Neutrino self interactions in Supernovae

Rencontres de Moriond 2008
Electroweak Interactions and Unified Theories

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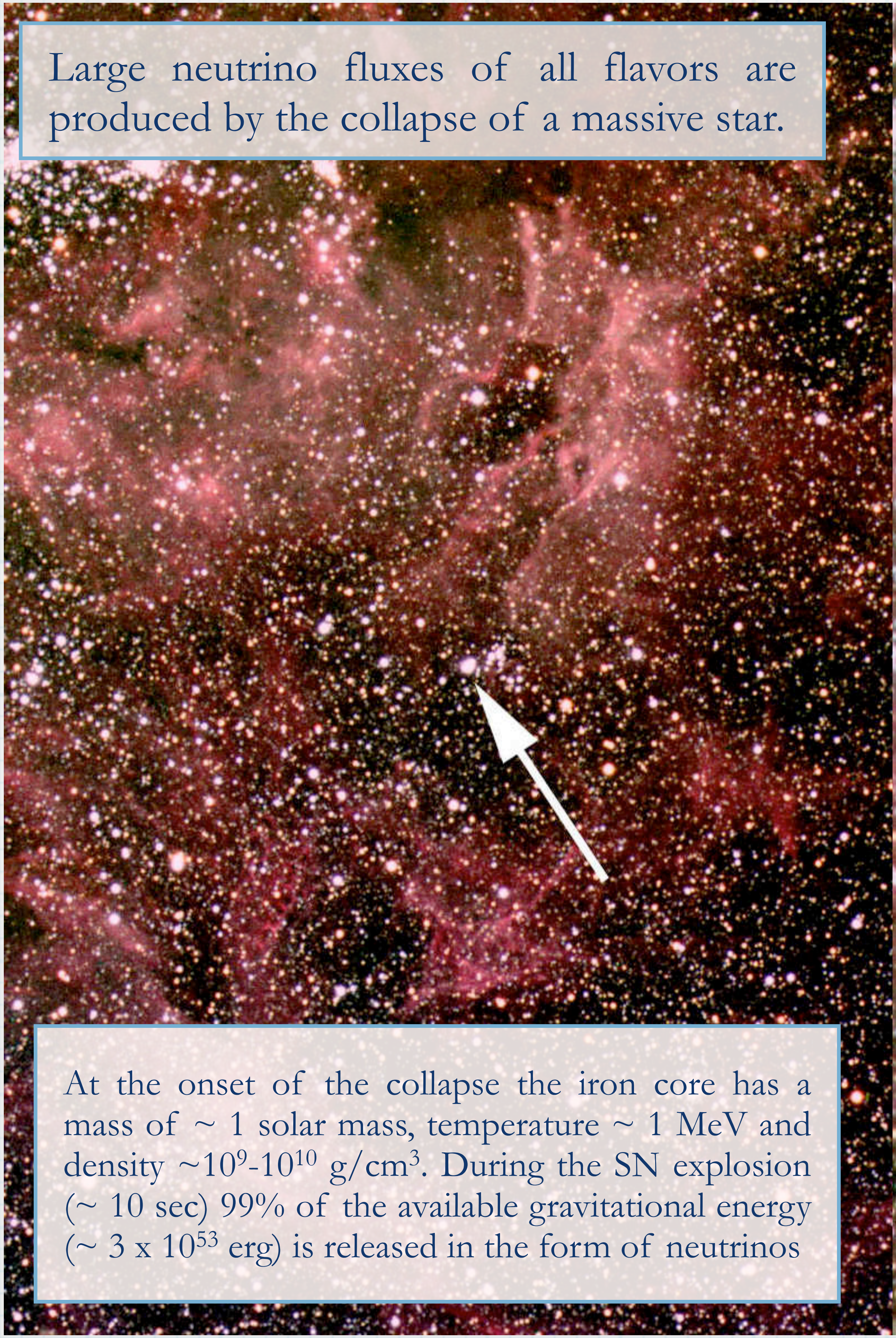
Large neutrino fluxes of all flavors are produced by the collapse of a massive star.



At the onset of the collapse the iron core has a mass of ~ 1 solar mass, temperature ~ 1 MeV and density ~10^9-10^{10} g/cm^3. During the SN explosion (~ 10 sec) 99% of the available gravitational energy (~ 3 x 10^{53} erg) is released in the form of neutrinos

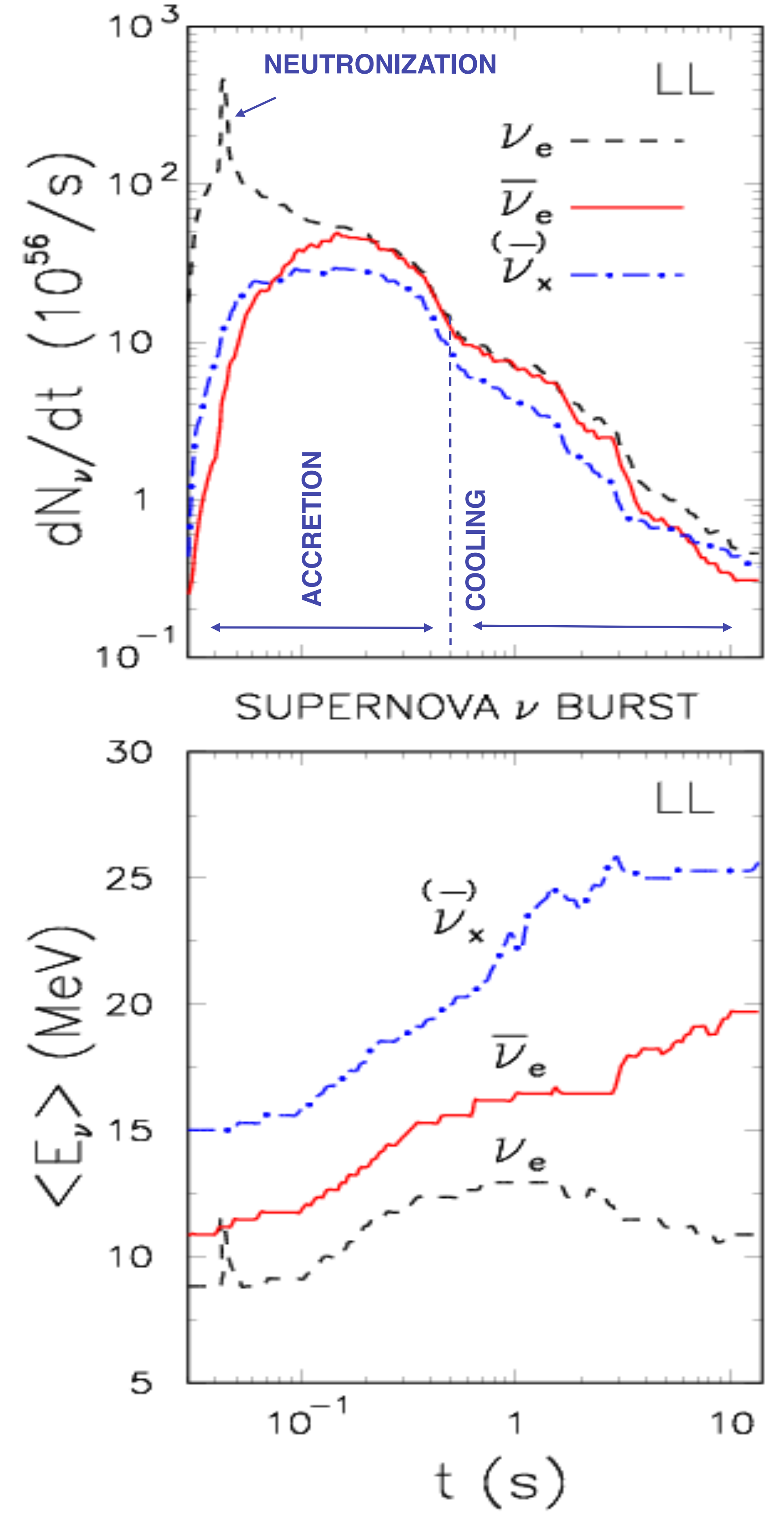
SN 1987A

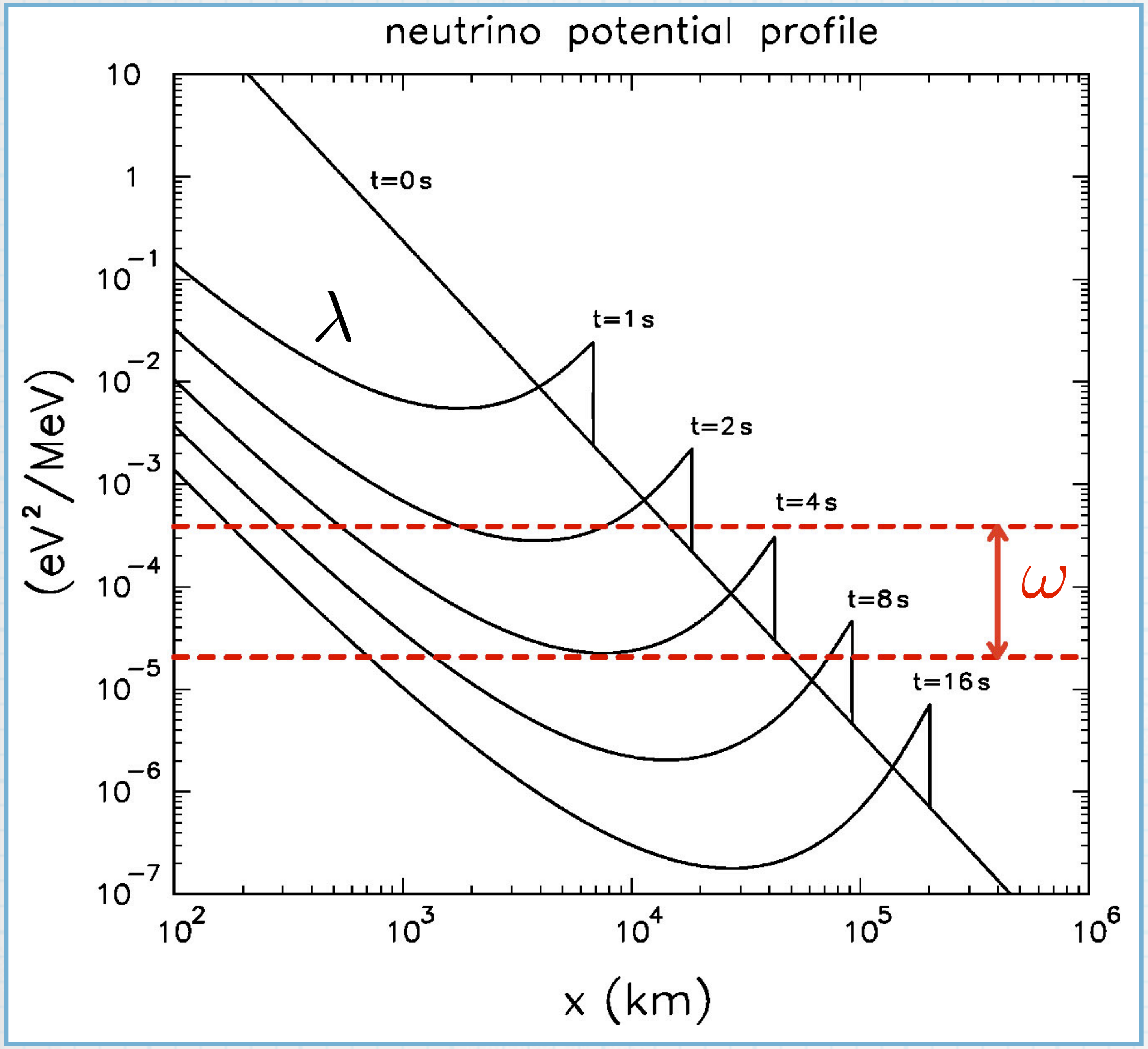
Muon and tau (anti)neutrino are collectively denoted as ν_x , since they can interact only through (nearly) flavor independent NC weak processes

Neutrinos are emitted in ~ 10 sec

Hierarchy of averages energies

$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle = \langle E_{\bar{\nu}_x} \rangle$$





MSW matter effects when the neutrino potential is close to the neutrino oscillation frequency, i.e. a resonance for δm^2_{sol} or Δm^2_{atm}

$$\lambda = \sqrt{2} G_F N_e \approx \omega = \Delta m^2/2E$$

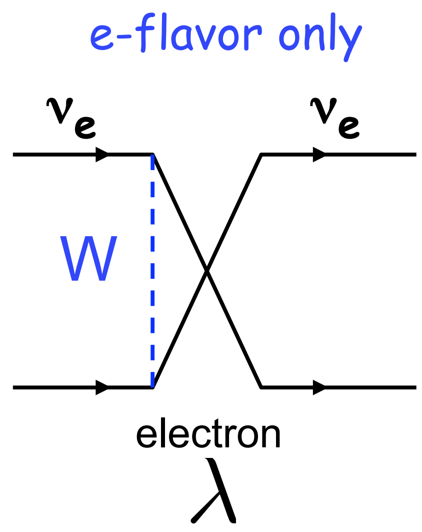
Resonance radius depends on the adopted matter potential profile. For time less than 10 sec the resonance condition is satisfied for $r \gtrsim 200\ km$

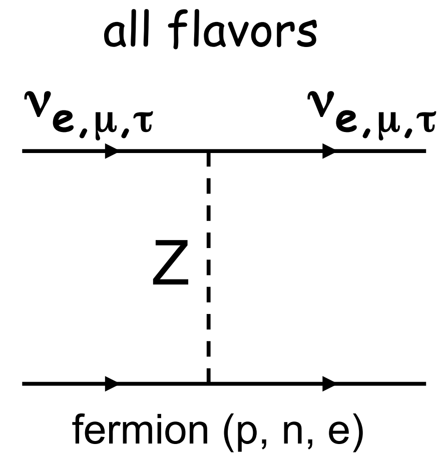
What happens when $r \lesssim 200\ km$?

Usual MSW effect: $\lambda \gg \omega$ oscillations are suppressed

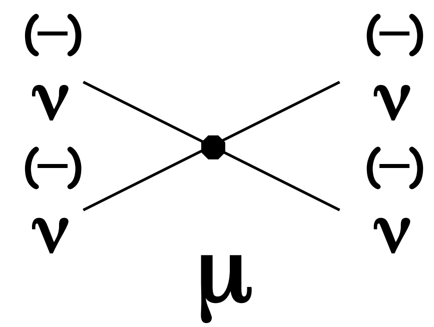
It turns out that the neutrino self interactions are not negligible at small radii and induce not trivial collective oscillation effects

In usual matter





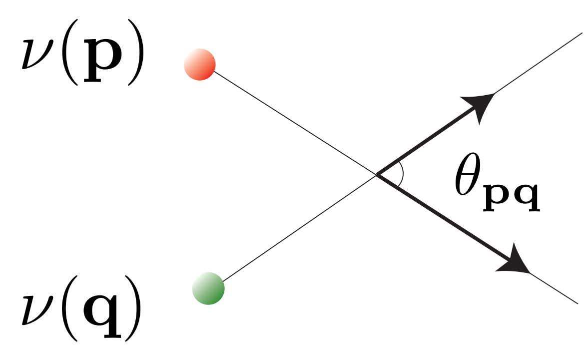
Near the SN core the neutrino density is so high that also neutrino-neutrino scattering is important



In analogy to the MSW effect the contribution to the Hamiltonian is proportional to $\sqrt{2}G_F n_\nu$

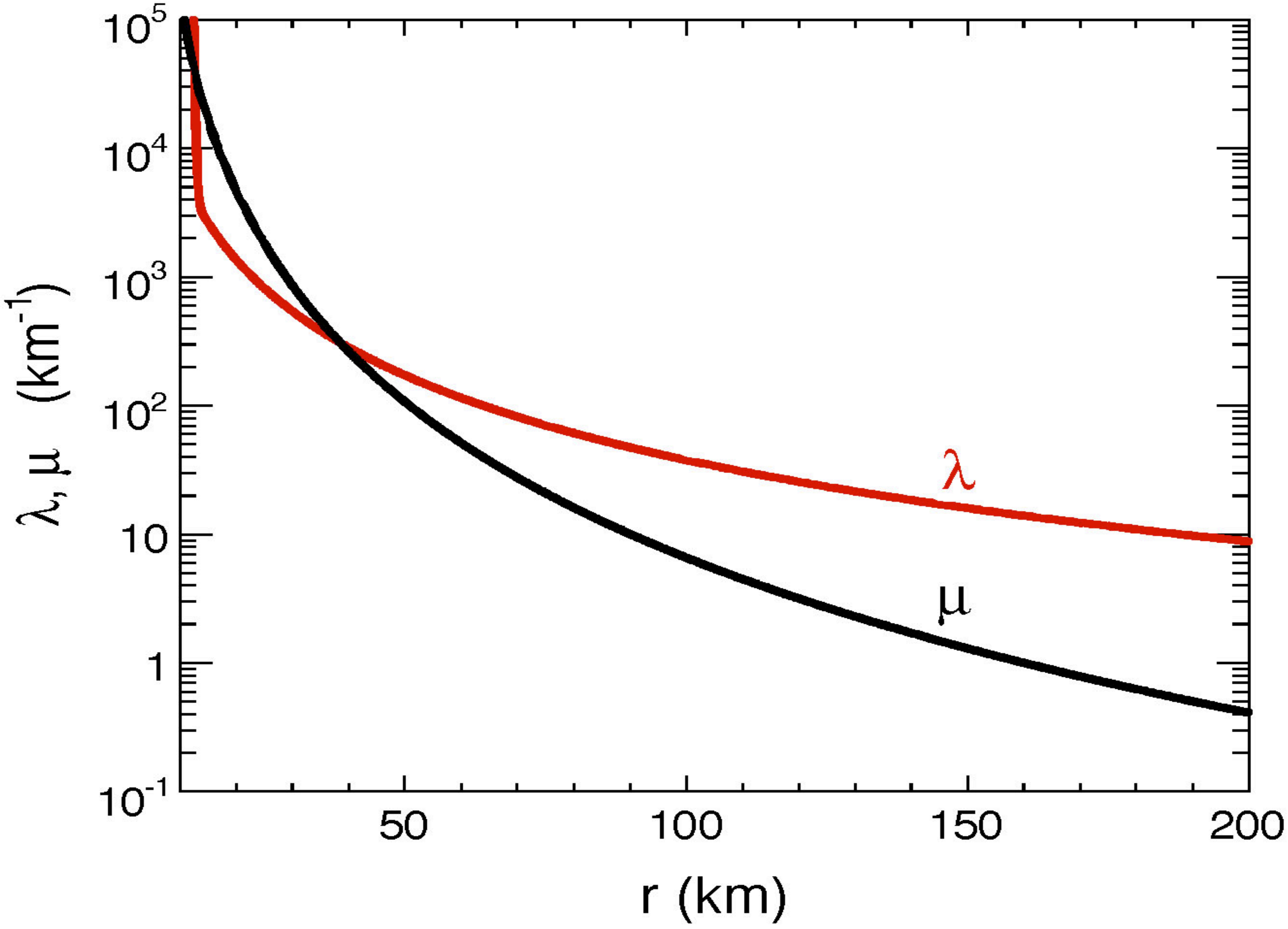
collinear neutrinos
no $\nu\nu$ scattering

the $\nu\nu$ cross section
is maximal



The cross section interaction $\propto \sqrt{2}G_F n_\nu (1 - \cos\theta_{\mathbf{pq}})$

Matter and self-interaction potential



$$\lambda(r) = \sqrt{2} G_F N_{e^-}(r)$$

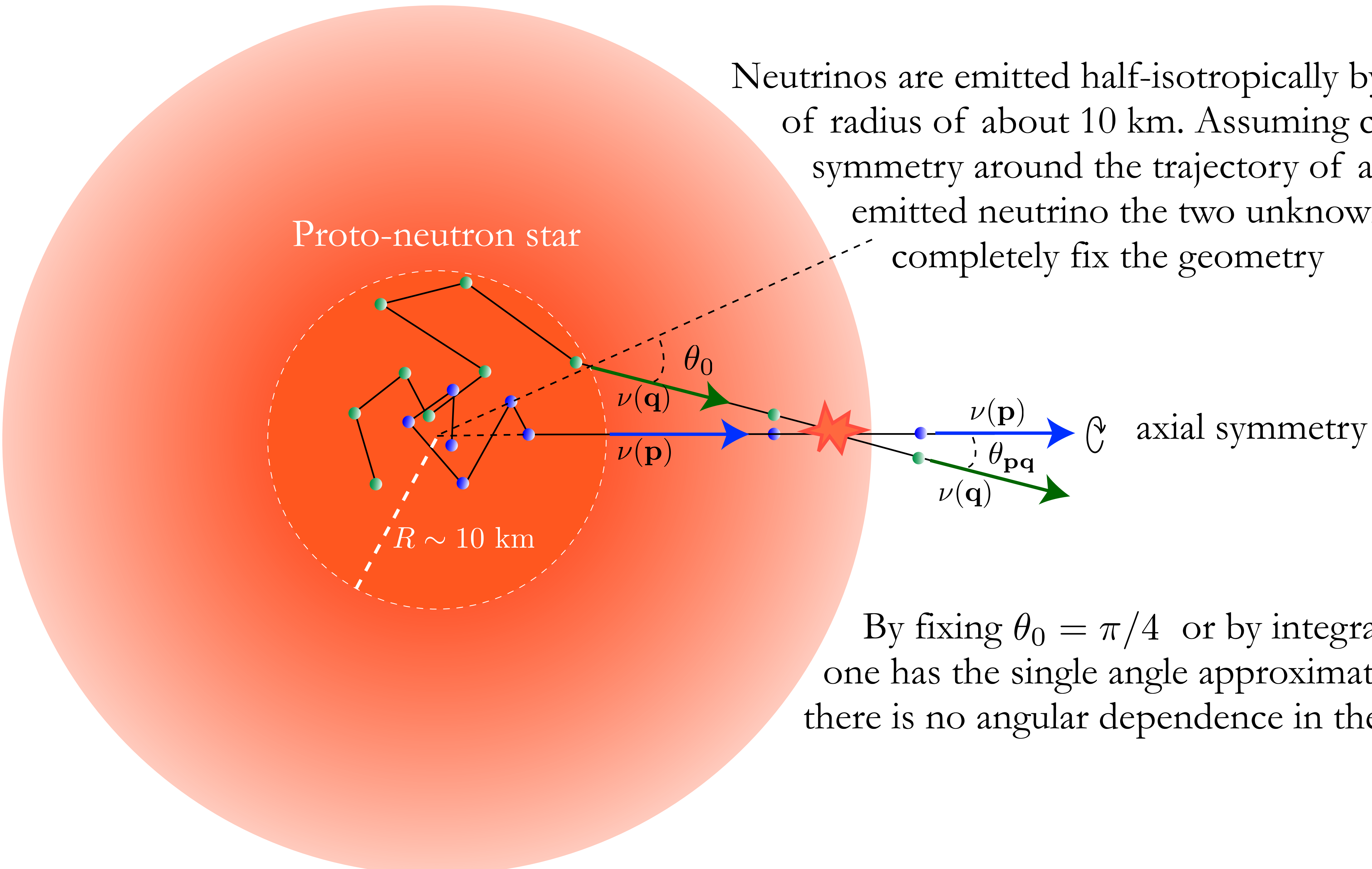
Matter potential profile from numerical SN simulation at t=5 sec after the bounce. With this kind of potential MSW effects operate well after the region studied here ($O(10^3)$ km)

$$\mu(r) = \sqrt{2}\, G_F\, [N(r) + \overline{N}(r)]$$

Total (i.e. integrated over the energy) number density of all neutrino and antineutrino species

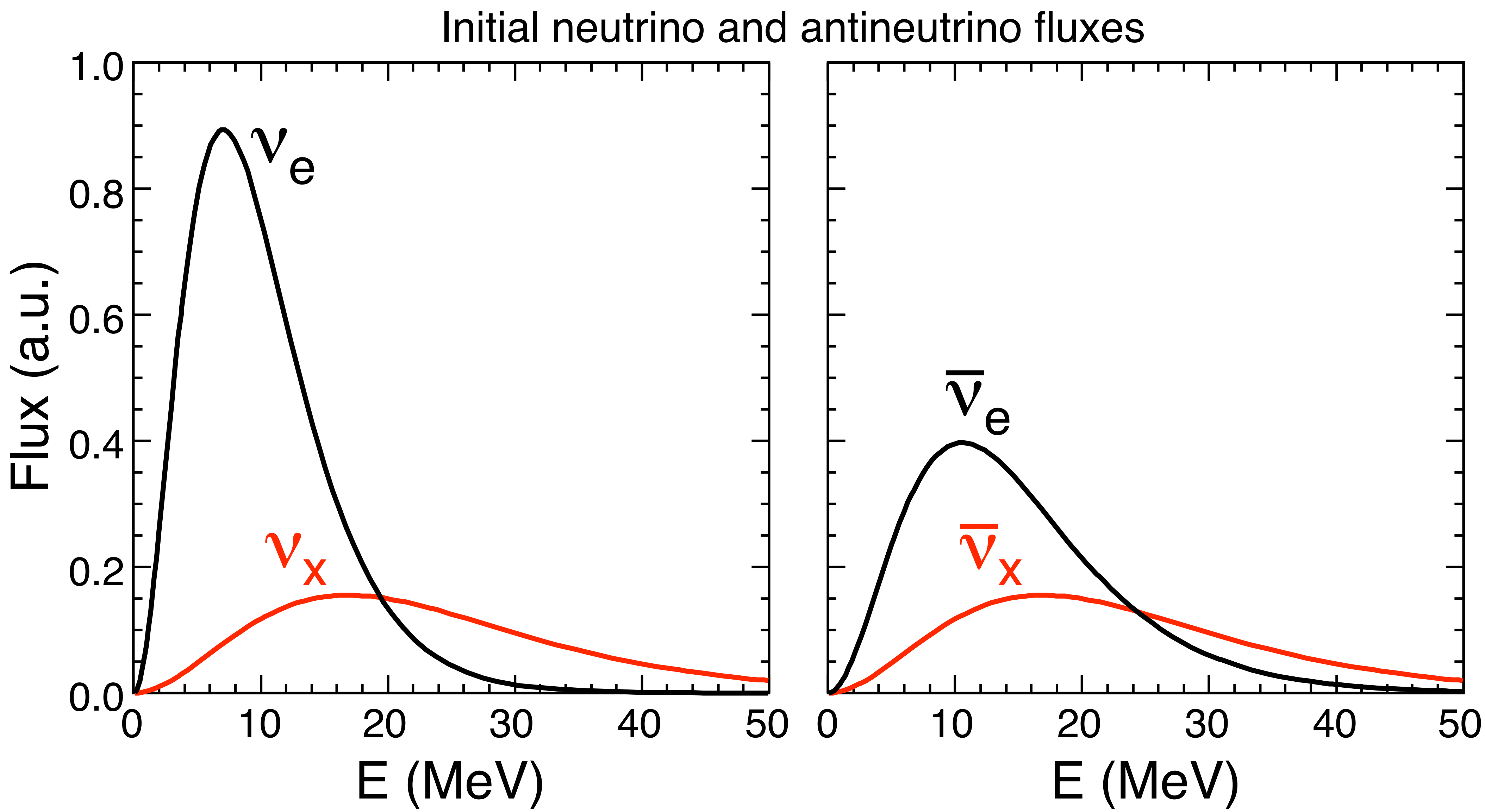
The self-interaction potential decreases as the fourth power of the distance, for large r

Geometry: the “bulb model”



Neutrinos are emitted half-isotropically by a sphere of radius of about 10 km. Assuming cylindrical symmetry around the trajectory of a radial emitted neutrino the two unknowns (r, θ_0) completely fix the geometry

By fixing $\theta_0 = \pi/4$ or by integrating it out one has the single angle approximation where there is no angular dependence in the problem



Two-neutrino scenario

$$\Delta m^2 = \Delta m^2_{atm} = 2 \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2\theta_{13} = 10^{-2}$$

$$\langle E_{\nu_e} \rangle = 10\ \mathrm{MeV}$$

$$\langle E_{\bar{\nu}_e} \rangle = 15\ \mathrm{MeV}$$

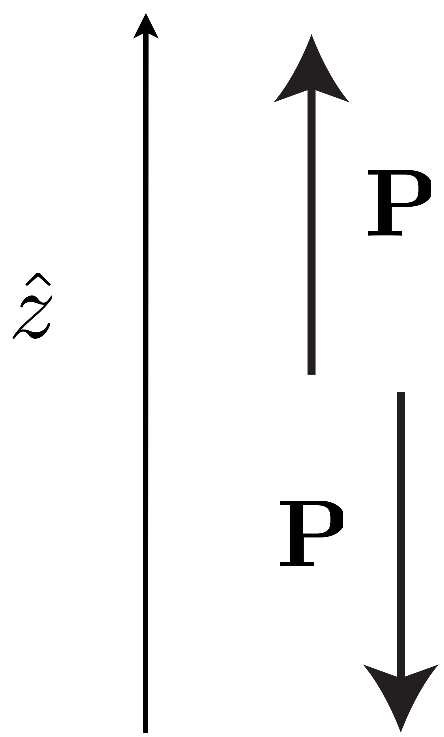
$$\langle E_{\nu_x} \rangle = \langle E_{\bar{\nu}_x} \rangle = 24\ \mathrm{MeV}$$

Density matrix ρ to study neutrino propagation

ρ decomposed in term of polarization vectors →

$$\mathbf{P} = \mathbf{P}(E, \theta_0) \quad \text{neutrinos}$$

$$\bar{\mathbf{P}} = \bar{\mathbf{P}}(E, \theta_0) \quad \text{antineutrinos}$$



Polarization vector in the upward direction

$$P(\nu_e \to \nu_e) = 1$$

Polarization vector in the downward direction

$$P(\nu_e \to \nu_e) = 0$$

Also important, the global vectors

$$\mathbf{J} = \int dE\ d\theta_0\ \mathbf{P}(E, \theta_0) \qquad \bar{\mathbf{J}} = \int dE\ d\theta_0\ \bar{\mathbf{P}}(E, \theta_0)$$

$$\mathbf{S} = \mathbf{J} + \bar{\mathbf{J}} \qquad \mathbf{D} = \mathbf{J} - \bar{\mathbf{J}}$$

$$\dot{\mathbf{P}}(E,\theta_0) = \mathbf{f}[\omega,\lambda,\mu,\mathbf{P}(E',\theta_0'),\bar{\mathbf{P}}(E',\theta_0')] \times \mathbf{P}(E,\theta_0)$$
$$\dot{\bar{\mathbf{P}}}(E,\theta_0) = \mathbf{g}[\omega,\lambda,\mu,\mathbf{P}(E',\theta_0'),\bar{\mathbf{P}}(E',\theta_0')] \times \bar{\mathbf{P}}(E,\theta_0)$$

After discretization, large set of non linear equatons

By integrating over emission angle $\theta_0 \longrightarrow$ single angle approximation

EOM must be solved numerically but some feature can be analytically understood in terms of $\mathbf{J}$ and $\bar{\mathbf{J}}$

In particular, the quantity $D_z = J_z - \bar{J}_z$ is conserved

$$(\nu_e\bar{\nu}_e \to \nu_x\bar{\nu}_x) \text{ but } (\nu_e - \bar{\nu}_e = \text{const})$$

The mixing angle enters the equations through the "magnetic field" vector

$$\mathbf{B} = \sin 2\theta_{13}\,\mathbf{x} \mp \cos 2\theta_{13}\,\mathbf{z}$$

Pendulum analogy

$$\mathbf{Q} = \mathbf{S} - (\omega_{ave}/\mu)\mathbf{B}$$

$$
\begin{aligned}
\mathbf{Q}/Q &\equiv \mathbf{r} \text{ (unit length vector)} \\
\mathbf{D} &\equiv \mathbf{L} \text{ (total angular momentum)} \\
\mu^{-1} &\equiv m \text{ (mass)} \\
\mathbf{D}\cdot\mathbf{Q}/Q &\equiv \sigma \text{ (spin)} \\
\omega_{\text{ave}}\,\mu\,Q\,\mathbf{B} &\equiv -\mathbf{g} \text{ (gravity field)}
\end{aligned}
$$

Pendulum analogy

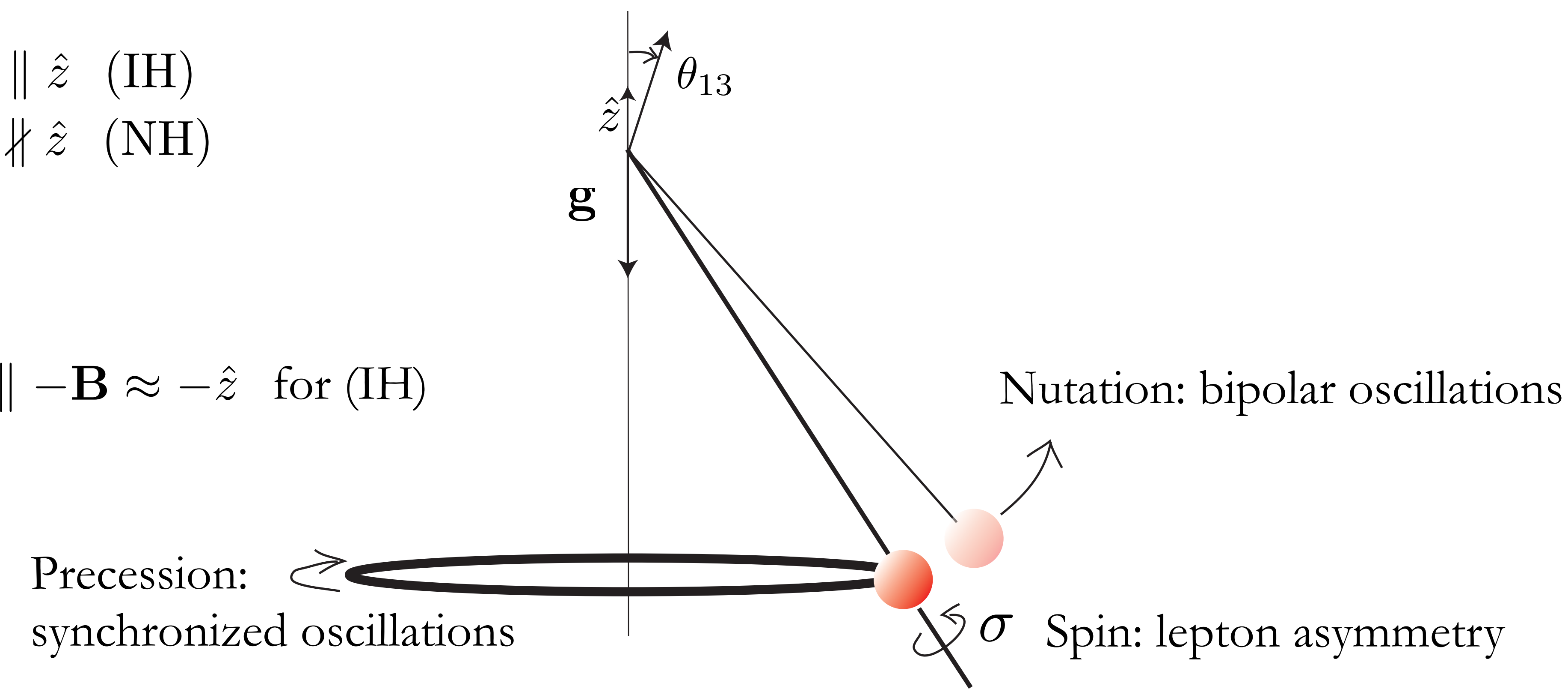
$$
\begin{aligned}
\mathbf{L} &= m\mathbf{r}\times\dot{\mathbf{r}} + \sigma\mathbf{r} \\
\dot{\mathbf{L}} &= m\mathbf{r}\times\mathbf{g}
\end{aligned}
$$

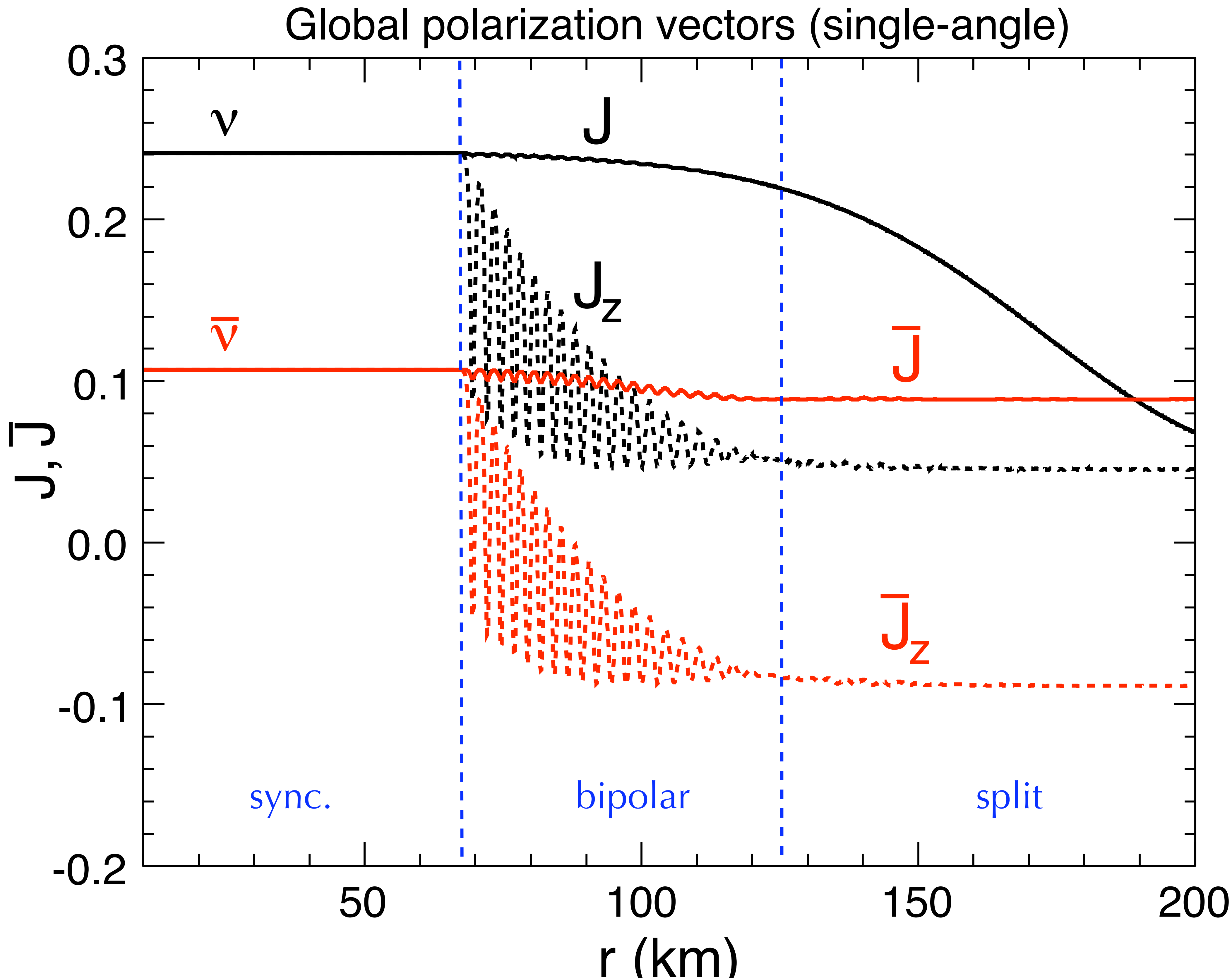
$$
\mathcal{E} = -m\,\mathbf{g}\cdot\mathbf{r} + \left(\frac{m}{2}\,\dot{\mathbf{r}}^2 + \frac{\sigma^2}{2m}\right)
$$

$\mathbf{B} \parallel \hat{z}$ (IH)

$\mathbf{B} \nparallel \hat{z}$ (NH)

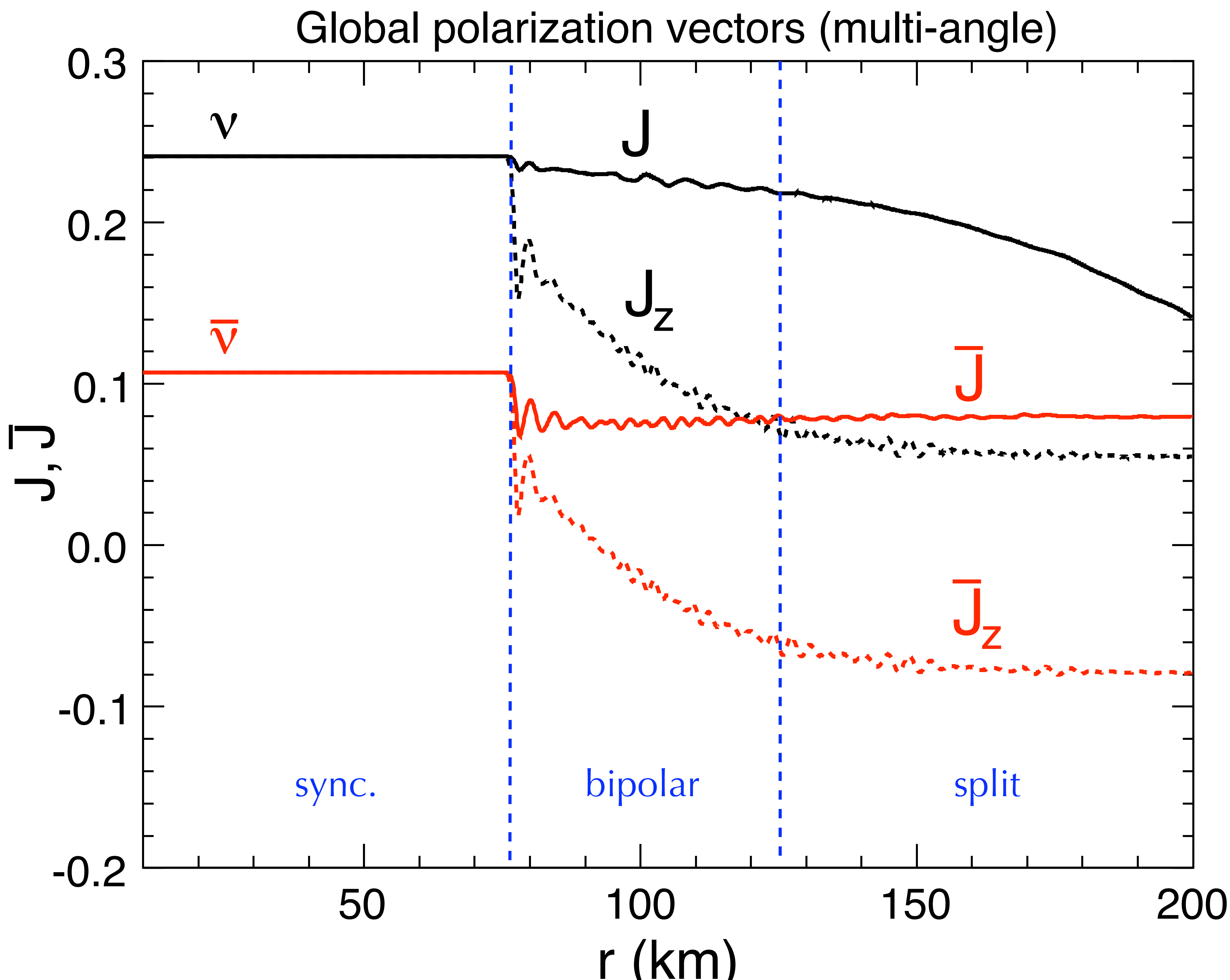
$\mathbf{g} \parallel -\mathbf{B} \approx -\hat{z}$ for (IH)





Note the inversion of $\bar{J}_z$ and the partial inversion of J_z

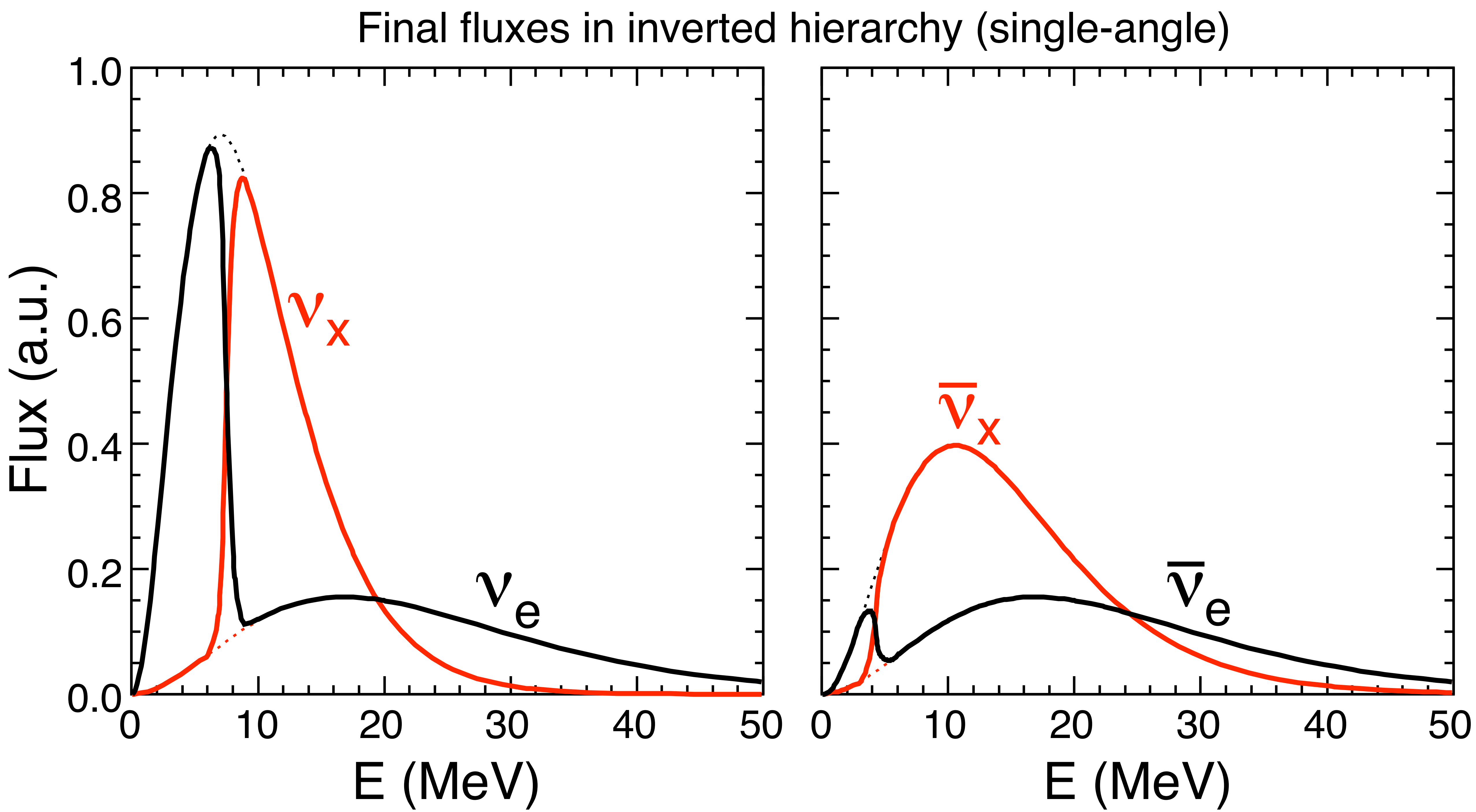
The onset of the bipolar regime depends on θ_{13} and on the matter potential



In multi-angle simulations, neutrino-neutrino angles can be larger than the (single-angle) average one, leading to somewhat stronger self-interaction effects

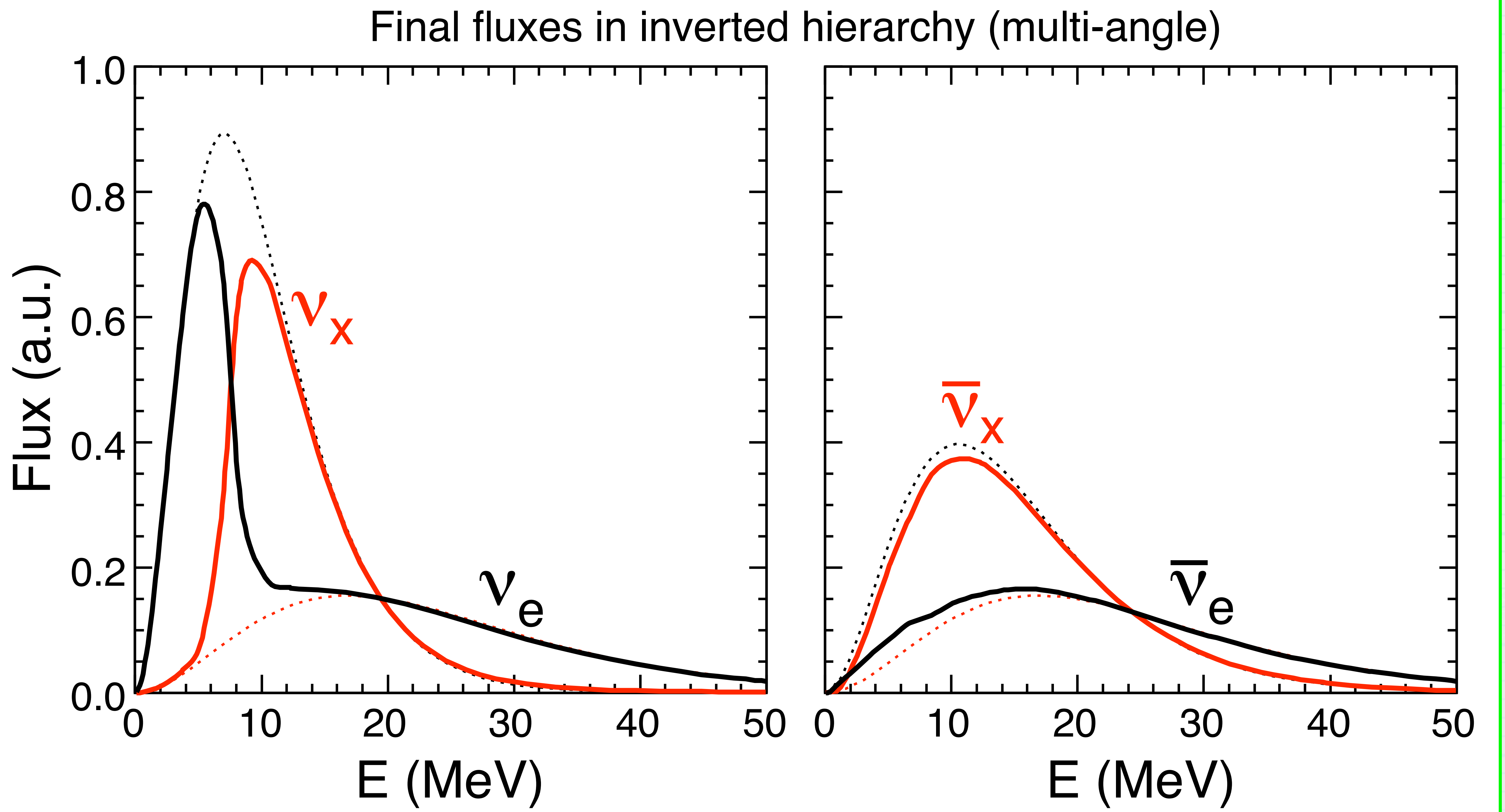
Two effects:

- Bipolar regime starts later
- More pronounced depolarization of $\bar{\mathbf{J}}$ and prolonged coherence of $\mathbf{J}$



Spectral split for neutrinos above ~ 7 MeV

Spectral split for antineutrinos at ~ 4 MeV



The neutrino spectral split is evident, although less sharp than in the single-angle case

Antineutrino split largely washed out

Conclusions

Neutrino self interactions near a supernova core cannot be neglected since they produce very interesting collective effects

Many features of the propagation can be understood by means of the single angle approximation (i.e. by averaging over neutrino trajectories)

There is a very useful analogy with a gyroscopic pendulum in flavor space to explain *synchronized* and *bipolar* regimes

For **inverted hierarchy**, swap of energy spectra above a critical energy. For neutrinos this can be explained by lepton number conservation

The spectral swap is observed also in the multi-angle simulation, even though the "fine structure" details tend to be smeared out

The end of collective phenomena sets the starting point for the usual neutrino matter propagation in the SN. Hence, the (partial) swapping of the spectra can have an impact on r-process nucleosynthesis, on the energy transfer to the stalling shock wave, and on the possibility of observing shock-wave propagation effects on neutrino oscillations