TeV-scale bileptons, see-saw type II and lepton flavor violation in core-collapse supernova

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O.Lychkovskiy, M. Vysotsky, S. Blinnikov, Eur. Phys. J. C67:213-227, 2010.

Plan

- Standard collapse scenario
- Collapse with lepton flavor violation (LFV)
- LFV due to see-saw type II
- Constraints from rare decays and neutrino oscillations
- Possible modifications of supernova dynamics and neutrino signal

Standard collapse

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

T	μ_e	μ_{ν_e}	μ_μ	$\mu_{\nu_\mu}, \mu_{\nu_\tau}$
10 MeV	200 MeV	160 MeV	40 MeV	0

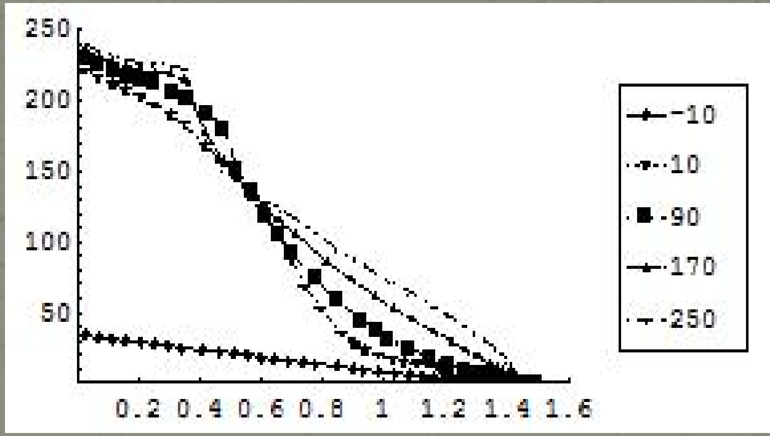
Table 1: Typical conditions in the inner supernova core ($m \lesssim 0.5 M_\odot$) during the first 50 ms after core bounce as obtained by us with the help of the open-code program Boom [19]. Only SM interactions are taken into account.

In the inner supernova core
electrons and electron neutrinos
are highly degenerate and numerous,
while leptons of other flavors —
nondegenerate and scarce.
This is due to the conservation of lepton flavor
in the Standard Model.

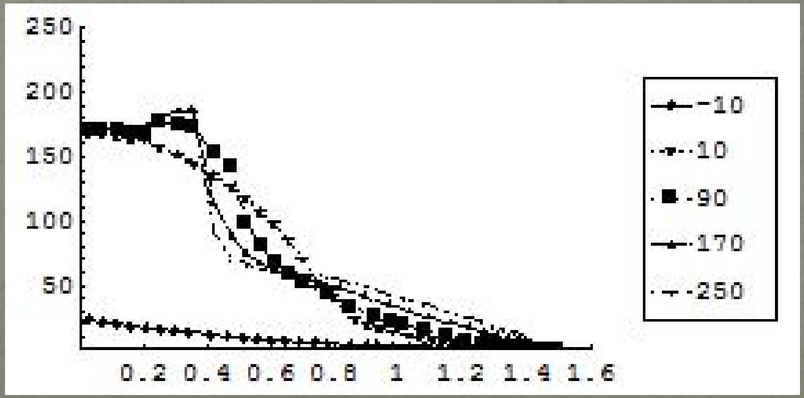
Standard collapse

Chemical potentials of electrons and electron neutrinos in the center are as high as (170 — 230) MeV!

Electron chemical potential (MeV)



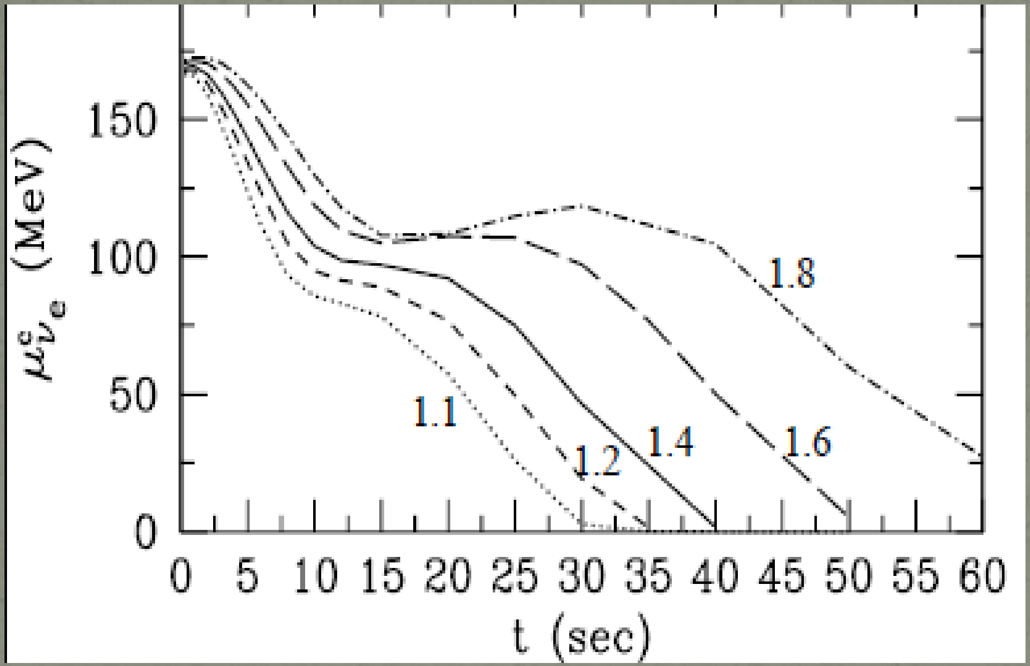
Neutrino chemical potential (MeV)



BOOM code (Chen-Yu Wang, 1998) simulations

Standard collapse

Chemical potentials remain high during few seconds.

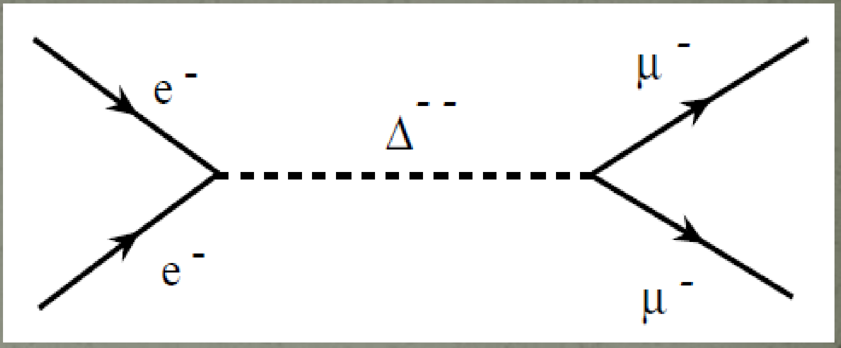


Reddy et al., astro-ph/9802310

Conservation of lepton flavor in the Standard Model keeps the concentrations of nonelectron leptons low.

Collapse with LFV

Assume that new heavy particles generate effective four-fermion interactions which do not conserve lepton flavor.



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

$$\mu_e = \mu_\mu$$

$$\mu_{\nu_e} = \mu_{\nu_x}$$

Equilibrium between flavors is established in the inner core.
Seas of degenerate nonelectron neutrinos arise.
Even muons may appear in appreciable amount!

Collapse with LFV

The equilibrium is established at a time scale Δt if

$$\sigma \gtrsim 1/(\Delta t n_e c) \simeq 3 \cdot 10^{-48} (300 \text{ ms}/\Delta t) \text{cm}^2$$

This may be fulfiled only for reactions with $|\Delta L_e|$=2.

Processes with $|\Delta L_e|$=1 ,

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

and others

are strictly constrained by rare lepton decays.

Thus we need a SM extension with suppressed $|\Delta L_e|$=1 LFV and allowed $|\Delta L_e|$=2 LFV.

See-saw type II
(an example of SM extension with suitable LFV)

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

$$\Delta \equiv \boldsymbol{\Delta\tau}/\sqrt{2} = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix},$$

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

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

$$m = 2\langle \Delta^0 \rangle \lambda,$$

$$\sigma(ee \to \mu\mu) = (|\lambda_{ee}|^2 |\lambda_{\mu\mu}|^2 / M_\Delta^4)(1 - m_\mu^2/2E_e^2)\sqrt{1 - m_\mu^2/E_e^2}\; E_e^2/2\pi,$$

$$\sigma(e\nu_e \to \mu\nu_\mu) = (|\lambda_{ee}|^2 |\lambda_{\mu\mu}|^2 / M_\Delta^4)(1 - m_\mu^2/4E_e^2)^2 E_e^2/4\pi, \quad E_e = E_{\nu_e},$$

$$\sigma(\nu_e\nu_e \to \nu_\mu\nu_\mu) = (|\lambda_{ee}|^2 |\lambda_{\mu\mu}|^2 / M_\Delta^4) E_{\nu_e}^2/2\pi,$$

$$\sigma(\nu_e\nu_e \to \nu_\tau\nu_\tau) = (|\lambda_{ee}|^2 |\lambda_{\tau\tau}|^2 / M_\Delta^4) E_{\nu_e}^2/2\pi,$$

Constraints from rare decays and neutrino oscillations

- Rare decays.

process	constraint on	bound, $\times(M_\Delta/\mathrm{TeV})^2$
$\mu^- \to e^+e^-e^-$	$\lvert\lambda_{e\mu}\lambda_{ee}\rvert$	$< 2.4 \cdot 10^{-5}$
$\tau^- \to e^+e^-e^-$	$\lvert\lambda_{e\tau}\lambda_{ee}\rvert$	$< 2.6 \cdot 10^{-2}$
$\tau^- \to \mu^+\mu^-\mu^-$	$\lvert\lambda_{\mu\tau}\lambda_{\mu\mu}\rvert$	$< 2.4 \cdot 10^{-2}$
$\tau^- \to \mu^+e^-e^-$	$\lvert\lambda_{\mu\tau}\lambda_{ee}\rvert$	$< 1.9 \cdot 10^{-2}$
$\tau^- \to e^+\mu^-\mu^-$	$\lvert\lambda_{e\tau}\lambda_{\mu\mu}\rvert$	$< 2.0 \cdot 10^{-2}$
$\mu \to e\gamma$	$\lvert\lambda^*_{e\mu}\lambda_{ee} + \lambda^*_{\mu\mu}\lambda_{e\mu} + \lambda^*_{\tau\mu}\lambda_{e\tau}\rvert$	$< 9.4 \cdot 10^{-3}$
$\mu^-e^+ \leftrightarrow \mu^+e^-$	$\lvert\lambda_{\mu\mu}\lambda_{ee}\rvert$	< 0.2

- Neutrino oscillations.

$$m = 2\langle\Delta^0\rangle\lambda,$$

$$m = U^* \cdot \mathrm{diag}(m_1, m_2, m_3) \cdot U^\dagger$$

The coupling matrix λ is proportional to neutrino mass matrix m in flavor basis, which is partly fixed by neutrino oscillation.

In order to suppress $|\Delta L_e|=1$ and keep $|\Delta L_e|=2$ processes we need an almost diagonal m

Constraints from rare decays and neutrino oscillations

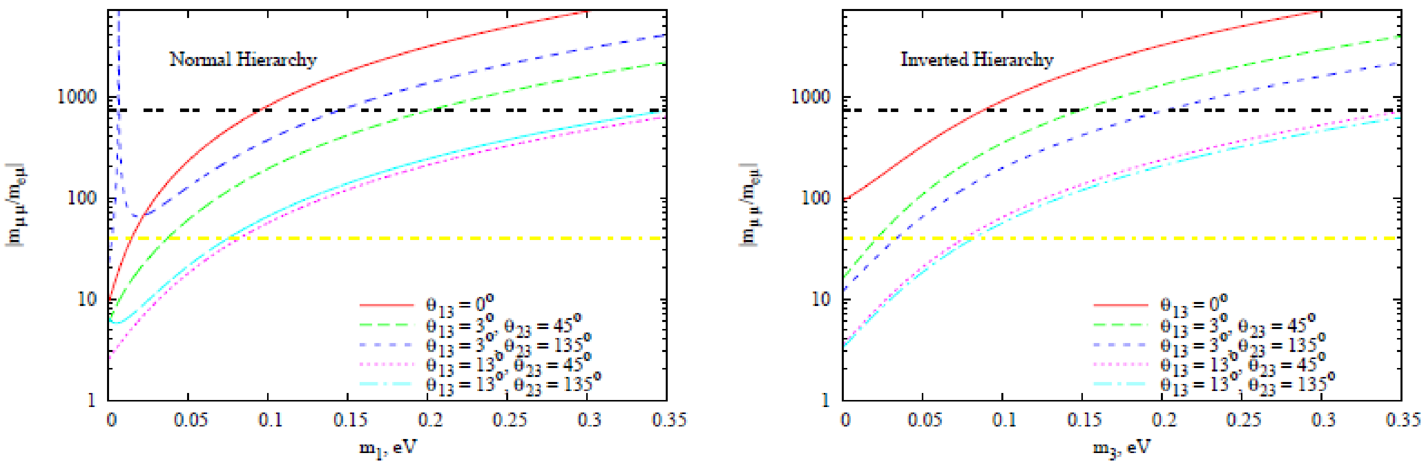


Figure 2: Ratio $|m_{\mu\mu}/m_{e\mu}|$ in case of exact CP-conservation ($\alpha_1 = \alpha_2 = \delta = 0$). If $\theta_{13} = 0$ then $|m_{\mu\mu}/m_{e\mu}|$ does not depend on the quadrant of θ_{23}. Two thick horizontal lines correspond to $|m_{\mu\mu}/m_{e\mu}| = 40$ and $|m_{\mu\mu}/m_{e\mu}| = 720$, which are minimal values sufficient for LFV in supernova core to proceed at scales 300 ms and 1 ms accordingly.

Constraints from rare decays and neutrino oscillations

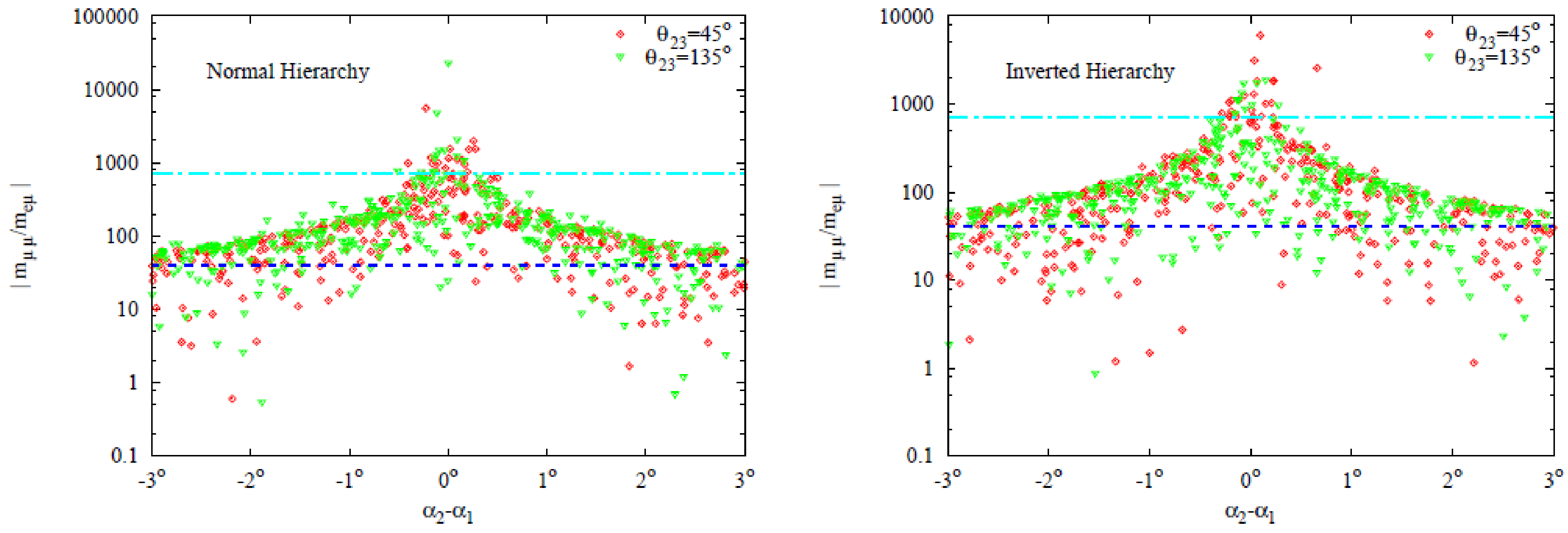


Fig. 3. Scatter plots for the ratio $|m_{\mu\mu}/m_{e\mu}|$. Each point corresponds to a random choice of neutrino parameters in the following ranges: $m_{\min} \in [0.05\text{ eV}, 0.35\text{ eV}], \theta_{13} \in [0^o, 3^o], \delta \in [-90^o, 90^o], \alpha_1 \in [-2\delta - 3^o, -2\delta + 3^o], \alpha_2 \in [-2\delta - 3^o, -2\delta + 3^o]$. If the hierarchy is normal, then $m_{\min} = m_1$, otherwise $m_{\min} = m_3$

Roughly speaking, LFV affects the supernova physics if the matrix of scalar-lepton couplings is approximately proportional to the unit matrix, $\lambda_{ll'} \simeq \lambda\delta_{ll'}$, and the effective coupling λ^2/M_Δ^2 is greater than 10^{-3} TeV$^{-2} \simeq 10^{-4}G_F$. The former condition corresponds to neutrino masses greater than 0.05 eV and neutrino phases which satisfy the relations $|\alpha_1 + 2\delta|, |\alpha_2 + 2\delta| \ll \pi$.

Possible modifications of supernova dynamics and neutrino signal

Increase of the inner core cooling rate (as nonelectron neutrinos do not interact with neutrons through charged current).

↓

Increase of the power and decrease of the duration of neutrino emission.

↓

Clear signatures in neutrino signal!

May help the supernova to explode in the delayed explosion scenario!

Possible modifications of supernova dynamics and neutrino signal

Other possible astrophysical effects include:

- Non-homologous collapse.
- Modification of the shock wave.
- Several shock waves.
- Modification of neutronization burst.
- Several neutronization bursts.
- ..?

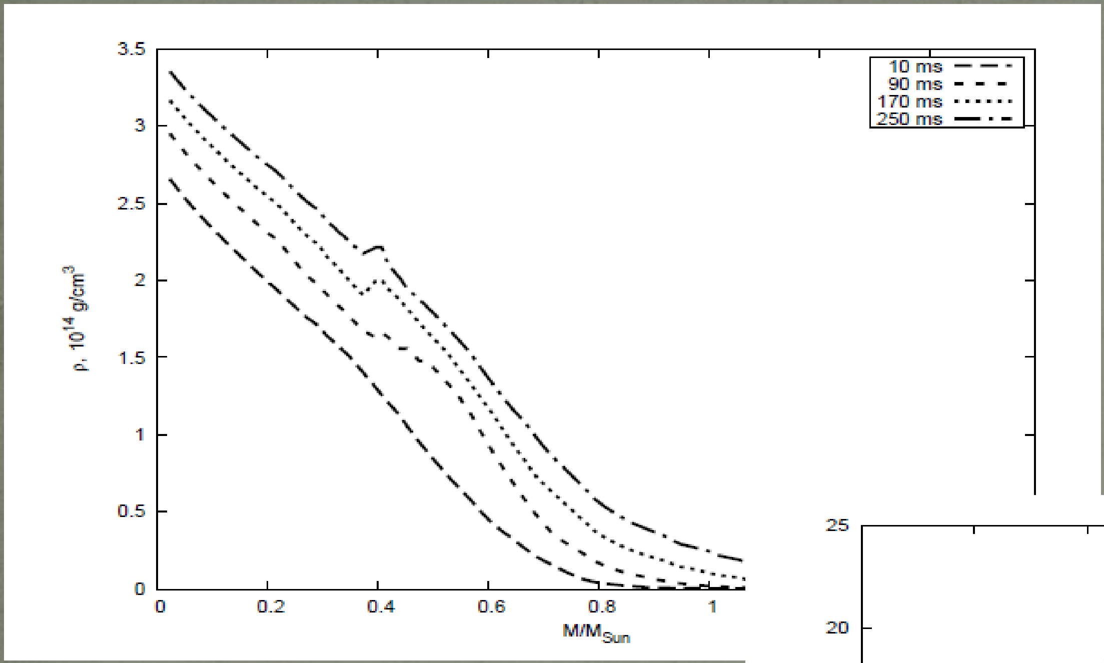
To describe the above effects quantatively
a numerical simulation of supernova explosion
is necessary!

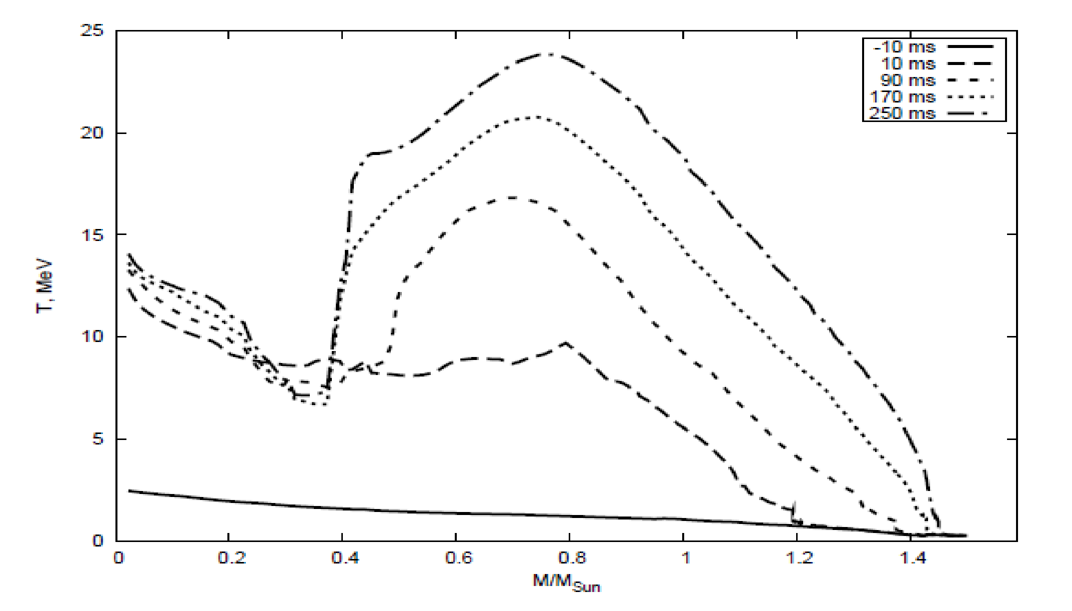
Conclusions

- New physics with lepton flavor violation can drastically change the conditions inside the collapsing supernova core.
- Such changes lead to modifications of SN dynamics (possibly facilitate the SN explosion!) and to clear signatures in neutrino signal.
- The see-saw type II model of neutrino mass generation provides a suitable pattern of LFV in a certain area of parameters.

Thank You!

Standard collapse





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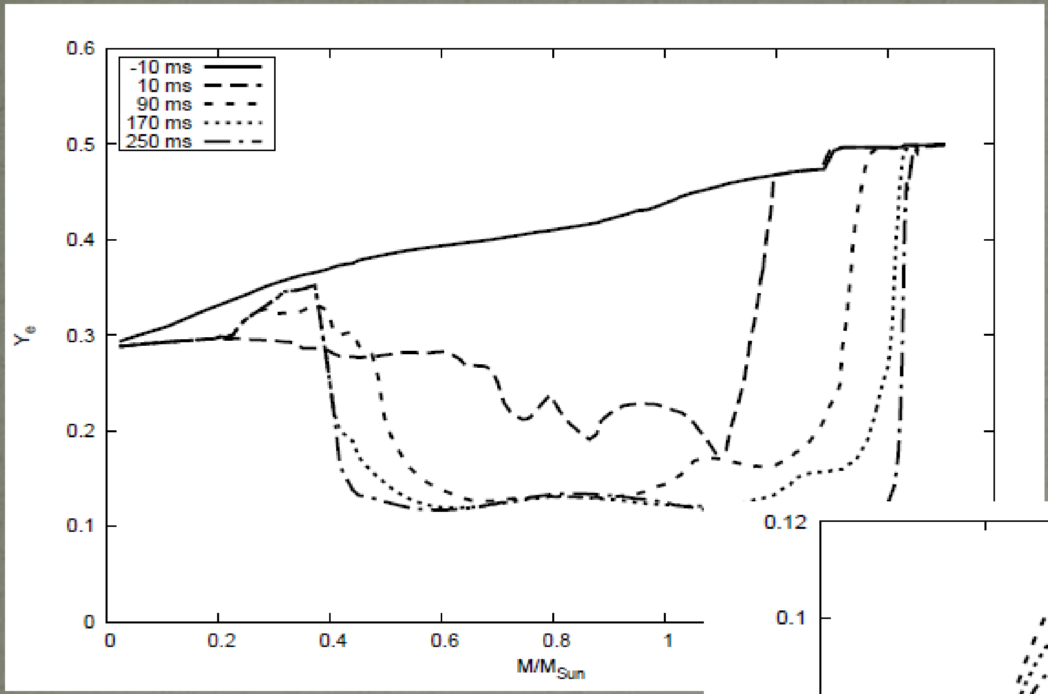

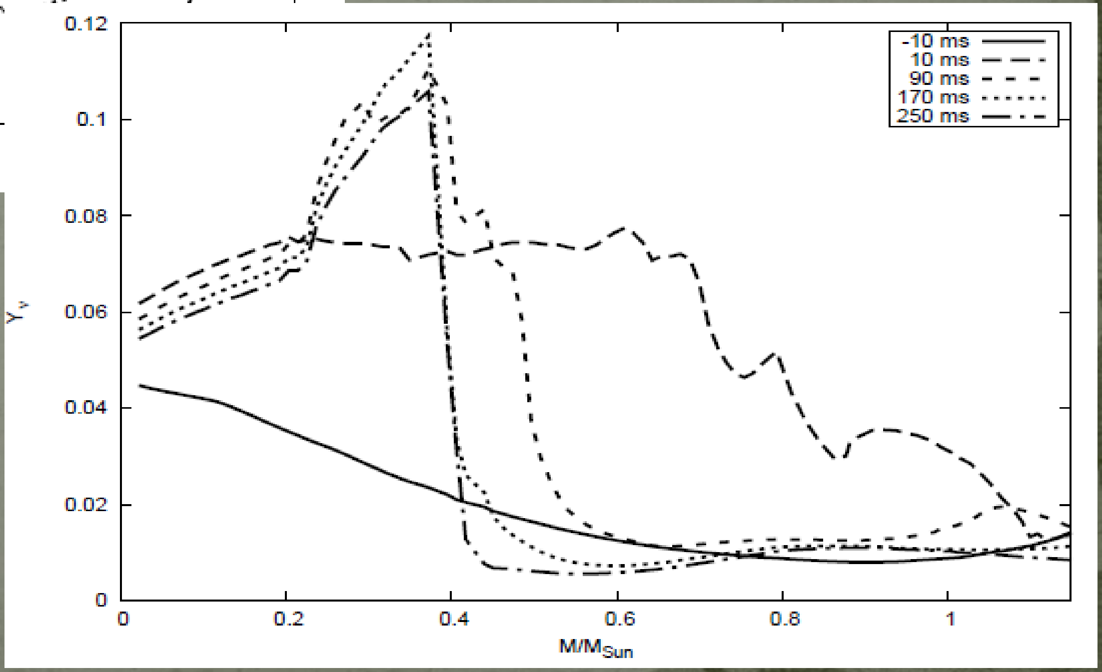

BOOM code (Chen-Yu Wang, 1998) simulations