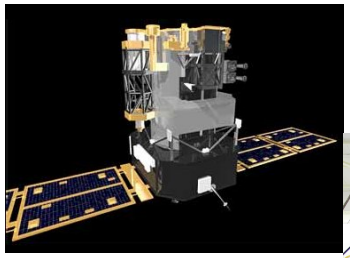
SPACE CLIMATE symposium number 5



THE ACTIVITY OF THE INNER SUN

S. Turck-Chièze,
SAp/IRFU/DSM/CEA Saclay France

with the collaboration of S. Couvidat, V. Duez, A. Hauchecorne, R. M. Meftah, L.Piau, R. Simoniello, and the PICARD team for the most recent works

$$P_{gas} >> P_{mag}$$

Direct and indirect measurements of the internal solar activity to progress on the long term variability

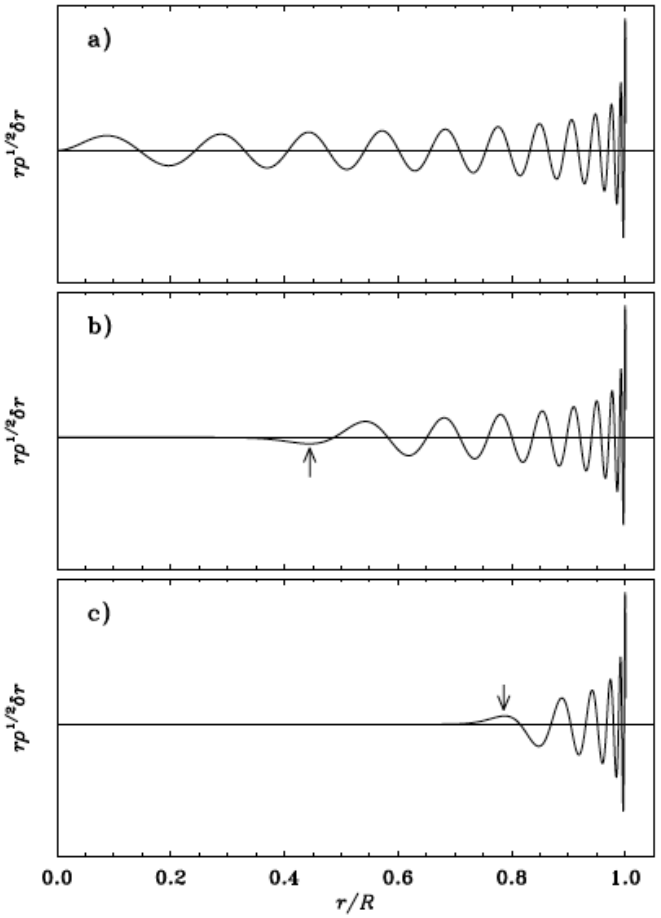
- What do we learn with 30 years of measurements?
- How could we hope to learn more
- What do we need to do?

Direct effects

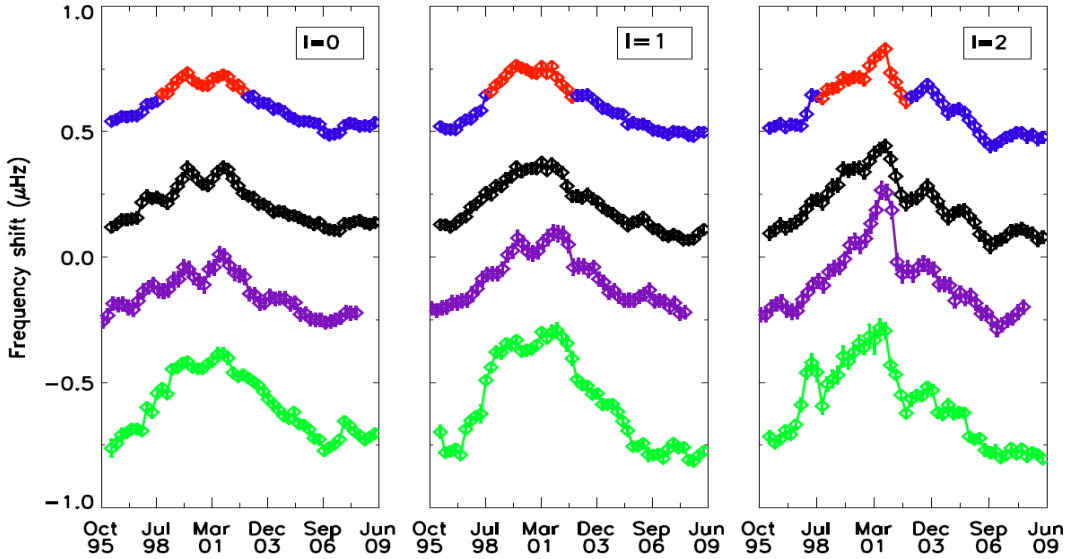
What have we learned with 30 years of seismic measurements ?

low and high degree acoustic modes

Low and high degrees acoustic modes are very good indicators of the 11 year cycle and of a well identified quasi biennal oscillation



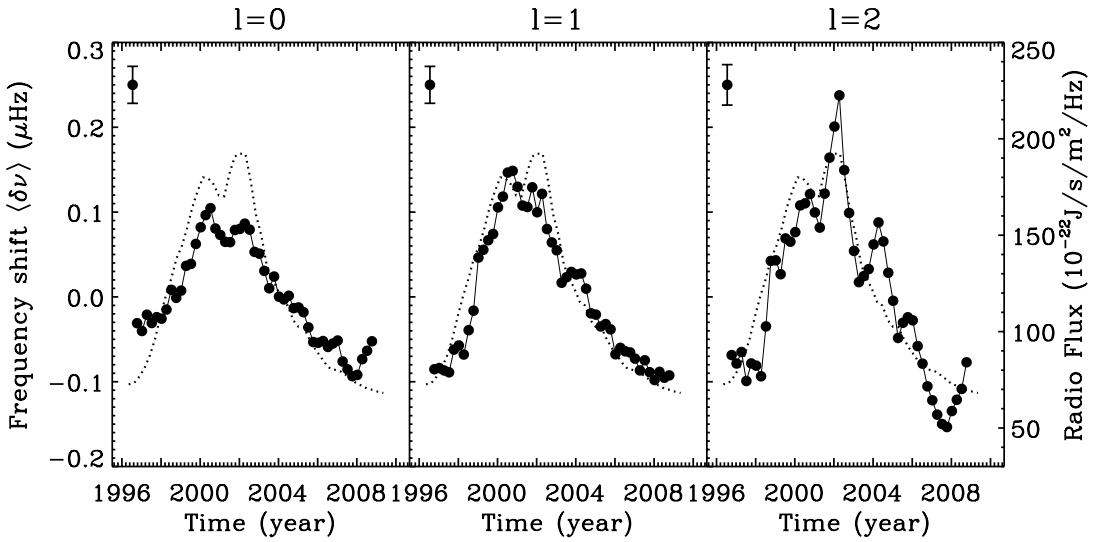
GOLF, BiSON, GONG, VIRGO



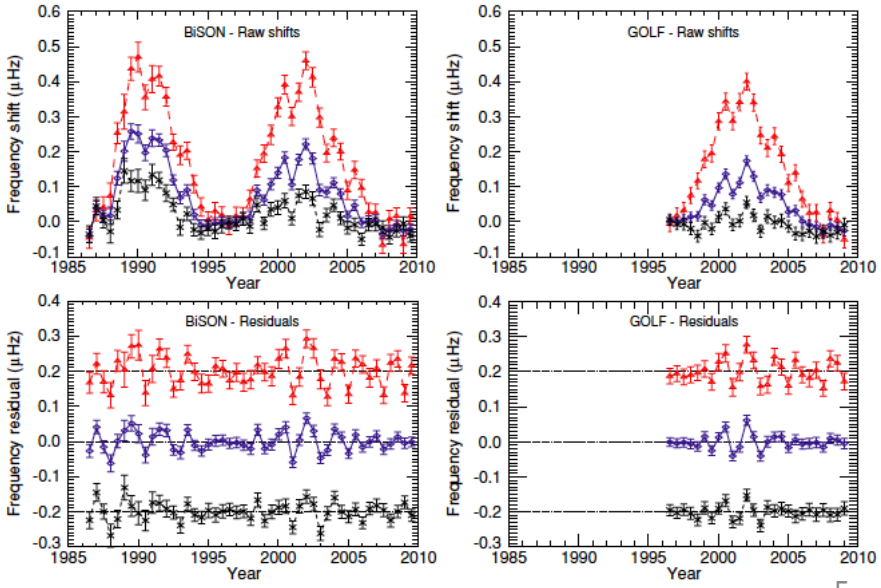
Simoniello et al. 2012

Very different behaviours

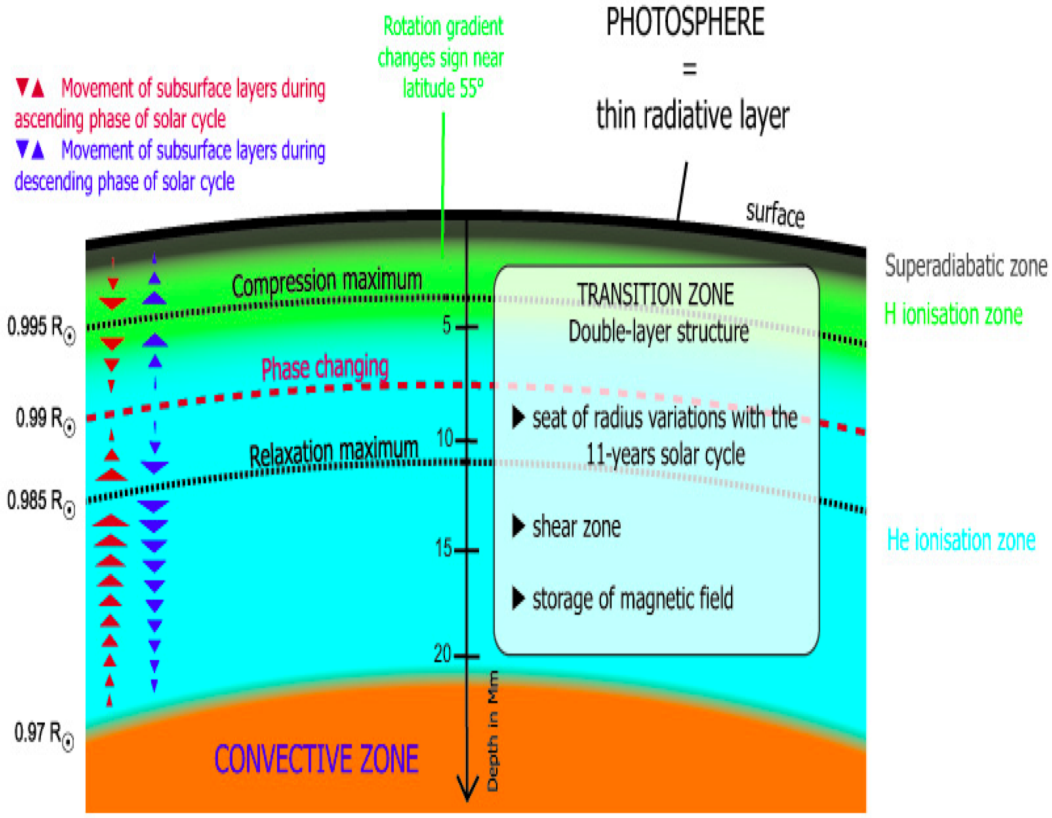
Salabert et al. 2009, Fletcher et al. 2010

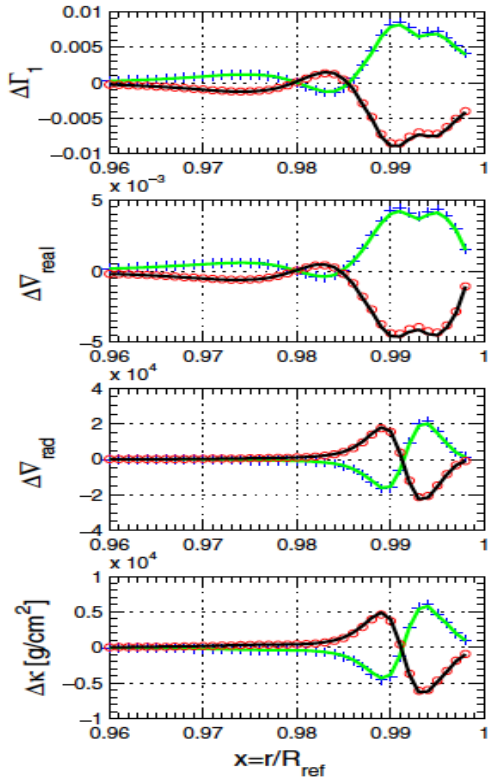


Could solar QBO a second dynamo of the Sun ?



Which kind of region is affected?



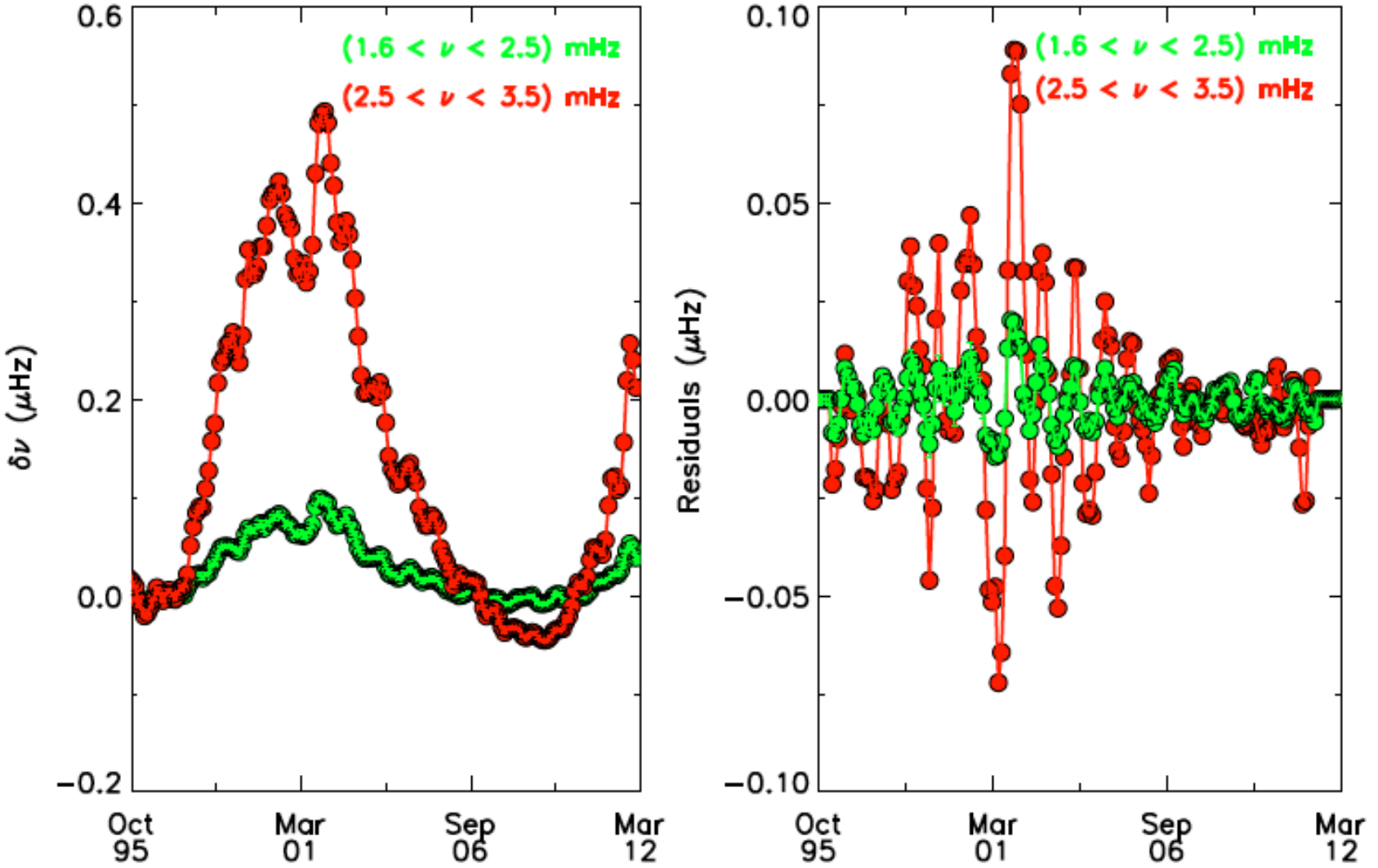


Lefebvre, T-C, Nghiem, A&A 2009

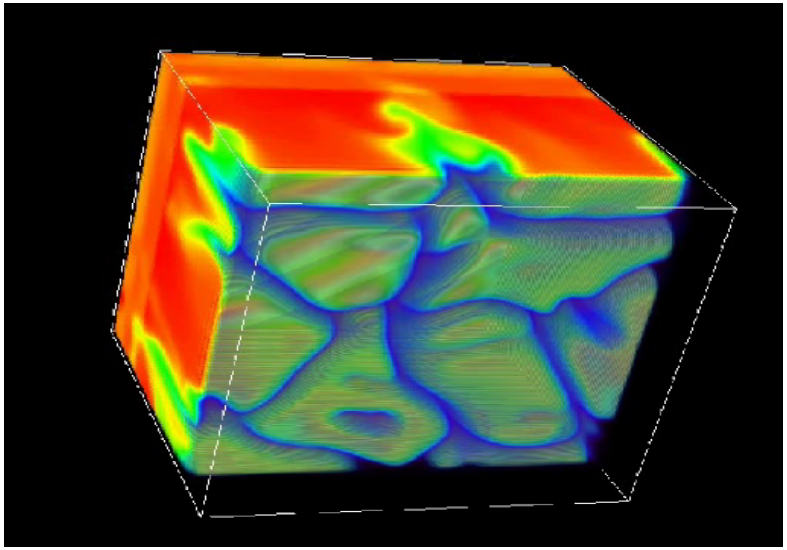
Lefebvre &Turck-Chièze 2010

GONG data: QBP a second dynamo ?

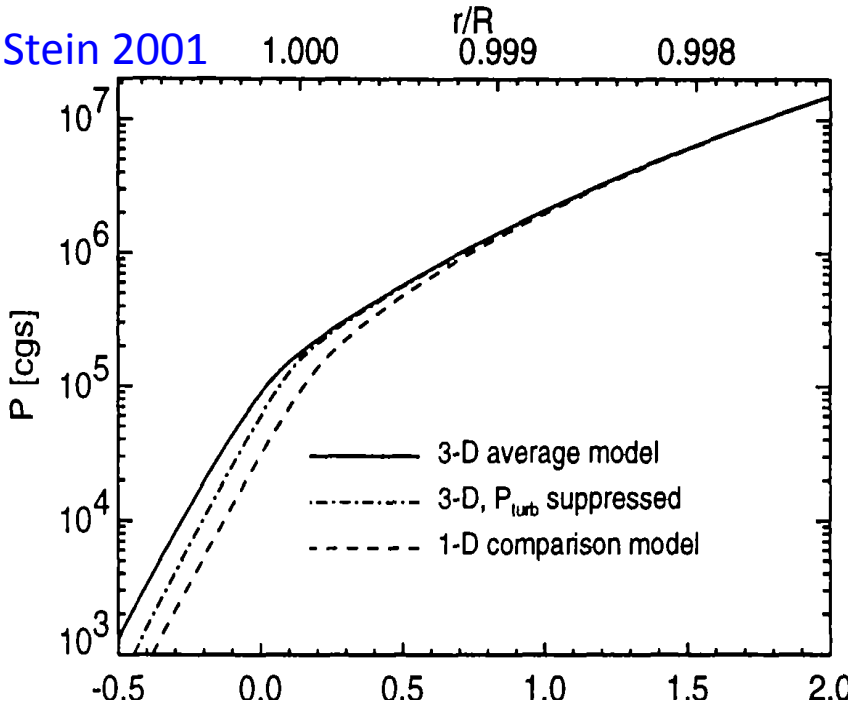
Simoniello et al. 2012, 2013

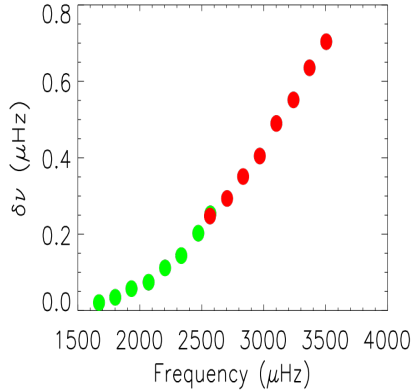


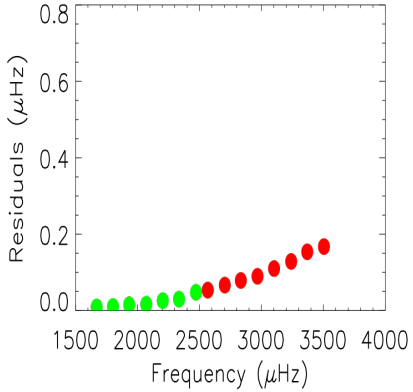
External turning points and 3D simulations with STAGGER

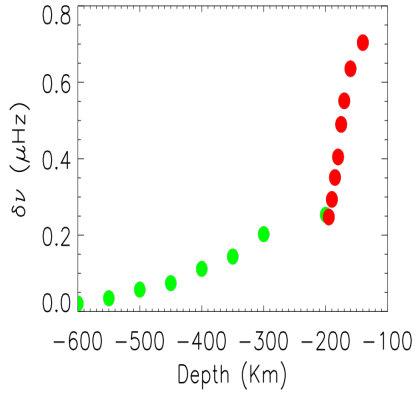


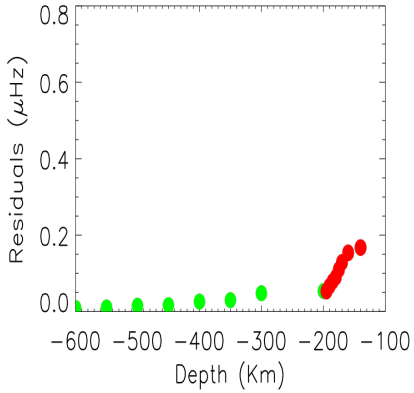
Nordlund & Stein 2001

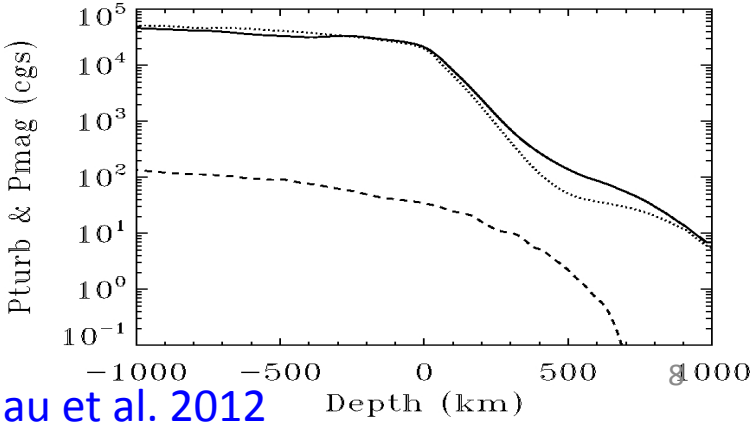












(1.6 < ν < 2.5) mHz

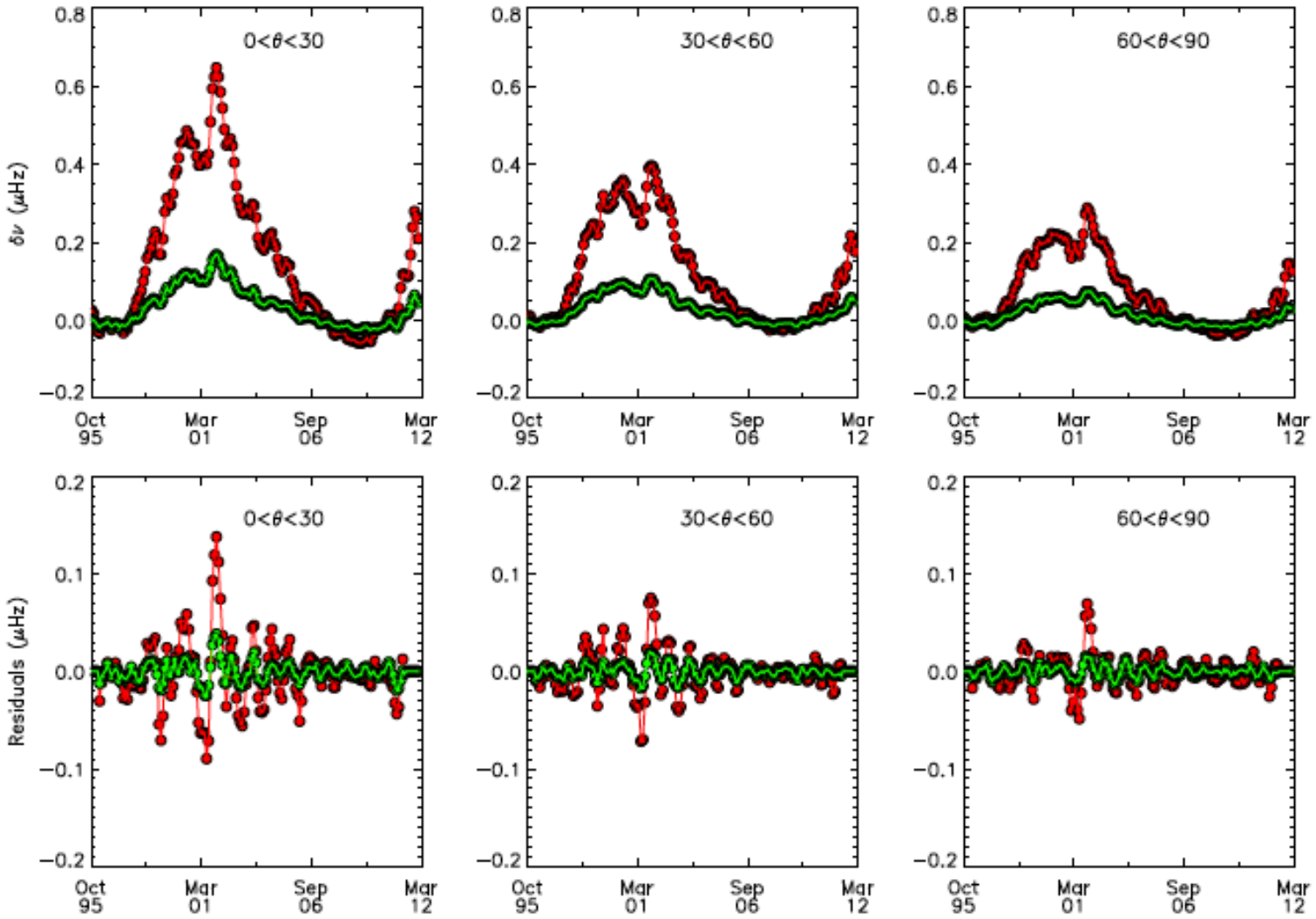
(2.5 < ν < 3.5) mHz

(2.5 < ν < 3.5) mHz

Piau et al. 2012

Frequency dependence analysis in the subsurface layers as function of latitude

Simoniello et al. 2013



1. The increase in the amplitude of the shift over the 11 and 2 yr cycles occurs over the same range of depths and it does not differ as a function of latitude → we do not visualize the need to invoke a further dynamo mechanism

2. Magnetic Rossby waves are predicted and observed to be located at higher latitudes (Tobias et al. 2011, Zaqarashvili et al. 2011) → does not fit with our observational findings on the latitudinal dependence of the shift

3. **The QBP might be the result of the beating between the dipolar and quadrupolar component of the magnetic dynamo configuration**

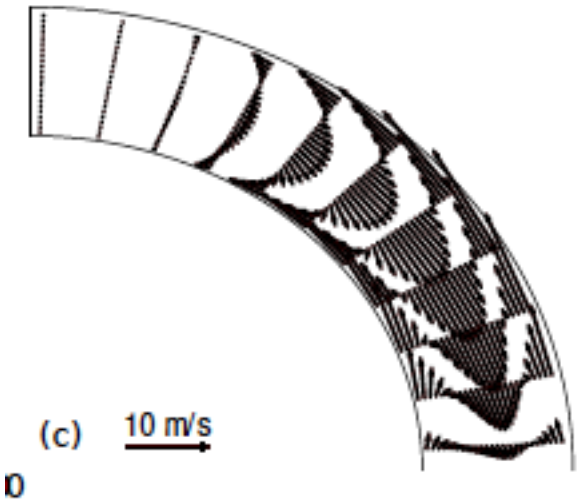
Tobias 2002, Moss et al. 1999, 2004, Fluri & Berdyugina 2004

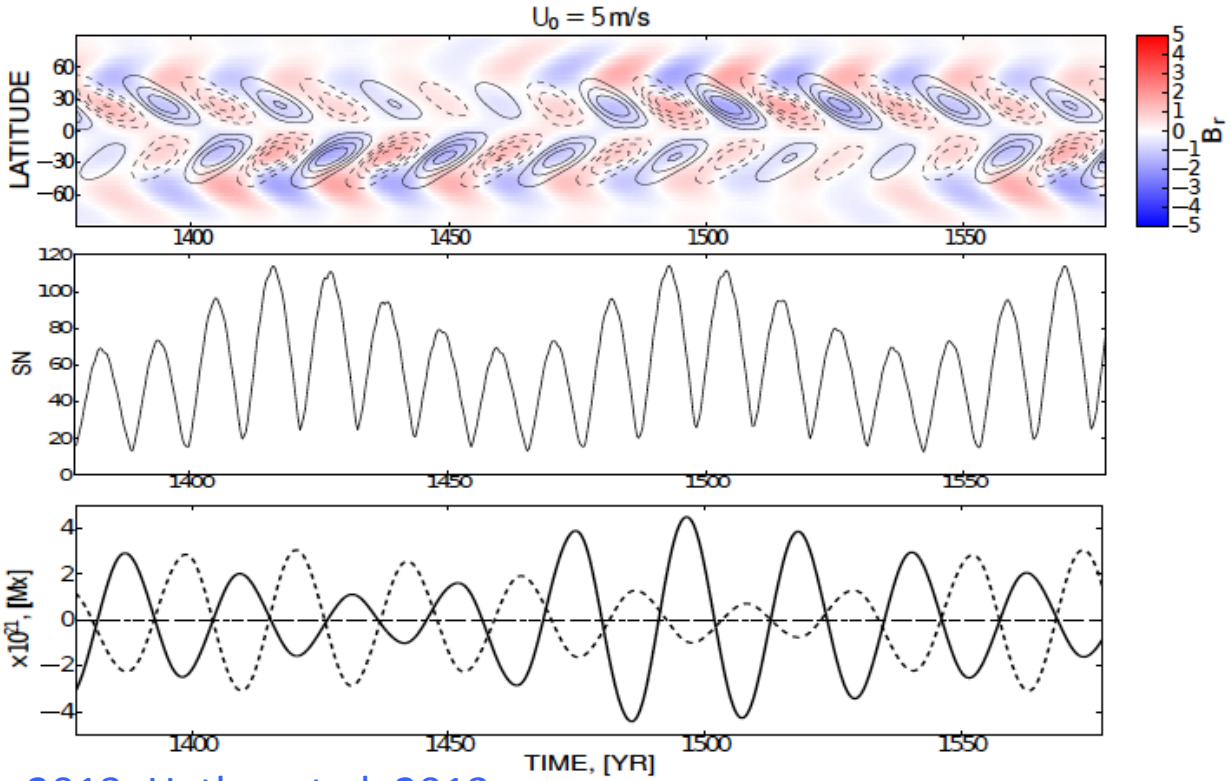
The 11 and 2 year cycle manifestations seen in acoustic modes correspond to very superficial subsurface < 600 km

What could we hope to learn more from the present measurements ?

SDO: Several radial cells in CZ

Could the Gleissberg cycle be generated by a non linear resonance between a dynamo wave and magnetic field at large scale ?

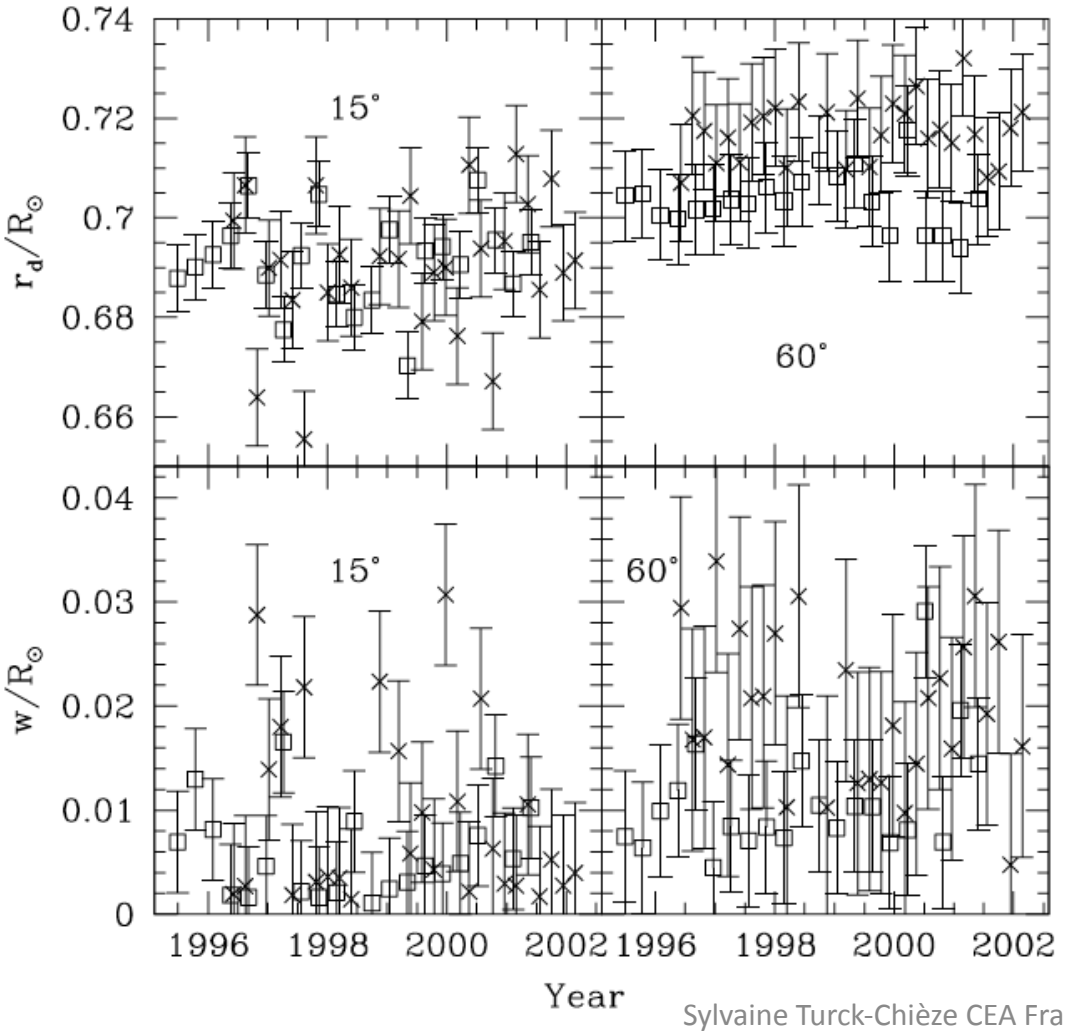




Zhao et al. 2012, Pipin & Kosovichev 2013, Hatlep et al. 2013

Variability of the tachocline: prolate radiative zone ?

Basu & Antia 2003



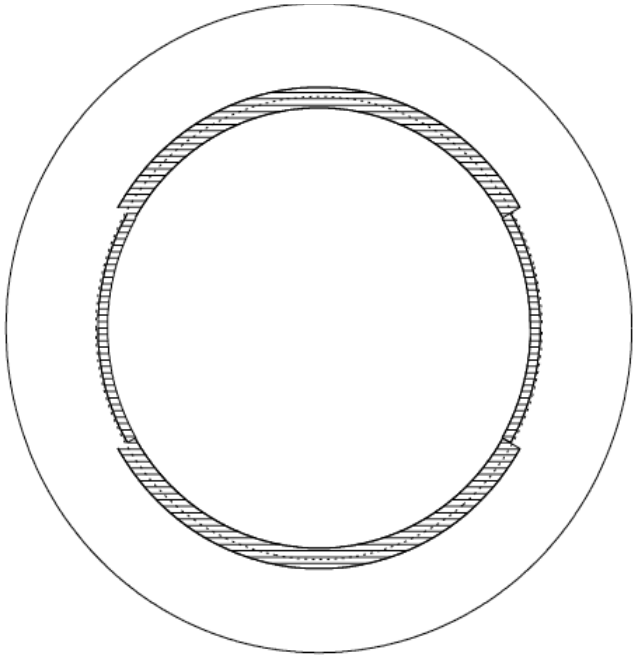


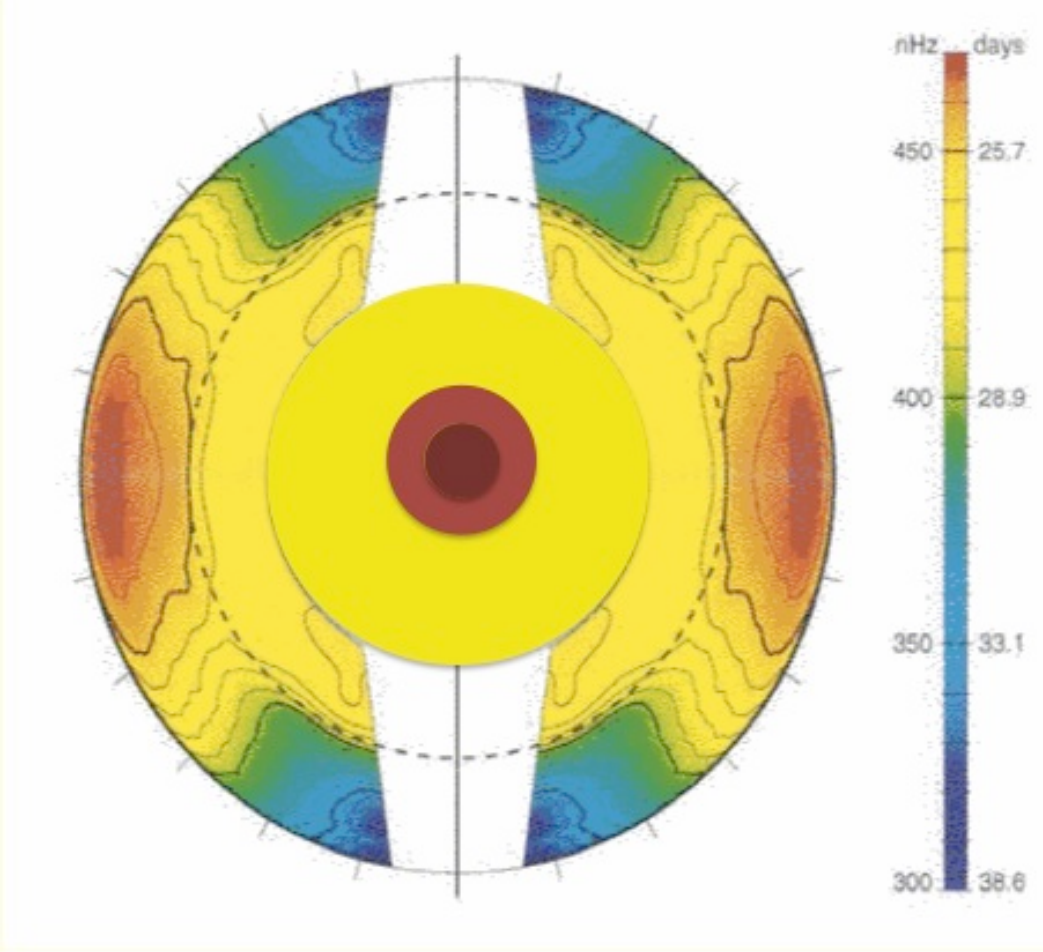
TABLE 2

PROPERTIES OF THE TACHOCLINE AT A FEW SELECTED LATITUDES

Latitude (deg)	$\delta\Omega_t$ (nHz)	r_t ($R_\odot$)	w ($R_\odot$)
0.....	20.82 ± 0.43	0.6916 ± 0.0019	0.0065 ± 0.0013
15.....	17.83 ± 0.24	0.6909 ± 0.0018	0.0078 ± 0.0013
45.....	-30.54 ± 0.54	0.7096 ± 0.0019	0.0103 ± 0.0012
60.....	-67.65 ± 0.74	0.7104 ± 0.0022	0.0151 ± 0.0020

A first attempt to detect the global internal rotation profile:

role of the RZ in the description of the field variability ?



GOLF is the only instrument which might have detected the first gravity modes. They seem to show that the central rotation is 5 to 8 greater than the rest of the rotation of the radiative zone.

Turck-Chièze et al ApJ 2004,
Garcia et al. Science 2007, 2008, 2011
Turck-Chièze et al 2010,
Turck-Chièze & Couvidat 2011,
Turck- Chièze & Lopes 2012

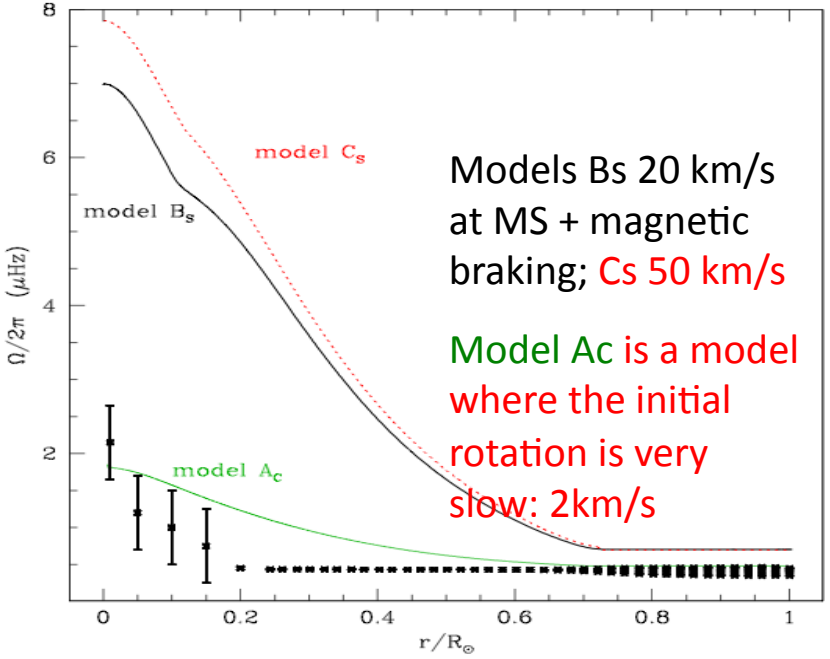
Solar 1D model includes transport of momentum by rotation

Zahn 1992, Turck-Chièze, Palacios, Marques, Nghiem ApJ 2010

$$\rho\frac{d}{dt}\left(r^2\overline{\Omega}\right)=\frac{1}{5r^2}\frac{\partial}{\partial r}\left(\rho r^4\overline{\Omega}U_2\right)+\frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho\nu_v r^4\frac{\partial\overline{\Omega}}{\partial r}\right)$$

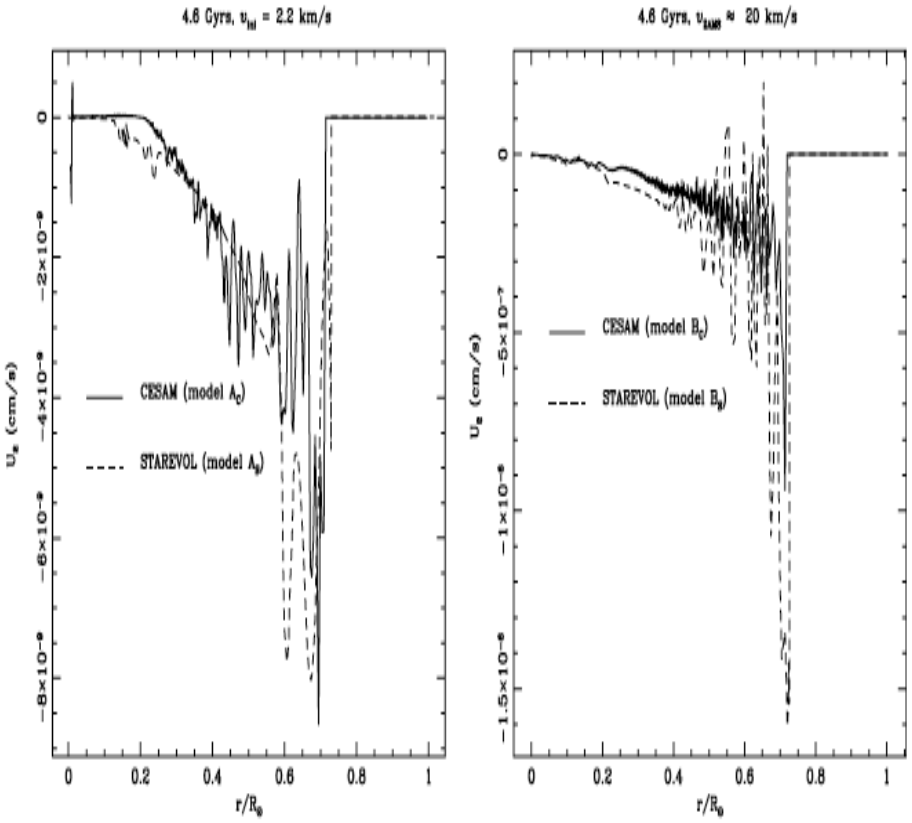
Advection term + diffusive term

Solar rotation extracted by GOLF+MDI



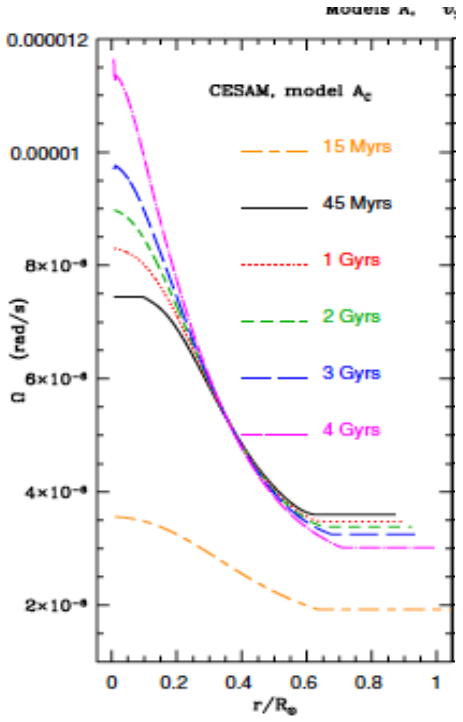
Models Bs 20 km/s at MS + magnetic braking; Cs 50 km/s

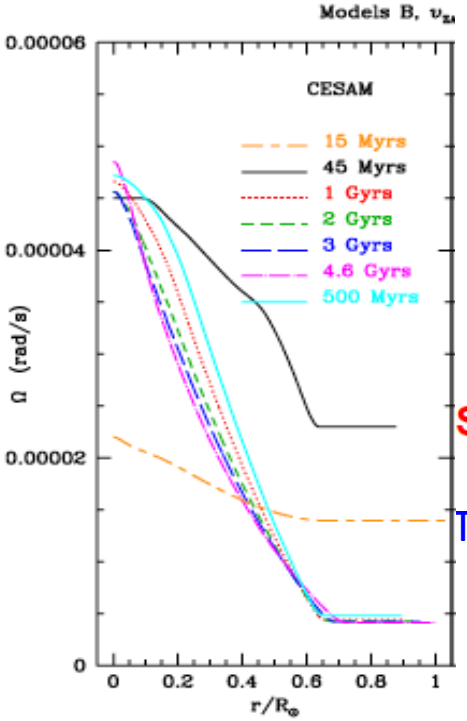
Model Ac is a model where the initial rotation is very slow: 2km/s

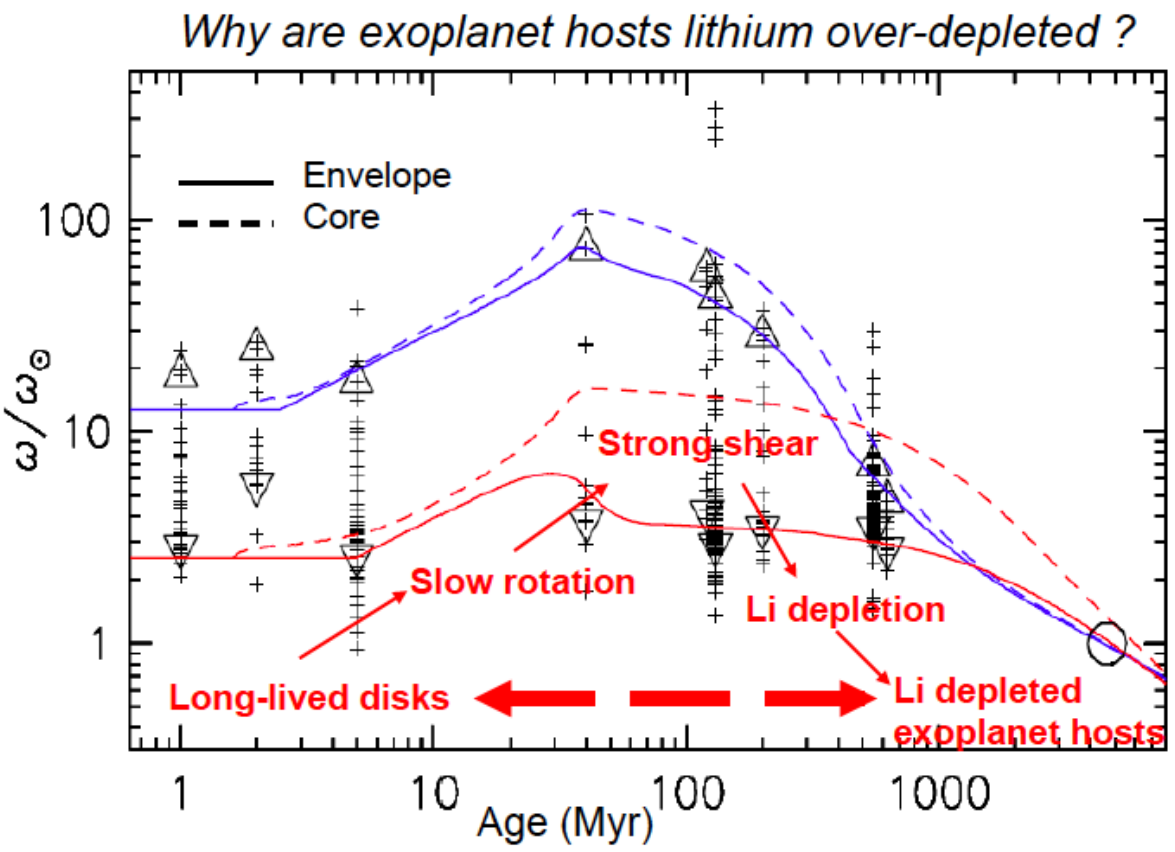


The meridional circulation of the RZ appears extremely slow: 10^{-8}-10^{-6}cm/s. Very different of MC of the CZ: 10m/s not far from the surface… at the bottom? This gives a natural hydrodynamical nature to the tachocline: 3D simulations ? Strugarek et al. 2012, Alvan et al. 2013

Central rotation strongly evolves during the premainsequence







Suggests that long lived disks (≥ 5 Myr) are required for planet formation

Turck-Chièze et al. 2010, Eggenberger et al. 2010, 2012, Bouvier 2008

Shape of the Sun: Solar oblateness

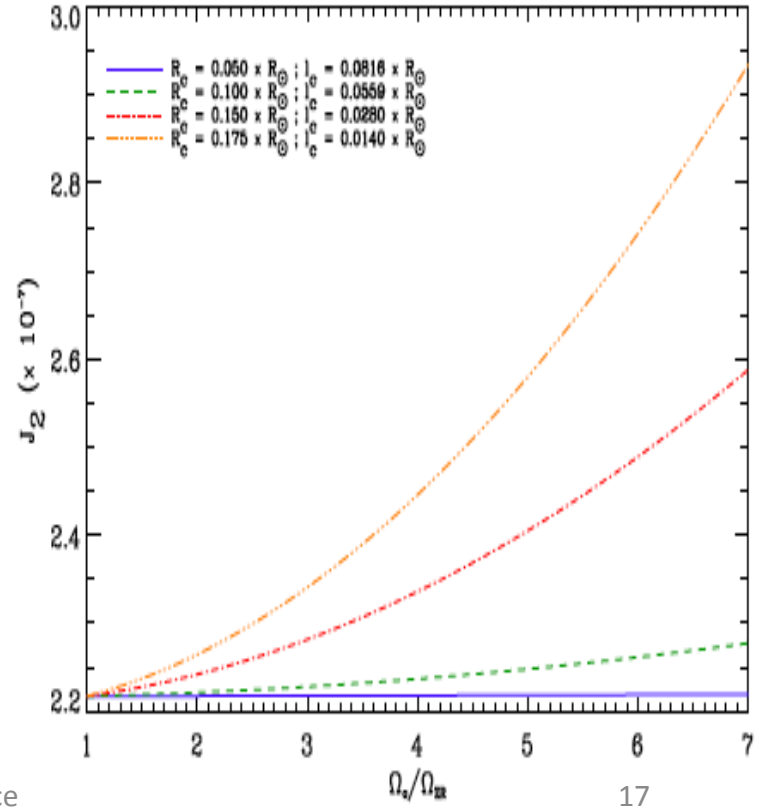
$$\varepsilon = \frac{r_E - r_P}{r_E} = \varepsilon_G + \varepsilon_S = \frac{3}{2} J_2 + \frac{1}{2} \frac{\Omega^2 R^3}{GM}$$

+ surface magnetic effects

ε_G is influenced by the rotation of the core and by a fossil magnetic field if any

$$2.21 \times 10^{-7} < J_2 < 2.94 \times 10^{-7}$$

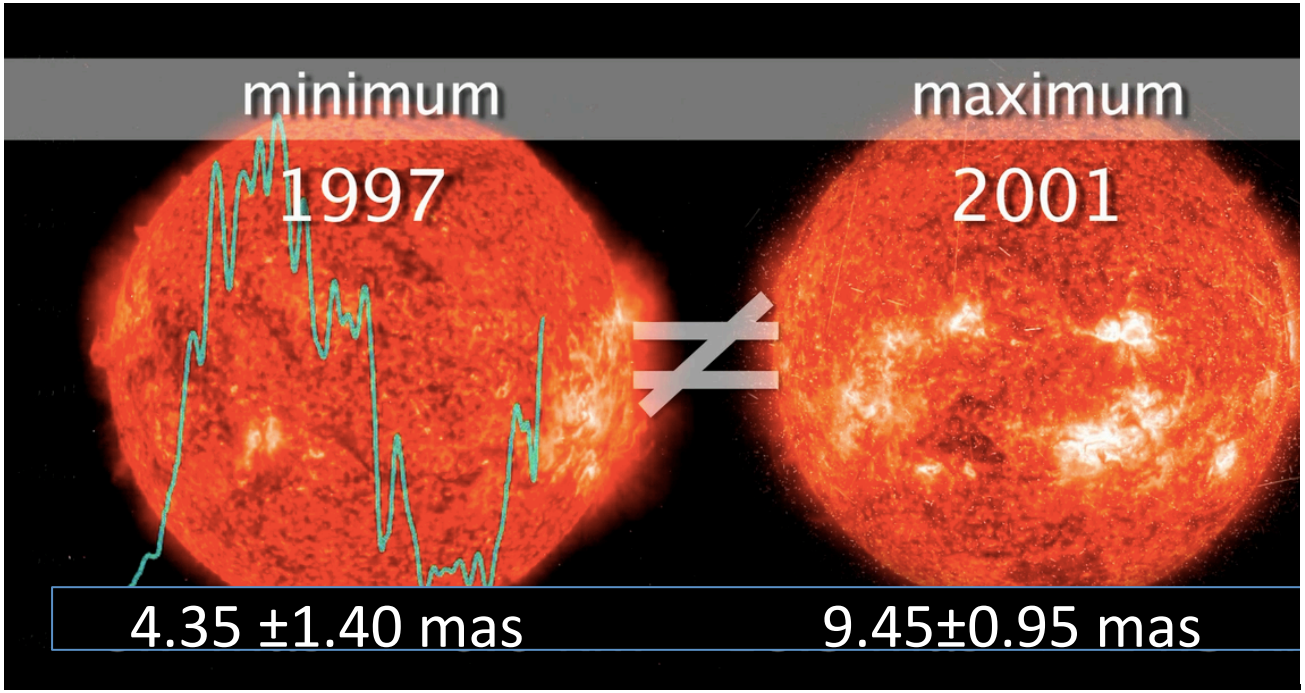
ε_s= 8.45 10^{-6} for Ω_s= 2.58 μrad/s

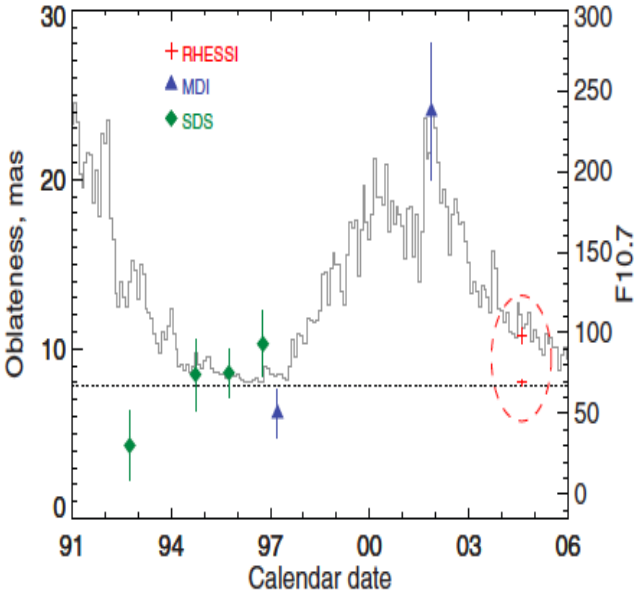


Shape of the Sun: Solar oblateness

MDI/SoHO- Rhessi, SDS, HMI/SDO and PICARD

Kuhn et al. 1998, Emilio et al. 2007, Fivian et al. 2008, Hauchecorne et al. 2014





With correction of the solar surface activity

8.01±0.14 mas: 8.4 10^{-6} Fivian et al. 2013

Both HMI, SDO and PICARD take several images in turning the satellite

HMI

no result from PICARD yet, error bars ?

1-5% to be informative, very difficult

What do we need for a real progress on the understanding of the sources of the solar variability at long term (centuries)

- We need to continue to observe the convective zone to see the meridional circulation at the BCZ and the different cells: SDO + Solar Orbiter

- We need to pursue the present investigation through observation of acoustic and gravity modes (GOLF-NG) and 3D simulations to have a real view of the global magnetism: no programmatic mission presently

What we want to study with new observations ?

- Temporal variability of the tachocline,
- Shape of the tachocline: acoustic modes and gravity modes
- Rotation axis of the solar core, confirmation of its rate
- Deep magnetic field? Core? Rest of the RZ?
- Topology of that field

- One needs to program a new space mission for horizon 2025-2040 like FF DynaMICCS for space climate: Gleissberg cycle

- Movie on the solar oblateness from LATMOS, CNES, CEA and CNRS: 15 mn