The Sun, our life-giving star

Sami K. Solanki

Lectures held in the Solar System School 2013

A Course in 8 Lectures

- **Lecture 0:** A brief overview of the Sun
- **Lecture 1:** What makes the Sun shine?
- **Lecture 2:** What messages does sunlight carry?
- **Lecture 3:** What do we see on the face of the Sun?
- **Lecture 4:** What makes the Sun so active?
- **Lecture 5:** The variable Sun: why do sunspots come and go?
- **Lecture 6:** Why is the Sun’s corona so hot and violent?
- **Lecture 7:** Is the Sun a normal star?
- **Lecture 8:** Global warming: is the Sun heating the Earth?

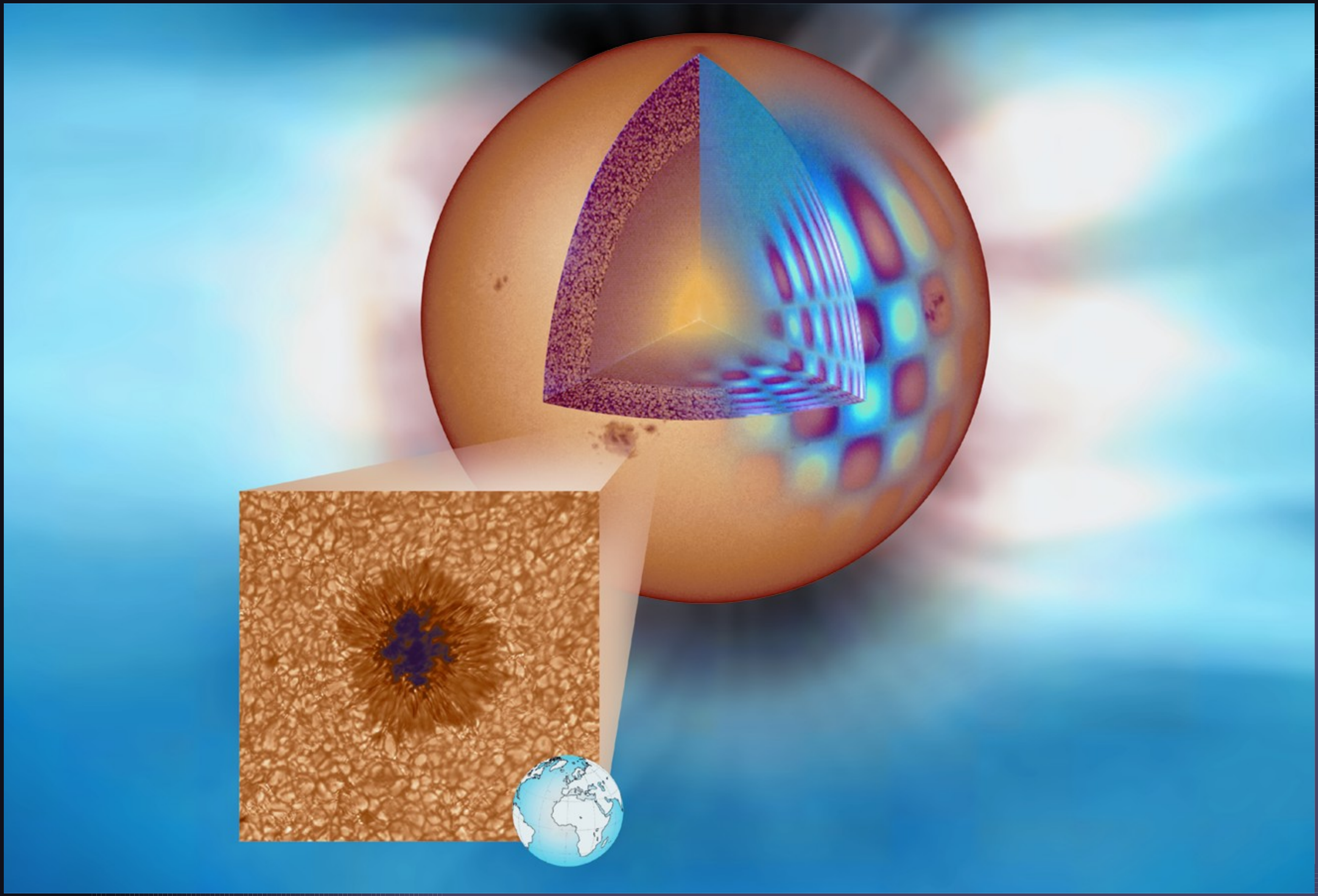
Lectures + exercises

- **Style:**
  - **Lectures** are descriptive, giving qualitative explanations with very few equations
  - **Exercises** provide you with the opportunity to get your teeth into a selection of more quantitative problems. The exercises are important. Please take them seriously

- My thanks go to (in alphabetical order):
  - **Robert Cameron**
  - **Maria Dasi**
  - **Alex Feller**
  - **Tino Riethmüller**

  for preparing and tutoring you through the exercises

A brief overview of the Sun



The Sun, our star

- The Sun is a normal star: middle aged (4.5 Gyr) main sequence star of spectral type G2
- The Sun is a special star: it is the only star on which we can resolve the spatial scales on which fundamental processes take place
- The Sun is a special star: it provides us with a unique laboratory in which to learn about various branches of physics
- The Sun is a special star: it provides almost all the energy reaching the Earth from outside

The Sun is our life-giving star!

The Sun: a few numbers I

- **Mass** = 1.989 10^{30} kg (= 1 $M_{\odot}$) ≈ 99.86% mass of solar system ≈ million times mass of Earth ($M_{\oplus}$)
- **Radius** = 6.963 10^{5} km = 109 $R_{\oplus}$ ≈ 2 x Earth-Moon distance
- **Average density** = 1.4 g/cm^3 (density of Earth = 5.5 g/cm^3)
- **Core density** = 1.5×10^2 g/cm^3 (Earth core: 10^4 g/cm^3)
- **Luminosity** = 3.84 10^{26} W (= 1 $L_{\odot}$)
- **Effective temperature** = 5777 K (G2 V)
- **Core temperature** = 15.7 10^6 K
- **Surface gravitational acceleration** g = 274 m/s^2 (≈ 28 $g_{\oplus}$ ≈ 10 m/s^2)

The Sun: a few numbers II

- Age = 4.55 10^9 years (from meteorite isotopes; same as Earth)
- Distance = 1 AU = 1.496 (+/-0.025) 10^8 km (≈8 light minutes)
- Composition: By number = H: 90%, He: ≈ 10%, all other elements: <1%; By mass = H: 74%, He: 24%, rest: 2%
- Rotation period ≈ 27 days at equator (synodic, i.e. as seen from Earth; Carrington rotation)
- Angular size: 31.6' – 32.7' (over Earth's elliptical orbit)
- 1 arc sec = 722±12 km on solar surface, at centre of solar disc (elliptical Earth orbit)

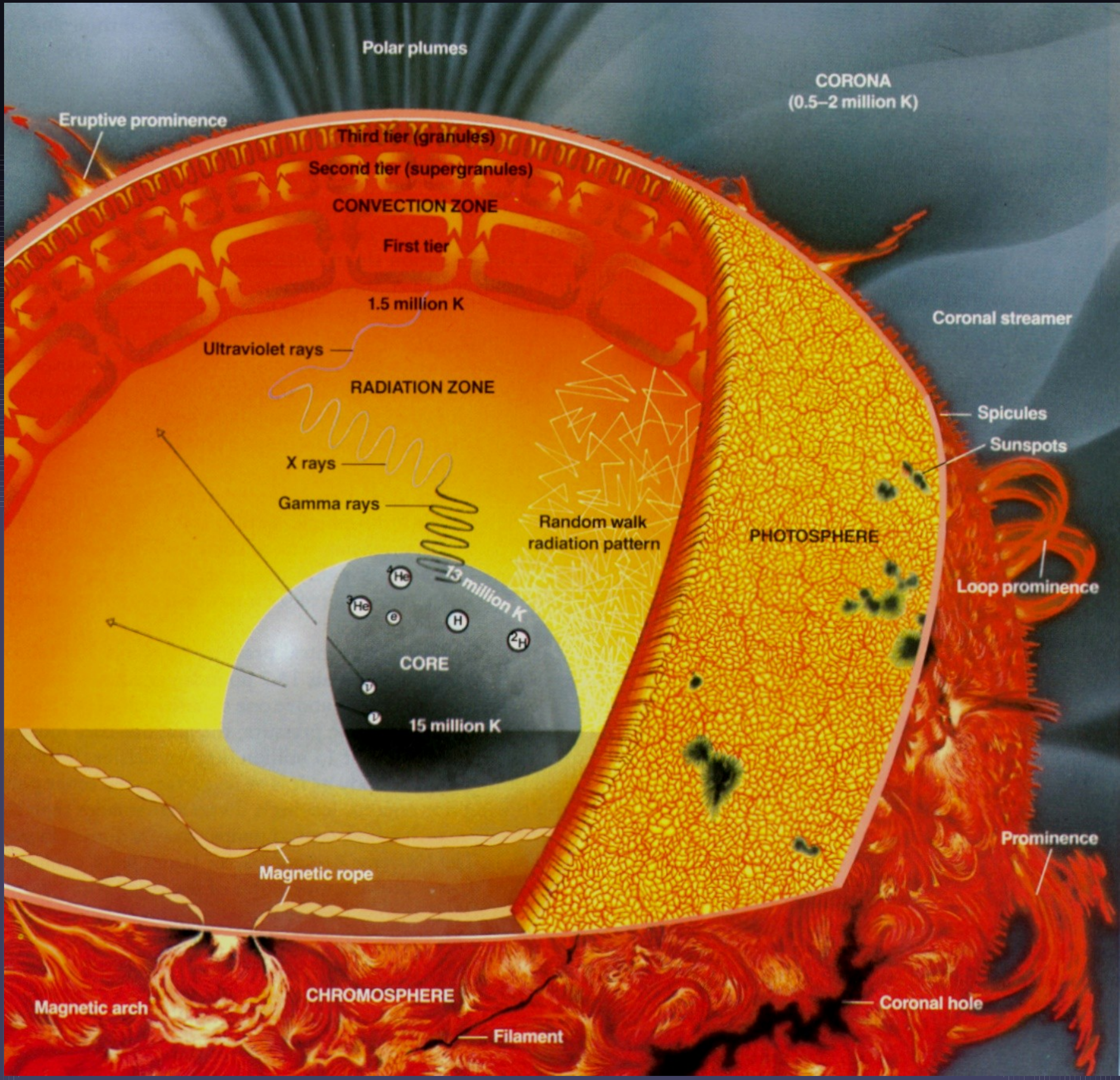
The Sun's Structure

Solar interior:

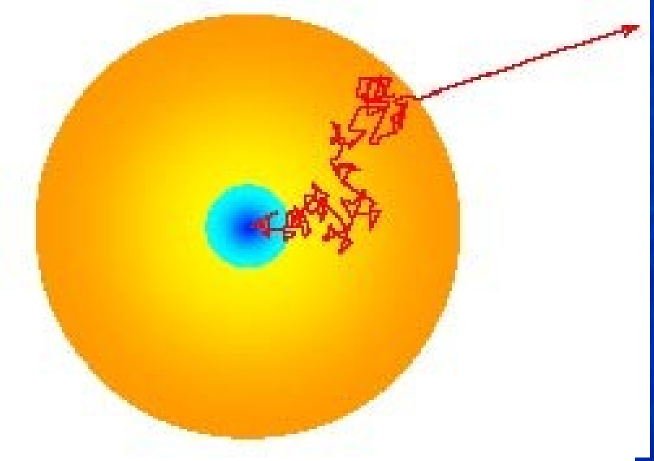
- Everything below the Sun's (optical) surface
- Divided into hydrogen-burning core, radiation and convection zones

Solar atmosphere:

- Directly observable part of the Sun
- Divided into photosphere, chromosphere, corona, heliosphere



The Sun as seen by radiation



- **Solar interior**: Photons are repeatedly absorbed & reemitted and make a random walk. Mean free path increases rapidly with distance from solar core (0.01 cm). Photon escape time: $\approx 10^5$ years.

- **Solar surface:** where photons escape from Sun. Location of the surface depends on the wavelength. For the standard surface, visible continuum is often used (next slide)

- **Solar atmosphere:** layers through which most photons can travel unhindered (optically thin layers). However, some photons are still produced, destroyed or scattered there

- **Heliosphere:** very low density. Almost no collisions between particles, nearly no interaction with photons (only scattering)

Optical depth and the solar surface

- Solar material exhibits no phase transition (e.g. from solid or liquid to gaseous as on Earth) → define solar surface through its radiation

- Photons in solar interior are repeatedly absorbed & reemitted → material is optically thick, i.e. optical depth τ is large. Def:

$$\mathrm{d}\tau_\lambda = \kappa_\lambda ds, \quad \kappa_\lambda = \text{absorption coeff.} \quad \Rightarrow \quad \tau_\lambda(s) = \int_0^s \kappa_\lambda ds$$

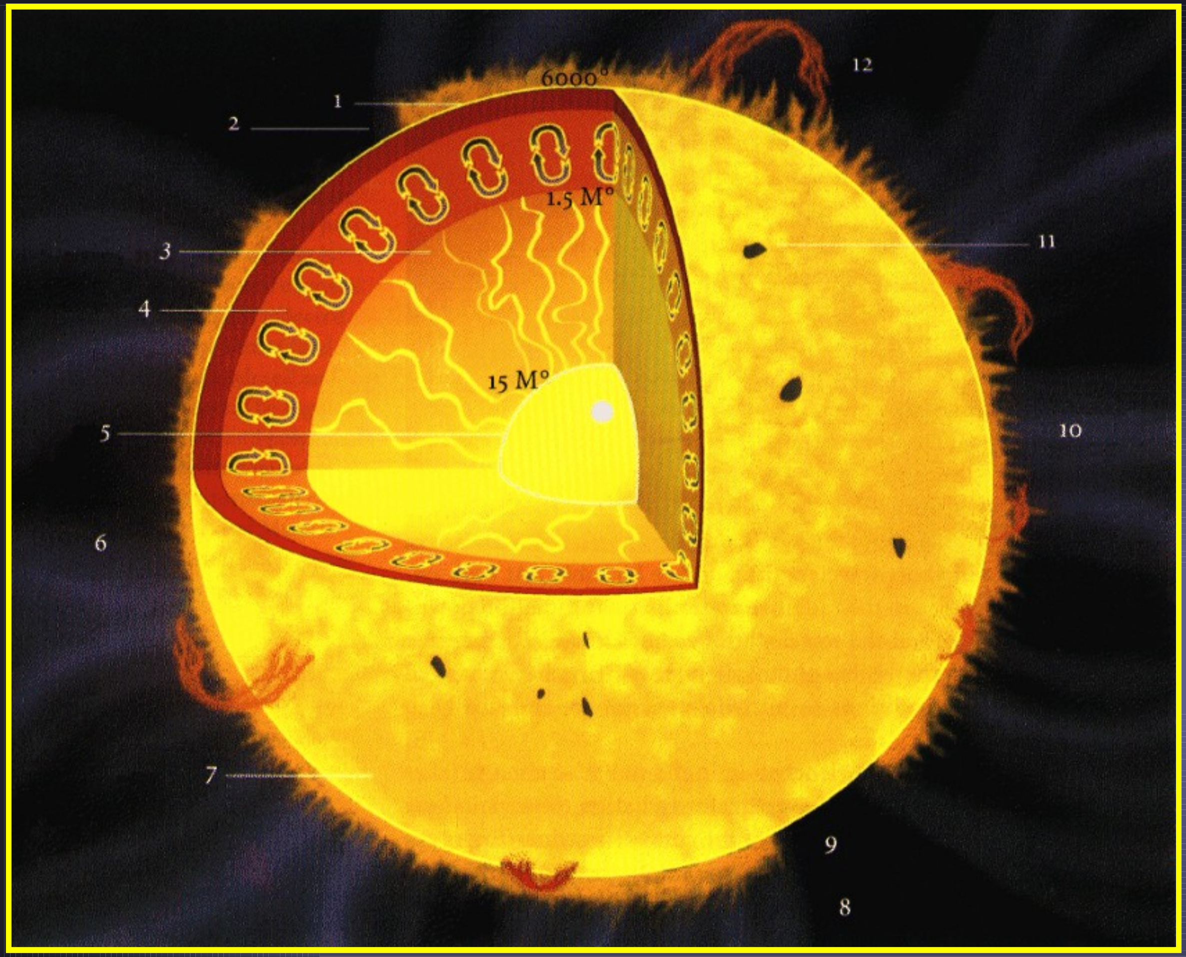
- Solar surface: where average vertical mean free path becomes so large that photons escape from Sun. Surface corresponds to optical depth $\tau = 1$. Its height depends on λ

- Often $\tau = 1$ at $\lambda = 5000$ Å is used as standard for the solar surface

- Other definitions, e.g. via acoustic waves, also possible

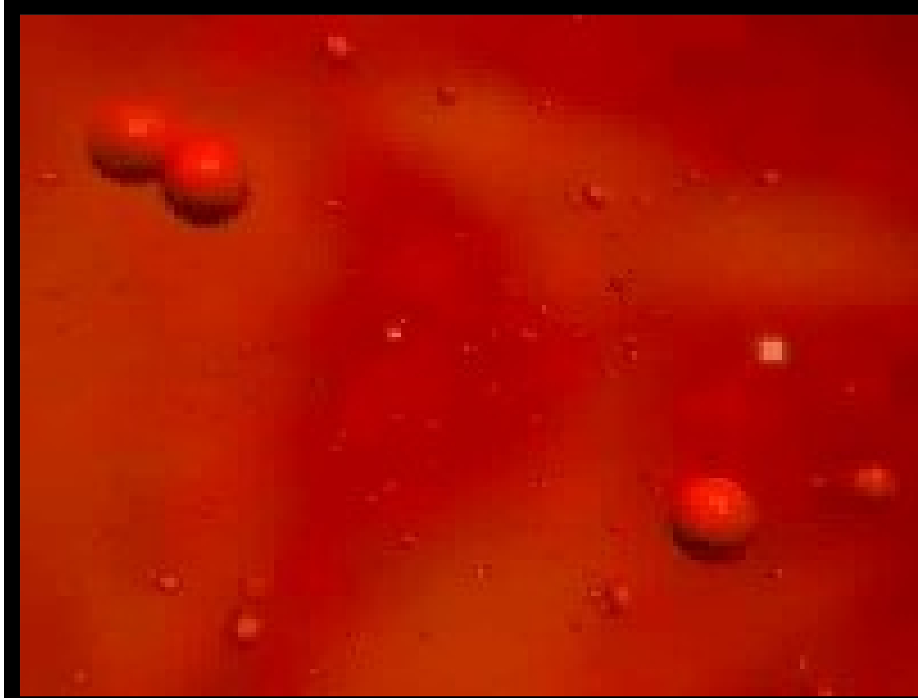
What makes the Sun shine?

The solar interior

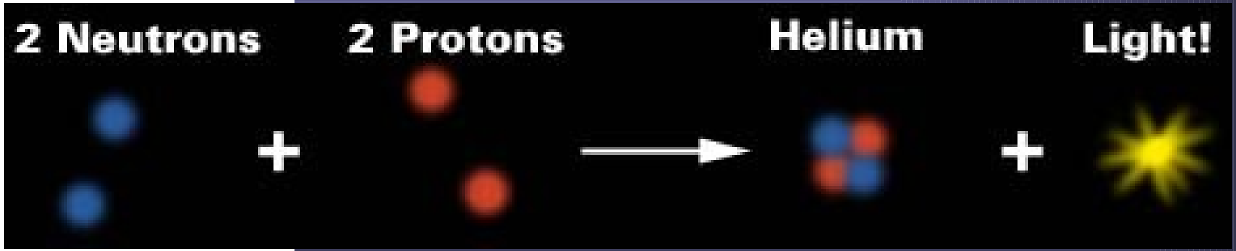


The Sun's core

- In the Sun's core, mass is turned into energy. 99% of energy is produced within 24% of solar radius
- Nuclear reactions burn 6×10^{11} kg/s of H into He
- → 3.7 10^{38} protons to α-particles (He nuclii) per sec
- In core, particle density and temperature are high → individual protons ram into each other at sufficient speed to overcome the Coulomb barrier, forming He nuclii and releasing energy



At high temperature of core: fully ionized plasma



Nuclear reactions in solar core

- Sun gains practically all its energy from the reaction
  $4p \rightarrow \alpha + 2e^{+} + 2\nu \longleftrightarrow 4H \rightarrow {}^{4}He + 2e^{+} + 2\nu$

- Two basic routes
  - p-p chain: yields about 99.2% of energy in Sun
  - CNO cycle : 0.8% of energy released in present day Sun (but dominant form of energy release in hotter stars)

- Both chains yield a total energy Q of 26.7 MeV per He nucleus, mainly in form of γ-radiation Q_{γ} (which is absorbed and heats the gas) and neutrinos Q_{ν} (which escapes from Sun)

- 0.7% of a proton's mass is converted into energy in the process

process

Nuclear reactions of pp-chain

- p = proton
- d = deuterium
- α = Helium
- γ = radiation
- ν = neutrino
- 2nd reaction replaces
  step 3 of
  1st r

Table 2.1. Nuclear reactions of the pp chains. Energy values according to Bahcall and Ulrich (1988) and Caughlan and Fowler (1988)

	Reaction	Q'[MeV]		Q_ν[MeV]	Rate symbol	
ppI	$p(p,e^+\nu)d$	1.177	(x2)	0.265	λ_{pp}	
	$d(p,\gamma)^3He$	5.494	(x2)		λ_{pd}	87%
	$^3He(^3He,2p)\alpha$	12.860			λ_{33}	
ppII	$^3He(\alpha,\gamma)^7Be$	1.586			λ_{34}	
	$^7Be(e^-,\nu\gamma)^7Li$	0.049		0.815	λ_{e7}	13%
	$^7Li(p,\alpha)\alpha$	17.346			λ'_{17}	
ppIII	$^7Be(p,\gamma)^8B$	0.137			λ_{17}	
	$^8B(,e^+\nu)^8Be^*$	8.367		6.711	λ_8	.015%
	$^8Be^*(,\alpha)\alpha$	2.995			λ'_8	

- 3rd reaction replaces steps 2+3 of 2nd reaction
- Branching ratios:
  - 1st vs. 2nd + 3rd 87 : 13
  - 2nd vs. 3rd $\longrightarrow$ 13 : 0.015

Solar neutrinos

- Neutrinos, ν, are produced at various stages of the pp-chain.
- Neutrinos are also produced by the reaction: p(p e$^-$, ν)d , so-called pep reaction. Being a 3-body reaction it is too rare to contribute to the energy, but does contribute to number of ν.

	Reaction	Q' [MeV]	Q_ν [MeV]
ppI	$p(p,e^+\nu)d$	1.177	0.265
	$d(p,\gamma)^3He$	5.494	
	$^3He(^3He,2p)\alpha$	12.860	
ppII	$^3He(\alpha,\gamma)^7Be$	1.586	
	$^7Be(e^-,\nu\gamma)^7Li$	0.049	0.815
	$^7Li(p,\alpha)\alpha$	17.346	
ppIII	$^7Be(p,\gamma)^8B$	0.137	
	$^8B(,e^+\nu)^8Be^*$	8.367	6.711
	$^8Be^*(,\alpha)\alpha$	2.995	

Solar neutrinos II

- Since 1968 the Homestake ^{37}Cl experiment has given a value of 2.1 ± 0.3 snu (solar neutrino units; 1snu =1 ν / 10^{36} target atoms) for rare, high energy ^{8}B ν
- Standard solar models predict: 7 ± 2 snu

□Solar Neutrino Problem! Problem with solar model?

- In 1980s & 90s water-based Kamiokande and larger Superkamiokande detectors found that ~1/2 of ^{8}B ν were missing
- ^{71}Ga experiments (GALLEX at Gran Sasso & SAGE in Russia) found too low neutrino flux, even including $p(p,e^{+}\boldsymbol{\nu})d$ neutrinos.

Ray Davis, Nobel Prize 2002

Homestake detector

Resolution of neutrino problem

- SNO (Sudbury Neutrino Observatory) in Sudbury, Canada uses D_2O and can detect not just the electron neutrino, but also μ and τ neutrinos

The neutrinos aren't missing, e^- neutrinos produced in the Sun just convert into μ and τ neutrinos on the way

The problem lies with the neutrino physics

- The neutrino has a small rest mass (10^{-8} m_e), which allows it to oscillate between the three flavours: e^- neutrino, μ neutrino and τ neutrino. First proposed 1959, 1968 by italo-russian theorist: Bruno Pontecorvo (partly together with Vladimir Gribov, 1969) … but nobody believed them
- Confirmation by measuring anti-neutrinos from power plant (with Superkamiokande).

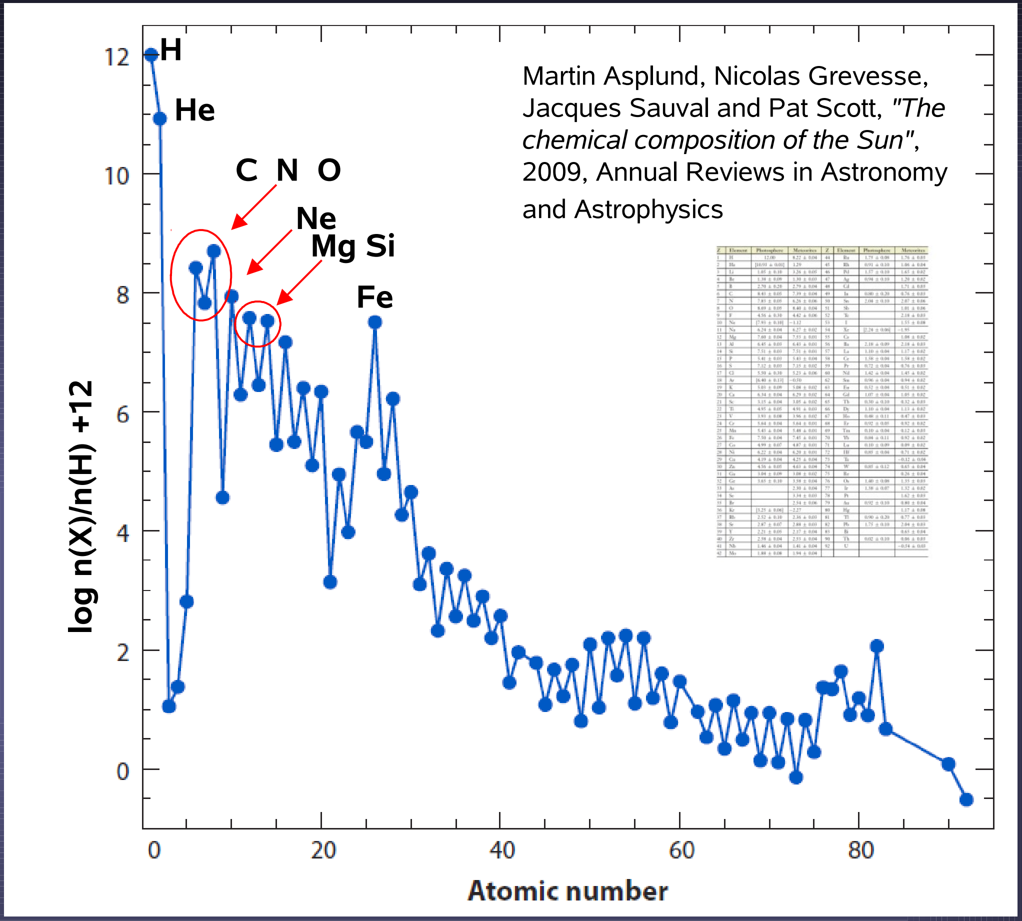
Standard solar model

- Ingredients: mainly Conservation laws and material dependent equations
  - Mass conservation
  - Hydrostatic equilibrium (= momentum conservation in a steady state)
  - Energy conservation
  - Energy transport
  - Equation of state
  - Expression for entropy
  - Nuclear reaction networks and reaction rates → energy production
  - Opacity
- Assumptions: standard abundances, no mixing in core or in radiative zone, hydrostatic equilibrium, i.e. model passes through a stage of equilibria (the only time dependence is introduced by reduction of H and build up of He in core).

Elemental abundances

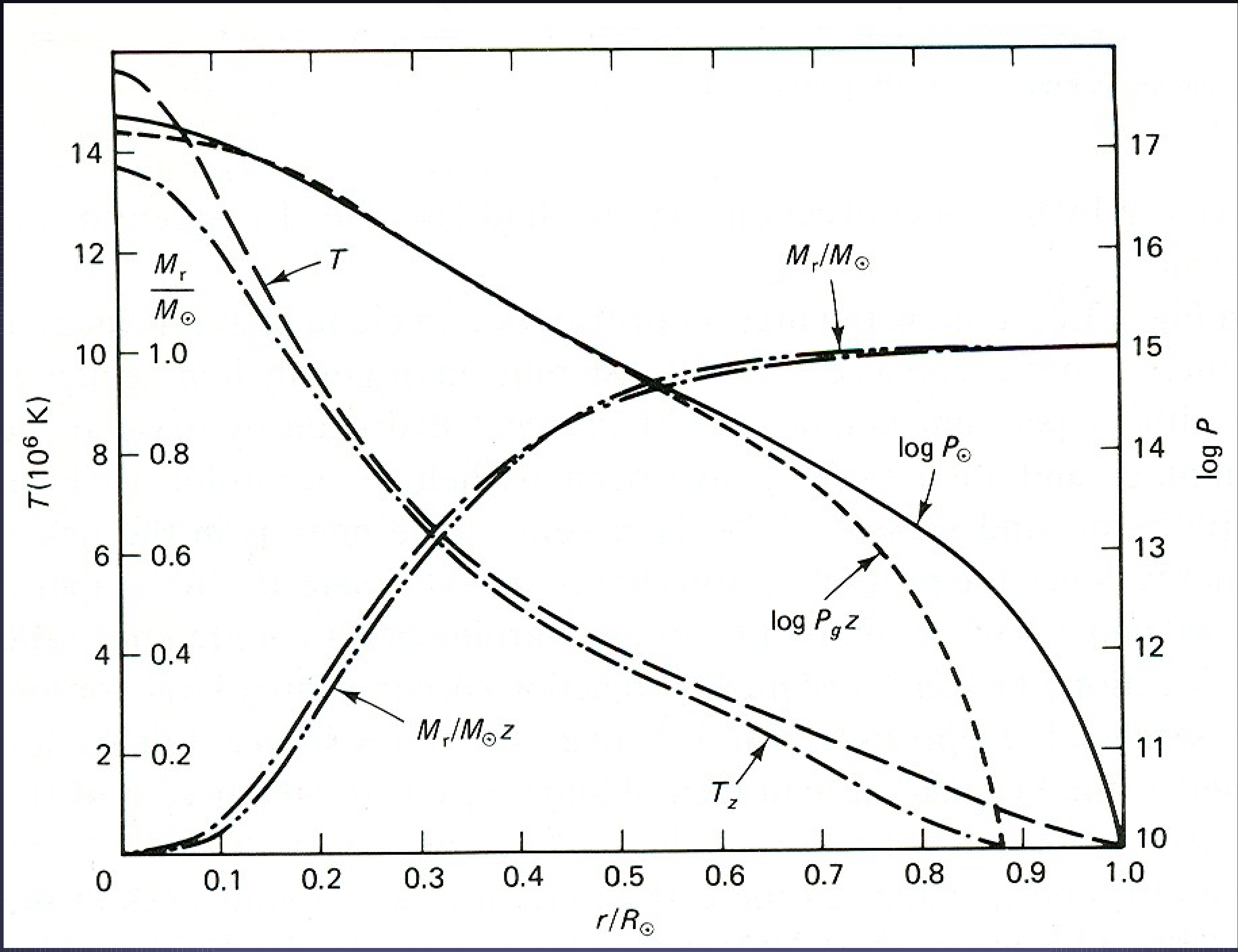
- **Photospheric values**
- Logarithmic (to base 10) abundances of elements on a scale on which H has an abundance of 12

- Solar photospheric abundances are very similar to those of meteorites, except Li, is depleted ×100
- All elements except H, He and Li were produced entirely within earlier generations of stars & released at their death
- Solar core has enhanced He; corona has different abundances (FIP effect)



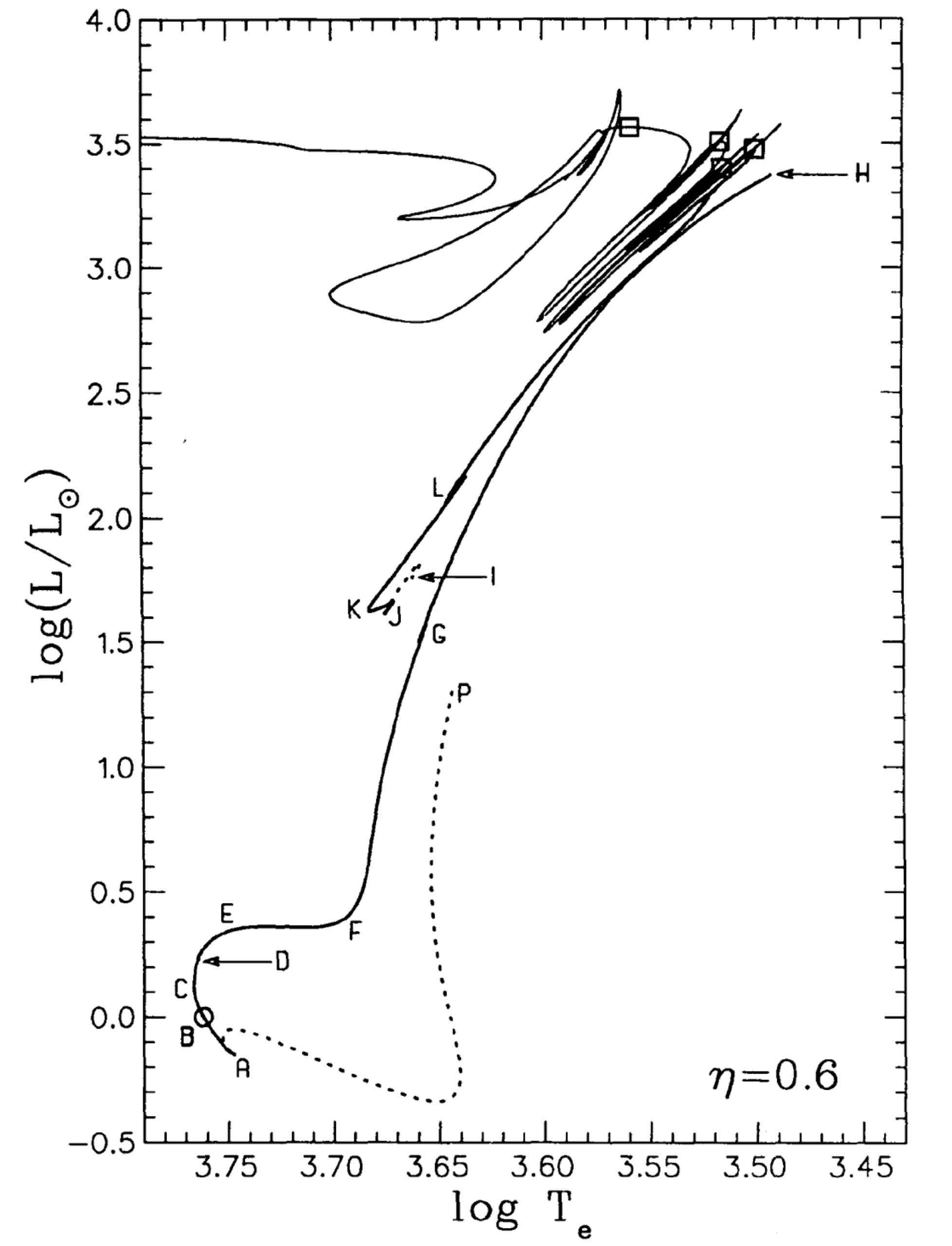
Internal structure of the Sun

- Internal models shown for ZAMS Sun (subscript z) and for present day Sun (radius reaching out to 1.0, subscript □)



Solar evolution

- Path of the Sun in the HR diagram, starting in PMS (pre-main-sequence) stage ‘P’ and ending at
  - Red giant stage
  - White dwarf stage
- Note the complex patch during the red giant phase due to various phases of Helium burning and core contraction and expansion, etc.
- η ~ mass loss rate



Solar evolution

- Path of the Sun in the HR diagram, starting in PMS (pre-main-sequence) stage ‘P’ and ending at
  - Red giant stage
  - White dwarf stage
- Note the complex patch during the red giant phase due to various phases of Helium burning and core contraction and expansion, etc.
- η ~ mass loss rate

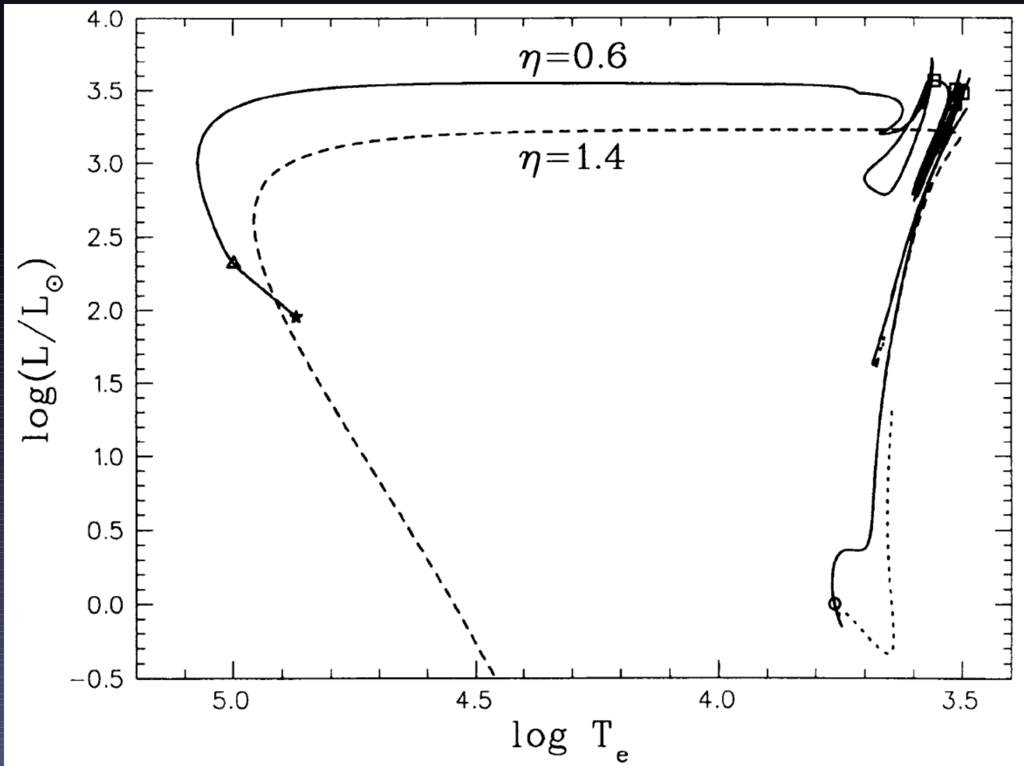
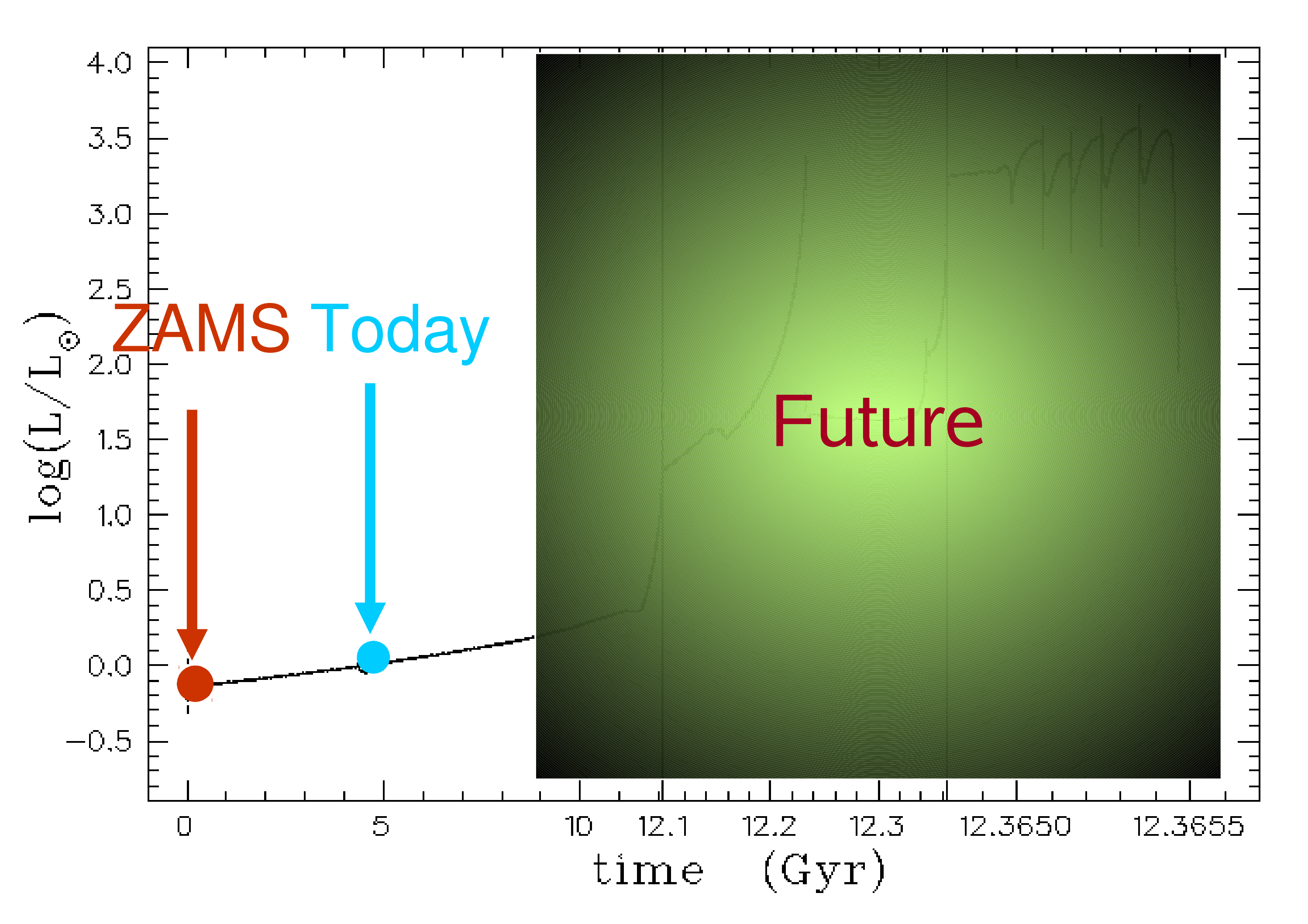


FIG. 5.—The Sun’s evolution in the HR diagram, from the pre–main-sequence state to the pre–white dwarf stage. For our preferred mass-loss case (*solid curve*: $\eta = 0.6$), the triangle indicates the beginning of the final helium shell flash, and the star its peak, where computations were terminated. The dashed curve shows our extreme mass-loss case ($\eta = 1.4$), which leaves the RGB to become a helium white dwarf.

Evolution of Sun's past luminosity

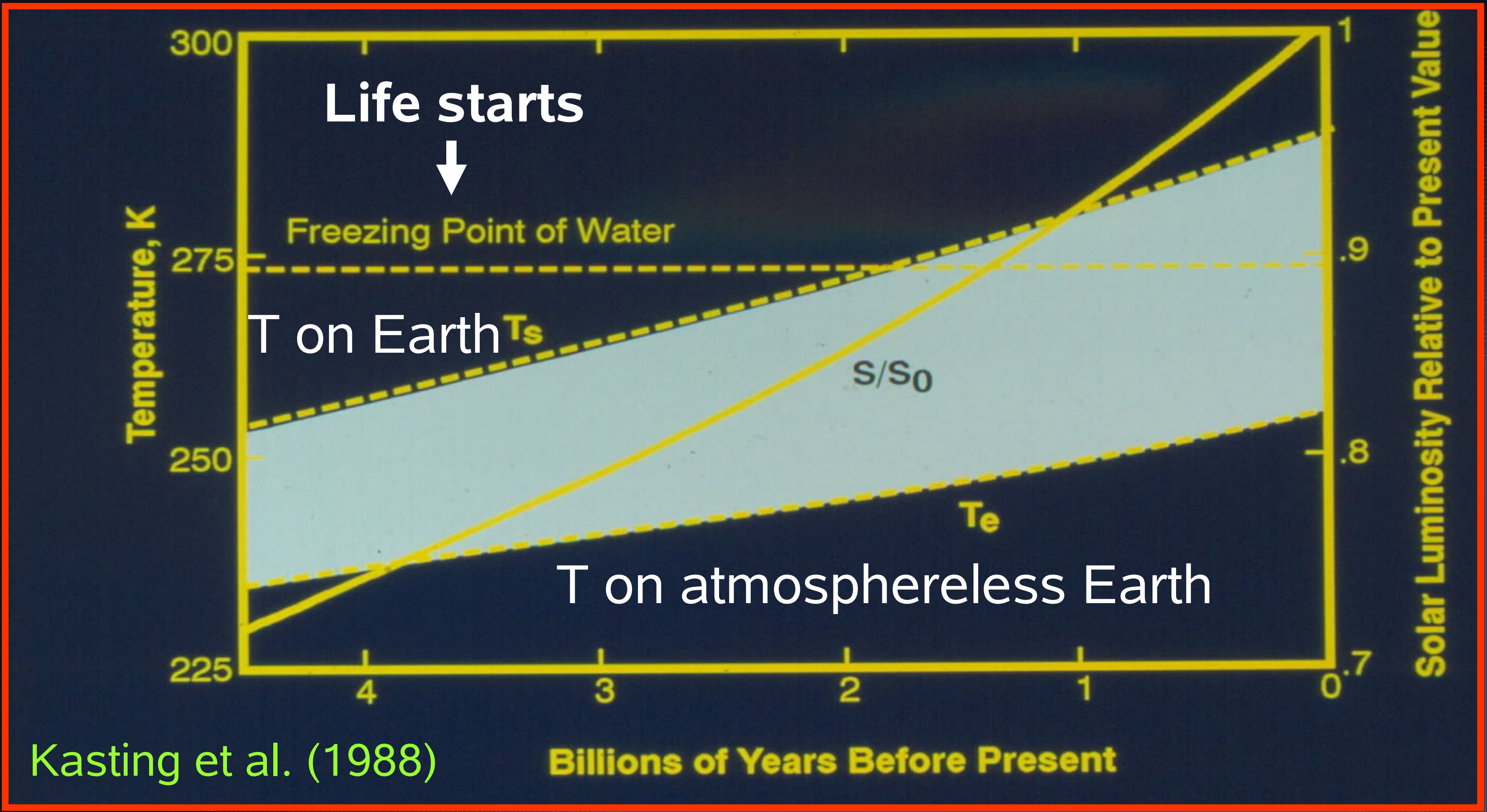


Faint young Sun paradox

- According to the standard solar model the Sun was approximately 30% less bright at birth than it is today
- Too faint to keep the Earth free of ice!
- "Problem": Life started at the Earth's surface at least 3.5 Billion years ago
- Obviously the Earth was not covered with ice at that time
- So what is the solution?

- This and next 3 slides kindly provided by Piet Martens

A Faint Young Sun Leaves the Earth Frozen Solid



Kasting et al, Scientific American, 1988

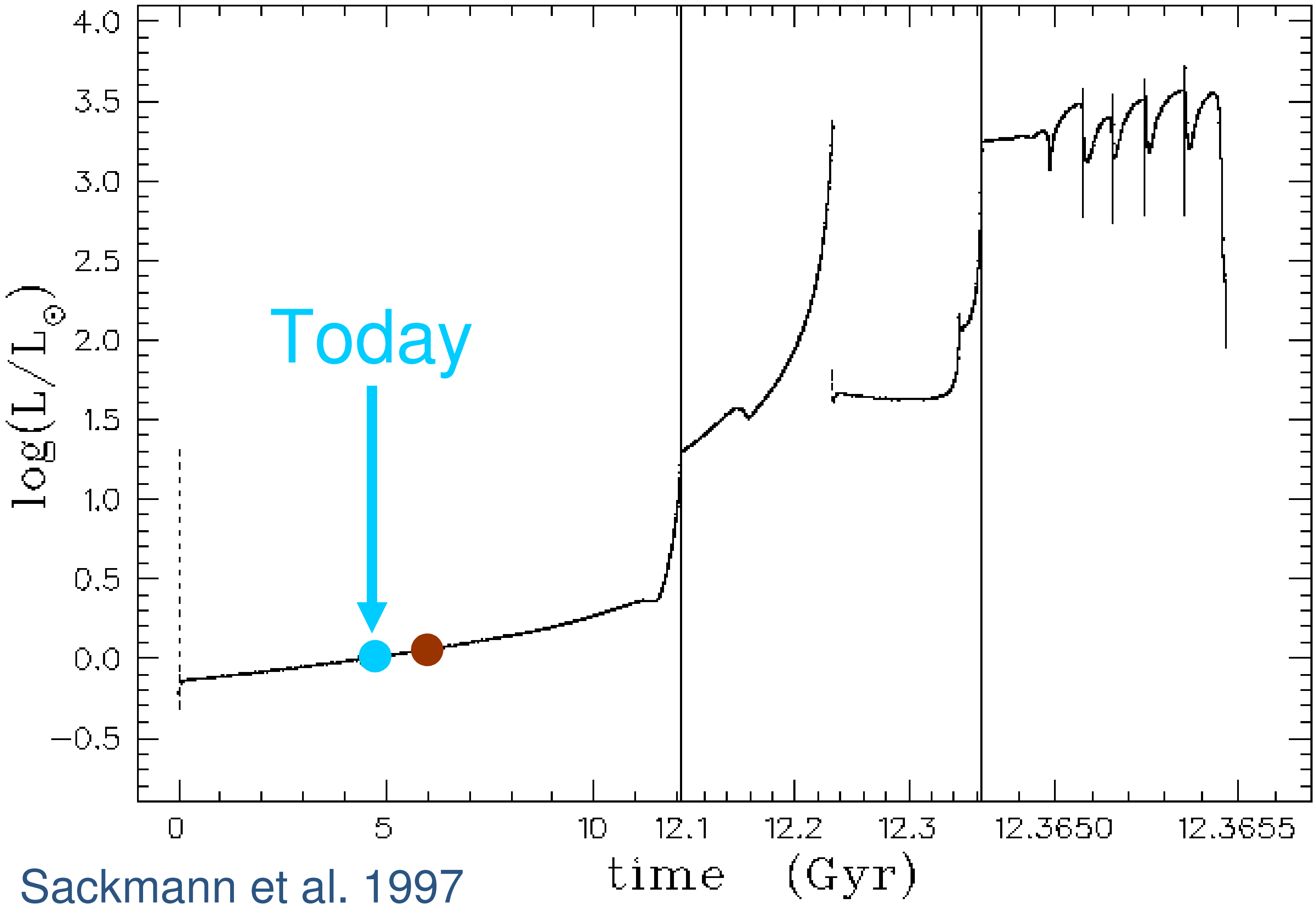
Where to look for a solution?

- Astrophysical Solutions: Young Sun was not faint
- **Early Earth Atmosphere: Much more greenhouse gases (seems most likely)**
- Geology: Much more geothermal energy
- Biology: Life developed on a cold planet
- Fundamental Physics: e.g., gravitational constant has varied

… and the future?

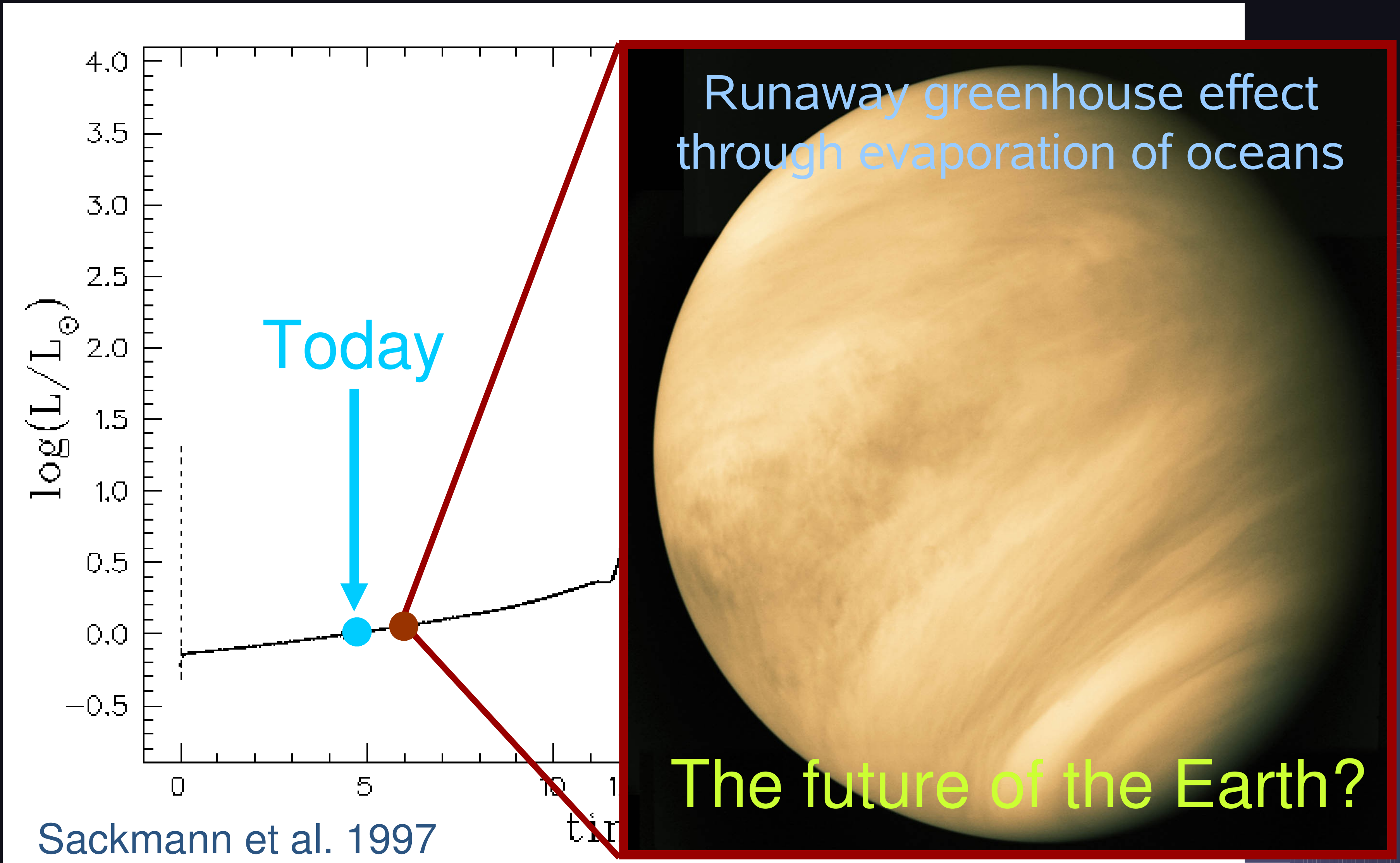
- Sun will continue to grow **brighter**… and **bigger**, first gradually, then rapidly.
- It will get 4000 times brighter than today
- Will the Sun eventually cook the Earth, even evaporate it? When will it become too hot for life?

Evolution of solar luminosity



Sackmann et al. 1997

Evolution of solar luminosity

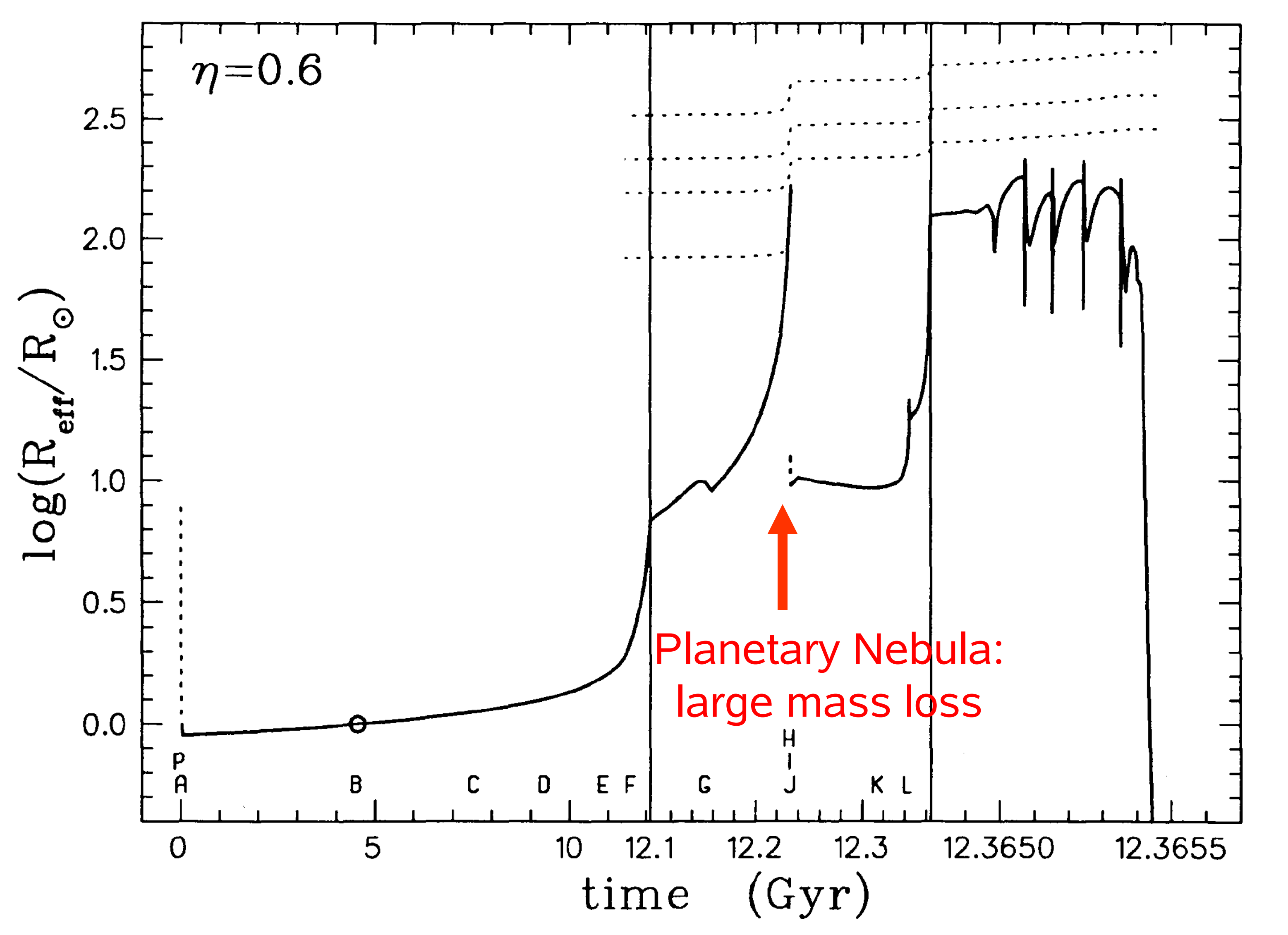


Sackmann et al. 1997

… and the future?

- Sun will continue to grow **brighter**… and **bigger**, first gradually, then rapidly.
- It will get 4000 times brighter than today
- Will the Sun eventually cook the Earth, even evaporate it? When will it become too hot for life?
- It will eventually be so bloated that it will extend up to today's orbit of Earth!
- Will the Sun eventually swallow the Earth?

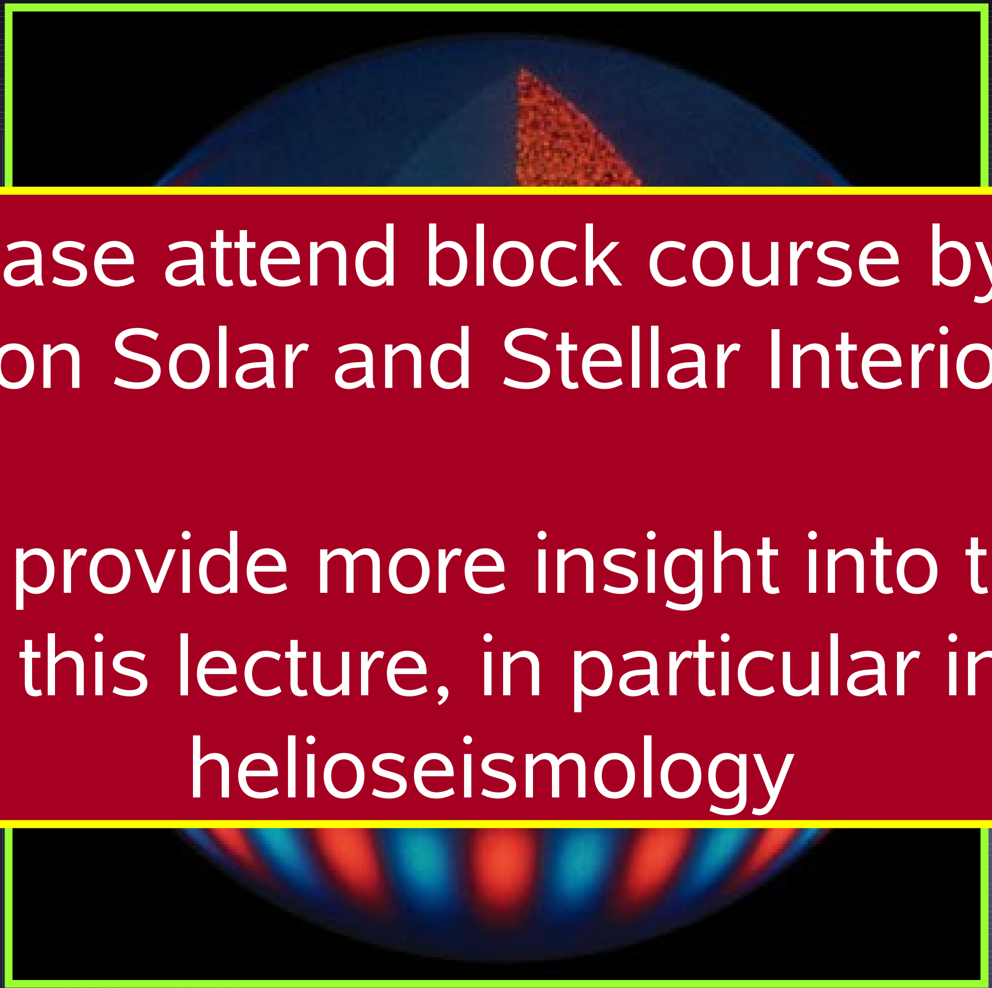
Will the Sun swallow the Earth?





Will the Earth really get away unharmed?


How do we see inside the Sun? Oscillations and helioseismology



Also, please attend block course by Laurent Gizon on Solar and Stellar Interiors.

That will provide more insight into the topics of this lecture, in particular into helioseismology

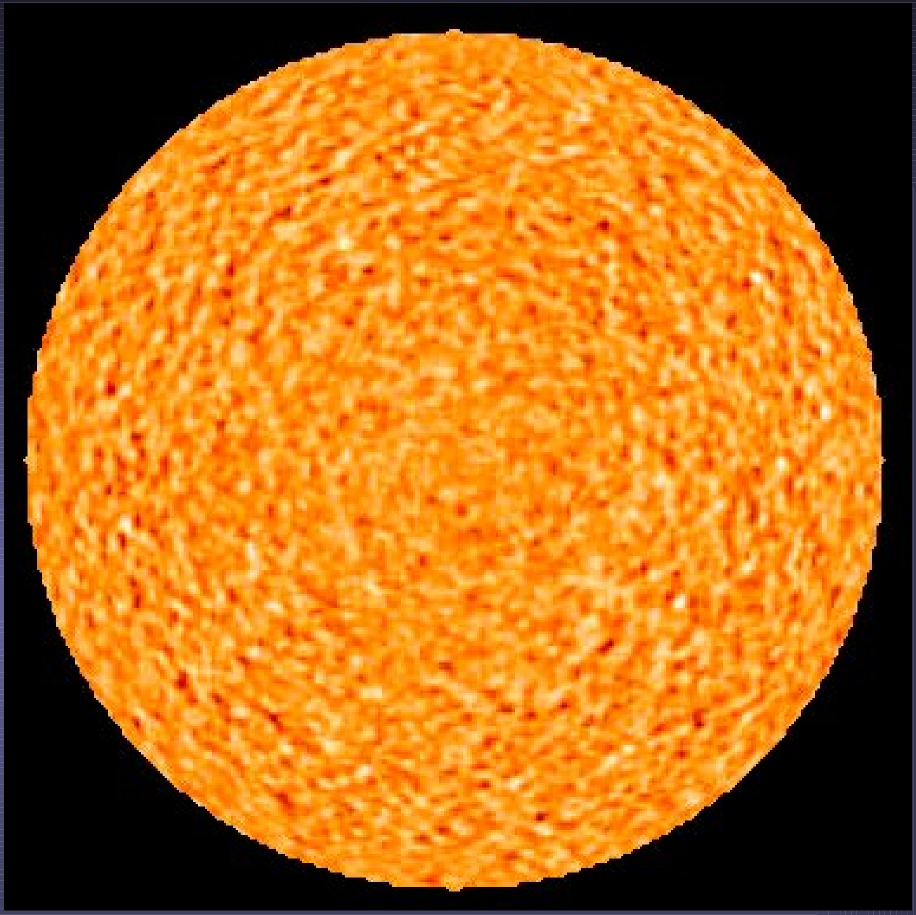
5-minute oscillations

- Entire Sun vibrates from a complex pattern of mainly acoustic waves (p-modes), with a period of around 5 minutes. Also visible are surface-gravity waves (f-modes)

- The oscillations are best seen as Doppler shifts of spectral lines, but are also visible as intensity variations.

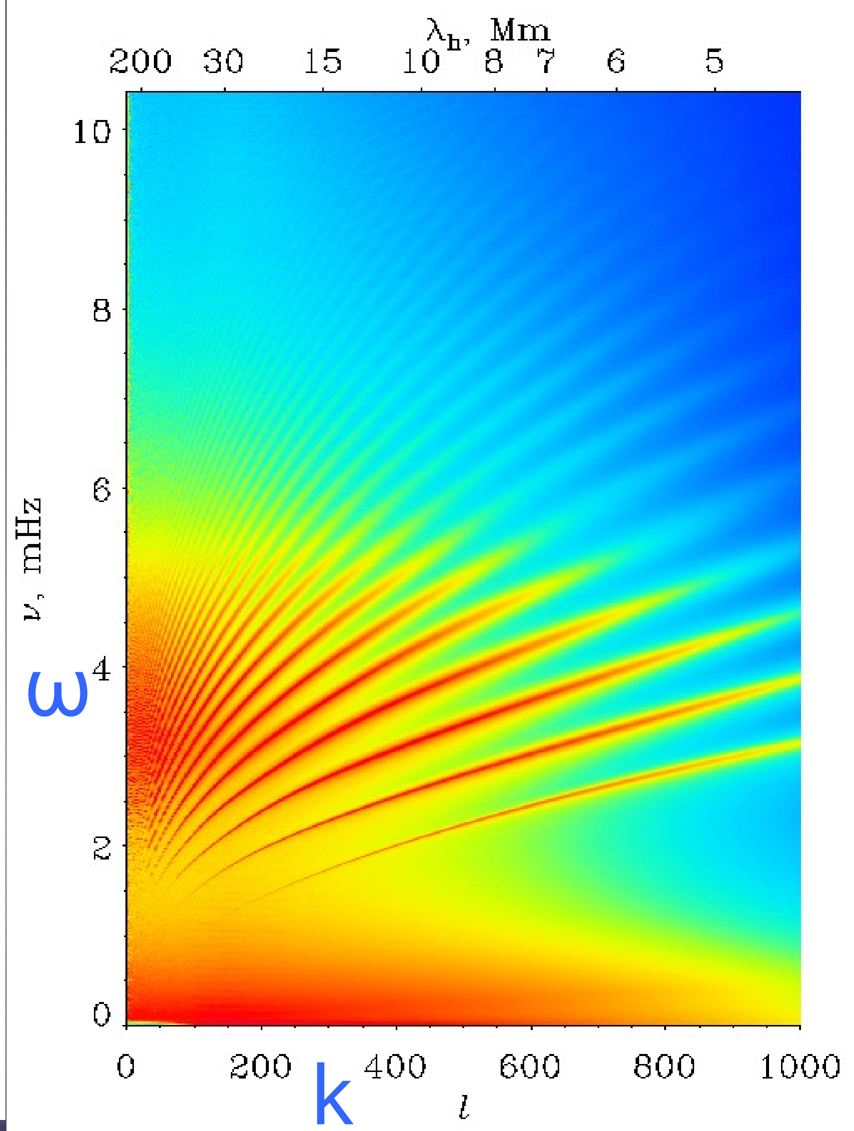
- Spatio-temporal properties of oscillations best revealed by 3-D Fourier transforms (2-D space + 1-D time)

Doppler shift



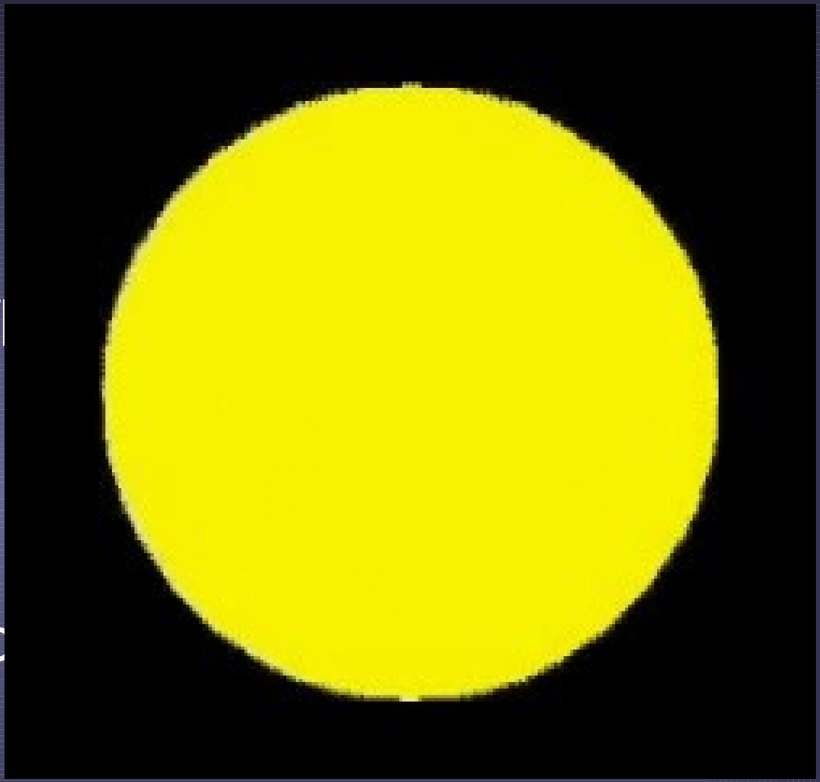
Solar Eigenmodes

- p-modes show a distinctive dispersion relation (k-ω diagram: $k \sim \omega^2$)
- Important: there is power only in certain ridges, i.e. for a given k ($= \sqrt{k_x^2 + k_y^2}$), only certain frequencies contain power
- This discrete spectrum suggests the oscillations are trapped, i.e. eigenmodes of the Sun



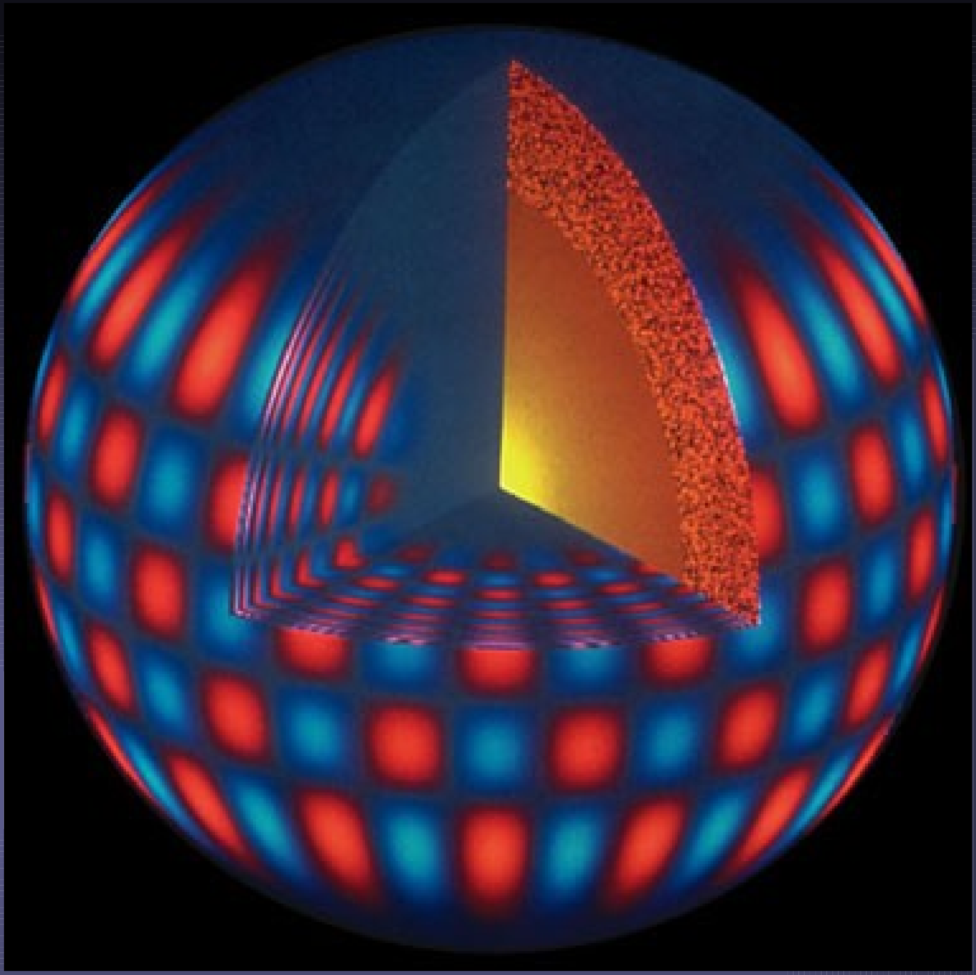
Global oscillations

- Sun's acoustic waves bounce (are reflected) at the solar surface, causing it to oscillate up and down.
- Modes differ in the depth to which they penetrate: they turn around due to refraction: because sound speed ($C_S \sim T^{1/2}$) increases with depth
- p-modes are influenced by conditions inside the Sun. E.g., E.g. they carry information on sound speed & on plasma fl
- By observing these oscillations on the solar surface we can surface we can learn about the structure of the solar interio

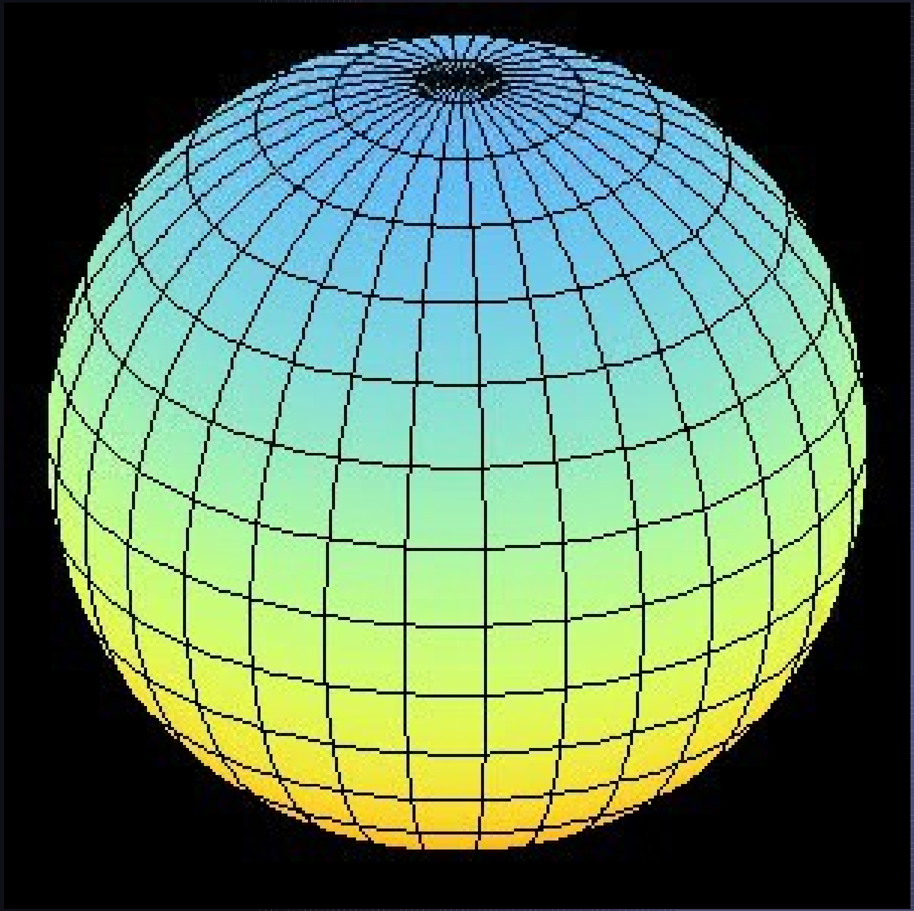


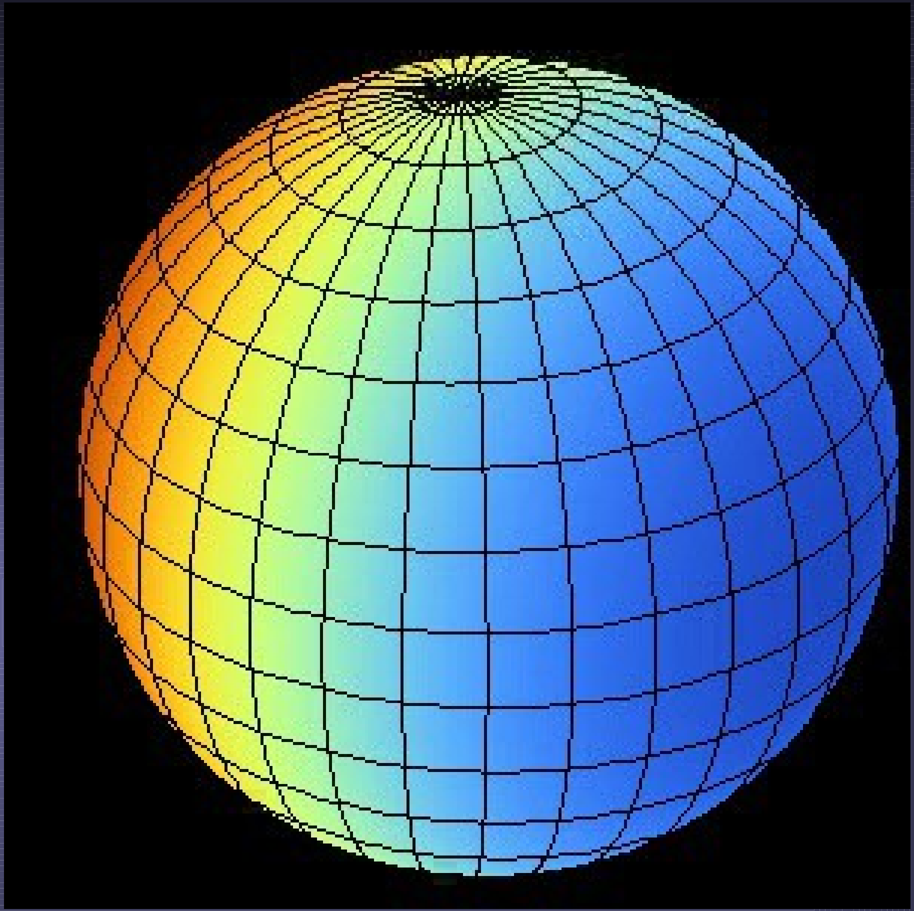
Description of solar eigenmodes

- 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 (next slides)

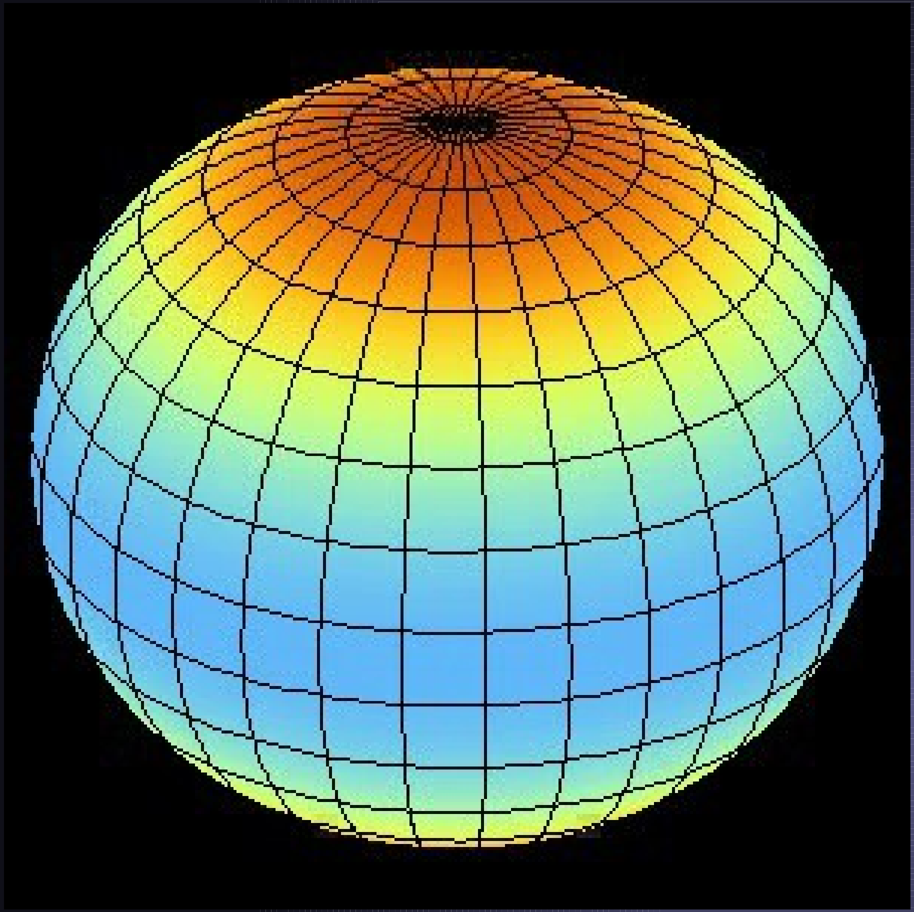


Examples of modes





Examples of modes



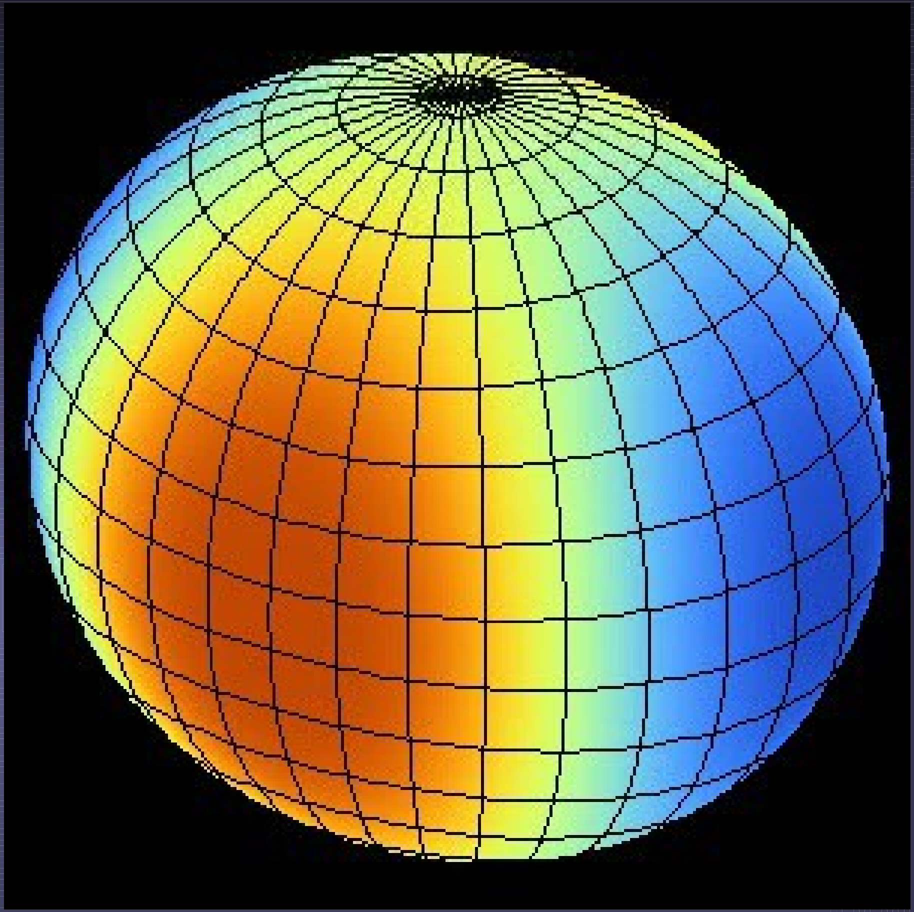
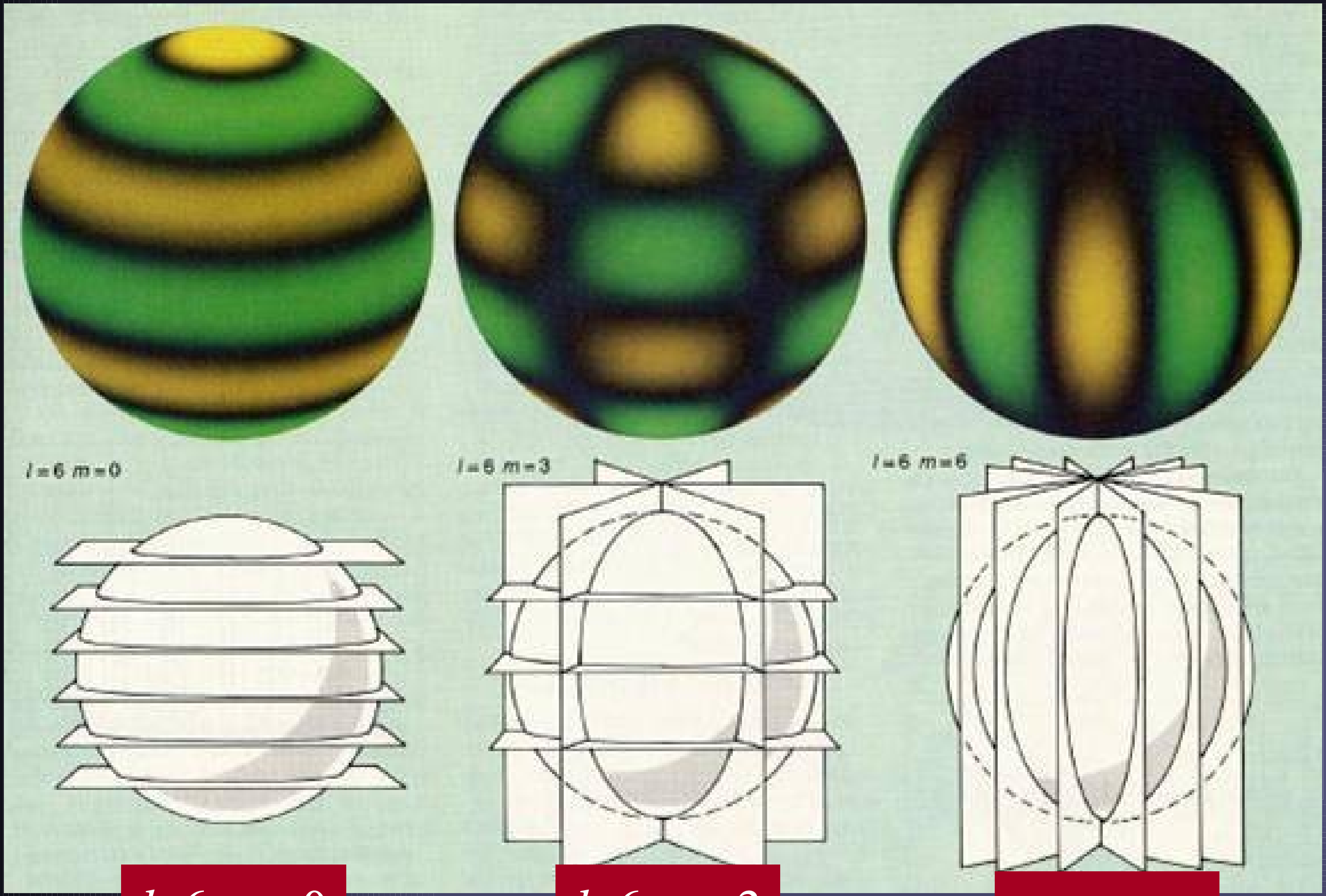


Illustration of spherical harmonics

- l = total number of node lines on solar surface (in images: $l = 6$) = degree
- m = number of nodes connecting the "poles" (longitudinal planes)

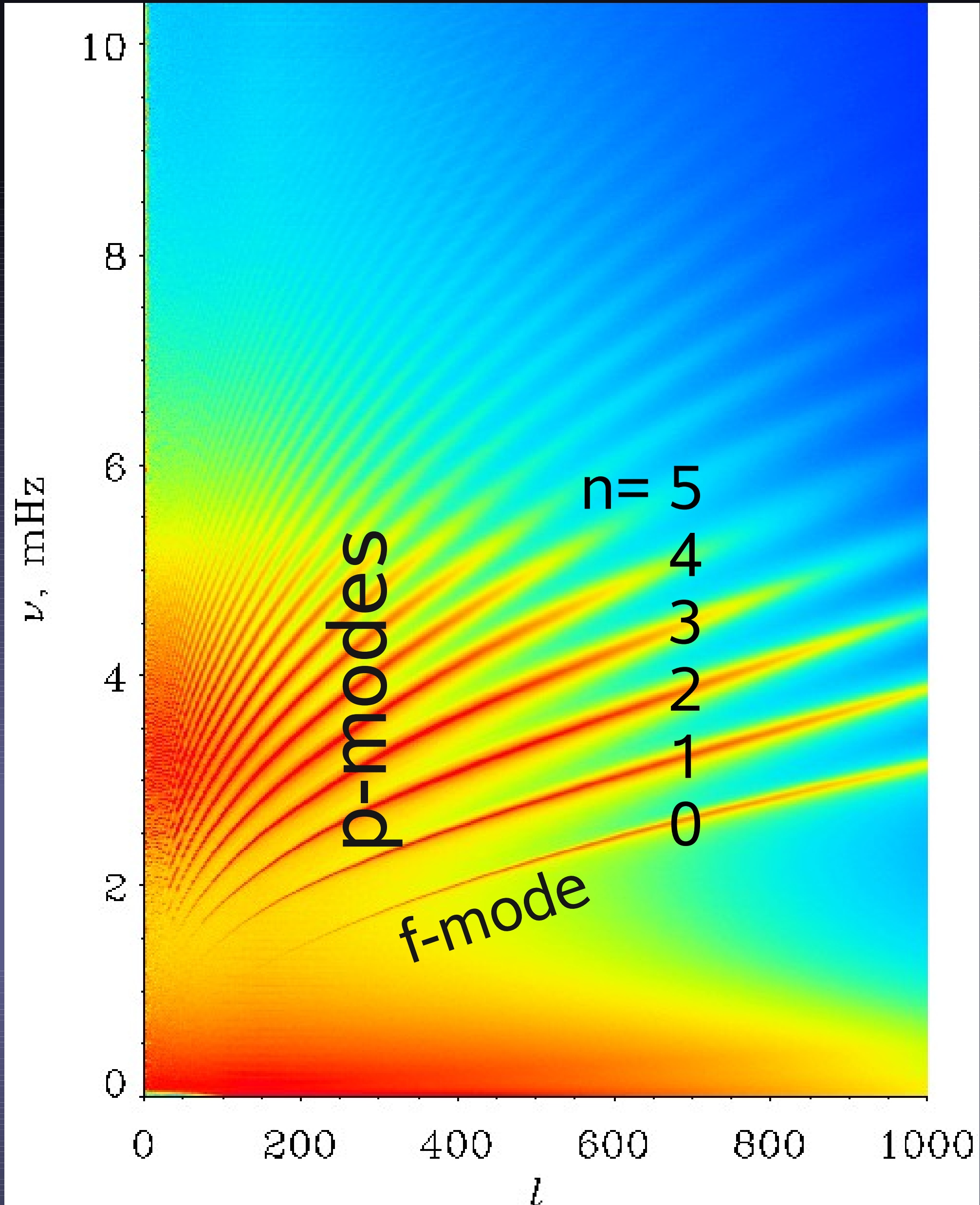


l=6, m=0 l=6, m=3 l=6, m=6

Interpretation of *k-ω* or *ν-l* diagram

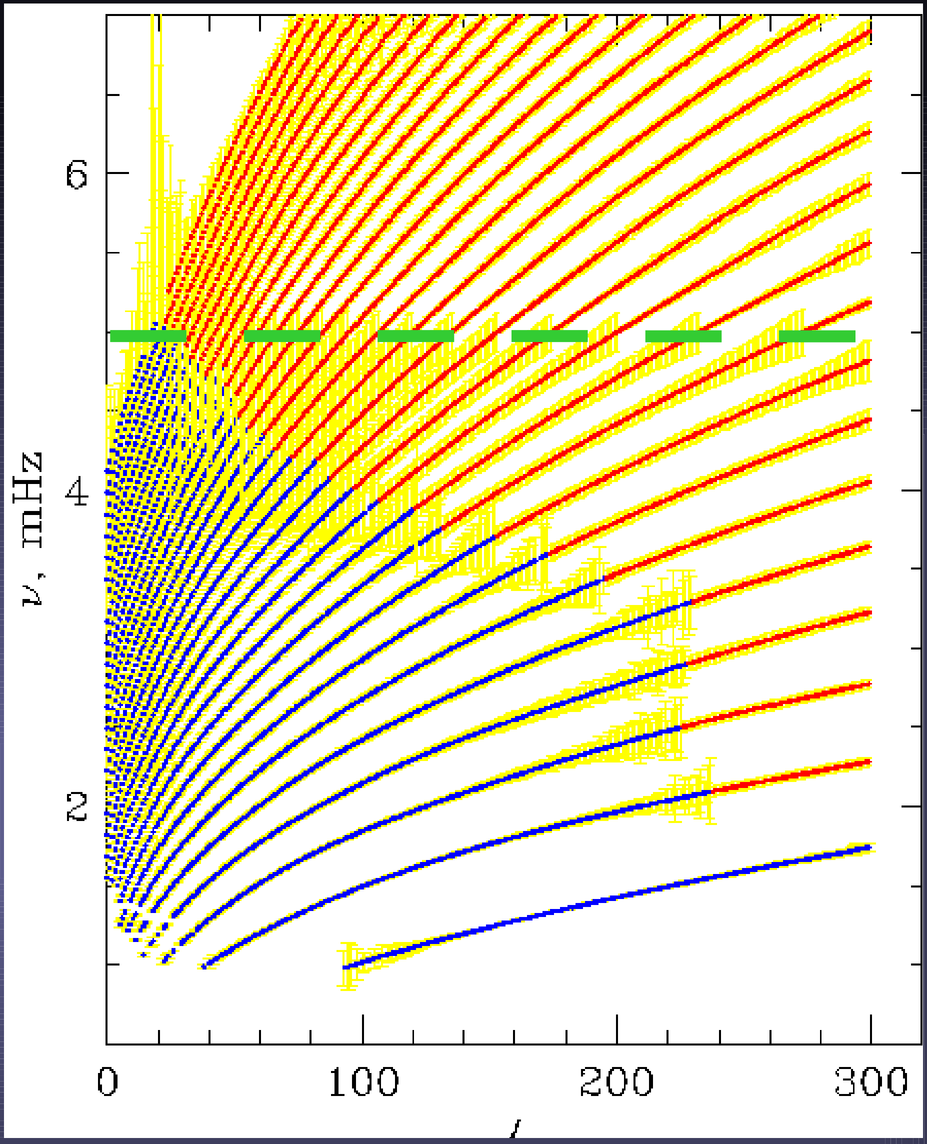
- At a fixed l, different frequencies show significant power. Each of these power ridges belongs to a different order n (n = number of radial nodes), with n increasing from bottom to top.

- Typical are small values of n, but intermediate to large degree l (10-1000; with some spatial resolution dependence)



Accuracy of frequency measurements

- Plotted are identified frequencies and error bars (yellow). They correspond to 1000σ for blue freq., 100σ for red freq. below 5 mHz and 1σ for higher freq.)
- Best achievable freq. resolution: a few parts in 10^5; limit set by mode lifetime ~100 d



The measured low-l eigenmode signal

- Sun seen as a star: Due to cancellation effects, only modes with l=0,1,2 (possibly 3) are visible simpler power spectrum.
- Low l modes are important for 2 reasons:
  - They reach particularly deep into the Sun
  - These are the only modes measurable on most other stars
- These modes are called “global”

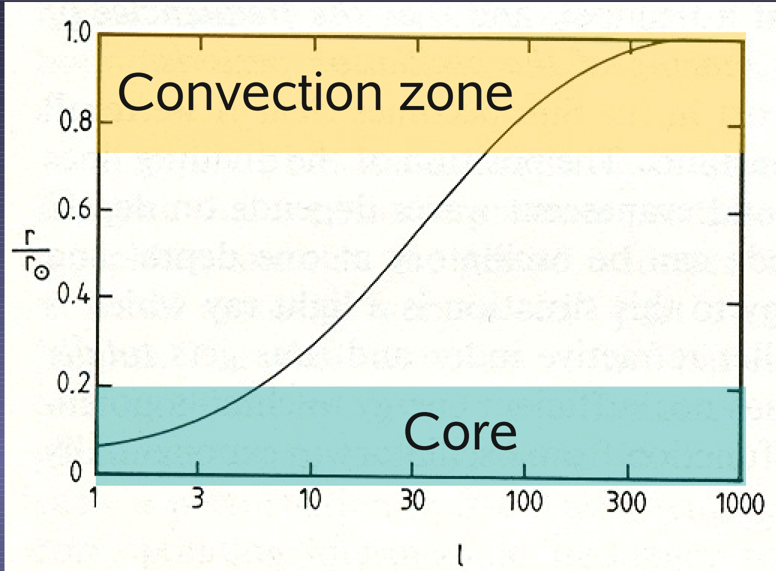
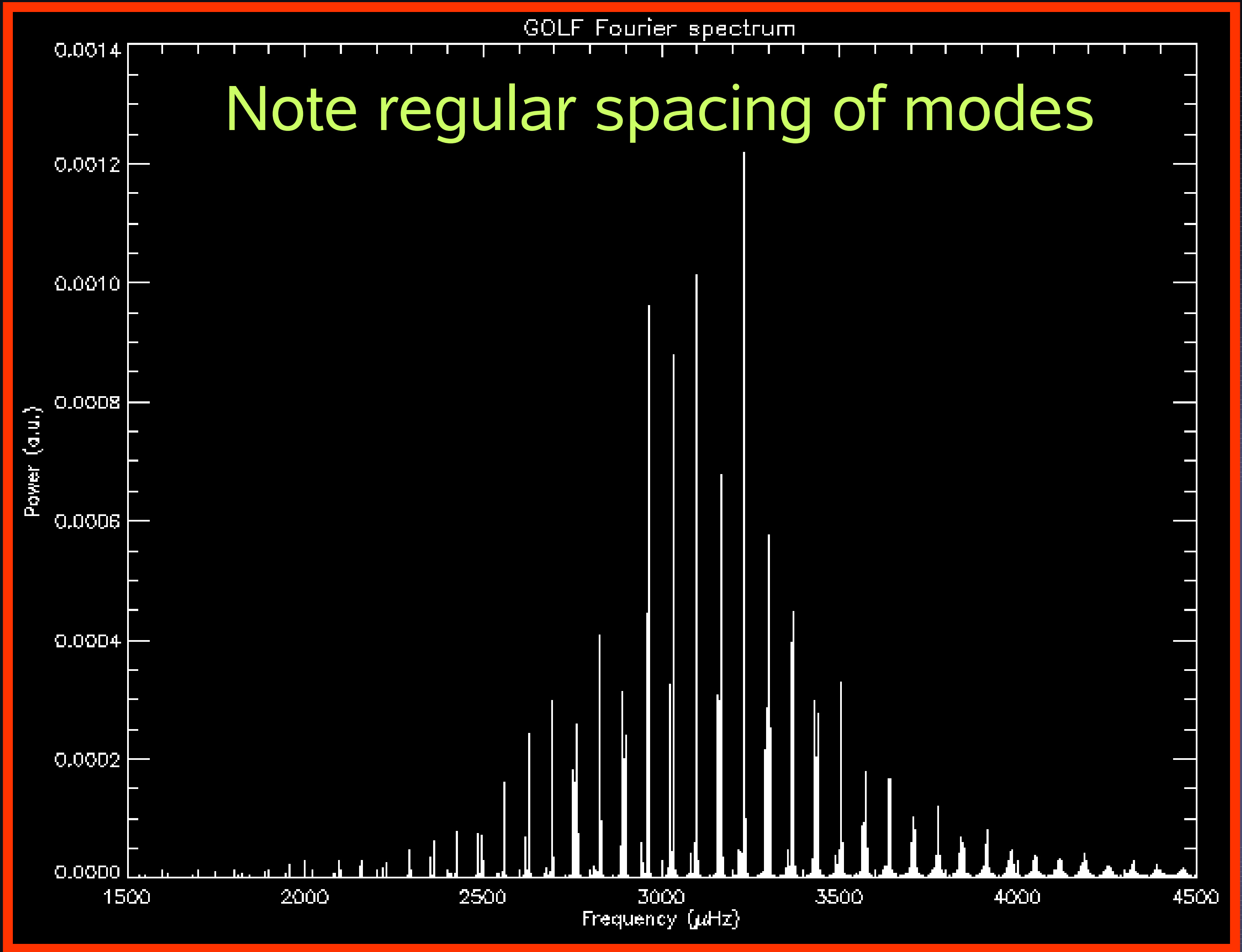


Fig. 5.13. Depth of internal reflection, according to (5.37), as a function of degree l, for modes with an oscillation frequency 3 mHz. Adapted from Noyes and Rhodes (1984)

Best current low-*l* power spectrum

Given l has different peaks: different n values (n=15…25 typical)



Types of oscillations

- Solar eigenmodes can be of 3 types:
  - p-modes: restoring force is pressure, i.e. normal sound waves
  - f-modes: restoring force is gravity, but they are restricted to the solar surface (surface gravity modes, similar to waves on water surface)
  - g-modes: restoring force is gravity (also called buoyancy modes)
- Of these only f & p-modes have been detected on Sun with certainty (except local, purely atmospheric g-mode waves)
- They are excited by turbulent convection, mainly granulation near solar surface (since there convection is most vigorous)
- p-modes travel with sound speed C_S. They dwell longest where $C_S \sim T^{1/2}$ is lowest → this is at solar surface
- f-modes decay exponentially with depth. They propagate on solar surface with a speed $\sqrt{g}/(2\sqrt{k})$. (dispersion: $\omega = g\sqrt{k}$)

p-modes vs. g-modes

- p-modes propagate throughout the solar interior, but are evanescent in the solar atmosphere
- g-modes propagate in the radiative interior and in the atmosphere, but are evanescent in the convection zone (their amplitude drops exponentially there, so that very small amplitudes are expected at the surface). Convection means buoyancy instability (density blobs keep rising or falling); gravity-based oscillations require stability (density blobs oscillate)
- g-modes are expected to be most sensitive to the very core of the Sun, while p-modes are most sensitive to the surface
- Current upper limit on amplitudes (at solar surface) of solar interior g-modes lies below 1 cm/s

Deducing internal structure from solar oscillations

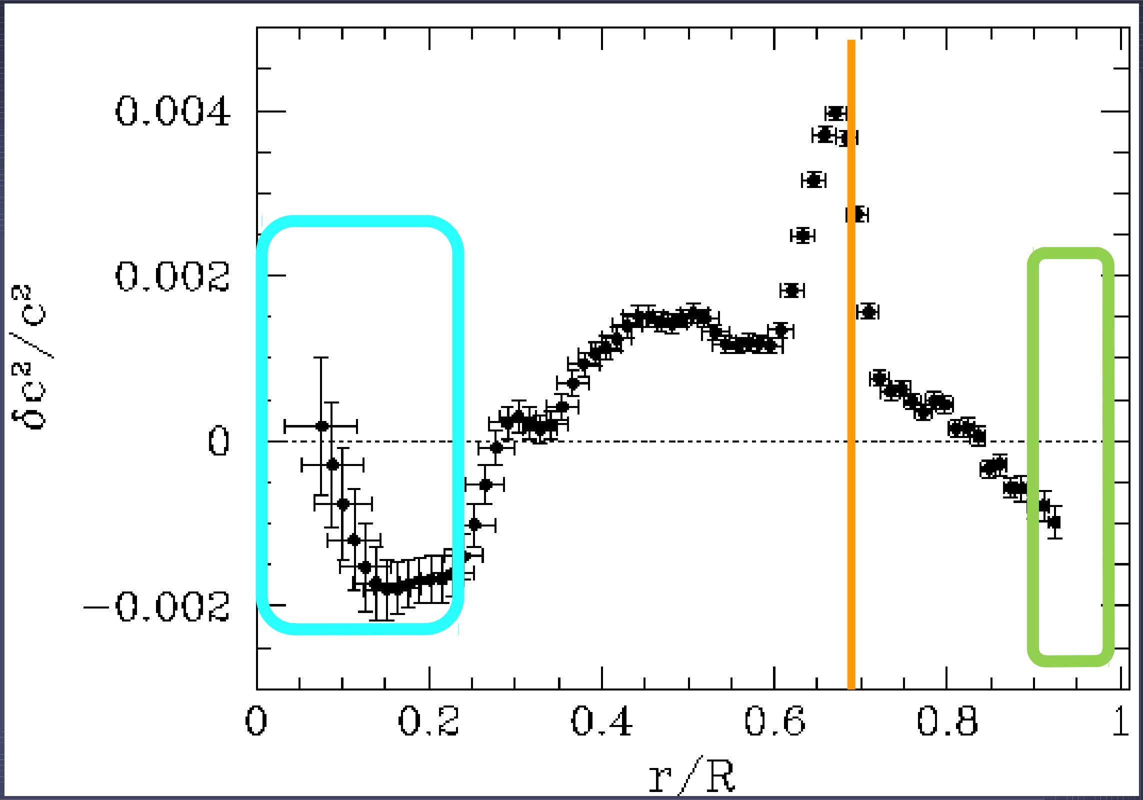
- Global helioseismology: Gives radial and latitudinal dependence of solar properties, but cannot give any longitudinal dependence. E.g.
  - Radial structure of sound speed
  - Structure of differential rotation (torsional velocities)
- Local helioseismology: Allows in principle 3-D imaging of solar interior. E.g. time-distance helioseismology does not measure frequencies, but rather the time that a wave requires to travel a certain distance

Global helioseismology

- Use frequencies of many modes (from power spectra)
- Basically two techniques for deducing information on the Sun’s internal structure
  - Forward modelling: make a model of the Sun’s internal structure (e.g. standard model discussed earlier), compute the frequencies of the eigenoscillations of the model and compare with observations
  - Inverse technique: Deduce the sound speed and rotation by inverting the oscillations (i.e. without any prior comparison with models)
- Note that forward modelling is required in order to first identify the modes. Only after that can inversions be carried out

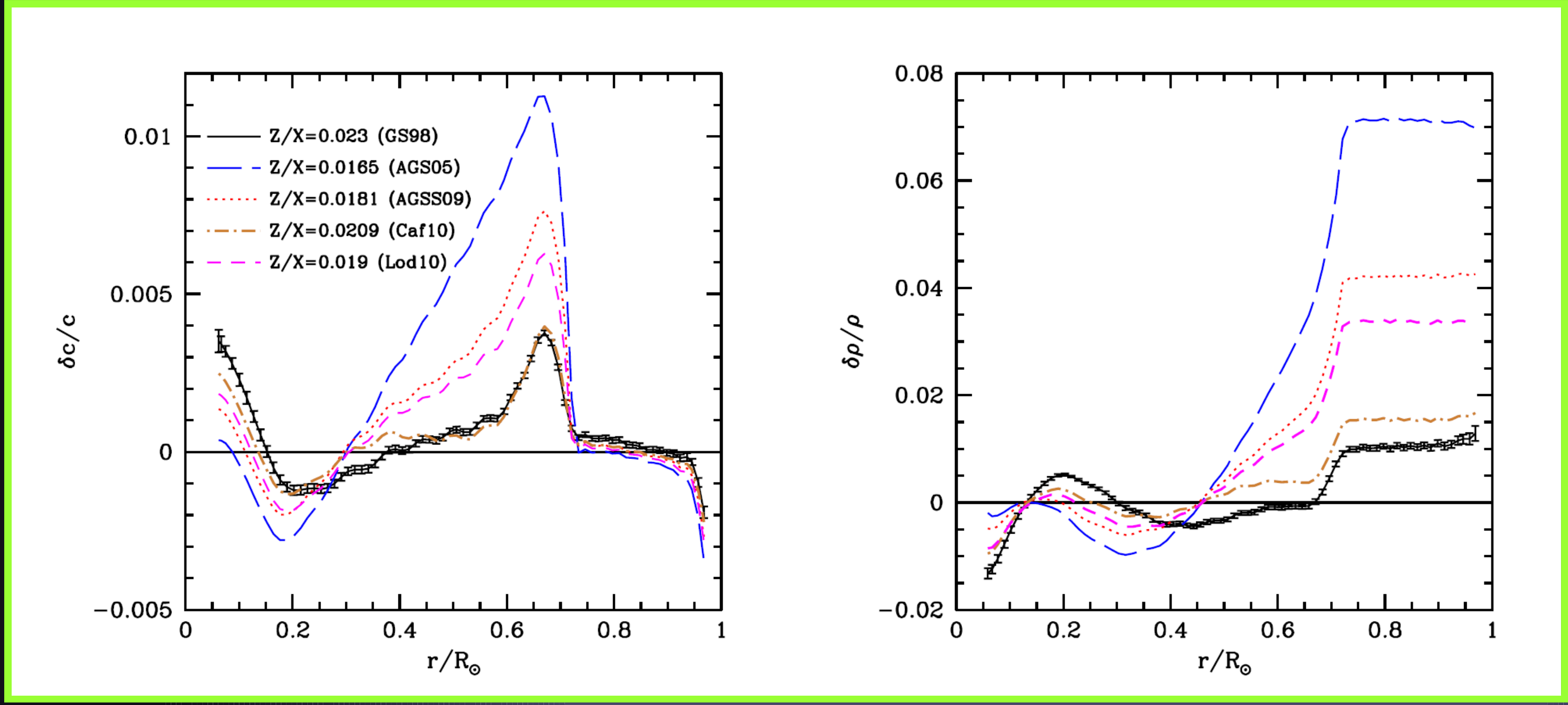
Testing the standard solar model: results of forward modelling

- Relative difference between C_S^2 obtained from inversions and from standard solar model plotted vs. radial distance from Sun centre.
- Typical difference: □ good!
- Typical error bars inversion: poor!
- Problem areas:
  - solar core
  - bottom of CZ
  - solar surface

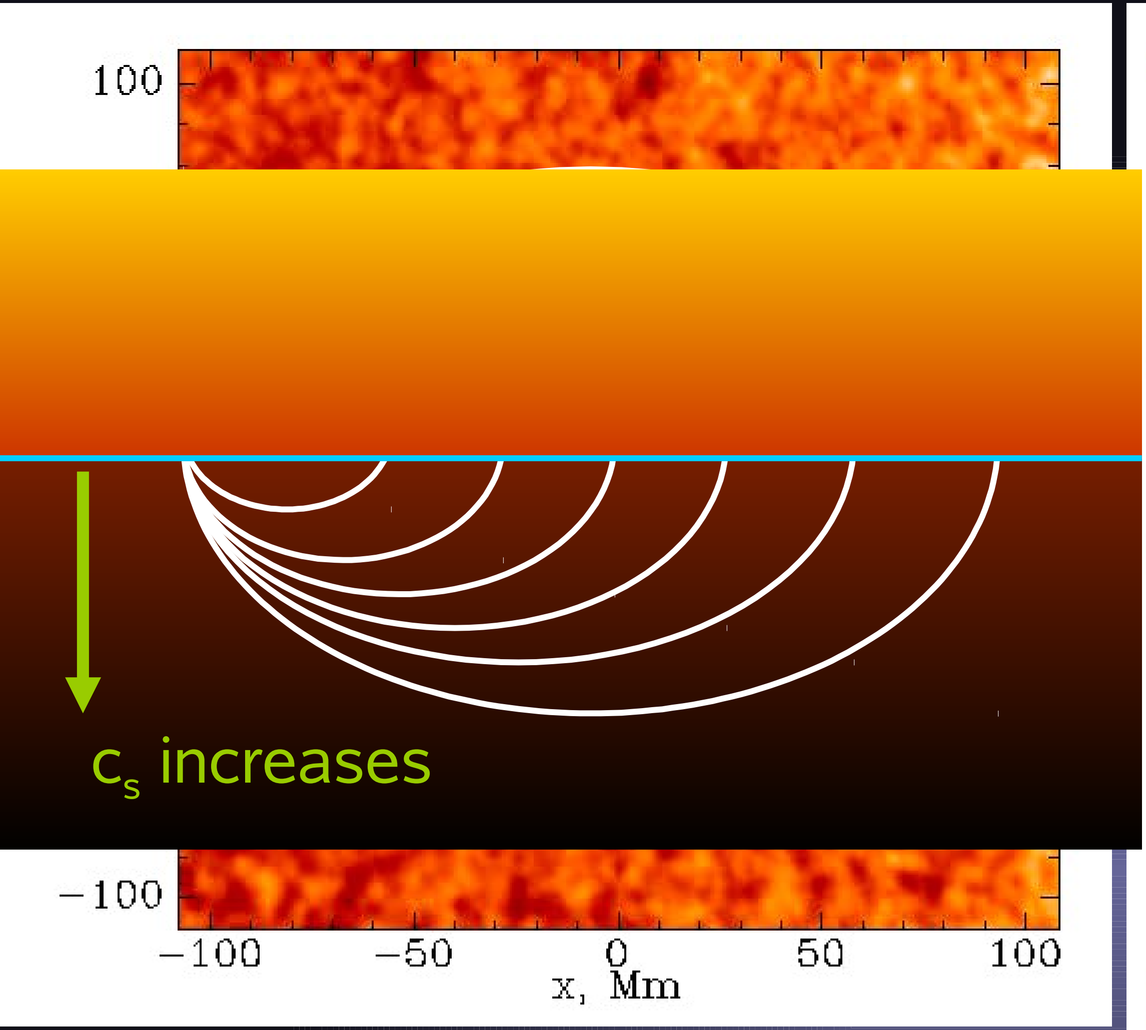


Setting constraints on elemental abundances

Relative difference between sound speed obtained from models and from inversions for different “metal” abundances proposed in the recent literature (between 0.0165 and 0.023)



Local excitation of waves by a flare

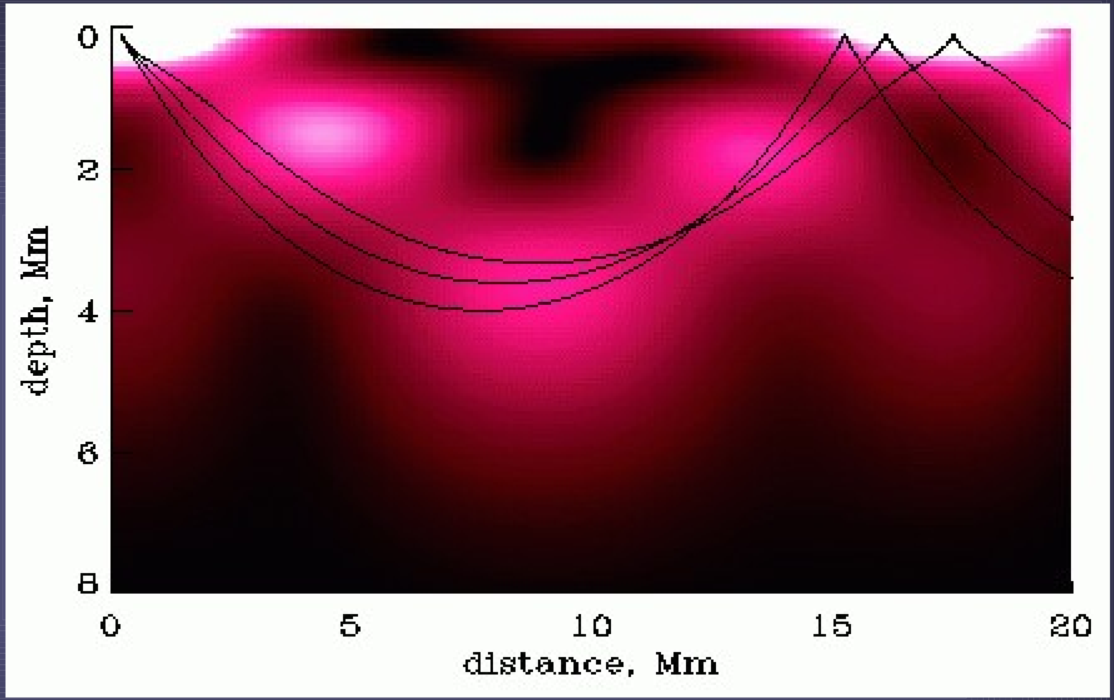


Particularly clear example of wave excitation

- *p*-modes are usually excited by turbulent convection
- Waves can also be triggered by flares
- Wave is not travelling at solar surface, but rather reaching the surface further out at later times
- Note how it travels ever faster. **Why?**

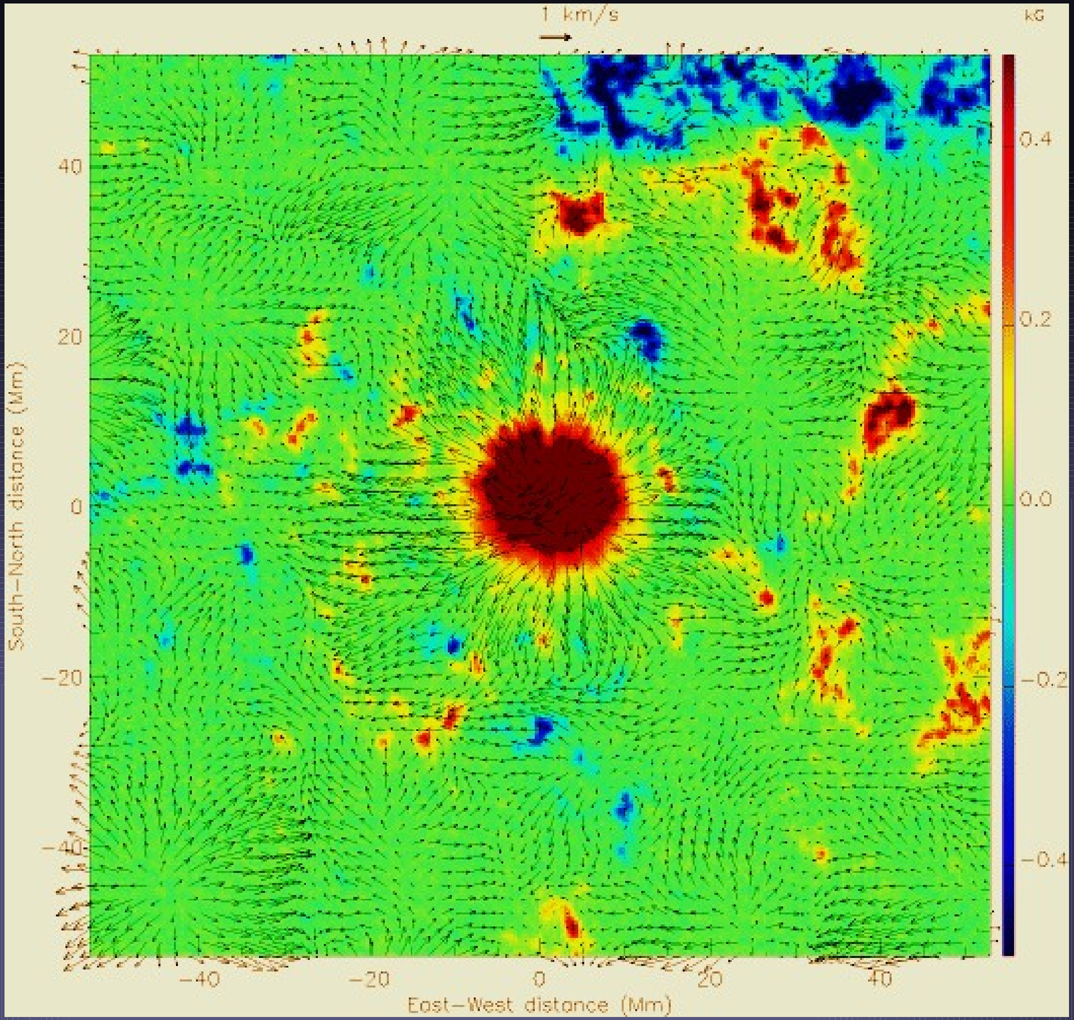
Local helioseismology

- Does not build upon measuring frequencies of eigenmodes, but rather measures travel times of waves through the solar interior, between two “bounces” at the solar surface (for particular technique of time-distance helioseismology)
- The travel time between source and first bounce depends on the structure of C_S below the surface. By considering waves following different paths inhomogeneous distributions of C_S can be determined



Local helioseismology II

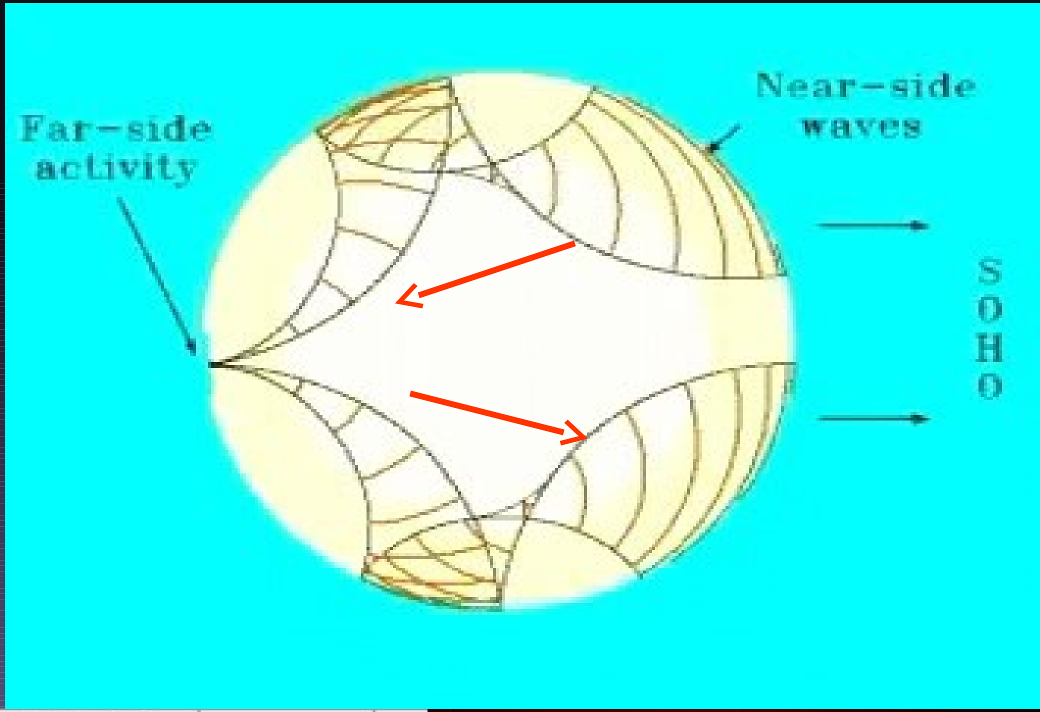
- Distinguish temperature and velocity structures
  - A wave propagates faster along a flow than against it
  - Consider waves passing in both directions to distinguish between T and velocity

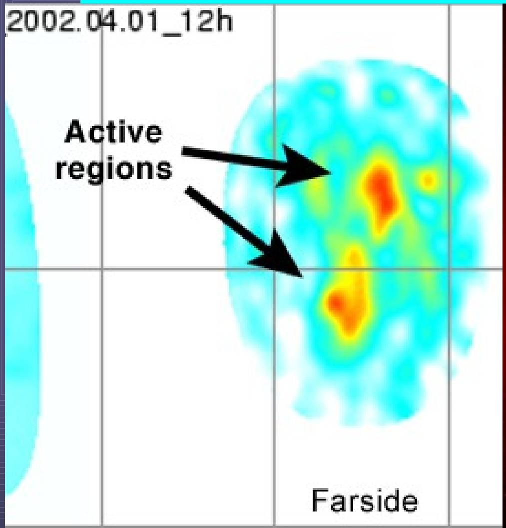


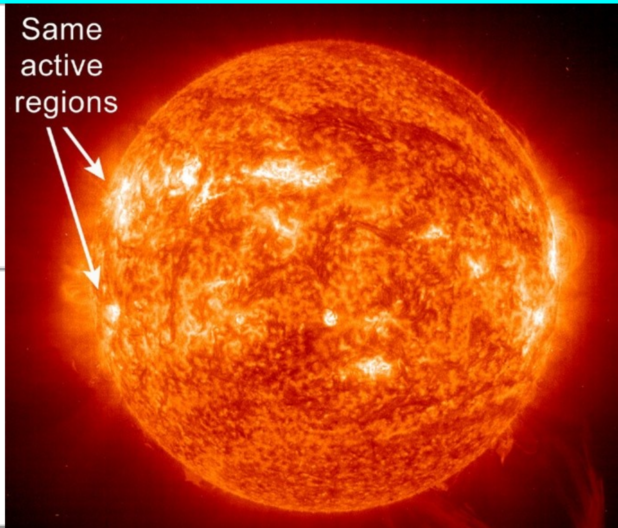
- At right: Flows (arrows) somewhat below solar surface; colours: magnetic field at surface

Seeing right through the Sun

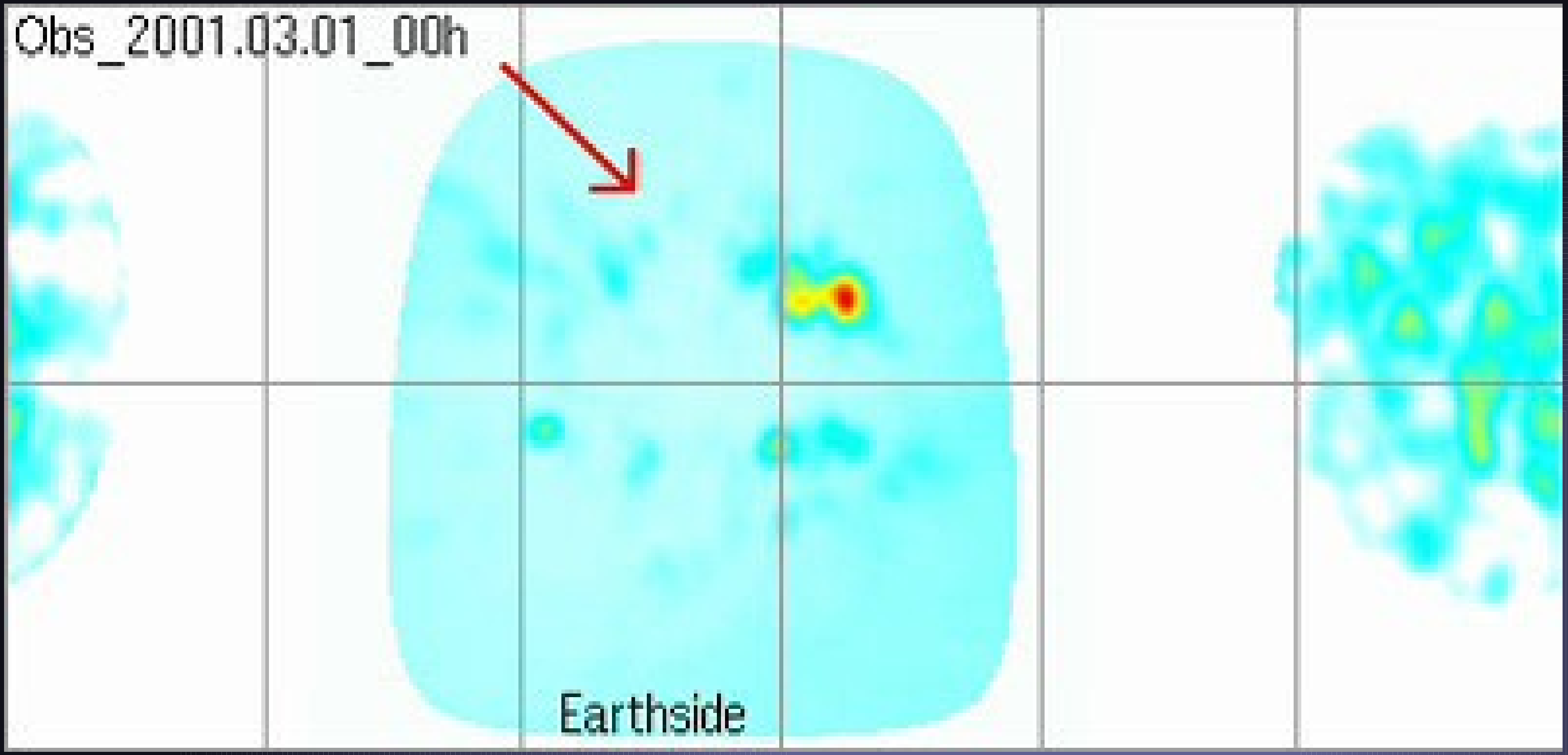
- A technique called far-side seismic holography gives images of the far side of the Sun
- Waves from back reach front, after skipping at the surface on the way
- Acoustic waves speed up in active regions (hotter subsurface layers)
- Sound waves delayed by ≈12 sec in a total travel time of 6 hours







Seeing right through the Sun II



Real-time far side images:
http://soi.stanford.edu/data/farside/index.html