Neutrino Properties Which Probe Physics Beyond the Standard Model

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Hawaii05
Double Beta Decay and Neutrino Mass Workshop

Neutrino Magnetic Moment

$$L_{\text{int}} = \frac{1}{2}\overline{\psi}_j \sigma_{\alpha\beta}(\beta_{ij} + \varepsilon_{ij}\gamma_5)\psi_i F^{\alpha\beta} + h.c.$$

$$\mu_{ij} \equiv \left| \beta_{ij} - \varepsilon_{ij} \right|$$

$$\mu_\nu^{\ 2}(\nu_l, L, E_\nu) = \sum_j \left| \sum_i U_{li} e^{-iE_\nu L} \mu_{ij} \right|^2$$

Neutrino mixing: $|\nu_f\rangle = \Sigma_i U_{fi} |\nu_i\rangle$

Magnetic moment operator: μ

$\sigma \propto \Sigma_i |\langle\nu_i| \mu |\nu_e\rangle|^2 = \langle\nu_e|\mu^t \mu|\nu_e\rangle$

Dirac magnetic moment: $\mu^t = \mu$

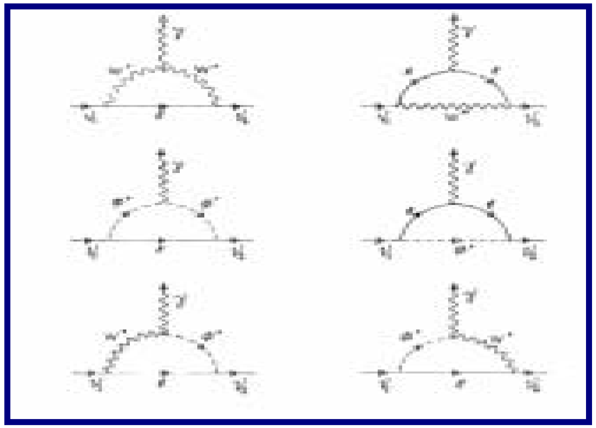
Majorana magnetic moment: $\mu^T = -\mu$

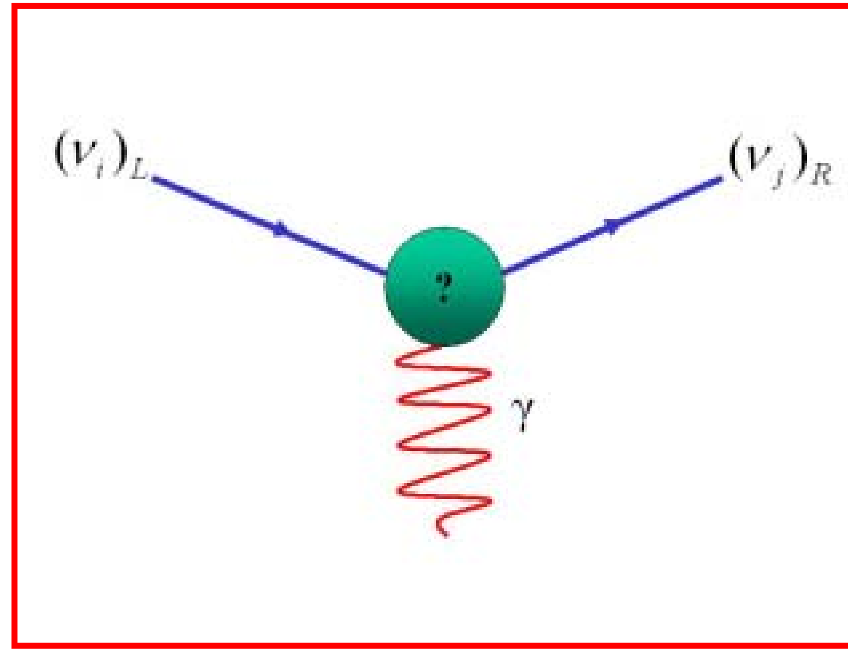
$$\mu_e^2 = \sum_j \left| \sum_k U_{ek} e^{-iE_k L} \mu_{jk} \right|^2$$

diagonal Dirac magnetic moment

$$\mu_e^2 = \sum_j |U_{ej}|^2 \, |\mu_j|^2$$

Neutrino Magnetic Moment





Symmetry Principles $\Rightarrow \mu_\nu \propto m_\nu$

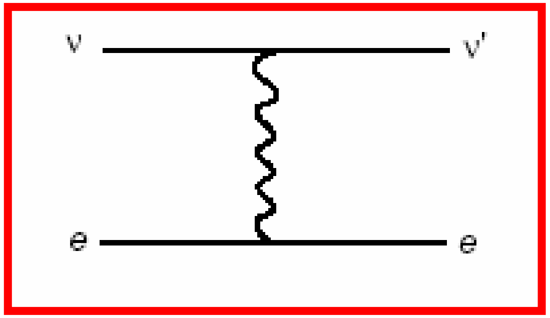
$$\mu_\nu = \frac{3 G_F m_e m_\nu}{4\sqrt{2}\pi^2} = 3.2 \times 10^{-19} \left(\frac{m_\nu}{1\ \mathrm{eV}} \right)$$

Standard Model

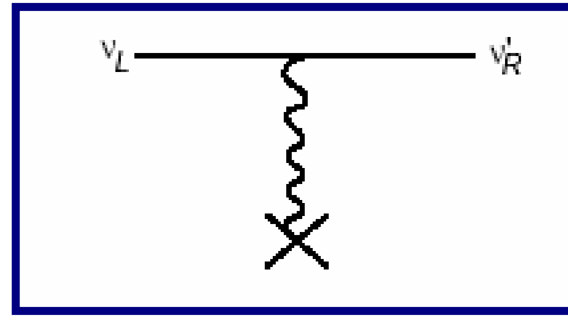
Combined solar, reactor, and atmospheric experiments imply a definite limit on neutrino magnetic moment

$$\mu \geq (4 \times 10^{-20})\ \mu_B$$

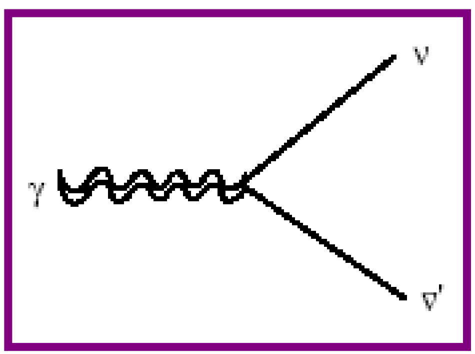
Physical Processes with a Neutrino Magnetic Moment



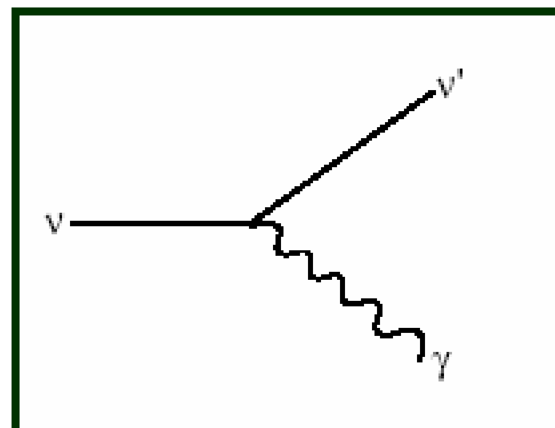
ν-e scattering



Spin-flavor precession



Plasmon decay



Neutrino decay

$$\frac{d\sigma}{dT} = \frac{G_F^2 m_e}{2\pi}\left[(g_V + g_A)^2 + (g_V - g_A)^2\left(1 - \frac{T}{E_\nu}\right)^2 + (g_A^2 - g_V^2)\frac{m_e T}{E_\nu^2}\right]$$

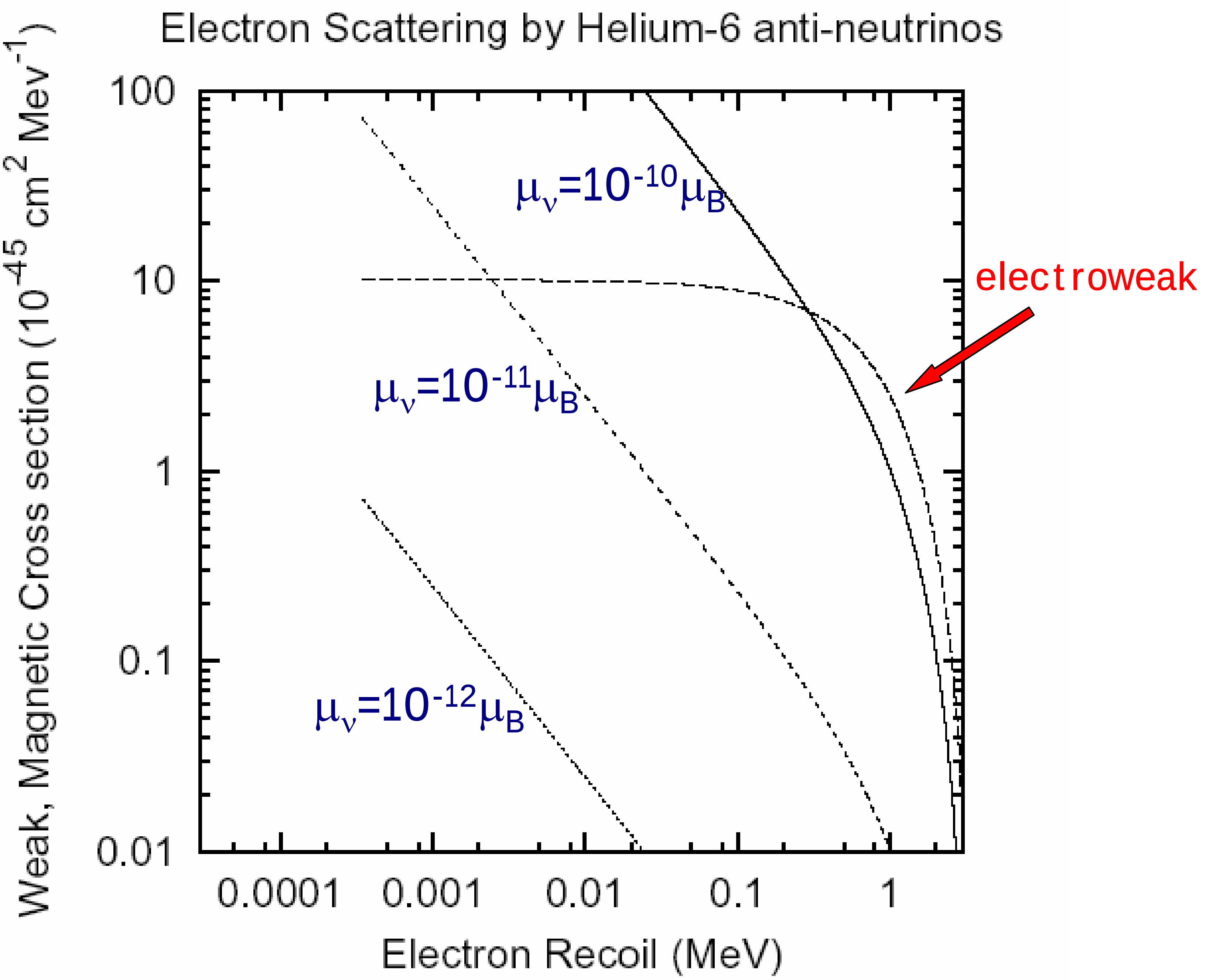
weak

$$+ \frac{\pi \alpha^2 \mu_\nu^2}{m_e^2}\frac{1 - T/E_\nu}{T}$$

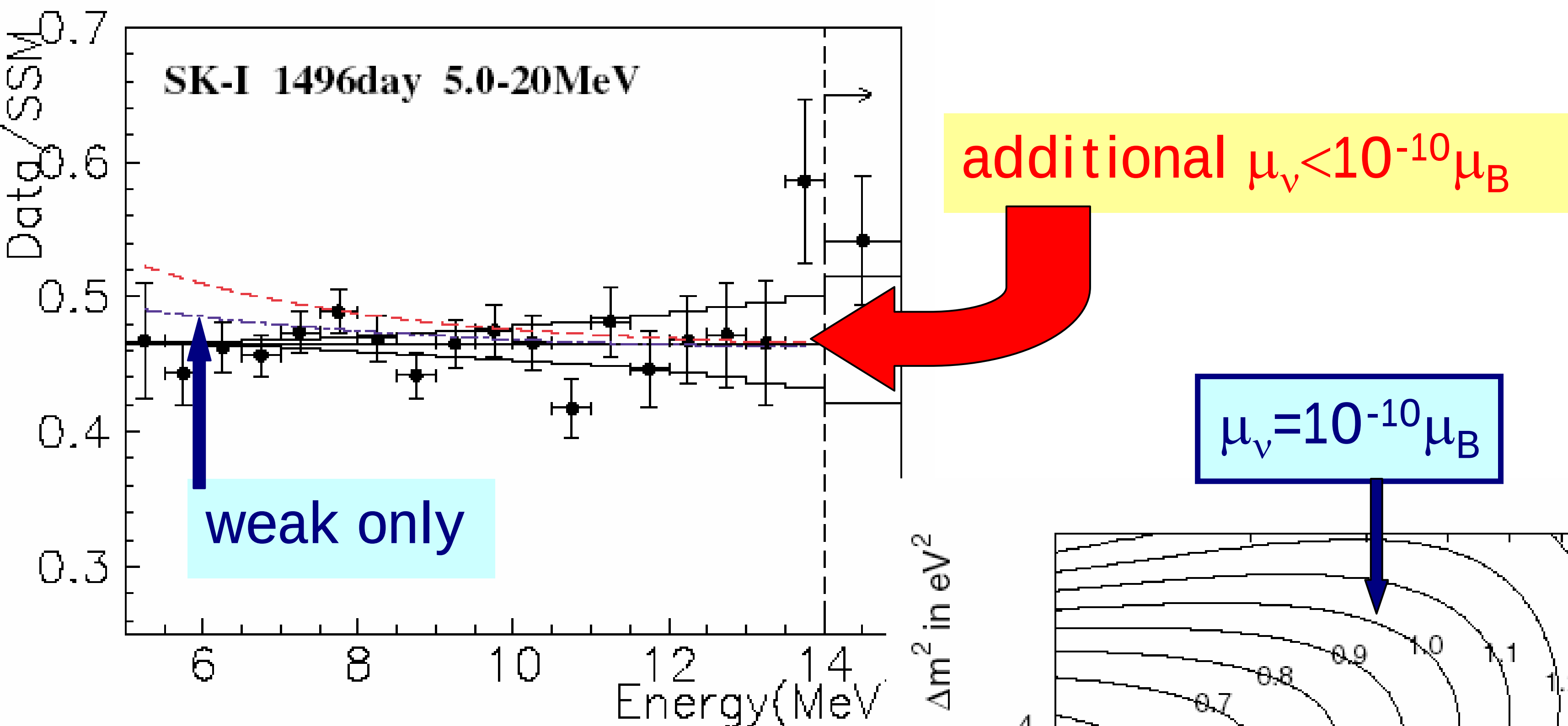
magnetic

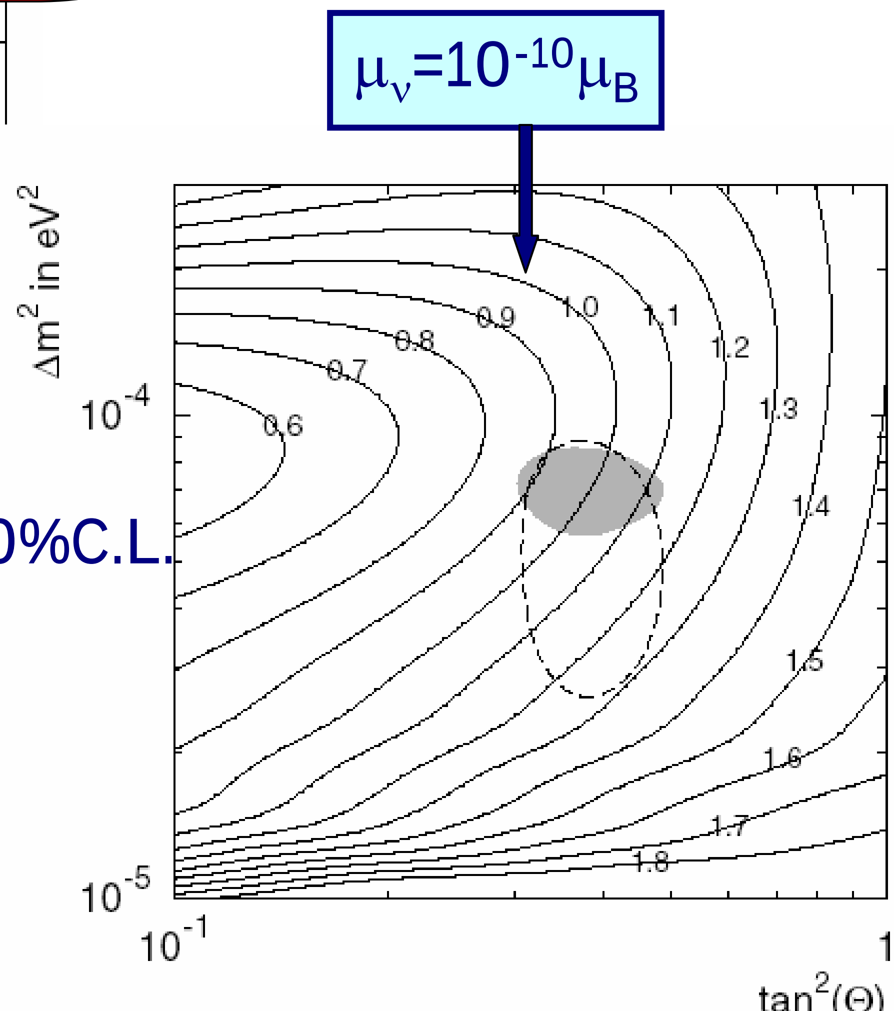
$g_V = 2 \sin^2\theta_W + 1/2$

$g_A =$ +1/2 for electron neutrinos; -1/2 for electron antineutrinos



Electron Scattering by Helium-6 anti-neutrinos
Weak, Magnetic Cross section (10^{-45} cm^2 Mev^{-1})
100
10
1
0.1
0.01
0.0001
0.001
0.01
0.1
1
Electron Recoil (MeV)
$\mu_\nu=10^{-10}\mu_B$
$\mu_\nu=10^{-11}\mu_B$
$\mu_\nu=10^{-12}\mu_B$
electroweak



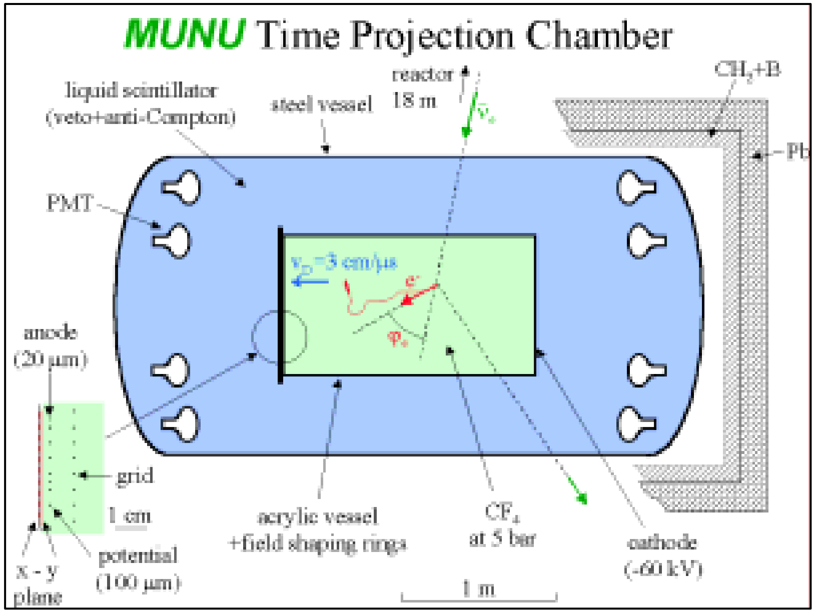


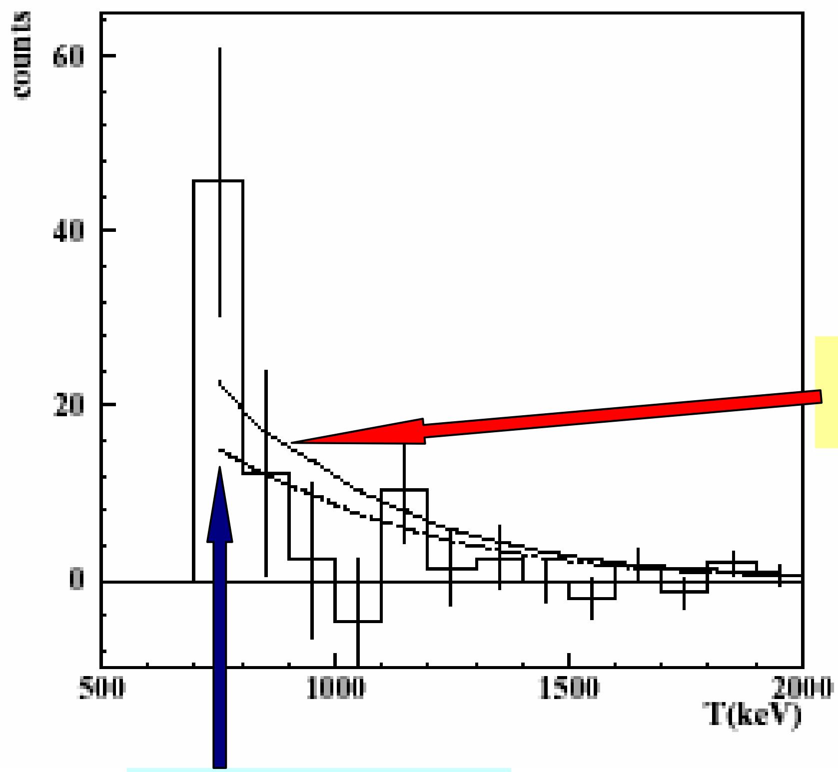
SuperK: $\mu_\nu \leq (3.6 \times 10^{-10})\mu_B$ at 90%C.L.

SuperK + KamLAND:
$\mu_\nu \leq (1.1 \times 10^{-10})\mu_B$ at 90%C.L.

MUNU Reactor Experiment

for magnetic moment



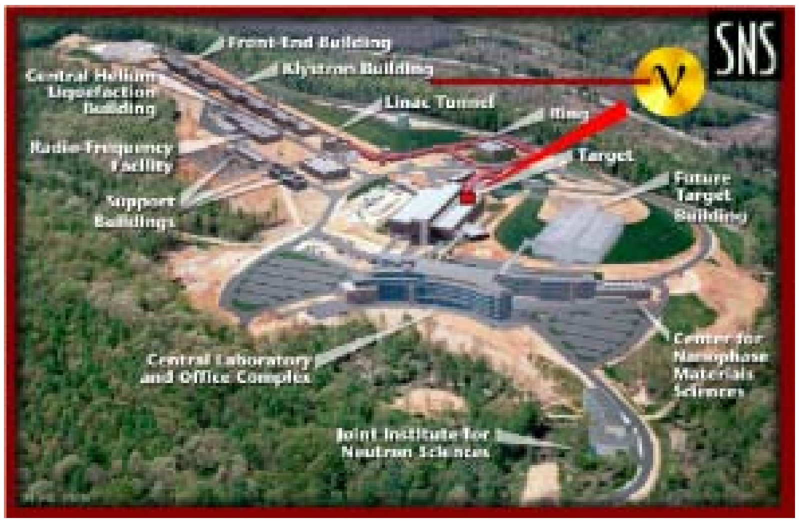


$\mu_\nu = 9 \times 10^{-11} \mu_B$

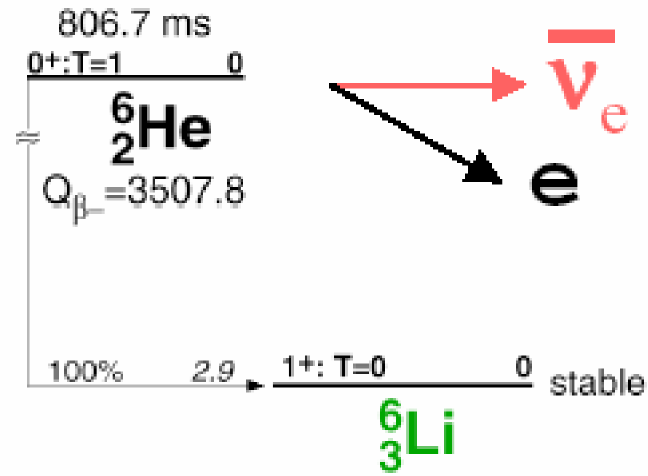
weak only

$\mu_\nu < 9 \times 10^{-11} \mu_B$ at 90% C.L.

Future possibilities?



SNS ?



Beta-beams?

Observational limits on μ_ν

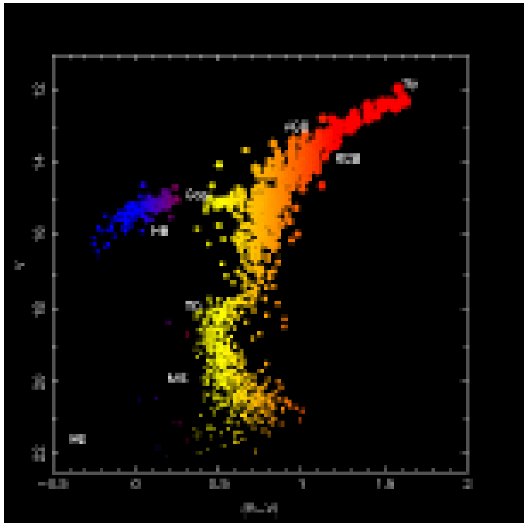
ν_R's are produced in magnetic moment scattering

- Core-collapse supernovae: Lattimer and Cooperstein; Barbieri and Mohapatra. If μ_ν is sufficiently large the proto-neutron star can cool faster since right-handed components are sterile. $\mu \geq 10^{-12}\mu_B$ would be inconsistent with the observed cooling time of SN1987A.

- Early Universe: Morgan. Dirac ν_R increase the effective degrees of freedom altering neutrino counting through big-bang nucleosynthesis yields. (Not so for the Majorana case since antiparticles are already counted).

Bound from the red-giant stars (Raffelt)

A large enough neutrino magnetic moment implies enhanced plasmon decay rate: $\gamma \rightarrow \nu\nu$. Since the neutrinos freely escape the star this is turn cools a red giant star faster delaying helium ignition.



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

Balantekin, Loreti, Pakvasa, Raghavan. Spin-flavor precession changes neutrino helicity. If the neutrinos are of Majorana type this yields a solar antineutrino flux.

Kamland and SNO bounds on solar antineutrino flux:

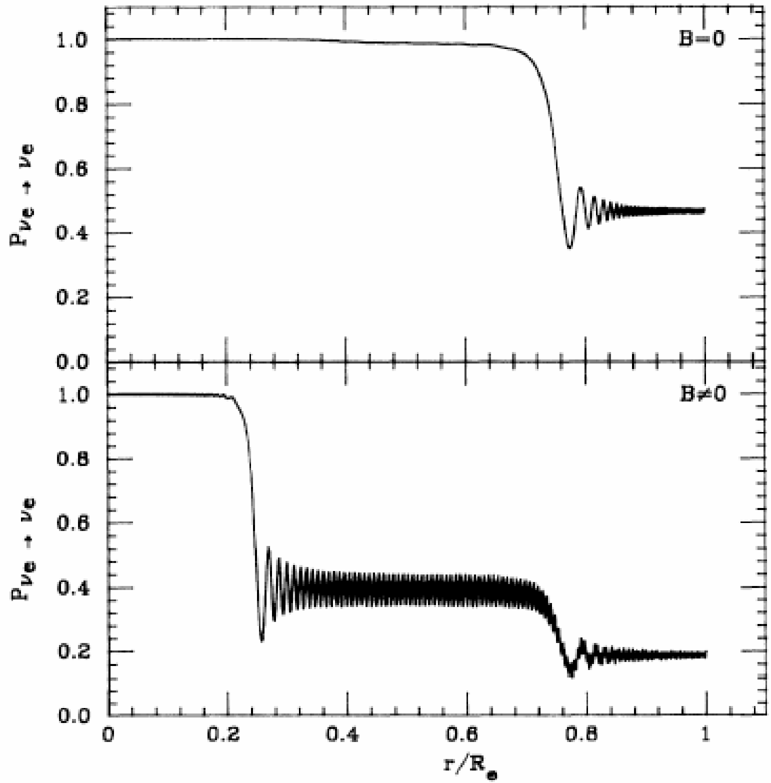
$$\varphi_{\text{antineutrino}} \leq 3 \times 10^{-4}\, \varphi_{\text{B8-neutrino}}$$

Spin-flavor precession

$$i\frac{d}{dt}\begin{pmatrix}\nu_{e_L}\\ \nu_{\mu_L}\\ \nu_{e_R}\\ \nu_{\mu_R}\end{pmatrix}=\begin{pmatrix}H_L & BM^\dagger\\ BM & H_R\end{pmatrix}\begin{pmatrix}\nu_{e_L}\\ \nu_{\mu_L}\\ \nu_{e_R}\\ \nu_{\mu_R}\end{pmatrix}$$

$$H_L=\begin{pmatrix}\frac{\Delta m^2}{2E}\sin^2\theta+a_e & \frac{\Delta m^2}{4E}\sin 2\theta\\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{2E}\cos^2\theta+a_\mu\end{pmatrix}$$

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



$$H_R=H_L(a_e=0=a_\mu)$$

$$a_e=\frac{G_F}{\sqrt{2}}(2N_e-N_n),\quad a_\mu=-\frac{G_F}{\sqrt{2}}N_n$$

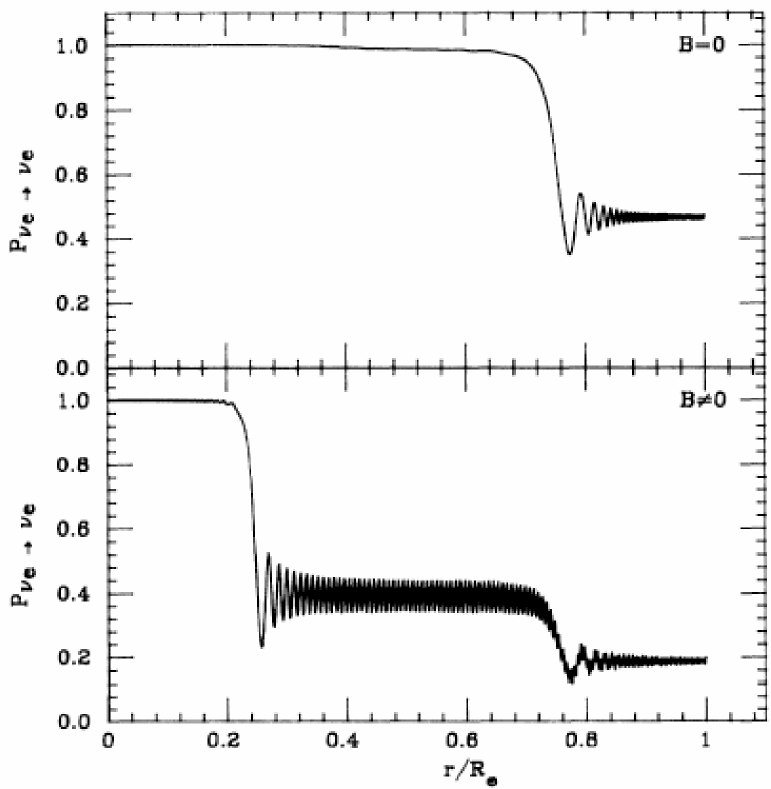
Dirac neutrinos

$$H_{\mathrm{Maj}} = \begin{pmatrix} a_e & \frac{\Delta m^2}{4E}\sin 2\theta & 0 & \mu^* B \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{2E}\cos 2\theta + a_\mu & -\mu^* B & 0 \\ 0 & -\mu B & -a_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \mu B & 0 & \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{2E}\cos 2\theta - a_\mu \end{pmatrix}$$

Majorana neutrinos

E_ν	SFP	MSW
2.50	0	0.07
3.35	0.05	0.10
5.00	0.10	0.13
8.00	0.15	0.18
13.00	0.20	0.22

Locations of the SFP and MSW resonances in the sun



$$\frac{d^2}{dt^2}\nu_e^{(L)} + \left(\phi^2 + i\frac{d\phi}{dt} + \Delta^2 + (\mu B)^2\right)\nu_e^{(L)} + \mu B\sqrt{2}G_F N_n \nu_\mu^{(R)} = 0.$$

$$P(\nu_e \to \nu_e) = \frac{1}{2} - \frac{1}{2}\cos 2\theta_\nu (1 - 2P_{\text{hop}}),$$

for the limiting case of $N_n = 0$, one gets

$$P_{\text{hop}}(\mu B \neq 0) = P_{\text{hop}}(\mu B = 0)\exp\left\{\frac{i}{\pi}\int_{r_0}^{r_0^*} dr \frac{\delta m^2}{2E}\left[\frac{(\mu B)^2}{\sqrt{\zeta^2(r) - 2\zeta(r)\cos 2\theta_\nu + 1}}\right]\right\},$$

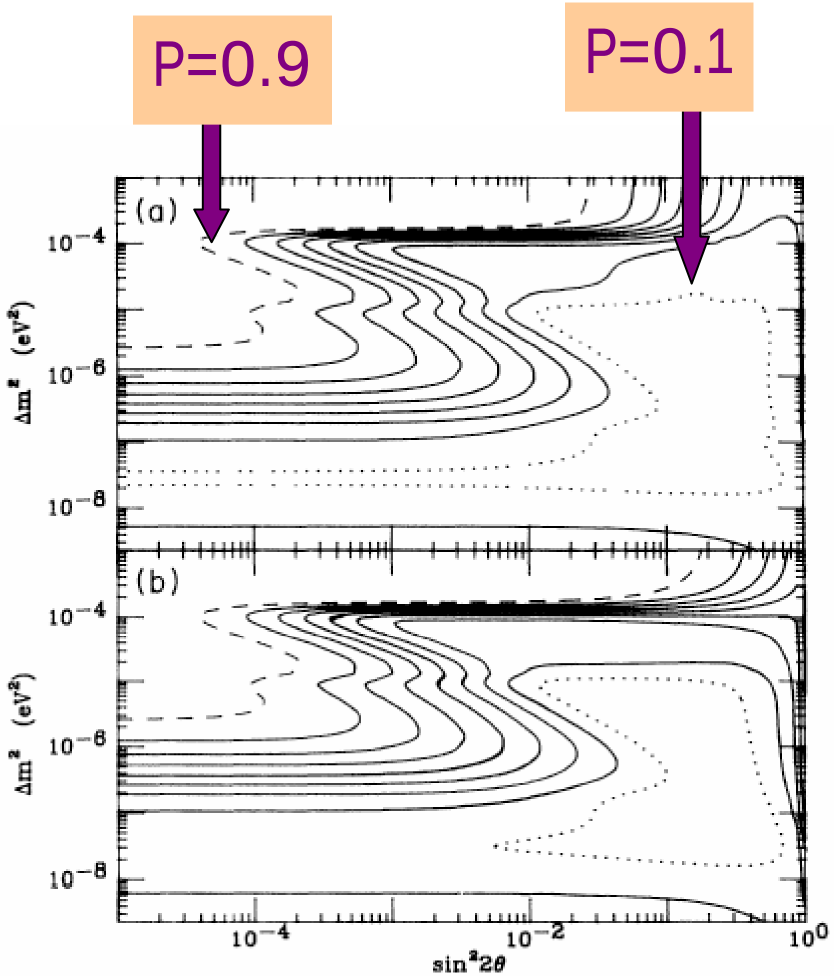
A.B. Balantekin and C. Volpe, Phys. Rev. D72, 033008 (2005)

Solar magnetic fields

- Standard Solar Model requires B < 10^8 G.

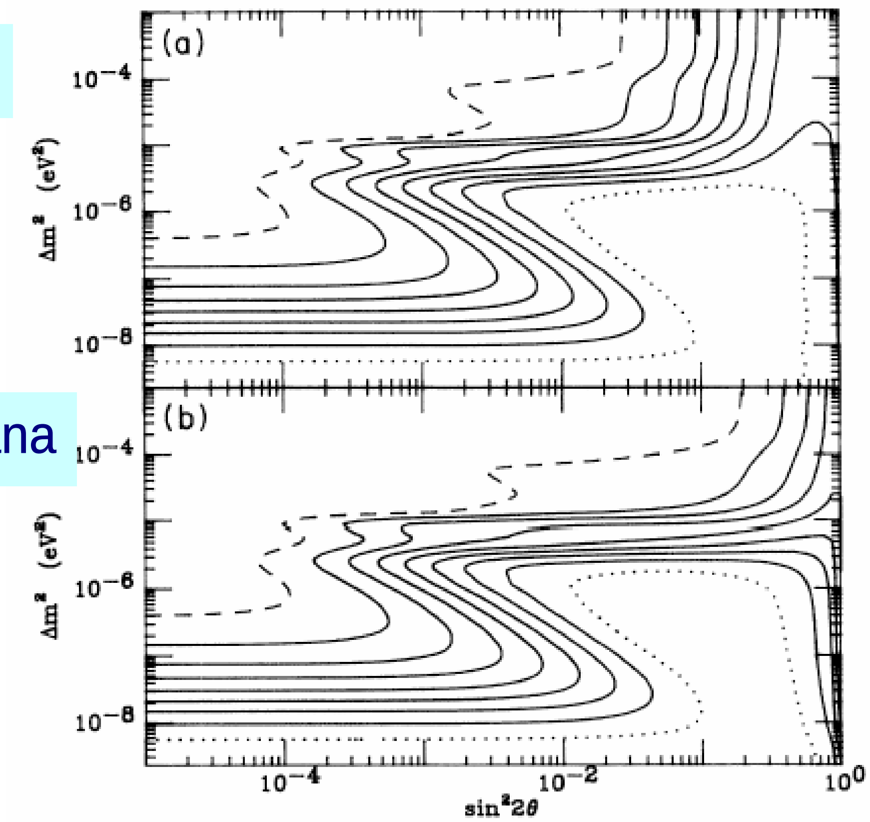
- Helioseismology: If B > 10^7 G, sound speed profile would deviate from the observed values Turck-Chieze.

- Solar neutrino flux variations with heliographic latitude may imply magnetic fields Caldwell.



Dirac

Majorana

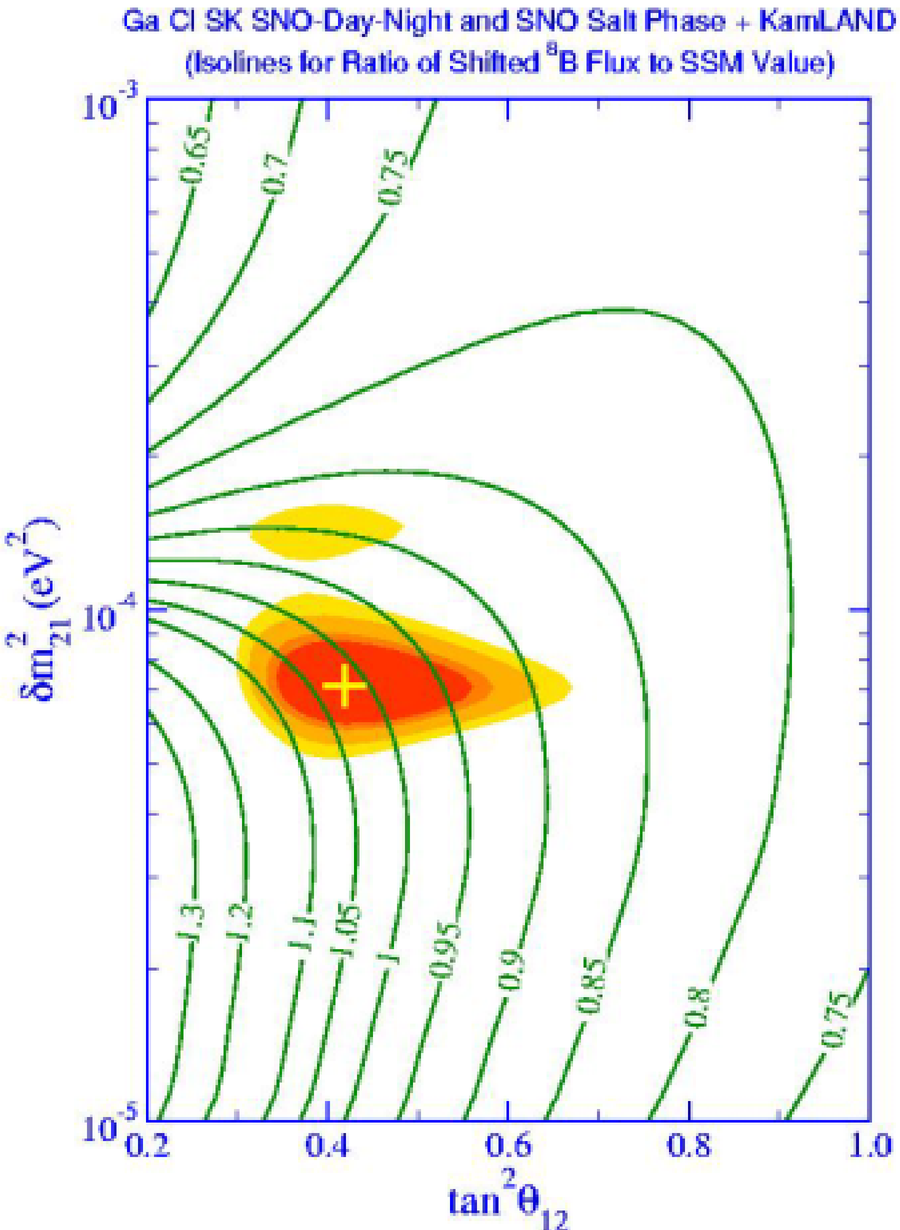


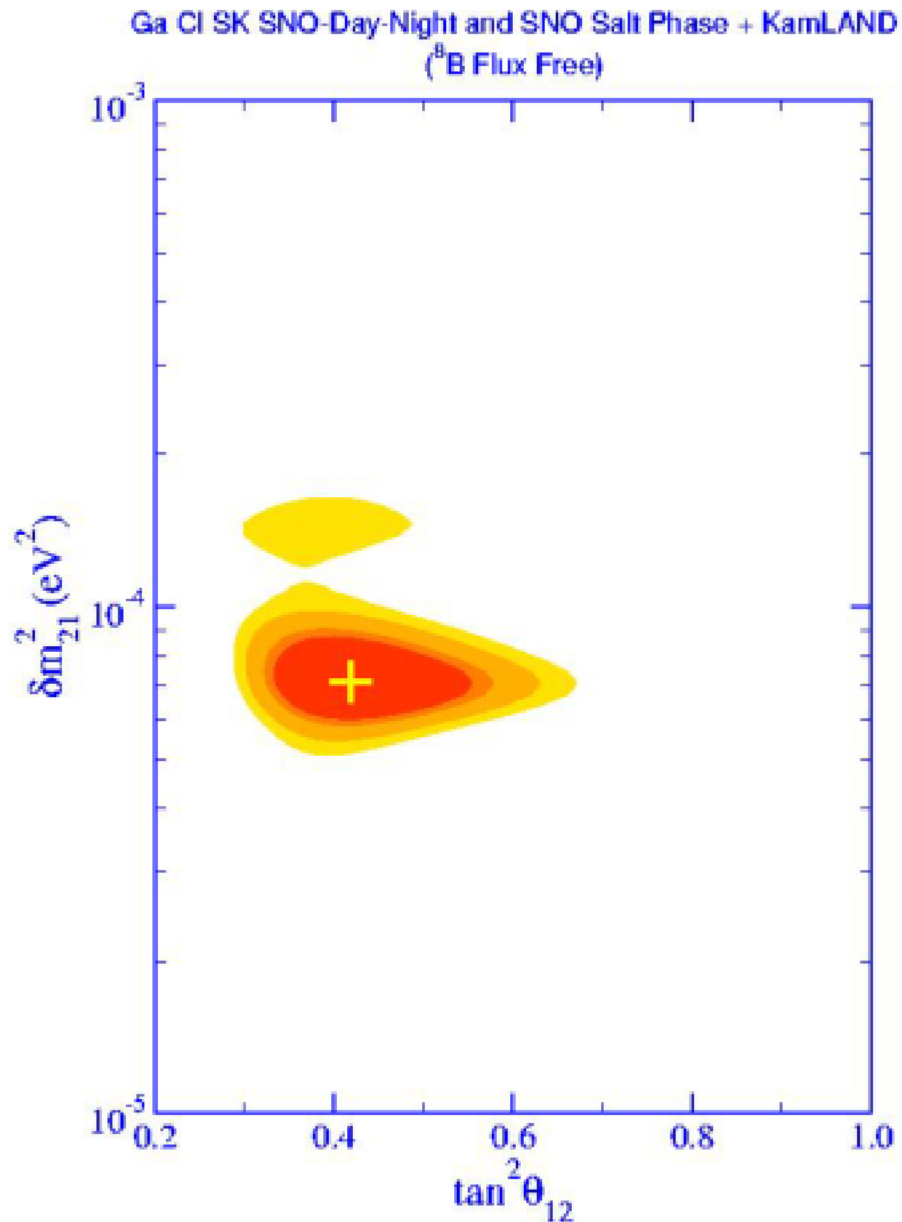
Cl-detector

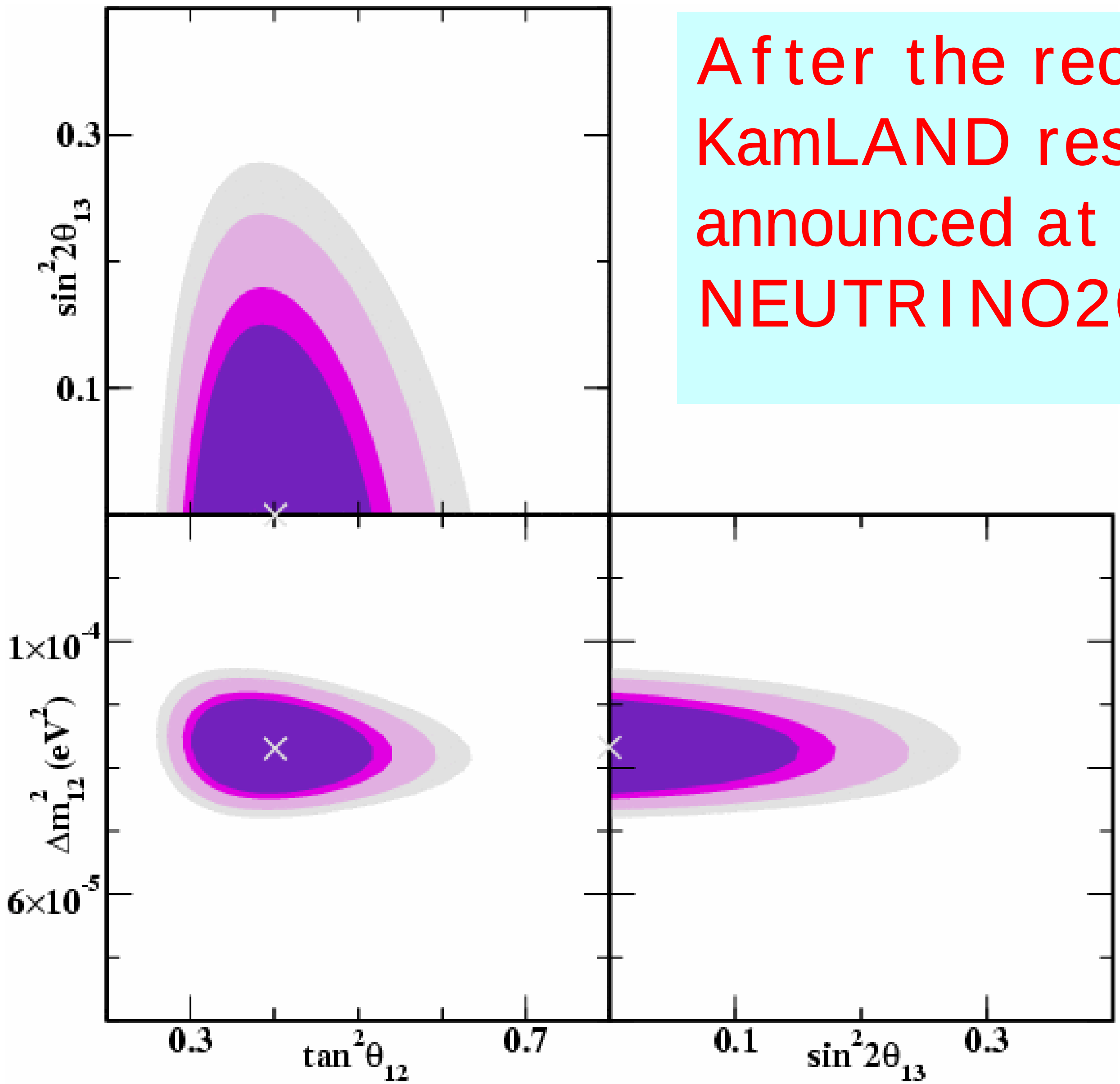
Ga-detector

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

SNO Salt Results , Balantekin and Yuksel, PRD 68, 113002 (2003)

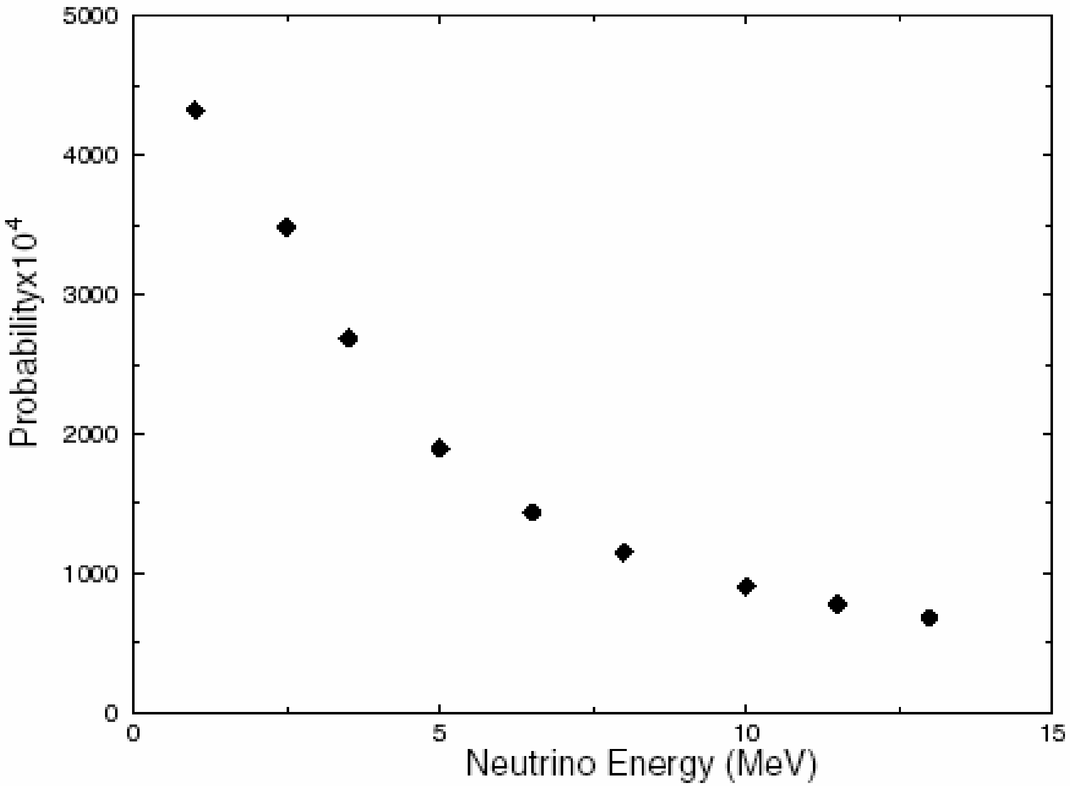






After the recent KamLAND results announced at NEUTRINO2004

Balantekin, et al., PLB 613, 61 (2005)



- $\mu = 10^{-11}\ \mu_B$
- $B = 10^5$ G
- $\delta m^2 = 8 \times 10^{-5}\ eV^2$
- $\tan^2\theta = 0.4$

For these parameters the difference between MSW only and SFP+MSW is less than 10^{-5}.

A.B. Balantekin and C. Volpe, Phys. Rev. D72, 033008 (2005)

Conclusions

- Neutrino magnetic moment is known to be in the range
$(9 \times 10^{-11})\ \mu_B \geq \mu \geq (4 \times 10^{-20})\ \mu_B$
The width of this range represents physics beyond the standard model.

- The effect of μ_ν on solar neutrino flux is miniscule. Even a field as large as 10^5 G and magnetic moment $10^{-11}\ \mu_B$ would change the observed solar neutrino flux in part per 10^5.