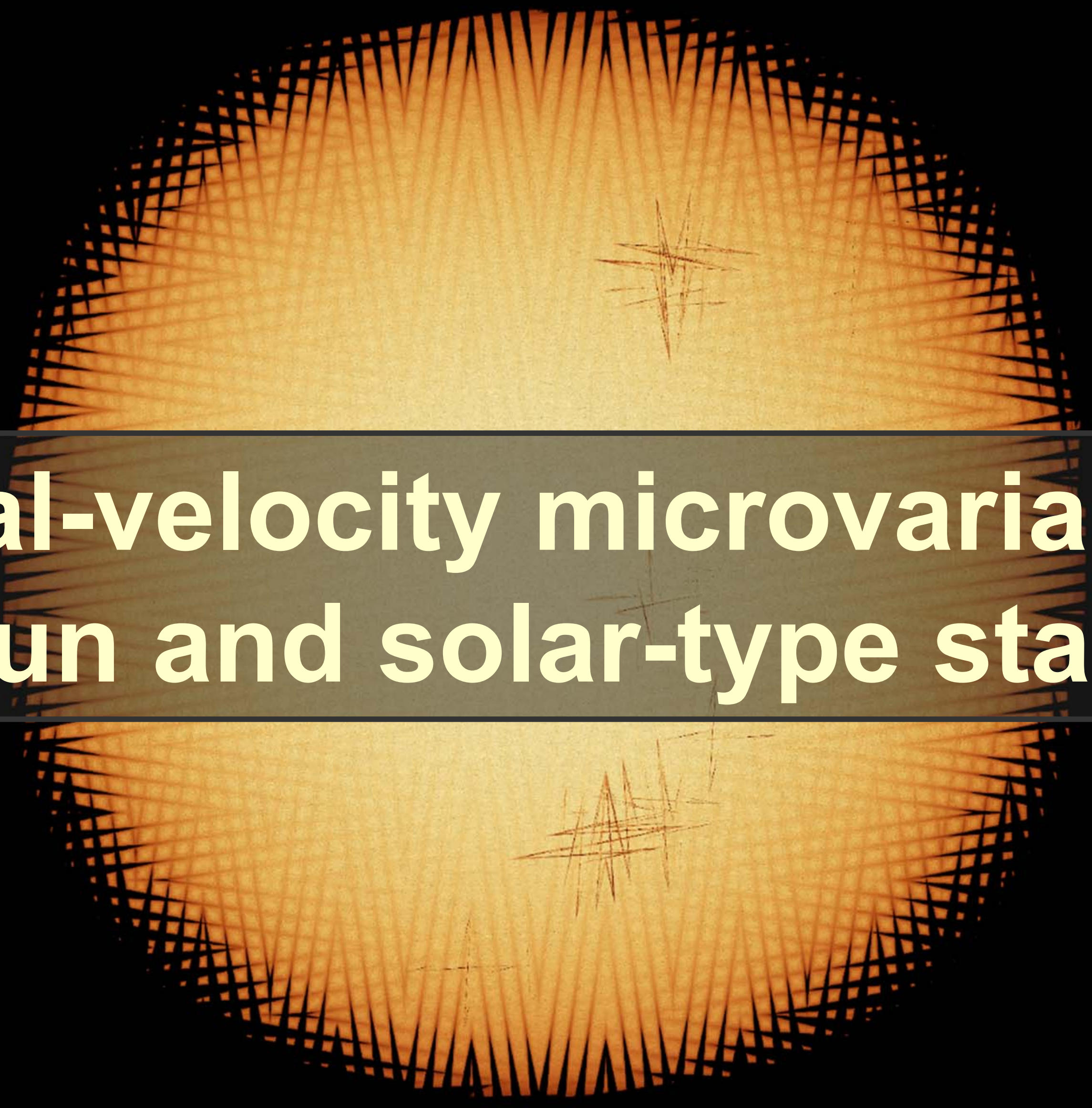
Radial-velocity microvariability: Sun and solar-type stars



Dainis Dravins

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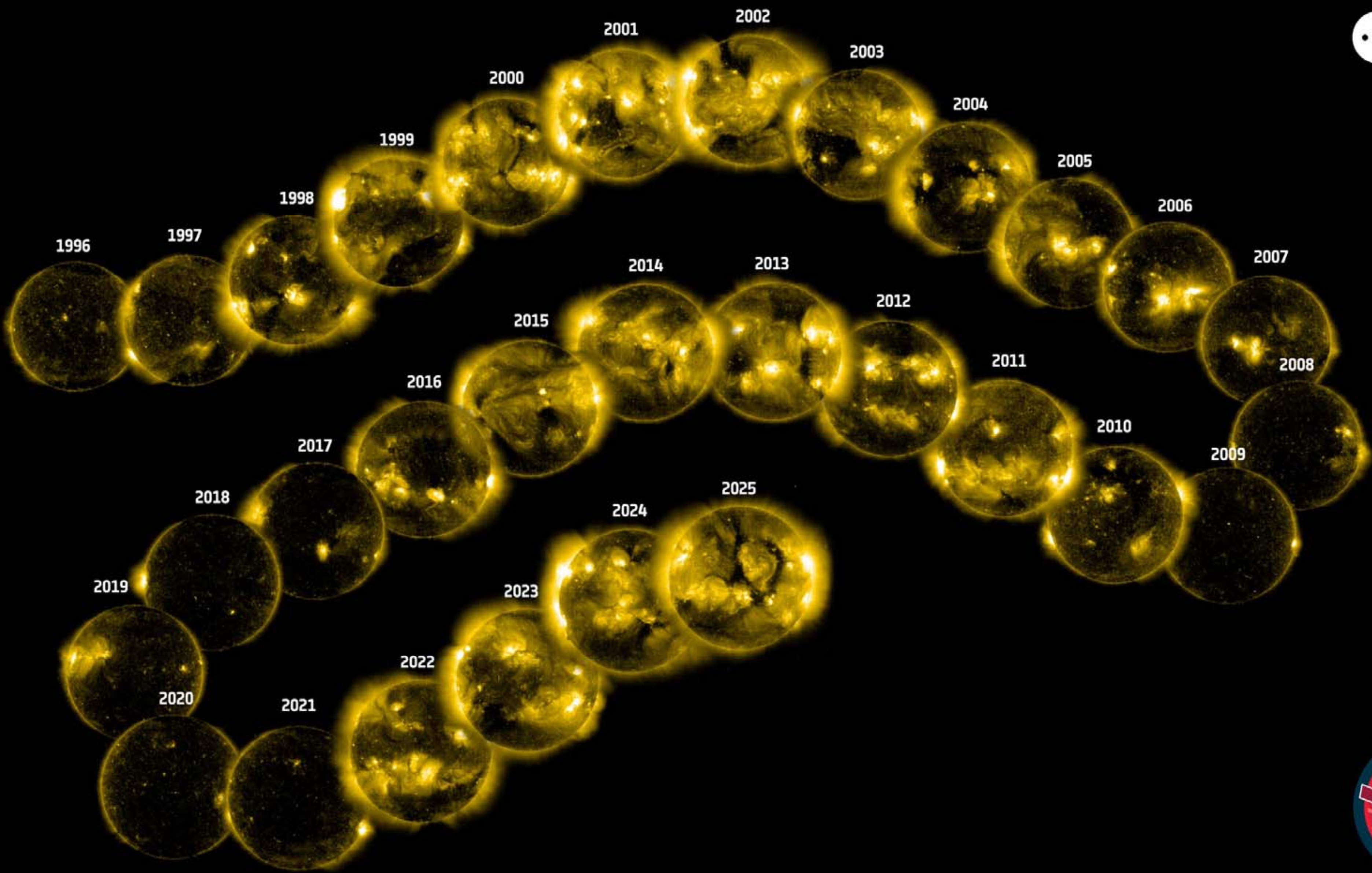
www.astro.lu.se/~dainis

Solar activity cycle

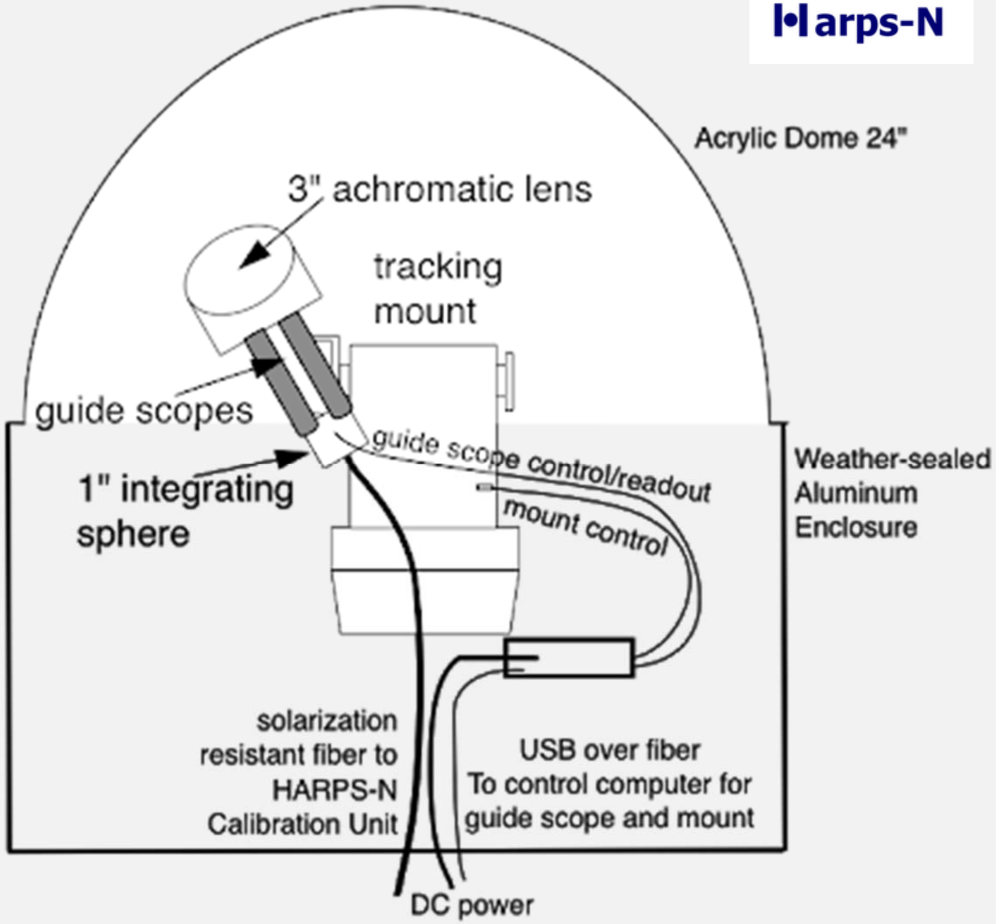


ESA/NASA Solar and Heliospheric Observatory (SOHO) has monitored the Sun during three 11-year cycles.
Here: Fe XV 28.4 nm coronal line maps out temperatures around 2 million K.
(SOHO - ESA & NASA; F.Auchère & ATG Europe)

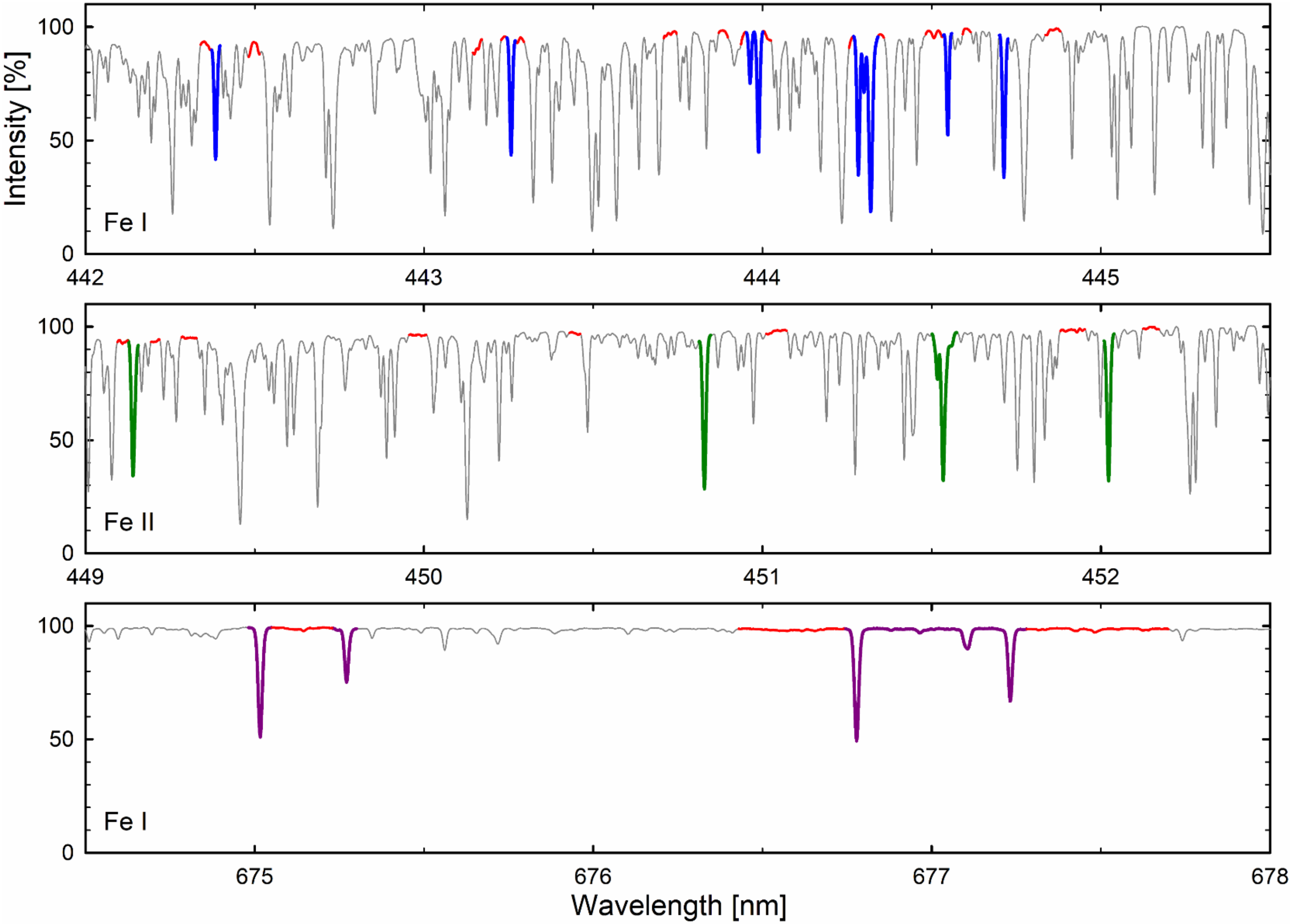
Photospheric proxies for magnetic activity?

Sun-as-a-star on La Palma

Solar telescope feeding sunlight to HARPS-N



Fe I and Fe II lines @ *HARPS-North*



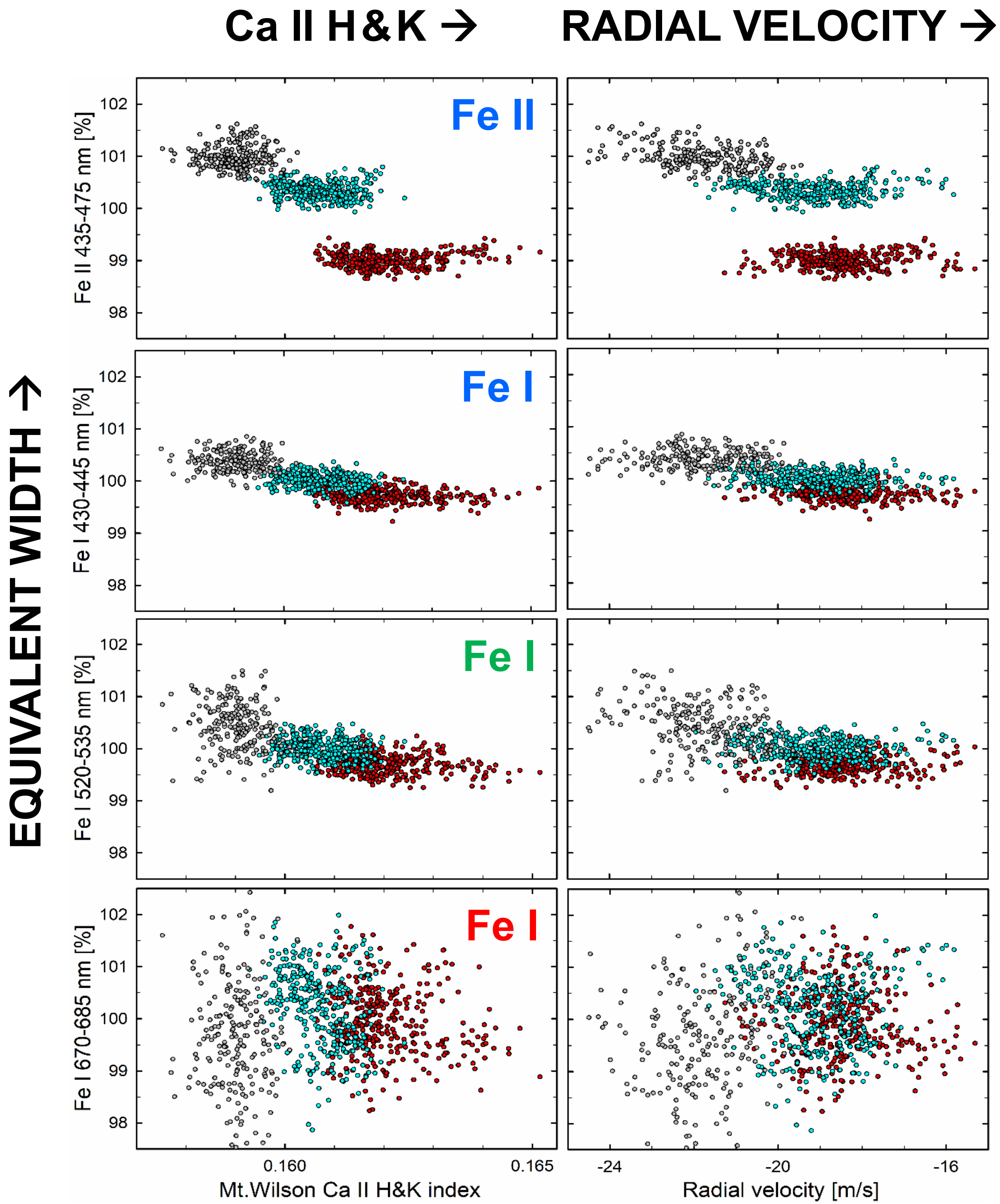
Selected Fe lines in different spectral regions

Red: Reference "continua"

Thin: 100-exposure average

D.Dravins, H.-G.Ludwig: *Solar photospheric spectrum microvariability. II. Observed relations to magnetic activity and radial-velocity modulation*, Astron.Astrophys. **687**, A60 (2024)

Data from X.Dumusque et al.: *Three Years of HARPS-N High-Resolution Spectroscopy and Precise Radial Velocity Data for the Sun* Astron.Astrophys. **648**, A103 (2021)



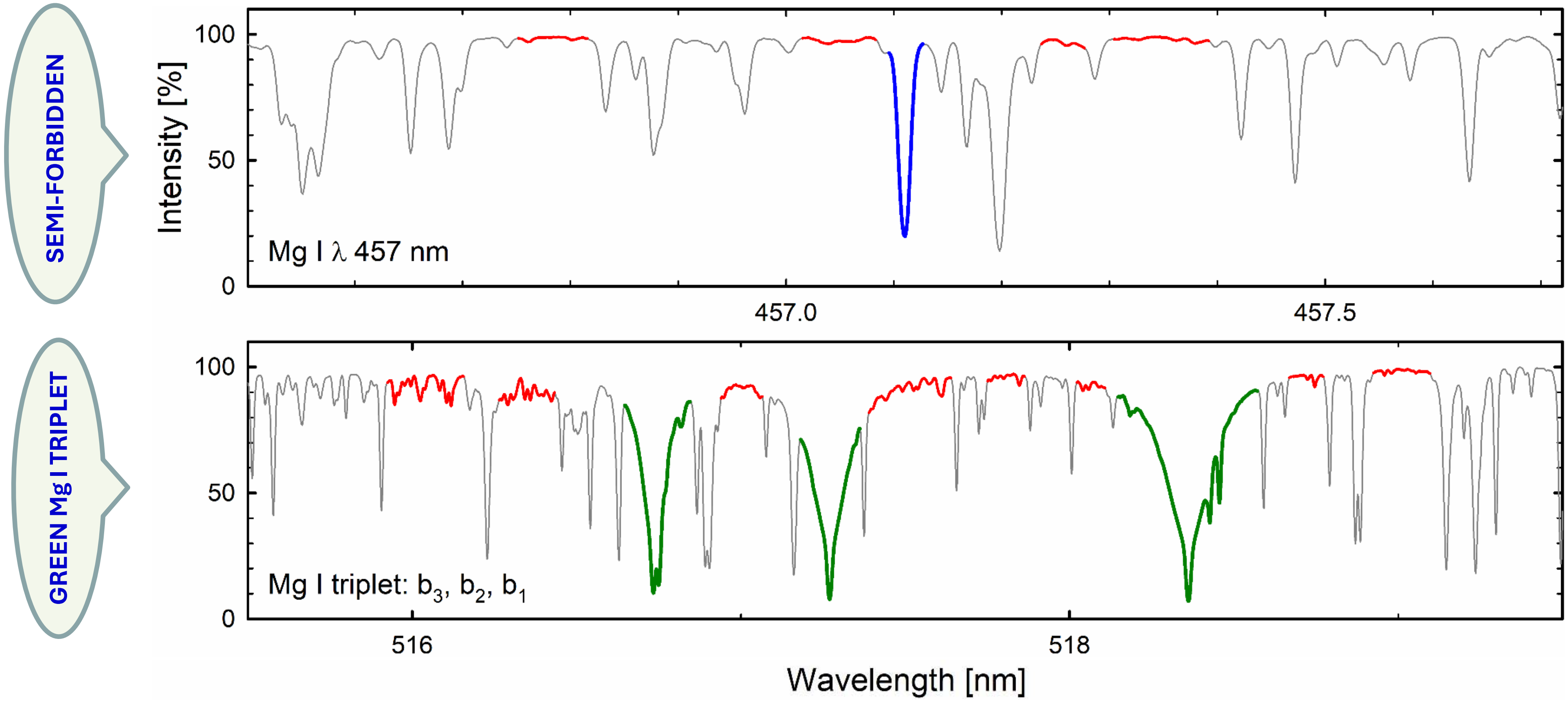
HARPS-N observed solar Fe I & Fe II microvariability

Relative equivalent widths for groups of Fe lines during summer seasons of 2016 (red), 2017 (cyan) and 2018 (gray).

Left: function of Ca II H & K activity index
Right: function of apparent radial velocity

D.Dravins, H.-G.Ludwig: *Solar photospheric spectrum microvariability. II. Observed relations to magnetic activity and radial-velocity modulation*, Astron.Astrophys. **687**, A60 (2024)

Mg I lines @ HARPS-North



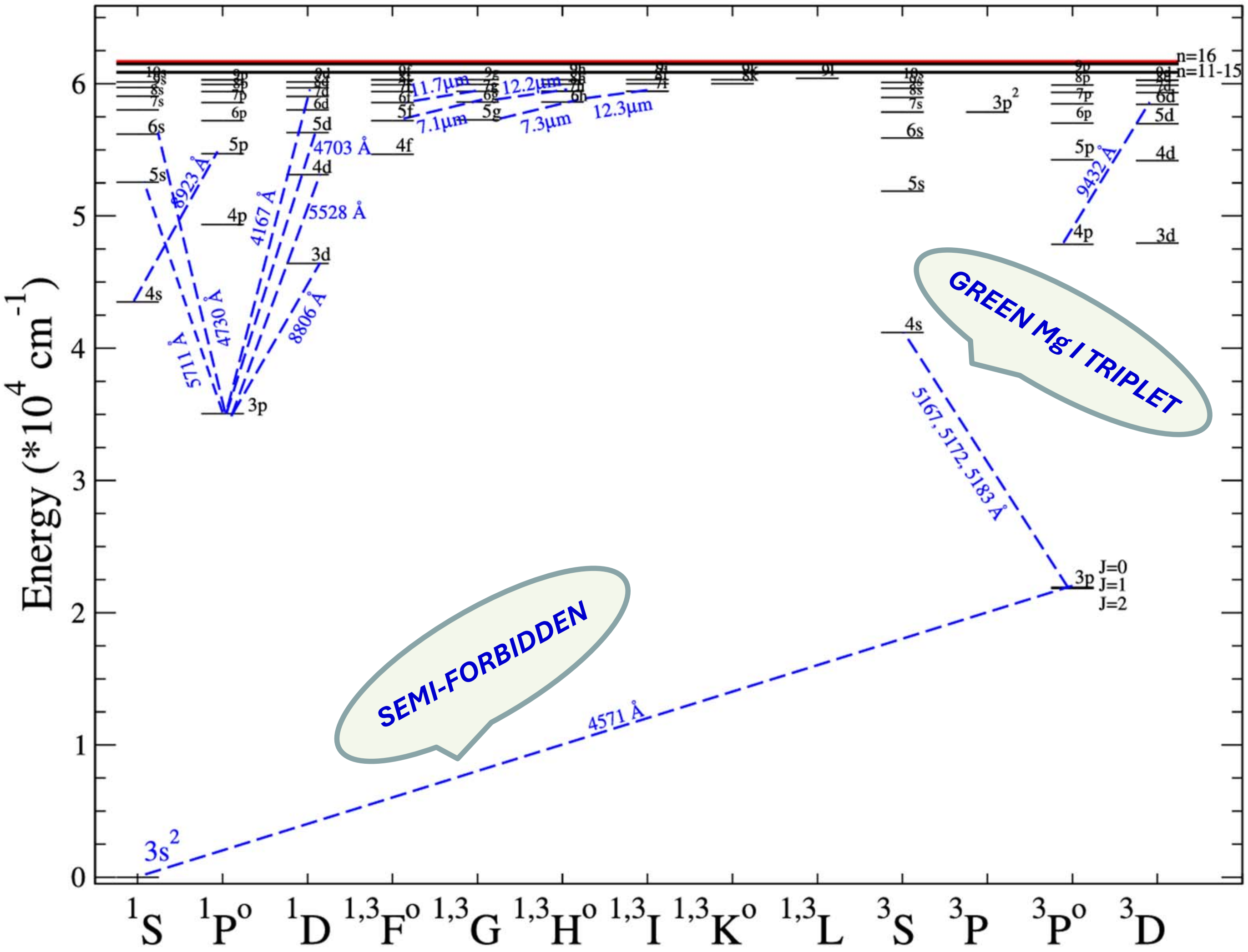
Selection of spectral regions for measurement.

Top: Mg I 457.1 nm “semi-forbidden” absorption line and its surrounding continuum reference segments (red).

Bottom: Mg I b triplet lines and their continuum reference segments.

D.Dravins, H.-G.Ludwig: *Solar photospheric spectrum microvariability. II. Observed relations to magnetic activity and radial-velocity modulation*, Astron.Astrophys. **687**, A60 (2024)

Mg I lines

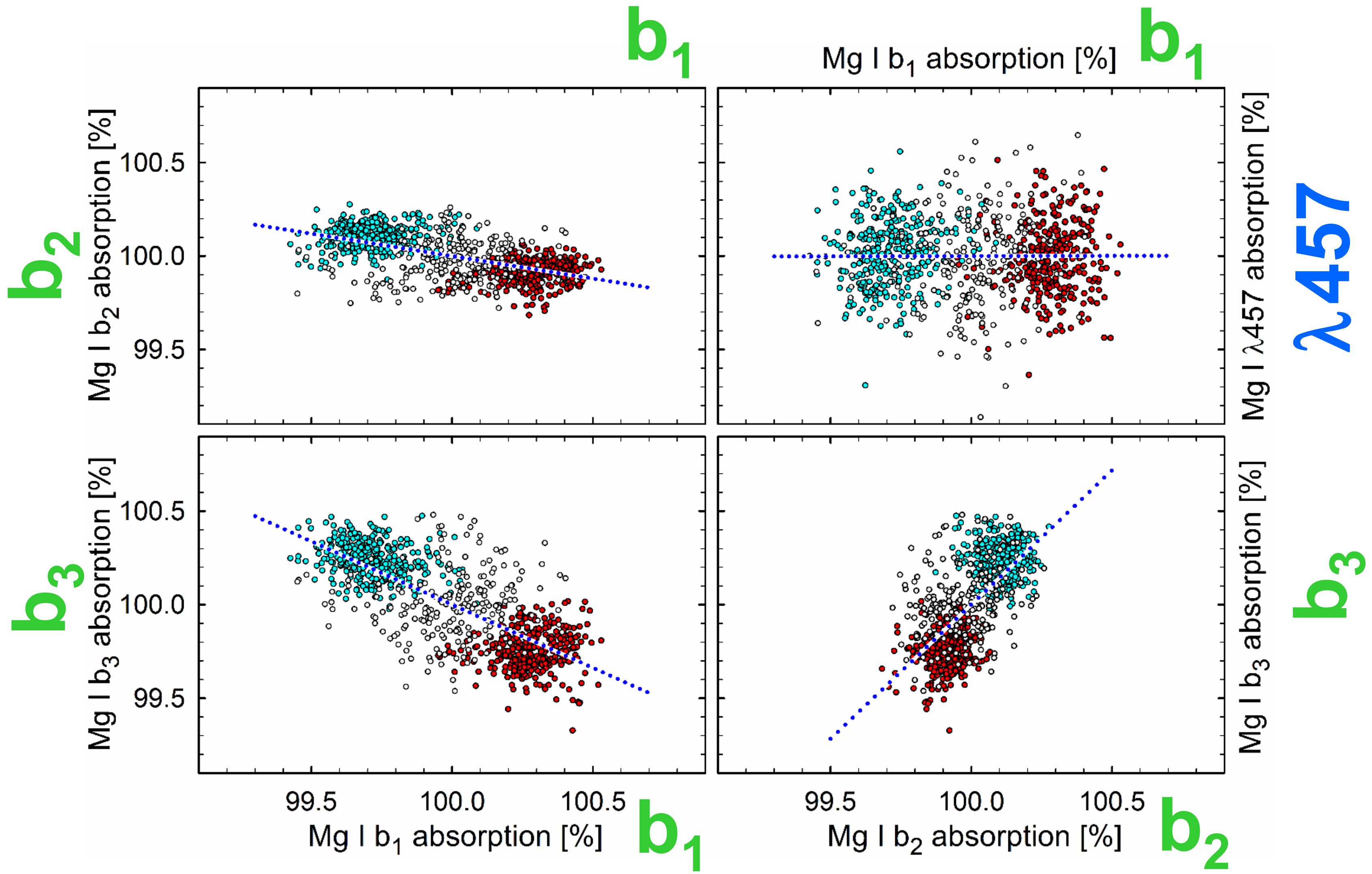


Grotrian term and energy diagram for Mg I

The “semi-forbidden” intersystem line Mg I 457.1 nm originates between the atomic levels $3s^2\ {}^1S_0 - 3p\ {}^3P_1$. Its upper energy level is same as the lower level of Mg I b_2 , from where it transits to the ground level.

Figure from: S.Alekseeva et al.: *NLTE Line Formation for Mg I and Mg II in the Atmospheres of B-A-F-G-K Stars*, Astrophys.J. **866**,153 (2018)

Mg I line microvariability @ HARPS-North



Observed absorption ratios among Mg I lines

Relative changes in Mg I equivalent widths during summer seasons of 2016-2017-2018 (red-cyan-gray).

D.Dravins, H.-G.Ludwig: *Solar photospheric spectrum microvariability. II. Observed relations to magnetic activity and radial-velocity modulation*, Astron.Astrophys. **687**, A60 (2024)

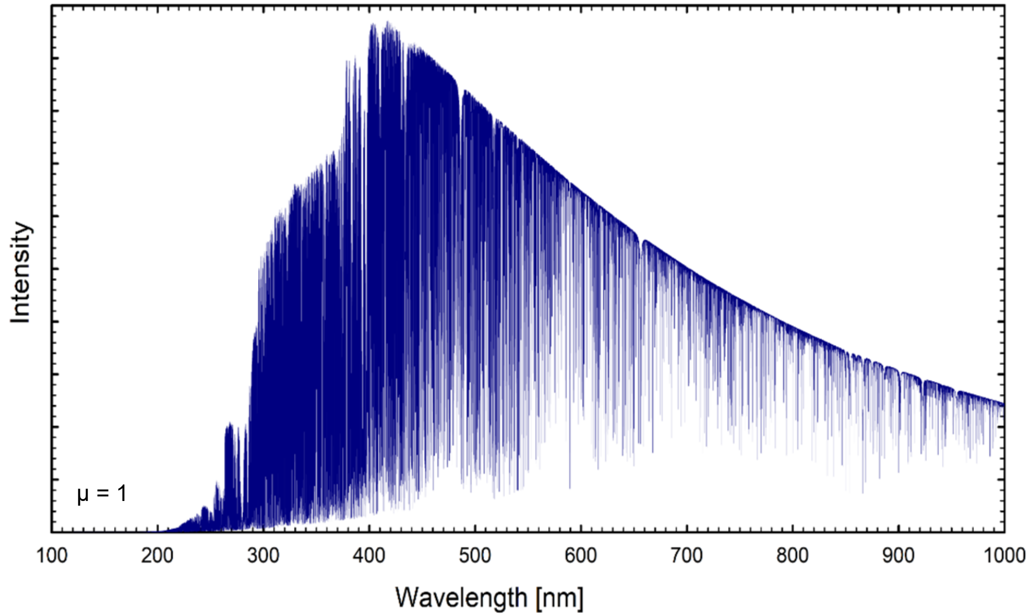
Data from X.Dumusque et al.: *Three Years of HARPS-N High-Resolution Spectroscopy and Precise Radial Velocity Data for the Sun* Astron.Astrophys. **648**, A103 (2021)

3D hydrodynamics: ‘Movies’ of high-resolution solar spectral atlases

CO^5BOLD Synthetic 3D Solar Spectra

Model 1: Complete spectrum

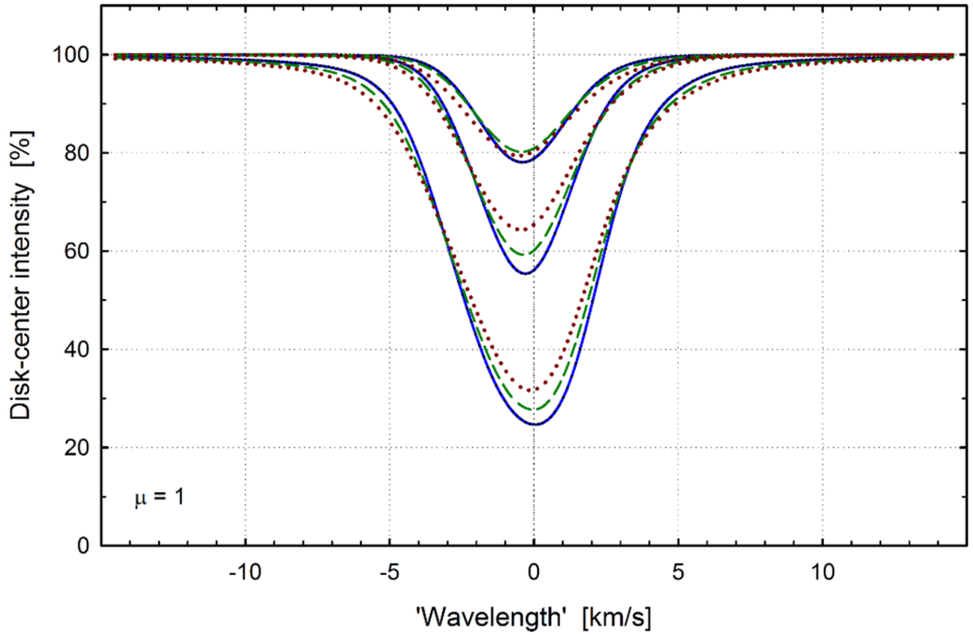
T_{eff} = 5774 K , $\lambda/\Delta\lambda \sim$ 1,000,000



Full spectrum synthesis
incorporating 636,837 lines

Model 2: Idealized spectral lines

T_{eff} = 5782 K, $\lambda/\Delta\lambda \sim$ 2,000,000

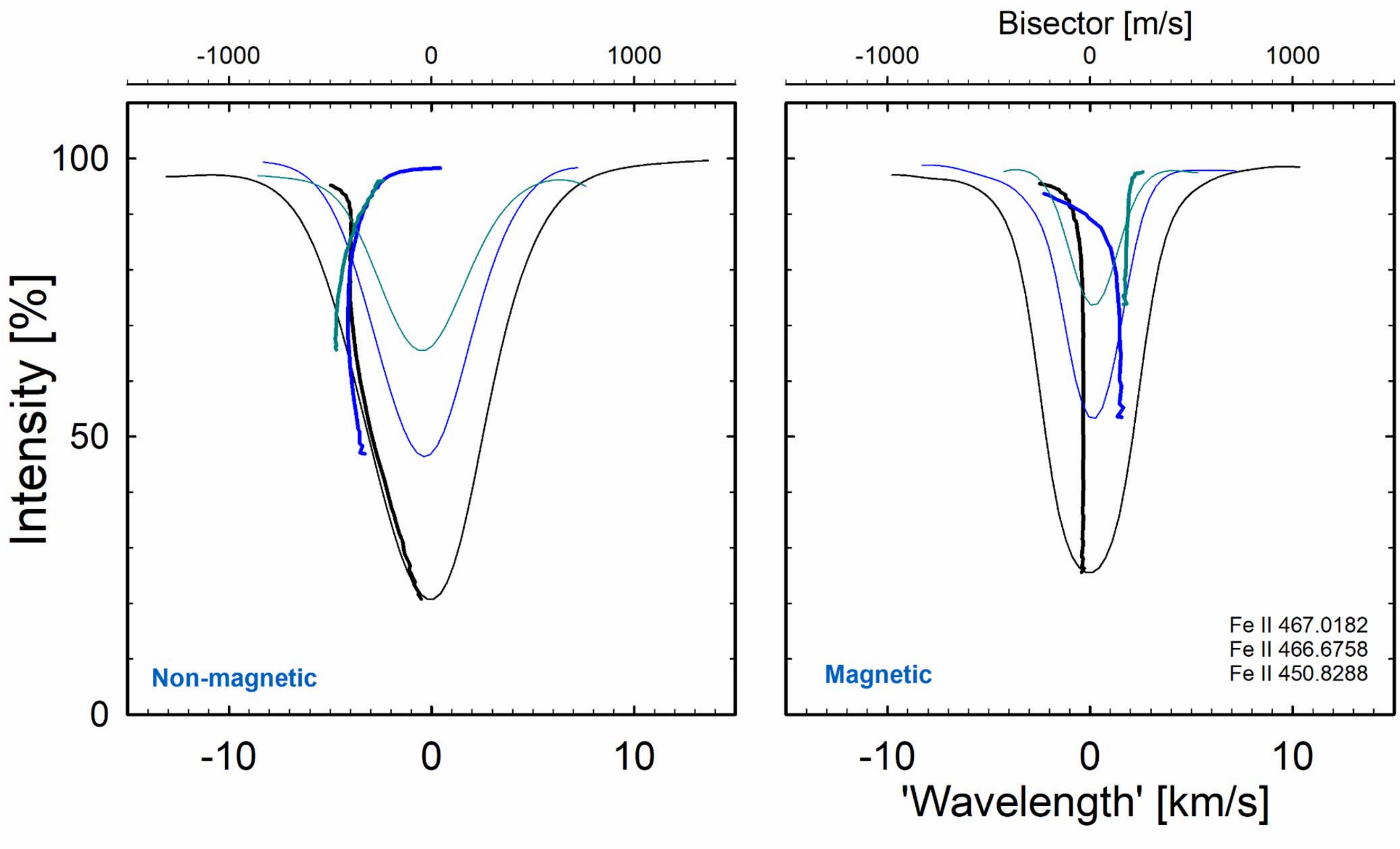


Fe I lines at λ 620 nm; varying strengths,
excitation potentials $\chi = 1, 3, 5$ eV

D.Dravins, H.-G.Ludwig: *Solar photospheric spectrum microvariability. I. Theoretical searches for proxies of radial-velocity jittering*
Astron.Astrophys. **679**, A3 (2023)

D.Dravins, H.-G.Ludwig, E.Dahlén, H.Pazira:
Spatially resolved spectroscopy across stellar surfaces. I.
Using exoplanet transits to analyze 3D stellar atmospheres
Astron.Astrophys. **605**, A90 (2017)

Non-magnetic vs. magnetic granulation



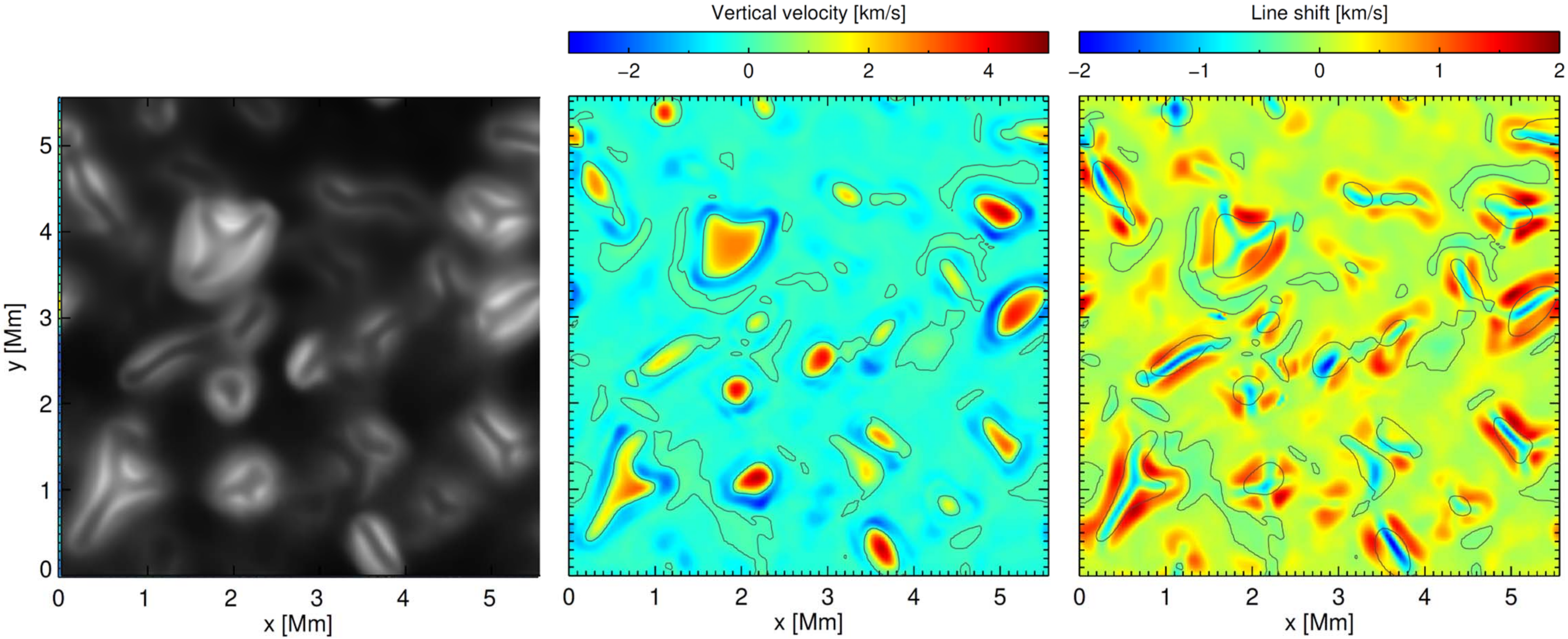
Synthetic Fe II lines from non-magnetic and magnetic 240 mT (2400 G) simulations

Line profiles and bisectors for integrated sunlight

D.Dravins, H.-G.Ludwig, M.Steffen, C.Allende Prieto, L.Koesterke: *Solar photospheric spectrum microvariability. III. Radial velocities and line profiles in magnetic active-region granulation*, Astron.Astrophys. **710**, A30 (2026)

Why redshift in magnetic areas？

Magnetic granulation



Brightness, gas motions, and radial velocities in a 3-D model snapshot from 240 mT (2400 G) simulation

Hot and bright elements develop through adiabatic compression when rising gas turns over into magnetically channelled downflows

Left: Continuum image near Fe I 683.7 nm

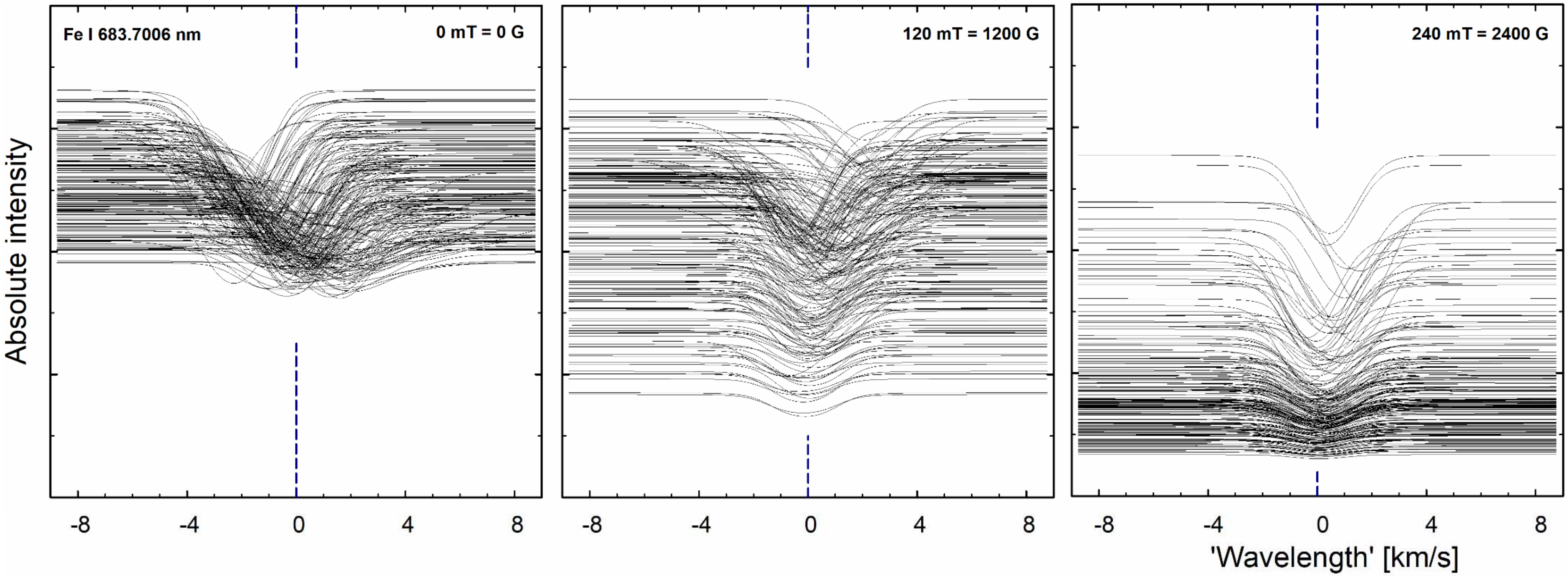
Center: Vertical velocities near optical depth unity. Black contours for $v_z = 0$ separate up- and downflows

Right: Measured radial velocities in Fe I 683.7 nm

Note: Color scales invert between vertical velocities (positive upwards) and radial velocities (positive receding inwards)

D.Dravins, H.-G.Ludwig, M.Steffen, C.Allende Prieto, L.Koesterke: *Solar photospheric spectrum microvariability. III. Radial velocities and line profiles in magnetic active-region granulation*, Astron.Astrophys. **710**, A30 (2026)

Spatially resolved line profiles

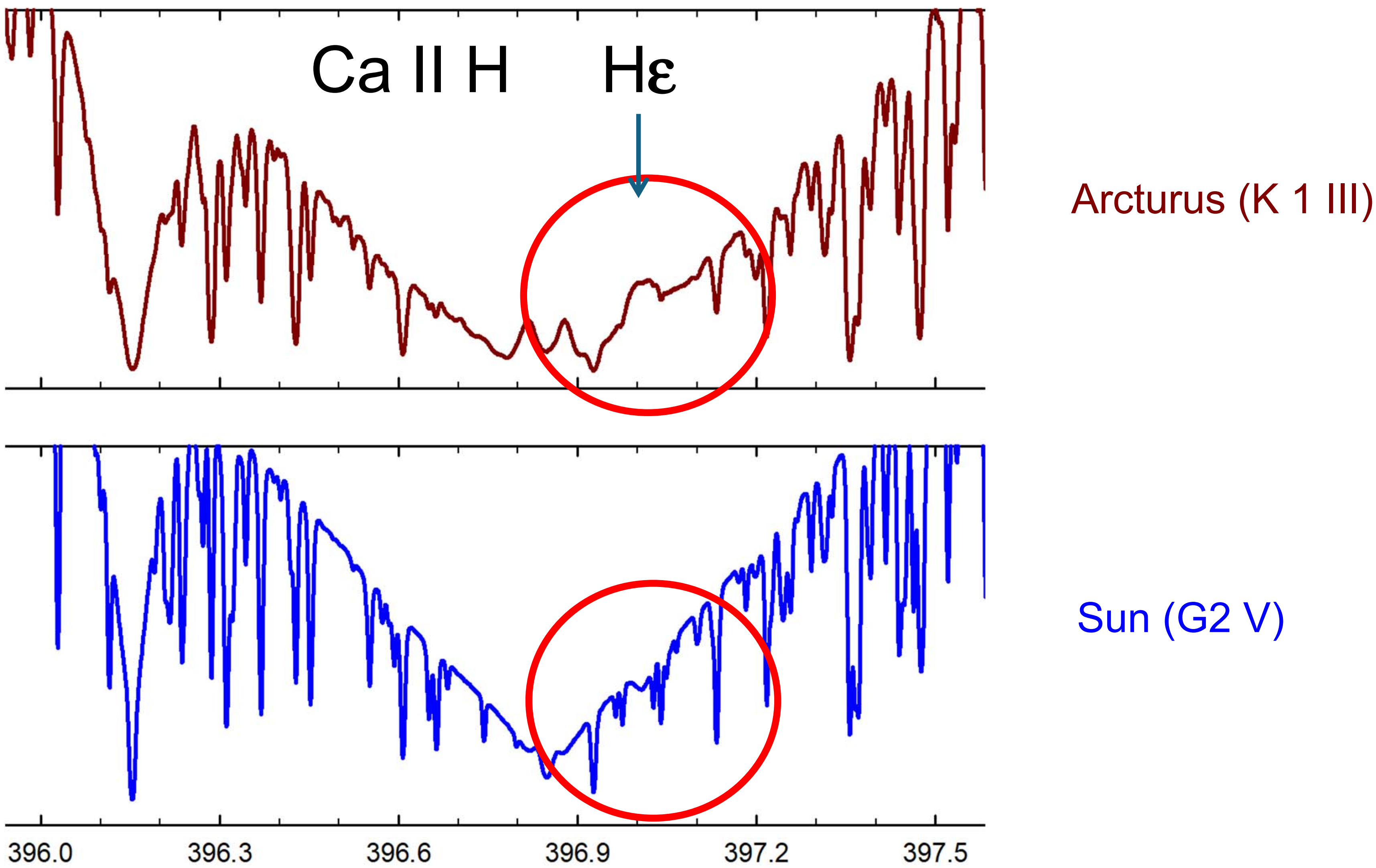


Fe I 683.7 nm line in simulations with magnetic fields 0, 120, and 240 mT

Convective non-magnetic blueshift turns into magnetic redshift.

D.Dravins, H.-G.Ludwig, M.Steffen, C.Allende Prieto, L.Koesterke: *Solar photospheric spectrum microvariability. III. Radial velocities and line profiles in magnetic active-region granulation*, Astron.Astrophys. **710**, A30 (2026)

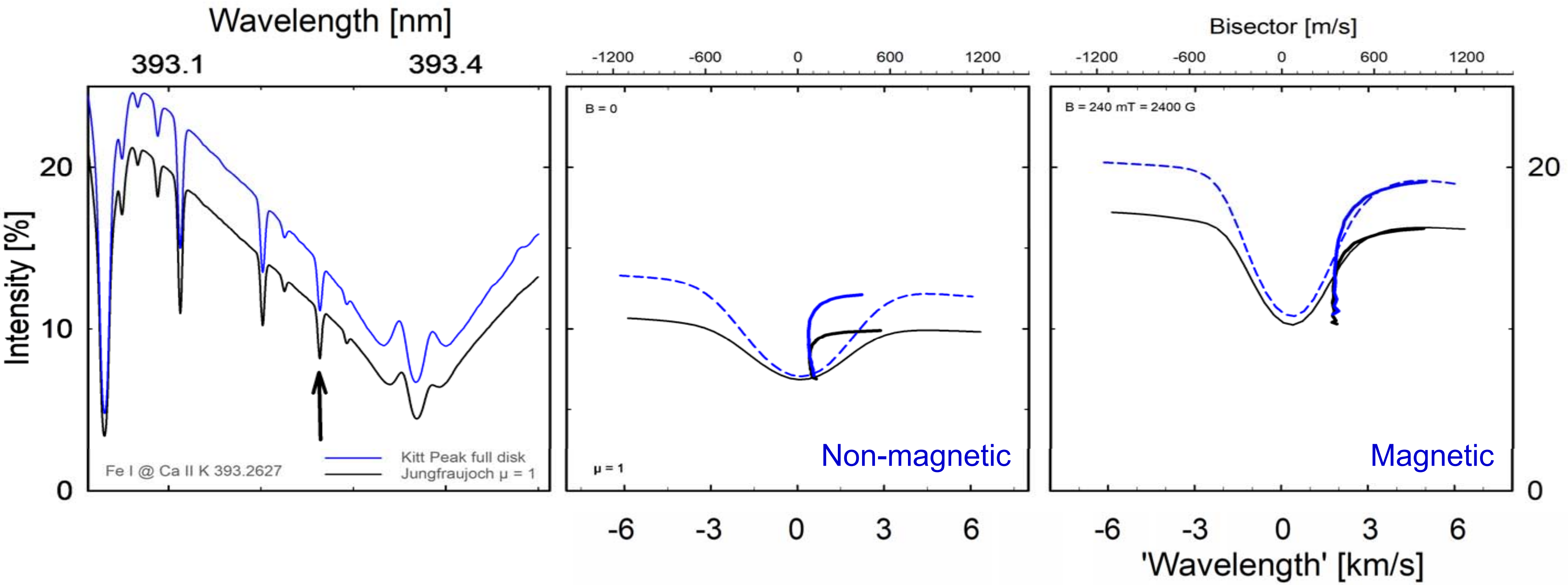
Lines in particular positions



Hydrogen Balmer H-epsilon overlays longward wing of the Ca II H line
Under combined opacity, it goes into chromospheric-like emission in some stars

K.Hinkle, L.Wallace, J.Valenti, D.Harmer: *Visible and Near Infrared Atlas of the Arcturus Spectrum, 3727-9300 A*

Lines in particular positions

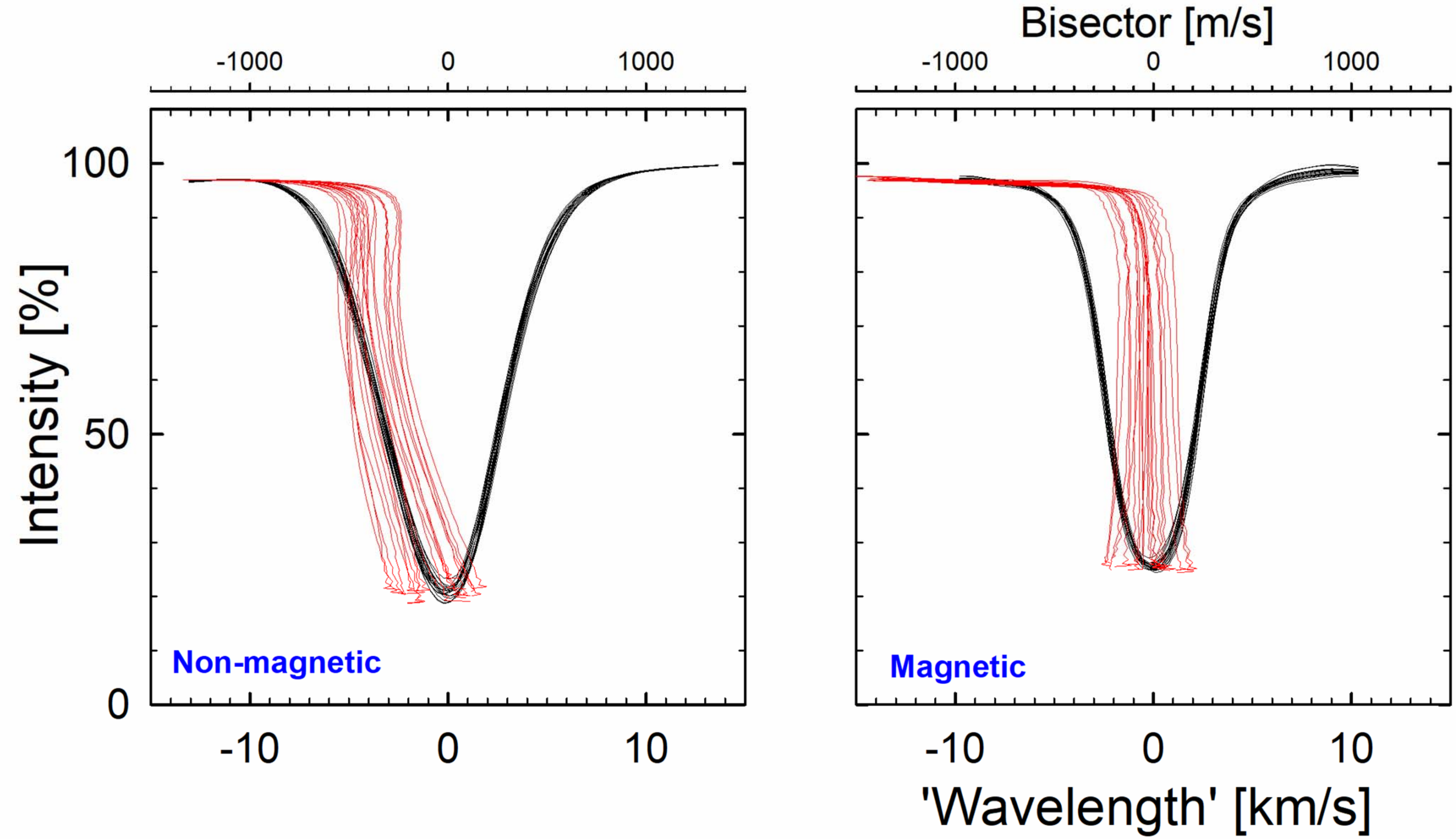


Fe I lines in absorption wings of Ca II H&K lines get formation heights lifted through combined opacities

Almost no difference in lineshift between disk center (solid) and integrated sunlight (dashed).

D.Dravins, H.-G.Ludwig, M.Steffen, C.Allende Prieto, L.Koesterke: *Solar photospheric spectrum microvariability. III. Radial velocities and line profiles in magnetic active-region granulation*, Astron.Astrophys. **710**, A30 (2026)

Spectral variability from 3D modeling

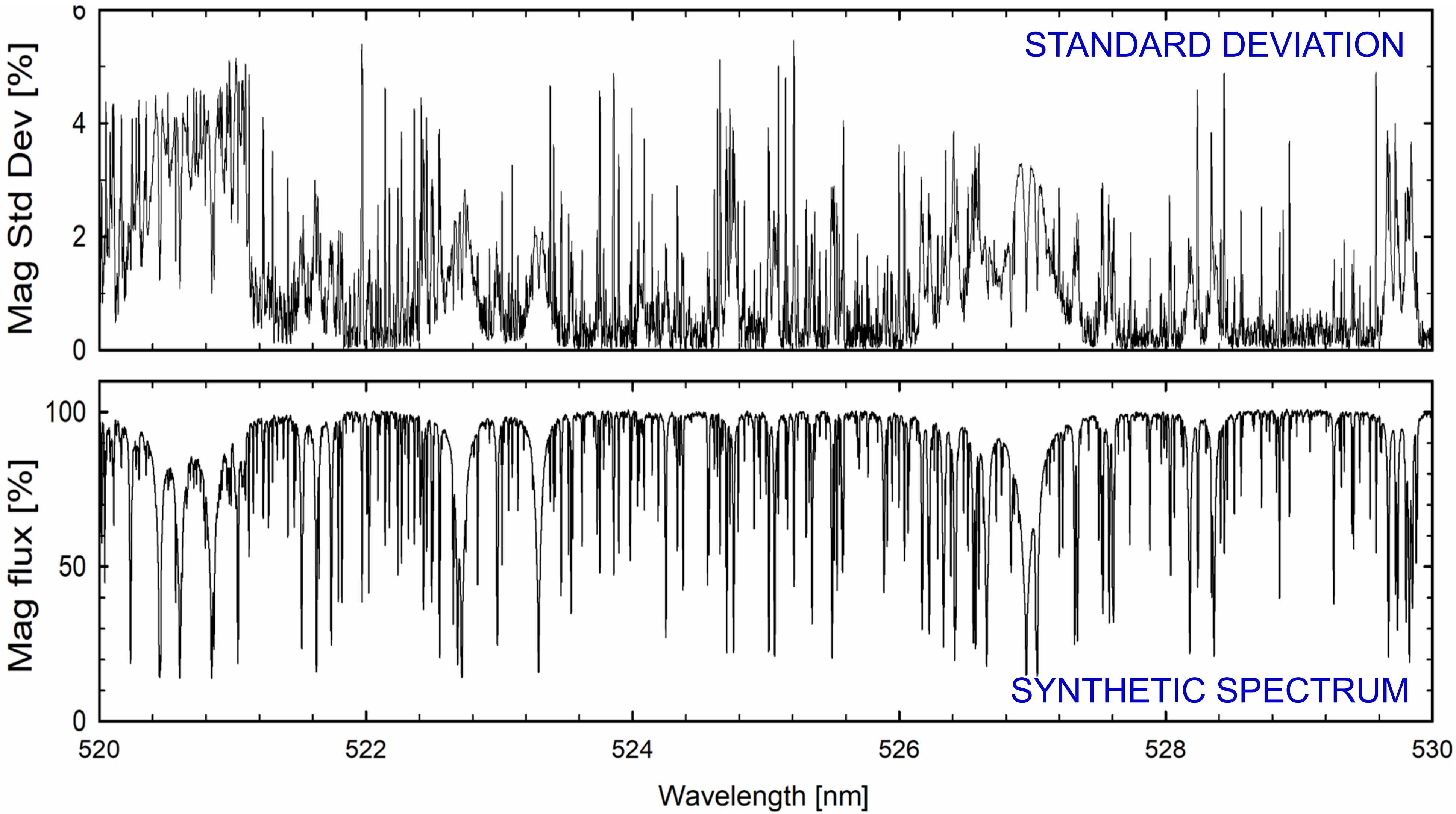


Line profile and bisector variability for a strong photospheric line in the solar flux spectrum (Fe II 450.8288 nm)

Profiles sampled at 20 times during 3D MHD simulations for non-magnetic and magnetic granulation

D.Dravins, H.-G.Ludwig, M.Steffen, C.Allende Prieto, L.Koesterke:
Solar photospheric spectrum microvariability. IV. Radial-velocity and line-profile fluctuations in (non-)magnetic granulation, in preparation

Spectral variability from 3D modeling

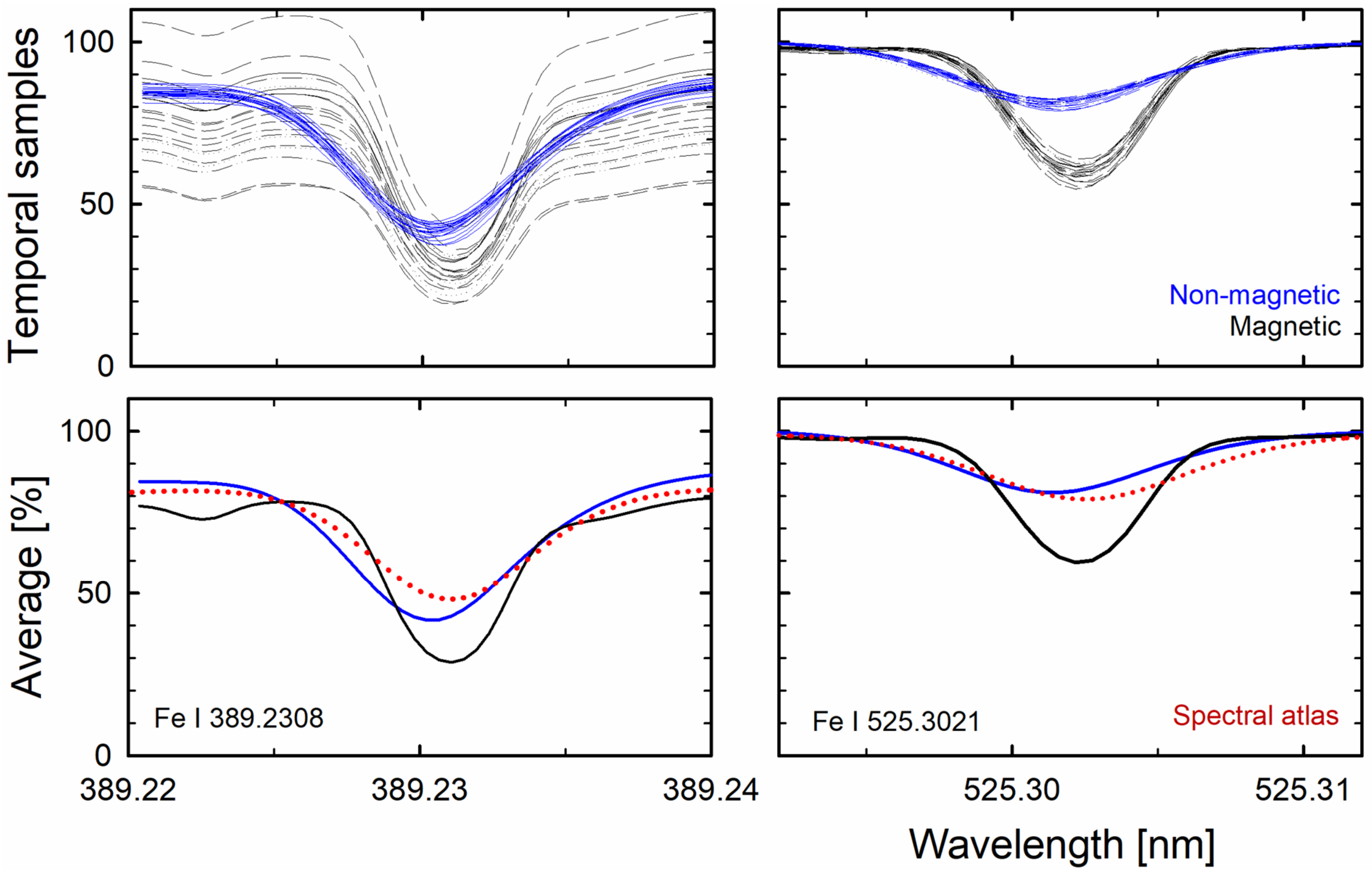


Synthetic spectrum and its temporal variability in a magnetic (240 mT = 2400 G) simulation

Data for integrated sunlight

D.Dravins, H.-G.Ludwig, M.Steffen, C.Allende Prieto, L.Koesterke:
Solar photospheric spectrum microvariability. IV. Radial-velocity and line-profile fluctuations in (non-)magnetic granulation, in preparation

Spectral variability from 3D modeling



Variability in Fe I lines of different strengths in the violet and green spectral regions.

Profiles sampled at 20 times during 3D MHD simulations for non-magnetic and magnetic granulation

D.Dravins, H.-G.Ludwig, M.Steffen, C.Allende Prieto, L.Koesterke:
Solar photospheric spectrum microvariability. IV. Radial-velocity and line-profile fluctuations in (non-)magnetic granulation, in preparation

Outstanding problems:

1. Laboratory wavelengths

2. Supergranulation'

3. "Full" spectral resolution

Laboratory wavelength uncertainties

NIST Atomic Spectra Database Lines Data

Fe I: 8 Lines of Data Found

Z **= 26, Fe isoelectronic sequence**

Observed Wavelength Air (nm)	Unc. (nm)	Rel. Int. (?)	A_{ki} (s^{-1})	Acc.	E_i (eV)		E_k (eV)
525.02086	0.00008	1550	9.30e+02	A	0.12126572	-	2.48211840
525.06456	0.00008	4470	2.28e+05	D+	2.19786640	-	4.55852281
525.19655	0.00008	2400			3.57321890	-	5.93328155
525.34614	0.00008	2290	2.15e+06	B	3.28302483	-	5.64241573
525.49551	0.00008	3310	8.31e+02	A	0.11011433	-	2.46883473
525.56651	0.00022	110			4.22036211	-	6.57876498
525.57353	0.00022	141			4.28330826	-	6.64167865
525.76549	0.00022	229			3.57321890	-	5.93072834

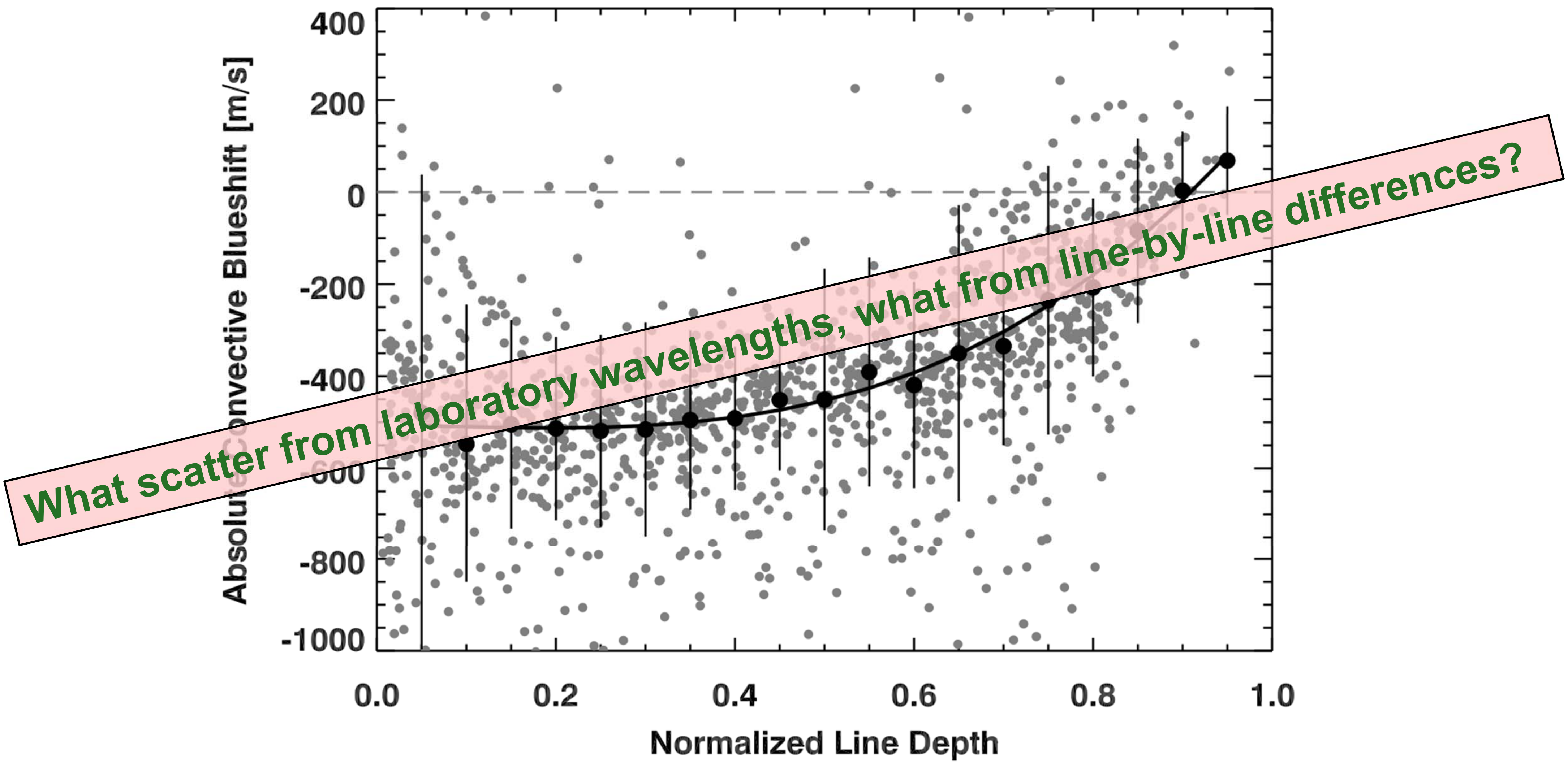
Observed Wavelength Air (nm)	Unc. (nm)
525.02086	0.00008
525.06456	0.00008
525.19655	0.00008
525.34614	0.00008
525.49551	0.00008
525.56651	0.00022
525.57353	0.00022
525.76549	0.00022

Strong lines
σ = 46 m/s

Weak lines
σ = 126 m/s

A.Kramida, Yu.Ralchenko, J.Reader, and NIST ASD Team: *NIST Atomic Spectra Database* (2024)
https://physics.nist.gov/asd

Scatter in observed lineshifts



Fe I lines in the Göttingen atlas of integrated sunlight, corrected for gravitational redshift

A.Reiners, N.Mrotzek, U.Lemke, J.Hinrichs, K.Reinsch:
The IAG solar flux atlas: Accurate wavelengths and absolute convective blueshift in standard solar spectra
Astron.Astrophys. **587**, A65 (2016)

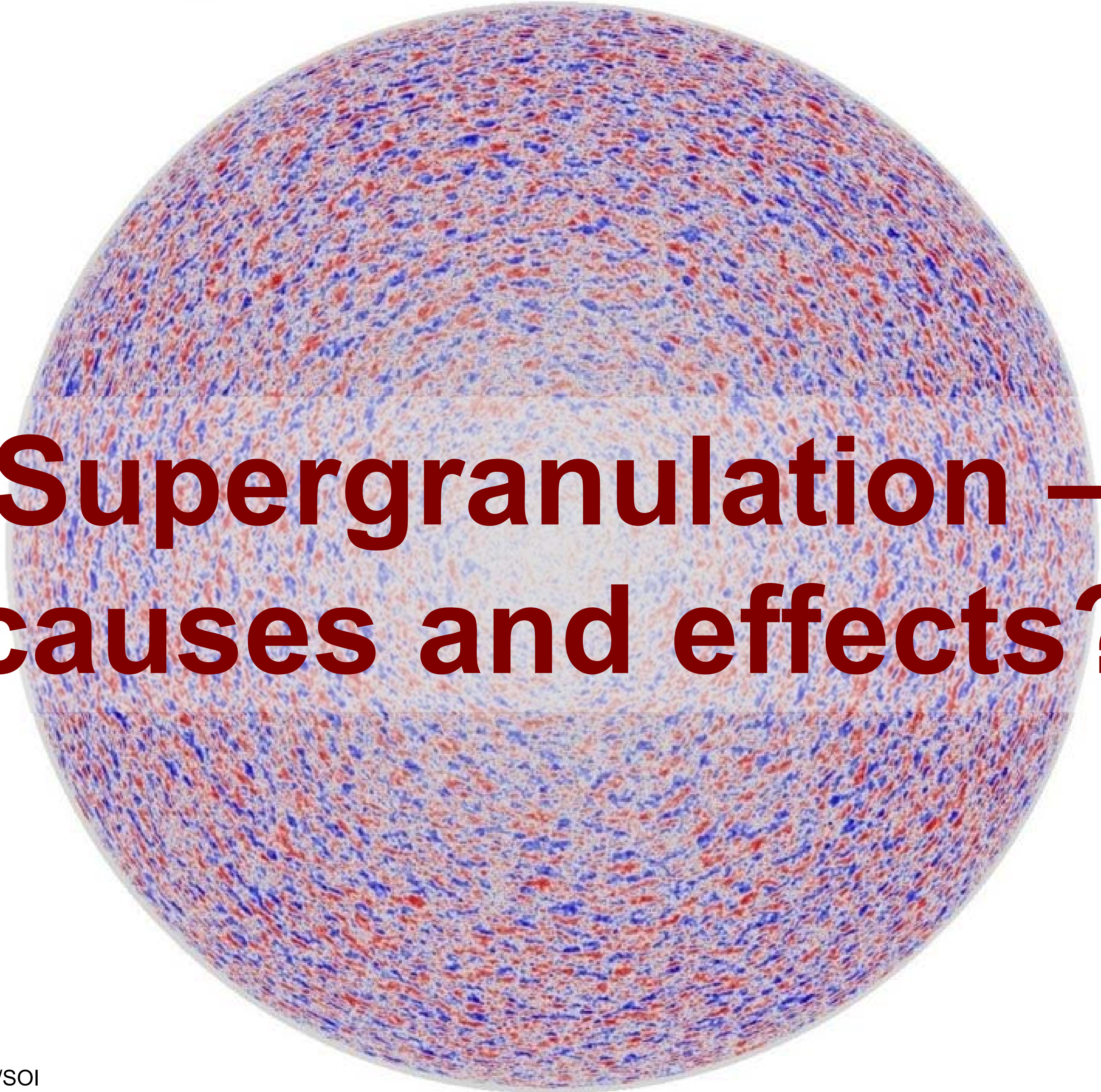
Outstanding problems:

1. Laboratory wavelengths

2. Supergranulation

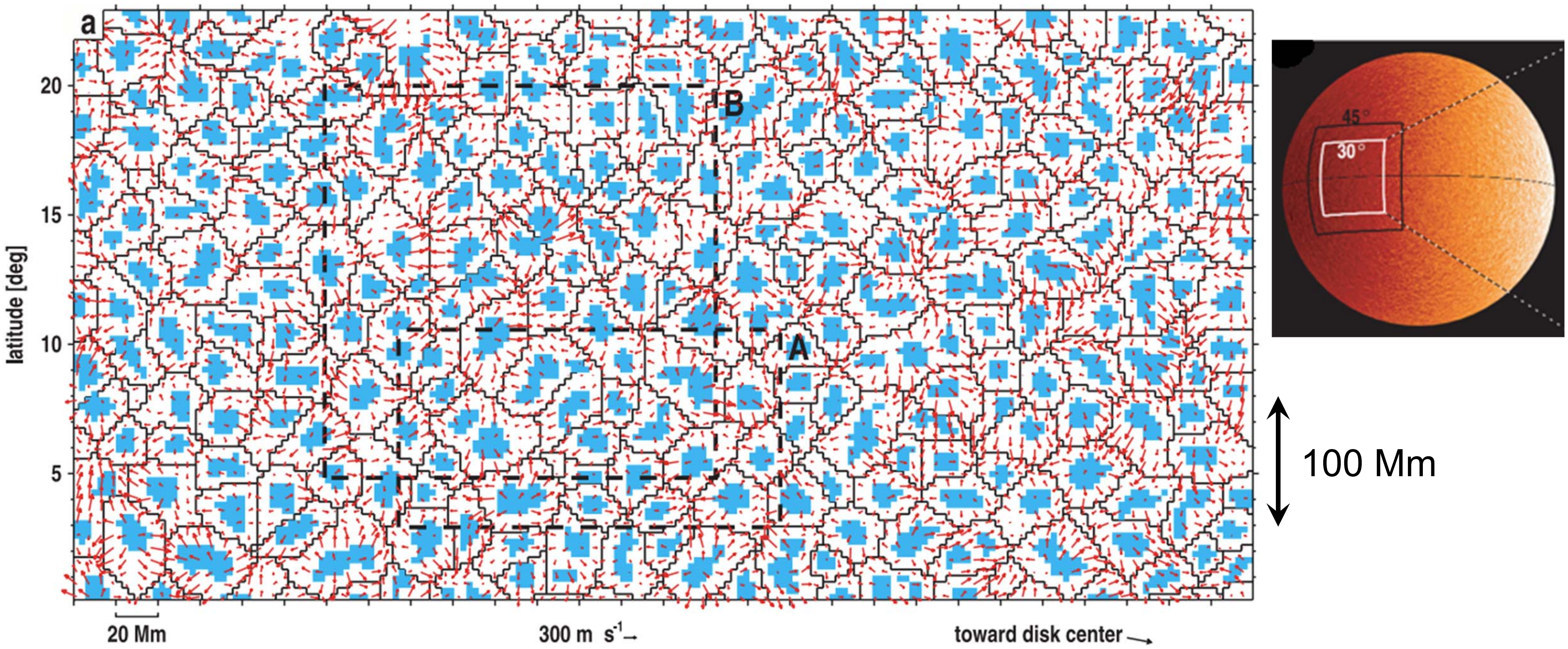
3. “Full” spectral resolution

Supergranulation – causes and effects?



ESA/NASA SOHO MDI/SOI

Supergranulation velocity patterns



45°×22.5° area on the Sun, with supergranule outflow cores (blue) and "watershed basin" cells (black lines), deduced from a 4-hour average

Flow field is shown with red arrows, scale of 300 m/s marked

M.L.DeRosa, J.Toomre: *Evolution of Solar Supergranulation,* Astrophys.J. **616**, 1242 (2004)

Outstanding problems:

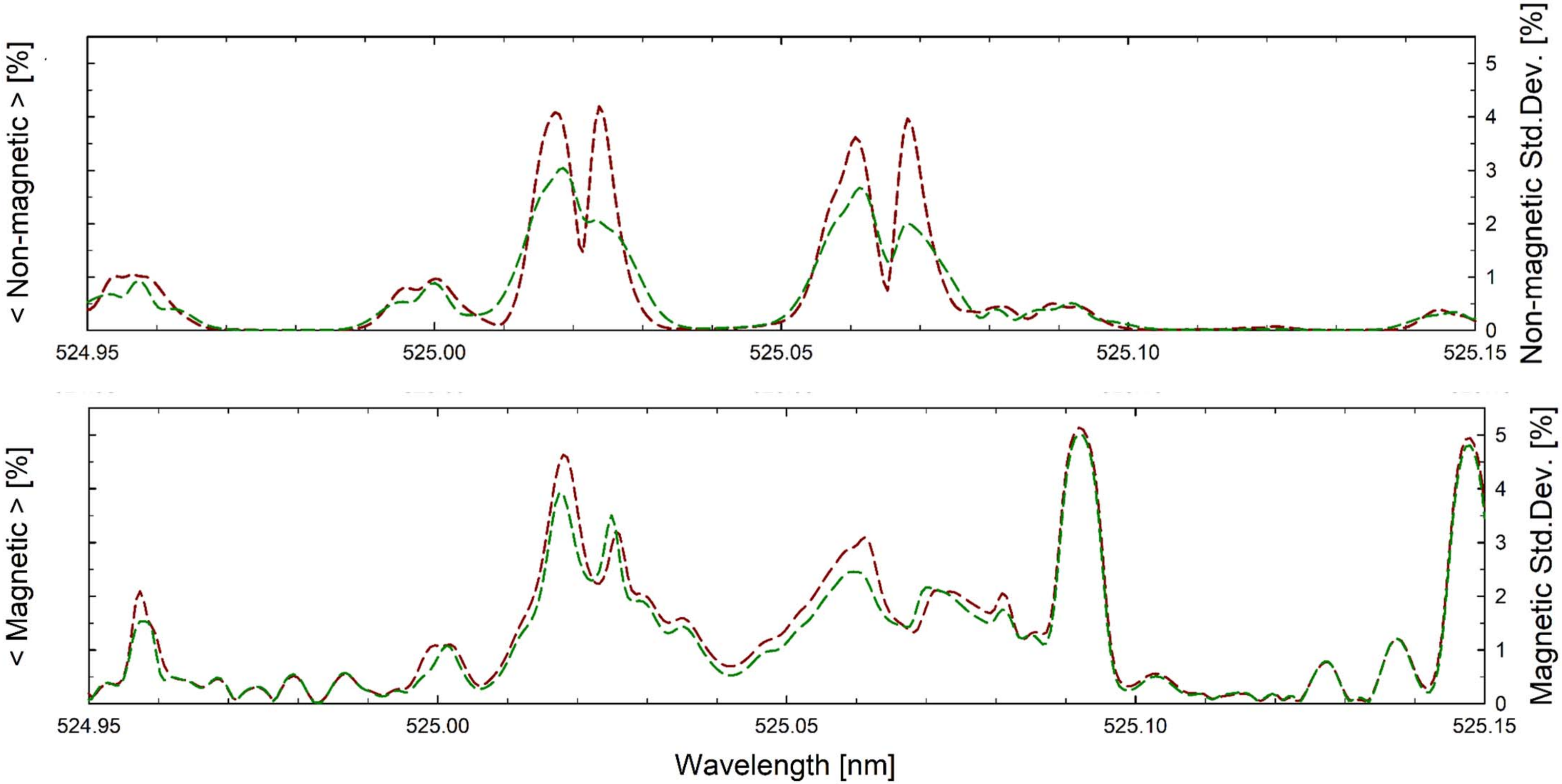
1. Laboratory wavelengths

2. Supergranulation'

3. "Full" spectral resolution

Exactly what inside the lines is varying?

Ordinary photospheric lines: Non-magnetic and magnetic



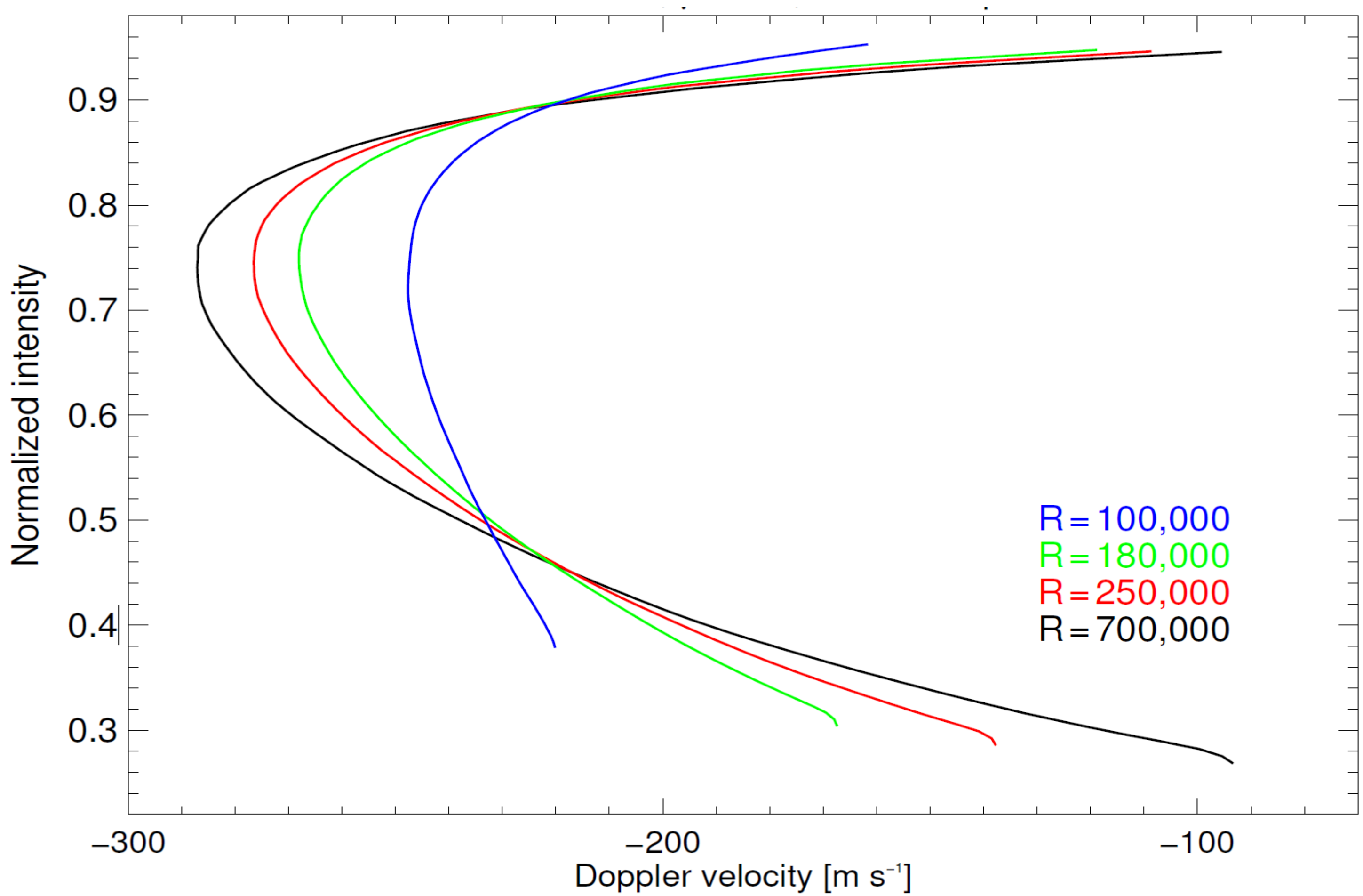
Synthetic 3D solar granulation spectra, $\lambda/\Delta\lambda$ = 900,000

Disk center – brown; Full-disk – green.   B = 240 mT / 2400 G

D.Dravins, H.-G.Ludwig, M.Steffen, C.Allende Prieto, L.Koesterke:
Solar photospheric spectrum microvariability. IV. Radial-velocity and line-profile fluctuations in (non-)magnetic granulation, in preparation

Need for hyper-high spectral resolution

Solar spectral lines observed at different $\lambda/\Delta\lambda$



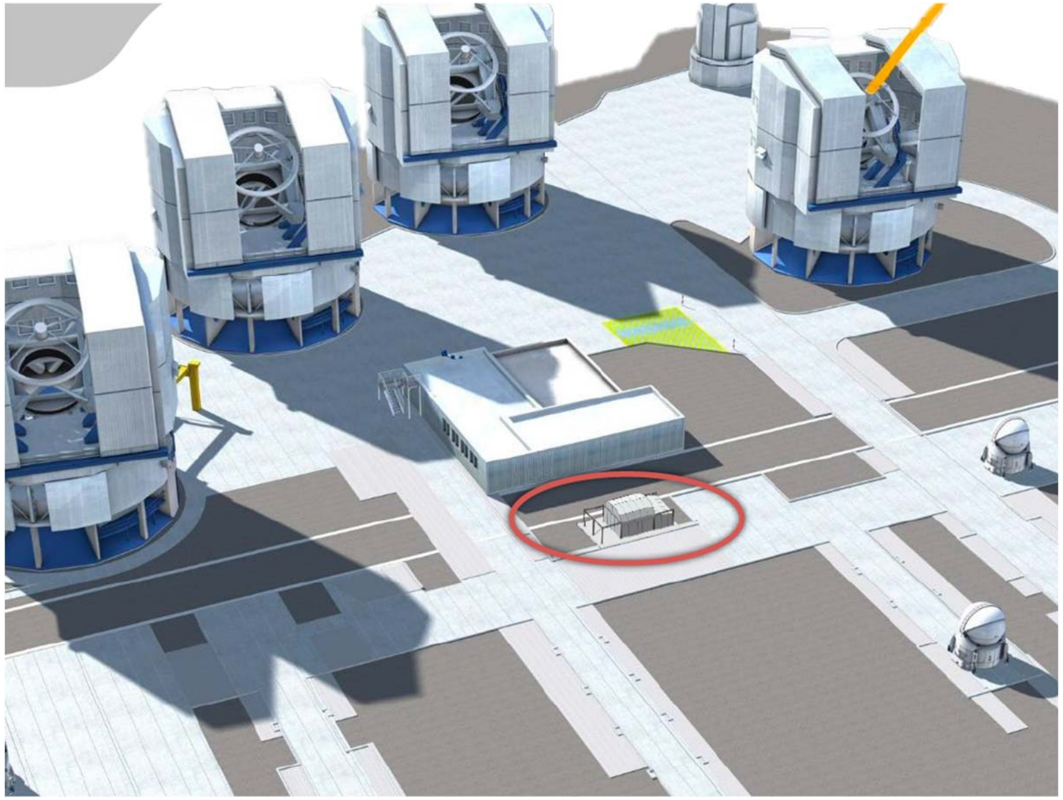
Line-shape and bisector dependence on spectral resolution

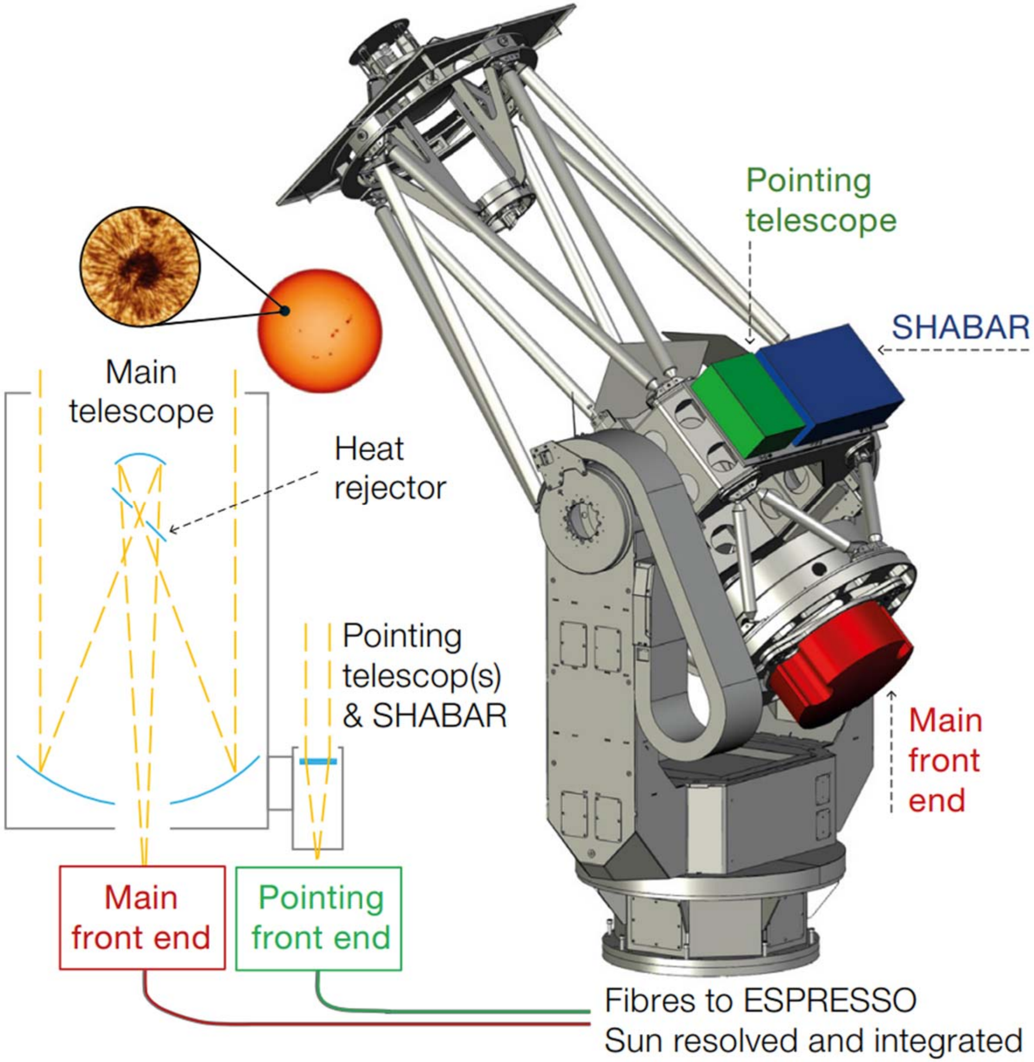
Fe I 525.02084 nm for $\lambda/\Delta\lambda$ = 700,000 (black) to 100,000 (blue)

J.Löhner-Böttcher, W.Schmidt, R.Schlichenmaier, T.Steinmetz, R.Holzwarth: *Convective blueshifts in the solar atmosphere. III. High-accuracy observations of spectral lines in the visible,* Astron.Astrophys. **624**, A57 (2019)

What’s next?

PoET: Paranal Solar ESPRESSO Telescope





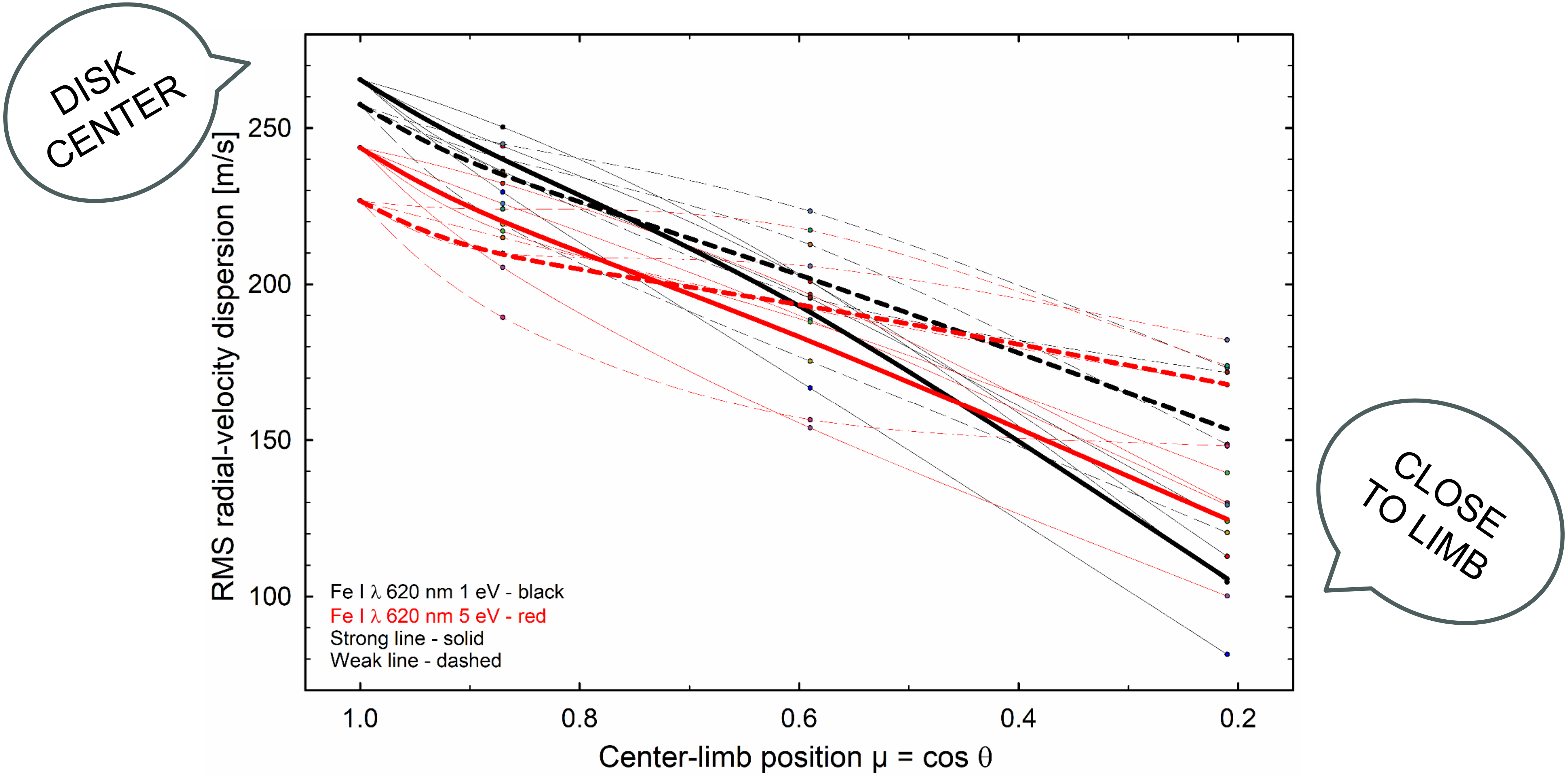
N.C.Santos et al.: *PoET: the Paranal solar ESPRESSO Telescope*
ESO Messenger 194, 21 (2025)

P.I. - Nuno C. Santos

`https://poet.iastro.pt/`

***PoET* first light April 2026**

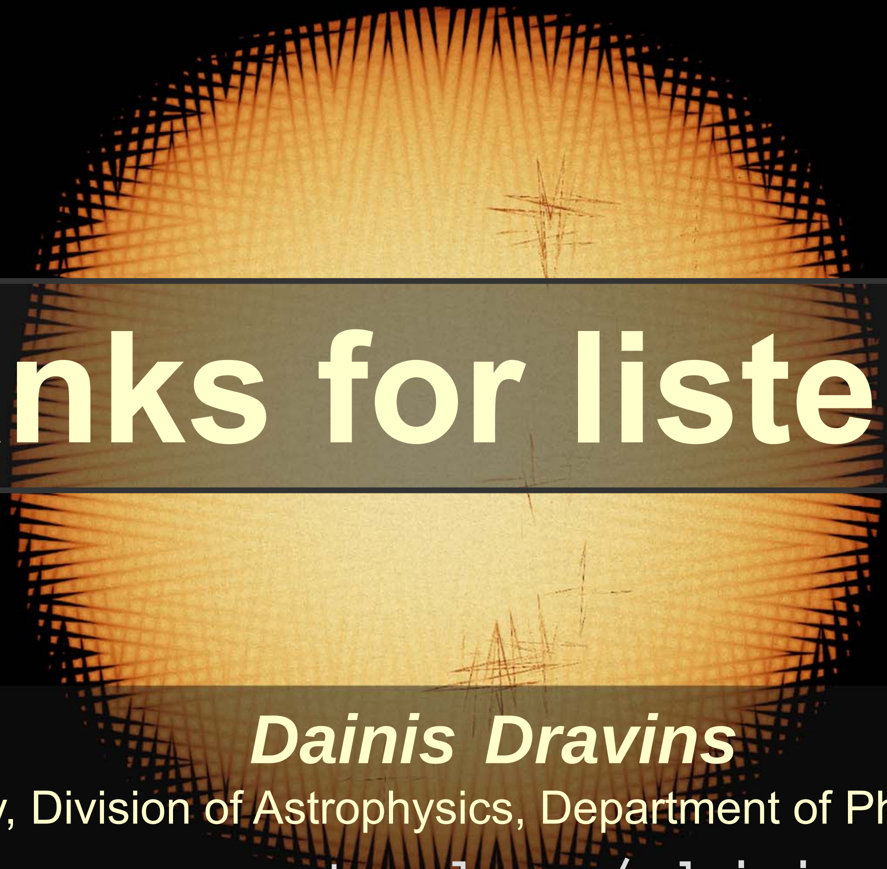
'Radial velocity' jittering across solar disk



Theoretically predicted jittering of Fe I λ 620 nm lines due to granulation

Bold: simulation averages; Thin: different azimuth angles; Full disk: Divide by ~150

D.Dravins, H.-G.Ludwig: *Solar photospheric spectrum microvariability. I. Theoretical searches for proxies of radial-velocity jittering,* Astron.Astrophys. **679**, A3 (2023)



Thanks for listening!

Dainis Dravins

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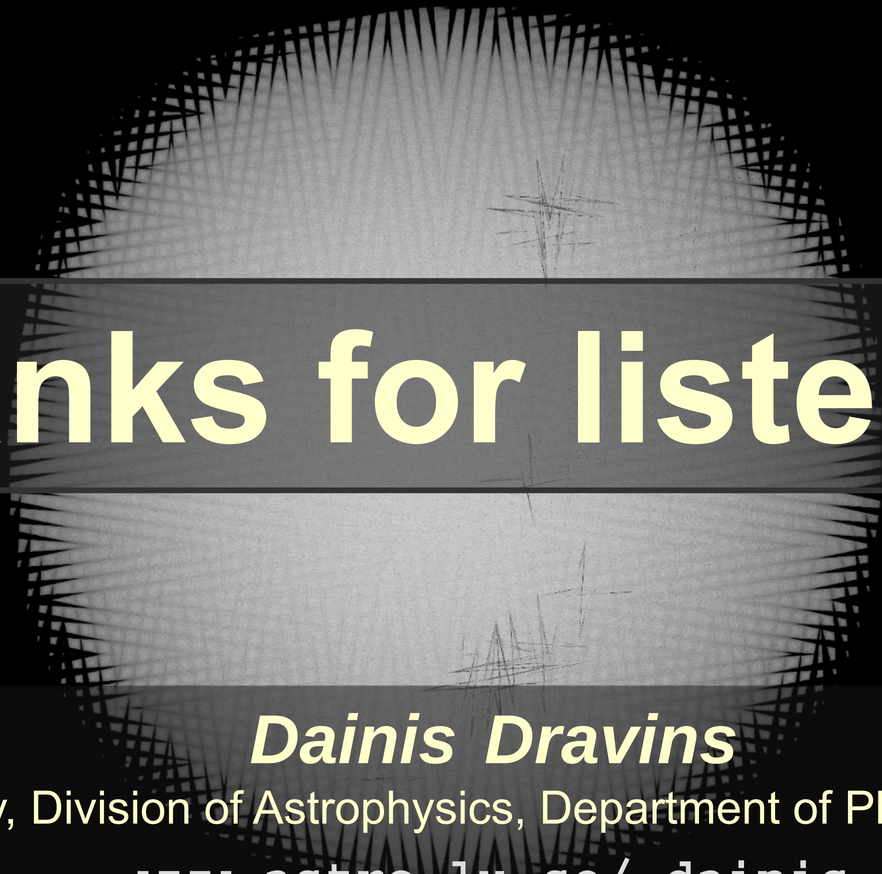

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