

AST5770

Solar and stellar physics

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Recap — Convection

- Convective energy transport is very **efficient** with $F_{\text{conv}} \gg F_{\text{rad}}$
- Small deviation from adiabatic temperature gradient sufficient - **Superadiabaticity** $\nabla - \nabla_{\text{ad}}$
- Convection cell size, convective velocity, convective turnover timescale scale with the pressure scale height
 - Large and slow deep in the convection zone
 - Smaller and faster higher up

pressure scale height

$$H_P = P/(\rho g)$$

- At lower and upper boundaries of a convection zone: **Overshooting!**
(Mixing beyond boundary)

- Convection cell size at the surface depend on global properties of a star

$$\frac{x_{\text{gran}}}{R_*} \approx 0.0025 * \frac{R_*}{R_{\odot}} \frac{T_{\text{eff},*}}{T_{\text{eff},\odot}} \frac{M_{\odot}}{M_*}$$

• (Freytag et al. 2002)

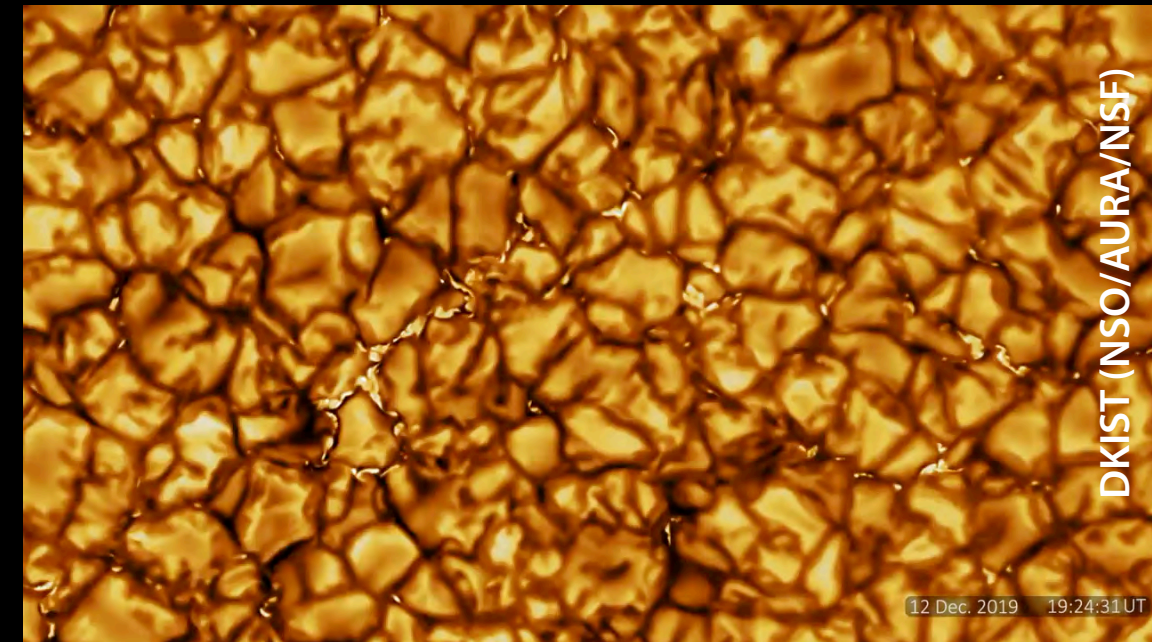
- Sun: $\sim 1000 - 2000$ km
- Granulation and supergranulation leaves different spatial pattern at the surface

Convection

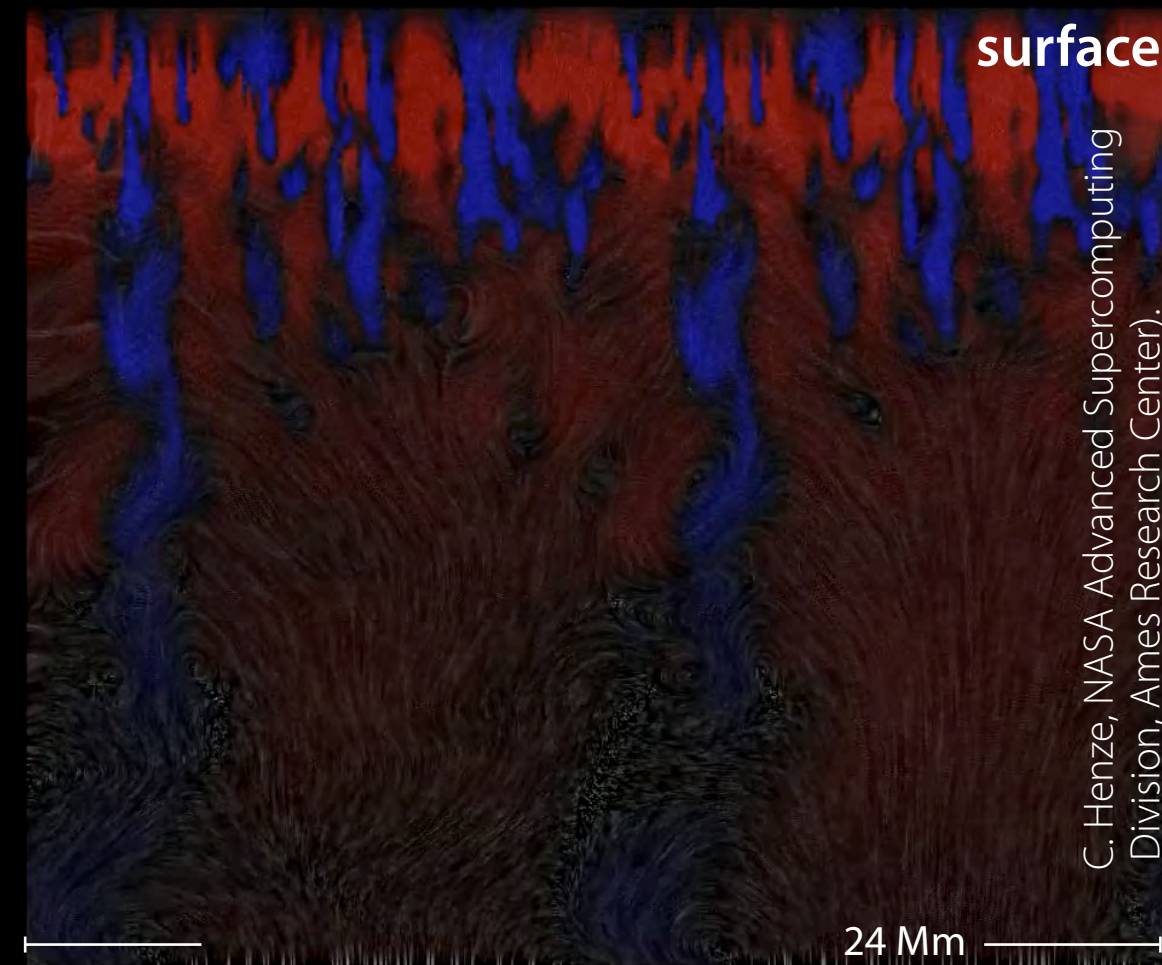
- Convection zone: Mass density, pressure change by orders of magnitudes
- Pressure scale height for a stratified medium!

$$P(z) = P_0 e^{-(z/H_P)} \quad z=r \text{ (vertical/radial coordinate)}$$
- ➔ Sets dominant spatial scale of convective motions (and convection cell sizes)
- ➔ Diverging upflows turn over within 1-2 scale heights, cover 2/3 of the area
- ➔ Downflows get compressed, fast and turbulent, occupy 1/3 of the area
- **At surface:** isolated upflows form **granules**, surrounded by connected downflows (**intergranular lanes**)

surface — photosphere seen from top



Vertical cross-section from simulation



Convection

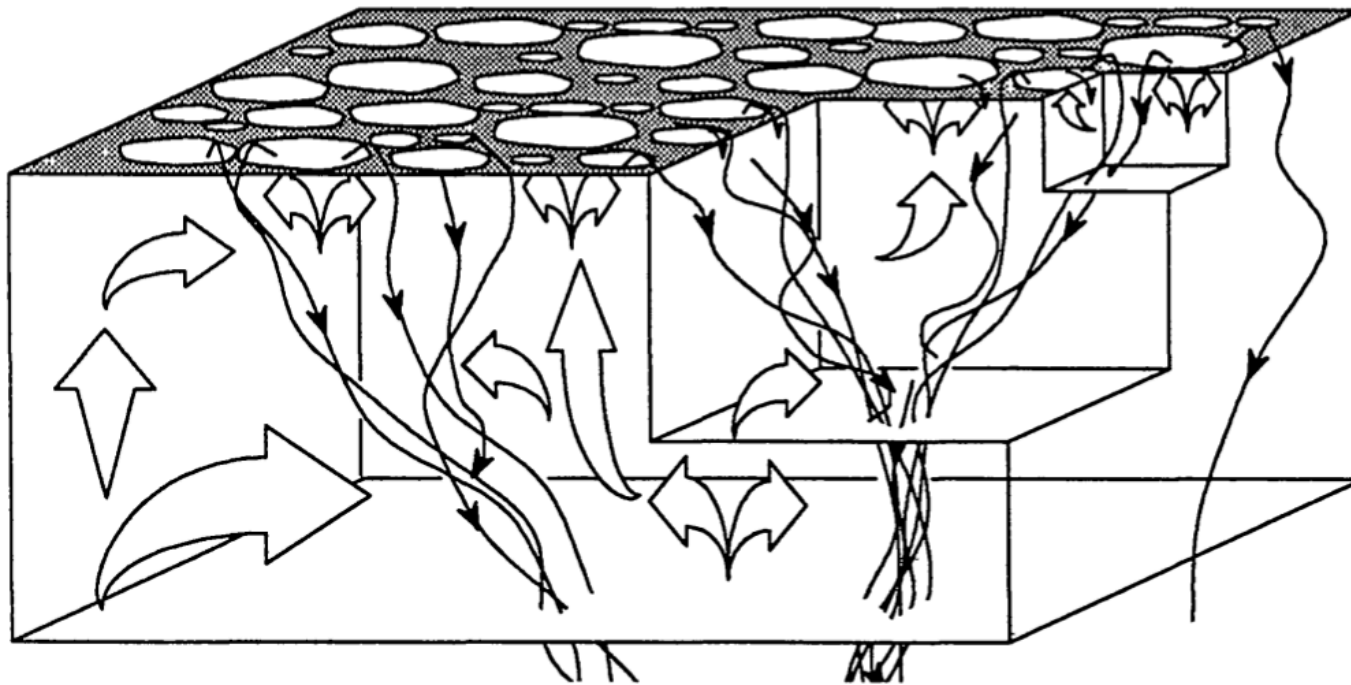
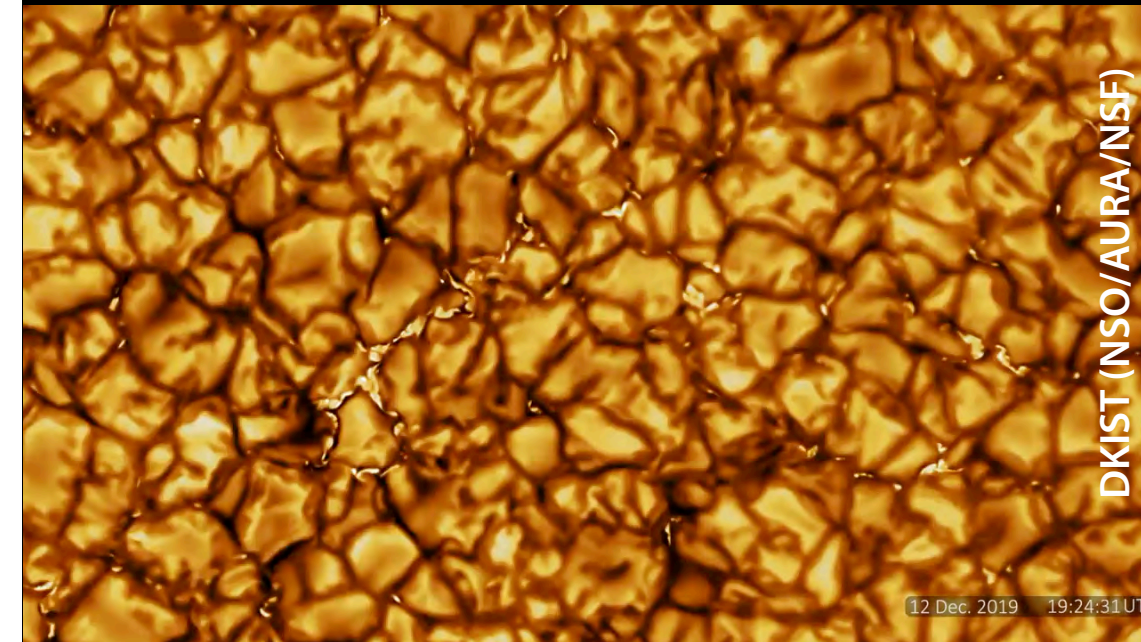


Figure 7 Flow lines showing the merging of the downdrafts on successively larger scales (schematic). The boxes cut out illustrate how the same process occurs on (in this illustration) three different scales.

- **At surface:** isolated upflows form **granules**, surrounded by connected downflows (**intergranular lanes**)
- **Downflows merge** with each other (Spruit et al. 1990)
- The deeper, the fewer (combined) downflows
- At greater depths:
Downdrafts in mesh-like pattern with larger diameters, eventually outlining supergranular scales.

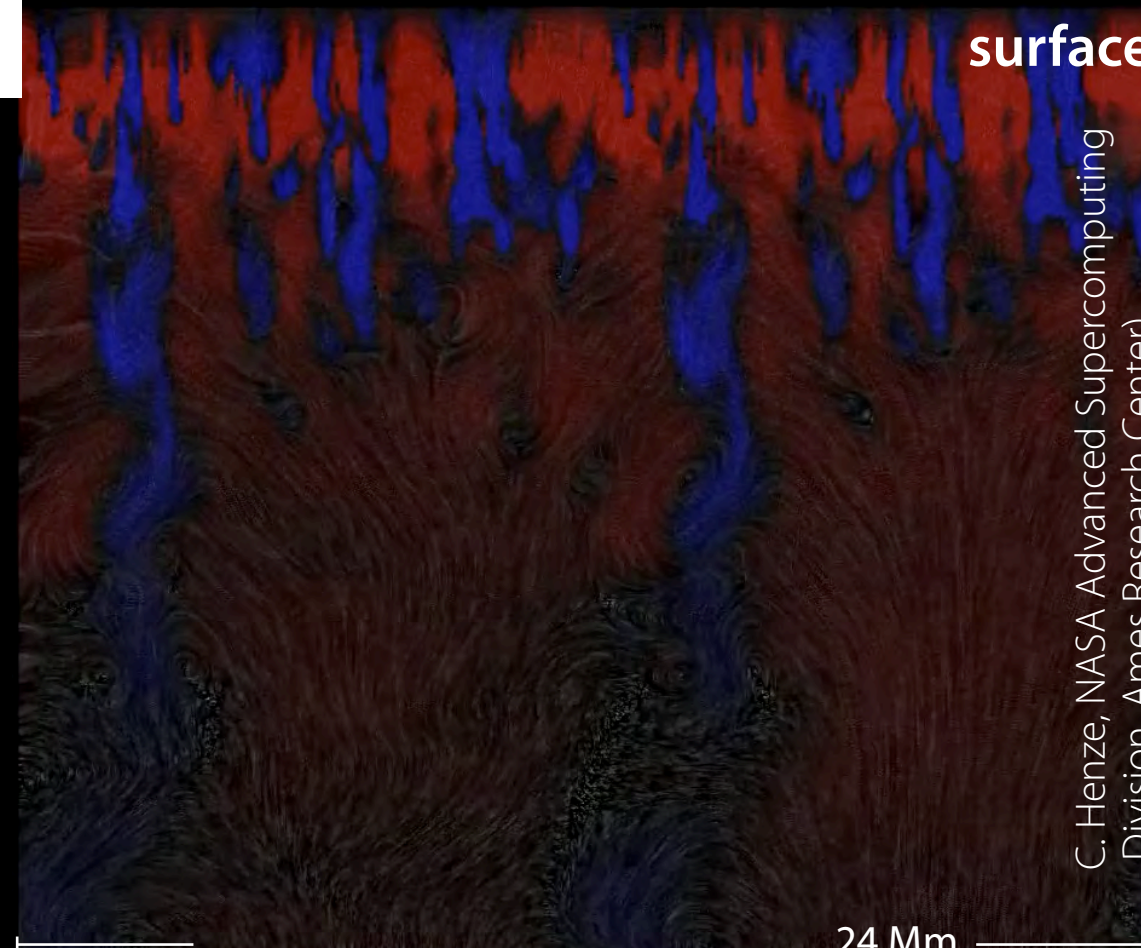
surface — photosphere seen from top



DKIST (NSO/AURA/NSF)

12 Dec. 2019 19:24:31 UT

Vertical cross-section from simulation



surface

C. Henze, NASA Advanced Supercomputing Division, Ames Research Center.

24 Mm

Granulation

Granule evolution

"Birth"

- **Appearing** as initially small features
- **Splitting** off larger granules

"Evolution"

- **Growing** larger in size until ...
- ... stopping to grow, start shrinking and fading (within 5-10 min)...
- ... becoming unstable and splitting

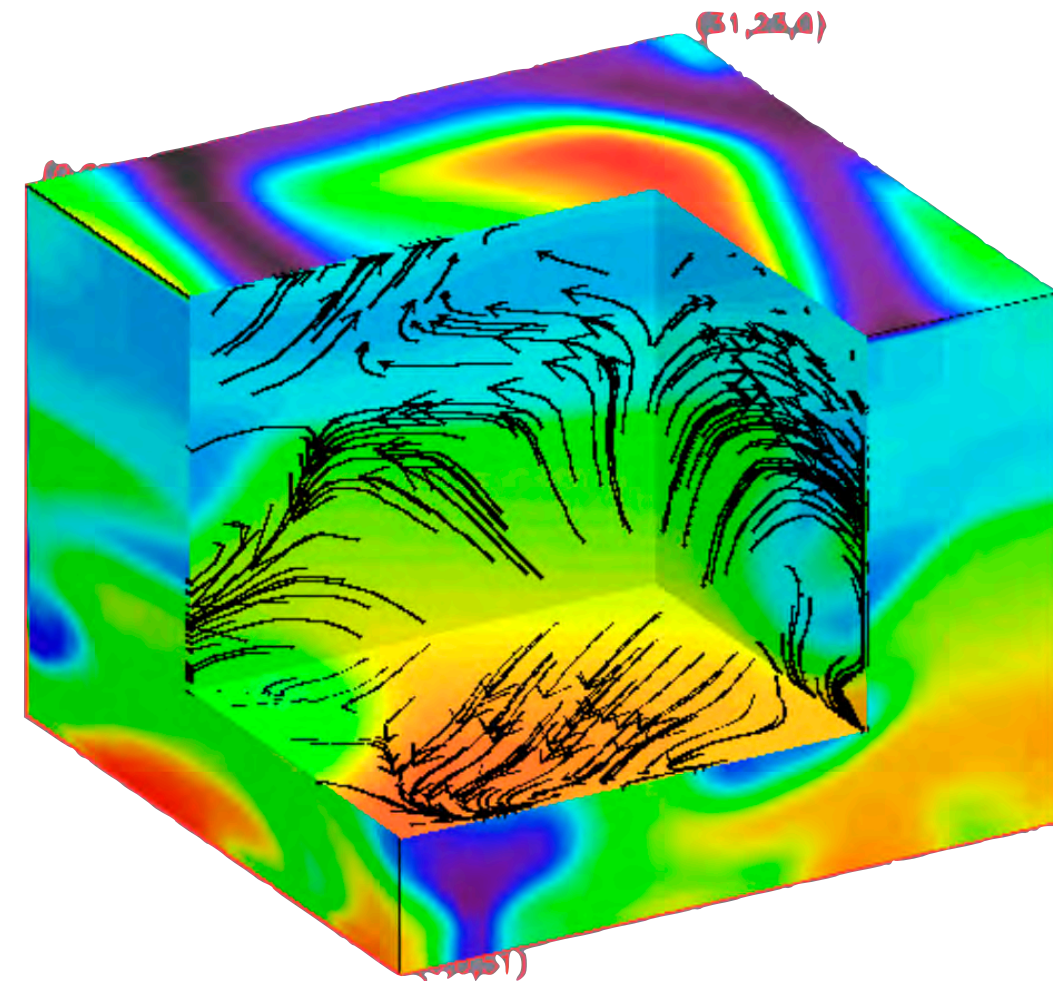
"Death"

- **Dissolving** (mostly smaller granules): Gets fainter and smaller until disappeared
- **Splitting** (large granules) into two smaller granules

Granulation

Granule fragmentation

- Upflow leads to increased pressure and density in the granule centre
- ➡ Pressure gradient with respect to radiatively cooled sides
- ➡ Lateral (horizontal) flow of gas, diverging
- Mass conservation:
 - ➡ Larger granules build up a larger pressure above its centre as more mass needs to be accelerated horizontally.
 - ➡ While growing in size, pressure becomes so large that the upflow from below becomes hampered (buoyancy becomes negative, not enough energy flux to sustain luminosity at surface), while gas continues to being cooled radiatively
 - ➡ New downflow lane forms at the granule centre
 - ➡ The granule splits.
 - Also referred to as “exploding granules”

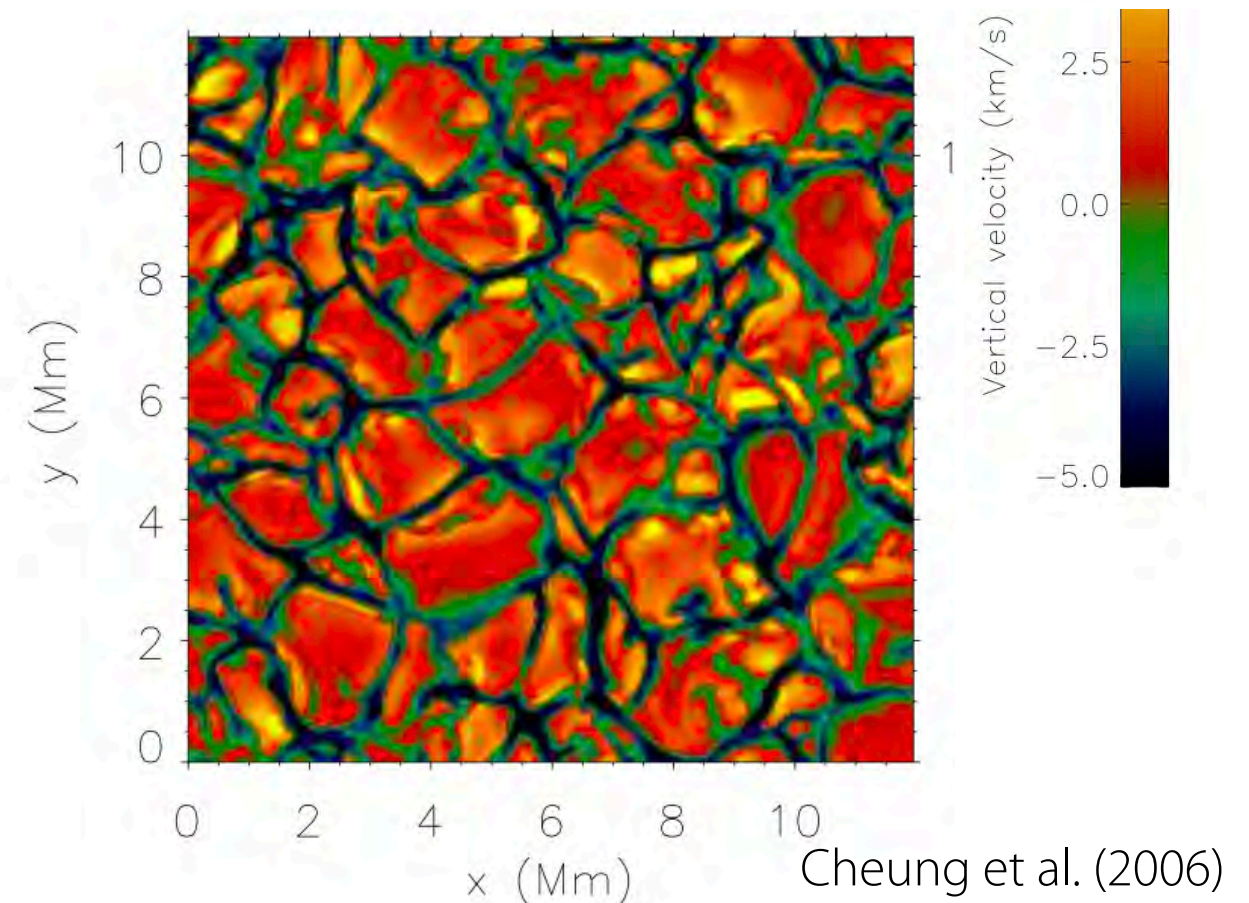
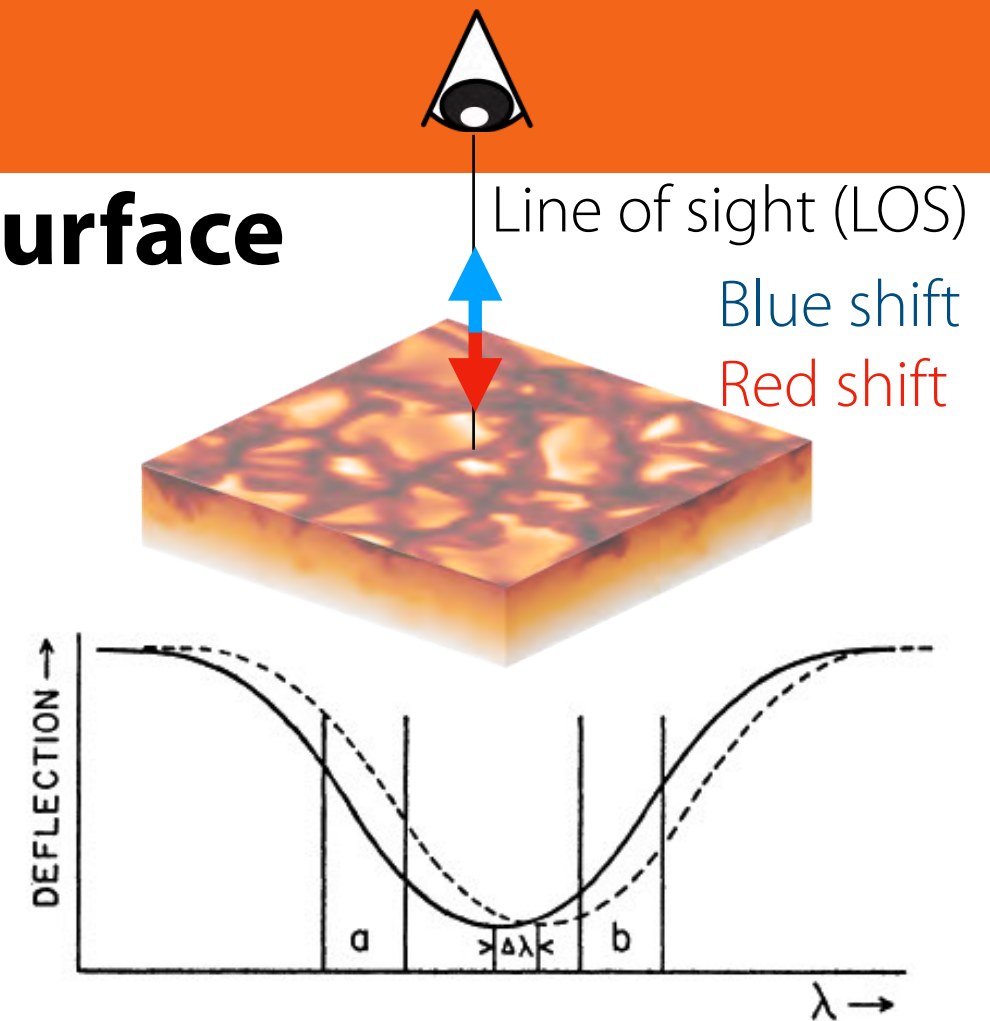


Close-up region from a 3D simulation showing gas temperature and streamlines inside and above a granule (Stein & Nordlund 1998)

Convection

Velocity field — observable at the surface

- Granules visible in intensity but also in vertical velocity
- Vertical velocity (at solar disk-centre, observing from above) can be determined from **Doppler shifts** of spectral line cores that are formed deep in the photosphere
- Horizontal velocities can be determined by tracing the horizontal motion of granules (or even smaller feature): **local correlation tracking**
- Be aware of **projection effects** when not looking at the centre of the disk

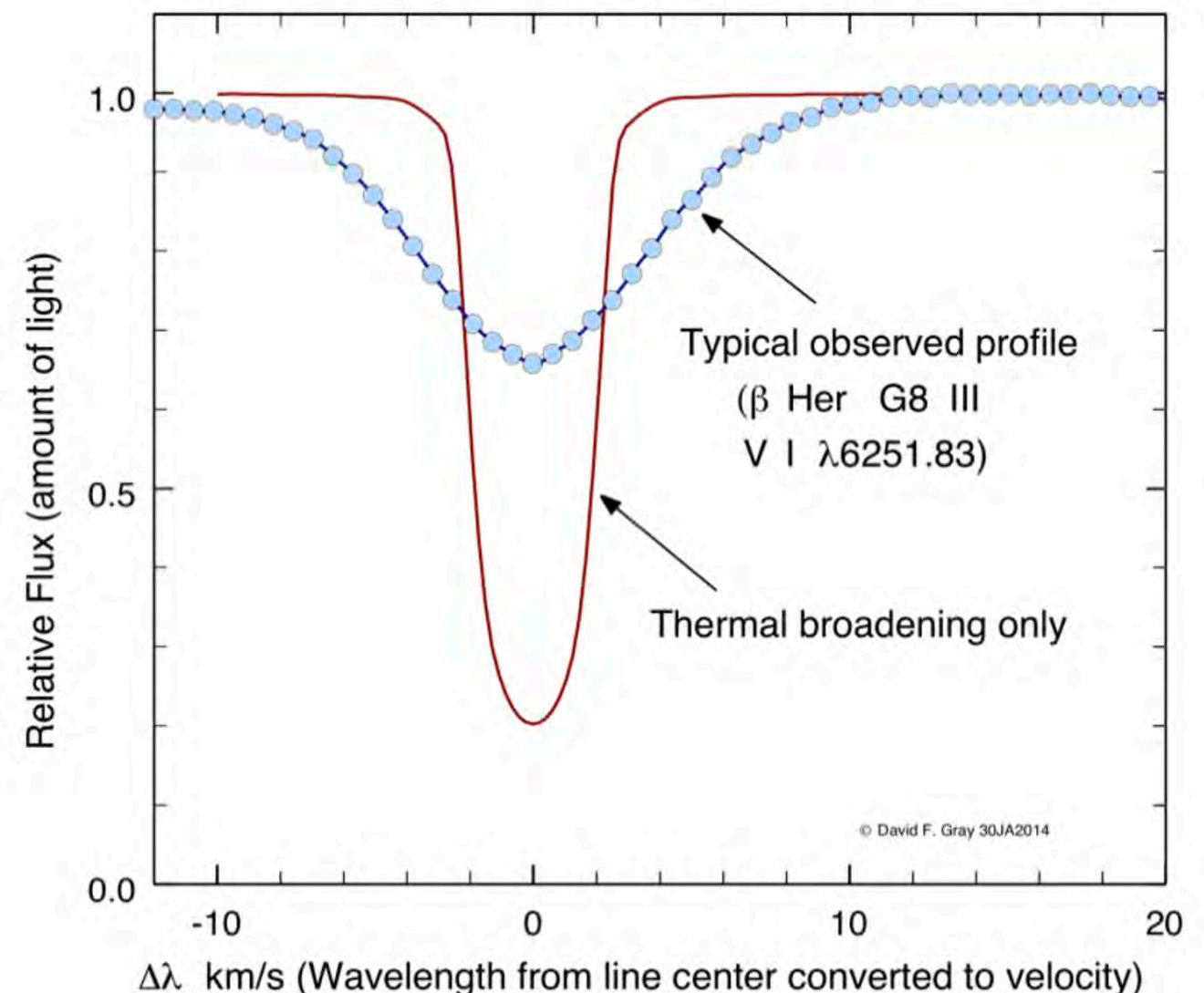


Convection

Observational indicators of convection on other stars

1. Spectral line broadening (macroturbulence)

- Stellar discs cannot be resolved (except for the Sun and some giant stars, marginally)
 ➡ How to detect if a star (point source) exhibits surface convection?
- **Spectral lines** provide information but “integrated” over the whole (unresolved) stellar disc
- Velocities of the surface flows (in the granulation) produce Doppler shifts
- ➡ **Spectral lines** formed in the (low) photosphere get **broadened** accordingly
- Called **macroturbulence**
- This effect is larger than broadening due to thermal motions and (non-radial) oscillations for most stars; Doppler shifts due to stellar rotation can (often) be separated from macroturbulence (via Fourier techniques)

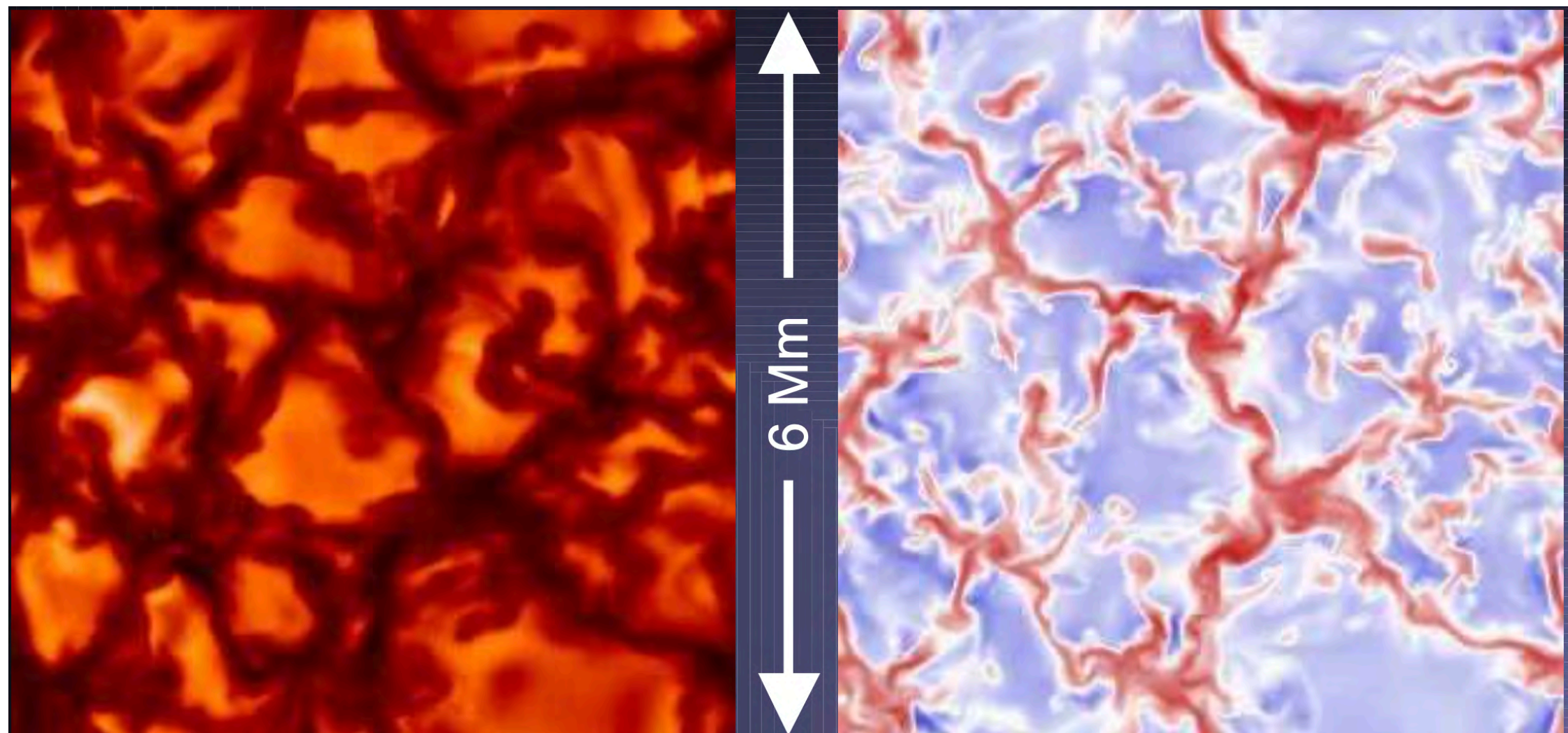


Convection

Observational indicators of convection on other stars

2. Spectral line asymmetry

- Rising gas in granules produce blueward Doppler shifts
- Sinking gas in inter granular lanes produce redward Doppler shifts
- Contributions from granules dominate (cover larger area and brighter)



Intensity

Doppler shift

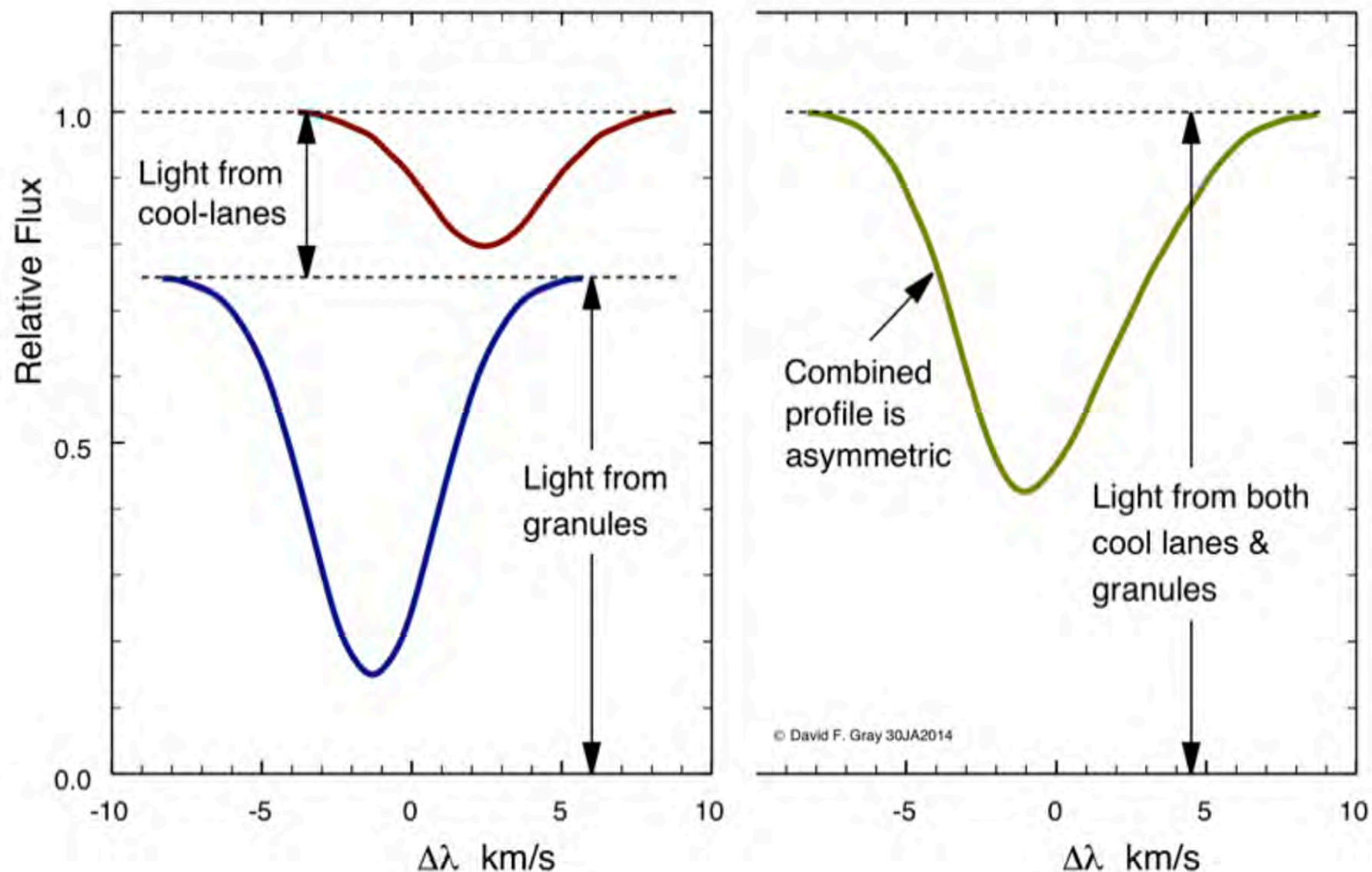
3D simulation (MuRAM)

Convection

Observational indicators of convection on other stars

2. Spectral line asymmetry

- Rising gas in granules produce blueward Doppler shifts
- Sinking gas in inter granular lanes produce redward Doppler shifts
- Contributions from **granules dominate** (cover larger area and brighter)
- Combined photospheric spectral line profiles (integrated over stellar disc) are **asymmetric**



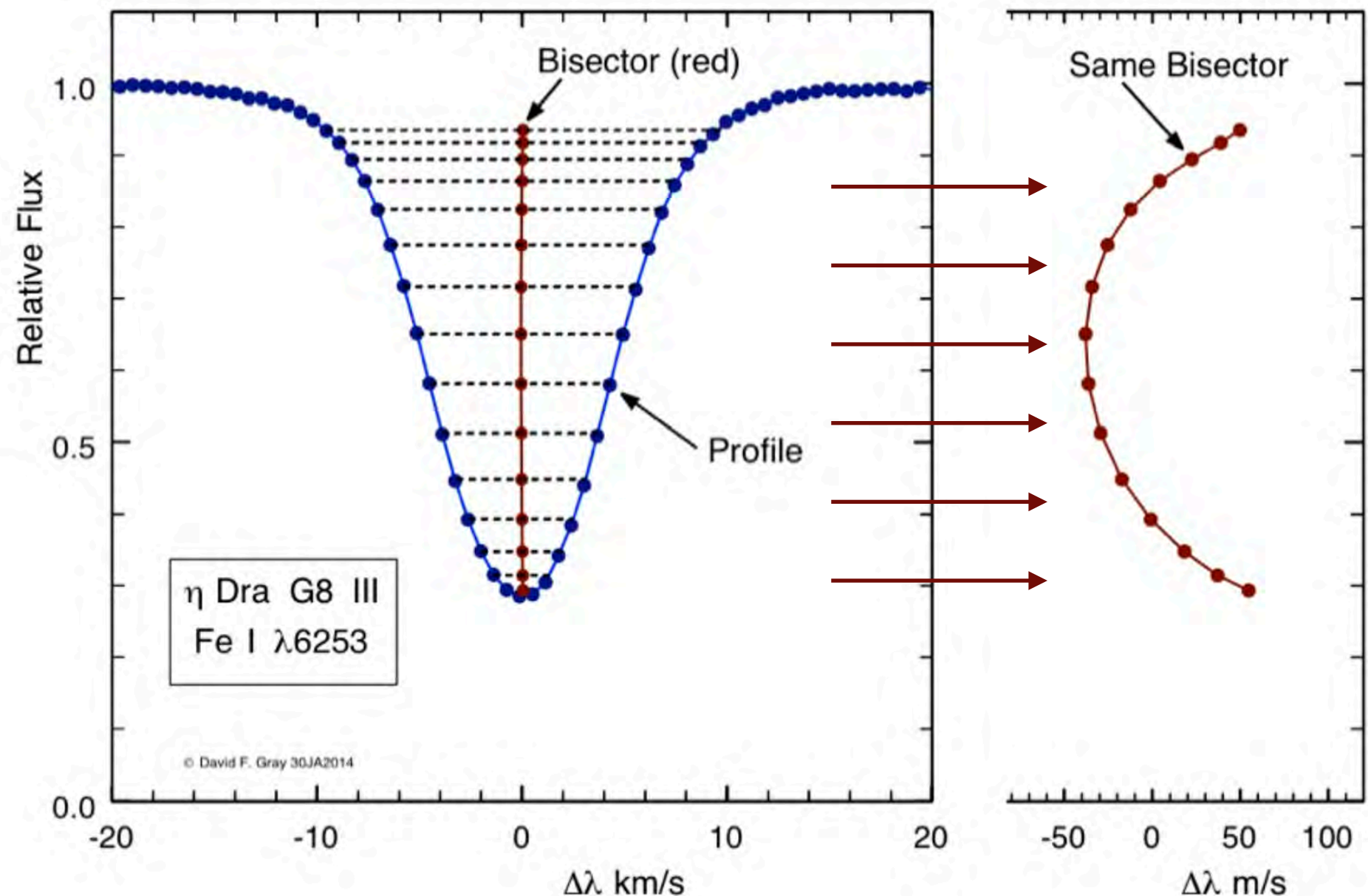
Convection

Observational indicators of convection on other stars

2. Spectral line asymmetry — line bisectors

- Spectral line asymmetries measured as **line bisector**
 - Determine midpoints between points at equal intensity level in the two line wings
 - Gives the relative shift of the midpoint for different parts of the spectral line

- Shifts can be subtle
- Bisector on the left looks almost like a straight vertical line.
- Right plot on smaller axis range reveals a C-shaped bisector

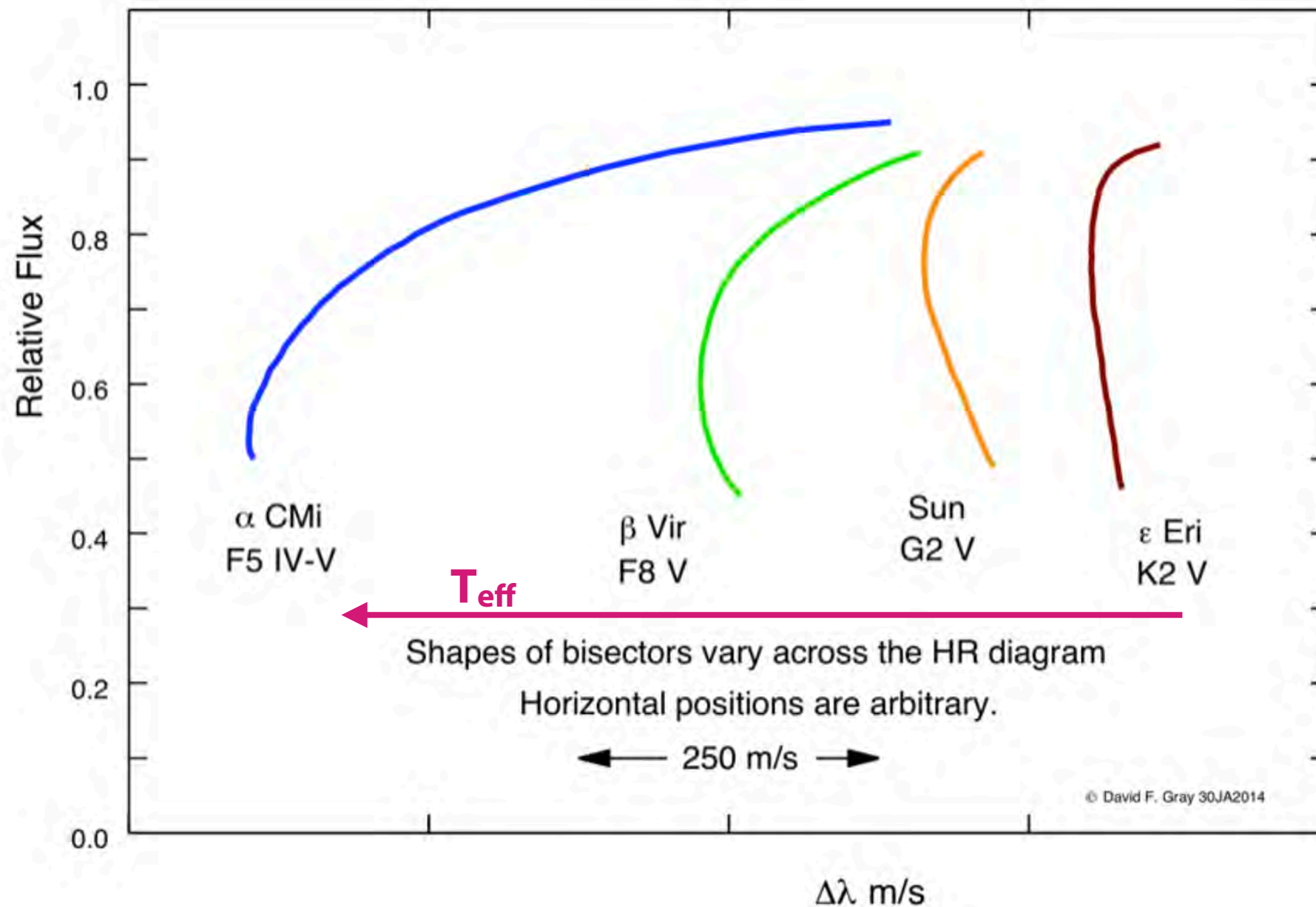


Convection

Observational indicators of convection on other stars

2. Spectral line asymmetry — line bisectors

- Cool stars (solar-like and low mass) typically exhibit C-shaped bisectors
- Reversed C-like shapes found for hotter stars (explained by Gray 2010ApJ...721..670G as normal continuation of observational granulation imprint along the main sequence)



Convection

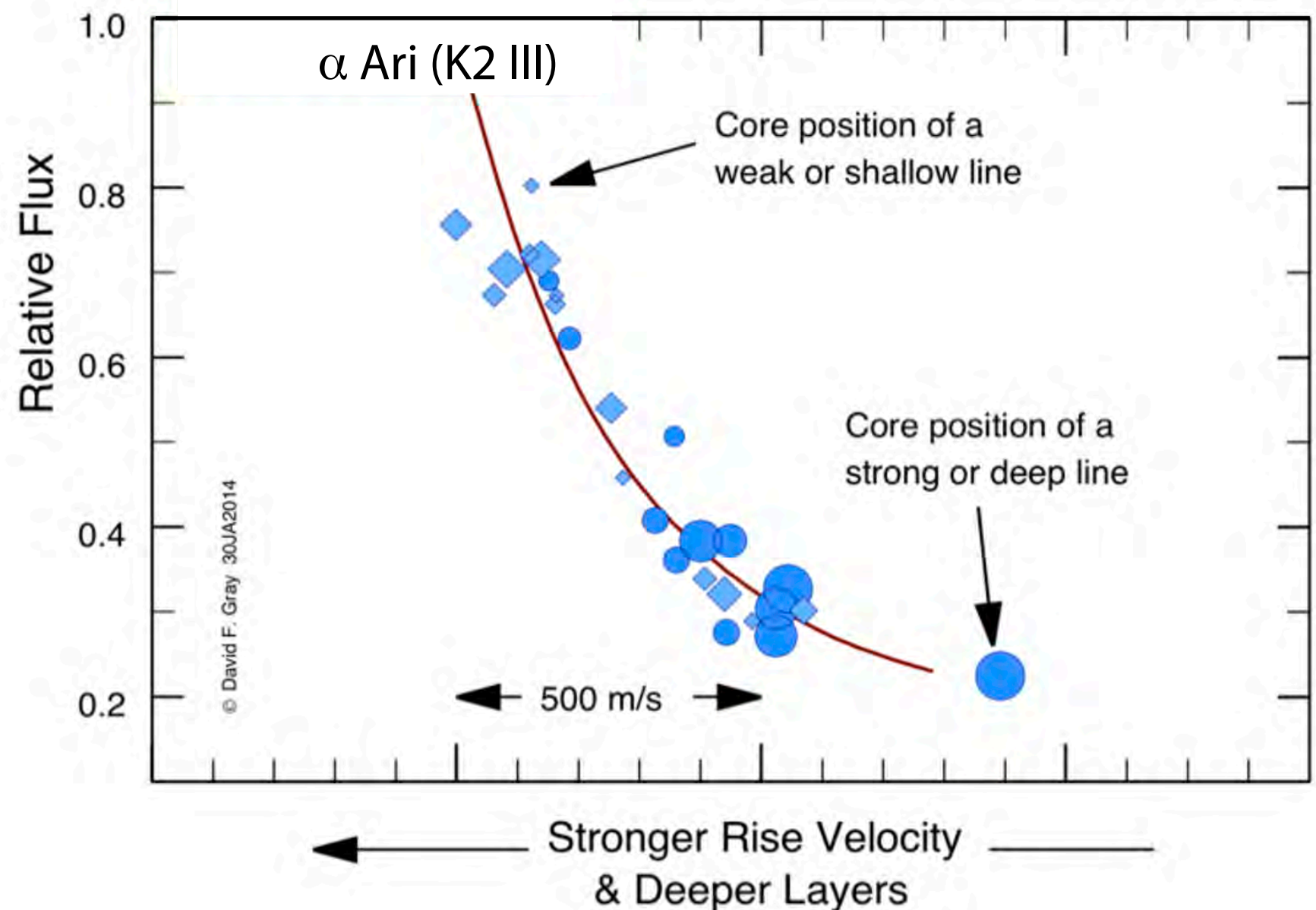
Observational indicators of convection on other stars

3. Spectral line strength — probed atmospheric layer

- Cores of weaker spectral lines are formed deep down in the stellar photosphere
- Cores of stronger spectral lines are formed higher in the stellar photosphere
- Means of probing different layers and thus the vertical velocity profile across the low photosphere and the convective overshoot region

Consider opacity along line of sight

Observations of a combination of weak and strong photospheric lines and analysis of broadening and bisectors provide important constraints for the **properties of the granulation on a star**

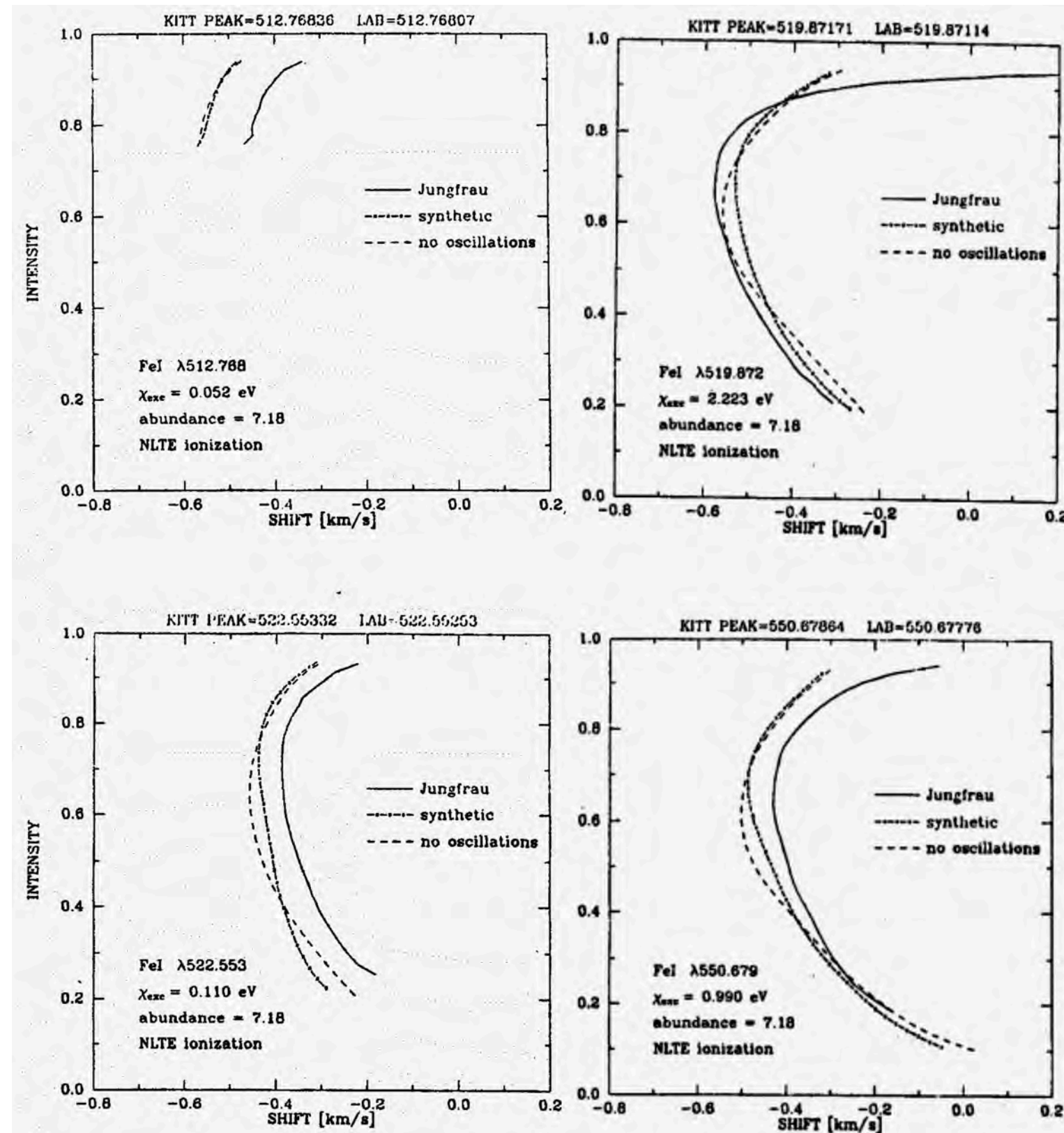


Convection

Observational indicators of convection on other stars

- Also for the Sun
(lower angular resolution in the past)
- Comparison between observed and computed bisectors for different spectral lines with different strengths

➔ Comparison with models help to interpret the bisectors and thus derive the properties of the granulation

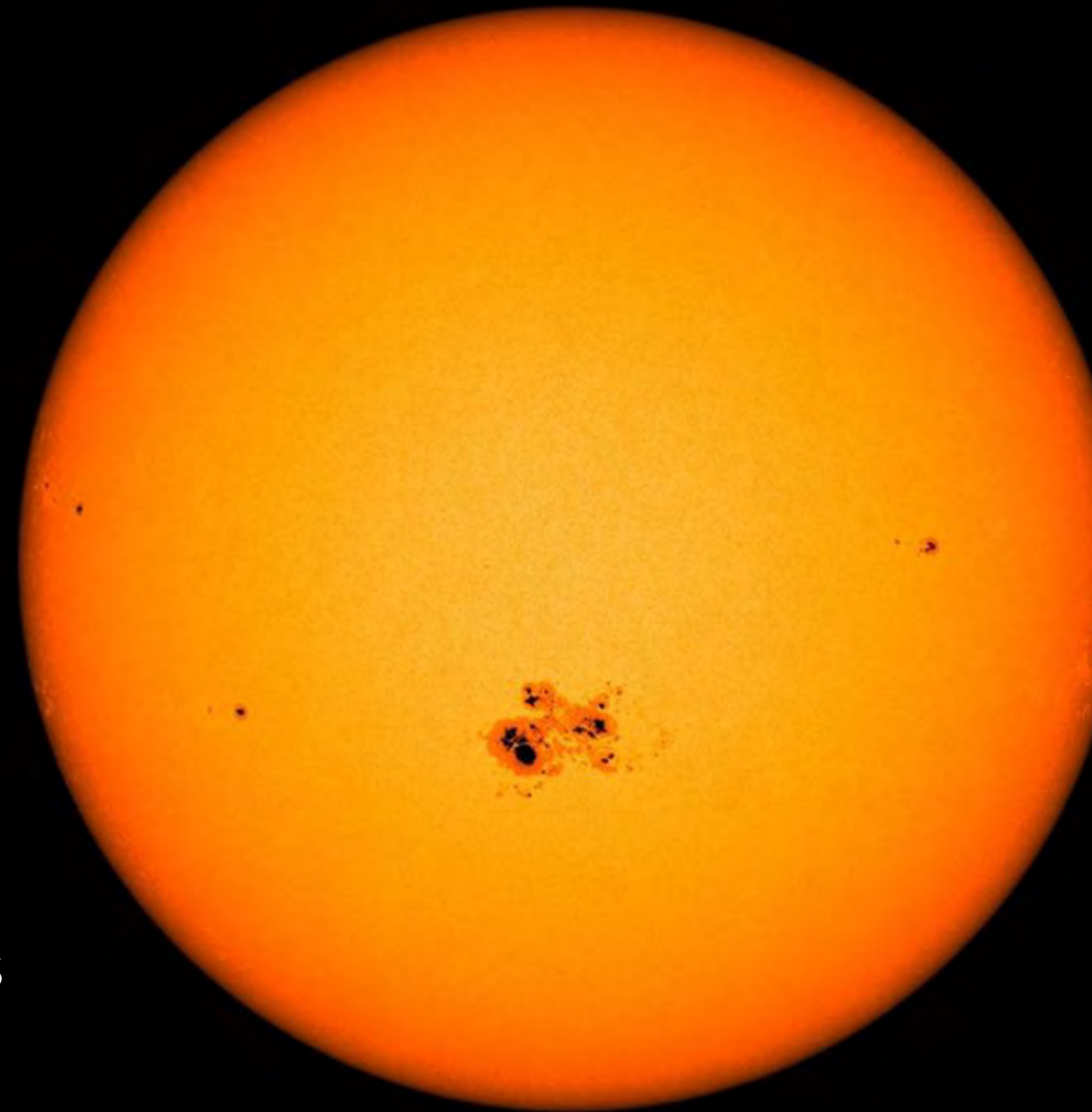


Rotation

Solar rotation

Introduction

- Solar rotation becomes obvious from observing over several days as sunspots move across the solar disk
- Already reported long ago by Galilei (1612) and Scheiner (1630)
- Standard value:
Carrington rotation period = 27.28 days
 - = time taken for the solar coordinate system to rotate once).
- The Sun rotates faster at the equator than at poles — both depending on latitude and depth
 - **Differential rotation**
- Rotation axis inclined by 7.1deg
(Sun's equator is inclined by 7.1deg relative to the ecliptic).



SDO/HMI Quick-Look Continuum 20141023_131500

Solar rotation

Differential rotation — surface

- Surface differential rotation from measurements of:
 - Tracking the movement of magnetic features (sunspots, magnetic field elements, coronal holes)
 - Doppler shifts (of the gas at the surface)

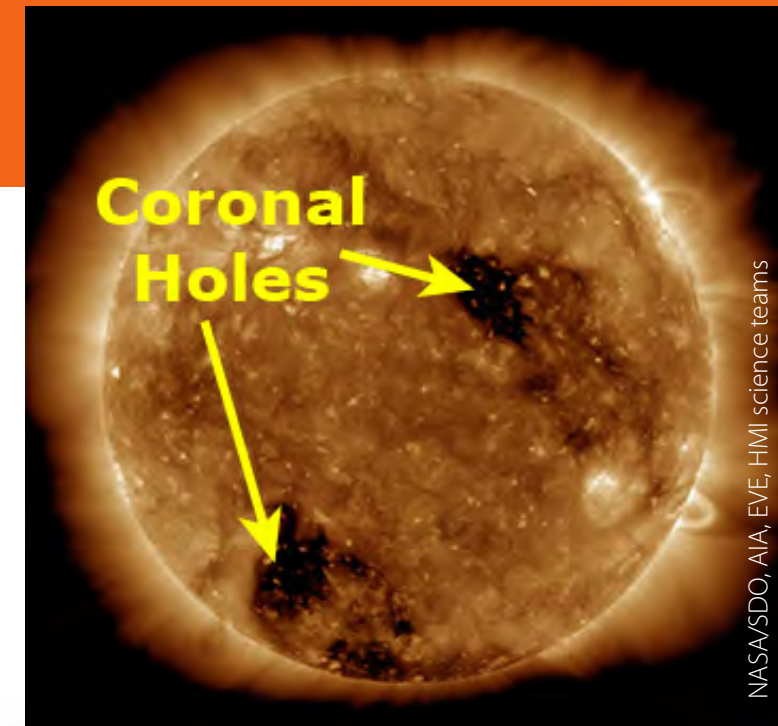
- **Empirical rotation law:** Rotation rate Ω as function of latitude ψ :

$$\Omega = A + B \sin \psi^2 + C \sin \psi^4$$

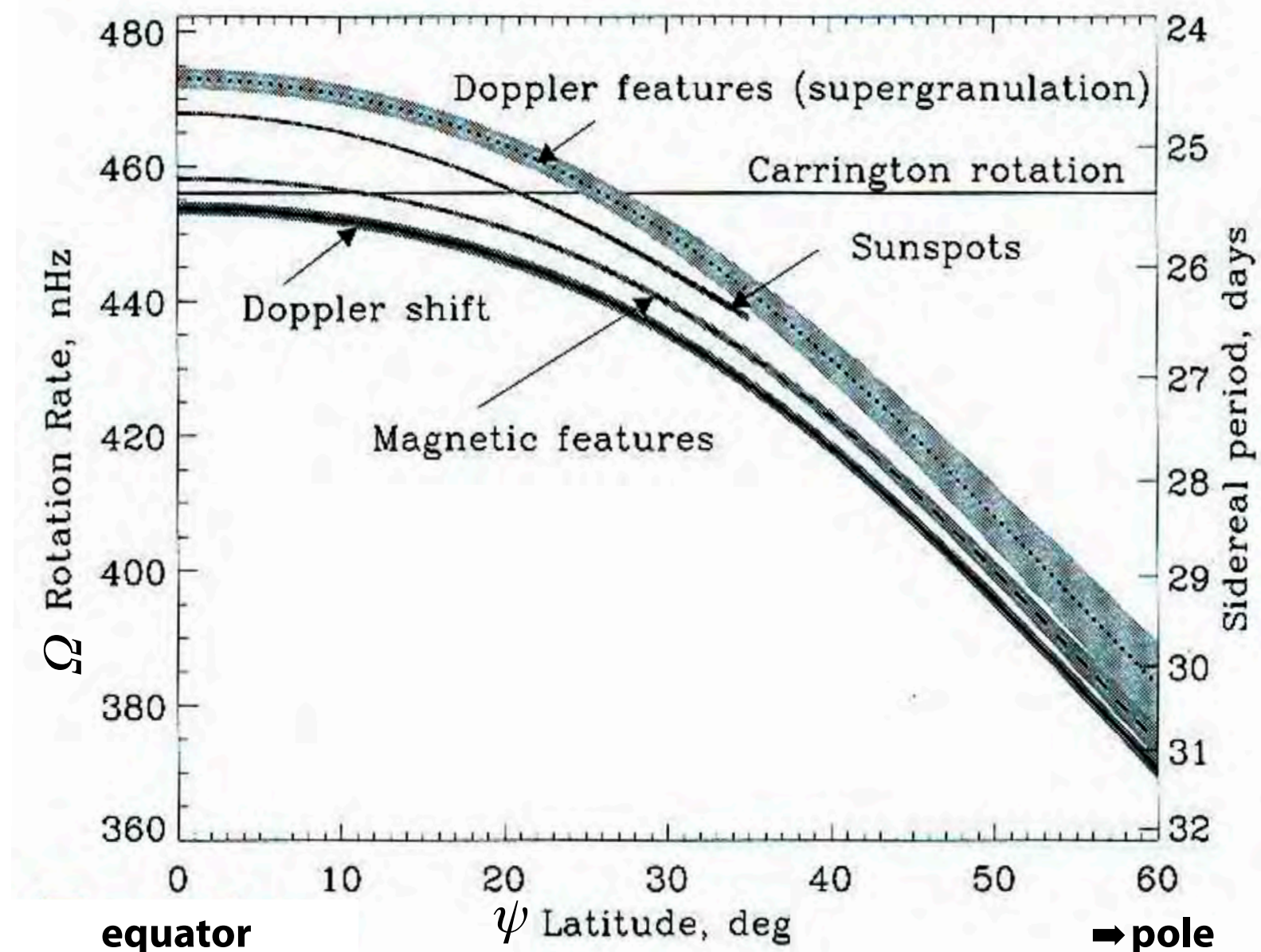
➡ Equator: $\Omega = A$

➡ Poles: $\Omega = A + B + C$

- Different tracers give different values of A, B, C!
(e.g. spots rotate faster than the gas at the surface!)



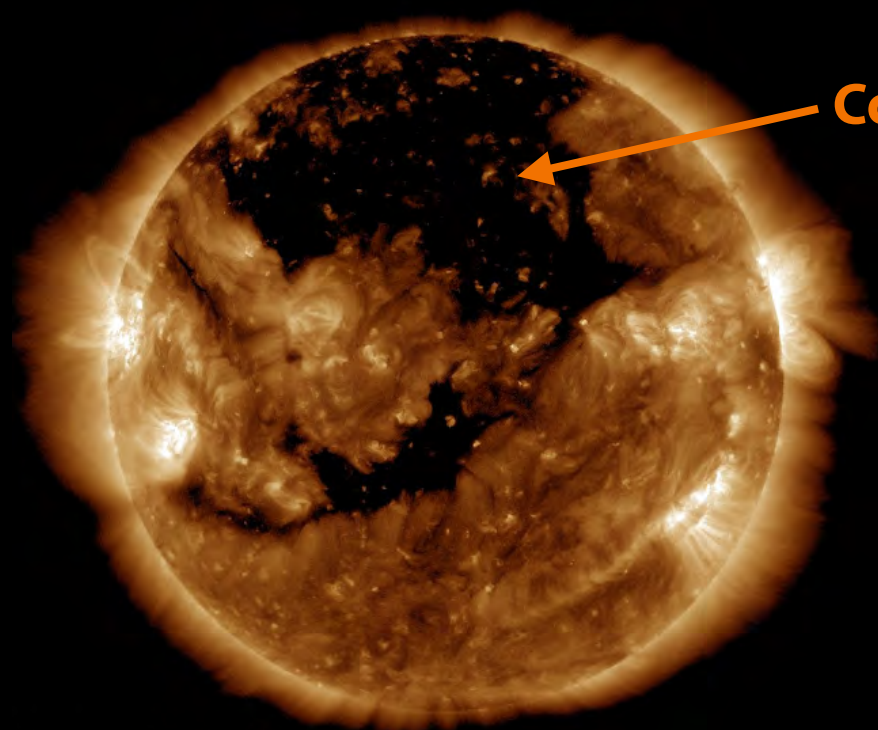
NASA/SDO, AIA, EVE, HMI science teams



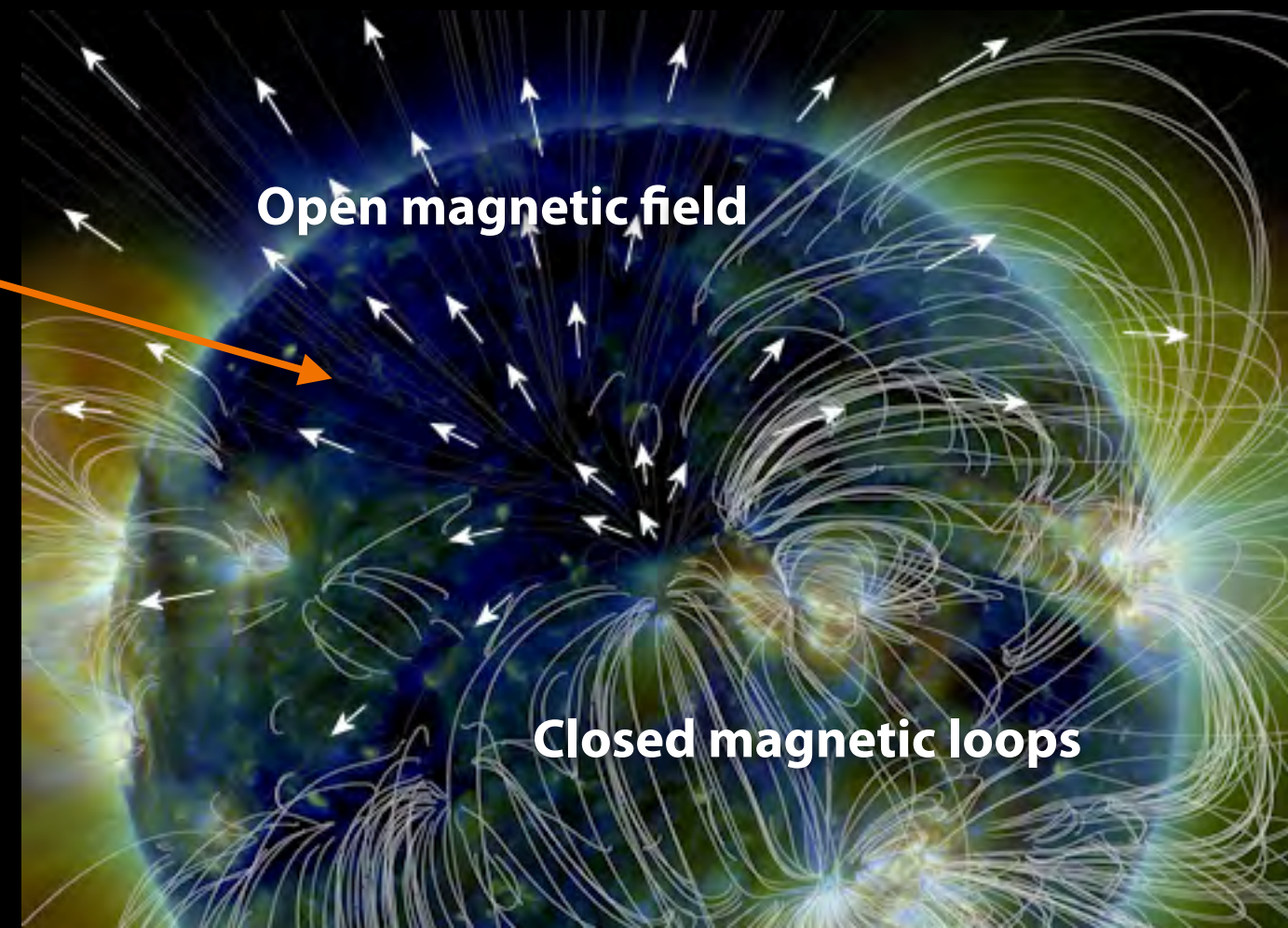
Solar rotation

Differential rotation — surface

- **Different tracers give different values of A, B, C!**
 - Sunspots rotate faster than the gas at the surface
 - Young sunspots rotate faster than older spots (older spots seem to be slowed down by the surrounding gas)
 - Coronal holes rigidly while photospheric magnetic field exhibits differential rotation
 - ➔ Magnetic features move in and out of coronal holes and would need to interact with the surrounding magnetic field (magnetic reconnection)
 - ➔ Observational confirmed.



Coronal hole



Open magnetic field

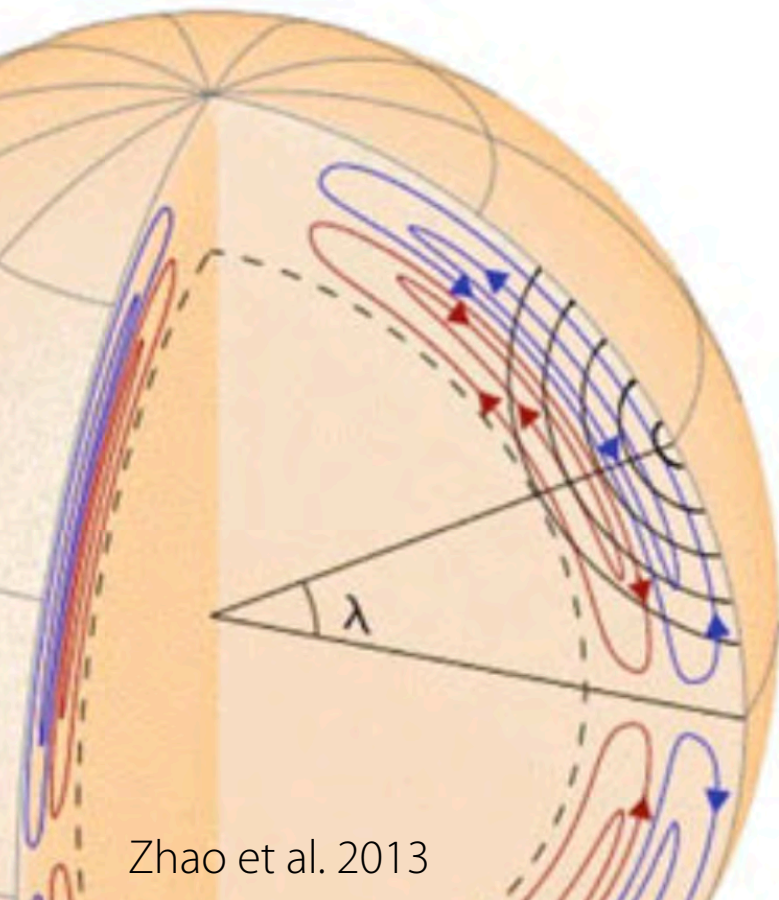
Closed magnetic loops

Solar rotation

Differential rotation — surface

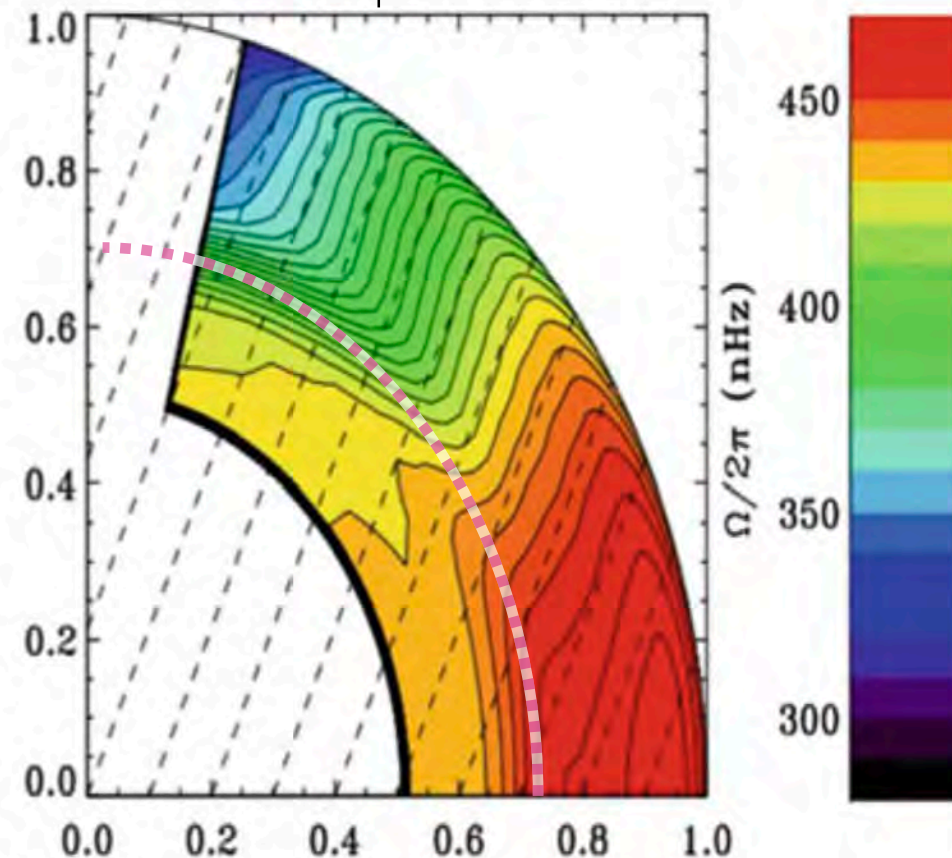
- **Different tracers imply different rotation laws $\Omega(\psi)$ — Why?**
 - Are different tracers anchored at different depths in the convection zone?
 - How does the magnetic field structure change as function of radius?
- Remember the internal rotation speeds and meridional flows as probed with helioseismological methods!

➔ Strong variation of rotation speed as function of radius, depending on latitude

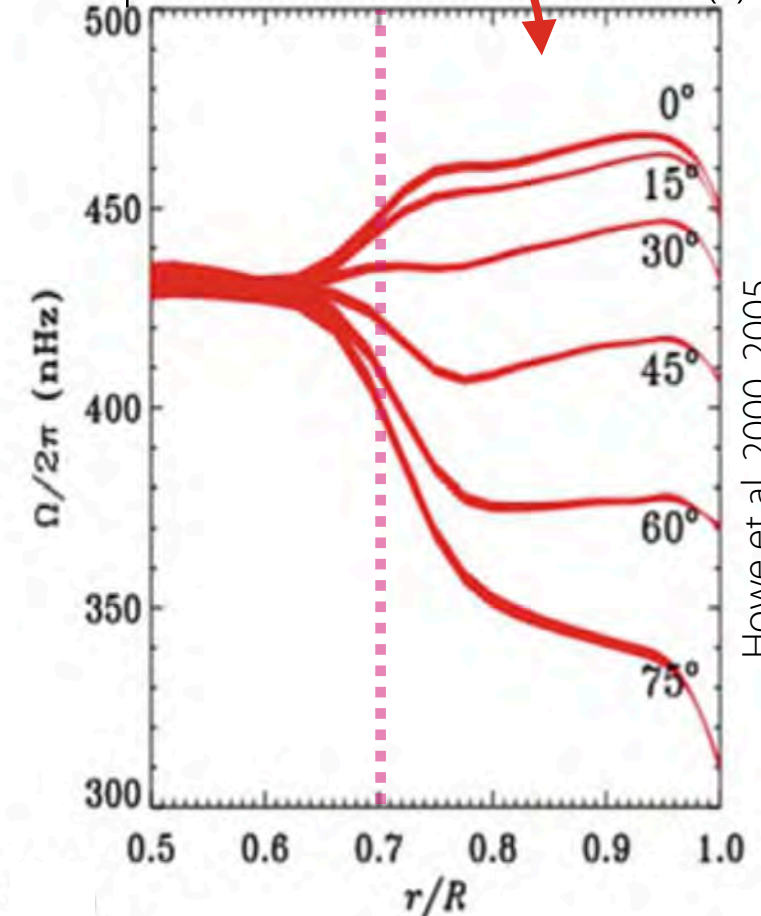


Zhao et al. 2013

Mean rotation profile from GONG data



Radial profiles at constant latitude(s)



Howe et al. 2000, 2005

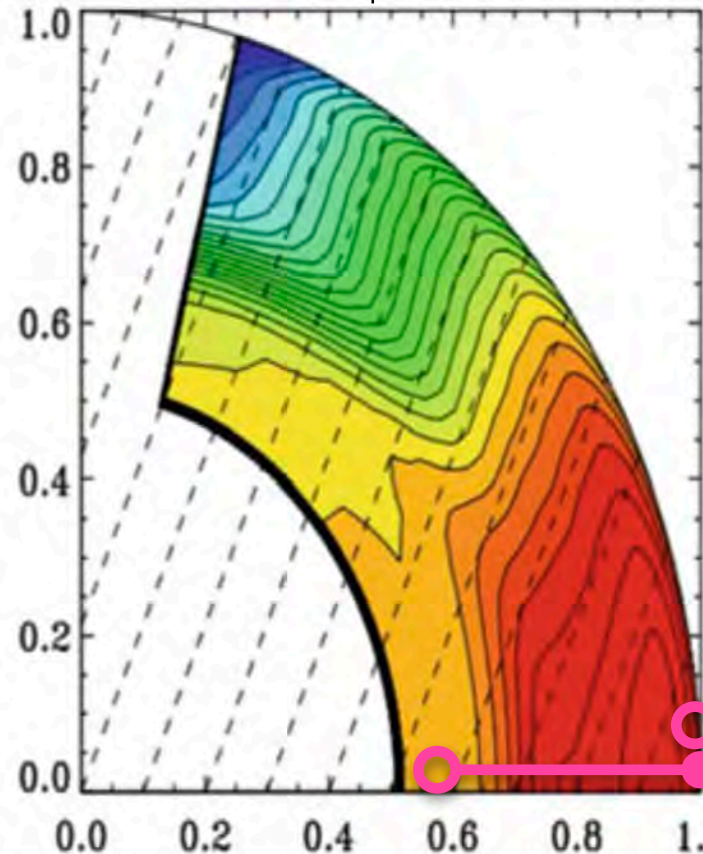
Solar rotation

Differential rotation — surface

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Mean rotation profile from GONG data



➔ What happens if a feature is anchored below the surface in gas that rotates slow compared to a feature at the surface that rotates faster?

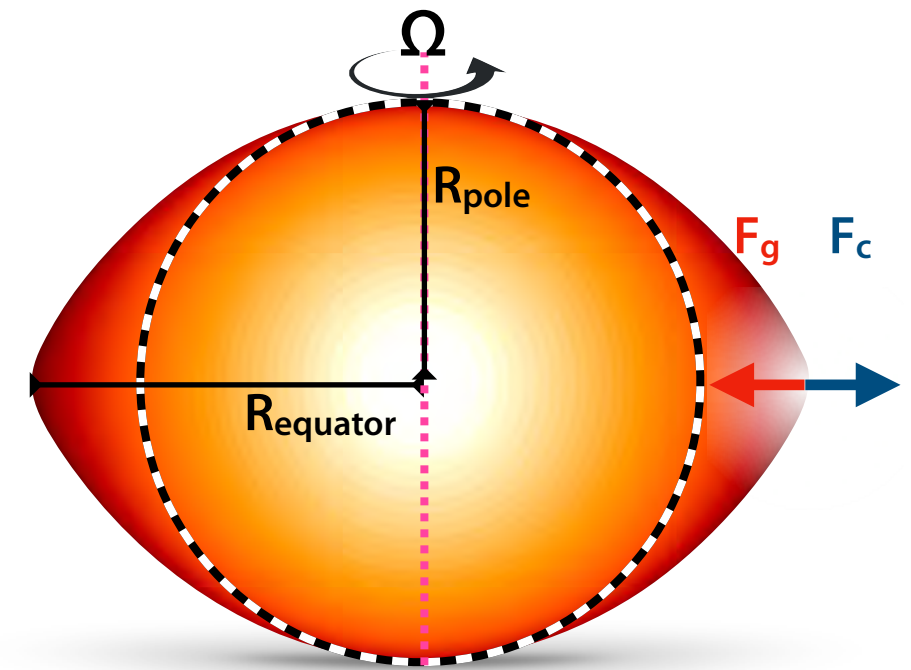
Feature A: anchored at surface, rotates fast

Feature B: anchored in deep convection zone, rotates slower

Solar rotation

Solar oblateness

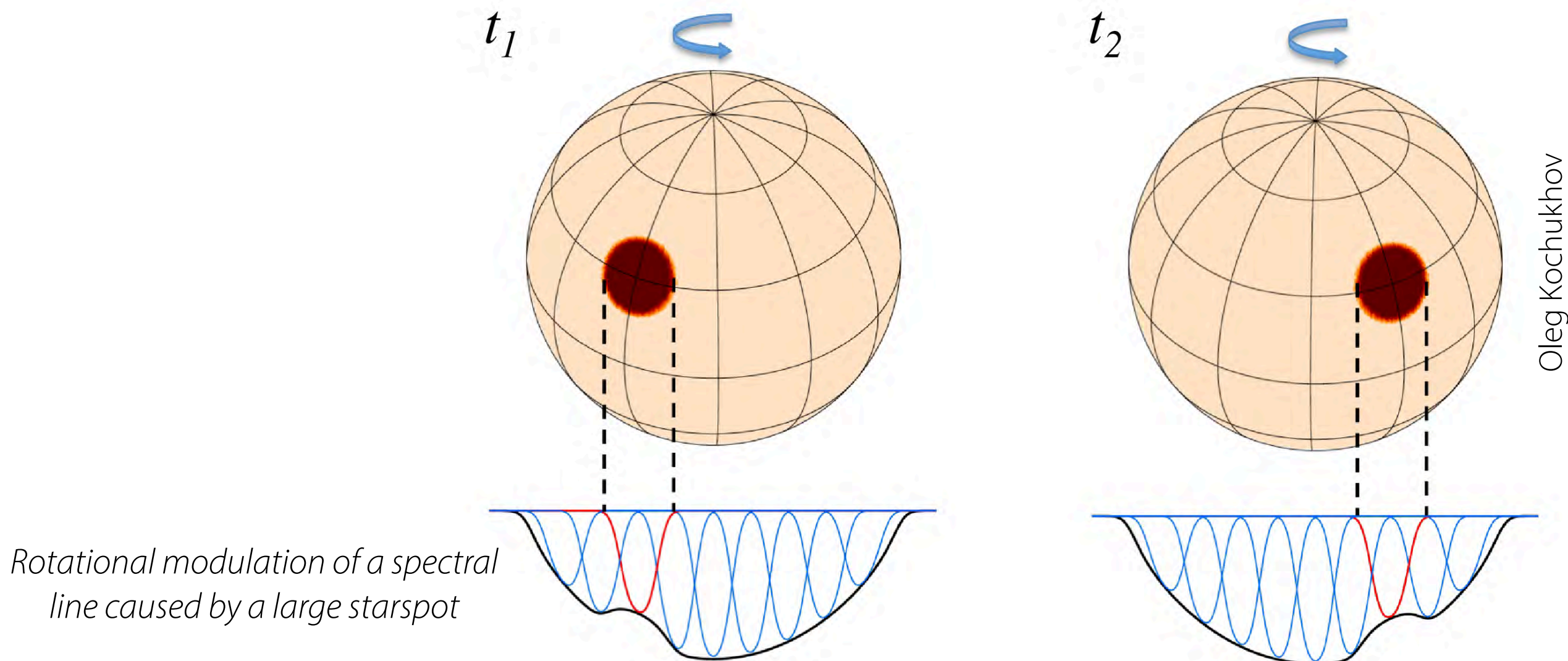
- Centrifugal force due to solar rotation leads larger solar diameter at equator than between the poles
- Oblateness $:= (R_{\text{equator}} - R_{\text{pole}}) / \langle R \rangle = \Delta R / \langle R \rangle$
 - Note: If core rotates more rapidly than surface, then oblateness will be larger than expected due to surface rotation rate*
- Direct measurements:** $(\Delta R / R)_{\odot} \approx 10^{-5}$ (which thus means $\Delta R \approx 14 \text{ km}$)
 - Best spatial resolution of images still $\sim 50 \text{ km}$
 - Systematic errors due to concentration of magnetic activity to low latitudes affects measurements of solar diameter since shape of limb is distorted.
- Helioseismic measurements** also: $(\Delta R / R)_{\odot} \approx 10^{-5}$ (Redouane Mecheri)



Stellar rotation

Measuring rotation periods

- **Spectroscopically**: rotational broadening of spectral lines.
- From **asteroseismic** measurements
- Detection of **rotational modulation** (over time) caused by a non-uniform surface on the star, .e.g. varying imprints of **starspots** in stellar spectra/light curves as they move across the unresolved stellar disk over time.



Stellar rotation

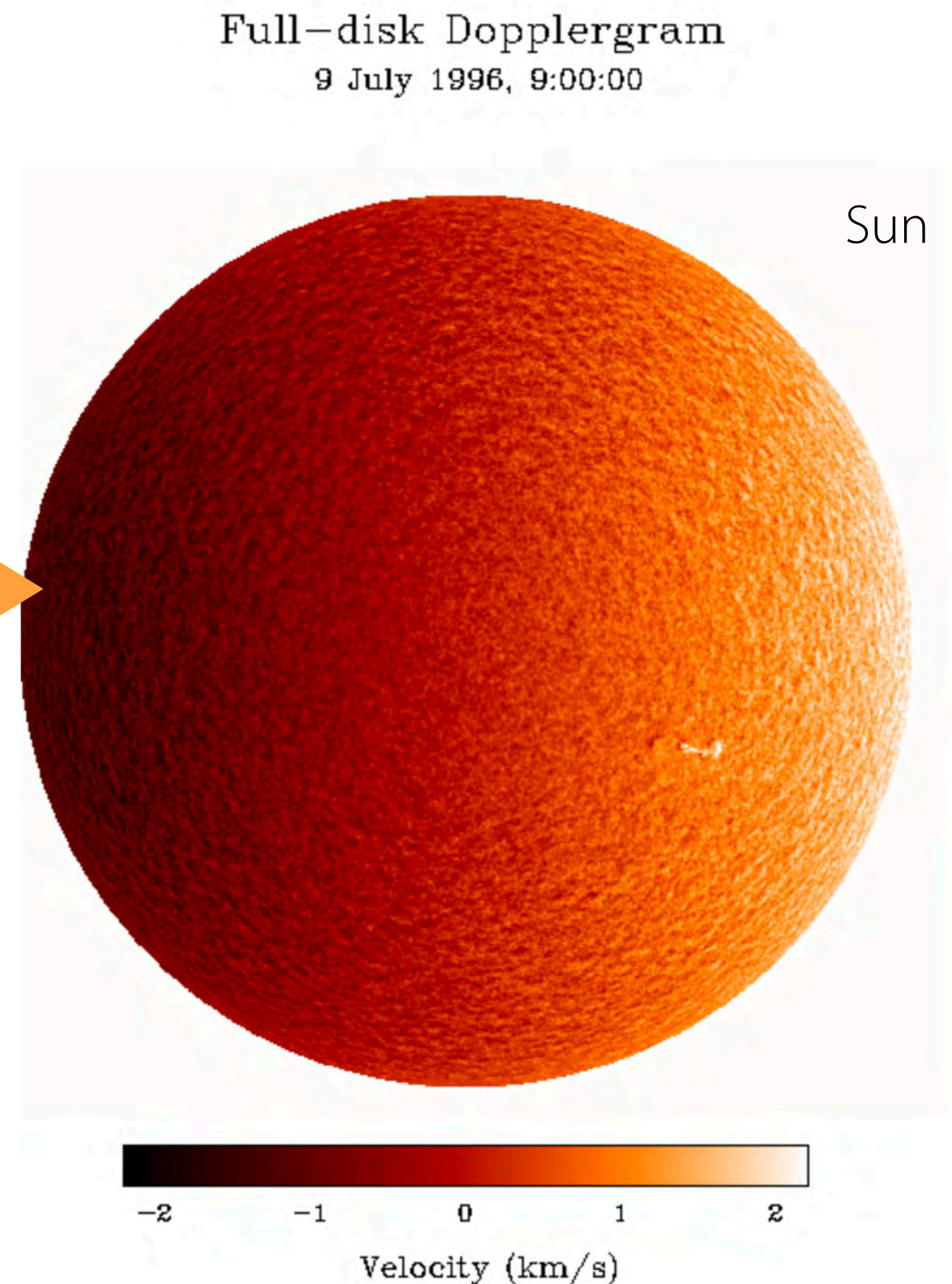
Spectral line broadening due to rotation

- Doppler effect — velocity component along line of sight (LOS)
- Stars: LOS velocity due to rotation of the different parts of the stellar disk integrated into a spatially averaged line profile
- Combining spectral line profiles that are Doppler-shifted between +/- LOS rotation velocity at the limb

➡ Broadening of spectral lines allows to derive only the **projected** rotation rate / apparent rotational velocity:

$$v' = v \sin i$$

- i : angle between LOS and rotation axis of the star



Stellar rotation

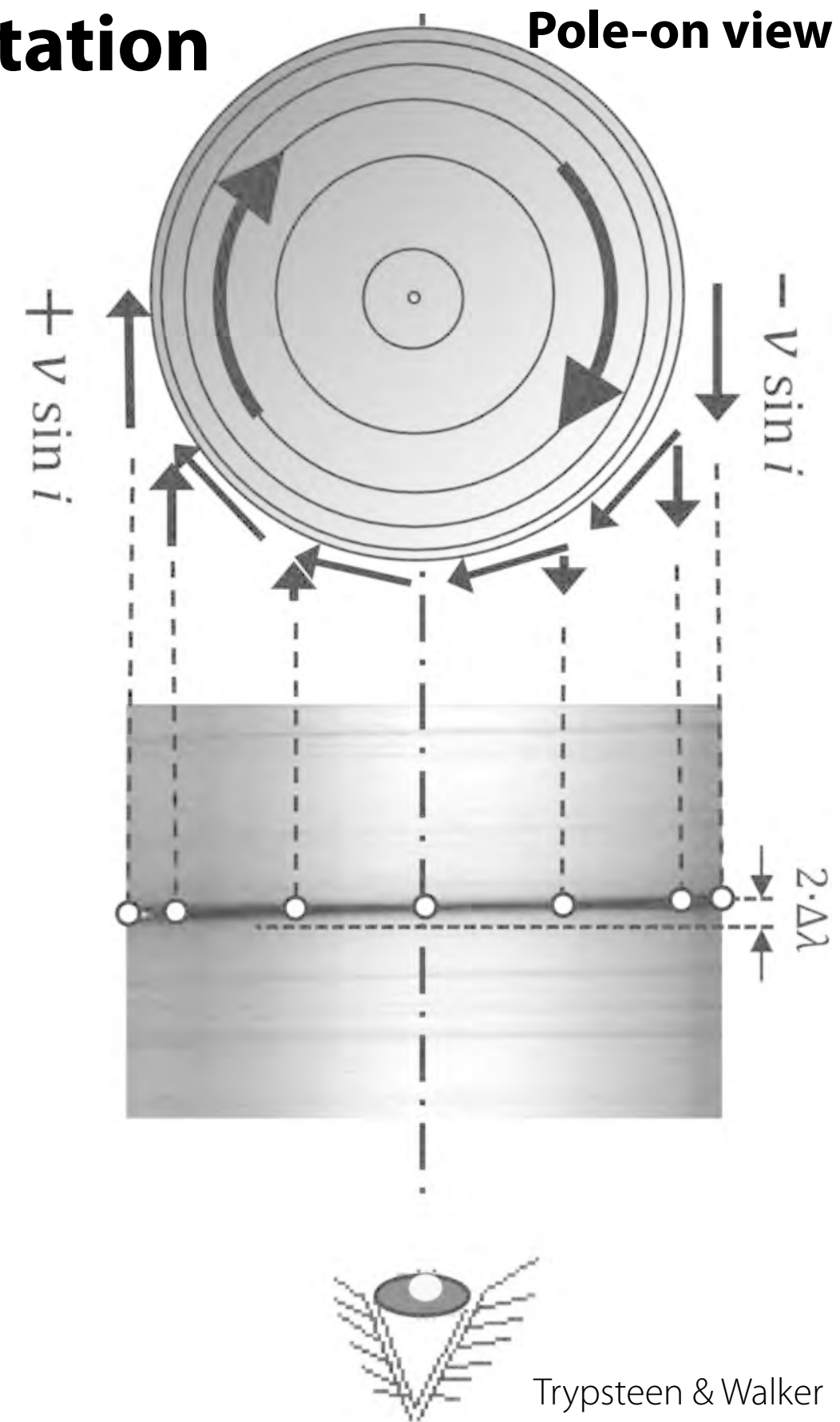
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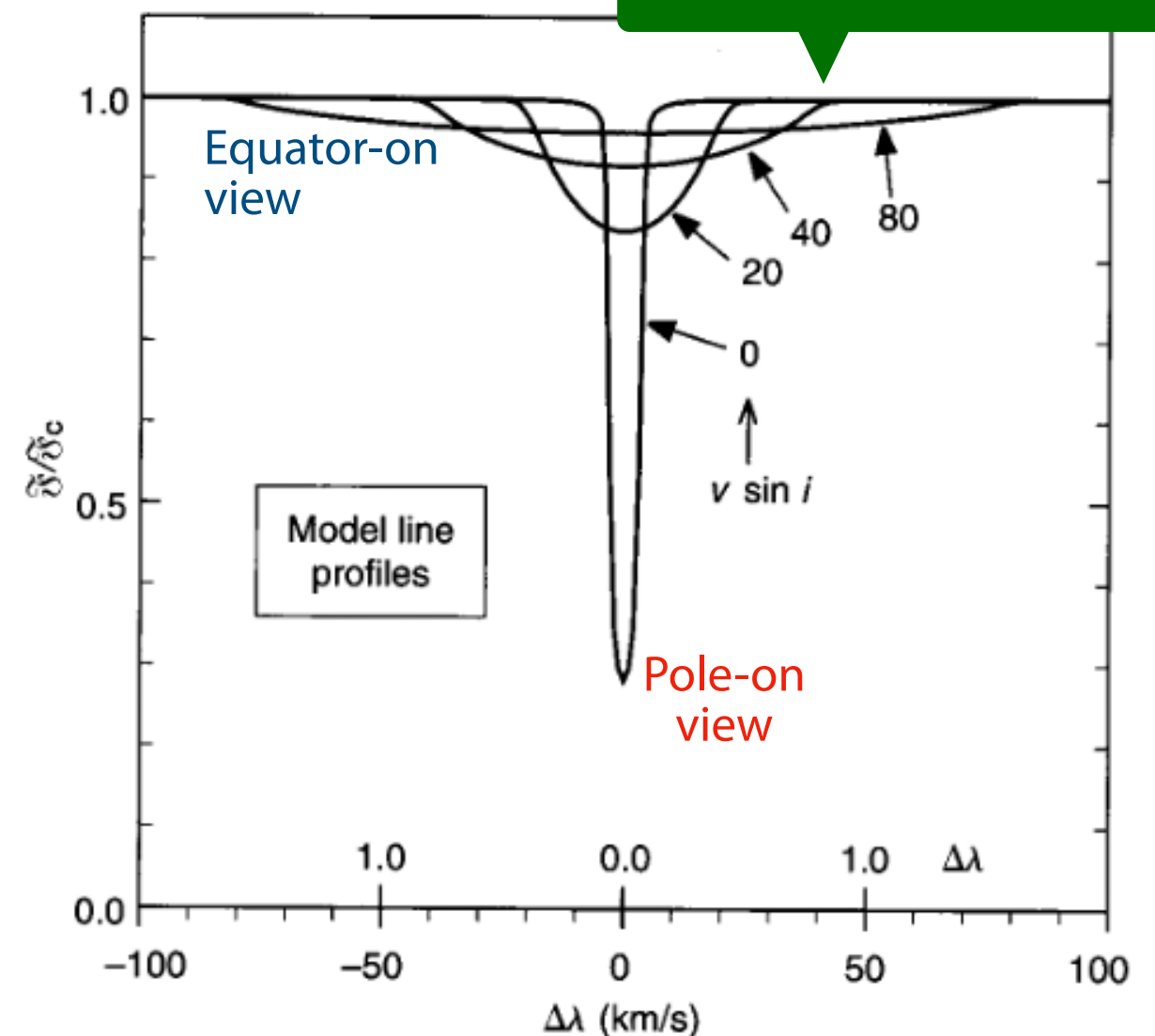
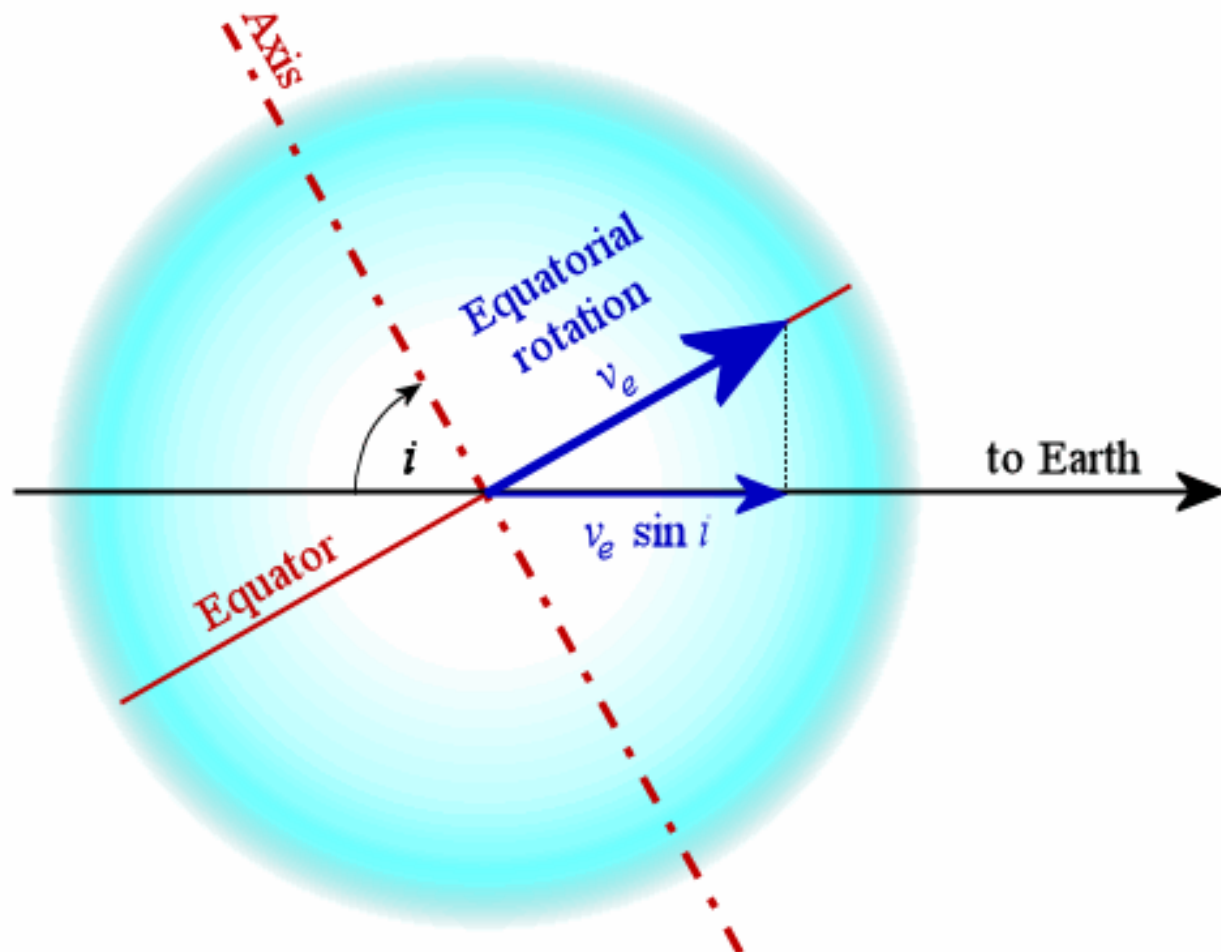
Stellar rotation

Spectral line broadening due to rotation

- Only the **projected** rotation rate can be derived from broadening of spectral lines

$v \sin i$ i : angle between LOS and rotation axis of the star

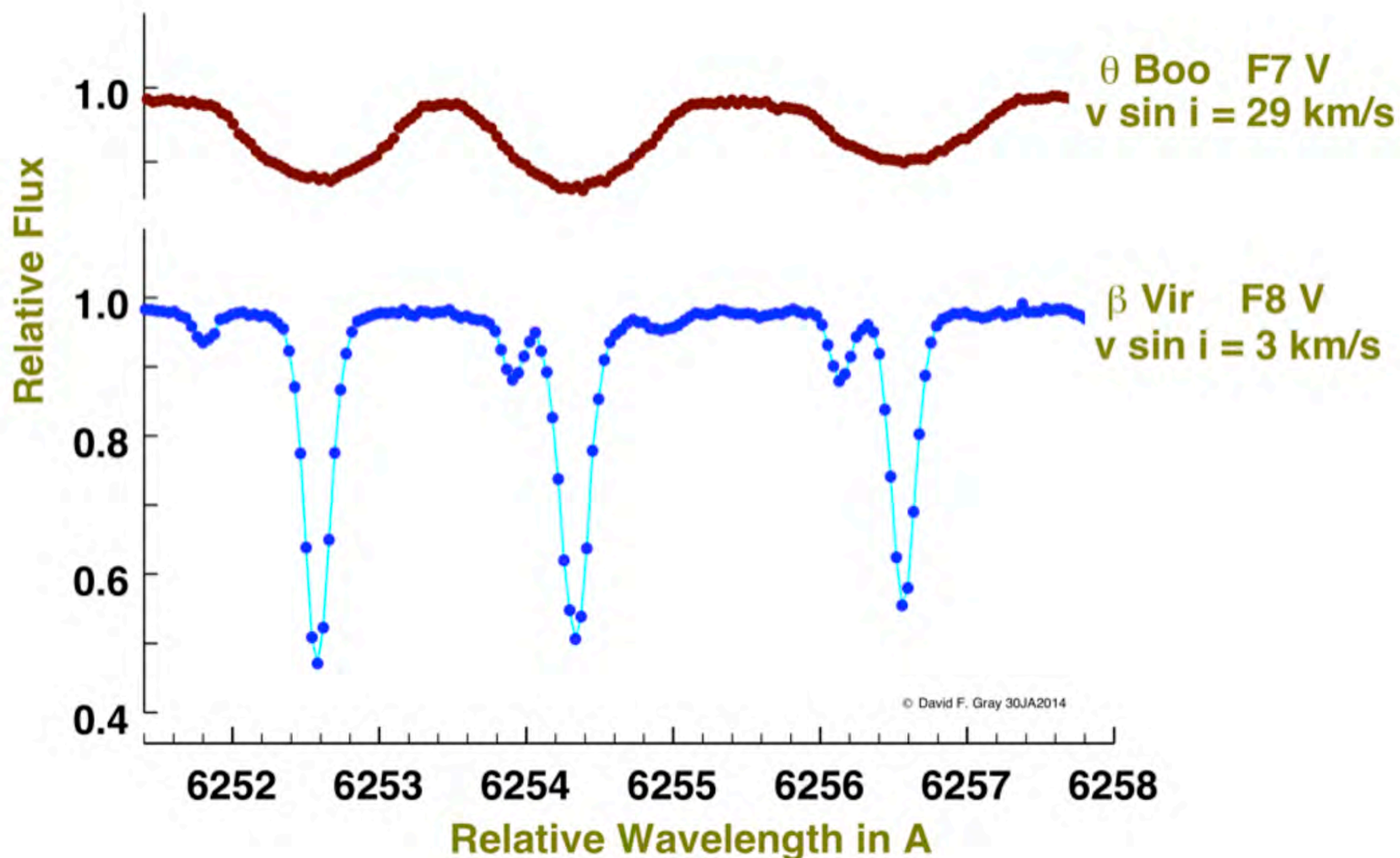
- View on pole: $i = 0$, no rotational broadening;
- View on equator: $i = 90^\circ$, maximum rotational broadening.



Stellar rotation

Spectral line broadening due to rotation

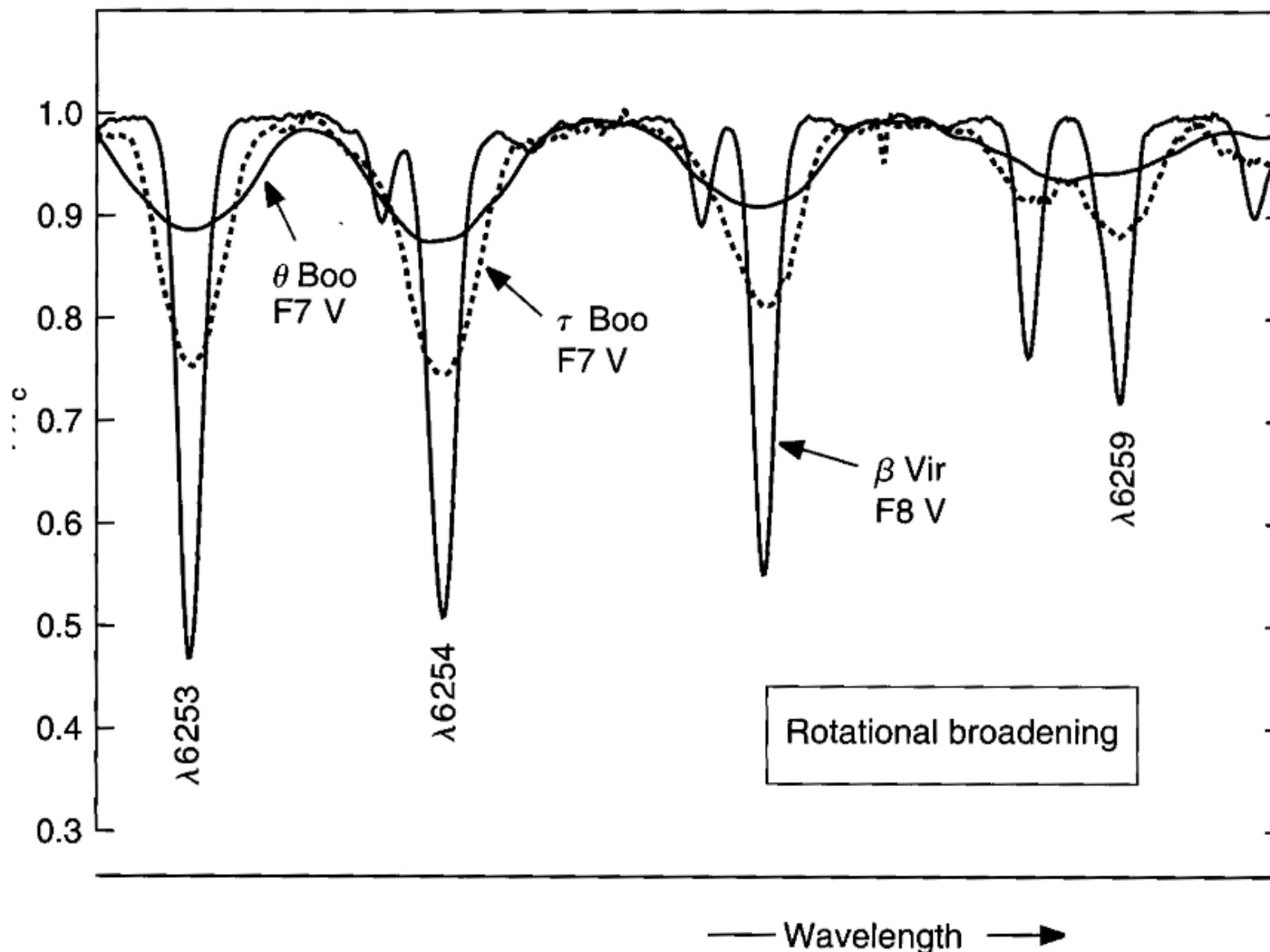
- Comparison of two (relatively) similar stars



Stellar rotation

Spectral line broadening due to rotation

- Comparison of three (relatively) similar stars



A small problem:

We measure only

$$v \sin i$$

➡ The true rotational velocity v will remain uncertain unless the inclination i of the rotation axis is known.

Stellar rotation

Differential rotation

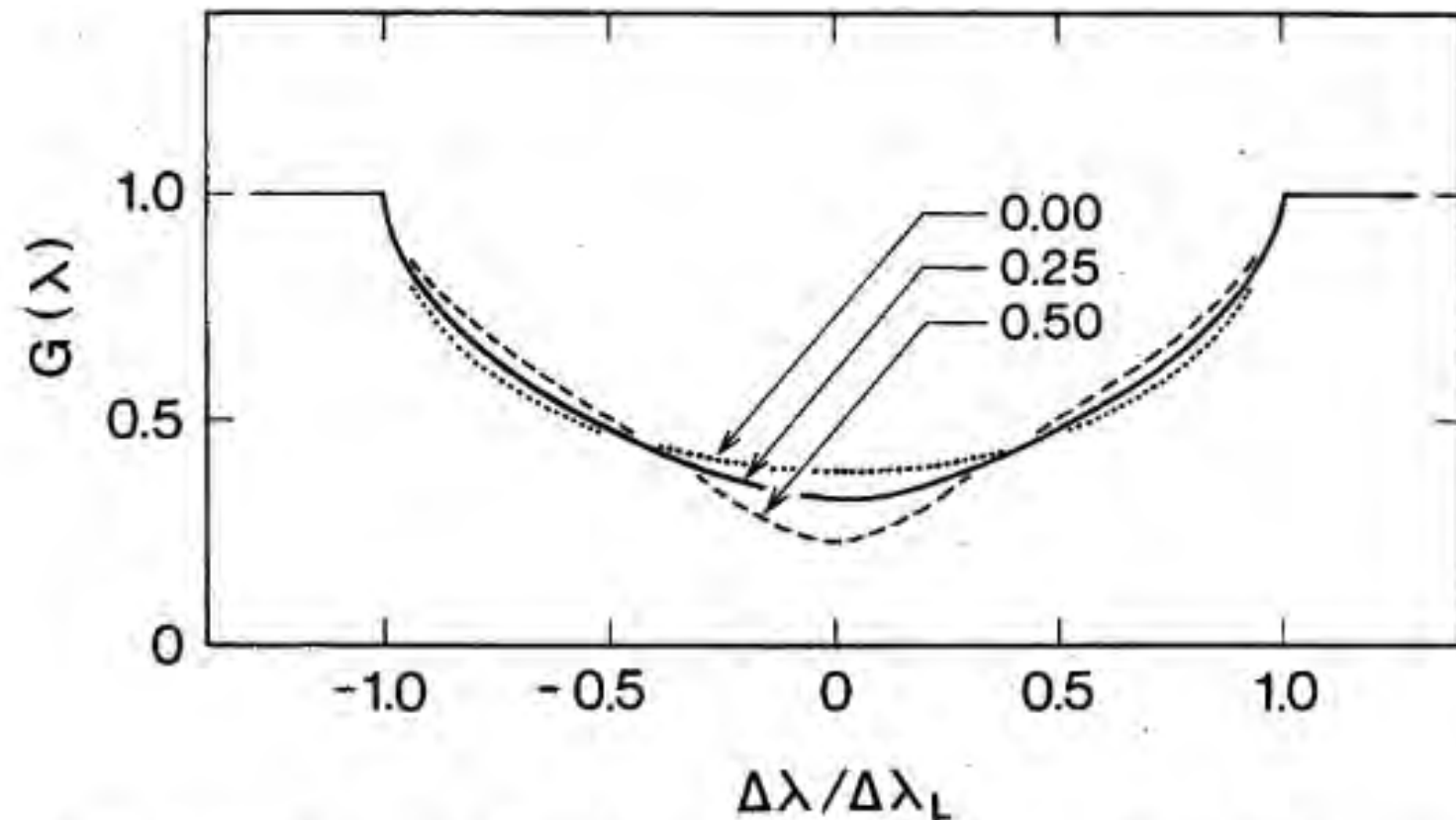


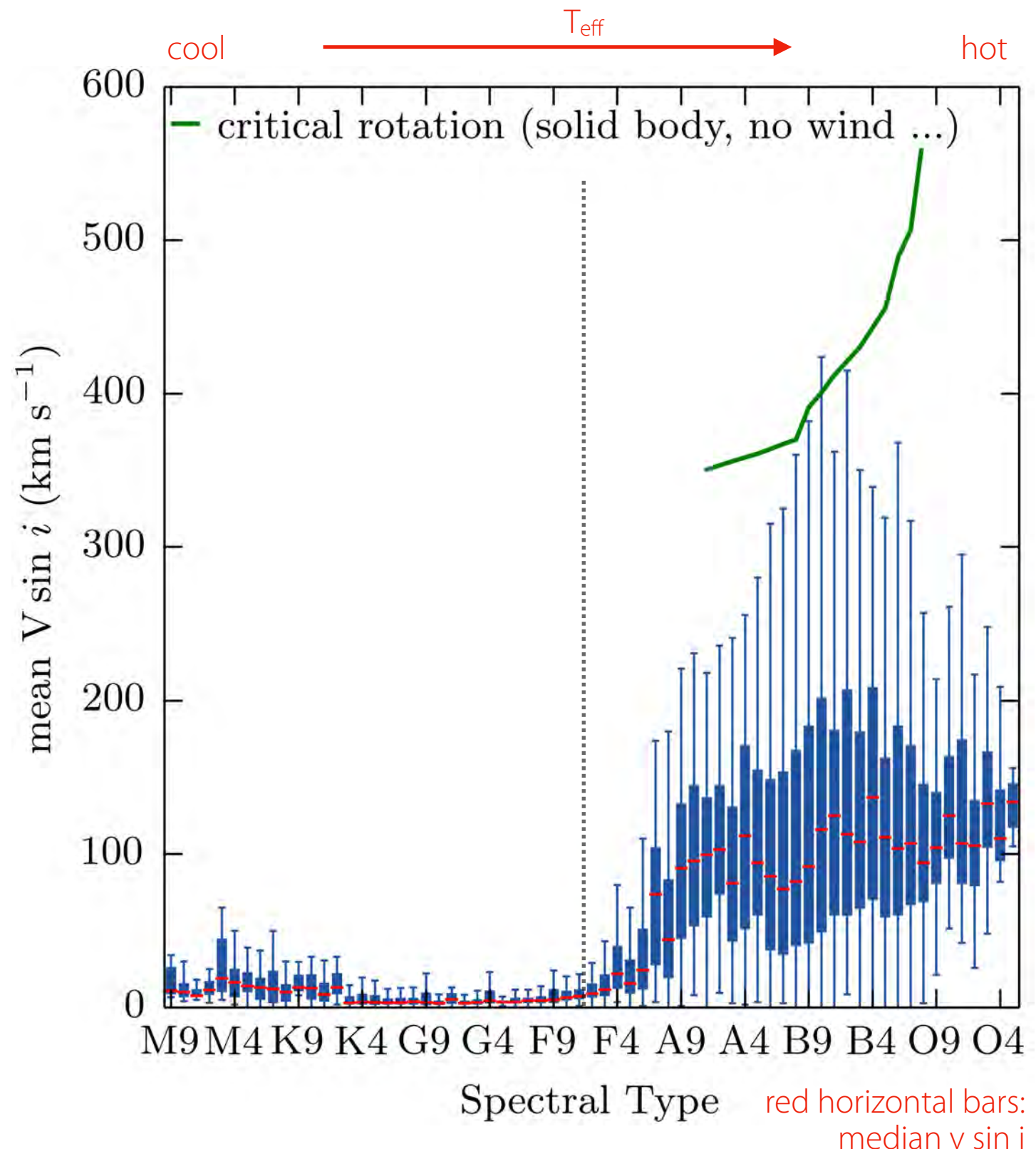
FIG. 3.—Rotation profiles for three values of the differential rotation parameter $\alpha = \omega_2/(\omega_0 + \omega_2)$.

- Equatorial acceleration $\rightarrow$ lines narrower and more V-shaped
- Polar acceleration $\rightarrow$ lines fatter and more U-shaped
- Evidence for differential rotation found in F-stars
- Significant rotational broadening of the line profile by several km/s needed to be detectable, solar-type stars rotate too slowly

Stellar rotation

Measured $v \sin i$

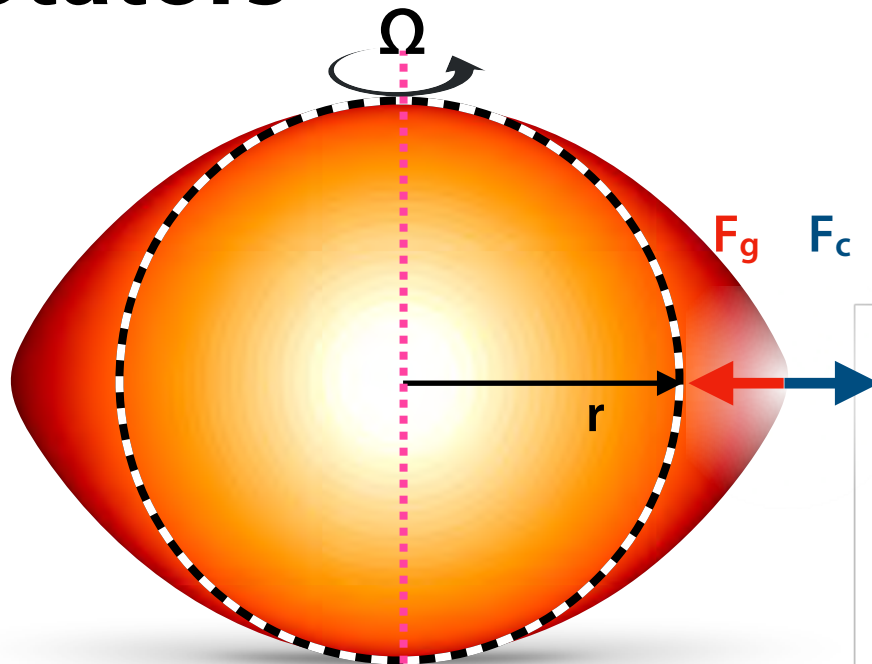
- Distribution of apparent rotational velocities ($v \sin i$) as a function of spectral type.
- Some hot stars rotate as fast as 450 km/s
- Two stellar populations:
 - **Slow rotators** — stars cooler than F7: typically $v \sin i < 50$ km/s; for many solar-like stars < 6 km/s.
 - **Fast rotators** — hotter stars: often $v \sin i > 100$ km/s.
- The Sun rotates comparatively slowly at ~ 2 km/s
- Wide range at earlier spectral types (hot stars) due to
 - Large spread in actual rotation rates
 - Large spread in inclination angles



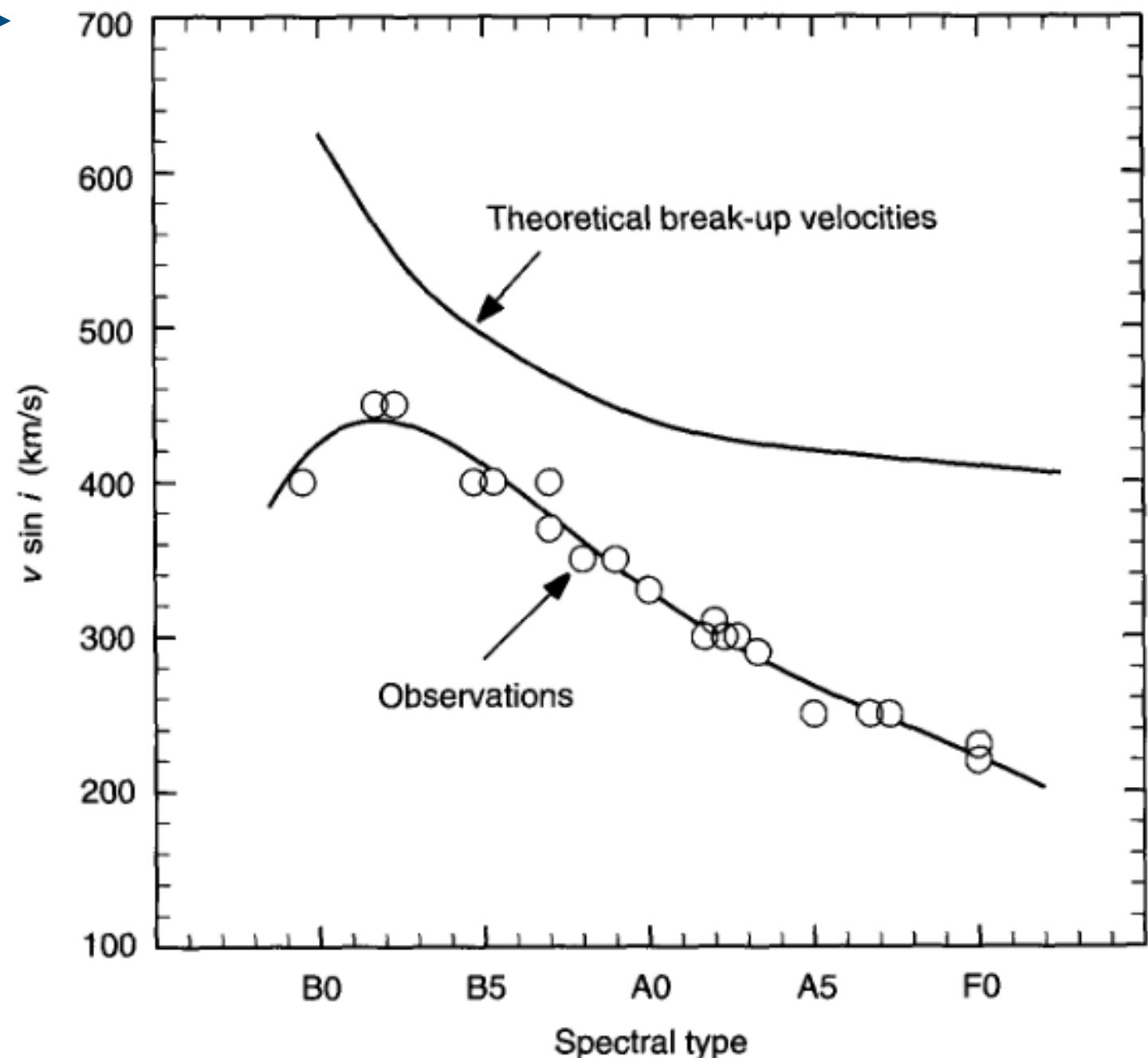
Y. Frémat

Values are taken from the catalog of Glebocki R. & Gnacinski P. 2005.

Fast rotators



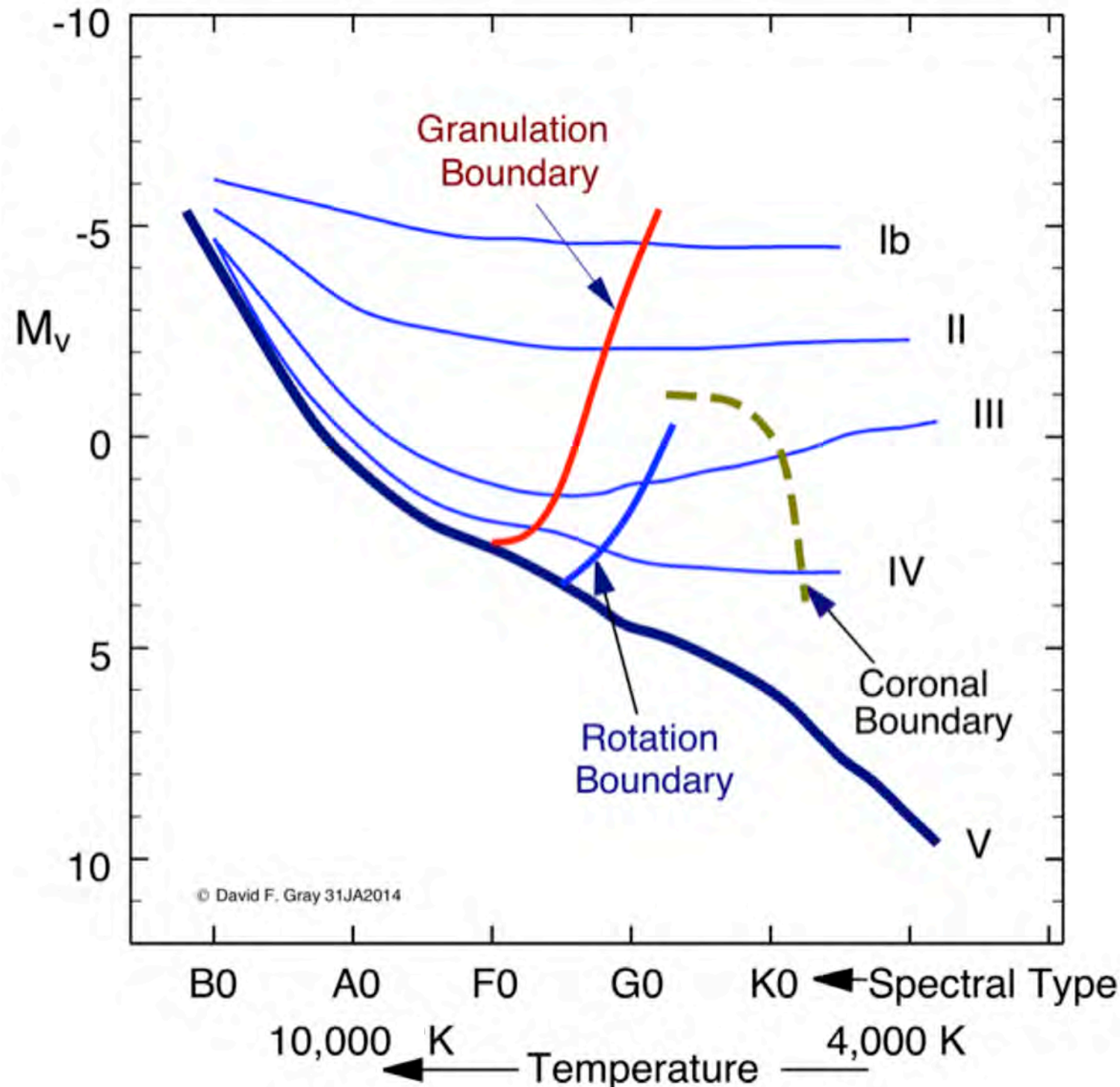
- Fast rotation causes centrifugal force, counteracts gravity, strongest effect at equator
 ➔ Oblateness
- Limiting **breakup velocity** = rotation speed at which the centrifugal force exceeds the gravitational force
 ➔ Stellar material in fastest rotating areas no longer gravitationally bound



Stellar rotation

Across the HRD

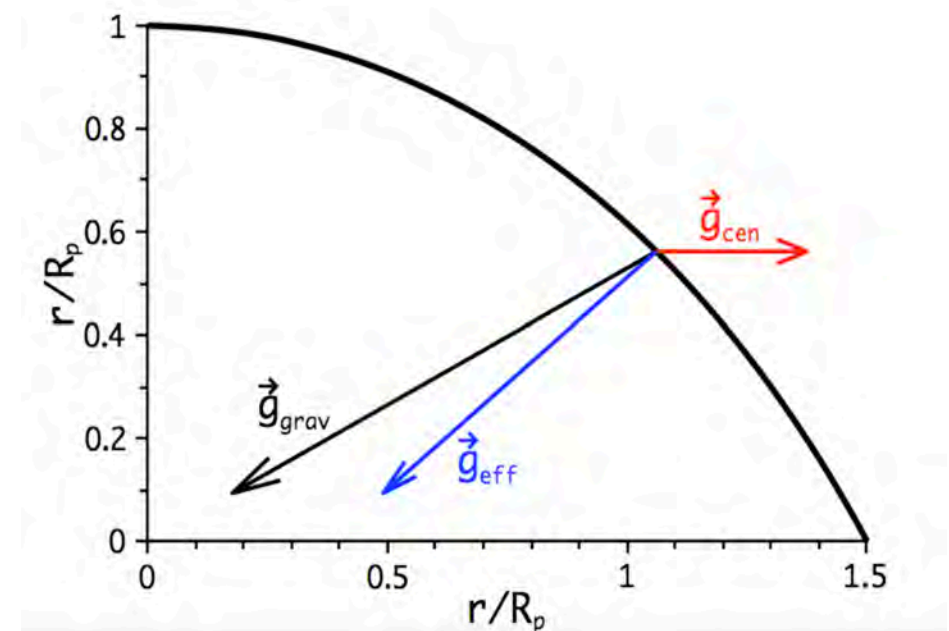
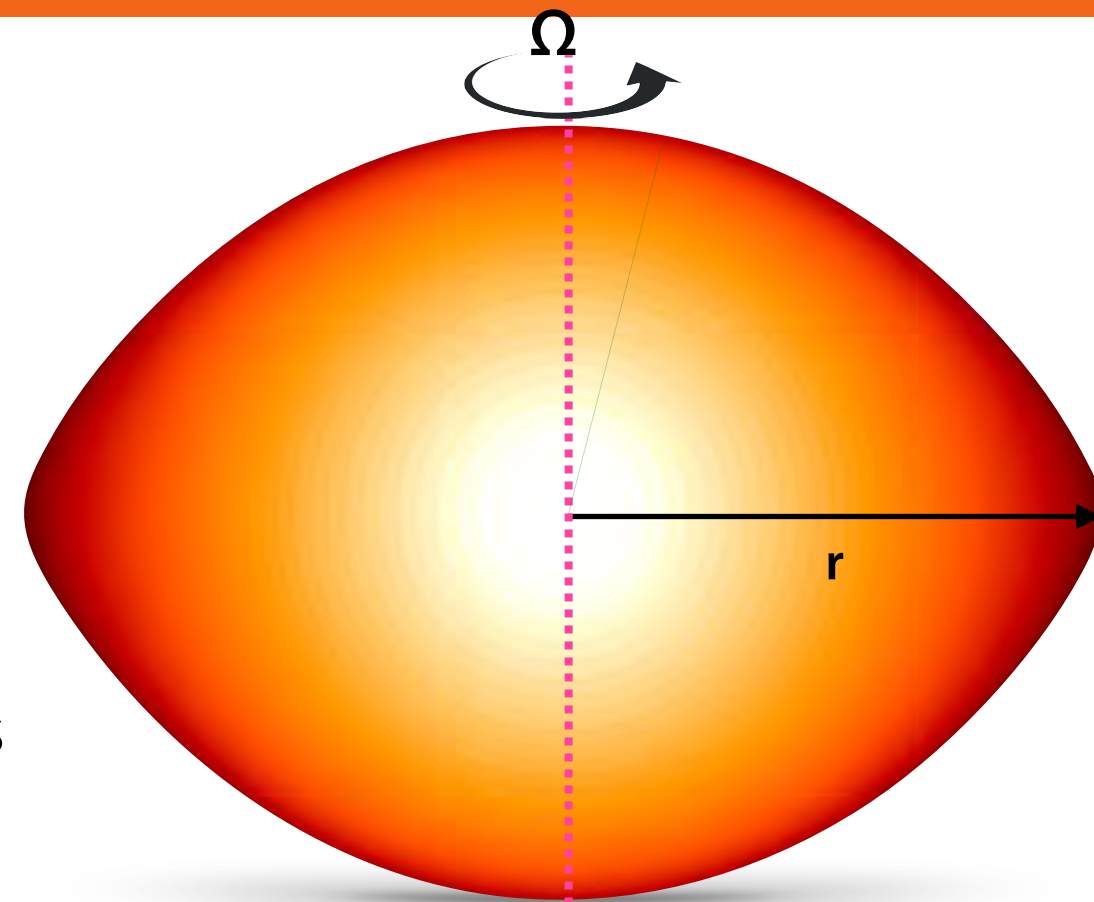
- “**rotation boundary**” — sharp transition between fast and slow rotators
- Stars on the cool side basically one value for any given effective temperature and evolutionary status.
- Possible explanation: magnetic braking of the star due to the impact of convection on rotation properties (*rotostat mechanism*)
- Note that the rotation boundary is found not far from the granulation boundary beyond which there is no more surface convection
- Exceptions: Close binary stars can transfer orbital angular momentum to companion star through gravitational coupling, resulting in anomalous rotation



Stellar rotation

Effects at fast rotation

- Oblateness due to fast rotation, star no longer spherical symmetric
- Surface further away from centre at the equator than at the pole
- ➡ Gravity acceleration at surface varies with latitude!
 - Effective gravity acceleration g_{eff} larger at the poles than at the equator
- At the equator: centrifugal force outwards “compensates” for parts of gravitational force inwards, provides “hydrostatic support”
- ➡ Effects the hydrostatic stratification:
 - ➡ Lower gas pressure required to maintain equilibrium
 - ➡ Lower temperature (equation of state! Ideal gas: $P \propto T$)
 - Lower temperature at the equator than at the poles
 - Von Zeipel law (1924): $T_{\text{eff}} \propto g_{\text{eff}}^{1/4}$

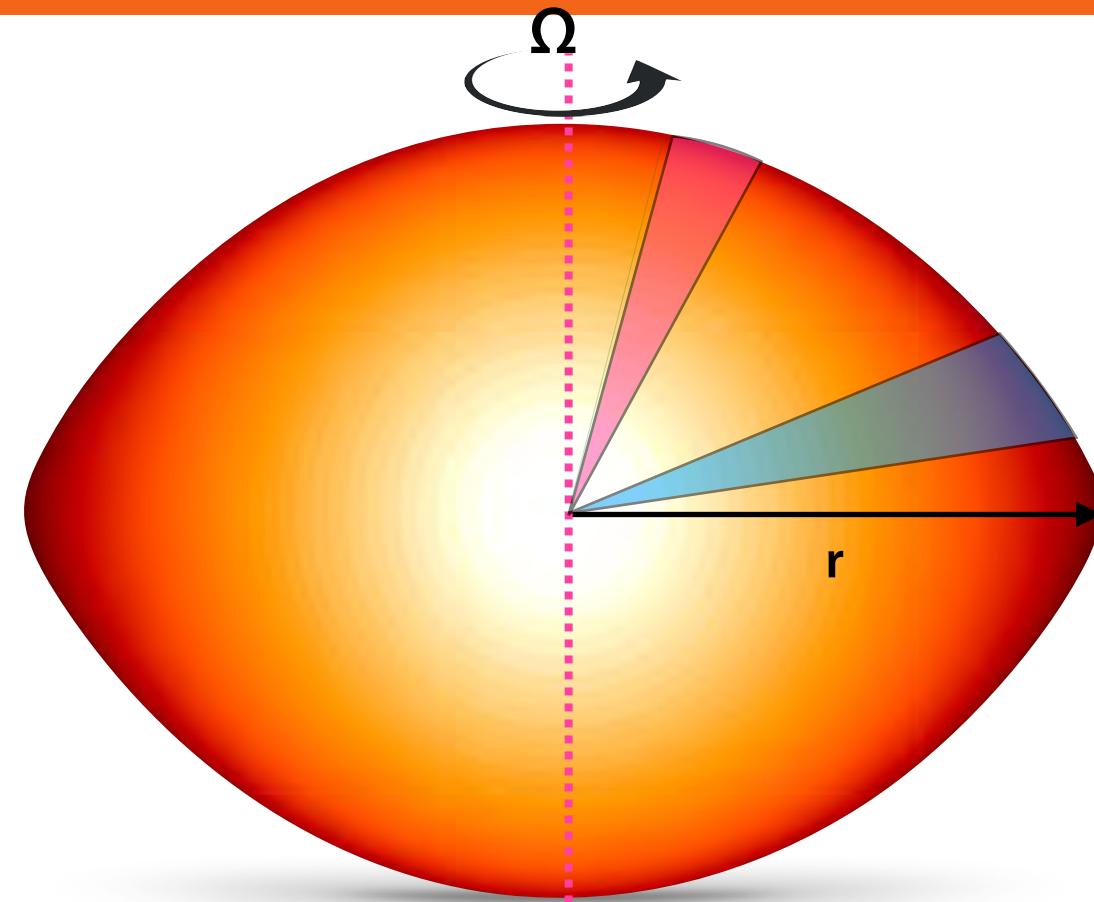


Stellar rotation

Effects at fast rotation

- Oblateness due to fast rotation, star no longer spherical symmetric
- Surface further away from centre at the equator than at the pole
- Energy flux in the interior radiated in all directions into solid angle
- Solid angle now corresponds to different area at the surface
 - Smaller area at poles and larger area at equator
 - Energy flux spread over different area at the surface
 - Stefan-Boltzmann law $T_{\text{eff}} = (F / \sigma)^{1/4}$
 - Smaller area, higher flux, higher effective temperature
 - T_{eff} is higher at the pole than at the equator

➡ Effect is called **gravity darkening**

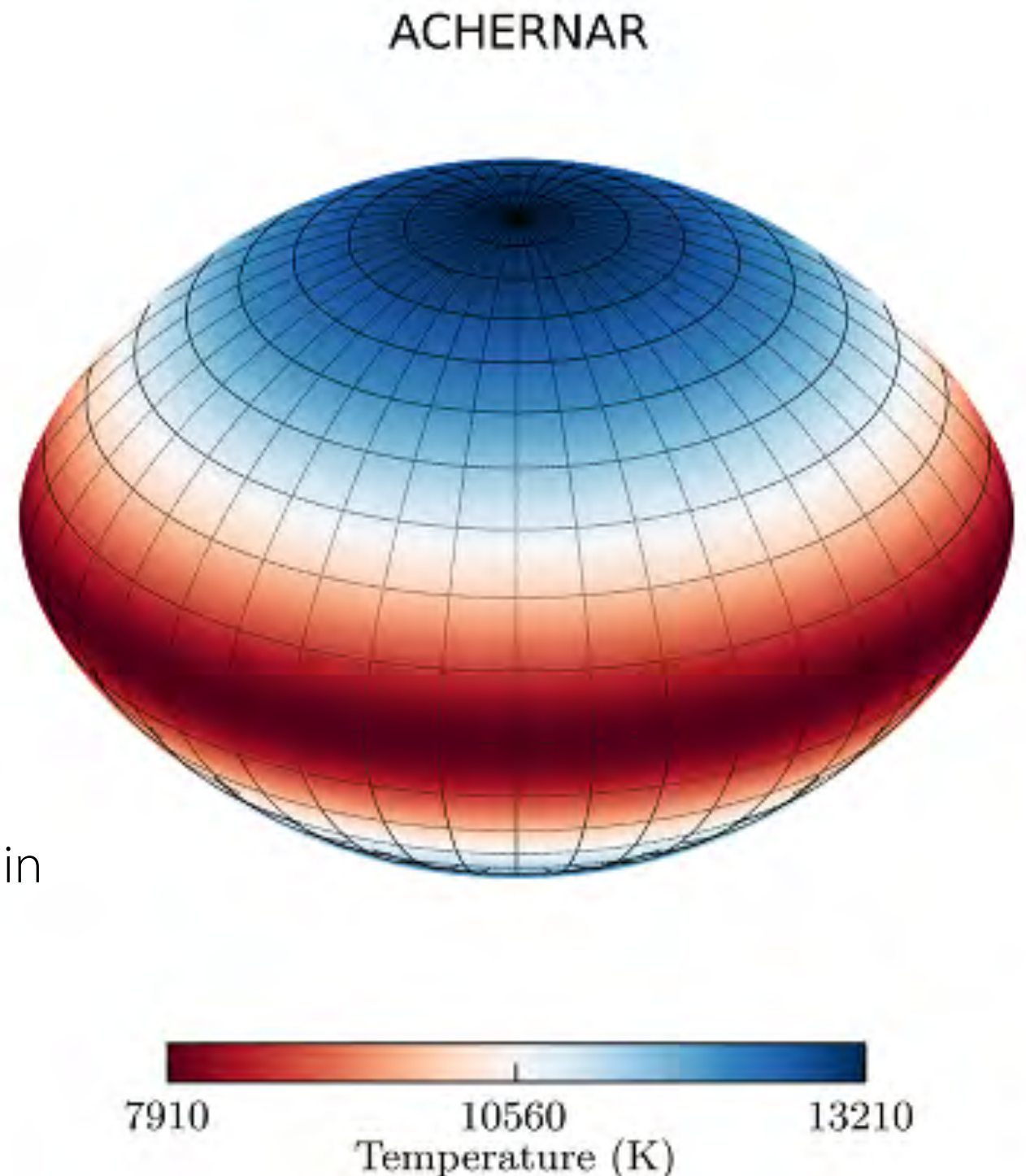


- Strong deviations from spherical symmetry
- To be considered:
 - Conservation of angular momentum
 - Impact on energy balance
- ➡ Meridional circulation might develop

Stellar rotation

Effects at fast rotation — gravity darkening

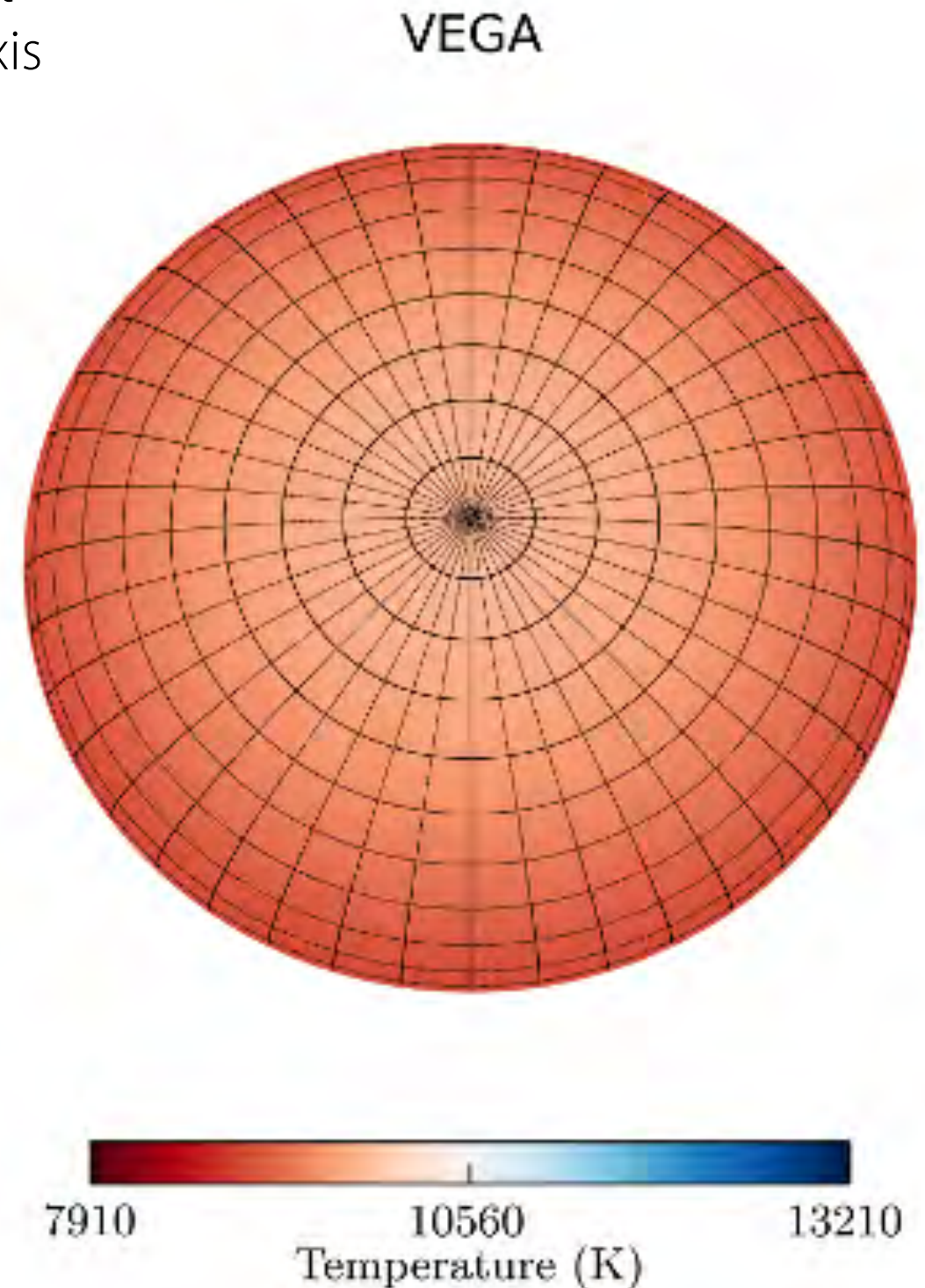
- **Example: α Eridani A — Achernar**
- 9th brightest star in the sky
- Distance ~ 140 ly (43 pc)
- Spectral type B6V
- Mass: $M = 6.7 M_{\odot}$
- **Rotational velocity ($v \sin i$) 250 km/s !**
- Radius:
 - Pole: $R = 7.3 R_{\odot}$
 - Equator: $R = 11.4 R_{\odot}$
 - ➔ Oblateness $\Delta R/R \sim 10$
- Gravity darkening produces large differences in surface temperature!



Stellar rotation

Effects at fast rotation — gravity darkening

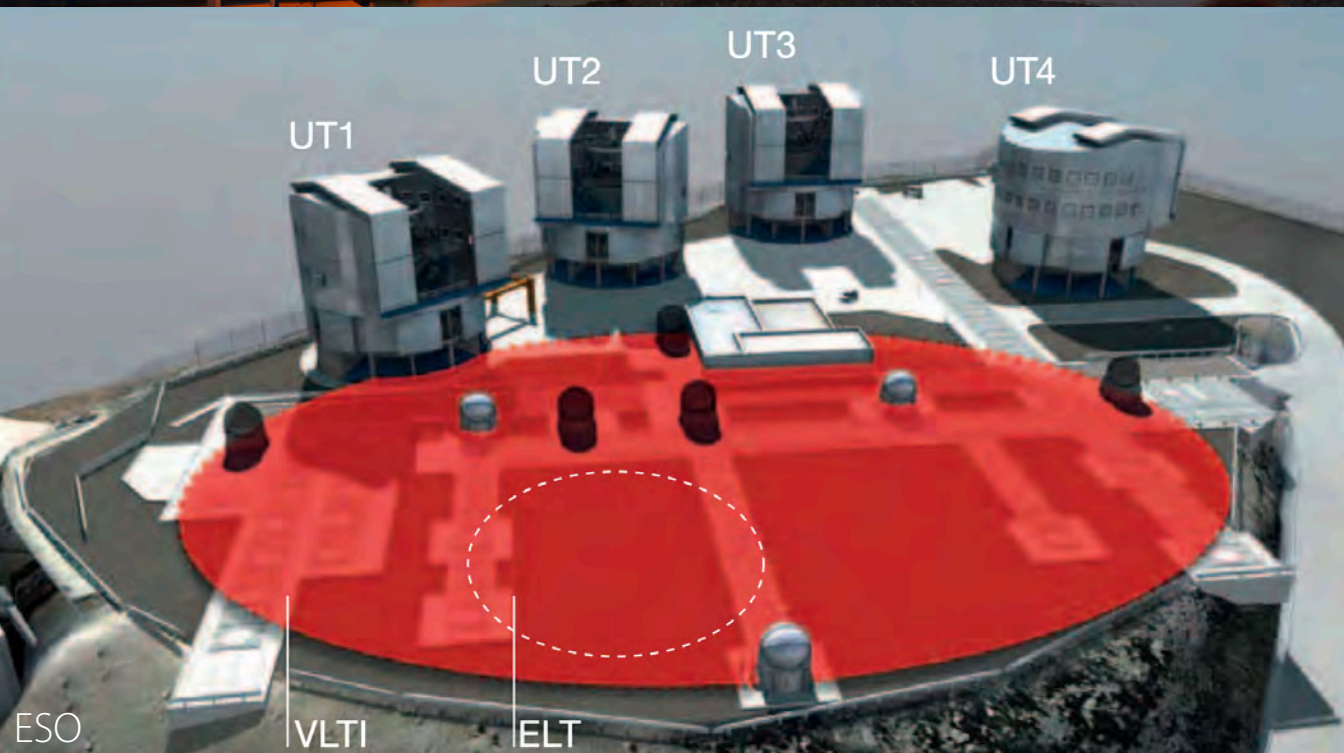
- Note: Effect only measurable directly when seen at large enough angle with respect to the rotation axis (i.e. not pole-on)
- **Example: α Lyrae — Vega**
 - 5th brightest star in the sky
 - Distance ~ 25 ly (7.7 pc)
 - Spectral type A0V
 - Mass: $M = 2.1 M_{\odot}$
 - **Rotational velocity ($v \sin i$) 20.5 km/s !**
 - Radius:
 - Pole: $R = 2.3 R_{\odot}$
 - Equator: $R = 2.8 R_{\odot}$
 - ➡ Oblateness $\Delta R/R \sim 2.2$
- We do not see gravity darkening as we observe Vega **pole-on**



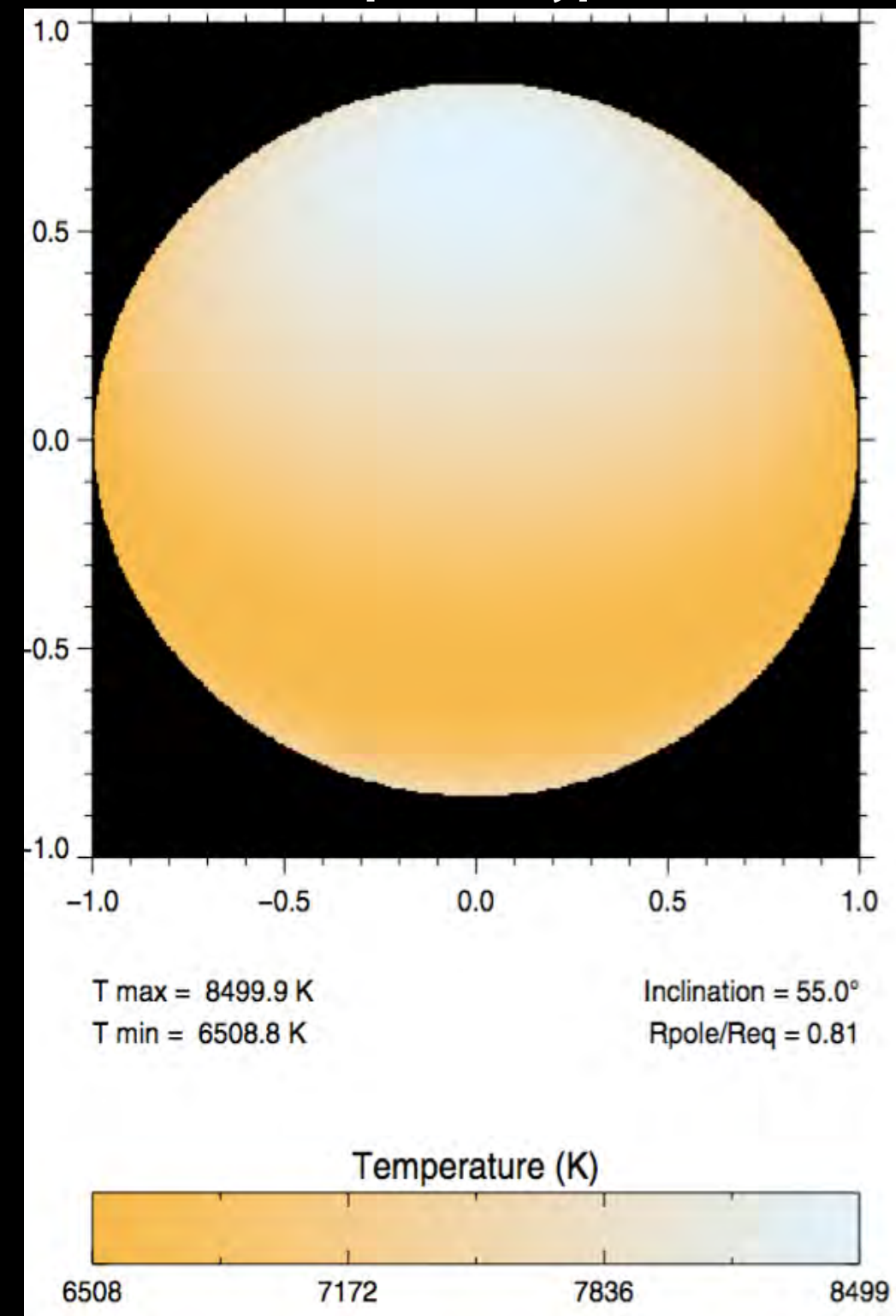
Stellar rotation

Effects at fast rotation — gravity darkening

- Gravity darkening: Direct observational confirmation by optical interferometry with VLTi: Altair
- Rotational velocity ($v \sin i$) 240 km/s !



Altair (spectral type A7IV-V)



Stellar rotation

Coriolis force

- Not a “real” force but due to rotation of the frame of reference
- Impact on motion depends on involved temporal and spatial scales and velocities

➔ Rossby number: $Ro = \frac{U}{fL}$

U : velocity, U

L : length scale

f : Coriolis parameter

Ω : rotation rate

φ : latitude

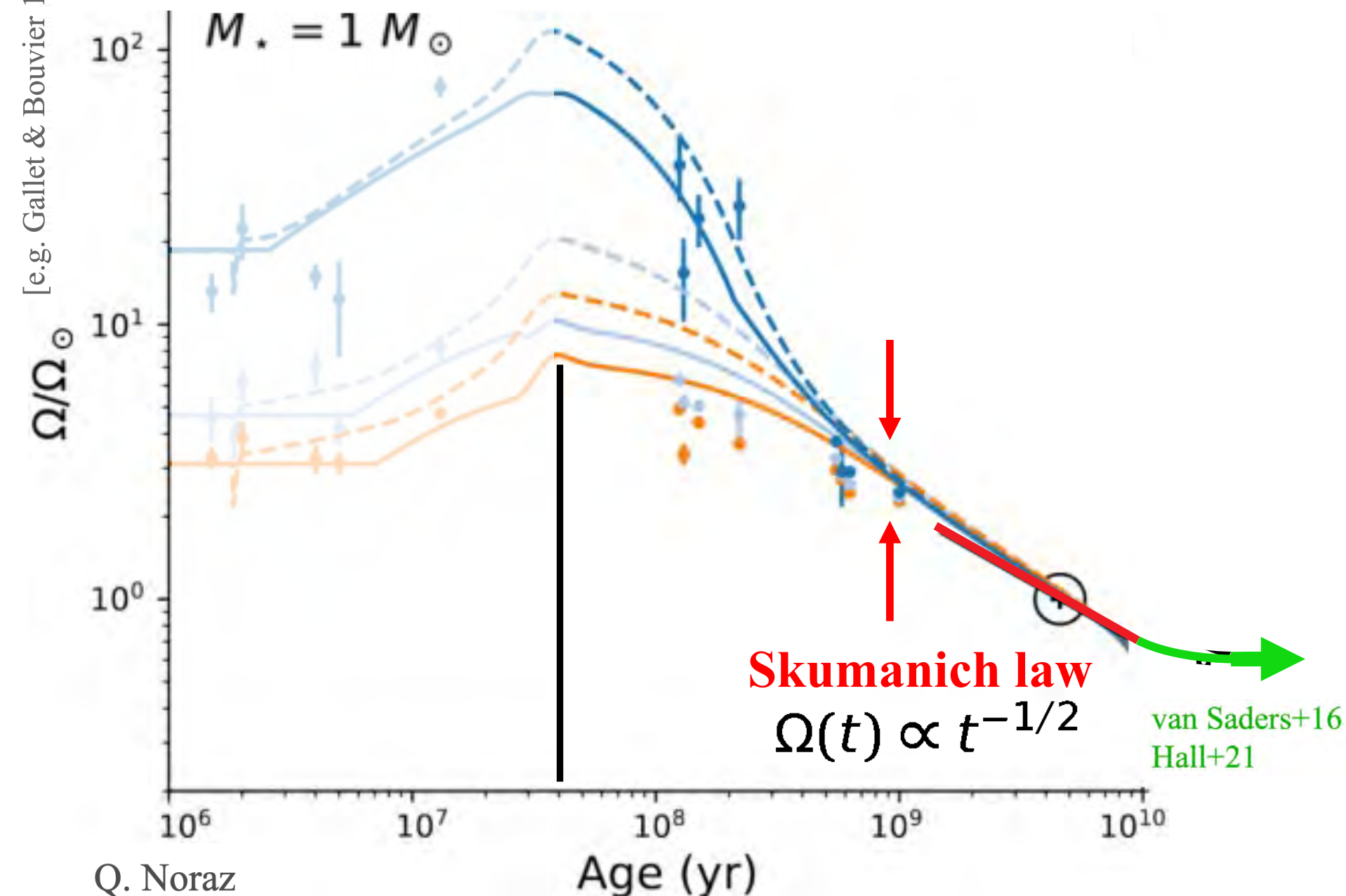
- The Rossby number is the ratio of inertial to Coriolis forces.
- Coriolis parameter: $f = 2\Omega \sin \varphi$.
($f = 0$ at the equator, $\varphi=0$)
- Ratio between the rotation period of a star and the local convective turnover time
- Large Rossby number: inertial and centrifugal forces dominate (e.g. in tornadoes on Earth, bathtub flow)
- Small Rossby number: Coriolis forces important, stellar rotation impacts resulting flow pattern — notably over large spatial scales on a star

Stellar rotation

Evolution of rotation

- **Young stars are seen to rotate up to 100 times faster than the Sun.**
 - Skumanich law: $\Omega \propto t^{-1/2}$ (t: age of the star)
 - Sun also rotated faster as a young star.

[e.g. Gallet & Bouvier 15; Ahuir+ 21]



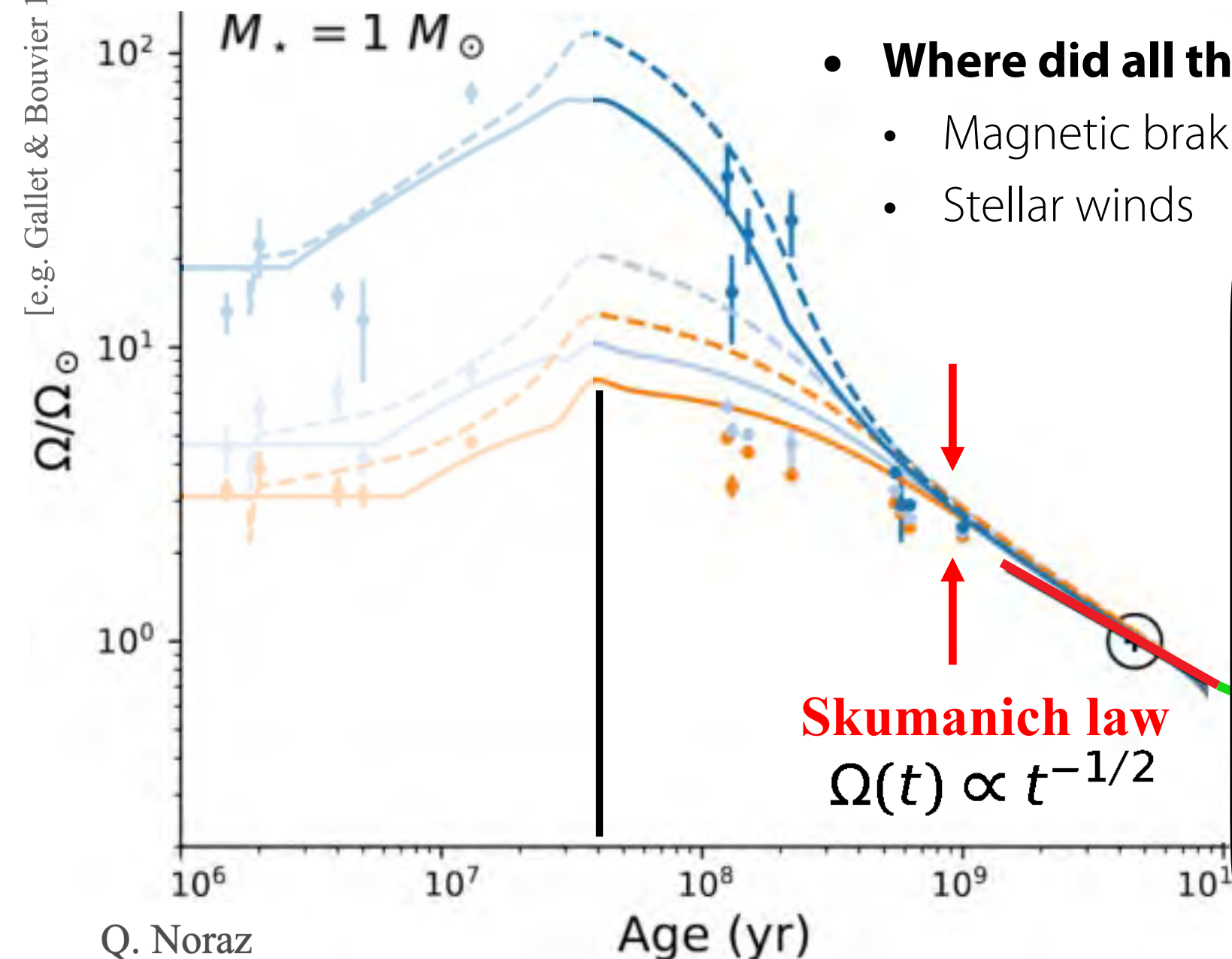
Stellar rotation

Evolution of rotation

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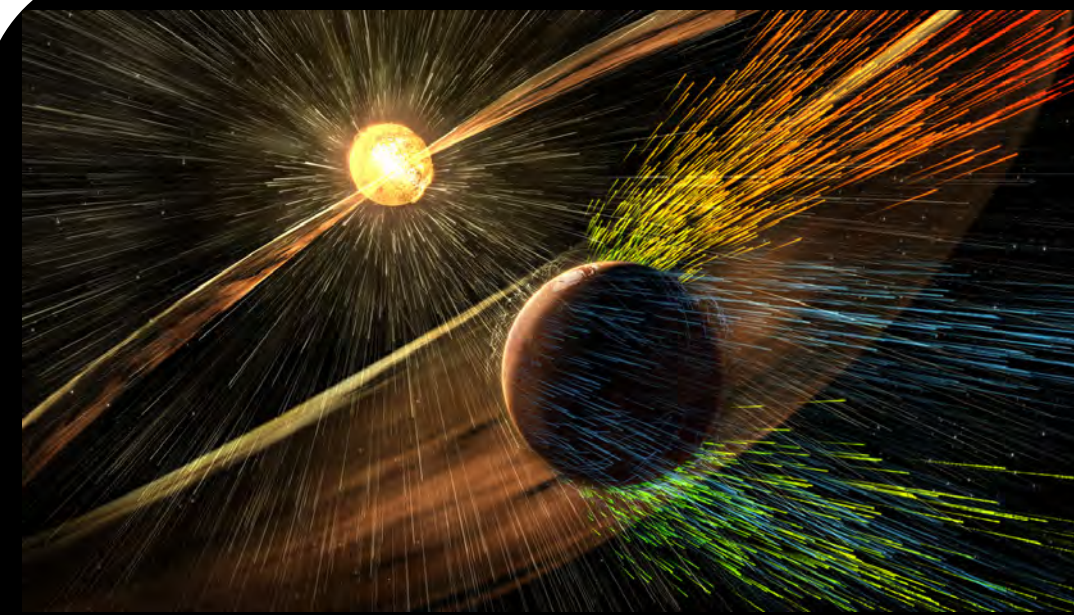
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[e.g. Gallet & Bouvier 15; Ahuir+ 21]



- **Where did all the angular momentum go?**

- Magnetic braking
- Stellar winds



NASA/GSFC

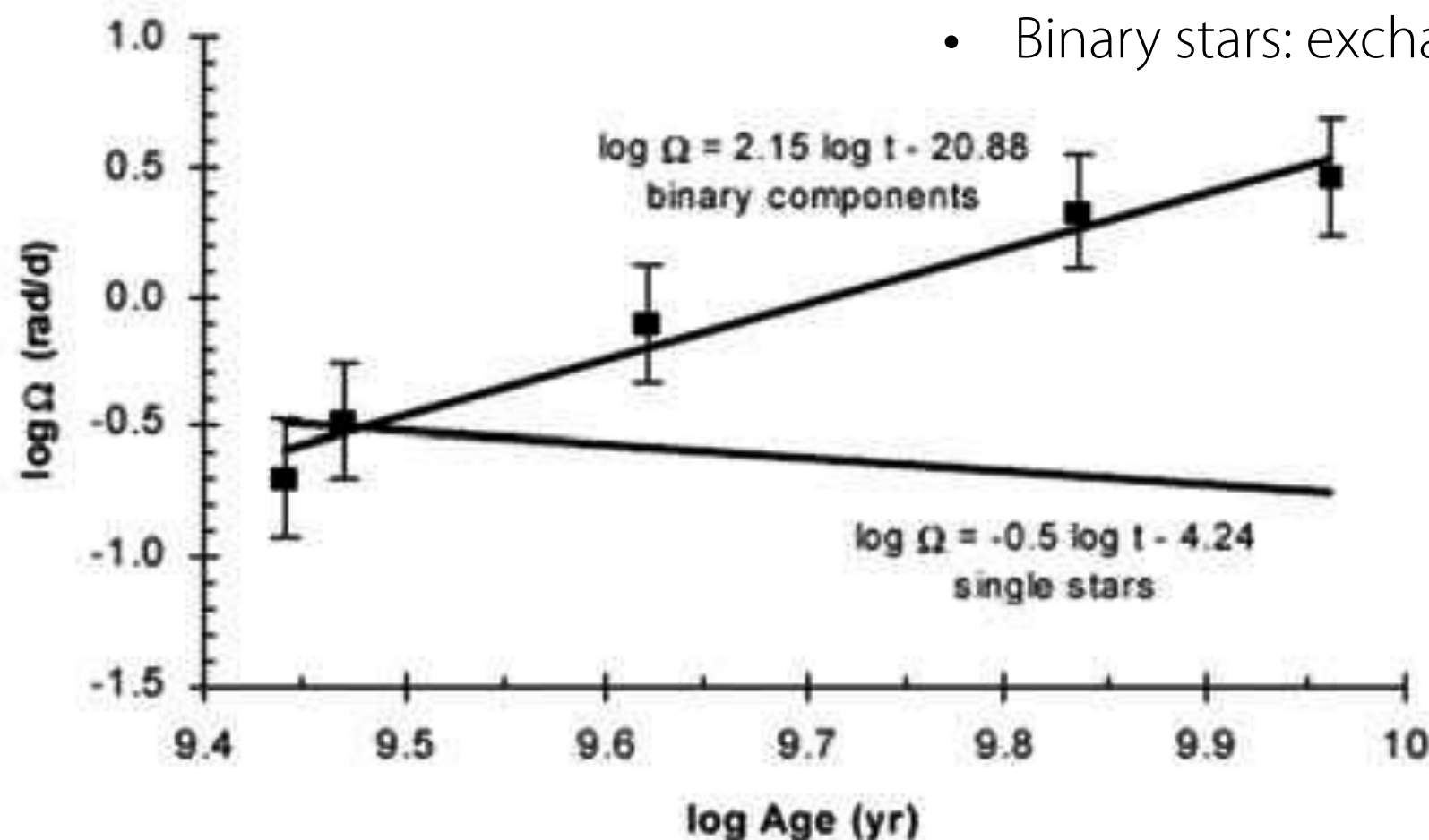
Solar/stellar wind:

Stream of charged particles released from the upper atmospheric layers of a star

Stellar rotation

Evolution of rotation

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 - Skumanich law: $\Omega \propto t^{-1/2}$ (t: age of the star)
 - Sun also rotated faster as a young star.
- **Where did all the angular momentum go?**
 - Magnetic braking
 - Stellar winds
 - Binary stars: exchange of orbital angular momentum



Stellar rotation

Summary

- Rotation velocities derived as $v \sin i$
 - Can be determined from rotational broadening of spectral lines
 - Inclination angle i must be known to determine actual rotation rate of the star
- Two distinct groups along main sequence
 - Fast rotators — hotter stars: often $v \sin i > 100$ km/s.
 - Some hot stars rotate as fast as 450 km/s
 - Slow rotators — stars cooler than F7: typically $v \sin i < 50$ km/s;
 - Sun ~ 2 km/s.
 - Surface convection leads to reduction of rotation rates
- Fast rotation results in oblateness (deviation from spherical symmetry), causing effects such as gravitational darkening
- Stellar rotation slows down (slowly) with time
 - Loss of angular momentum due to stellar wind