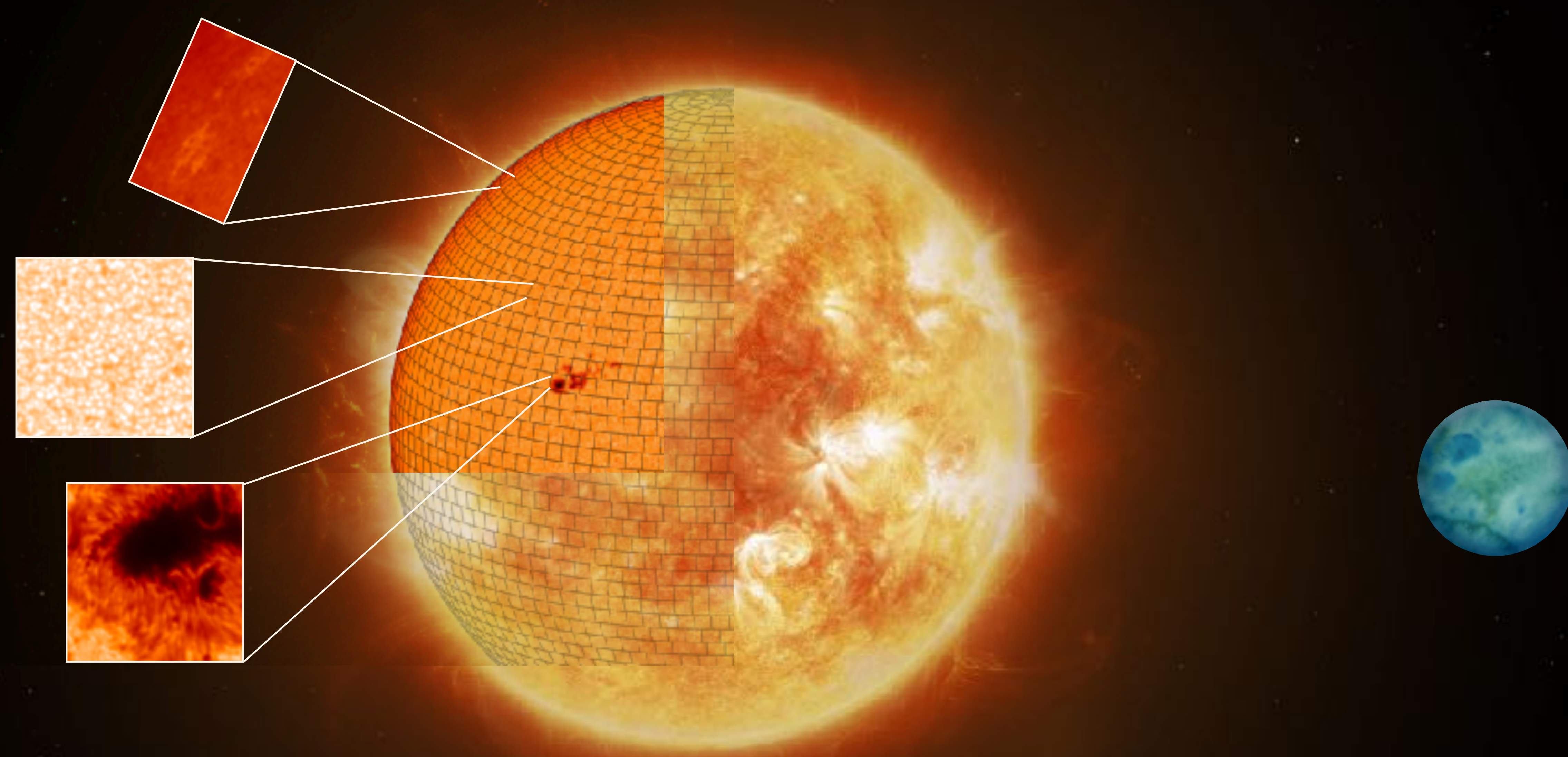
Characterising small planets in the face of intrinsic stellar variability



Dr Raphaëlle D. Haywood

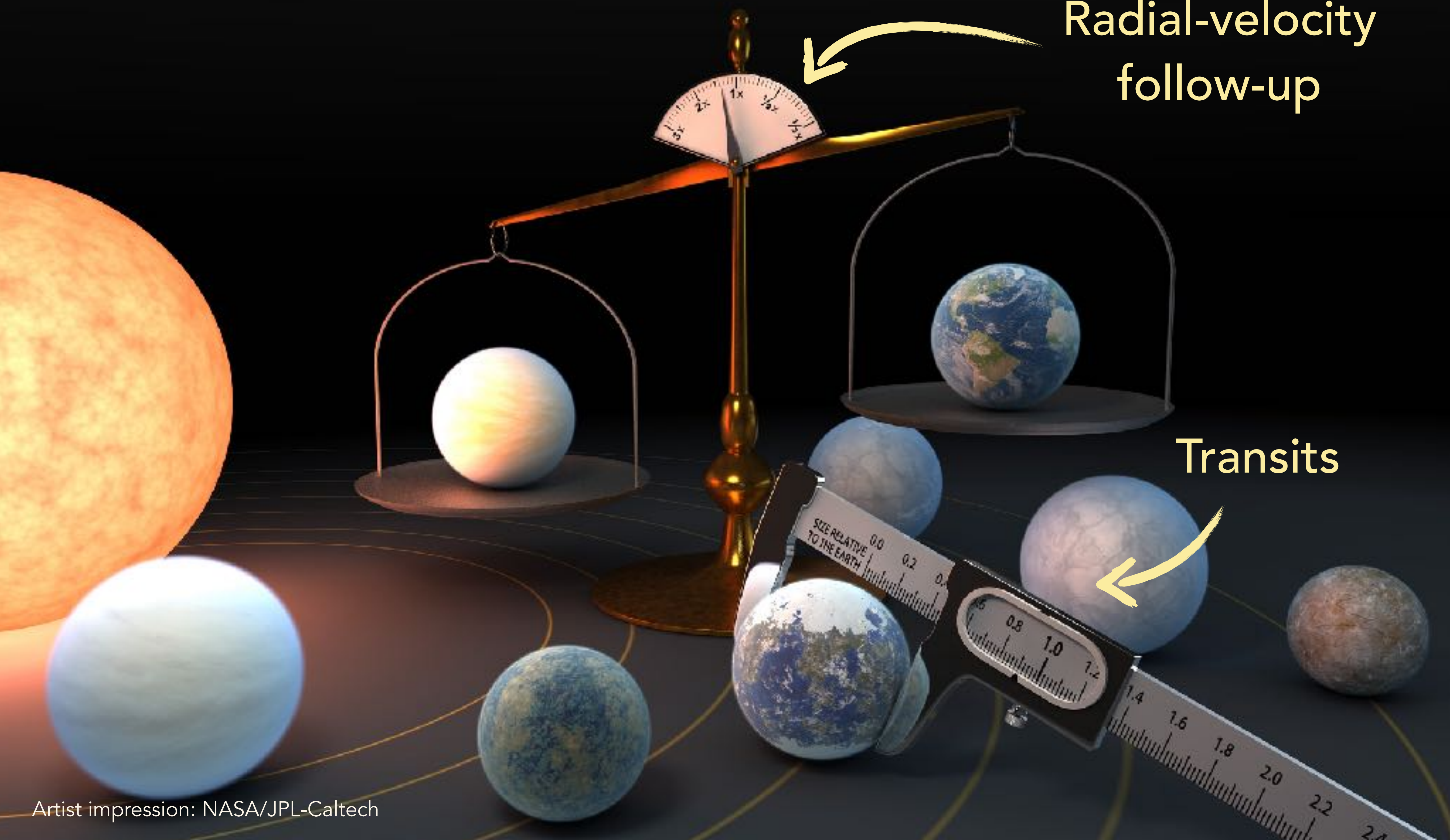
Ernest Rutherford Fellow, Senior Lecturer in Physics & Astronomy

UNIVERSITY OF EXETER

Solar observations: SDO/NASA; Artist impression: ESA/ATG medialab; graphics: H. Cegla, Fotolia; edited by R. Haywood based on graphic by H. Cegla

PLATO’s goals for characterising small planets:

- Radii measurements to 3% precision
- Mass determinations to 10% precision

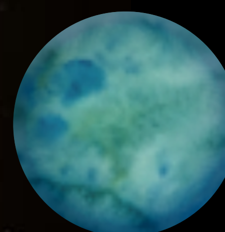


Artist impression: NASA/JPL-Caltech

The main barrier to characterising small planets is the natural variability of the host stars.

How does stellar variability impact RVs?

What are we learning from the Sun?



Findings & recommendations from the EPRV WG

Crass et al., inc. Haywood 2021: *Extreme Precision Radial Velocities Working Group Final Report*

See also Fischer et al., 2016; Dumusque et al., 2017; Meunier, 2021

Artist impression: ESA/ATG medialab; graphic: Fotolia

Extreme Precision Radial Velocity Working Group

Final Report

The EPRV WG is an international, interdisciplinary group commissioned by NASA and NSF to design a roadmap to "measure the masses of temperate terrestrial planets orbiting Sun-like stars".

Analysis group on intrinsic stellar variability
(co-chairs: H. Cegla & R. Haywood)

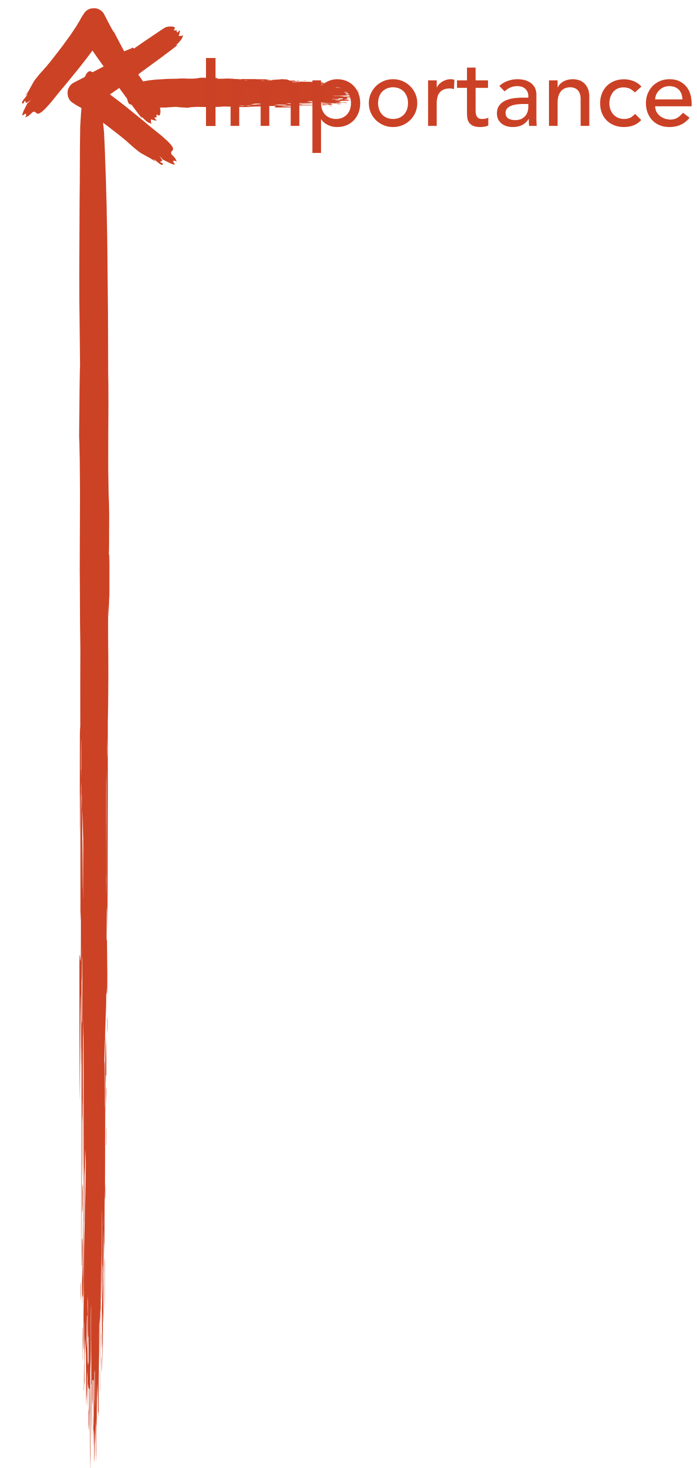
"variability":
magnetic activity
+ magnetoconvection

Crass et al., 2021: EPRV WG Report

arXiv:2107.14291

EPRV WG findings on stellar variability

Physical effect
Understanding the Sun *in connection to EPRV*
Spectral line formation and behaviour in the stellar atmosphere *in connection to EPRV*
Magnetic fields
Faculae/plage
Spots
Evershed flows, moat flows, plage inflows ...
Granulation
Super-Granulation
Meridional flows
Long-term magnetic cycles
Pulsations - p modes
Pulsations - r modes
Flares
Gravitational redshift



Full stellar variability "error budget": Crass et al., 2021, Table A-4

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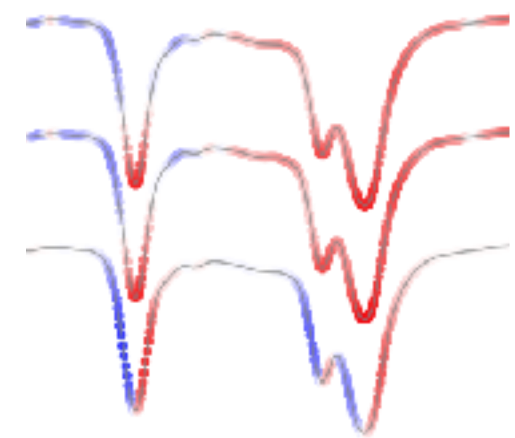


e.g. Davis et al., 2017;
Thompson et al., 2017, 2020;
Dumusque, 2018;
Crétignier et al., 2021

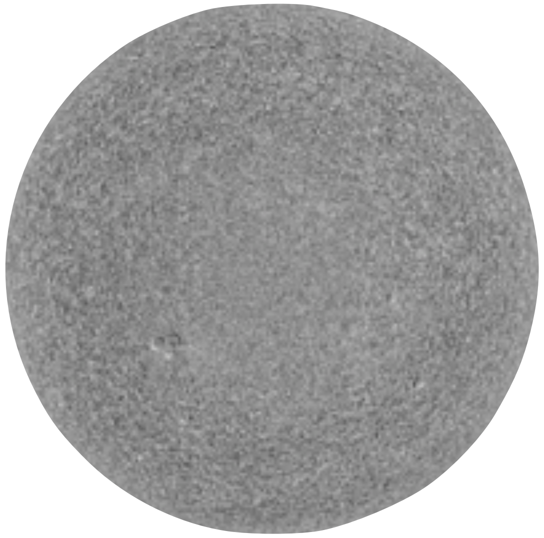
Figure from Davis et al., 2017

Full stellar variability "error budget": Crass et al., 2021, Table A-4

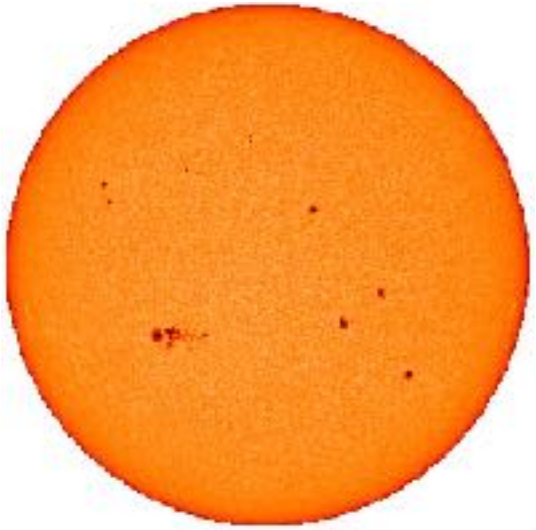

SDO/HMI continuum intensity

Estimating solar RV variations from spatially resolved images:

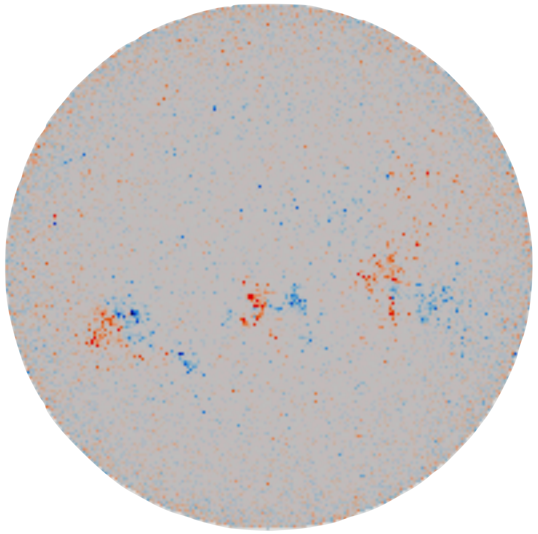
Helioseismic & Magnetic Imager onboard the Solar Dynamics Observatory (SDO/HMI)



Doppler image



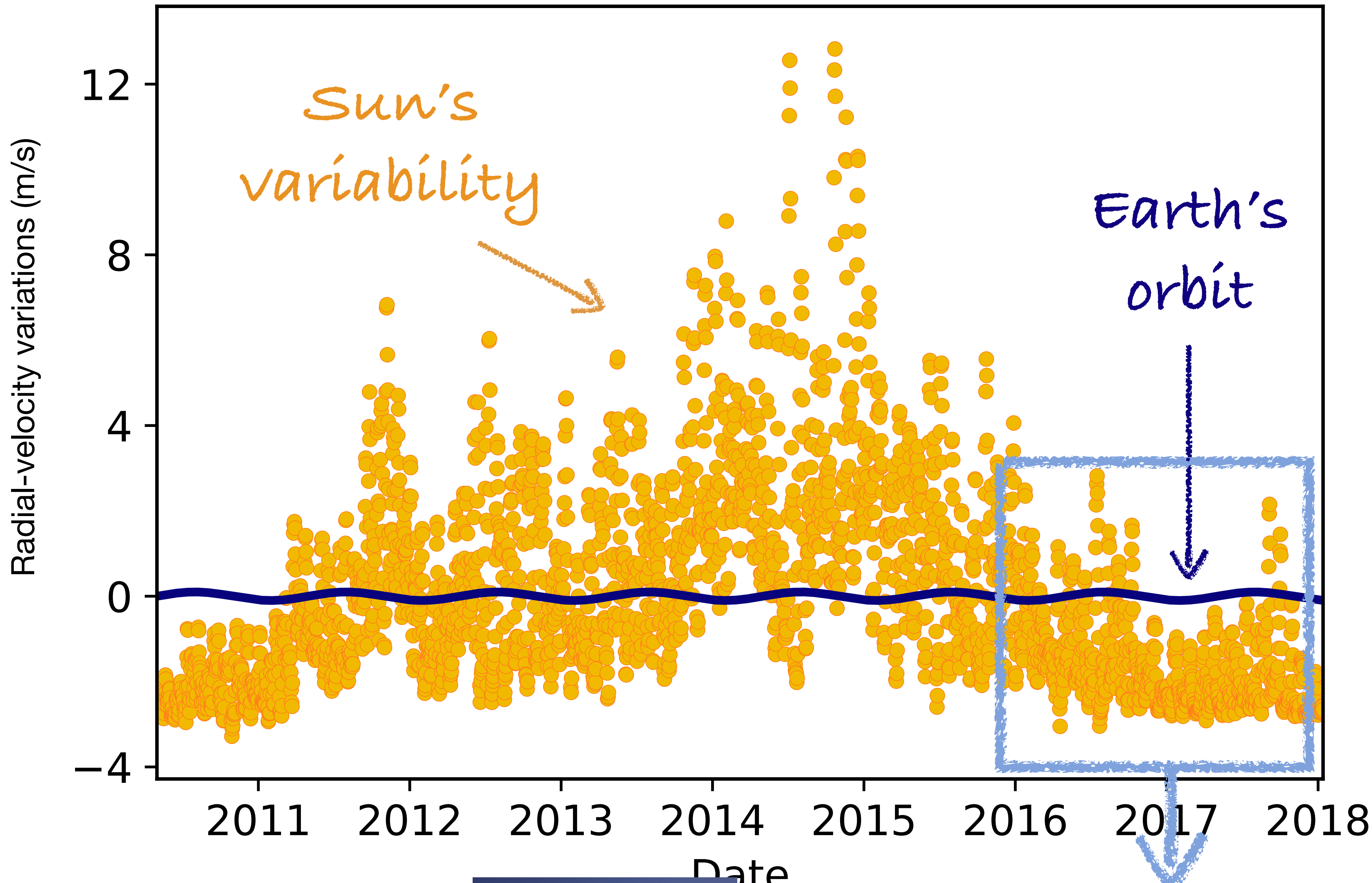
Continuum intensity



Magnetic field

Haywood et al. (2016)
Based on a technique developed by Meunier, Lagrange & Desort (2010) for SoHO/MDI images.

Estimating solar RV variations from spatially resolved images:

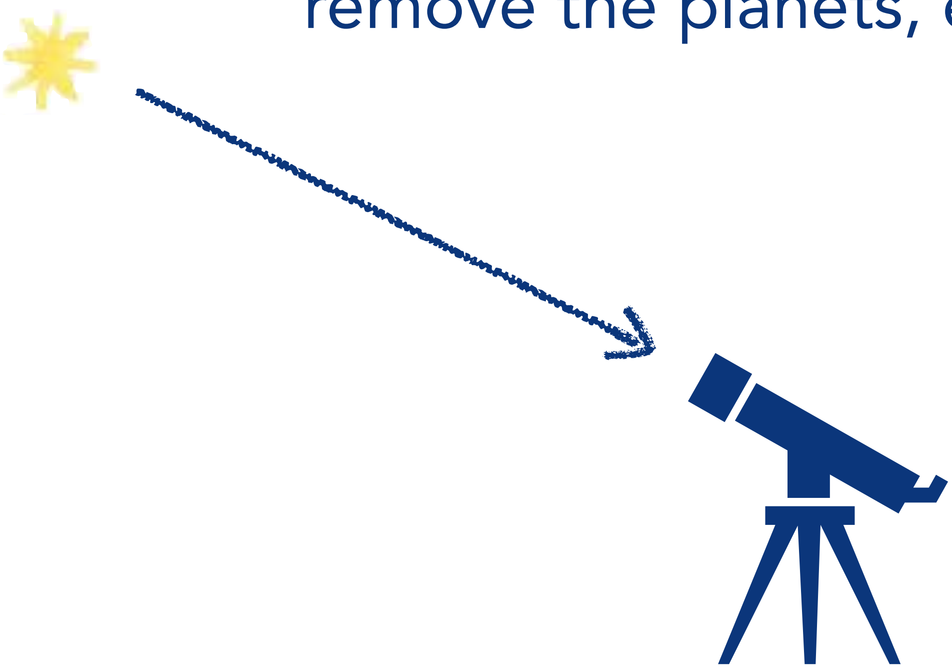


We compared against direct observations of the Sun as a star with HARPS-N (Milbourne et al., 2019)

Haywood et al. (in review at ApJ, arXiv:2005.13386)

We are observing the Sun as a distant, point-like star with the exoplanet hunter HARPS-N

Place the Sun in its own rest frame,
remove the planets, etc.



Solar/HARPS-N Project:
See Glenday, Phillips et al. (2012),
Dumusque et al. (2016), Phillips et al. (2016),
First 3 years of data now public! → Dumusque et al. (2021, arXiv:2009.01945)

Photo by D. Phillips

HARPS-N: High Accuracy Radial-Velocity Planet Searcher in the Northern hemisphere

Our RVs estimated from SDO/HMI images closely match RVs observed directly by HARPS-N.

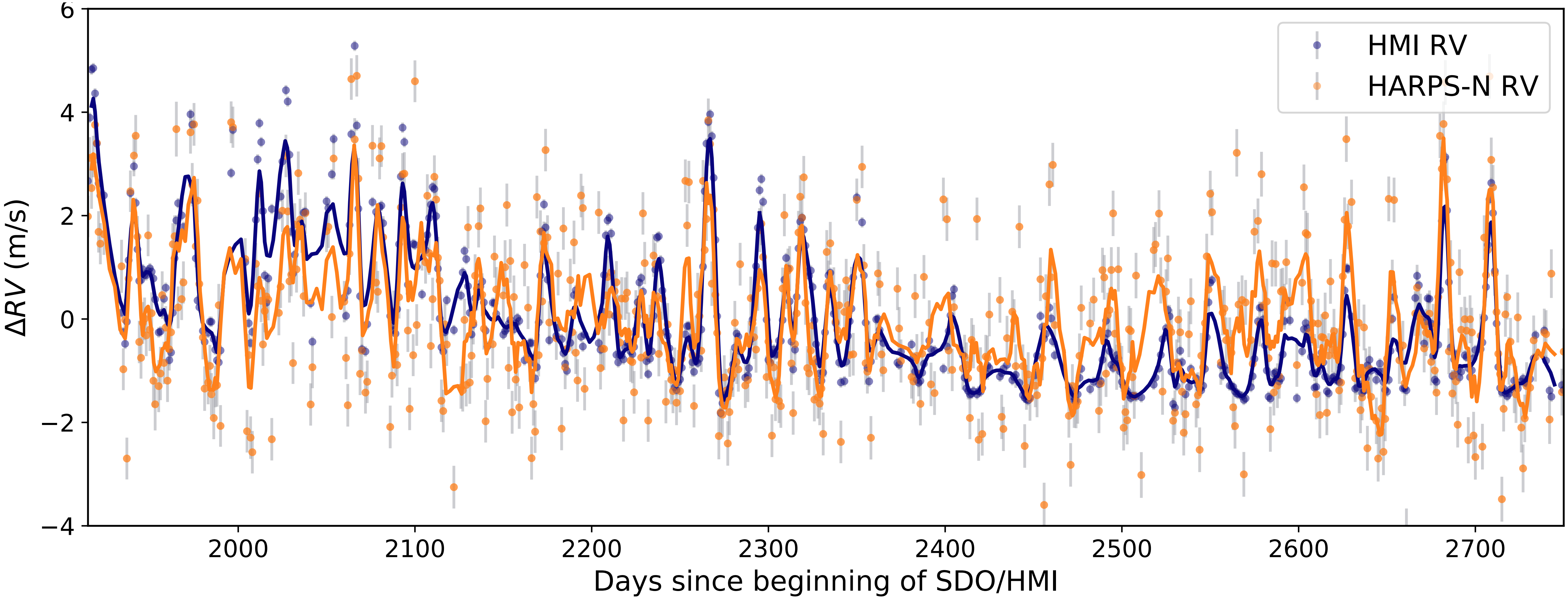
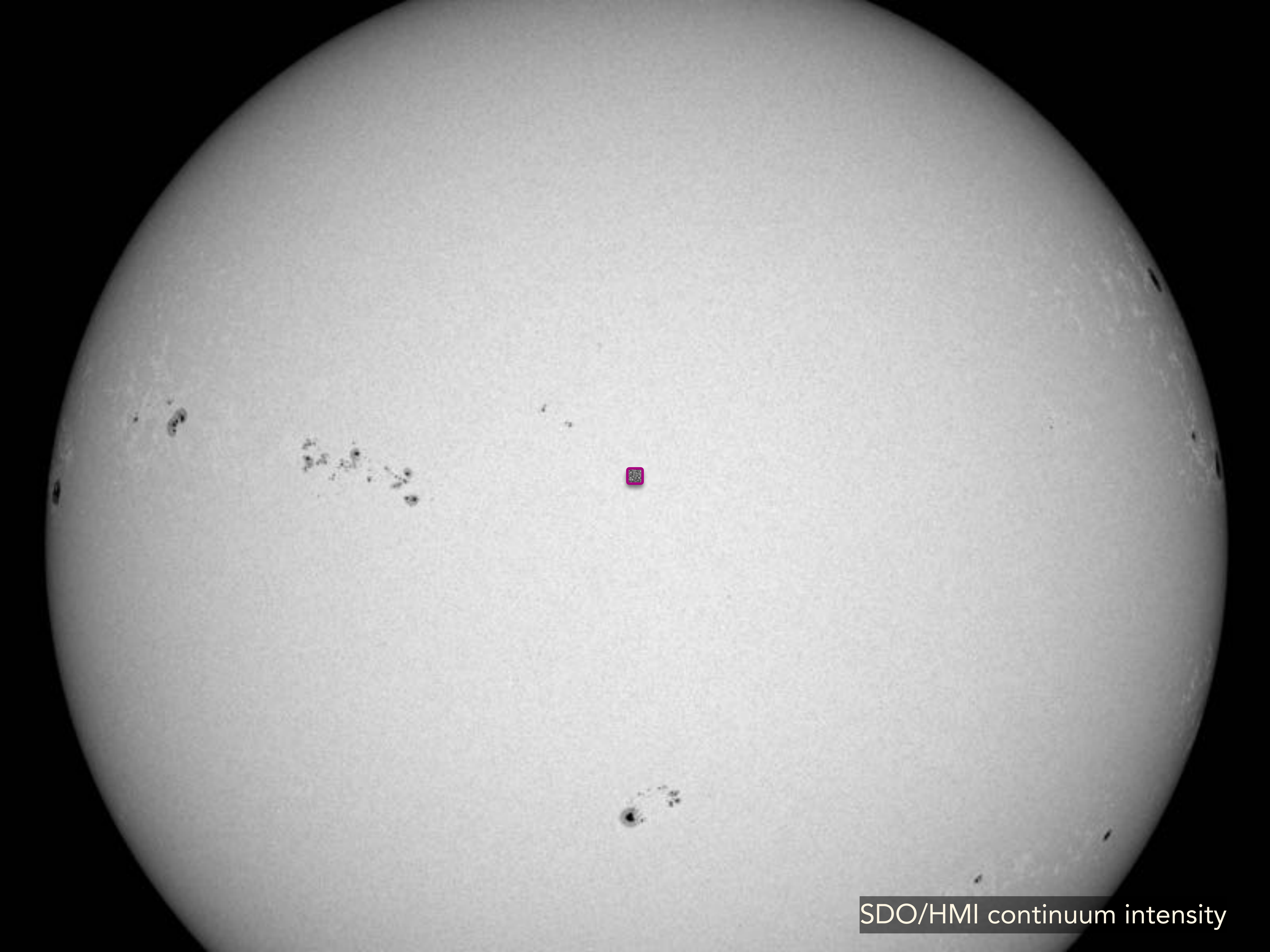
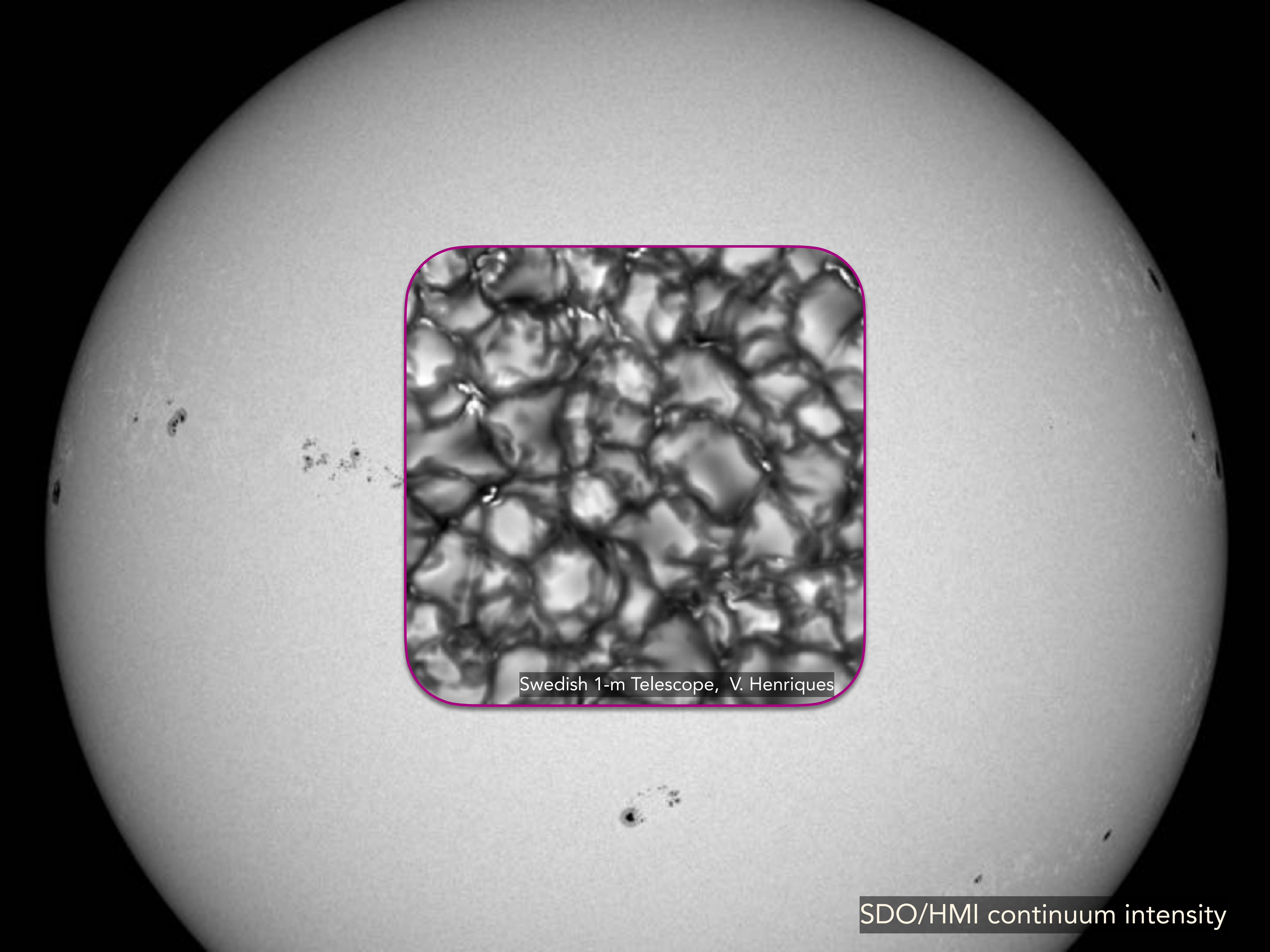
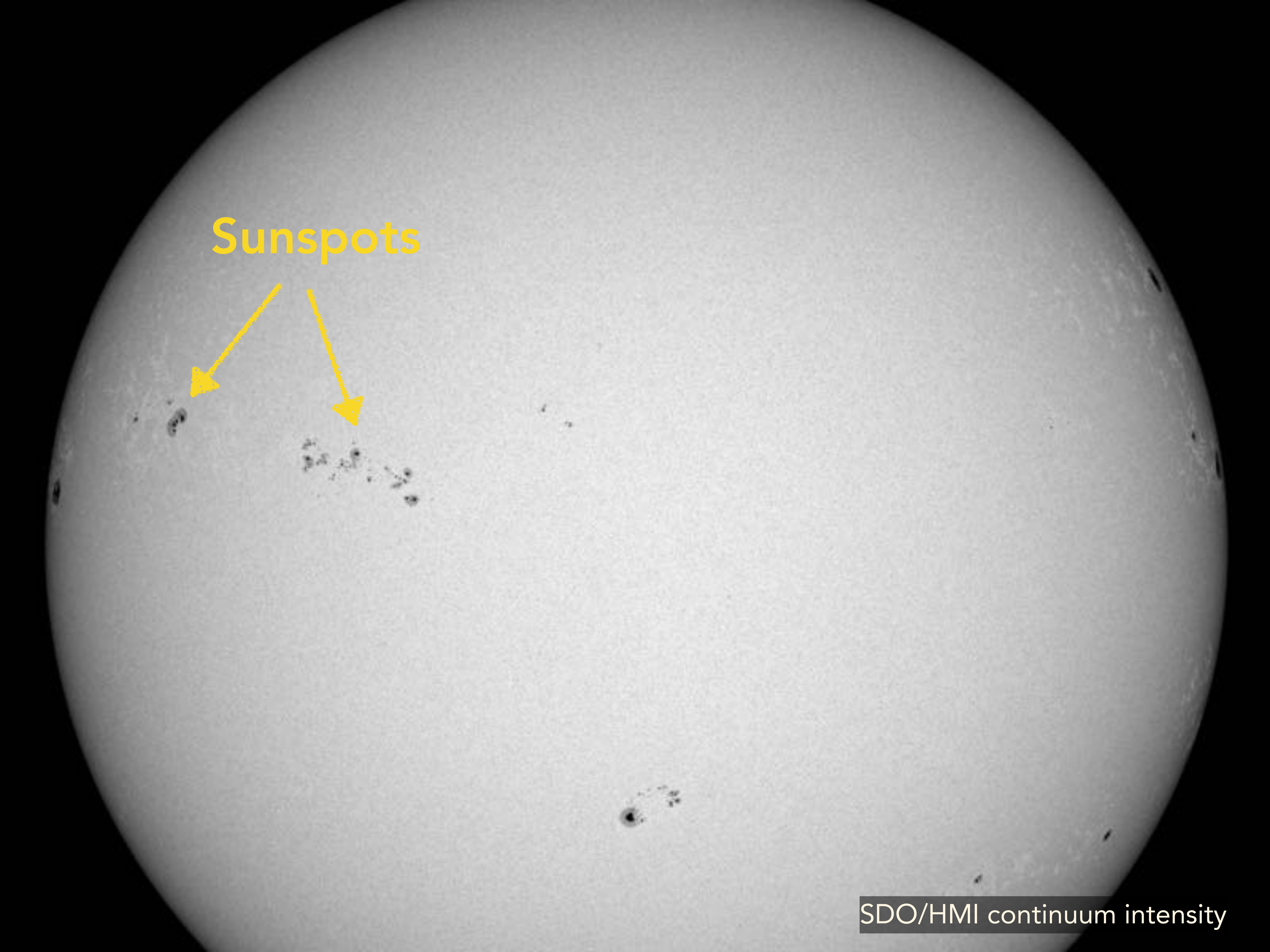


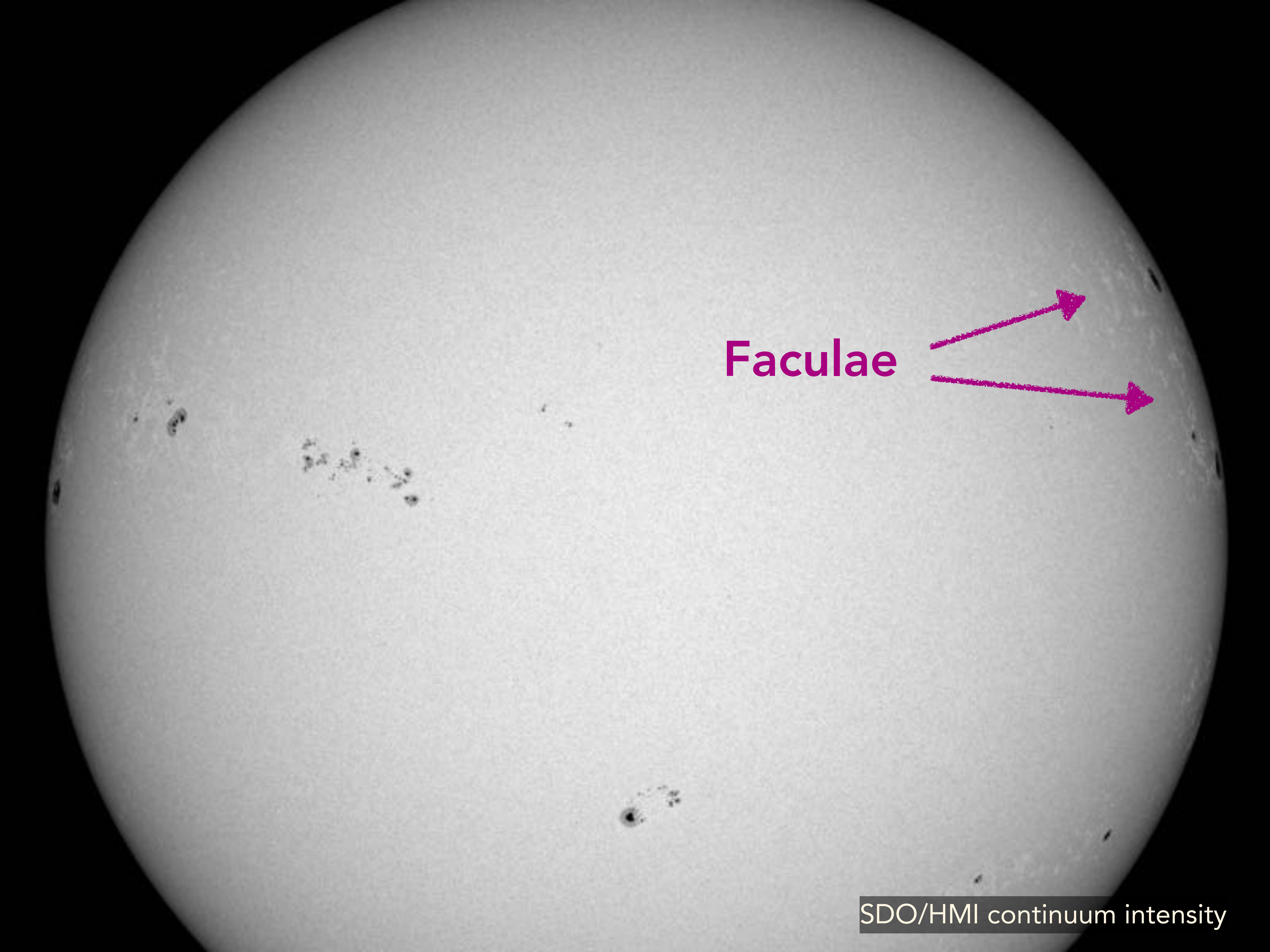
Figure adapted from Milbourne, Haywood et al. (2019)
Haywood et al. (in review at ApJ, arXiv:2005.13386)

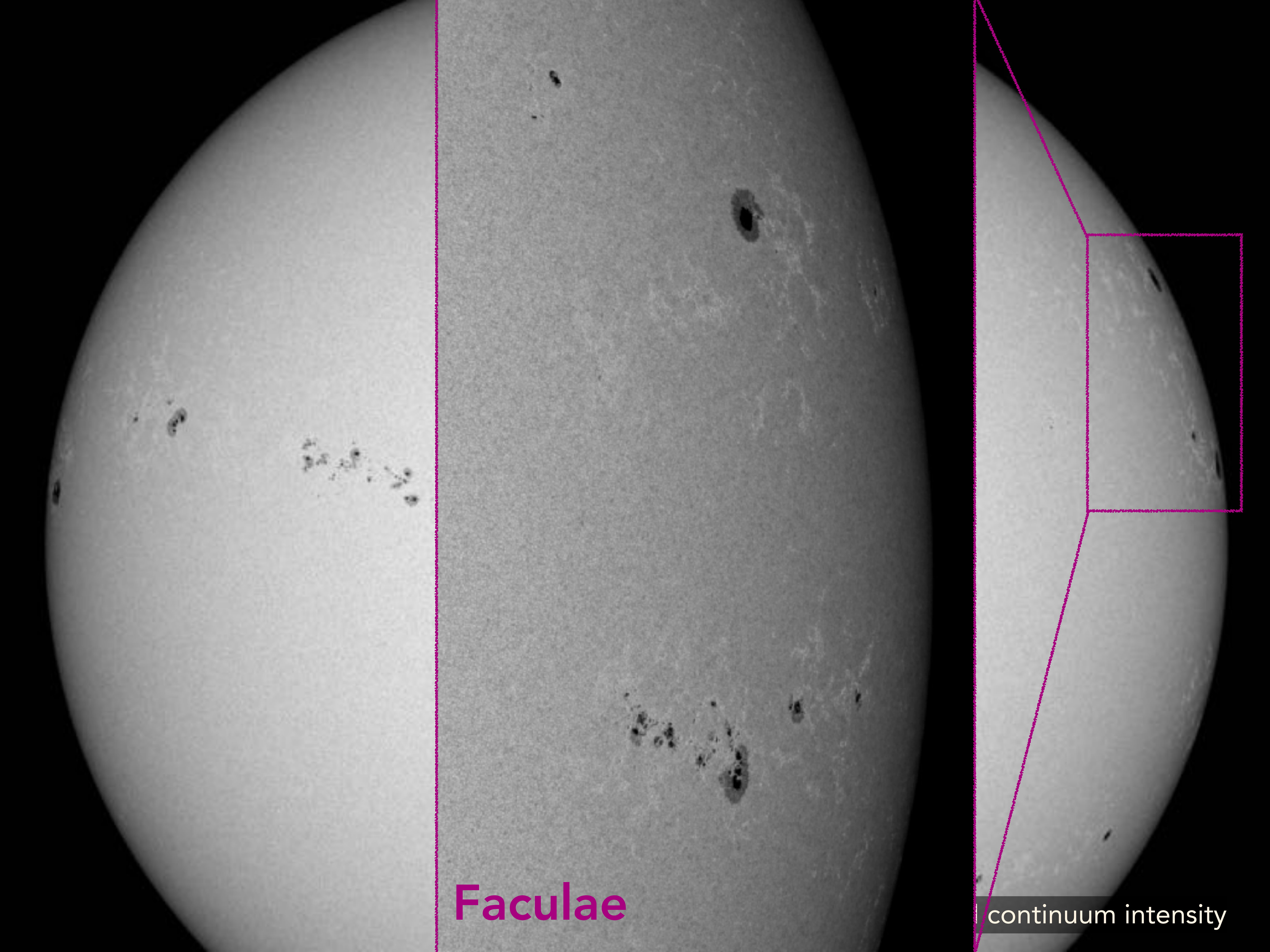

SDO/HMI continuum intensity


SDO/HMI continuum intensity

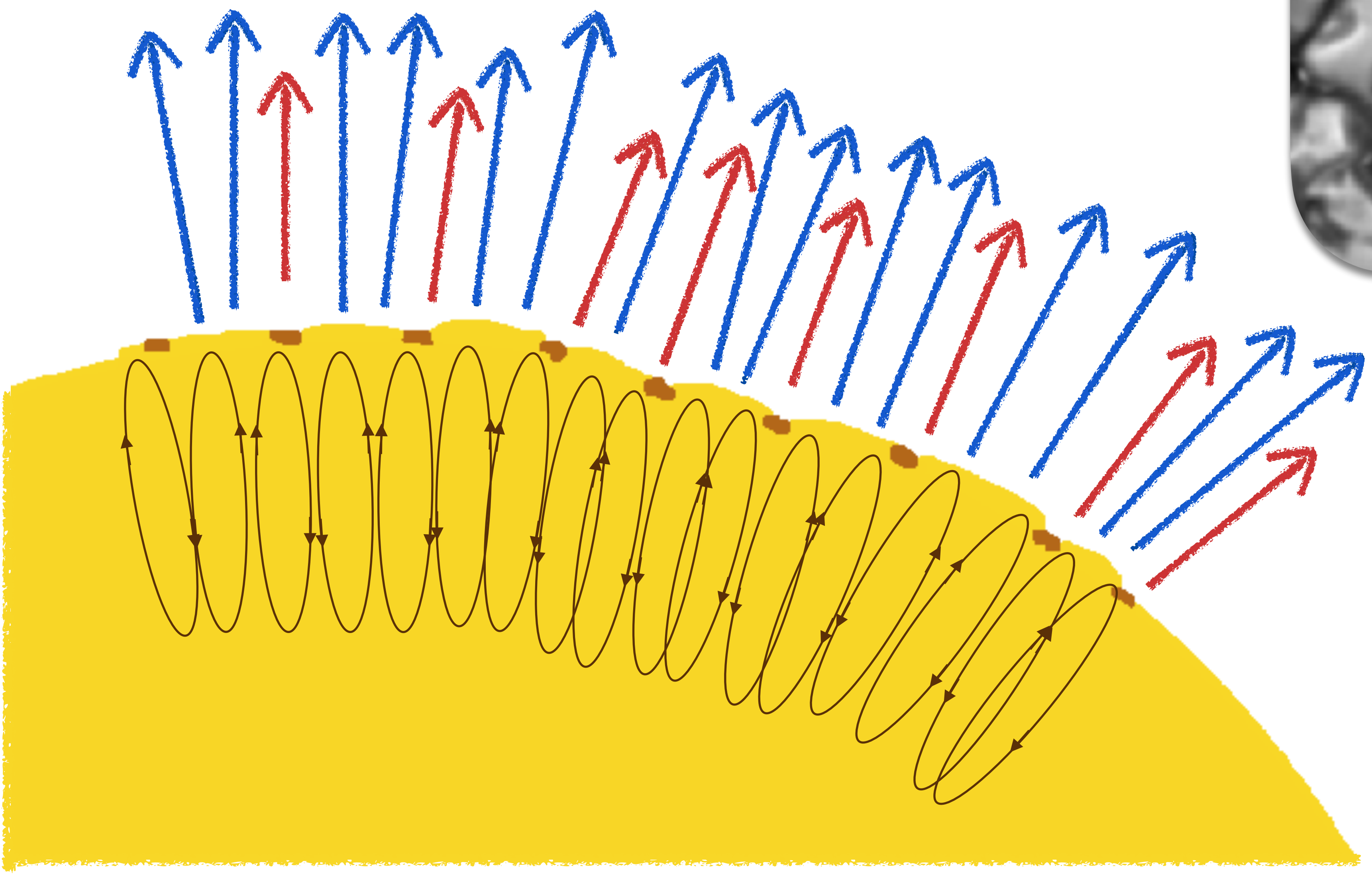

Swedish 1-m Telescope, V. Henriques
SDO/HMI continuum intensity

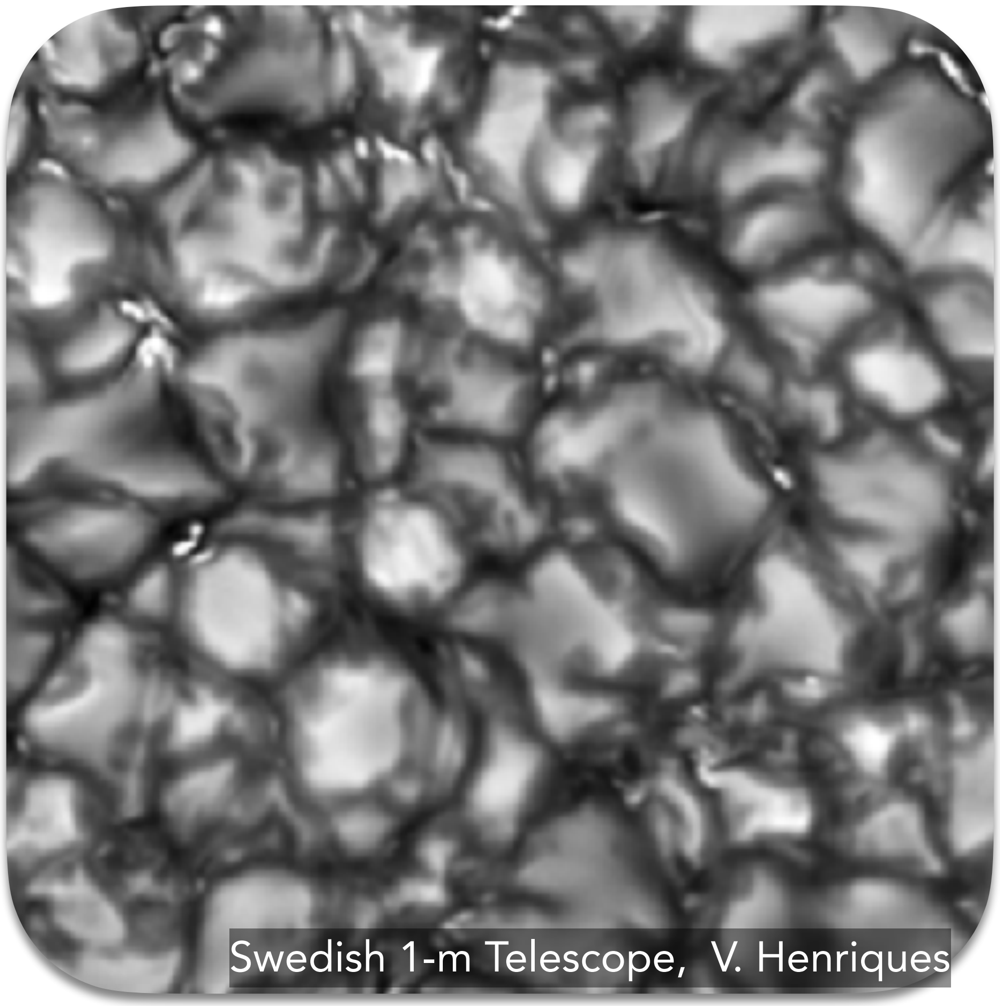

Sunspots
SDO/HMI continuum intensity


Faculae
SDO/HMI continuum intensity


Faculae
continuum intensity

We identified the dominant process responsible for solar RV variability:

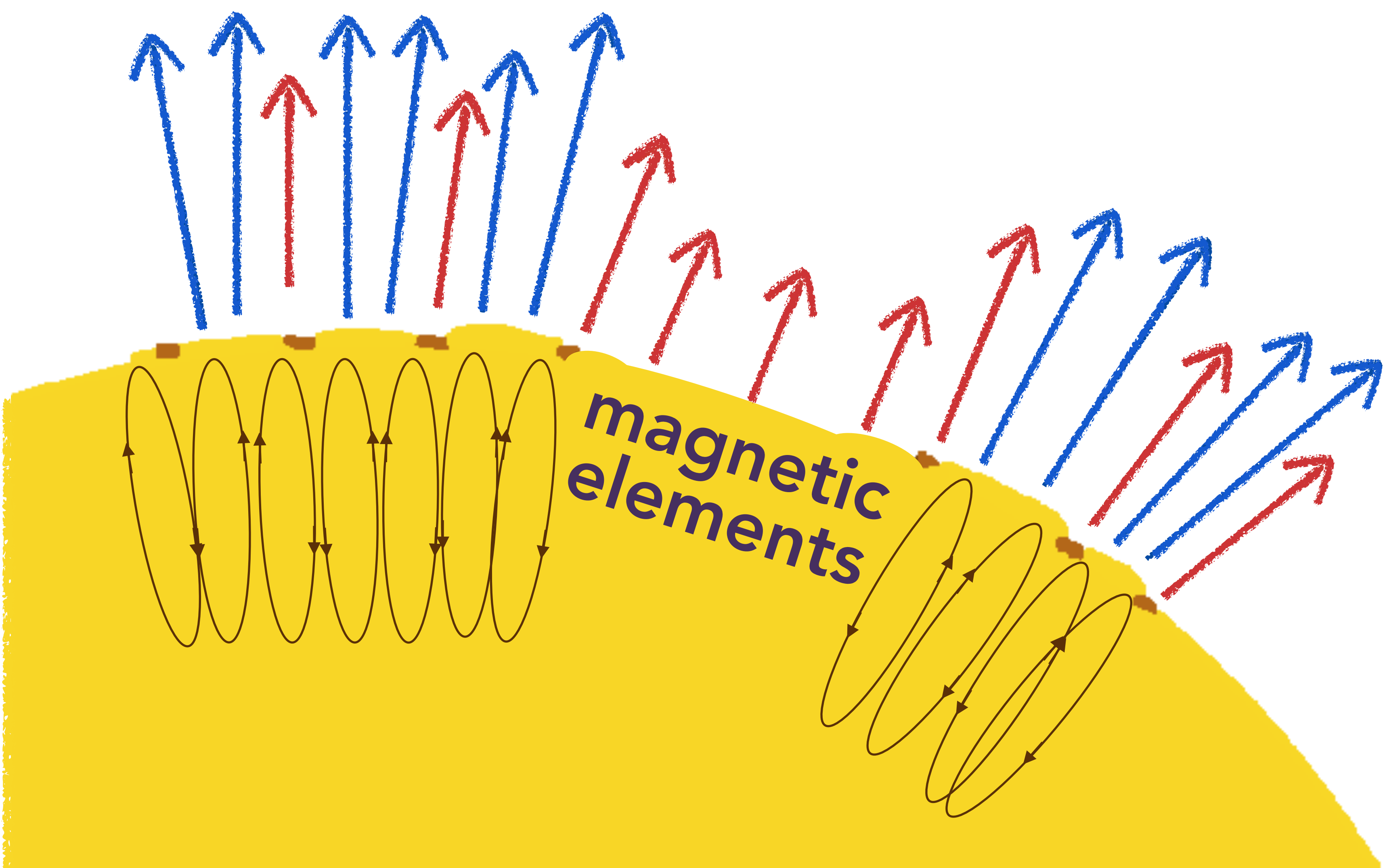




e.g. Dravins (1982)
Gray (2005)

We identified the dominant process responsible for solar RV variability:

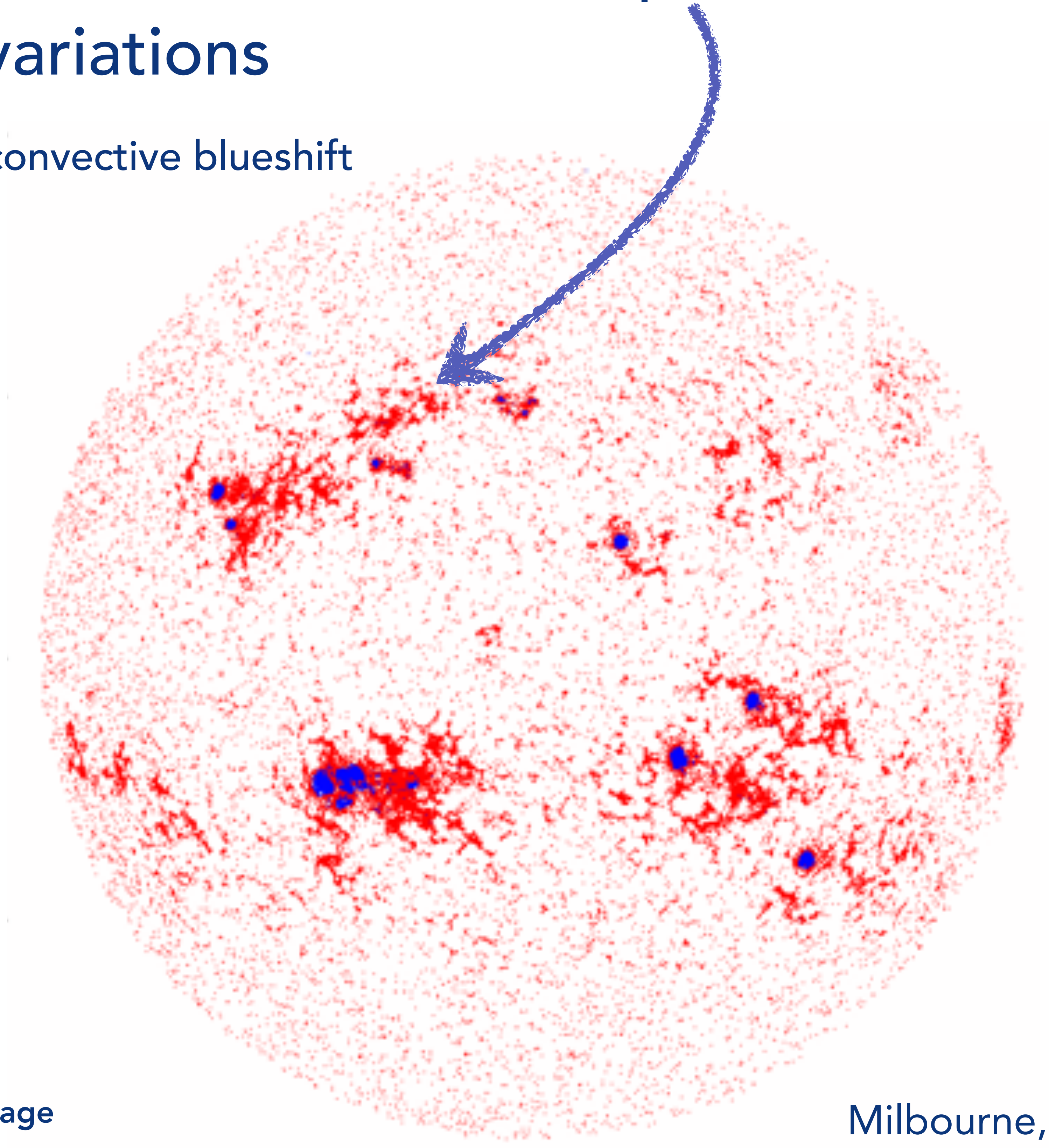
Magnetic elements suppress convective blueshift.



Haywood et al. (2016)
Meunier et al. (2010a,b)
Dumusque et al. (2014)

Faculae in concentrated areas of plage are the main drivers of solar RV variations

via suppression of convective blueshift



SDO/HMI continuum image
blue: sunspots
red: faculae/plage
white: non-active Sun

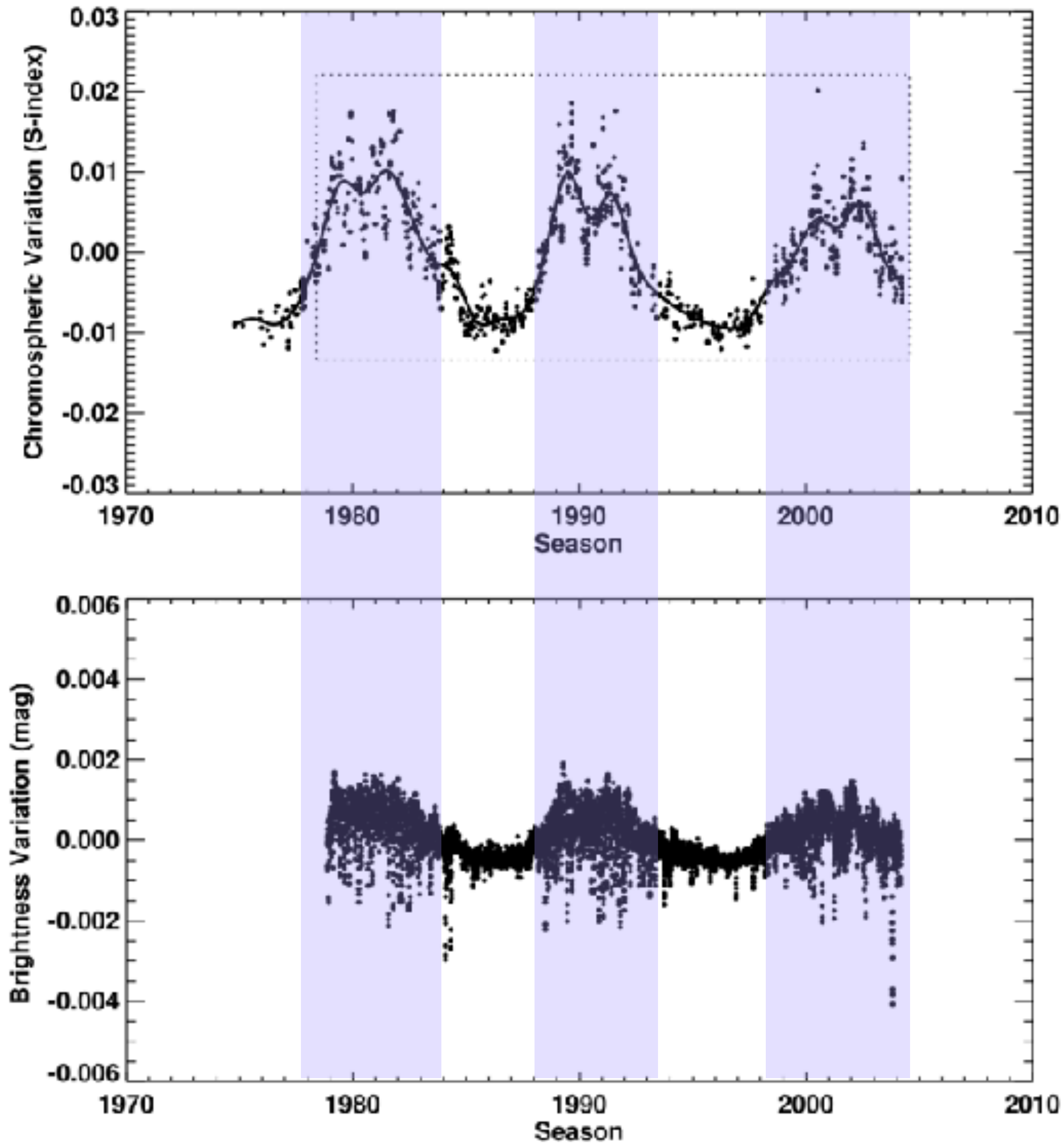
Milbourne, Haywood et al. (2019)
Haywood et al. (2016)
Meunier et al. (2010)

Old, slowly rotating stars like the Sun are faculae-dominated.

Sun

Ca H&K emission

Optical photometry



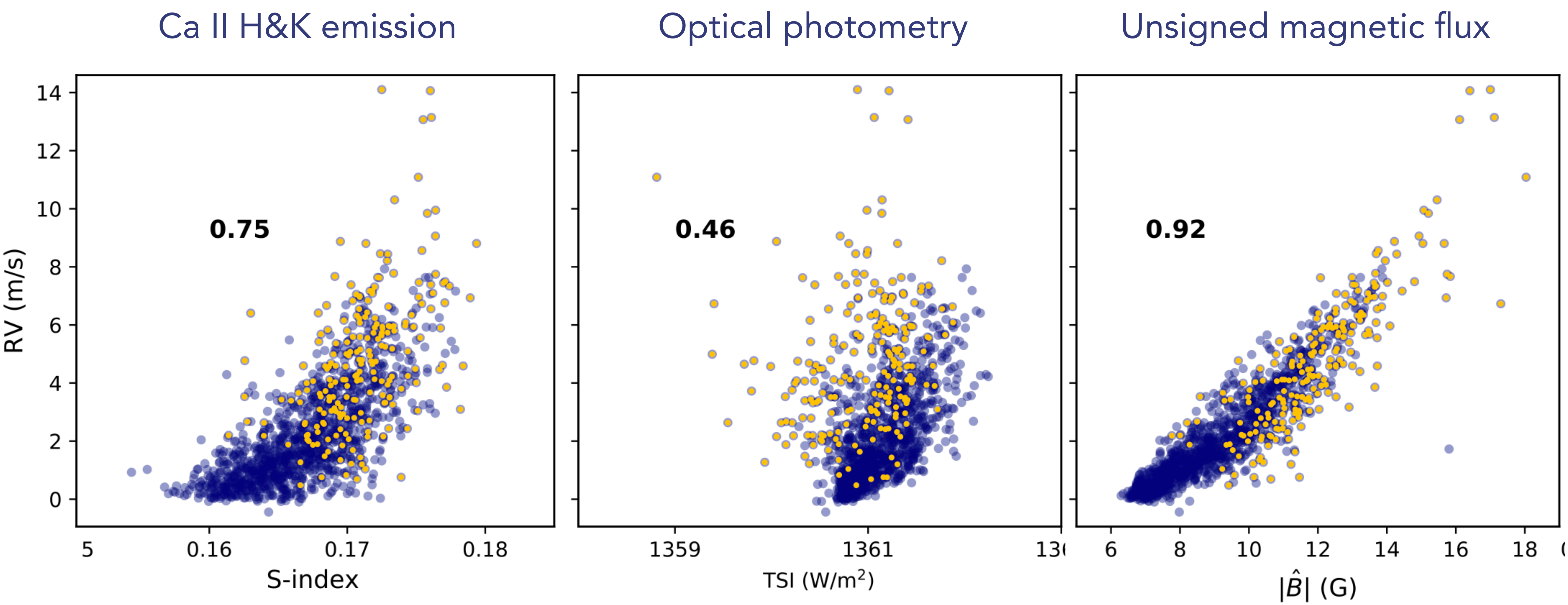
Mount Wilson HK Project (Mt Wilson Observatory, Lowell Observatory)

Radick et al. (1988), Lockwood et al. (2007), Radick et al. (2018)

Figure from Lockwood et al. (2007)

Existing variability indicators do not trace stellar variability down to sub m/s precision.

Crass et al., 2021: EPRV WG Report
and refs therein



We need to develop techniques to measure $|B|$ in slowly rotating, relatively inactive stars.

e.g. Lehmann et al., 2015; Mortier, 2016; Kochukhov et al. 2020; Lienhard et al., in prep.

Solar observations from SDO/HMI

Figure from Haywood et al. (in review at ApJ, arXiv:2005.13386)

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Crass et al., 2021: EPRV WG Report

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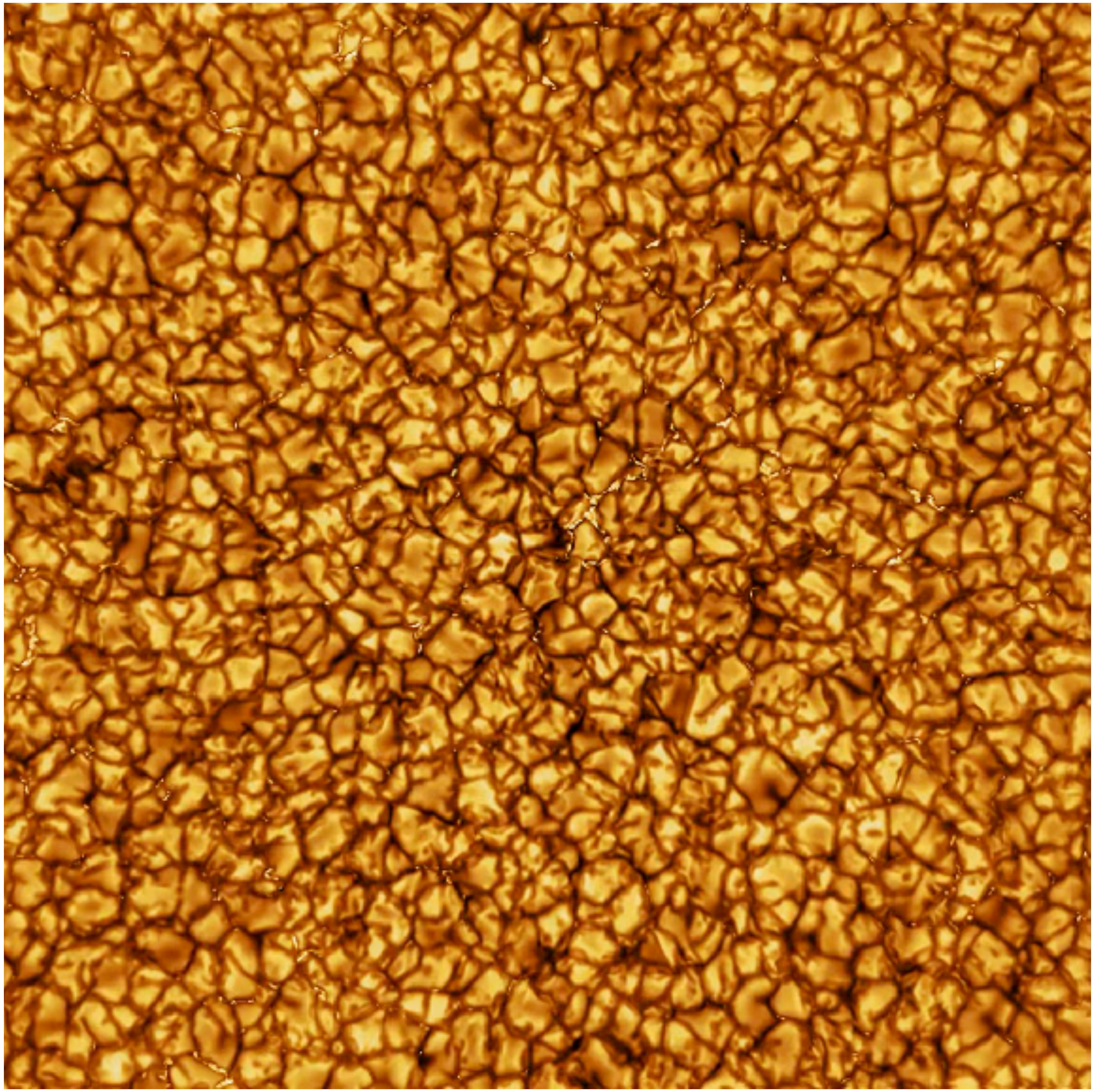
Crass et al., 2021: EPRV WG Report

Magnetoconvection (granulation, supergranulation)



Observations: DKIST, video credit: NSO/NSF/AURA.

On the Sun:

- Granulation RMS: 0.8 m/s
- Supergranulation RMS: up to 1.1 m/s

Meunier et al. (2015)

Not easily averaged out over multiple exposures/ nights to <≈ 0.5 m/s level.

cf. upcoming talk by L. Fernanda & R. Díaz

Meunier et al., 2015; Cegla et al., 2019; Dumusque et al., 2011; cf. review by Cegla, 2019 and refs therein.

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Stellar oscillations can be binned to < 10cm/s by choosing the right exposure time.

Chaplin et al., 2019

Code: https://github.com/grd349/ChaplinFilter

Full stellar variability "error budget": Crass et al., 2021, Table A-4

Final remarks

"We recommend immediately implementing a *long-term, large-scale, interdisciplinary* reseach and analysis program in [intrinsic stellar variability]."

EPRV WG Report Exec. Summary
arXiv:2107.14291

This is a great opportunity for solar/stellar science; it's a necessity for exoplanet science.

Thank you to Annelies Mortier and Heather Cegla for slide inputs! ☺