Helioseismology, neutrinos and dark matter

S. Turck-Chièze

SAp/IRFU/CEA France

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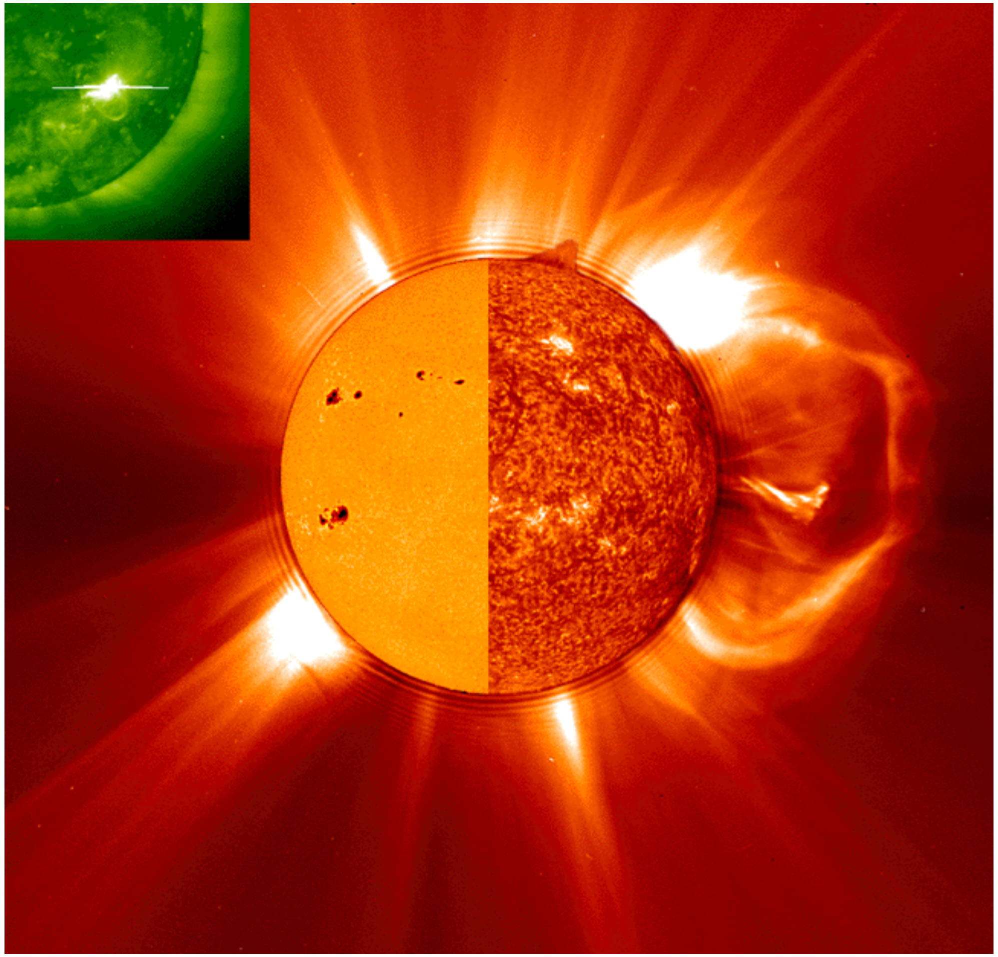
The Sun is the best known star



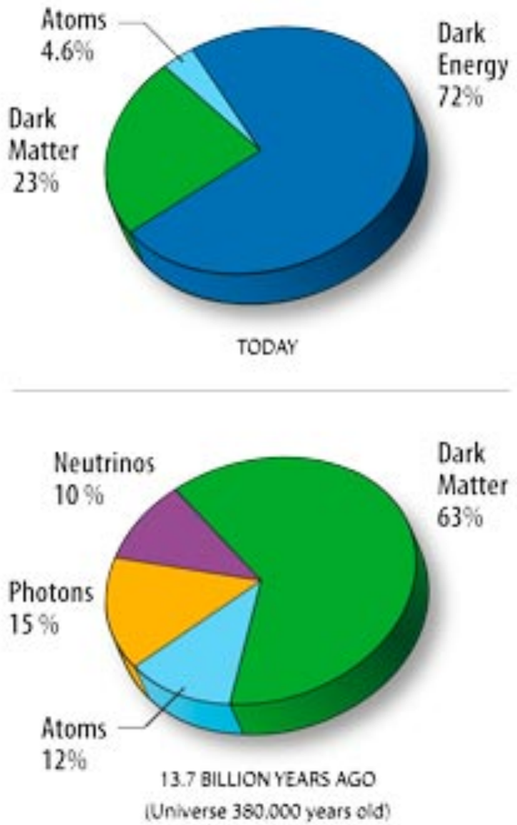
But we do not know its initial mass so its real influence on the planets in formation

We are not able to predict its degree of activity of the next 20 years and its real impact of the Earth environment

We do not explain up to now as we will see the recent observations without doubt ….

Nevertheless, its knowledge has reached an impressive level that transforms it in a real laboratory of physics

Can it tells us something about dark matter in stars ?



Could we put some indirect evidence from the precise observation of the Sun?

or some limits on their properties ?

This idea appears in the eighties: Spergel & Press 1985 at a time where people was trying to solve the "solar neutrino problem"

In this case it was CDM, it could be also sterile neutrinos

If WIMPs exist, they may be trapped inside the stars

- If these particles exist and are present everywhere in the Universe, they are also trapped in stars.

- Due their mass, they could migrate toward the stellar centre with time and interact with the present nuclei, very weakly.
- Depending on their interaction, they play a role of conduction in the core and slightly cool the core of OUR SUN in the real central region.

Today, and for the first time, we get a very good knowledge of the solar core thanks to neutrinos and first detected gravity modes

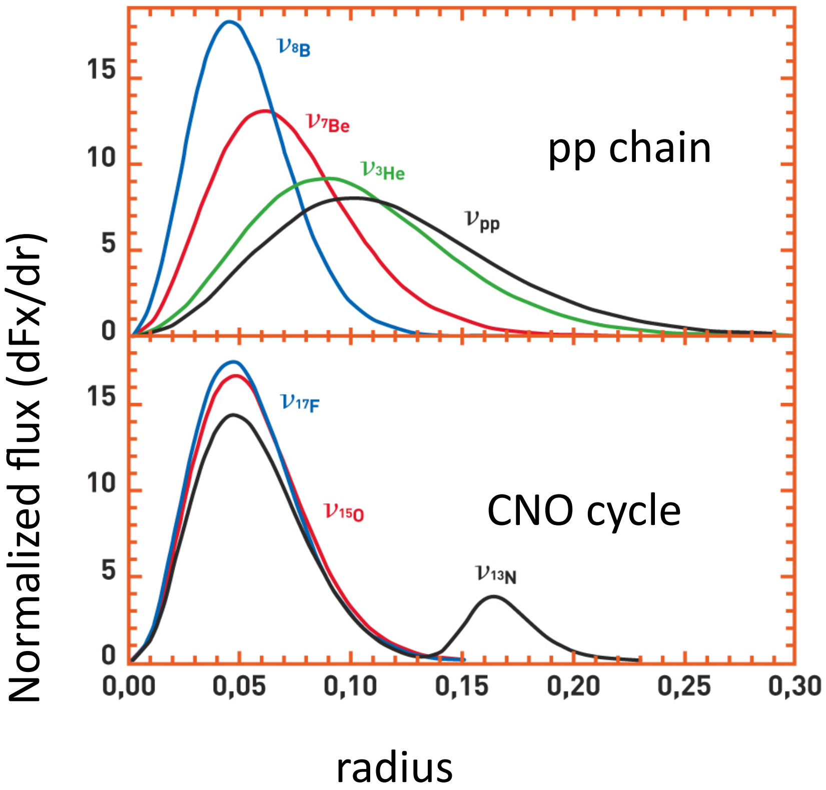
- The solar neutrinos: a good test of the central temperature
- The gravity modes: a good test of the central density
- The WIMPs properties constrained by Sun observations

The solar neutrinos: a good test of the central temperature of the Sun

$4p \rightarrow {}^4He + 2e^+ + 2\,\nu_e + E$

Ray Davis, Nobel Prize with Koshiba in 2002

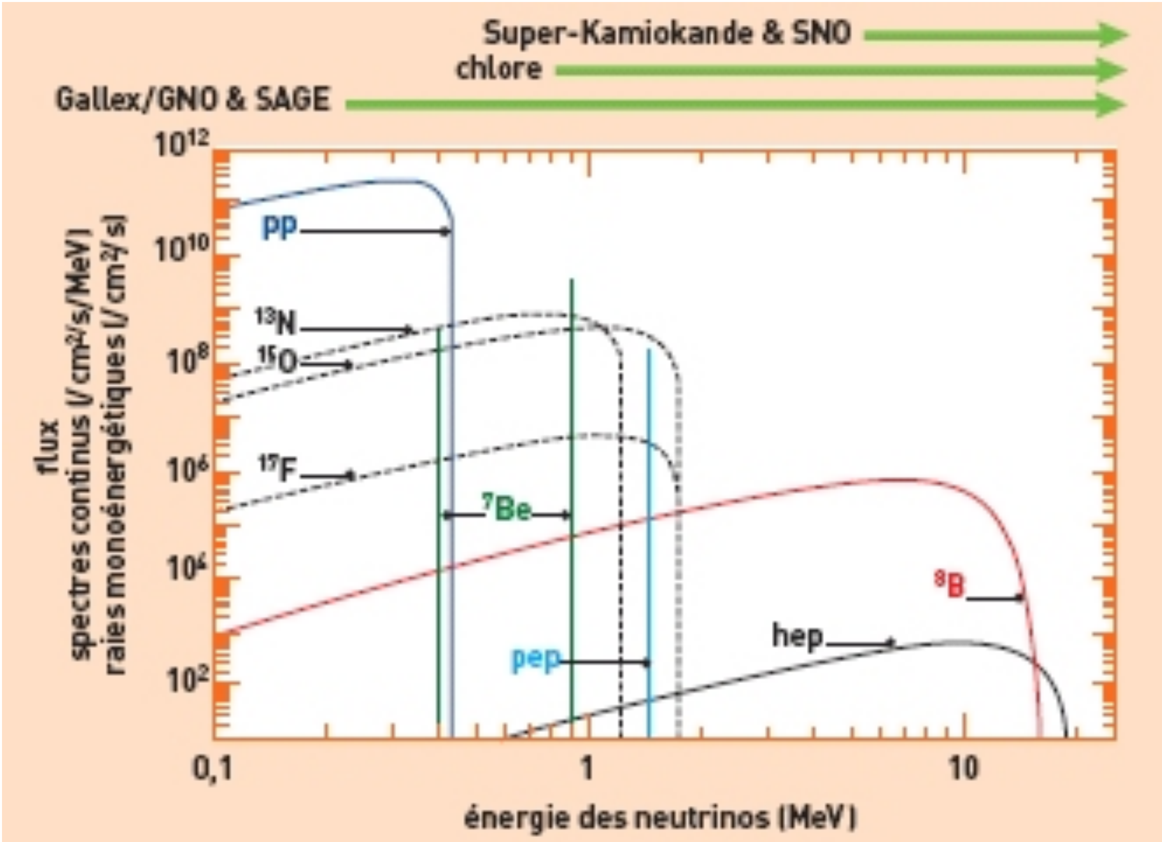
Boron neutrinos: $^{7}Be + p \rightarrow {}^{8}B + \nu_e$



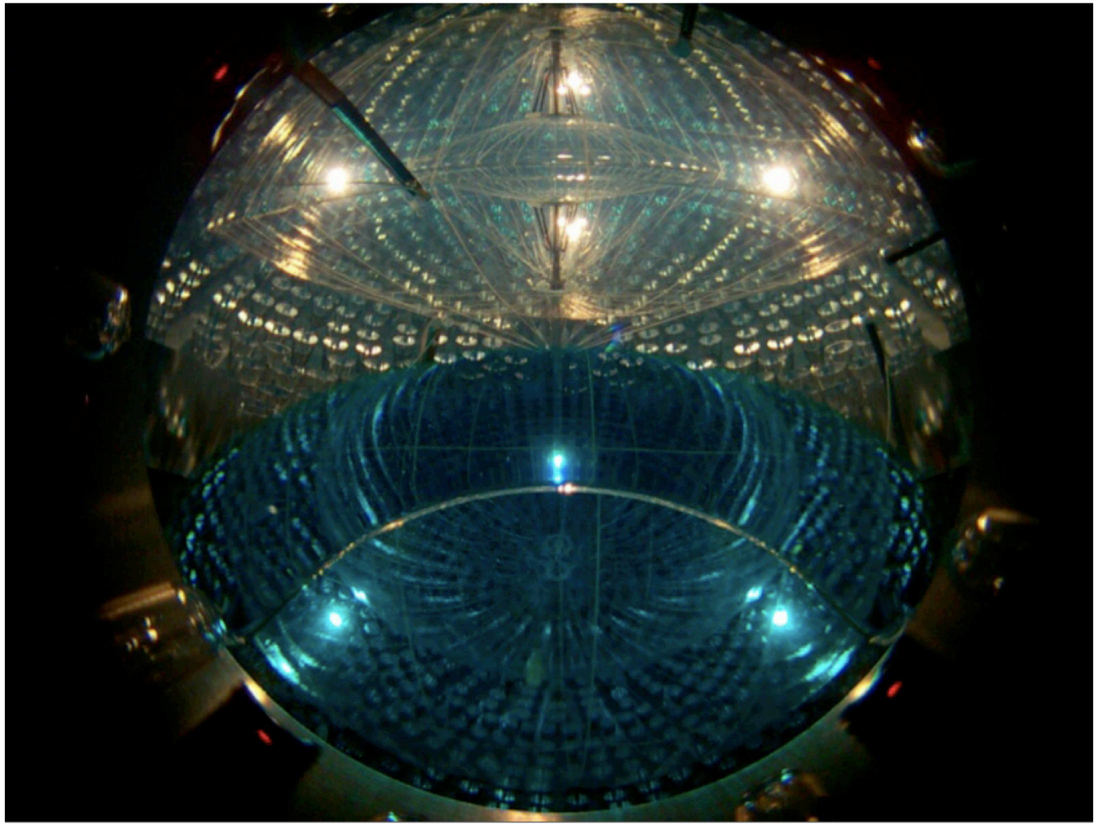
These neutrinos are the most sensitive to the solar core

Moreover they are sensitive to the central temperature at the power 24 !

These neutrinos have been measured extremely precisely this last decade



SNO: For the first time the emitted neutrinos have been ALL detected



5.27 ±0.27± 0.38 10^6 neutrinos/cm2/s

ES: ν_x + e- -> ν_x + e- x= e-, μ, τ

CC: ν_e + D -> p +p + e-

NC: ν_x + D -> p + n + ν_x

SNO detects the sum of all the emitted neutrinos coming from the Sun and appearing on Earth in the form of $\nu_{e,}\, \nu_\mu\, \nu_{\tau.}$

SNO confirms also the SuperKamiokande results

Ahmad et al. Phys. Rev. Lett. 87, (2001) 071301 + 2002,
Aharmim et al, 2005

Are they easy to predict ? No

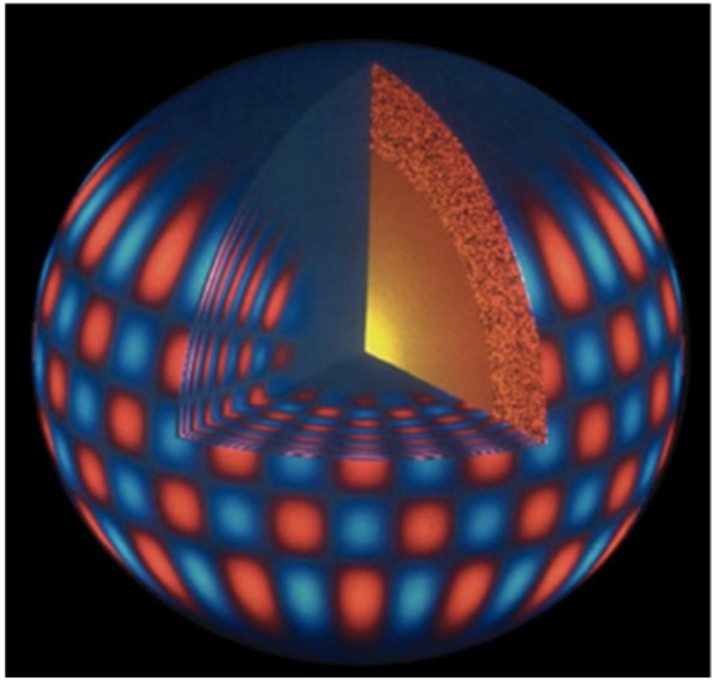
- Boron neutrinos are extremely dependent to the detailed microscopic physics

Year	Boron flux	T_c	Y_0	Problem solved
1988	3.8 ± 1.1	15.6	0.276	CNO opacity, $^7Be(p,\gamma)$
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	$3.98. \pm 1.1$	15.54	0.262	- 30% in CNO composition
2004	5.31 ± 0.6	15.75	0.277	Seismic model + updated ingred.

SNO results $5.27 \pm 0.27 \pm 0.38$ (2004)

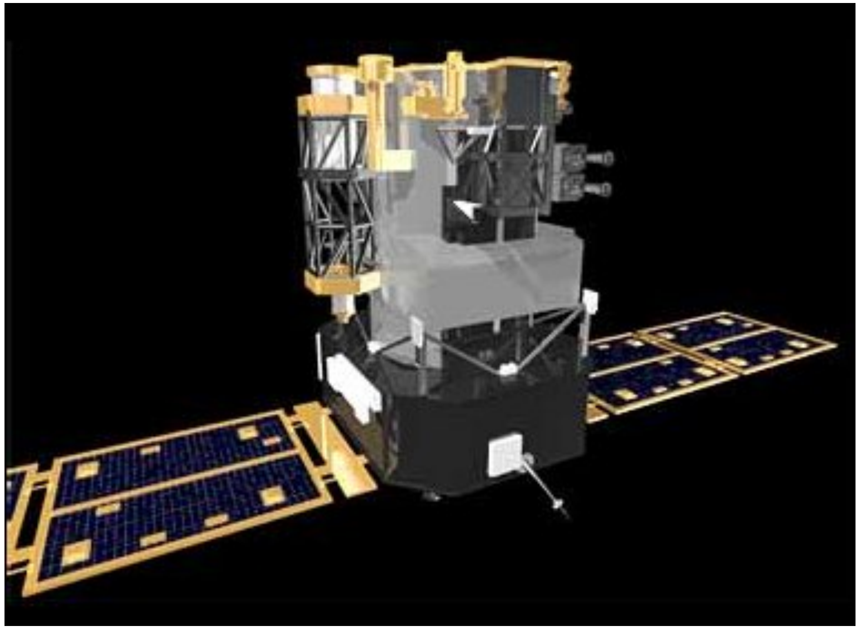
Turck-Chièze and Couvidat, 2011 Report in progress in Physics, 74

So how to be sure of the number of emitted neutrinos



- Of course generally people use the Standard Solar Model (SSM) predictions but
- Are the equations of the SSM representative of the real Sun ?
- Certainly not
- Helioseismology can help

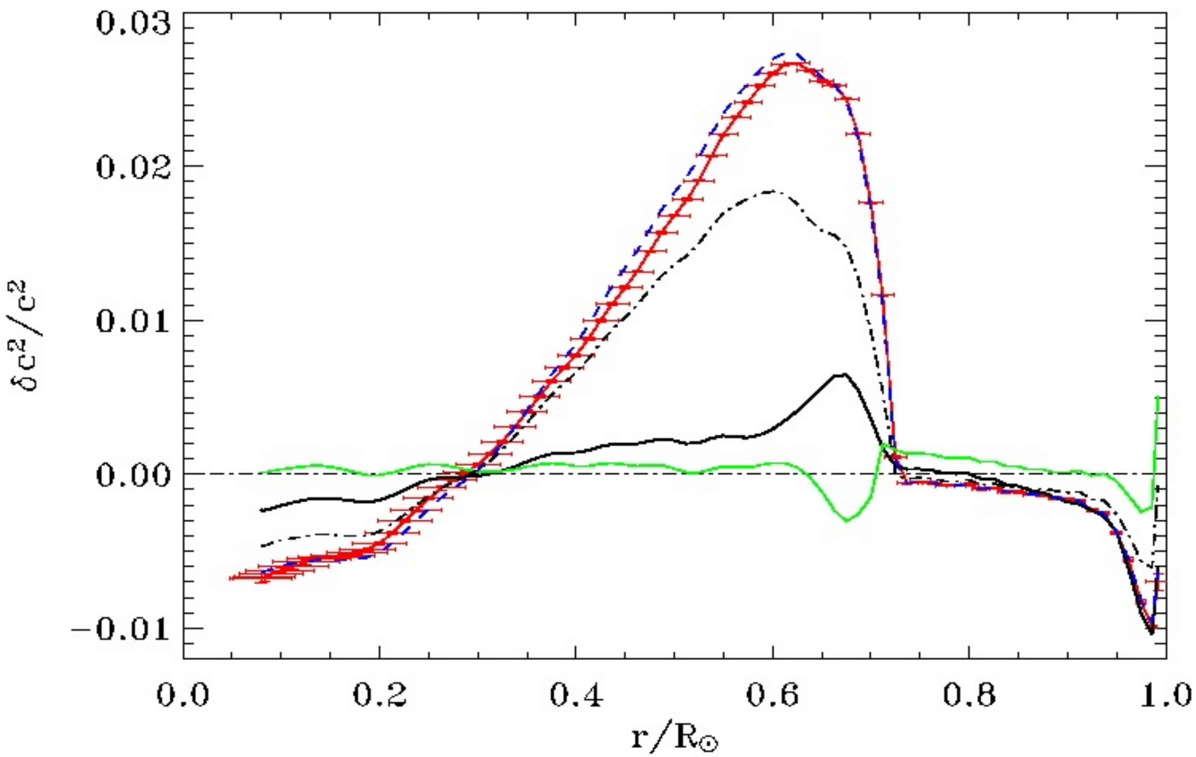
SoHO satellite: 1995 -2015 !!



Millions of acoustic modes $\omega_{n,l}$ from the surface down to the core which allow to reconstitute the internal sound speed In comparing them to the modes calculated by a model

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

Extraction of the sound speed from acoustic modes and compared to the sound speed coming from models



Red: SSM

Green: SSeM seismic model Using the same equations than the SSM but that reproduces as properly as possible the observed sound speed

Turck-Chièze et al. 2001, 2004, Basu et al. 2009, Turck-Chièze et al. 2010

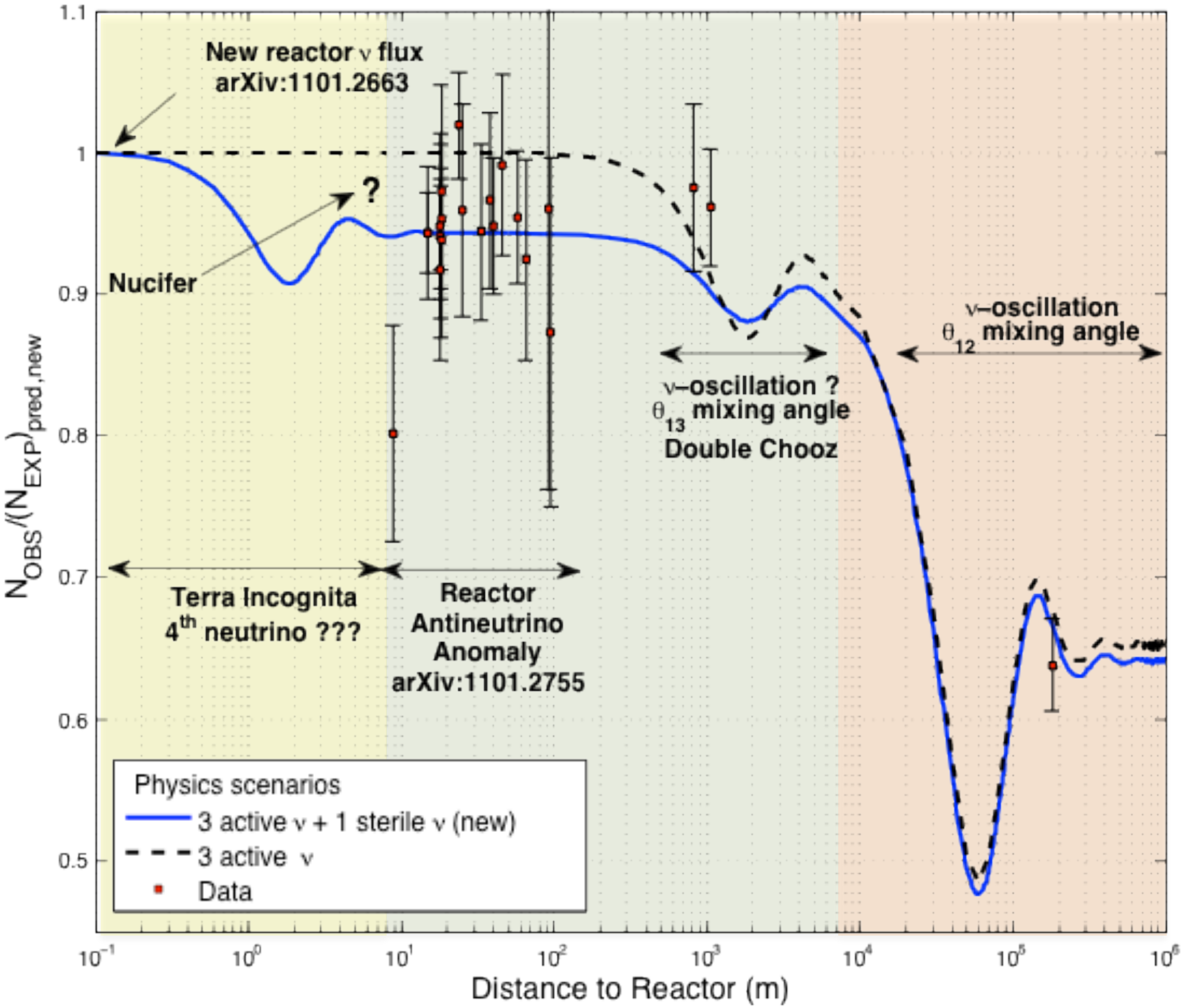
SSeM predictions agree with all the neutrino detections but not the SSM predictions

	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 10^9cm^{-2}s^{-1}**
Standard model		
Seismic model	4.72 10^9cm^{-2}s^{-1}	**3.045 ± 0.35 10^9cm^{-2}s^{-1}**

Water detectors	Predictions or Detections B^8 electronic neutrino flux
SNO	**5.045 ± 0.13 (stat)± 0.13 (syst) 10^6cm^{-2}s^{-1}**
SNO +SK	**5.27 ± 0.27 (stat)± 0.38 (syst) 10^6cm^{-2}s^{-1}**
Standard model 2009	4.21 ± 1.2 10^6cm^{-2}s^{-1}
Seismic model	**5.31 ± 0.6 10^6cm^{-2}s^{-1}**

Turck-Chièze and Couvidat, 2011 Report in progress in Physics, 74

Could sterile neutrinos be forgotten ?



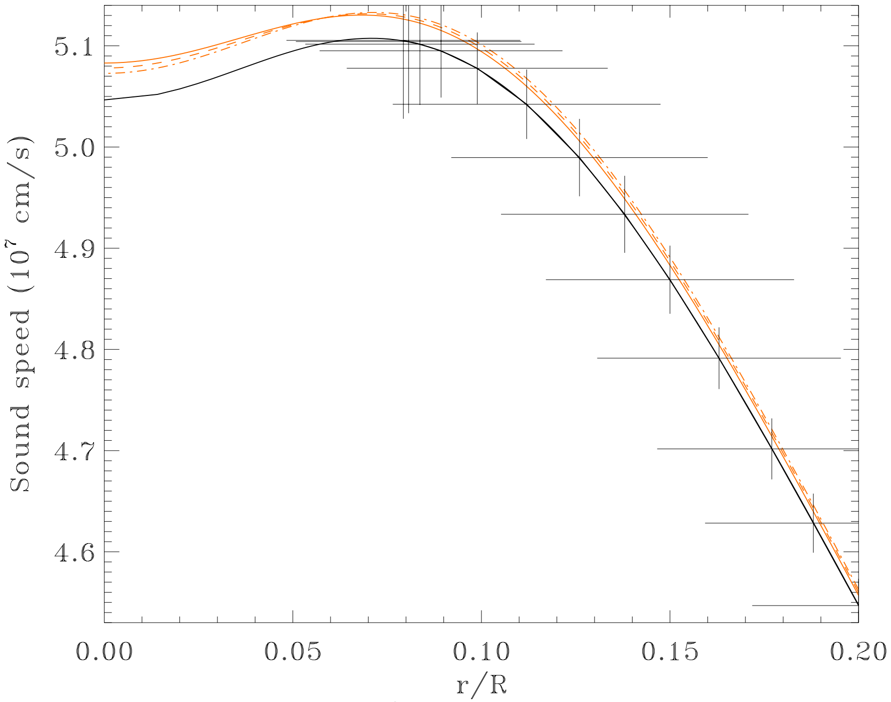
Mueller et al. 2011

It could be possible

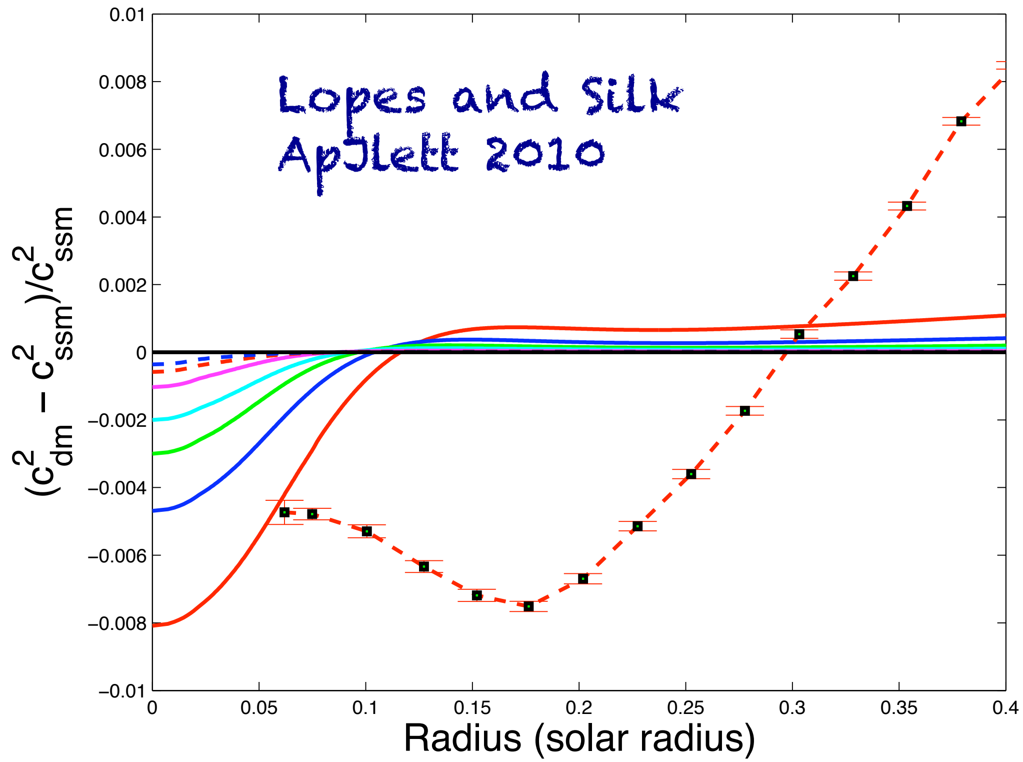
Effect of about 7%
(inside the error bar of today predictions)

But their mass could be extremely small

But the real center is not really explored by acoustic modes



Vertical error bars * 100
Still large horizontal error bars
In black is the seismic model, in red the SSM



Turck-Chièze, Piau and Couvidat, 2011, ApJlett, 731 L 29

One has noticed that the central temperature of SSeM is greater than the central temperature of the SSM

Year	Boron flux	T_c	Y_0	Problem solved
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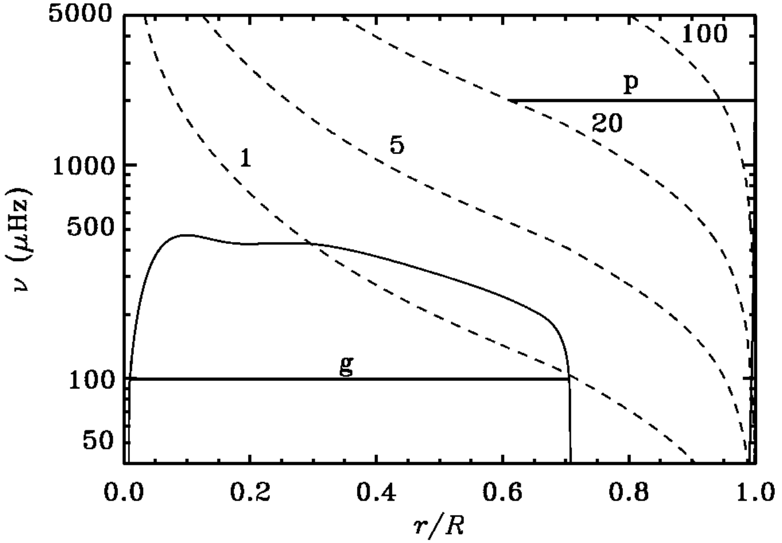
S[illegible]O results[illegible].27 ± 0.27 ± 0.38 (2004)

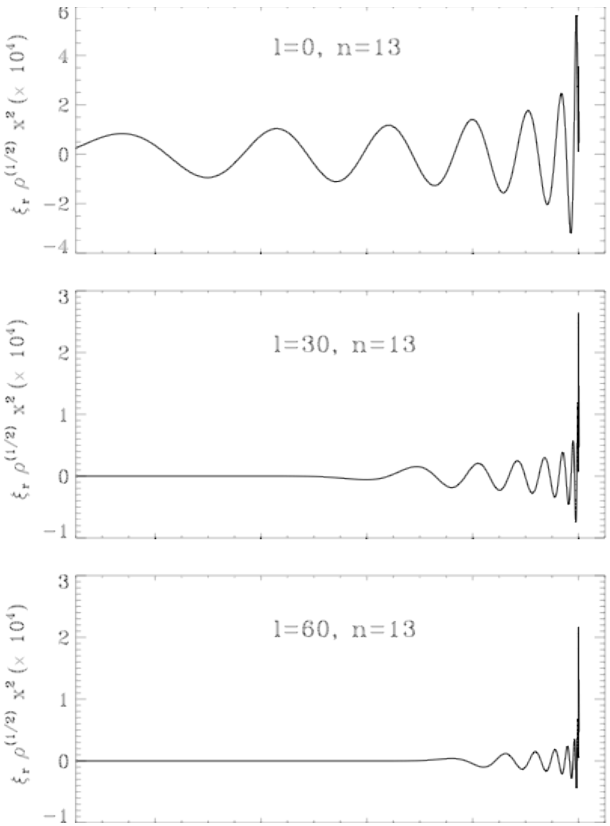
Can we confirm the sound speed profile near the center and the supposed increase of the temperature thanks to gravity modes?

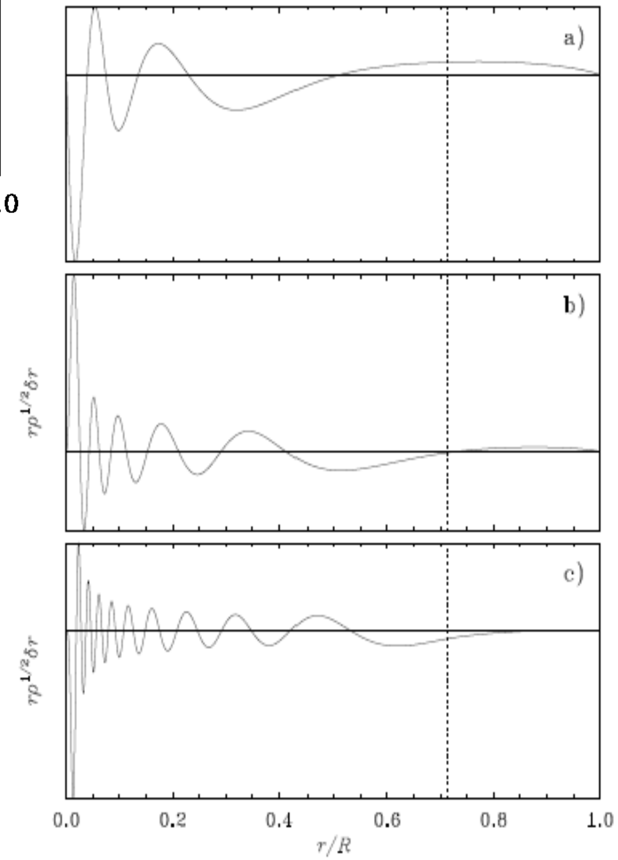
- **The gravity modes: a good test of the central density**

GOLF french-spanish instrument aboard SOHO
Global Oscillations at low frequency

Sensitivity of the modes





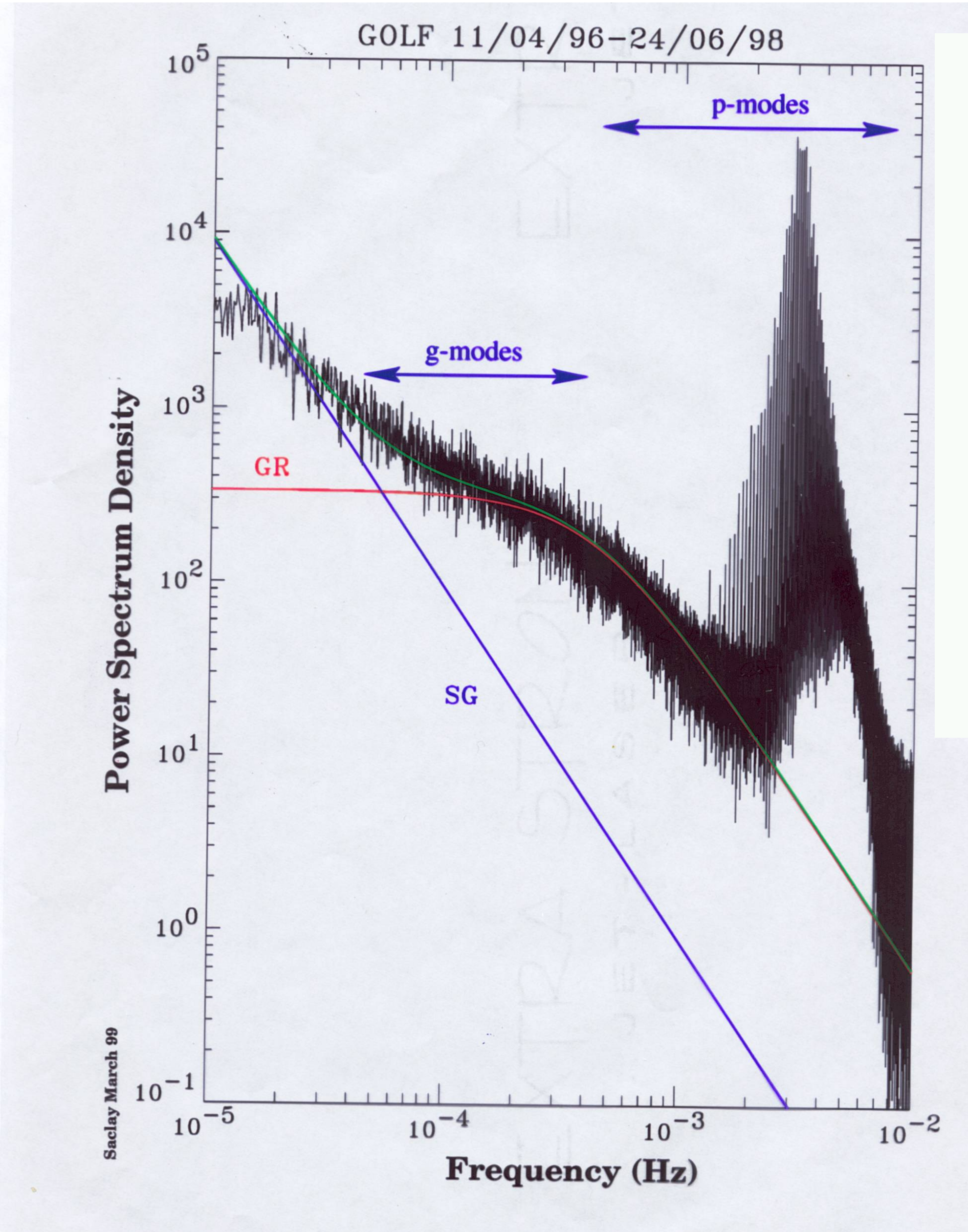


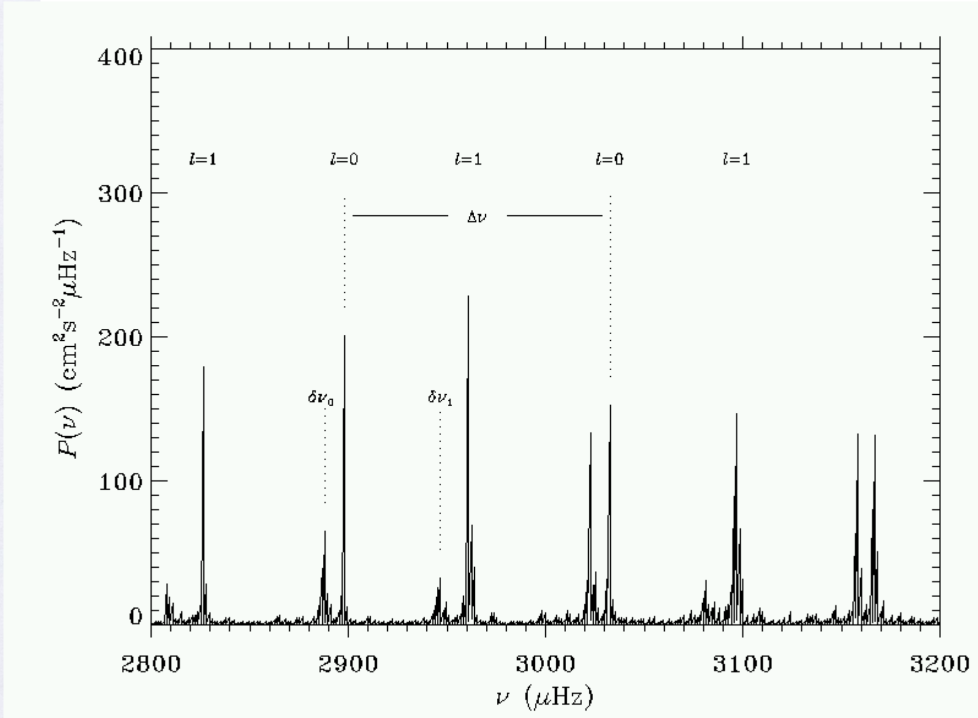
$$N^2 = \frac{g^2 \rho}{p}\left(\nabla_{\mathbf{ad}} - \nabla + \nabla_{\mu}\right)$$

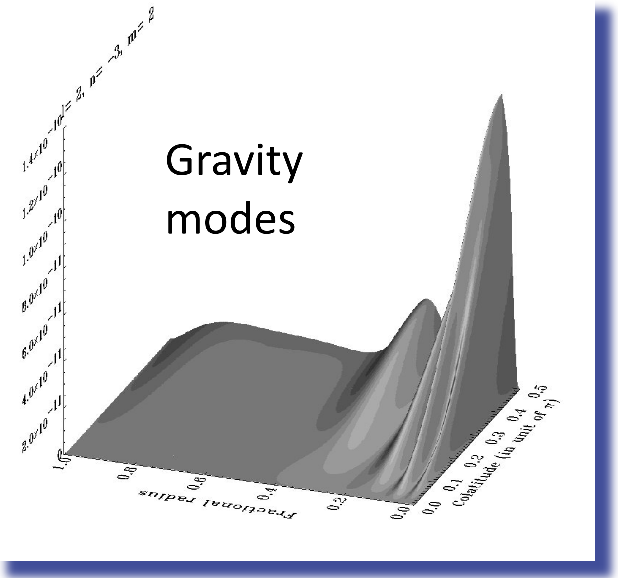
$$S_l^2 = L^2 c_s^2 / r^2$$

$\omega^2 > S_l^2, N^2$ **p modes**

$\omega^2 < S_l^2, N^2$ **g modes**

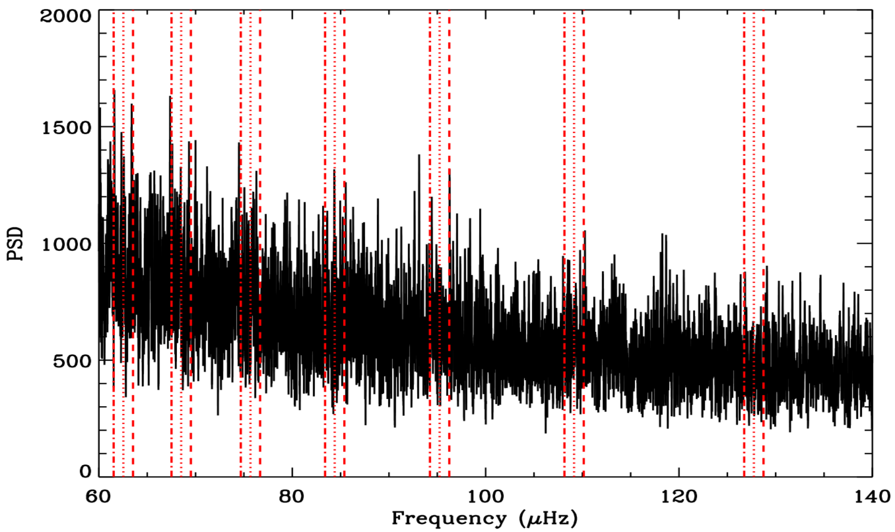

GOLF 11/04/96–24/06/98
p-modes
g-modes
GR
SG
Power Spectrum Density
Frequency (Hz)
Saclay March 99

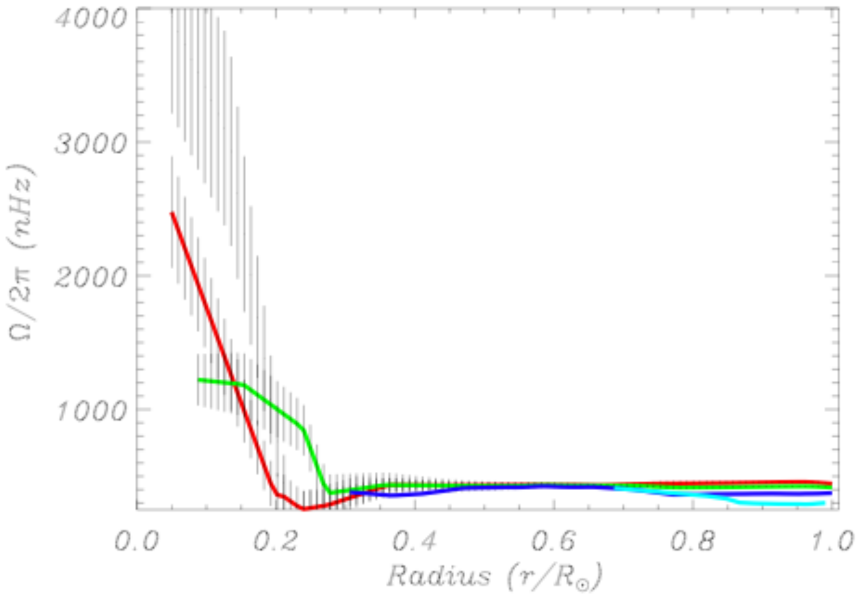

l=1
l=0
l=1
l=0
l=1
Δν
δν0
δν1
P(ν) (cm²s⁻²μHz⁻¹)
ν (μHz)


Gravity modes
Fractional radius
Colatitude (in unit of π)

Dipolar gravity modes integrated on more than 10 years: m=±1

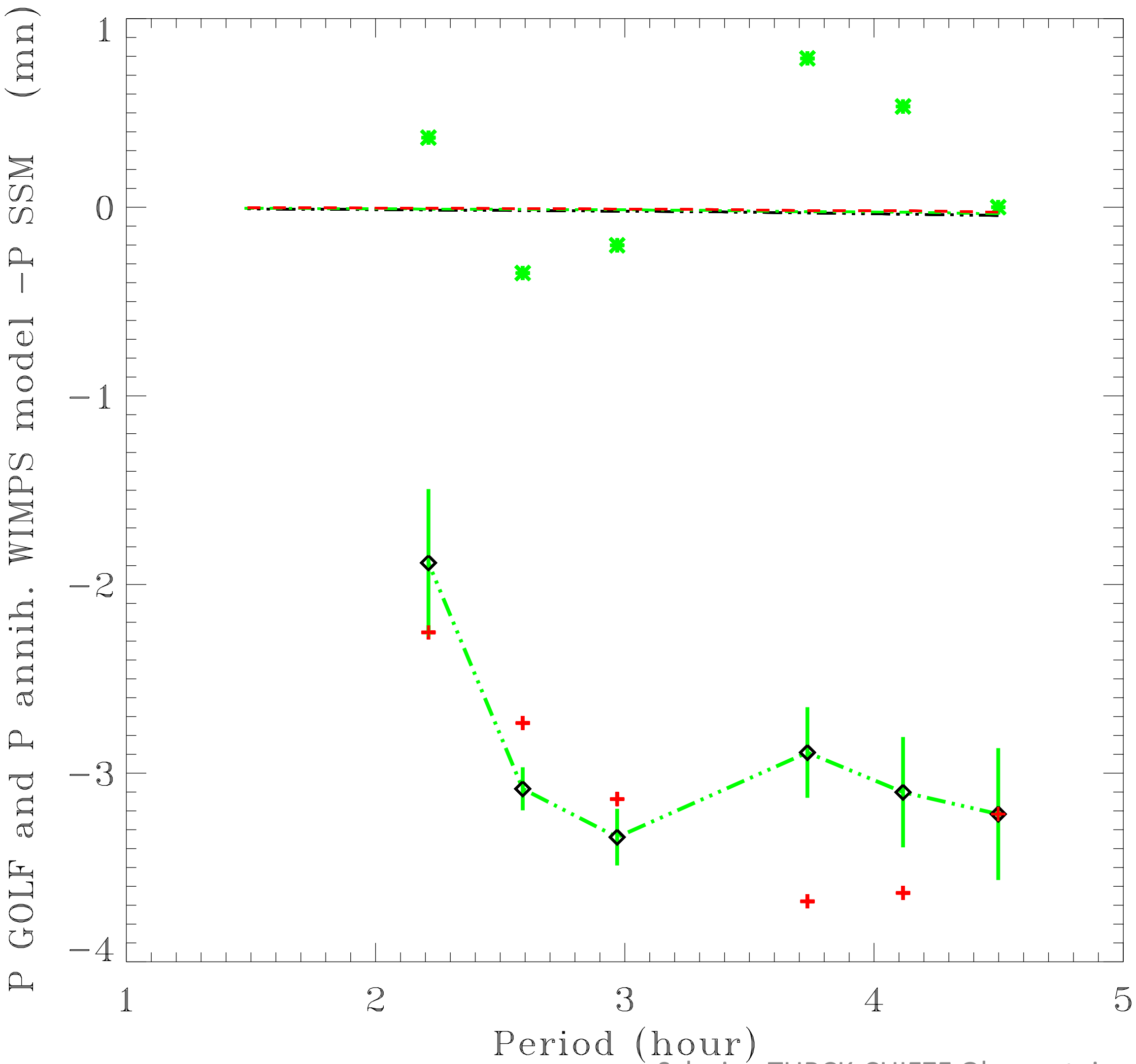
Garcia et al. 2007, Turck-Chièze et al. 2010, Garcia et al. 2011





6 detected modes in integrating the signal on at least 10 years: velocity of several mm/s

Comparison of model predictions and GOLF observations



Comparison of SSM, SSeM and GOLF periods

The solar gravity mode periods are very near from the values of the seismic model

Density of the seismic model: 153.6 g/cm^3

The WIMPs properties constrained by Sun observations

Cox, Guzik and Raby, 1990, Giraud-Herraud..Turck-Chièze et al. 1990, Dearborn, Griest and Raffelt, 1991, Kaplan ... T-C et al. 1991

Lopes and Silk, 2010, ApJ, 722, L95 and Science;
Taoso et al. 2010, ApJ;
Turck-Chièze, Garcia, Lopes, Silk et al. 2011, ApJlett submitted

$$\frac{dN_X}{dt} = C - 2AN_X^2 - EN_X$$

$$C = \sum_i 4\pi \int_0^R r^2 \frac{dC_i}{dV} dr$$

$$\frac{dC_i}{dV} \propto \sigma_{X,Ni} \frac{\rho_i}{M_i}(r) \frac{\rho_X}{M_X} \frac{v^2}{\bar{v}^2}$$

$$A = \int_0^R \varepsilon_{ann} r^2 4\pi\rho(r) dr$$

C: Capture rate A: annihilation rate, E: evaporation rate, this last term is negligible above 4 GeV

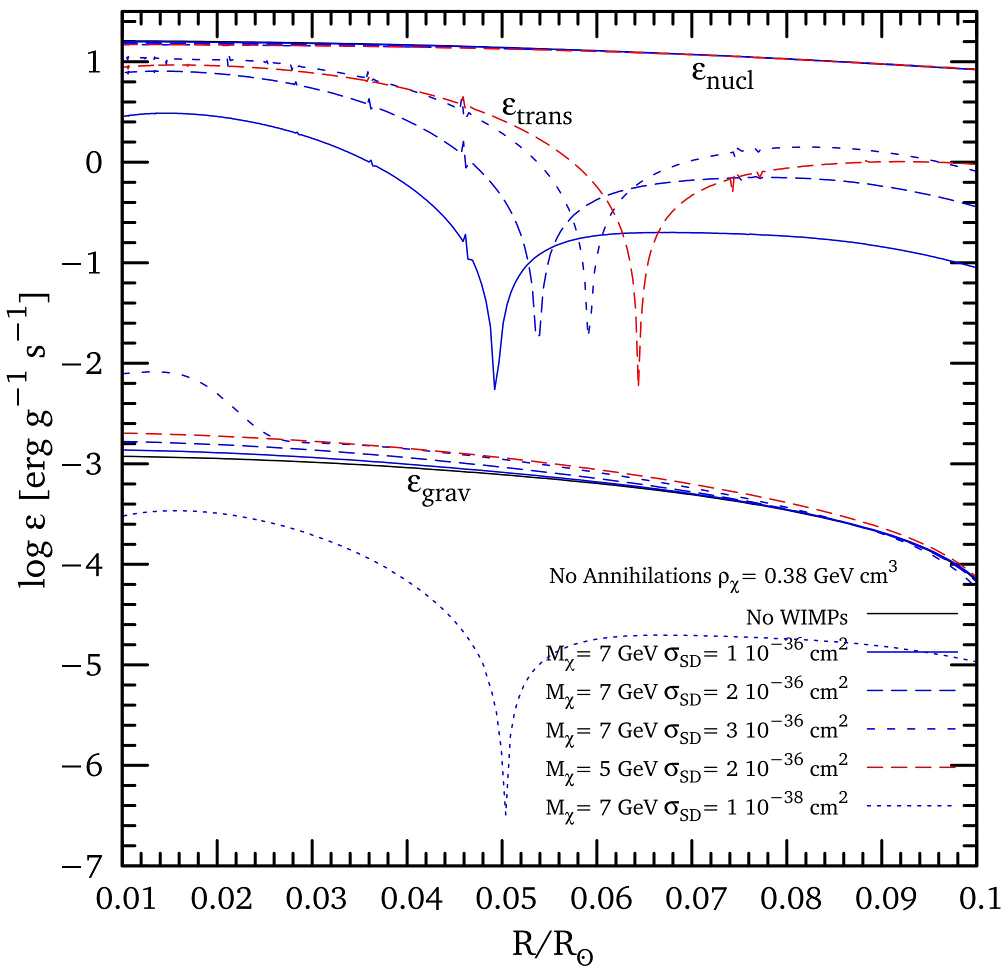
WIMPs thermalize inside the Sun within typically 1 day for a mass of 10 GeV ; $\bar{v}^2$ = 270 km/s

Rapid equilibrium between capture and annihilation

Negligible evaporation

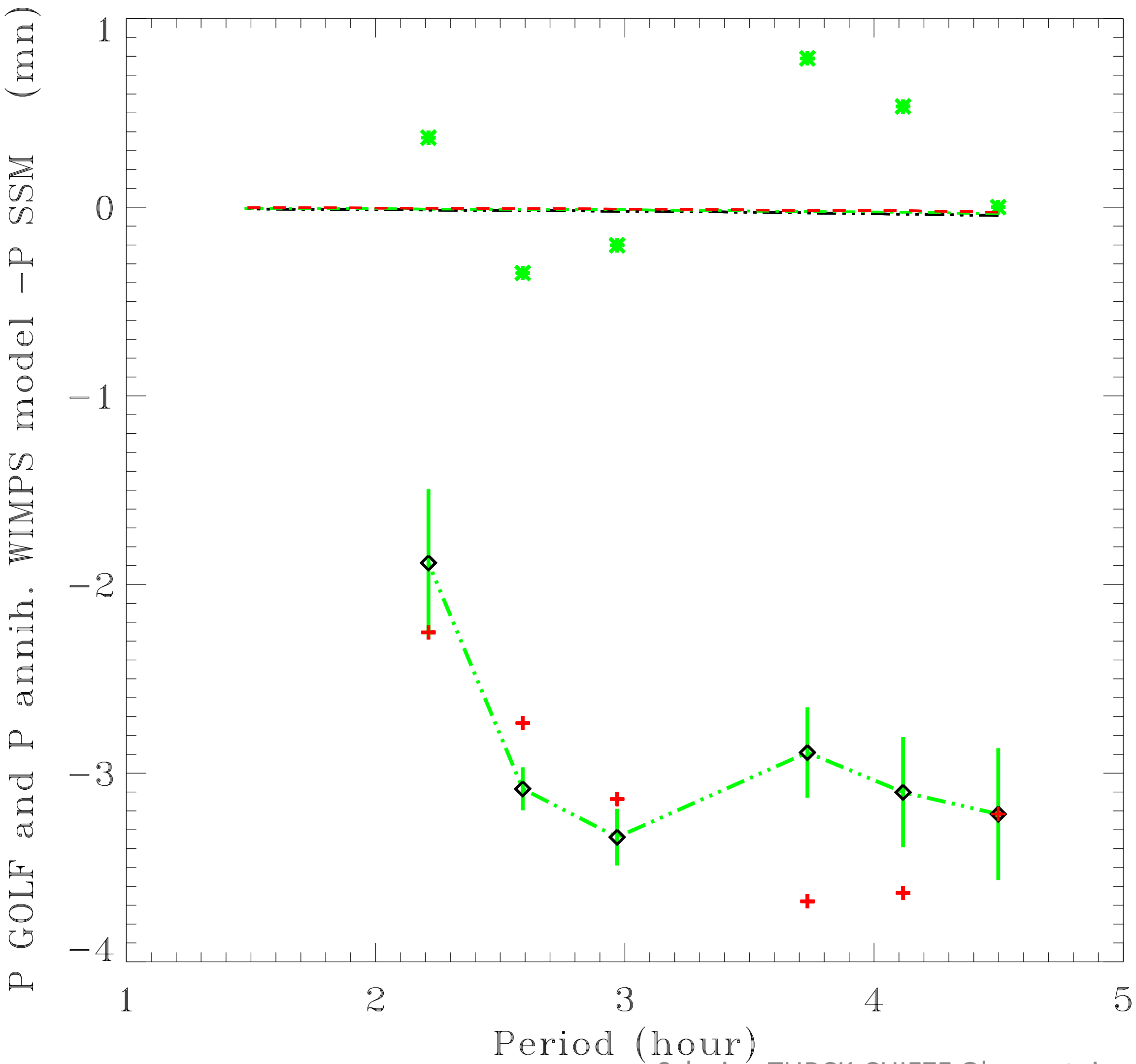
$$\varepsilon_{trans} = \frac{1}{\rho(r)} \frac{d}{dr} \left[f(r) h(r) K(r) N_X(r) l(r) \left(\frac{kT_X(r)}{M_X} \right)^{1/2} k \frac{dT_X(r)}{dr} \right]$$

Gould and Raffelt, 1990



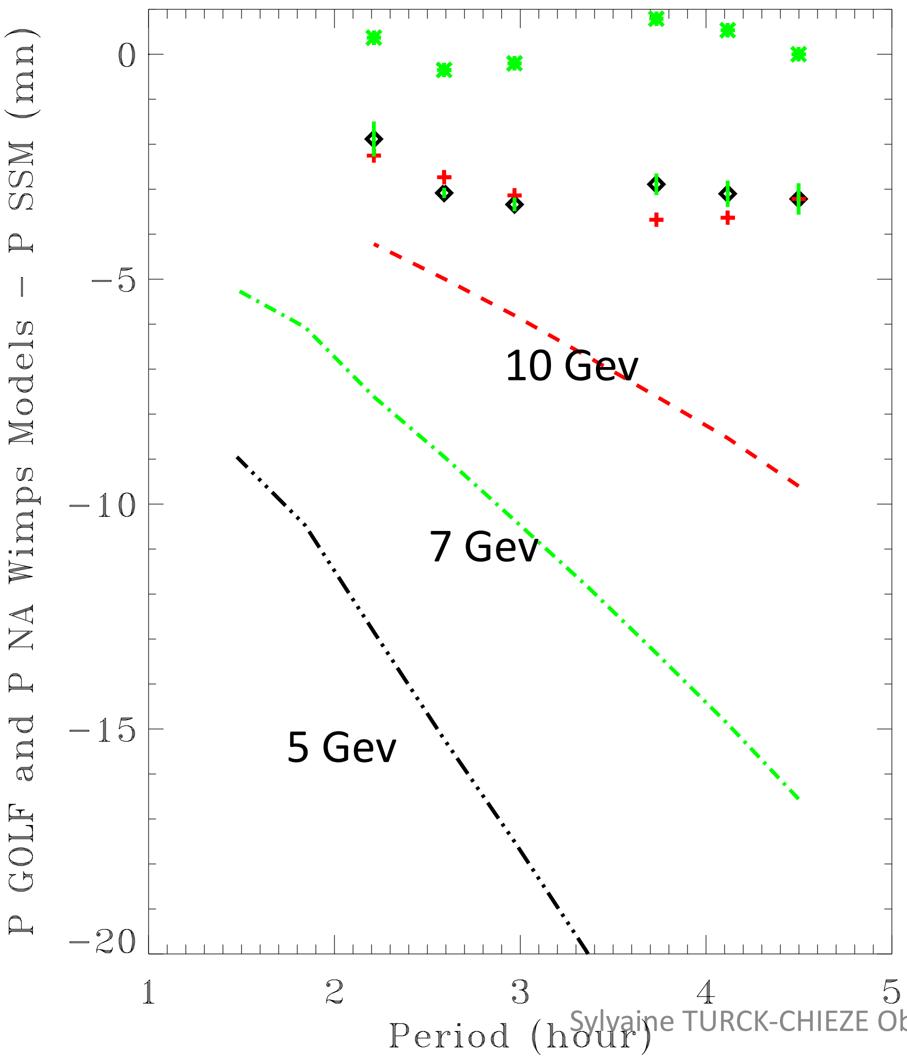
Taoso et al. 2010, ApJ

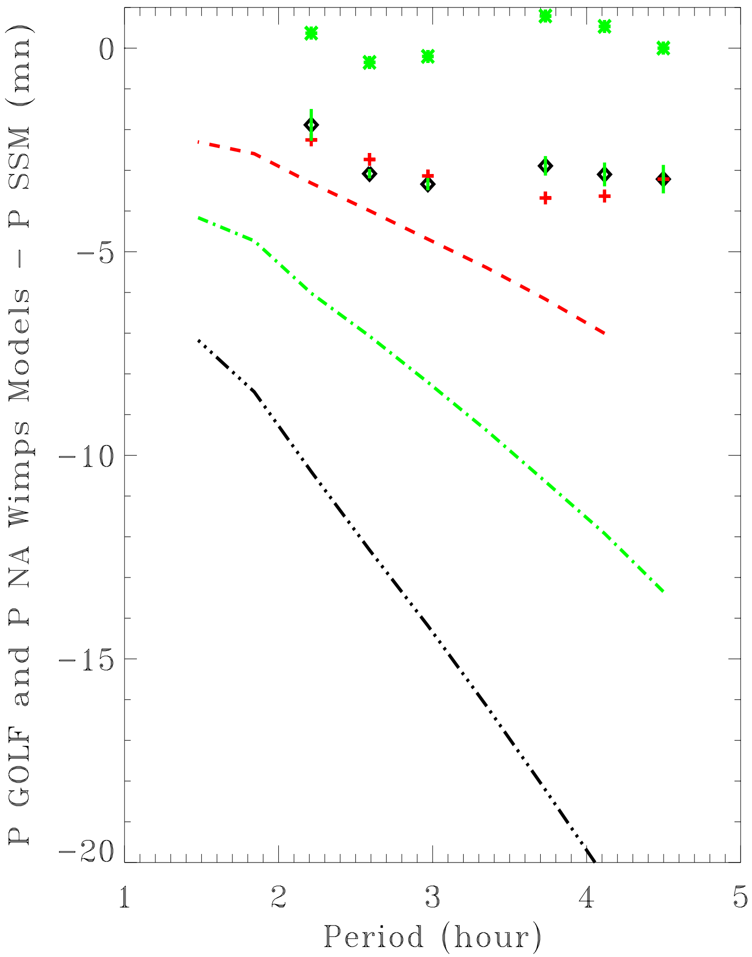
Annihilation: $\sigma_{ann} = 10^{-27} cm^2$



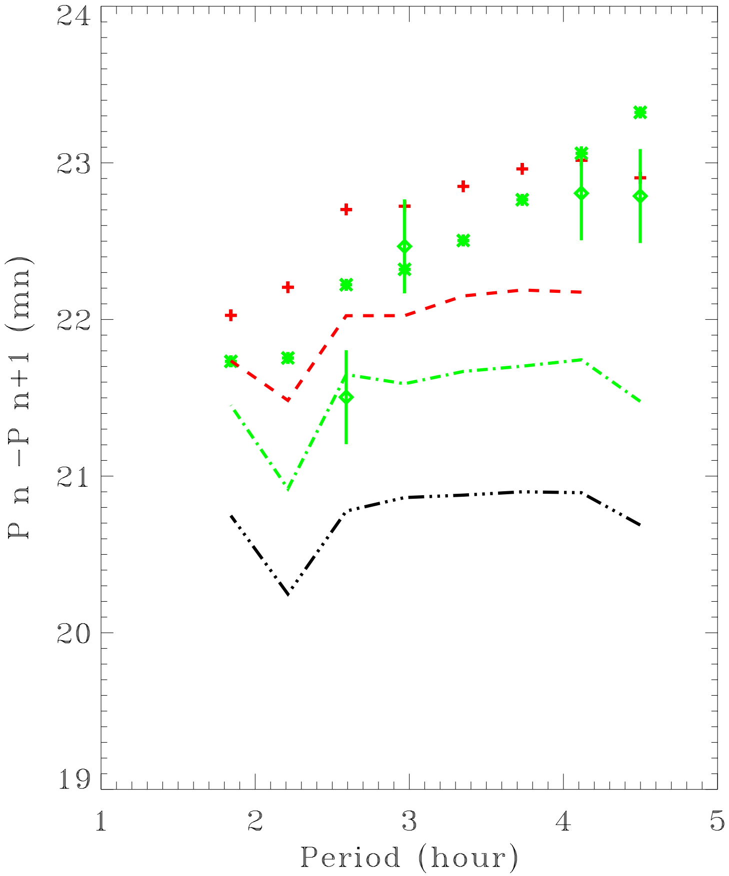
$$A = \int_0^R \varepsilon_{ann} r^2 4\pi\rho(r) dr$$

Σ_{ann} of 10^{-50} cm^2 σ_{SD}=7 to 5 10^{-36} cm^2 σ_{SI}= 10^{-40} cm^2





Equidistance between periods

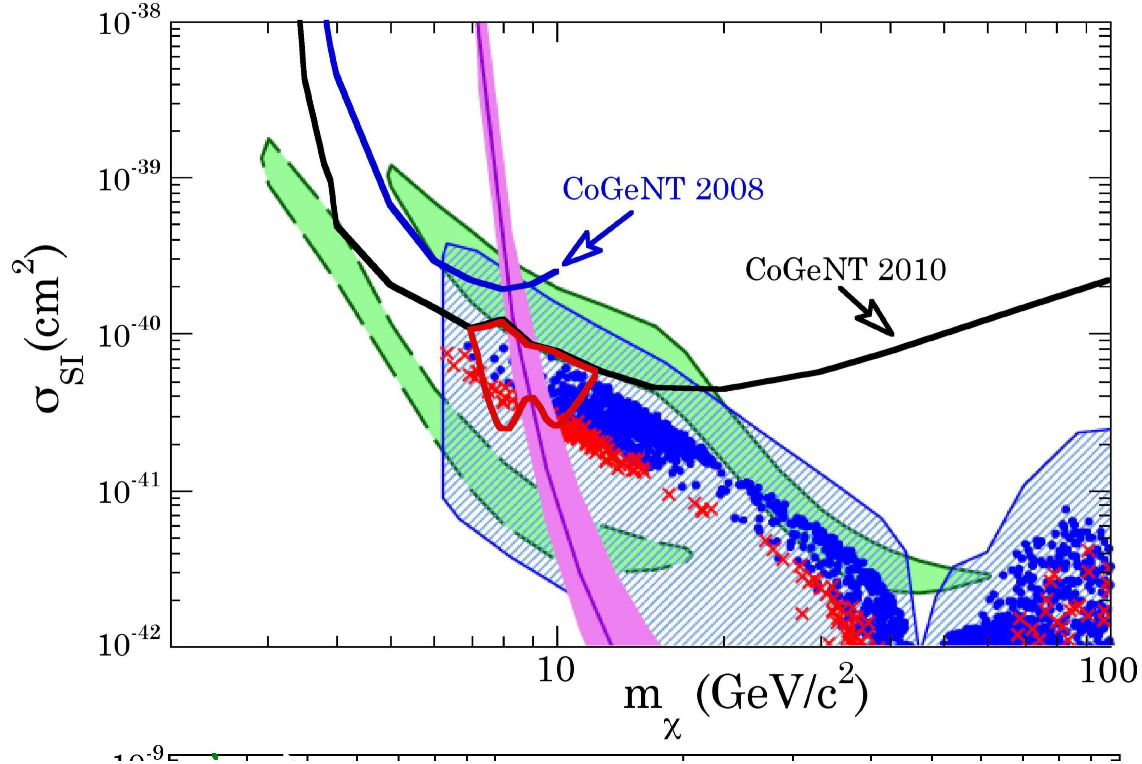


$$\Delta P = P_{n+1} - P_n \approx \frac{P_0}{\sqrt{2}}$$

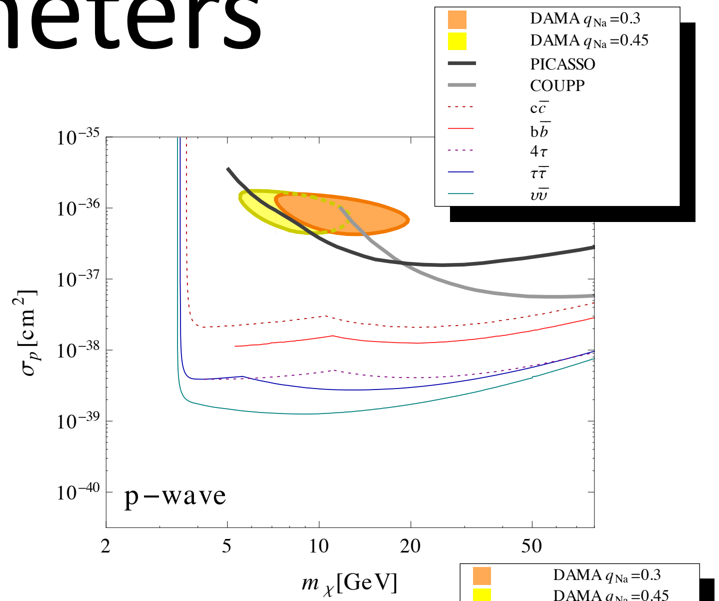
$$P_0 = 2\pi^2 \left[\int_0^R \frac{|N|}{r} dr \right]^{-1}$$

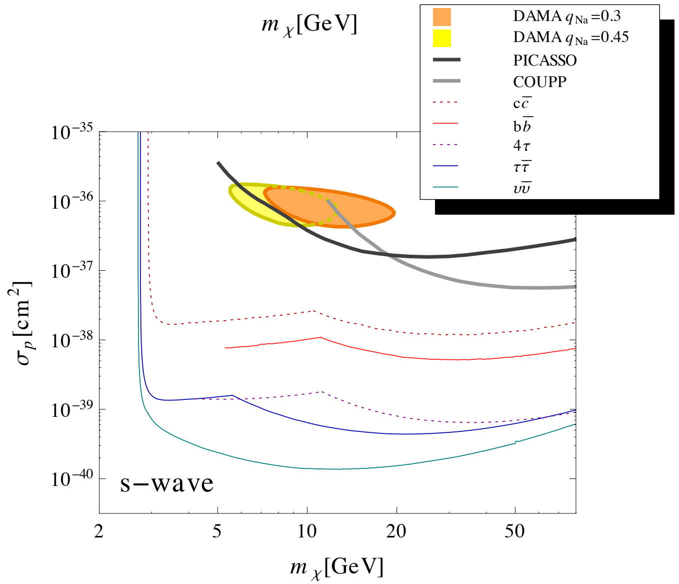
$$N^2 = g\left[\frac{1}{\Gamma_1} \left(\frac{d}{dr} \log P(r) - \frac{d}{dr} \log \rho(r) \right) \right]$$

Domain of parameters



Kappl and Winkler, 2011, Nucl. Phys B



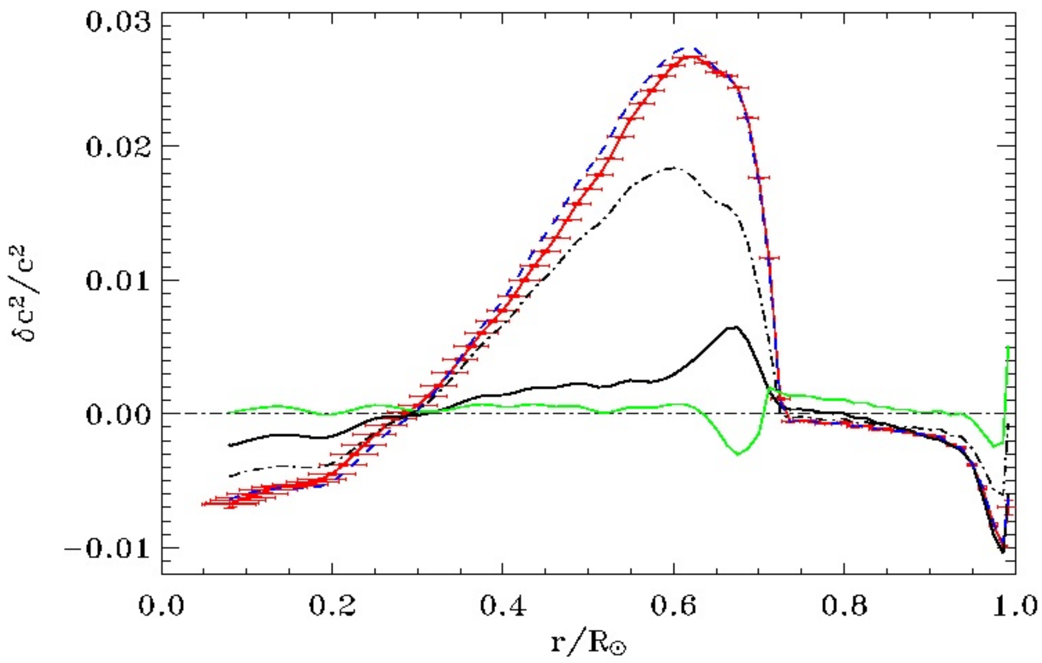


CONCLUSION

- The core of the Sun is now scrutinized with both neutrinos and gravity modes
- We do not see significant evidence for dark matter through WIMPs interaction, if we would like to say something on sterile neutrinos, one needs to reduce the predicted fluxes below 5%, this could be possible
- We can already put some limits on properties of WIMPs

$M_X > 10$ Gev and $\sigma_{SD} < 5\ 10^{-36}$ cm^2

Interpretation of the present discrepancies



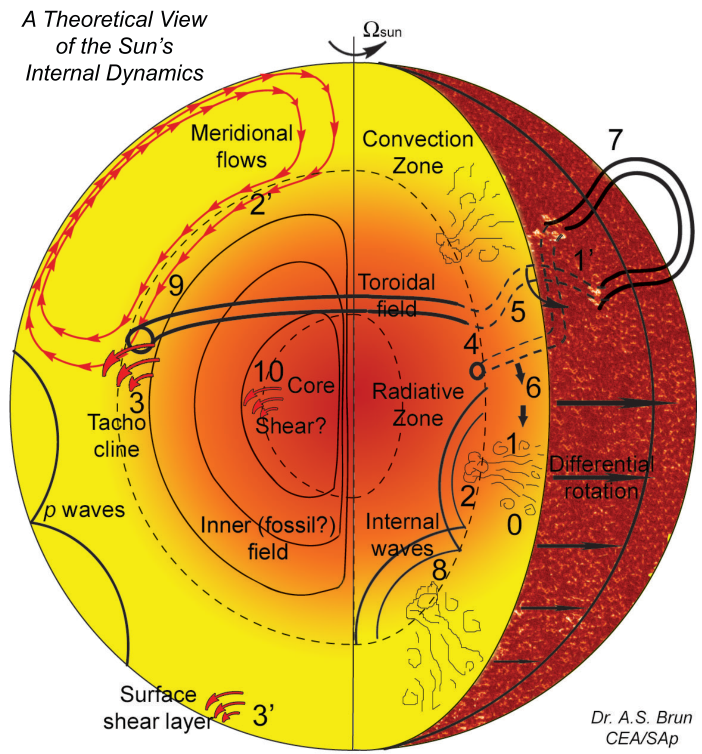


Figure Caption:
0: Turbulent convection (plumes); 1: Generation/self-induction of B field ("alpha-effect") or 1': Tilt of active region, source of B poloidal; 2: Turbulent pumping of B field in tachocline or 2': Transport of B field by meridional flows from CZ into tachocline; 3: Field ordering into toroidal structures by large scale (radial and latitudinal) shear in tachocline ("omega-effect"); 3': Surface shear layer, Sub surface weather (SSW), surface dynamics of sun spot?; 4: Toroidal field becomes unstable to m=1 or 2 longitudinal instability (Parker's); 5: Rise (lift) + rotation (tilt) of twisted toroidal structures; 6: Recycling of weak field in CZ or; 7: Emergence of bipolar structures at the surface; 8: Internal waves propagating in RZ and possibly extracting angular momentum; 9: Interaction between dynamo induced field and inner (fossil?) field in the tachocline along with shear, turbulence, waves, etc...
10: Instability of inner field (stable configuration?) + shearing via omega-effect at nuclear core edge?
Is there a dynamo loop realized in RZ?

More than 1000 stars are now studied through asteroseismology, so one may find different cases to look for dark matter…