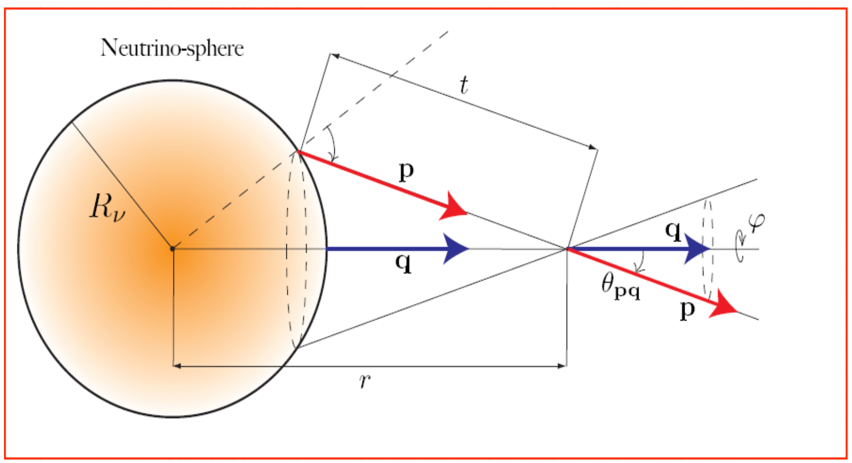
Bari Xmas Theory Workshop 2013
Bari, 23 December 2013

SELF-INDUCED FLAVOR EVOLUTION OF SUPERNOVA NEUTRINOS WITHOUT AXIAL SYMMETRY

(Based on 1308.1402; 1308.5255)

(Alessandro MIRIZZI, Hamburg U.)



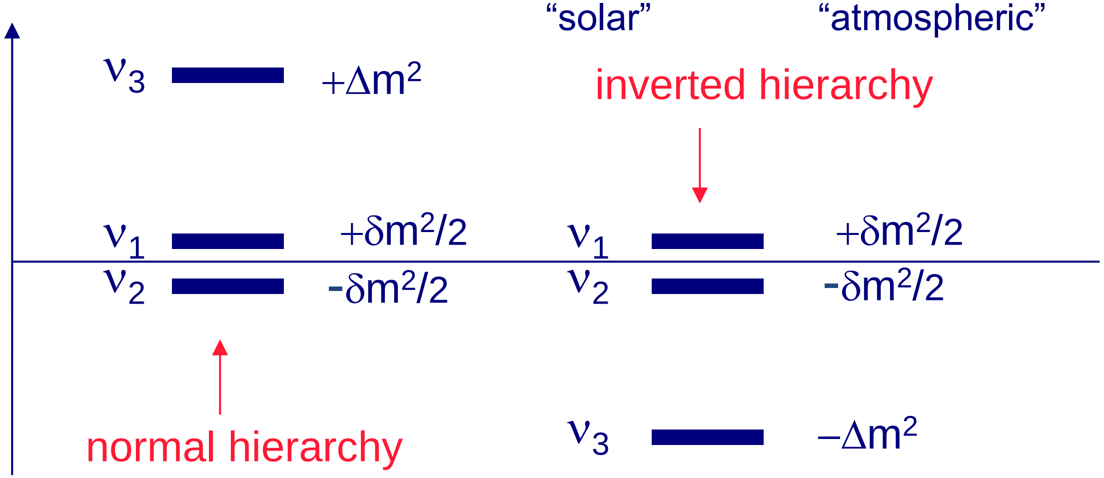
3ν FRAMEWORK

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

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & e^{-i\delta} s_{13} \\ & 1 & \\ -e^{-i\delta} s_{13} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

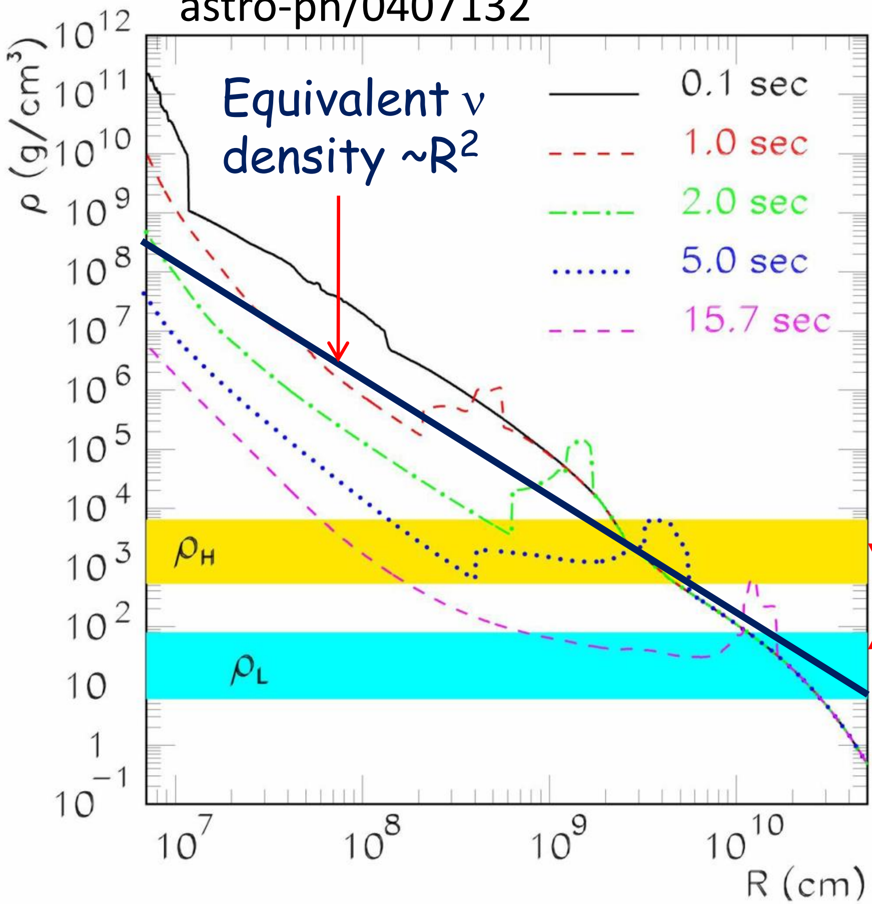
$c_{12} = \cos\theta_{12}$, etc., δ CP phase

- **Mass-gap parameters:** $M^2 = \left[\underbrace{-\frac{\delta m^2}{2}, +\frac{\delta m^2}{2}}_{\text{"solar"}}, \underbrace{\pm \Delta m^2}_{\text{"atmospheric"}} \right]$



- **2ν subsector:** $(\Delta m^2, \theta_{13})$

SNAP-SHOTS OF SN DENSITY PROFILES



- Matter bkg potential

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

- ν–ν interaction

$$\mu = \sqrt{2} G_F n_\nu \quad \sim R^{-2}$$

- Vacuum oscillation frequencies

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

When $\mu >> \lambda$, SN ν oscillations dominated by ν-ν interactions

Collective flavor transitions at low-radii [O (10^2 – 10^3 km)]

Two seminal papers in 2006 triggered a torrent of activities
Duan, Fuller, Qian, astro-ph/0511275, Duan et al. astro-ph/0606616

[see Duan et al, arXiv:1001.2799 for a review]

DENSITY MATRIX FOR THE NEUTRINO ENSEMBLE

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

- In 2ν scenario. Decompose density matrix over Pauli matrices to get the "**polarization**" (Bloch) vector **P**. Survival probability Pee =1/2(1+$\mathbf{P_z}$) .
  $\mathbf{P_z}$ = -1 -> Pee =0 ; $\mathbf{P_z}$ = 0 -> Pee =1/2 (flavor decoherence)

- The EOMs for the time evolution in a homogeneous medium are the Liouville equations (e.g. Early Universe)

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

MULTI-ANGLE (M.A.) EOMs FOR SN NEUTRINOS

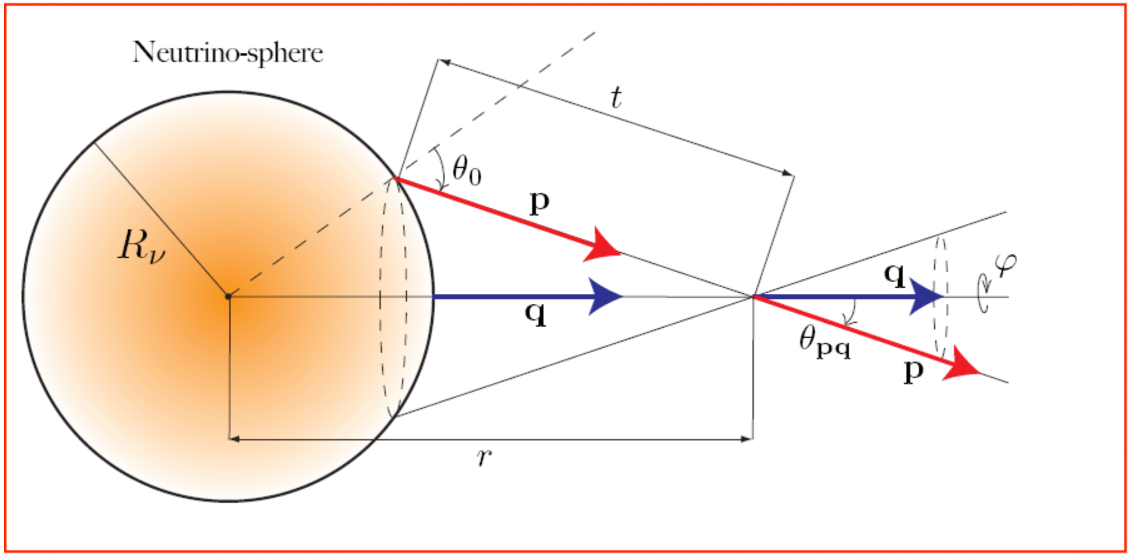
Evolution in space for ν's streaming from a SN core in quasi-stationary situation

$$i\,\vec{\mathrm{v}}_{\mathrm{p}}\cdot\vec{\nabla}_x\rho_{p,x} = \left[H(\omega,\lambda,\rho_{p',x}),\rho_{p,x}\right]$$

Liouville operator for free streaming ν

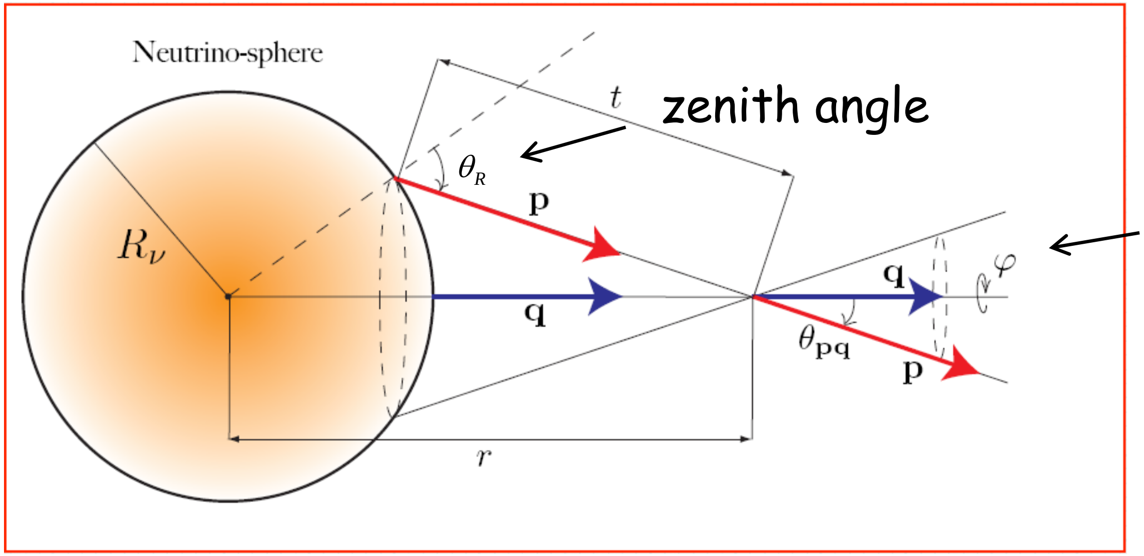
MULTI-ANGLE ν–ν HAMILTONIAN

$$H_{\nu\nu} = \sqrt{2}G_F\int d\vec{q}\left(1-\vec{\mathrm{v}}_{\mathrm{p}}\cdot\vec{\mathrm{v}}_q\right)\left(\rho_{q,x}-\bar{\rho}_{q,x}\right)$$



BULB MODEL

[see, e.g., Duan et al., astro-ph/0606616] ⟶ First large-scale multi-angle simulations



- Neutrinos are emitted uniformly and (half)-isotropically from the surface of a sphere (ν-sphere), like in a blackbody.
- Physical conditions depend only on the the distance r from the center of the star (azimuthal symmetry)
- Only multi-zenith-angle (MZA) effects in terms of $u = \sin^2 \theta_R$
- Project evolution along radial direction (ODE problem) $\vec{v}_p \cdot \vec{\nabla}_x \to v_r d_r$

SINGLE-ZENITH-ANGLE (SZA) APPROXIMATION

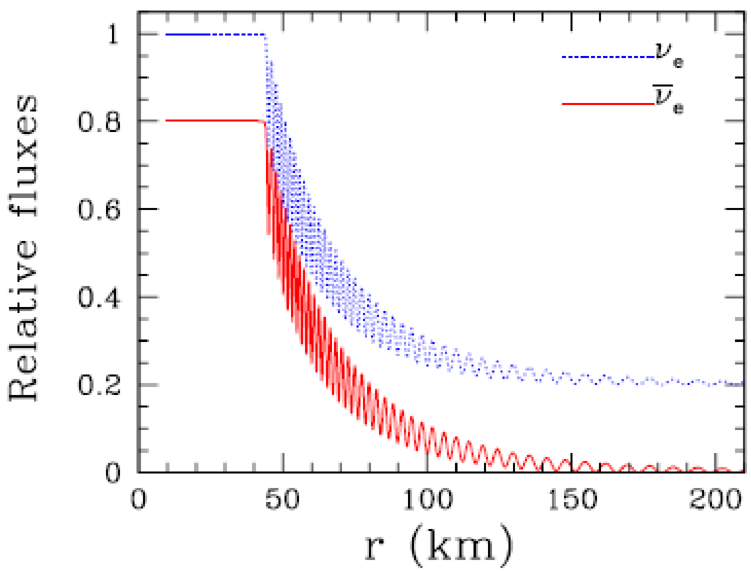
Introduce an average of the MZA factor $(1-\cos\theta_{pq})$.

SZA $\nu-\nu$ Hamiltonian

$$H_{\nu\nu} = \mu(r)(\rho - \bar{\rho})$$

$$\mu(r) = \sqrt{2} G_F n_\nu \langle 1 - \cos\theta \rangle$$

[Hannestad et al., astro-ph/0608695]



Toy model:
Monochromatic ν beam.

Only ν_e and $\overline{\nu}_e$, with an excess of ν_e

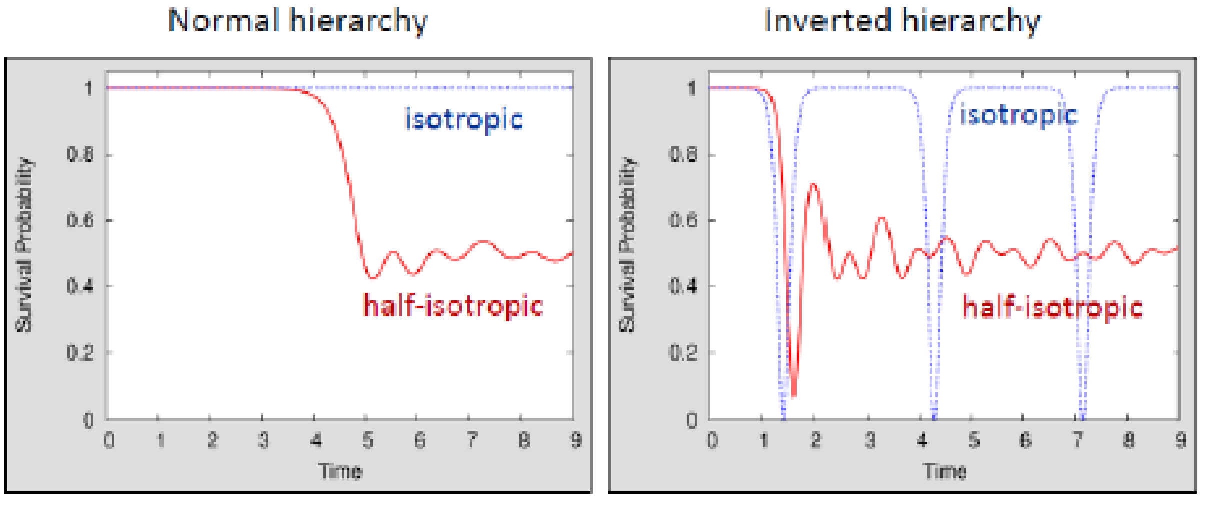
- No effect in NH
- Complete self-induced conversions in IH. Bimodal instability

MULTI-ZENITH-ANGLE DECOHERENCE

$$H_{\nu\nu} = \sqrt{2}G_F \int d\vec{q}\ \left(1-\cos\theta_{pq}\right)\ \left(\rho_{q,x} - \bar{\rho}_{q,x}\right)$$

Flux term

Symmetric $\nu_e\,\bar{\nu}_e$ systems decoheres in both hierarchies [*Raffelt & Sigl, hep-ph/0701182*]



Flux term does not vanish in a non-isotropic medium, like ν streaming off a SN

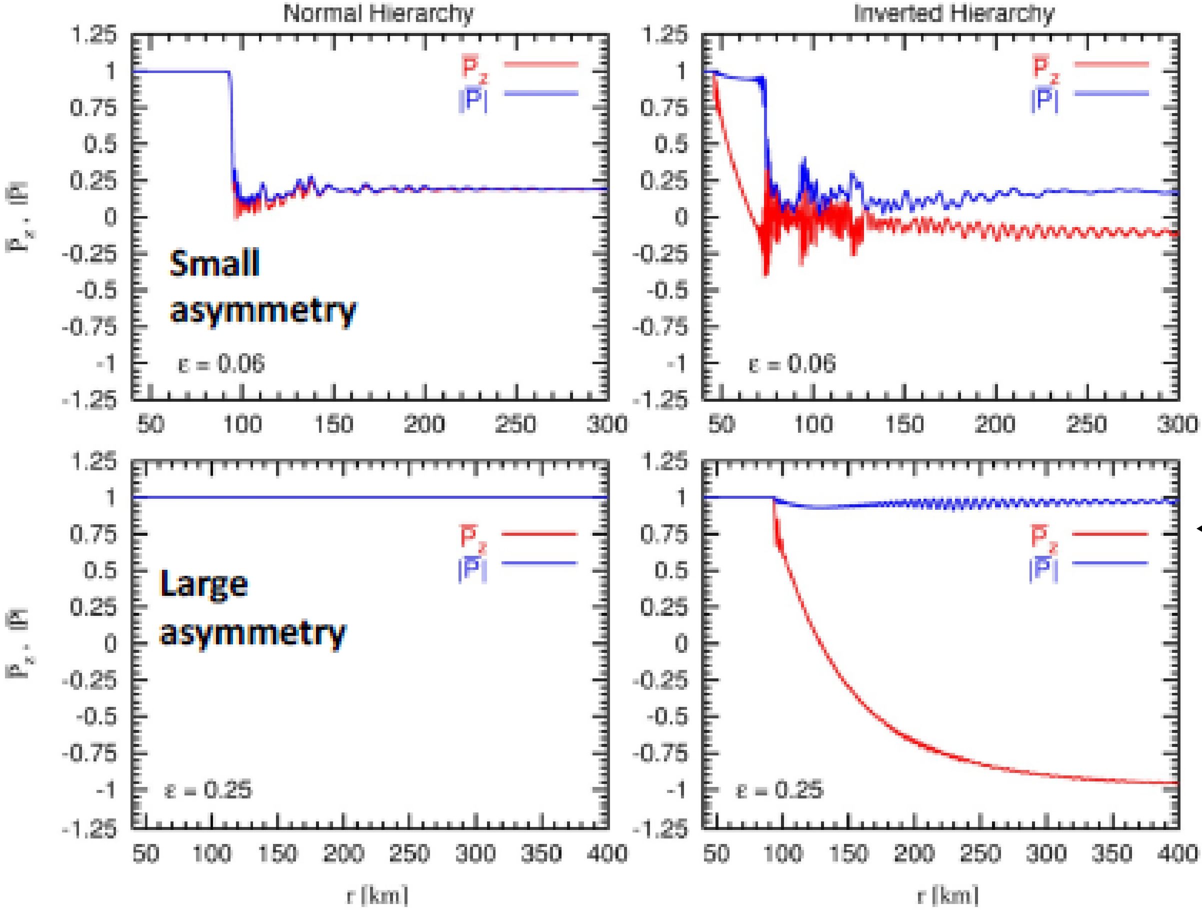
Is the MZA decoherence relevant for SN neutrinos?

MZA EFFECTS FOR SN NEUTRINOS

$$\varepsilon = \frac{F(\nu_e) - F(\bar{\nu}_e)}{F(\bar{\nu}_e) - F(\bar{\nu}_x)}$$

Flavor asymmetry

[*Esteban-Pretel et al.,0706.2498*]



decoherence

- Flavor equilibration in both NH & IH

Quasi single-angle behaviour

- Nothing occurs in NH (stable configuration)
- Complete conversions in IH (bimodal instability)

Large $\nu_e\bar{\nu}_e$ asymmetry required to suppress multi-angle decoherence

MULTI-AZIMUTHAL-ANGLE (MAA) INSTABILITY

- Self-induced flavor conversions are associated to an instability in the flavor space [*Sawyer,0803.4319; Banerjee, Dighe & Raffelt, 1107.2308*]

- Instability required to get started (exponential growth of the off-diagonal density matrix part)

- The onset of the conversions can be found through a stability analysis of the linearized EOMs.

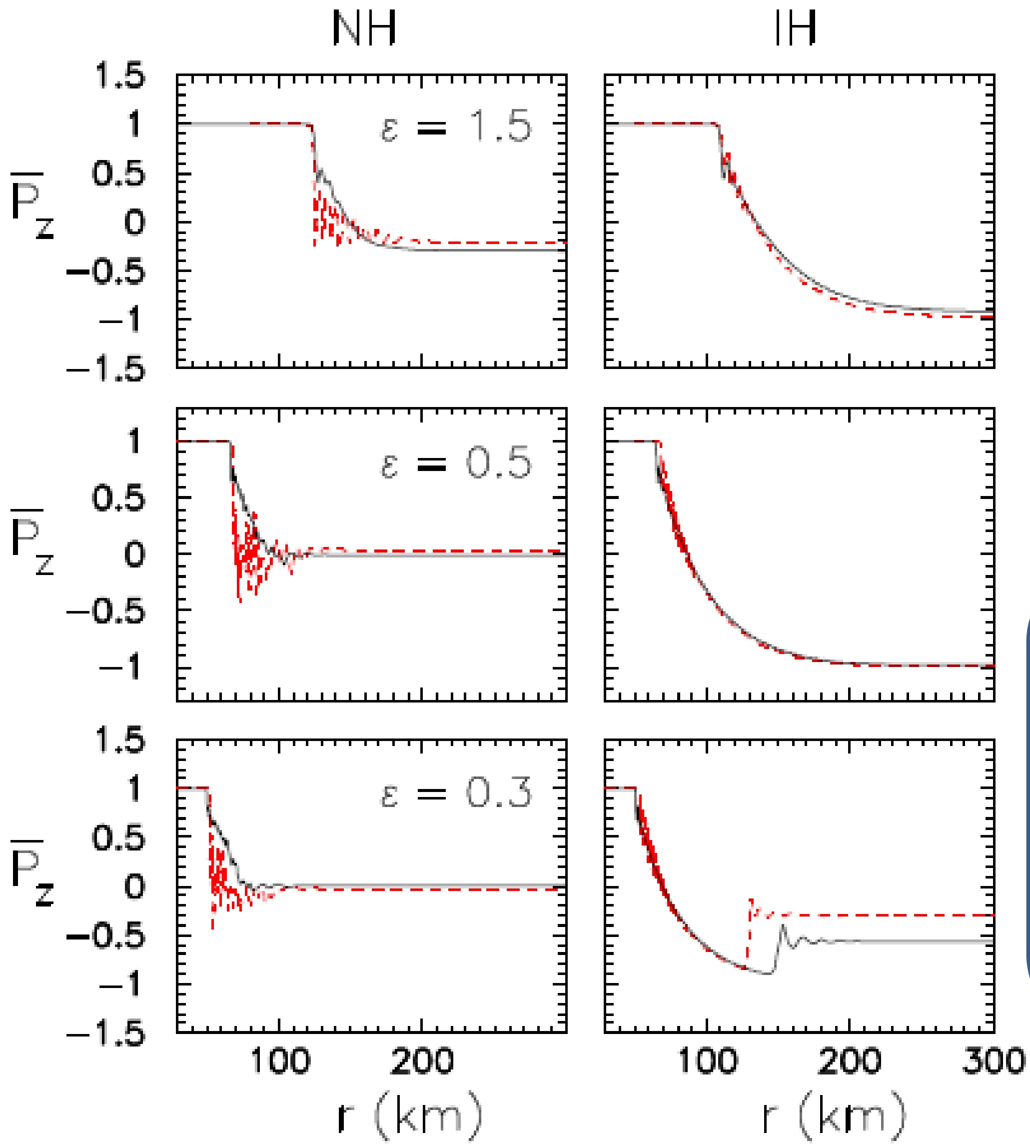
In [*Raffelt, Sarikas, Seixas, 1305.7140*] a stability analysis of the EOMs has been performed including the azimuthal angle ϕ of the ν propagation and without enforcing axial symmetry also starting with an intial axial symmetric ν emission.

A new multi-azimuthal-angle (MAA) instability has been found!!

- In the unstable case, numerical simulations are mandatory.

MAA EFFECTS FOR SN NEUTRINOS

[A.M., 1308.1402]



Monochromatic ν beam

System of only ν_e and $\overline{\nu}_e$ with an excess of ν_e

MZA & MAA

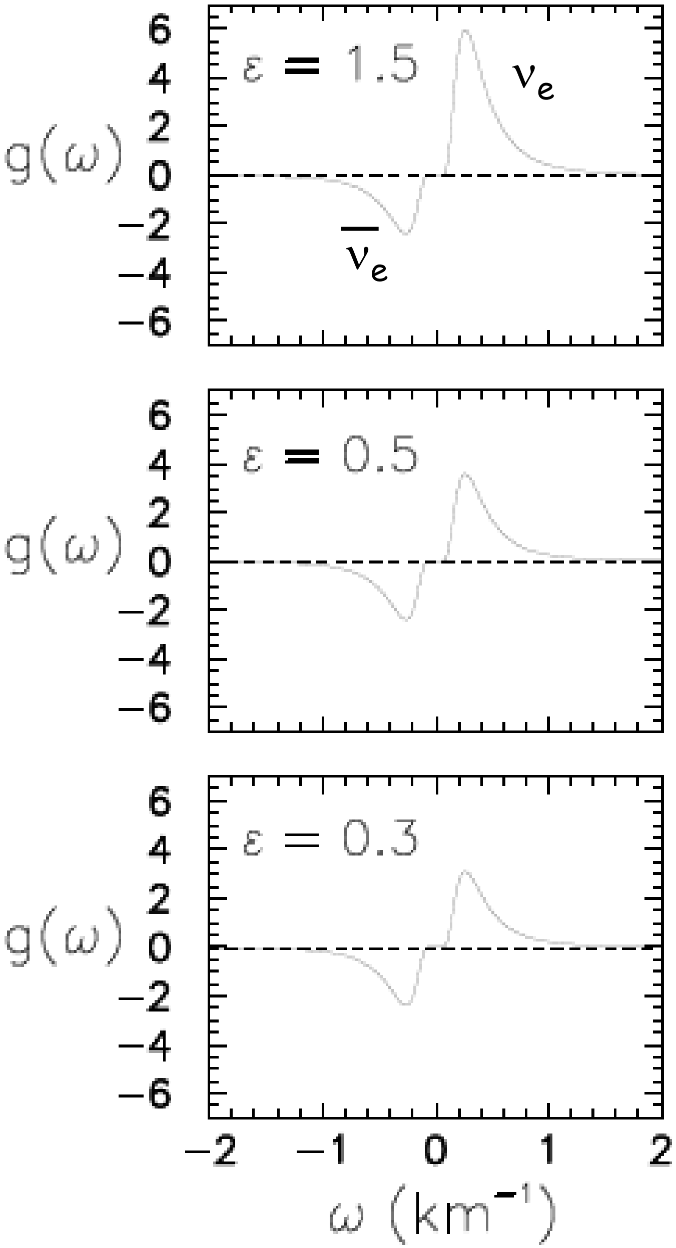
SZA & MAA

NH becomes unstable under MAA effects!

SZA vs MZA marginal impact

New effects in IH only for small ε

TOY MODEL NEUTRINO SPECTRA



System of only ν_e and $\bar{\nu}_e$ with an excess of ν_e

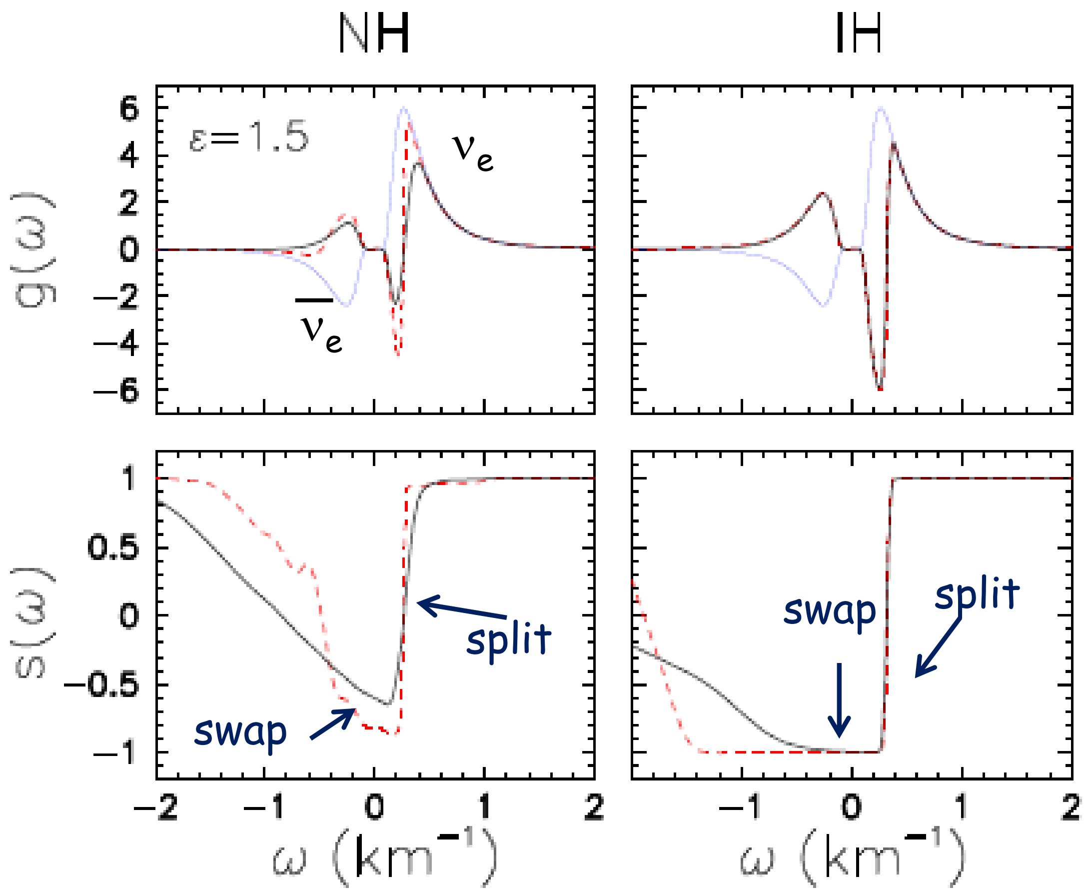
Fermi-Dirac energy distributions with <E>=15 MeV

$$g_\omega \equiv \frac{|\Delta m^2|}{2\omega^2} \times \begin{cases} f_{\nu_e}(E_\omega) - f_{\nu_x}(E_\omega) & \text{for } \omega > 0 \\ f_{\bar{\nu}_x}(E_\omega) - f_{\bar{\nu}_e}(E_\omega) & \text{for } \omega < 0 \end{cases}$$

$$E_\omega = \left|\frac{\Delta m^2}{2\omega}\right|$$

SPECTRAL SPLITS (ε=1.5)

[A.M., 1308.1402]



- Oscillated spectra
  - Initial
  - Final SZA & MAA
  - Final MZA & MAA
- Swap function

$$s(\omega) = \frac{g(\omega)^{final}}{g(\omega)^{initial}}$$

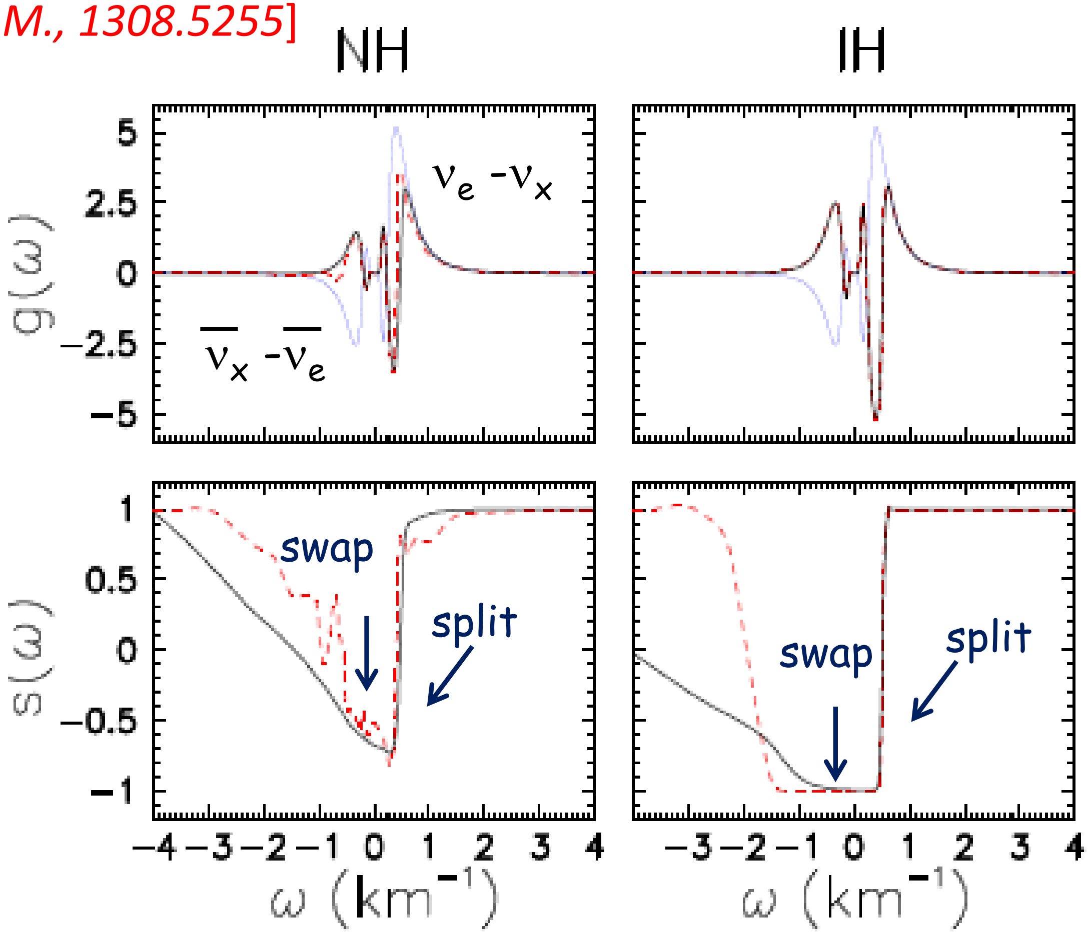
  - SZA & MAA
  - MZA & MAA

- Spectral swaps and splits in both NH (MAA) & IH (Bimodal)
- Antinu split smeared by MZA effects

SPECTRAL SPLITS FOR SN NEUTRINO FLUXES

[A.M., 1308.5255]

(accretion phase)



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

$\langle E_e \rangle = 12\ MeV;$

$\langle E_{\bar{e}} \rangle = 15\ MeV;$

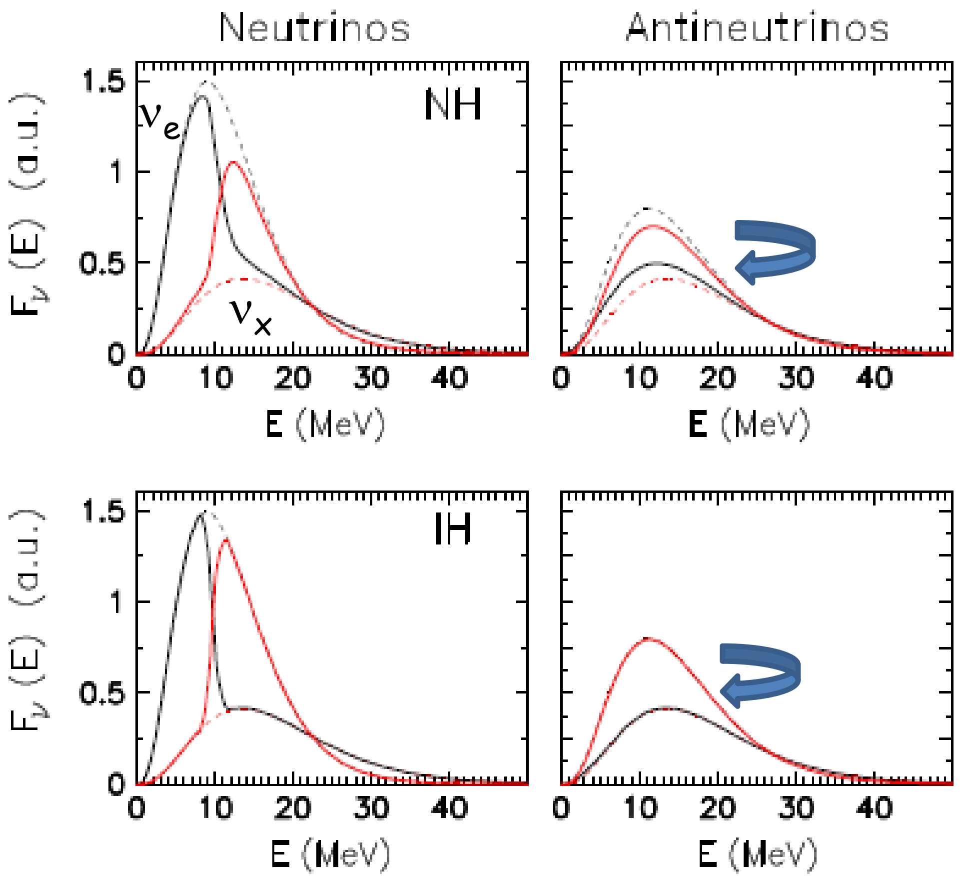
$\langle E_x \rangle = 18\ MeV$

$\varepsilon = 1.34$

- Spectral swaps and splits in both NH & IH !!
- In the axial symmetric case, only IH instable

SPECTRAL SPLITS FOR SN NEUTRINO FLUXES

[A.M., 1308.5255]



- Nu fluxes present a spectral split at E= 12 MeV (fixed by lepton number conservation)
- Antinu fluxes are swapped

CONCLUSIONS

- A new multi-azimuthal-angle (MAA) instability emerges in the dense SN neutrino gas, removing the axial symmetry in the nu-nu interaction term

- For simple systems of only ν_e and $\overline{\nu}_e$, with an excess of ν_e, MAA effects can lead to spectral splits (for large flavor asymmetry) or flavor decoherence (for small flavor asymmetry) in NH.

- For SN ν spectra as in the accretion phase, MAA effects would induce swaps and splits in NH.

- *A change of paradigm in the SN neutrino self-induced effects?*

Still many open points (e.g. role of dense ordinary matter, initial nu angular distributions...)

LOT OF WORK TO BE DONE ...WAITING THE NEXT SN EXPLOSION !