Impact of the neutrino magnetic moment on Supernova r-process Nucleosynthesis

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28/06/2007-ECT*, Trento

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Outline

- *Heavy elements are produced by the R-process i.e. Rapid neutron capture*
- *Type II supernovae are a possible site for it (high T and high neutron density).*

but some difficulties remain...

1. Introduction : SNII, Alpha effect

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   - The Core-collapse Supernova
   - The Neutrino Magnetic Moment

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3. Results for Dirac Neutrinos

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Type II supernova

- *Explosion at the endlife of a* **massive** *star ($\geq 8\ \mathcal{M}_{SUN}$) due to the* **gravitationnal collapse** *of the iron-core into a* **hot** & **dense** *object, the Proto-Neutron Star (NS)*
- *99% of the energy ($\simeq 10^{53}$ ergs$\simeq 10^{59}$ MeV) is released by* **neutrinos** *and* **anti-neutrinos** *of all flavors*

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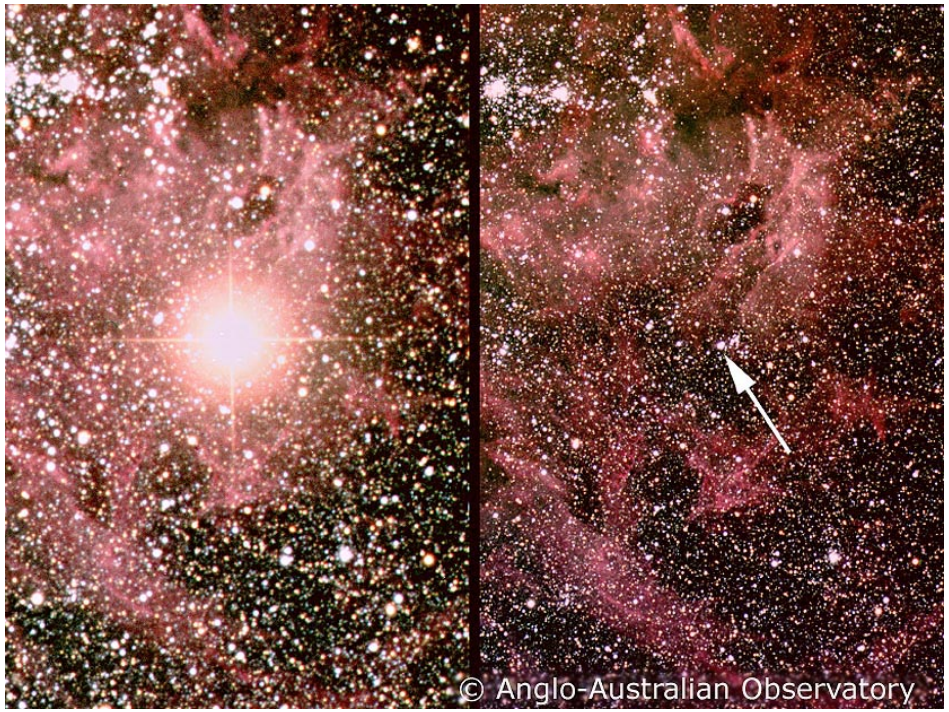
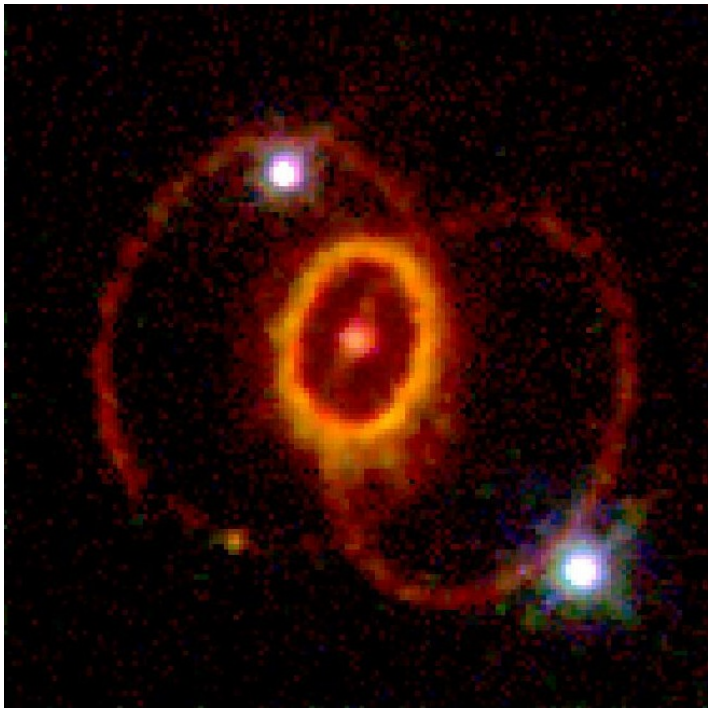


(LEFT) SN1987A 10 days after.



(RIGHT) SN1987A Remnant (NS)

Alpha effect

Electron fraction

$$Y_e = \frac{N_e}{N_{prot} + N_{neut}} = \frac{1}{1 + N_{neut}/N_{prot}} \tag{1}$$

- $Y_e < 1/2 \Rightarrow n/p > 1$: *neutron-rich medium*
- $Y_e \geq 1/2 \Rightarrow n/p \leq 1$: *no heavy elements nucleosynthesis possible.*

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Alpha Effect

=Formation of too many alpha-particles in the presence of a strong neutrino flux :
• *Almost all the protons and an equal amount of neutrons combine into alpha particles (which have a large binding energy).*
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Supernova neutrinos

- *Large ν flux $\Rightarrow$ the neutrino-induced reaction $\nu_e + n \rightarrow p + e^-$ can modify N_{neut}/N_{prot}.*
- **Non-standard neutrino properties** *can influence the heavy elements nucleosynthesis.*

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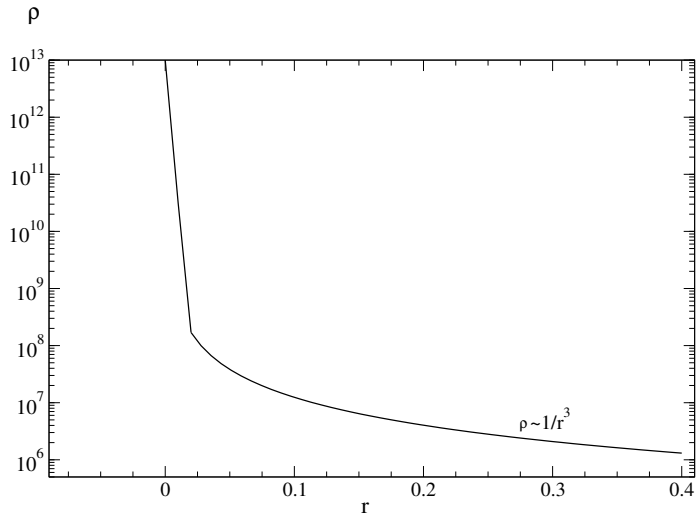
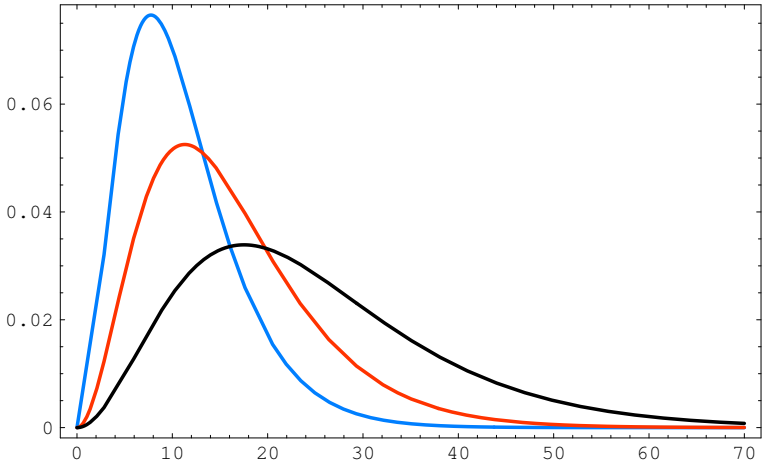
Can the neutrino magnetic moment help r-process nucleosynthesis ?

Density & ν fluxes (few sec. after the collapse)





(LEFT) Nucl. density (g.cm^3), as a function of r=distance from the NS surface (RIGHT) ν's energy distributions as a function of E_ν.

Nucleon (electron) density

- *Very high density*
- *Falls off steeply close to the NS surface*
- *For regions sufficiently far,* $\sim 1/r^3$

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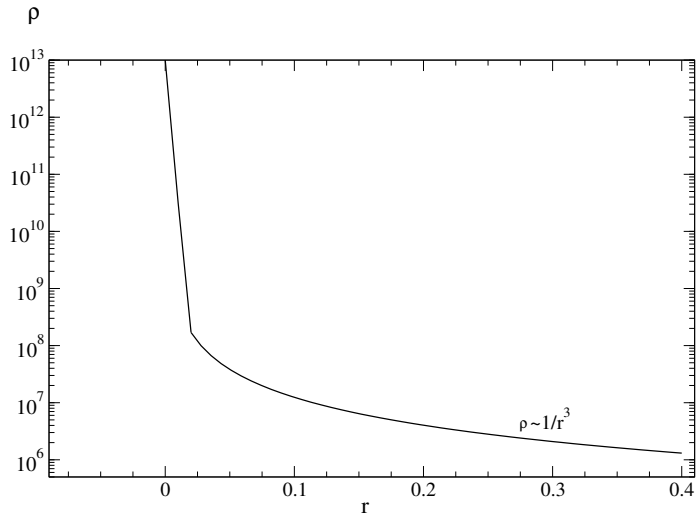

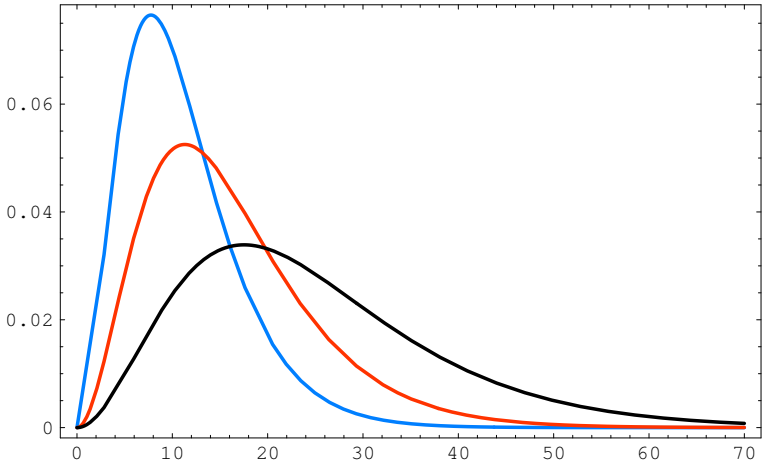

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Neutrinos fluxes at the neutrino sphere

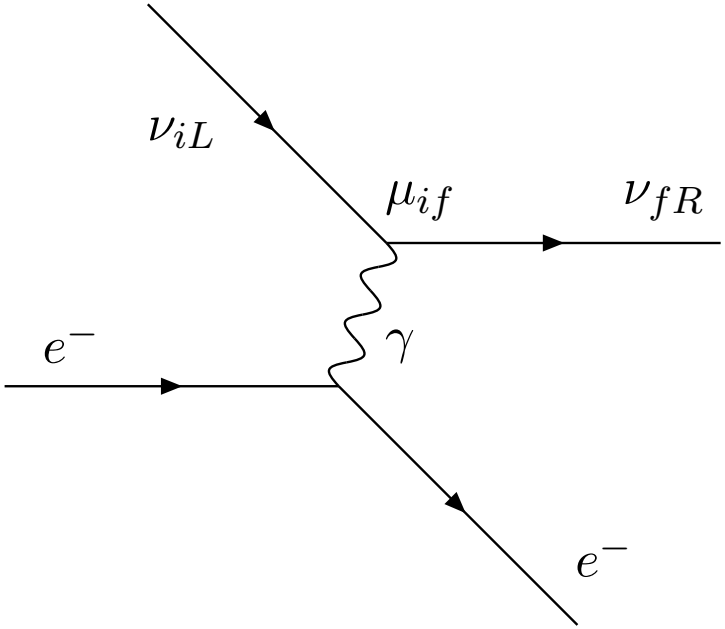
- **Fermi-Dirac** *distributions*
- **Hierarchical** *neutrinos energies* $\langle E_{\nu_e} \rangle \leq \langle E_{\bar{\nu}_e} \rangle \leq \langle E_{\nu_x} \rangle$

Magnetic moment interaction in the SN plasma

Neutrino magnetic moment interaction

$$\mathcal{L} \supset \frac{1}{2}\mu_{if}\overline{\psi}^{f}_{\nu}\sigma^{\mu\nu}\psi^{i}_{\nu}F_{\mu\nu} \qquad (2)$$

This interaction with the electromagnetic field **flips the chirality of the neutrino**.
Of order $10^{-19}\mu_B(m_\nu/1eV)$ *in the SM+*ν_R.



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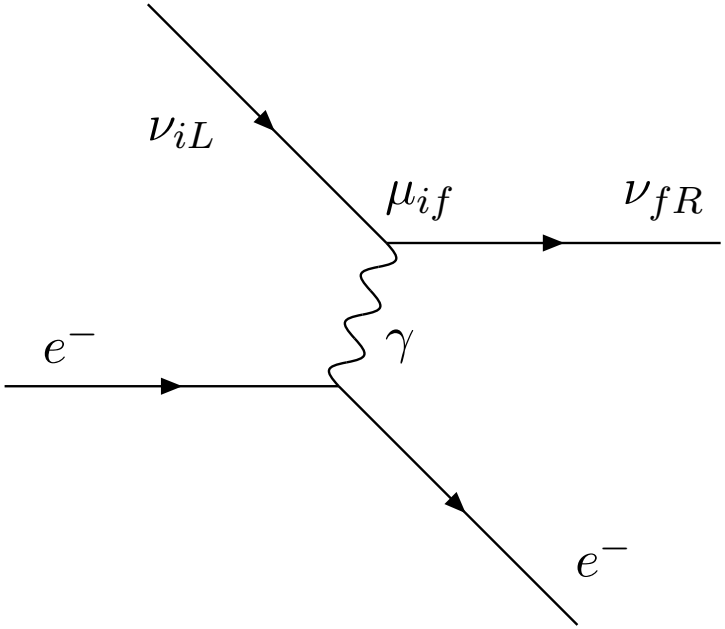


Differential cross-section

$$\frac{d\sigma}{dt} = \left(\sum_f {\mu_{if}}^2\right)\frac{\pi\alpha^2}{m_e^2}\frac{s+t-m_e^2}{(t-{m_\gamma}^2)(s-m_e^2)}. \qquad (3)$$

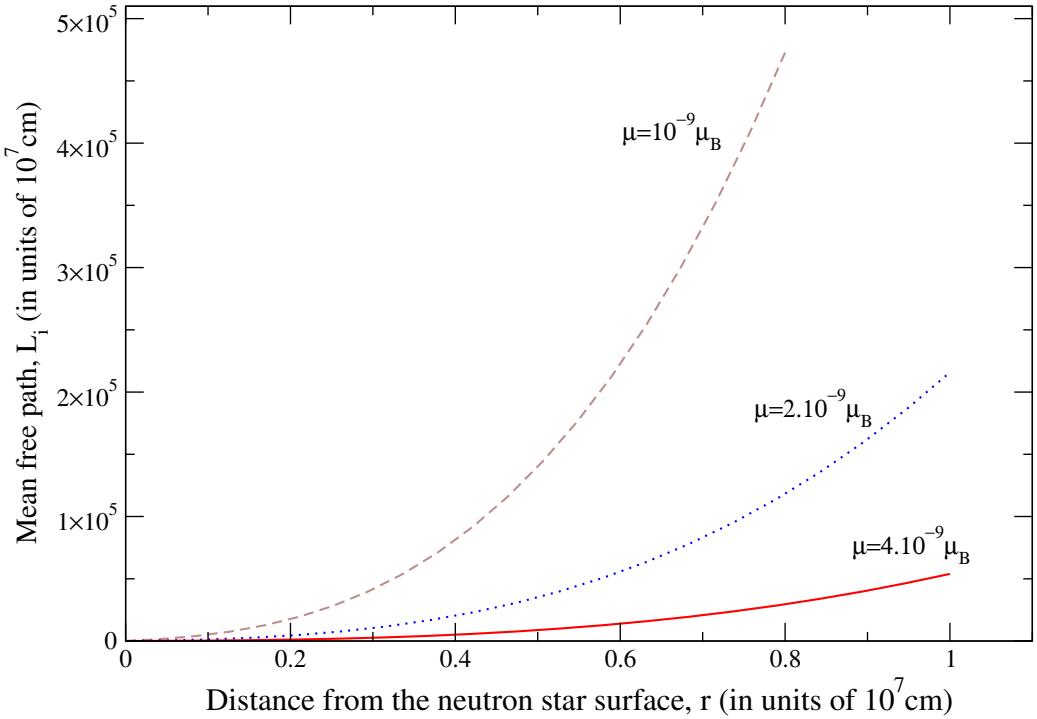
SN plasma (relativistic & degenerate near the NS) $\Rightarrow$ **Effective photon mass**

$$m_\gamma = m_\gamma(N_e(r), T) \qquad (4)$$

Cross-section and Neutrino Mean Free Path

Cross-section

$$\sigma = \left(\sum_f {\mu_{if}}^2\right) \frac{\pi\alpha^2}{m_e^2} \left[\left(1 + \frac{m_\gamma^2}{2m_e E_\nu}\right) \times \log\left(\frac{2m_e E_\nu + m_\gamma^2}{m_\gamma^2}\right) - 1\right]. \quad (5)$$



Neutrino mean free path

$$L_i = \frac{1}{\sigma(r, E_\nu, \sum \mu_{if}^2) N_e(r)}. \quad (6)$$

Fig.1 : L_i very large, $\gg R_{SN}$

Magnetic moment interactions significant only for $r \ll 1$

Dirac Neutrinos

RESULTS IN THE CASE OF DIRAC-TYPE NEUTRINOS

- $\nu_{\alpha L} \longrightarrow$ *sterile states : net loss of flux,* $|\psi_\nu|^2 \sim e^{-r/L_i}$
- *Both* ν_e & $\bar{\nu}_e$ *fluxes are reduced.*

Evolution equation

Standard matter effects ($\hat{H}_{\rm MSW}$) + magnetic moment interactions :

$$i\frac{\partial}{\partial r}\begin{bmatrix} \Psi_{\nu_e}(E_\nu,r) \\ \Psi_{\nu_\mu}(E_\nu,r) \\ \Psi_{\nu_\tau}(E_\nu,r) \end{bmatrix} = \left(\hat{H}_{\rm MSW} + \begin{bmatrix} -\frac{i}{2L_e} & 0 & 0 \\ 0 & -\frac{i}{2L_\mu} & 0 \\ 0 & 0 & -\frac{i}{2L_\tau} \end{bmatrix}\right)\begin{bmatrix} \Psi_{\nu_e}(E_\nu,r) \\ \Psi_{\nu_\mu}(E_\nu,r) \\ \Psi_{\nu_\tau}(E_\nu,r) \end{bmatrix}. \quad (7)$$

(*same form for anti-neutrinos*)

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Electron fraction at equilibrium

$$Y_e \simeq \frac{1}{1+\frac{\lambda(\bar{\nu}_e p\to en)}{\lambda(\nu_e n\to ep)}} \tag{8}$$

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Reaction rates

$$\lambda(r)\propto\int\sigma_{weak}(E_\nu)\overbrace{\underbrace{f_D(E_\nu,T_\nu)}_{E_\nu\ \text{Distributions}}\ \underbrace{|\psi(r,E_\nu)|^2}_{\text{Probabilities}}}^{\sim\text{Fluxes}}\,dE_\nu \quad (9)$$

Effect on Y_e

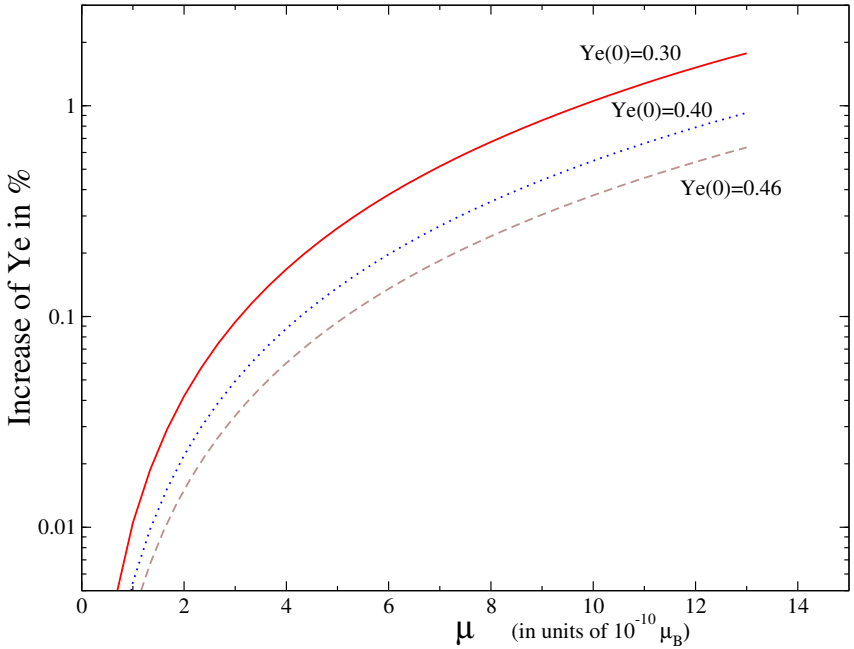

Figure :

- $Increase(r) = \dfrac{Y_e(r) - Y_e(r=0)}{Y_e(r=0)}$
- *Evaluated at $r = 4$ km from the NS surface where magnetic moment interactions become* **ineffective** *(cf L_i).*
- $\mu = \left(\sum_f \mu_{ef}^2 \right)^{1/2}$

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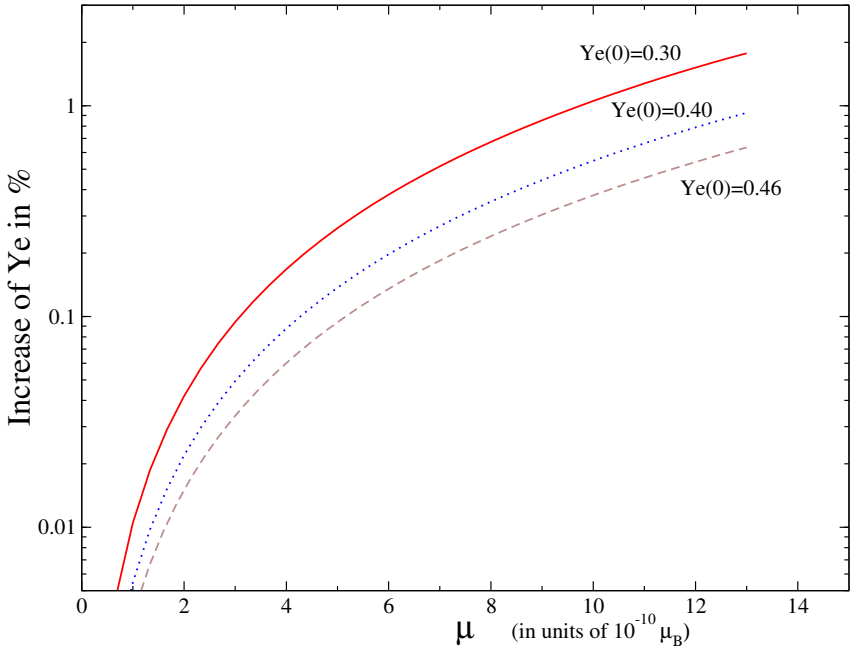

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Comments

- *Strong dependence on μ (cf L_i)*
- $\mu = O(10^{-9})\ \mu_B$: *Increase of Y_e of 1%;* $\mu = \mu_{exp}^{MAX} = 7.4 \times 10^{-11}\ \mu_B \Rightarrow$ *Less than 0.01%*
- *Smaller effect for a $Y_e(0)$ closer to the critical value 0.5 (=less pronounced hierarchy).*

Majorana Neutrinos

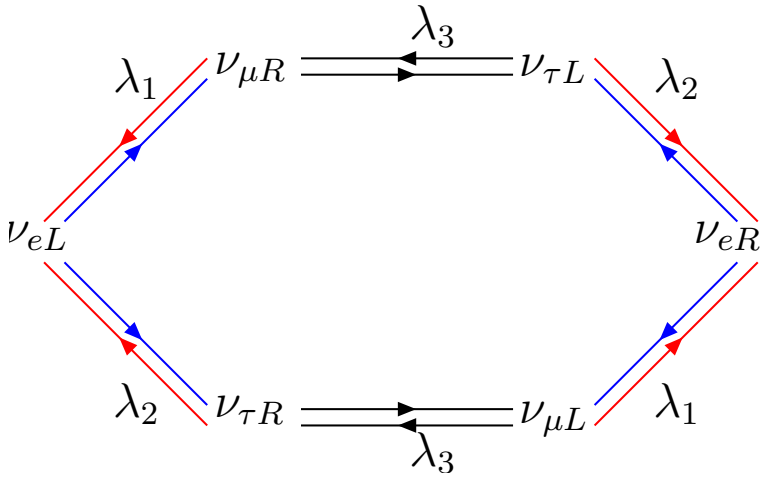
RESULTS IN THE CASE OF MAJORANA-TYPE NEUTRINOS

- ν_R's are *not sterile* anymore
- $\nu_{\alpha L} \longrightarrow \nu_{\beta R}$ = *conversion* between Neutrinos & Antineutrinos
- *transition* magnetic moment only :

$$\mu = \begin{pmatrix} 0 & \mu_{e\mu} & \mu_{e\tau} \\ -\mu_{e\mu} & 0 & \mu_{\mu\tau} \\ -\mu_{e\tau} & -\mu_{\mu\tau} & 0 \end{pmatrix} \tag{10}$$

Evolution equation

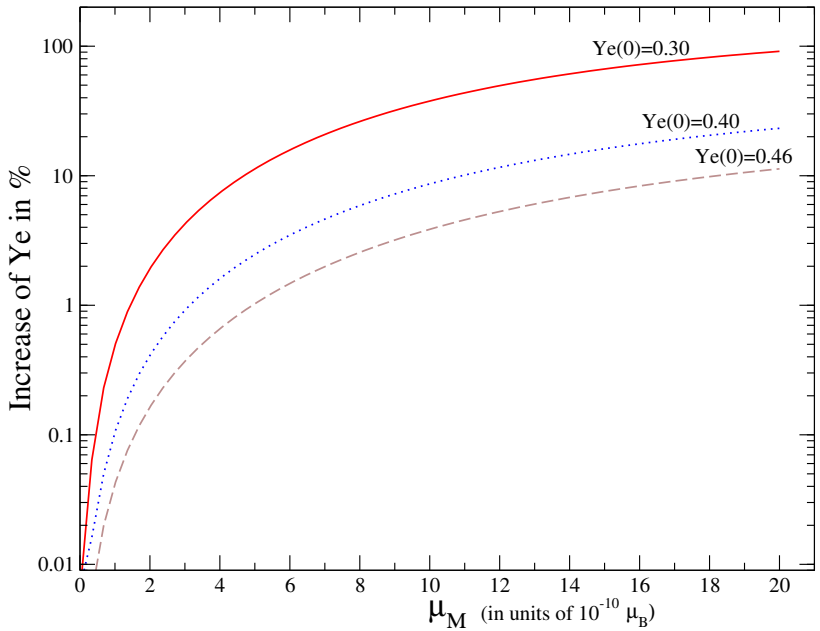
- *For each $\nu_{iL,R}$, there are* **four conversions** *: two contribute positively (gain), two negatively (loss).*
- *$\hat{H}_{\rm MSW}$ very small effect for $r \ll 1$ (MSW resonances are far)*
- *Evolution equation directly for neutrino number fractions $\mathcal{N}_\nu$ (~probabilities)*

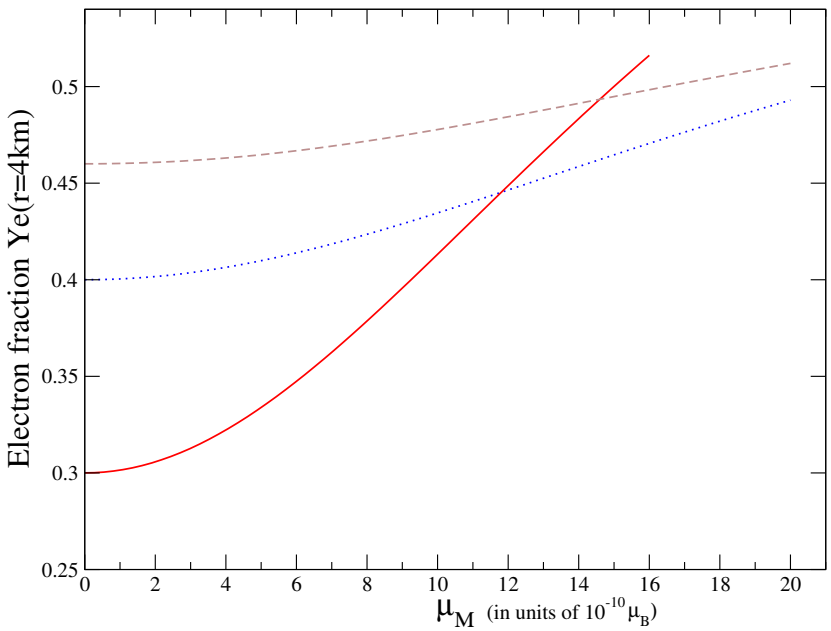


$$\frac{\partial}{\partial r}\begin{bmatrix} \mathcal{N}_{\nu_{eL}} \\ \mathcal{N}_{\nu_{\mu L}} \\ \mathcal{N}_{\nu_{\tau L}} \\ \mathcal{N}_{\nu_{eR}} \\ \mathcal{N}_{\nu_{\mu R}} \\ \mathcal{N}_{\nu_{\tau R}} \end{bmatrix} = \begin{bmatrix} -\lambda_1-\lambda_2 & 0 & 0 & 0 & \lambda_1 & \lambda_2 \\ 0 & -\lambda_1-\lambda_3 & 0 & \lambda_1 & 0 & \lambda_3 \\ 0 & 0 & -\lambda_2-\lambda_3 & \lambda_2 & \lambda_3 & 0 \\ 0 & \lambda_1 & \lambda_2 & -\lambda_1-\lambda_2 & 0 & 0 \\ \lambda_1 & 0 & \lambda_3 & 0 & -\lambda_1-\lambda_3 & 0 \\ \lambda_2 & \lambda_3 & 0 & 0 & 0 & -\lambda_2-\lambda_3 \end{bmatrix} \begin{bmatrix} \mathcal{N}_{\nu_{eL}} \\ \mathcal{N}_{\nu_{\mu L}} \\ \mathcal{N}_{\nu_{\tau L}} \\ \mathcal{N}_{\nu_{eR}} \\ \mathcal{N}_{\nu_{\mu R}} \\ \mathcal{N}_{\nu_{\tau R}} \end{bmatrix}$$

with $\lambda_1 = 1/L_{e\mu}$, $\lambda_2 = 1/L_{e\tau}$, $\lambda_3 = 1/L_{\mu\tau}$ (L_{if} = mean free path with μ_{if})

Effect on Y_e





(LEFT) $(Y_e(r = 4km) - Y_e(r = 0))/Y_e(r = 0)$ as a function of $\mu_M = \mu_{e\mu} = \mu_{e\tau}$, (RIGHT) $Y_e(r = 4km)$

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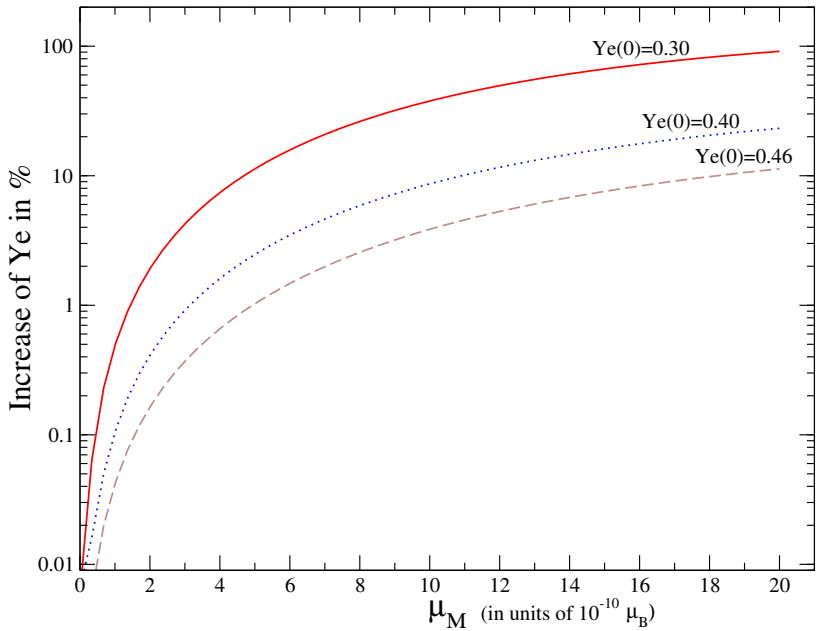

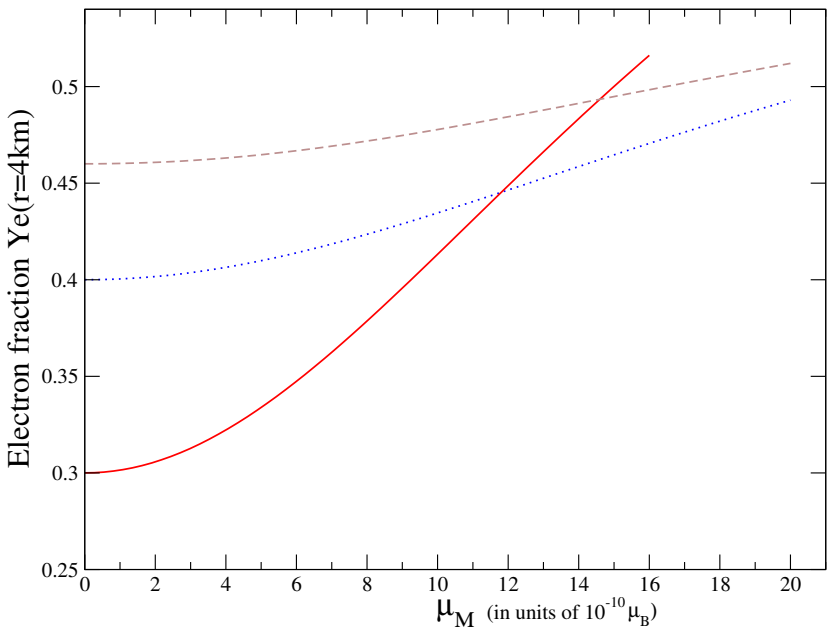

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Comments

- *For $\mu_{e\mu}$, $\mu_{e\tau}=\mathcal{O}(1.5-2\times10^{-9}\mu_B)$, Y_e meets the critical value of 0.5 for all $Y_e(0)$.*
- *Strong dependence on μ & smaller effect for a $Y_e(r=0)$ closer to 0.5. (idem Dirac)*
- *Larger effects than in the Dirac case*

Summary and conclusions

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- *We included the neutrino magnetic moment*
- *We studied its impact on the electron fraction Y_e which is a key quantity for nucleosynthesis*
- *We studied both Dirac & Majorana cases*

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- *Neutrino magnetic moment* $\mathcal{O}(1.5 - 2 \times 10^{-9} \mu_B)$ **prevents nucleosynthesis** *(*MAJORANA*)*
- *But* $< 1\%$ *effects on nucleosynthesis with actual experimental upper-limits on* μ*'s*

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Perspectives

However, *$\nu - \nu$ interactions (not included) could play a* **significant role** *near the neutron star* **and since** 10^{-9} *is not so far from experimental limits, the question of magnetic moment should be* **reconsidered** *once $\nu - \nu$'s interactions can be calculated exactly.*