AST5770

Solar and stellar physics

Sven Wedemeyer, University of Oslo, 2023

Assignment III

Data and method

- **Requirements:** 1500 - 3000 words and at least one figure illustrating the used data set(s).
- **Content:** Please describe the data set(s) and methods used in your scientific study.

- **Method(s)** with which the data was
  - obtained/produced (e.g., instrumentation/code, observational/numerical technique)
  - processed (if applicable: e.g., post-processing/adjustment incl. noise reduction, rescaling, filtering etc.)
  - analysed (analysis steps that are central for the presented data analysis — as being presented in the next assignment).

- **Aim - REPRODUCIBILITY:** This section should allow any reader with access to the described data, methods and resources to **reproduce** the results (to be) reported in your paper! (However, trivial/unimportant details are usually left out.)

- Remember: You are supposed to deliver a **tentative draft** of this section that reflects your current ideas and plans.
  - You will get ideas how to adapt/update/improve this part as you work on the data analysis during the next weeks. Updated version as part of the final project assignment.

Assignment III

Data and method

- **Level of detail: Describe on a lower level than in a real scientific article.**
  - Examples:
    - If you use data from a telescope (SST, SDO, etc)., then please **outline** how the telescope (and instrument) works: Principle of the employed telescope and instrument (not every optical component).
    - If you use numerical data, then please describe the basic workings the numerical code(s): General numerical approach/method used (but not all details of its implementation).

- Please let us know if you are missing information regarding how the data was produced!
- **Typical details** provided:
  - Type of region observed/simulated, set into context with additional data (if applicable)
  - Size of the field-of-view or computational domain, duration of used time series, time & date … (if applicable)
  - Resolution (in relevant domains) and other fundamental parameters (especially for simulations)
- Please have a look at data/method section of scientific articles to check the extent and level of detail of the typical content and how it is typically structured and presented.

Assignment III

Data and method

- **Section structure:**
  - Typically divided into subsections dealing with different stages (e.g. observation, post-processing, analysis methods…)
- **Figure:**
  - At least 1 figure (and preferably not more than 3) that illustrate(s) the properties of the data (and method(s) if applicable).
- **References**
  - Known/standard methods can be addressed with the proper reference and a short summary (to extent useful for the reader to understand what you are doing)
  - Example: You would explain briefly how the equation of state is handled in the simulation code but not how the Fast Fourier Transform algorithm is implemented

Solar & stellar cycles
Recap

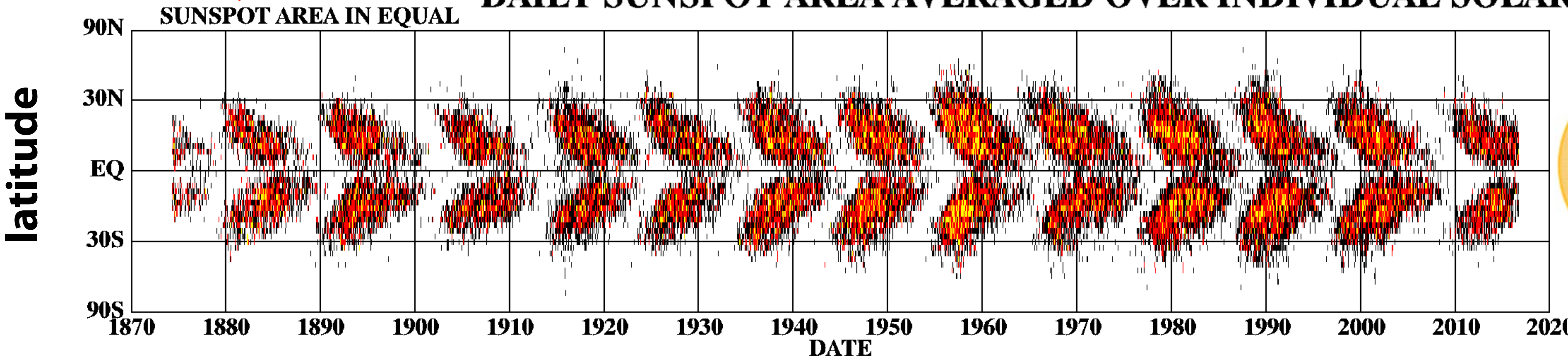
Dynamo — Solar cycle

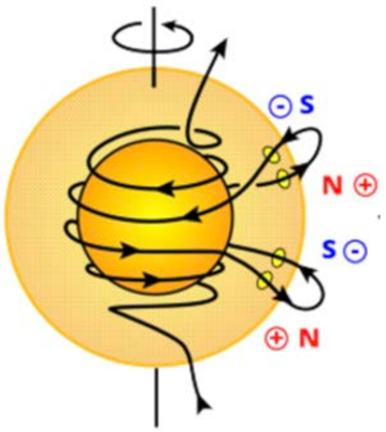
Solar magnetic patterns and diagrams

- **Solar cycle : 11-yrs activity** (Schwabe) ; 22-yrs magnetic (Hale) ; 100-yrs modulation (Gleissberg)

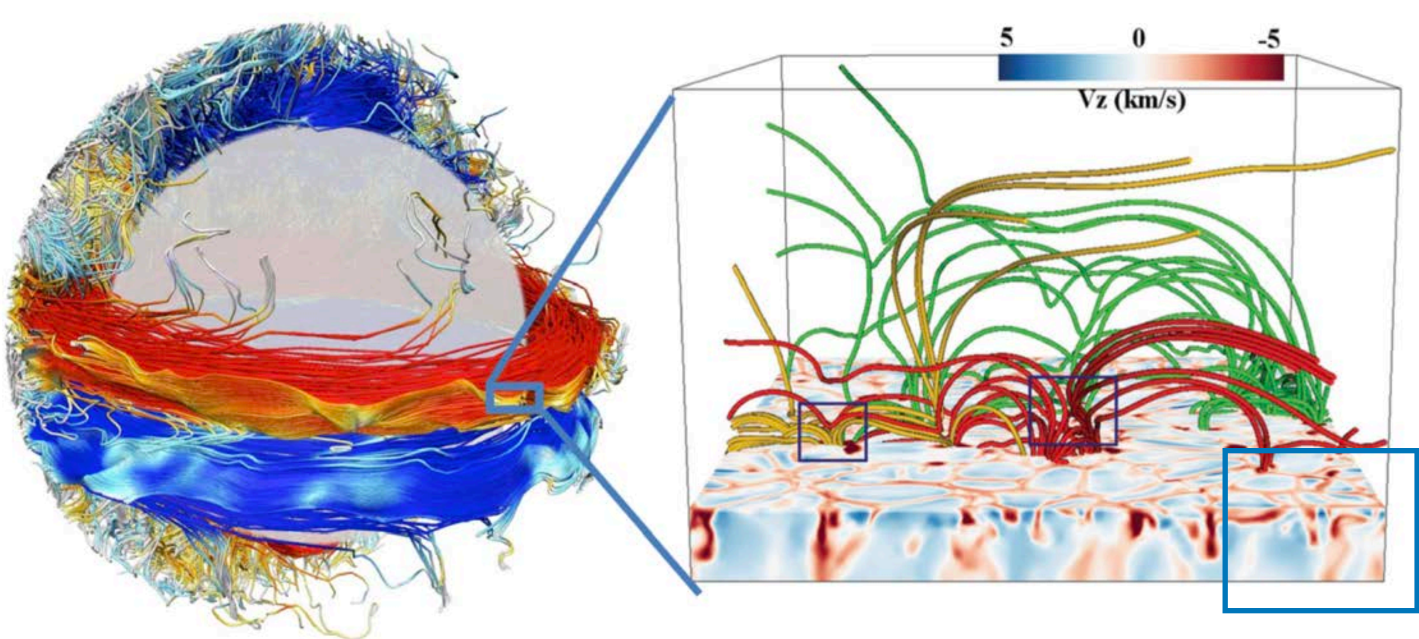
Butterfly diagram:

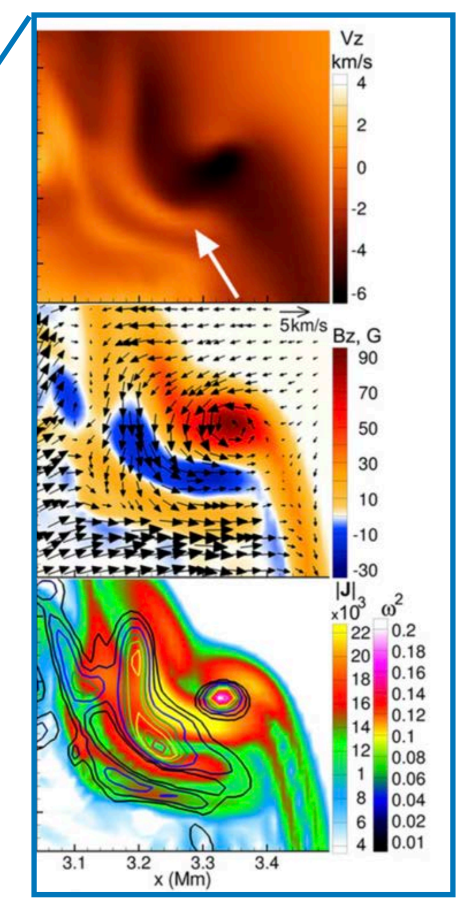
DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS





- **Observations** show: equatorward migration (Spörer's law) ; Tilt angle increases with lat. (Joy's law) ; inversion of polarity with respect to the equator (Hale's law)
- Current investigation with **numerical simulations** to understand and link dynamo process at large/small **scales** (temporal/spatial)

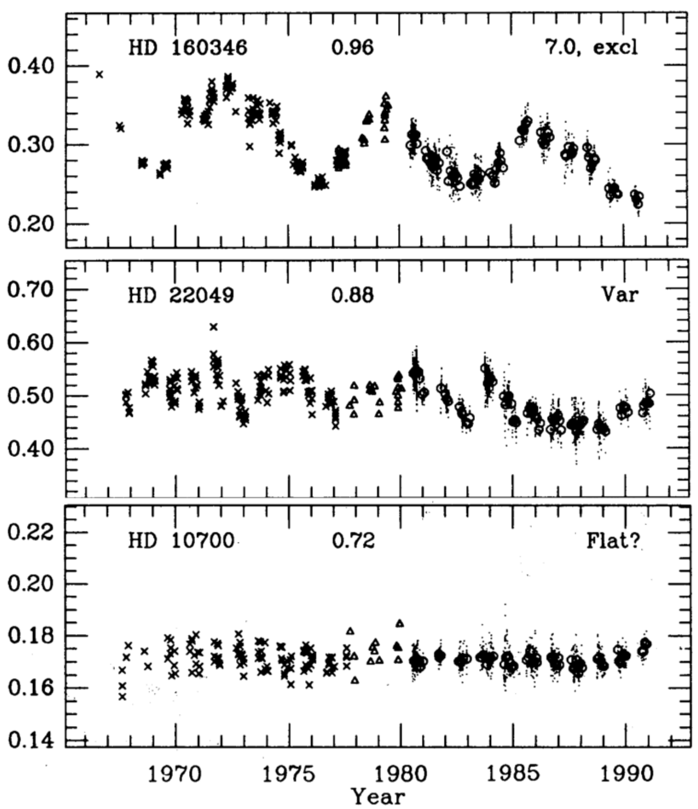




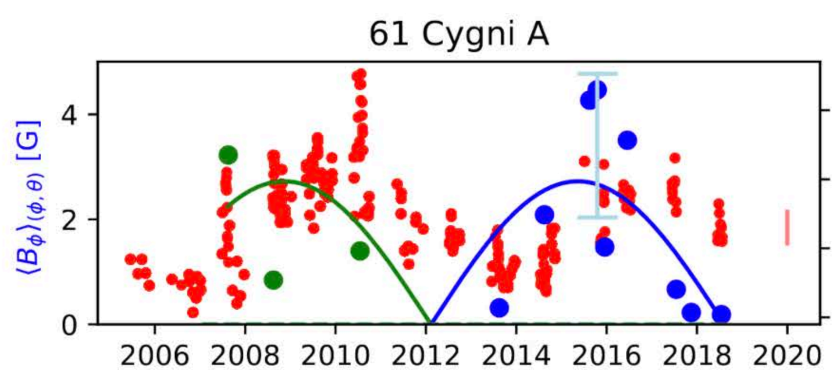
Stellar activity

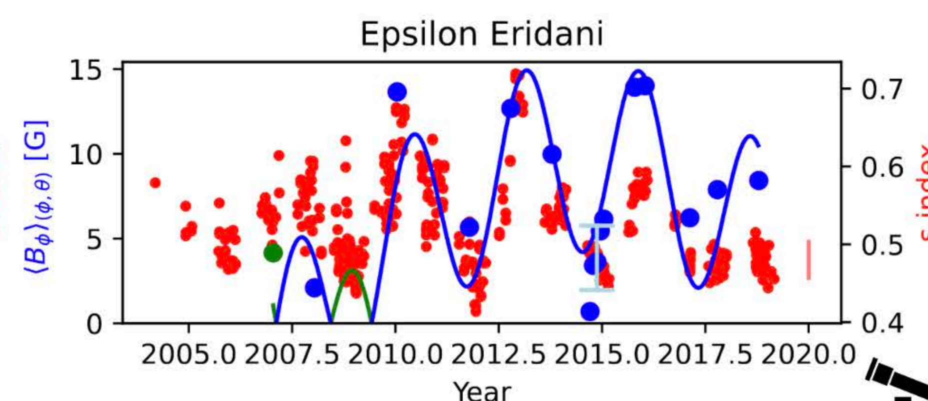
Do other stars have magnetic cycles?

- Activity = **variability resulting from magnetism** (spots, cycles, heating…)
- **Chromospheric variations** (CaII, Hα…) suited to probe magnetic activity : $R_{HK'}$, S-index



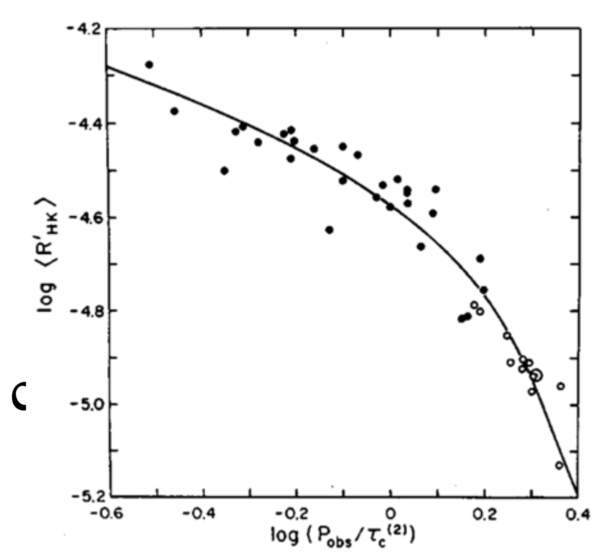
- Stellar cycles observations need a **long monitoring** in **several wavelength** to be characterised
- Some stars have cycles, some don't (**stationary dynamo**)
- Different nature of cycle activity : with or without reversals





- **Fast/young** rotators tend to be **more active** than old/slow rotators, with **shorter cycles**
- When considering different mass, **low-mass full convective stars** tend to be more active
- A **common behaviour** is found all over the masses when considering the **Rossby number (low Ro = active)**

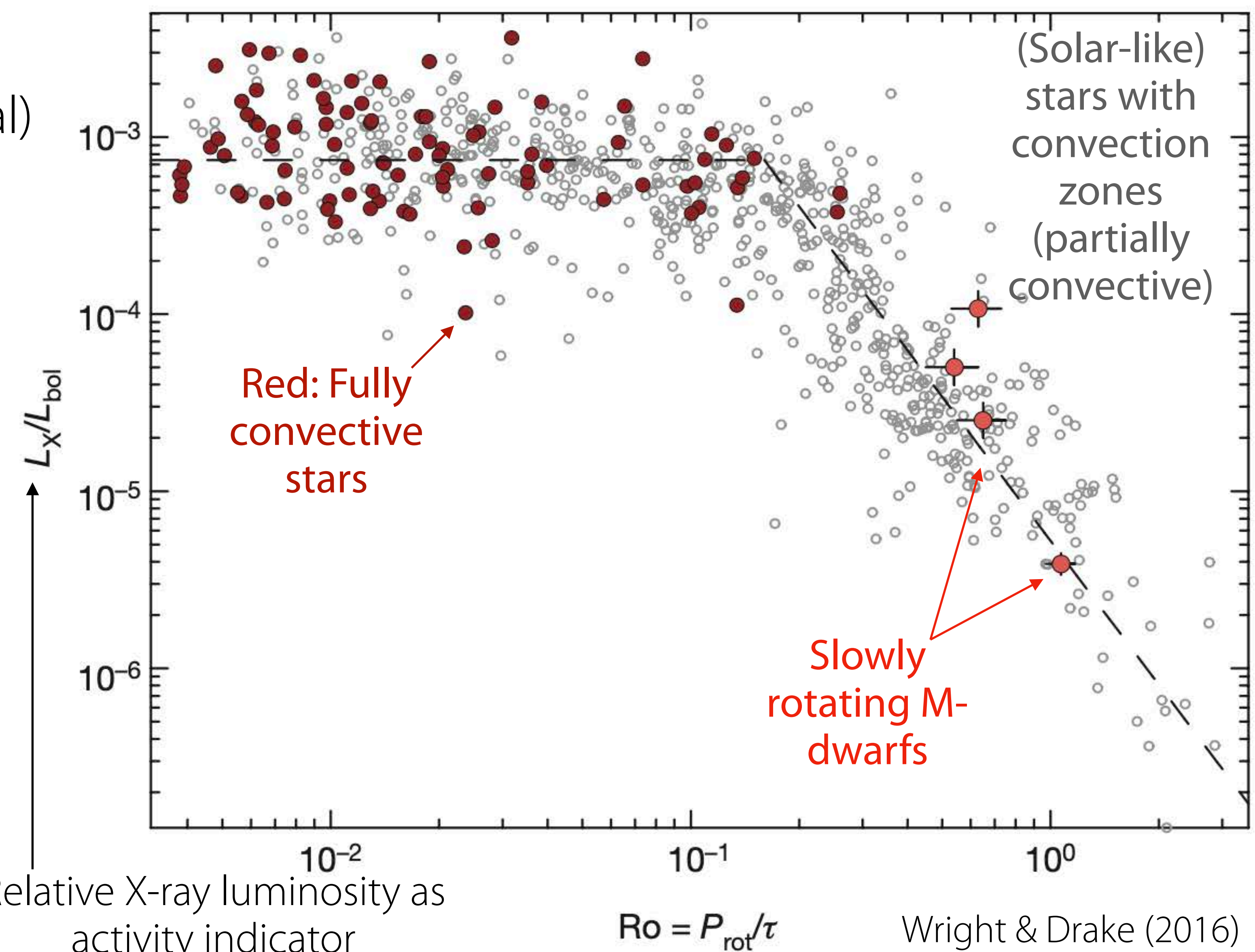
$$Ro = \frac{\text{Advection}}{\text{Coriolis}} = \frac{\text{Convection}}{\text{Rotation}}$$



Stellar dynamos and activity

Rotation-activity relation

- Despite lack of a tachocline: Fully convective M-dwarfs fit the same rotation–activity sequence as solar-type stars with outer convection zones!
  - Activity and magnetism of late-type stars increase with decreasing Rossby number, then saturate
- Most likely explanation (Wright & Drake 2016):
  - Both rotation and turbulence (convection) important for (global) dynamos in <u>all</u> late-type stars (Lehtinen et al 2020)
  - Fully and partially convective stars have rotation-dependent dynamos that share important properties
  - Tachocline not a vital ingredient.
    — **Differential rotation**
    + **Coriolis force is sufficient!**
  - **Still many open questions, active field of research!**



Relative X-ray luminosity as activity indicator

Wright & Drake (2016)

Convection and granulation continued

Convection

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

  $P(z) = P_0 \, e^{-(z\,/\,H_P)}$ $z = r$ (vertical/radial coordinate)

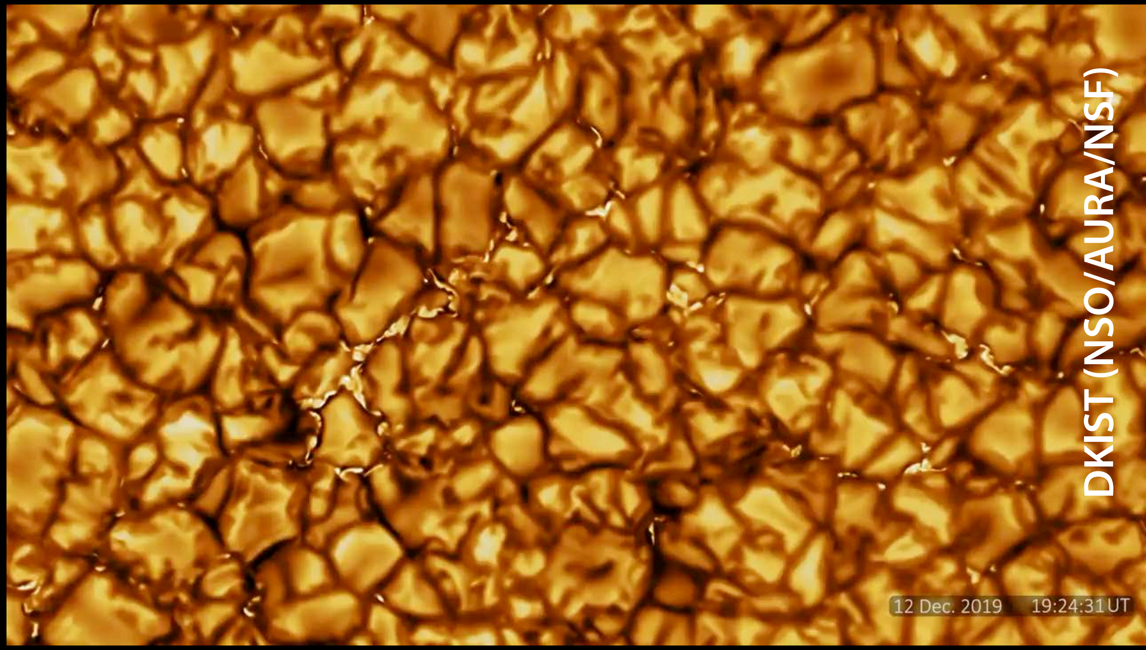
➡ Sets dominant spatial scale of convective motions (and convection cell sizes)

➡ Diverging upflows turn over within 1-2 scale heights, cover 2/3 of the area

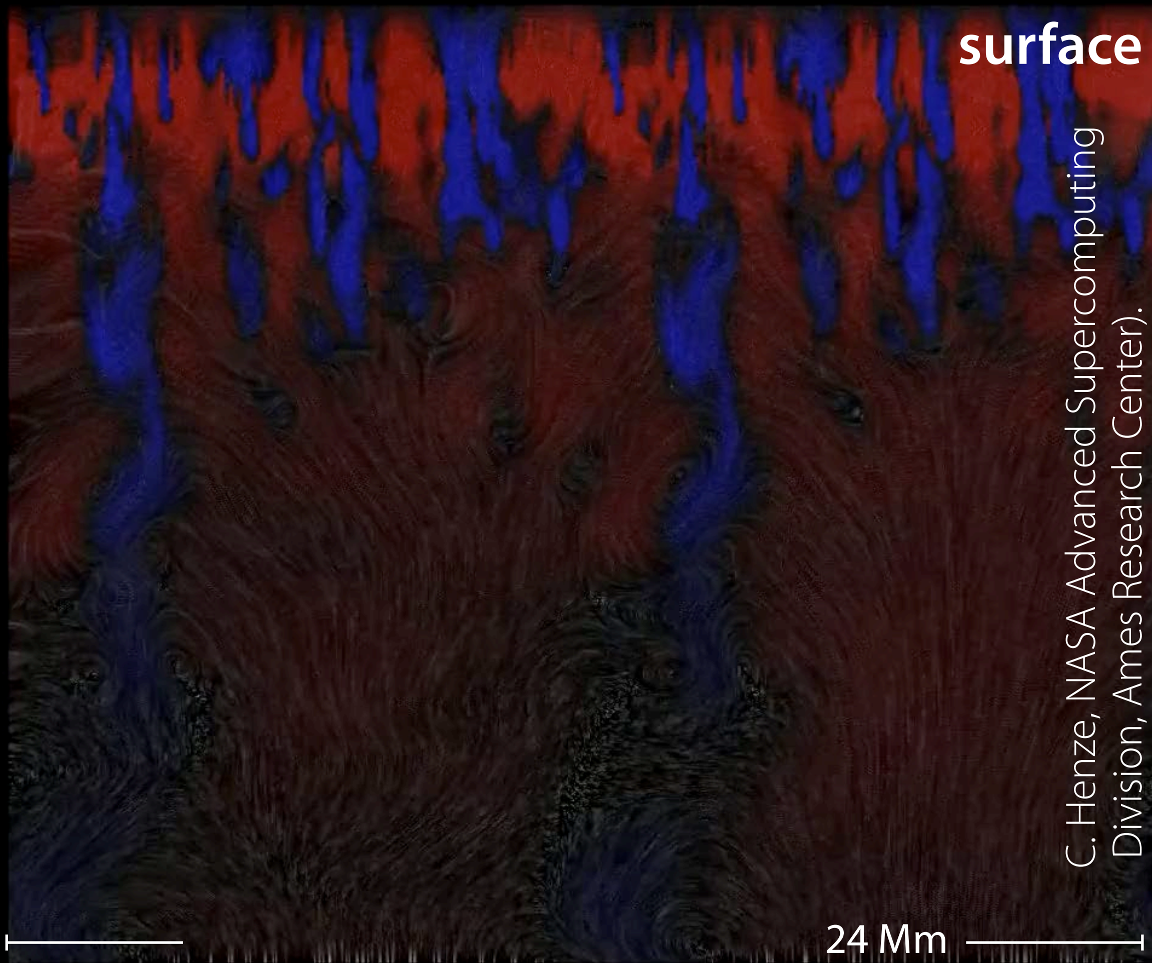
➡ Downflows get compressed, fast and turbulent, occupy 1/3 of the area

- **At surface:** isolated upflows form **granules**, surrounded by connected downflows (**intergranular lanes**)

surface — photosphere seen from top



Vertical cross-section from simulation



Convection

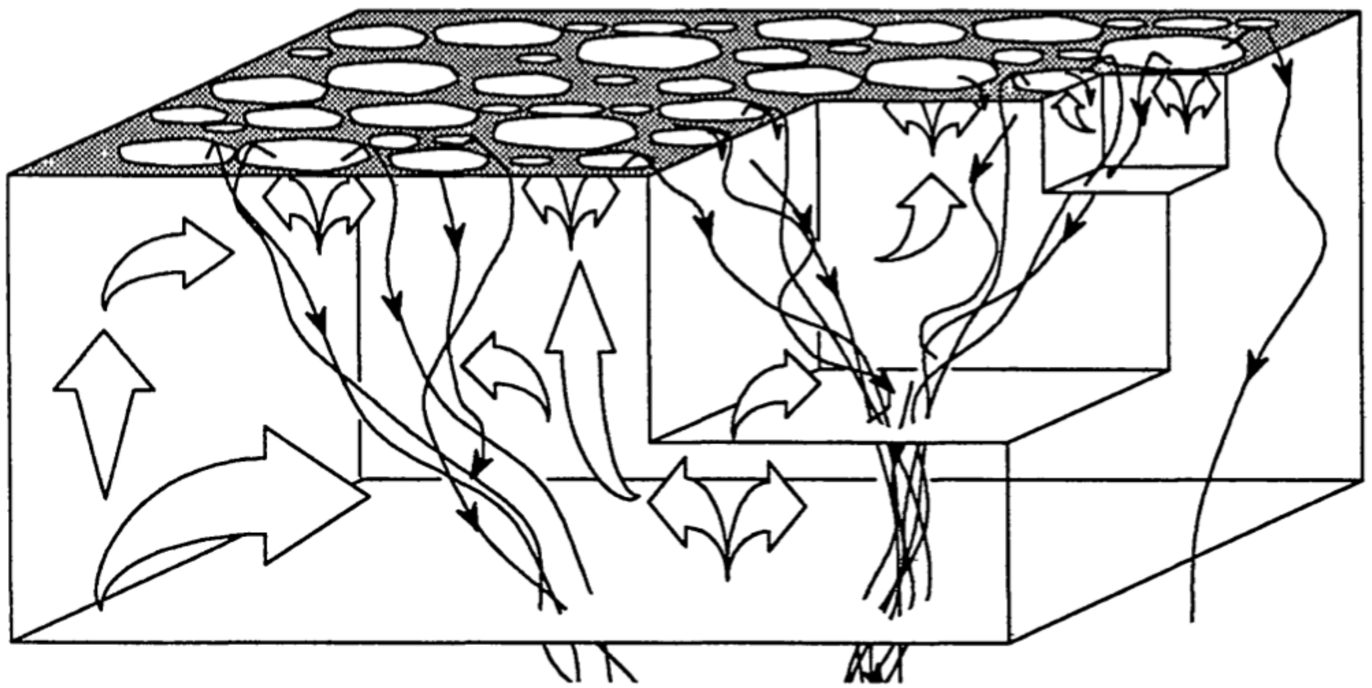
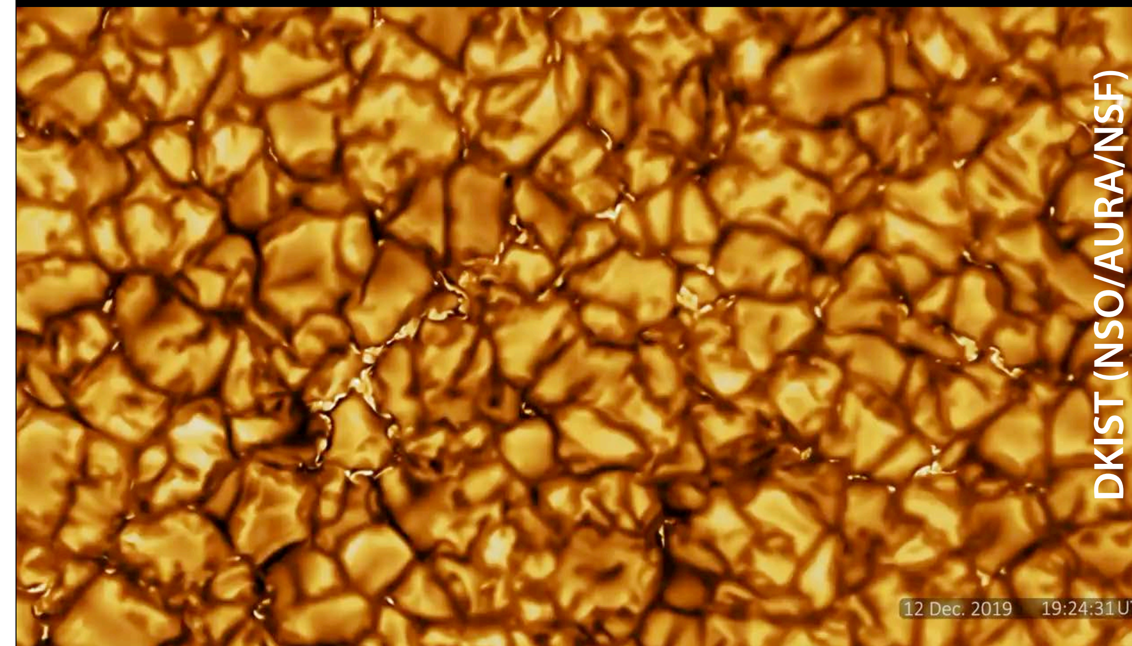


Figure 7 Flow lines showing the merging of the downdrafts on successively larger scales (schematic). The boxes cut out illustrate how the same process occurs on (in this illustration) three different scales.

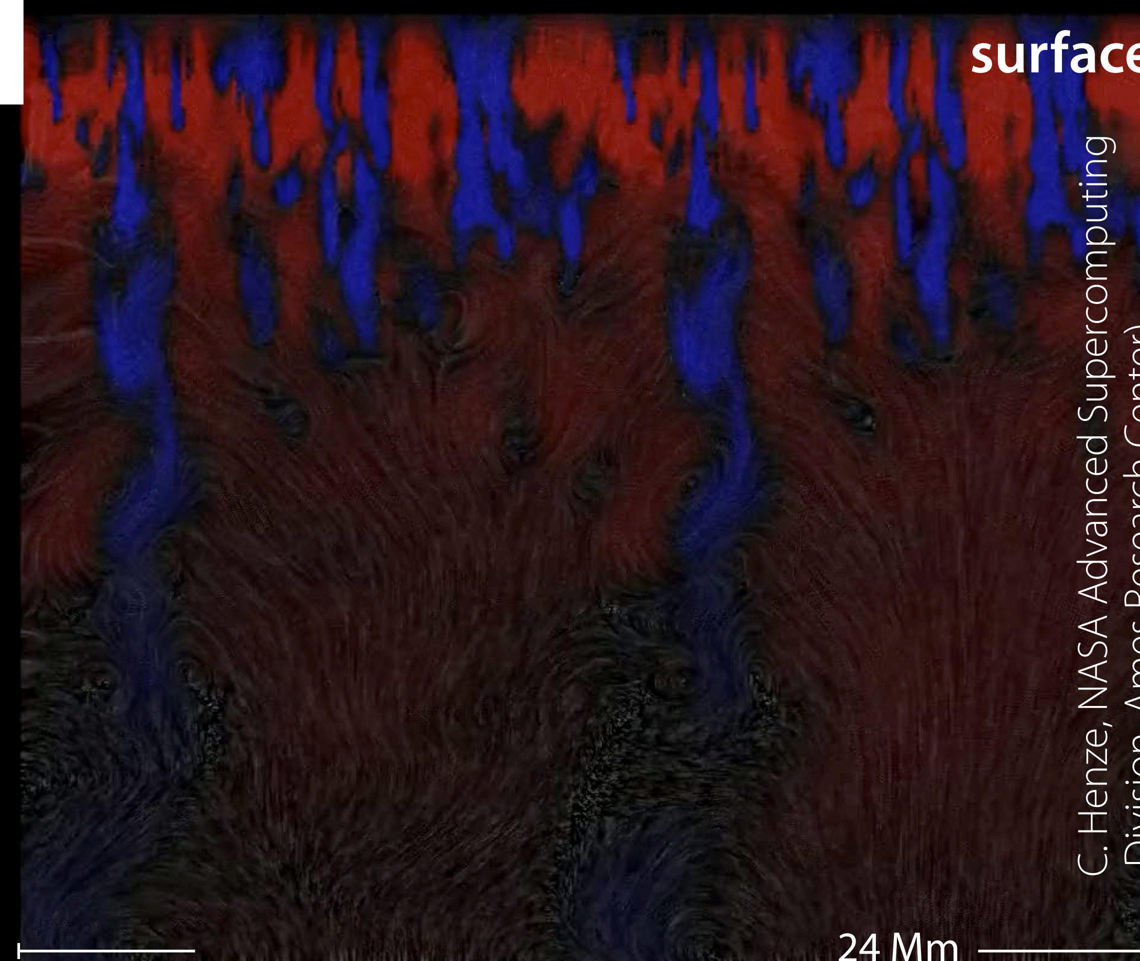
occupy 1/3 of the area

- **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



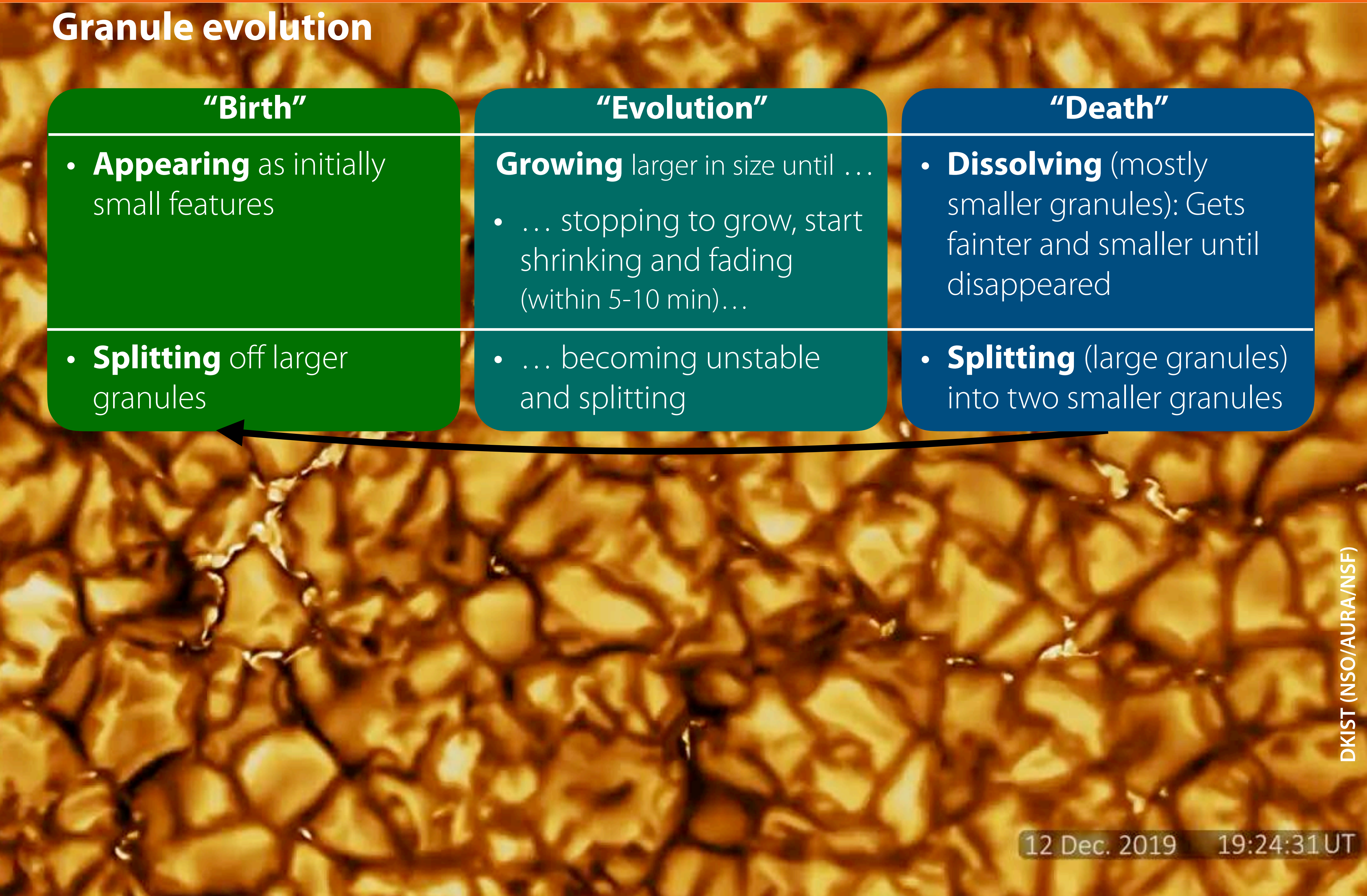
Vertical cross-section from simulation



Granulation

Granule evolution

"Birth"	"Evolution"	"Death"
• **Appearing** as initially small features	**Growing** larger in size until … • … stopping to grow, start shrinking and fading (within 5-10 min)…	• **Dissolving** (mostly smaller granules): Gets fainter and smaller until disappeared
• **Splitting** off larger granules	• … becoming unstable and splitting	• **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:

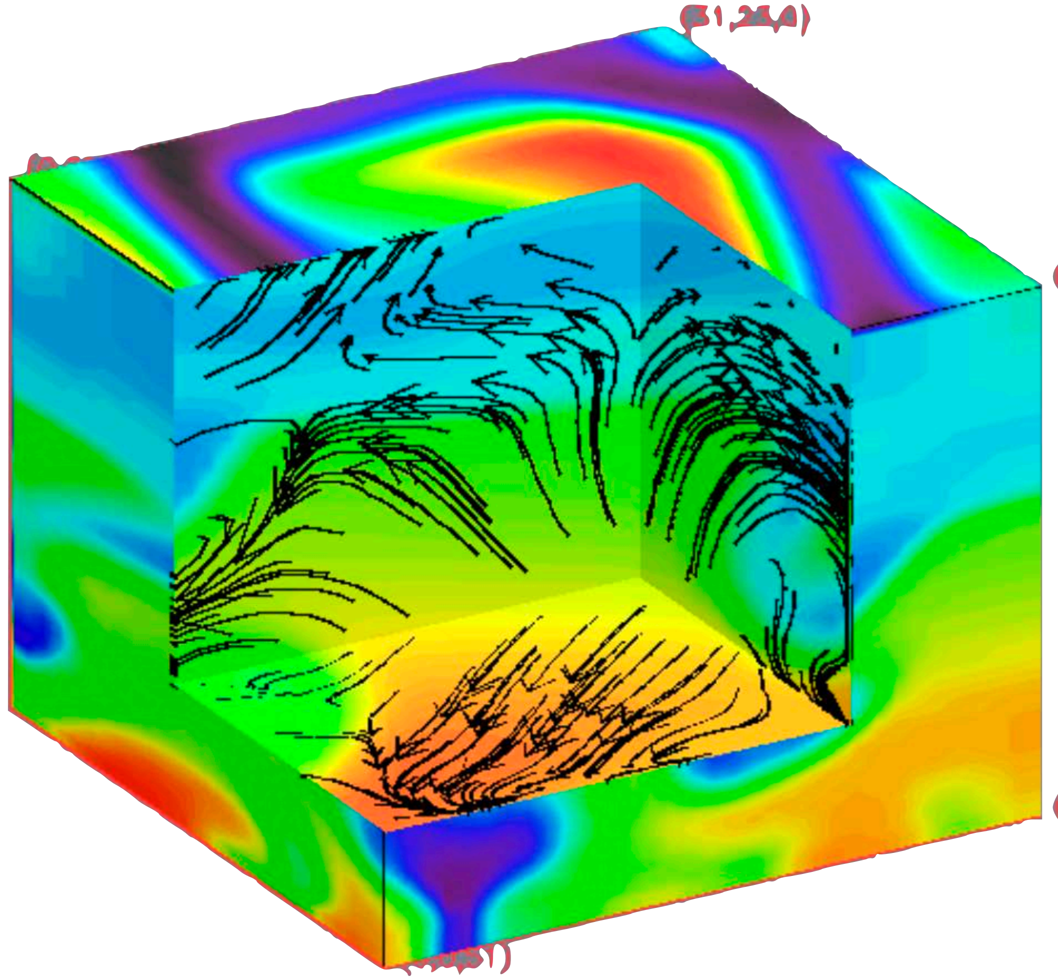
➡ Larger granules build up a larger pressure above its centre as more mass needs to be accelerated horizontally.

➡ 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"

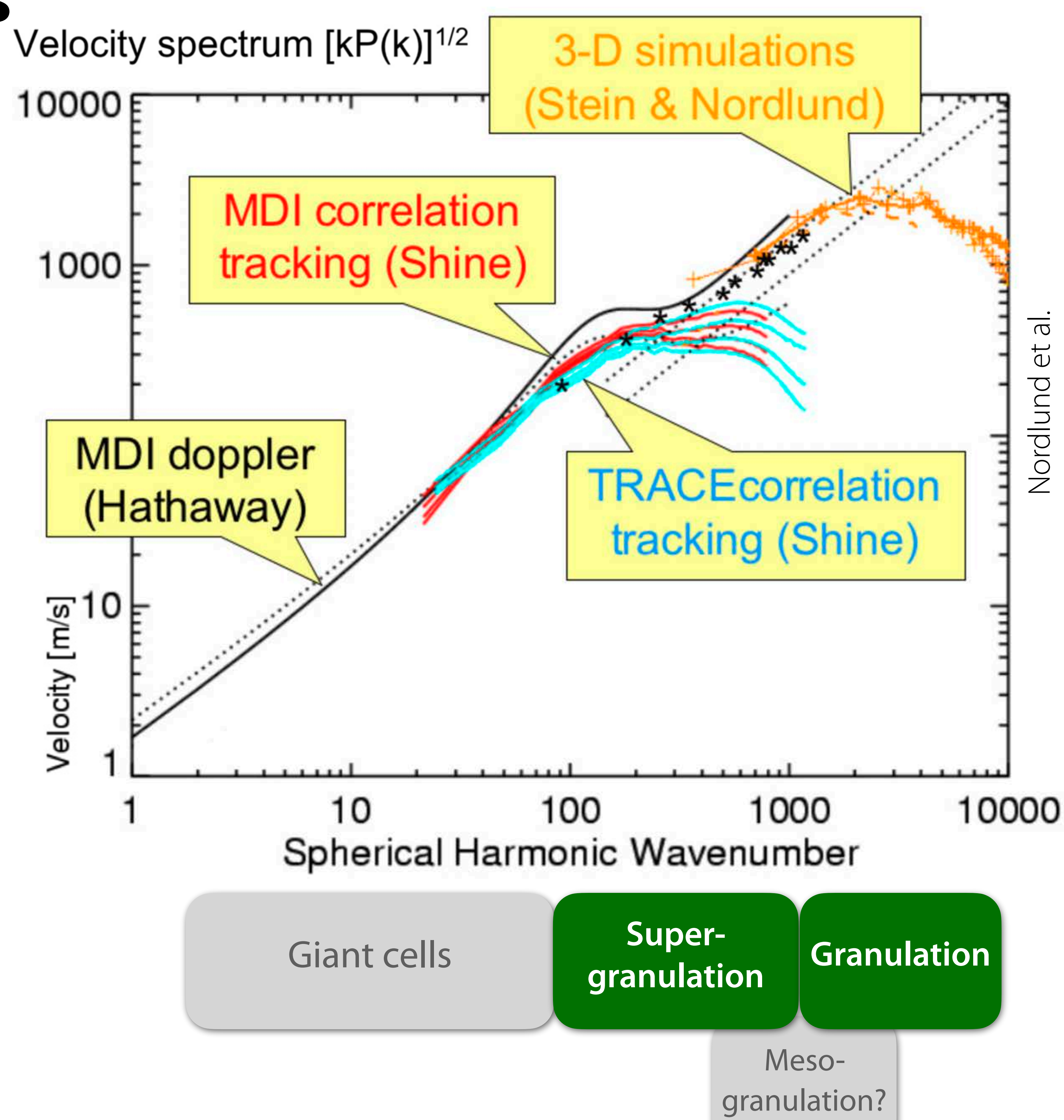


Close-up region from a 3D simulation showing gas temperature and streamlines inside and above a granule (Stein & Nordlund 1998)

Surface convection

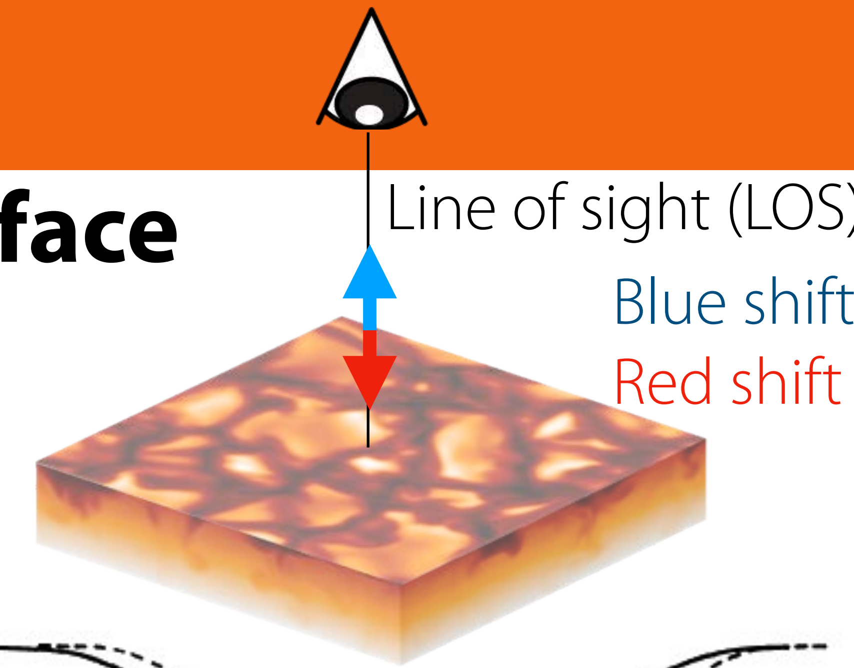
Recap — Spatial scales

- Spatial power spectra reveal particular spatial scales imprinted by the Sun's convection on the surface
- **Granulation** (1-2Mm, 8-10min)
- **Supergranulation** (typically 30-40Mm, ~40h)
- Indications for giant cells (>100 Mm)
- Existence of mesogranulation (between granulation and super granulation) uncertain, debated

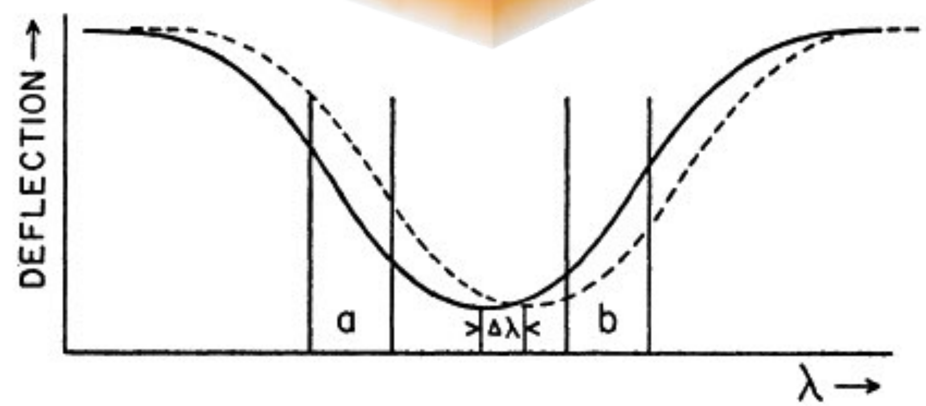


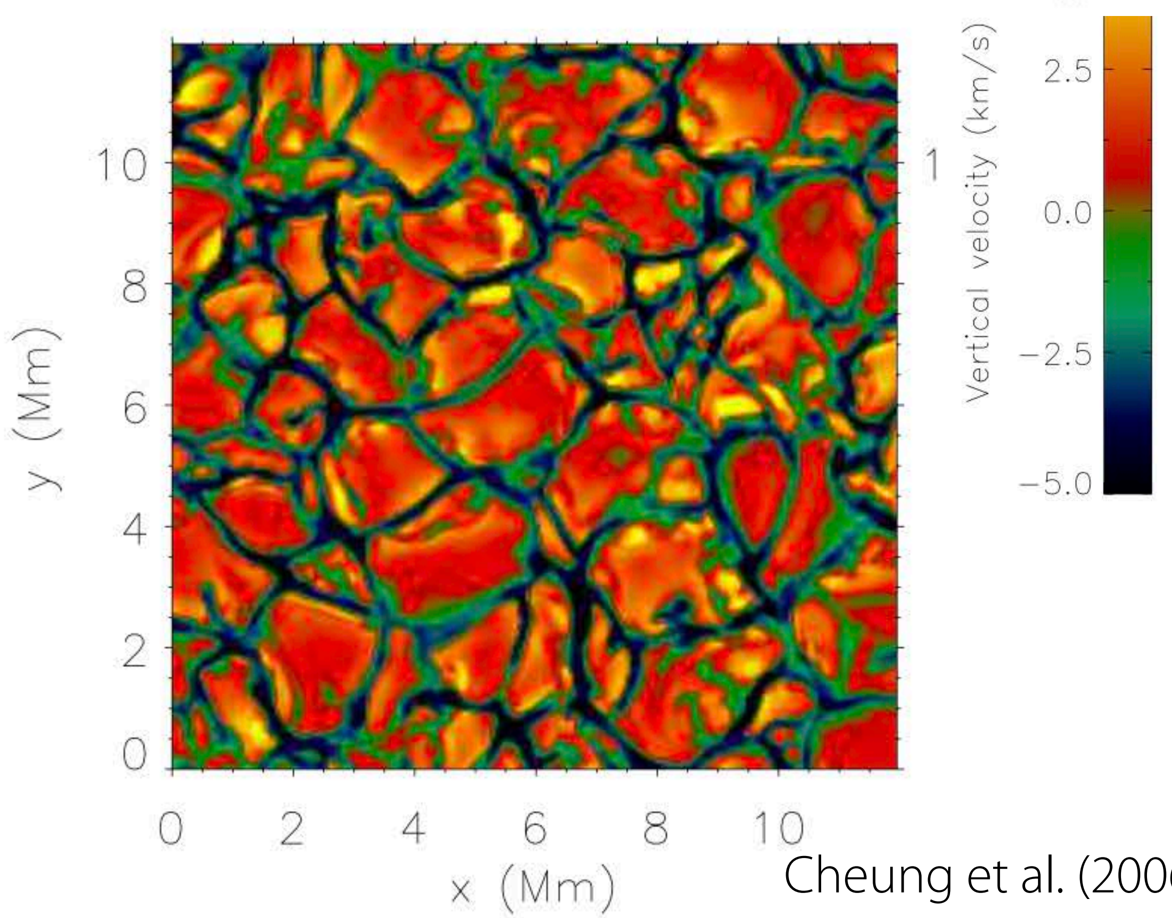
Convection

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





Cheung et al. (2006)

Convection

Observational indicators of convection on other stars

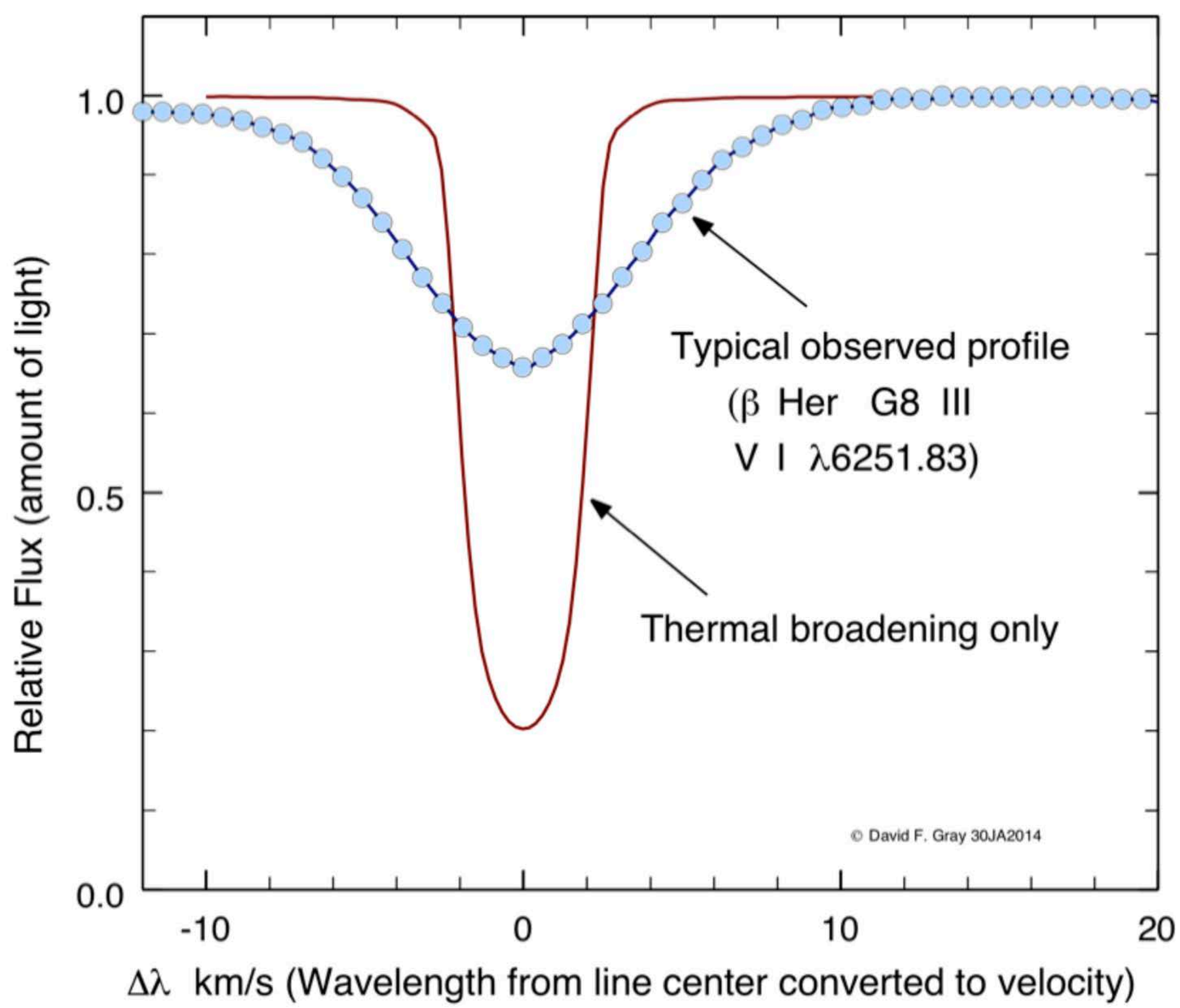
1. Spectral line broadening (macroturbulence)

- 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)

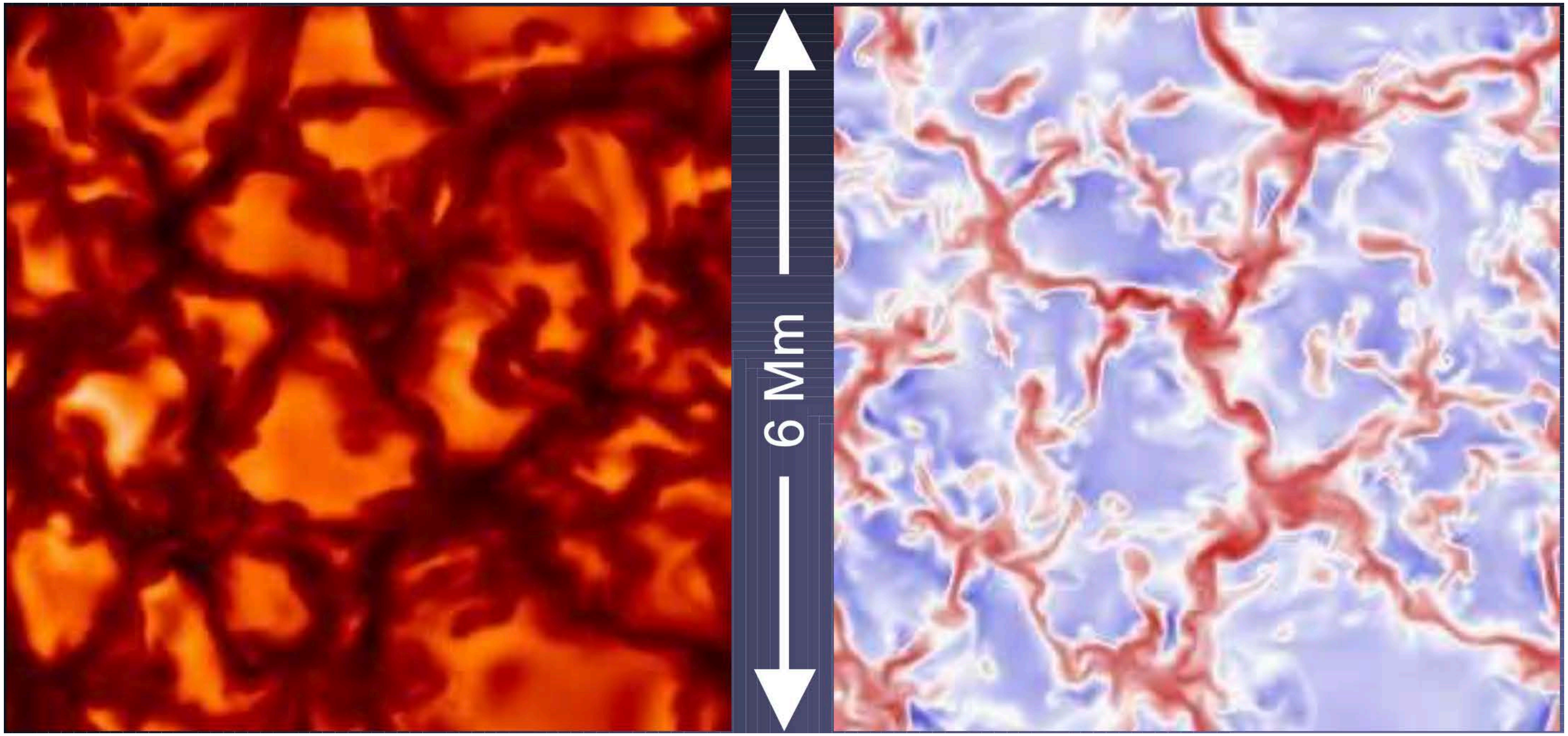


Convection

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

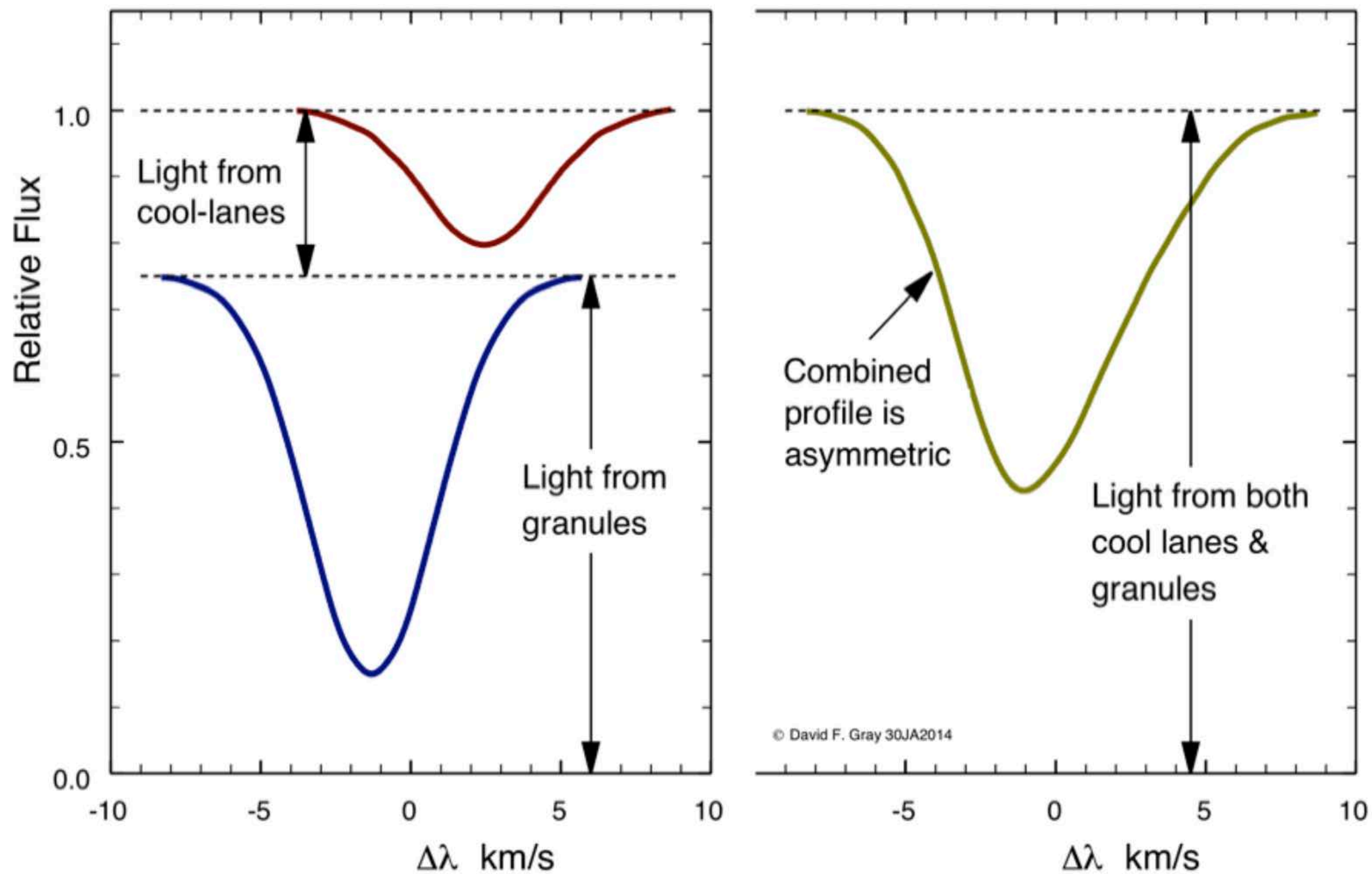
3D simulation (MuRAM)

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**



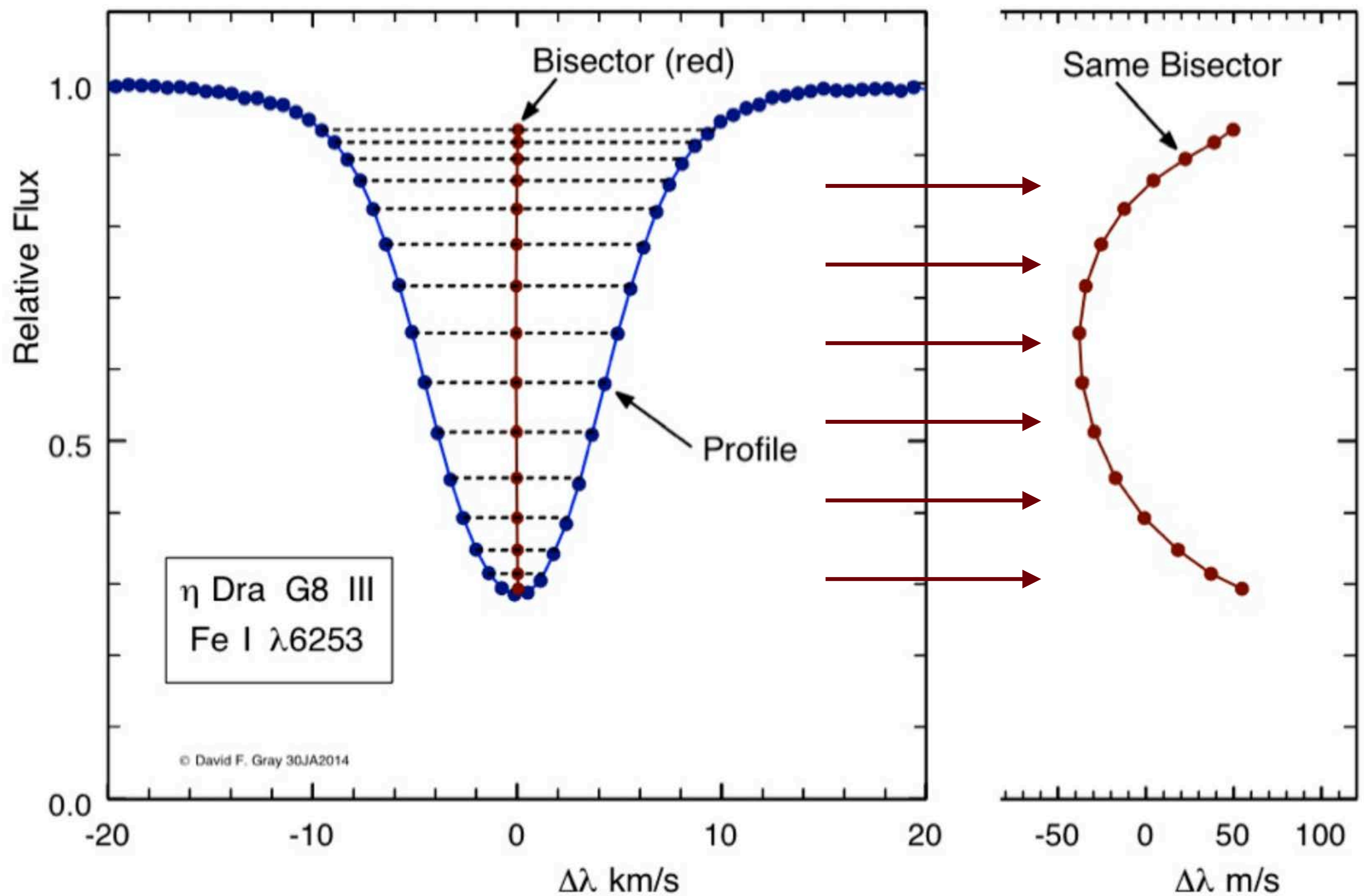
Convection

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

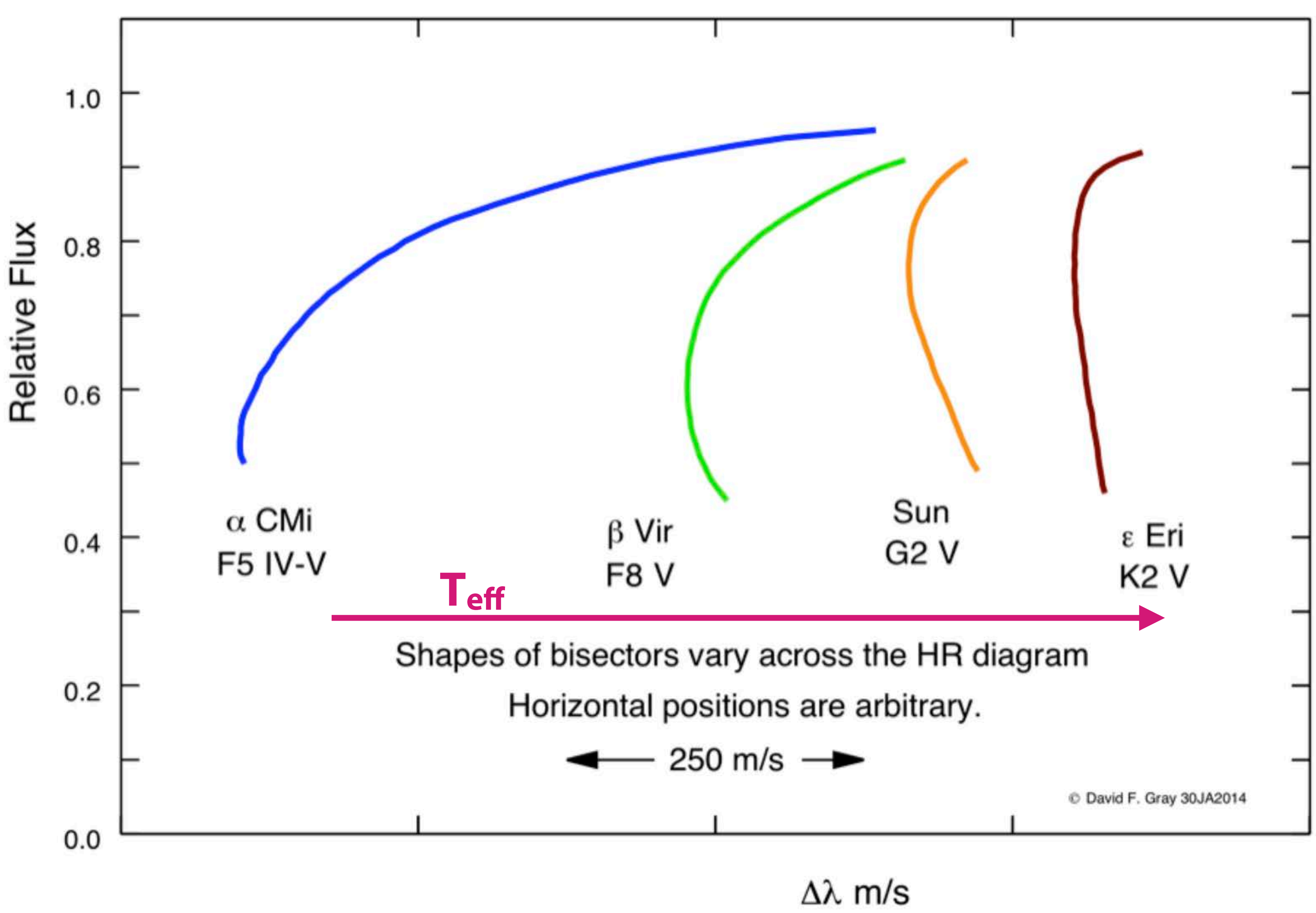


Convection

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

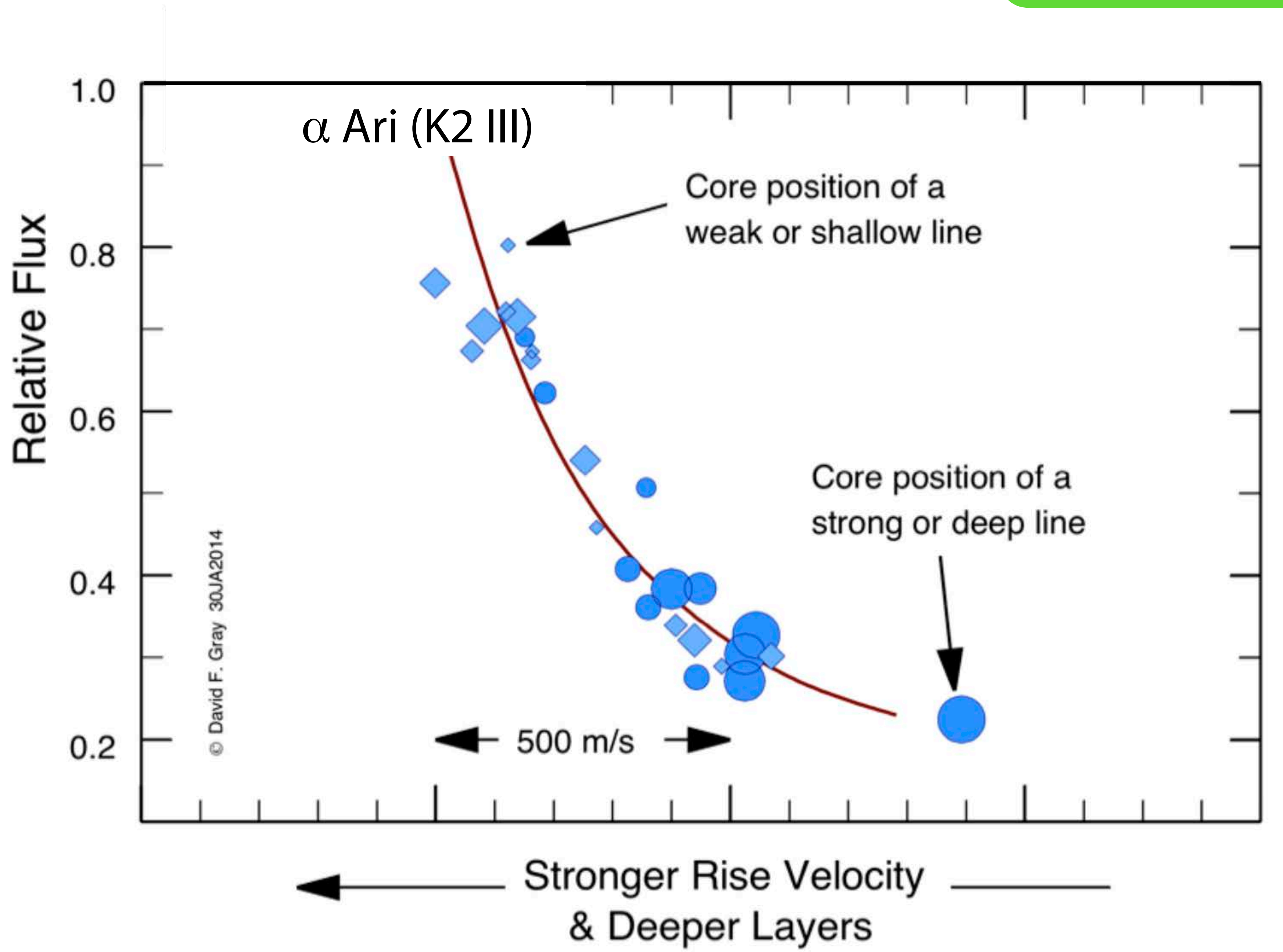
Observational indicators of convection on other stars

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

Consider opacity along line of sight

- Means of probing different layers and thus the vertical velocity profile across the low photosphere and the convective overshoot region



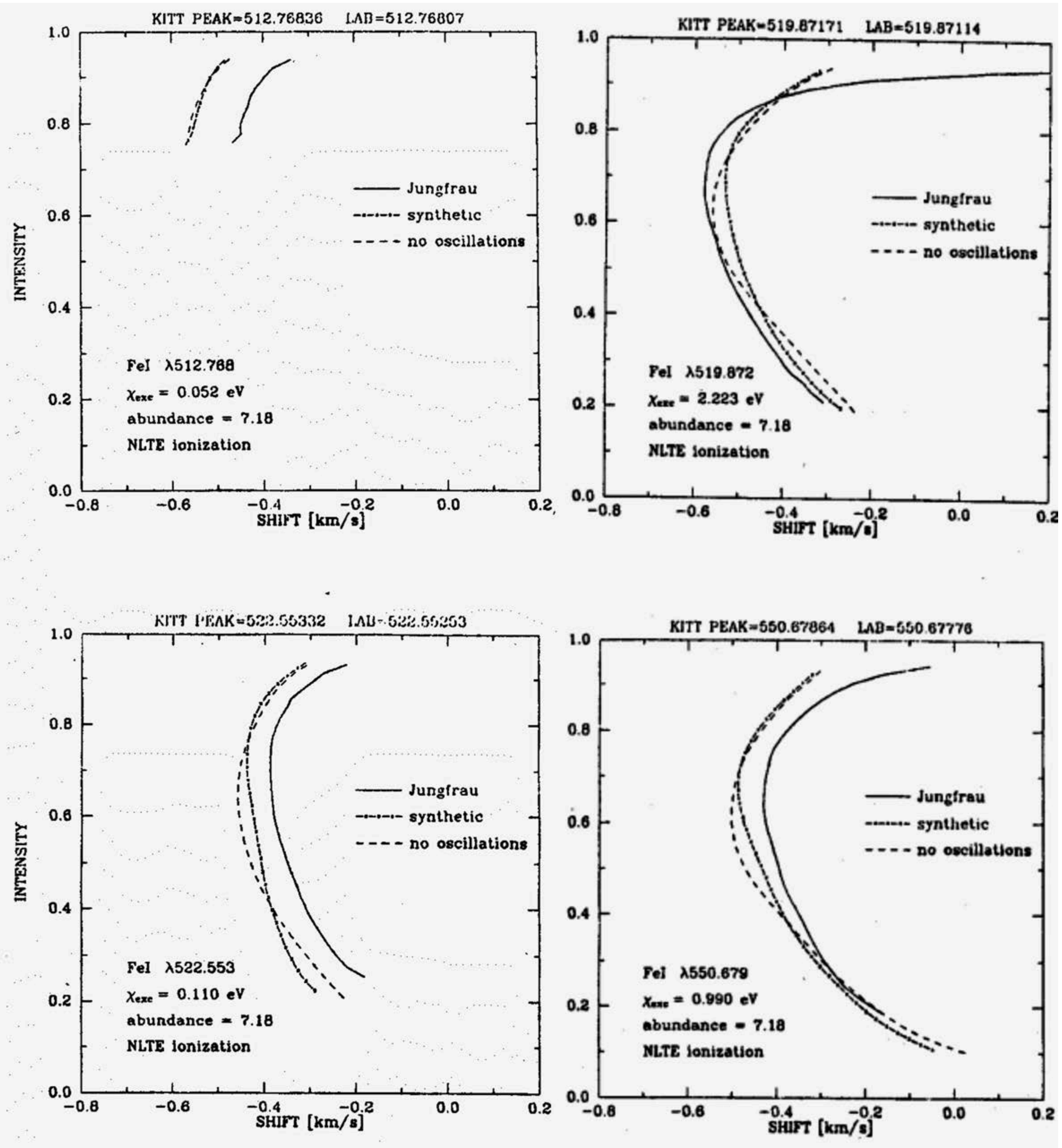
Observations of a combination of weak and strong photospheric lines and analysis of broadening and bisectors provide important constraints for the **properties of the granulation on a star**

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

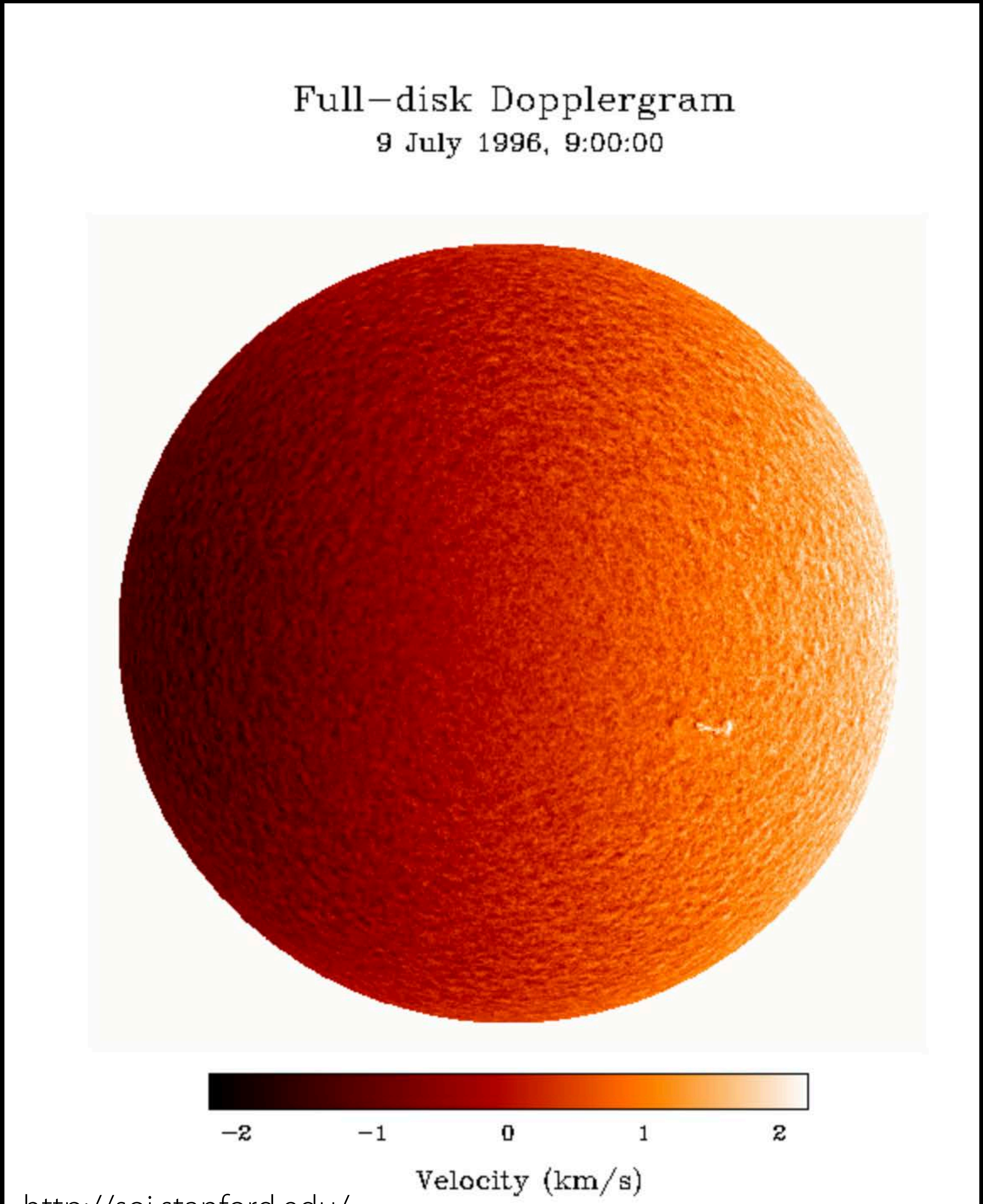
➡ Comparison with models help to interpret the bisectors and thus derive the properties of the granulation



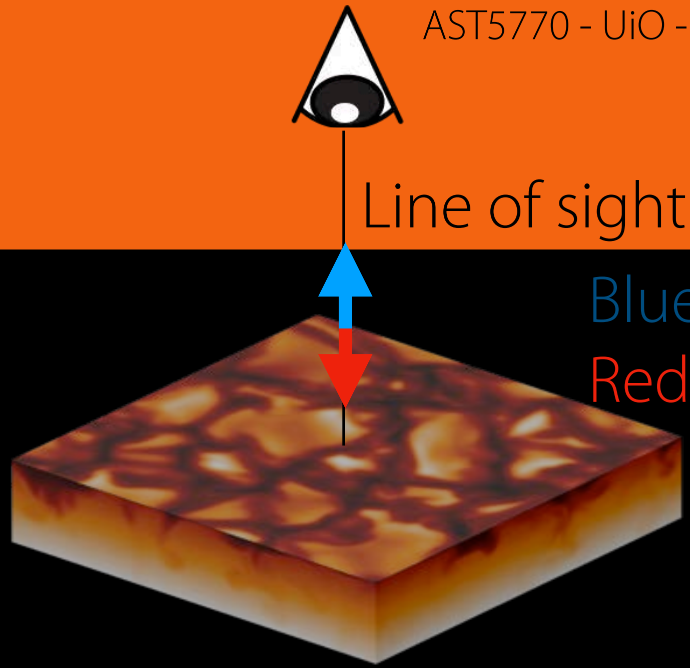
Helioseismology

Helioseismology

Oscillations



http://soi.stanford.edu/

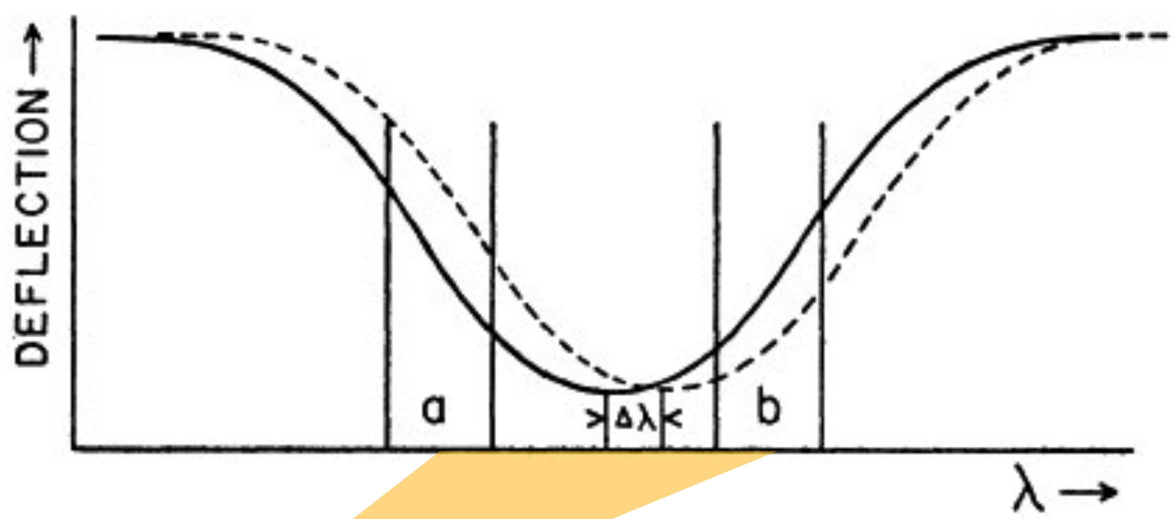


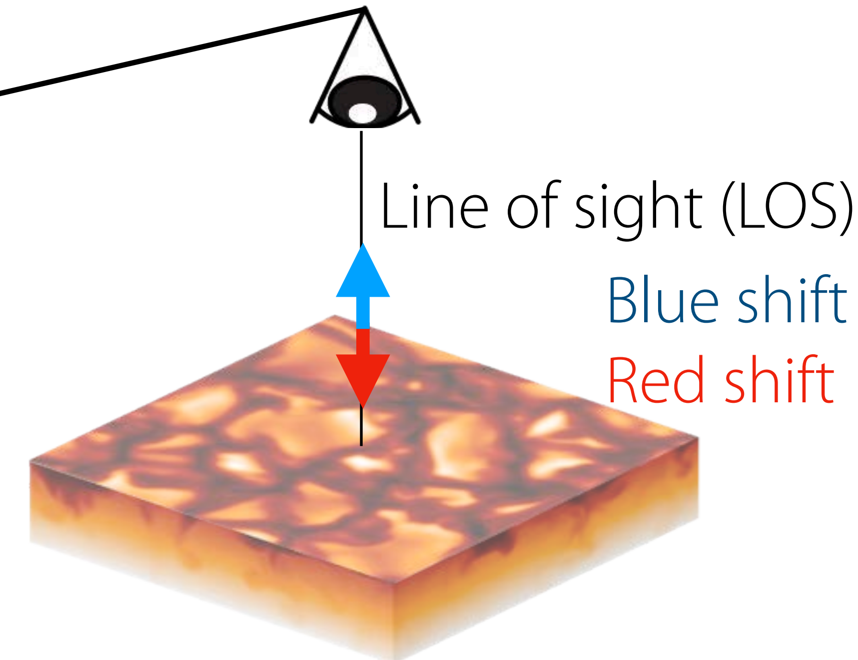
- **Oscillations at surface observed as Doppler shifts of photospheric lines**

- **What do you see in this Dopplergram?**

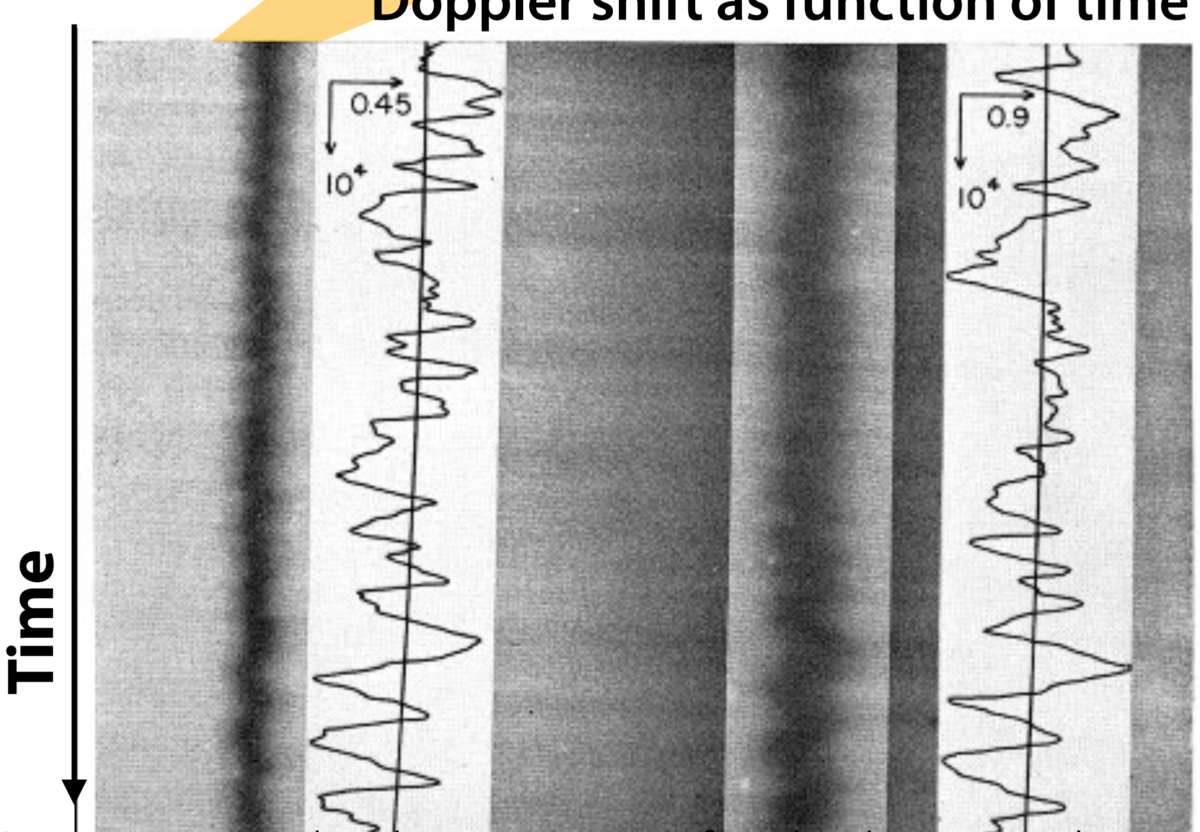
Helioseismology

Photospheric oscillations





Doppler shift as function of time



- Doppler shifts of spectral lines formed in the photosphere found to **oscillate** back and forth with **periods ~5 min**, seen allover the Sun
- Discovered in 1960 (Leighton et al. 1962)
- Also seen in the intensity itself with relative amplitudes of a few percent

Spectrum and velocity curves for the lines Mg b2 and Ti I λ = 517.37 nm, obtained at Sacramento Peak Observatory. The arrows indicate the velocity in km/s and the distance on the Sun in km. (Evans and Michard 1962)

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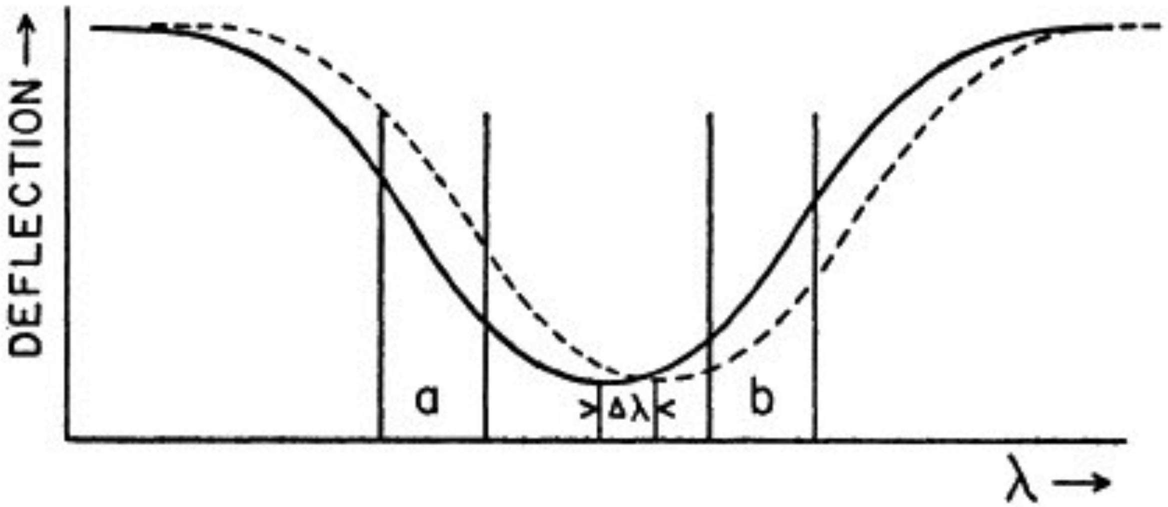
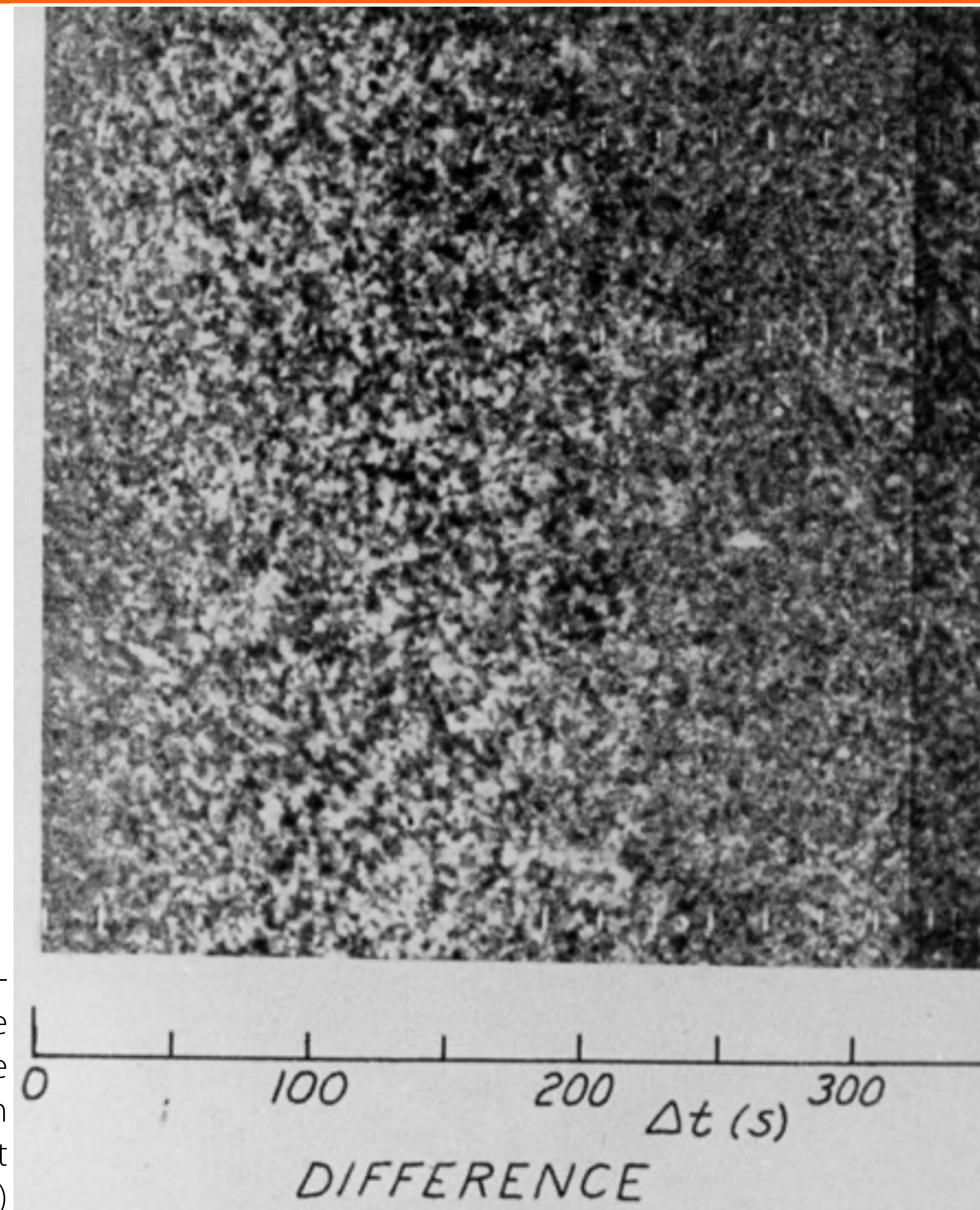
Photospheric oscillations



- **Doppler-difference plate:** Two spectroheliograms recorded simultaneously in the red and blue wings of a spectral line, then photographically subtracted
- Plates were scanned (over some minutes) resulting in varying time difference between the two plates…



Doppler-difference plate for Ba II line $\lambda = 455.4$ nm (Leighton et al.1962)

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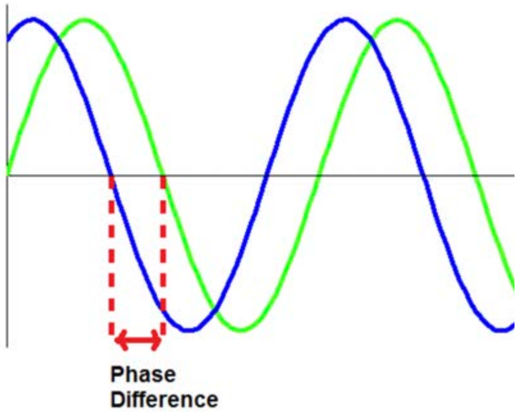
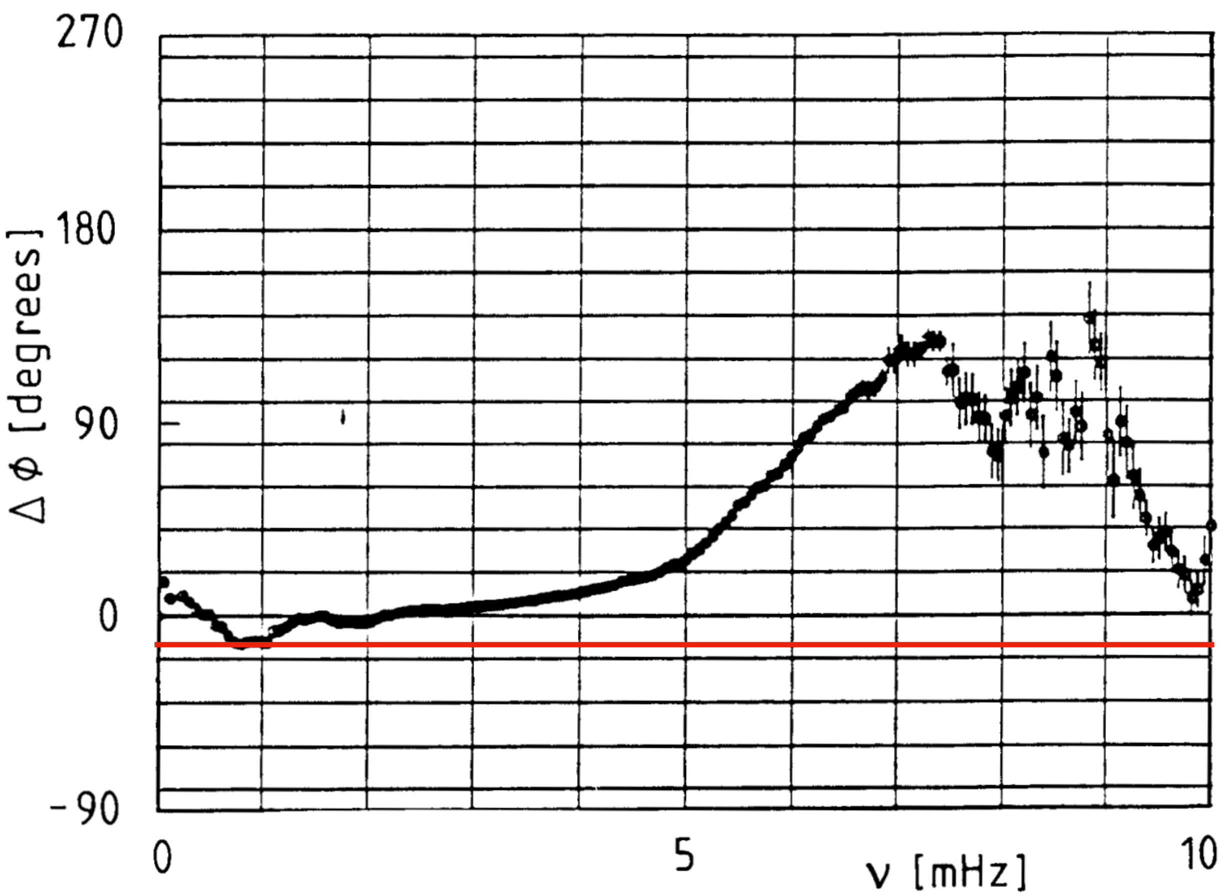
Photospheric oscillations

- Oscillations in vertical velocity
- Oscillations in photospheric lines exhibit typical velocity amplitude ~0.5 — 1 km/s, highest amplitude at a period just below ~**5min**
- Spectral lines formed here in photosphere: amplitude decreases with height
  - Max. amplitude shifts towards shorter periods higher up in the atmosphere, in the chromosphere (observed, e.g., in Hα): typically **3-min** oscillations

- **Phase difference:** Compare velocity oscillation at same location at different heights in the atmosphere (observing two different spectral lines at the same time)
- Only a small phase lag in the frequency range 2–5mHz, i.e., periods 3 — 8 min

➡ Implies a **standing wave**.





Staiger (1987)

Helioseismology

The sound of the Sun

NASA's Goddard Space Flight Center

Helioseismology

Fourier analysis — recap

- Origin of oscillations identified as acoustic waves, called **p-modes**
- Spatio-temporal properties of oscillations best revealed by **Fourier transforms**.

- Input signal (e.g. velocity) of duration t' and time resolution Δt:
  - Frequency resolution $\Delta\omega = 2\pi/t'$
  - Lowest frequency $= \Delta\omega$ (set by signal length t')
  - Highest frequency = Nyquist frequency $\omega_{\mathrm{Ny}} = \pi/\Delta t$
- To resolve two neighboring frequencies ω and $\omega + \Delta\omega$: Observation over a time span $t' = 2\pi/\Delta\omega$ needed (for the two oscillations to acquire a phase difference of exactly 2π)
- Equivalently: Variation (signal) across a distance x' with spatial resolution Δx

$$\omega = 2\pi\nu$$

$$\nu = \omega/2\pi$$

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Fourier analysis — recap

- The temporal and spatial scales that can be accessed from an observation are limited as

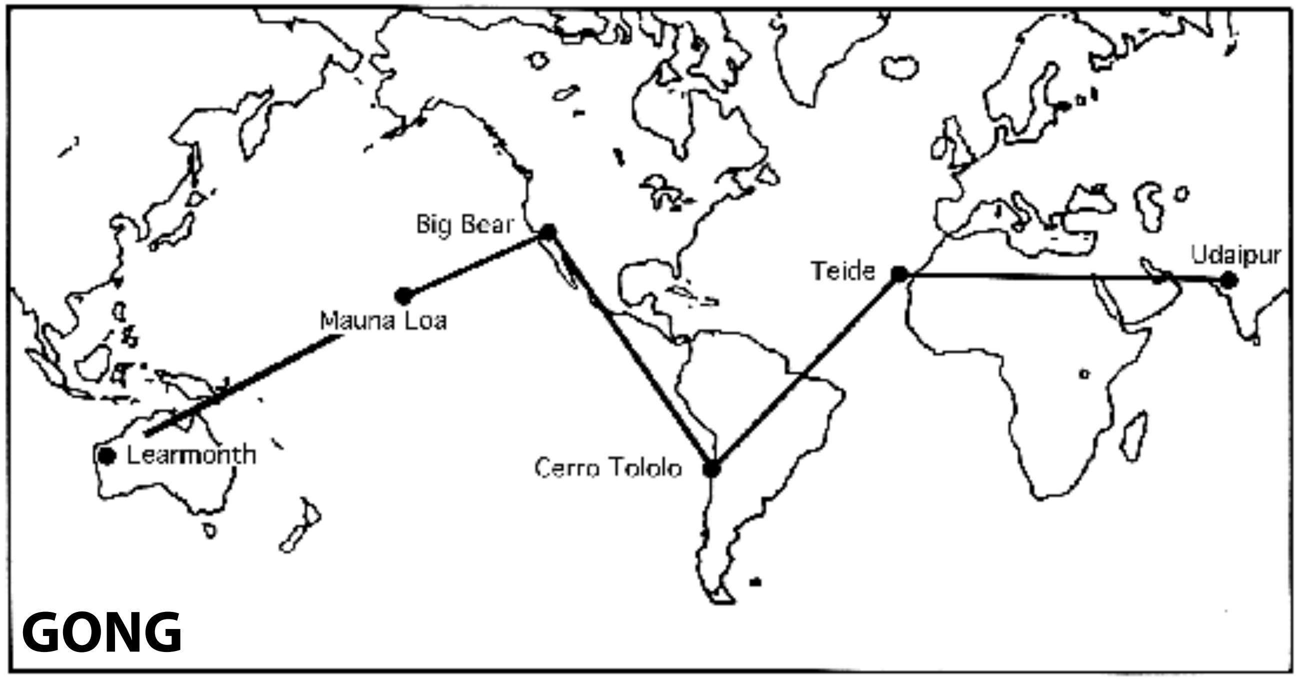
$$\Delta\omega = 2\,\pi / t' \leq \omega < \pi / \Delta t$$

$$\Delta k_x = 2\pi / x' \leq k_x < \pi / \Delta x$$

- Depends on seeing + instrumental limitations
(e.g. field-of-view, angular resolution/detector pixel size etc.)
- Duration of time series « duration of day from ground

➡ Long observations from space (or South Pole)

➡ GONG global oscillation network group (since late 1980ties) combing dedicated telescopes around the globe



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Fourier analysis — recap

- Input signal = vertical velocity signal as a function of time t and position (x, y): $v\ (x,y,t)$
- **Fourier transform** f defined as

$$v(x,y,t) = \int f(k_x, k_y, \omega) \exp[\mathrm{i}(k_x x + k_y y + \omega t)]\, dk_x dk_y d\omega$$

In practice done with sums (and Fast Fourier transform)

- **Power spectrum:** $P(k_x, k_y, \omega) = f f^*$

- Note: The spatial dimensions can be collapsed into single horizontal dimension (no preferred direction here)

$$k_\mathrm{h} = (k_x^2 + k_y^2)^{1/2}$$

➡ **Power spectrum** $P(k_\mathrm{h}, \omega) = \frac{1}{2\pi} \int_0^{2\pi} P(k_\mathrm{h} \cos\phi, k_\mathrm{h} \sin\phi, \omega)\, d\phi$

Helioseismology

k-ω diagram

- Observation *v (x,y,t)*

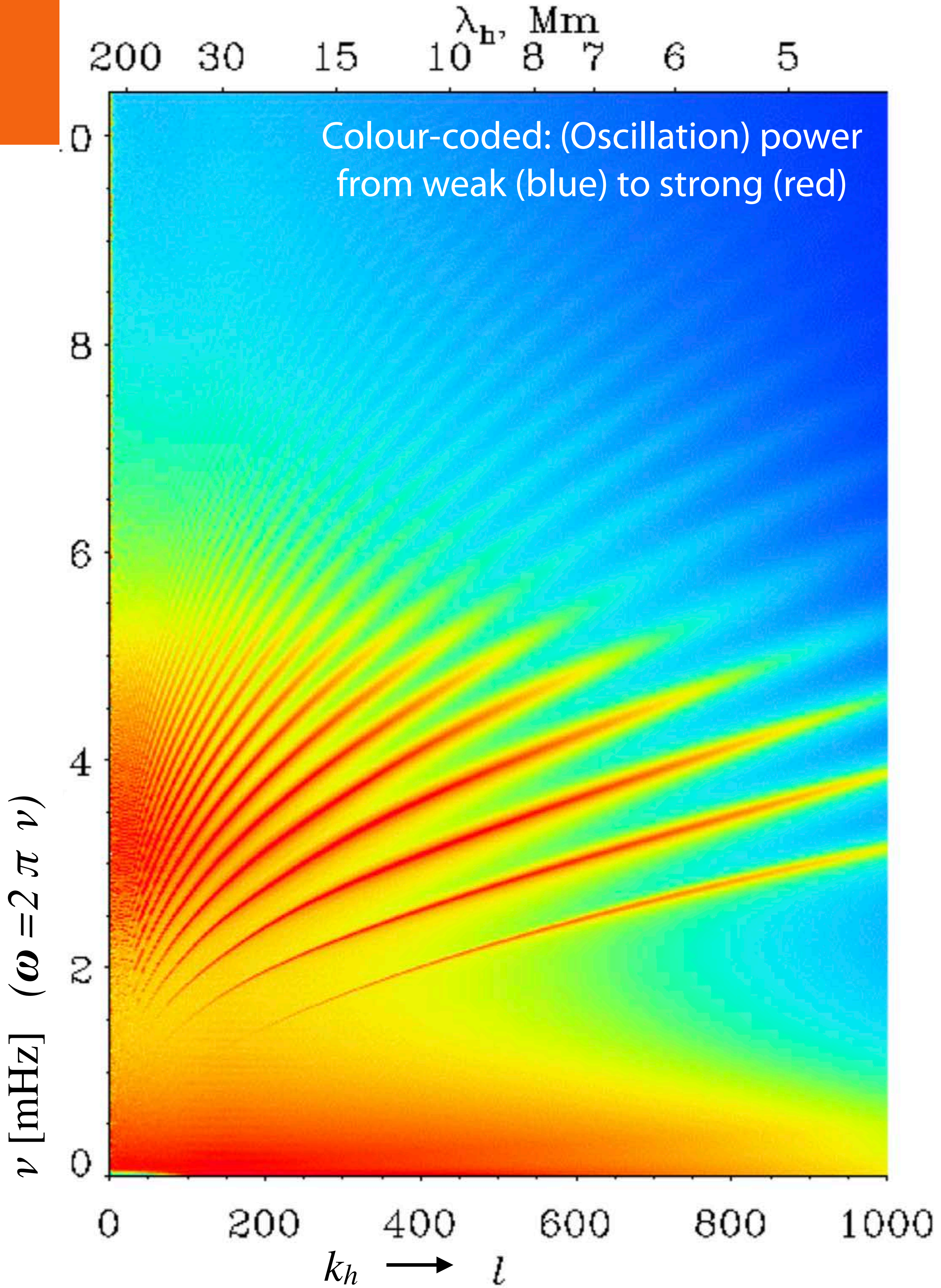
  ➡ ”Spatiotemporal power spectrum (“2D power spectrum”): **k-ω diagram**

- The p-modes show a distinctive dispersion relation!

- Important: power only in distinct **ridges:** for a given k^2 only power at certain frequencies

➡ Discrete spectrum suggests the oscillations are trapped, eigenmodes of the Sun

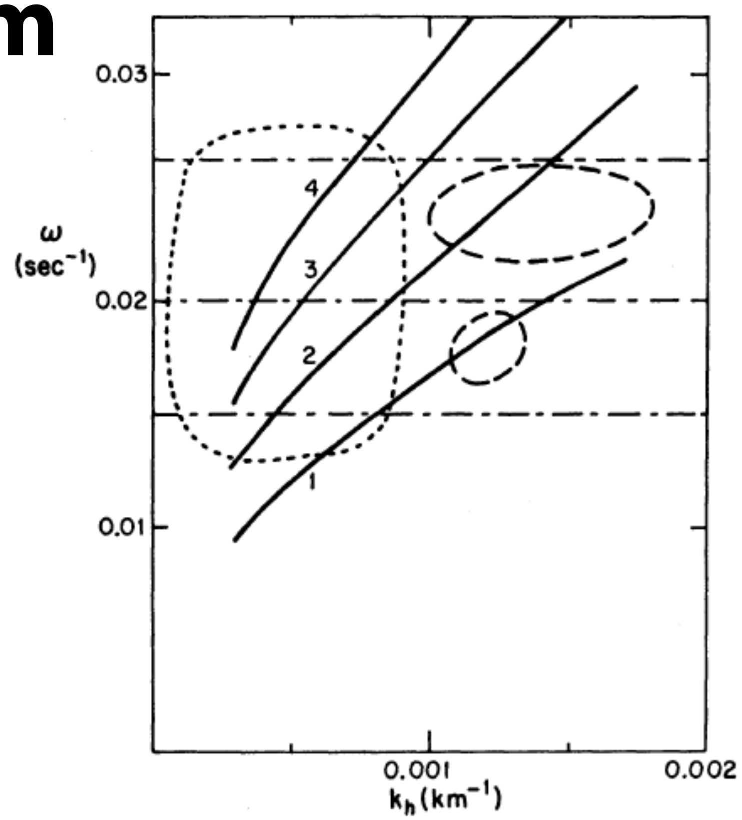
➡ Set by the interior structure of the Sun



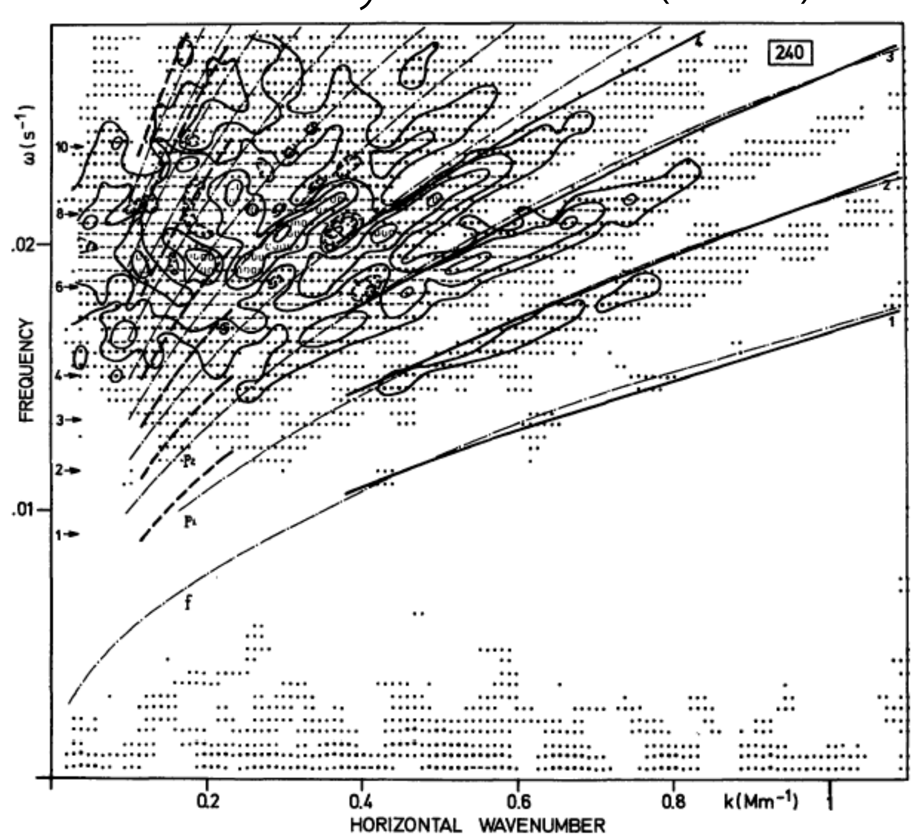
Helioseismology

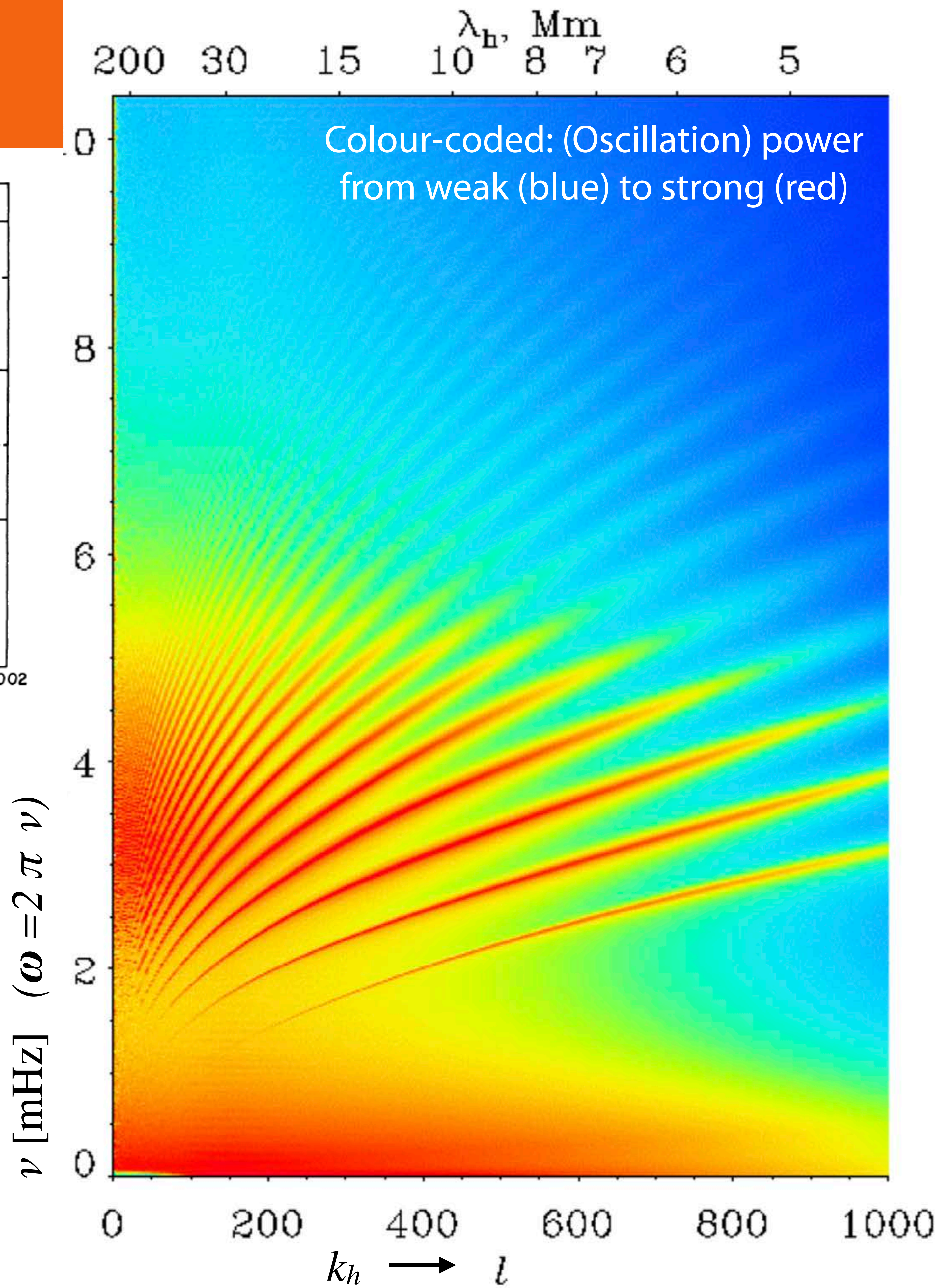
k-ω diagram

- Theoretically predicted by Ulrich (1970)



- First observed by Deubner (1974)

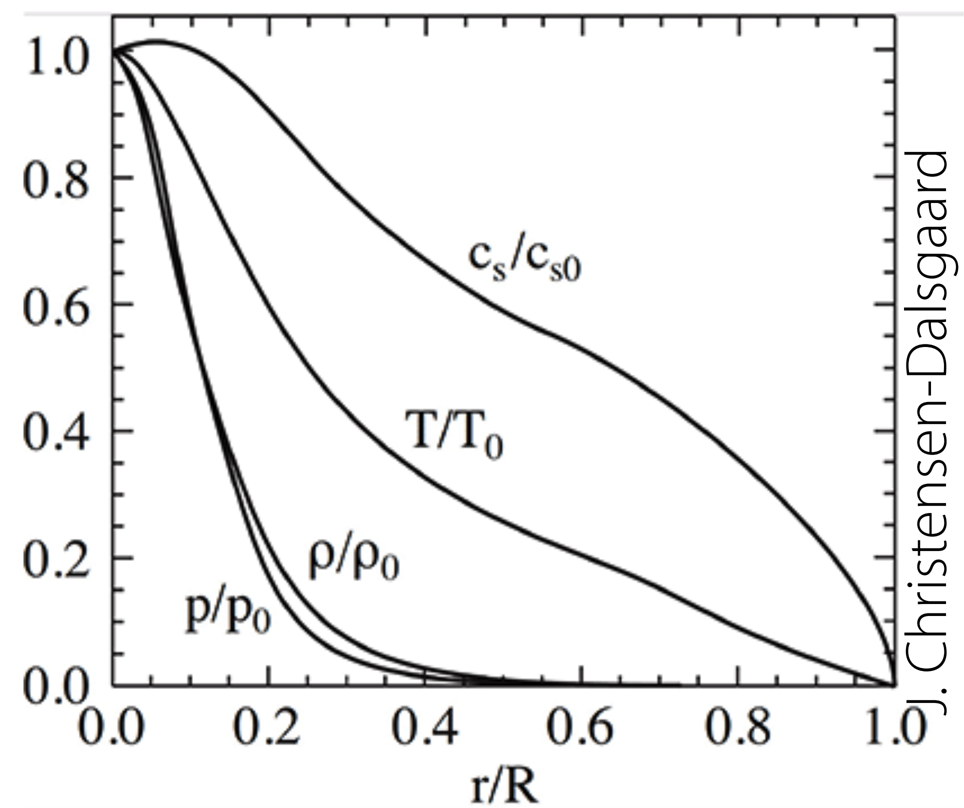


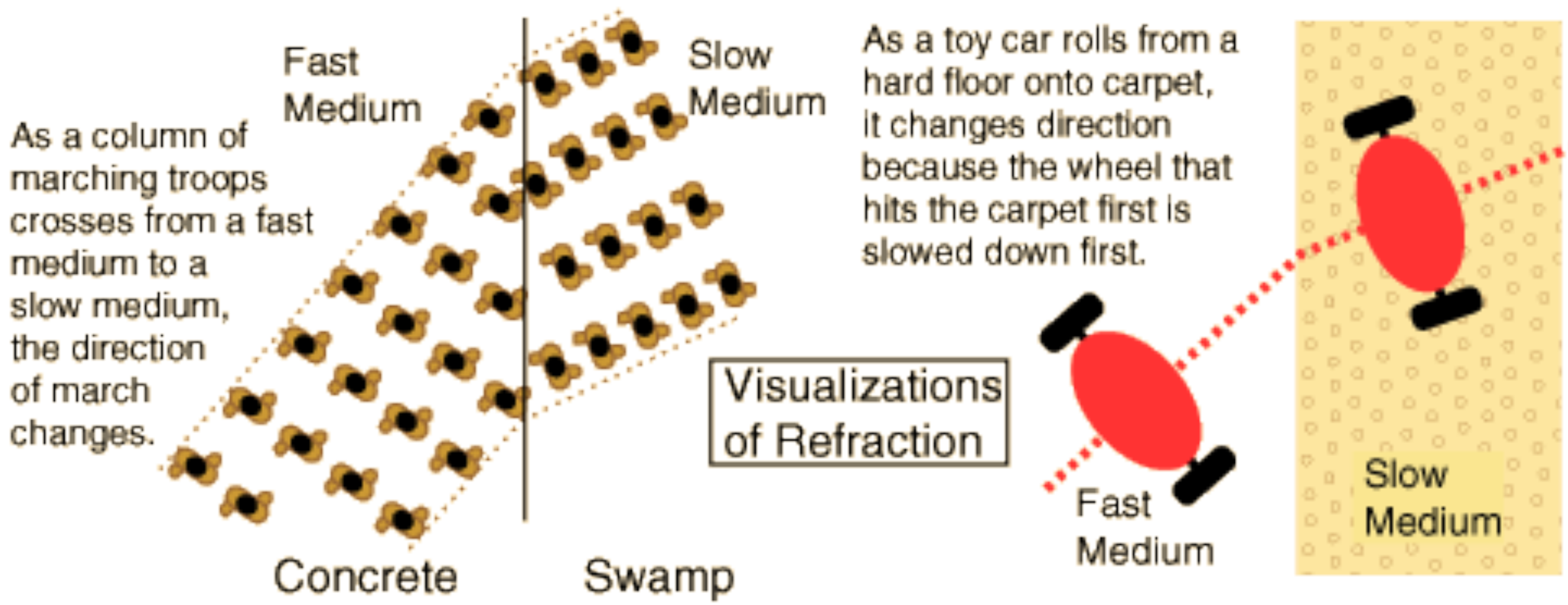


Helioseismology

Refraction & Reflection

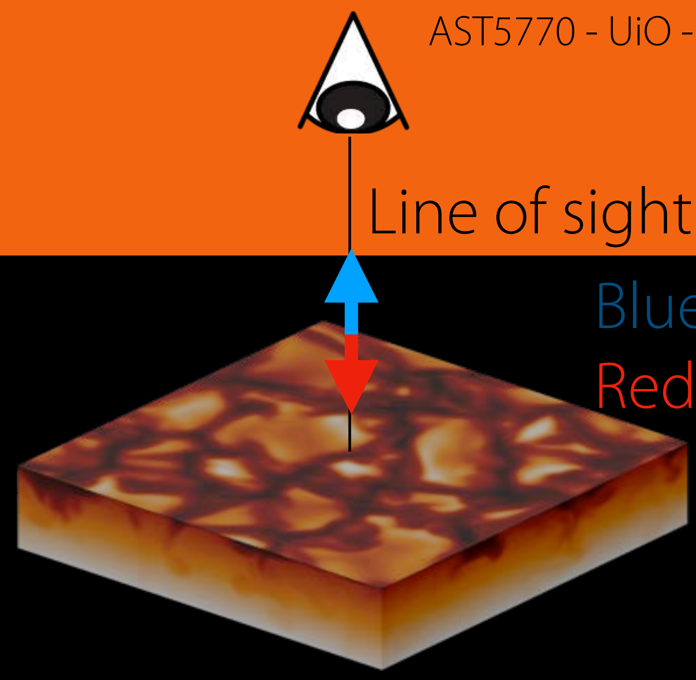
- **Sound waves** excited and propagate through interior
- **At surface: reflection** when wavelength ~ density scale height
- Continuous spectrum of different wavelengths
- Remember: Sound speed $c_s \sim T^{1/2}$
  - ➡ Sound speed changes as function of radius
  - ➡ Sound waves get refracted
    - Shorter wavelengths refracted higher up
    - Longer wavelengths refracted deeper down





Helioseismology

Refraction & Reflection



- **Recap: sound speed $c_s \sim T^{1/2}$**

➡ **c_s changes strongly as function of radius**

➡ **Sound waves get refracted in the solar interior.**

➡ **Penetration depth of sound waves depends on their wavelength.**

- Different wavelengths probe different depths
- All wavelengths together probe the stratification of the solar interior!
- Sound waves reflected at surface results in surface (patch) to oscillate up and down accordingly
- Observation (Doppler shifts, intensity variation) and interpretation of these oscillations at the surface provides information about the interior structure of the Sun!