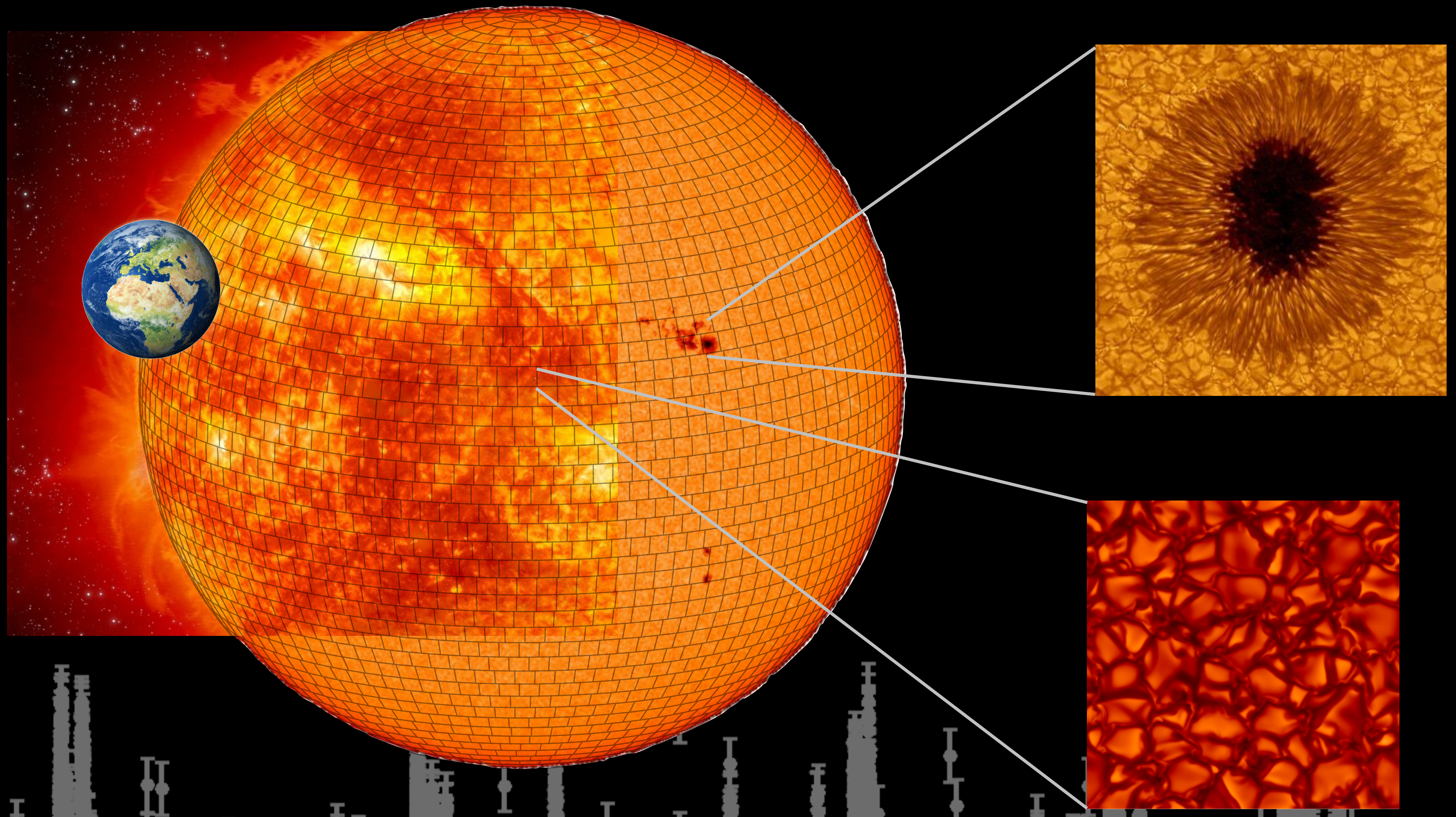
Physics Responsible for Various Sources of Stellar Variability



Dr. Heather Cegla

Senior Research Fellow

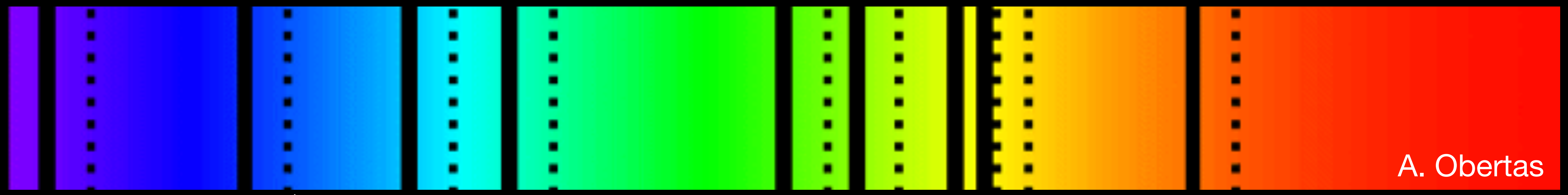
UKRI Future Leaders Fellow

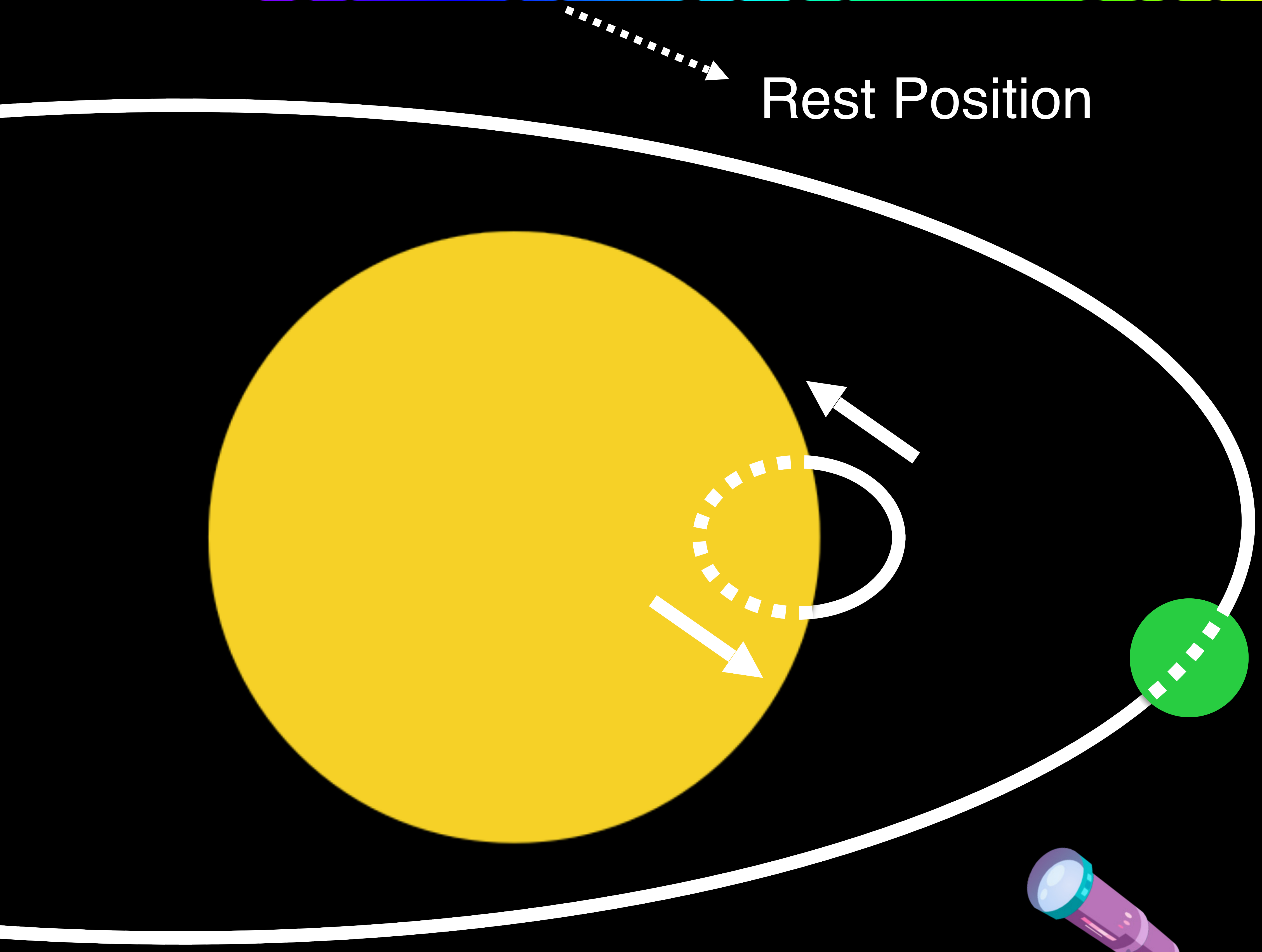
WARWICK

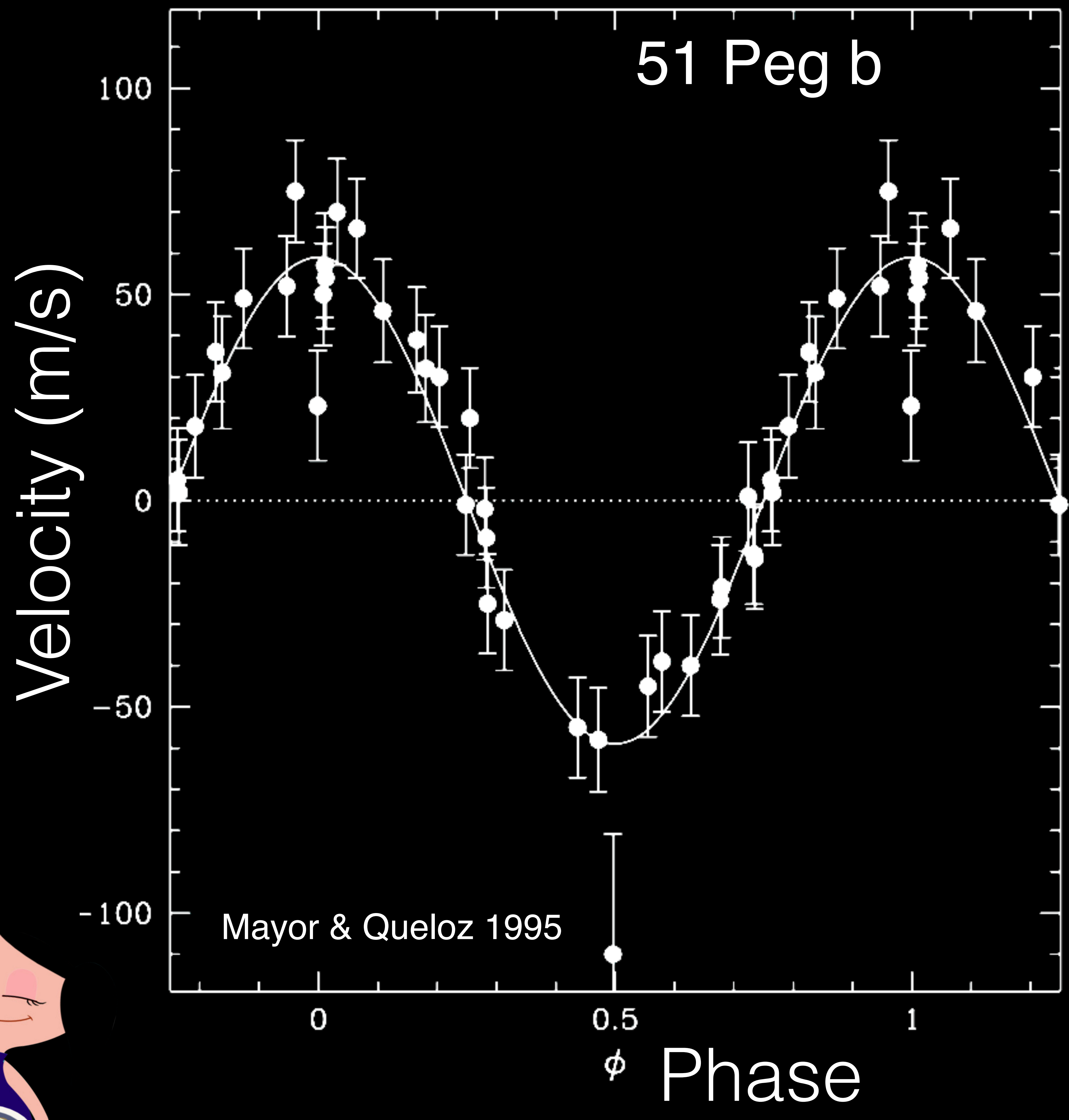
THE UNIVERSITY OF WARWICK

Image credits: NASA, ESA, SDO/HMI, MURAM, Big Bear Solar Observatory, HARPS-N. Cegla/Haywood/Watson

Confirming Alien Worlds & Determining Planet Mass

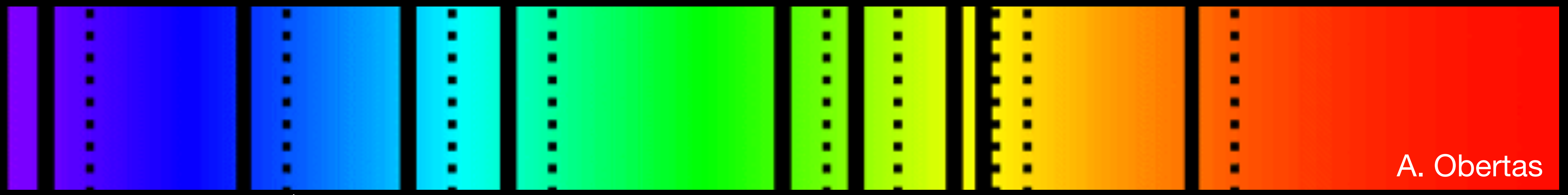


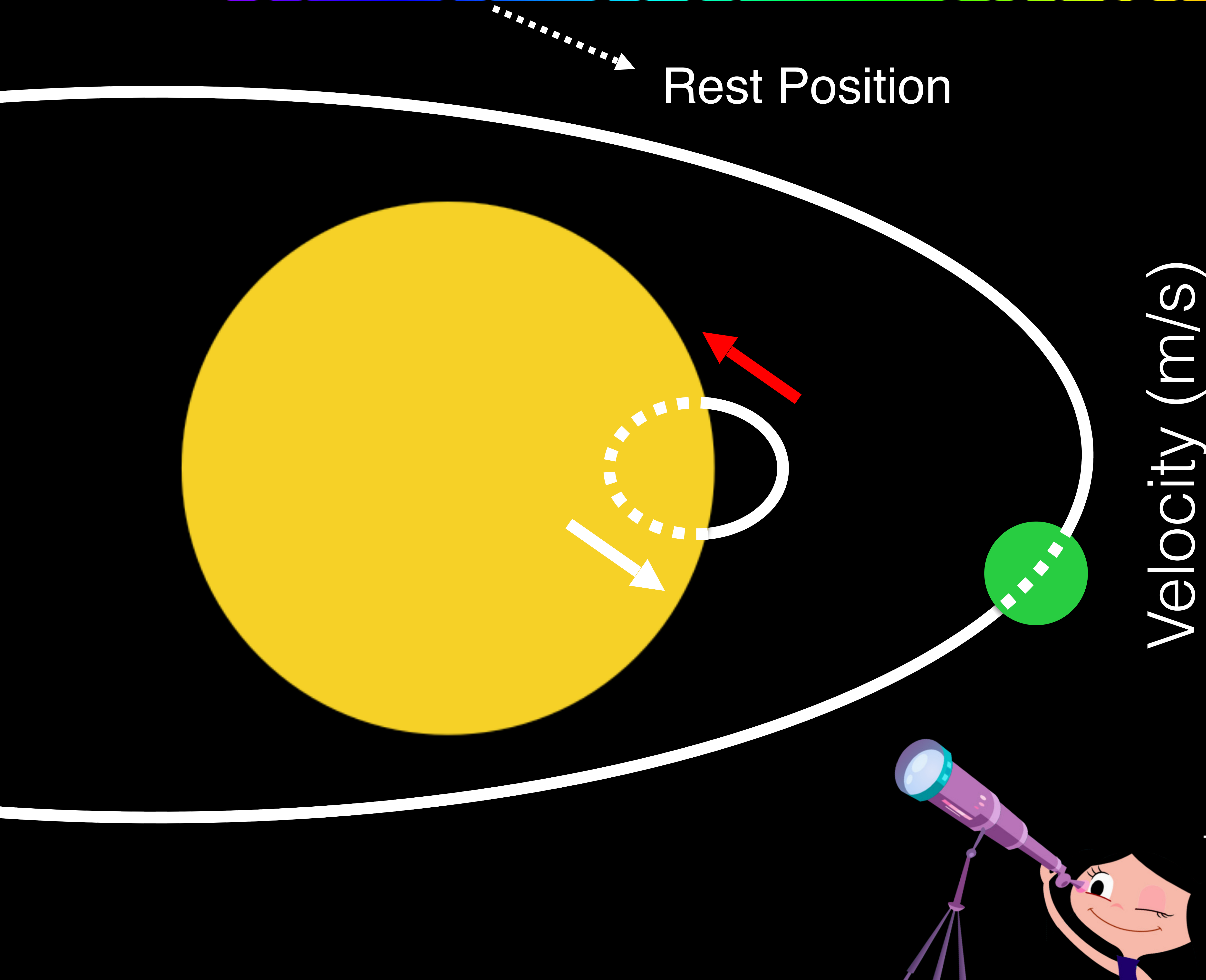


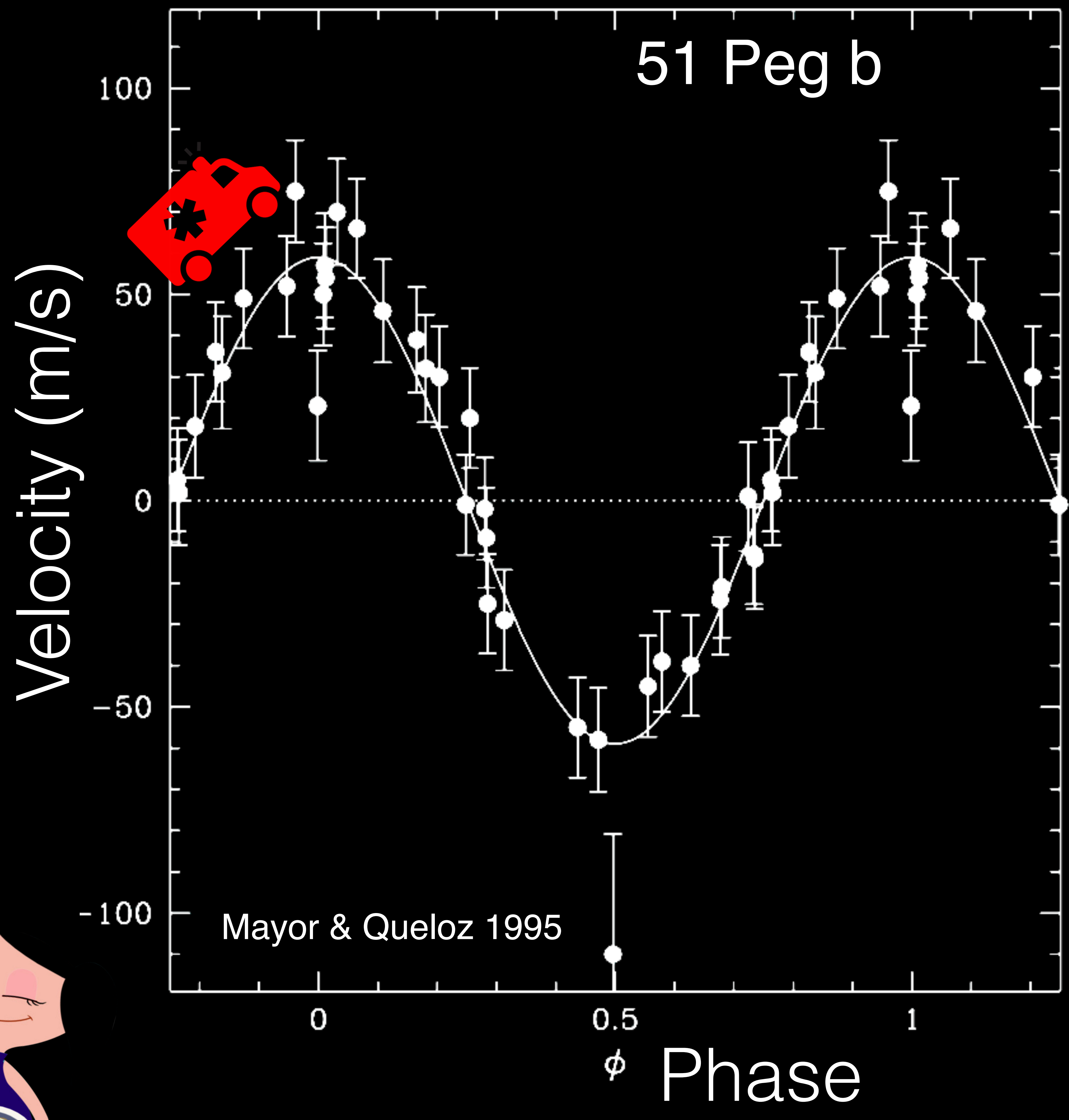


Cartoon credit: Earth to Luna; Universal Kids

Confirming Alien Worlds & Determining Planet Mass

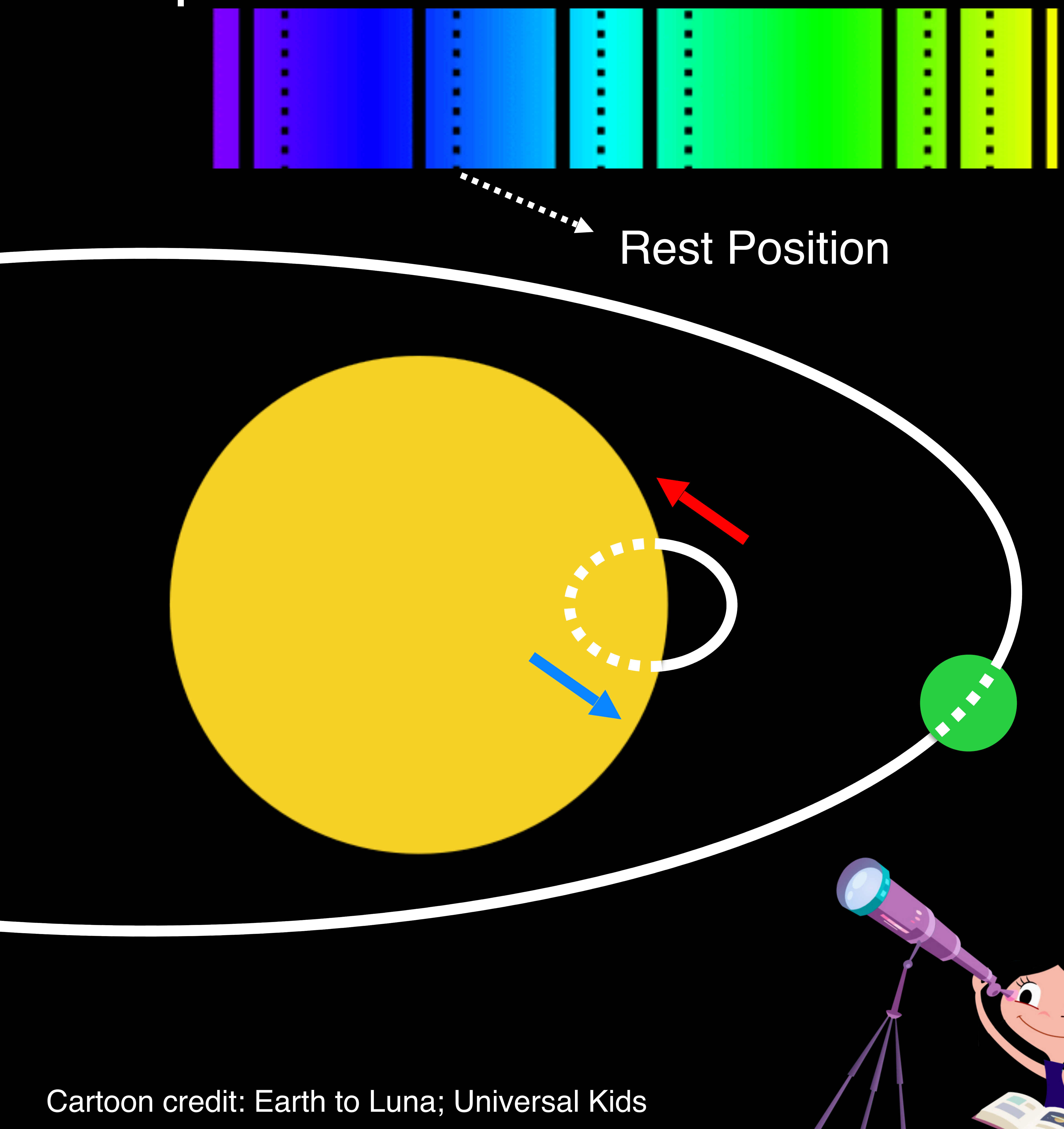


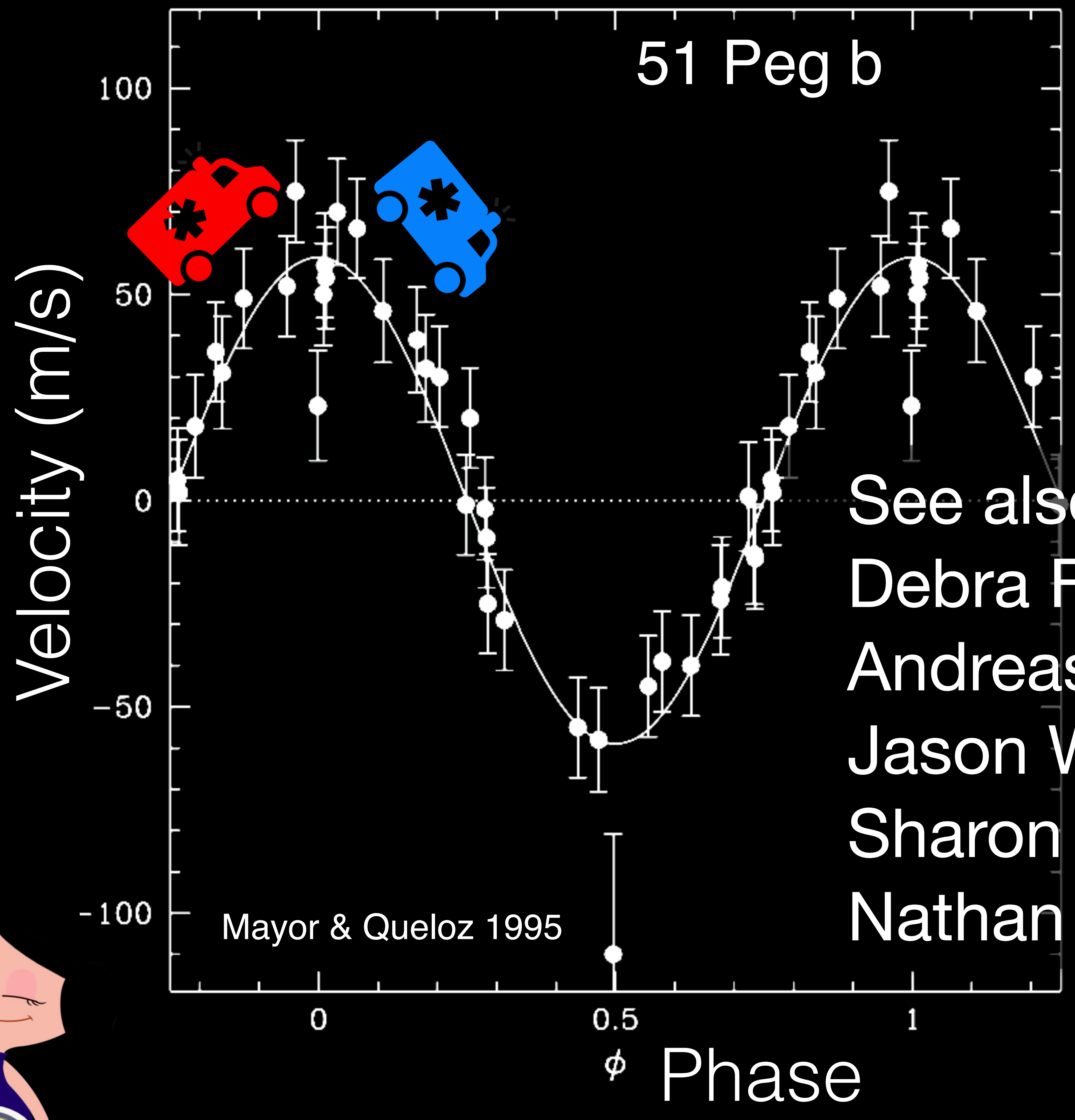




Cartoon credit: Earth to Luna; Universal Kids

Confirming Alien Worlds & Determining Planet Mass

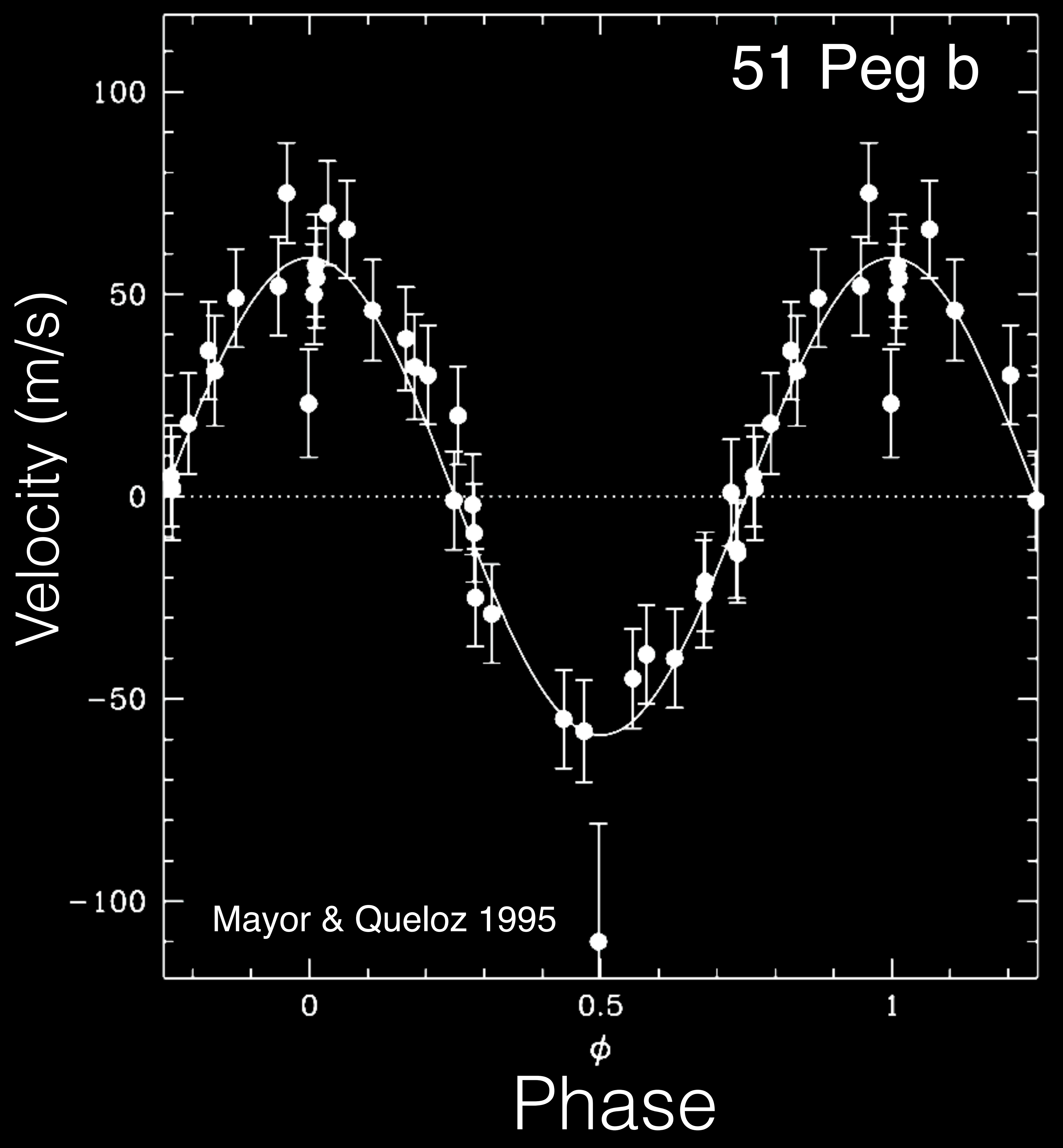




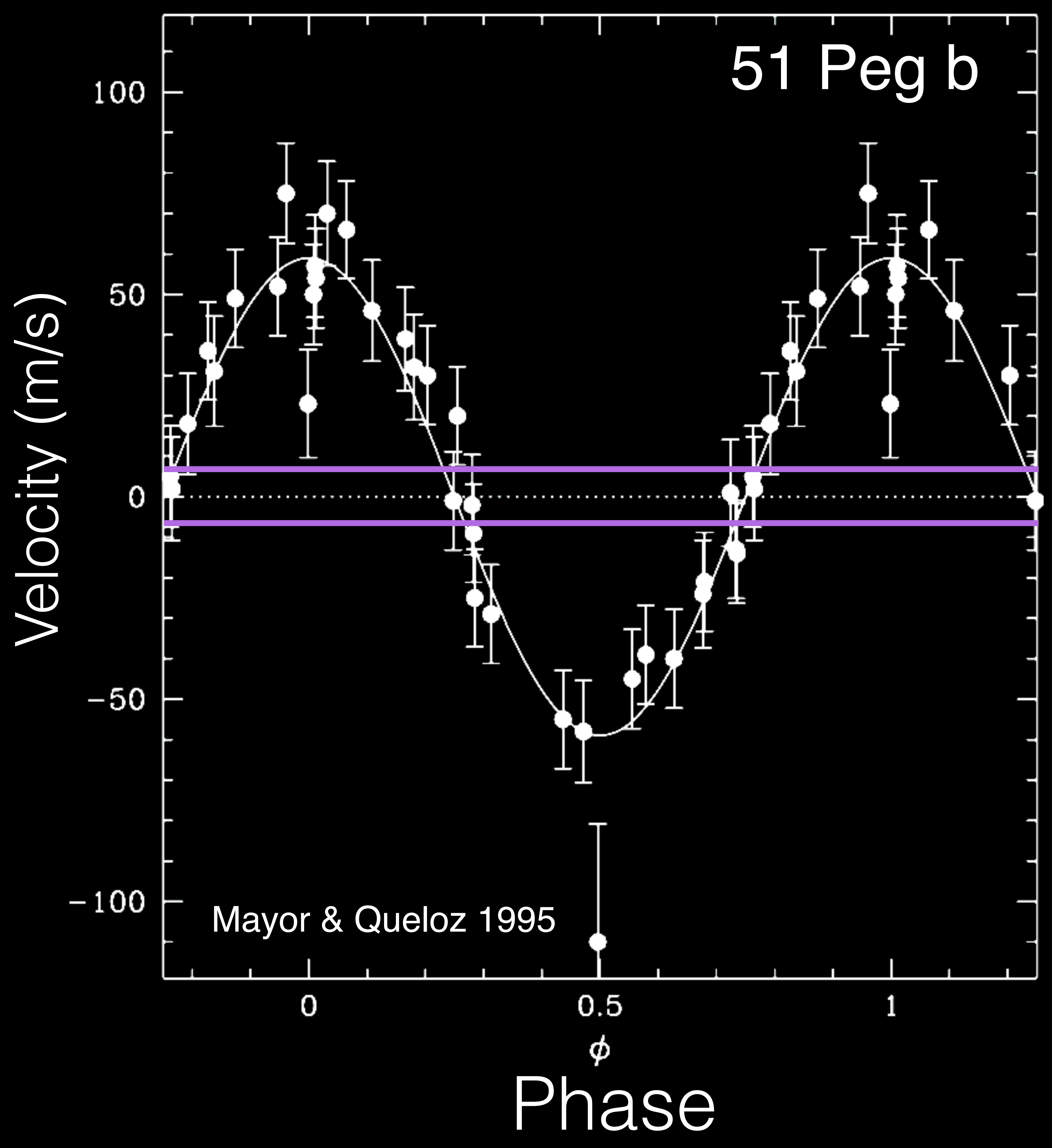
See also talks by:
Debra Fischer
Andreas Quirrenbach
Jason Wright
Sharon Wang
Nathan Hara

Cartoon credit: Earth to Luna; Universal Kids

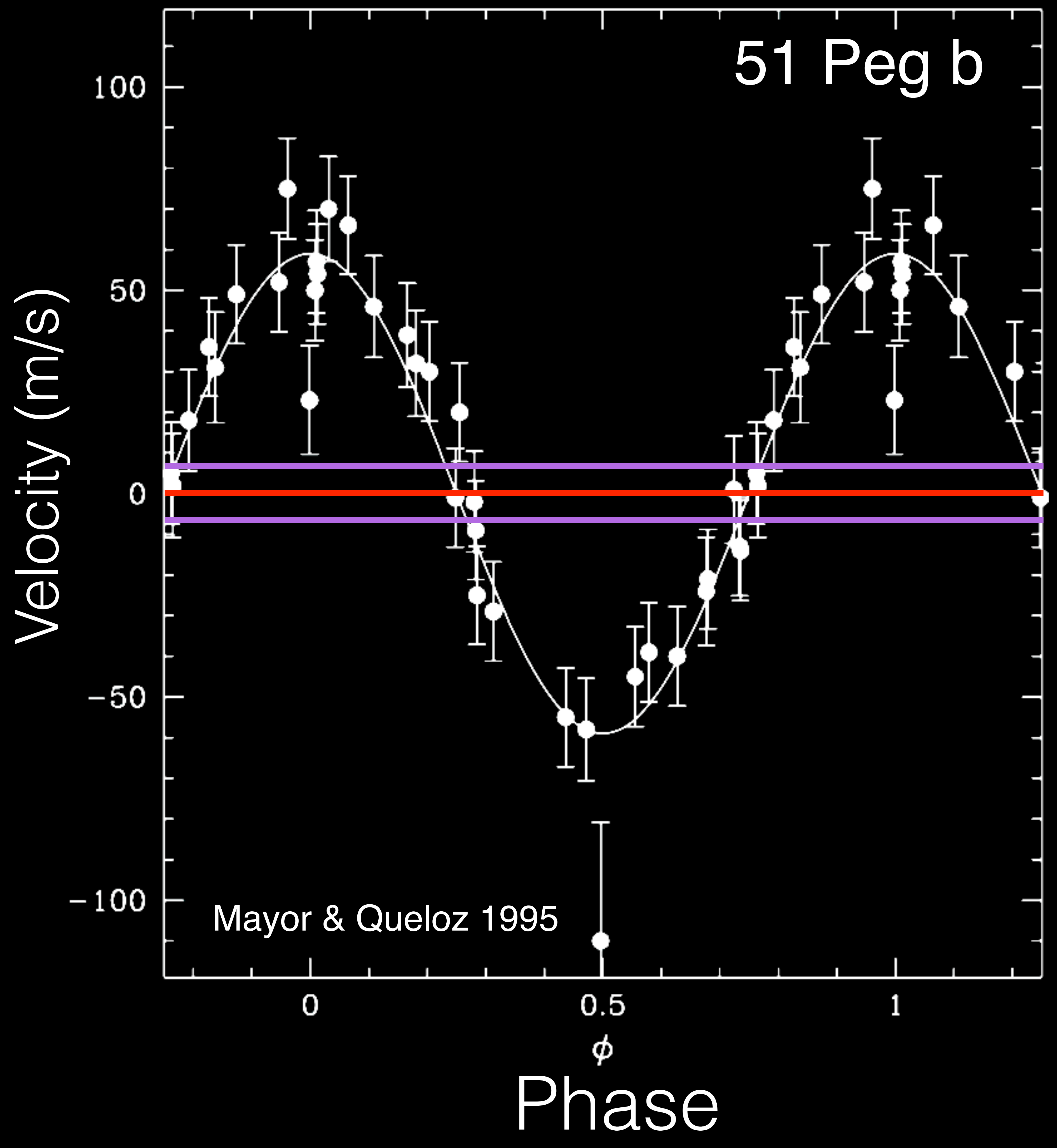
Confirming Alien Worlds & Determining Planet Mass

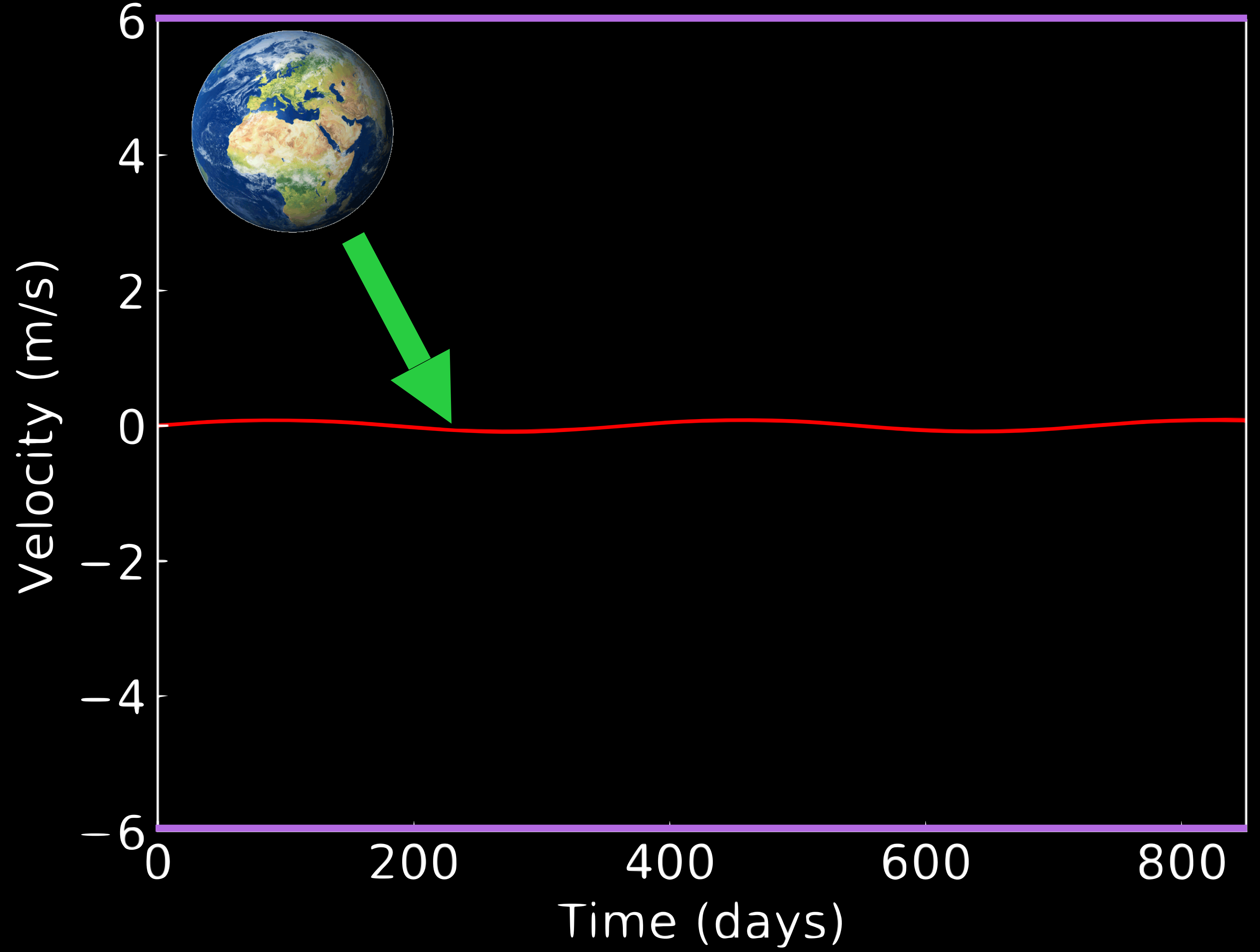


Confirming Alien Worlds & Determining Planet Mass

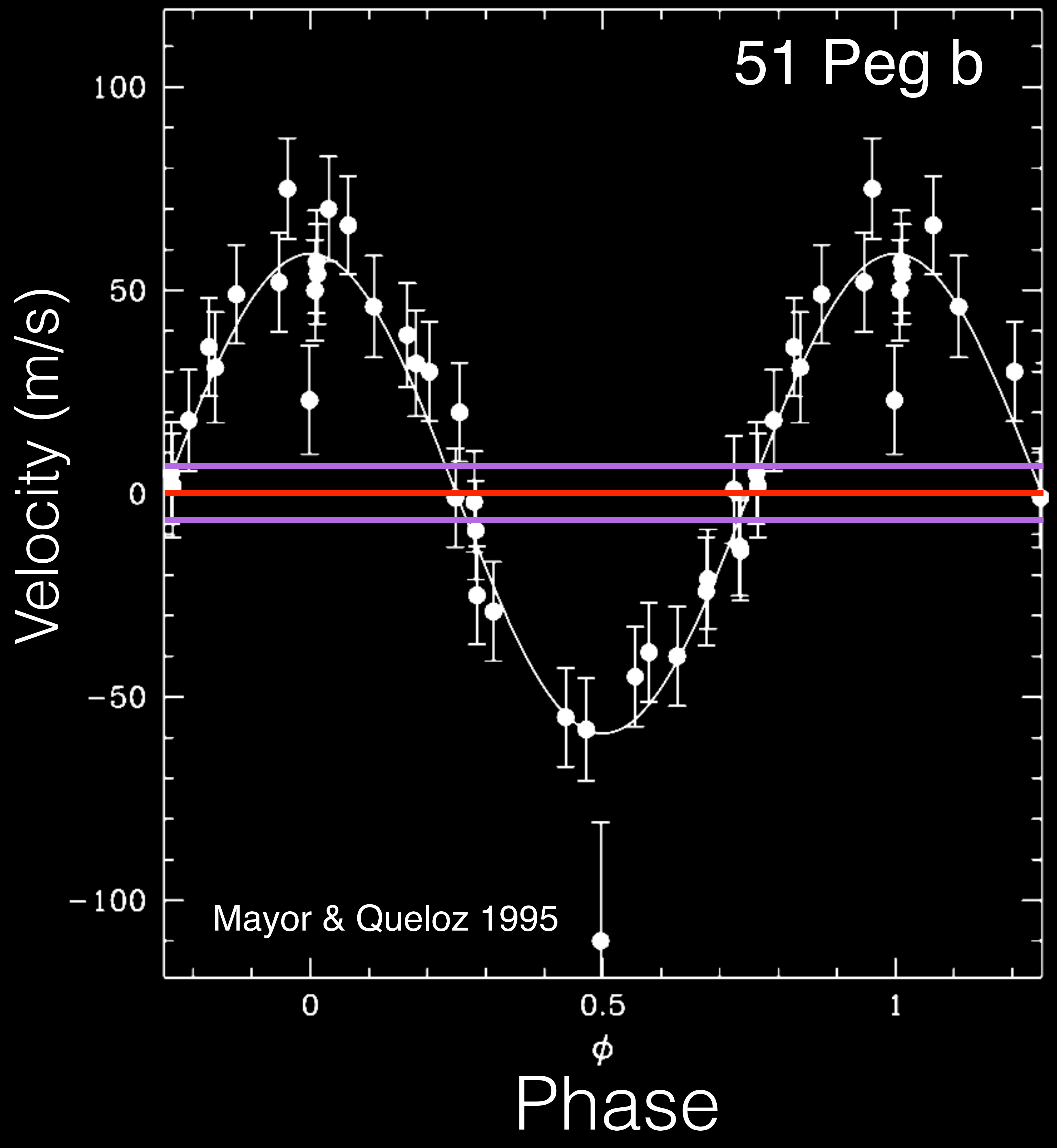


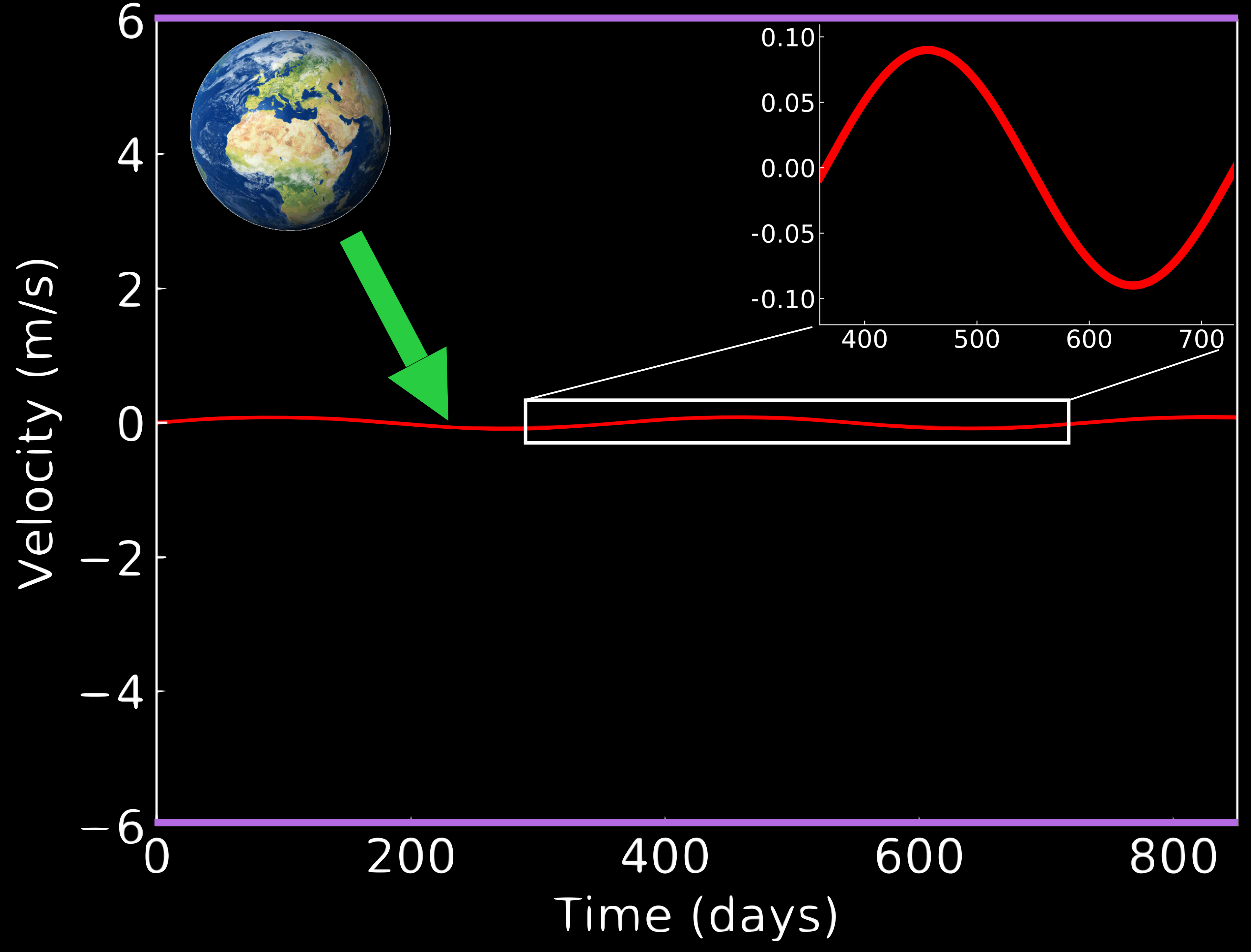
Confirming Alien Worlds & Determining Planet Mass



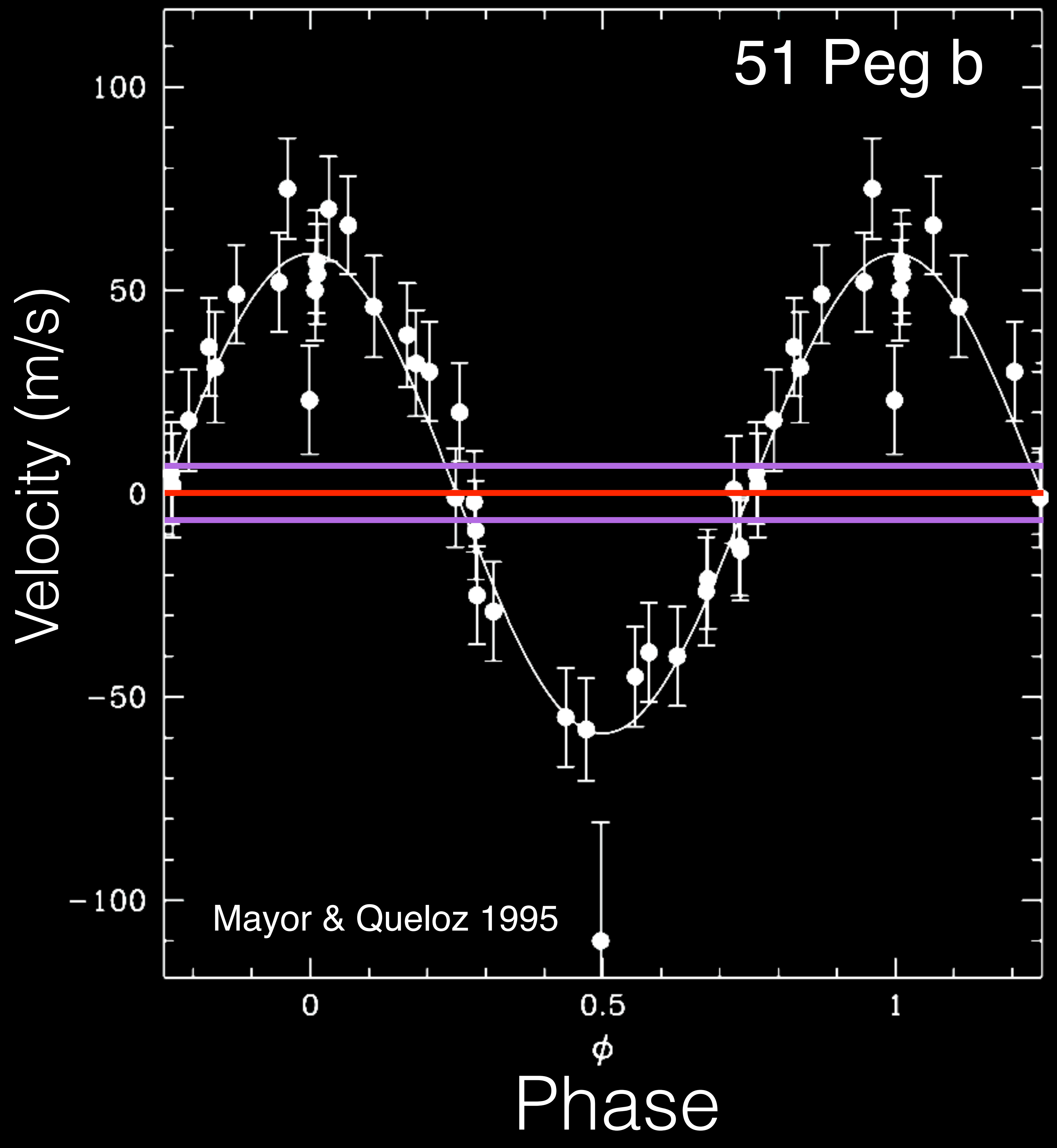


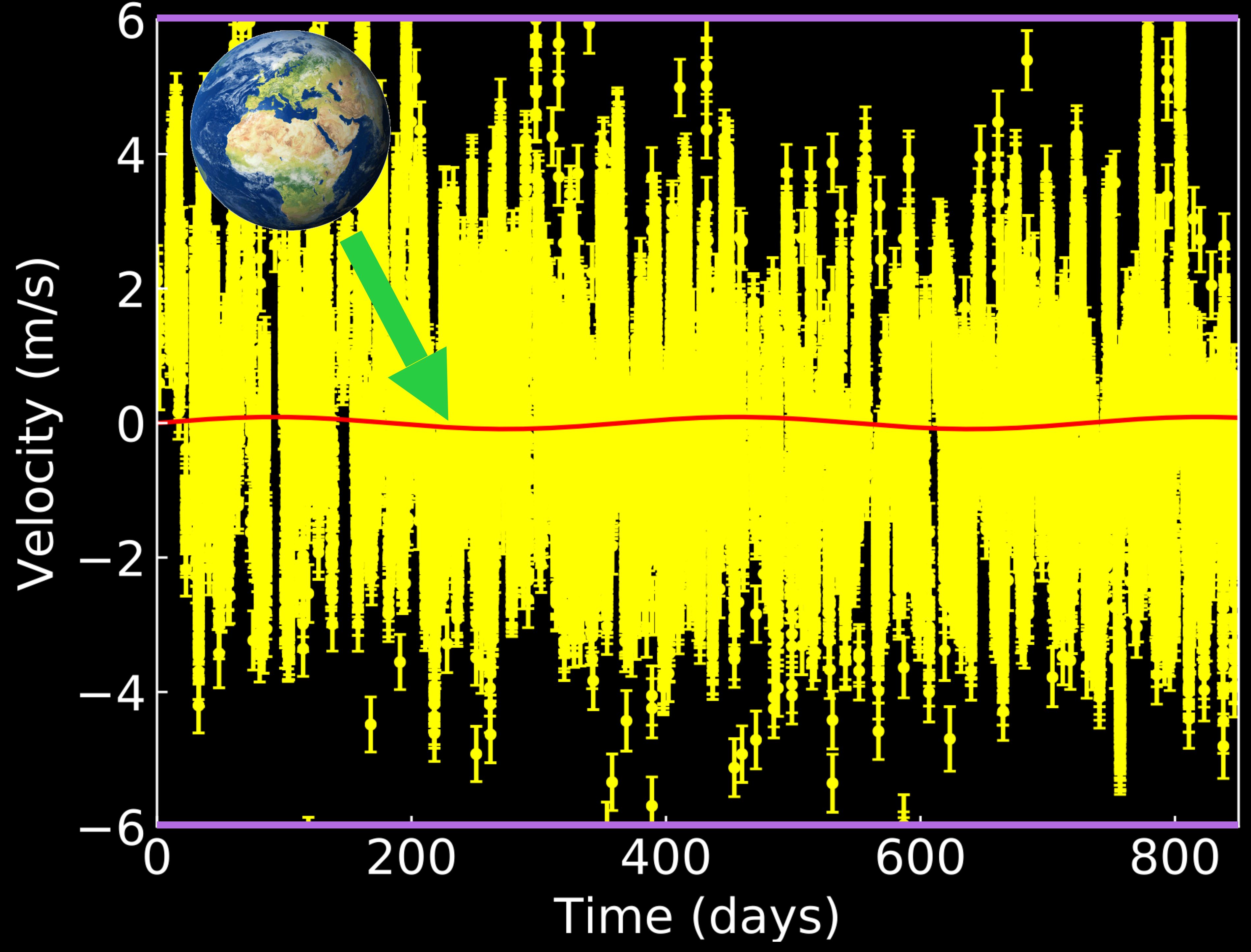
Confirming Alien Worlds & Determining Planet Mass





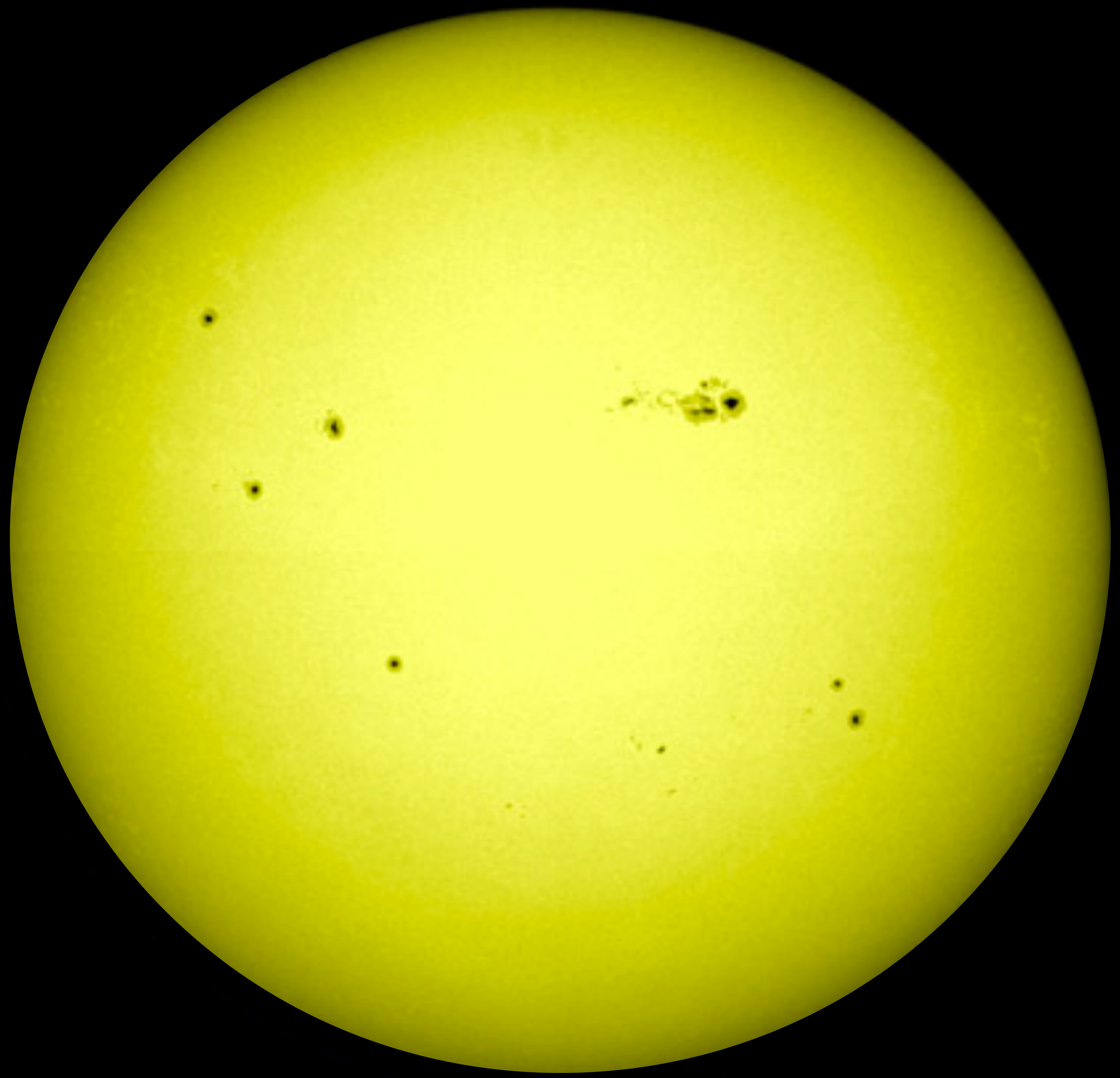
Confirming Alien Worlds & Determining Planet Mass

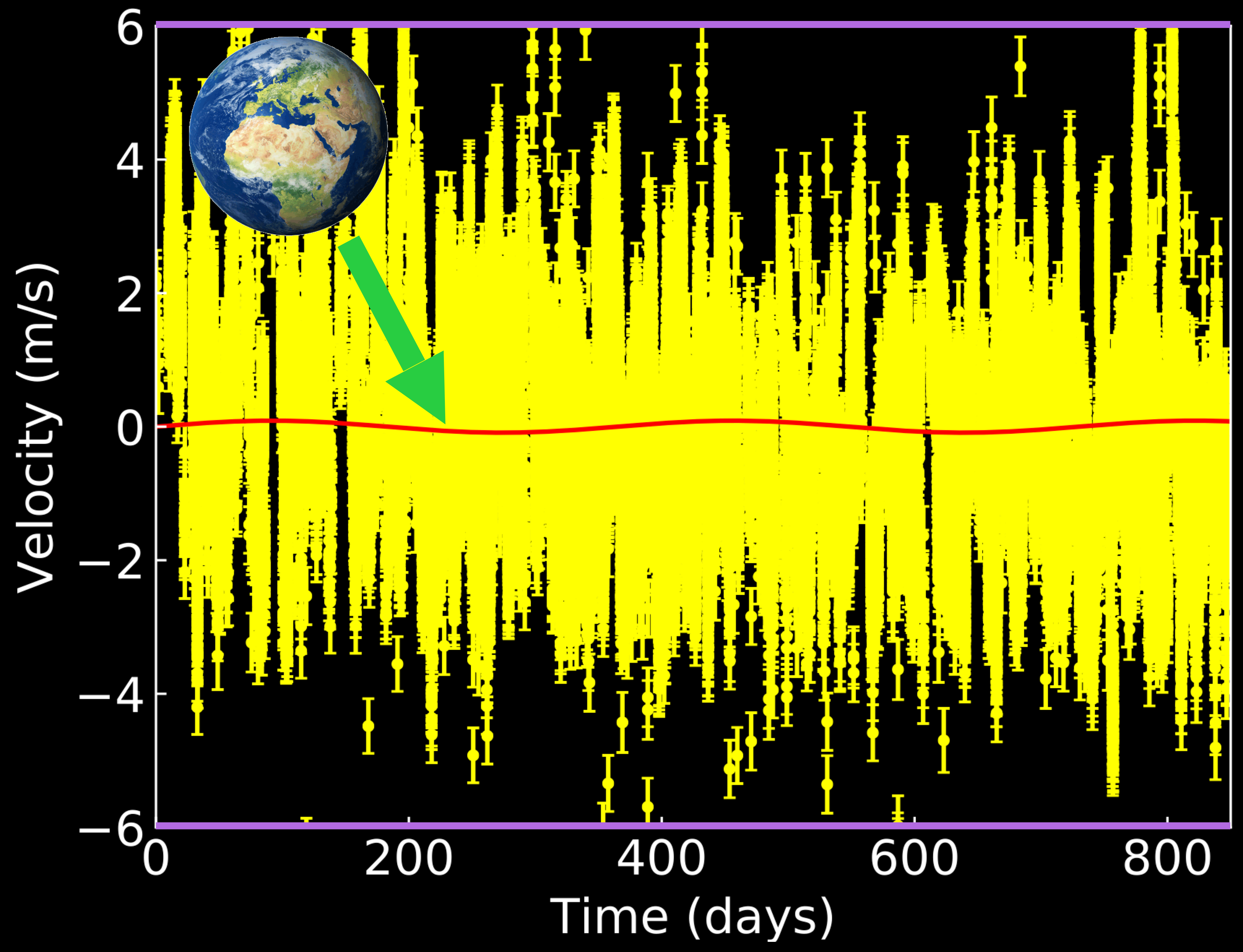




Solar data from HARPS-N Solar Telescope

Stellar Variability Induces Spurious Velocity Shifts





Solar data from HARPS-N Solar Telescope; Solar image from SDO

See talk by Annelies Mortier for more on the Solar data

Stellar Variability

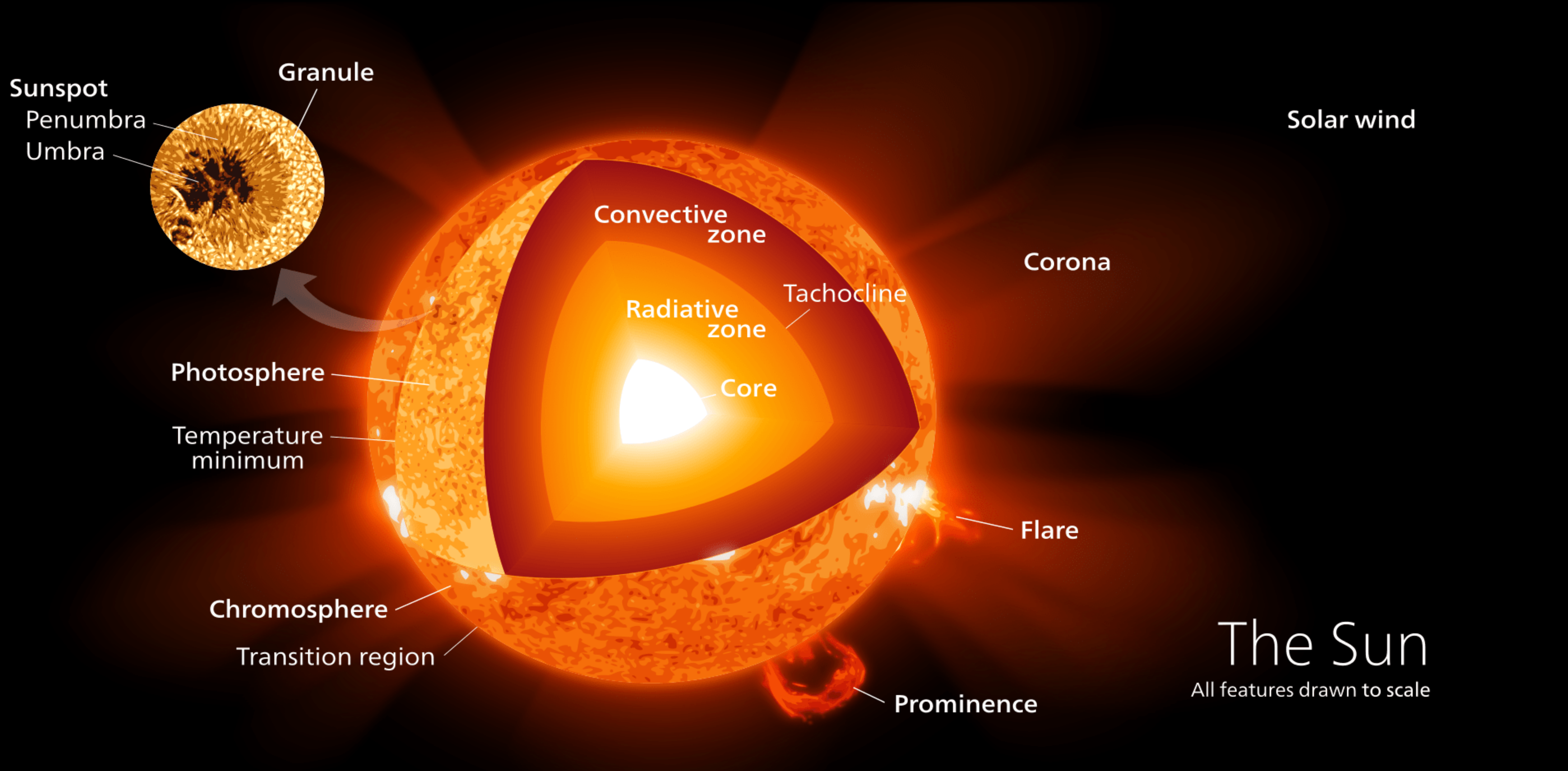


Image credit: Kelvin Song, Wikipedia

Stellar Photosphere Components

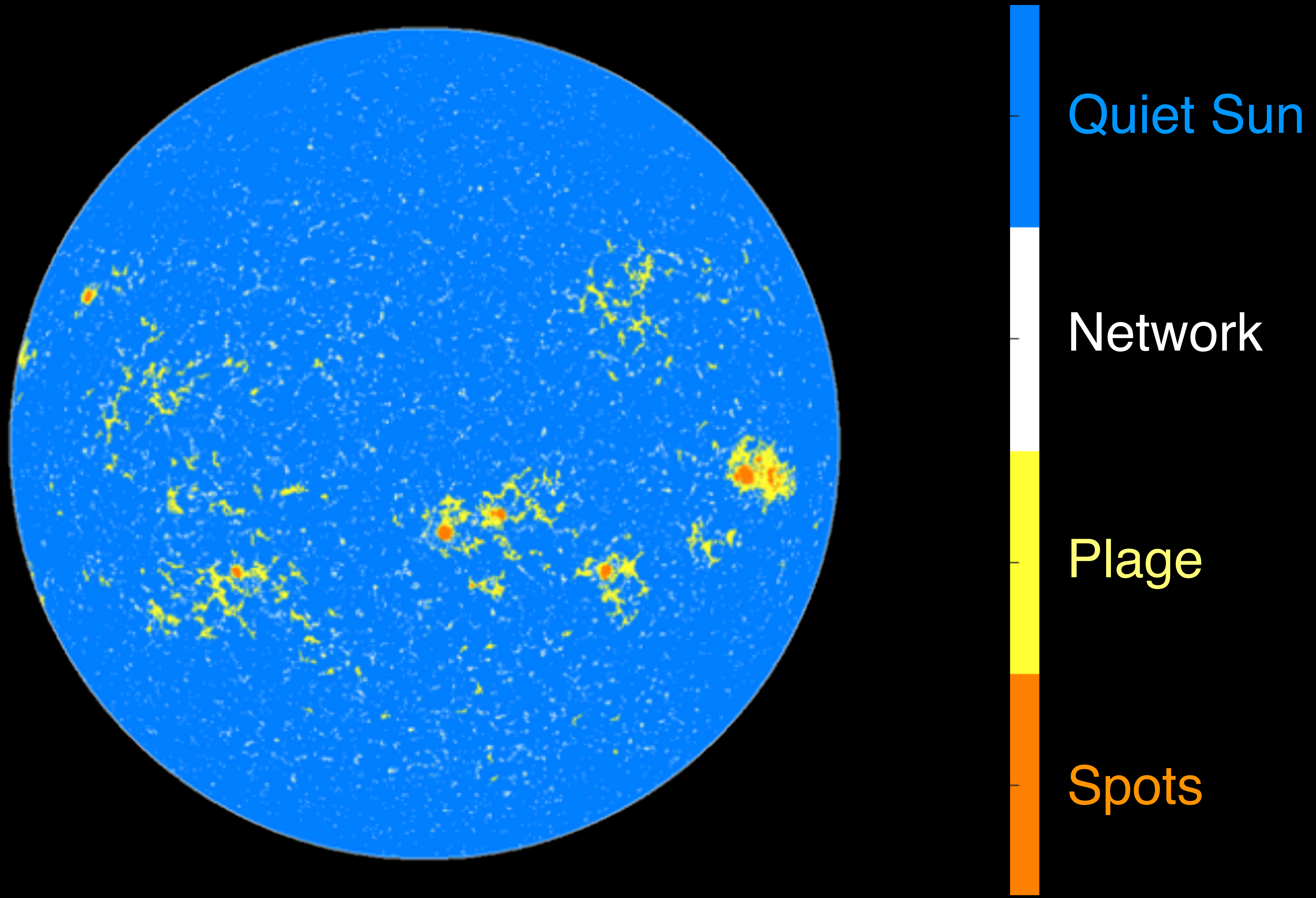
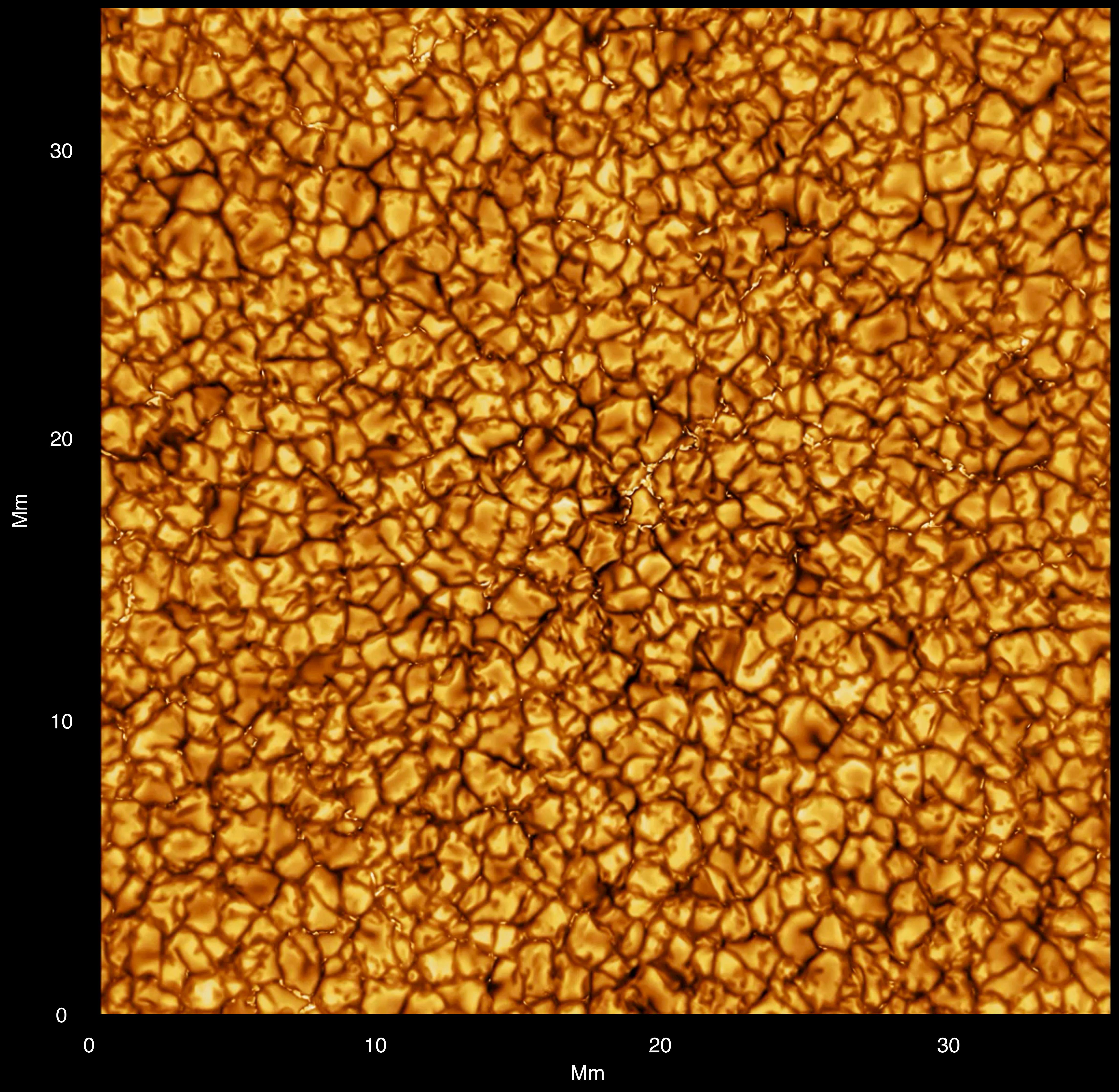


Image credit: T. Milbourne (See Milbourne et al 2019 & Haywood et al 2016 for definition details)

Stellar Variability: Convection/Granulation



DKIST Solar Observations

"Quiet Sun"

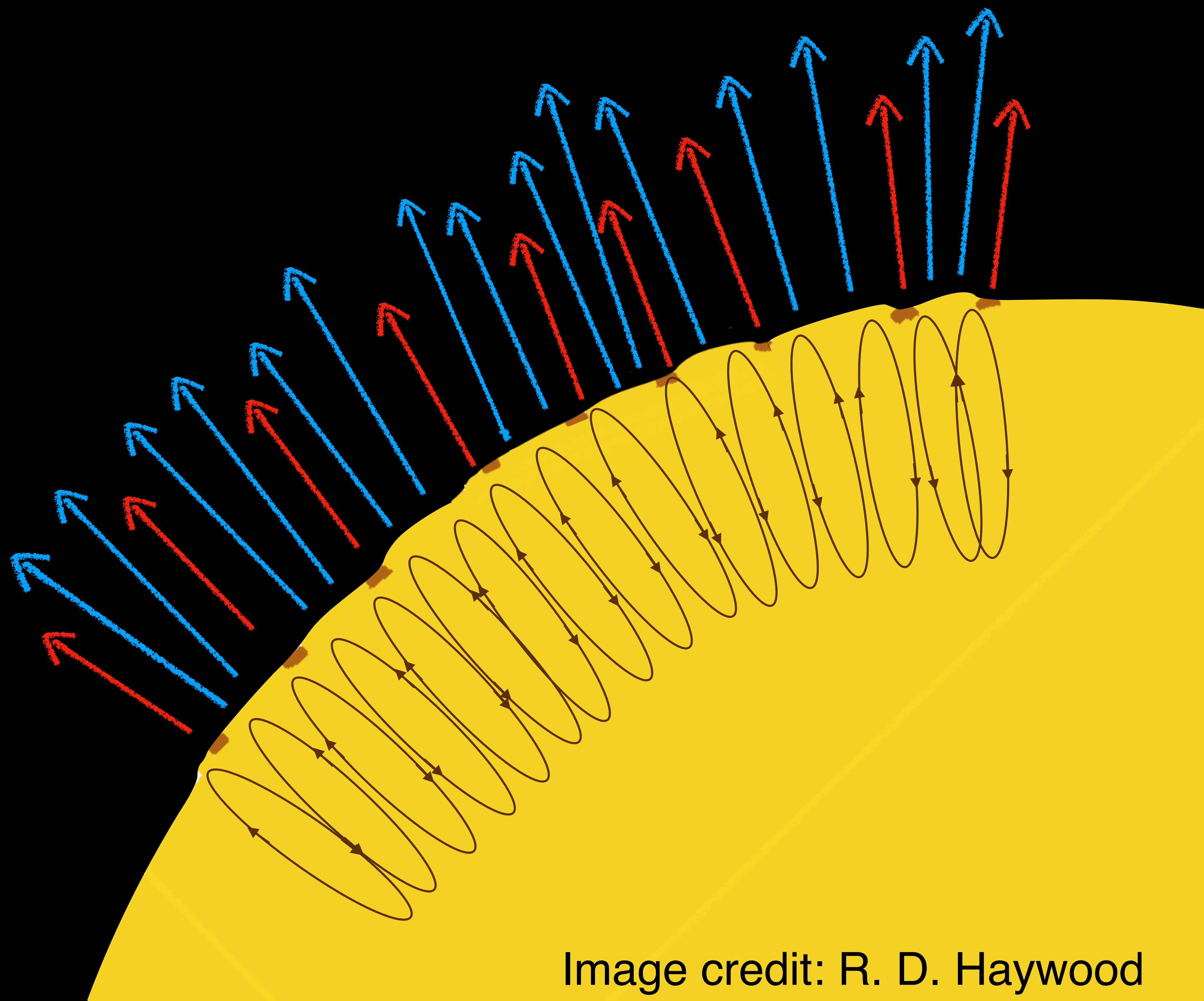
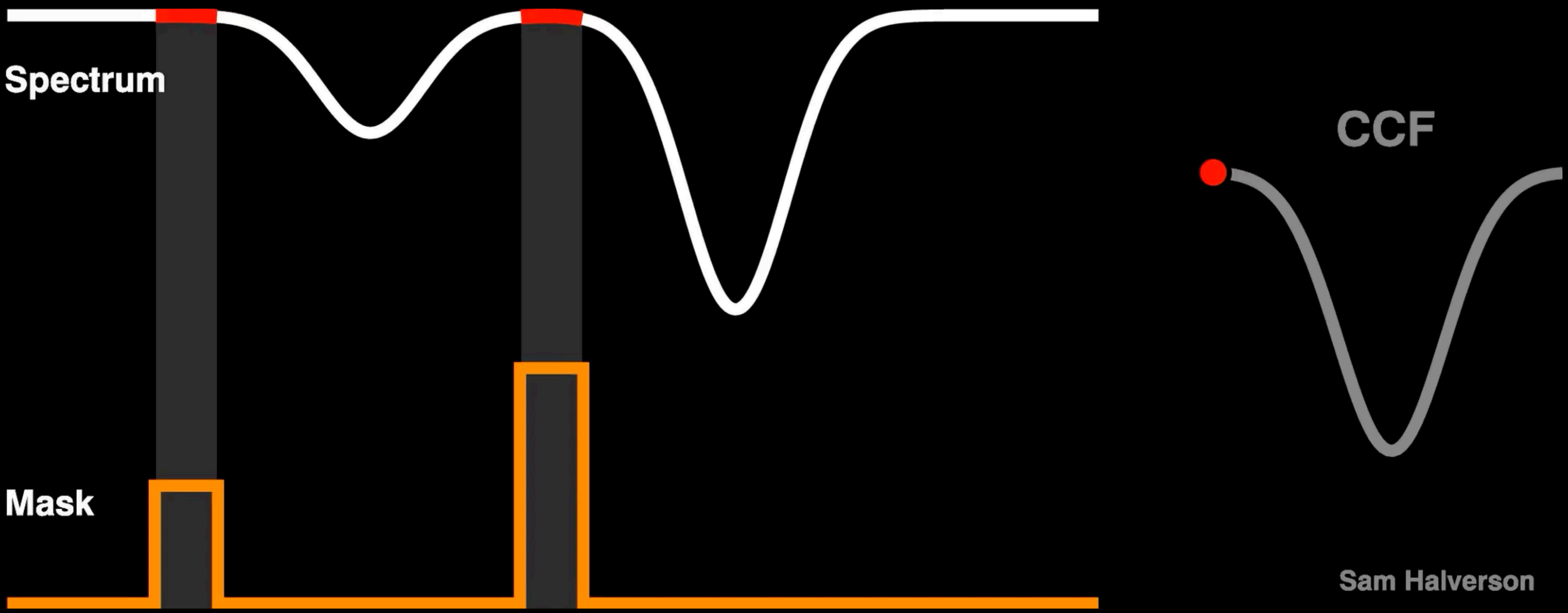


Image credit: R. D. Haywood

Confirming Alien Worlds: Measuring Velocities



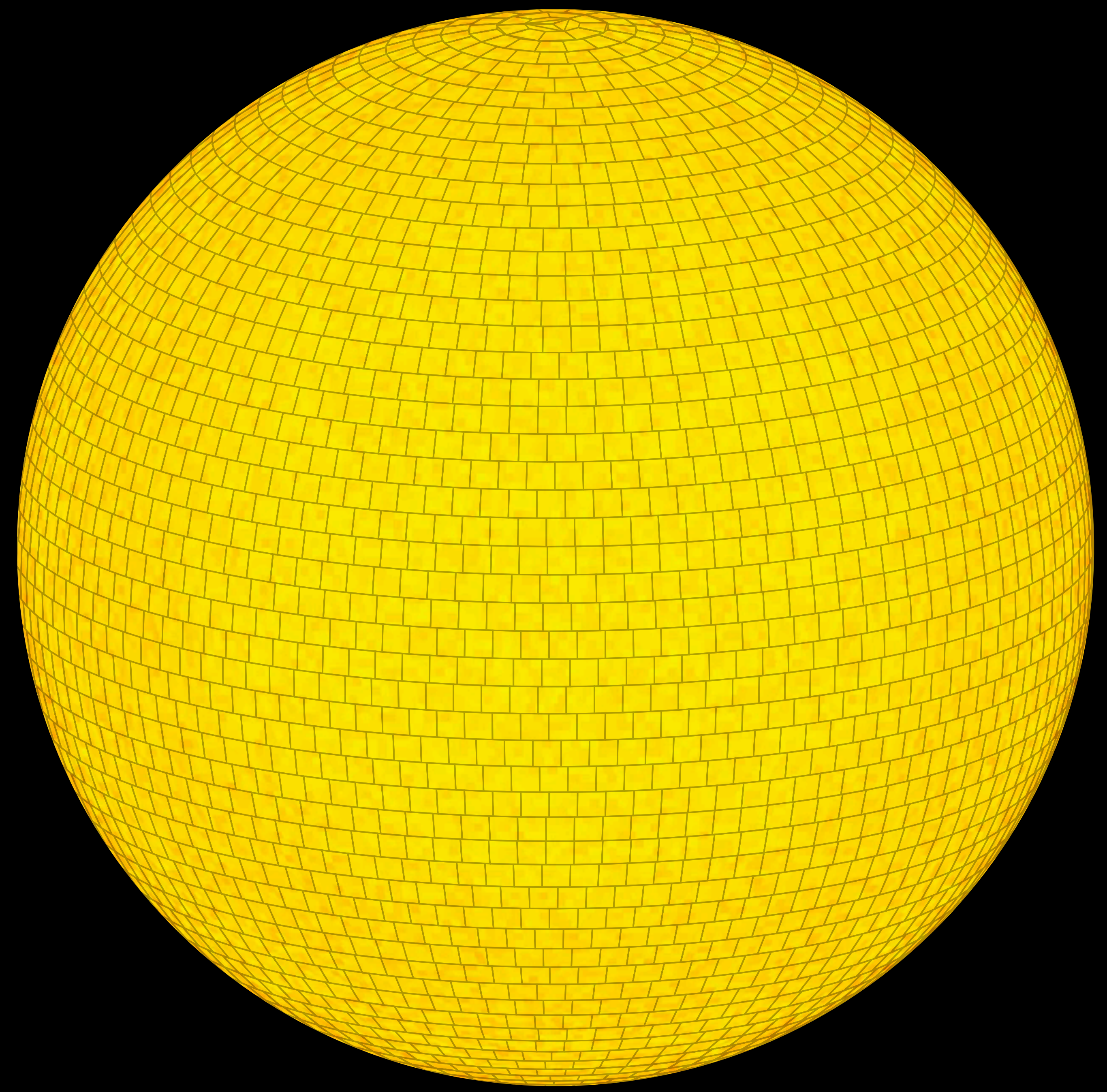
See talks by Sharon Wang, Stephanie Leifer and Sam Halverson for more details

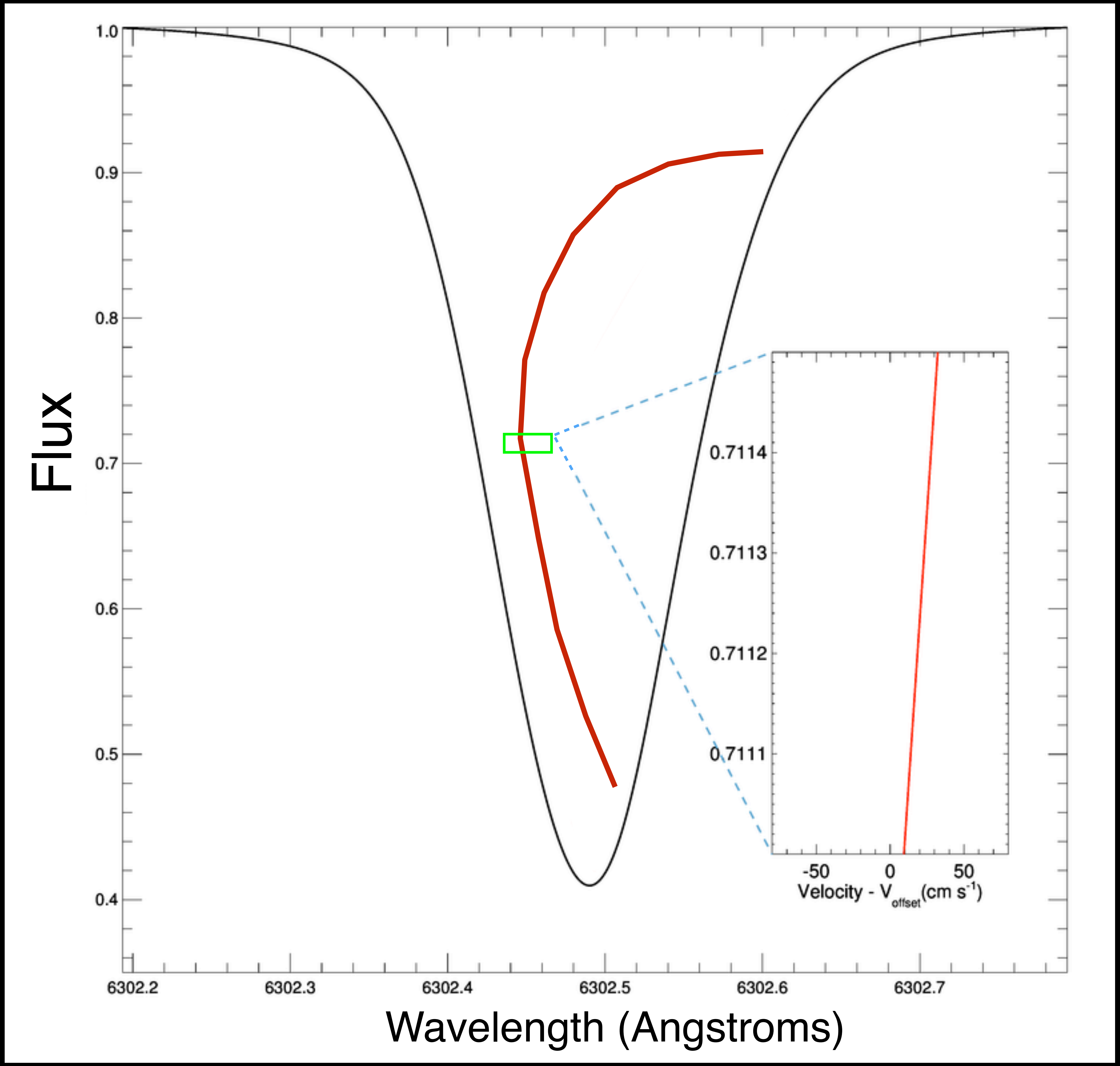
Stellar Variability: Convection/Granulation

Convection induces asymmetries, a net blueshift, and temporal velocity shifts

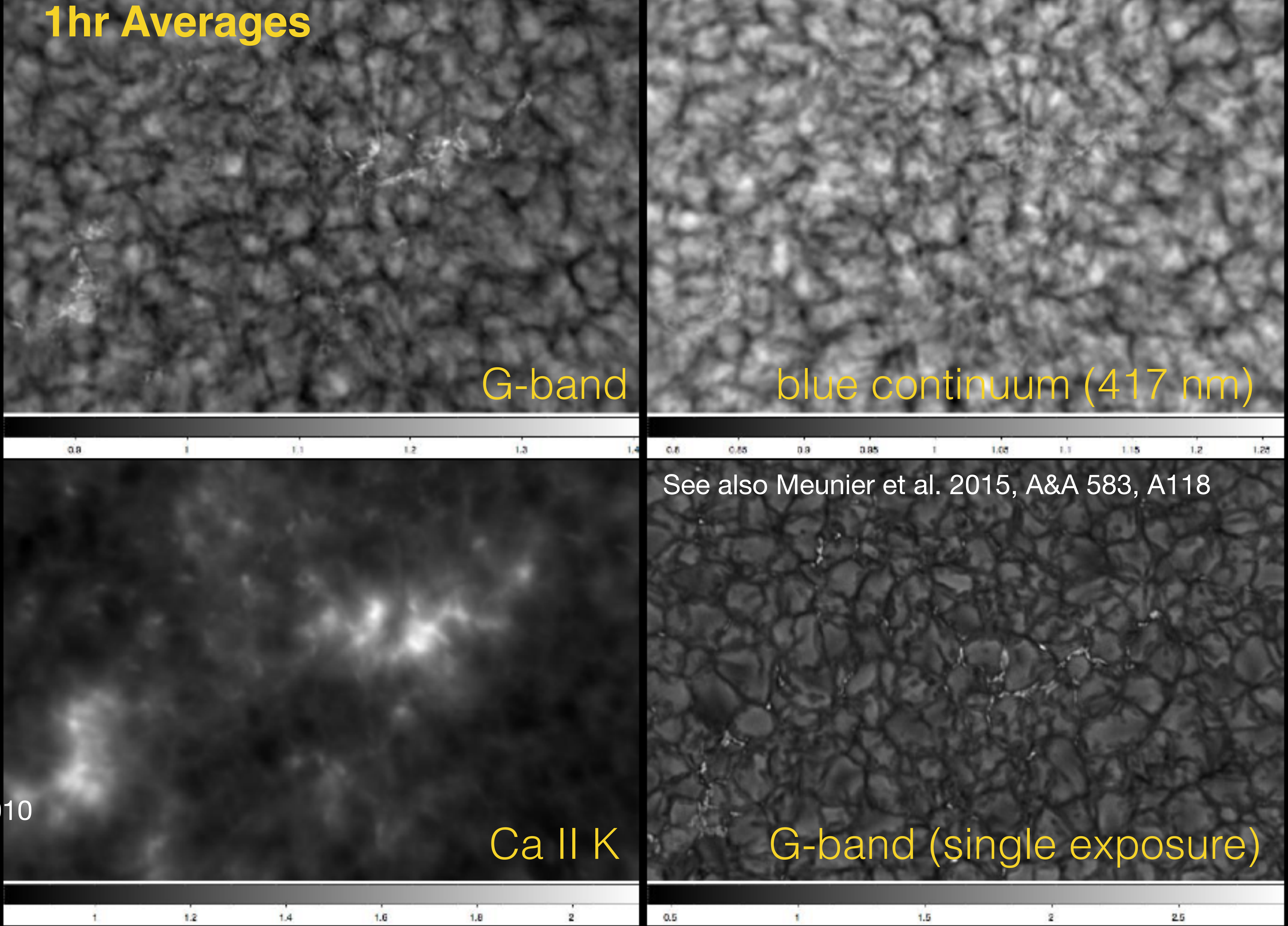
Image credit: R. D. Haywood

Stellar Variability: Convection/Granulation



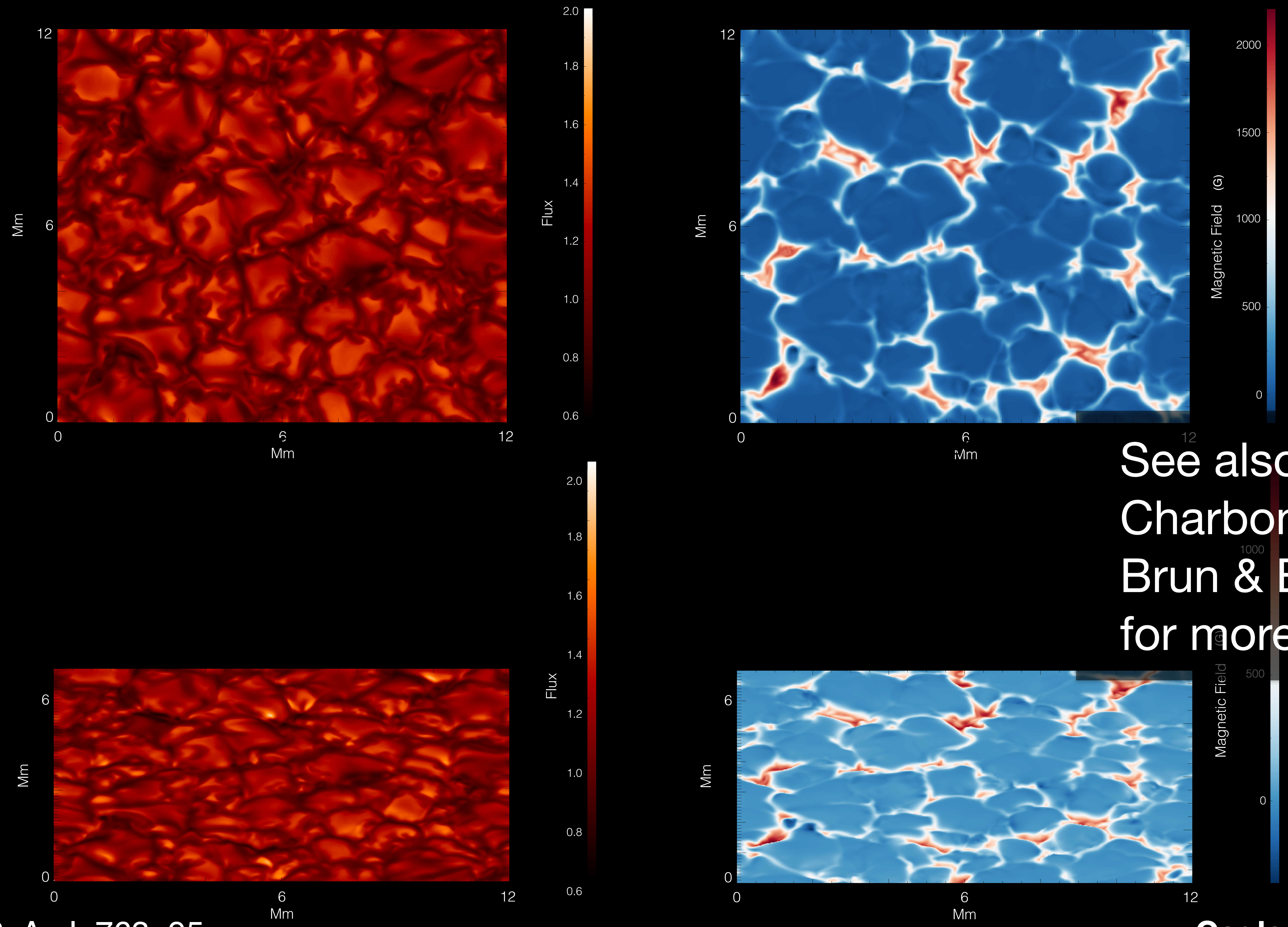


Cegla, H. M. et al 2019, ApJ, 879, 55



Jess et al 2010
Dunn Solar
Telescope

Stellar Variability: Convection—> Magneto-convection



See also Charbonneau 2010/14, Brun & Browning 2017 for more on dynamos

Cegla et al. 2013, ApJ, 763, 95

Cegla et al, 2018, ApJ, 866, 55

Takeaways: Magneto-convection/Granulation

Granule lifetimes from ~2 to 10 min

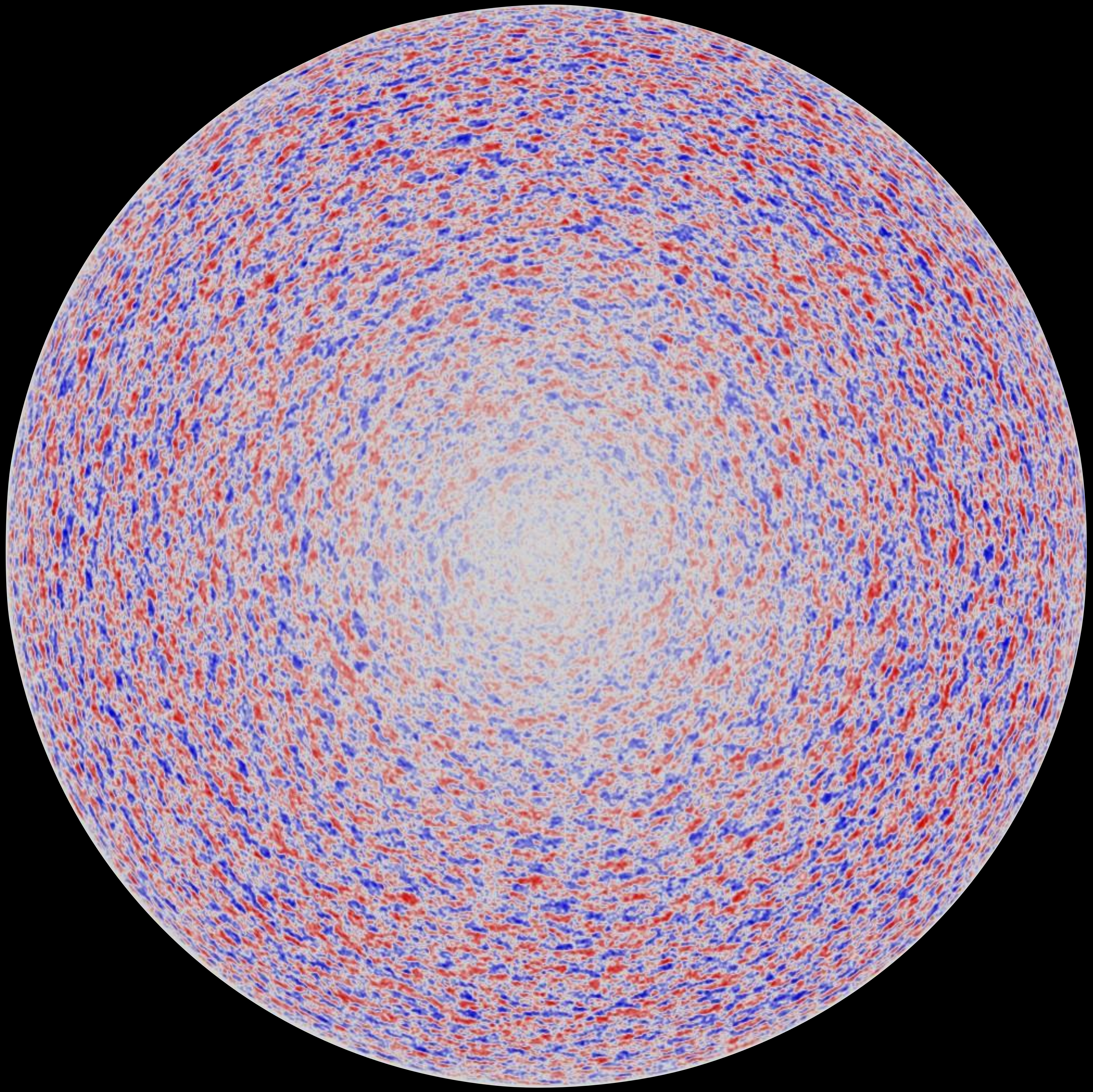
Individual granules have 1-4 km/s velocities

Net effect is several 10s of cm/s

Net RV effect decreases for cooler stars and increases for evolved stars

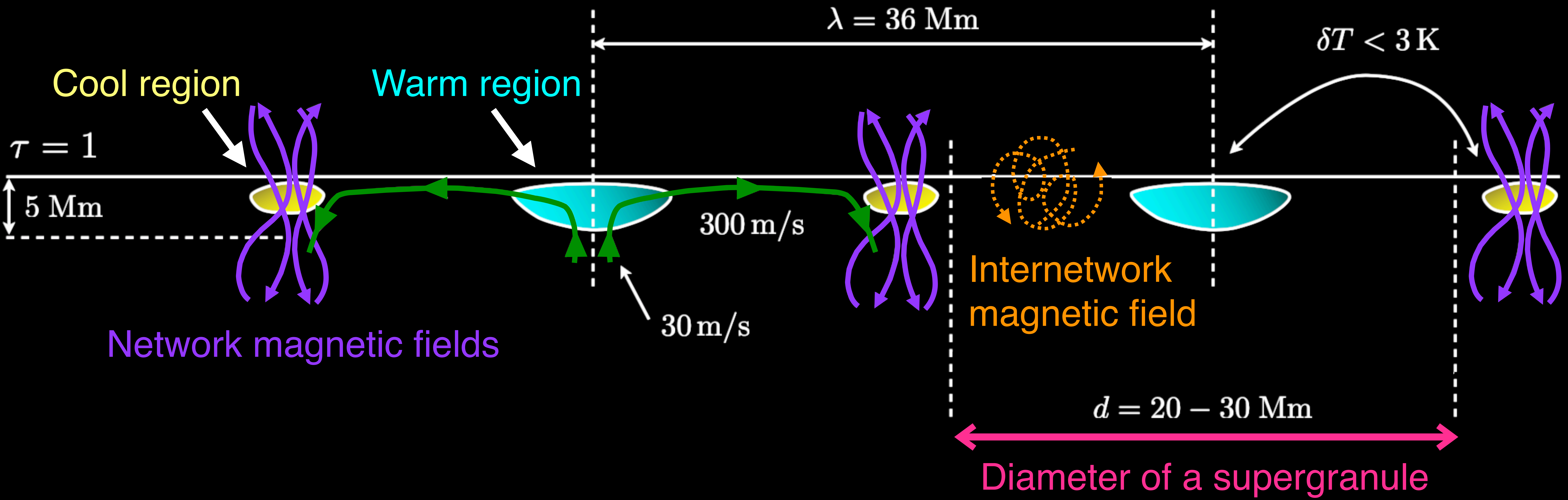
Most ‘stellar variability’ governed by interplay between convection and magnetic fields

Stellar Variability: Supergranulation



MDI/SOHO Dopplergram

Stellar Variability: Supergranulation



Rieutord & Rincon 2010

Takeaways: Supergranulation

Supergranular lifetime on the Sun is ~1.8 days

Collections of granules in ~30 Mm diameter

Horizontal flows of ~300 m/s on the Sun

Net effect is on the m/s level

Origin remains unclear, largely only studied on the Sun

Stellar Variability: Mesogranulation

"… it is very likely that mesogranulation is a ghost feature of surface convection generated by averaging procedures."

Rieutord & Rincon 2010

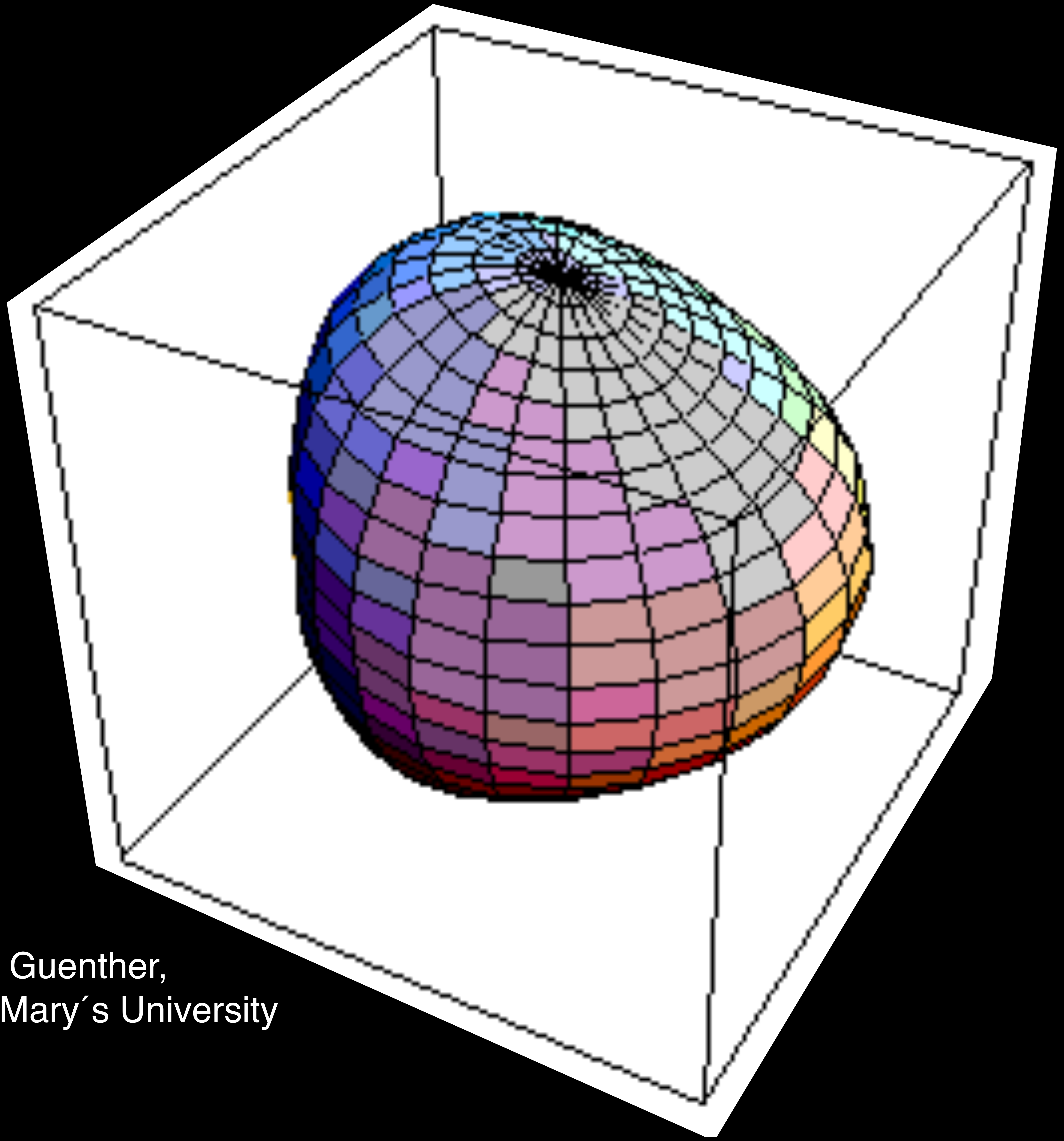
"… high-resolutions, space-based observations with the SDO … have now clearly confirmed the lack of a distinctive spectral bump at mesogranulation scales"

Rincon & Rieutord 2018

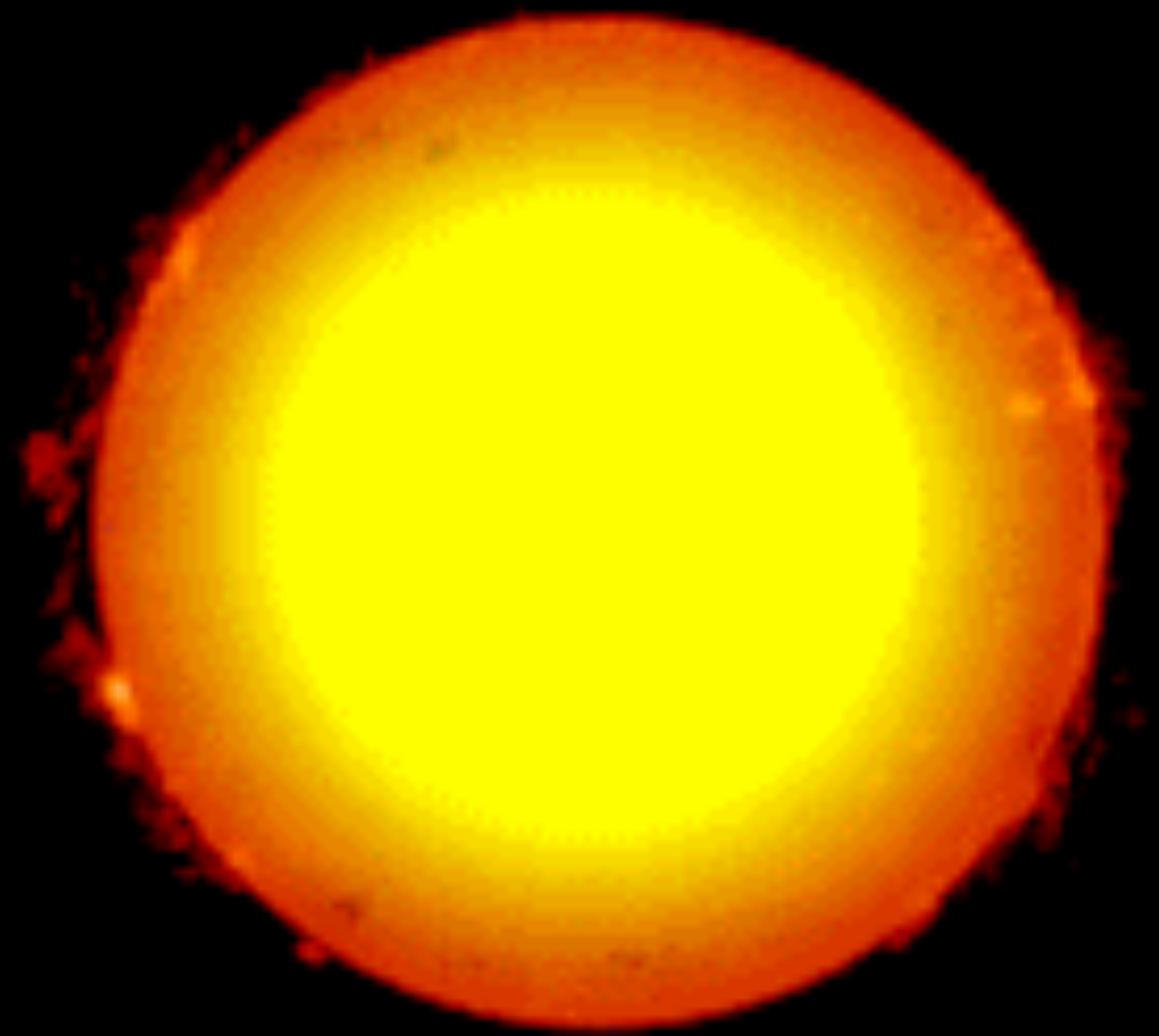
But this remains somewhat controversial …

Corsaro et al. 2017; Kessar et al. 2019

Stellar Variability: Pressure-mode Oscillations

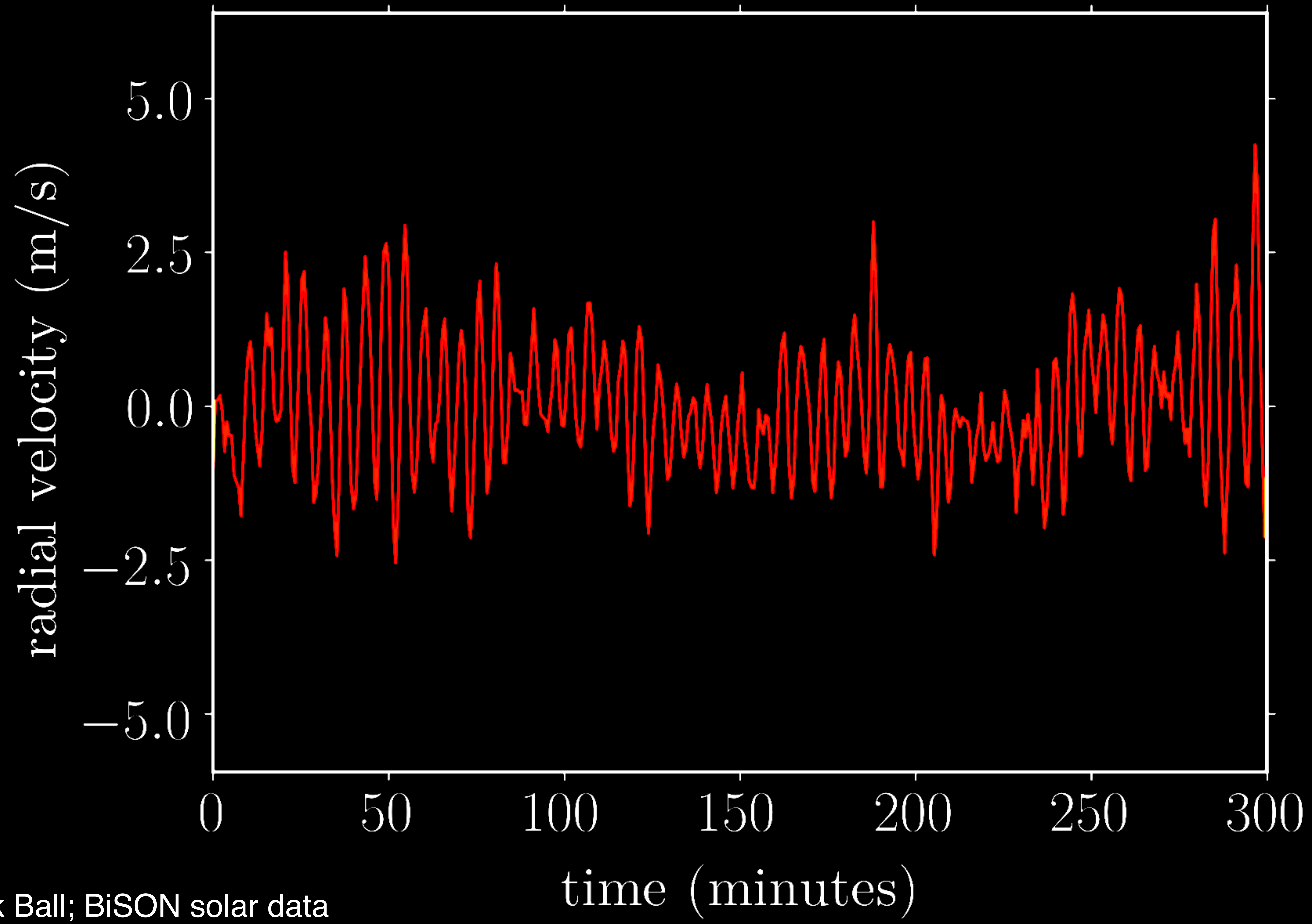


David Guenther,
Saint Mary´s University



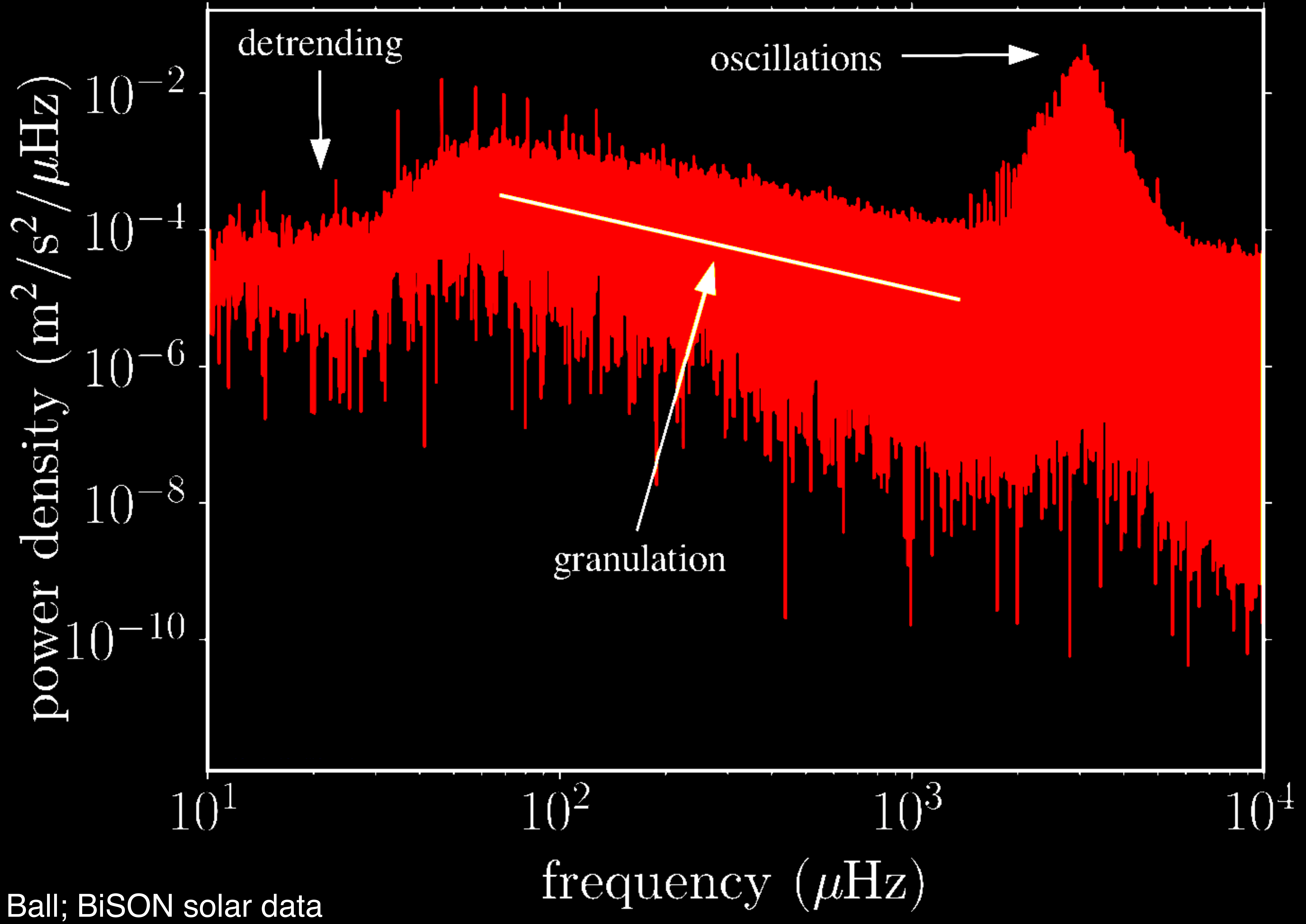
http://bison.ph.bham.ac.uk

Granulation & Oscillations



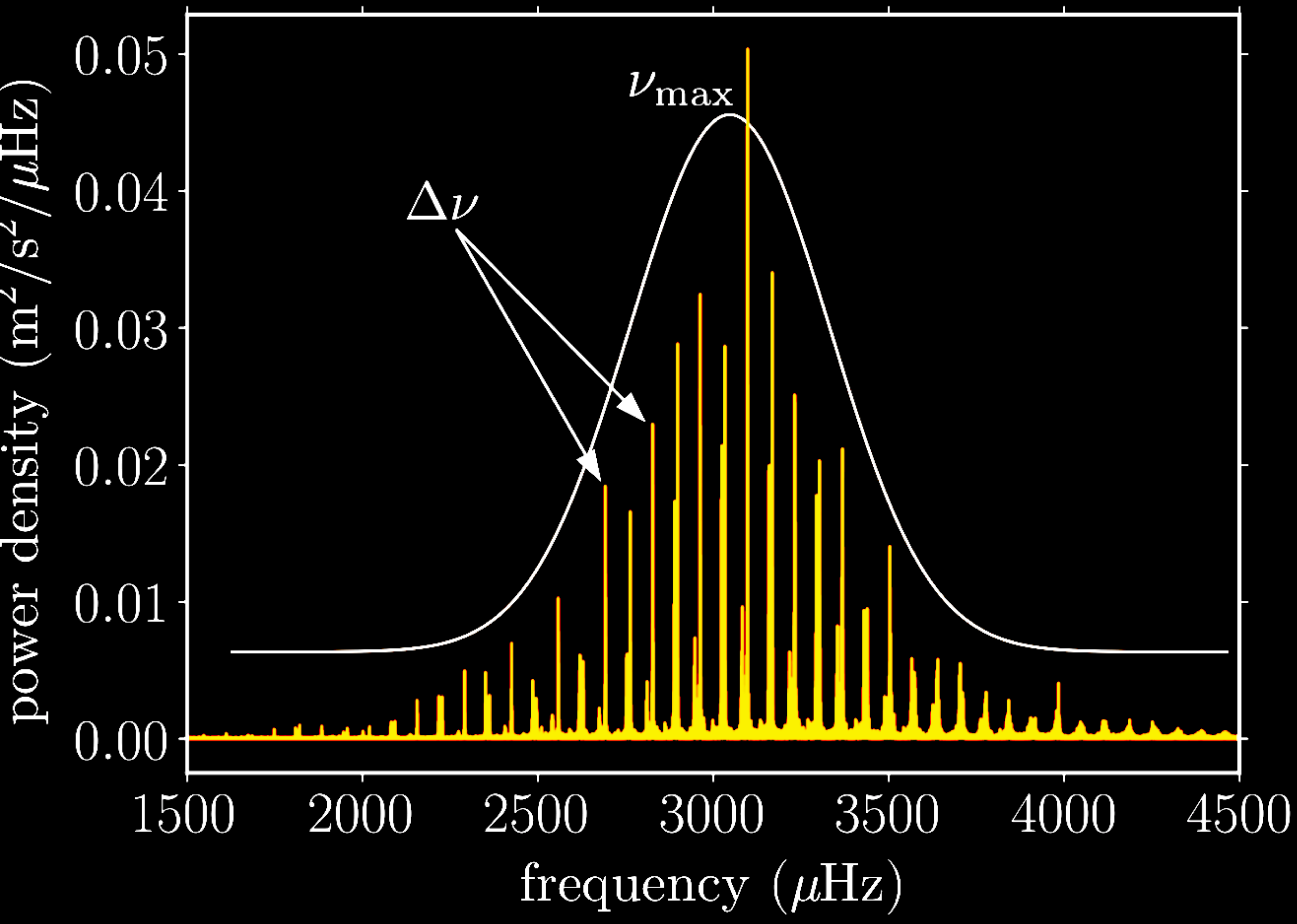
Slide credit: Warrick Ball; BiSON solar data

Granulation & Oscillations



Slide credit: Warrick Ball; BiSON solar data

Global Oscillation Properties



Slide credit: Warrick Ball

See **Chaplin, Cegla,** et al 2019 & Medina et al 2018 for mitigation strategies

Scaling relations

Kjeldsen & Bedding (1995)

$$\Delta\nu \propto \sqrt{\bar{\rho}} \propto \sqrt{\frac{M}{R^3}}$$

$$\nu_{\max} \propto \frac{g}{\sqrt{T_{\mathrm{eff}}}} \propto \frac{M}{R^2\sqrt{T_{\mathrm{eff}}}}$$

$$\Rightarrow$$

$$M \propto \frac{\nu_{\max}^3}{\Delta\nu^4} T_{\mathrm{eff}}^{3/2}$$

$$R \propto \frac{\nu_{\max}}{\Delta\nu^2} T_{\mathrm{eff}}^{1/2}$$

Slide credit: Warrick Ball

See also review by García & Ballot 2019

Stellar Variability: Pressure-mode Oscillations

Excited by convection

‘5-minute’ solar oscillation

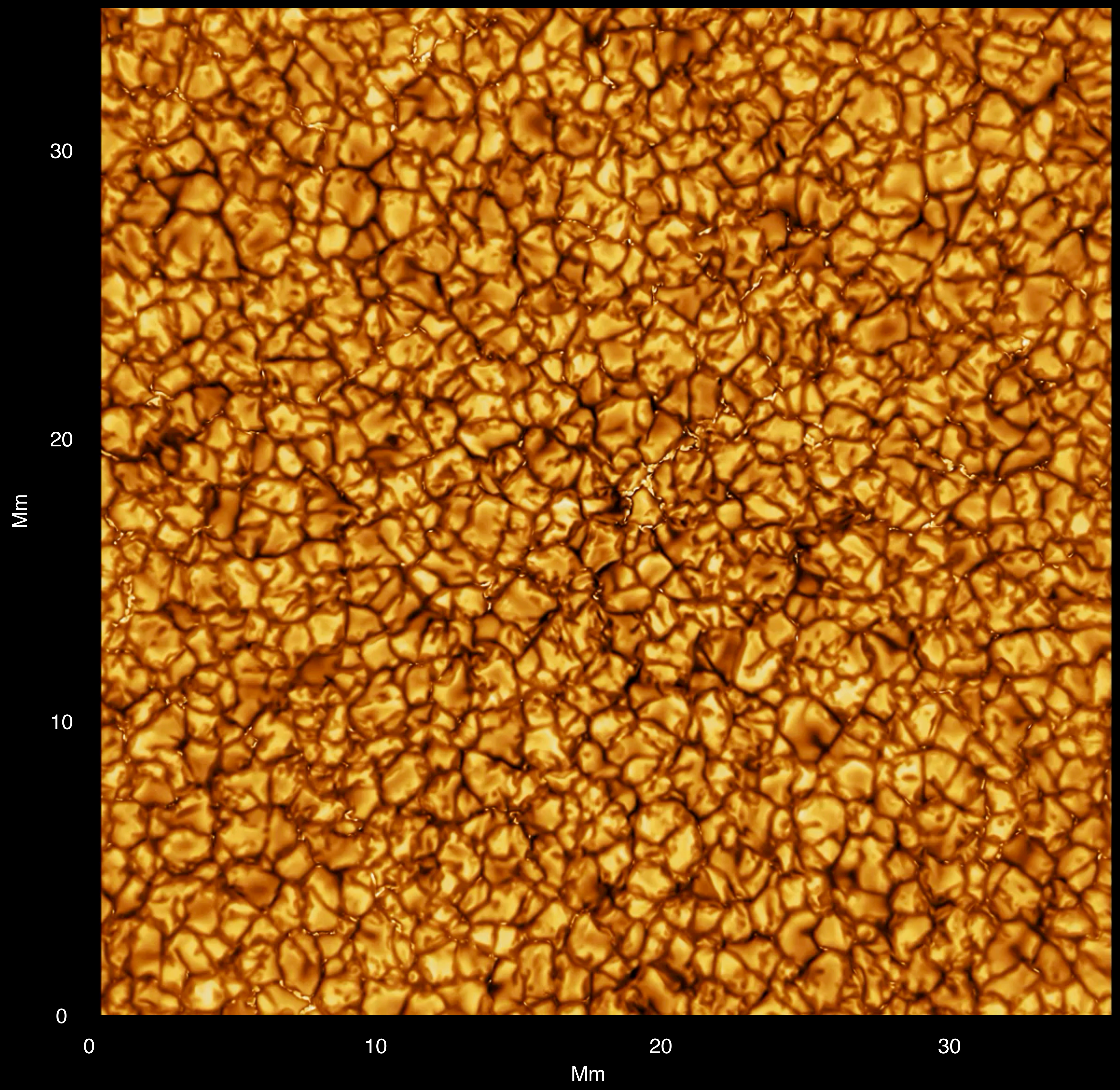
Individual mode lifetimes of a few days on the Sun

Net effect is a few m/s on the Sun

Net RV effect decreases for cooler stars and increases for evolved stars

Can fine-tune observations to largely mitigate RV effect

Stellar Variability: Convection



DKIST Solar Observations

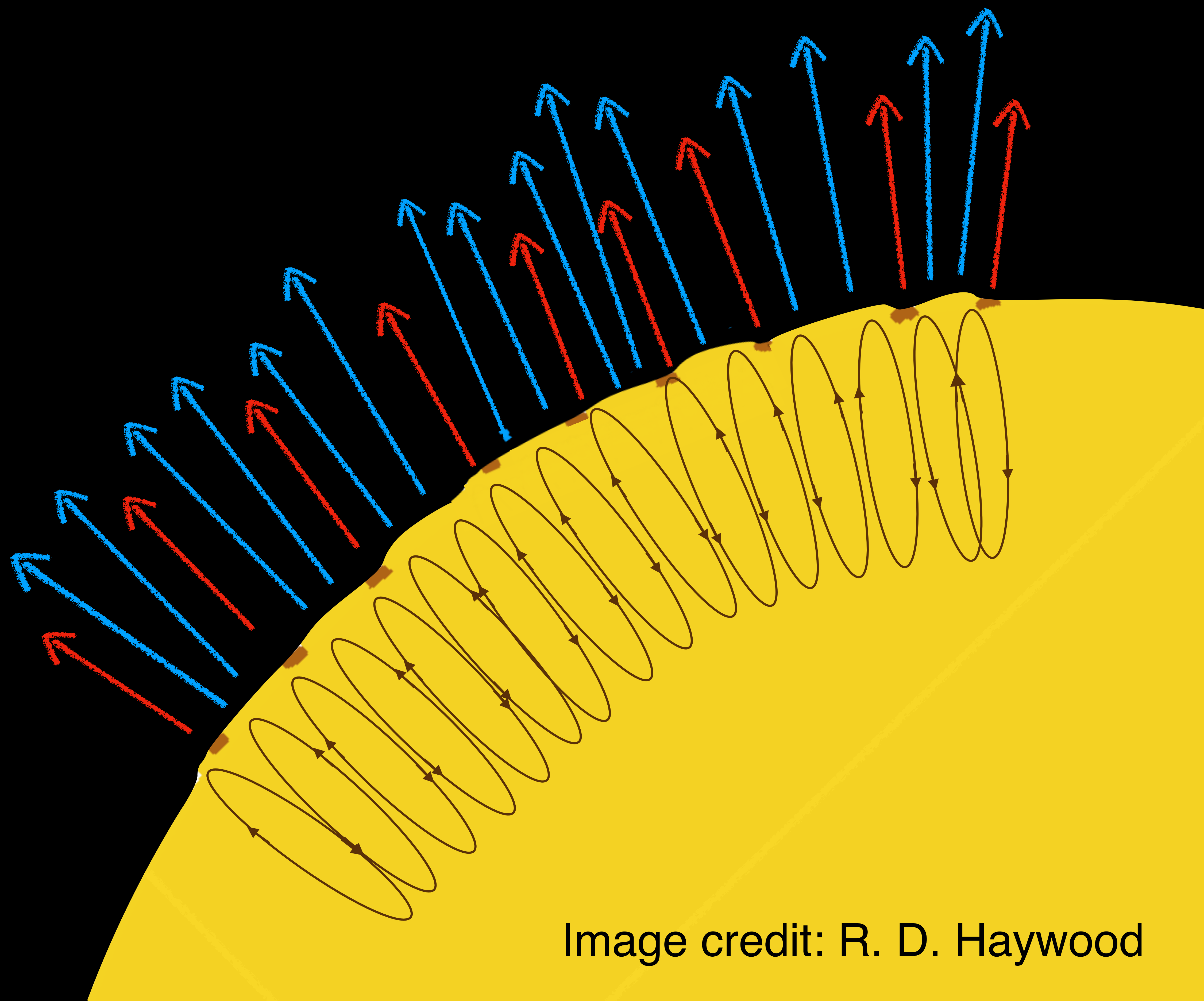
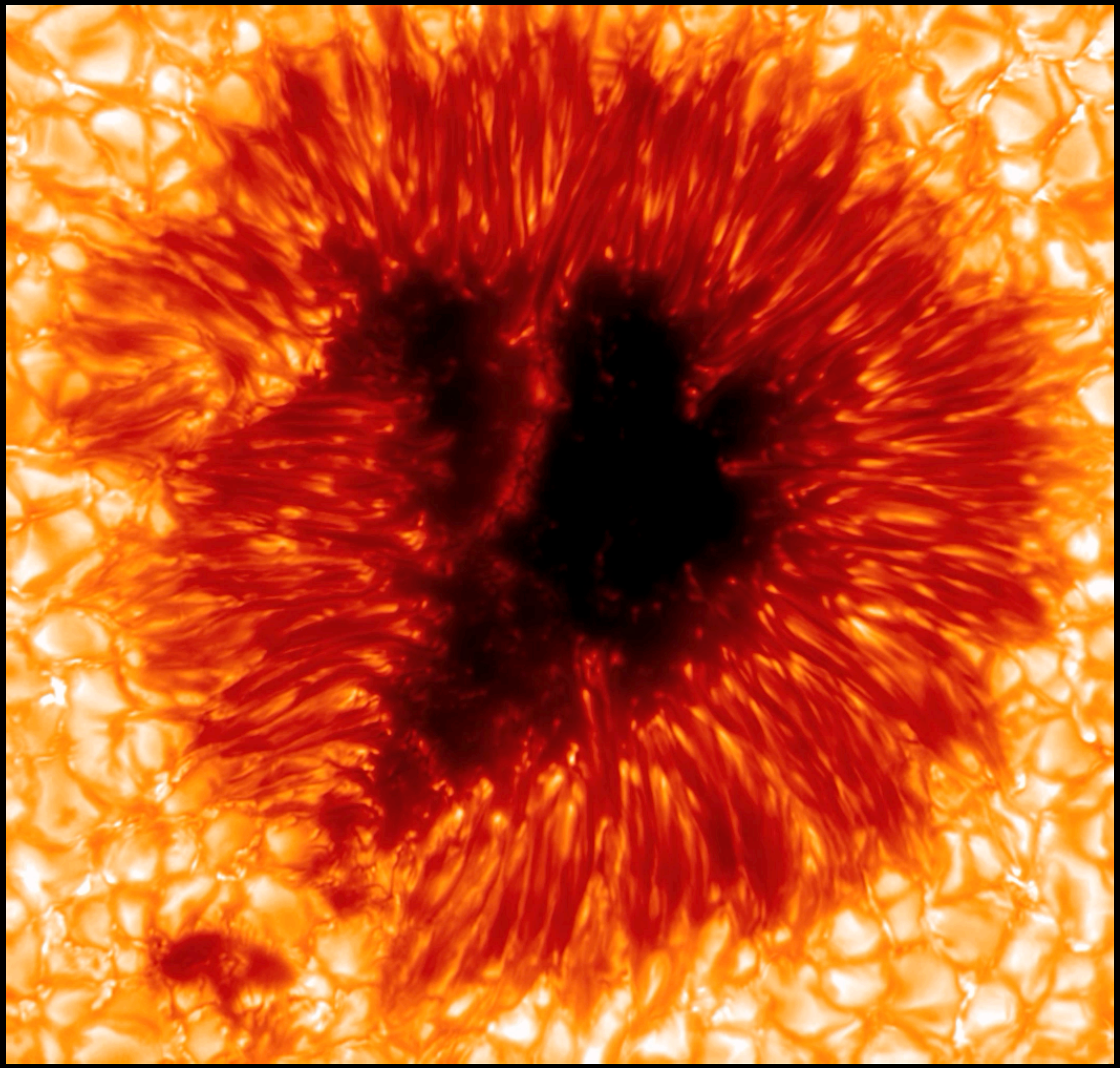


Image credit: R. D. Haywood

Stellar Variability: Suppression of Convection



Swedish Solar Telescope

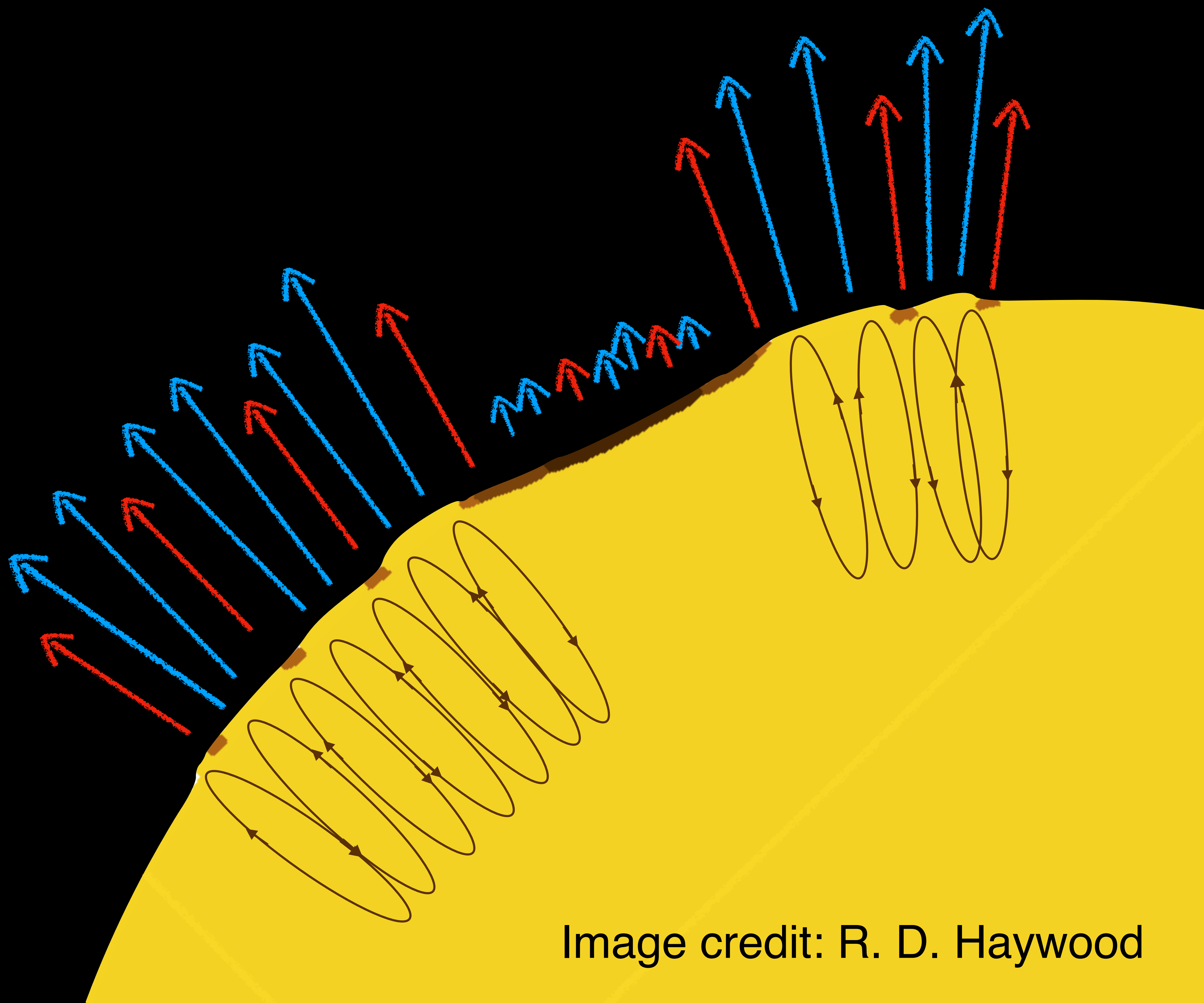
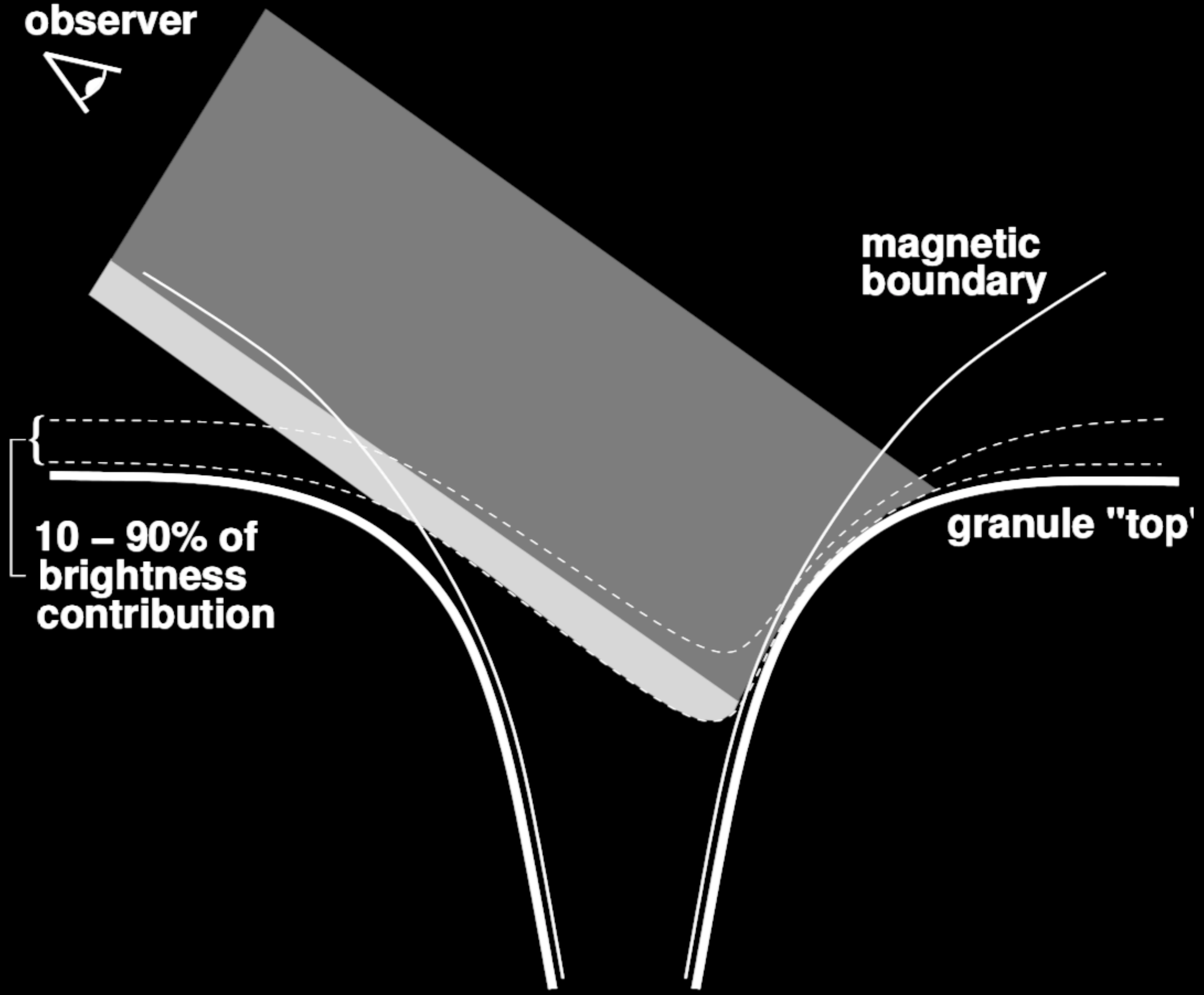


Image credit: R. D. Haywood

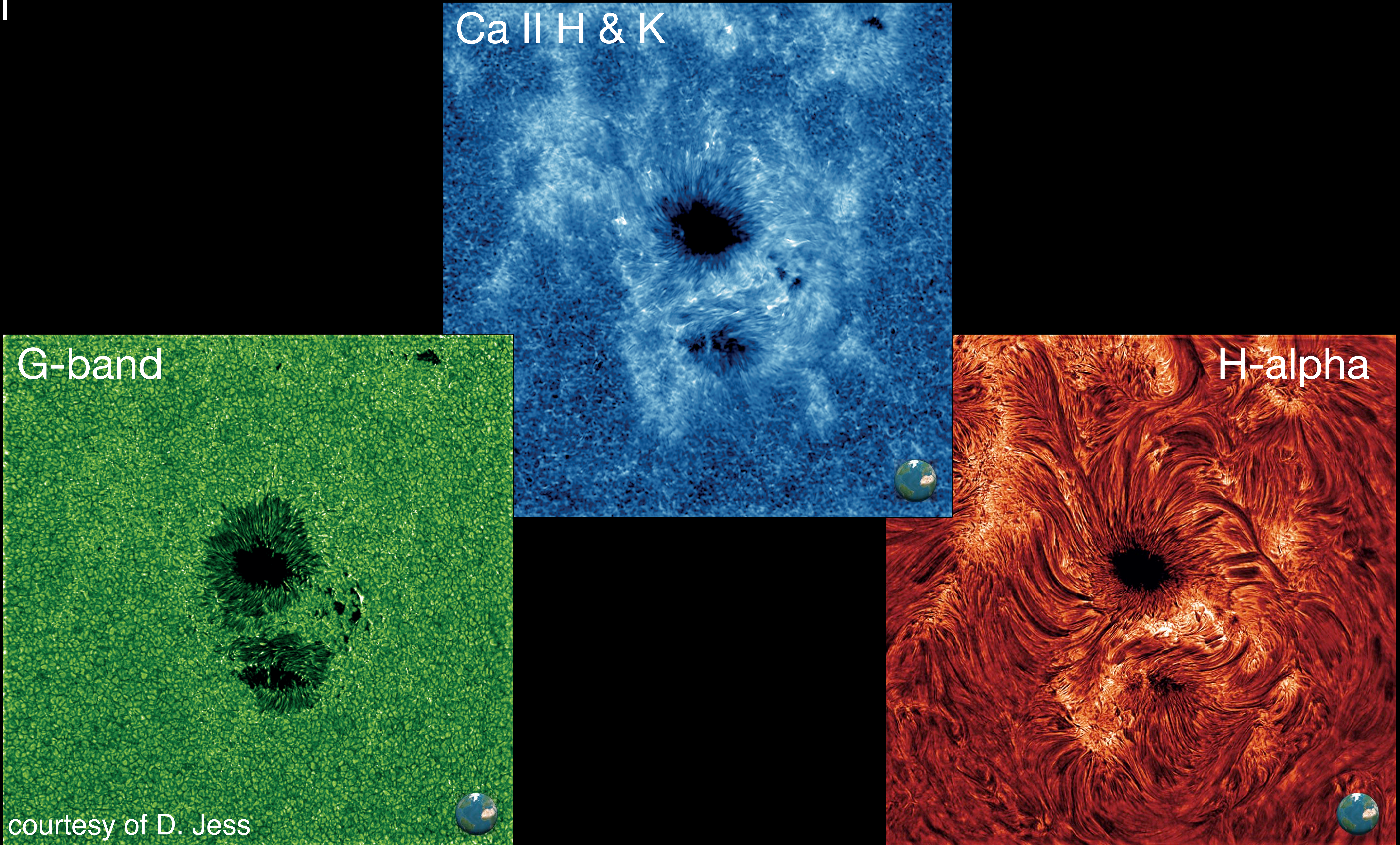
Stellar Variability: Spots & Faculae/Plage



Faculae Schematic: Keller et al 2004

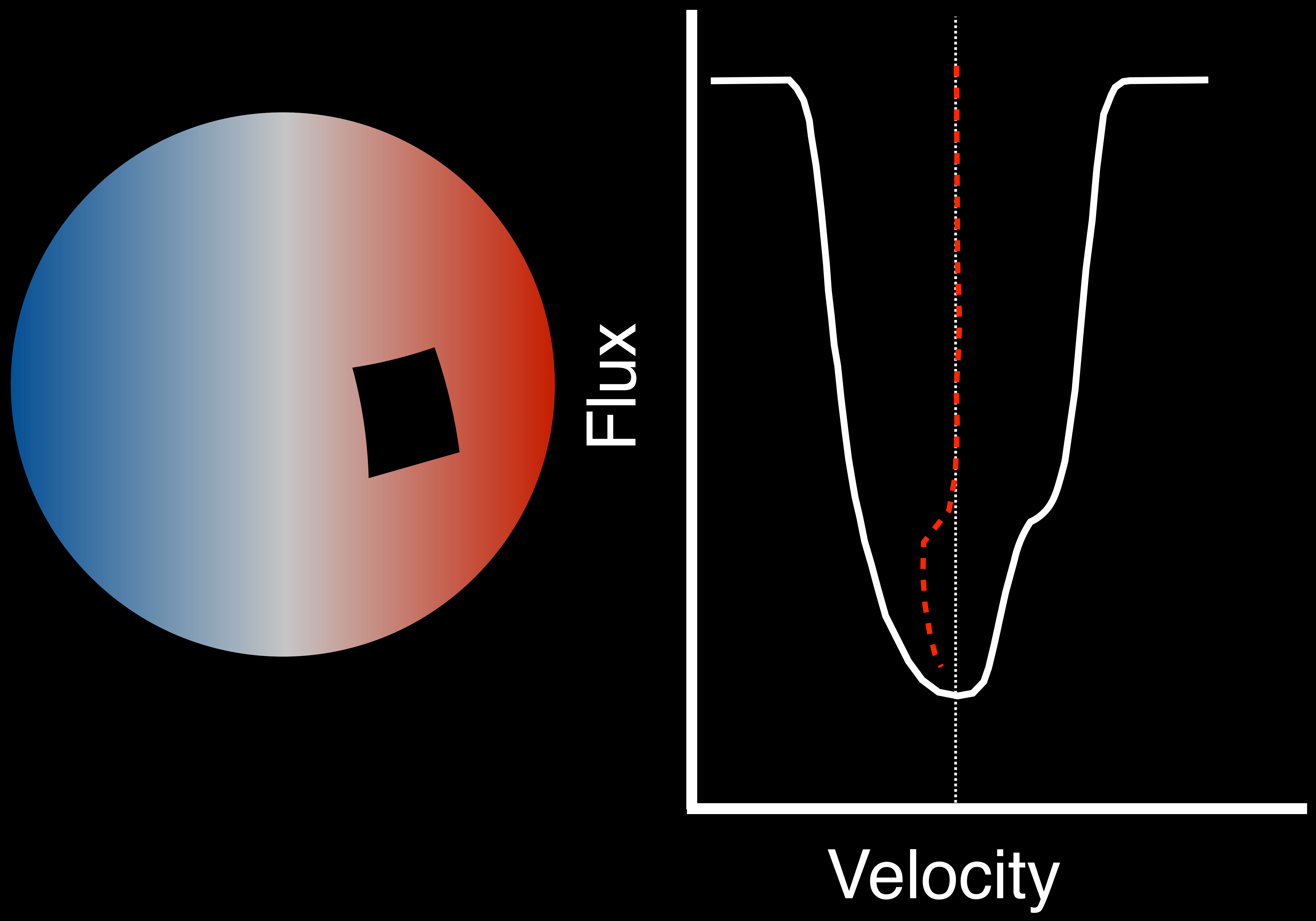
SDO/HMI

Stellar Variability: Spots & Faculae/Plage



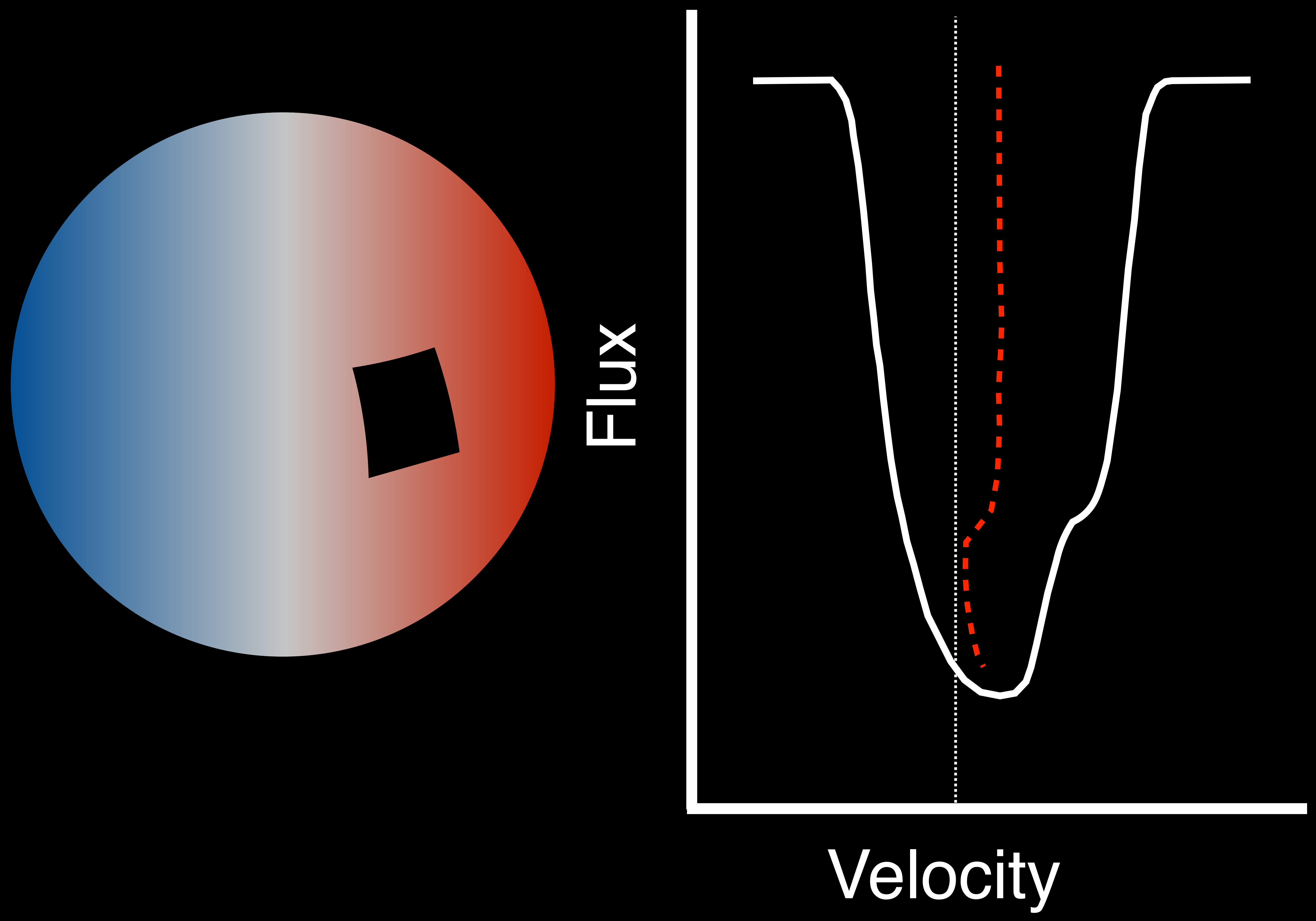
Images courtesy of D. Jess

Stellar Variability: Spots & Faculae/Plage



Photometric Effect

Stellar Variability: Spots & Faculae/Plage



Photometric Effect + Suppression of Convective Blueshift

Stellar Variability: Spots & Faculae/Plage

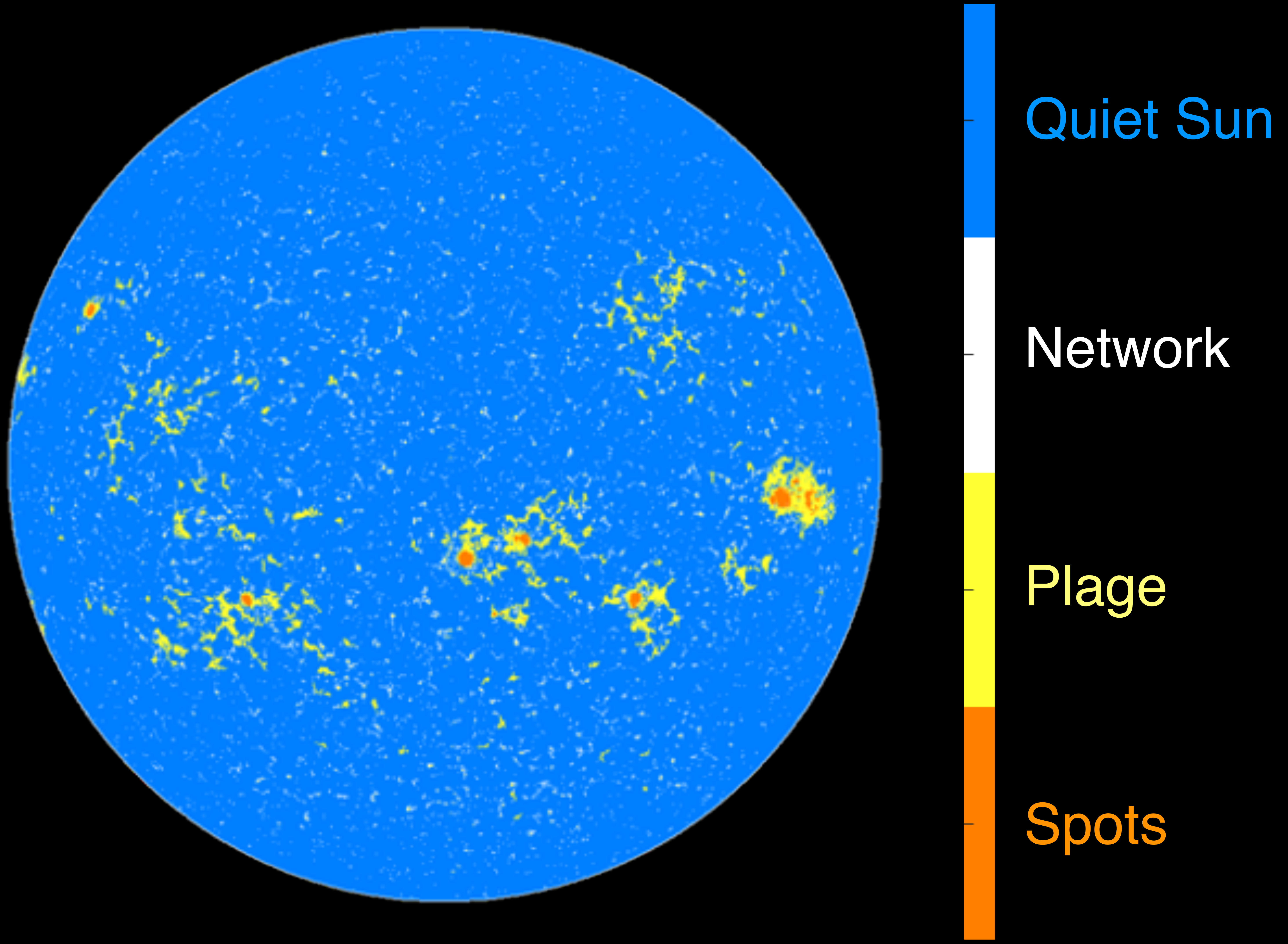


Image credit: T. Milbourne

Takeaways: Plage/Spots

Faculae/Plage are bright: high magnetic fields evacuate flux tubes & alter opacity -> see hotter/deeper regions

- At disc centre: MBPs; near limb: hot granular walls

Spots are dark: cooler because magnetic fields significantly suppress the convection, despite also being physically deeper

- Additional velocity flows: Moat flows/Evershed flows
- Pores: small spots without a penumbra

Both alter brightness and suppress convection

Takeaways: Plage/Spots

RV effect tied to the stellar rotation

Spot lifetimes similar to rotation period (~27 d for the Sun), but plage can survive several rotations

Active region to quiet star contrast decreases for cooler stars

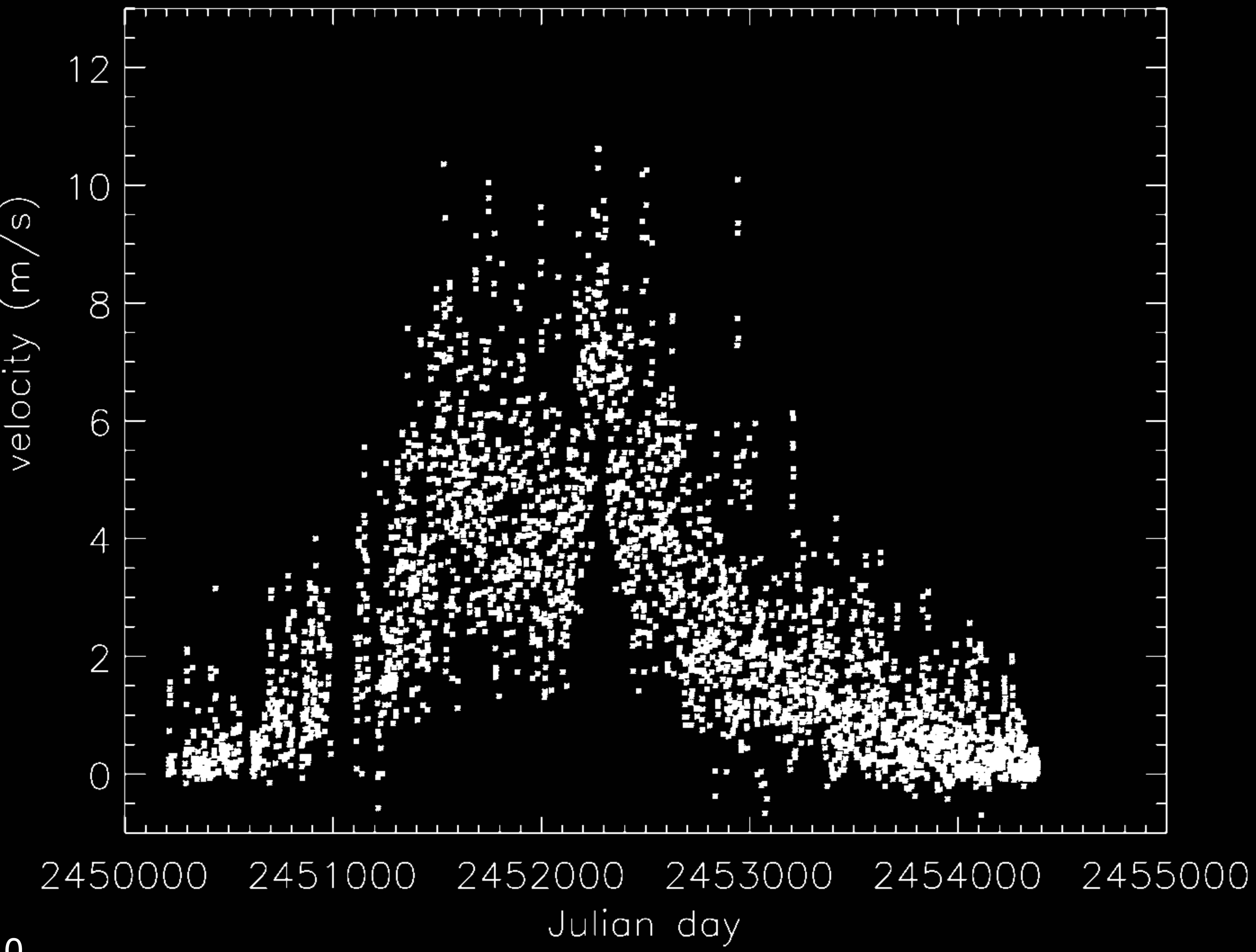
Net RV effect for the Sun is a few m/s, but can be much larger for spot-dominated, young stars

Dominant effect for Sun-like stars is the suppression of convective blueshift in sufficiently large magnetic regions

Solar Butterfly Diagram

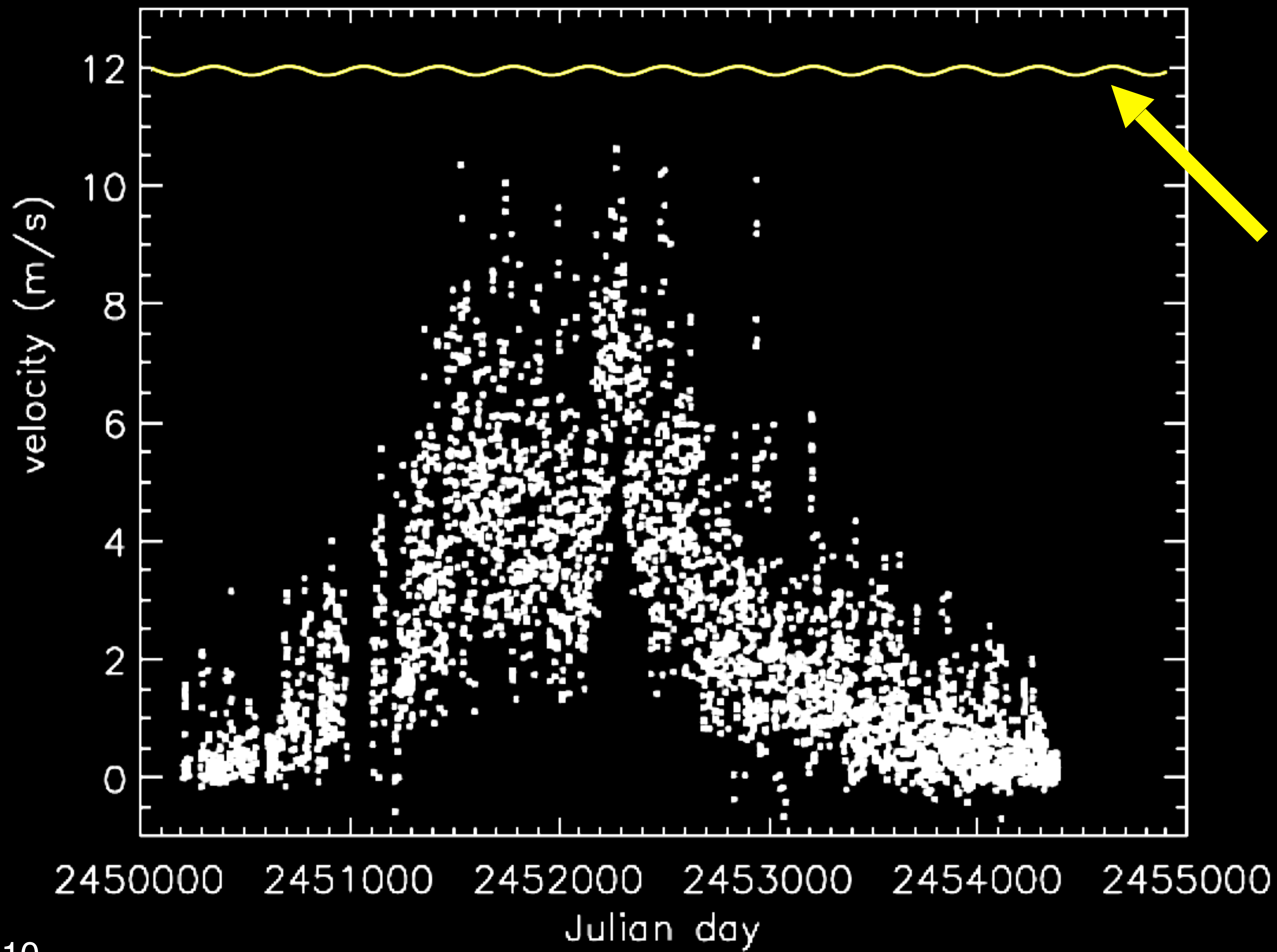
HAO/SMM Archives and NASA/MSFC (D. Hathaway)

Stellar Variability: Magnetic Activity Cycles



Meunier et al 2010

Stellar Variability: Magnetic Activity Cycles



Meunier et al 2010

Takeaways: Magnetic Activity Cycles

Timescale of few years to decades, solar cycle ~11 (22) years

Amplitudes on the ~10 m/s level

Impacts any stellar variability source related to magnetic field

Net increase in magnetic field increases the suppression of the convective blueshift over the cycle

Stellar Variability: Other Sources

Flares/CMEs

Meridional flows / active regions flows

R-mode oscillations

Variable gravitational redshift

+ more!

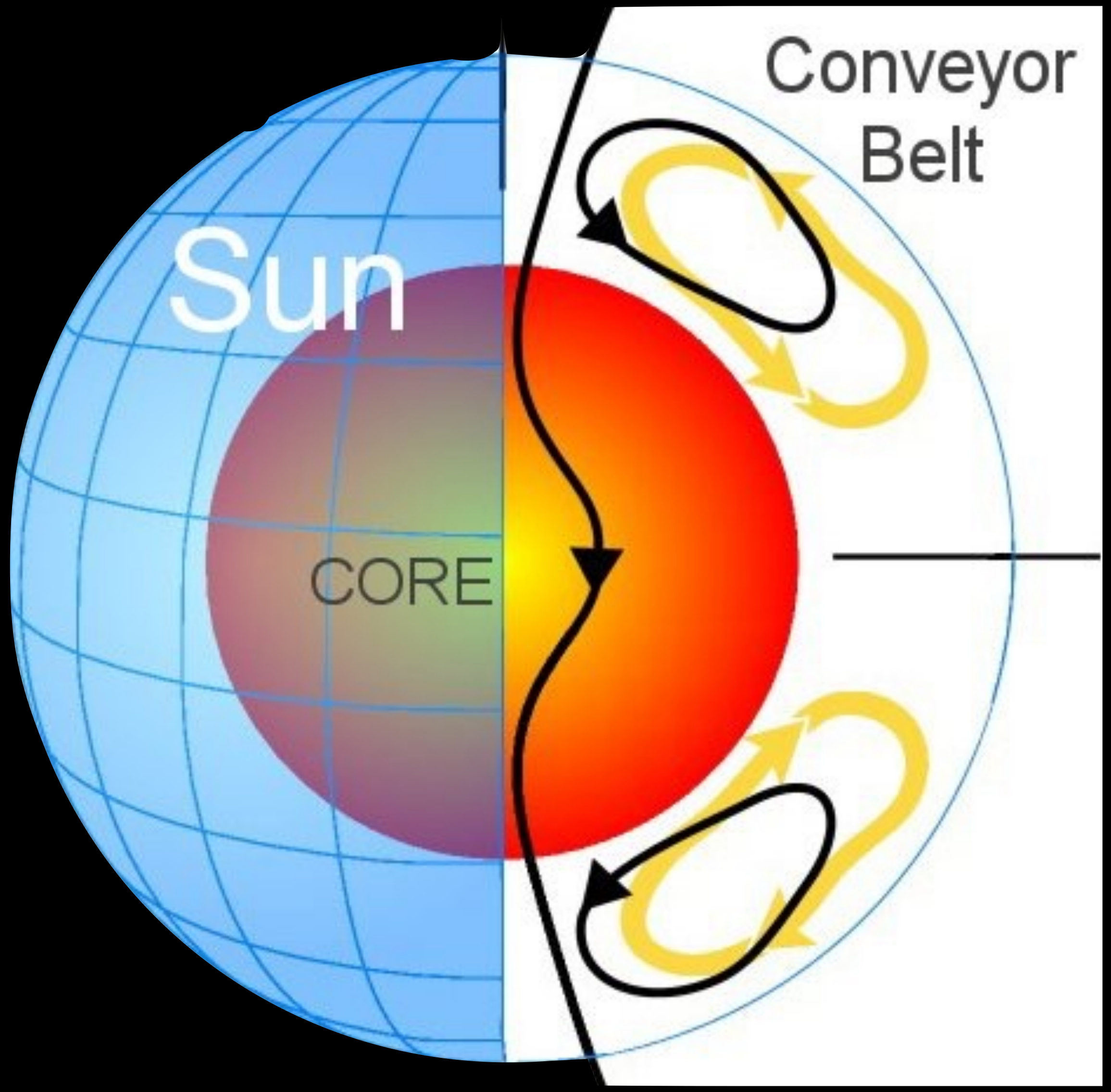
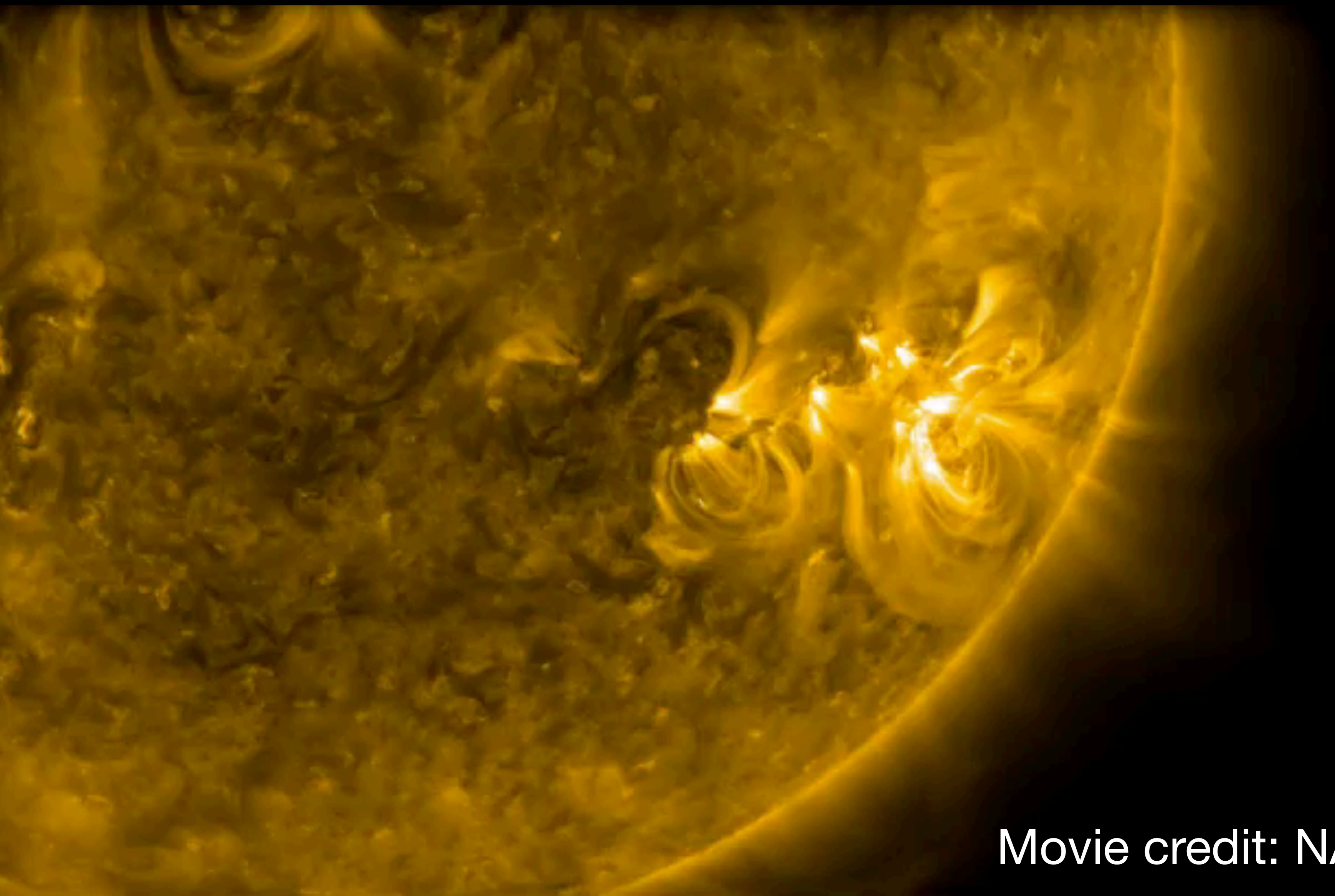


Image Credit: NASA



Movie credit: NASA

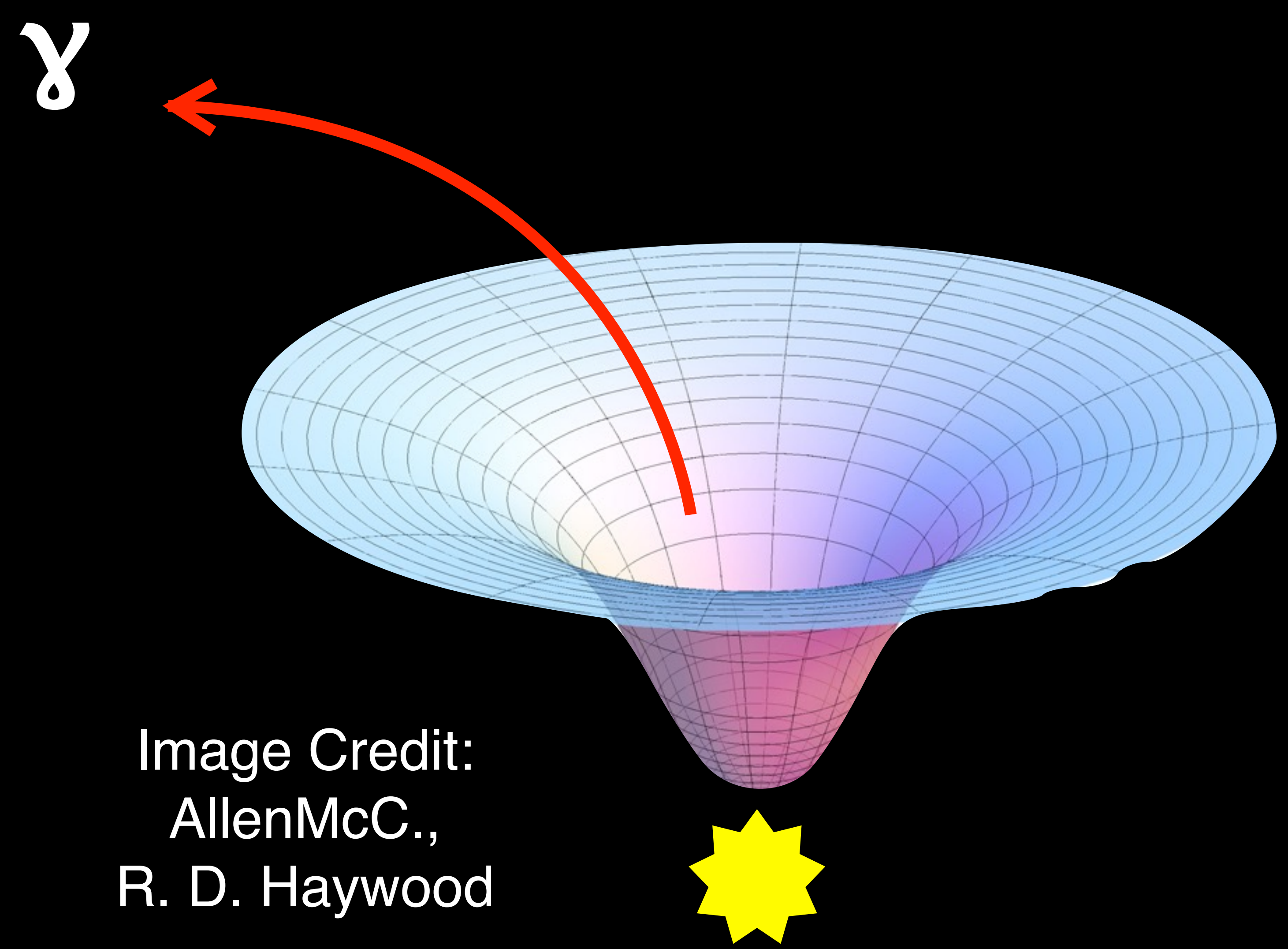


Image Credit:
AllenMcC.,
R. D. Haywood

See also:
Reiners 2009
Suárez Mascareño et al 2020
Beckers 2007
Makarov 2010
Lanza et al 2019
Cegla et al 2012

Don’t miss these!

Debra Fischer - Fundamentals of PRV

Andreas Quirrenbach - Fundamentals of instrumentation

Jason Wright - How planets manifest in RVs and how to find them

Sharon Wang - How to measure RVs

Annelies Mortier - What we can learn from the Sun

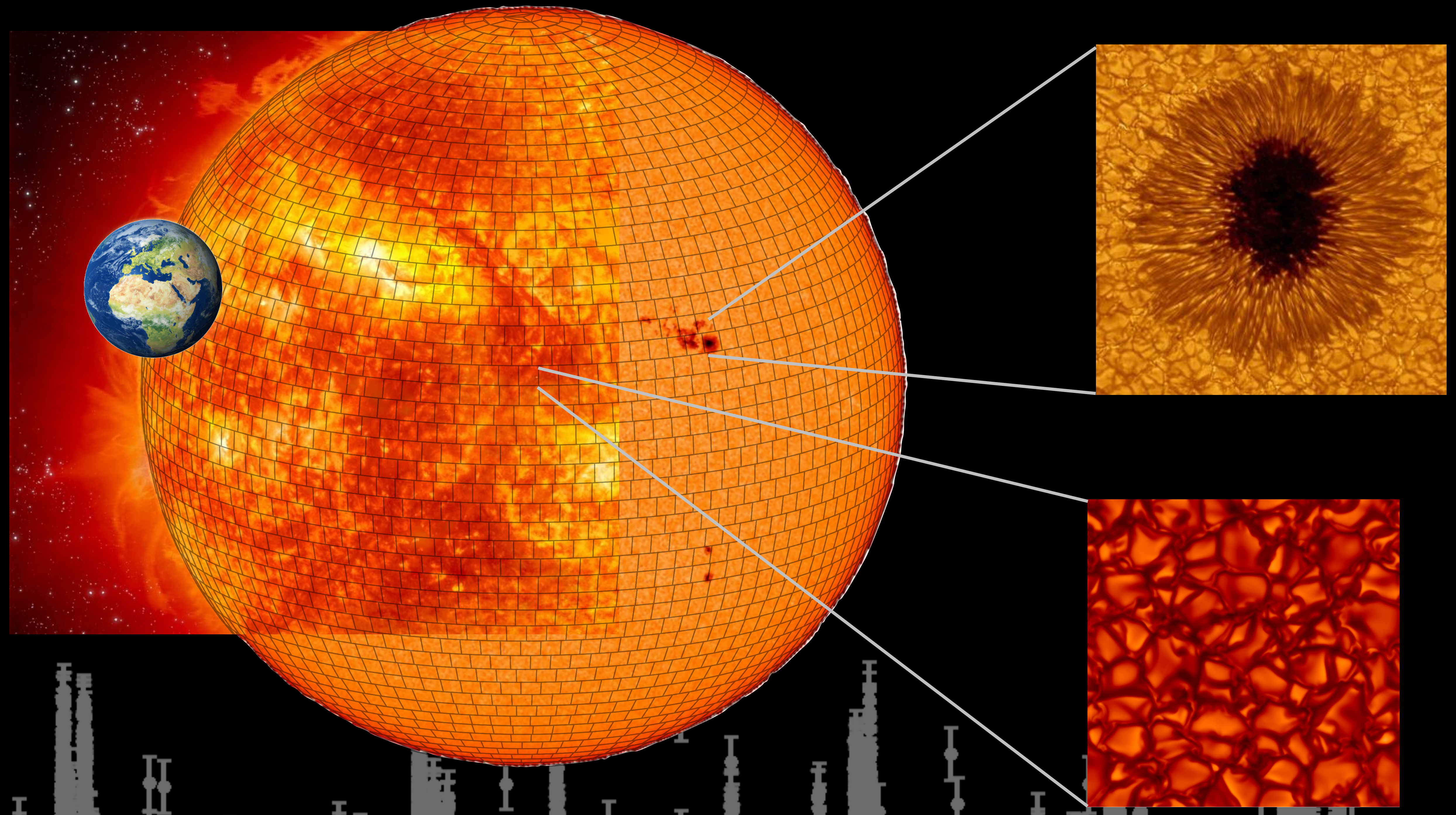
Jenn Burt - Techniques to mitigate stellar variability

Nathan Hara - How to evaluate the significance of stellar/planetary signals

Vinesh Maguire-Rajpaul - Power and danger of Gaussian Processes

Scott Gaudi - The EPRV initiative

Stellar Variability: Next Steps

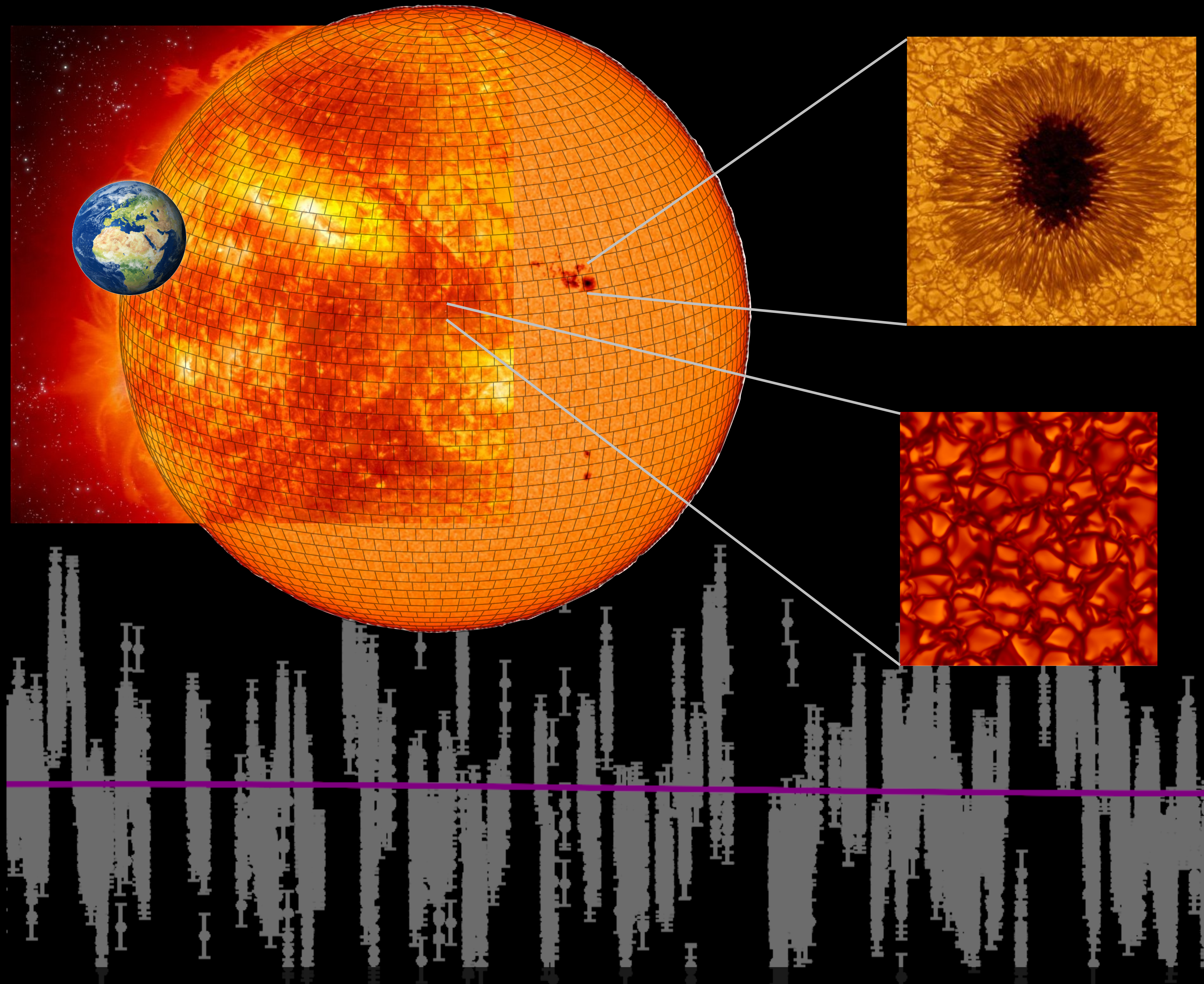


Physical effect
Understanding the Sun *in connection to EPRV*
Spectral line formation and behaviour in the stellar atmosphere *in connection to EPRV*
Magnetic fields
Faculae/plage
Spots
Evershed flows, moat flows, plage inflows ...
Granulation
Super-Granulation
Meridional flows
Long-term magnetic cycles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

H. M. Cegla
University of Warwick

Image credits: NASA, ESA, SDO/HMI, MURAM, Big Bear Solar Observatory, HARPS-N. Cegla/Haywood/Watson

Stellar Variability: Next Steps



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H. M. Cegla
University of Warwick

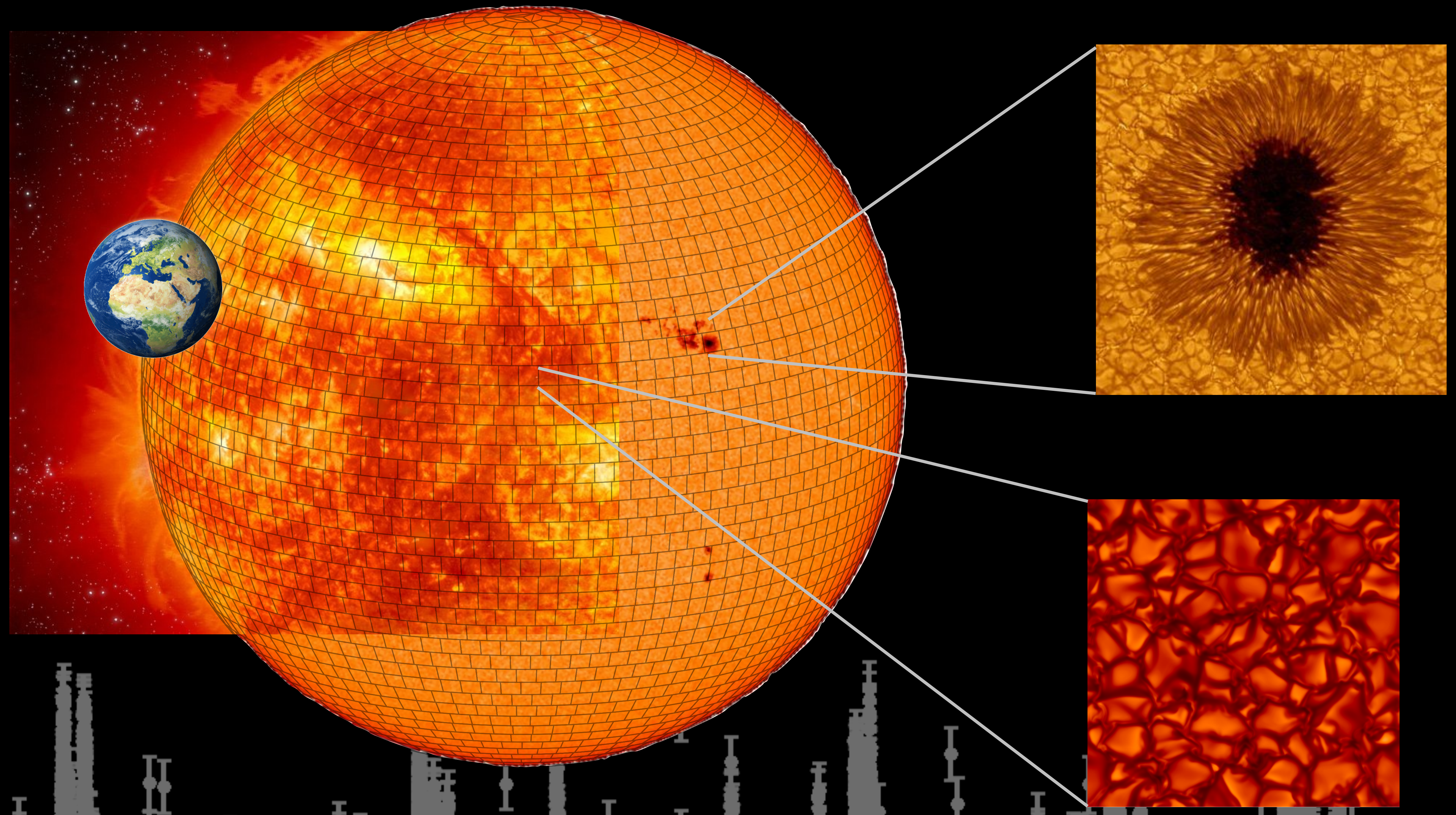
Image credits: NASA, ESA, SDO/HMI, MURAM, Big Bear Solar Observatory, HARPS-N. Cegla/Haywood/Watson

Interplay between convection & magnetic fields drives most stellar surface variability

H. M. Cegla
University of Warwick

Image credits: NASA, ESA, SDO/HMI, MURAM, Big Bear Solar Observatory, HARPS-N. Cegla/Haywood/Watson

Interplay between convection & magnetic fields drives most stellar surface variability

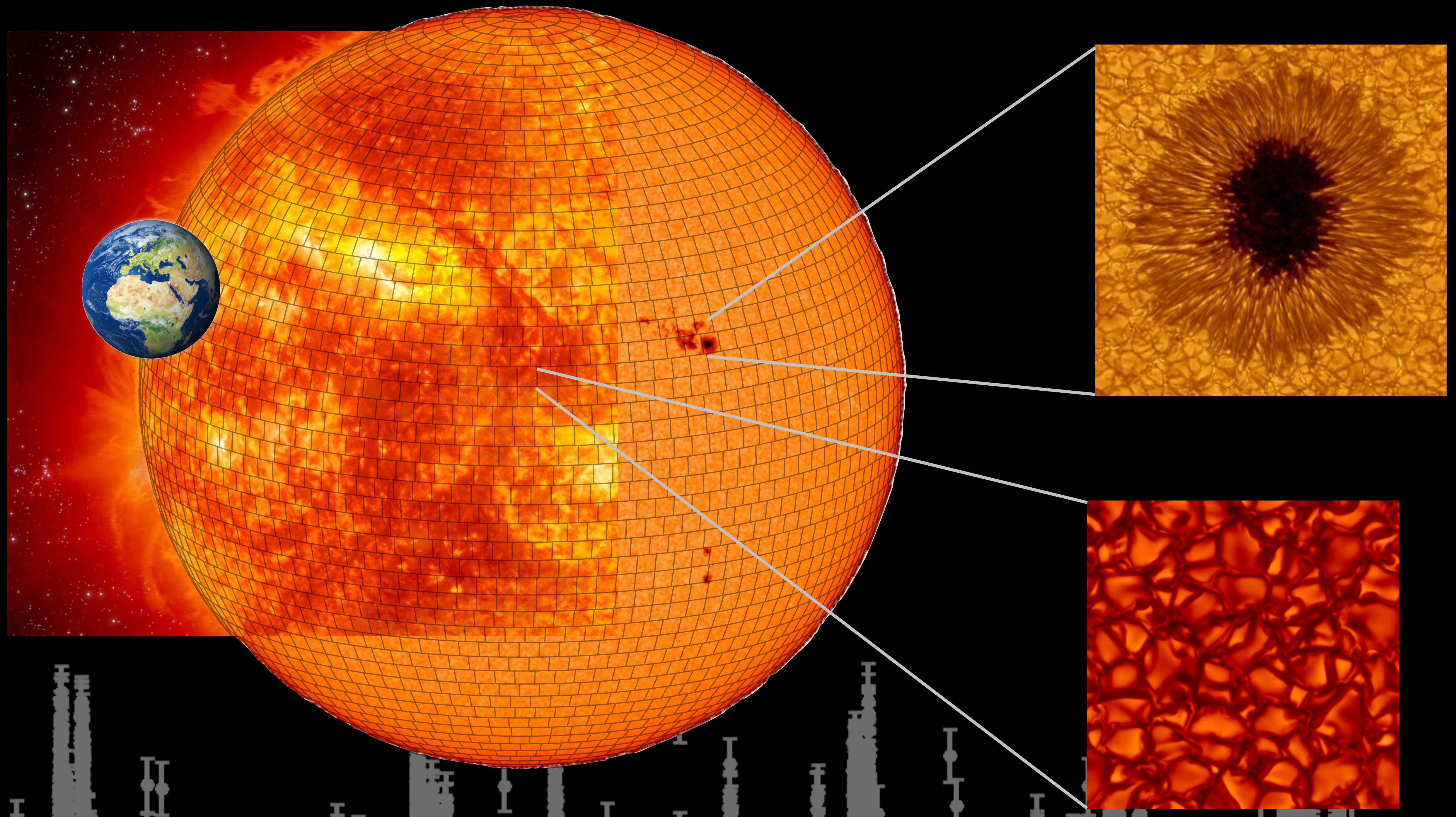


and swamps the Doppler wobble from low-mass, long-period planets

H. M. Cegla
University of Warwick

Image credits: NASA, ESA, SDO/HMI, MURAM, Big Bear Solar Observatory, HARPS-N. Cegla/Haywood/Watson

Interplay between convection & magnetic fields drives most stellar surface variability



We must understand the host stars to unveil rocky, temperate alien worlds

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Image credits: NASA, ESA, SDO/HMI, MURAM, Big Bear Solar Observatory, HARPS-N. Cegla/Haywood/Watson