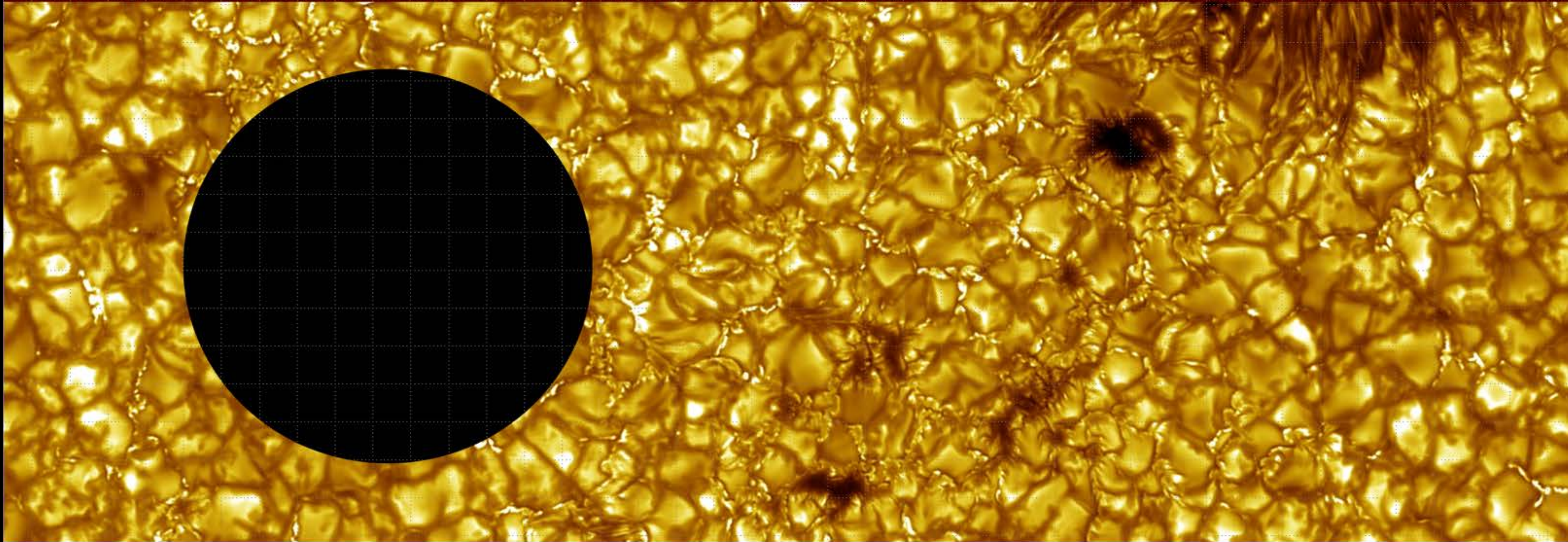
Solar surface granulation in Ca II H λ 396.37 nm wideband. Observations and image processing by Vasco Henriques; Swedish 1-meter solar telescope on La Palma; Royal Swedish Academy of Sciences



Stellar Atmospheres behind Transiting Exoplanets

***Dainis Dravins*[1], *Hans-Günter Ludwig*[2], *Erik Dahlén*[1], *Martin Gustavsson*[1], *Hiva Pazira*[1]**

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arXiv:1709.05941v1 [astro-ph.EP] 18 Sep 2017

Exoplanet Atmosphere Measurements from Transmission Spectroscopy and other Planet-Star Combined Light Observations

Laura Kreidberg

The Host Star: Friend or Foe?

Know Thy Star – Know Thy Planet

Know thy enemy!

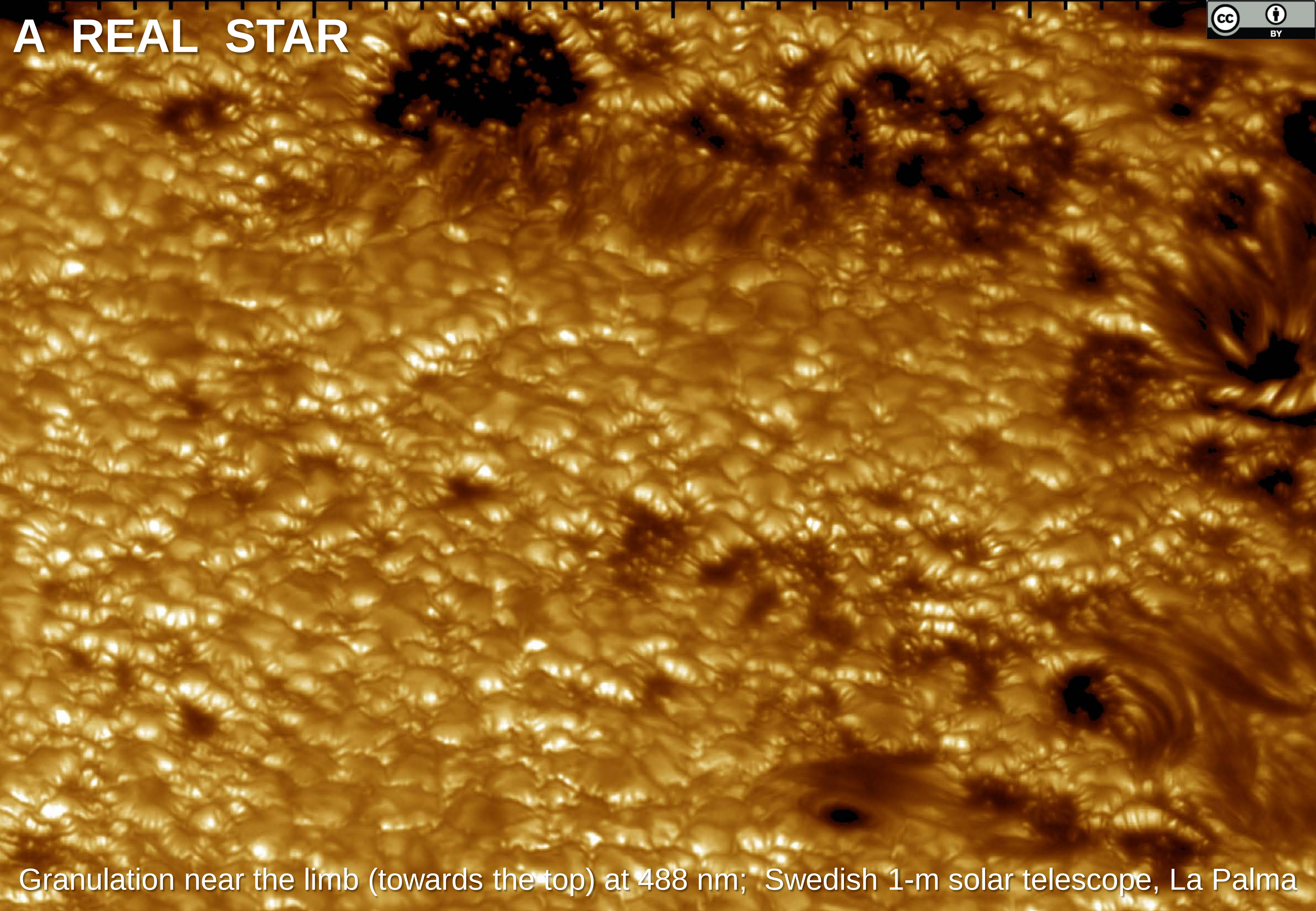
What (besides exoplanets) is shifting stellar spectral lines?

Exoplanet atmospheric signatures?

Exoplanet properties deduced differentially to stellar spectra

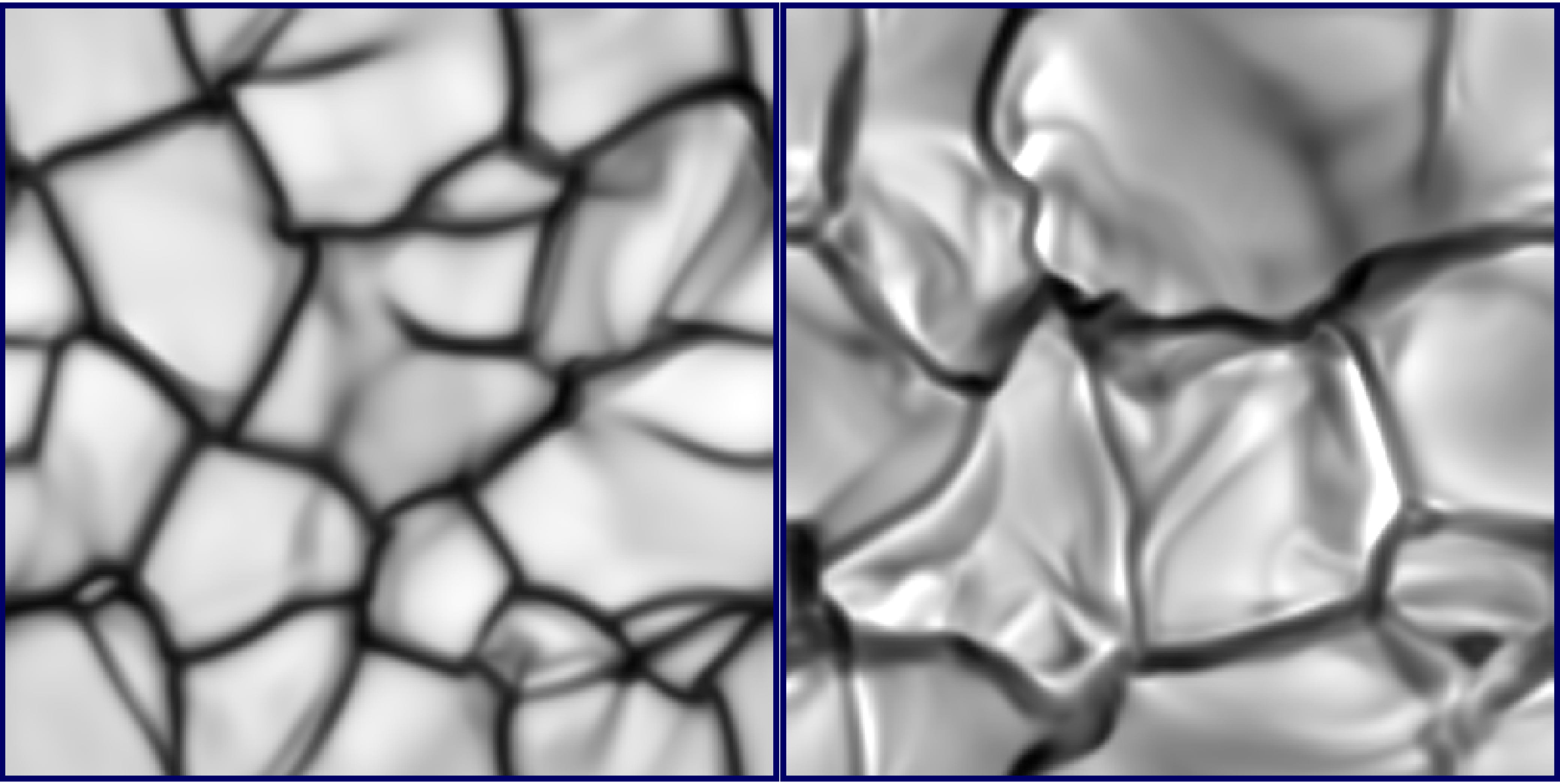
Finding “true” Earth analogs?

Stellar variability much greater than planetary perturbation



Granulation near the limb (towards the top) at 488 nm; Swedish 1-m solar telescope, La Palma

MODELING STELLAR SURFACES

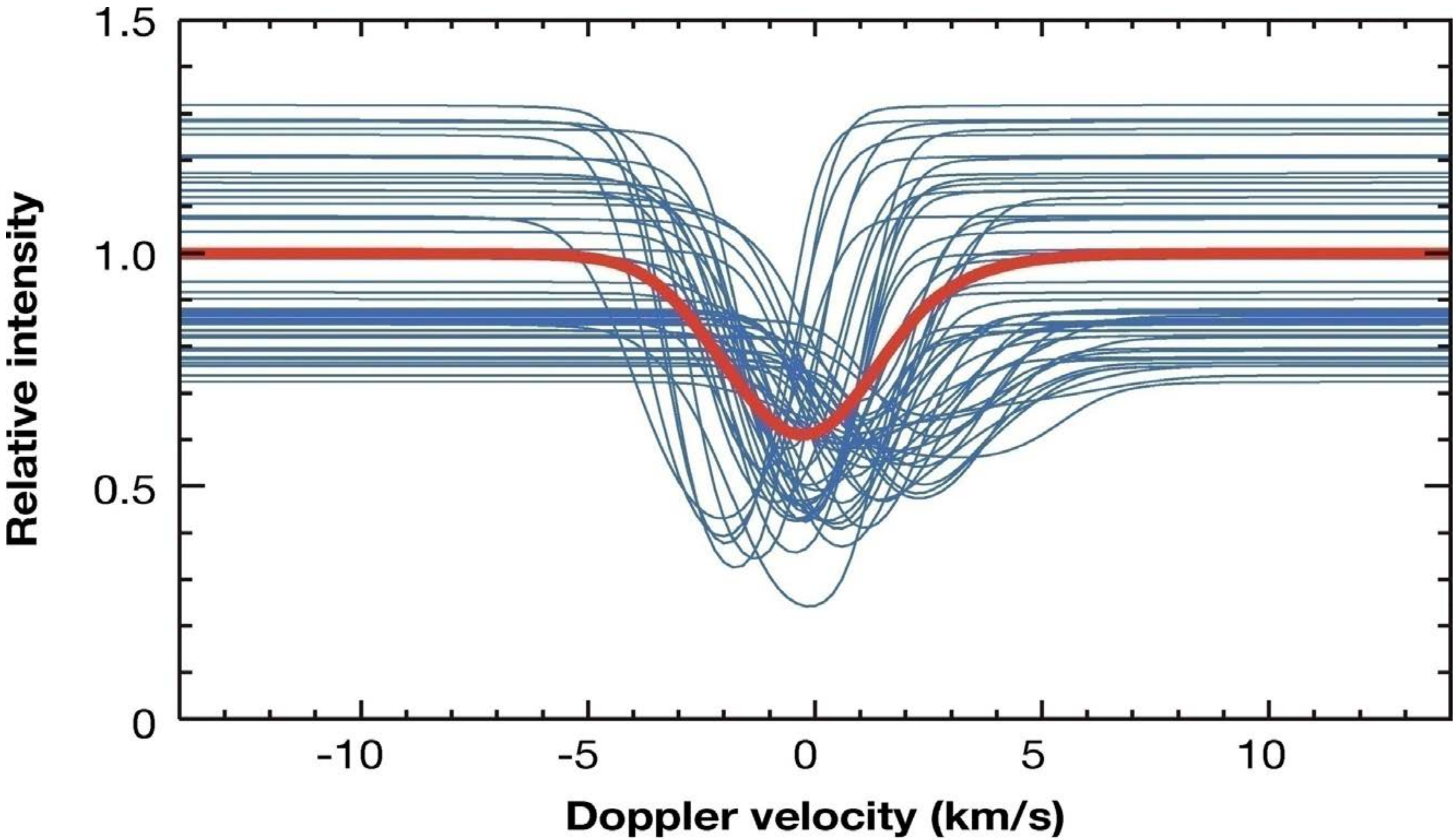


Surface intensity during granular evolution on a 12,000 K white dwarf (left) and a 3,800 K red giant. Areas differ by orders of magnitude: 7x7 km^2 for the white dwarf, and 23x23 R_{Sun}^2 for the giant.

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

How to verify or falsify 3-D models ?

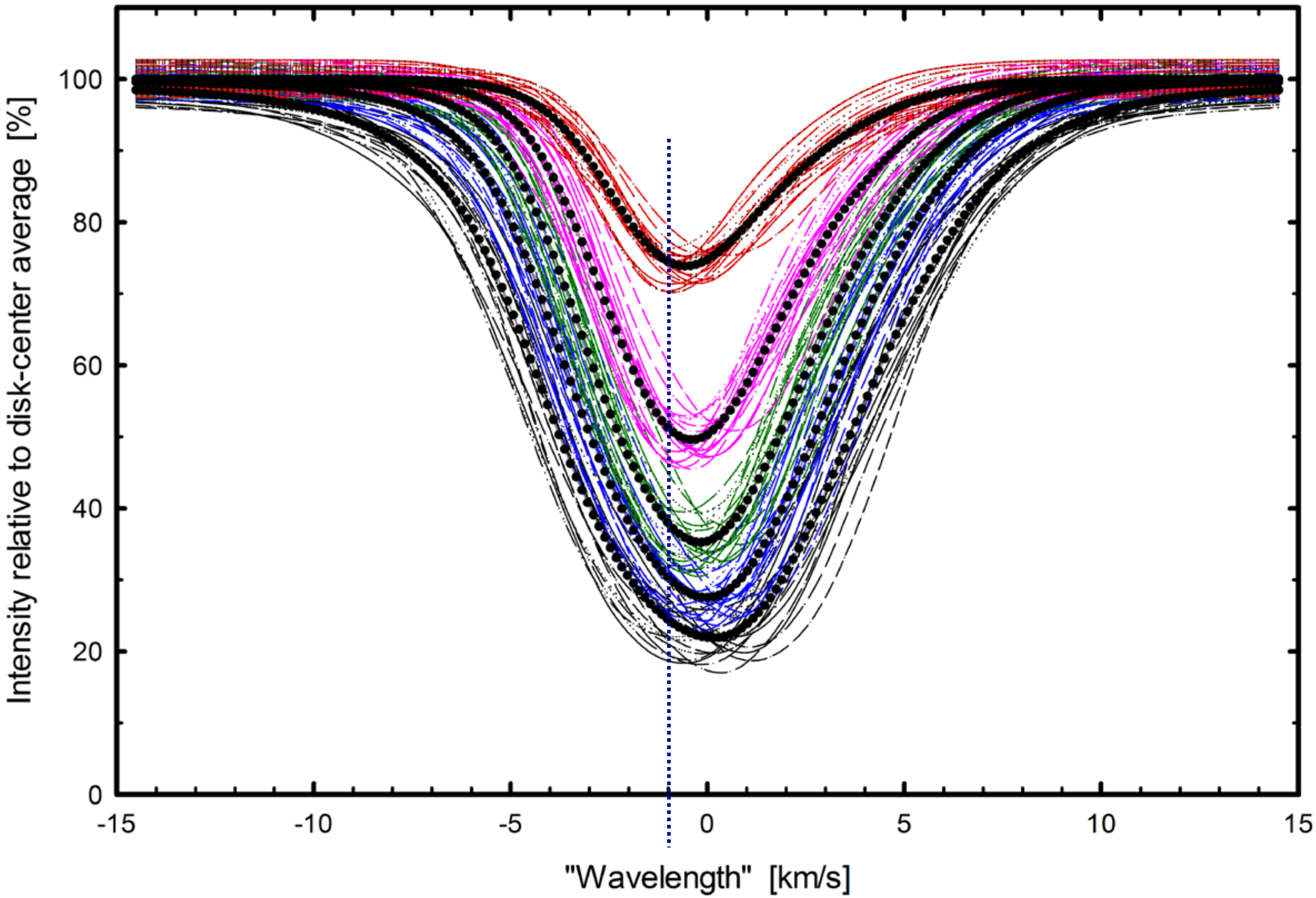
Spatially *resolved* spectra across stellar granulation



Spatially resolved line profiles of the Fe I 608.27 nm line in a 3-D solar simulation.
Thick red line is the spatially averaged profile.
The steeper temperature structures in hotter upflows tend to make their lines stronger (blue-shifted components).

M.Asplund: *New Light on Stellar Abundance Analyses: Departures from LTE and Homogeneity*, Ann.Rev.Astron.Astrophys. **43**, 481

Spatially *averaged* spectra across stellar granulation



Spatially averaged line profiles from 20 timesteps, and temporal averages.

λ = 620 nm
χ = 3 eV
5 line strengths

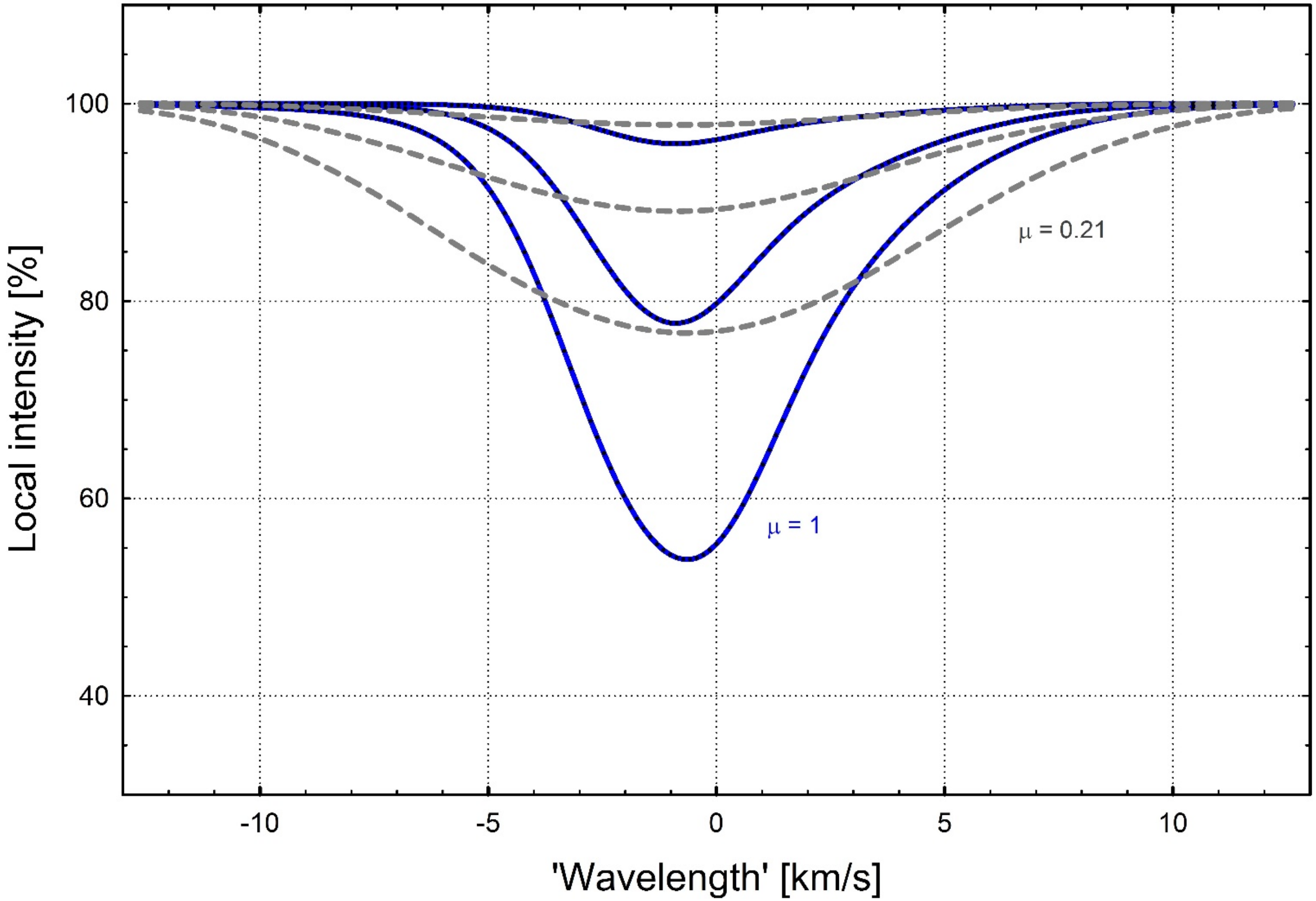
GIANT STAR

T_{eff}= 5000 K
log g [cgs] = 2.5
(approx. K0 III)

Stellar disk center;
$\mu = \cos\theta = 1.0$

(D.Dravins, H.-G.Ludwig, E.Dahlén, H.Pazira, *Proc. 18th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun*, 2014)

Line profiles from 3-D hydrodynamic simulations



Synthetic Fe I profiles from a CO^5BOLD model for a dwarf star with T_{eff} = 6730 K. Three line strengths; χ = 3 eV, λ = 620 nm. Solid: Disk center $\mu = \cos\theta = 1$; dashed near limb, μ = 0.21. Lines are broader near the limb since horizontal motions are greater than vertical ones.

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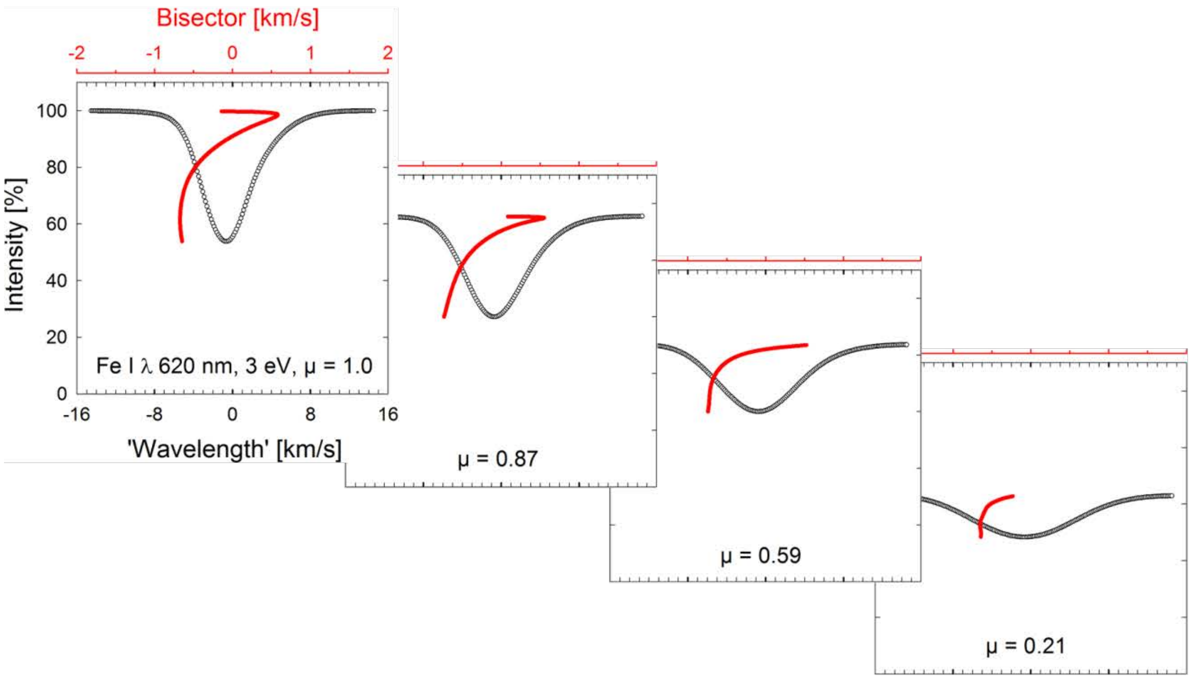
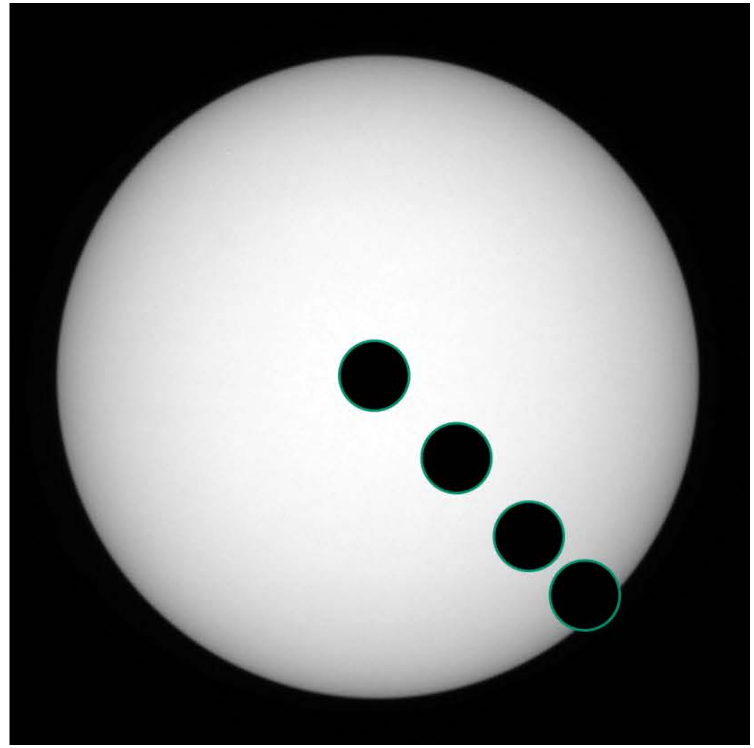
Spectral line profiles across stellar disks

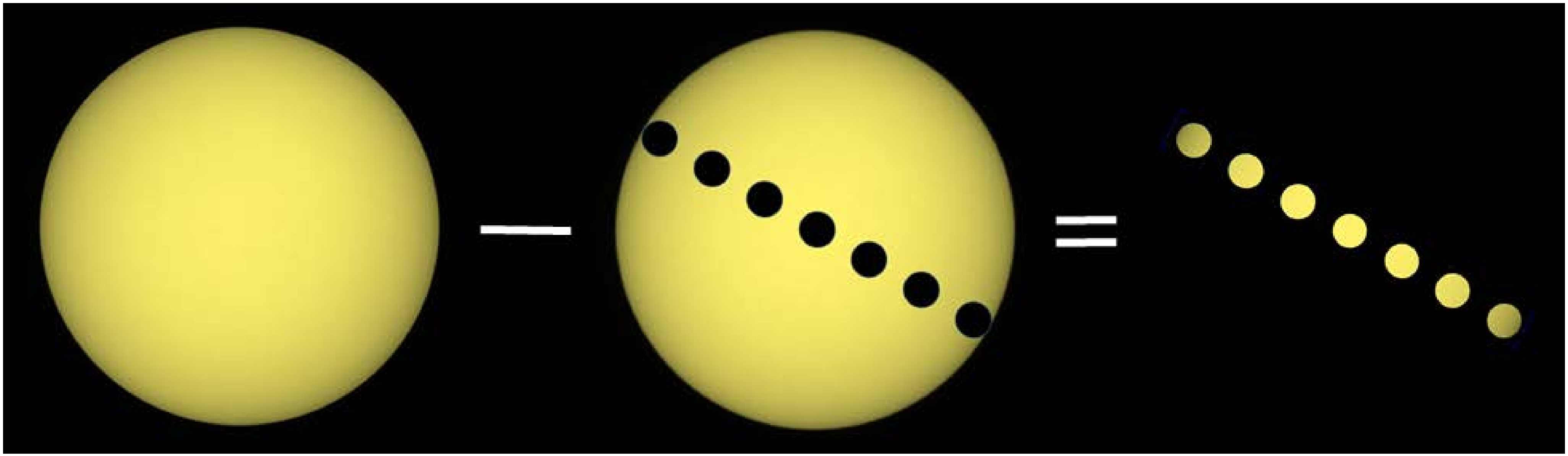




Spectral lines, spatially and temporally averaged from 3-D models, change their strengths, widths, asymmetries and convective wavelength shifts across stellar disks, revealing details of atmospheric structure. These line profiles from disk center ($\mu = \cos\theta = 1$) towards the limb are from a CO^5BOLD model of a main-sequence star; solar metallicity, T_{eff} = 6800 K.

(D.Dravins, H.-G.Ludwig, E.Dahlén, H.Pazira, *Proc. 18th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun*, 2014)

Spatially resolving stellar surfaces using exoplanet transits



Differences during exoplanet transit reveal temporarily hidden stellar surface segments.

Changing continuum flux measured by photometry, spectral changes by spectroscopy.

D.Dravins, H.-G.Ludwig, E.Dahlén, H.Pazira:
Spatially resolved spectroscopy across stellar surfaces. I. Using exoplanet transits to analyze 3-D stellar atmospheres
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Stellar Spectroscopy during Exoplanet Transits

* Exoplanets successively hide segments of stellar disk

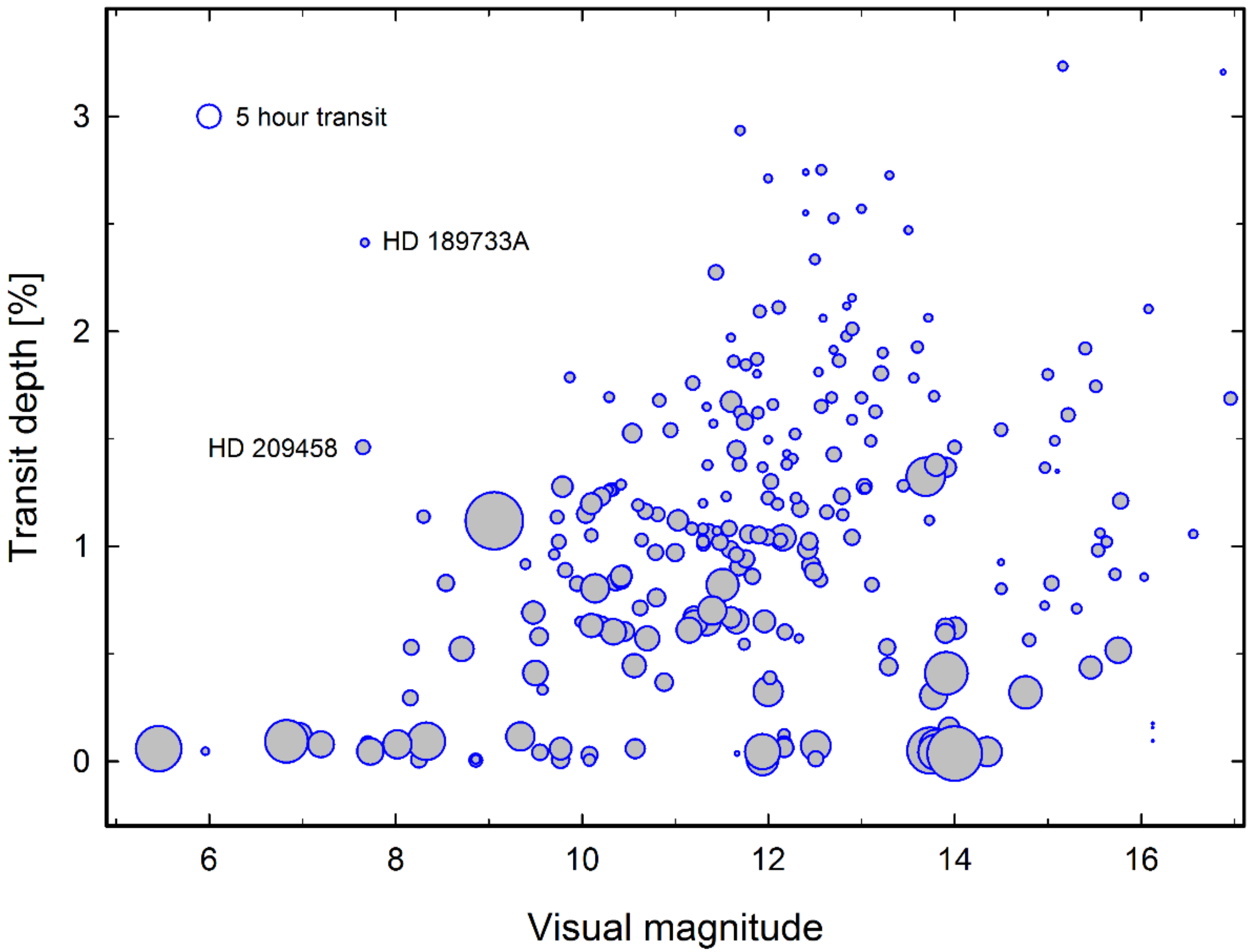
* Differential spectroscopy provides spectra of those surface segments that were hidden behind the planet

* 3-D hydrodynamics studied in center-to-limb variations of line shapes, asymmetries and wavelength shifts

* Retrieving good spectra from behind exoplanet covering ~1% of star requires S/N ~10,000 (!)

Which stars can realistically be observed?

Transiting exoplanet hosts



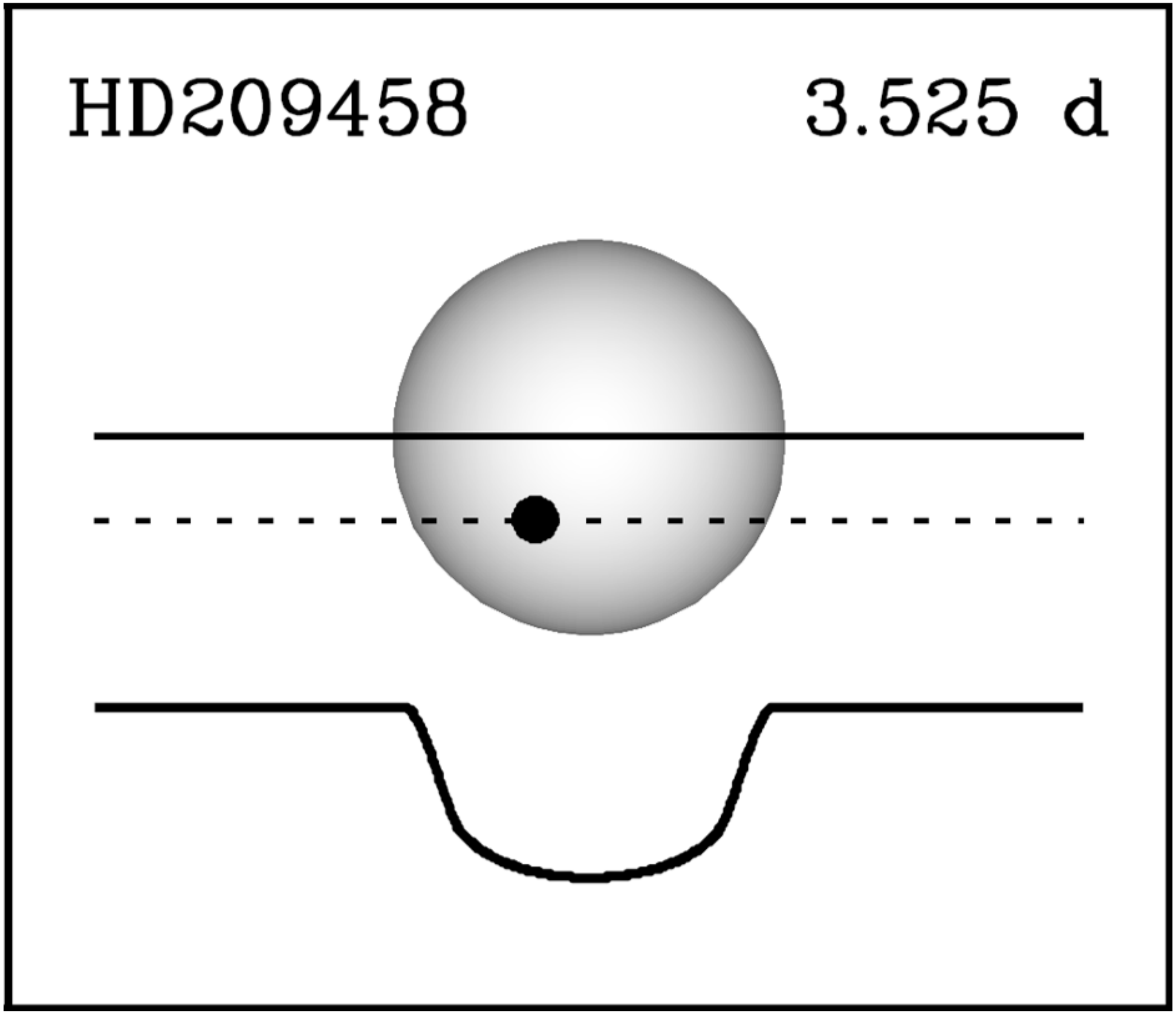
&
KELT-20b
0.8%
m_V~7.6
A2 V

Photometric transit depth for transiting exoplanet systems.

Symbol diameters are proportional to the duration of transit.

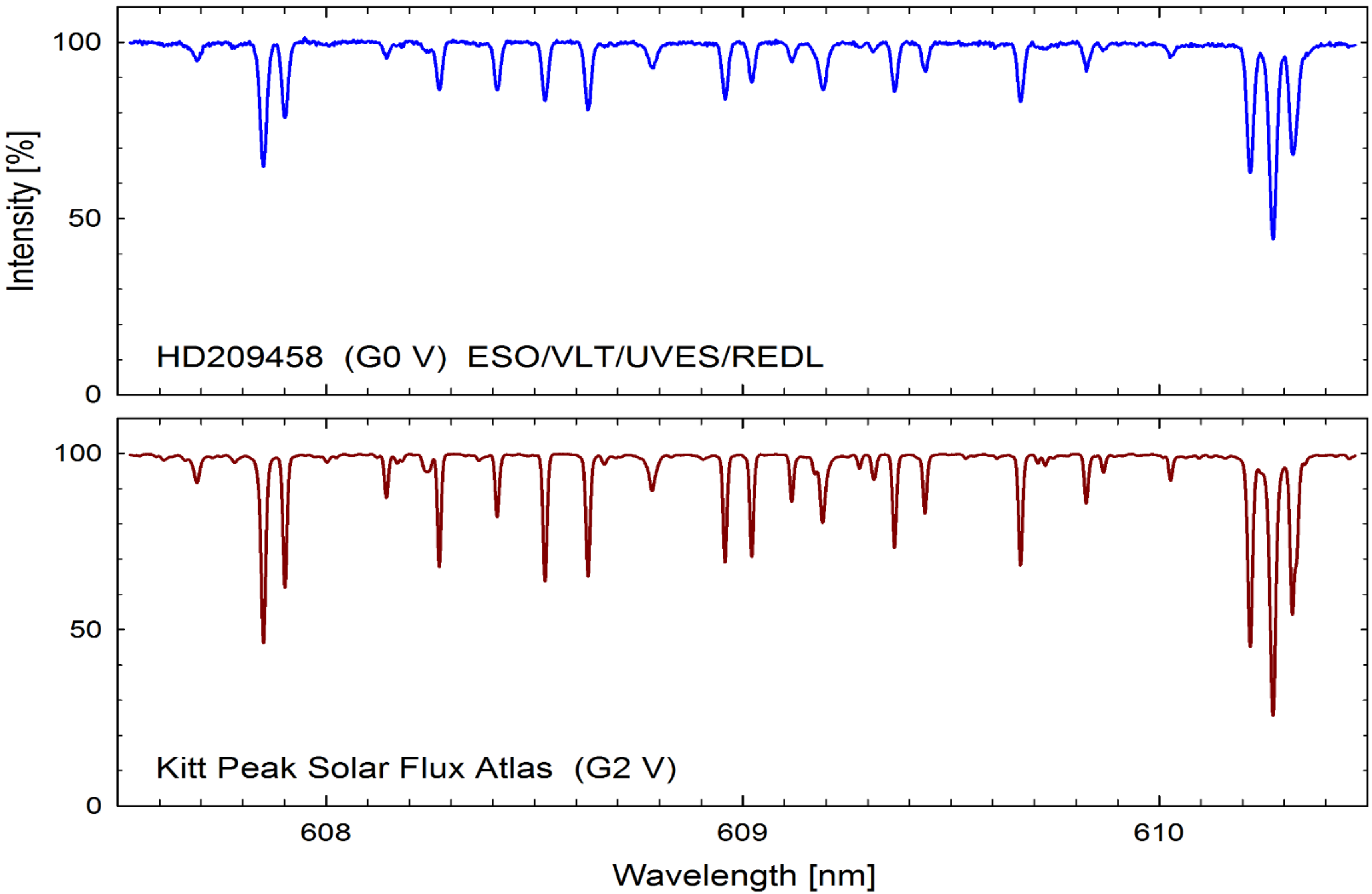
D.Dravins, H.-G.Ludwig, E.Dahlén, H.Pazira:
Spatially resolved spectroscopy across stellar surfaces. II. High-resolution spectra across HD 209458 (G0 V)
Astron.Astrophys. **605**, A91, 2017

Exoplanet transit geometry



G.Torres, J.Winn, M.J.Holman: *Improved Parameters for Extrasolar Transiting Planets*, ApJ **677**, 1324

Spectrum of HD209458 resembles solar



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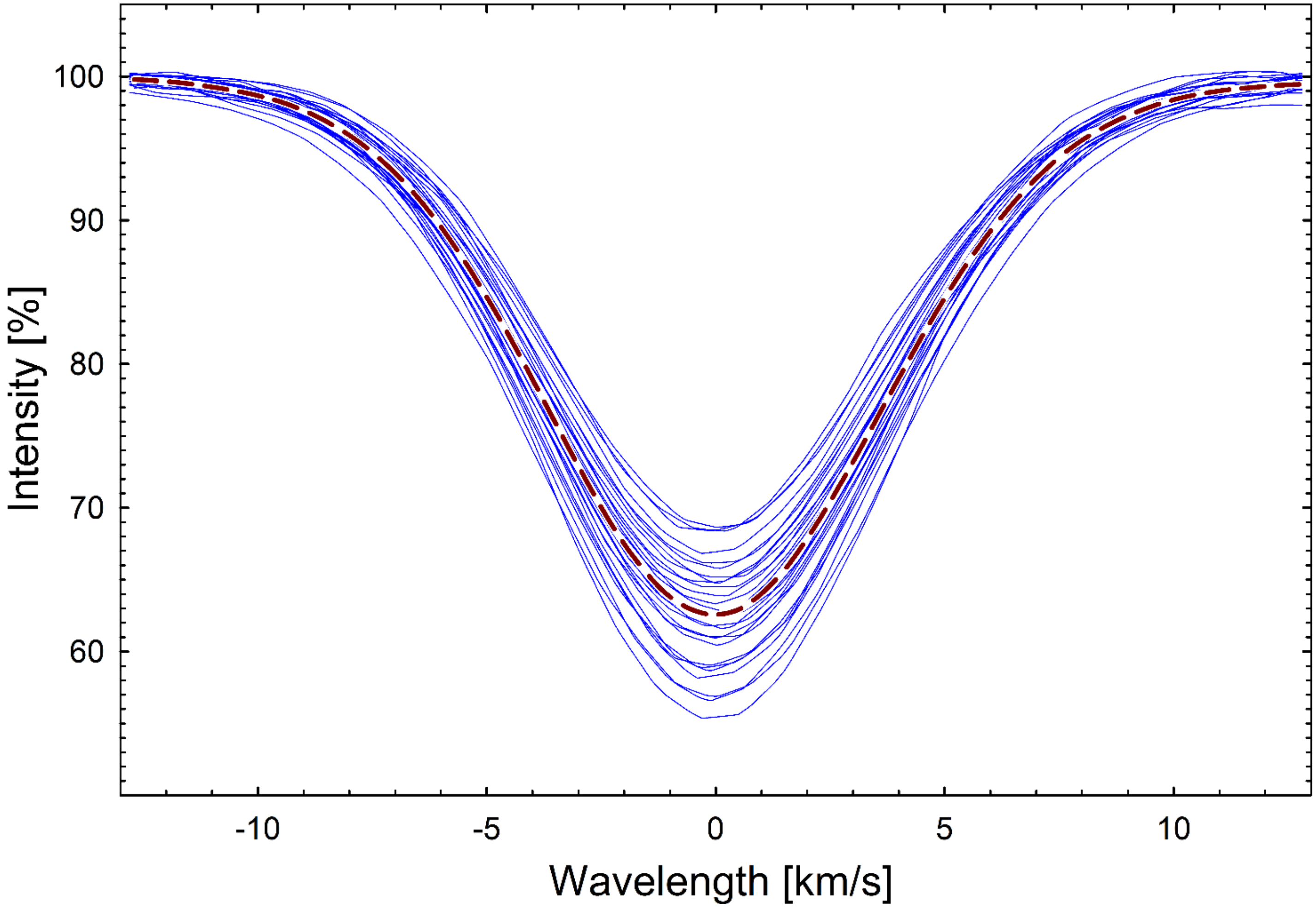
Averaging photospheric Fe I lines



Photospheric Fe I lines of similar strengths in HD 209458 carry redundant information.

Averaging multiple exposures gives a representative profile with $\lambda/\Delta\lambda \sim 80{,}000$, S/N ~7,000.

D.Dravins, H.-G.Ludwig, E.Dahlén, H.Pazira:
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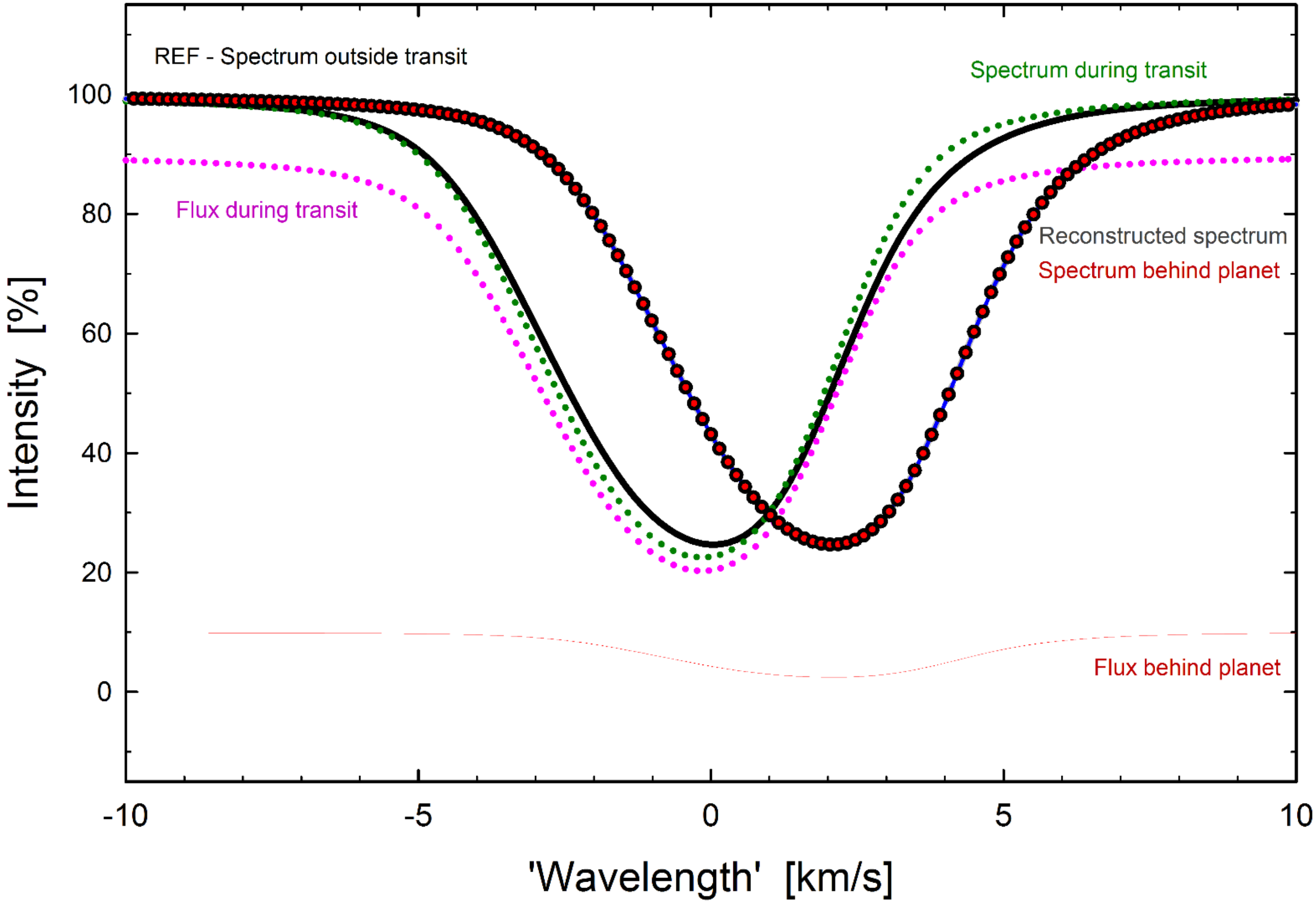
Retrieving spatially resolved stellar line profiles

Principle of spectral reconstruction



Spectrum behind the planet is obtained as that line profile (weighted with the amount of flux temporarily obscured) that – summed with the temporarily observed profile – produces the profile outside of transit

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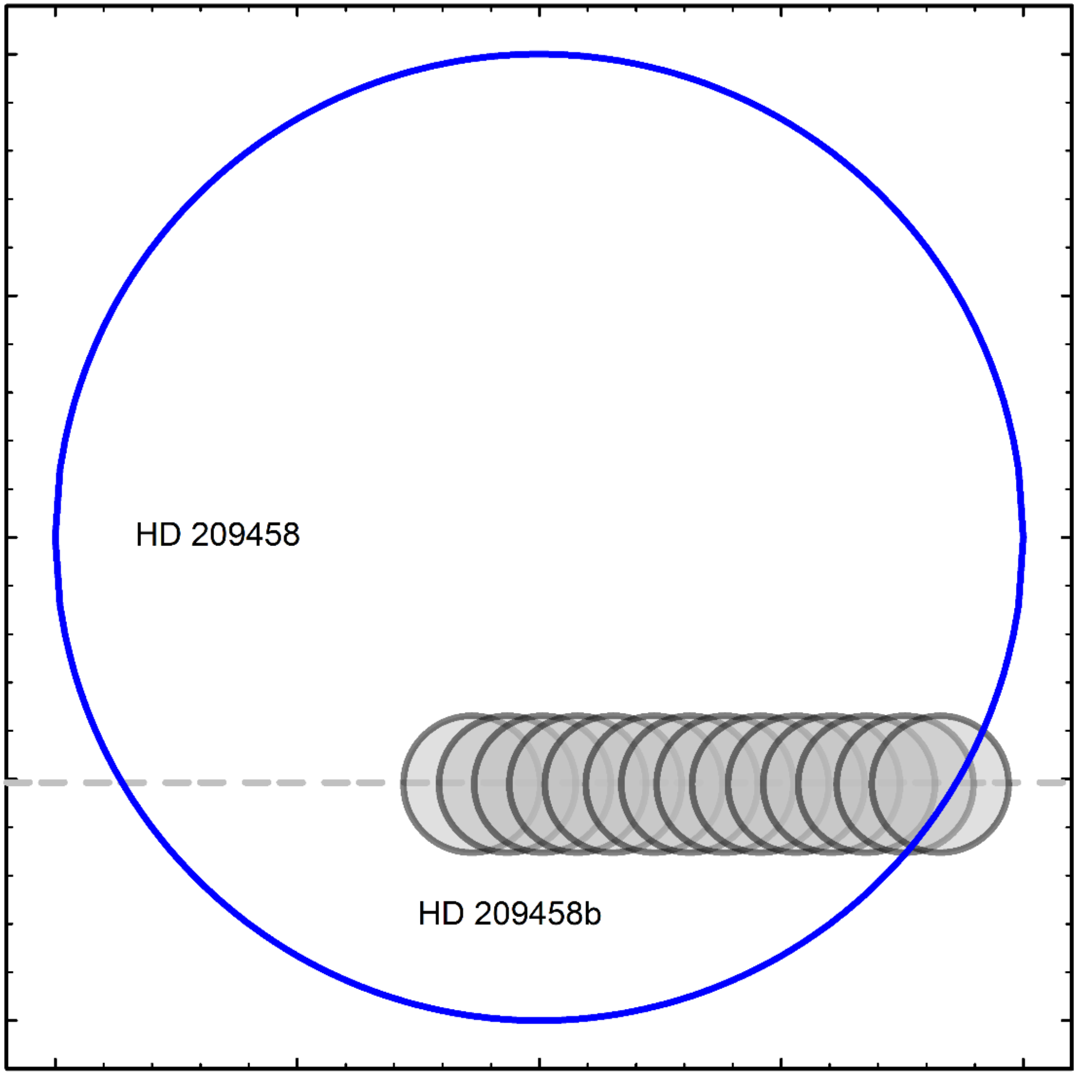
Exoplanet transit geometry



Planet size and positions during an observing night

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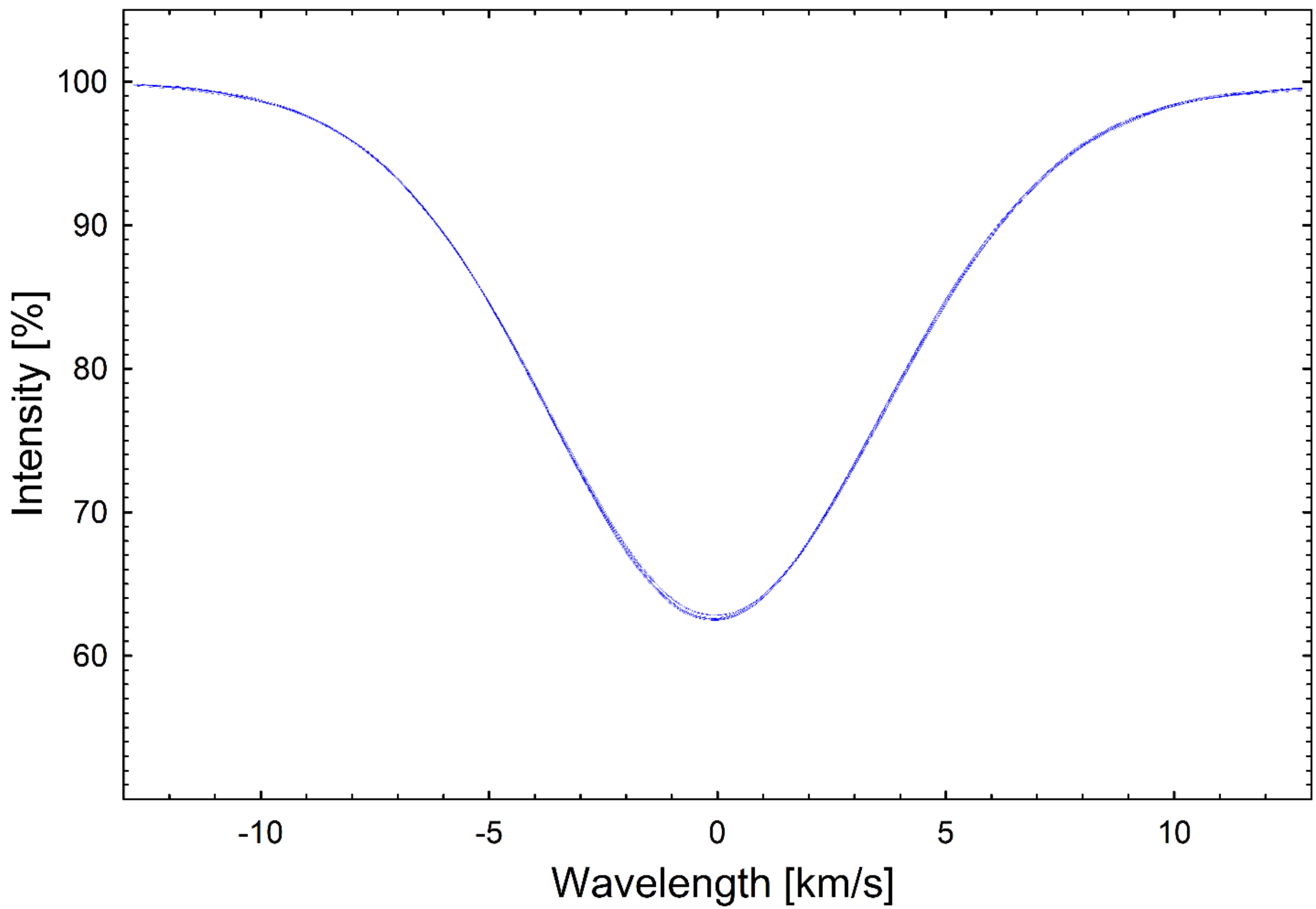
Observed changes of an Fe I line during transit



Profiles (26-line averages) at 14 successive positions during the exoplanet transit; photometric S/N ~2,500

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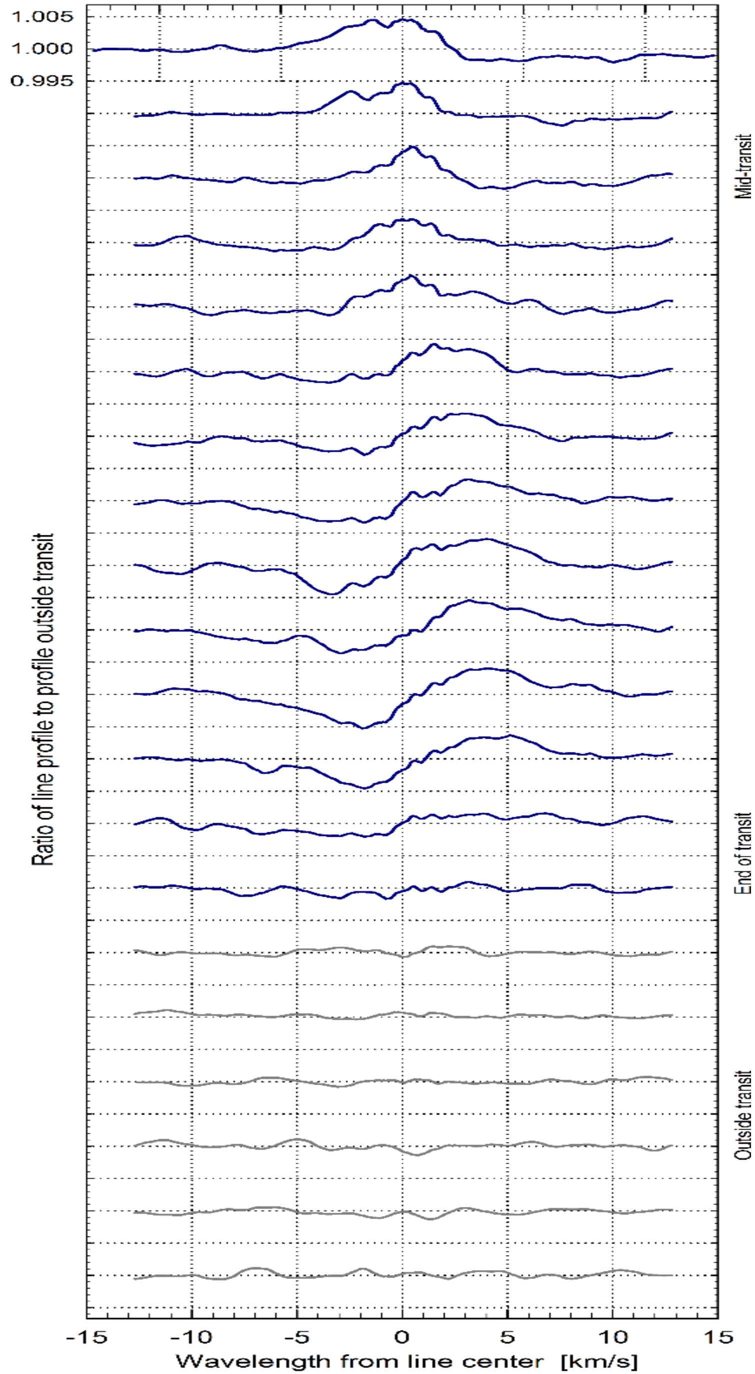

Observed changes of an Fe I line during transit

Ratios of observed line profiles to that from outside transit.

Sequence starts with the planet already in transit.

Time increases from top down.

Profiles are 26-line averages of Fe I lines in HD 209458.

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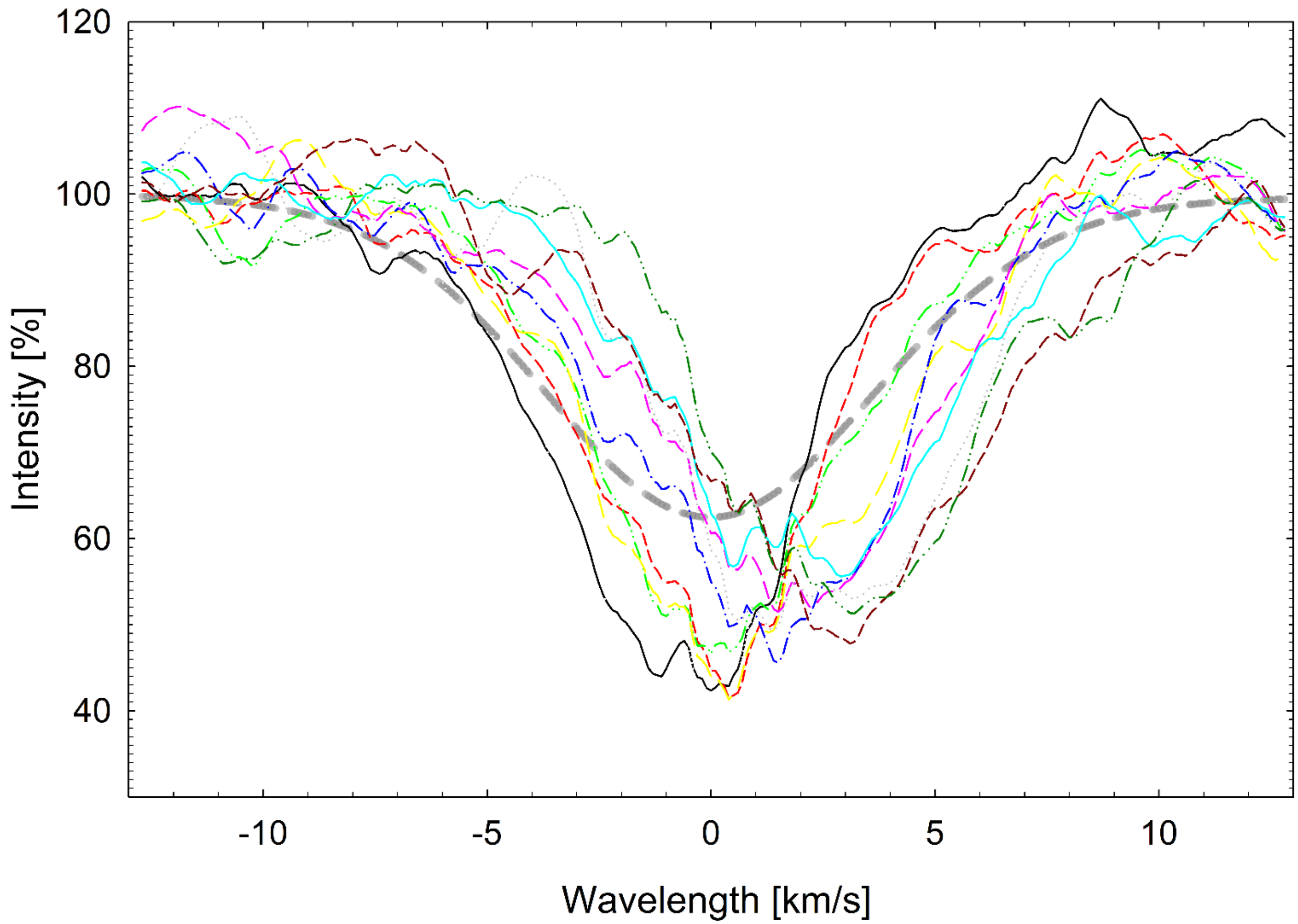
Retrieved line profiles across HD 209458



Reconstructed profiles for an Fe I line at 11 locations across the disk of HD 209458.

Spatially resolved lines are not rotational broadened and are deeper than the disk average outside transit (dashed gray).

During transit, the profiles shift in wavelength, illustrating stellar rotation and prograde orbital motion of the exoplanet.

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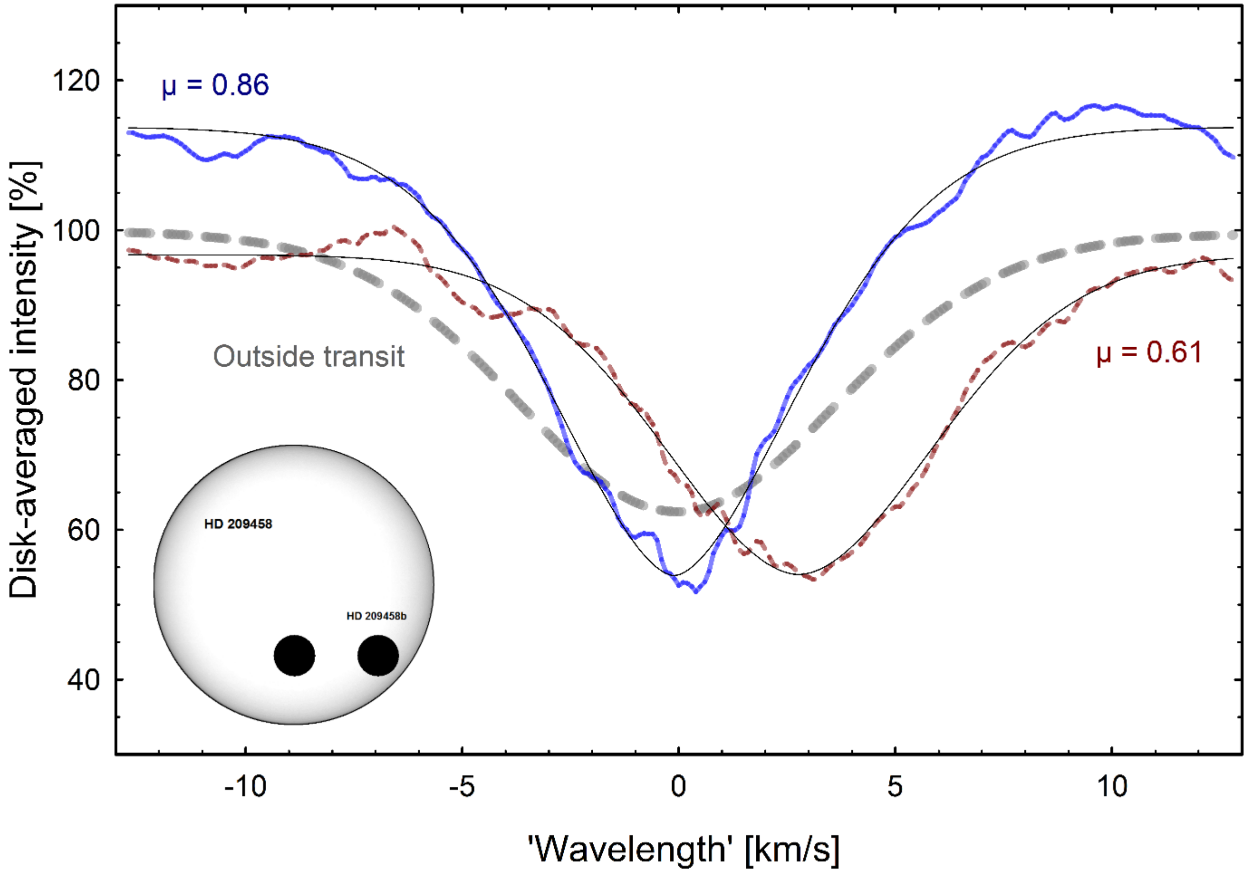
Retrieved line profiles across HD 209458



Solid blue: near disk center, dashed brown: closer to limb.

Spatially resolved lines are not rotationally broadened and are deeper than the disk average.

Wavelength shift during transit illustrates stellar rotation and prograde orbital motion of the exoplanet.

Planet size and positions on the stellar disk are to scale.

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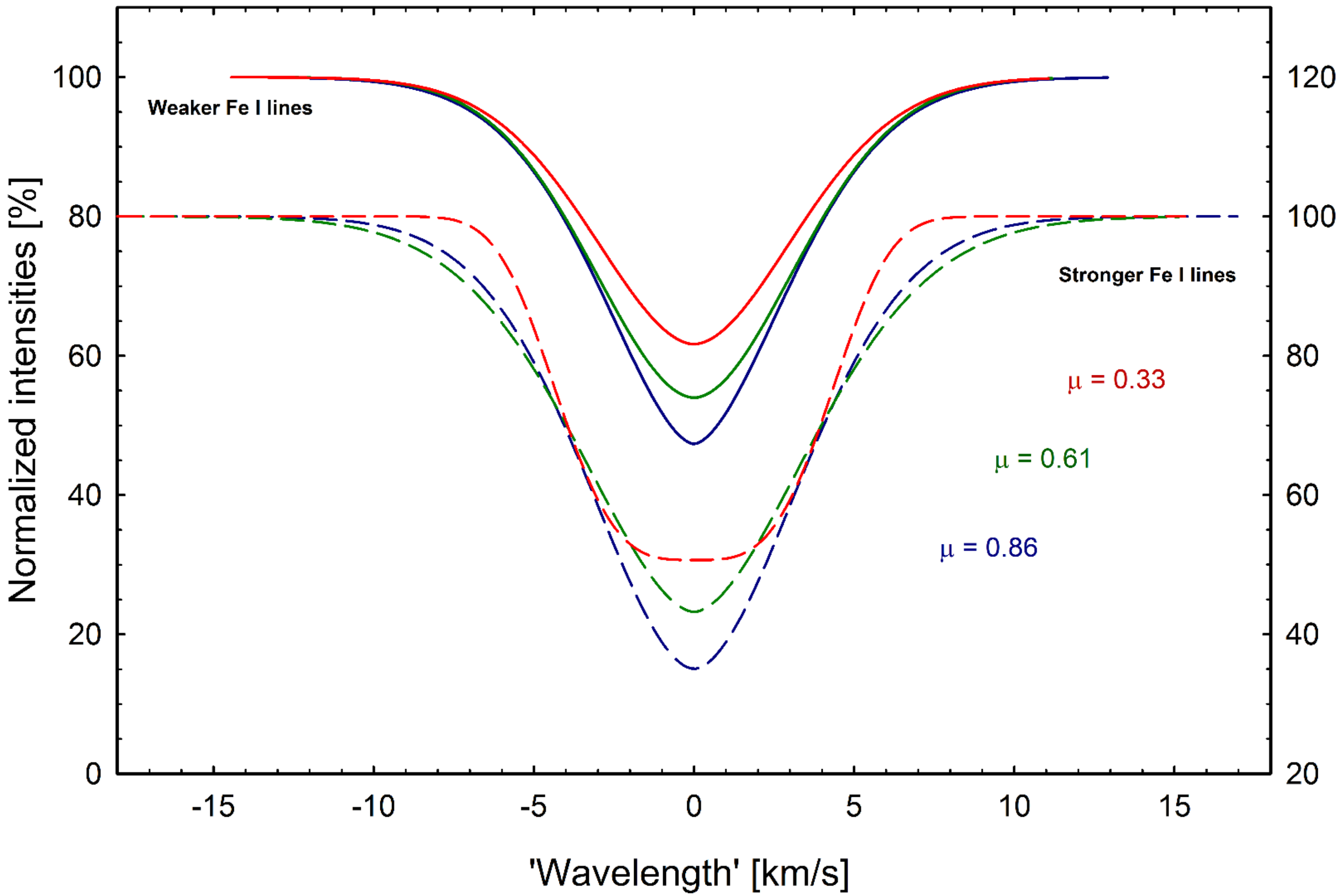
Stronger & weaker Fe I lines in HD 209458



Spectral lines become broader, shallower, and weaker from stellar disk center toward the limb

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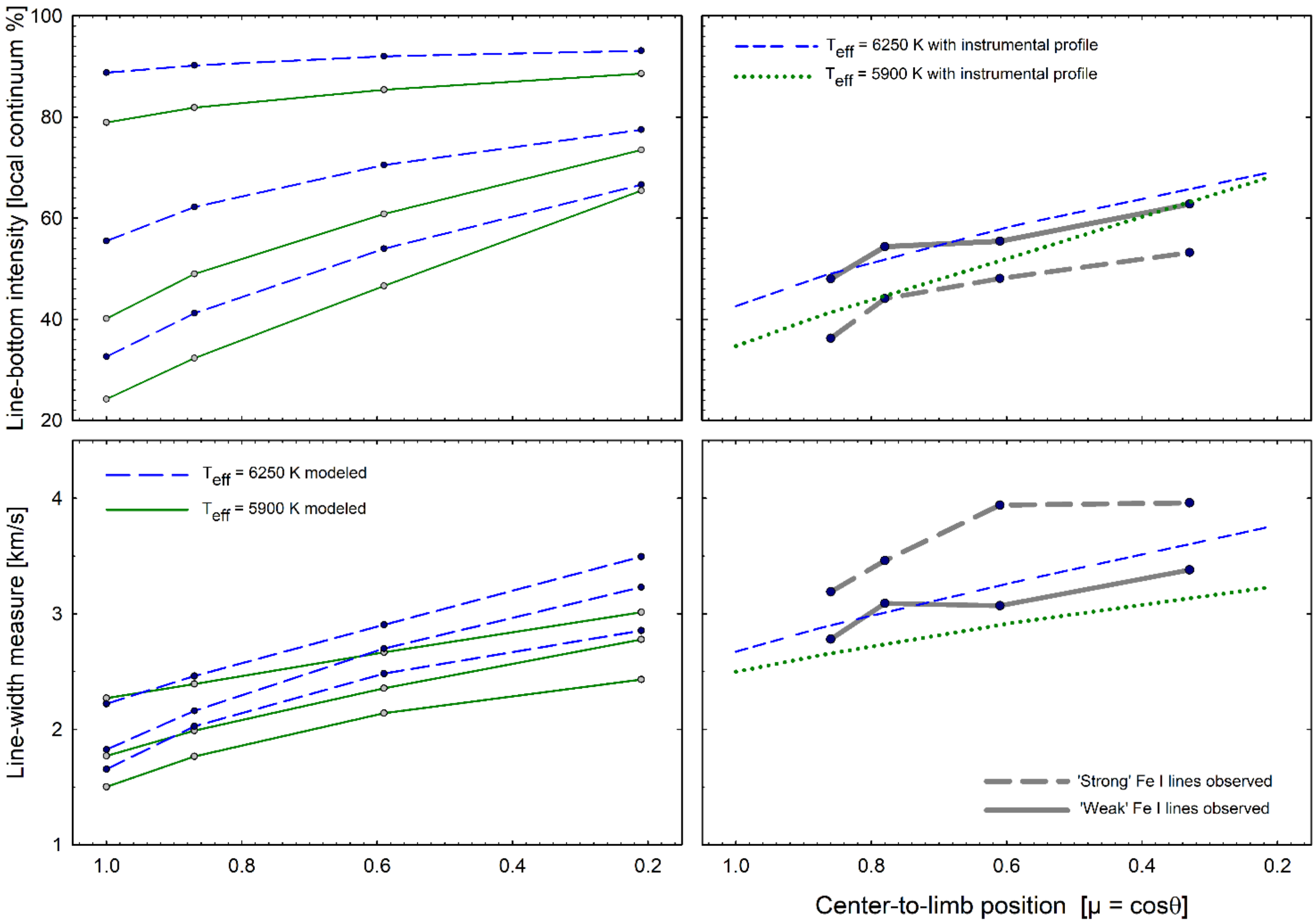
Comparing Fe I lines to 3-D models



Observed and modeled line-depths and widths (CO^{5}BOLD models with parameters bracketing those of HD 209458).

From disk center towards the limb, lines are predicted to become shallower and broader, consistent with observations.

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Spatially resolved spectroscopy across stellar surfaces. II. High-resolution spectra across HD 209458 (G0 V)
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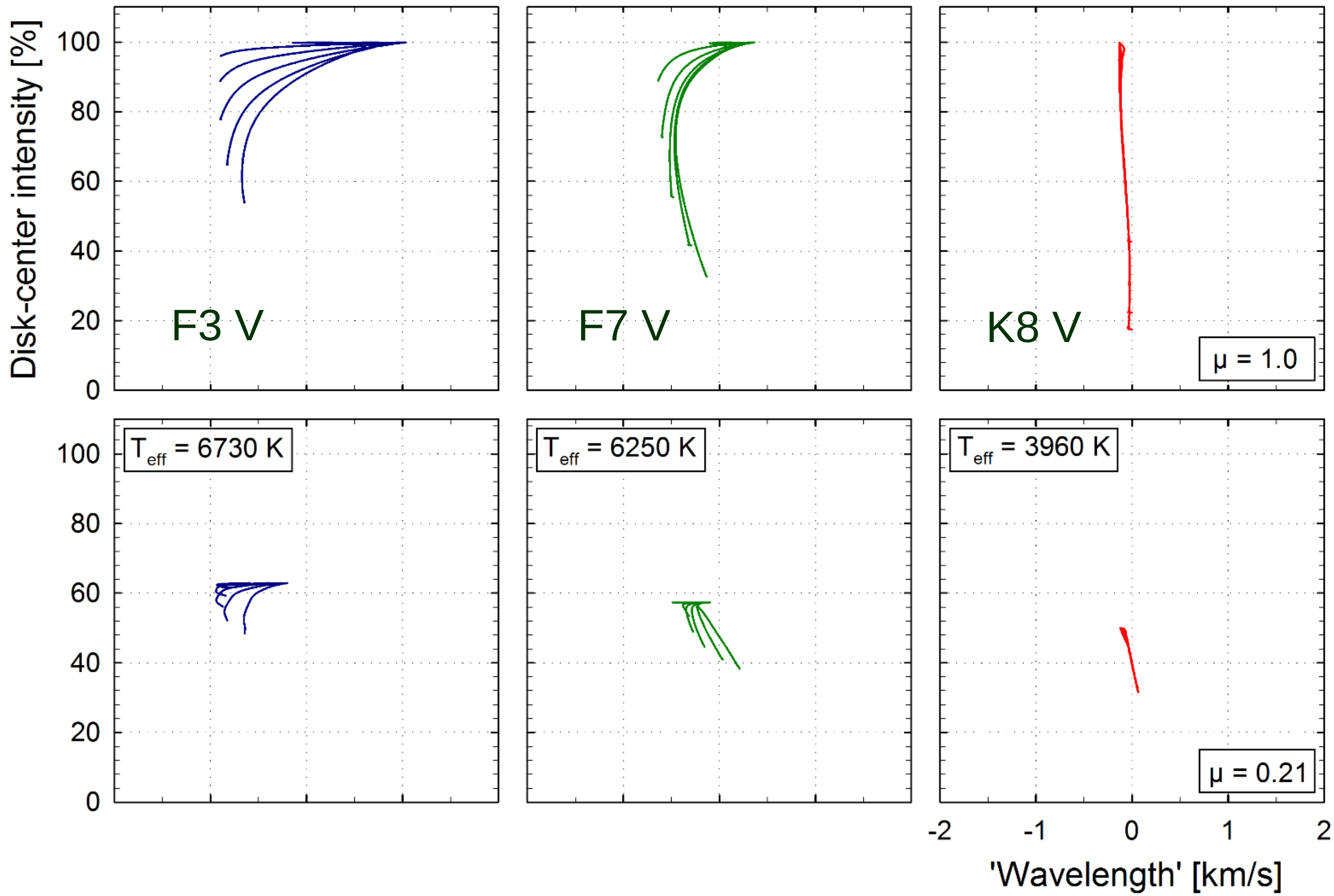
Find a 'true' Earth-analog?

Induced stellar V_{rad} ~10 cm/s

Transit depth ~10^{-4}

Calibrate stellar microvariability?

Stellar surface granulation varies among stars



Modeled bisectors show spectral line asymmetries for stars hotter and cooler than the Sun.

Top: Lines of different strength at stellar disk centers; Bottom: Near the limb.

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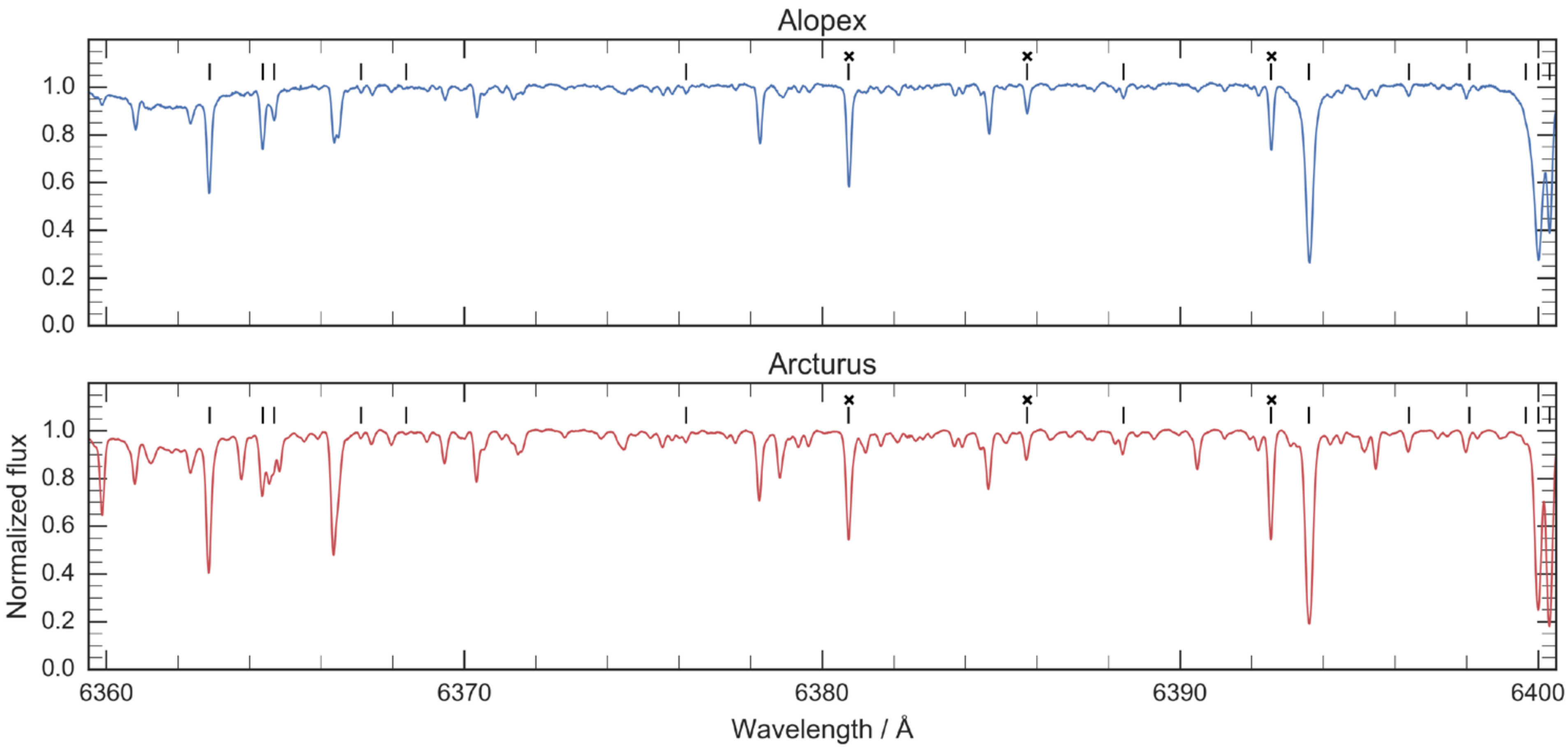
A cooler star with a quieter surface:

HD189733A (K1 V)

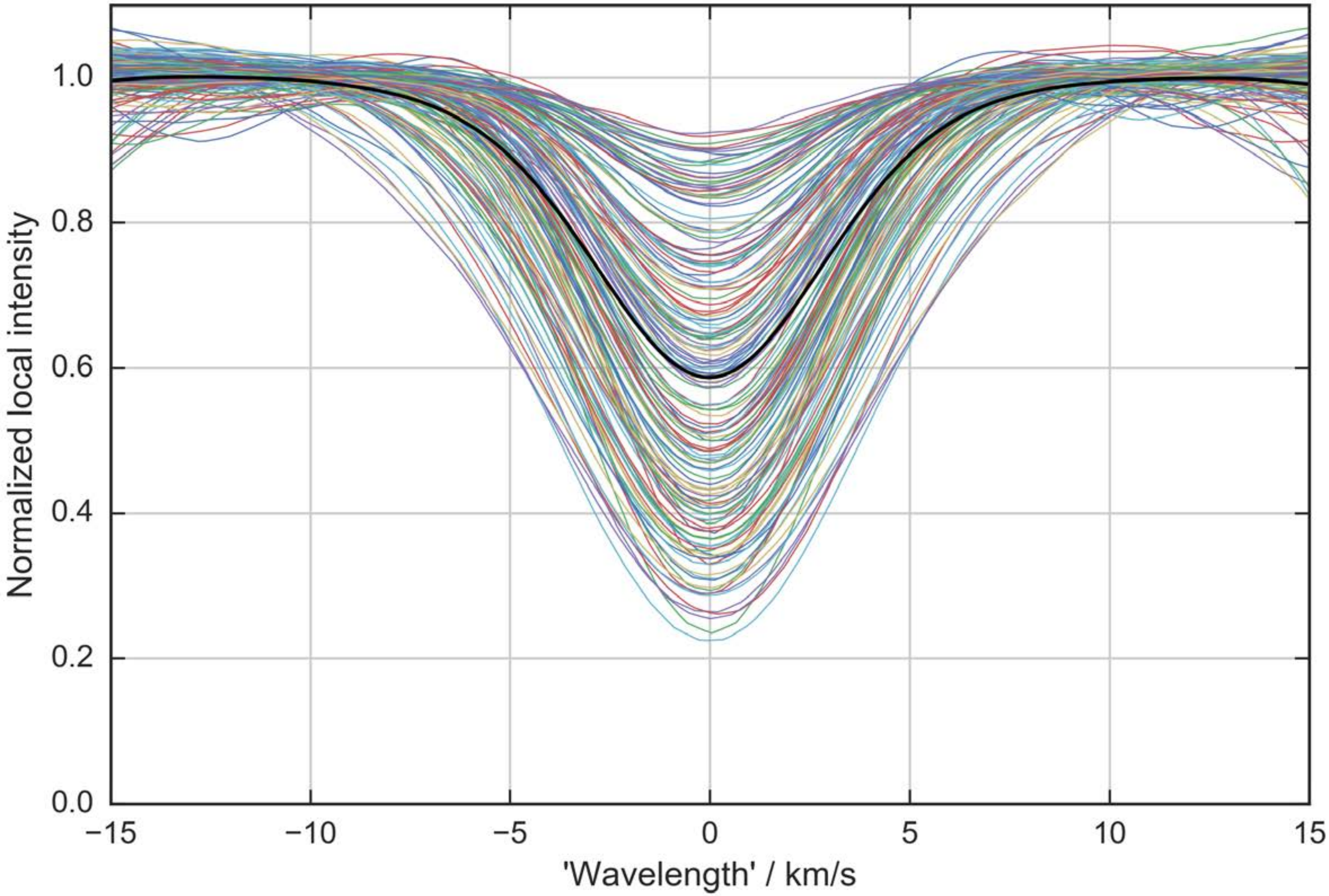
Spectrum of HD189733A (K1 V)



Spectrum of HD189733A ('Alopex'); K1 V at ~4800 K resembles that of the well-studied giant Arcturus (K1 III), ~4300 K

D.Dravins, M.Gustavsson, H.-G.Ludwig:
Spatially resolved spectroscopy across stellar surfaces. III. High-resolution spectra across HD 189733A (K1 V)
Astron.Astrophys., in preparation

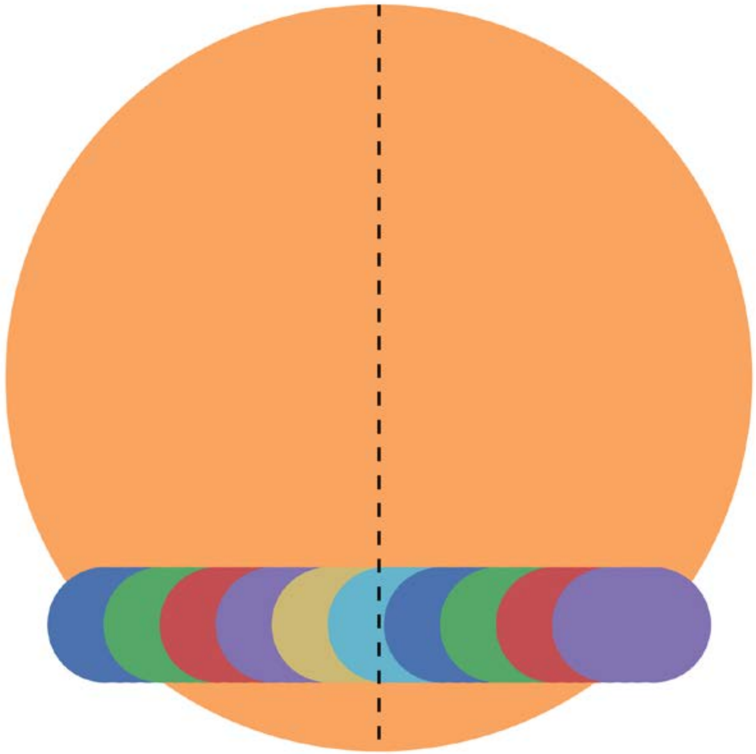
Fe I lines in HD189733A (K1 V)

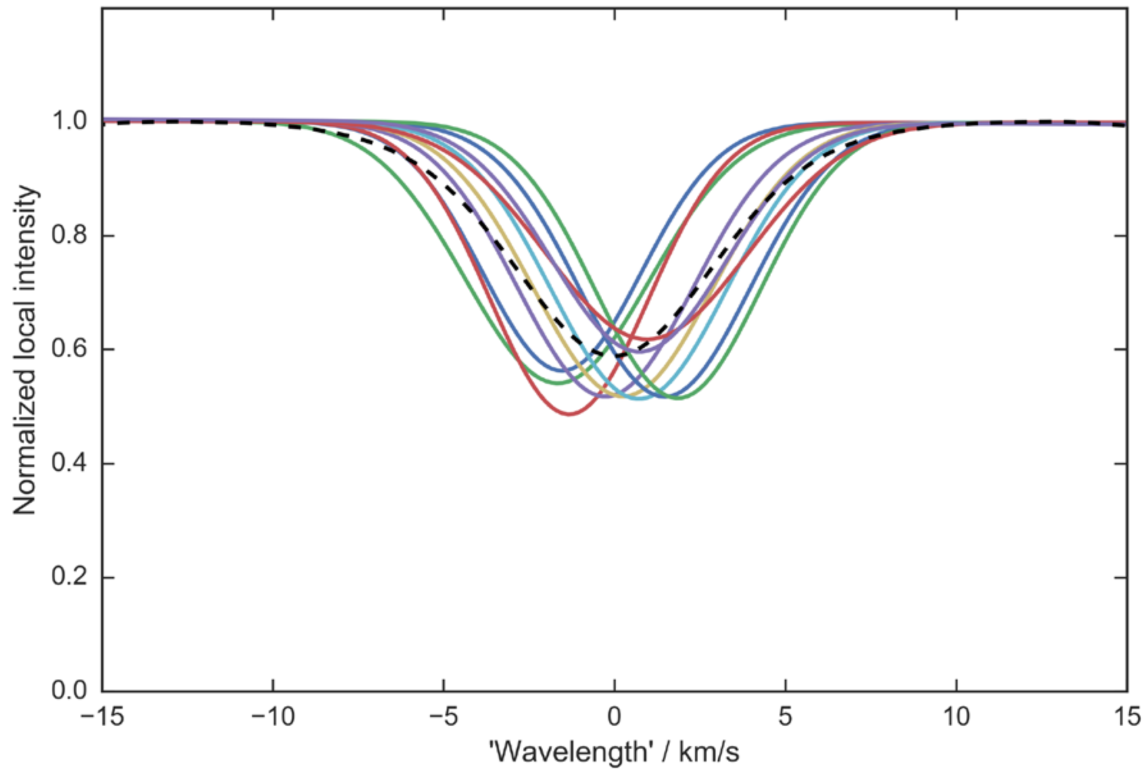


Averaging 158 Fe I lines over many HARPS exposures produces a representative profile (S/N ~9 000)

D.Dravins, M.Gustavsson, H.-G.Ludwig:
Spatially resolved spectroscopy across stellar surfaces. III. High-resolution spectra across HD 189733A (K1 V)
Astron.Astrophys., in preparation

Reconstructed profiles across HD189733A





Left: Exoplanet transit geometry to scale

Reconstructed (and curve-fitted) Fe I line profiles at different positions across the disk of HD 189733A.

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Astron.Astrophys., in preparation

Stellar Spectroscopy during Exoplanet Transits

* Now: Marginally feasible with, UVES @ VLT, HARPS

* Immediate future: PEPSI @ LBT

* Near future: ESPRESSO @ VLT

* Future: HIRES @ ELT ?

Anytime soon: More exoplanets transiting bright stars ☺

THE END