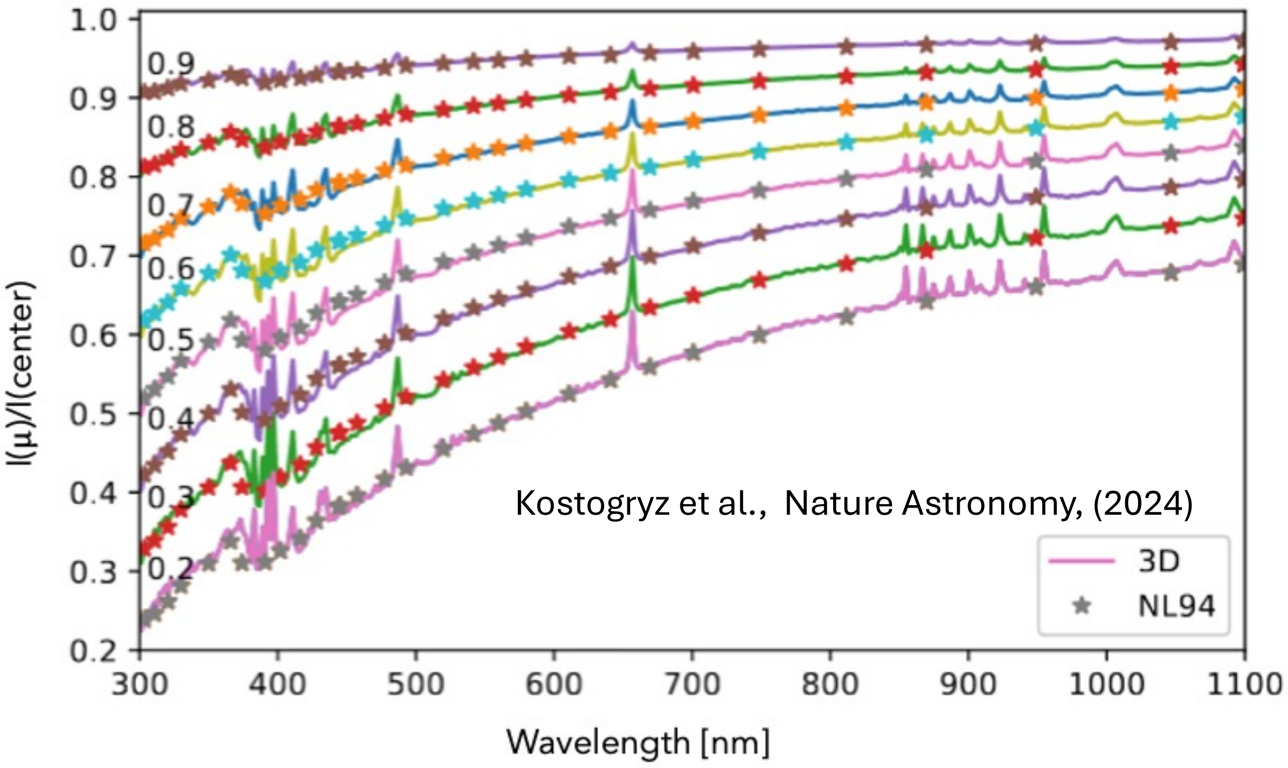
MPS-ATLAS: turns it into spectra

- Merged Parallelized Simplified ATLAS code (Witzke et al. 2021)
- Fast and flexible all-in-one code: opacity tables, atmospheric structures, spectral synthesis
- Low- and high-resolution spectral synthesis employ different approaches

Validation of the quiet Sun simulations

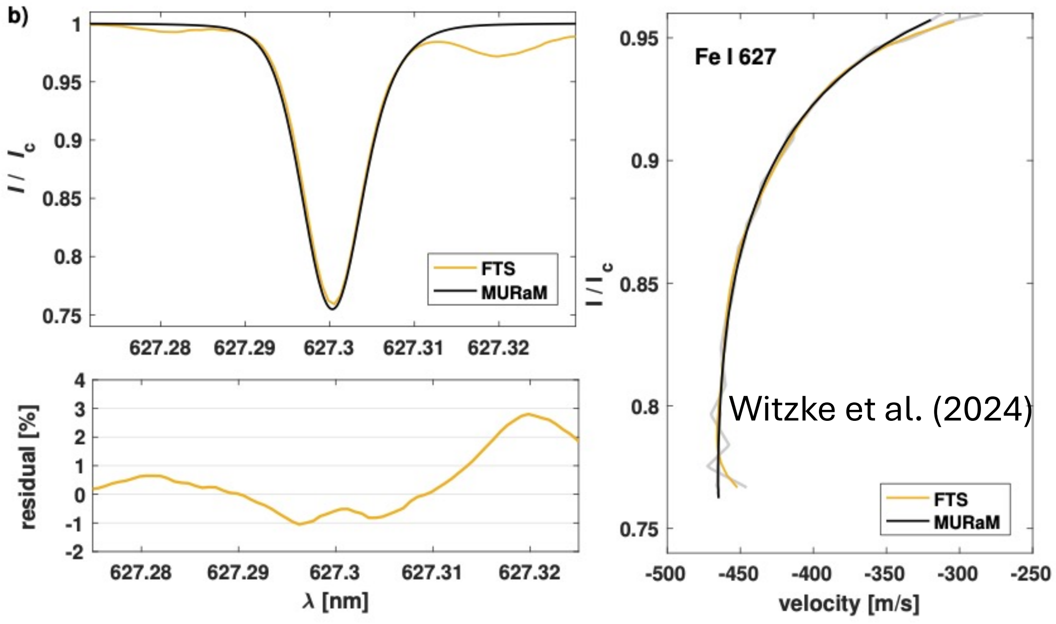
Nadiia Kostogryz Veronika Witzke

Magnetic limb darkening



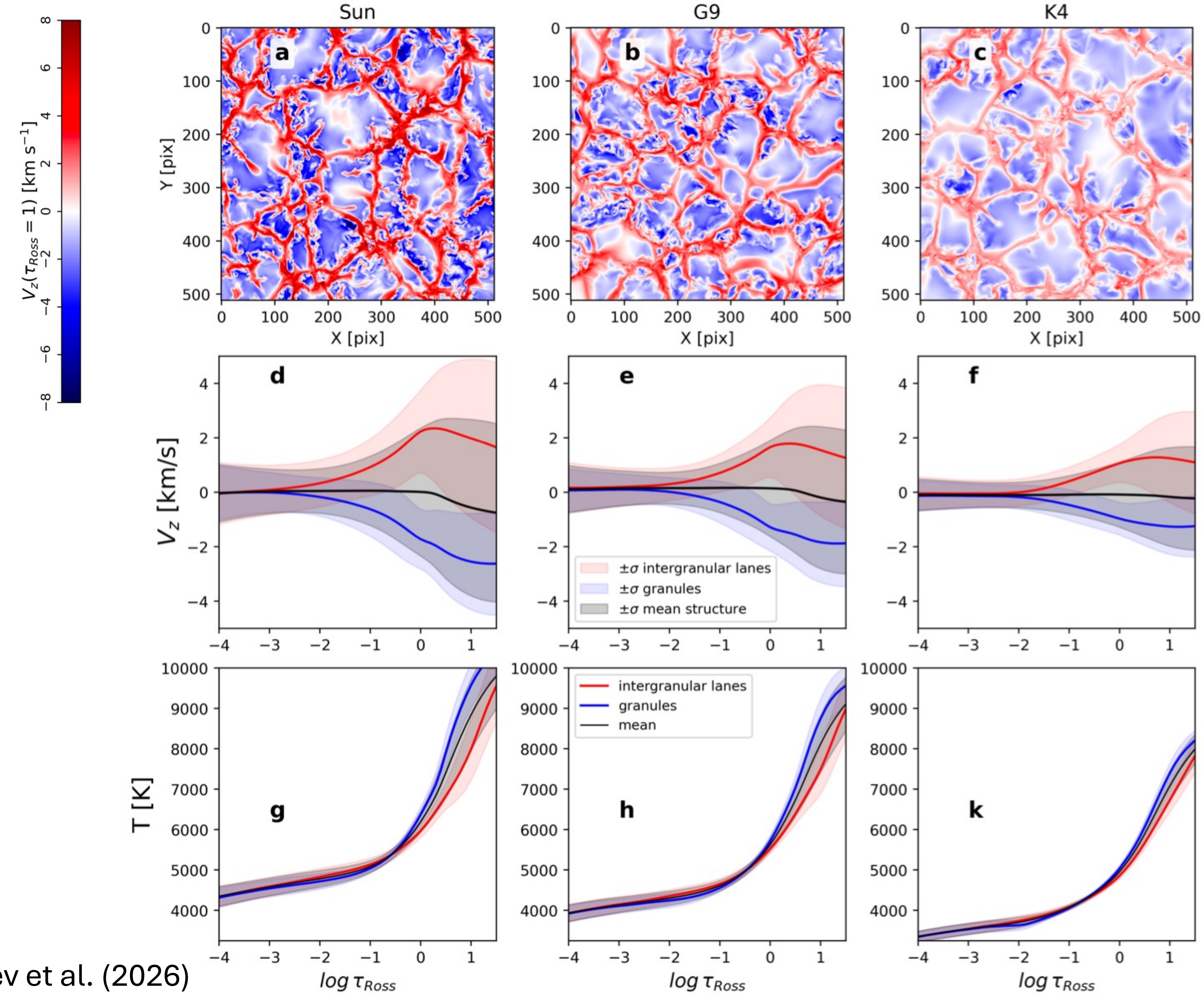
Kostogryz et al., Nature Astronomy, (2024)

Line profiles



Witzke et al. (2024)

MURaM simulations: from the Sun to K-type

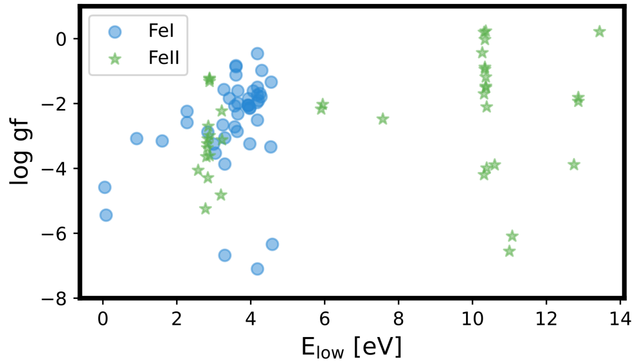


Vasilyev et al. (2026)

Atmospheric structure from the Sun to K4:

- Teff decreases
- convective velocities weaken

Spectral line computations for 85 FeI and FeII lines between 430-550 nm ($R=2*10^6$)

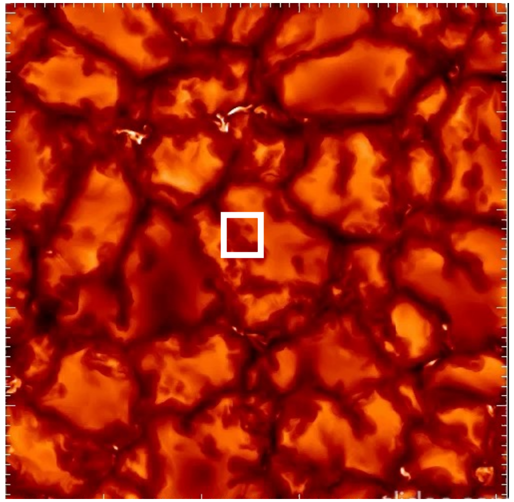


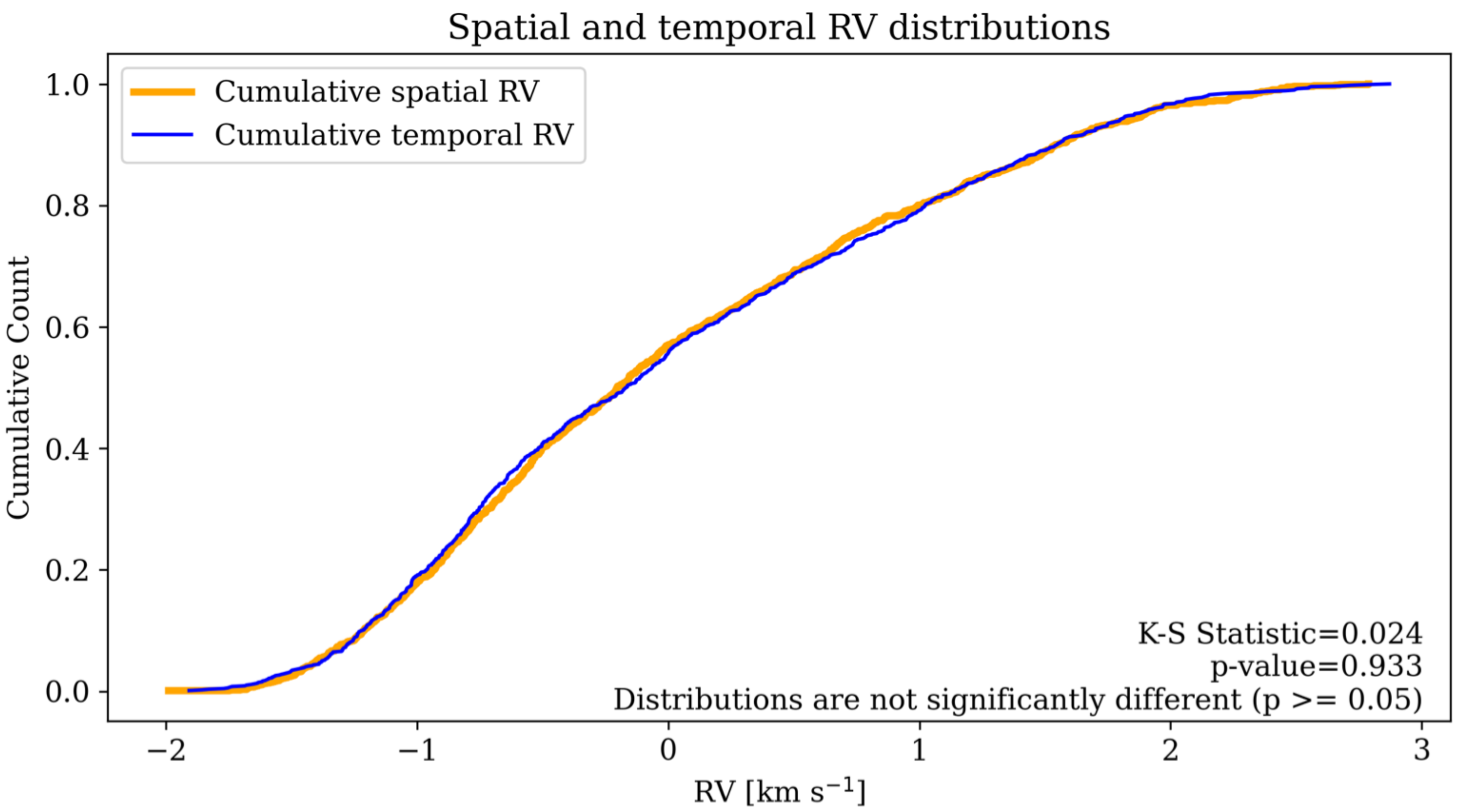
Ergodicity of granulation

Andrew Cameron

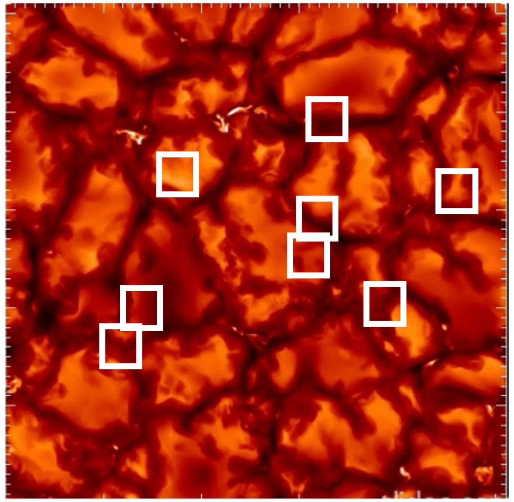
Spatially averaged properties of granulation are **equivalent** to the **temporally** averaged properties

Single patch time evolution





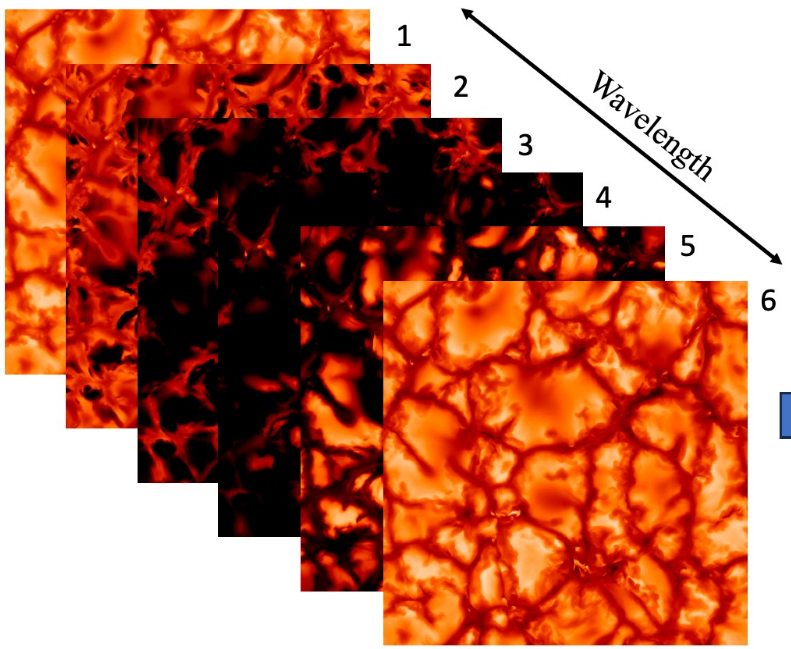
Many patches at single snapshot



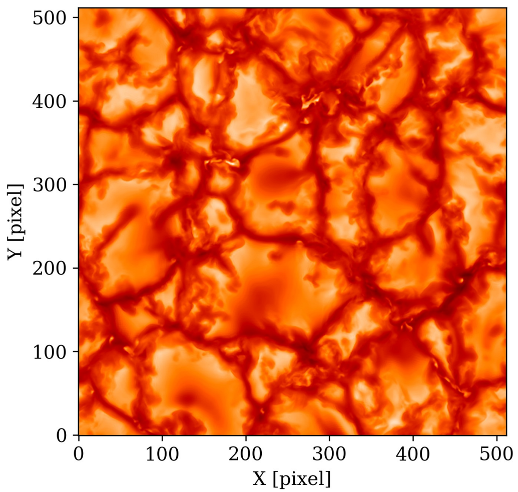
Ergodicity lets us to use a **single snapshot.** It provides sufficient sampling of granulation states to yield stable line-sensitivity diagnostics

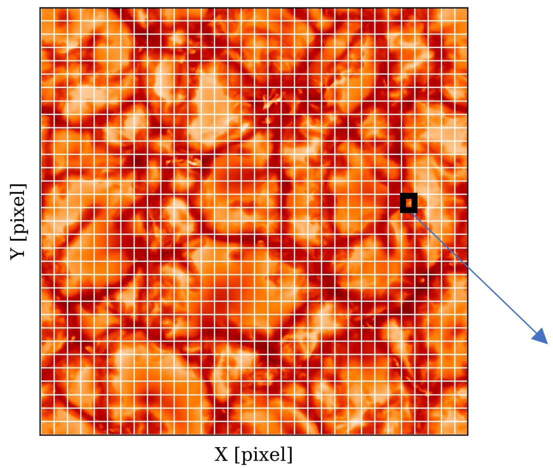
Sowmya et al. (2026)

Approach to study spectral line sensitivity to granulation



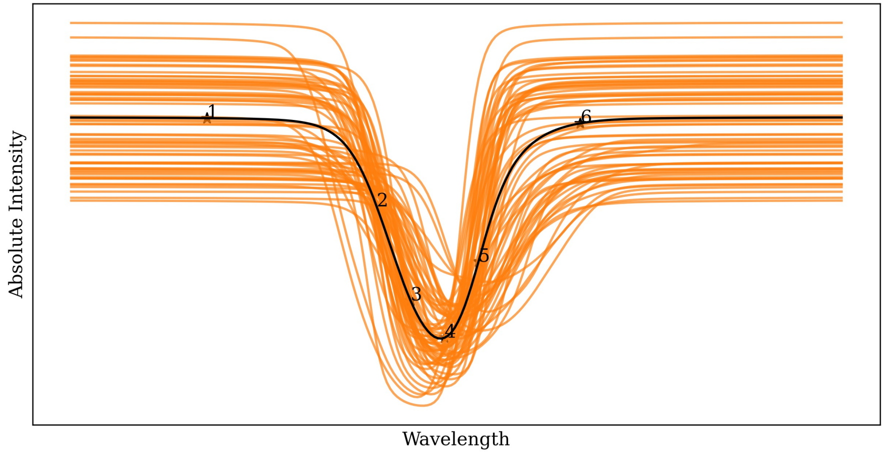
512 x 512 → 32 x 32





Sowmya Krishnamurthy

Spaxel (I_λ averaged over a small domain)



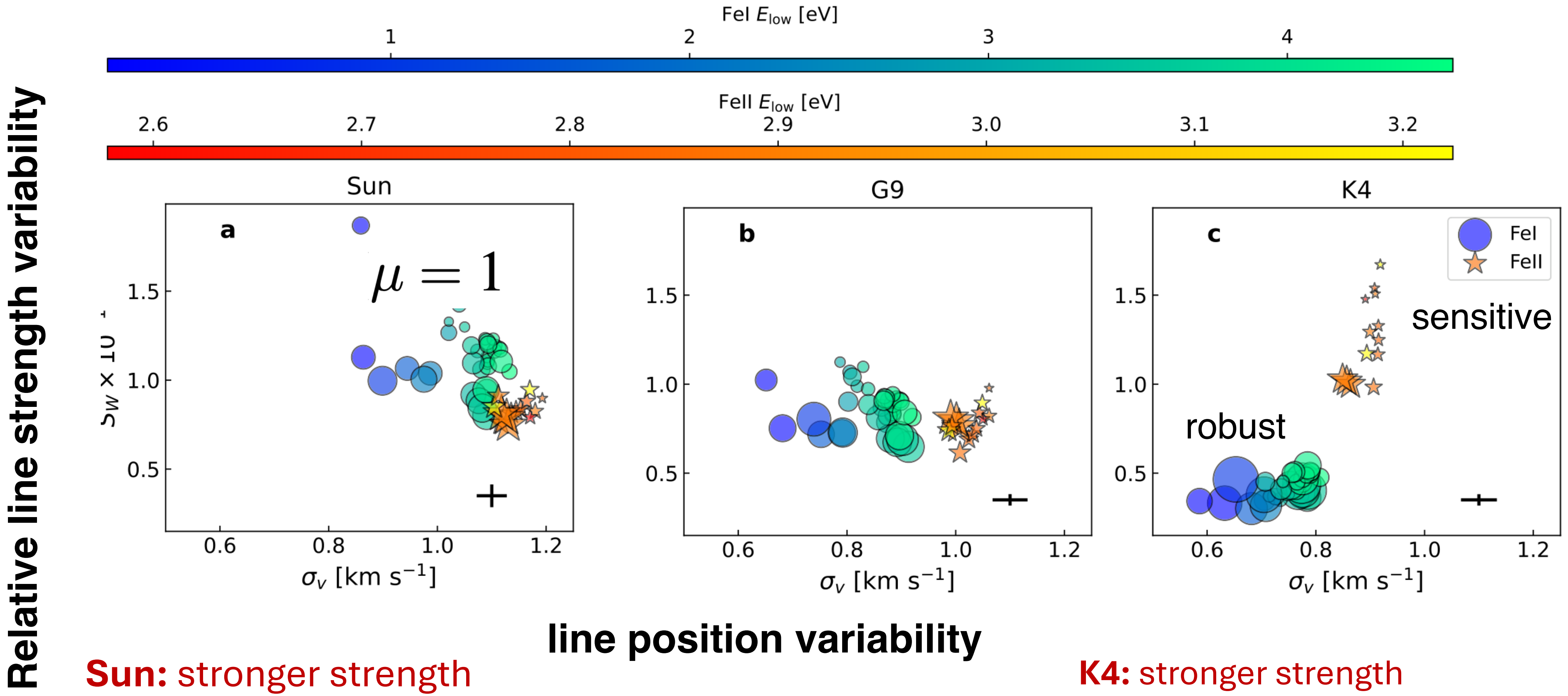
- **Line strengths -** equivalent width (W)
- **Line positions -** center of gravity $\lambda_{\rm COG}$

$$(\boldsymbol{\sigma}_{\rm COG}\,,\quad S_W = \boldsymbol{\sigma}_W/\boldsymbol{W})$$

- primarily to convective motions (V inhomogeneities)
- primarily to convection-driven fluctuations of thermal structure, T and opacity (also V)

Sowmya et al. (2026)

Line sensitivities to granulation



Sun: stronger strength variability for FeI, but larger COG motions for FeII

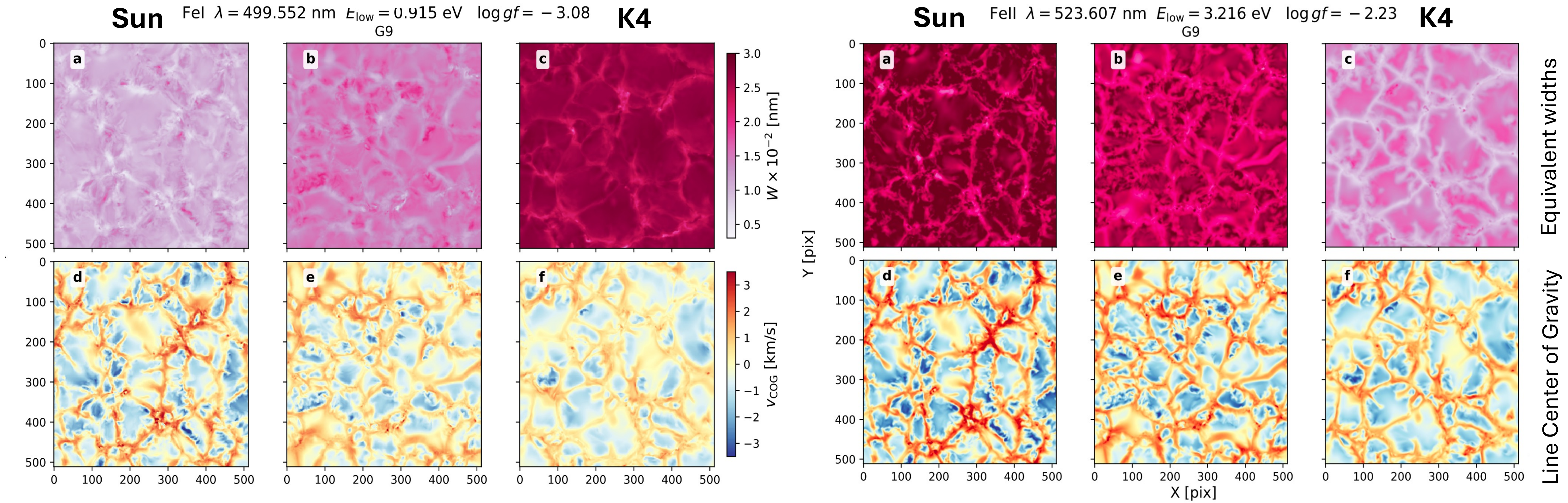
K4: stronger strength variability for FeII and larger COG motions for FeII

FeI candidates for upweighting
FeII candidates for downweighting

Vasilyev et al. (2026)

Spatial equivalent width and COG maps

Fe I	Fe II

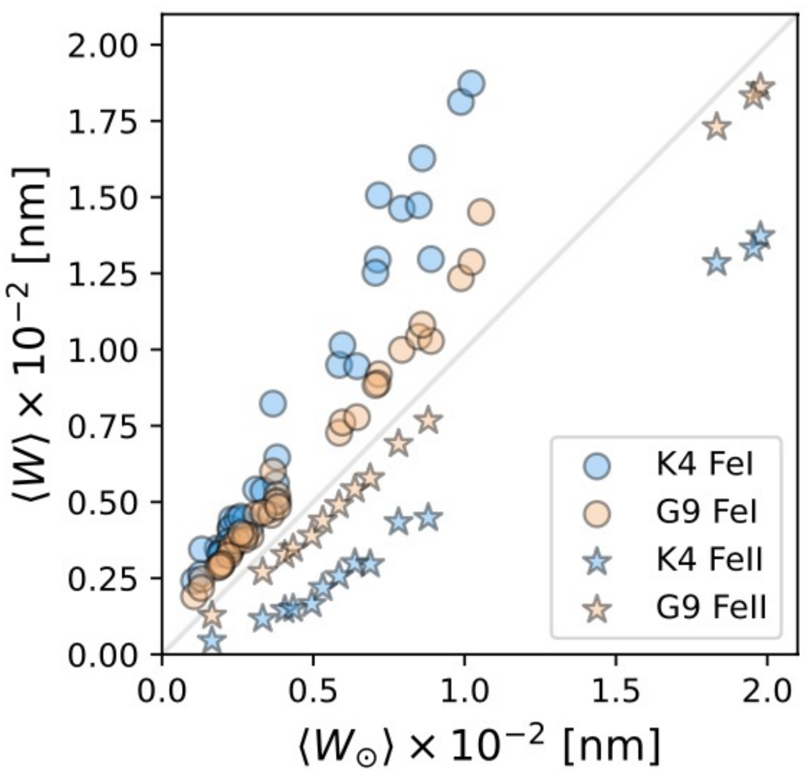


Toward cooler stars:

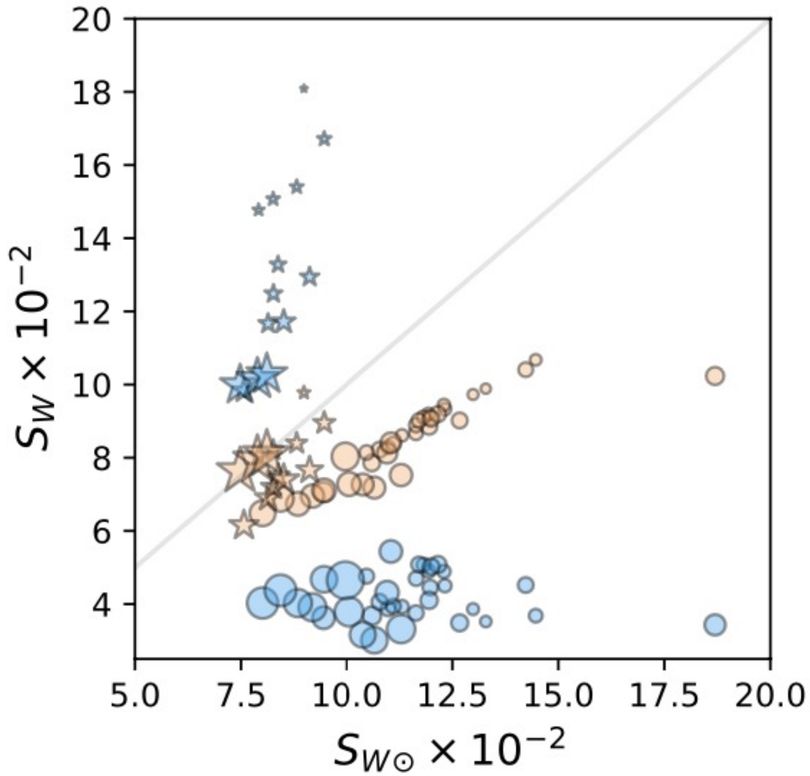
- FeI becomes majority species, FeII becomes minority → separation in the line strength variability
- Vcog decrease - reduction of the convective velocity and granule-lane contrast → $\sigma_{\rm COG}$ variability decreases

Vasilyev et al. (2026)

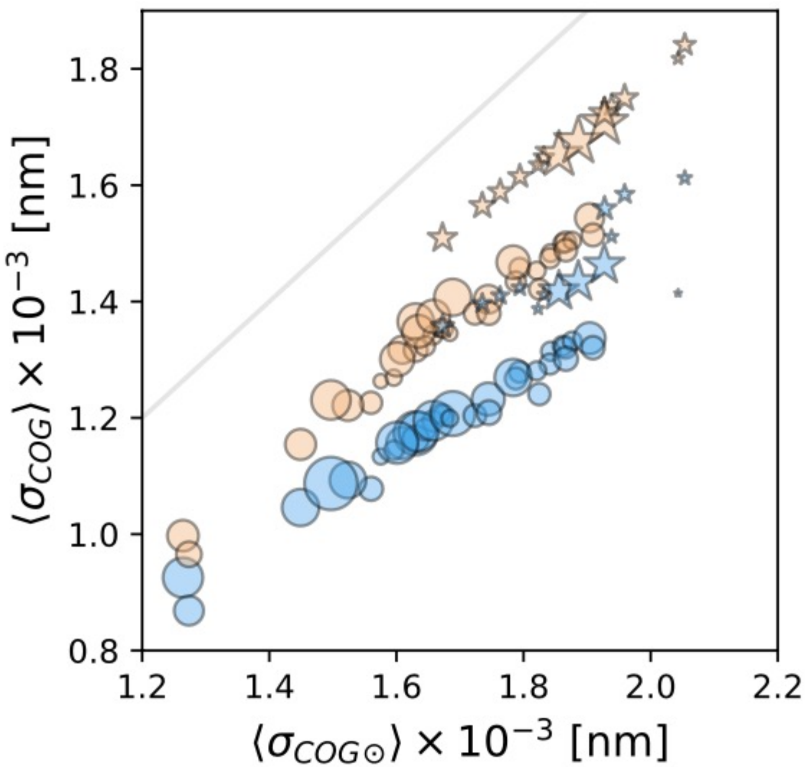
Comparison of line sensitivities to the Sun



FeI and FeII move in opposite directions -- majority/minority switch of the two species wrt the Sun



Lose correlation between solar S_W **and for K4** -- the strong change in ion. balance and the response of line opacity to local thermodynamic fluctuations



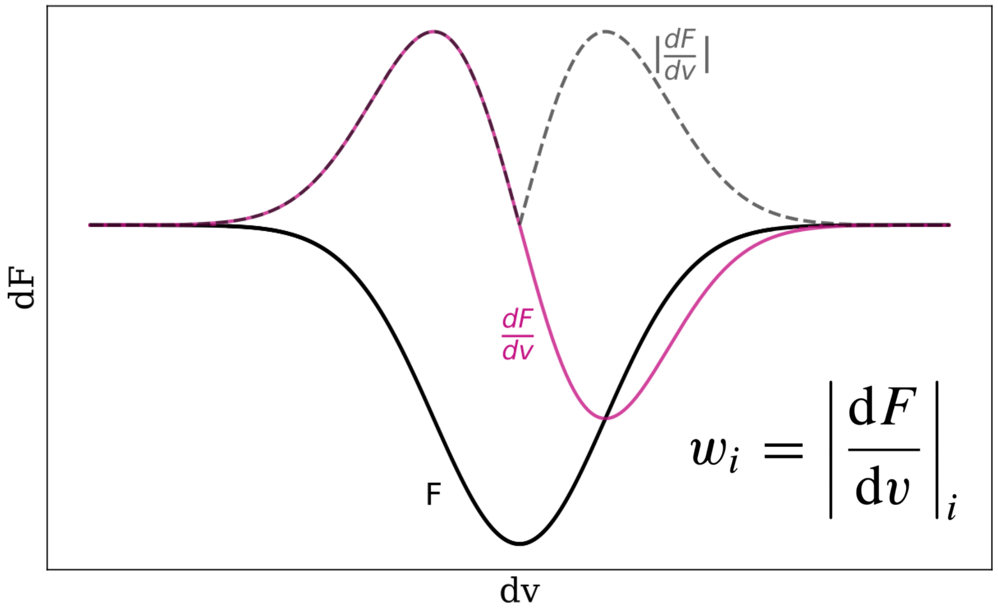
COG variability systematically decreases

Line selections optimized on the Sun cannot be assumed to carry over unchanged to early-K dwarfs, particularly if they rely on equivalent-width stability rather than velocity sensitivity alone

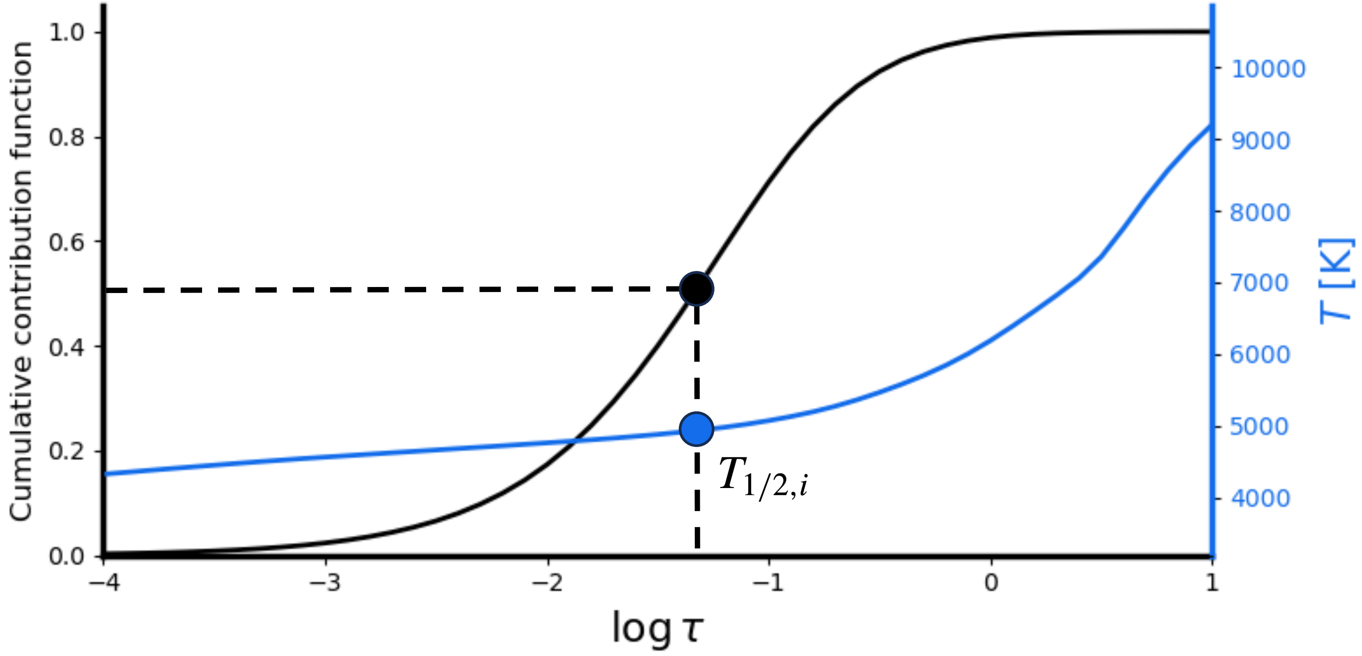
Vasilyev et al. (2026)

Formation temperature

Small shift δv of spectral line perturbs the profile: $\delta f \simeq (\mathrm{d}f/\mathrm{d}v)\,\delta v$
Most of the Doppler information comes from large $|df/dv|$



Anna John et al. 2025

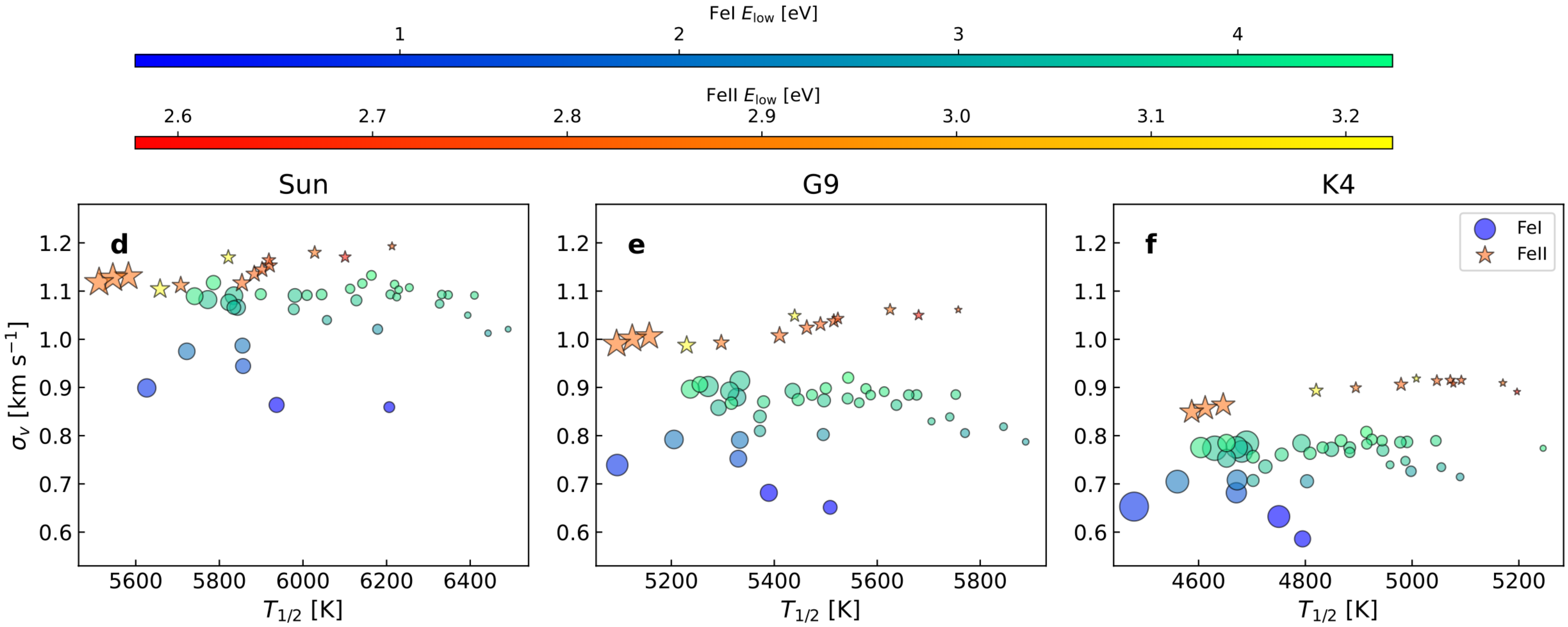


Formation temperature - temperature at depth below which 50% of the emergent flux originates (Al Moulla et al. 2022)

$$\hat{T}_{1/2} = \frac{\sum w_i T_{1/2,i}}{\sum w_i}$$

the temperature of the photospheric layers that **dominate the Doppler information content of the line.** (primarily the line flanks)

Formation temperature in our simulations



Lines with higher formation temperature tend to have stronger variability of the COG
For FeI at fixed form. temperature there is a scatter due to variation of atomic parameters

Vasilyev et al. (2026)

Takeaway messages

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Sensitivity of Spectral Lines to Granulation: The Sun

K. Sowmya[1], A. I. Shapiro[1,2], V. Vasilyev[2], V. Witzke[1], A. Collier Cameron[3], and S. K. Solanki[2]
[1] Institute of Physics, University of Graz, Universitätsplatz 5, 8010 Graz, Austria; sowmya.krishnamurthy@uni-graz.at
[2] Max-Planck-Institut für Sonnensystemforschung, Justus-von-Liebig-Weg 3, 37077, Göttingen, Germany
[3] Centre for Exoplanet Science, SUPA School of Physics and Astronomy, University of St Andrews, North Haugh, St Andrews KY16 9SS, UK
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Sensitivity of Spectral Lines to Granulation: From the Sun to K-type Stars

V. Vasilyev[1], K. Sowmya[2], A. I. Shapiro[1,2], N. Kostogryz[1], D. Vukadinovic[2], V. Witzke[2], T. Bhatia[1], A. Collier Cameron[3], L. Gizon[1,4], and S. K. Solanki[1,5]
[1] Max-Planck-Institut für Sonnensystemforschung, Justus-von-Liebig-Weg 3, 37077, Göttingen, Germany; vasilyev@mps.mpg.de
[2] Institute of Physics, University of Graz, Universitätsplatz 5, 8010 Graz, Austria
[3] Centre for Exoplanet Science, SUPA School of Physics and Astronomy, University of St. Andrews, North Haugh, St. Andrews KY16 9SS, UK
[4] Institut für Astrophysik und Geophysik, Georg-August-Universität Göttingen, 37077, Göttingen, Germany
[5] School of Space Research, Kyung Hee University, Yongin, Gyeonggi 17104, Republic of Korea
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- We use **ergodicity** of granulation to replace expensive time-series simulations with the single snapshot
- We introduce a way **to characterize the line sensitivity to granulation**
- Moving from solar to late-G/K dwarfs **decreases Vconv** and shifts **FeI to majority, FeII to minority**
- **Stellar-type-specific line selection is necessary:** EW-based masks optimized on the Sun should not be assumed to transfer unchanged to late-G and K dwarfs. FeI lines provide robust candidates for upweighting, whereas FeII lines are prime candidates for downweighting on K4
- **Future steps:** generalization to larger number of lines and elements (incl atomic parameters), test spectral-type-specific masks.
  - **Sensitivity to granulation as a function of metallicity → see poster P2160 (D. Vukadinović)**