Review of solar models and Helioseismology

Sylvaine TURCK-CHIEZE
Service d 'Astrophysique
CEA Saclay, FRANCE

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

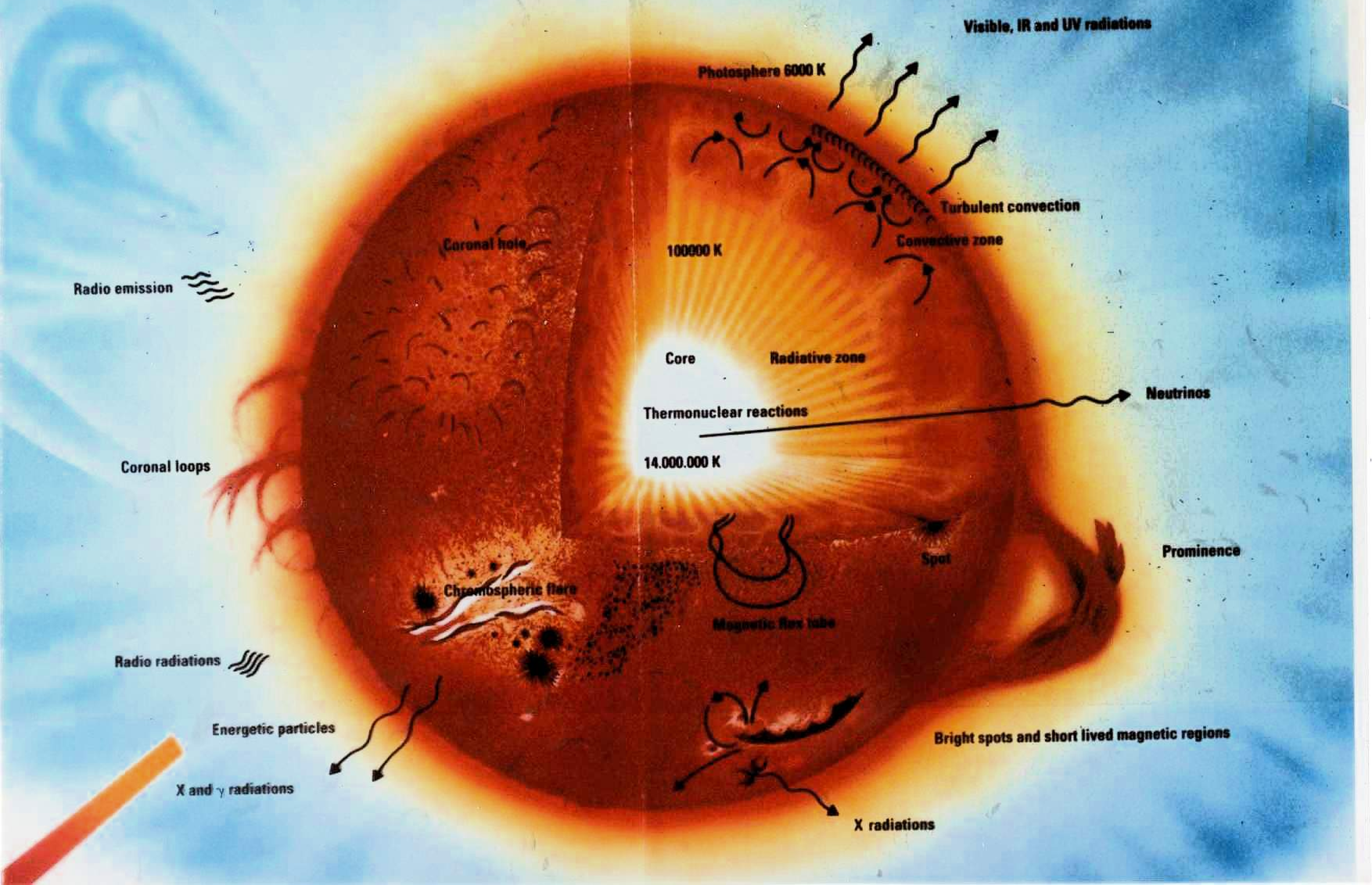
Collaborators

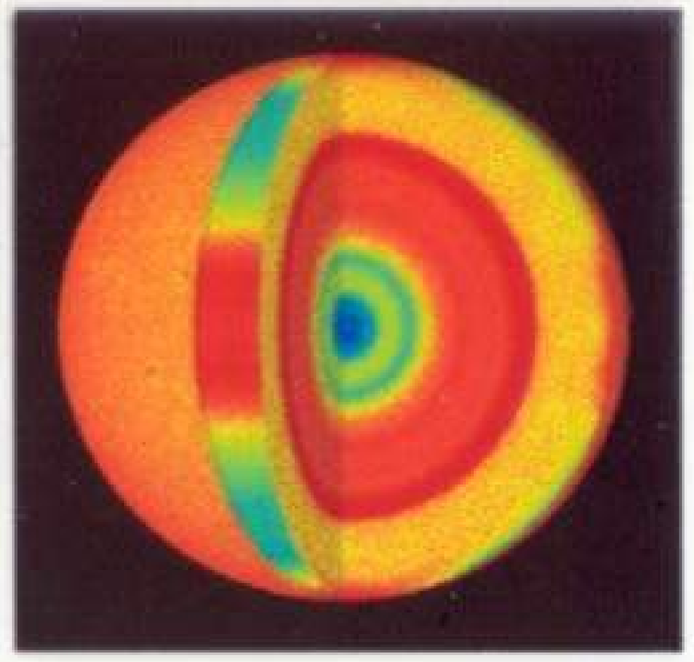
- **Theory and models**: Berthomieu, Basu (USA), Brun (PD), Cassé (SAp), Christensen-Dalsgaard (DK), Couvidat (T), Dzitko (SAp), Kosovishev (USA), Lagrange (DAM), Lopes (PD), Nghiem (SAp), Piau (T), Provost, Vuillemin (DAM), Zahn ...
- **Comparisons:** Bahcall-Pinsonneault, Christensen Dalsgaard, Turcotte-Michaud
- **Observations,data analysis**: Garcia (SAp), Bertello
- **GOLF:** Gabriel, Grec, Robillot, Roca Cortés, Ulrich…
- **MDI :** Scherrer, Rhodes…
- IRIS (Fossat) , BISON (Elsworth) , GONG (Leibacher)

HELIOSEISMOLOGY

- Unique discipline to check the hypotheses of stellar modelling
- Since 1970, important progresses
- GOLDEN AGE with SOHO satellite since 1995
- New constraints on rotation, magnetic fields and mixing
- Present informations on the solar core

VERS UNE VISION DYNAMIQUE DES ETOILES

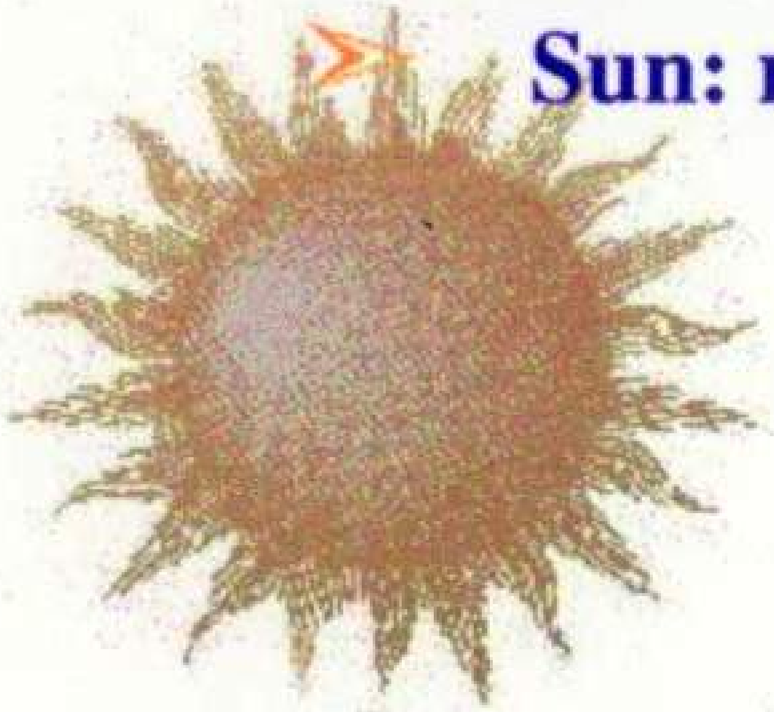




DSM - DAPNIA SAp

PROGRESS IN SOLAR (STELLAR) INTERIOR MODELLING

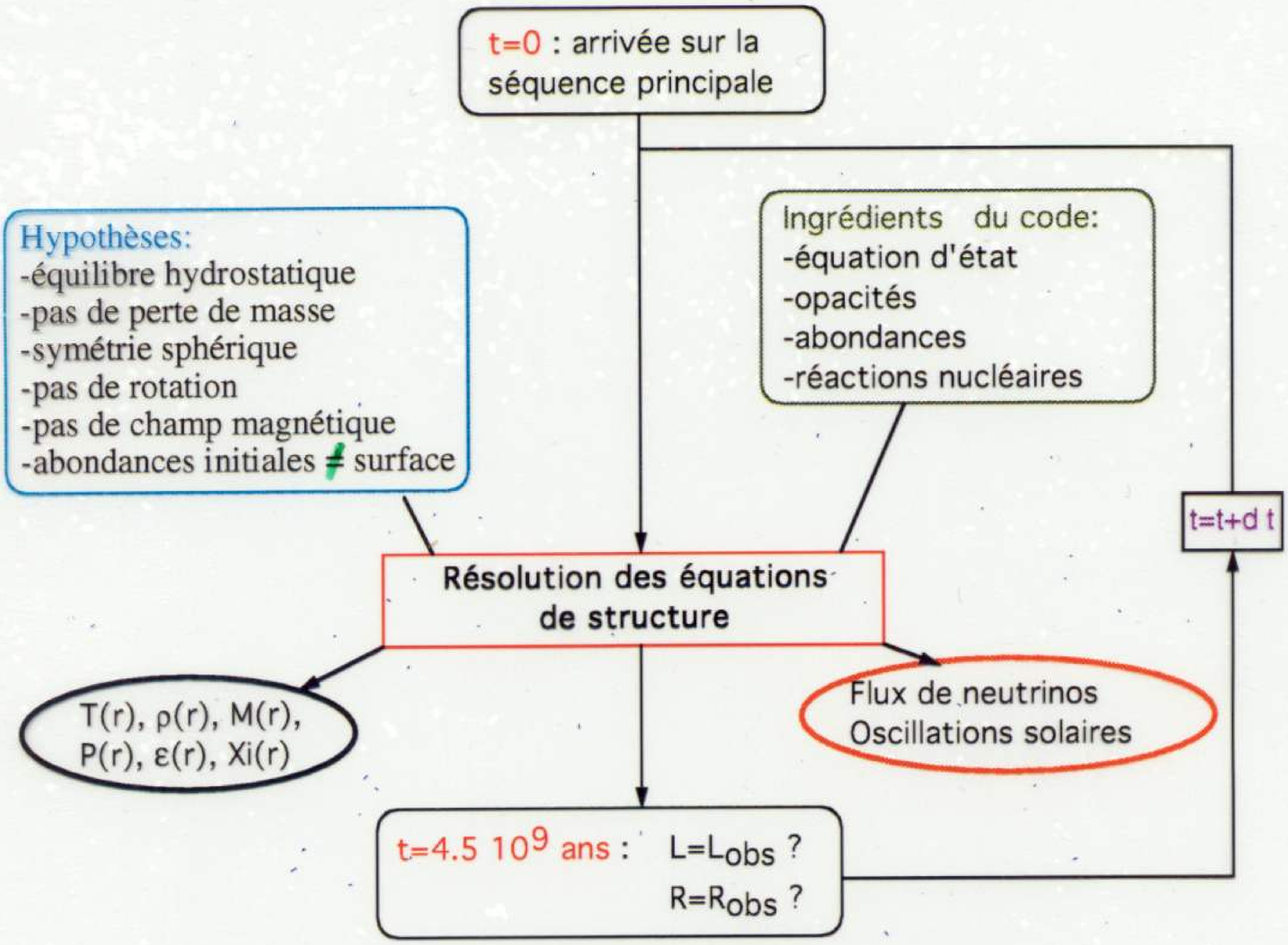
- **Theoretical assumptions based on gravity, electromagnetism, weak or strong interaction**
- **Advanced physics: atomic, nuclear, plasma physics**
- **One dimensional calculation showing the great stages of evolution, static star**
- **Observations: colours, photospheric abundances**
- **Sun: mass, radius, age**



- Astero **(Helio)seismology: Very ambitious task**
- **Verification of the assumptions**
- **Go beyond the minimal hypotheses, effect of rotation and magnetic field**
- **Static vision -> Dynamical vision**
- **Where are we and why ?**

Le modèle solaire

Equations de structure



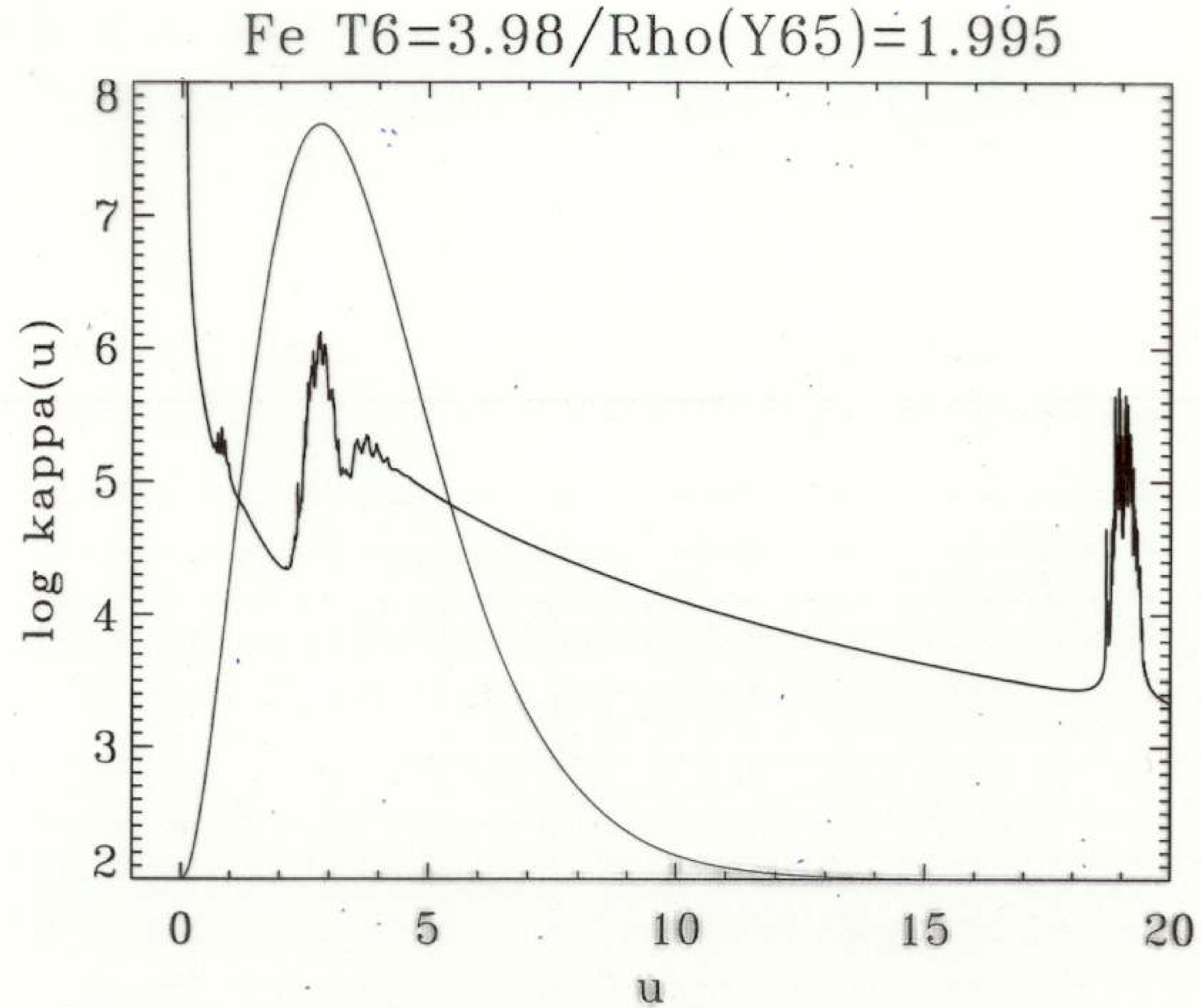
Eq hyd: $dP/dr = - M(r)\, G / r^2\, \rho$

Cons masse: $dM/dr = 4\pi\, r^2 \rho$

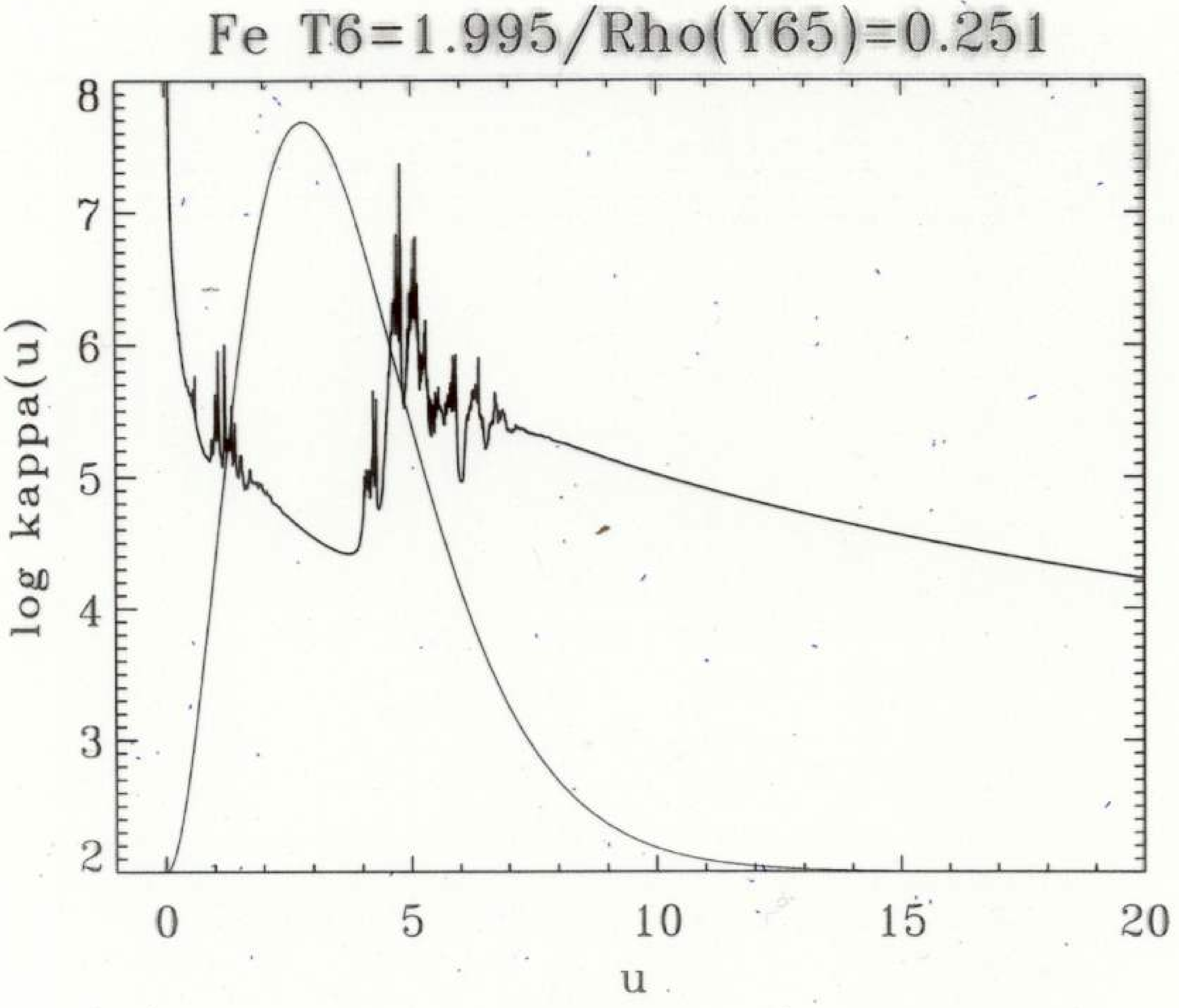
Eq thermique: $dL/dr = 4\pi r^2 \rho(\varepsilon_{nucl} - TdS/dt)$

Régime radiatif: $dT/dr = -3/4ac\ \kappa\rho(r)/\ 4\pi r^2$

Régime convectif: $dT/dr = (\Gamma_2 - 1)/\Gamma_2\ T/P\ dP/dr$

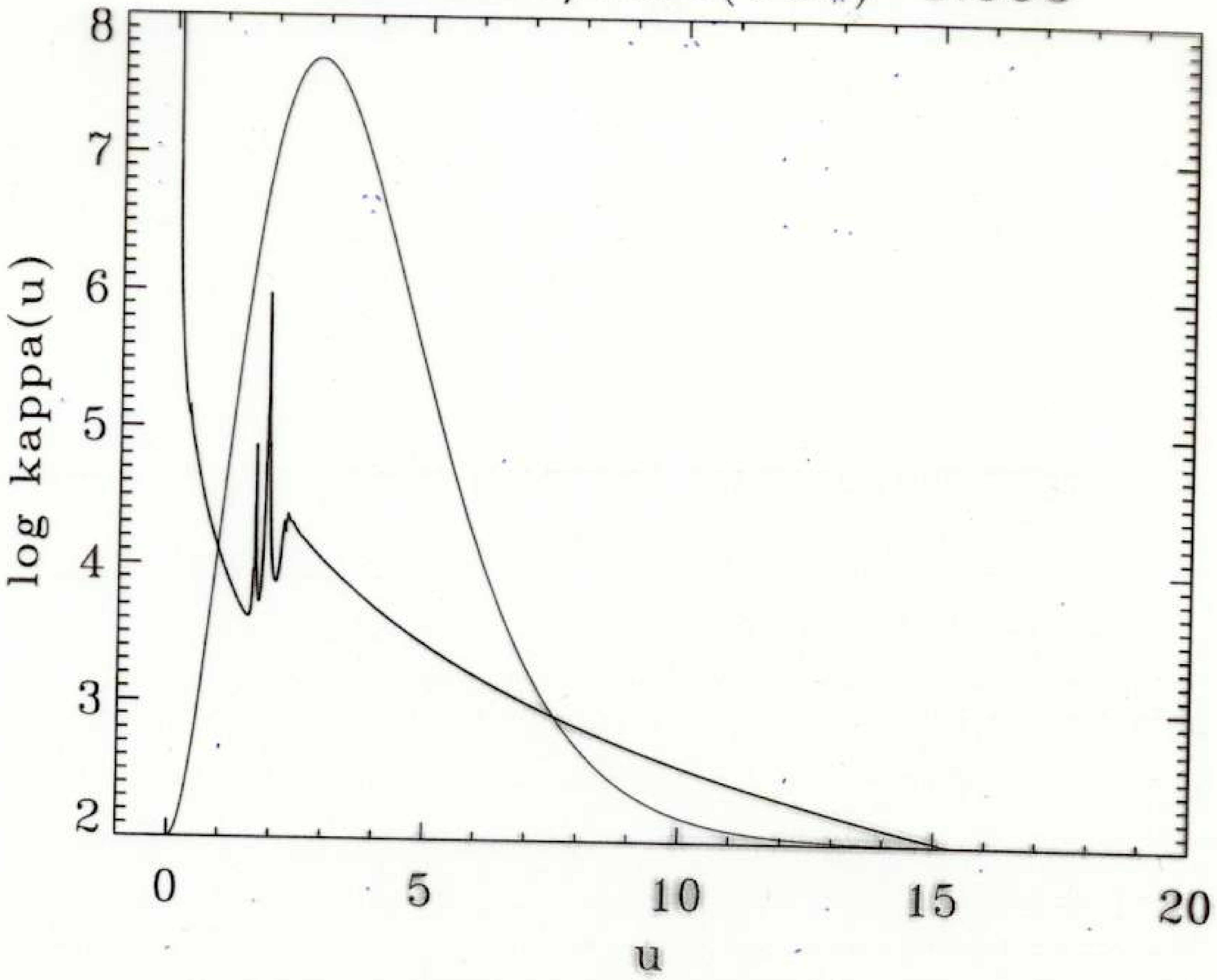


Fe T6=3.98/Rho(Y65)=1.995
log kappa(u)
8
7
6
5
4
3
2
0
5
10
15
20
u

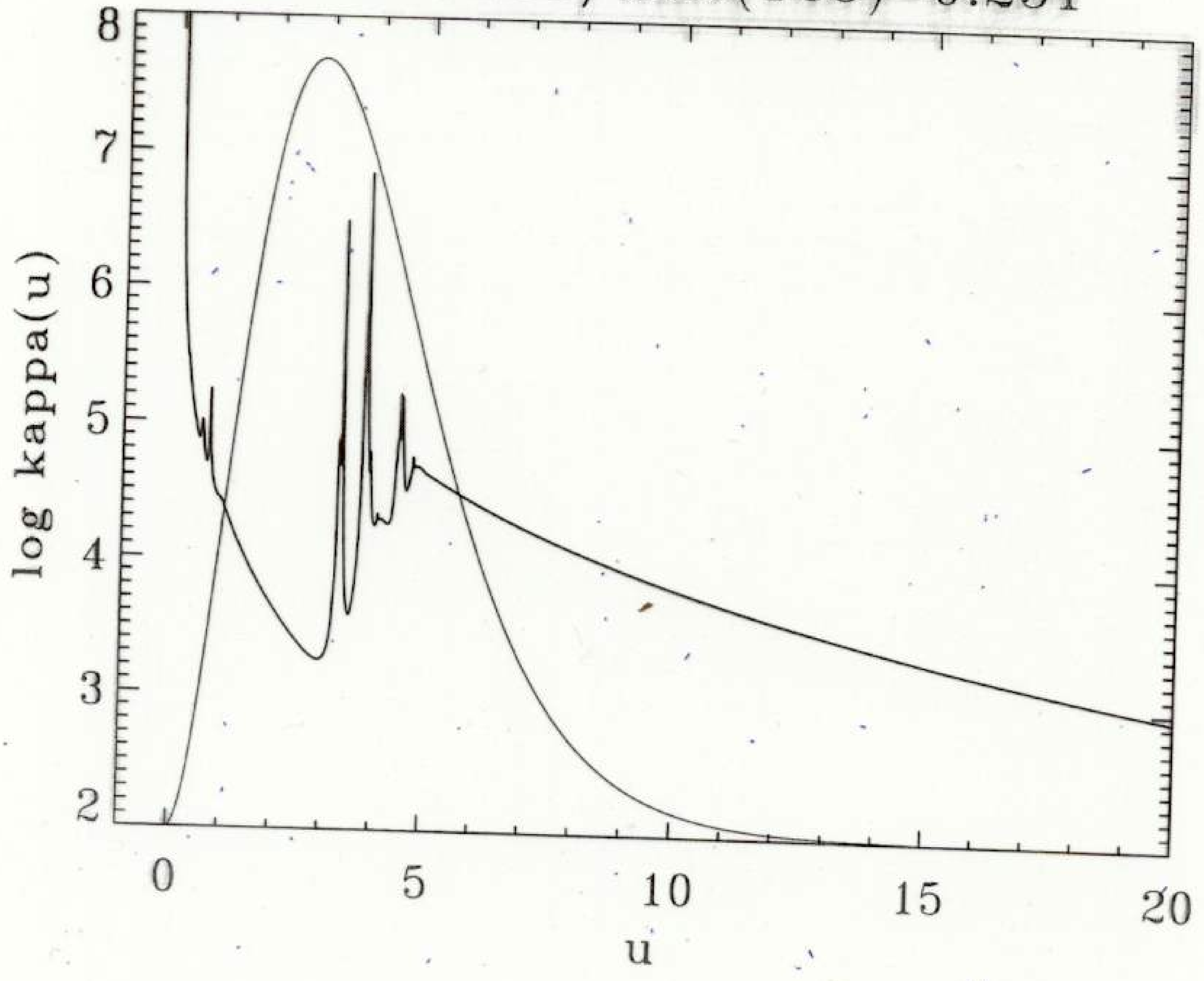


Fe T6=1.995/Rho(Y65)=0.251
log kappa(u)
8
7
6
5
4
3
2
0
5
10
15
20
u

O T6=3.98/Rho(Y65)=1.995



O T6=1.995/Rho(Y65)=0.251



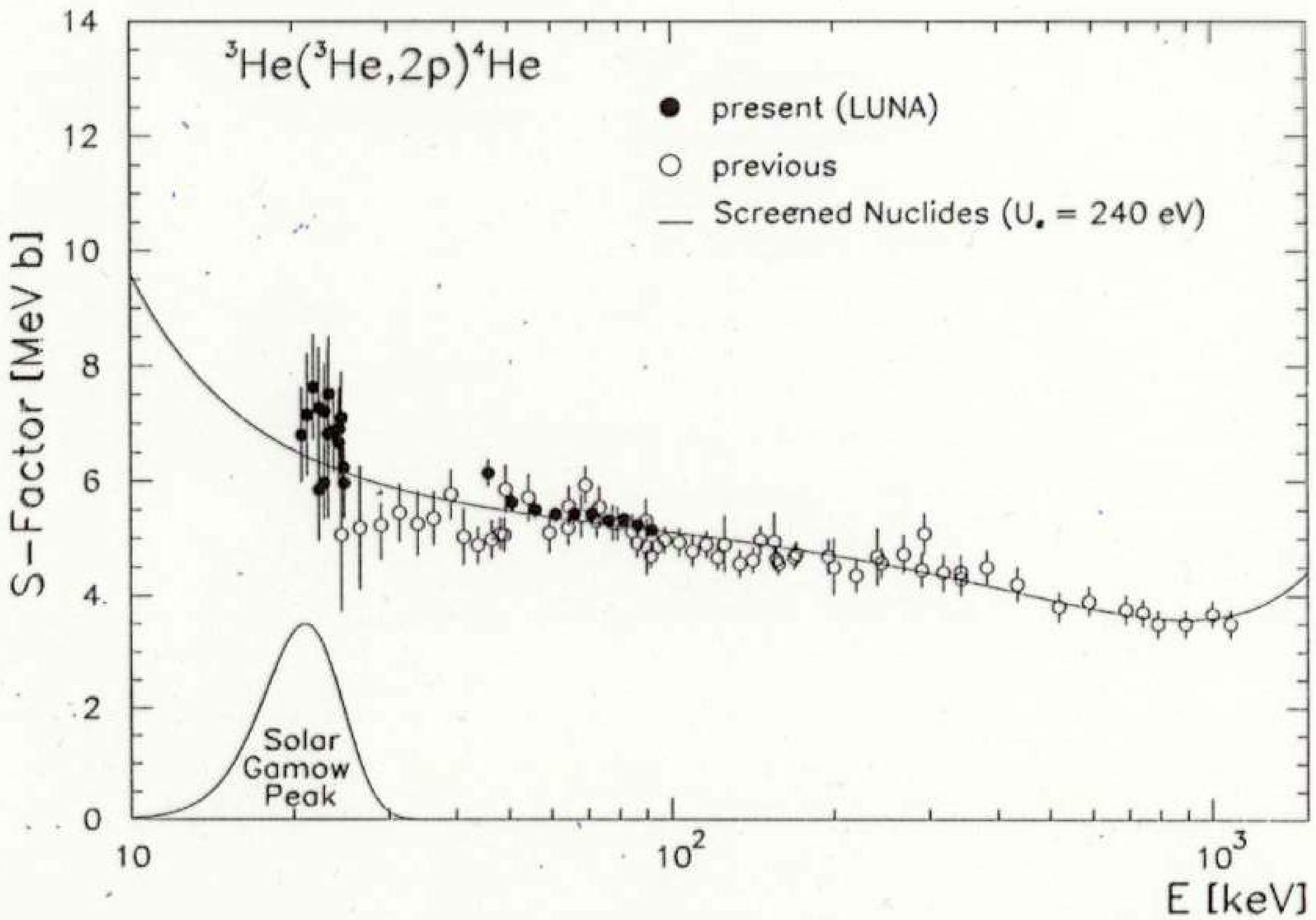
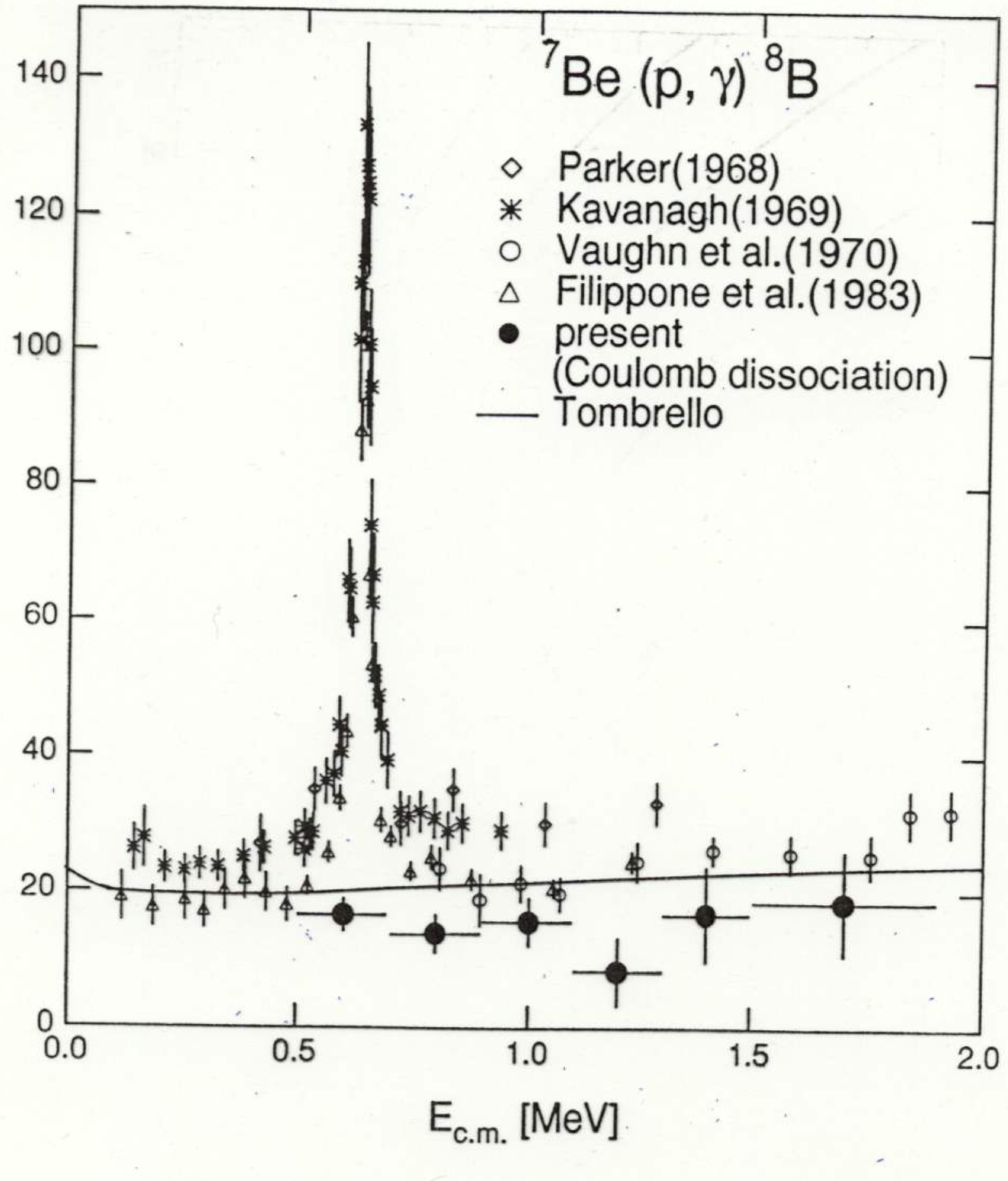


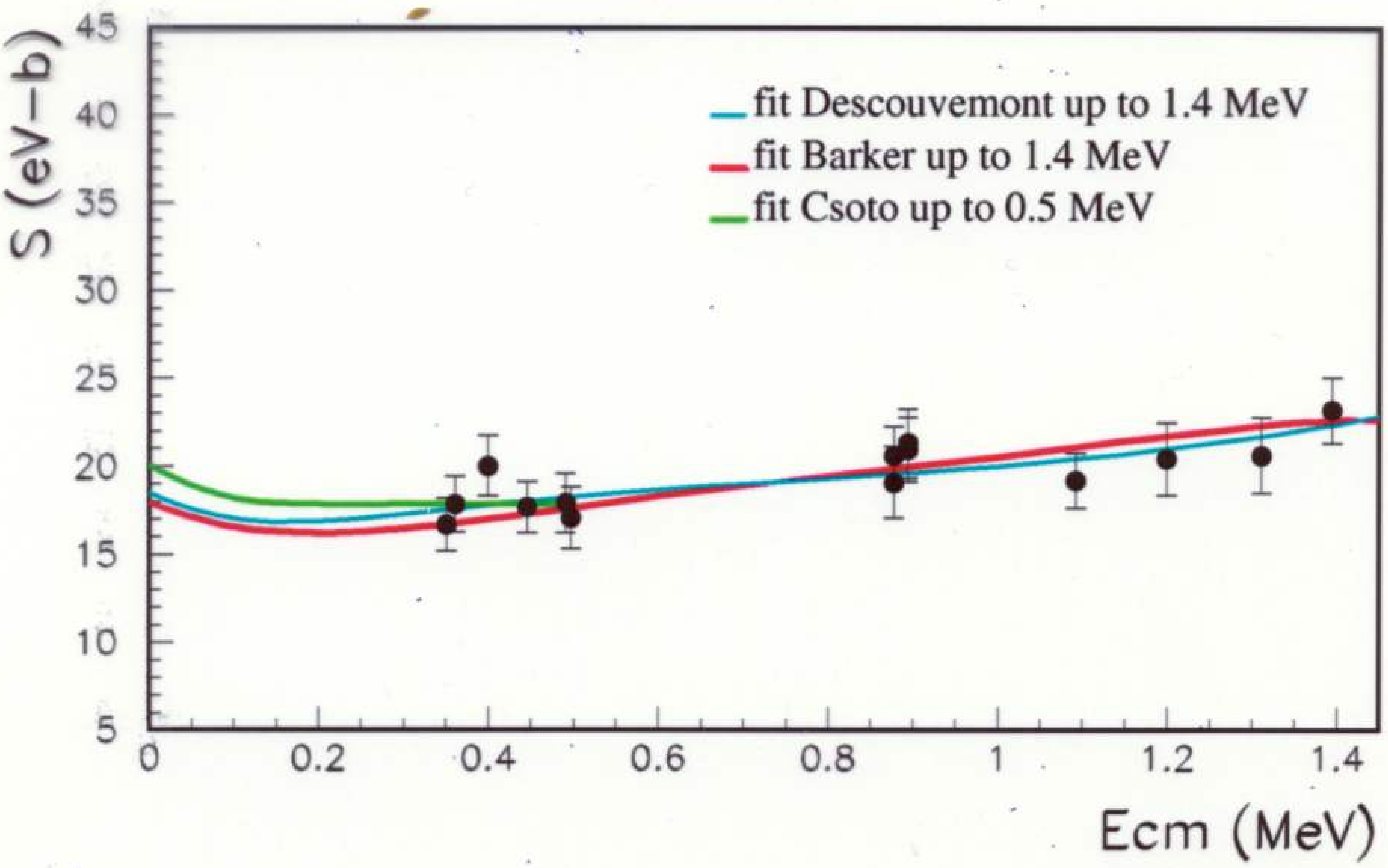
FIG. 2: This figure is adapted from Fig. 9 of Arpesella *et al.* (1997), a recent paper by the LUNA Collaboration. The measured $S(E)$ factor for the $^3He(^3He, 2p)^4He$ reaction is shown and a fit with a screening potential U_e is illustrated. The solar Gamow peak is shown in arbitrary units. The data shown here correspond to a bare nucleus value at zero energy of $S(0) = 5.4 MeV\ b$ and a value at the Gamow peak of $S(\text{Gamow Peak}) = 5.3$ MeV b.



$^7Be\ (p, \gamma)\ ^8B$
Parker(1968)
Kavanagh(1969)
Vaughn et al.(1970)
Filippone et al.(1983)
present
(Coulomb dissociation)
Tombrello
S_{17} [eV-b]
$E_{c.m.}$ [MeV]
0
20
40
60
80
100
120
140
0.0
0.5
1.0
1.5
2.0

Fig. 5

$^7Be(p,\gamma)^8B$



from Hammache et al. 1999

S(0) = 19.2 +- 1.3 keV.b

S(18 keV) = 18.8 keV.b

Extrapolation must be constrained by the quadrupole moment measurement

Screening effect

Dzitko, Turck-Chiege, Delbourgo, Lagrange
ApJ 447, (1995), 428

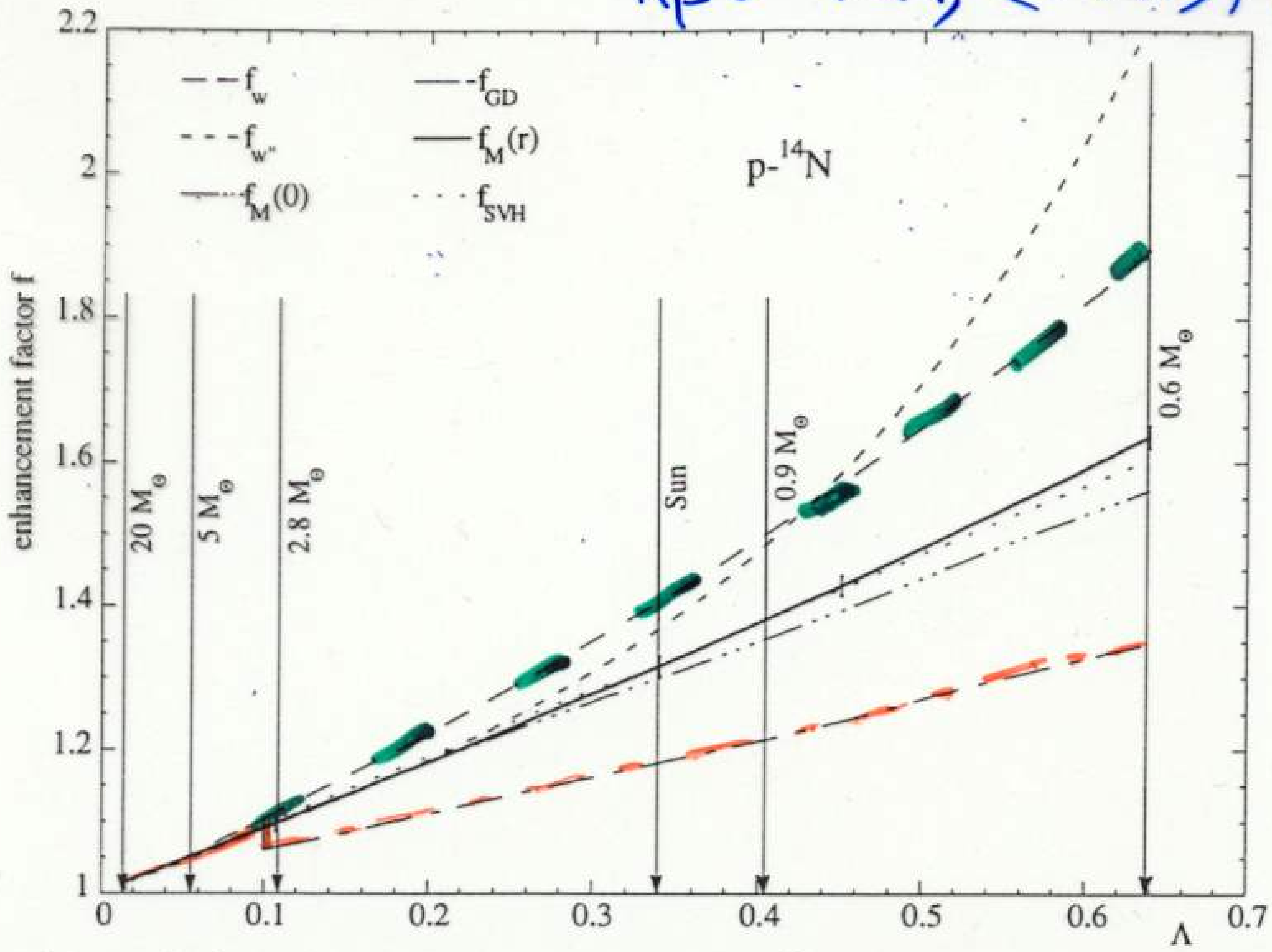


FIG. 3.—Comparison of the screening factors given by the various formalisms for the (p, ^{14}N) reaction, in central stellar conditions, vs. the screening strength parameter Λ; f_w is S54 WS, f_{w^*} is the extended WS, $f_M(0)$ is Mitler's prescription, f_{SVH} and f_{GD} are respectively SVH and GDGC screening, and $f_M(r)$ is the enhancement factor obtained with radial-dependent formalism.

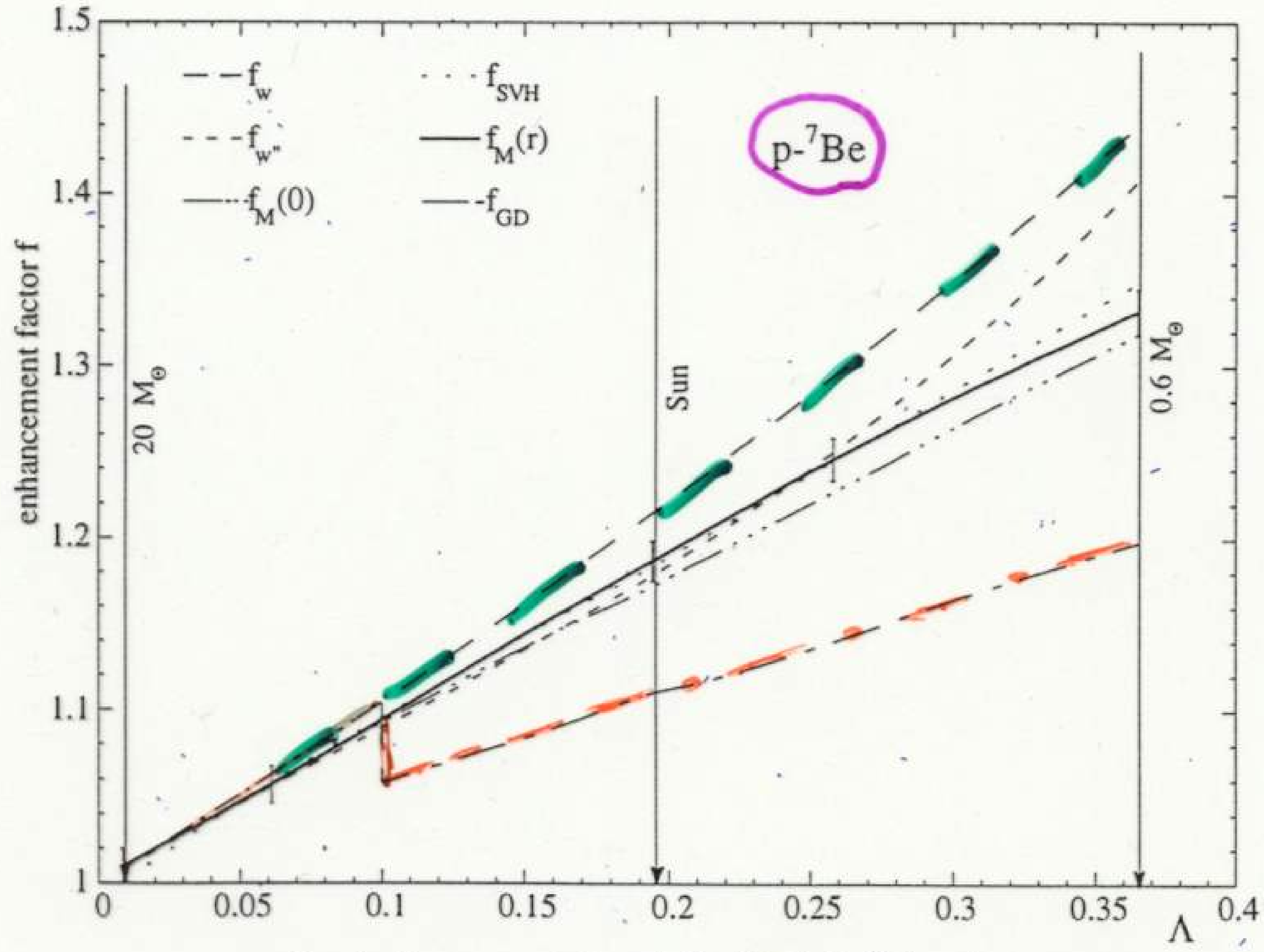


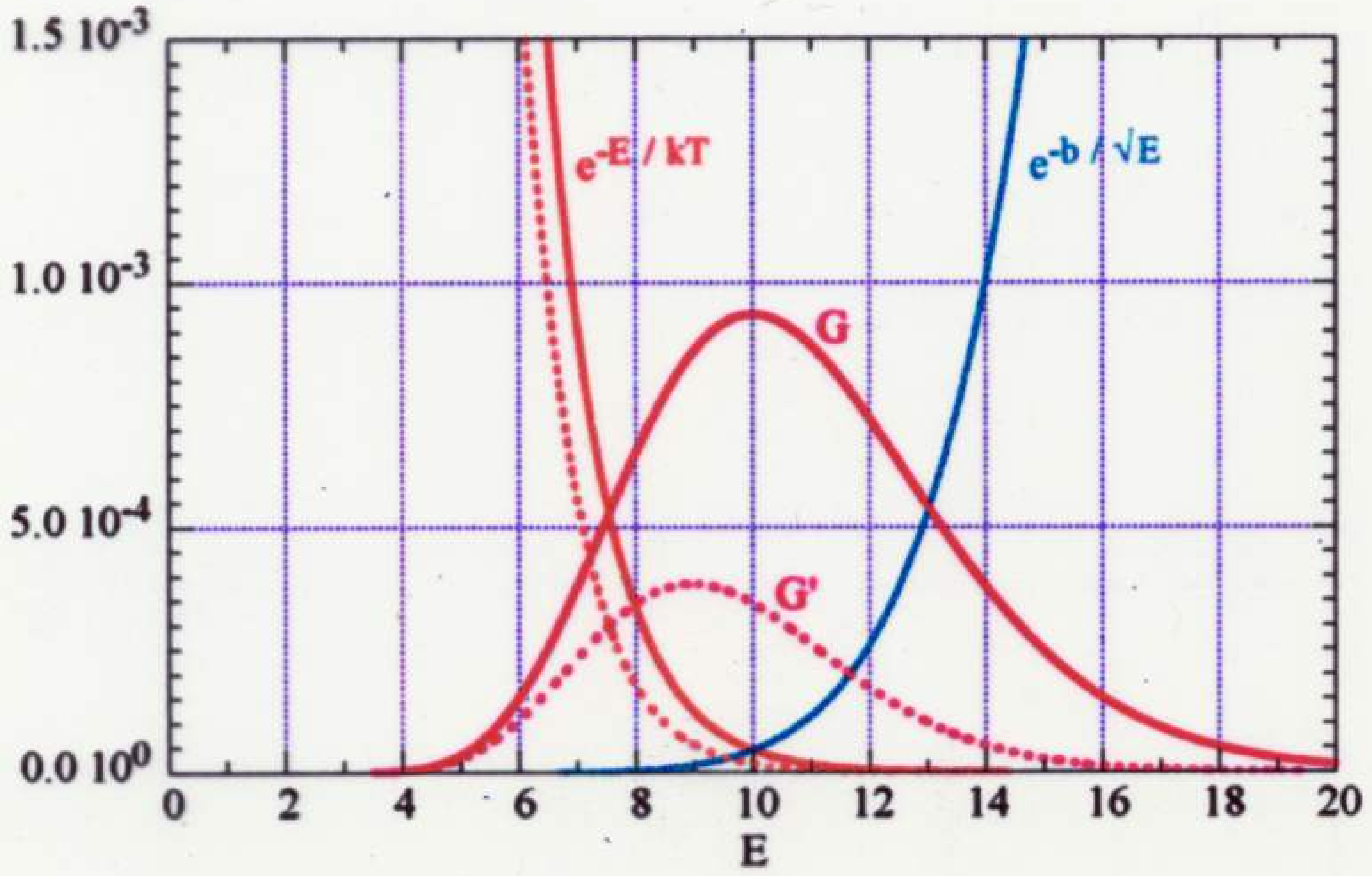
FIG. 4.—Same representation as in Fig. 3, for the (p, ^7Be) reaction.

Turck~ - 19

DEVIATION FROM MAXWELLIAN DISTRIBUTION

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

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



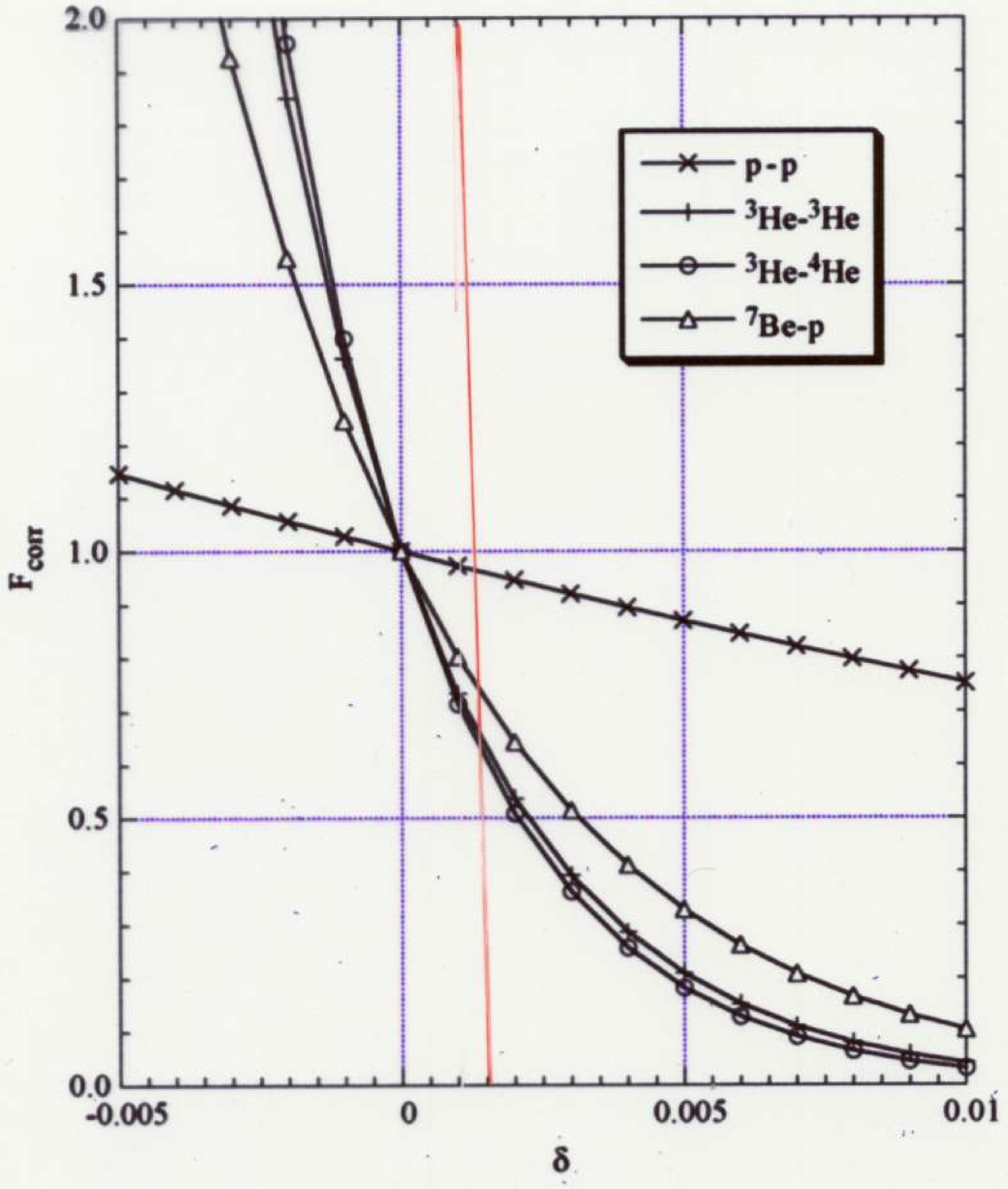
and

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

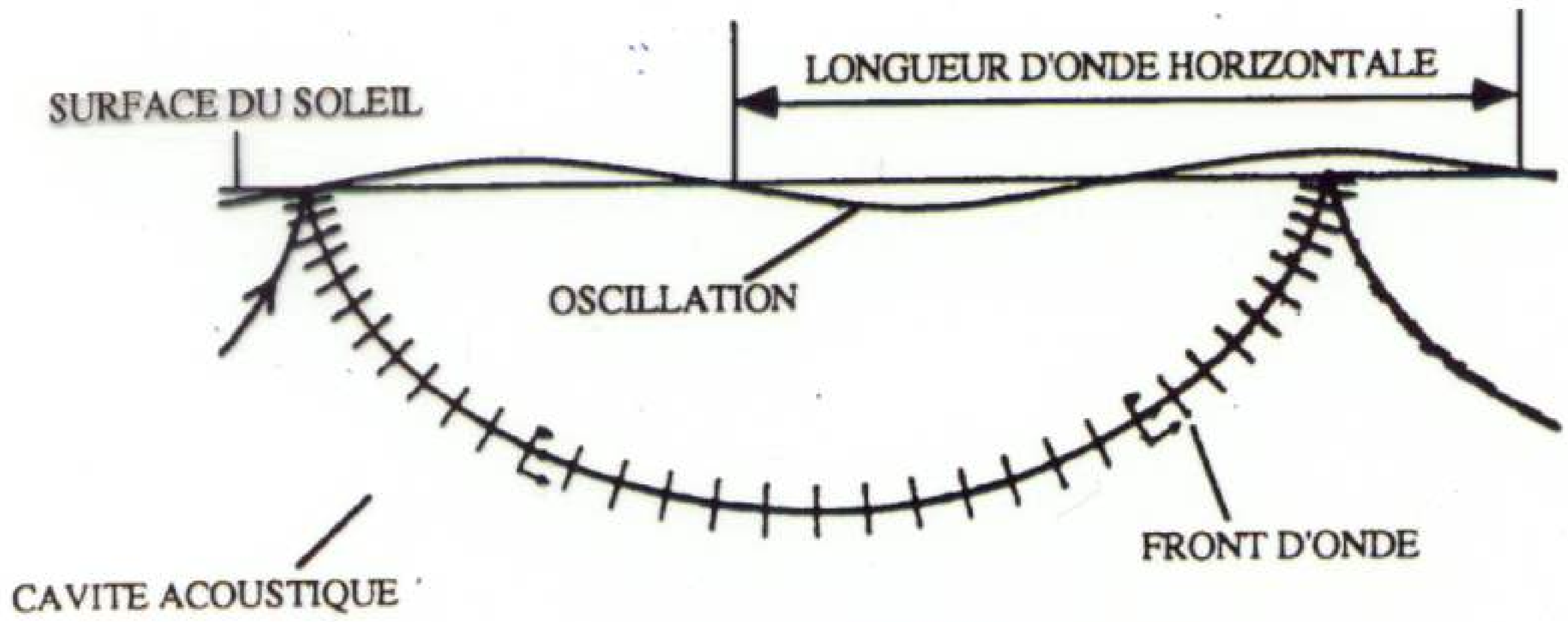
With : $kT = 1$, $E_0 = 10$, $\delta = 0.01$

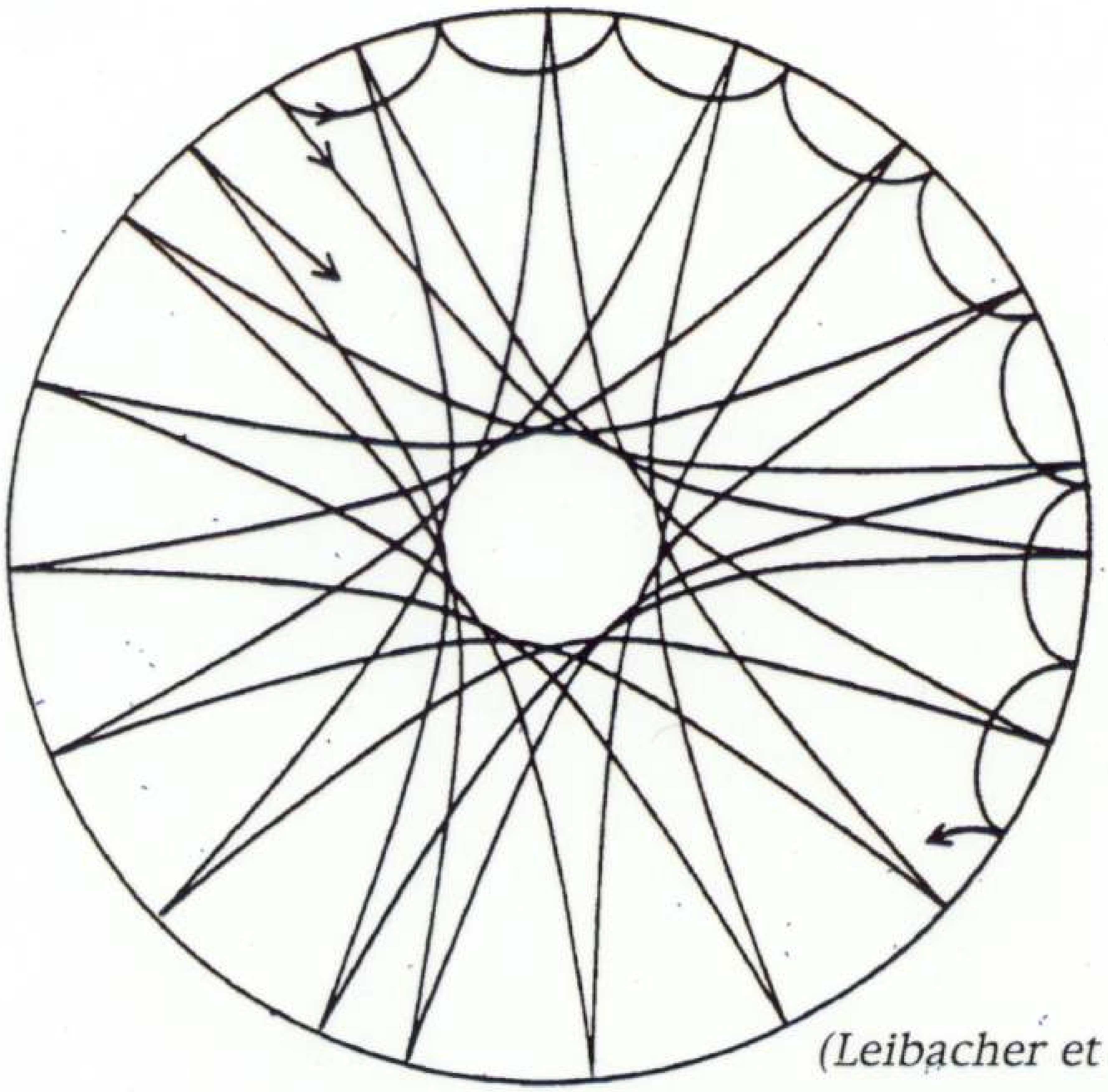
$E_{0\delta} = 0.87\ E_0$
$\Delta E_\delta = 0.77\ \Delta E$
$G(E_{0\delta}) = 0.37\ G(E_0)$
$(r_{12})_\delta = 0.30\ r_{12}$

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



Ondes acoustiques dans le Soleil





(Leibacher et al 1985)

Soleil objet à symétrie sphérique

développement en terme d'harmoniques sphériques :

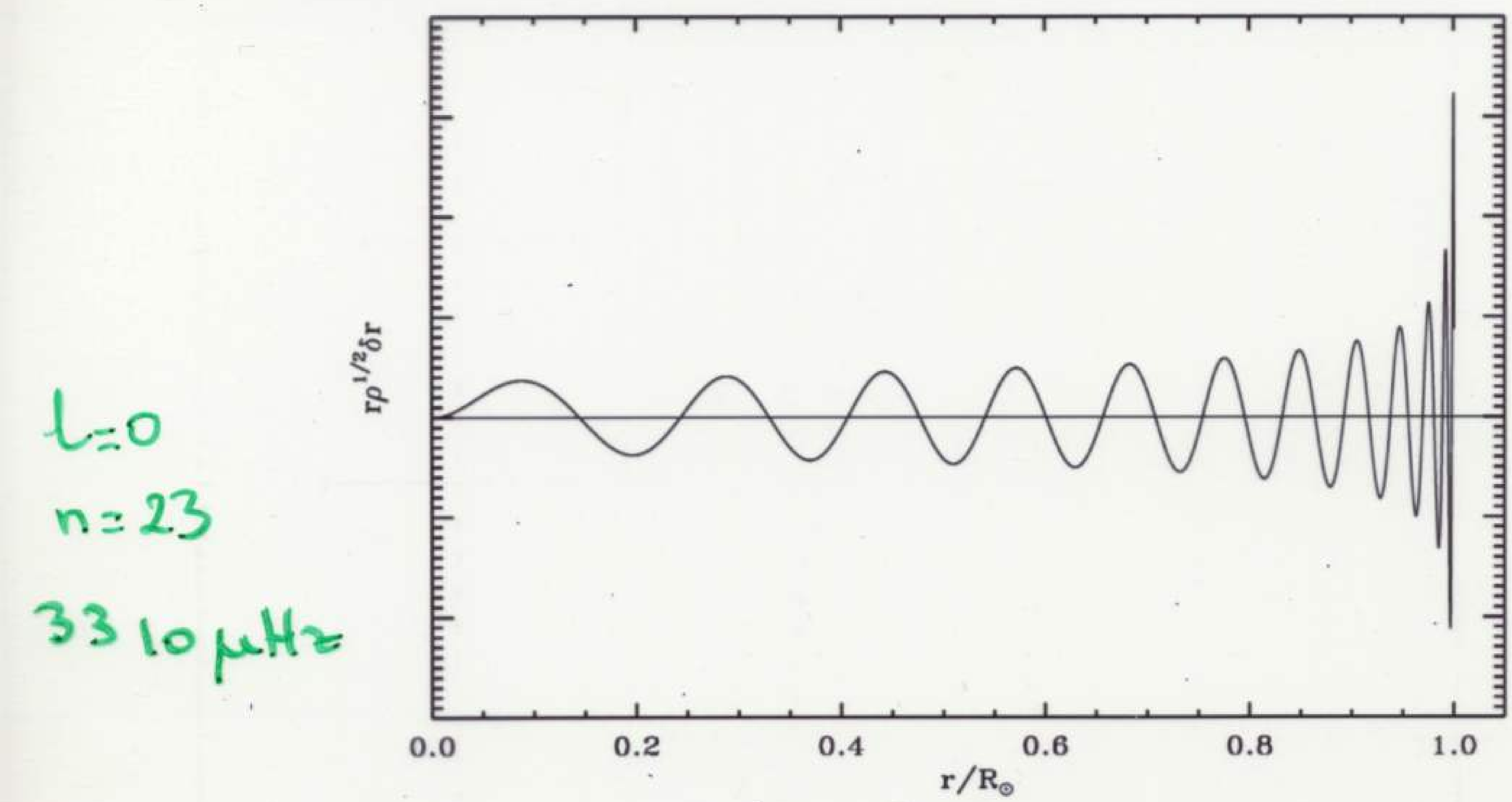
$$X_{l,m,n}(r,\theta,\phi,t) = X_{l,m,n}(r)Y_l^m(\theta,\phi)e^{-i\omega_{l,m,n}t}$$

mode repéré par 3 nombres quantiques :

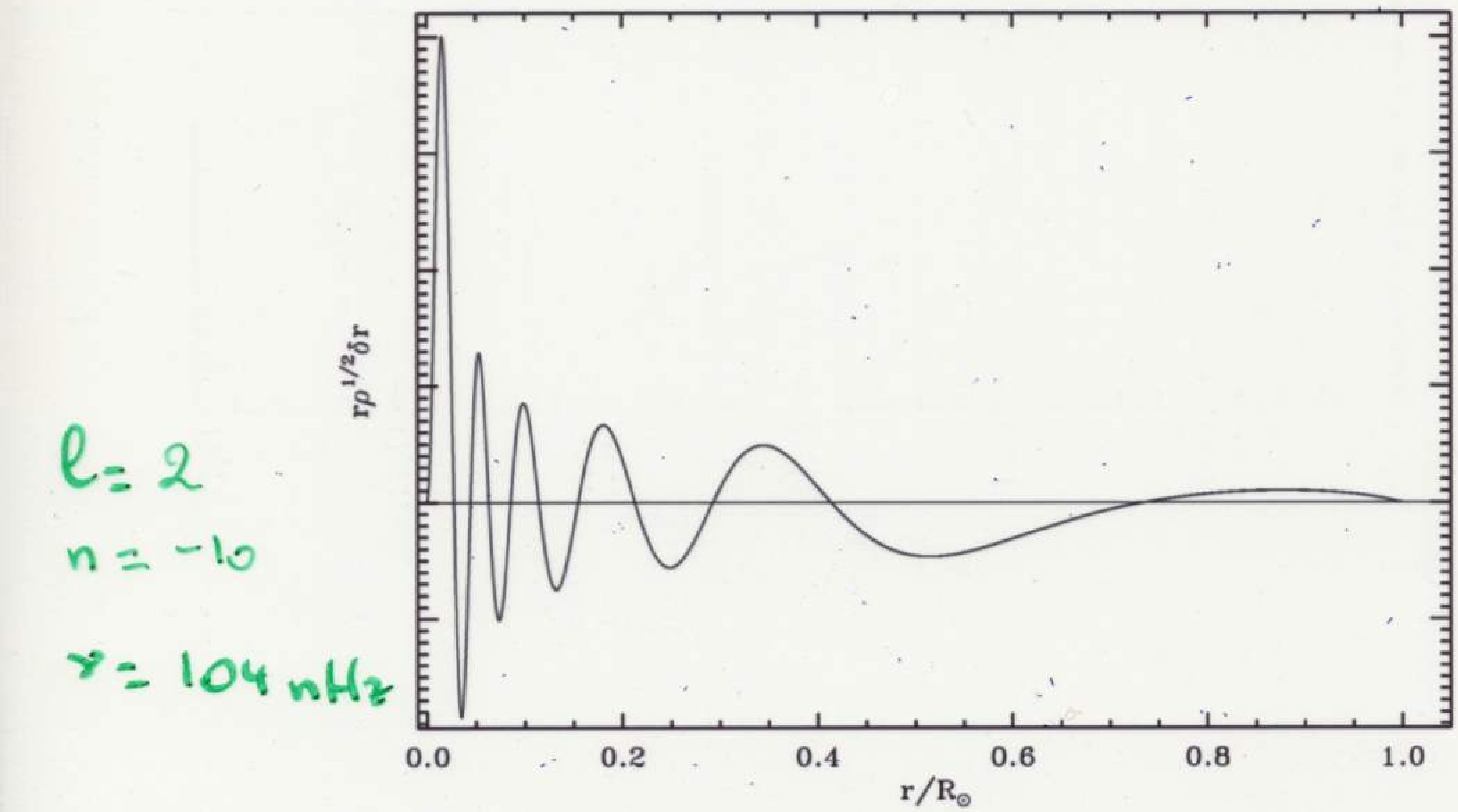
- l: degré du mode.
- m: -l < m < +l .Ordre azimutal.
- n: ordre radial

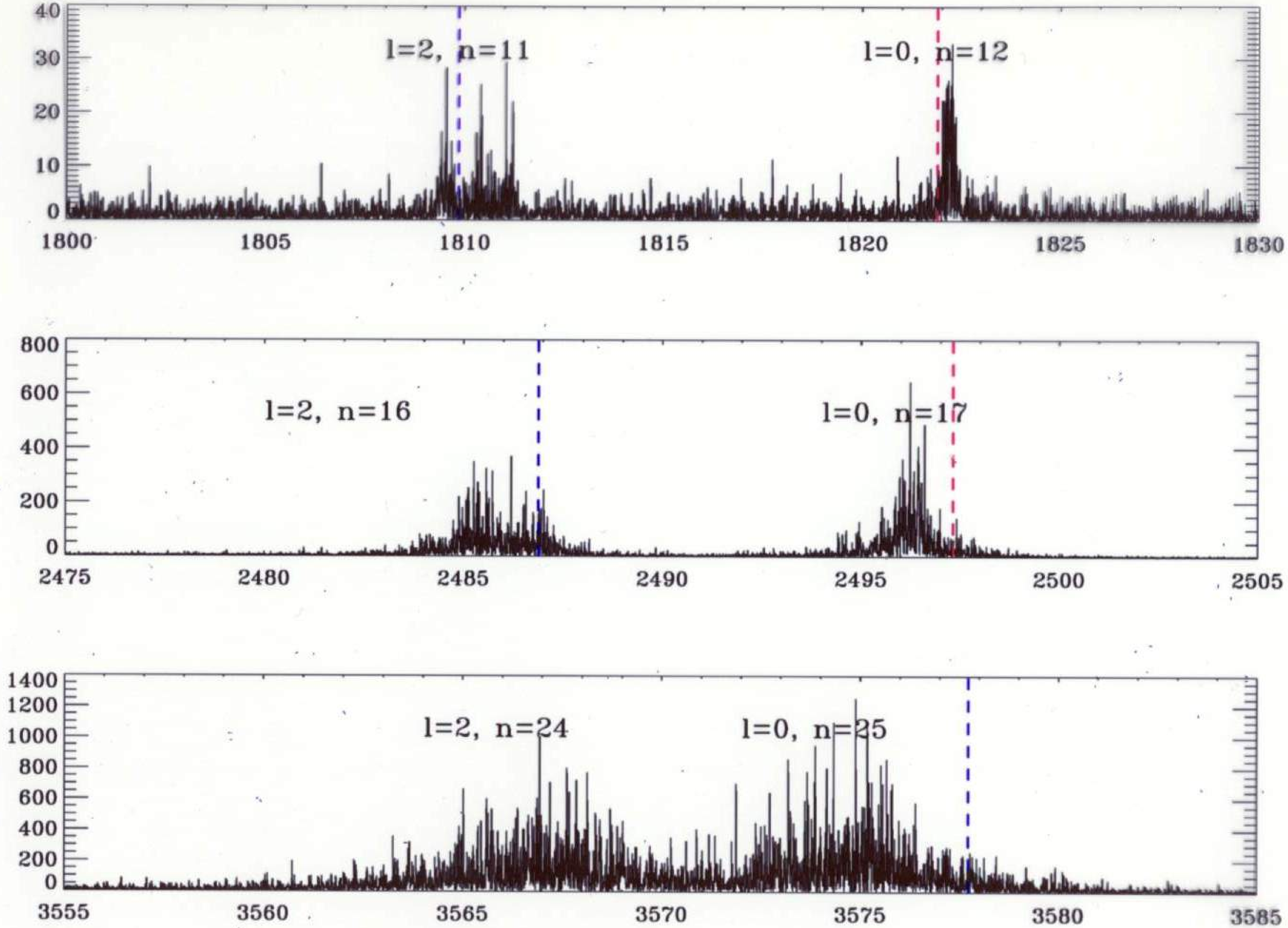
Sensitivity of the modes to the solar structure

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



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

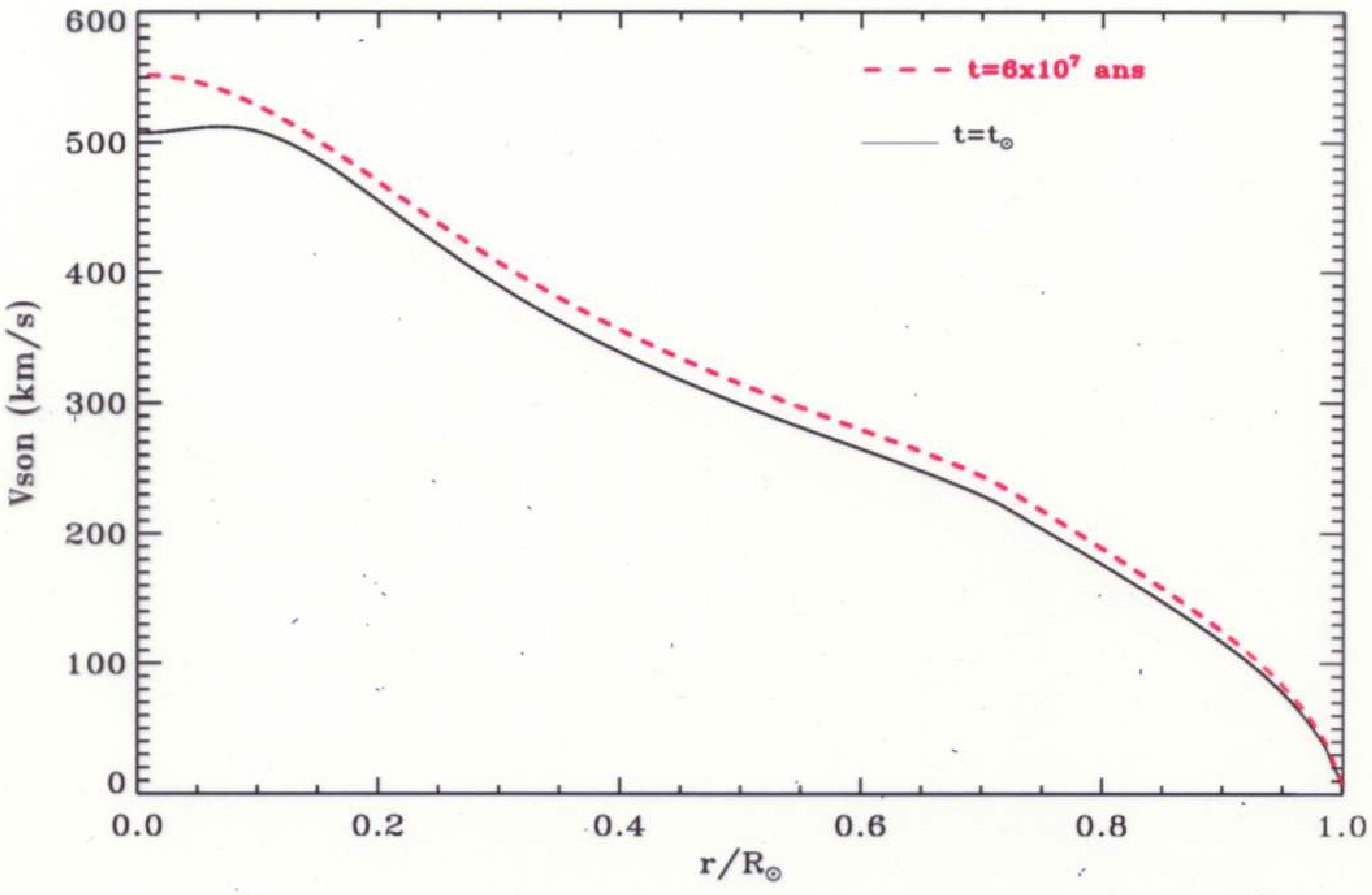




l=2, n=11
l=0, n=12
0
10
20
30
40
1800
1805
1810
1815
1820
1825
1830
l=2, n=16
l=0, n=17
0
200
400
600
800
2475
2480
2485
2490
2495
2500
2505
l=2, n=24
l=0, n=25
0
200
400
600
800
1000
1200
1400
3555
3560
3565
3570
3575
3580
3585

WHICH ACCURACY DO WE NEED ?

Δ T/T = +13% $\Delta\mu/\mu$ =+34% Δ c/c= -9%



From SuperKamiokande

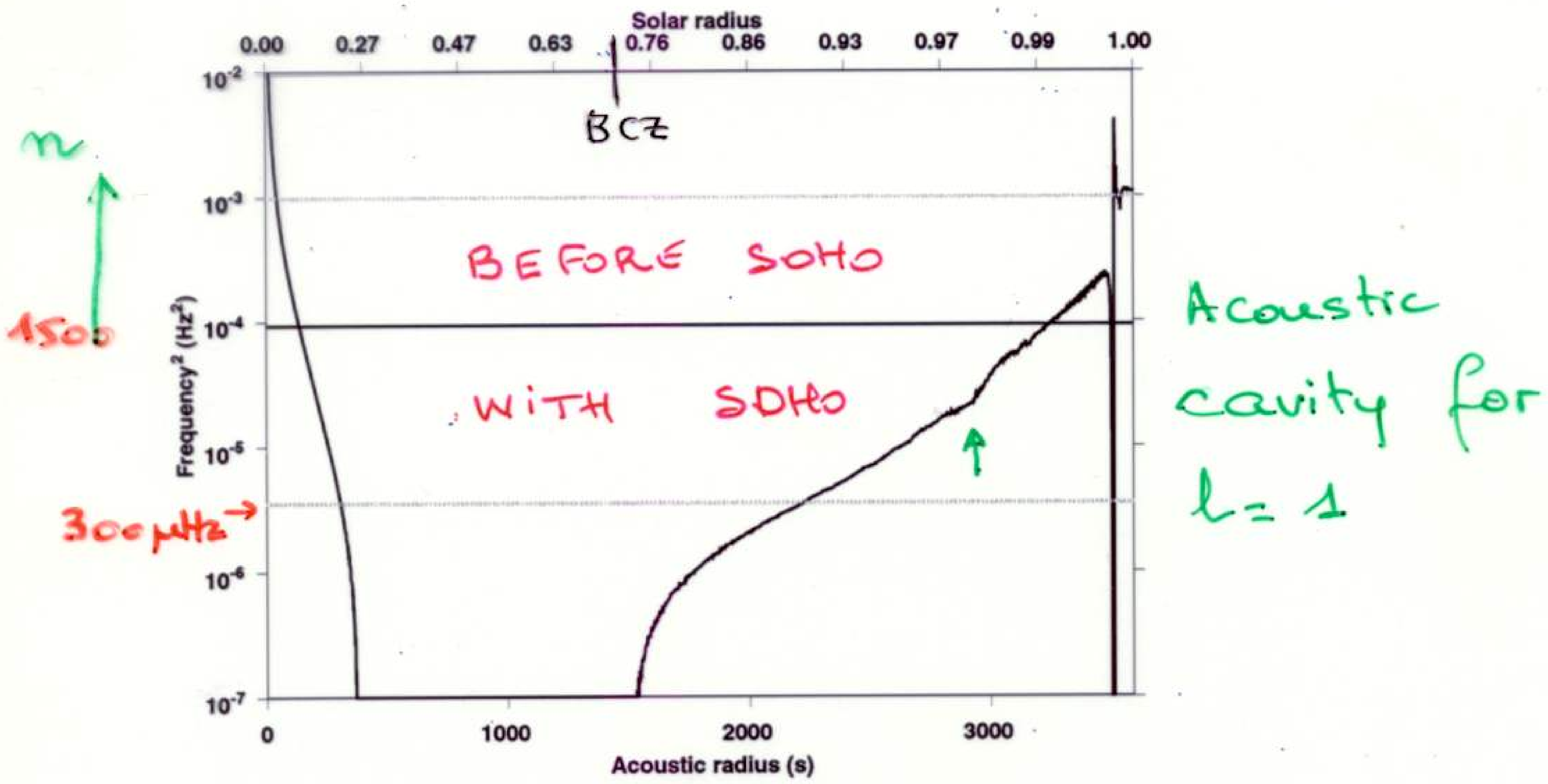
Neutrino detection/Neutrino prediction = 0. 5

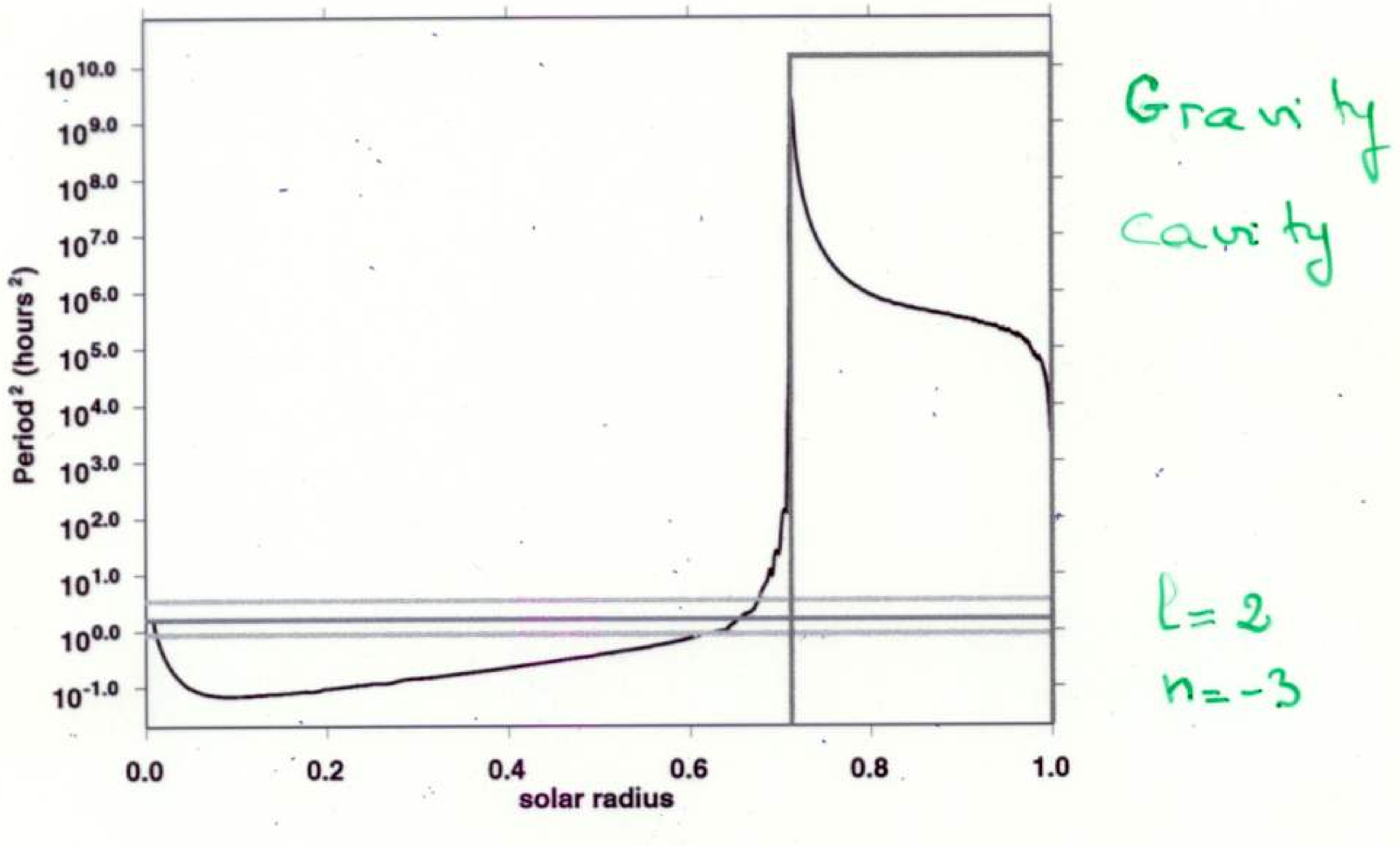
ΔT/T = 2 %   => Δ c/c = 1% or less   **accuracy about 10^{-5} !**

$\Delta\nu$ core/ν tot =1-5%

Turck-Chieze, Brun, Garcia, Venice 1999

Solar cavity



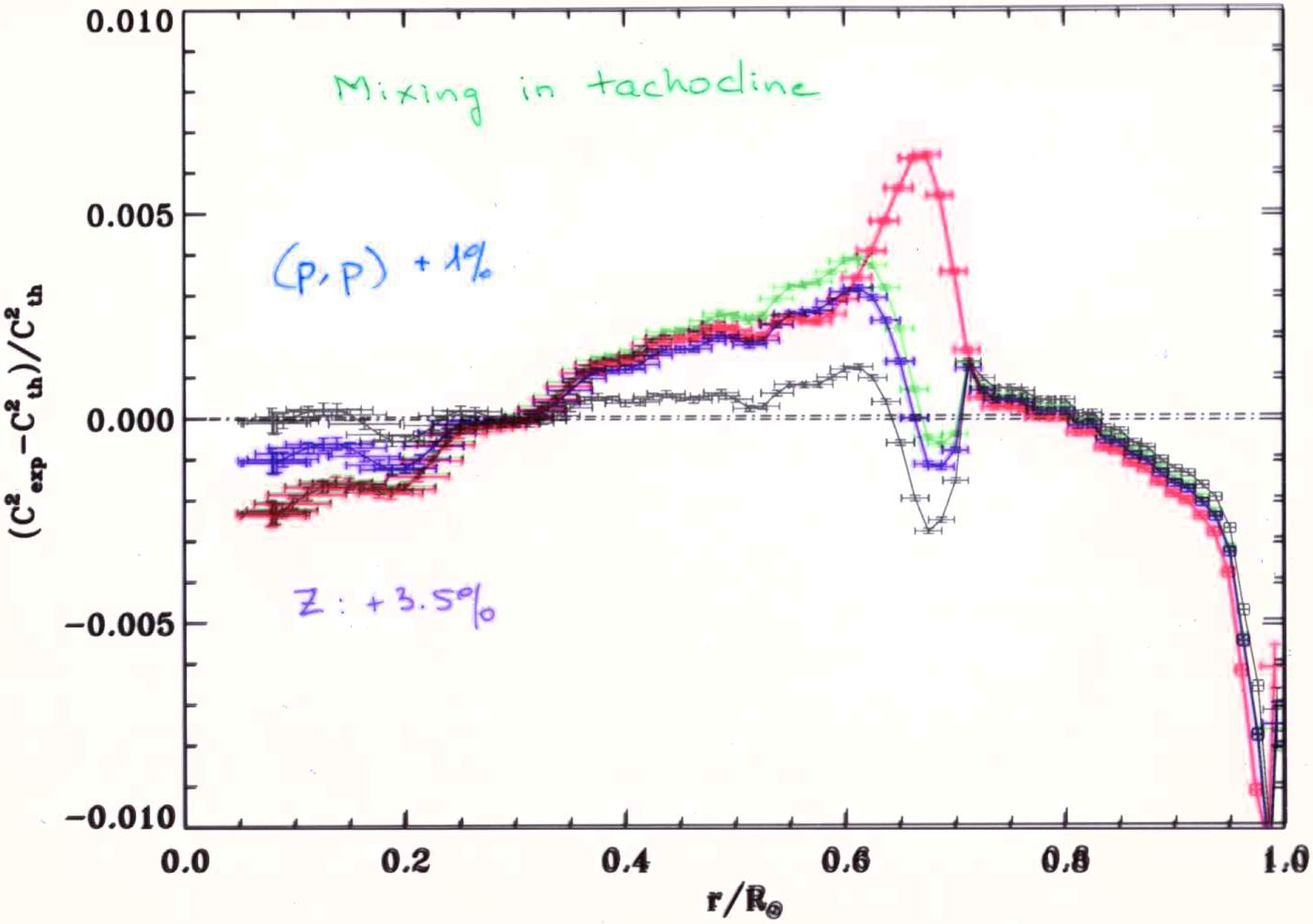


from Turck-Chièze, et al 2000
Lopes 1999, 2000

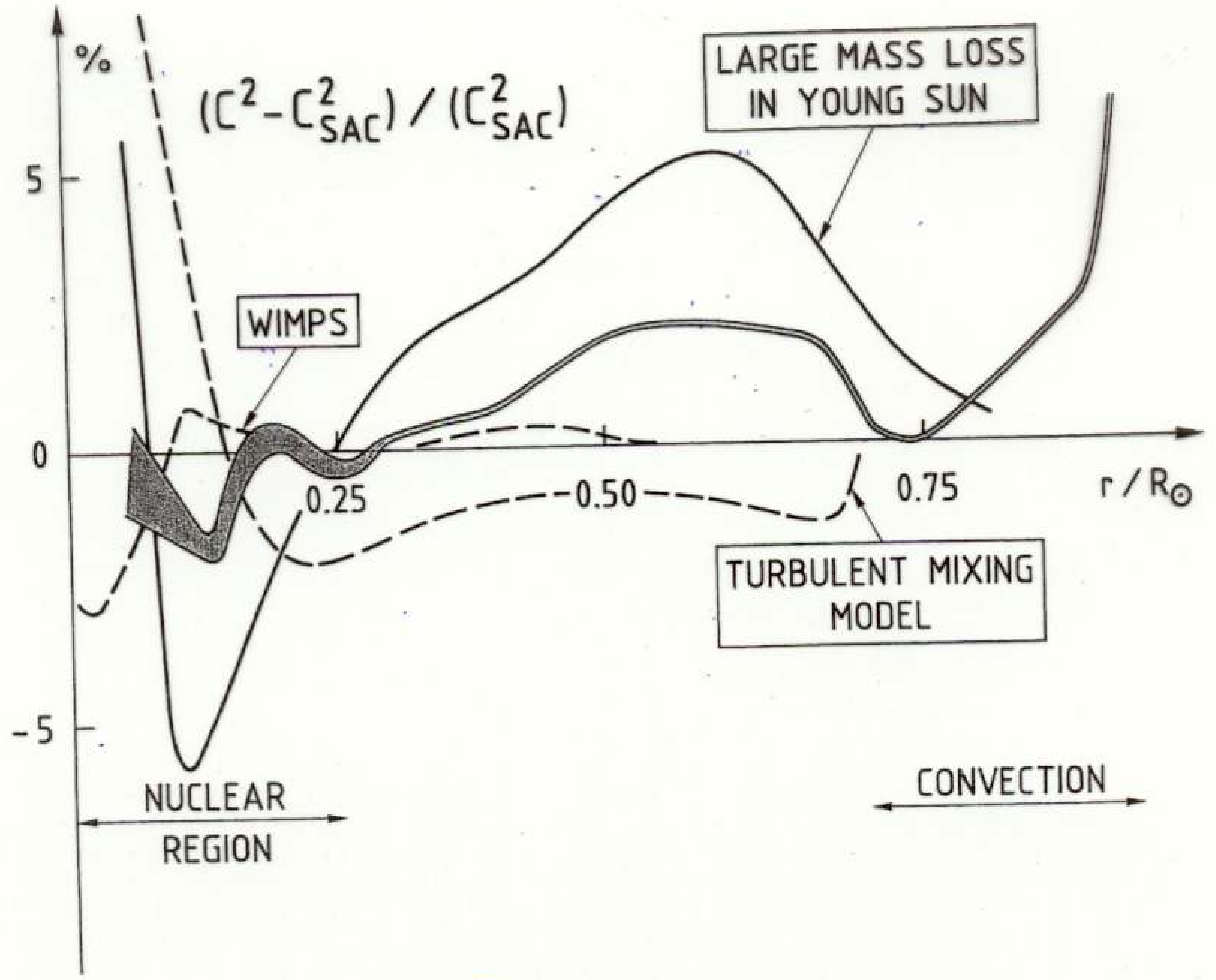
Table I. Sensitivity of the sound speed to the physical processes

Quantity	variation	$\Delta c^2/c^2$ variation
T	1 %	1%
κ	1 %	0.1 %
$X_c\,^{56}Fe$	4 %	0.1 %
$X\,^3He$	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

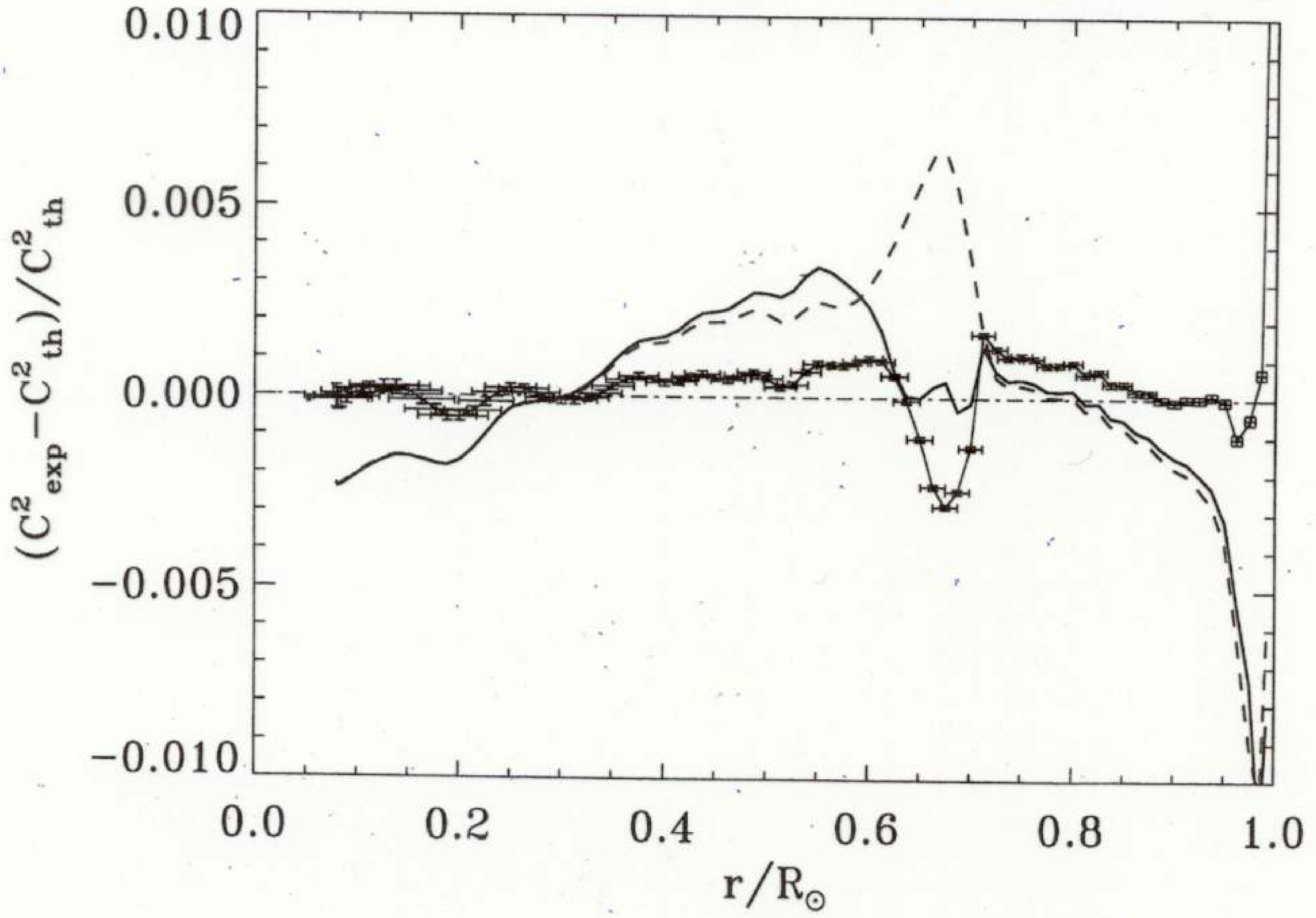
Seismic Model



Turck-Chieze, Couvidat, Kosovichev et al ApJ lett 2001

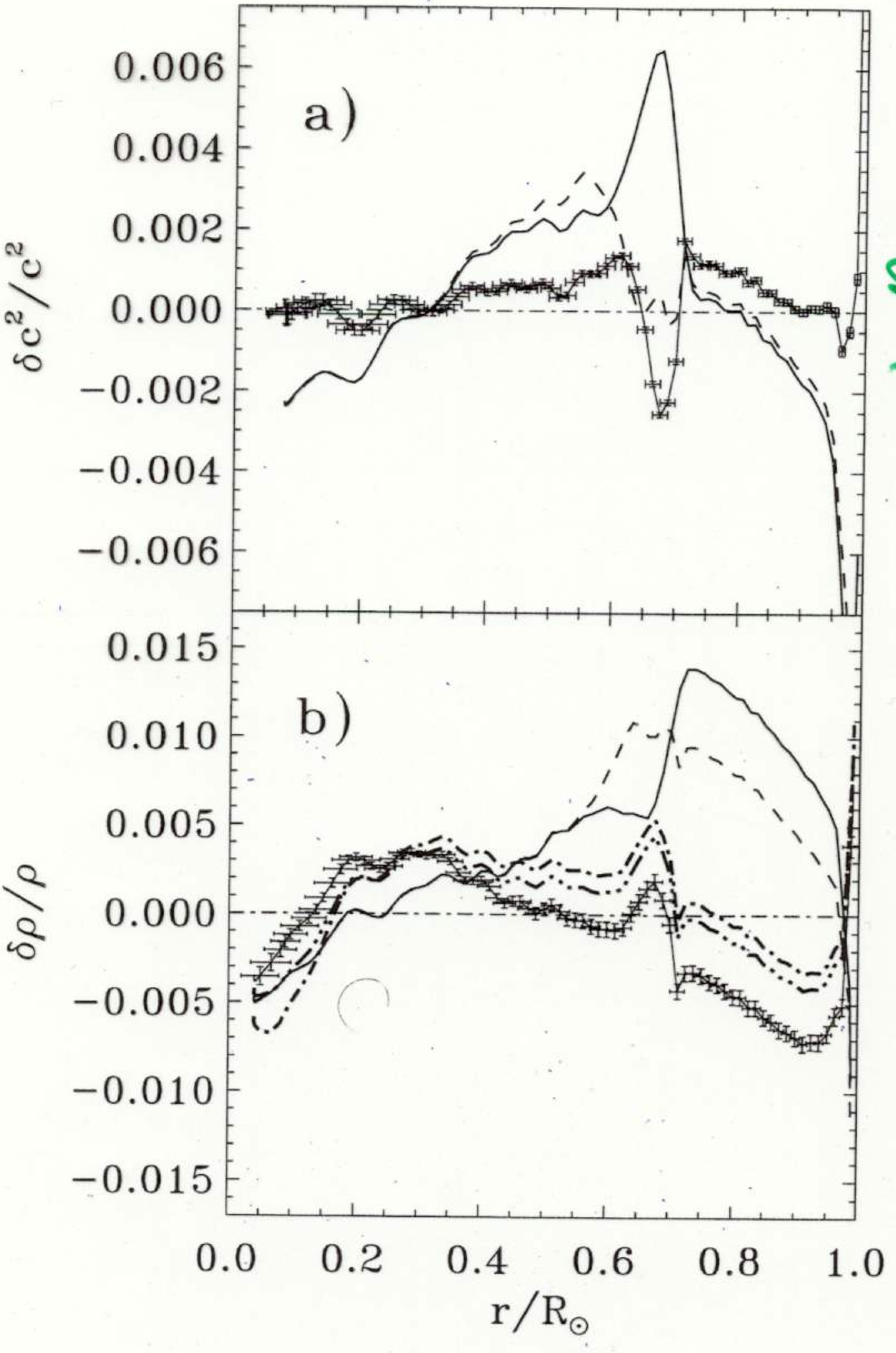


Gain of factor 20



Turck-Chieze et al 2001

 ApJ Lett July 2001



GOLF/MDI

Garcia et al. Sol.Phy 2001

Bertello et al. ApJ 2000

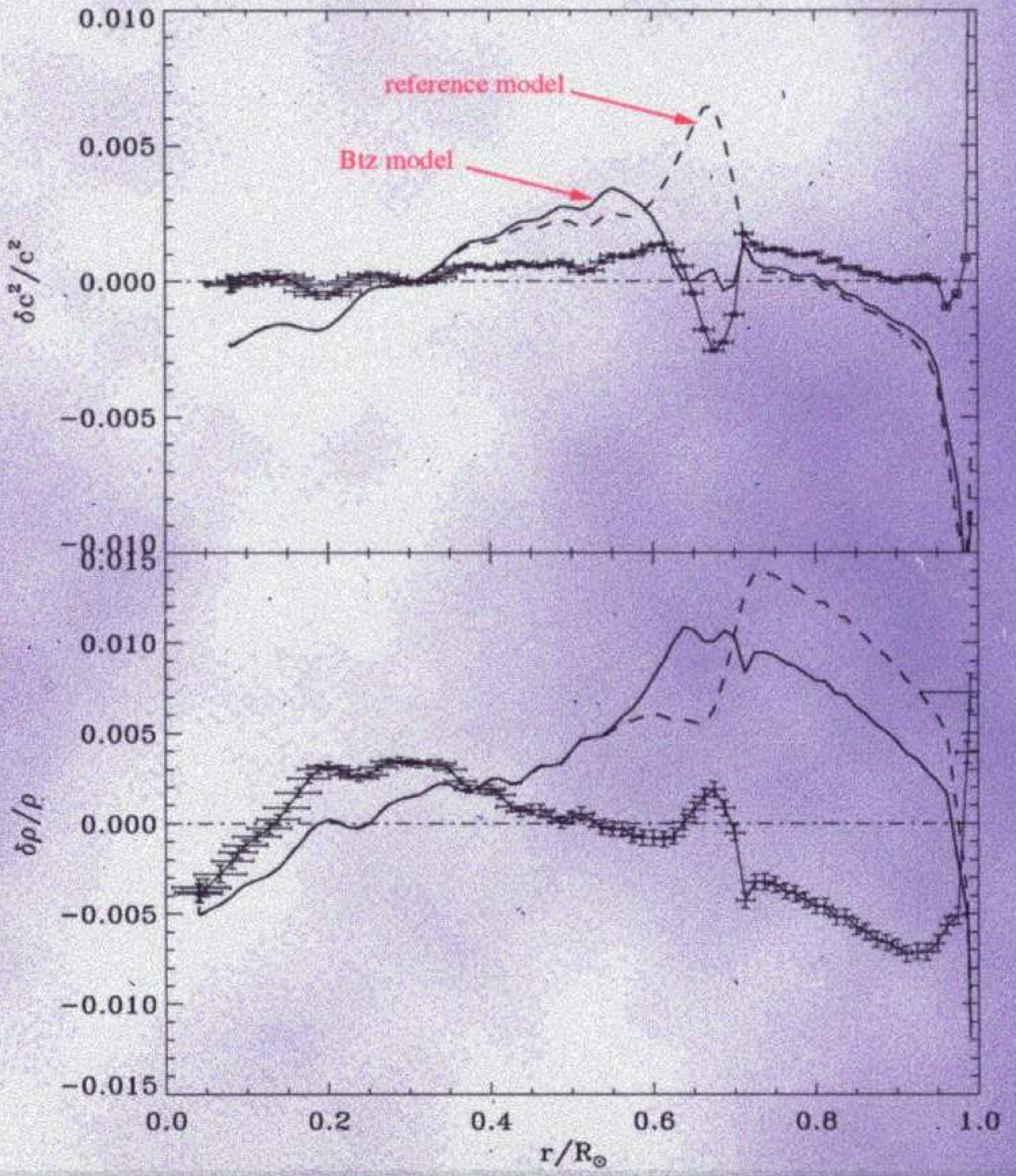
Check for Screening? effects.

. 2.— Relative differences between (a) the square of the sound speed and (b) the density uced for the Sun using the GOLF/MDI frequencies described in section 3 and those of erent Saclay solar models. The models are: Reference model (continuous curve), model of BTCZ99 (dashed curve), and the Seismic model (points with error bars joined by ight lines). Superimposed on the density profile

Seismic Model

(Turck–Chièze, Couvidat, Kosovichev et al, ApJ letters, *in press*)

July 2001 V 555



Age = 4.6 Gyr (including PMS)

$X_0 = 0.7040$

$Y_0 = 0.2757$

$Z_0 = 0.02027$

$(Z/X)_s = 0.0263$

$\alpha = 1.774$

$R_{bcz} = 0.7121\ R_\odot$

$h = 0.05\ R_\odot$ (width of the tachocline)

$N = 40\ \mu Hz$ (Brunt–Väisälä frequency in the tachocline)

Time–dependent rotation following Piau and Turck–Chièze, 2001

Emitted Neutrino Fluxes

➔ Neutrino fluxes (in $cm^{-2}.s^{-1}$)

	ν_{pp}	ν_{pep}	$\nu_{^7Be}$	$\nu_{^8B}$	$\nu_{^{13}N}$	$\nu_{^{15}O}$	$\nu_{^{17}F}$
production	$1,67.10^{38}$	$3,94.10^{35}$	$1,37.10^{37}$	$1,45.10^{34}$	$1,62.10^{36}$	$1,39.10^{36}$	$8,64.10^{33}$
on earth	$5,92.10^{10}$	$1,39.10^{8}$	$4,84.10^{9}$	$5,14.10^{6}$	$5,72.10^{8}$	$4,92.10^{8}$	$3,05.10^{6}$
^{71}Ga	69,35	2,84	34,69	12,33	3,45	5,60	$3,48.10^{-2}$
^{37}Cl	0,0	0,223	1,15	5,86	$9,49.10^{-2}$	0,325	$2,04.10^{-3}$

➔ Neutrino capture predictions

^{71}Ga : 128.3±8.95 SNU (detection : 74.7±5)

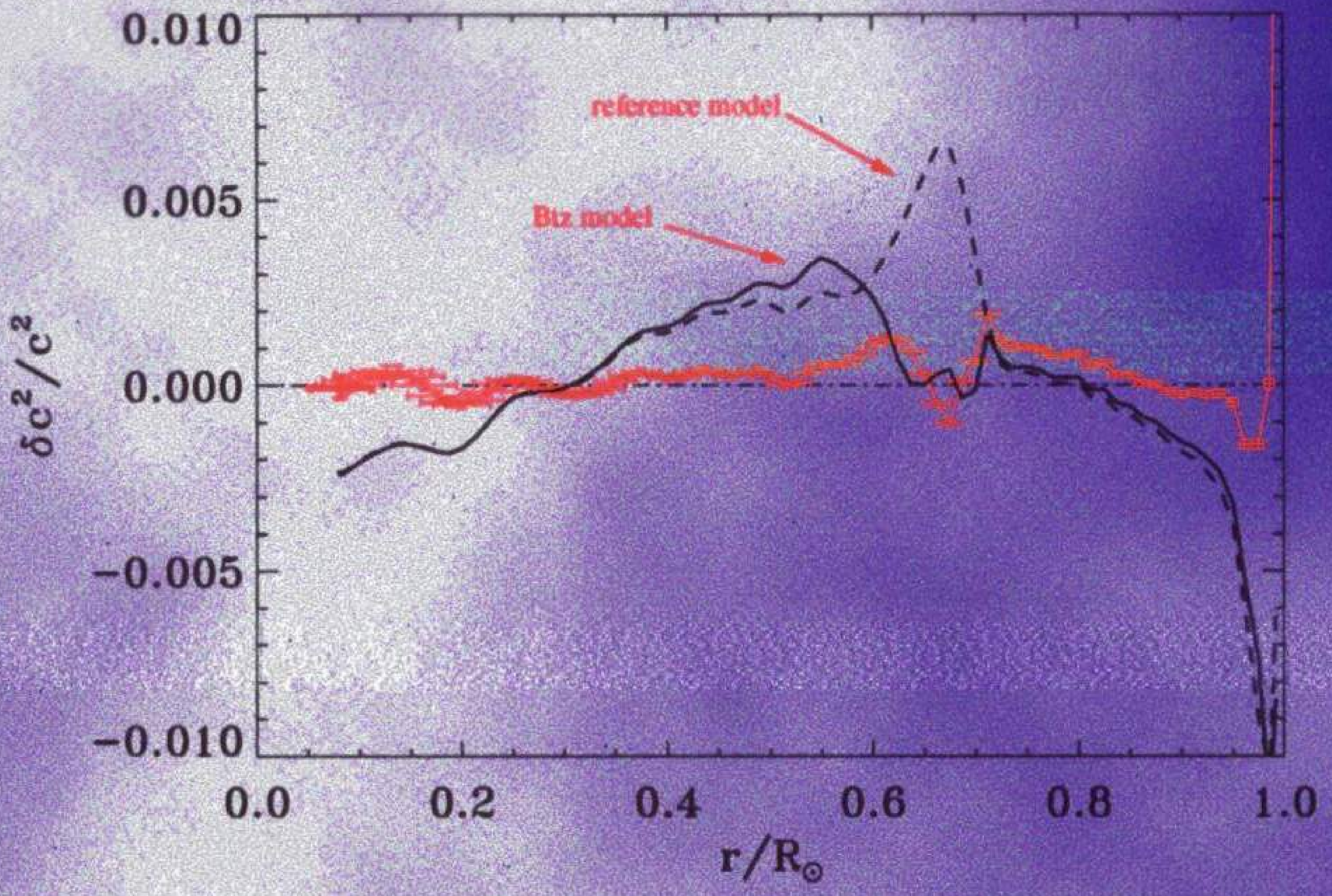
^{37}Cl : 7.65±1.3 SNU (detection : 2.56±0.23)

^{8}B : 5.14±1 $cm^{-2}.s^{-1}$(detection 2.4±0.08)

0.7

See real numbers on paper

Second Seismic Model



Model Btz but :

1/ $h = 0.025\ R_\odot$ and $N = 40\ \mu$Hz

2/ p−p reaction rate +1.3%

3/ opacities modified from the core (~+1.5%) to the tachocline (~+5%) in a way simulating an increase of the opacities of the heavy elements

4/ $(Z/X)_s = 0.0245$ fixed

^{71}Ga = 126.4±8.82 SNU

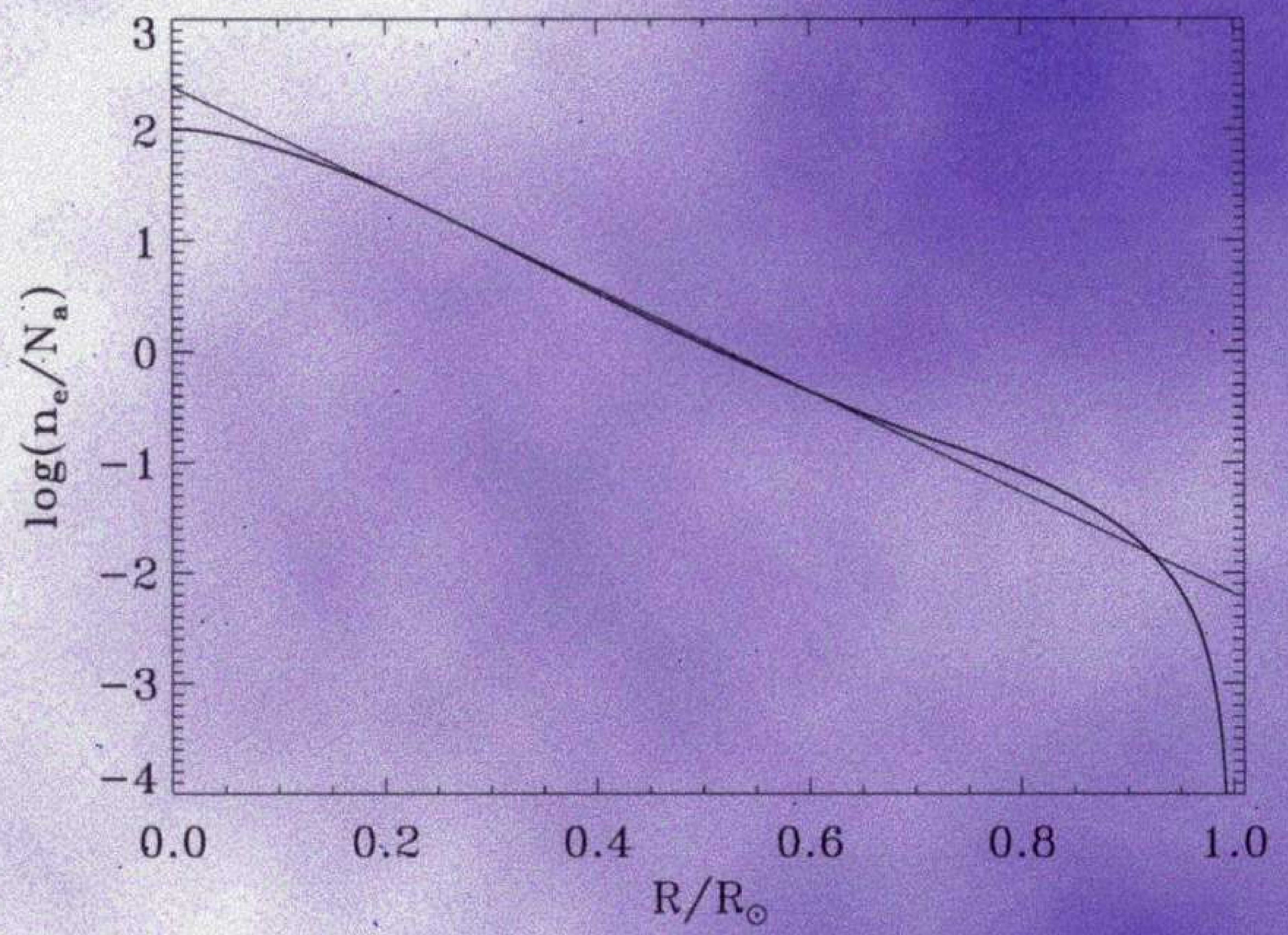
^{37}Cl = 7.32±1.23 SNU

^{8}B = 4.901±1 cm^{-2}.s^{-1}

0.7

Electron Density Number

for the first seismic model



Brun, Turck-Chiéze, Zahn
ApJ (1999) 525, 1032

Turck~ - 08

Kosovichev et al 1997 Sol. Phys.,

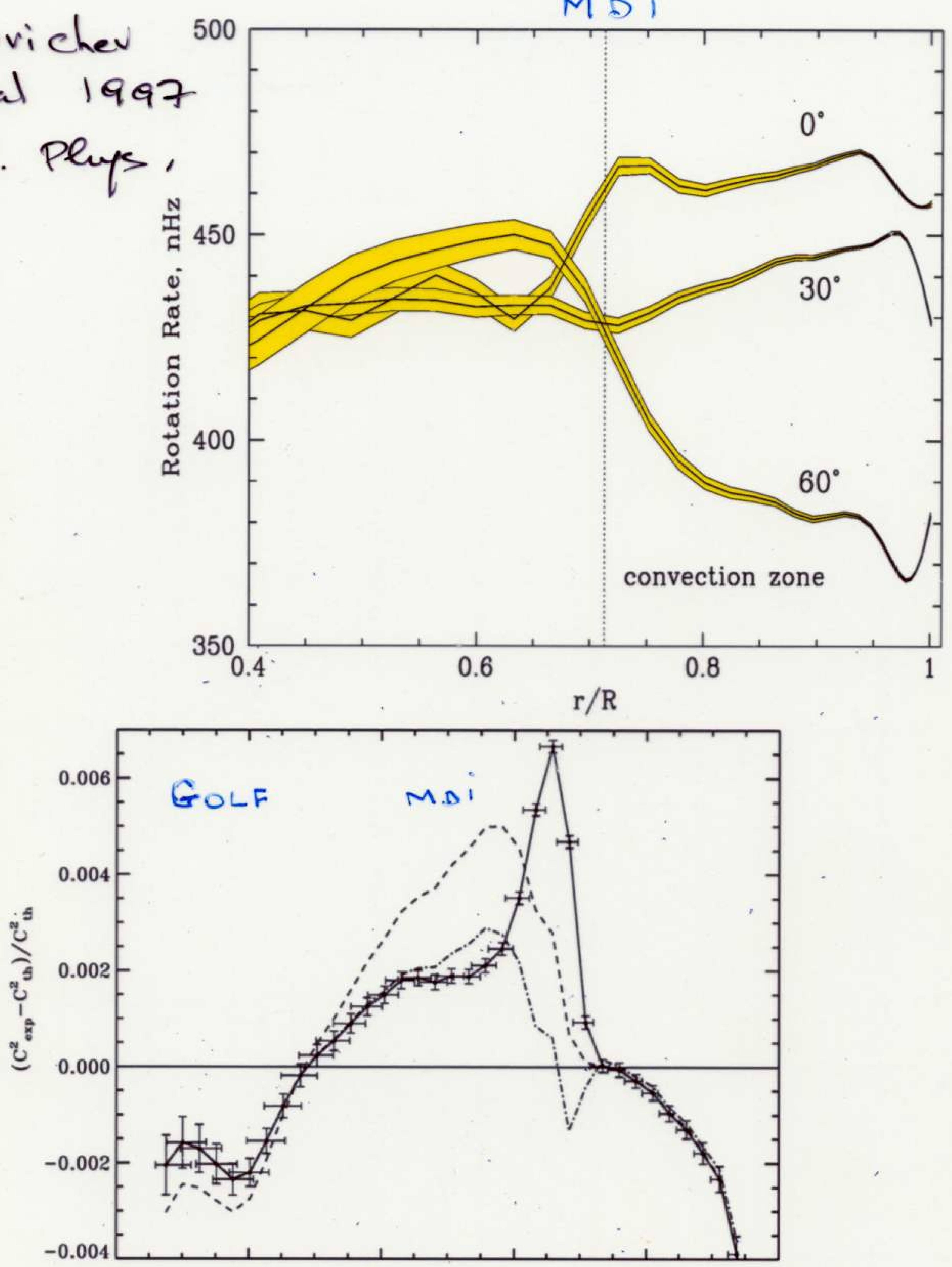
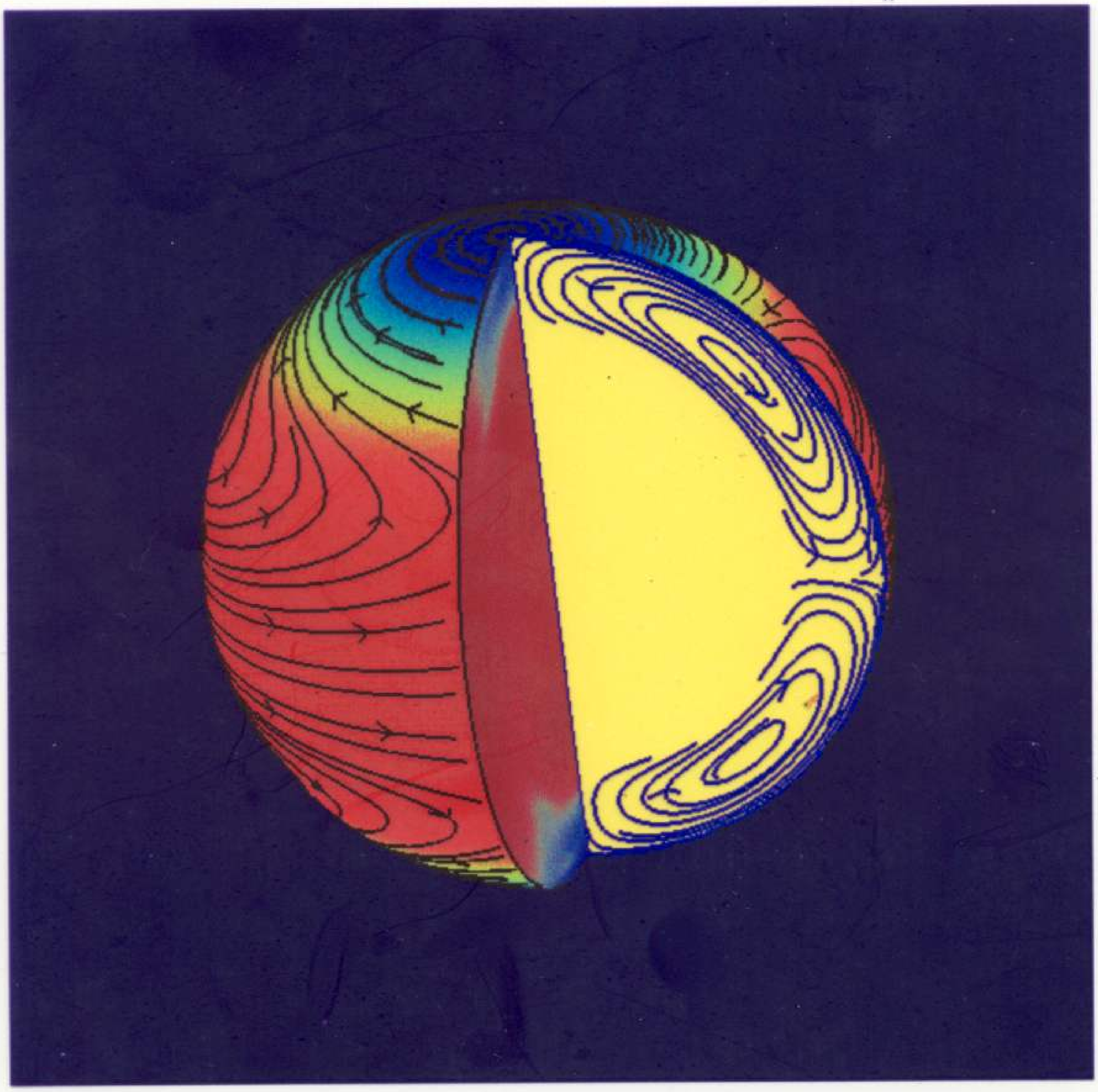
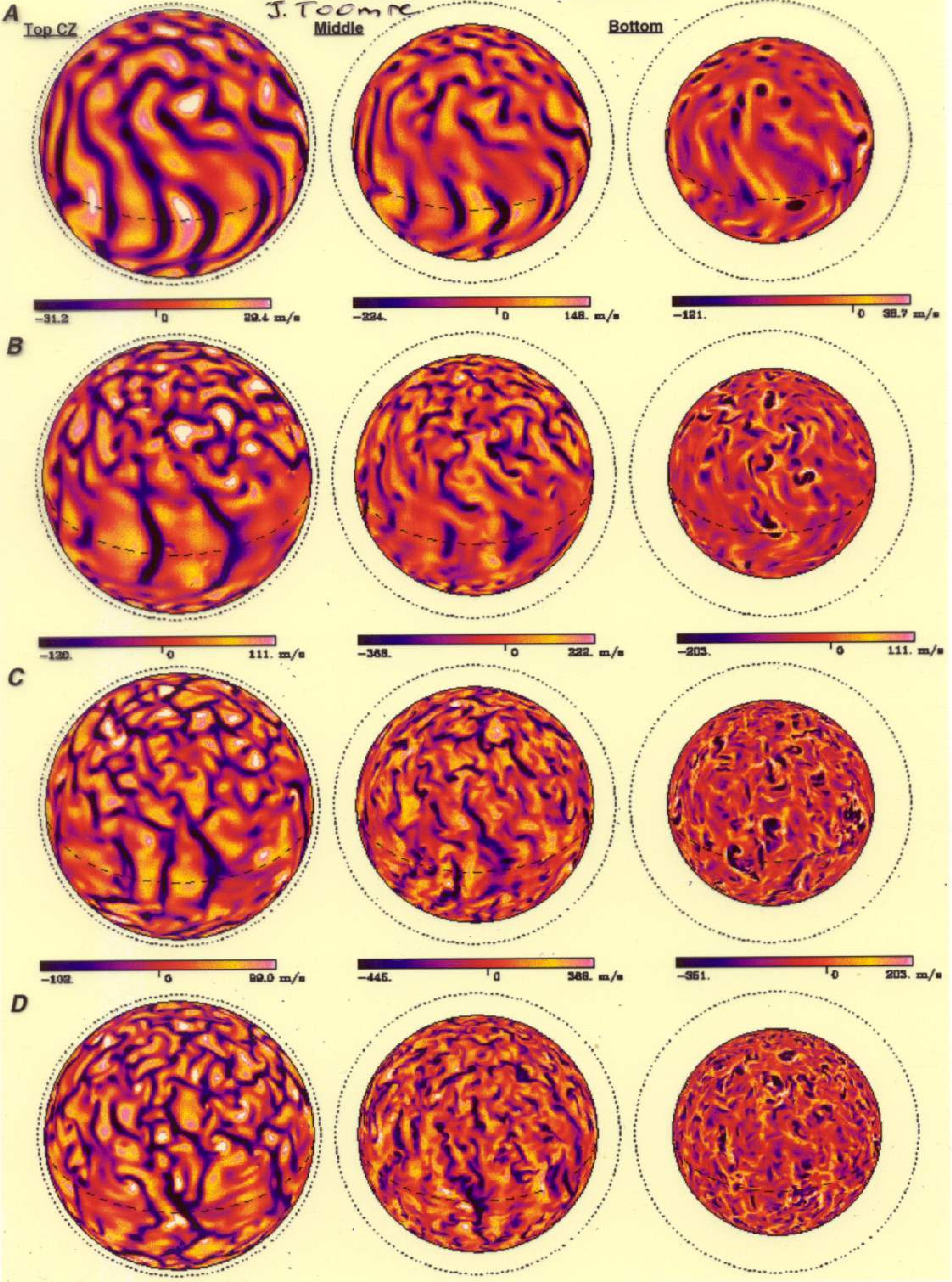


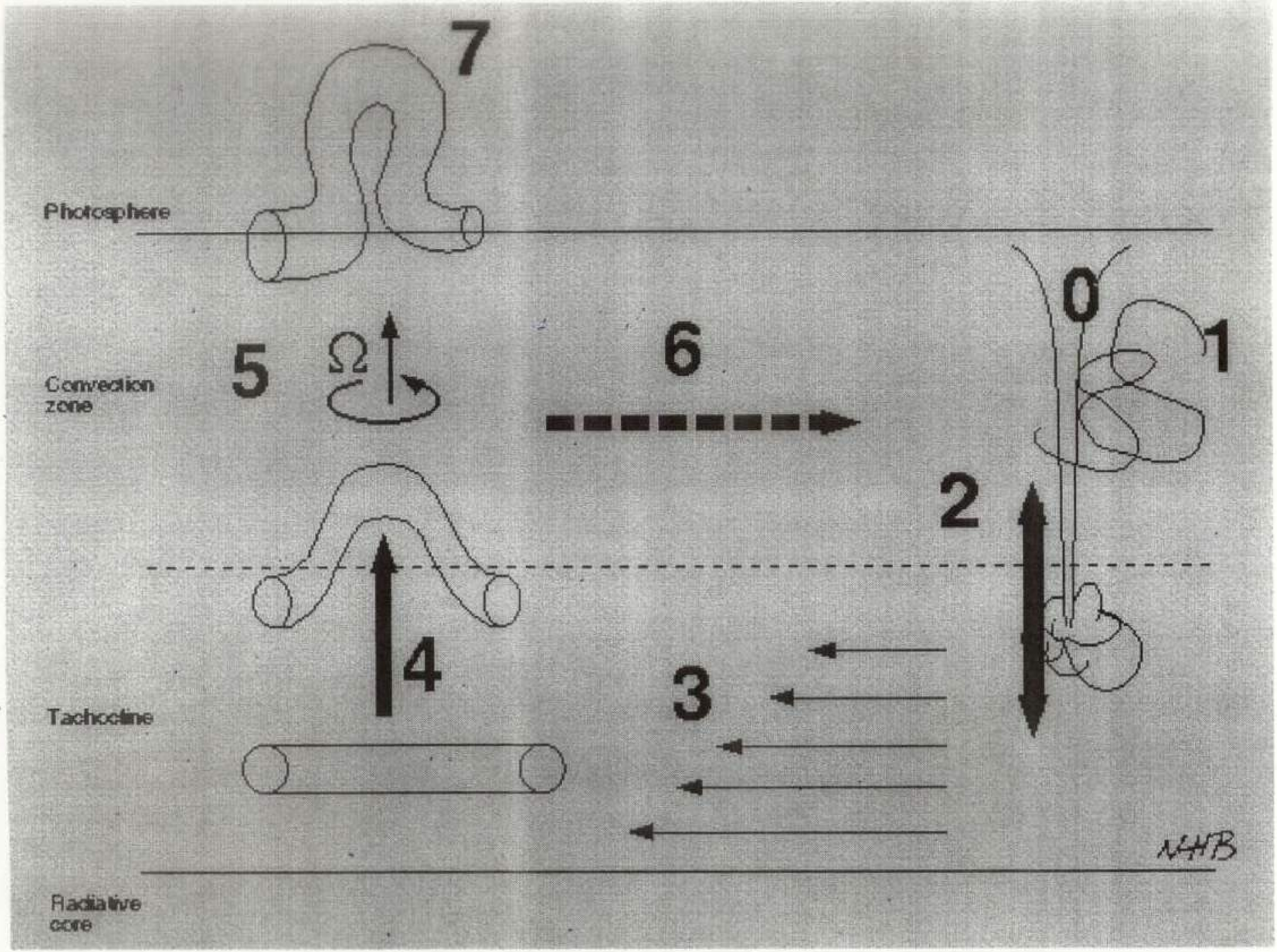
Figure 1. a) Internal rotation profile from MDI (from Kosovishev et al. 1997). b) Sound speed square difference between the Sun seen by GOLF + MDI instruments aboard SOHO and solar models. The full line corresponds to a reference model where the microscopic diffusion is included, the other models include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



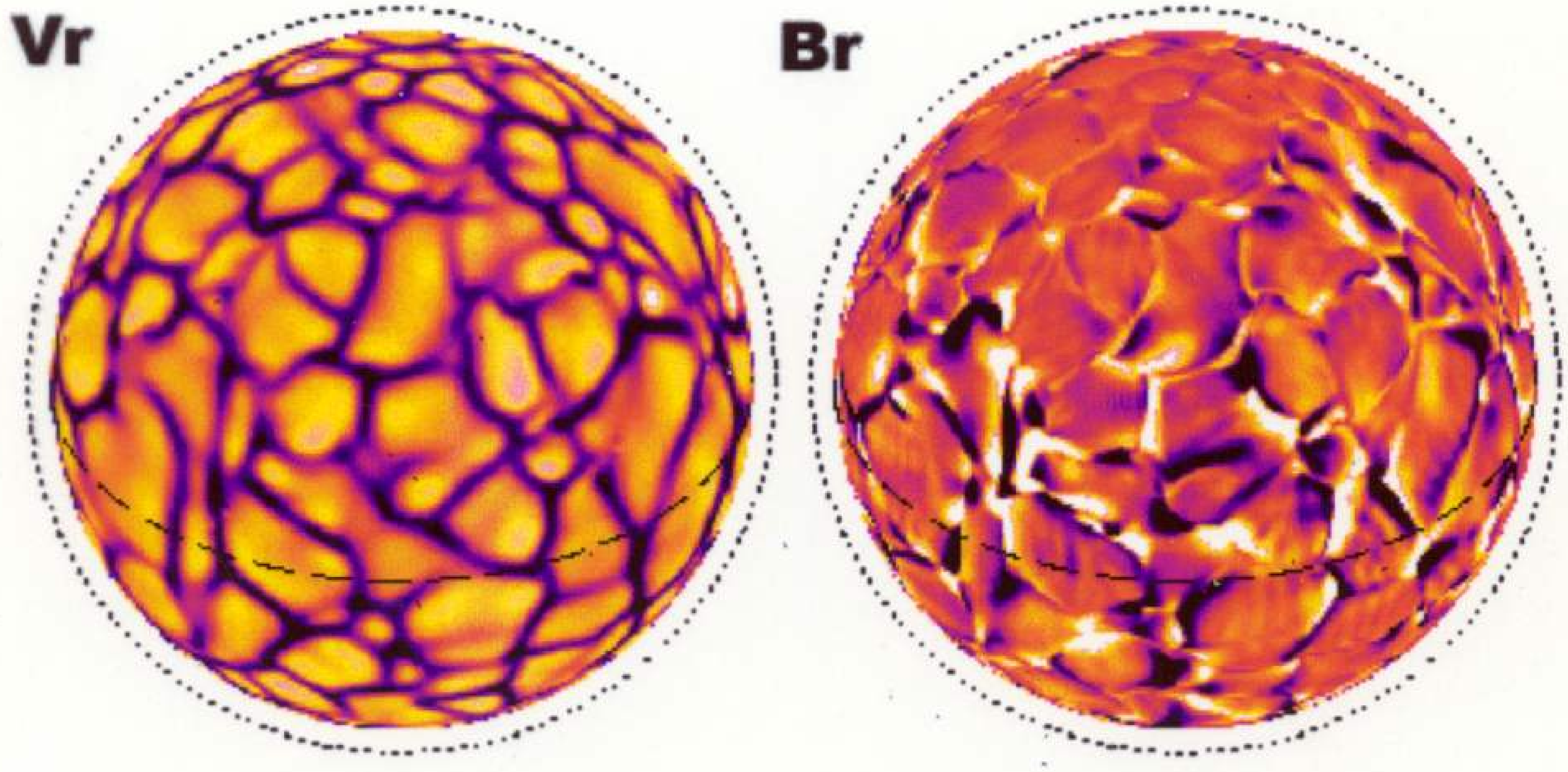
Turbulent Convection in Rotating Spherical Shells

(A.S. Brun, University of Colorado)
J. Toomre



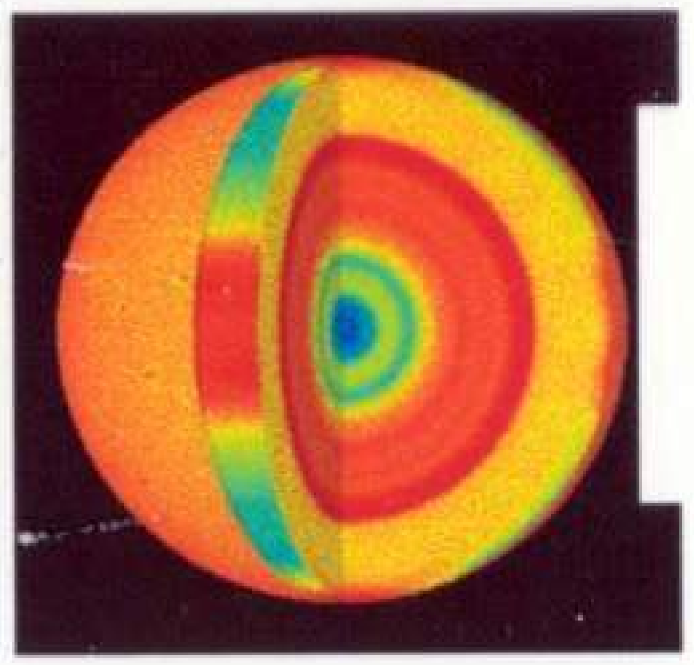


7
Photosphere
0
1
5
Ω
6
Convection zone
2
4
3
Tachocline
MHB
Radiative core



Code MHD Toomre

Brun .... to be published



Impact of magnetic field on neutrinos ?

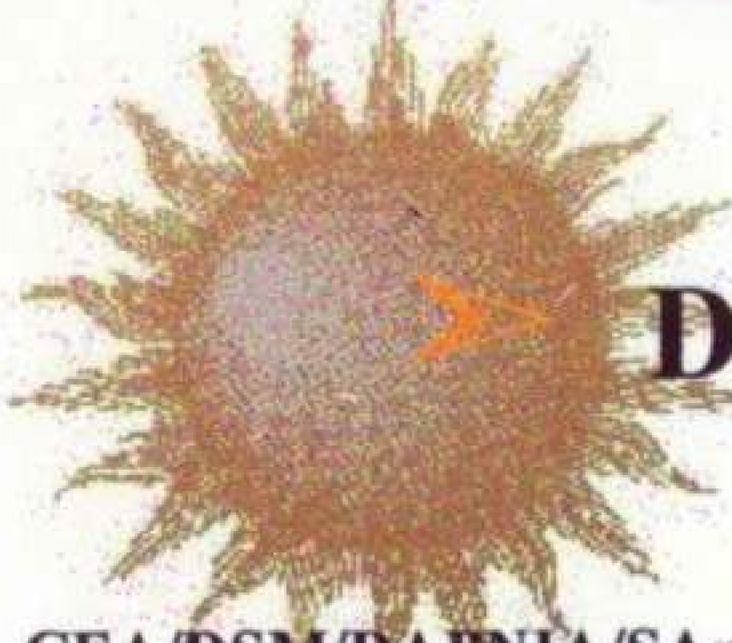
- **Measurement of the magnetic field : 20 kG just below the phostosphere**

- **Base of the convective zone : < 10^5 G**

- **Tubes of fluxes on the limits of the supergranulation cells: about 4kG, everywhere at the surface**

- **Above the magnetic field spreads everywhere**

- **During activities: CME idem, but more localized**



CONCLUSION

- We have now a way to check the nuclear region of the SUN.

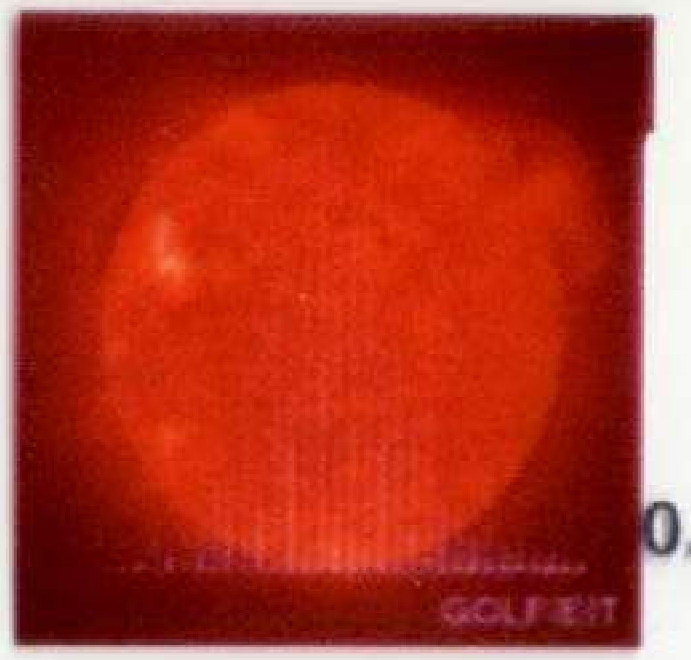
Progress in solar modeling allows to deduce neutrino fluxes from helioseismic observations

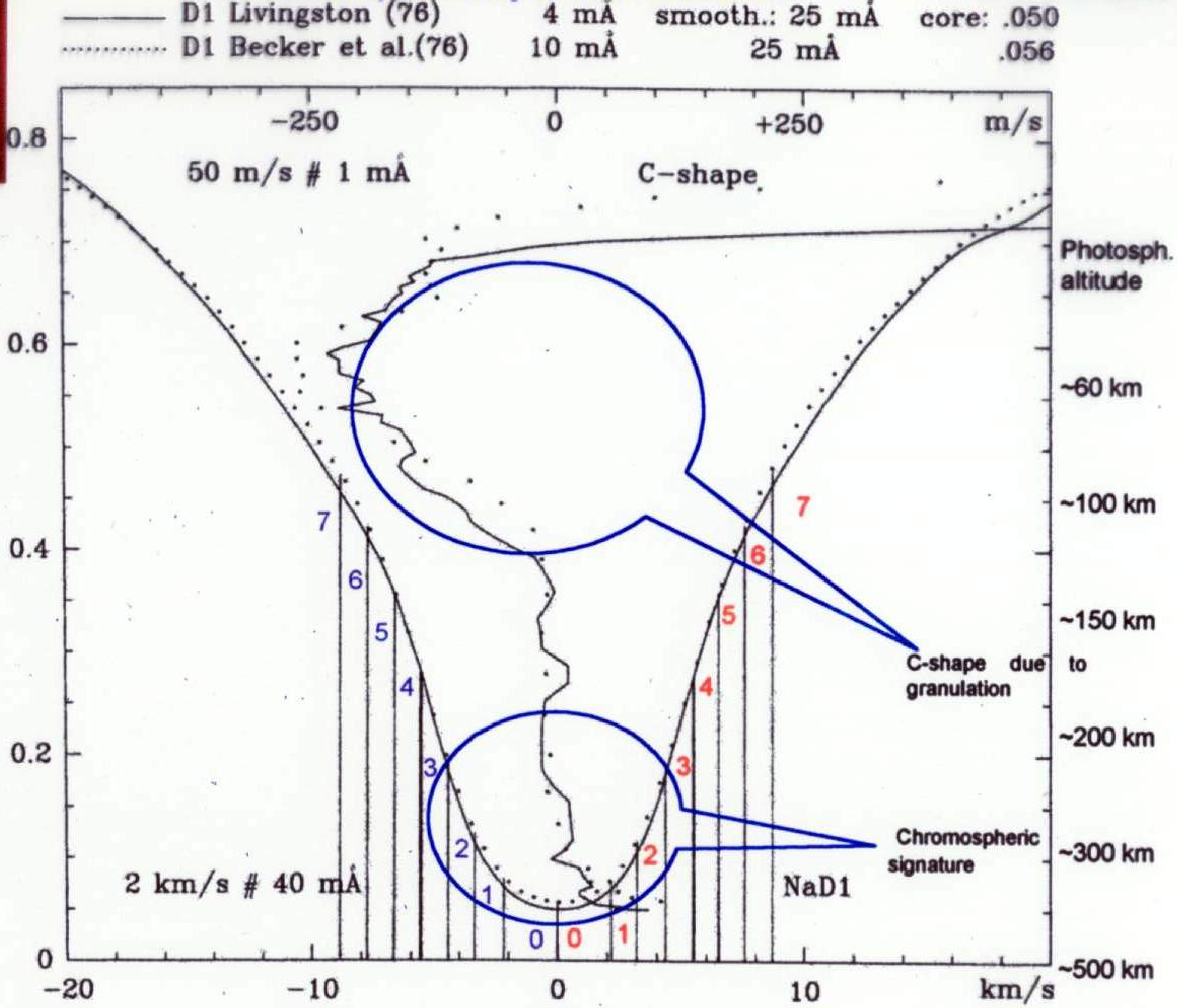
which are <u>much more</u> significant than along theoretical estimates due to the complexity of the calculation.

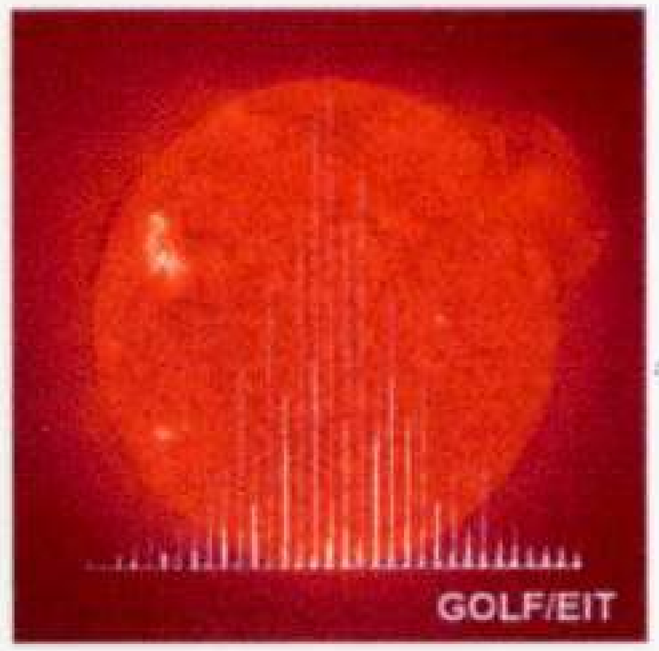
These results are obtained assuming symmetrical hydrostactic SUN well represented by 1D model

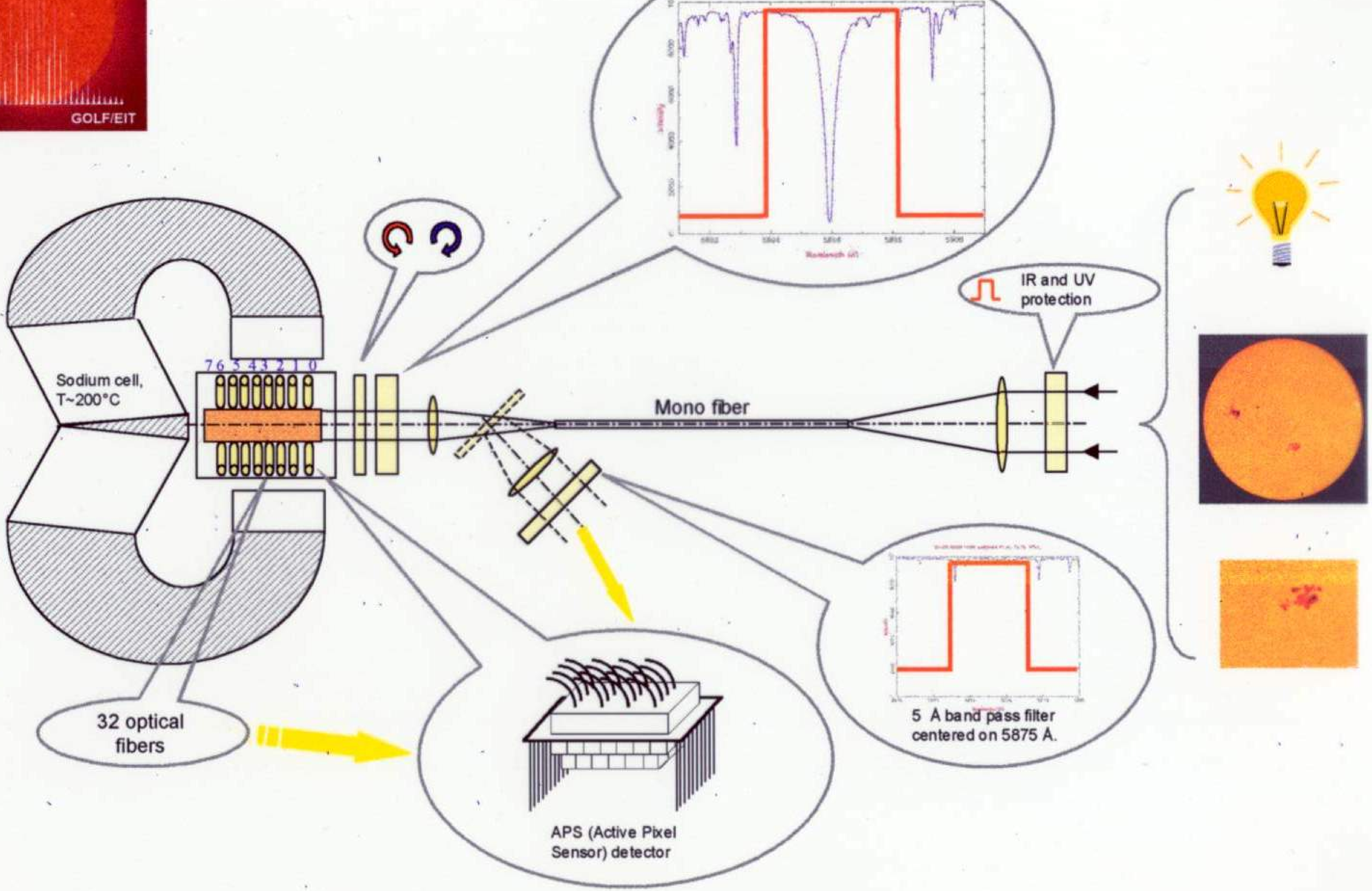
- We will continue to look for dynamical effects and to determine the rôle of the magnetic fields in the SUN

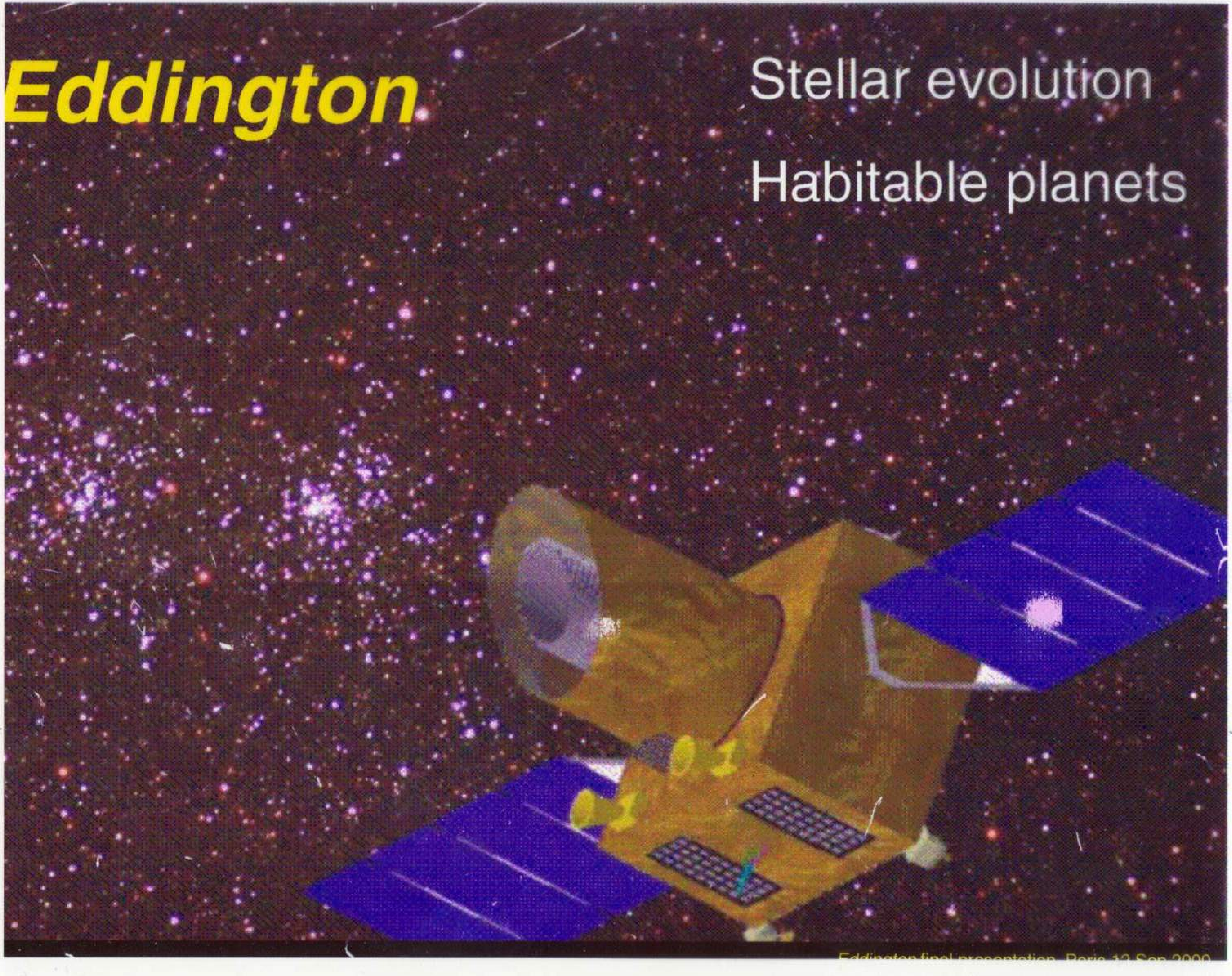
15 channel spectrometry on Na D1 sodium line






GOLF/EIT


Sodium cell,
T~200°C
7 6 5 4 3 2 1 0
Mono fiber
IR and UV
protection
32 optical
fibers
APS (Active Pixel
Sensor) detector
5 Å band pass filter
centered on 5875 Å.


Eddington
Stellar evolution
Habitable planets

Eddington

Two Major Science Goals

Reliable tested theory stellar evolution to be used in astrophysics	Detection of habitable Earth-like planets - their frequency and properties
Ages of stars, structure, chemical evolution	Properties of other planets and planetary systems
Stellar oscillations Asteroseismology	Planetary Transits

High precision long duration photometry from space