New upper bound for the neutrino magnetic moment from its Dirac/Majorana nature and Borexino data

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Is the neutrino a Dirac or a Majorana particle?

1) To show that the neutrino-electron scattering with polarized neutrinos might have different cross sections for the Dirac or the Majorana case

2) Use that fact to constrain the neutrino magnetic moment

What is the relevance of being Majorana?

I. The equation that dictates the dynamics is different
II. The neutrino will be its own antiparticle
III. There will be another processes like the Neutrinoless double beta decay

There is a crucial difference between Dirac and Majorana neutrinos if we consider neutrino-electron scattering. At low energies, the effective Lagrangian is:

$$\mathcal{L}_{\nu e} = \frac{G_F}{\sqrt{2}}[\bar{u}_{\nu_\ell}\gamma^\mu(1-\gamma^5)u_{\nu_\ell}][\bar{u}_e\gamma_\mu(g_V^\ell - g_A^\ell\gamma^5)u_e]$$

If the neutrino is a Majorana particle, then the following identity holds:

$$\bar{v}^f_{\nu_\ell}\gamma_\mu(1-\gamma^5)v^i_{\nu_\ell} = \bar{u}^f_{\nu_\ell}\gamma_\mu(1+\gamma^5)u^i_{\nu_\ell}$$

Then, the amplitudes for each case are:

Dirac case:

$$\mathcal{M}^D(\nu_\ell e \to \nu_\ell e) = -i\frac{G_F}{\sqrt{2}}[\bar{u}_e^f \gamma^\mu (g_V^\ell - g_A^\ell \gamma^5) u_e^i][\bar{u}_{\nu_\ell}^f \gamma_\mu (1-\gamma^5) u_{\nu_\ell}^i]$$

Majorana case:

$$\mathcal{M}^M(\nu_\ell e \to \nu_\ell e) = i\frac{2G_F}{\sqrt{2}}\left[\bar{u}_e^f \gamma^\mu (g_V^\ell - g_A^\ell \gamma^5) u_e^i\right]\left[\bar{u}_{\nu l}^f \gamma_\mu \gamma^5 u_{\nu l}^i\right]$$

If amplitudes are so different: why are not the cross sections for Majorana and Dirac cases different?

A: Neutrinos have negative helicity. An extra factor

$$(1-\gamma_5)/2$$

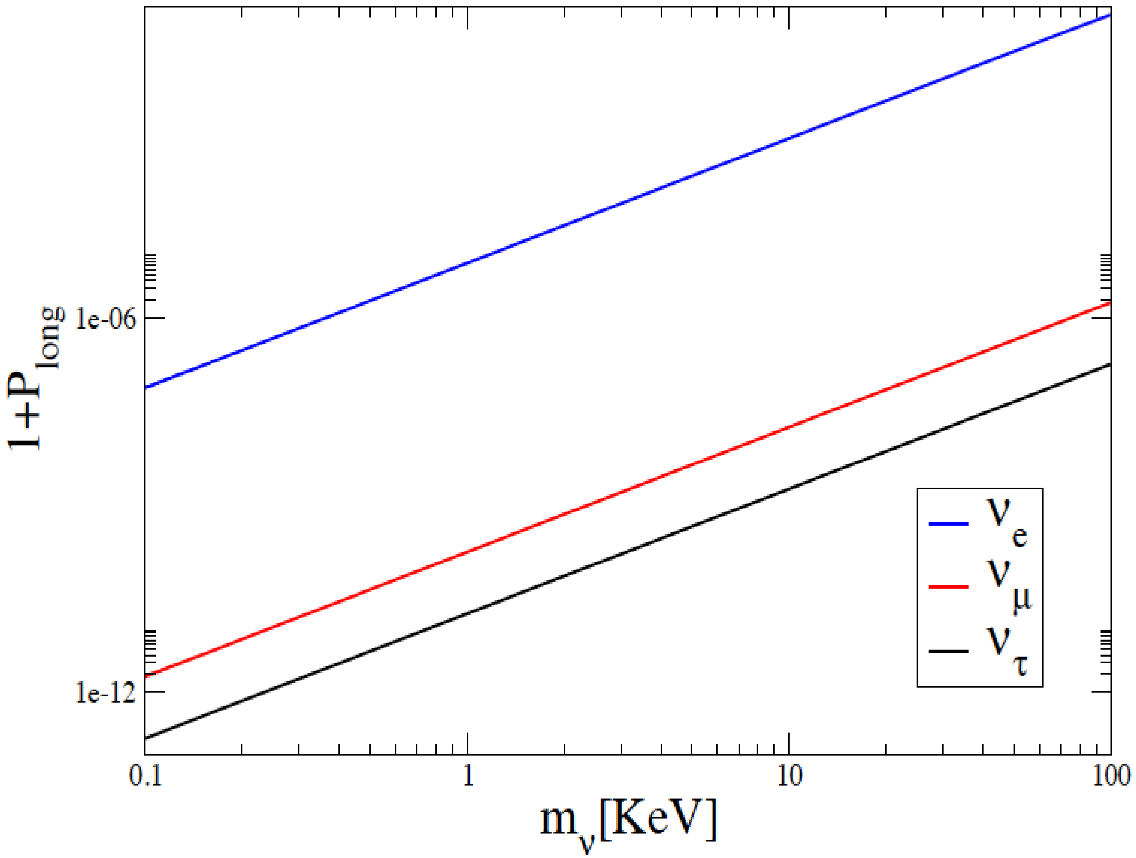
should be added and both amplitudes become identical

Neutrinos are almost completely left handed.
Consider the pure leptonic deacy of a pseudoscalar meson:

$$P^+ \to \ell^+ + \nu_\ell$$

The neutrino longitudinal polarization: $P_{\text{long}} = \frac{(E-W)|\vec{k}|}{WE - |\vec{k}|^2}$,

Here $\vec{k}$ is the neutrino moment and E,W the lepton energies



In any case...forget for a moment the value of the neutrino polarization and compute:

neutrino-electron scattering $\nu_\ell(p_\nu, s_\nu) + e(p_e) \to \nu_\ell(p'_\nu) + e(p'_e)$

$$s_\nu = (0, s_\perp, 0, s_{||})$$

For the Dirac case (in CM) [B. Kayser, R. Schrock PLB 112 (1982) 137]

$$\begin{aligned}
\frac{d\sigma^D}{d\Omega} &= \frac{G_F^2}{8\pi^2 s}((m_e^2(E_\nu - p^2\cos\theta)({g_A^\ell}^2 - {g_V^\ell}^2) \\
&+ (E_\nu E_e + p^2)(g_V^\ell + g_A^\ell)^2 + (E_\nu E_e + p^2\cos\theta)^2(g_V^\ell - g_A^\ell)^2 \\
&- p[s^{1/2}(E_\nu E_e + p^2)s_{||}(g_V^\ell + g_A^\ell)^2 + (E_\nu E_e + p^2\cos\theta) \\
&\times ((E_e + E_\nu\cos\theta)s_{||} + m_\nu s_\perp \sin\theta\cos\phi]) (g_V^\ell - g_A^\ell)^2 \\
&+ m_e(E_\nu(1-\cos\theta)s_{||} - m_\nu|s_\perp|\sin\theta\cos\phi)({g_A^\ell}^2 - {g_V^\ell}^2))),
\end{aligned}$$

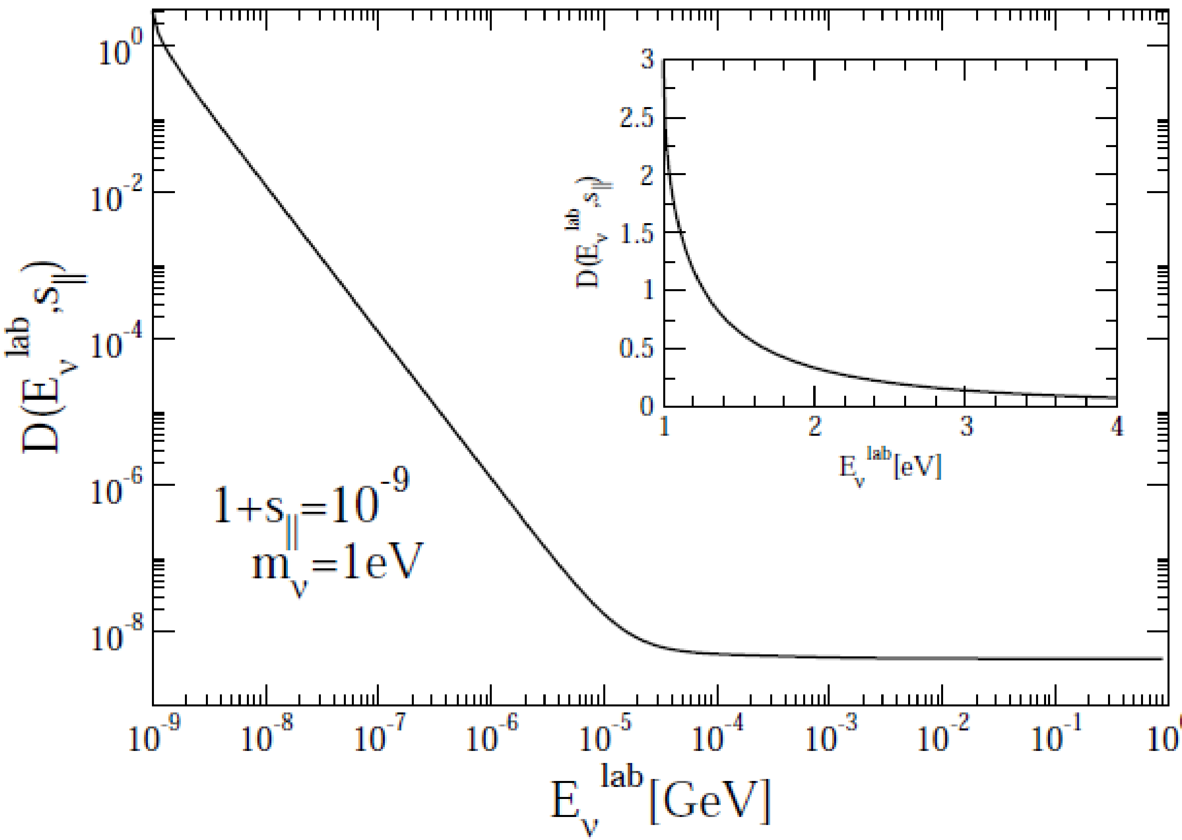
For the Majorana:

$$
\begin{aligned}
\frac{d\sigma^M}{d\Omega} &= \frac{G_F^2}{4\pi^2 s}(((E_\nu E_e + p^2)^2 + (E_\nu E_e + p^2\cos\theta)^2 \\
+ & \quad m_\nu(E_\nu^2 - p^2\cos\theta))({g_V^\ell}^2 + {g_A^\ell}^2) + m_e^2(E_\nu^2 - p^2\cos\theta + 2m_\nu^2) \\
\times & \quad ({g_A^\ell}^2 - {g_V^\ell}^2) - 2g_V^\ell g_A^\ell p(2E_\nu E_e + p^2(1+\cos\theta)) \\
\times & \quad (E_\nu s_{||}(1-\cos\theta) - m_\nu|s_\perp|\sin\theta\cos\phi))\,.
\end{aligned}
$$

They are different!!!!

Seriously?

$$D(E_\nu^{\text{lab}}, s_{||}) = \frac{|\sigma(\nu_{pol}^D e) - \sigma(\nu_{pol}^M e)|}{\sigma(\nu_{pol}^D e)},$$

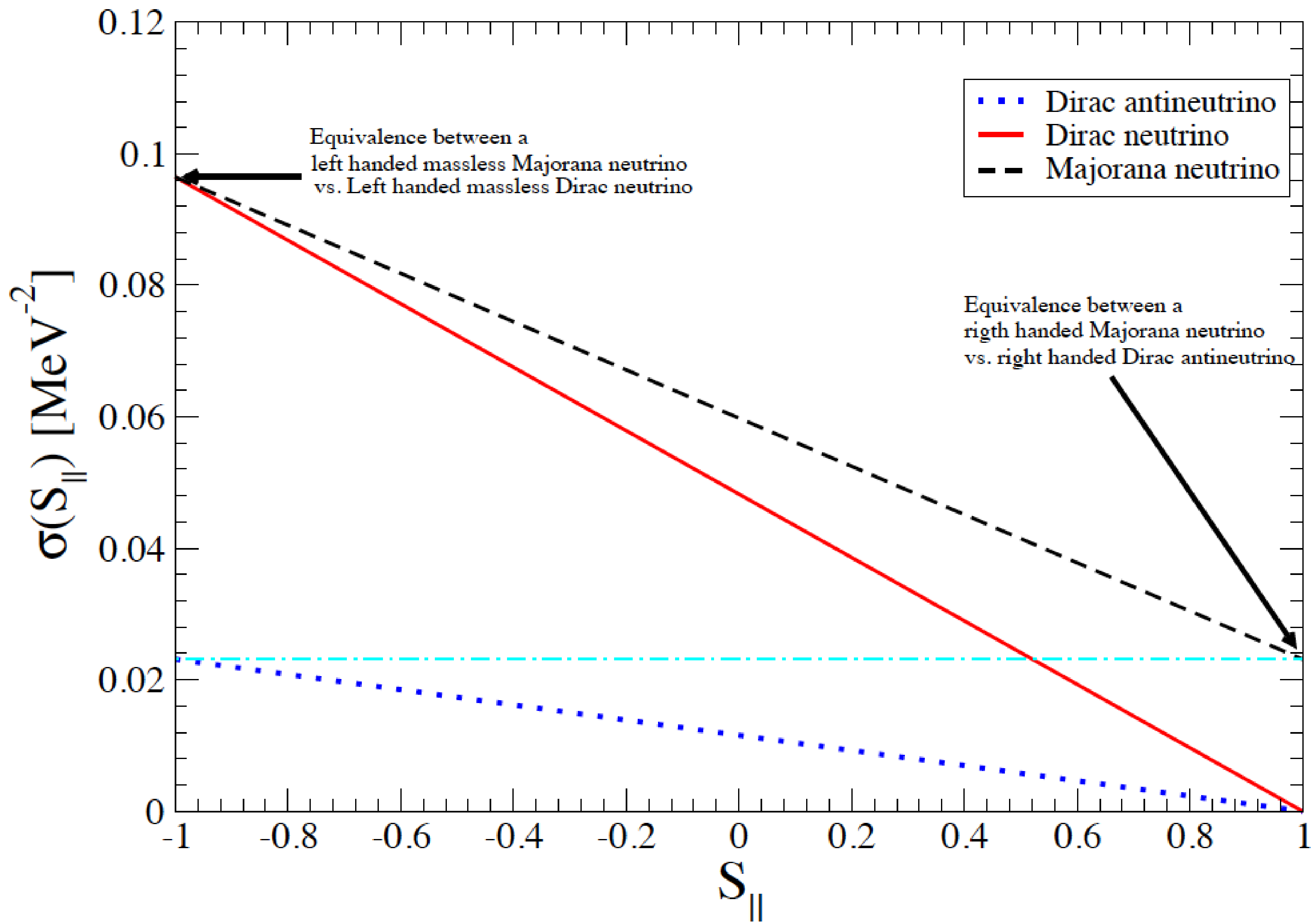


For man made neutrinos, which are produced via charged currents, it is extremely difficult to have significant differences between Dirac and Majorana neutrinos.

Don't lose your faith...

Consider the integrated cross section in a Borexino type detector

$$\sigma(s_{||}) = \int dT \int dE_\nu \lambda(E_\nu) \frac{d^2\sigma}{dE_\nu dT}$$



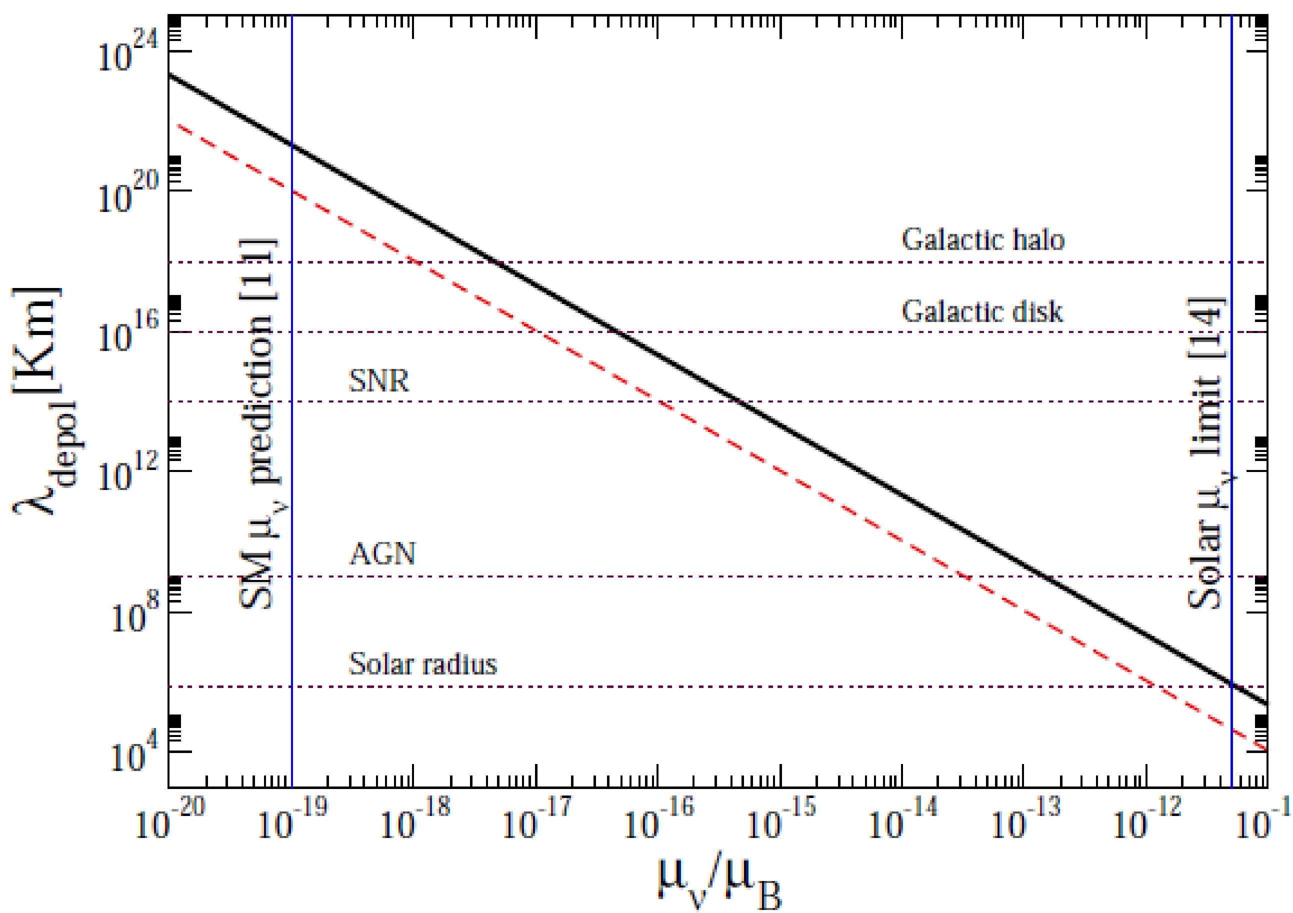
Can we (or nature) change the neutrino initial polarization?

Yes, we (nature) can...
Bargmann-Michel-Telegdi:

$$\frac{dS^\mu}{d\tau} = 2\mu(G^{\mu\nu}S_\nu - u^\mu G_{\alpha\beta}u_\alpha S_\beta) + 2\varepsilon(\tilde{G}^{\mu\nu}S_\nu - u^\mu \tilde{G}_{\alpha\beta}u_\alpha S_\beta)$$

What is the magnetic field needed in order to have such changes in the neutrino's helicity? In order to estimate this, we recall previous studies where the depolarization rate of neutrinos was calculated [15, 16, 17]. In the case of a random distribution of electromagnetic fields, the average neutrino's helicity $\langle h \rangle$ changes as dictated by the equation $\langle h(t)\rangle = exp(-\Gamma_{depol})\langle h(0)\rangle$, where

$$\Gamma_{depol} = 0.0132\mu_\nu^2 T^3 \,, \tag{11}$$



J. Barranco, D. Delepine, V. G. Macias, C. Lujan-Peschard and M. Napsuciale, Phys. Lett. B **739**, 343 (2014) [arXiv:1408.3219 [hep-ph]].

Not fully polarized, but partially polarized neutrinos.

1. Consider a model for the magnetic field of the Sun:

Solutions to magnetostatic Equations
[O.G. Miranda et al.
Nucl.Phys. B595 (2001) 360-380]

$$B_r^k(r,\theta) \;=\; 2\hat{B}^k\cos\theta\left[1-\frac{3}{r^2 z_k\sin z_k}\left(\frac{\sin(z_k r)}{z_k r}-\cos(z_k r)\right)\right],$$

$$B_\theta^k(r,\theta) \;=\; -\hat{B}^k\sin\theta\left[2+\frac{3}{r^2 z_k\sin z_k}\left(\frac{\sin(z_k r)}{z_k r}-\cos(z_k r)-z\right.\right.$$

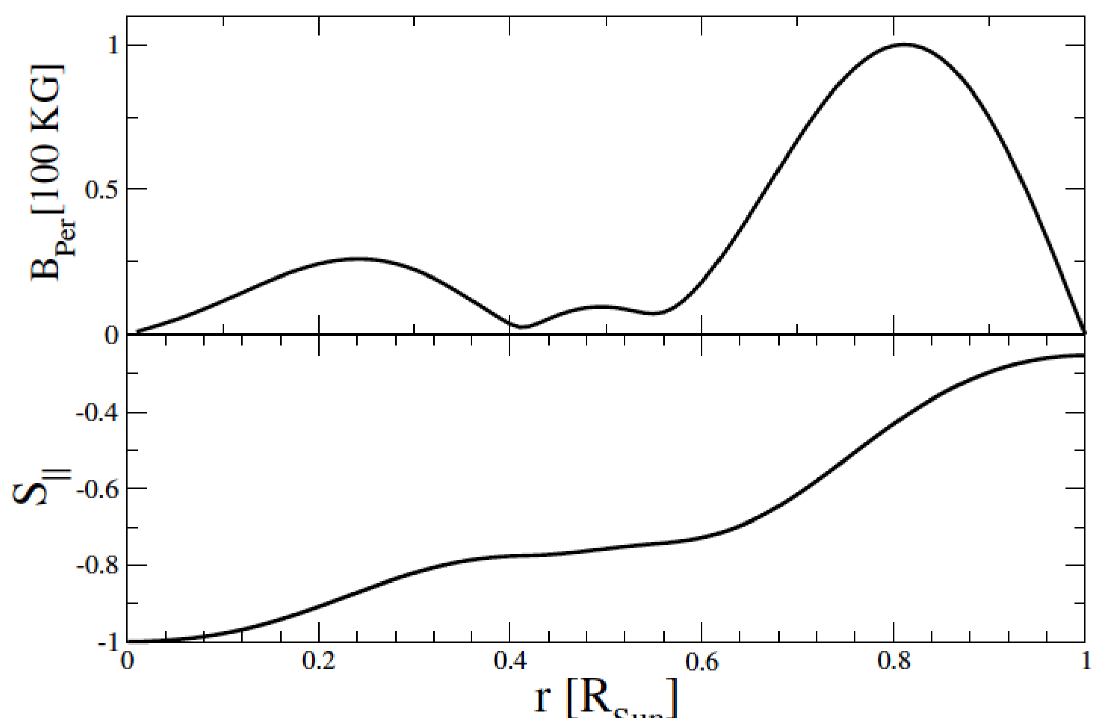
$$B_\phi^k(r,\theta) \;=\; \hat{B}^k z_k\sin\theta\left[r-\frac{3}{r z_k\sin z_k}\left(\frac{\sin(z_k r)}{z_k r}-\cos(z_k r)\right)\right],$$

$$B_\perp = \sqrt{B_\phi^2+B_\theta^2} = B_{core}\frac{\sin\theta}{r}f(r)$$

2. With this magnetic field, solve the BMT equation:

$$\frac{ds_{||}}{dr} = -2\mu_\nu B_\perp s_{||}$$

For a given magnetic field, and a neutrino magnetic moment, the final $s_{||} \neq -1$



Possible differences between Dirac and Majorana neutrino observable with astrophysical fluxes

1. A neutrino magnetic moment
2. External magnetic field
3. Massive neutrinos

Then, we expected number of neutrinos change from:

$$N_{Obs}^{th} = \sum_i \phi_i \times t \times N_e \times \int dE_\nu \int dT \lambda_i(E_\nu) \times \frac{d\sigma(E_\nu, T)}{dT} \times P(\Delta m^2, \theta)$$

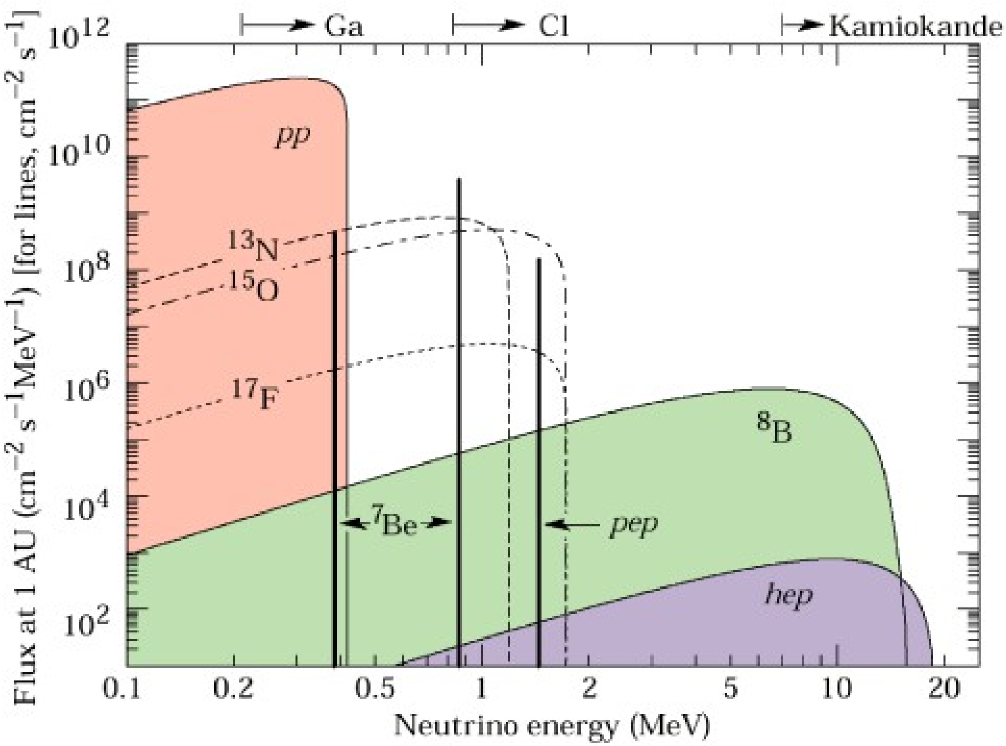
to...

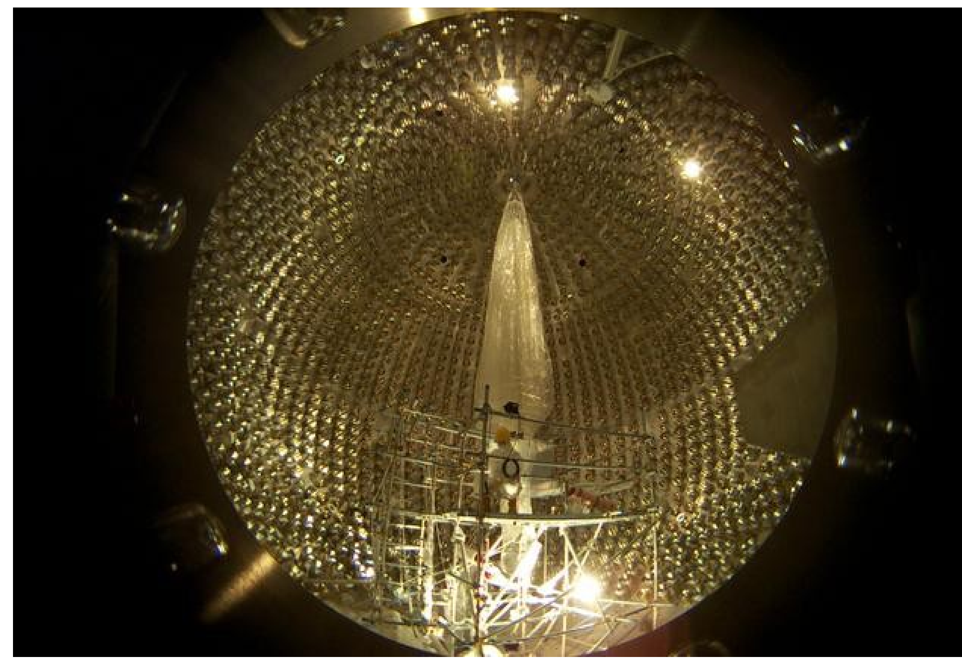
$$N_{Obs}^{th}(\mu_\nu, s_{||}) = \sum_i \phi_i \times t \times N_e \times \int dE_\nu \int dT \lambda_i(E_\nu) \times \frac{d\sigma(E_\nu, T, \mu_\nu, s_{||})}{dT} \times P(\Delta m^2, \theta, \mu_\nu)$$

Borexino

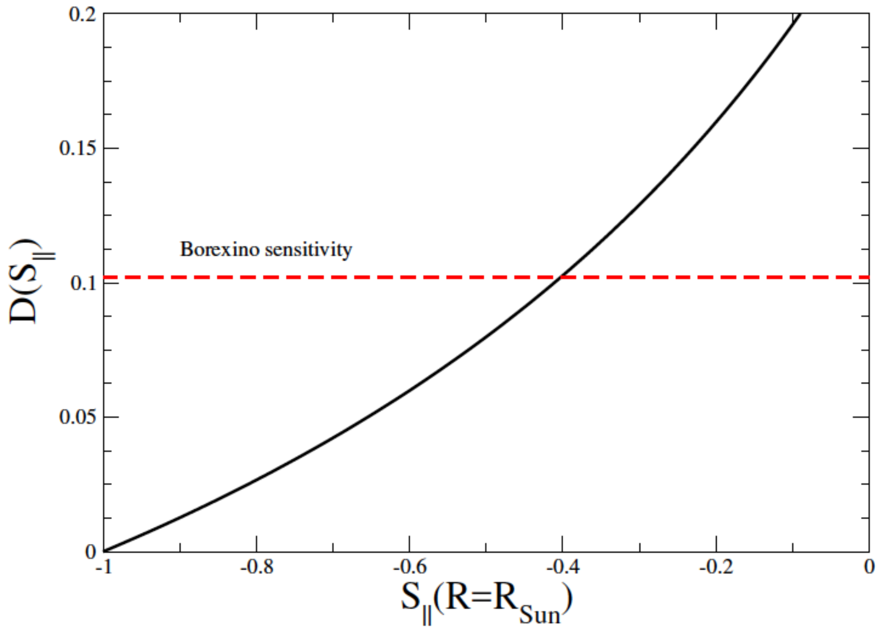
PRL **101,** 091302 (2008) PHYSICAL REVIEW LETTERS week ending 29 AUGUST 2008

Direct Measurement of the ^{7}Be Solar Neutrino Flux with 192 Days of Borexino Data



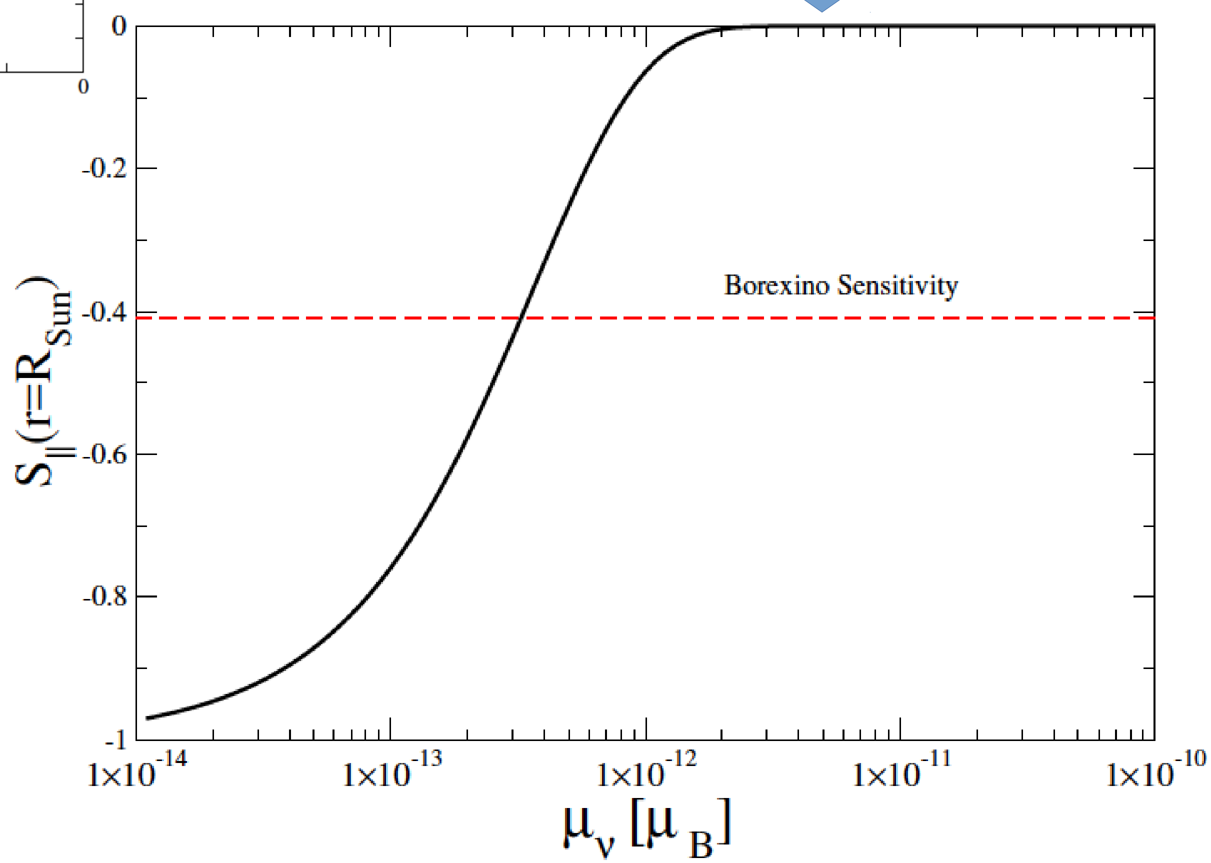


$$\text{Borexino's relative error} = \frac{|\mathrm{N^M} - \mathrm{N^D}|}{\mathrm{N^D}} = \frac{|\sigma^{\mathrm{M}} - \sigma^{\mathrm{D}}|}{\sigma^{\mathrm{D}}} = \mathrm{D}(\mathrm{s}_{||})$$



Borexino relative error = 4%
It implies a maximum value for the Neutrino polarization at the surface of the Sun

Maximum polarization implies an Upper bound on the neutrino magnetic moment



$$\mu_\nu < 3.3 \times 10^{-13} \mu_B.$$

J. Barranco, D. Delepine, M. Napsuciale, A. Yebra arXiv:1704.01549

Is it possible to obtain more information about's neutrino nature using astrophysical neutrinos? YES

Magnetic field amplification and magnetically supported explosions of collapsing, non-rotating stellar cores

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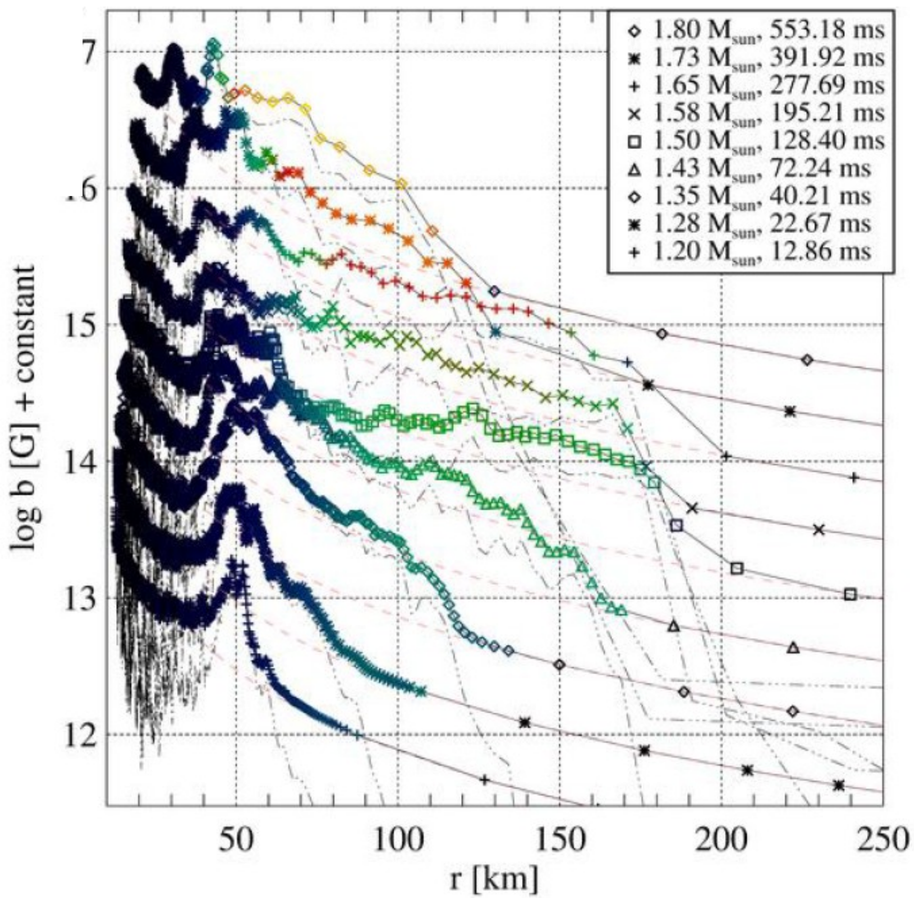
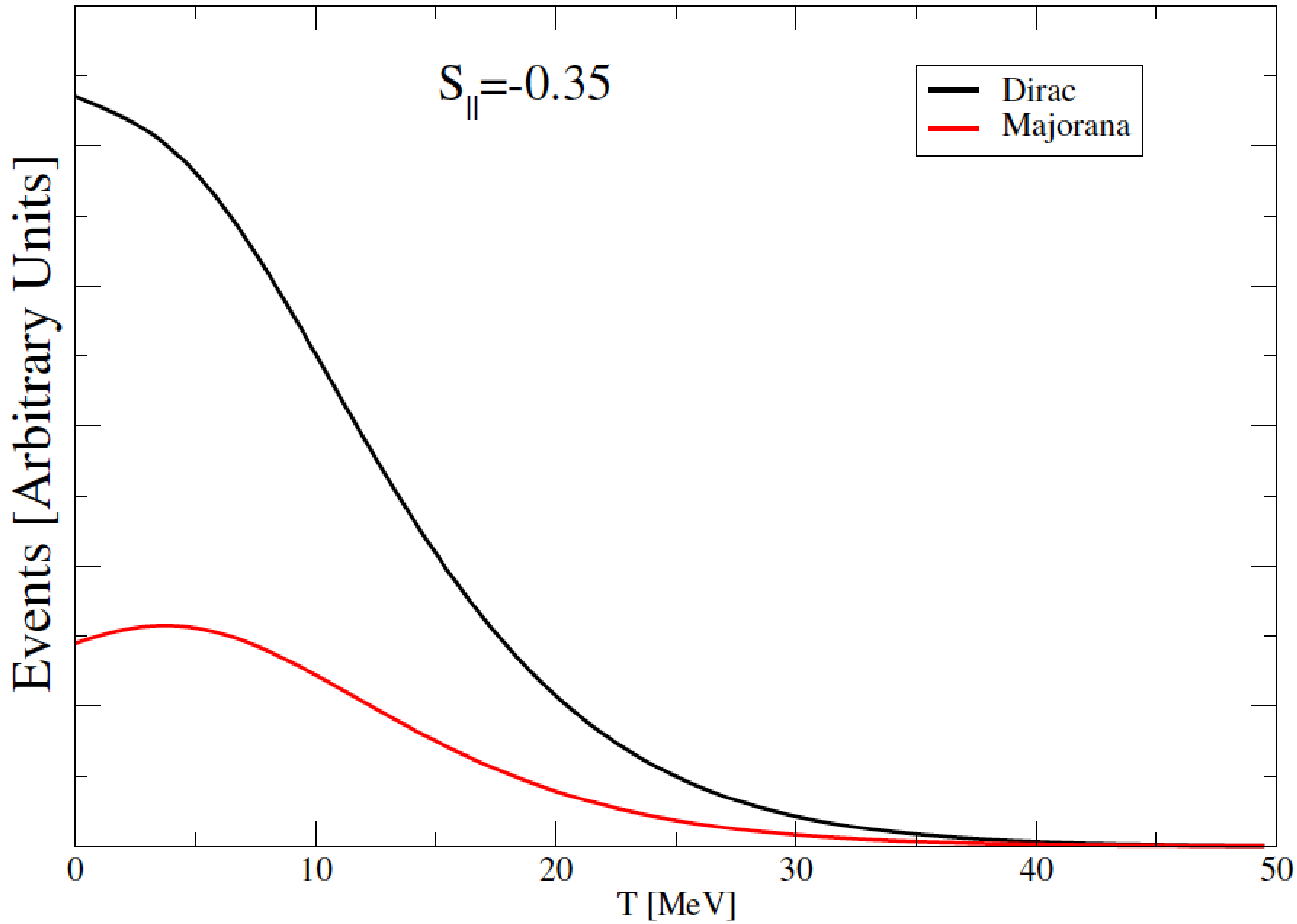
Supernova neutrinos



Difference between Majorana and Dirac with SN neutrinos

Even with a neutrino magnetic moment as small as the predicted by the standard model, the Huge magnetic fields In the SN explosions might generate observable differences in both spectra and number of neutrinos.



Conclusions:

1) We have shows that the neutrino-electron scattering with polarized neutrinos might have different cross sections for the Dirac or the Majorana case

2)We have shown that this fact allows us to constrain the neutrino magnetic moment

3)Future neutrino supernova might tell us the nature of the neutrino