Neutrino and NSI physics in supernovae

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BSM Physics with neutrinos

- Neutrinos have been a great way of discovering Beyond the Standard Model physics.

- Neutrino mass and mixing are 'cracks' in the Standard Model:
  - what kind of mass, Dirac or Majorana
  - is there large CP violation in the leptons,
  - ...

- Many experiments looking for further BSM physics are underway / under construction / being planned / proposed.

- Experimentalists must build large / radiogenically quiet / sensitive (expensive) detectors often deep underground.

- The lifetime of a neutrino experiment can be 20+ years.
  - The SNO collaboration held its first meeting in 1984,
  - The experiment was funded in January 1990,
  - It turned on in May 1999,
  - It stopped taking data November 2006.
  - Still publishing papers as of 2013

Neutrino Astrophysics

- Neutrinos become important in environments where Nature pushes the envelope of energy, temperature, density etc.

- The dynamics or signals of the system change if the properties of the neutrino are altered:
  - the abundance of primordial Helium from BBN changes with the number of neutrino flavors Peebles, PRL **16** 410 (1966),
  - the first indications of neutrino oscillations came from observing solar neutrinos,
  - the strongest limits on neutrino magnetic moments come from the cooling of Asymptotic Giant Branch stars,
  - it is expected cosmology will be the first to measure the effects of a non-zero neutrino mass,
  - ...

Non-standard interactions

- We shall consider new, Non-Standard Interactions (NSI), of neutrinos with matter in supernovae.
  - see also Amanik, Fuller and Grinstein, Astropart. Phys. **24** 160 (2005)
  - Amanik and Fuller, PRD **75** 083008 (2007)
  - Esteban-Pretel, Tomas and Valle, PRD **76** 053001 (2007)
  - Blennow, Mirizzi and Serpico, PRD **78** 113004 (2008)

    Esteban-Pretel, Tomas and Valle, PRD **81** 063003 (2010)

    ...
- These NSI will alter the neutrino flavor evolution by adding new terms to the neutrino Hamiltonian.

$$i\frac{d\rho}{dr}=[H,\rho]$$

$$H=H_V+H_\nu+H_{MSW}+H_{NSI}$$

- If we allow NSI with electrons, up and down quarks then

$$H_{NSI} = \sqrt{2} G_F \sum_f n_f \epsilon^f$$

- The ε's are matrices.
- We replace the number density $n_f = Y_f n_N$ where Y_f is the fermion fraction and n_N is the nucleon density n_N.
  - for the up quarks $Y_u = 1+Y_e$,
  - for down quarks $Y_d = 2-Y_e$.

- The NSI Hamiltonian can be written as

$$H_{NSI} = \sqrt{2} G_F n_N \left(Y_e \epsilon^e + (1+Y_e) \epsilon^u + (2-Y_e) \epsilon^d \right)$$

- The NSI are functions of the composition of the matter.

- The model independent limits from Biggio et al. JHEP 903 139 (2009) are upon the combination

$$\epsilon^{m}=\sum_{f}\left(\frac{n_f}{n_e}\right)\epsilon^{f}$$

- In Earth like matter

$$\begin{pmatrix} |\epsilon_{ee}|<4.2 & |\epsilon_{e\mu}|<0.33 & |\epsilon_{e\tau}|<3.0 \\ & |\epsilon_{\mu\mu}|<0.068 & |\epsilon_{\mu\tau}|<0.33 \\ & & |\epsilon_{\tau\tau}|<21 \end{pmatrix}$$

- In solar like matter (only protons and electrons!?)

$$\begin{pmatrix} |\epsilon_{ee}|<2.5 & |\epsilon_{e\mu}|<0.21 & |\epsilon_{e\tau}|<1.7 \\ & |\epsilon_{\mu\mu}|<0.046 & |\epsilon_{\mu\tau}|<0.21 \\ & & |\epsilon_{\tau\tau}|<9.0 \end{pmatrix}$$

- If NSI are not to destroy the MSW solution for solar neutrinos then we can require that in the Sun

$$Y_{\odot}\,\delta\epsilon^{e}+\left(1+Y_{\odot}\right)\delta\epsilon^{u}+\left(2-Y_{\odot}\right)\delta\epsilon^{d}=0$$

- where $\delta\varepsilon = \varepsilon_{ee} - \varepsilon_{xx}$.

- Using this constraint we rewrite the NSI potential as

$$H_{NSI}=\sqrt{2}G_F n_N\left(\frac{Y_{\odot}-Y_e}{Y_{\odot}}\right)\begin{pmatrix}\delta\epsilon^{n} & \epsilon_{ex}\\ \epsilon_{ex}^{*} & 0\end{pmatrix}$$

- where $\delta\varepsilon^{n} = 2\,\delta\varepsilon^{d} + \delta\varepsilon^{u}$.

The effect of NSI

- The total matter potential is

$$H_M = \sqrt{2} G_F n_N \left[Y_e \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} + \left(\frac{Y_\odot - Y_e}{Y_\odot} \right) \begin{pmatrix} \delta\epsilon^n & \epsilon_{ex} \\ \epsilon_{ex}^* & 0 \end{pmatrix} \right]$$

- It is possible for the matter potential to become ‘negative’.

$$Y_e + \delta\epsilon^n \left(\frac{Y_\odot - Y_e}{Y_\odot} \right) < 0$$

- Solving for Y_e

$$Y_e < \frac{-\delta\epsilon^n Y_\odot}{Y_\odot - \delta\epsilon^n} = Y_0$$

- In order for $Y_0 > 0$ we require $\delta\varepsilon^n < 0$.

- If we set Y_0 and solve for $\delta\varepsilon^n$ then

$$\delta\epsilon^n = \frac{-Y_0 Y_\odot}{Y_\odot - Y_0}$$

- If $Y_\odot = 0.7$ and $Y_0 = 0.3$ then $\delta\varepsilon^n = -0.5$.

- To explore the consequences we solve for the neutrino flavor evolution in a very simple model.
  - single energy, 20 MeV, two flavor: $\delta m^2 = 2.4 \times 10^{-3}\ \mathrm{eV}^2$, $\theta = 9°$
  - matter profile of the form

$$\sqrt{2}\, G_F\, n_N = \lambda_0 \left(\frac{r_0}{r} \right)^3$$

  - $\lambda_0 = 10^6$ eV, $r_0 = 10$ km
  - self interaction of the form

$$H_\nu = \mu_\nu \left(\rho - \alpha\, \bar{\rho}^* \right)$$

  - α is the neutrino/antineutrino asymmetry set to 0.8
  - self interaction strength follows

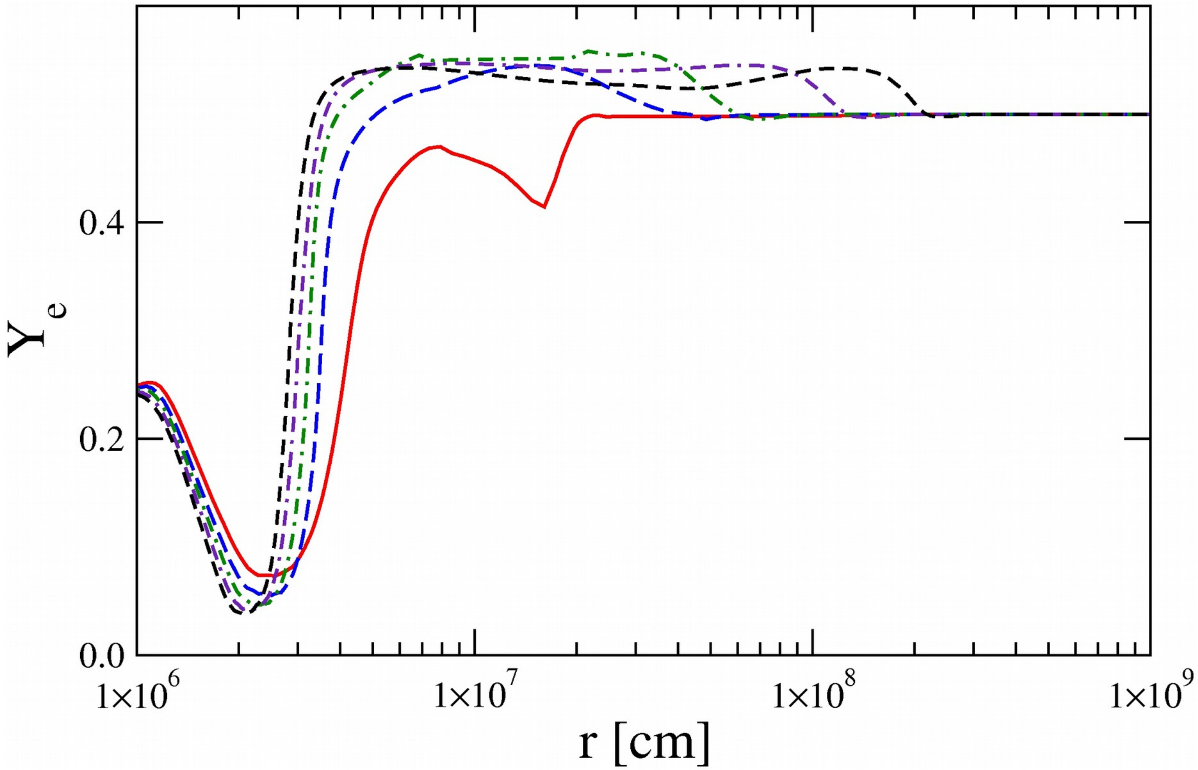
$$\mu_\nu = \mu_0 \left(\frac{r_0}{r} \right)^4$$

  - $\mu_0 = 10^6$ eV

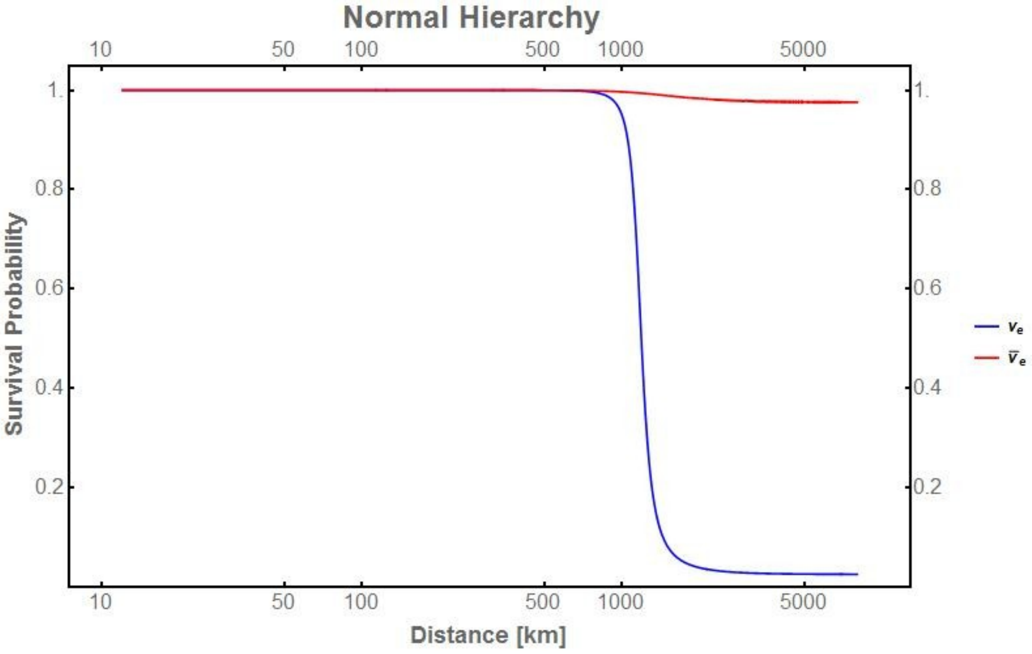
- The electron fraction is taken to be

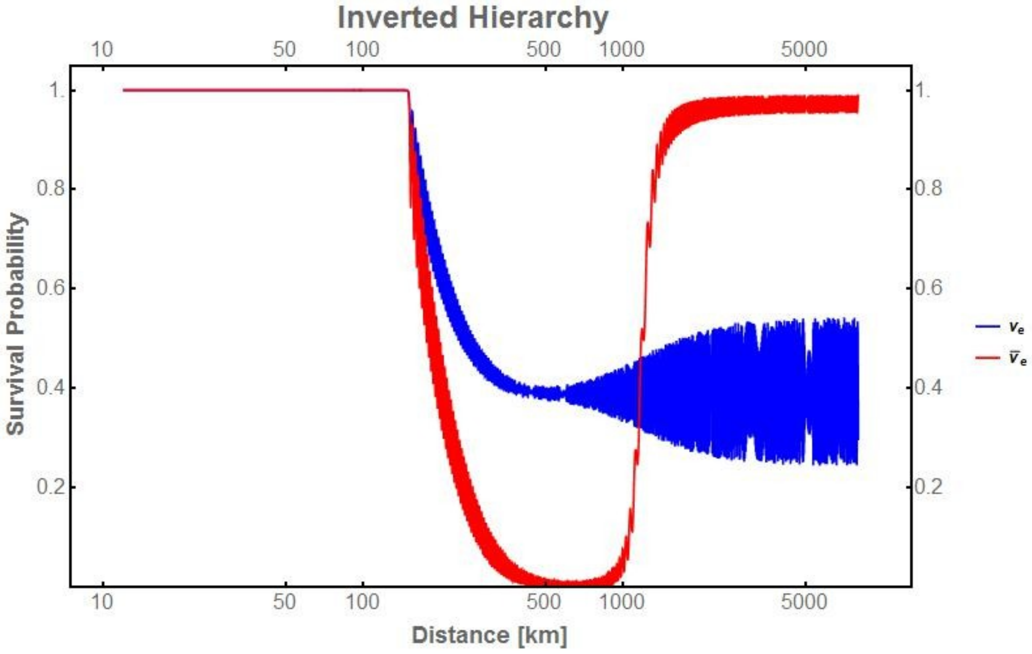
$$Y_e = a + b \tan^{-1}\left(\frac{r - r_0}{r_s}\right)$$

- which was used by Esteban-Pretel et al.
- We use a = 0.308, b = 0.121, r_0 = 10 km, r_s = 42 km which are a fit to Y_e at t = 0.3 s from the Fischer et al 10.8 M simulation.



- With the NSI parameters set to zero:

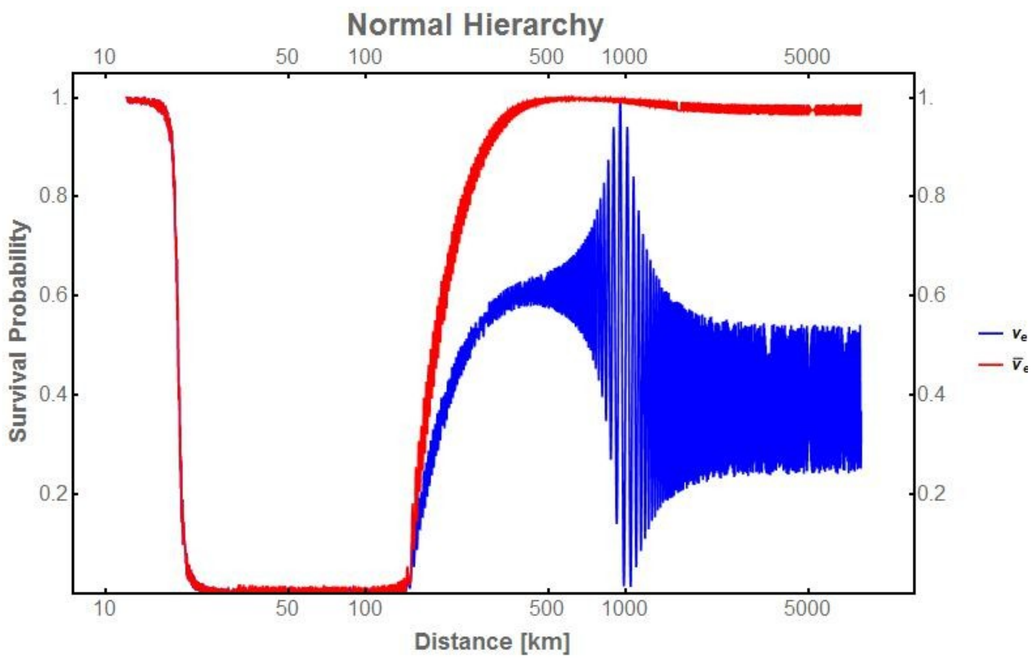


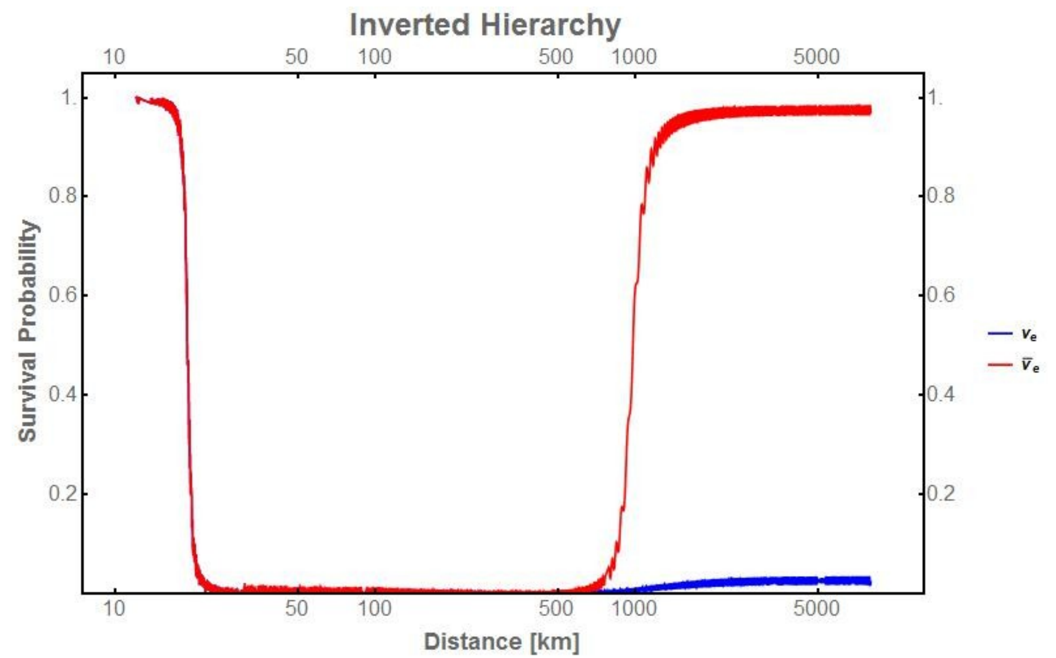


In the Normal Hierarchy:
- MSW H resonance at 1000 km

In the Inverted Hierarchy:
- Nutation/Bipolar beginning at 150 km
- MSW H resonance at 1000 km

- With NSI $\delta\varepsilon^n = -0.66$, $\varepsilon_{ex} = 0.0007$



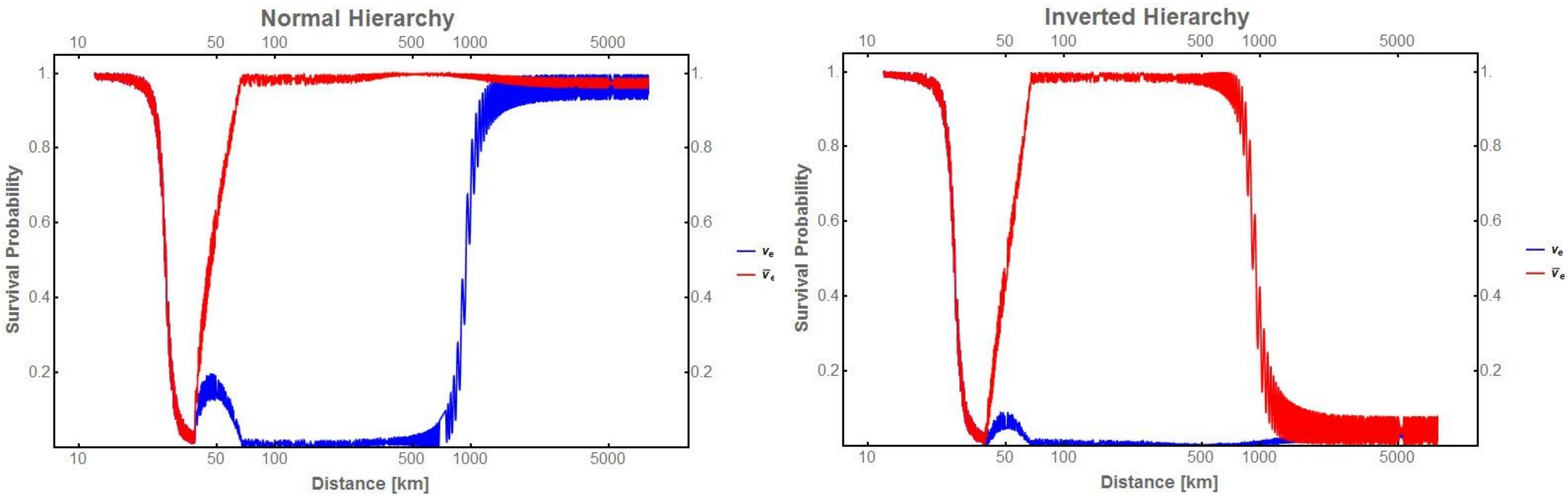


In the Normal Hierarchy:
- I resonance at 20 km
- Bipolar transition at 150 km
- MSW H resonance at 1000 km

In the Inverted Hierarchy:
- I resonance at 20 km
- MSW H resonance at 1000 km

Bipolar has disappeared!

- With NSI $\delta\varepsilon^n = -0.76$, $\varepsilon_{ex} = 0.002$

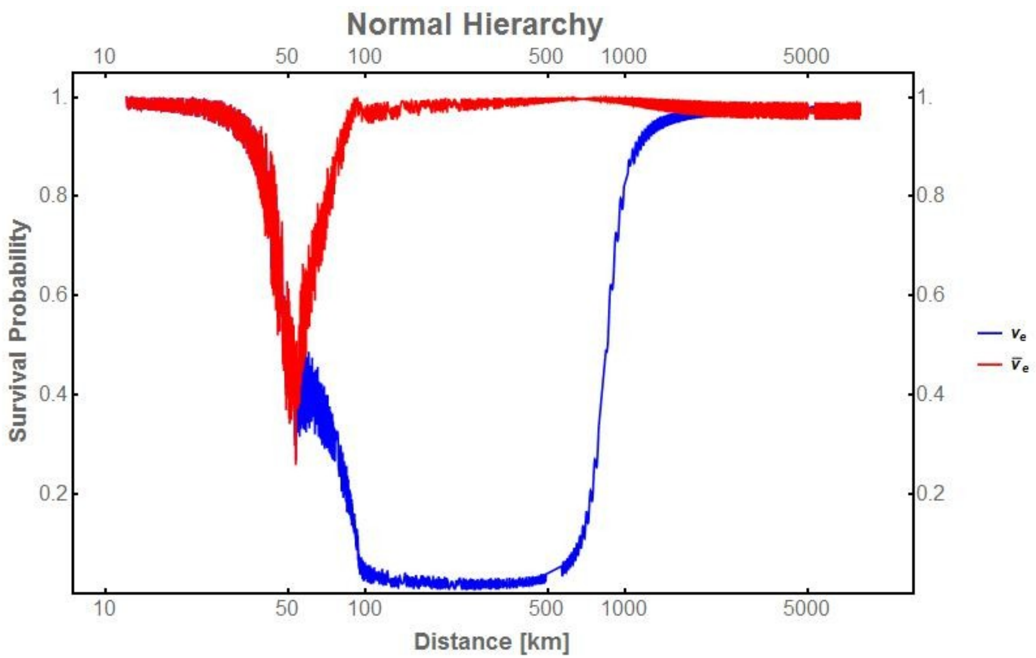


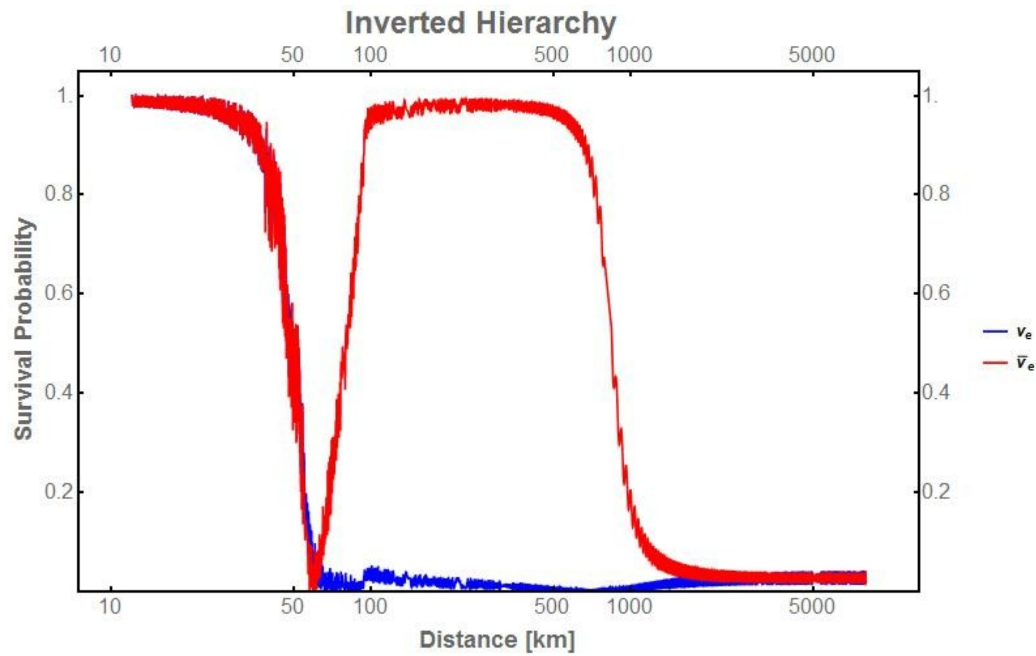
In the Normal Hierarchy:
- I resonance at 30 km
- Standard MNR at 40 km
- MSW H resonance at 1000 km

In the Inverted Hierarchy:
- I resonance at 30 km
- Standard MNR at 40 km
- MSW H resonance at 1000 km

Bipolar has disappeared.

- With NSI $\delta\varepsilon^n = -0.96$, $\varepsilon_{ex} = 0.005$

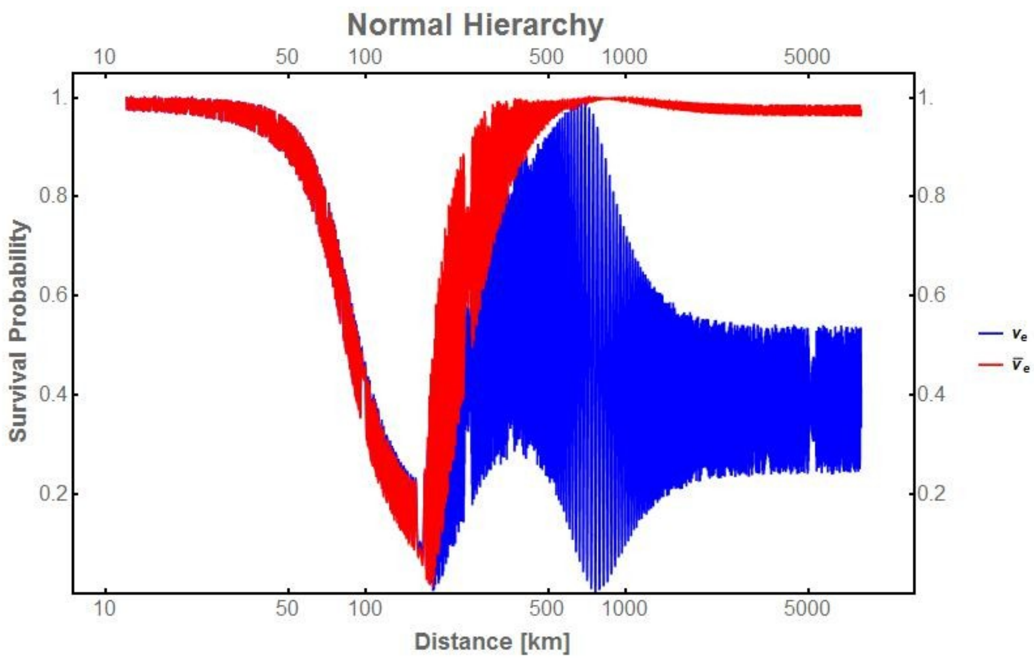


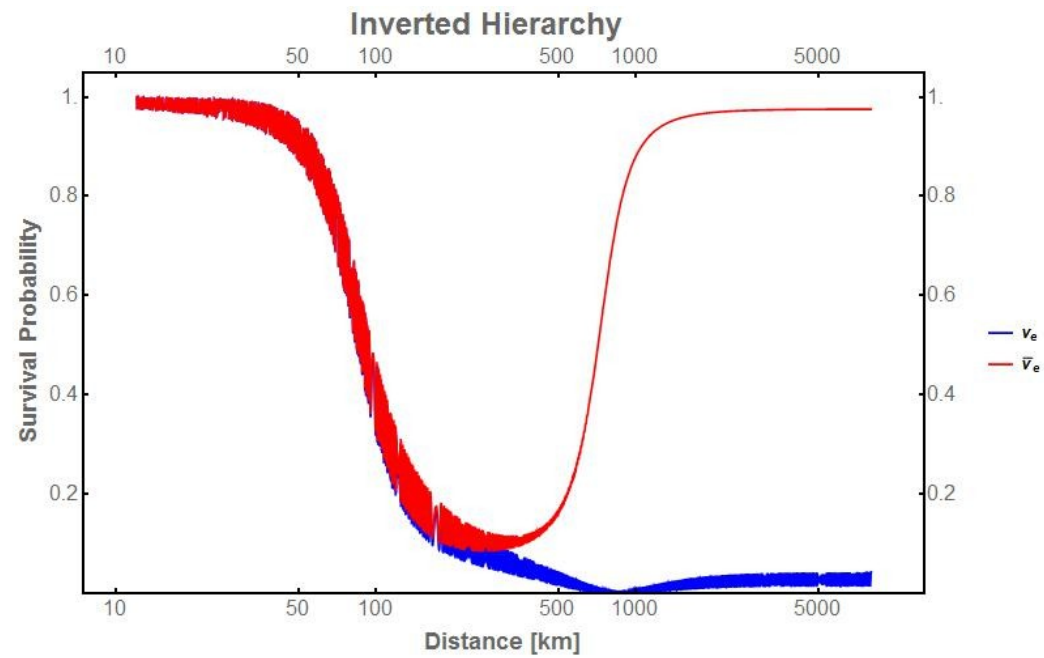


In the Normal Hierarchy:
- partial I resonance at 50 km
- partial Standard MNR at 60 km
- MSW H resonance at 1000 km

In the Inverted Hierarchy:
- I resonance at 50 km
- Standard MNR at 60 km
- H resonance at 1000 km

- With NSI $\delta\varepsilon^n = -1.16$, $\varepsilon_{ex} = 0.008$





In the Normal Hierarchy:
- I resonance at 100 km
- bipolar at 150 km
- MSW H resonance at 1000 km

In the Inverted Hierarchy:
- I resonance at 100 km
- H resonance at 1000 km

Standard MNR disappears

- As a consequence of the NSI new flavor transformation effects can occur:
  - I resonance – complete swap of neutrinos and antineutrino flavors due to matter potential crossing zero.
  - standard MNR – a cancellation between H_M and H_ν due to preceding I resonance.
  - symmetric MNR (small or not seen) – cancellation between H_M and H_ν before the I resonance
- The Matter – Neutrino Resonance has been previously seen in neutrinos from compact object mergers.

Malkus et al. PRD **86** 085015 (2012)

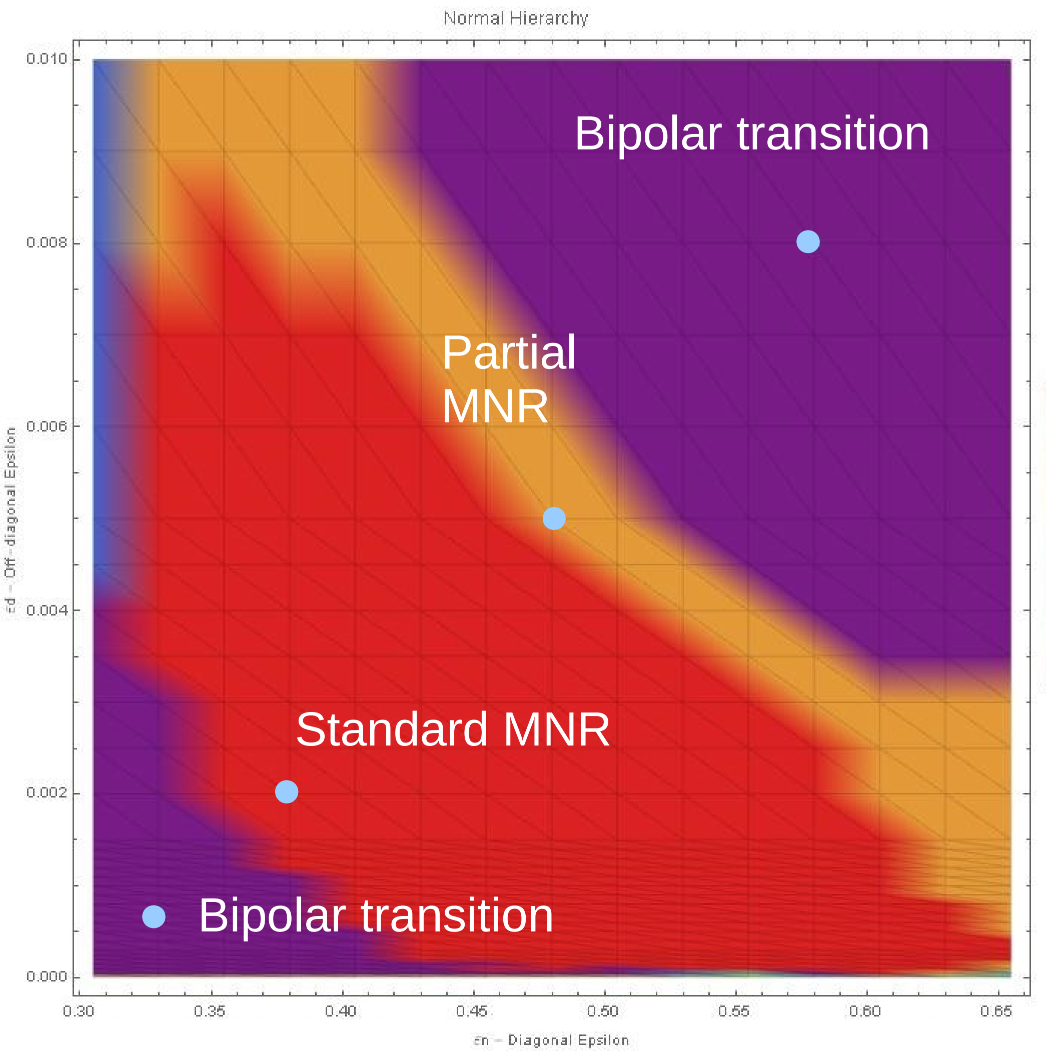
Malkus, Friedland and McLaughlin, arXiv:1403.5797

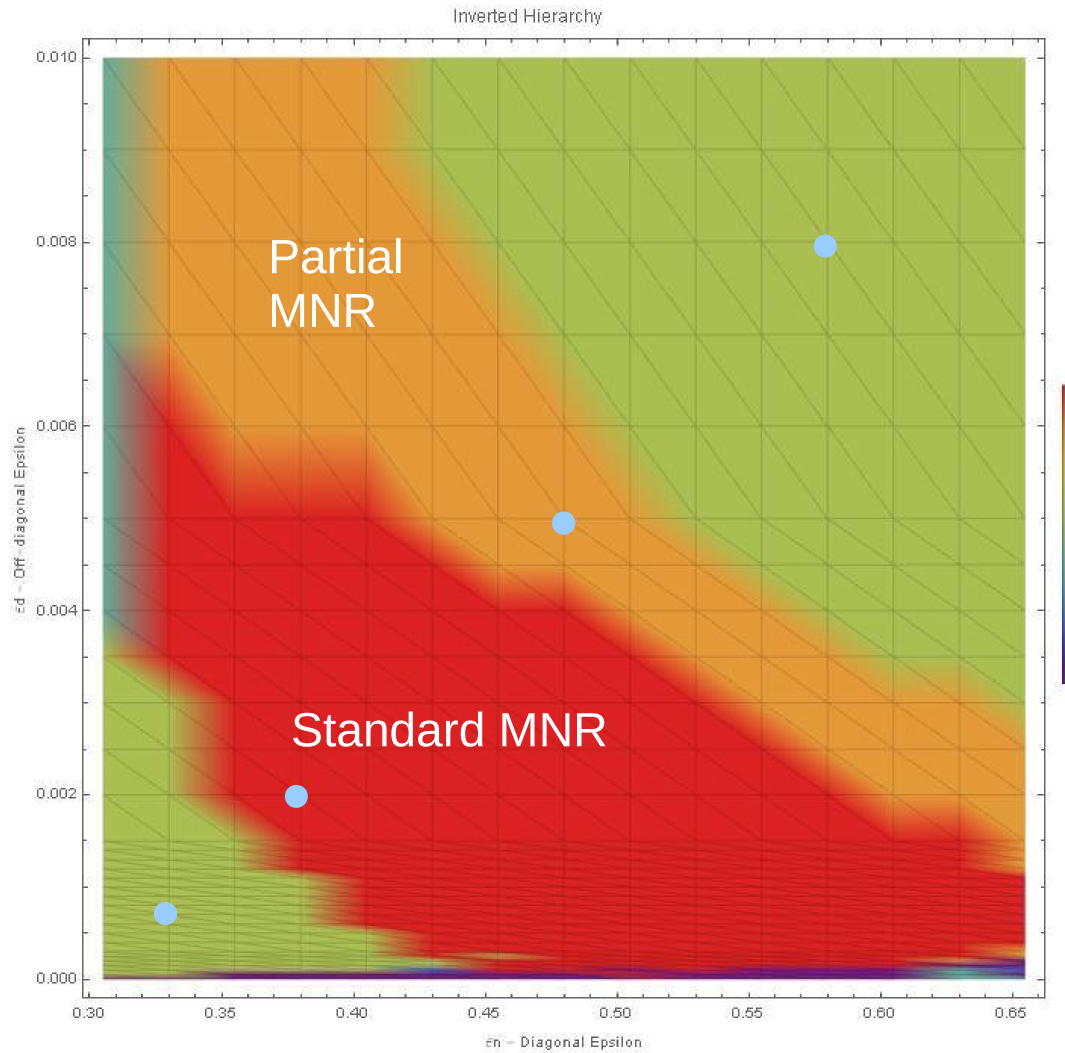
Vaananen and McLaughlin, arXiv:1510.00751

Wu and Duan and Qian, PLB **752** 89 (2016)

- The neutrinos evolve so as to maintain the equality between H_M and H_ν.

- Knowing the origin of the different effects allows us to partition the parameter space.





Summary

- Supernova neutrinos are sensitive to NSI within current bounds.
- In some regions of NSI parameter space the matter potential can become negative
  - this can occur without greatly modifying solar neutrinos
- A negative matter potential leads to an I resonance which can then lead to a Standard MNR.

- Changing the neutrino spectra so deep with the supernova has potential to alter the dynamics and nucleosynthesis.