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Resonance Spin Flavour Precession and Solar Neutrinos

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Abstract

We examine the prospects for the resonance spin flavour precession as a solution to the solar neutrino problem. We study seven different realistic solar magnetic field profiles and, by numerically integrating the evolution equations, perform a fit of the event rates for the three types of solar neutrino experiments (Ga, Cl and SuperKamiokande) and a fit of the energy spectrum of the recoil electrons in SuperKamiokande. A χ^2 analysis shows that the quality of the rate fits is excellent for two of the field profiles and good for all others with $\chi^2/d.o.f.$ always well below unity. Regarding the fits for the energy spectrum, their quality is better than that for the small mixing angle MSW solution of the solar neutrino problem, at the same level as that for the large mixing angle MSW solution but worse than that for the vacuum oscillations one. The experimental data on the spectrum are however largely uncertain especially in the high energy sector, so that it is too early yet to draw any clear conclusions on the likeliest type of particle physics solution to the solar neutrino problem.

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Resonant Spin Flavour Precession and ⊙ Neutrinos

Mechanism to solve the solar neutrino problem as an alternative to oscillations (both MSW and vacuum). Proposed in 1988 by Lim + Marciano and by Akhmedov

Based on the precession of spin ($\nu_{e_L} \to \nu_{e_R}$ for Dirac neutrinos) or spin flavour ($\nu_{e_L} \to \bar{\nu}_{\mu_R}$, Majorana neutrinos) by means of interaction of magnetic moment μ_ν with the ⊙ magnetic field. This is resonantly enhanced in matter in analogy with MSW.

Why has it not been much investigated and become popular?

Possibly because it requires a large magnetic moment ($\mu_\nu \gtrsim 10^{-12} \mu_B$), six orders of magnitude or more above the SM value (with one singlet right-handed neutrino) and the ⊙ magnetic field is scarcely known.

Nevertheless RSFP is quite possible and attractive as we shall see.

[$\mu_\nu = O(10^{-12}\mu_B)$ lies two orders of magnitude below its lab limit and does not conflict with most astrophysical bounds. Also it is consistent with the smallness of ν mass].

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Starting point is the neutrino propagation equation through solar matter (Maj. ν's, for Dirac just take $V_\mu = 0$).

$$i\frac{d}{dt}\begin{pmatrix}\nu_{e_L}\\ \bar{\nu}_{\mu_R}\end{pmatrix} = \begin{pmatrix}V_e & \mu_\nu B\\ \mu_\nu B & \frac{\Delta m_{21}^2}{2E} - V_\mu\end{pmatrix}\begin{pmatrix}\nu_{e_L}\\ \bar{\nu}_{\mu_R}\end{pmatrix}$$

$$V_e = G\sqrt{2}\left(N_e - \tfrac{1}{2}N_n\right)$$
$$V_\mu = G\sqrt{2}\left(-\tfrac{1}{2}N_n\right)$$

electric neutrality condition assumed

$N_e = N_p$

Resonance (maximal mixing) occurs when diagonal elements are equal

$$G\sqrt{2}\,(N_e - N_n) = \frac{\Delta m_{21}^2}{2E}$$

$\odot$ magnetic field is not entirely free:

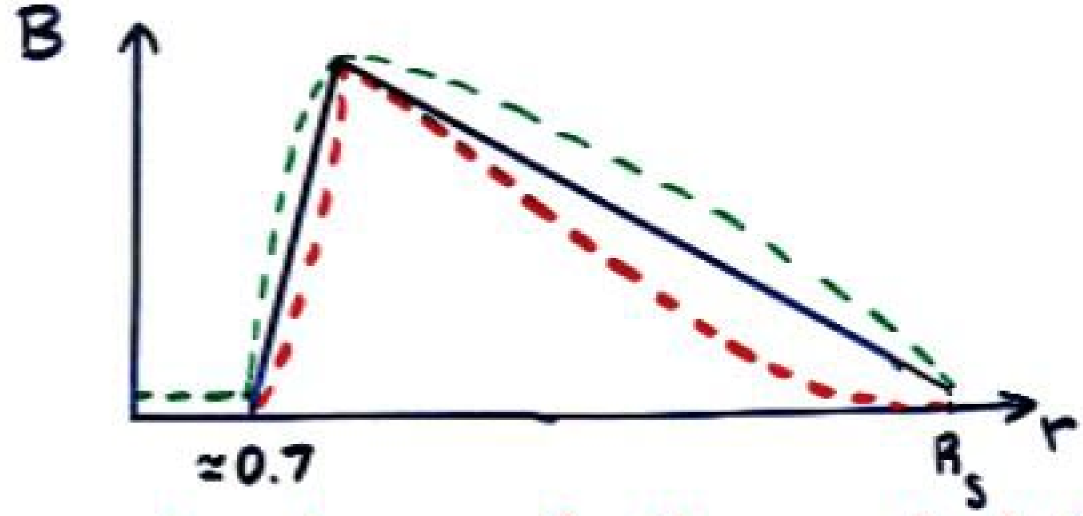
solar physics arguments suggest it is maximal around the bottom of convective zone possibly reaching a peak of approx.

$$3 \times 10^5 G$$

Also: if μ_ν exists, then solar ν data indicate that the field possibly undergoes a sharp rise over a relatively short distance along the radial direction (7 - 9% of R_S)

This is to account for a strong suppression of intermediate energy ν's (mainly ^7Be, $E_{^7Be} = 0.86\,MeV$) together with an almost full survival of pp ones ($E_{pp} \leq 0.42\,MeV$). High energy (^8B) ones are moderately suppressed, so the solar field must gradually decrease past the intermediate en. resonance densities.

Therefore explore field profiles with a general shape



The general shape of the probability is such that for large energies it always becomes close to 1/2.

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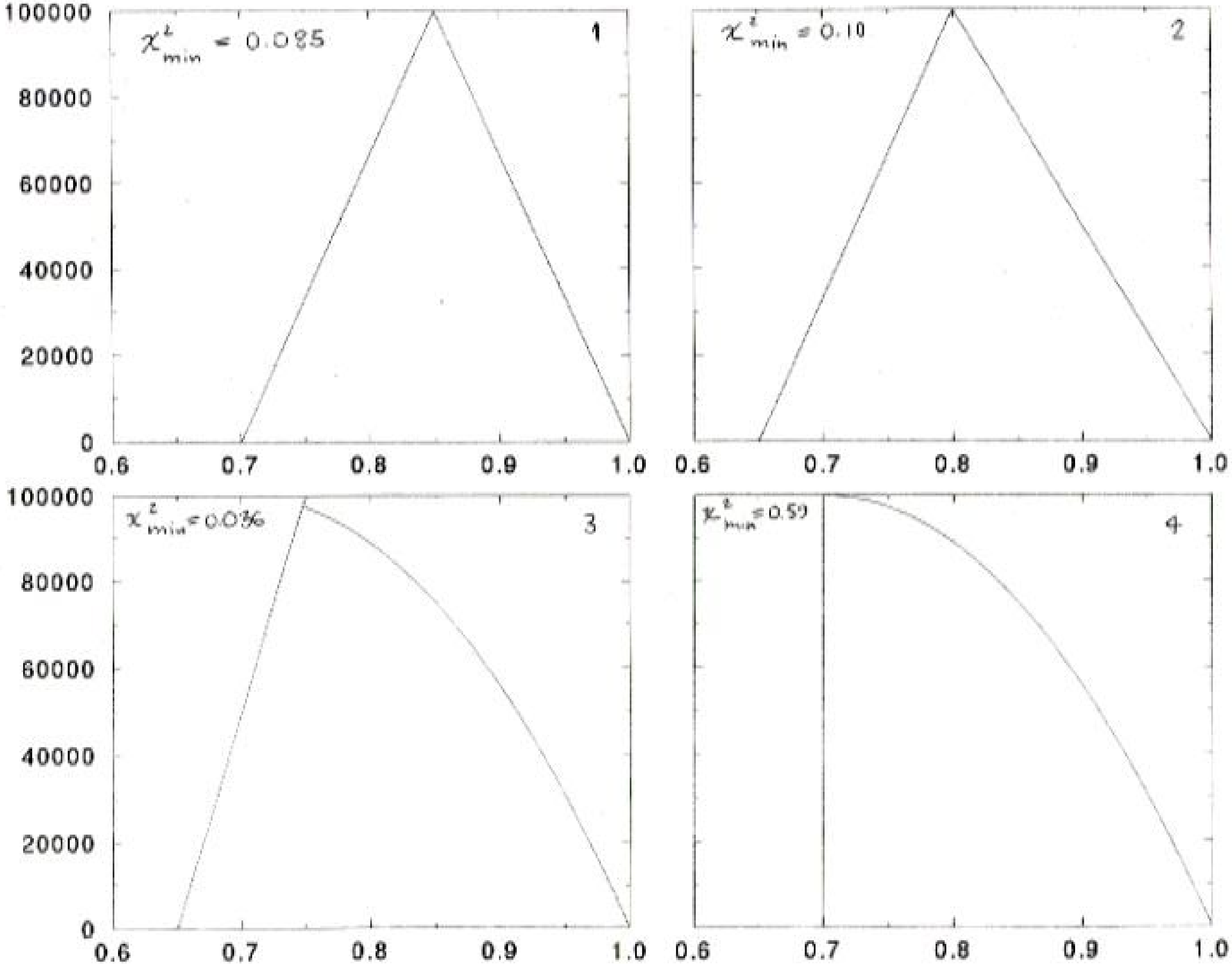
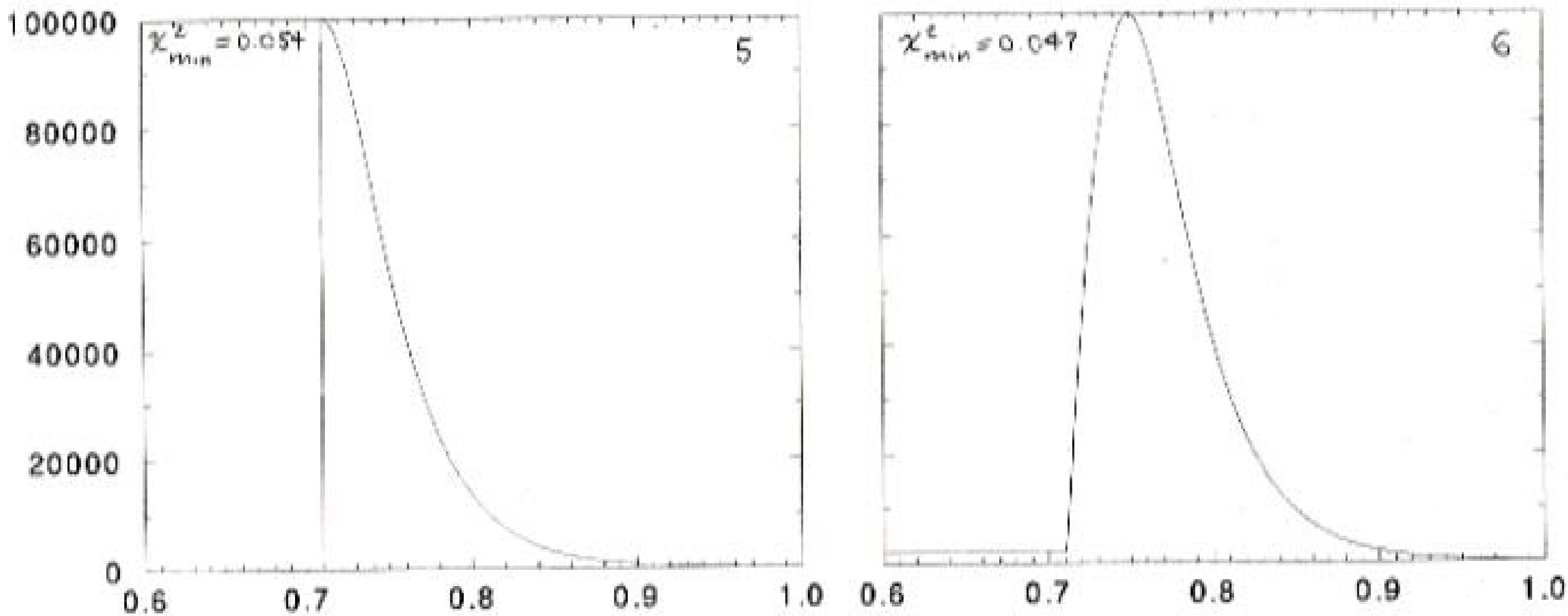
We integrated numerically the evolution equation and explored 7 profiles, performing for all of them fits of the total experimental rates (Ga, Cl, SuperK) and of the recoil electron energy spectrum

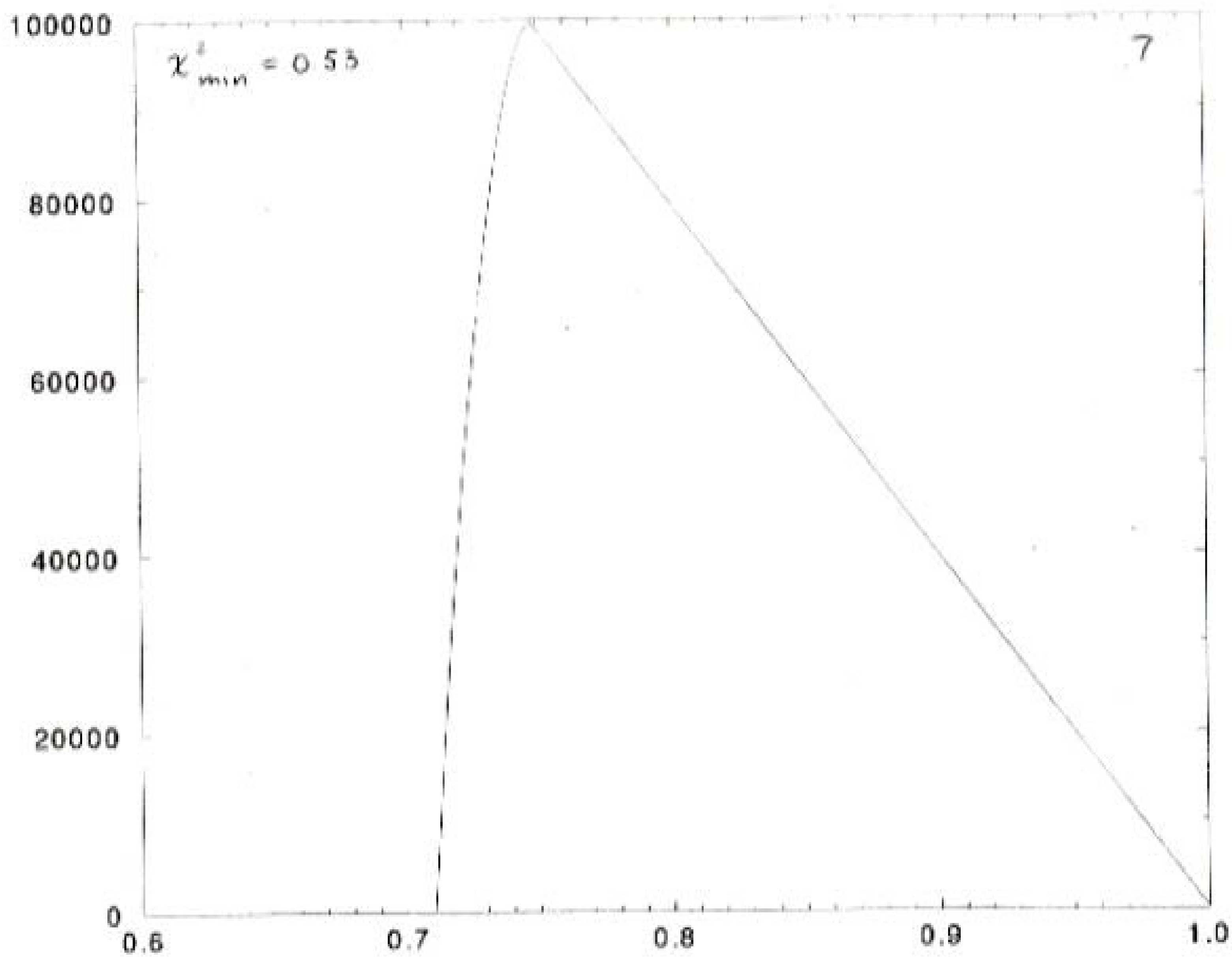
χ^2 fits for the rates



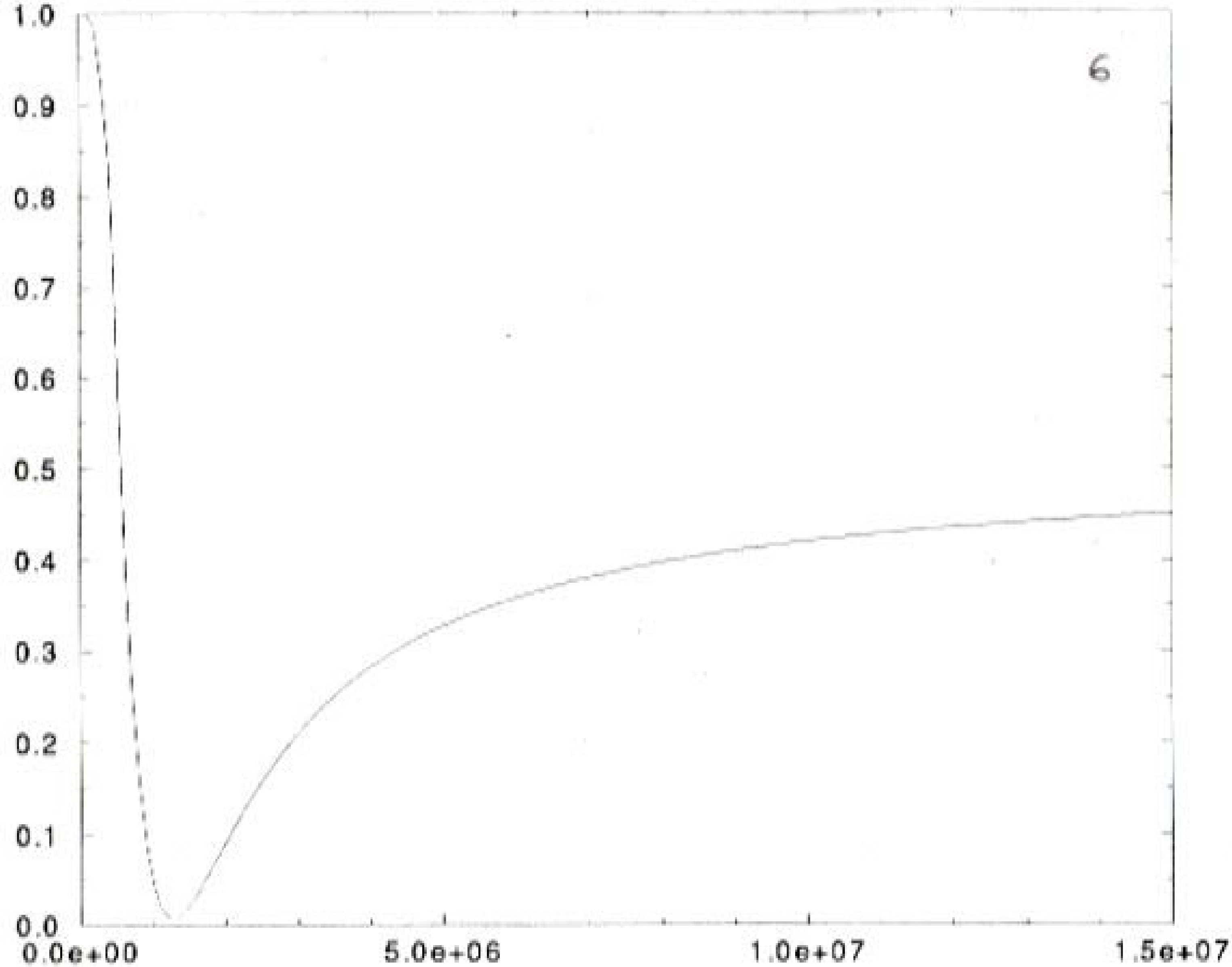
$\chi^2_{min} = 0.085$
1
$\chi^2_{min} = 0.10$
2
$\chi^2_{min} = 0.036$
3
$\chi^2_{min} = 0.59$
4
100000
80000
60000
40000
20000
0
0.6
0.7
0.8
0.9
1.0



100000
80000
60000
40000
20000
0
0.6
0.7
0.8
0.9
1.0
$\chi^2_{min} = 0.054$
5
$\chi^2_{min} = 0.047$
6



100000
80000
60000
40000
20000
0
0.6
0.7
0.8
0.9
1.0
$\chi^2_{min} = 0.53$
7



6
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0e+00
5.0e+06
1.0e+07
1.5e+07

χ^2 fits for the rates

$$\chi^2 = \sum_{j_1, j_2 = 1}^{3} \left(R_{j_1}^{th} - R_{j_1}^{exp}\right) \left[\sigma^2(tot)\right]^{-1}_{j_1 j_2} \left(R_{j_2}^{th} - R_{j_2}^{exp}\right)$$

where

$$R_j^{th} = \underset{\text{(fluxes)}}{\sum_i} R_{ji}^{th} = \sum_i \int_{E_{i_{min}}}^{E_{i_{max}}} \sigma_j(E)\, \underbrace{P(E)}_{\text{calculated from evolution equation}}\, f_i(E)\, dE$$

$j =$ Ga, Cl

For $j =$ SuperK,

$$R_j^{th} = \frac{\int_{E_m}^{E_M} f(E_{^8B}) \int_{T_m}^{T_M} \left[P(E)\frac{d^2\sigma_W}{dT\,dE} + (1-P(E))\frac{d^2\sigma_{\bar{W}}}{dT\,dE}\right] dT\,dE}{\int_{E_m}^{E_M} f(E_{^8B}) \int_{T_m}^{T_M} \frac{d^2\sigma_W}{dT\,dE}\, dT\,dE}$$

R_j in SNU for Ga, Cl

" " data/SSM for SuperK

Error matrices

$$\sigma^2_{j_1 j_2}(\text{tot}) = \sigma^2_{j_1 j_2}(\text{exp}) + \underbrace{\sigma^2_{j_1 j_2}(\text{ap}) + \sigma^2_{j_1 j_2}(\text{cs})}_{\sigma^2_{j_1 j_2}(\text{th})}$$

Where

$$\sigma^2_{j_1 j_2}(\text{exp}) = \delta_{j_1 j_2}\, \sigma^{\text{exp}}_{j_1}\, \sigma^{\text{exp}}_{j_2}$$

$$\sigma^2_{j_1 j_2}(\text{cs}) = \delta_{j_1 j_2} \sum_{\substack{i \\ \text{(fluxes)}}} R^{\text{th}}_{j_1 i} \left(\Delta \log C_{i j_1}\right)^2$$

$$\underset{\text{astrophysical}}{\sigma^2_{j_1 j_2}(\text{ap})} = \sum_{\substack{i_1 i_2 \\ \text{(fluxes)}}} R^{\text{th}}_{j_1 i_1} R^{\text{th}}_{i_2 j_2} \sum_k \alpha_{i_1 k}\, \alpha_{k i_2} \left(\Delta \log \underset{\substack{\text{9 astrophysical} \\ \text{variables}}}{X_k}\right)^2$$

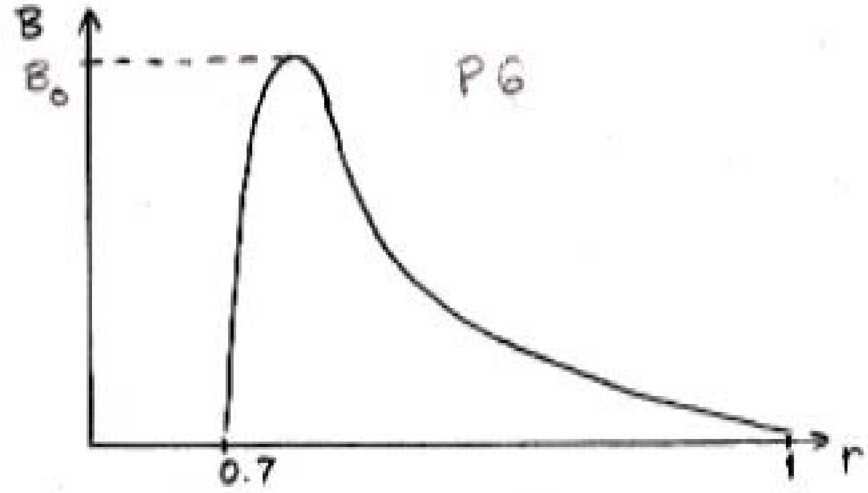
S_{11}, S_{33}, S_{34}, $S_{1,14}$, S_{17}, Lum, Z/X, Age, Opac

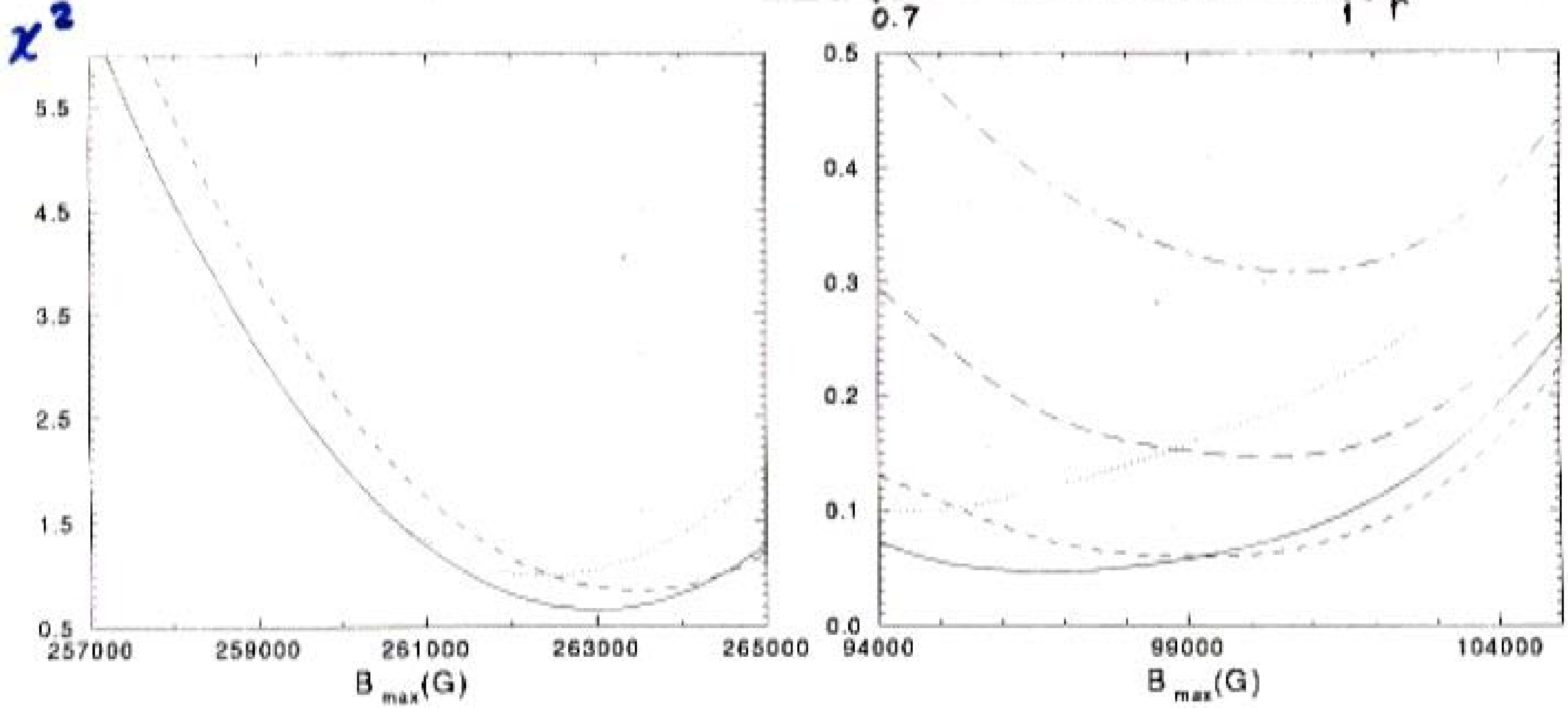
and : $\alpha_{ik} \equiv \dfrac{\partial \log f_i}{\partial \log X_k}$

Best fit $\Delta^2 = 1.6 \times 10^{-8} eV^2$

(rates) $B_0 = 9.6 \times 10^4 G$

$\chi^2_{min}/dof = 0.0477$

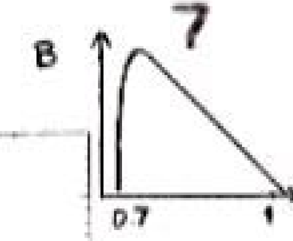




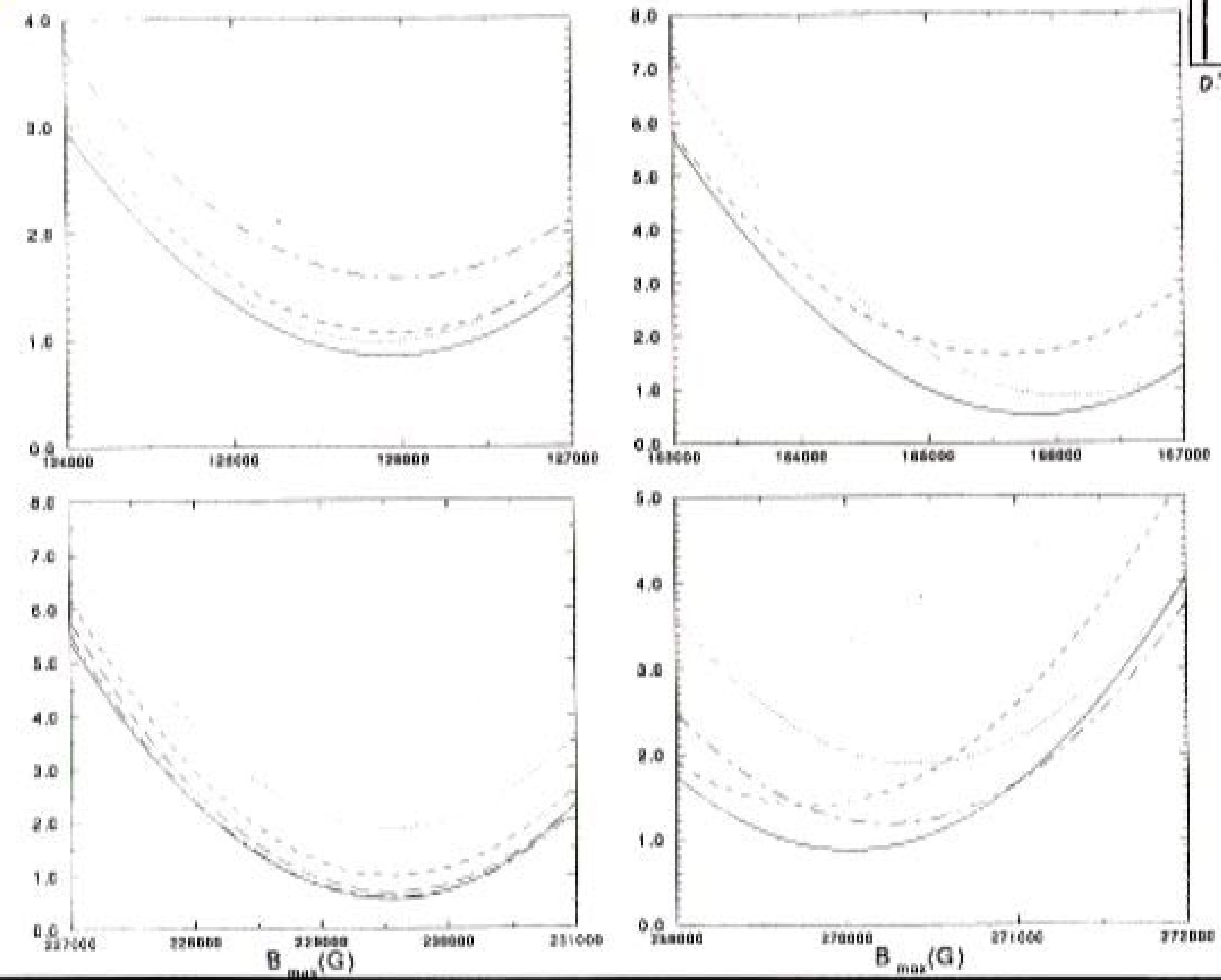
Best fit $\Delta^2 m_{21} = 1.2 \times 10^{-8}\, eV^2$

(rates) $B_0 = 1.66 \times 10^5 G$

$\chi^2_{min}/dof = 0.53$



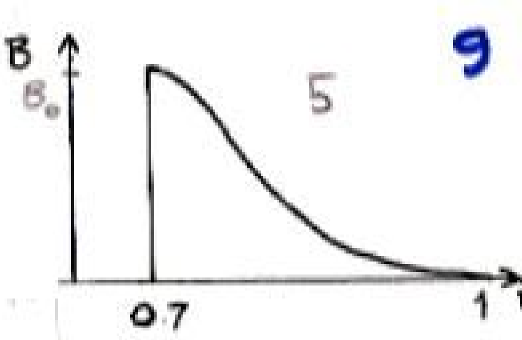
χ^2

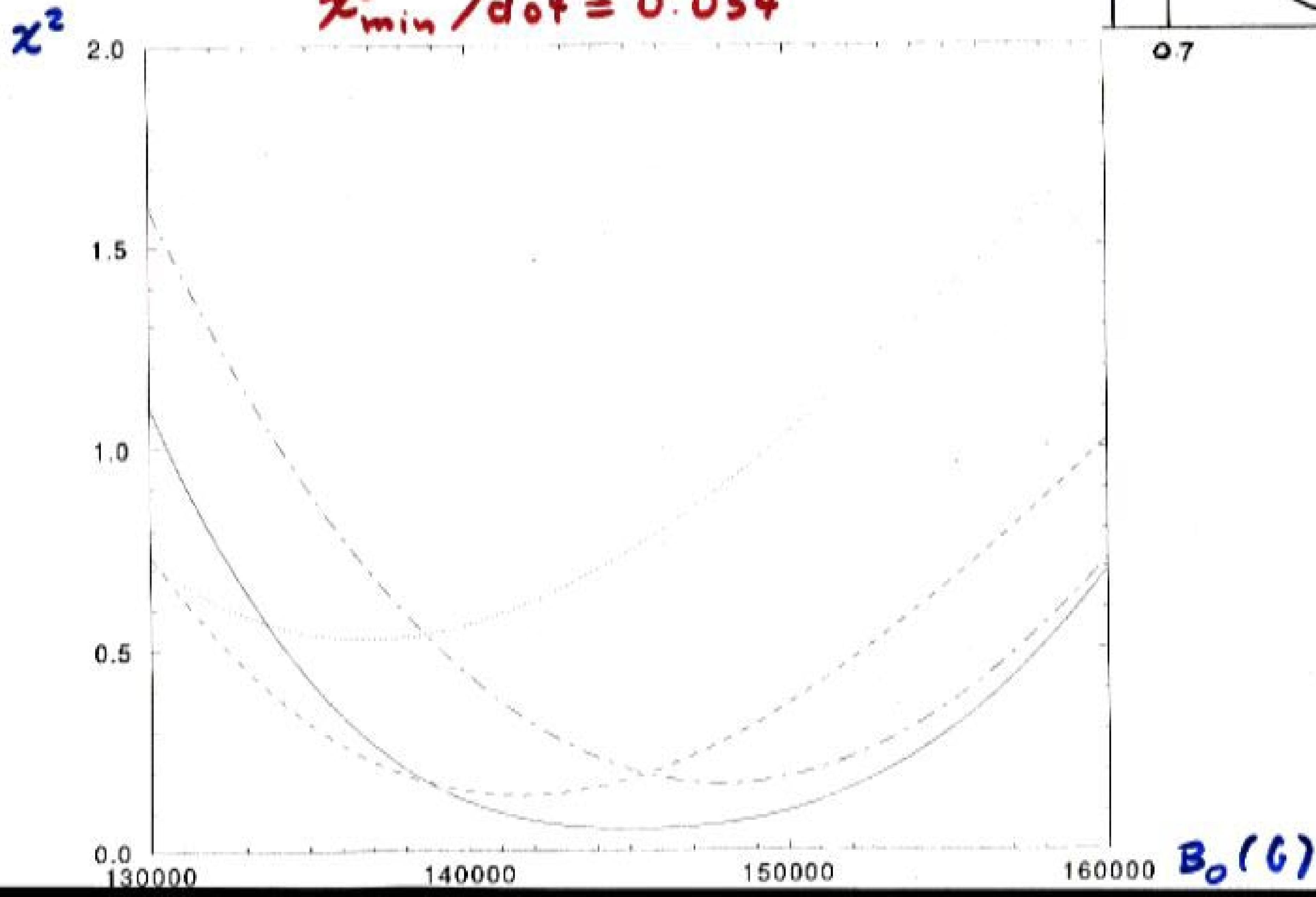


Best fit (rates) $\Delta m^2_{21} = 2.1 \times 10^{-8}\,eV^2$

$B_0 = 1.45 \times 10^5\,G$

$\chi^2_{min}/dof = 0.054$



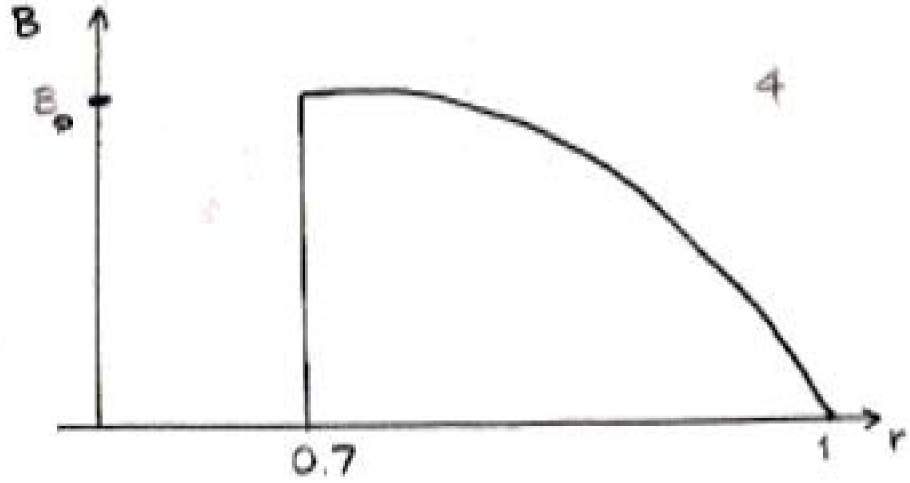


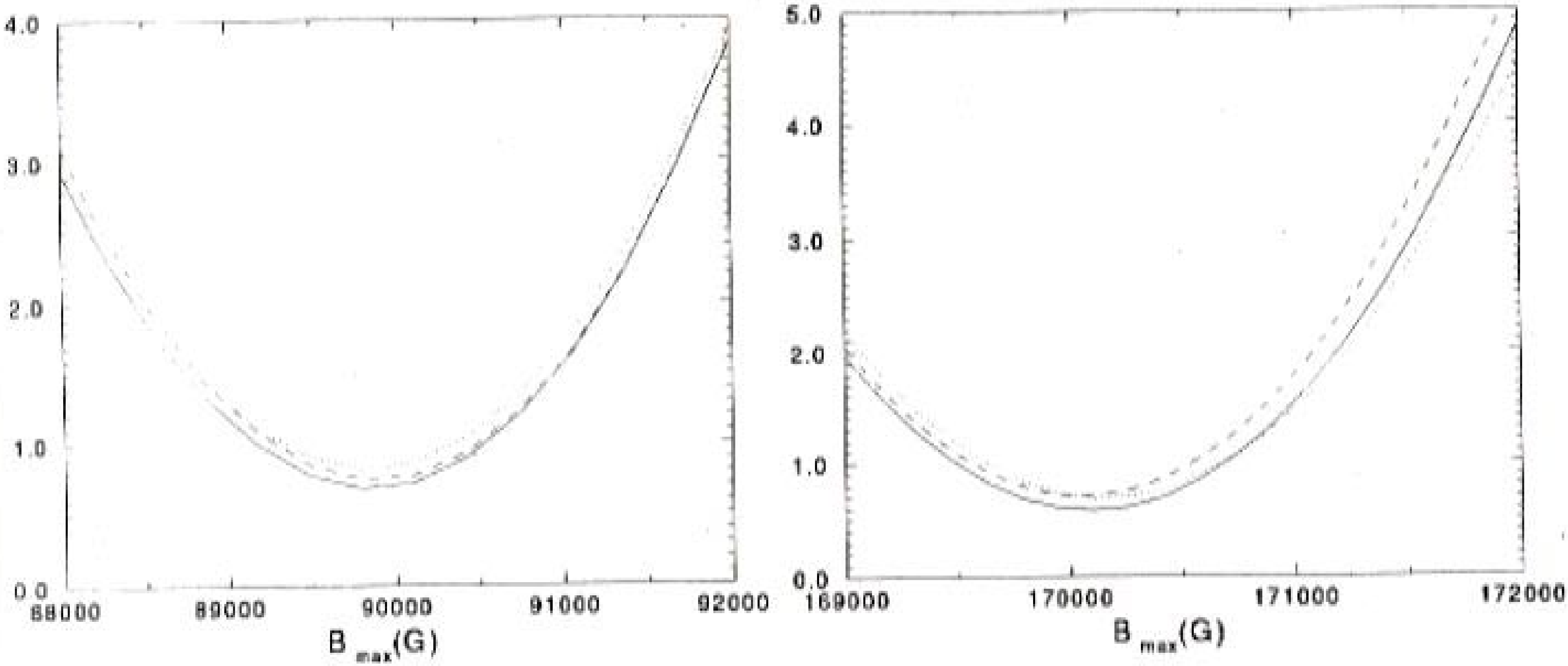
Best fit (rates)

$\Delta^2 m_{21} = 1.6 \times 10^{-8} eV^2$

$B_0 = 1.7 \times 10^5 G$

$\chi^2_{min}/dof = 0.59$





Expect an upward facing concavity of the field along the convective zone.

Because low energy sector of ^8B ν's is much suppressed: their energies (critical densities) lie close to ^7Be and CNO ones in a zone where $\odot$ field is supposedly maximal. So in order to ensure a moderate suppression ($P_{surv} \simeq 0.4 - 0.5$) of ^8B ν's the remainder of them ($E \gtrsim 1.8$ MeV) should be hardly suppressed.

Consequently the field is to decrease fast shortly after its maximum and become shallow towards the surface.

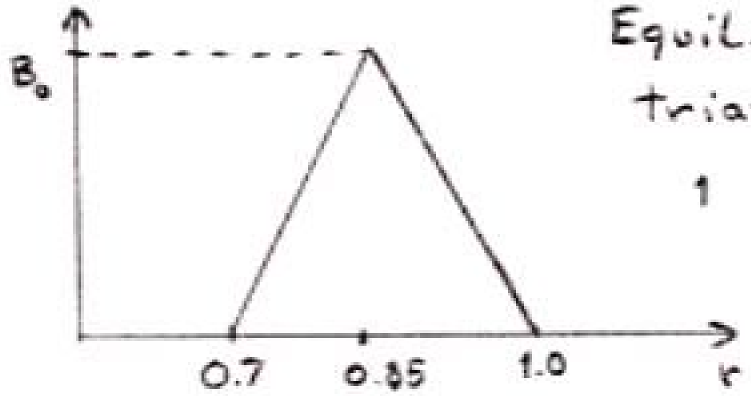
Remaining profiles (rates)

$\Delta m^2_{21} = 8 \times 10^{-9}\, eV^2$

$B_0 = 1.68 \times 10^5\, G$

$\chi^2_{min}/dof = 0.085$

quite unstable



Equil. triangle

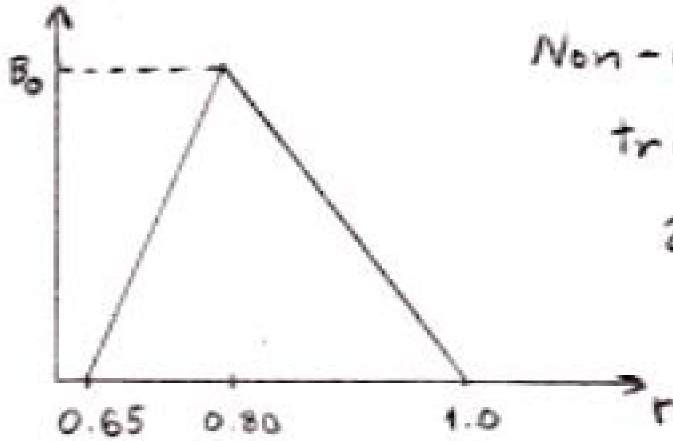
1

$\Delta m^2_{21} = 1.2 \times 10^{-8}\, eV^2$

$B_0 = 1.23 \times 10^5\, G$

$\chi^2_{min}/dof = 0.100$

more stable



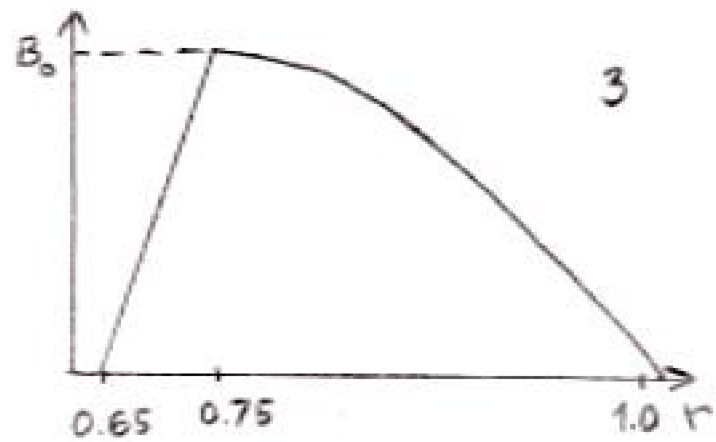
Non-equil. triangle

2

$\Delta^2 m_{21} = 1.2 \times 10^{-8}\, eV^2$

$B_0 = 9.54 \times 10^4\, G$

$\chi^2_{min}/dof = 0.036$



3

deep and narrow minimum (unstable against small variations of B_0). $\Delta B_0 = 3\, kG \rightarrow \dfrac{\Delta \chi^2}{\chi^2_{min}} = 50$

Conclusions (rates)

1. An overall smoother descent than rise is preferred.
2. Upward facing concavity is preferred, along convective zone.

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Spectrum fits

$$\chi^2 = \sum_{j_1 j_2}^{18} (R_{j_1}^{th} - R_{j_1}^{exp}) [\sigma^2(tot)]^{-1}_{j_1 j_2} (R_{j_2}^{th} - R_{j_2}^{exp})$$

Include now energy resolution function in the definition of R^{th} (important for spectrum).

Profile	χ^2_{sp} (708 days)	χ^2_{sp} (825 days)
1	22.5	24.8
2	21.9	23.9
3	22.5	24.8
4	25.9	29.5
+5	21.6	23.5
+6	21.7	23.6
7	22.3	24.5

16 dof

+ Best two: rates and fits

12a

825 days

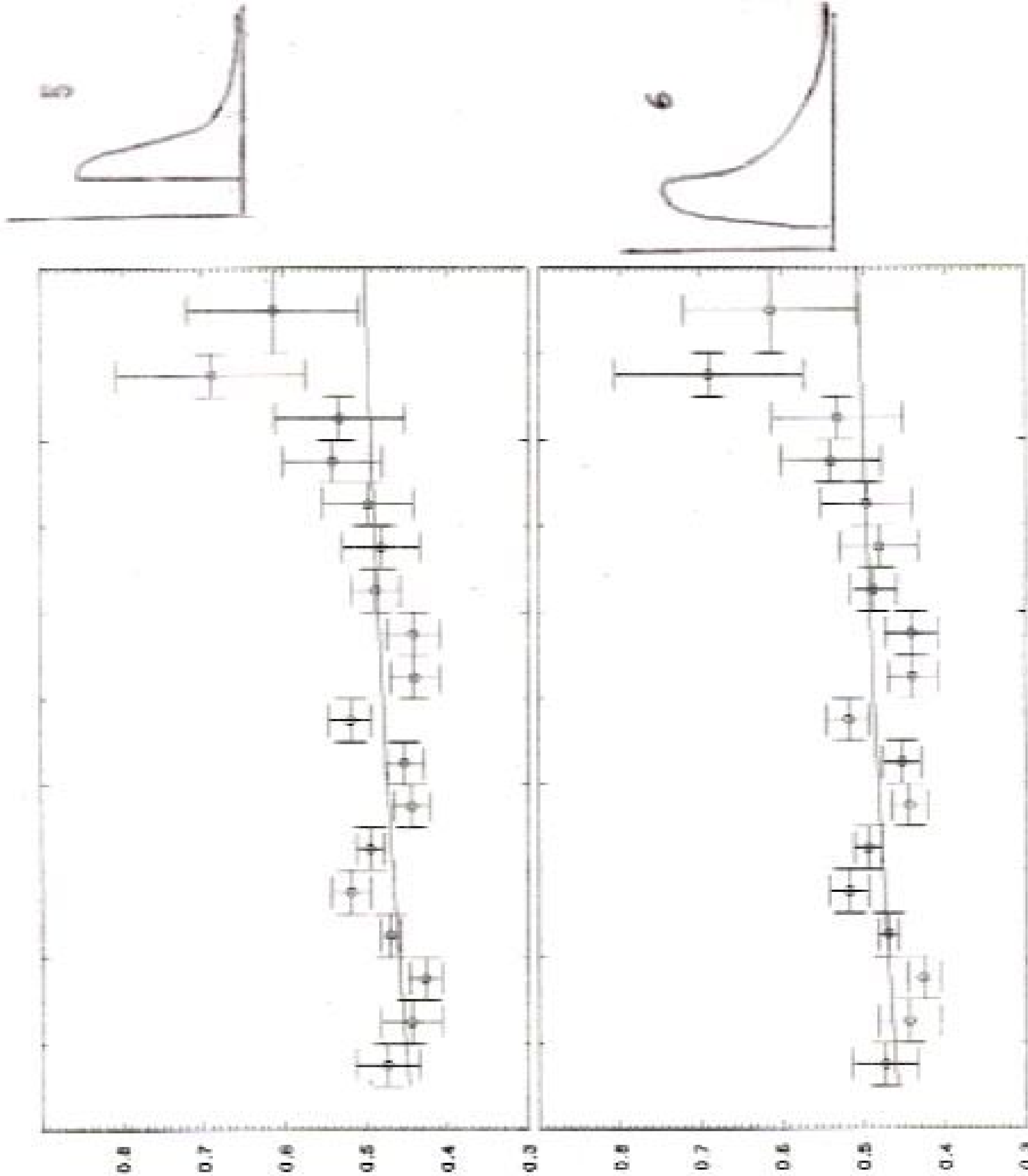

Figure 18: Spectrum fits: for profiles 5 (top) and 6 (bottom) we show the predicted electron recoil spectrum as a function of total electron energy superimposed on data set (II), ref. [30], with Δm^2_{21} and B_8 given by their values corresponding to the rates best fits (see figs.15, 16). For both, $\chi^2_{sp}/d.o.f. = 23.0/16$, the same as $\chi^2_{sp_{min}}/d.o.f.$ up to three digits. Profiles 5 and 6 (figs. 5 and 6) are those providing the best fits for both the rates and spectrum.

These χ^2 were calculated for Δ^2, B_0 at the rates best fits (for each case)

$\chi^2_{sp_{min}} = 23.2$ for P5 and P6 with

P5

$\left.\begin{array}{l} 3.2 \times 10^{-8}\,eV^2 \\ 1.14 \times 10^5\,G \end{array}\right\}$ spect rates $\left\{\begin{array}{l} 2.1 \times 10^{-8}\,eV^2 \\ 1.45 \times 10^5\,G \end{array}\right.$

P6

$\left.\begin{array}{l} 2.4 \times 10^{-8}\,eV^2 \\ 1.12 \times 10^5\,G \end{array}\right\}$ spect rates $\left\{\begin{array}{l} 1.6 \times 10^{-8}\,eV^2 \\ 9.6 \times 10^4\,G \end{array}\right.$

COMPARISONS (MSW, VO)

Rates (χ^2_{min})

0.036 − 0.59
(RSFP) 1d.o.f.

for all 7 profiles investigated

Bahcall, Krastev, Smirnov $\left\{\begin{array}{l} 1.7 \text{ (MSW, SMA) 2 d.o.f.} \\ 4.3 \text{ (MSW, LMA) VO} \end{array}\right.$

MCGG, PCH, CPG, Valle $\left\{\begin{array}{l} 0.44 \text{ (MSW, SMA) 1 d.o.f} \\ 2.7 \text{ (MSW, LMA) VO} \end{array}\right.$

Spectrum (χ^2_{min})

23.2 (RSFP)
(P5 and P6)

SK 25.0 (MSW, SMA)
BKS 23.5 (MSW, LMA)
SK 17.4 (VO)

Final notes

1. Spectrum fits seem to confirm indications from rate fits.

2. Calculations were done with $\mu_\nu = 10^{-11}\mu_B$.

Given the expectation of a 3×10^5 G peak field and since the order parameter is $\mu_\nu B$, our results indicate

$$\mu_\nu = (3 - 5) \times 10^{-12} \mu_B$$

for the solution to the $\odot$ ν problem.