Lepton Flavor Violation beyond the Standard Model and Stellar Collapse

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Based on

- O.Lychkovskiy, M. Vysotsky, S. Blinnikov, Eur. Phys. J. C67:213-227, 2010 [arXiv 0912.1395]
- O.Lychkovskiy, M. Vysotsky, S. Blinnikov, arXiv 1010.0883
- O.Lychkovskiy, M. Vysotsky, arXiv 1010.1694v2

Plan

1. Lepton Flavor Violation beyond the SM and neutrino transport in PNS
2. LFV in Sea-Saw type II model of neutrino mass generation
3. Conclusions

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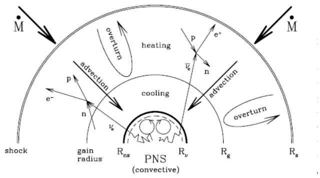
Collapse of stellar core

Massive stars experience core collapse at the end of evolution. After the collapse stellar core turns into a dense hot Proto Neutron Star (PNS) which cools due to neutrino losses.



Sketch of processes in PNS.
Fig. from [Janka 2001].

Our focus is on diffusive neutrino transport in the central region ($M \lesssim (0.5 - 0.8) M_\odot$) of PNS.

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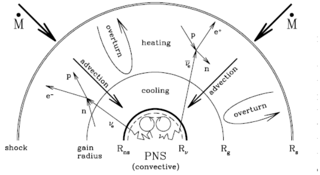

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Our focus is on diffusive neutrino transport in the central region ($M \lesssim (0.5 - 0.8) M_\odot$) of PNS.

Neutrino oscillation are absent in this region due to high matter density.
No LFV within SM!

Conditions in the center of PNS

Extreme values of density, temperature, electron and electron neutrino chemical potentials are reached in PNS.

ρ	n_B	Y_e	Y_{ν_e}	Y_μ	$Y_{\nu_\mu},\ Y_{\nu_\tau}$
$2 \cdot 10^{14}\ \mathrm{g/cm^3}$	$1.2 \cdot 10^{38}\ \mathrm{cm^{-3}}$	0.30	0.07	$\sim 10^{-5}$	$\sim 10^{-4}$

T	μ_e	μ_{ν_e}
10 MeV	200 MeV	160 MeV

Typical conditions in the central region of PNS ($m \lesssim 0.5 M_\odot$) during the first 0.5 s after the collapse. Only SM interactions are taken into account.

Energy of electrons is high enough even to produce muons. However, in SM this is prohibited by lepton flavor conservation.

LFV in PNS

What if LFV processes do occur due to some new physics? (see earlier works [Mazurek 1979; Kolb, Tubbs, Dicus 1982; Fuller et al 1987; Amanik, Fuller, Grinstein 2005; Amanik, Fuller 2007])

$$\begin{aligned} e^- e^- &\rightarrow \mu^- \mu^- \\ e^- \nu_e &\rightarrow \mu^- \nu_{e,\mu,\tau} \\ e^- \nu_e &\rightarrow e^- \nu_{\mu,\tau} \\ \nu_e \nu_e &\rightarrow \nu_{\mu,\tau} \nu_{e,\mu,\tau} \end{aligned}$$

LFV in PNS

LFV processes are relevant when

$$R_{\rm LFV} \gtrsim R_{\rm diff}$$

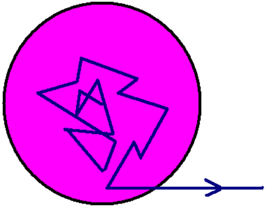
$R_{\rm diff} \simeq 4 \cdot 10^{36} {\rm cm}^{-3} {\rm s}^{-1}$ – rate of total lepton number decrease due to ν diffusion
$R_{\rm LFV} \simeq 4 \cdot 10^{36} {\rm cm}^{-3} {\rm s}^{-1}$ – rate of LFV

This is achieved even for tiny LFV four-fermion constant: $G_{\rm LFV} \sim 10^{-4} G_F$

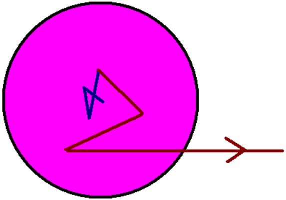
DISCLAIMER:

Neutrino oscillations are NOT considered in the present work, as they are suppressed below neutrino sphere due to huge matter density. "LFV" is used as a shortcut notation for "LFV in *incoherent* scattering".

Neutrino transport with and without LFV



ν_e diffusion from PNS



ν_μ diffusion from PNS

ν_μ and ν_τ do not participate in CC interactions in contrast to $\nu_e \Rightarrow$ $\lambda_{\nu_\mu,\nu_\tau} > \lambda_{\nu_e} \Rightarrow$ total luminosity (total energy emitted from neutrino sphere per unit time) is increased in the first second.

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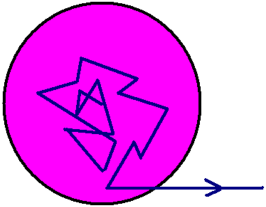

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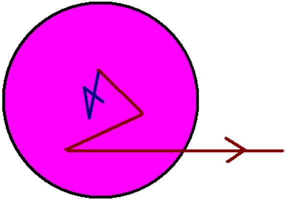

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Subtlety: flavor composition at the neutrino sphere is almost unchanged (every ν while traveling from the center effectively produces several $\nu\bar{\nu}$ pairs of different flavors).

Neutrino transport with and without LFV

Increase of neutrino luminosity in the first second after the collapse tends to facilitate the supernova explosion in the neutrino heating scenario!
[Burrows, Goshy 1993; Janka 2001; Murphy, Burrows 2008]

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See-Saw type II model of neutrino mass generation

New scalars: Δ^{--}, Δ^{-}, Δ^{0}

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Scalar-lepton interaction:

$$\mathcal{L}_{ll\Delta} = \sum_{l,l'} \lambda_{ll'} \overline{L_l^c} i\tau_2 \Delta L_{l'} + h.c.$$

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Scalar potential

$$V = -M_H^2 H^\dagger H + f(H^\dagger H)^2 + M_\Delta^2 Tr(\Delta^\dagger \Delta) + \frac{1}{\sqrt{2}}(\tilde{\mu} H^T i\tau_2 \Delta^\dagger H + h.c.)$$

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Δ^0 acquires vev:

$$\langle \Delta^0 \rangle = \frac{\tilde{\mu} v^2}{2\sqrt{2} M_\Delta^2} \tag{1}$$

This vev provides neutrinos with Majorana mass:

$$m_{ll'} = 2\langle \Delta^0 \rangle \lambda_{ll'} \tag{2}$$

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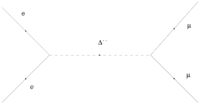
Important: coupling matrix is proportional to the neutrino mass matrix.

LFV processes in SN

Exchange of Δ in s-channel gives rise to LFV scatterings:

$$
\begin{array}{rcl}
e^- e^- & \to & \mu^- \mu^- \\
e^- \nu_e & \to & \mu^- \nu_{e,\mu,\tau} \\
e^- \nu_e & \to & e^- \nu_{\mu,\tau} \\
\nu_e \nu_e & \to & \nu_{\mu,\tau} \nu_{e,\mu,\tau}
\end{array}
$$



Cross sections:

$$
\begin{array}{rcl}
\sigma(ee \to \mu\mu) & = & (|\lambda_{ee}|^2 |\lambda_{\mu\mu}|^2 / M_\Delta^4)(1 - m_\mu^2/2E^2)\sqrt{1 - m_\mu^2/E^2}\; E^2/2\pi \\
\sigma(e\nu_e \to \mu\nu_l) & = & (|\lambda_{ee}|^2 |\lambda_{\mu l}|^2 / M_\Delta^4)(1 - m_\mu^2/4E^2)^2 E^2/2\pi, \\
\sigma(e\nu_e \to e\nu_l) & = & (|\lambda_{ee}|^2 |\lambda_{el}|^2 / M_\Delta^4) E^2/2\pi, \quad l = \mu, \tau, \\
\sigma(\nu_e\nu_e \to \nu_l\nu_l) & = & 2(|\lambda_{ee}|^2 |\lambda_{ll}|^2 / M_\Delta^4) E^2/\pi, \quad l = \mu, \tau, \\
\sigma(\nu_e\nu_e \to \nu_l\nu_{l'}) & = & 4(|\lambda_{ee}|^2 |\lambda_{ll'}|^2 / M_\Delta^4) E^2/\pi, \quad l, l' = e, \mu, \tau, \quad l \neq l'.
\end{array}
$$

LFV processes in SN plus $\mu \to e\gamma$

See-Saw type II provides relevant rate of LFV in SN in wide range of parameters [Lychkovskiy, Vysotsky, Blinnikov 2009].

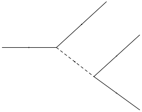
LFV processes in SN plus $\mu \to e\gamma$

See-Saw type II provides relevant rate of LFV in SN in wide range of parameters [Lychkovskiy, Vysotsky, Blinnikov 2009].

Can we add an additional requirement: $\mathrm{Br}(\mu \to e\gamma) \sim 10^{-12}$ (observable in MEG in the nearest future, see talk by Paolo Walter Cattaneo)?
Remind: $\mathrm{Br}(\mu \to eee) < 10^{-12}$.

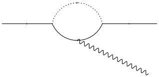
$\mu \to eee$:

tree-level amplitude



$\mu \to e\gamma$:

penguin amplitude



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Solution: take $\lambda_{e\mu} \simeq 0$

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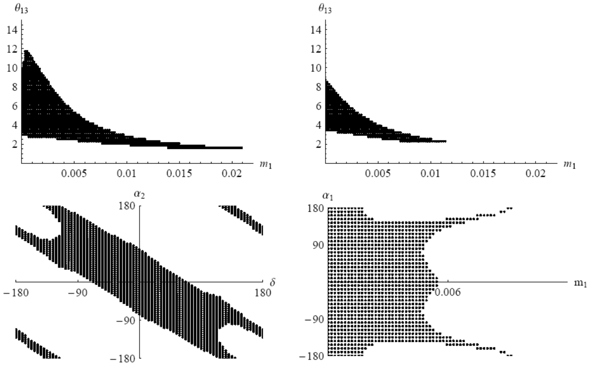
This determines a "Golden Domain" of the see-saw type II model in which:

1. all the experimental constraints from neutrino oscillations, and rare lepton decays are satisfied,
2. $\mathrm{Br}(\mu \to e\gamma) \sim 10^{-12}$,
3. the rate of LFV in supernova is high enough to affect the neutrino transport .

[Lychkovskiy, Vysotsky 2010]

Golden Domain of See-Saw type II



- $\theta_{23} \simeq 135^o$
- $m_1 < m_2 \ll m_3$.
- $2^o \lesssim \theta_{13} \lesssim 12^o$.

Predictions for LFV processes

process	experimental upper bound on Br	Br(process)
$\mu \to e\gamma$	$1.2 \cdot 10^{-11}$	10^{-12}
$\mu^- \to e^+ e^- e^-$	$1.0 \cdot 10^{-12}$	$\lesssim 10^{-13}$
$\mu\ \mathrm{Au} \to e\ \mathrm{Au}\ (M_\Delta = 150\ \mathrm{GeV})$	$7 \cdot 10^{-13}$	$1.2 \cdot 10^{-13}$
$\mu\ \mathrm{Au} \to e\ \mathrm{Au}\ (M_\Delta = 1\ \mathrm{TeV})$		$3.1 \cdot 10^{-13}$
$\tau^- \to \mu^+ \mu^- \mu^-$	$3.2 \cdot 10^{-8}$	$1.0 \cdot 10^{-9}$
$\tau^- \to e^+ \mu^- \mu^-$	$2.3 \cdot 10^{-8}$	$7.6 \cdot 10^{-11}$
$\tau^- \to e^+ e^- e^-$	$3.6 \cdot 10^{-8}$	$9.6 \cdot 10^{-13}$
$\tau^- \to \mu^+ e^- e^-$	$2.0 \cdot 10^{-8}$	$1.3 \cdot 10^{-11}$
$\tau^- \to e^+ e^- \mu^-$	$2.7 \cdot 10^{-8}$	$\lesssim 10^{-11}$
$\tau^- \to \mu^+ e^- \mu^-$	$3.7 \cdot 10^{-8}$	$\lesssim 10^{-13}$
$\tau \to \mu\gamma$	$3.3 \cdot 10^{-8}$	$1.6 \cdot 10^{-11}$
$\tau \to e\gamma$	$4.4 \cdot 10^{-8}$	$3.5 \cdot 10^{-13}$

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SN explosion in the ν-heating scenario is facilitated
and SN neutrino signal is shortened.

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LFV of relevant magnitude may be realized in the See-Saw type II model of neutrino mass generation. A domain in the See-Saw II parameter space exists in which in addition

$$\mathrm{Br}(\mu \to e\gamma) \sim 10^{-12}$$

(testable at MEG in the nearest future, see the talk by Paolo Walter Cattaneo).

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- $\mathrm{Br}(\tau \to \mu\mu\mu) \sim 10^{-9}$ (measurable in Belle II, see talk by Toru Iijima),

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- $\mathrm{Br}(\tau \to \mu\mu\mu) \sim 10^{-9}$ (measurable in Belle II, see talk by Toru Iijima),
- relative probability of $\mu - e$ conversion in heavy muonic atoms is $\sim 10^{-13}$ (close to present experimental μAu bound).

Thank you for your attention!