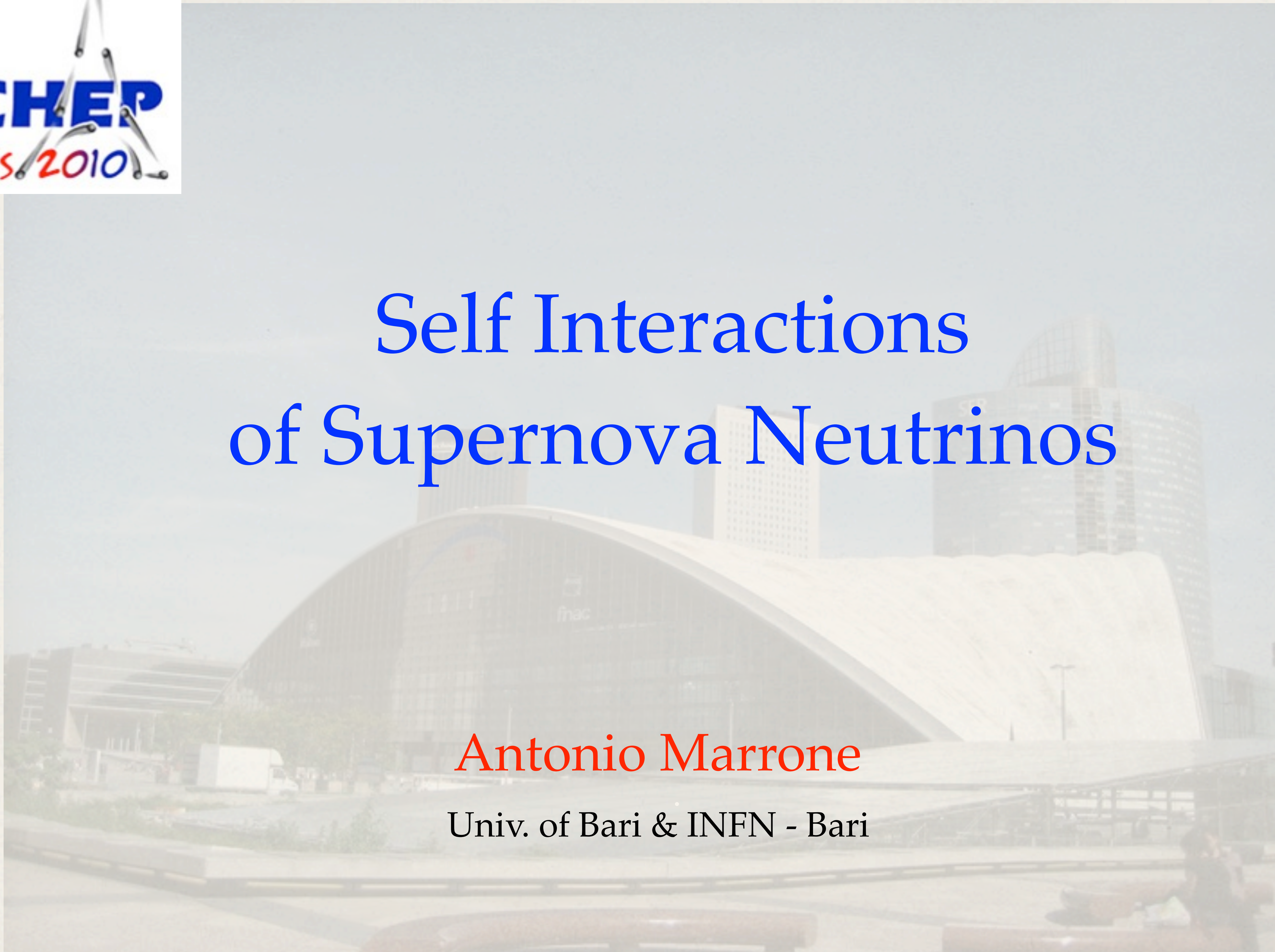
July 22-28, Palais des Congrès, Paris



Self Interactions of Supernova Neutrinos

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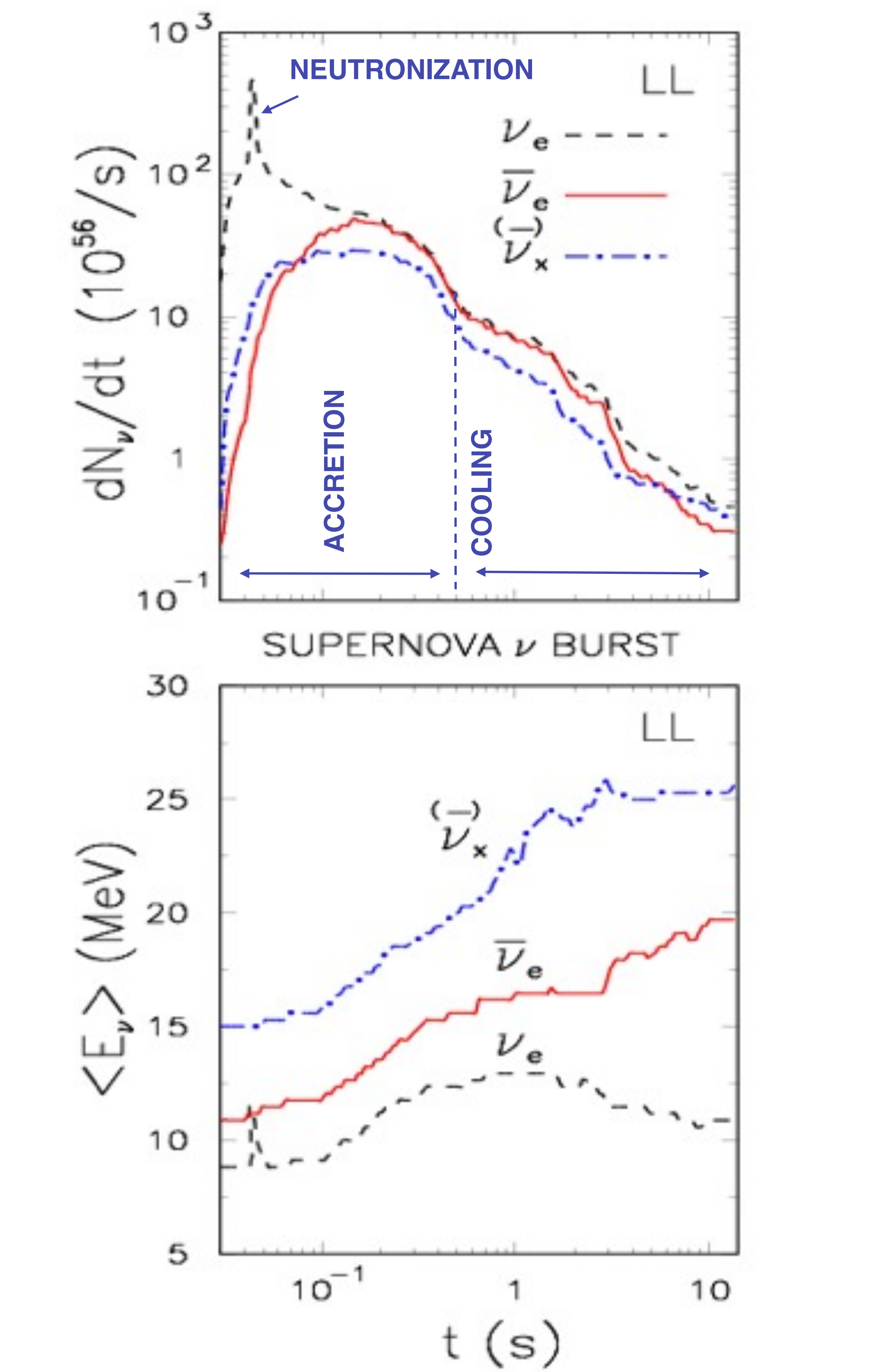
Supernova Neutrinos

Neutrinos emitted during the explosion of massive stars on a time scale of about ~10 sec

Released energy of the order of 10^{53} erg

Hierarchy of luminosities and energy, (at least during the accretion phase)

Flavor oscillations can significantly affect the final flavor composition



Collective Flavor Conversions

The Hamiltonian is the sum of three terms depending on

$$\omega = \frac{\Delta m^2}{2E}$$ vacuum oscillation frequency

$$\lambda = \sqrt{2} G_F n_e$$ matter potential

$$\mu = \sqrt{2} G_F (n_\nu + n_{\bar{\nu}})$$ neutrino-neutrino interaction potential

Collective oscillations when μ dominates (typically $r \lesssim 100$ Km)

In many practical cases matter effects and collective effects induced by self interactions factorize and the range in which they are effective are well separated

Oscillations described by means of polarization vectors $\mathbf{P} = \mathbf{P}(E, r)$

$$\dot{\mathbf{P}} = (+\omega \mathbf{B} + \lambda \hat{\mathbf{z}} + \mu \mathbf{D}) \times \mathbf{P}$$

$$\dot{\overline{\mathbf{P}}} = (-\omega \mathbf{B} + \lambda \hat{\mathbf{z}} + \mu \mathbf{D}) \times \overline{\mathbf{P}}$$

Equations of motion

$\mathbf{B} \parallel \hat{\mathbf{z}}$ when $\theta_{13} = 0$

($\lambda = 0$ in the following)

Global vectors

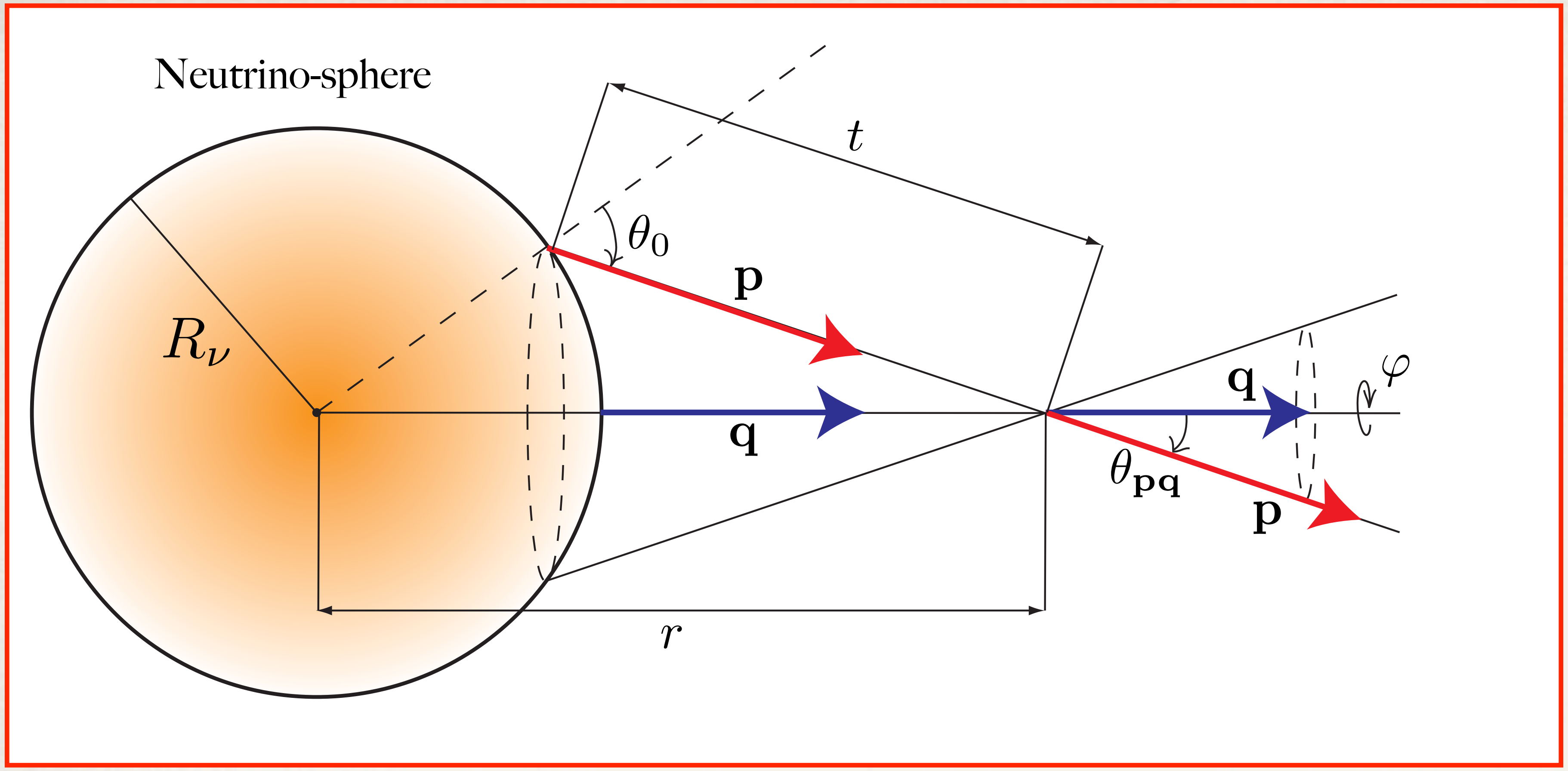
$$\mathbf{J} = \sum \mathbf{P}$$

$$\mathbf{D} = \mathbf{J} - \overline{\mathbf{J}}$$

Initial conditions

$$J = J_z^i = \int (n_{\nu_e}(E) - n_{\nu_x}(E)) dE$$

$$D = D_z^i = \int (n_{\nu_e}(E) - n_{\overline{\nu}_e}(E)) dE$$



Bulb model

Duan et al., PRD74,105014(2006)

$$H_{\nu\nu} = \sqrt{2} G_F \int \frac{d^3\vec{q}}{(2\pi)^3} (\mathbf{P}_{\vec{q}} - \overline{\mathbf{P}}_{\vec{q}})(1 - \cos\theta_{pq})$$

Multi-angle effect: the interaction depends on the relative angle of the colliding neutrinos

When this angle is averaged out the single-angle approximation is obtained

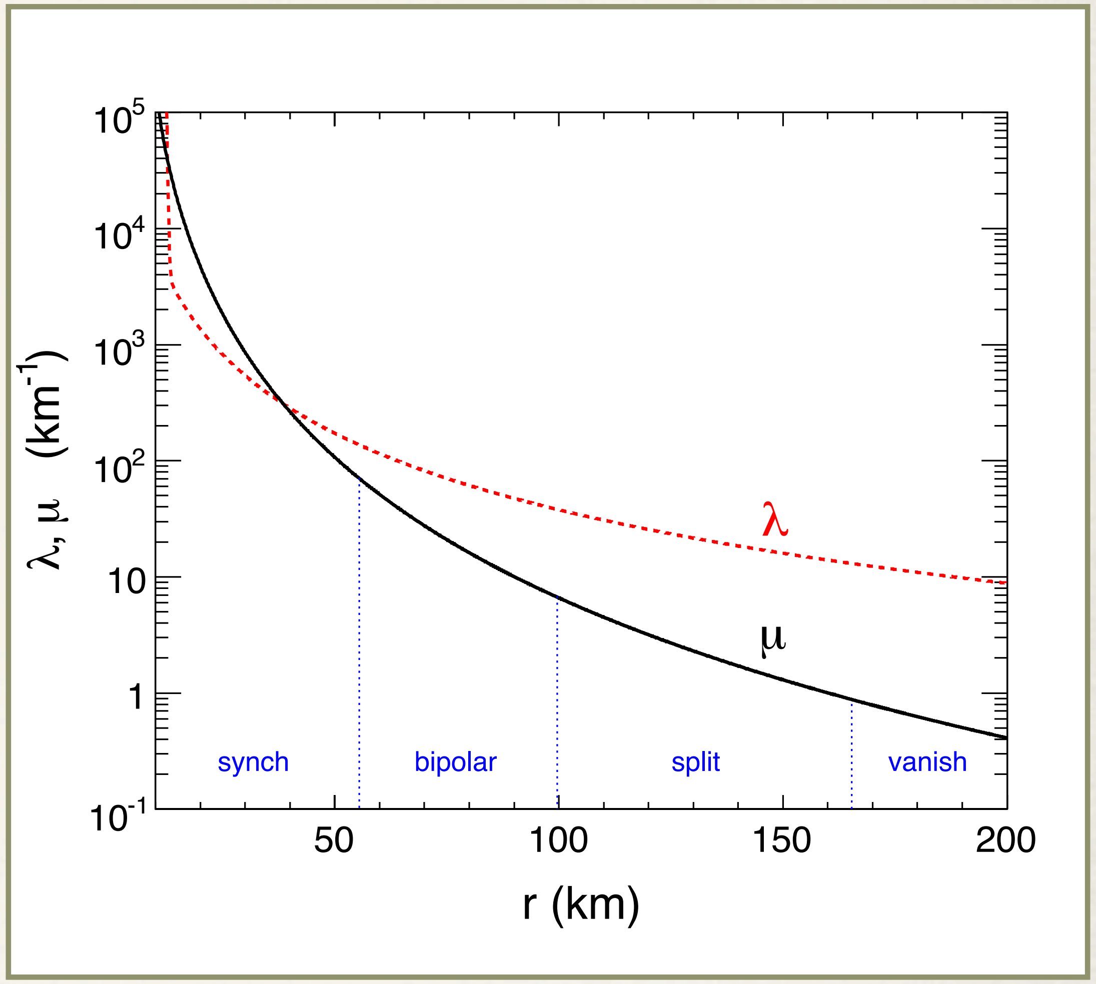
$$H_{\nu\nu} = \mu \int dq (\mathbf{P}_{\vec{q}} - \overline{\mathbf{P}}_{\vec{q}}) = \mu(\mathbf{J} - \overline{\mathbf{J}}) = \mu \overline{\mathbf{D}}$$

Regimes of Collective flavor Conversions

Near the neutrino-sphere (few tens of kilometers) all polarization vectors stay aligned with the z-axis: synchronized oscillations

At a certain point, the polarization vectors start to move but the **P**'s remain (approximately) parallel to their sum **J** (same for antineutrinos). This regime has a mechanical analogy with the motion of a spherical pendulum and corresponds to the so called bipolar oscillations

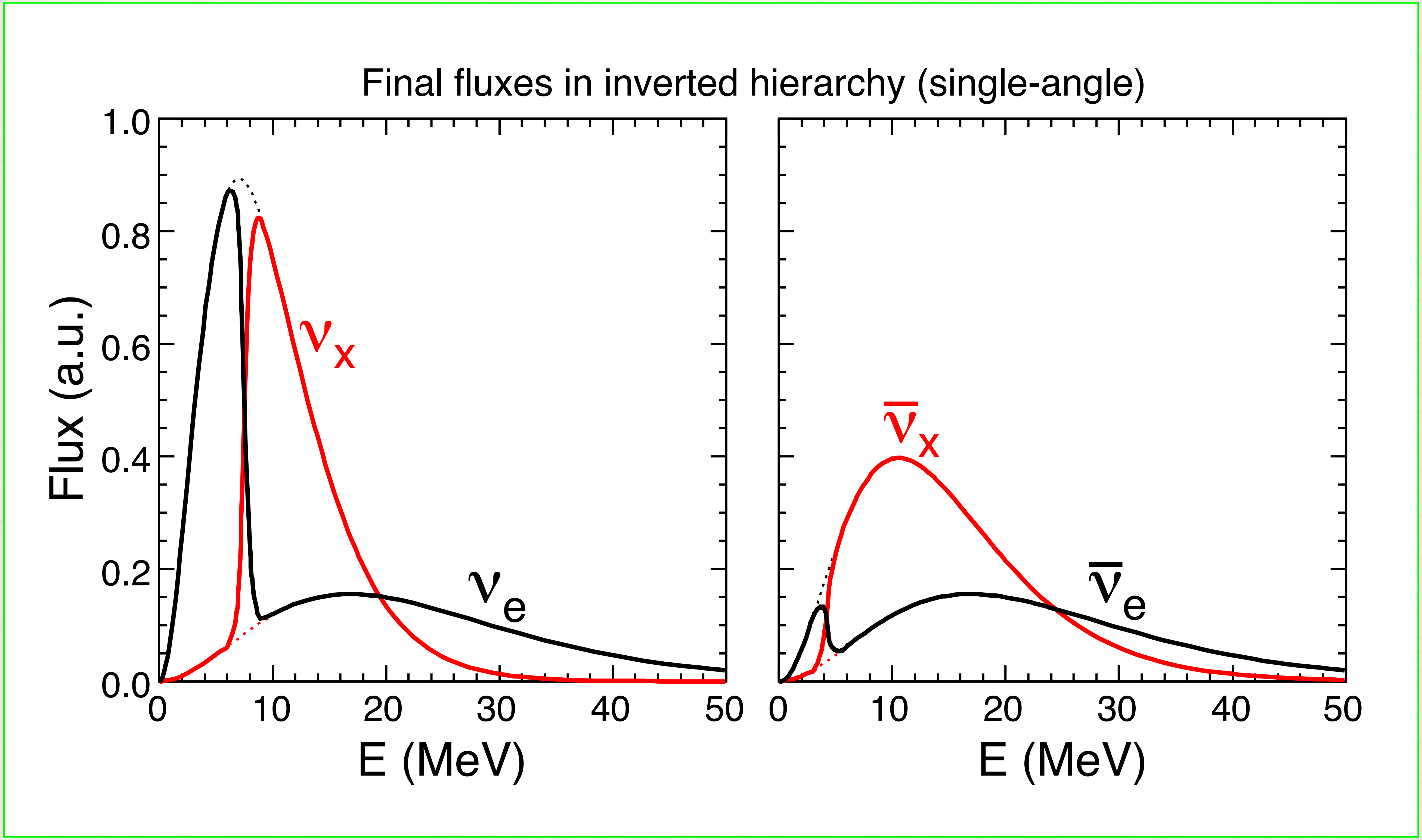
Hannestad, Raffelt, Sigl and Wong, PRD74,105010(2006)



Inverted hierarchy corresponds to the pendulum starting close the unstable position while in normal hierarchy it starts close the stable one

The bipolar regime ends when the vacuum frequencies of the **P**'s are of the same order of the self-interaction potential. After that, the spectral split fully develops until the neutrino-neutrino potential is completely negligible

Typical outcome of a single-angle simulation: spectra are completely swapped above a critical energy that is different in the neutrino and antineutrino sectors



(Partially) Open questions about collective effects

Which features (swaps of spectra, single or multiple splits) are robust and survive in the multi-angle simulations? or in the three-generation scenario? ...

Single-angle vs Multi-angle simulations

Duan and Friedland, arxiv:1006.2359 Cherry et al., arxiv:1006.2175

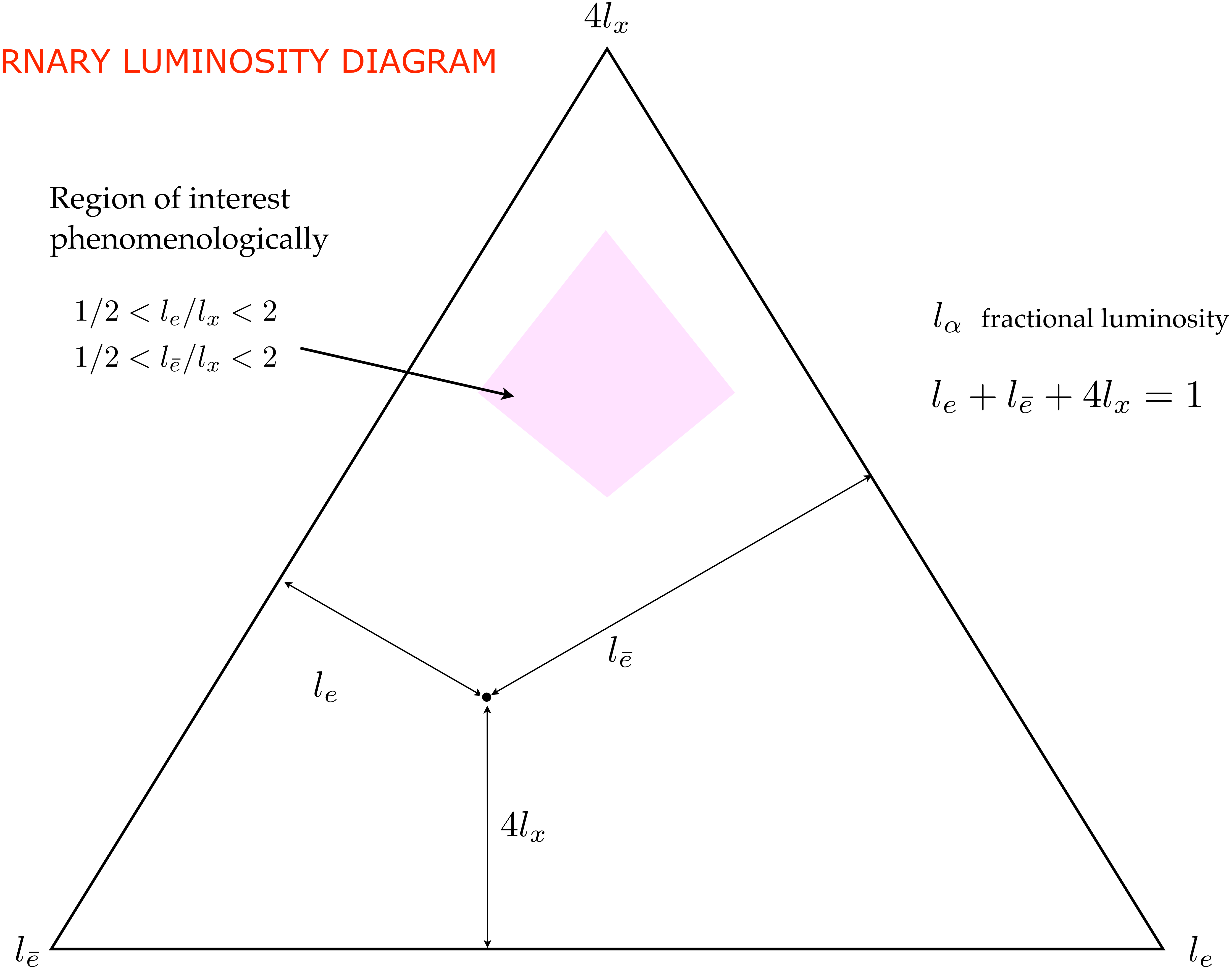
Three-generation mixing

Dasgupta et al., PRD81,093008(2010) Dasgupta et al., PRD81,073004(2010) Friedland, PRL104,191102(2010)

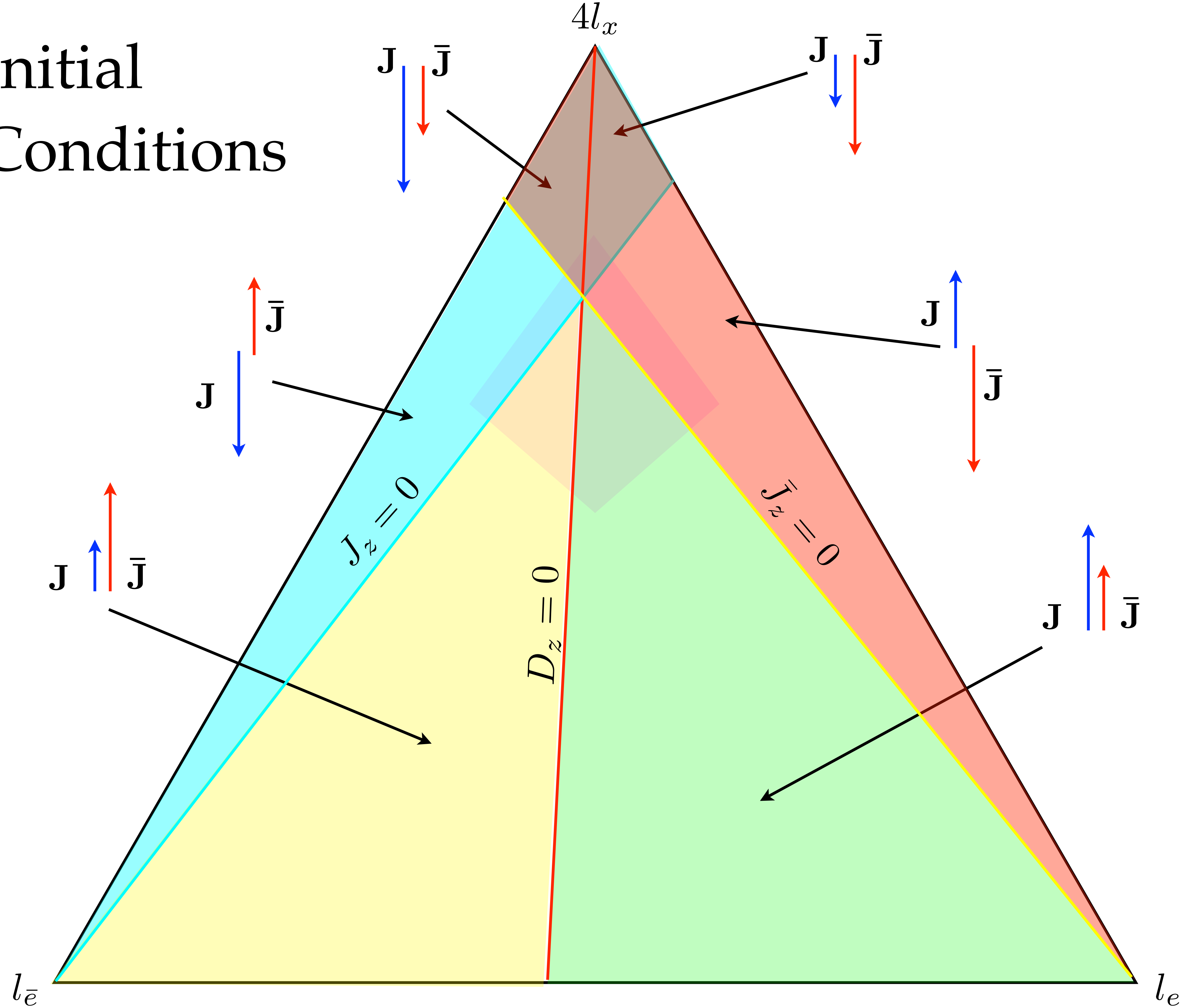
We need to understand the possible effect of reduced symmetry, as asphericities, inhomogeneities, turbulence, ...

→ Important to *fully* understand single-angle, two-flavor collective oscillations

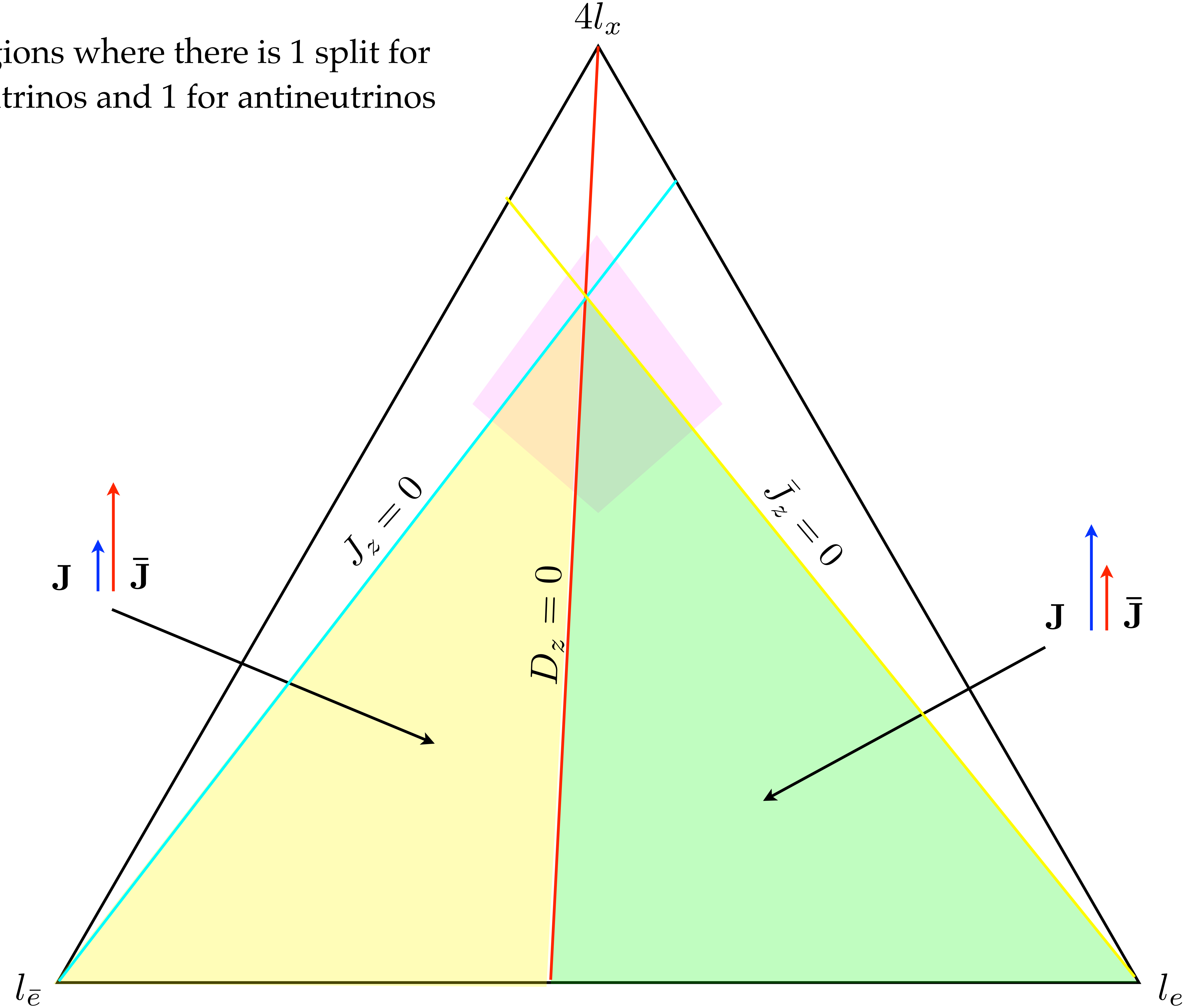
TERNARY LUMINOSITY DIAGRAM



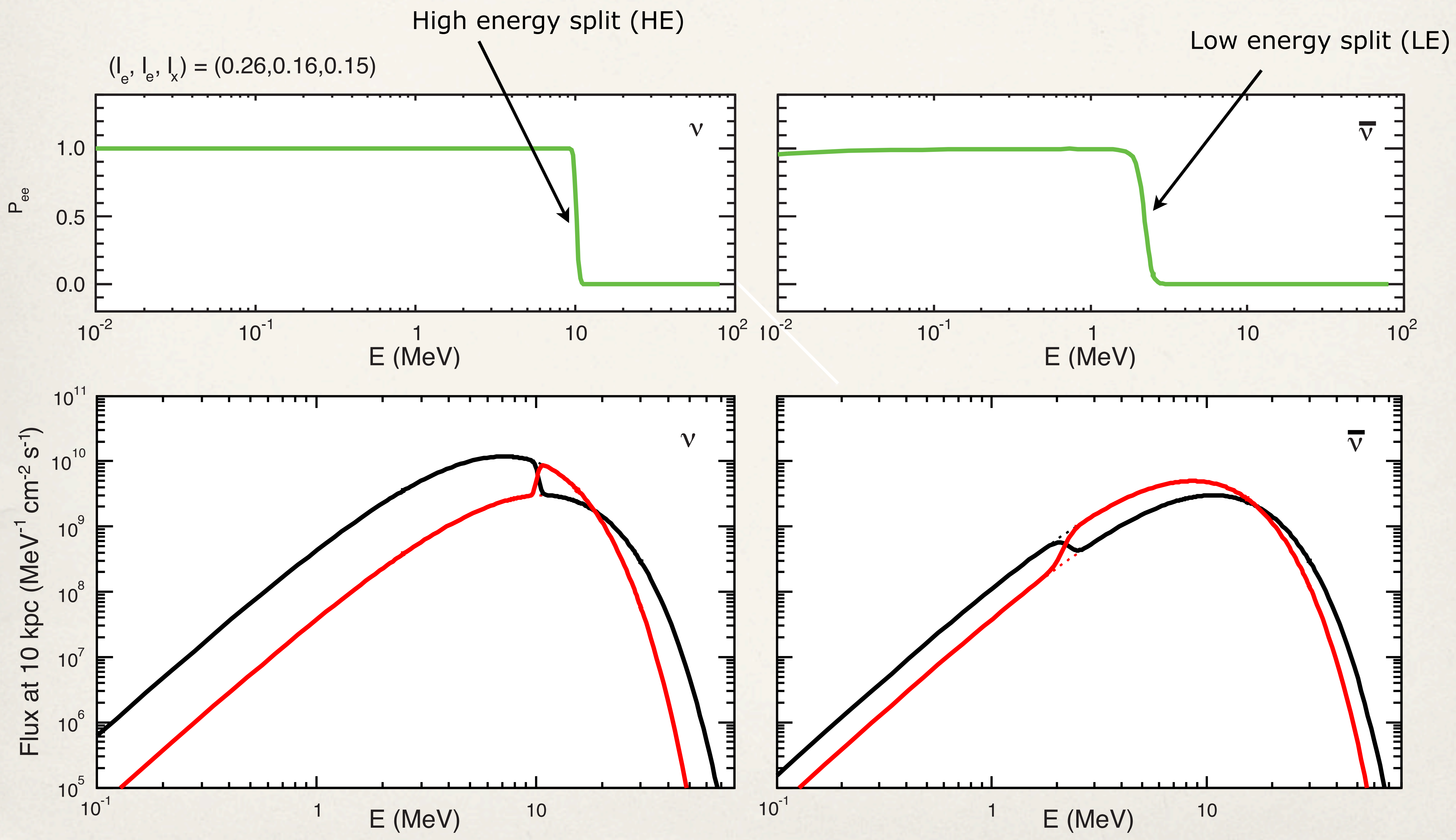
Initial Conditions



Regions where there is 1 split for neutrinos and 1 for antineutrinos



Single split - an example



Predicting split energy - I

Collective oscillations proceed through $\nu_e\overline{\nu}_e \rightarrow \nu_x\overline{\nu}_x$ so that leptonic number is conserved

$$\int (n_{\nu_e}(E) - n_{\overline{\nu}_e}(E))dE = D_z^i$$

Minimization of the total potential energy of the system requires complete swap of antineutrino spectra and partial swap of neutrino spectra above a critical energy E_c (for $D_z > 0$)

In the hypothesis of complete antineutrino spectral swap E_c can be well estimated from the lepton number conservation equation

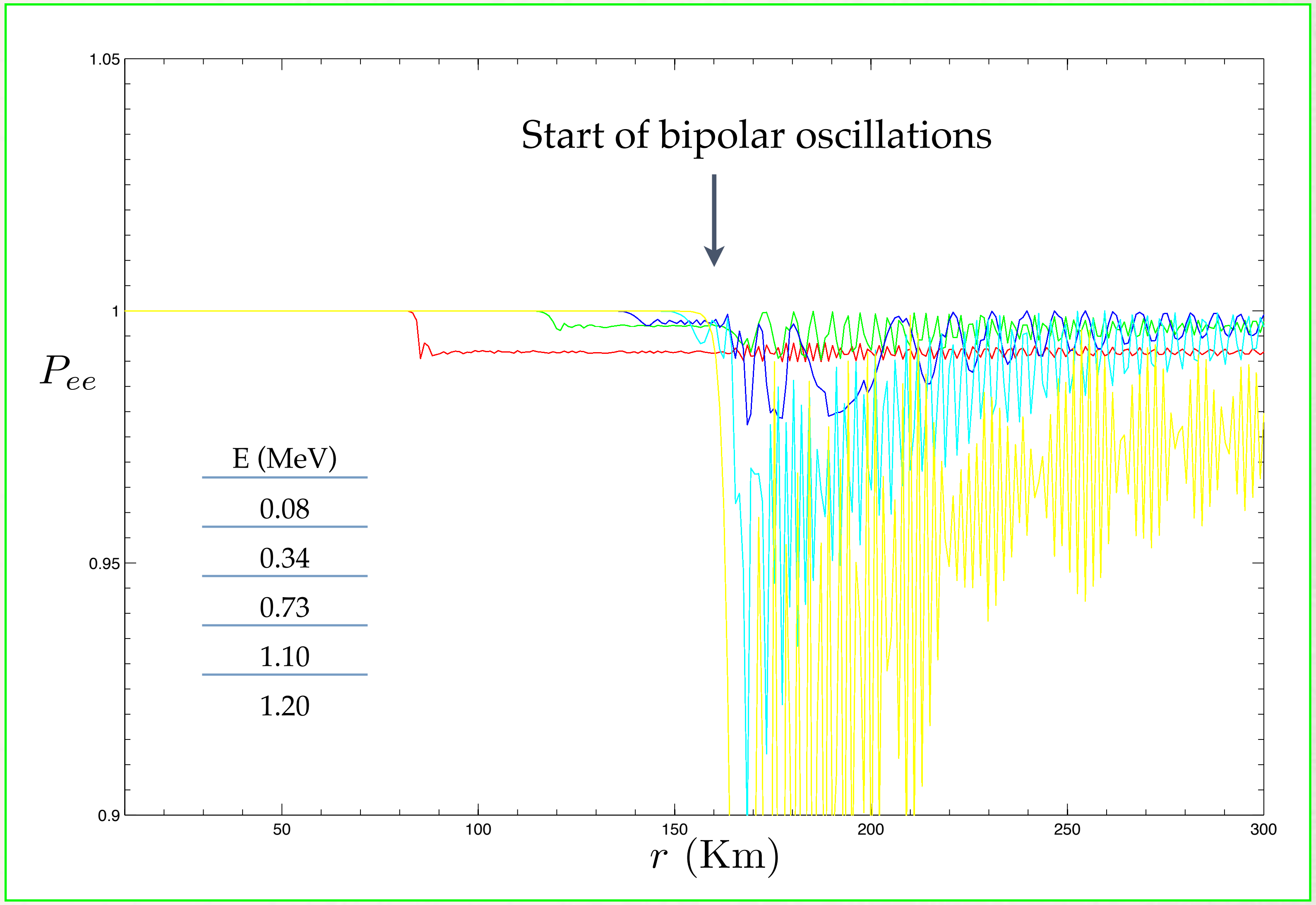
Predicting split energy - II

$$\dot{\overline{\mathbf{P}}} = (-\omega \mathbf{B} + \mu \mathbf{D}) \times \overline{\mathbf{P}}$$

When $D_z > 0$

antineutrinos modes can undergo a resonance on the self-interaction potential

The crossing probability at the resonance is very near to one for all modes, only the resonance radius changes notably



Bipolar oscillation frequency

$$\omega_{\text{bip}} \sim \sqrt{\mu\, \omega_{\text{ave}} D_z}$$

average frequency

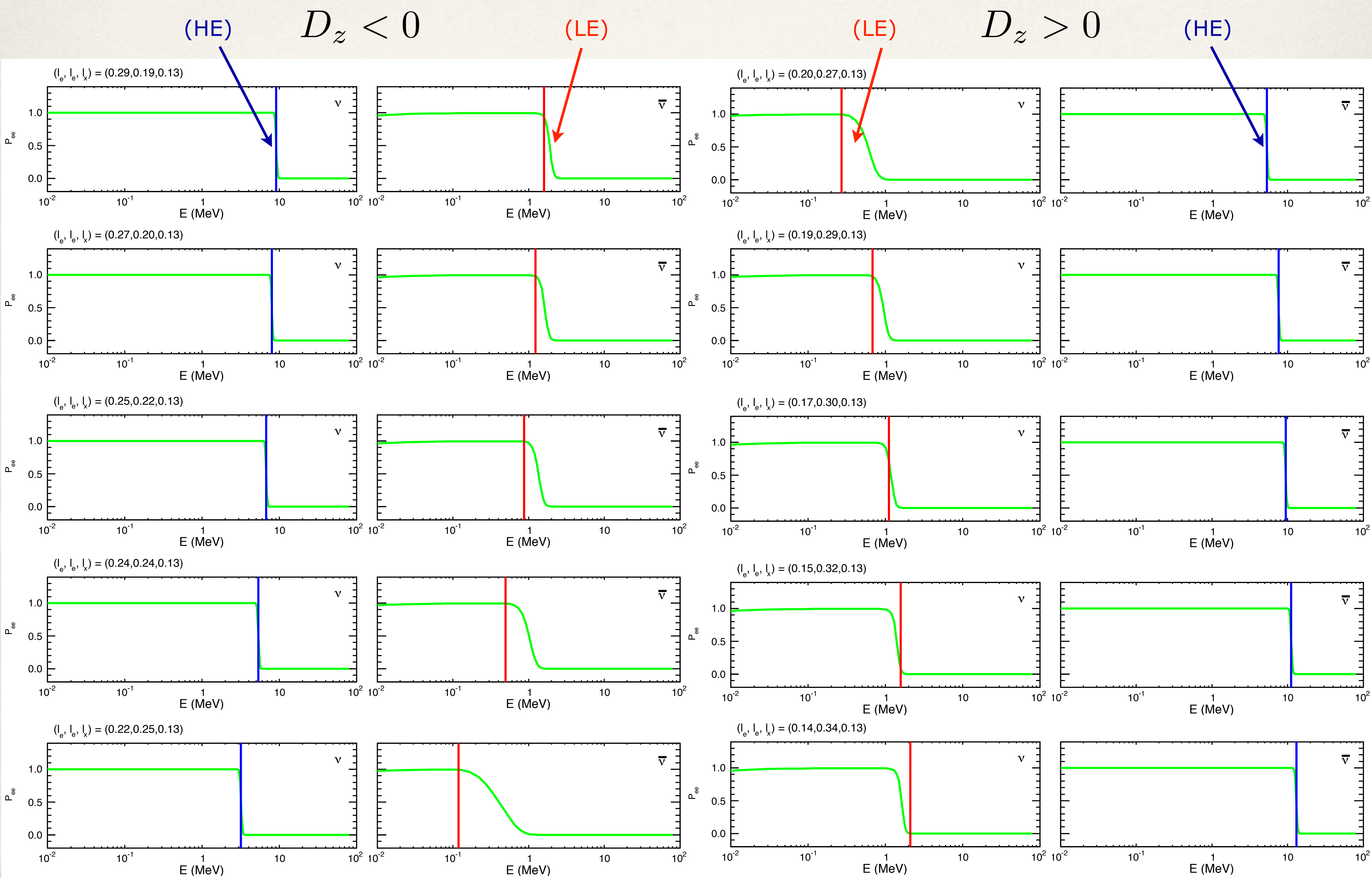
Modes with $\omega \lesssim \omega_{bip}$ participate to bipolar oscillation and do not feel the resonance since D is no more parallel to z

Modes with $\omega > \omega_{bip}$ encounter the resonance and thereafter precess with their vacuum frequency

$$\omega(\overline{E}_c) = \sqrt{\mu(r_{\text{bip}})\omega_{\text{ave}} D_z} \longrightarrow \text{determine } \overline{E}_c$$

When $D_z < 0$ the role of neutrinos and antineutrinos is interchanged

Split energies - examples



Summarizing

When there is one split energy for neutrinos and one for antineutrinos the two split energies can be estimated by means of

- conservation of lepton number during collective oscillations

- comparison of the vacuum frequency with the frequency of bipolar oscillations at the onset of the bipolar regime

Conclusions

Collective oscillations of supernova neutrinos can have a large impact on the flavor composition of the neutrino fluxes

- Physics of Supernova explosion
- Neutrino oscillation parameters

Many features of collective oscillations captured by two-flavor, single-angle approximation, some of which survive in the three-generation, multi-angle calculation

For instance, when the single-angle calculations give one split for neutrinos and one for antineutrinos the final neutrino spectra can be analytically predicted

Varying the fractional luminosities of $(\nu_e, \overline{\nu}_e, \nu_x)$ the split energies change but can be predicted by using lepton number conservation and the frequency of the bipolar oscillations