Lecture 13

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

Helioseismology

(continued)

Helioseismology

Oscillation equations — k_h-ω-plane

- **Dispersion relation**:

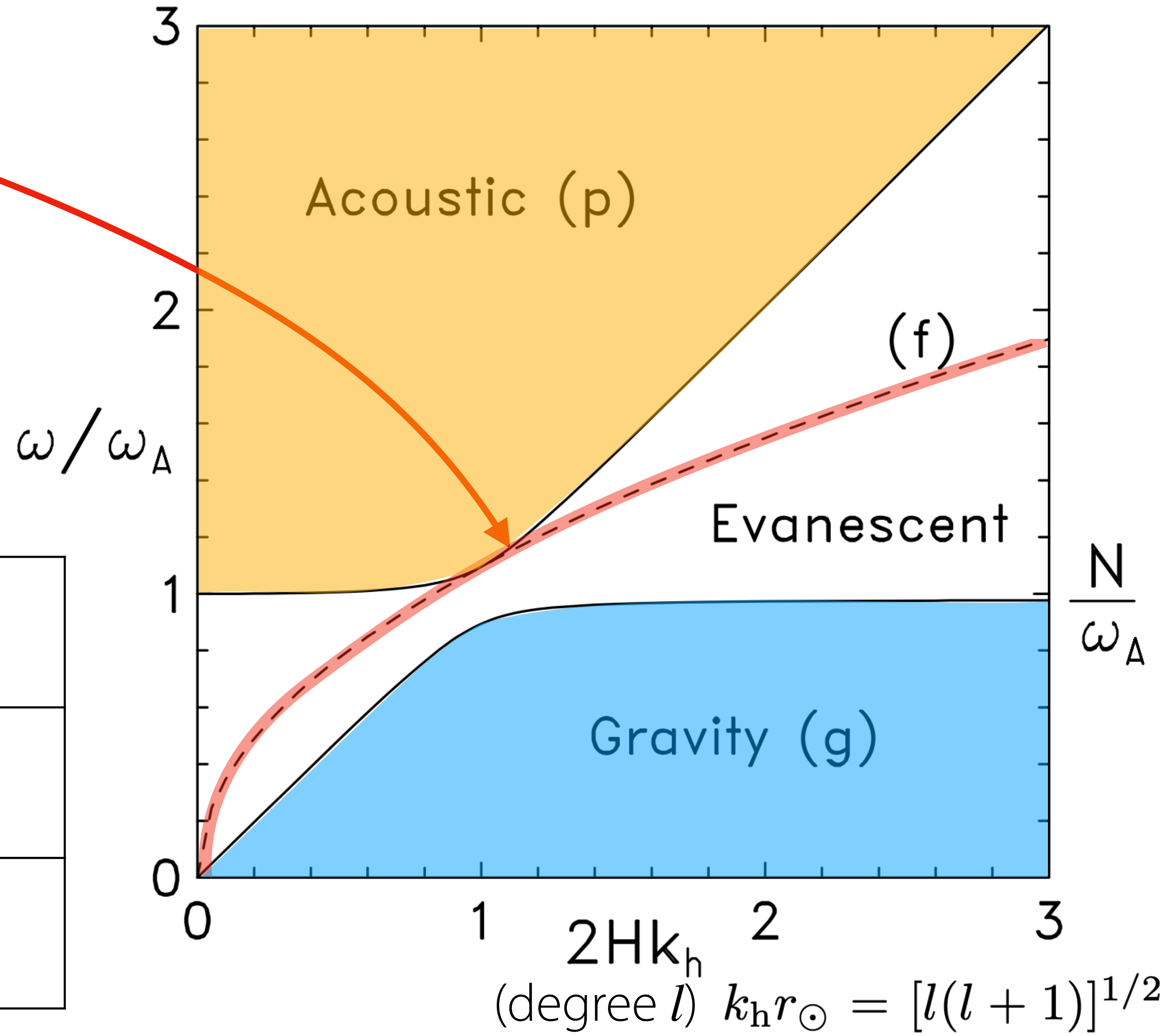
$$\boxed{k_r^2 = \frac{\omega^2 - \omega_A^2}{c^2} + S_l^2 \frac{N^2 - \omega^2}{c^2 \omega^2}}$$

- **Fundamental mode (f-mode):** essentially without compression, resembles a surface wave on deep water

$$\omega = \sqrt{g k_h}$$

- ω_A : Acoustic cutoff frequency
- N : Brunt–Väisälä frequency
- S_l : Lamb frequency

k_h-ω-plane, solid curves: $k_r^2 = 0$



Acoustic waves	➡ p-modes
Buoyancy waves	➡ g-modes
Surface gravity waves	➡ f-mode

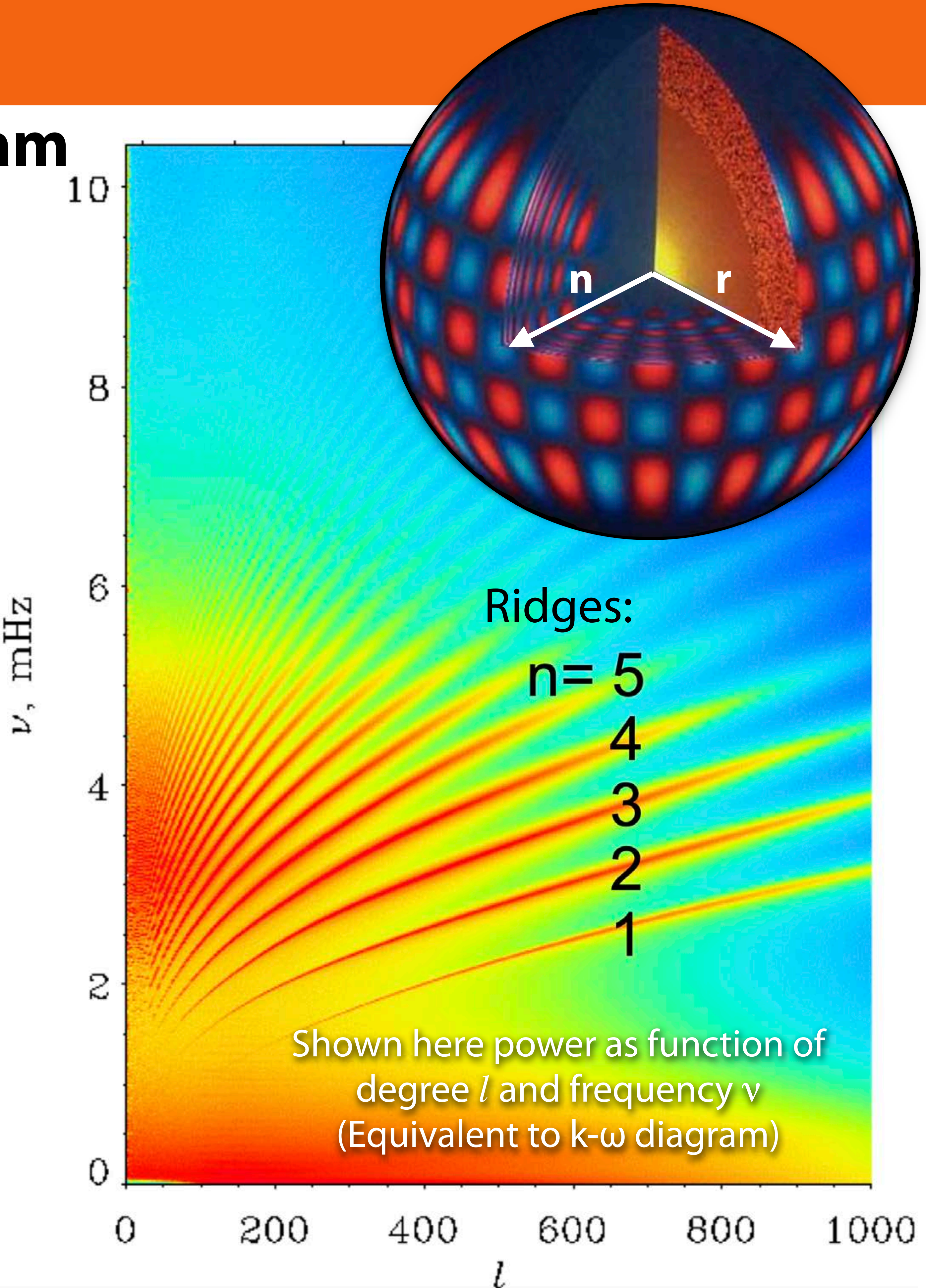
Helioseismology

Interpretation of k-ω diagram

- Eigen-oscillations of a sphere are described by spherical harmonics
- Each oscillation mode is identified by a set of three parameters:
  - n = number or radial nodes
  - l = number of nodes on the solar surface
  - m = number of nodes passing through the poles

- Power ridges belong to different orders n
- Power in ridge with increasing l

  ➡ Increase in frequency ν (or ω)
- Most prominent power along ridges for small n intermediate/large degree l



Shown here power as function of degree l and frequency ν (Equivalent to k-ω diagram)

Helioseismology

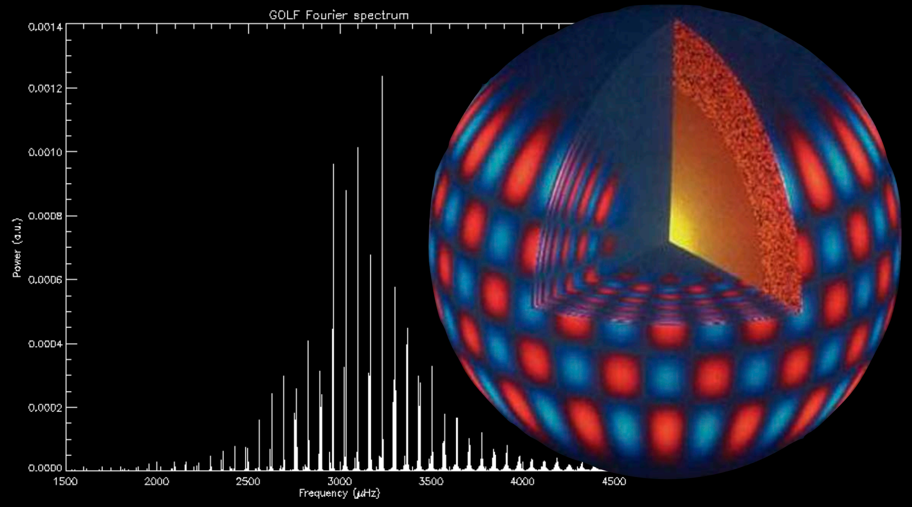
Rotational splitting

- So far neglected dependence on m
  (azimuthal, number of nodes passing through poles)
- Closer look: Frequency spectrum is (finely) split regarding m due to the Sun's rotation

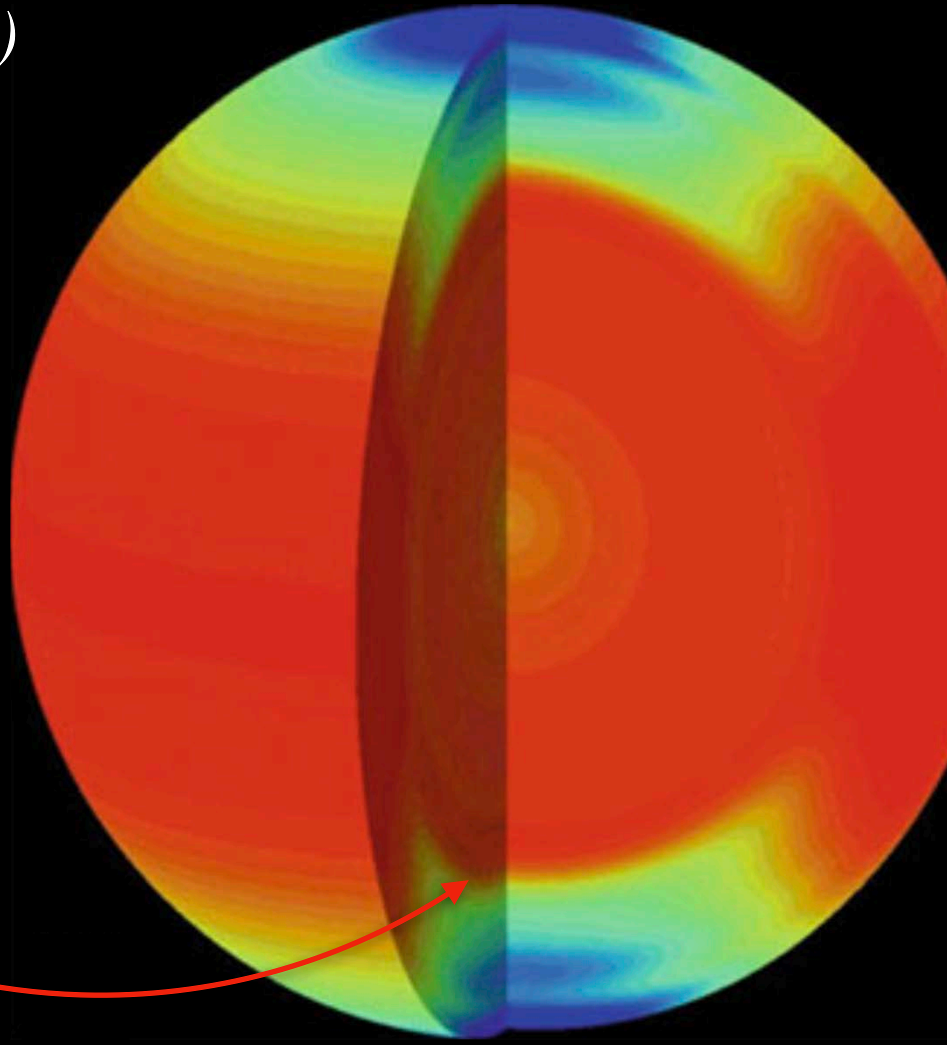
➡ **Rotational splitting**

  - Waves propagate prograde or retrograde $(\nu_{-m,l} - \nu_{+m,l})$

- Can be exploited to derive the rotation rate throughout the solar interior
- Discovery of a rapid change in rotation rate at the bottom of the convection zone
- That layer is called **tachocline**
  - Depth: $r = 0.712 \pm 0.005\ R_\odot$ with a
  - Thickness $\Delta r = 0.04 \pm 0.01\ R_\odot$



fast rotation rate (P ≈ 25 days)
slow rotation rate (P ≈ 35 days)

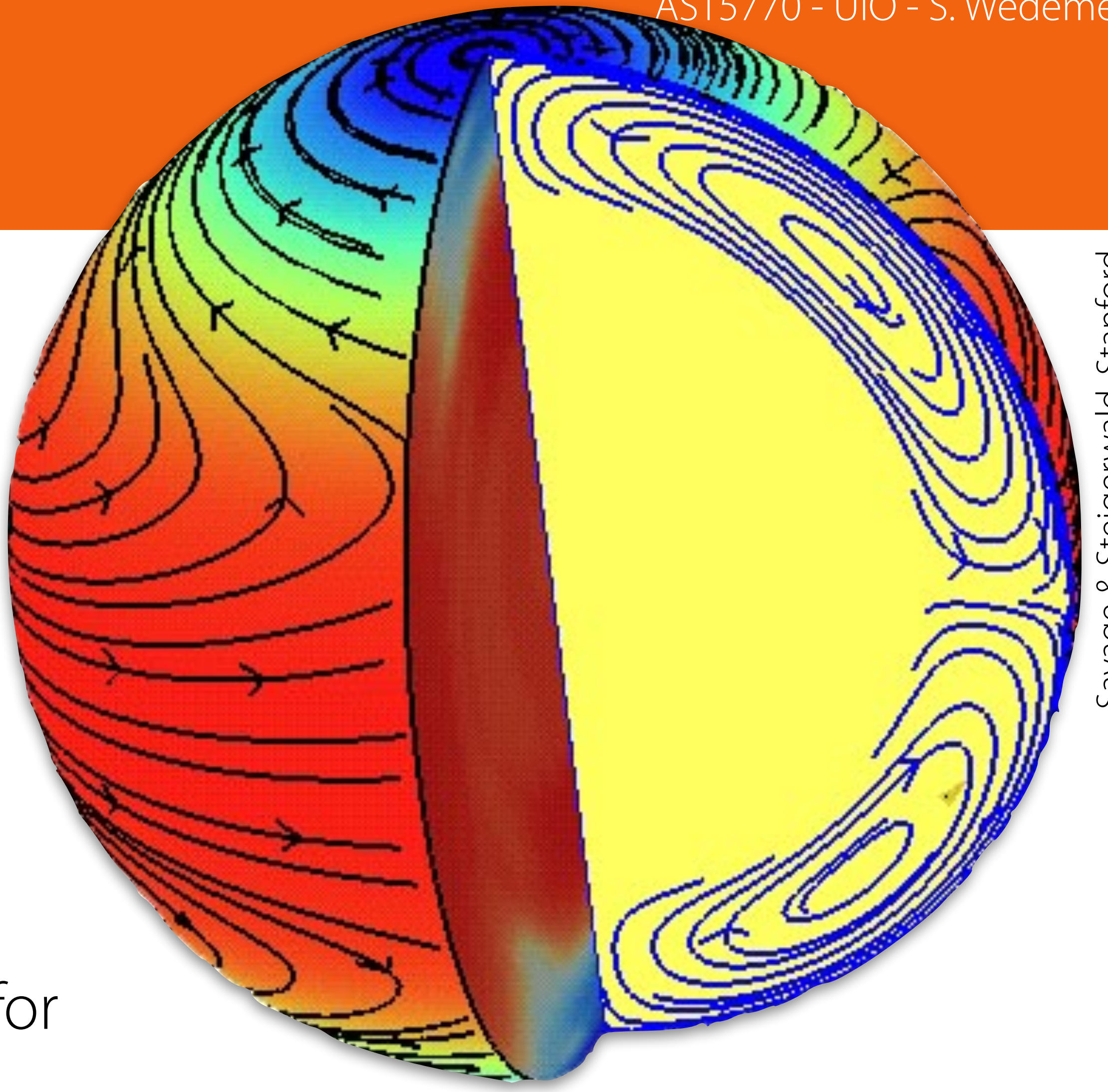


MDI/SOHO Team

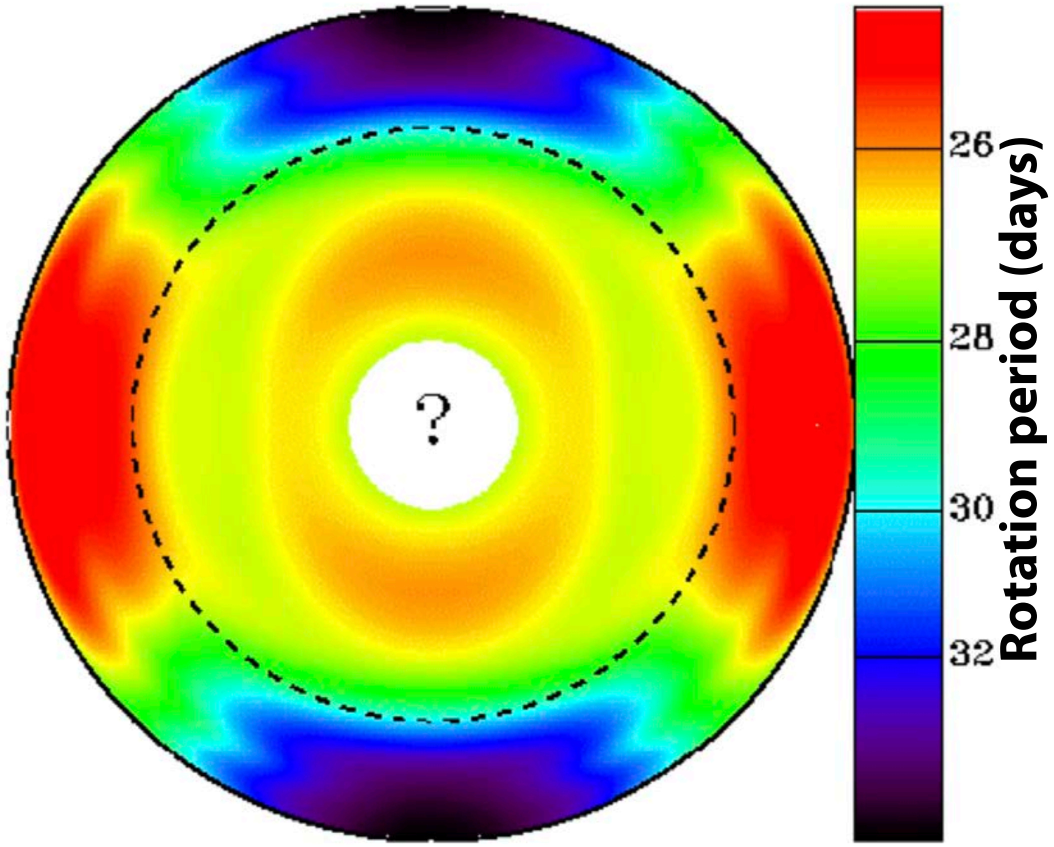
Helioseismology

Rotation and meridional flows

- From helioseismology:
  meridional flow poleward at /close to the surface
  (down to ~30 Mm), speeds ~ 20 m/s
- "Return flow" towards equator at a depth ~ 0.77 $R_\odot$
  (deep convection zone)
- Bottom of convection zone = lower turning point for oscillation modes with l ≈ 20
- Below convection zone (0.2 – 0.7 $R_\odot$):
  - rotation approx. constant with radius
  - spherically symmetric
  - Well-described by rigid-body rotation
- Not much known about rotation of the innermost core
  (probed only by very low-l degree p-modes,
  internal g-modes not accessible)



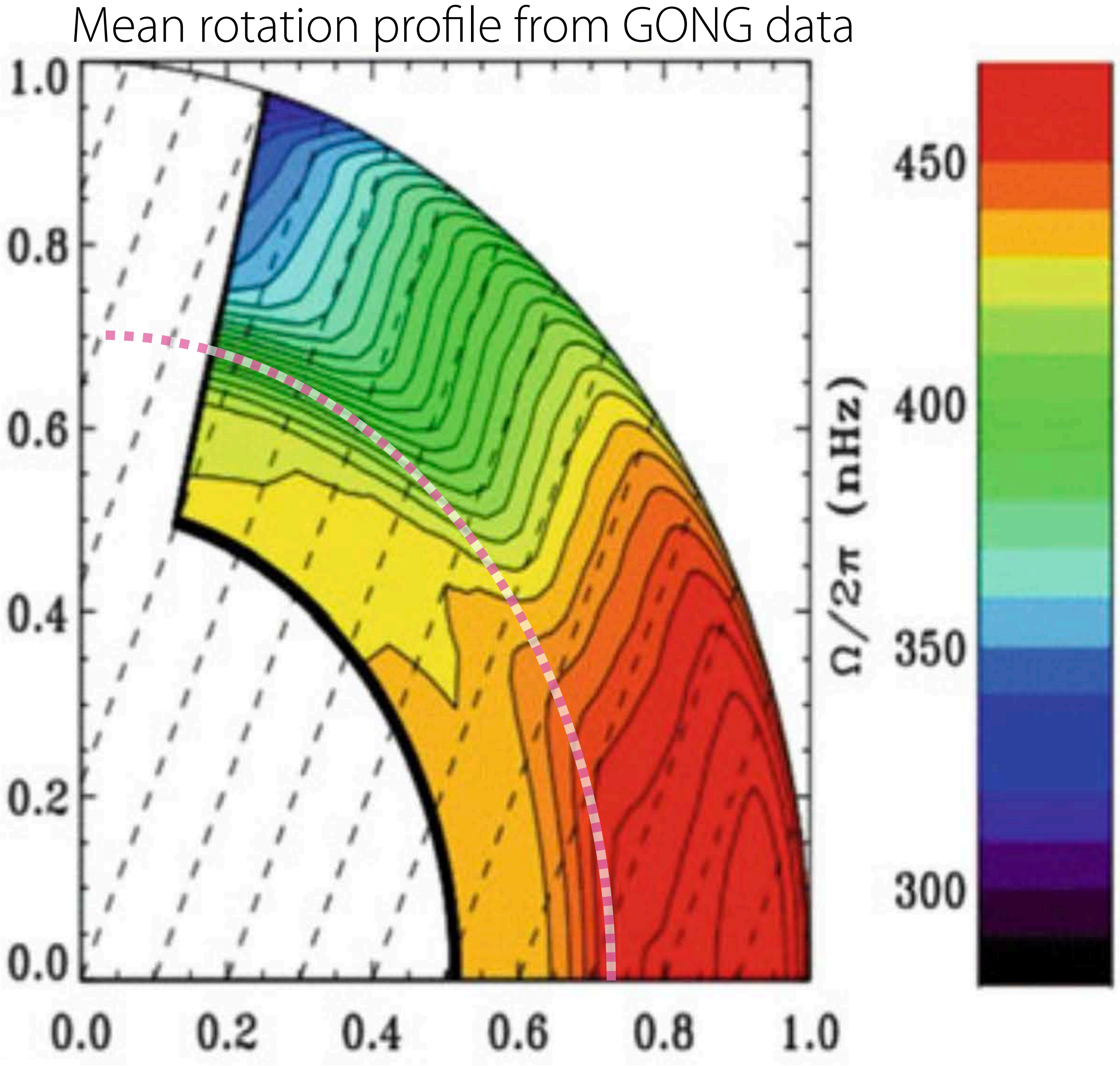
Savage & Steigerwald, Stanford
ESA/NASA Solar and Heliospheric Observatory (SOHO)

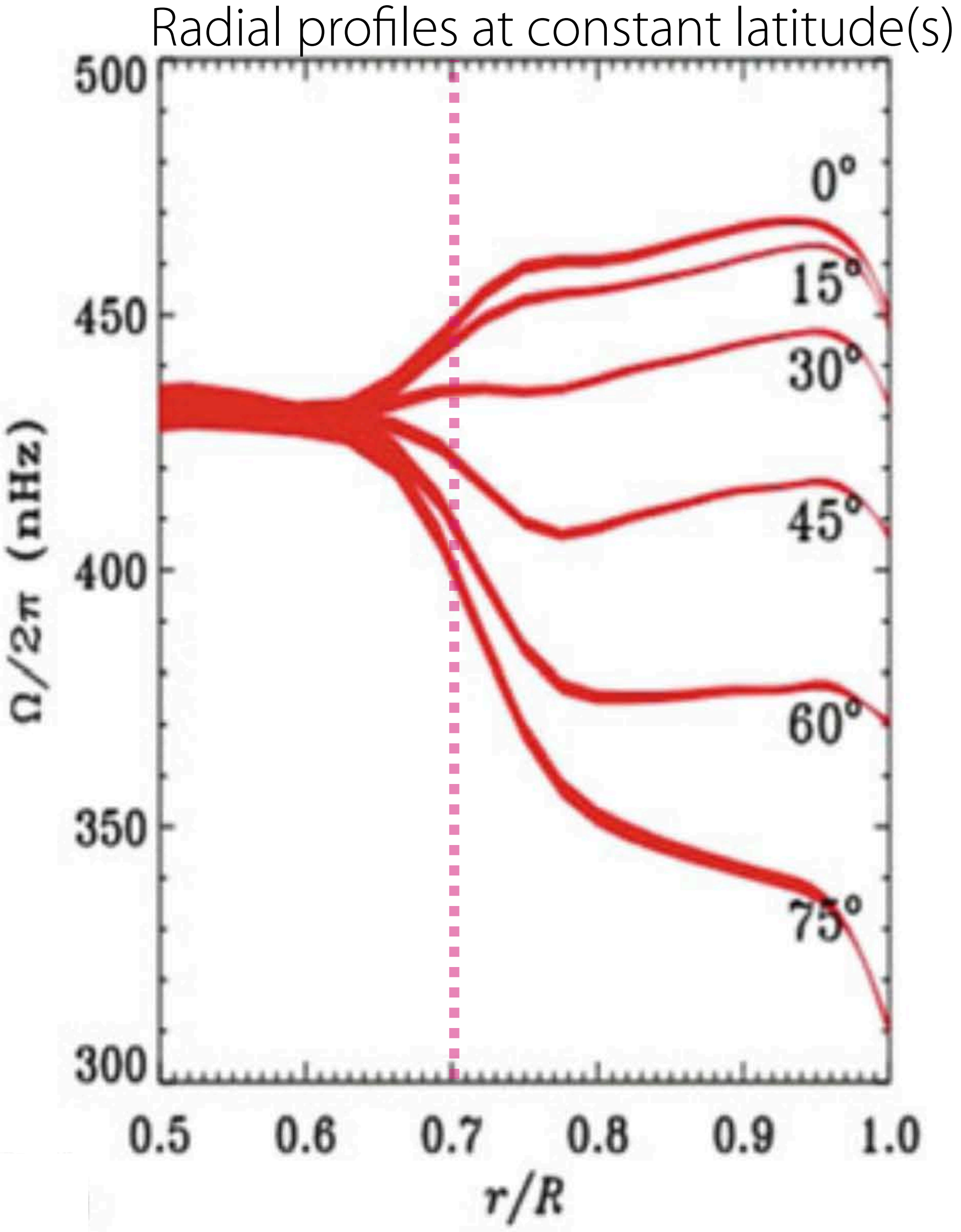


Helioseismology

Rotation and meridional flows

- Rotation speed in the convection zone (and at the surface) varies with latitude and depth!
- Differential rotation: The Sun's equator rotates faster than the poles.


Mean rotation profile from GONG data


Radial profiles at constant latitude(s)

Howe et al. 2000, 2005

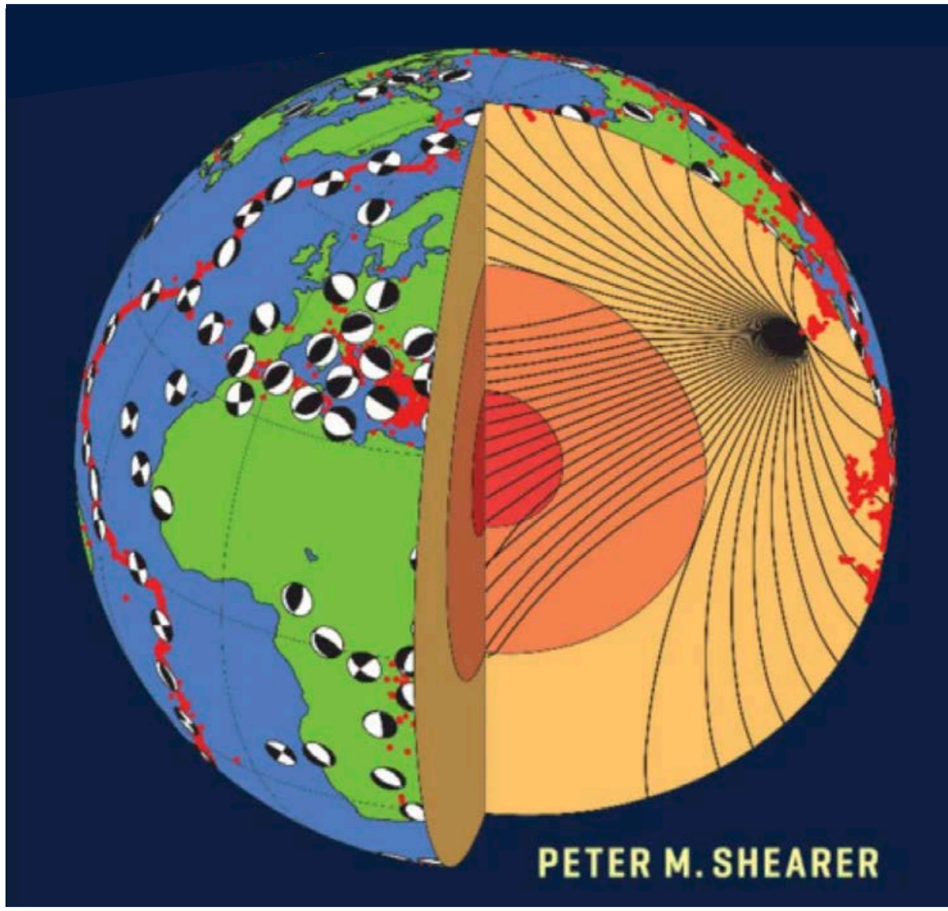
Helioseismology

Time-Distance Methods

- **Seismology on Earth:**
  - Measure arrival time of the initial onset of the disturbance at different locations on the surface
  - If we know the variation of seismic velocity with depth within the earth, then we can calculate the travel time of rays between an earthquake and a receiver.

  ➡ Locate the epicentre of any earthquake

  ➡ Also: Learn about variations of the velocity due to differences in structure/density inside Earth
  (the Earth is not a perfect homogeneous sphere!)



Helioseismology

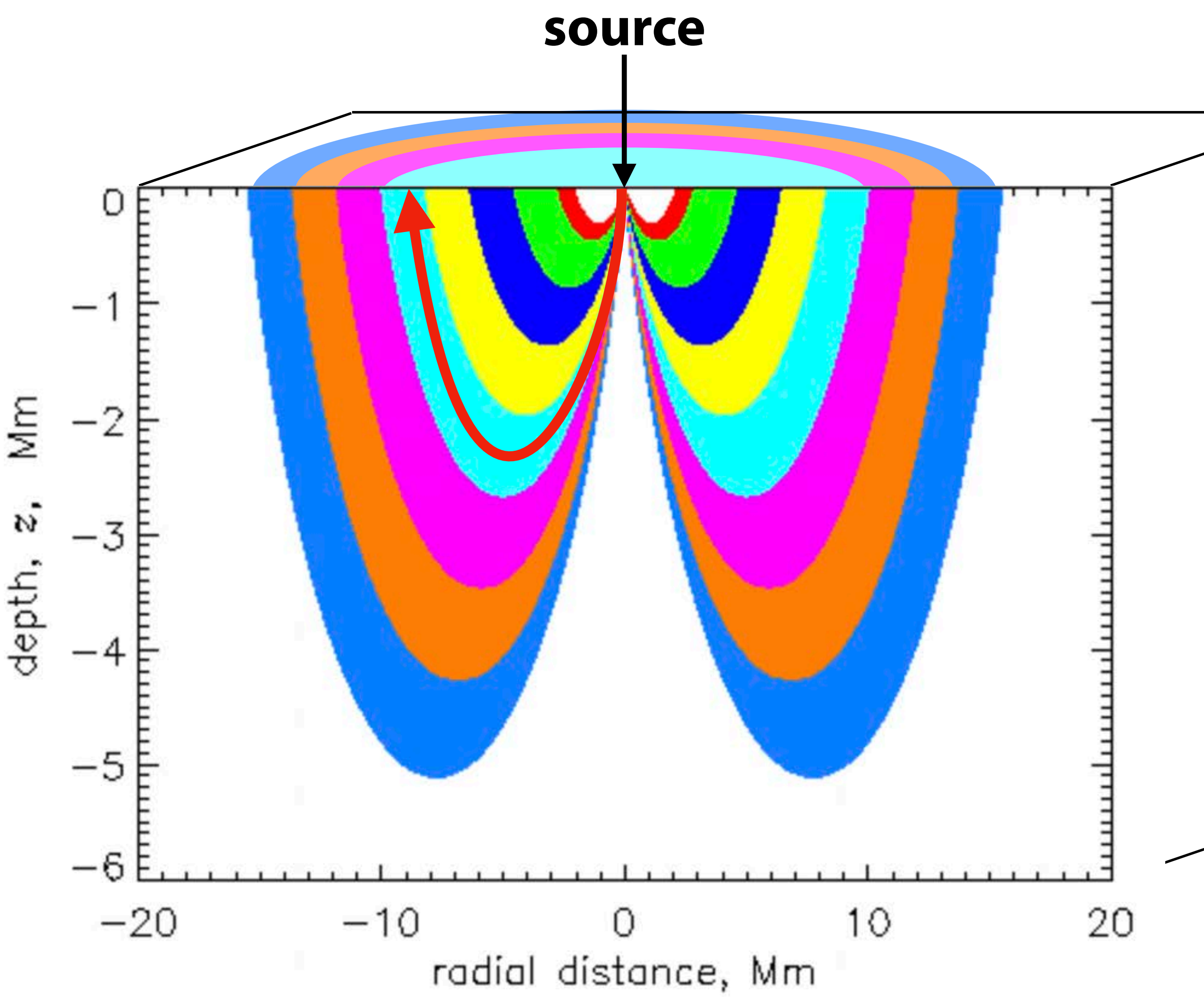
Time-Distance Methods — local helioseismology

- **Time-distance helioseismology**
  — similar idea for the Sun:
  - Select point on surface as the “source"
  - Assume an annulus at some great circle around that point as a destination
  - Calculate correlations between all points in the annulus
  - Any pulse in the correlation function reveals time and distance

  ➡ Probes the sub-surface medium through which the sound waves have traveled

  - Deviations in the arrival times due to inhomogeneities under the surface
  - Remember: Probed depth depends on wavelength of observed p-mode

  ➡ Mapping of sub-surface structure



Helioseismology

Time-Distance Methods — local helioseismology

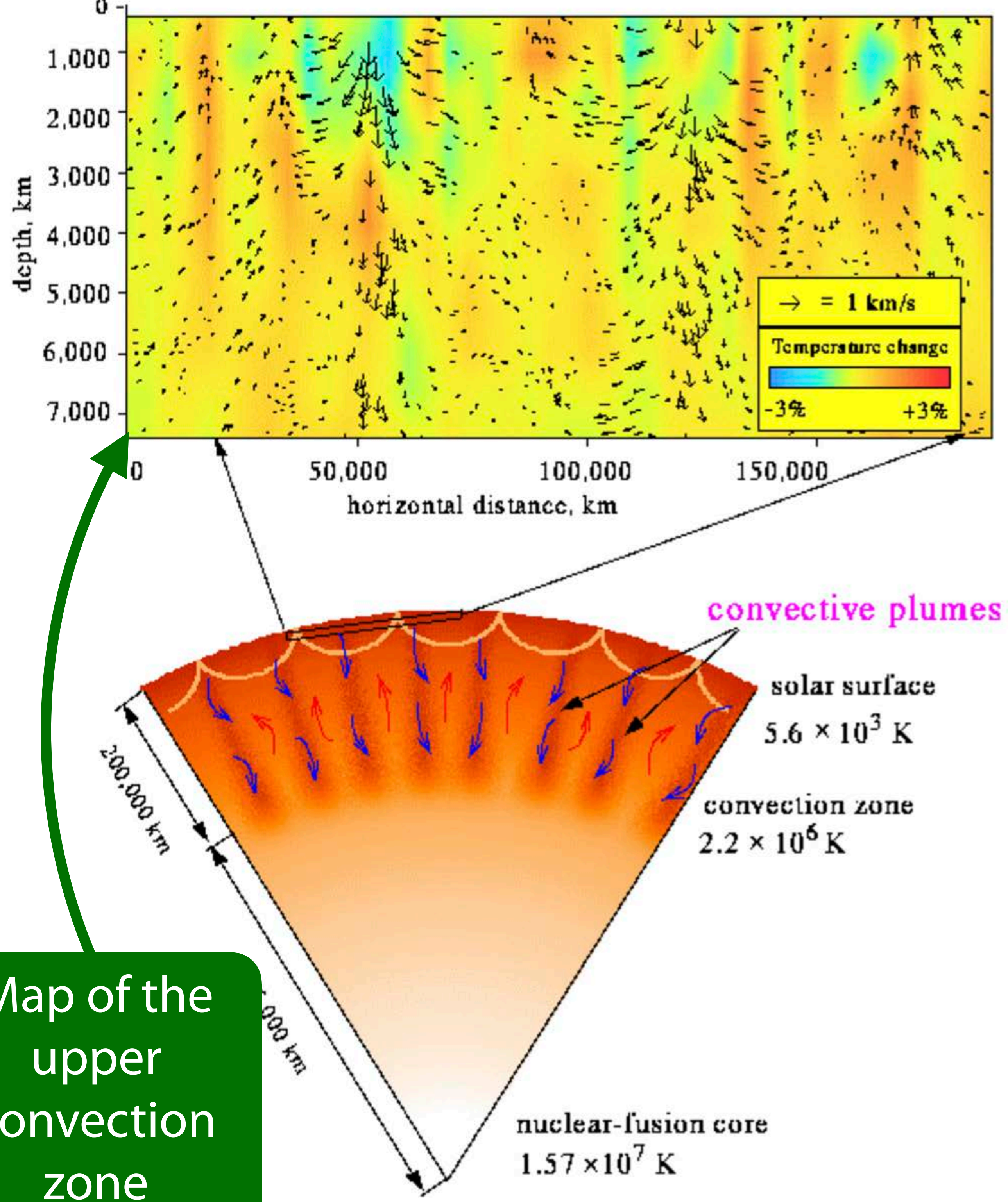
- **Time-distance helioseismology**
  — similar idea for the Sun:
  - Select point on surface as the “source"
  - Assume an annulus at some great circle around that point as a destination
  - Calculate correlations between all points in the annulus
  - Any pulse in the correlation function reveals time and distance

  ➡ Probes the sub-surface medium through which the sound waves have traveled

  - Deviations in the arrival times due to inhomogeneities under the surface
  - Remember: Probed depth depends on wavelength of observed p-mode

  ➡ Mapping of sub-surface structure

Convective flows below the Sun’s surface

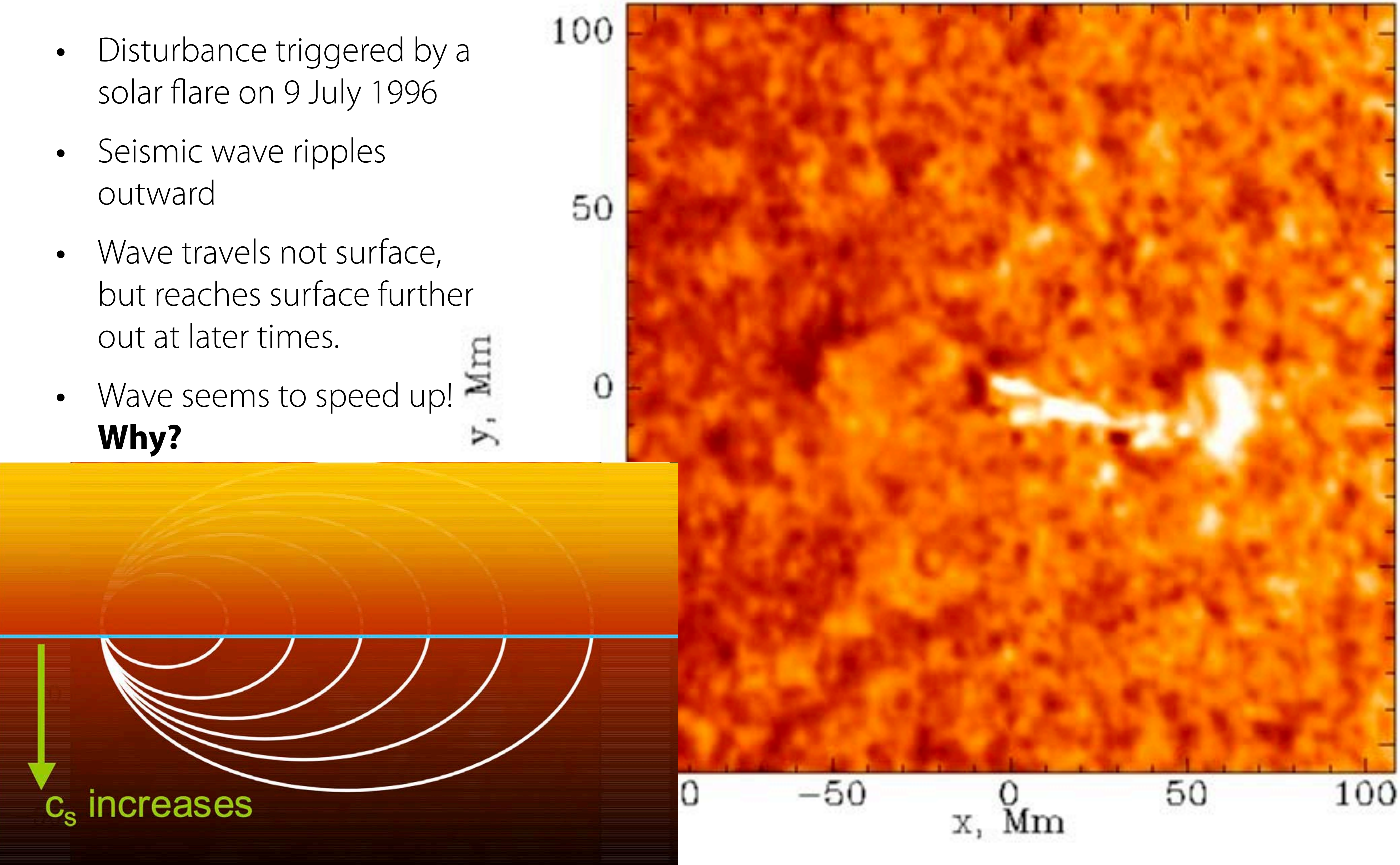


Map of the upper convection zone

Helioseismology

Sunquake

- Disturbance triggered by a solar flare on 9 July 1996
- Seismic wave ripples outward
- Wave travels not surface, but reaches surface further out at later times.
- Wave seems to speed up! **Why?**



Kosovichev et al (1998)

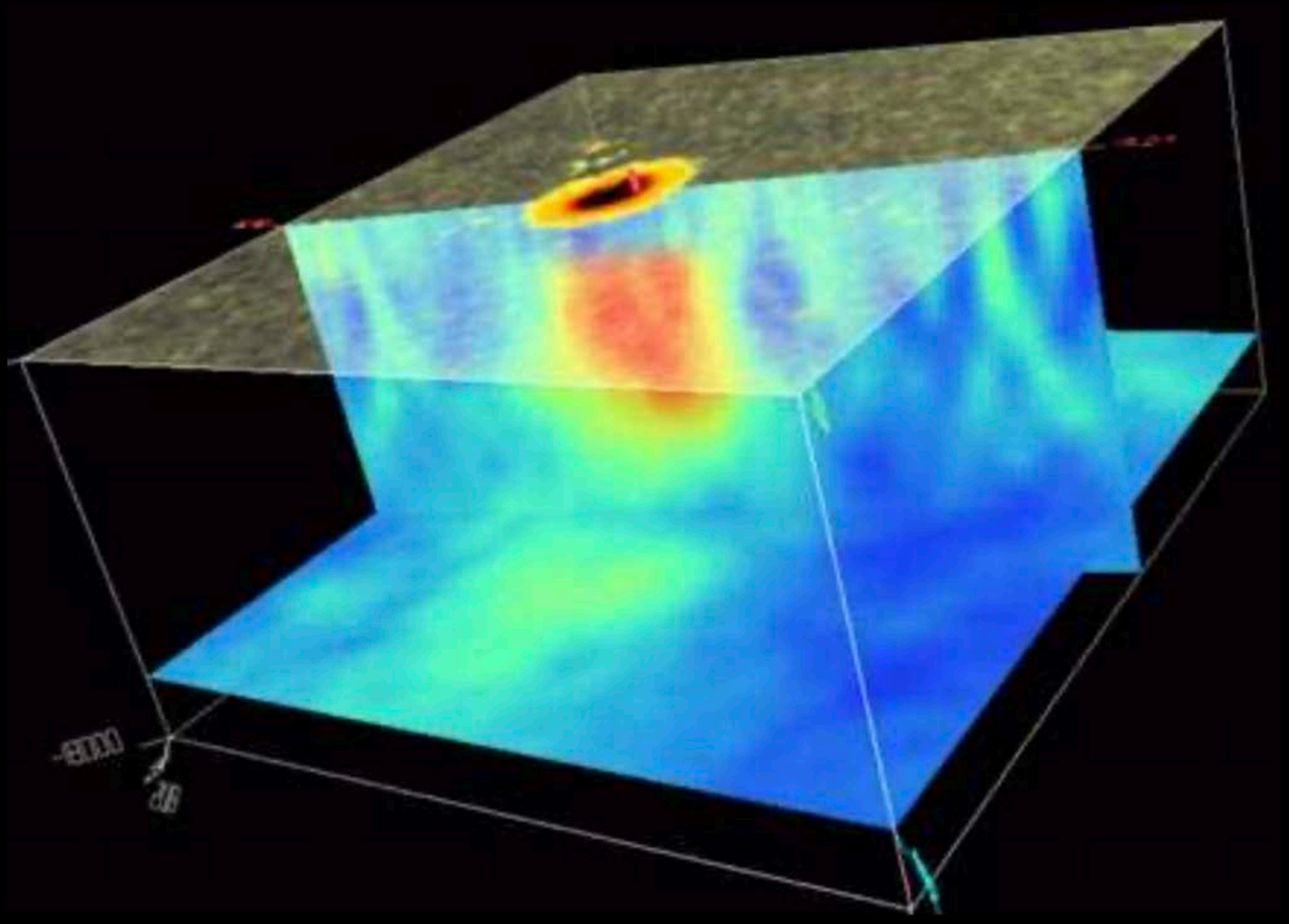
Helioseismology

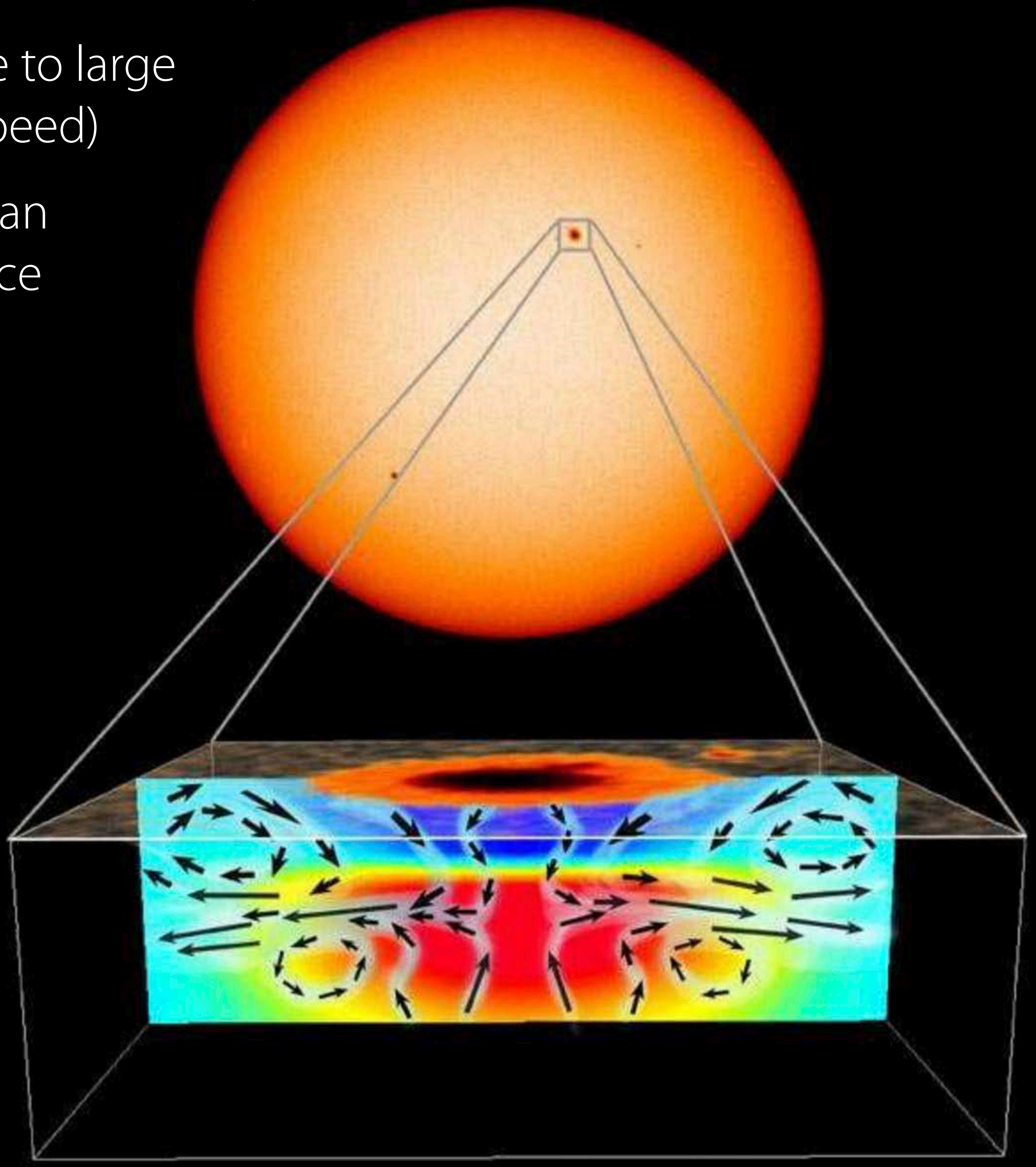
Time-Distance Methods — local helioseismology

- **Subsurface structure of sunspots** (Kosovichev et al. 2000)
- Sunspots good targets for this technique due to large change in temperature (and thus in sound speed)

➡ **Sunspots surprisingly shallow**: warmer than surroundings already ~ 4000 km below surface

- Remaining uncertainty: unknown influence of magnetic field on the wave propagation



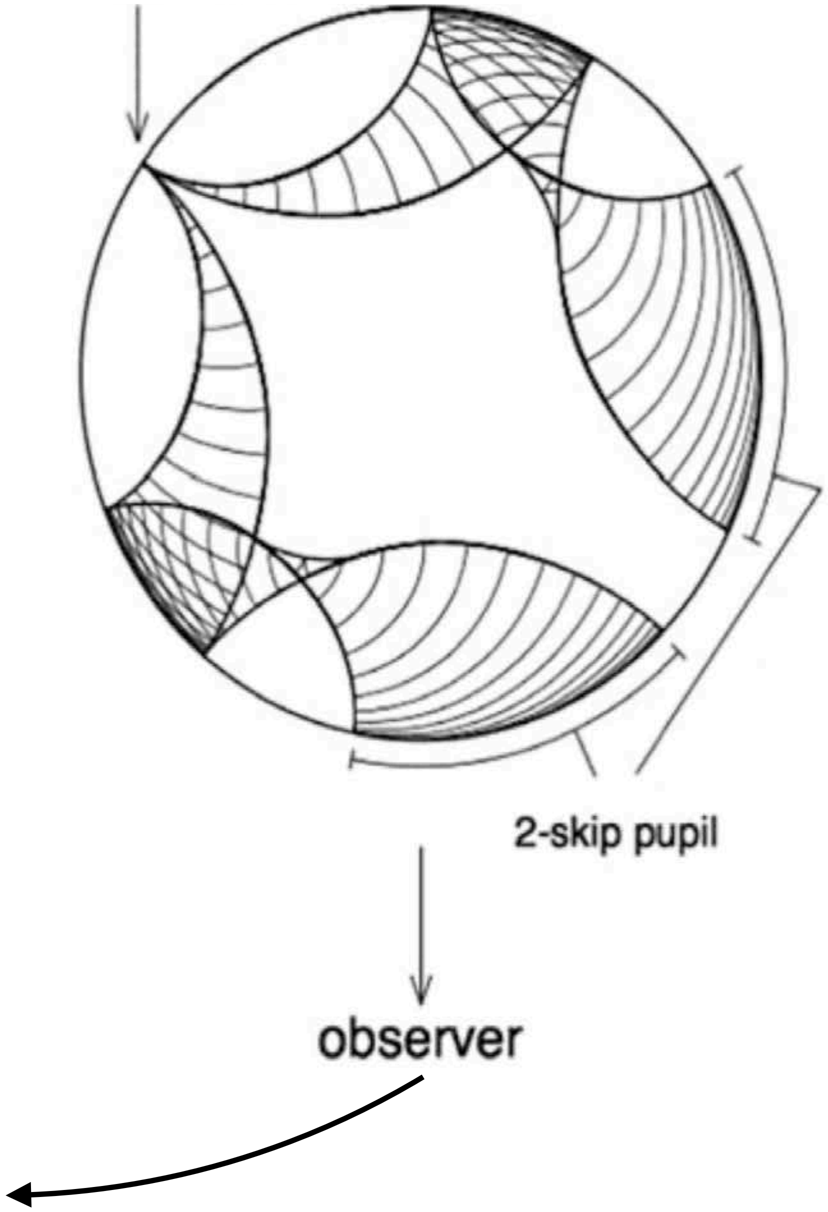


Helioseismology

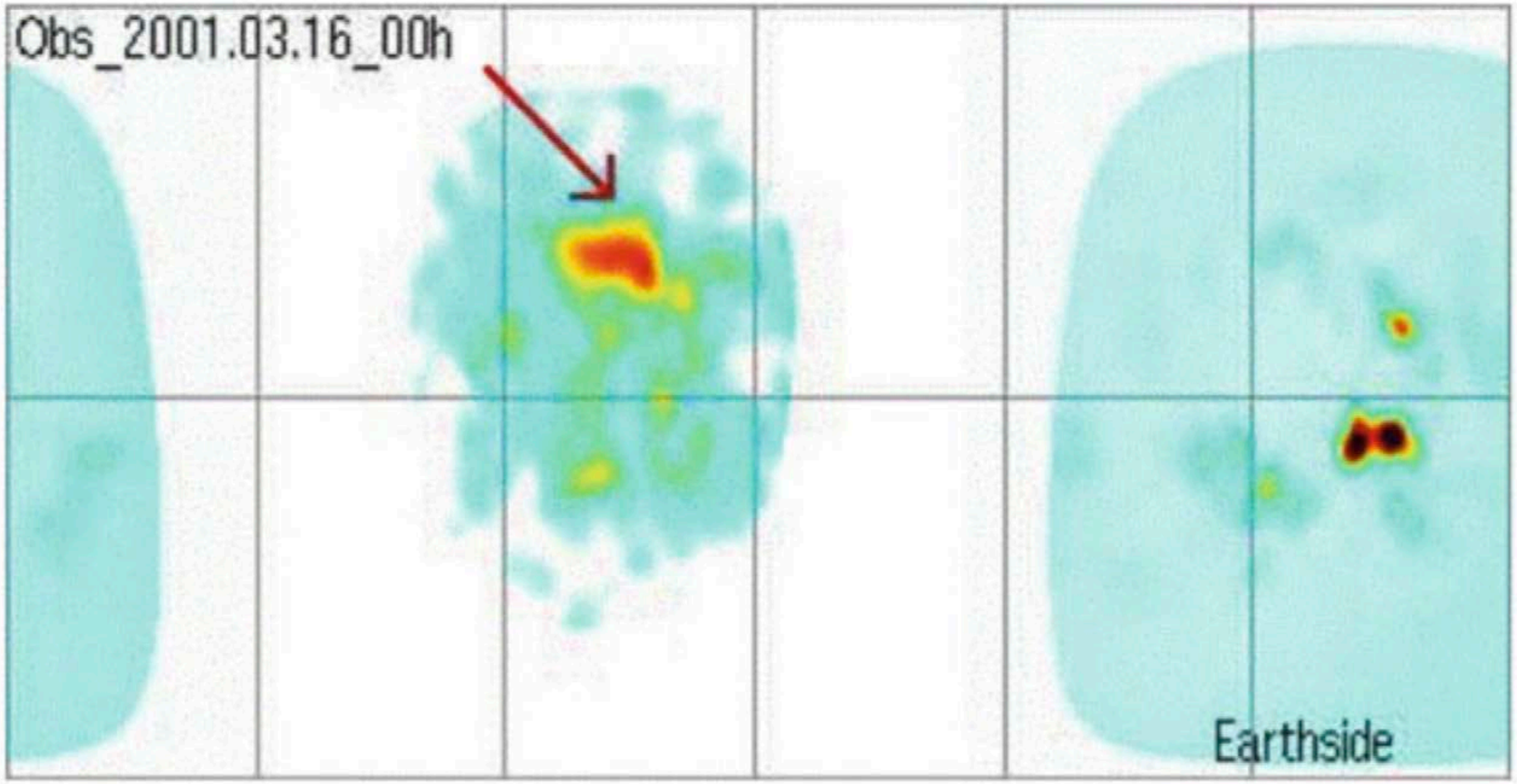
Mapping the far side

- Two-skip far-side seismic holography
- Difference (delay) in travel time of sound waves from active region on the far-side of the Sun as compared to Quiet Sun ~10 s (on a total travel time of ~6 hr)
- Confirmed by other observations (STEREO satellites)
- Very helpful for space weather forecast — knowing about Active Regions before they rotate on the visible (Earth) side

Focal point (location on the other side that is mapped)



Braun and Lindsey 2001



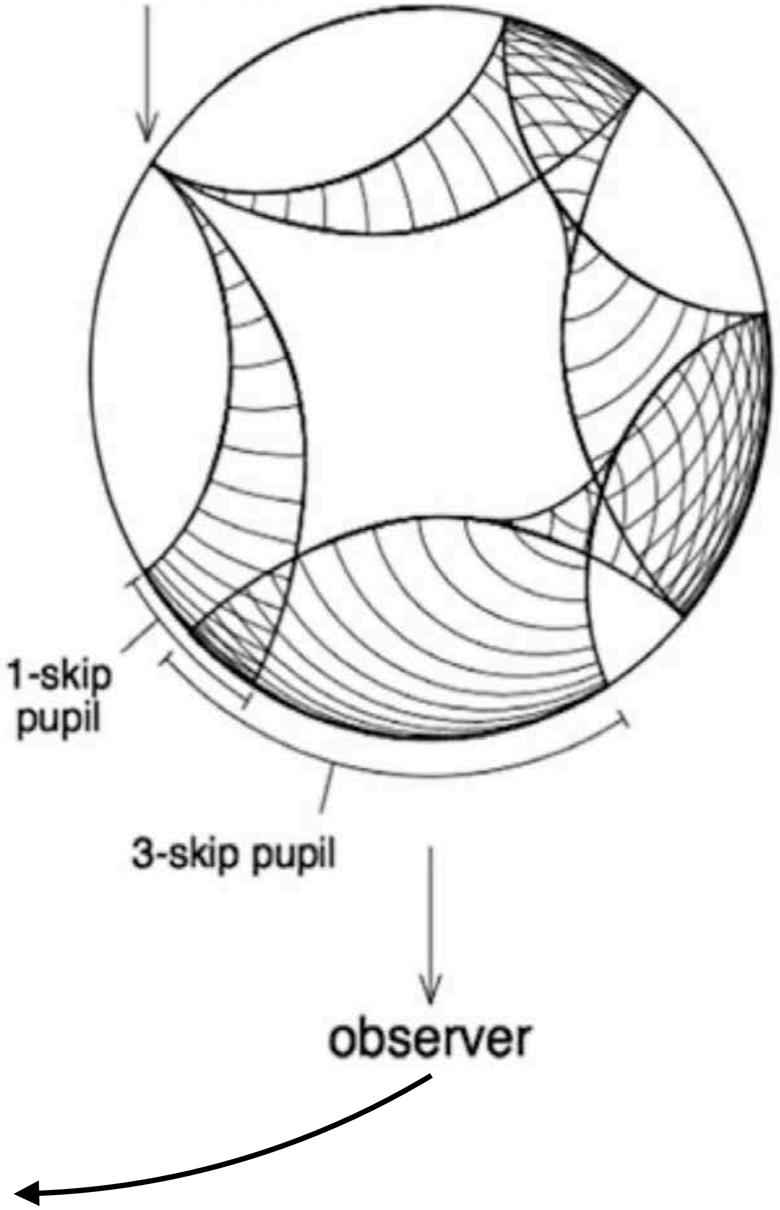
Braun and Lindsey 2001; Gizon and Birch 2005)

Helioseismology

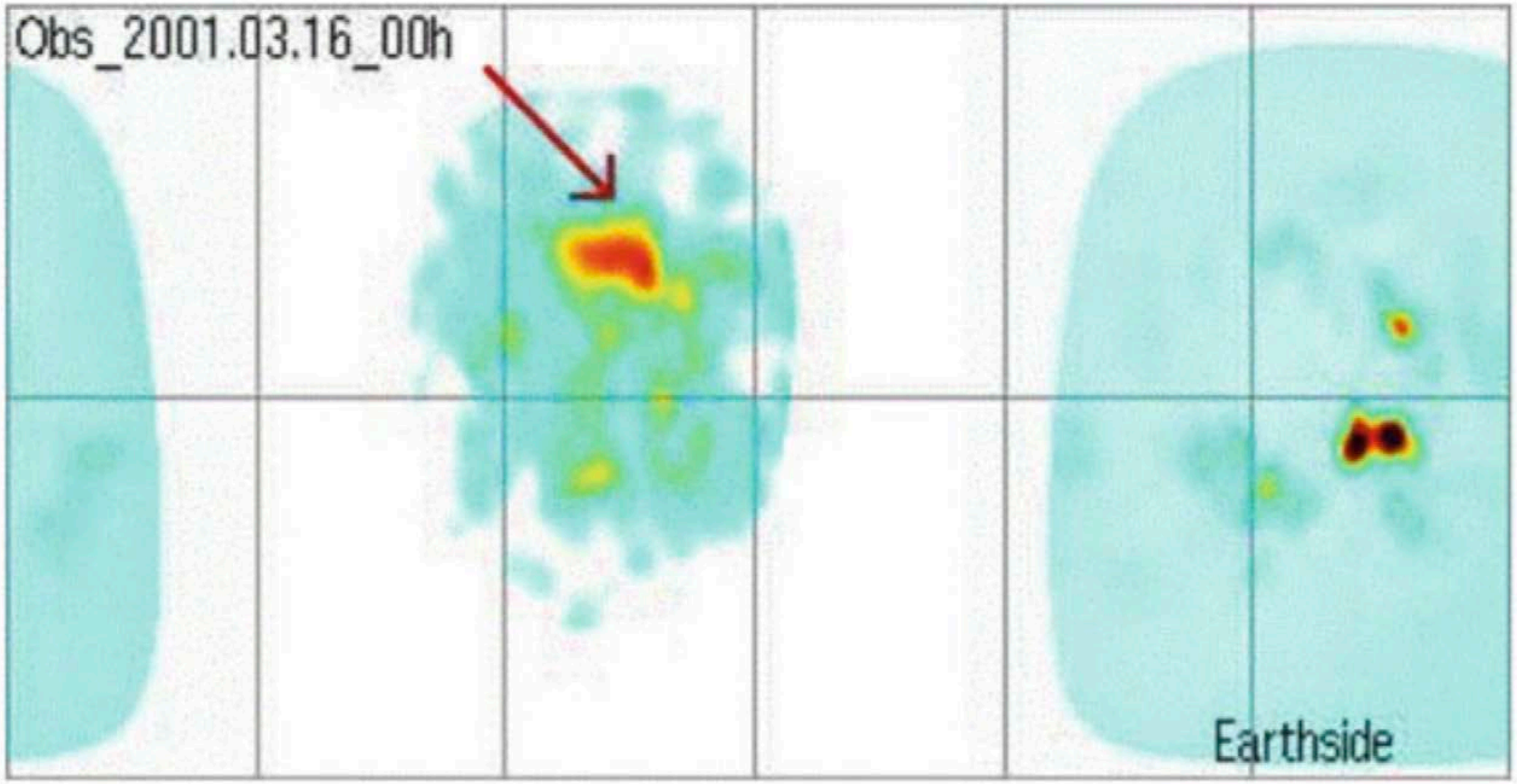
Mapping the far side

- Two-skip far-side seismic holography
- Difference (delay) in travel time of sound waves from active region on the far-side of the Sun as compared to Quiet Sun ~10 s (on a total travel time of ~6 hr)
- Confirmed by other observations (STEREO satellites)
- Very helpful for space weather forecast — knowing about Active Regions before they rotate on the visible (Earth) side

Focal point (location on the other side that is mapped)



Braun and Lindsey 2001



Braun and Lindsey 2001; Gizon and Birch 2005)

Helioseismology

Sun as a star — implications for asteroseismology

- **“Our usual problem”:** Stars (except for the Sun) observed **not (well) spatially resolved**
- Stellar observations return simpler power spectrum with **only modes with low l**
  - Up to $l = 3$ for intensity variations
  - Up to $l = 4$ for radial velocity variations
  - Imprints of higher modes (with more nodes on stellar surface) cancel out when not spatially resolved, much information on non-radial oscillations lost

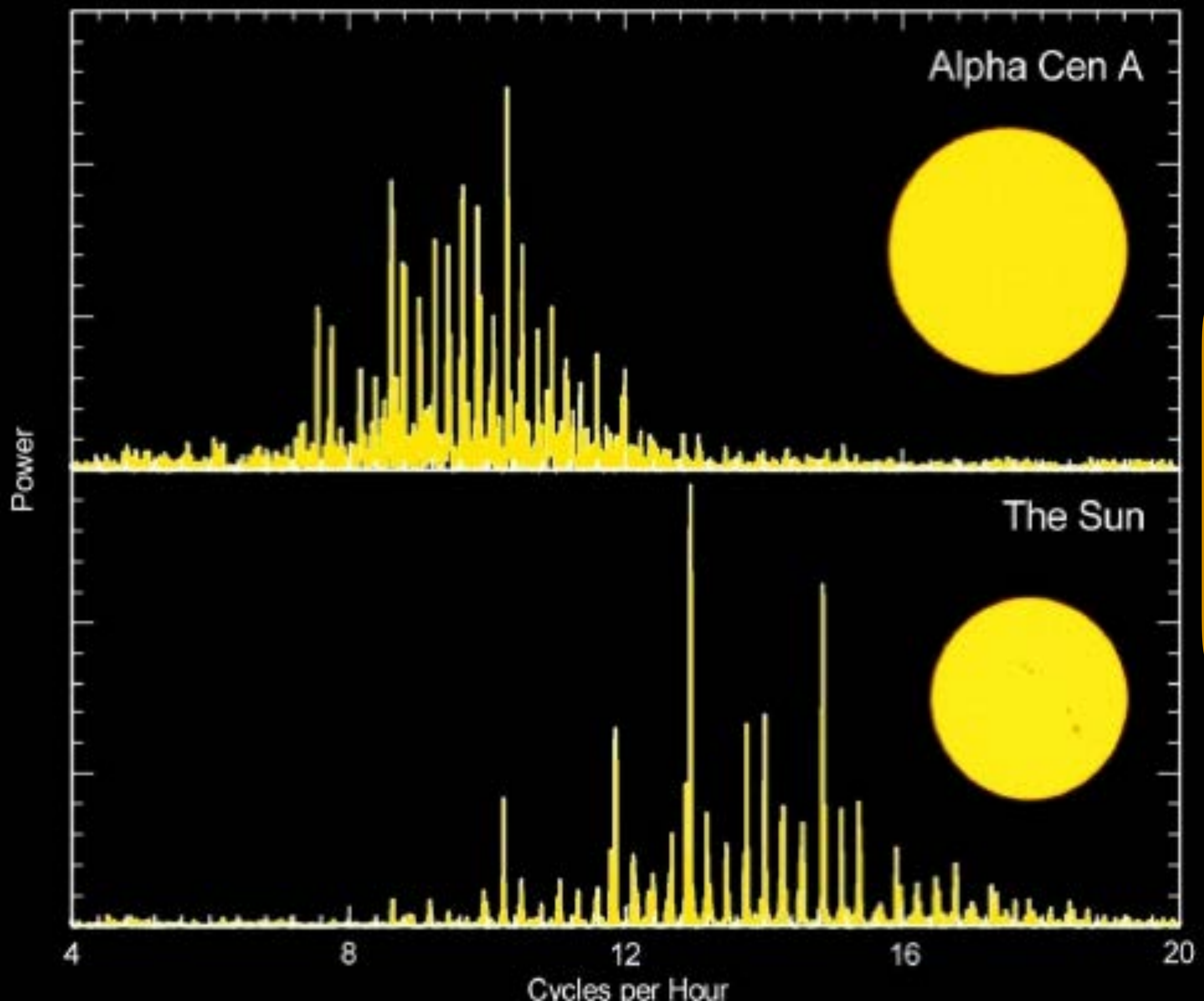
- **Low-l modes**:
  - Probe the deep interior (of the Sun)

    ➡ Sometimes called “global” modes.
  - Different peaks in power spectrum for given l correspond to different values of n

    (radial nodes, $n = 15 ... 25$ are typical)

Asteroseismology

- First reliable detection of oscillations on α Centauri A (our nearest solar analogue)
- Power spectrum shifted towards lower frequencies for α Centauri A compared to the Sun



α Cen A vs. Sun

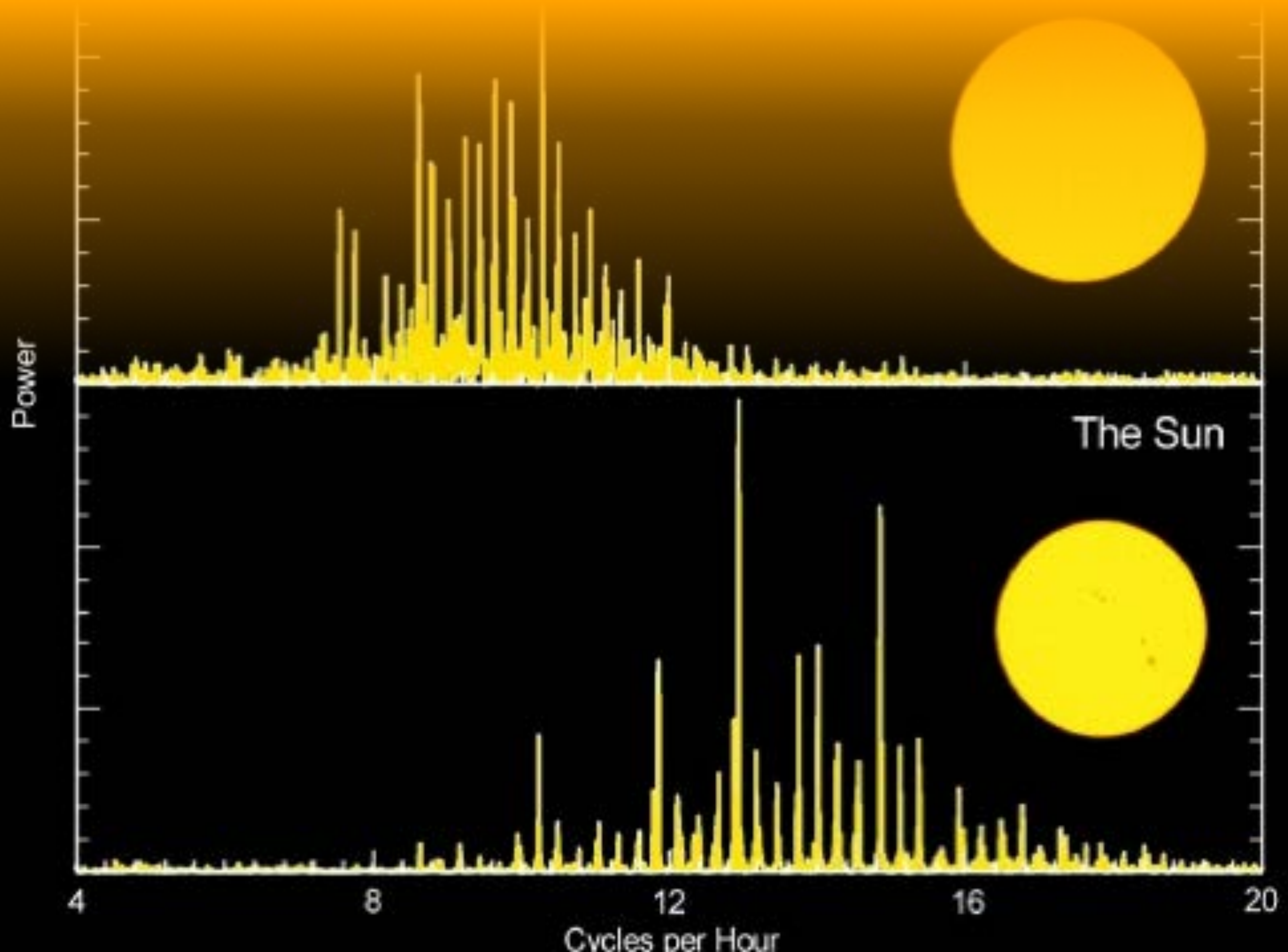
- Age: slightly older
- Mass: a bit more
- Radius: a bit more
- log g: a bit less
- Rotation: a bit faster
- Metallicity: a bit higher

Asteroseismology

- Frequency of the fundamental radial mode $l = 0$, is proportional to a star's dynamical time scale (t_{dyn})

➡ Large frequency spacing $\Delta\nu$ (between adjacent radial modes in oscillation spectrum) proportional to the dynamical time scale

$$\Delta\nu \propto \frac{1}{t_{dyn}} \propto \sqrt{\rho} \propto \left(\frac{M}{R^3}\right)^{\frac{1}{2}}$$



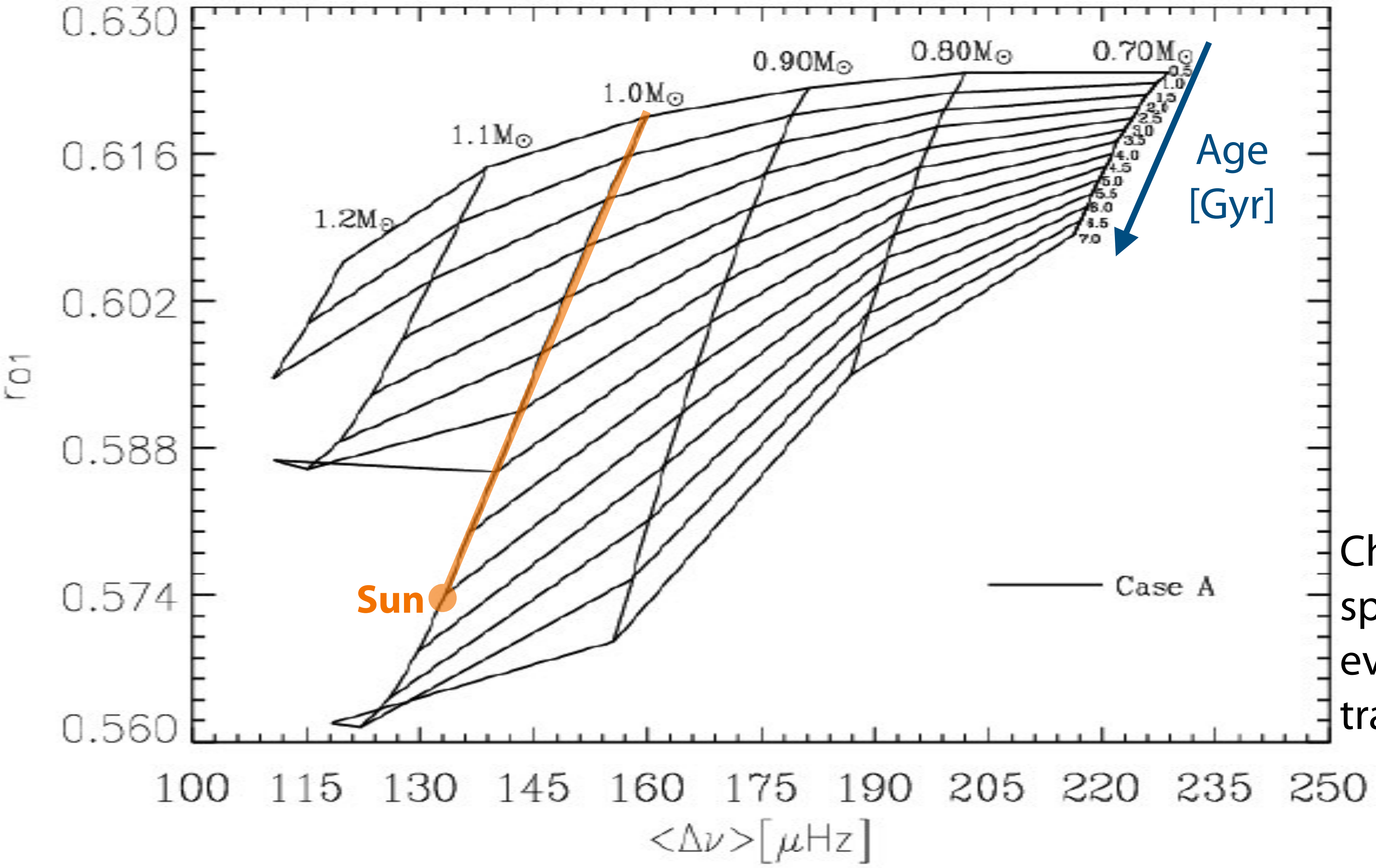
Asteroseismology

- Frequency of the fundamental radial mode $l = 0$, is proportional to a star's dynamical time scale (t_{dyn})

➡ Large frequency spacing $\Delta\nu$ (between adjacent radial modes in oscillation spectrum) proportional to the dynamical time scale

$$\Delta\nu \propto \frac{1}{t_{dyn}} \propto \sqrt{\rho} \propto \left(\frac{M}{R^3}\right)^{\frac{1}{2}}$$

➡ **Freq. spacing depends on stellar properties, changes as star evolves.**



Change of freq. spacing along evolutionary track

For the Sun (today)

$\Delta\nu \approx 136\ \mu\mathrm{Hz}$

Asteroseismology

Summary

- Asteroseismology provides additional constraints on the determinations of stellar parameters (e.g., masses, radii, mean densities, ages)
  - Important tests for stellar structure and evolution models
  - Important constraints for stellar interiors and thus generations of magnetic fields (dynamo) and stellar activity
- Synergies with exoplanet missions that look for small variations in the host star
  - Missions like Kepler, CoRoT, TESS, …
  - Mostly on radial pulsations as limited to low -l modes
- Stellar pulsations to be discussed as part of late evolution stages

- **Kavli prize in Astrophysics 2022 awarded for the field of Helio- and Asteroseismology**
  - Conny Aerts
  - Jørgen Christensen-Dalsgaard
  - Roger Ulrich

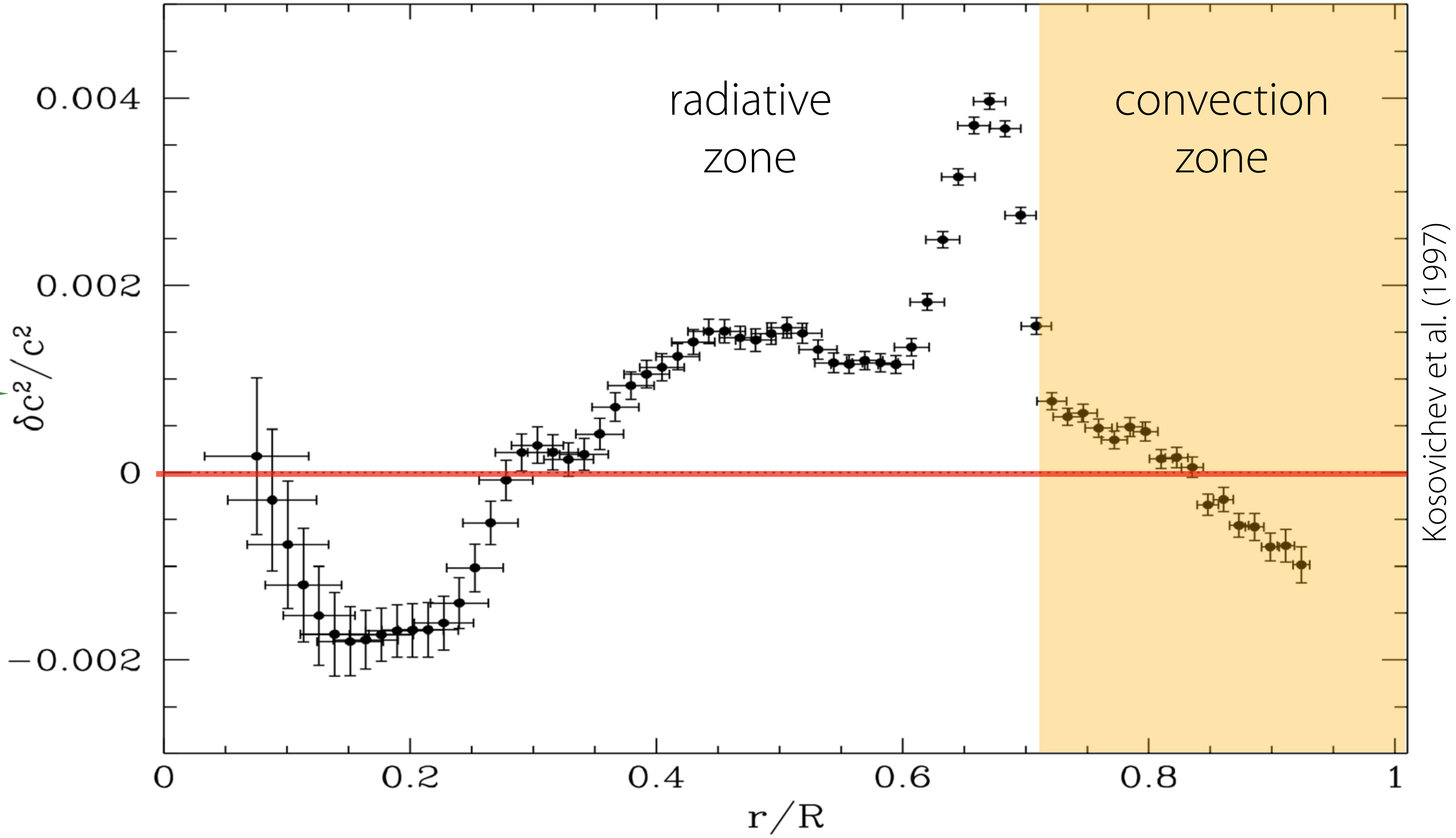
Solar neutrinos

Helioseismologic implications

Models for the structure of the solar interior

- The measured oscillation mode spectrum allows for deriving the stratification of the solar interior
- Derived sound speed **differs from the standard model** of the Sun!

Only small errors but improvements to the solar model can be made!



Relative difference between the squared sound speed as inferred from 2 months of MDI data and the standard solar model of Christensen-Dalsgaard et al. (1996)

Solar neutrinos

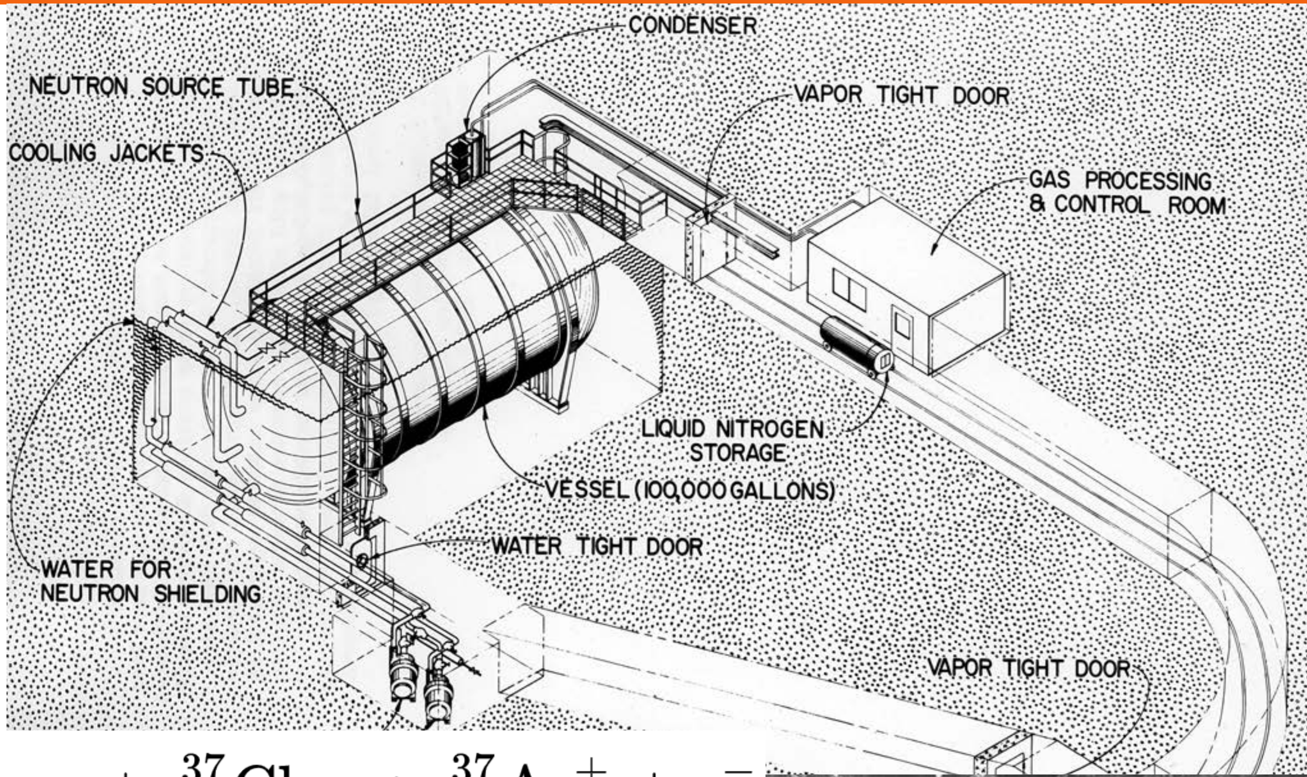
Problematic detection

- 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



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

Solar neutrinos

Problematic detection

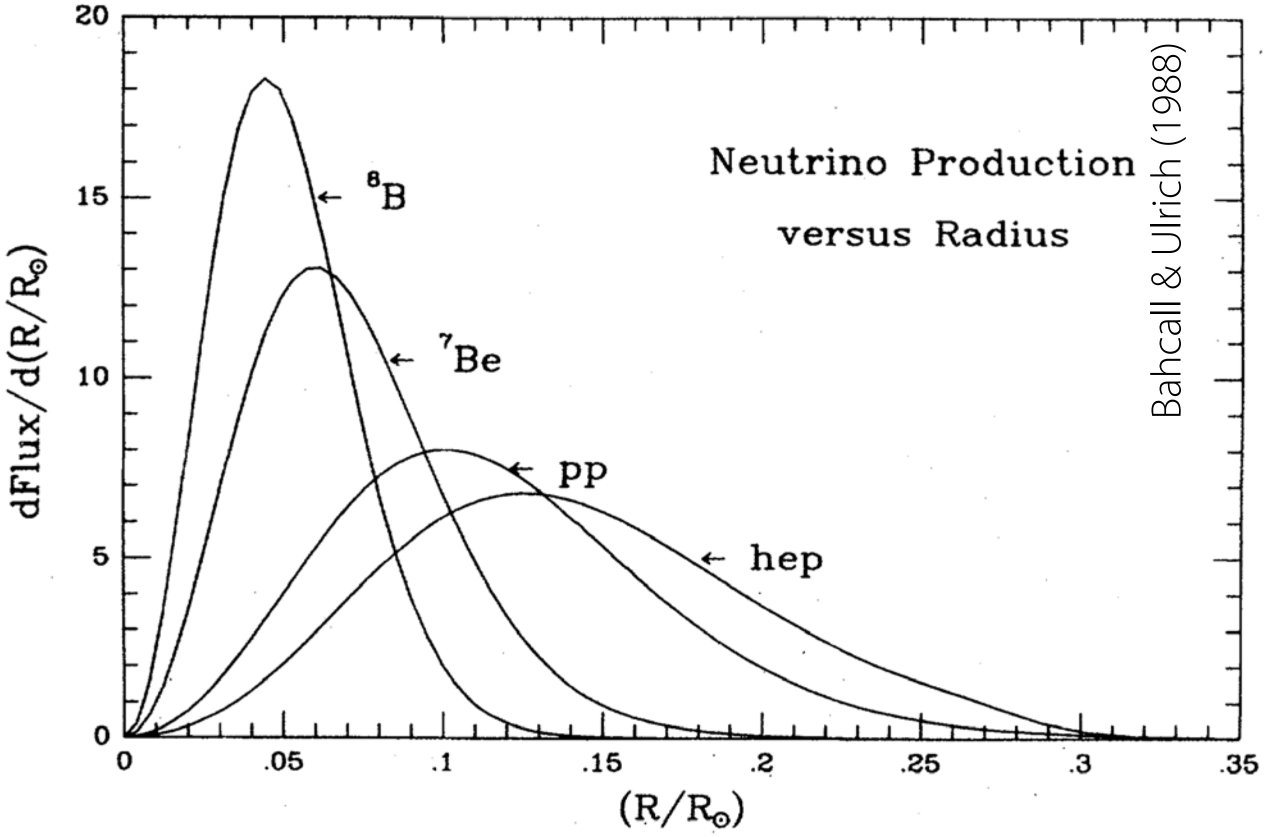
- Detection since 1967 with large chlorine tank in Homestake Gold Mine (USA, Davis Jr)

➡ 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**

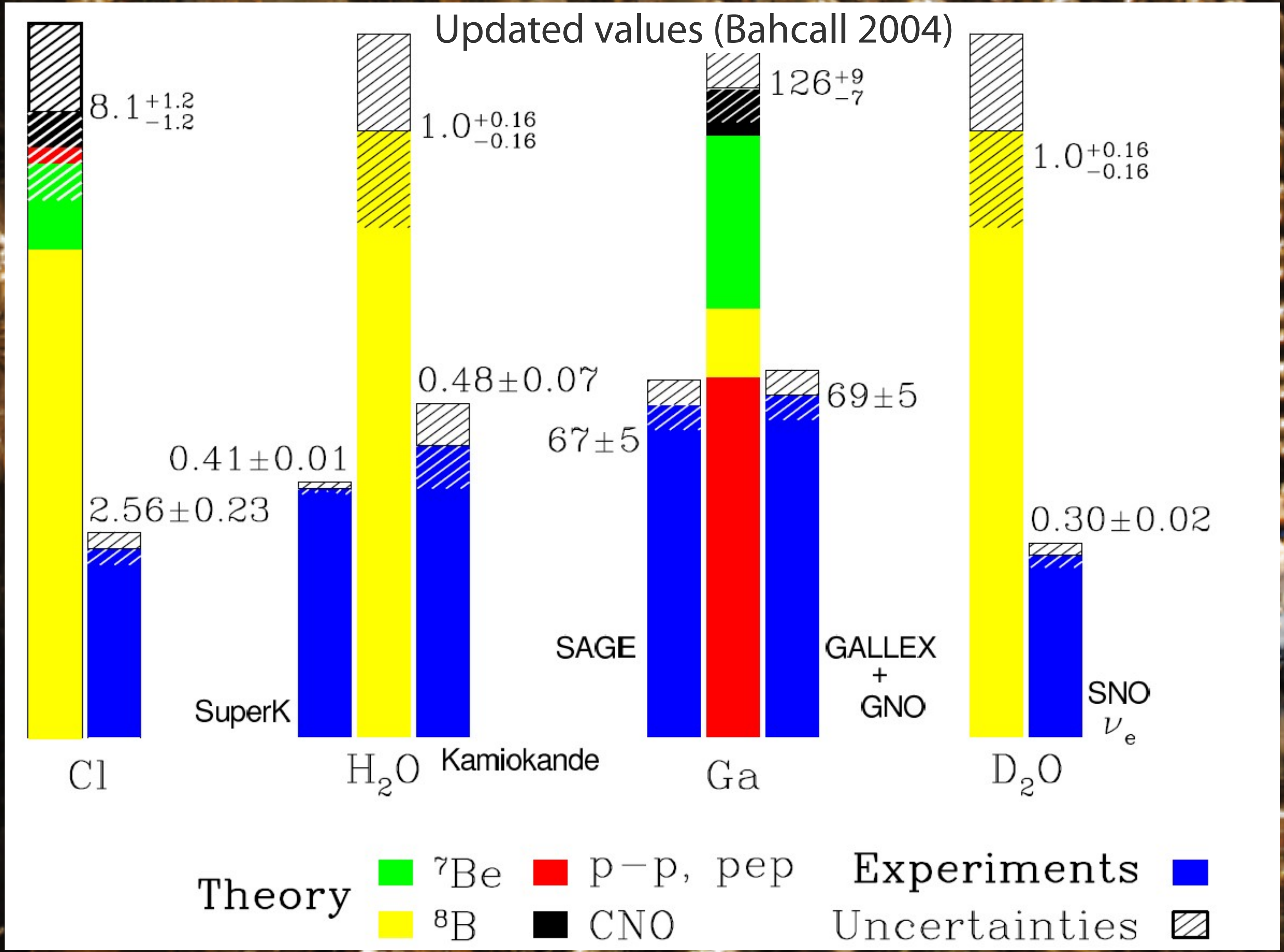
(Theoretical) neutrino production as function of radius

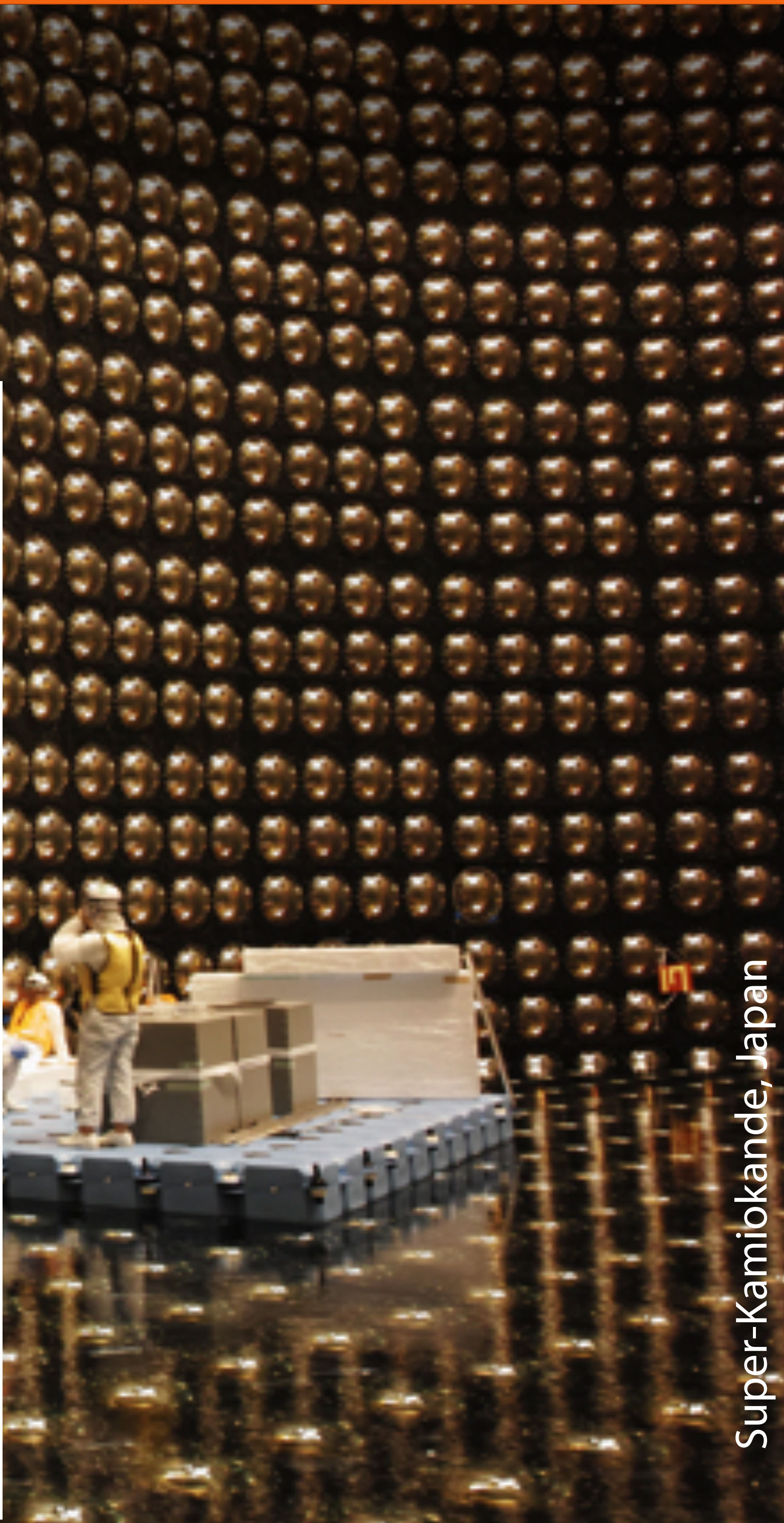


Solar neutrinos

Where are the neutrinos?

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




Super-Kamiokande, Japan

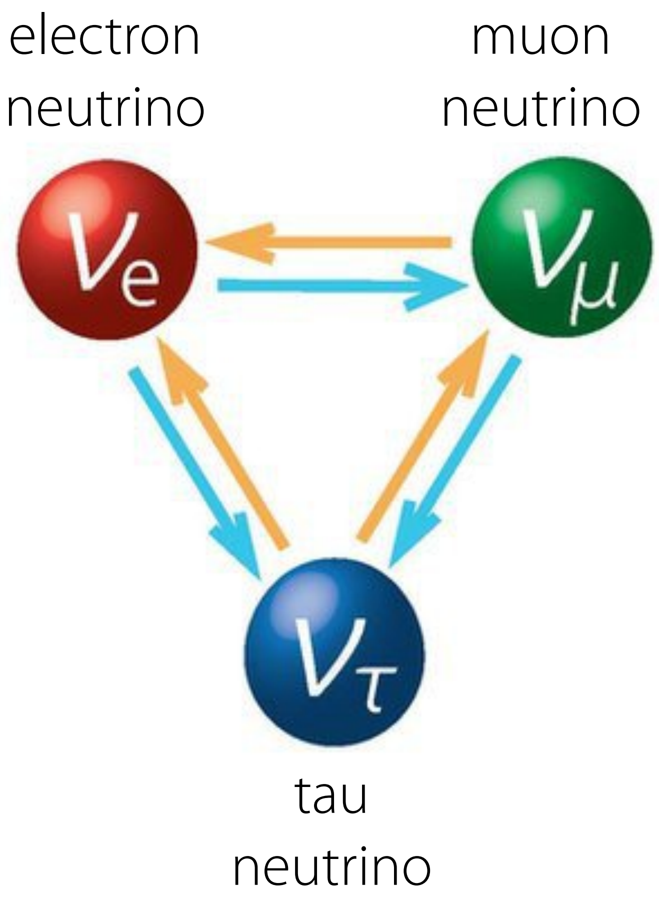
Solar neutrinos

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)

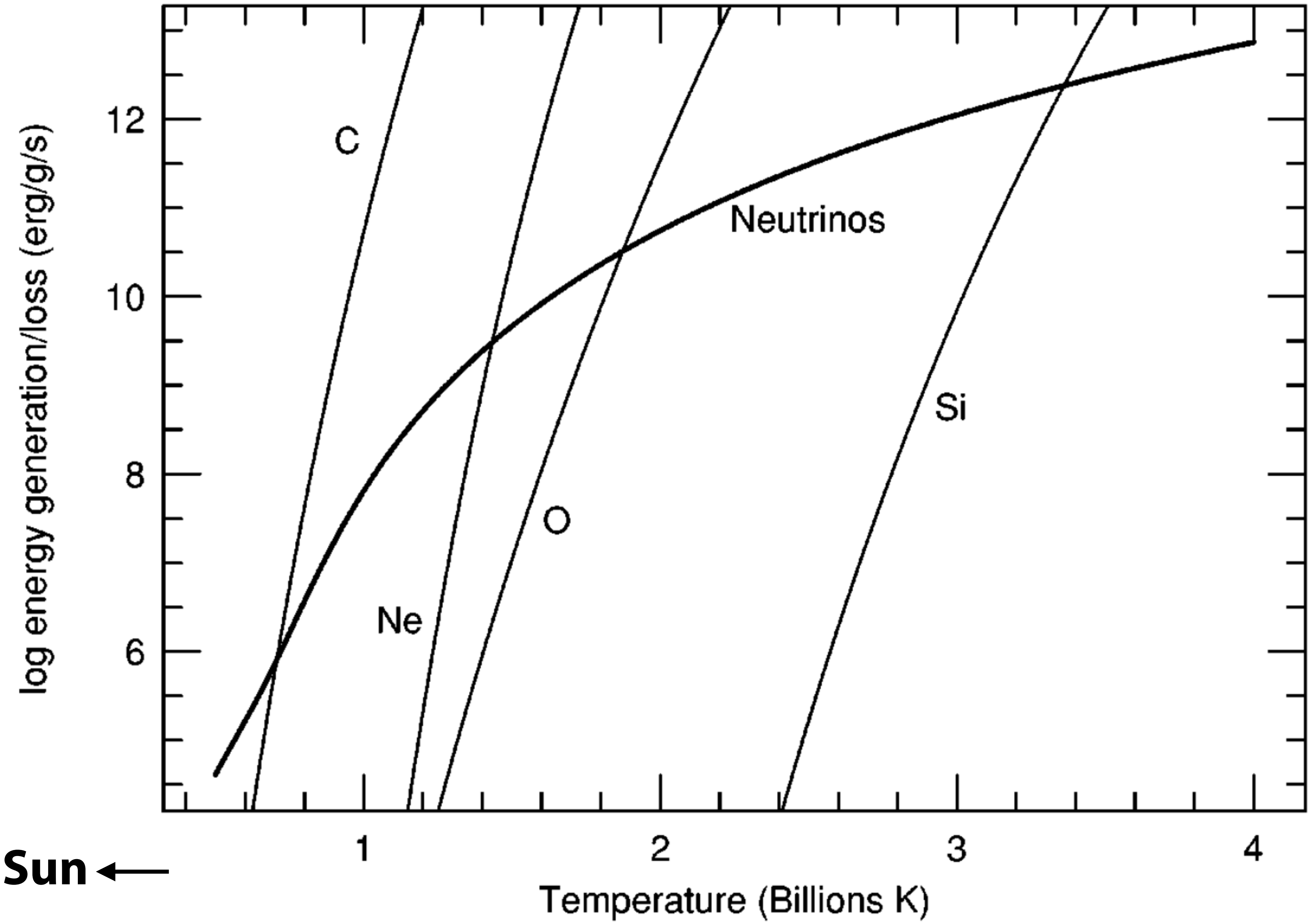
➡ Nobel prize for physics 2002 (Davis Jr., Koshiba, Giacconi)



Solar neutrinos

Neutrino production at higher temperatures

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

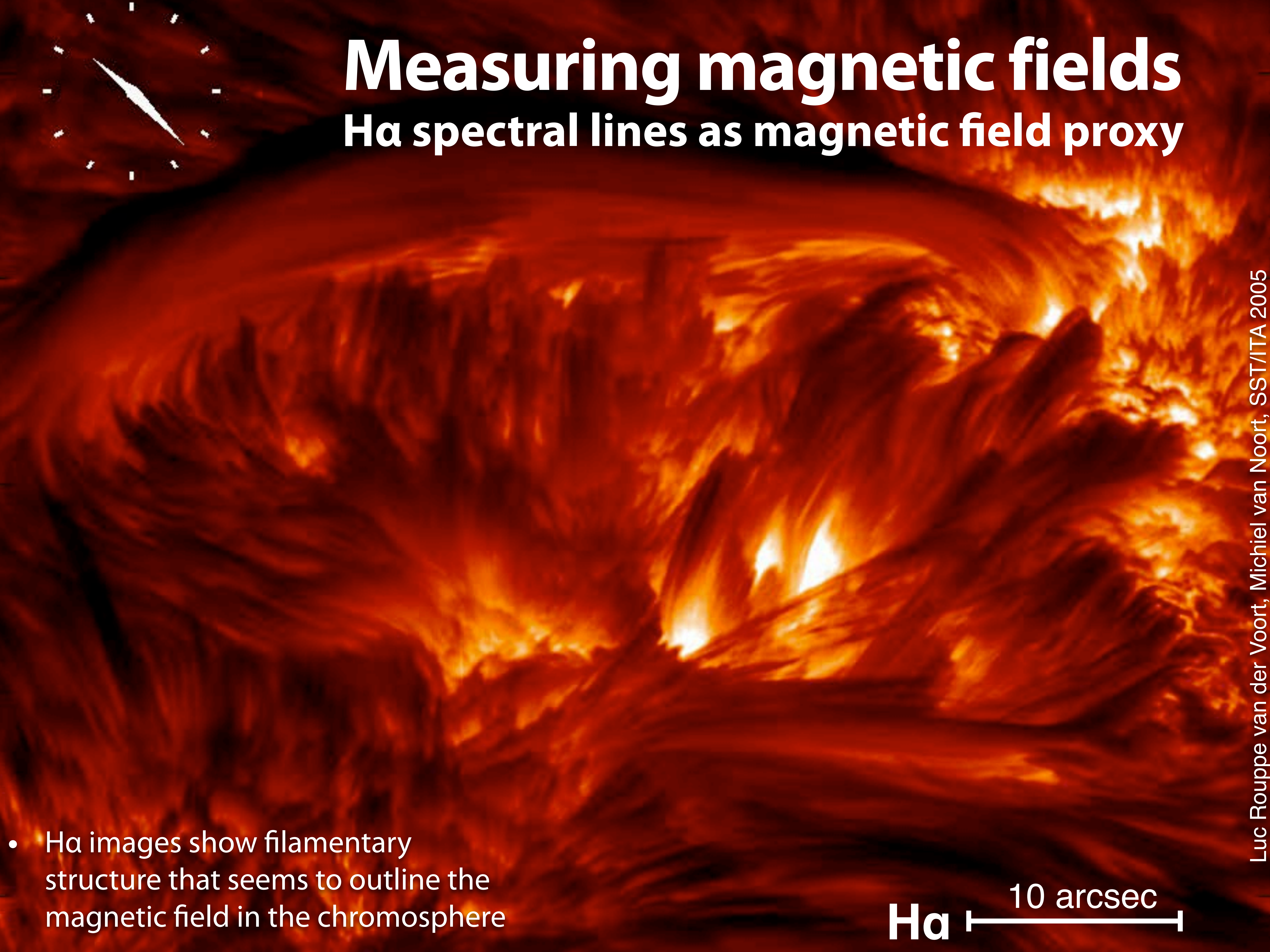


Woosey, Heger, Weaver (2002)

Measuring magnetic fields in stellar atmospheres

Measuring magnetic fields

Hα spectral lines as magnetic field proxy



Luc Rouppe van der Voort, Michiel van Noort, SST/ITA 2005

- Hα images show filamentary structure that seems to outline the magnetic field in the chromosphere

Measuring magnetic fields

Methods of magnetic field measurement

- **Direct methods:**
  - Zeeman effect — polarized radiation
  - Hanle effect — polarized radiation (scattering)
  - Gyroresonance — radio spectra

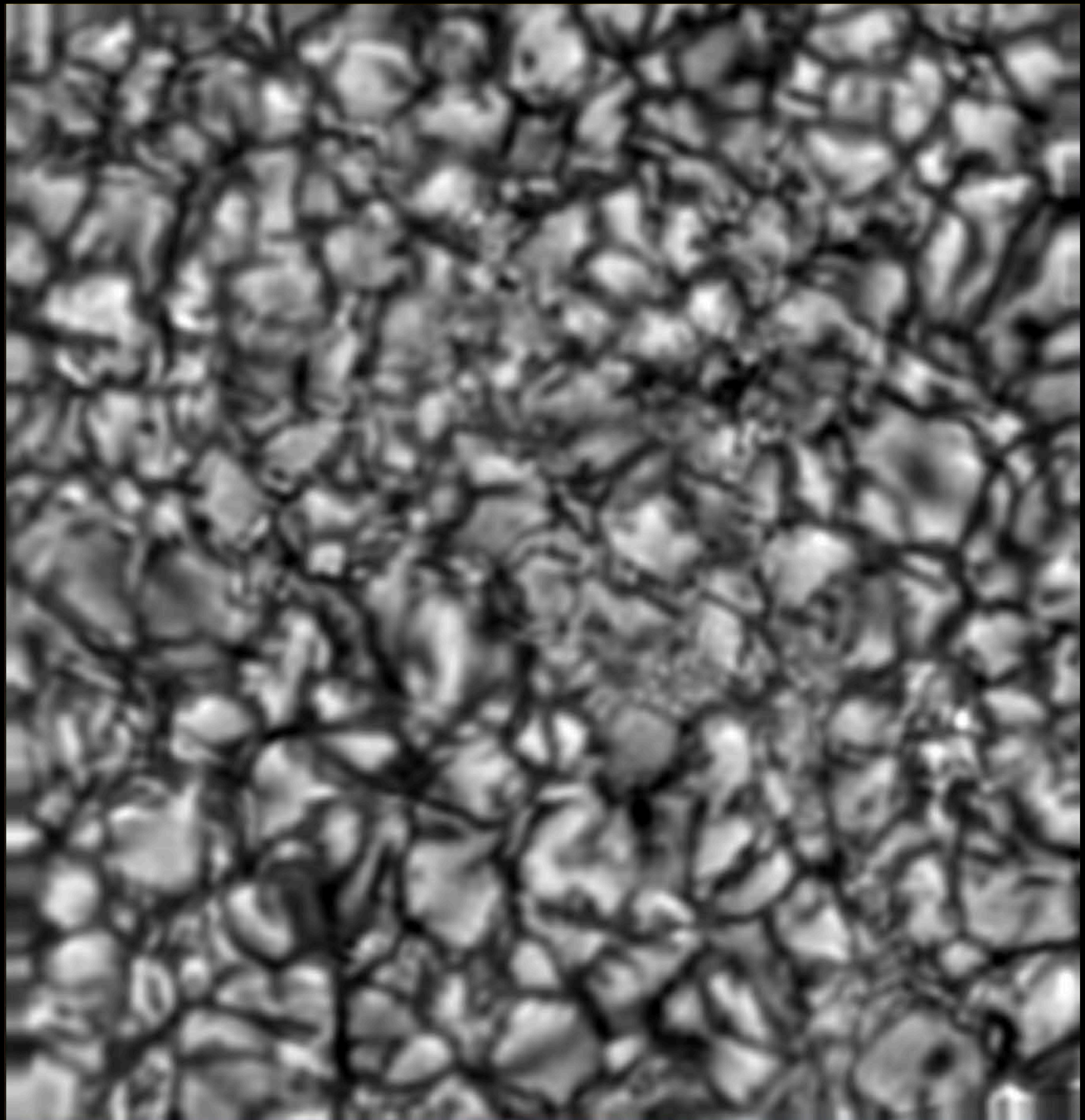
- **Indirect methods** (proxies)
  - Bright or dark features in photosphere (sunspots, G-band bright points)
  - Ca II H and K plage
  - Fibrils seen in chromospheric lines, e.g. Hα
  - Coronal loops seen in EUV or X-radiation

Measuring magnetic fields

Indirect methods

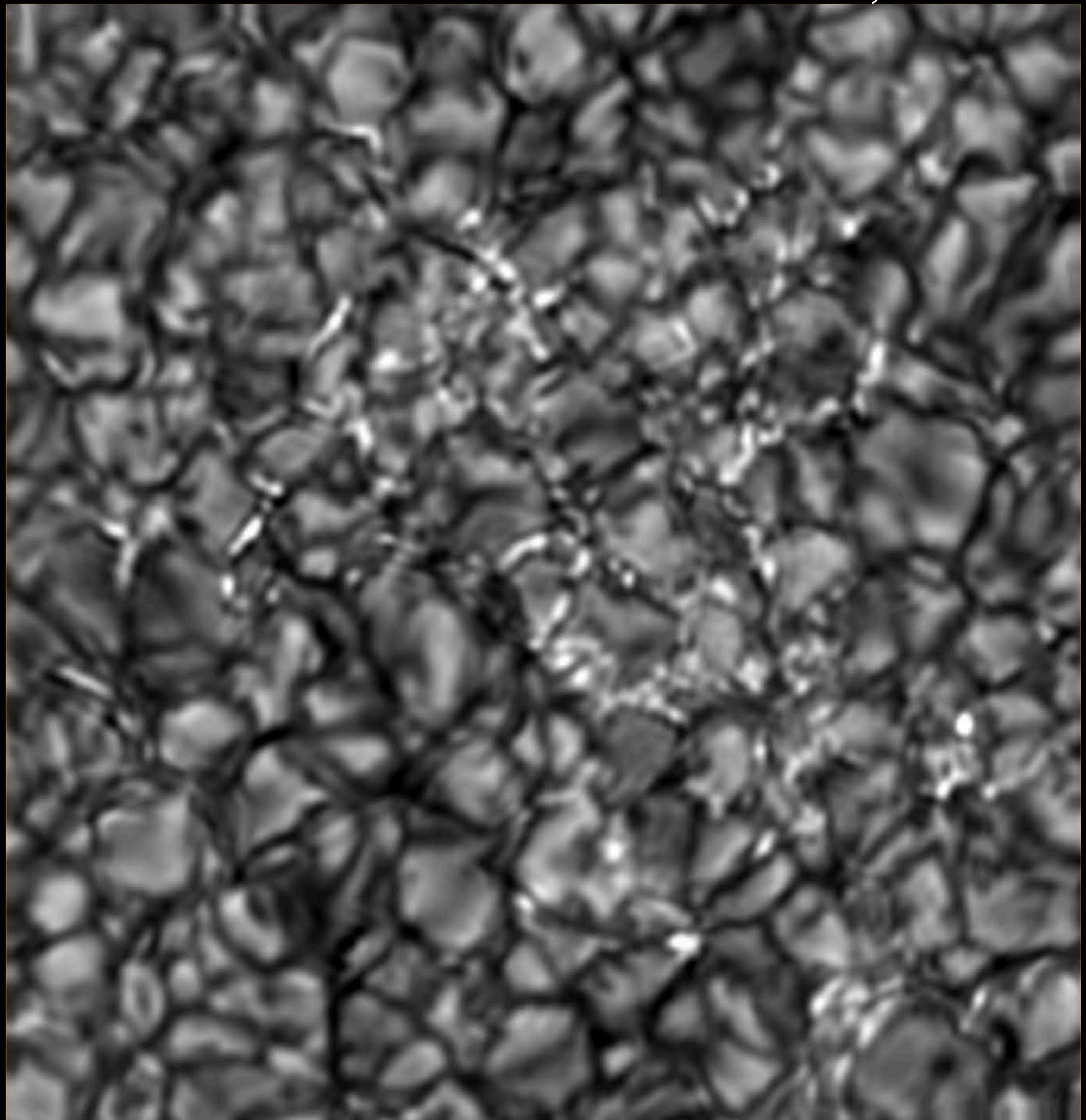
- **G-band:** Spectral range at ~431nm with a lot of absorption due to CH molecules + Fe I lines
  - Results in higher contrast for magnetic field than (regular) visible continuum

Visible continuum



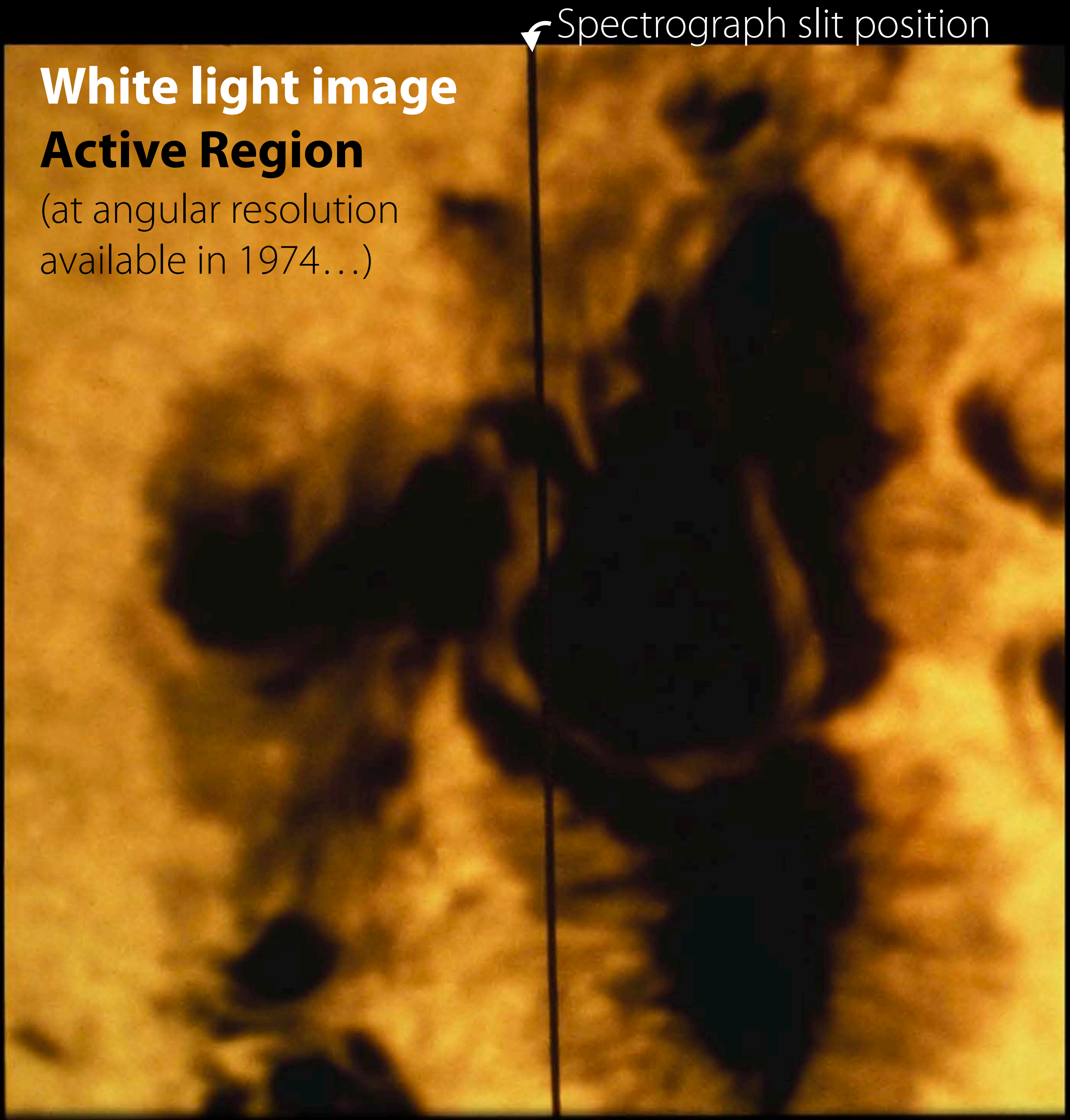
G-band

Spectral feature G
classified by Fraunhofer



Measuring magnetic fields

Zeeman diagnostics

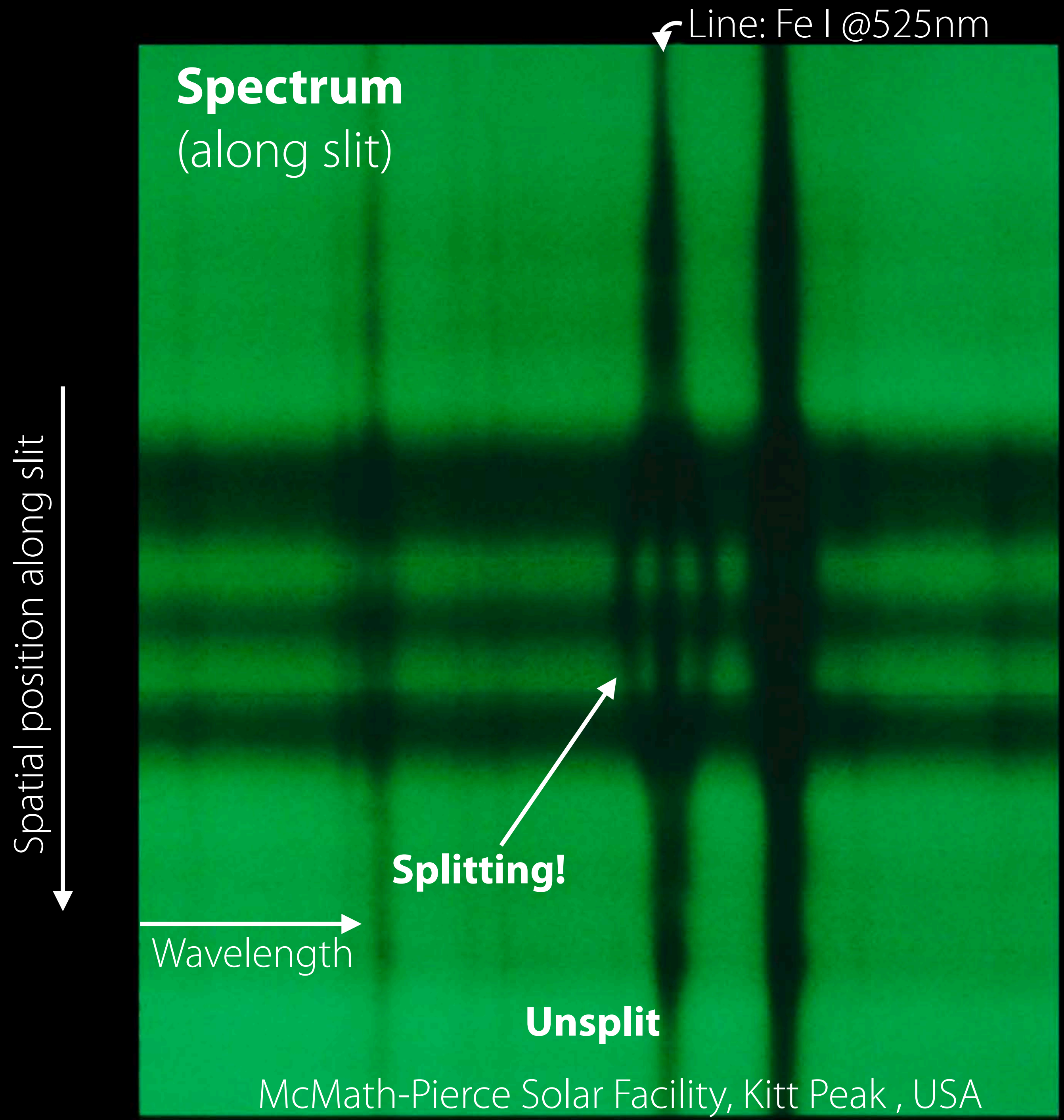


Spectrograph slit position

White light image

Active Region

(at angular resolution available in 1974…)



Line: Fe I @525nm

Spectrum

(along slit)

Spatial position along slit

Wavelength

Splitting!

Unsplit

McMath-Pierce Solar Facility, Kitt Peak , USA

- Zeeman splitting in this example indicates a magnetic field strength of ~4 kG in the sunspot