# The crucial role of the leptocline in improving predictions of solar activity.

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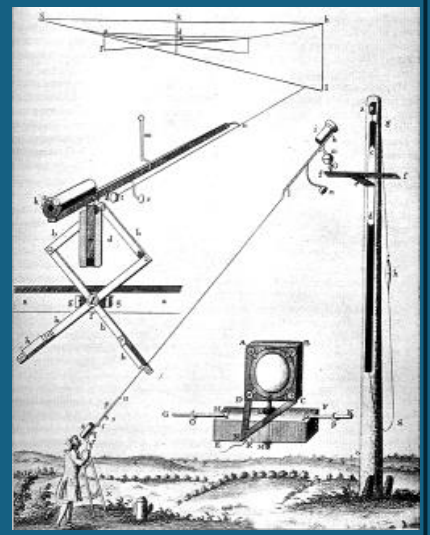
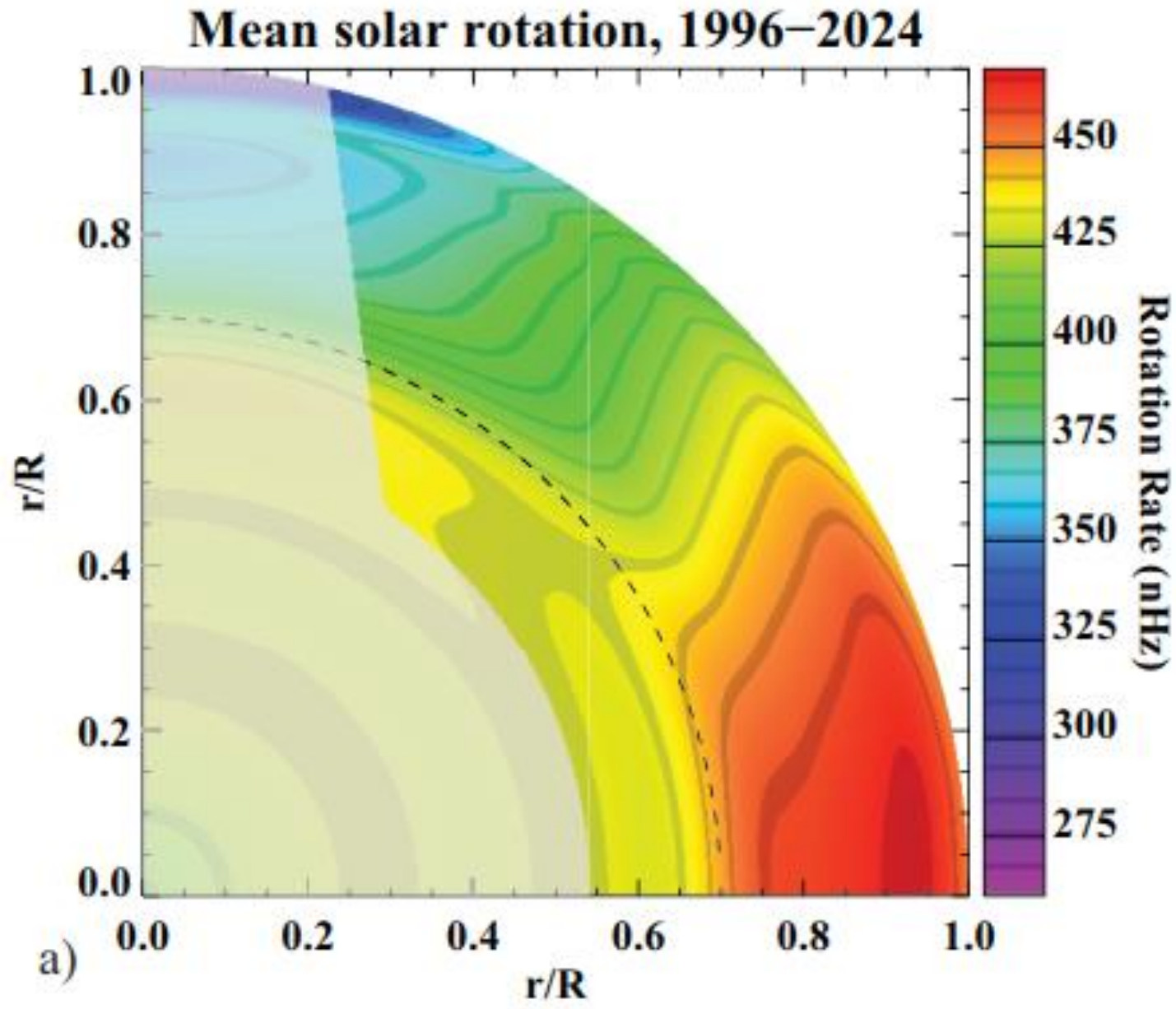
**A. Kilcik, (Akdeniz University, Antalya T)**



**Sun and Space Weather, Antalya, T, 2026**

# Last results from SDO, HMI



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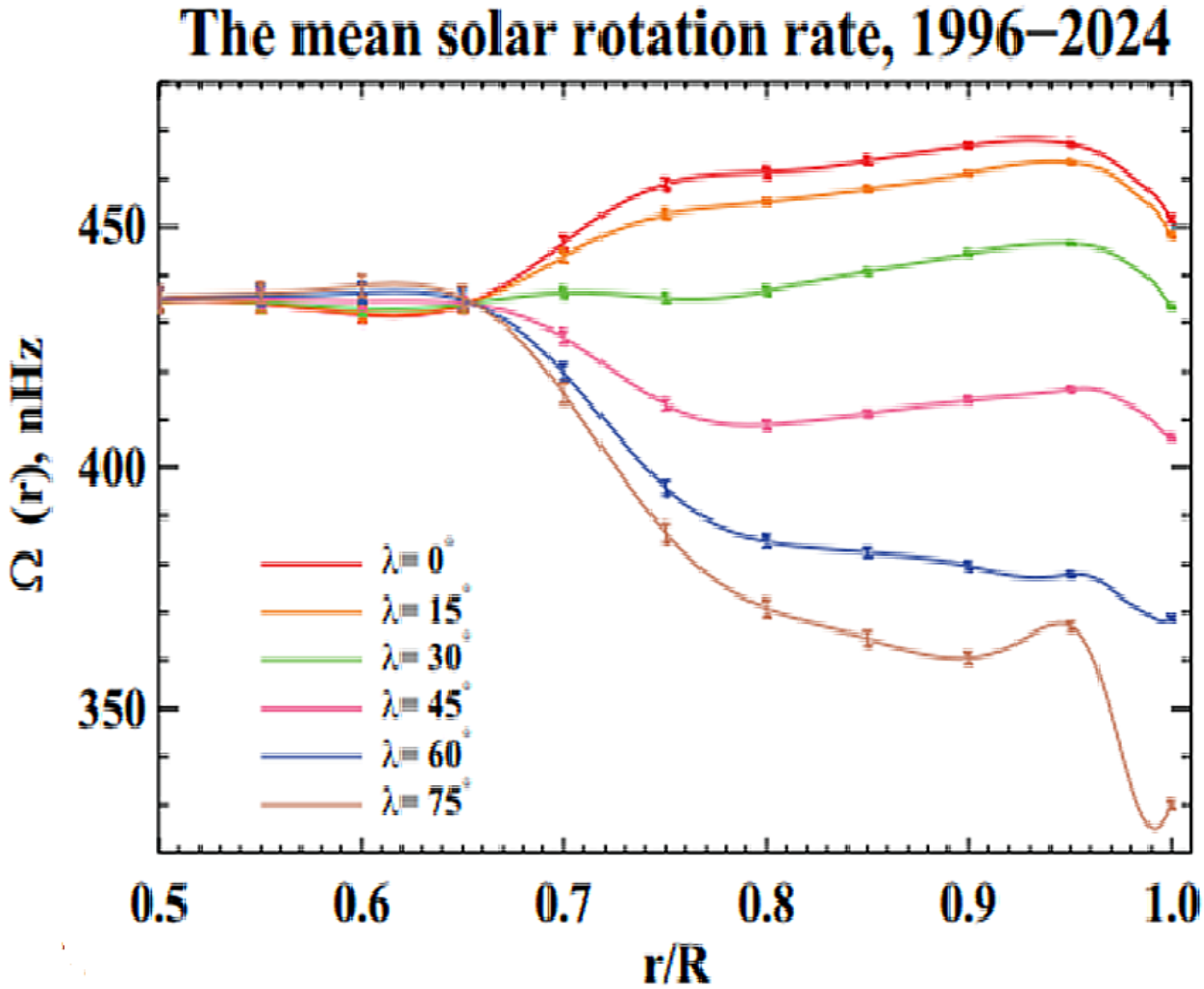

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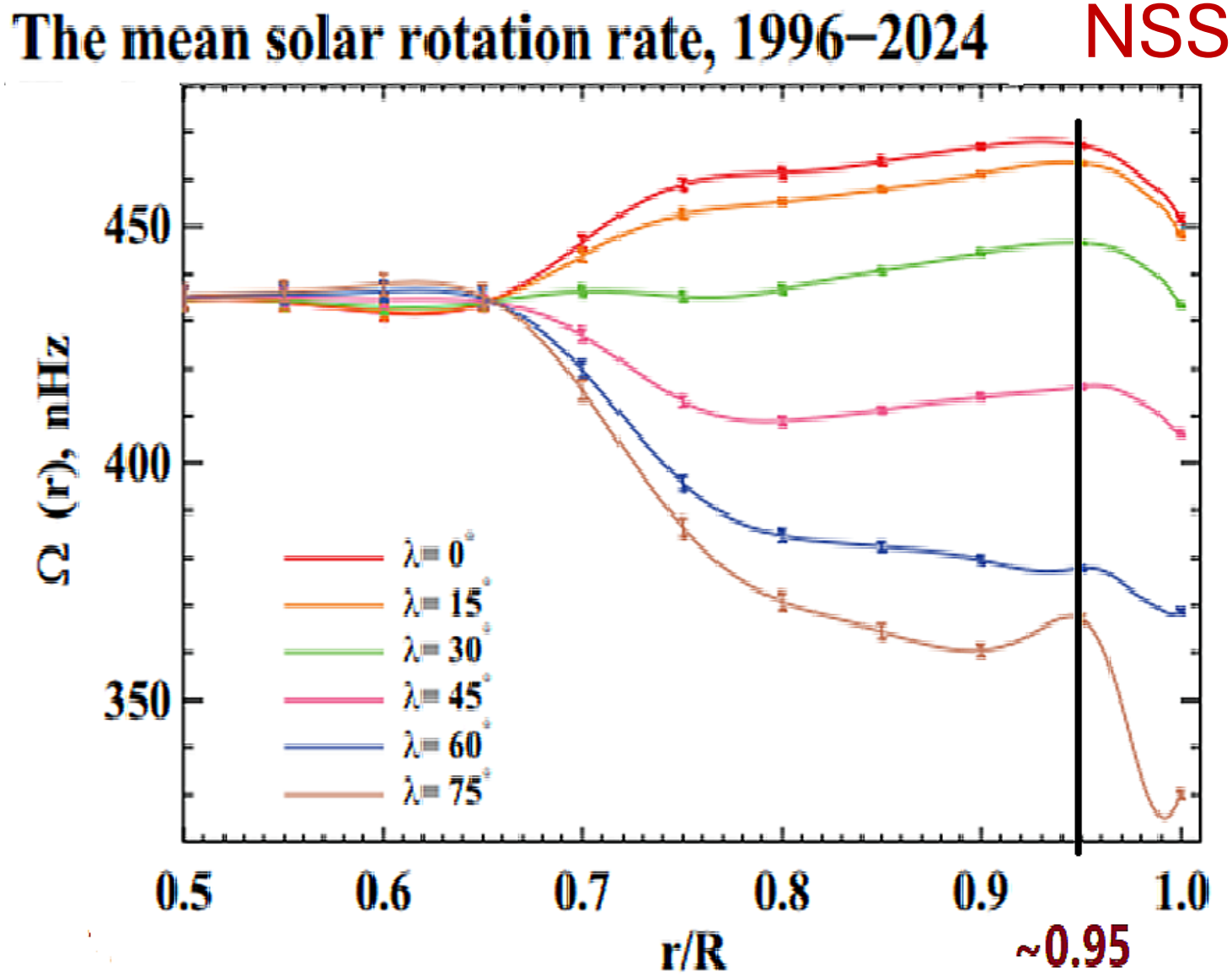
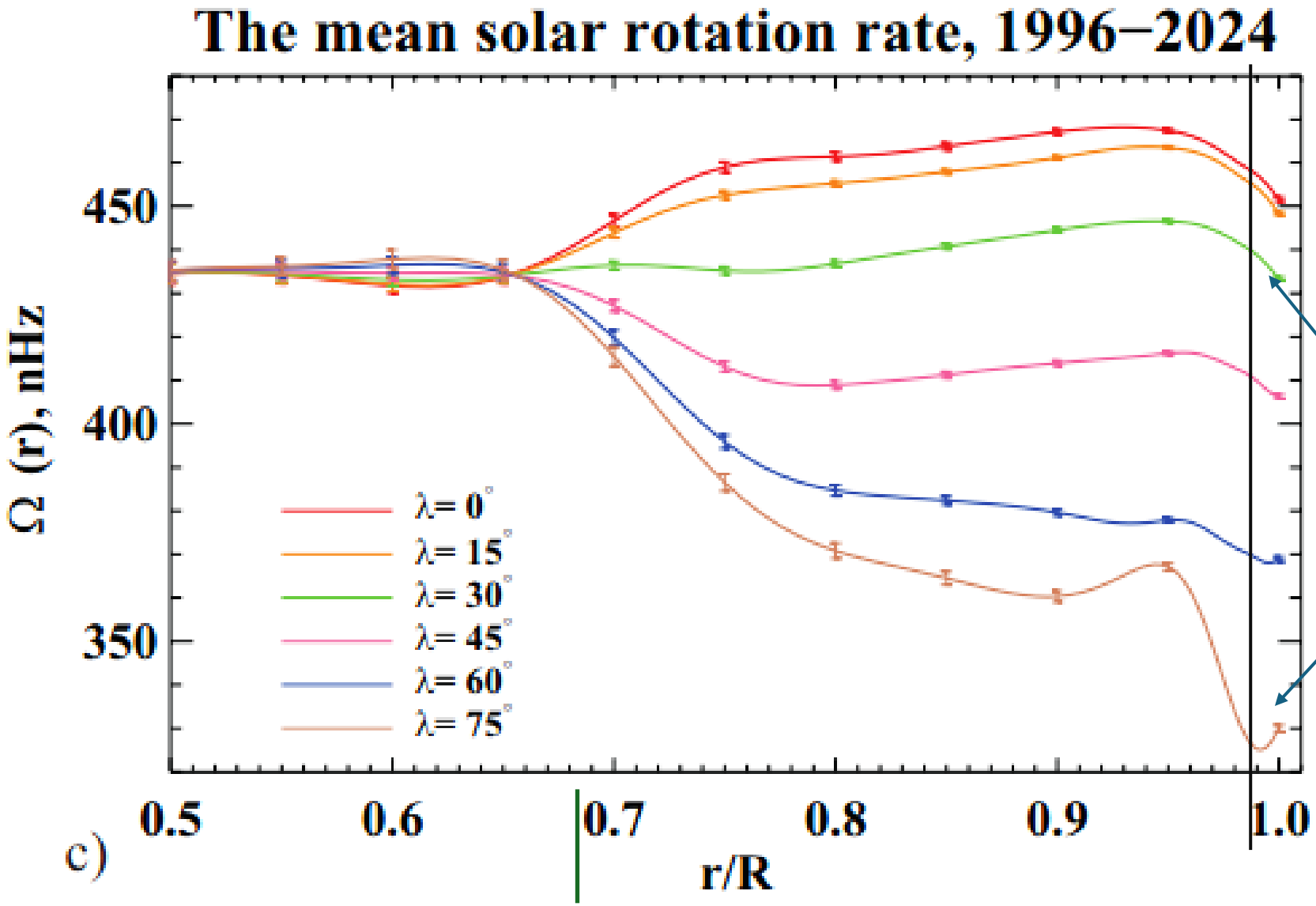


# Last results from SDO, HMI

NSSL




Leptocline

Tachocline

**~0.988 or ~ -8 Mm depth**

**The tachocline:** Spiegel & Zahn, « The solar tachocline », Astronomy and Astrophysics, 265, 106–114, 1992

→ Seat of the differential rotation.

**The leptocline:** Godier, S. & Rozelot, J. P. « A new outlook on the 'Differential Theory of the solar Quadrupole Moment and Oblateness », Sol. Phys. 199(2), 217–229, 2001.

→ Seat of the reversal of the rotational gradient.

*Tacho-cline: from Greek tachos (ταχηω) = speed*
*Lepto-cline: from Greek leptos (λεπτω) = thin*
*Cline: from Greek klinos (κλινω) = slope (or bending)*

# Take an interest in the leptocline for (at least) 3 reasons:

***How near subsurface layer dynamics affect solar acoustic mode properties?***

***→making it difficult to match observed and modelled frequencies.***

*(see for instance Ball & Gizon, A&A, 2014, 568, A123)*

***How the structure and behavior of active regions at the surface reflect the physical conditions in the Sun's subsurface layers and the nature of the magnetic flux tubes in these regions?***

*(see for instance Bessila et al. 2026 , A&A, in press)*

***Why the solar rotation  varies both in latitude and depth ?***

*(see for instance Mandal, et al., ApJ, 2025,993,71)*

***→and, how are $R_\odot$ measurements impacted in this very specific region?***

Ongoing research increasingly delves into the role of the NSSL , and leptocline, in solar dynamos, with studies examining its potential impact

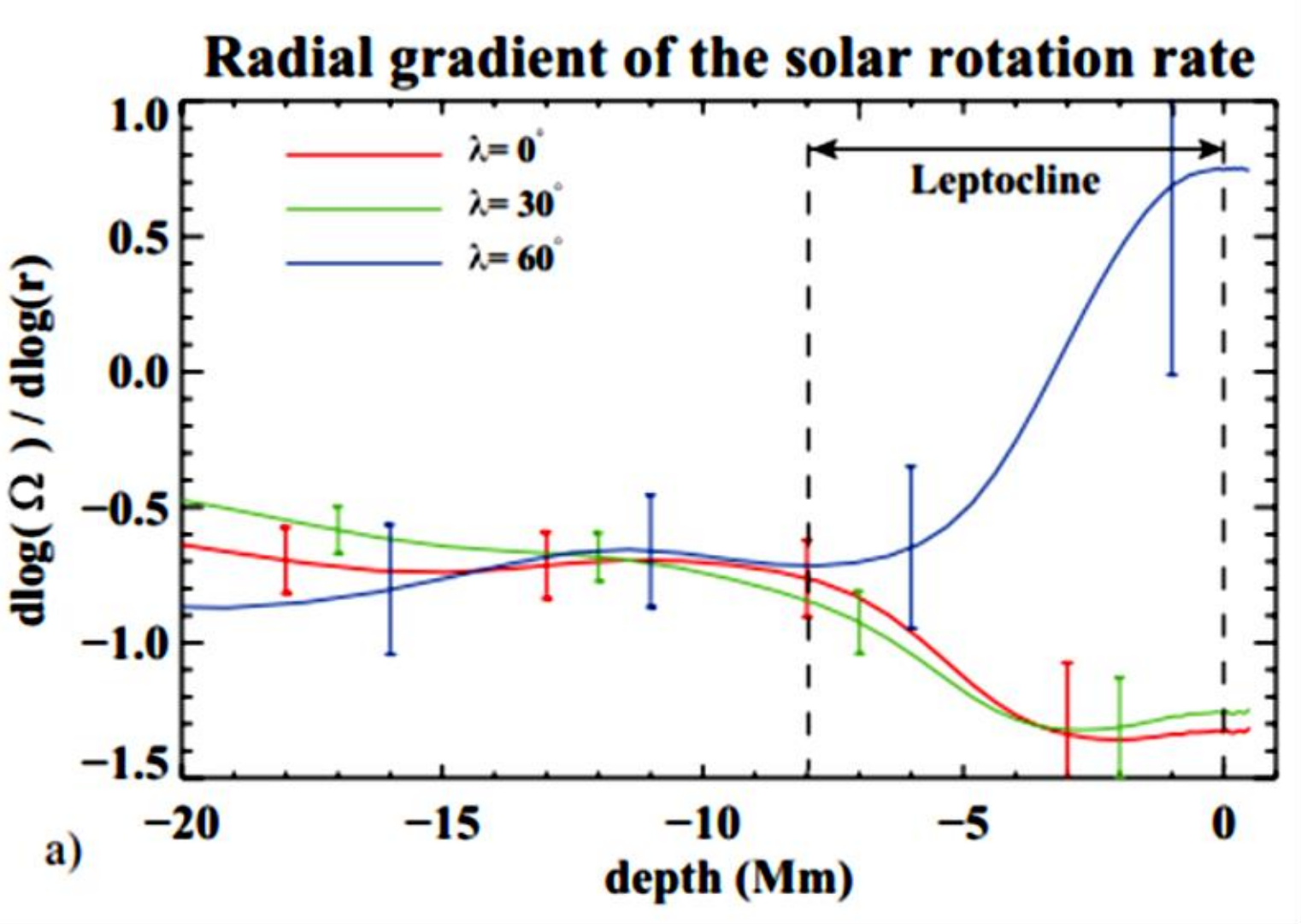
The radial gradient averaged over time, $\delta\nabla_r(\Omega)$, exhibit torsional oscillation-like behavior

$$\delta(\nabla_r(\Omega)) = \nabla_r(\Omega) - \langle\nabla_r(\Omega)\rangle_t$$

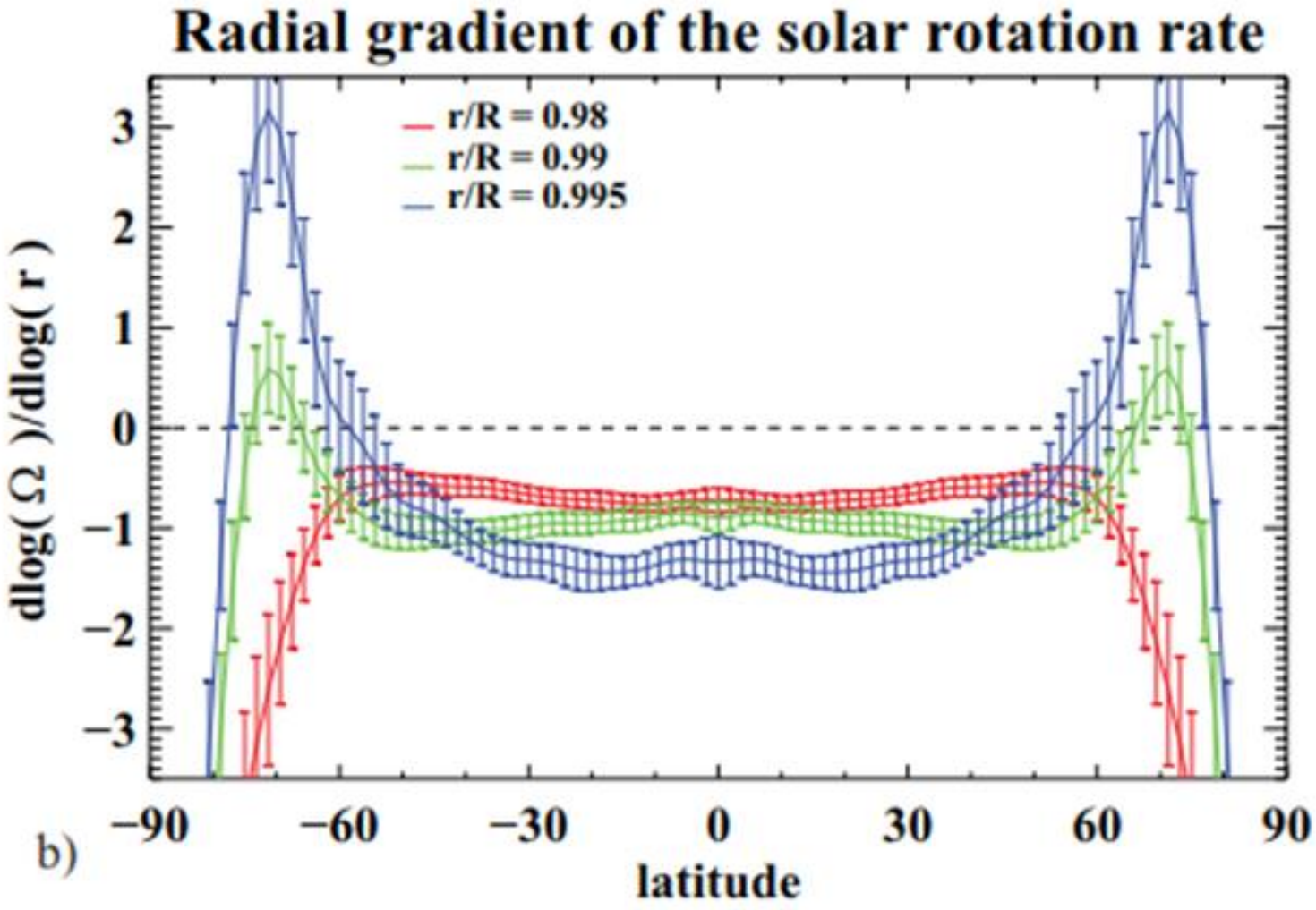
$$\nabla_r(\Omega) = \frac{\partial \log \Omega}{\partial \log r}$$

varies in latitude, depth, and in time.

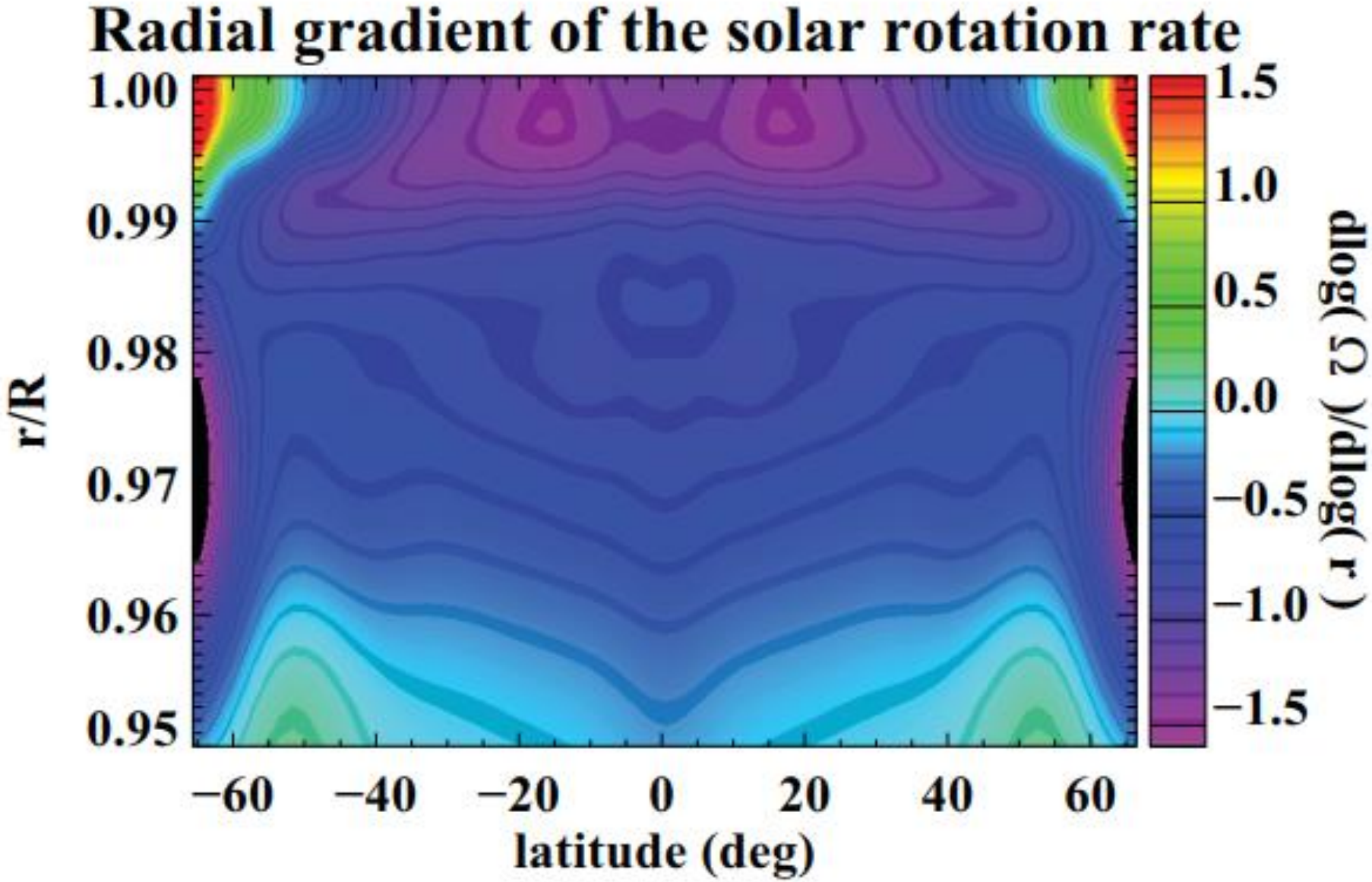
The gradient, ∂ log Ω/ ∂ log r, in depth (a) and latitude (b)



**The gradient, ∂ log Ω/ ∂ log r, in depth (a) and latitude (b)**



**The gradient, ∂ log Ω/ ∂ log r**



# The solar cycle signature

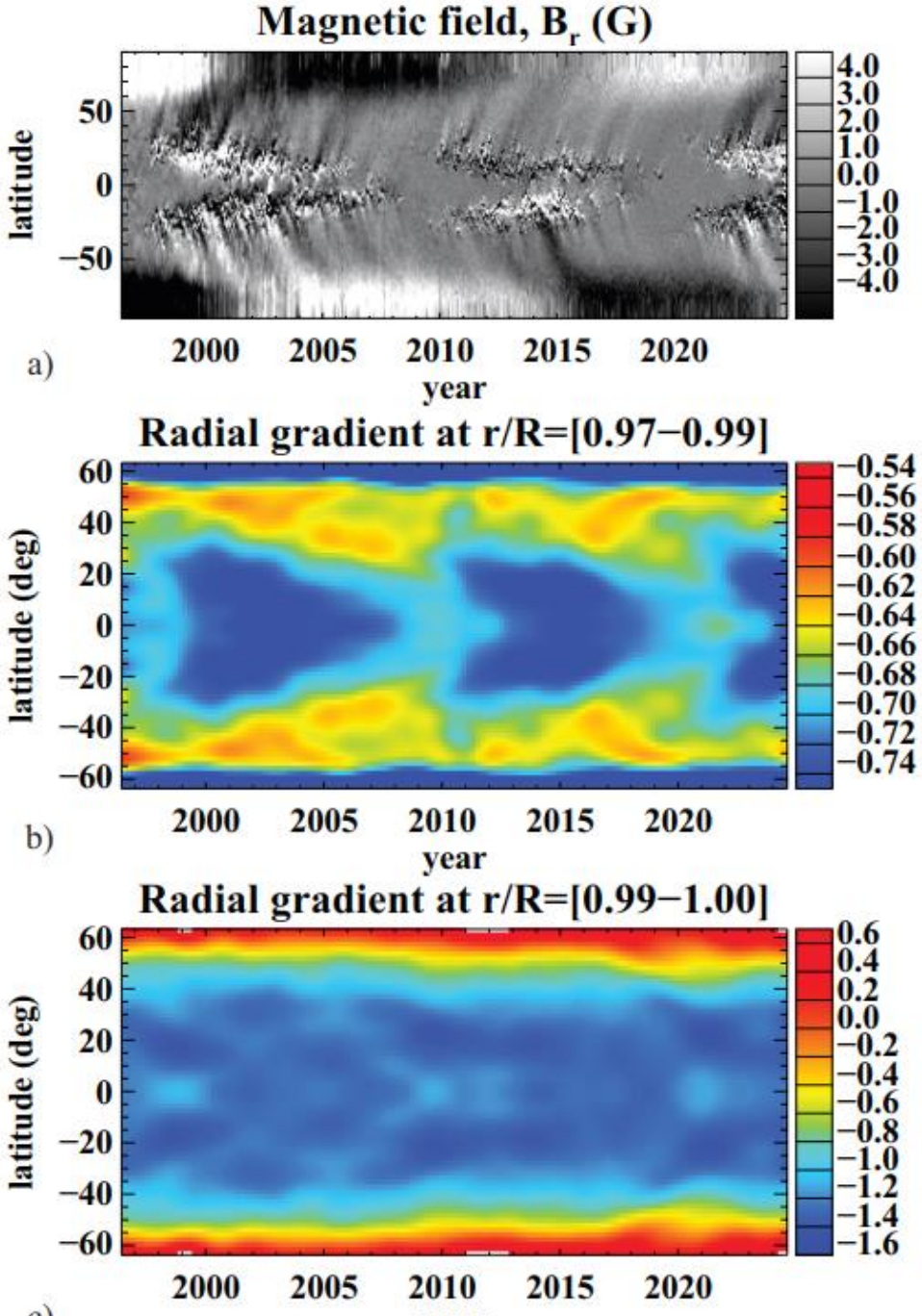
**The gradient, ∂ log Ω/ ∂ log r, in time**

**Observations**

- Rotational shear varies with solar cycle
- Strong gradients accompany active latitudes
- Extended-cycle patterns appear in the leptocline

**Take-home**

The leptocline remembers the solar cycle.




0.950 Re (35 Mm deep)
0.970 Re (21 Mm)
0.980 Re (14 Mm)
0.990 Re (7 Mm)

# Convection Scales Change with Activity

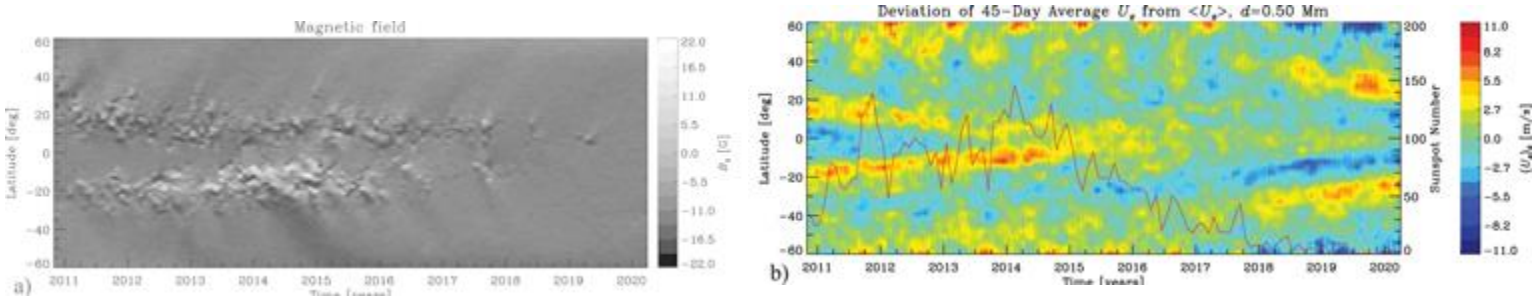
**-Results**

✅ Supergranulation remains stable

✅ Giant-cell scales increase during activity maxima

✅ Convection becomes stronger and larger during active periods

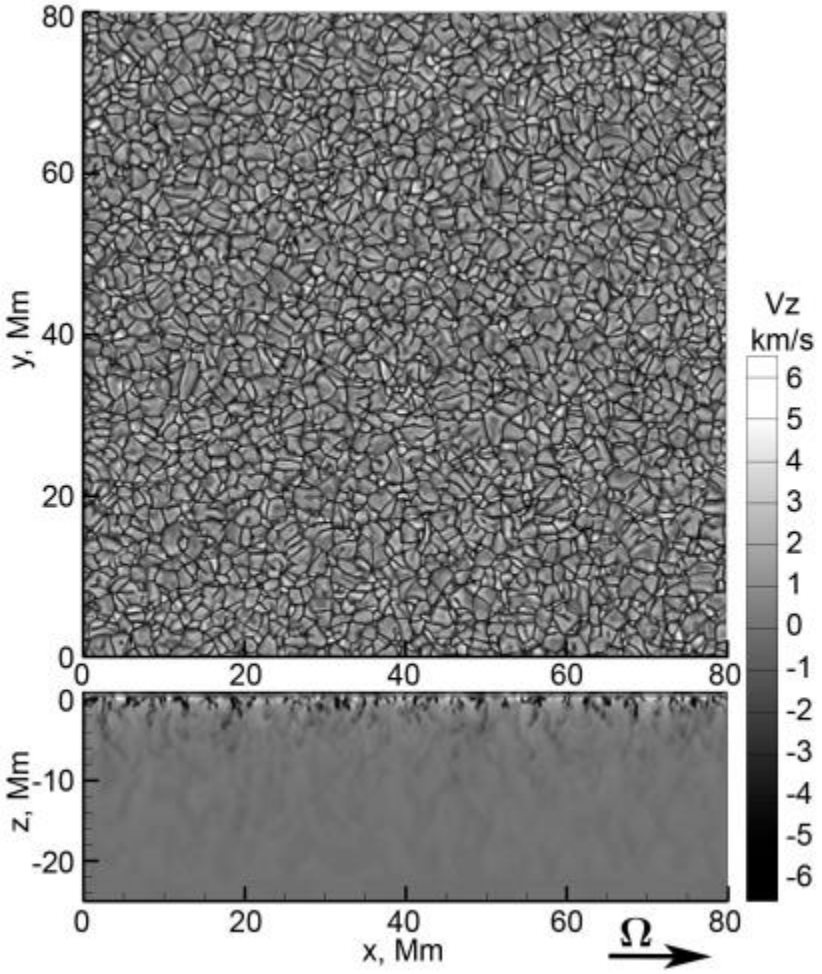
The flow variations originate at about 50°–60° latitude during a solar maximum and migrate toward the equator during the following 22 yr so that, at each moment, we observe a superposition of two wave-like migrating patterns.
the zonal- and meridional-flow variations are driven by temperature variations near the surface due to the enhanced emission of radiation by the small-scale magnetic-field elements in active regions.




Time–latitude diagrams: (a) monthly averaged $B_z$; (b) the deviation, of the 45 day running zonal-velocity average, $U_x$, from its mean over the whole interval considered, $\langle U_x \rangle$, at $d$ = 0.50 Mm. The red curve shows the variation of the monthly sunspot number.

Alexander V. Getling, Alexander G. Kosovichev) Sol. Phys 2025, 300

# Numerical Simulations 1




*Kitiashvili et al. MNRAS 2023*

**Model:** The horizontal size of the computational domain is 80 Mm × 80 Mm, and the vertical domain extends to a depth of 25 Mm.

The grid resolution is 100 km in the horizontal directions; the vertical resolution varies from 50 km in the photosphere and low atmosphere to 82 km near the bottom boundary.

The extended duration of the simulation, over 250 hours, permits to reach dynamically stationary conditions before investigating the influence of rotational effects.

# Numerical simulations 2

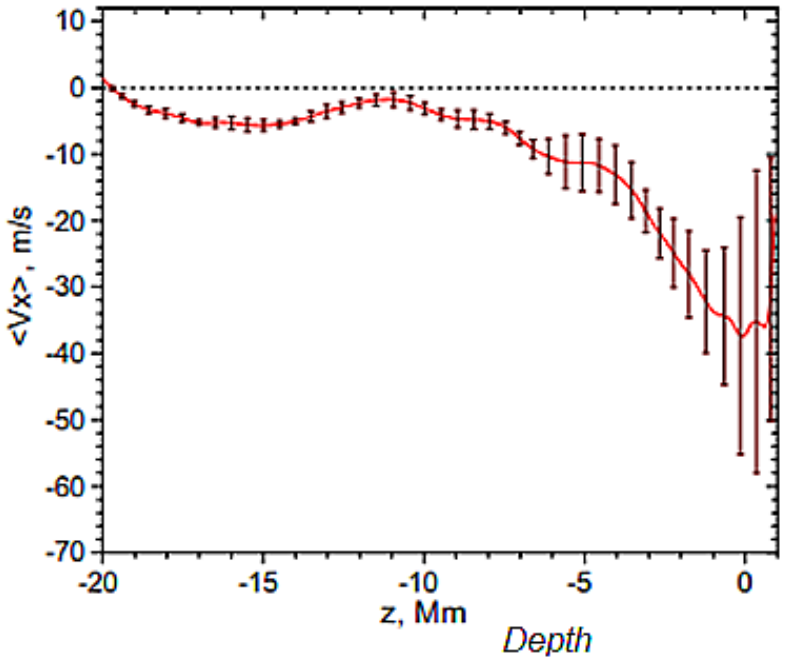
**3D MHD simulations show**

Development of an 8-Mm deep leptocline
Enhanced turbulence
Strong rotational gradients
Overshooting flows

**Take-home**

Observations and simulations tell the same story.

*Kitiashvili et al. MNRAS 2023*

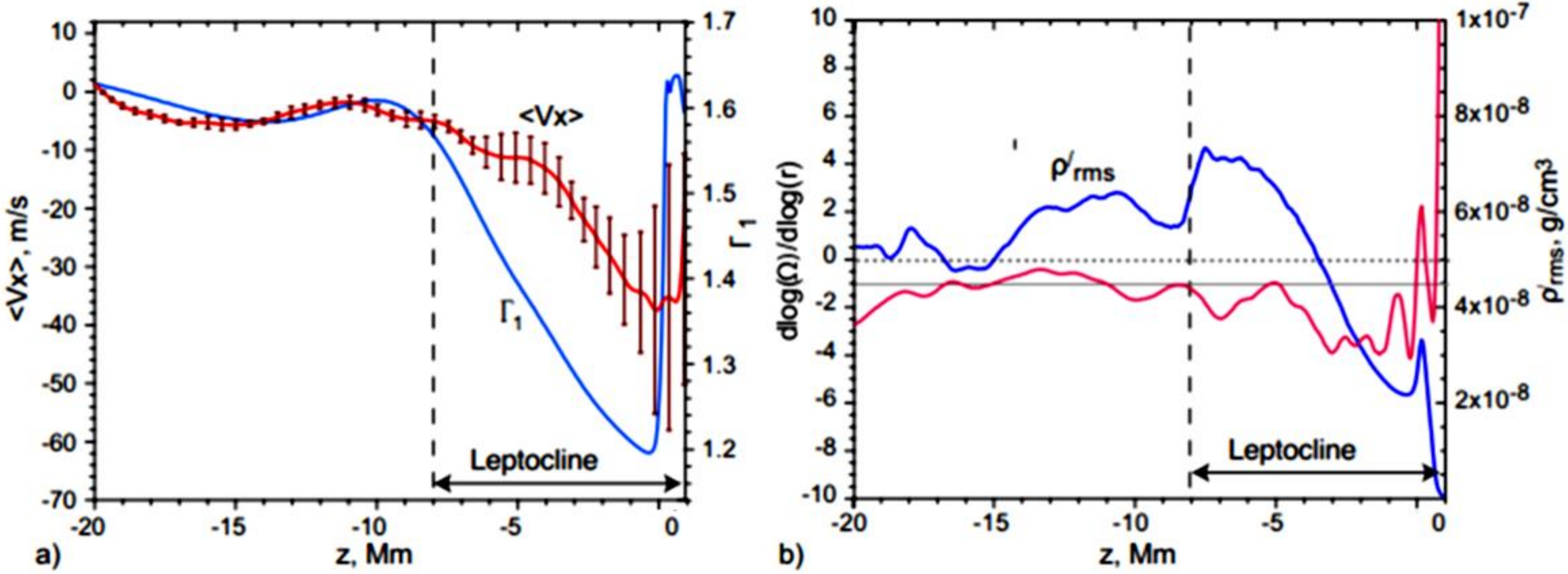



Results: a significant decrease in the azimuthal velocity with depth by 38 m/s in a 2 Mm deep layer below the photosphere. Below 7 Mm, the rotation rate is slower than the imposed mean rotation rate by about 5 m/s.
The rotation rate increase with depth is not uniform: from the sub-photospheric layers to about 4 Mm below, the velocity increases by 6 – 7 m/s per Mm, while below 4 Mm the flow accelerates by about 2 m/s per Mm.

The identified 0-10-Mm thick near-surface shear layer, or 'leptocline' is clearly visible in the relative differential rotation profile.

# Simulation 3-D (2)

Radiative Hydrodynamics Simulations of the Leptocline




Adiabatic index, Γ1; Density ρ; Flow speed Vx

the formation of the leptocline is likely driven by enhanced anisotropic turbulent convective downdrafts within the hydrogen and first helium ionization zone.

*Kitiashvili et al. MNRAS 518, 504–512 (2023)*
*246th Meeting of the American Astronomical Society, 2025*

# Take an interest in the leptocline

**Why at 8 Mm?**

**Visual**
Ionization zones
Hydrogen and Helium ionization layers

**Key idea**

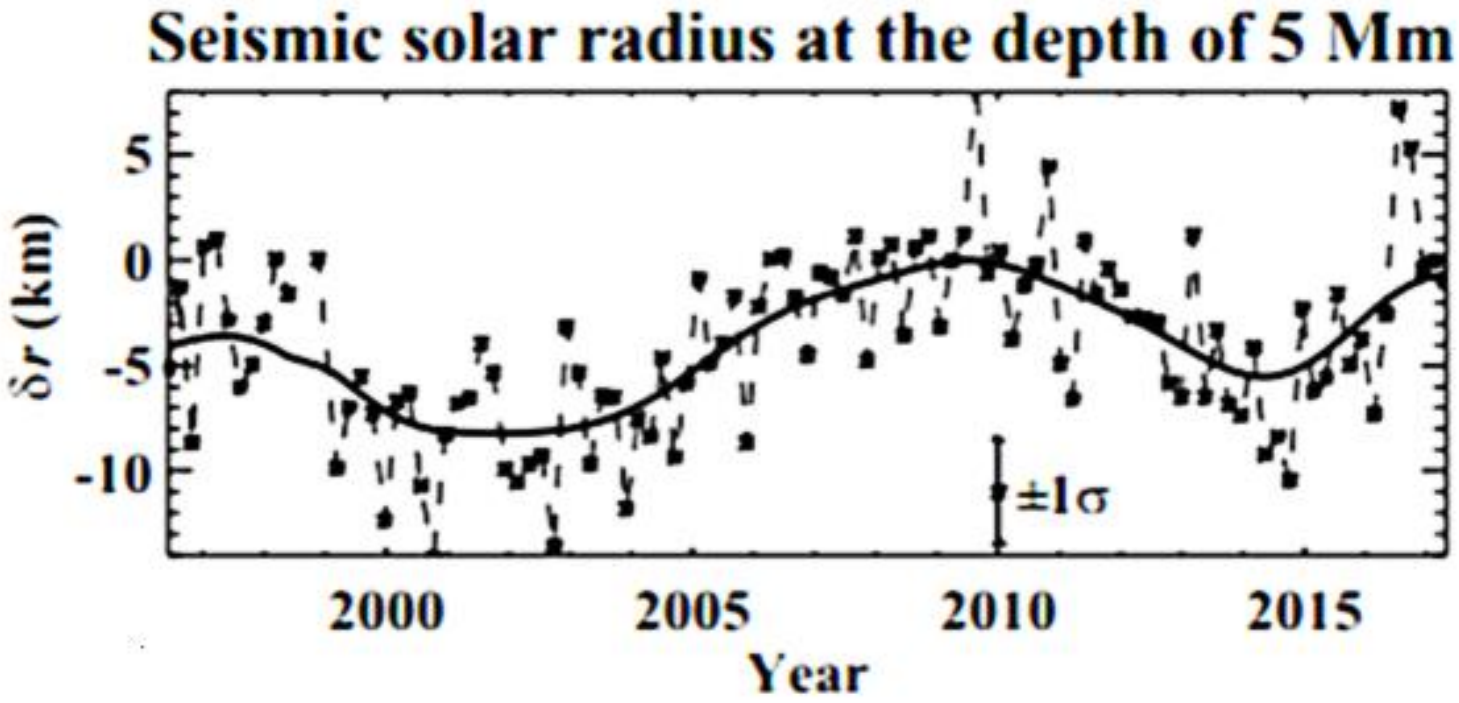
The leptocline coincides with:
- H/He-I ionization zone
- Enhanced overshooting convection
- Increased turbulent mixing

This is likely not a coincidence.

*Kosovichev and Rozelot, IAU, 2026  astro-ph > arXiv:2501.08021*

# Take an interest in the leptocline

→ *How $R_\odot$ measurements are impacted in this very specific region?*




*Kosovichev and Rozelot, IAU, 2026*
*astro-ph > arXiv:2501.08021*

How the seismic radius is obtained and what does it stand for?

# Solar seismic radius (1)

From MDI (SoHO) and HMI (SDO):

« conventional » helioseismological inversions lead to a resolution of the so-called « seismic » solar radius.

$$\frac{\delta \nu_{n,l}}{\nu_{n,l}} = \int K^{(n,l)}_{\psi,\rho} \; f(\psi, G, \rho, x) \; dx + S_{n,l}$$

relative frequency variations

seismic radius relative variations (data kernels)

surface term

x is the fractional radius r / R, where R is a fiducial radius

$\psi := c/r$ , c, adiabiadic speed of the sound in the solar plasma, ρ density; *G*, Gravitational constant

→ Be aware of the surface term, $S_n$ introduced to take account of uncertainties in the near-surface regions of the Sun *(cf. Dziembowski et al., 1990)*

# Solar seismic radius (2)

- 1. Calibrated through **f-mode** $\ell$ (130 – 300)

f-radius value is lower than the conventional adopted $R_\odot$

One can imagine to identify a unique limiting f-mode radius (at the surface, i.e. 1.0 $R_\odot$) by extrapolating $\ell$ to infinity.

Not possible: going from the inner to the outer atmosphere, the acceleration due to gravity decreases, but the energy density of the mode increases, causing the apparent limiting radius to vary with the range of $\ell$ adopted for the extrapolation.

→ Will it be a “phantom” surface (Takada and Gough, 2024)

# Solar radius (3)

- 2. Calibrated through **p-mode**: « acoustic radius » (Takada & Gough, 2024)

The main interest is to understand better the role of the total mass constraint in the structure inversions, suggesting that the positions of the photosphere and the adiabatically stratified layers in the convective envelope differ **non-homogeneously** from those of the standard solar model.

# Solar radius (4)

## ➢ Results

Schou et al.: ApJ 1997, f-modes 695.68 ± 0.03 Mm

Tripathy and Antia: Sol Phys 1999, f-modes 695.77±0.10 Mm

Takata and Gough: MRAS 2024, p-modes 695.78 ± 0.16 Mm

Different either from the "canonical" value (Auwers) or the Allen's ephemerides

$[R_\odot]_{\text{canonic (1895-2015)}} = 695.997 \pm 0.36$ Mm $\qquad R_{ph} = 695.508 \pm 0.26$ Mm

We still do not know how to reconcile the discrepancy (317 to 172 km) between the seismic radius and its conventional value : attempts *are model dependent*.

# Solar radius (5)

- Seismic radius (Calibrated through f or p-modes):

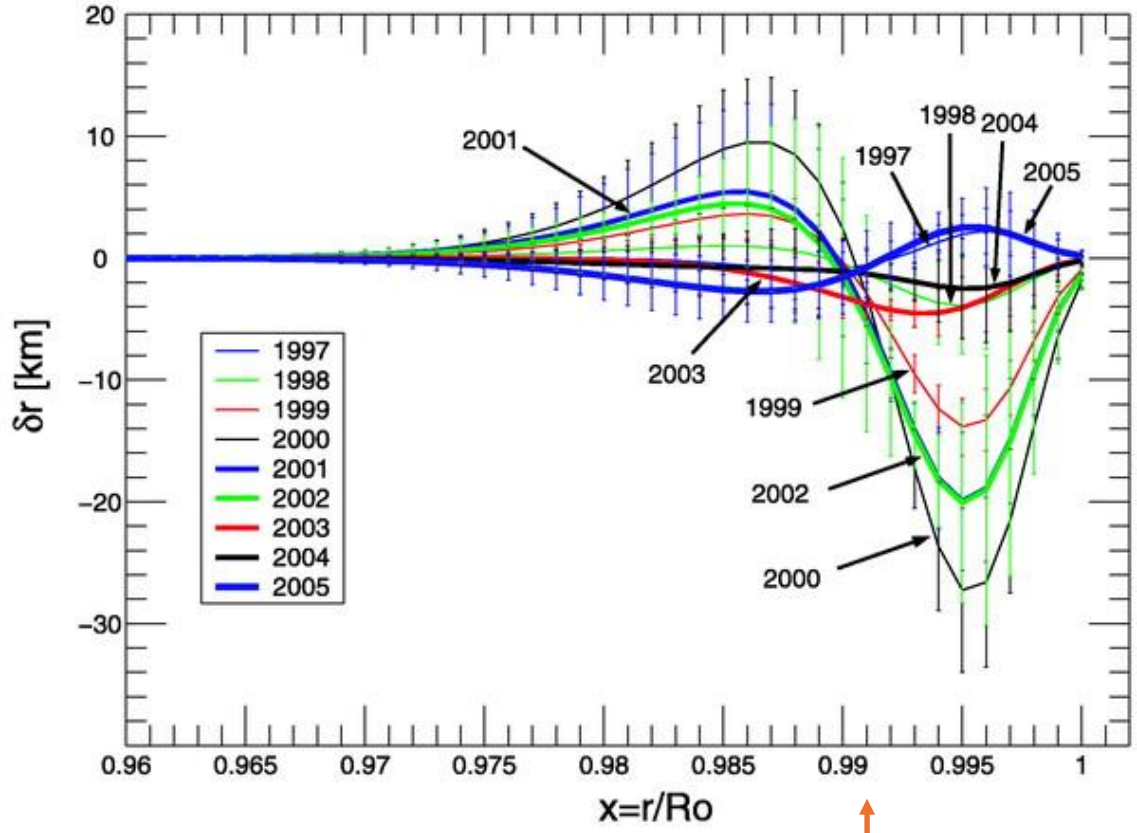
$$\frac{\delta \nu_{n,l}}{\nu_{n,l}} = \int K^{(n,l)}_{\psi,\rho} \; f(\psi, \sigma, \rho, x) \; dx + S_{n,l}$$

- f-mode or p-mode frequencies are modified by the changes in both magnetic field and the solar seismic radius. Because the change in seismic radius is estimated assuming that the fractional change ($x$) in *radius is uniform* in the range of sensitivity of the method, its value corresponds to the change at a radius where the modes are concentrated.

What happens if fractional change in radius is not uniform ?

# Radius variations (4)

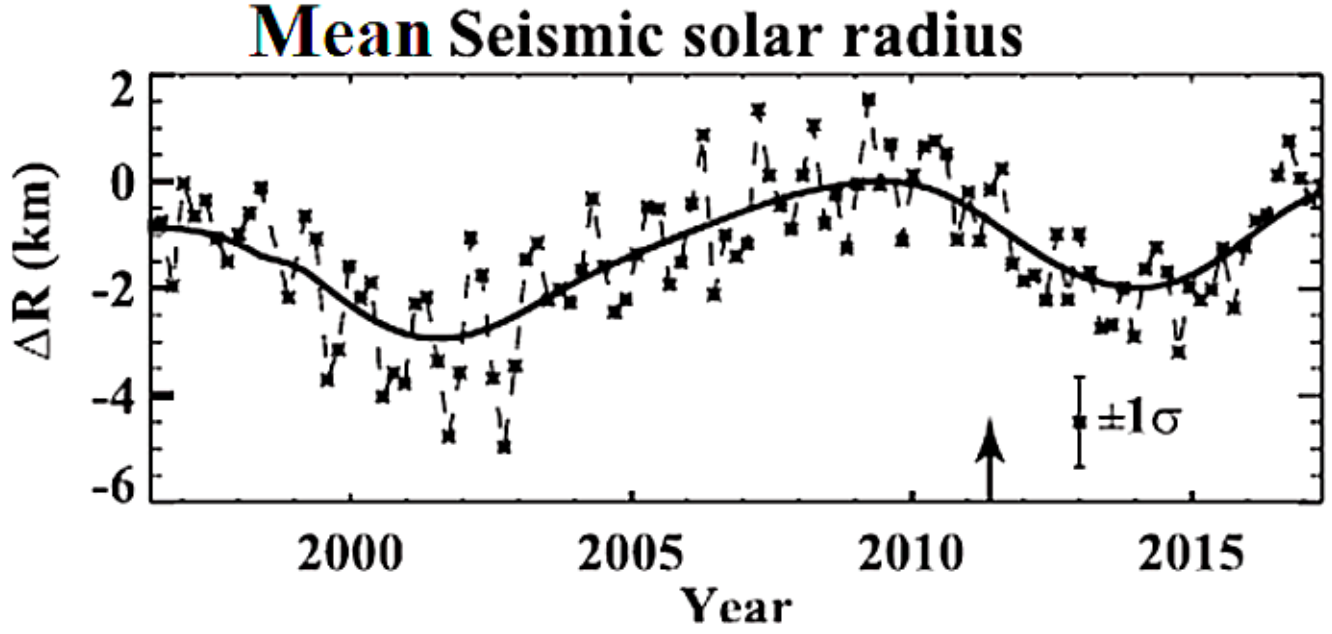
- fractional change in radius is not uniform (f-modes):

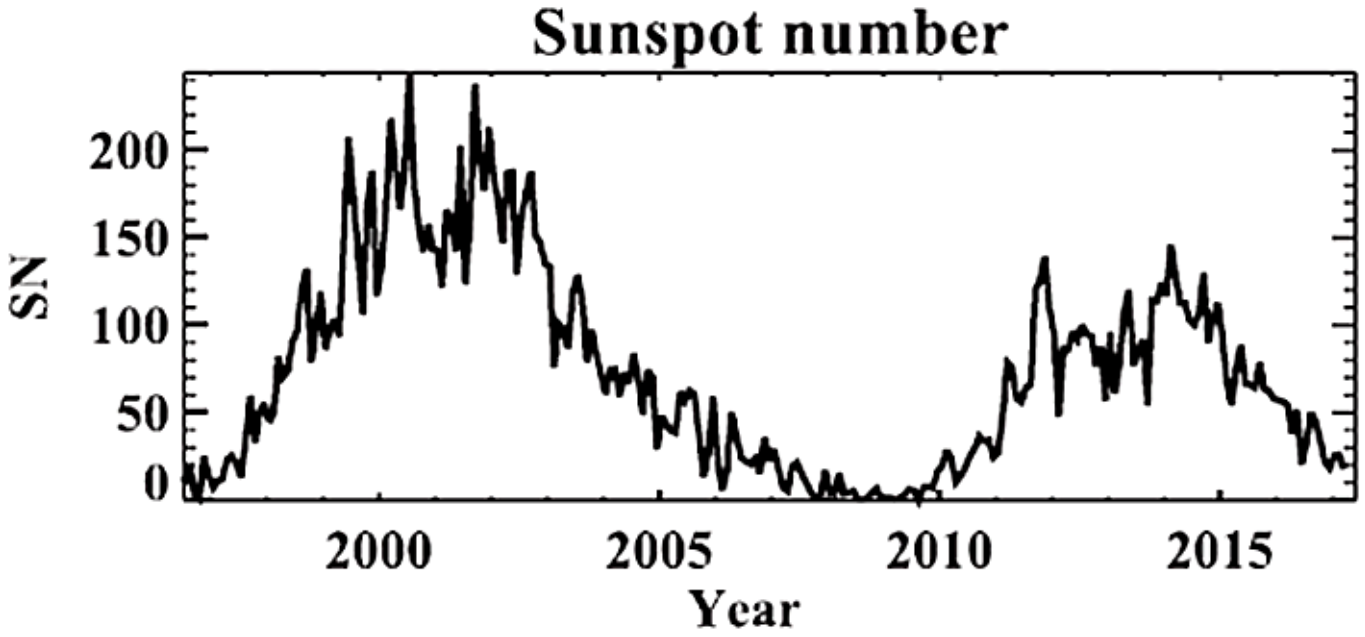



Radial variation for each year by reference to 1996, as a function of the fraction a radius x = r/$R_{\odot}$. **Note the curves near x = 0.992 (0.6 Mm depth**).

The error bars are the standard deviation after averaging over a set of random noise added to the relative frequencies.

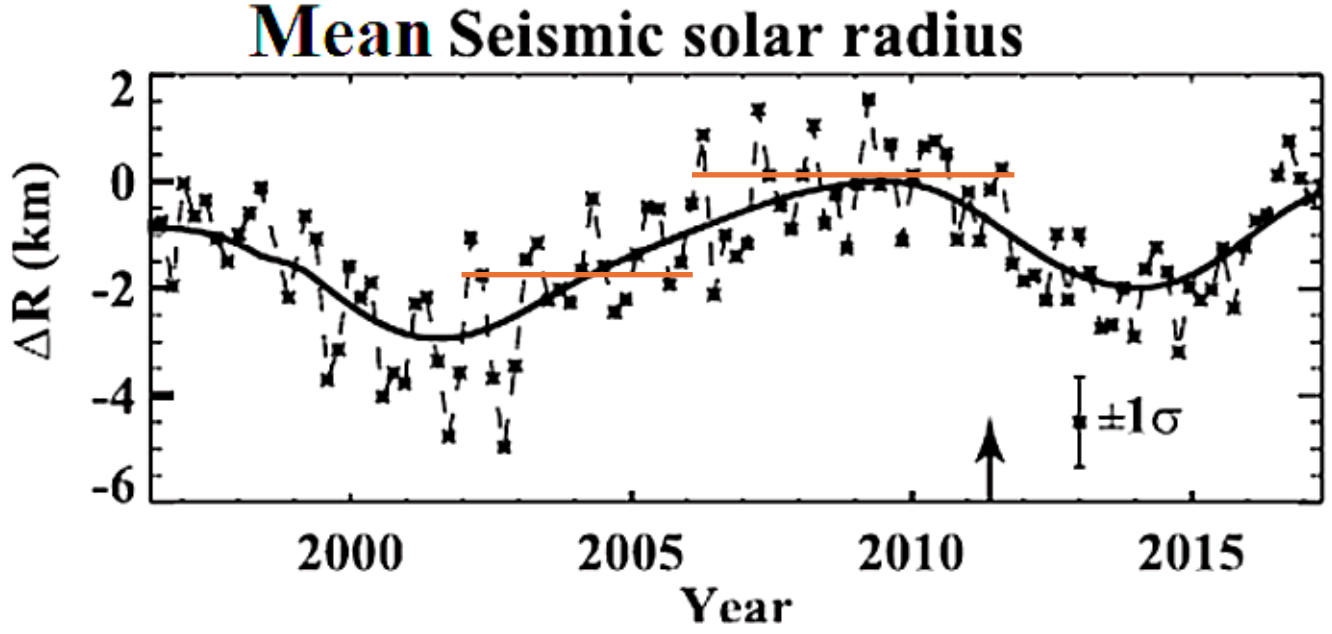
# Seismic radius

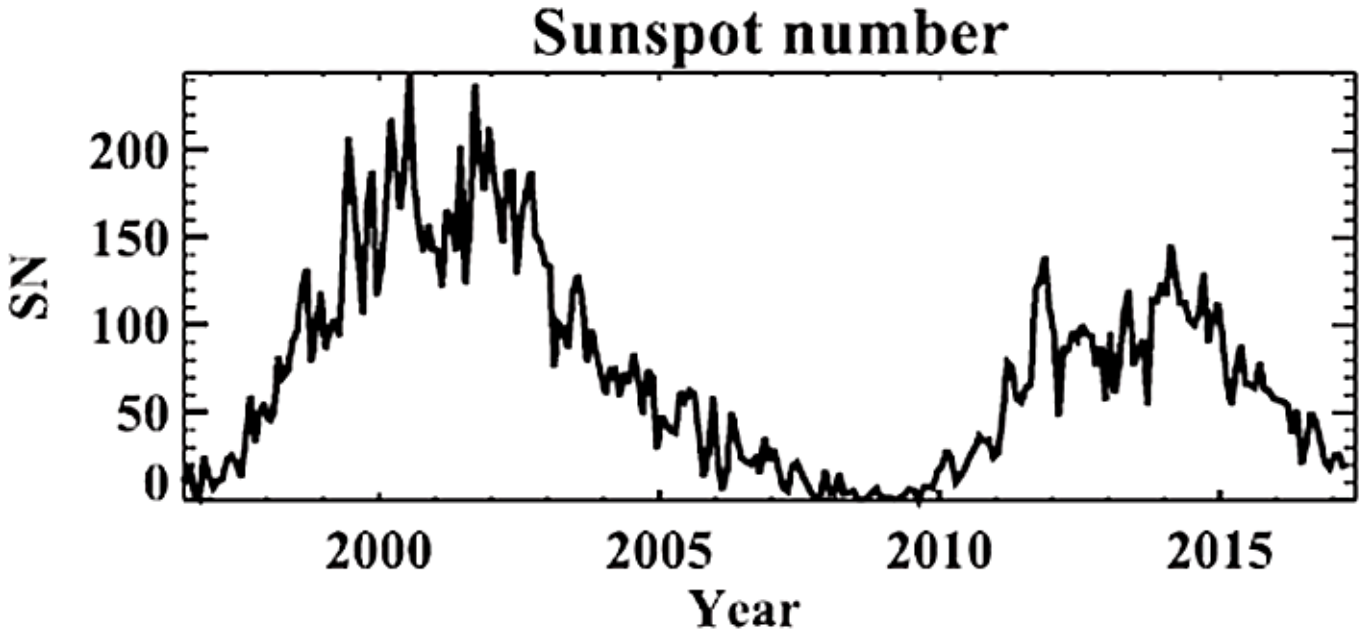



*Kosovichev, Rozelot, ApJ, May 2018*

# Seismic radius




*Kosovichev, Rozelot, ApJ, May 2018*

# Seismic radius

- decreased by about 3-4 km during the Cycle 23 maximum (2000–2003)

- by about 2-3 km during the Cycle 24 maximum (2013–2015)

The most significant changes occurred in the depth range of 3–8 Mm beneath the photosphere.

Highlights the role of the leptocline

Also noted by other authors (i.e. Antia)

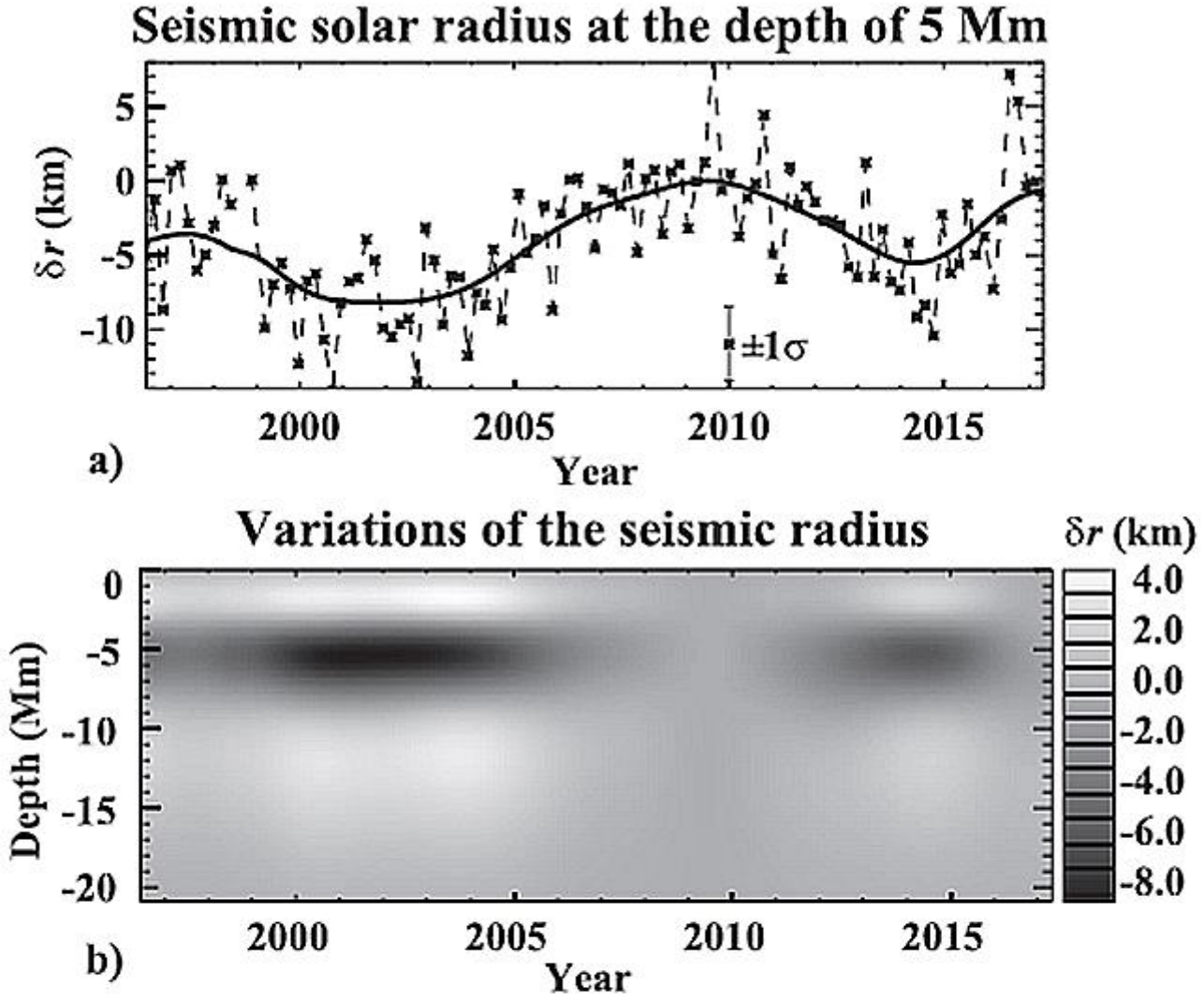



**Figure 5.** Variations of the seismic radius: (a) changes of the seismic radius at the depth of 5 Mm and (b) variations with time and depth beneath the solar surface. The dark color (negative values) corresponds to contraction and the light color (positive values) corresponds to expansion of subsurface layers.

| Radius name | Label | Meaning |
|---|---|---|
| **Photospheric** | $R_{ph}$ | a/ Distance from the solar center to the photospheric surface, defined as the layer where the optical depth t = 1 for a particular wavelength, usually 500 nm.<br><br>b/ Defined by the depth where the temperature equals the effective temperature:<br><br>$R_{\mathrm{ph}}^2 T_{\mathrm{eff}}^4 = L_\odot/(4\pi\sigma)$.<br><br>c/ Distance measured at the inflection point, for a given wavelength.<br><br>• $R_{ph}$ must be focused on the wavelength dependence, i.e., the height or depth at which the measurement is made. |
| **Canonical** | $R_C$ | Adopted radius through a consensus (1895-2015).<br><br>$[R_\odot]_{\text{canonique (1895-2015)}}$ = 695 997 ± 36 km |
| **Nominal** | $\mathcal{R}_\odot^{\mathrm{N}}$ | Adopted radius by the IAU GA (2015), chosen to standardize calculations, $\mathcal{R}_\odot^{\mathrm{N}}$ to match each new best measurement.<br>= 6.957 $10^8$ m |
| **Generic** | $R_\odot$ | a/ Generic term, without reference to any particular concept of time, depth, latitude…<br><br>b/ Used to calibrate models. |
| **Seismic:** | $R_s$ | Radius calculated using helioseismology, f_modes: fundamental -- p_modes: acoustic |
| **1. Fundamental** | $R_f$ | Fundamental photospheric radius scaled through f-modes, which is the distance from the solar center to the center of energy of each f-mode (essentially the peak in the kinetic-energy distribution). |
| **1. Acoustic** | $R_{ac}$ | Acoustic photospheric radius scaled through p-modes, which is the distance from the center to the subphotospheric layer where the acoustic cut-off frequency changes extremely rapidly. |

*Proposed new glossary of the various solar radius in use. Modified from Takada & Gough (2024).*

*Rozelot & Kosovichev, Sol. Phys., 2026.*

*http://arxiv.org/abs/2605.23794*

# Perspectives

**Main Messages**

✅ The NSSL contains a distinct shallow sublayer: the leptocline.
✅ It is associated with:
strong rotational shear,
ionization zones,
turbulent convection.
✅ It evolves with the solar cycle.
✅ The leptocline may be a key ingredient of the solar dynamo and magnetic butterfly diagram.

**Future Challenges**

Distinguish convection from inertial modes.
Measure magnetic fields in the leptocline.
Couple helioseismic observations with 3D simulations.
Understand its role in solar-cycle predictability.

# Some Conclusions ($R_\odot$)

● $R_\odot$ Temporal variations : around 2-4 km over the cycle

Anti-phase from the surface down to around 0.995 $R_\odot$ (about 3.5 Mm below the surface), changing in phase in the deeper layers of the Sun (between 0.975 and 0.99 $R_\odot$).

 Changes due to subsurface magnetic fields and changes in the temperature distribution.

 May explain differences between measurements

 **$R_\odot$ must be proposed with - reference date t, - heliographic latitude $\theta$, - depth (Mm) and wavelength $\lambda$)**

(otherwise, impossible to compare)

● *To date, best proposed accurate value:* ***$R_{fs\ ac}$= 695 780 ± 160 km*** *(959.34 ± 0.22 arcsec)*

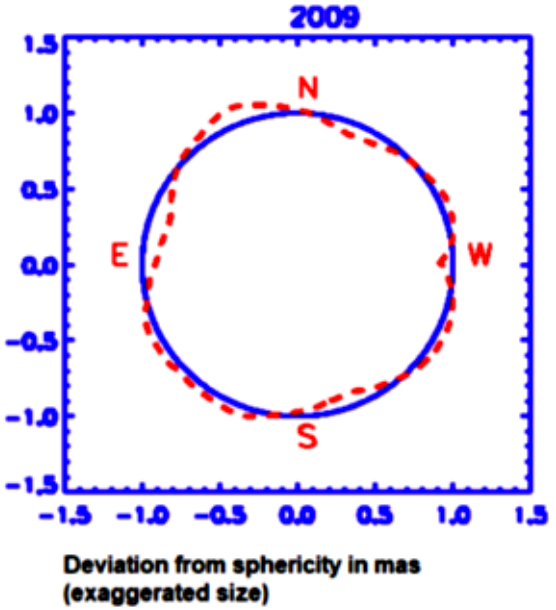
Need TO CONTINUE TO GET SHARPER DETERMINATIONS OF THE SOLAR RADIUS

# Some Conclusions (leptocline)

● The *HMI data analysis* and supporting *numerical simulation* revealed the '**leptocline**', a highly dynamical shallow substructure of the NSSL in the top **~8 Mm** of the convection zone
**Downdrafts create an overshooting-type layer at the base of this zone, where turbulent mixing is intensified.**

 The leptocline is the seat of the **temporal variations of the solar radius**: around 3 km over the solar cycle;

 May explain why radius measurements are sometimes contradictory.



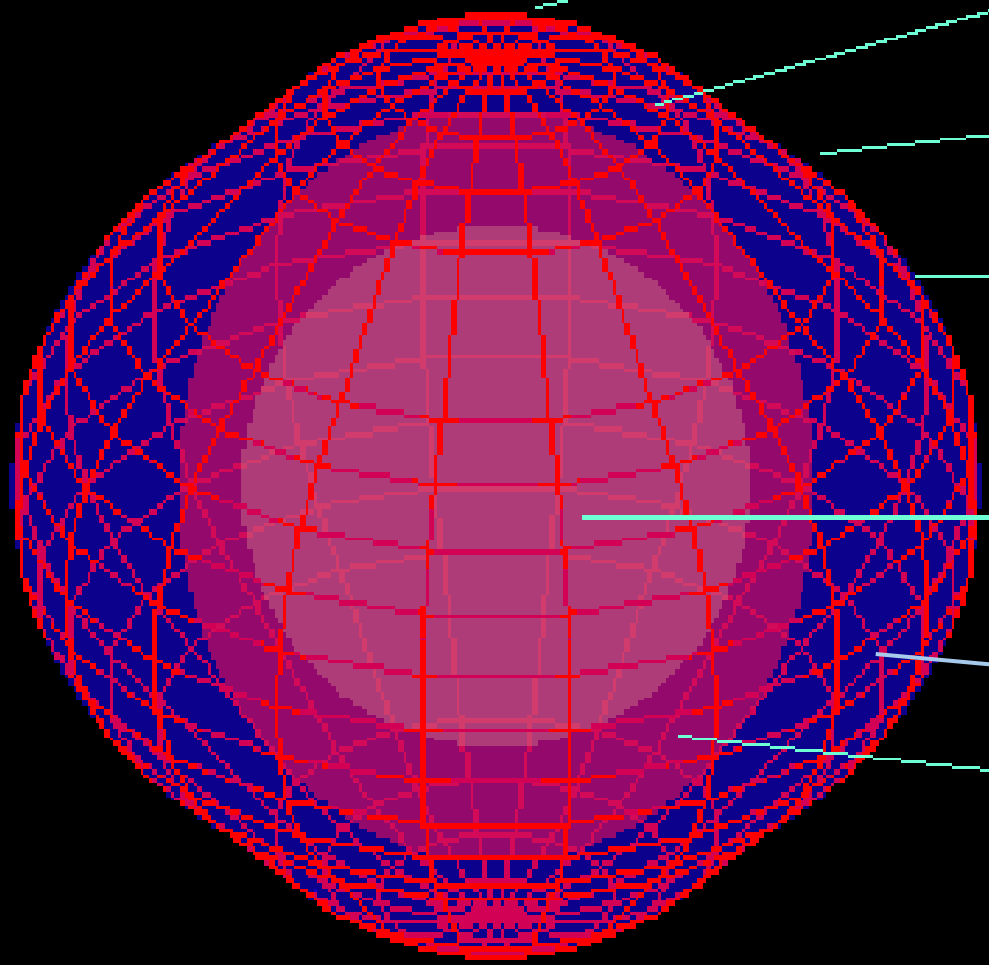

● Shape distorsions (and oblateness) **not taken here into account**

 Within the leptocline: a complex behavior of the variation of the **radial gradient of rotation** $\partial \log \Omega / \partial \log r$ , in latitude, depth and time.

# THANKS



2006 ECLIPSE in T.



A slight oblate outer shape

Shear layer

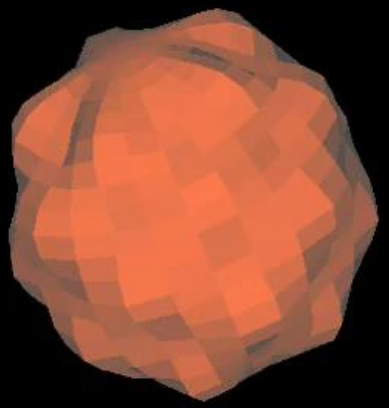
Depressed zone at higher latitude

Bulge zone from equator to mid-latitude

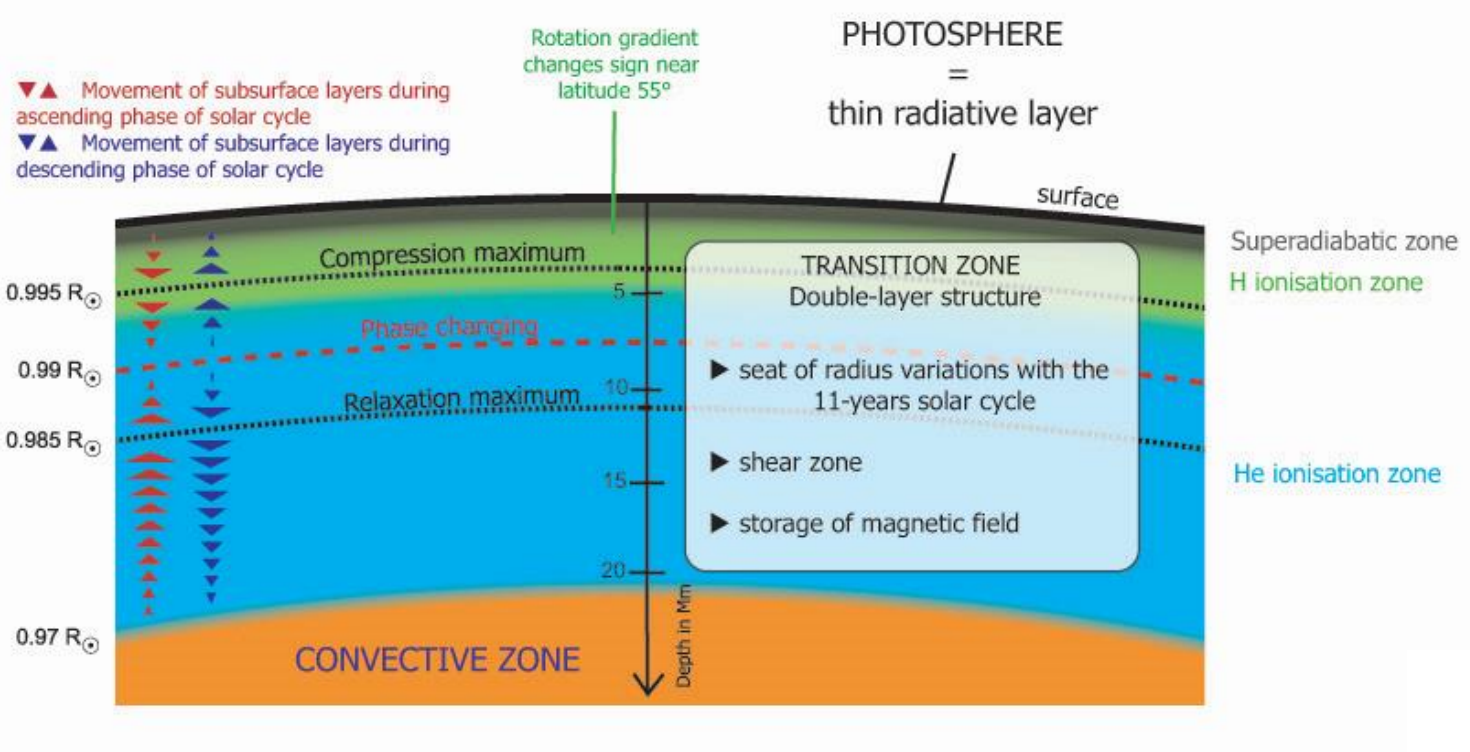
A nearly spherical core

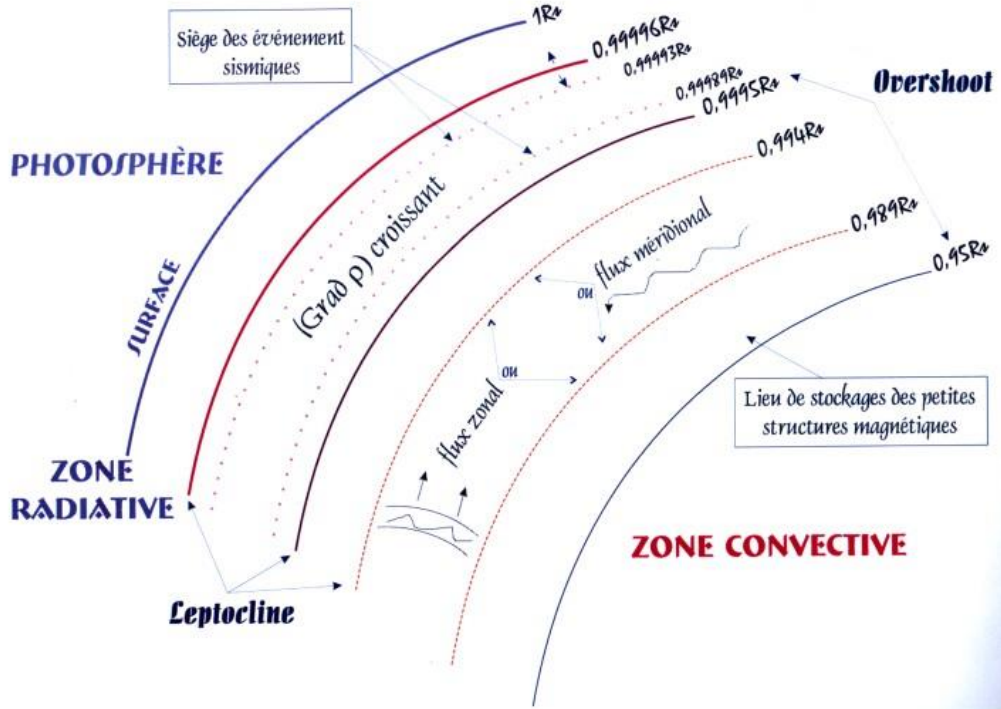
Leptocline

A prolate thin tachocline (seat of the dynamo -magnetic-effects)



# THANKS


▼▲ Movement of subsurface layers during ascending phase of solar cycle
▼▲ Movement of subsurface layers during descending phase of solar cycle
Rotation gradient changes sign near latitude 55°
PHOTOSPHERE
=
thin radiative layer
surface
Compression maximum
Phase changing
Relaxation maximum
0.995 R⊙
0.99 R⊙
0.985 R⊙
0.97 R⊙
5
10
15
20
Depth in Mm
TRANSITION ZONE
Double-layer structure
▶ seat of radius variations with the 11-years solar cycle
▶ shear zone
▶ storage of magnetic field
CONVECTIVE ZONE
Superadiabatic zone
H ionisation zone
He ionisation zone


Siège des évènement sismiques
1R⊙
0,99996R⊙
0,99993R⊙
0,99989R⊙
0,9995R⊙
0,994R⊙
0,989R⊙
0,95R⊙
Overshoot
PHOTOSPHÈRE
SURFACE
(Grad ρ) croissant
flux méridional
ou
flux zonal
ou
Lieu de stockages des petites structures magnétiques
ZONE RADIATIVE
ZONE CONVECTIVE
Leptocline