Neutrino NSI 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 terrestrial experiments looking for further BSM neutrino physics are underway / under construction / being planned / proposed, including at ORNL.

- Determining the properties of neutrinos in terrestrial experiments is hard.

  - neutrinos interact so weakly, few will be detected and interactions must be found among significant backgrounds

- Neutrinos cannot hide in environments where Nature pushes the envelope of density, temperature, etc.

  - these environments don't exist on Earth.

- A complimentary approach to study neutrino properties is to go to astrophysical environments.

- Given their importance to the explosions of massive stars, supernovae are the ultimate neutrino experiment.

Non-standard interactions

- Consider new, Non-Standard Interactions (NSI), of neutrinos with matter in supernovae.

    - see 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)

    - Stapleford et al, PRD **94** 093007 (2016)

    ...

- NSI will alter the location of the neutrinosphere but, more interestingly, the flavor evolution beyond it.

- Neutrino flavor oscillations are a quantum mechanical problem and can be described by the von Neumann equation.

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

$$H=H_V+H_{SI}+H_{MSW}+H_{NSI}$$

- The first three, SM, terms are:
    - The vacuum (kinetic energy) term,
    - The neutrino self-interaction term,
    - The MSW term.

- The MSW term is

$$H_{MSW}=\sqrt{2}\,G_F\,n_e$$

- where n_e is the net electron density.

- 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.

  - 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 (equal protons and neutrons)

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

- 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

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

- where $\delta\epsilon = \epsilon_{ee} - \epsilon_{xx}$.

- Using this constraint we rewrite the NSI potential as

$$H_{NSI} = \sqrt{2}\, G_F\, n_N \left(\begin{matrix} \left(\dfrac{Y_\odot - Y_e}{Y_\odot} \right)\delta\epsilon^n & (3 + Y_e)\epsilon_0 \\[2ex] (3 + Y_e)\epsilon_0^* & 0 \end{matrix} \right)$$

- where $\delta\epsilon^n = 2\,\delta\epsilon^d + \delta\epsilon^u$ and $\epsilon^u_{ex} = \epsilon^d_{ex} = \epsilon^e_{ex} = \epsilon_0$

The effect of NSI

- The total matter $H_M = H_{MSW} + H_{NSI}$ potential is

$$H_M = \sqrt{2}\, G_F\, n_N \left[\begin{pmatrix} Y_e & 0 \\ 0 & 0 \end{pmatrix} + \left(\begin{pmatrix} \dfrac{Y_\odot - Y_e}{Y_\odot} \end{pmatrix} \delta\, \epsilon^n \quad (3 + Y_e)\epsilon_0 \\ (3 + Y_e)\epsilon_0^* \qquad 0 \end{pmatrix} \right) \right]$$

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

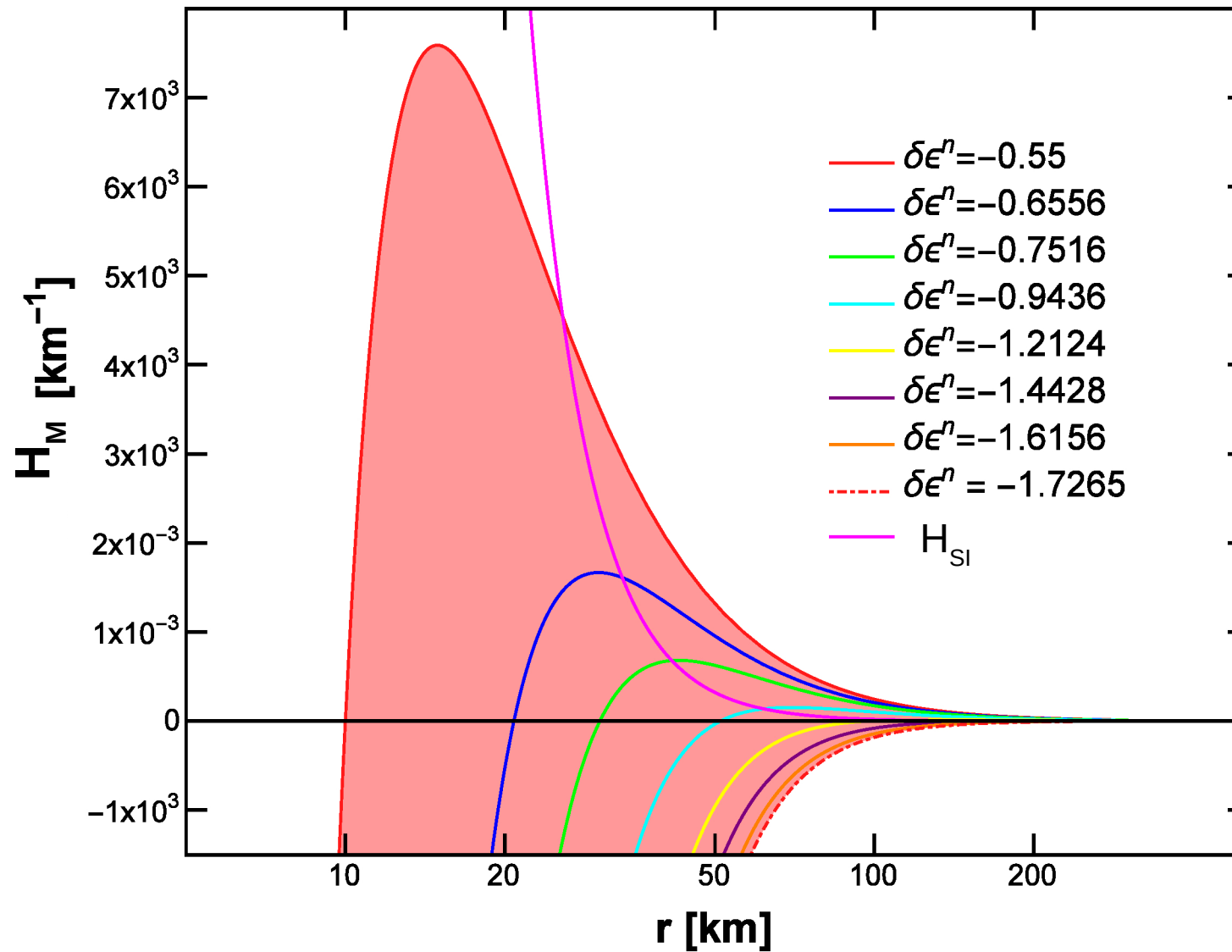$$Y_e + \delta\, \epsilon^n \left(\frac{Y_\odot - Y_e}{Y_\odot} \right) < 0$$

- 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 $\delta\epsilon^n < 0$.

- 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 $\delta\varepsilon^n = -0.5$ - well within limits.

- Neutrinos are sensitive to the off-diagonal element, ε_0, when $|\varepsilon_0| \sim 10^{-5}$ or greater.

As $\delta\epsilon^n$ becomes more negative, the zero-crossing moves outwards and the potential maximum becomes smaller.

I Resonances

- Close to the zero-crossing of the potential, it is possible to have a new MSW resonance called an inner (I) resonance.

- I resonances occur in either neutrinos or antineutrinos or both.

- Since the zero-crossing can be close to the proto-neutron star, an I resonance can affect later flavor transformation.

- To explore the consequences we solve for the neutrino flavor evolution in a very simple model.

  - single energy, 20 MeV, two flavor: $|\delta m^2| = 2.4 \times 10^{-3}$ 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

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

  - 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. PRD **81** 063003 (2010)
- 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 $M_\odot$ simulation.
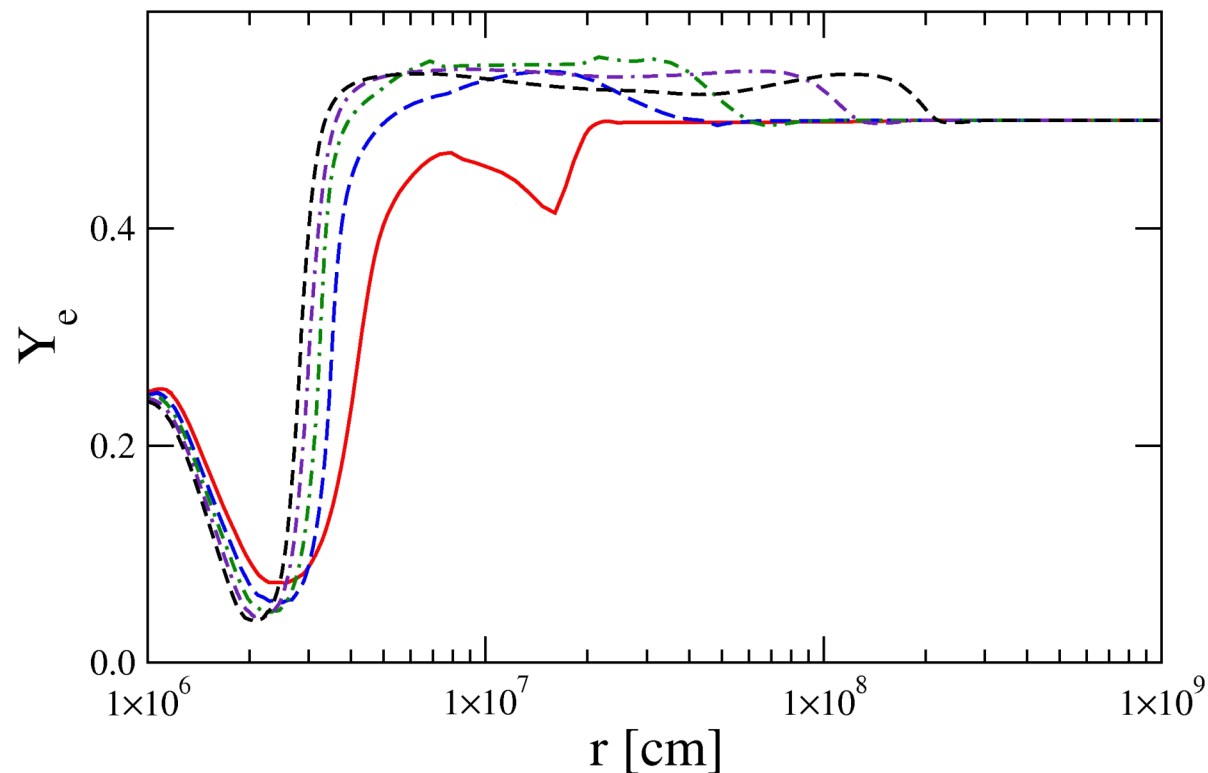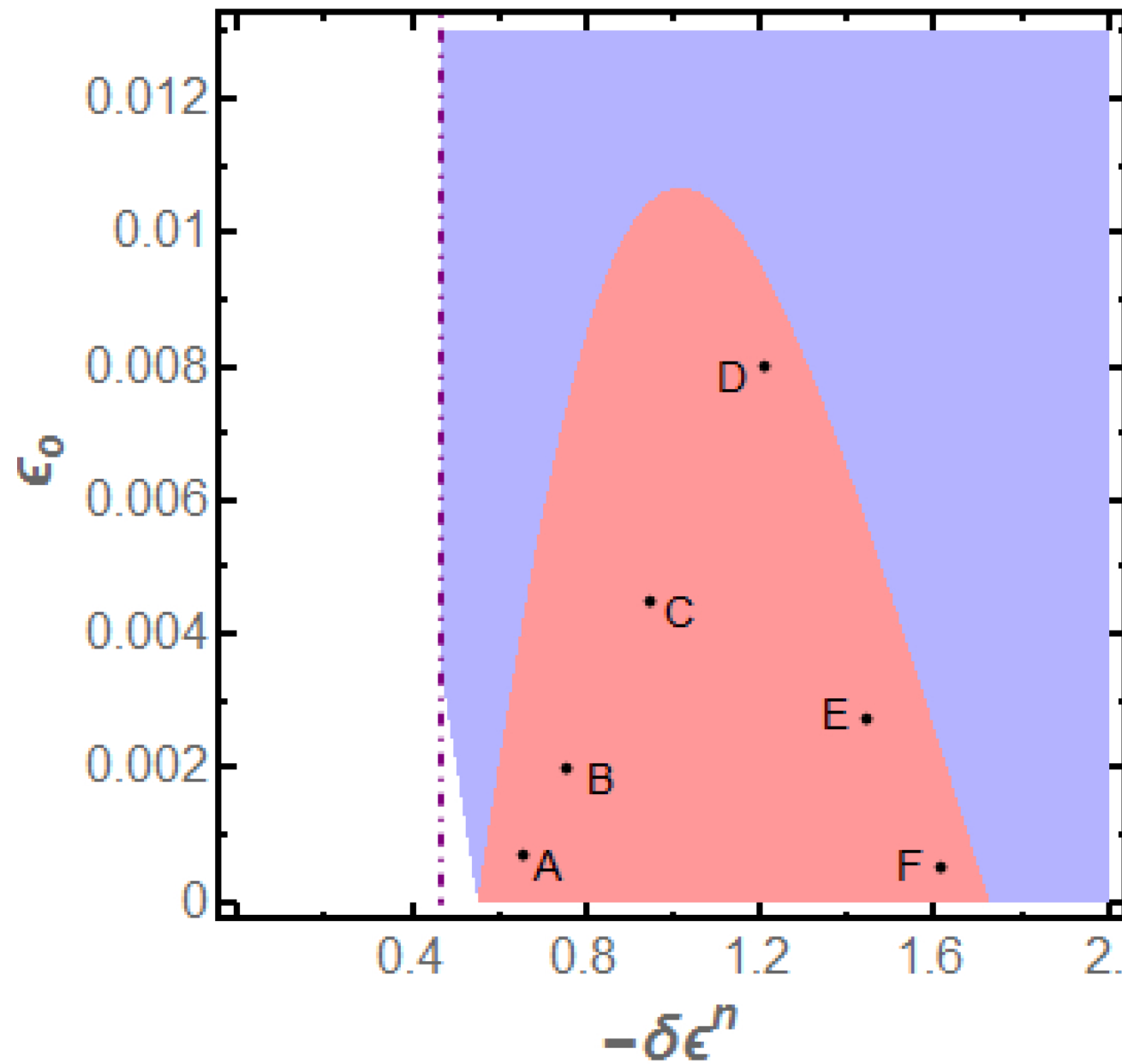
- **With the NSI parameters set to zero:**

Blue = neutrinos
Red = antineutrinos
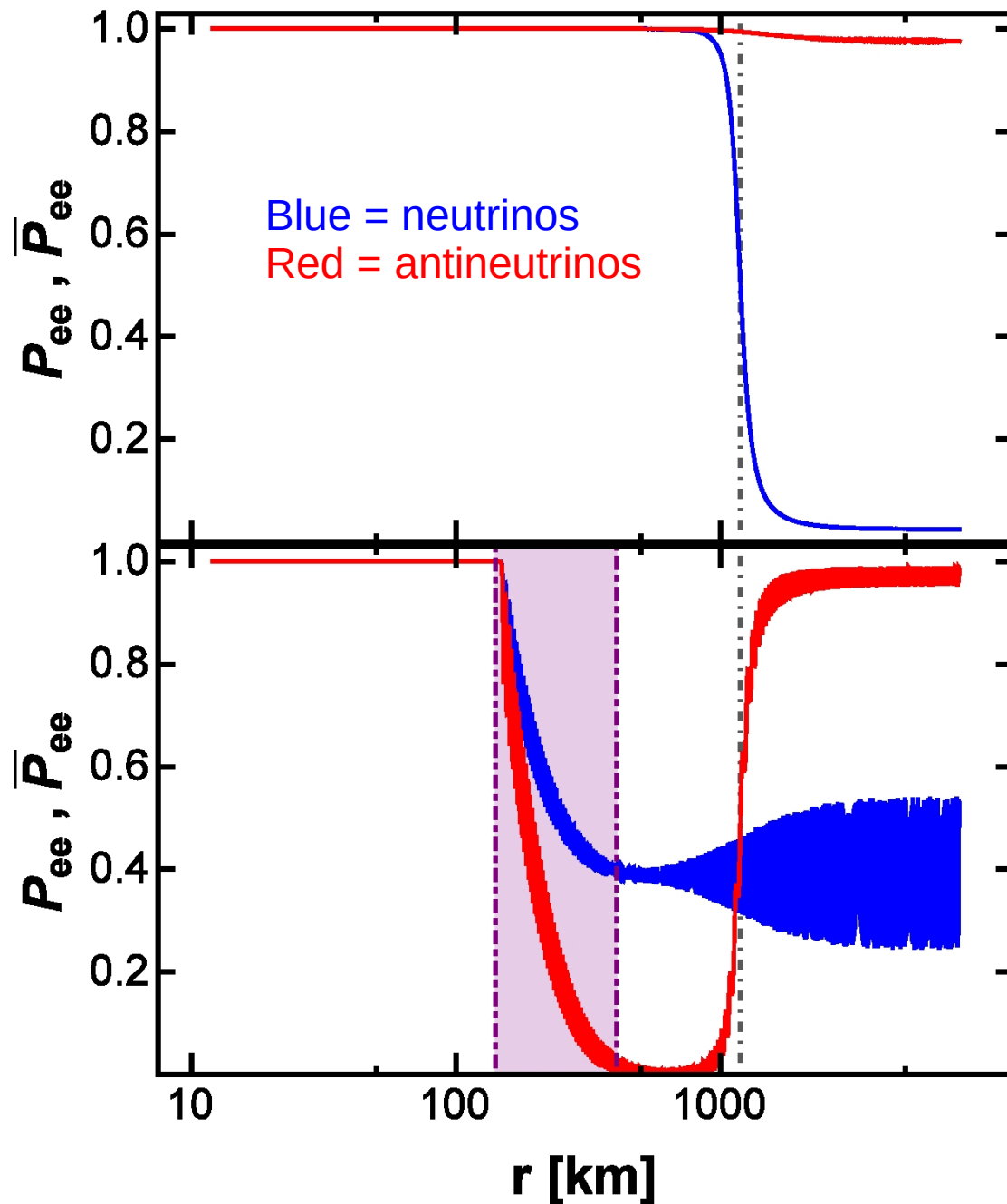
In the Normal Hierarchy:
- MSW H resonance at 1000 km

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

- Lets sample a few points in the parameter space.

Point A: $\delta\varepsilon^n = -0.6556$, $\varepsilon_0 = 0.0007$
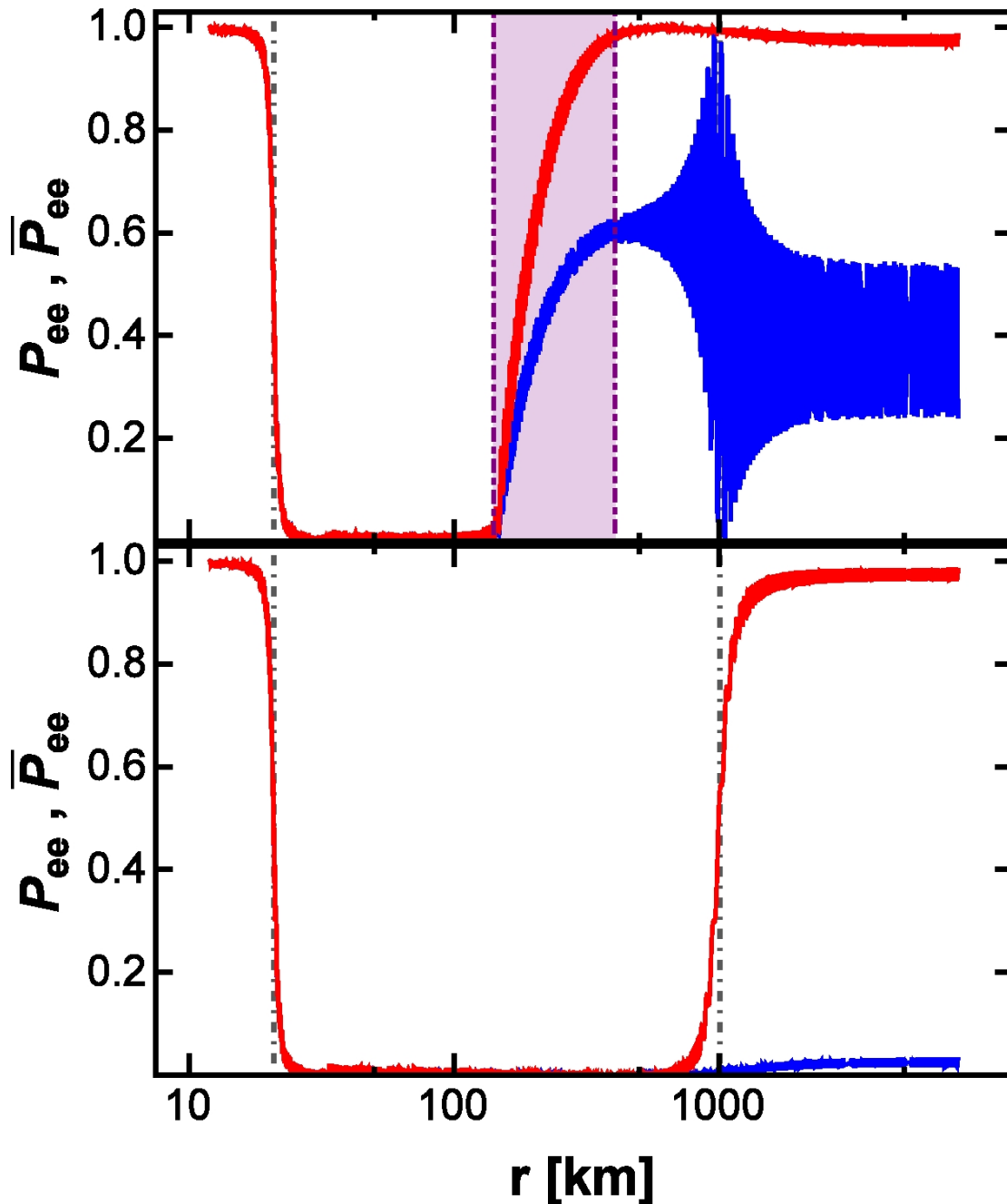
In the Normal Hierarchy:
- I resonance at 20 km
- Bipolar transition at 150 km
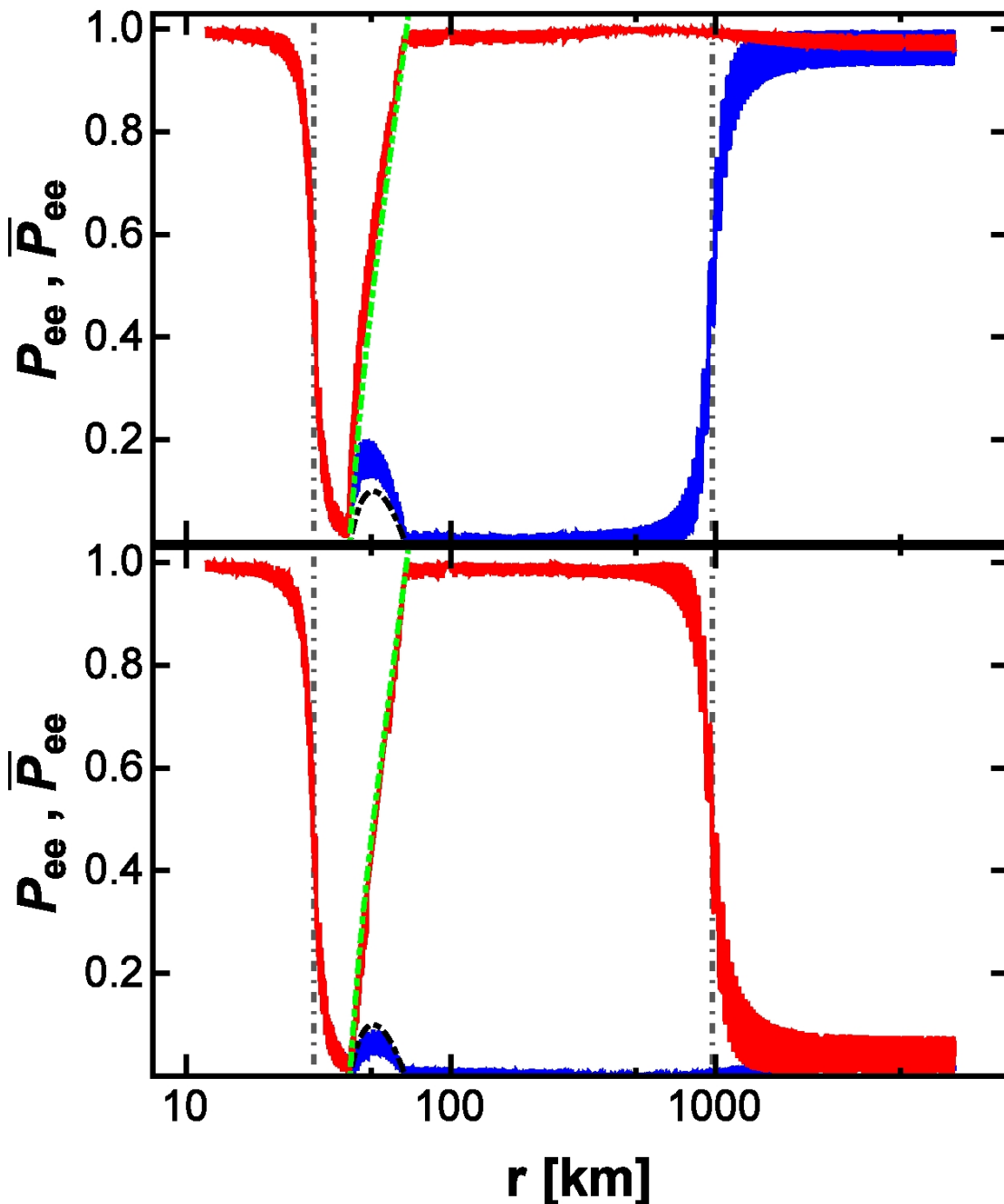- MSW H resonance at 1000 km

Compared to no NSI, a bipolar has appeared.

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

Compared to no NSI, bipolar has disappeared.

Point B: $\delta\varepsilon^n = -0.7516$, $\varepsilon_0 = 0.002$

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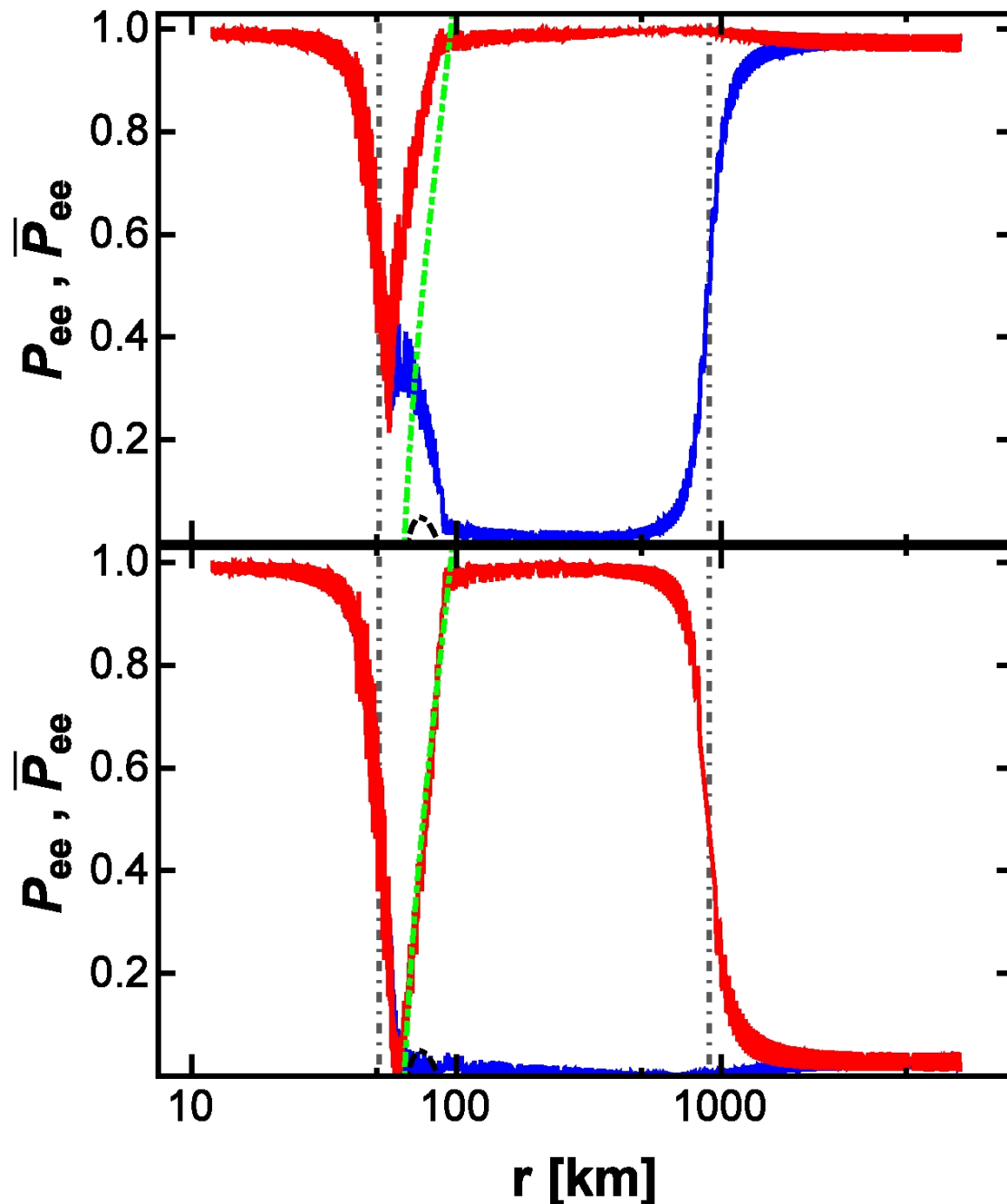- Standard MNR at 40 km
- MSW H resonance at 1000 km

Compared to A, bipolar has disappeared, standard MNR has appeared.

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

Compared to A, standard MNR has appeared.

Point C: $\delta\varepsilon^n = -0.9436$, $\varepsilon_0 = 0.0045$
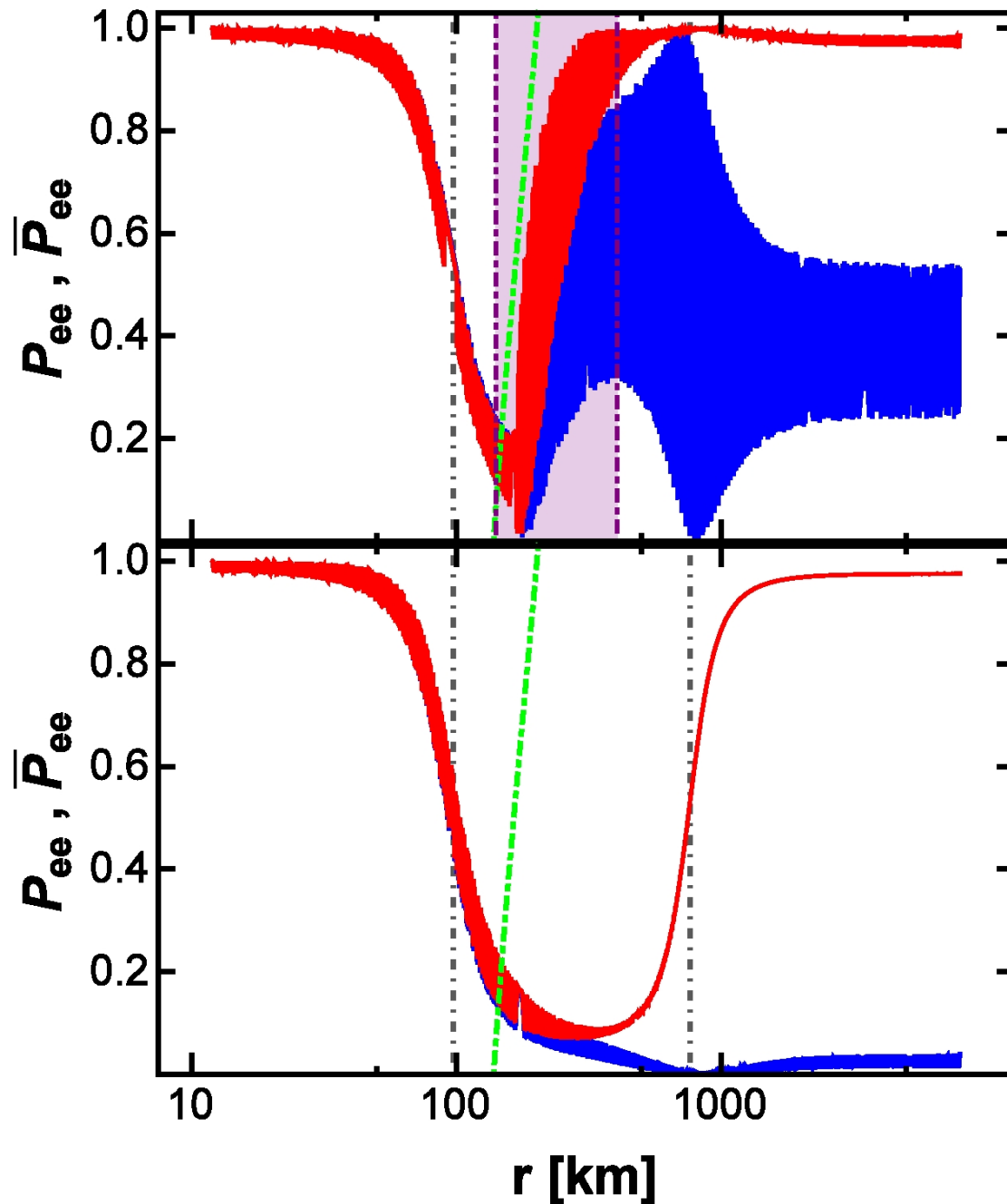

In the Normal Hierarchy:
- partial I resonance at 50 km
- partial Standard MNR at 60 km
- MSW H resonance at 1000 km

Compared to B, the resonances are now partial.

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

Point D: $\delta\varepsilon^n = -1.2124$, $\varepsilon_0 = 0.008$

In the Normal Hierarchy:
- I resonance at 100 km
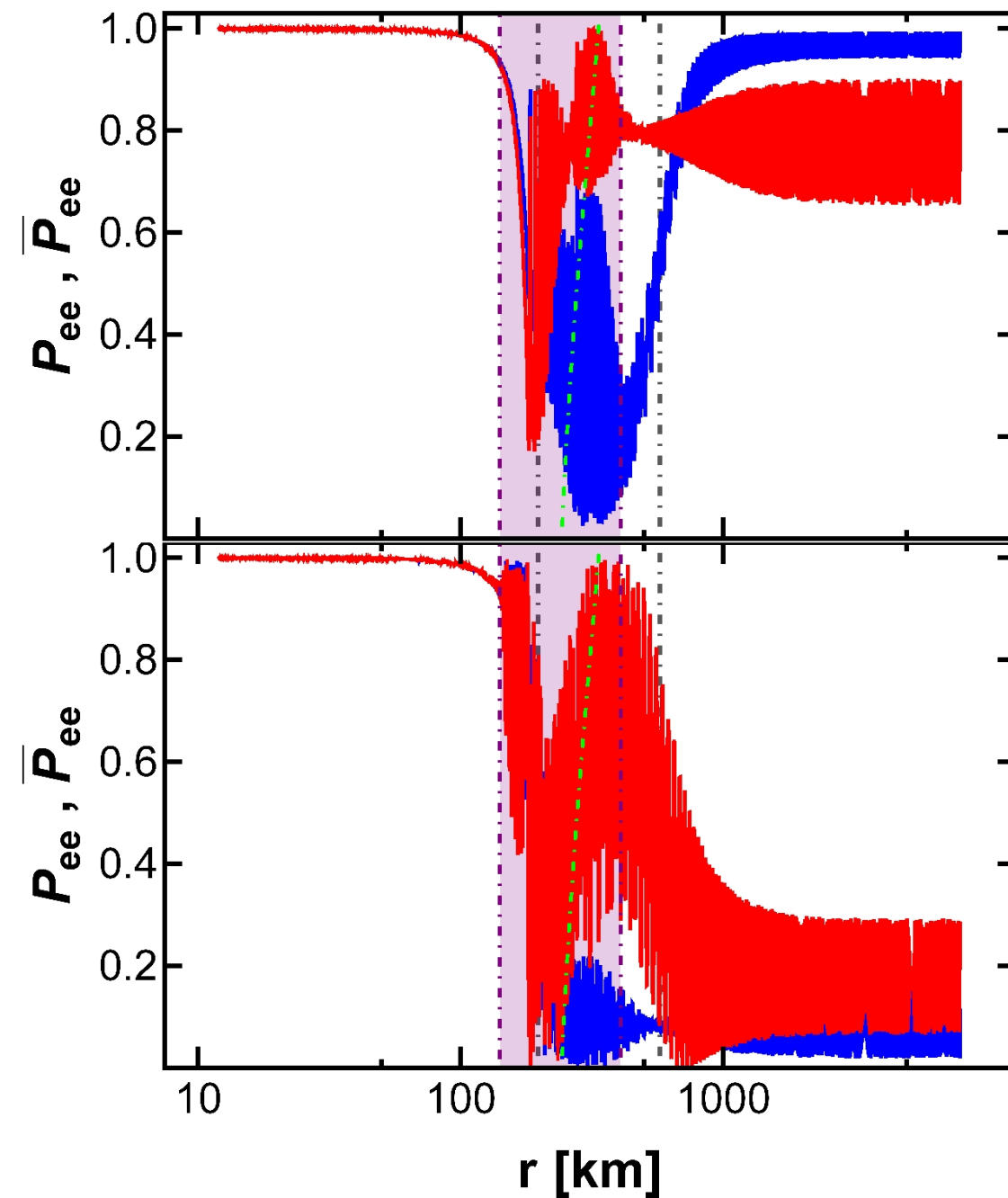- H resonance at 950 km
- bipolar at 150 km

Compared to C, standard MNR disappears, bipolar returns, looks like case A.

In the Inverted Hierarchy:
- I resonance at 100 km
- H resonance at 950 km

Compared to C, Standard MNR disappears, also looks just like case A.

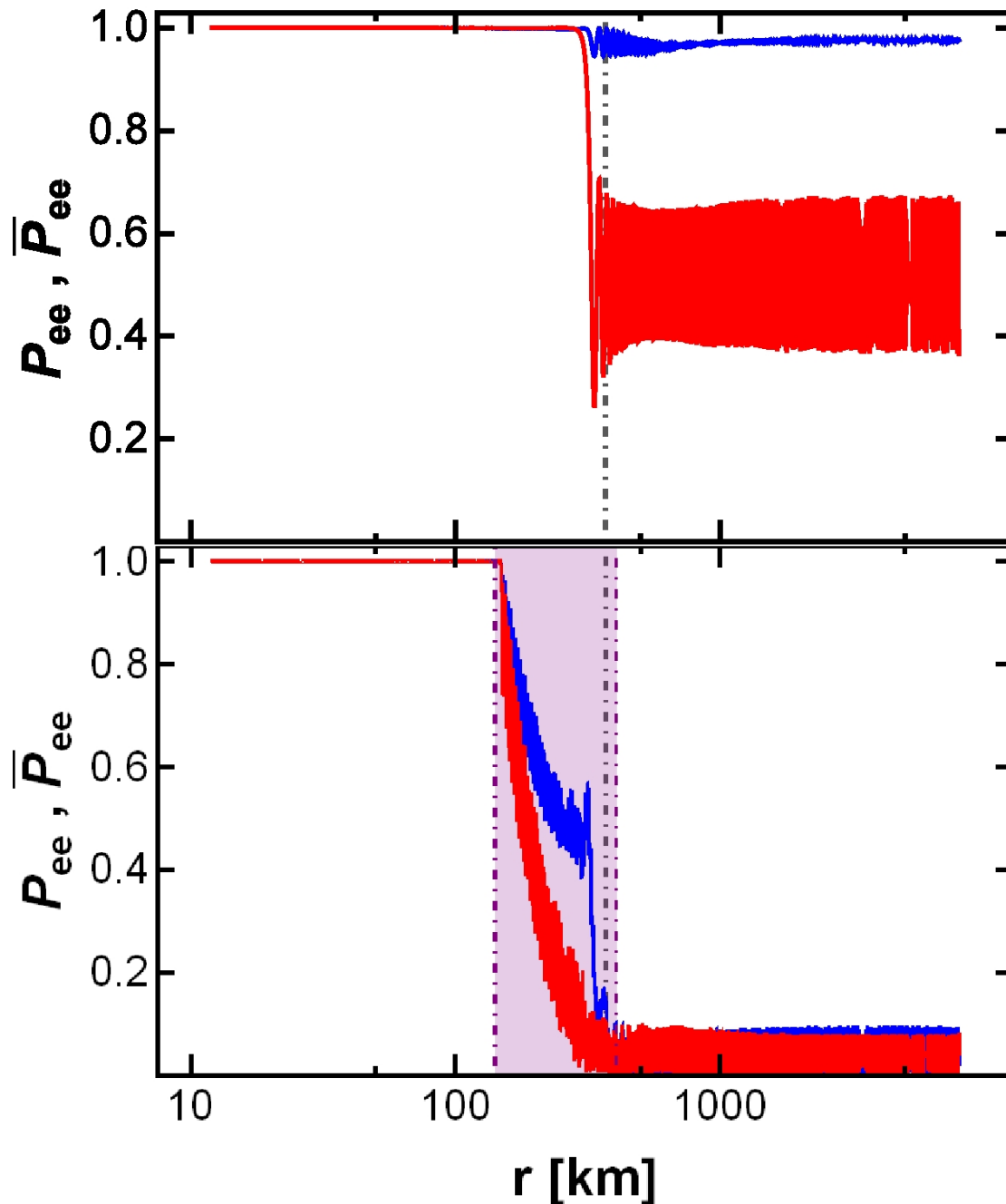Point E: $\delta\varepsilon^n = -1.4428$, $\varepsilon_0 = 0.00275$

In the Normal Hierarchy:
- H resonance at 650 km
- ?

In the Inverted Hierarchy:
- H resonance at 650 km
- ?

Point F: $\delta\varepsilon^n = -1.6156$, $\varepsilon_0 = 0.0005$

In the Normal Hierarchy:
- I resonance in antineutrinos only at 350 km

Compared to all previous figures, H resonance disappears

In the Inverted Hierarchy:
- bipolar at 150 km
- I resonance, for neutrinos only, at 350 km

Compared to all previous figures, H resonance 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 canceling vacuum Hamitlonian

  - standard MNR – a cancellation between H_M and H_{SI} that occurs if there is a preceding I resonance.

  - symmetric MNR (small or not seen) – cancellation between H_M and H_{SI} that can occur before the I resonance – typically not adiabatic

- The Matter – Neutrino Resonance has been previously seen in neutrinos from compact object mergers but not supernovae.
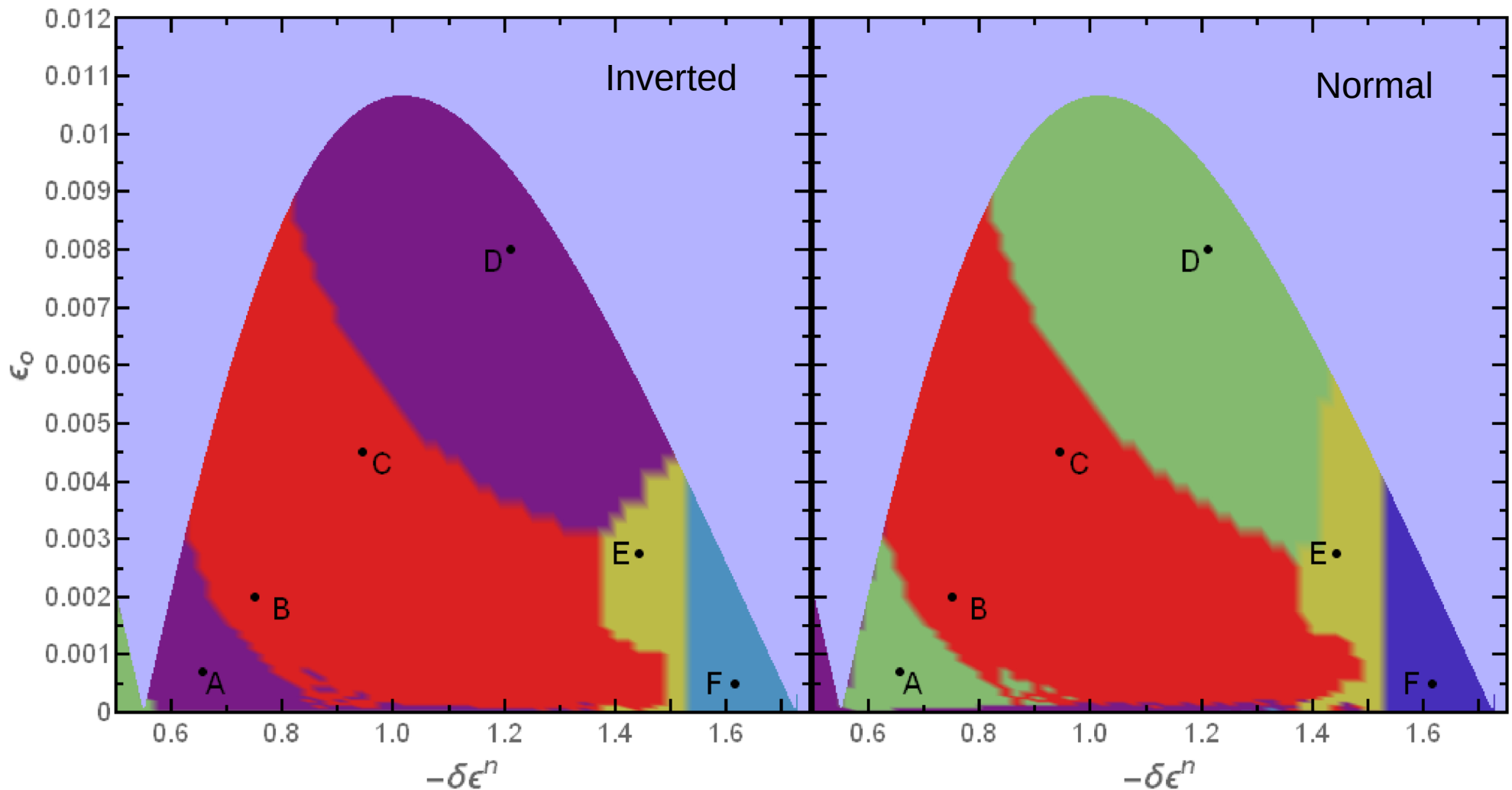
Malkus et al. PRD **86** 085015 (2012)

Malkus, Friedland and McLaughlin, arXiv:1403.5797

Vaananen and McLaughlin, arXiv:1510.00751

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

- We can partition the parameter space into what effects occur.

- There is not one effect of NSI for supernova neutrinos, the parameter space is fragmented.

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 interfere with usual flavor transformation effects,

  - can lead to a Standard MNR which is not possible in SM only

  - it can even remove the H resonance

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