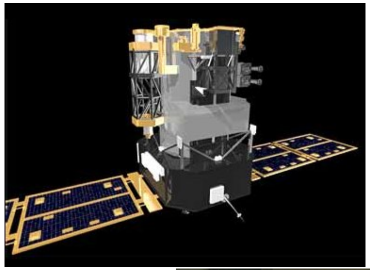
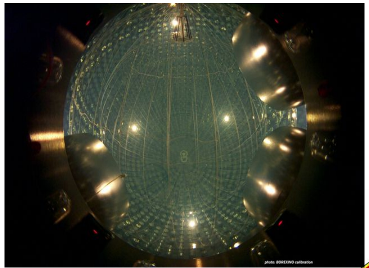
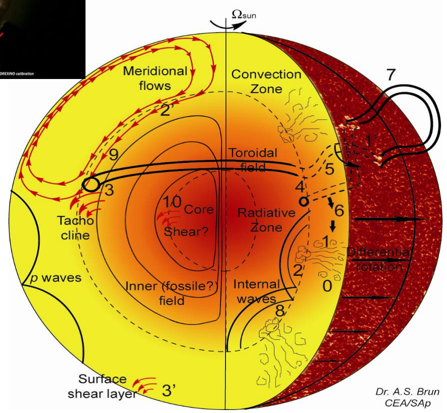
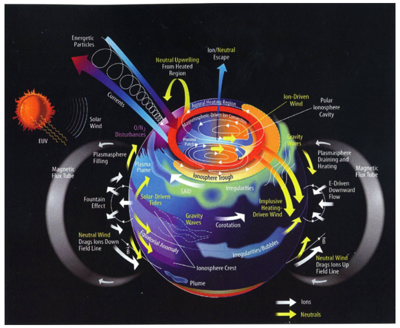
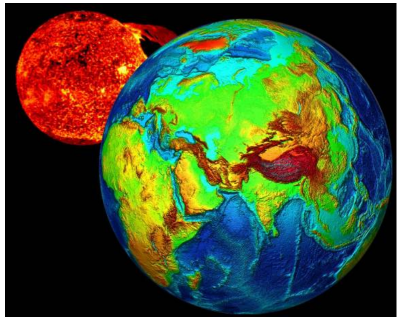
# Solar neutrino emission and related questions on the solar core



**S. Turck-Chièze**
**CEA/IRFU/SAp, Saclay France Sylvaine.Turck-Chieze@cea.fr**

- Historical context
- The SSM framework and beyond ?
- Consequences for neutrinos and dark matter

*Most of the results presented in this talk, including neutrino predictions, discussion on error bars, tables of acoutic and gravity mode frequencies, sound speed and density profiles values are summarized in the three invited reviews*

**Turck-Chièze, S., W. Däppen, E. Fossat, J. Provost, E. Schatzman, and D. Vignaud, 1993, "The Solar Interior", Physics Report, 230,2-4, 59-235.**

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

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

**They summarize more than 100 papers from our community**

Gamow 1929

# The initial period

# 1964- 1986

**1.5 ±1 SNU instead 22 SNU**

**200 neutrinos in 20 years**

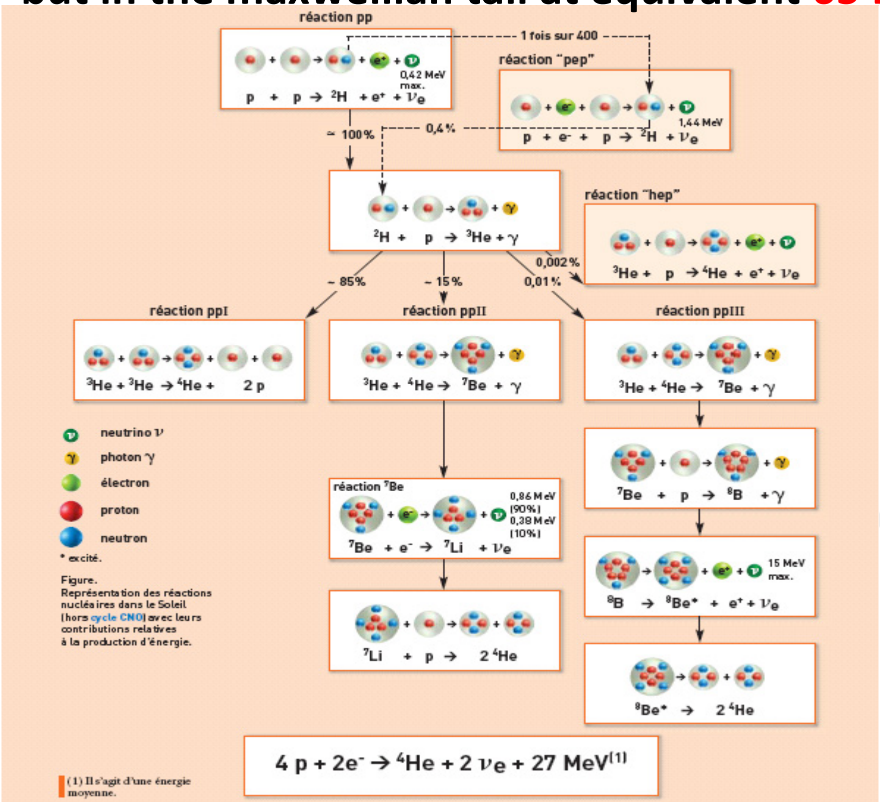
**2.3 for a prediction of about 7 SNU**

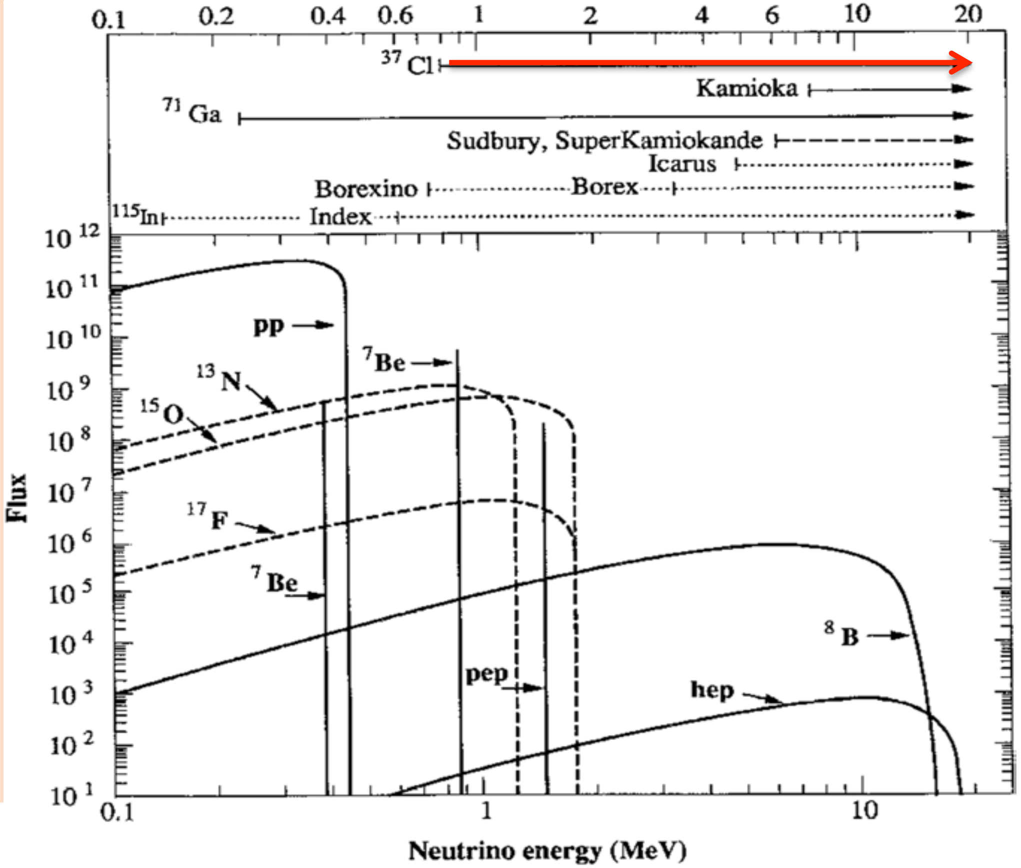
Ray Davis

John Bahcall

**coulomb barrier $H^+ + H^+$ reactions ~~at 15 $10^6$ K~~**

**but in the maxwellian tail at equivalent 65 $10^6$ K**

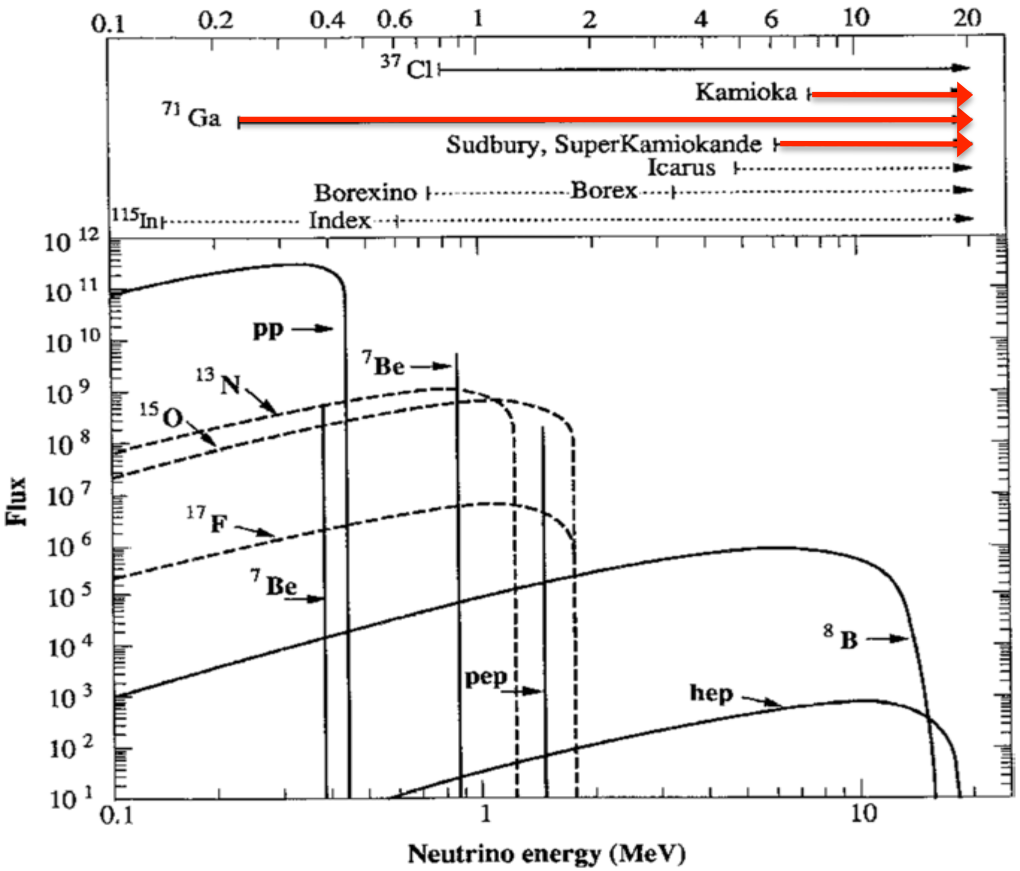


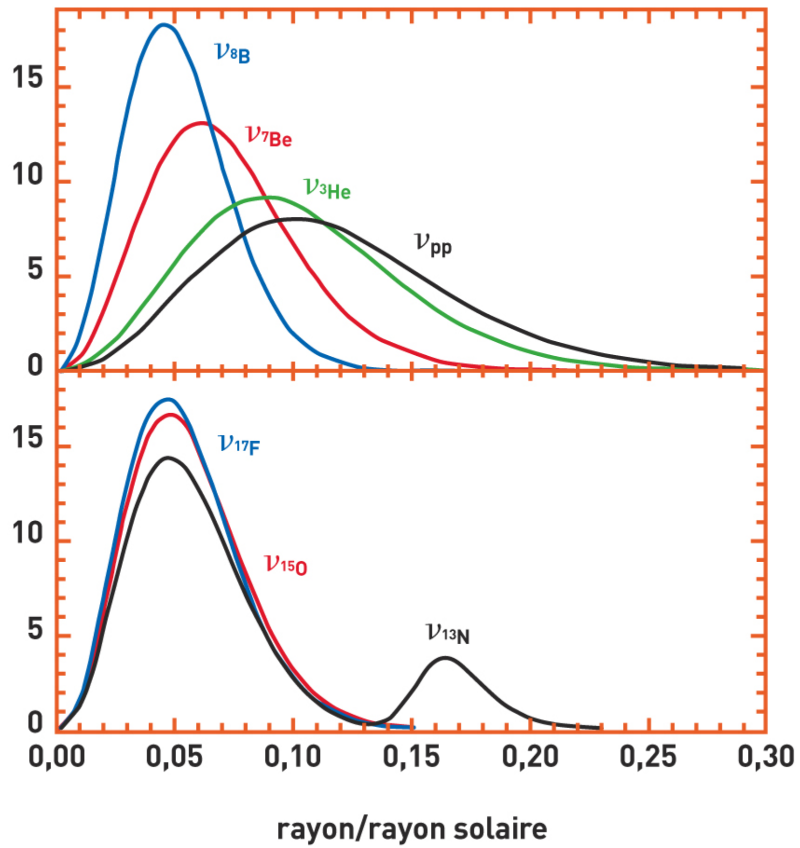




**Hans Bethe 1906-2005 Nobel Prize 1967**

# The golden age of solar neutrinos and solar neutrino predictions 1988-2001

$^8$B predictions: Bahcall & Ulrich (1988) 5.8 $10^6$ $cm^{-2}$ $s^{-1}$ , Turck-Chièze et al. (1988): 3.8 $10^6$ $cm^{-2}$ $s^{-1}$ .
Kamiokande confirmed the solar neutrino deficit (Hirata et al 1989 ): 2.8 ±0.33
Chlorine prediction: 5.8 ±1.3 SNU, Gallium: 125±5 SNU 1 SNU= $10^{-36}$ capture/s/atm



# SSM assumptions

- Hydrostatic equilibrium
- Nuclear energy equilibrates lost of energy at the surface
- Mass conservation
- Transport of energy through photons interaction or convective motion
- At present age, present luminosity and radius

Equation of state, opacity, reaction rates determined at each position in the star X(r, t, Xi)

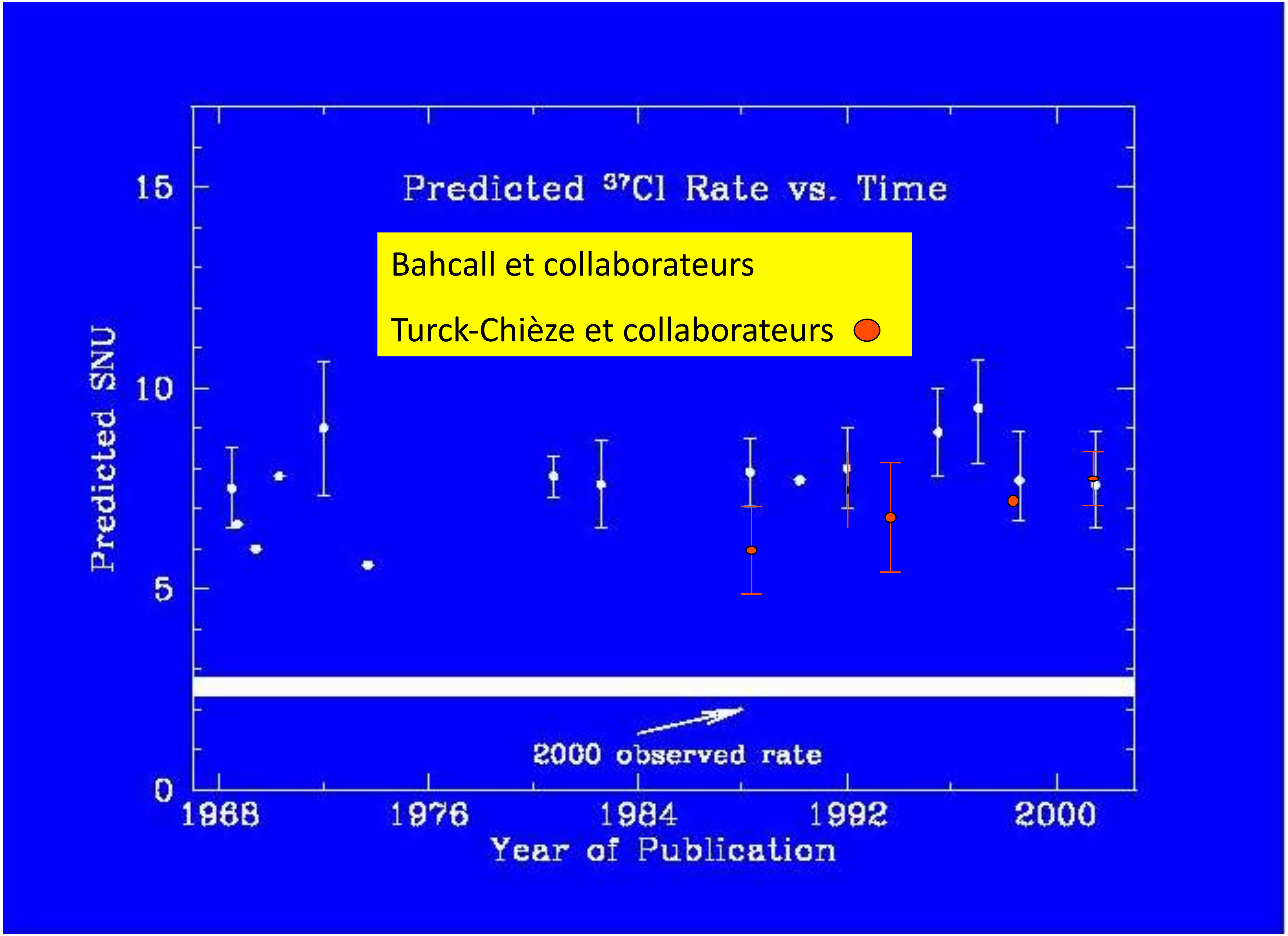
No dynamical phenomena except convection

From Turck-Chièze et al. 1988

TABLE 8

NEUTRINO CAPTURE RATES AND UNCERTAINTIES

| | NEUTRINO CAPTURE RATE (SNU) | | | | |
|---|---|---|---|---|---|
| | $^{71}$Ga : 125 ± 5 | | $^{37}$Cl : 5.8 ± 1.3 | | |
| UNCERTAINTIES Sources ($p_j$) | Uncertainty (1 $\sigma$ error) | $\frac{\partial \ln \phi_{pp}}{\partial p_j}$ | $\frac{\partial \ln \phi_{8_B}}{\partial p_j}$ | $^{71}$Ga Detector | $^{37}$Cl Detector |
| ($p$, $p$) reaction .................. | 2% | 0.14 | −2.7 | 1.8% | 3.9% |
| ($^3$He, $^3$He) reaction ........... | 5% | 0.03 | 0.42 | ≤0.1% | 1.6% |
| ($^3$He, $^4$He) reaction ........... | 4% | −0.06 | 0.83 | 1% | 2.7% |
| ($^7$Be, $p$) reaction ................ | 15% | 0. | 1. | 1% | 15% |
| $L_\odot$ ........................... | 0.5% | 0.69 | 7.2 | 0.3% | 3.6% |
| $Z/X$ ........................... | 10% | −0.05 | 1.26 | 1.8% | 9% |
| Age ........................... | 2% | −0.07 | 1.4 | ≤1% | 2% |
| Opacity: | | | | | |
| $T \leq 5 \times 10^5$ K ............. | ≥10% | 0.02 | 0.13 | 1% | 1% |
| $\geq 5 \times 10^5$ K ............. | 5% | −0.012 | 2.6 | ≤1% | 12% |
| $\sigma_{abs}$ ........................... | ... | ... | ... | 2.5% | 4% |
| Total uncertainty ............. | | | | 4.2% | 22% |




Model predictions depend on the state of art of the microscopic physics, macroscopic physics ?

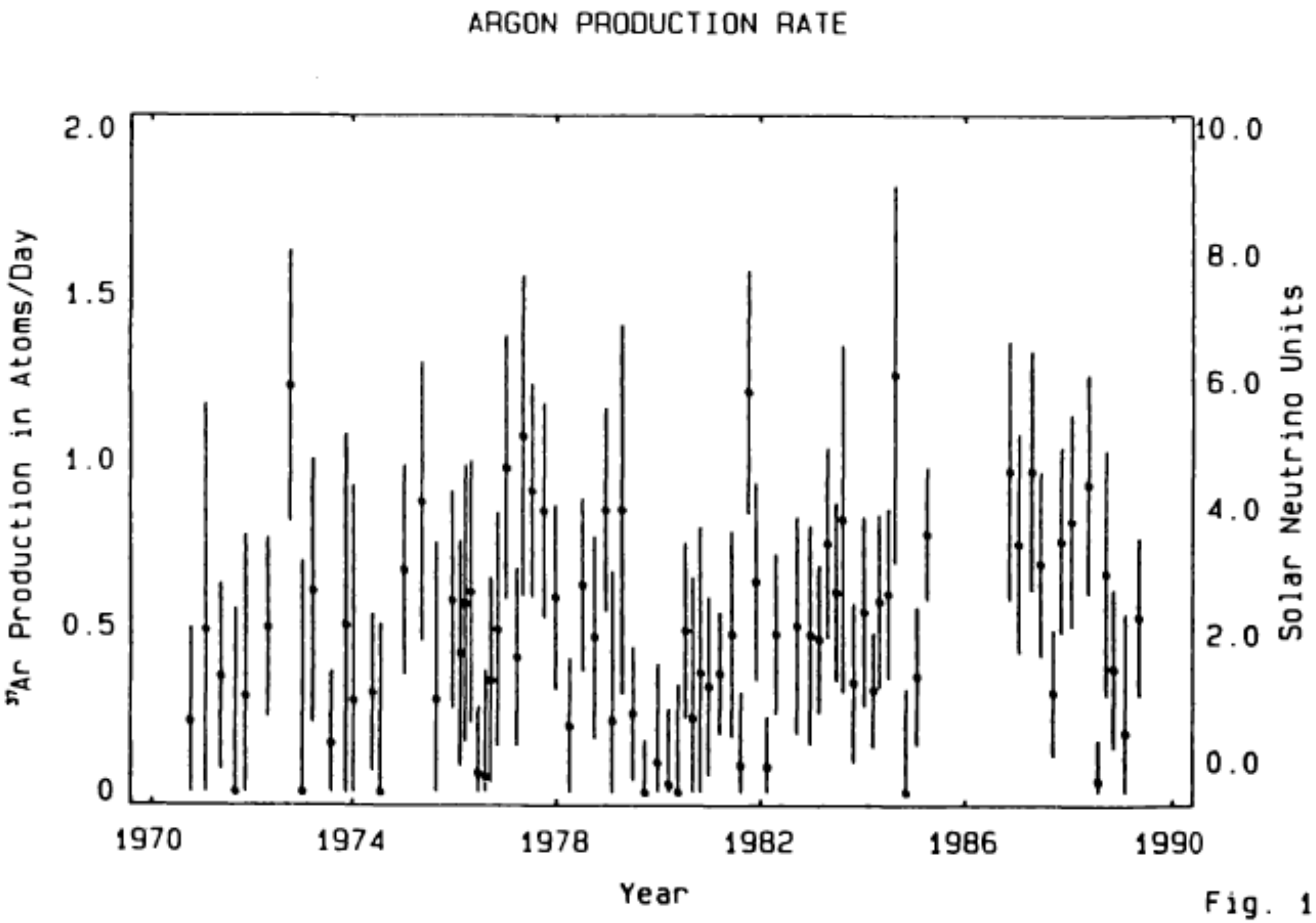



Fig. 1

Davis et al. 1990

# **1988**: Two probes of the core will be detected simultaneously

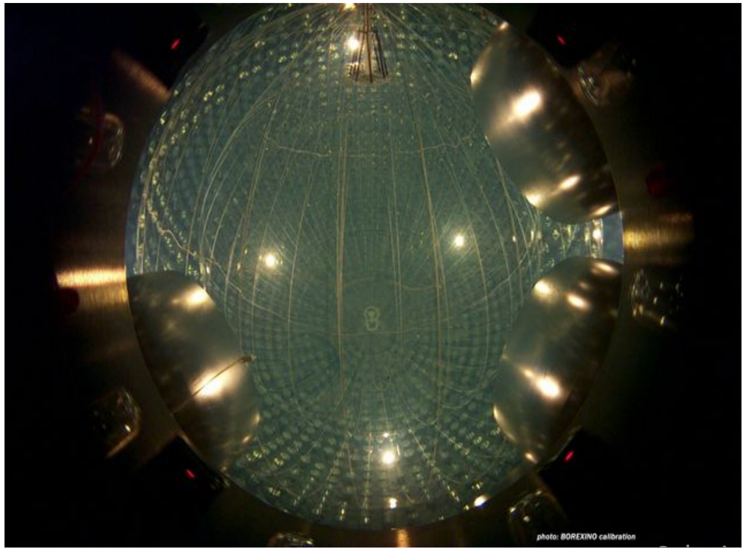
# Neutrinos and
# space helioseismology with SoHO (1995-2016)

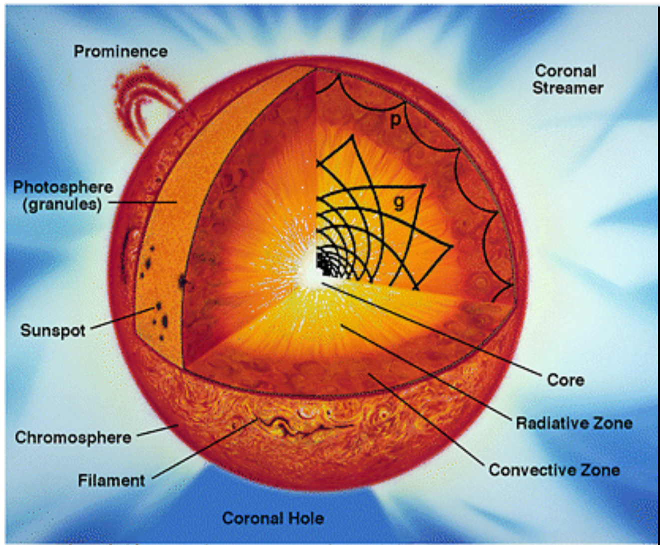
GALLEX, SAGE $\phi(SAGE) = 65.4^{+3.1}_{-3.0}(\text{stat.})^{+2.6}_{-2.8}(\text{sys.})$ SNU $\phi(GALLEX) = 73.1^{+6.1}_{-6.0}(\text{stat.})^{+3.7}_{-4.1}(\text{sys.})$ SNU $\phi(GNO) = 62.9^{+5.5}_{-5.3}(\text{stat.})^{+2.5}_{-2.5}(\text{sys.})$ SNU.

SuperKamiokande $\phi^{ES}_{SK\text{-}I} = 2.35 \pm 0.02(\text{stat.}) \pm 0.08(\text{sys.})$

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

1995: more and more suspicion that neutrinos are oscillating





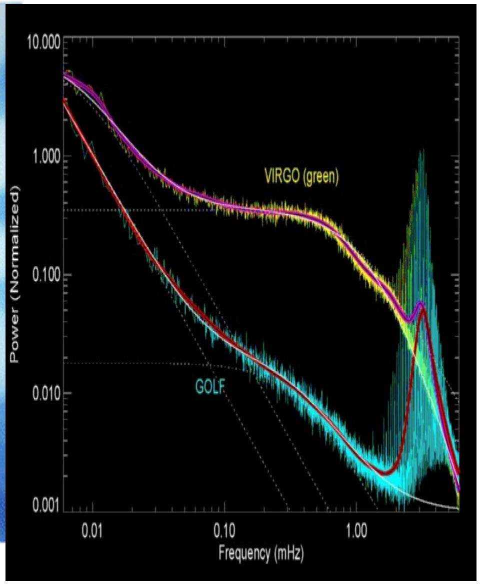



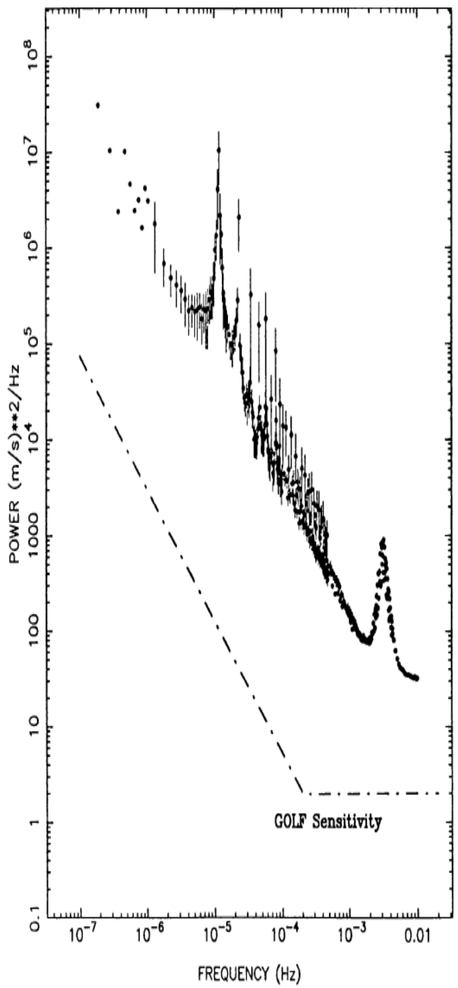
**Table 6.** Evolution with time of the SSM or seismic predictions of the $^{8}B$ neutrino flux in $10^6$ cm$^{-2}$ s$^{-1}$. Added are the central temperature $T_C$ in $10^6$ K, the initial helium abundance $Y$ in mass fraction and a specific problem that was solved. From Turck-Chièze *et al* (2010a).

| | $^{8}B$ flux | $T_C$ | $Y_{initial}$ | Problem solved | Reference |
|---|---|---|---|---|---|
| | $3.8 \pm 1.1$ | 15.6 | 0.276 | CNO opacity, $^{7}Be(p, \gamma)$ | Turck-Chièze *et al* (1988) |
| | $4.4 \pm 1.1$ | 15.43 | 0.271 | −30% Fe abundance, screening | Turck-Chièze and Lopes (1993) |
| | 4.82 | 15.67 | 0.273 | Microscopic diffusion | Brun *et al* (1998) |
| SSM | 4.82 | 15.71 | 0.272 | Turbulence tachocline | Brun *et al* (1999) |
| | $4.98 \pm 0.73$ | 15.74 | 0.276 | Seismic model | Turck-Chièze *et al* (2001b) |
| | $5.07 \pm 0.76$ | 15.75 | 0.277 | Seismic model, magnetic field | Couvidat *et al* (2003) |
| SSM | $3.98 \pm 1.1$ | 15.54 | 0.262 | −30% CNO composition | Turck-Chièze *et al* (2004a) |
| | $\mathbf{5.31 \pm 0.6}$ | 15.75 | 0.277 | Seismic model + $^{7}Be$ and $^{14}N(p, \gamma)$ | Turck-Chièze *et al* (2004b) |
| SSM | $4.21 \pm 1.2$ | 15.51 | 0.262 | SSM (Asplund 2009) | Turck-Chièze *et al* (2010a, 2010b) |

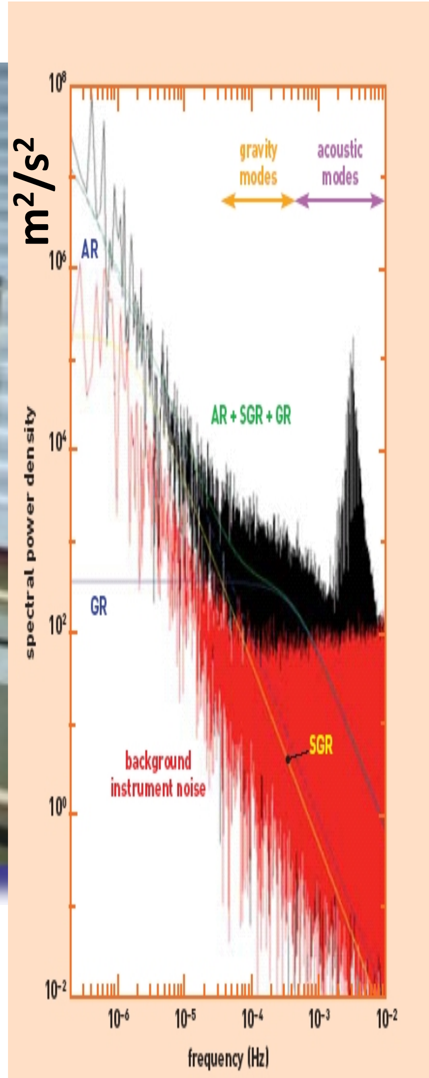
**Are the hypotheses of the SSM correct ??**

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

*Dzitko Thesis, 1995; Gabriel et al.1995; Garcia et al. A&A 2005*



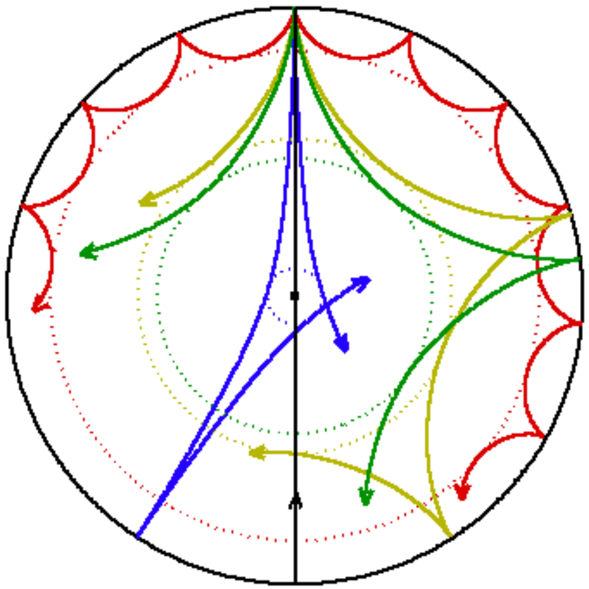

*Pallé et al 1995 seismology on ground*



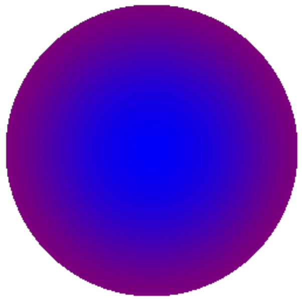

*Turck-Chièze et al ApJ 2004*

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**

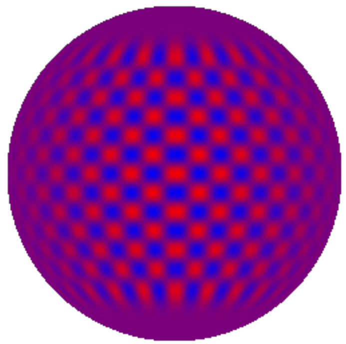
# Observed Acoustic modes



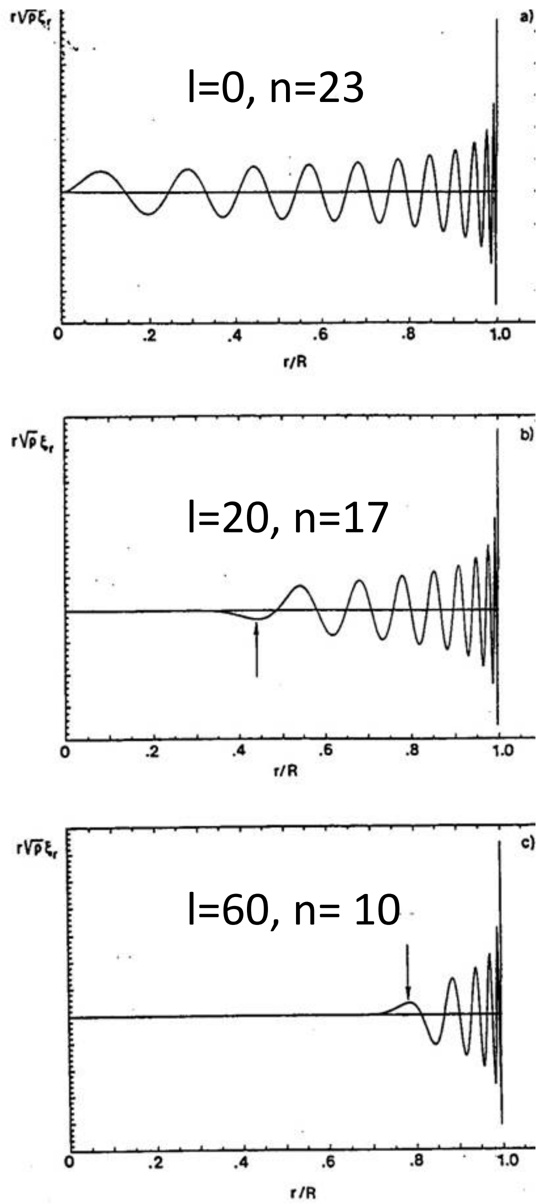
Degree l and order n



GOLF



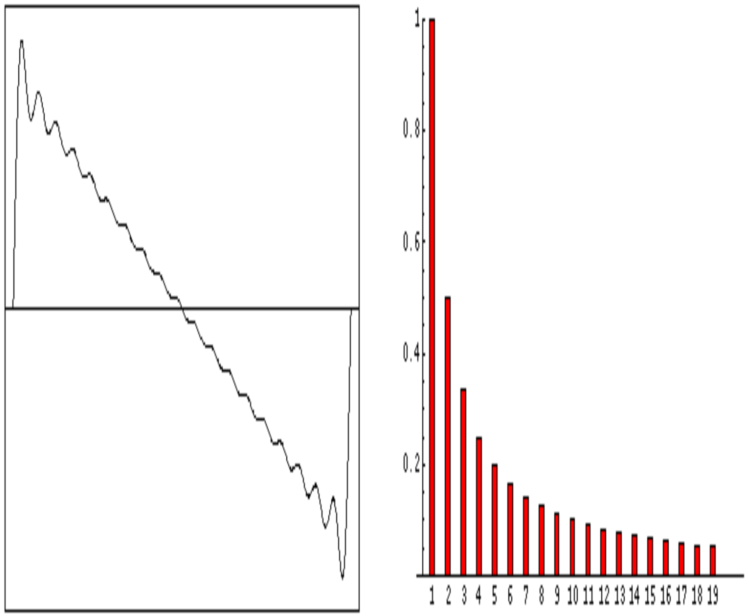
MDI



# Low degree acoustic modes penetrate down to the core

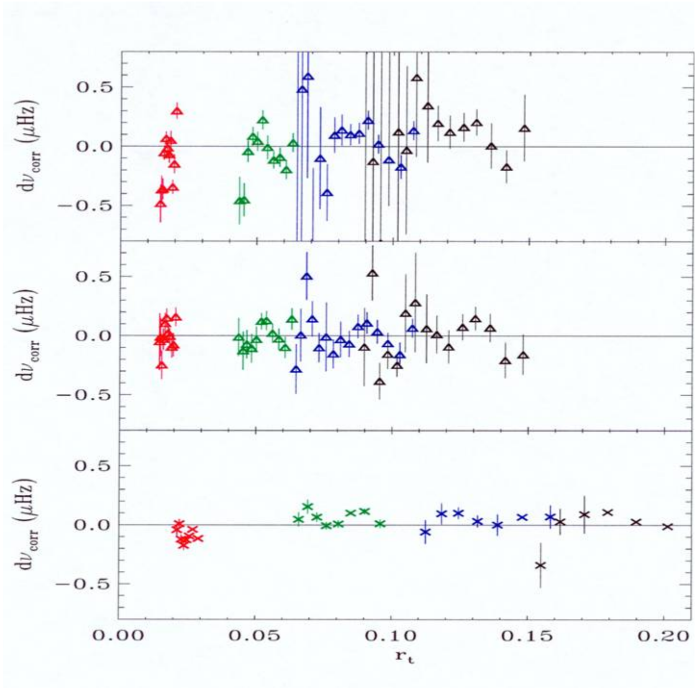
## but one must be cautious to the surface effects!!

John Bahcall remarks…. Helioseismology will determine mainly the solar surface, not the core




Harmoniques n   1 -> 40

GOLF space data



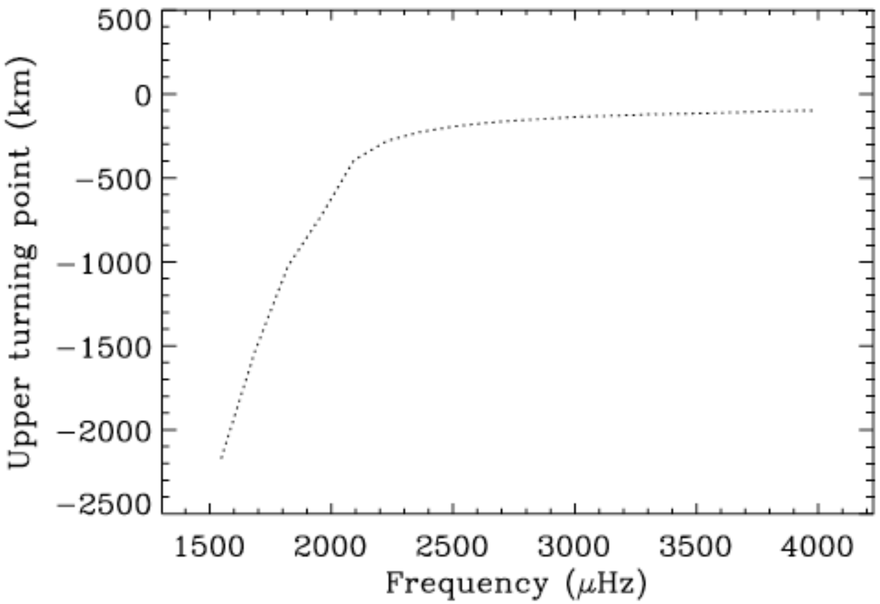

1 year

5 years n >15

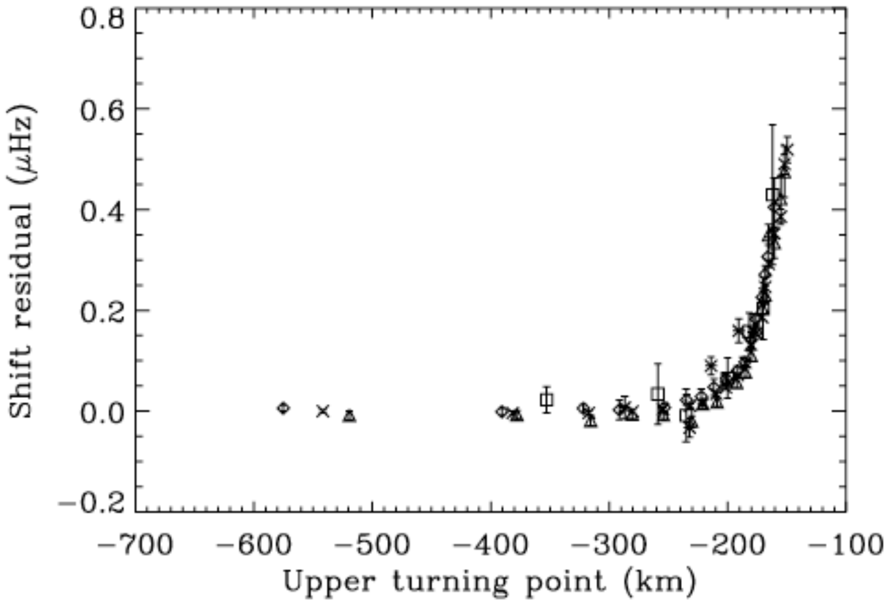
5 years n <15

**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

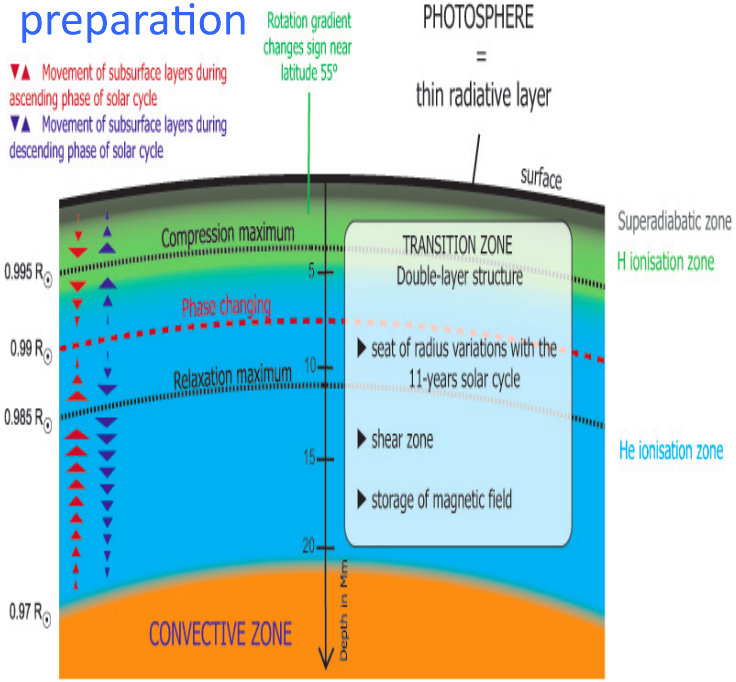


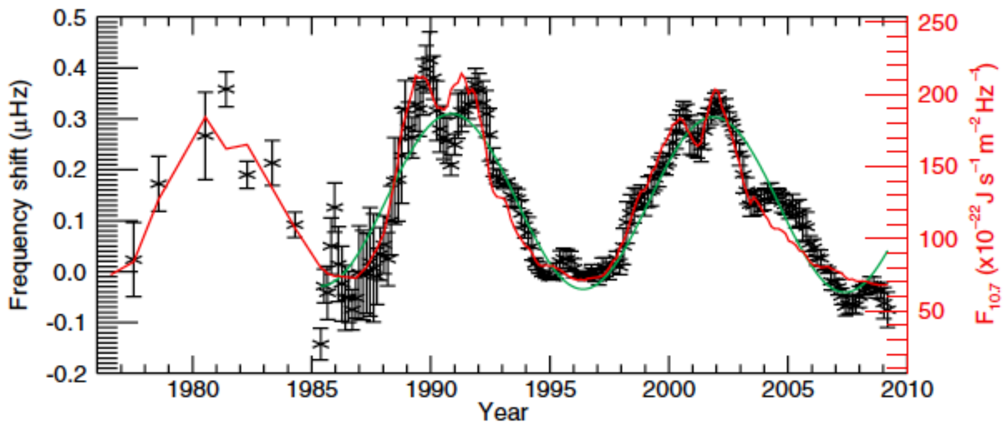

**n <16 no effect of sub surface variability.**

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

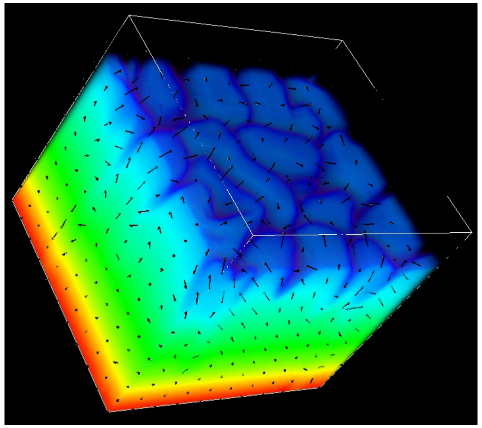
# Acoustic modes n>16 reveal the near surface

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




3D simulations 6000*3000 km



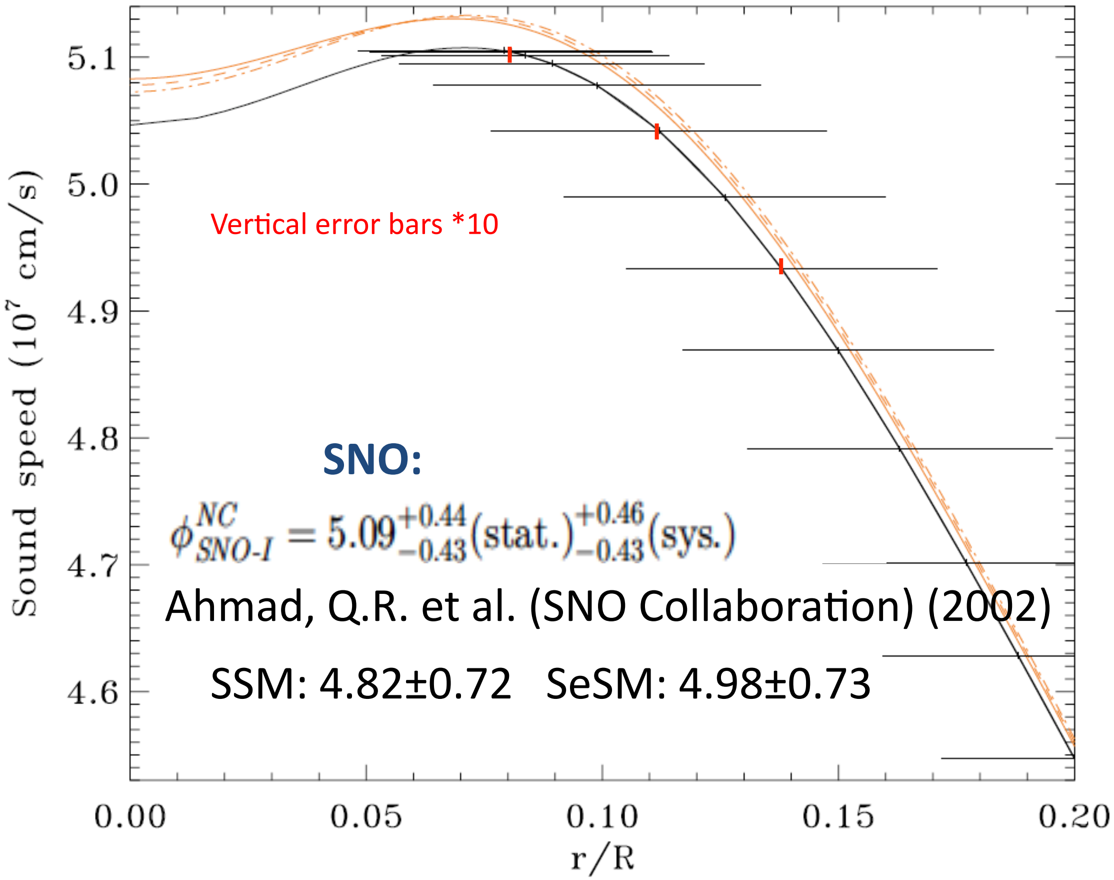
3D simulation with STAGGER (Stein & Nordlund 2006) shows the impact of turbulence (Rosenthal et al. 1999). 1D coupled to 3D outputs shows the impact on frequencies of the variation of the toroidal field along the 11 year cycle: Piau et al. 2012, Simoniello, T-C et al. 2012

**Beating between poloidal and toroidal configurations**

# 2001: glorious year: GOLF acoustic modes n <16 reveal the core, SNO measures all the flavours of neutrinos

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

GOLF/SoHO: collaboration
IAS-CEA-IAC

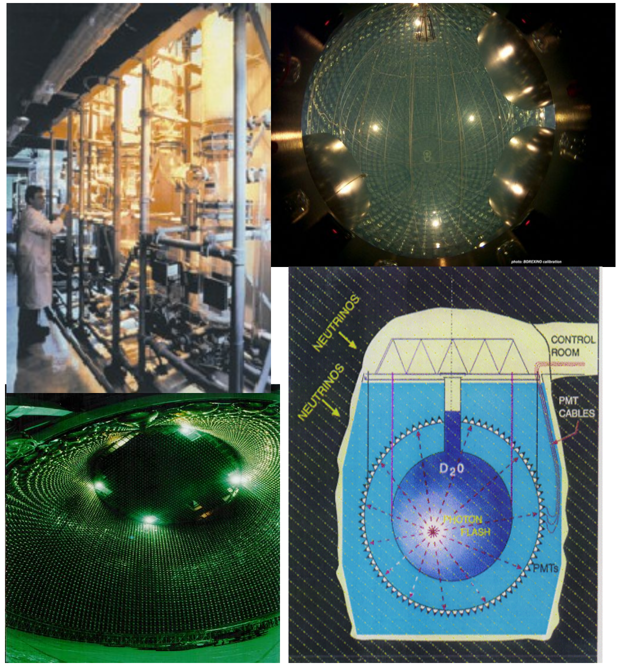



**SNO:**

$$\phi^{NC}_{SNO\text{-}I} = 5.09^{+0.44}_{-0.43}(\text{stat.})^{+0.46}_{-0.43}(\text{sys.})$$

Ahmad, Q.R. et al. (SNO Collaboration) (2002)

SSM: 4.82±0.72 SeSM: 4.98±0.73




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

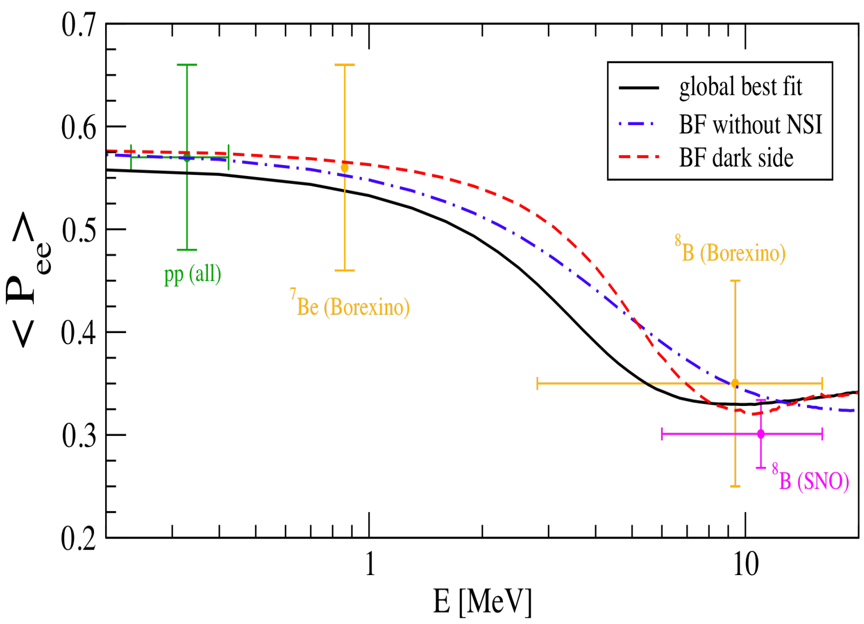
# 2002: Nobel Prize

**Ray Davis 1914-2006**
**Nobel Prize 2002**

**Masatoshi Koshiba 1926-**
**Nobel Prize 2002**

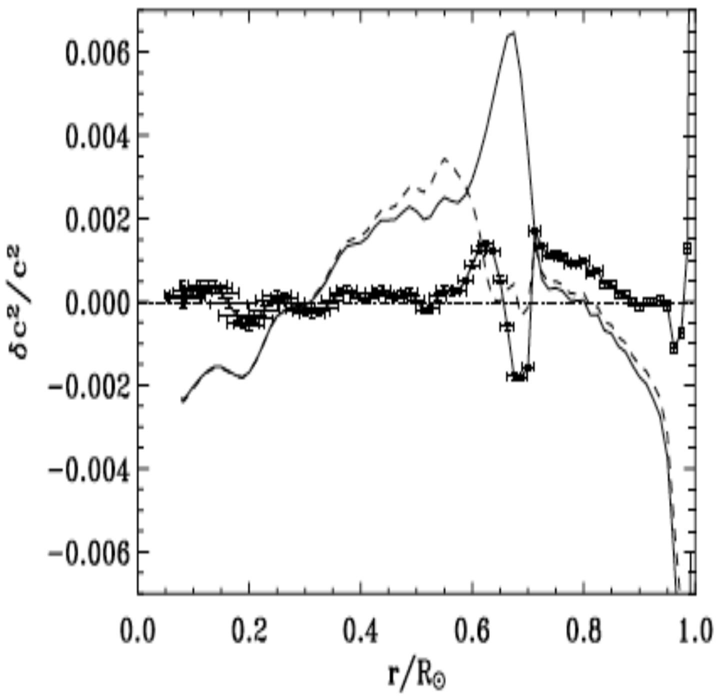
Davies was right, and the neutrinos change of savours along their travel

# Now we know also how electronic neutrinos disapear

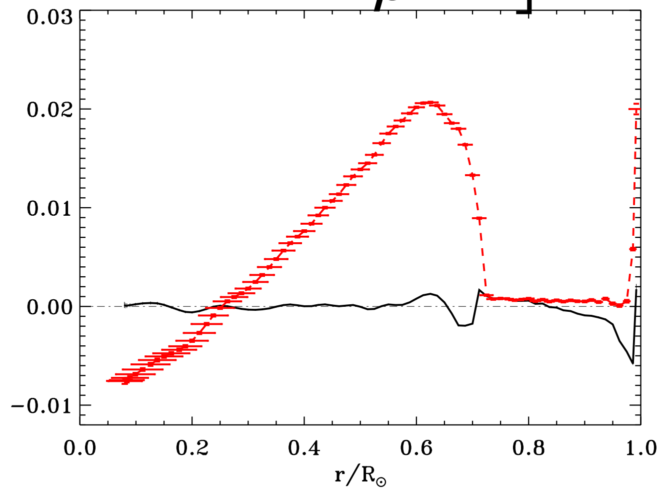


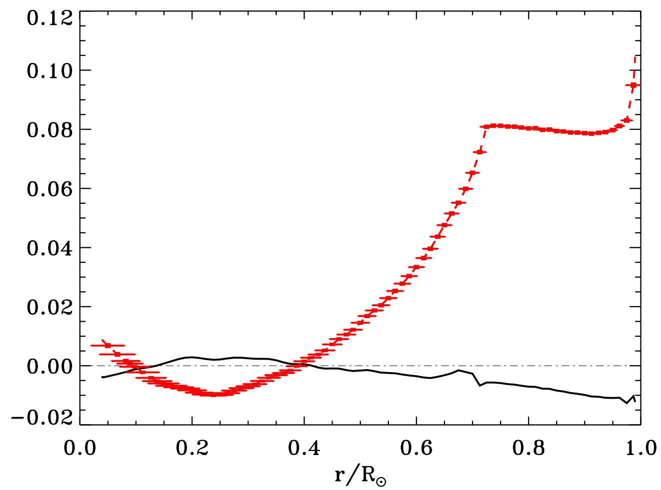
# Seismic diagnostic of the core from SoHO (GOLF+ MDI)

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




2001




Our 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 %

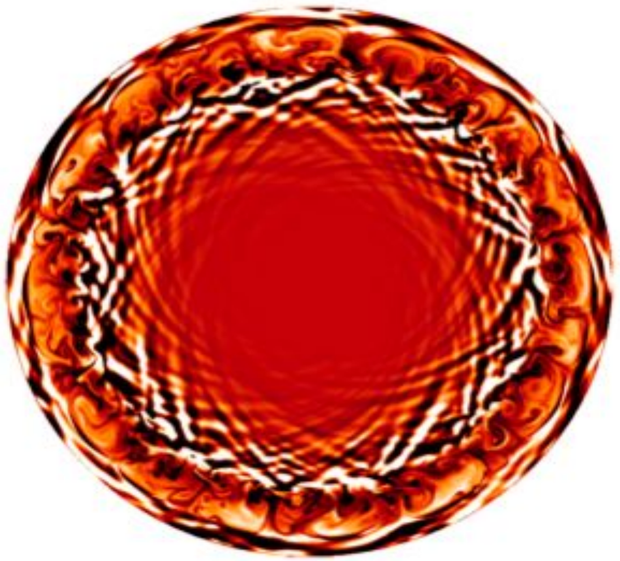
*Turck-Chièze et al 2001; Couvidat et al. 2003; T-C, Piau, Couvidat 2011;*

2011

**SSM is an excellent basis but may be not the end of the story**

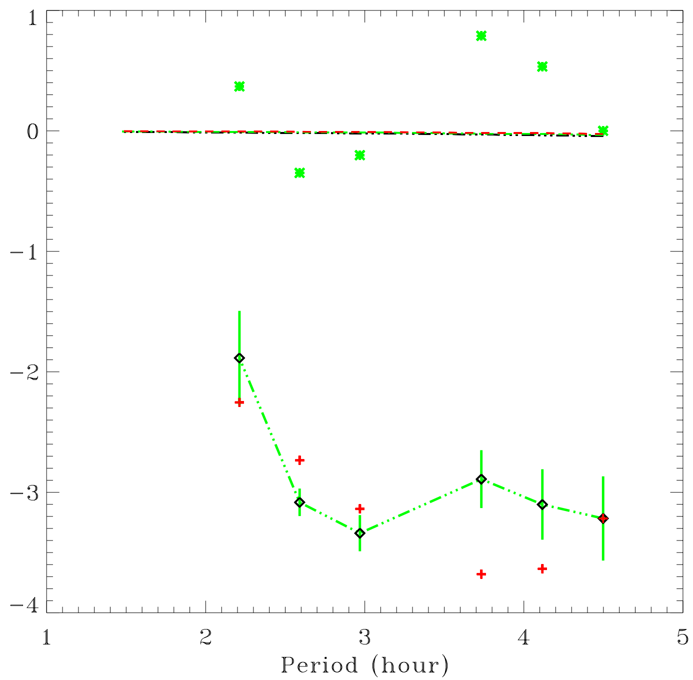
# Gravity modes from GOLF

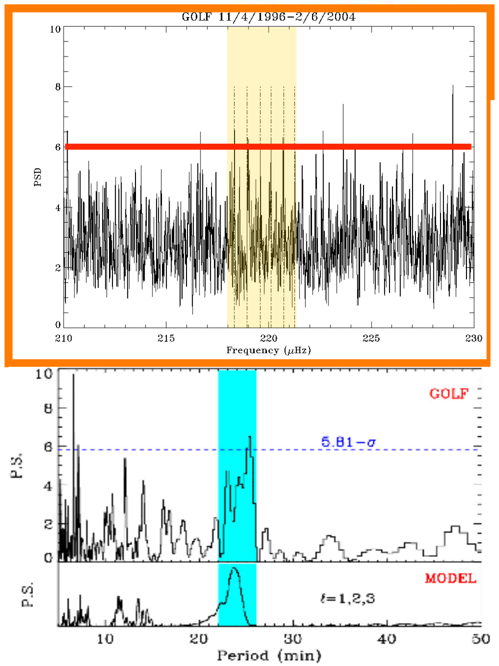
*T-C et al. 2004, Garcia, T-C et al. Science 2007, Garcia et al. 2011, see Turck-Chièze & Lopes 2012*

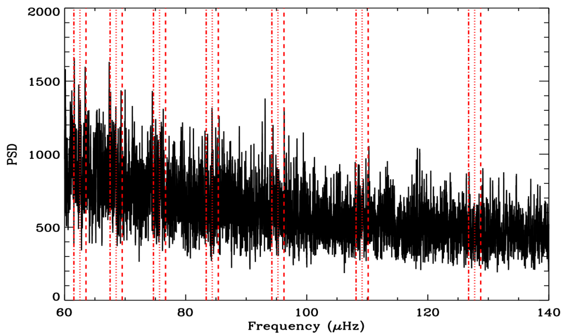


First determination of 6 individual values of dipole modes
Gravity mode periods are in agreement with SSeM prediction but not with SSM ones

G-mode Period – g-mode SSM




Green: observed g-modes
Red crosses: Seismic predictions

# Helioseismology and neutrinos agree totally today T-C, Palacios et al. 2010

| | 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)** | |

# Error bars on neutrino predictions

SSM error bars: minimum error bars

- Error bars on ingredients , can change with time …
- Not on the hypotheses

SeSM error bars: more realistic error bars
more stable predictions for the
astrophysical part of the calculation

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

- ~~Bad photospheric determination ????~~
- Bad energetic balance: hypothesis of SSM
- Bad transfer of energy: opacities calculations
- Fundamental physics: WIMPs and others

- Extra phenomena: rotation, magnetic field, gravity waves … ???

# Bad energetic balance ?

## Turck-Chièze, Piau, Couvidat 2010

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

- $\rho_c$ seismic model 153.02 g/cm$^3$
- $\rho_c$ SSM 150.06 g/cm$^3$

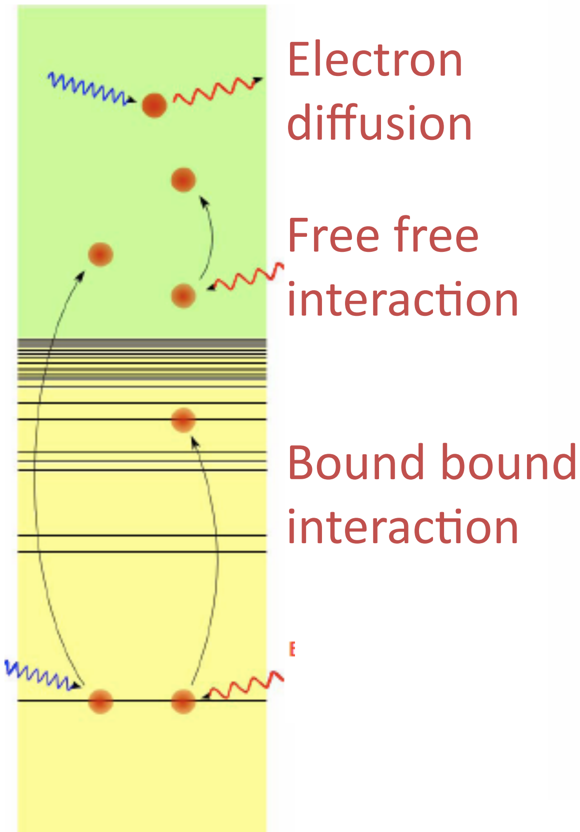
- X c seismic model 0.339
- Yinitial 0.277 Ysurf 0.251

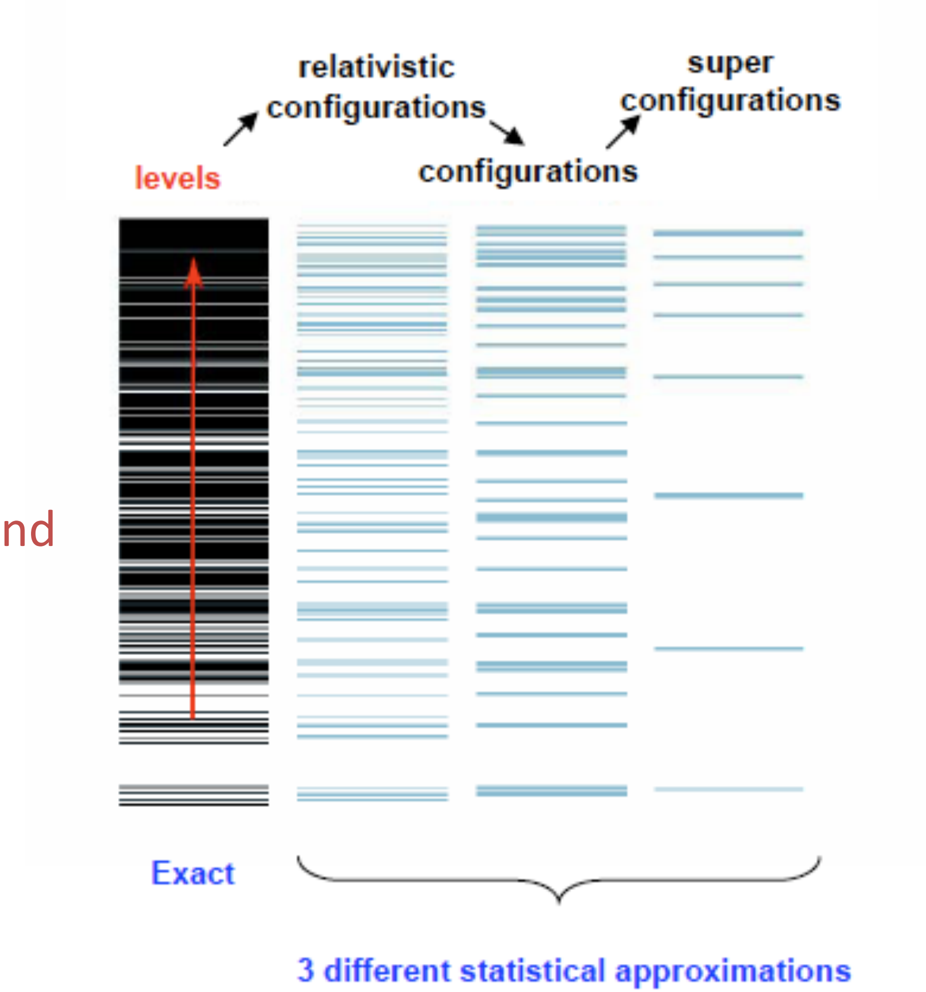
- 1.5% difference in central temperature=>
  no more than 5- 6% difference in luminosity

**$L_{nuc}$ could be slightly greater than $L_{sol}$**

**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**

# Bad energy transport by photons ?



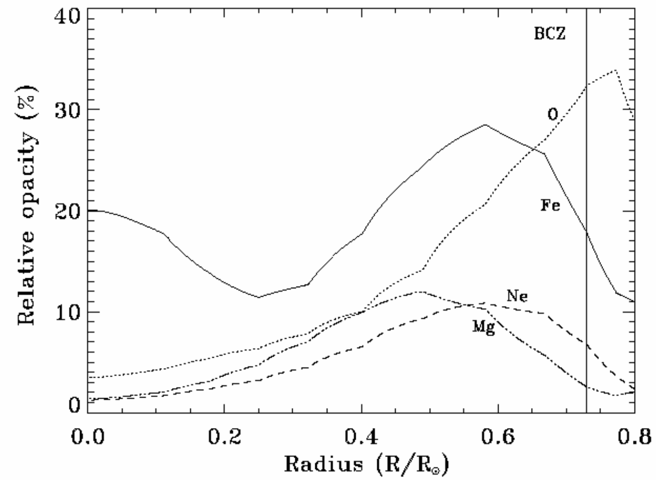



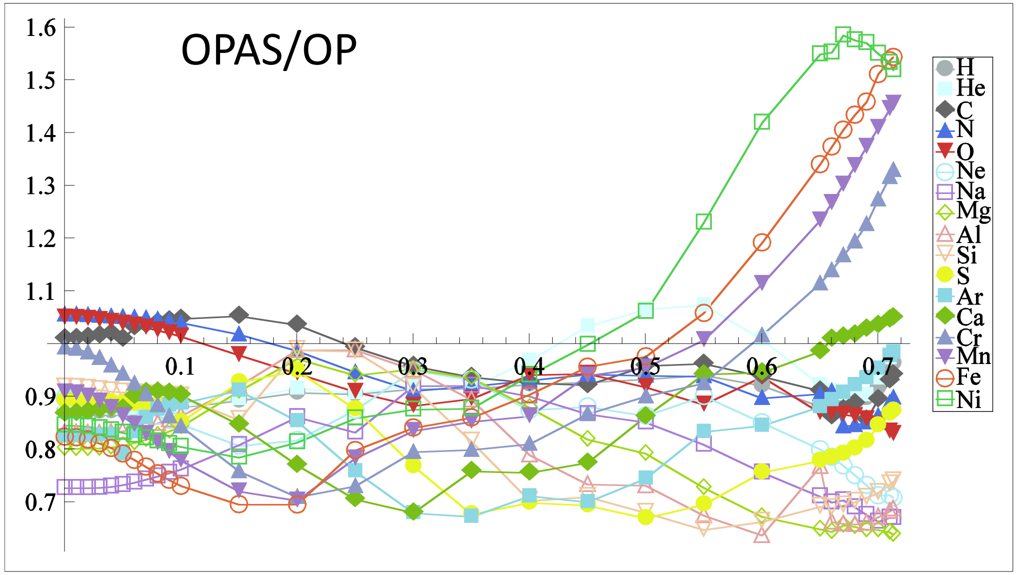

Mean Rosseland value

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% sound speed
Impact on microscopic diffusion

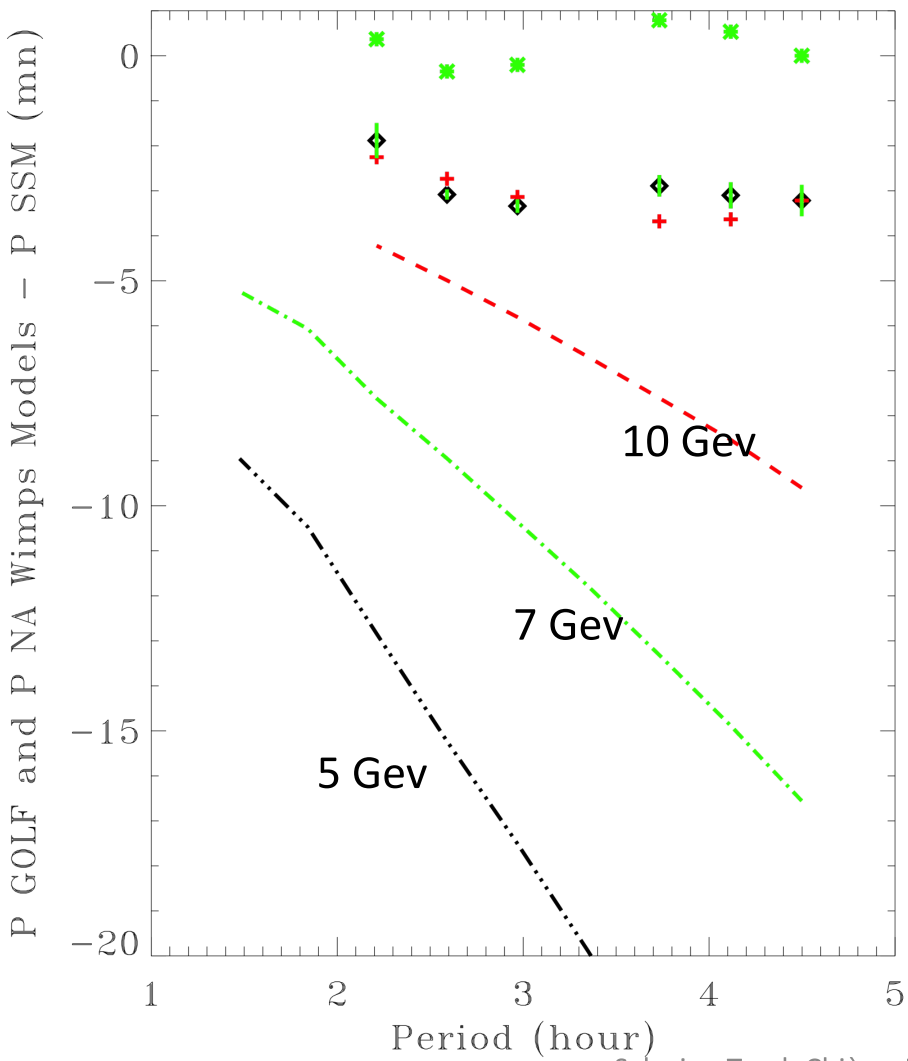
**Comparison OPAS/OPAL differences smaller except for Ca, Cr, Mn that are small contributors** but one cannot exclude some % on $K_R$ : 1.03 at the BCZ (incomplet M shells), work in progress on the whole RZ

Experiments are difficult: 2 or 3 designs in study to get density greater the solid density: chocs

**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**

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

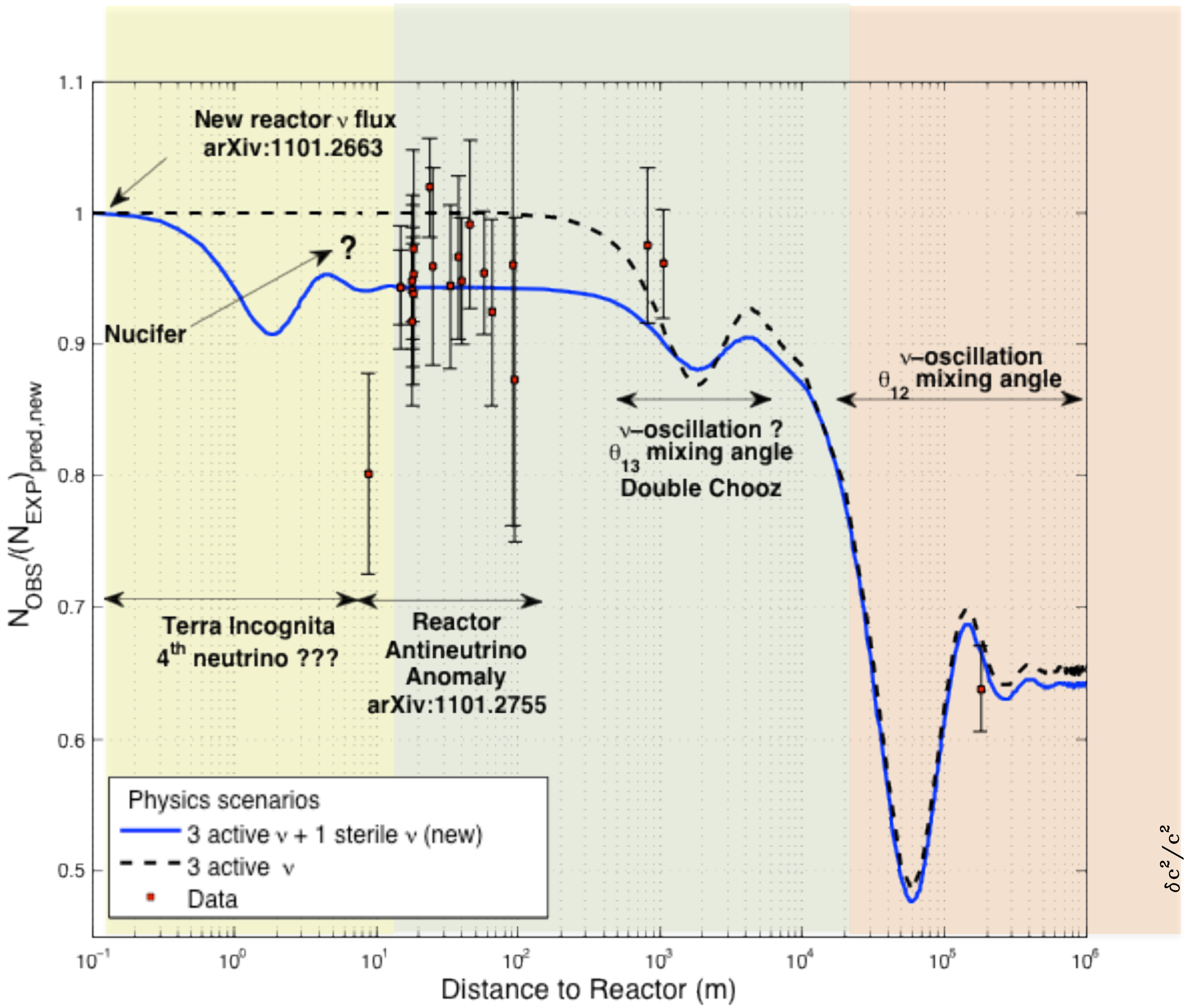
***Turck-Chièze, Lopes et al. 2012, ApJ lett February 2012***




- 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 $10^6$K**
- **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$^2$ $\sigma_{SD}$=7 to 5 $10^{-36}$ cm$^2$ $\sigma_{SI}$= $10^{-40}$ cm$^2$ **M $_{WIMPS}$ < 10 GeV are rejected, no real signature of WIMPs**

# Could sterile neutrinos be forgotten ?

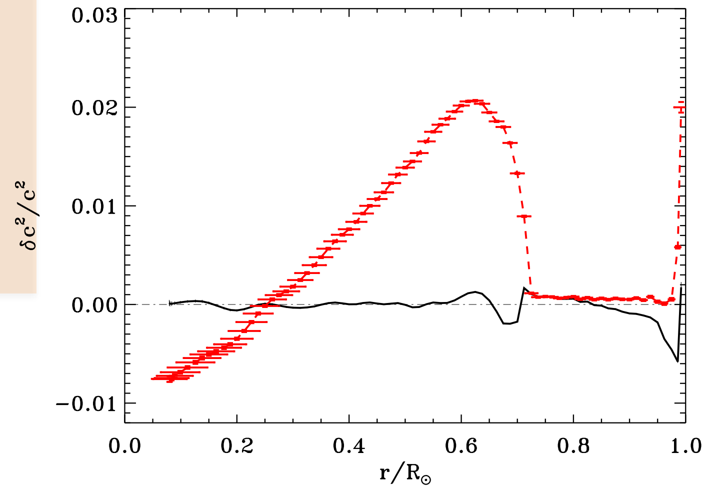


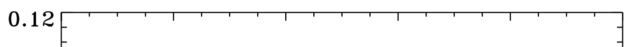

Mueller et al. 2011

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



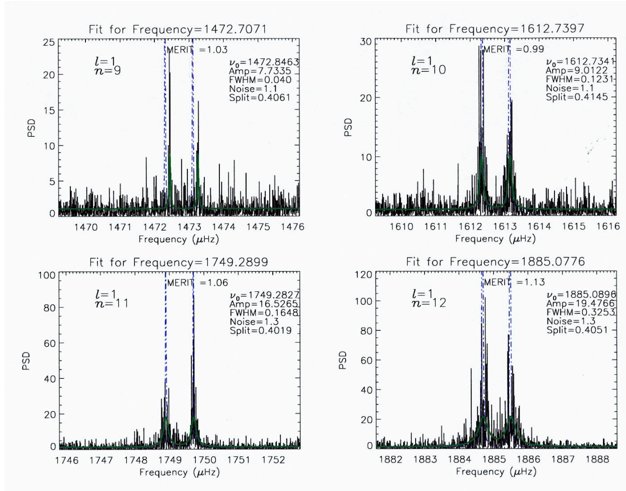



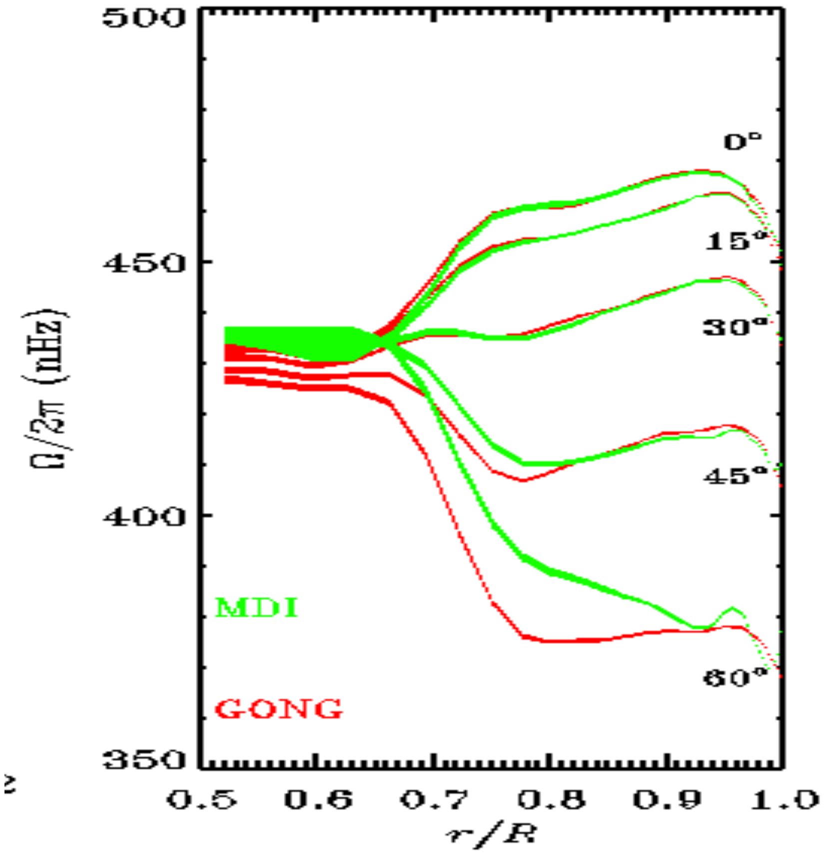
# Extra phenomena:

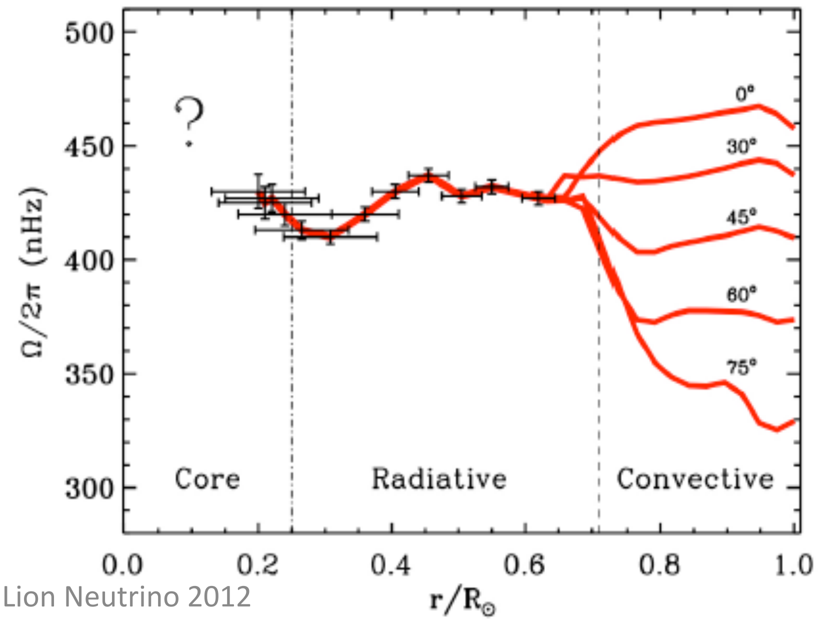
## Constraints from acoustic modes on the rotation profile

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

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

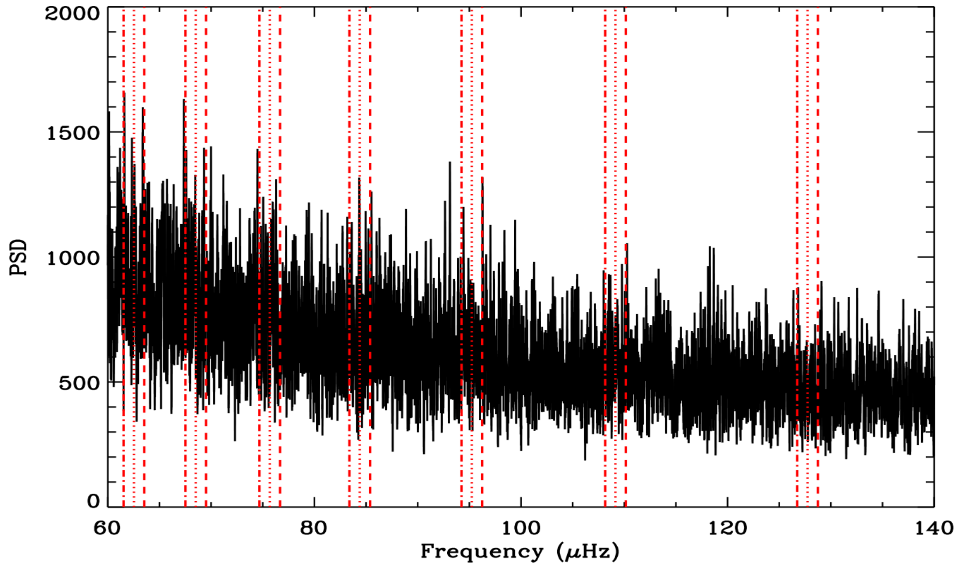


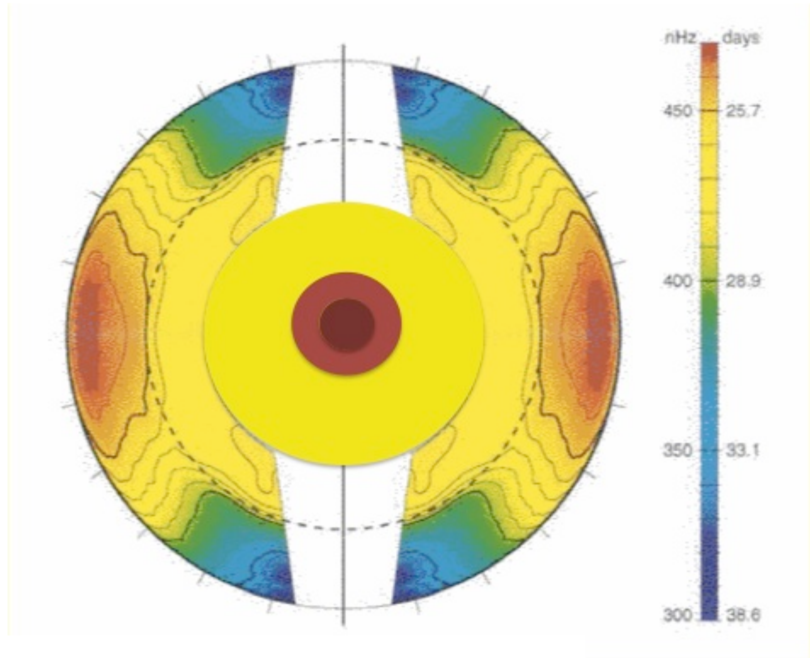



# Extra phenomena: internal rotation from gravity and acoustic modes: the core rotates quicker

## No direct evidence of magnetic field but splitting estimates



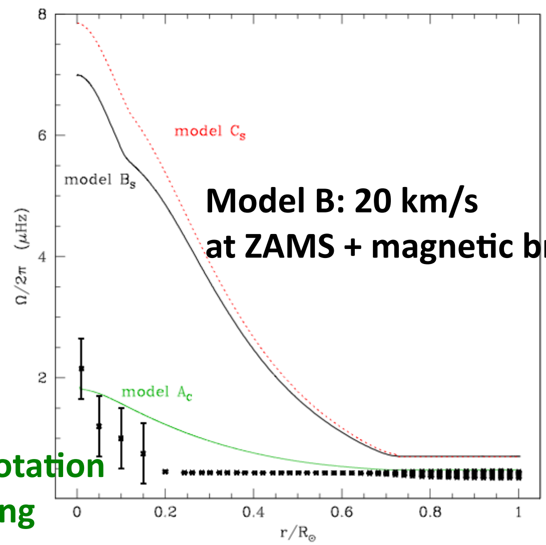

Garcia et al. 2007, 2008, 2010 SOHO24,
Turck-Chièze et al., 2004, 2010, 2011, 2012




**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**

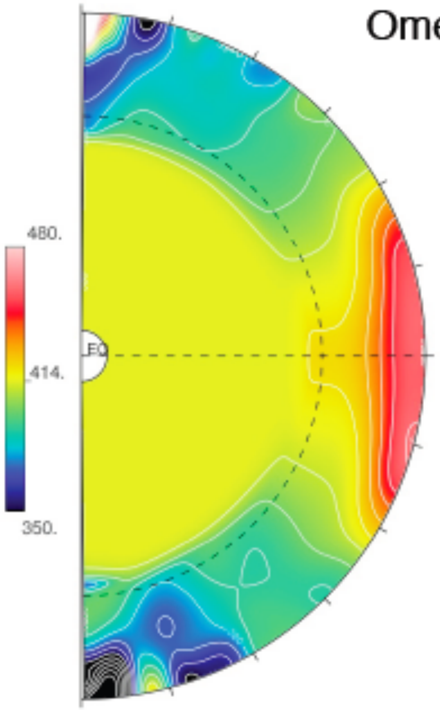
**Model A: Weak initial rotation without magnetic braking**

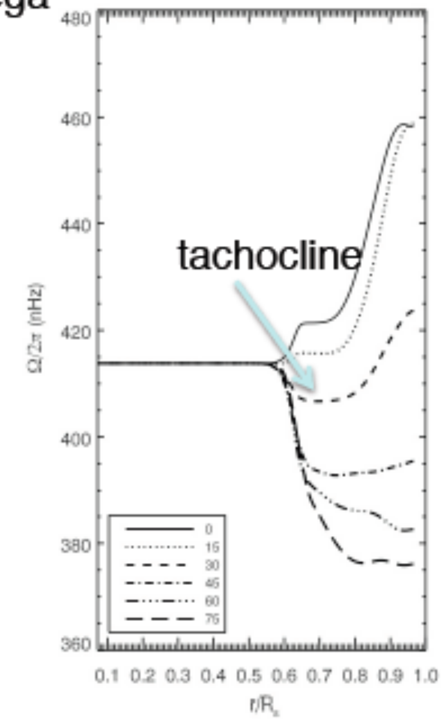
Sub surface differential rotation

# Omega Profile & Meridional Circulation

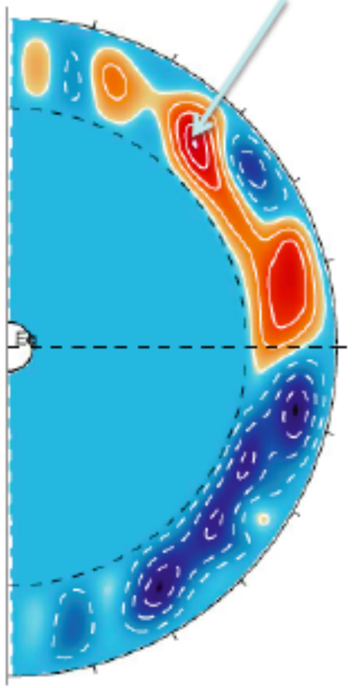
First 3D simulations of RZ

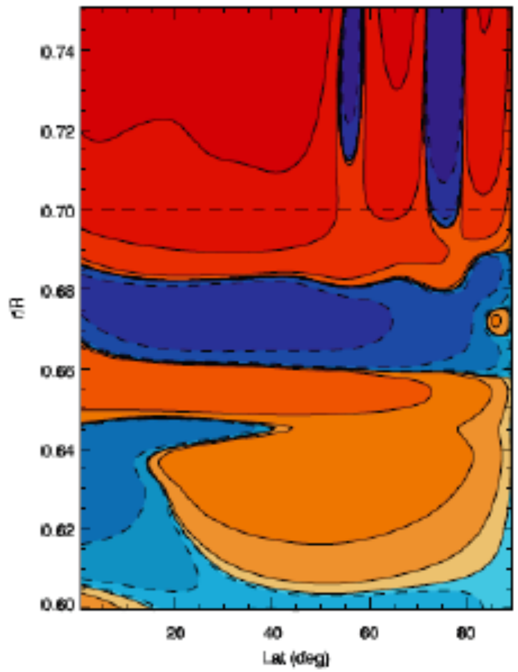
Omega




Almost unicellular flow




Penetrationof MC flow
< 0.02 Rsol

Fast equator/slow poles

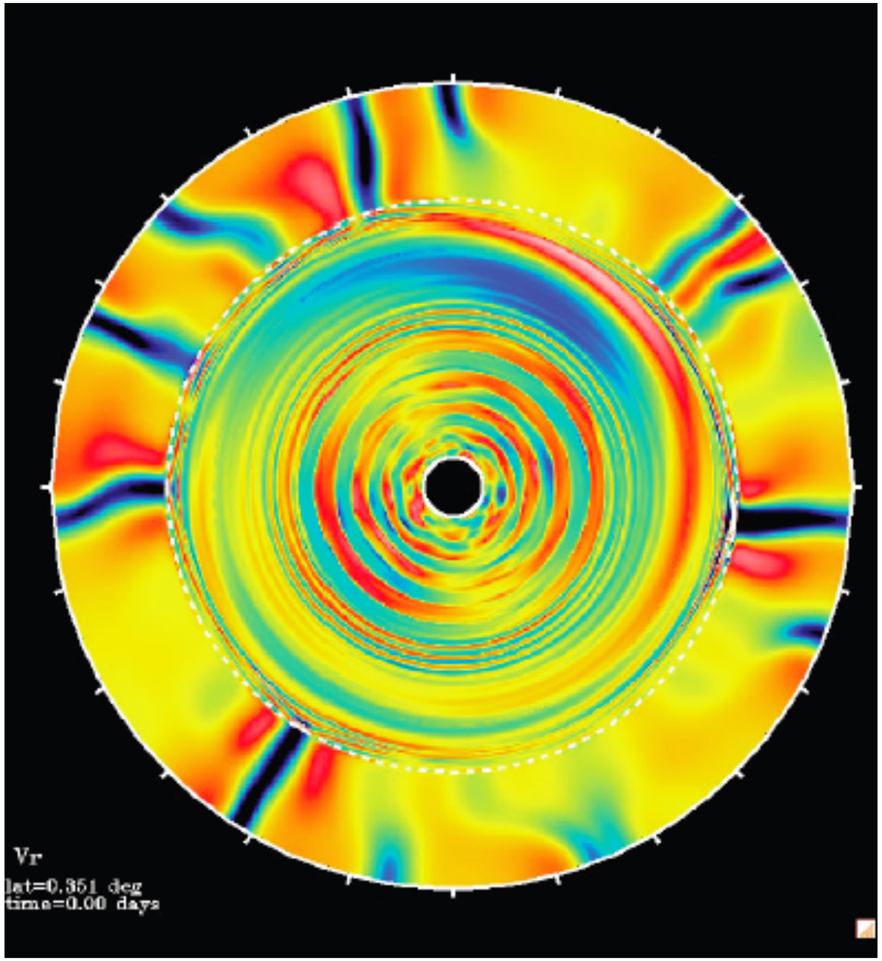
Drop by
3 orders of
magnitude
over 0.04 R

Brun, Miesch, Toomre, 2011, ApJ , 742

# Gravity waves and magnetic field inside the Sun

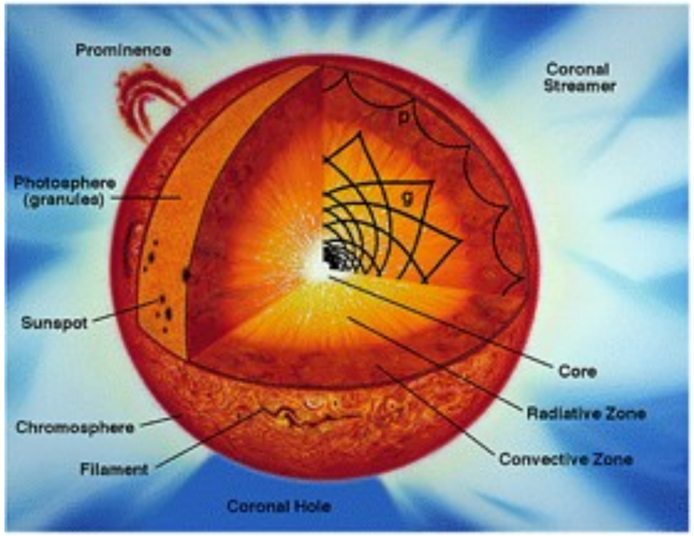
Strugarek et al. 2011,

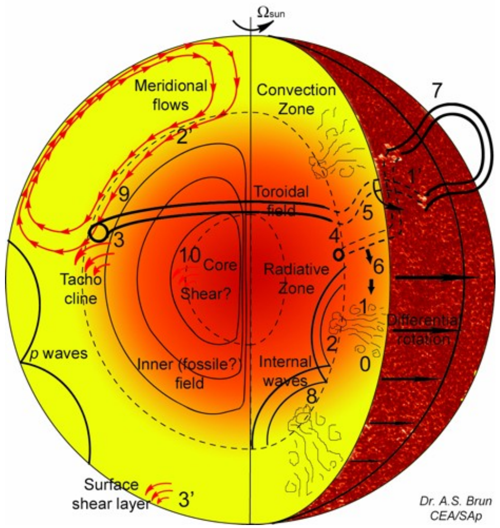
Alvan et al. to appear
2012 or 2013



# From 1D to 3D

- 3D still in infancy
- Not secular models
- Noticed differences between the two
- For example 1D RZ meridional circulation $10^{-6}$ cm/s versus 5cm/s in 3D
- 3D simulations are promising to go beyond the SSM framework
- A lot to do in the next decade: fossil field, detailed rotation in the core for which neutrinos are valuable probes



# How neutrinos can help to describe the internal dynamical Sun ?

- $L_{nuc} > L_{ext}$ ? pp flux or pep flux at 1%
- Composition of the core: CNO neutrinos at 10%
- Gravity waves action: time variability (months or largely longer)
- Fossil field: impact on magnetic moment of neutrinos
- Individual neutrinos detection: extraction of the electronic density inside the Sun (Lopes & T-C 2012 to appear)
- ……

*Solar neutrinos are just entered in the area of neutrino astronomy, they will still be extremely useful to detect*

**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.**

**Astrophysicists continue to explore the internal magnetic field: young Sun, interaction with planets**

**Thousand solar-like stars are now observed by asteroseismology, so we are getting complementary constraints also useful to enrich our view of internal dynamics.**