NOW 2010

"Neutrino Oscillation Workshop"

Conca Specchiulla, 4-11 September 2010

SELF-INDUCED SPECTRAL SPLITS IN SUPERNOVA NEUTRINOS: THREE-FLAVOR EFFECTS

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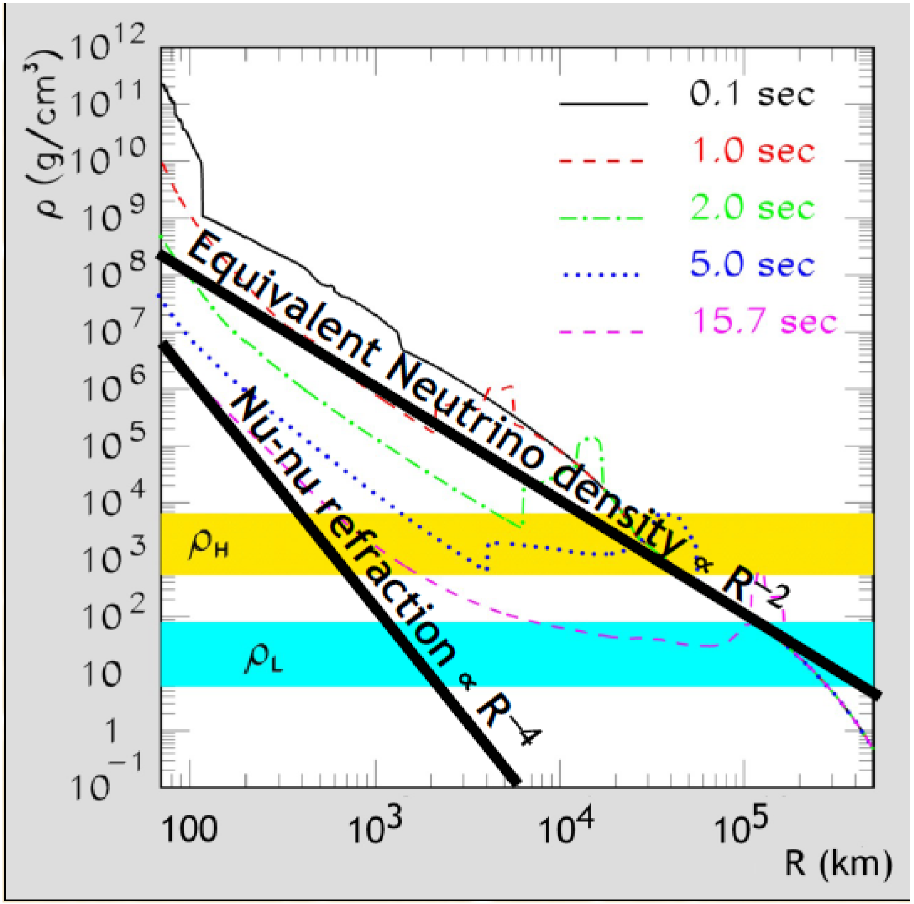
[Based on Dasgupta, A.M, Tamborra & Tomas, PRD81, 093008 (2010), arXiv:1002:2943]

NEUTRINO-NEUTRINO INTERACTIONS

In the region just above the neutrino-sphere the neutrino density exceeds the ordinary electron background. Neutrinos themeselves form a background medium



$\nu-\nu$ NC interactions important!

- Matter bkg potential

$$V = \sqrt{2} G_F N_e \quad \sim R^{-3}$$

- $\nu-\nu$ potential — Multi-angle effects

$$\mu = \sqrt{2} G_F n_\nu < 1 - \cos\theta_{pq} > \sim R^{-2} \times R^{-2} = R^{-4}$$

Lesson: self-interactions (μ) can induce large, non-MSW flavor change at small radii, despite large matter density V

TALK BY G.RAFFELT

FORMALISM AND EVOLUTION EQUATIONS

The evolution equation of the density matrix for each mode p

$$i\partial_t \rho_{\mathrm{p}} = [H_{\mathrm{p}}, \rho_{\mathrm{p}}]$$

Diagonal elements related to flavor content

$$\rho_{\alpha\alpha} = \frac{F_{\nu_\alpha}(E,r)}{F(E,r)}$$

$$\rho = \begin{pmatrix} \rho_{ee} & \rho_{e\mu} & \rho_{e\tau} \\ \rho^*_{e\mu} & \rho_{\mu\mu} & \rho_{\mu\tau} \\ \rho_{e\tau} & \rho^*_{\mu\tau} & \rho_{\tau\tau} \end{pmatrix}$$

Off-diagonal elements responsible for flavor conversions

- "Single-angle" Hamiltonian

$$H_p = \Omega_p + V + \mu \int \frac{d^3q}{(2\pi)^3} (\rho_p - \bar{\rho}_p)$$

Matter term (V)

ν–ν interaction term

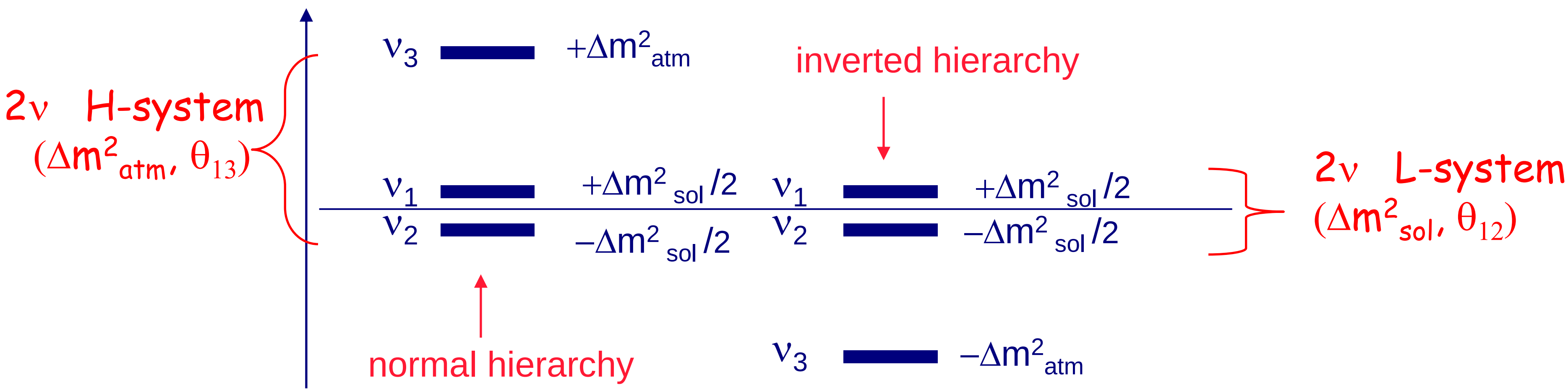
$$\Omega_p = \left(-\frac{\Delta m^2_{sol}}{2}, \frac{\Delta m^2_{sol}}{2}, \Delta m^2_{atm} \right) / 2|p|$$

Vacuum oscillations

VACUUM OSCILLATIONS: 3ν FRAMEWORK

- **Mixing parameters:** $U = U(\theta_{12}, \theta_{13}, \theta_{23})$ as for CKM matrix

- **Mass spectrum**



$$\begin{cases} \Delta m^2_{atm} = 2.0 \times 10^{-3}\,\mathrm{eV}^2 \\ \Delta m^2_{sol} = 8. \times 10^{-5}\,\mathrm{eV}^2 \\ \theta_{12} = 0.6 \\ \theta_{23} = \pi / 4 \\ \theta_{13} \leq 0.1 \end{cases}$$

PENDULUM IN FLAVOR SPACE

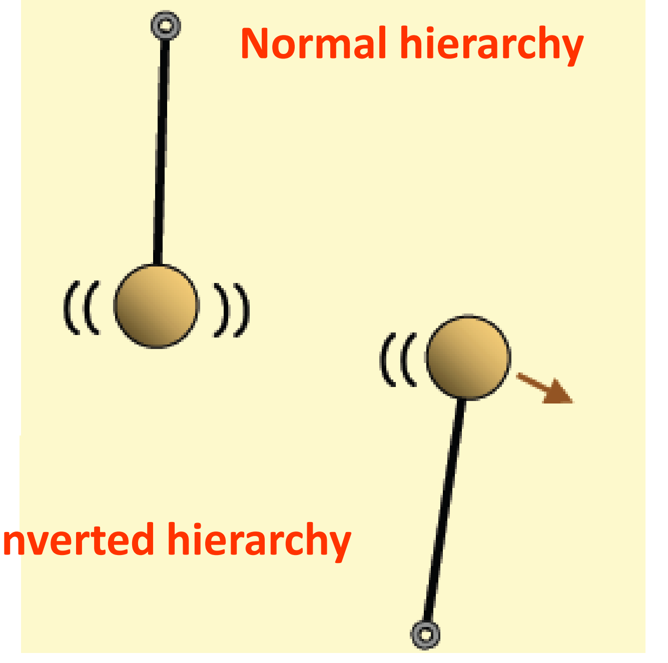
[*Hannestad, Raffelt, Sigl, Wong, astro-ph/0608695, Duan, Carlson, Fuller, Qian, astro-ph/0703776*]

Neutrino mass hierarchy (and θ_{13}) set initial condition and fate

With only initial ν_e and $\overline{\nu}_e$:

- **Normal hierarchy**

Pendulum starts in ~ downard (stable) positions and stays nearby. No significant flavor change.



- **Inverted hierarchy**

Pendulum starts in ~ upward (unstable) positions and eventually falls down. Significant flavor changes.

θ_{13} sets initial misalignment with vertical. Specific value not much relevant.

Which mass hierarchy?

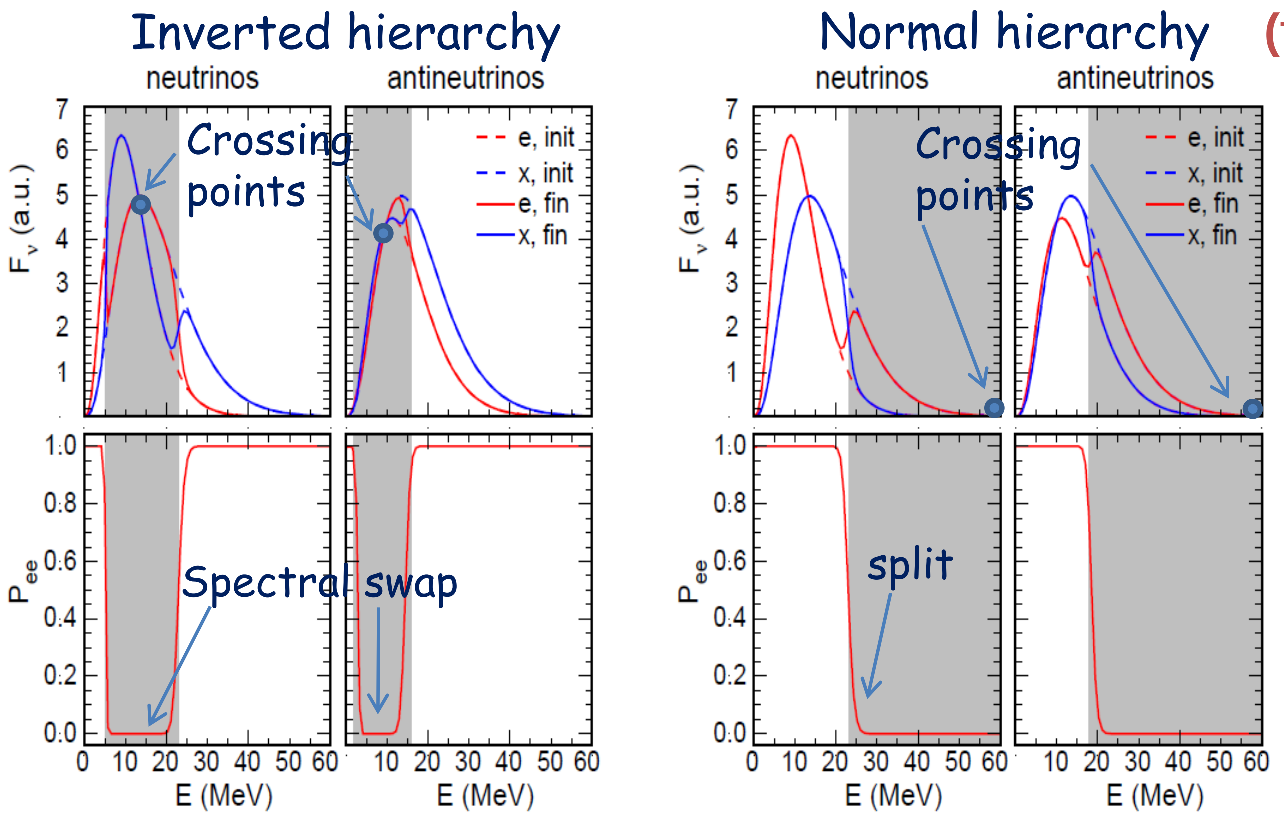
With only initial ν_μ and $\overline{\nu}_\mu$ large flavor conversions in NH. The unstable case is when the initial ensemble consists of that flavor which is dominated by the heavier mass eigenstate.

SPECTRAL SPLITS IN 2 FLAVORS (H-SYSTEM)

[Dasgupta, Dighe, Raffelt, Smirnov, 0904.3542]

$F_{\nu e} : F_{\bar{\nu}e} : F_{\nu x} = 0.85 : 0.75 : 1.00$

(typical in cooling phase)

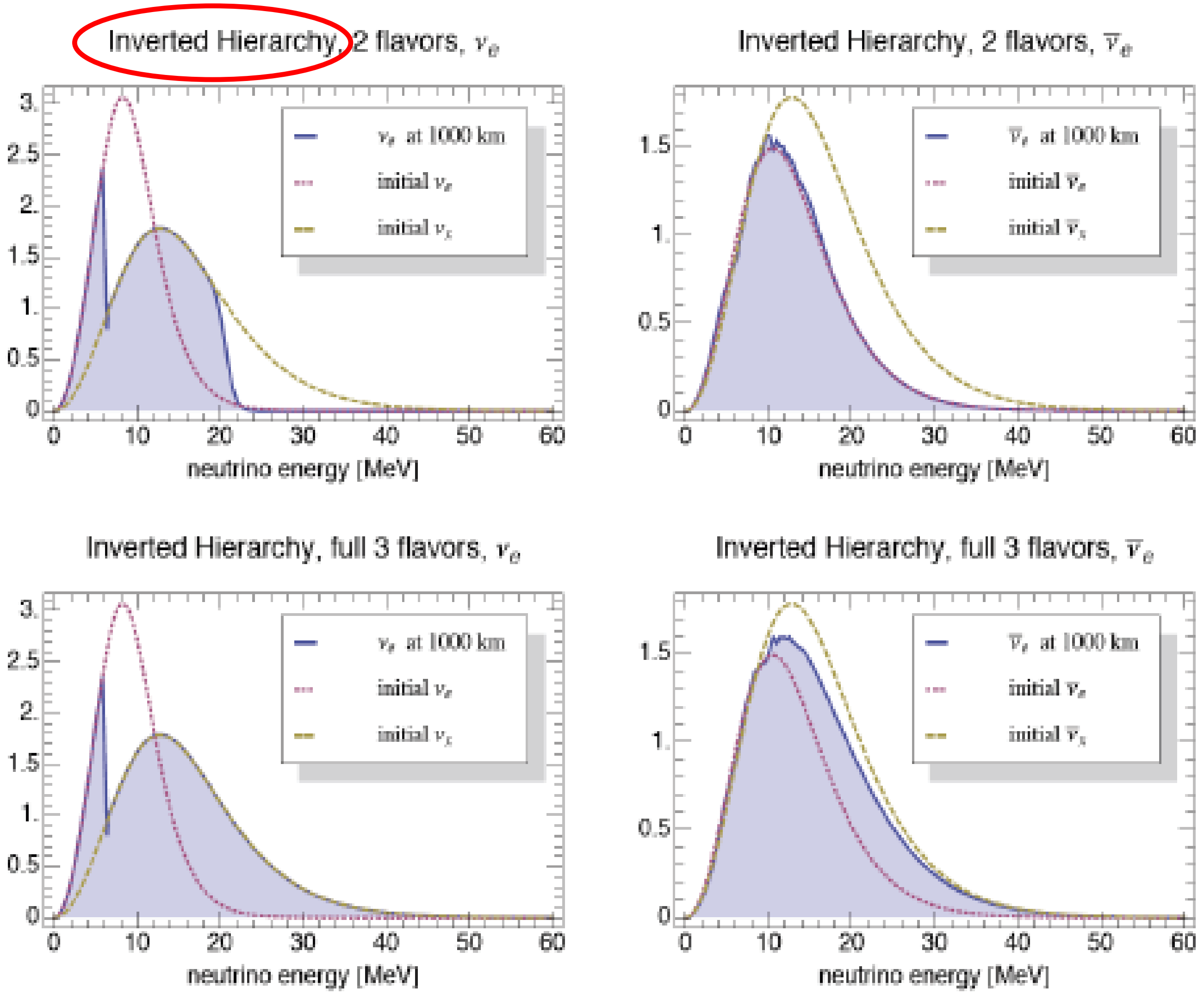


Spectral splits can develop around the crossing points of the original neutrino spectra.

A given crossing point is unstable if

- $d(F_e-F_x)/dE < 0$ for inverted mass hierarchy
- $d(F_e-F_x)/dE > 0$ for normal mass hierarchy

THREE-FLAVOR EFFECTS



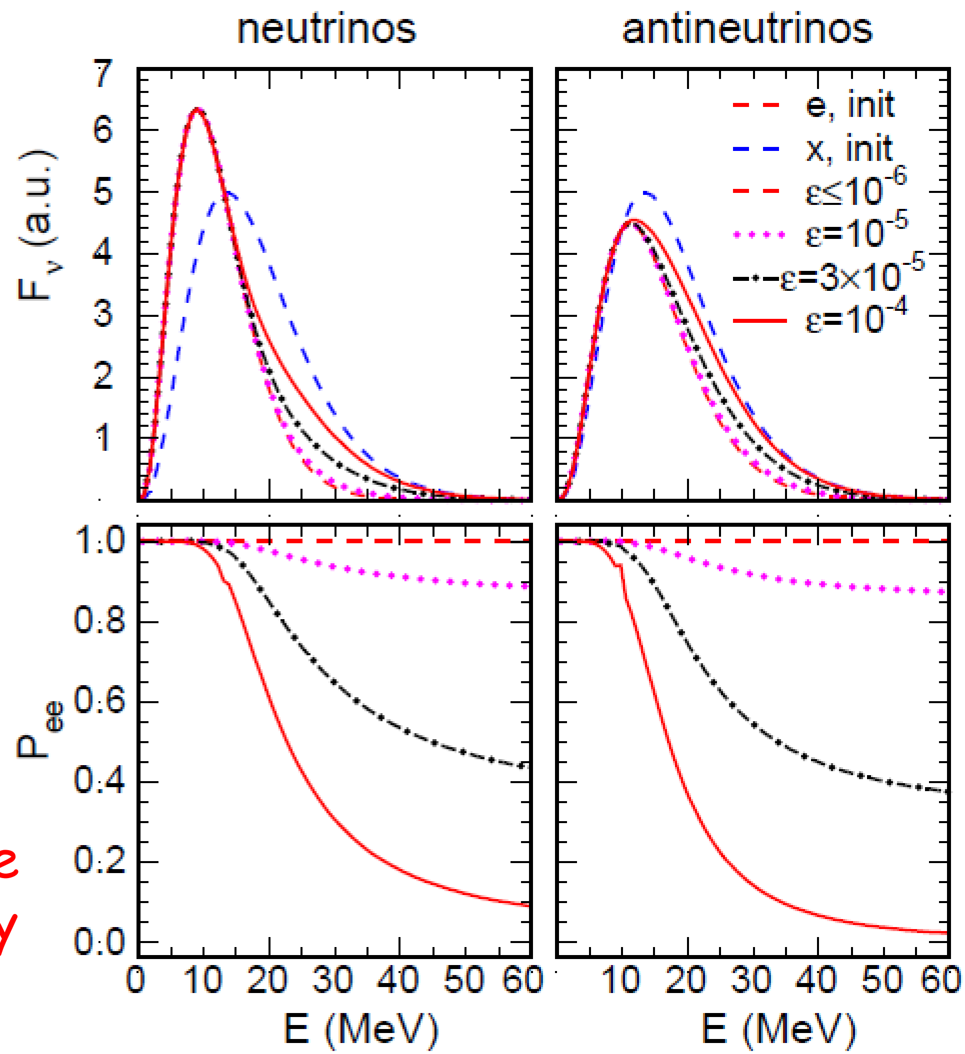
Alexander Friedland, arXiv:1001:0996

SPECTRAL SPLITS IN 2 FLAVORS (L-SYSTEM)

We would expect a behavior similar to that of the H-system in NH. However, no flavor conversion occurs.

Two reasons:

- insufficient growth of instability $[\tau \approx (\omega\mu)^{-1/2}]$
- lack of adiabaticity: $\omega < d \ln \mu / dr$



Some initial disturbance helps to kick-start swaps

Strength of instability given by the off-diagonal terms in the density matrix. We put as initial seeds

$$\rho_{ex} = \varepsilon\, |\rho_{ee} + \rho_{xx}|$$

FLAVOR DYNAMICS IN 3 GENERATIONS

We work in the rotated basis

$$(\nu_e, \nu_x, \nu_y) = R^T(\theta_{23})(\nu_e, \nu_\mu, \nu_\tau)$$

Let's split the density matrix and the Hamiltonian in (0) +(1) parts

$$\rho^{(0)} = \begin{pmatrix} \rho_{ee} & \rho_{ex} & 0 \\ \rho^*_{ex} & \rho_{xx} & 0 \\ 0 & 0 & \rho_{yy} \end{pmatrix}$$

e-x block. Oscillations in the L= (Δm^2_{sol}, θ_{12}) sector

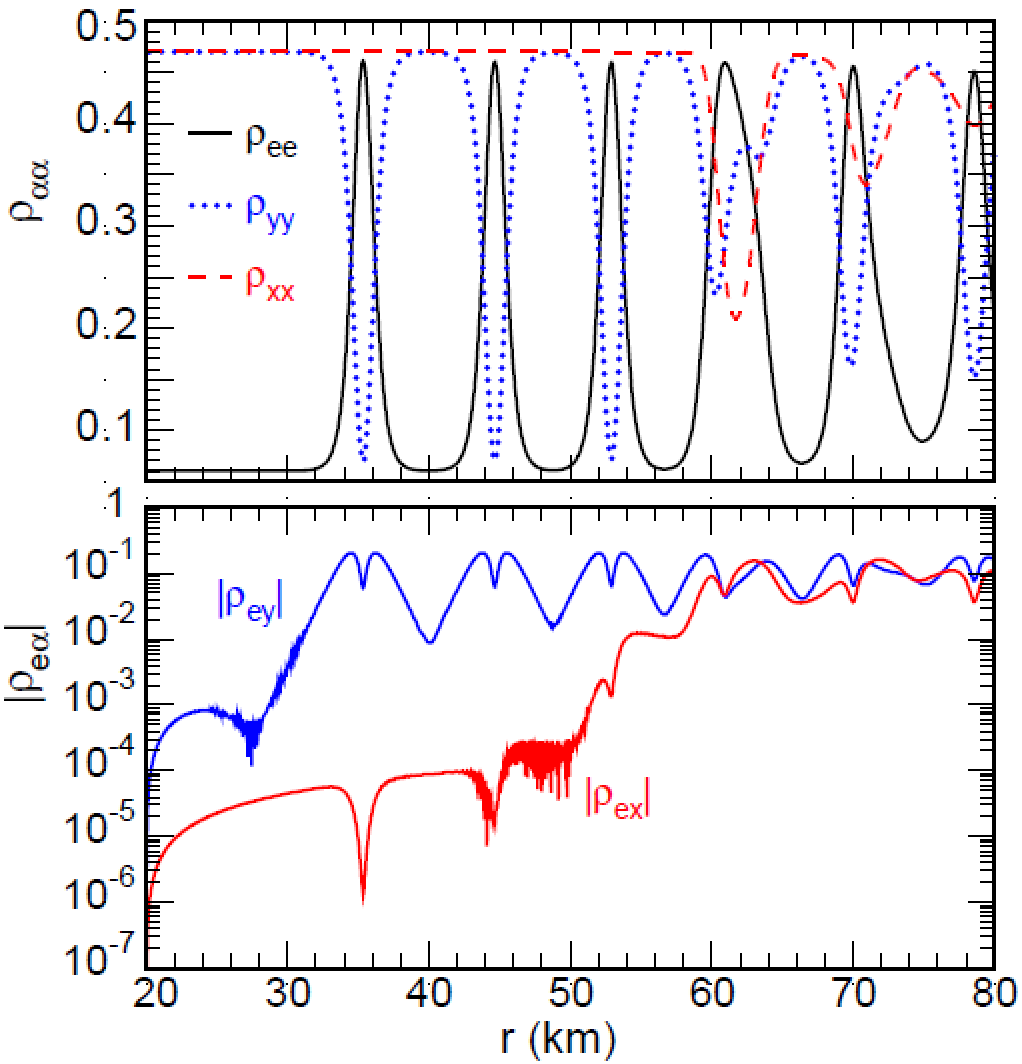
$$\rho^{(1)} = \begin{pmatrix} 0 & 0 & \rho_{ey} \\ 0 & 0 & \rho_{xy} \\ \rho^*_{ey} & \rho^*_{xy} & 0 \end{pmatrix}$$

e-y block. Oscillations in the H= (Δm^2_{atm}, θ_{13}) sector

For $\theta_{13} \neq 0$, H and L sectors are coupled

$H^{(1)}$ produces the off-diagonal components first in $\rho^{(1)}$ in and subsequently in $\rho^{(0)}$ by θ_{13} effects.
The growth is speeded up by $H^{(1)}$ which induces oscillations Δm^2_{atm}-dependent at the leading order.

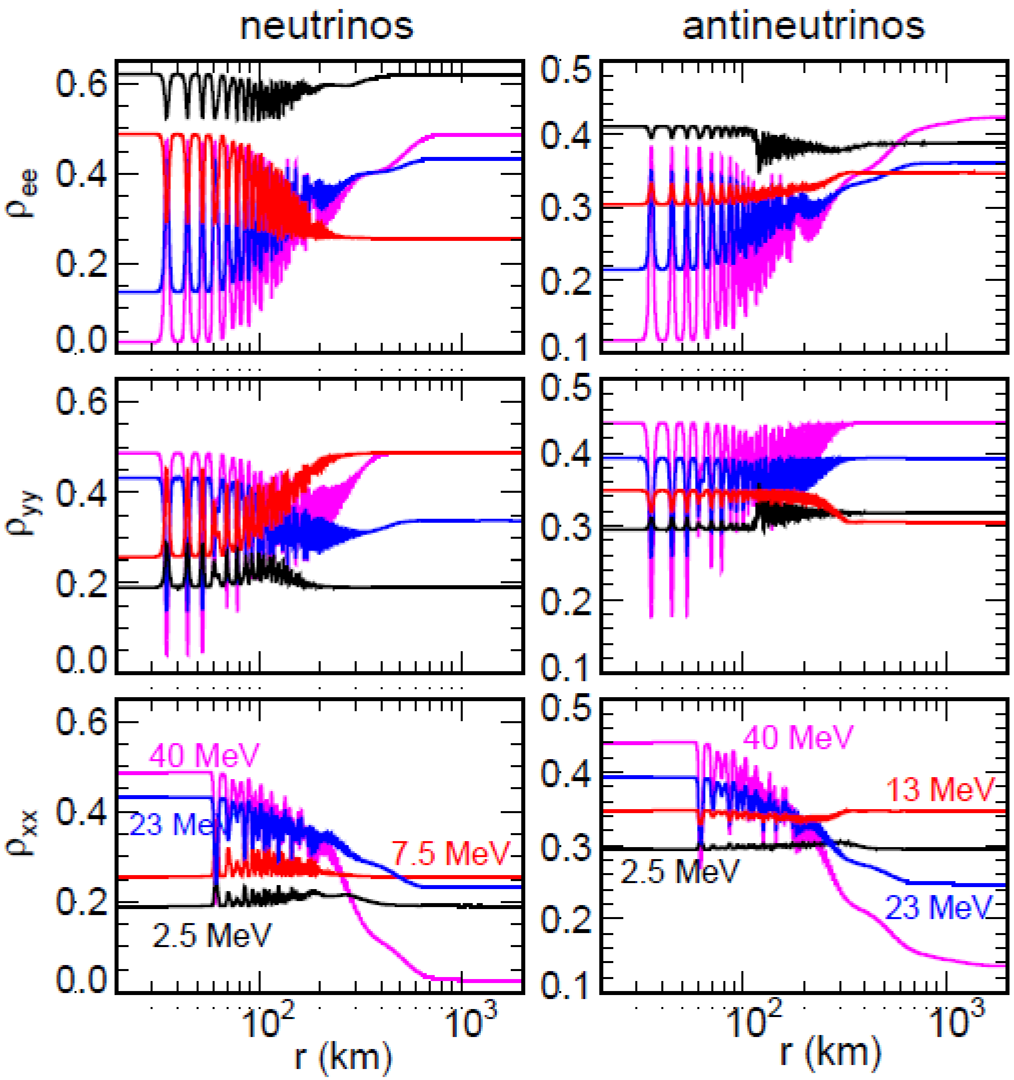
GROWTH OF THE INSTABILITIES IN 3ν



The coupling between the L and H sectors induces 3ν effects.

The initial kick, associated with Δm^2_{atm}, is necessary to trigger the instability in the L system.

THREE-FLAVOR EVOLUTION IN INVERTED HIERARCHY



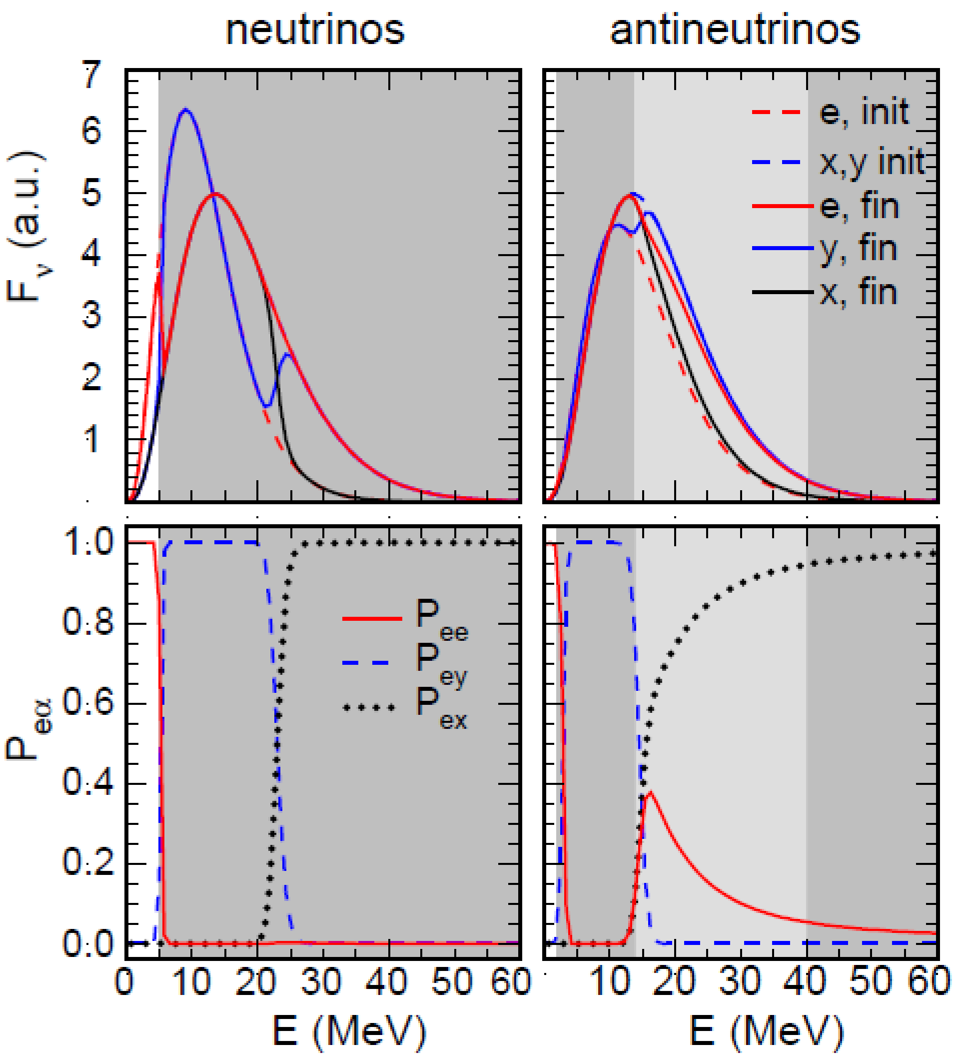
The two mass differences Δm^2_{atm} <0 and Δm^2_{sol} >0 process complementary parts of the ν spectra.

Their effects do not interfere in the same energy range.

ν_e and ν_y swap part of their spectra unstable under the action of Δm^2_{atm} .

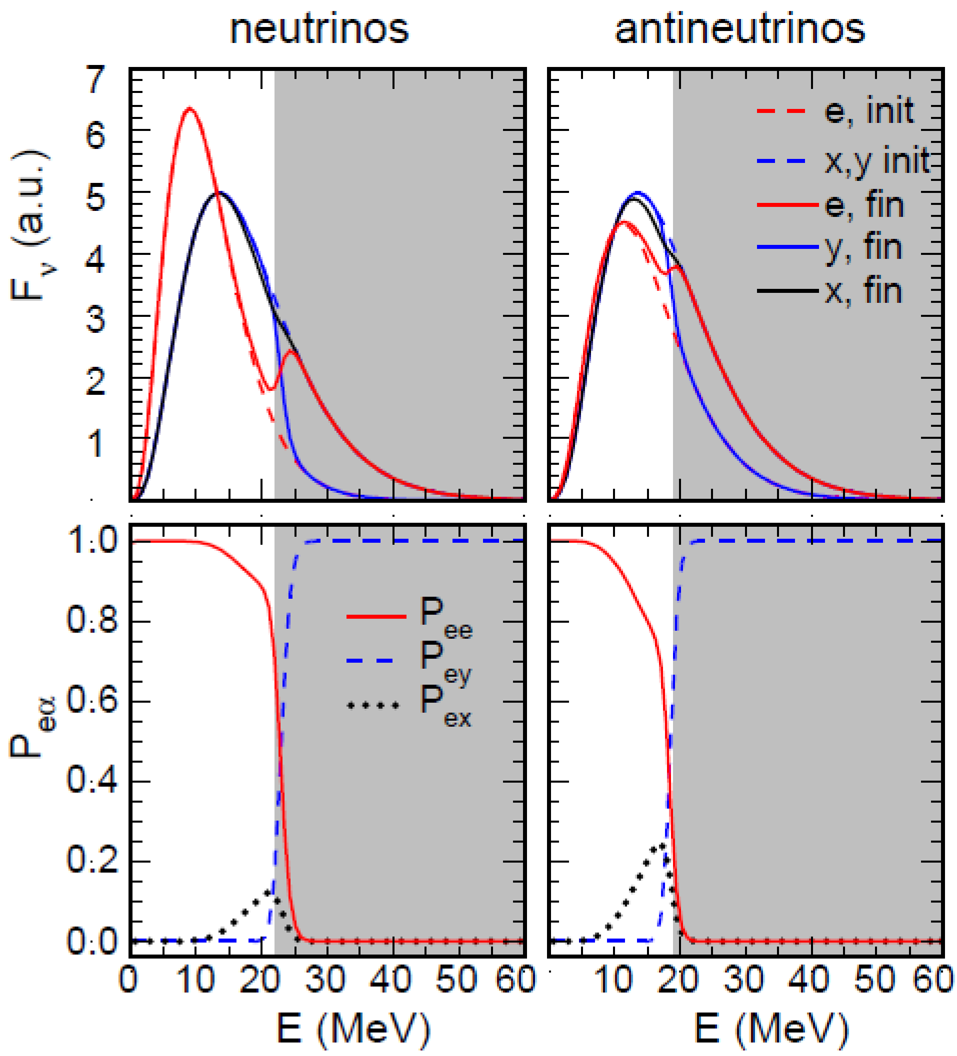
ν_e and ν_x swap part of their spectra unstable under the action of Δm^2_{sol} .

3ν SPECTRAL SPLITS IN INVERTED HIERARCHY



- Atmospheric swaps (e,y)
- Solar swaps (e,x)
- Higher energy split is transferred from e to x
- Non-adiabatic effects (especially for anti-nu)

3ν SPECTRAL SPLITS IN NORMAL HIERARCHY



- **Almost same as 2-flavors (e-y).**
- **Solar driven conversions are too slow to compete.**

In this case 3 and 2ν instabilities act in the same regions of the ν spectrum leading only to minor departures from the 2ν evolution.

CONCLUSIONS

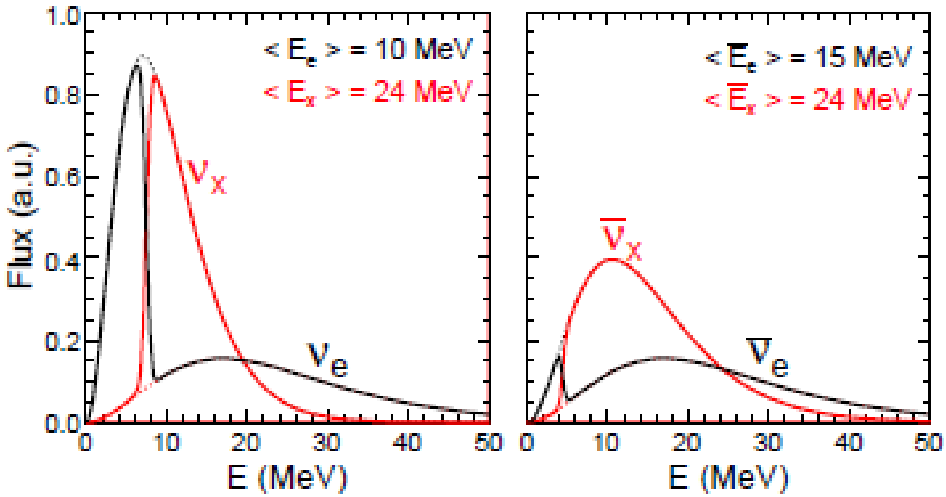
- Neutrino-neutrino interactions induce peculiar spectral swaps among different neutrino flavors.

- The development of these features is associated with instabilities in the flavor space.

- In inverted hierarchy, during the cooling phase, the presence of $\Delta m^2_{sol} > 0$ gives rise to instabilities in regions of the neutrino energy spectra that were stable under the two-flavor evolution governed by $\Delta m^2_{atm} < 0$ and θ_{13}. The combinations of these two instabilities would produce a wash-out of the high-energy splitting spectral features in ν_e

- In normal hierarchy the three-flavor instabilities and the two-flavor ones act in the same regions of the neutrino energy spectrum leading only to minor departures from the two-flavor evolution.

SPECTRAL SPLITS IN THE ACCRETION PHASE



$$F_{\nu e} : F_{\bar{\nu} e} : F_{\nu x} = 2.4 : 1.6 : 1.0$$

We should have seen 4 splits, but we see 2 only, because the inner swap is exponentially narrower.