Collective flavour transitions of supernova neutrinos

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Outline

- Introduction
- Self-interactions in 2-flavor scenario
- Self-interactions in 3-flavour scenario
- Conclusions

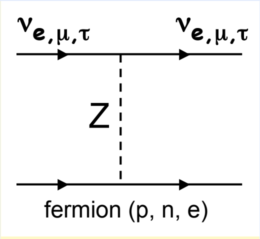
This talk is based on work in collaboration with G.L. Fogli, E. Lisi, A. Marrone and A. Mirizzi:
- arXiv: 0808.0807 [hep-ph]
- arXiv: 0812.3031 [hep-ph].

See references therein for credit to previous relevant papers.

Introduction: neutrino interactions

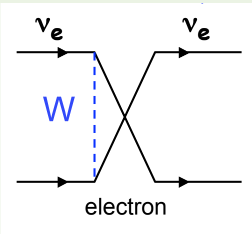
In a core-collapse supernova not only ν-matter interactions are important ...

Neutrino-matter interactions: MSW flavour changes



all flavours

all neutrino flavors have neutral current (NC) interactions with ordinary matter background

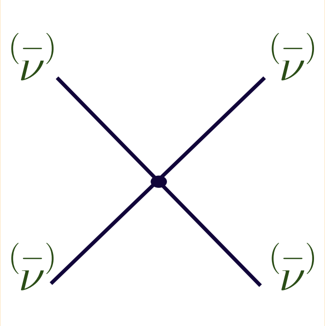


e-flavour only

only ν_e has charged current (CC) interactions too

... but also $\nu - \nu$ interactions

Neutrino-neutrino interactions: non-linear flavour conversions



all flavours

when an high density of ν is present, $\nu - \nu$ interactions become not negligible. Self-interactions induce large, non-MSW flavour change. Different neutrino flavours with different energies are coupled in their evolution history.

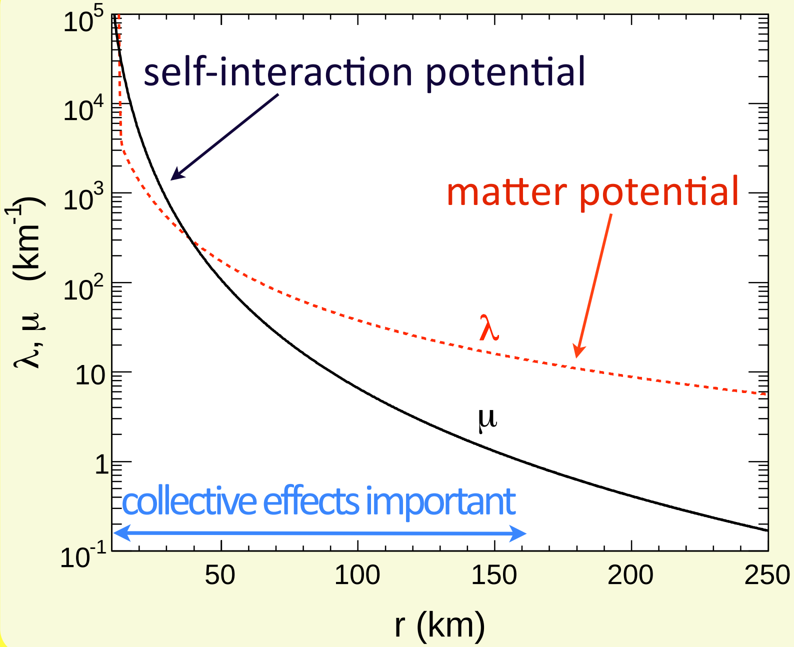
Introduction: supernova relevance

Core-collapse supernovae can help us improving our knowledge about neutrino physics and astrophysics. In fact, as a consequence of neutrino self-interactions, oscillated neutrino fluxes show great sensitivity to:

★ the non-zero mixing angle θ_{13}
★ the neutrino mass hierarchy

If the hierarchy is inverted and if $\theta_{13} \neq 0$, a full flavour conversion takes place. Otherwise oscillated fluxes are equal to non-oscillated ones.
In the following we use the inverted hierarchy scenario with $\theta_{13} \neq 0$.

effects of neutrino self-interactions



We use three main frequencies:

★ the self-interaction potential $\mu = \sqrt{2} G_F (N + \bar{N})$
★ the matter potential $\lambda = \sqrt{2} G_F N_e$
★ the vacuum frequency $\omega = (\Delta m^2 / 2E)$.

When

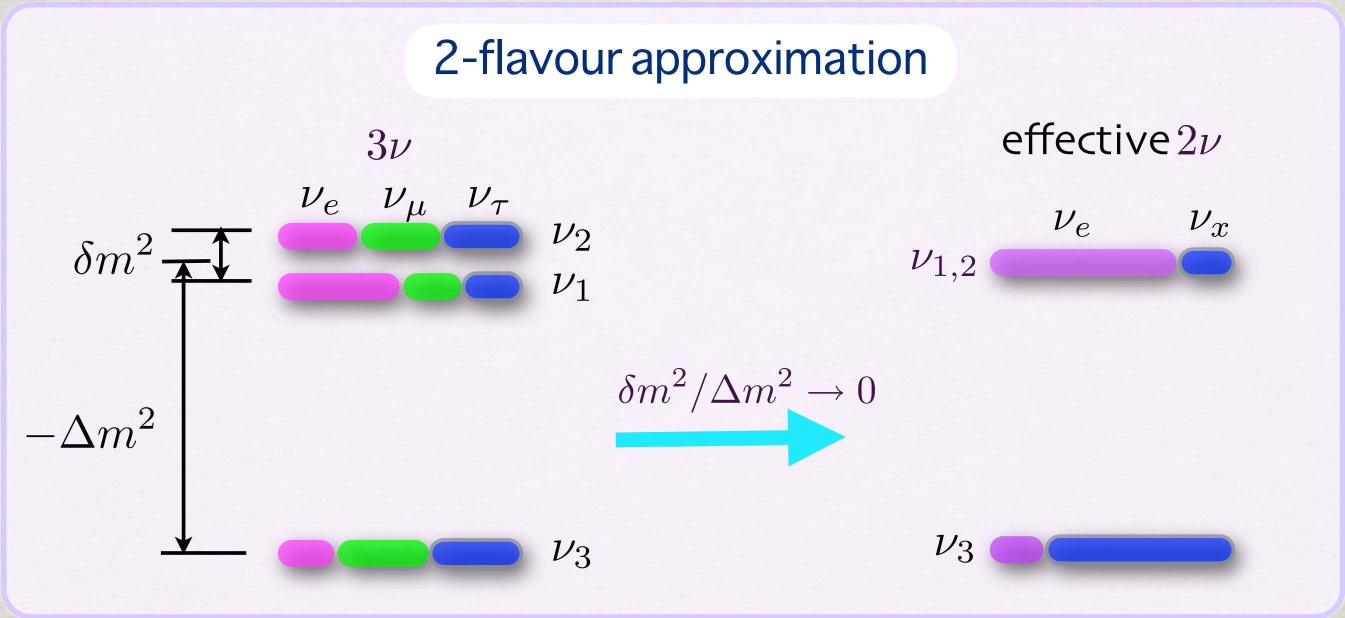
- $\mu > \omega$: self-interactions dominant [r < 100 km]
- $\lambda \sim \omega$: MSW effects leading [r > 100 km]
- $\lambda, \mu << \omega$: vacuum oscillations

Self-interaction and matter potentials are chosen for t = 5 s after the core-bounce.

Plot taken from G.L. Fogli, E. Lisi, A. Marrone, A. Mirizzi, I. Tamborra, arXiv: 0808.0807 [hep-ph]

Self-interactions in 2-flavour scenario

Typical supernova neutrino energies [E ~ O(10) MeV] are below threshold for μ and τ production via CC. ν_μ and ν_τ behave in a similar way, and are often denoted by ν_x.
As a consequence, in this context one may use the 2-flavour approximation, assuming $\delta m^2 = 0$.

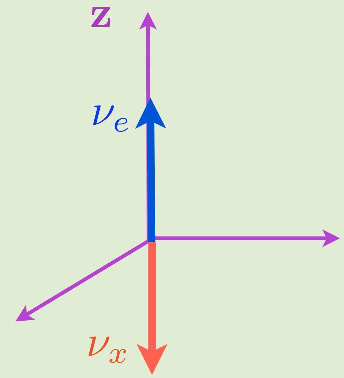


Some papers on collective effects in 2-flavour approximation:

- S. Pastor, G. Raffelt, arXiv: astro-ph/0207281
- H. Duan, G.M. Fuller, Y.Z. Qian, arXiv: astro-ph/0511275
- S. Hannestad, G. Raffelt, G. Sigl, Y.Y.Y. Wong, arXiv: astro-ph/0608695
- H. Duan, G.M. Fuller, J. Carlson, Y.Z. Quian, arXiv: astro-ph/0703776
- G. Raffelt, A.Y. Smirnov, arXiv: hep-ph/0705.1830
- G.L. Fogli, E. Lisi, A. Marrone, A. Mirizzi, arXiv: hep-ph/0707.1998

Self-interactions in 2-flavour: evolution equations

For each neutrino energy mode i, decompose the 2 x 2 (anti)neutrino density matrix over Pauli matrices to get the Bloch 3-vector. In the flavour basis, the Bloch vectors associated to ν_e and ν_x are respectively aligned and anti-aligned with the $\mathbf{z}$ axis.



Considering the Bloch vector's evolution equation for each energy mode, one has to solve a large system of non-linear differential equations:

$$\dot{\mathbf{P}}_i = \mathbf{H}_i \times \mathbf{P}_i = (+\omega_i \mathbf{B} + \lambda \mathbf{z} + \mu \mathbf{D}) \times \mathbf{P}_i$$

$$\dot{\overline{\mathbf{P}}}_i = \overline{\mathbf{H}}_i \times \overline{\mathbf{P}}_i = (-\omega_i \mathbf{B} + \lambda \mathbf{z} + \mu \mathbf{D}) \times \overline{\mathbf{P}}_i$$

vacuum term (with $\mathbf{B}$ function of the mixing angle θ_{13})

matter term

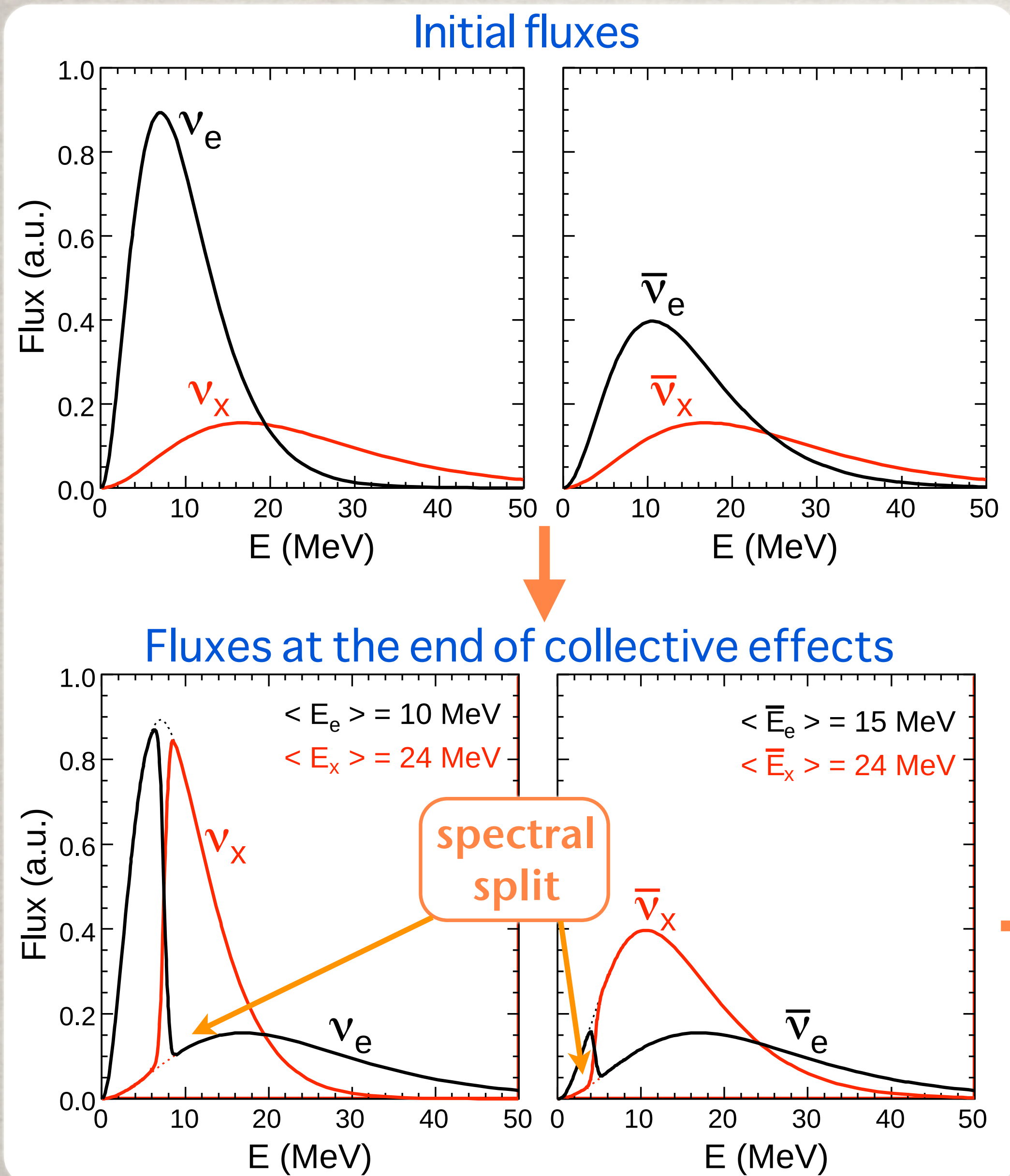
self-interaction term with $\mathbf{D} = \sum_i \mathbf{P}_i - \bar{\mathbf{P}}_i$

The third component of the Bloch vector ($|\mathbf{P}_i| = 1$) is related to the survival probability:

$$P(\nu_e \to \nu_e) = \frac{1}{2}\left(1 + \frac{P_z^f}{P_z^i}\right)$$

with P_z^i and P_z^f the initial and the final value of the third component of $\mathbf{P}_i$.

Self-interactions in 2-flavour: numerical results



SPECTRAL SPLIT OF ν (AND MAYBE $\bar{\nu}$) FLUXES APPEAR TO BE OBSERVABLE SIGNATURES OF SELF-INTERACTIONS IN INVERSE HIERARCHY FOR ANY $\theta_{13} \neq 0$

As a result of collective effects for E greater than certain critical energies (E_c for ν and $\bar{E}_c$ for $\bar{\nu}$) a full flavour change takes place.

low energy limit ($E < E_c$):

$$F'_e = F^0_e$$
$$F'_x = F^0_x$$

high energy limit ($E > E_c$):

$$F'_e = F^0_x$$
$$F'_x = F^0_e$$

Plots taken from G.L. Fogli, E. Lisi, A. Marrone, A. Mirizzi, I. Tamborra, arXiv: 0808.0807 [hep-ph]

Self-interactions: 2-flavour vs 3-flavour

★ In a core-collapse supernova ν_μ and ν_τ have the same behavior because of typical energies. A two-flavour approximation give us a qualitative explanation of neutrino spectra features.

★ In inverted hierarchy and with $\theta_{13} \neq 0$, above certain critical energies a full flavour swap takes place. This is a robust signature of collective effects.

★ If the hierarchy is direct or if $\theta_{13} = 0$, the oscillated fluxes are equal to the non-oscillated ones.

But if we consider a three-flavour scenario, how do these features change?

We develop a three flavour scenario analysis including:

★ the mixing angles θ_{12}, θ_{13} and θ_{23}

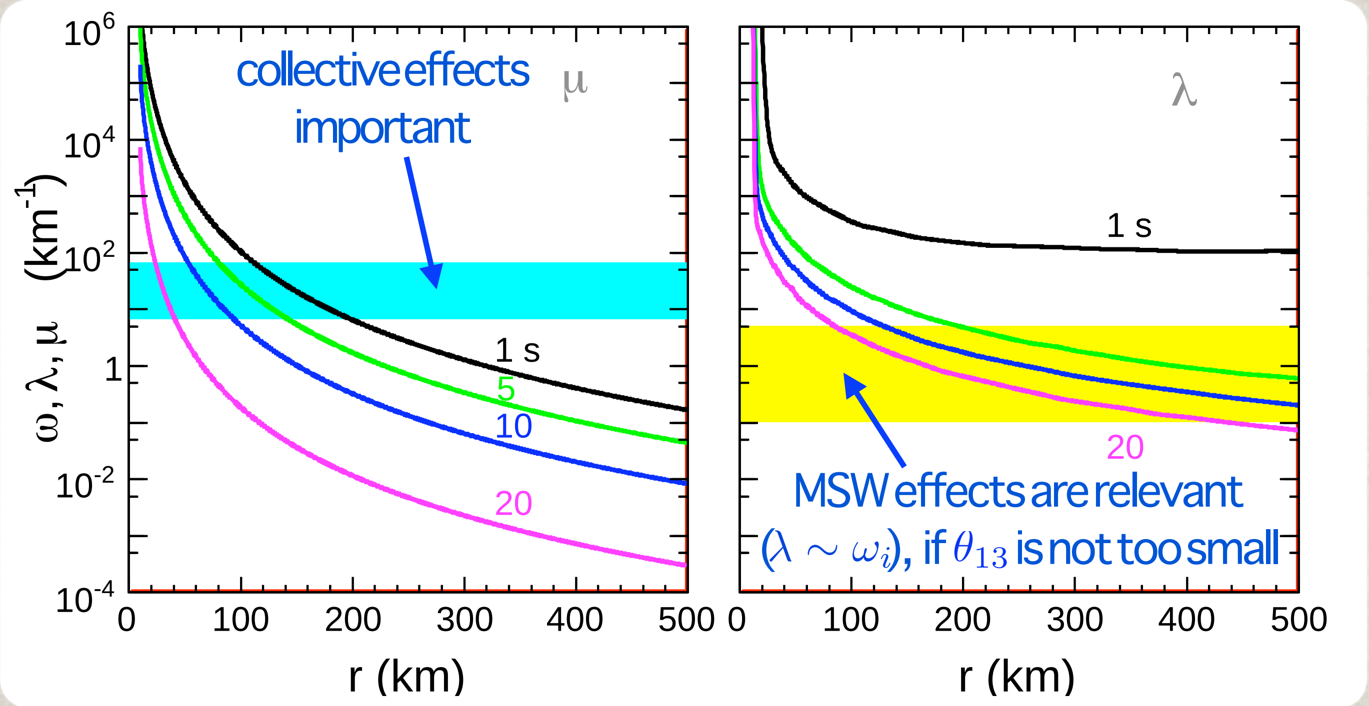
★ the mass differences Δm^2 and δm^2

★ 1-loop $\nu_\mu - \nu_\tau$ matter interaction potential.

We consider the evolution for different times after the core-bounce, and check the evolution for the three flavour separately.

Self-interactions in 3-flavour scenario

We consider four different times (t = 1, 5, 10, 20 s) after the core-bounce.



We expect that:

- ★ collective effects take place at different radii for each t after the core-bounce
- ★ MSW effects take place after collective ones

We choose a small value for θ_{13} ($\sin^2\theta_{13} = 10^{-6}$). In this way MSW effects are negligible for each t after the core-bounce.

Some papers on collective effects in 3-flavour approximation:
- A. Esteban-Pretel, S. Pastor, R. Tomas, G. Raffelt, G. Sigl, arXiv: astro-ph/0712.1137
- B. Dasgupta, A. Dighe, arXiv: hep-ph/0712.3798
- H. Duan, G.M. Fuller and Y.Z. Qian, arXiv: 0801.1363 [hep-ph]
- B. Dasgupta, A. Dighe, A. Mirizzi and G.G. Raffelt, arXiv: 0801.1660 [hep-ph]

Plot taken from G.L. Fogli, E. Lisi, A. Marrone, I. Tamborra, arXiv: 0812.3031 [hep-ph]

Self-interactions in 3-flavour: evolution equations

For each neutrino mode *i*, decompose the 3 x 3 (anti)neutrino density matrix over Gell-Mann matrices to get the Bloch 8-vector.
Self-interactions may be explained in terms of evolution equations for the Bloch vectors of ν $(\mathbf{P}_i)$ and $\bar{\nu}$ $(\overline{\mathbf{P}}_i)$:

$$\dot{\mathbf{P}}_i = [+(\omega_{L,i}\mathbf{B}_L + \omega_{H,i}\mathbf{B}_H) + \mathbf{v} + \mu\mathbf{D}] \times \mathbf{P}_i$$
$$\dot{\overline{\mathbf{P}}}_i = [-(\omega_{L,i}\mathbf{B}_L + \omega_{H,i}\mathbf{B}_H) + \mathbf{v} + \mu\mathbf{D}] \times \overline{\mathbf{P}}_i$$

two vacuum terms
[with $\omega_{H,i} = (\Delta m^2/2E)$ and $\omega_{L,i} = (\delta m^2/2E)$]

matter term

self-interaction term with
$\mathbf{D} = \sum_i \mathbf{P}_i - \bar{\mathbf{P}}_i$

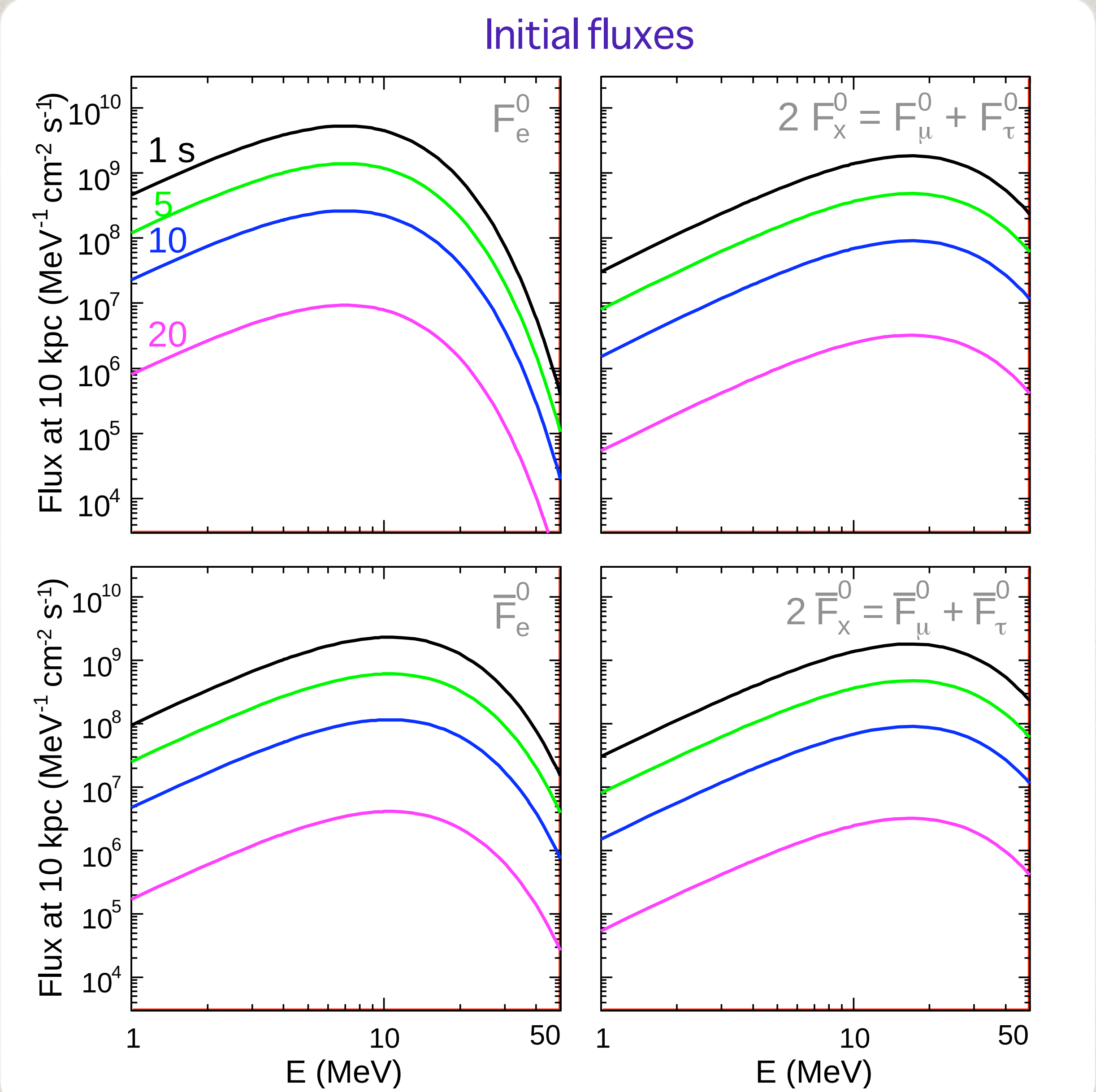
We numerically solve a large system of non-linear differential equations✢.

A linear combination of P3 and P8 $(|\mathbf{P}_i| = 2/\sqrt{3})$ is related to $P(\nu_e \rightarrow \nu_e)$ and is the analogous of the third component in the two-flavour limit:

$$P_z \rightarrow P_3 + \frac{P_8}{\sqrt{3}}$$

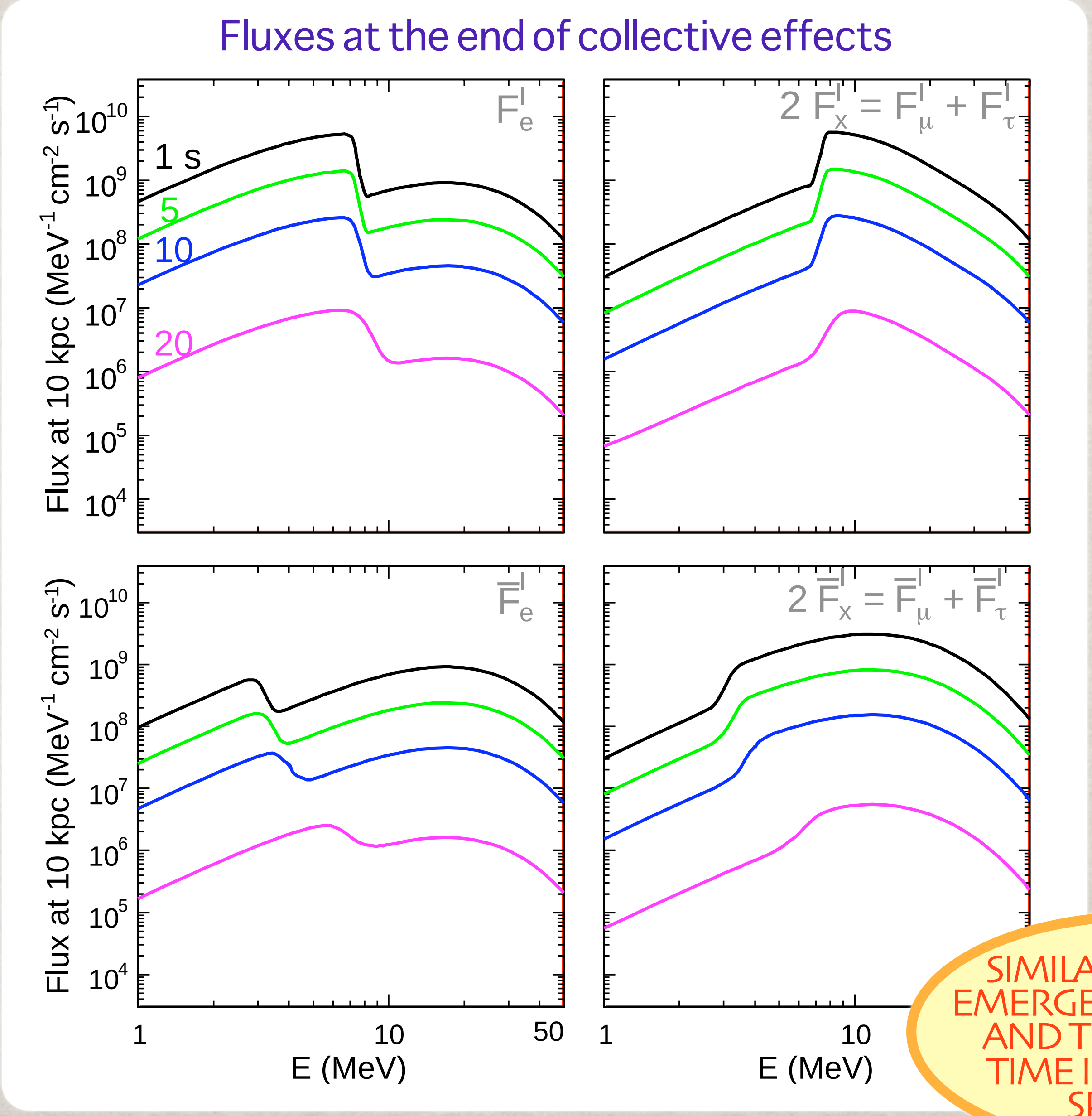
✢ G.L. Fogli, E. Lisi, A. Marrone, I. Tamborra, arXiv: 0812.3031 [hep-ph]

Self-interactions in 3-flavour: numerical results



Plot taken from G.L. Fogli, E. Lisi, A. Marrone, I. Tamborra, arXiv: 0812.3031 [hep-ph]

Self-interactions in 3-flavour: numerical results

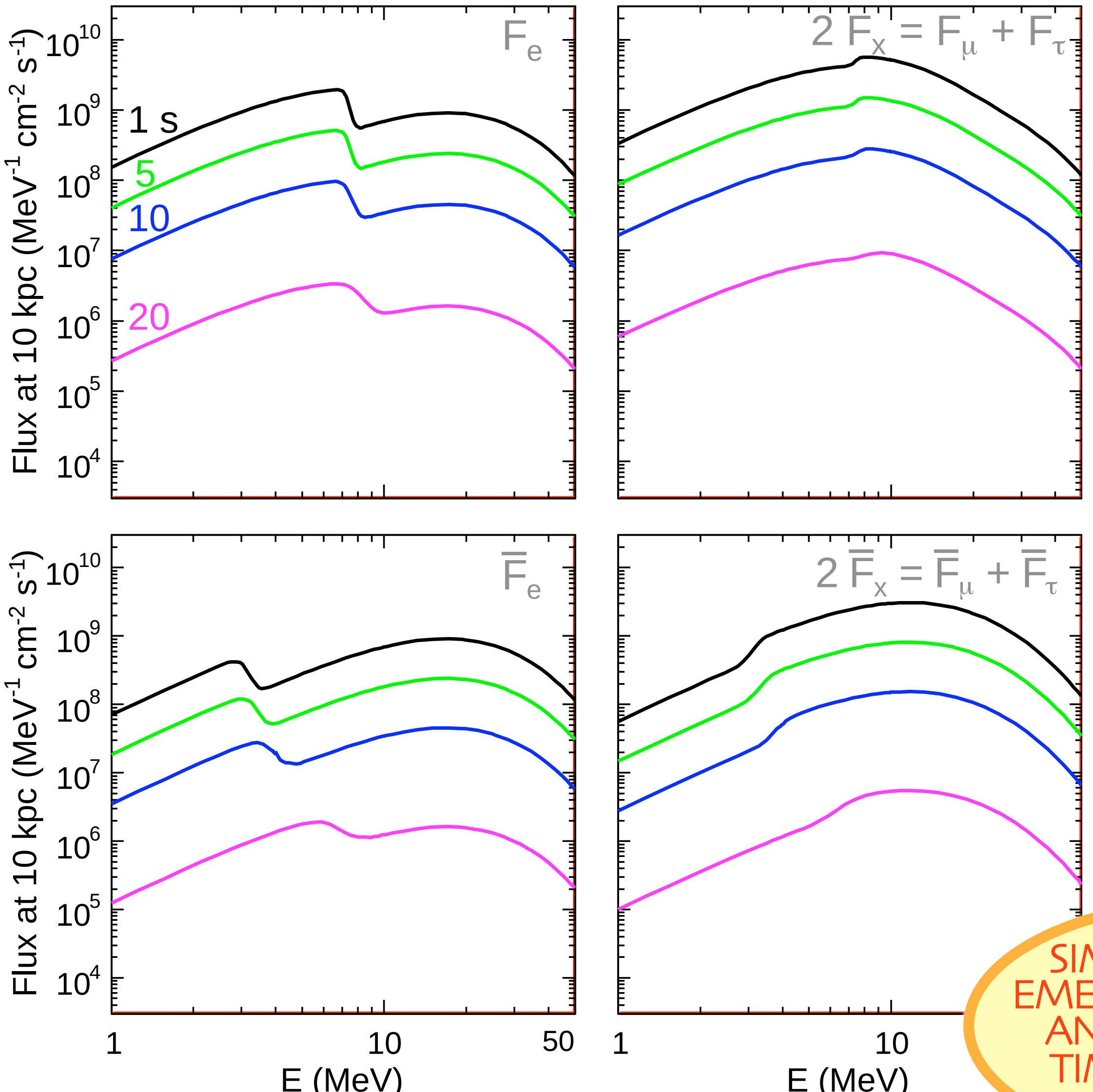


SIMILAR FEATURES EMERGE AT ALL TIMES, AND THUS ALSO IN TIME INTEGRATED SPECTRA.

Plot taken from G.L. Fogli, E. Lisi, A. Marrone, I. Tamborra, arXiv: 0812.3031 [hep-ph]

Self-interactions in 3-flavour: numerical results

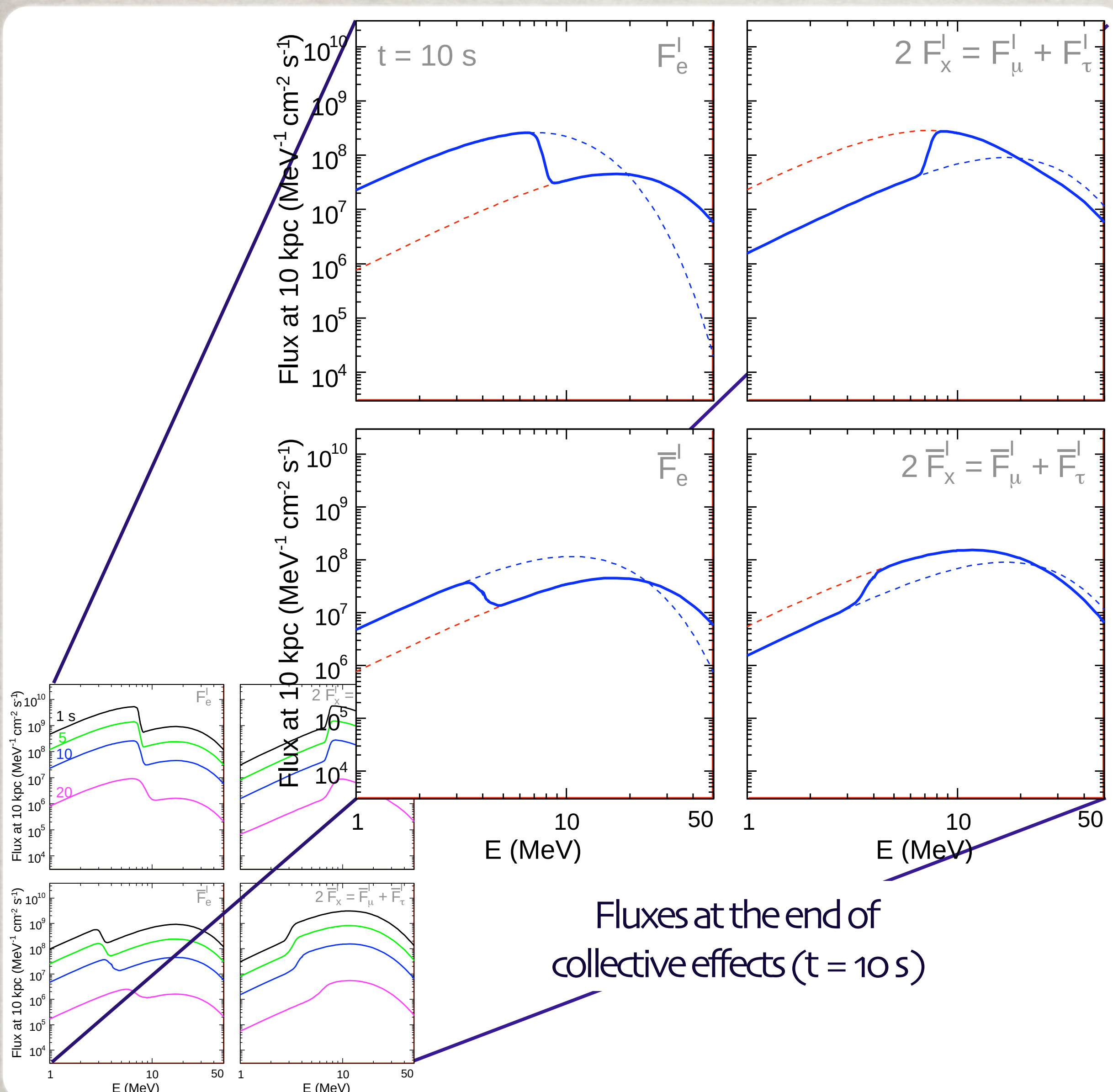
Fluxes at the Earth



SIMILAR FEATURES EMERGE AT ALL TIMES, AND THUS ALSO IN TIME INTEGRATED SPECTRA.

Plot taken from G.L. Fogli, E. Lisi, A. Marrone, I. Tamborra, arXiv: 0812.3031 [hep-ph]

Self-interactions in 3-flavour: $\nu_e - \nu_x$ oscillated fluxes



In the three flavour case the oscillated fluxes can be expressed as simple combinations of the non oscillated ones:

low energy limit $(E < E_c)$:

$$F'_e = F^0_e$$
$$2F'_x = 2F^0_x$$

high energy limit $(E > E_c)$:

$$F'_e = F^0_x$$
$$2F'_x = F^0_e + F^0_x$$

Plots taken from G.L. Fogli, E. Lisi, A. Marrone, I. Tamborra, arXiv: 0812.3031 [hep-ph]

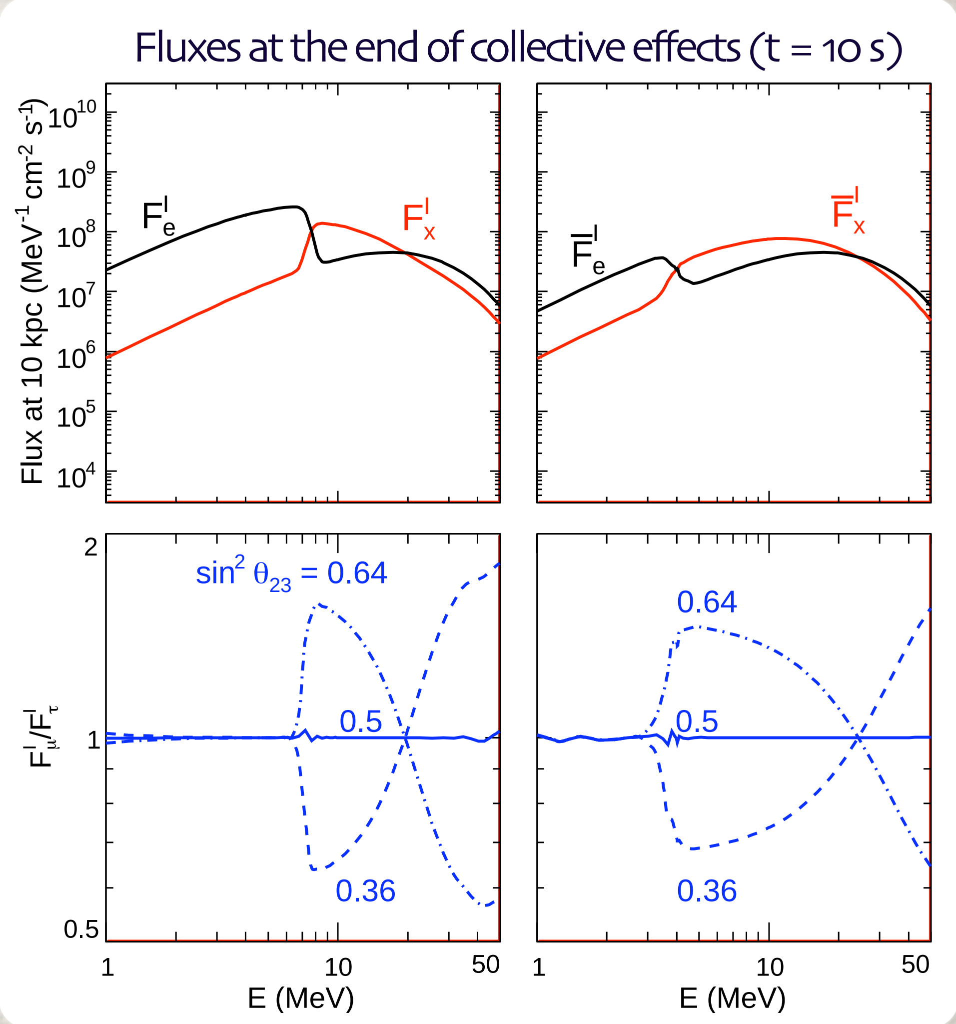
Self-interactions in 3-flavour: $\nu_\mu - \nu_\tau$ oscillated fluxes

We explore the $\nu_\mu - \nu_\tau$ mixing for different values of θ_{23}. ν_x oscillated flux is not sensitive to θ_{23}.

When θ_{23}

- ★ belongs to the first octant, we have a leading $\nu_e \rightarrow \nu_\tau$ conversion
- ★ belongs to the second one, we have a leading $\nu_e \rightarrow \nu_\mu$ conversion
- ★ is maximal ($\theta_{23} = \pi/4$), ν_μ and ν_τ fluxes are exactly equal.

This different behavior between ν_μ and ν_τ fluxes, although is not observable nowadays, could be detected in a future supernova explosion.



Plot taken from G.L. Fogli, E. Lisi, A. Marrone, I. Tamborra, arXiv: 0812.3031 [hep-ph]

Self-interactions: 2-flavour vs 3-flavour's remarks

⋆ The three flavour case is similar, but does not reduce to the two flavour one.

⋆ In particular the coupled evolution equations are sensitive to the absolute luminosity for each flavour. It makes a difference if the total neutrino-luminosity is distributed on two or three flavours.

	2ν	3ν
low energy limit ($E < E_c$):	$F'_e = F^0_e$ $F'_x = F^0_x$	$F'_e = F^0_e$ $2F'_x = 2F^0_x$
high energy limit ($E > E_c$):	$F'_e = F^0_x$ $F'_x = F^0_e$	$F'_e = F^0_x$ $2F'_x = F^0_e + F^0_x$

⋆ The split features are the same at different times. This may be more "visible" collective effects in the next supernova explosion.

⋆ Minor three-flavour features are basically unobservable.

Conclusions

★ Neutrino-neutrino interactions are not negligible when neutrino density is high, like in core-collapse supernovae.

★ Collective effects are important to improve our knowledge about the neutrino mass hierarchy and the mixing angle θ_{13}.

★ In direct hierarchy or if $\theta_{13} = 0$, the oscillated spectra are equal to the non-oscillated ones.

★ In inverted hierarchy and for any $\theta_{13} \neq 0$:

- spectral split takes place with the same features at different times after the core-bounce. This feature may make collective effects more evident in the next supernova explosion.
- in a two-flavour scenario a full flavour swap takes place
- in a three-flavour scenario oscillated fluxes can be expressed as simple combinations of non-oscillated ones. An "effective" two flavour reduction is not possible because all three flavour evolve.
- ν_x is not sensitive to different values of θ_{23}.
- the effect of $\delta m^2 \neq 0$ and 1-loop $\nu_\mu - \nu_\tau$ corrections are negligible.

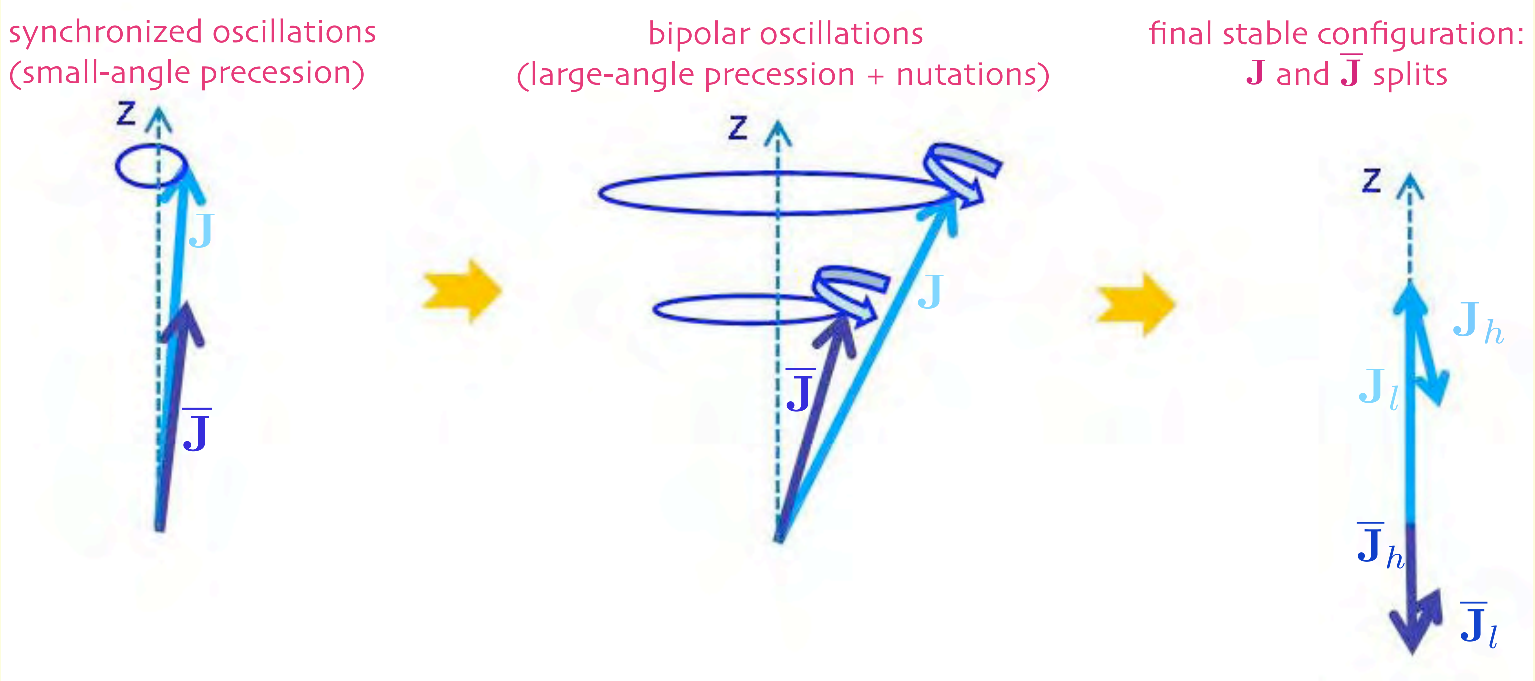

Waiting for the next supernova explosion...thanks for your attention!

Backup slides

Self-interactions in 2-flavour: global evolution

When the collective effects are dominant, the alignment approximation is valid: the Bloch vectors are closely pinned to their sum ($\mathbf{P}_i || \mathbf{J}$ and $\overline{\mathbf{P}}_i || \overline{\mathbf{J}}$). The flavour evolution can be understood in terms of the global vectors $\mathbf{J} = \sum_i \mathbf{P}_i$ and $\bar{\mathbf{J}} = \sum_i \bar{\mathbf{P}}_i$.

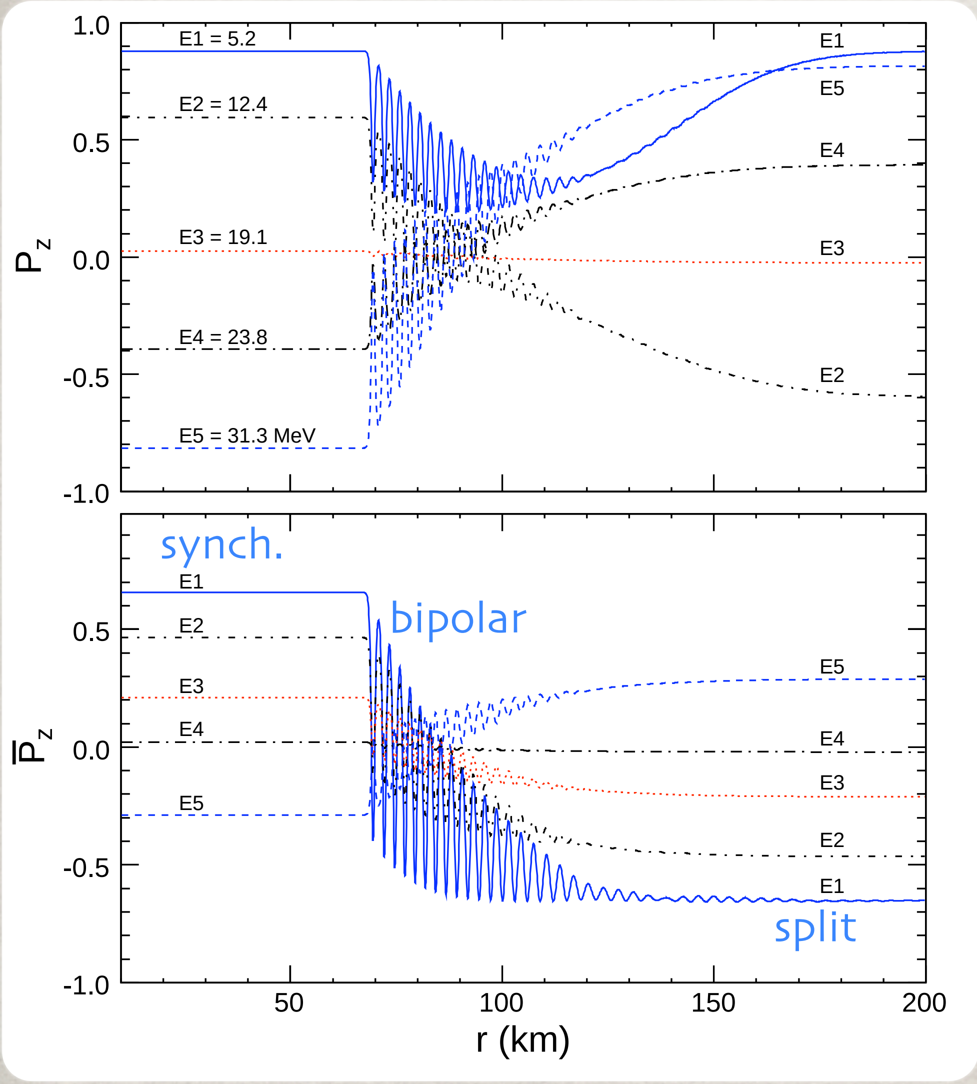
At the end, alignment approximation is no longer valid (split).



θ_{13} sets initial misalignment of $\mathbf{J}$ and $\overline{\mathbf{J}}$ with vertical. Its specific value is not much relevant (provided that $\theta_{13} > 0$). Only for $\theta_{13} = 0$ initial conditions are frozen.

Self-interactions in 2-flavour: spectral split

In terms of the third components of the Bloch vectors at different energies, we have:



neutrinos

For $E > E_c(\simeq 7 \text{ MeV}) : P_z^f = -P_z^i$

full flavour conversion

For $E < E_c(\simeq 7 \text{ MeV}) : P_z^f = P_z^i$

absence of flavour conversion

antineutrinos

For $E > \overline{E}_c(\simeq 4 \text{ MeV}) : \overline{P}_z^f = -\overline{P}_z^i$

full flavour conversion

Plot taken form: G.L. Fogli, E. Lisi, A. Marrone, A. Mirizzi, arXiv: hep-ph/0707.1998

Self-interactions in 2-flavour: spectral split

Neutrino spectral split

- ★ The alignment approximation is not able to explain the neutrino spectral split.
- ★ The critical energy E_c is predicted using the fact that $\#\nu_e - \#\bar{\nu}_e = \mathrm{const.}$
- ★ Alternatively, the neutrino spectral split can be explained using the adiabatic hypothesis.

According to the this hypothesis, when μ slowly decreases:

$$\mathbf{P}_i || \mathbf{H} \qquad \text{and} \qquad \overline{\mathbf{P}}_i || \overline{\mathbf{H}}$$

It is applicable to the end of the collective effects.

Antineutrino spectral split (G.L. Fogli, E. Lisi, A. Marrone, A. Mirizzi, I. Tamborra, arXiv: 0808.0807 [hep-ph])

- ★ The antineutrino split is related to the breaking of the global alignment
- ★ The antineutrino split depends on the adiabatic hypothesis violation
  [it happens at low energies when $\mu \sim \omega$]
- ★ The critical energy $\overline{E}_c$ is a function of the matter potential and the mixing angle.