SOLAR NEUTRINOS AND HELIOSEISMOLOGY

Bases of the stellar evolution concepts: 1st part of the XX century

Role of B. Pontecorvo 1957, 1967: Majorana? Flavour, Oscillations

1962: 1st seismic observations –1970: understood 1995 space helioseismology

1968: 1st solar neutrinos by Homestake then Gallex, Sage, SK,SNO, Borexino…

1970-2000: Improvements of the physics of the SSM

1995: Launch of SoHO which continues to observe the Sun (18 yrs!) up to 2016

2001-2011: Confrontation Seismic results- SNO neutrinos: role of SSeM

2008: Space asteroseismology: generalization to other stars

2010-…Building of the dynamical solar model DSM

2010-… Solar neutrinos detection for solar and stellar Physics

2013-… New neutrino properties from this field ???….

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- The joined effort from Solar Standard Model, neutrino detections and seismology: results, accuracy, questions

- The development of precise neutrino detections, laser facilities and accelerators to build the DSM: Dynamical Solar Model

Review papers

- Turck-Chièze, S., Cahen, S. & Cassé, M, 1988, ApJ, 335, 415
  Revisiting the standard solar model

- Turck-Chièze, S., Däppen, W, Fossat, E., Provost, J., Schatzman, E. & Vignaud, D., 1993, Phys. Report, 230, 57
  The solar interior

- Turck-Chièze, S. & Couvidat, S., 2011, Report Prog. Phys., 74, 86901
  Solar neutrinos, helioseismology and the solar internal dynamics

- Turck-Chièze, S. & Lopes, I., 2012, Rev Astron. Astrophys., 12, 1107
  Solar and stellar astrophysics and dark matter

Hypotheses, building and accuracy of the SSM

From Turck-Chièze et al. ApJ 1988

TABLE 8

NEUTRINO CAPTURE RATES AND UNCERTAINTIES

Uncertainties Sources (p_j)	Uncertainty (1 σ error)	$\frac{\partial \ln \phi_{pp}}{\partial p_j}$	$\frac{\partial \ln \phi_{^8B}}{\partial p_j}$	Neutrino Capture Rate (SNU): ^{71}Ga: 125 ± 5 — ^{71}Ga Detector	^{37}Cl: 5.8 ± 1.3 — ^{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%
σ_{abs}	...	...	...	2.5%	4%
Total uncertainty				4.2%	22%

No oscillation of neutrinos

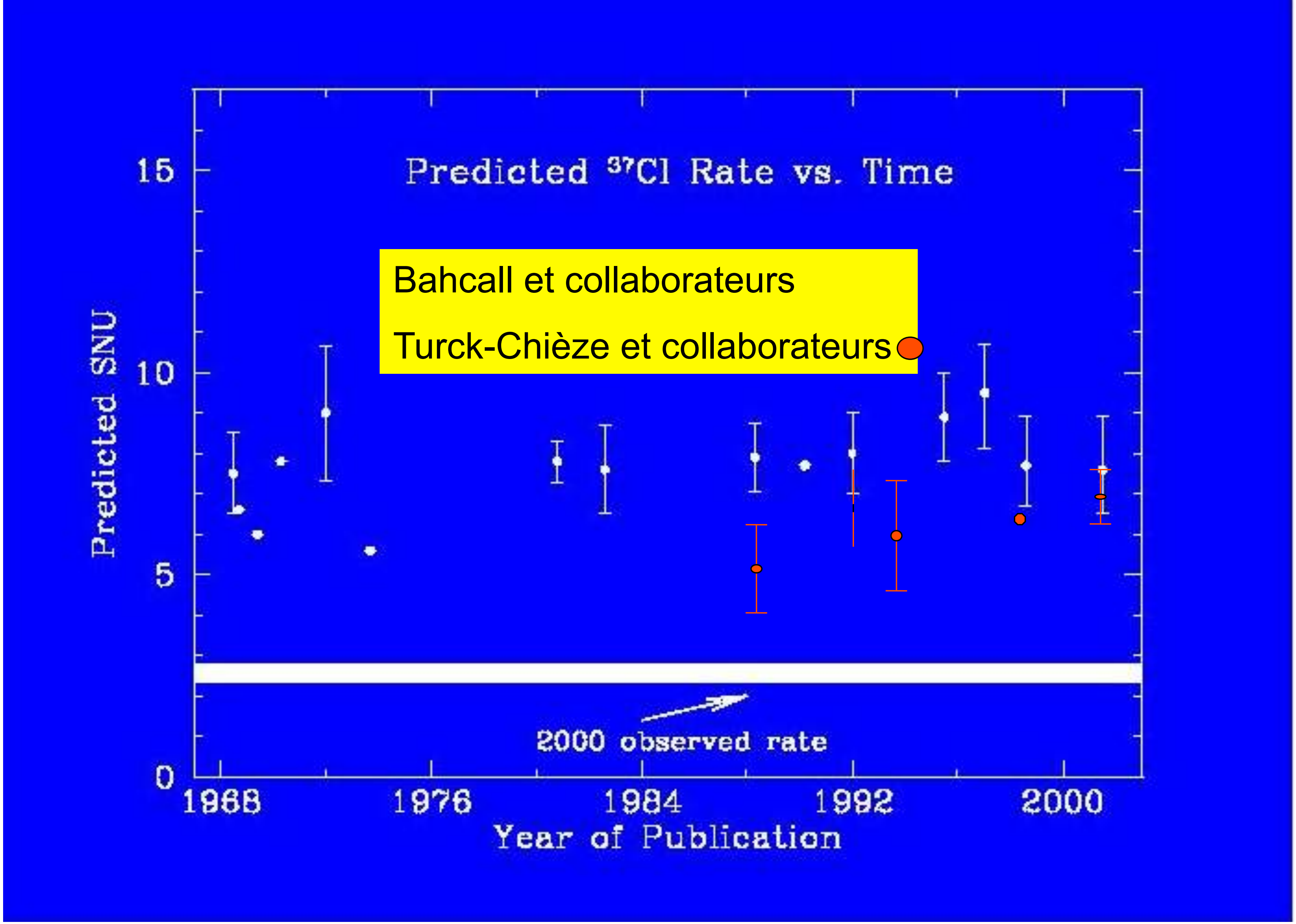
B.Pontecorvo waiting the first gallium results in 1992: small uncertainty as pp flux is directly connected to the solar luminosity

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

SNO + Super Kamiokande: 5.27 ± 0.27 ±0.38 10^{6} cm^{-2} s^{-1}

Are the hypotheses of the SSM correct ??

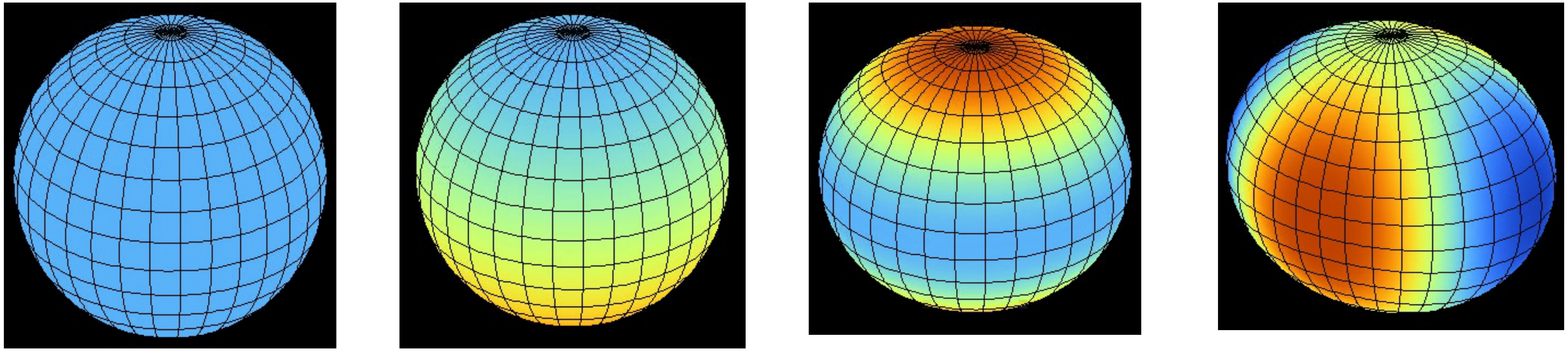


Neutrino predictions depend on the state of art of the microscopic physics of the SSM.

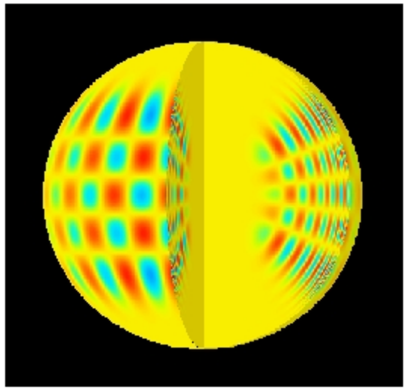
The joined effort from neutrino detections and seismology: results, accuracy, questions

Sun: globally and locally => millions of modes

Other stars : globally only about one hundred modes



ℓ= 0 ℓ =1 ℓ =2



1D and 2D sound speed and rotation inversions

Methods:

-variability of the radial velocity: SoHO, SDO and ground asteroseismology

-variability of the stellar photometry: COROT, KEPLER, PICARD

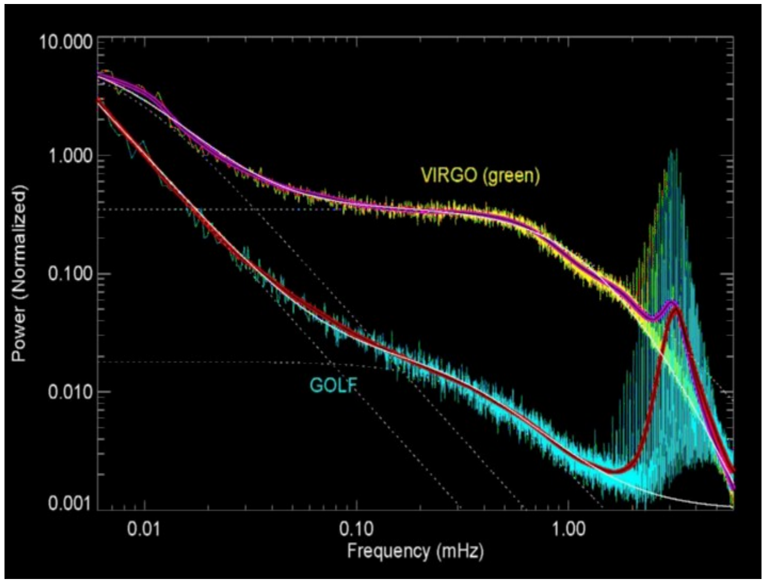
Photospheric helium: 0.25 in mass fraction which checks the microscopic diffusion for that element and BZC: 0.713 R_{sol}

Solar Space SoHO / MDI + GOLF oscillations

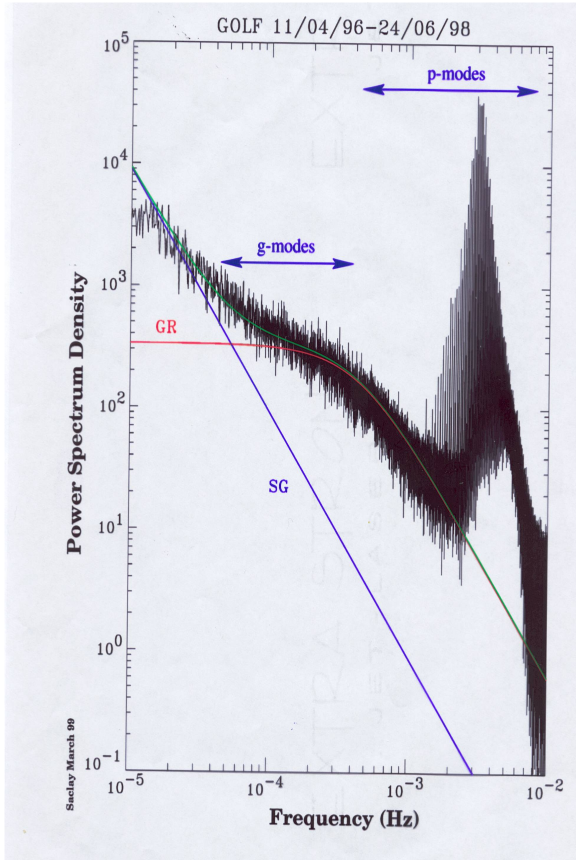
Turck-Chièze & Couvidat ROP 2011, Turck-Chièze & Lopes RAA 2012

and included references

The GOLF instrument: IAS/CEA/IAC collaboration Gabriel et al. 1995

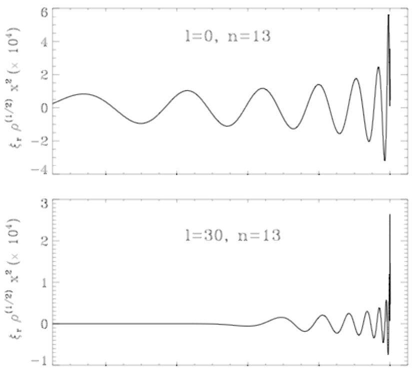


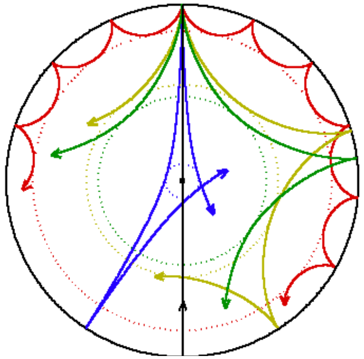
The performances of GOLF allow to detect low frequency acoustic modes that penetrate in the core and first gravity modes by contrast to high frequency acoustic modes that are sensitive to the solar activity

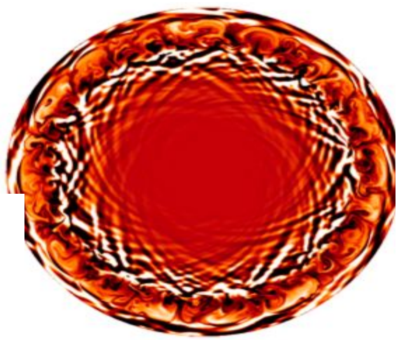


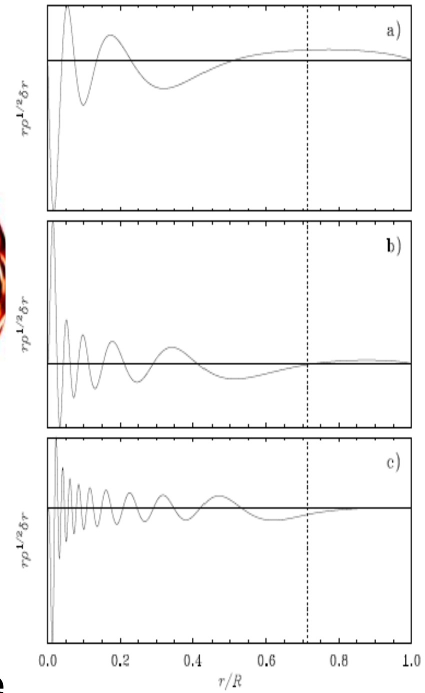
The modes are characterized by 3 numbers:

Ulrich 1971, Leibacher & Stein 1972









degree l, order n,
azimutal order m:
degeneracy of the mode in 2l+1components:
Information on rotation and magnetic field

Acoustic modes

Gravity mode

Acoustic frequencies (l,n) allow to extract the solar sound speed and density

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

Gravity and acoustic modes splittings (m) allow also to extract solar rotation and magnetic field (??)

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

The sound speed profile is strongly sensitive to main reaction rates

Turck-Chièze et al. Sol.Phys. 1997, Turck-Chièze et al., 2001
Turck-Chièze, Piau, Couvidat ApJ lett. 2010

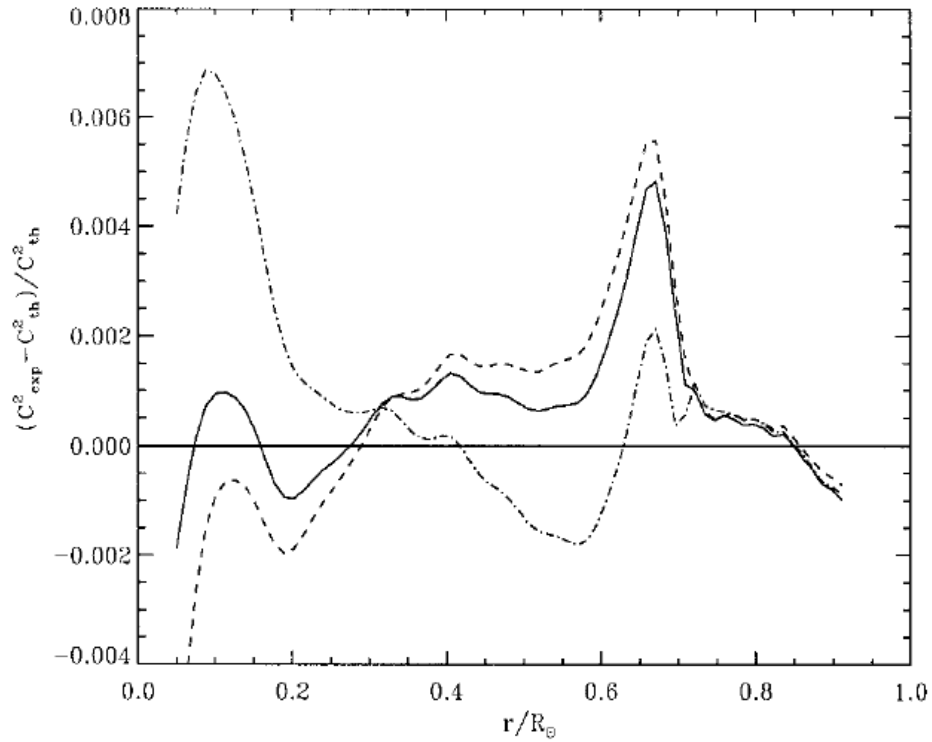
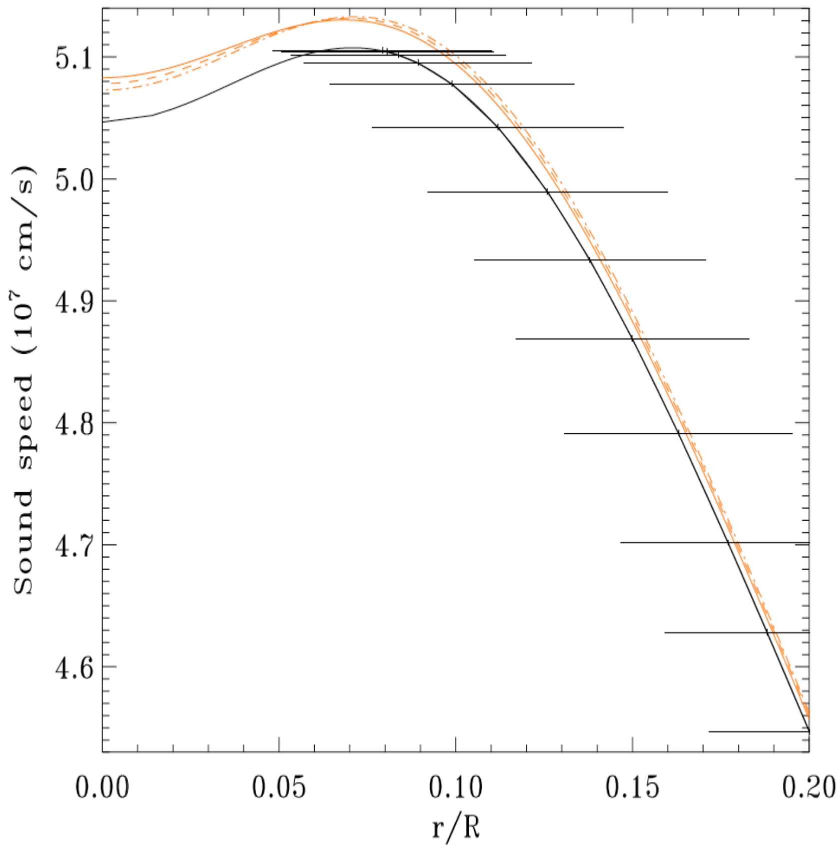


Figure 10. Sound-speed difference between the Sun (GOLF + LOWL acoustic mode frequencies) and different solar models: continuous line for the reference model of Brun *et al*. (1997), — · — · — idem with pp reaction rate modified by +5%; — — — idem with the reaction rate (^{3}He, ^{4}He) reduced by 30%.



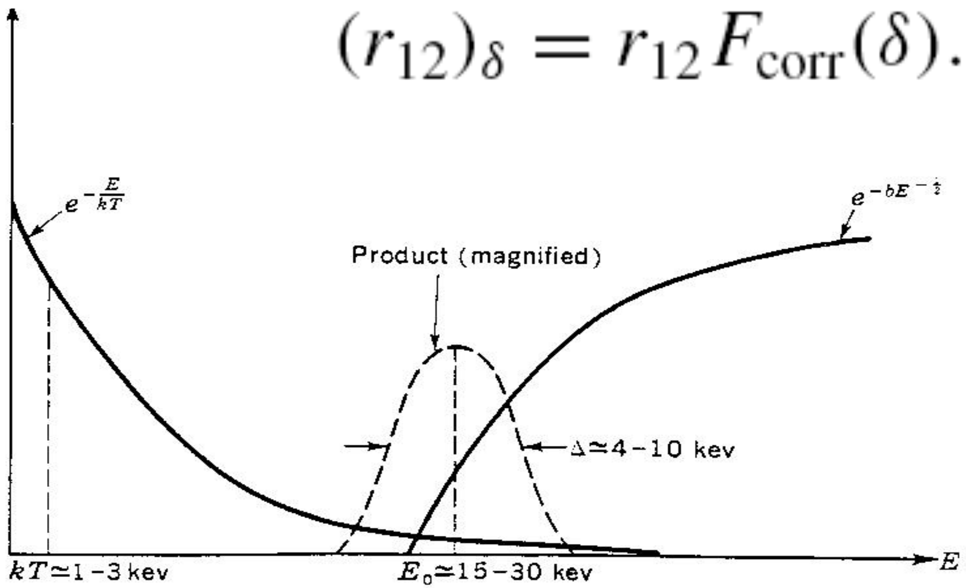
Accuracy sound speed: 3 10^{-4} at 0.08 R $_{sol}$

See all the values in T-C et al. 2001
Turck-Chièze & Lopes 2012 RAA

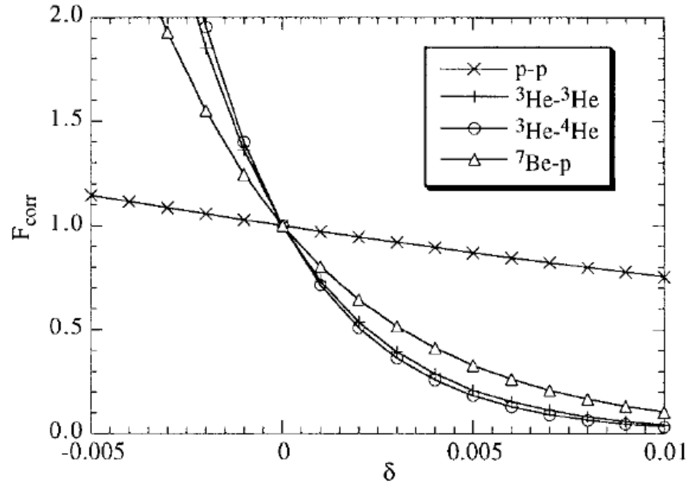
The seismic results have allowed to check the maxwellian distribution of reactant velocities

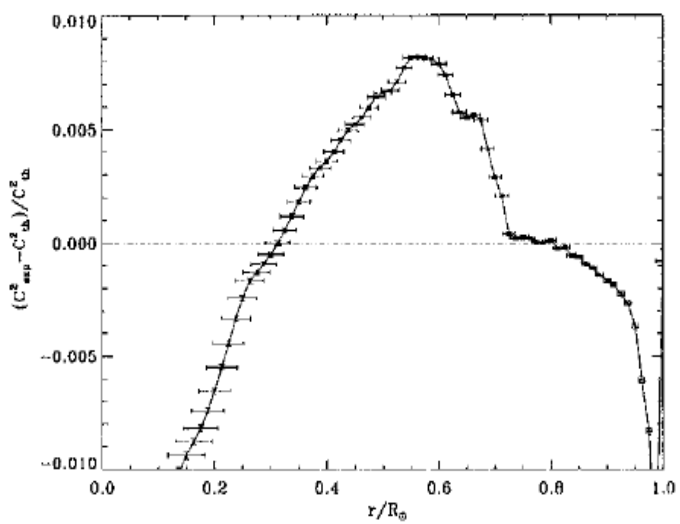
$$r_{12} \sim \int S(E)\exp(-E/kT - b/\sqrt{E})\mathrm{d}E,$$

$$(r_{12})_\delta = r_{12} F_{\mathrm{corr}}(\delta).$$



$E_0 = [\mathrm{b\ kT}/2]^{2/3}$ $E_0 = 1.220\ (Z_1^2 Z_2^2\ \mathrm{A} T_6^2)^{1/3}$ keV

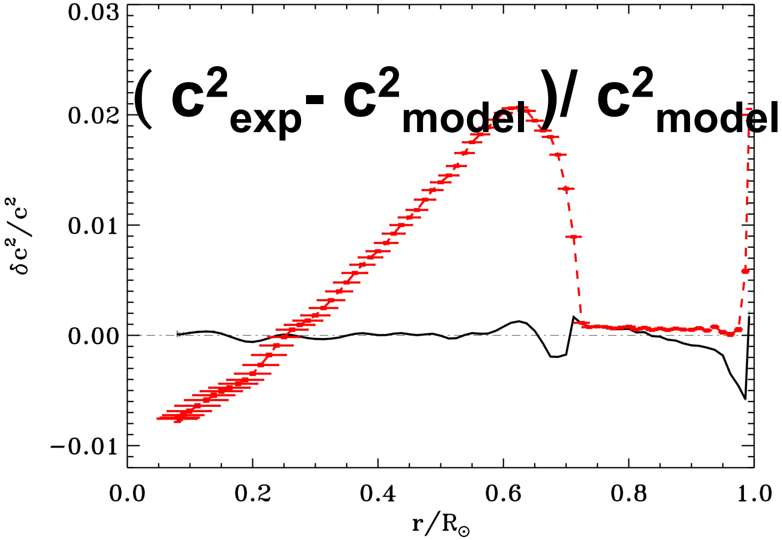




Turck-Chièze, Nghiem, Couvidat, Turcotte,

Sol. Phys., 200, 323 (2001)

Since 2001, SSeM uses the sound speed profile from surface down to the core to stabilize the neutrino predictions contrary to SSM

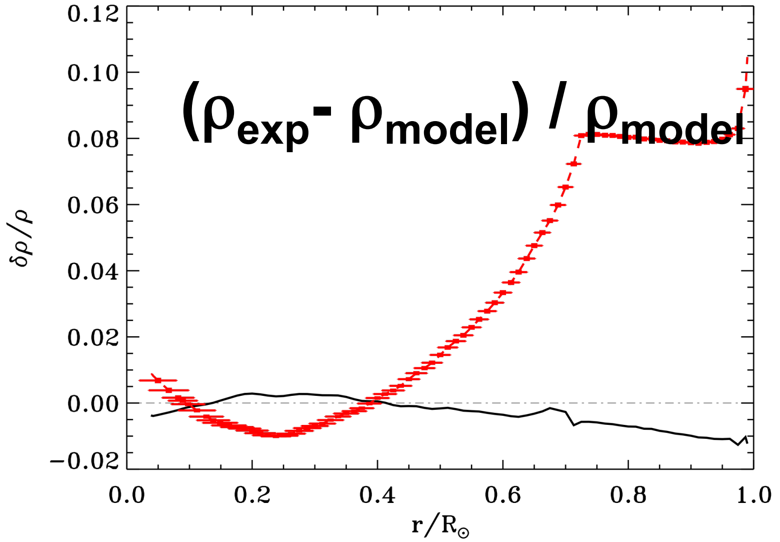


The differences between **SSM** with Asplund et al. composition (2009), the reduction with new CNO composition and observations appear in red.

These differences are extremely large in comparison with the observed error bars

problem in the thermodynamic physics

of the internal Sun ? Or in Dynamics ?

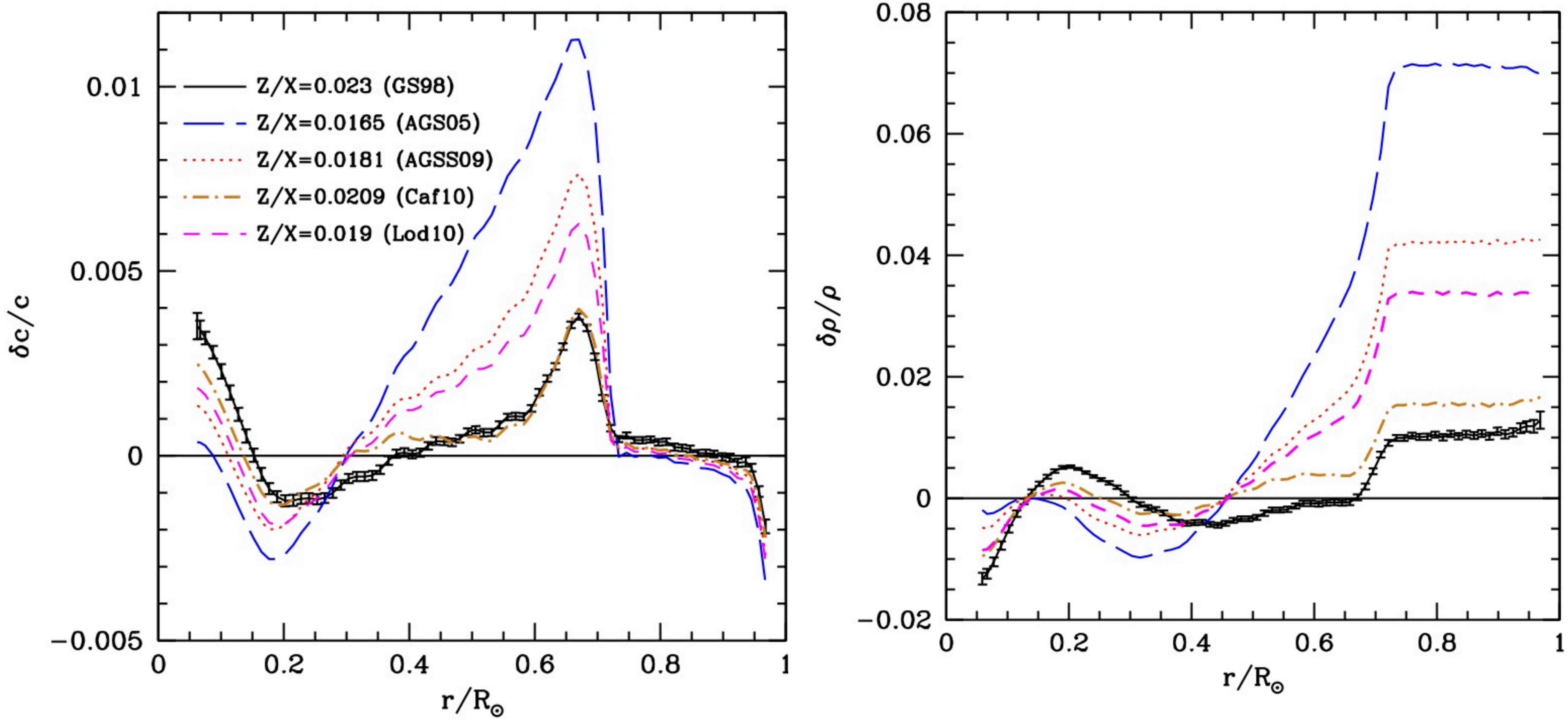


- A **seismic solar model** has been **built in black** for a better prediction of observables

  Interest for fundamental physics

Turck-Chièze et al. ApJ 2001, Phys. Rev 2004, ApJ 2010, Basu et al. 2009
T-C and Couvidat, Rep. Prog. Phys 2011, T-C, Piau, Couvidat, ApJ lett 2011

Dependence of the thermodynamical quantities to the solar photospheric composition



Basu, Grevesse, Mathis, Turck-Chièze 2013, in ISSI book, to appear

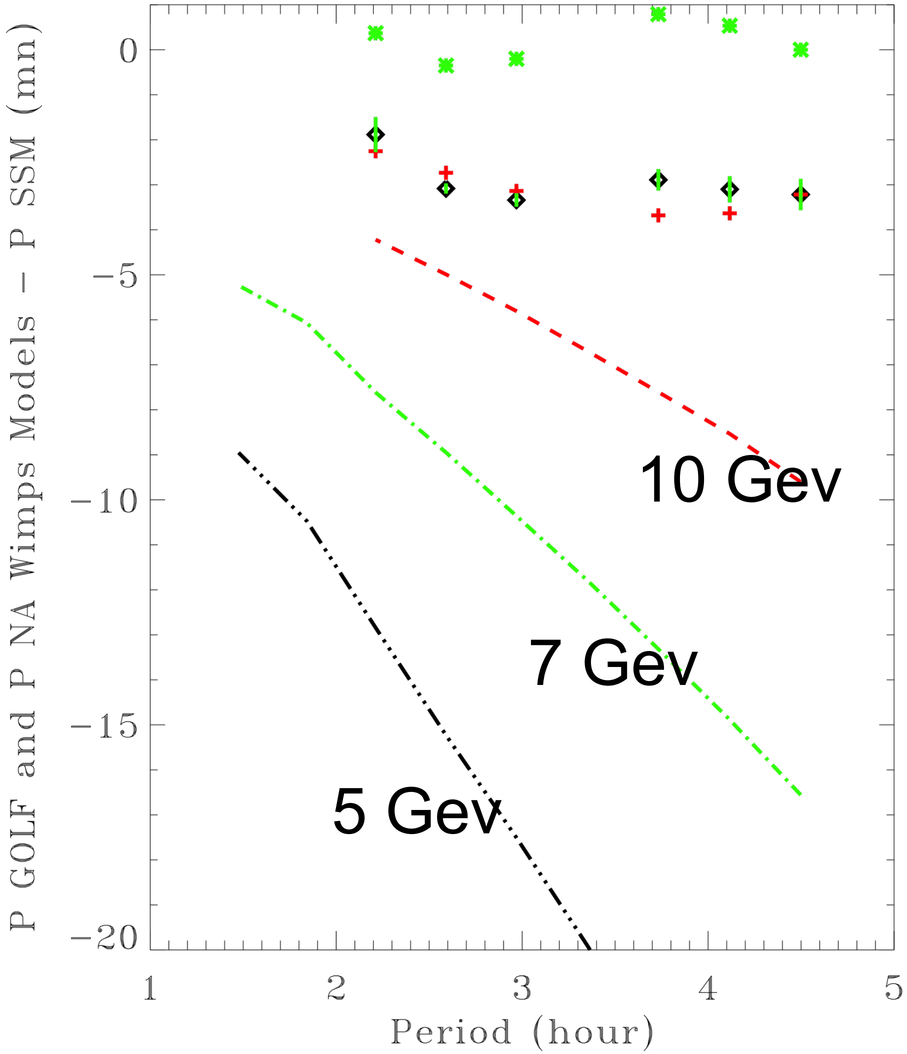
Helioseismology and neutrinos agree today through SSeM

The agreement with SSM predictions is not so good including new $^{14}N(p, \gamma)$ estimate and new CNO photospheric abundances

	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)**	

WIMPs properties from the knowledge of the solar core

Turck-Chièze et al. 2012, ApJ lett 2012



- The core of the Sun is now well constrained by SNO+SK **neutrinos** detection: constraints on the **central temperature** and **gravity modes:** constraints on the **central density** through the seismic model that predicts correctly both detections:
- **T_c = 15.74 10^6K**
- **ρ_c = 153.6 g/cm^3**
- This fact puts some constraints on the mass of WIMPs, first candidates for dark matter if one considers realistic 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} < 12 GeV are rejected**

We see no signature of WIMPs from observations of the Solar Core

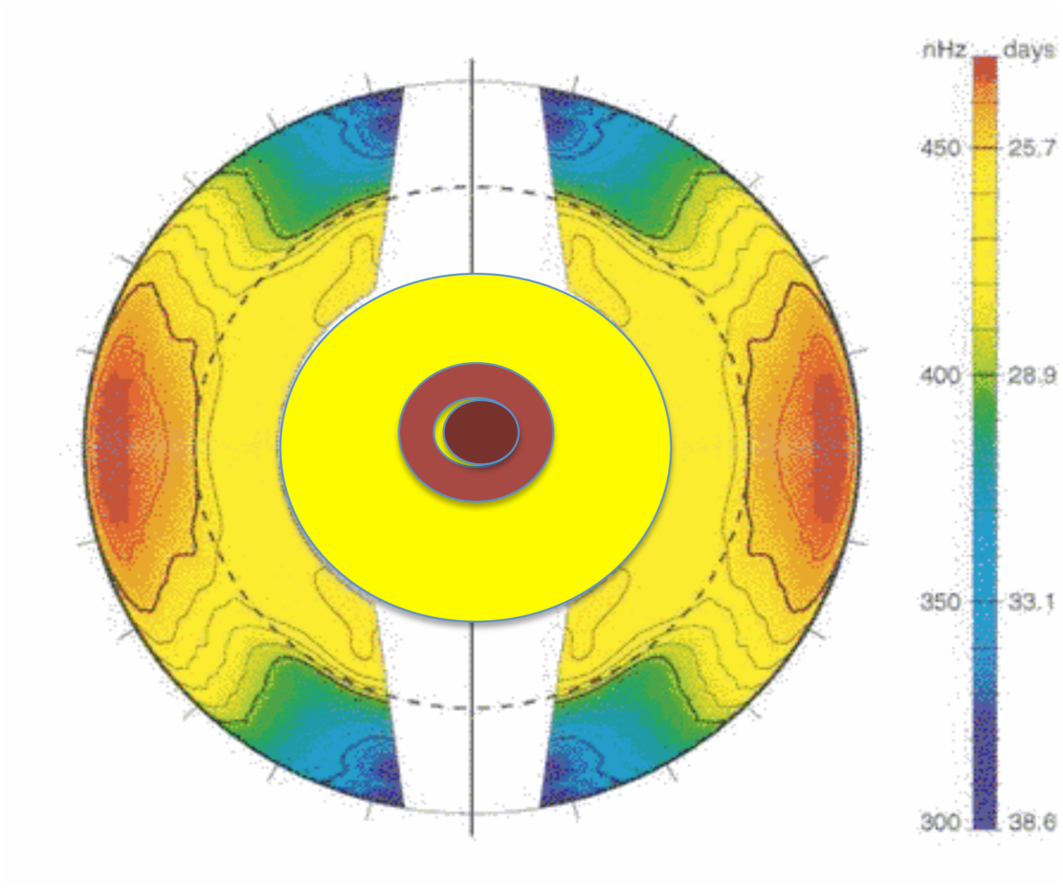
Future solar neutrino observations

Precise neutrino measurements: 1 to 5%

to build the

Dynamical Solar Model

2004-2013: Extraction of the rotation profile from the surface to the core thanks to acoustic and gravity modes and of the magnetic field just near the surface



The GOLF instrument has determined a first insight on the core solar rotation.
It rotates about 6-8 times greater than the rest of the radiative zone.
This is probably a relic of the initial contracting phase, so some insight on the solar system formation. At that period, a dynamo could have been created in the solar central region: impact of our Sun on young planets, which may help to explain a believed warm young Mars.

The observed 11 and 2 year helioseismic periodicities are connected to the sub-surface magnetic field. No direct magnetic field estimate of the solar interior is given by helioseismology up to now.

Turck-Chièze et al. ApJ 2004, Garcia et al., Science 2007,
Turck-Chièze et al. 2010,
Garcia et al. 2011, Simoniello et al., 2012, 2013, Piau et al. 2013

Solar Neutrino Astrophysics

- Production of energy: pp and pep fluxes
- CNO fluxes: CNO abundance and screening in the core

- Electronic density
- Time variability of neutrino fluxes due to gravity modes or gravity waves

The energetic balance of Sun and stars in SSM

Are stellar structure equations enough ?

Other stars, formation of planets, present Sun-Earth relationship

Transformation of produced energy, transport of energy, transport of angular momentum

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Check the energetic balance and the electronic density profile

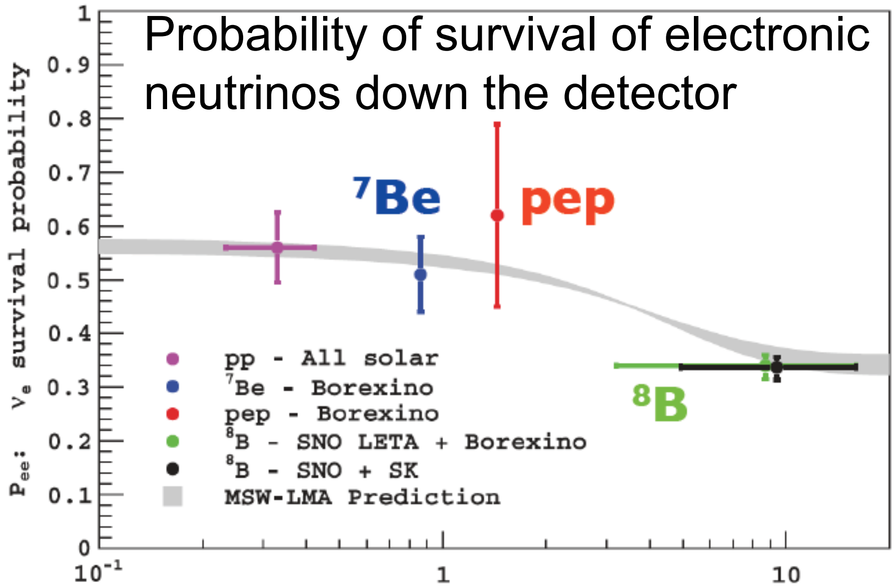
Turck-Chièze, Piau, Couvidat 2010; T-C & Couvidat Rep. Prog. Physics 2011,
T-C & Lopes 2012, RAA, Lopes & Turck-Chièze 2013, ApJ lett

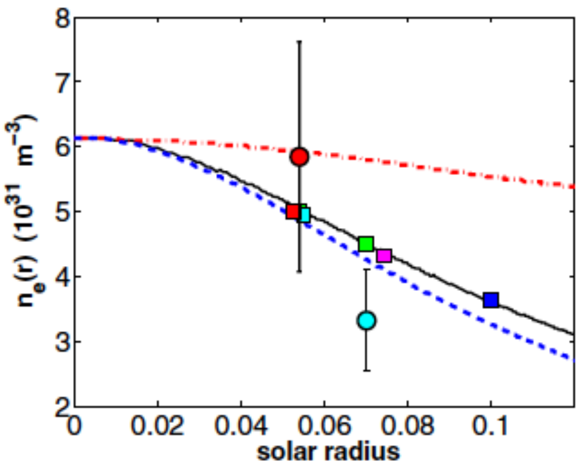
- T_c seismic model 15.74 10^6 K
- T_c SSM 15.54 10^6 K

- 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}



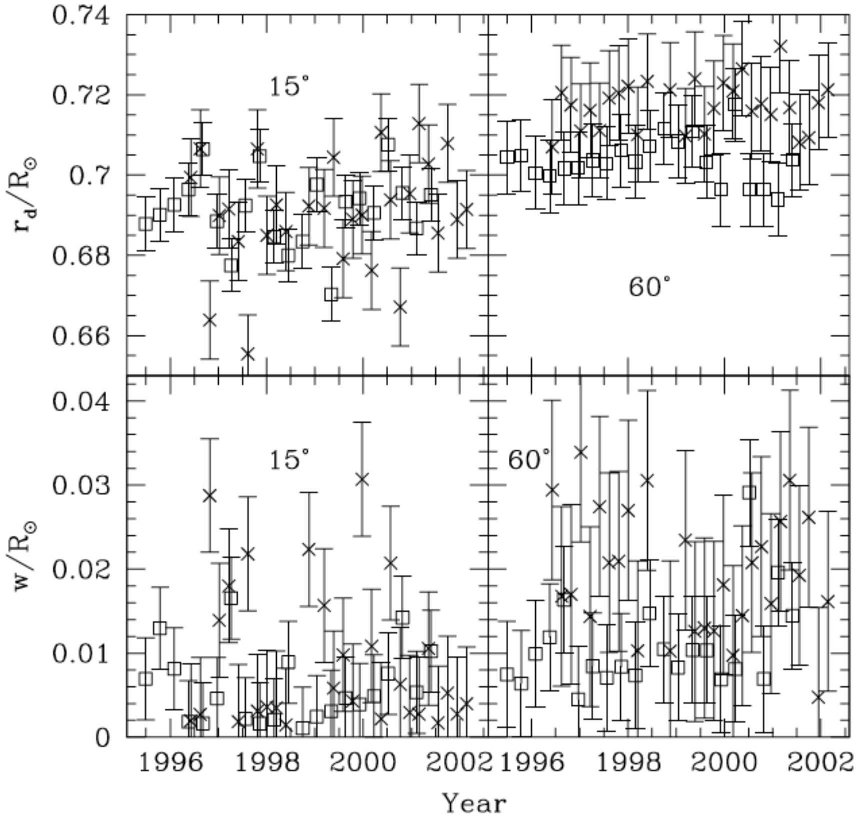


Redistribution in kinetic energy, magnetic energy, meridional motions, energy of the gravity waves
Another part through transfer of energy by photons.

- Core CNO given by N^{15} and $0^{15}\nu$ fluxes
- Spectroscopy of neutrinos gives access to the electronic density profile.

Time variability in the RZ

Can we see the generated gravity waves through time variability of the ^{8}B neutrino flux or other neutrino fluxes: periods of hours ?



Basu & Antia 2003

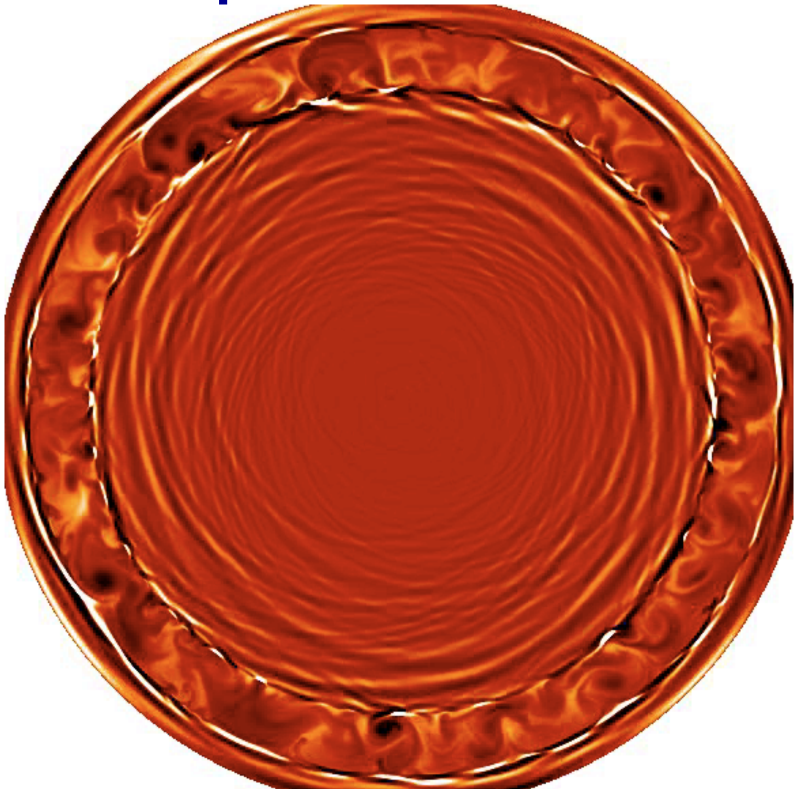
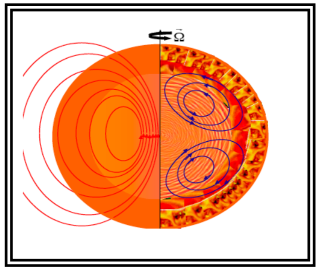


TABLE 2
PROPERTIES OF THE TACHOCLINE AT A FEW SELECTED LATITUDES

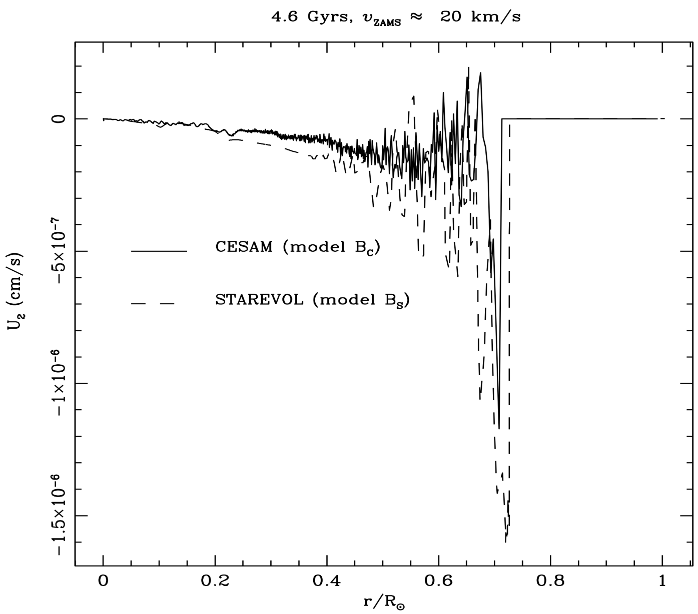
Latitude (deg)	$\delta\Omega_t$ (nHz)	r_t ($R_\odot$)	w ($R_\odot$)
0...............	20.82 ± 0.43	0.6916 ± 0.0019	0.0065 ± 0.0013
15.............	17.83 ± 0.24	0.6909 ± 0.0018	0.0078 ± 0.0013
45.............	-30.54 ± 0.54	0.7096 ± 0.0019	0.0103 ± 0.0012
60.............	-67.65 ± 0.74	0.7104 ± 0.0022	0.0151 ± 0.0020

Macroscopic effect on microscopic physics



Prediction of two different meridional circulation velocity in RZ and CZ

Brun, T-C, Zahn 1999, Turck-Chièze, Palacios, Marques et al. 2010



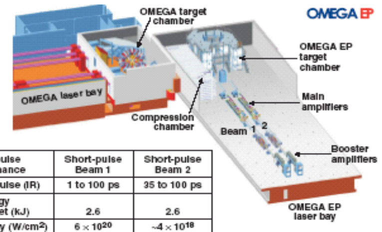
10^{-6}-10^{-7} cm/s in RZ compared to several cm/s in CZ

We need to calculate the impact of the tachocline shear on the microscopic diffusion of the Sun: 10% or more impact of CNO, Si, Fe in the core!!
Can we constrain the CNO abundance in the core by neutrinos ?…

We develop a program to reestimate opacity calculations and measure opacities and reaction rates in plasmas generated by HE lasers like LMJ (Bordeaux, France)

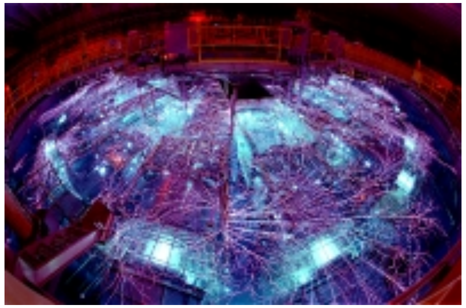
Academic facility
LULI Palaiseau France 500 J ns 1 ω_0+ 30 J 100 TW

NIF USA 1,8 MJ 3 ω_0
Military Livermore facility

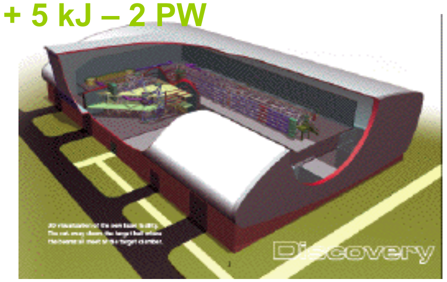


Short-pulse performance	Short-pulse Beam 1	Short-pulse Beam 2
Short pulse (IR)	1 to 100 ps	35 to 100 ps
IR energy on-target (kJ)	2.6	2.6
Intensity (W/cm²)	6×10^{20}	$\sim 4 \times 10^{18}$
Focusing	>80% in 20 μm	>80% in 40 μm

kJ ns 3 ω_0
+ 5 kJ – 2 PW



Z pinch Sandia



ORION UK 5 kJ ns 3 ω_0
+ 1 kJ - 2 PW

LMJ Bordeaux France
Military CEA facility 1,8 MJ 3 ω_0 + PETAL 3,5 kJ - 7 PW?

Production of equivalent T and ρ than center of the Sun during some ps

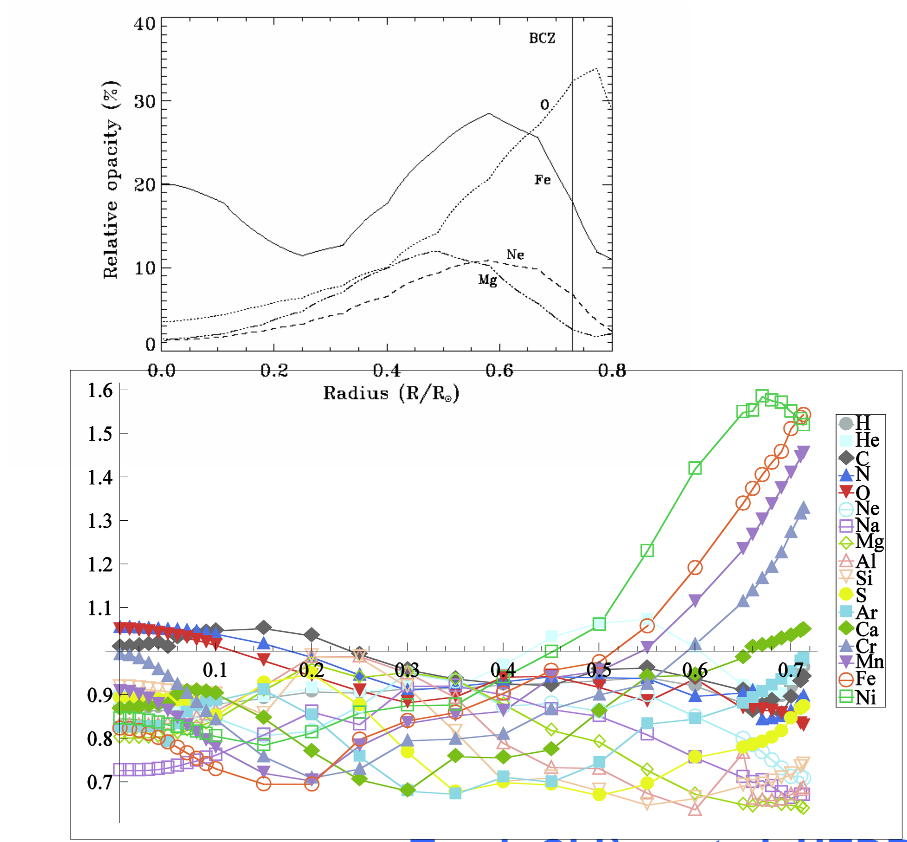
Program for the next decade: d+p -> ^{3}He +γ; d+d -> ^{3}He+n; p +^{7}Li; p+^{11}B-> 3 α ….

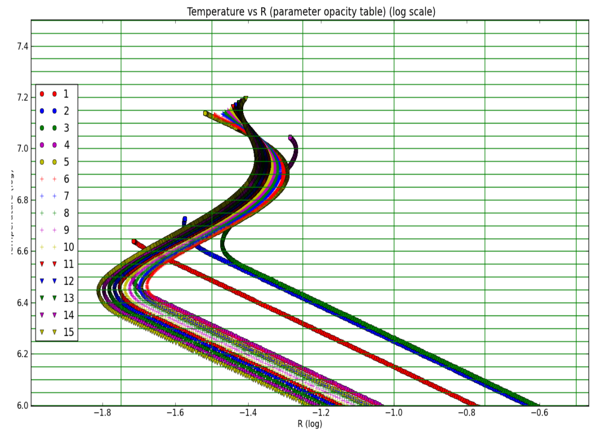
How we shall progress ?

We are preparing new calculations for stellar physics and we begin to understand the differences with OPAL

New experiments on laser facilities: ORION, LMJ

New interpolations with OPAS calculations of opacity





Turck-Chièze et al. HEDP 2009, 2013

Summary

SSM is today checked and compared to two kinds of observations: neutrinos & seismology
Its quality is clearly reasonable : 1% for central temperature, 1% for radial sound speed

Observed differences between SSM and the Sun are significant:
We can learn more on microscopic and dynamical Physics of the solar core

Accurate neutrino flux predictions still depend on crucial nuclear reaction rates
their screening effects and the abundance of pp and CNO elements

Precise neutrino astronomy is coming:

- CNO neutrino for CNO abundance and screening,
- pep or pp neutrino flux for energetic balance,
- ^{8}B and ^{7}Be neutrino fluxes for electronic density, time gravity waves variability

In parallel and independently, large laser facilities are promising to check the screening effects and the transfer of radiation in plasmas => Dynamical model of the Sun

May be these new developments can also improved our knowledge of neutrinos, like in the past

Main collaborators

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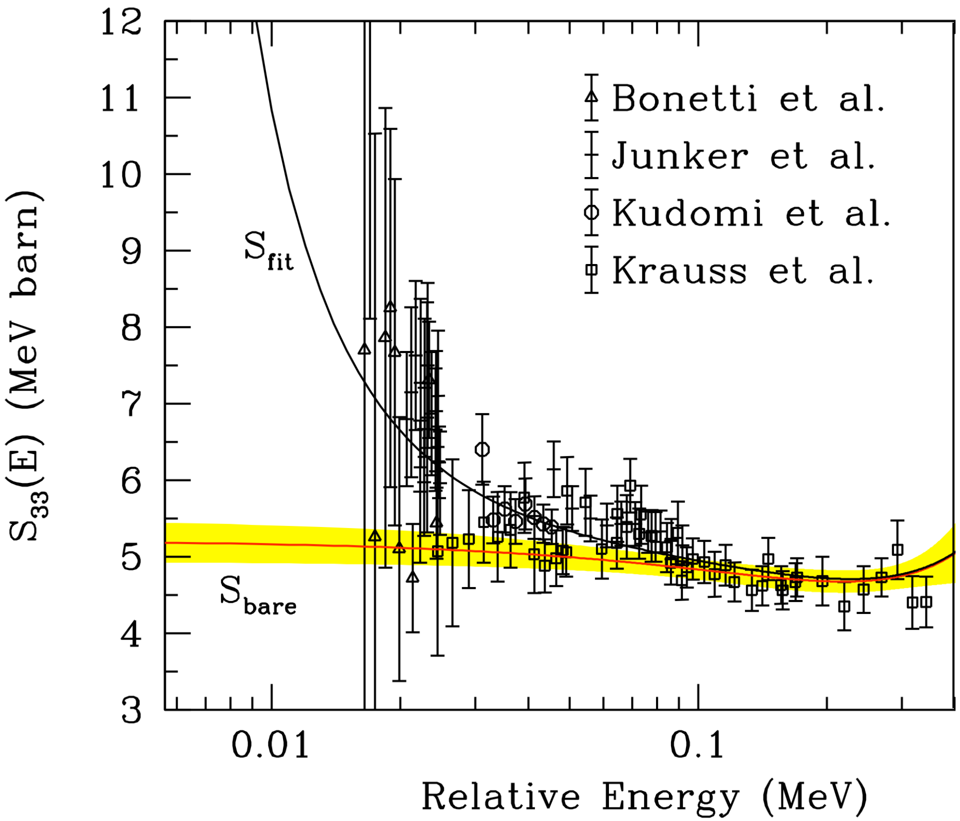
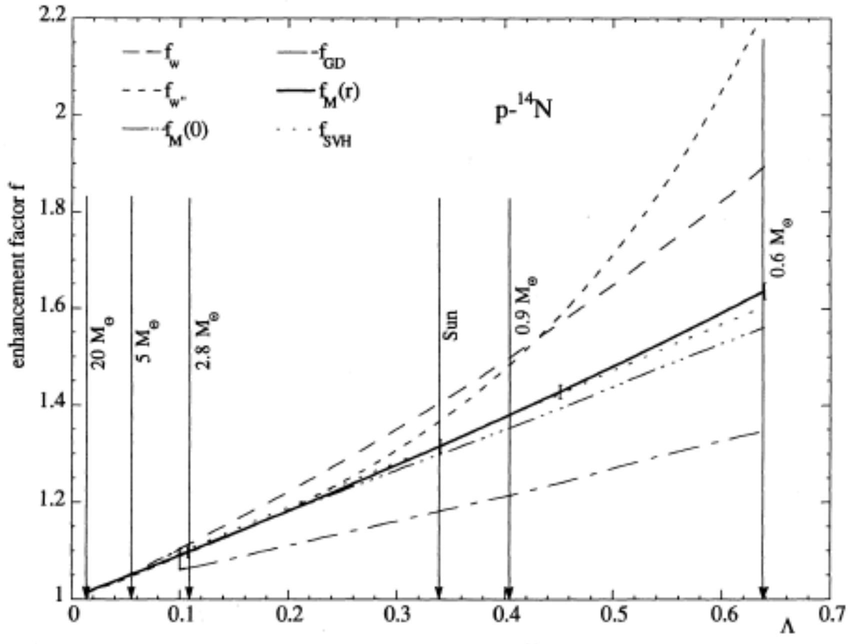


Screening factor ?

Dzitko, T-C et al. 1995,
Gruzinov & Bahcall 1998

This effect has never been measured before

f= logΛ where Λ= U(0)/kT



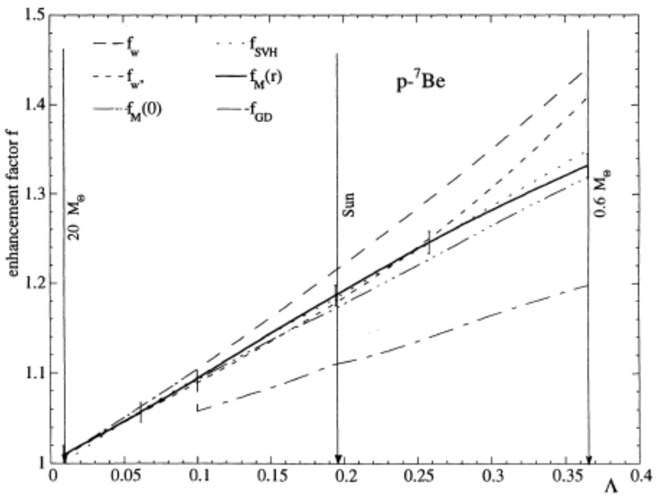
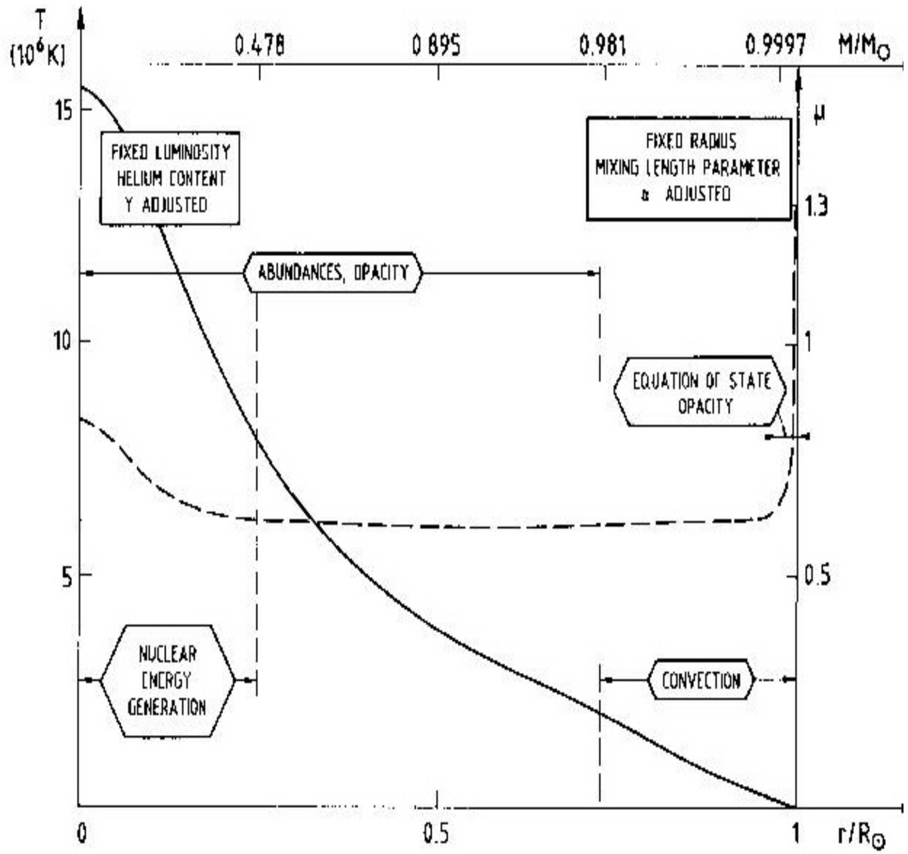


FIG. 4.—Same representation as in Fig. 3, for the (p, ^{7}Be) reaction.

Helium content and base of the convective zone

$c^2 = \Gamma_1 P / \rho$ proportional to T / μ



Vorontsov 1989, 1992,
Basu 1995,
Christensen-Dalsgaard et al. 1991

Photospheric helium: 0.25 in mass fraction which checks the microscopic diffusion for that element and BZC: 0.713 R_{sol}