Internal Structure of the Sun and Helioseismology

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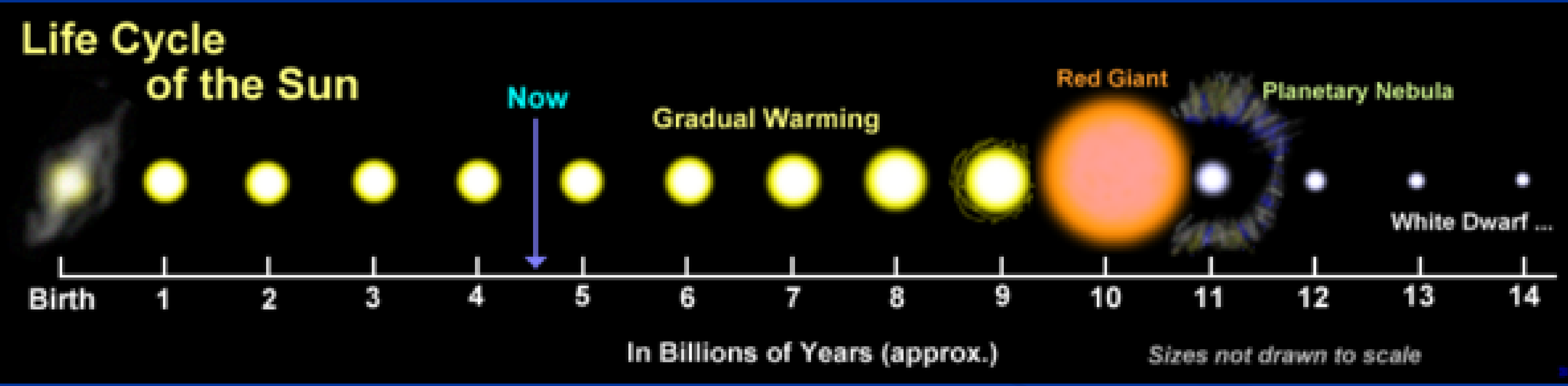
(uses material from the web and the HELAS site)

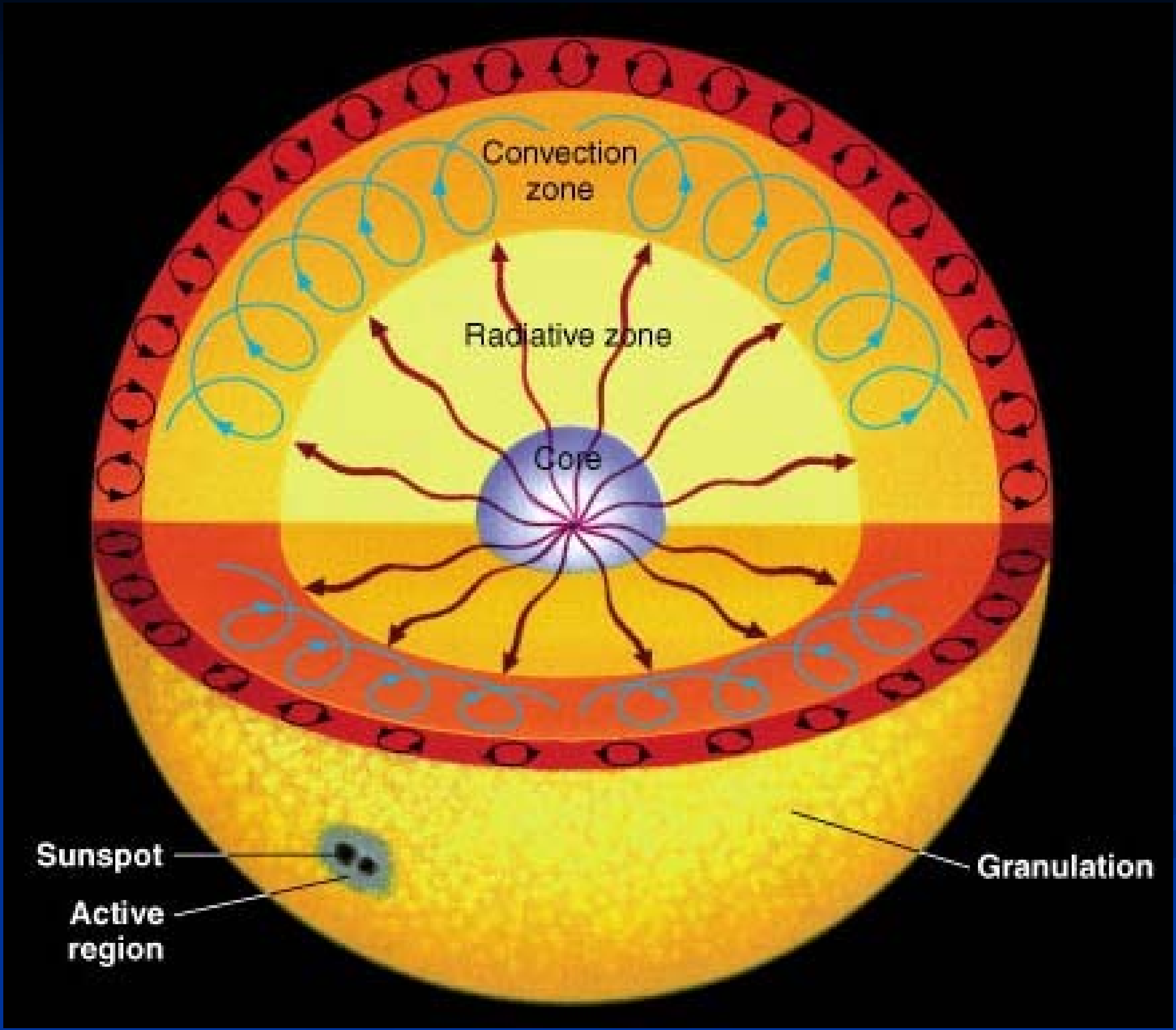
Goettingen, 9 June 2008

Solar evolution



Standard solar model

- Must be consistent with present observations:
  - solar luminosity L=3.844 10^33 erg/s
  - solar radius R=6.9598 10^10 cm
  - photospheric chemical composition
    - Z=0.0181 (old value)
    - Z=0.0122 (new value?)
  - total mass M=1.989 10^33 g
  - age constraints (e.g. zircon >4.4 Gyr)
- Must use most plausible physics
- Should also be a particular application of the general theory of stellar structure and evolution


Convection
zone
Radiative zone
Core
Sunspot
Active
region
Granulation

Model assumptions

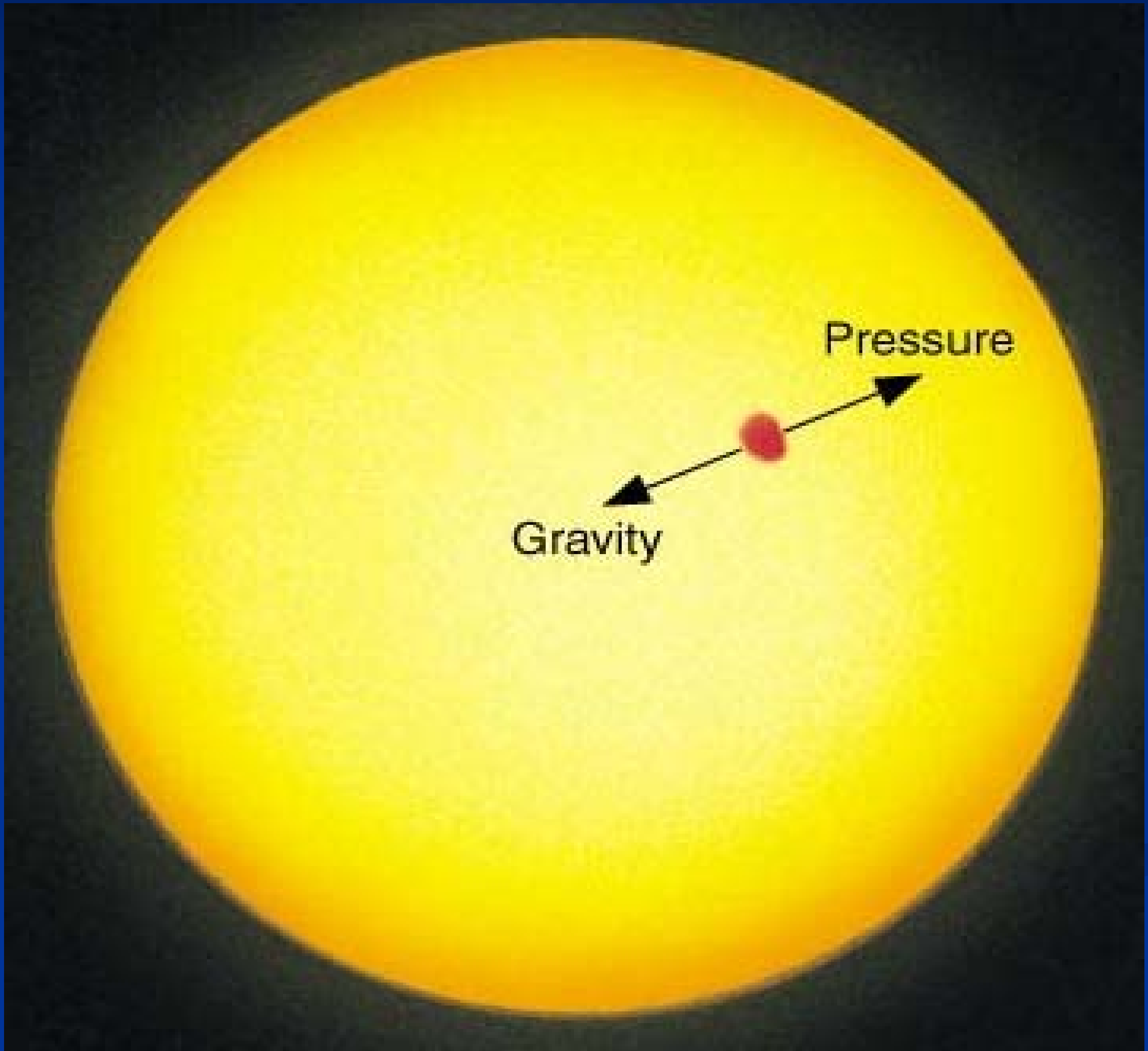
- Spherically symmetric structure
- No rotation
- No magnetic field
- Slow time evolution
- No mass loss

Basic equations

- Hydrostatic equilibrium
- Conservation of mass
- Equation of state
- Equation of nuclear energy production
- Equations of energy transport by radiation and by convection

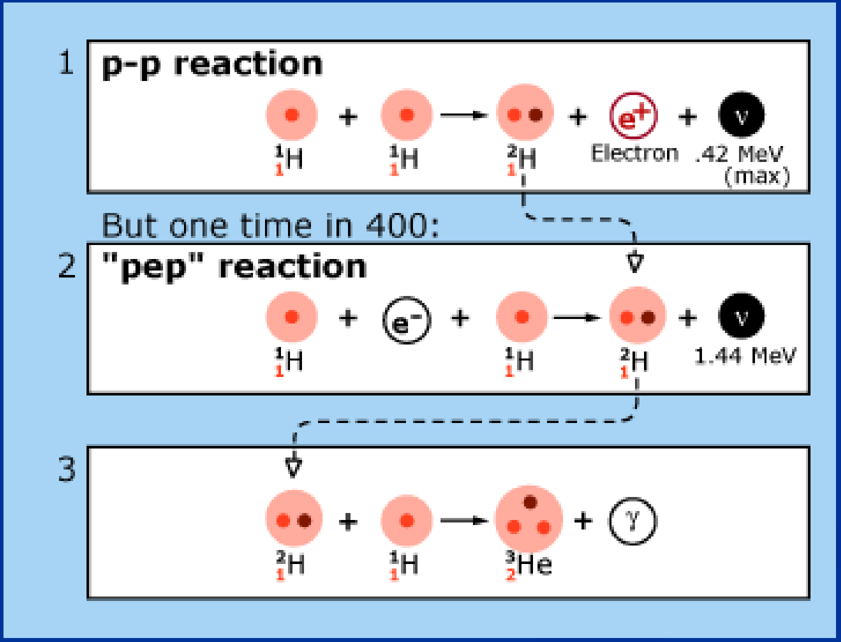
- The model is first computed with a given initial chemical composition
- The time evolution is assumed to be slow. Solution is iterated in time after updating chemical composition at each step

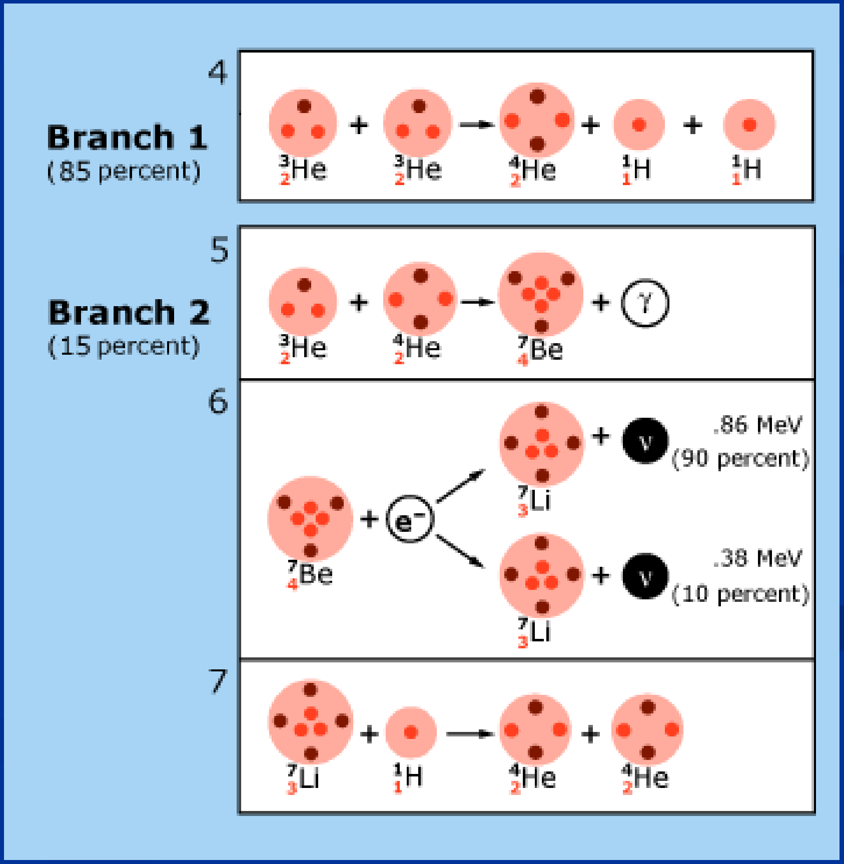
Hydrostatic equilibrium



Nuclear energy

- Nuclear reaction rates depend sensitively on temperature and density





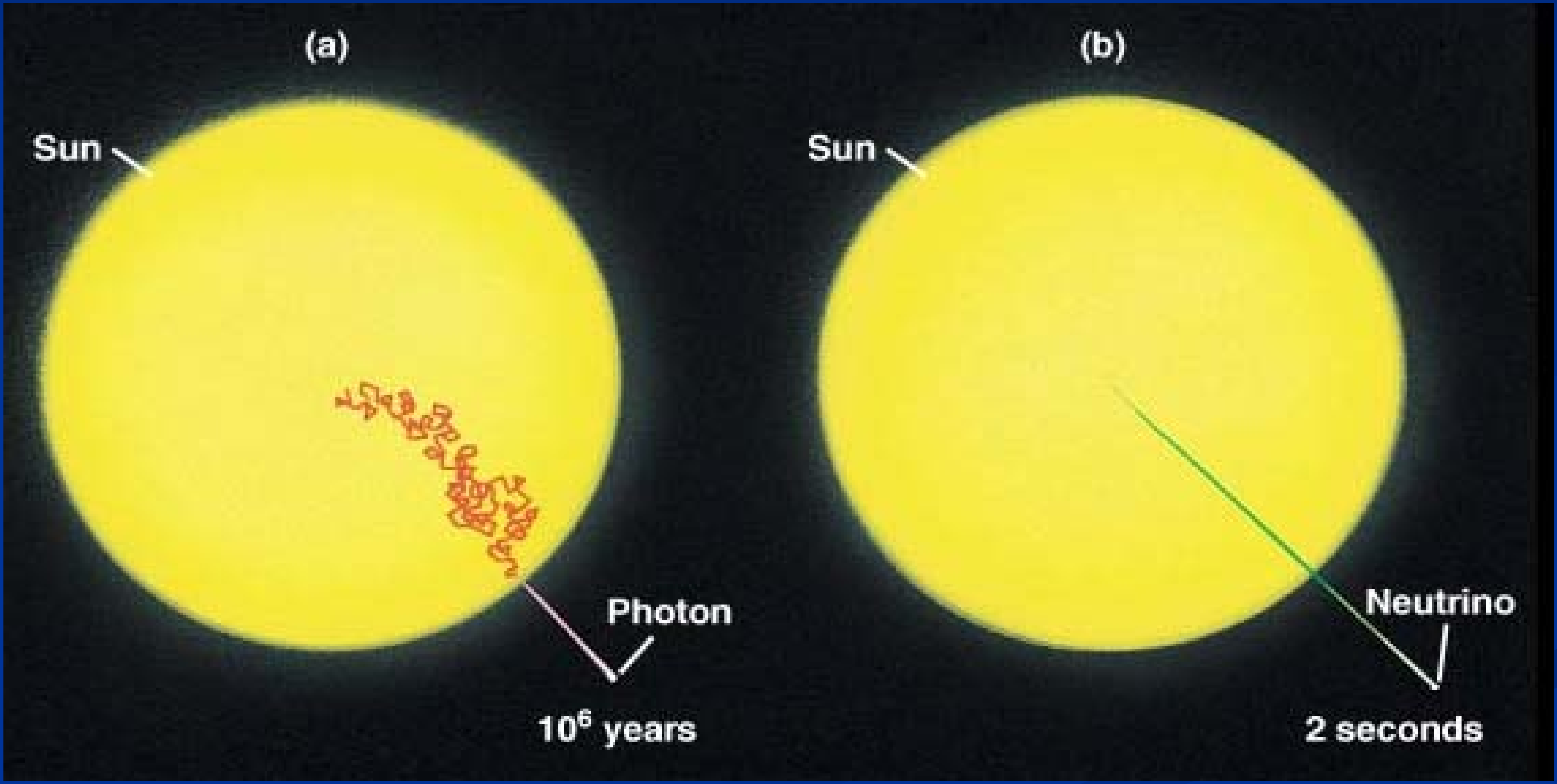
Equation of state

- The solar material is a plasma
- To a first approximation, the equation state is given by the perfect gas law

- Several addition effects must be included (Coulomb interactions, screening, electron degeneracy, relativistic effects, etc.)

Radiative opacity

- Opacity is inversely proportional to the photon mean free path
- Opacity depends on density, temperature, chemical composition
- In the radiative interior, the opacity controls the temperature gradient
- The computation of the opacity requires detailed knowledge of the interaction of photons with atoms and nuclei
- OPAL tables : opacity is accurate to a few percents



(a)
Sun
Photon
10^6 years
(b)
Sun
Neutrino
2 seconds

Transport of energy by convection

- All was said in last week's lecture
- Stellar convection is not easy to model
- Transport of energy by convection is usually described by a phenomenological model, the mixing length theory
- The mixing length is a fraction of the pressure scale height

Tunable parameters

- Initial Helium abundance
  - → affects solar luminosity
- Initial "metal" abundance
  - → affects surface ratio X/Z
- Mixing length parameter
  - → affects solar radius

Standard Solar Model

Distance from the Sun's center (solar radii)	Fraction of luminosity	Fraction of mass	Temperature ($\times 10^6$ K)	Density (kg/m^3)	Pressure (relative to pressure at center)
0.0	0.00	0.00	15.5	160,000	1.00
0.1	0.42	0.07	13.0	90,000	0.46
0.2	0.94	0.35	9.5	40,000	0.15
0.3	1.00	0.64	6.7	13,000	0.04
0.4	1.00	0.85	4.8	4,000	0.007
0.5	1.00	0.94	3.4	1,000	0.001
0.6	1.00	0.98	2.2	400	0.003
0.7	1.00	0.99	1.2	80	4×10^{-5}
0.8	1.00	1.00	0.7	20	5×10^{-6}
0.9	1.00	1.00	0.3	2	3×10^{-7}
1.0	1.00	1.00	0.006	0.00030	4×10^{-13}

Helioseismology

is the study of solar oscillations

(1) to test the standard model of solar structure and evolution

(2) to go beyond the standard model and learn about rotation, convection, magnetic fields...

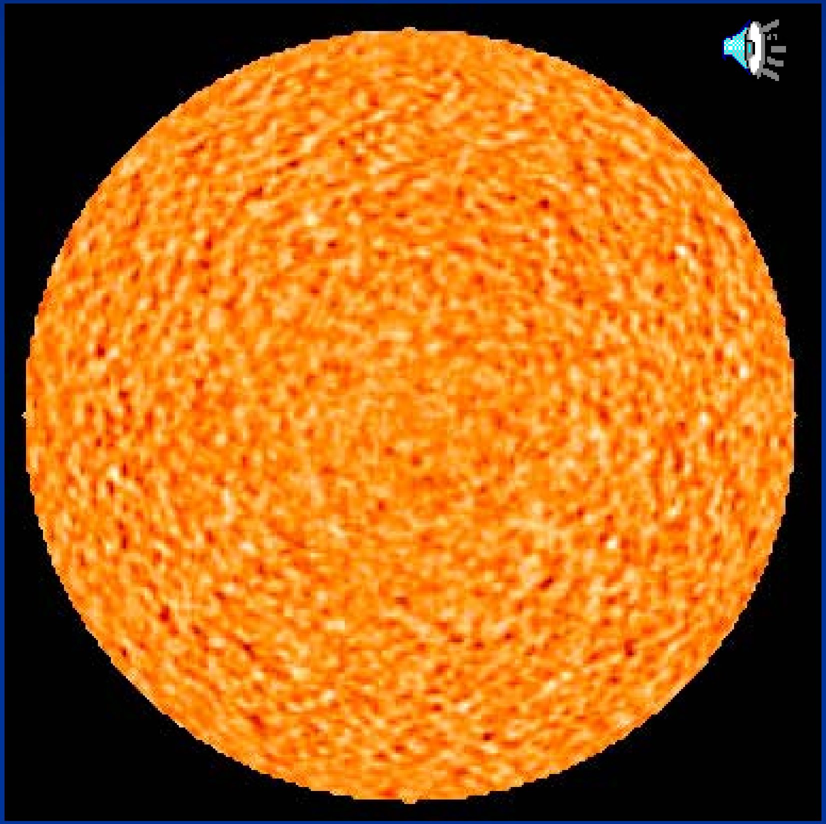
(3) to answer fundamental physics questions (e.g. solar neutrino problem)

Notable Successes of helioseismology

(PM di Mauro)

- **Depth of the solar convection zone** **(Christensen-Dalsgaard 1985)**
- **Opacities**
- **Neutrino Problem**
- **Diffusion of helium and heavy elements (Basu et al. 1996)**
- **Helium abundance**
- **Relativistic effect in the core (Elliot & Kosovichev 1998)**
- **Internal Dynamics (rotation, Schou et al. 1996)**

Solar oscillations

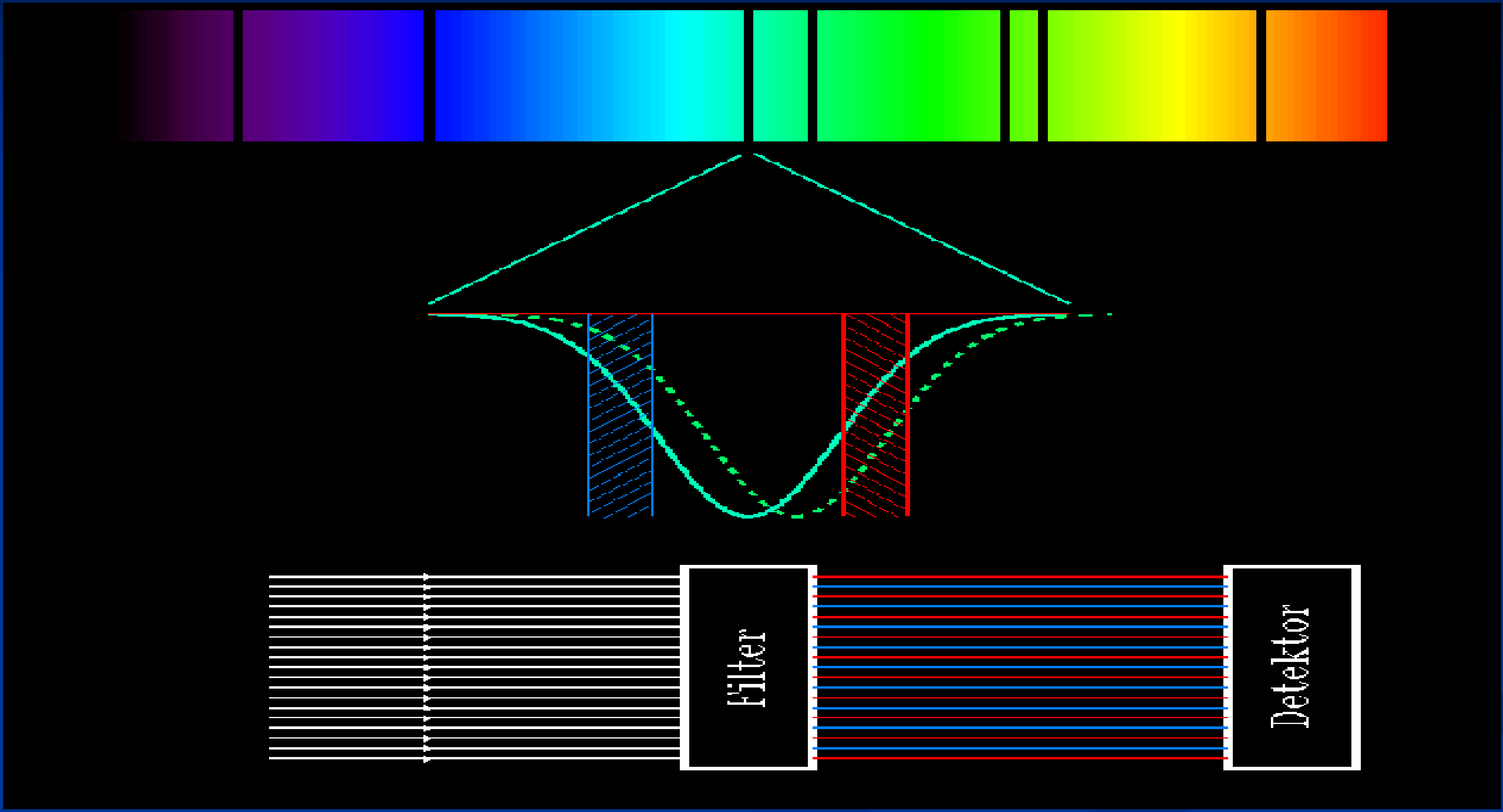


- The Sun is filled with acoustic waves, with periods near 5 min.

- Waves are excited by near-surface turbulent convection

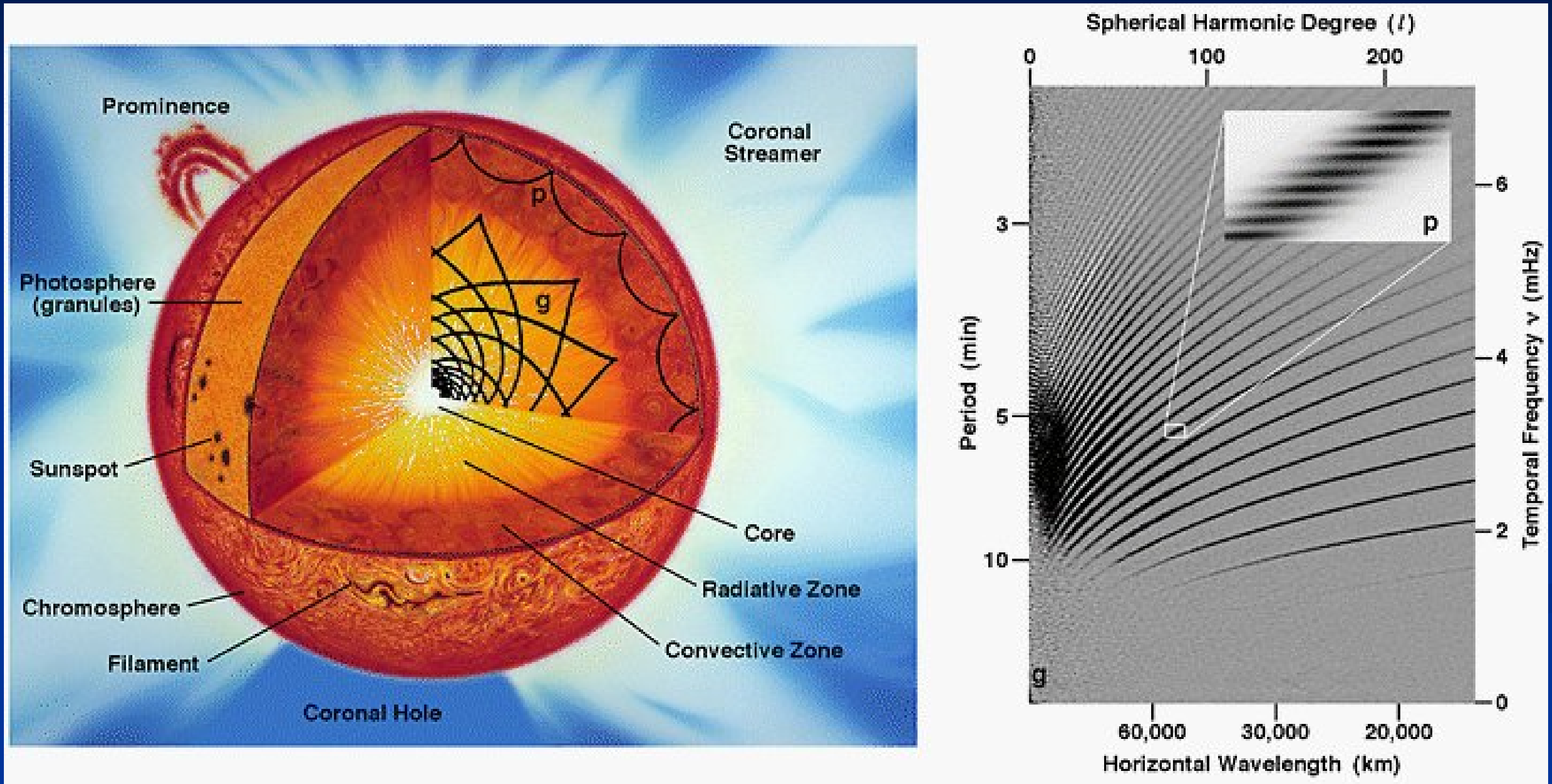
- Surface motions are a few 100 m/s, superimposed on the 2 km/s solar rotation.

Line-of-sight velocity measured from
the Doppler shifts of spectral lines (SOHO satellite)


Filter
Detektor


SOHO
Solar and
Heliospheric
Observatory
Observatoire
Solaire et
Héliosphérique
esa
european space agency
agence spatiale européenne
NASA

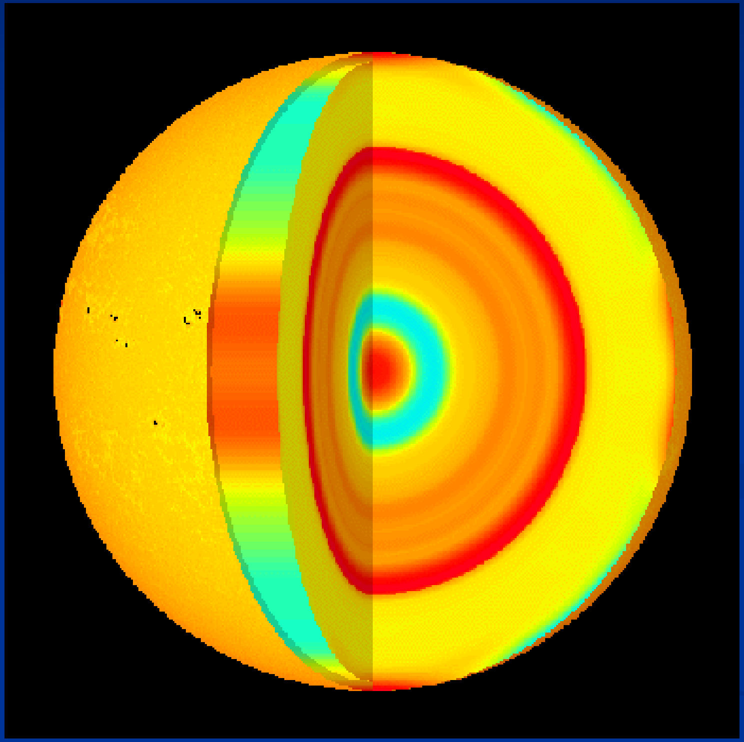
Global helioseismology



- Measurement and inversion of the frequencies of the global modes of resonance (millions of modes).

- Among the most precise measurements in astrophysics: some frequencies are known with a precision of 1 ppm.

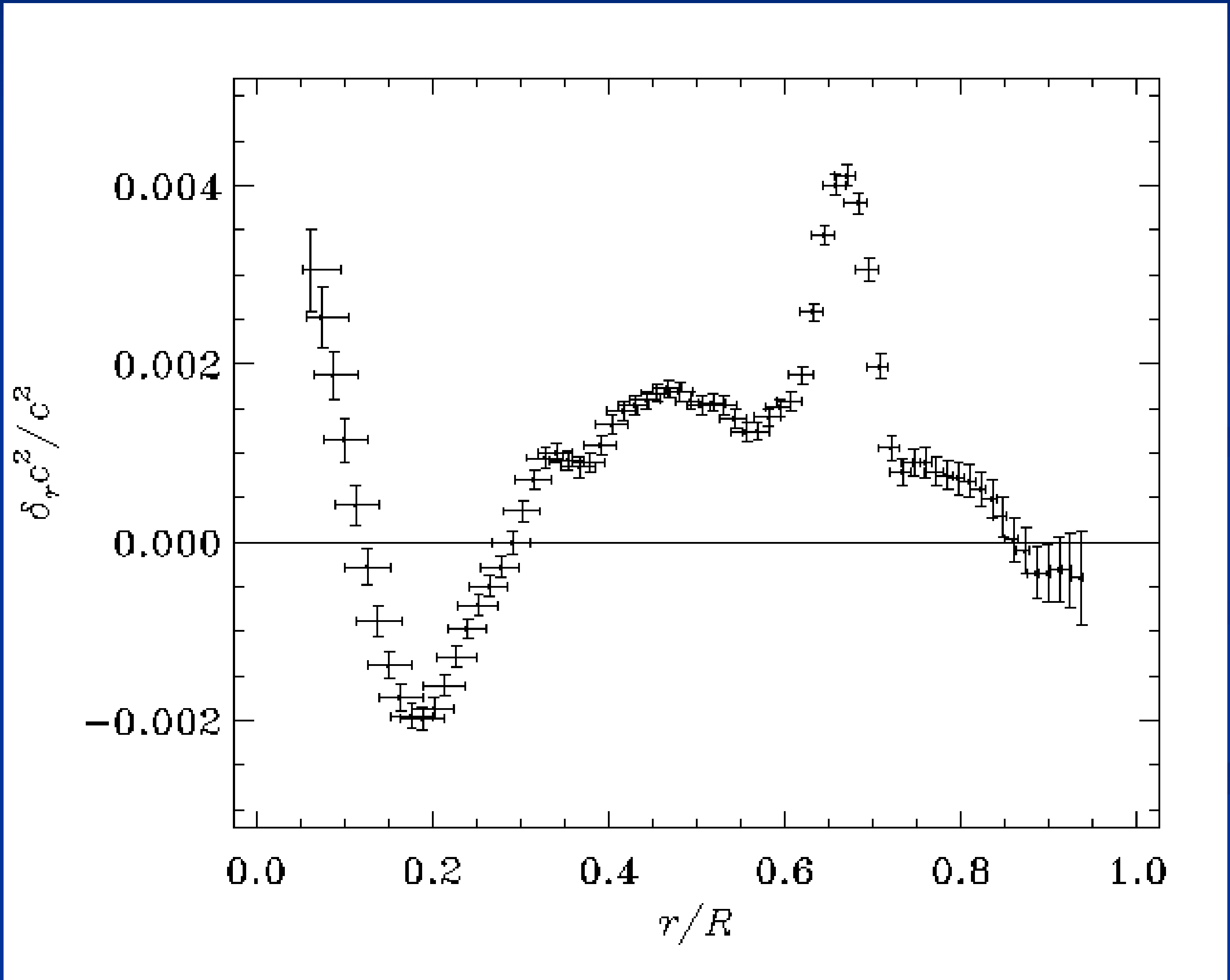
Solar structure



- Sound speed difference from best solar model.
- Maximum deviation is 2% (red is faster, blue is slower than model).
- Small surface variations on 11-yr time scale.

The solar internal sound speed

Sun - Model S



Revision of solar surface abundances

Asplund et al. (2004; A&A 417, 751)

$$N(\mathrm{O})/N(\mathrm{H})|_{\mathrm{old}} = 8.5\times10^{-4}\,, \qquad Z_{\mathrm{old}} = 0.0193$$

$$N(\mathrm{O})/N(\mathrm{H})|_{\mathrm{new}} = 4.6\times10^{-4}\,, \qquad Z_{\mathrm{new}} = 0.0122$$

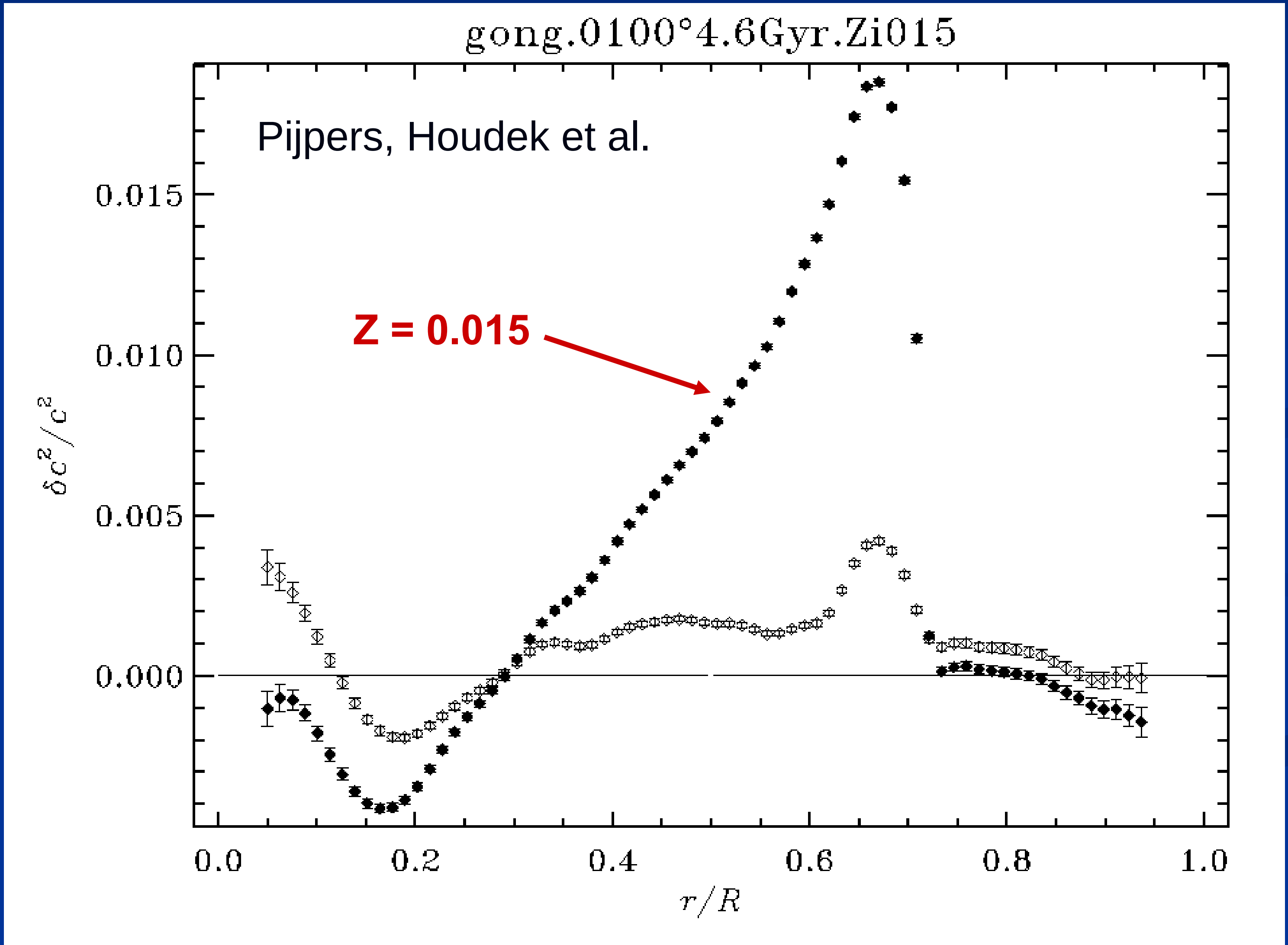
Improvements:

•Non-LTE analysis

•3D atmosphere models

Consistent abundance determinations for a variety of indicators

Revision of solar surface abundances



HELIUM ABUNDANCE IN CZ

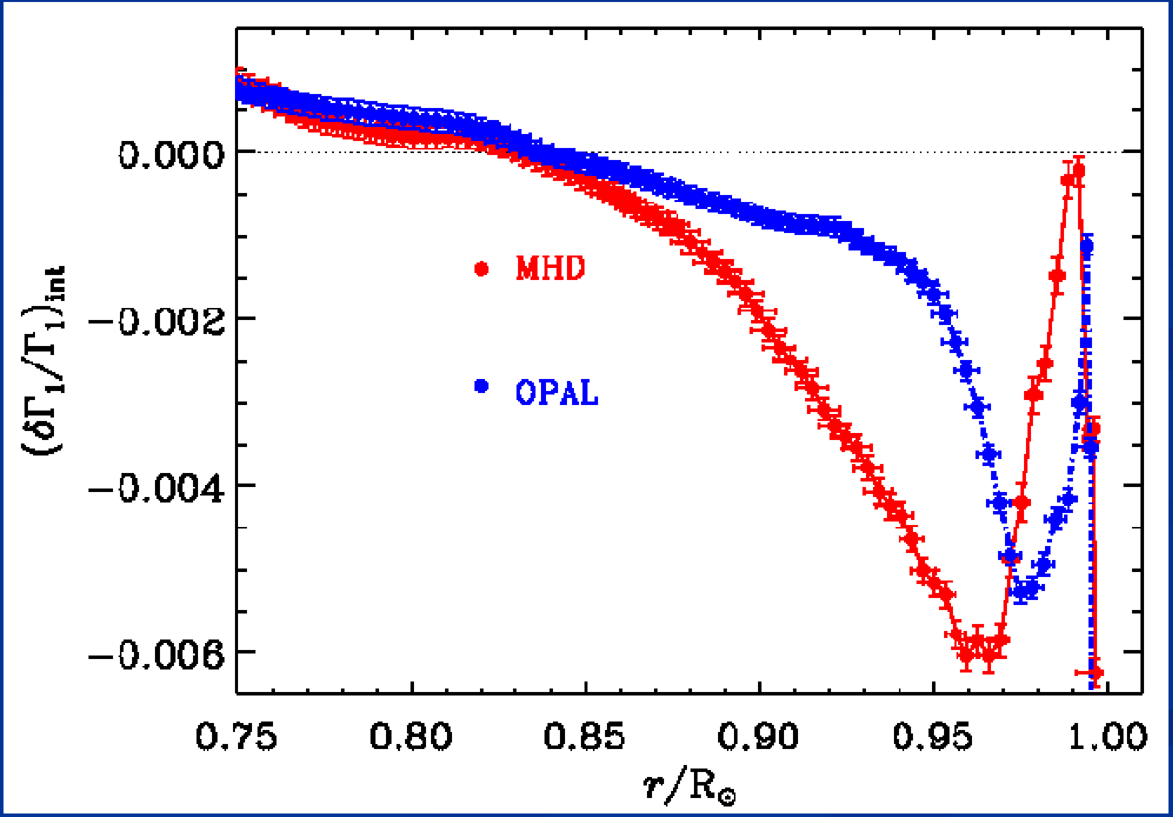
- ***Y* cannot be directly obtained by spectroscopy**
- ***Y* by solar Models matching $L_{\odot}$ $Y \approx$ 0.27-0.28**

Now: Helioseismic inversions

REFERENCE	DATA	Y MHD	Y OPAL
Basu & Antia (1995)	HLH $100 \le l \le 1200$	0.2456±0.007	0.2489±0.0028
Kosovichev (1996)	BBSO $4 \le l \le 140$	0.232±0.006	0.248±0.006
Richard et al. (1998)	MDI $0 \le l \le 140$	0.242±0.002	0.248±0.002
Basu (1998)	MDI $l \le 194$	0.2524±0.0001	0.2488±0.0001
Di Mauro et al. (2002)	MDI $l \le 1000$	0.2457±0.0005	0.2539±0.0005

Equation of state near the surface

Difference between SUN (MDI/SOHO) and Model S (w/ two different equation of states)

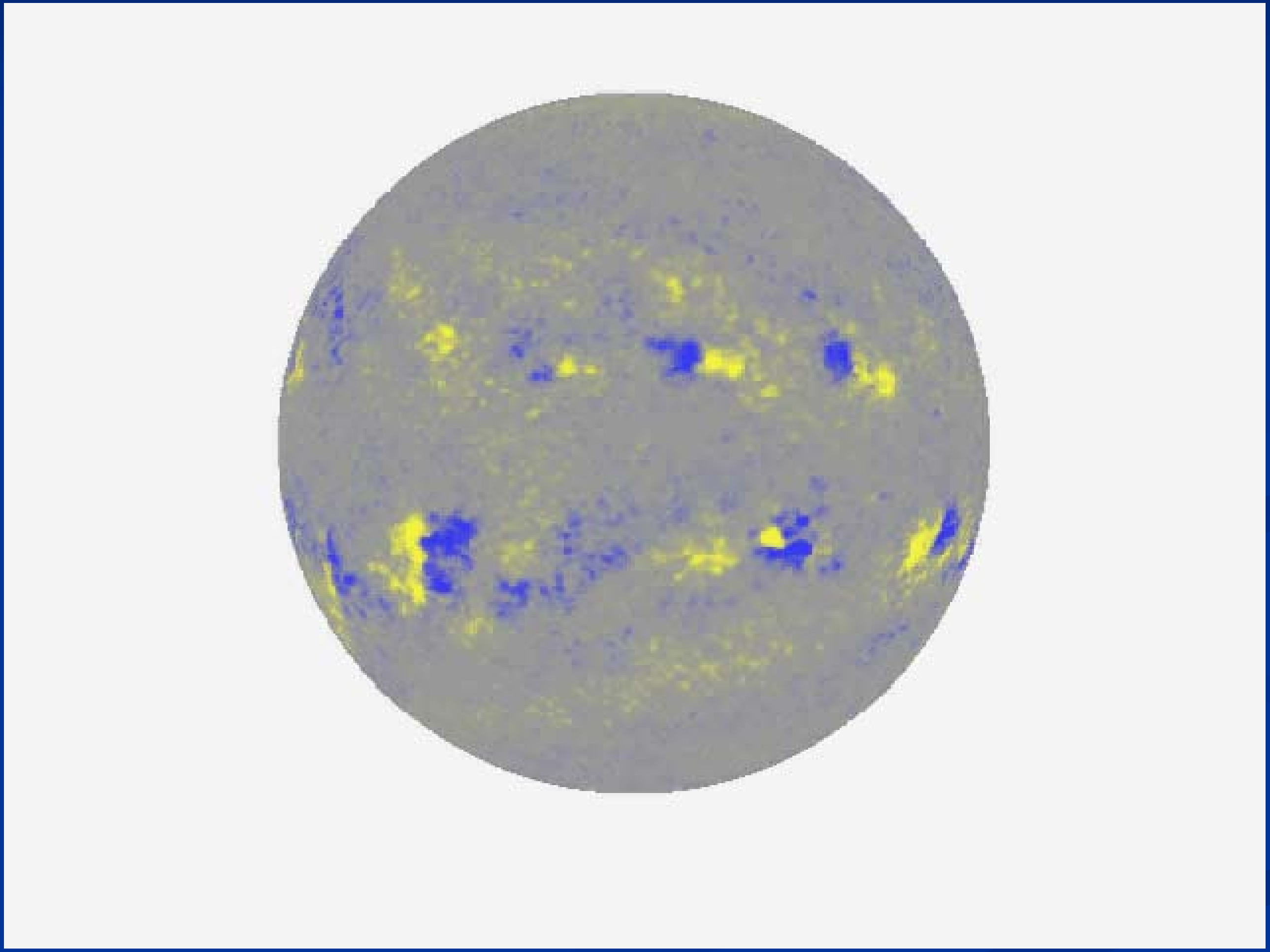


MP Di Mauro

Beyond the 1D Sun

- Rotation
- Asphericities
- Magnetic field
- Time dependence → solar cycle

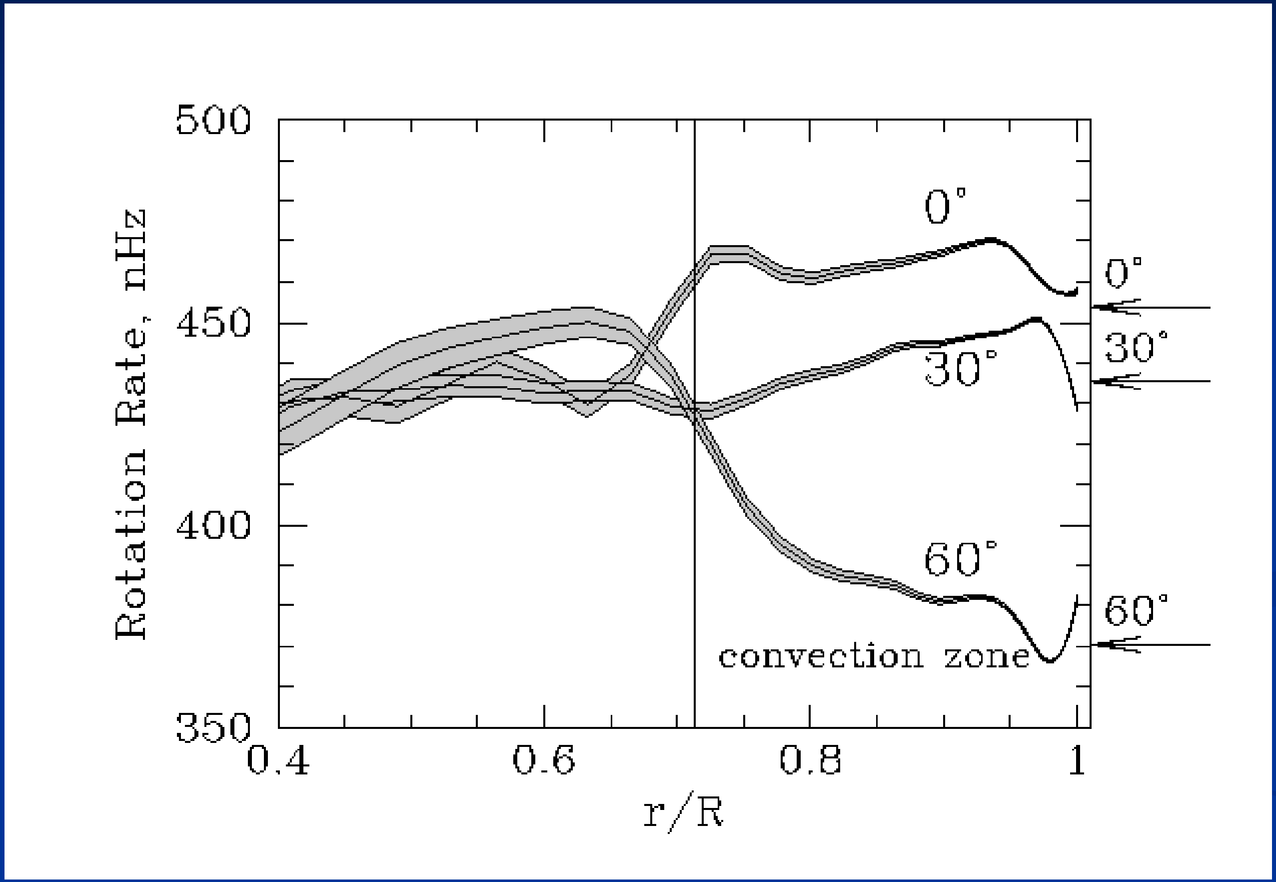
The eleven-year solar cycle

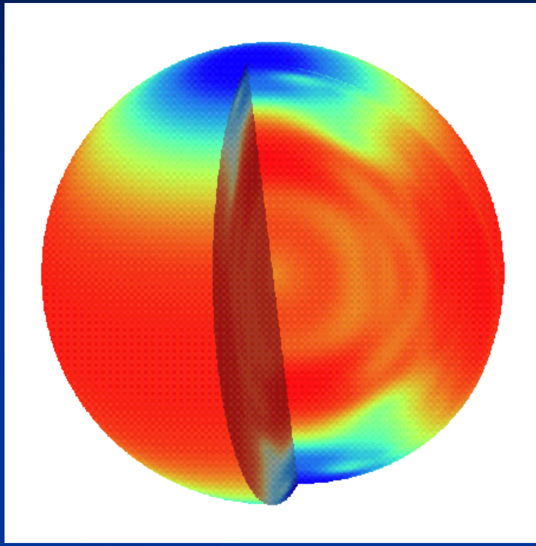


What is the mechanism of the solar cycle?

- Dynamo theory: motions generate magnetic field
- Rotation, meridional circulation
- convective flows
- Internal magnetic field
- Active regions: structure, emergence, evolution
- Drivers of space weather

Internal rotation

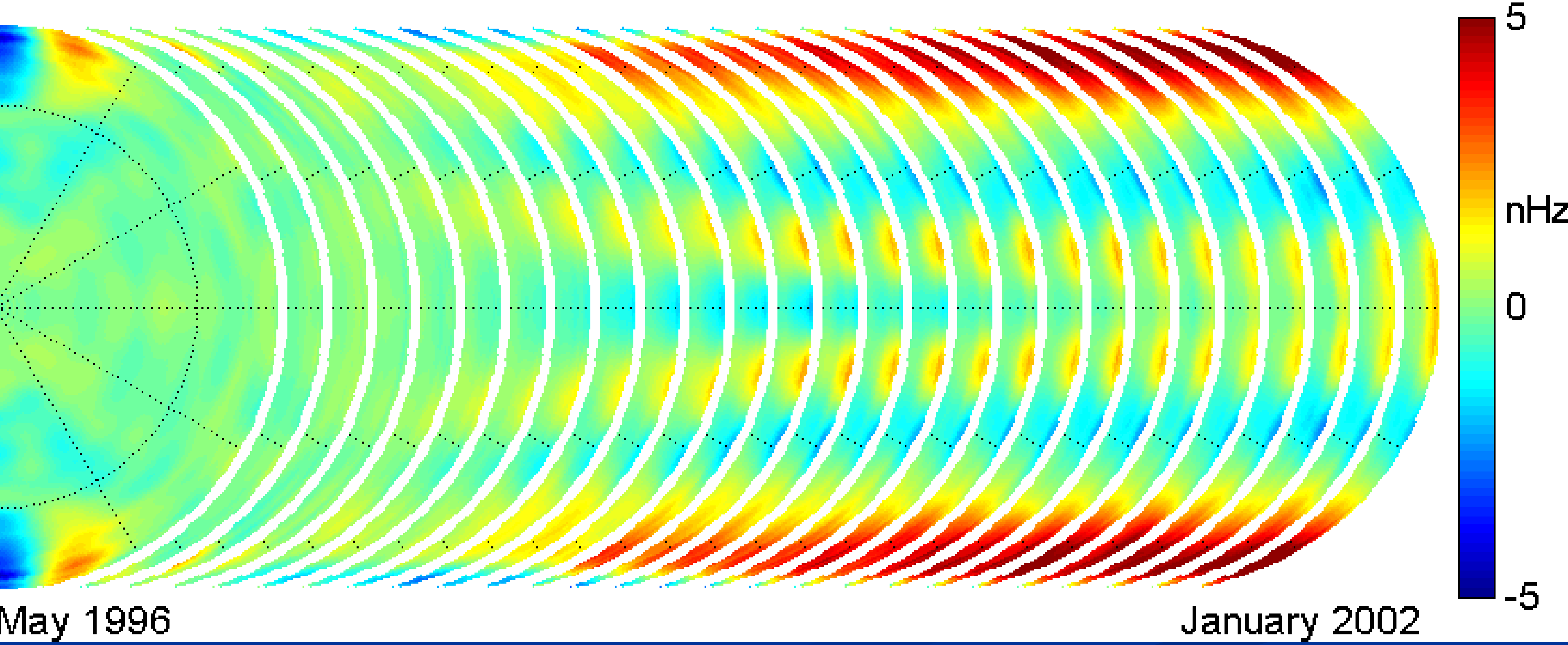




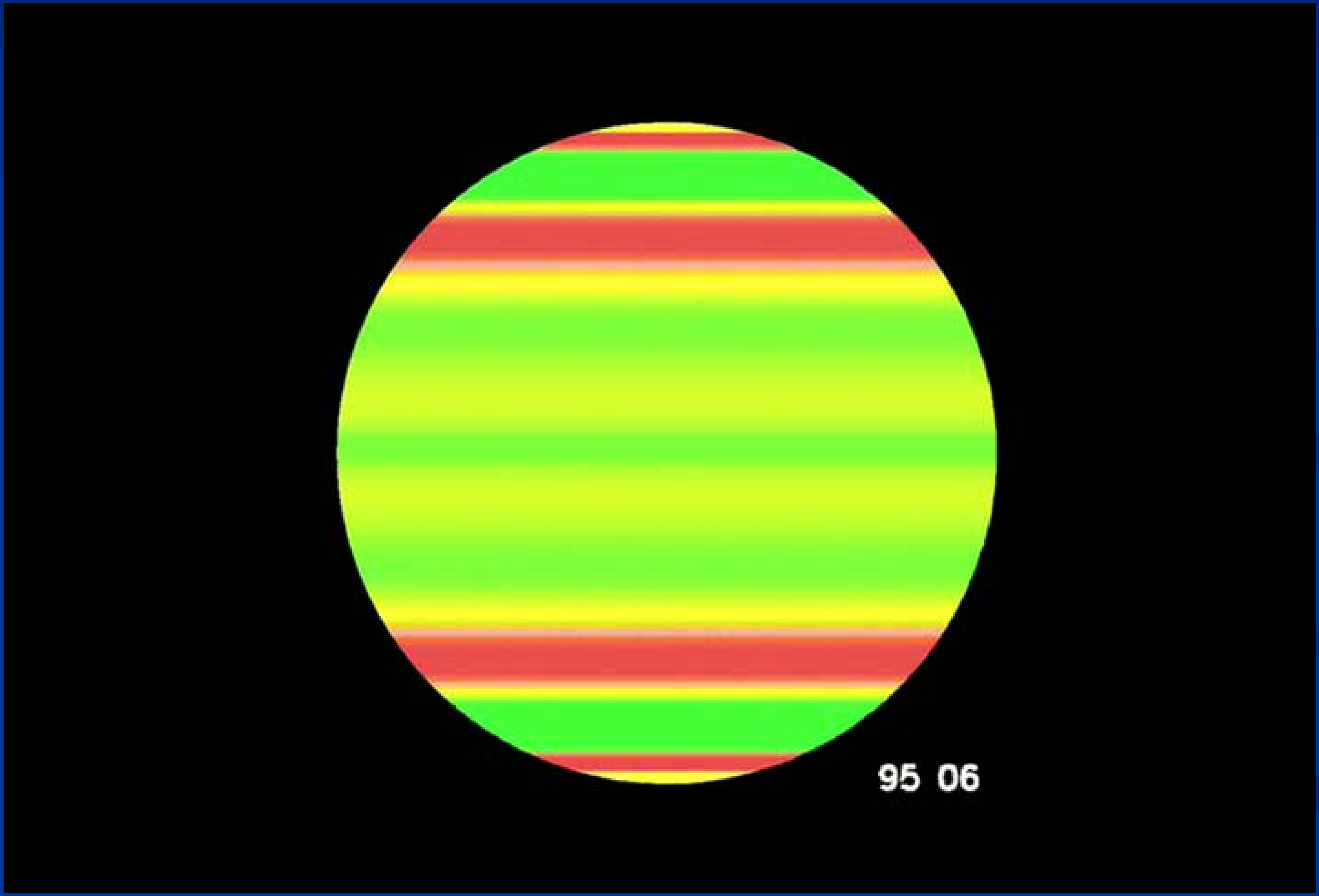
red is faster (26 days)
blue is slower (35 days).

- Differential rotation in the convective envelope.
- Uniform rotation in the radiative interior.
- Near-surface shear layer.

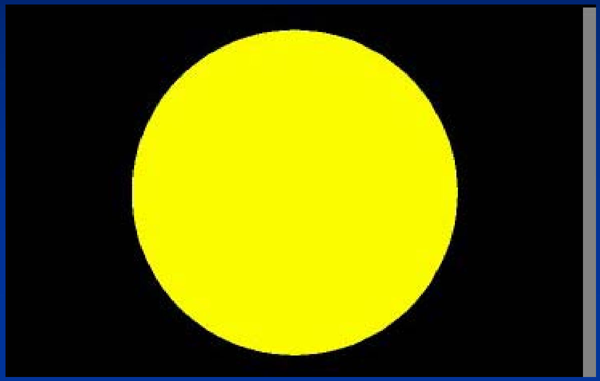
zonal flows

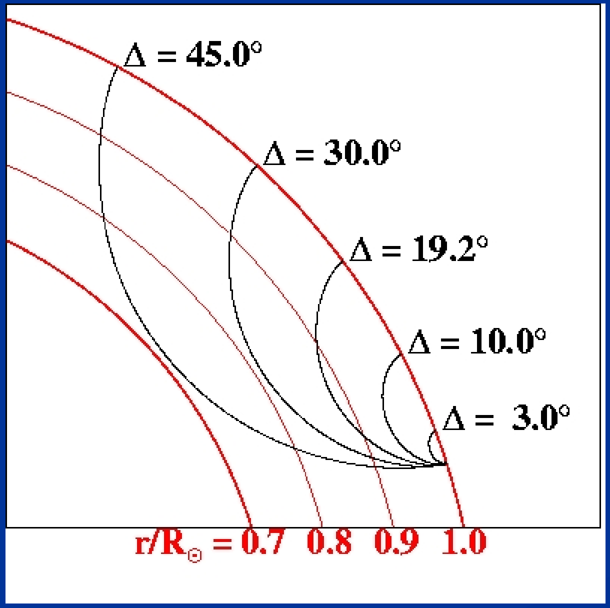


The pulse of the solar dynamo?



Local helioseismology

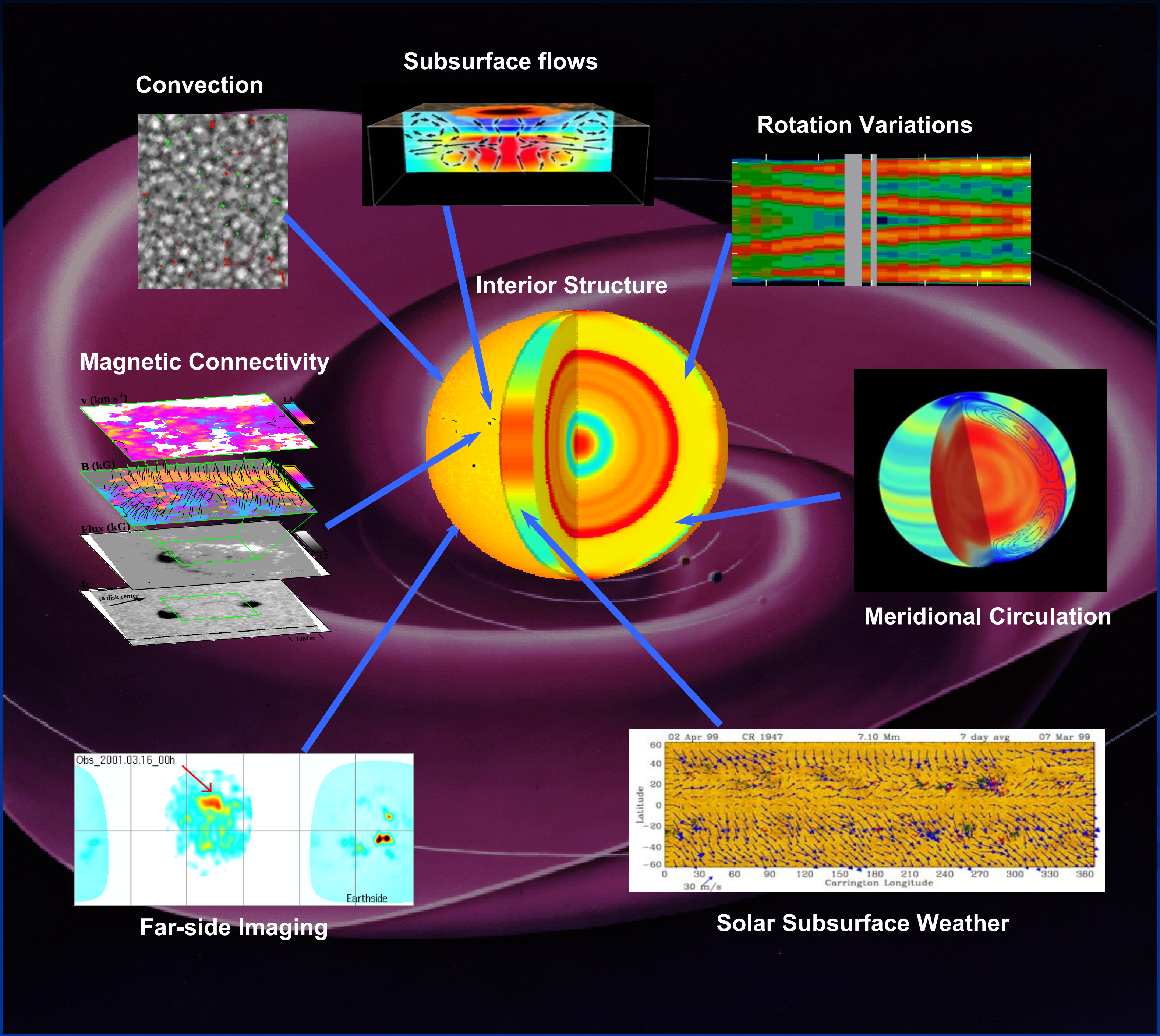




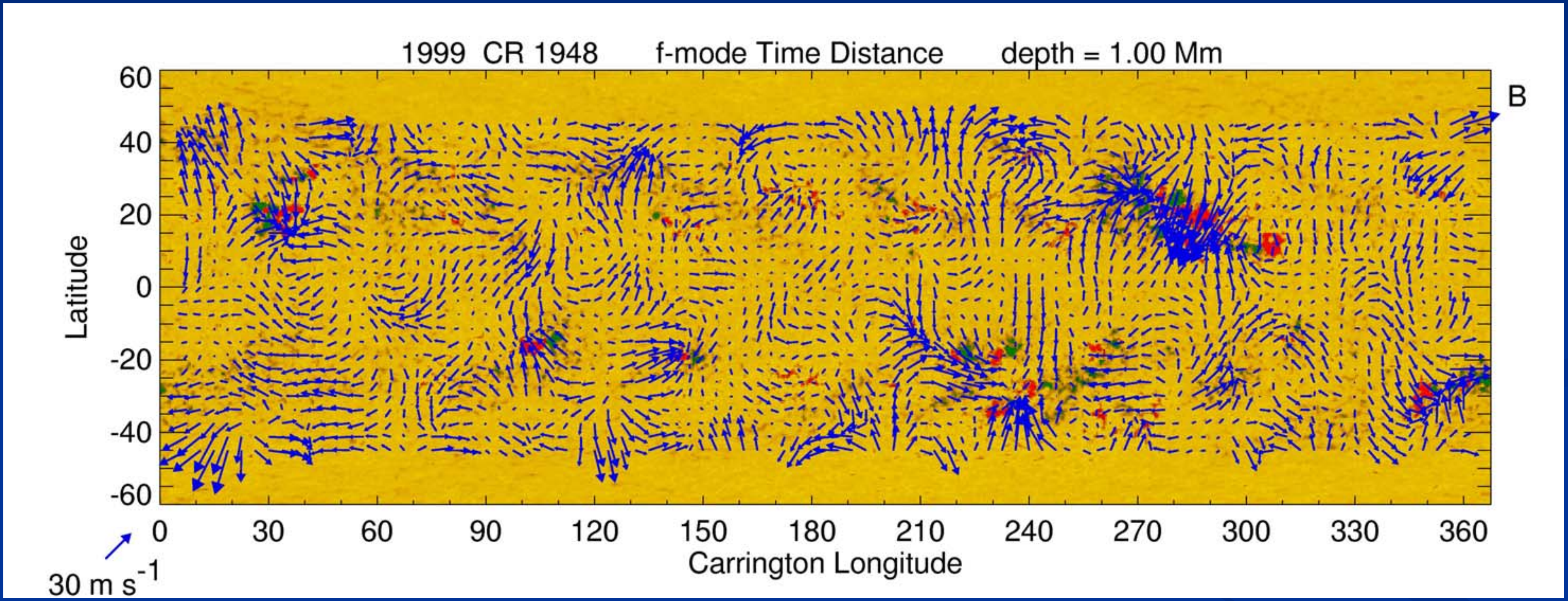
- Measure travel times of wavepackets travelling between any two points A and B on the solar surface.

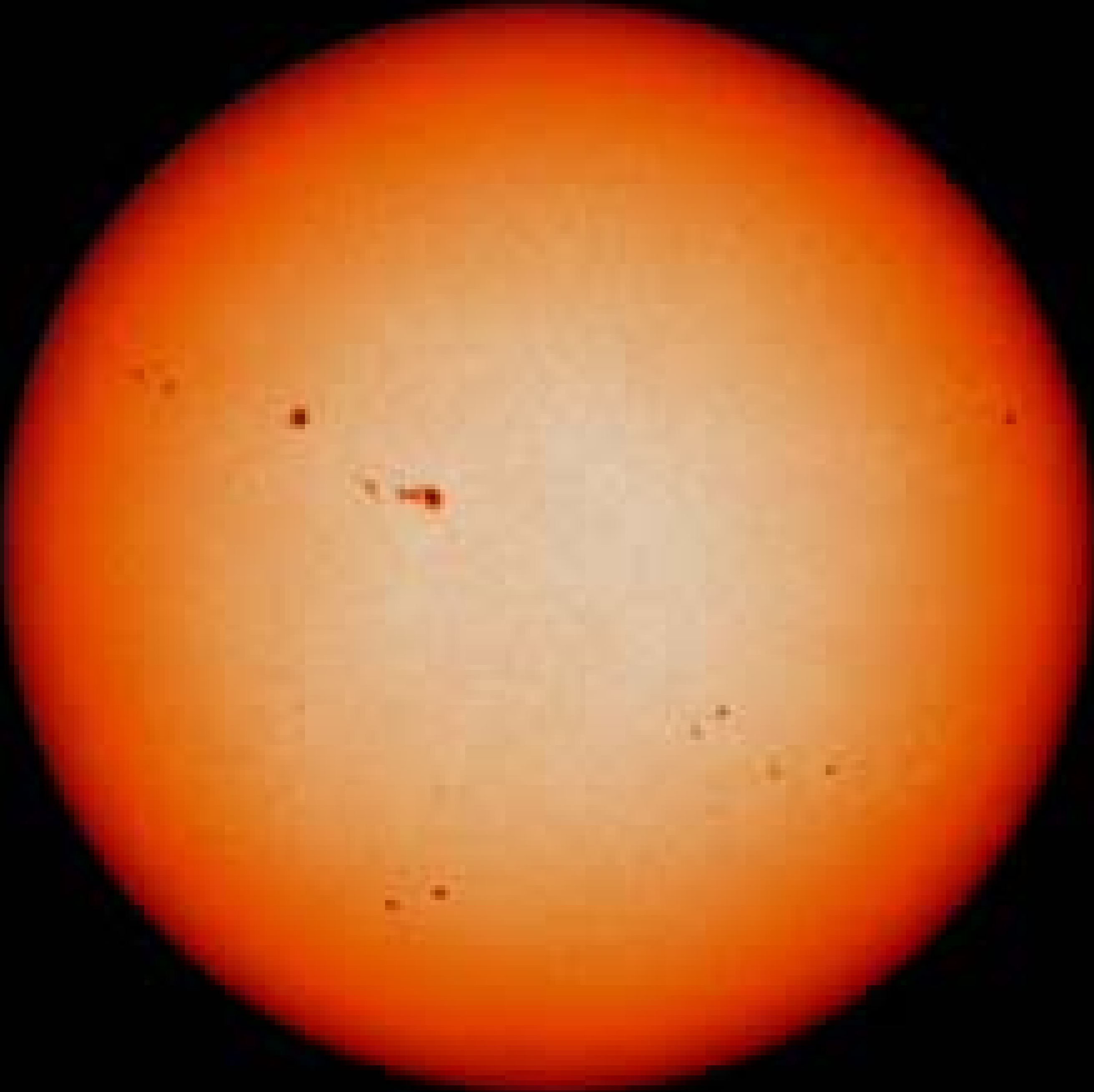
- Differences between the A→B and B→A directions arise from bulk motion along the path.

- 3-D maps of flows and temperature beneath the surface.


Subsurface flows
Convection
Rotation Variations
Interior Structure
Magnetic Connectivity
v (km s-1)
B (kG)
Flux (kG)
Ic
to disk center
10Mm
Meridional Circulation
Obs_2001.03.16_00h
Earthside
Far-side Imaging
02 Apr 99
CR 1947
7.10 Mm
7 day avg
07 Mar 99
Latitude
Carrington Longitude
30 m/s
Solar Subsurface Weather

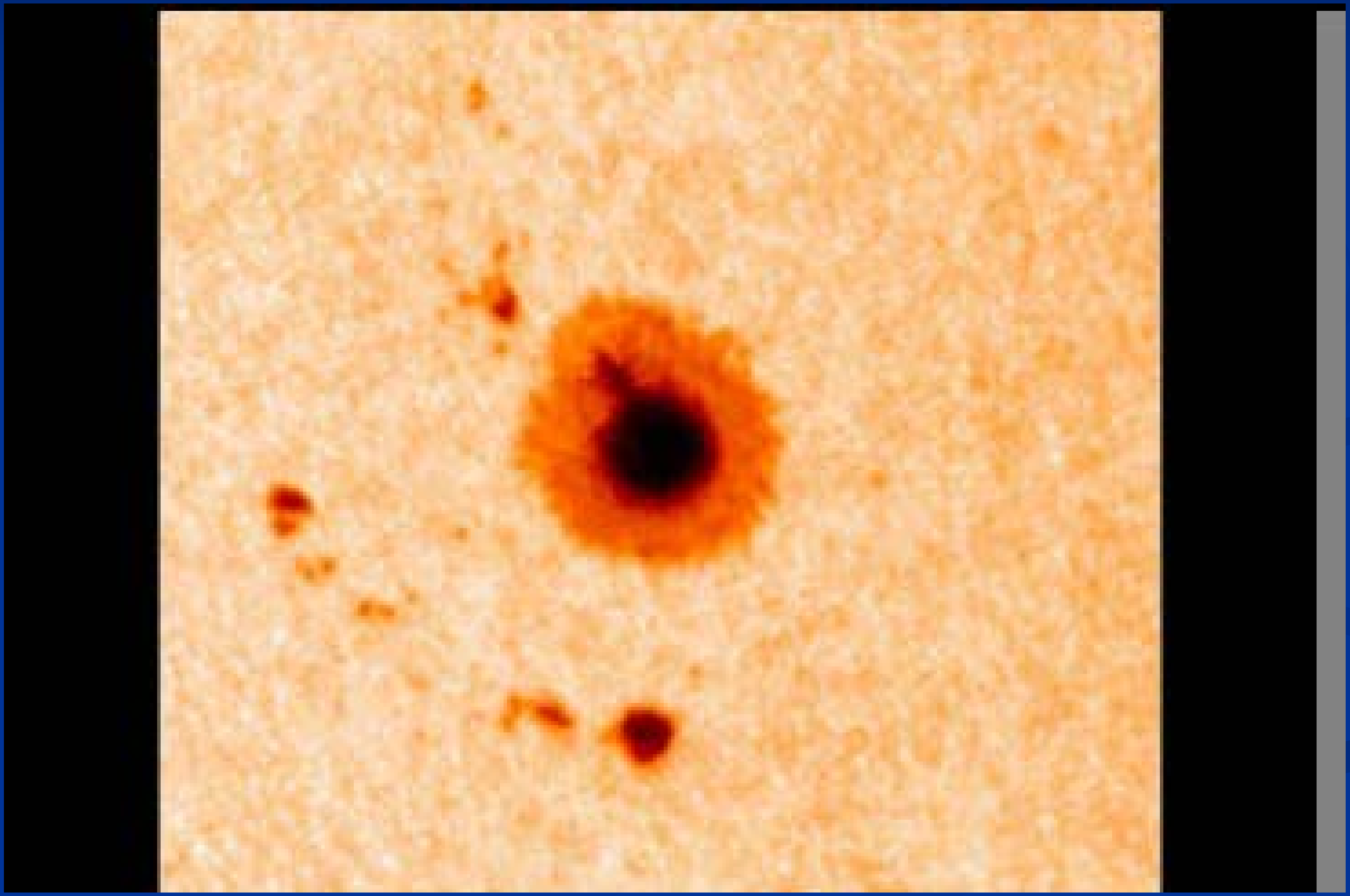
Solar subsurface 'weather'



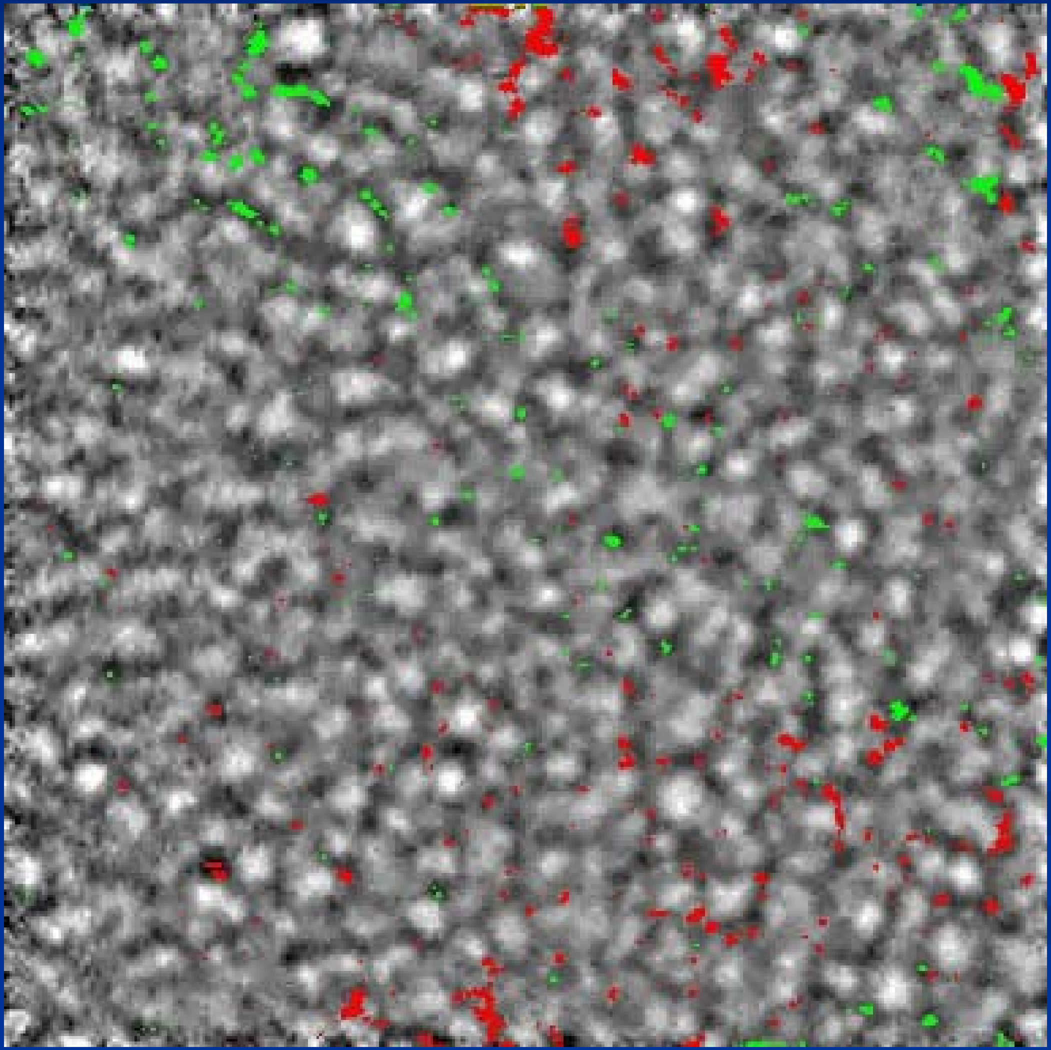


Sunspot internal structure

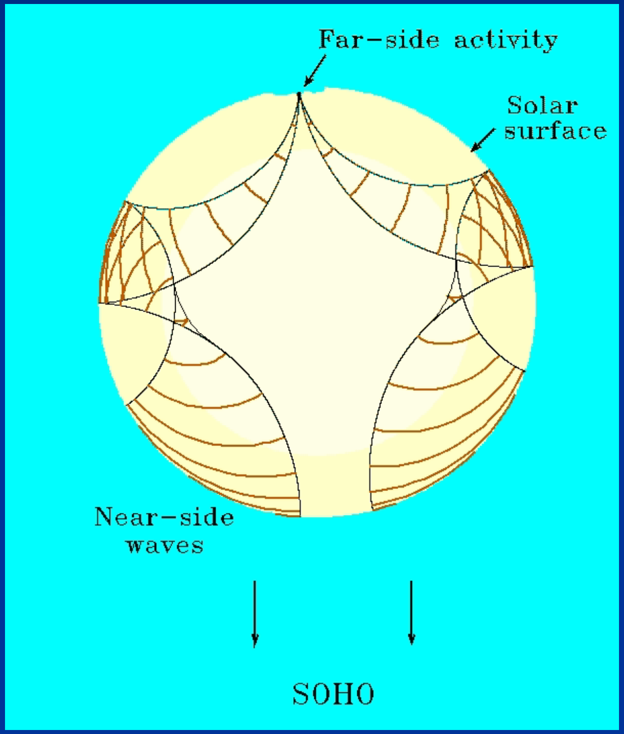
Red regions have higher wave speed, blue slower.



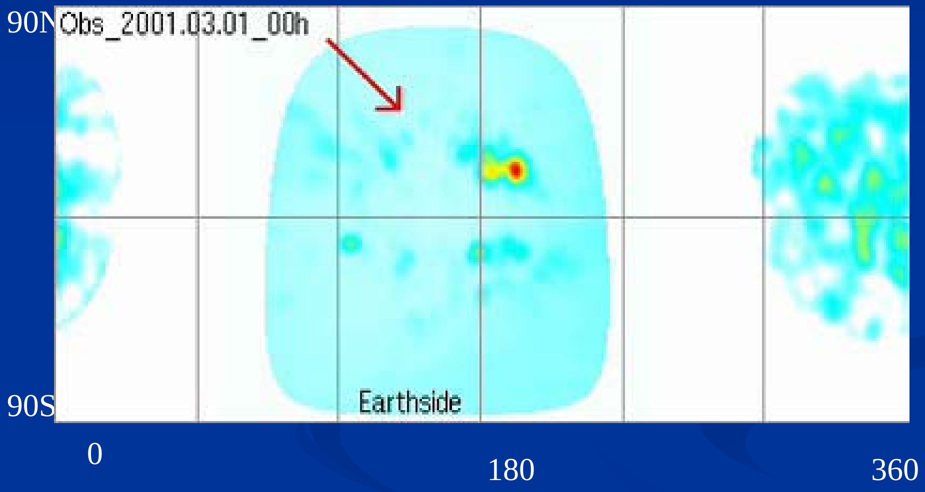
Supergranulation and network evolution



Far-side imaging

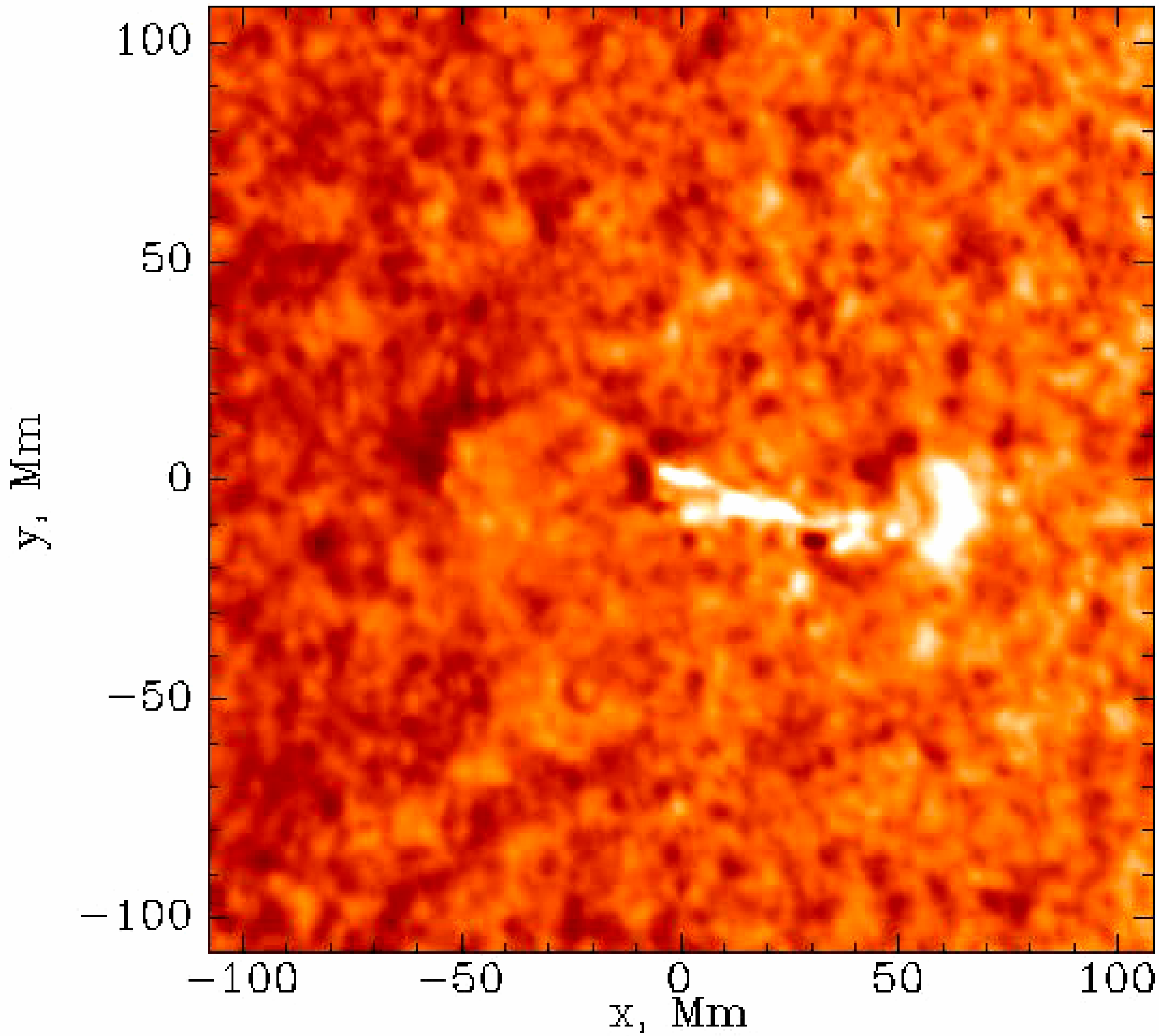


Map of Sun's large magnetic regions



Sun rotates in 27 days so images will move to left since map grid is fixed

Solar tsunami (flare induced)



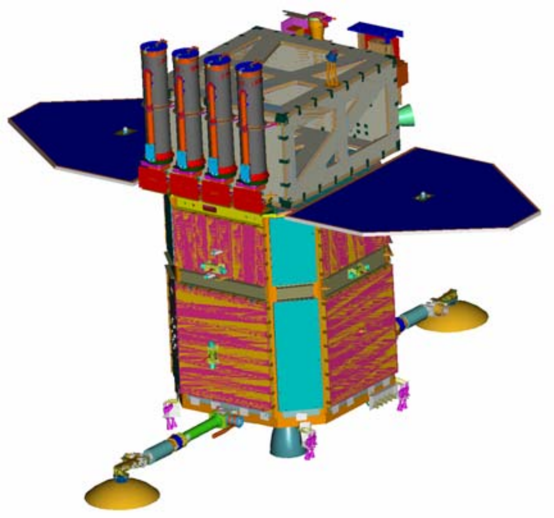
Current topics of research

- Detect magnetic field in the solar interior, i.e. decouple magnetic from other types of perturbations
- Emergence and evolution of active regions from limb to limb
- Probe deeper layers in the convection zone

- Improve models
  - diffusion
  - non-adiabatic effects
  - convection
  - equation of state

Missions ahead

Solar Dynamics Observatory (LWS NASA)



Launch Date: April 2008

Mission Duration: 5 years, 10 yr of expendables

Orbit: 36000 km, circular, 28.5º geo. synch. Inclined

1’’ resolution, full disk, high duty cycle.

Ideal for local helioseismology.

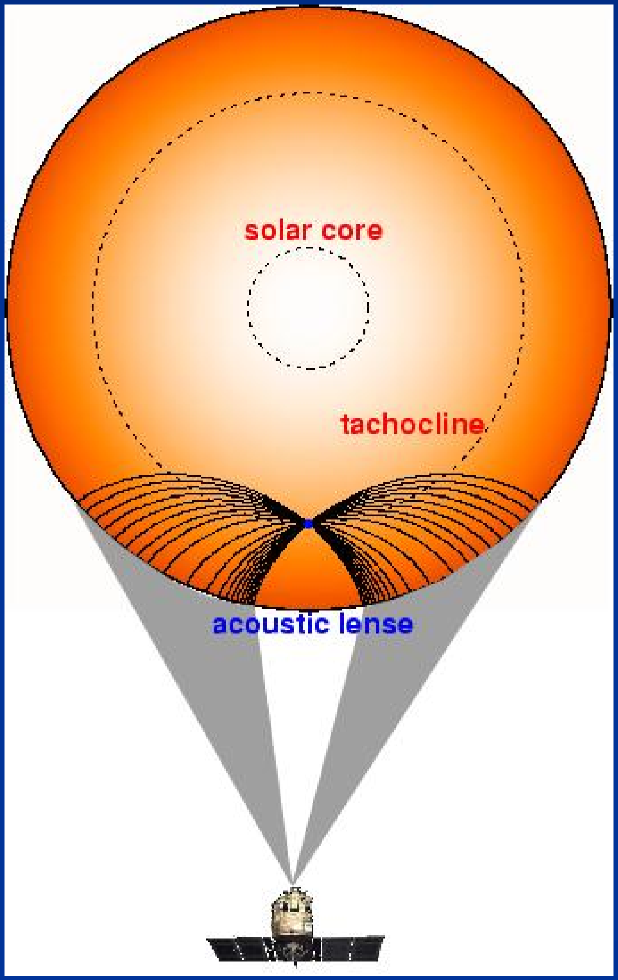
Solar Orbiter (ESA)

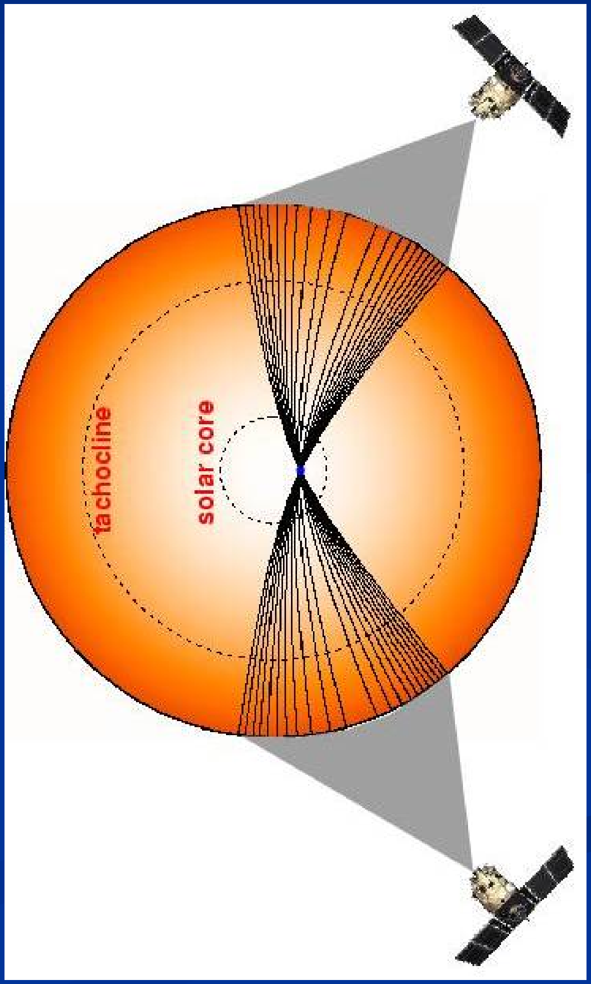
Launch Date: 2015

Mission Duration: 5 (nominal) to 7 years (ext.)

Orbit: Assisted by Venus swing-bys, the spacecraft's 150-day orbit will evolve gradually over the mission lifetime from an inclination of about 12 to 35 degrees to the solar equator.

Stereoscopic observations: Solar Orbiter, Sentinel, Safari (?)

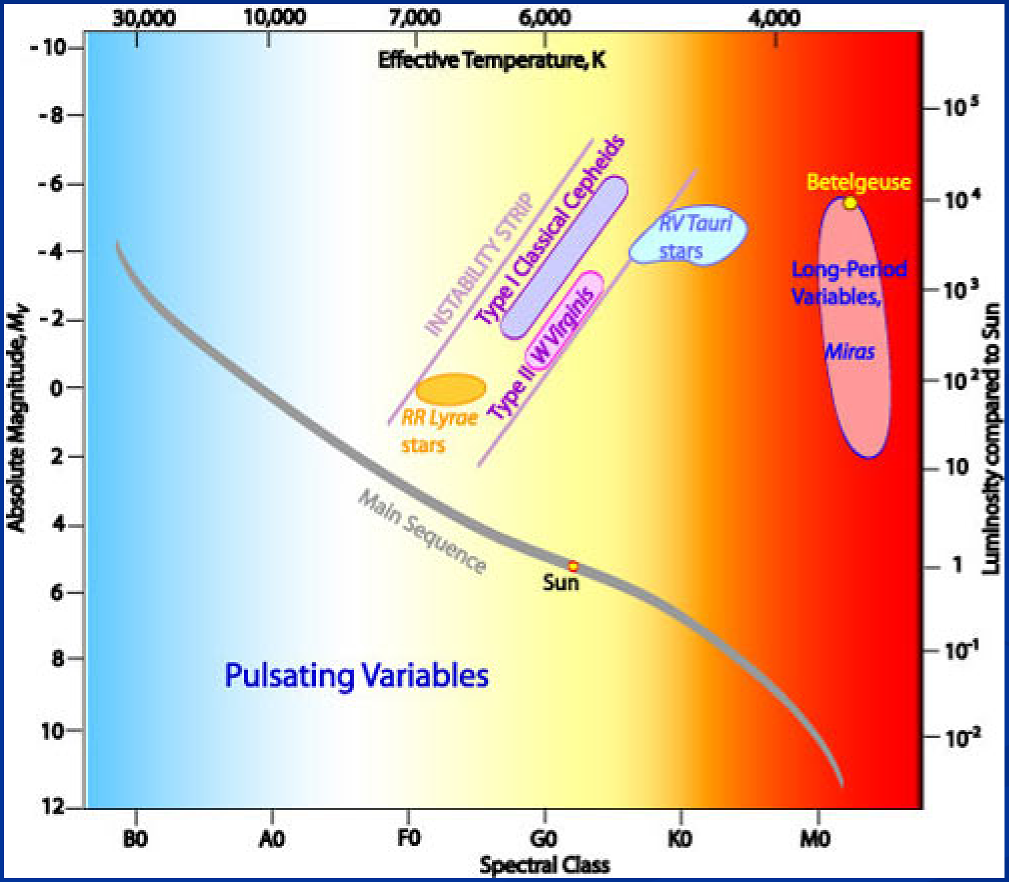




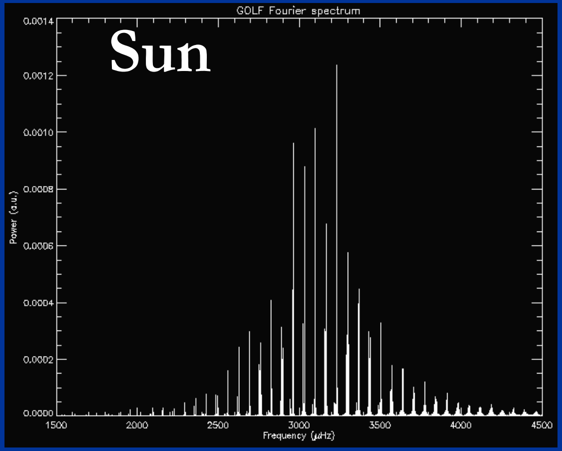
Asteroseismology

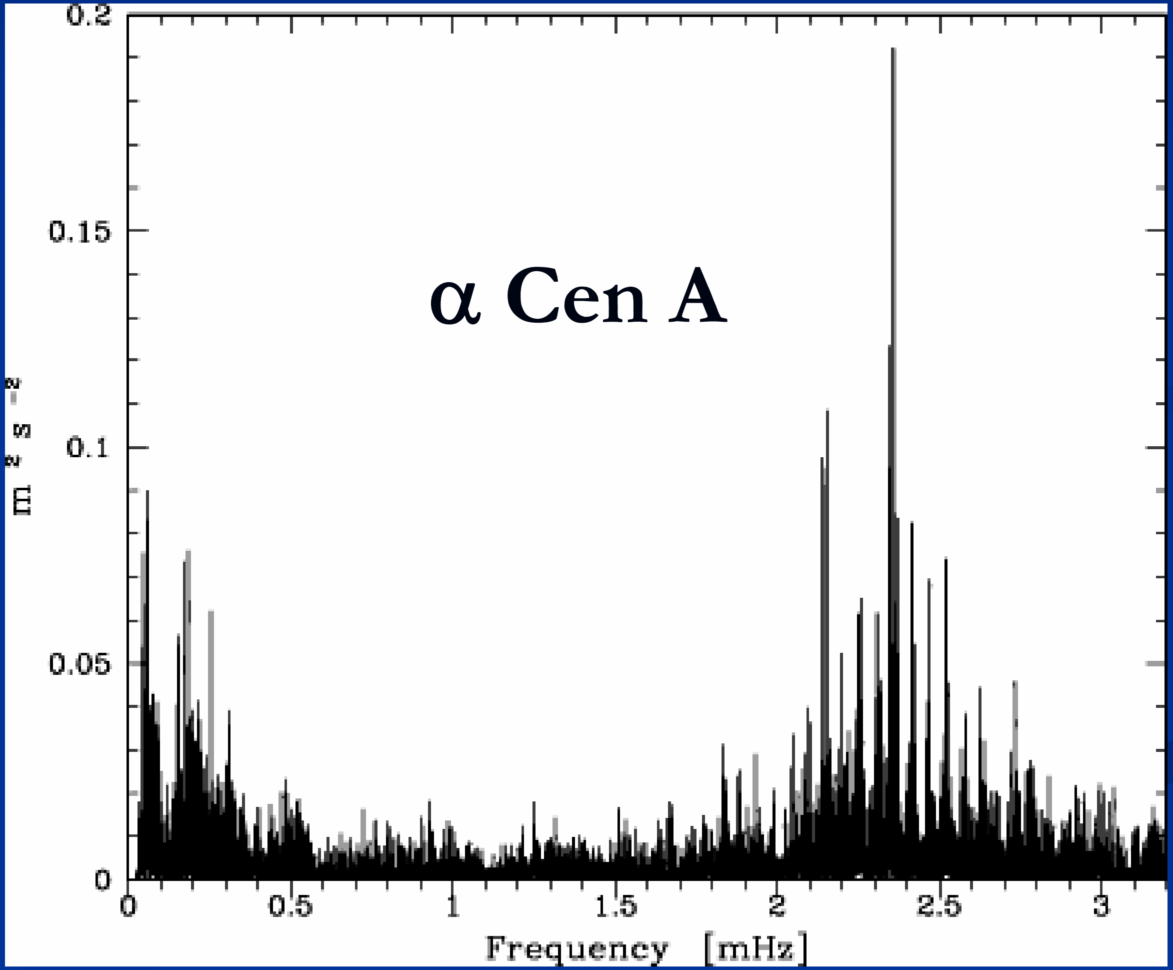
- Mass, radius, chemical composition, and age of isolated stars
- Independent test of theory of stellar structure and evolution
- Internal stellar rotation
- Constraints on dynamo theories
- Convection
- Implications for planetary system formation

All stars are suspected to pulsate



Solar-like oscillations





Asteroseismology projects

- Ground
- MOST (Canada)
- COROT (ESA, 2006)
- Kepler (NASA, 2006)
- Eddington? (ESA)
- Stellar Imager?

Summary

- Helioseismology provides important tests of the standard model of solar structure and evolution
- Helioseismology will help understand the origin of solar activity.
- In particular, techniques of local helioseismology in combination with high-resolution space data will be key in revealing the interactions between flows and magnetic fields in the interior.
- Asteroseismology will be become an extremely valuable tool to study stellar activity and evolution.
- Important upcoming mission: the Solar Dynamics Observatory