Tutorials: ПОНАВЛАНЕ ЈЕ МАЈКА ЗНАНА

E l e n a   G a v r y u s e v a

National Institute of Astrophysics , Florence, Italy

THE FIRST SUMMER SCHOOL IN ASTRONOMY AND GEOPHYSICS

BELGRADE, SERBIA, 06.08. - 10.08. 2007

The Sun: a few numbers

- Mass = 1.99 10^{30} kg (= 1 $M_{\odot}$)
- Average density = 1.4 g/cm^3
- Luminosity = 3.84 10^{26} W (= 1 $L_{\odot}$)
- Effective temperature = 5777 K (G2 V)
- Core temperature = 15 10^6 K
- Surface gravitational acceleration g = 274 m/s^2
- Age = 4.55 10^9 years (from meteorite isotopes)
- Radius = 6.96 10^5 km
- Distance = 1 AU = 1.496 (+/-0.025) 10^8 km
- 1 arc sec = 722±12 km on solar surface (elliptical Earth orbit)
- Rotation period = 27 days at equator (sidereal, i.e. as seen from Earth; Carrington rotation)

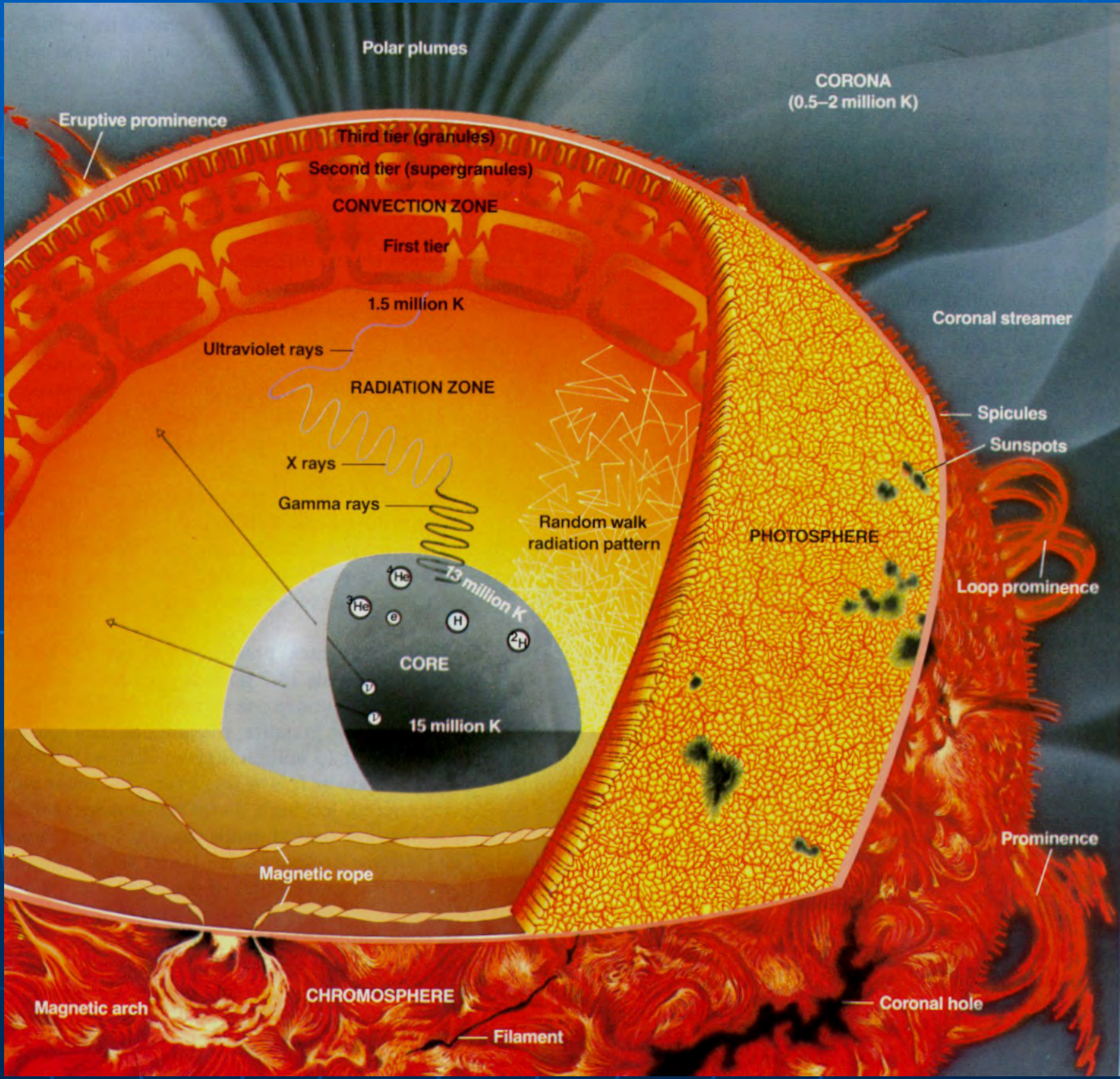
The Sun's Structure

Solar interior:

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

Solar atmosphere:

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



Nuclear reactions of CNO-cycle

- C, N and O act only as catalysts: Basically the same things happens as with proton chain.

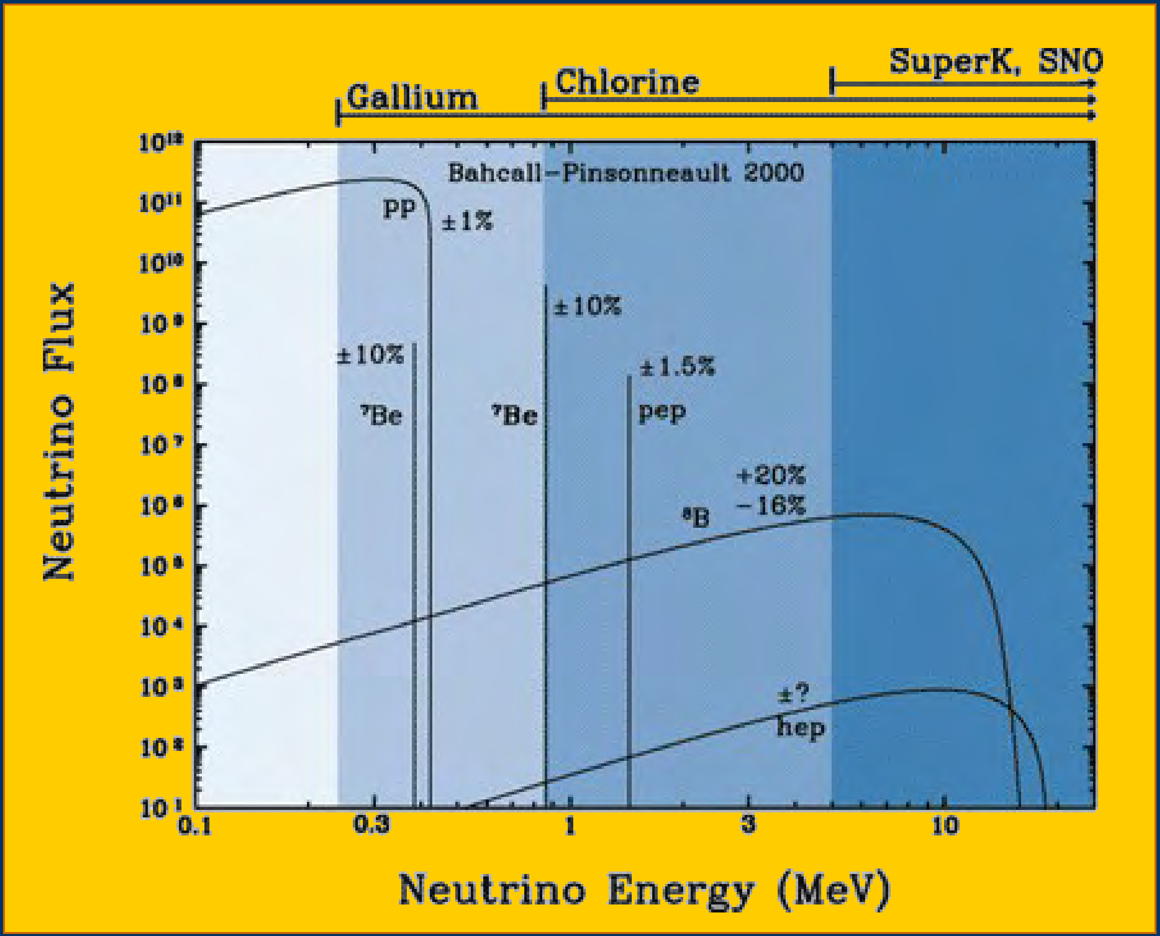
Table 2.2. Nuclear reactions of the CNO cycle. Energy values according to Bahcall and Ulrich (1988) and Caughlan and Fowler (1988)

Reaction	Q' [MeV]	Q_ν [MeV]	Rate symbol
$^{12}C(p,\gamma)^{13}N$	1.944		λ_{p12}
$^{13}N(,e^+\nu)^{13}C$	1.513	0.707	λ_{13}
$^{13}C(p,\gamma)^{14}N$	7.551		λ_{p13}
$^{14}N(p,\gamma)^{15}O$	7.297		λ_{p14}
$^{15}O(,e^+\nu)^{15}N$	1.757	0.997	λ_{15}
$^{15}N(p,\alpha)^{12}C$	4.966		λ_{p15}

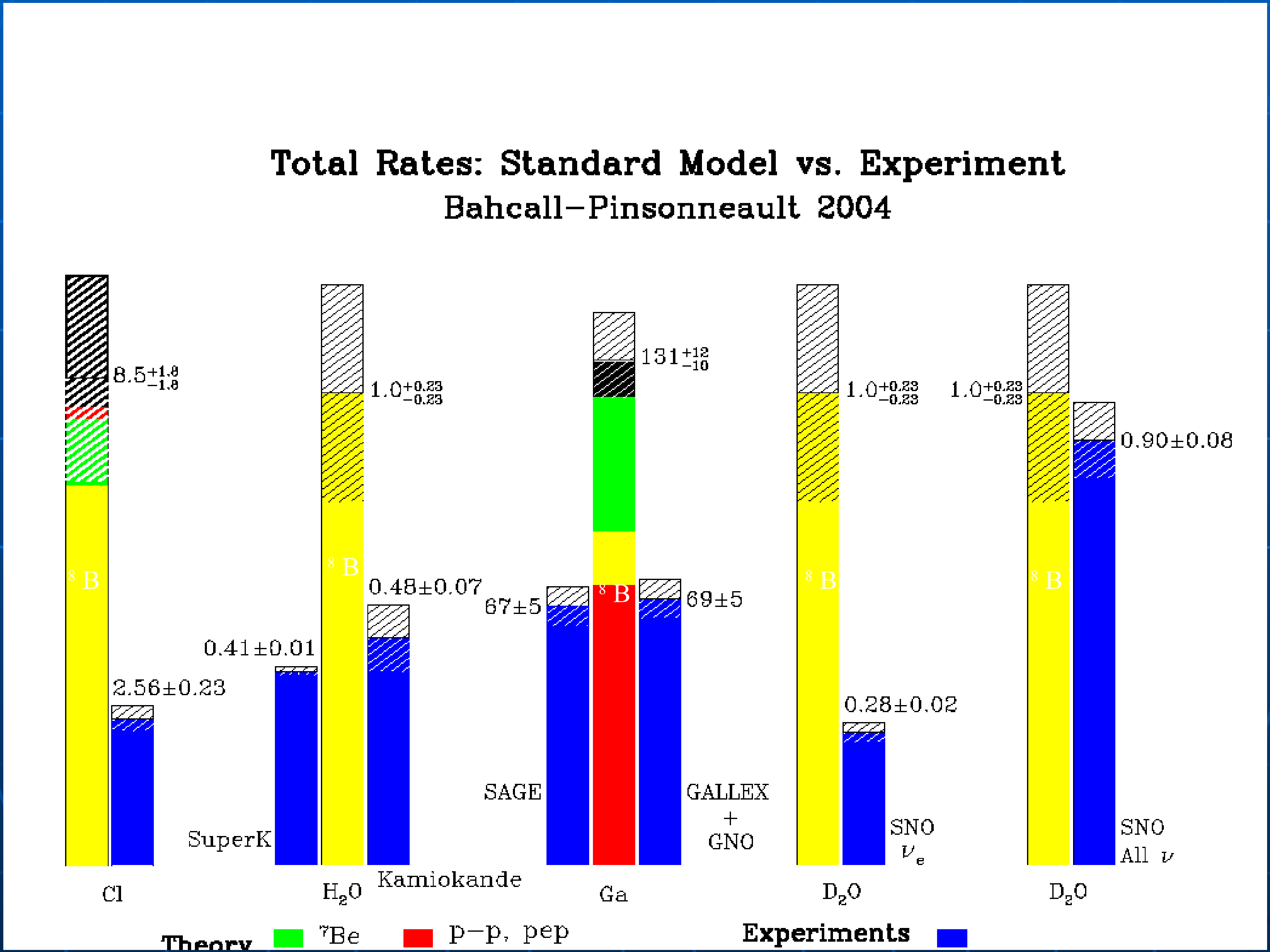
Solar Neutrinos

J. Bahcall

- Solar neutrinos escape from the solar centre in seconds, have been observed on Earth, and so bring us direct immediate information about the deep solar interior.



Neutrino results



Neutrino oscillations

$$\nu_{\rm e} \longleftrightarrow \nu_\mu \longleftrightarrow \nu_\tau$$

Neutrinos produced: $\nu_{\rm e}$

Neutrinos detected:

- ^{37}Cl, ^{71}Ga : $\nu_{\rm e}$
- H_2O: $\nu_{\rm e}$ (and some ν_μ or ν_τ)

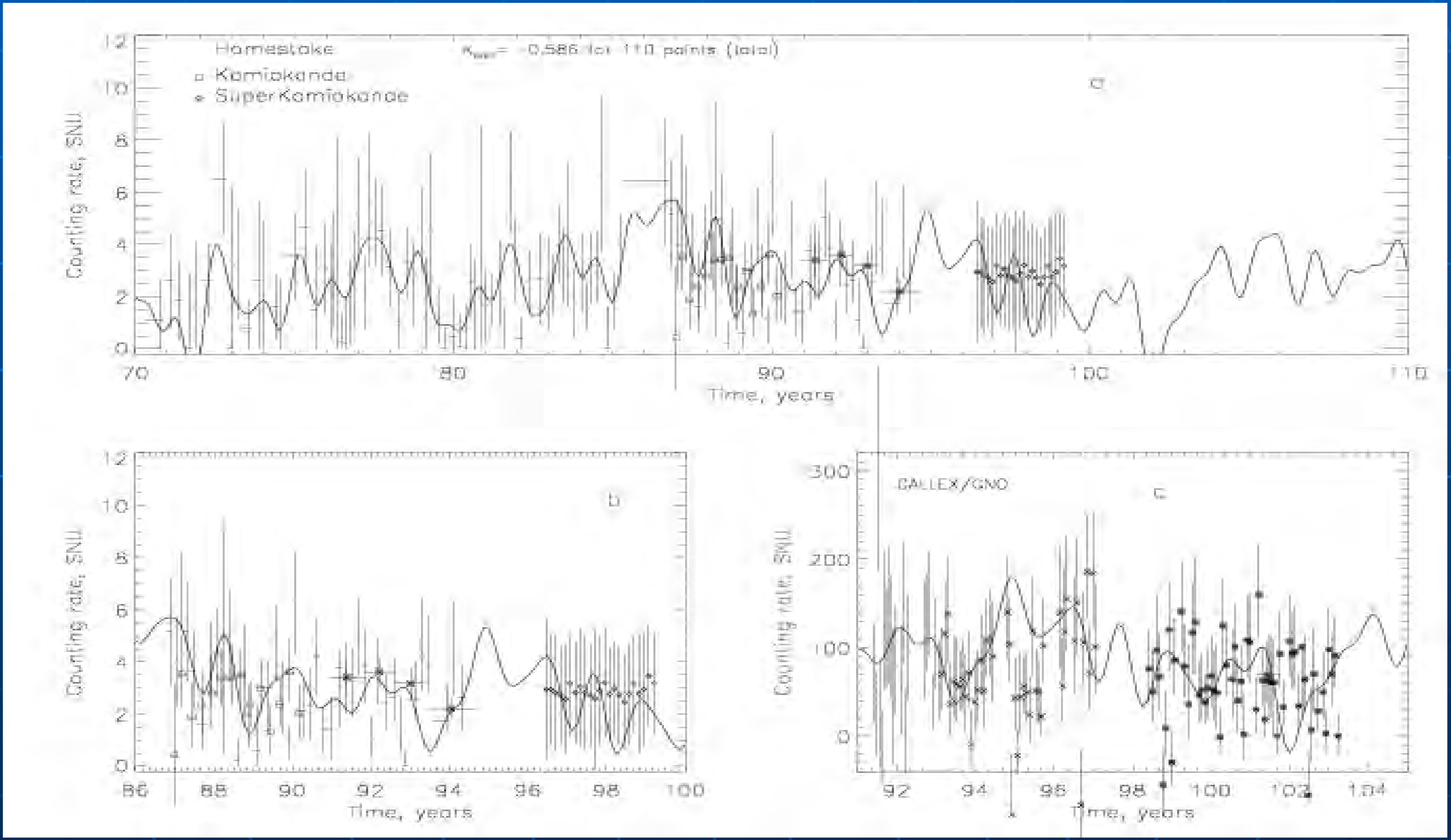
Sudbury Neutrino Observatory (heavy-water detector):

$$\nu_{\rm e} + {}^2{\rm D} \rightarrow {}^1{\rm H} + {}^1{\rm H} + {\rm e}^- \qquad ({\rm CC})\,,$$

$$\nu_x + {}^2{\rm D} \rightarrow {}^1{\rm H} + {\rm n} + \nu_x \qquad ({\rm NC})\,,$$

$$\nu_x + {\rm e}^- \rightarrow \nu_x + {\rm e}^- \qquad ({\rm ES})$$

Neutrino detectors and Phenomenological model



Evolution of Sun's luminosity

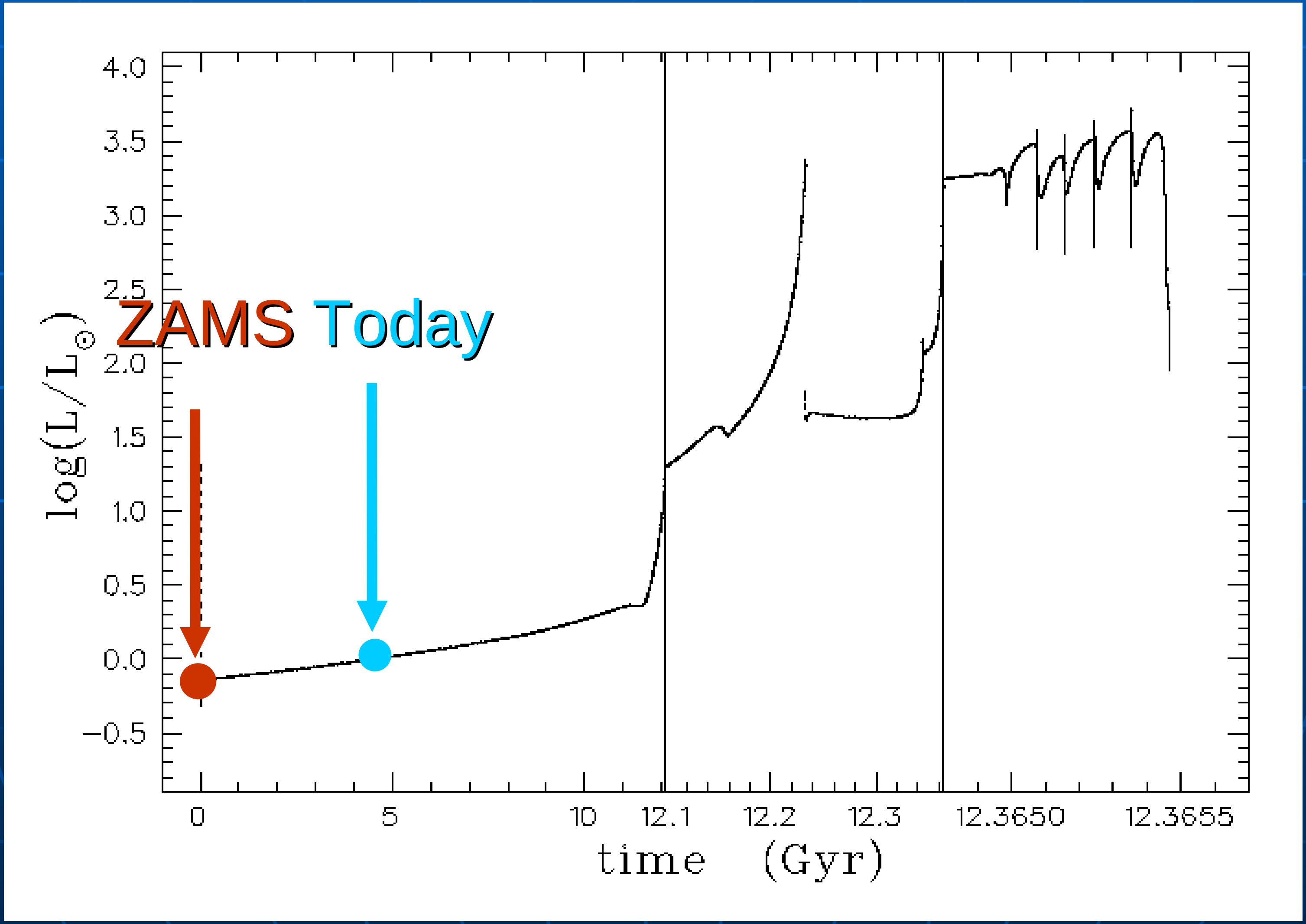
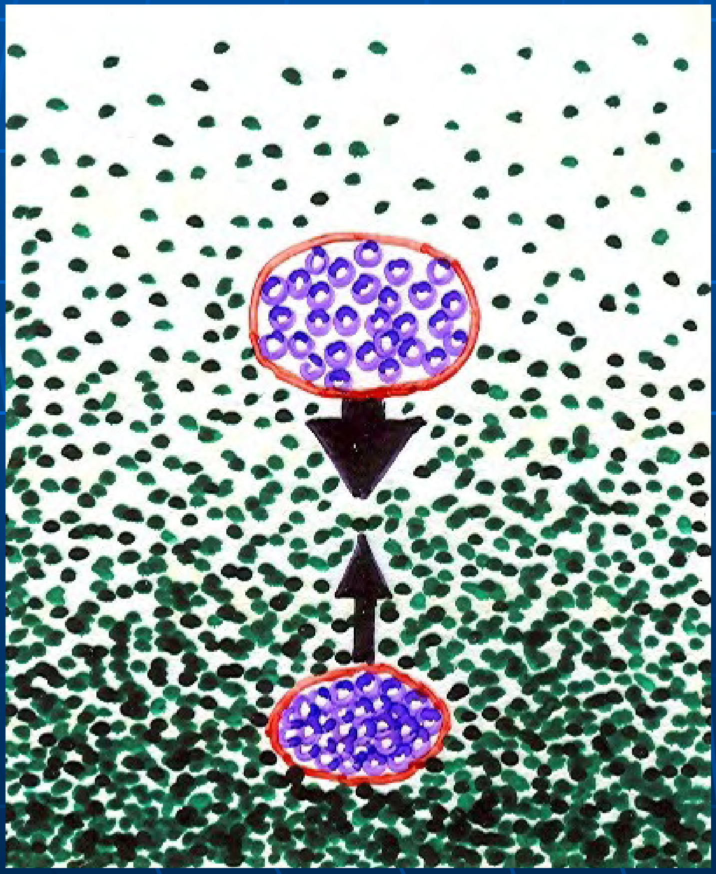
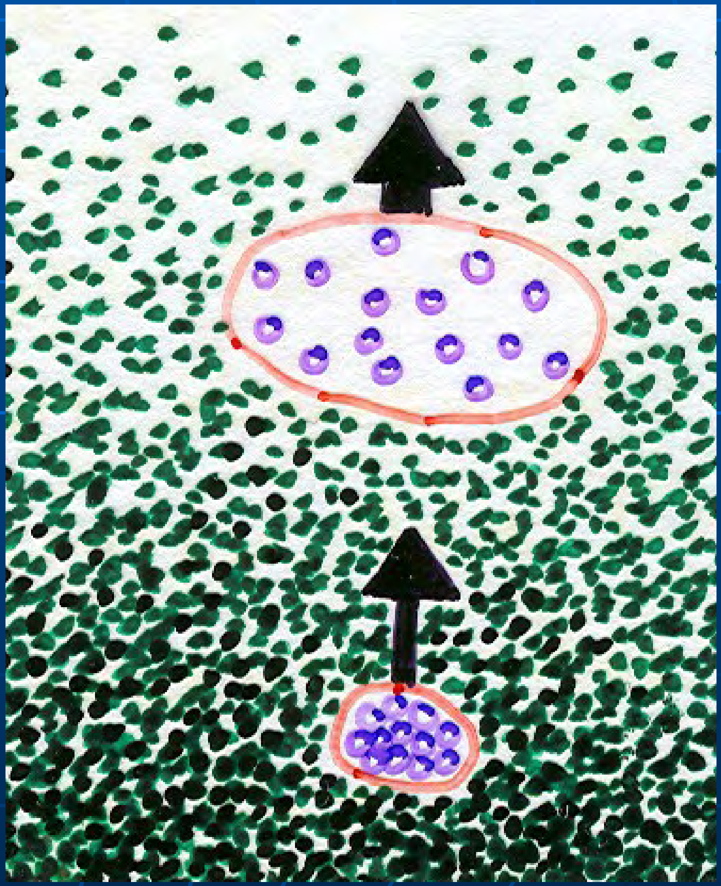


Illustration of convectively stable and unstable situations

Convectively stable



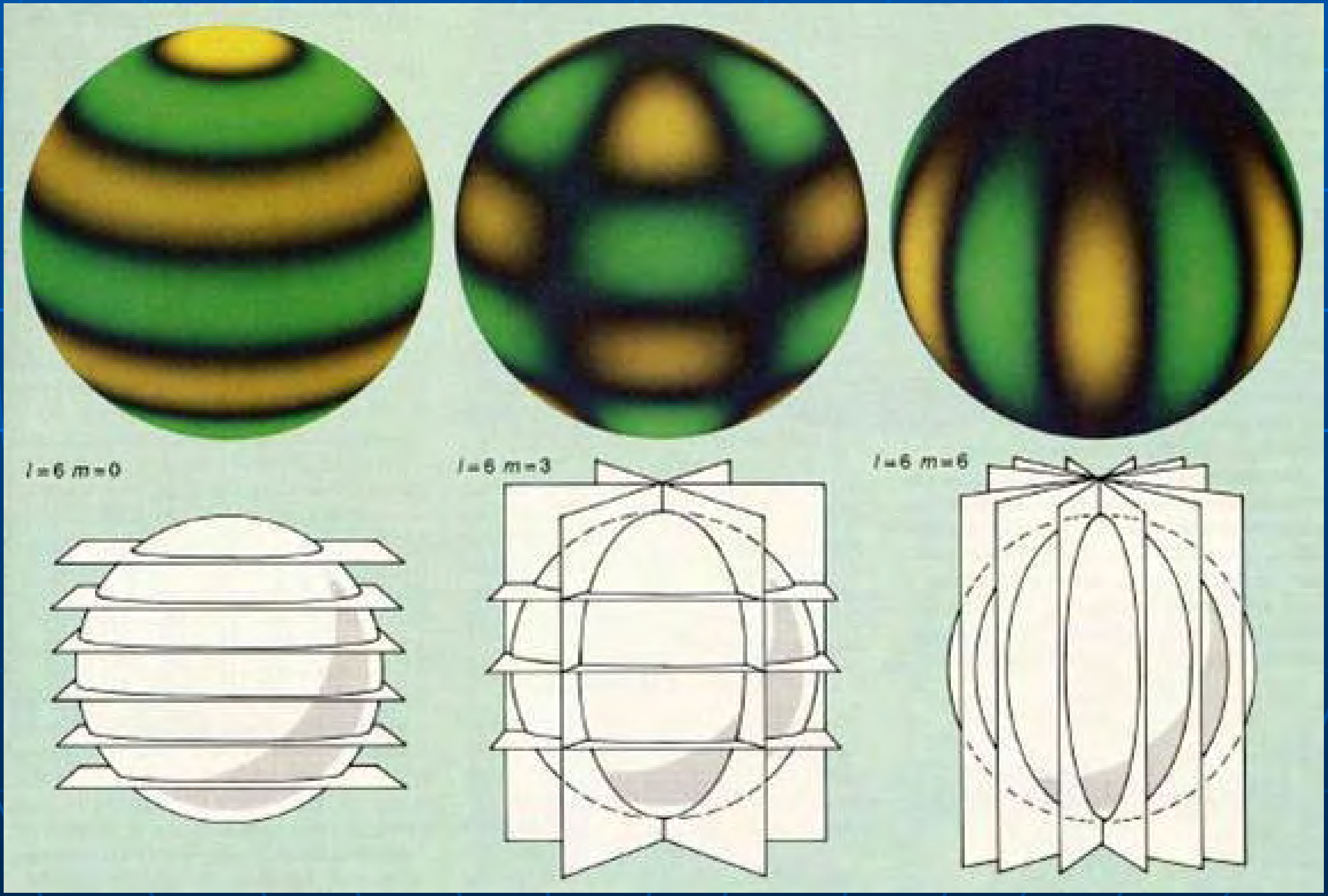
Convectively unstable



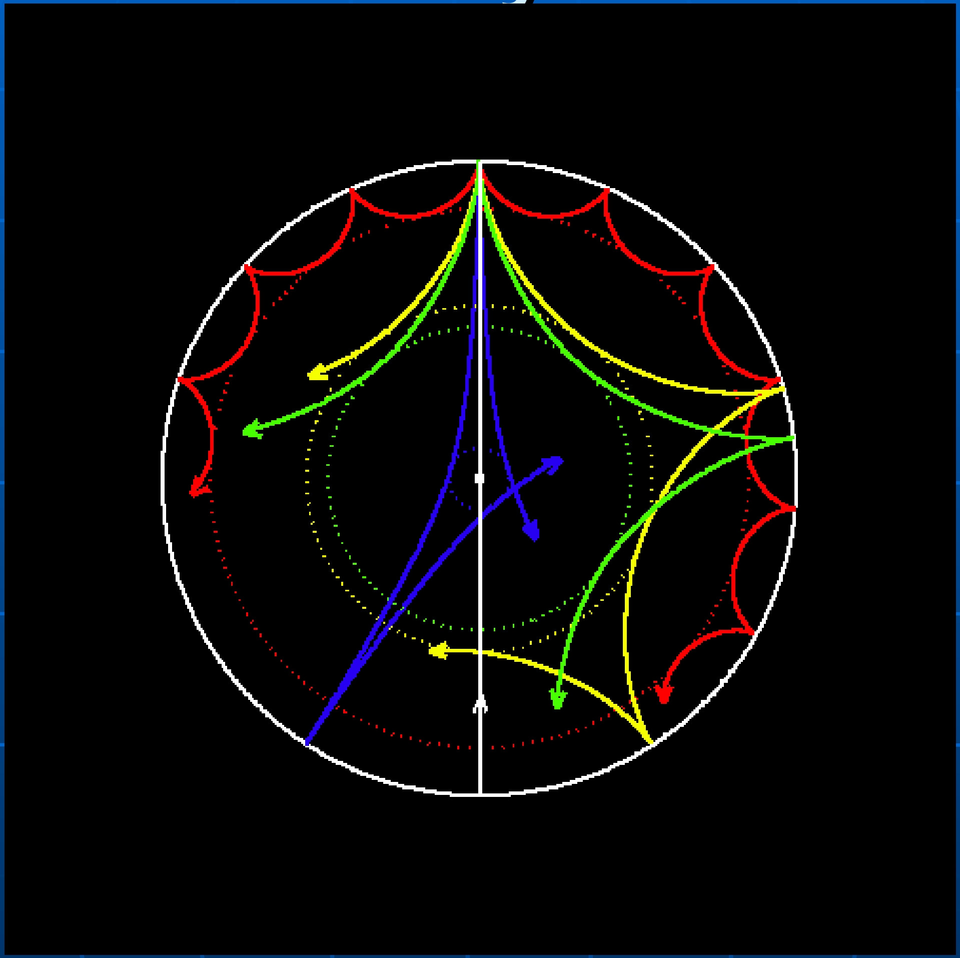
Oscillations and helioseismology

Illustration of spherical harmonics

- l = total number of nodes (in images: l = 6) = degree
- m = number of nodes connecting the "poles"



Rays



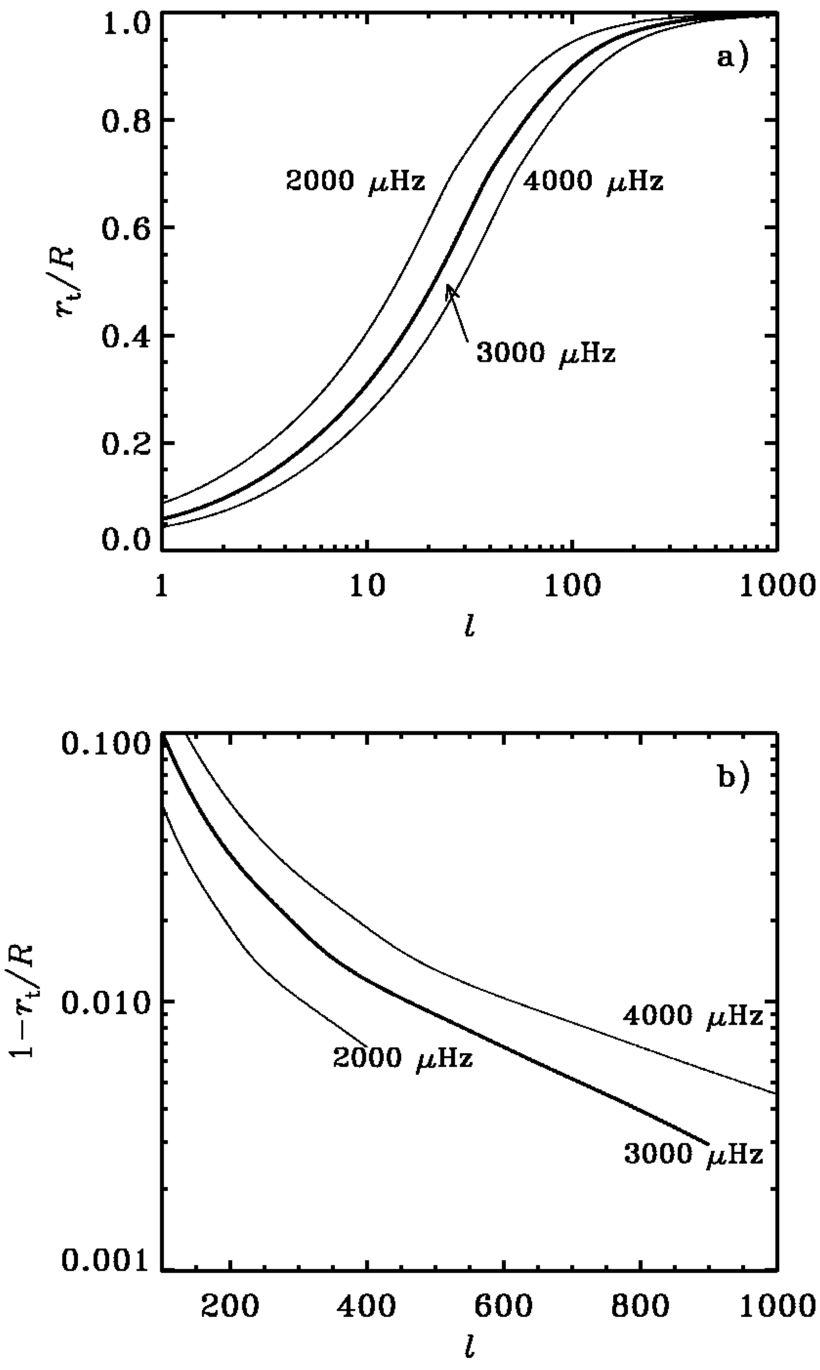
$$k_r = \left[\frac{\omega^2}{c^2} - \frac{l(l+1)}{r^2}\right]^{1/2}$$

Turning point: $\dfrac{c(r_t)}{r_t} = \dfrac{\omega}{\sqrt{l(l+1)}}$

Global oscillations

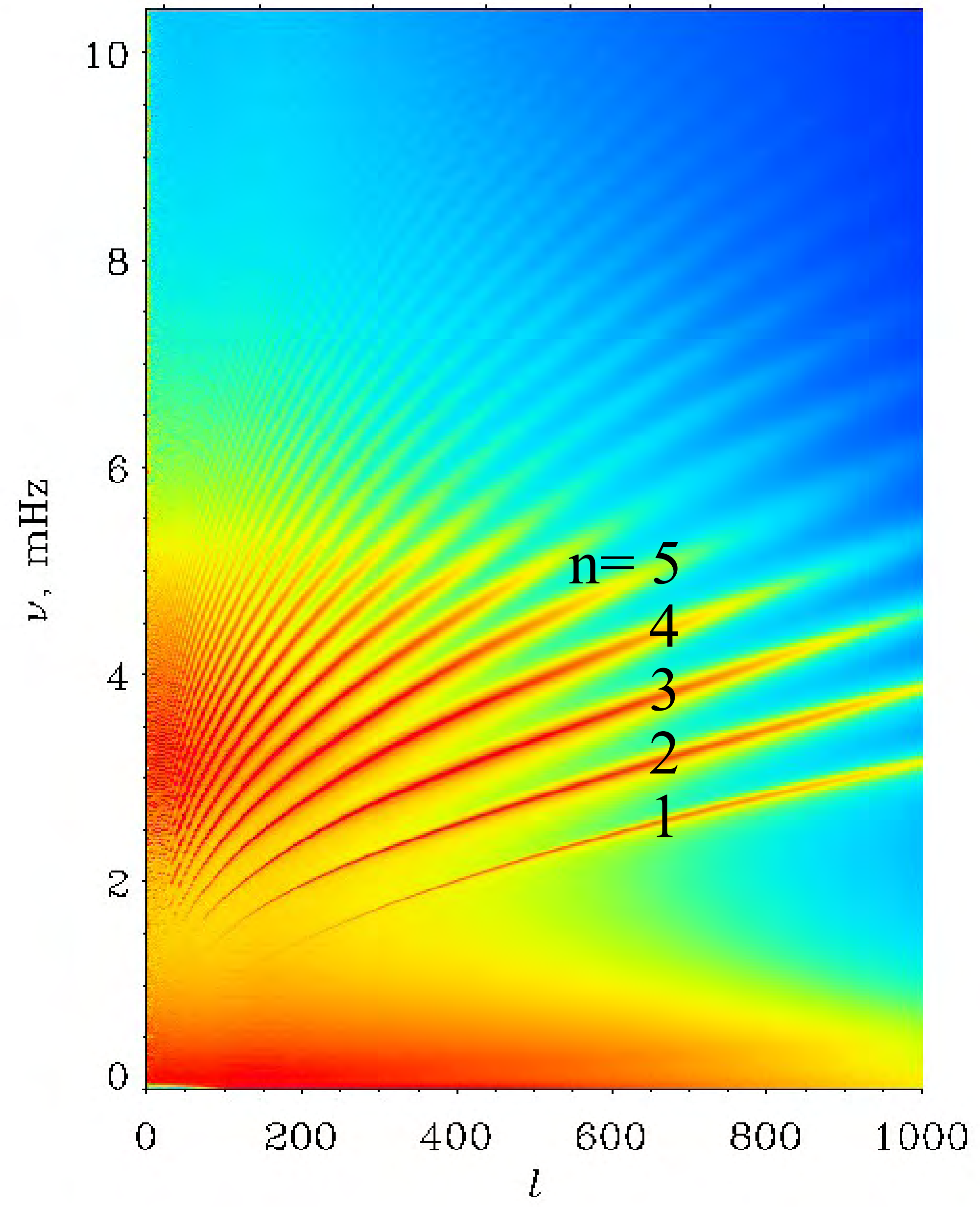
- The Sun's acoustic waves bounce from one side of the Sun to the other, causing the Sun's surface to oscillate up and down. They are reflected at the solar surface.
- Modes differ in the depth to which they penetrate: they turn around because sound speed ($C_S \sim T^{1/2}$) increases with depth (refraction)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

Location of turning point



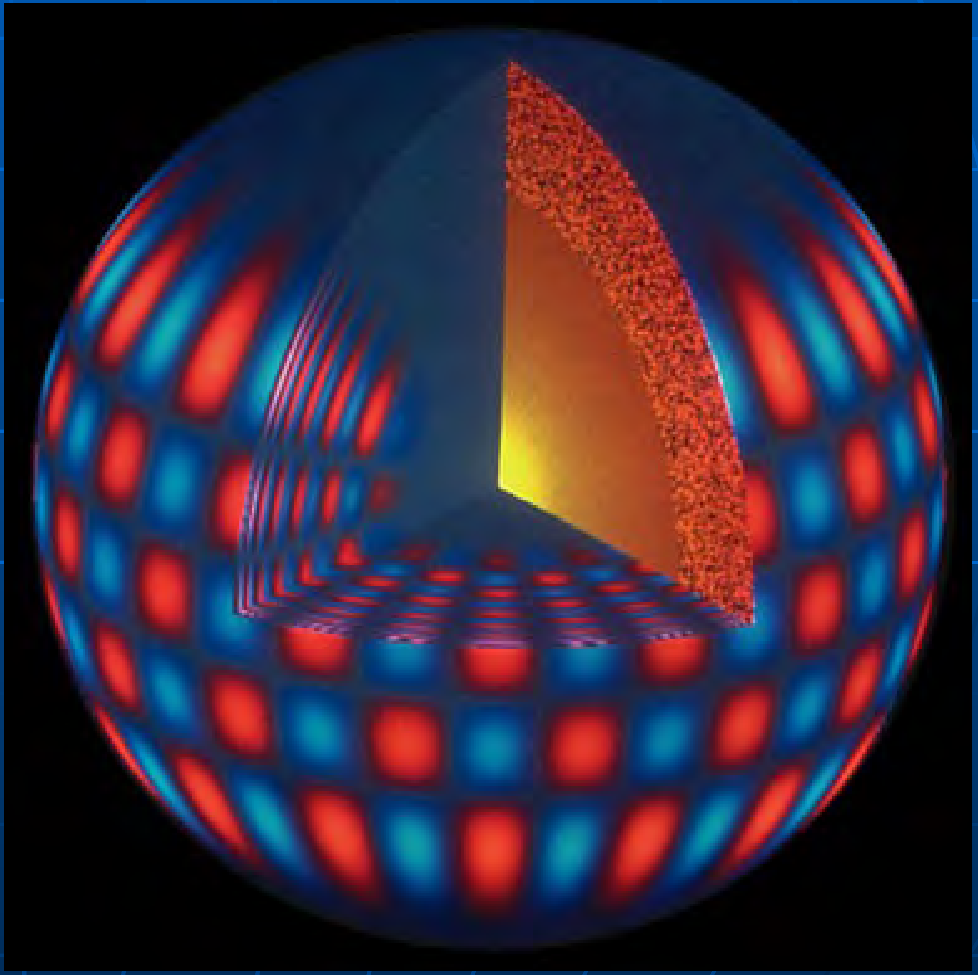
Interpretation of *k-ω* or *ν-l* diagram

- 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*.



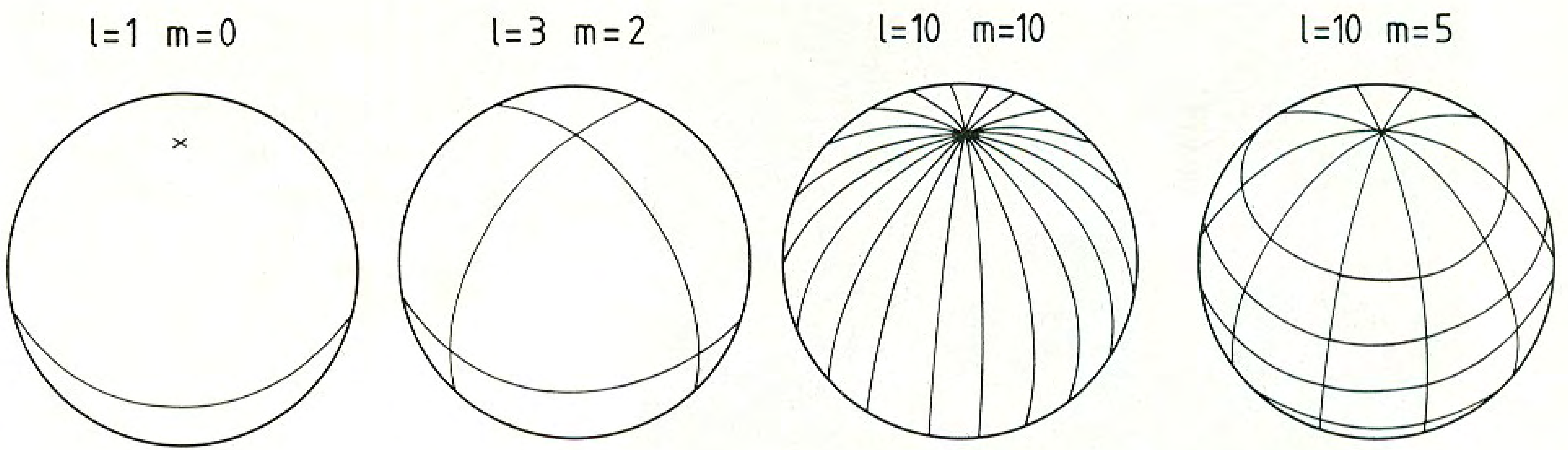
Description of solar eigenmodes

- 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 slide)



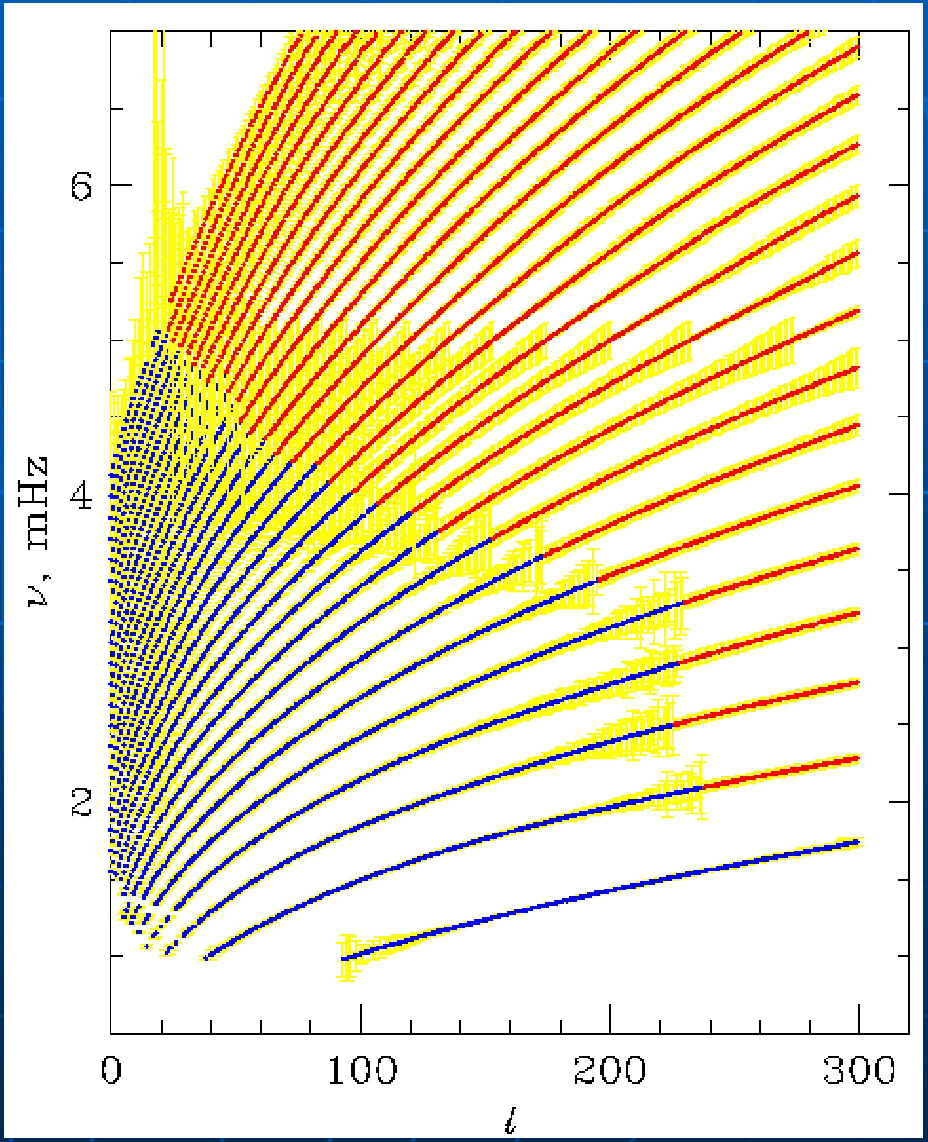
More examples and a problem with identifying spherical harmonics

- General problem: Since we see only half of the Sun, the decomposition of the sum of all oscillations into spherical harmonics isn't unique.
- This results in an uncertainty in the deduced *l* and *m*



Accuracy of frequency measurements

- Plotted are identified frequencies and error bars (yellow; 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



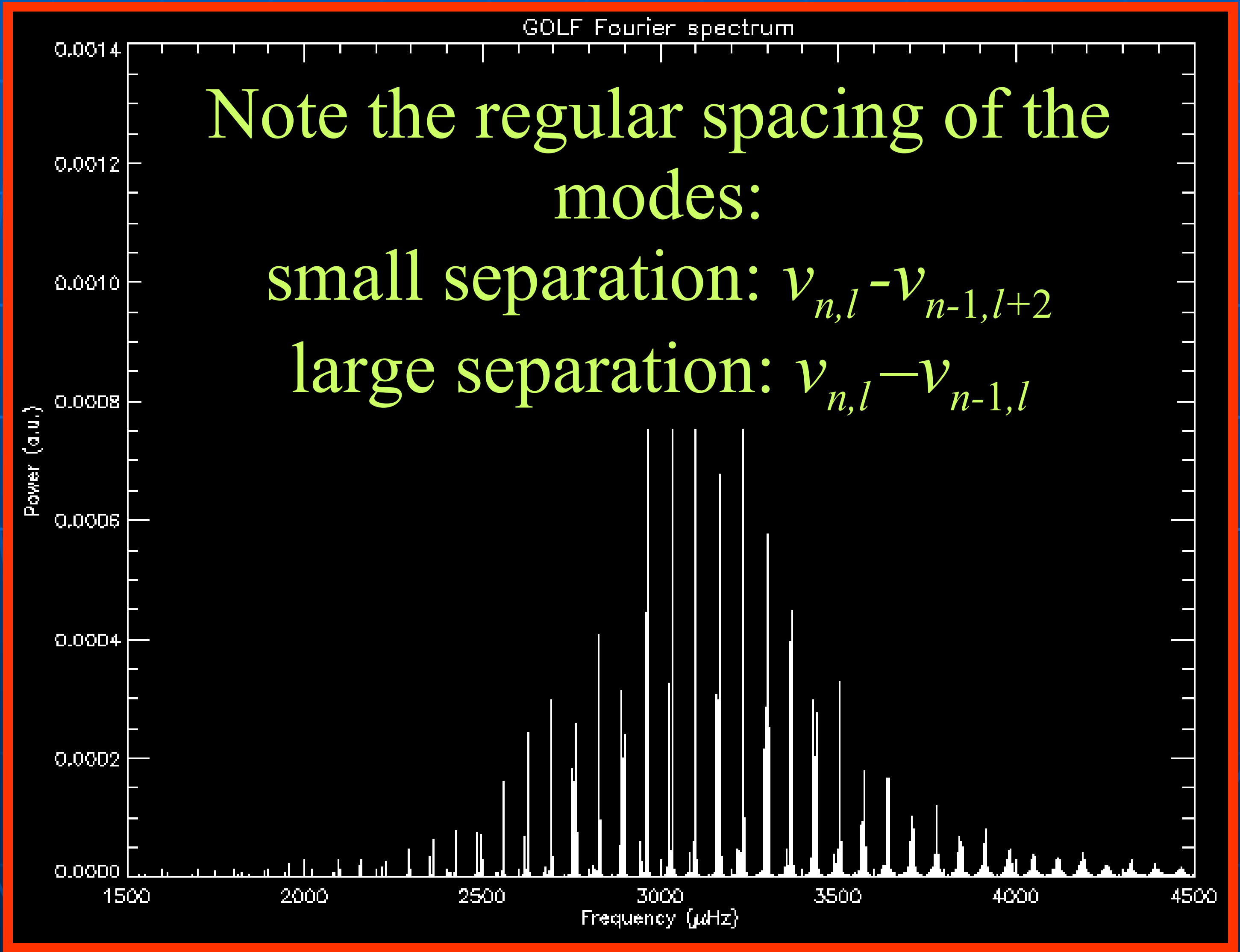
Frequency vs. amplitude

- Frequencies are the important parameter, more so than the amplitudes of the modes or of the power peaks.
- The amplitudes depend on the excitation, while the frequencies do not. They carry the main information on the structure of the solar interior.
- p-modes are excited by turbulence, which excites all frequencies. However, only at Eigenfrequencies of the Sun can eigenmodes develop.
- Frequencies (being more constant) are also measured with greater accuracy.

The measured low-*l* eigenmode signal

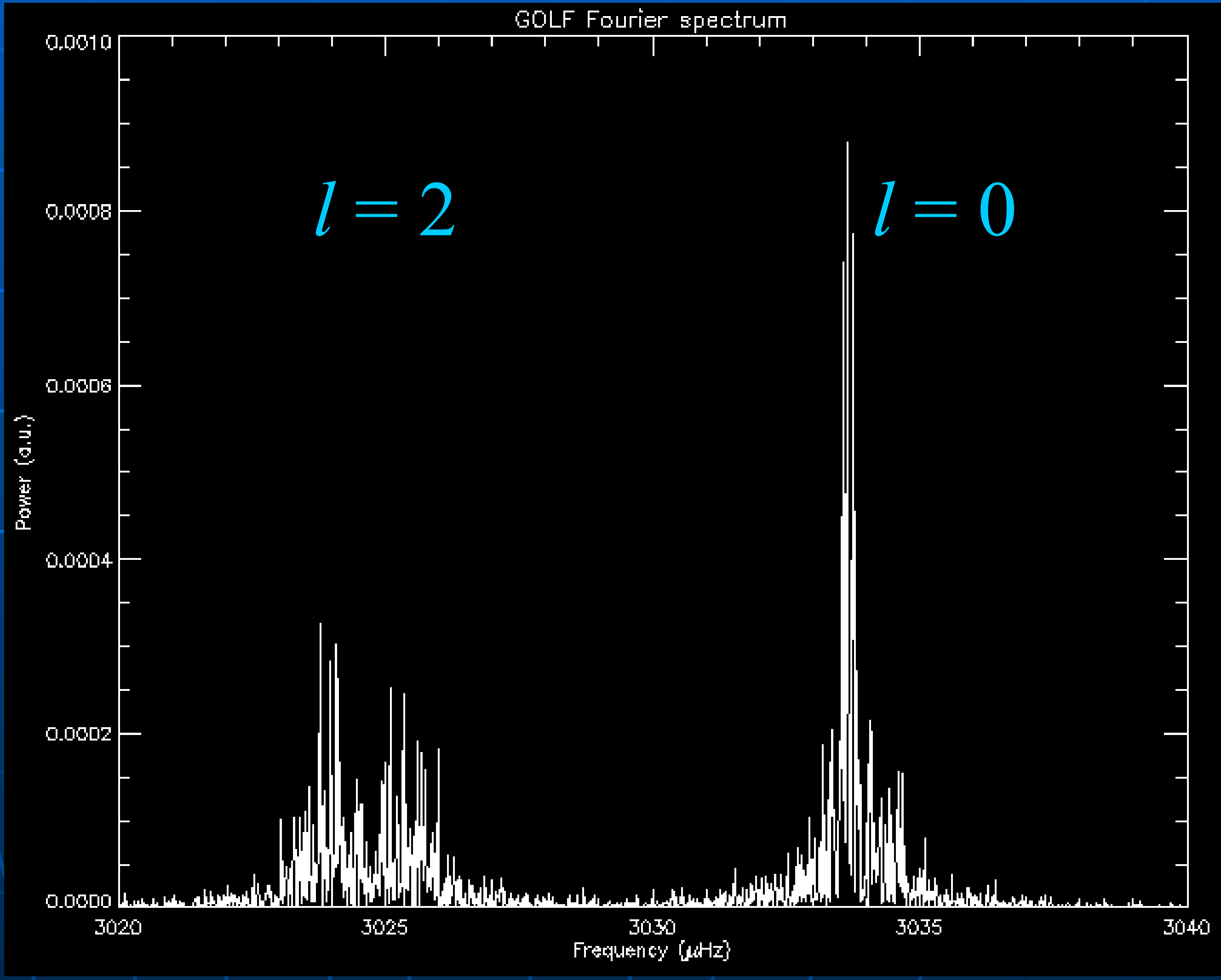
- Sun seen as a star: Due to cancellation effects, only modes with *l*=0,1,2 are visible → simpler power spectrum.
- Low *l* modes are important for 2 reasons:
  - They reach particularly deep into the Sun (see cartoon on earlier slide).
  - These are the only modes measurable on other Sun-like stars.
- These modes are sometimes called “global” modes.
- The different peaks of given *l* correspond to different *n* values (*n*=15...25 are typical).

Best current low-*l* power spectrum



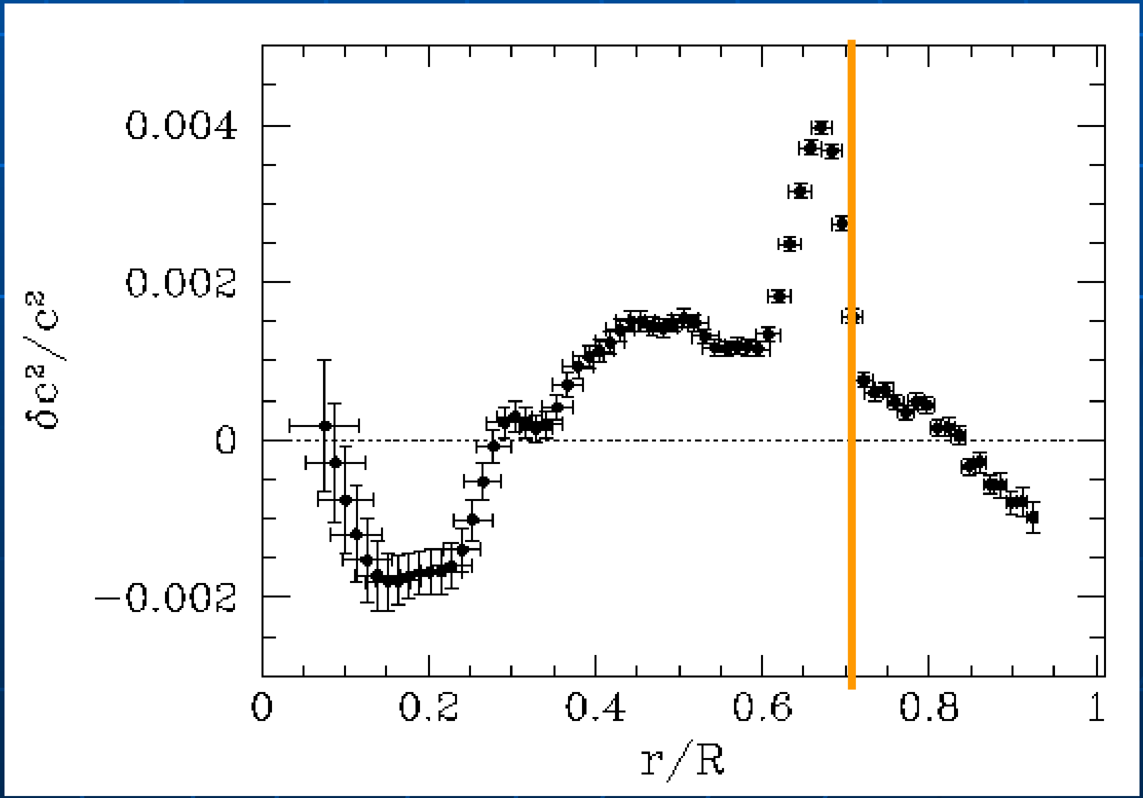
Mode structure of low *l* spectrum

- GOLF/SOHO observations showing a blowup of the power spectrum with an $l = 0$ and an $l = 2$ mode.
- The noise is due to random re-excitation of the oscillation mode by turbulence

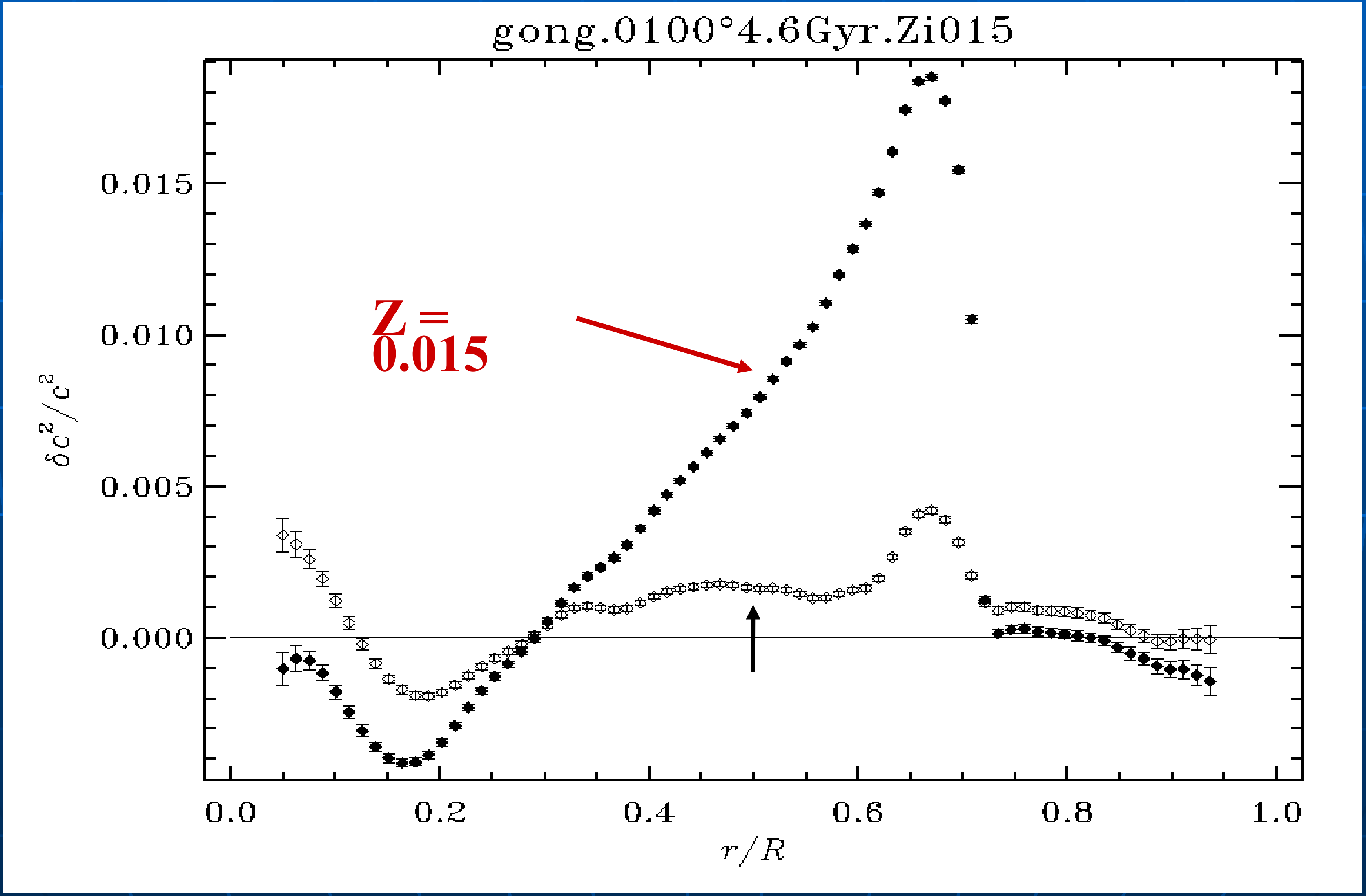


Testing the standard solar model: results of forward modelling

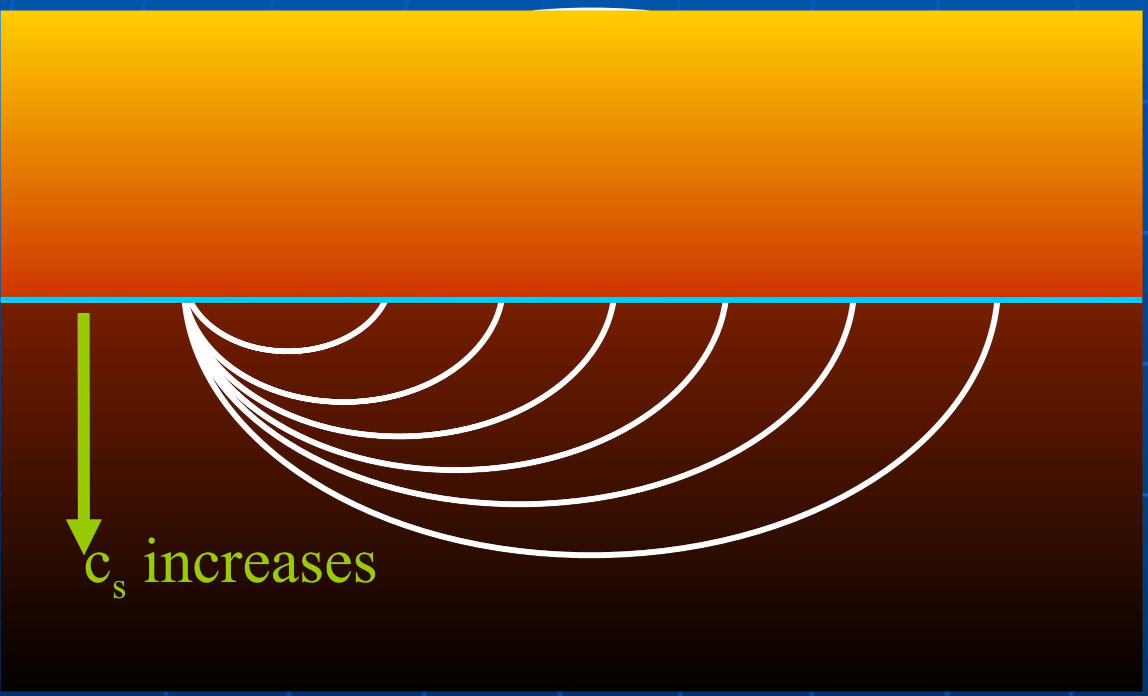
- Relative difference between C_S^2 obtained from inversions and from standard solar model plotted vs. radial distance from Sun centre.
- Typical difference: ➔ good!
- Typical error bars inversion: poor!
- Problem areas:
  - solar core
  - bottom of CZ
  - solar surface



Revision of solar surface abundances



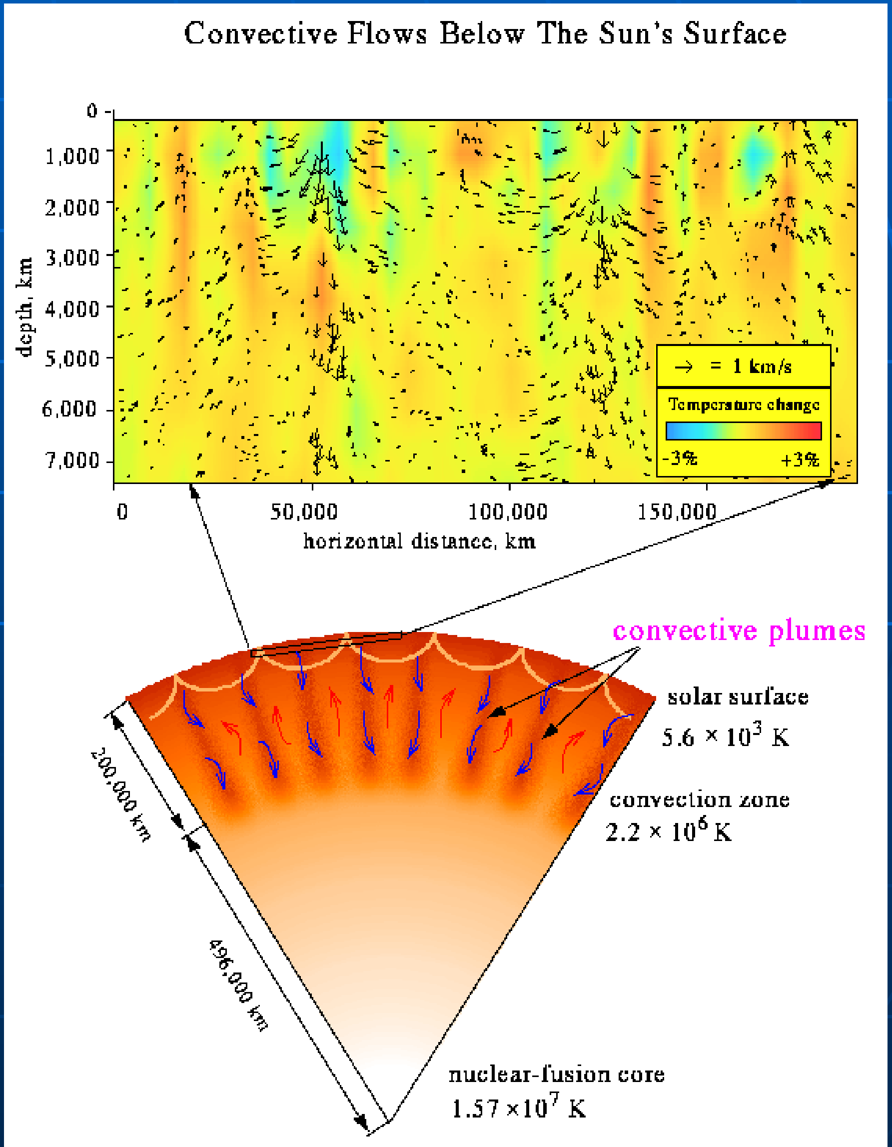
Local excitation of wave by a flare



- Clear example of wave being triggered.
- The wave is not travelling at the surface, but rather reaching the surface further out at later times. Note how it travels ever faster. Why?

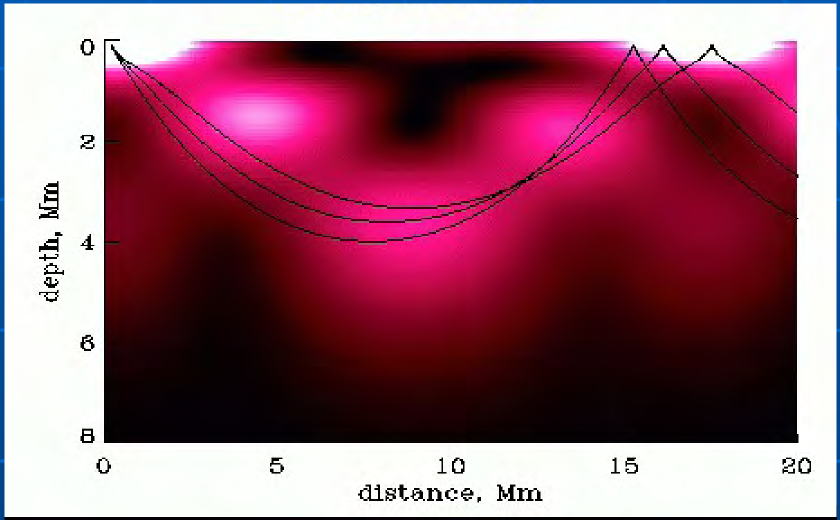
Local helioseismology II

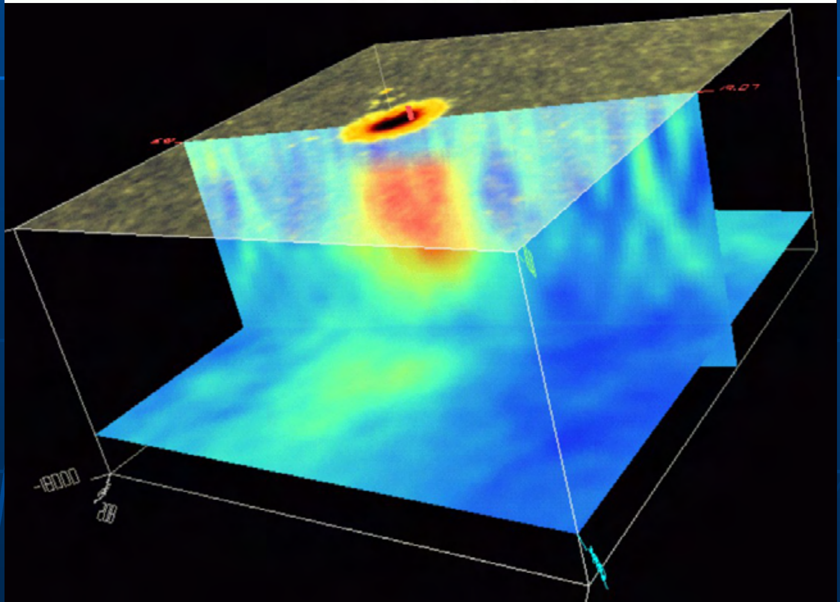
- Temperature and velocity structures can be distinguished, since a flow directed with the wave will affect it differently than a flow directed the other way (increase/decrease the sound speed).
- By considering waves passing in both directions it is possible to distinguish between T and velocity.
- At right: 1st images of convection zone of a star!



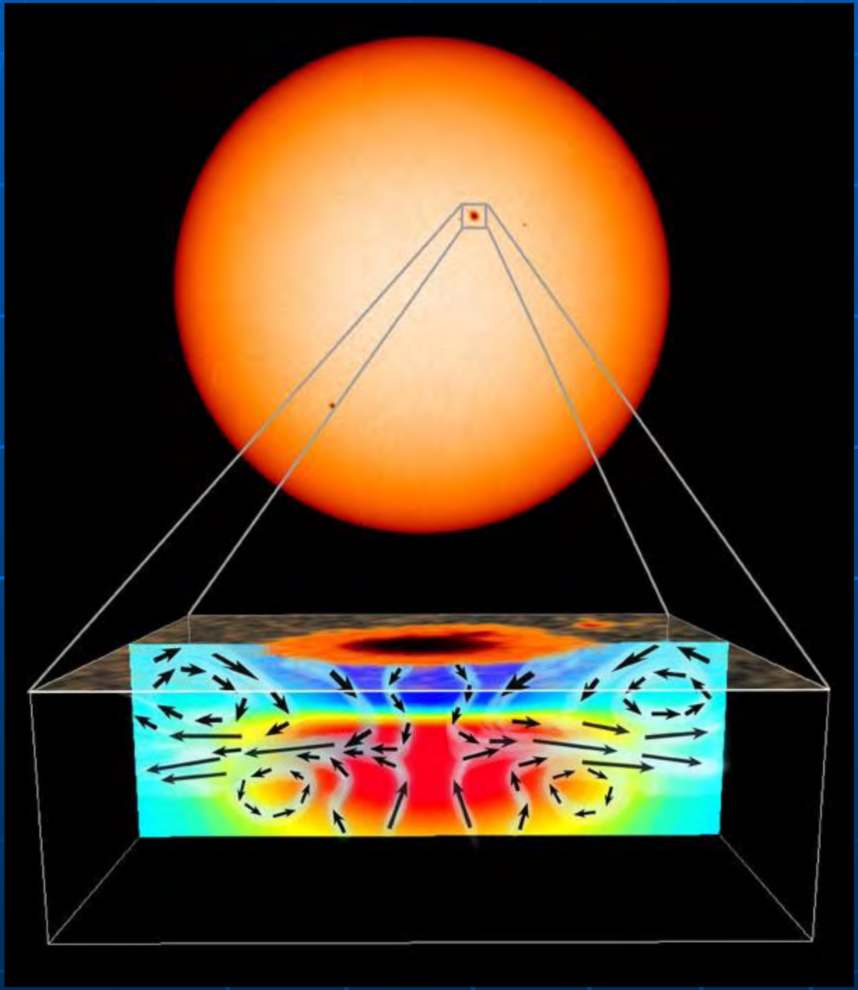
Time-Distance Helioseismology of a sunspot

- Subsurface structure of sunspots
- Sunspots are good targets, due to the large temperature contrast.
- Major problem: unknown influence of the magnetic field on the waves.





Time-Distance Helioseismology of a sunspot II

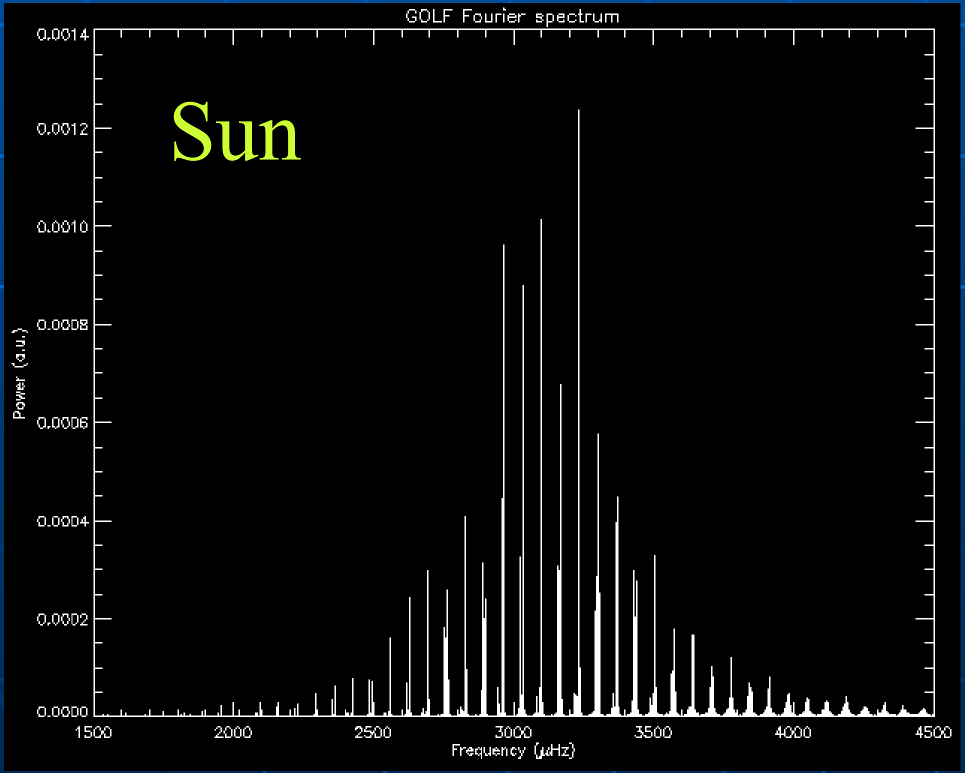


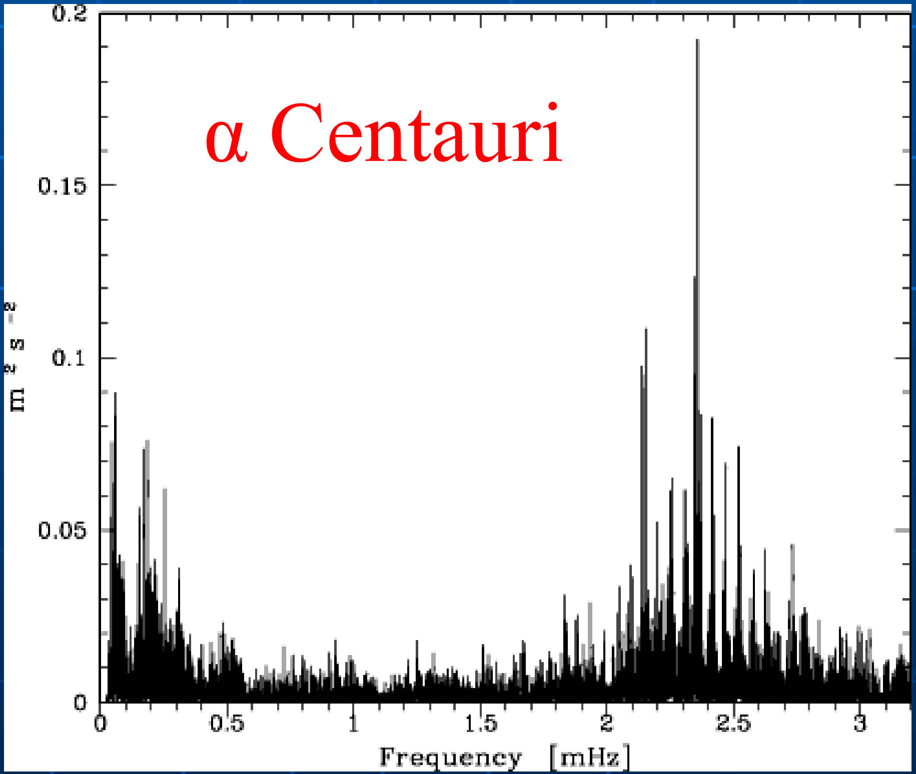
Kosovichev et al. 2000

Zhao et al. 2004

Asteroseismology

First reliable detection of oscillations on the near solar analogue, α Centauri, and other Sun-like stars. Note the shift in the p-mode frequency range to lower values for α Centauri, which is older than the Sun (note also factor 10^3 difference in ν scale)



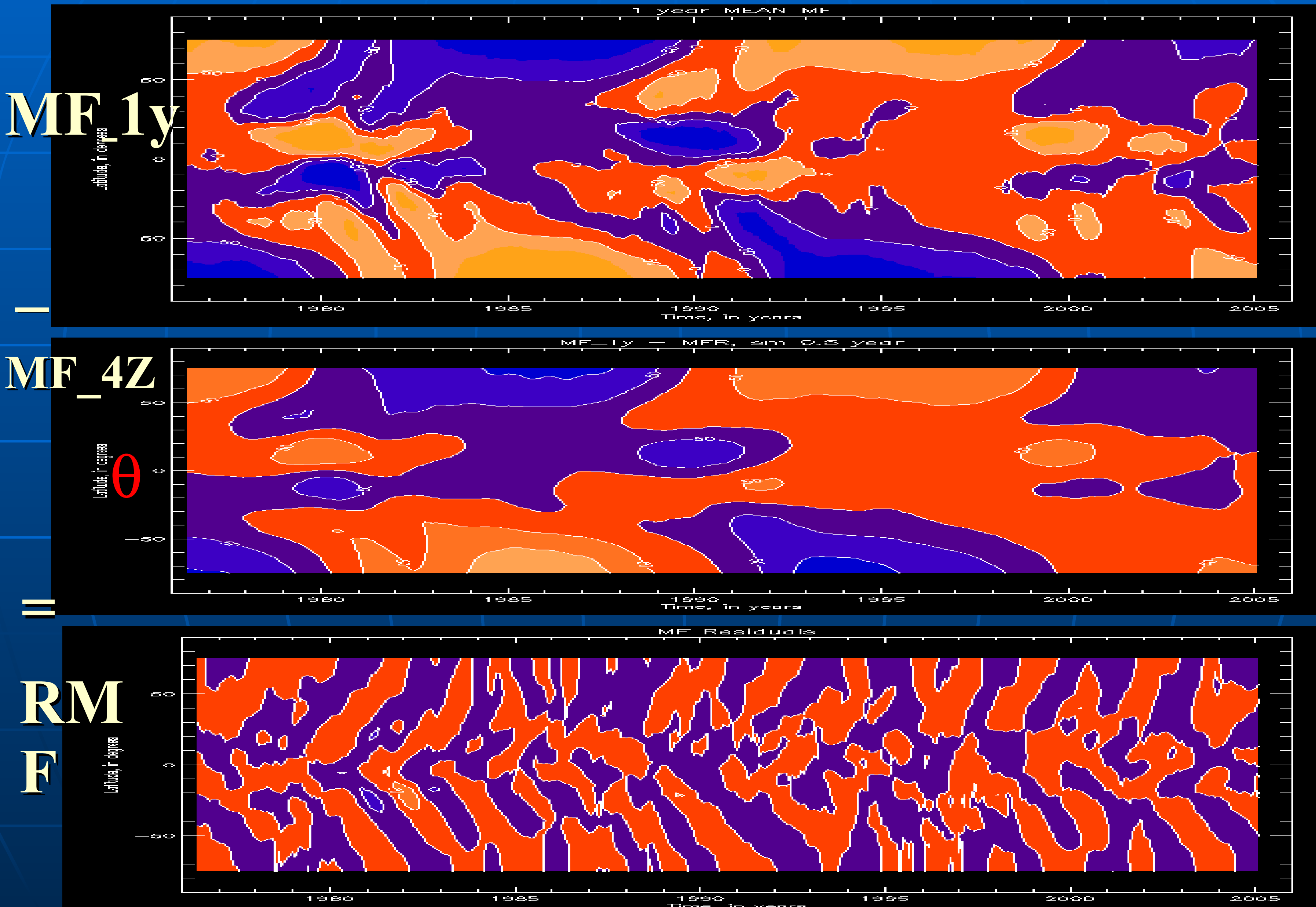


Projects

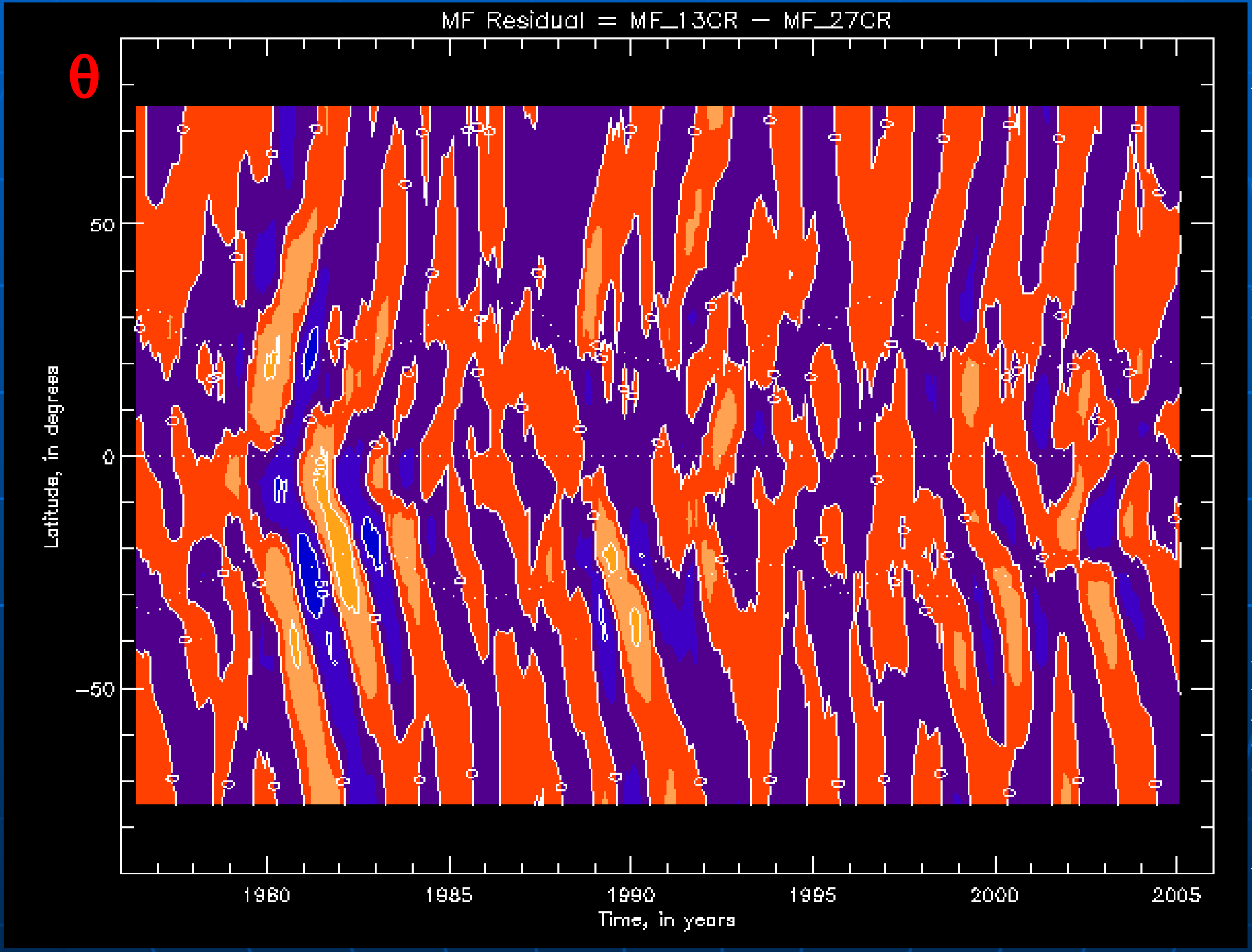
- Major asteroseismic Space missions:
  - COROT
  - Kepler
- Ground based:
  - ESO 3.6m (HARPS)
  - ESO VLT (UVES)
  - Networks of smaller Telescopes

Latitudinal structure of Solar Magnetic Field

MF_1y – MF_4zones = RMF



MFR = 1-year MF mean - 2-year MF mean



Velosity 40 km/h

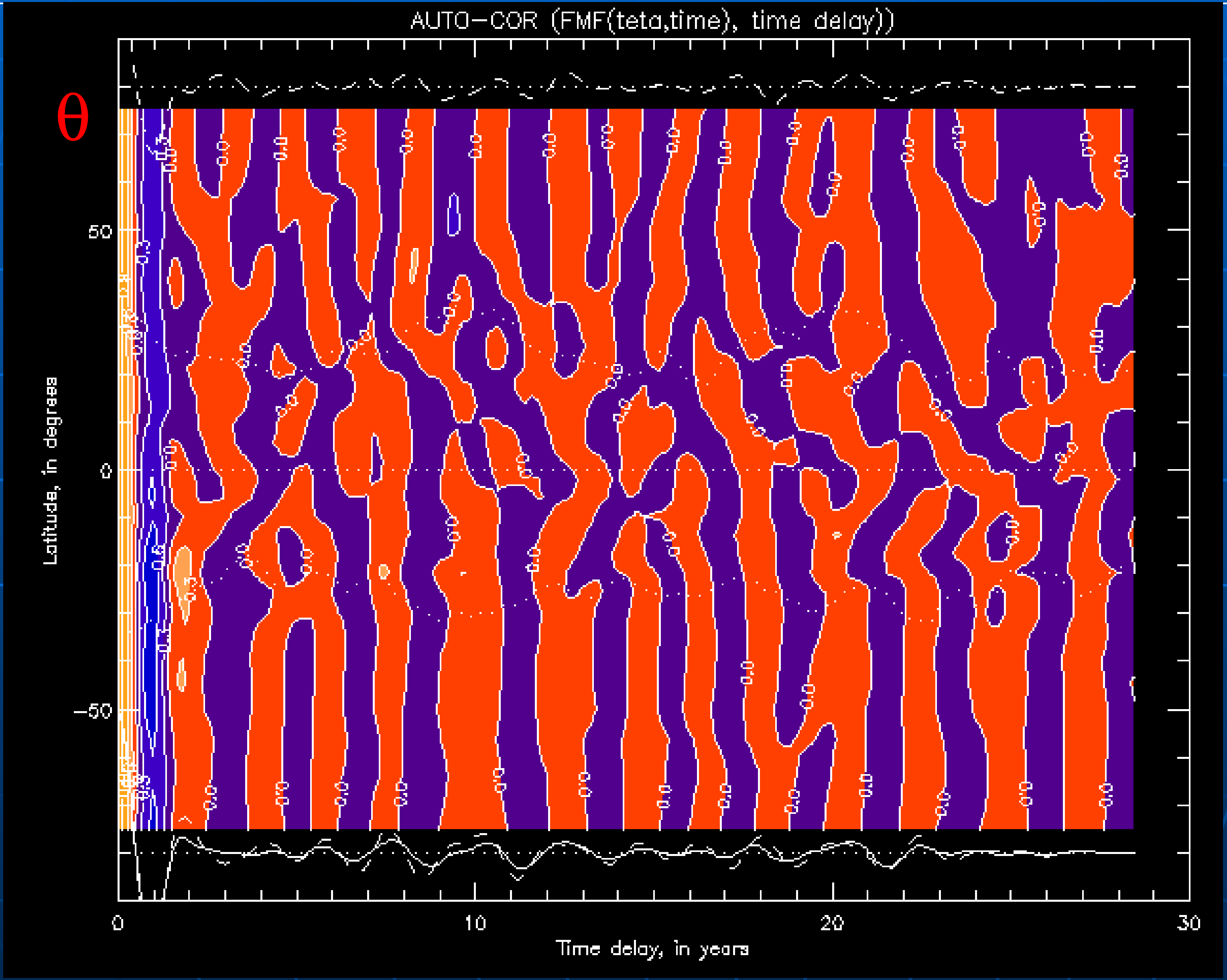
Interference of streams

Double Maxima

It takes 2-3 years to run from equator to pole

Time shift, in years

Auto-correlation of SMF Residuals



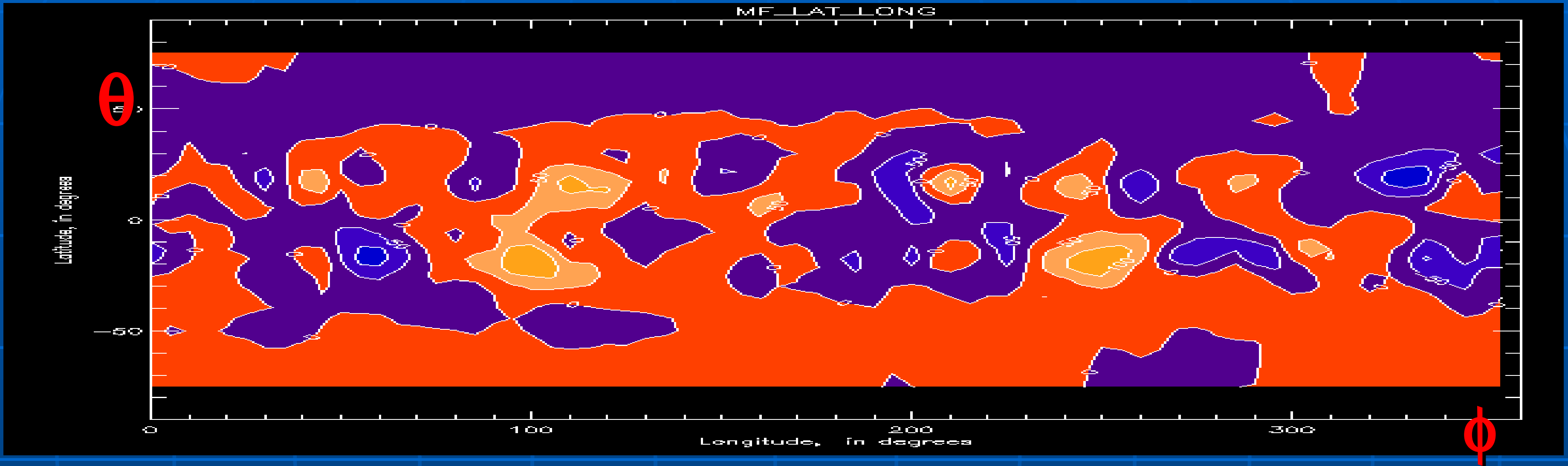
Quasi 2-3-year periodicity over all latitudes θ

Different in the Northern ans in the Southern Hemispheres

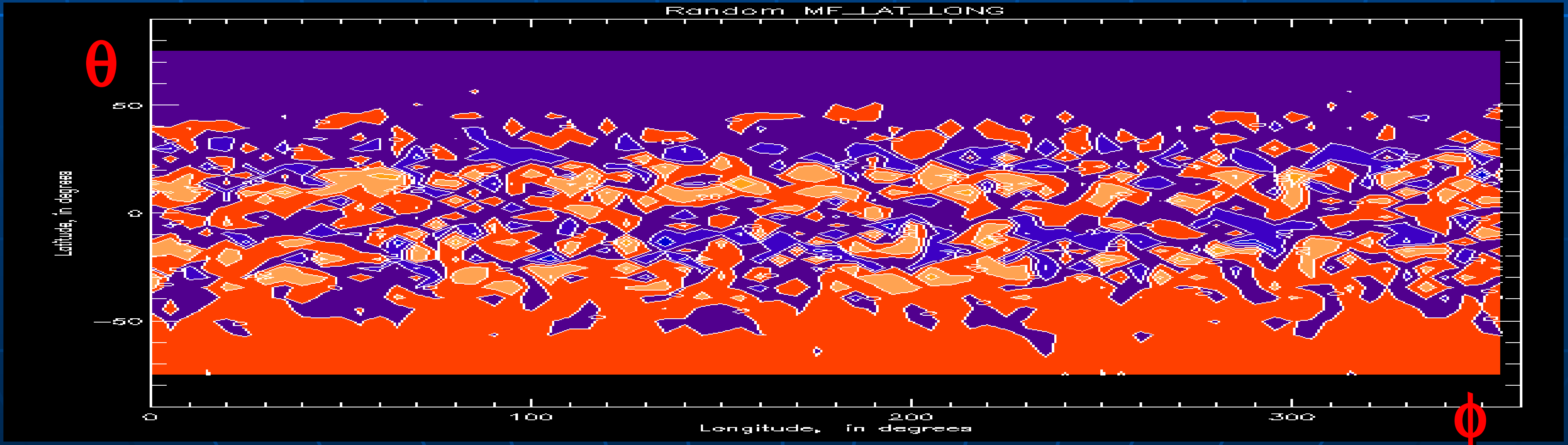
Longitudinal structure of Solar Magnetic Field

Longitudinal structure

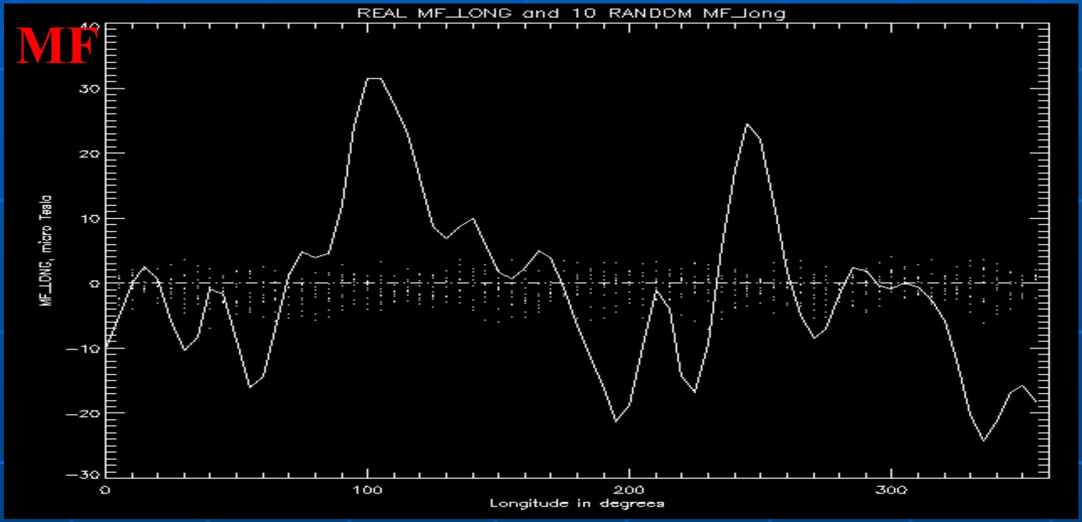
of Real SMF in Carrington System



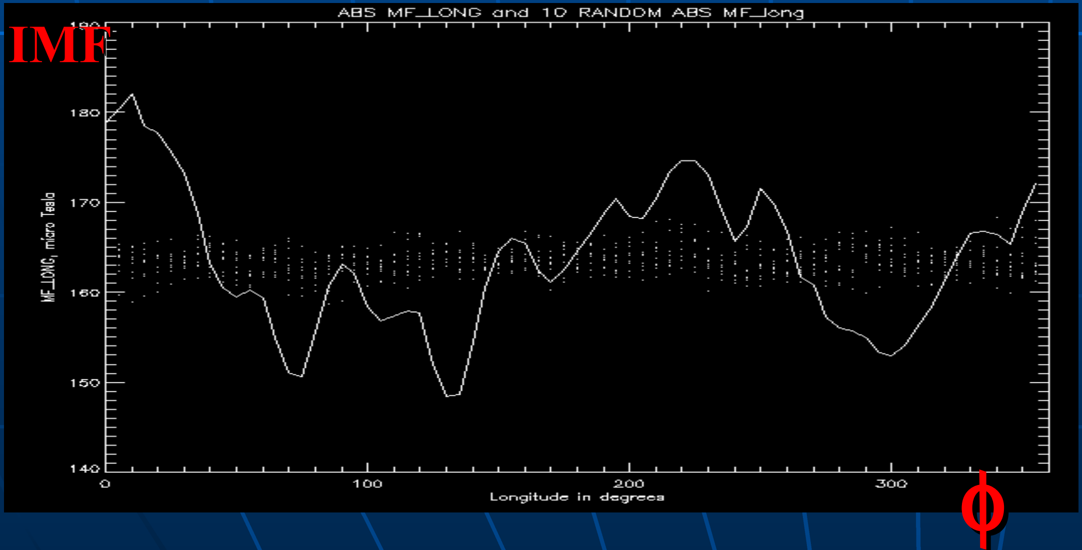
of Random SMF in Carrington System



Longitudinal structure
in Carrington System



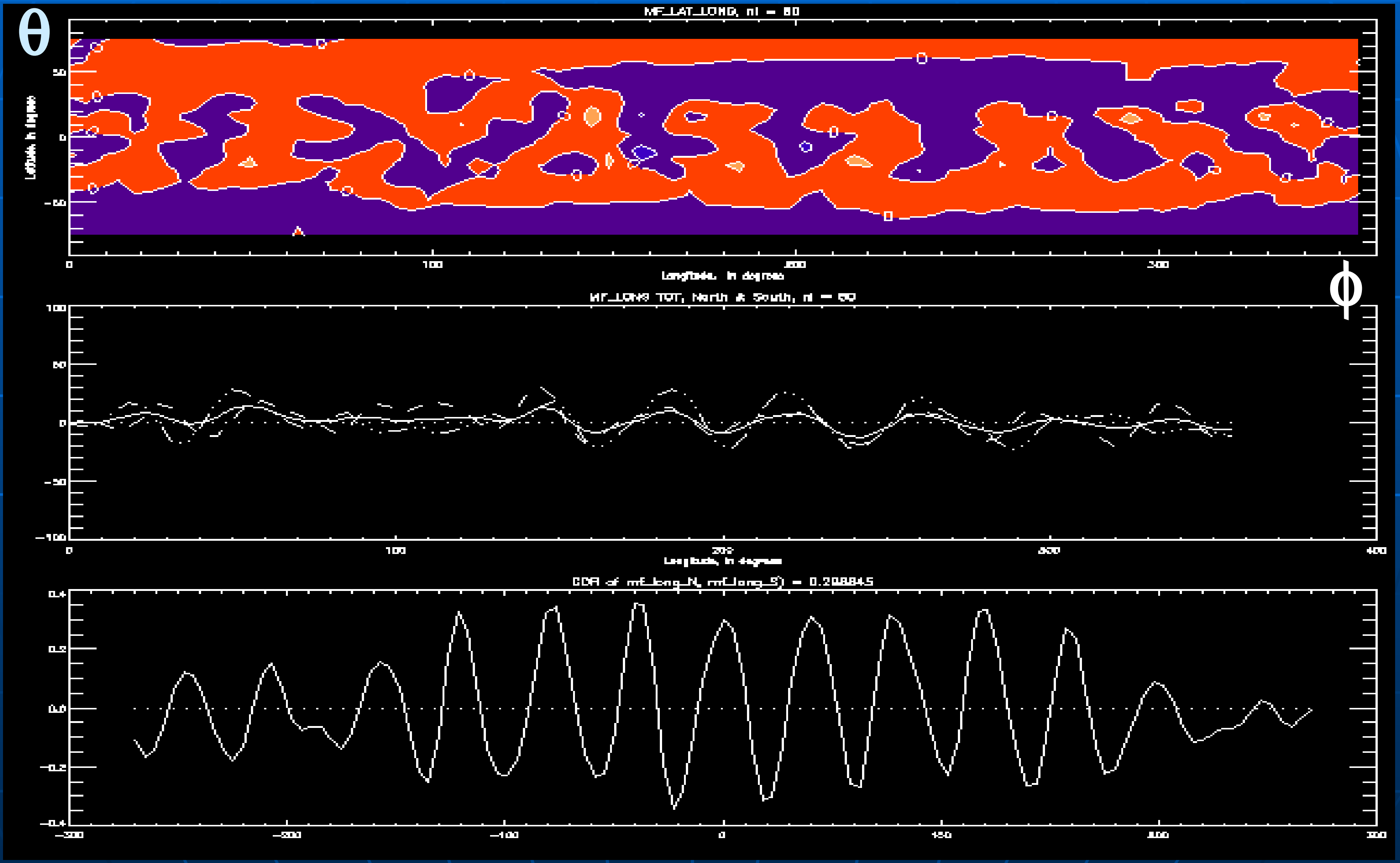
Longitudinal structures for Real and 10 Random Distributions



Longitudinal structures for SMF Intensity and 10 Random SMFI Distributions

Longitude structure of Solar Magnetic Field

T synodic = 30.31 d



Solar rotation

Solar rotation

- The Sun rotates differentially, both in latitude (equator faster than poles) and in depth (more complex).
- Standard value of solar rotation: Carrington rotation period: 27.2753 days (the time taken for the solar coordinate system to rotate once).
- Sun's rotation axis is inclined by 7.1^{o} relative to the Earth's orbital axis (i.e. the Sun's equator is inclined by 7.1^{o} relative to the ecliptic).

Discovery of solar rotation

- Galileo Galilei and Christoph Scheiner noticed already that sunspots move across the solar disk in accordance with the rotation of a round body

➔ Sun is a rotating sphere

- Movie based on Galileo Galilei's historical data

Surface differential rotation

- Poles rotate more slowly than equator.
- Surface differential rotation from measurements of:
  - Tracers, such a sunspots or magnetic field elements (always indicators of the rotation rate of the magnetic field)
  - Doppler shifts of the gas
  - Coronal holes (not plotted) rotate rigidly

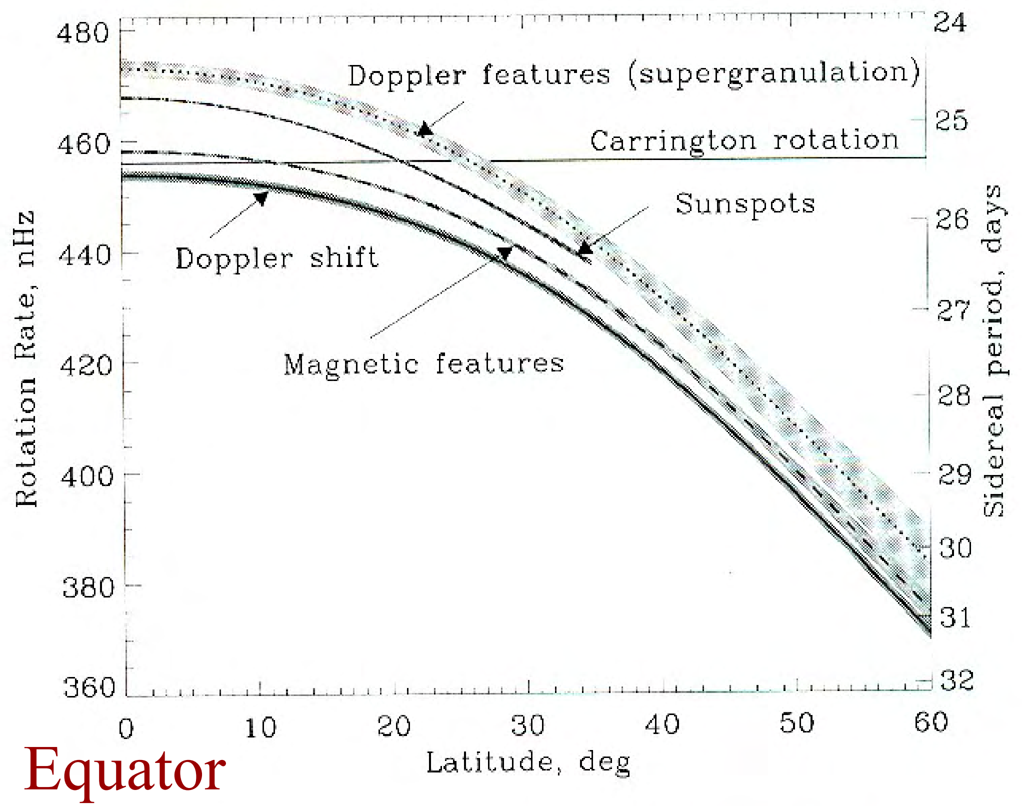
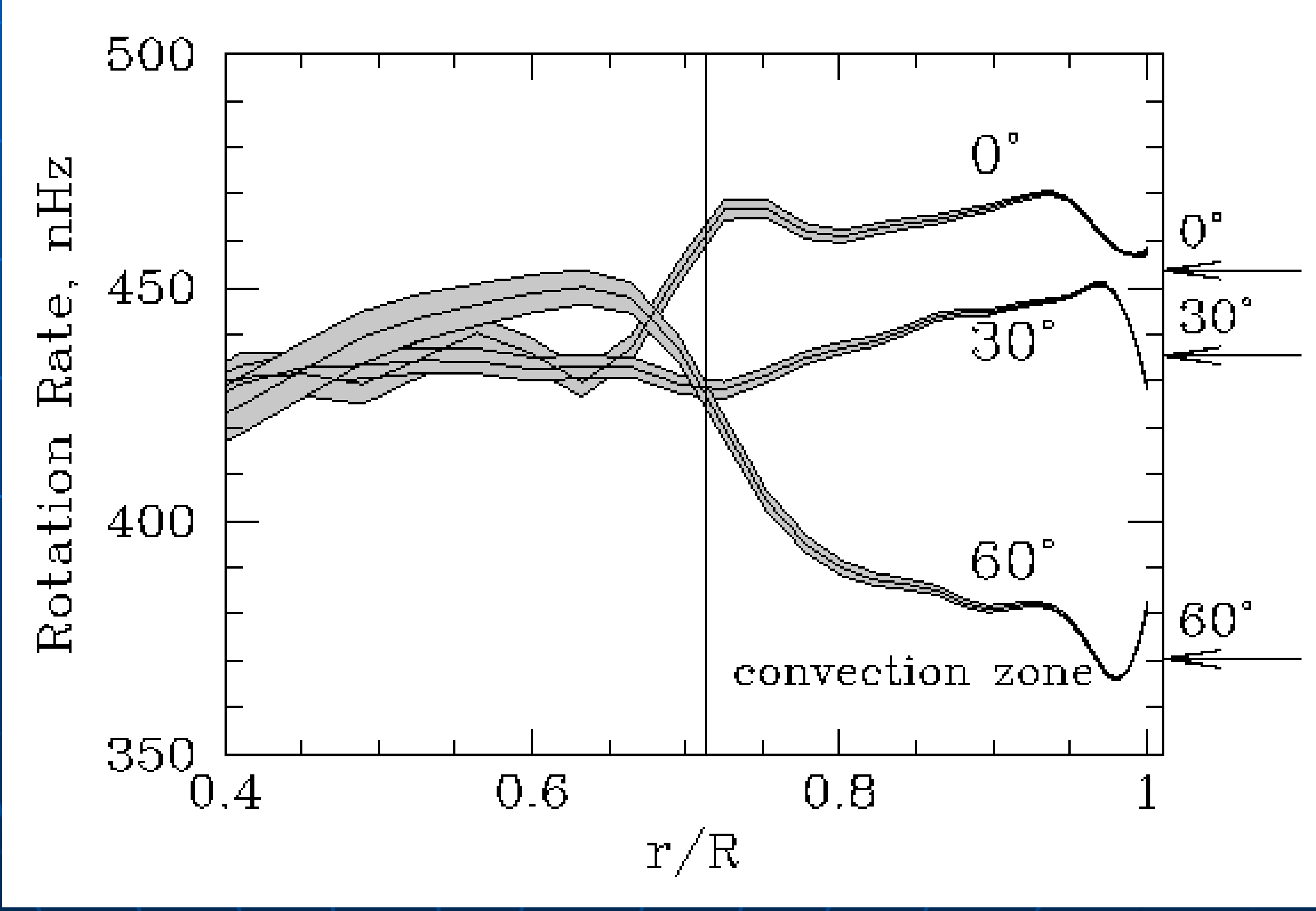


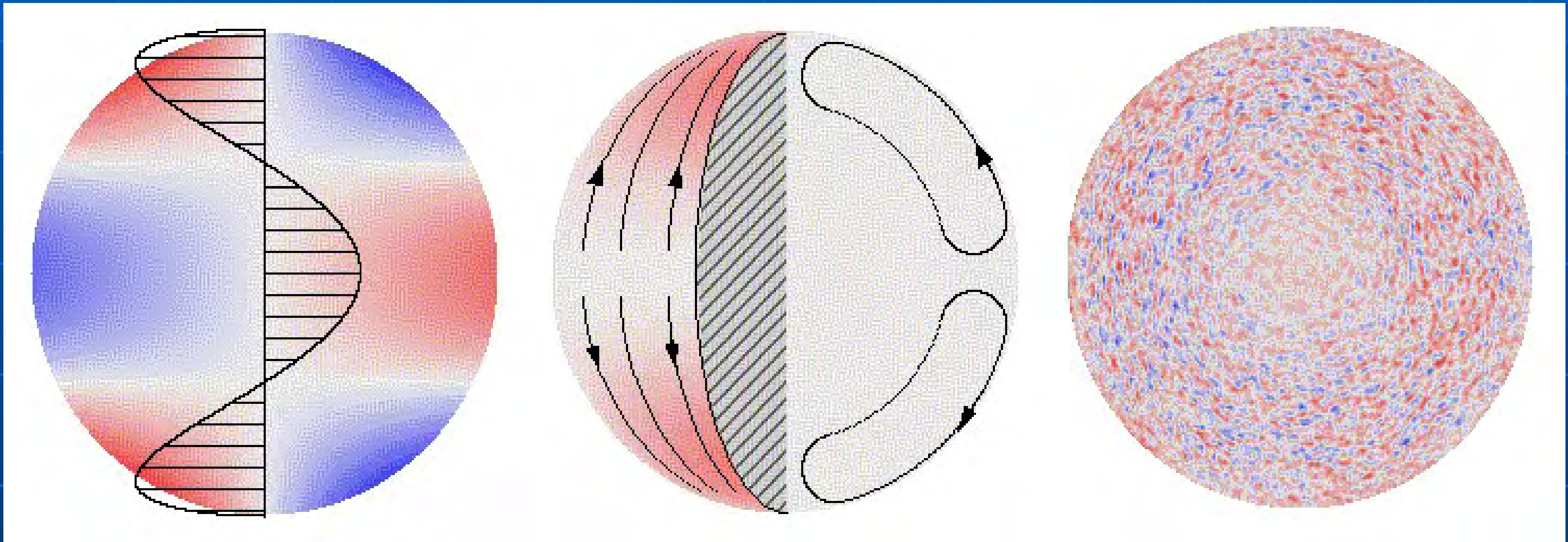
Figure 1. Rotation rate, $\Omega/2\pi$, and period of various tracers on the Sun's surface: recurrent (old) sunspots (dashed curve), magnetic features (dot–dash), and Doppler features (dots). The rotation rate and period determined spectroscopically through the Doppler shift are shown by the full curve. The shaded areas show the 1σ error estimates.

Internal differential rotation III : tachocline

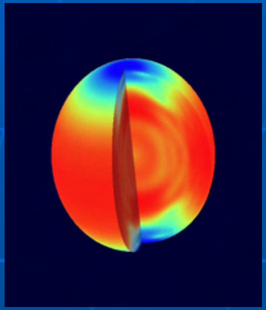
Large radial gradients in rotation rate at bottom of CZ (tachocline), but also just below solar surface (enigmatic). Note the slight missmatch of helio-seismic and Doppler measurements

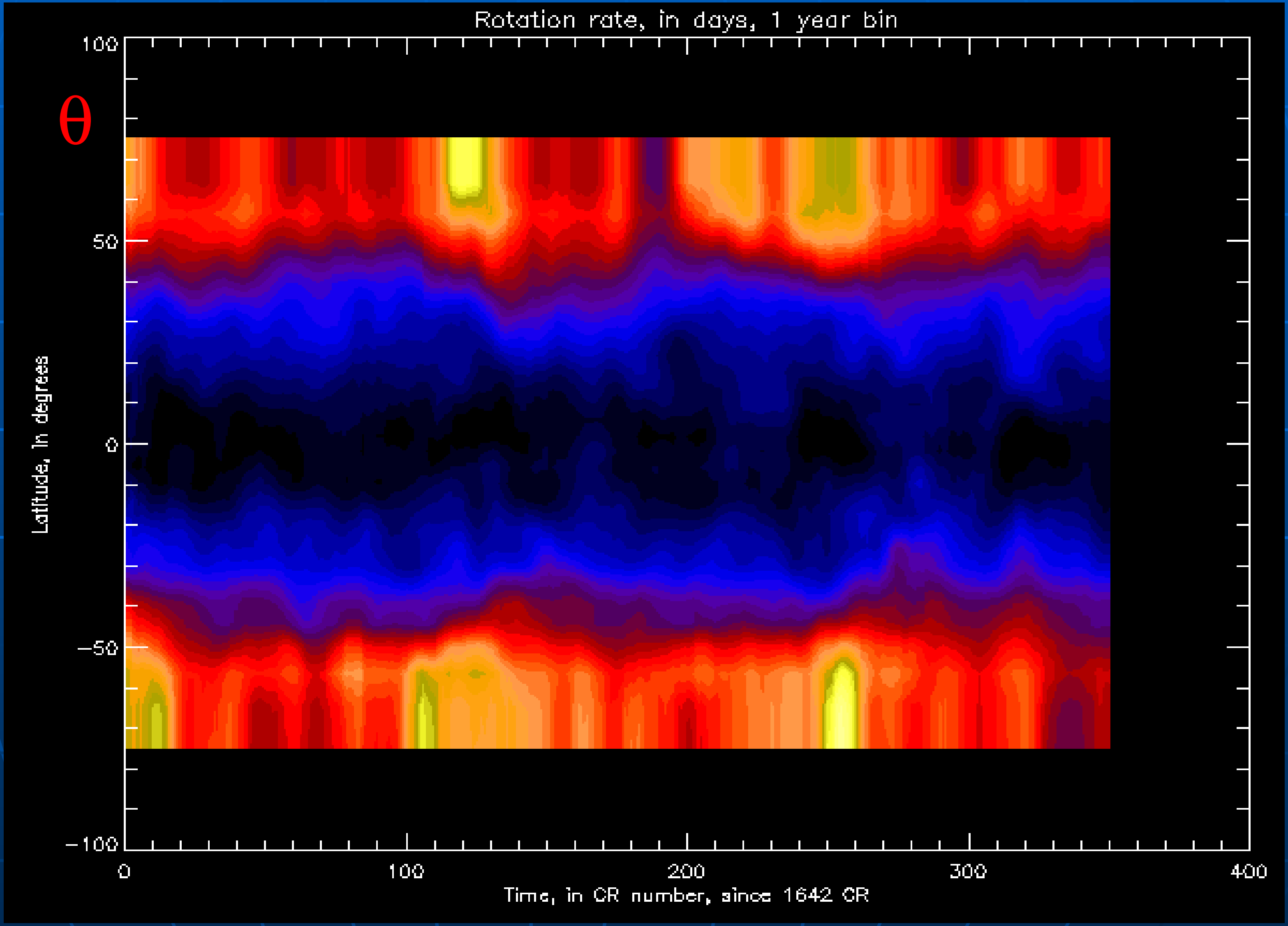


Flows in the Sun,
Stanford Group of SOI/MDI



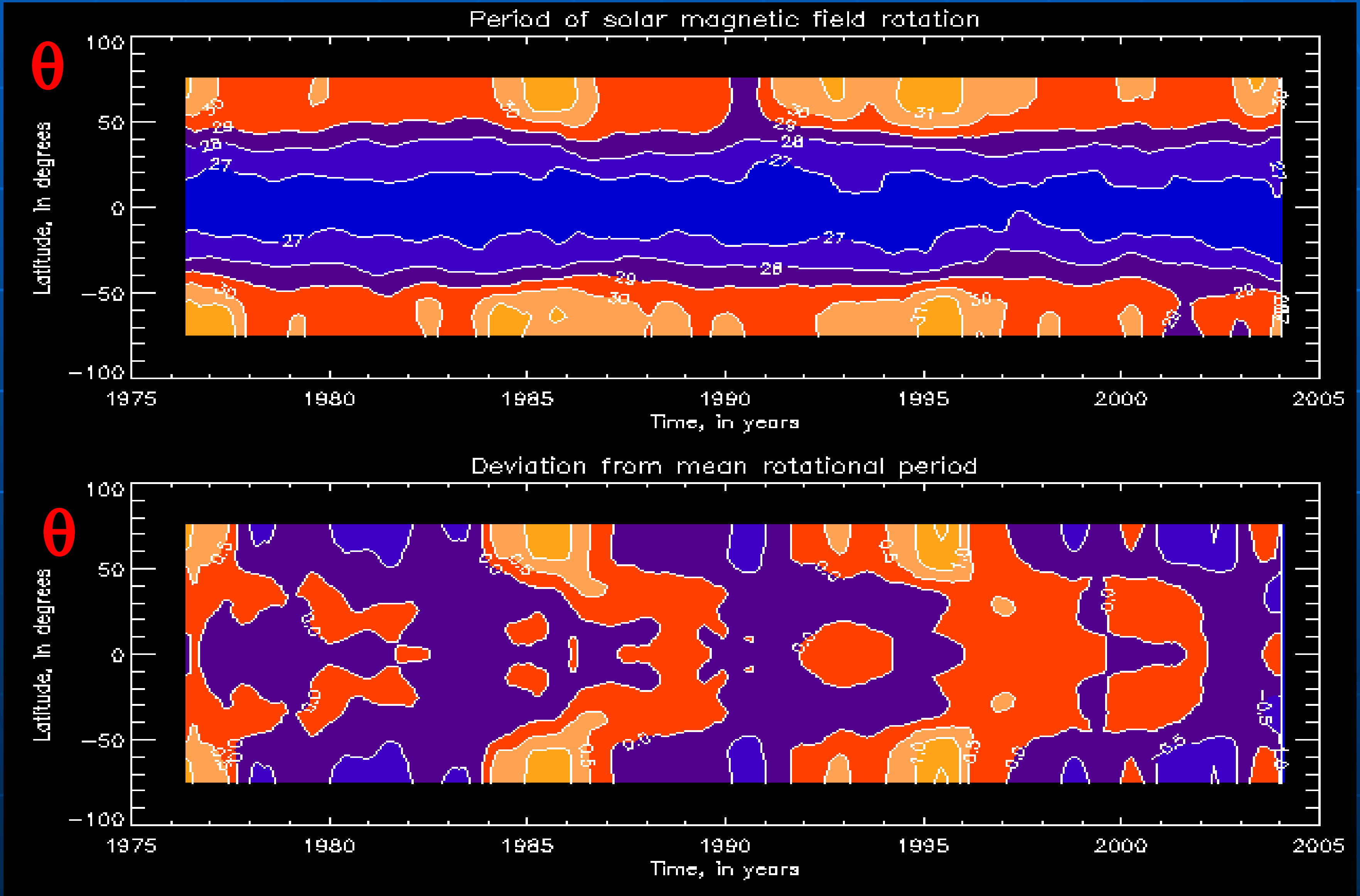
Differential Rotation of the SMF





Differential Rotation of the SMF

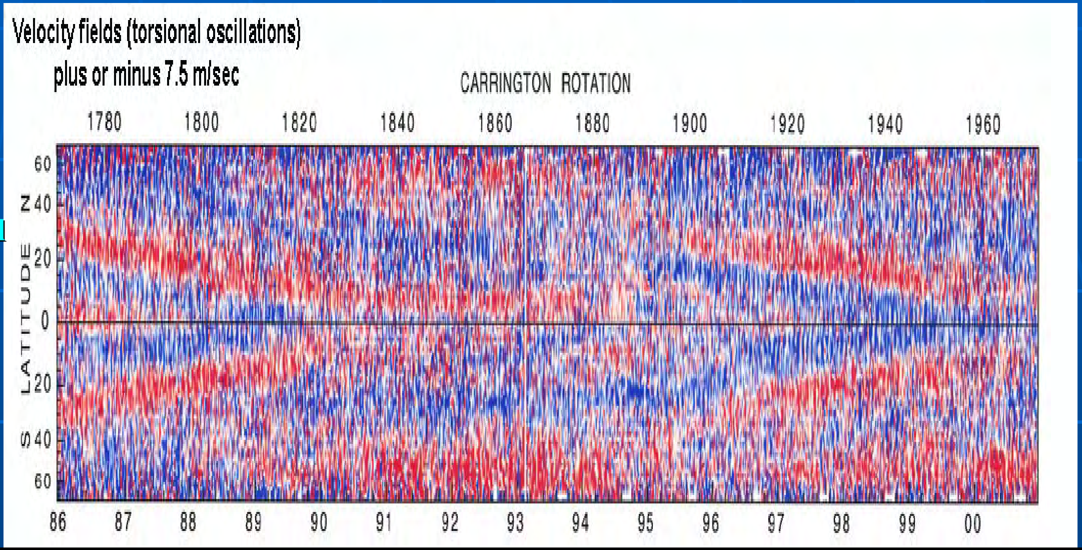
Sideral Periods & Deviations from P mean, in days



Torsional waves, $P(\theta, t) - P(\theta)$

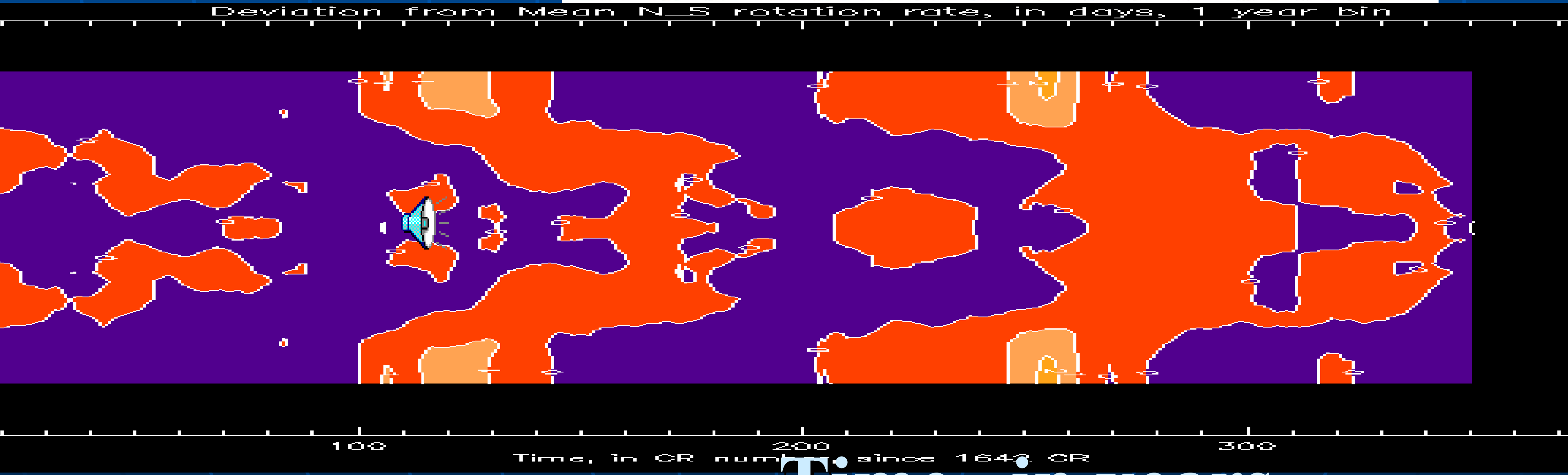
The torsional waves firstly discovered by Howard and LaBonte in sunspot rotation are present in the magnetic field rotation rate as well (Snodgrass, 1985, 1987; Gilman and Howard, 1984; Makarov et al., 1997) up to high latitudes as it is seen on the bottom plot of Fig. 5. The 11-year variability of the deviations of the period from the mean one in the sub-polar zones correspond to the torsional waves. The rotational rate of the pre-equatorial zones varies in time with a periodicity of 55--60 CR about (4 -- 5 years).

Dopler velocity, Howard R, LaBonte B.J., 1980



WSO MF Sun

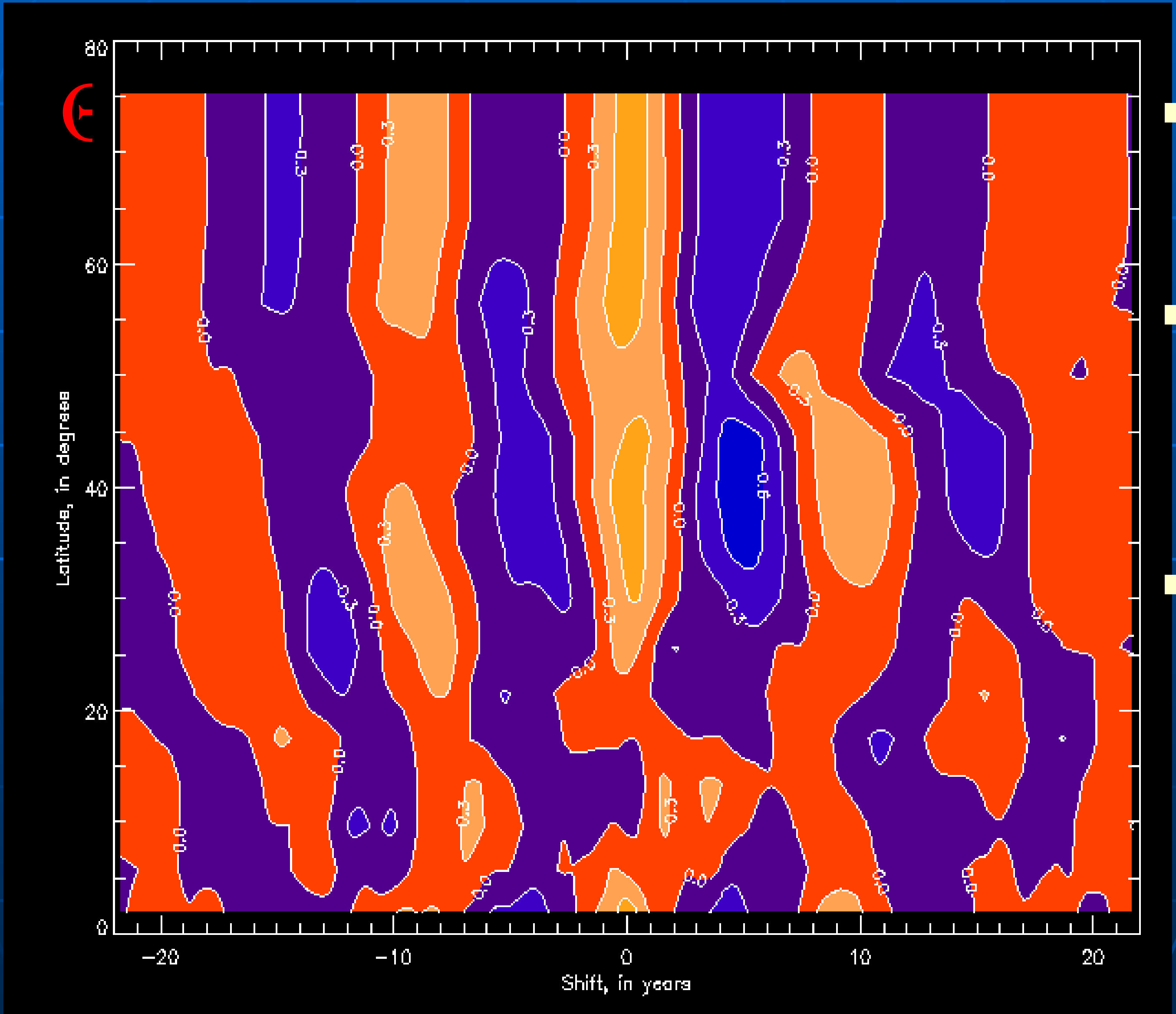
Gavryuseva, 2006



Time, in years

K cor ($\Omega(\theta, t)$, $\Omega(-\theta, t)$),

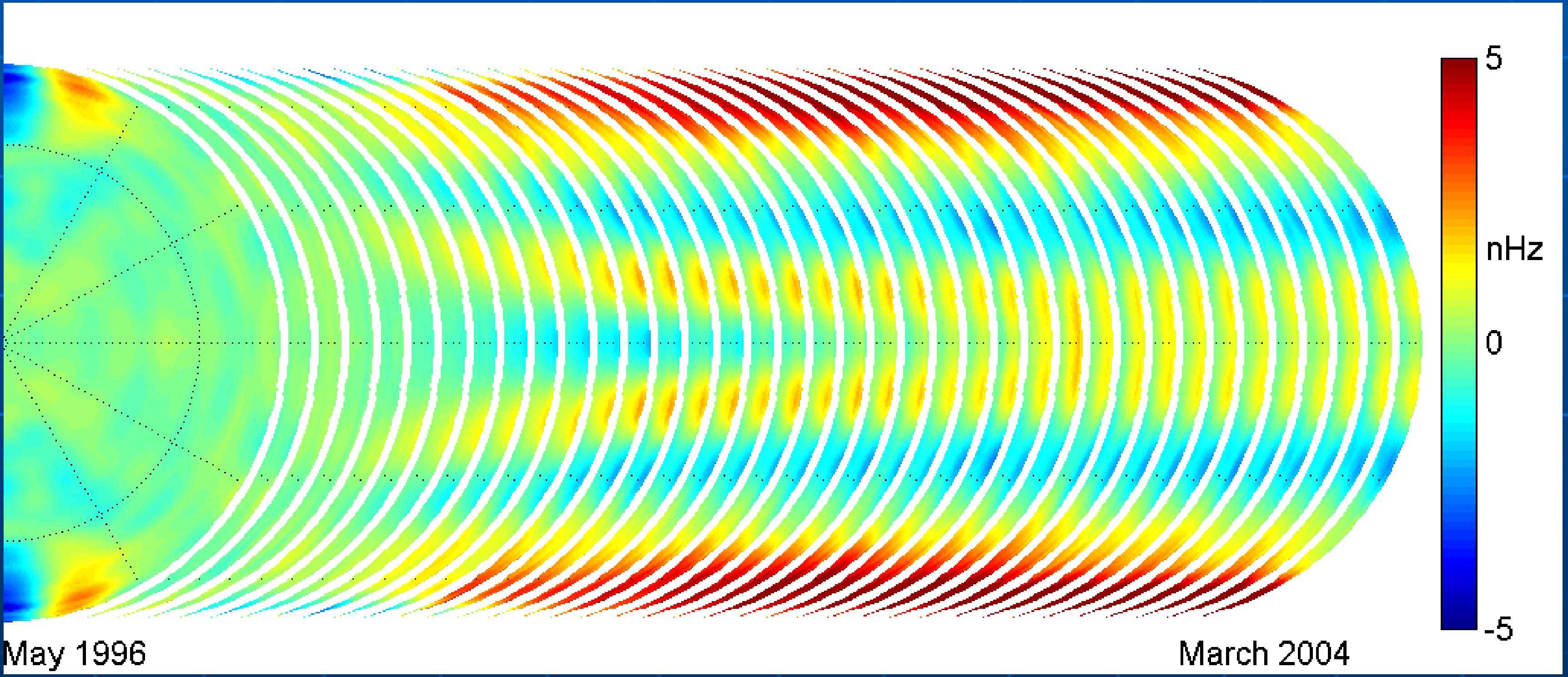
$\Omega(\theta, t)$ = smooth($\Omega(\theta, t)$ over 1 year)



- **Correlation at 0- shift**
- **Quasi-10 year periodicity**
- **No correlation at +/-25 degrees**

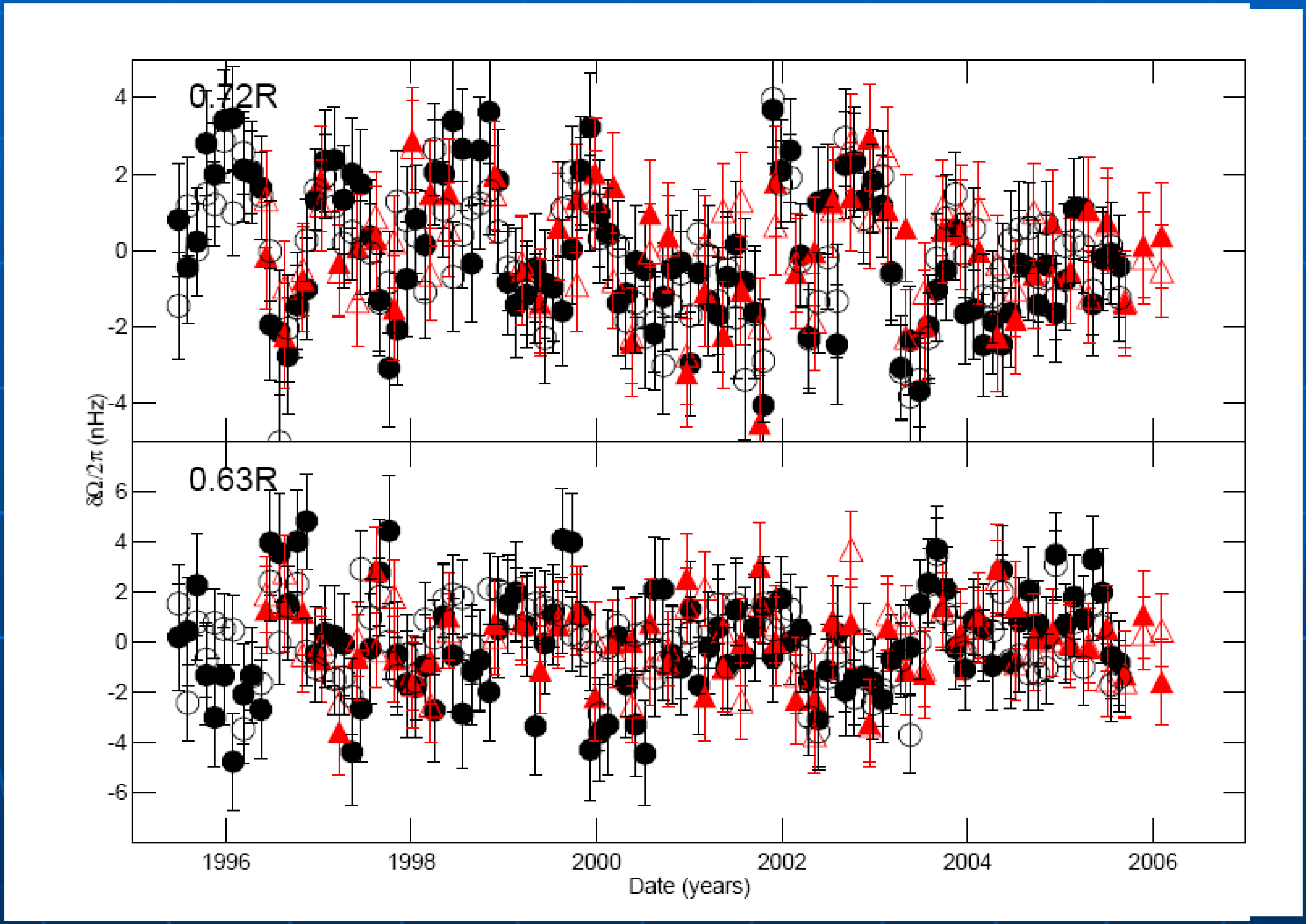
Zonal flows

Rotation rate - average value at solar minimum



Vorontsov et al. (2002; Science 296, 101)

Tachocline oscillations?



GONG-RLS

MDI-RLS

MDI-OLA

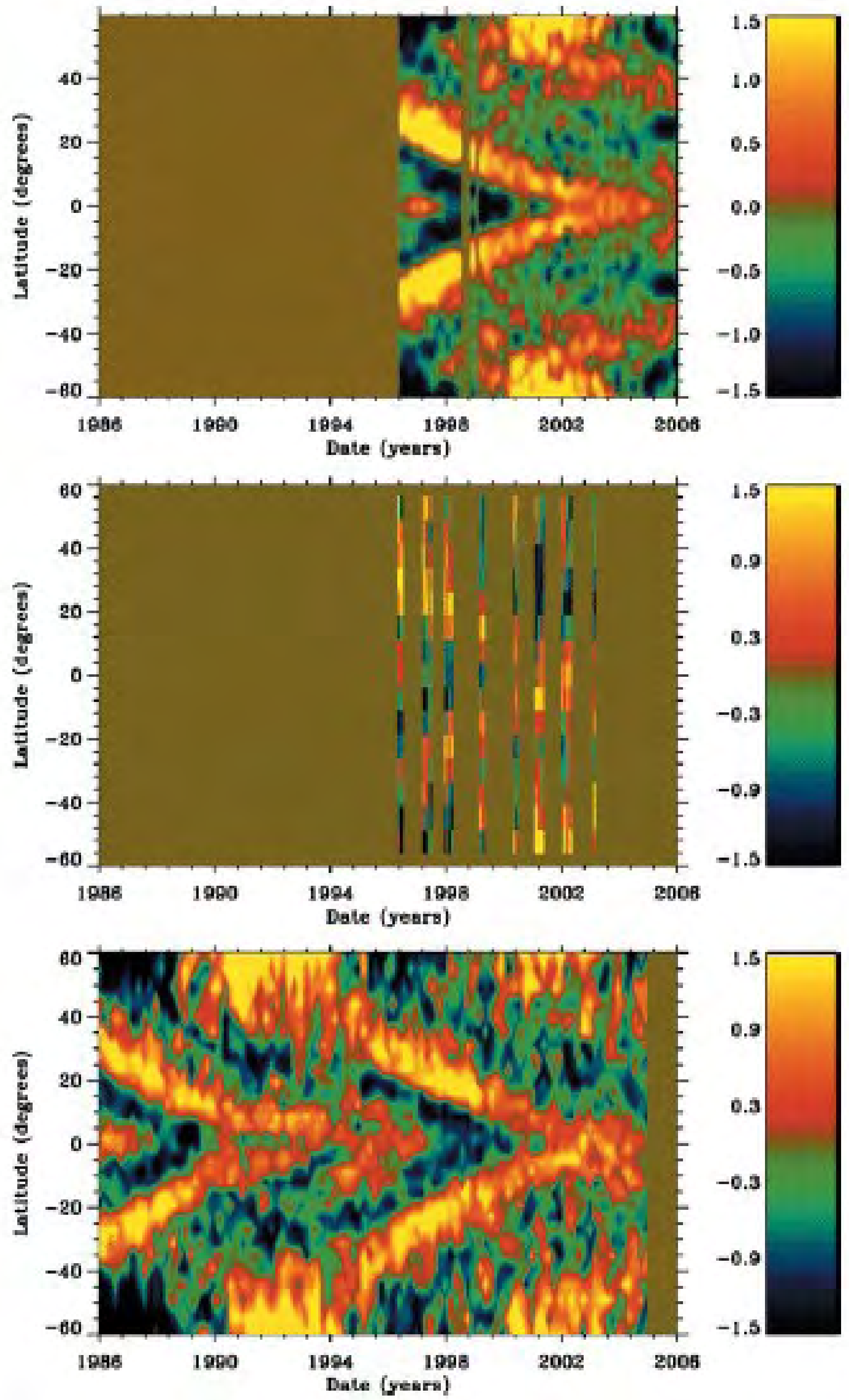
Howe, SOGO meeting, Sheffield, 2006

Global helioseismology, 0.99 R–

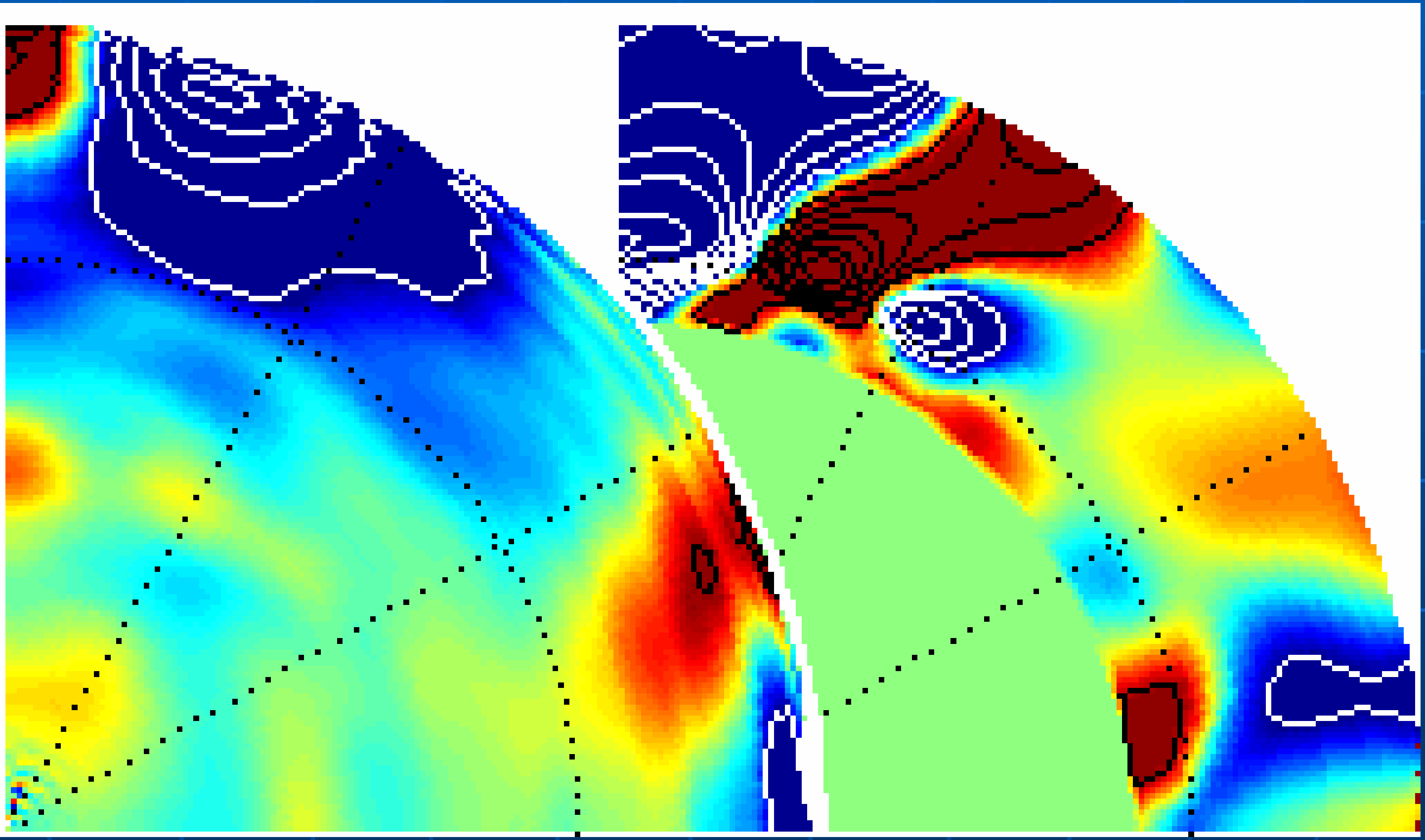
Local helioseismology, 0.99 R–
(note asymmetry)

Surface flow (Mt Wilson)

Howe et al. (2006; Solar Phys 235, 1)



Observed and modeled dynamics



6 1/2 year MDI inversion, enforcing 11-yr periodicity

Vorontsov et al.

Non-linear mean-field solar dynamo models

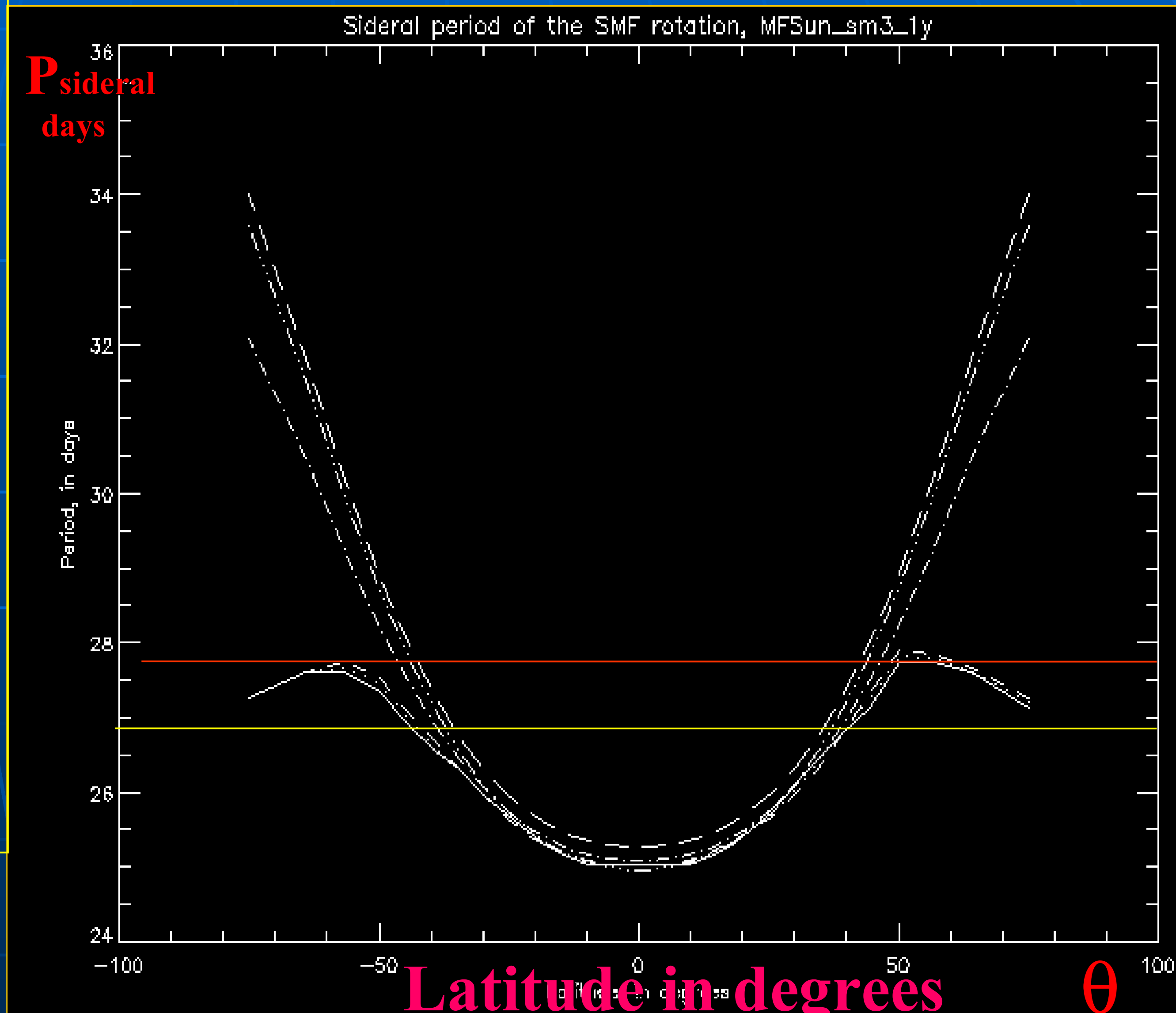
Covas, Tavakol and Moss

Period of Differential Rotation of the SMF

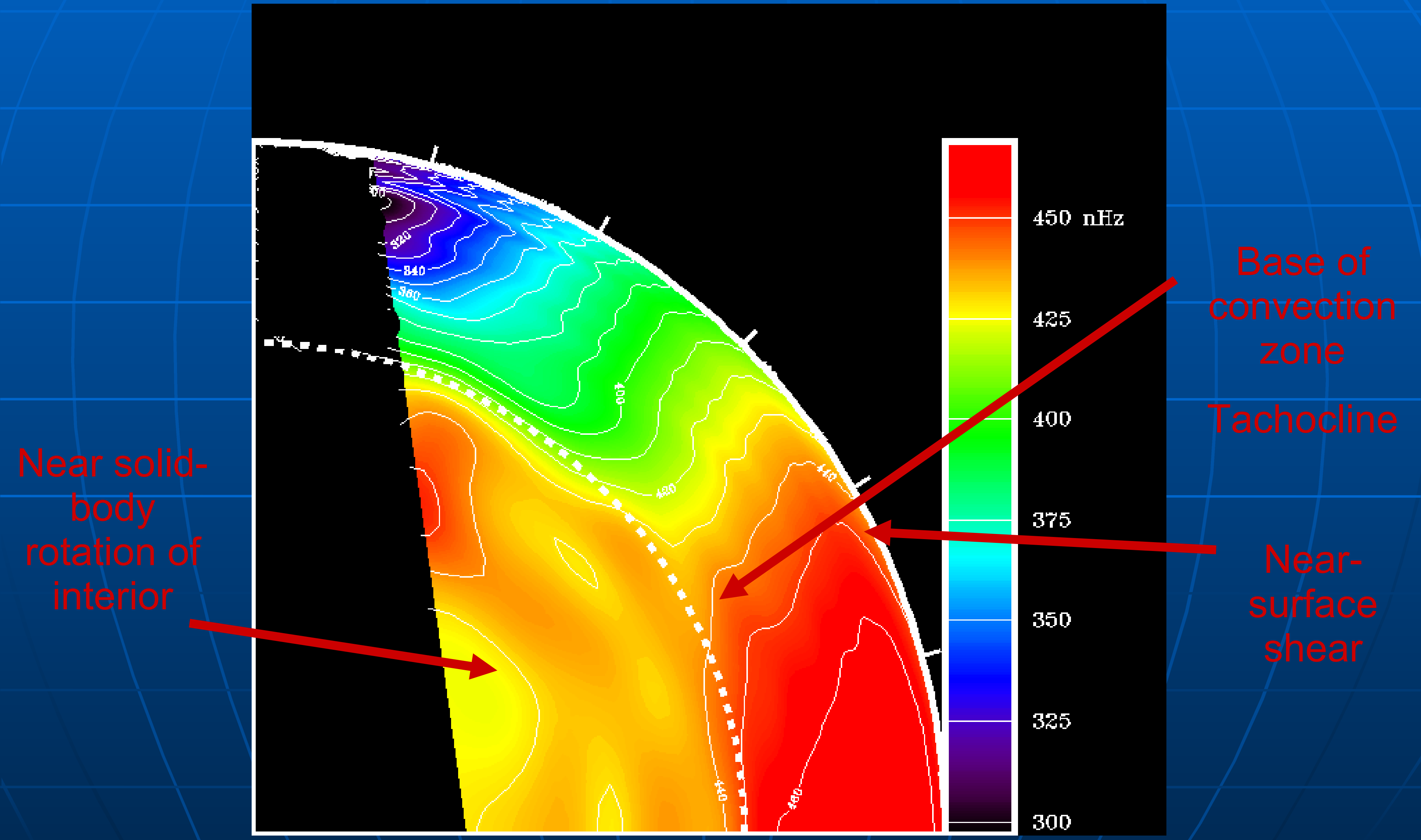
Continuos line is a sideral period of the SMF by auto-correlation method.
Dashed line is periods of plasma rotation by different methods.

Red line corresponds to Sideral Rotational Period of the longitudinal structure of the SMF
(P synodic = 30.3 day, or
T sideral = 27.8 day, or
ν sideral = 424.326 nHz).

Yellow line coresponds to P sideral = 26.92 days equal to P rotation rate at the bottom of the convective zone).



Inferred solar internal rotation



Some questions:

1) Mass, Radius, Rotation of the Sun ???

- 2) Who got Nobel Prize in Solar Physics?
- 3) What is more informative for the study
- of the solar interior structure study:
- Frequency or Amplitude of p-modes oscillations ?
- 4) - ,, - ,, - ,, - ,, - ,, - ,, - ,, - P or G modes ?
- 5) Which p-modes penetrate deeper l=0 or l=4 ?
- 6) What is a period of MAGNETIC activity ?
- 7) Does the LONGITUDINAL structure depend
- on the rotation rate of the coordinate system ?
- 8) Haw many LATITUDINAL zone exist ?
- 9) What is the rotation period in tachocline zone ?
- 10) Does the STANDARD SOLAR model has some limits ?