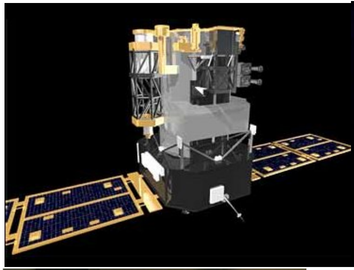
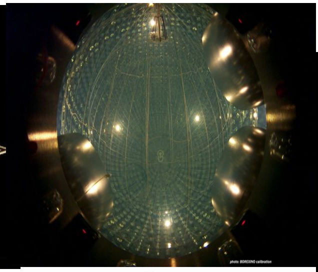
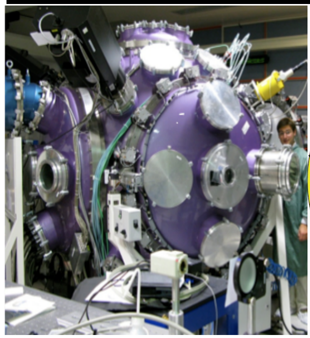
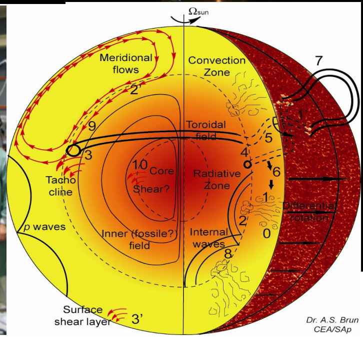
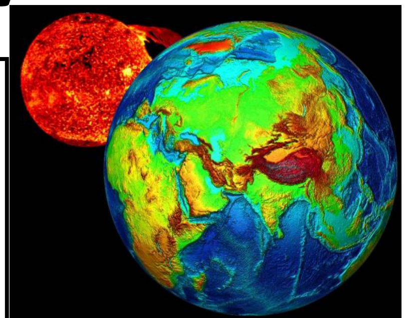
Progress in solar modelling, helioseismology, neutrino predictions and fundamental physics

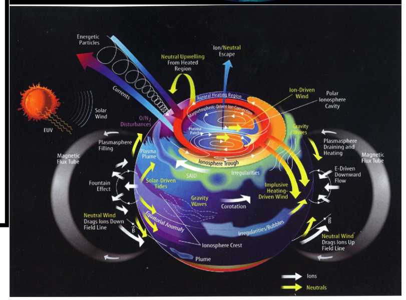








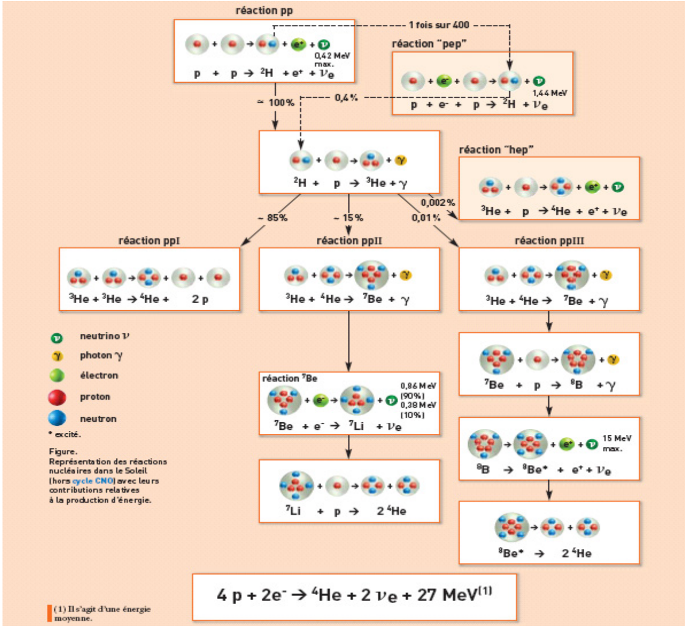




S. Turck-Chièze and the GOLF team,
CEA/IRFU/SAp, Saclay France
Sylvaine.Turck-Chieze@cea.fr

- What have we learned on the solar structure these last 2 decades, in particular on the solar core? From which modes ? Sound speed and rotation profiles,
- Solar structure and astrophysics: what have we checked on the SSM framework and beyond ?
- Sun and dark matter, news hints and other directions of investigation beyond SSM framework.

Marie Curie 1867-1934
Nobel Prizes 1903 and 1911



Ray Davis 1914-2006
Nobel Prize 2002

coulomb barrier $H^+ + H^+$ reactions ~~at 15 10^6 K~~
but in the maxwellian tail at equivalent 65 10^6 K
Gamow 1929

Hans Bethe 1906-2005 Nobel Prize 1967

Masatoshi Koshiba 1926-
Nobel Prize 2002

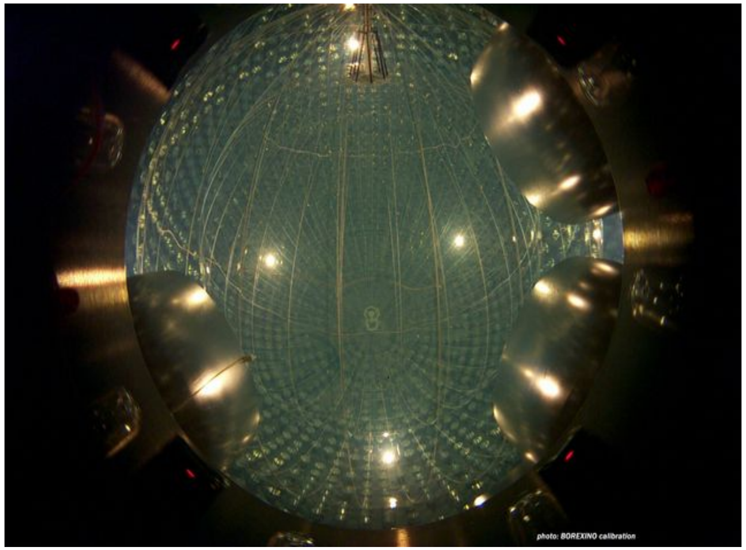
What have we learned since 1988?

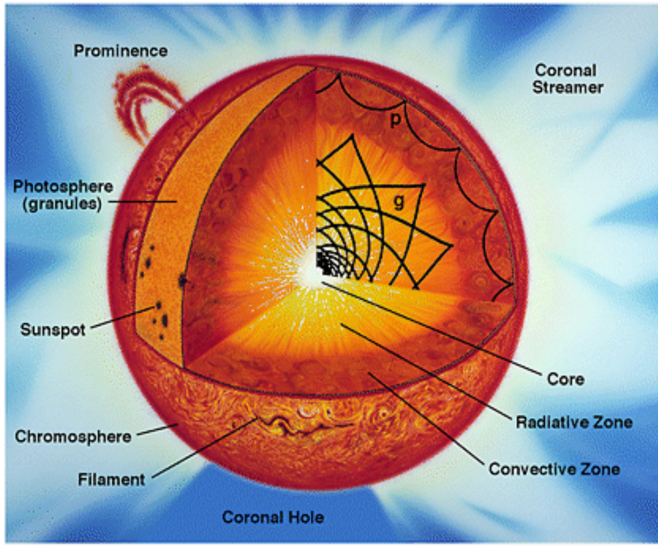
Two probes of the core are detected simultaneously

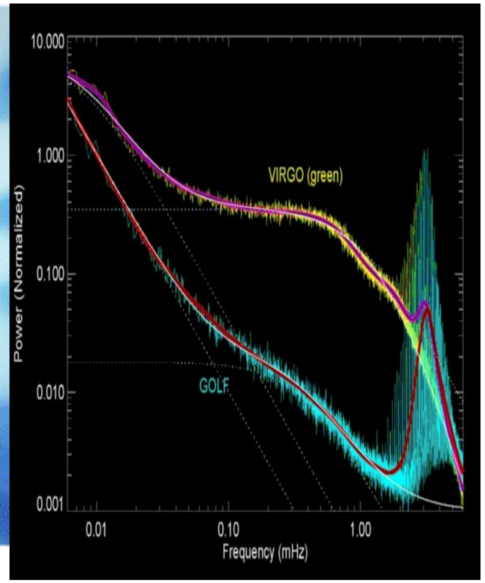
Neutrinos emitted by the Sun and SoHO helioseismology in space

SDO and PICARD are not so well adapted to the core study

SNO, Borexino: individual neutrino species GOLF-MDI acoustic and gravity modes   Doppler v>>l

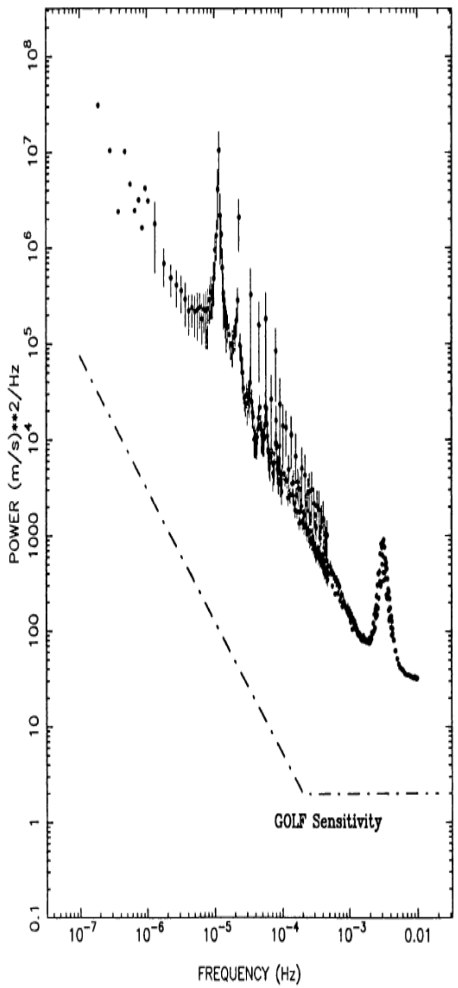






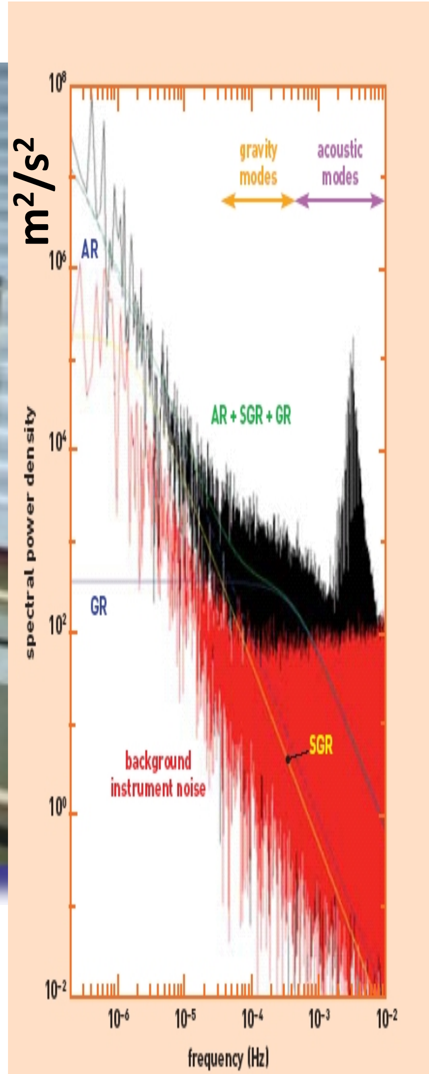
Global Oscillations at low frequency: GOLF/SOHO IAS/CEA/IAC launch in 1995

Dzitko Thesis, 1995; Gabriel et al.1995, Turck-Chièze et al., ApJ, 2004, Garcia et al. A&A 2005



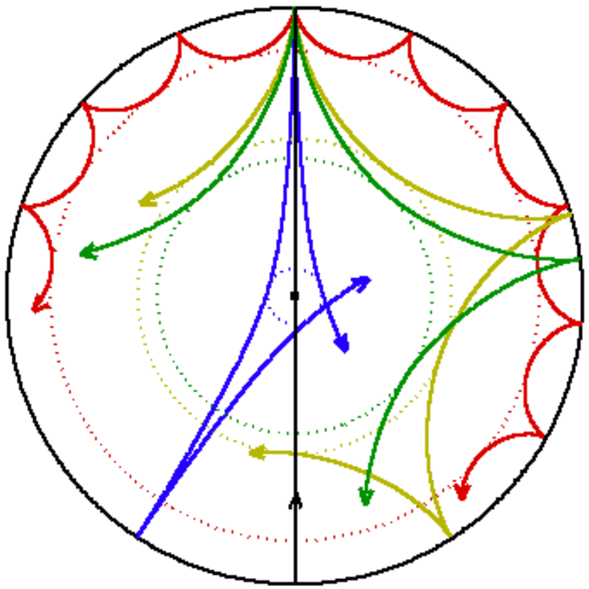
Pallé et al 1995
seismology on ground

1.2 10^7 cts/s 4s every 5s since January 1996…
ageing -10%/yr today 400000-500000 cts/s
Electronic noise << statistical noise above 10^{-4} Hz

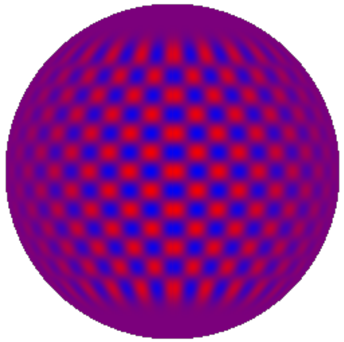


Turck-Chièze et al ApJ 2004

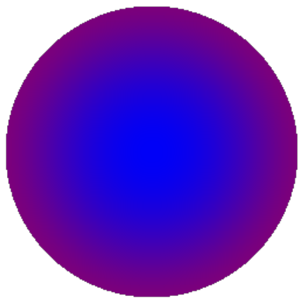
Observed Acoustic modes



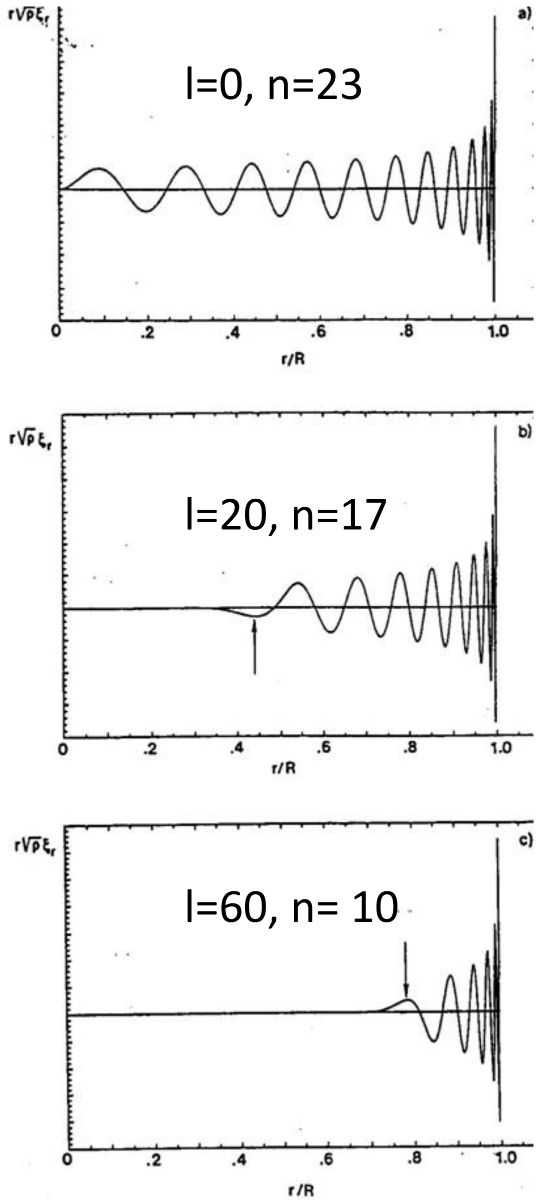
Degree l and order n



MDI



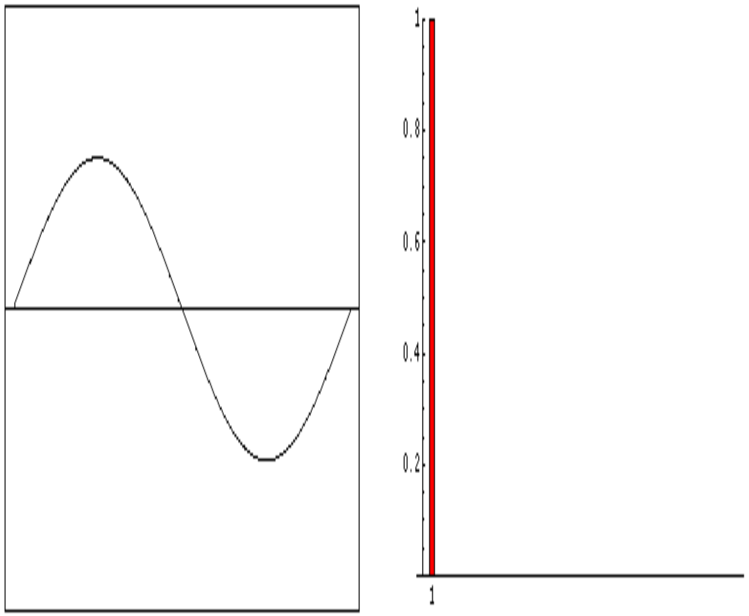
GOLF



Low degree acoustic modes penetrate down to the core

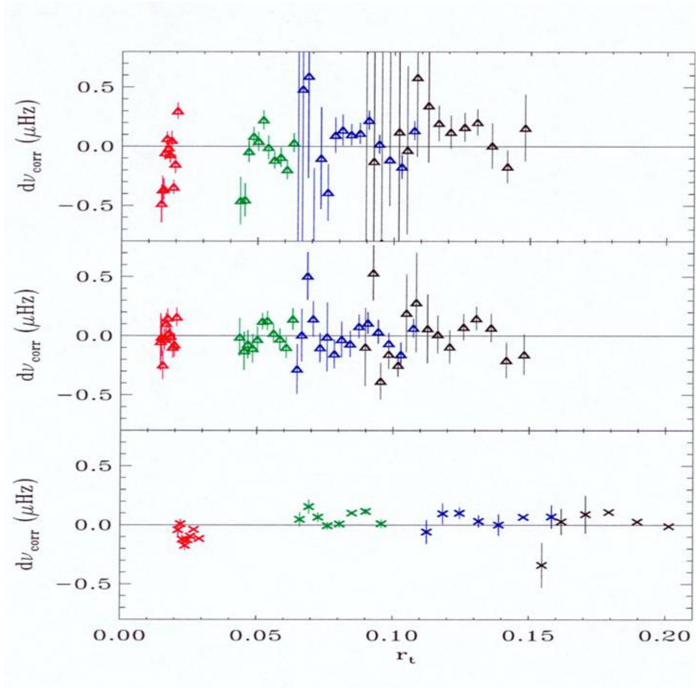
but one must be cautious to the surface effects!!

John Bahcall advise….



Harmoniques n 1 -> 40

GOLF space data



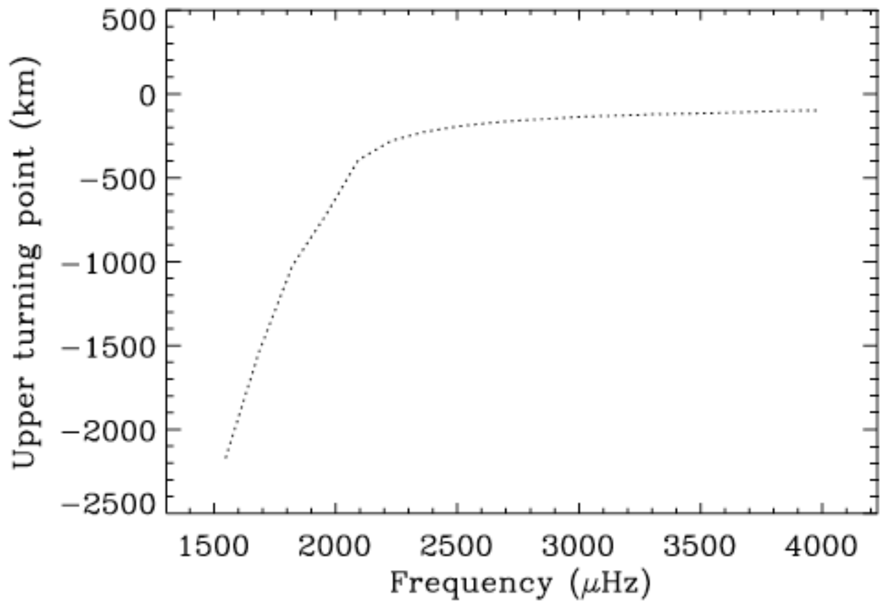
1 year

5 years n>15

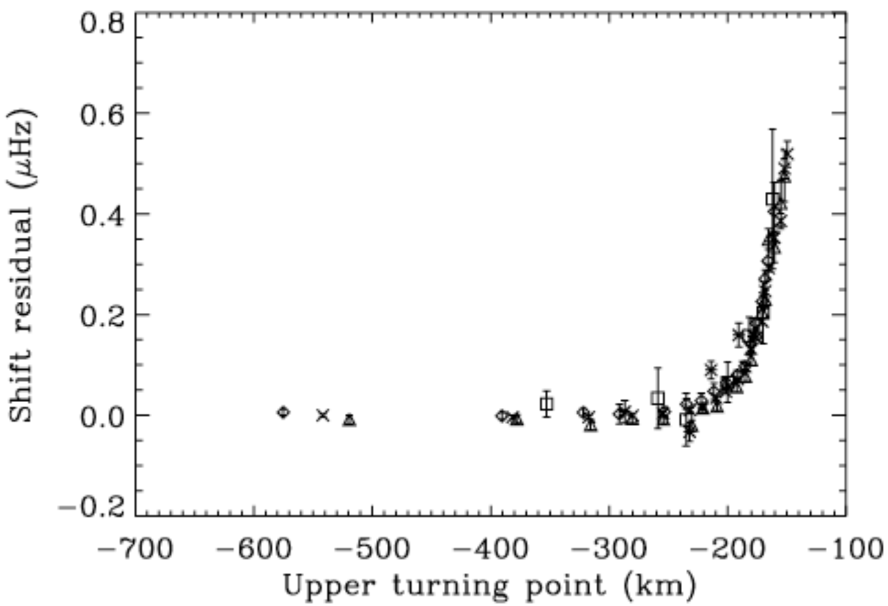
5 years n<15

Degrees l = 0,1, 2 n > 15 more sensitive of the surface

n <or = 15 <1600 μHz not sensitive to the surface



Degrees l = 0,1, 2   n > 16 more sensitive to the surface as their external turning point is very near from the surface



n <16 no effect of sub surface variability.

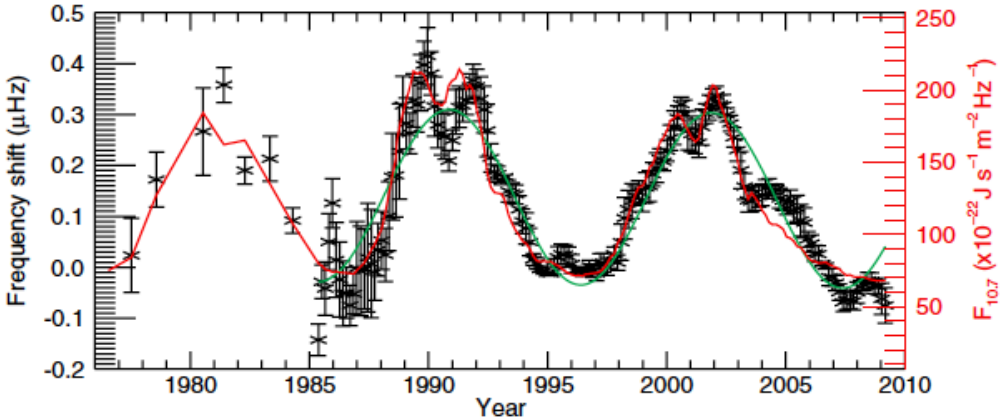
These modes have been used in the sound speed and density inversion using GOLF +MDI

Low degree modes for n> 16 are sensitive to the surface

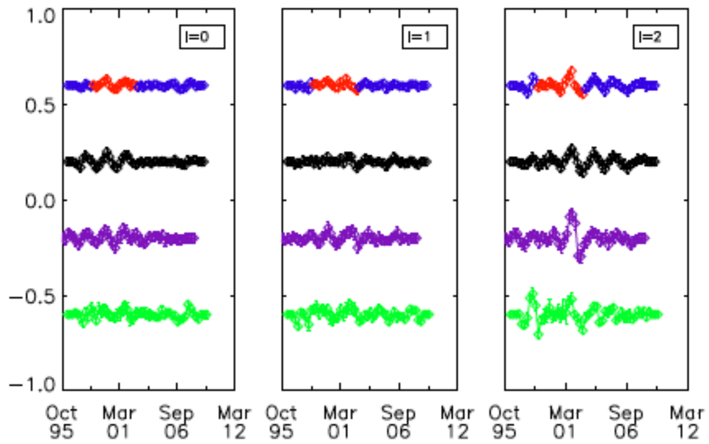
The subsurface layers shown by SoHO and ground networks

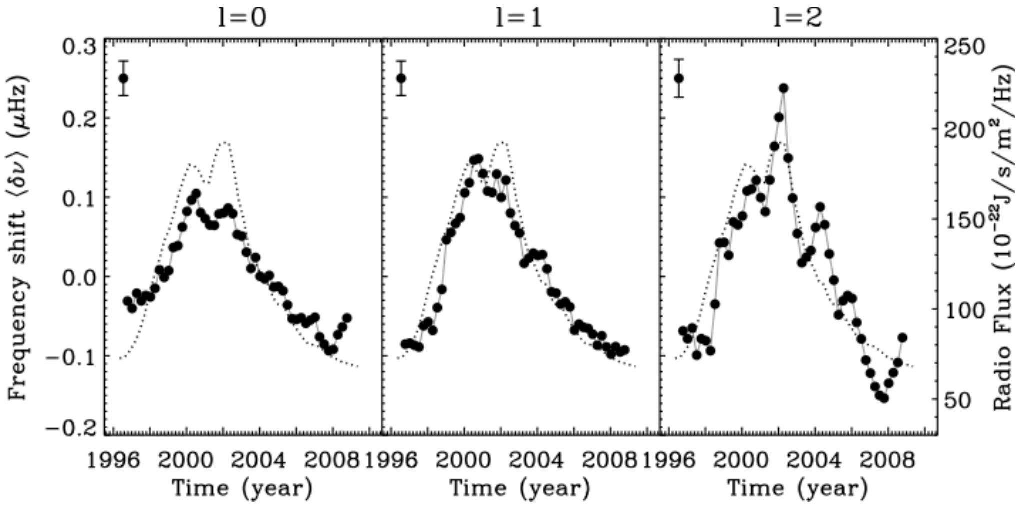
2 periods are visible: 11 years and quasi biennal period

Broomhall et al. 2009, Salabert et al. 2009, Simoniello et al. 2011, 2012



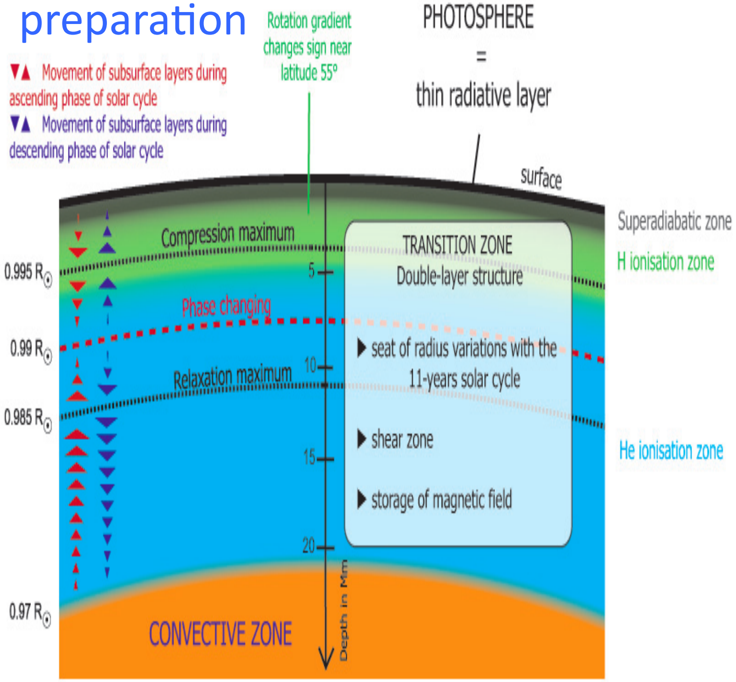
Very interesting activity indicators

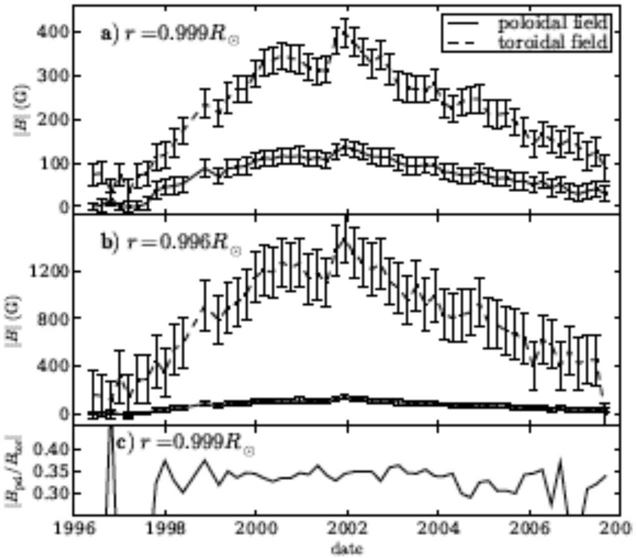


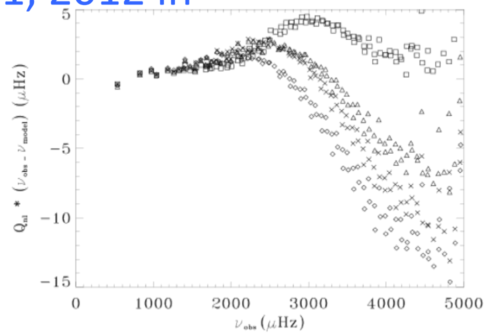


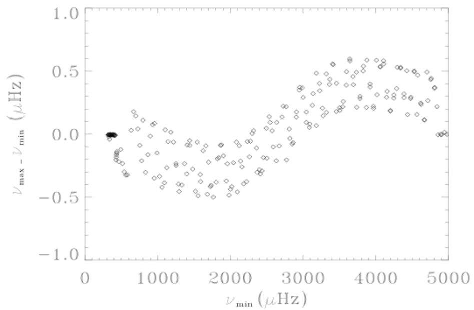
Acoustic modes n>16 reveal the near surface

Lefebvre et al. 2007, 2009, 2010, Baldner et al. 2009, Piau, T-C et al. 2011, 2012 in preparation

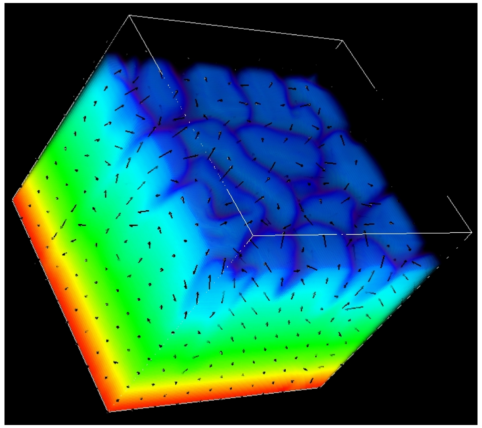








3D simulations 6000*3000 km



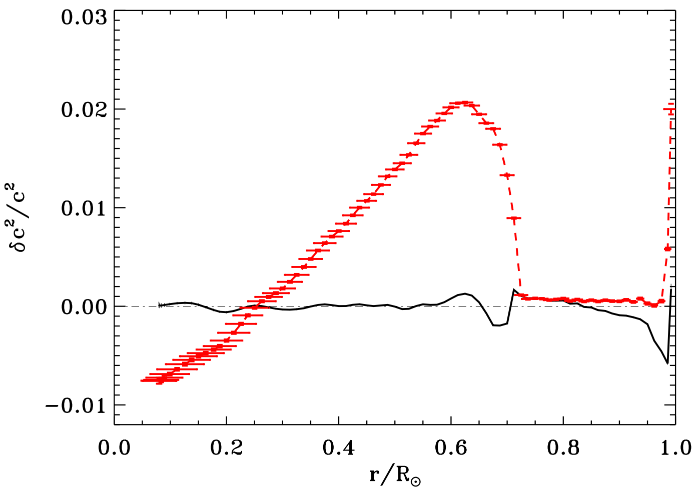
3D simulation with STAGGER (Stein & Nordlund 2006) shows the impact of turbulence (Rosenthal et al. 1999). 1D coupled to 3D outputs shows the impact on frequencies of the variation of the toroidal field along the 11 year cycle: Piau et al. 2012, Simoniello, T-C et al. 2012

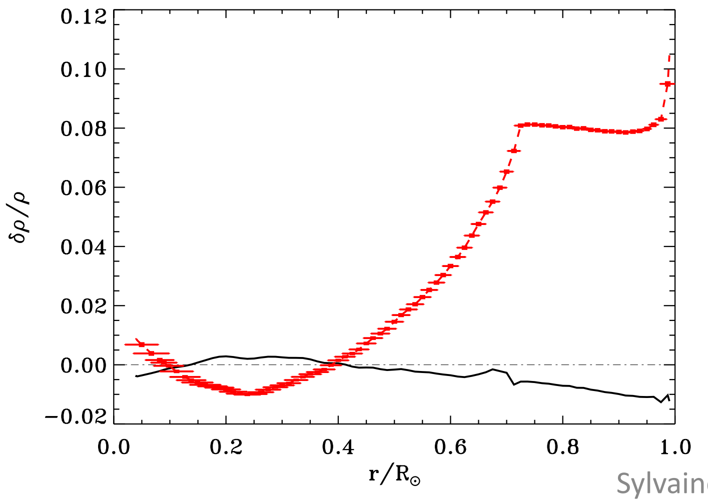
Beating between poloidal and totroidal configurations

Seismic diagnostic of the core from SoHO (GOLF+ MDI)

$$\frac{\delta\omega_{nl}}{\omega_{nl}} = \int_0^R \left[K_c^{(nl)}(r)\frac{\delta c}{c}(r) + K_\rho^{(nl)}(r)\frac{\delta\rho}{\rho}(r) \right] dr + Q_{nl}^{-1} G(\omega_{nl})$$

Turck-Chièze et al 2001; Couvidat et al. 2003; T-C et al. 2004 new CNO, confirmed by Basu et al. 2009; T-C, Piau, Couvidat 2011; Turck-Chièze & Lopes, RAA 2012 (all the numerical values)





Low degrees with low n n< 16 (no activity correction)

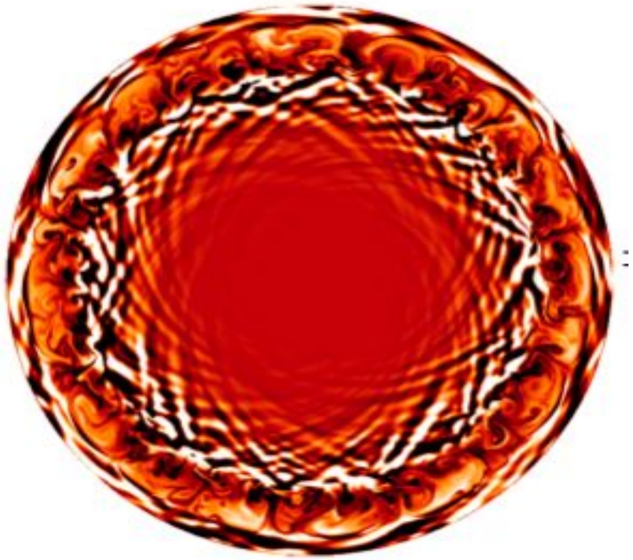
5 years in space= 30 years on ground (Basu et al. 2009)

SSM with Asplund 2009 composition in red
Includes all the improved physics; relativistic effect in the central EOS, new reaction rates

The seismic model reproduces the observed sound speed by changing pp reaction rate by 1% and some opacity coefficients by several %

Gravity modes from GOLF

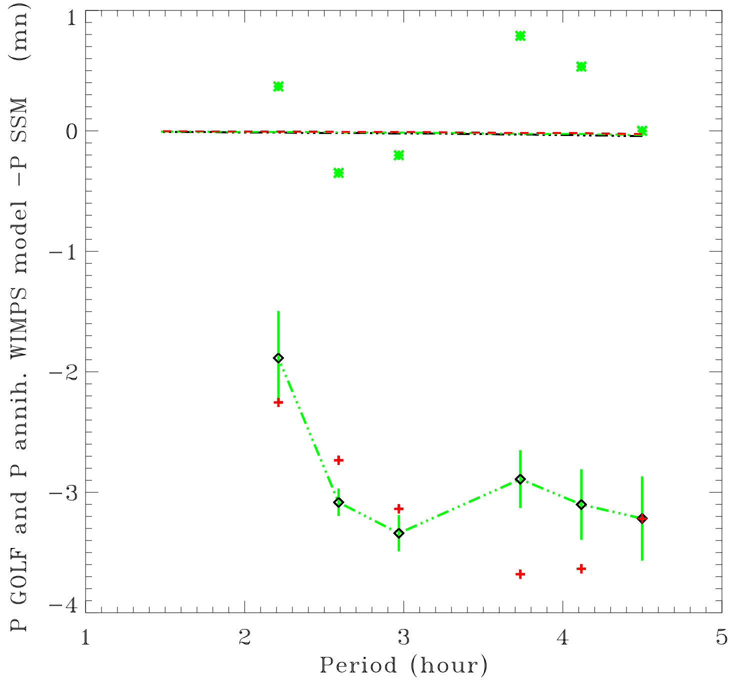
T-C et al. 2004, Garcia, T-C et al. Science 2007, Garcia et al. 2011

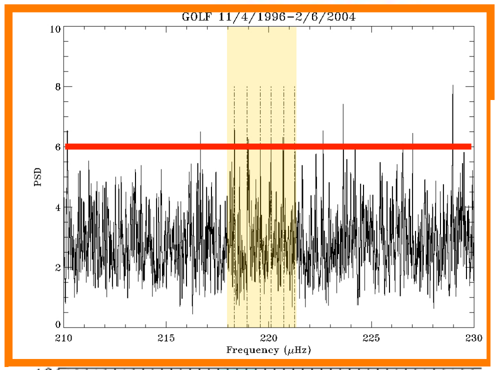


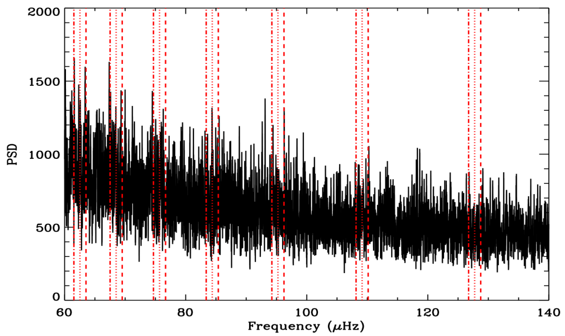
First determination of 6 individual values of dipole modes

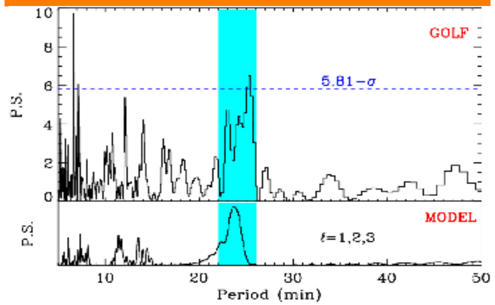
Comparison of gravity mode periods in agreement with SSeM prediction

But not with SSM ones









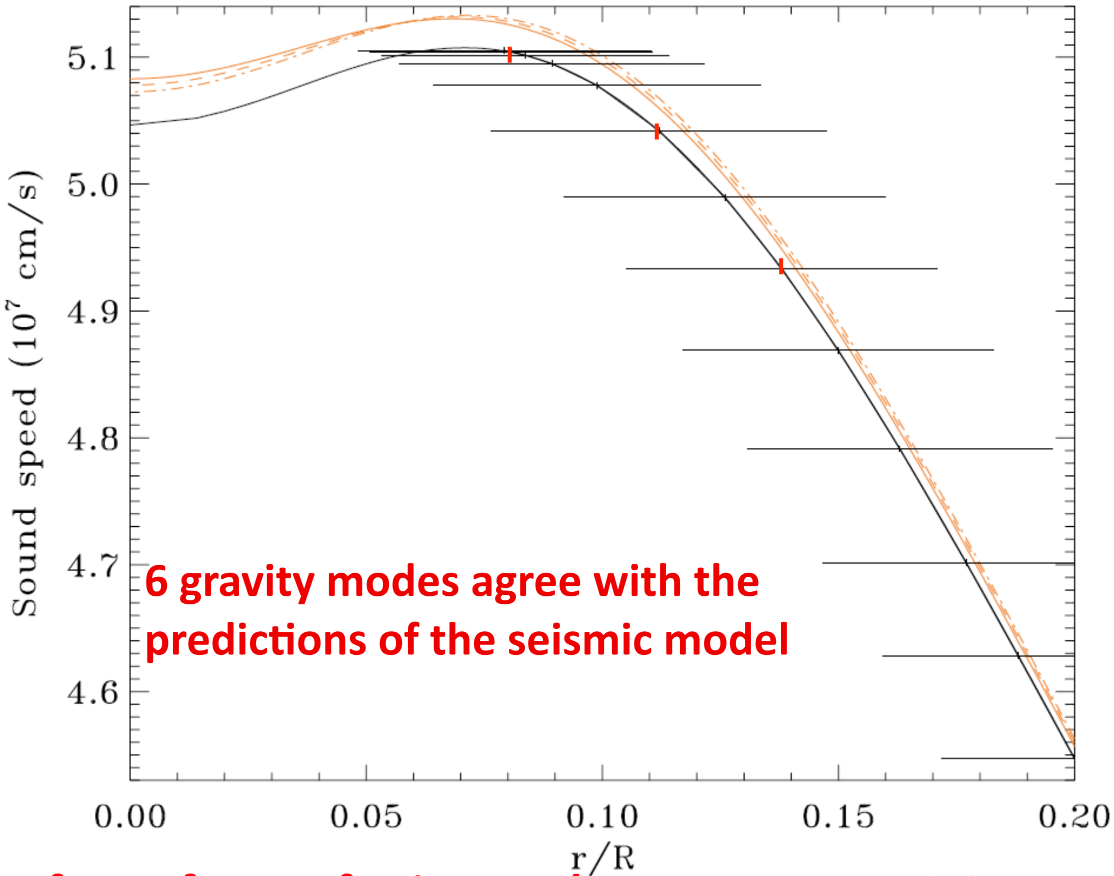
Zoom on the solar core

Comparison of data to Standard and seismic models

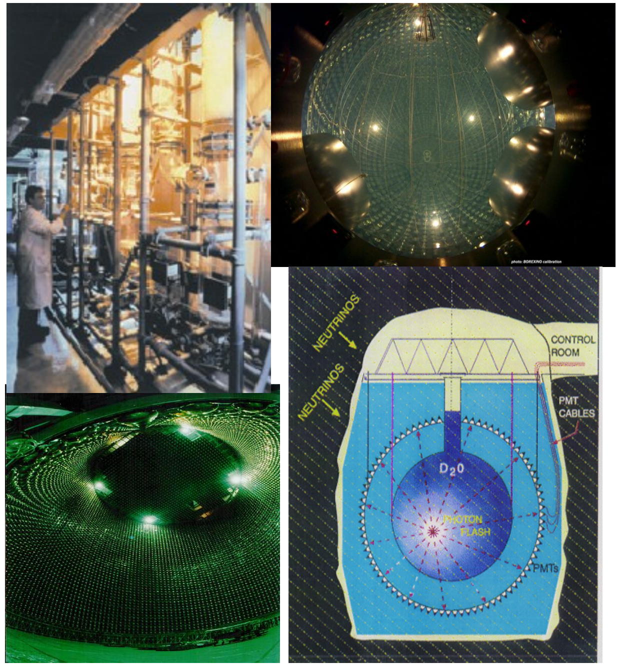
T-C et al. 2001, Couvidat et al. 2003; Basu et al. 2009

Asplund 2009 SSM T-C, Piau, Couvidat ApJlett 2011, T-C et al. 2012

GOLF/SoHO: collaboration IAS-CEA-IAC



6 gravity modes agree with the predictions of the seismic model



Coherence between all the predictions of the seismic model and the 5 neutrino detectors (T-C & Couvidat 2011 Report in Progress in Physics)

$^7Be + p \rightarrow {}^8B + \gamma$; $^8B + e^+ \rightarrow {}^8Be^* + \nu_e \rightarrow {}^4He$ Seismic model: 5.31 ±0.6 millions/cm^2/s

How could we interpret the differences in sound speed and density with SSM ?

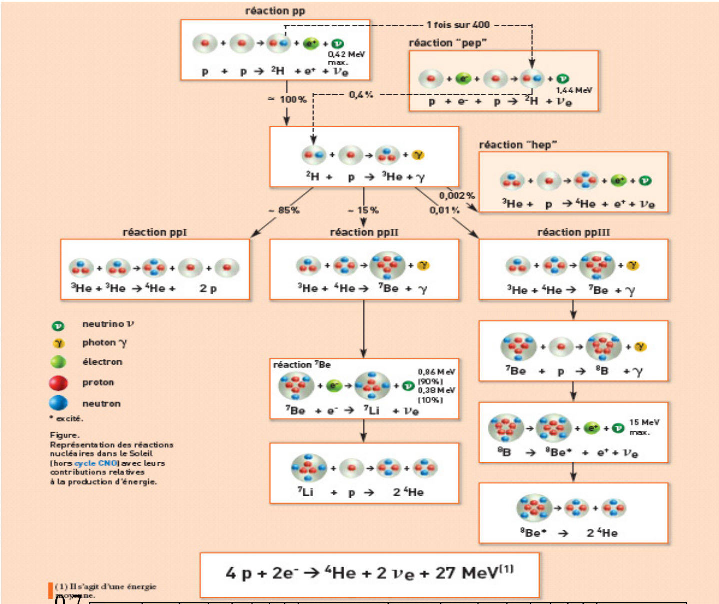
- ~~Bad photospheric determination ????~~
- Bad energetic balance: hypothesis of SSM
- Fundamental physics: WIMPs and others
- Bad transfer of energy: opacities calculations
- Extra phenomena: rotation, magnetic field, gravity waves … ???

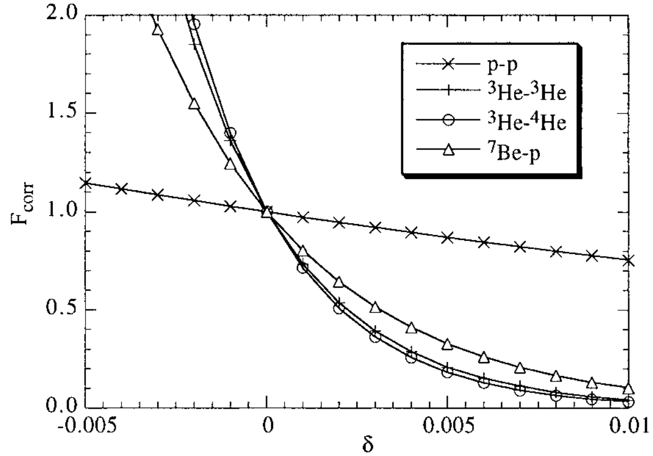
Bad energetic balance ?

today pp governs 98.7% of this energy through the weak interaction

Seismology+ solar models+ observed neutrinos + oscillations of neutrinos

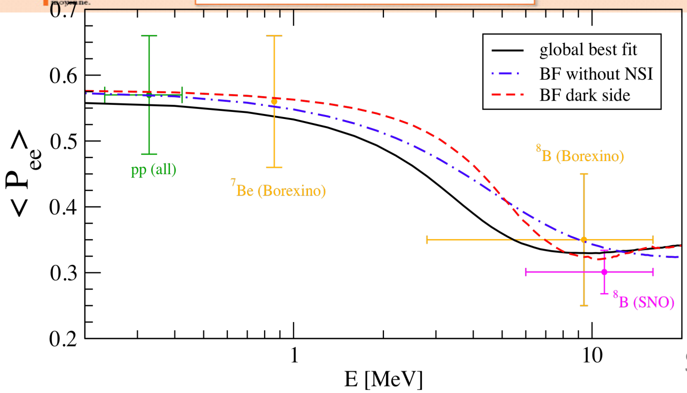
Turck-Chièze & Couvidat Report in Progress in Physics 2011, 74, 086901;
Turck-Chièze et al. Phys. Report, 1993, 230, 57-235





Maxwellian distribution
Screening checked

Turck-Chièze, Nghiem, Couvidat, Turcotte 2001, Sol Phys.



pp, ^{7}Be, ^{8}B electronic neutrinos detected, part of them are changed in muon or tau neutrinos

We can directly compare observed neutrinos to predictions by SSM, predictions by seismology

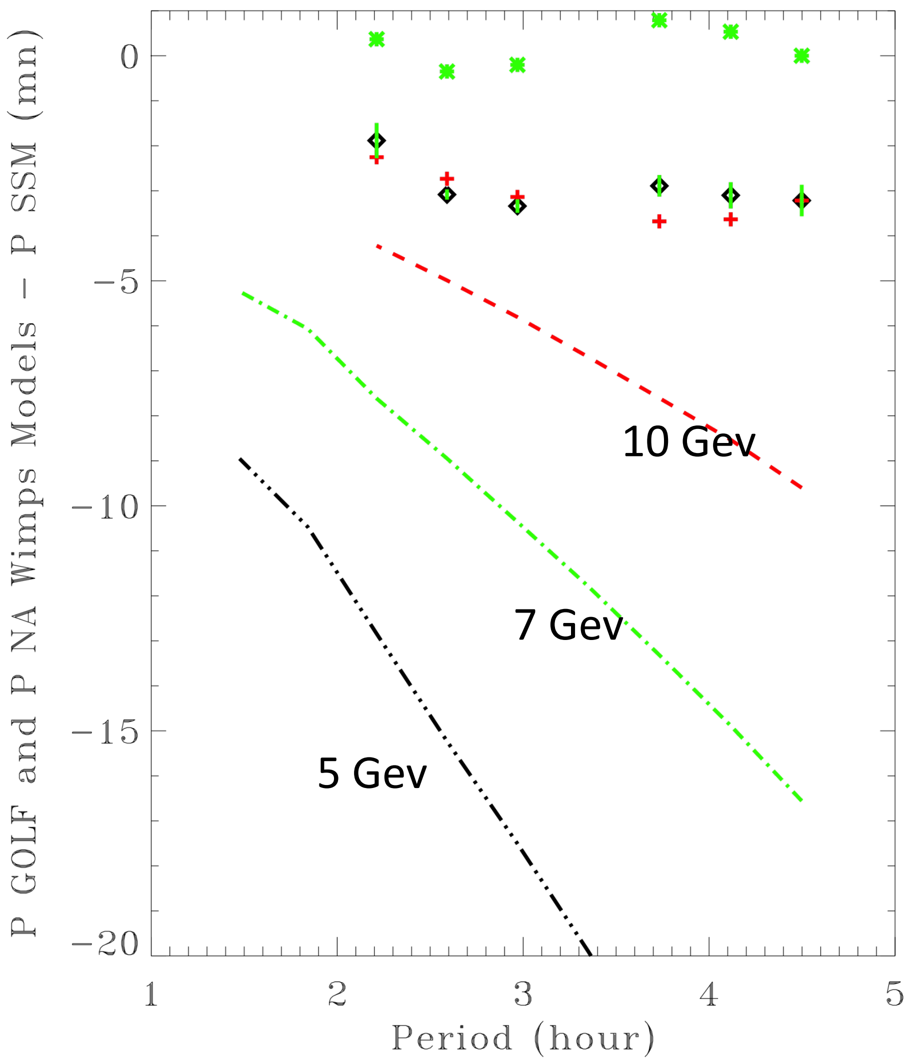
Helioseismology and neutrinos agree totally today through SSeM not SSM

	Predictions without neutrino oscillation	Predictions with neutrino oscillation
HOMESTAKE		**2.56 ± 0.23 SNU**
Standard model 2009	6.315 SNU	2.24 SNU
Seismic model	7.67 ± 1.1 SNU	**2.76±0.4 SNU**
GALLIUM detectors	GALLEX	73.4 ± 7.2 SNU
	GNO	62.9 ± 5.4 ± 2.5 SNU
	GALLEX + GNO	**67.6 ± 3.2 SNU**
	SAGE	**65.4 ± 3.3 ± 2.7 SNU**
	GALLEX+GNO+SAGE	**66.1 ± 3. SNU**
Standard model 2009	120.9 SNU	64.1 SNU
Seismic model	123.4 ± 8.2 SNU	**67.1 ± 4.4 SNU**
BOREXINO ^{7}Be		**3.36 ± 0.36 $10^9 cm^{-2} s^{-1}$**
Standard model		
Seismic model	4.72 $10^9 cm^{-2} s^{-1}$	**3.045 ± 0.35 $10^9 cm^{-2} s^{-1}$**

Water detectors	Predictions or Detections B^8 electronic neutrino flux
SNO	**5.045 ± 0.13 (stat)± 0.13 (syst) $10^6 cm^{-2} s^{-1}$**
SNO +SK	**5.27 ± 0.27 (stat)± 0.38 (syst) $10^6 cm^{-2} s^{-1}$**
Standard model 2009	4.21 ± 1.2 $10^6 cm^{-2} s^{-1}$
Seismic model	5.31 ± 0.6 $10^6 cm^{-2} s^{-1}$
B^8 neutrino flux	electronic + other flavors in $10^6 cm^{-2} s^{-1}$
SK1 (5 MeV)	**2.35 ± 0.02 (stat) ± 0.08 (syst)**
SNO D_2O (5 MeV)	**2.39 ± 0.23 (stat) ± 0.12 (syst)**
BOREXINO (2.8 MeV)	**2.65 ± 0.44 (stat) ± 0.18 (syst)**

Strong limits on dark matter properties from the knowledge of the solar core

Turck-Chièze, Lopes et al. 2012, ApJ lett February 2012



- The core of the Sun is now well constrained by **neutrinos** detection (constraints on the **central temperature**) and **gravity modes** (constraints on the **central density**) through the seismic model that predicts correctly both detections:
- **Tc = 15.75 10^6K**
- **Rho= 153.6 g/cm^3**
- This fact puts strong constraints on the mass of WIMPs, first candidates for dark matter if one considers realist spin dependent and independent cross sections:

For $\Sigma_{ann}$of 10^{-50}cm^2 σ_{SD}=7 to 5 10^{-36} cm^2 σ_{SI}= 10^{-40} cm^2 **M $_{WIMPS}$ < 10 GeV are rejected, no real signature of WIMPs**

Energetic balance

Turck-Chièze, Piau, Couvidat 2010

- T_c seismic model 15.74 10^6 K
- T_c SSM 15.54 10^6 K

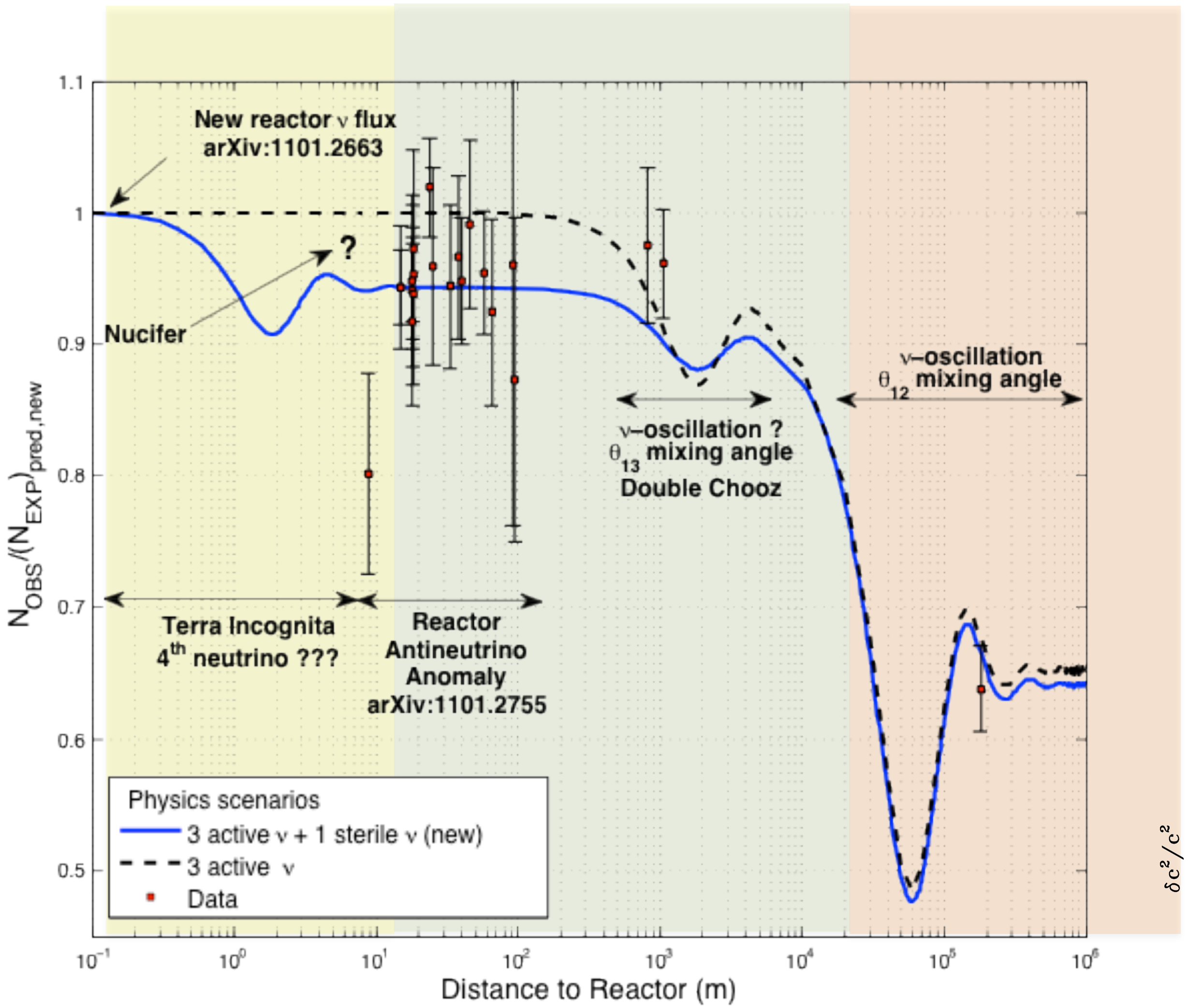
- ρ_c seismic model 153.02 g/cm^3
- ρ_c SSM 150.06 g/cm^3

- X c seismic model 0.339
- Yinitial 0.277 Ysurf 0.251

- 1.5% difference in central temperature=>
  no more than 5- 6% difference in luminosity $L_{nuc} > L_{sol}$

Part of it could be redistributed in kinetic energy, magnetic energy in the RZ , another part through transfer of energy by photons or other species

Could sterile neutrinos be forgotten ?

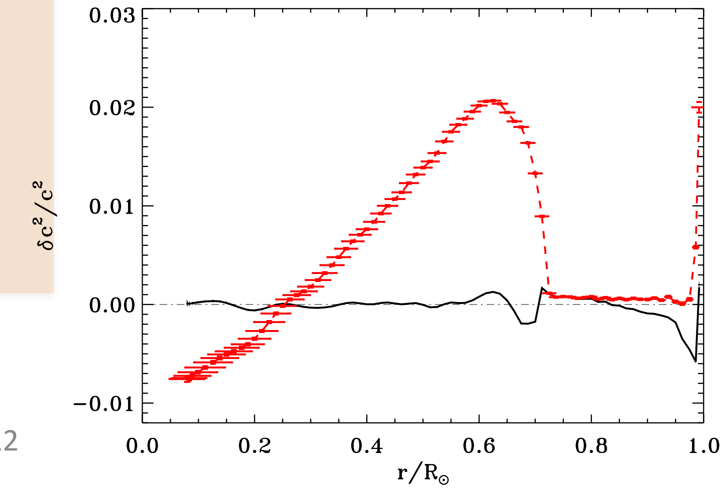


Mueller et al. 2011

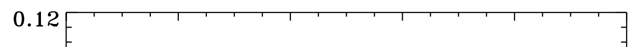
Effect of about 7%
(inside the error bar of today predictions)

But their mass could be extremely small

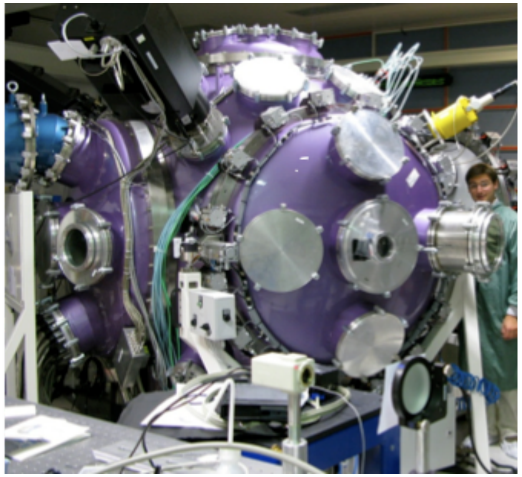
And Axions???
Their effect on transport of energy would be different



Sylvaine Turck-Chièze, Gran Sasso 8/10/12



Bad transfer of energy by photons ?



LULI

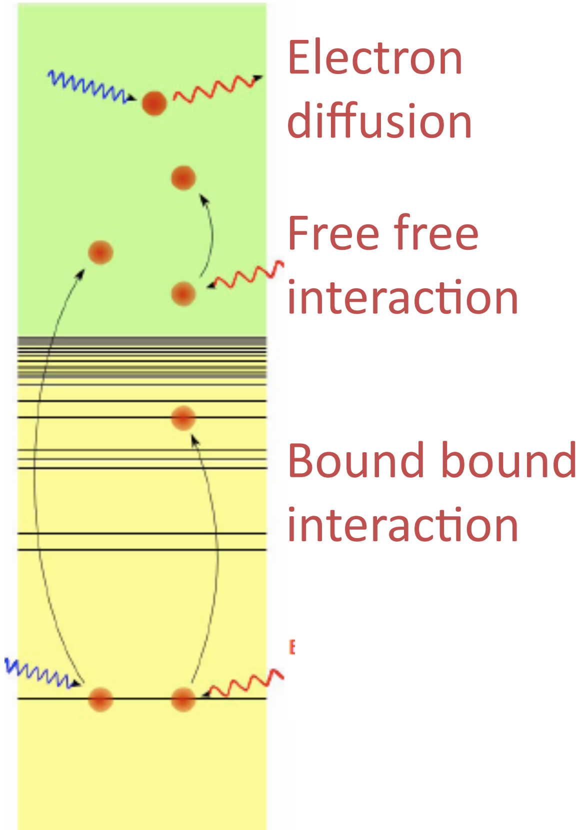
LMJ+PETAL

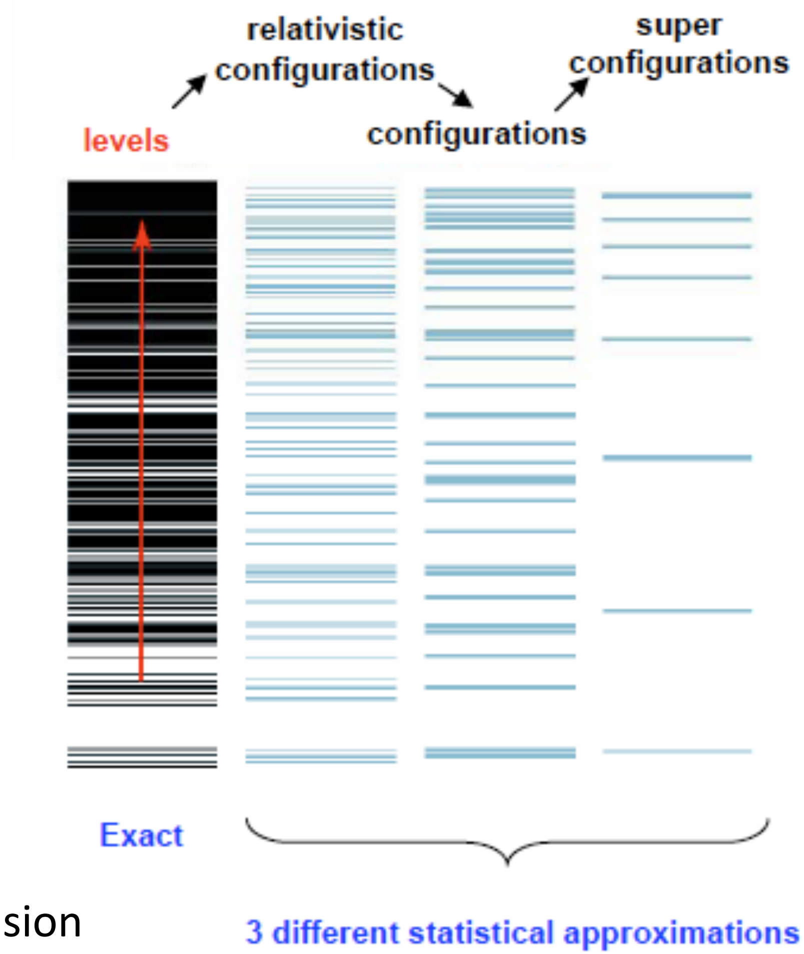
Envelopes of massive stars 4-12 Msol
Experiences 2010-2013: Cr, Fe, Ni, Cu

Radiative zone of solar-like stars

OPAC international consortium: Sylvaine Turck-Chièze
C. Blancard, T. Caillaud, P. Cosse, T. Blenski, J. E. Ducret, J. Farriaut,
G. Faussurier, D. Gilles, F. Gilleron, M. Le Pennec, L. Piau,
J. C. Pain, M. Poirier, C. Reverdin, V. Silvert, F. Thais, B. Villette CEA France
F. Delahaye, C. Zeippen Obs. Meudon France, S. Bastiani Ecole Polytechnique France
M. Busquet, ARTEP, USA; J. Bailey, G. Loisel Albuquerque, USA, Carlson, J. Guzik, D.P. Kilcrease,
N.H. Magee Los Alamos, USA, J. W. Harris, D Hoarty AWE England

Comparison between 7 different calculations Experimental validation is useful to study the plasma effects and the line broadening.



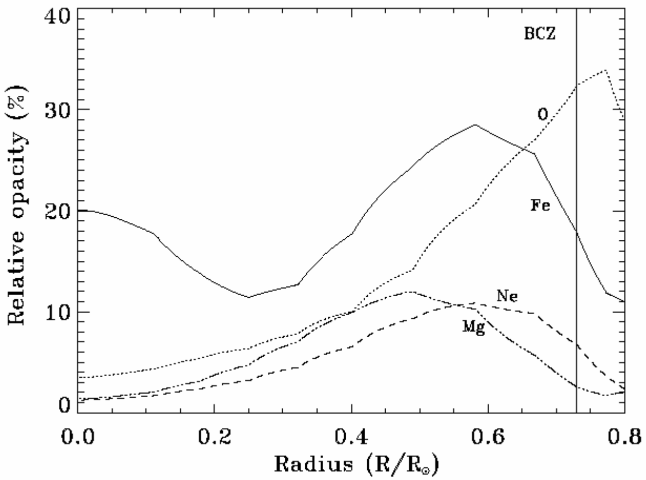


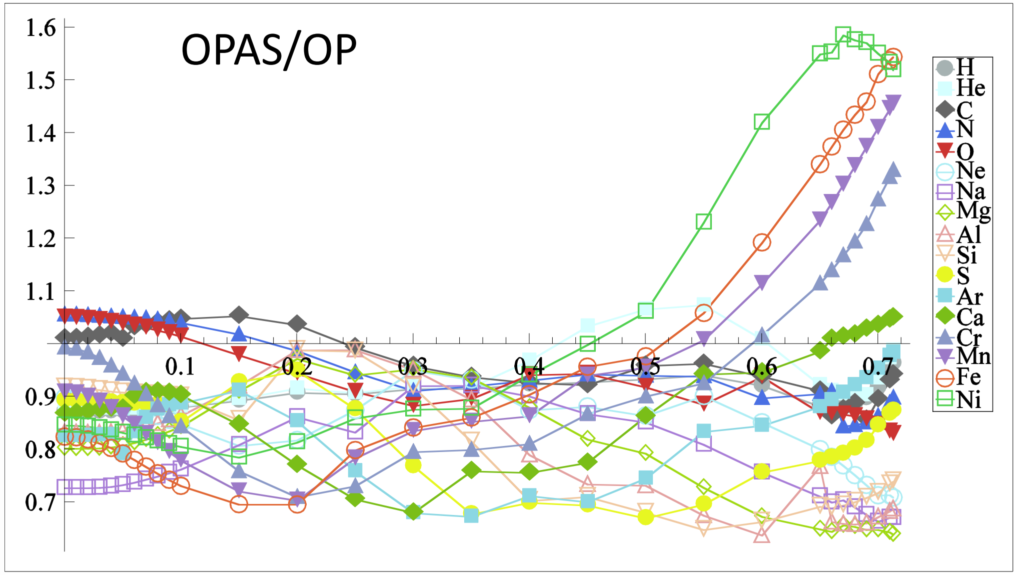
Mean Rosseland value

Radiative acceleration for microscopic diffusion

Radiative zone of the Sun

Turck-Chièze et al. HEDP 2010: Adv. Space Res. 2011, Blancard, Cosse & Faussurier (CEA) 2012





10% oxygen, 3% opacity, 0.3% soundspeed
Neon is difficult to determine precisely

Impact on microscopic diffusion

Comparison OPAS/OPAL differences smaller except for Ca, Cr, Mn that are small contributors but one cannot exclude some % on K_R :1.03 at the BCZ (incomplet M shells), work in progress on the whole RZ

Experiments will be difficult: two or three designs in study to get density greater the solid density: chocs , LTE proposals for 2015-2016 + measurements of reaction rates

Measurements of N13 and O15 neutrinos with Borexino: good test of their composition in the core, even problem of accuracy or screening or reaction rates

Bellini et al. 2011 neutrino detection

- pep neutrino flux $1.6 \pm 0.3\ 10^8\ cm^{-2}s^{-1}$

  prediction $1.4\ \ 10^8\ cm^{-2}s^{-1}$
- CNO neutrino flux $< 7.7 \pm 0.3\ 10^8\ cm^{-2}s^{-1}$
- prediction N13 has decreased from 6.27 to about 4 $10^8\ cm^{-2}s^{-1}$
- Prediction O15 from 5.6 10^8 to about 3.5 $cm^{-2}s^{-1}$

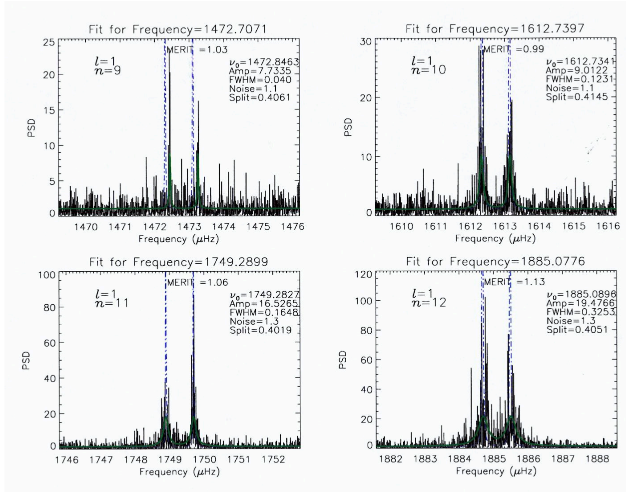
  work in progress : screening , reaction rate ^{14}N +p, composition

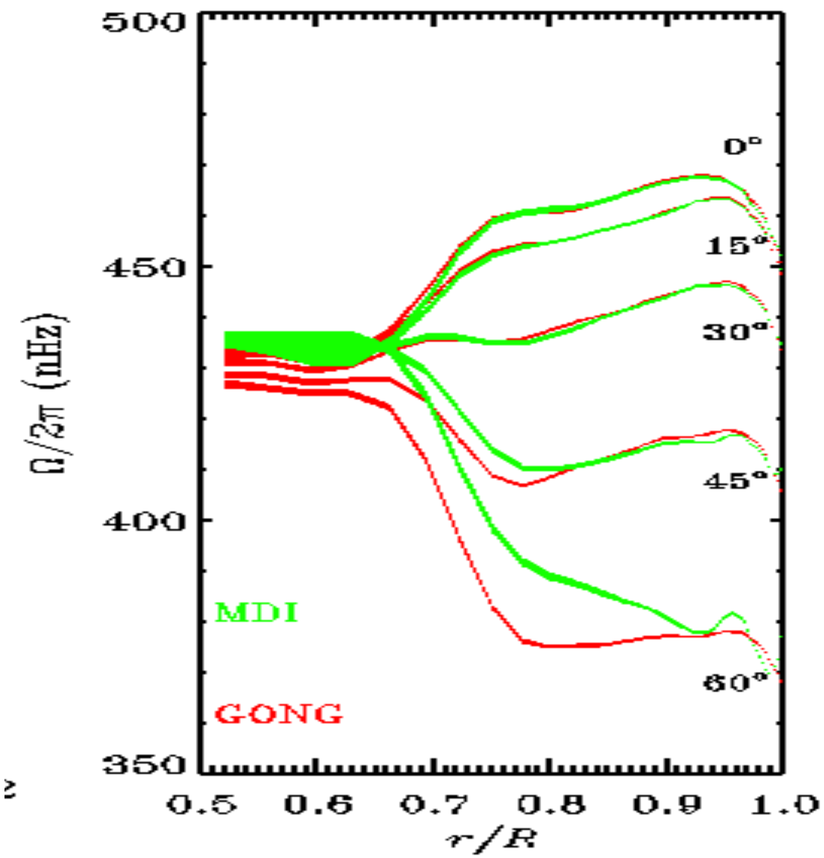
Extra phenomena:

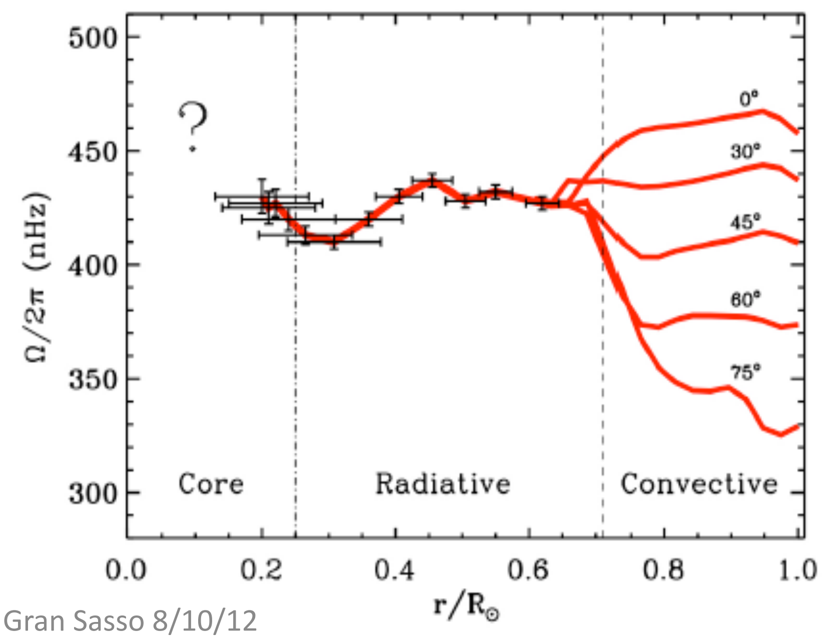
Constraints from acoustic modes on the rotation profile

$$\delta\omega_{nlm} = m\int_0^R\int_0^\pi K_{nlm}(r,\theta)\Omega(r,\vartheta)rdrd\vartheta$$

Kosovichev et al, 1997, Howe et al. 2000, Garcia et al. 2007,
Eff Darwich et al. 2008, Mathur et al. 2008

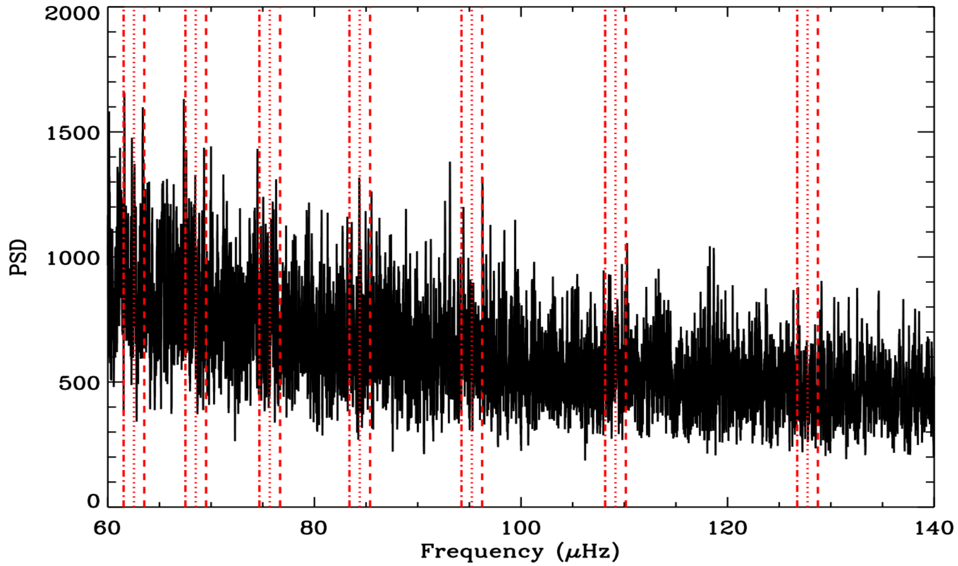




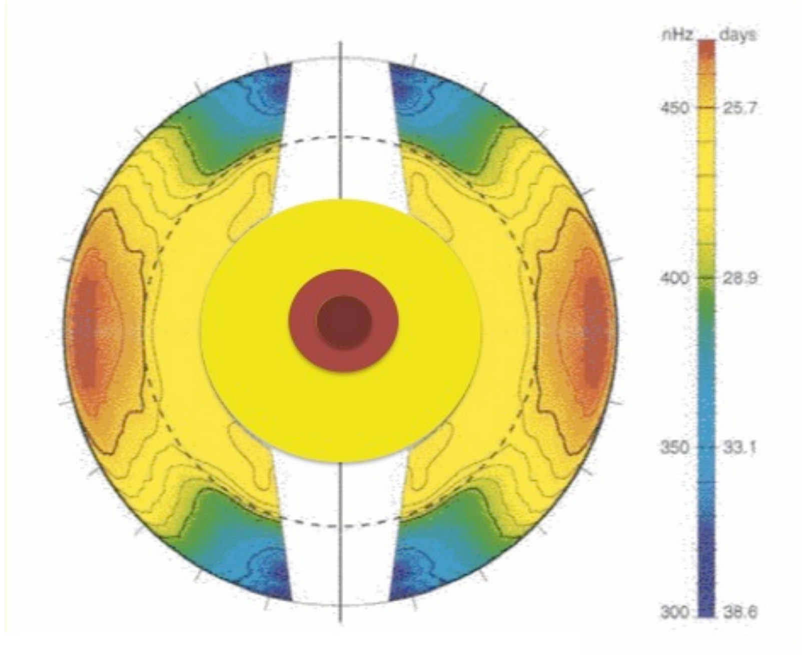


New constraints from the sum of 20 modes +individual g modes on the rotation of the core

No direct evidence of magnetic field but splitting estimates



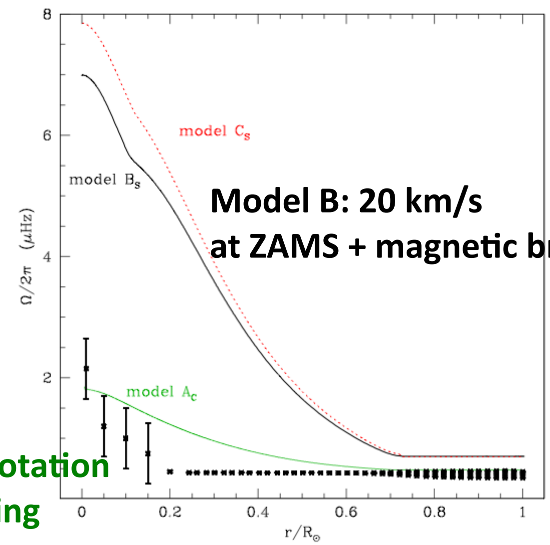
Garcia et al. 2007, 2008, 2010 SOHO24,
Turck-Chièze et al., 2004, 2010, 2011, 2012



The solar rotation increases in the core by a factor 5 to 8

Transport of angular momentum by rotation:
Turck-Chièze, Palacios et al. 2010

All models surestimate the rotation in the core



Model B: 20 km/s at ZAMS + magnetic braking

Model A: Weak initial rotation without magnetic braking

Sub surface differential rotation

Summary and perspectives

Most of the hypotheses of the SSM are submitted to verification thanks to helioseismology and neutrinos: screening, maxwellian distribution, balance of energy…

Energetic balance: L nucl could be > L surf but by no more than 5%

part of this difference may come from energy transfer still slightly underestimated

Coherence between helioseismology and neutrinos is important

The seismic model leads to a good prediction of all the detected neutrinos,

CNO neutrinos are ABSOLUTELY useful to compare central CNO composition to photospheric values, screening effect and cross sections must be checked

Our knowledge of the core: helioseismology + neutrinos puts constraints on WIMPS effect, no visible effect WIMPs M> 12 GeV other dark matter candidates sterile neutrinos, axions …. M < 1 eV must be considered also.

Absolute values of frequency are more and more under control in coupling 1D to 3D role of turbulence in 3D, magnetic field appears directly visible only 0.1% below the surface radius.

We continue to explore the internal magnetic field: young Sun, interaction with planets and to prepare if possible reaction rates measurements near large laser facilities,

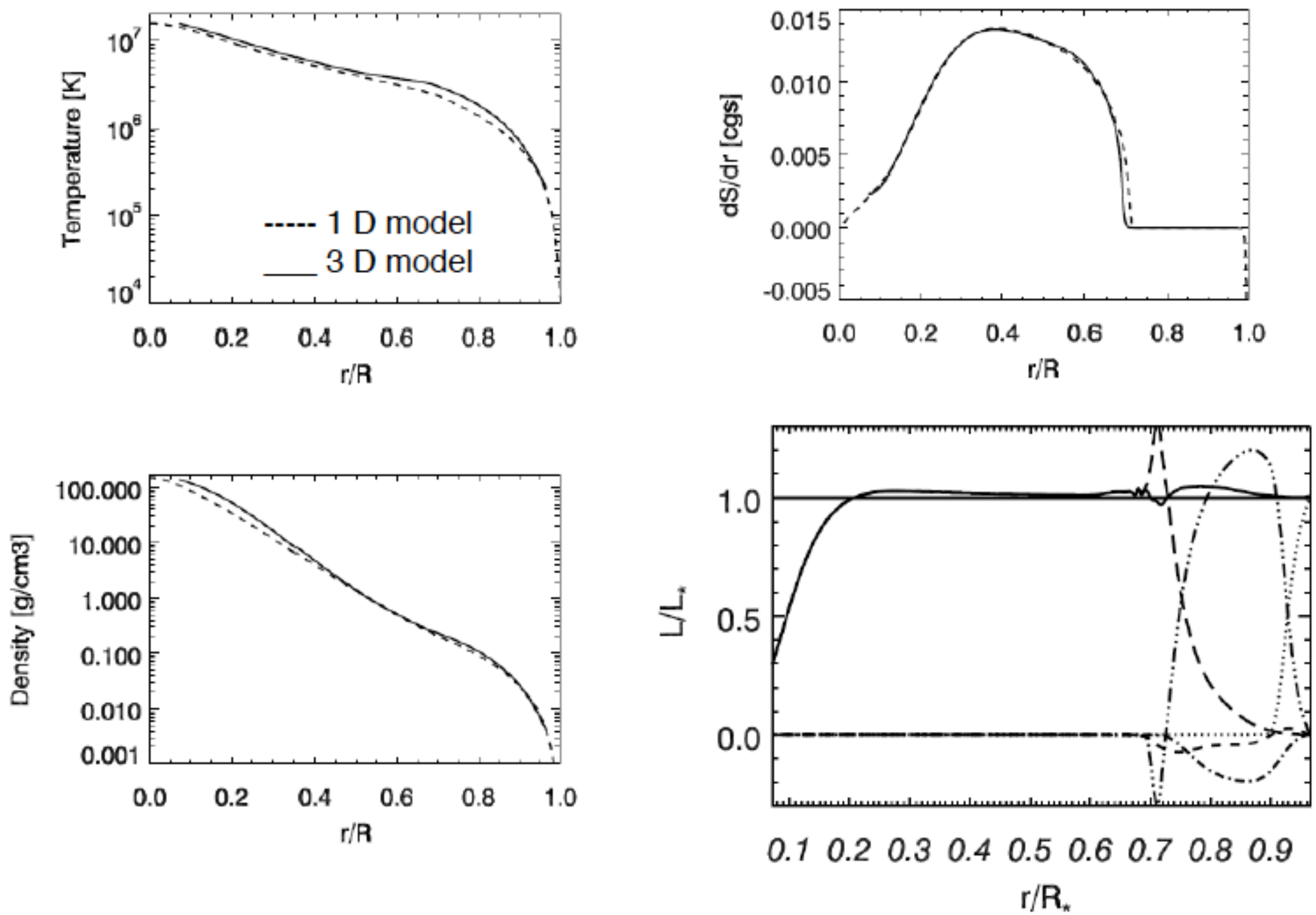
Most of the results presented in this talk, including tables of frequencies and sound speed and density profiles values, are summarized in our two recent invited reviews

Turck-Chièze, S. and Couvidat, S., Solar neutrinos, helioseismology and the dynamical Sun, 2011, Report on Progress in Physics, 74, 086901 (35 pages)

Turck-Chièze, S. & Lopes, I., Solar and stellar Astrophysics and Dark matter, 2012, Research in Astron Astrophys, 12, 8, 1107-1138

Some flavours from Bern, in particular on 3D developments of the Sun

Realistic Solar Stratification Background State

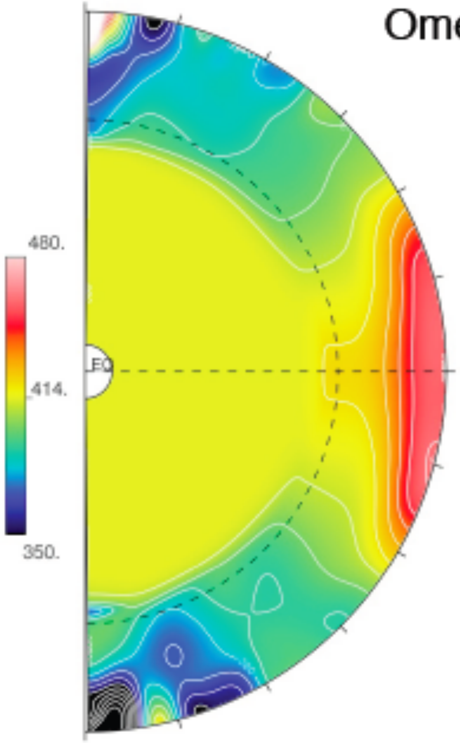


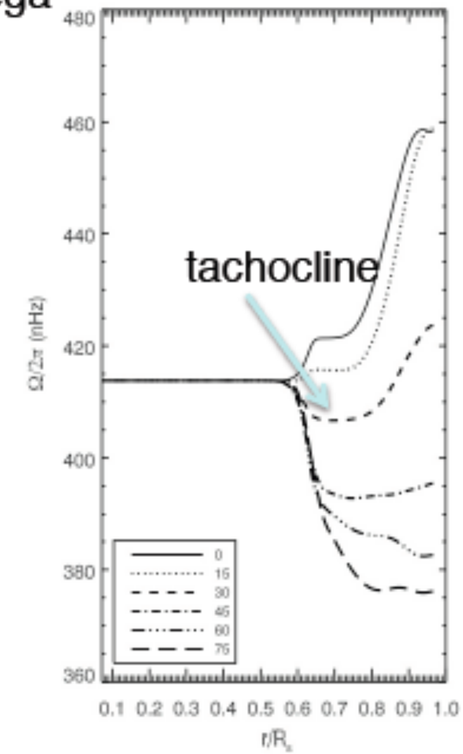
Brun, Miesch, Toomre, 2011, ApJ , 742

Omega Profile & Meridional Circulation

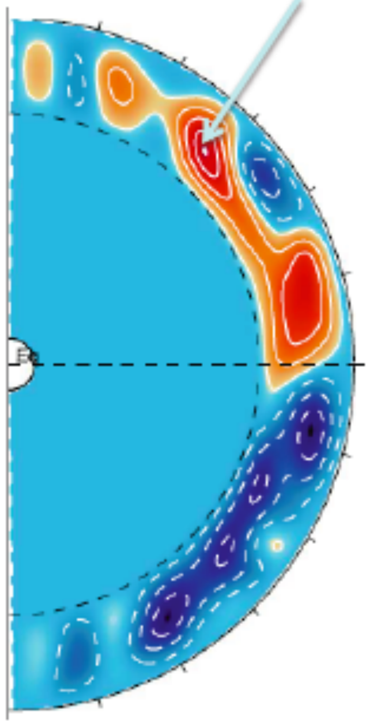
Almost unicellular flow

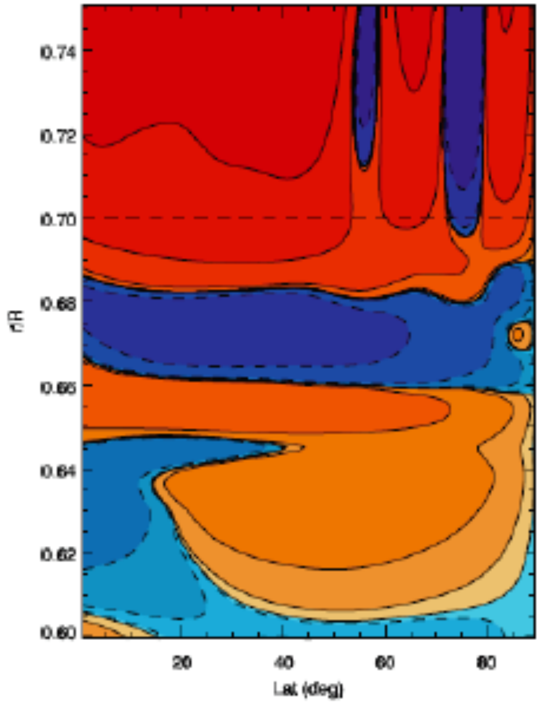
Omega





tachocline





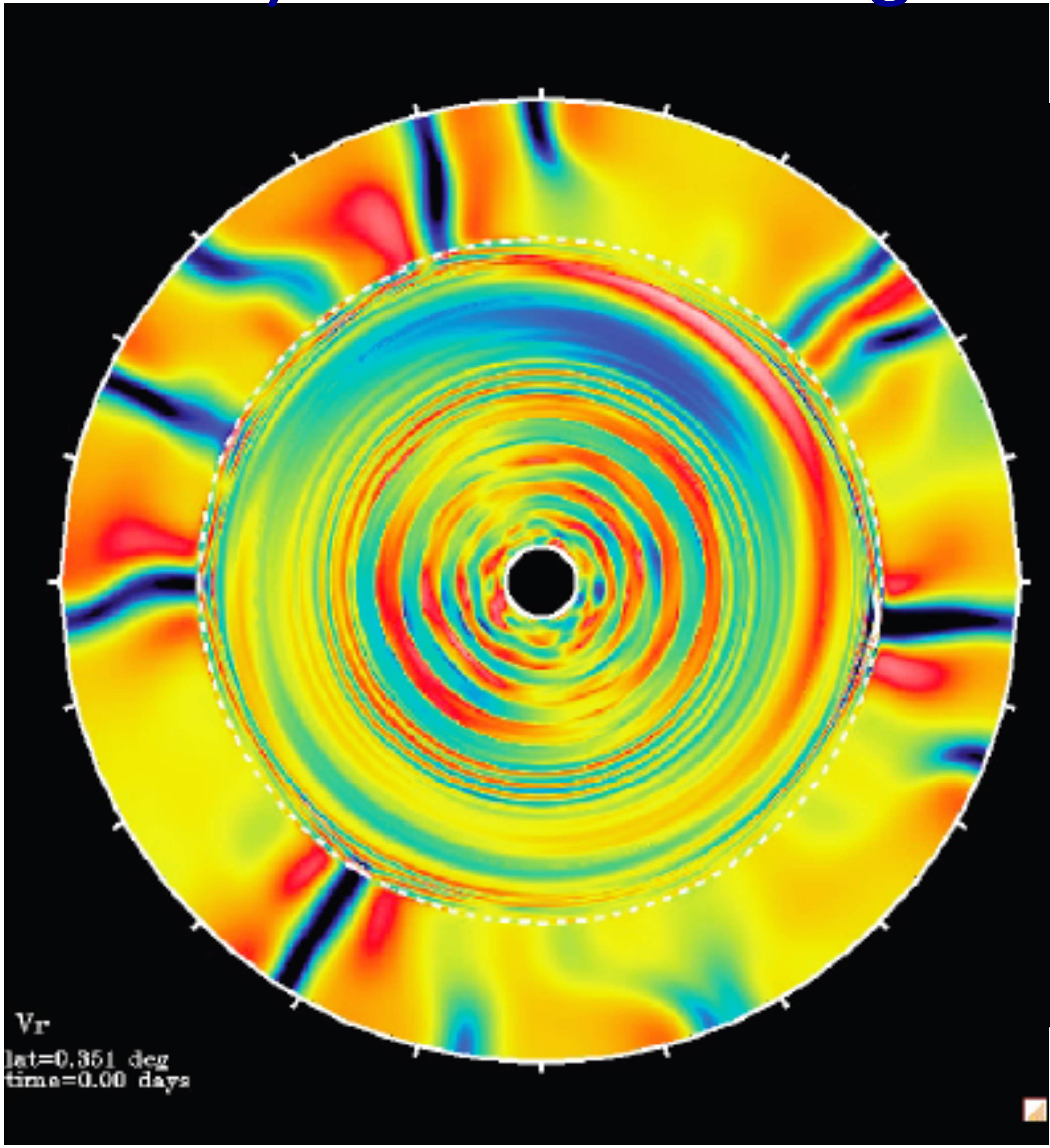
Penetrationof MC flow
< 0.02 Rsol

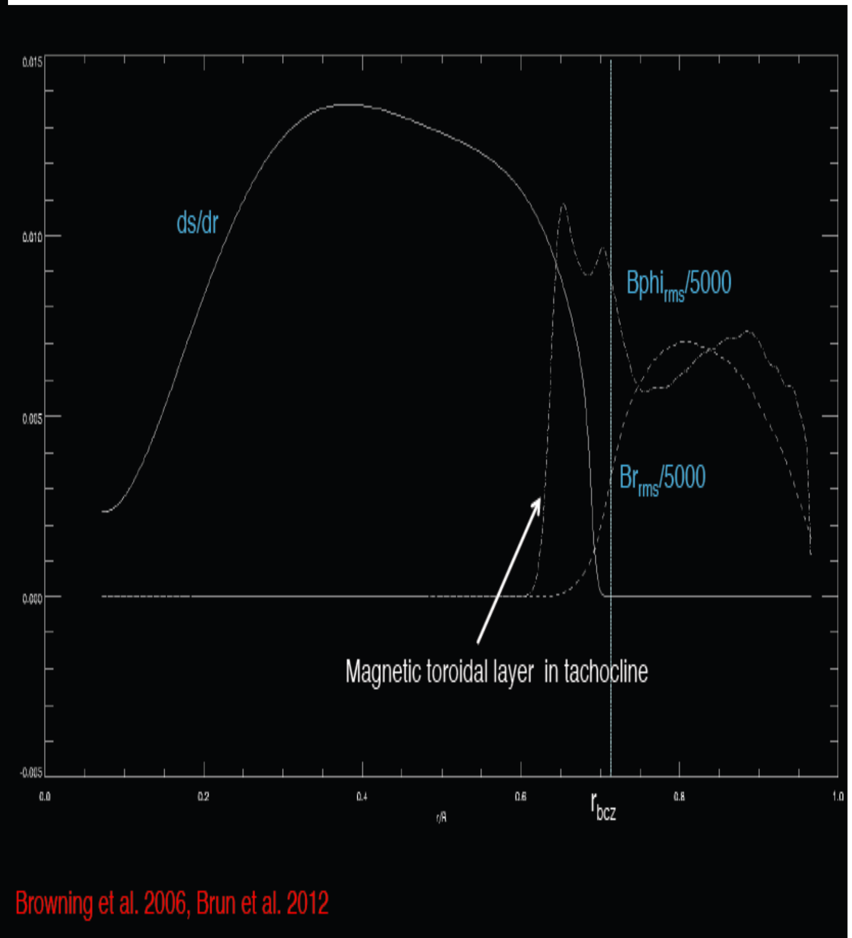
Fast equator/slow poles

Drop by
3 orders of
magnitude
over 0.04 R

Brun, Miesch, Toomre, 2011, ApJ , 742

Gravity waves and magnetic field inside the Sun





From 1D to 3D

- 3D still in infancy
- Not secular models
- Noticed differences between the two
- For example meridional circulation 10^{-6} cm/s versus 5cm/s in RZ
- A lot to do in the next decade (fossil field, detailed rotation in the core) to pursue the work of John and Raju in a lot of domains and in particular in neutrino fields