NEUTEL'09, Venice   March 11, 2009

Core-collapse supernovae:
When neutrinos get to know each other

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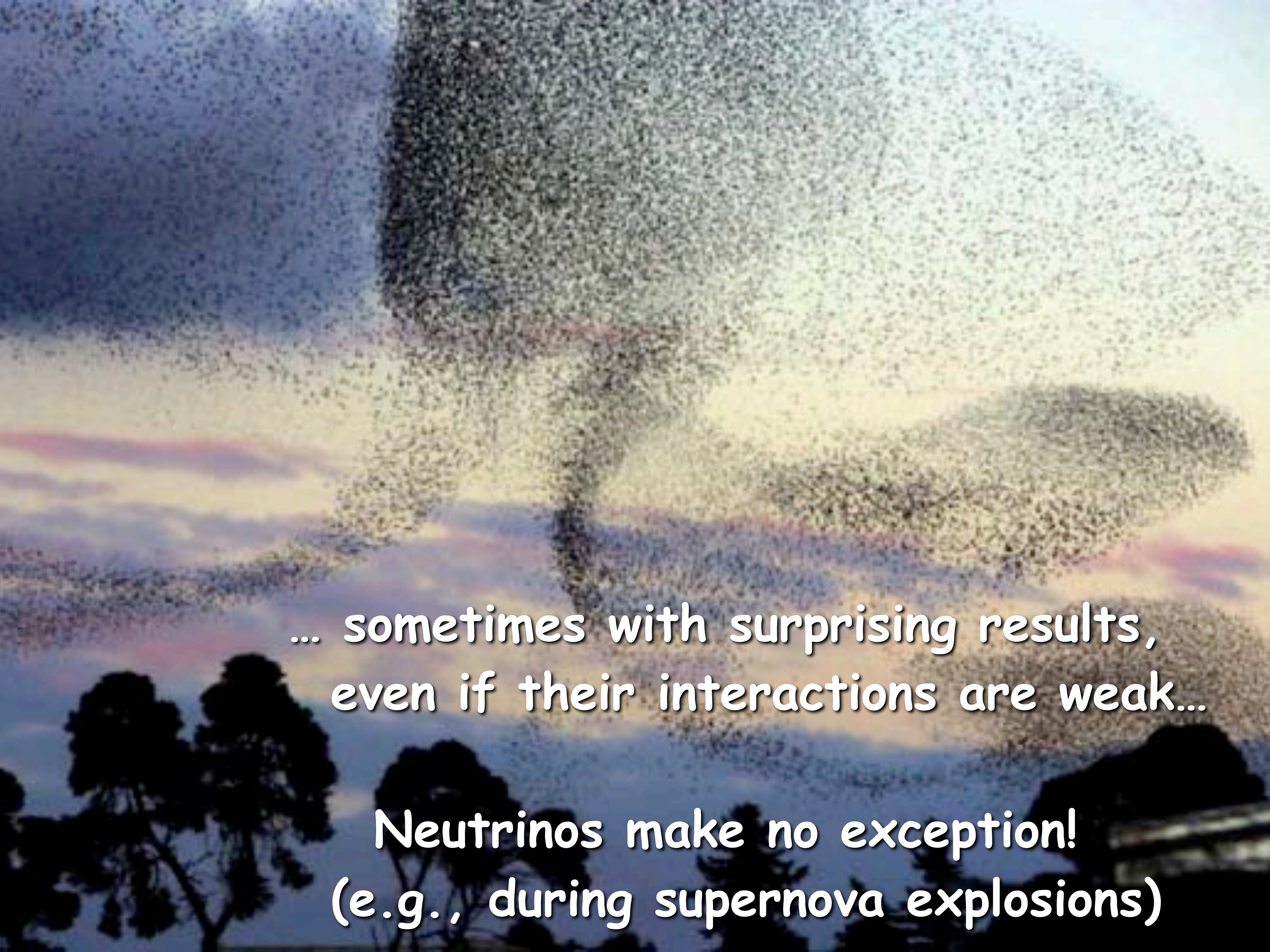
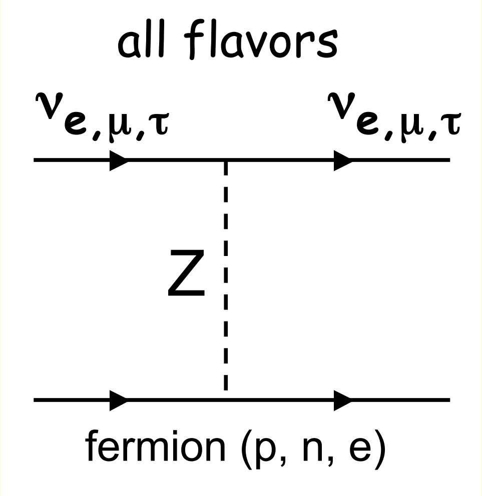
In low-density environments,
individuals tend to behave
independently from each other…

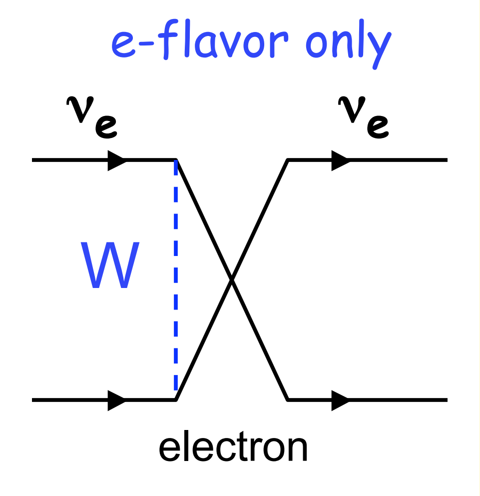

… but they may behave coherently
when densely packed…


… sometimes with surprising results,
even if their interactions are weak…
Neutrinos make no exception!
(e.g., during supernova explosions)

Low neutrino density

In this case, neutrino flavor transitions are mainly sensitive to the difference in ν_e forward scattering amplitude ($\propto G_F$) over background fermions (Mikheyev-Smirnov-Wolfenstein effect)





Interaction energy difference depends on electron density N_e:

$$\lambda = \sqrt{2}\, G_F\, N_e$$

Typical SN ν energies, $E \sim O(10)$ MeV, are below threshold for μ and τ and production via CC. The ν_μ and ν_τ behave in a similar way during production, propagation, detection, and are often denoted by a common symbol ν_x.

Low neutrino density (cont'd)

Well-known MSW effects can occur in a SN envelope when the ν potential $\lambda=\sqrt{2}\, G_F\, N_e$ is close to osc. frequency $\omega=\Delta m^2/2E$ ($\Delta m^2=|m^2_3-m^2_{1,2}|$, $\theta_{13}\neq 0$).

For t~few sec after bounce,

$\lambda \sim \omega$ at $x \gg 10^2$ **km** (large radii).

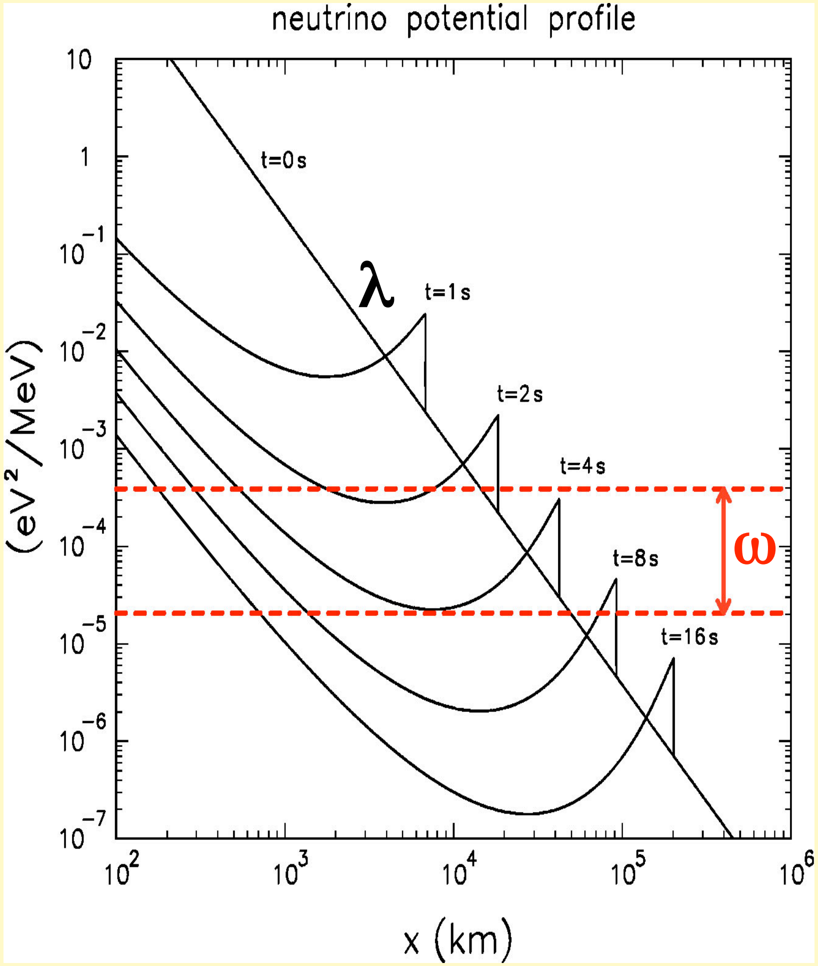
What about small radii?

Popular wisdom:

$\lambda \gg \omega$ at $x < O(10^2)$ **km**,

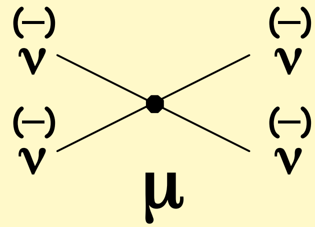
thus flavor transitions suppressed.

Incorrect!



Large neutrino density:

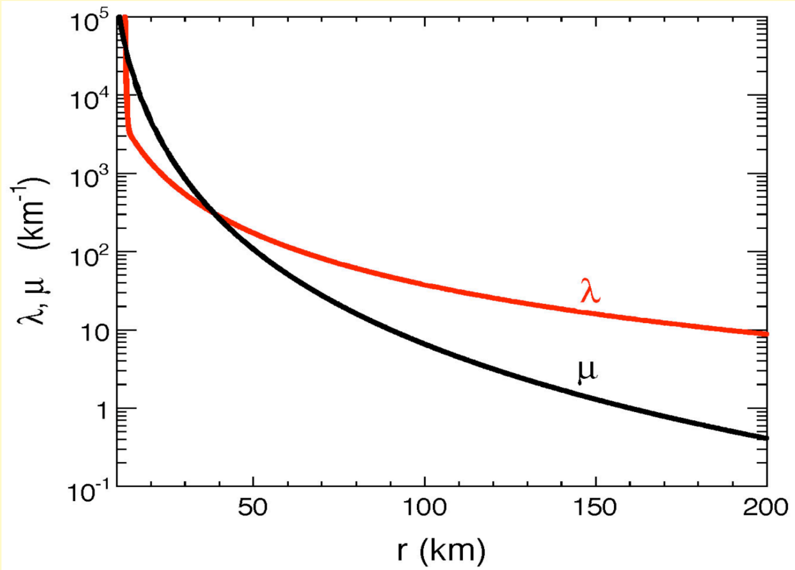
neutrinos "get to know each other" via neutral currents!



(NC)

At small r, neutrino and antineutrino density (n and $\bar{n}$) high enough to make self-interactions important. Strength: $\mu = \sqrt{2}\, G_F\, (n + \bar{n})$

Angular modulation factor: $(1 - \cos\Theta_{ij})$
If averaged: "**single-angle**" approxim.
Otherwise : "**multi-angle**" (difficult)



Self-interaction effects known for ~20 y in SN. But, recent boost of interest after new crucial results by Duan, Fuller, Carlson, Qian '05-'06

Lesson: self-interactions (μ) can induce non-MSW, nonlinear flavor evolution at small radii, despite the large matter density λ

Recent "wave" of papers on SN neutrino self interactions (time-ordered):

[01] Fuller & Qian	astro-ph/0505240	
[02] Duan, Fuller & Qian	astro-ph/0511275	<– The "synchronized" and "bipolar" regimes
[03] Duan, Fuller, Carlson & Qian	astro-ph/0606616	<– Large-scale multi-angle calculations
[04] Balantekin & Pehlivan	astro-ph/0607527	
[05] Duan, Fuller, Carlson & Qian	astro-ph/0608050	
[06] Hannestad, Raffelt, Sigl & Wong	astro-ph/0608695	<– The "flavor pendulum" analogy
[07] Raffelt & Sigl	hep-ph/0701182	
[08] Duan, Fuller, Carlson & Qian	astro-ph/0703776	
[09] Raffelt and Smirnov	hep-ph/0705.1830	<– The "spectral split"
[10] Esteban, Pastor, Tomas, Raffelt & Sigl	astro-ph/0706.2498	
[11] Duan, Fuller & Qian	astro-ph/0706.4293	
[12] Duan, Fuller, Carlson & Qian	astro-ph/0707.0290	<– The "spectral split"
[13] Fogli, Lisi, Marrone & Mirizzi	hep-ph/0707.1998	<– Our work **(this talk)**
[14] Raffelt & Smirnov	hep-ph/0709.4641	
[15] Duan, Fuller, Carlson & Qian	astro-ph/0710.1271	
[16] Esteban, Pastor, Tomas, Raffelt & Sigl	astro-ph/0712.1137	<– The mu-tau flavor difference
[17] Dasgupta & Dighe	hep-ph/0712.3798	<– The three neutrino formalism
[18] Duan, Fuller & Qian	hep-ph/0801.1363	<– Three-neutrino spectral split
[19] Dasgupta, Dighe, Mirizzi & Raffelt	hep-ph/0801.1660	<– Three-neutrino spectral split
[20] Dasgupta, Dighe & Mirizzi	hep-ph/0802.1481	<– Earth effects + hierarchy
[21] Duan, Fuller & Carlson	astro-ph/0803.3650	
[22] Chakraborty, Choubey, Dasgupta & Kar	hep-ph/0805.3131	
[23] Dasgupta, Dighe, Mirizzi & Raffelt	hep-ph/0805.3300	<- Non-spherical geometry
[24] Gava & Volpe	astro-ph/0807.3418	<- CP-violation effects
[25] Esteban-Pretel & al.	astro-ph/0807.0659	
[26] Duan, Fuller & Qian	astro-ph/0808.2046	
[27] Fogli, Lisi, Marrone, Mirizzi & Tamborra	hep-ph/0808.0807	<- Our work **(this talk)**
[28] Dighe	hep-ph/0809.2977	
[29] Raffelt	hep-ph/0810.1407	
[30] Blennow, Mirizzi, Serpico	hep-ph/0810.2297	<- Nonstandard interactions
[31] Fogli, Lisi, Marrone, Tamborra	hep-ph/0812.3031	<- Our work **(this talk)**
[32] Sigl & al.	hep-ph/0901.0725	
[33] Gava, Kneller, Volpe, McLaughlin	hep-ph/0902.0317	

Outline

- Coupled equations of motion
- The “pendulum” and the “split”
- Discussion of our work(*)
- Conclusions

(*) hep-ph/0707.1998
hep-ph/0808.0807
hep-ph/0812.3031

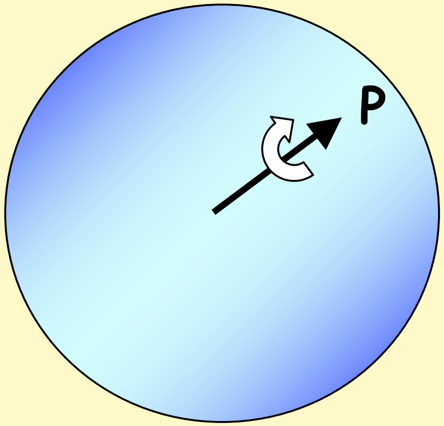
Coupled equations of motion (for 2 flavors, e and $x=\mu,\tau$)

Neutrino wavefunction sensitive to neutrino density -> use density matrix.

Liouville equations: $i\partial_t \rho=[H,\rho]$ (for each neutrino mode)

Decompose 2x2 (anti)neutrino density matrix over Pauli matrices to get a "**polarization**" (Bloch) 3-vector $\mathbf{P}=(P_1,P_2,P_3)=(P_x,P_y,P_z)$. [Ditto for H.]

Bloch equations: $\partial_t \mathbf{P} = \mathbf{V}\times\mathbf{P}$ (precession-like, $|P|$=const)



Any mode P moves on a Bloch sphere (abstract "flavor space").

"up" direction : ν_e flavor

"down" direct. : ν_x flavor

generic direct. : mixed flavor state

Probability P_{ee} related to $P_3=P_Z$

Coupled equations of motion (cont'd)

The problem is that there are lots of kinematical neutrino modes: continuous distributions over energy and angle(s) -> no less than ∞^2 !

Discretize over energy spectrum (**N_E bins**), and over angular distribution in multi-angle simulations (**N_Θ bins**) -> *Get discrete index (indices),* **P_i** .

Evolution governed by **$6 \times N_E \times N_\Theta$ coupled Bloch equations** of the form (or, in single-angle, by **$6 \times N_E$ coupled equations**):

$$
\begin{aligned}
\dot{\mathbf{P}}_i &= \mathbf{V}_{\mathrm{ector}}[+\omega,\ \lambda,\ \mu,\ \mathbf{P}_j,\ \overline{\mathbf{P}}_j] \times \mathbf{P}_i \\
\dot{\overline{\mathbf{P}}}_i &= \mathbf{V}_{\mathrm{ector}}[-\underset{\substack{\uparrow \\ \text{vacuum}}}{\omega},\ \underset{\substack{\uparrow \\ \text{matter}}}{\lambda},\ \underset{\substack{\uparrow \\ \text{self-interaction}}}{\mu},\ \underbrace{\mathbf{P}_j,\ \overline{\mathbf{P}}_j}_{\text{ij couplings}}] \times \overline{\mathbf{P}}_i
\end{aligned}
$$

Large, "stiff" set of (strongly) coupled differential equations.

EOM in single-angle approximation:

$$\dot{\mathbf{P}} = \left[+\omega\mathbf{B} + \lambda\mathbf{z} + \mu \sum_E (\mathbf{P} - \overline{\mathbf{P}})\right] \times \mathbf{P}$$
$$\dot{\overline{\mathbf{P}}} = \left[-\omega\mathbf{B} + \lambda\mathbf{z} + \mu \sum_E (\mathbf{P} - \overline{\mathbf{P}})\right] \times \overline{\mathbf{P}}$$

$\mathbf{P} = \mathbf{P}_E$
$\mathbf{z} = (0,\, 0,\, 1)^T$
$\mathbf{B} = (\sin 2\theta_{13},\, 0,\, \pm\cos 2\theta_{13})$

Subcases and analogies:

(1) $\dot{\mathbf{P}} = [+\omega\mathbf{B}] \times \mathbf{P}$	Vacuum
(2) $\dot{\mathbf{P}} = [+\omega\mathbf{B} + \lambda\mathbf{z}] \times \mathbf{P}$	MSW
(3) $\dot{\mathbf{P}} = \left[+\omega\mathbf{B} + \lambda\mathbf{z} + \mu \sum_E (\mathbf{P} - \overline{\mathbf{P}})\right] \times \mathbf{P}$	**Self-int.**

(1) Precessing "spin" **P** in external "magnetic" field **B** with frequency ω

(2) Precession in magnetic field with variable frequency and direction

(3) Precession in variable m.f. plus additional fields from other spins
-> collective effects and spin coupling show up

Strong couplings between polarization vectors make the problem difficult, but also make an analytical understanding possible after all !
Key tool of "**near-alignment**" or "**strong polarization**", e.g.:

$$\mathbf{P}_i\text{'s} \longrightarrow \mathbf{J} = \Sigma_i \, \mathbf{P}_i$$

(global polarization vector)

In general, bunches of P's seem to be "pinned" to some global vector, provided that the global configurations obey net lepton # conservation:

$$(\nu_e \overline{\nu}_e \rightarrow \nu_x \overline{\nu}_x, \ \text{but } \#(\nu_e - \overline{\nu}_e) = \text{const})$$

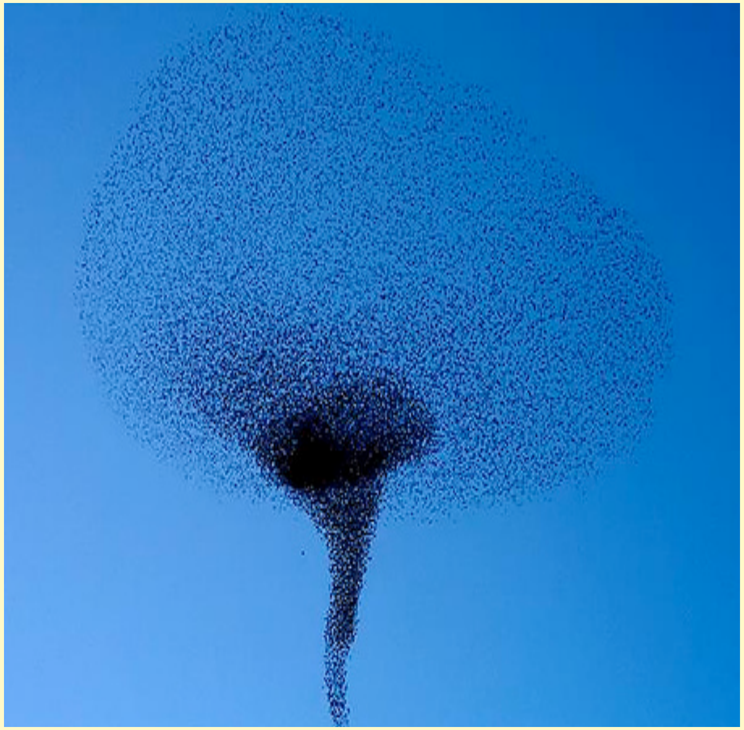
Equations become more complicated in three flavors:
- Need to project 3x3 density matrices onto Gell-Mann matrices
- Get 8-dimensional polarization vectors (larger system of eqs.)
- Need to include/check possible subtle 3-neutrino effects

Note that three-family scenarios do not admit exact two-family subcases in the presence of neutrino self-interactions:
e.g., it matters whether the absolute SN neutrino luminosity is shared among three or two families.

[Unlike the "usual" neutrino oscillations at low density, whose description does not depend on the beam luminosity.]

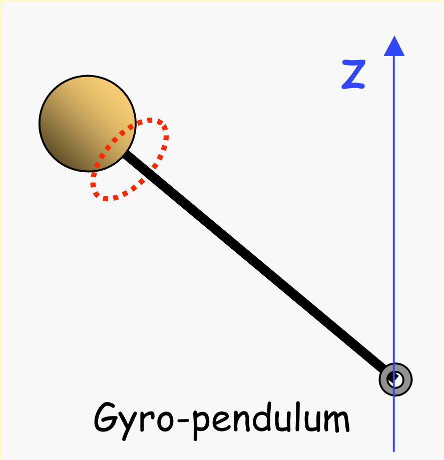
Nevertheless, in both two- and three-flavor scenarios, similar features characterize the most important collective phenomena, such as…

… the flavor pendulum



… and the spectral split

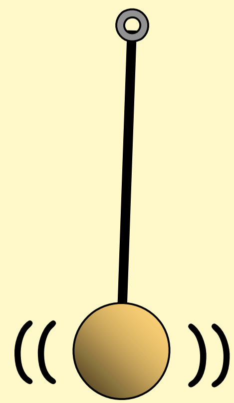
One global polarization vector obeys the eqs. of a gyroscopic pendulum!



Roughly speaking:

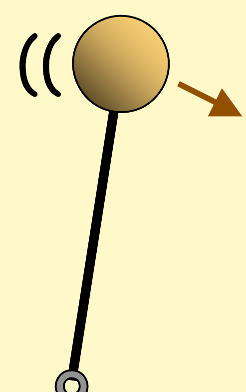
Mass^{-1} ~ (anti)neutrino density

Spin ~ #neutrino - #antineutrino



Normal hierarchy:

Pendulum starts in ~downward (stable) position and stays nearby. No significant flavor change.

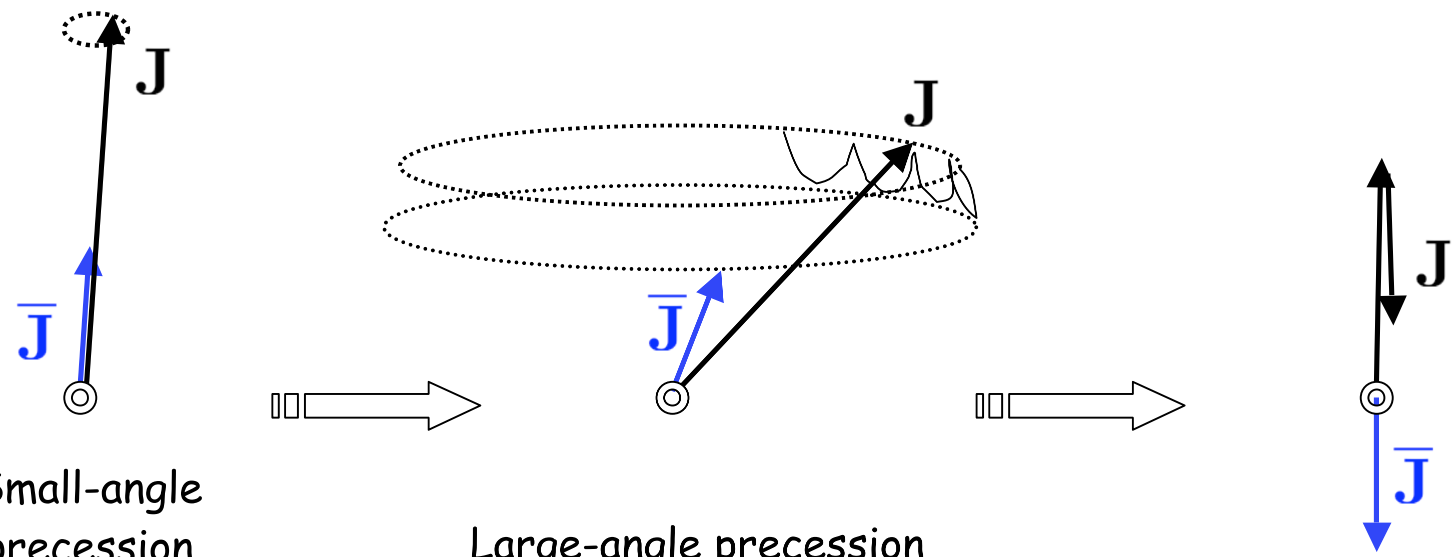


Inverted hierarchy:

Pendulum starts in ~upward (unstable) position and eventually falls down (wiggling) for any $\theta_{13} > 0$! Significant flavor changes.

Hereafter, inv. hierarchy and $\theta_{13}>0$ assumed.

Global polarization vectors of neutrinos and antineutrinos (**J** and $\underline{\mathbf{J}}$, with $|\mathbf{J}|>|\underline{\mathbf{J}}|$) follow pendulum motion as far as near-alignment holds. Eventually $\underline{\mathbf{J}}$ reaches the stable downward position, while **J** can't, to preserve lepton number conservation ($\sim J_z-\underline{J}_z$)



Small-angle precession ("synchronized oscillations")

Large-angle precession +nutations ("bipolar oscillations ")

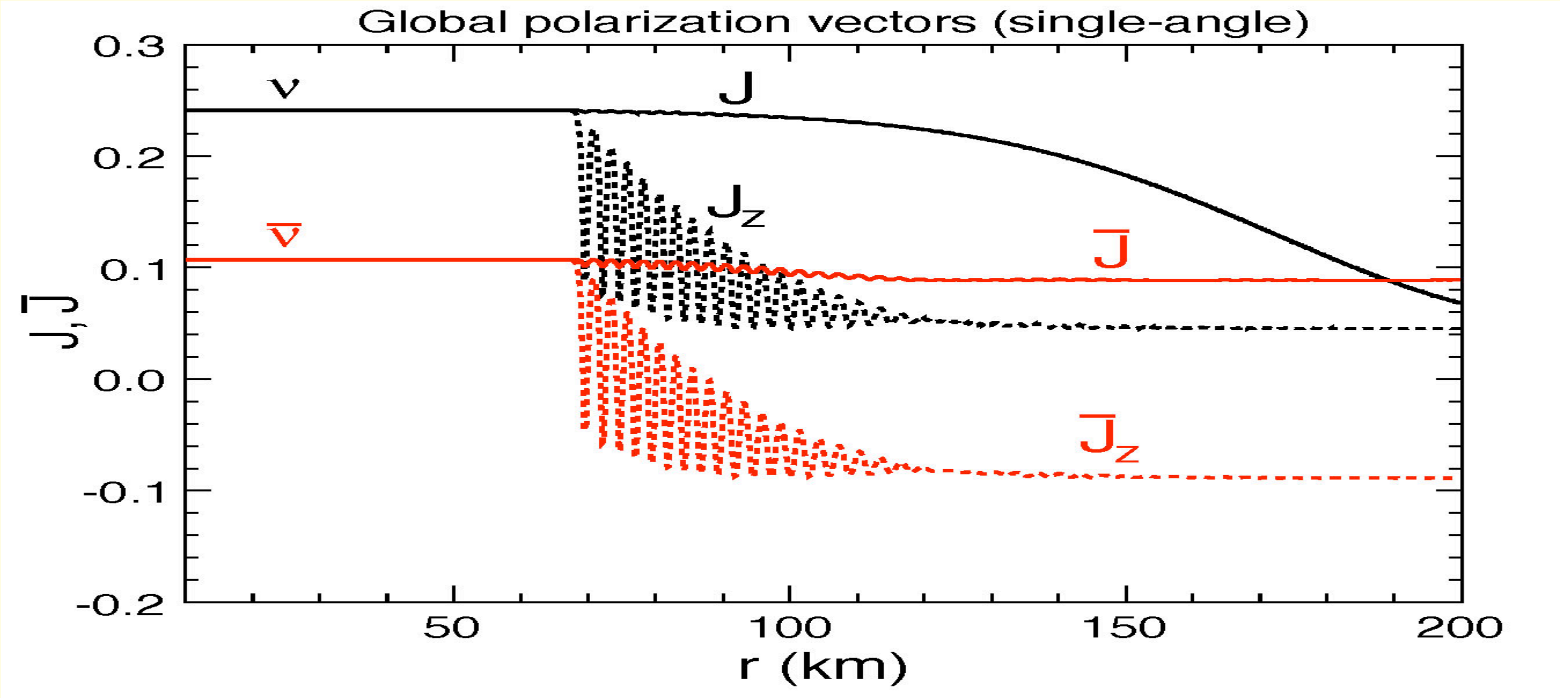
Final stable configuration (**J** "splits")

Final state: whole $\underline{\mathbf{J}}$ and **high-E part of J** inverted (**spectral split/swap**)

(Inversion = complete flavor change)

Some results from our calculations

Evolution of global polarization vectors (two flavors)

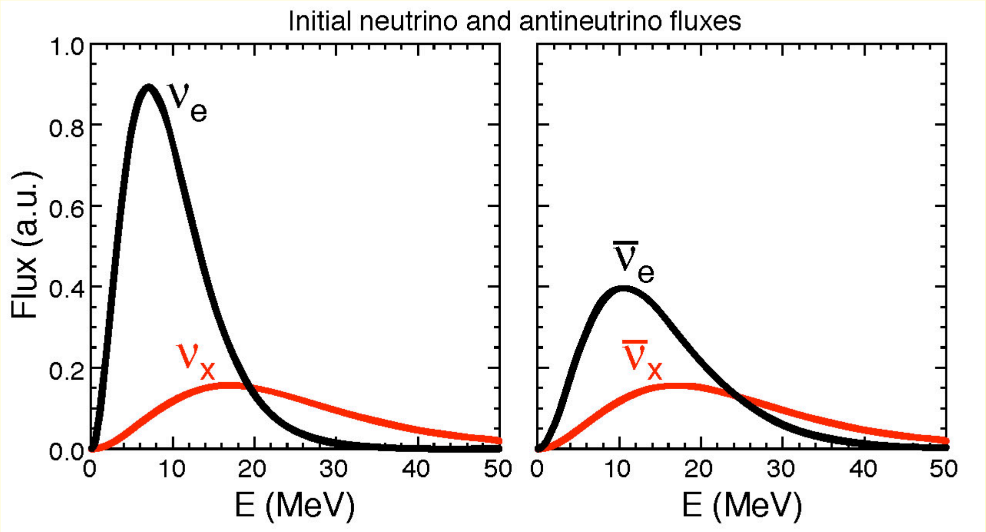


...alignment

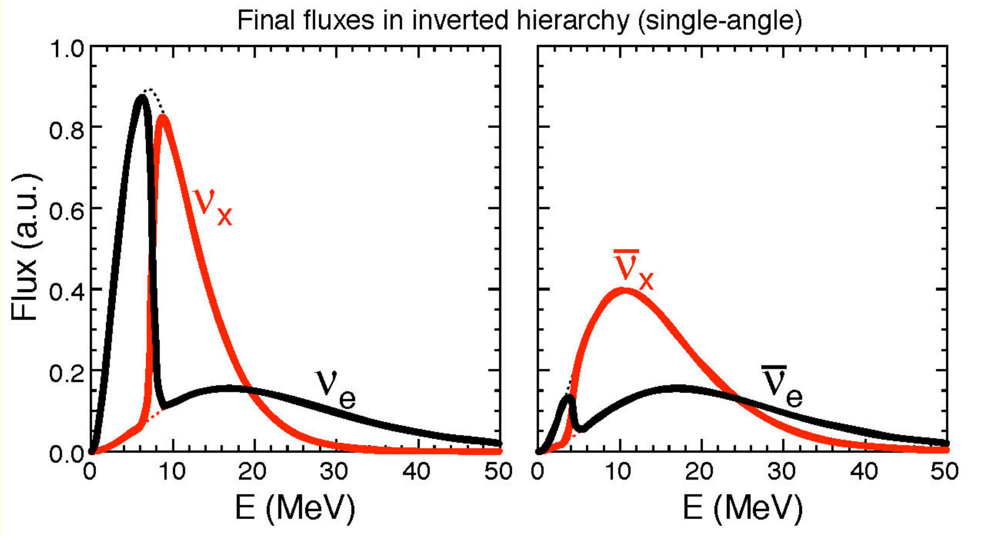
... swings

... split

Energy spectra (two-flavors)



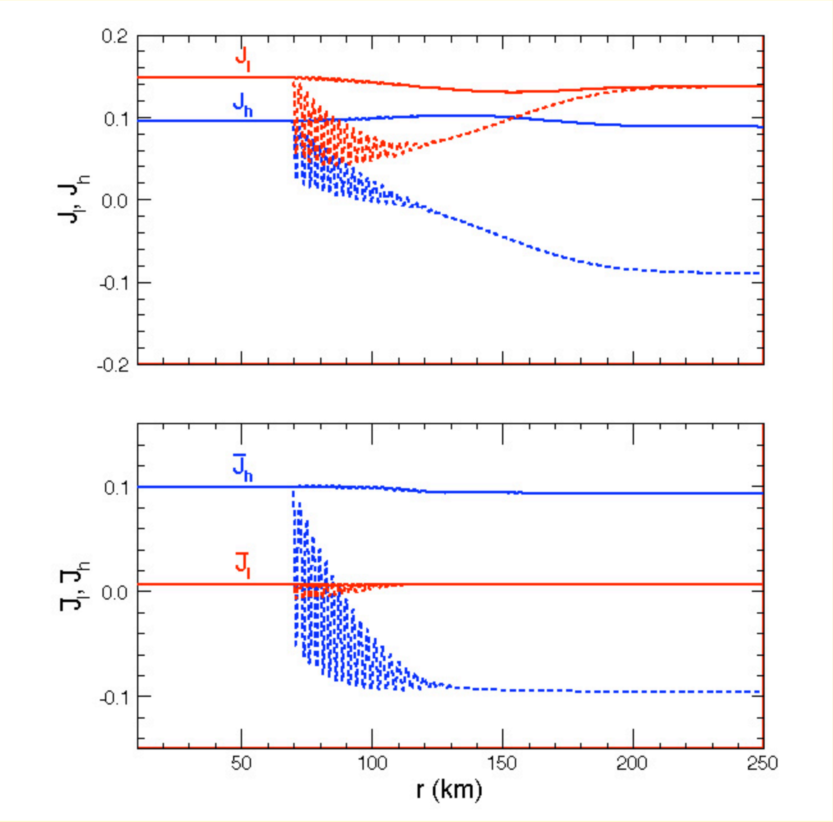
Initial fluxes at the neutrinosphere (r~10 km)



Final fluxes at the end of collective effects (r~200 km)

Expected neutrino split

+unexpected antineutrino split at lower energy



The antineutrino split is related, in a still unclear way, to nonadiabatic features of the flavor evolution.

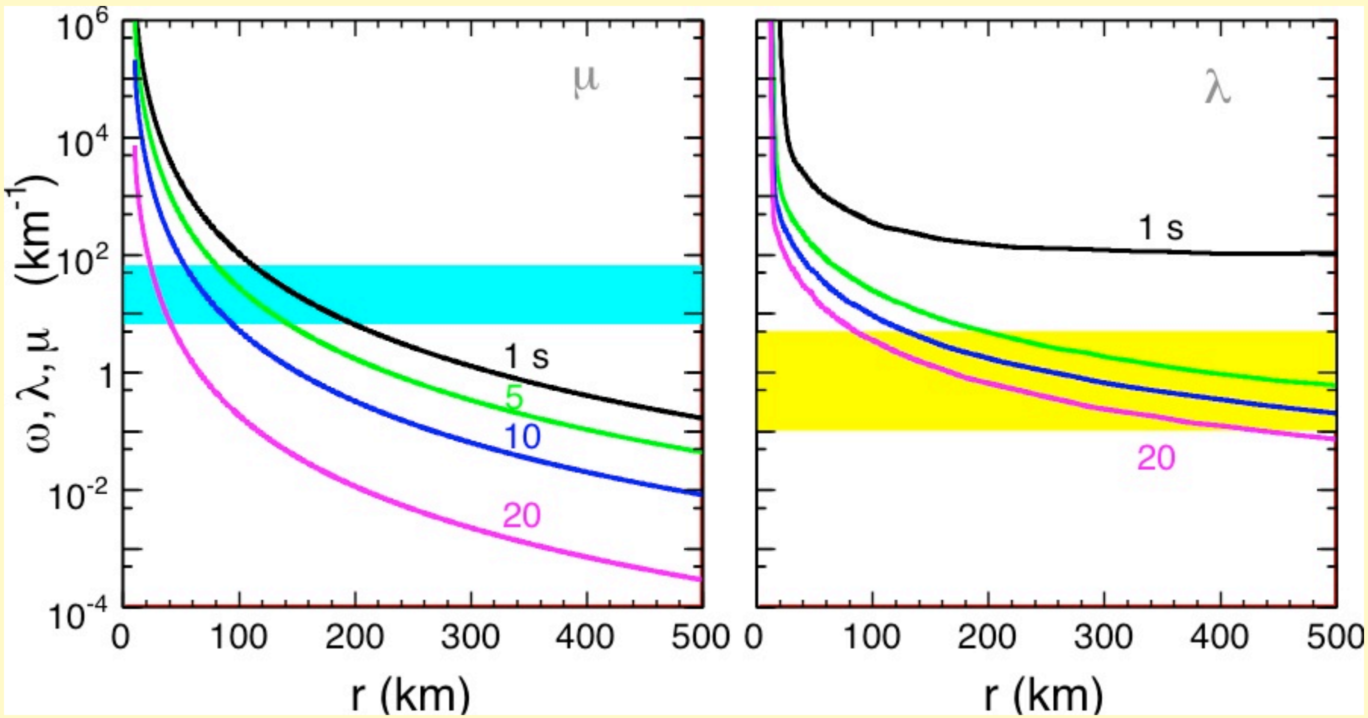
It appears that a decription in terms of four global vectors (low/high energy neutrinos and antineutrinos) may capture this behavior.

$$
\begin{aligned}
\dot{\mathbf{J}}_l &= (+\omega_l \mathbf{B} + \lambda \mathbf{z} + \mu \mathbf{D}) \times \mathbf{J}_l \ , \\
\dot{\mathbf{J}}_h &= (+\omega_h \mathbf{B} + \lambda \mathbf{z} + \mu \mathbf{D}) \times \mathbf{J}_h \ , \\
\dot{\overline{\mathbf{J}}}_l &= (-\overline{\omega}_l \mathbf{B} + \lambda \mathbf{z} + \mu \mathbf{D}) \times \overline{\mathbf{J}}_l \ , \\
\dot{\overline{\mathbf{J}}}_h &= (-\overline{\omega}_h \mathbf{B} + \lambda \mathbf{z} + \mu \mathbf{D}) \times \overline{\mathbf{J}}_h \ .
\end{aligned}
$$

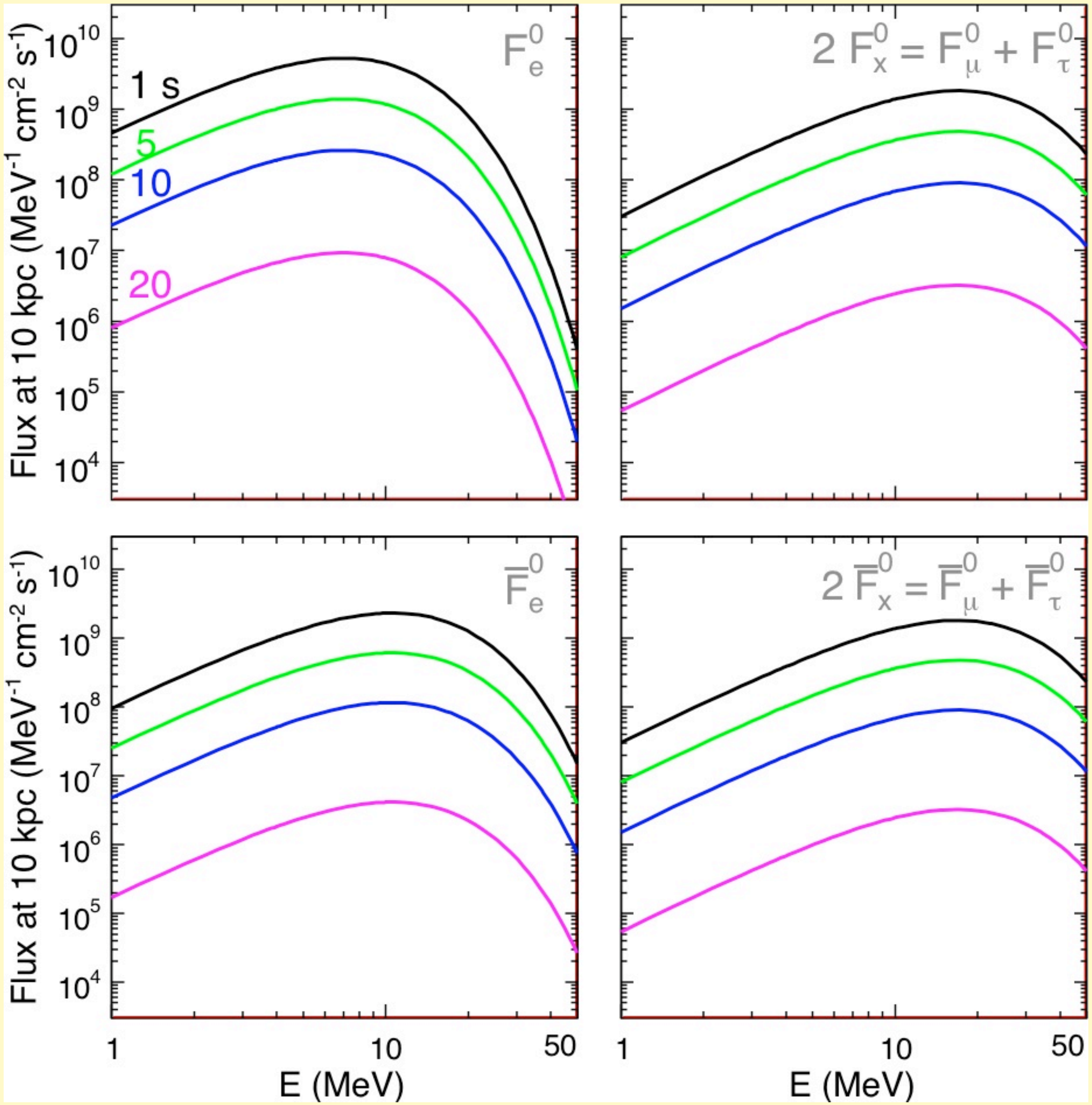
When passing to multi-angle simulations, the neutrino split feature is robust, while the antineutrino one seems to be more fragile. More work is needed to understand the low-energy behavior of antineutrinos, and the conditions for their (observable) split.

Recently, we have carried out a full three-flavor calculation in a benchmark supernova model at different post-bounce times (in single-angle approximation), in order to provide estimates for absolute observable fluxes of (anti)neutrinos at d = 10 kpc. We have taken $\sin^2\theta_{13} = 10^{-6}$ to suppress later MSW effects.

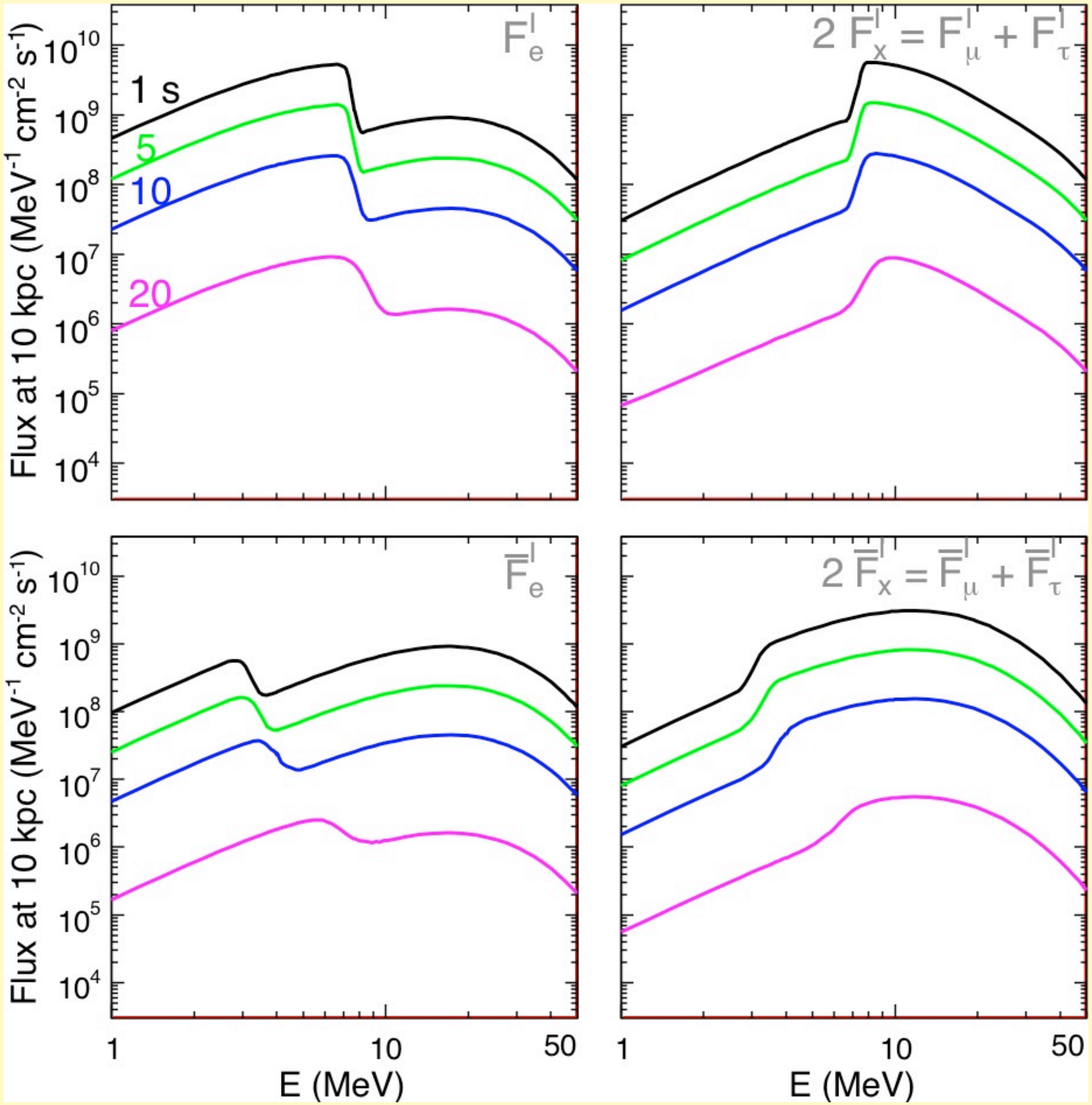
SN self-interaction potential and matter potential:



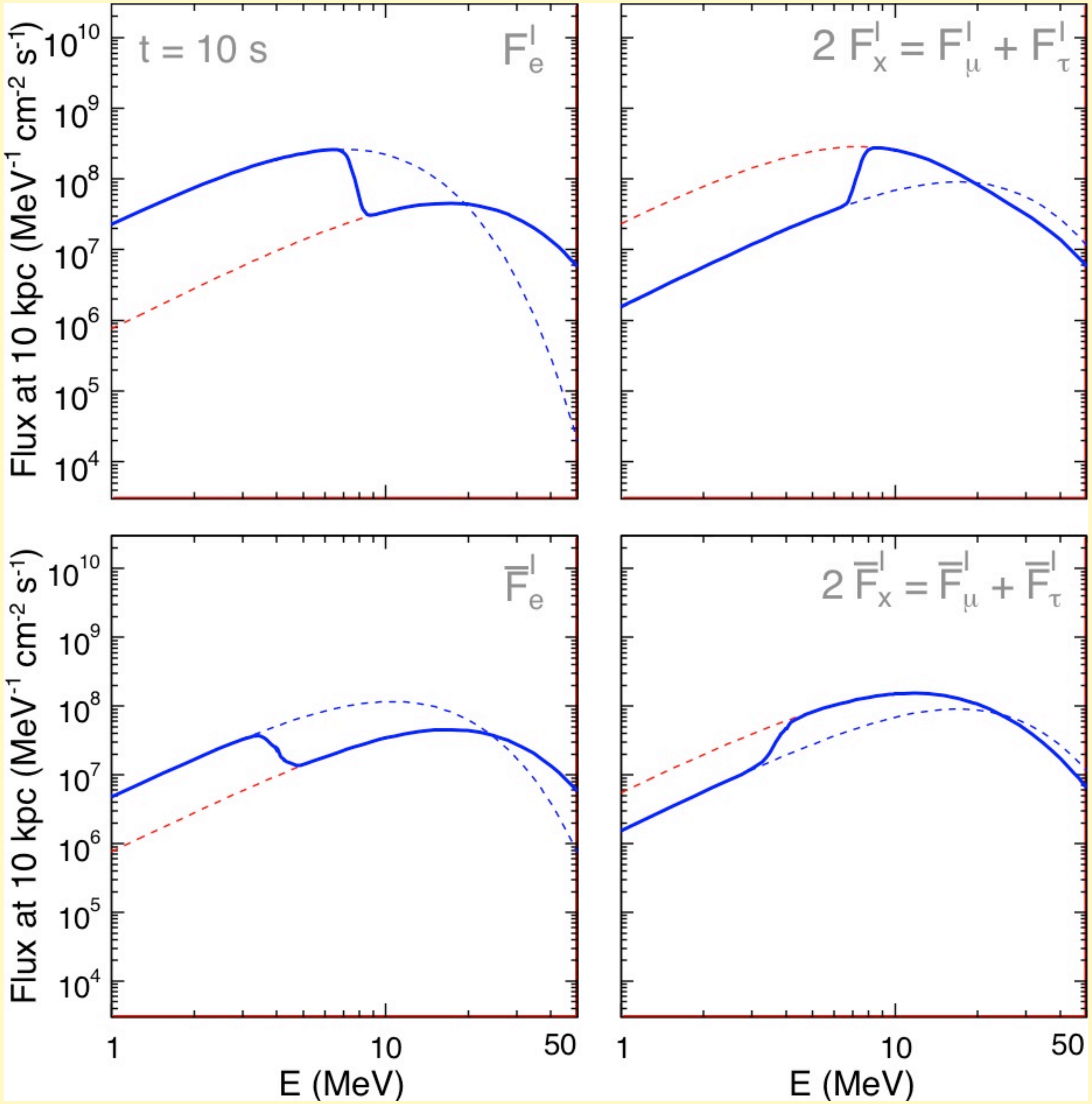
Unoscillated fluxes at the neutrinosphere (projected at d=10 kpc)



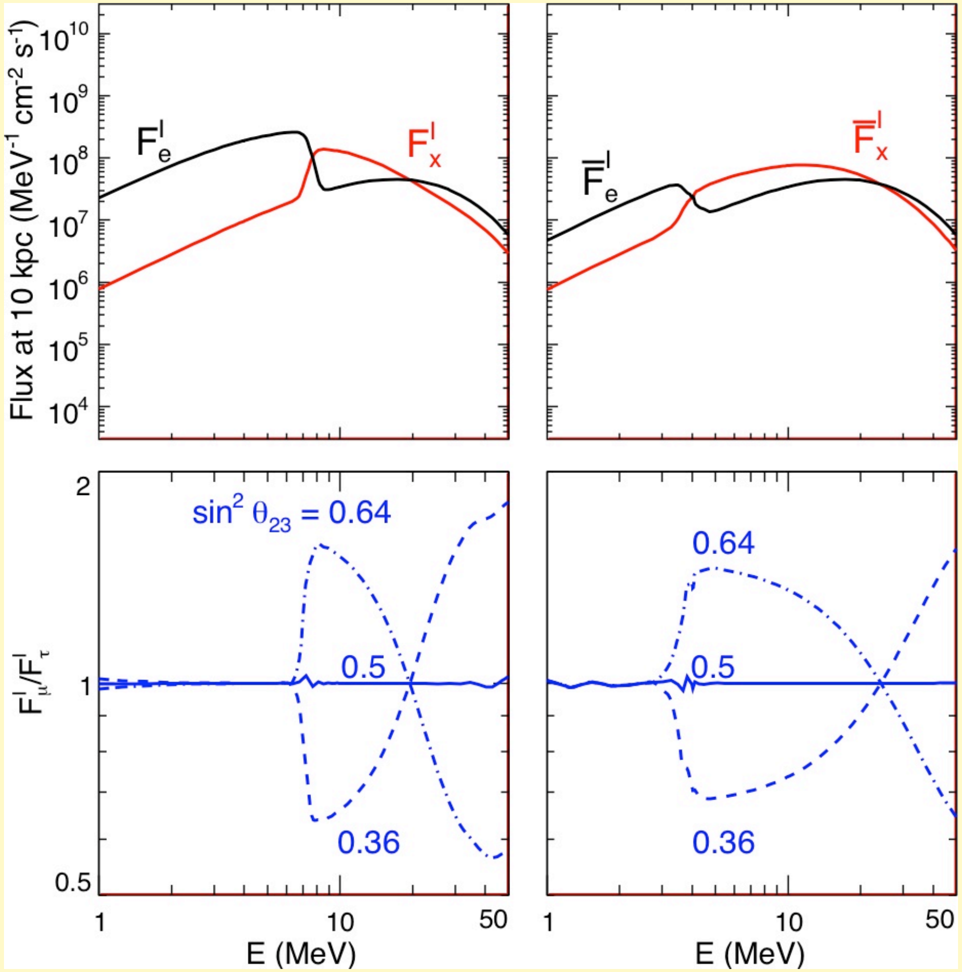
Intermediate fluxes at the end of collective effects



Complete swap above some critical energies:

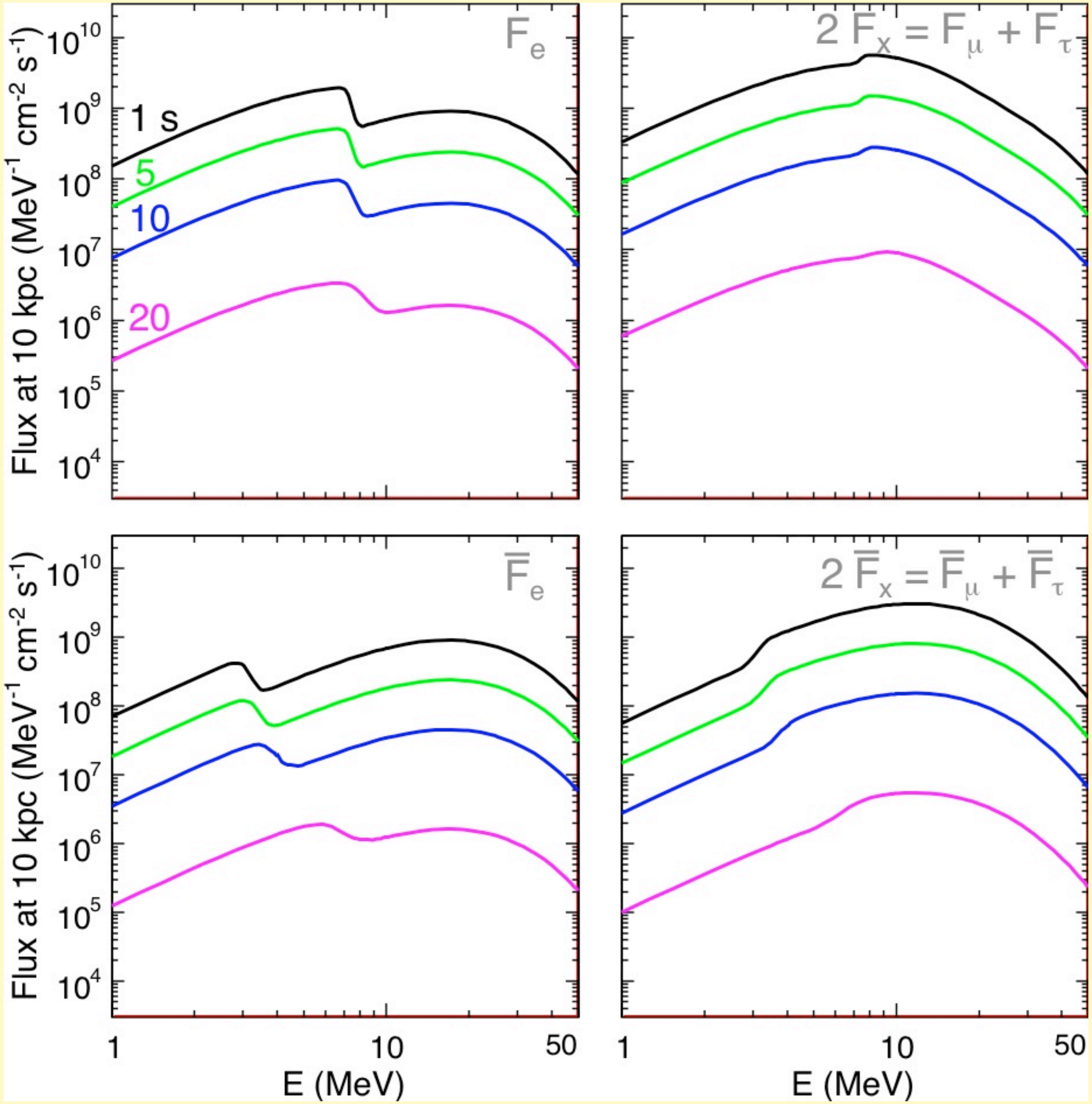


In principle, the mu/tau fraction (unobservable!) could probe θ_{23}

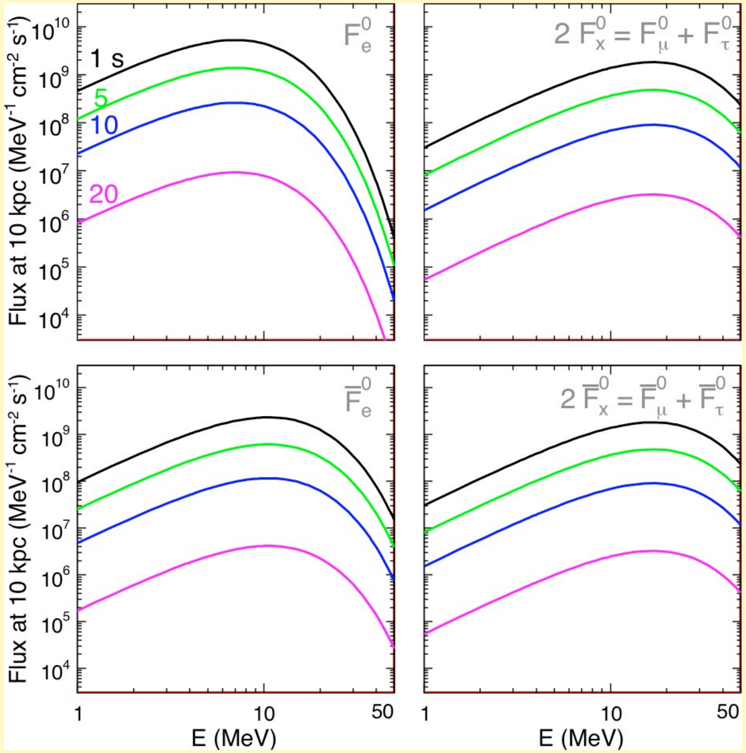


Effects due to solar δm^2 terms and to 1-loop mu-tau neutrino potential turn out to be small (at or below percent level)

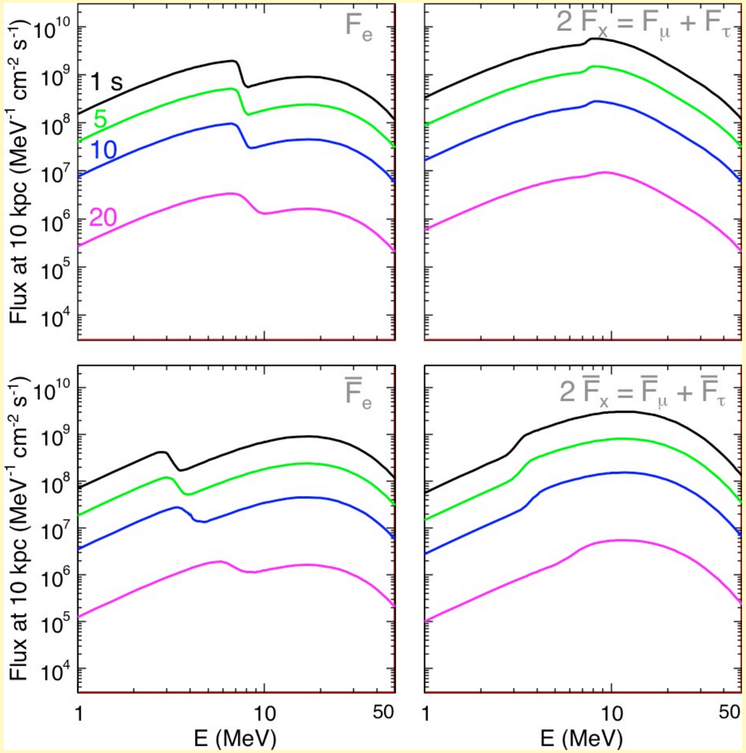
Final fluxes at the detector



Unoscillated

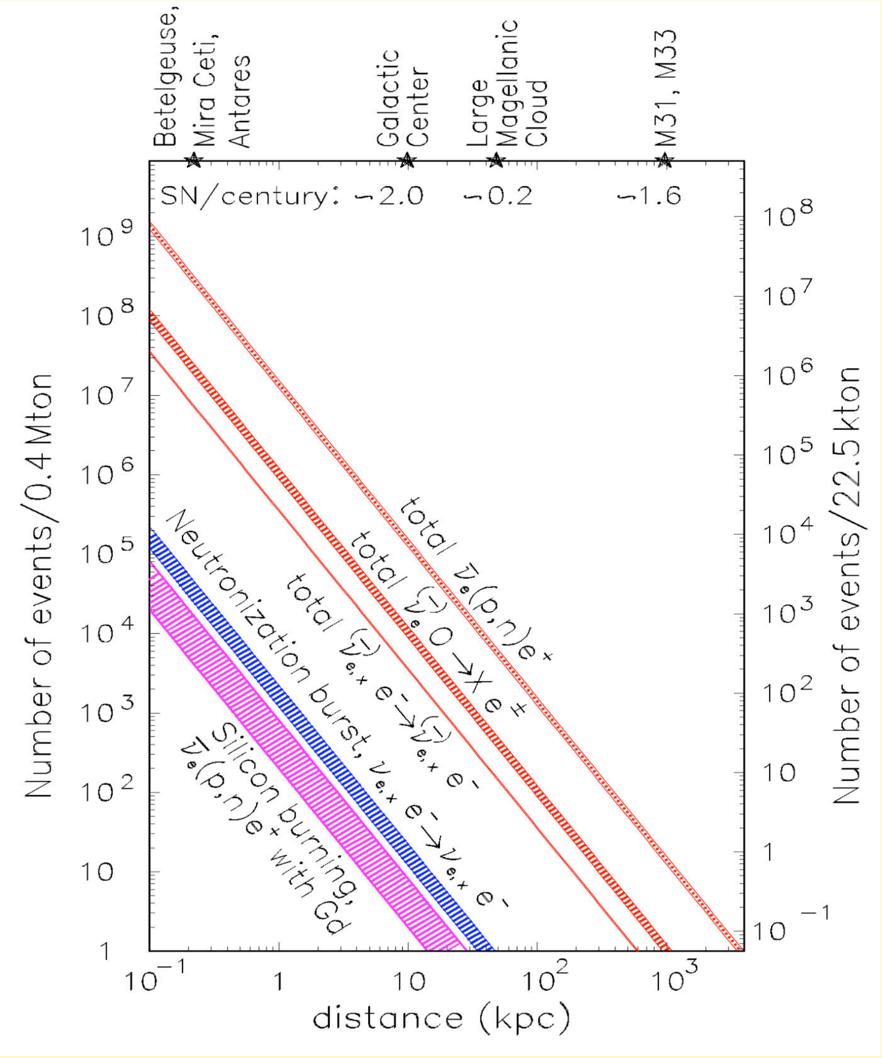


Oscillated



The spectral split features emerge at any time in the interval ~1-20 s. If realized in nature, they should be observable in time-integrated energy spectra.

Total event rates may be high; but low-energy thresholds for (anti)neutrinos are challenging.



CONCLUSIONS

In the dense supernova core, neutrinos are a nontrivial background to themselves - perhaps more important than the matter background

As a consequence, collective flavor transformation phenomena occur. Their understanding has significantly improved in the last few years.

Spectral splits seem to provide relevant observable signatures of self-interactions in inverted hierarchy (provided that θ_{13} is nonzero)

It remains to understand how robust such collective effects are in non-idealized SNe (e.g., in turbulent and asymmetric explosions)

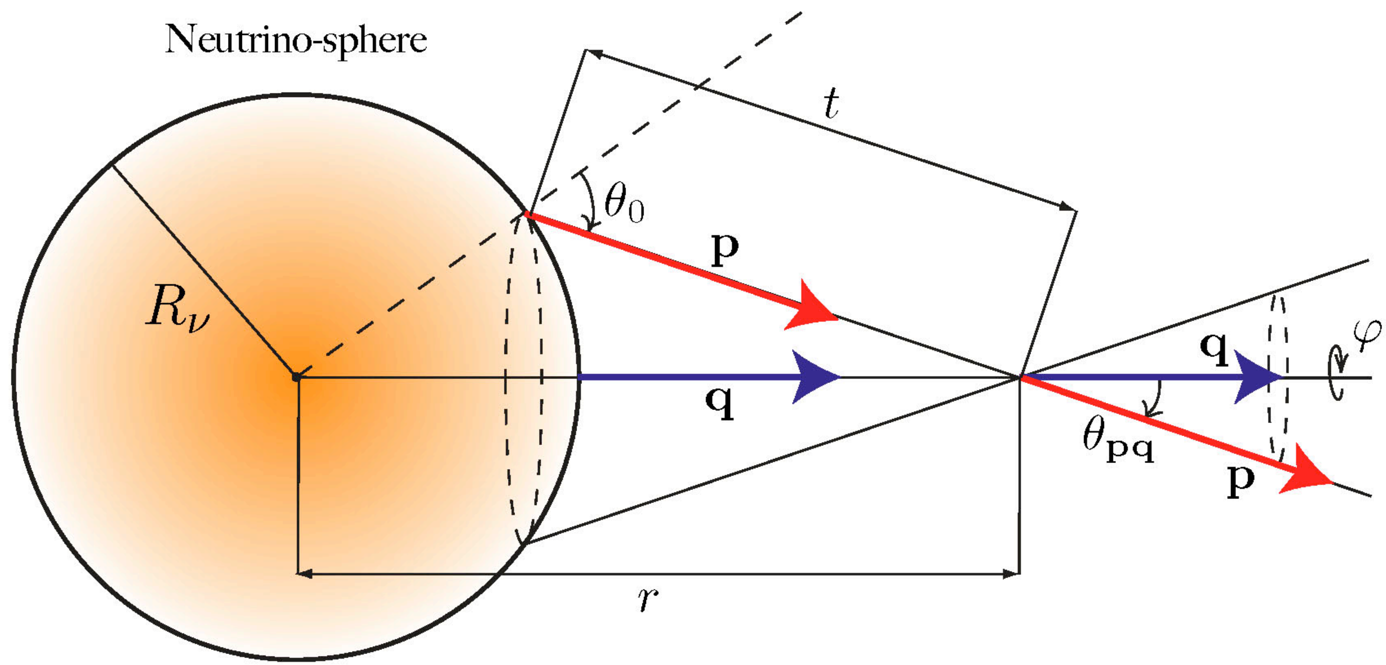
Furthermore, one may wonder whether collective effects may have a feedback on the explosion dynamics itself (hard to implement!)


The next galactic supernova might reveal
collective effects we never thought we'd see!


Thank you
for your
attention.

Backup slides

Geometry: the neutrino bulb model



$$r \sin\theta_{\mathbf{pq}} = R_\nu \sin\theta_0 \qquad t = \sqrt{r^2 - R_\nu^2 \sin^2\theta_0} - R_\nu \cos\theta_0$$

Single-angle vs Multi-angle (individual components P_i)