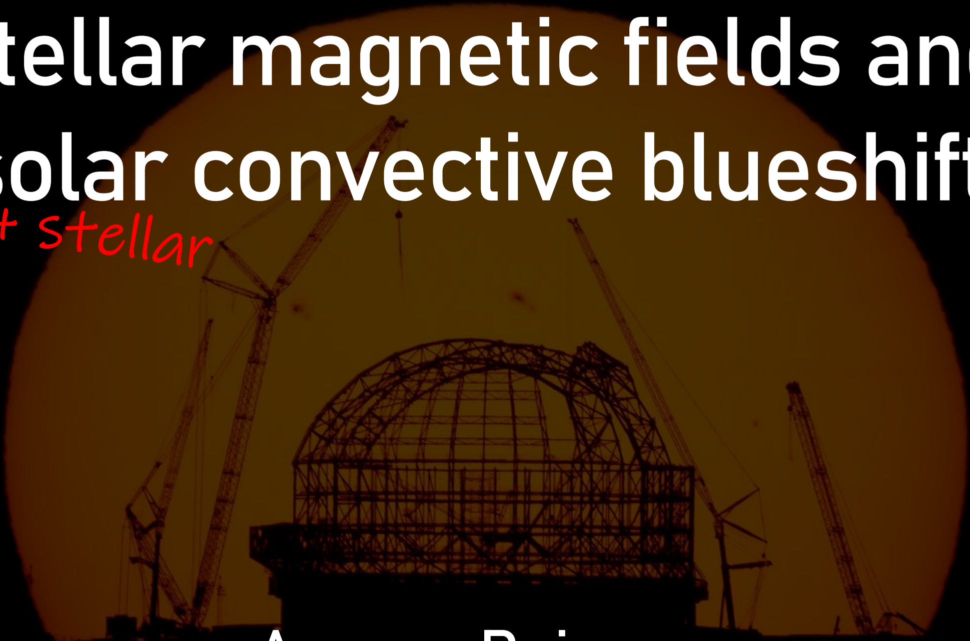
Empirical constraints on convection:

Stellar magnetic fields and solar convective blueshift

+ stellar



Ansgar Reiners

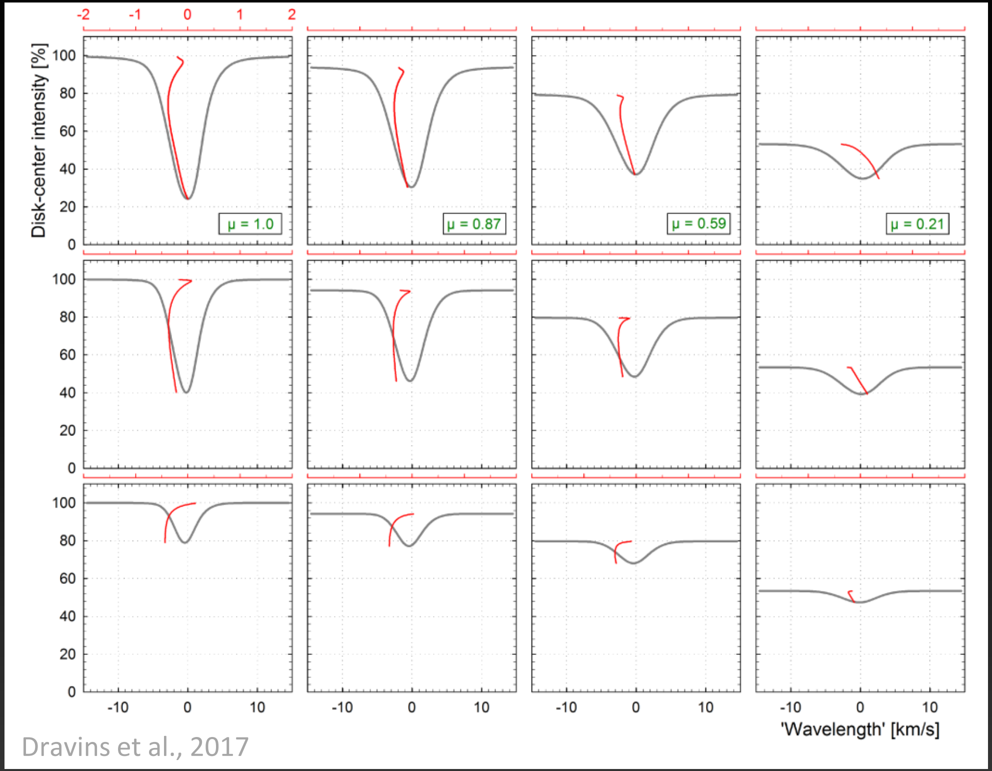
Georg-August Universität Göttingen

INSTITUT FÜR
ASTROPHYSIK &
GEOPHYSIK

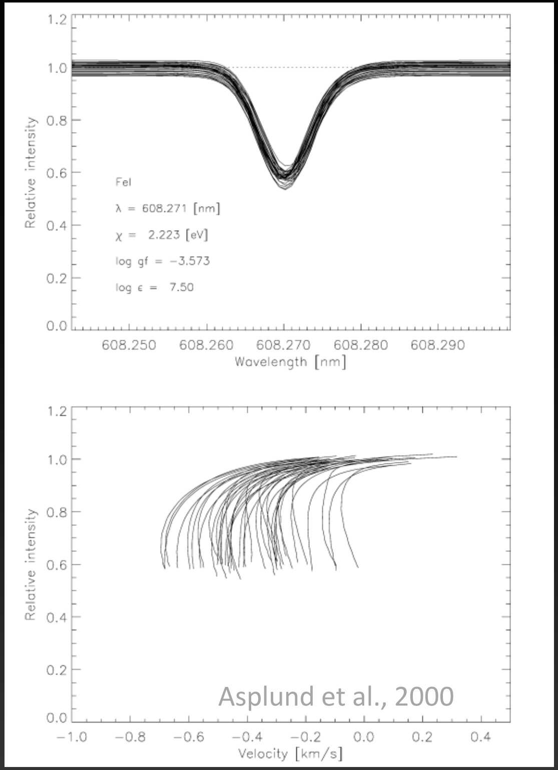
Stellar Convection: Modelling, Theory and Observations – Aug 29

Spectral lines vary with wavelength, time, and limb position

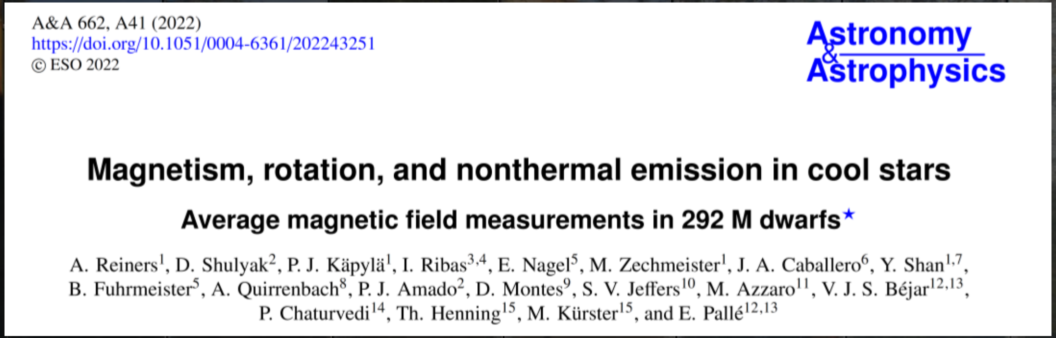
Plots show models that desperately want to be compared to observations!



three lines at different limb positions



one line variable in time



A&A 662, A41 (2022)
https://doi.org/10.1051/0004-6361/202243251
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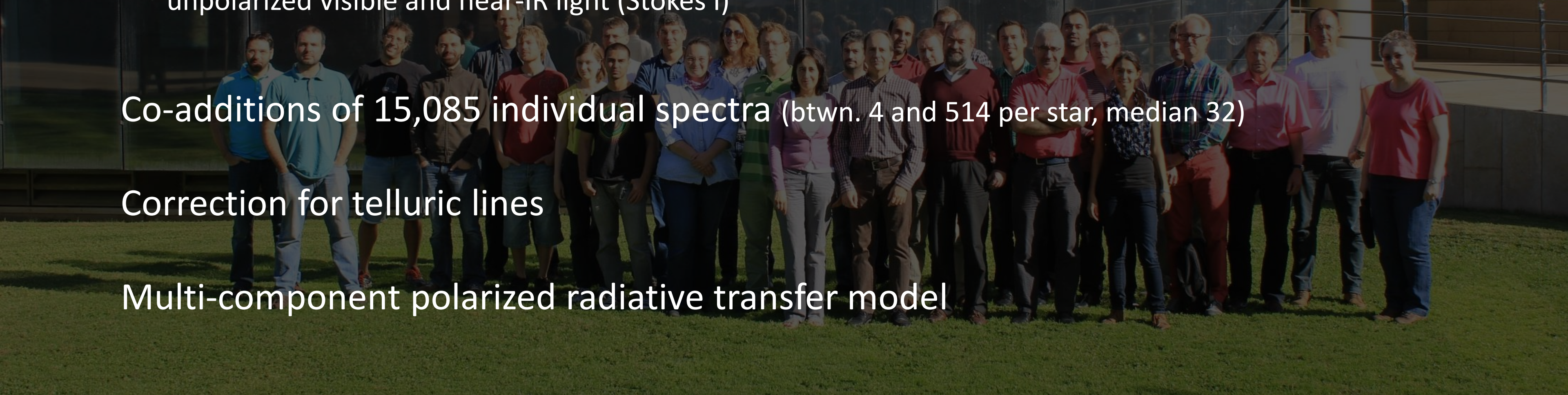
Astronomy & Astrophysics

Magnetism, rotation, and nonthermal emission in cool stars

Average magnetic field measurements in 292 M dwarfs*

A. Reiners[1], D. Shulyak[2], P. J. Käpylä[1], I. Ribas[3,4], E. Nagel[5], M. Zechmeister[1], J. A. Caballero[6], Y. Shan[1,7], B. Fuhrmeister[5], A. Quirrenbach[8], P. J. Amado[2], D. Montes[9], S. V. Jeffers[10], M. Azzaro[11], V. J. S. Béjar[12,13], P. Chaturvedi[14], Th. Henning[15], M. Kürster[15], and E. Pallé[12,13]

unpolarized visible and near-IR light (Stokes I)

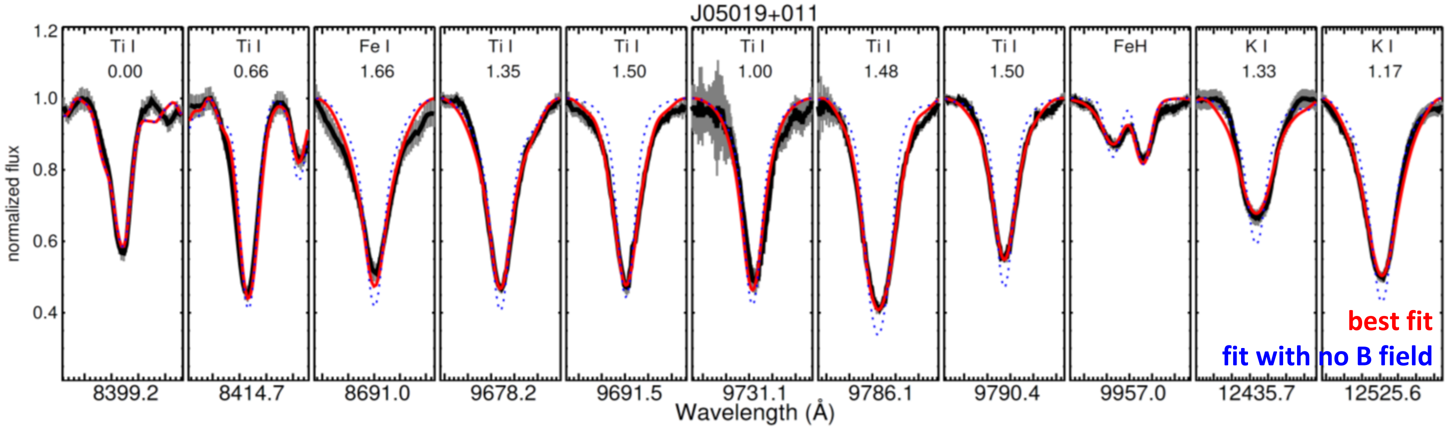


Co-additions of 15,085 individual spectra (btwn. 4 and 514 per star, median 32)

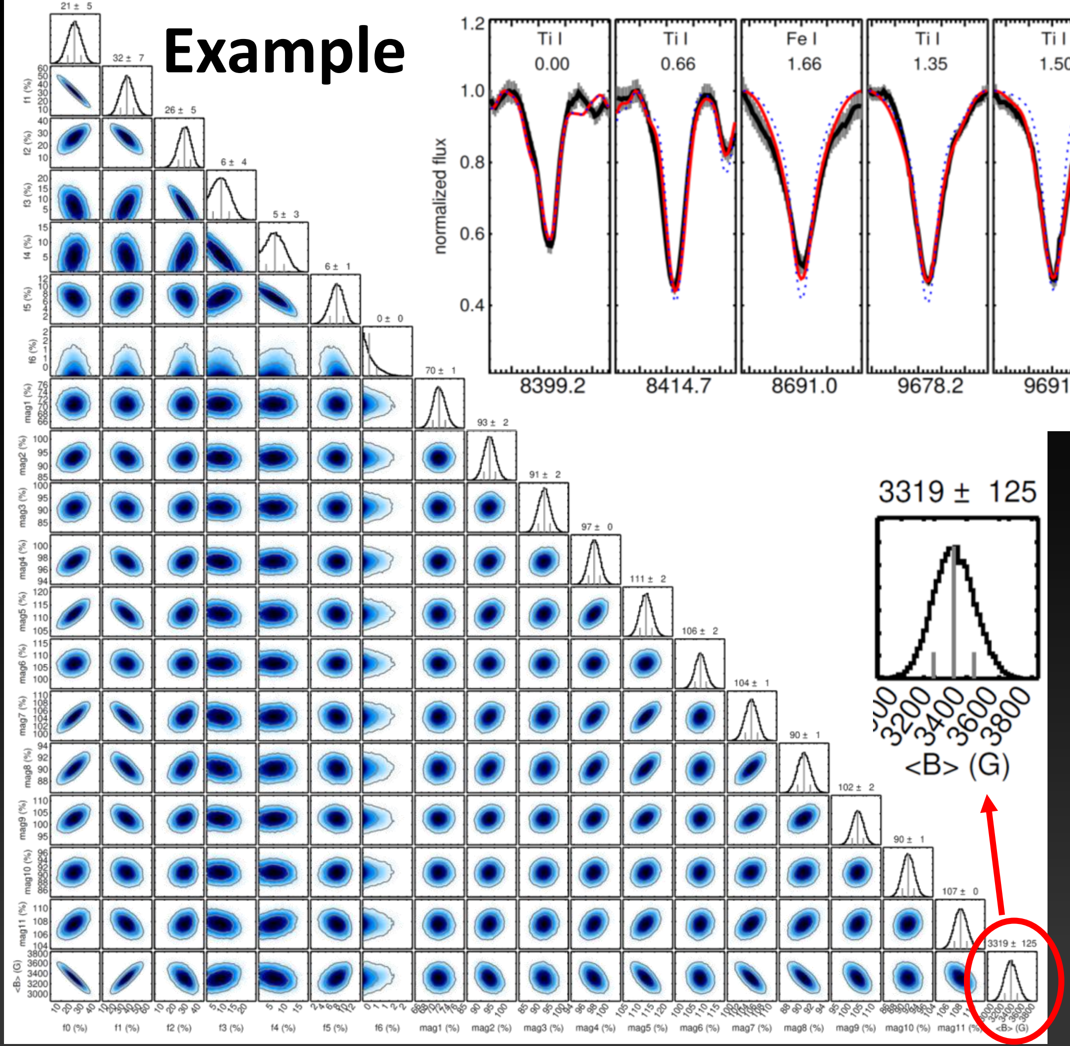
Correction for telluric lines

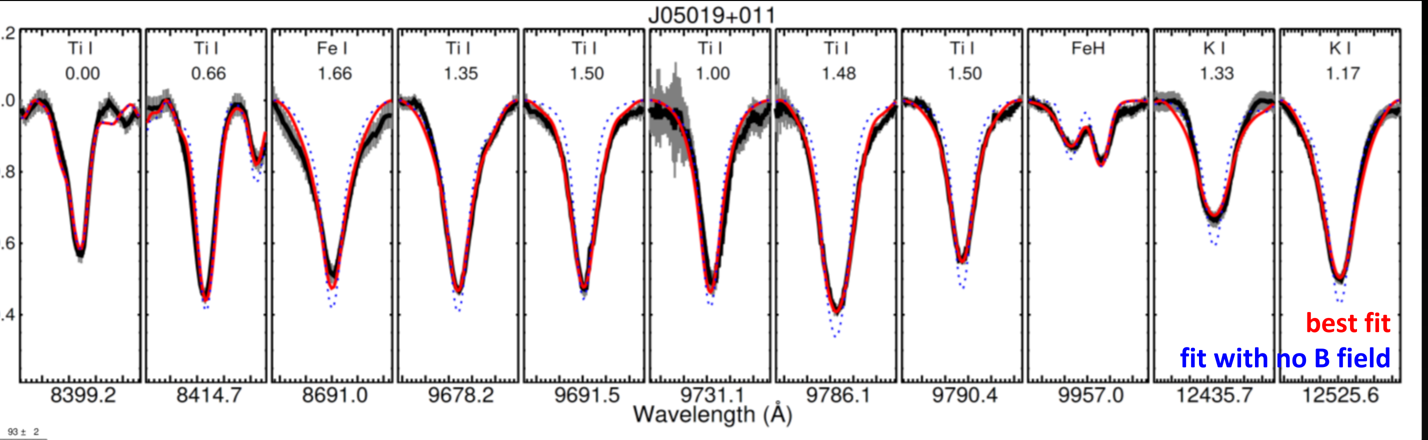
Multi-component polarized radiative transfer model

Example

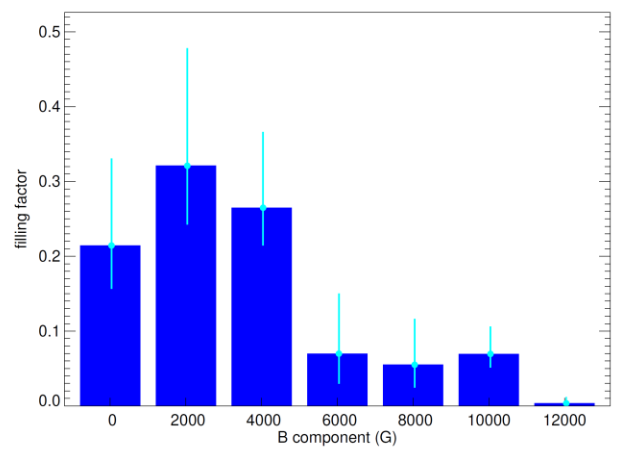

J05019+011
normalized flux
1.2
1.0
0.8
0.6
0.4
Ti I 0.00
Ti I 0.66
Fe I 1.66
Ti I 1.35
Ti I 1.50
Ti I 1.00
Ti I 1.48
Ti I 1.50
FeH
K I 1.33
K I 1.17
8399.2
8414.7
8691.0
9678.2
9691.5
9731.1
9786.1
9790.4
9957.0
12435.7
12525.6
Wavelength (Å)
best fit
fit with no B field

Example

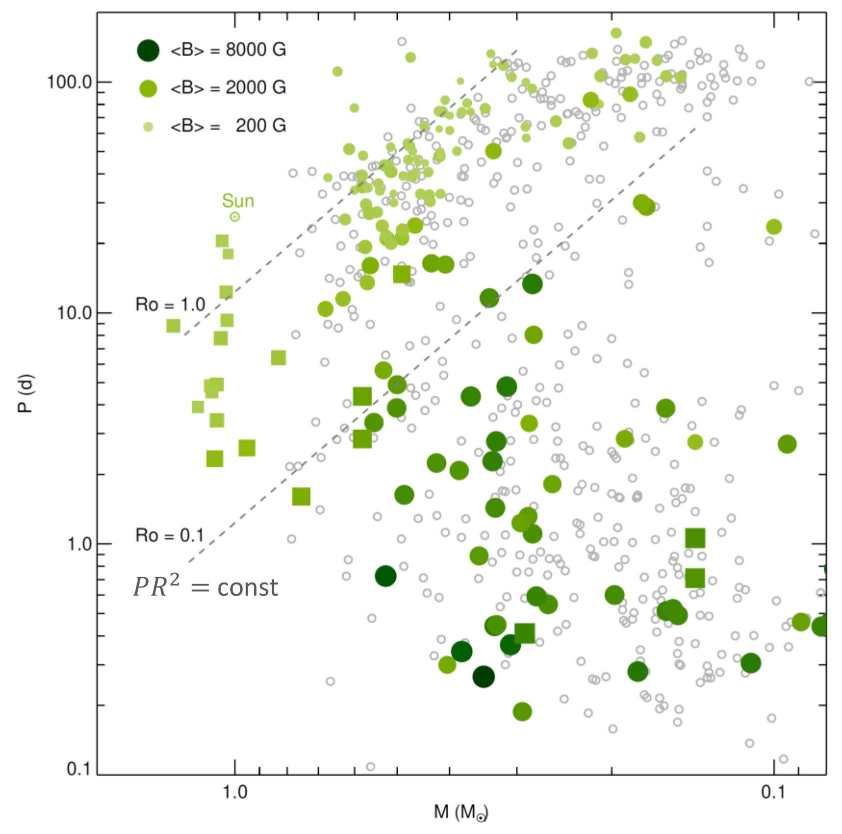




Best fit
field components:



Field measurements cover a large area in the mass-period diagram

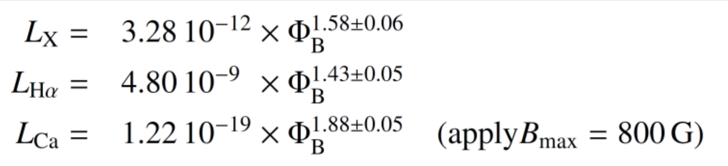


○ – no B fields
(rotation from Newton et al., 2017)

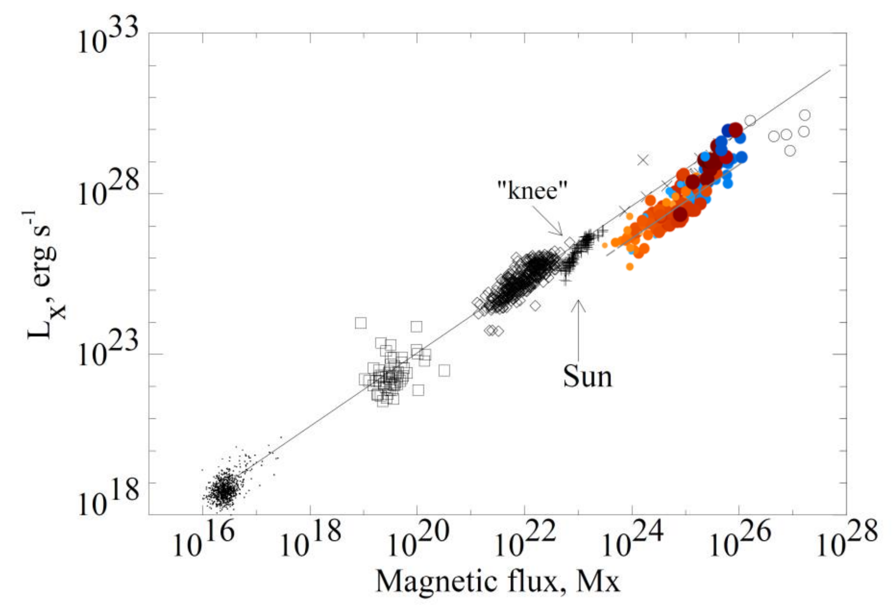
● – our results

■ – literature

We see a relation btw. non-thermal heating and ϕ_B …but this may partly be due to $R^2 \propto R^2$



$$L_X = 3.28\,10^{-12} \times \Phi_B^{1.58\pm0.06}$$
$$L_{H\alpha} = 4.80\,10^{-9} \times \Phi_B^{1.43\pm0.05}$$
$$L_{Ca} = 1.22\,10^{-19} \times \Phi_B^{1.88\pm0.05} \quad (\text{apply} B_{max} = 800\,\text{G})$$

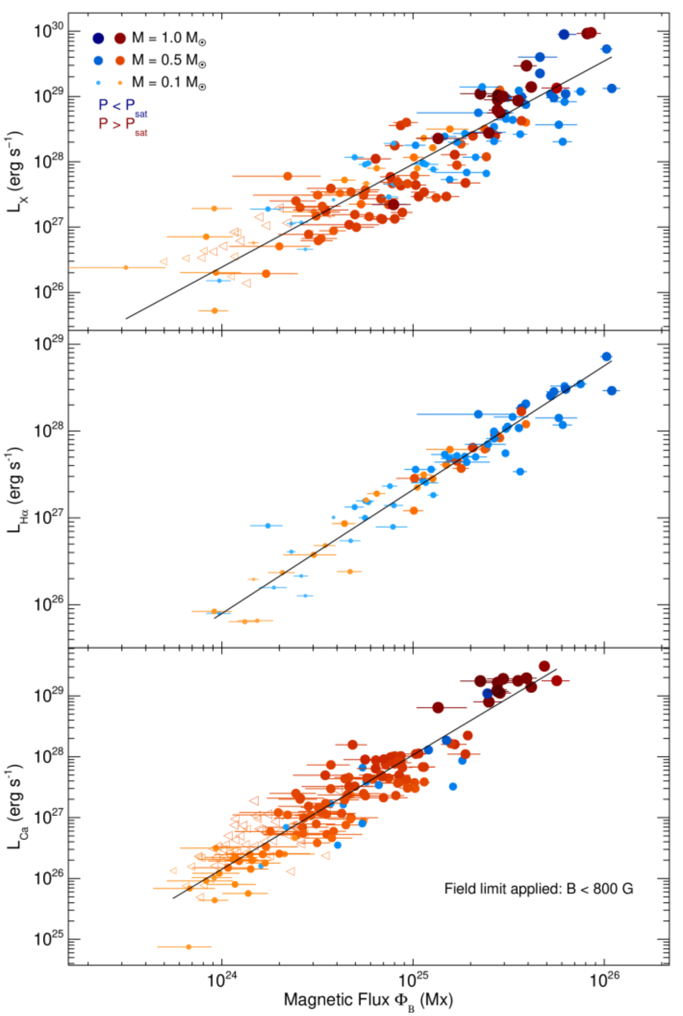


Pevtsov et al., 2003

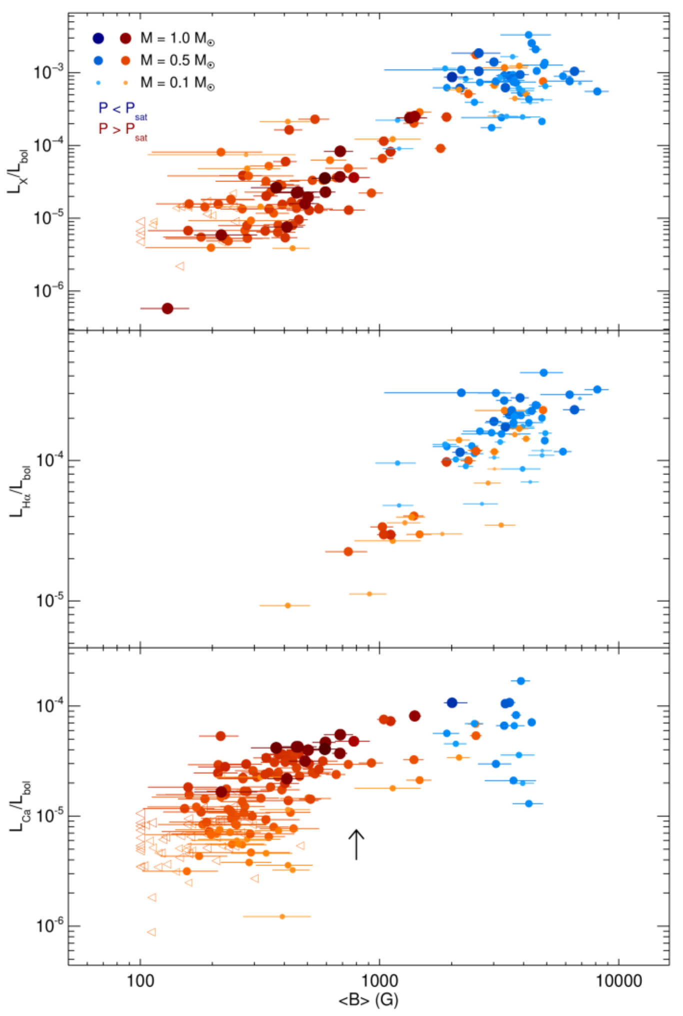
X-ray

Hα

Ca H&K



In our sample, we observe a relation between non-th. heating and <*B*>



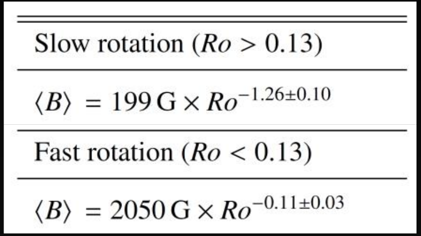
X-ray

Hα

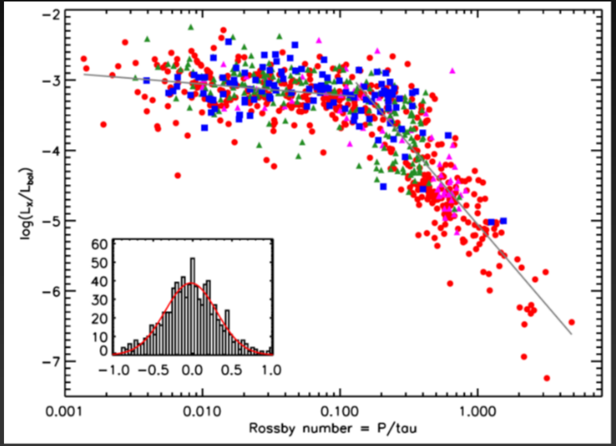
Ca H&K

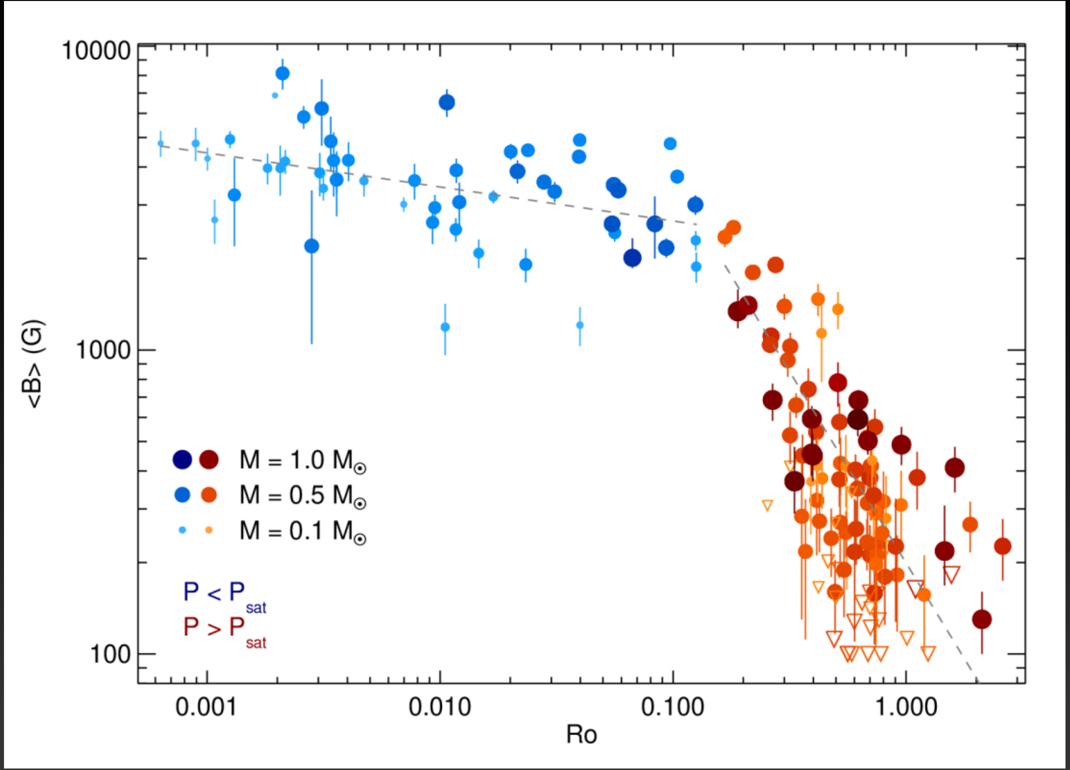
shows some sort of saturation

The average field-rotation relation is very similar to the „rotation-activity relation“ (e.g., X-rays)

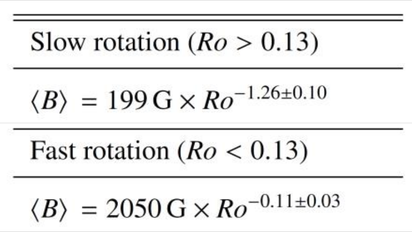


Slow rotation ($Ro > 0.13$)	
$\langle B \rangle$	$= 199\,\mathrm{G} \times Ro^{-1.26\pm0.10}$
Fast rotation ($Ro < 0.13$)	
$\langle B \rangle$	$= 2050\,\mathrm{G} \times Ro^{-0.11\pm0.03}$

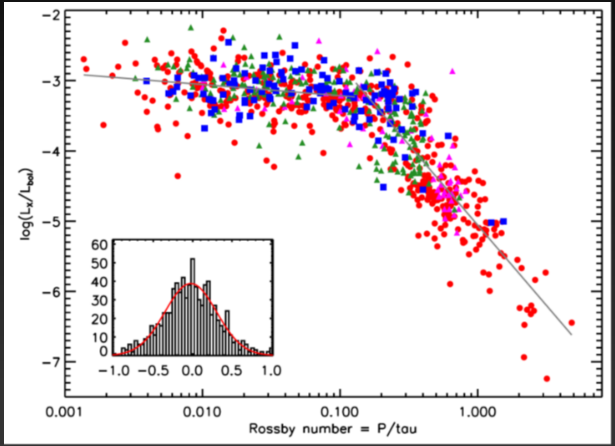


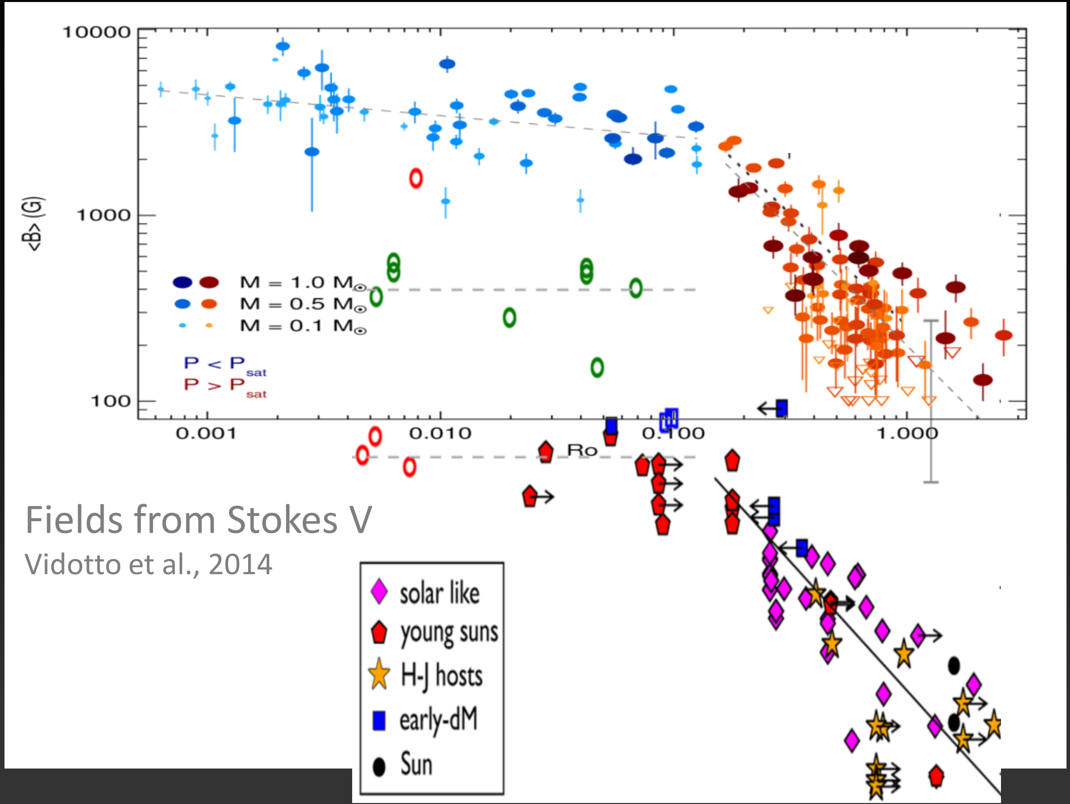


The average field-rotation relation is very similar to the „rotation-activity relation“ (e.g., X-rays)



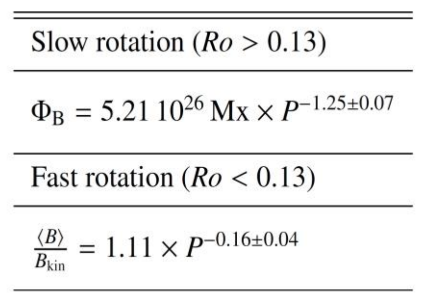
Slow rotation ($Ro > 0.13$)
$\langle B \rangle = 199\,\mathrm{G} \times Ro^{-1.26\pm0.10}$
Fast rotation ($Ro < 0.13$)
$\langle B \rangle = 2050\,\mathrm{G} \times Ro^{-0.11\pm0.03}$



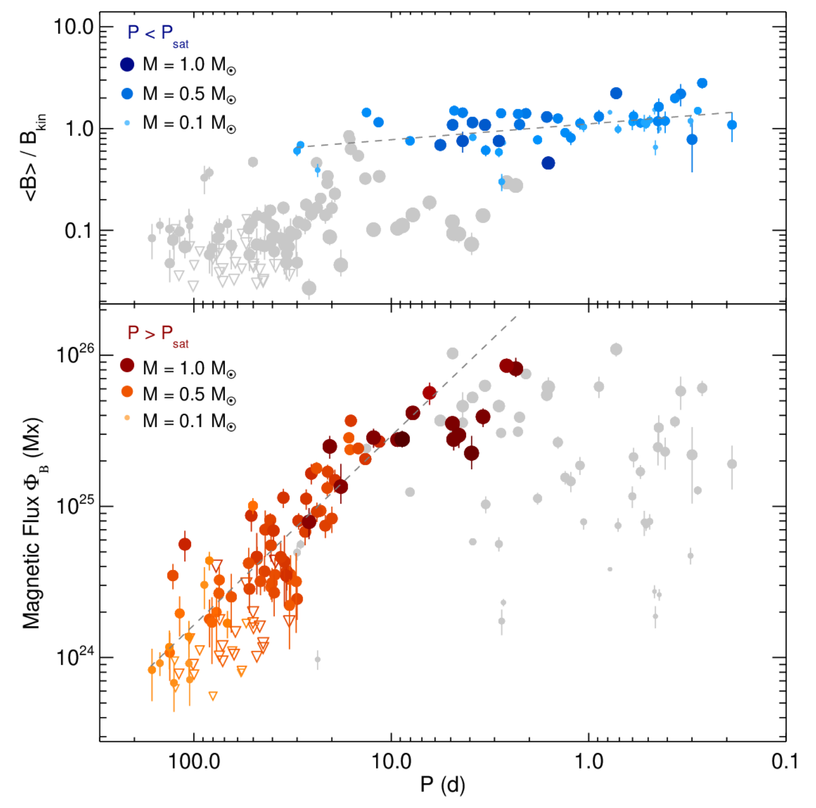


Fields from Stokes V
Vidotto et al., 2014

Magnetic flux grows with rotation, and field strength saturates at B_{kin} (convection)



Slow rotation ($Ro > 0.13$)
$\Phi_B = 5.21\,10^{26}\,\mathrm{Mx} \times P^{-1.25\pm0.07}$
Fast rotation ($Ro < 0.13$)
$\frac{\langle B\rangle}{B_{kin}} = 1.11 \times P^{-0.16\pm0.04}$



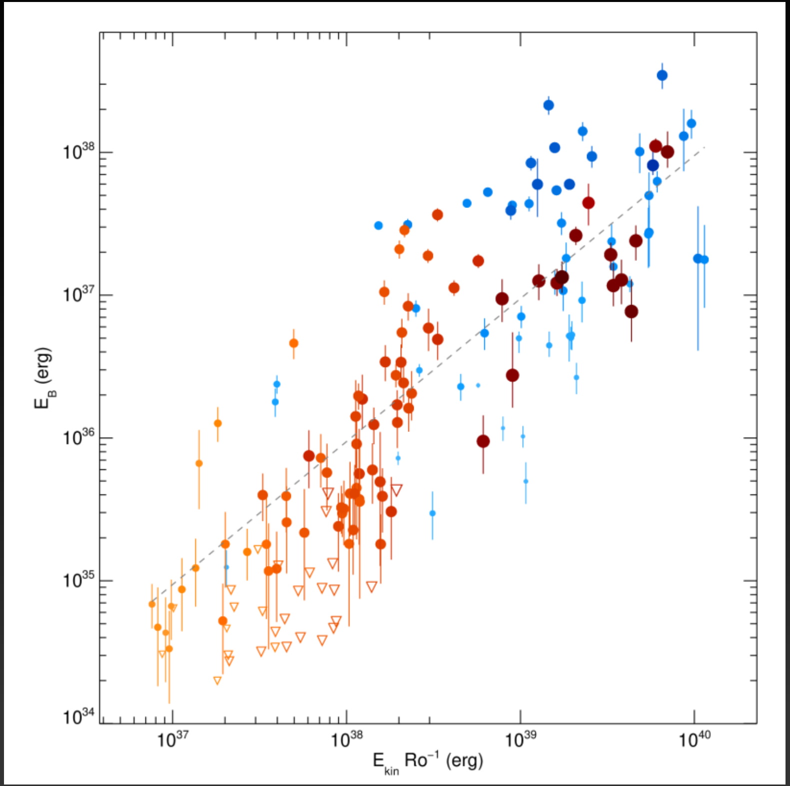
This is analog to B ∝ Ro because

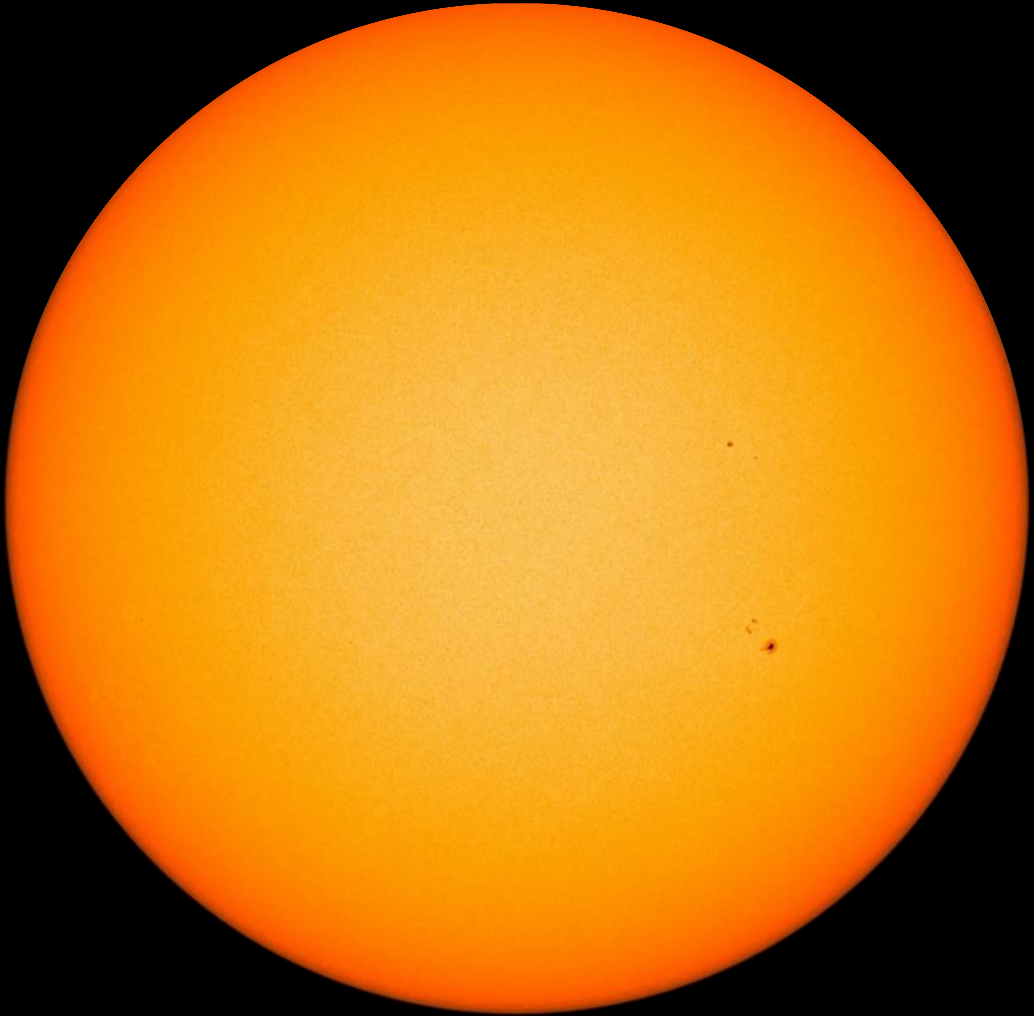
$$\tau \propto \frac{1}{\sqrt{L_{bol}}}$$

Balance btw. Coriolis, buoyancy, and Lorentz forces may be expected in fast rotators (blue)

Force balance predicts:

$E_B \propto E_{kin}/Ro$





Solar Observations @ IAG

Institut für
Astrophysik &
Geophysik

50cm Siderostat

Fourier Transform Spectrometer (FTS)

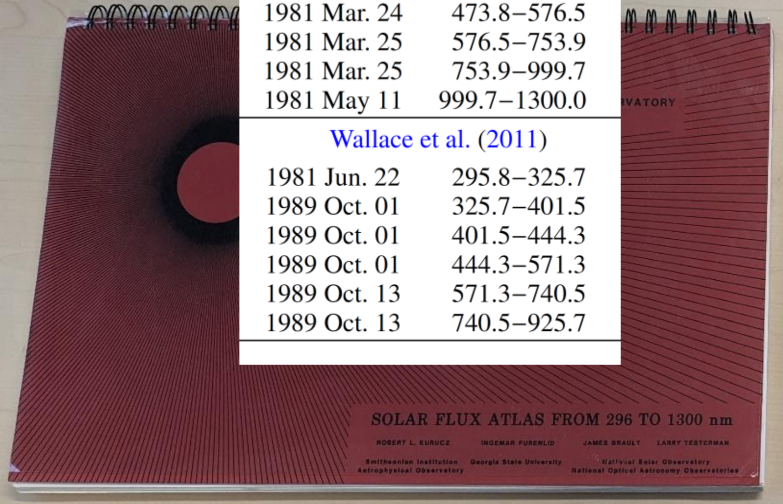
Wavelength coverage
(each simultaneous):
VIS: 420 – 1000 nm
NIR: 1000 – 2300 nm

Resolution ~ 10^6

Standard FTS solar flux atlases (disc-integrated)

McMath-Pierce (Kitt Peak)

Date	λ-range [nm]
Kurucz et al. (1984)	
1981 Jun. 22	296.0–329.9
1981 Jun. 21	329.9–378.3
1981 Jun. 22	378.3–402.0
1980 Nov. 23	402.0–473.8
1981 Mar. 24	473.8–576.5
1981 Mar. 25	576.5–753.9
1981 Mar. 25	753.9–999.7
1981 May 11	999.7–1300.0
Wallace et al. (2011)	
1981 Jun. 22	295.8–325.7
1989 Oct. 01	325.7–401.5
1989 Oct. 01	401.5–444.3
1989 Oct. 01	444.3–571.3
1989 Oct. 13	571.3–740.5
1989 Oct. 13	740.5–925.7



SOLAR FLUX ATLAS FROM 296 TO 1300 nm

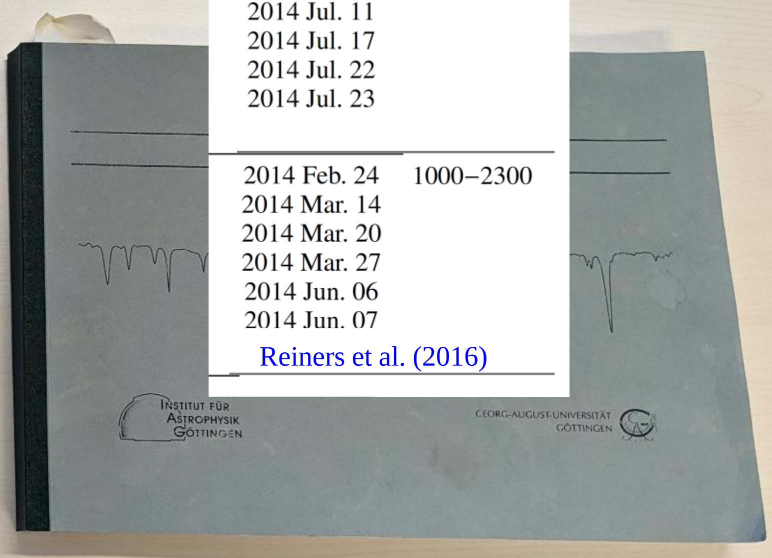
ROBERT L. KURUCZ   INGEMAR FURENLID   JAMES BRAULT   LARRY TESTERMAN

Smithsonian Institution Astrophysical Observatory   Georgia State University   National Solar Observatory National Optical Astronomy Observatories

Göttingen (IAG)

Date	Range [nm]
2014 Mar. 07 2014 Mar. 10 2014 Apr. 16 2014 Apr. 17 2014 Apr. 20 2014 Jul. 11 2014 Jul. 17 2014 Jul. 22 2014 Jul. 23	405–1065
2014 Feb. 24 2014 Mar. 14 2014 Mar. 20 2014 Mar. 27 2014 Jun. 06 2014 Jun. 07	1000–2300

Reiners et al. (2016)



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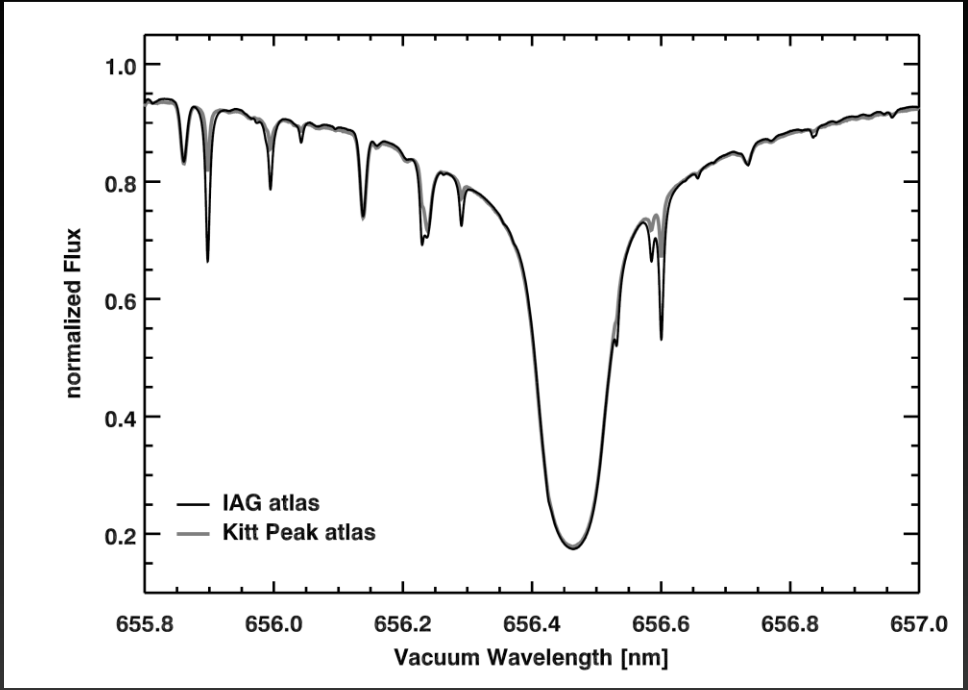
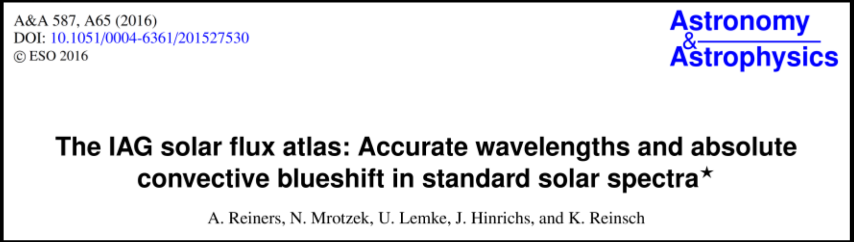
GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

Data from Kitt Peak and IAG match very well



Reiners et al. (2016)

Solar Observations @ IAG


A&A 587, A65 (2016)
DOI: 10.1051/0004-6361/201527530
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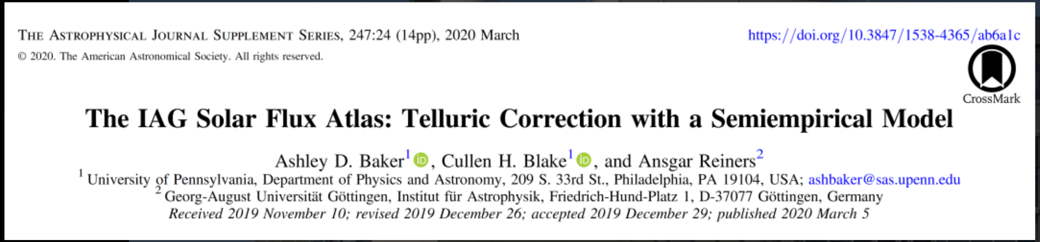
Astronomy & Astrophysics

The IAG solar flux atlas: Accurate wavelengths and absolute convective blueshift in standard solar spectra★

A. Reiners, N. Mrotzek, U. Lemke, J. Hinrichs, and K. Reinsch


The Astrophysical Journal Supplement Series, 247:24 (14pp), 2020 March https://doi.org/10.3847/1538-4365/ab6a1c
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CrossMark

The IAG Solar Flux Atlas: Telluric Correction with a Semiempirical Model

Ashley D. Baker[1], Cullen H. Blake[1], and Ansgar Reiners[2]
[1] University of Pennsylvania, Department of Physics and Astronomy, 209 S. 33rd St., Philadelphia, PA 19104, USA; ashbaker@sas.upenn.edu
[2] Georg-August Universität Göttingen, Institut für Astrophysik, Friedrich-Hund-Platz 1, D-37077 Göttingen, Germany
Received 2019 November 10; revised 2019 December 26; accepted 2019 December 29; published 2020 March 5

https://www.astro.physik.uni-goettingen.de/research/flux_atlas/


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Astronomy & Astrophysics

The IAG spectral atlas of the spatially resolved Sun: Centre-to-limb observations★

M. Ellwarth, S. Schäfer, A. Reiners, and M. Zechmeister


A&A 680, A62 (2023)
https://doi.org/10.1051/0004-6361/202347615
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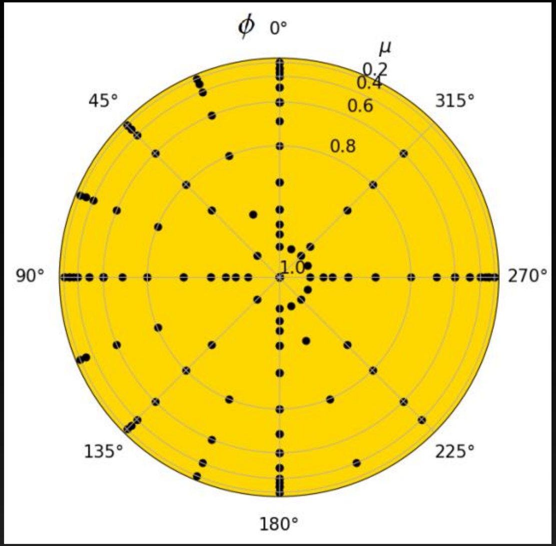
Astronomy & Astrophysics

Convective characteristics of Fe I lines across the solar disc

M. Ellwarth, B. Ehmann, S. Schäfer, and A. Reiners

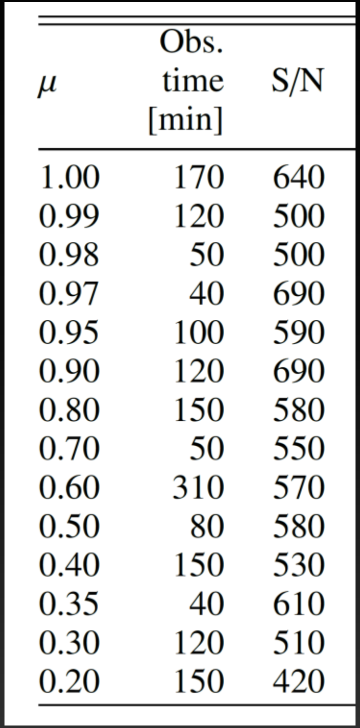
https://www.astro.physik.uni-goettingen.de/research/solar-lib/

The IAG spectral atlas of the spatially resolved Sun: Centre-to-limb observations



Wavelength range 4200–8000 Å
(continuous)

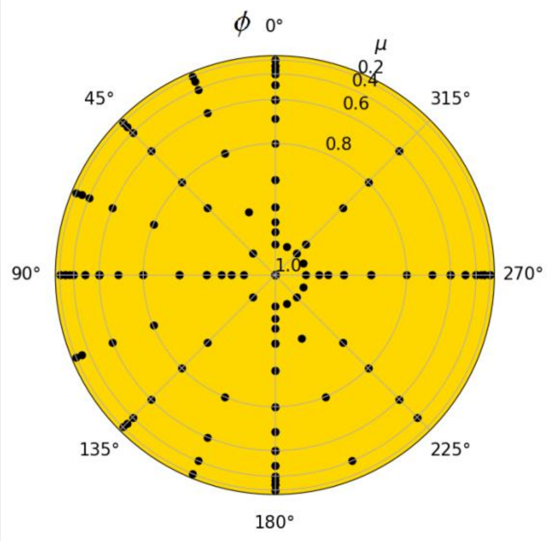
R = 700,000 @ 6000 Å



μ	Obs. time [min]	S/N
1.00	170	640
0.99	120	500
0.98	50	500
0.97	40	690
0.95	100	590
0.90	120	690
0.80	150	580
0.70	50	550
0.60	310	570
0.50	80	580
0.40	150	530
0.35	40	610
0.30	120	510
0.20	150	420

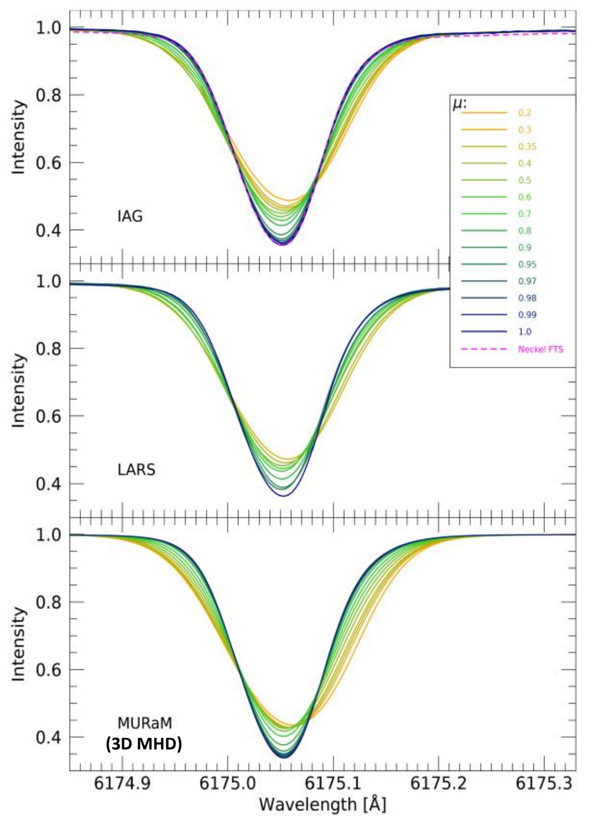
Ellwarth et al. (2023)

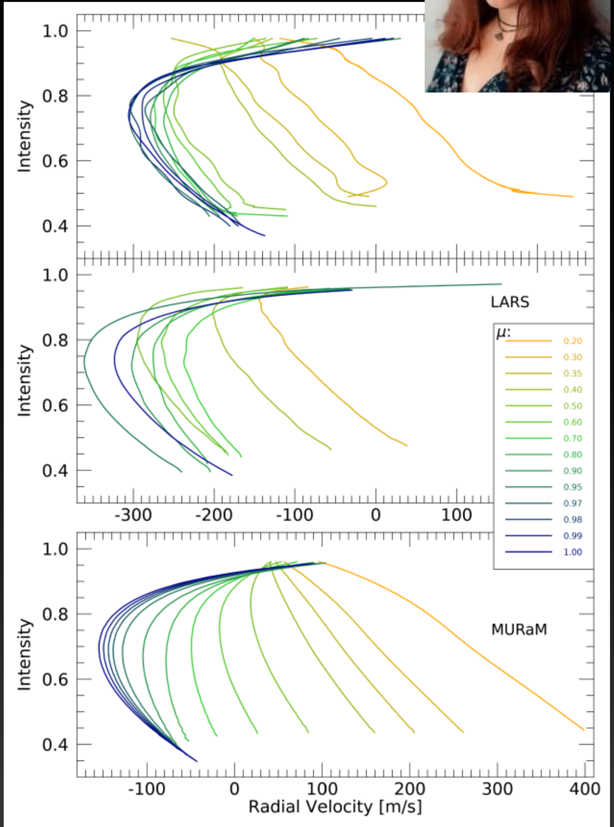
The IAG spectral atlas of the spatially resolved Sun: Centre-to-limb observations



Wavelength range 4200–8000 Å
(continuous)

R = 700,000 @ 6000 Å





Ellwarth et al. (2023)

Detailed models excellently match and were used to redetermine solar oxygen abundance

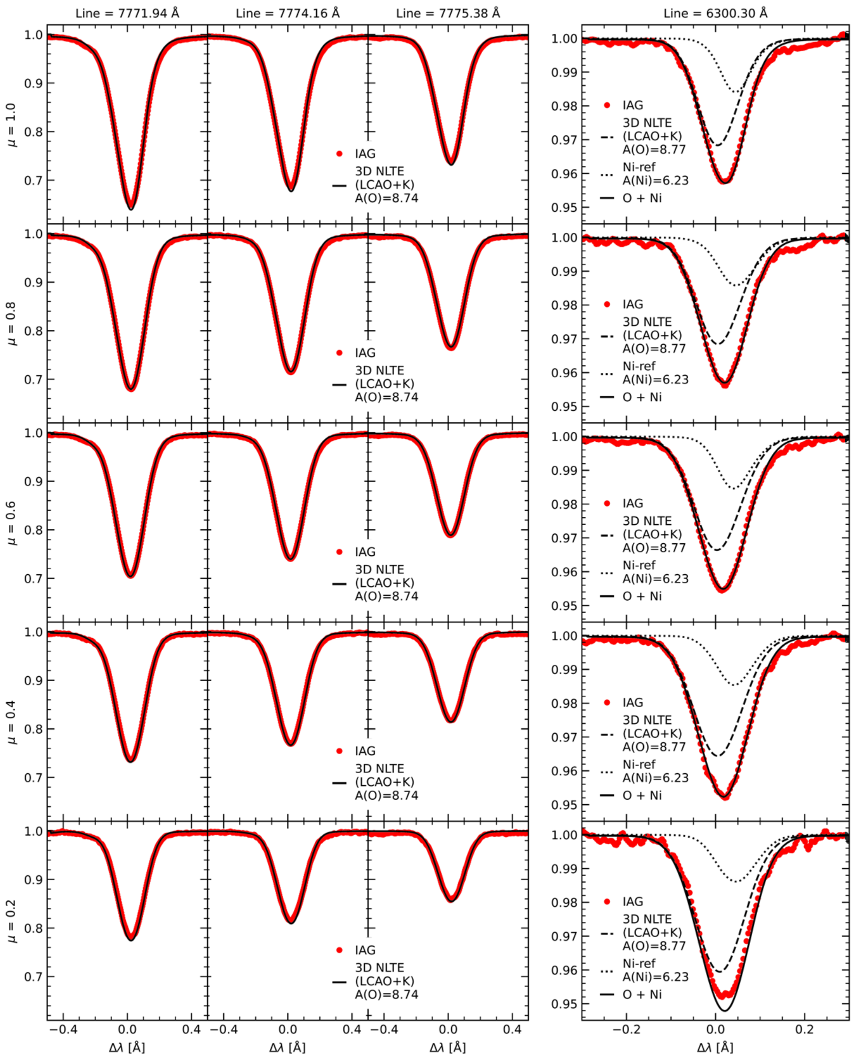
Bergemann et al., 2021

New values appear to resolve inconsistency with helioseismology

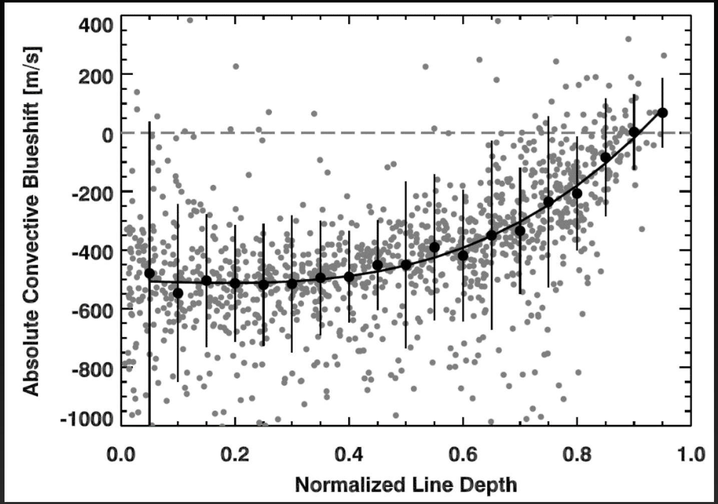
Magg et al., 2022

Validate models using the observed CLV in many spectral lines

see Lind & Amarsi, 2024

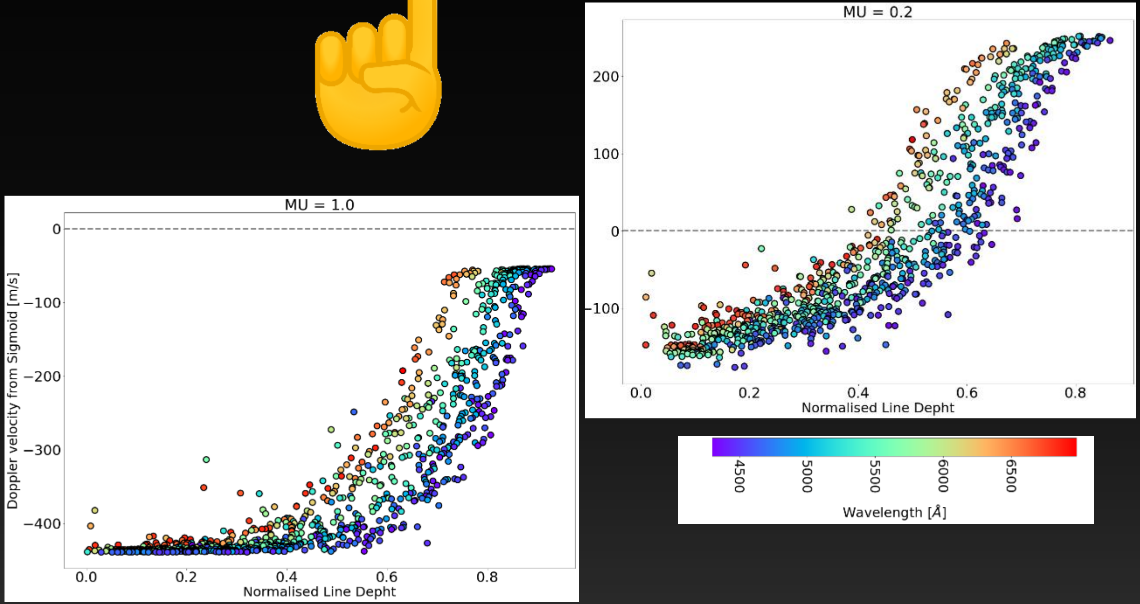


Our spectra provide comprehensive information about convective blueshift across the solar disc and for different formation heights



Disc-integrated solar atlas

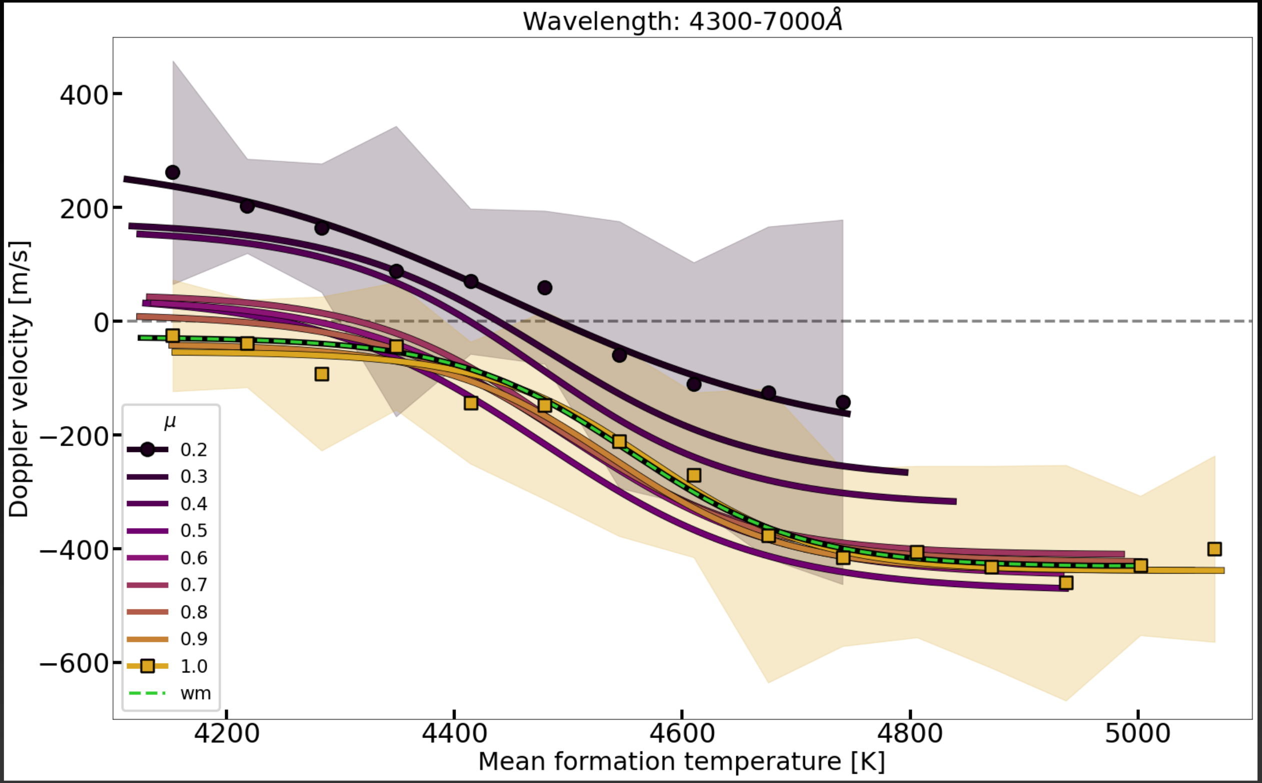
(Reiners et al., 2016)



Solar atlas at different μ-angles

(Ellwarth et al., 2023)

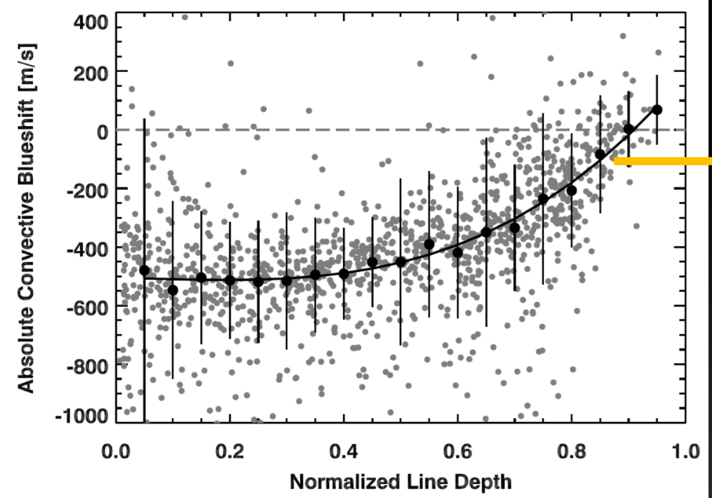
Our spectra provide comprehensive information about convective blueshift across the solar disc and for different formation heights



Ellwarth et al., 2023

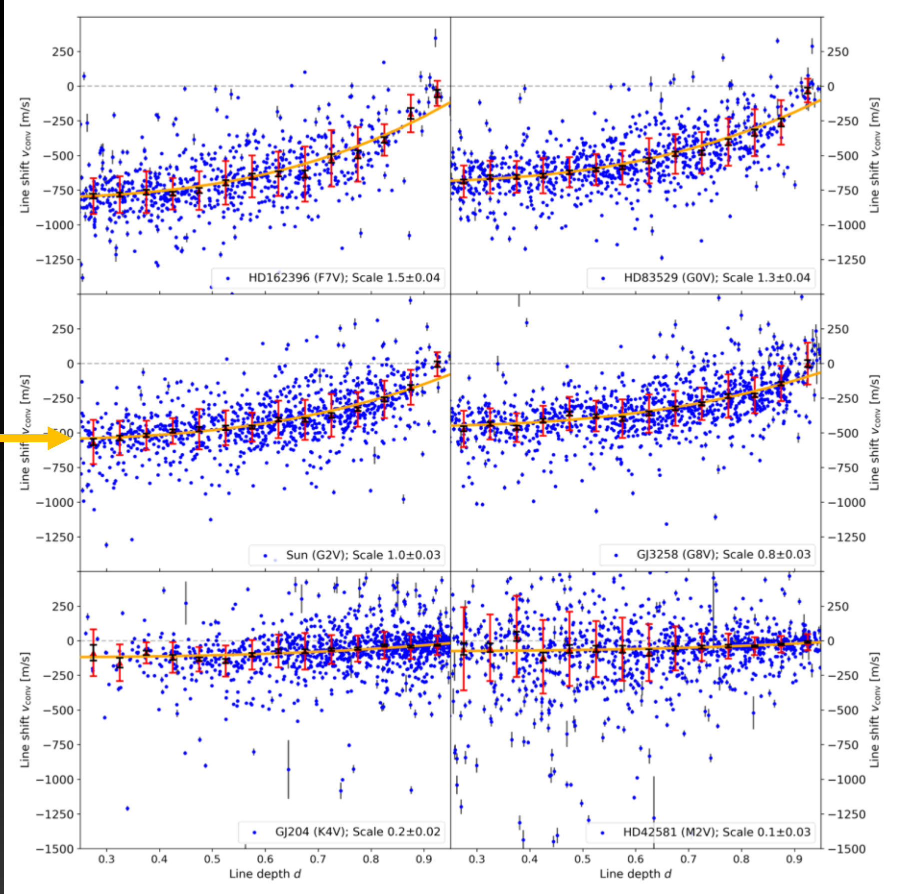
<u>ongoing:</u>
observations for different magnetic field strengths to determine influence of activity on RVs

Back to the stars…



Disc-integrated solar atlas

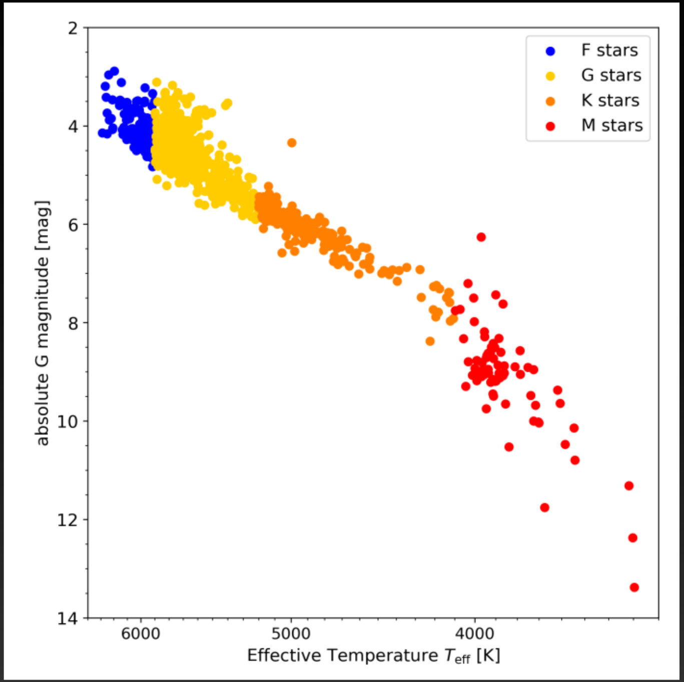
(Reiners et al., 2016)

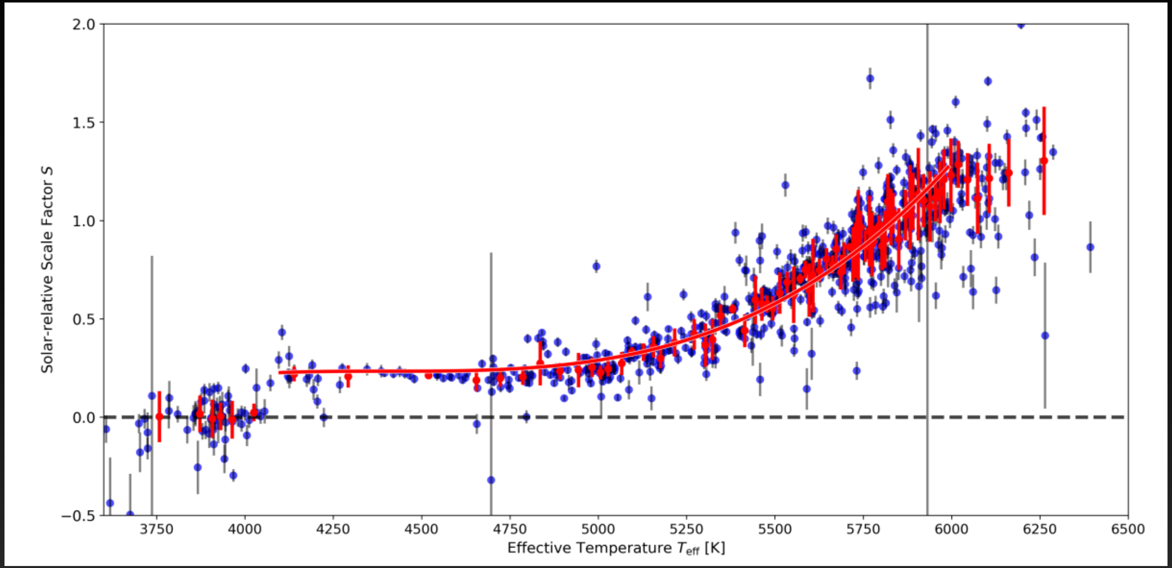


Convective signature **S** from stellar observations

(Liebing et al., 2021)

The convective signature scales with surface properties, e.g., temperature

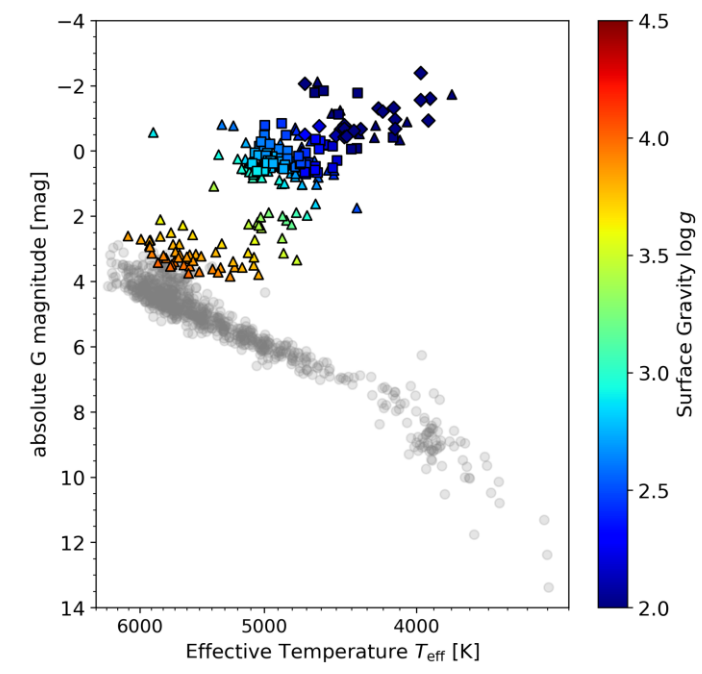


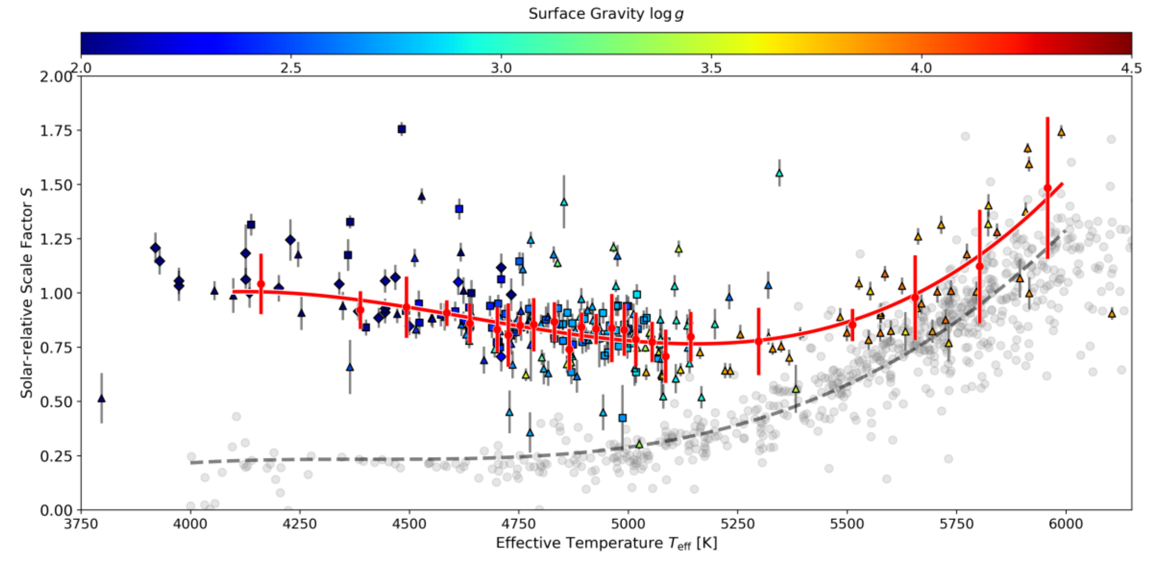


810 F- to M-type dwarf stars observed HARPS

(Liebing et al., 2021)

The convective signature scales with surface properties, e.g., temperature and gravity





242 evolved stars observed HARPS

(Liebing et al., 2023)

Summary

1. In very active stars, convection determines stellar magnetic activity.
   In slow rotators, surface magnetic flux is proportional to P.
   Coronal and chromospheric heating is proportional to magnetism.

2. Accurate solar spectral line measurements map convection in 3-D.

3. Convective velocities in different stars depend on temperature and gravity.