Neutrino Magnetic Moment and Sterile Neutrinos

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Neutrino News from the Lab and the Cosmos
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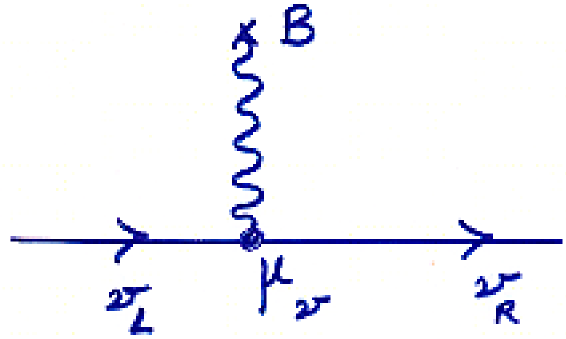
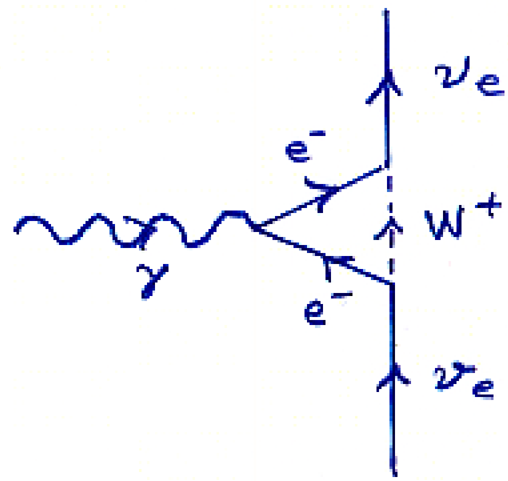
NEUTRINO MAGNETIC MOMENT:



Standard Model:



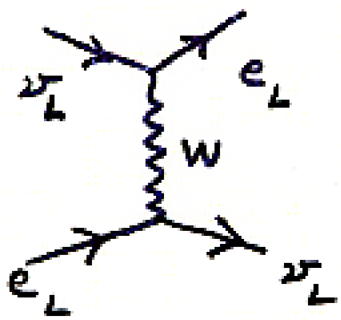
$$\mu_\nu = 3.2 \times \left(\frac{m_\nu}{1\,\mathrm{eV}} \right) \times 10^{-19} \mu_B$$

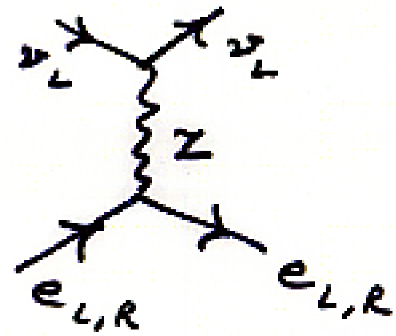
Current Laboratory limit:

$$\mu_\nu < 1.8 \times 10^{-10} \mu_B$$

Antineutrino - electron scattering :

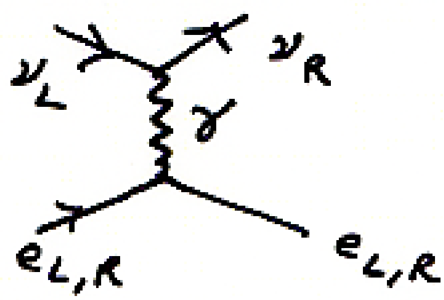
Standard contribution :





$$\frac{d\sigma}{dE} = \frac{2G_F^2 m_e}{\pi}\left[\sin^2\theta_W + \left(\frac{1}{2} + \sin^2\theta_W\right)\left(1 - \frac{E_e}{E_\nu}\right)^2 - \sin^2\theta_W\left(\frac{1}{2} + \sin^2\theta_W\right)\frac{m_e E_e}{2E_\nu^2}\right]$$

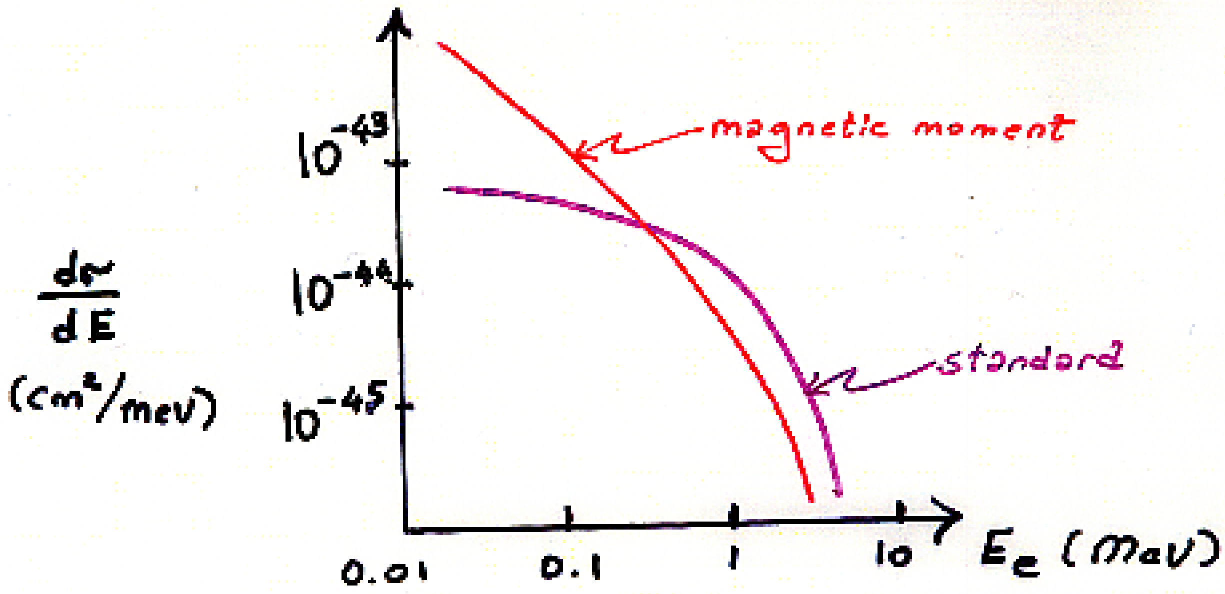
Magnetic moment contribution :



$$\frac{d\sigma}{dE} = \mu^2 \pi^2 r_0^{\,2}\left(\frac{1}{E_e} - \frac{1}{E_\nu}\right)$$

$r_0 = 2.8 \times 10^{-13}$ cm.

classical radius of electron



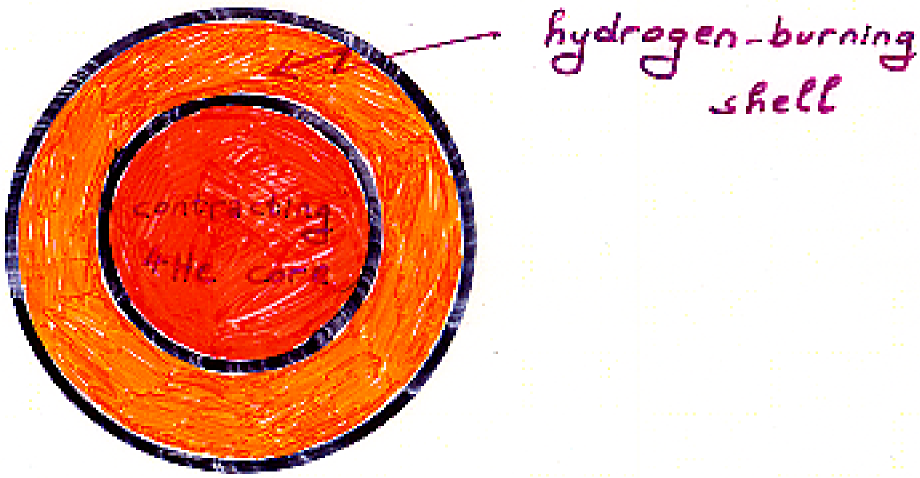
Given a neutrino source (e.g. reactor) with energy spectrum $N(E_\nu)$, experiments measure the integrated cross-section between two recoil electron energies E_1 & E_2

$$\sigma = \int_{E_1}^{E_2} dE_e \int_{E_{min}}^{\infty} dE_\nu \, N(E_\nu) \frac{d\sigma}{dE}$$

$$\mu_{\nu_e} < 1.5 \times 10^{-10} \mu_B$$

Red giant stars :

Raffelt



burning hydrogen shell ➡ more ^{4}He added to the core
(core mass increases)

⇓

gravitational potential at the shell increases

⇐

more intense burning, star reddens

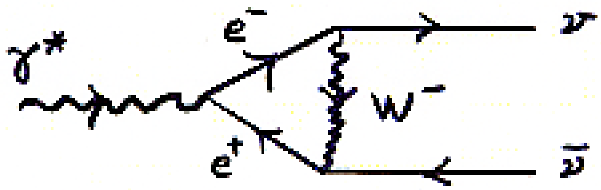
⇑

helium-flash rate :

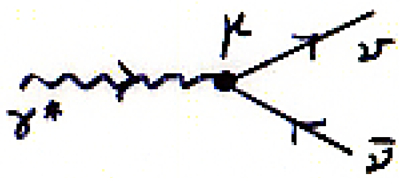
$$\text{rate}\ (3\alpha \to {}^{12}C) \sim T^{30}$$

Neutrino cooling lowers T and delays α-ignition.

Effective cooling delays the onset of He-burning, hence increases the core mass at He-flash.



standard plasmon coupling



magnetic-moment coupling

neutrino magnetic moment would cause additional cooling $\Rightarrow$ He ignition could get delayed

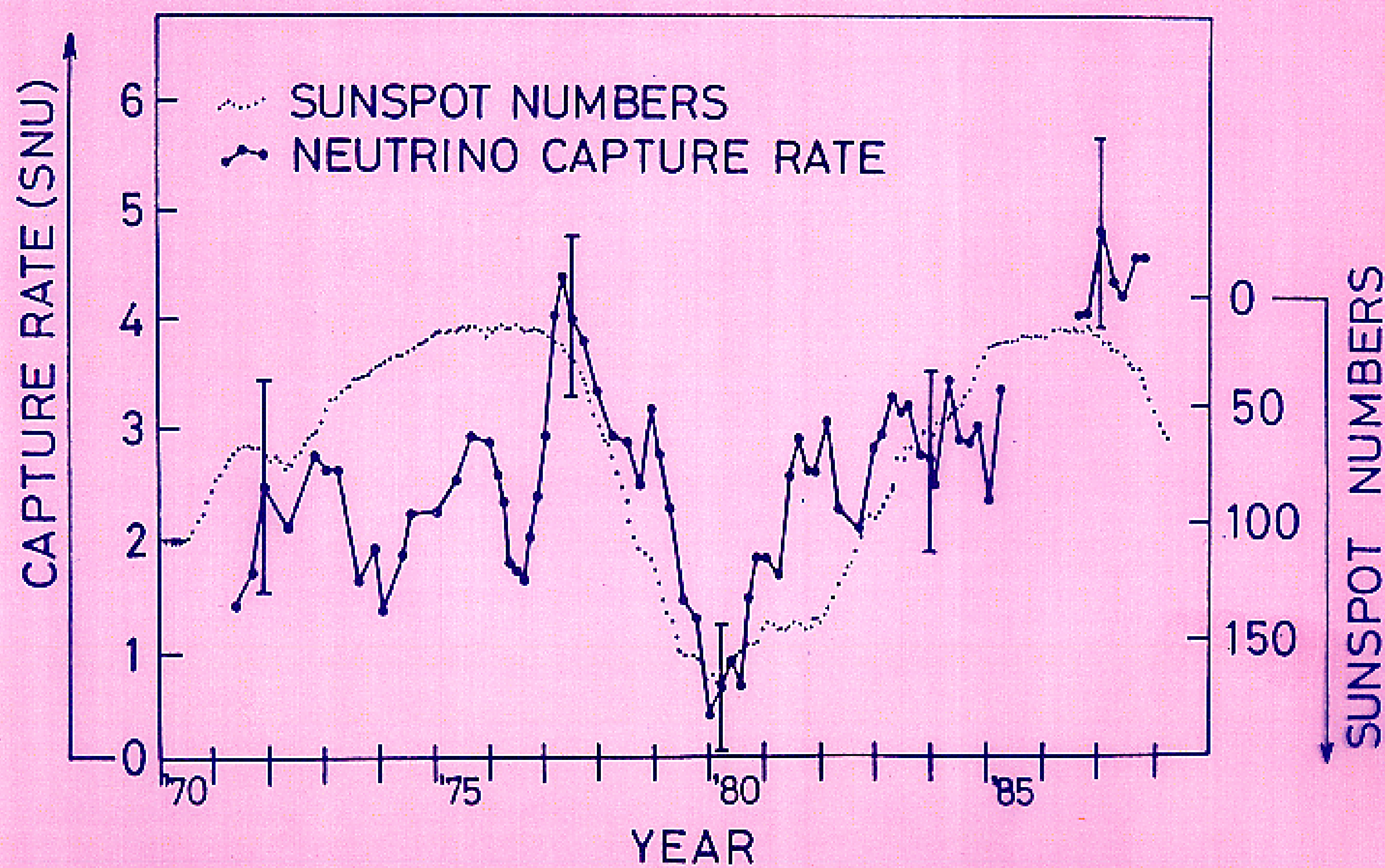
$\Rightarrow$ # of stars at the red-giant branch increases

$$\Rightarrow \quad \mu_\nu \lesssim 3 \times 10^{-12} \, \mu_B$$

NEUTRINO MAGNETIC MOMENT LIMITS

Limit ($10^{10}\mu_B$)	**Method**	**Authors**
$\lesssim 1.9$	Reactor $\overline{\nu_e} + e \longrightarrow \overline{\nu_e} + e$	Derbin (1993)
$\lesssim 1.9$	LAMPF $\nu_e + e \longrightarrow \nu_e + e$	Krauker, *et al.* (1990)
$\lesssim 1.5$	SuperKamiokande ν spectrum shape	Beacom and Vogel (1999)
$\lesssim 4$	Helioseismology limit on solar cooling	Raffelt (1999)
$\lesssim 0.03$	Red Giant Luminosity	Raffelt (1999)
$\lesssim 0.2$	^{4}He abundance in the Early Universe	Morgan (1981)

CL experiment



Evolution of Chiral Components

$$i\frac{\partial}{\partial t}\begin{bmatrix}\nu_L\\ \\ \nu_R\end{bmatrix}=\begin{bmatrix}\frac{G_F}{\sqrt{2}}(2N_e-N_n) & \mu B\\ \\ \mu B & 0\end{bmatrix}\begin{bmatrix}\nu_L\\ \\ \nu_R\end{bmatrix},$$

Cisneros, Astrophys. Space Sci. **10**, 87 (1970); Okun, Voloshin, and Vysotsky, Sov. J. Nucl. Phys. **44**, 440 (1986).

Spin-Flavor Precession

$$i\frac{\partial}{\partial t}\begin{bmatrix}\nu_e^L\\ \nu_\mu^L\\ \nu_e^R\\ \nu_\mu{}^R\end{bmatrix}=\begin{bmatrix}H_L & BM^\dagger\\ & \\ BM & H_R\end{bmatrix}\begin{bmatrix}\nu_e^L\\ \nu_\mu^L\\ \nu_e^R\\ \nu_\mu{}^R\end{bmatrix}$$

Dirac neutrinos

$$H_L=\begin{bmatrix}\frac{\delta m^2}{2E}\sin^2\theta_v+\frac{G_F}{\sqrt{2}}(2N_e-N_n) & \frac{\delta m^2}{4E}\sin 2\theta_v\\ & \\ \frac{\delta m^2}{4E}\sin 2\theta_v & \frac{\delta m^2}{2E}\sin^2\theta_v-\frac{G_F}{\sqrt{2}}N_n\end{bmatrix}$$

$$H_R=\begin{bmatrix}\frac{\delta m^2}{2E}\sin^2\theta_v & \frac{\delta m^2}{4E}\sin 2\theta_v\\ & \\ \frac{\delta m^2}{4E}\sin 2\theta_v & \frac{\delta m^2}{2E}\sin^2\theta_v\end{bmatrix}$$

$$M=\begin{bmatrix}\mu_{ee} & \mu_{e\mu}\\ & \\ \mu_{\mu e} & \mu_{\mu\mu}\end{bmatrix}$$

C.-S. Lim, W.J. Marciano, Phys. Rev. D **37**, 1368 (1988); E. Kh. Akhmedov, Phys. Lett. B 213, 64 (1988).

RESONANCES

$\nu_e \rightarrow \nu_\mu$ (MSW) :

$$\frac{\Delta m^2}{2E} \cos 2\theta = \sqrt{2}\, G_F N_e$$

$\nu_e \rightarrow \bar{\nu}_\mu$ (Resonant spin-flavor precession) :

$$\frac{\Delta m^2}{2E} \cos 2\theta = \sqrt{2}\, G_F (N_e - N_n) - \dot{\varphi}$$

$\nu_\mu \rightarrow \bar{\nu}_e$:

$$\frac{\Delta m^2}{2E} \cos 2\theta = \dot{\varphi} - \sqrt{2}\, G_F (N_e - N_n)$$

$\nu_e \rightarrow \bar{\nu}_e$:

$$\dot{\varphi} = \frac{G_F}{\sqrt{2}} (2 N_e - N_n)$$

$\nu_\mu \rightarrow \bar{\nu}_\mu$:

$$\dot{\varphi} = - \sqrt{2}\, G_F N_n$$

Majorana neutrinos

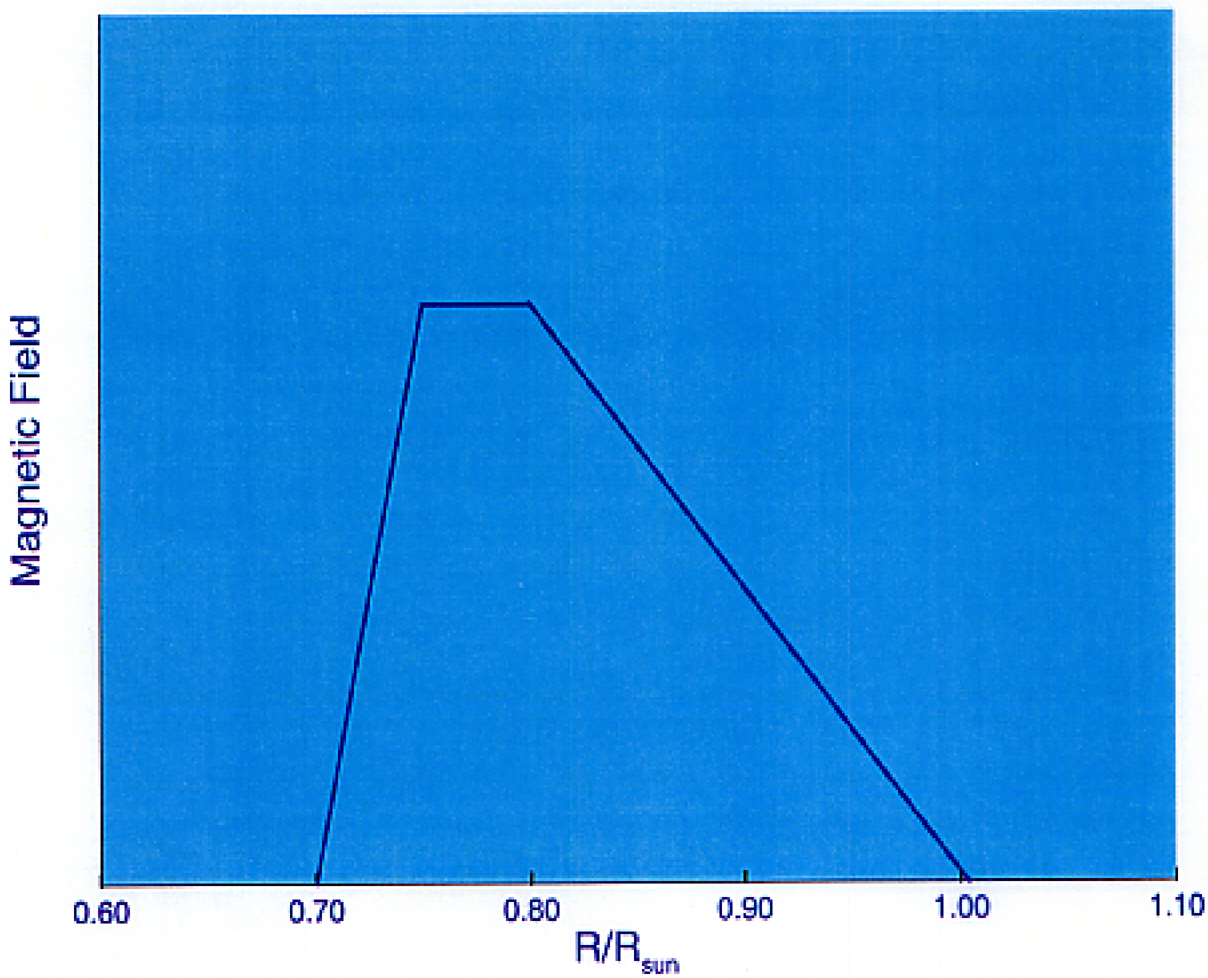
$$\begin{bmatrix} \frac{G_F}{\sqrt{2}}(2N_e - N_n) & \frac{\delta m^2}{4E}\sin 2\theta_v & 0 & \mu^* B \\ \frac{\delta m^2}{4E}\sin 2\theta_v & \frac{\delta m^2}{2E}\cos 2\theta_v - \frac{G_F}{\sqrt{2}}N_n & -\mu^* B & 0 \\ 0 & -\mu B & -\frac{G_F}{\sqrt{2}}(2N_e - N_n) & \frac{\delta m^2}{4E}\sin 2\theta_v \\ \mu B & 0 & \frac{\delta m^2}{4E}\sin 2\theta_v & \frac{\delta m^2}{2E}\cos 2\theta_v + \frac{G_F}{\sqrt{2}}N_n \end{bmatrix}$$

Solar Magnetic fields
What we already know

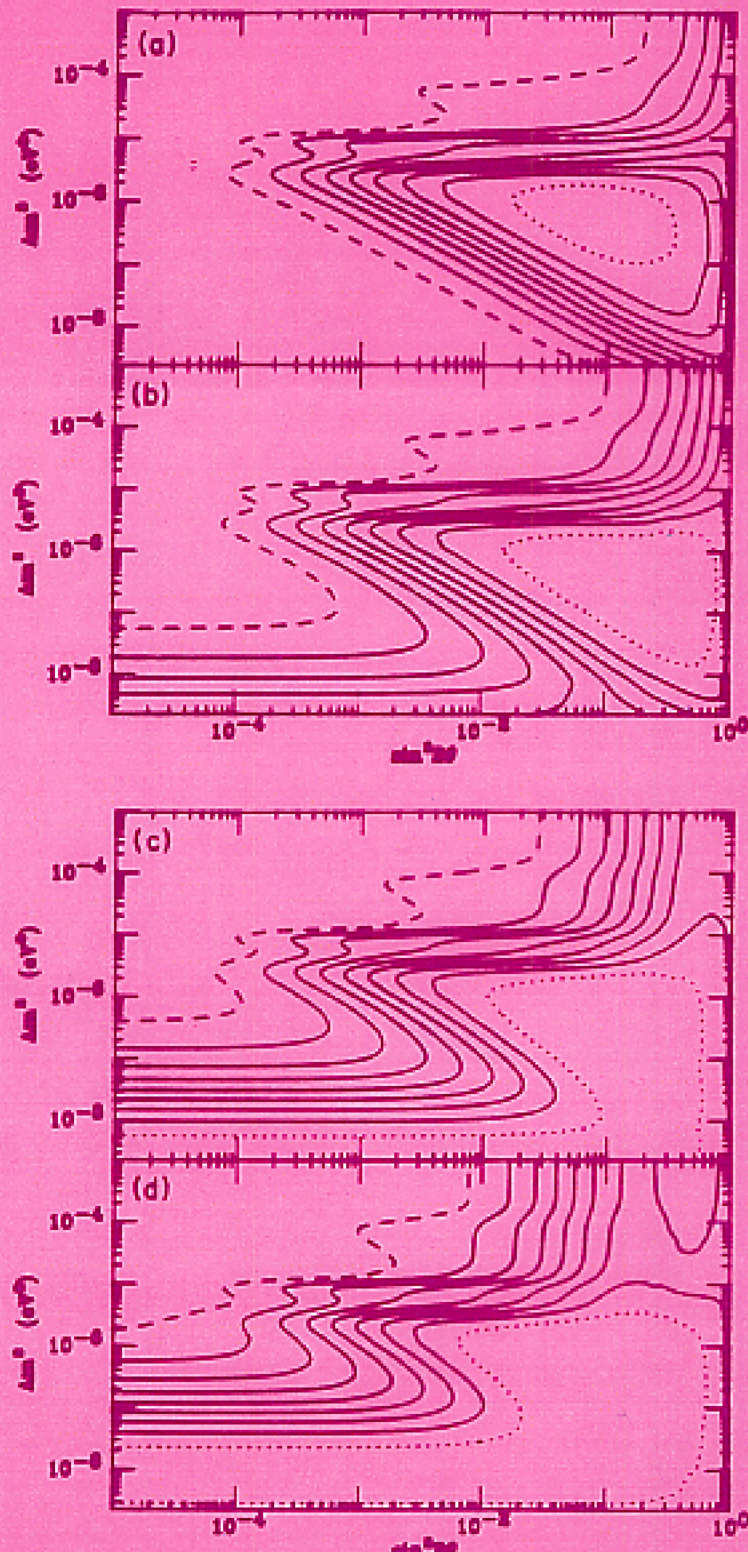
- Surface magnetic field at sunspots is 10^3 G.
- The large toroidal field changes direction every 11 years.
- Speckle interferometry can resolve flux tubes of ~200 km.
- Field inside should be weak enough so that the magnetic pressure $(B^2/8\pi)$ is less than a few percent of the gas pressure.
  $B < 10^7$ Gauss

Magnetic Field in the Convective Zone

Balantekin, Loreti, Akhmedov, and others



Magnetic moment effects in the Ga detectors:



$\mu B = 0$

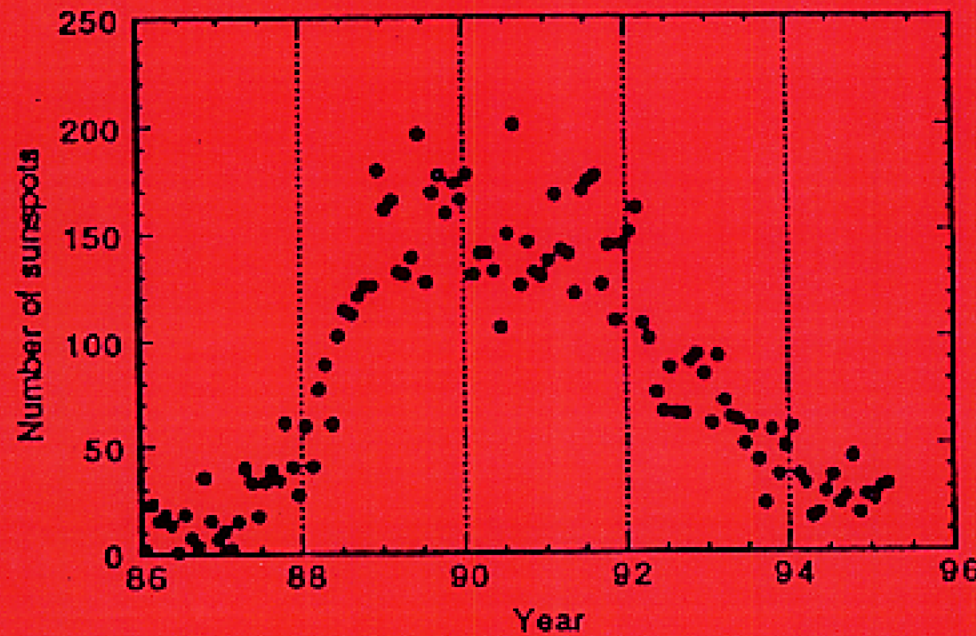
$\mu B = 2 \times 10^{-7} \mu_B G$

$\mu B = 5 \times 10^{-7} \mu_B G$

$\mu B = 10 \times 10^{-7} \mu_B G$

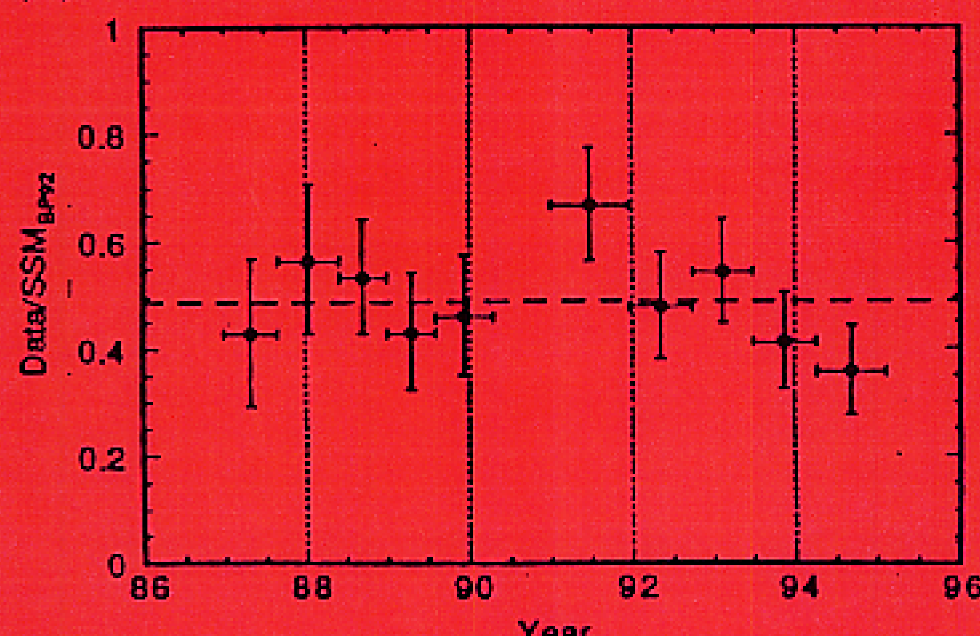
A. B. Balantekin, P. J. Hatchell, and F. Loreti, Phys. Rev. D41, 3583 (1990).

(a)



Variation of sunspot numbers in solar cycle 22

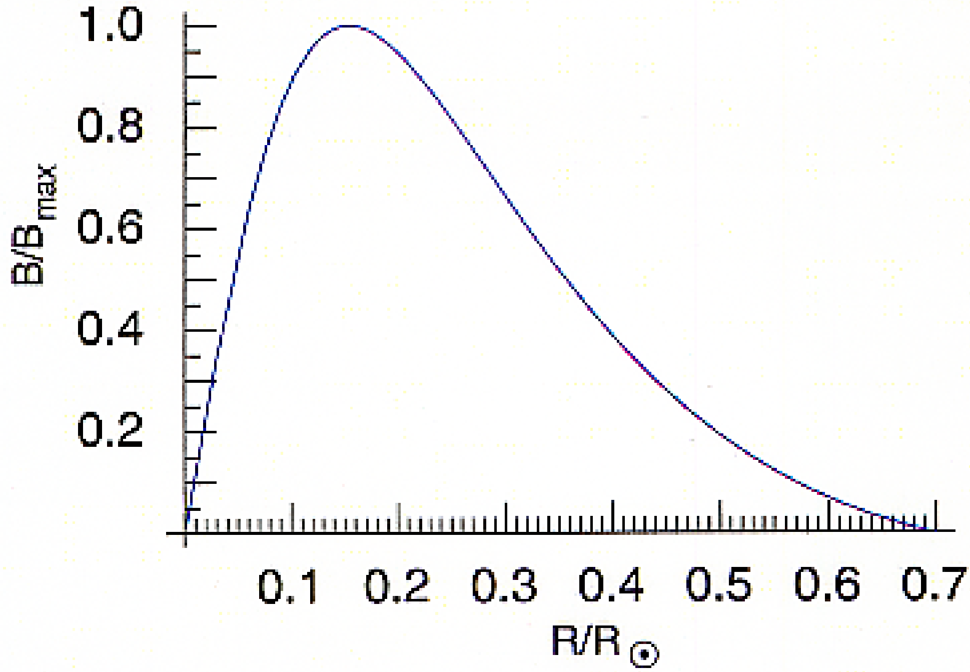
(b)

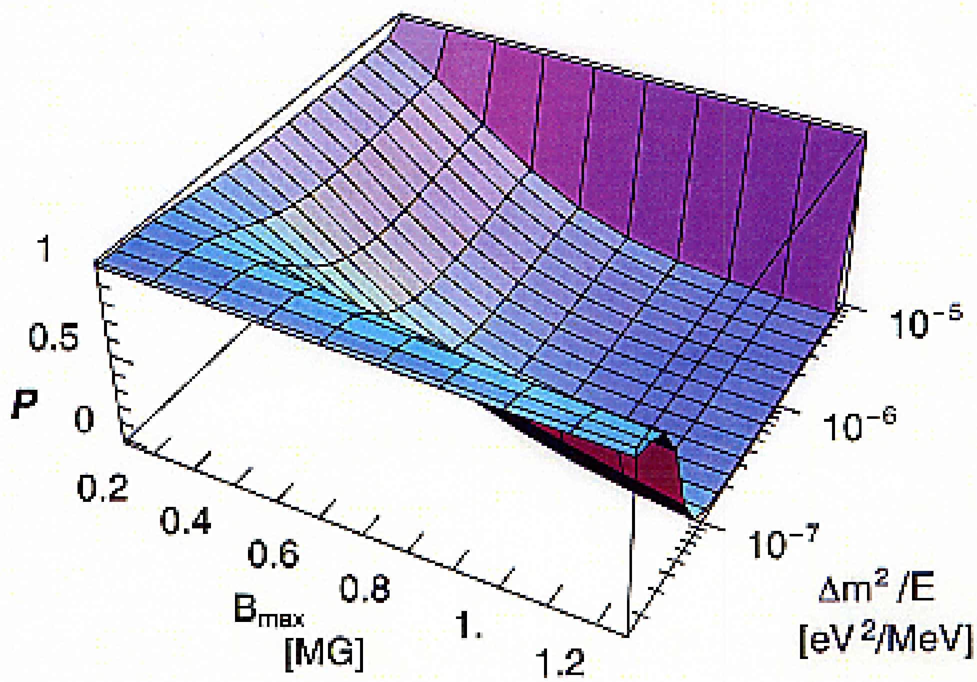


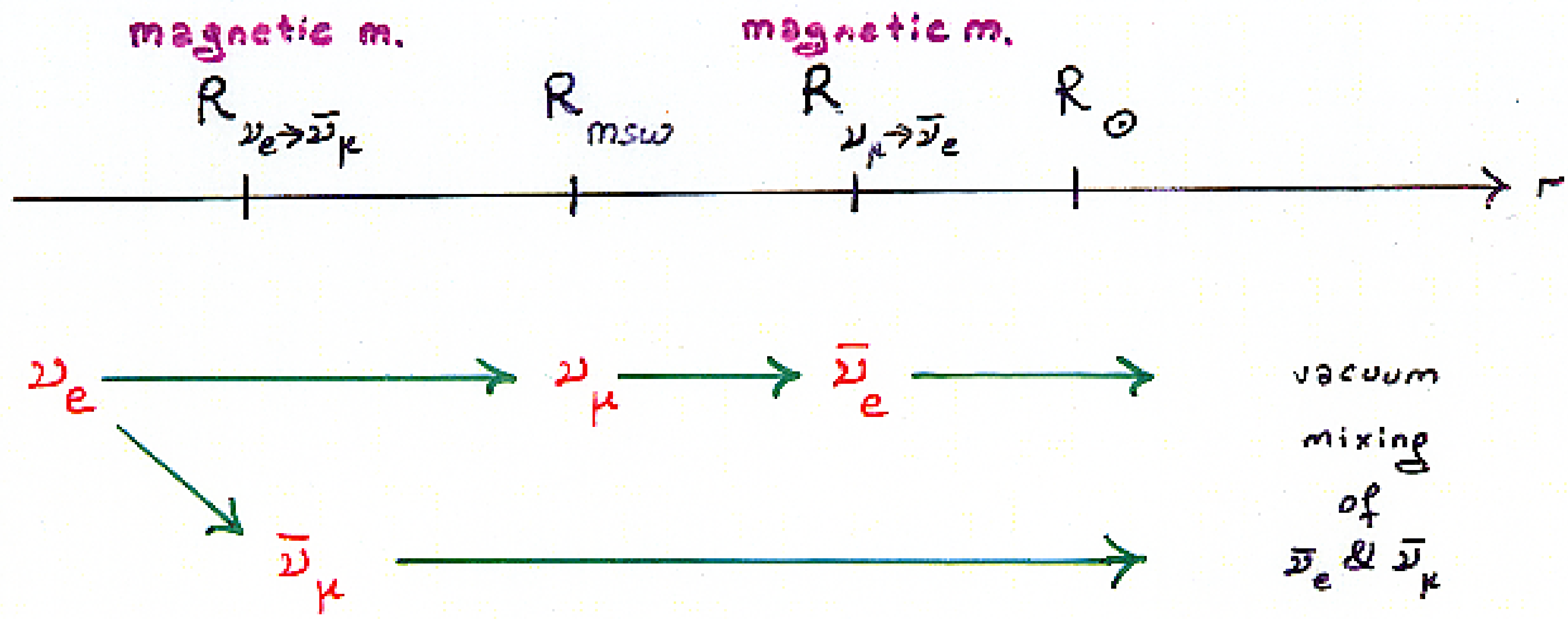
Kamiokande data for solar cycle 22

Magnetic Field in the Radiative Zone

Friedland and Gruzinov, hep-ph/0202095

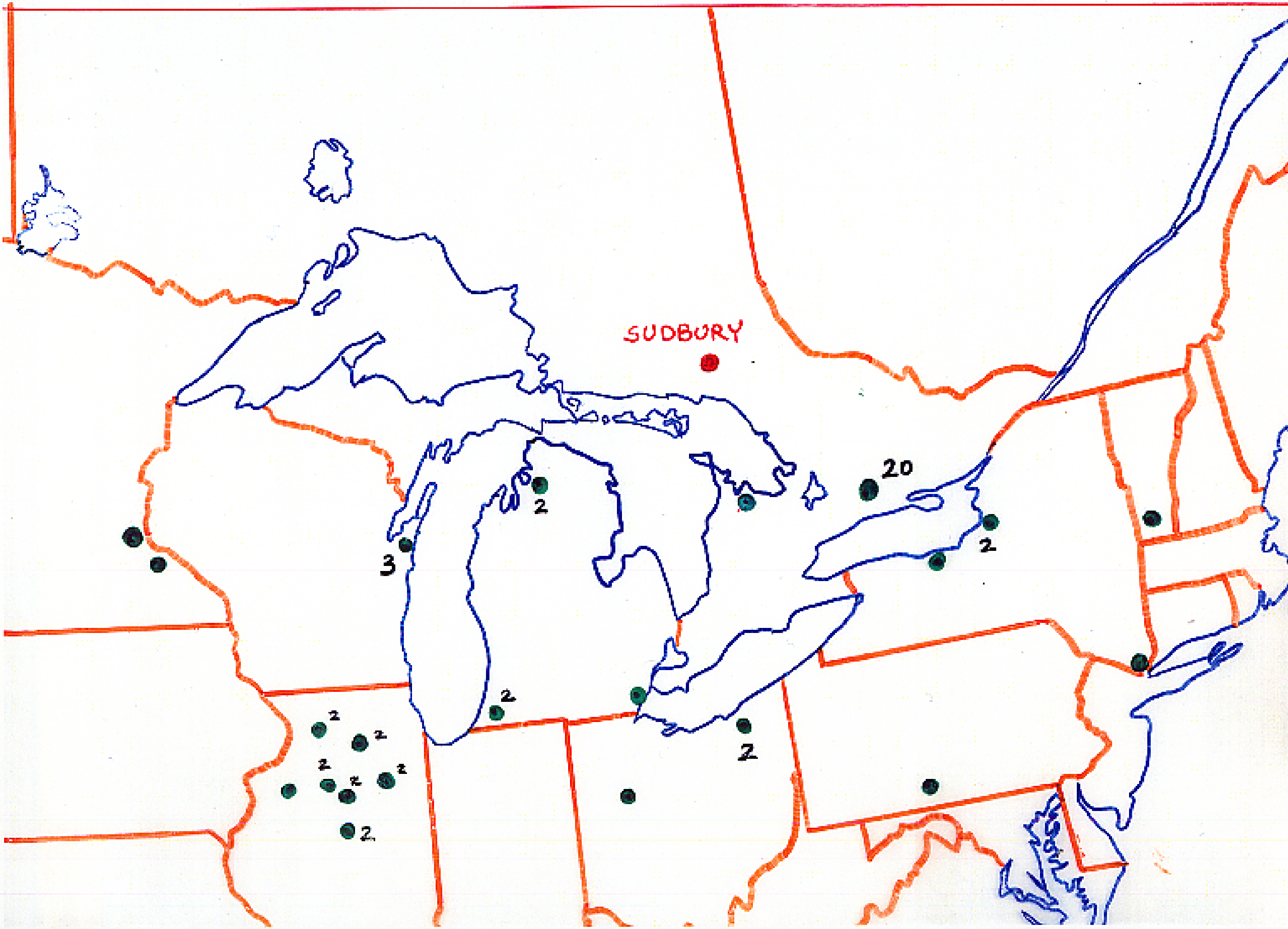




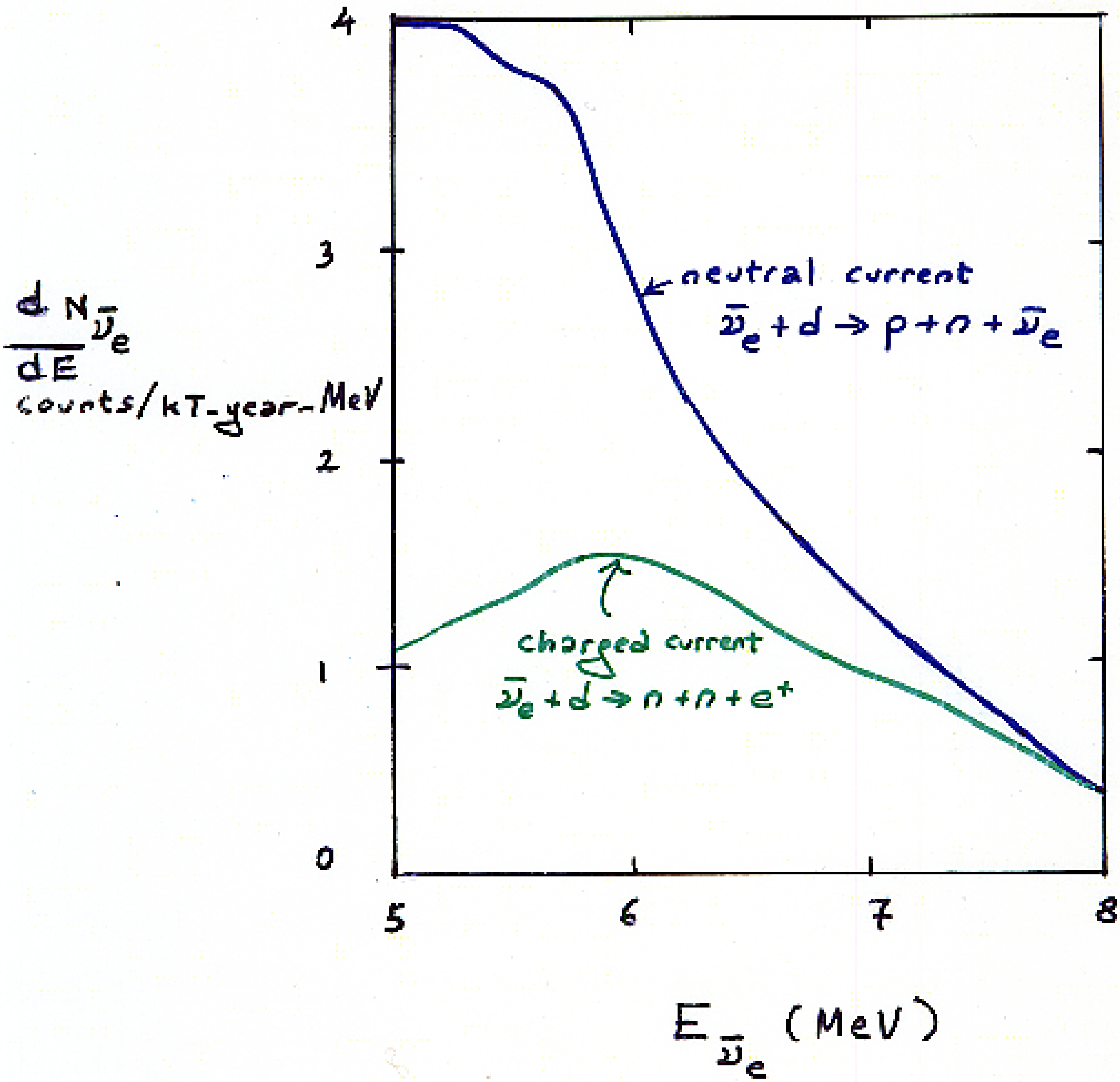


$N_{\bar{\nu}_e}$ on earth $\sim (\mu B)^2$

COMMERCIAL POWER REACTORS NEAR SUDBURY

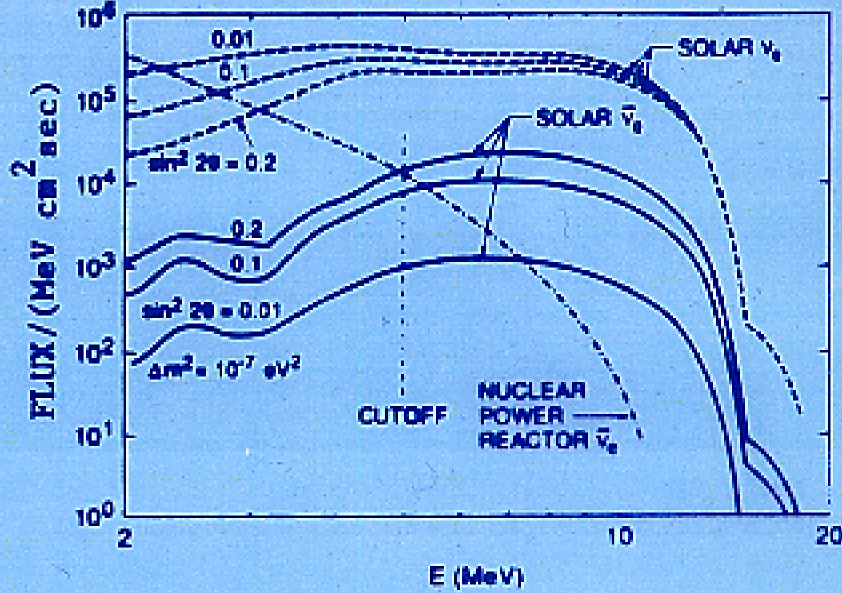


SNO capture rate of power reactor $\bar{\nu}_e$'s



Solar antineutrinos $\nu_e \to \bar{\nu}_\mu \to \bar{\nu}_e$

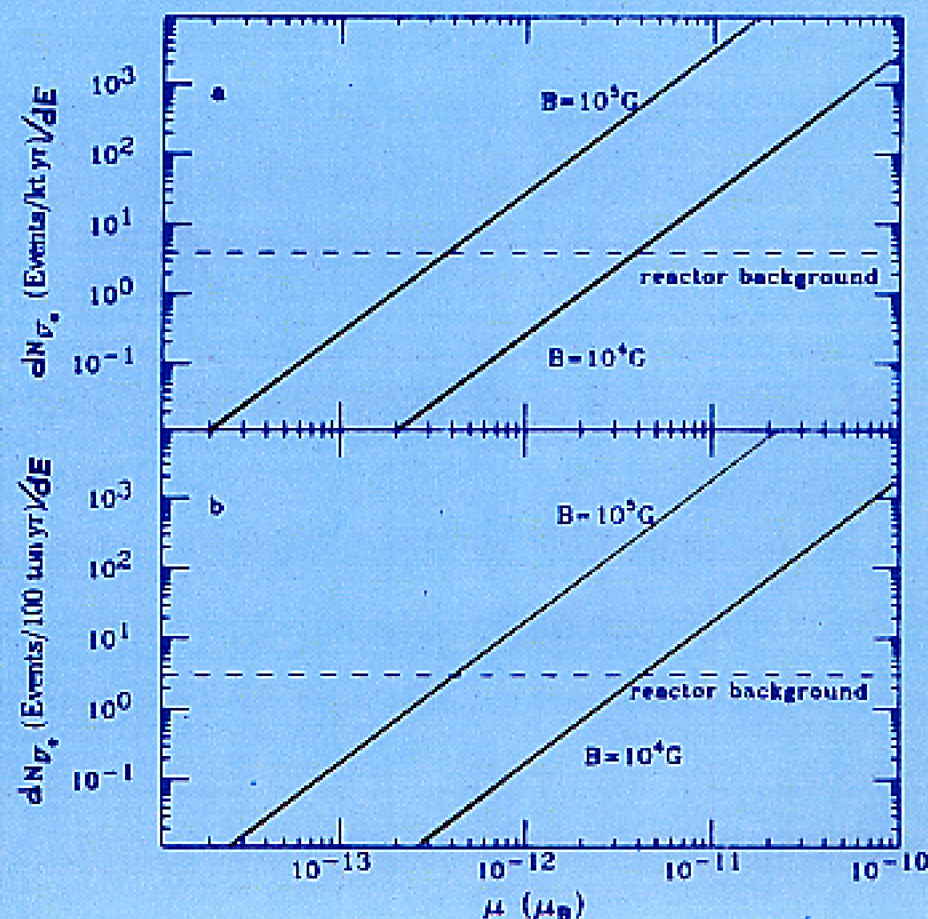
(at Gran Sasso)



R. Raghavan, A. B. Balantekin, F. Loreti, A. J. Baltz, S. Pakvasa, and J. Pantaleone, Phys. Rev. D44, 3786 (1991)

SNO

Borexino

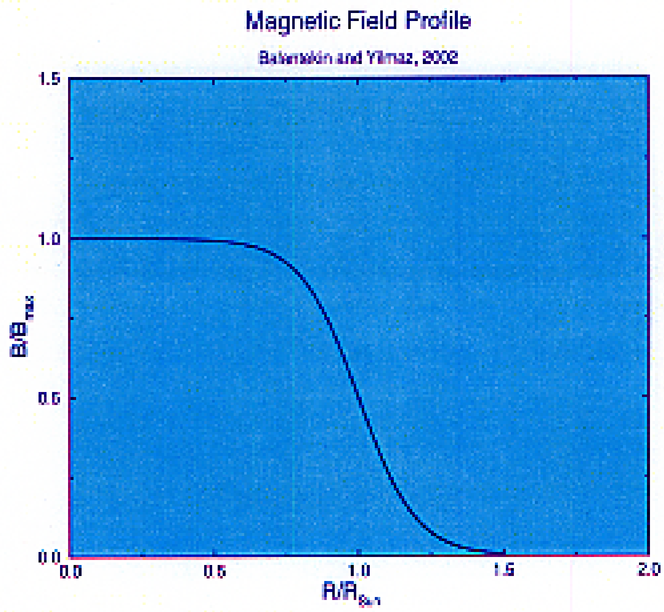


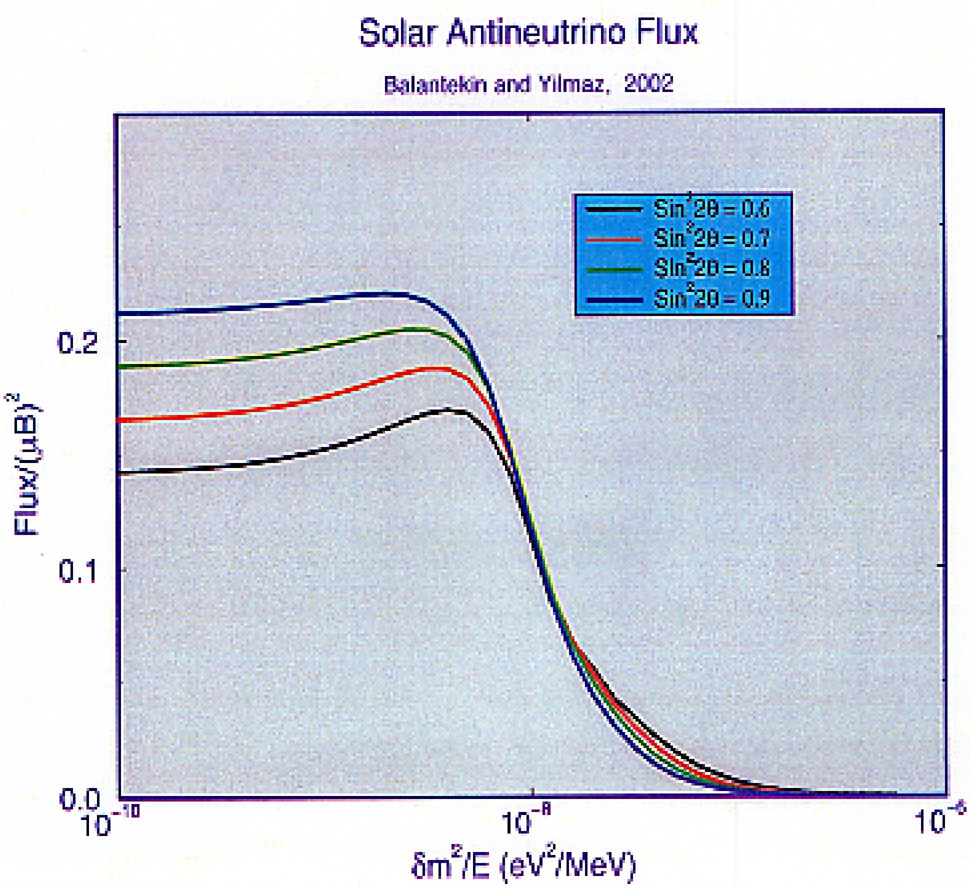
$\Delta m^2 = 1.5 \times 10^{-7}$ eV^2

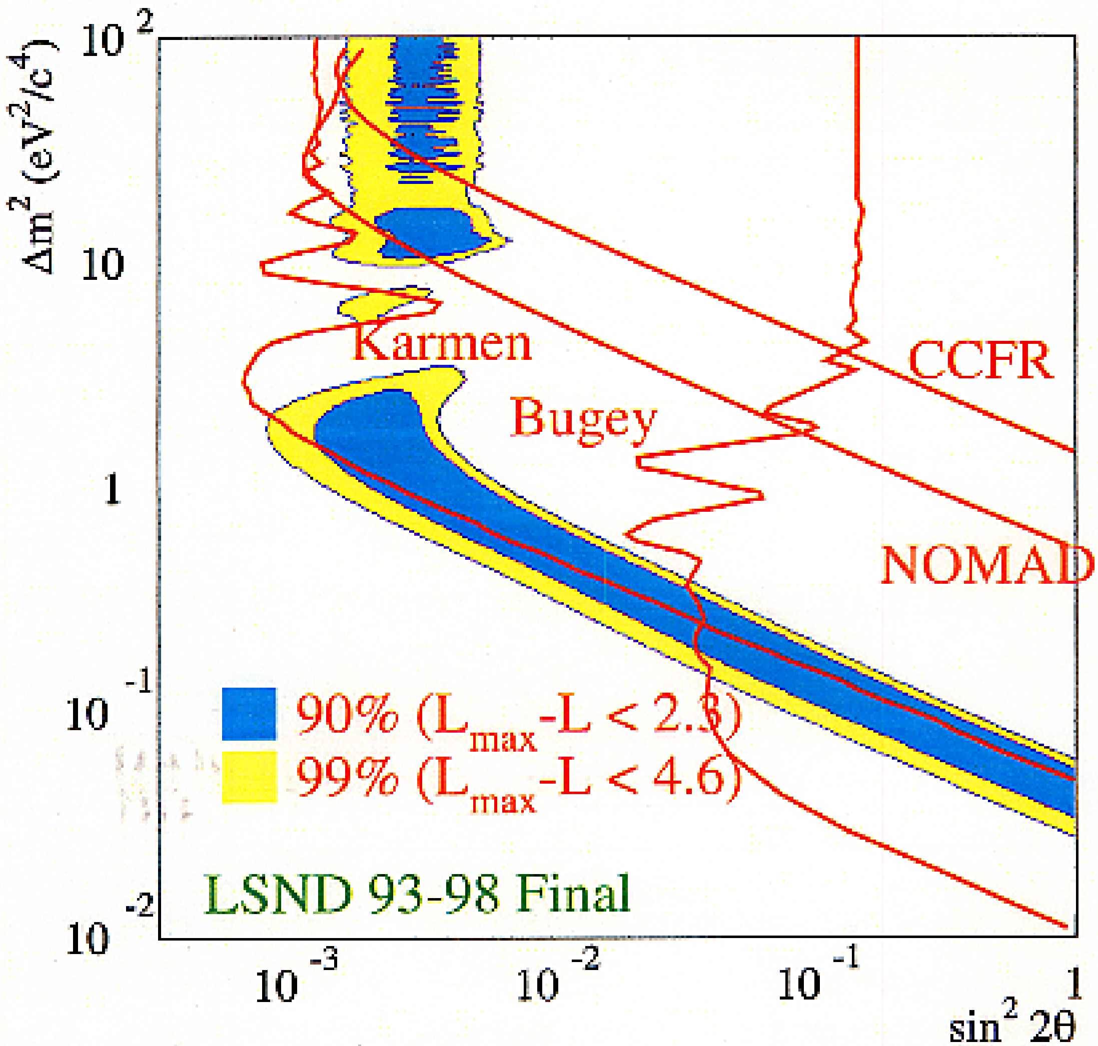
$\sin^2 2\theta = 0.7$

A. B. Balantekin and F. Loreti, Phys. Rev. D48, 5496 (1993).

Solar Electron Antineutrino Flux







Δm^2 (eV^2/c^4)
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2 2\theta$
Karmen
CCFR
Bugey
NOMAD
90% (L_{max}-L < 2.3)
99% (L_{max}-L < 4.6)
LSND 93-98 Final

Core-collapse Supernovae

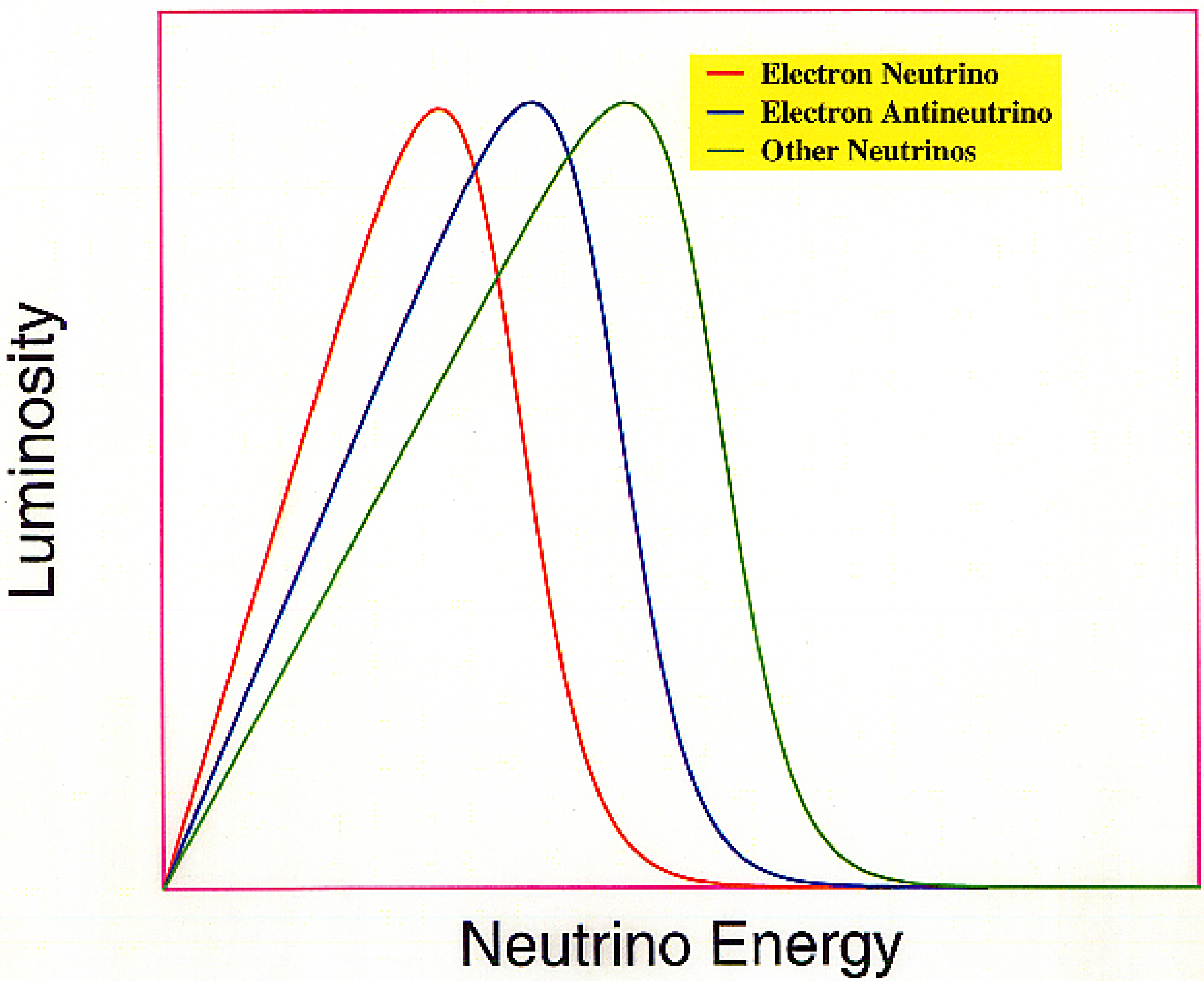
$$M_{\mathrm{prog.}} \geq 8 M_\odot$$

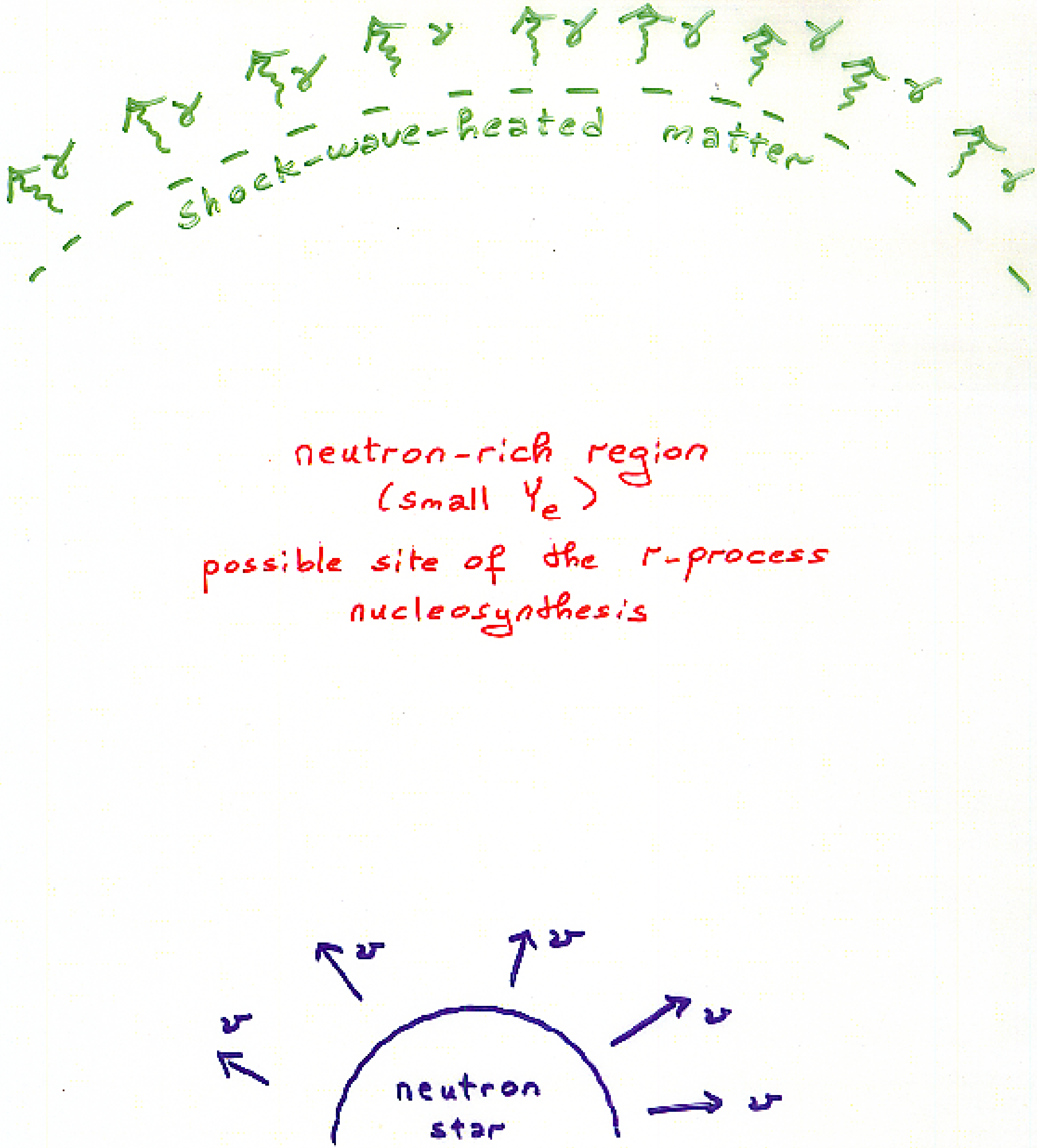
$$\Delta E \sim 10^{53}\mathrm{ergs} \sim 10^{59}\mathrm{MeV}$$

99 % of the energy is carried by ν's and $\overline{\nu}$'s

$$10\mathrm{MeV} \leq E_\nu \leq 30\mathrm{MeV}$$

10^{58} neutrinos


Electron Neutrino
Electron Antineutrino
Other Neutrinos
Luminosity
Neutrino Energy



$$E_{\nu_\mu,\nu_\tau} > E_{\bar{\nu}_e} > E_{\nu_e}$$

Two alpha Problems

Fuller and Meyer

1. ν spallation on α's:

    - too many seed nuclei
    - too few free neutrons
    - wrecks the r-process (The higher the entropy the worse is the wreck).

2. The "α-effect":

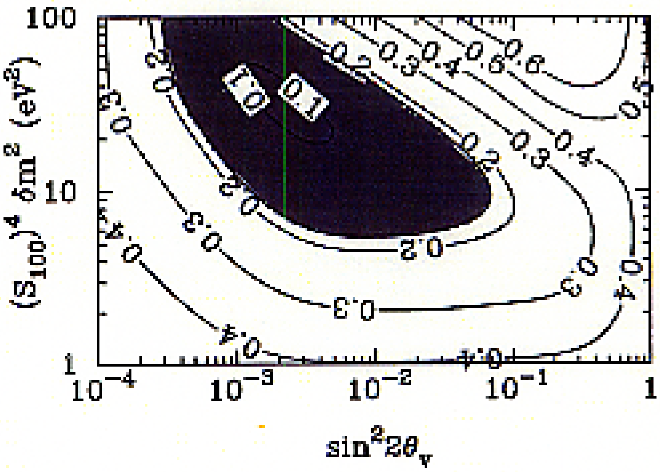
$$\nu_e + n \to p + e^-$$

captures neutron

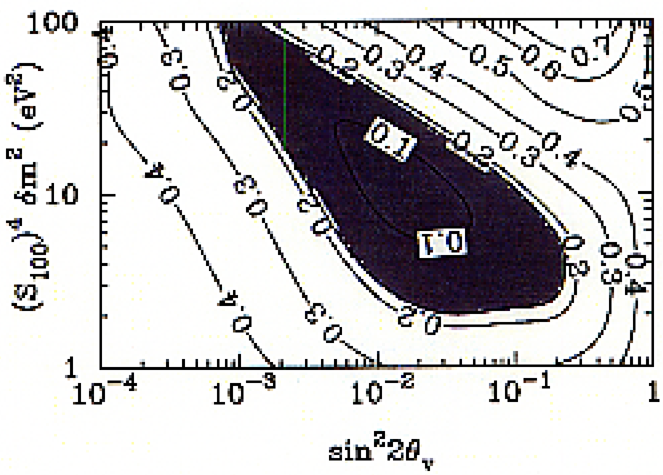
$$\alpha$$

pushes Y_e towards 0.5

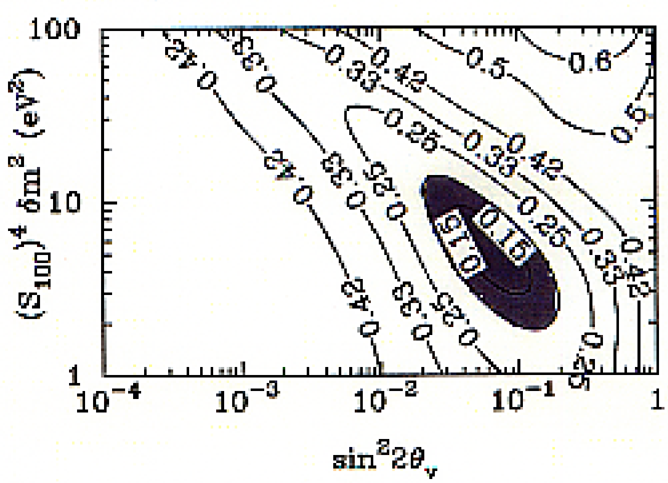
Y_e FROM THE $\nu_e \to \nu_s$ CONVERSION



$\tau = 0.1\,s$

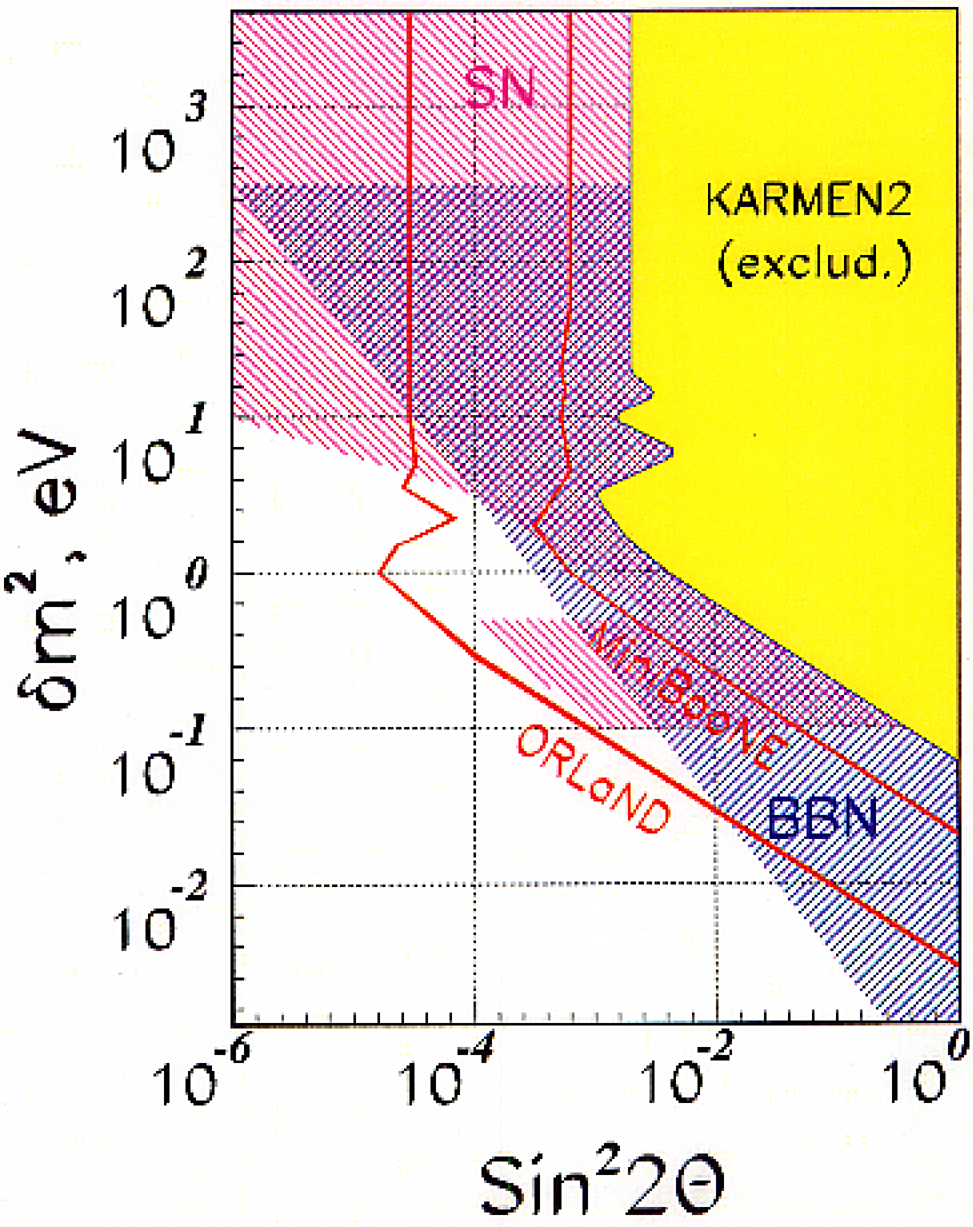


$\tau = 0.3\,s$



$\tau = 0.9\,s$

McLaughlin, Fetter, Balantekin, Fuller



SN
KARMEN2
(exclud.)
MiniBooNE
ORLaND
BBN
10^3
10^2
10^1
10^0
10^-1
10^-2
δm², eV
10^-6
10^-4
10^-2
10^0
Sin²2Θ

Strong magnetic field

$$m^2_{eff} = m^2_{\substack{unpolarized\\ MSW}} + \underbrace{(\ )\langle\vec{\sigma}\rangle}_{\propto B}$$

Semikoz, 1987

D'Olivo, Nieves, & Pal, 1989

Nunokawa, Semikoz, Smirnov, Valle, 1997

Pulsar proper motions:

ν - emission is asymmetric due to the modified MSW effect

Kusenko & Segre, 1996 $\quad B \gtrsim 3 \times 10^{14}\, G$

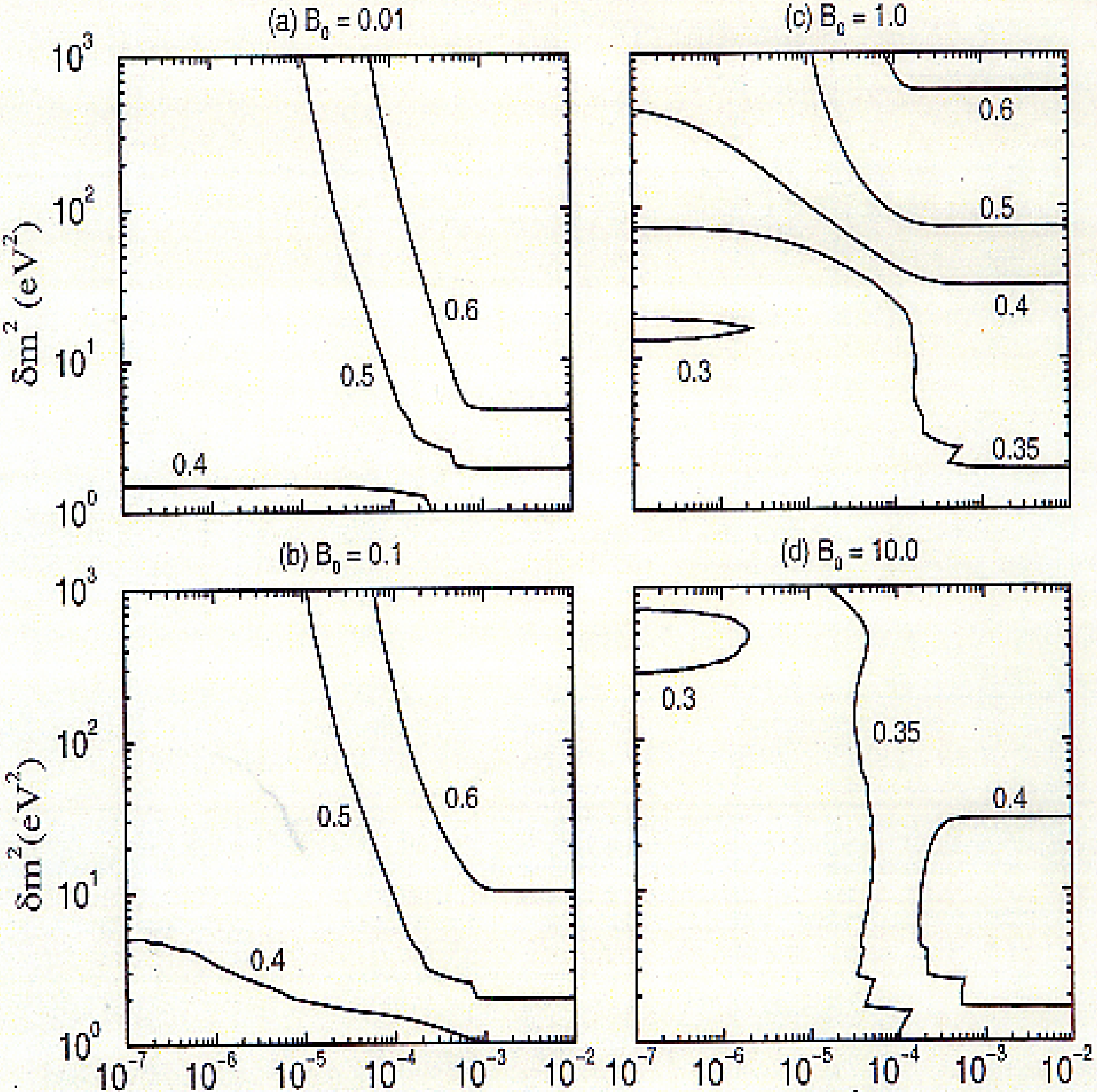
Qian, 1997 $\quad B \gtrsim 10^{16}\, G$

Akhmedov, Lanza, & Sciama, 1997

Resonant spin-flavor precession

$B > 4 \times 10^{15}\, G \ , \ \mu > 10^{-14}\, \mu_B$

Electron Fraction



$$B(r) = B_0 \left(\frac{10\,\text{km.}}{r}\right)^2 \times 10^{12}\ G$$

$$\mu_\nu = 10^{-12}\mu_B$$

Nunokawa, Qian, Fuller