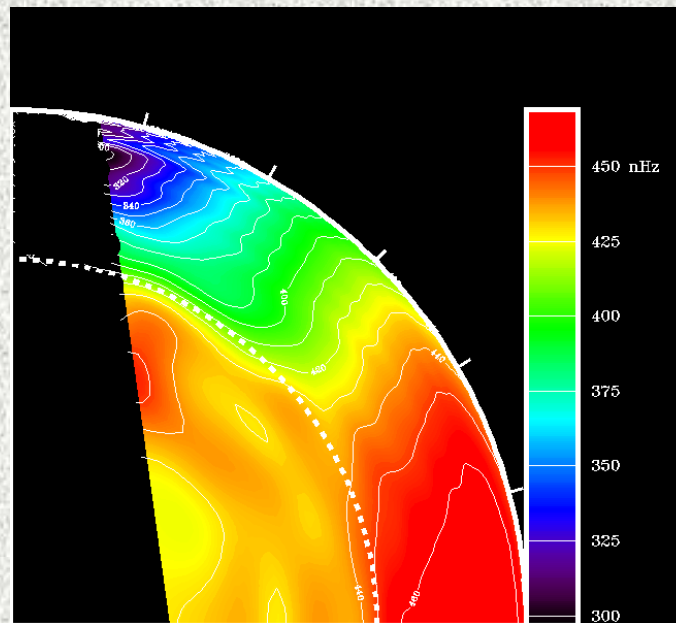


# What does helioseismology tell us about the Sun?



Jørgen Christensen-Dalsgaard

Department of Physics and Astronomy, University of Aarhus &  
Danish AsteroSeismology Centre (DASC)

Sir Arthur Stanley Eddington:  
The Internal Constitution of the Stars  
1926



Sir Arthur Eddington  
(1882 – 1944)

At first sight it would seem that the deep interior of the sun and stars is less accessible to scientific investigation than any other region of the universe.

Our telescopes may probe  
farther and farther  
into the depths of space;  
but how can we ever obtain  
certain knowledge  
of that which is hidden  
behind substantial barriers?

What appliance  
can pierce through  
the outer layers of a star  
and test  
the conditions within?

# Collaborators

- M. J. Thompson
- R. Howe
- J. Schou
- S. Basu
- R. M. Larsen
- J. M. Jensen
- Hans Kjeldsen
- Teresa Teixeira
- Tim Bedding
- Maria Pia Di Mauro
- Andrea Miglio



HDI 4000 Karen K C.-Dalsg... BABYVIEW.CO.UK MI 0.9 24-02-2006  
OB 3D7-4 Tib 0.1 10:37:29 am

Lossy 15:1



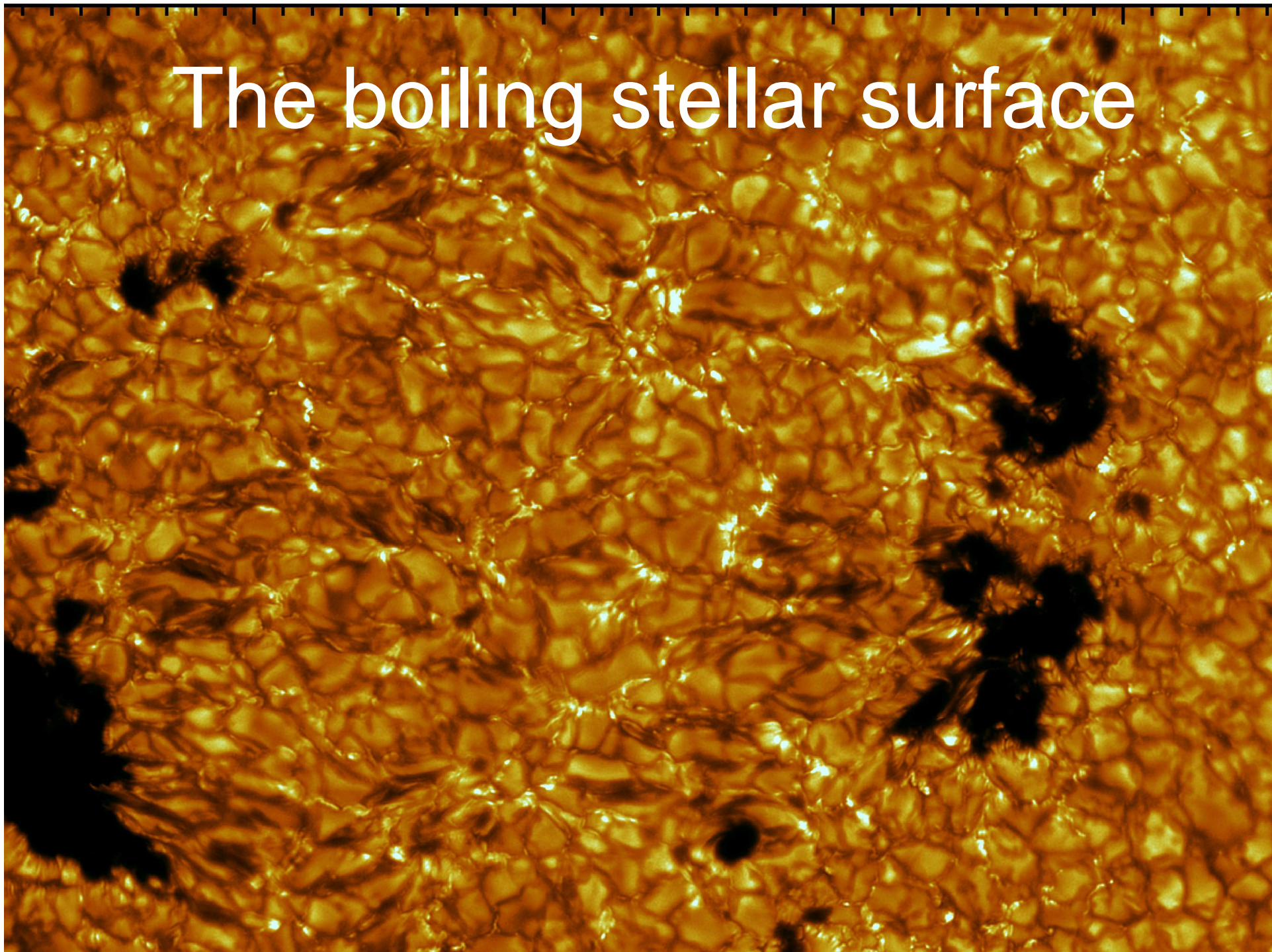
# **ASTEROSEISMOLOGY**

The goal: to understand the structure, evolution and dynamics of stellar interiors

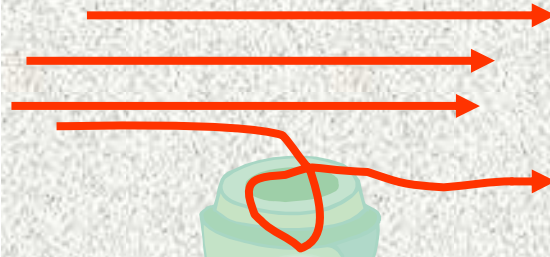
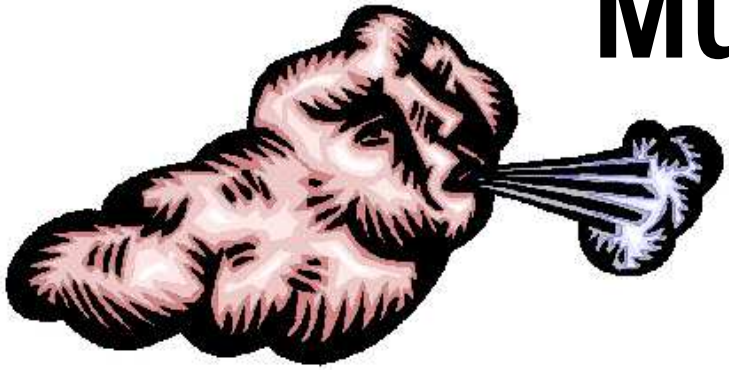
**Using observations and analysis of oscillations of stellar surfaces**



# The boiling stellar surface

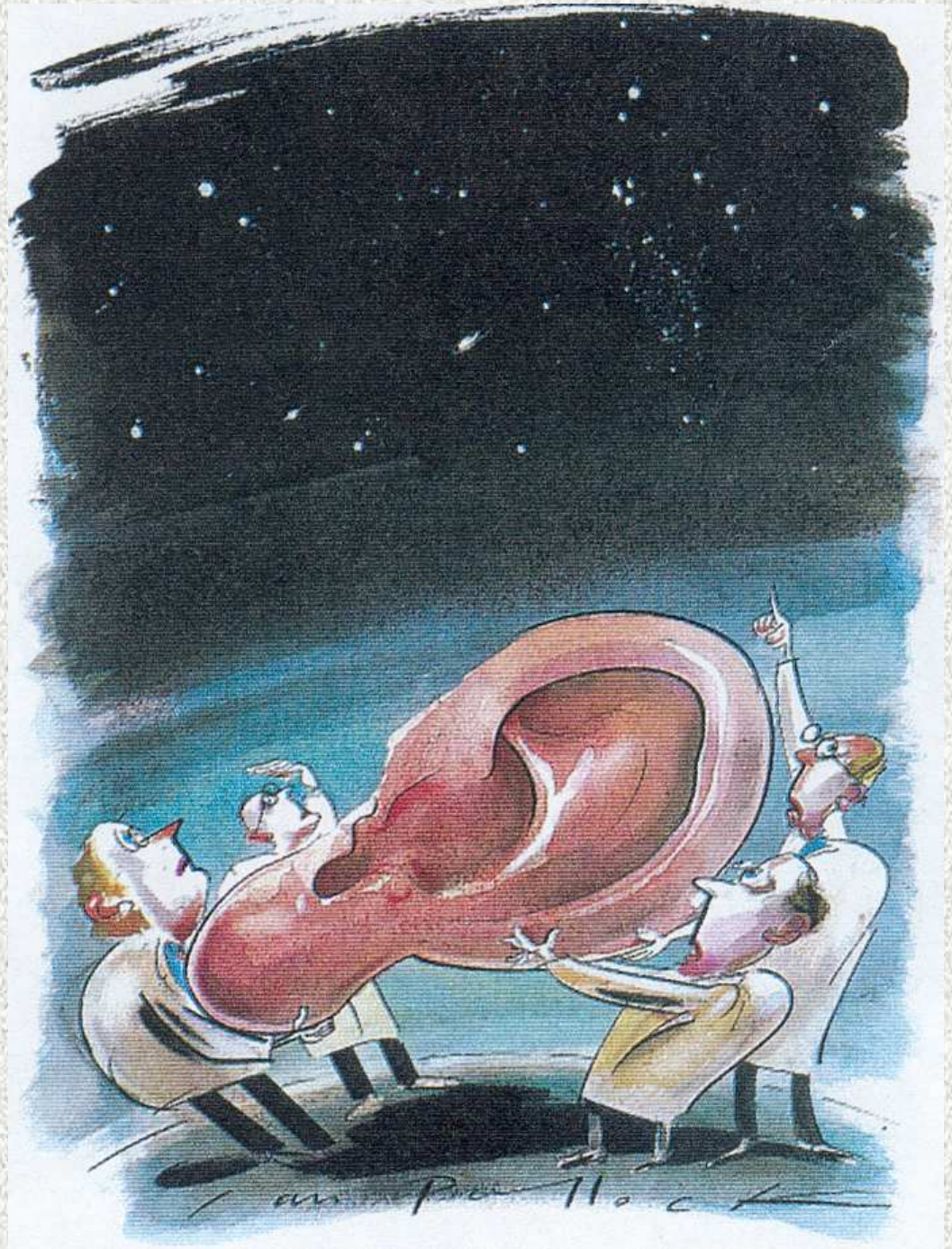


# Music from a bottle

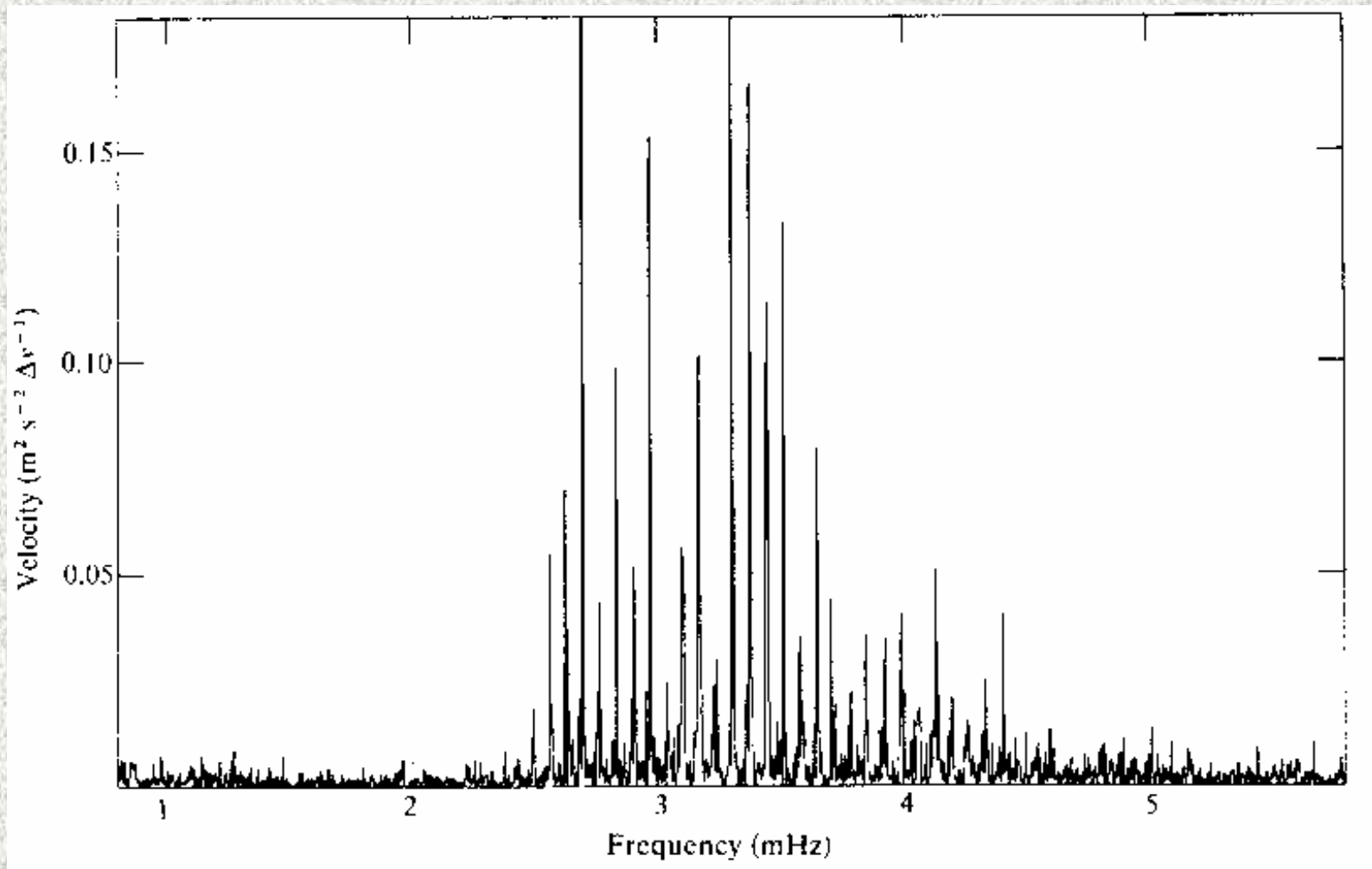


# How do we listen to the stars?

- Doppler velocity
- Intensity

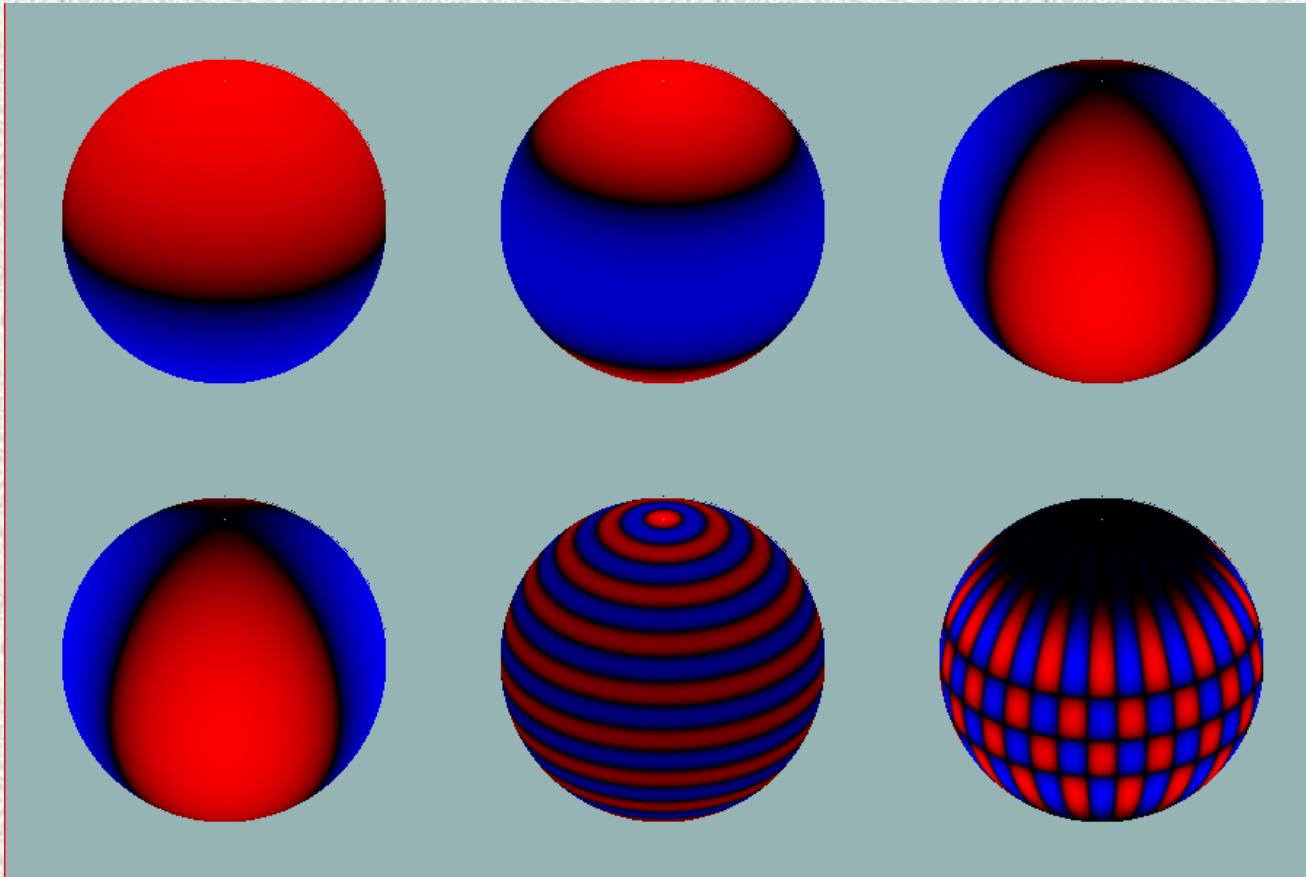


# Where it all started



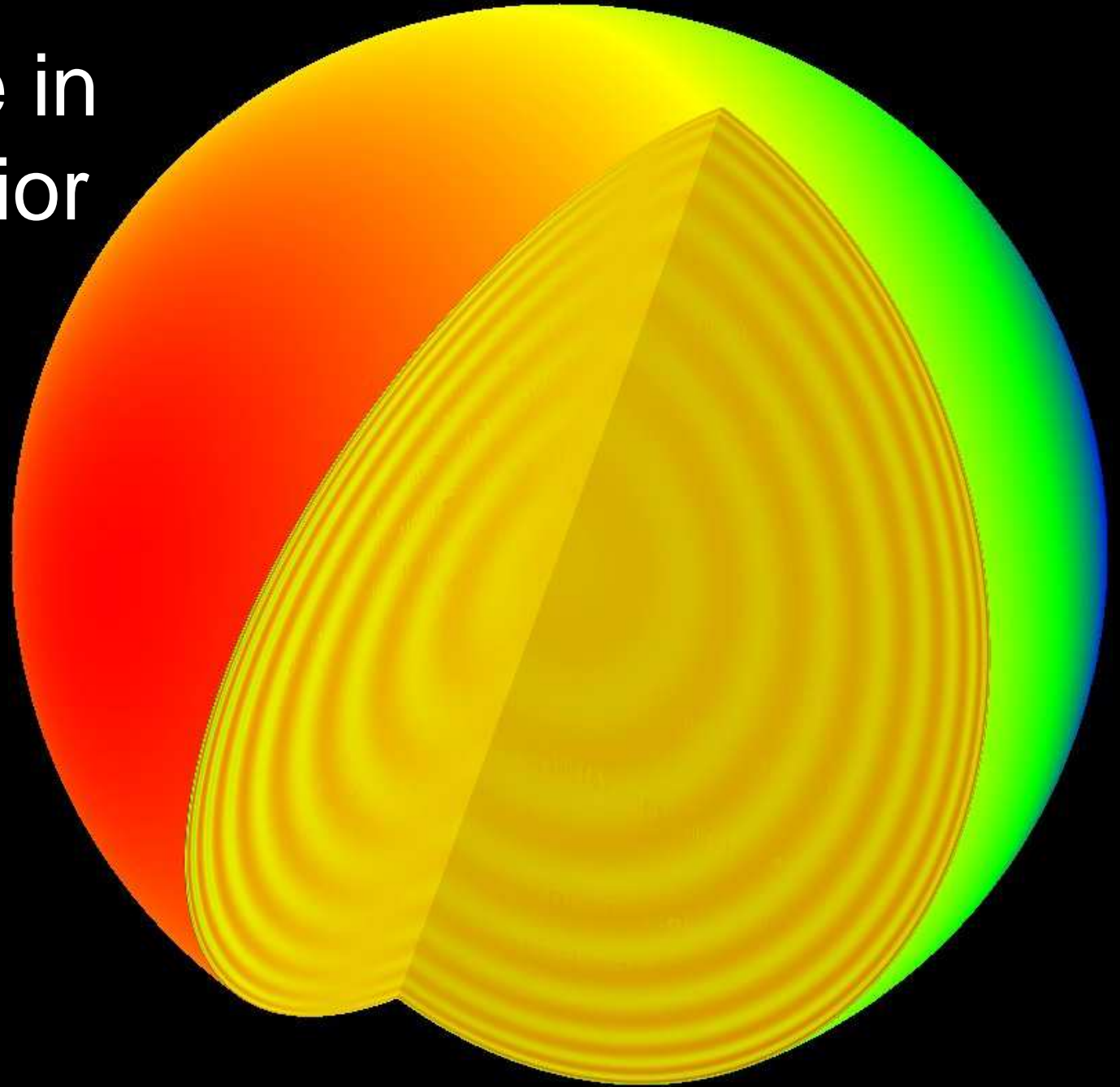
Grec et al., Nature 288, 541; 1980

# Basic properties of oscillations

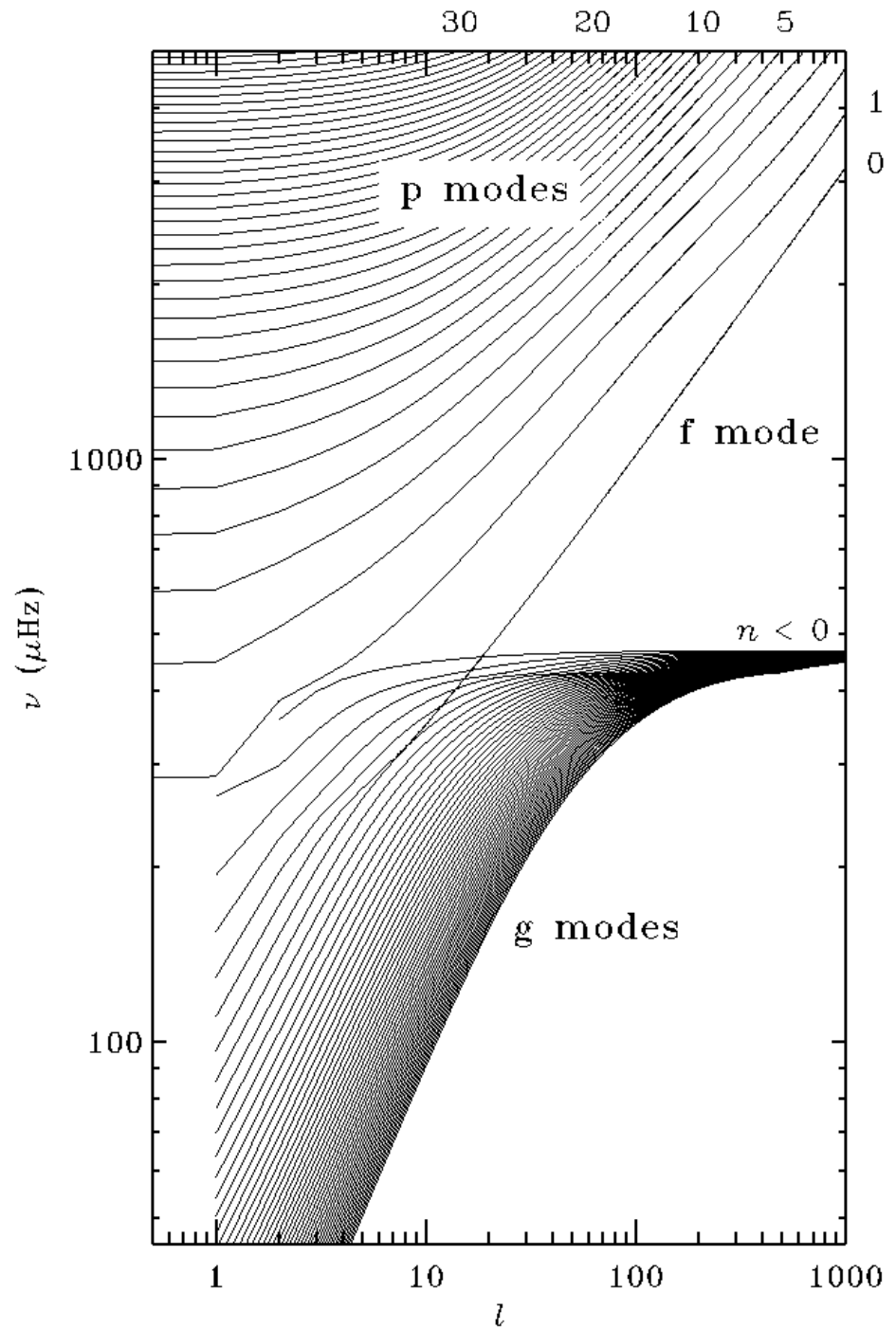


- Behave like spherical harmonics:  $P_l^m(\cos \theta) \cos(m \phi - \omega t)$
- $k_h = 2 \pi / \lambda_h = [l(l+1)]^{1/2}/r$

Mode  
structure in  
the interior



# Computed oscillation frequencies



# Asymptotics of frequencies

Acoustic-wave dispersion relation

$$\omega^2 = c^2 |\mathbf{k}|^2 = c^2 (k_r^2 + k_h^2) = c^2 \left( k_r^2 + \frac{l(l+1)}{r^2} \right)$$

Hence

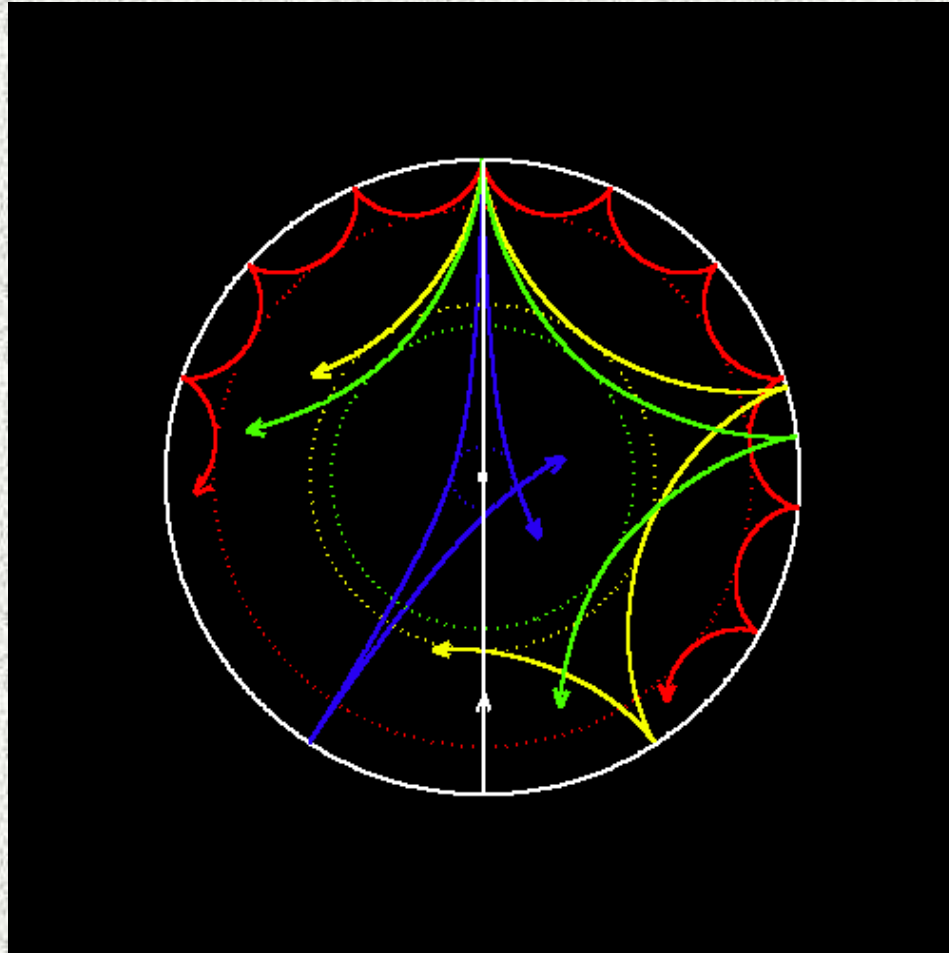
$$k_r = \left[ \frac{\omega^2}{c^2} - \frac{l(l+1)}{r^2} \right]^{1/2}$$

Lower turning point  $r_t$  where  $k_r = 0$ :

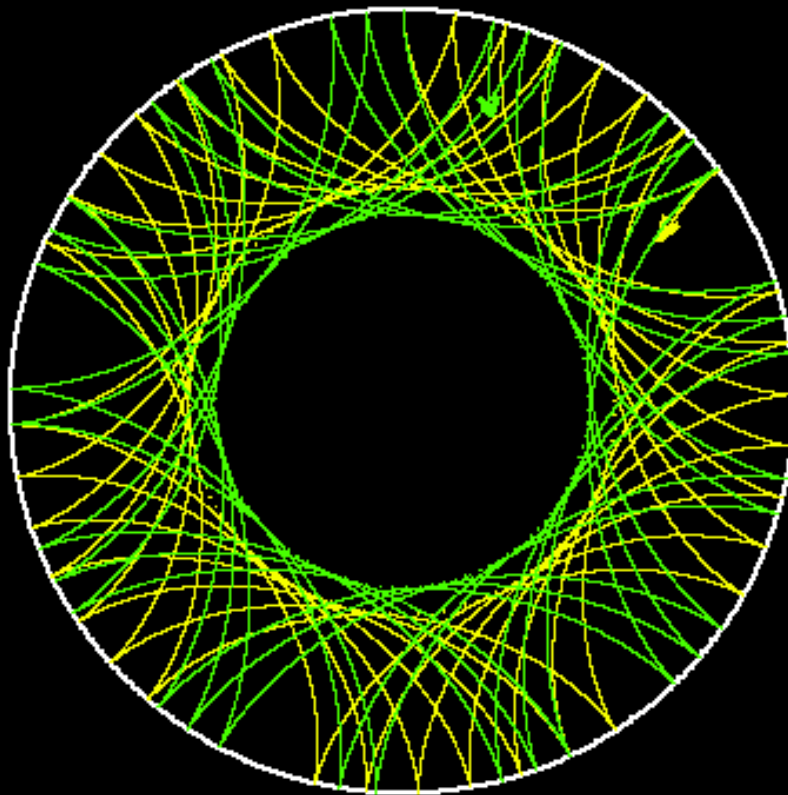
$$\frac{c(r_t)}{r_t} = \frac{\omega}{\sqrt{l(l+1)}}$$



# Rays



# Inversion with rays



# Birmingham Solar Oscillations Network (BiSON)



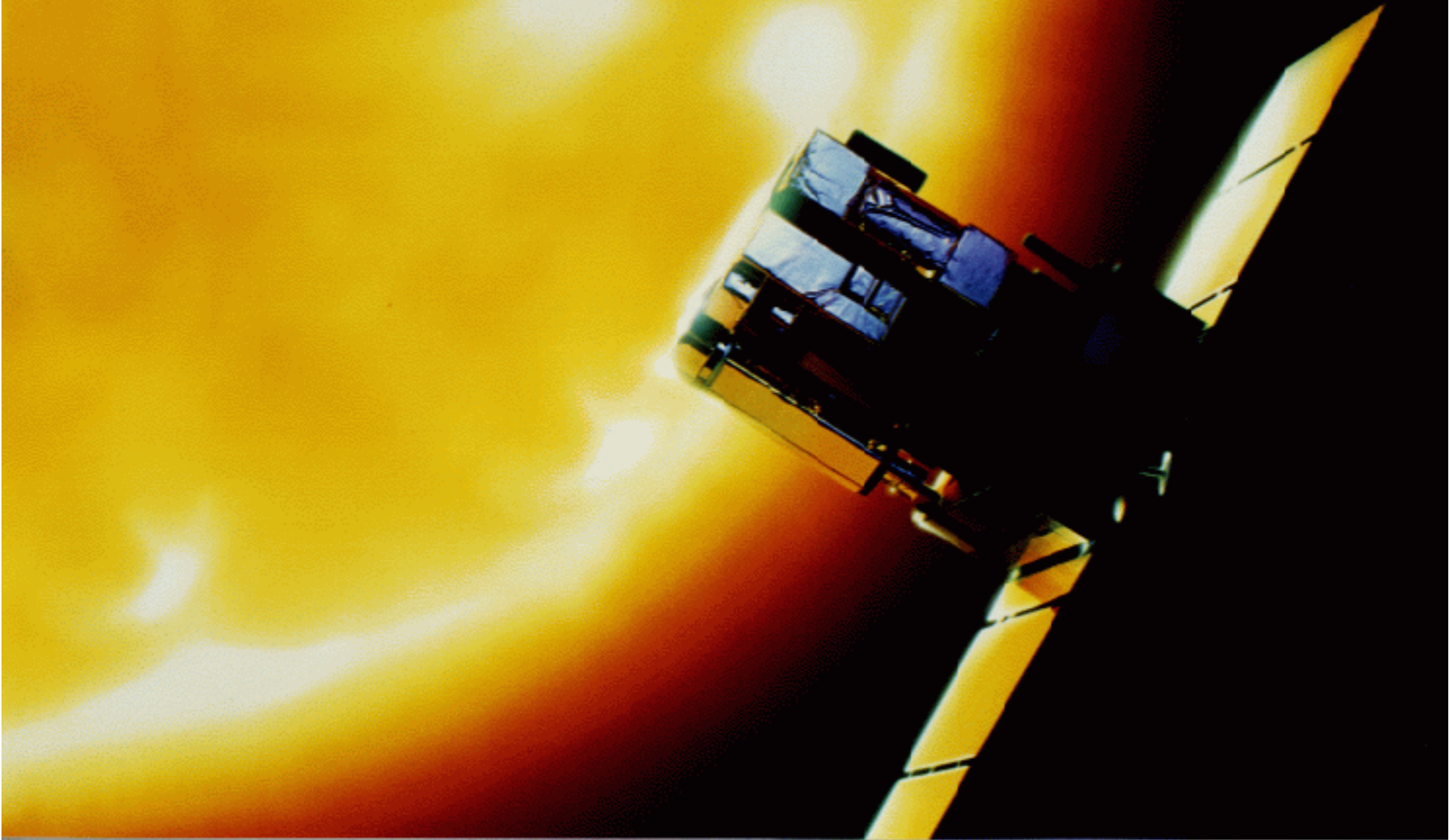
Low-degree modes:  $l \leq 3$

Sutherland  
site



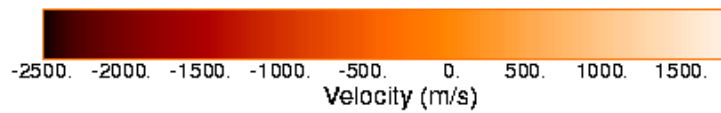
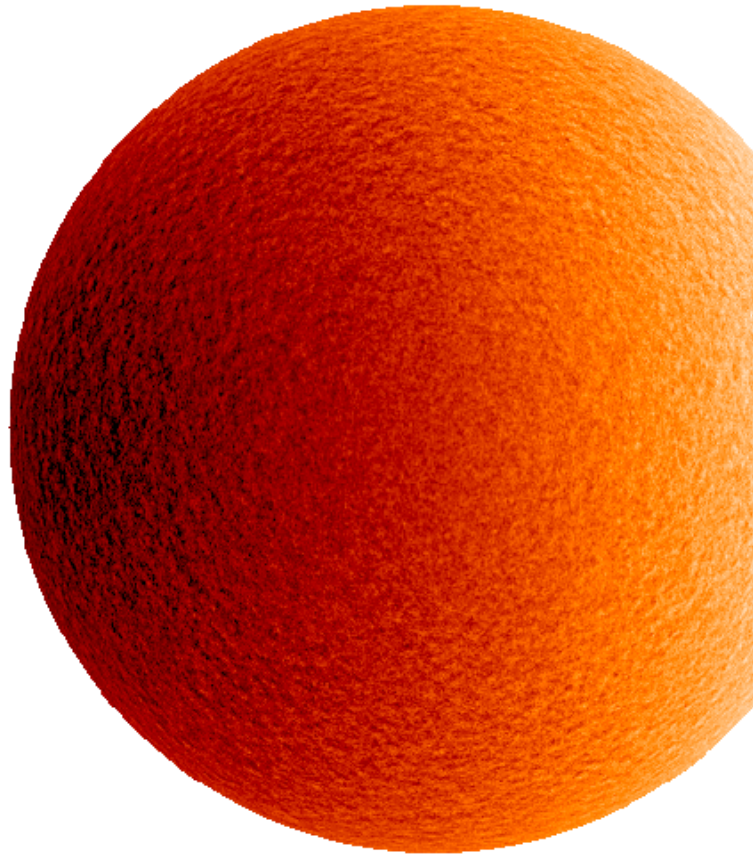


# MDI, VIRGO and GOLF on SOHO



# Single Dopplergram

(30-MAR-96 19:54:00)

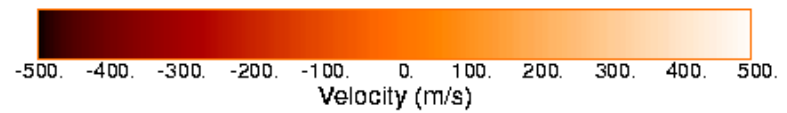


SOI / MDI

Stanford Lockheed Institute for Spa

# Single Dopplergram Minus 45 Images Average

(30-MAR-96 19:54:00)



SOI / MDI

Stanford Lockheed Institute for Space Research

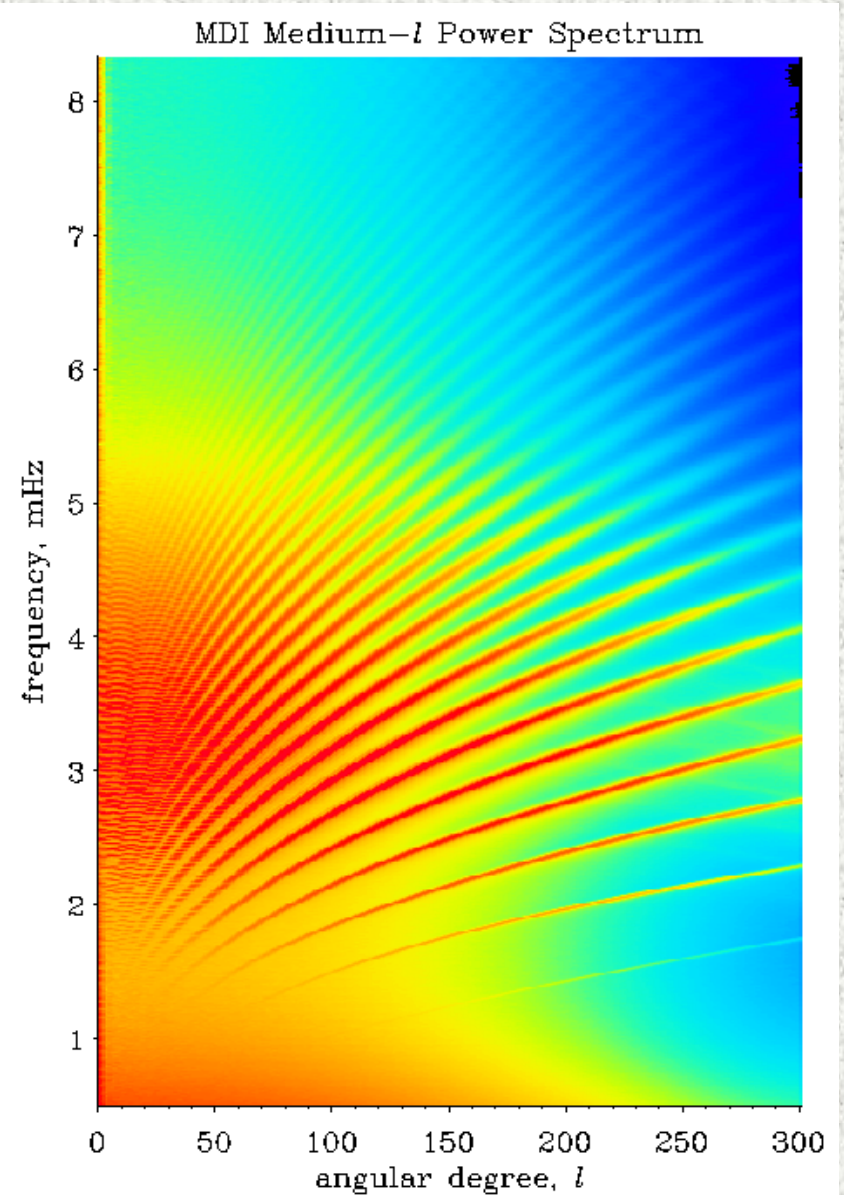
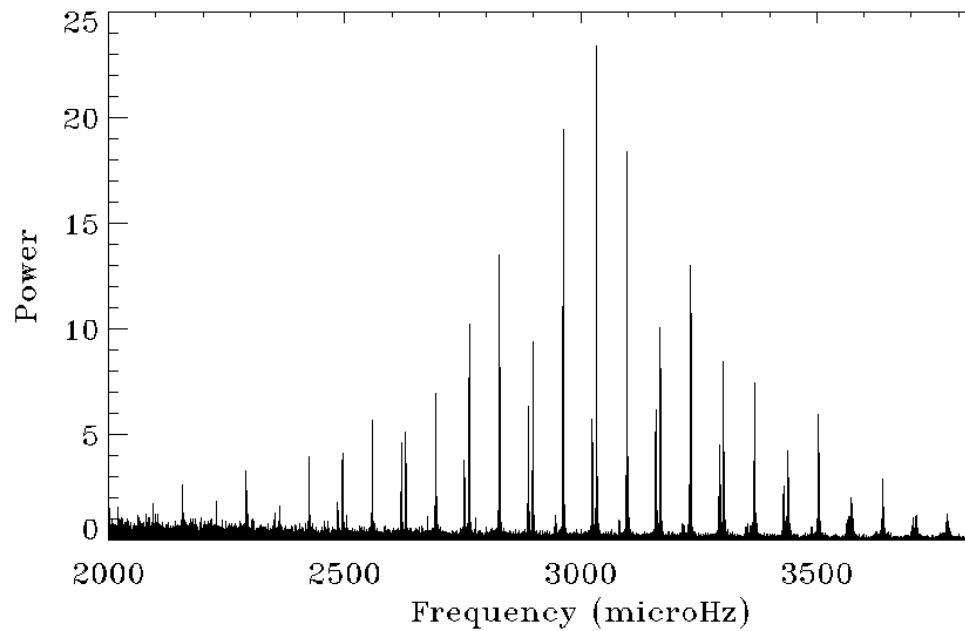


# Data on solar oscillations

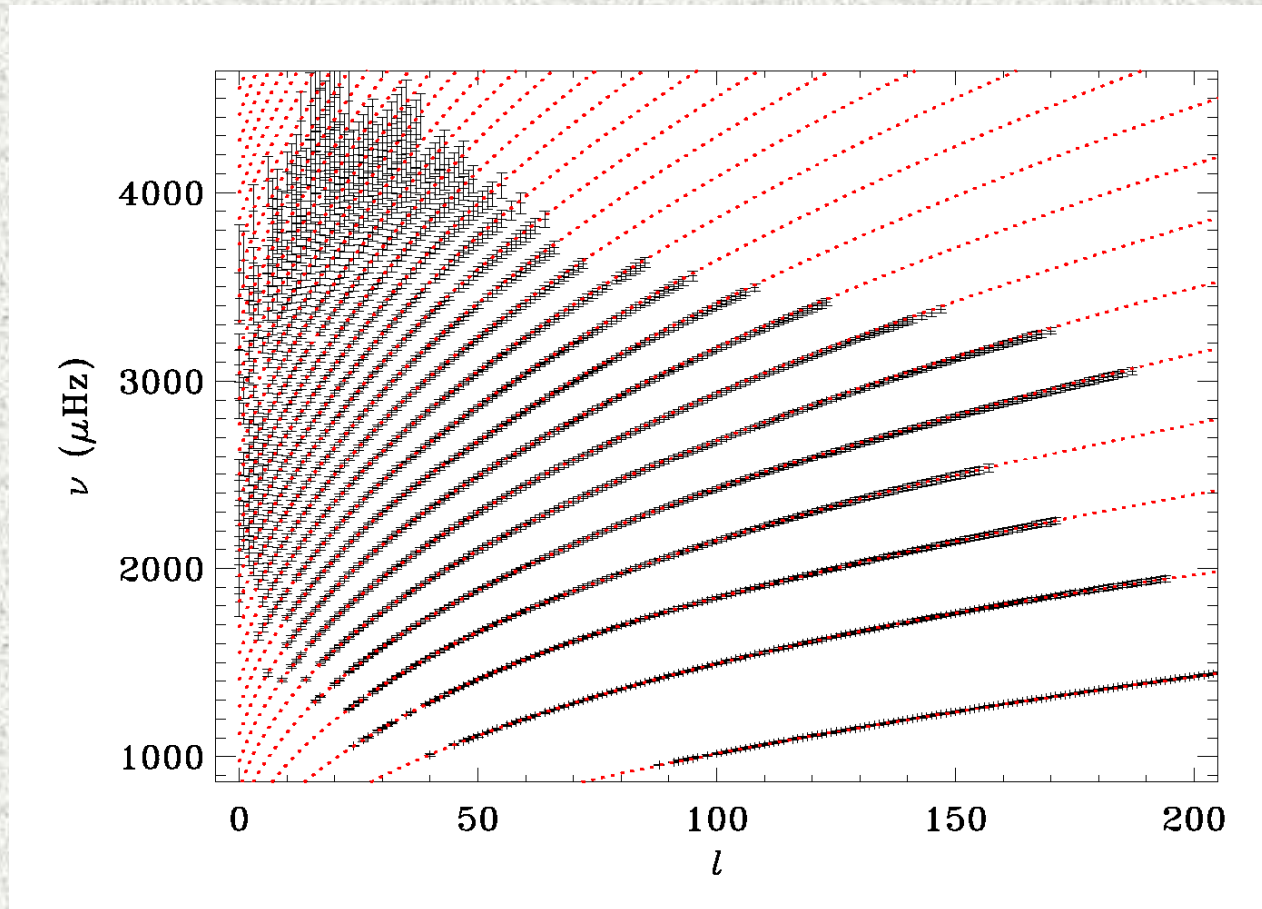
Observations:

MDI on SOHO

VIRGO on SOHO (whole-disk):



# Observed frequencies



m-averaged frequencies from MDI instrument on SOHO

1000  $\sigma$  error bars



# KNOWN 'GLOBAL' PROPERTIES OF THE SUN

- Total mass  $M$ - (assume no mass loss)
- Present surface radius  $R$ -
- Present surface luminosity  $L$ - (assuming isotropic radiation)
- Present age (depending slightly on models of solar-system formation)
- Present surface heavy-element composition, relative to hydrogen, (somewhat uncertain).
- Composition **not** known for helium

# CALIBRATION OF SOLAR MODELS

- Adjust initial helium abundance  $Y_0$  to obtain the observed present luminosity
- Adjust initial heavy-element abundance  $Z_0$  to obtain observed present ratio  $Z_s/X_s$
- Adjust parameter of convection treatment (e.g. mixing-length parameter  $\alpha_c$ ) to obtain observed present radius.

# Properties of Model S

- OPAL96 equation of state
- OPAL 92 opacities
- Nuclear parameters from Bahcall & Pinsonneault (1994)
- Diffusion and settling of helium and heavy elements from Michaud & Proffitt (1993)
- Mixing-length theory of convection

# Frequency dependence on solar structure

Frequencies depend on dynamical quantities:

$$p(r), \quad \rho(r), \quad g(r), \quad \gamma_1(r)$$

However, from hydrostatic equilibrium and Poisson's equation  $p$  and  $g$  can be determined from  $\rho$

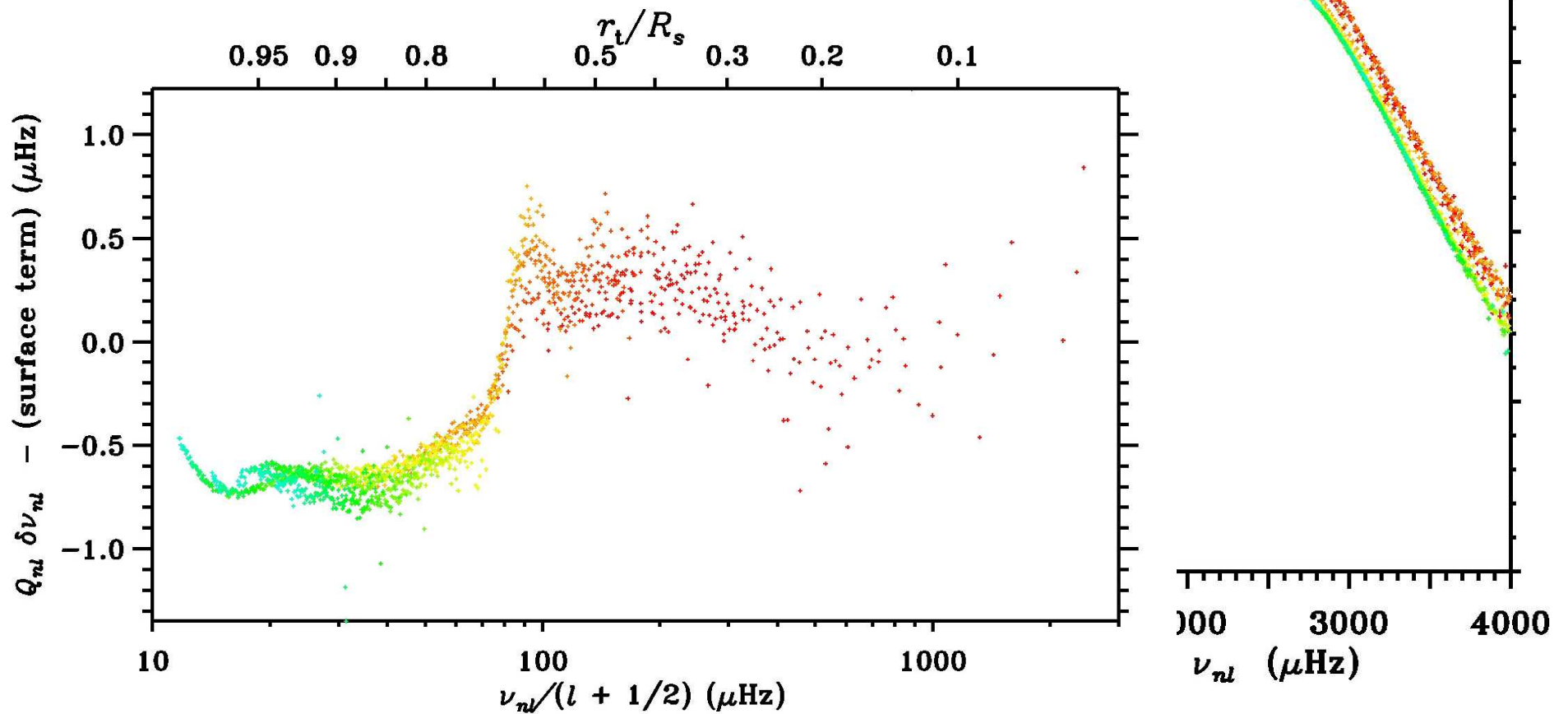
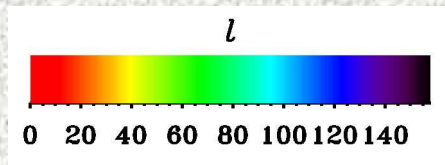
Hence adiabatic oscillations are fully characterized by

$$\rho(r), \quad \gamma_1(r)$$

or, equivalently

$$\rho(r), \quad c^2(r)$$

# Frequency differences, Sun - model



# Inverse analysis

From

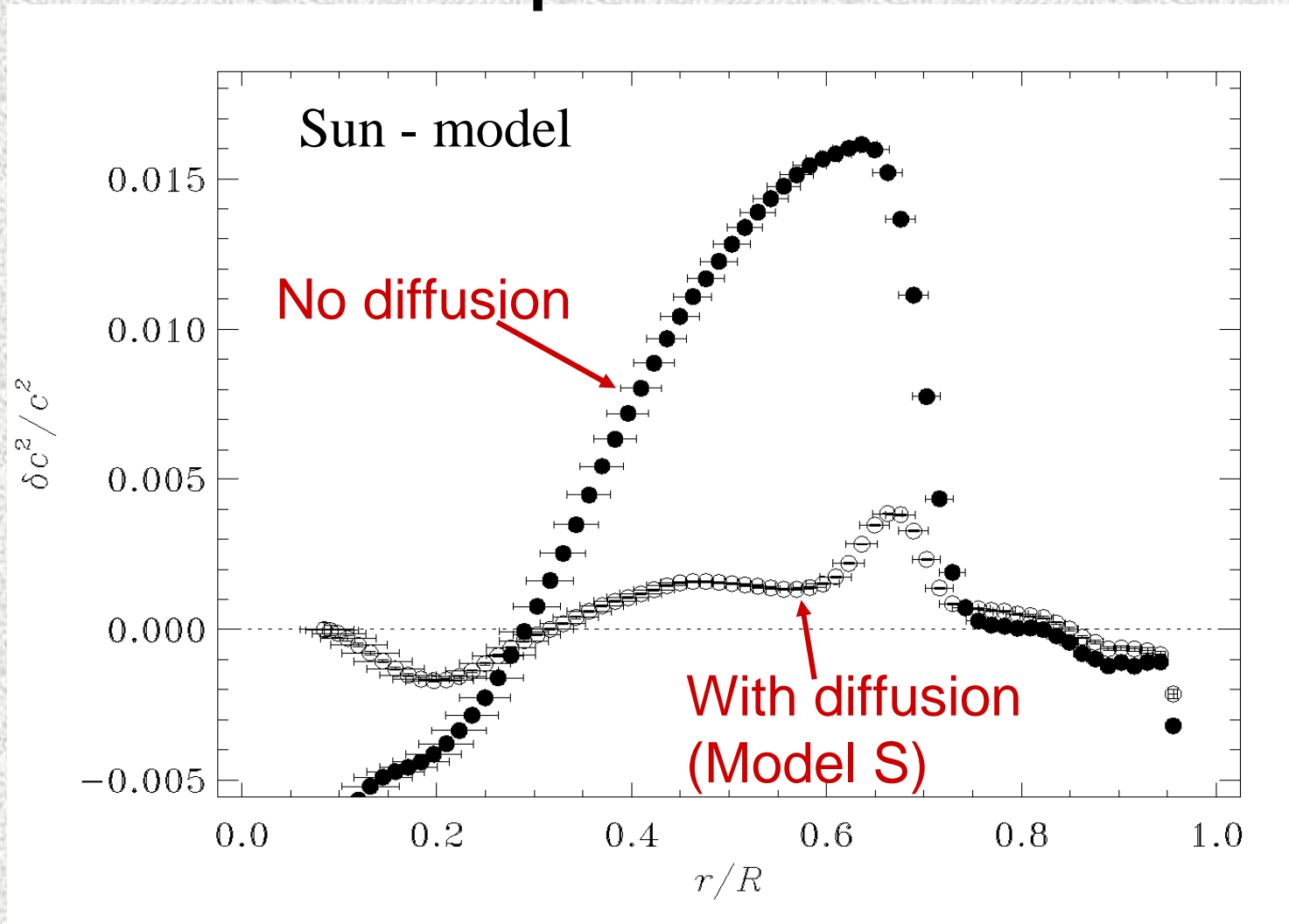
$$\delta\nu_{nl} = \nu_{nl}^{\odot} - \nu_{nl}^{(\text{mod})}$$

infer

$$\delta_r c(r) = c^{\odot}(r) - c^{(\text{mod})}(r)$$

Inversion code developed with M. J. Thompson,  
S. Basu, M. P. Di Mauro

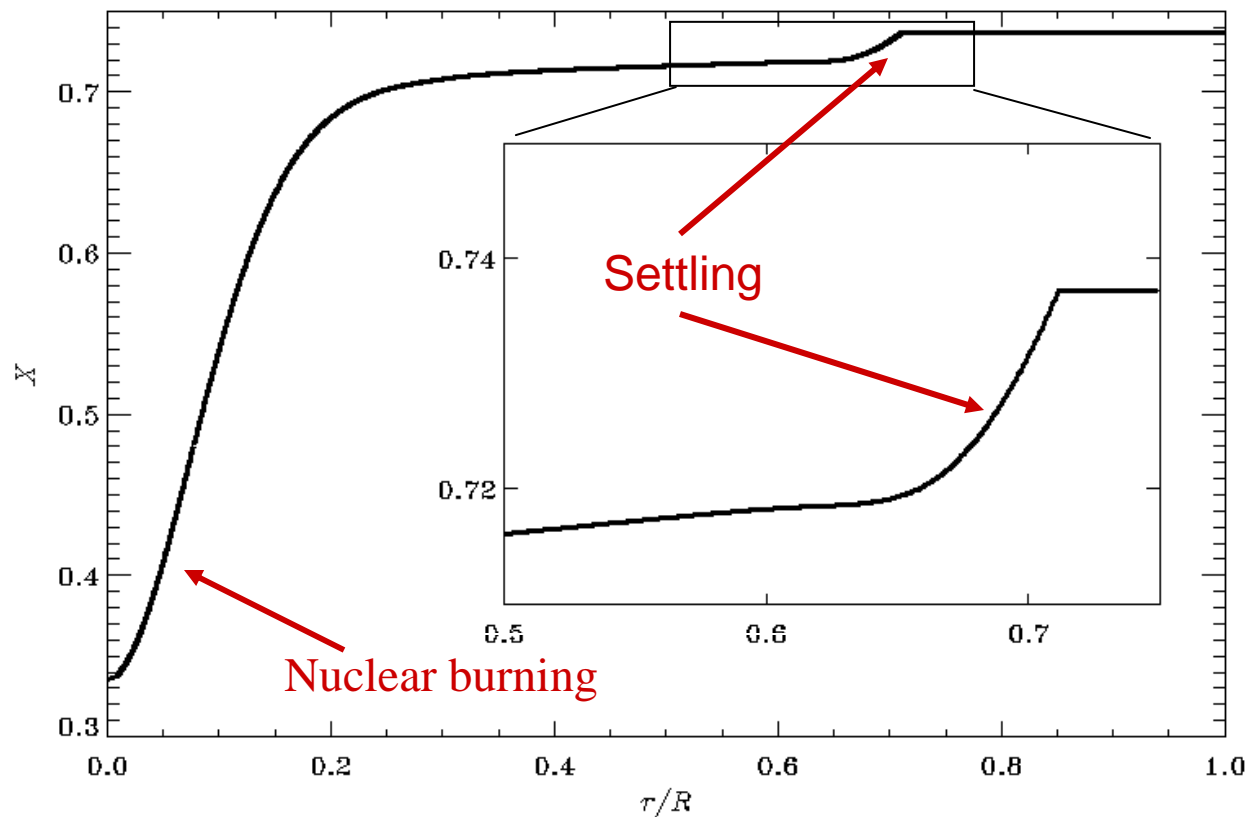
# The solar internal sound speed



Christensen-Dalsgaard & Di Mauro (2007)

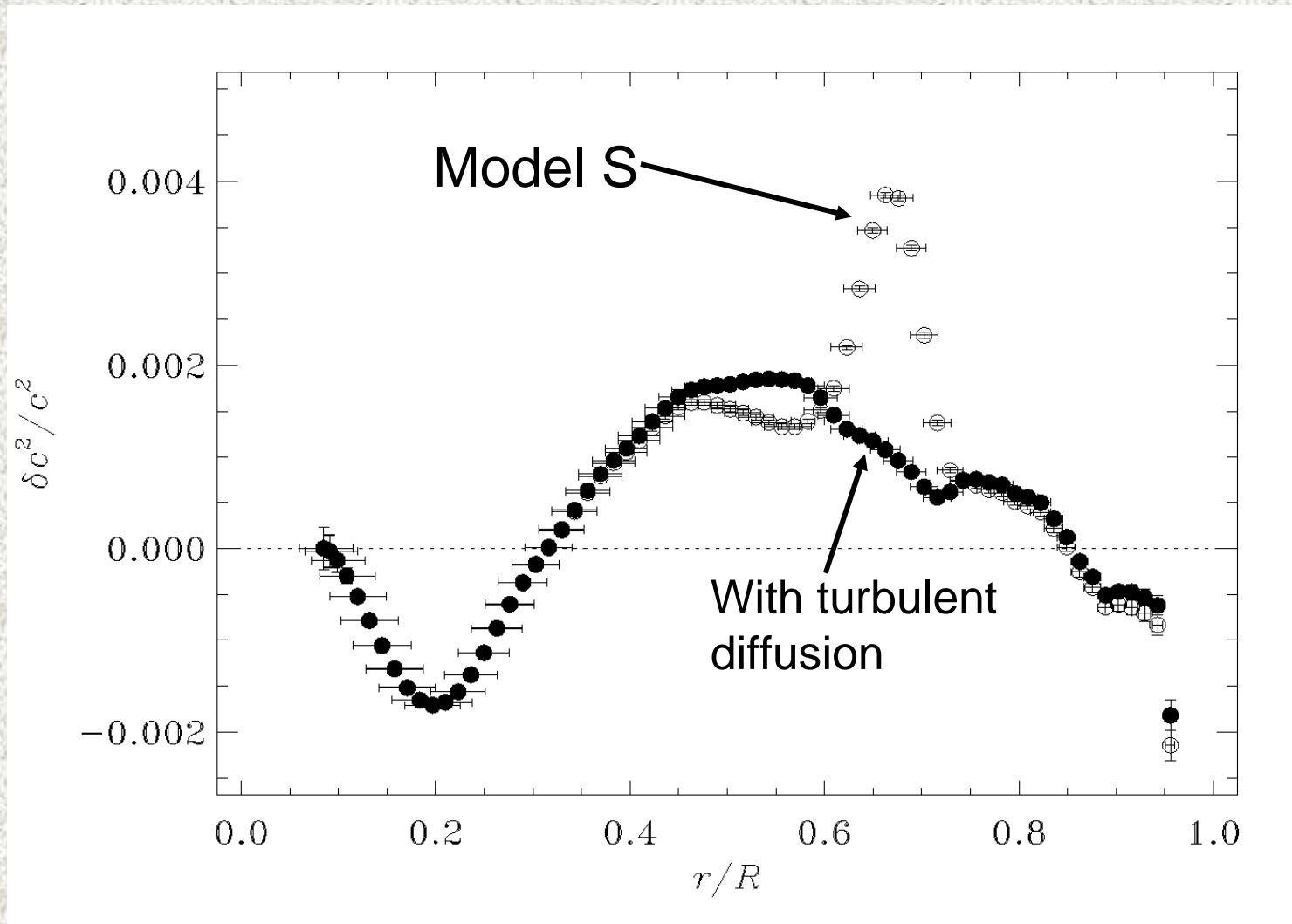
# Changes in composition

The evolution of stars is controlled by the changes in their interior composition:





# The solar internal sound speed



Christensen-Dalsgaard & Di Mauro (2007)

# Revision of solar abundances

Asplund et al. (2004; A&A 417, 751); Asplund (2005; ARAA 43, 481)

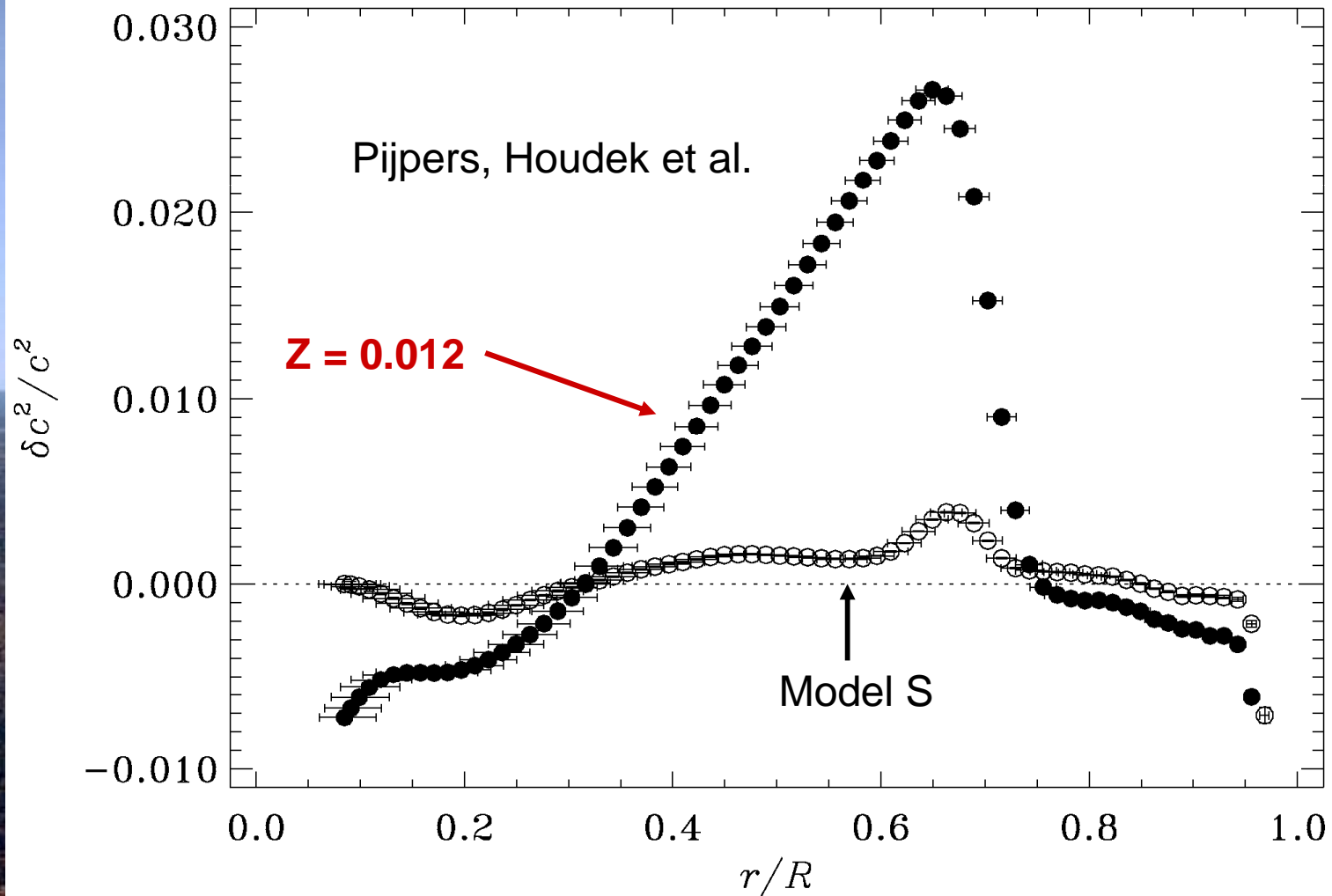
$$N(\text{O})/N(\text{H})|_{\text{old}} = 8.5 \times 10^{-4}, \quad Z_{\text{old}} = 0.0193$$

$$N(\text{O})/N(\text{H})|_{\text{new}} = 4.6 \times 10^{-4}, \quad Z_{\text{new}} = 0.0122$$

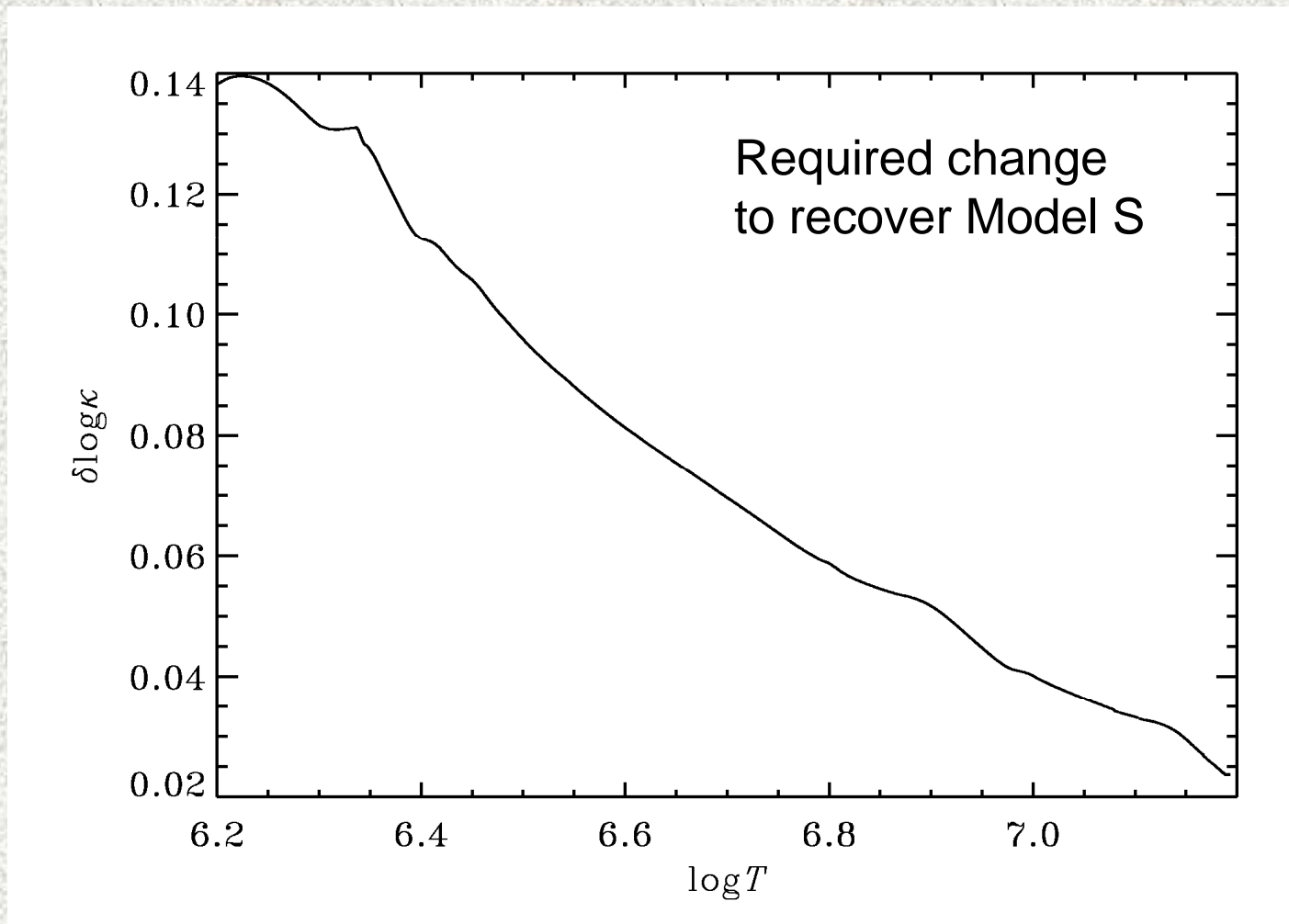
Improvements:

- Non-LTE analysis
- 3D atmosphere models
- **Consistent abundance determinations for a variety of indicators**

# Effect on solar modelling: a grain of sand or a rock?

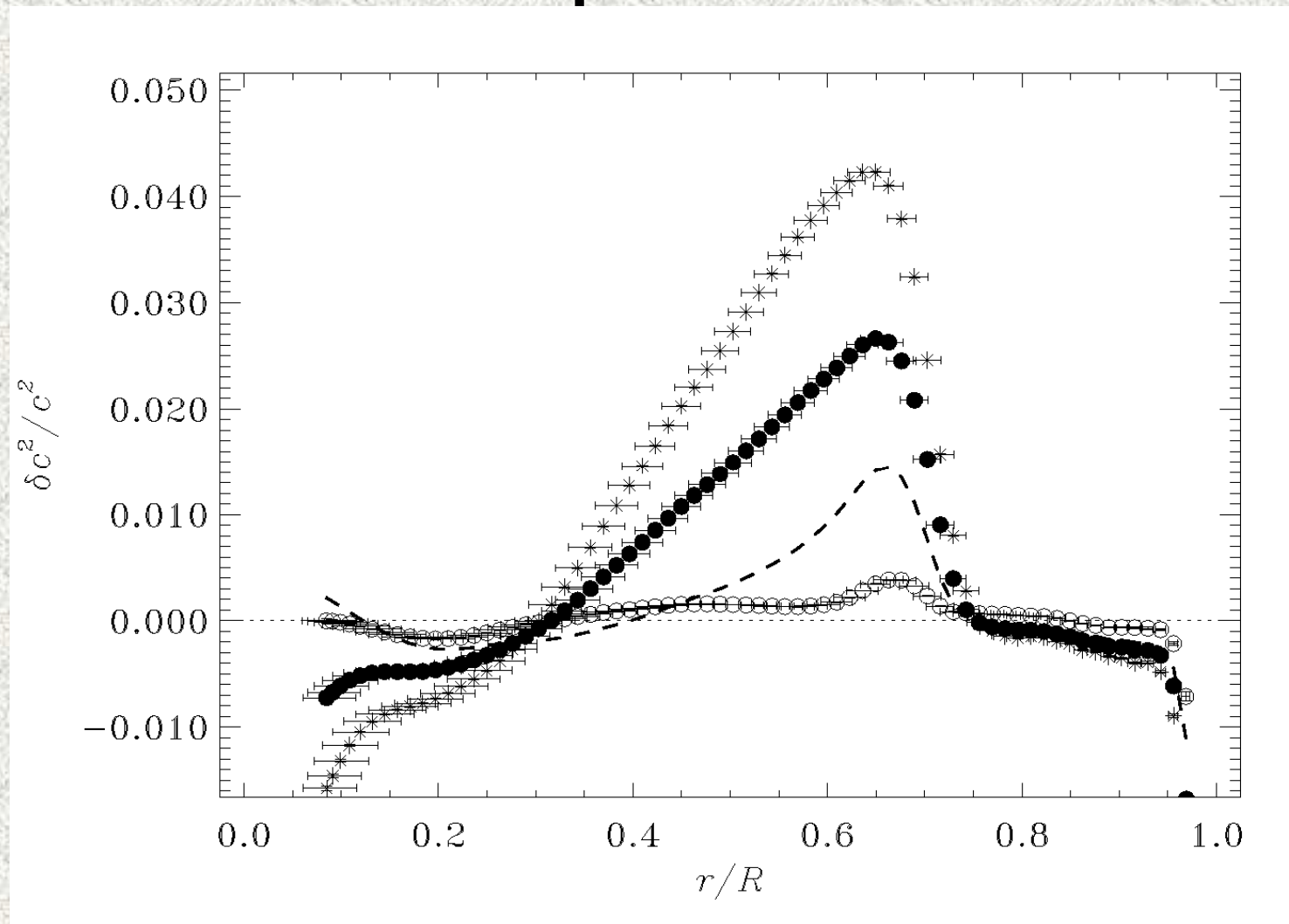


# Obvious solution: change the opacity



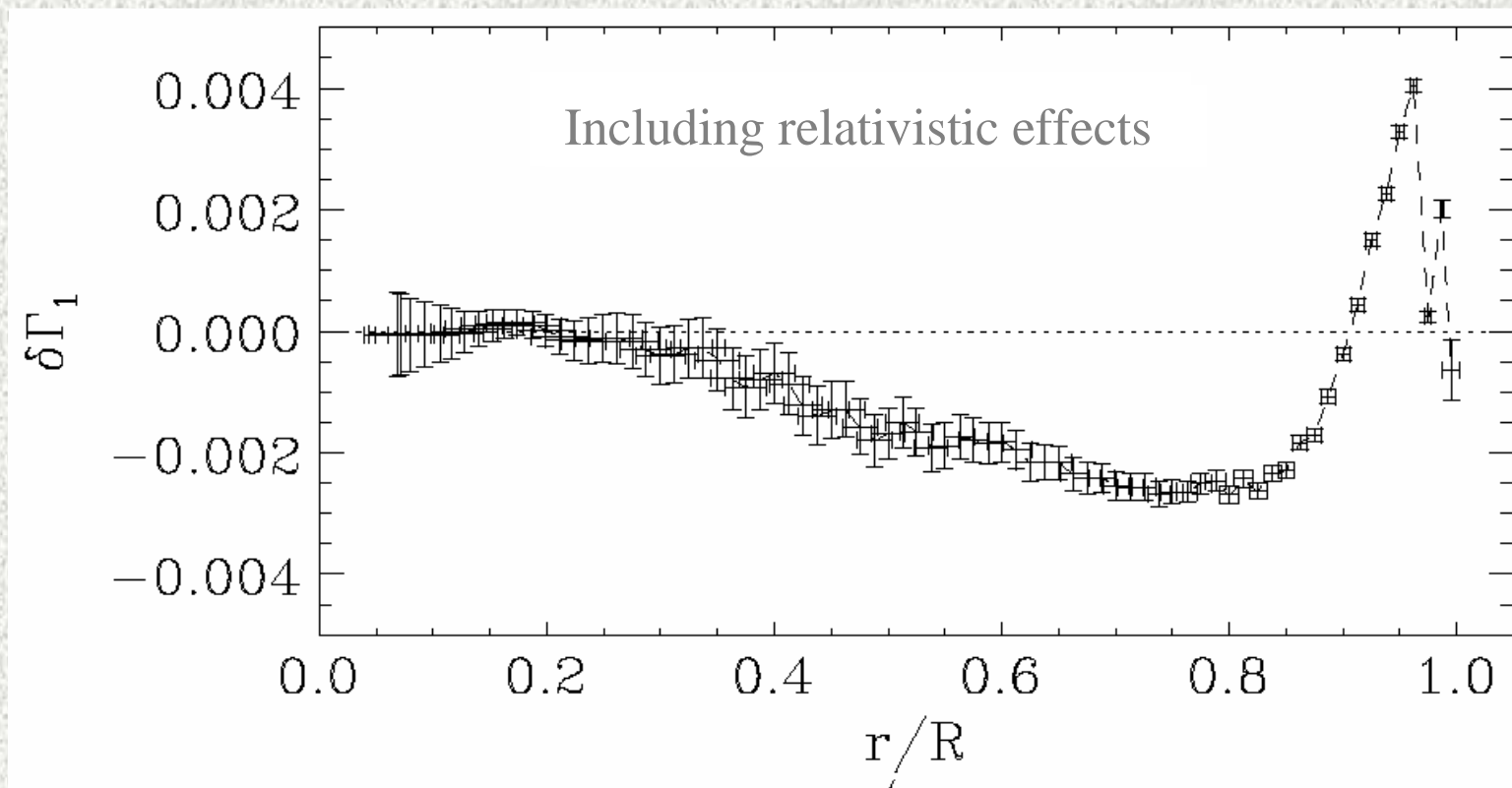
**Is this physically realistic???**

# The solar internal sound speed



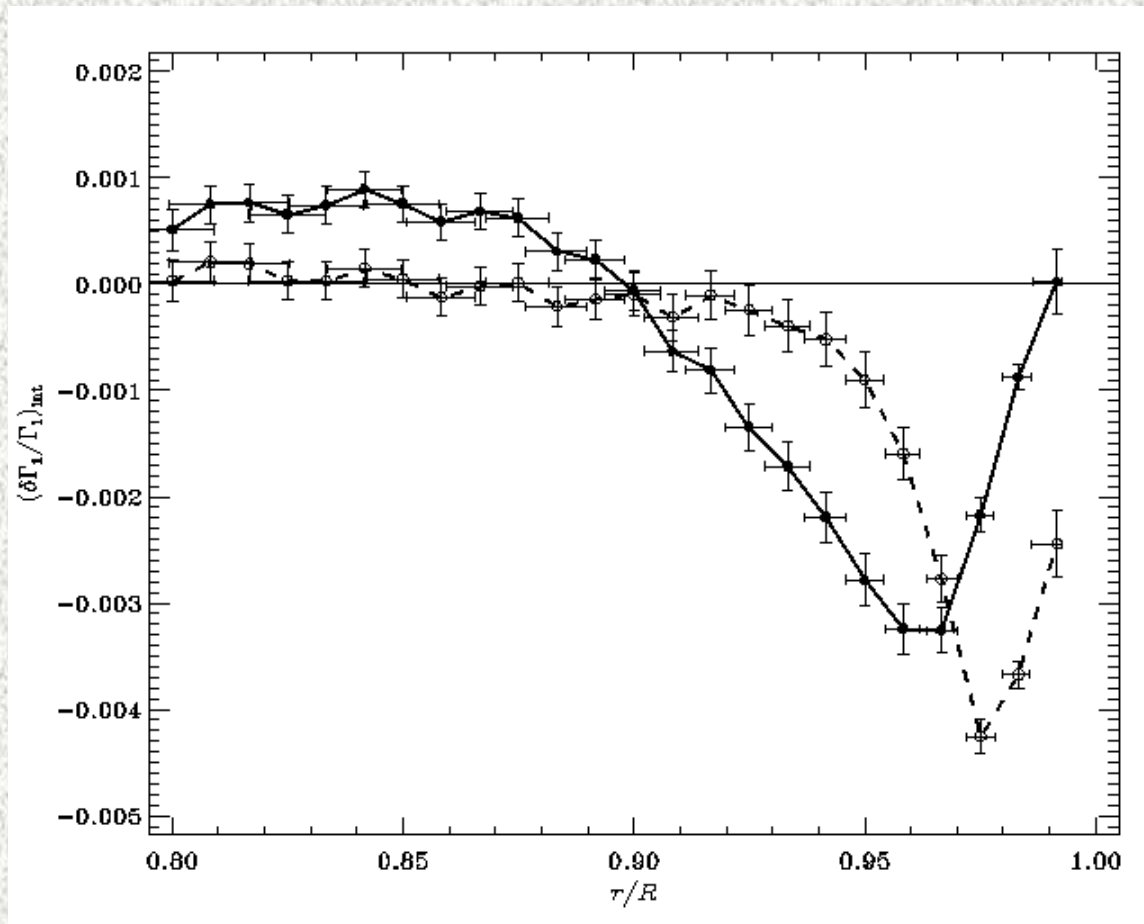
Christensen-Dalsgaard & Di Mauro (2007)

# Relativistic electrons in the Sun



Elliot & Kosovichev (1998; ApJ 500, L199)

# Testing solar thermodynamics

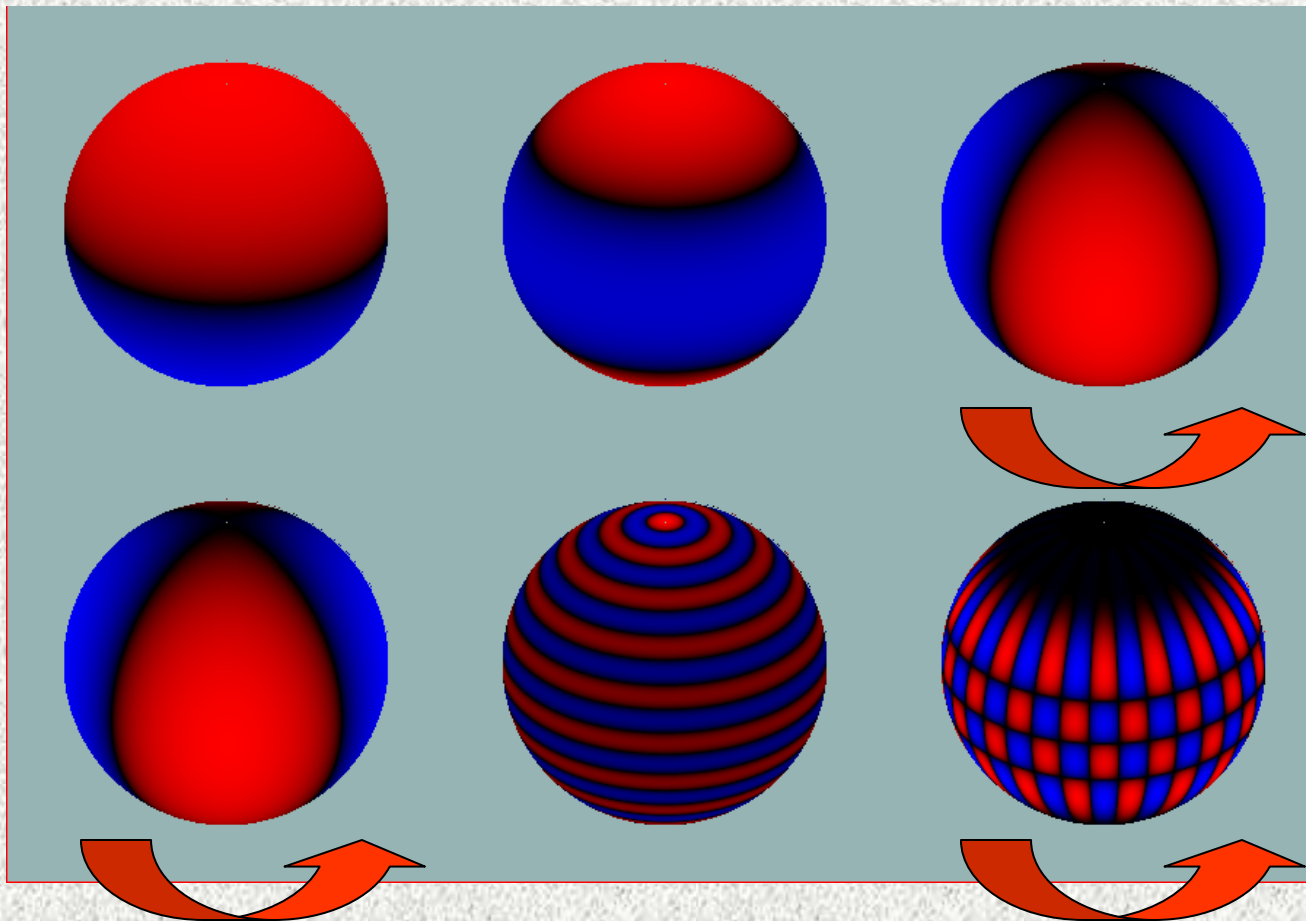


• MHD

○ OPAL

Basu, Däppen & Nayfonov (1999; ApJ 518, 985)

# Rotational splitting

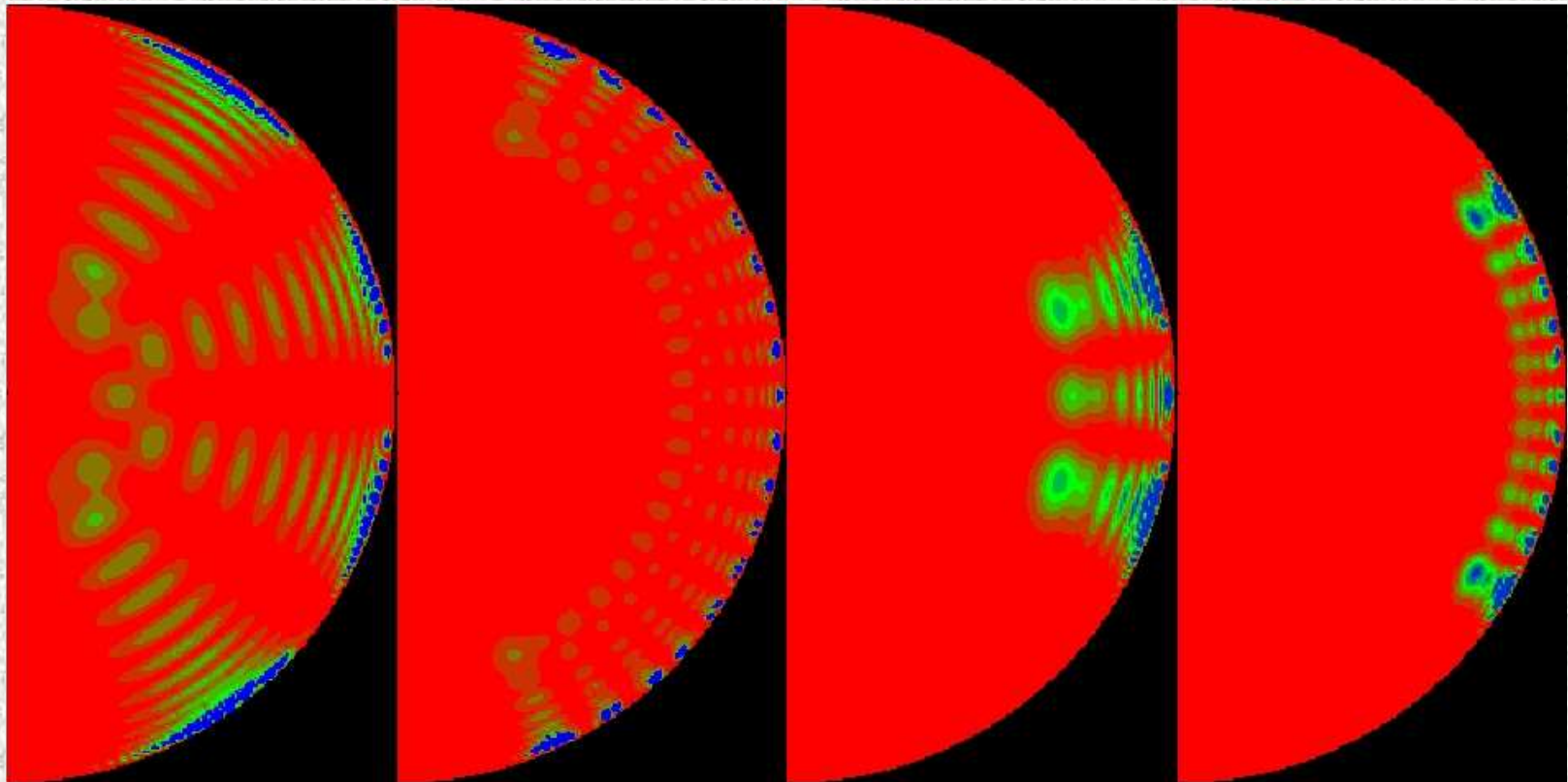


$$\omega_{nlm} = \omega_{nl0} + m\langle\Omega\rangle$$

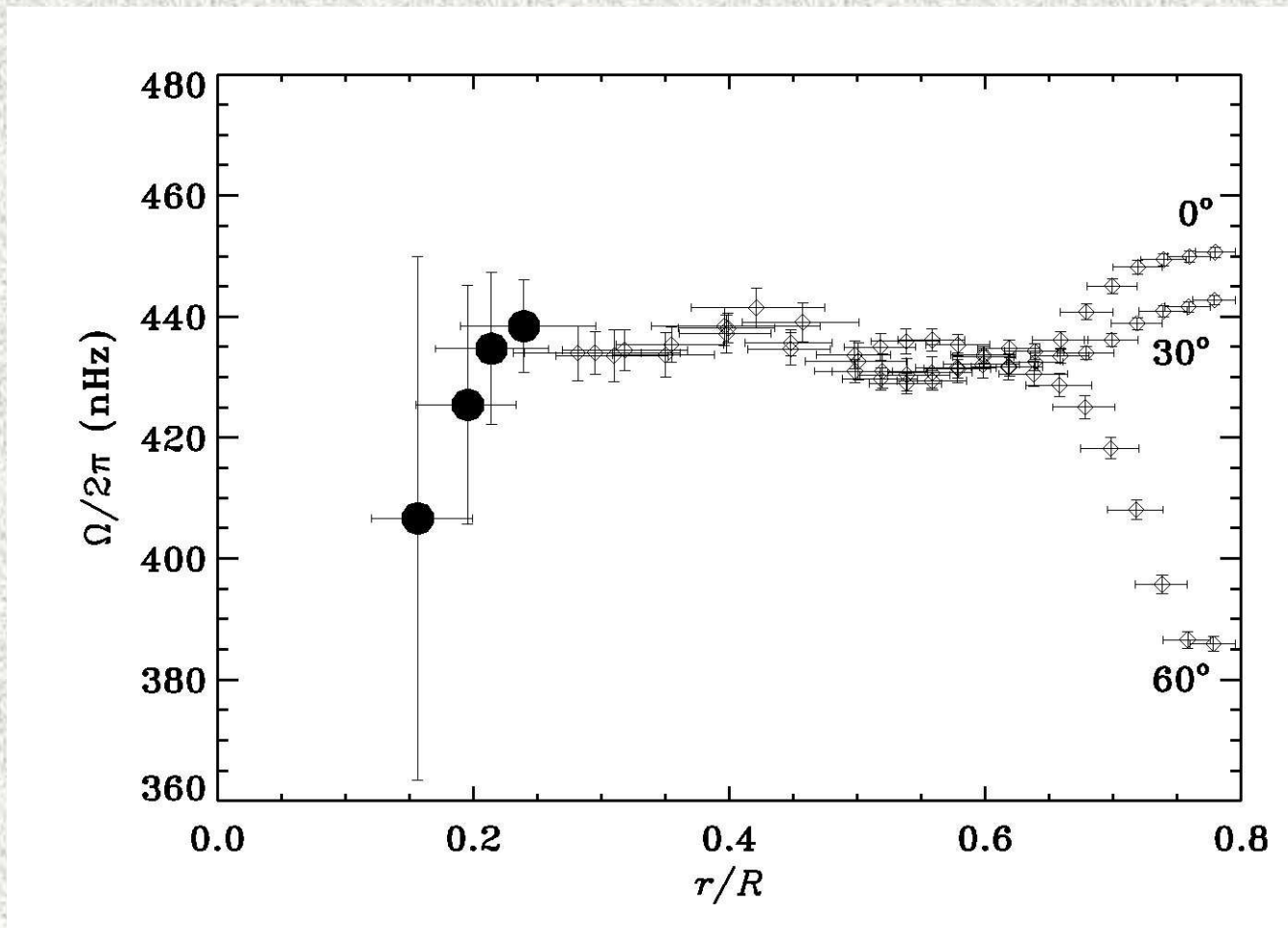


# Kernels for rotational splitting

$$\omega_{nlm} = \omega_{nl0} + m \int_0^R \int_0^\pi K_{nlm}(r, \theta) \Omega(r, \theta) r dr d\theta$$

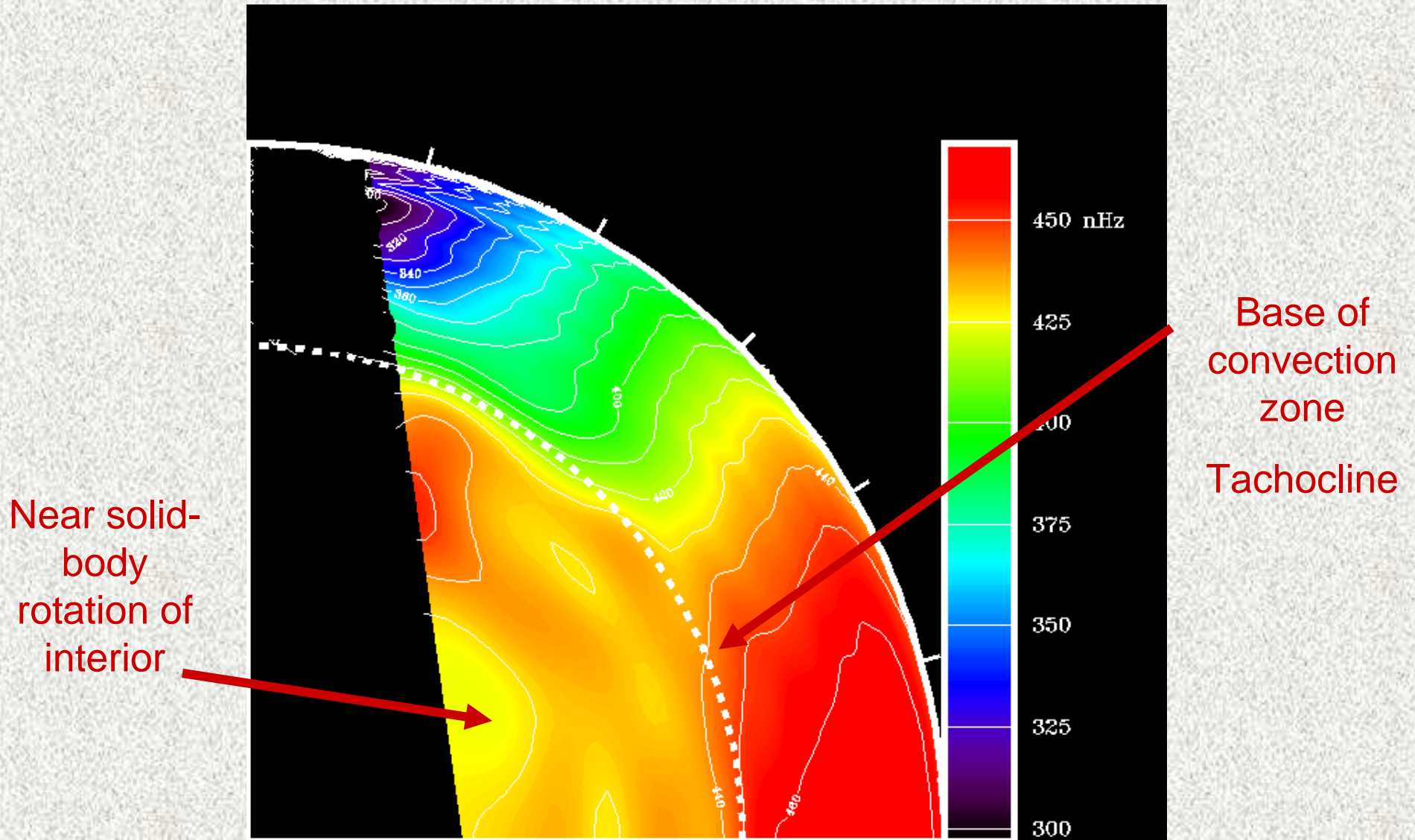


# Rotation of the solar interior



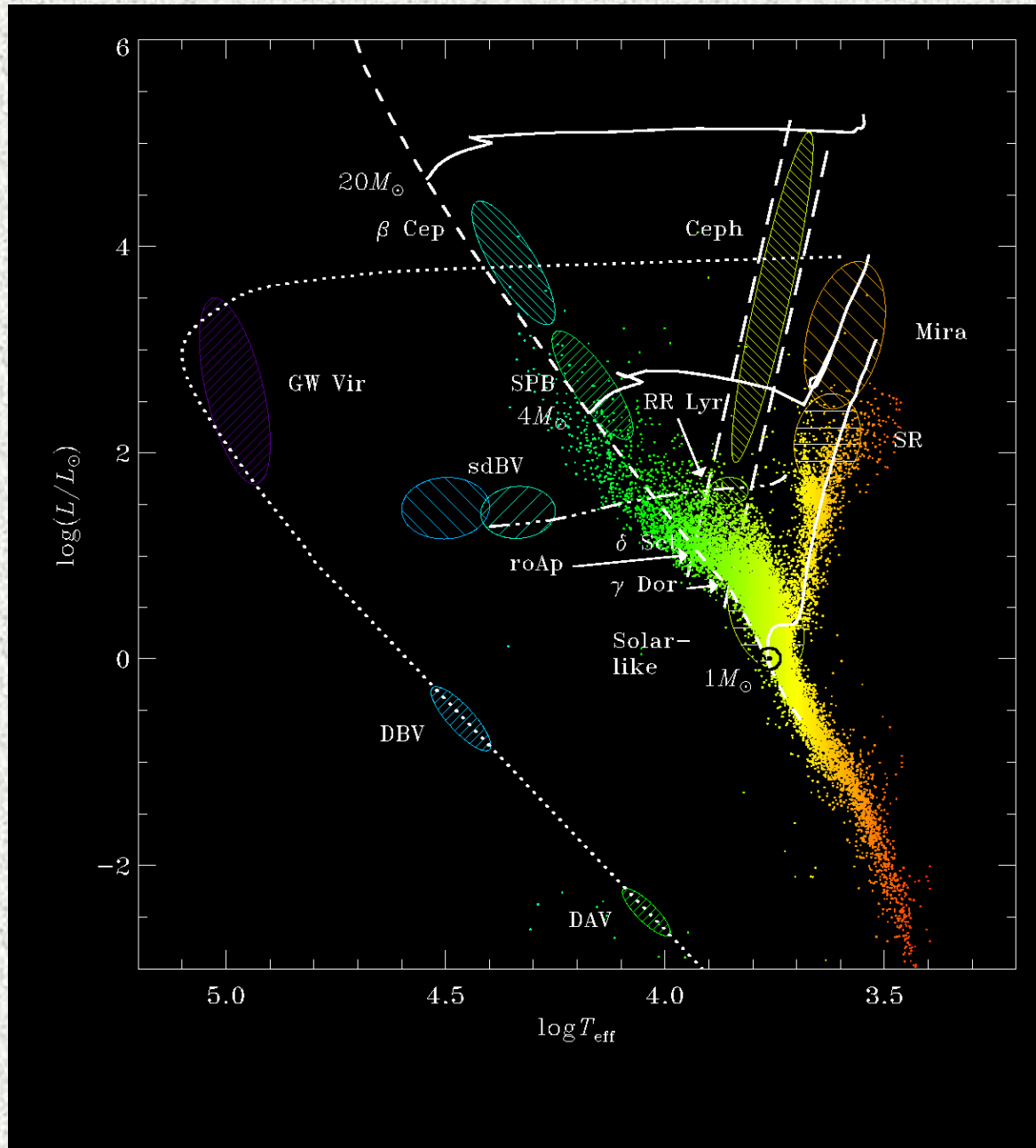
BiSON and LOWL data; Chaplin et al. (1999; MNRAS 308, 405)

# Rotation in the solar interior



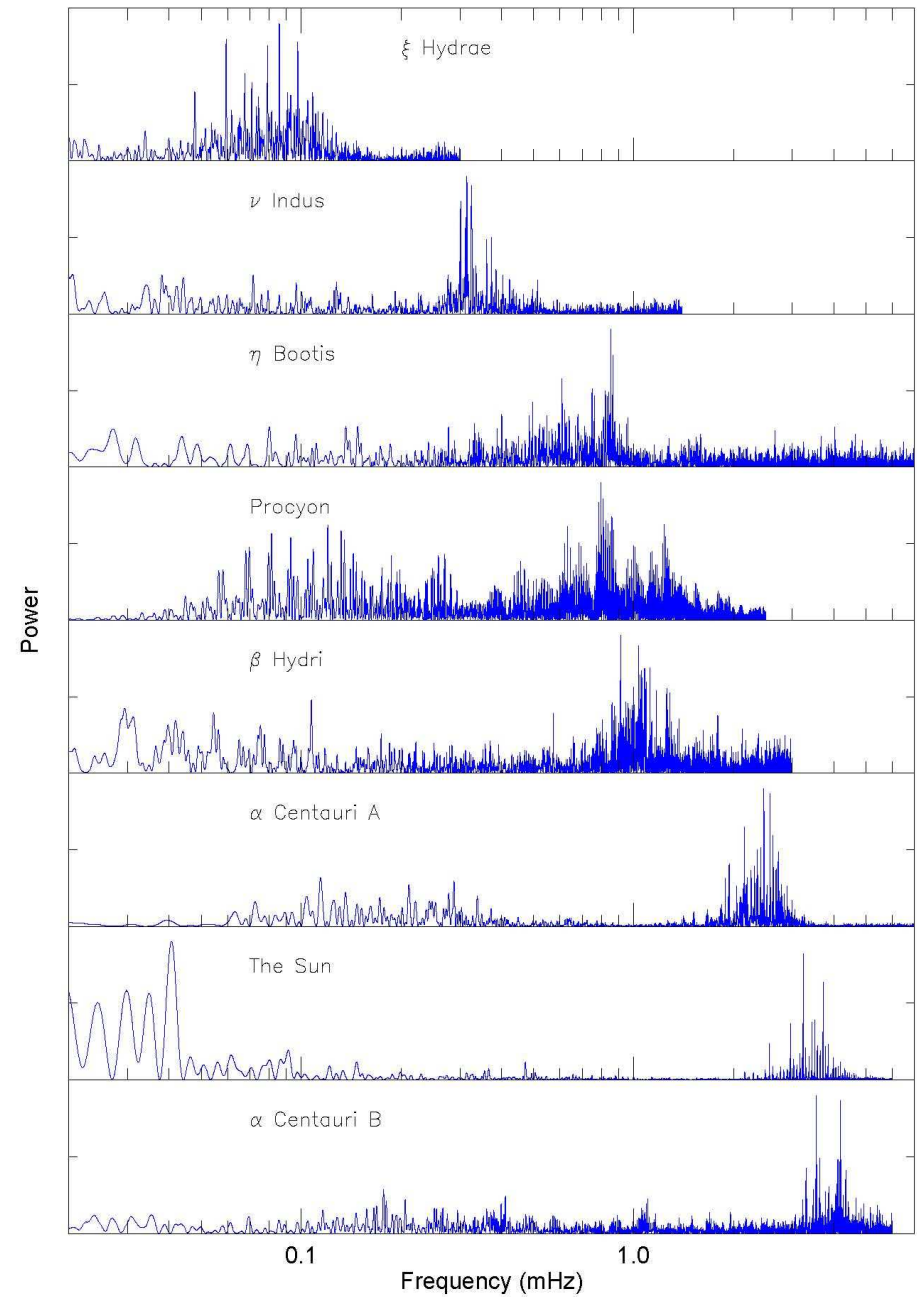
MDI data. Schou et al. (1998; ApJ 505, 390)

# From the Sun to the stars



# Solar-like oscillators

Bedding & Kjeldsen

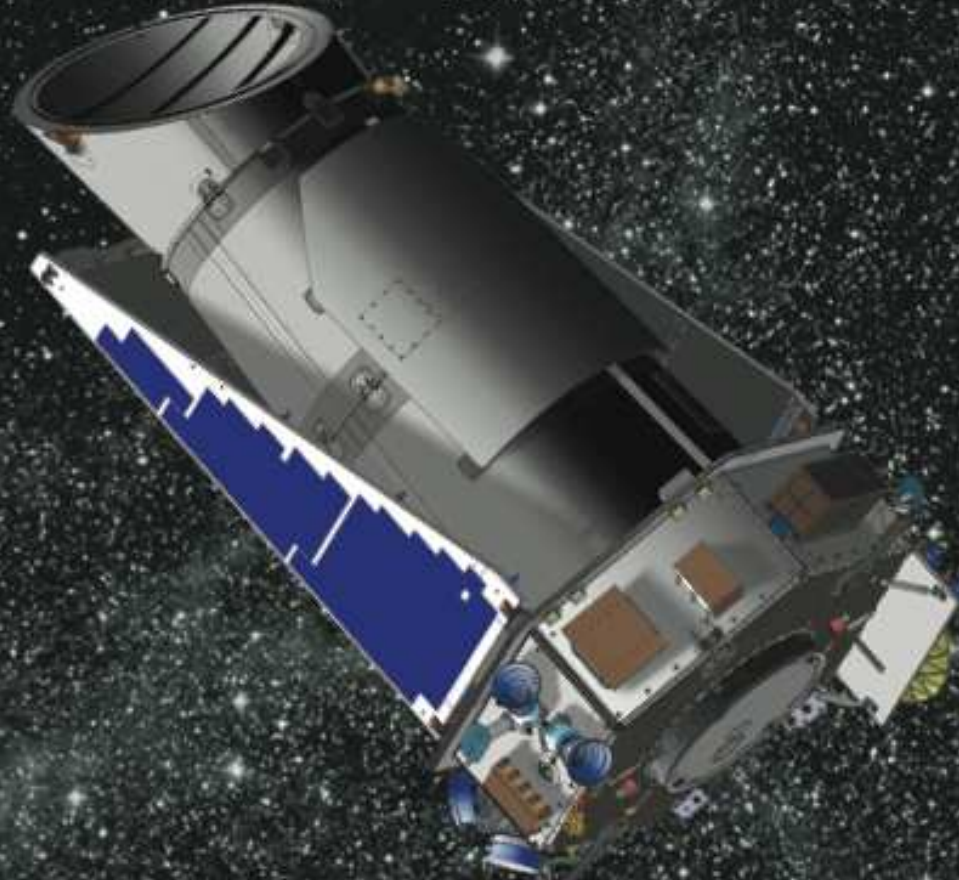
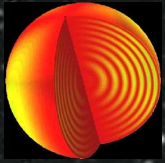
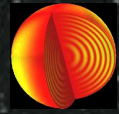
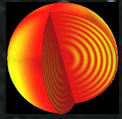


# CoRoT

(France, ESA, ...);  
launched December 2006



# Asteroseismology with Kepler

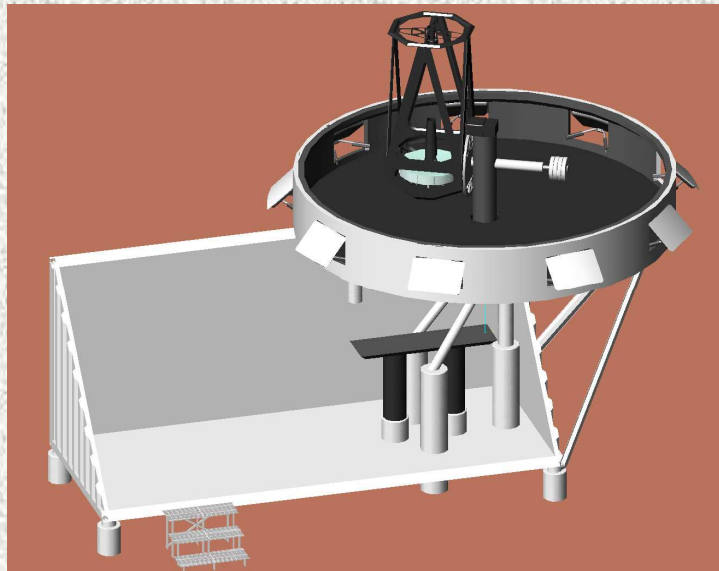
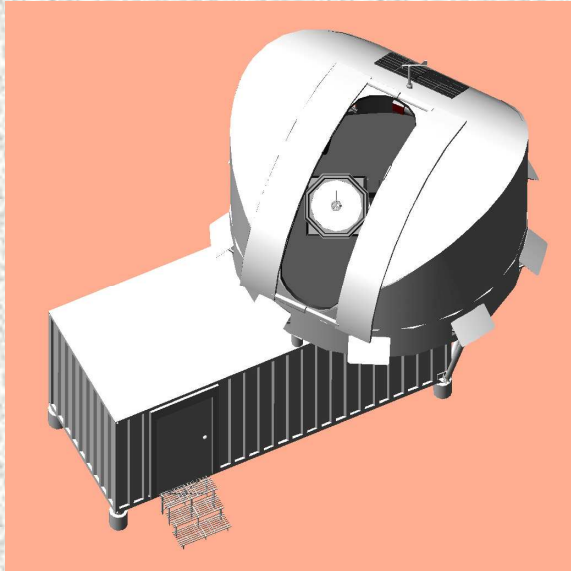


# SONG: the Stellar Observations Network Group









SONG Conceptual Design Review – Århus, March 1,2 – 2007, Baseline Configuration

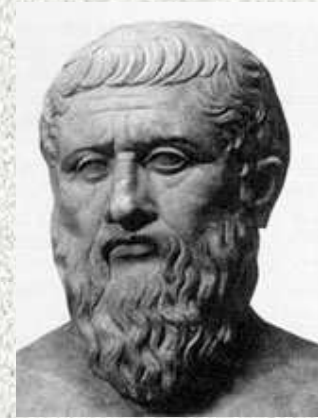
# Planned schedule

- 2006 – 2007: Conceptual design
- 2008: Prototype Phase A
- 2008 – 2011: Prototype design, construction and test
- 2010 – 2013: Network construction
- 2013 – ????: Network operation



***PLATO***

***Πλάτων***



***PLAnetary Transits & Oscillations of stars***

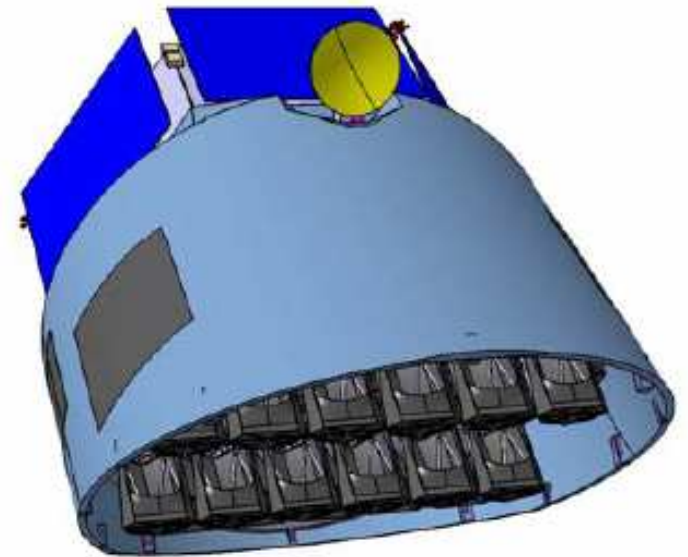
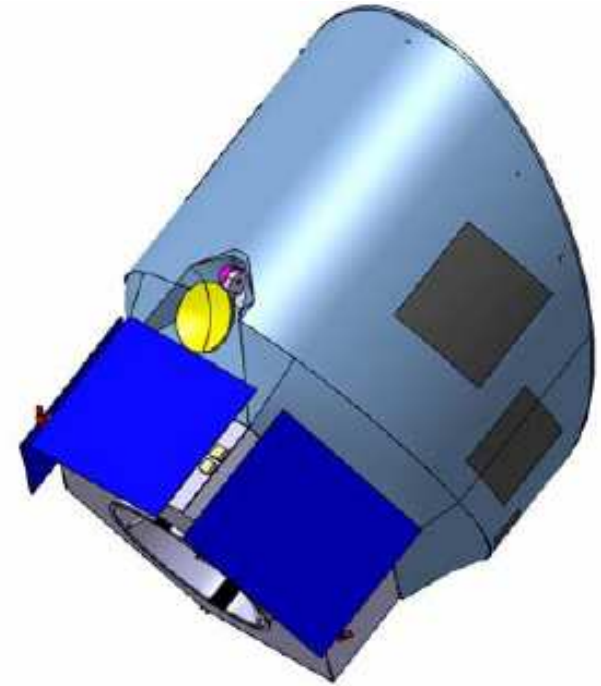
***« The life of stars & their planets »***

***Reply to the ESA Call  
« Cosmic Vision » 2015-2025***

Based on presentation by Claude Catala

# Asteroseismology and planet search for 100 000 relatively bright stars

Currently in assessment  
phase



# The future: stellar tachoclines??

The diagram illustrates the Stellar Imager (SI) mission concept. It shows a satellite in orbit around Earth, receiving light from a distant star. The light is collected by a large, segmented primary mirror and focused onto a secondary mirror. The light then passes through a series of optical elements, including a coronagraph, to produce a high-resolution image of the star's surface. The diagram also shows the Earth and the satellite's orbit.

**NASA**  
Goddard Space  
Flight Center

## Stellar Imager (SI)

<http://hires.gsfc.nasa.gov/~si>

NASA vision study.  
Launch 20??