Review of solar models and Helioseismology

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THE TEAMS

Saclay: S. Turck-Chièze, S. Brun, H. Dzitko, R. Garcia, I. Lopes
P. Nghiem

Networks: IRIS: Fossat et al., BISON: Elsworth et al.
LOWL: Tomczyk et al., GONG: Leibacher et al.
Spatial measurements on board SOHO
GOLF: Gabriel et al., MDI Scherrer et al.,
VIRGO: Frohlich et al.

Interpretation team: S. Basu, G. Berthomieu, J. Christensen-Dalsgaard, T. Corbard, J. Provost, S. Kosovishev, I. Sekii, <u>S. Turck-Chièze</u>

Model intercomparison: Bahcall-Pinsonneault, Nice, Saclay, Aarhus,Montreal.

Solar Neutrino Puzzle

- Less neutrinos detected on earth than emitted by the Sun (30% à 2.5)
- Verification of the number of emitted neutrinos, variation with time?
- Transport of neutrinos from central Sun
- Distribution of energy of the neutrinos
- Interaction cross sections between neutrinos and detectors

Sensitivity of the modes to the solar structure

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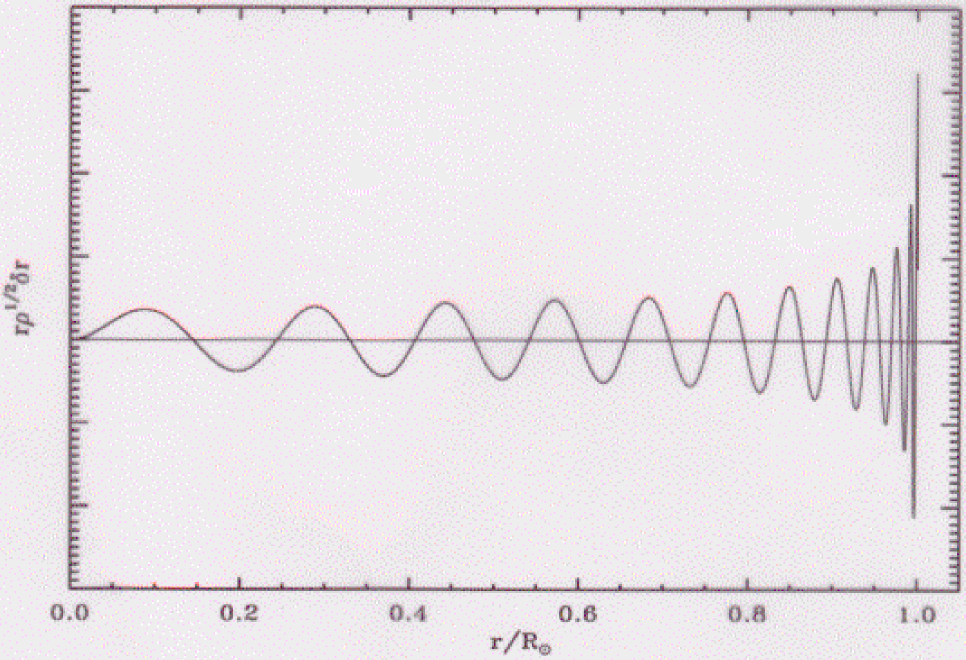
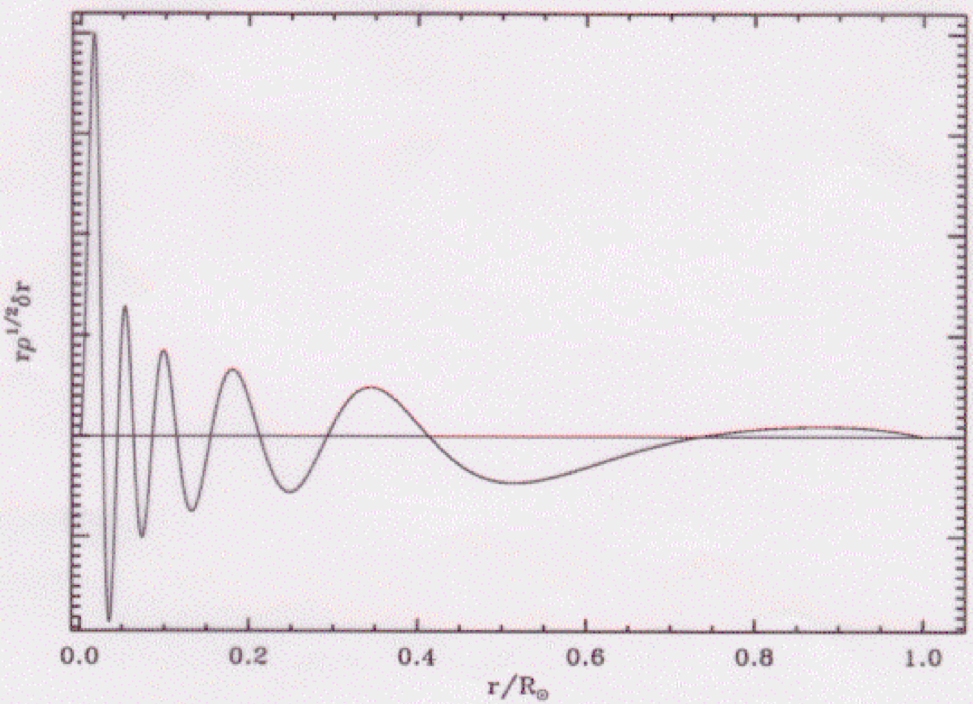
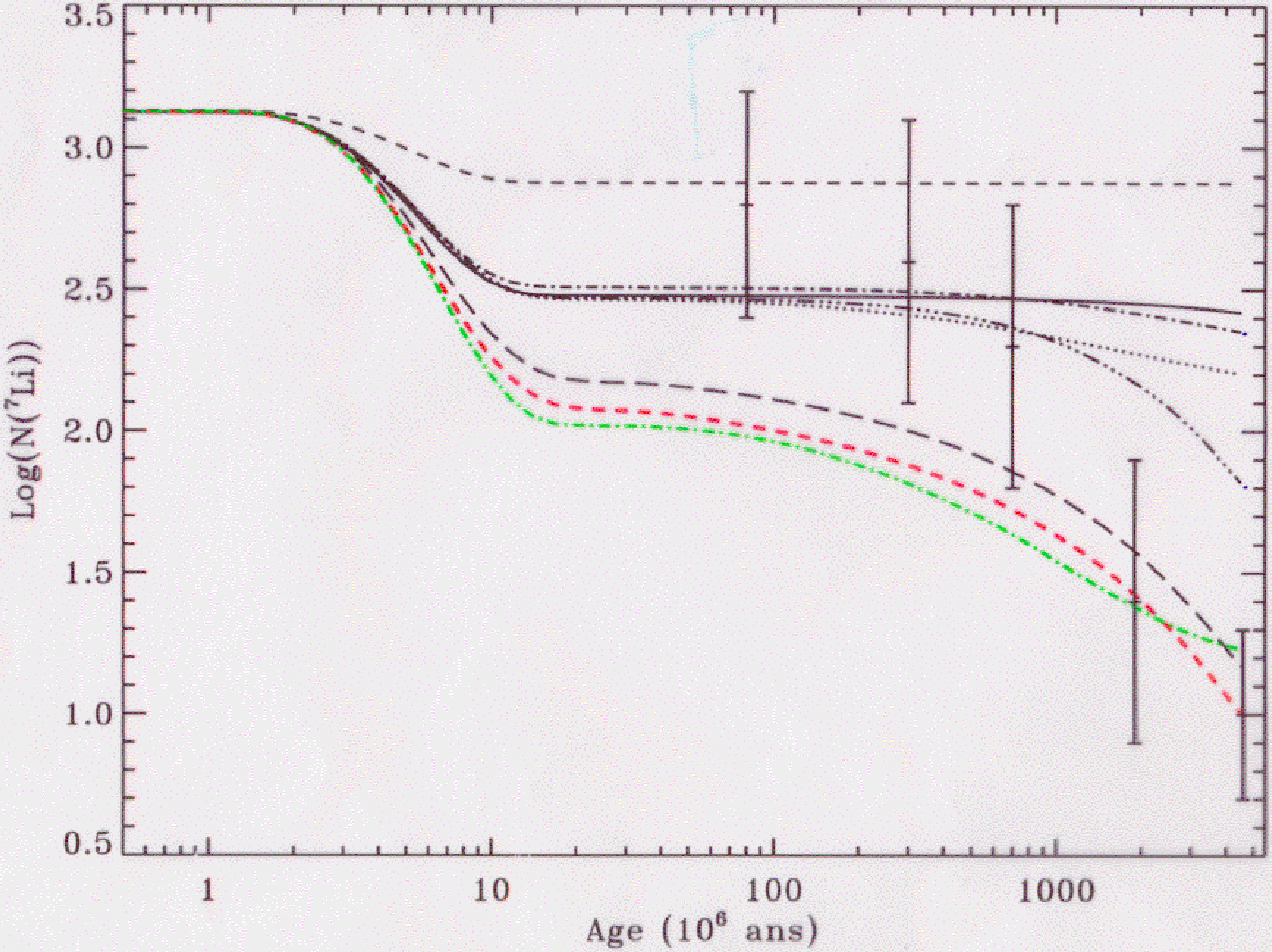
Acoustic modes: sensitivity to the surface, 5% to the nuclear core



Gravity modes: sensitivity to the nuclear core, 75% from the nuclear core





Lithium depletion

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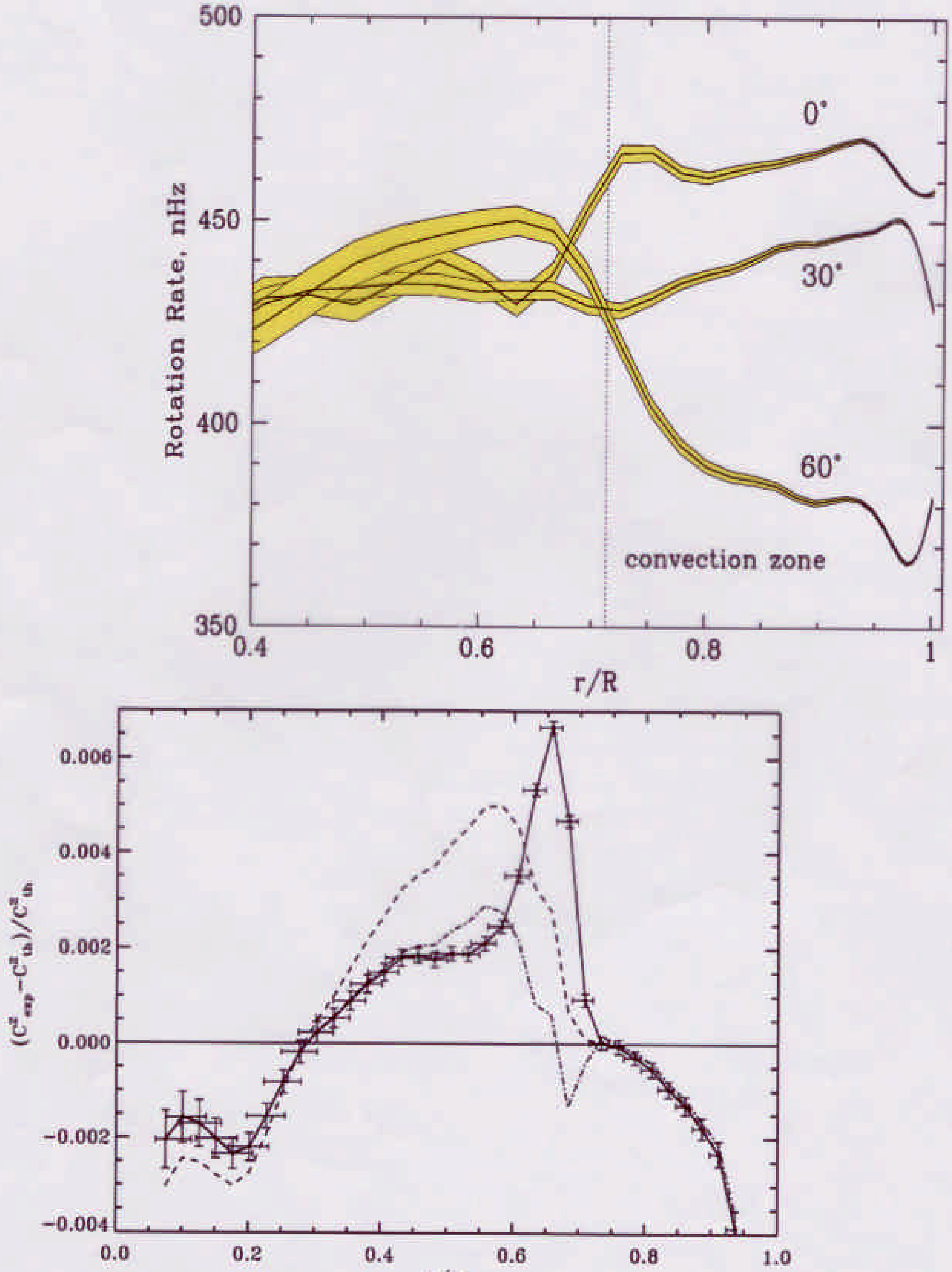
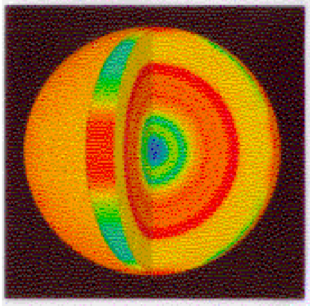


Figure 1. a) Internal rotation profile from MDI (from Kosovishev et al. 1997). b) Sound speed square difference between the Sun seen by GOLF + MDI instruments aboard SOHO and solar models. The full line corresponds to a reference model where the microscopic diffusion is included, the other models include also turbulent terms, the dashed line corresponds to a model where the photospheric Z/X=0.0245

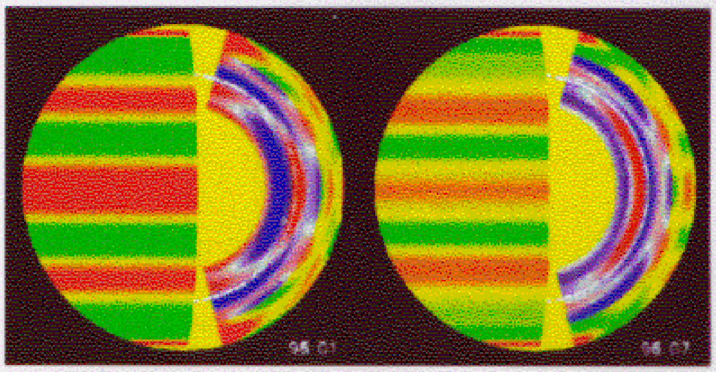
PHYSICS ABOVE 0.4 R_O

- Latitudinal dependence of the rotation
- Tomography of the outer convective zone
- Mixing at the basis of the convective zone
- Progress on the understanding of the solar cycle
- Bi-cycle: above 0.92 R_O B=20 kG 11year cycle
- below the convective transition, B <300 kG

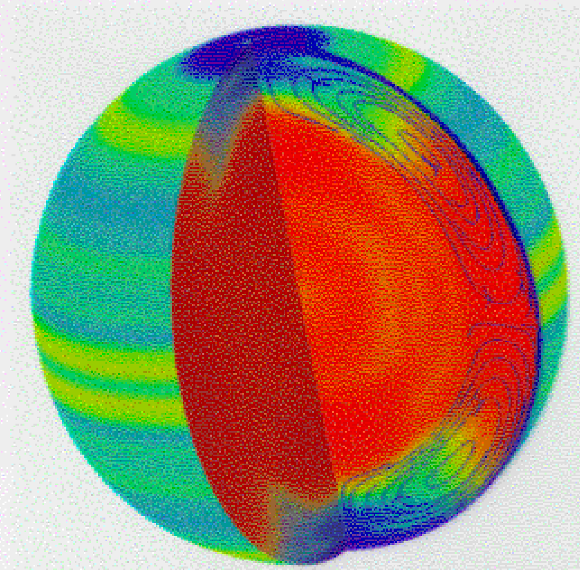


Stellar interior seen by acoustic modes

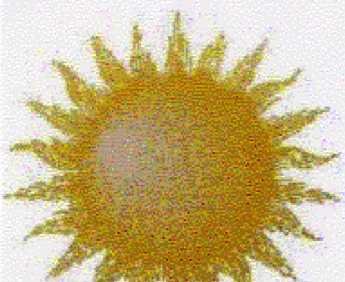
	Static Sun	
Static core R < 0.3 Ro M < 0.6 Mo	Dynamic Sun R ~ 0.7 Ro Solar dynamo	Dynamic Sun R > 0.6 Ro M > 0.9 Mo



Howe et al Science march 2000



SOHO (ESA & NASA), MDI/SOI and VIRGO



Sensitivity to the reaction rates

PHYSICS BELOW 0.4 $R_{\odot}$

- Accuracy of the determination of the frequencies
- Bias due to the variation along the solar cycle
- Importance of the radial acoustic modes
- Sensitivity of the sound speed to the internal physics
- Rejection of mixing in the central part

Table I. Sensitivity of the sound speed to the physical processes

Quantity	variation	$\Delta c^2/c^2$ variation
T	1 %	1%
κ	1 %	0.1 %
$X_c\,^{56}Fe$	4 %	0.1 %
$X\,^{3}He$	25%	0.1 %
(p,p) reaction rate	1%	± 0.1%
(^{3}He, ^{3}He) reaction rate	- 25 %	- 0.1 %
(^{3}He, ^{4}He) reaction rate	-25%	+0.2%
(p, ^{7}Be) reaction rate	10%	none
(p, ^{16}O) reaction rate	-50%	- 0.1-0.2 % just at the center

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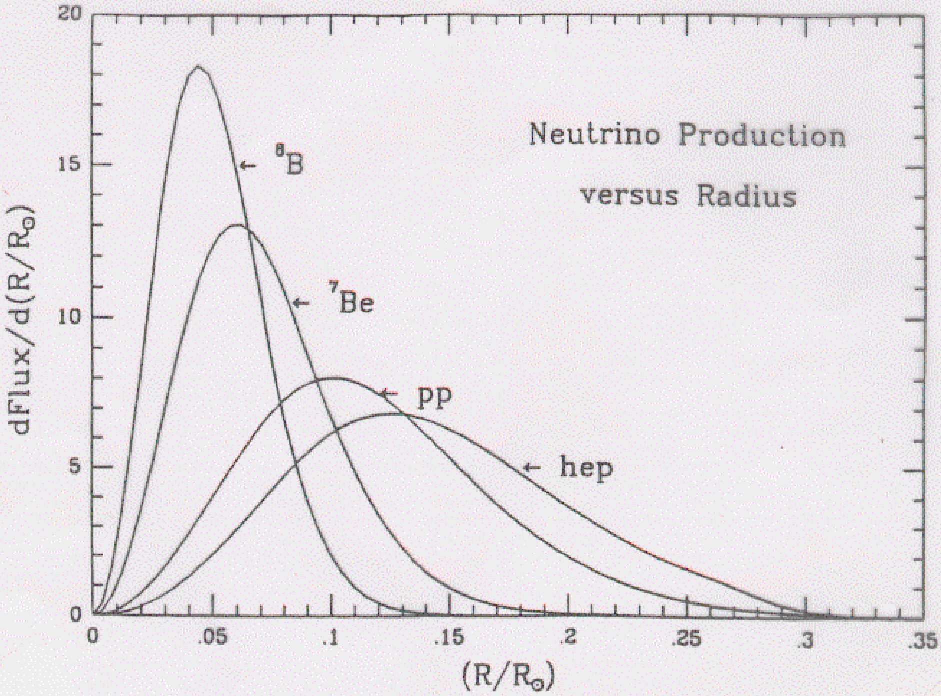
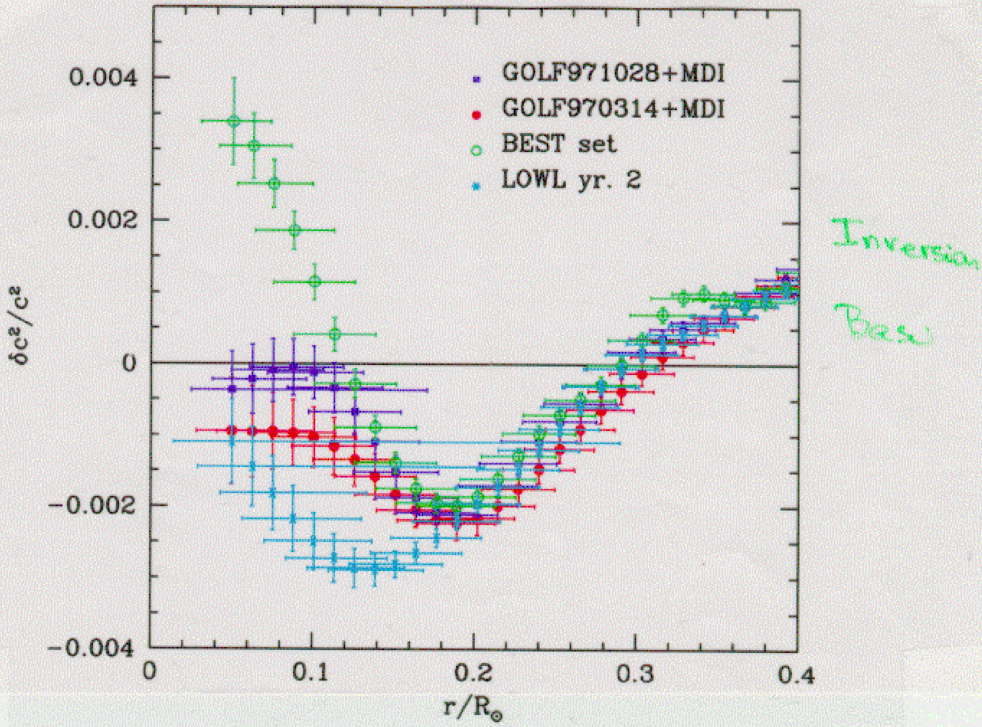
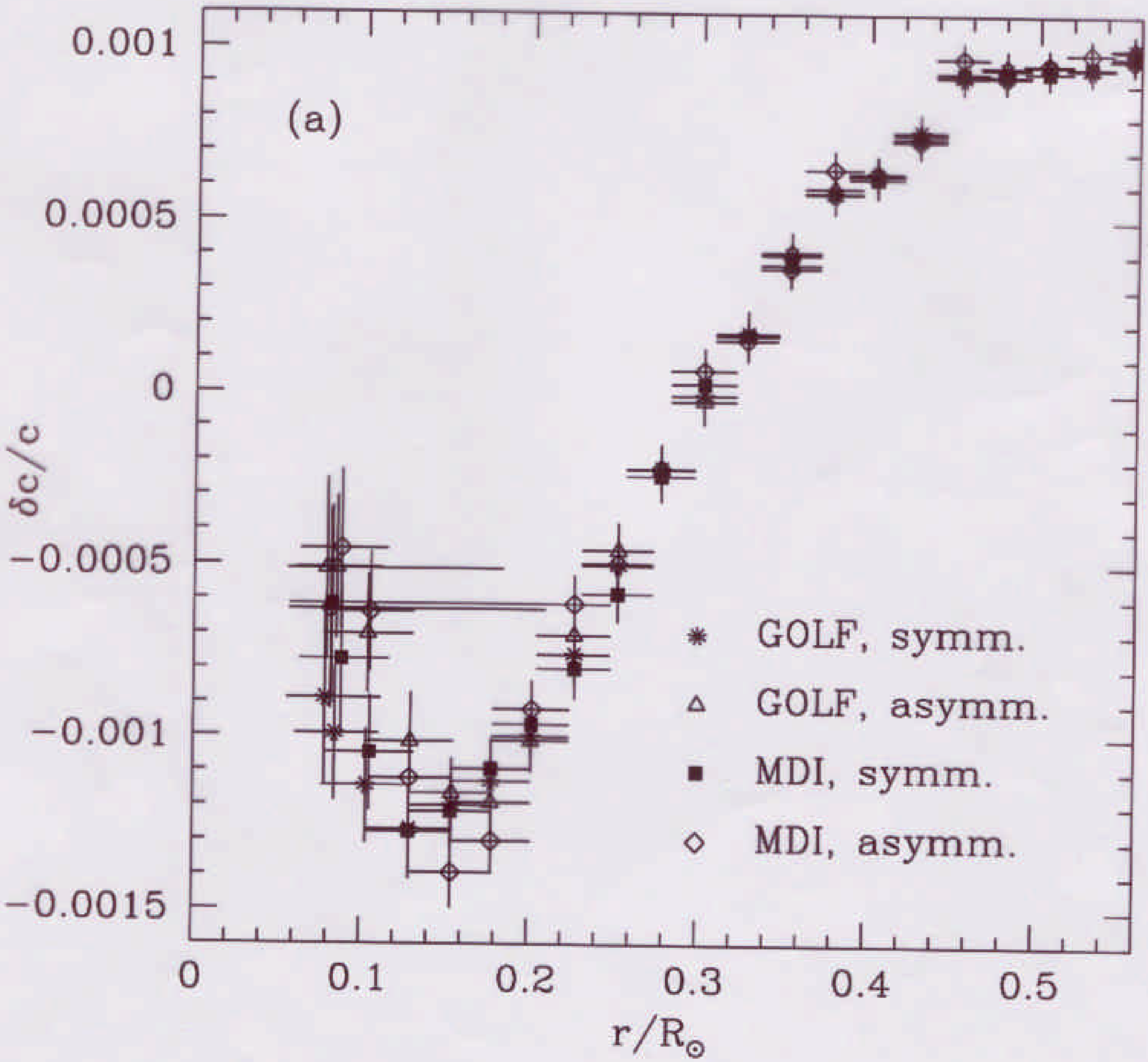

Neutrino Production
versus Radius
^{8}B
^{7}Be
pp
hep
dFlux/d(R/R$_\odot$)
(R/R$_\odot$)

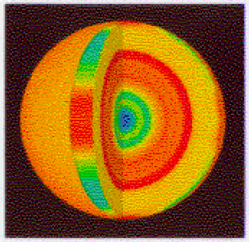

GOLF971028+MDI
GOLF970314+MDI
BEST set
LOWL yr. 2
$\delta c^2/c^2$
r/R$_\odot$
Inversion
Base

Knowledge of the solar core

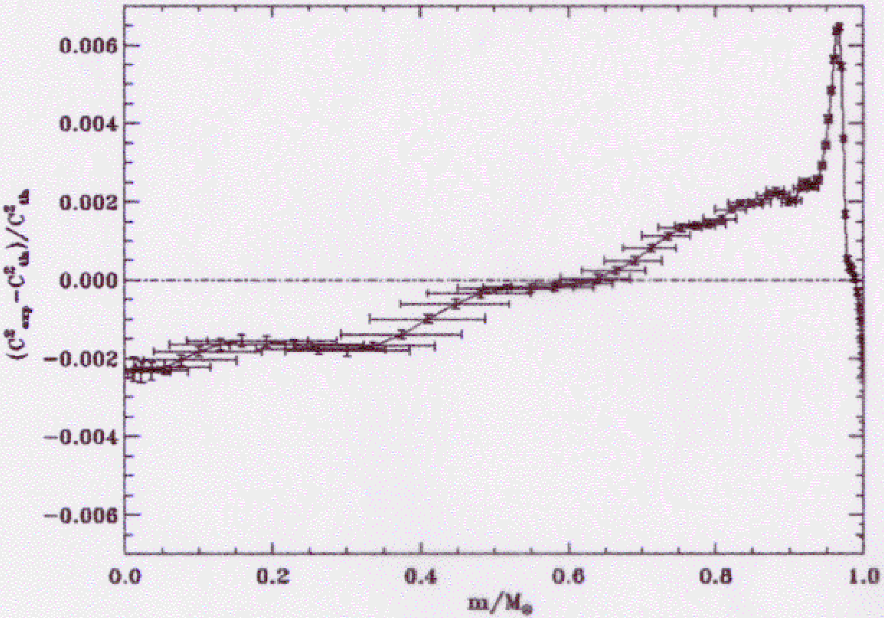


From Basu, Turck-Chieze, Berthomieu et al. 1999

ApJ 2000



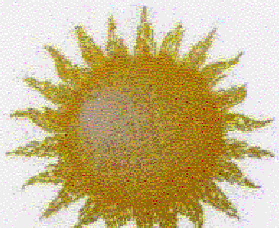
Solar interior shown by acoustic modes



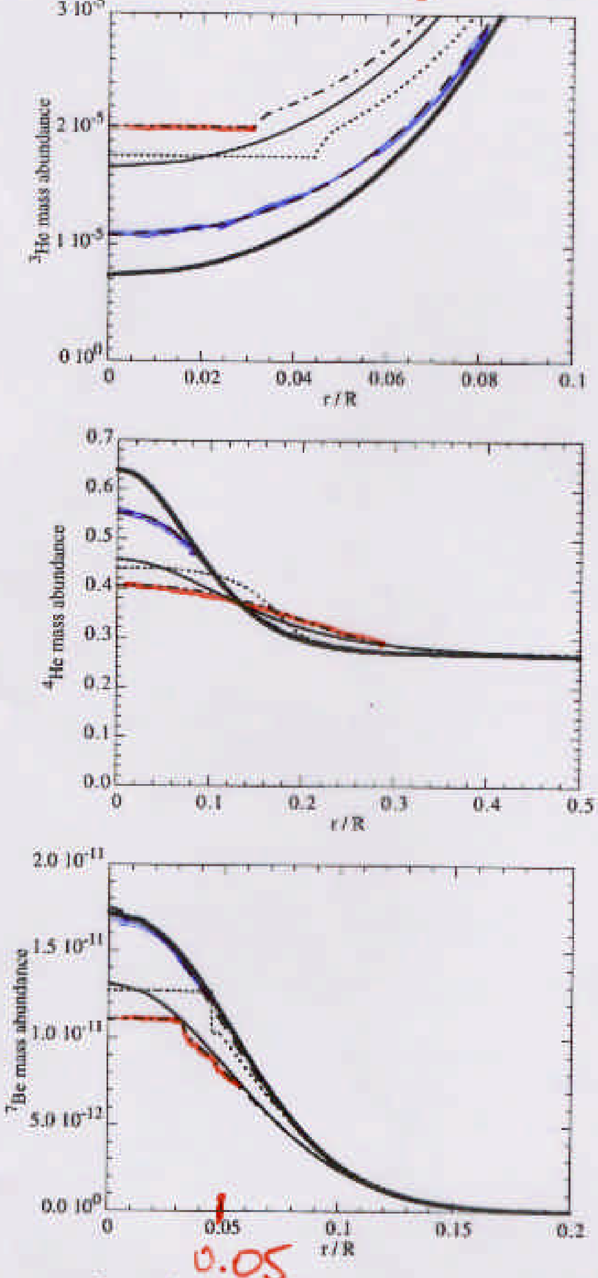
in including low order radial modes

Bertello et al 2000

Garcia, Turck-Chièze, Regulo et al 2000



Mixing in the very central core?



^{3}He

^{4}He

^{7}Be

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Figure 1. Variation of the ^3He, ^4He, ^7Be abundance in the solar core for the reference model (heavy full line) and for the models including different prescriptions for the turbulent coefficient (same representation than previous figures)

Turck-Chieze, Nghiem, Couvidat, Turcotte, Solar Phys 2000 submitted

Table I. Central mass abundances of ^3He, ^4He, ^7Be, hydrogen, central temperature and neutrino predictions of the different detectors for the reference model of Brun, Turck-Chièze and Zahn 2000 and different models (see definition in the text) including turbulence in the central region of the Sun. Solar neutrino detections with uncertainties from Gallex, Homestake and Superkamiokande.

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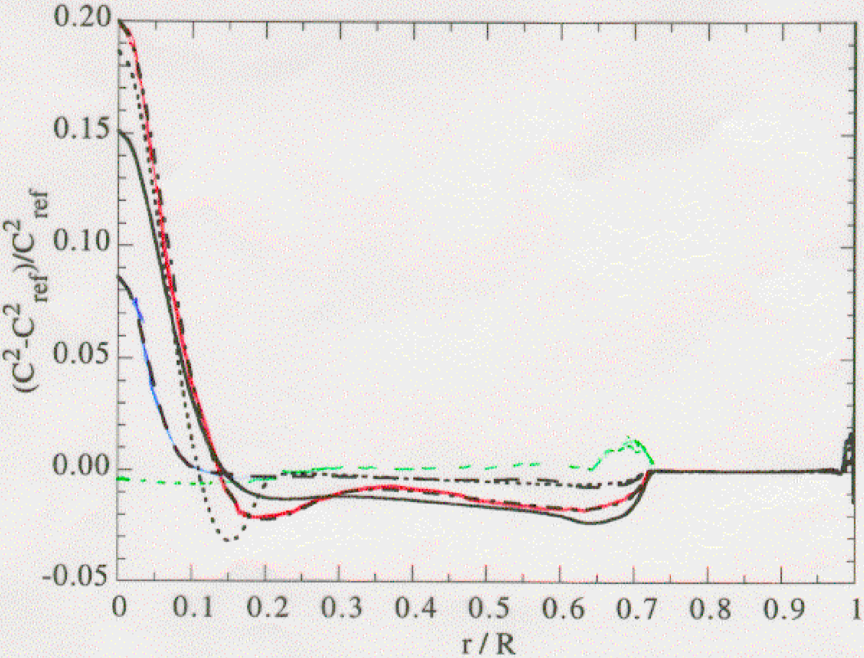
model	^3He_C	^4He_C	^7Be_C	H_C	T_C (10^6 K)	^{71}Ga(SNU)	^{37}Cl(SNU)	^{8}B(10^6/cm^{2}s^{-1})
Reference	7.35 10^{-6}	0.64	1.72 10^{-11}	0.339	15.71	127.2	7.06	5.00
uncert.						±8	±1.25	±1.7
case 1	1.67 10^{-5}	0.46	1.31 10^{-11}	0.523	15.15	108.7	3.87	2.50
case 2	1.08 10^{-5}	0.55	1.75 10^{-11}	0.429	15.57	122.1	6.23	4.36
case 3	2.02 10^{-5}	0.40	1.11 10^{-11}	0.575	15.10	107.1	3.62	2.31
case 4	1.77 10^{-5}	0.44	1.27 10^{-11}	0.539	15.39	116.0	5.22	3.59
Experiment						76	2.55	2.44±0.26
uncert.						±8	±0.25	±0.26



DEVIATION FROM MAXWELLIAN DISTRIBUTION

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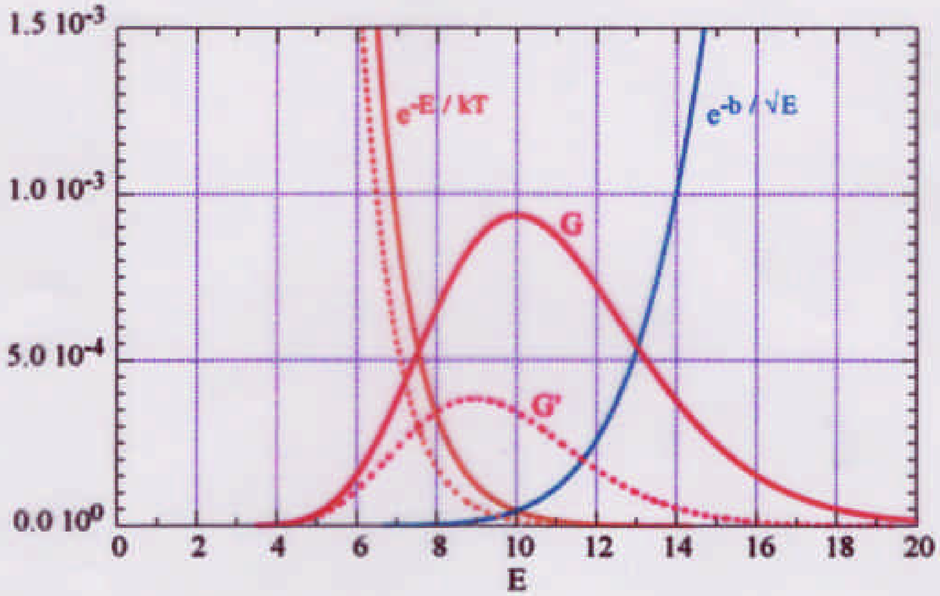
Many physical mechanisms can lead to a depletion of the Maxwellian tail at high energy :

$$f(E) \propto \exp\left(-\frac{E}{kT} - \delta\left(\frac{E}{kT}\right)^2\right)$$



and

$$\left(r_{12}\right)_\delta = r_{12} F_{corr}(\delta)$$

With : $kT = 1$, $E_0 = 10$, $\delta = 0.01$

$E_{0\delta} = 0.87\ E_0$
$\Delta E_\delta = 0.77\ \Delta E$
$G(E_{0\delta}) = 0.37\ G(E_0)$
$(r_{12})_\delta = 0.30\ r_{12}$

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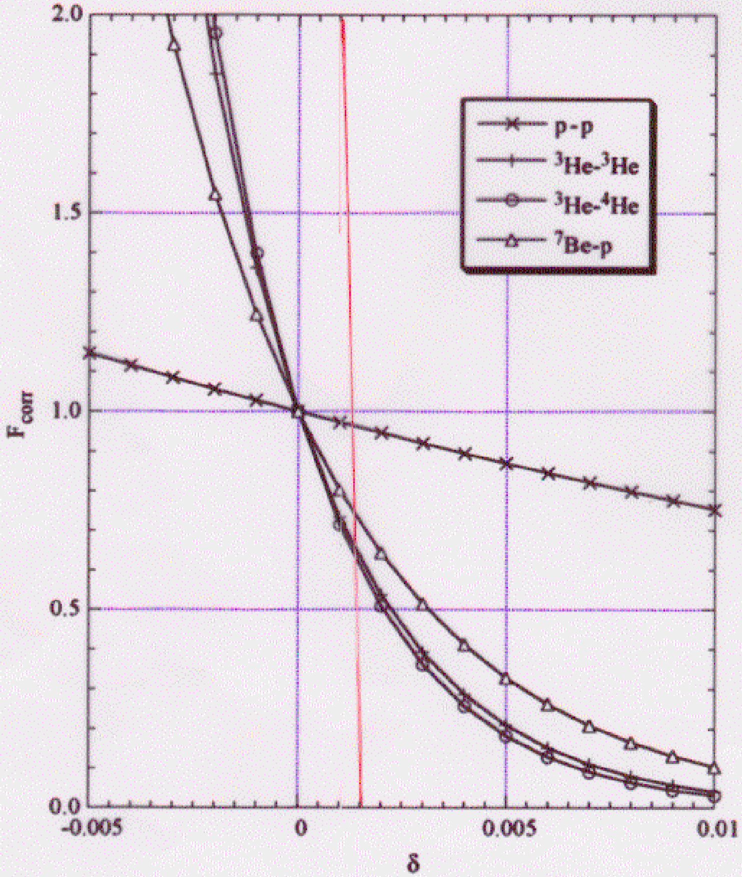
F_{corr} for some reactions of the p-p chain
At $T=15\ 10^6K$



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(p p) : + 2%

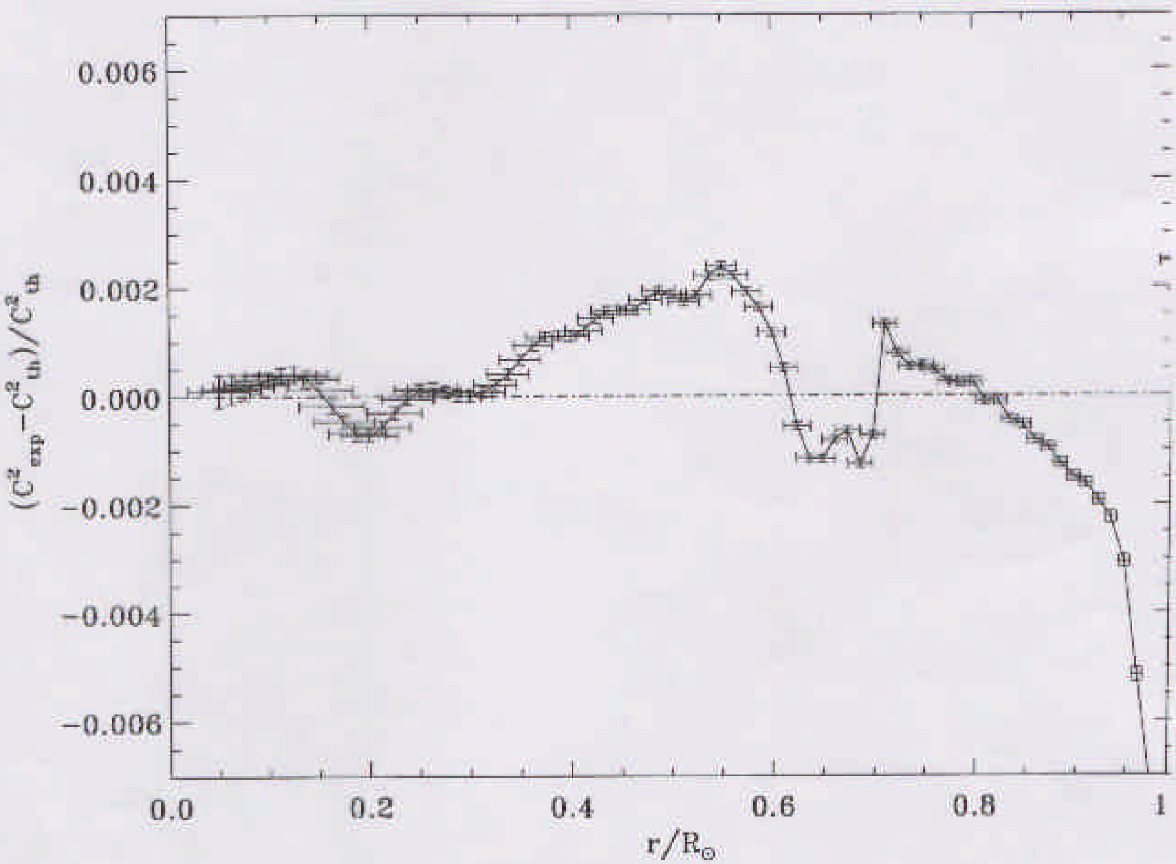
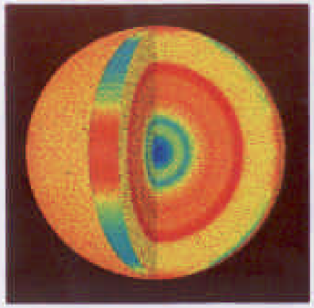
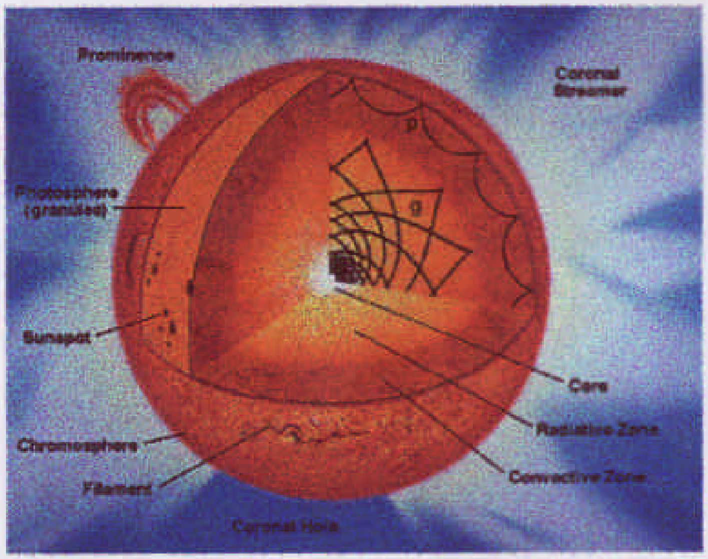
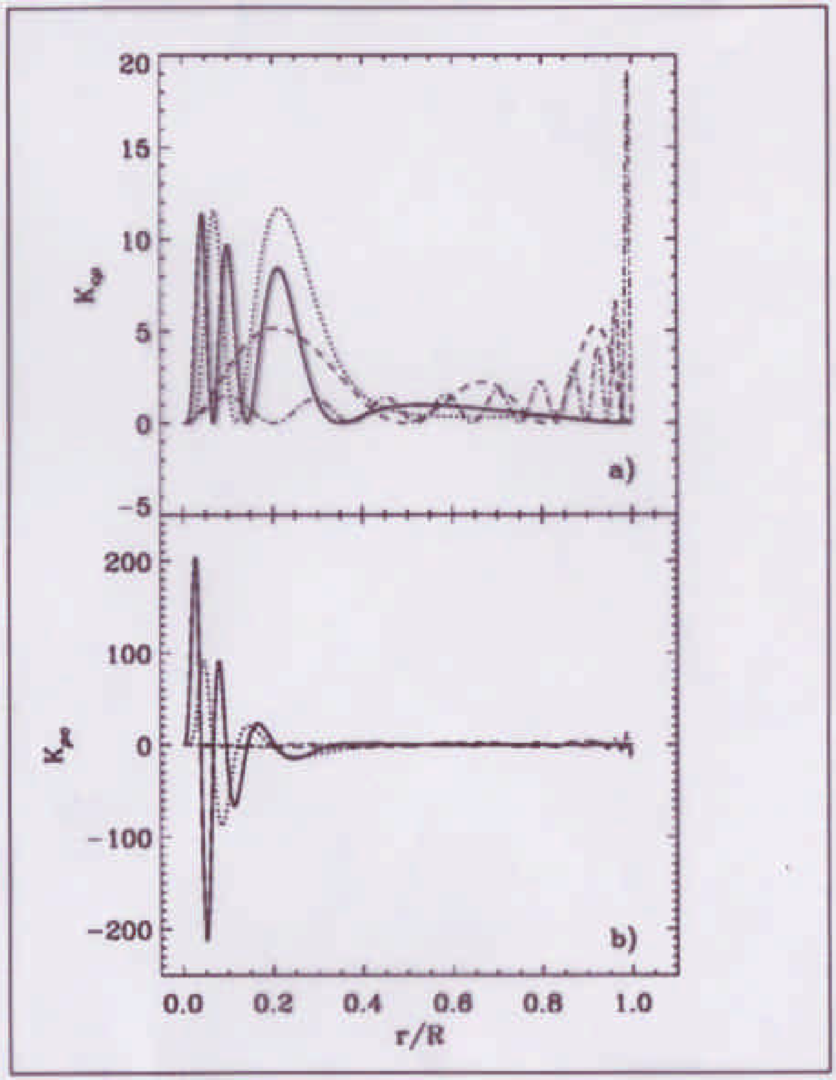


Figure 5. a) top: Relative difference between the sound speed squared in the Sun (derived from Bertello et al. 2000b) and the corresponding sound speed of a solar including turbulence at the base of the convective zone and an increase by 2% of the reaction (p,p).

Gravity modes: nuclear core observation







WHAT HAVE WE LEARNED FROM ACOUSTIC MODES ?

- Properties of the modes, Technical methods,…
- Internal structure above 0.4 $R_\odot$ AM appropriate
- below 0.4 $R_\odot$ AM appropriate ?
- Mixing at the basis of the convective zone
- The solar core ? ?
- The neutrino puzzle
- Could we hope to progress ?