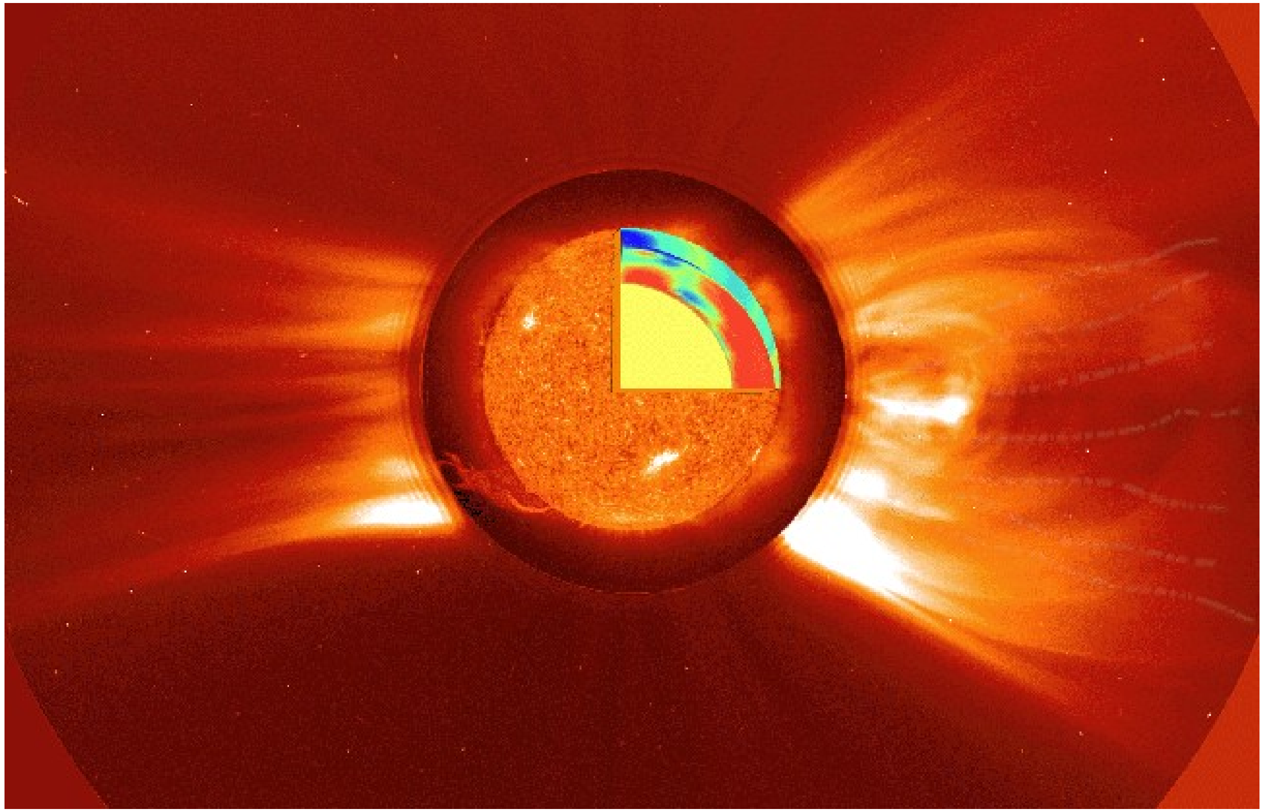
How helioseismology constrains solar neutrino properties ?



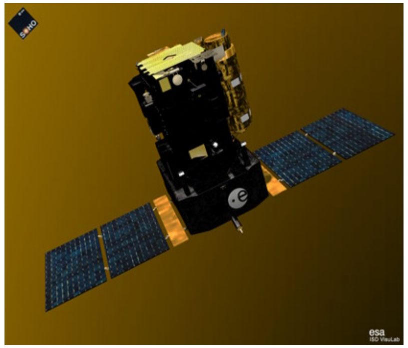
- The Sun, different sources of neutrinos

- A new picture of the Sun

- Perspectives for the Sun, other stars links between astrophysics and particle physics

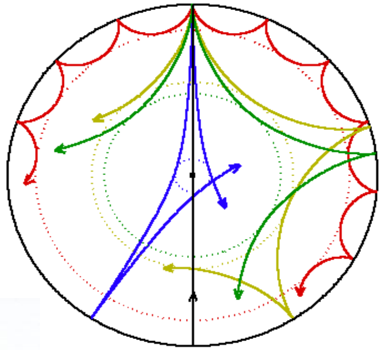
Sylvaine Turck-Chièze, SAp/DAPNIA/CEA

A special case : The Sun as a laboratory, for physics and astrophysics



Knowing the source <=>

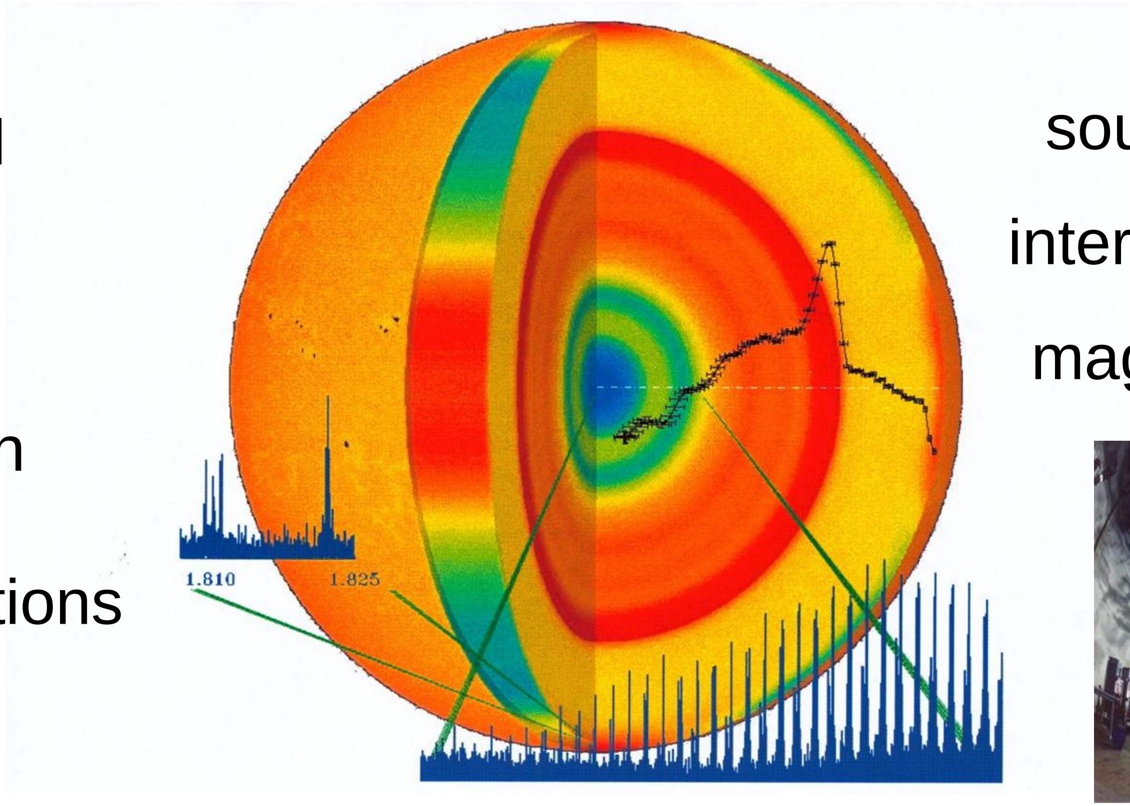
Neutrino properties



Theoretical progress

Seismic investigation

Neutrino detections



sound speed

internal rotation

magnetic field

The production of the solar neutrino fluxes

from theory to observational determination

Improvements on classical physical phenomena 1988- 2001

- a proper description of the metal opacity coefficients ApJ 1988, 1993

- a proper description of the role of the plasma in reaction rates ApJ 1995

- a proper description of the microscopic diffusion ApJ 1998

- the existence of mixing in the radiation-convection transition and consequent inhibition in the microscopic diffusion ApJ 1999

- no mixing in the core Sol. Phys. 2001

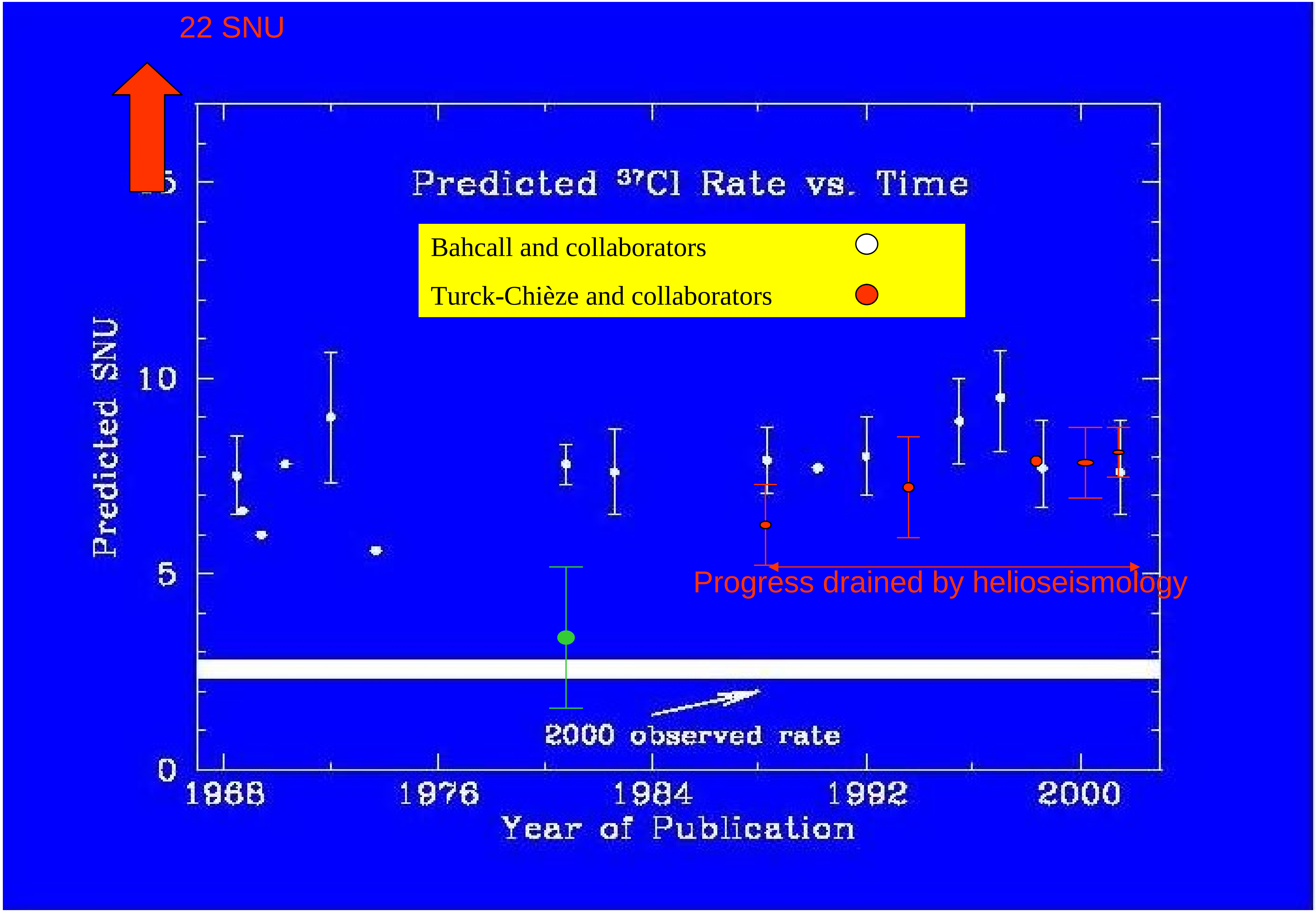
- support for a mawxellian distribution for the particle velocities Sol. Phys 2001

- a proper description of the pp reaction rate ApJ 2001

-a proper description of the relativistic effects in the equation of state ApJ 2003

Improvements of solar models constrained by seismology

Turck-Chièze and collaborators ApJ 1988, 1993, 1995, 1998, 1999, 2001, 2003, 2004


22 SNU
Predicted ³⁷Cl Rate vs. Time
Bahcall and collaborators
Turck-Chièze and collaborators
Predicted SNU
15
10
5
0
Progress drained by helioseismology
2000 observed rate
1968
1976
1984
1992
2000
Year of Publication

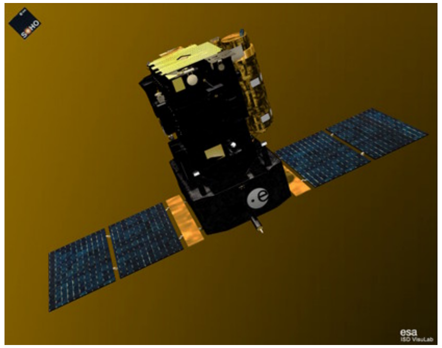
^{8}B neutrino flux in $10^{6} cm^{-2} s^{-1}$, Tc in $10^{6}K$

	Flux	Tc	Y initial	Problem solved
1988	3.8 ± 1.1	15.6	0.276	CNO opacity, 7Be(p,g)
1993	4.4 ± 1.1	15.43	0.271	Fe opacity, screening
1998	4.82	15.67	0.273	Microscopic diffusion
1999	4.82	15.71	0.272	Turbulence in tachocline
2001	4.98 ± 0.73	15.74	0.276	Seismic model
2003	5.07 ±0.76	15.75	0.277	Seismic model +magnetic field
2004	3.98. ± 1.1	15.54	0.262	- 30% in CNO composition

SNO results

5.44 ± 0.99 (CC+ES 2001) 5.09 ±0.44 ±0.45 (NC 2002) 5.27 ±0.27 ±0.38 (2003)

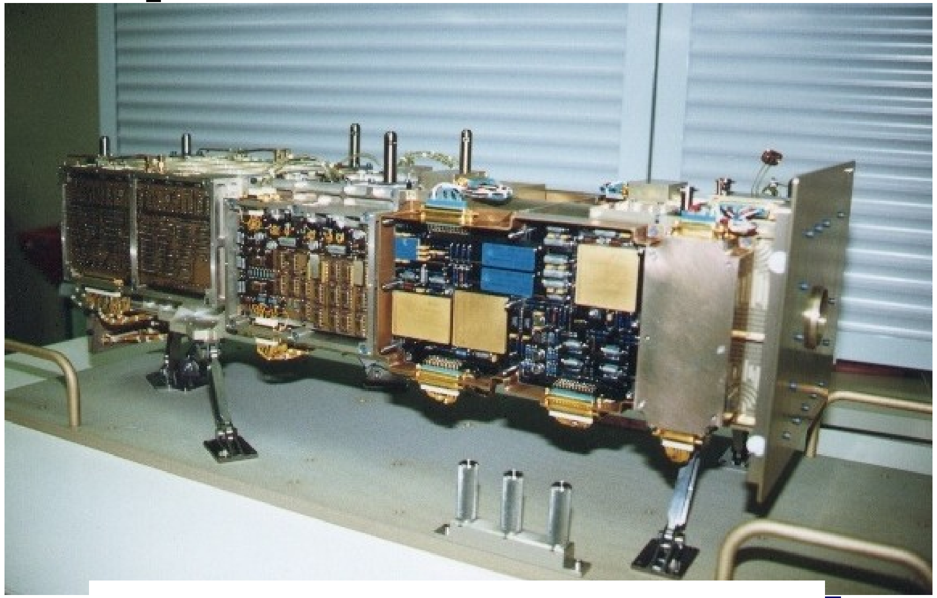
in grey pure theoretical models with improved physics,
in red models which fit seismic observations

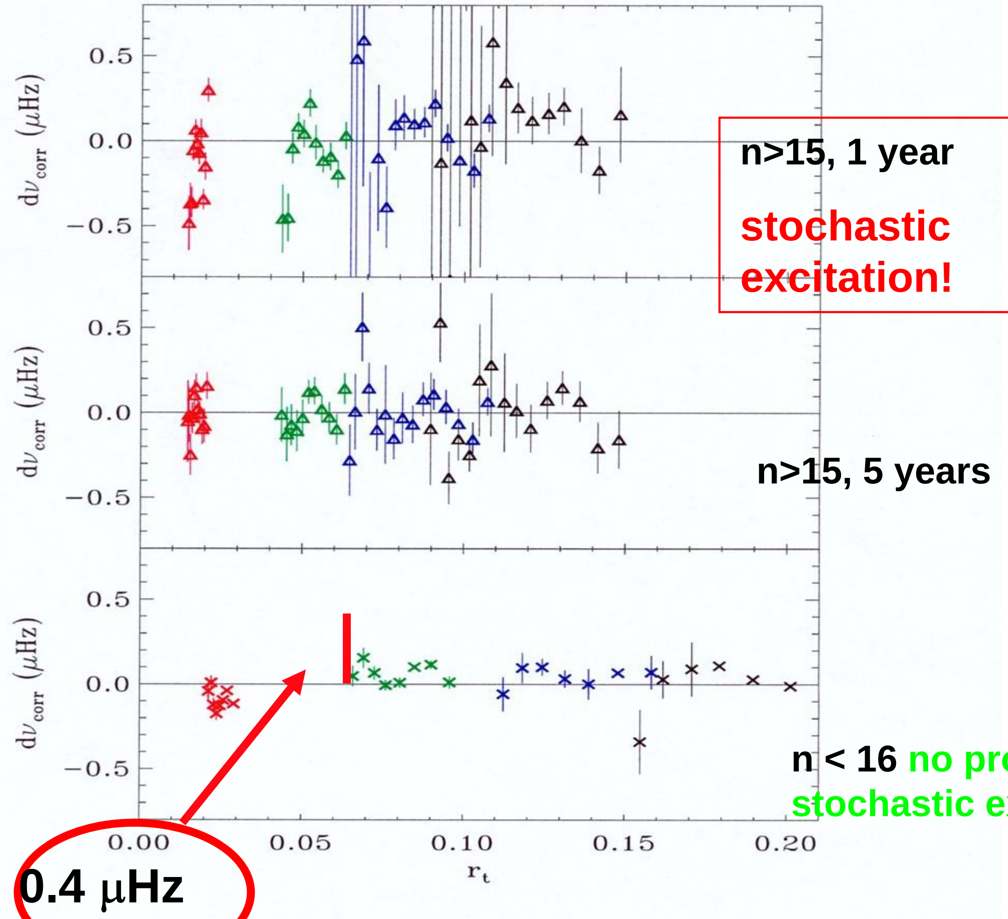


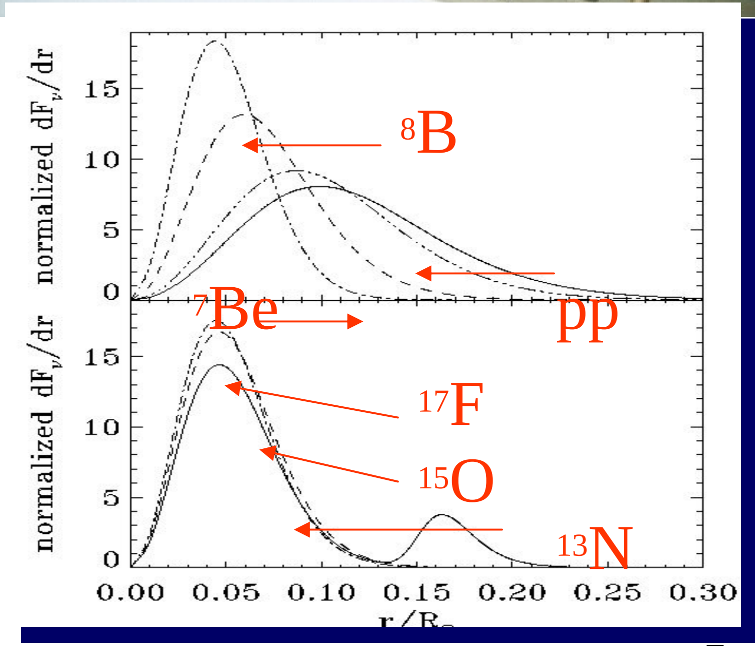
GOLF/SoHO experiment

Gabriel, Turck-Chièze, Roca-Cortes, Grec, Robillot

a french-spanish collaboration



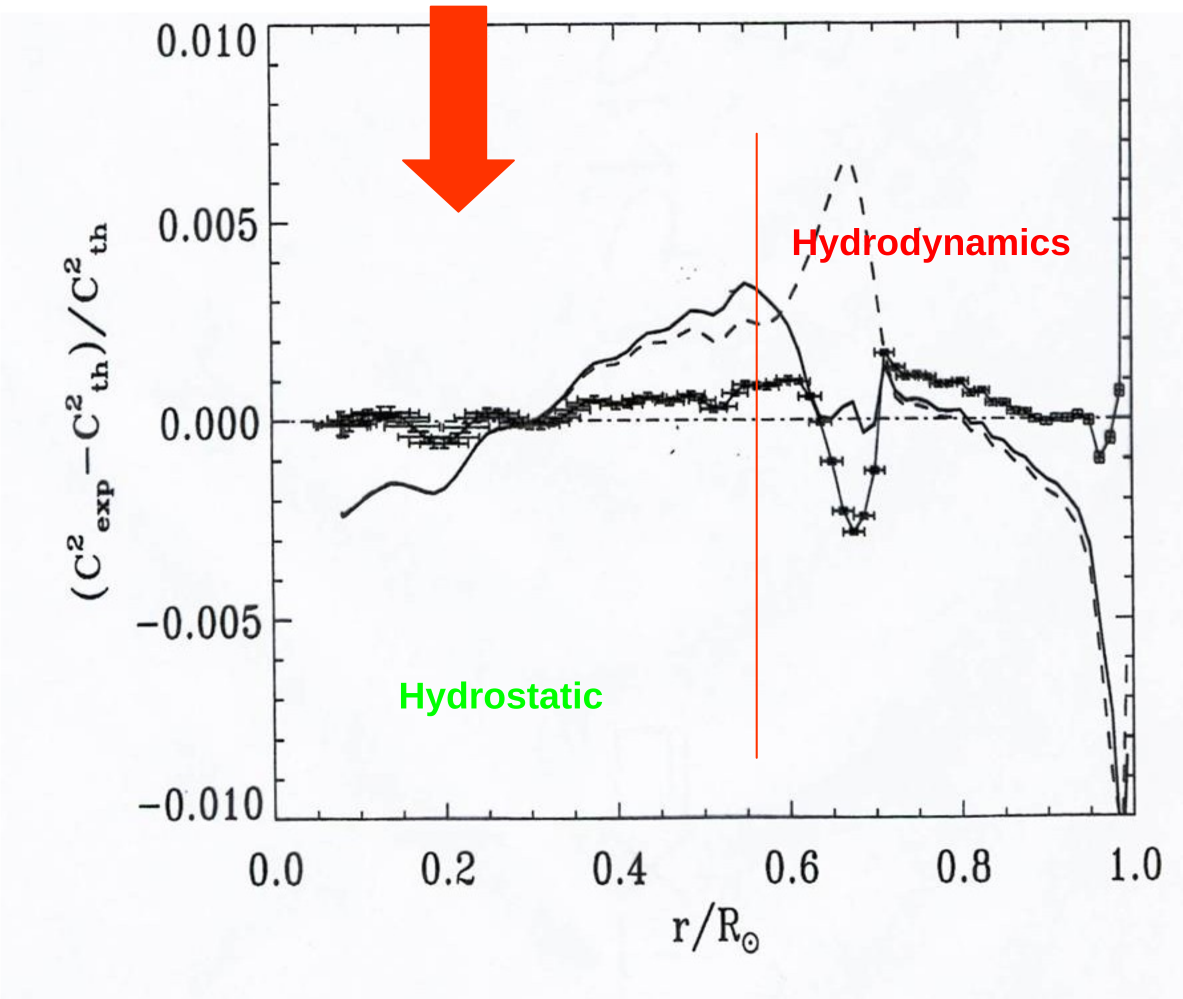




The Seismic model: GOLF+ MDI

includes the best physics and an ajustment to reproduce the seismic results

Turck-Chièze et al. 2001, ApJ lett, 555, L69



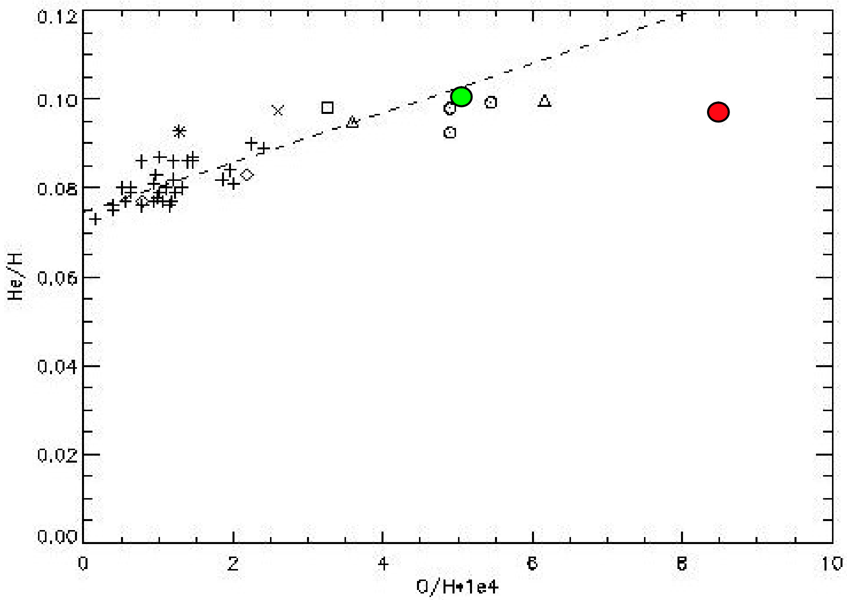
a very good constrain on the central temperature

Couvidat, Turck-Chièze, Kosovichev, 2003, ApJ, 599

Solar composition in C,N, O recently reduced by 30%

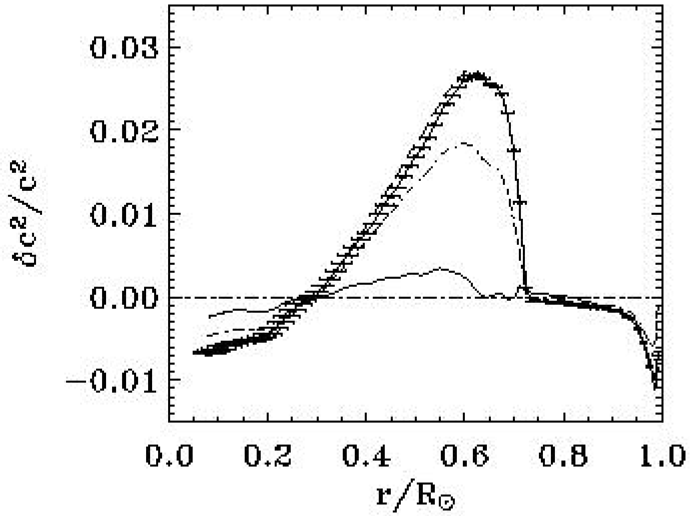
The Sun is no more an « enriched » star in heavy

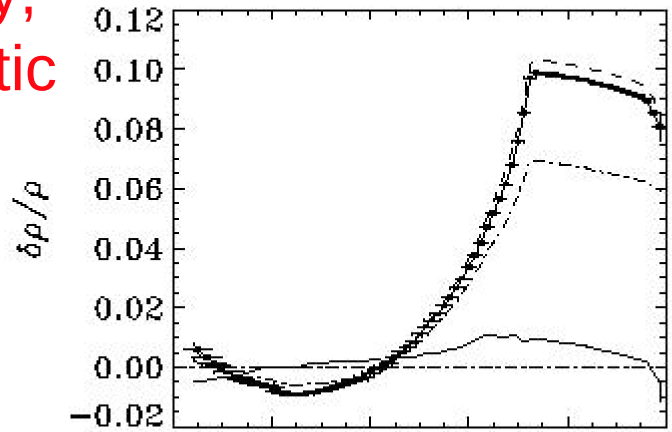
a new problem solved



?

opacity, magnetic field





^{8}B neutrino flux = 4 **10^6 cm^{-2}s^{-1}**

^{8}B seismic model = 5 10^6 cm^{-2}s^{-1}

- It is better to compare neutrino results
- to seismic models than to « standard models » !

- Do not hesitate to quote seismic data and
- models constrained by in situ observations

- Progress toward a coherent and complete picture of the Sun useful for progressing in Astrophysics and Particle physics

Oscillation parameters

$\Delta m^2 = 7\ 10^{-5}\ eV^2\ tg^2\theta_{12} = 0.45$ BPG2003

Chlorine experiment	Seismic model			Detected neutrinos
pep	0.228		→	0.13
^{7}Be	1.155	57%		0.66
^{8}B	5.676	31%		1.76
^{13}N	0.096	57%		0.054
^{15}O	0.328	57%		0.187
total	7.44 SNU (0.96)			2.79 SNU (0.36)
			experiment	2.56 (0.23)

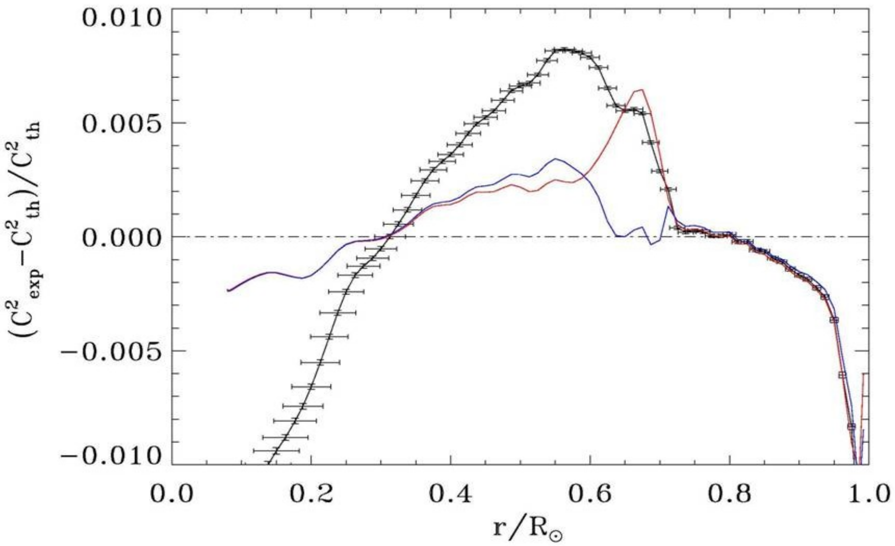
Gallium experiment	Seismic model			Detected neutrinos
pp	69.4	57%	→	39.6
pep	2.84	57%		1.62
7Be	34.79	57%		19.83
8B	11.95	31%		3.70
13N	3.48	57%		1.98
15O	5.648	57%		3.22
total	128.2 SNU (7)			69.95 SNU
			experiment	70.8 SNU (4.4)

Interest of low energy experiments: Borexino, Lens to verify , some discrepancy ?...

Already beautiful constraints on pp and CNO chains

Turck-Chièze et al. Sol. Phys. 2001

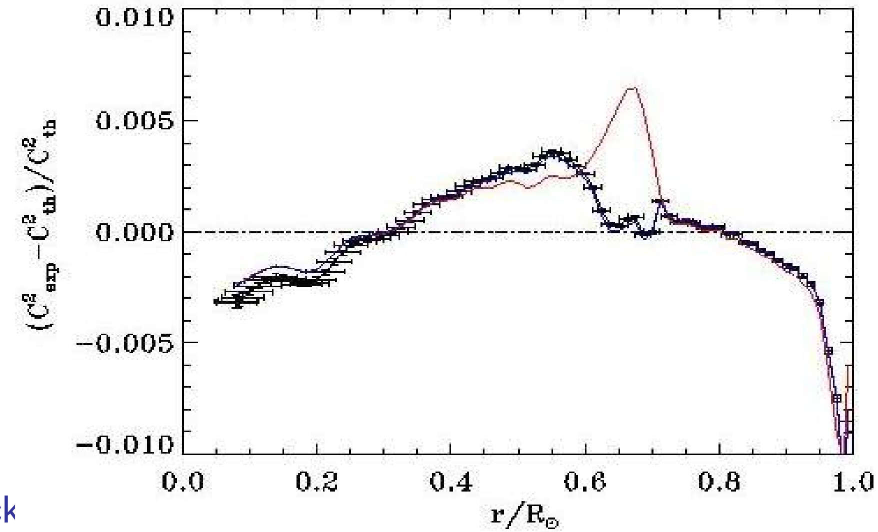
pp: -5% for check of screening or Maxwell distribution



The Sun energy production is under control thanks to helioseismology + SNO results !

- **-65% CNO**
- **Cl: 6.1 SNU**
- **Ga: 121SNU**
- **^{8}B: 3.81 10^6**

not compatible with SNO

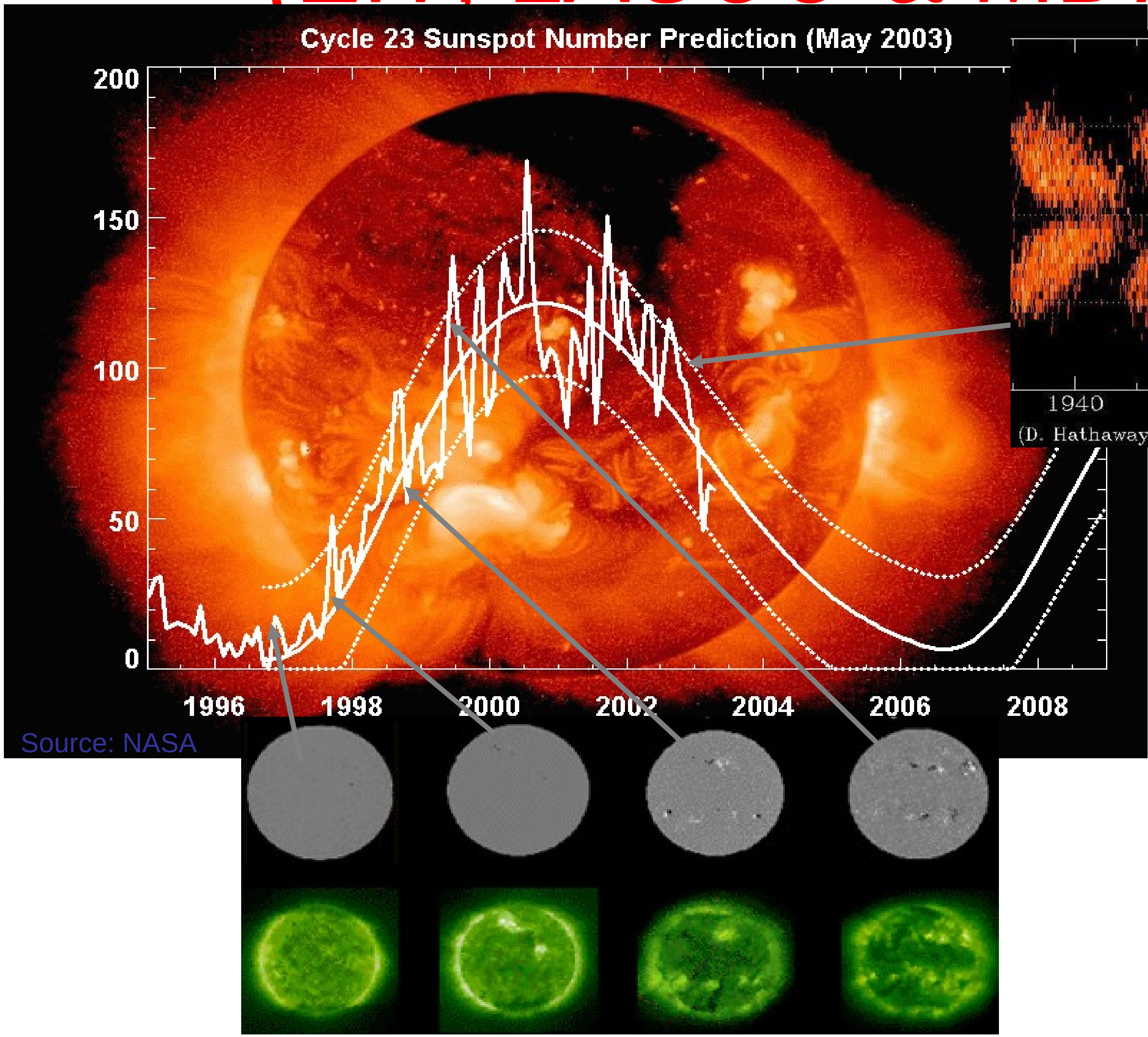


A new vision of the Sun

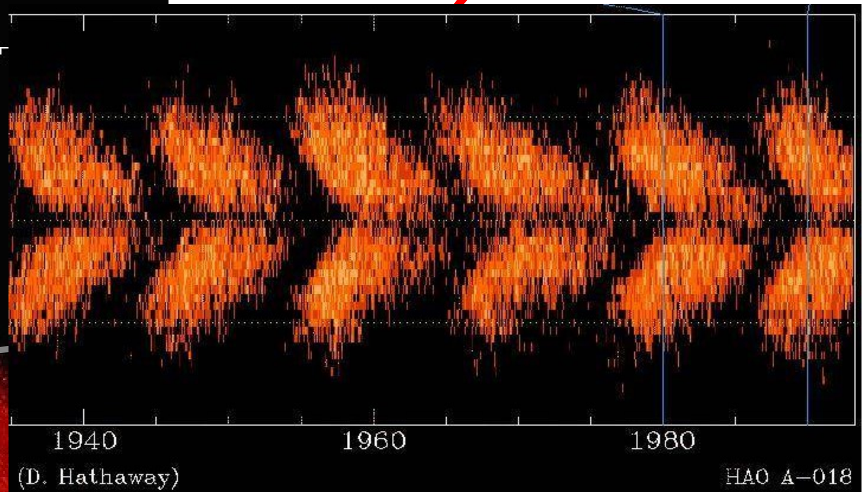
The Sun is a magnetic Sun

the Sun is not standard !!!

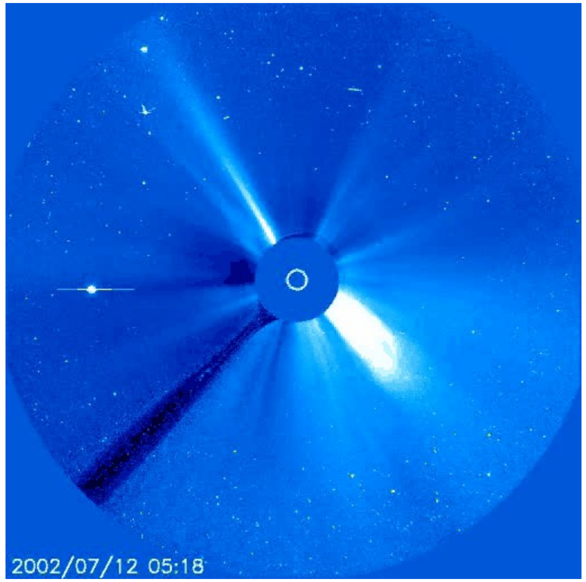
Magnetic Solar Cycle 23 (EIT, LASCO & MDI Data)



Source: NASA

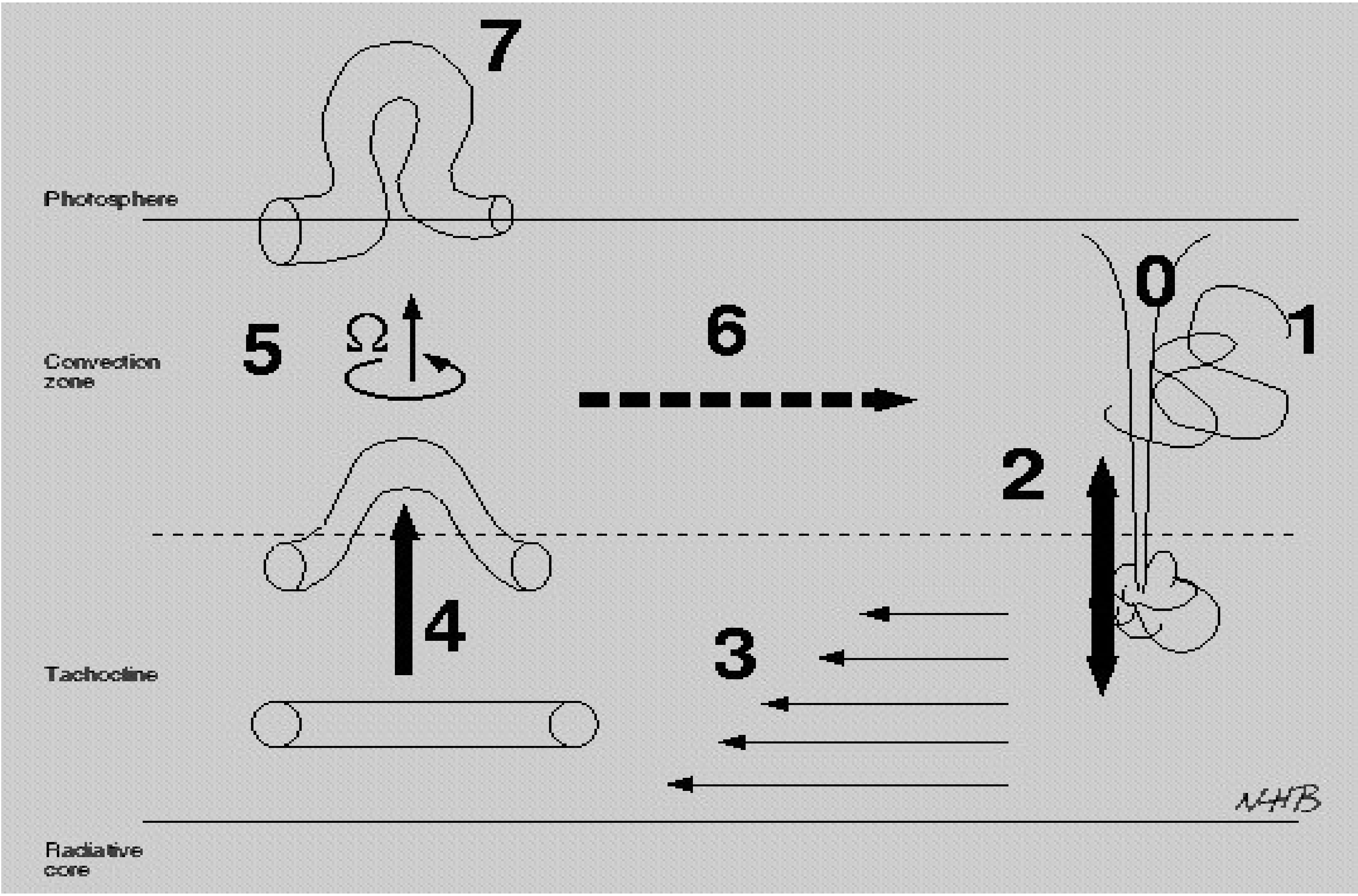


Source: Soho

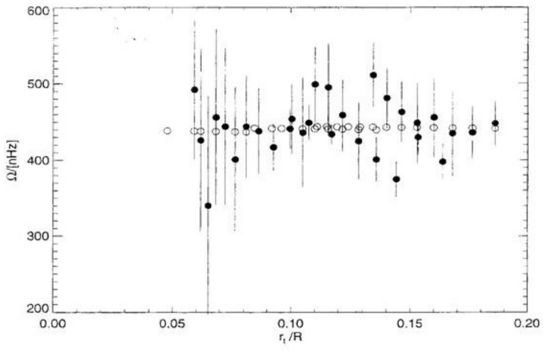


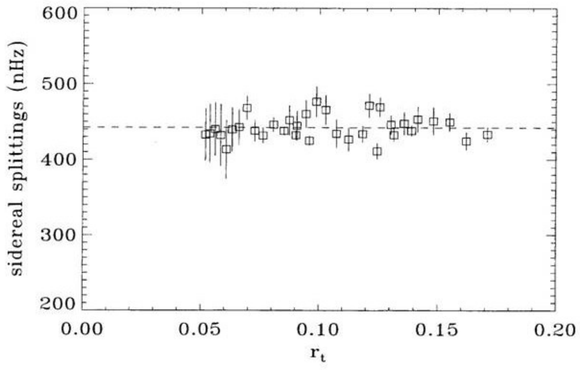
Theoretical Solar Cycle: Internal origin

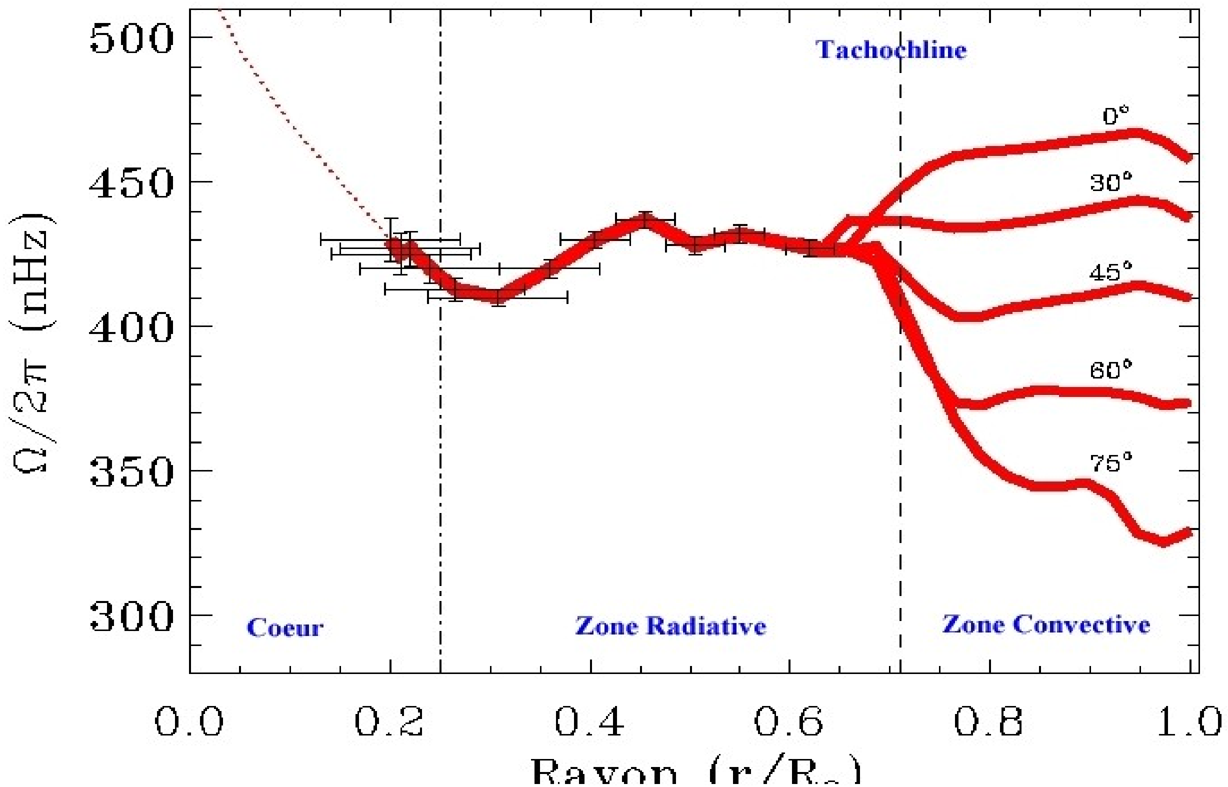
we need to understand the role of the rotation to estimate the magnetic field



First step: the rotation profile GOLF + MDI







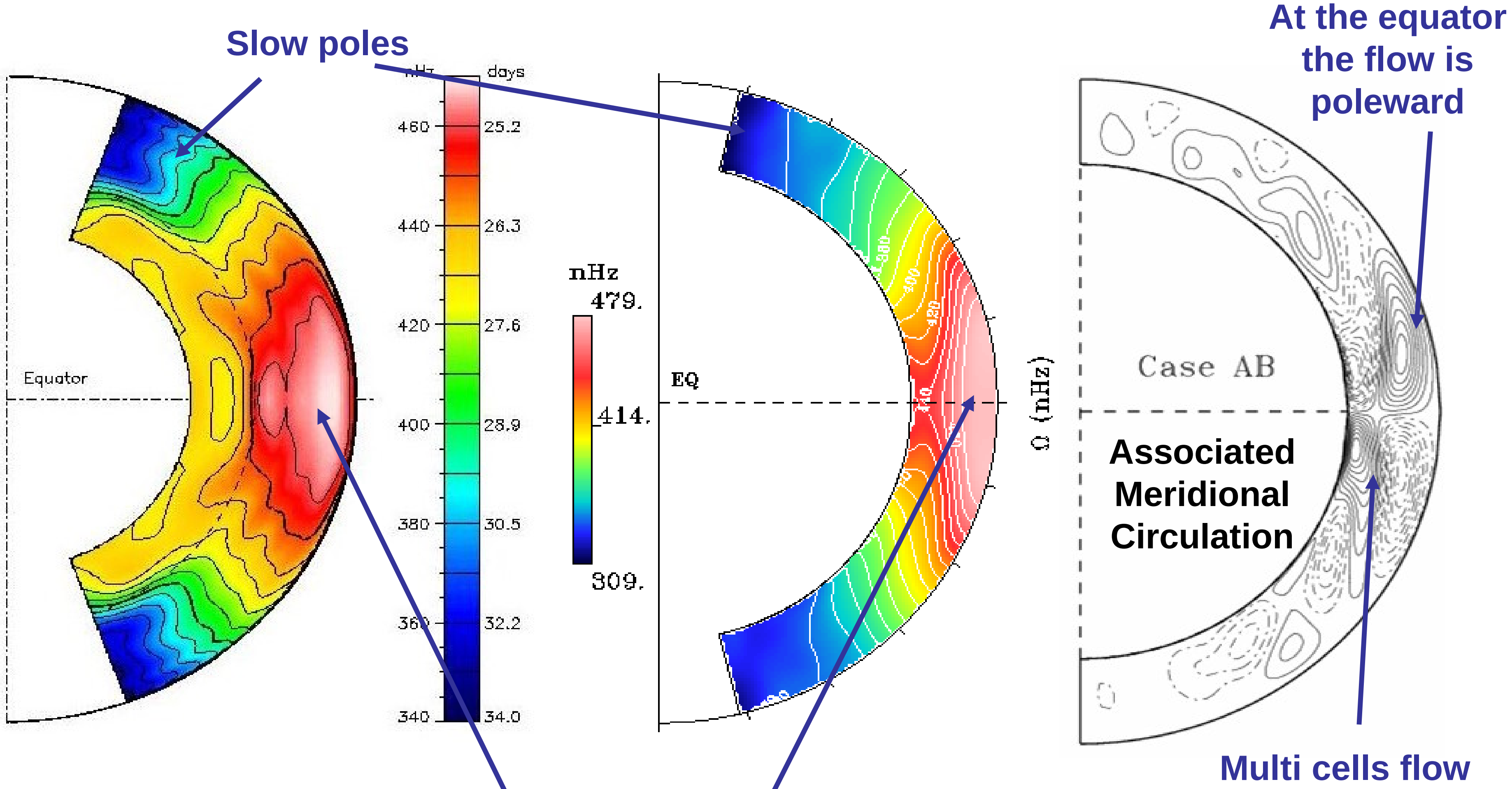
Progress in radiative zone

Couvidat et al, 2003, ApJ, 597, L77

Magnetohydrodynamical 3D calculations

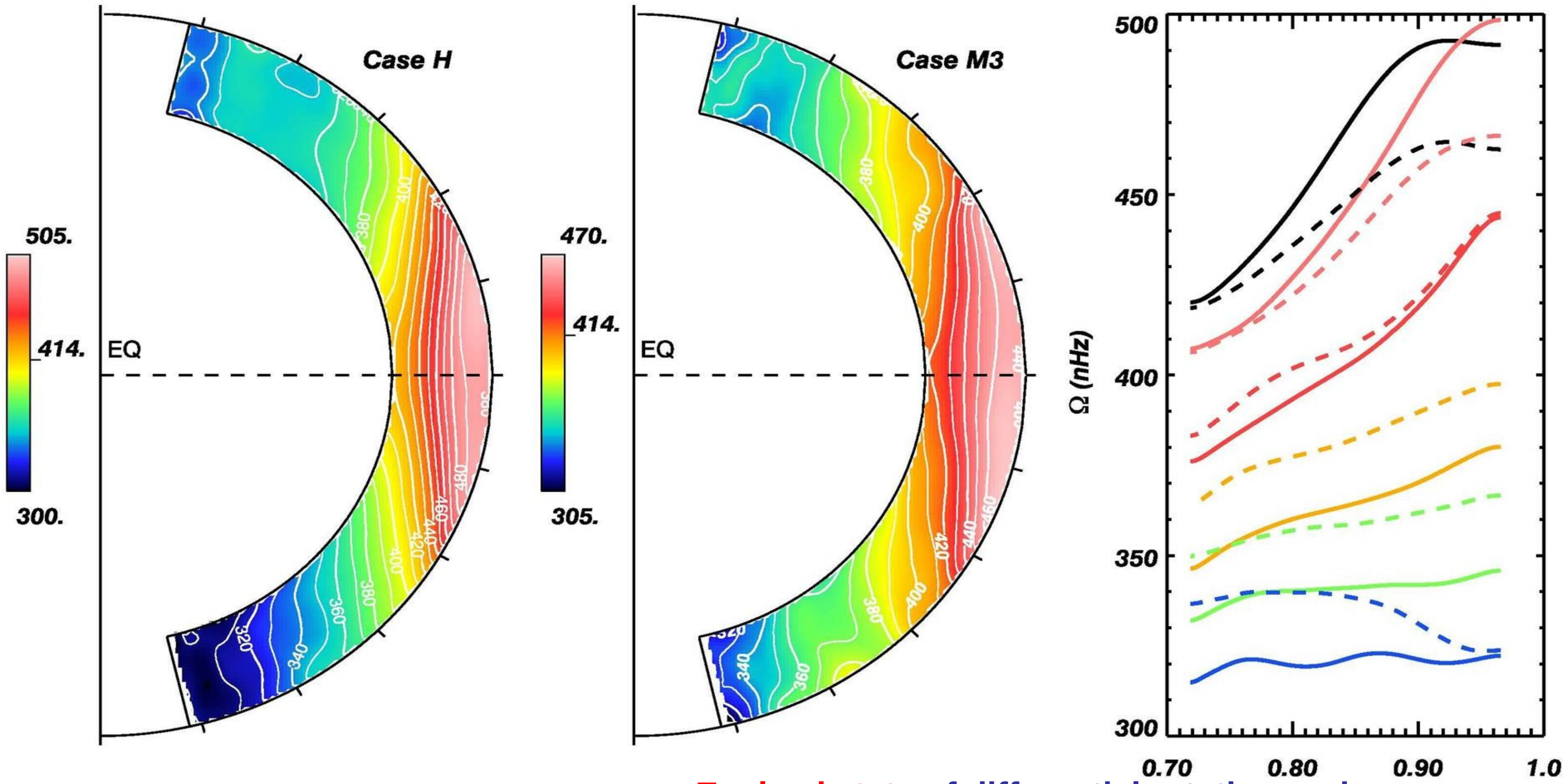
Mean Angular Velocity Ω

Brun & Toomre 2002, ApJ 570, 865



GONG DATA **SIMULATION**

Mean Angular Velocity Ω



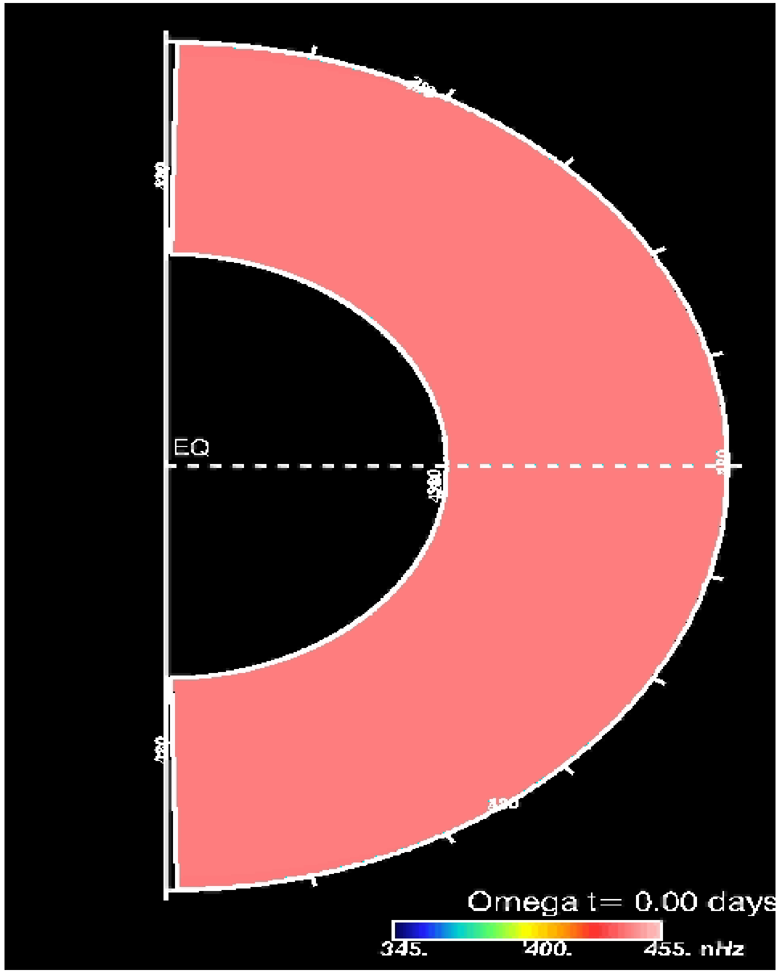
Initial state of differential rotation

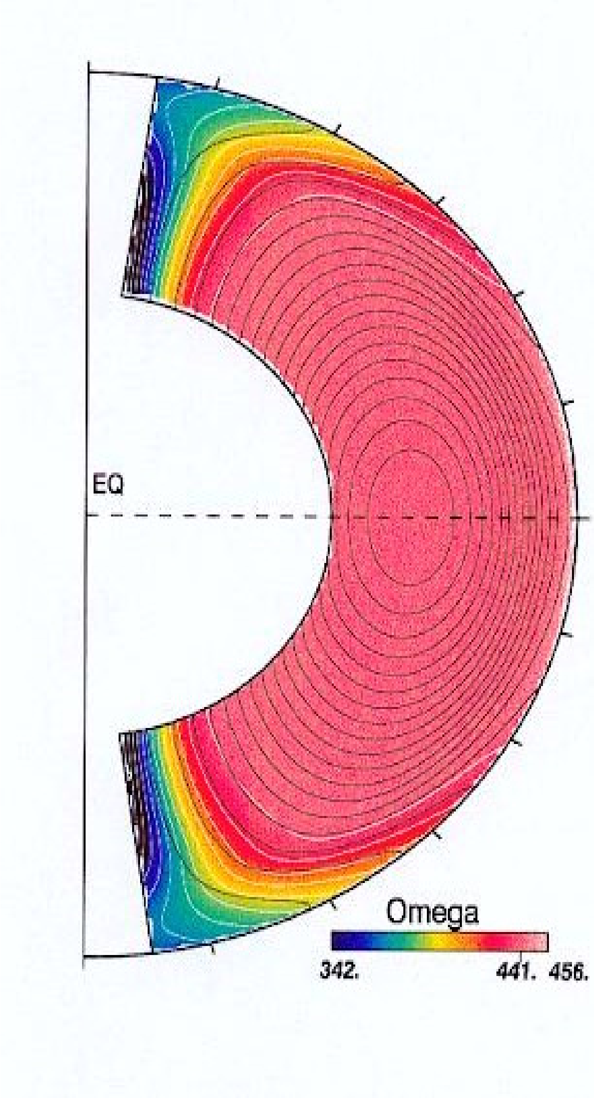
Evolved state of differential rotation under the influence of the Lorentz force

Brun Toomre 2003

The important role of the magnetic field in the radiative zone

MHD simulation Brun et al.





Rudiger & Kitchatinov 1997

Mc Gregor & Charbonneau 1999

tachocline

$B\phi = 2\ 10^6 B_0^{1/3}$

$B_0 \sim 2\ 10^{-4}$G,

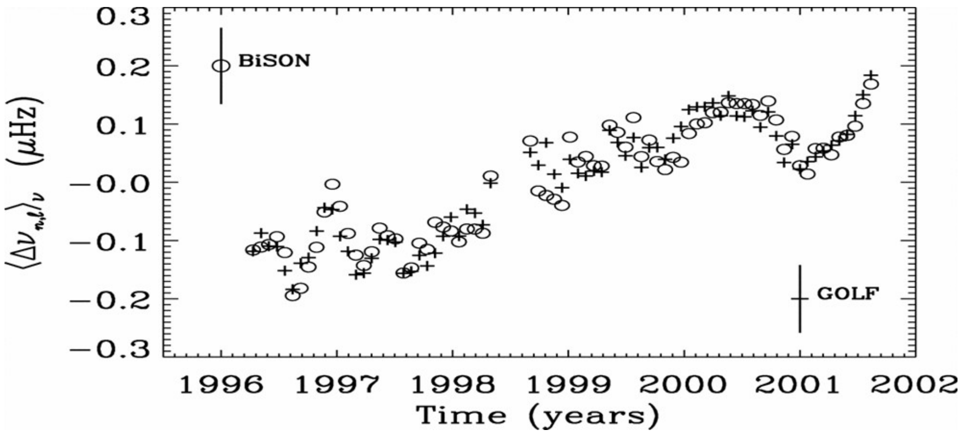
$B\phi \sim 10^5$G

Magnetic field in the Sun and Neutrino Properties

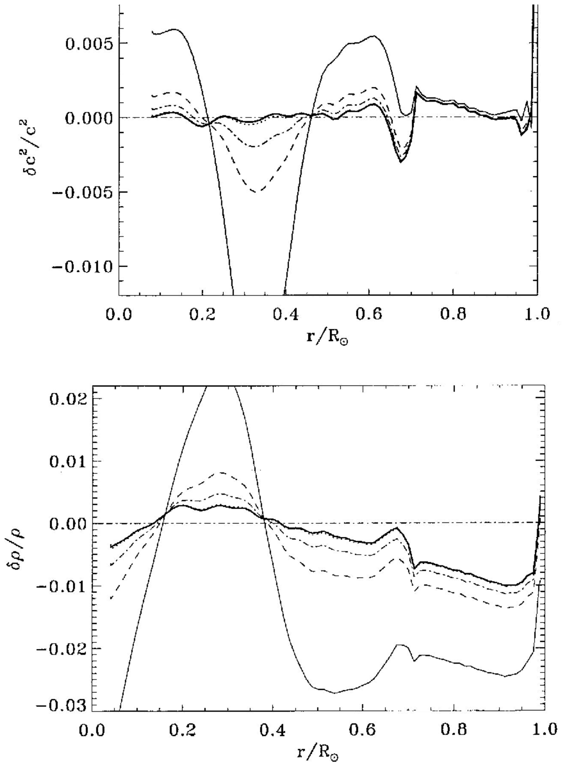
B= 10 kG at 0.995

ΔB= 100G along the cycle

Nghiem et al, 2004



Jimenez et al. ApJ, 2004, 604, 976, 2004



External zone, flux tube, B =4000G
Tachocline B < 300kG, mν > 3 10^{-12} μ B
Radiative zone: B < 30MG, mν > 5 10-15 μB
limit of 7 MG ? from deformed Sun

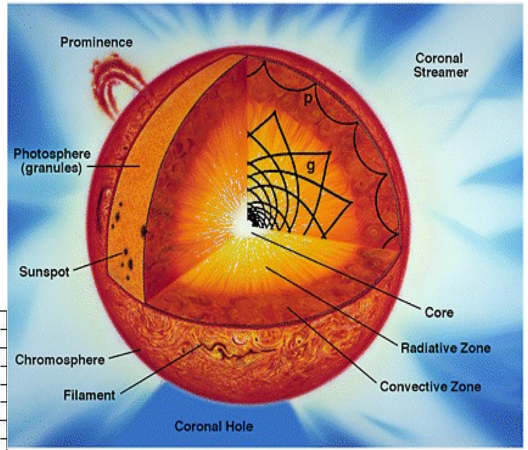
Couvidat, T-C, Kosovichev 2003

Perspectives

Sun, other stars,

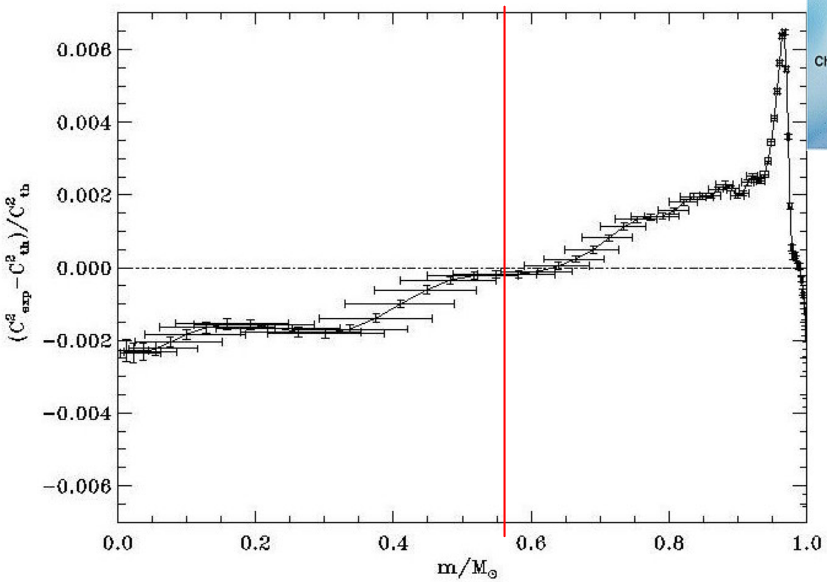
new links between Astrophysics and Particle Physics

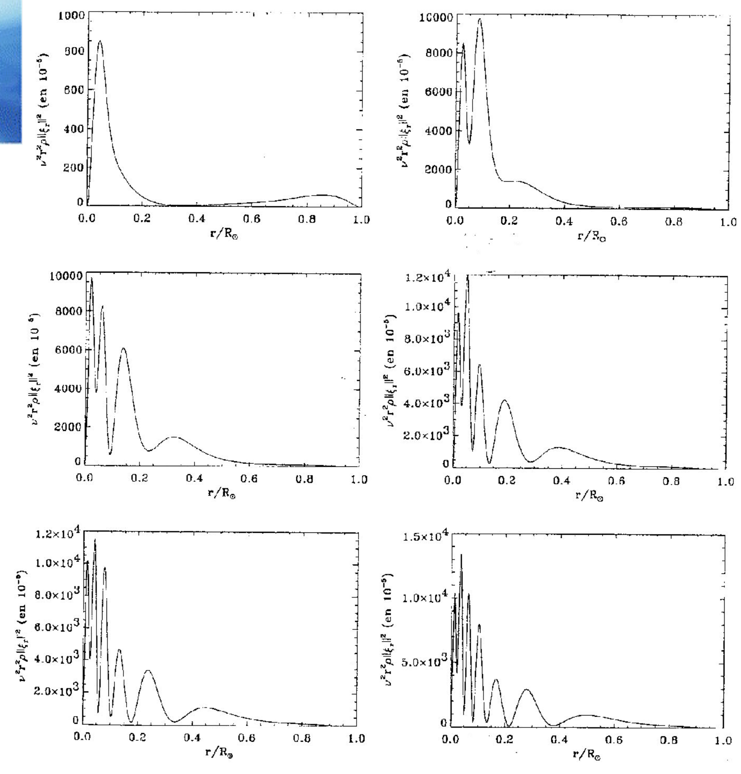
A better insight on the radiative region and solar core



Gravity Modes

l=1 n=1 à 6



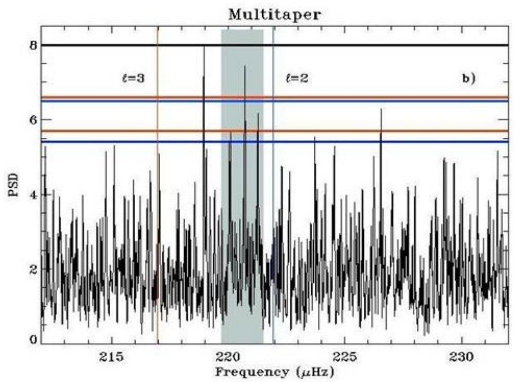


It contains 98% of the solar mass

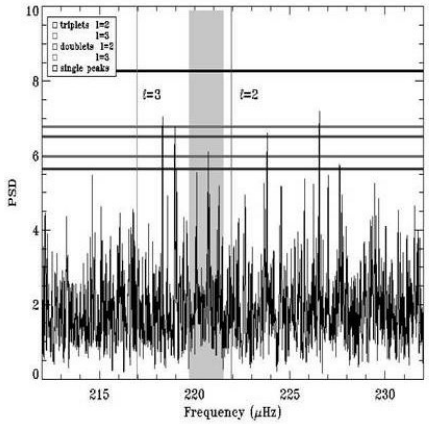
Improvements on the spatial resolution, density, rotation and central magnetic field

A new project to progress on gravity modes

Turck-Chièze et al. 2004, ApJ, 604, 455

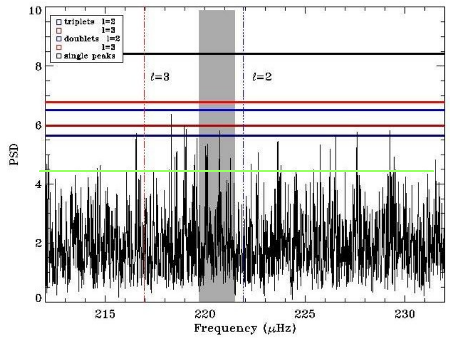


800 days



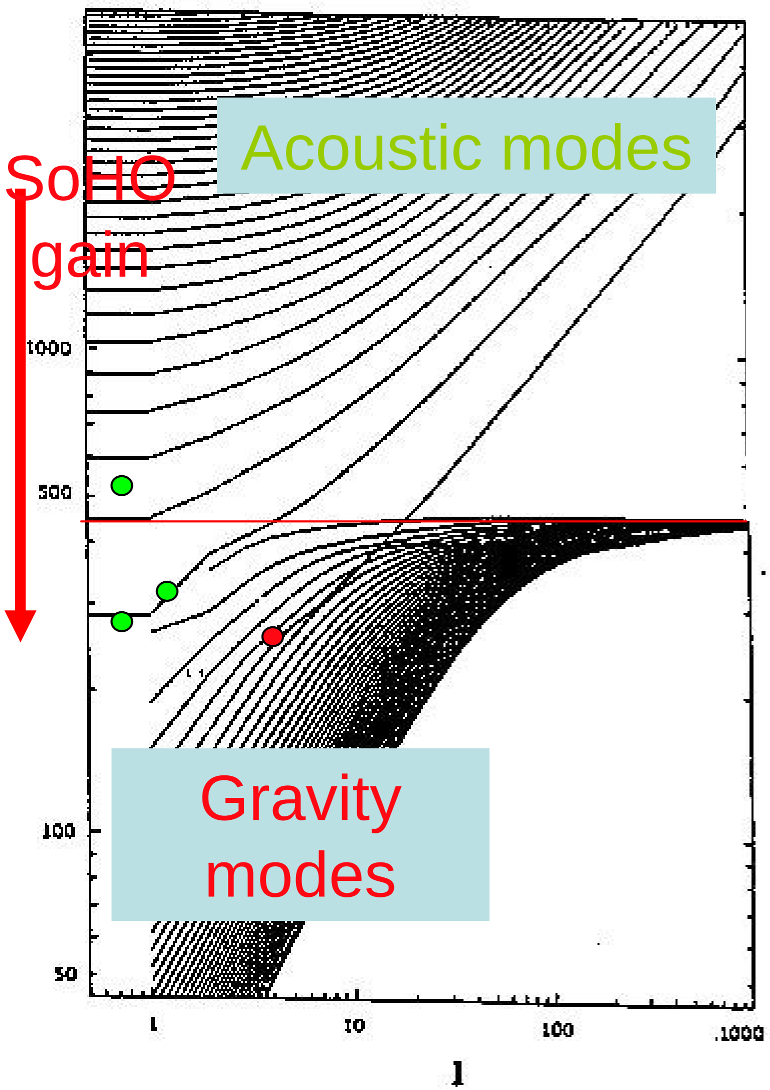
1700 days

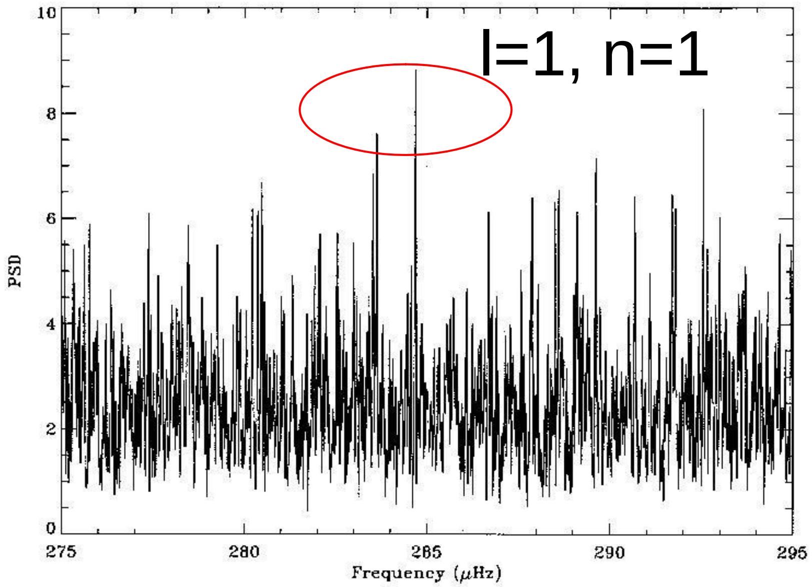
gravity modes candidates (2004)

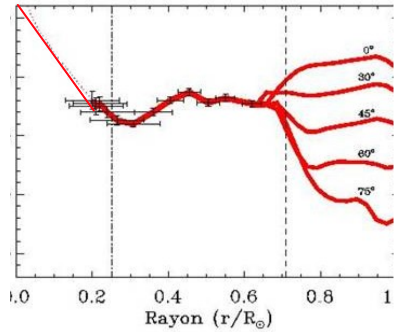


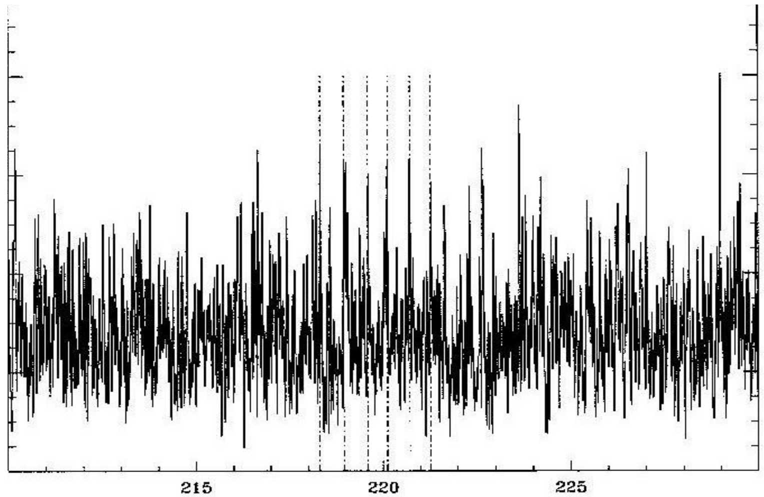
2100 days

New analysis after 3000 days





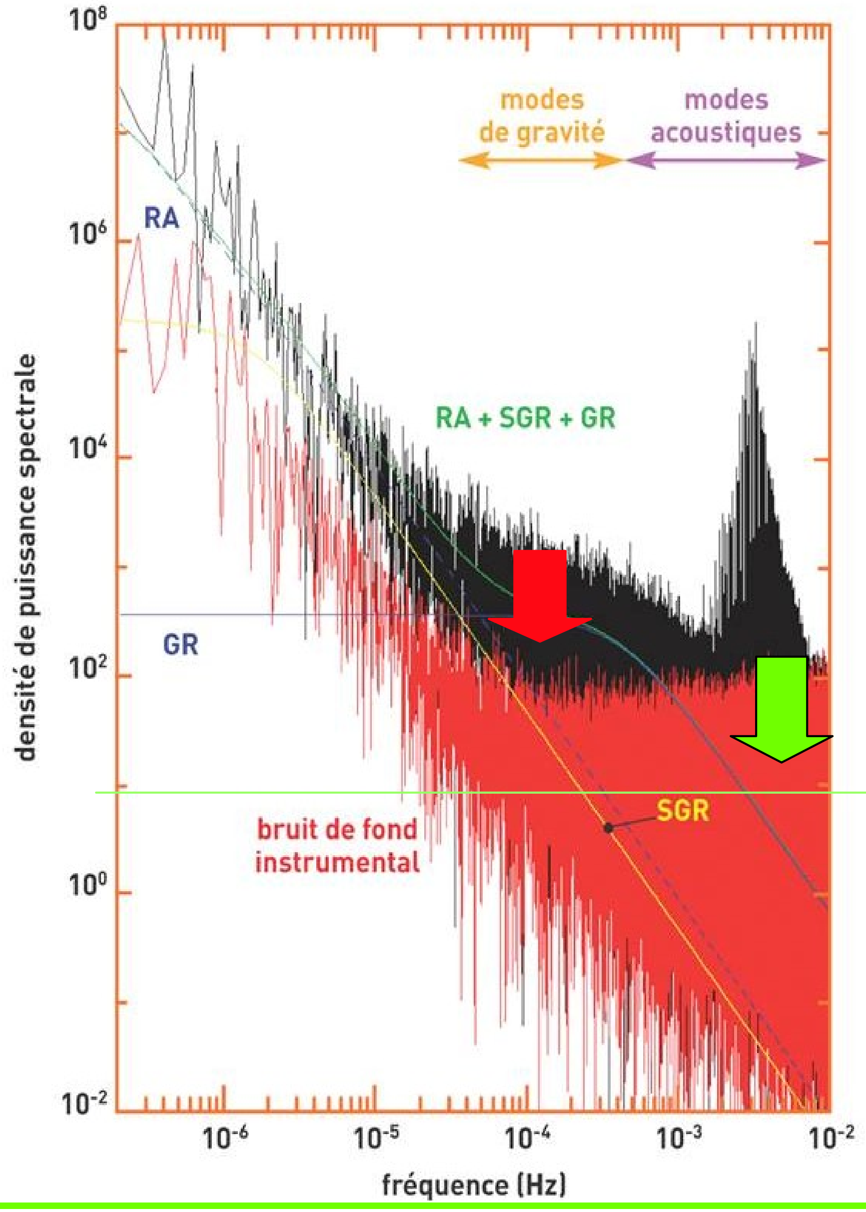




gravity mode

l=5 ?

velocity down to 2mm/s



Decrease of the solar noise due to granulation by a factor 5 to 10

Decrease of the statistical error by a factor 5 to 10

GOLF-NG: Scientific objectives

GOLF-NG : Solar study of the temporal variability of internal processes, improvement of the solar core knowledge, progress on internal magnetic field

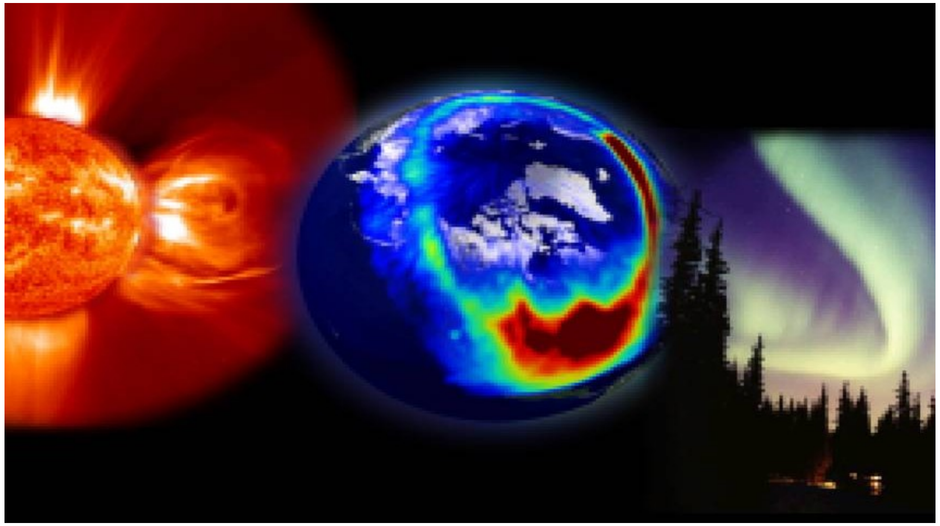
GOLF-NG

- **Deep understanding of the Sun as a magnetic star**

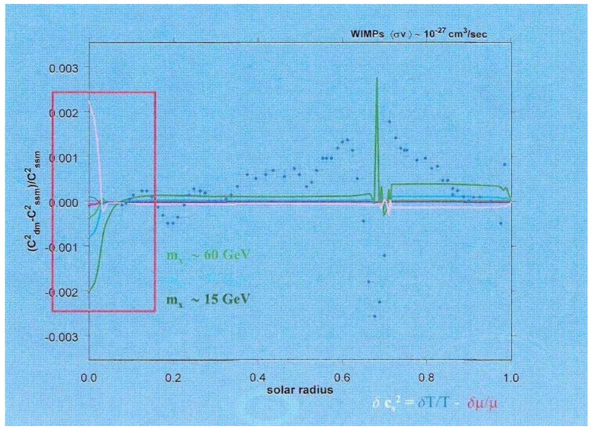
- **Relation Sun-Earth: long variability, climate, cycles**

Constraints on dark matter

- **Microsatellite CNES 2008-2009 ?**
in parallel and (or) complement to SDO/
- **then 2010-2012 sentinel ILWS ??**

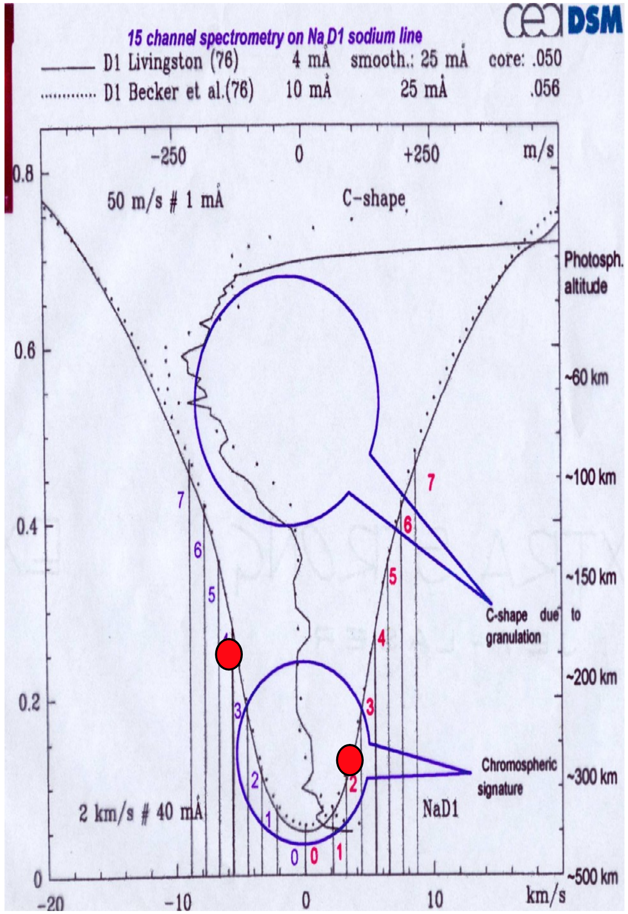


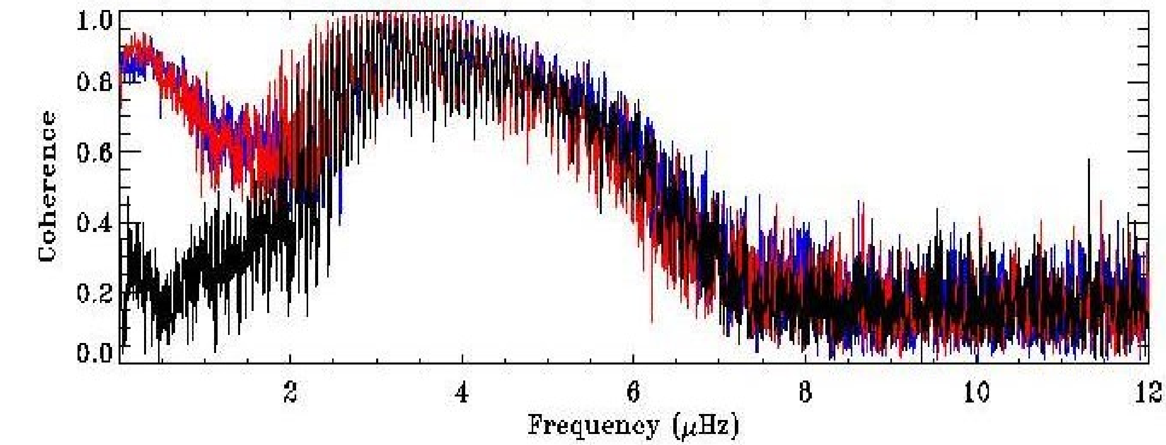
-**Successor of GOLF**
- **Prototype phase on ground**
- **Measurements in Canaries Teide, Summer 2005**

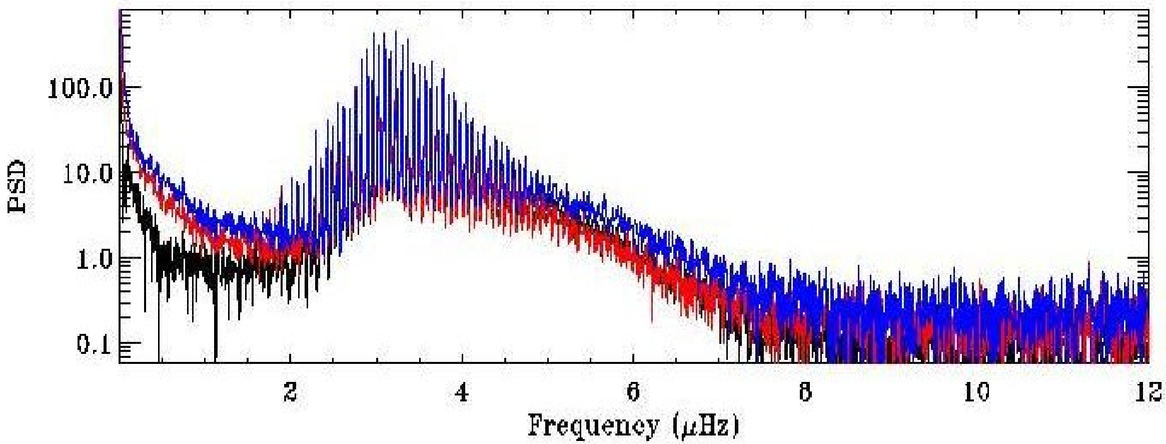


Measurement of lower velocities
in understanding better the sodium line and in measuring quicker to get the temporal variations

We know already from GOLF







On ground Prototype GOLF-NG 1999-2005

PI: S. Turck-Chièze

- technological validation

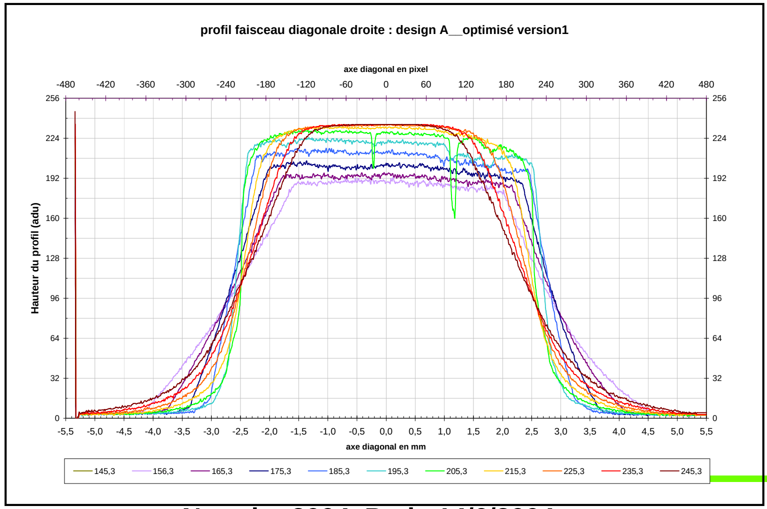
variable magnet from 2 to 8 kG: OK

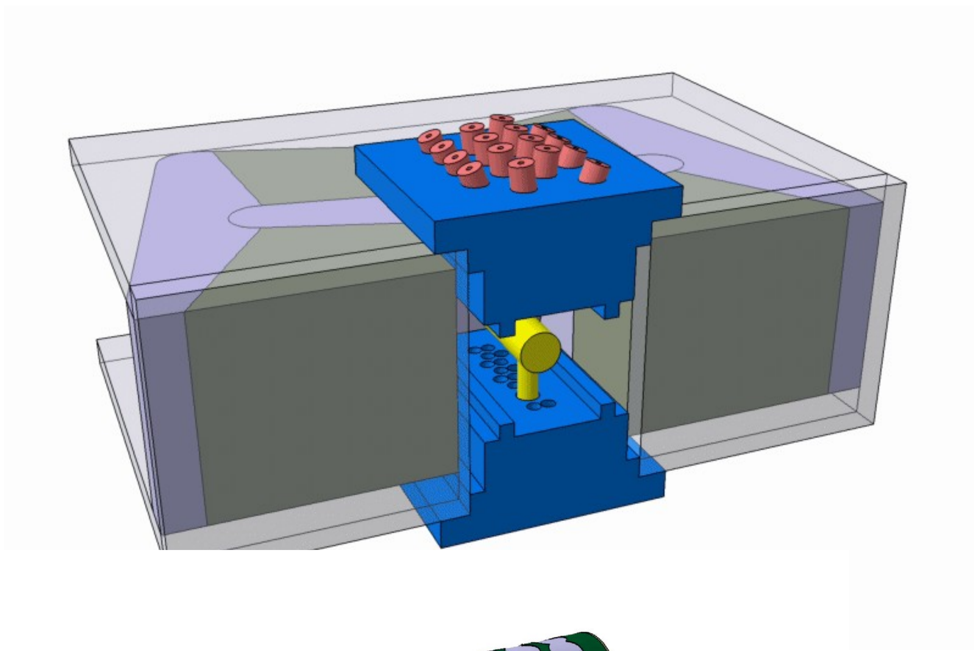
thermic study

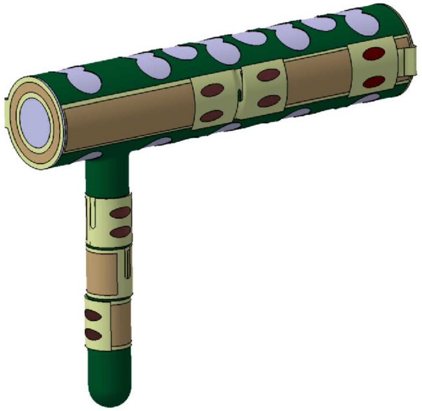
resonance cell

suppression of the mechanisms

photodiodes







Microsatellite project 2008 ?

I need your support

GOLF-NG: microsatellite version

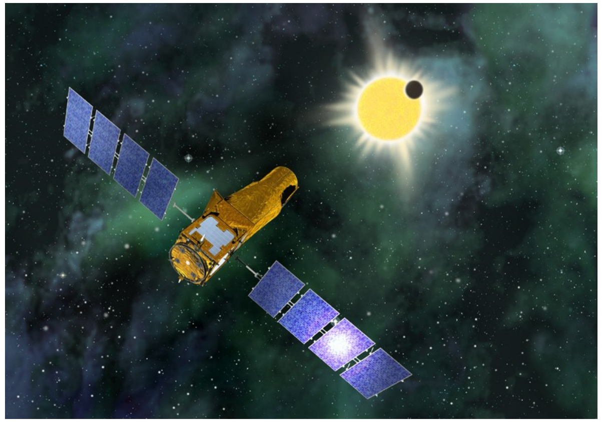
International project CEA-France Spain

launch in GOLF-NG 2008-2009

launch of COROT 2006: asteroseismology and exoplanets

launch of HMI / SDO in 2008

HMI/SDO 2008



Then if convincing other spatial projects on long missions: several years

Constant progress has been noticed on the knowledge of the Sun and solar neutrinos

We will use soon constraints coming from gravity modes

Special and competitive case to continue to learn news properties of the neutrinos: Majorana? or magnetic moment ? or to put constraints on dark matter

Prepare next generation of neutrino investigations: supernovae or high energy sources

Need of new generation of instruments on both sides

mutual assistance to get these projects

Responsabilités fonctionnelles

- Responsable Scientifique : Sylvaine TURCK-CHIEZE, CEA SAp
- Responsable Instrument : Jean-Maurice ROBILLOT, Obs.de Bordeaux -> R. Garcia
- Chef de Projet : Pierre-Henri CARTON , CEA SEDI

Responsabilités techniques

SEDI : - Etudes design Optique
- Etudes et réalisation Photodétecteurs, chaîne de mesure, Acquisition
- Intégration matériels et logiciels, Tests et calibration, Installation sur site

SIS : - Etudes mécano-thermiques
- Etudes Ctrl/Cde
- Conception et réalisations sous-systèmes

IAC : - Réalisation du sous-système de polarisation optique
- Réalisation des interfaces (mécaniques, DAQ, …) liées au site d'installation

NICE : - Suivi instrumental et définition de l'analyse

Ressources humaines Saclay aujourd'hui

- 2 astrophysiciens, 3 ingénieurs, 4 techniciens **+ IAC: contrat 3 ans. Futur IAS ? Imagerie ?**