DENSE NEUTRINO OSCILLATIONS : 3 FLAVOR SCENARIO

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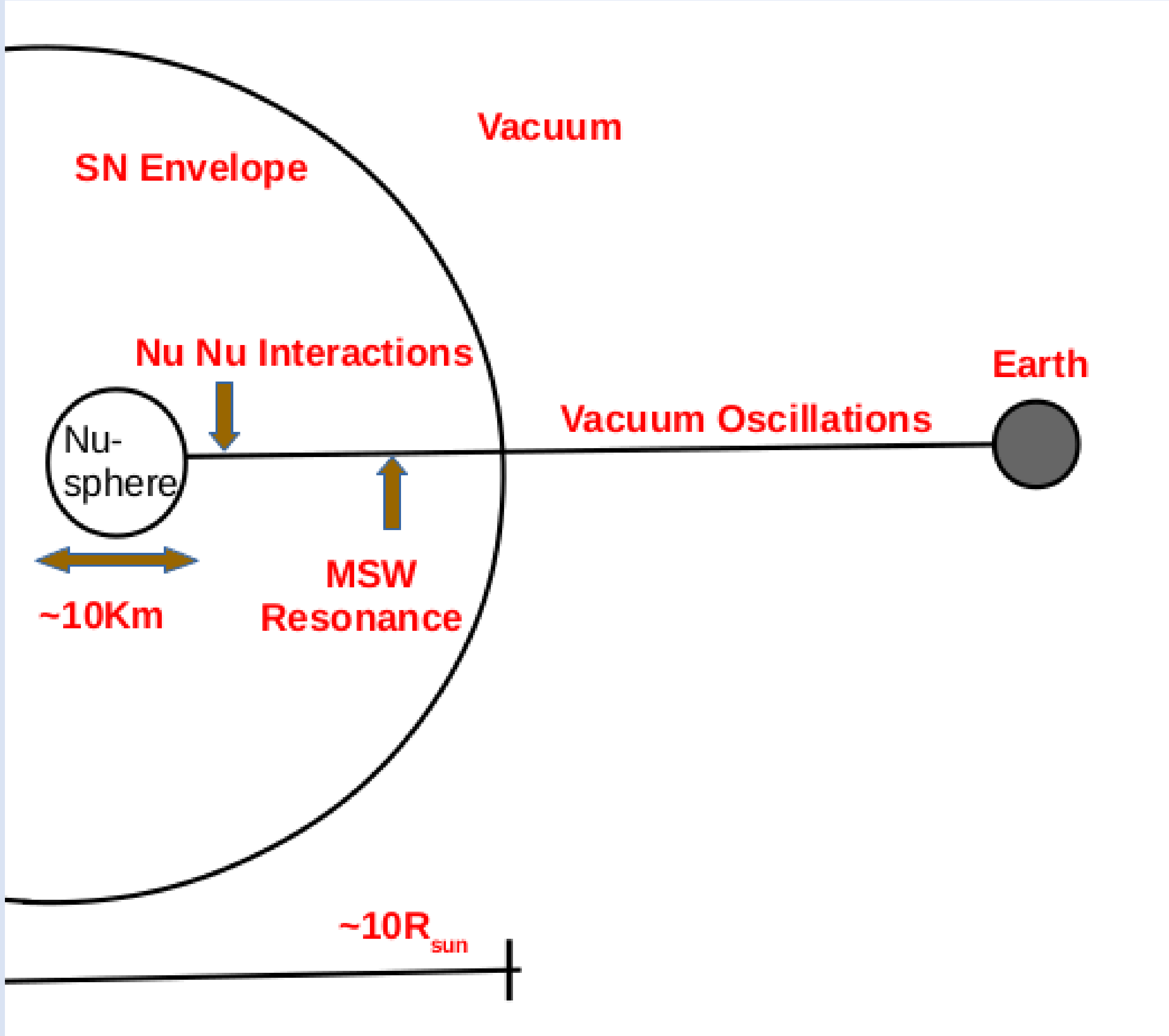
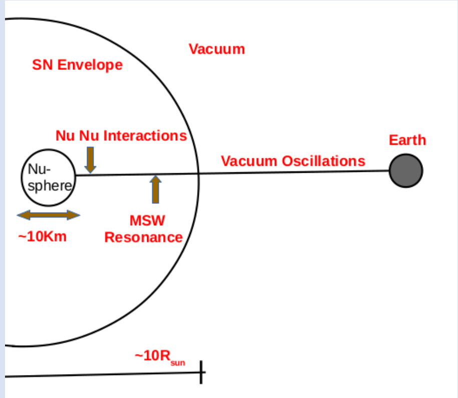
NEUTRINOS AFTER THE SUPERNOVA EXPLOSION



EVOLUTION OF NEUTRINOS



$$iv^{\beta}\partial_{\beta}\rho_p = [H_p, \rho_p]$$

$$\beta = 0, 1, 2, 3$$

$$H_p = H_{vac} + H_{matter} + H_{\nu\nu}$$

$$\frac{M^2}{2E} = \omega$$

Responsible for

COLLECTIVE OSCILLATIONS

$$\rho_{\mathbf{p}} = \begin{pmatrix} \rho_{\mathbf{p}}^{ee} & \rho_{\mathbf{p}}^{e\mu} & \rho_{\mathbf{p}}^{e\tau} \\ \rho_{\mathbf{p}}^{\mu e} & \rho_{\mathbf{p}}^{\mu\mu} & \rho_{\mathbf{p}}^{\mu\tau} \\ \rho_{\mathbf{p}}^{\tau e} & \rho_{\mathbf{p}}^{\tau\mu} & \rho_{\mathbf{p}}^{\tau\tau} \end{pmatrix}$$

$$H_{\nu\nu} = \sqrt{2}G_F v_{\beta} \int d\mathbf{p}\; v^{\beta}\; (\rho_{\mathbf{p}} - \bar{\rho}_{\mathbf{p}})$$

$$\mu \sim \sqrt{2}G_F n_{\nu}$$

Growth Rate ~ ω ⟶ SLOW OSCILLATIONS

μ>>ω ⟶ FAST OSCILLATIONS(Growth Rate~μ, ω~0)

S. Chakraborty et.al. PRD 92(2015)

EVOLUTION OF NEUTRINOS

$$\rho_{\mathbf{p}} = \frac{f_{\mathbf{p}}^{\nu_e} + f_{\mathbf{p}}^{\nu_\mu} + f_{\mathbf{p}}^{\nu_\tau}}{3}\mathbb{1} + \frac{f_{\mathbf{p}}^{\nu_e} - f_{\mathbf{p}}^{\nu_\mu}}{3}\begin{pmatrix} s_{\mathbf{p}} & S_{1\mathbf{p}} & 0 \\ S_{1\mathbf{p}}^{*} & -s_{\mathbf{p}} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$+ \frac{f_{\mathbf{p}}^{\nu_e} - f_{\mathbf{p}}^{\nu_\tau}}{3}\begin{pmatrix} s_{\mathbf{p}} & 0 & S_{2\mathbf{p}} \\ 0 & 0 & 0 \\ S_{2\mathbf{p}}^{*} & 0 & -s_{\mathbf{p}} \end{pmatrix} + \frac{f_{\mathbf{p}}^{\nu_\mu} - f_{\mathbf{p}}^{\nu_\tau}}{3}\begin{pmatrix} 0 & 0 & 0 \\ 0 & s_{\mathbf{p}} & S_{3\mathbf{p}} \\ 0 & S_{3\mathbf{p}}^{*} & -s_{\mathbf{p}} \end{pmatrix}$$

$$i\, v^{\beta}\partial_{\beta}S_{jE,\mathbf{v}} = (\omega_j + v^{\beta}\lambda_{j\beta})S_{jE,\mathbf{v}} - \sqrt{2}\,G_F\, v^{\beta}\int d\Gamma'_j\, v'_{\beta}\, g_{jE',\mathbf{v}'}S_{jE',\mathbf{v}'}$$

j=1,2,3

$$\omega_1 = \frac{(m_1^2 - m_2^2)}{2E}, \omega_2 = \frac{(m_1^2 - m_3^2)}{2E} \simeq \omega_3 = \frac{(m_2^2 - m_3^2)}{2E} \text{ as } \frac{\omega_1}{\omega_2} \simeq 10^{-2}$$

Three independent two flavor evolution equations

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EVOLUTION EQUATION : SOLUTION

RADIAL EVOLUTION

LINEAR STABILITY ANALYSIS

Off-diagonal element

$$S_j = Q_j e^{-i\Omega_j r}$$

$\Omega_j = \gamma_j + i\kappa_j$ j=1,2,3

Growth of κ signifies instability

SPATIAL AND TEMPORAL EVOLUTION

$$S_j = Q_j e^{-i(K_j^0 t - \mathbf{K}_j \cdot \mathbf{r})}$$ j=1,2,3

DISPERSION RELATION

$D(K^0,\mathbf{K})=0$

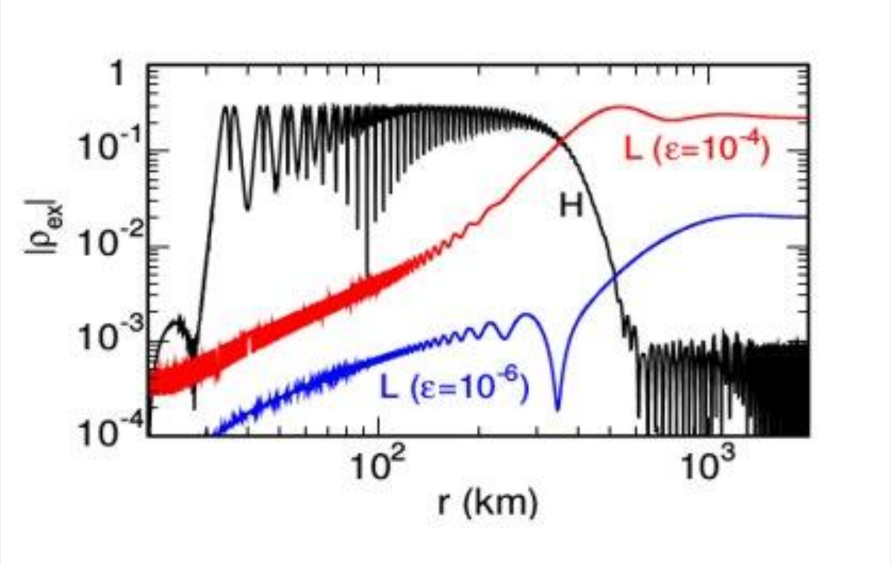
Presence of complex K^0 for real $\mathbf{K}$ and vice versa leads to instability

INSTABILITY=FLAVOR CONVERSION

TWO FLAVOR SCENARIO STUDIED TILL NOW

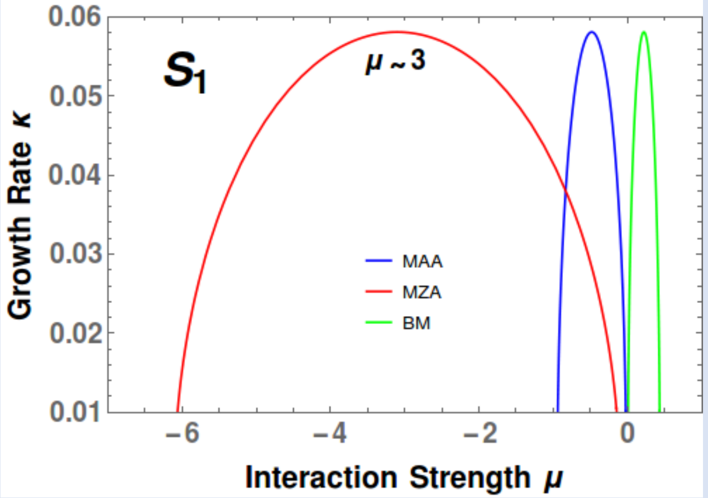
A. Banerjee, A. Dighe and G. Raffelt, PRD 2011, I.Izaguirre et. al, PRL(2017)

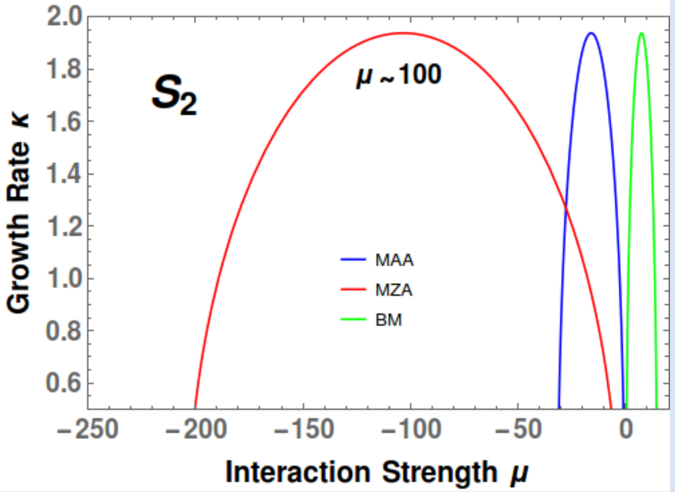
STABILITY ANALYSIS

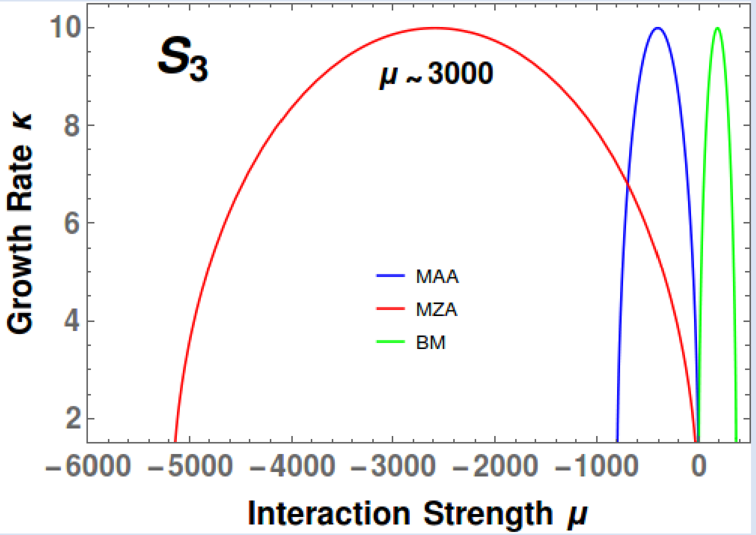


H ⟶ Atmospheric sector
L ⟶ Solar sector

(B. Dasgupta et al, PRD 2010)







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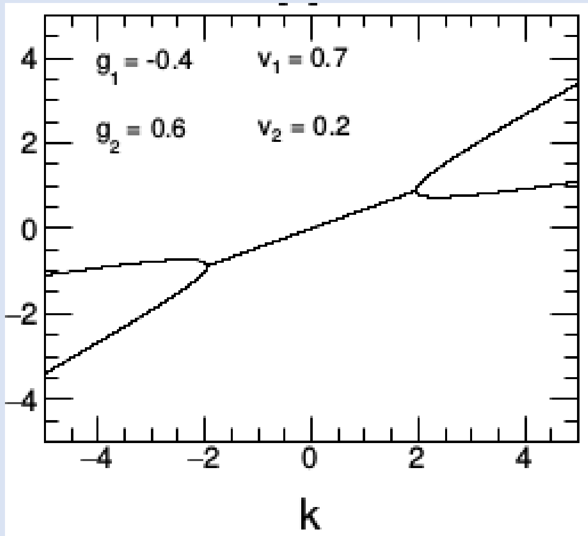
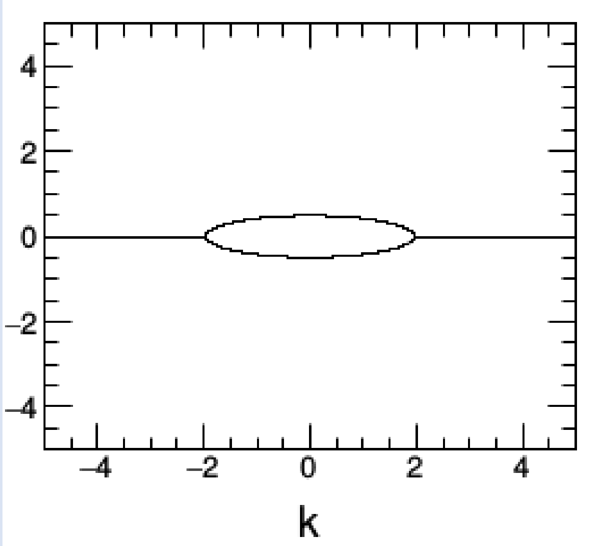
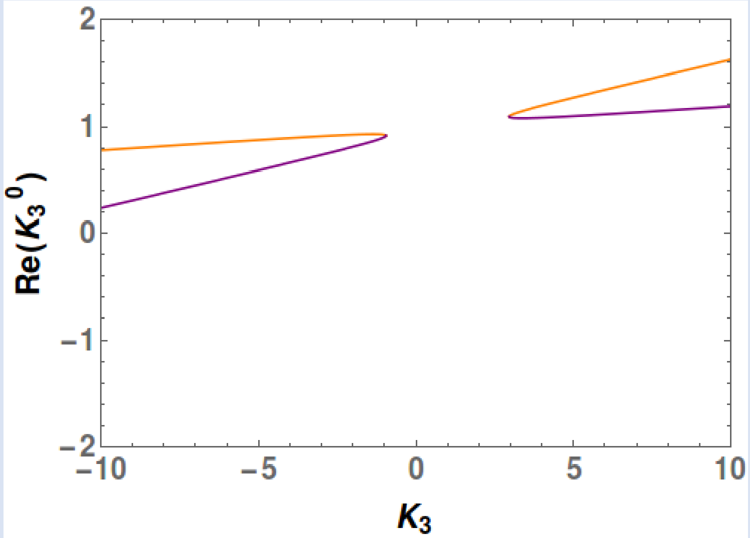
DISPERSION RELATION

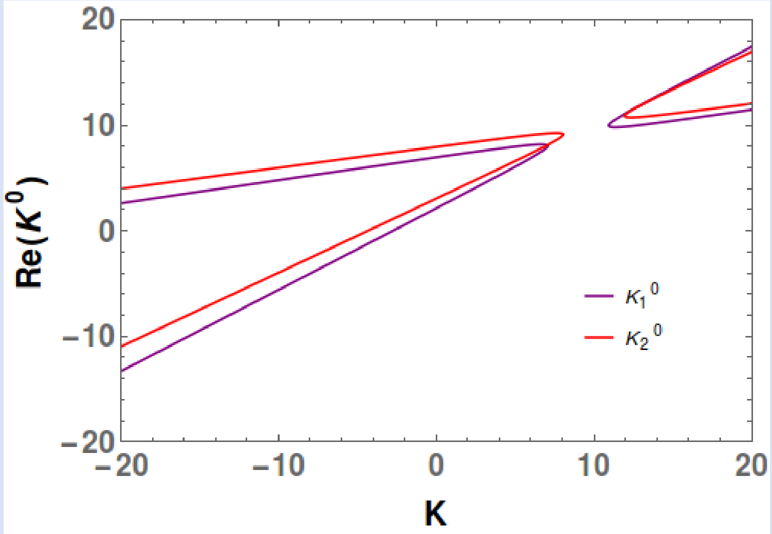


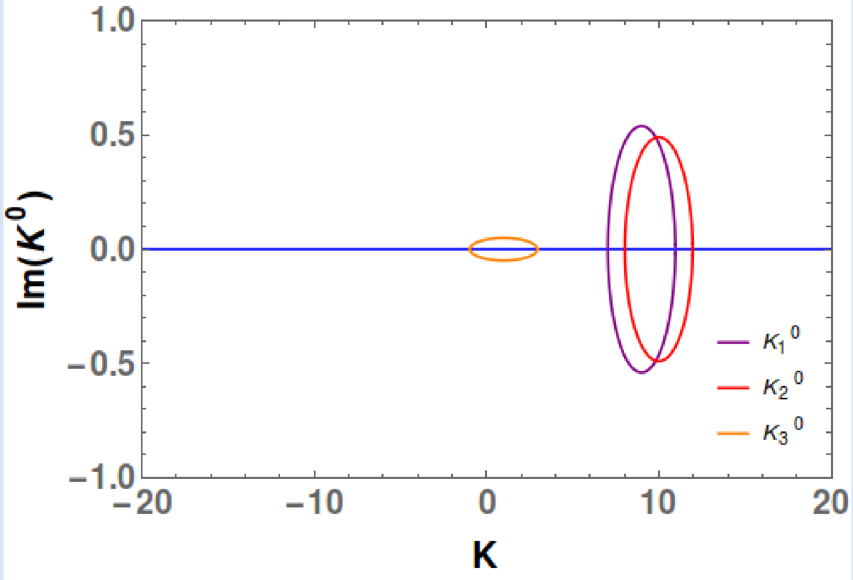


2 Flavor Case

F.Capozzi et. al, PRD(2017)







3 Flavor Case

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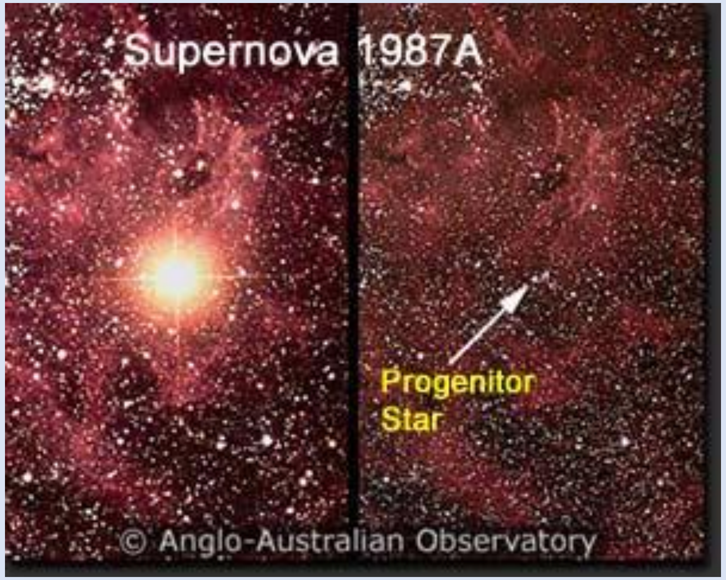
CONCLUSIONS

- Supernova neutrinos : Collective oscillations important
- Numerical analysis : a challenging task
- Semi-analytical way of solving problem : Linearized stability analysis
- Spatial and temporal evolution studied : Dispersion Relation Approach
- Both slow and fast modes considered
- 3 Flavor Scenario : 3 factorized evolution equations, instability present in all modes
- 3 flavor effects can speed up the effect of solar sector

THANK YOU

CORE-COLLAPSE SUPERNOVA



- Occurs from the death of a massive star > 8 solar mass
- Also known as the type II supernova
- 99% of Gravitational Energy emitted as neutrinos($\sim 10^{58}$)
- Average energy of neutrinos around 10 MeV emitted within 10 seconds

NEUTRINOS : RICH SOURCE OF INFORMATION