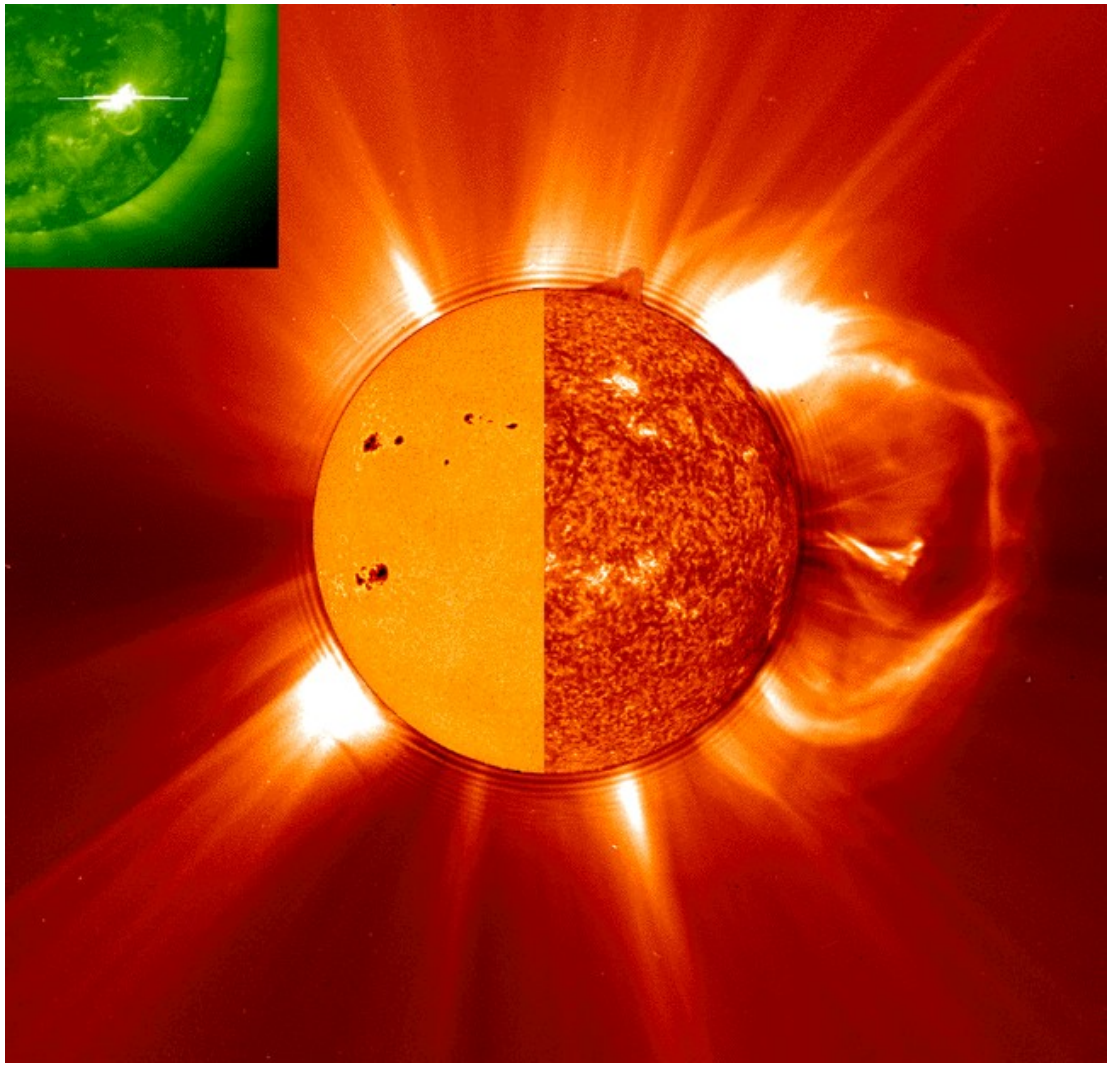


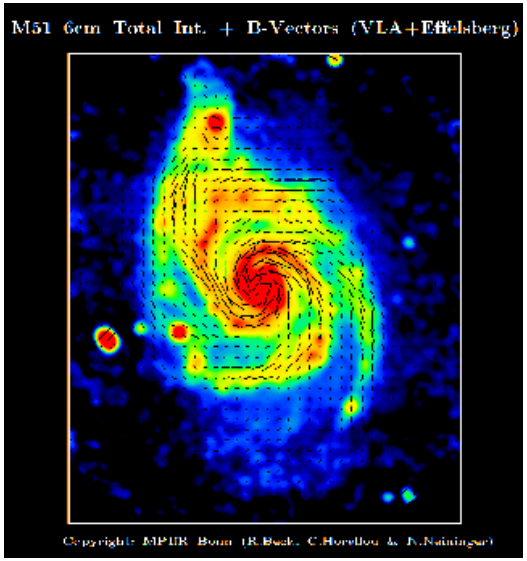
The magnetism of the solar interior

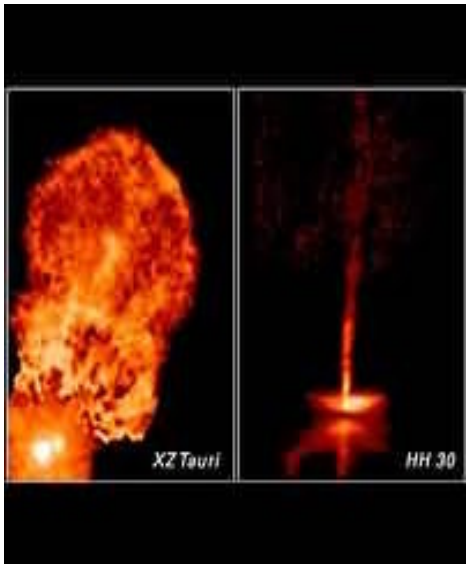
Towards a full 3D solar vision

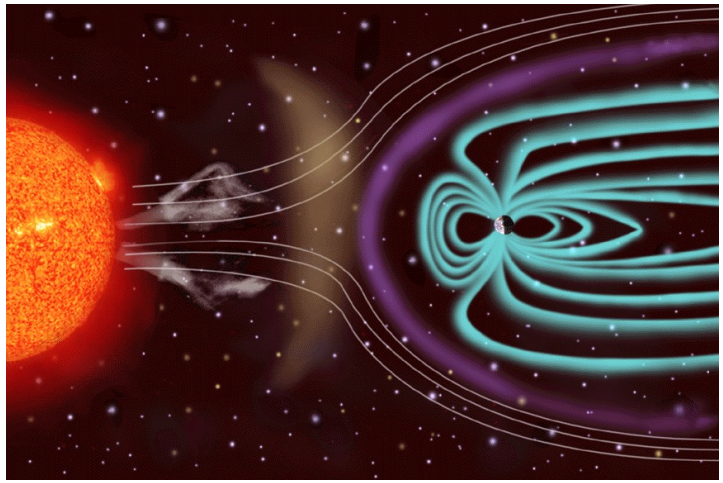
Turck-Chièze, S.[1], Appourchaux, T.[2], Boumier, P.[2], Ballot, J.[1], Berthomieu, G.[3]; Brun, A. S.[1,] Cacciani, A.[4],Christensen-Dalsgaard, J.[5], Corbard, T.[3], Couvidat, S.[6], Darwich, A. M.[7], Fossat, E.[3], Garcia, A. R.[1],Gelly, B.[7], Gizon, L[8], Gough, D.[9], Jimenez, A. J.[7]; Jimenez-Reyes, 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







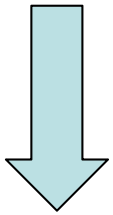
But magnetism is still poorly known. Magnetic field is not yet present in most of the equations describing our Universe.
It is not yet present in the equations which describe the life of stars.

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

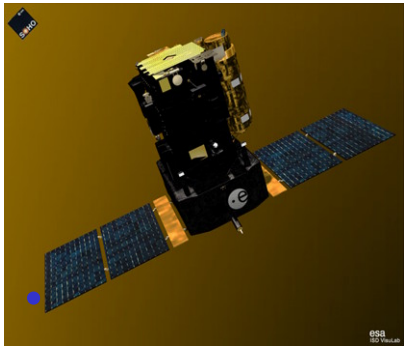
It will help to build a unified vision of stars

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)



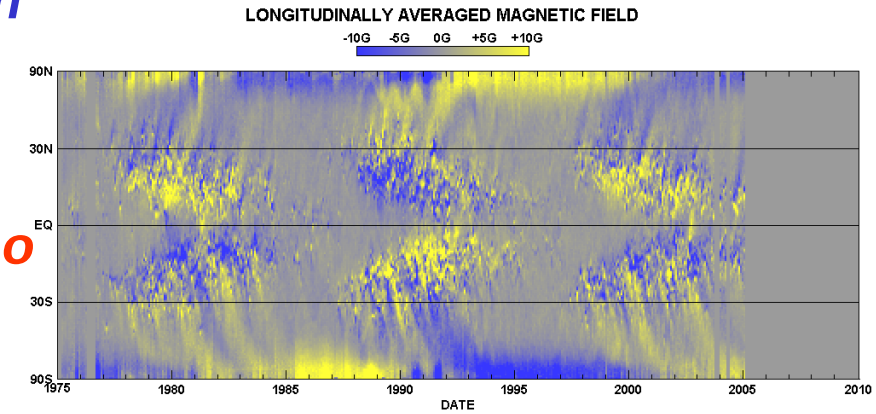
The Sun is a unique object for which we may hope a quantitative approach before generalization to other more energetic objects (young stars, final evolution stages) during the period of the Cosmic Vision.



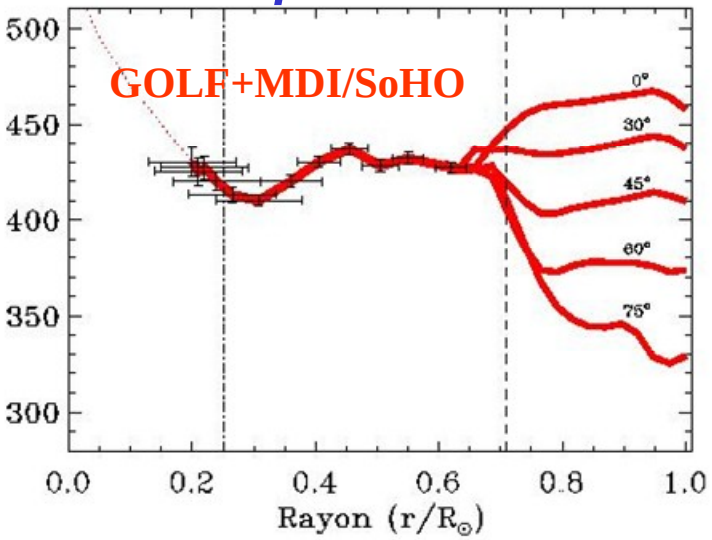
What have we learned these last 10 years with the development of helioseismology?

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

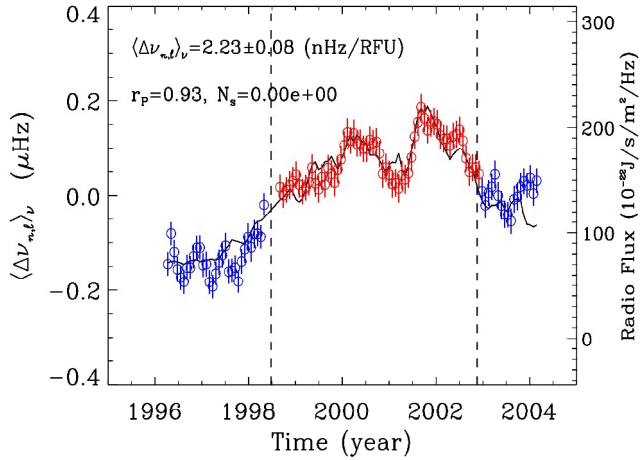
- ***It concerns at least the 30% outer convective zone and the dynamo process depends clearly on the rotation profile***



Photosphere



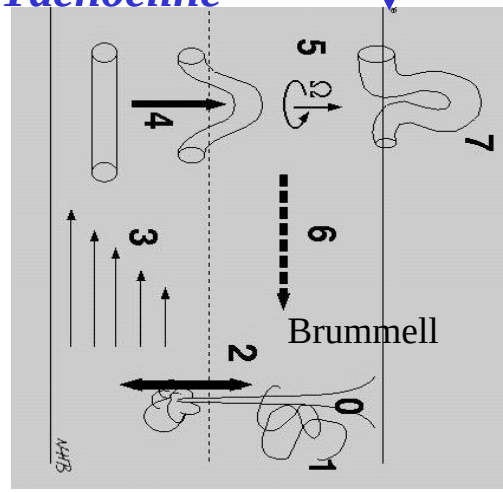
Couvidat et al. 2003



Kosovichev et al. 1997

Garcia et al. 2003

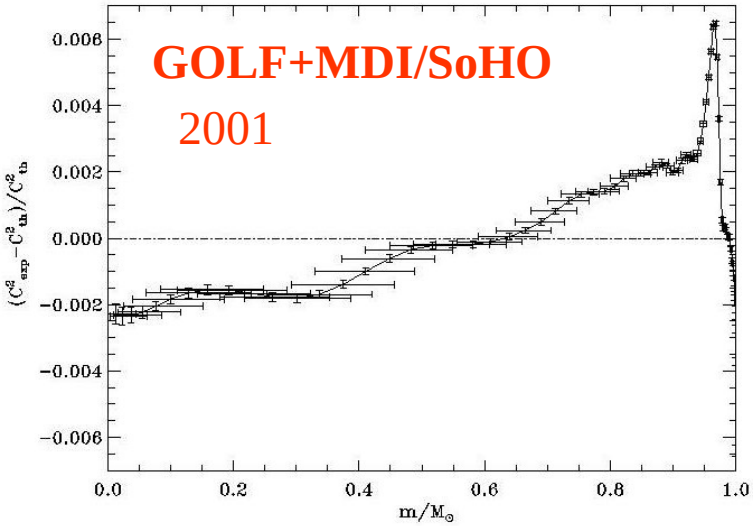
Tachocline

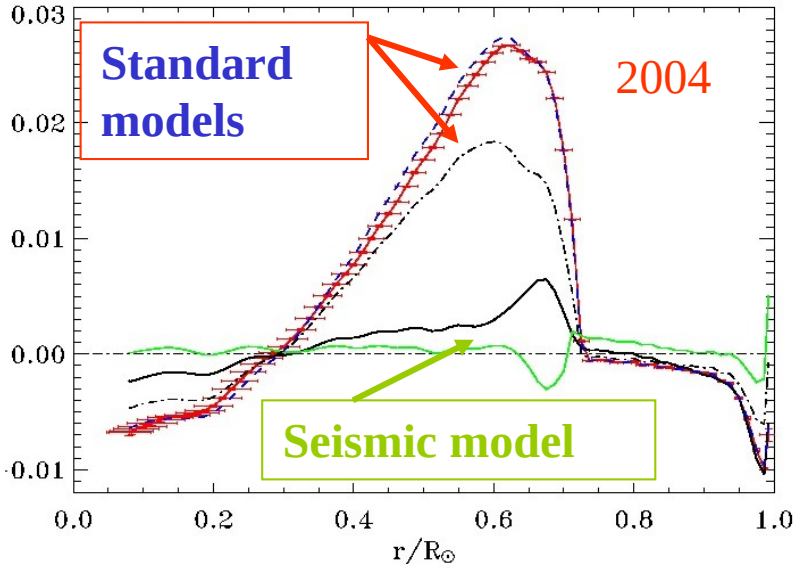


The solar radiative zone: 98% of the mass is nowadays « visible » but not yet under control !

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

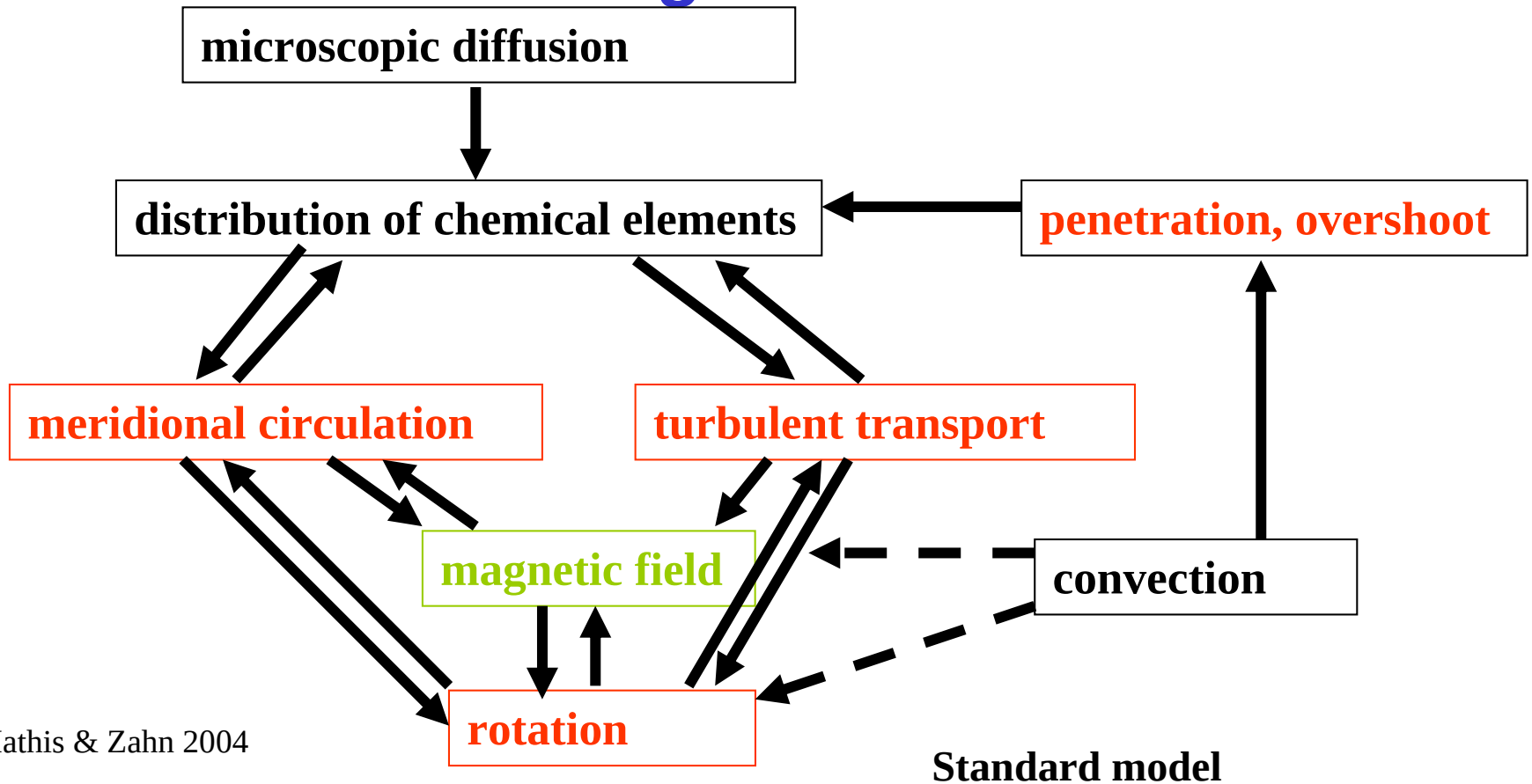
Turck-Chièze et al, 2001a,b, 2004





- ***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



Mathis & Zahn 2004

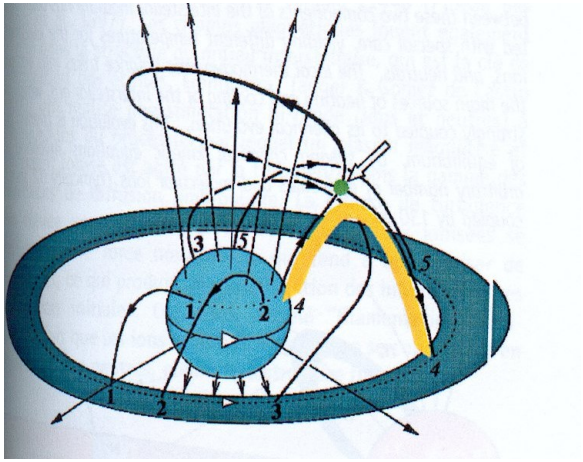
Standard model

Seismic model

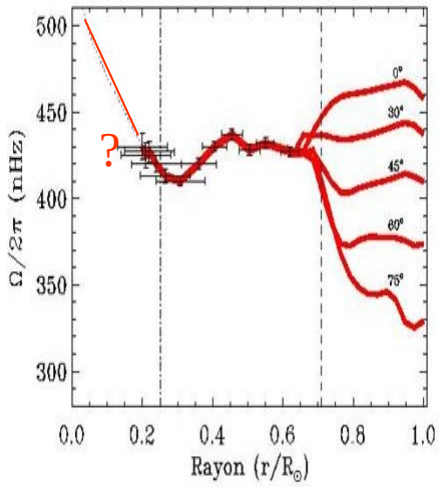
Magnetohydrodynamical model

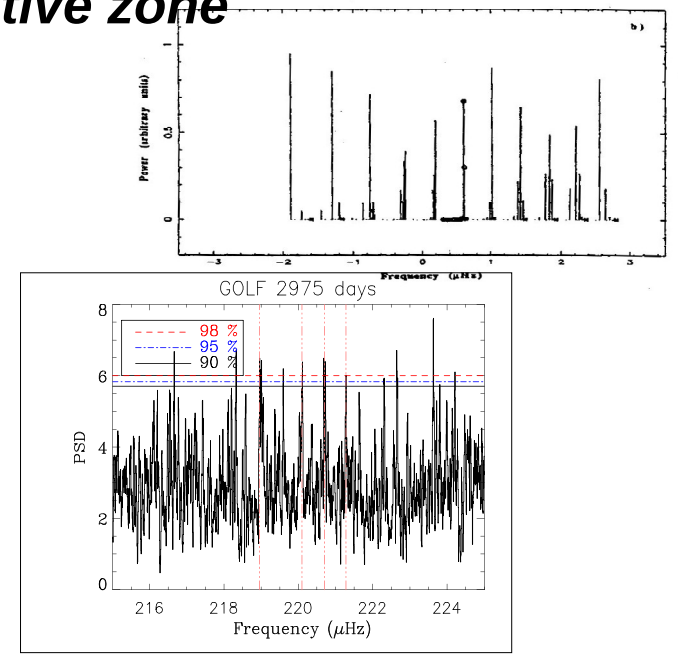
What we would like to know ?

- *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

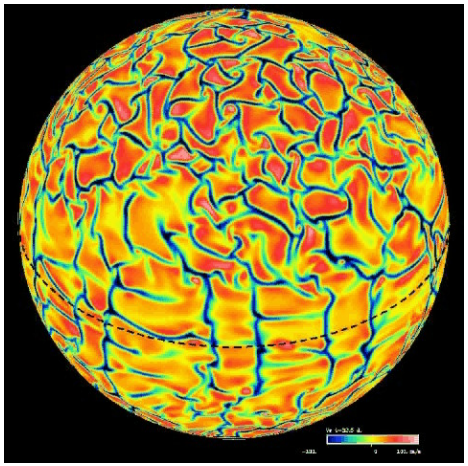


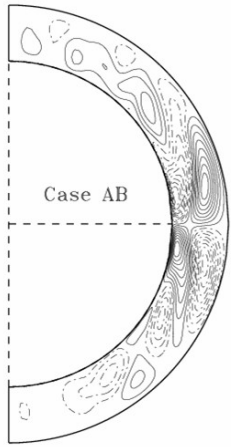


We want to quantify the real energy balance and its variabilities

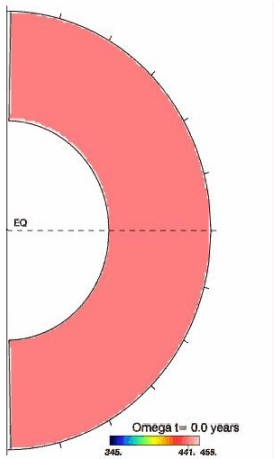
Importance of the 3D simulations

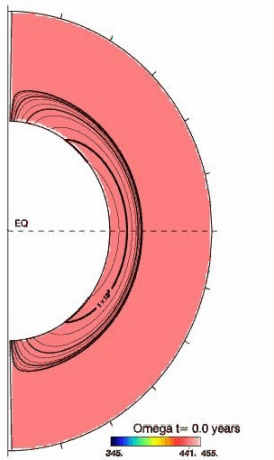
Nordlund & Stein, Brun &Toomre 2002

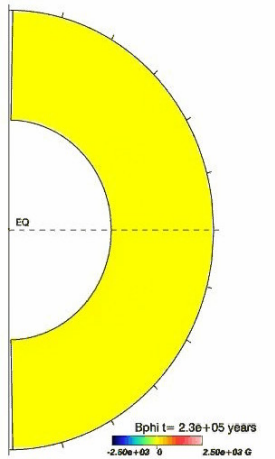




Rudiger & Kitchakinov; Brun & al. 2005







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

Simulations of the radiative zone:

Without magnetic field

With primordial seed of magnetic field

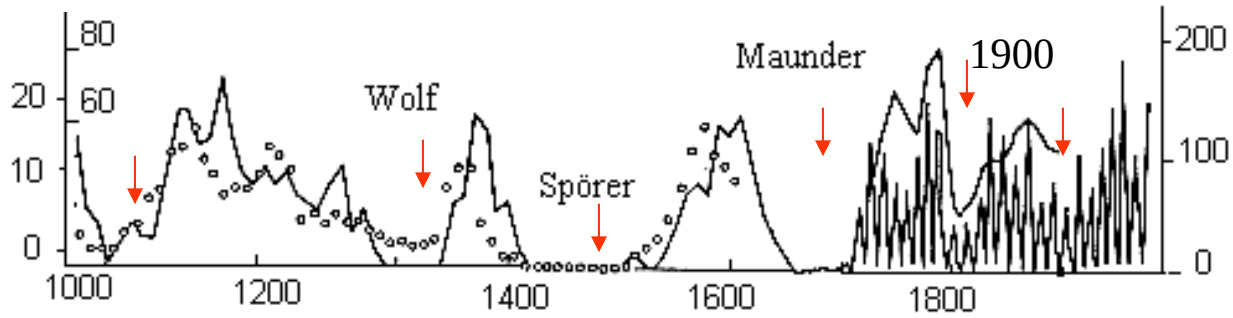
We need to understand the great variations of solar activity and its impact on the earth climate

See Solanki et al, 2004

Aurorae

and activity from ^{14}C

Sunspots



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

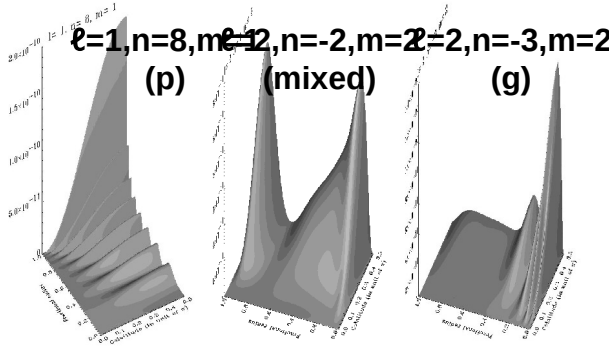
Can we imagine several kinds of dynamos, even in the radiative zone, several cycles ?

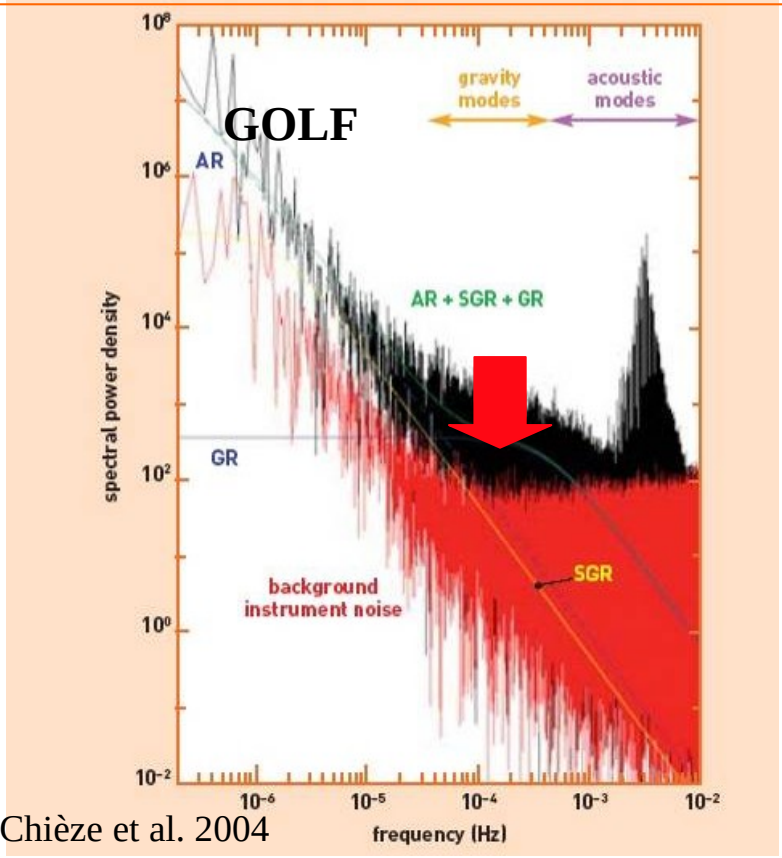
Can we imagine interconnection of the magnetic field between radiative and convective zones ?

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

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 the best technique for acoustic modes but gravity mode velocities at the surface are very small: candidates from SoHO < 2mm/s

Moreover 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

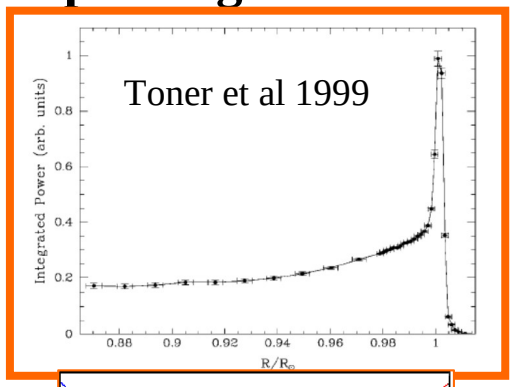
structure & dynamics of the tachocline,
variability of the convective differential rotation
evolution of the meridional circulation, dynamics of the near surface
origin and evolution of the sunspots, drivers of solar activity or disturbance

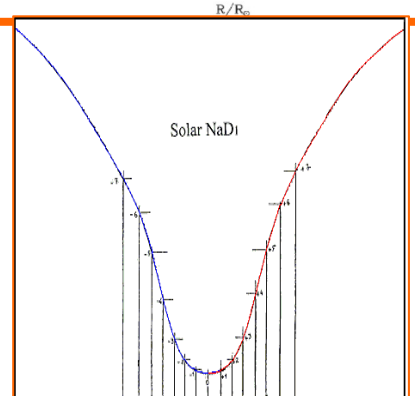
study of the radiative zone is a secondary objective

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





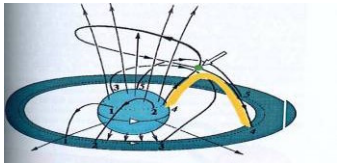
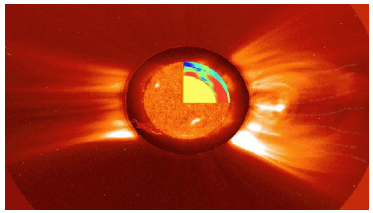
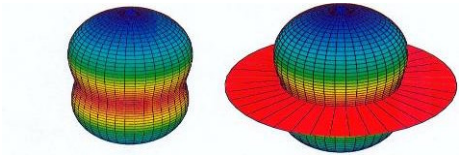
To improve the scientific return, we propose to launch in parallel an improved resonant spectrometer (european expertise) for reducing the solar granulation noise of the previous experiments at low frequency in measuring the Doppler velocity variations at different heights: *Espagnet et al. 1998* **GOLFNG** ***prototype available in 2006***

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

Roadmap for deriving the magnetism of the solar interior

An « International Solar Mission », launched at the next minimum 2018-2030 with seismic instruments (using different techniques, at least 3) + variability studies + instruments of Solar Polar Orbiter or a multi scale mission ?),

is crucial to build a complete 3D dynamical view of the solar magnetic field from the core to the surface !!!

Europe has developed a lot of expertises (including 3D simulations) useful to estimate the real energetic (and magnetic) relationship between the Sun and the Earth. We need to use them for societal applications and climate predictions.

Europe must pursue its efforts during the coming solar cycle. Europe will gain to add a small seismic mission as « GOLFNG » around 2009-2010+ macro pixels to increase the scientific return of SDO(NASA)/PICARD (CNES) on the Solar Radiative zone Dynamics SolRaD

a CNES microsatellite or a participation to the sentinel L1 of ILWS must be examined.

These missions will be also useful for stellar evolution, for better understanding star-planet relationship and for progresses in fundamental physics.

- **Helioseismology is a wonderful tool**

- **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**

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