INTERNAL STELLAR STRUCTURE

Structural equations

Hydrostatic equilibrium: $dP/\ dr = -\ M(r)\ G\ /r^2\ \rho$
Mass conservation: $dM/dr\ = 4\pi\ r^2 \rho$
Thermal equilibrium: $dL/dr\ = 4\pi r^2 \rho (\varepsilon_{nucl}\ -\ TdS/dt)$

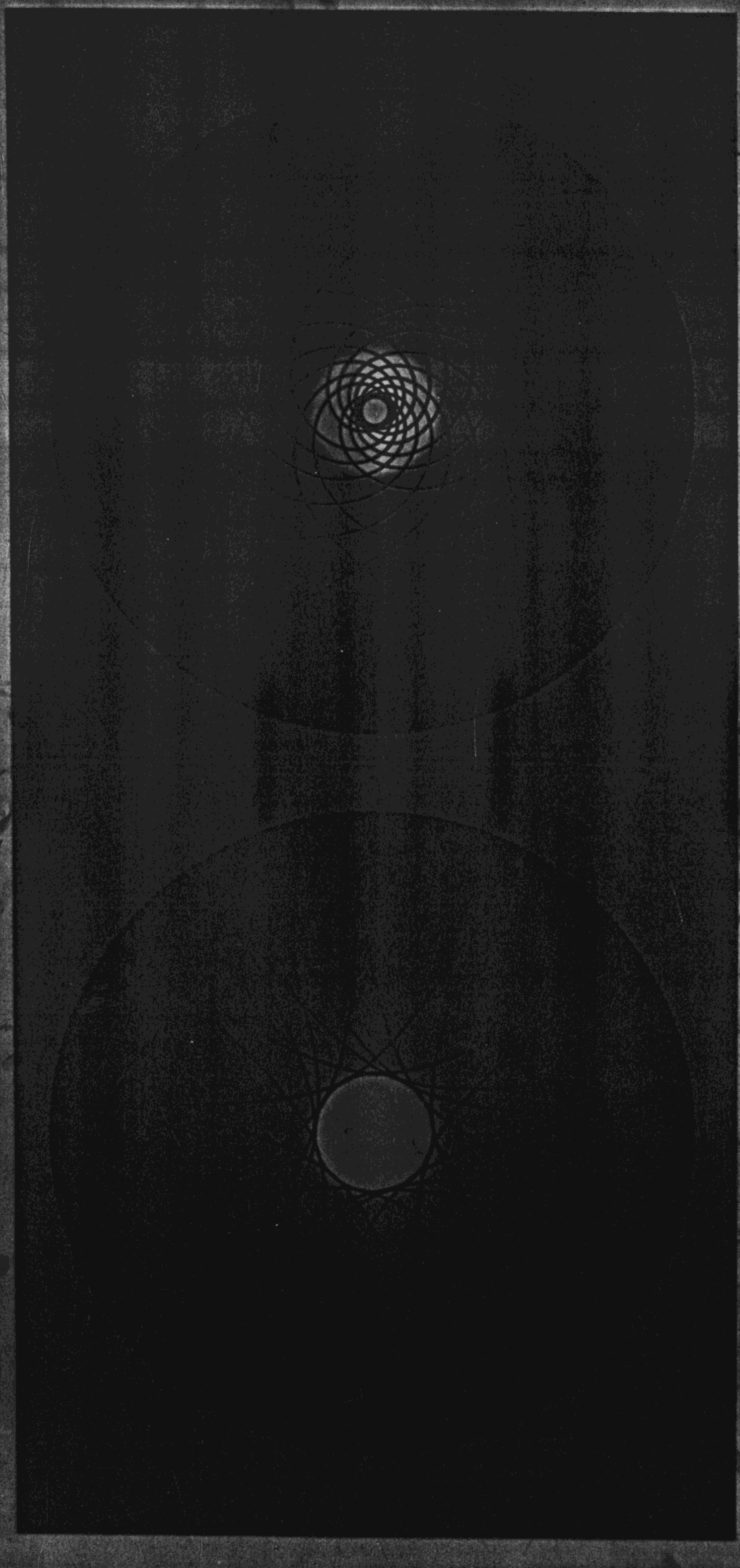
Radiative transfert: $dT/dr\ =\ -3/4ac\ \kappa\rho(r)/\ 4\pi r^2$
Convective transfert: $dT/dr\ =\ (\Gamma 2-1)/\Gamma 2\ \ T/P\ \ dP/dr$

Hypotheses:

- Hydrostatic equilibrium
- Spherical symetry
- No mass loss
- No offect of rotation
- No effect of magnetic field
- Initial abundances = Photospheric abundances

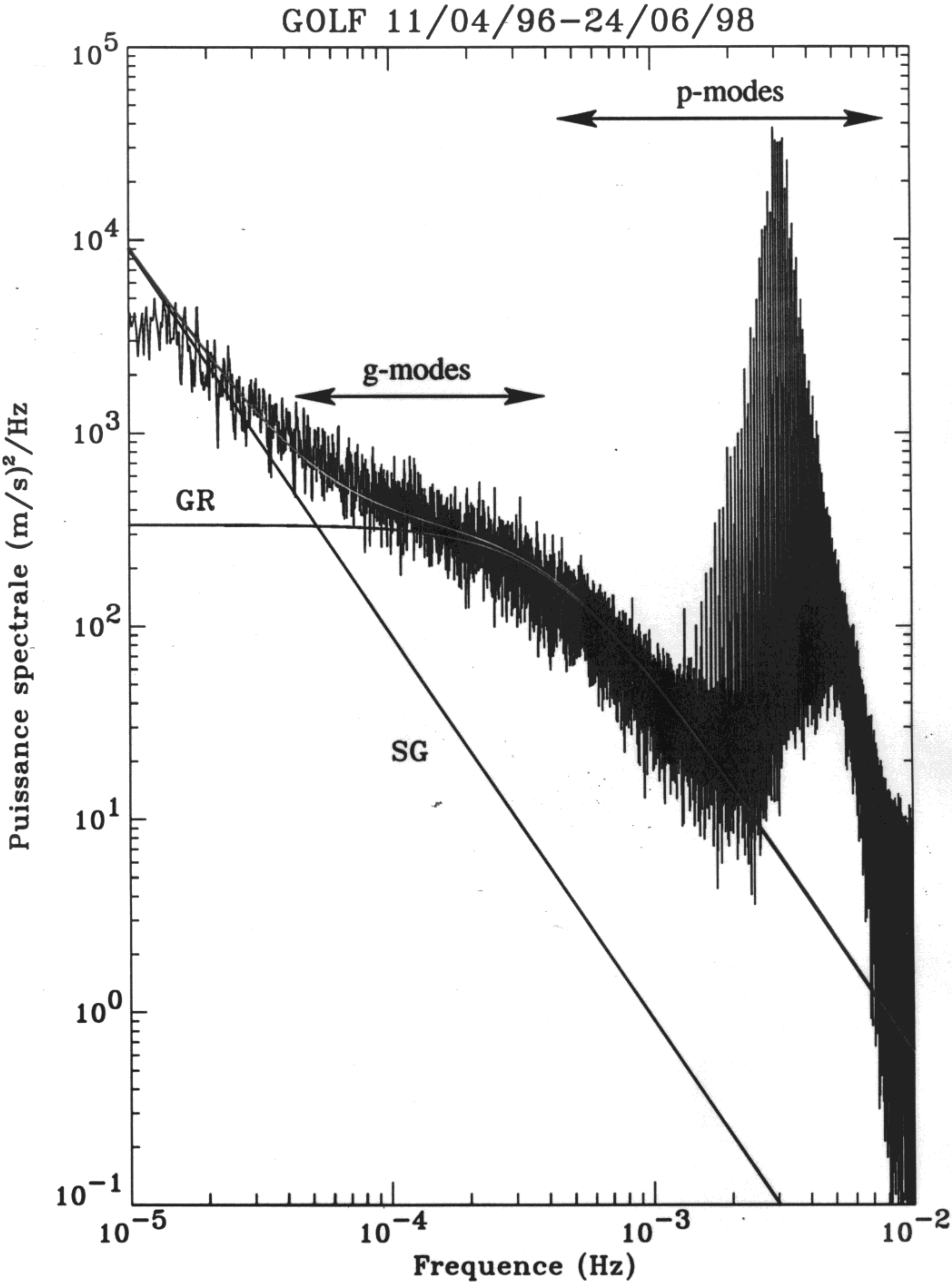
STELLAR SEISMOLOGY

Sylvaine Turck-Chièze, International Neutrino Telescopes, Venice, 23th February 1999.



75% Gravity Modes

5% Acoustic modes



GOLF 11/04/96-24/06/98
p-modes
g-modes
GR
SG
Puissance spectrale (m/s)²/Hz
Frequence (Hz)
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-5
10^-4
10^-3
10^-2

Solar Gravity modes (g-modes)

Very small amplitudes (< ~ 0.5 mm/s)

[Kumar et al ApJ, 458, L83, 1996]

Actual upper limit for their amplitudes ~ 1 cm/s

Search based in their theoretical properties

Frequencies, Splittings & life times

Two different methods:

1) Searching a whole pattern

By comparison with a model

Exact fraction method **[Palle et al, 1998]**

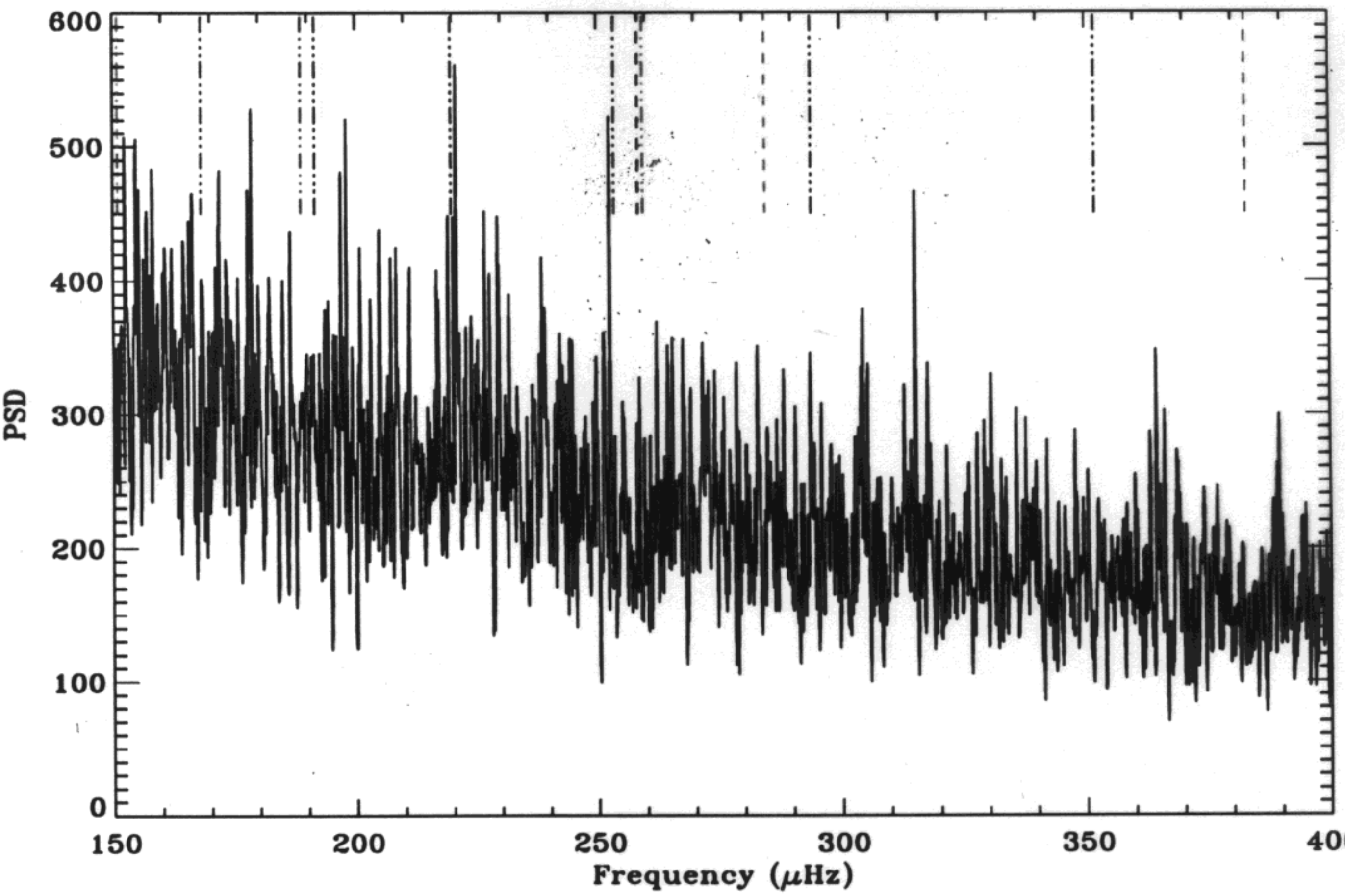
2) Looking for individual multiplets

Above 150 μHz

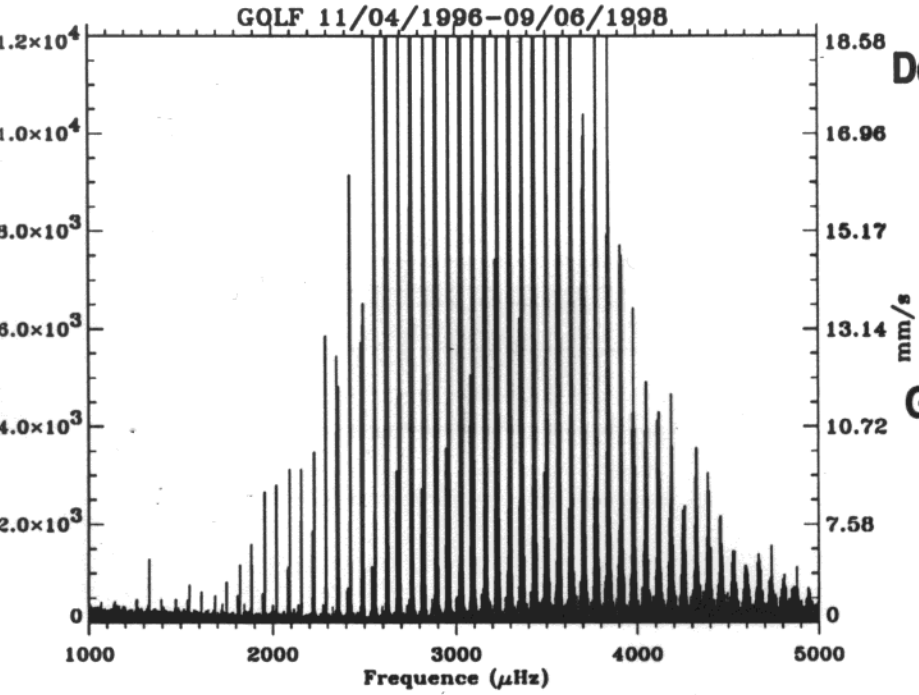
2 possible candidates ~252 & 220 μHz (l=2, n=2,3)

[Gabriel et al [redacted], 1998]

[Turck-Chieze 1998]



Solar Acoustic modes (p-modes)

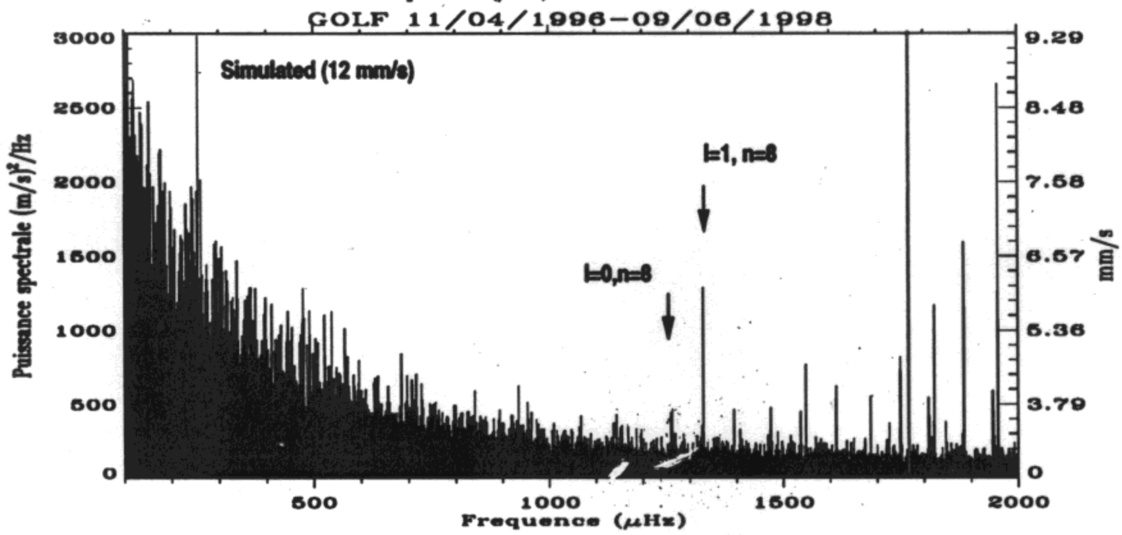


Determination:

- Frequency
- Amplitud
- Line width
- Splitting

GOLF:

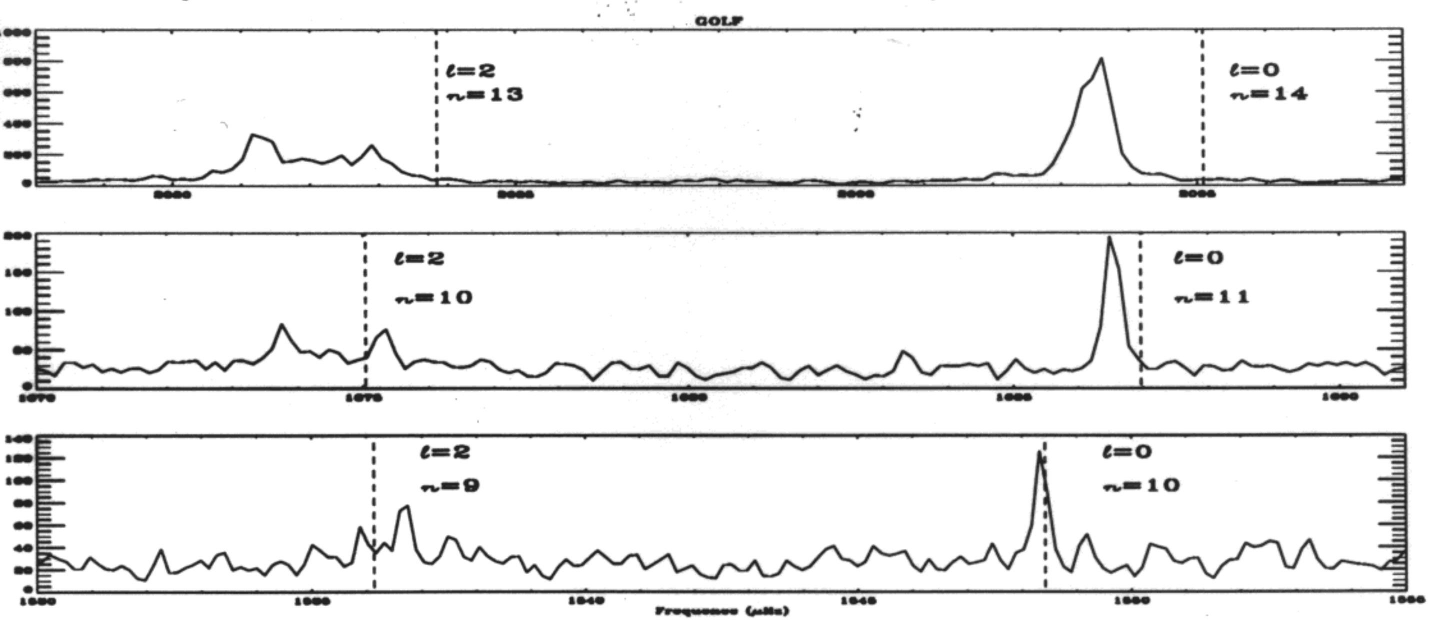
- Low degree modes < 5
- Highest precision possible
- Asymetries ?



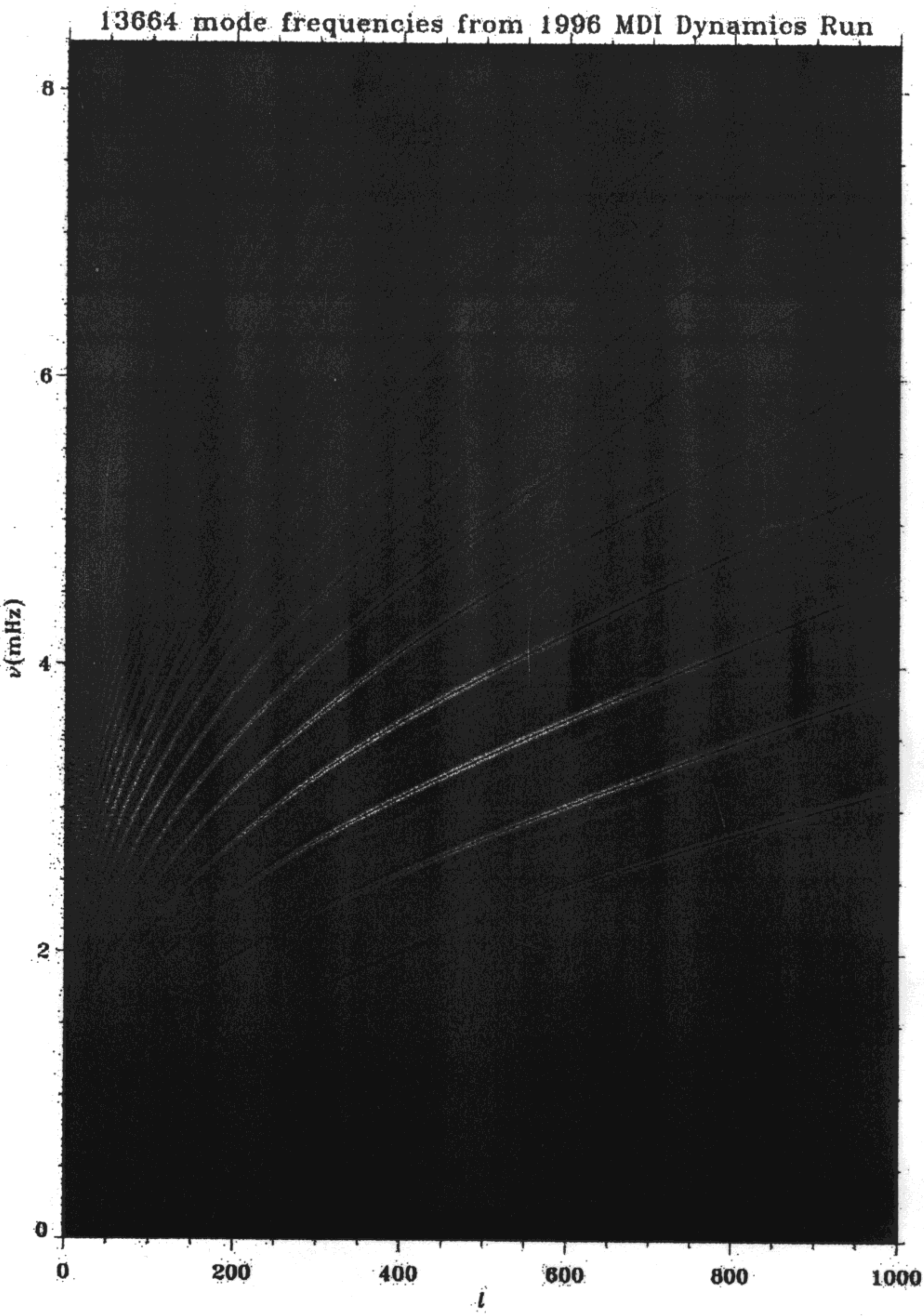
Low frequencies

- Amplitudes ↓↓
- Solar Background ↑

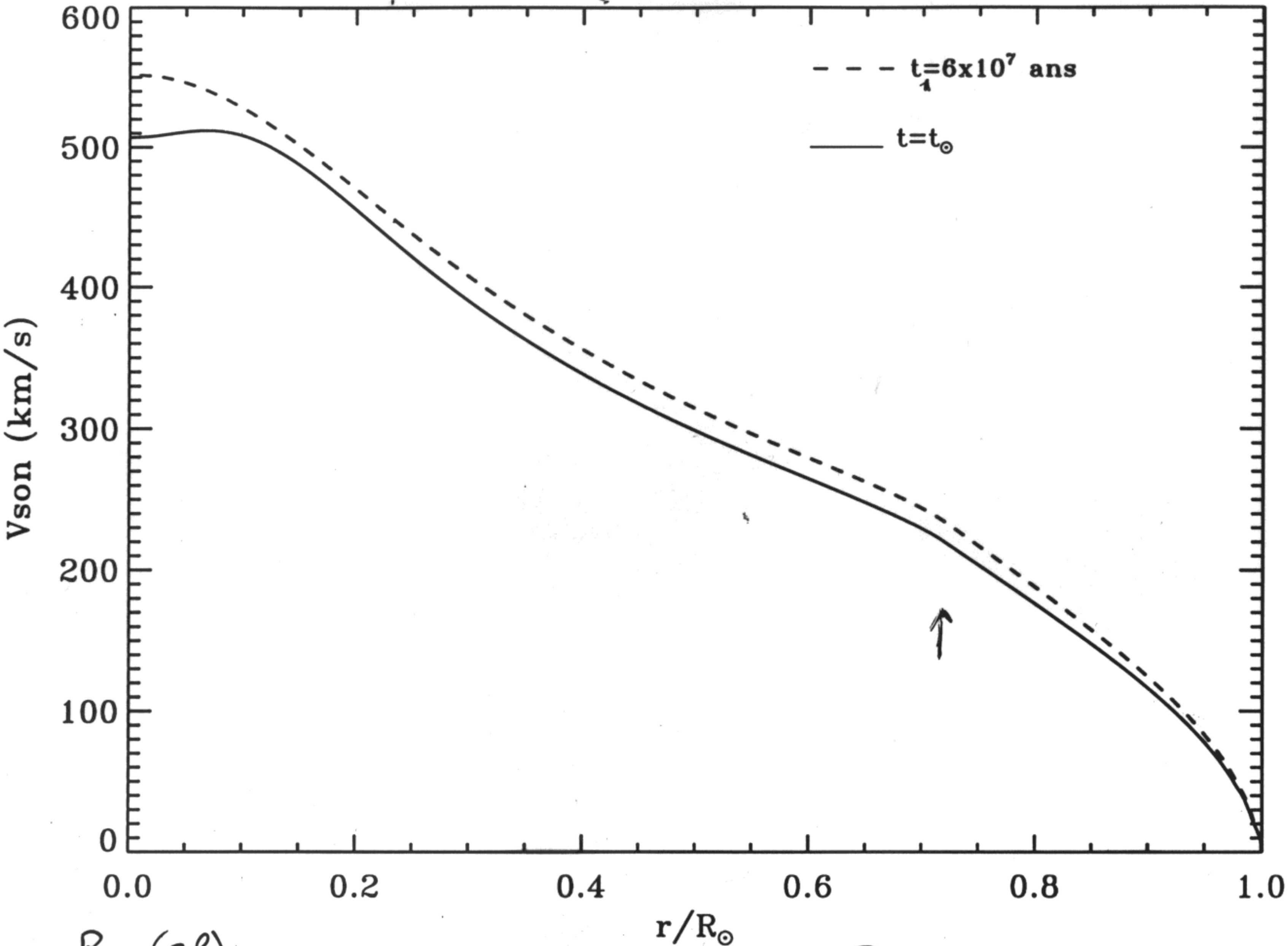
Improvements in the solar models at lower frequencies:



[Brun, Turck-Chieze & Morel ApJ, 506, 1998]

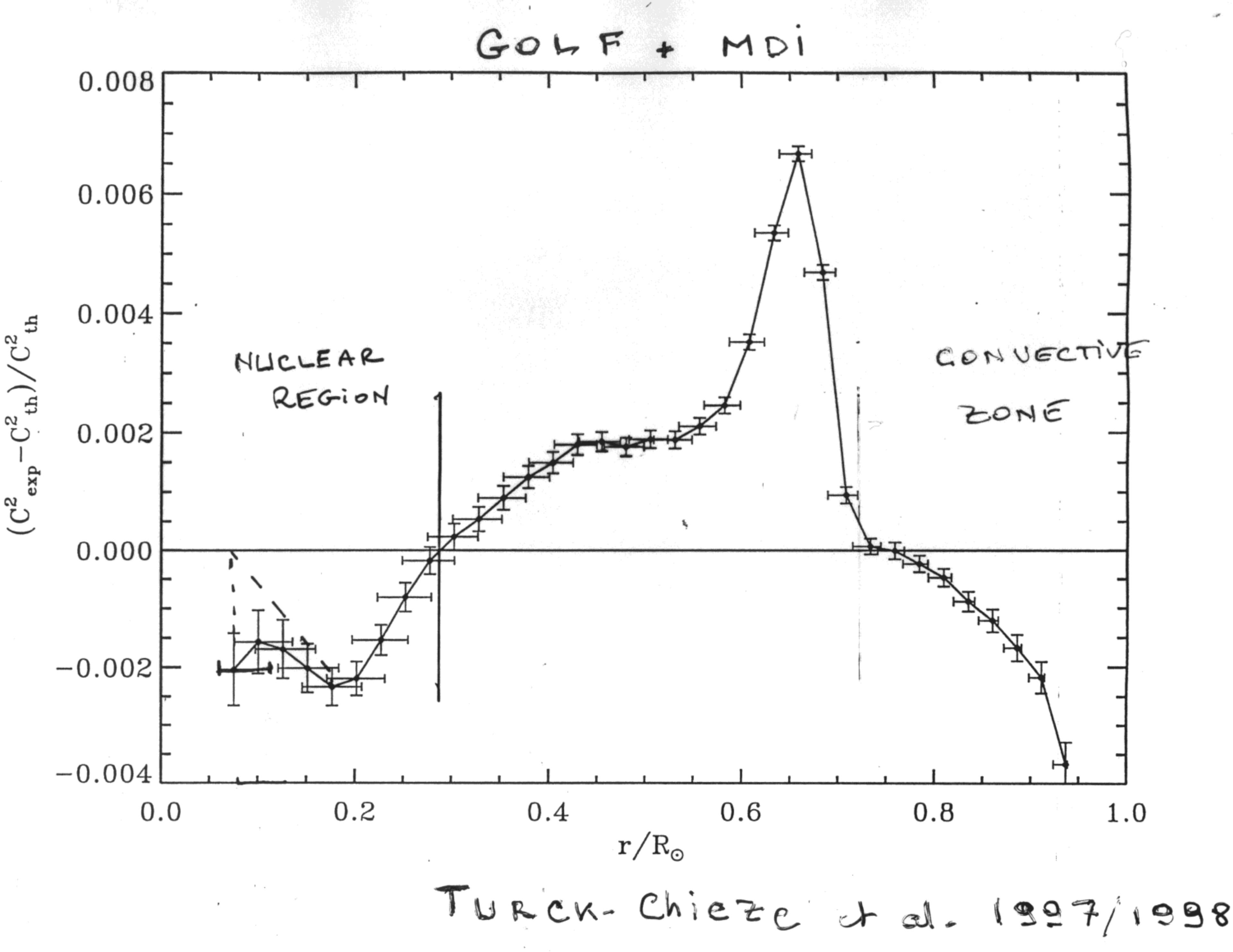

13664 mode frequencies from 1996 MDI Dynamics Run
8
6
4
2
0
ν(mHz)
0
200
400
600
800
1000
l

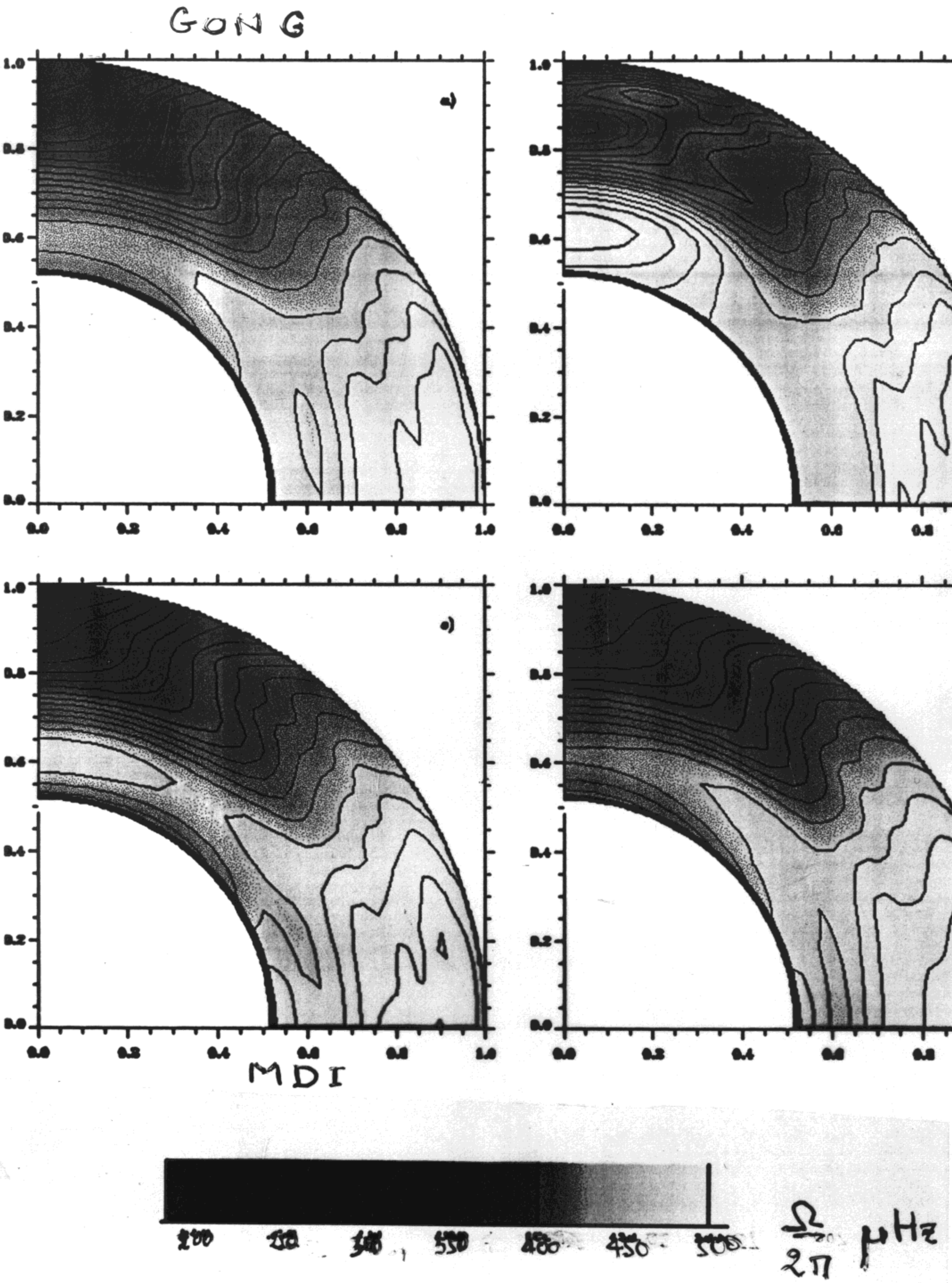
$c^2 \propto \frac{T}{\mu} : \gamma \frac{P}{\rho}$ $\frac{\Delta c^2}{c^2} \lesssim 1\%$



$R_\nu(Cl)_{t_1}$: 0.58 SNU $R_\nu(Cl)_{t_\odot}$: 7.2 SNU

$R_\nu(Ga)_{t_1}$: 67 SNU $R_\nu(Ga)_{t_\odot}$: 127 SNU


GOLF + MDI
0.008
0.006
0.004
0.002
0.000
−0.002
−0.004
$(C^2_{exp} - C^2_{th})/C^2_{th}$
NUCLEAR REGION
CONVECTIVE ZONE
0.0
0.2
0.4
0.6
0.8
1.0
$r/R_\odot$
Turck-Chieze et al. 1997/1998


GONG
a)
b)
c)
d)
MDI
$\frac{\Omega}{2\pi}$ μHz

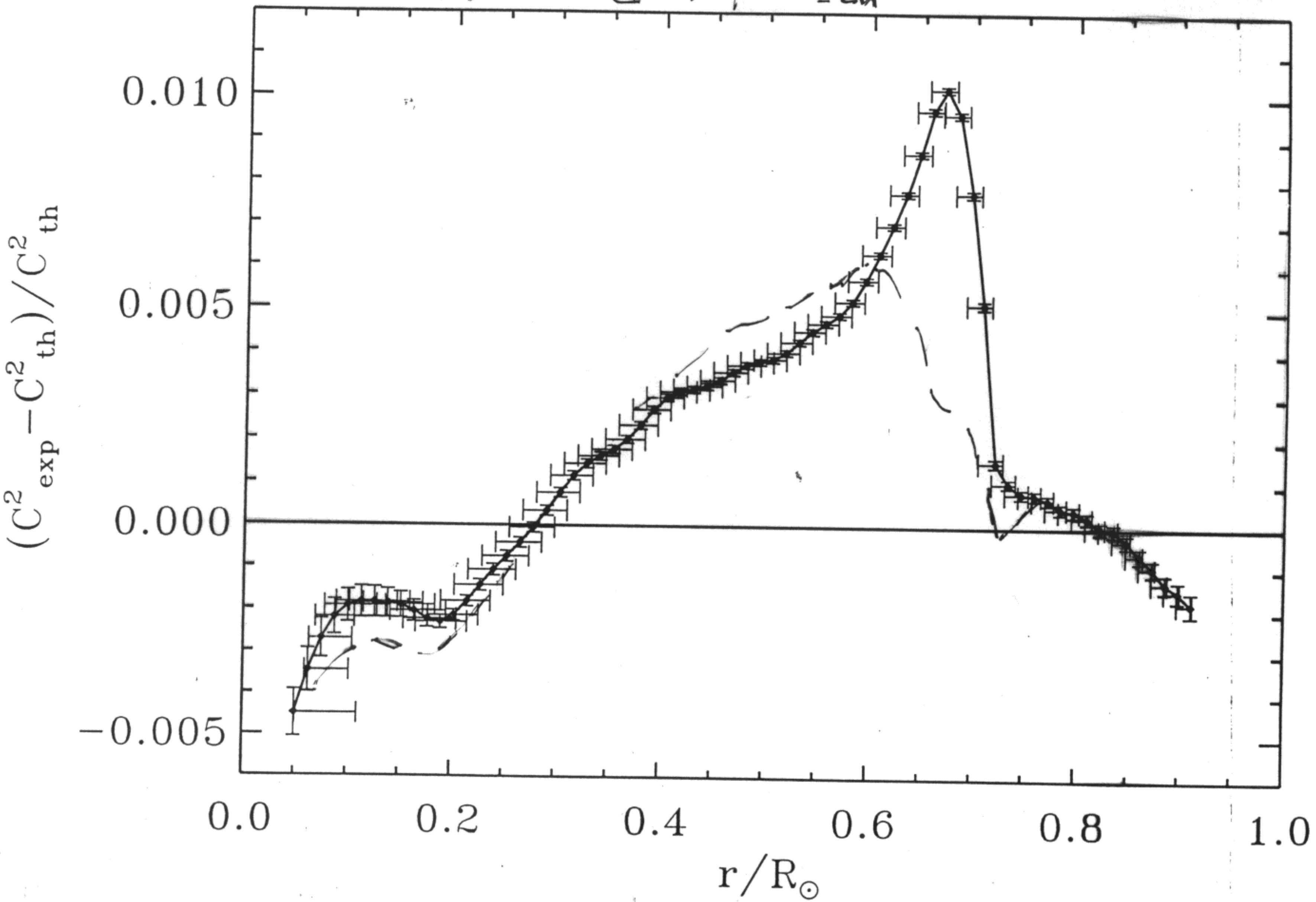
Brun, Turck-Chièze, Zahn ApJ 99

	Observations	Standard 93*	Reference 98**	Turbulent	Time turb
Yin		0.276	0.273	0.270	0.273
Ys	0.249±0.003	0.276	0.243	0.247	0.248-0.250
Rbcz	0.713±0.003	0.729	0.715	0.715	0.715
(Z/X)s	0.0245±0.003	-	0.0245	0.0245	0.0255
$(^3He/^4He)_s$	10% max		2.5%	2%	2%
$(^7Li_i/^7Li)_s$	about 100	1	about 5	6-20	90-130
$(^9Be_i/^9Be)_s$	1.1±0.003		1.11	1.09	1.10-1.14
Chlore (SNU)	2.56±0.16±0.14	5.87	7.18	6.7	6.95 ±2 at least
Gallium (SNU)	77.5±6.2±4.5	119	127.2	125	126.5± 10 at least
Water 10^6 $cm^{-2}s^{-1}$	2.44±0.05±0.08	4.28	4.82	4.7	4.9 ± 1.5 at least

* Turck-Chièze, Lopes ApJ 9[illegible]

** Brun, Turck-Chièze, Morel ApJ 506 (1998) 913

$D_T \propto \left(\frac{2\Omega}{N}\right)^2 \left(\frac{r_{bcz}}{d}\right) \mu_n^6 \frac{\Delta\Omega_n}{\Omega_n} \exp(-2\xi)\cos^2\xi$ from Zahn Spiegel 1998



Brun, Turck-Chièze, Zahn 1999

MACROSCOPIC MOTIONS

NUCLEAR PHYSICS

Reaction rates Screening Absorption cross sections

SOLAR NEUTRINO PUZZLE

ASTROPHYSICS

Theoretical prediction of neutrino emission

Φpp, $\Phi^{7}Be$, $\Phi^{8}B$, Φ CNO

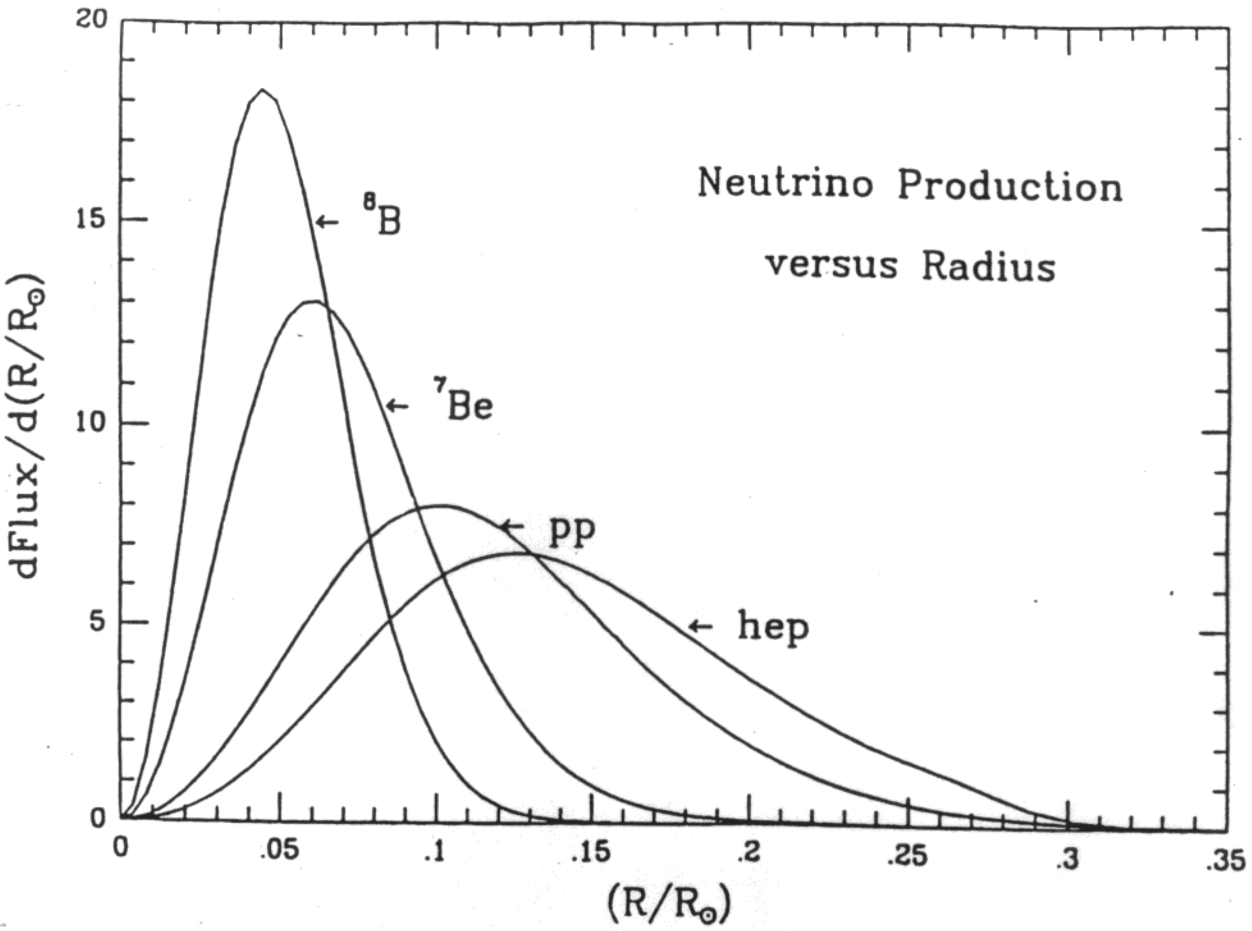
Helioseismology

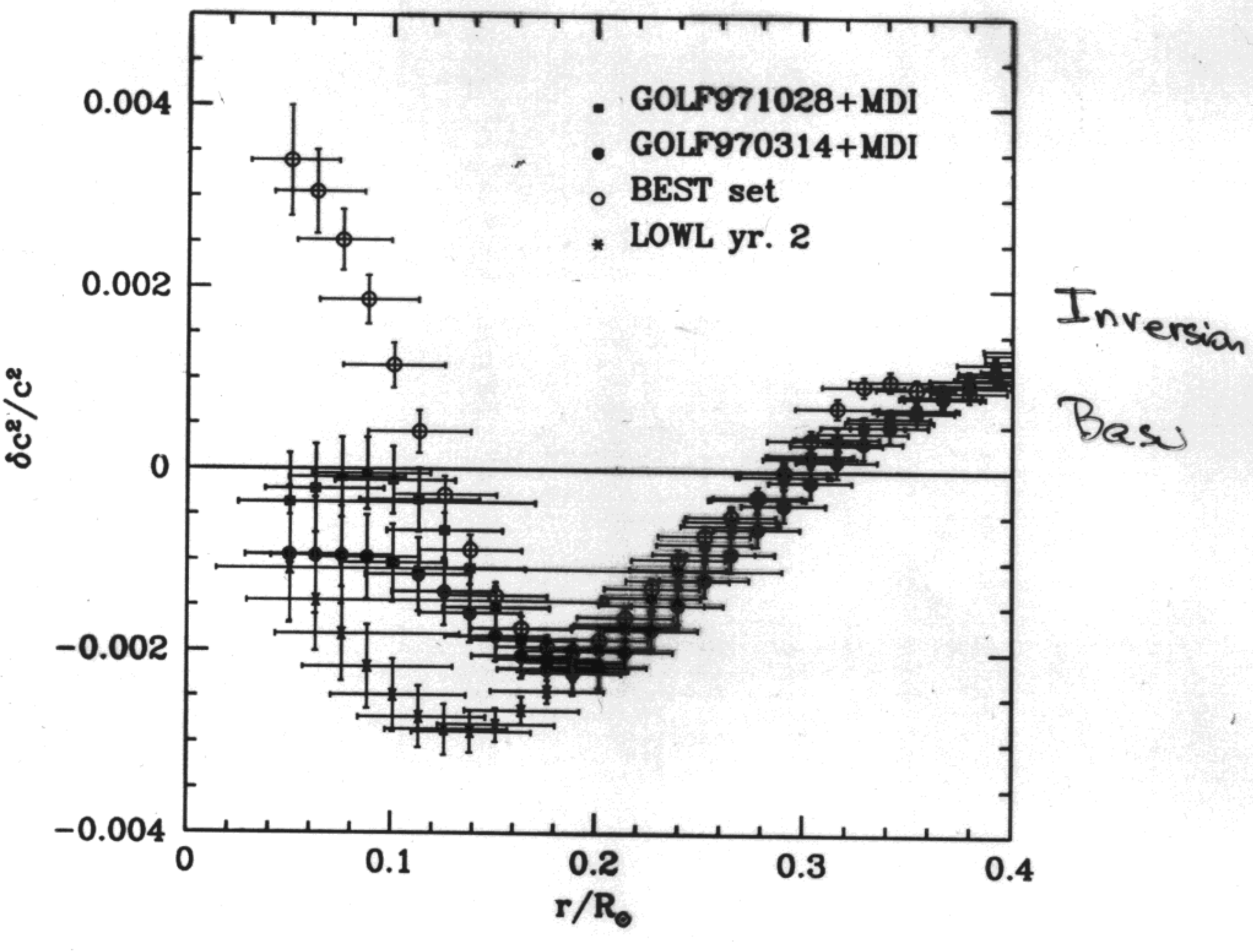
PARTICLE PHYSICS

Neutrino detection on earth

$\Sigma \Phi i(E) \sigma i(E)$

Neutrino oscillations ?


Neutrino Production
versus Radius
^{8}B
^{7}Be
pp
hep
dFlux/d(R/R$_\odot$)
(R/R$_\odot$)
0
.05
.1
.15
.2
.25
.3
.35
20
15
10
5


GOLF971028+MDI
GOLF970314+MDI
BEST set
LOWL yr. 2
$\delta c^2/c^2$
r/R$_\odot$
0.004
0.002
0
−0.002
−0.004
0.1
0.2
0.3
0.4
Inversion
Basu

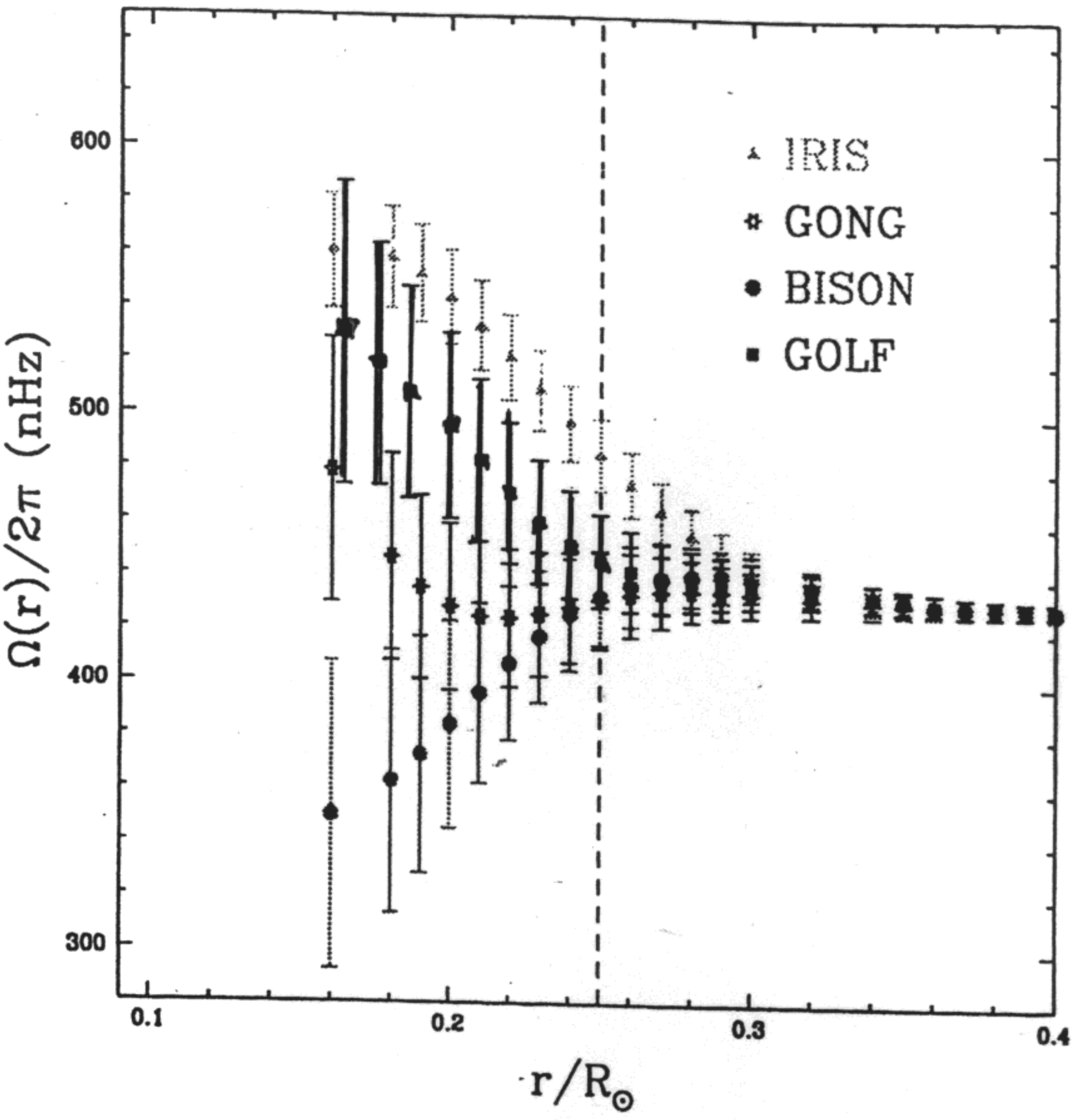
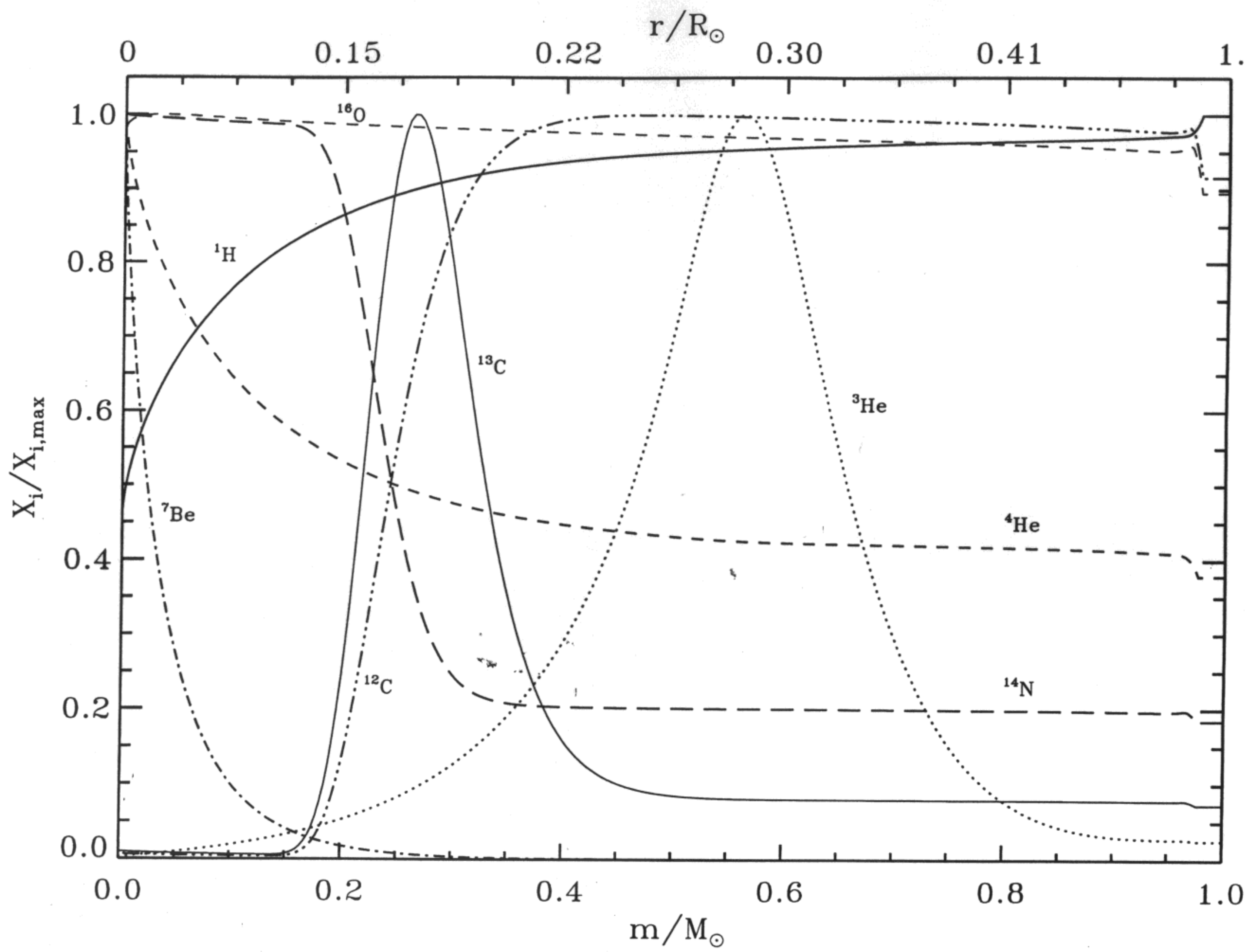


Figure 5. Rotation of the sun's core as deduce by inversion of the BiSON (filled circles), IRIS (filled triangles), GONG (starred symbols) and GOLF (filled squares) sets of lowest degree splittings ($\ell = 1 - 4$), all combined with SOI-MDI higher degree data set.


r/R⊙
0
0.15
0.22
0.30
0.41
1.
X_i/X_i,max
1.0
0.8
0.6
0.4
0.2
0.0
16O
1H
7Be
13C
3He
4He
12C
14N
0.0
0.2
0.4
0.6
0.8
1.0
m/M⊙

^{7}Be in the Sun

Produced by ^{3}He, ^{4}He,
it is destroyed by
ppII: $e + {}^{7}Be \rightarrow \nu + {}^{7}Li$
ppIII: $p + {}^{7}Be \rightarrow \gamma + {}^{8}B$; ${}^{8}B \rightarrow {}^{8}Be + \nu + e^{+}$

Check of the nuclear reaction rates and ^{7}Be ion properties

How to check the ^{7}Be abundance ?
mixing
destruction by other nuclear processes

If ^{7}Be reduced by a factor 2,

Chlore: 3.87 SNU
Water: 2.4 10^{-6} $cm^{-2}s^{-1}$
Gallium: 105 SNU

NUCLEAR OR ASTROPHYSICAL SOLUTIONS!

No distortion of neutrino spectrum

* ^{7}Be abundance reduced by a factor 2
  - reduction factor 2 ^{7}Be line
  - " ^{8}B flux

* ^{7}Be(p, γ) modified
  - ^{7}Be line unchanged
  - ^{8}B flux reduced

* T ↘ 2%
  - ^{8}B flux reduced by a factor 2
  - ^{7}Be flux reduced by 20%

CONCLUDING REMARKS

Helioseismology is a wonderful tool.
It allows to introduce macroscopic motions which improve stellar evolution (rotation,instabilities...)

Helioseismology does not check all the plasma properties

For the study of the solar core, acoustic waves are not the best tool and already constraints the physics down 0.2 RO.

Three directions of improvement are under investigation:

- **nuclear progress on $^7Be(p,\gamma)$ cross section and on properties of the ion ^7Be.**
- **gravity mode detection.**
- **solar neutrino energy spectrum at low energy (HELLAZ, LENS, SUPERMUNU).**