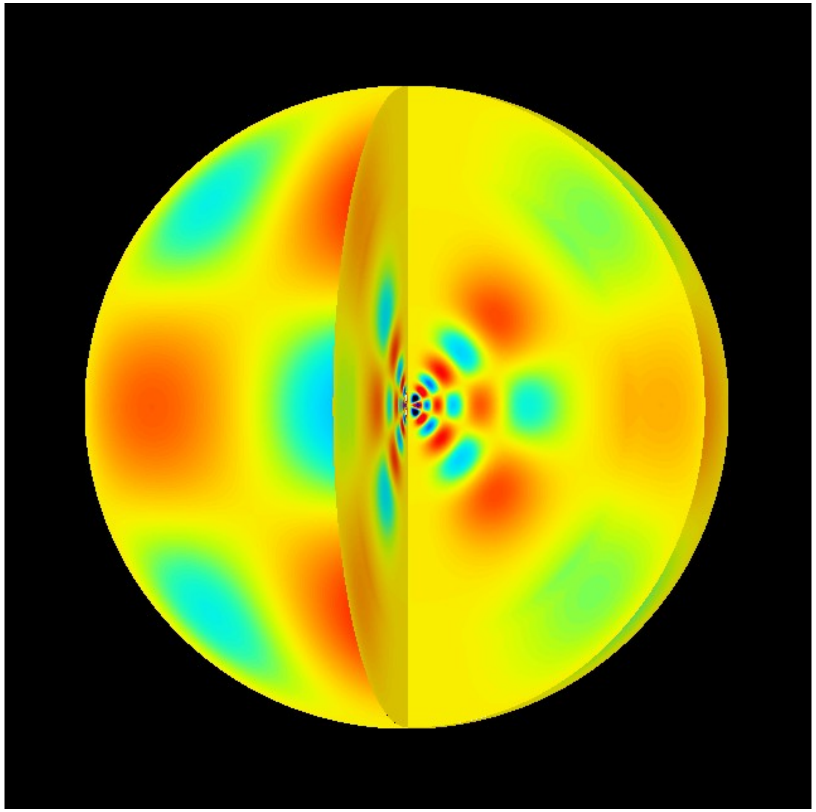
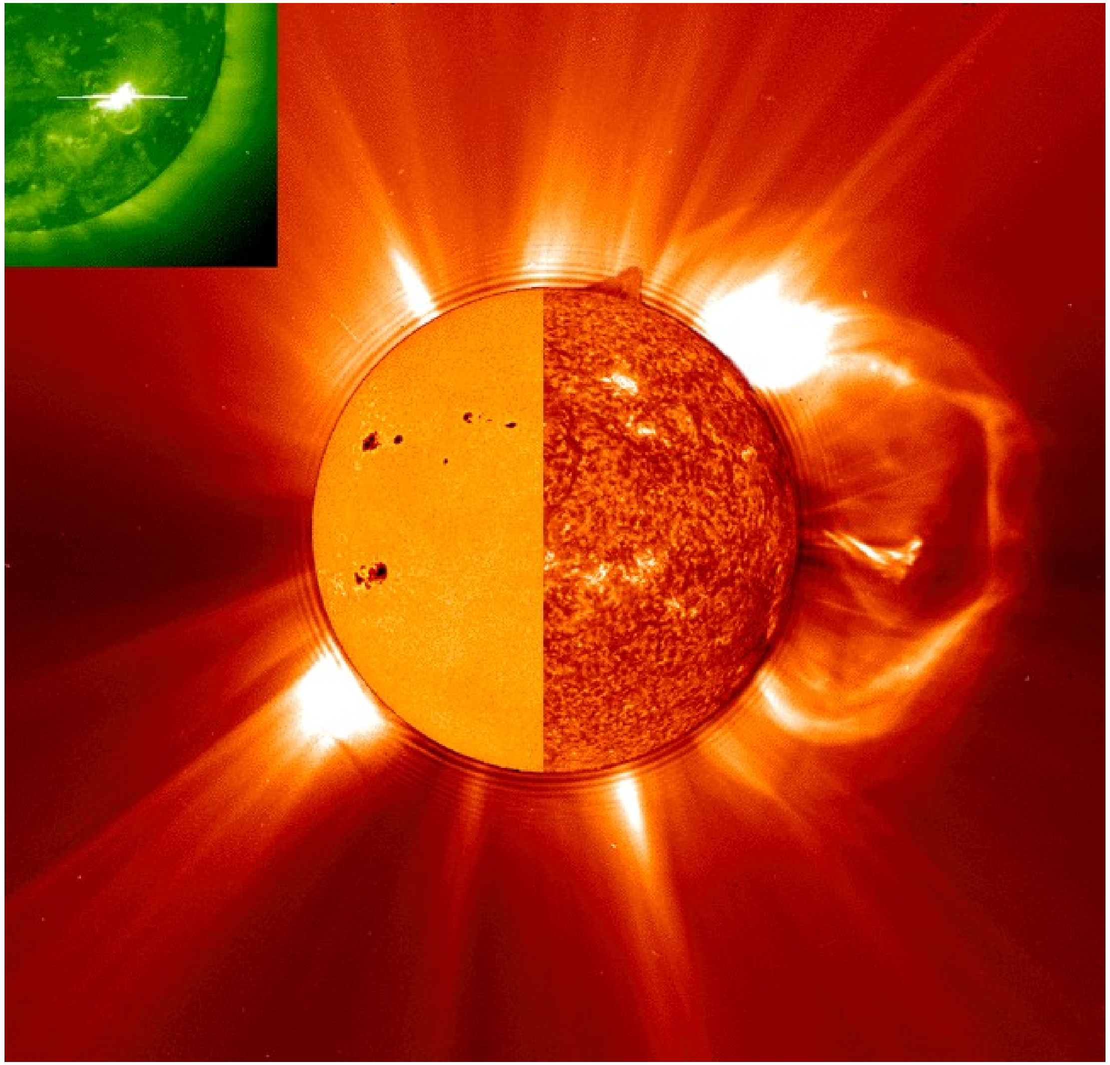


# Mesure du champ magnétique interne du Soleil: présent et futur

*Sylvaine Turck-Chièze, Beaulieu, PNST, May 27th, 2005*



# The magnetism of the solar interior

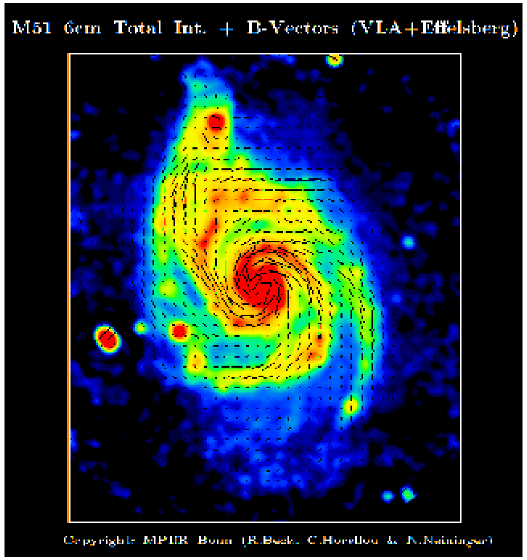
## *Towards a full 3D solar vision*

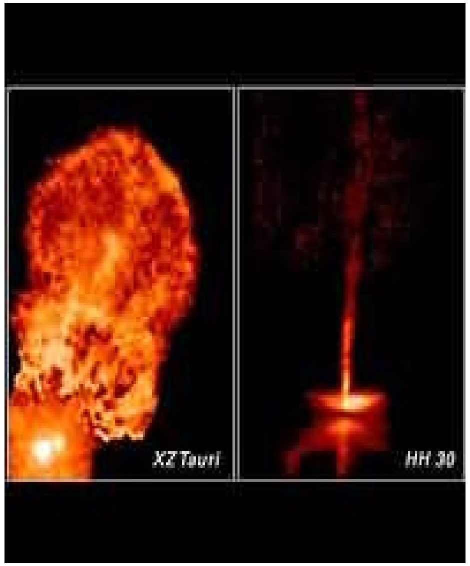
*(Cosmic Vision 2020)*

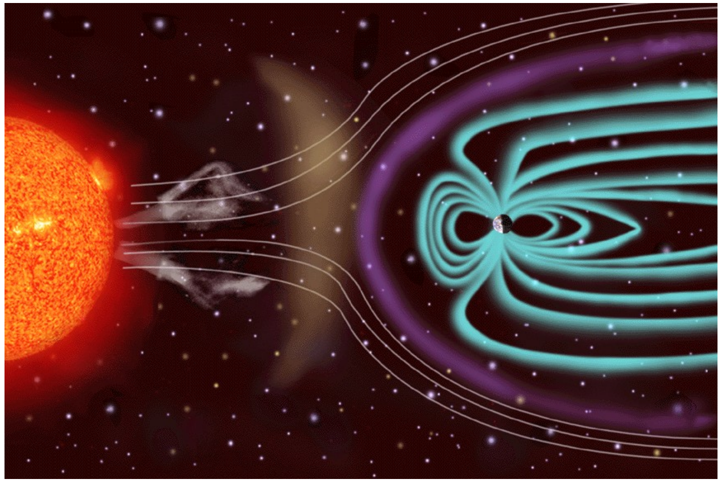
**Turck-Chièze, S.[1], Appourchaux, T.[2], Boumier, P.[2], Ballot, J.[1], Berthomieu, G.[3]; Brun, A. S.[1], Cacciani, A.[4],Christensen-Dalsgaard, J.[5], Corbard, T.[3], Couvidat, S.[6], Darwich, A. M.[7], Fossat, E.[3], Garcia, A. R.[1],Gelly, B.[7], Gizon, L[8], Gough, D.[9], Jimenez, A. J.[7]; Jimenez-Reyes, S.[7]; Kosovishev, A.[6]; Lambert, P.[1]; Lopes, I.[10]; Martic, M.[11]; Mathis, S.[12]; Nghiem, P. A. P.[1]; Palle, P.[6]; Piau, L.[13]; Provost, J.[3]; Rieutord, M.[14];Robillot, J. M.[15]; Roxburgh, I.[16]; Rozelot, J. P.[3]; Solanki, S[8],Thompson, M.[17]; Thuillier, G.[11]; Vauclair, S.[18]; Zahn, J. P.[12].**

[1]CEA, **FRANCE**; [2]IAS, **FRANCE**; [3]Observatoire Cote d'Azur, **FRANCE**; [4]Dipartimento di Fisica Università degli Studi di Roma, **ITAL.Y**; [5]Aarhus Universiteit, **DENMARK**; [6]HEPL, Stanford, **UNITED STATES**; [7]IAC, **SPAIN**,[8] Max Planck Lindau, **GERMANY**; [9]Cambridge, **UNITED KINGDOM,** [10]Istituto Superior Técnico, Lisboa, **PORTUGAL**; [11]Service d'Aéronomie, **FRANCE**; [12]LUTH Meudon, **FRANCE**; [13]Dept of Astron. & Astroph., Chicago, **UNITED STATES**; [14]Laboratoire d'Astrophysique de Tarbes, **FRANCE,** [15]Observatoire de Bordeaux, **FRANCE,** [16]Queen Mary College London, **UNITED KINGDOM,** [17] University of Sheffield, **UNITED KINGDOM**, [18]Observatoire de Toulouse, **FRANCE.**

## *The baryonic Universe is mainly composed of plasma, so, magnetism plays a fundamental role in our Universe*





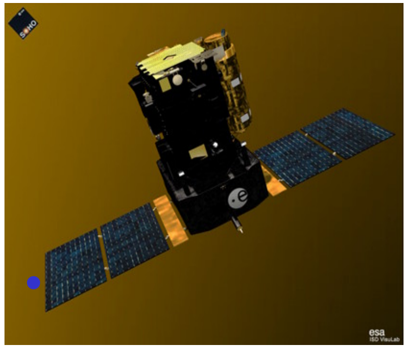


*But magnetism is still poorly known. Magnetic field is not yet present in most of the equations describing our Universe.*
*It is not yet present in the equations which describe the life of stars.*

# *In this context, the magnetism of the solar interior has a key role !*

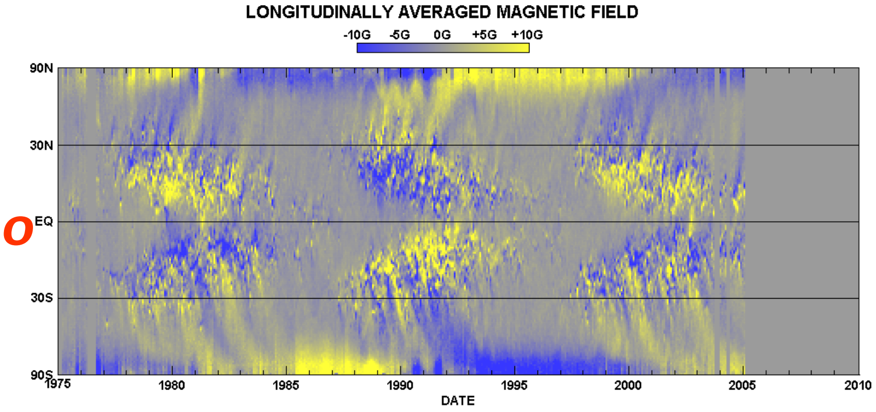
- ***It will help to build a unified vision of stars***
- ***It will help to understand the real solar role on the earth climate***
- ***Understanding all the instabilities, connected to magnetic field, is also useful for terrestrial magnetic fusion (ITER)***

***The Sun is a unique object for which we may hope a quantitative approach before generalization to other more energetic objects (young stars, final evolution stages …) during the period of the Cosmic Vision.***



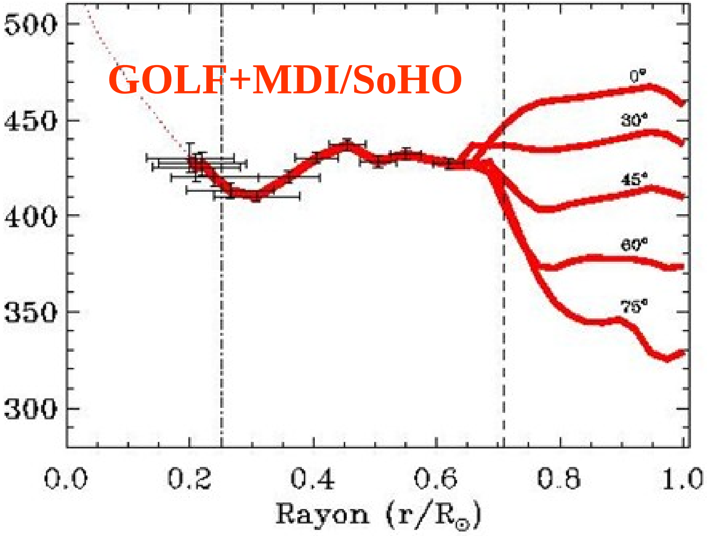
# *What have we learned these last 10 years with the development of helioseismology?*

***The slow and organized solar activity is not a purely superficial phenomenon***

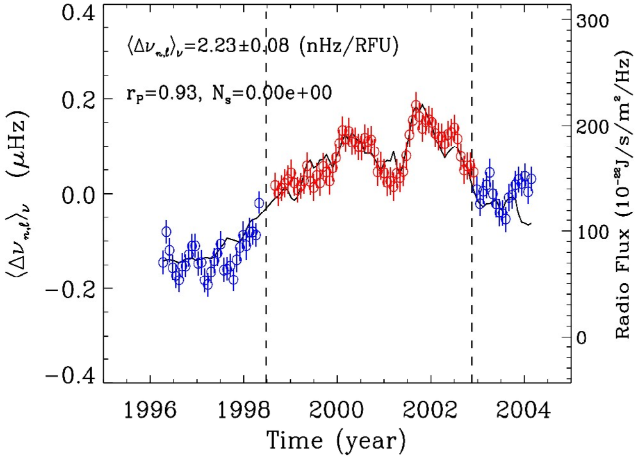


NASA/NSSTC/Hathaway 2005/02

- ***It concerns at least the 30% outer convective zone and the dynamo process depends clearly on the rotation profile***



Couvidat et al. 2003 Kosovichev et al. 1997

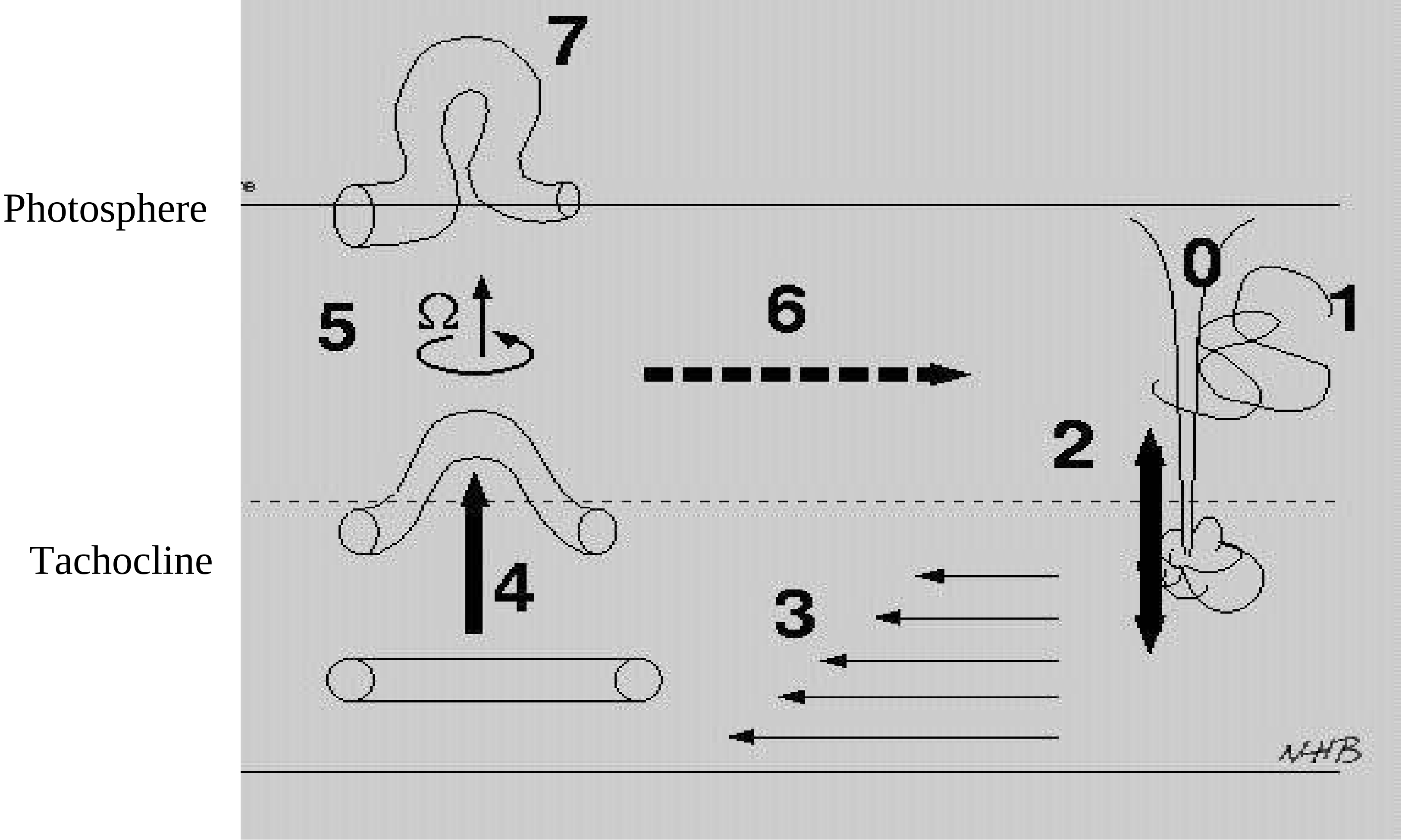


Garcia et al. 2003

**Tachocline B < 300kG,**
**Radiative zone: B < 30MG**
**limit of 7 MG ?**
**from deformed Sun**

Couvidat et al., 2003

# *Role of the tachocline*

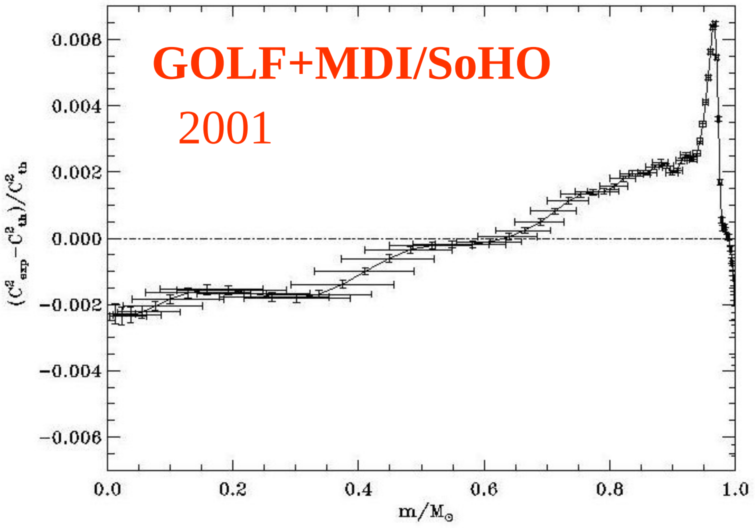


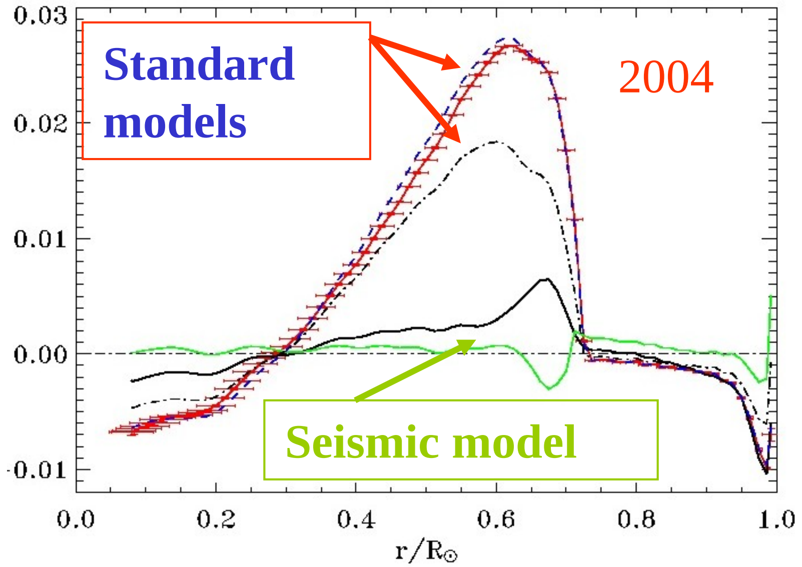
Brummell

# The solar radiative zone: 98% of the mass is nowadays « visible » but not yet under control !

- *Standard solar model is marginally consistent with observations (neutrinos + acoustic modes).*
- *But, seismic measurements agree very well with neutrino observations*

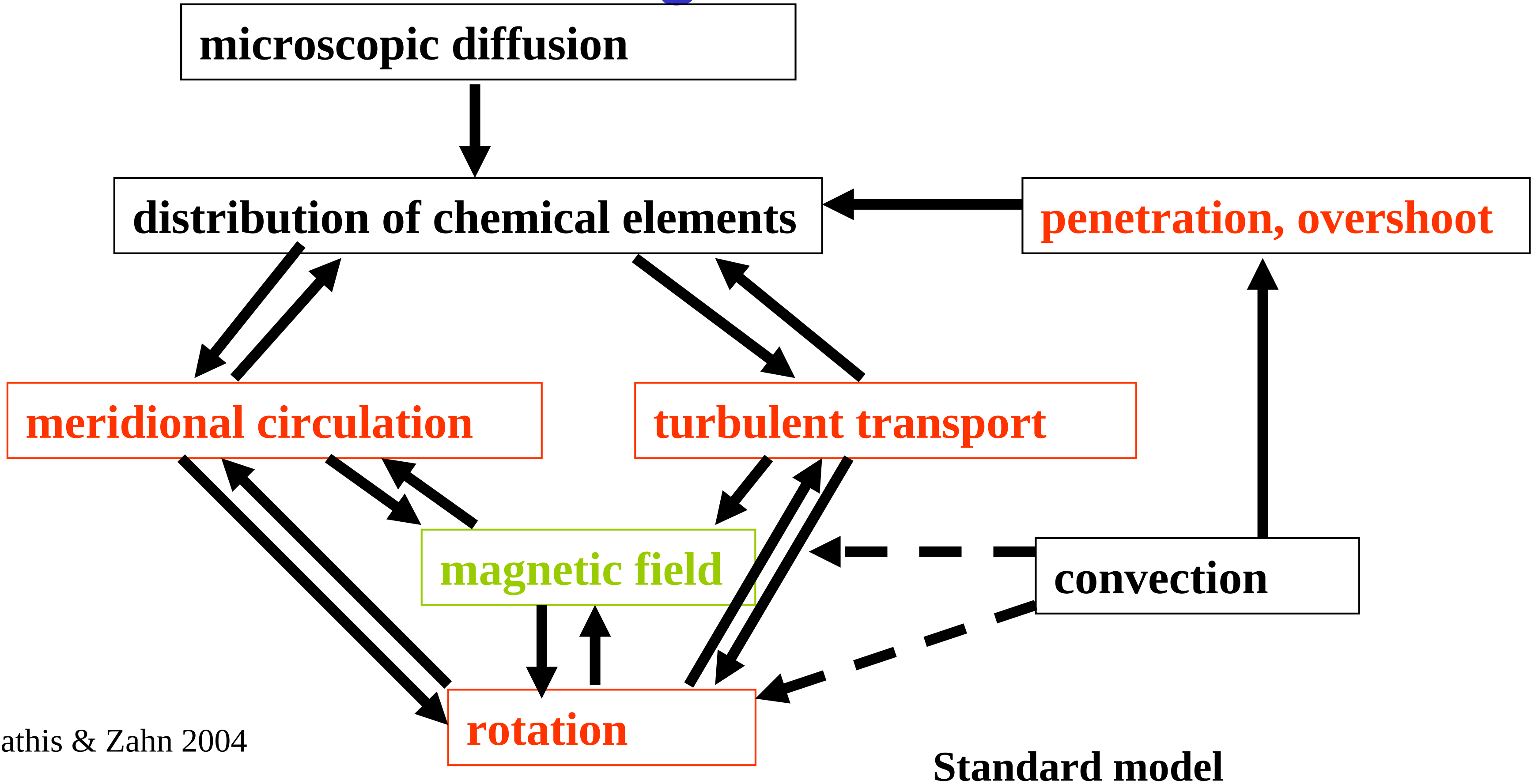
Turck-Chièze et al, 2001a,b, 2004; Couvidat et al., 2003





- *Hypotheses are too simple !!*
    - *Instantaneous interaction of photons with matter*
    - *No effect of transport of matter or of magnetic field …*
    - *We conclude that the energetic balance is not precise today…*
    - *Dynamics in the radiative zone is not yet observed but the flat rotation profile suggests the presence of magnetic field…*

# We will introduce dynamical processes in stellar radiative zones to estimate the solar real energetic balance



microscopic diffusion

distribution of chemical elements

penetration, overshoot

meridional circulation

turbulent transport

magnetic field

convection

rotation

Mathis & Zahn 2004

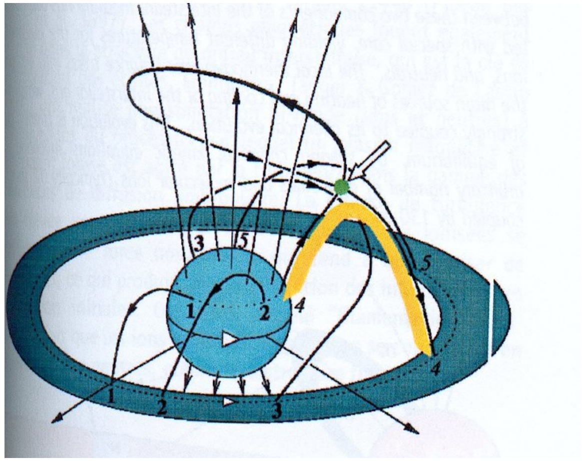
**Standard model**

**Seismic model**

**Magnetohydrodynamical model**

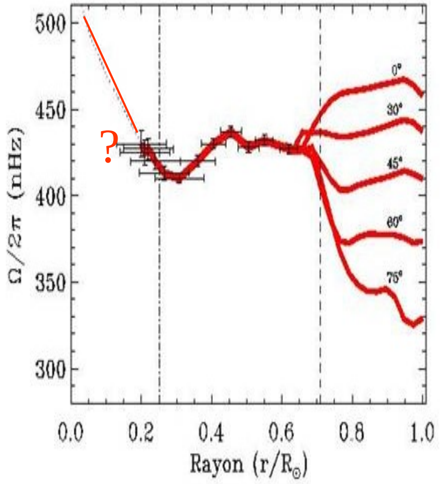
# What we would like to know ?

- ***The latitudinal rotation of the inner radiative zone***
- ***A dynamical description of the core***
- ***Is there a relic of the formation of the solar system: higher rotation profile ?***
- ***Some magnetic constraints in the radiative zone***

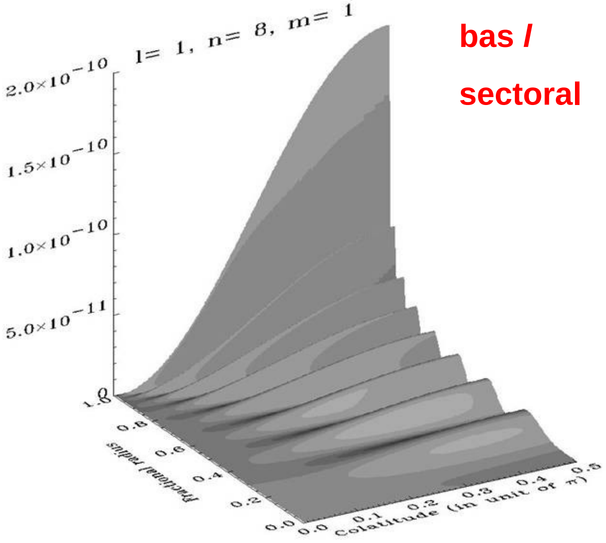


*Montmerle 2000*

**Rotation profile from GOLF+MDI / SOHO acoustic modes**



*Couvidat et al. 2004*



bas *l*

sectoral

***We want to quantify the real energy balance and its variabilities***

# Simplified 1D equations of stellar evolution

## « standard solar model »,

## no rotation, no magnetic field

$dP/dr = - [M(r)\, G/r^2]\, \rho$ static equilibrium

$dM/dr = 4\pi\, r^2\, \rho$

$dL/dr = 4\pi\, r^2\, \rho\, (\varepsilon_{nucl} - T\, dS/dt)$

$dT/dr = - 3/\, 4ac\, [\kappa\rho\, /T^3]\, [L(r)/\, 4\pi\, r^2]$ radiative zone

$dT/dr = [\Gamma_2 - 1/\Gamma_2]\, T/P\;\; dP/dr$ convective zone

successive static equilibria

$\partial X_i/\partial t = - \partial(4\pi\rho r^2 X_i V_i)/\partial m$ + nucl. terms

$Vi = - 4\pi\rho r^2 (D_i + D_T)\, \partial \ln X_i/\partial m + v_i$

# MHD General Equations for stellar evolution

$\nabla\cdot(\rho v) = 0$ mass conservation

$\nabla\cdot B = 0$

$$\rho\,(\partial v/\partial t + (v\cdot\nabla)\,v + 2\Omega \times v) = -\nabla P + \rho g + 1/4\pi(\nabla\times B)\times B - \nabla\cdot D - (\nabla P - \rho g)$$

momentum equation

$$\rho T\,\partial S/\partial t + \rho T\, v\cdot\nabla(S + S) = \nabla\cdot[\kappa_r \rho c_p \nabla(T + T) + \kappa \rho T \nabla(S + S)] + 4\pi\eta/c^2 j^2 + 2\rho\nu[e_{ij}e_{ij} - 1/3(\nabla\cdot v)^2] + \rho\varepsilon$$

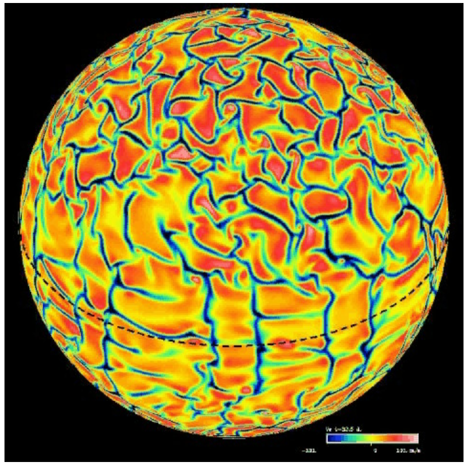
energy equation

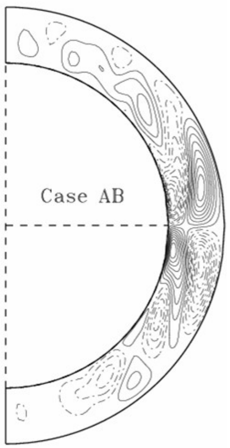
$\partial B/\partial t = \nabla\times(v\times B) - \nabla\times(\eta\nabla\times B)$ induction equation

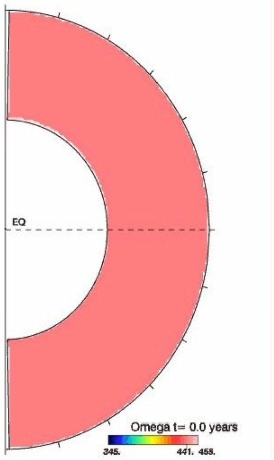
$v=(v_r, v_\theta, v_\phi)$   $B=(B_r, B_\theta, B_\phi)$ $j=c/4\pi(\nabla\times B)$, $c_p, \kappa_r, \nu, \kappa, \eta, D$

# *Importance of the 3D simulations*

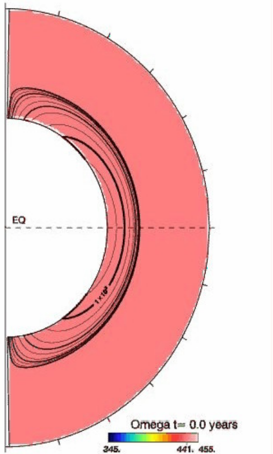
Nordlund & Stein, Brun &Toomre 2002

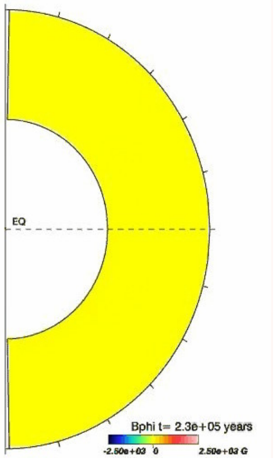






Rudiger & Kitchakinov; Brun & al. 2005





**Asymetry between pole and equator Convection => thermal asymetry, meridional circulation**

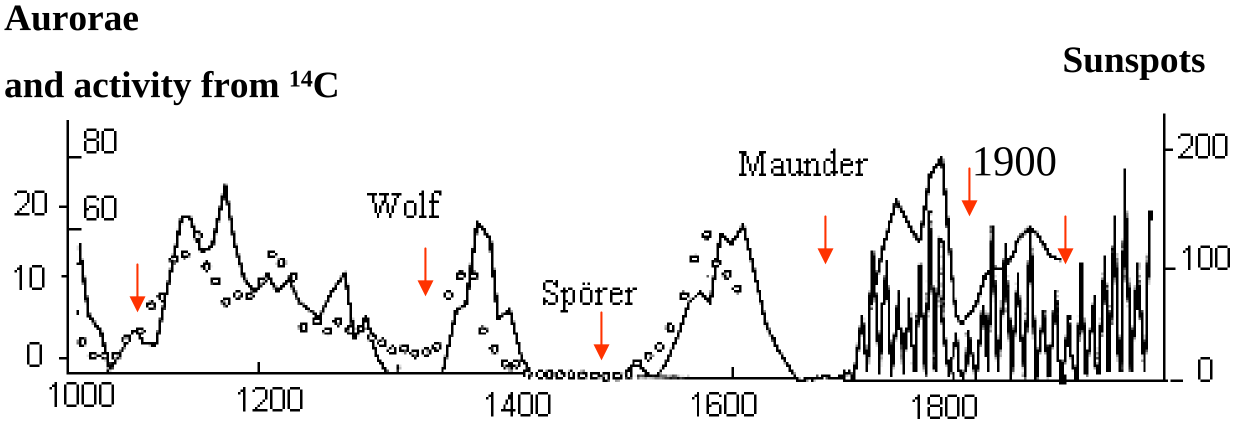
**Simulations of the radiative zone:**

Without magnetic field: the tachocline penetrates the radiative zone

With a primordial seed of magnetic field: it blocks this region, but the configuration is not well established

# *We need to understand the great variations of solar activity and its impact on the earth climate*

See Solanki et al, 2004



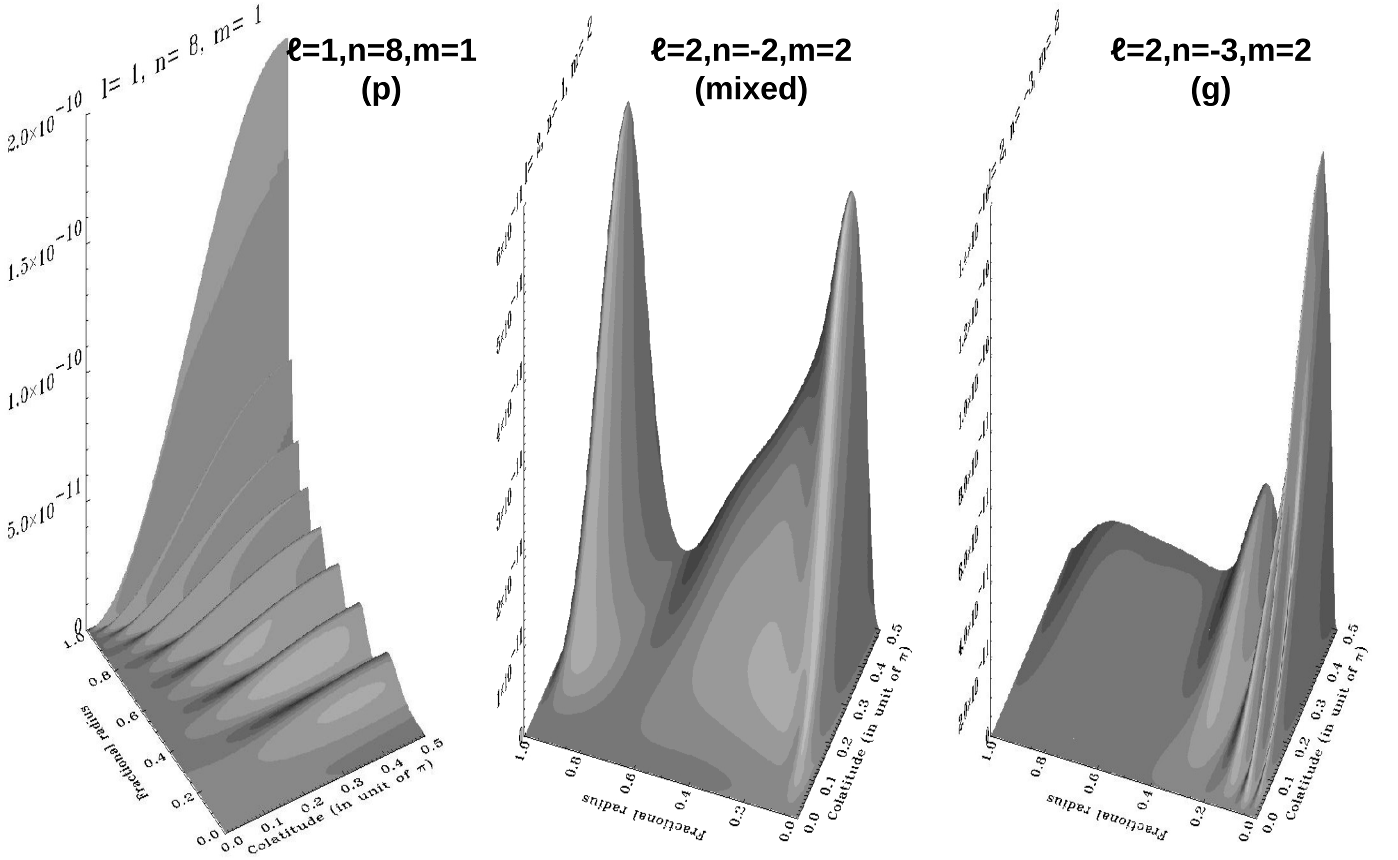
*Could we associate some variations of luminosity due to longer magnetic cycles or other magnetic variabilities ?*

*Can we imagine several kinds of dynamos, even in the radiative zone, several cycles ?*

*Can we imagine interconnection of the magnetic field between radiative and convective zones ?*

*3D MHD simulations have to be guided by more observations of the solar radiative zone, which magnetic field configurations are stable? poloidal + toroidal fields ….*

# The only way to learn more information on radiative zone from observations:
# detection of gravity modes



**ℓ=1,n=8,m=1**
**(p)**

**ℓ=2,n=-2,m=2**
**(mixed)**

**ℓ=2,n=-3,m=2**
**(g)**

# Evolution of ideas on gravity modes

Lifetime of the modes !!!
Rotation on an axis different from that of the solar envelope
An oblique core magnetic field

# Magnetic fields and stellar oscillations: M. Thompson

In a non-magnetised, non-rotating, spherically symmetric star the adiabatic wave equation (neglecting the Eulerian gravitational perturbation) is

$$\mathcal{L}\xi \ + \ \rho\omega^2\xi \ = \ 0$$

where $\mathcal{L}\xi \ = \ -\nabla[(p-\rho c^2)\nabla\cdot\xi-\xi\cdot\nabla p]+p\nabla(\nabla\cdot\xi)-\xi\cdot\nabla(\ln\rho)\nabla p$

In a magnetised, rotating star this is modified to

$$\mathcal{L}\xi \ + \ \rho\omega^2\xi \ = \ \omega\mathcal{M}\xi+\mathcal{N}\xi+\mathcal{B}\xi$$

where $\mathcal{M}\xi \ = \ -2i\rho v\cdot\nabla\xi$

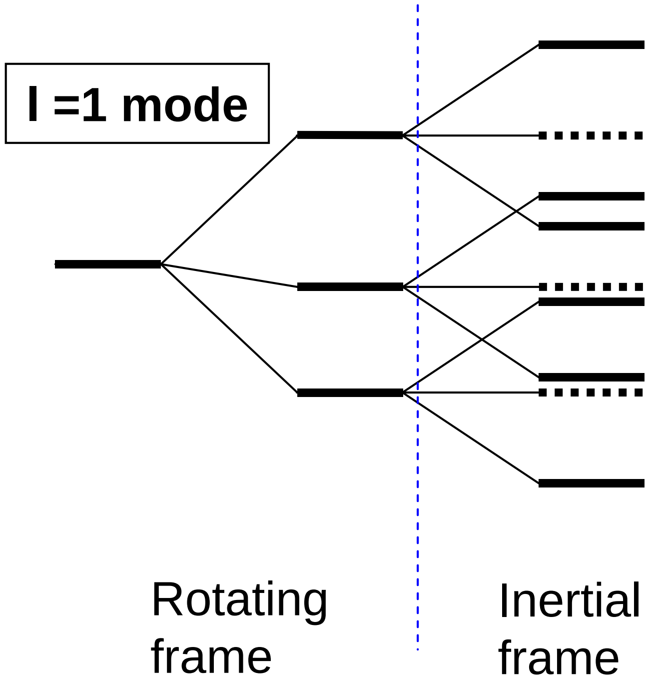
$$\mathcal{N}\xi \ = \ -\rho\xi\cdot\nabla(v\cdot\nabla v) \ + \ \rho(v\cdot\nabla)^2\xi$$

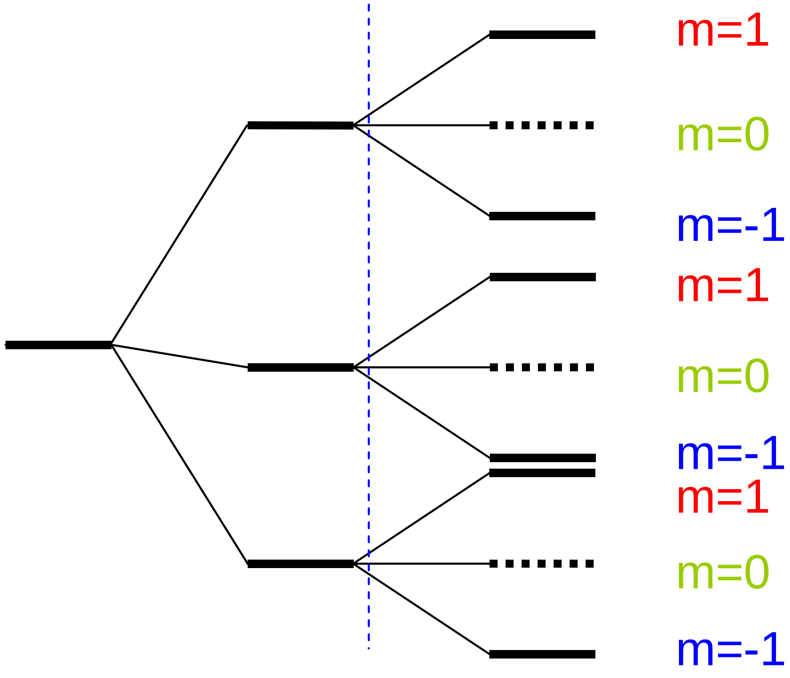
$$\mathcal{B}\xi \ = \ -\frac{\nabla\cdot(\rho\xi)}{\rho}(\nabla\times B)\times B-(\nabla\times B')\times B-(\nabla\times B)\times B'$$

and

$$B' \ = \ \nabla\times(\xi\times B)$$

# Hyperfine splitting from M. Thompson



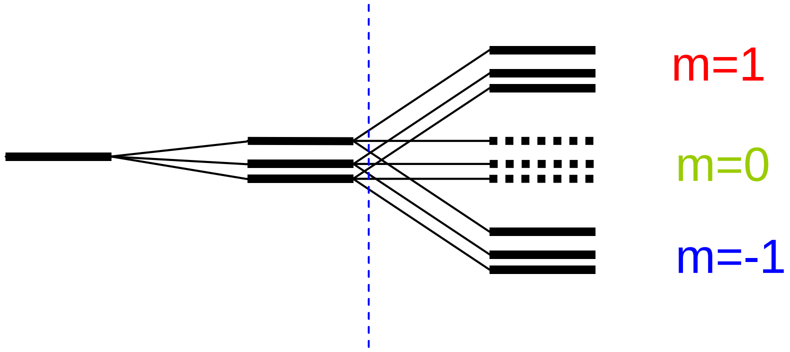


Large perturbation in frame S

Each normal mode in the rotating frame is a mix of different m’s (in general)

Transforming back to the observer’s frame, the frequency of each m component gets shifted by $m\Omega c$

Hence number of apparent components increased from $2l+1$ to (in principle) $(2l+1)^2$



Small perturbation in frame S

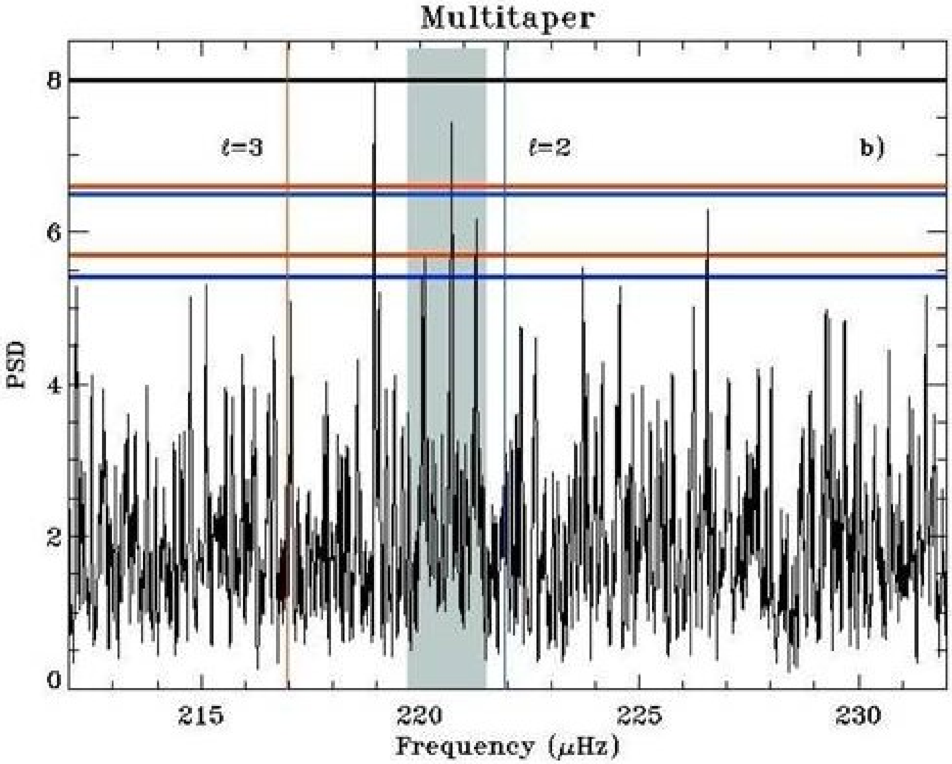
# Our search strategy

- Limit of gravity modes on ground before SoHO 7cm/s
- GOLF design: 1 mm / s Problem of the solar noise
- Kumar predictions: Fraction of mm/s Great reduction below 150 μHz
- Use our knowledge of the Sun through acoustic modes to approach the range of gravity modes; determine seismic so predictable model
- Look for gravity modes in the continuity of acoustic modes: between 150 to 450 μHz
- Look for multiplets instead single peaks (Appourchaux: 1cm/s;Gabriel 2002: 6mm/s)
- to reduce the level of detection
- Calculate statistical significances and estimate different techniques; follow the patterns in time

# Gravity modes: search of multiplets

**Doublets, triplets**

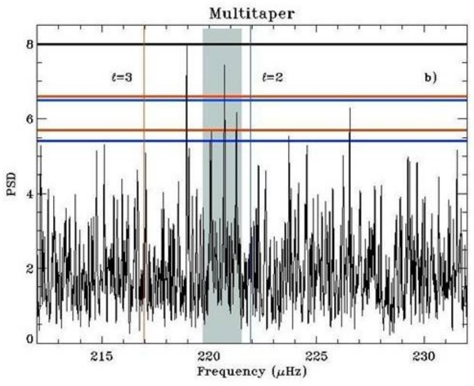
**l=1, l=2**



**Different techniques:**
**Periodogram**

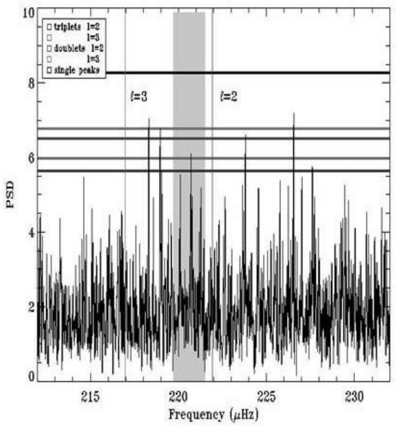
**Multitaper, RLSCSA**

# Gravity modes : evolution with time



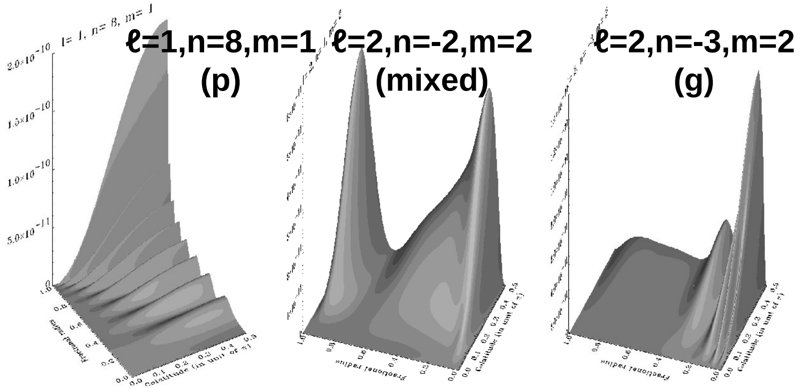
**1200 days**

Turck-Chièze et al. 2004,
ApJ, 604, 455 + erratum 609



**1700 days**

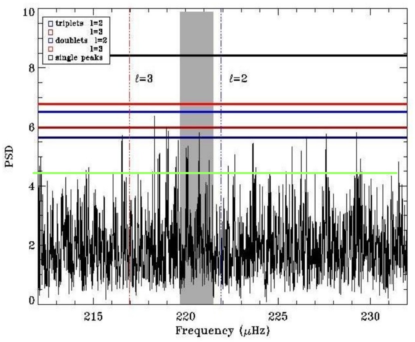
## gravity modes candidates (2004)



**ℓ=1,n=8,m=1 (p)**

**ℓ=2,n=-2,m=2 (mixed)**

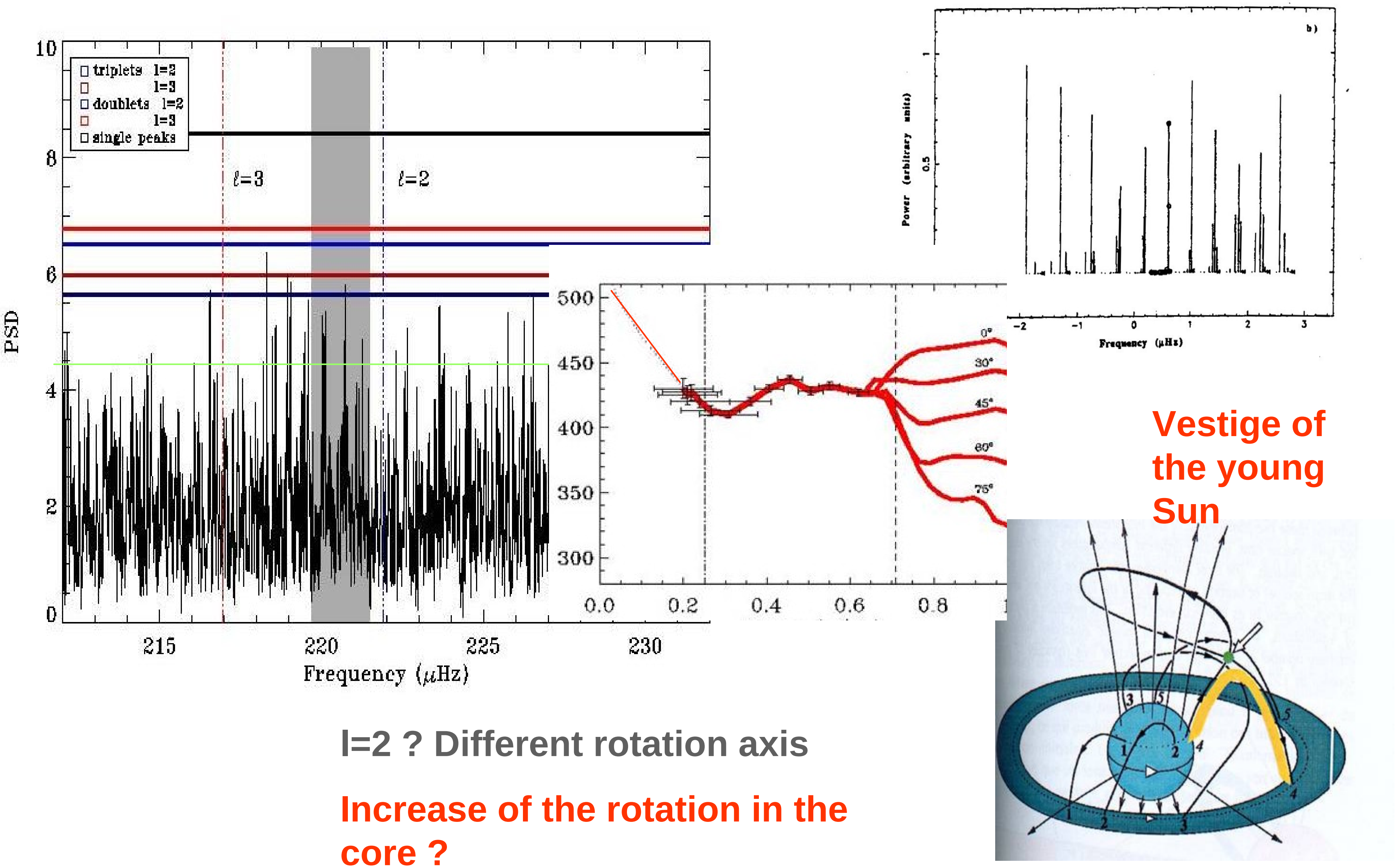
**ℓ=2,n=-3,m=2 (g)**



**2100 days**

# Evidence of a magnetic field ?

Goode and Thompson 1992

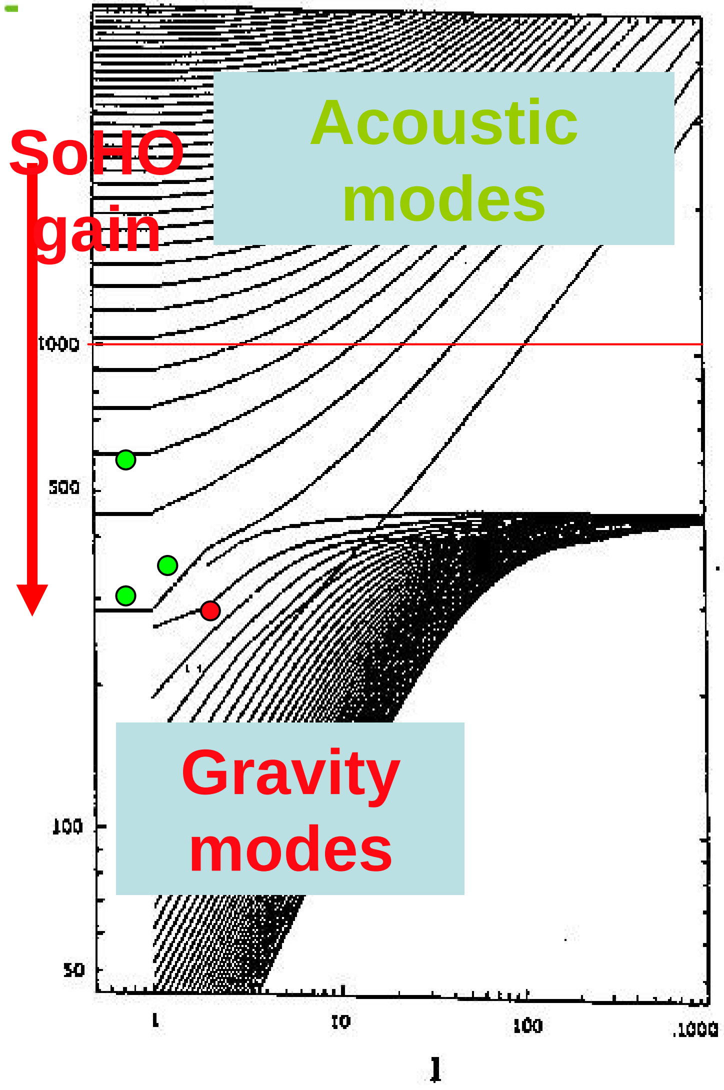


**Vestige of the young Sun**

**l=2 ? Different rotation axis**

**Increase of the rotation in the core ?**

# New analysis after 3000 days

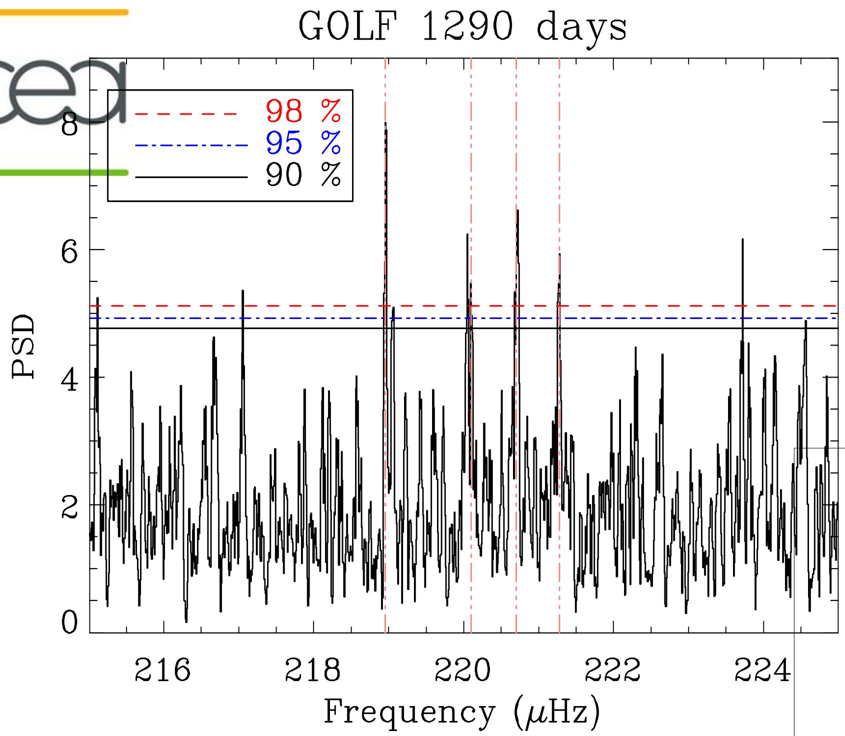


SoHO gain

Acoustic modes

Gravity modes

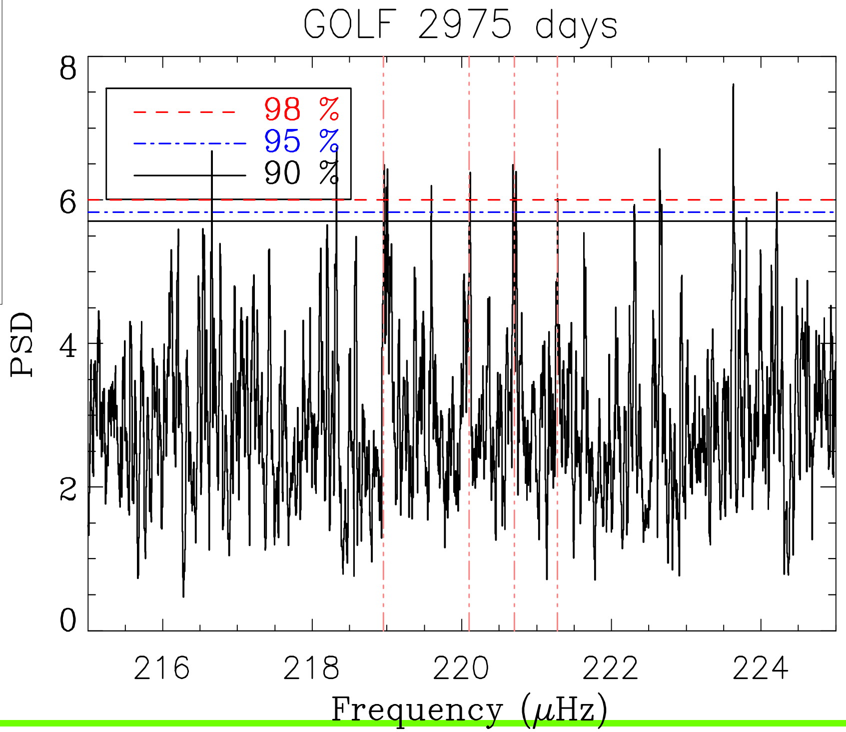
# New statistical analysis



Cox et Guzik ApJ 2005

Visibility of the candidate

Quintuplet more than 98% CL

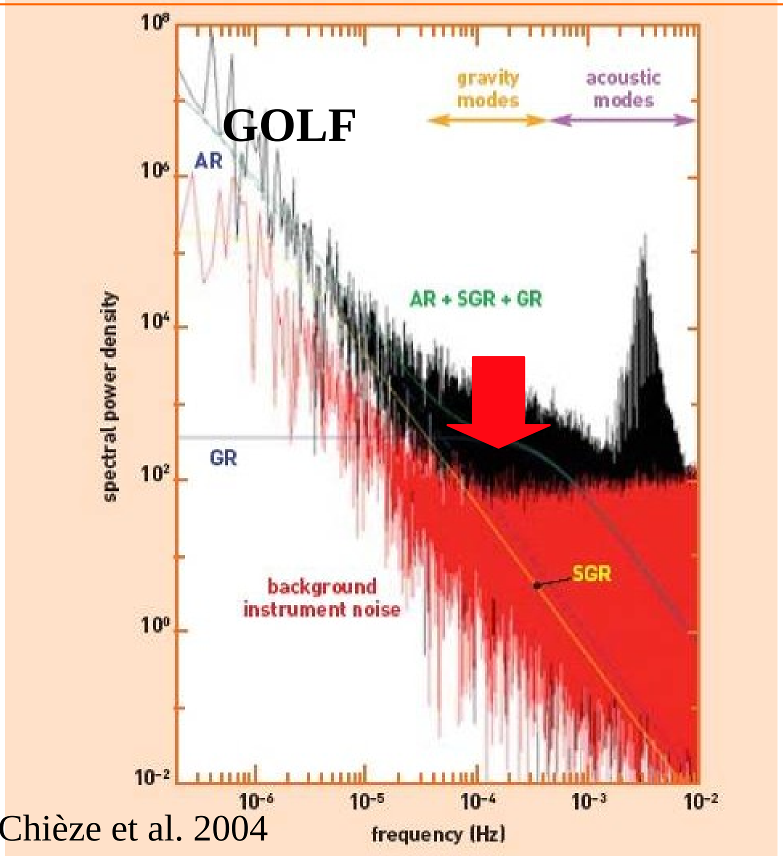


Quadruplets more than 98% CL

Turck-Chièze et al. 2004 SoHO 14, 85

# Low degree solar acoustic modes and detection of gravity modes up to l=5

**With SoHO we have improved detection by a factor 40,
in increasing the sensitivity of the instruments,
we want to measure quicker, improve the signal/ noise
and be more sensitive to the dynamics of the solar interior**



Turck-Chièze et al. 2004

**Knowledge of gravity modes will improve the spatial resolution in the radiative zone, determine the core rotation, put constraints on the central magnetic field**

**Doppler velocity is clearly up to now the best techniquefor acoustic modes but gravity mode velocities at the surface are very small: candidates from SoHO < 2mm/s**

**But the region of the gravity modes
is polluted by the solar granulation noise**

# *Improvements before the Cosmic Vision*

- **HMI/SDO : ILWS, NASA launch 2008: Doppler imager with ↗ resolution**

**will improve the convective region and the connection with solar external part**

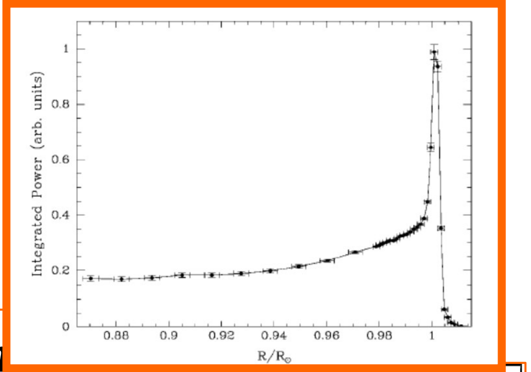
*structure & dynamics of the tachocline,*
*variability of the convective differential rotation*
*evolution of the meridional circulation, dynamics of the near surface*
*origin and evolution of the sunspots, drivers of solar activity or disturbance*

*study of the radiative zone is a secondary objective*

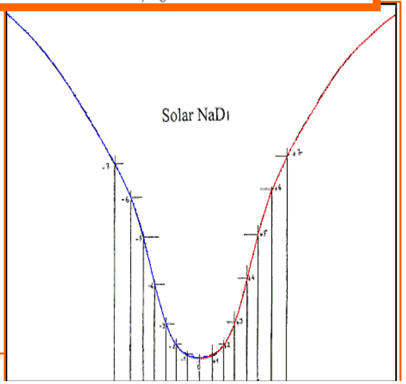
- **PICARD: microsatellite CNES: F,B,S launch 2008: telescope imager**

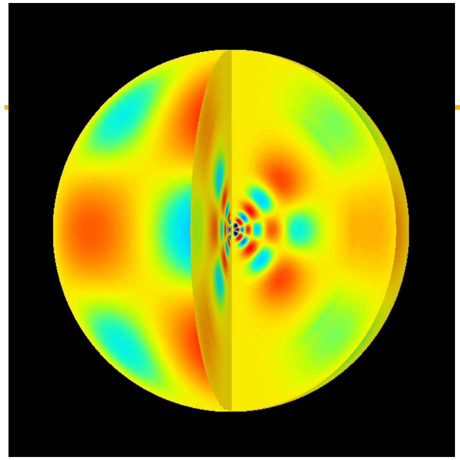
*measurement of the solar diameter,*
*solar shape and variabilities*
*variability of irradiance in different wavelengths,*
*seismology in a specific wavelength :*

*Amplification of intensity signal at the limb*

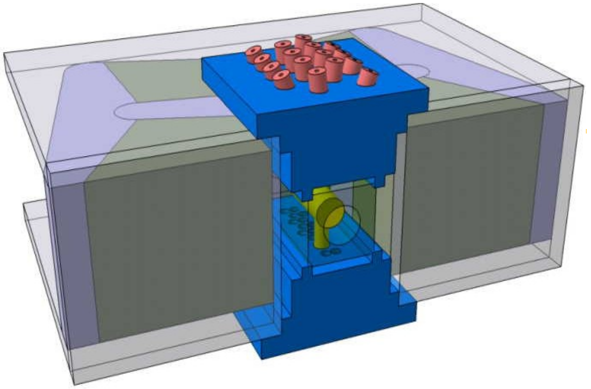


*To improve the scientific return on the radiative region, we h*
*to launch also an improved resonant spectrometer (european expertise) for reducing the solar granulation noise of the previous experiments at low frequency in measuring the Doppler velocity variations at different heights:* *Espagnet et al. 1995* **GOLFNG: 15 points on the sodium line** ***prototype available in Ténérife in 2006***





# GOLF-NG



S. Turck-Chièze, J. Ballot, J.C. Barrière, A.S. Brun, P. H. Carton, R. Garcia, P. Lambert, P.A. P. Nghiem

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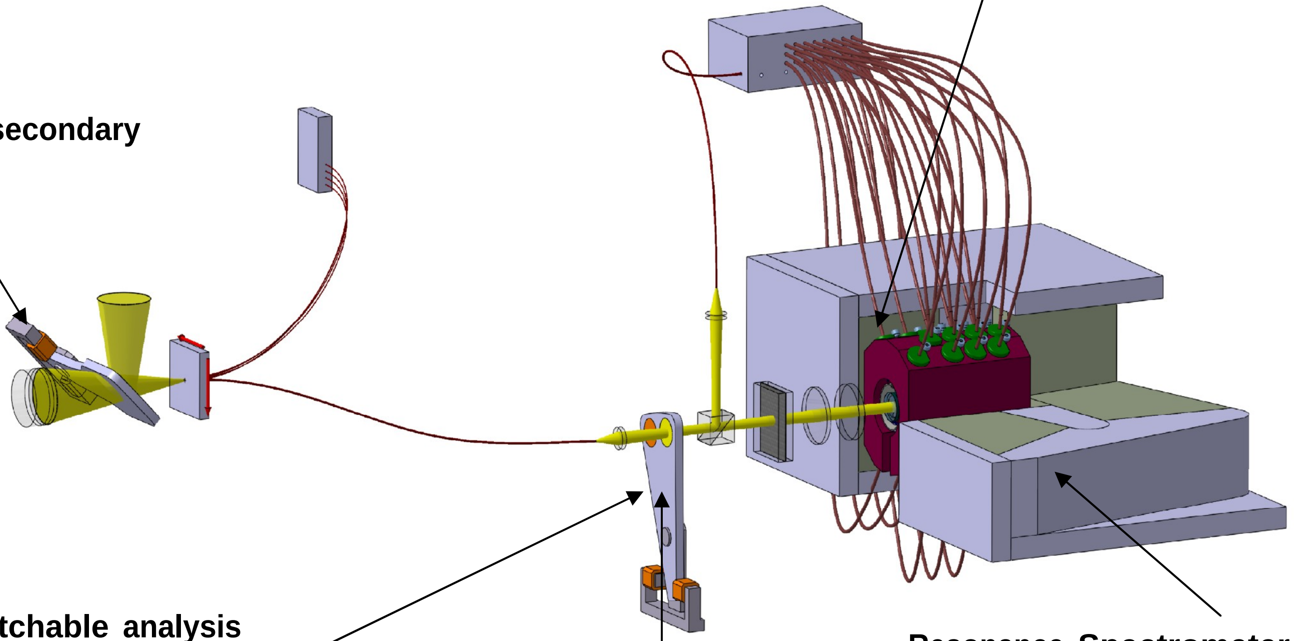
E. Fossat, Université de Nice, France

B. Gelly, Themis, C./ Saturno n3 38205 La Laguna, Ténérife

# Scheme of Instrument's Principle : see Turck- Chièze et al. 2005, COSPAR



Photodetectors ( 32 + 1)

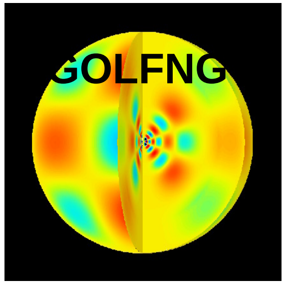
32 optical channels:
Simultaneous
measurement of 8*4
points along the line

Entrance stage with secondary
optical source and
alignment tuning

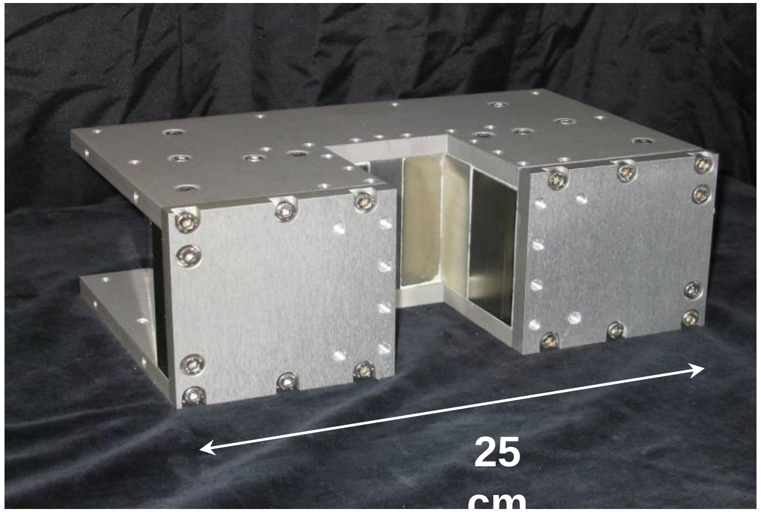
Switchable analysis
Filters: continuum +NaD1

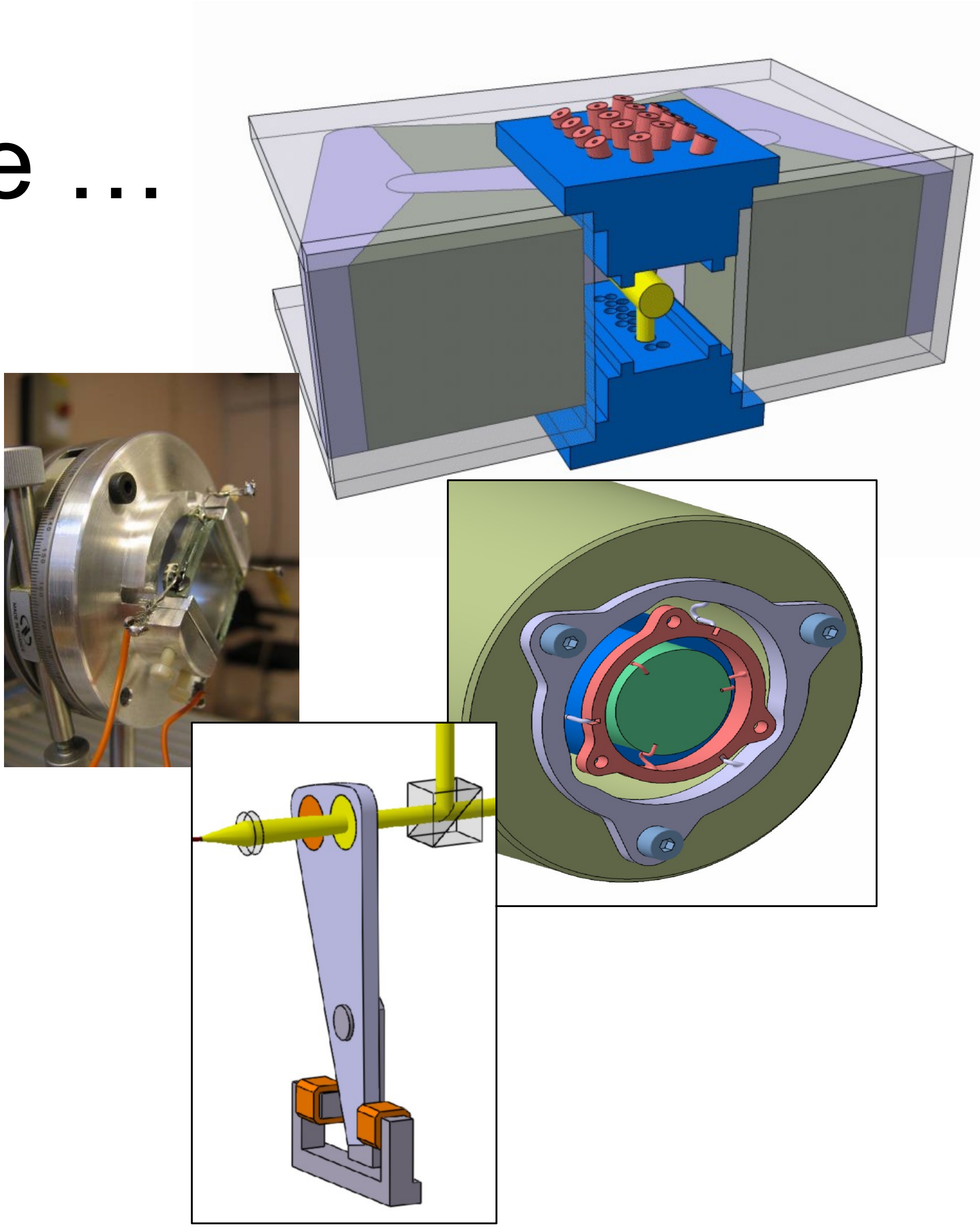
Resonance Spectrometer
0 - > 12 kG
(under vacuum cond$^{ts}$)

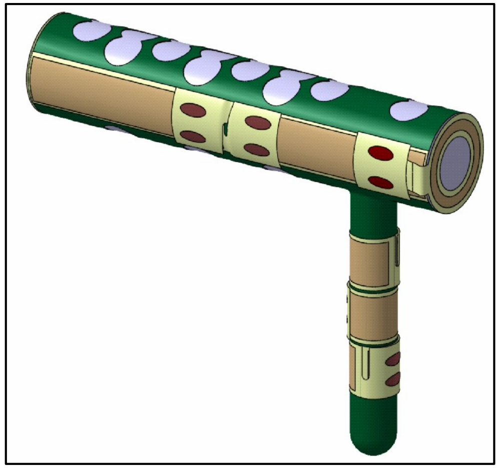
Shaping and polarizing Optics
Red or blue part of the line



# Where we are …

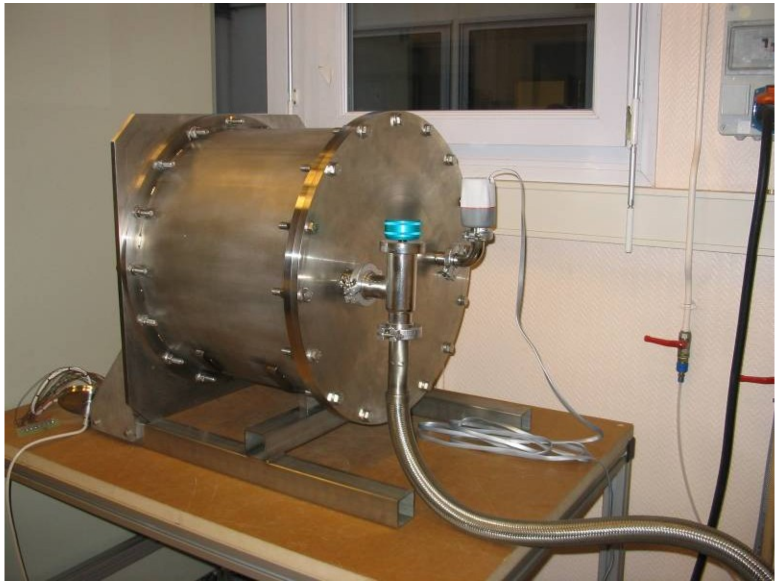




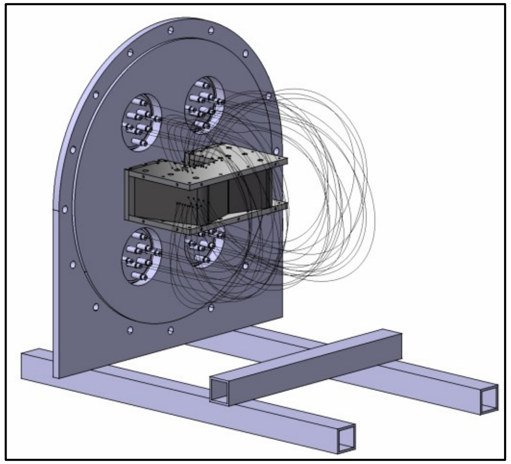


*Sylvaine Turck-Chièze, Beaulieu, PNST, May 27th, 2005*

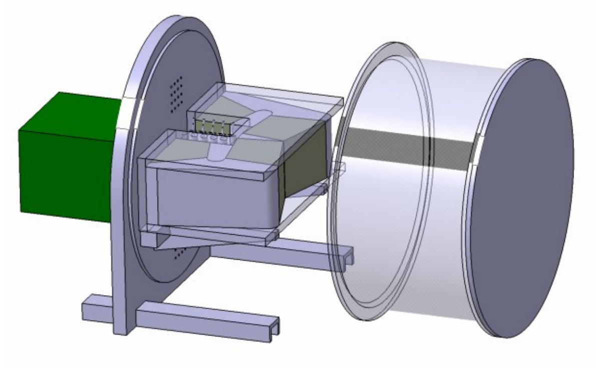
# Tests en laboratoire



Front tapes with sealed
optical throughoutputs



Front tapes with sealed
optical throughoutputs



# Planning

**Tests globaux en laboratoire du prototype**

**Automne 2005, photodiodes Hamamatsu**

**->CCD**

**Prototype à Ténérife début 2006**

**Etude de la raie du sodium à Thémis**

**Phase 0: Dossier spatial: M, P, D automne 2005: lecture globale**

**Microsatellite CNES**

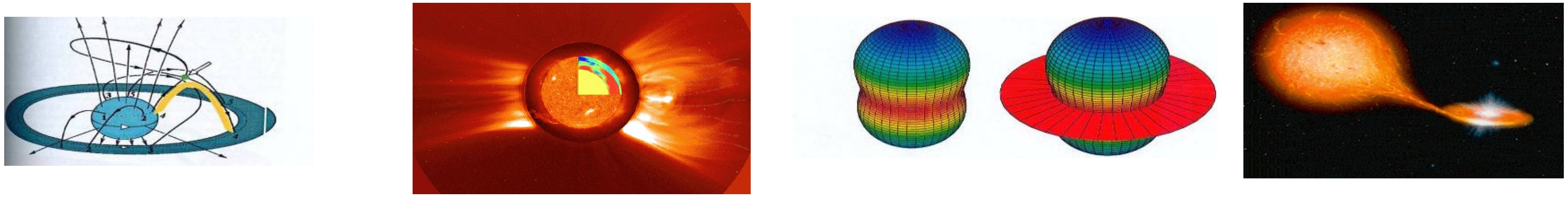
**Minisatellite ou autres**

# *The Sun as a star near our planet*

**The Sun stays the only star where million modes can be detected, low degree modes are those which are accessible for other stars, any good new technique can be generalized for other stars, useful for stellar-planet connection**

**The Sun stays the best case to check theoretical assumptions, in parallel to asteroseismogy and contributes to an unified view of the stars**

**=> A complete renewal of stellar evolution**



# *The Sun and fundamental physics*

**The description of the solar core is useful to predict neutrinos => Nowadays solar neutrinos detection+ helioseismolgy put constraints on the central temperature at better than 0.5%, any fluctuation could be observed: a real beginning of neutrino astronomy.**

**Moreover the detailed description of the solar core will put strong constraints on exotic particles and dark matter,**

**The density measurements in the core will put constrains on gravitational moments J2, J4, general relativity and planet orbits**

- **Helioseismology is a wonderful tool: we need to continue the efforts**

- **Putting quantitative answer to the real role of the Sun on the earth climate is a very exciting subject for the cosmic vision 2020, this is possible if we prepare this step during the next solar cycle**

- **To reach this objective, we need a small european mission (low cost) dedicated to the solar core, in complement to SDO and PICARD, very soon 2009-2010.**

- **Collaborations are welcome: sodium line, analysis of the outer layers….**