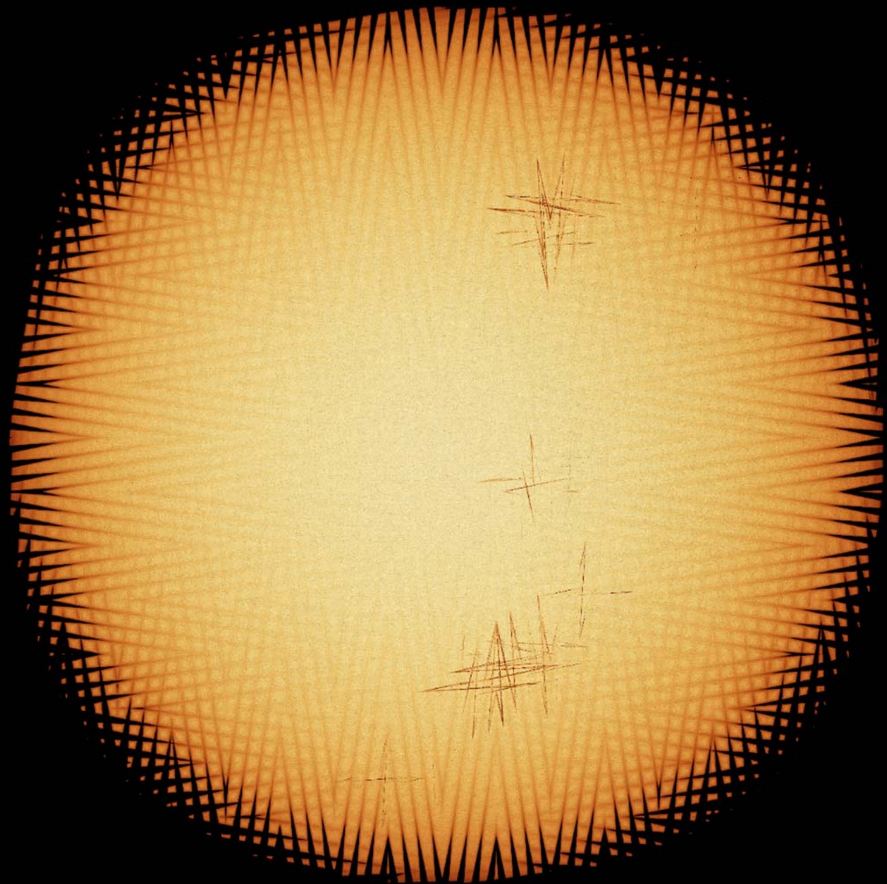
Solar photospheric spectrum microvariability



Dainis Dravins

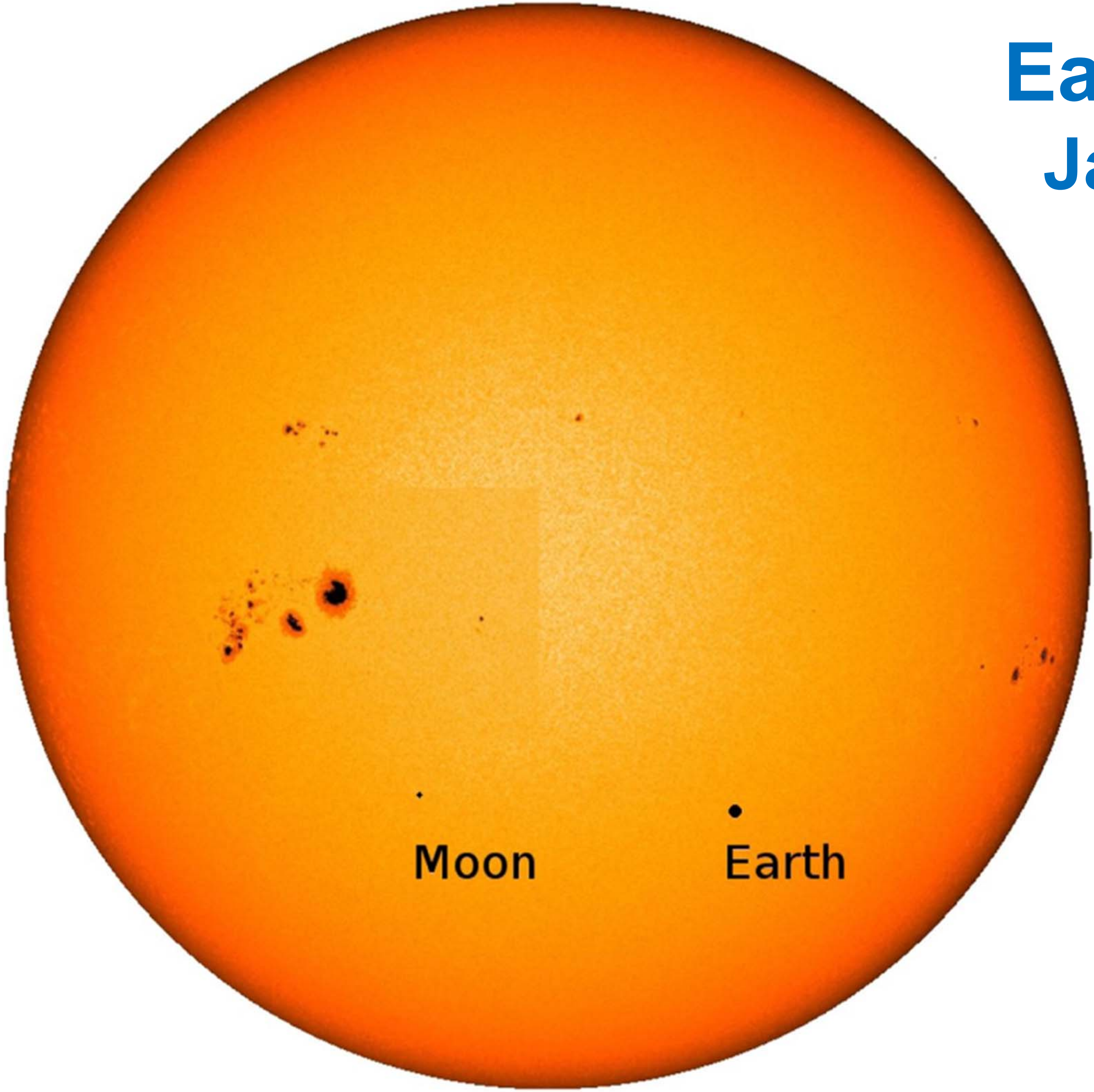
Lund Observatory, Sweden

www.astro.lu.se/~dainis

How to find an “exo-Earth”?

The problem?

- Instrumentation is (finally!) precise enough to detect also Earth-like planets around solar-type stars
- But … the limitation is instead set by stellar variability, which overwhelms the tiny signal from any exoEarth



Earth transit
January 5, 2014

Composite image of the Earth transiting the Sun, as viewed from Jupiter

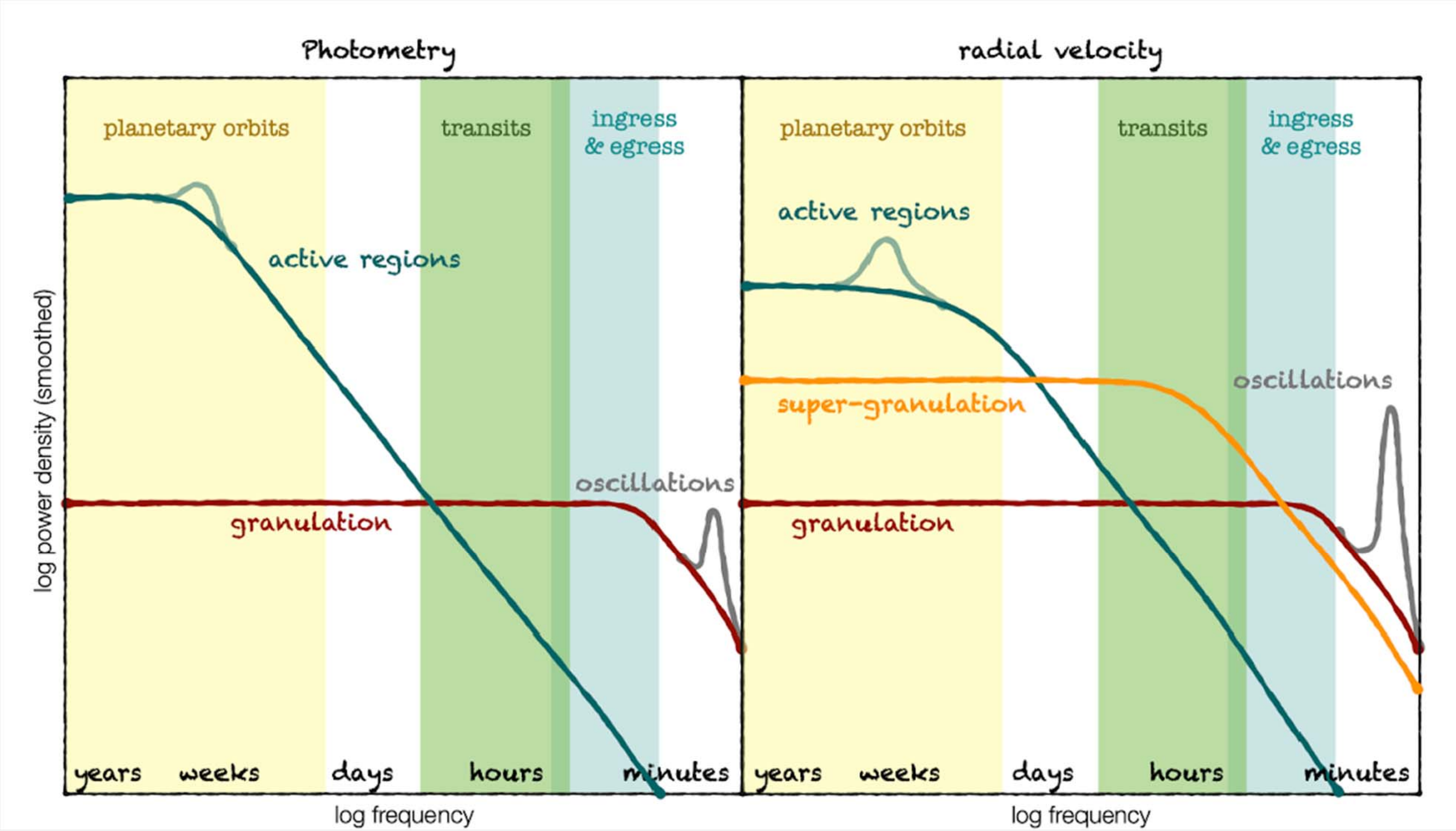
Earth diameter 4.2 arcsec
Sun 369 arcsec

Solar image: SDO/NASA

P.Molaro et al.: *The Earth transiting the Sun as seen from Jupiter's moons: detection of an inverse Rossiter-McLaughlin effect produced by the opposition surge of the icy Europa*

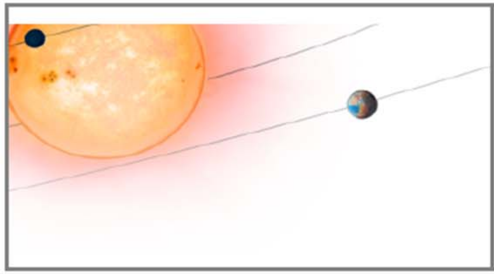
Monthly Notices of the Royal Astronomical Society, **453**, 1684 (2015)

PLATO STELLAR VARIABILITY WORKING GROUP



PSVWG: ***PLATO Stellar Variability Working Group***

Topical Team TT2: Radial Velocity



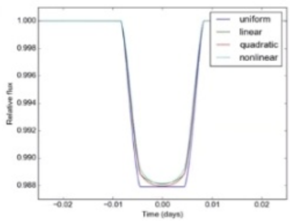
PLATO STELLAR VARIABILITY WORKING GROUP

Sample slides from SVWG meeting May 13, 2025

3D MHD simulation of stellar disks for exoplanet transits

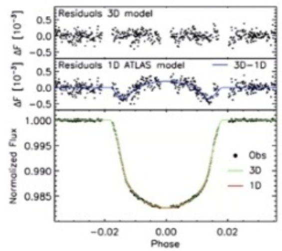
Lionel Bigot
Observatoire de la Côte d'Azur

Work done in collaboration with Suzanne Aigrain, Luisa F. Rodriguez Diaz, Sophia Sulis, …



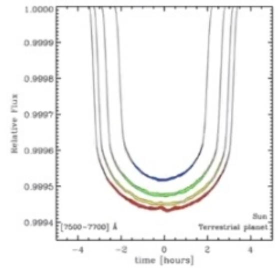
Made with the Batman code
1D LD (Kurucz)

HD 209458



Hayek et al. (2013)
3D LD (stagger)

Sun



Chiavassa+ 2017
Very small effects ?

+work by Dravins & Ludwig on inferring the stellar surface with transits

Stellar mapping & Orthographic projection

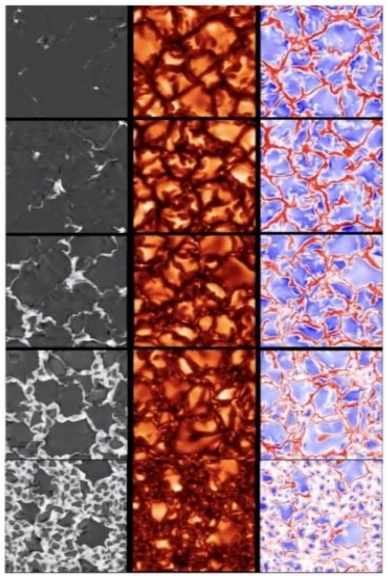
Setup

- ✓ Discretize the stellar surface
- ✓ Feed by outputs of 3D simulations from previous work (For the moment only the horizontal mean intensities (memory constraints)
- ✓ Randomly distributed $|t_{init,\,i} - t_{init\ j\neq i}| > ACT$
- ✓ Use orthographic projection to have 2D stellar disk in the plane of the sky (as observed)
- ✓ Combine with Keplerian motion code

Goals

- ✓ Try to reproduce the observed transits
- ✓ Advantages: we controle what we are doing. (Pure effect of convection)
- ✓ Test/tune detection algorithms to counteract convecti
- ✓ Quantify the uncertainty in planetary parameters

First step towards more sophisticated procedure (magnetic activity, …)



B=10 G (solar Max)

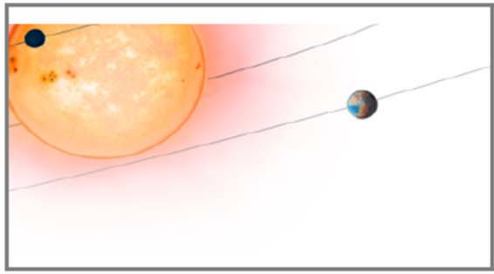
B=50 G

B=200 G

B=400 G

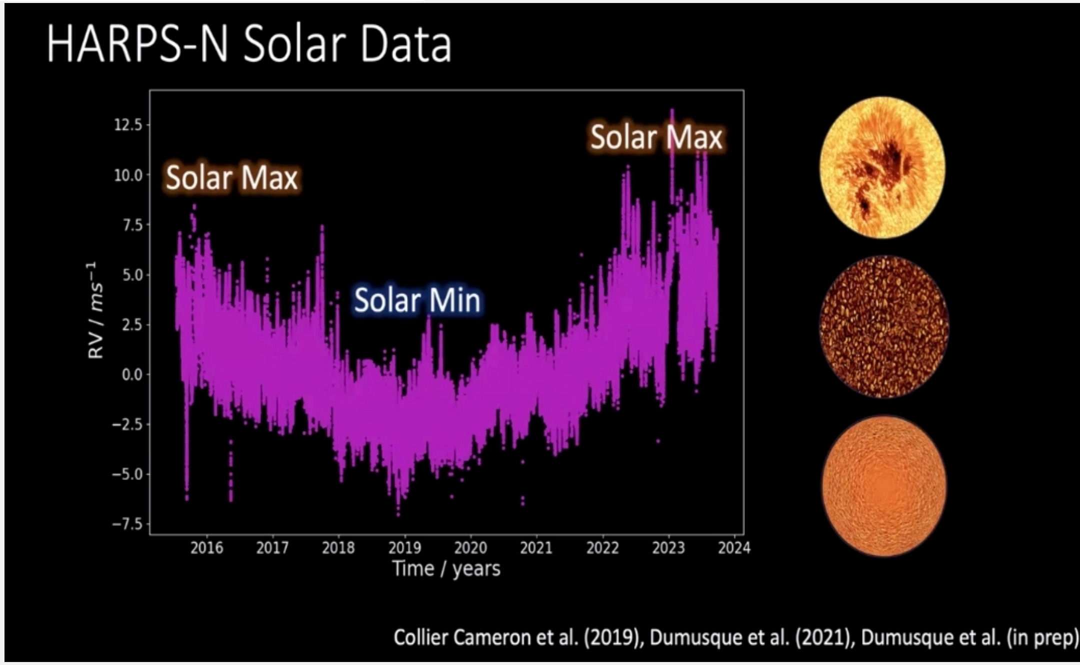
B=800 G

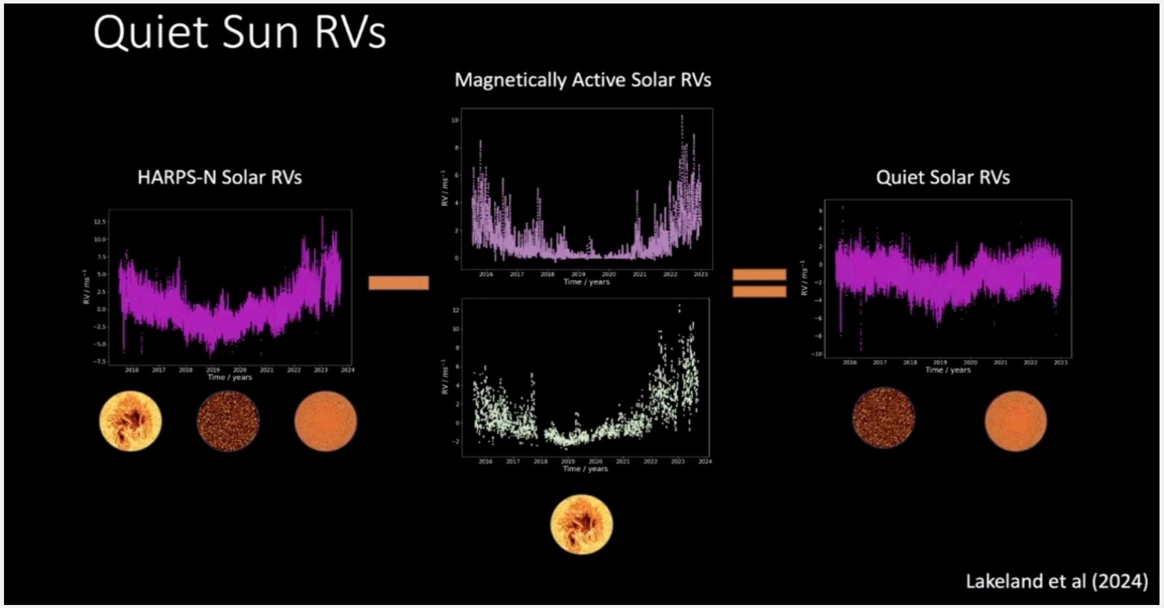
MURAM simulations (Vögler)

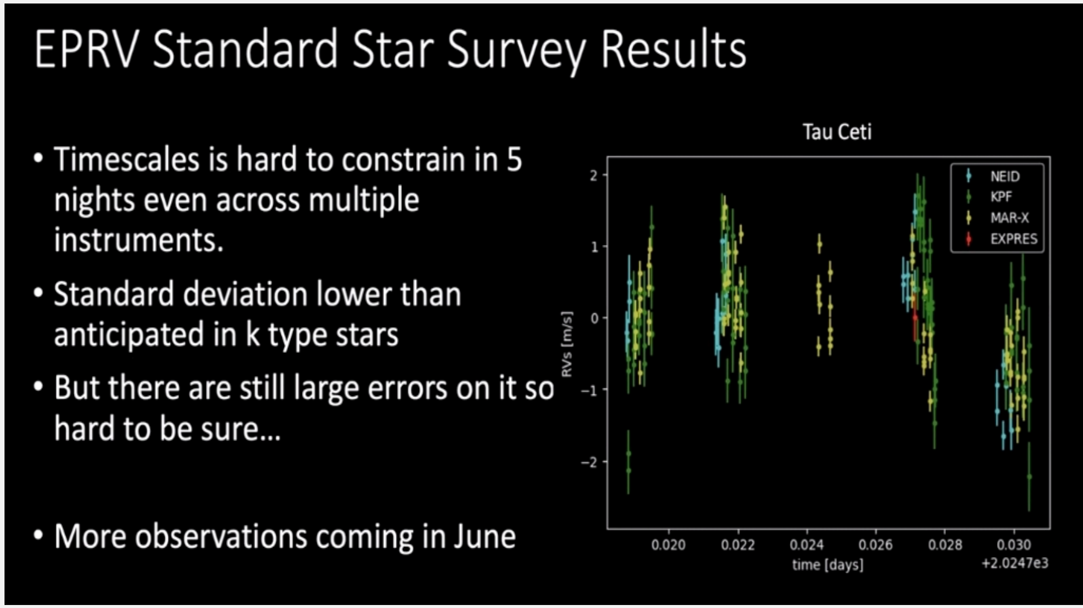


PLATO STELLAR VARIABILITY WORKING GROUP

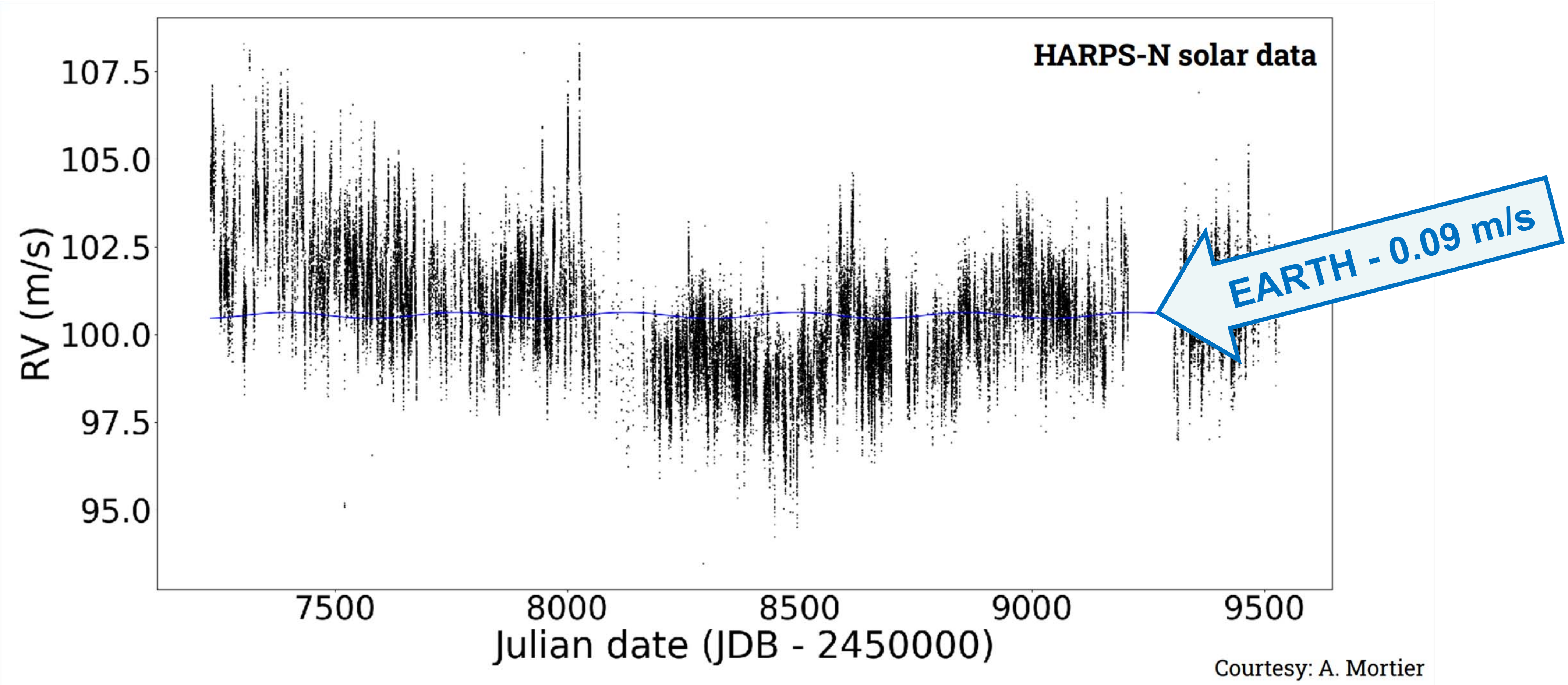
Sample slides from SVWG meeting May 13, 2025







‘Radial velocity’ jittering of the Sun



Solar apparent radial velocity at 5-minute cadence, corrected for barycentric motion and differential extinction

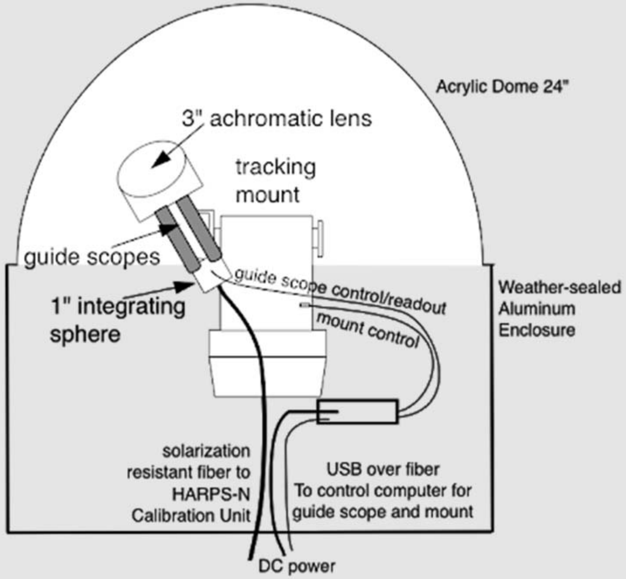
Data release: X. Dumusque et al.: *Three Years of HARPS-N High-Resolution Spectroscopy and Precise Radial Velocity Data for the Sun*, Astron.Astrophys. **648**, A103 (2021)

Can we find planets around the Sun…

… if observing the Sun-as-a-star?

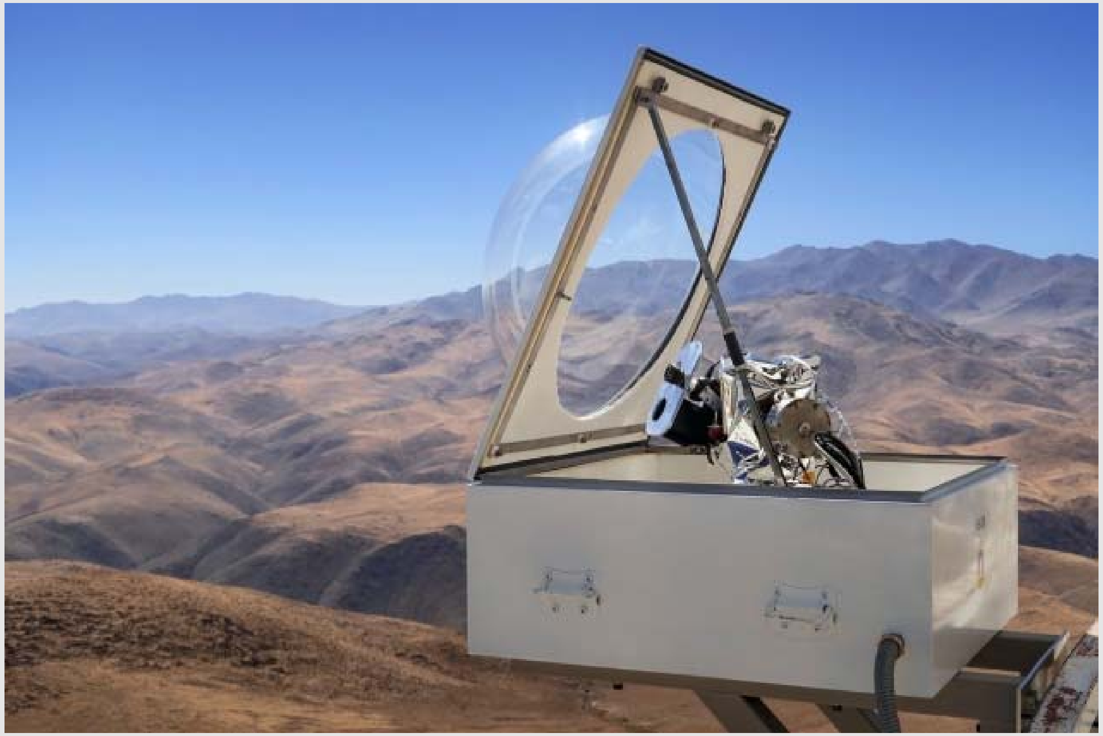
La Palma
Sun-as-a-star spectroscopy @ HARPS-North

Telescopio Nazionale Galileo (TNG), Roque de los Muchachos, La Palma



Data release: 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)

ESO Chile, La Silla
Sun-as-a-star spectroscopy @ HARPS / NIRPS



A small sunlight-integrating telescope ("HELIOS") is mounted outside the ESO 3.6 m telescope on La Silla in Chile. Through an optical fiber, sunlight is fed into the same spectrometers (HARPS and NIRPS) which, during nighttime, are used to search for exoplanets. (Photo: ESO/T.Wildi)

Right: HARPS (visual) and NIRPS (infrared) radial-velocity spectrometers are inside the dome of the 3.6 meter telescope. (Photos: Dainis Dravins)

Arizona: LBT Telescope:

Sun-as-a-star spectroscopy & polarimetry @ PEPSI

Klaus G. Strassmeier, Ilya Ilyin, Manfred Woche, Frank Dionies, Michael Weber, Arto Järvinen, Carsten Denker, Ekaterina Dineva, Meetu Verma, Thomas Granzer, Wilbert Bittner, Svend-Marian Bauer, Jens Paschke, Hakan Önel

Solar disk integration polarimeter: An automated disk-integration full-Stokes-vector solar feed for the Potsdam Echelle Polarimetric and Spectroscopic Instrument spectrograph

Astron. Nachr. e20240033 (2024)

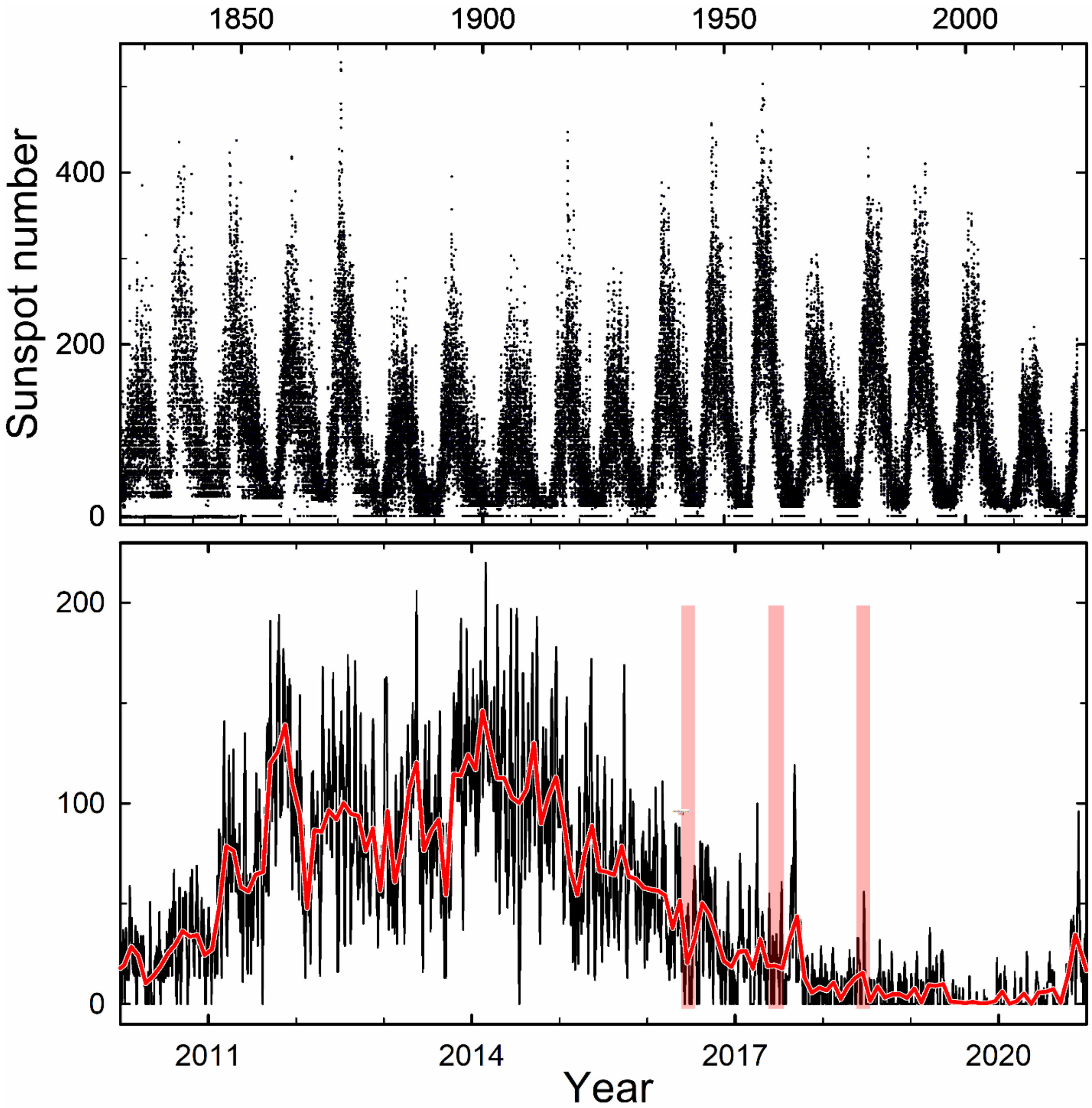
Huge number of statistical analyses made of the full solar spectrum to deduce radial velocities

Conclusion: To extract "full" information, need to understand the details of line formation, not only compute correlations and such

Solar photospheric spectral microvariability

I. Observations

Sun-as-a-star spectroscopy
@ HARPS-North

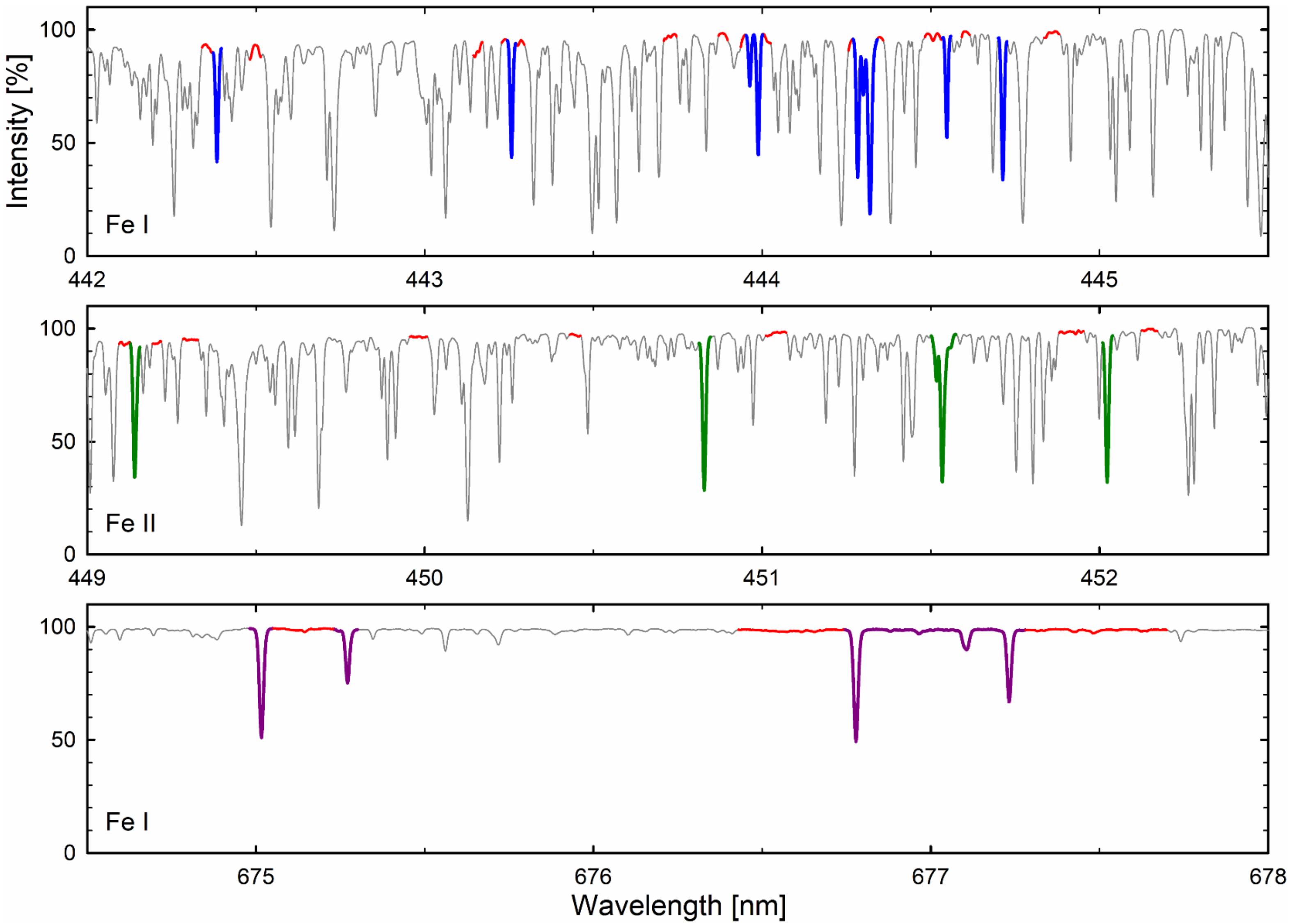


Sunspots over 200 years

Cycle 24 with HARPS-N data periods marked

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

Fe I and Fe II lines @ HARPS-North



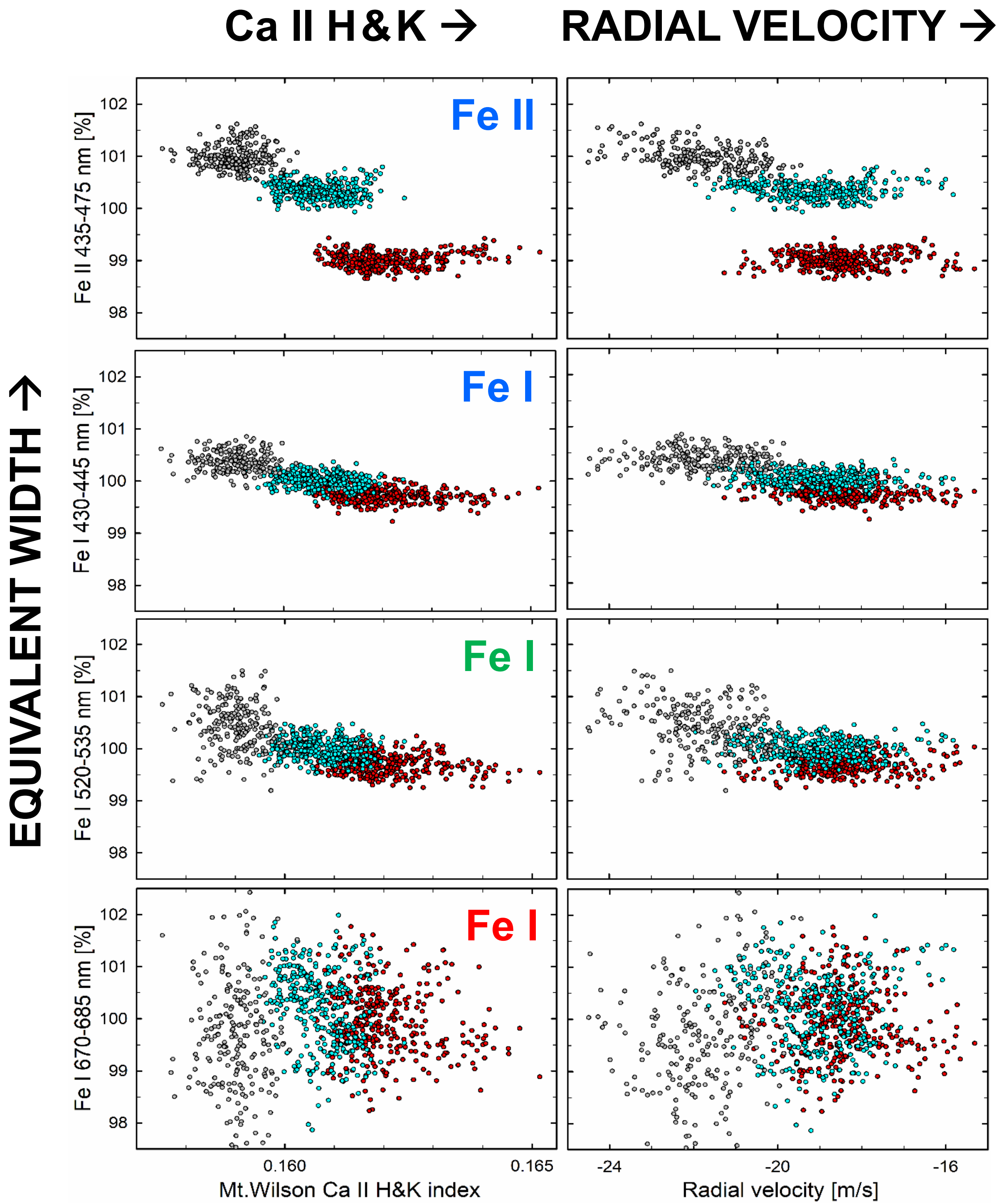
Selected Fe lines in different spectral regions

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)



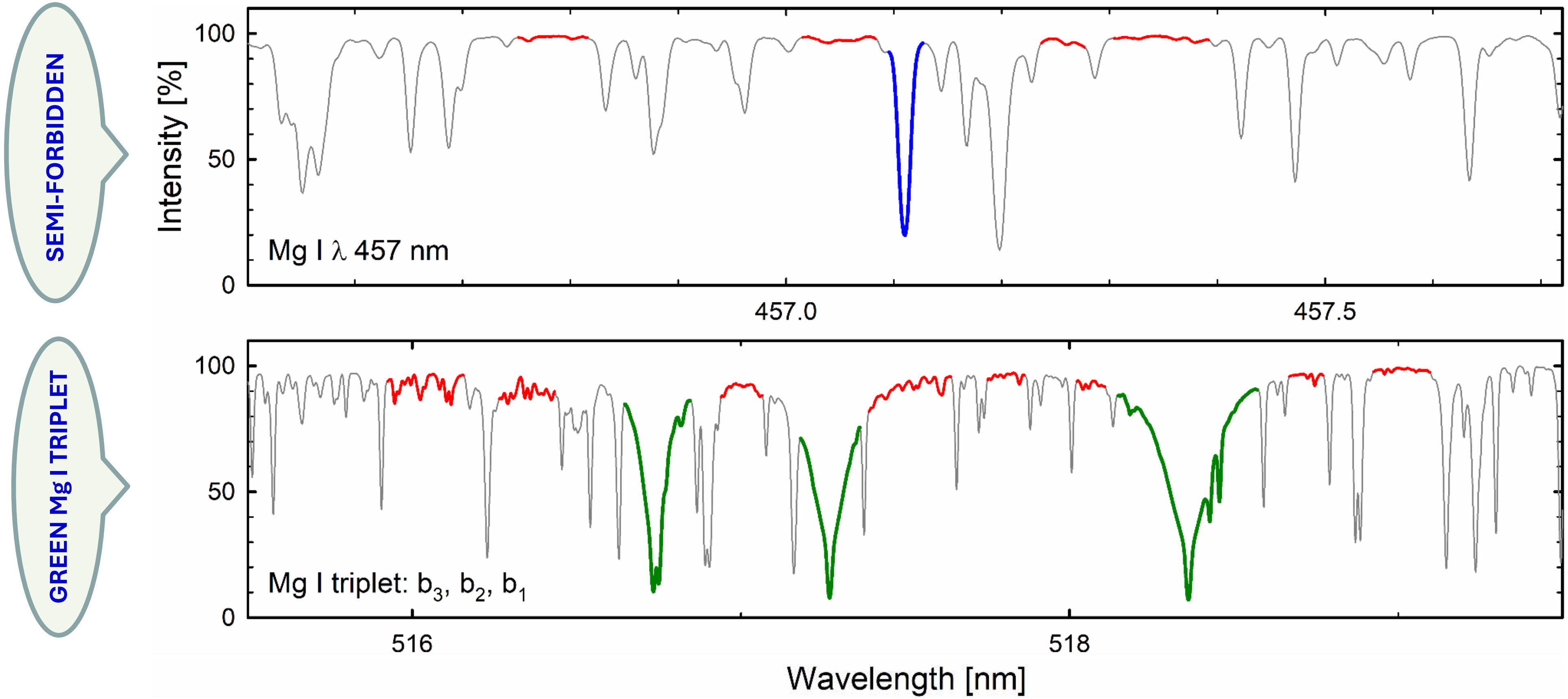
HARPS-N observed solar Fe I & Fe II microvariability

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



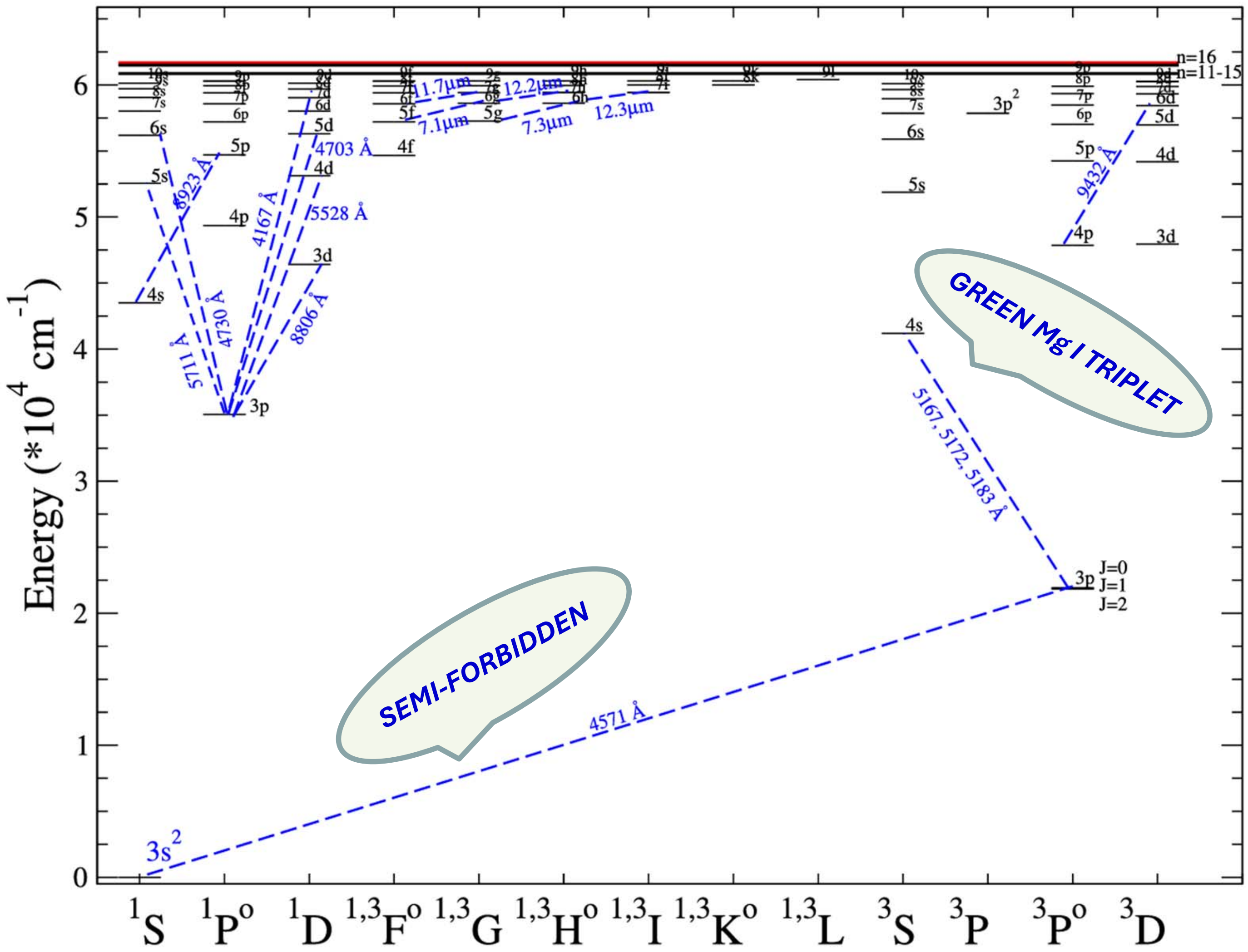
Selection of spectral regions for measurement.

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

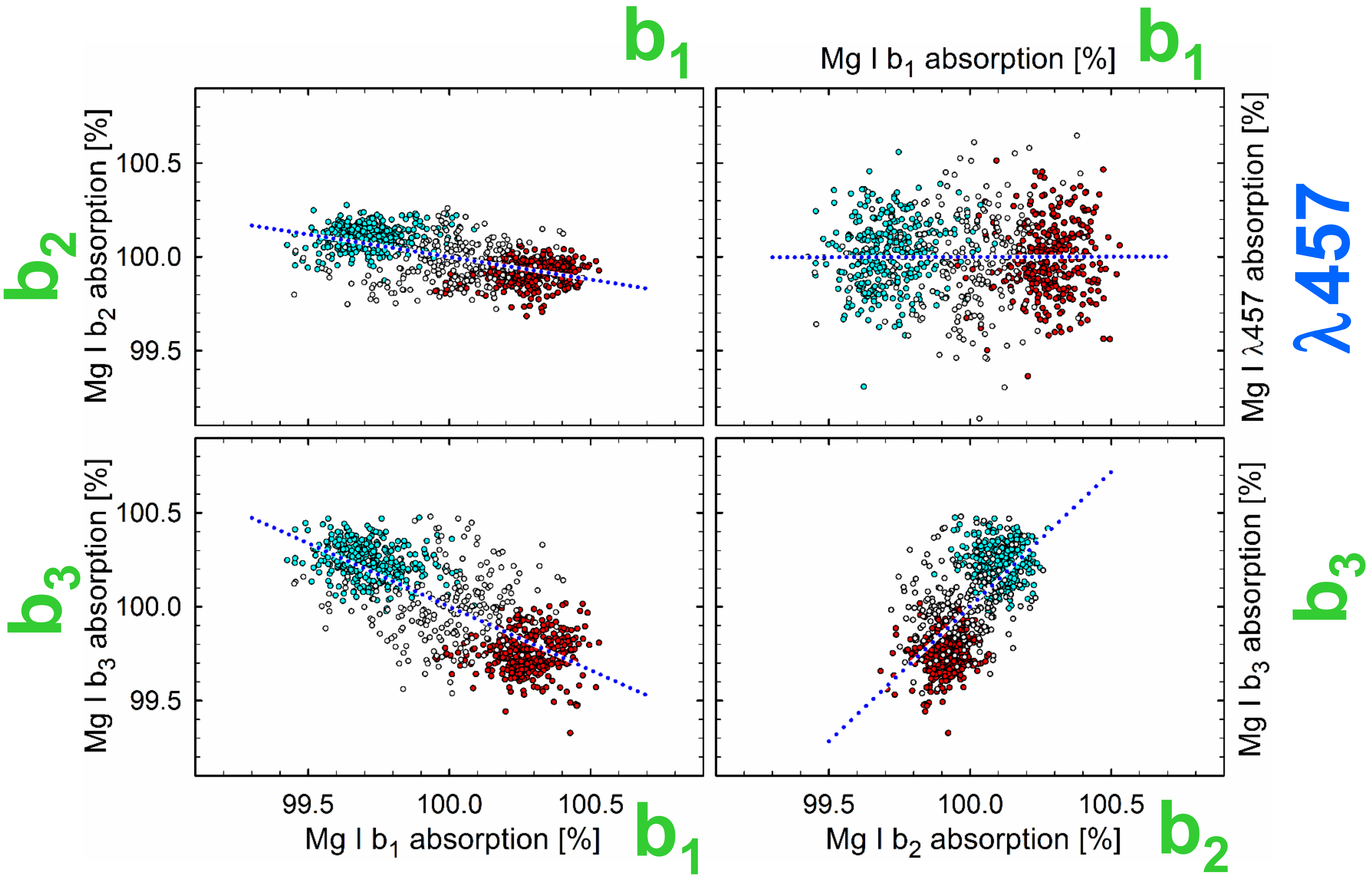


Grotrian term and energy diagram for Mg I

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 variations @ 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).

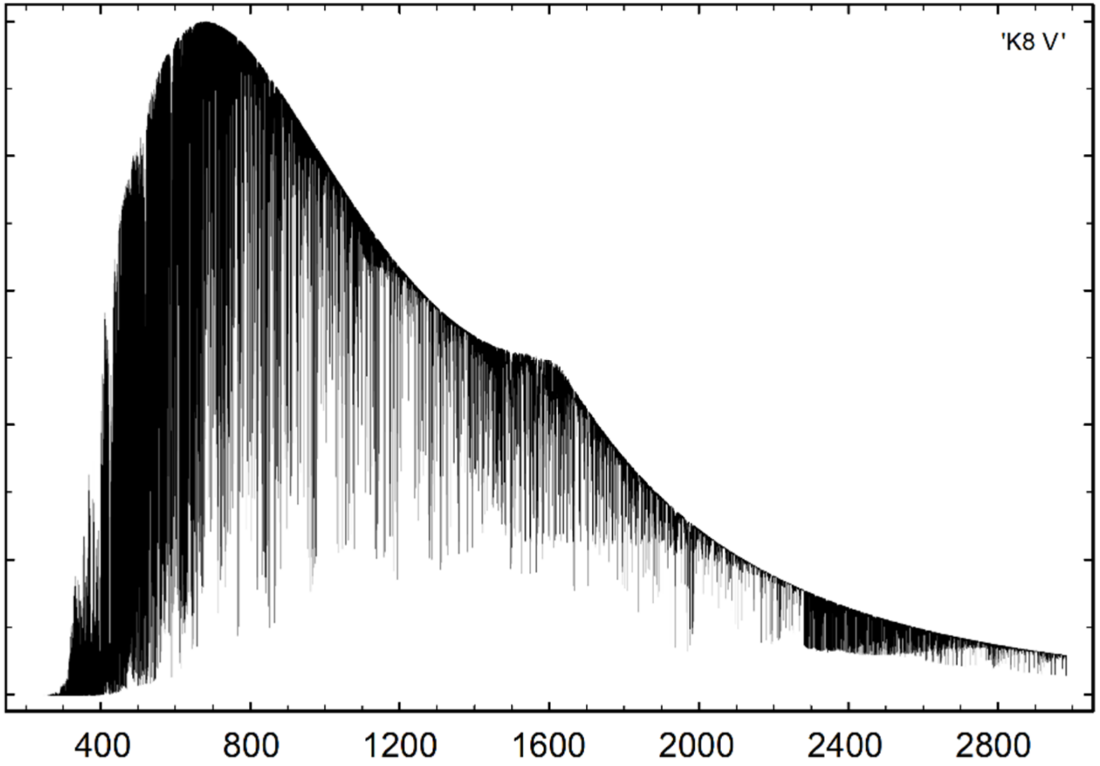
D.Dravins, H.-G.Ludwig: *Solar photospheric spectrum microvariability. II. Observed relations to magnetic activity and radial-velocity modulation*, Astron.Astrophys. **687**, A60 (2024)

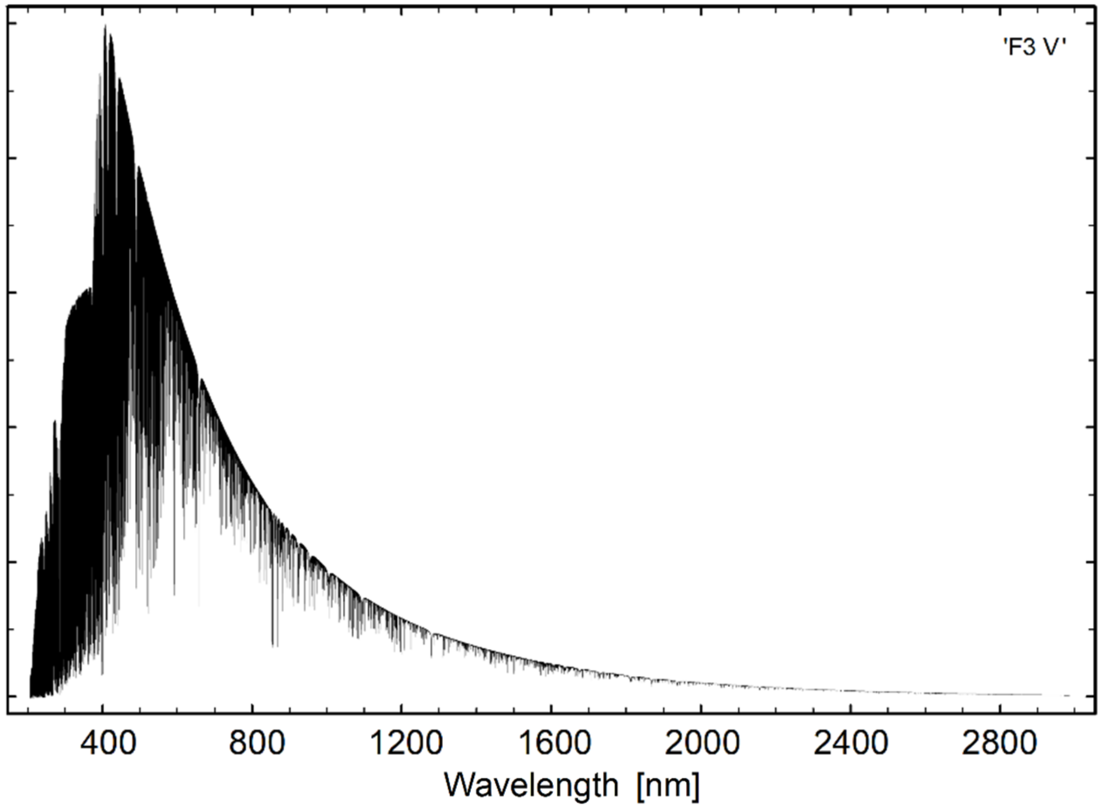
Data from X.Dumusque et al.: *Three Years of HARPS-N High-Resolution Spectroscopy and Precise Radial Velocity Data for the Sun* Astron.Astrophys. **648**, A103 (2021)

Solar photospheric spectral microvariability

II. Theory

Synthetic 3-D spectra at $\lambda/\Delta\lambda > 1{,}000{,}000$



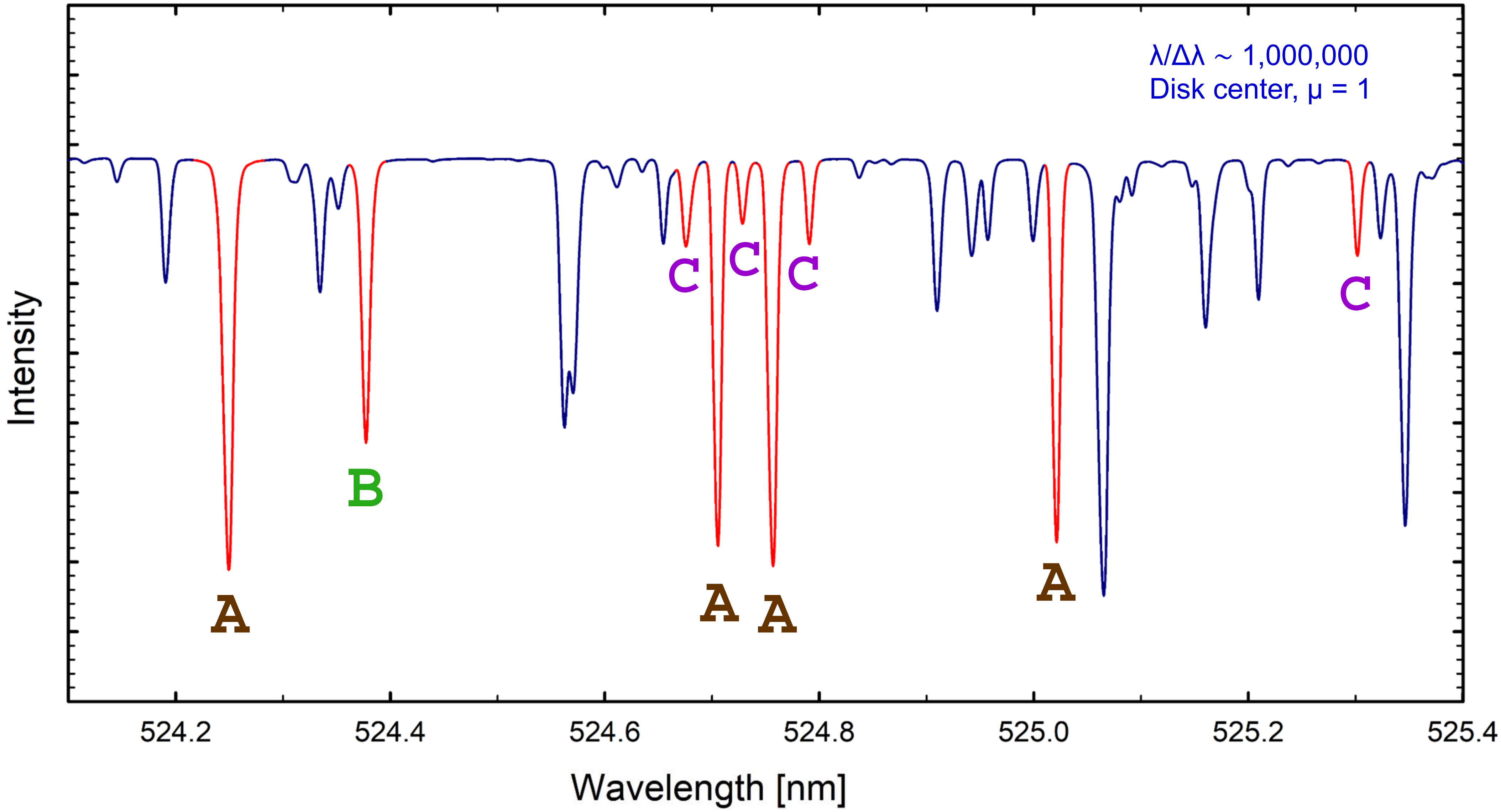


'K8 V', T_{eff} = 3964 K

'F3 V', T_{eff} = 6726 K

D.Dravins, H.-G.Ludwig, B.Freytag:
Spatially resolved spectroscopy across stellar surfaces. IV. F, G, & K-stars: Synthetic 3-D spectra at hyper-high resolution
Astron.Astrophys. **649**, A16 (2021)

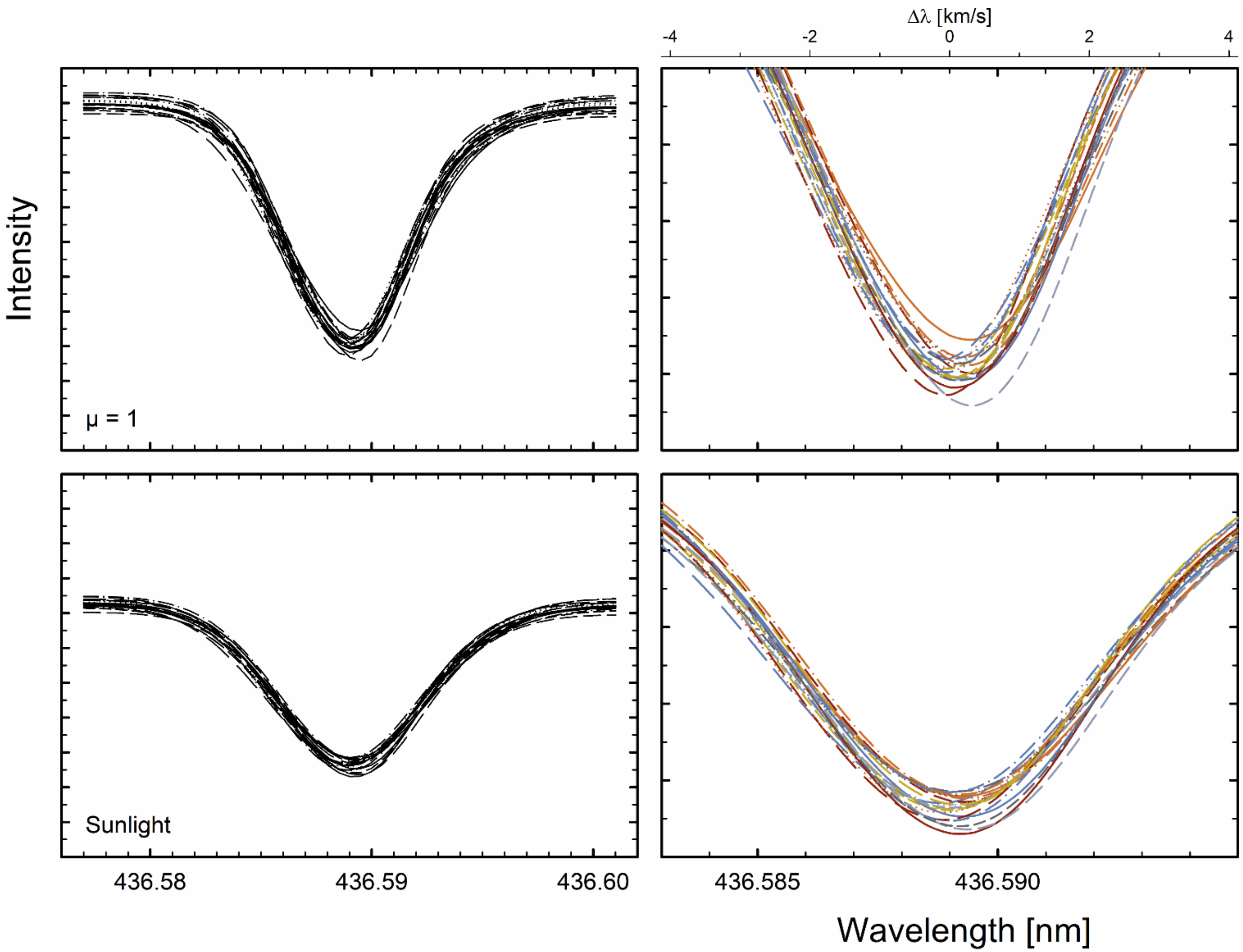
Synthetic solar spectrum: Specific features



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

Watching ‘movies’ of high-resolution spectral atlases

3D non-magnetic solar simulation:
Spatially averaged but temporally resolved



Typical Fe I line

$\lambda/\Delta\lambda \sim$ 1,000,000, CO[5]BOLD
Solar model with T_{eff} = 5774 K

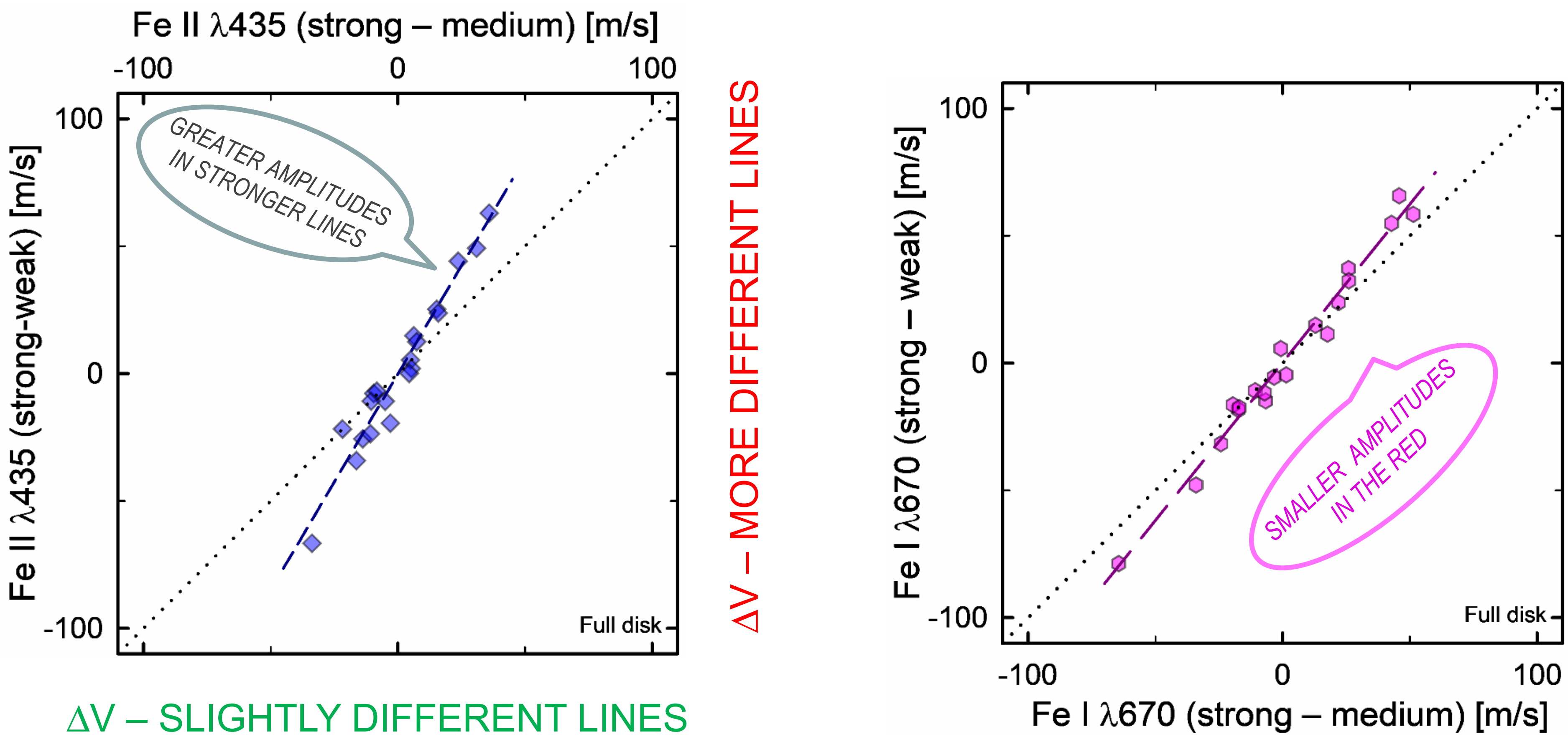
20 instances in time, averaged over 5.6 × 5.6 Mm^2 model area

Top: Disk center (μ = 1)
Bottom: integrated sunlight

Right: zoomed-up line centers

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

Velocity jittering due to solar granulation

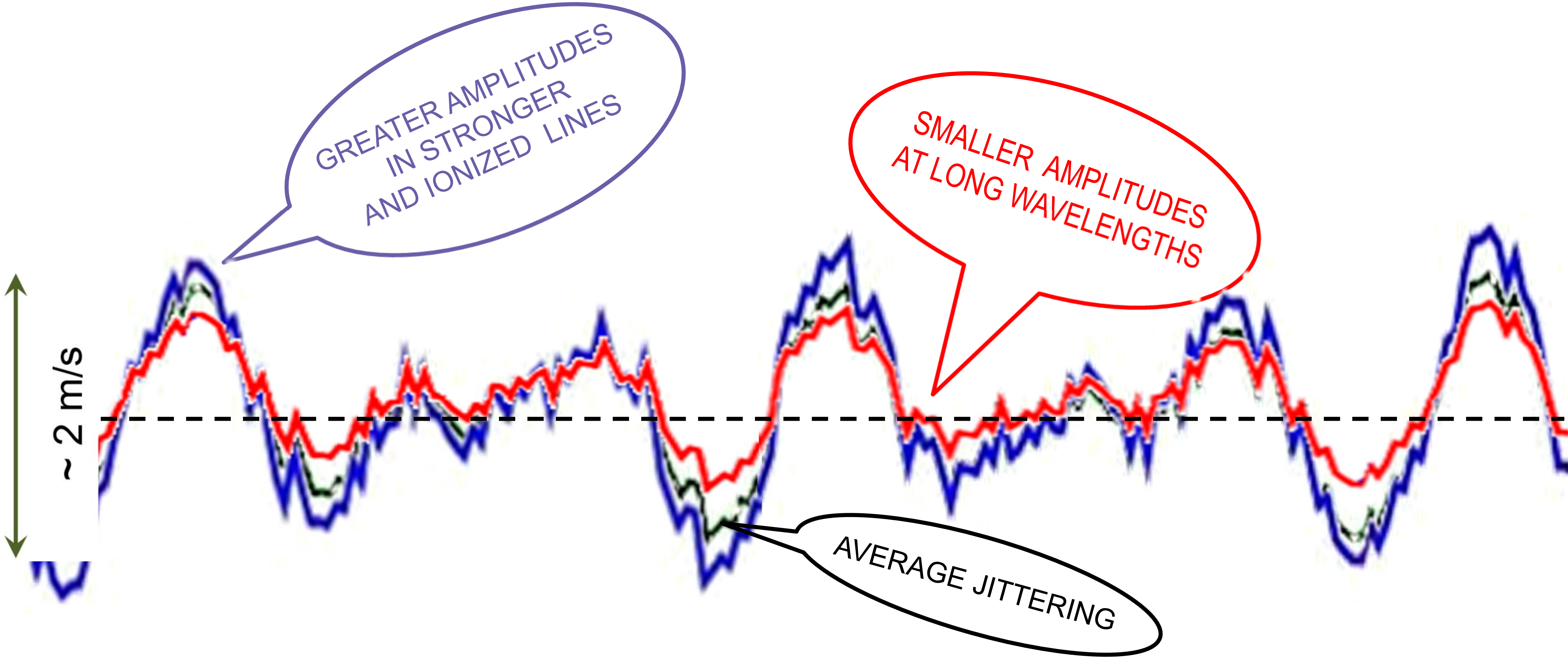


Radial-velocity excursions are greater for stronger and for ionized lines, decreasing at longer wavelengths

Numbers [m/s] refer to a small simulation area; for full-disk Sun, divide by ~150-200: amplitude ~2 m/s

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

Meaning of modeled jittering



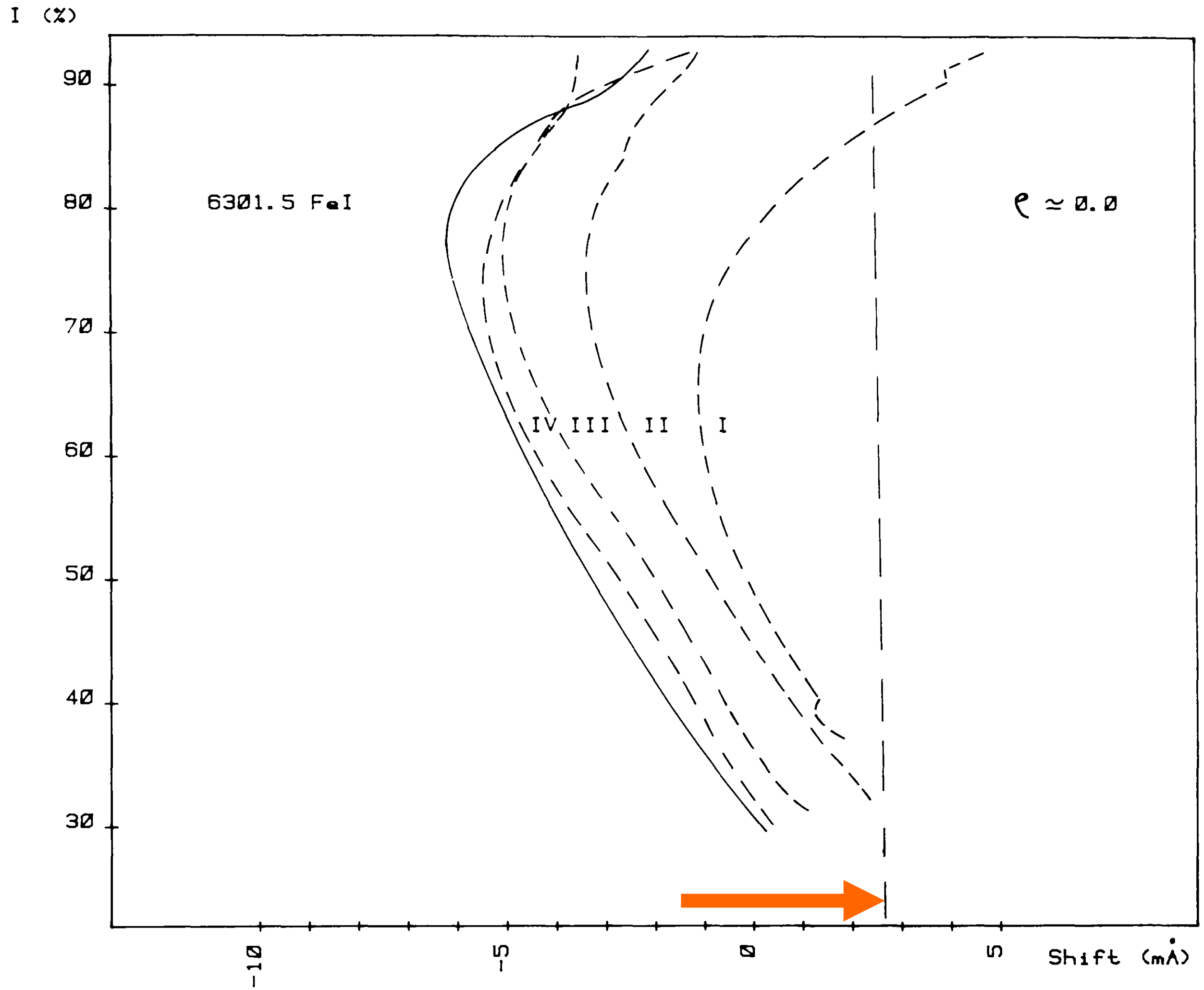
Conclusions from theoretical 3D modeling of non-magnetic granulation.

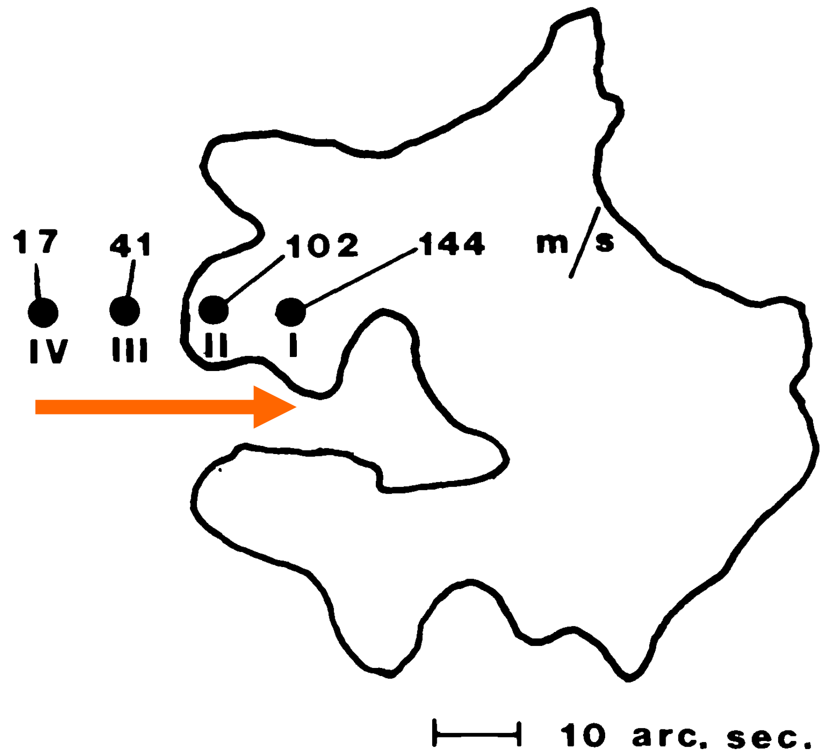
Fluctuations occur in phase, but amplitudes differ among different lines.

Short-term radial-velocity jittering

- Line profiles and wavelengths followed through simulations
- Simulation-area jittering ~300 m/s, scales to ~2 m/s for full disk
- Different lines vary in phase, but amplitudes vary
- Different line-groups differ by ~1/10 of their jittering amplitude

Magnetic & Non-magnetic granulation

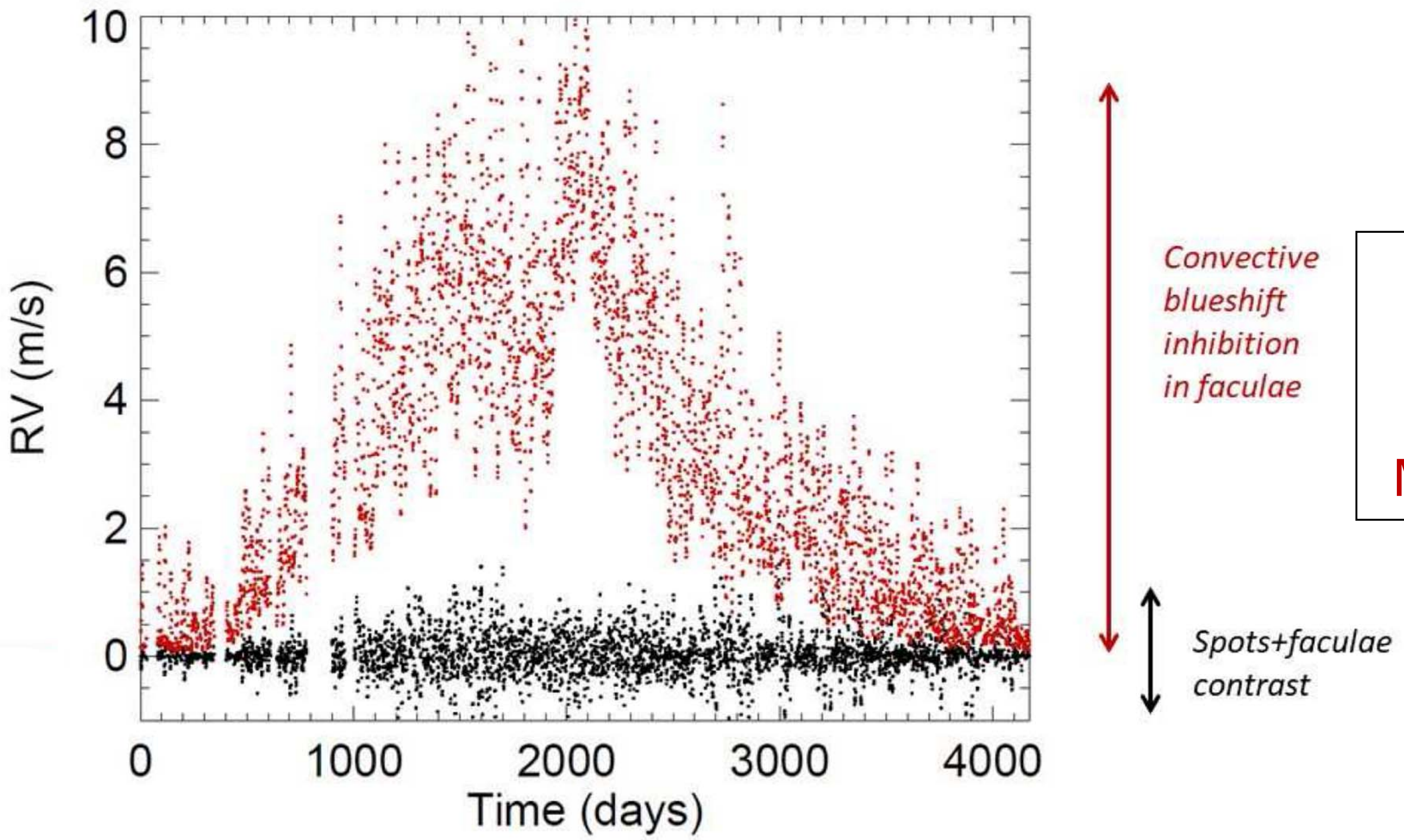




Line bisectors gradually closer to an active region (dashed), compared to that of the quiet Sun. Positions relative to the Ca II K plage are indicated.

F.Cavallini, G.Ceppatelli, A.Righini, *Astron.Astrophys.* **143**, 116 (1985)

Solar ‘radial-velocity’ modulation



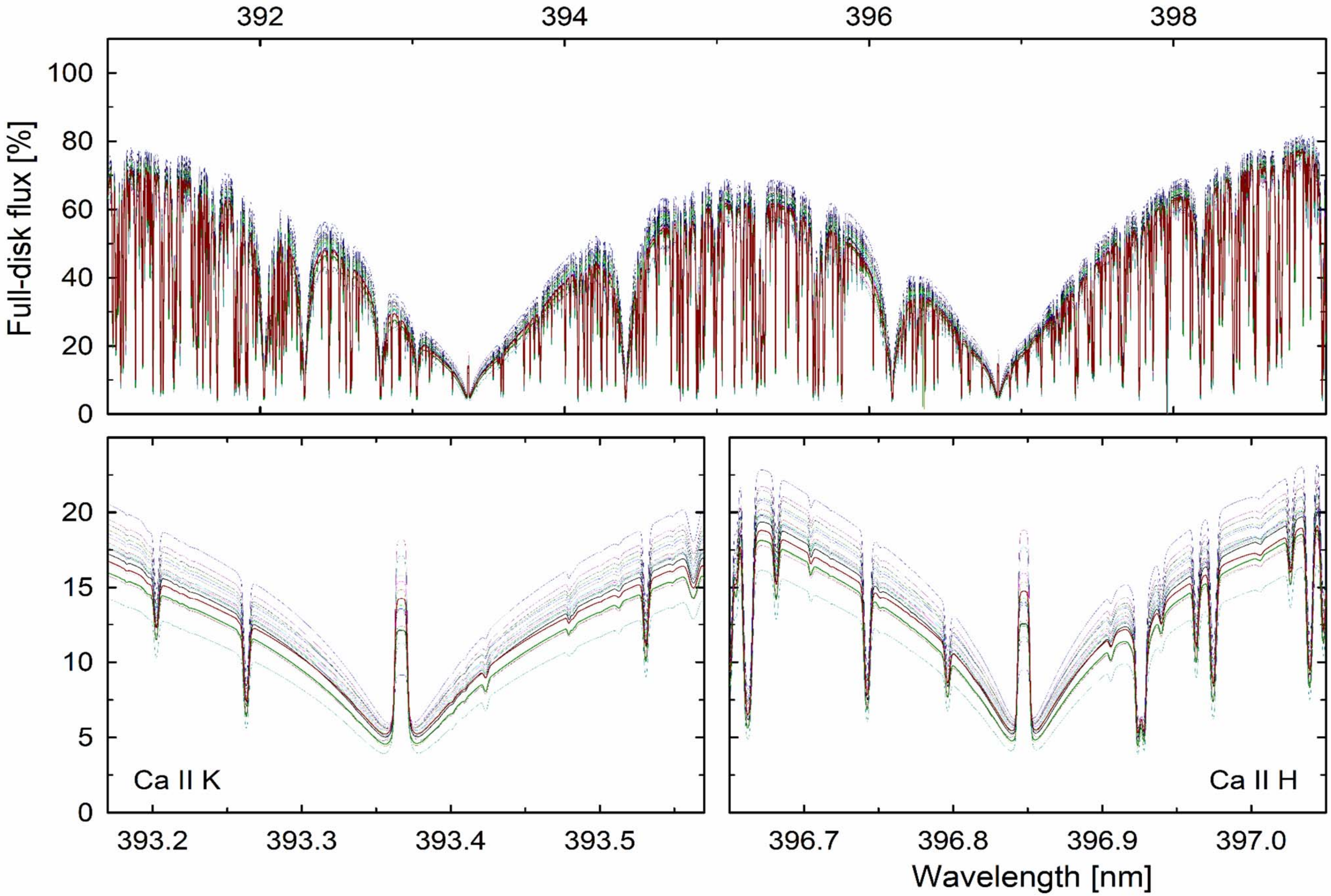
Main driver of solar ‘radial-velocity’ variations:

Modulated granulation

Reconstruction of the apparent radial velocity during an activity cycle, due to inhibition of convective blueshift in magnetic plage regions (red) and due to the brightness contrast in sunspots and plages

N.Meunier: *Stellar Variability in Radial Velocity*, Proc. Evry Schatzman School "*Interactions star-planet*", `arXiv:2104.06072` (2021)

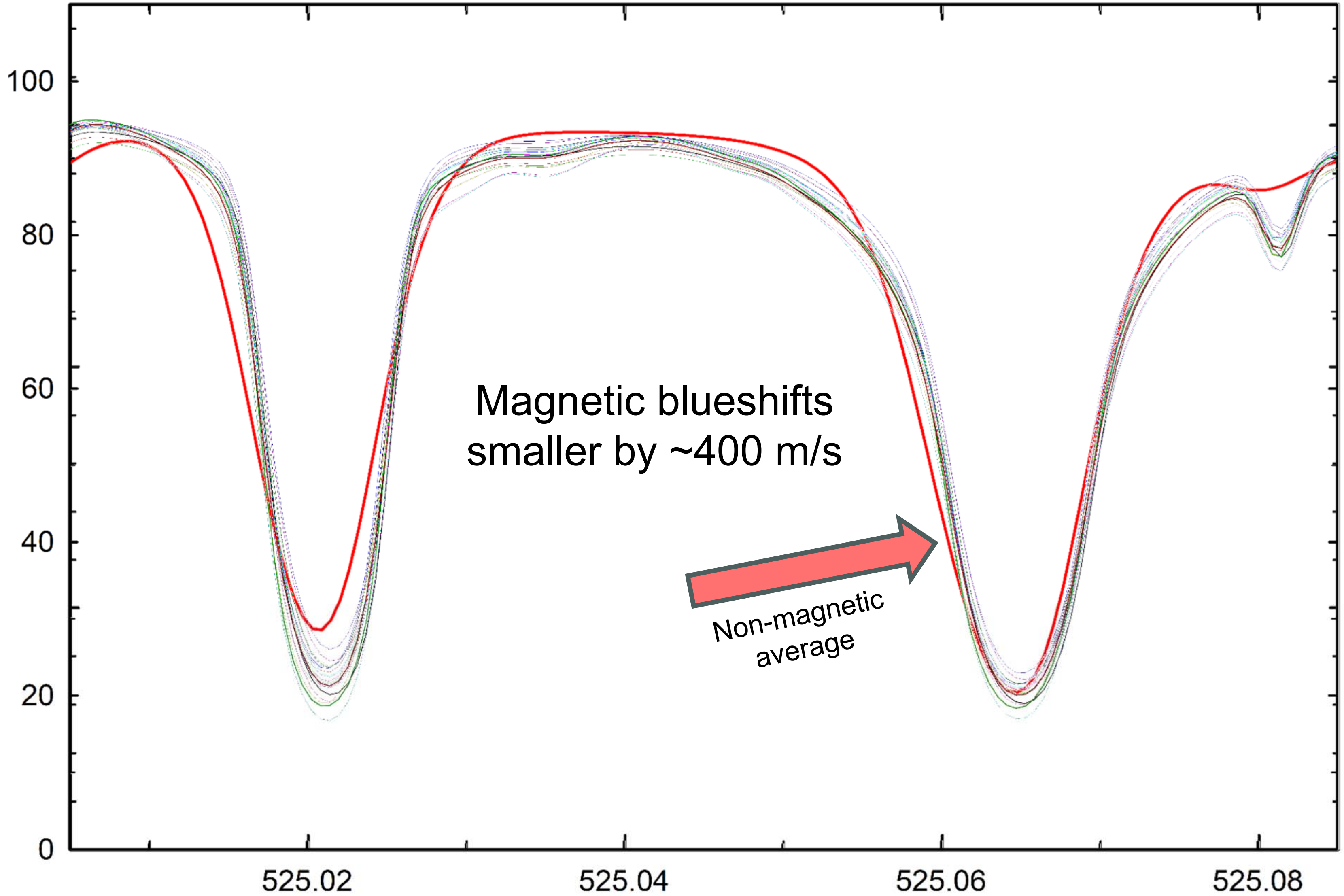
Snapshots during evolving magnetic granulation



Ca II H & K lines, full disk, $\lambda/\Delta\lambda$ ~ 900,000

D.Dravins, H.-G.Ludwig, C.Allende Prieto, M.Steffen: *Solar photospheric spectrum microvariability. III.*, in preparation

Magnetic vs. non-magnetic granulation



Fe I line magnetic snapshots vs. non-magnetic 3D profiles (red)

Full disk, $\lambda/\Delta\lambda$ ~ 900,000

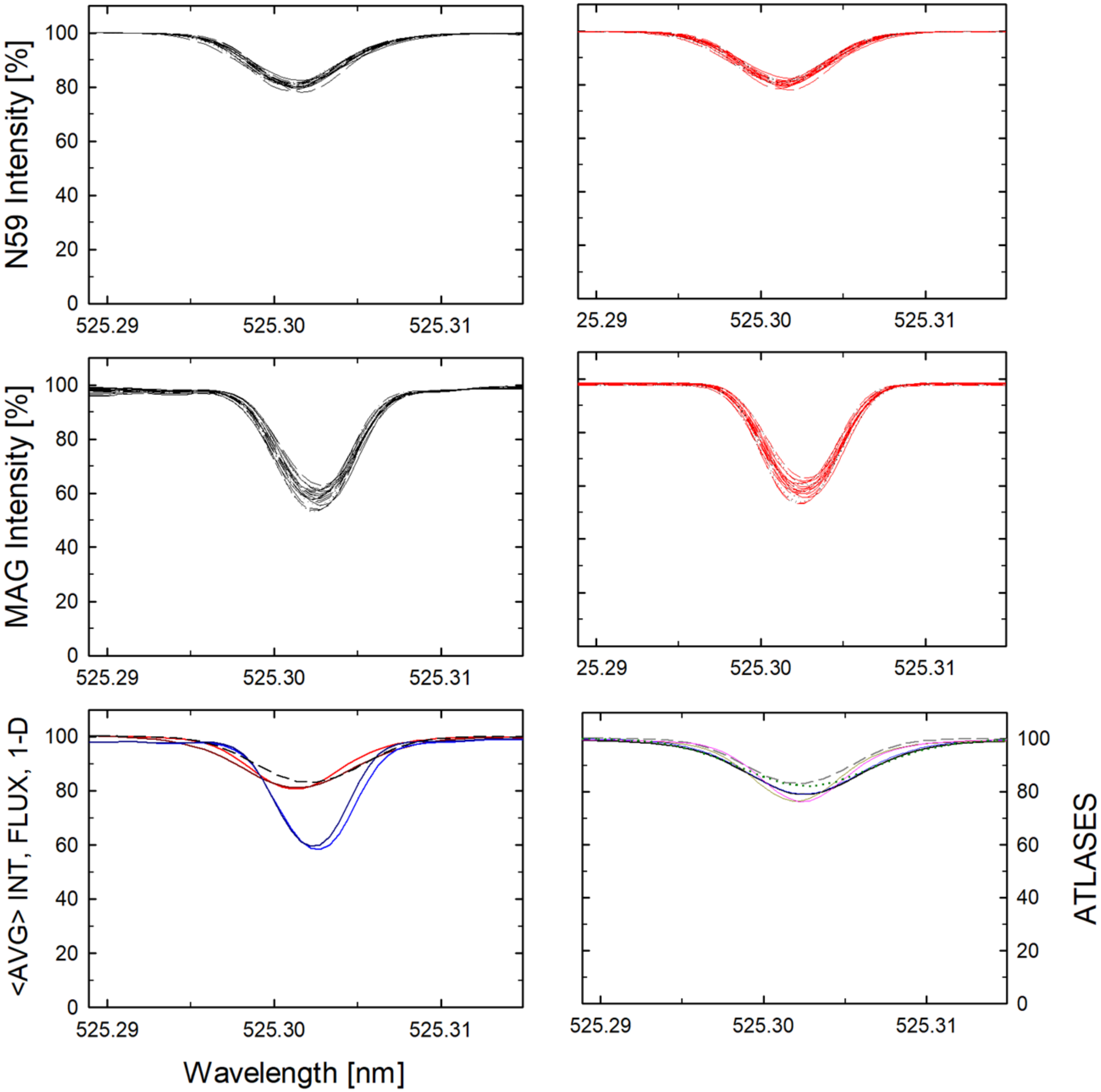
D.Dravins, H.-G.Ludwig, C.Allende Prieto, M.Steffen: *Solar photospheric spectrum microvariability. III.*, in preparation

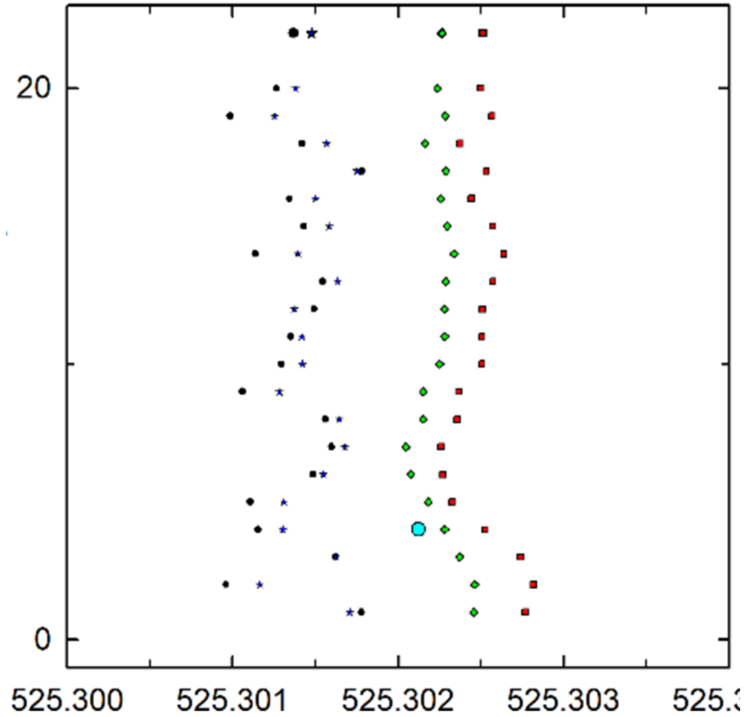
Snapshots during evolving magnetic granulation

Fe I 525.302 nm – Ordinary, moderately weak line

Left: Synthetic profiles for 20 snapshots (black); fitted profiles (red)

Right: Fitted wavelengths for 20 snapshots; larger blueshifts for non-magnetic N59 INT and for MAG FLUX



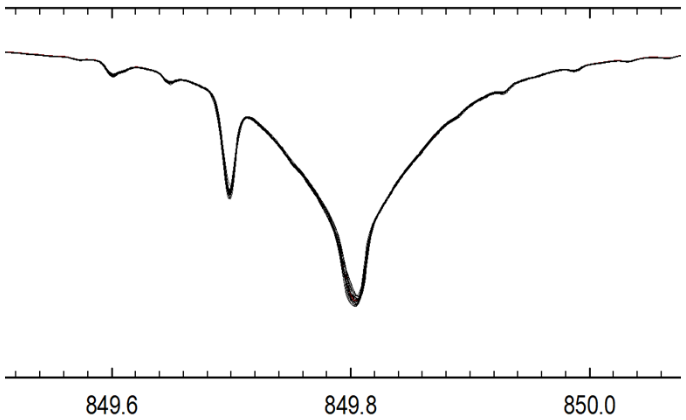


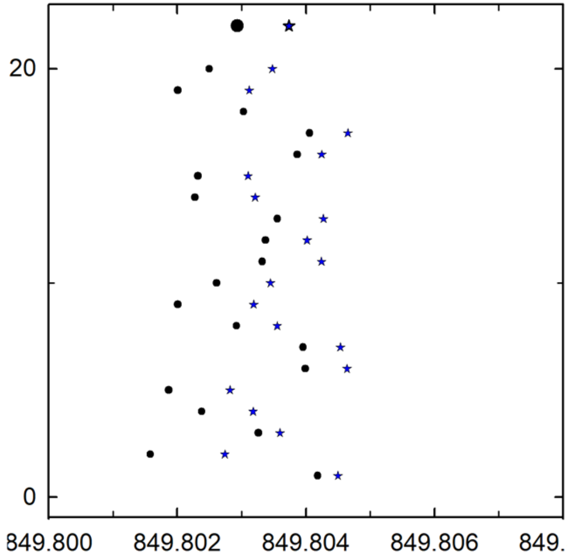
D.Dravins, H.-G.Ludwig, C.Allende Prieto, M.Steffen: *Solar photospheric spectrum microvariability. III.*, in preparation

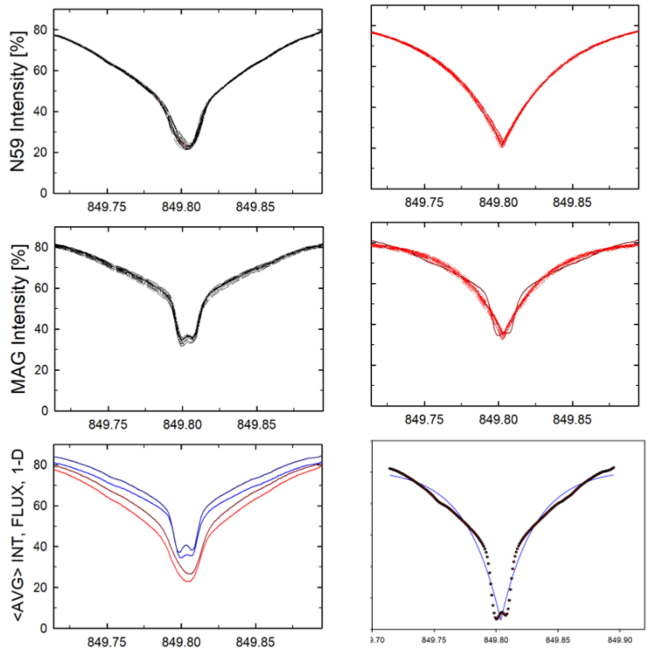
Snapshots during evolving magnetic granulation

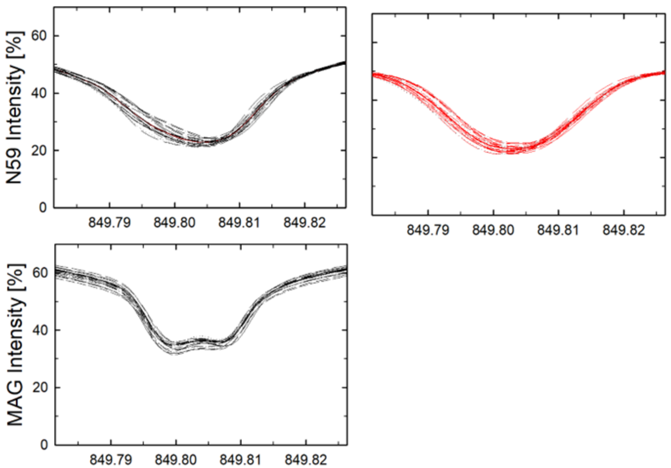
Ca II IR triplet 849.8 nm - Example of strong line

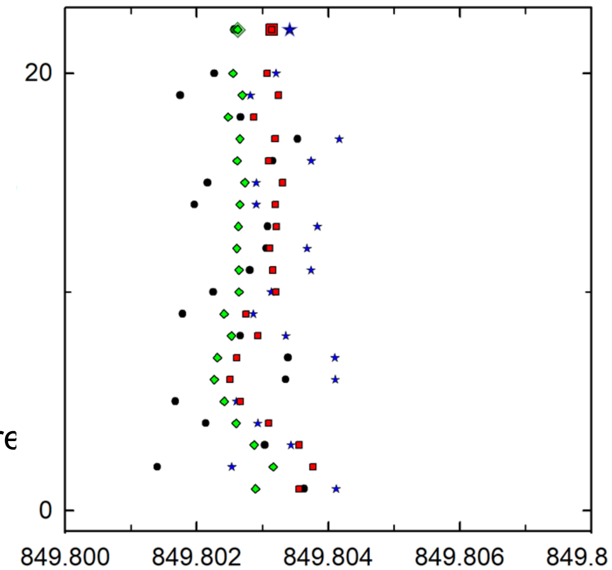
Line core (left) behaves differently from line flanks (right)











LINE CORE

Synthetic profiles for 20 snapshots (black); Fitted profiles (re
N59 INT: Black circles; N59 FLUX: Blue stars
No fits to complex magnetic profiles

LINE FLANKS

Synthetic profiles (black)
Fitted profiles (red)
Example of fit to one snapshot

Fitted wavelengths for 20 snaps

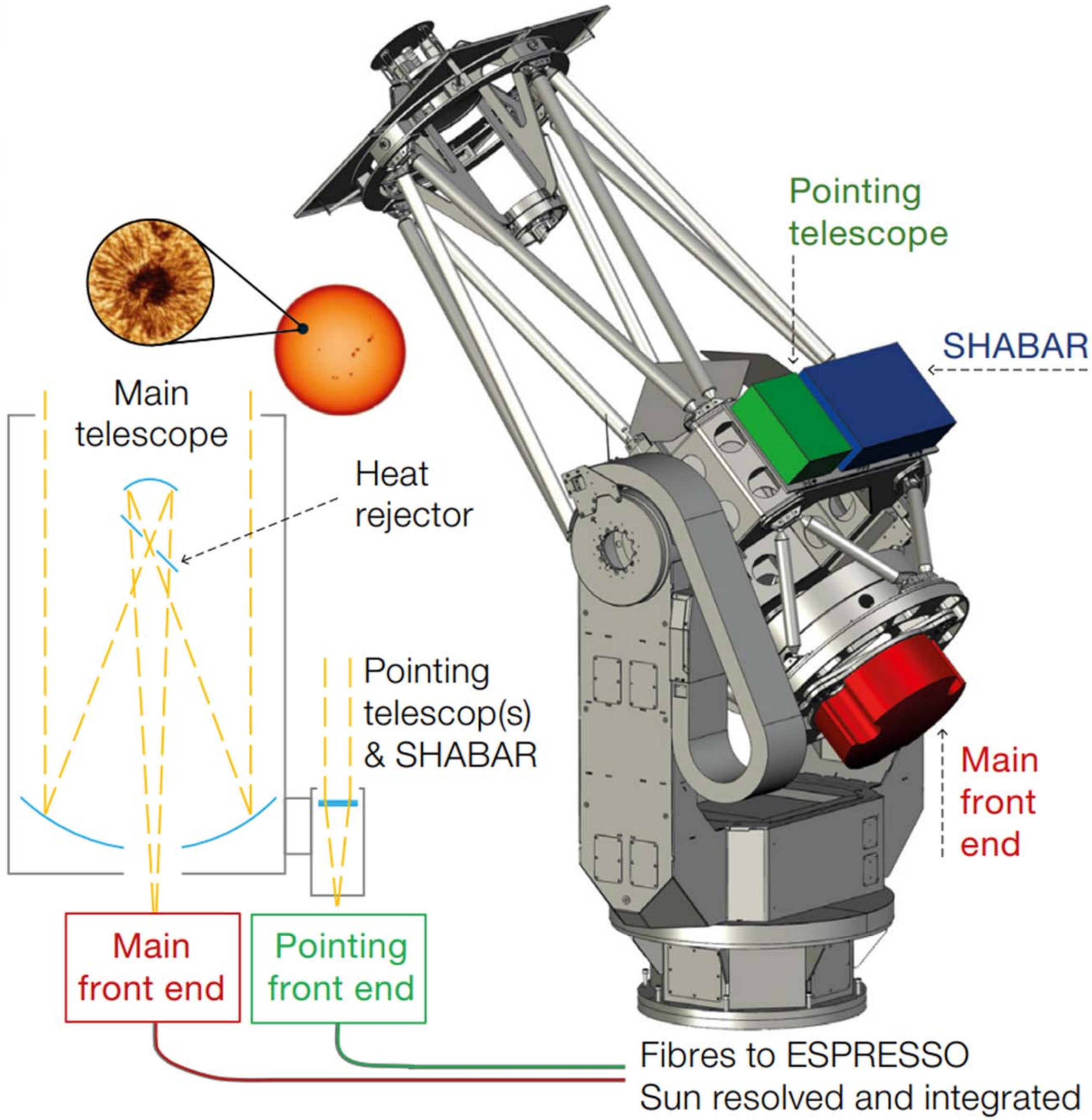
N59 INT: Black circles
N59 FLUX: Blue stars
MAG INT: Red squares
MAG FLUX: Green diamonds

D.Dravins, H.-G.Ludwig, C.Allende Prieto, M.Steffen: *Solar photospheric spectrum microvariability. III.*, in preparation

What’s next?

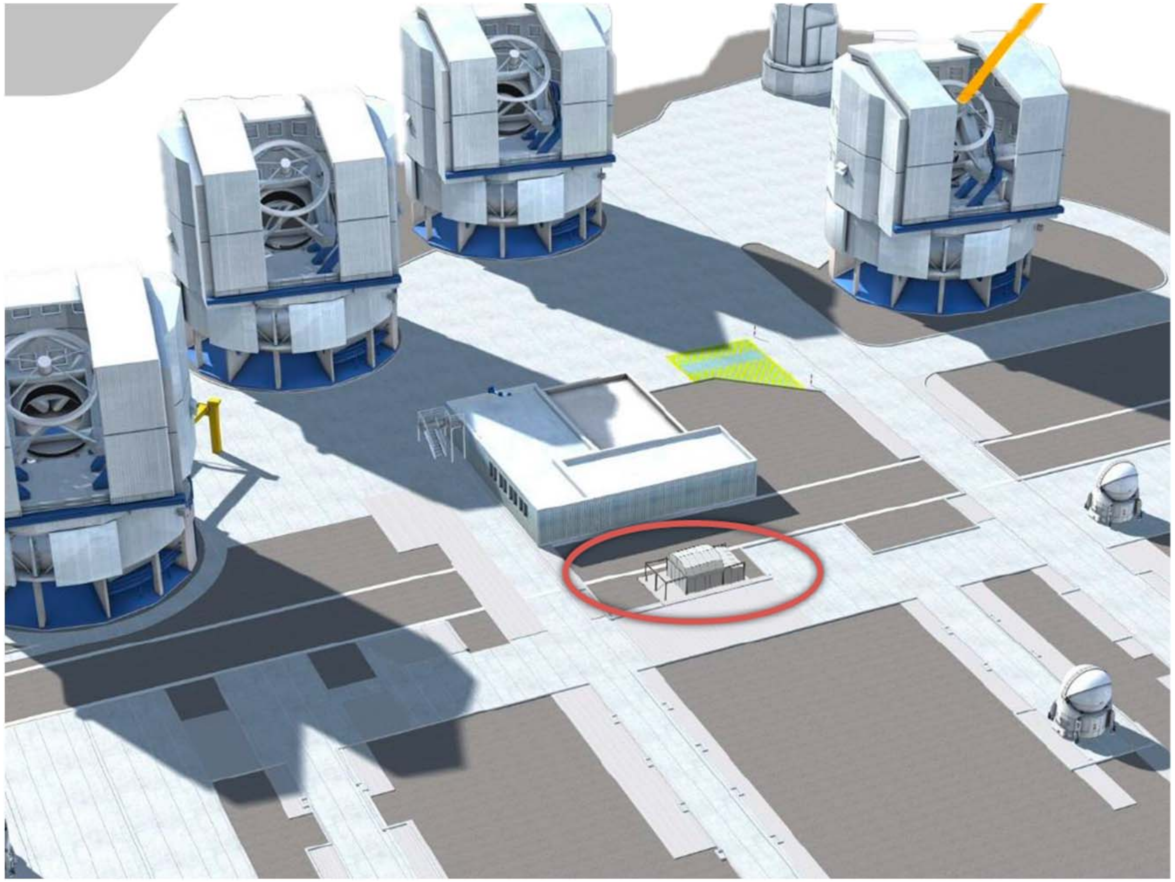
PoET: the Paranal solar ESPRESSO Telescope

Nuno C. Santos[1,2]
Alexandre Cabral[3,4]
Inês Leite[3,4]
Alain Smette[5]
Manuel Abreu[3,4]
David Alves[3,4]
Jorge H. C. Martins[1]
Manuel Monteiro[1]
André Silva[1,2]
Bachar Wehbe[3,4]
Jimmy Arancibia[5]
Gerardo Ávila[3]
Stephane Brillant[5]
César Cárdenas[5]
Ricardo Clara[3]
Ricardo Gafeira[6,7]
Daniel Gaytan[5]
Christophe Lovis[8]
Nicolas Miranda[5]
Pedro Moreno[1]
António Oliveira[3,4]
Angel Otarola[5]
Francesco Pepe[8]
Pascual Rojas[5]
Ricardo Schmutzer[5]
Danuta Sosnowska[8]
Pierre van der Heyden[5]
Khaled Al Moulla[1]
Vardan Adibekyan[1]
Alba Barka[1,2]
Susana C. C. Barros[1,2]
Pedro Branco[1,2]
Eduardo Cristo[1]
Yuri Damasceno[1,2]
Olivier Demangeon[1]
William Dethier[1]
João P. Faria[8]
João Gomes da Silva[1]
Eduardo Gonçalves[1,2]
Jennifer P. Lucero[1,2]
José Rodrigues[1,2]
Carmen San Nicolas Martinez[1,2]
Ângela Santos[1,2]
Sérgio Sousa[1]
Pedro T. P. Viana[1,2]



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

PoET – Paranal Solar ESPRESSO Telescope



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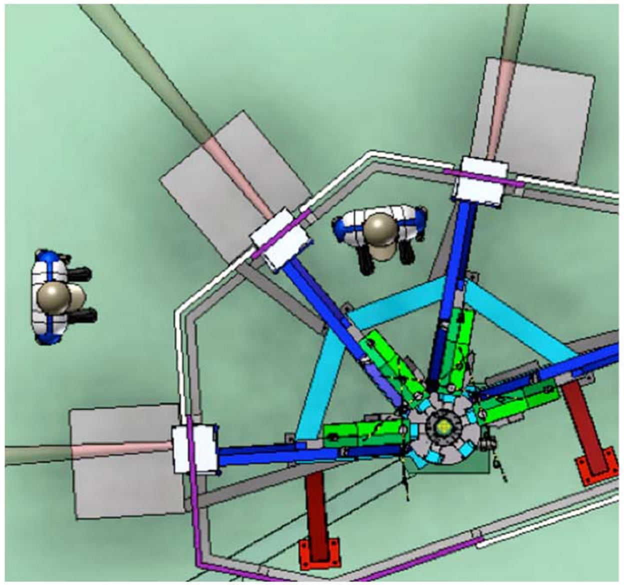
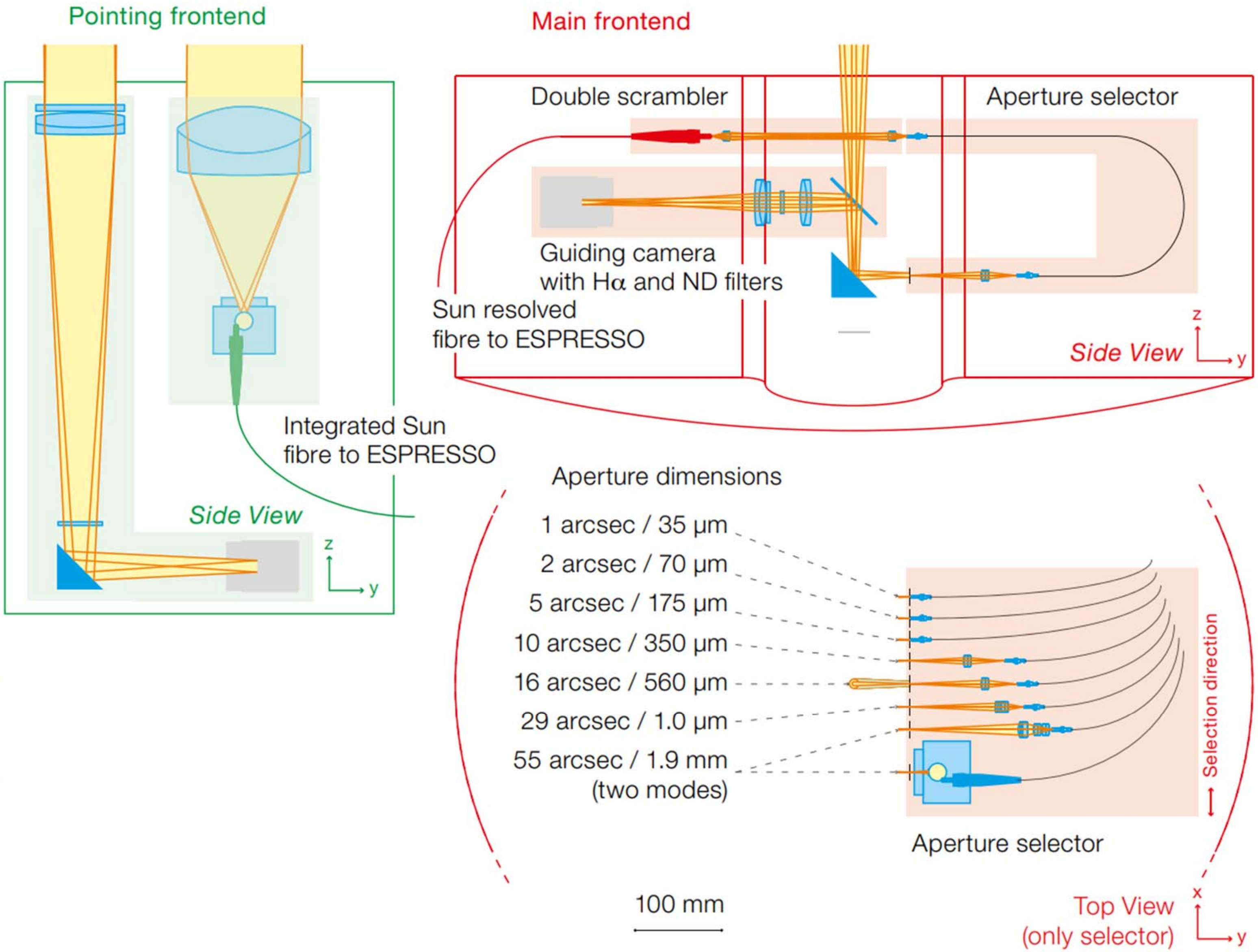
PoET: the Paranal solar ESPRESSO Telescope

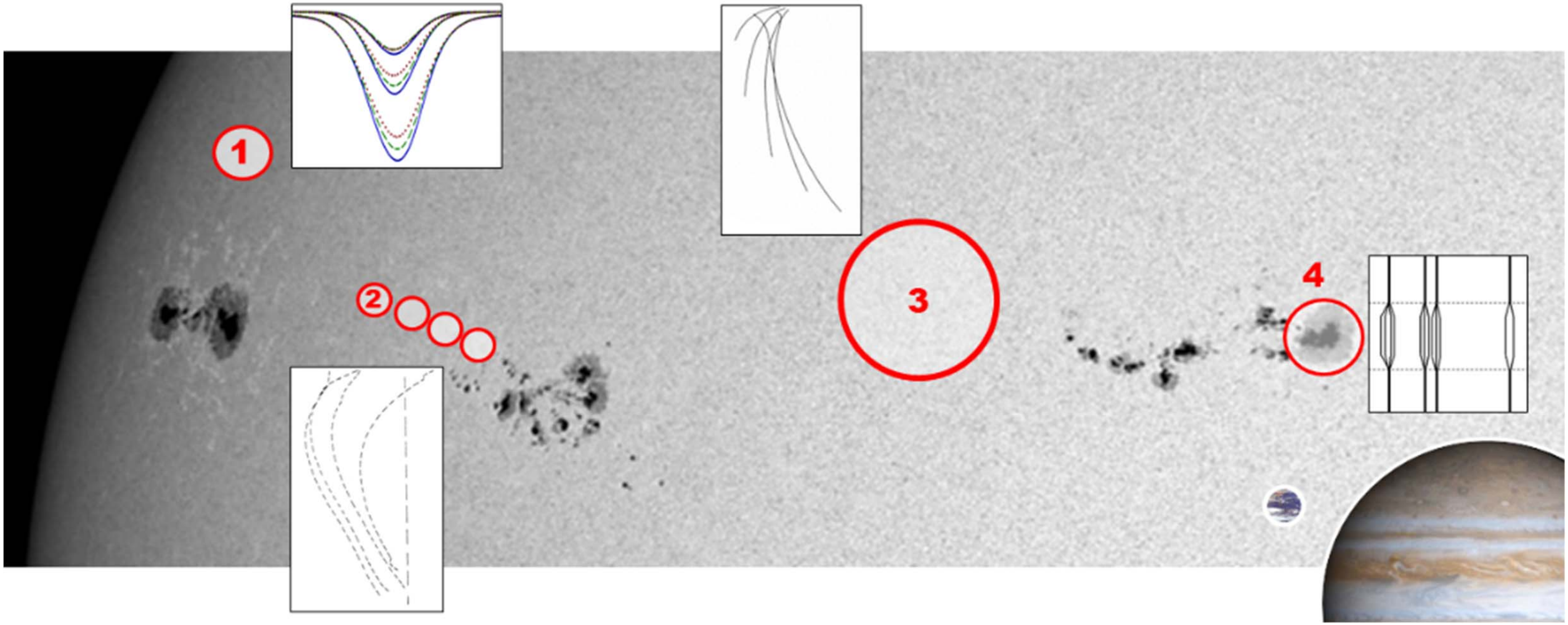




First light expected 2025/26

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

PoET – Paranal Solar ESPRESSO Telescope



Examples of phenomena to be studied with PoET

(1) Lines of different strengths and excitation potentials across inhomogeneities (Dravins et al. AA 605, A90)
(2) Line bisectors change shapes and shifts close to magnetic plage regions (Cavallini et al. AA 143, 116)
(3) Differently strong lines show different convective shifts across the disk (Allende Prieto et al. ApJ 567, 544)
(4) Spectral-line behavior in magnetic sunspots varies with each line's Landé g-factor.

Solar image: NASA SDO; Earth and Jupiter superposed to scale.

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PoET

THE

END