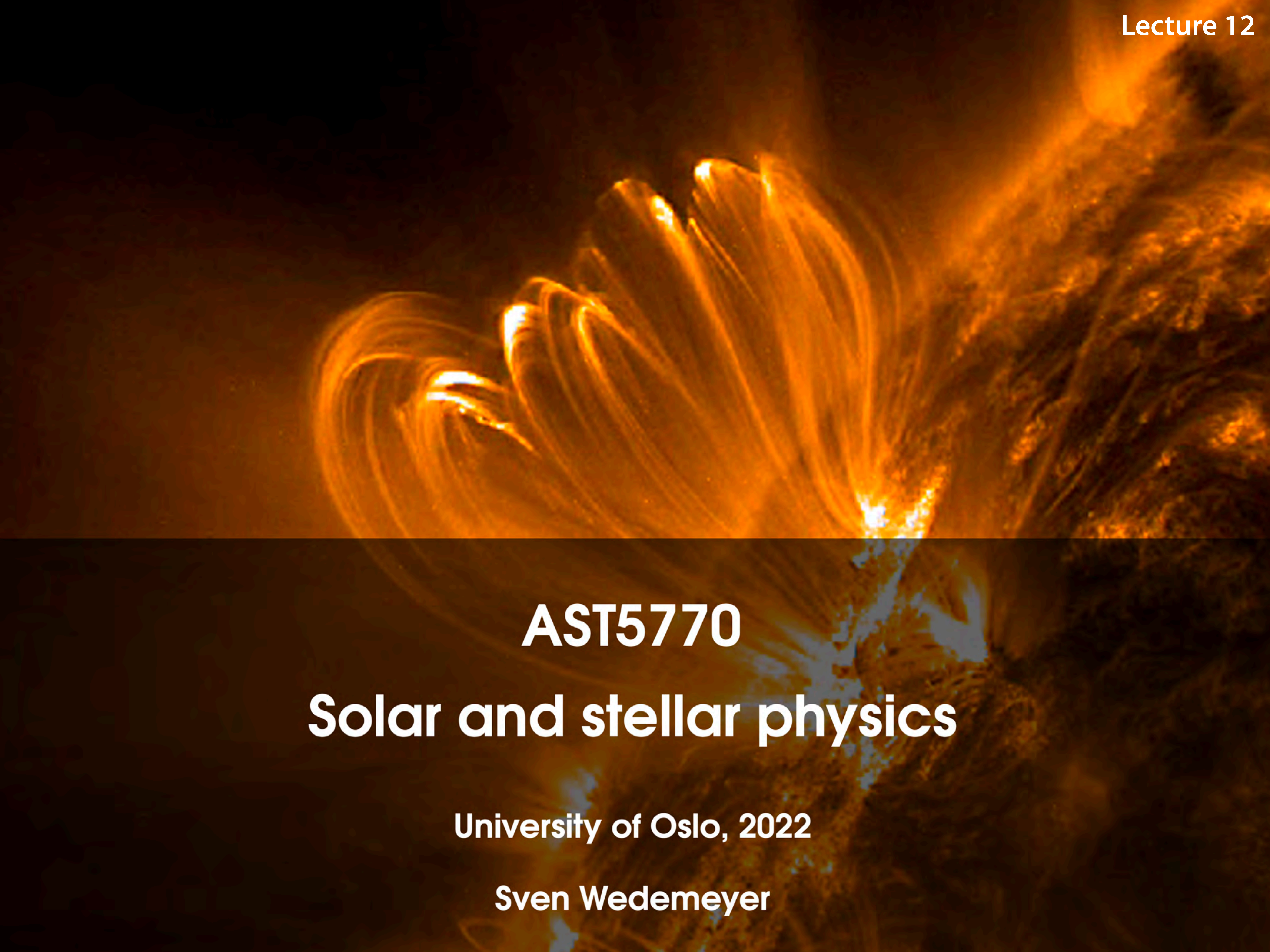


AST5770

Solar and stellar physics

University of Oslo, 2022

Sven Wedemeyer

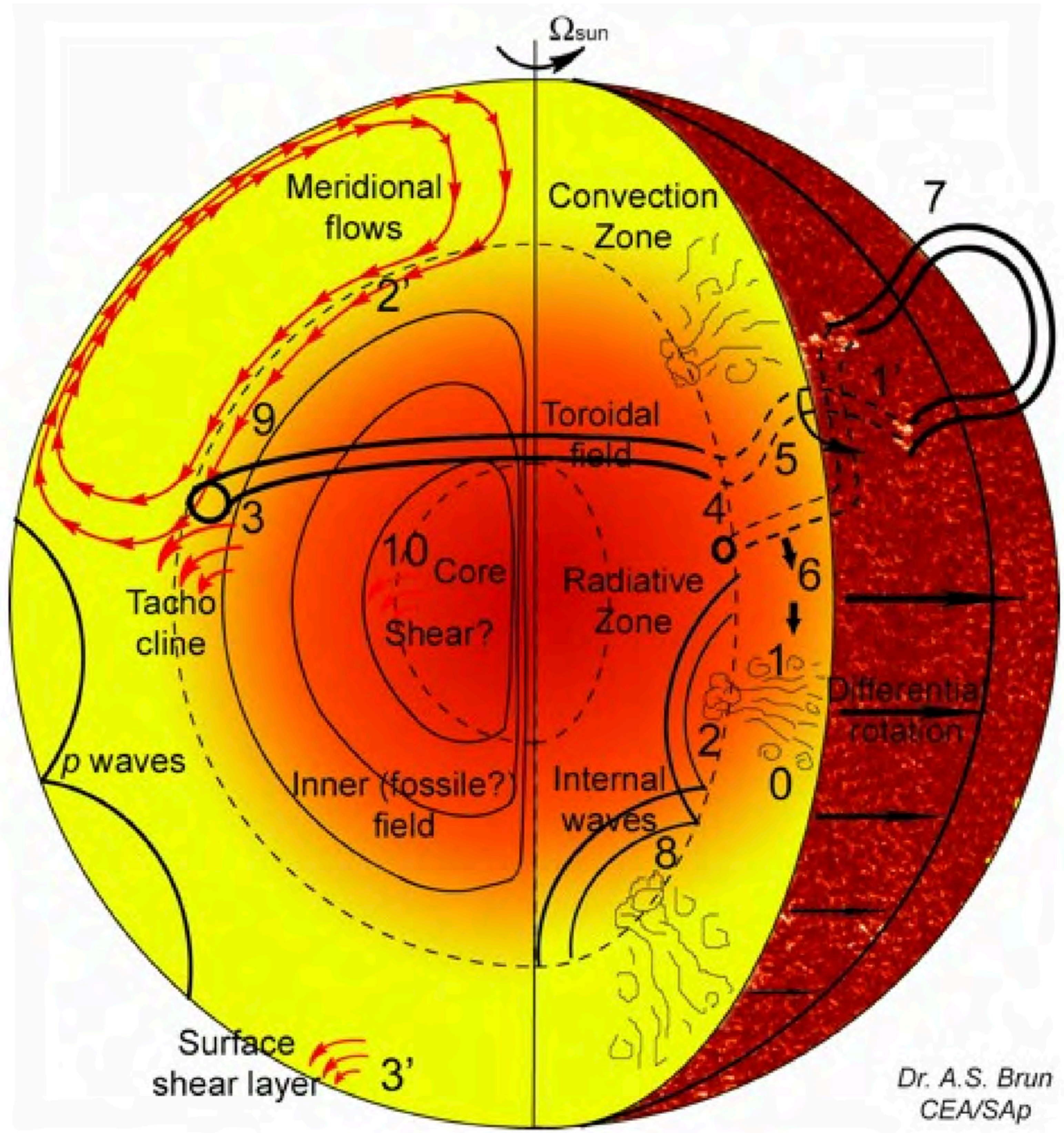
Recap — the solar interior so far

We have covered so far:

- Energy production and transport
- Stratification and interior structure:
  - Radiative core
  - Convection zone
  - Tachocline
- p-modes and (internal) g-modes
- Differential rotation and meridional flows
- These effects produce small deviations from the standard solar model (which assumes spherical symmetry and no rotation).

We would like to learn more about:

- Magnetic field generation (dynamo)
- Magnetic fields at the surface
- The atmosphere



Solar neutrinos

Solar neutrinos

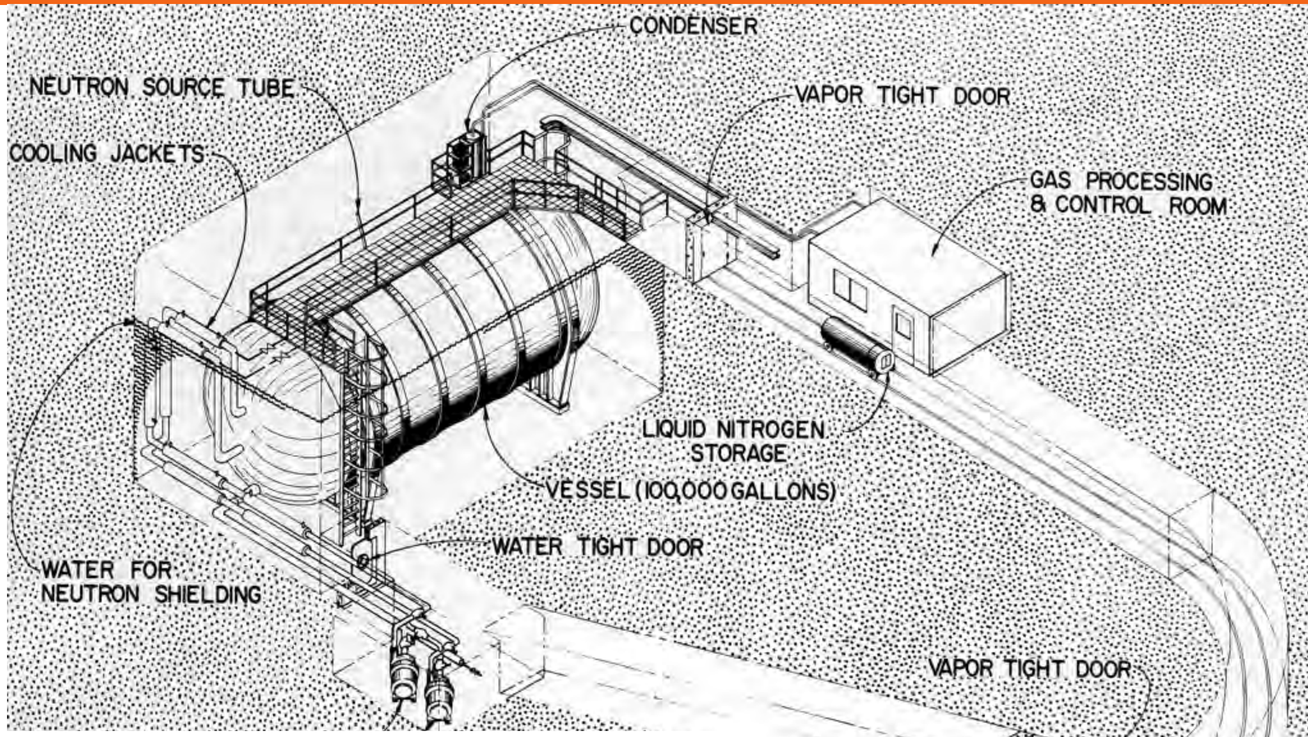
Problematic detection

- Detection since 1967 with large chlorine tank in Homestake Gold Mine (USA, Davis Jr)

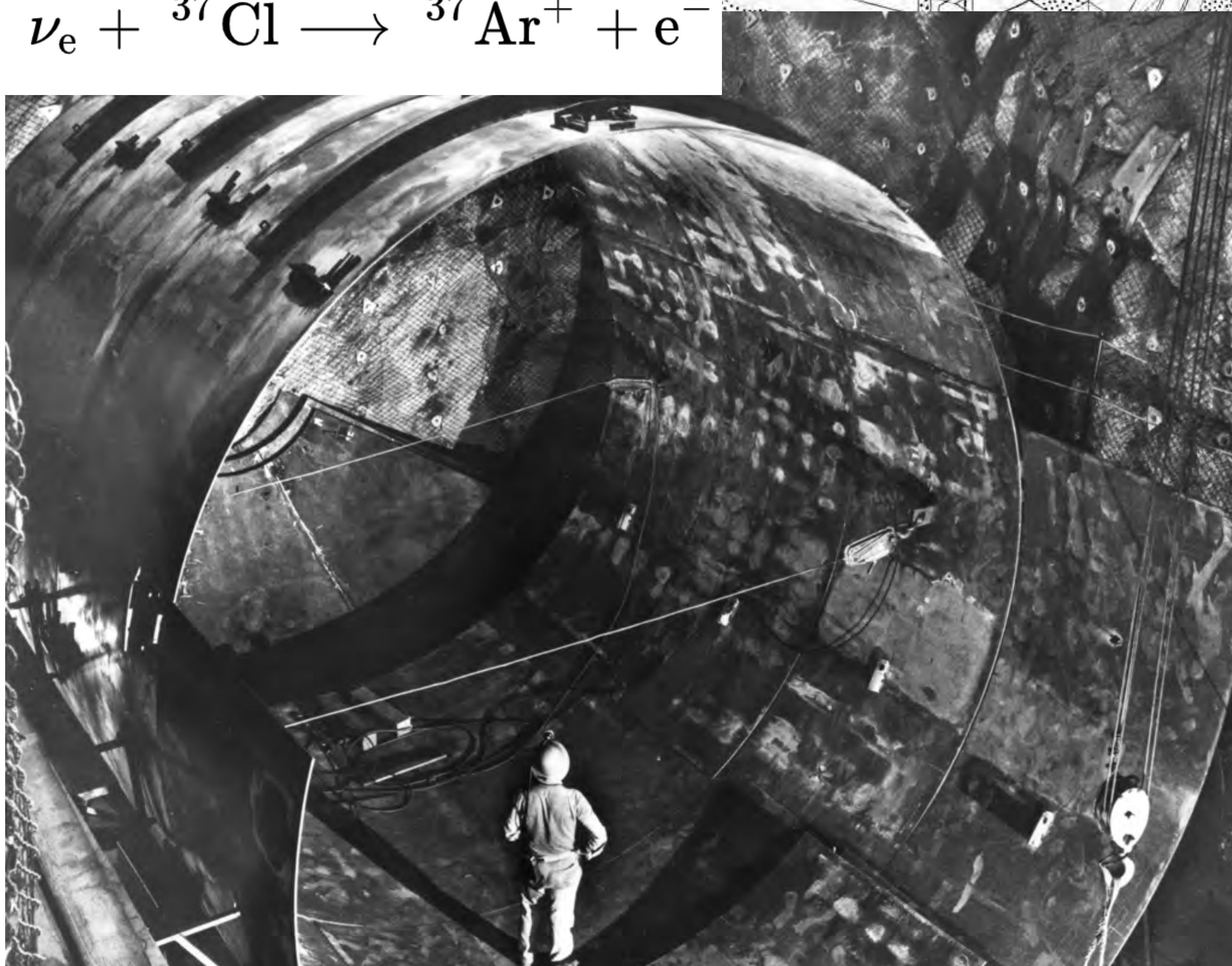
➡ Average rate 2.56 ± 0.23 SNU (solar neutrino units)

- Theoretically expected rate 7.5 ± 1.0 SNU (Bahcall)
- Theoretical value in line with standard models of the solar interior (and thus with the assumed conditions in the solar centre under which fusion occurs and neutrinos are emitted) as confirmed by helioseismology!

➡ **Solar Neutrino Problem**



$$\nu_e + {}^{37}\mathrm{Cl} \longrightarrow {}^{37}\mathrm{Ar}^+ + e^-$$



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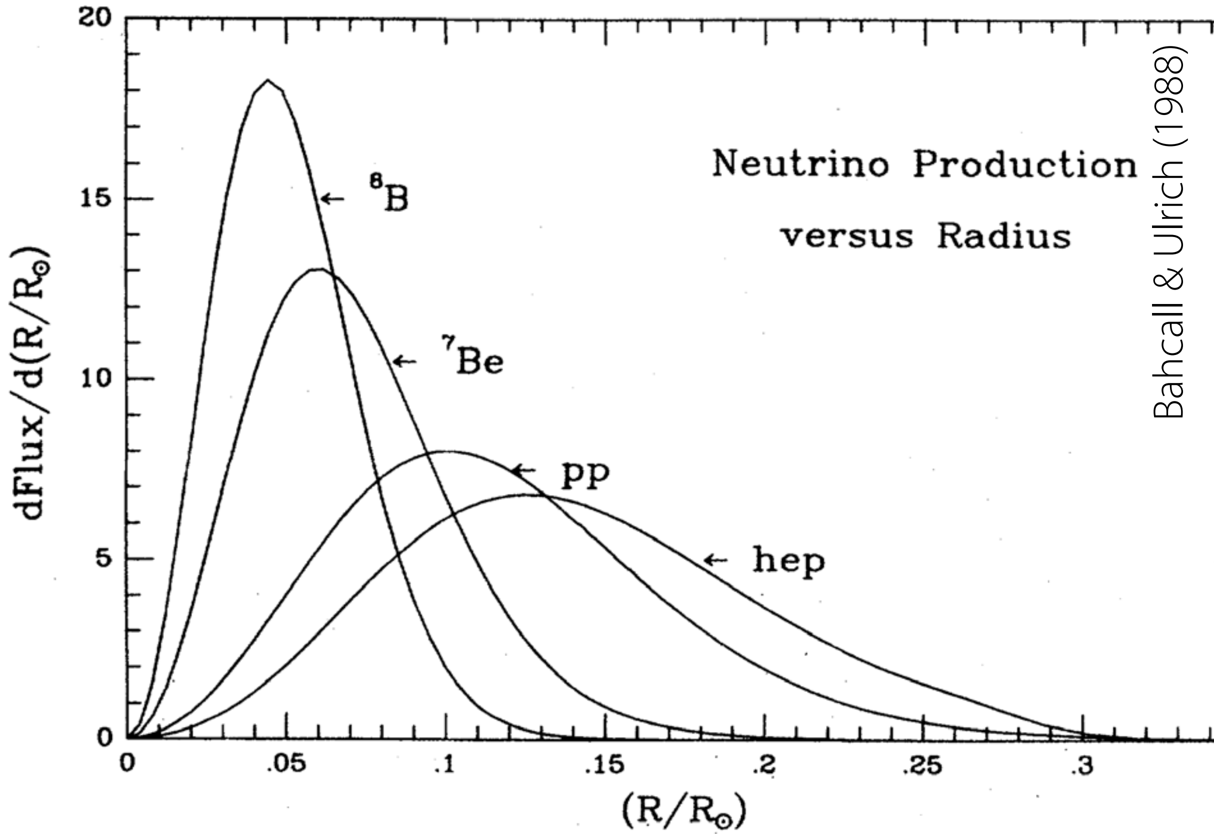
➡ Solar Neutrino Problem

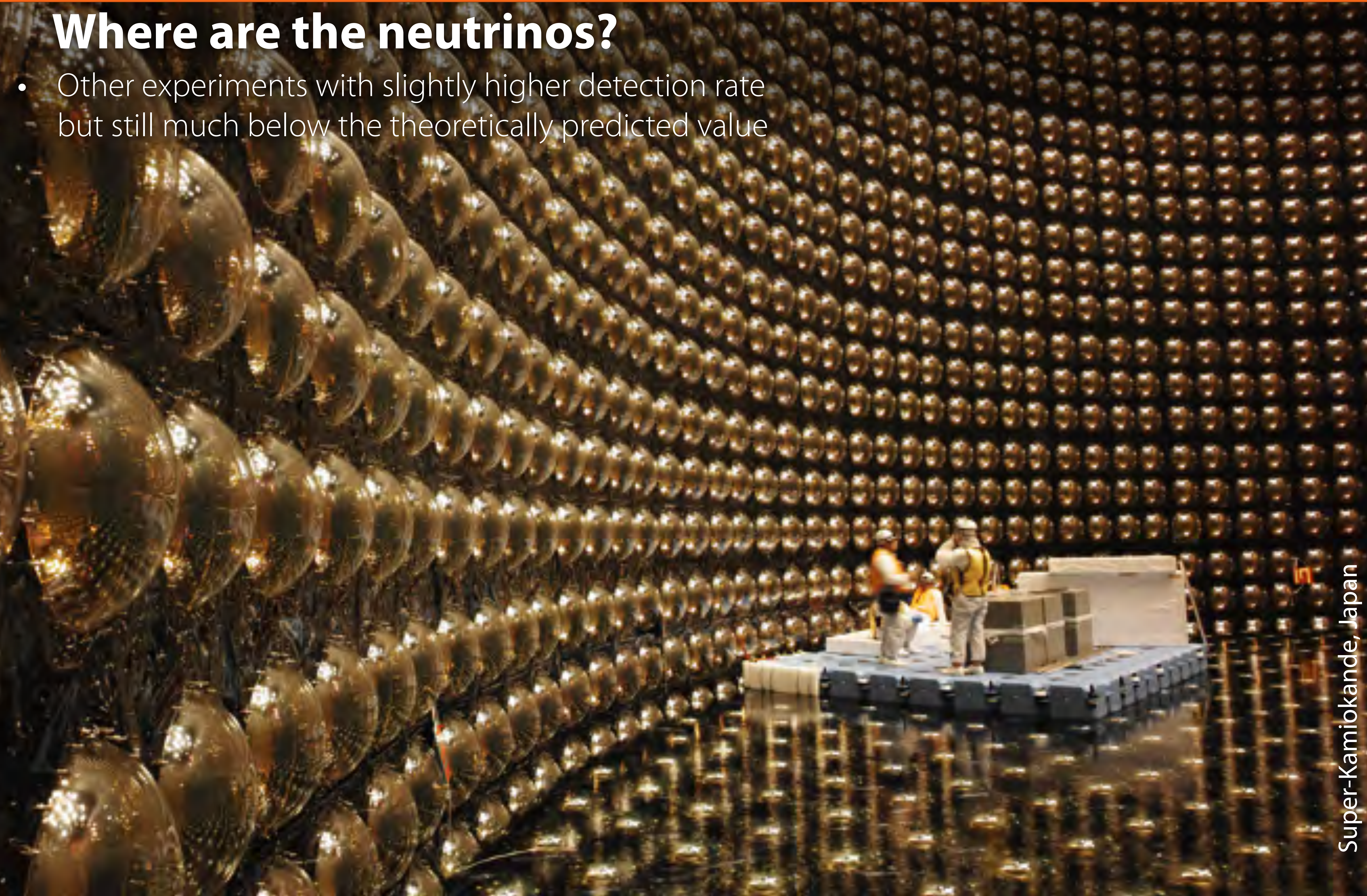
(Theoretical) neutrino production as function of radius



Solar neutrinos

Where are the neutrinos?

- Other experiments with slightly higher detection rate but still much below the theoretically predicted value



Super-Kamiokande, Japan

Solar neutrinos

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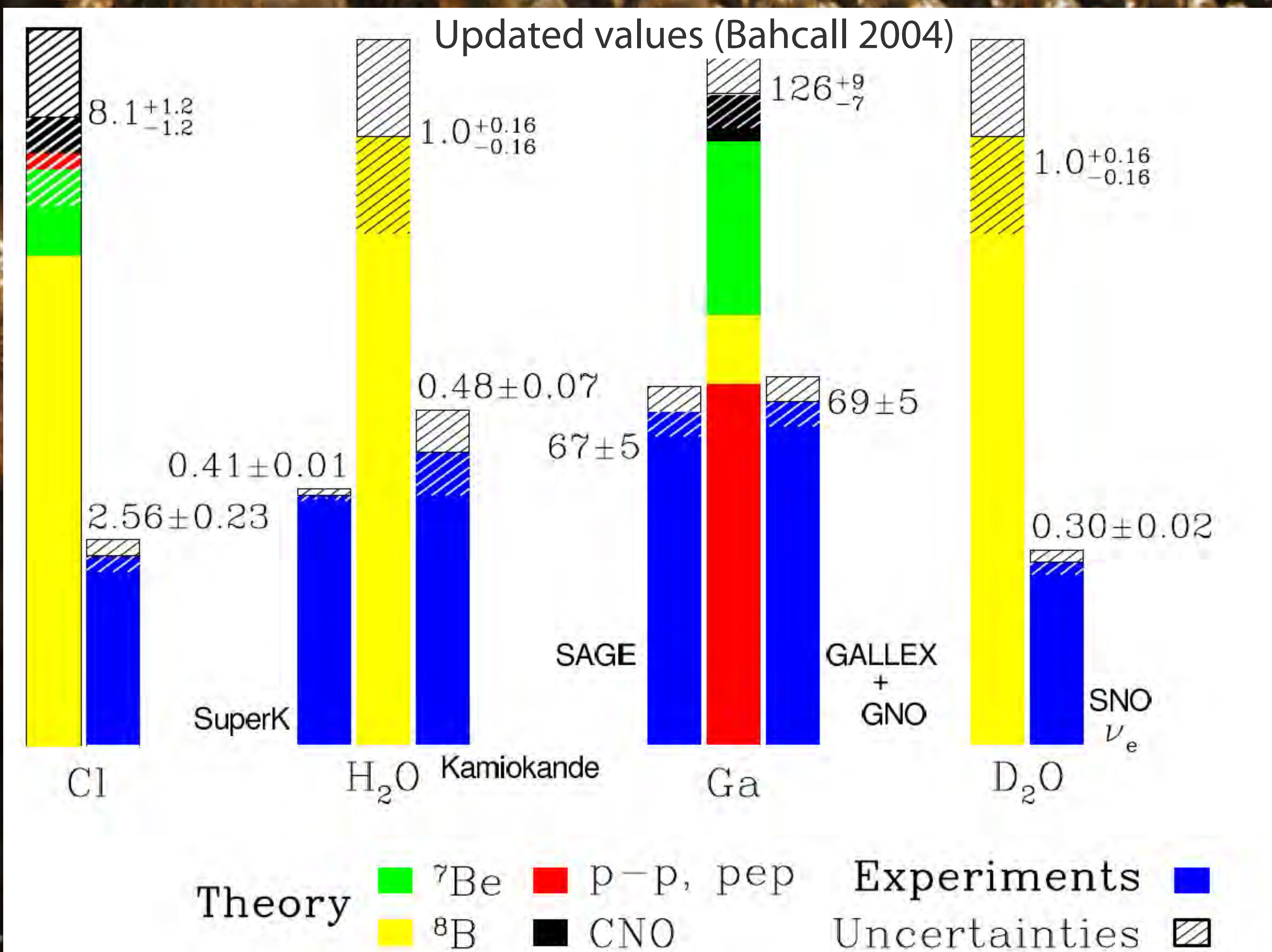
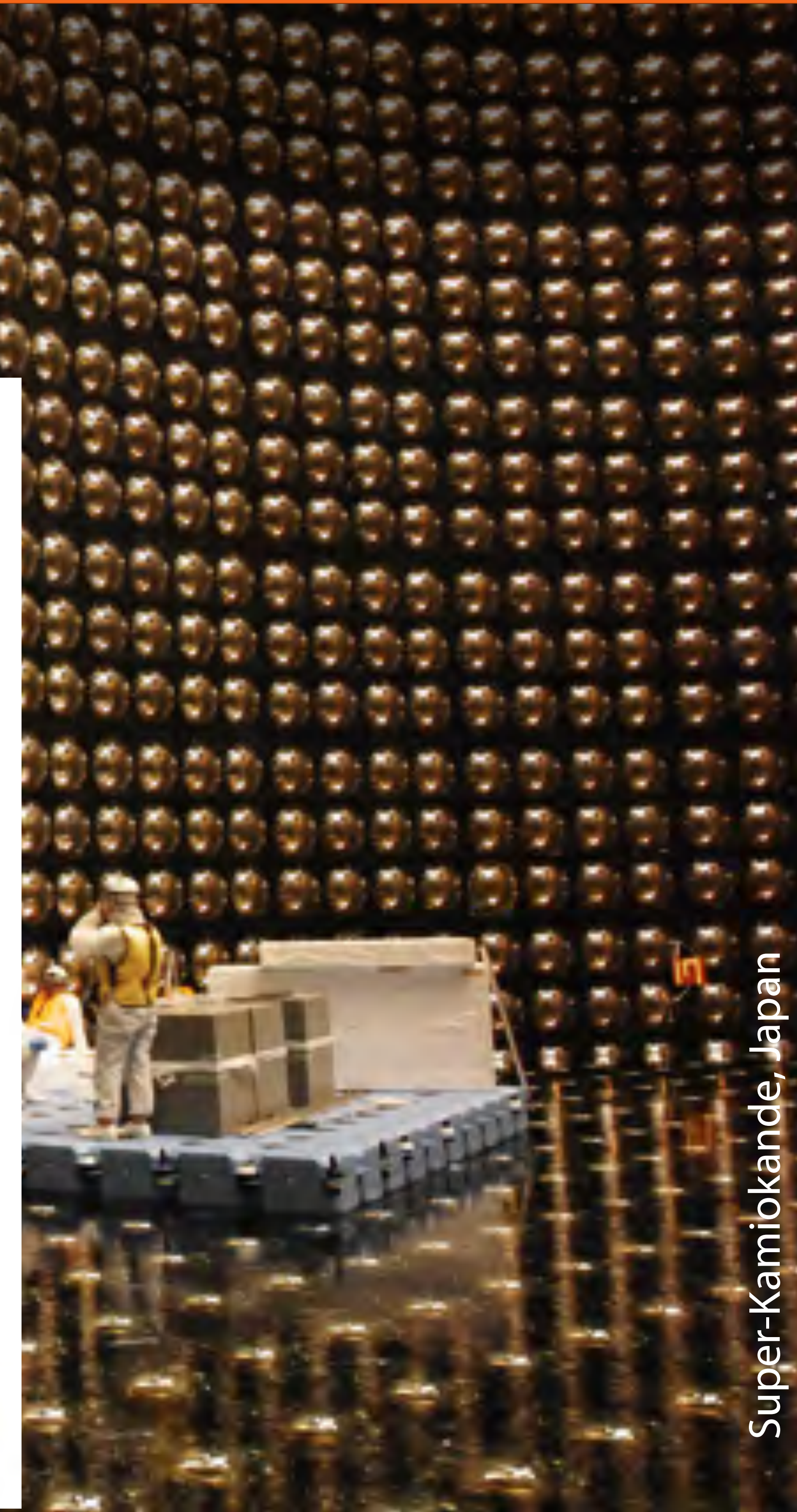




Super-Kamiokande, Japan

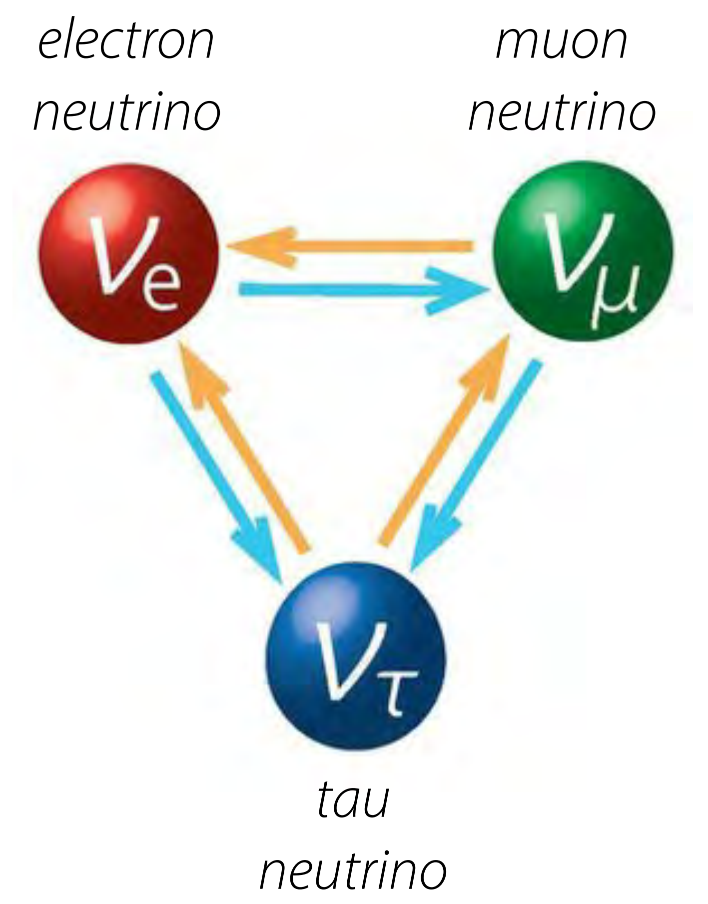
Solar neutrinos

The solution

- Theoretically predicted (Gribov & Pontecorvo 1969):
  - (Low-energy) solar neutrinos **oscillate** between lepton flavours on the way between the Sun and detection on Earth
- Some/early detectors (incl. Homestake, GALLEX, SAGE) only sensitive to the high-energy electronic neutrinos
  - **Practically blind for muonic (ν_μ) and tauonic neutrinos (ν_τ)**
  - **Found only part of produced neutrinos**
- Detectors that are sensitive to all flavours (to some degree; e.g. Super-Kamiokande)
- Measurement with heavy-water experiment at Sudbury Neutrino Observatory (Canada) in 2001: for the first time all three lepton flavors detected

➡ Found the "missing" neutrinos after 35 years (Bahcall et al. 2001)

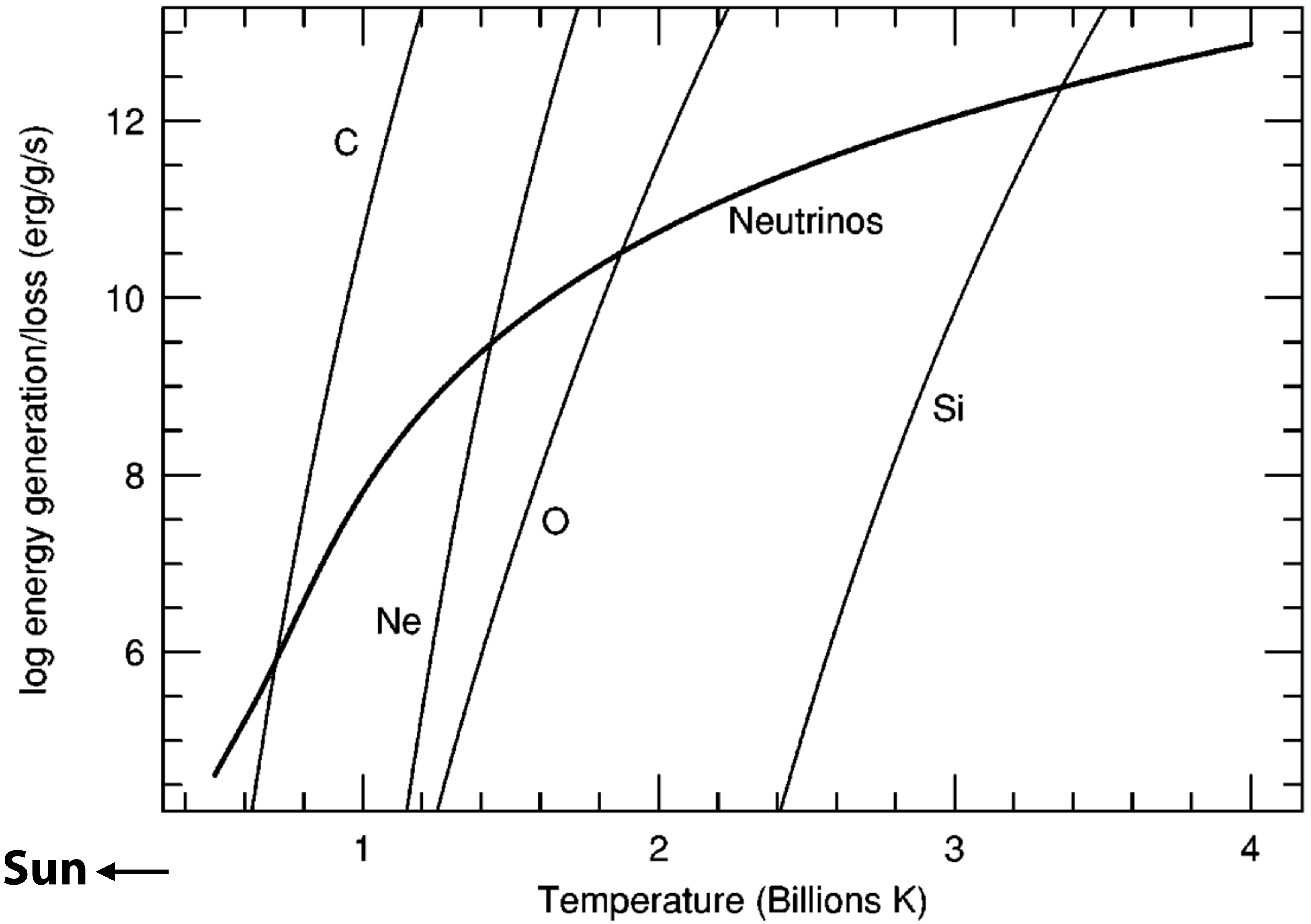
➡ Nobel prize for physics 2002 (Davis Jr., Koshiba, Giacconi)



Solar neutrinos

Neutrino production at higher temperatures

- Neutrino production (and energy carried away) much larger at higher core temperatures (in more massive stars)

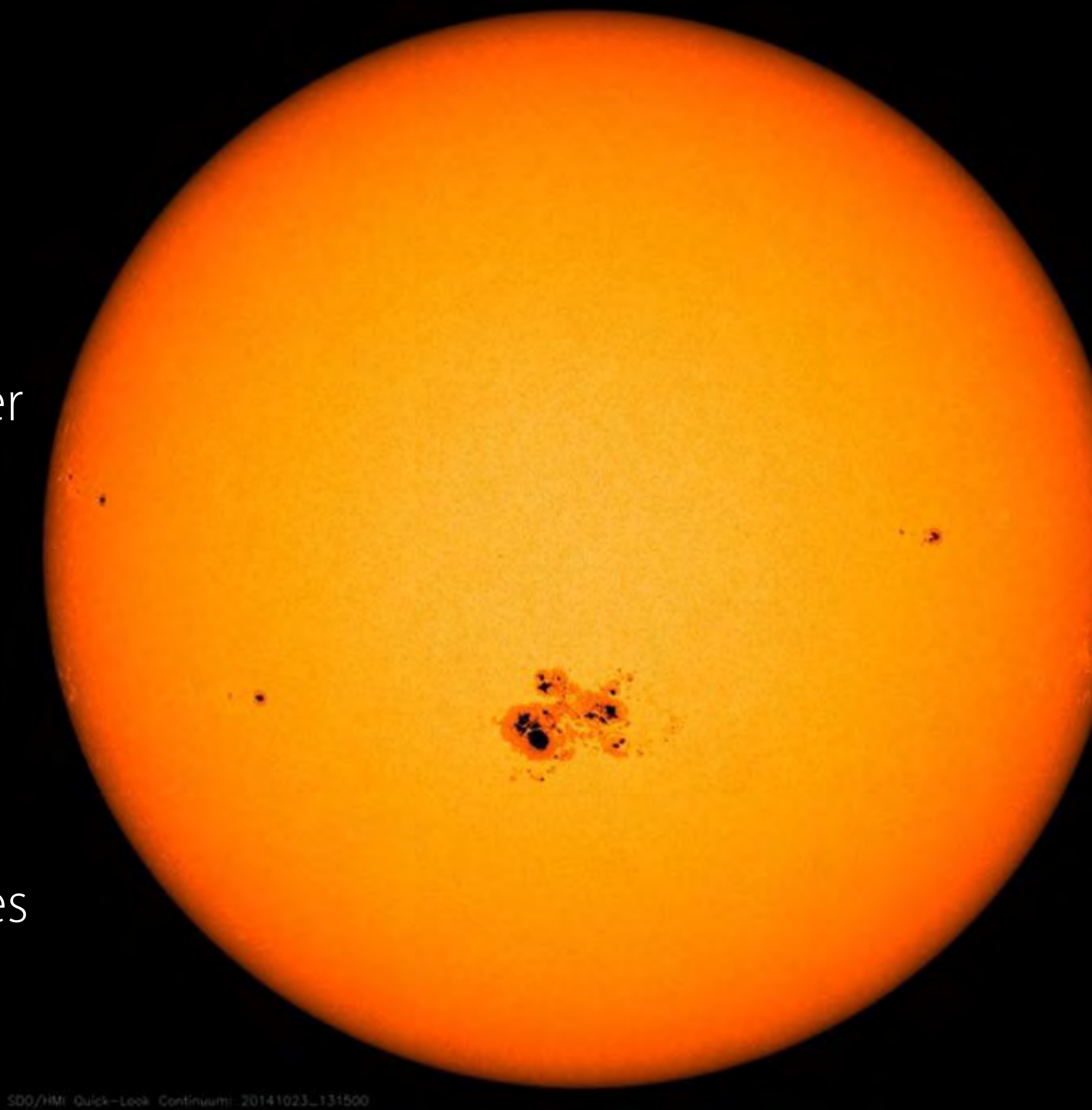


Woosey, Heger, Weaver (2002)

Rotation

Solar rotation

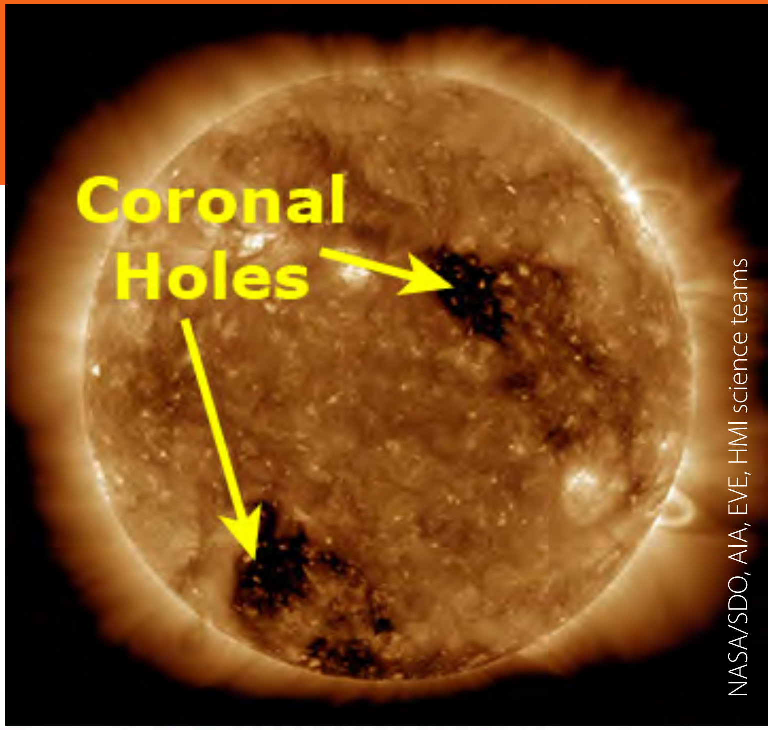
Introduction



- Solar rotation becomes obvious from observing over several days as sunspots move across the solar disk
- Already reported long ago by Galilei and Scheiner
- 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).

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)

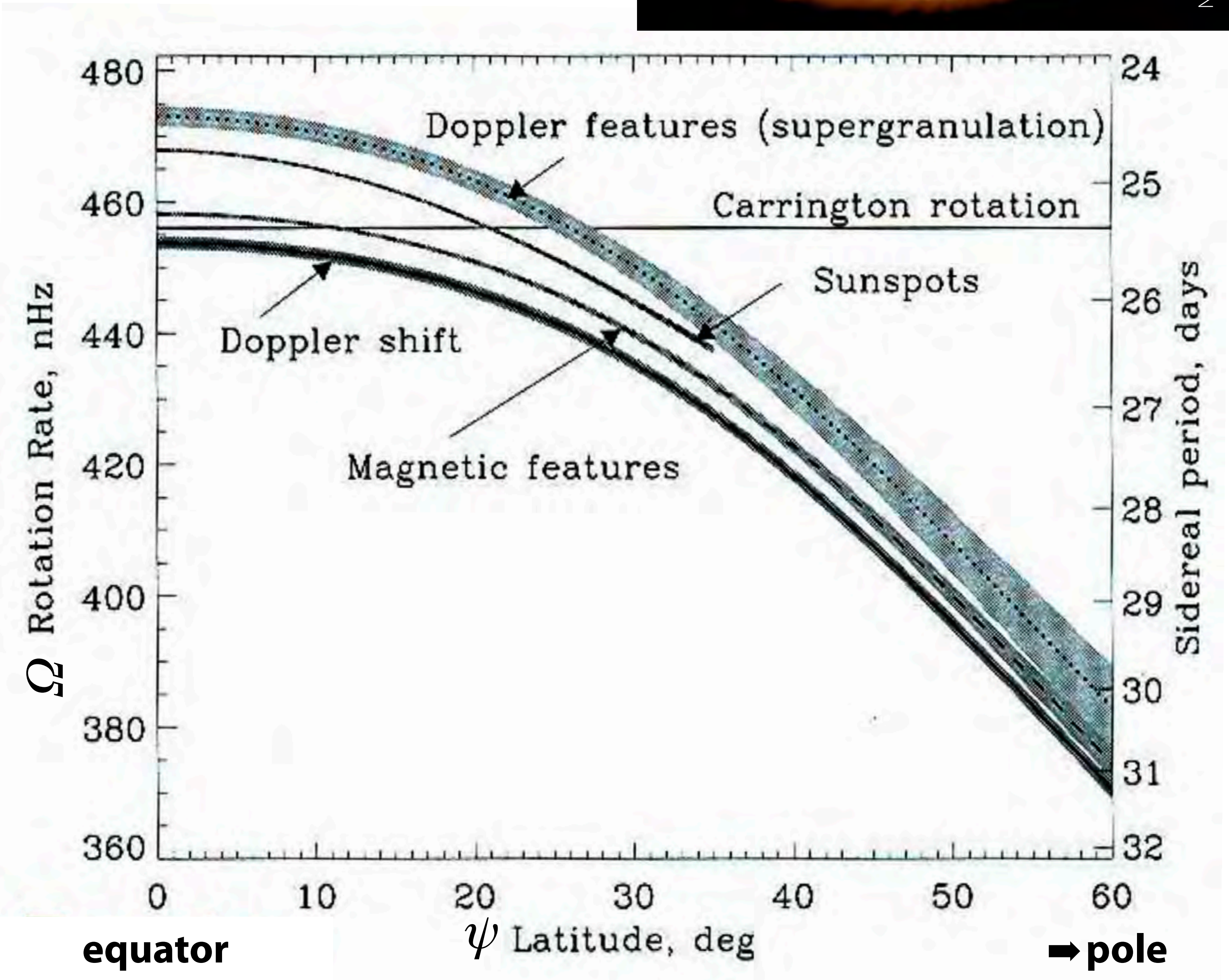
- **Empirical rotation law**: Rotation rate Ω as function of latitude ψ:

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

➡ 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!)



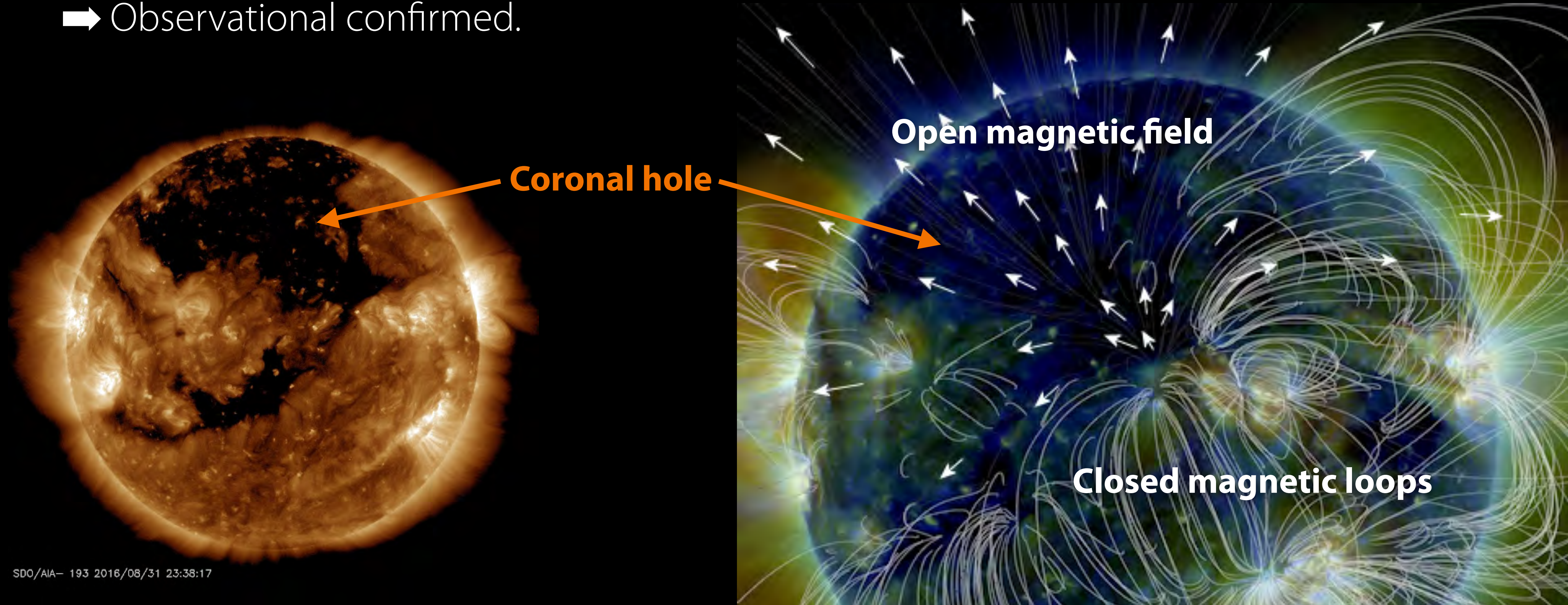
Solar rotation

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.



NASA/SDO

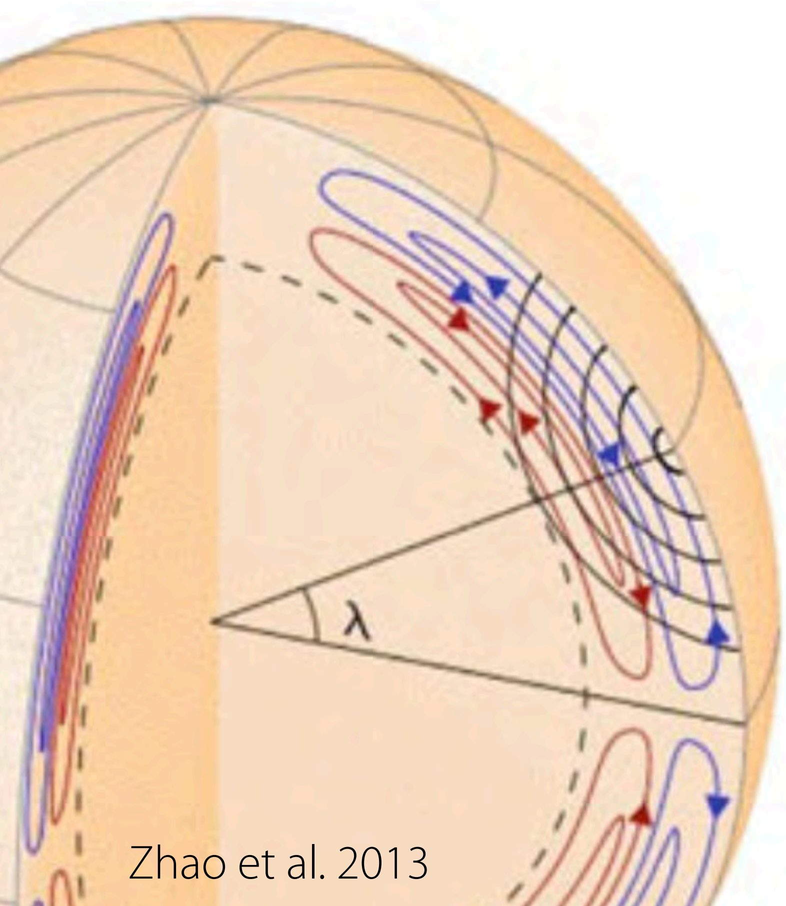
Solar rotation

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 changes as function of radius?

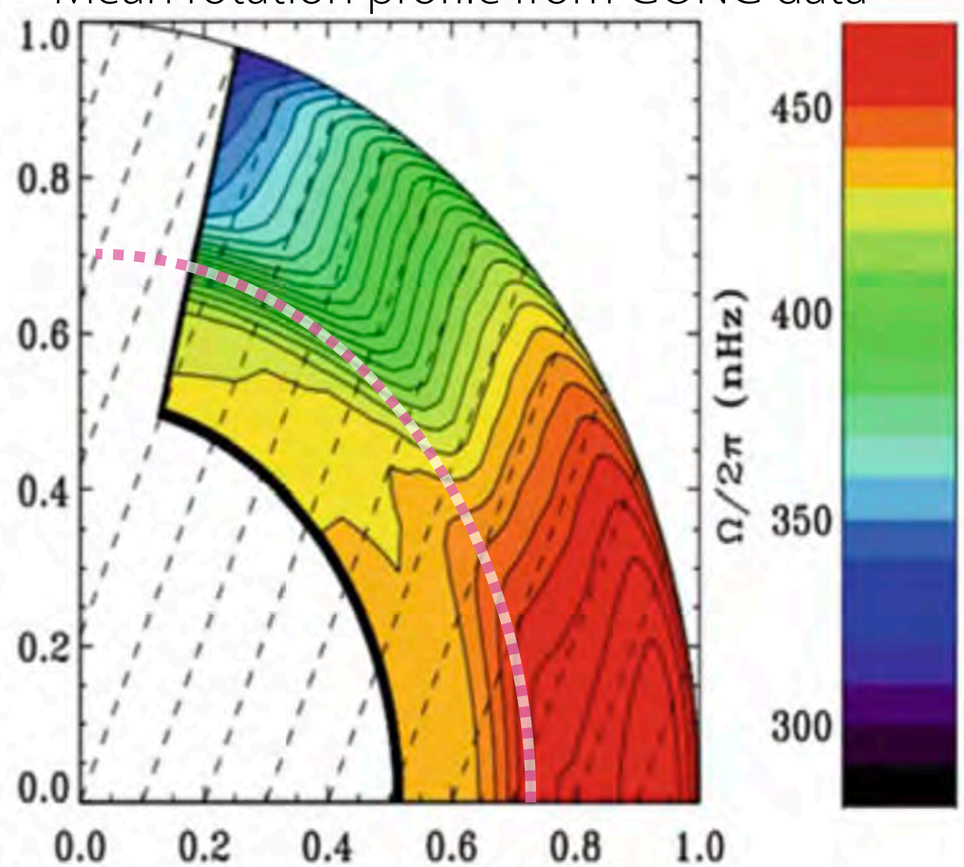
- Remember the internal rotation speeds and meridional flows as probed with helioseismological methods!

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

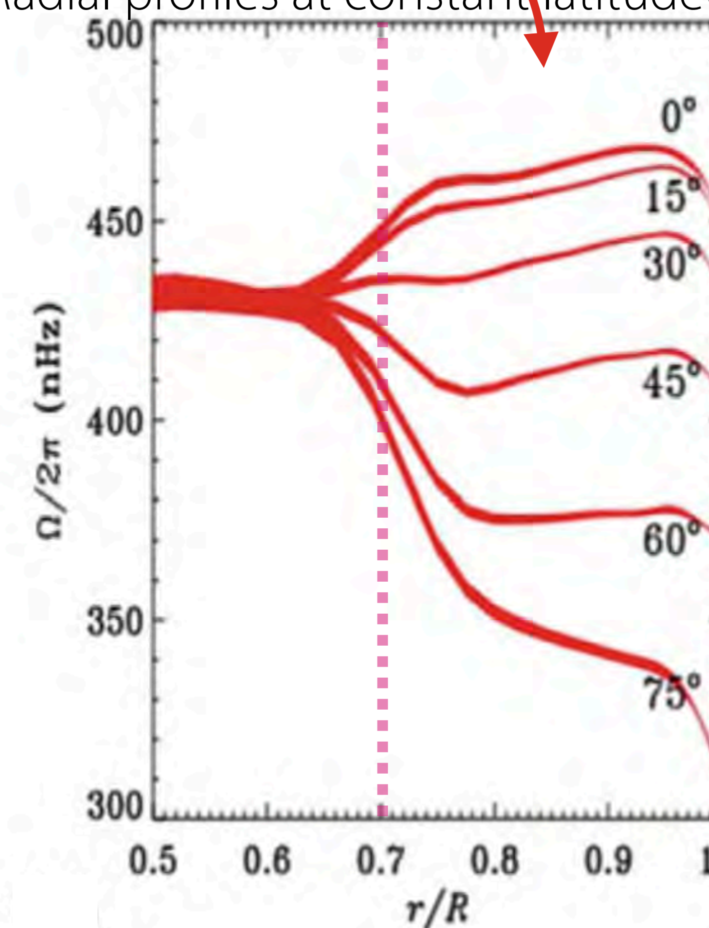


Zhao et al. 2013

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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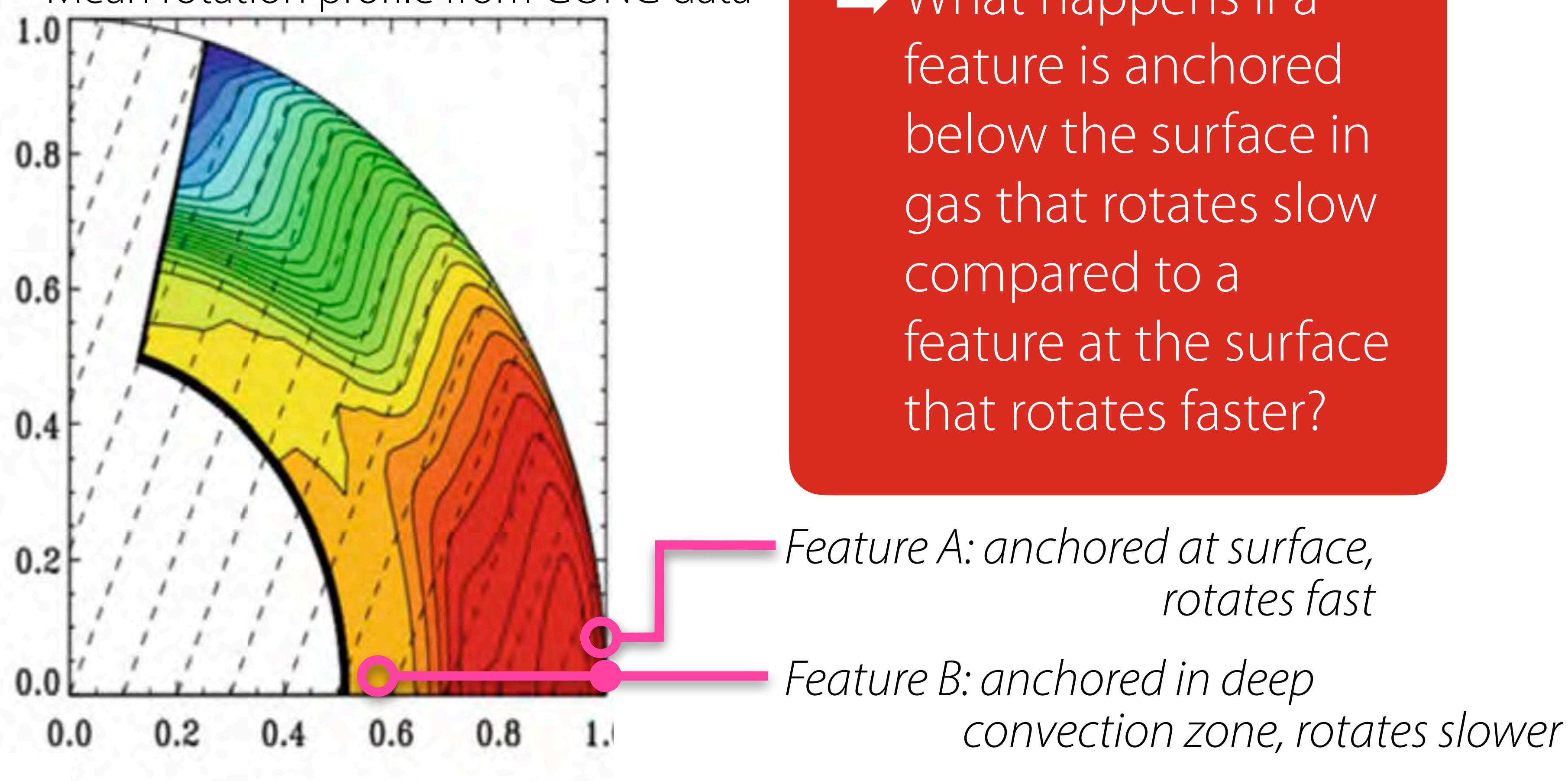
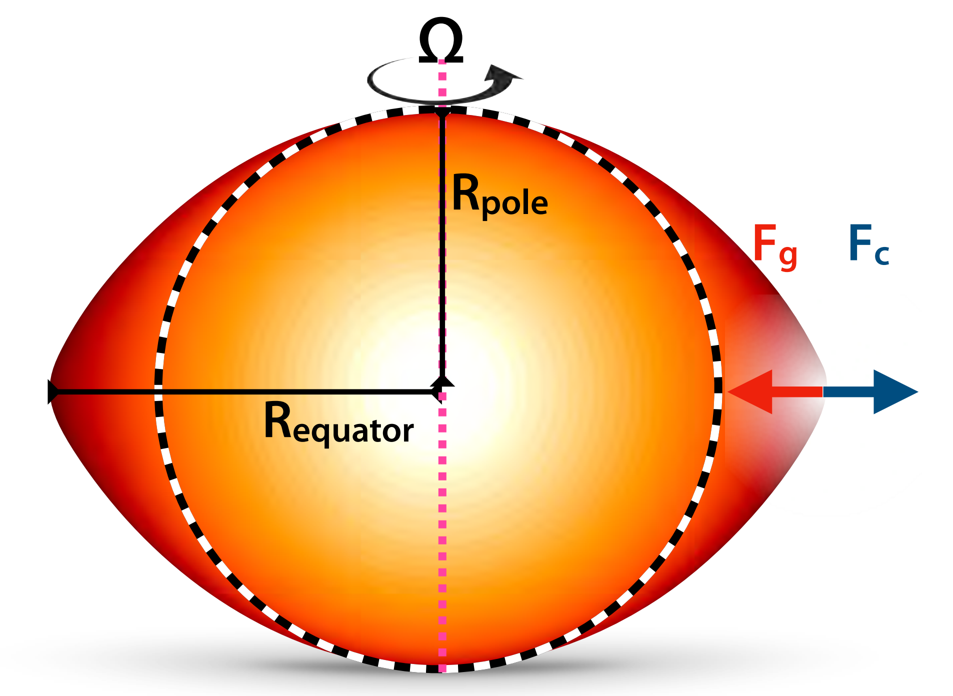


➡ What happens if a feature is anchored below the surface in gas that rotates slow compared to a feature at the surface that rotates faster?

Solar rotation

Solar oblateness



- Centrifugal force due to solar rotation leads larger solar diameter at equator than between the poles
- Oblateness := $(R_{equator} - R_{pole}) /\langle R\rangle = \Delta R/\langle R\rangle$
  - *Note: If core rotates more rapidly than surface, then oblateness will be larger than expected due to surface rotation rate*

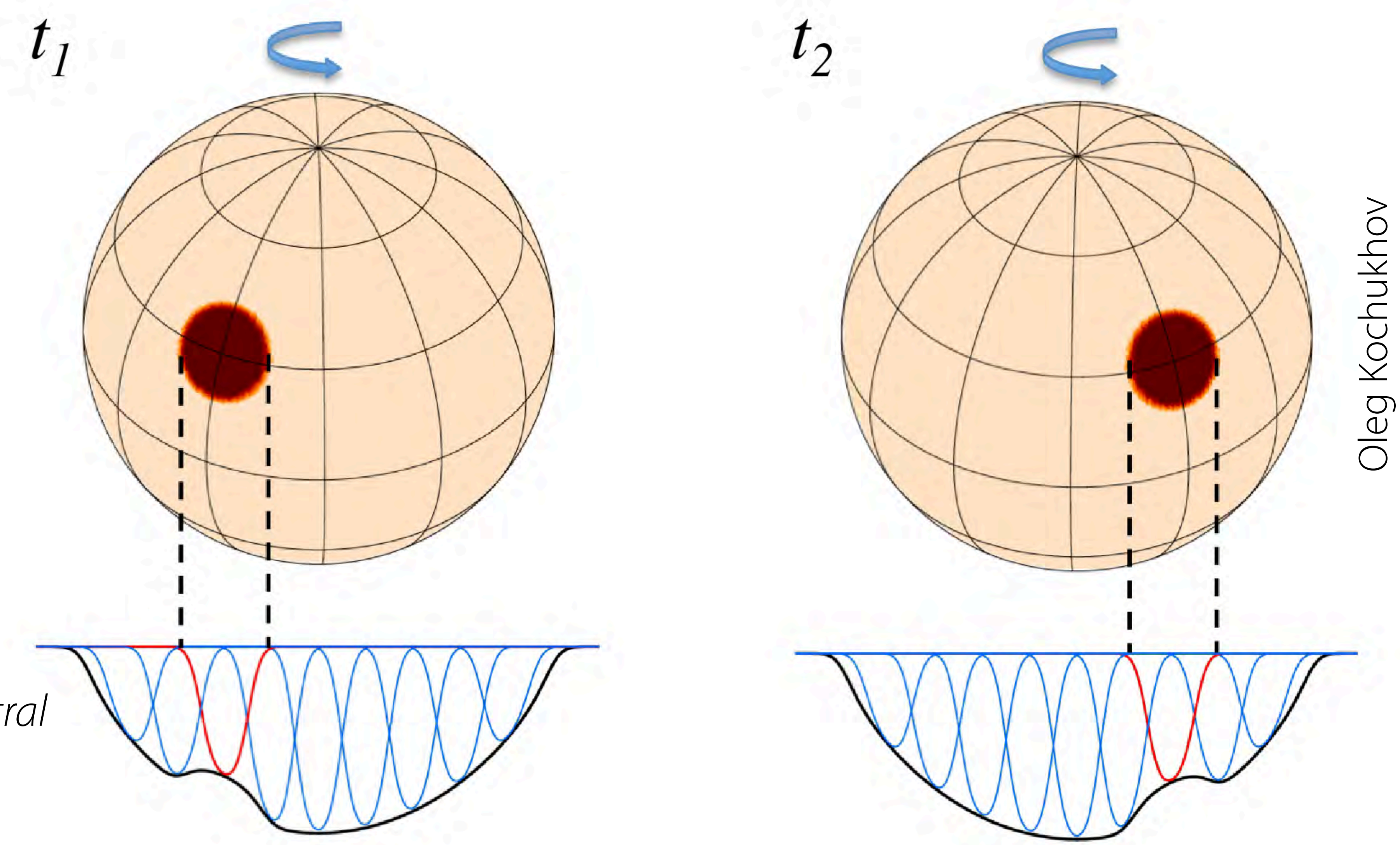
- **Direct measurements**: $(\Delta R/R)_\odot \approx 10^{-5}$ (which thus means $\Delta R \approx 14$ km)
  - Best spatial resolution of images still ~50 km
  - Systematic errors due to concentration of magnetic activity to low latitudes affects measurements of solar diameter since shape of limb is 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.



Rotational modulation of a spectral line caused by a large starspot

Stellar rotation

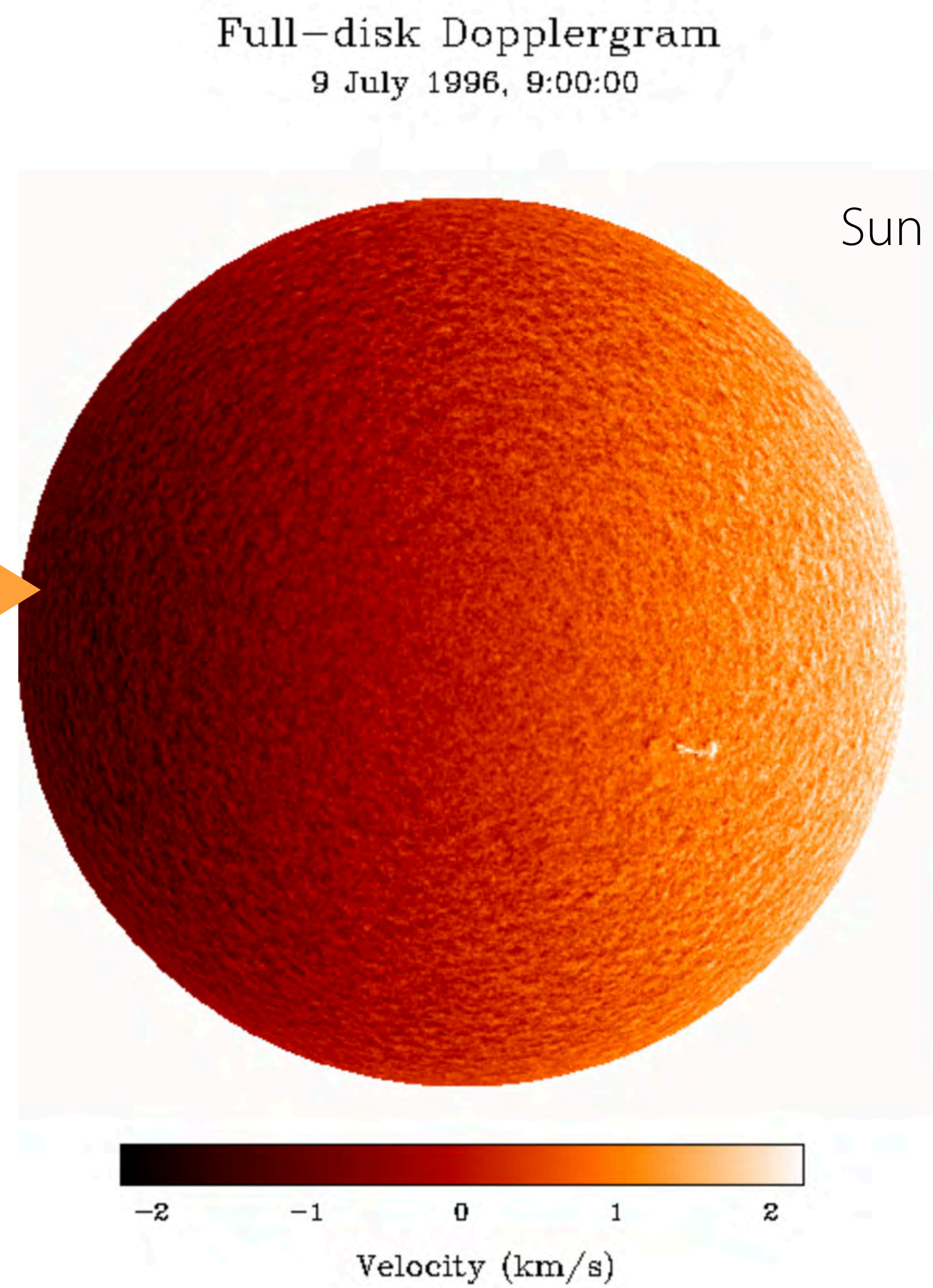
Spectral line broadening due to rotation

- 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



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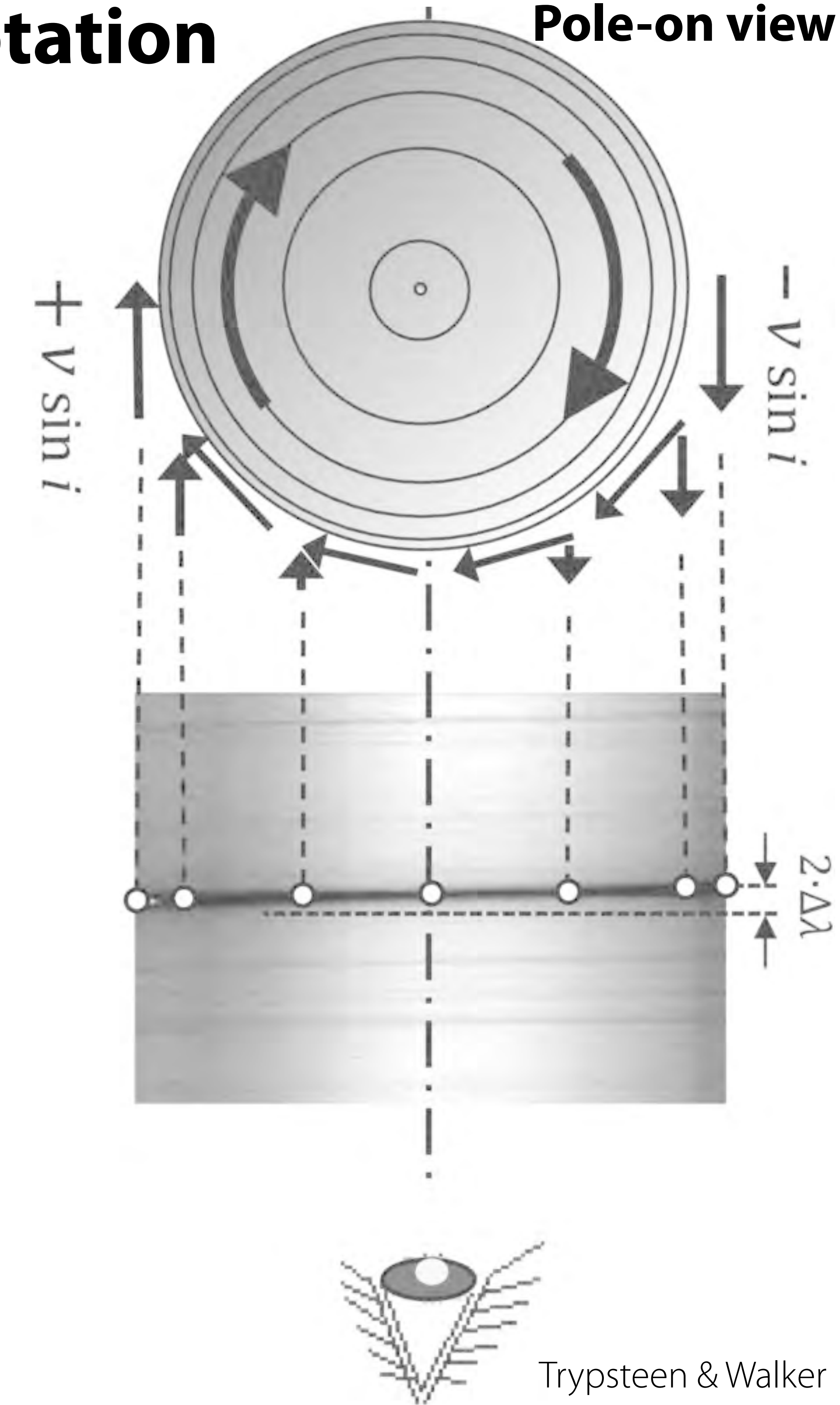
Pole-on view



Trypsteen & Walker

Stellar rotation

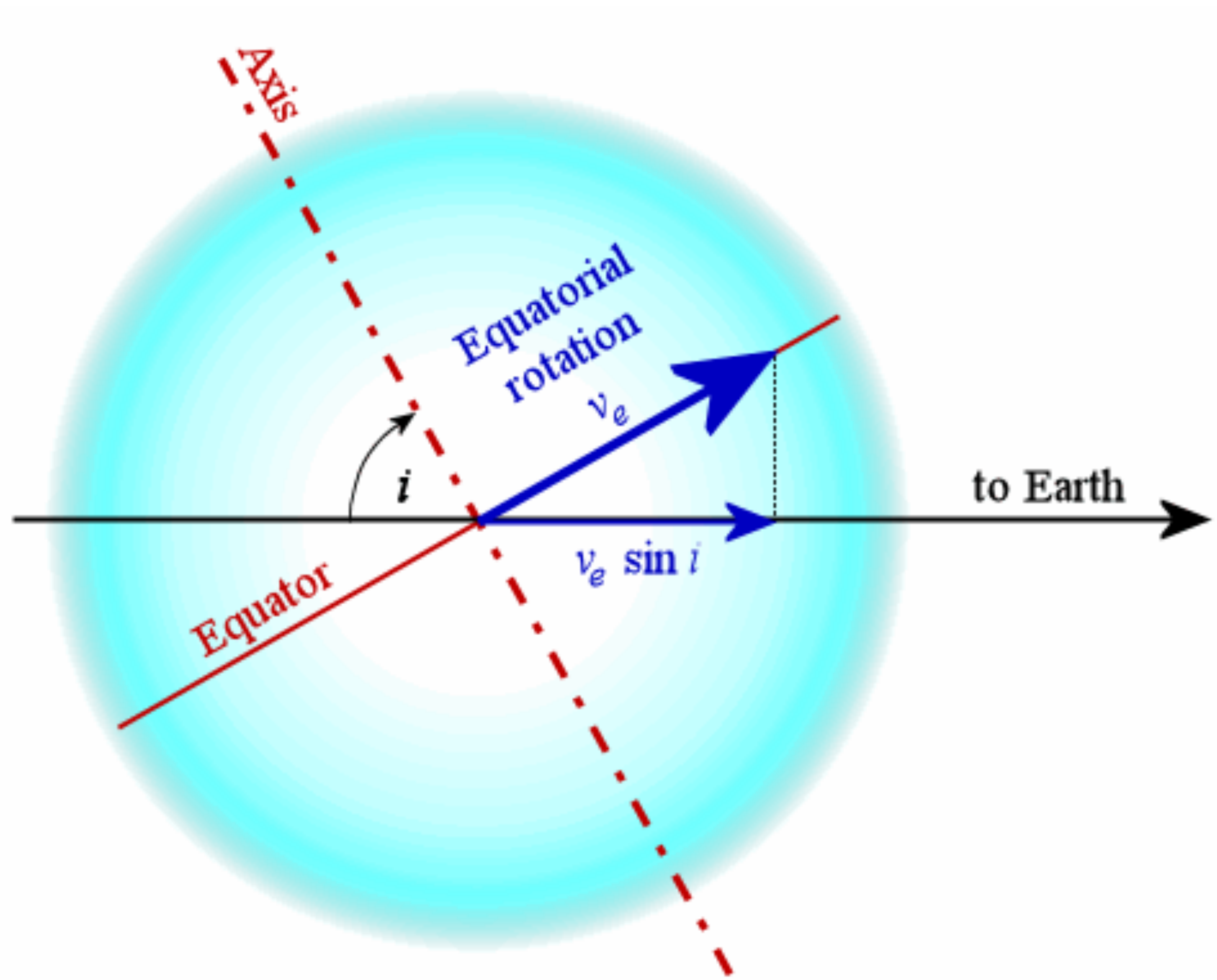
Spectral line broadening due to rotation

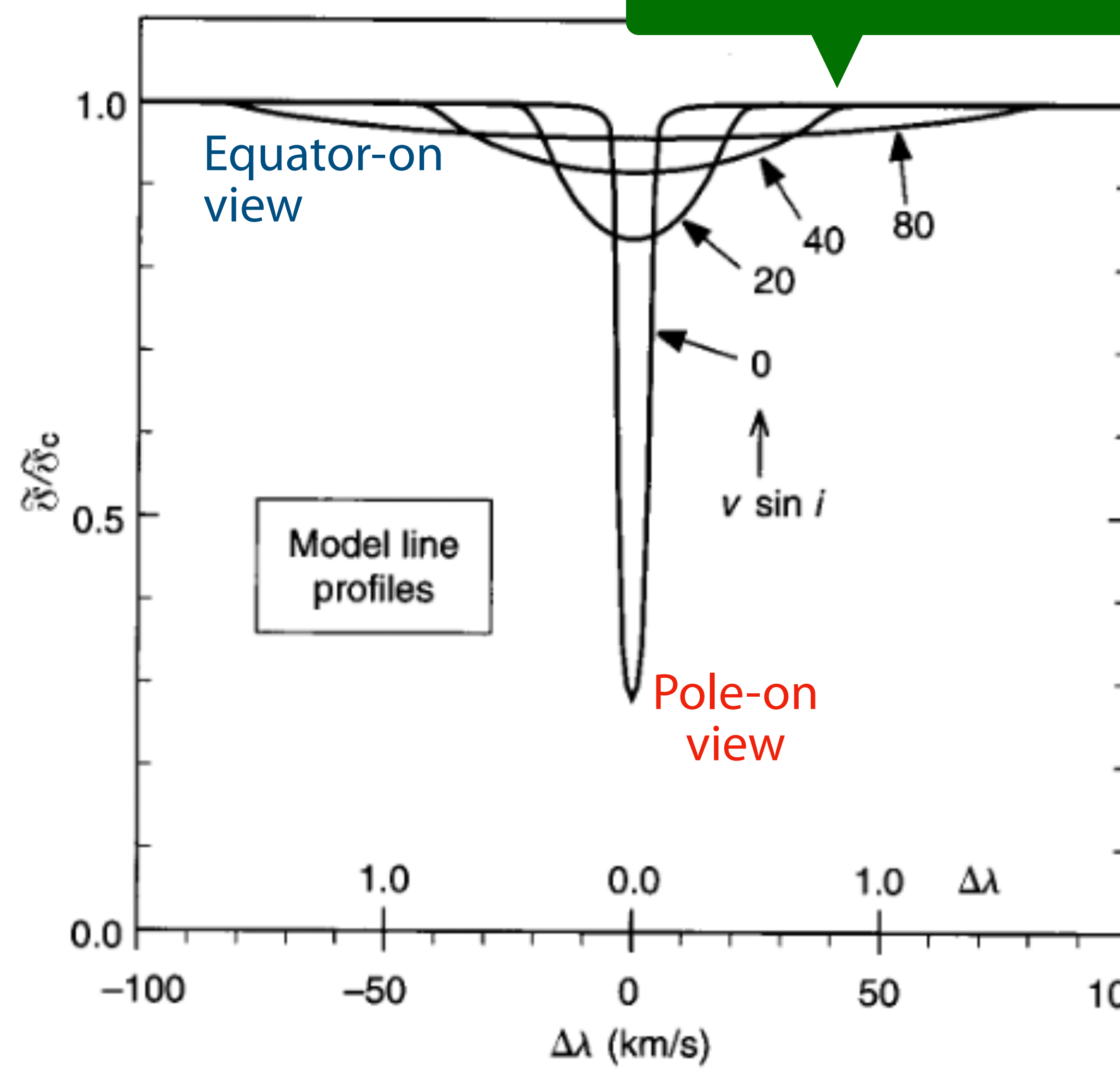
- Only the **projected** rotation rate can be derived from broadening of spectral lines

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

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

The equivalent width of the line is conserved.

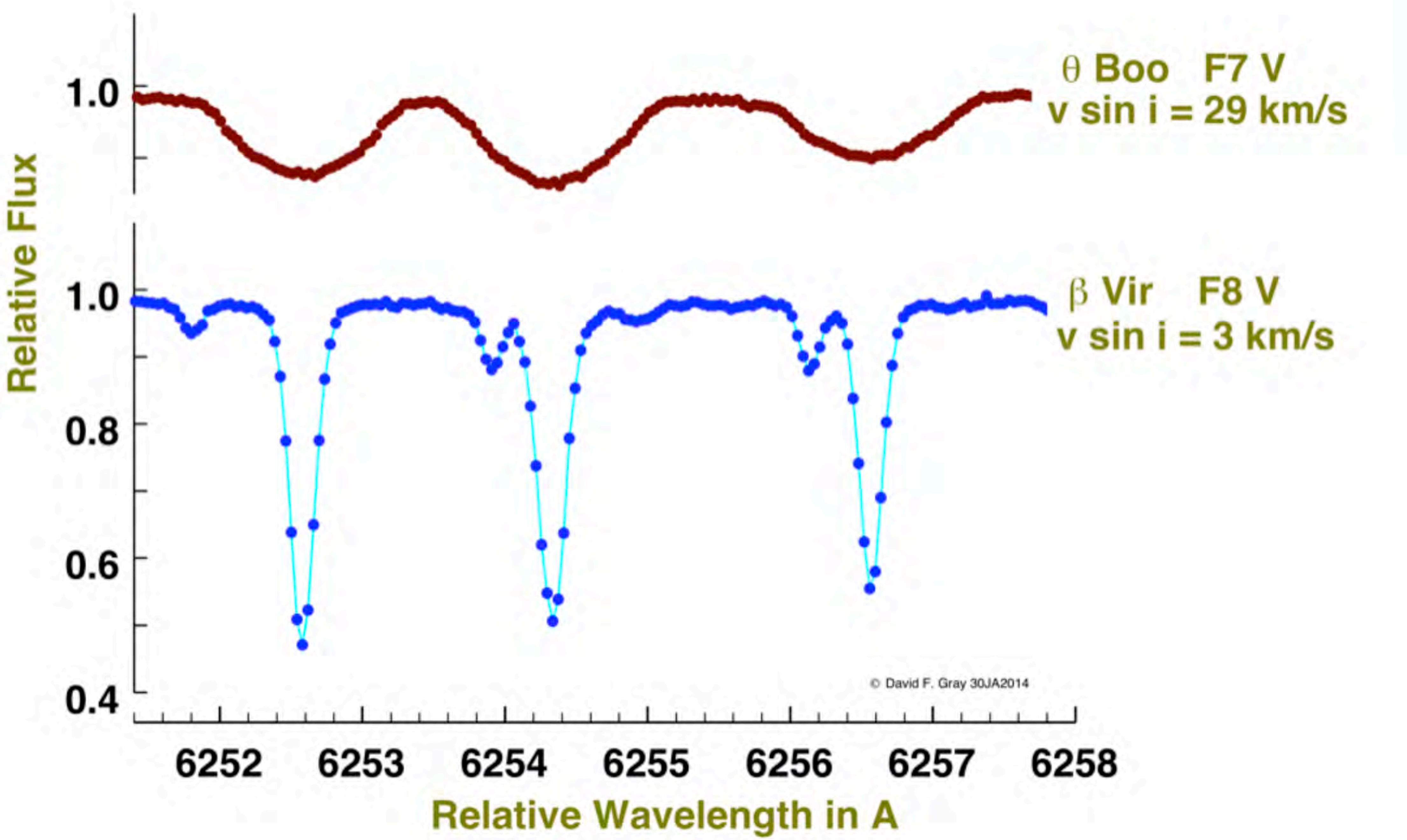




Stellar rotation

Spectral line broadening due to rotation

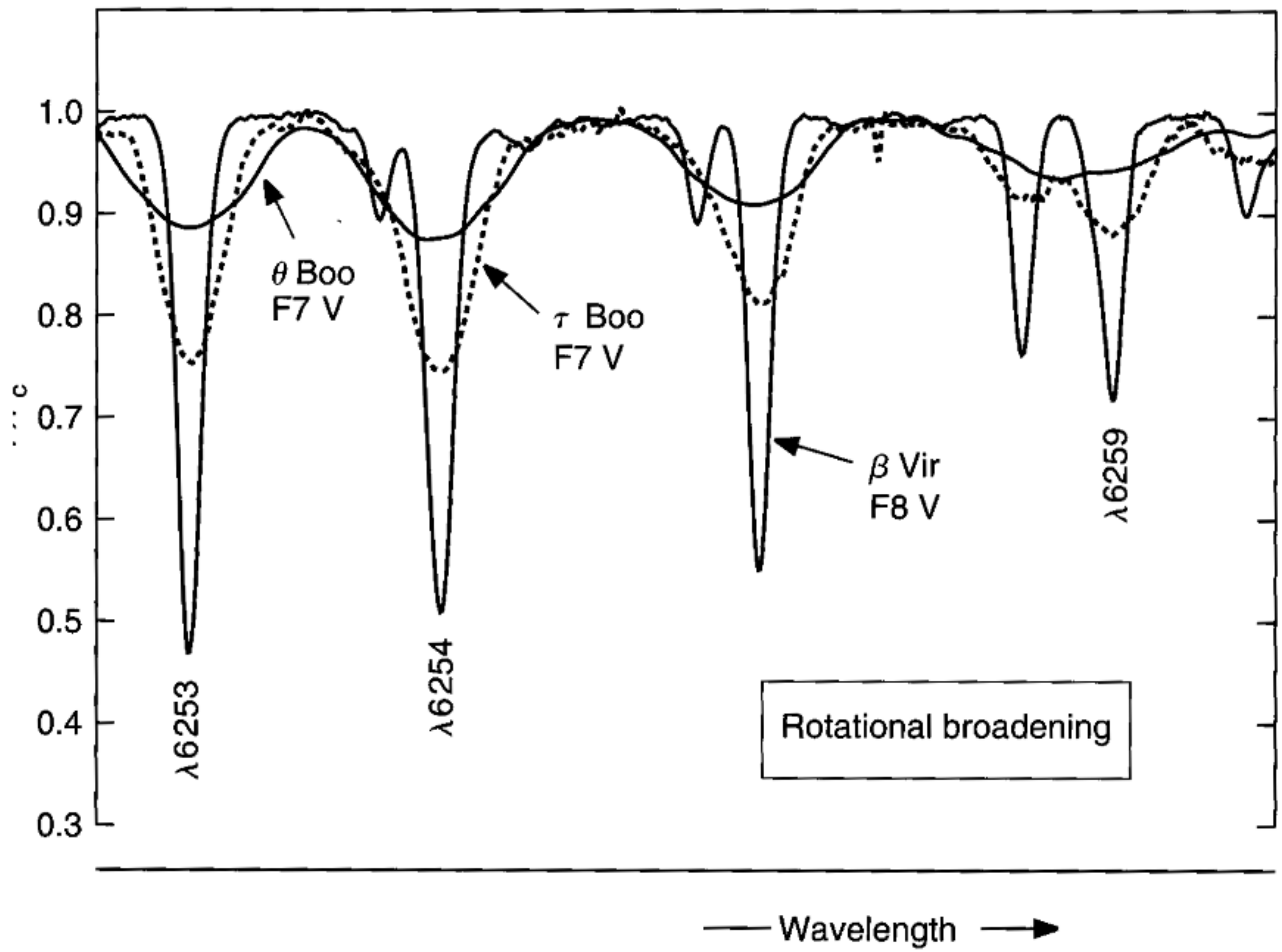
- Comparison of two (relatively) similar stars



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

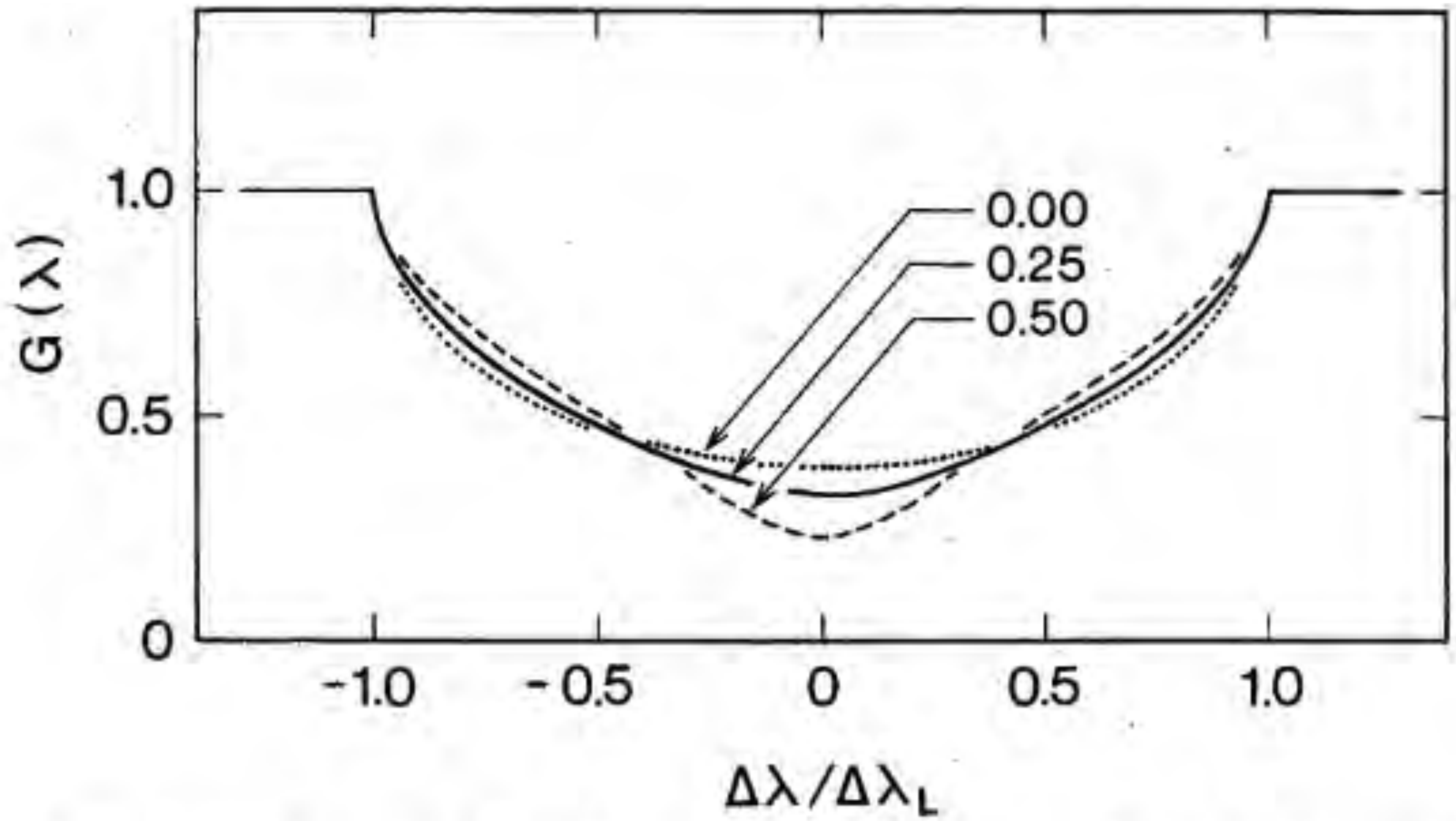


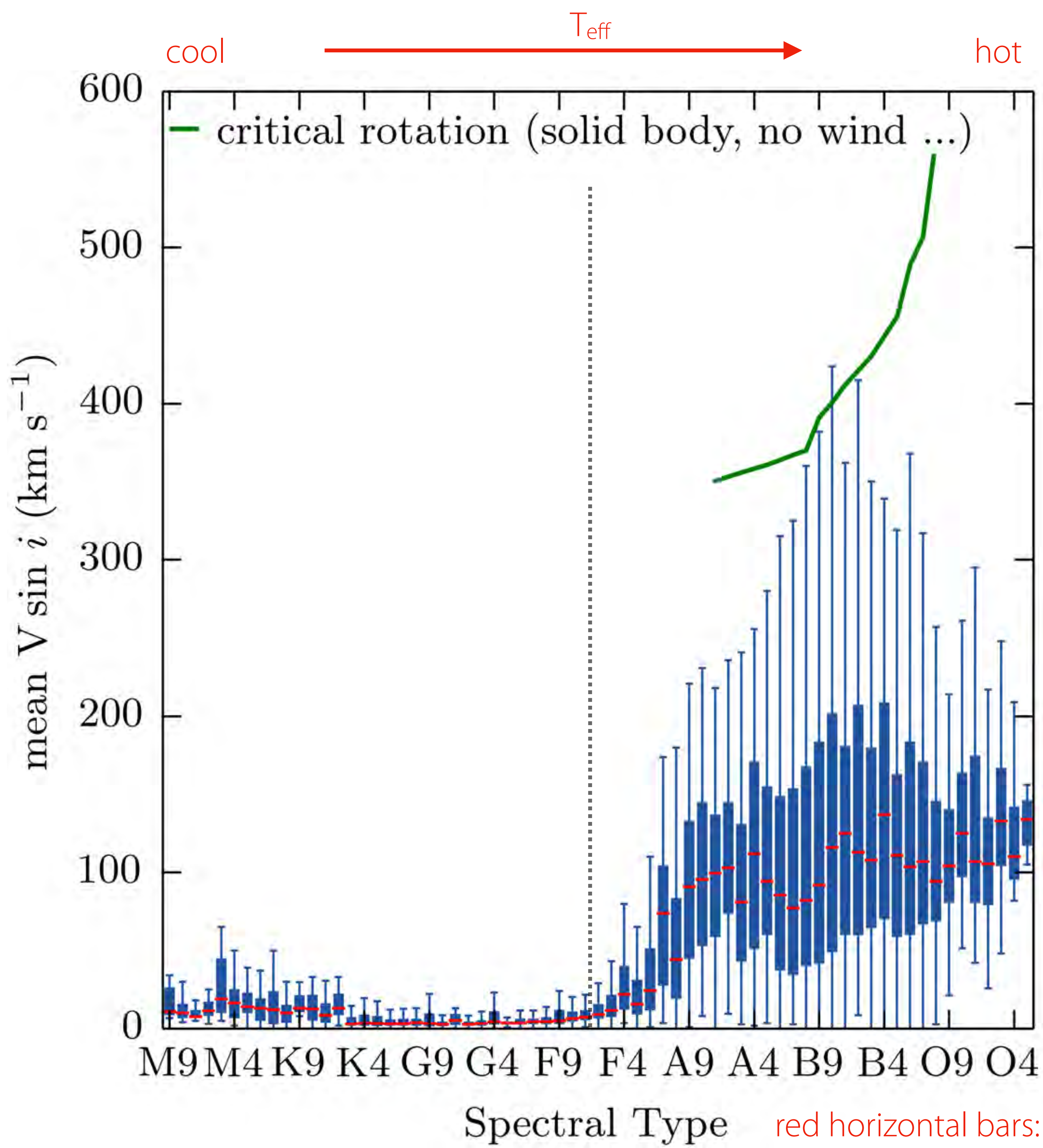
FIG. 3.—Rotation profiles for three values of the differential rotation parameter $\alpha = \omega_2/(\omega_0 + \omega_2)$.

- Equatorial acceleration → lines narrower and more V-shaped
- Polar acceleration → 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

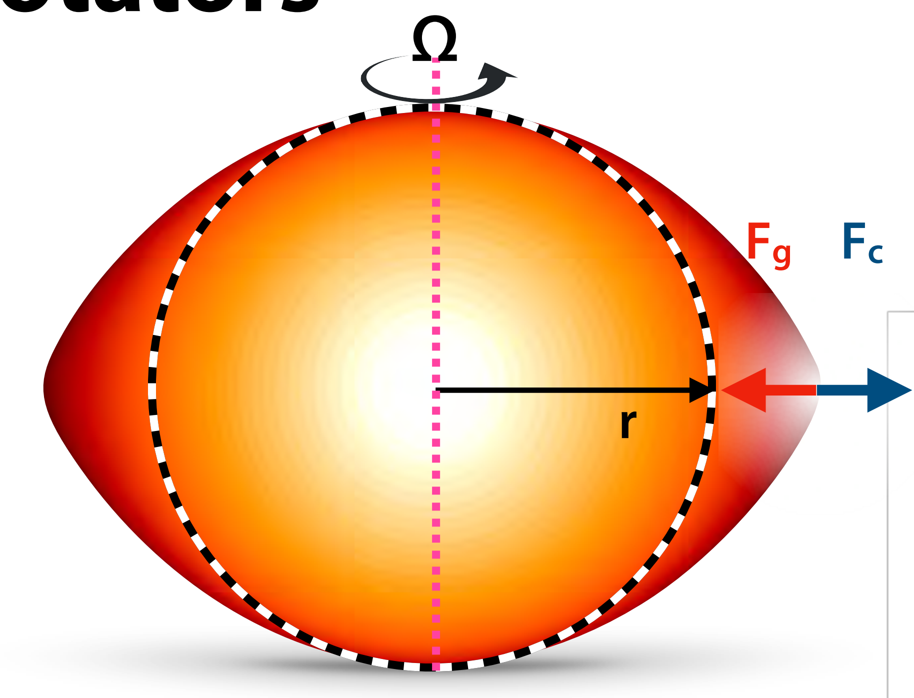
Measured v sin I

- 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

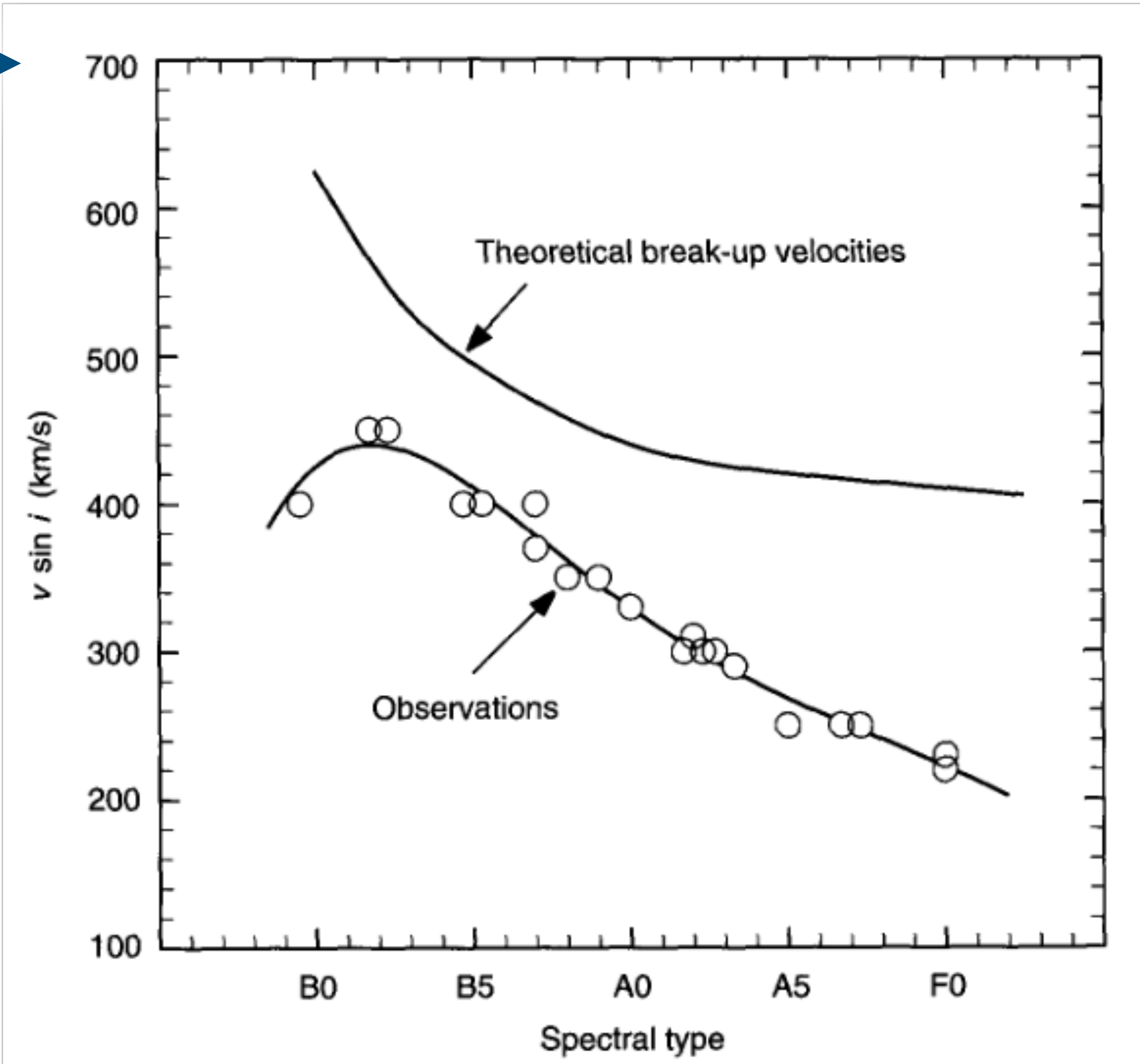


- Fast rotation causes centrifugal force, counteracts gravity, strongest effect at equator

  ➡ Oblateness

- Limiting **breakup velocity** = rotation speed at which the centrifugal force exceeds the gravitational force

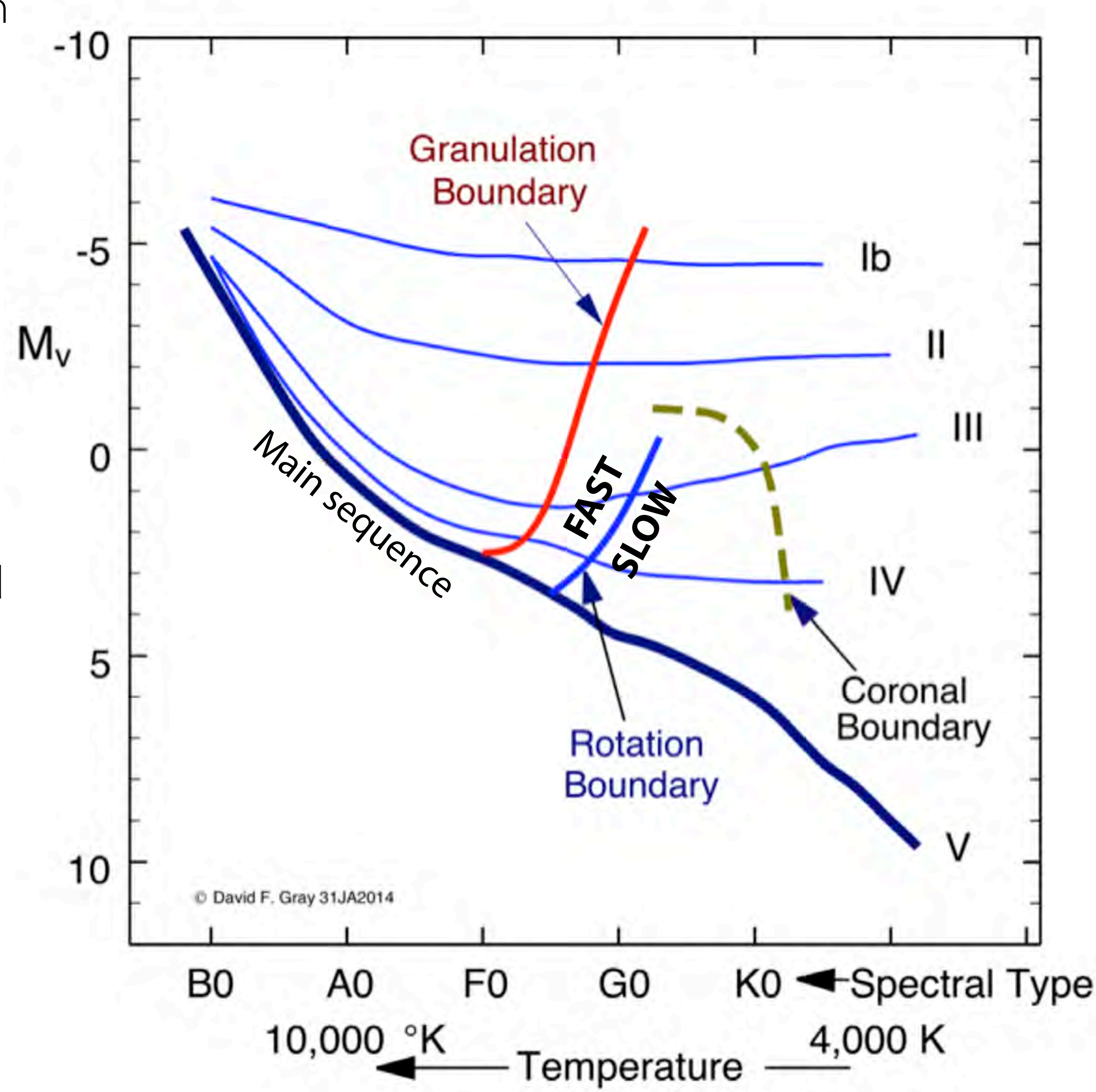
  ➡ Stellar material in fastest rotating areas no longer gravitationally bound



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"

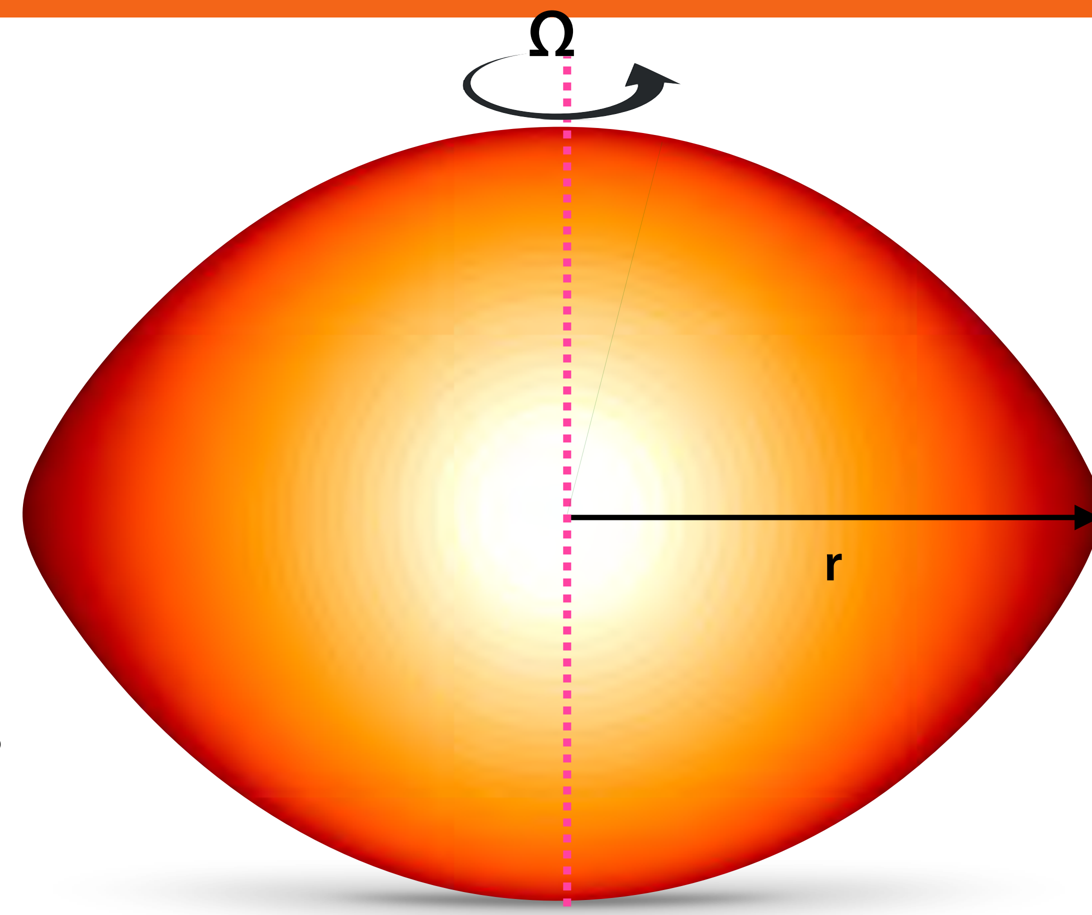
➡ Effects the hydrostatic stratification:

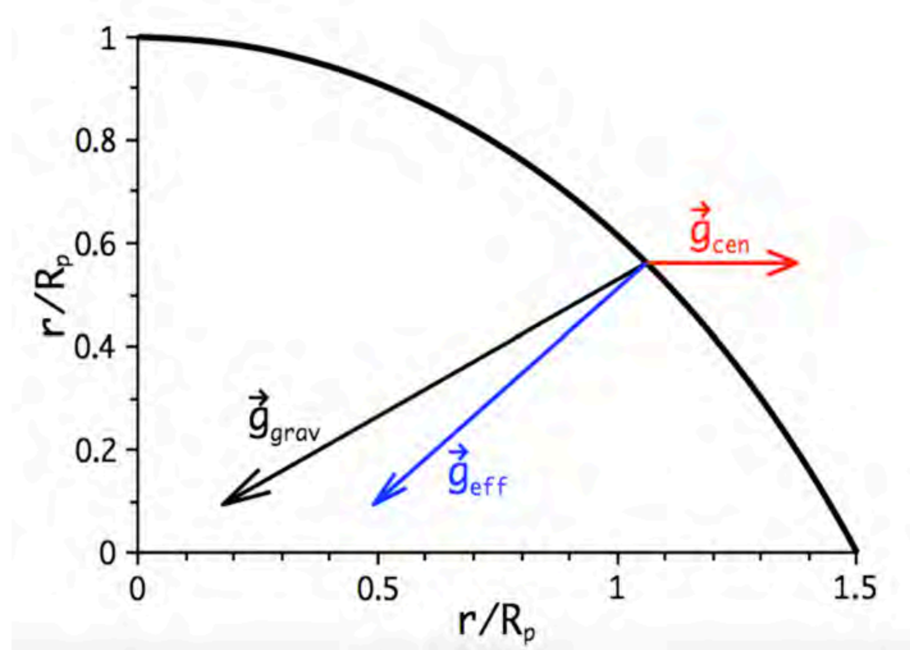
  ➡ Lower gas pressure required to maintain equilibrium

  ➡ Lower temperature (equation of state! Ideal gas: $P \propto T$)

  - Lower temperature at the equator than at the poles

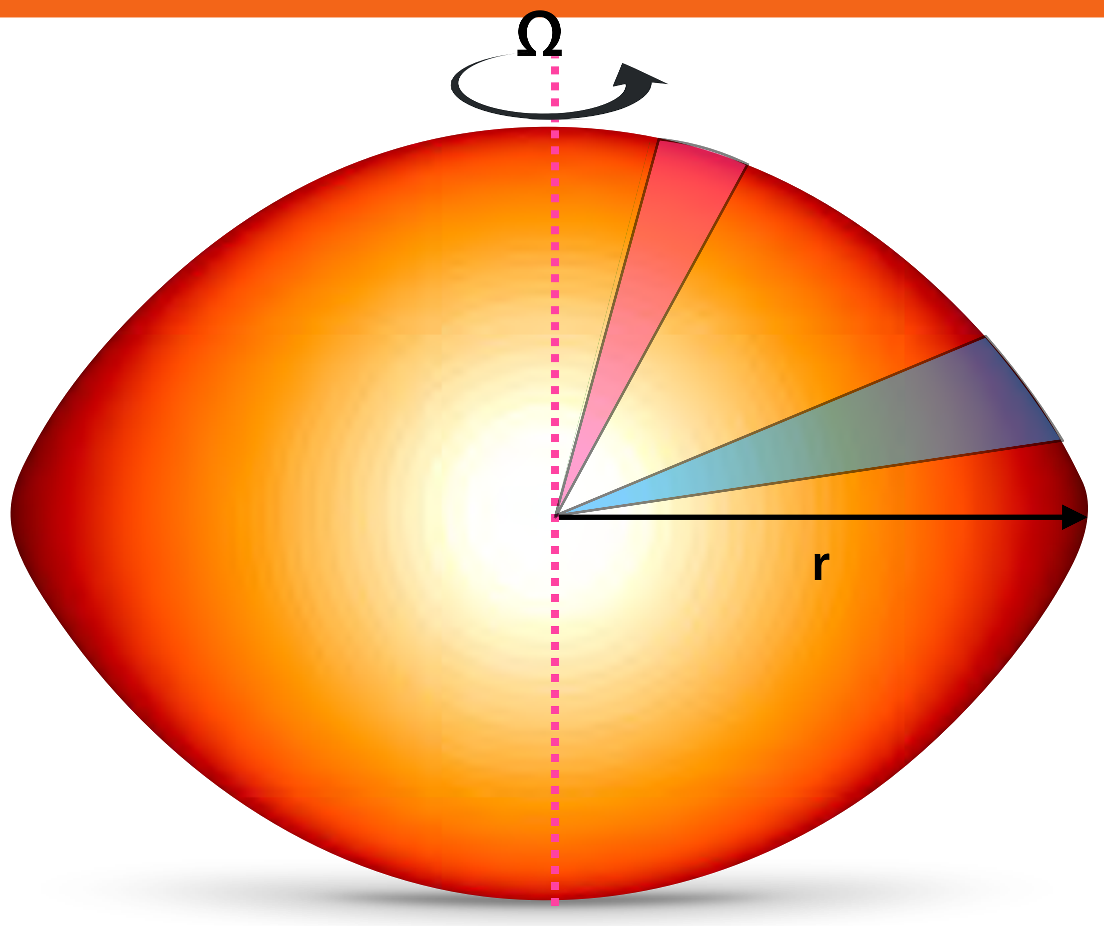
  - Von Zeipel law (1924): $T_{\mathrm{eff}} \propto g_{\mathrm{eff}}^{\,1/4}$





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 $T_{\mathrm{eff}} = (F / \sigma)^{1/4}$
    - 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

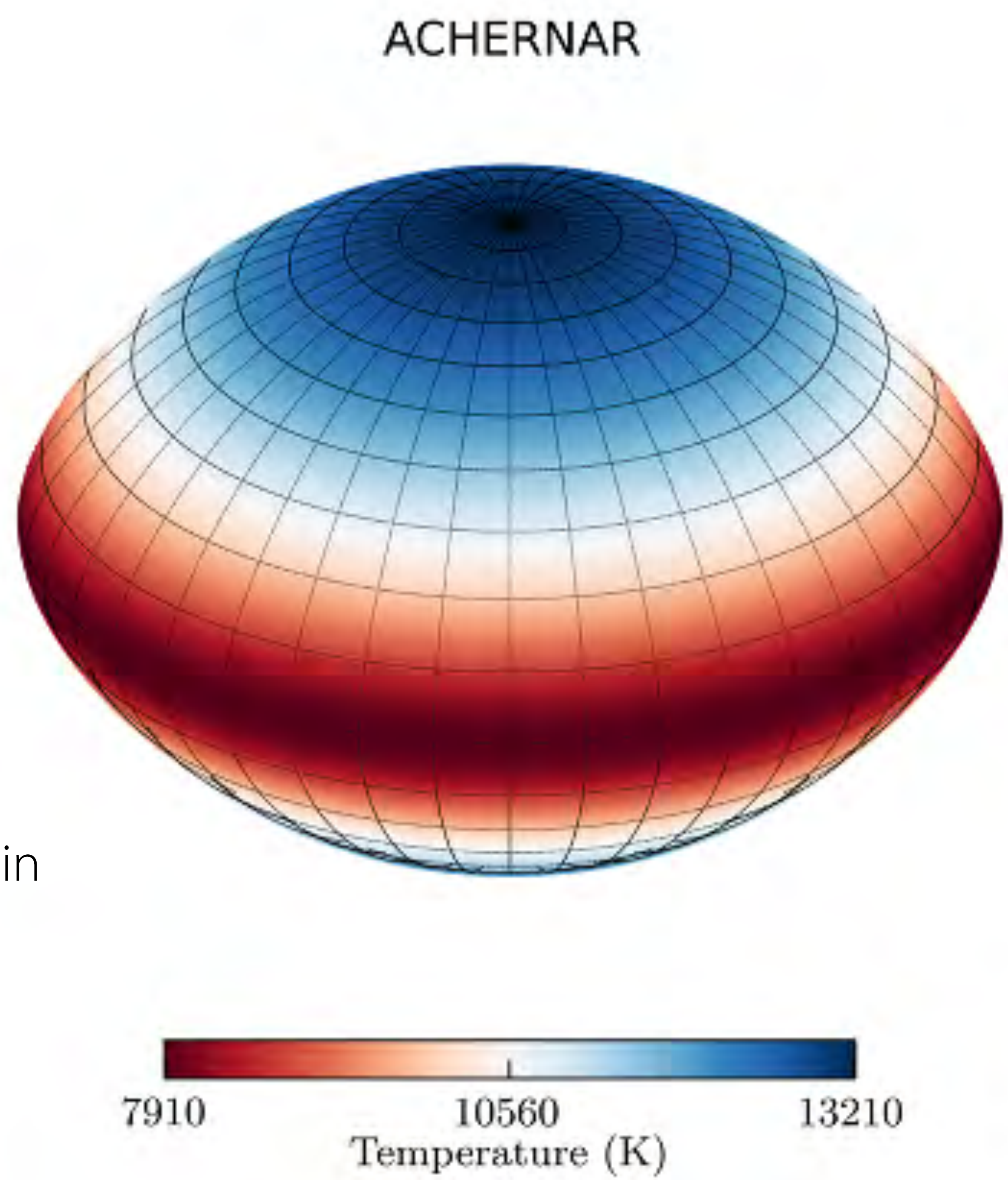
➡ Meridional circulation might develop

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 ΔR/R ~ 10
- Gravity darkening produces large differences in surface temperature!



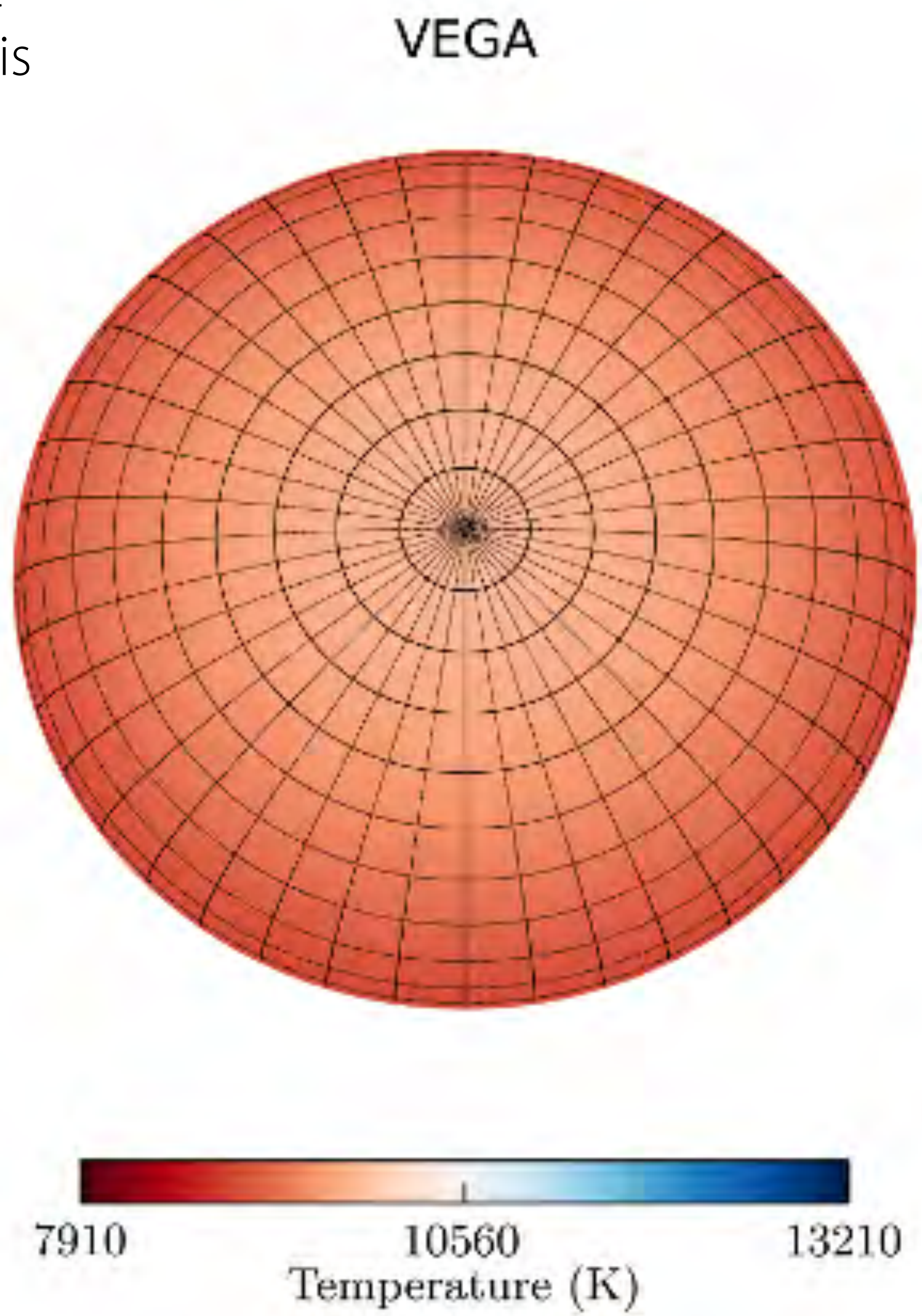
Stellar rotation

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 ΔR/R ~ 2.2

- We do not see gravity darkening as we observe Vega **pole-on**

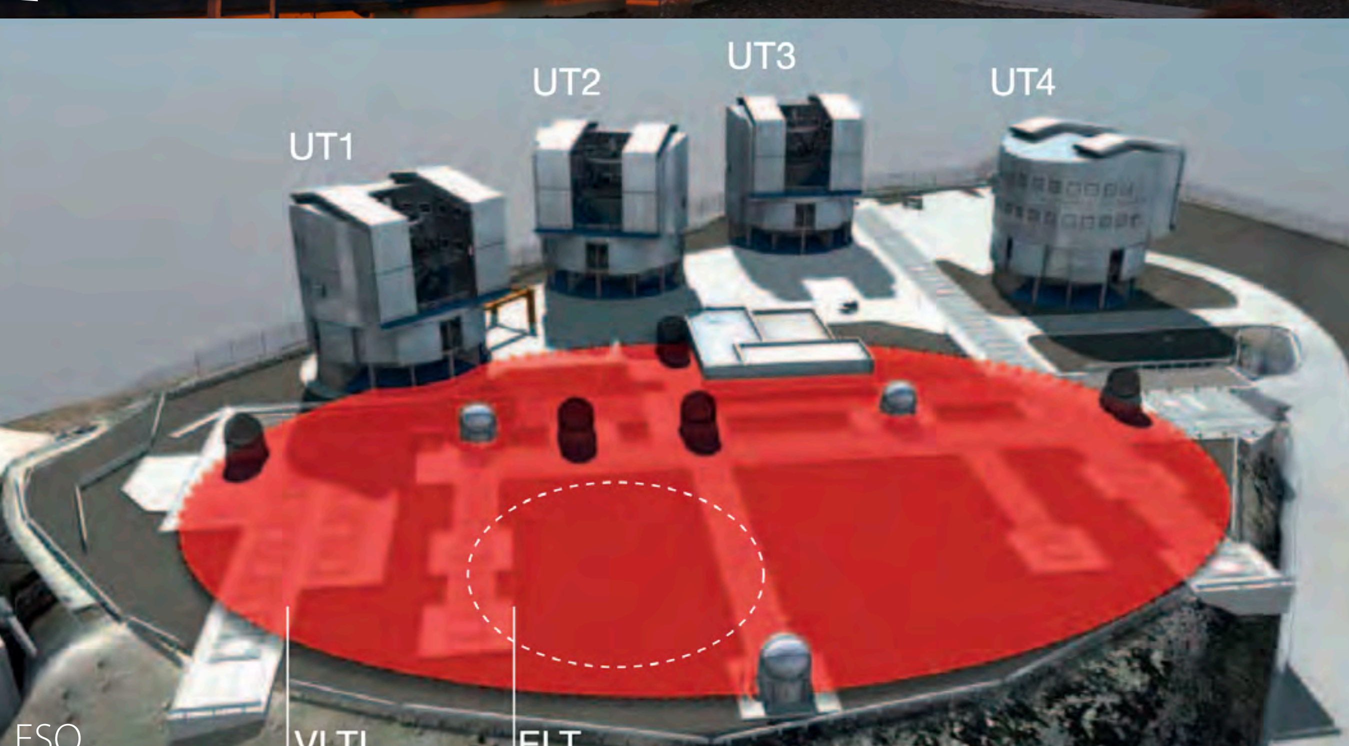


Stellar rotation

Effects at fast rotation — gravity darkening

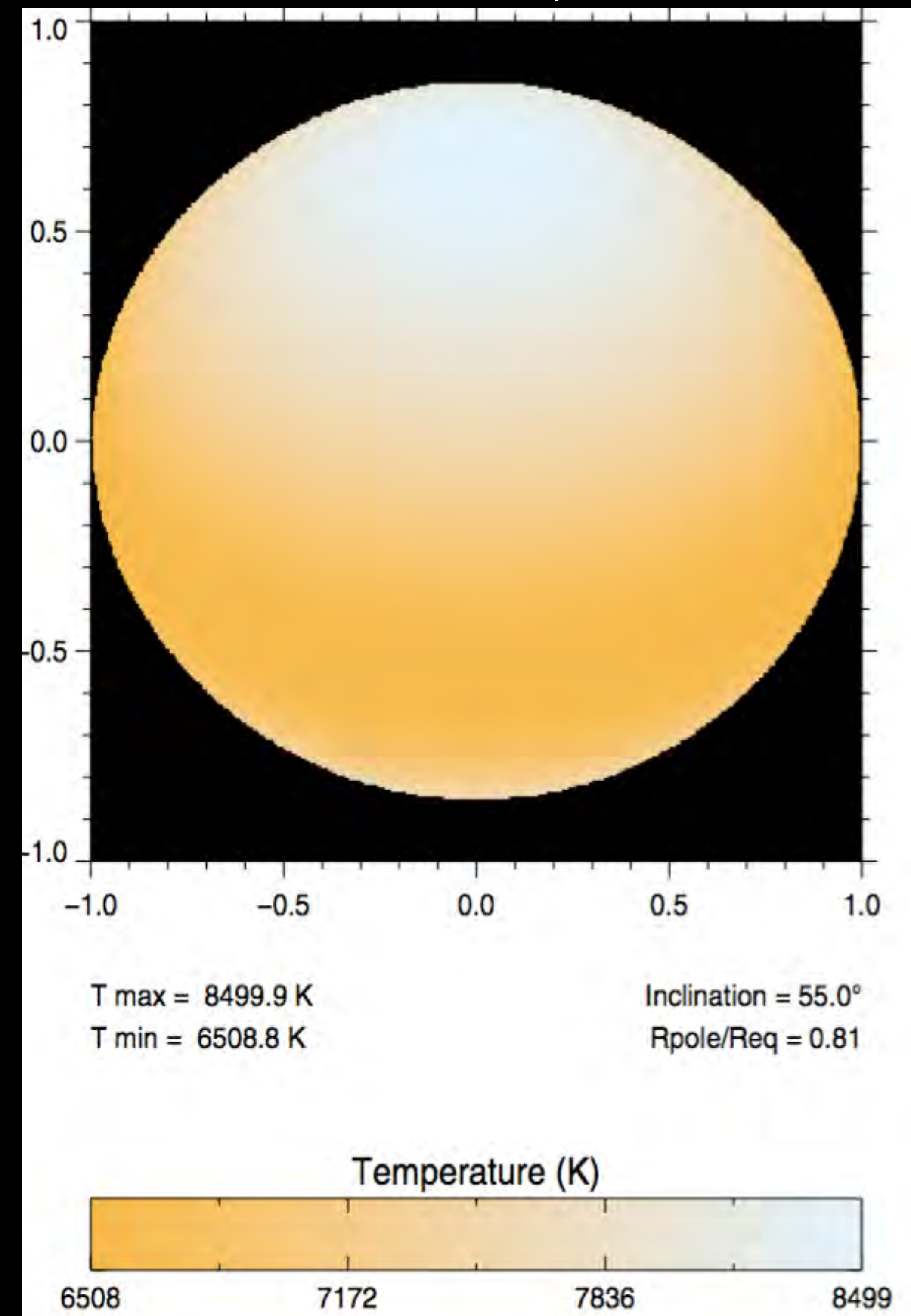
- Gravity darkening: Direct observational confirmation by optical interferometry with VLTI: **Altair**
- **Rotational velocity (*v sin i*) 240 km/s !**

My own :-)



ESO

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: $$Ro = \frac{U}{fL}.$$

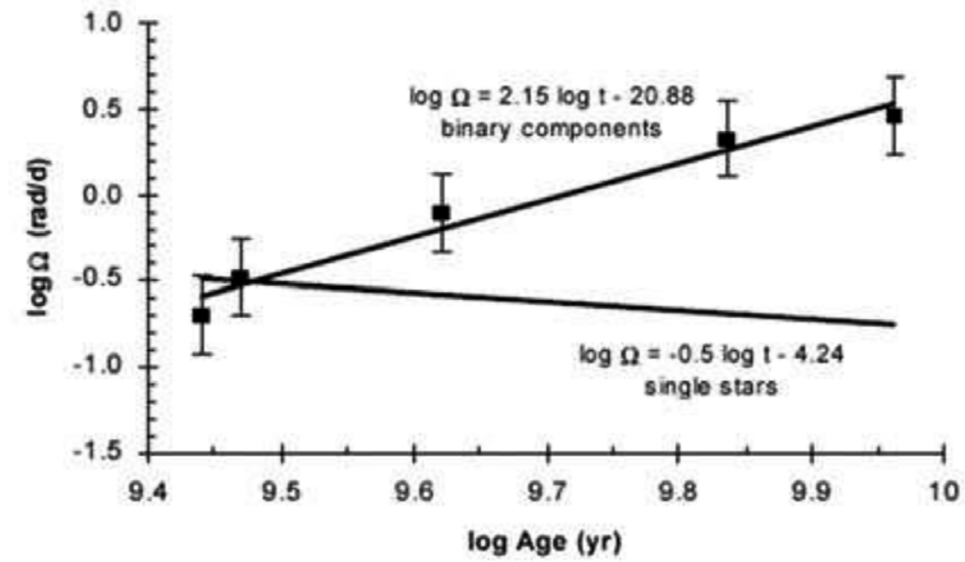
- The Rossby number is the ratio of inertial to Coriolis forces.
- Coriolis parameter: $$f = 2\Omega \sin\varphi.$$
  ($f = 0$ at the equator, $\varphi=0$)
- Ratio between the rotation period of a star and the local convective turnover time
- Large Rossby number: inertial and centrifugal forces dominate (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

U: velocity, U
L: length scale
f: Coriolis parameter
Ω: rotation rate
φ: latitude

Solar rotation

Evolution of solar 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.



Demircan et al

- **Where did all the angular momentum go?**
  - Binary stars: exchange of orbital angular momentum
  - Magnetic braking
  - Stellar winds

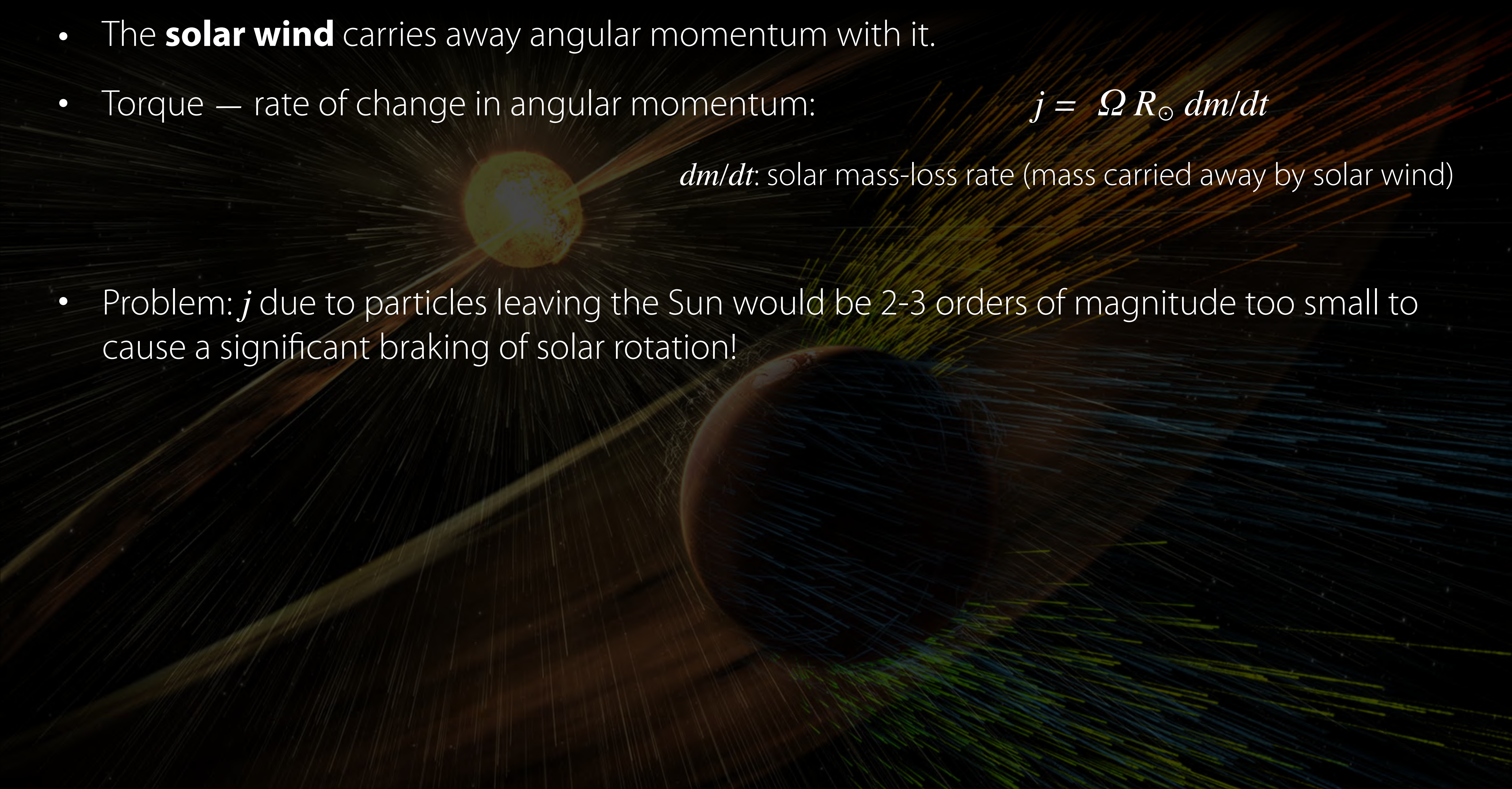
Stellar rotation

Solar/stellar winds

- Stream of charged particles released from the upper atmospheric layers of a star
- The **solar wind** carries away angular momentum with it.
- Torque — rate of change in angular momentum: $j = \Omega R_{\odot} \, dm/dt$

  dm/dt: solar mass-loss rate (mass carried away by solar wind)

- Problem: j due to particles leaving the Sun would be 2-3 orders of magnitude too small to cause a significant braking of solar rotation!



This artist's rendering shows a solar storm hitting Mars and stripping ions from the planet's upper atmosphere. NASA/GSFC

Stellar rotation

Solar/stellar winds

- **Solution:**
  - Solar wind = charged particles
  - Particles propagate along magnetic field up to Alfvén radius R_A (at $R = R_A$: wind speed becomes larger than Alfvén speed)
  - At $R < R_A$: Wind rotates rigidly with the solar surface (forced to do so by magnetic field)
  - At $R > R_A$: Wind carries away angular momentum.
  - Typically R_A > 10-20 $R_\odot$

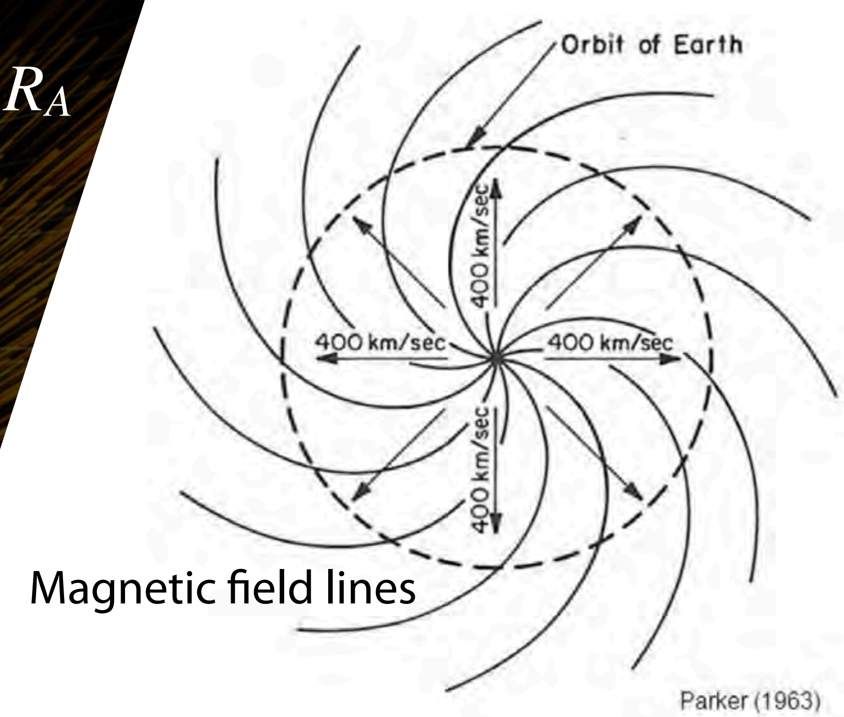
➡ Torque: Relevant radius not $R_\odot$ but R_A!

➡ Loss of angular momentum scales with this critical radius and thus much higher!

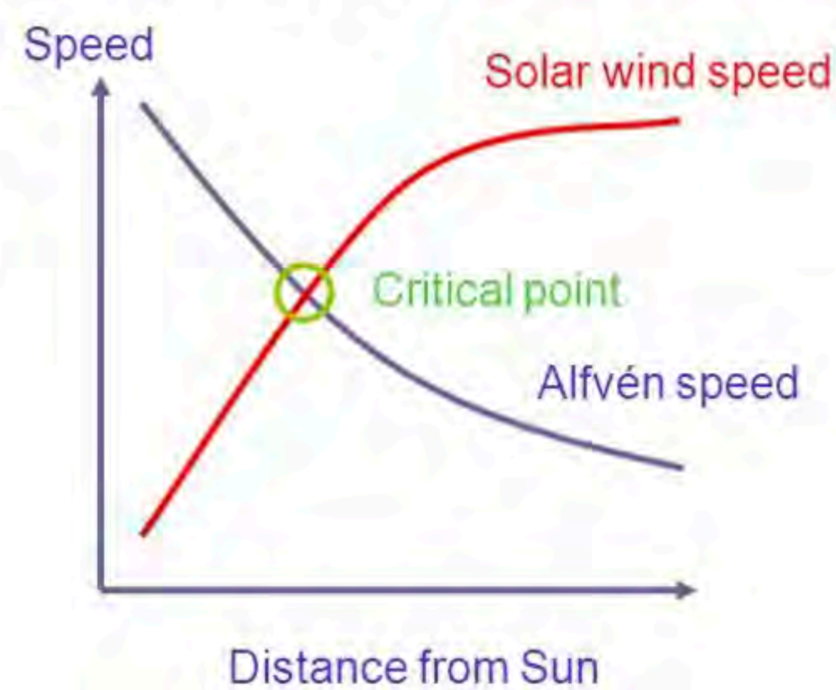
$$j = \Omega R_A \, dm/dt$$

Alfvén speed

$$v_A \equiv \frac{B}{\sqrt{\mu_0 \rho}}$$



Parker (1963)



NASA/GSFC

Stellar rotation

Solar/stellar winds

$j = \Omega R_A \, dm/dt$

- Additional comments:
  - $j \propto \Omega$: The faster the star rotates, the quicker it spins down.
  - Mass loss rate dm/dt depends a lot on the properties and evolutionary stage of a star
    - Dependence on Ω: More rapidly rotating stars produce stronger magnetic field, hotter corona, and thus larger dm/dt)
    - Mass loss rates in late evolutionary stage can become large (> 10^{-3} $M_\odot$ / yr)
  - R_A depends on Ω
    - Relation not straightforward: more rapidly rotating stars produce stronger magnetic field, but also winds with larger density and velocity of wind
  - In general $j = k \, \Omega^{\alpha}$
    - Typically $\alpha > 1$
    - Note: might become saturated for very large Ω

This artist's rendering shows a solar storm hitting Mars and stripping ions from the planet's upper atmosphere. NASA/GSFC

Stellar rotation

Summary

- Rotation velocities derived as $v \sin i$
  - Can be determined from rotational broadening of spectral lines
  - Inclination angle i must be know 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