

# *FAST FLAVOR SUPERNOVA NEUTRINO CONVERSIONS IN 3 FLAVORS*

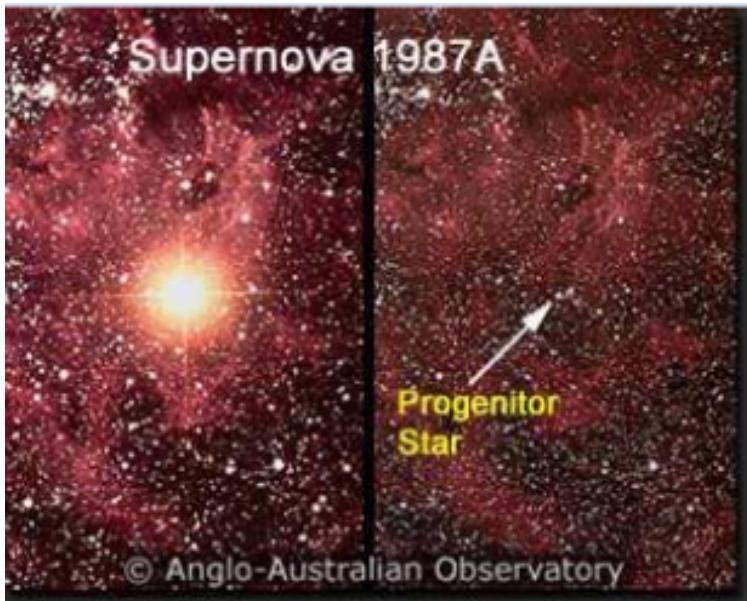
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# PLAN OF TALK

- *Introduction*
- *Fast Oscillations*
- *Nonlinear Analysis*
- *Conclusion*

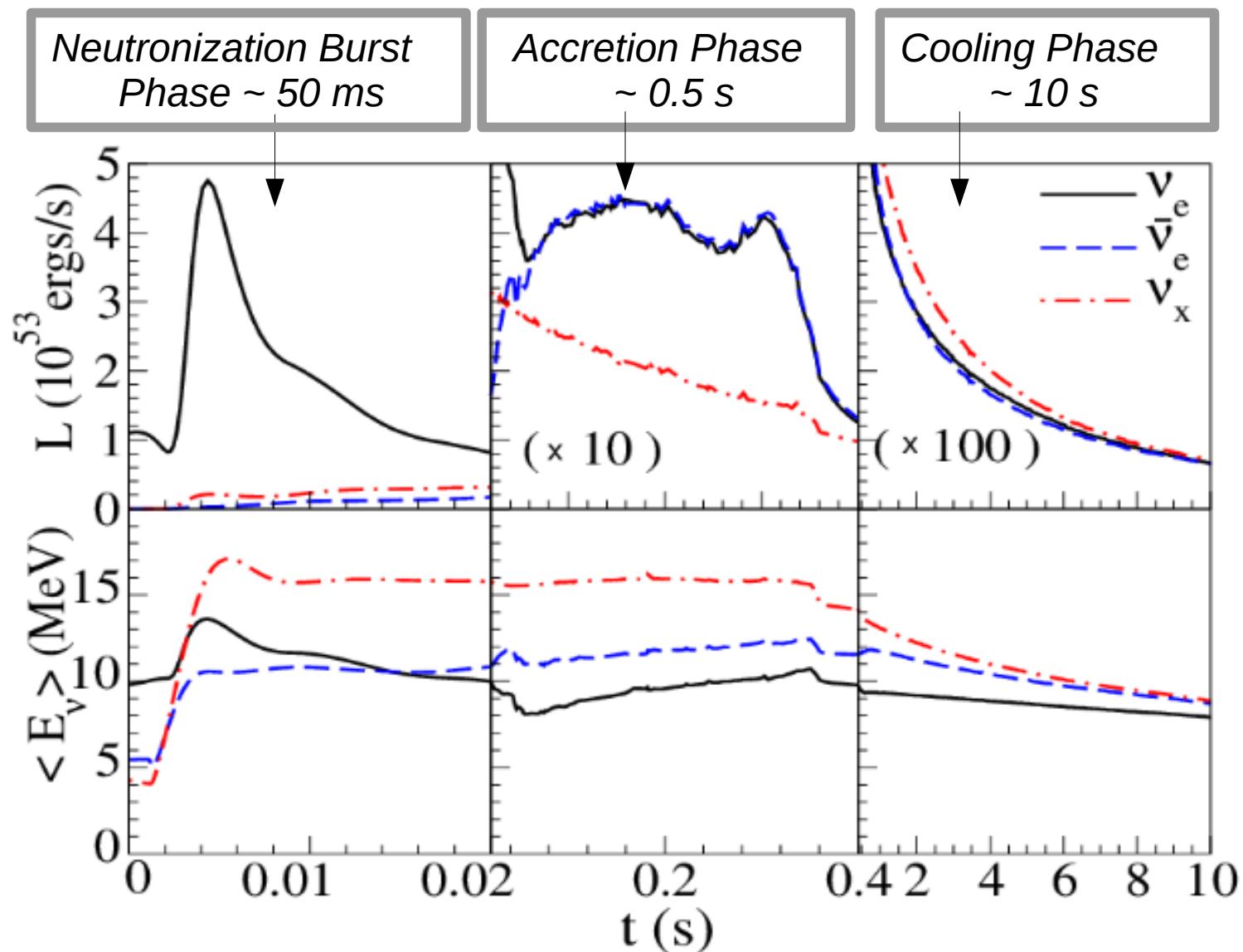
# CORE-COLLAPSE SUPERNOVA



- Occurs from the death of a massive star  $> 8 M_{\text{sun}}$
- 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*

# NEUTRINO EMISSION PHASES

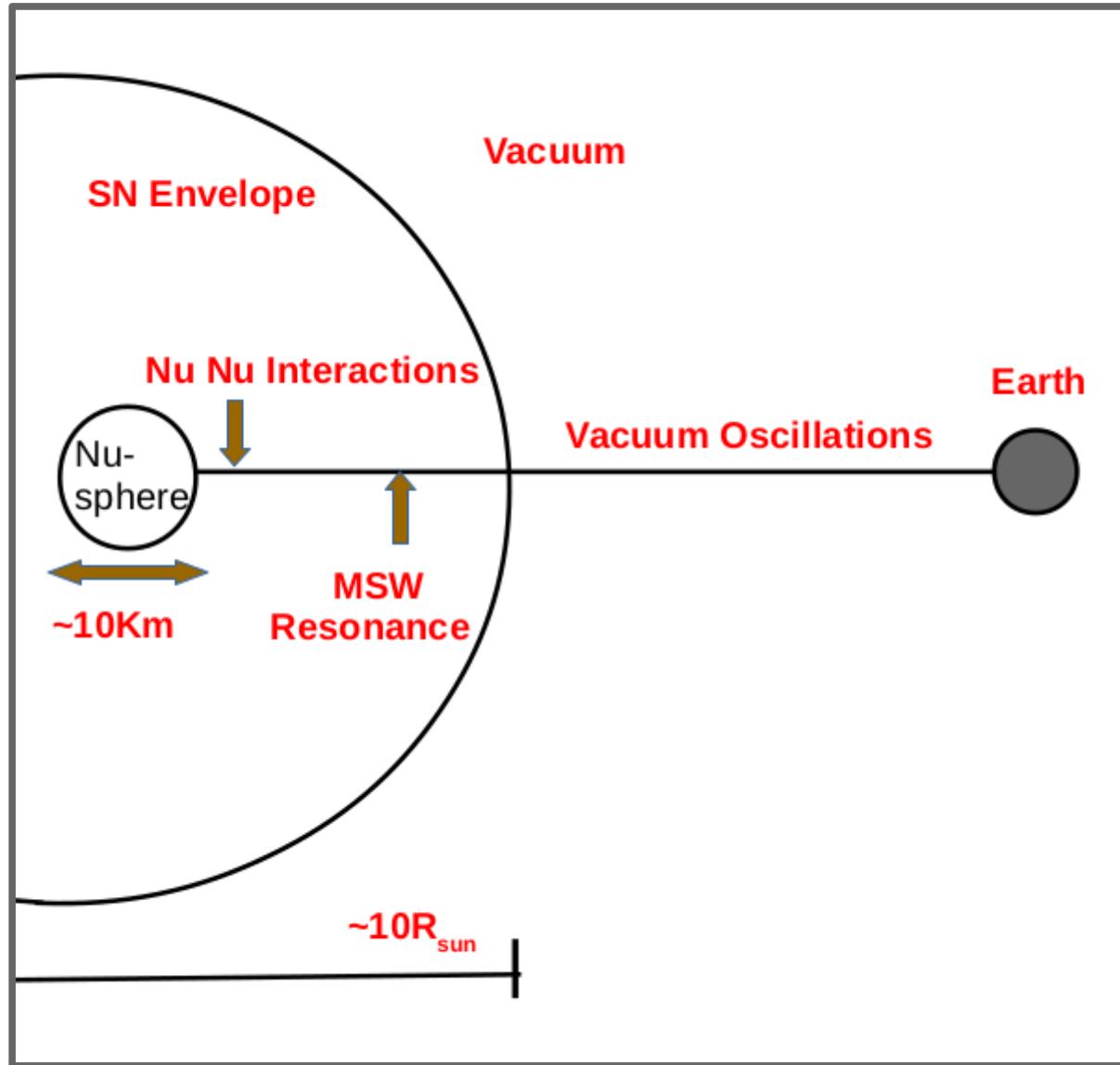


Obtained from the results of the Basel/Darmstadt simulation

of a  $18 M_{\odot}$  progenitor SN

Chakraborty et al Phys. Rev. D95 (2017)

# NEUTRINOS AFTER SUPERNOVA EXPLOSION



# EVOLUTION OF NEUTRINOS

$$v^\beta \partial_\beta \rho_p = -i [H_p, \rho_p] \quad \beta=0,1,2,3$$

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

*Responsible for  
Collective Oscillations*

# EVOLUTION OF NEUTRINOS

$$v^\beta \partial_\beta \rho_p = -i [H_p, \rho_p]$$

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

*Responsible for Collective Oscillations*

$$\rho_p = \begin{pmatrix} \rho_p^{ee} & \rho_p^{e\mu} & \rho_p^{e\tau} \\ \rho_p^{\mu e} & \rho_p^{\mu\mu} & \rho_p^{\mu\tau} \\ \rho_p^{\tau e} & \rho_p^{\tau\mu} & \rho_p^{\tau\tau} \end{pmatrix}$$

*Responsible for flavor conversion*

*Correspond to overall flavor content*

$$H_{vac} = \frac{1}{2E} diag(m_1^2, m_2^2, m_3^2)$$

$$H_{matter} \propto diag(n_e - n_{\bar{e}}, n_\mu - n_{\bar{\mu}}, n_\tau - n_{\bar{\tau}})$$

$$H_{\nu\nu} = \sqrt{2} G_F v_\beta \int d\mathbf{p} v^\beta (\rho_p - \overline{\rho_p})$$



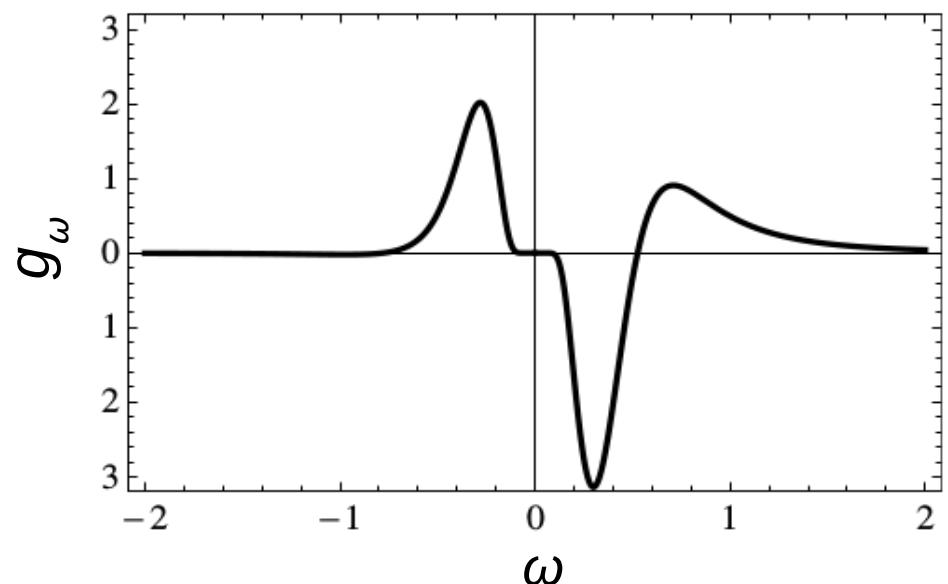
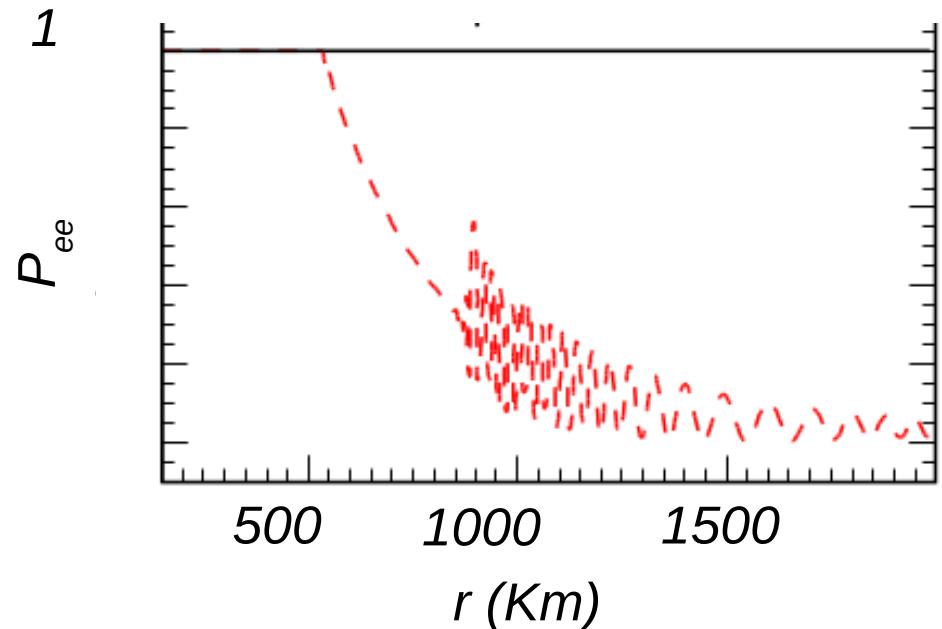
*Makes evolution non linear*

# SLOW OSCILLATIONS

- *Driving frequency -  $\omega$*

$$\omega = \frac{\Delta m^2}{2E} \sim O(1 \text{ km}^{-1})$$

- *Occurs  $\sim 10^2 \text{ km}$  from the neutrinosphere*
- *Growth Rate  $\sim \omega$*
- *Spectrum only energy dependent*

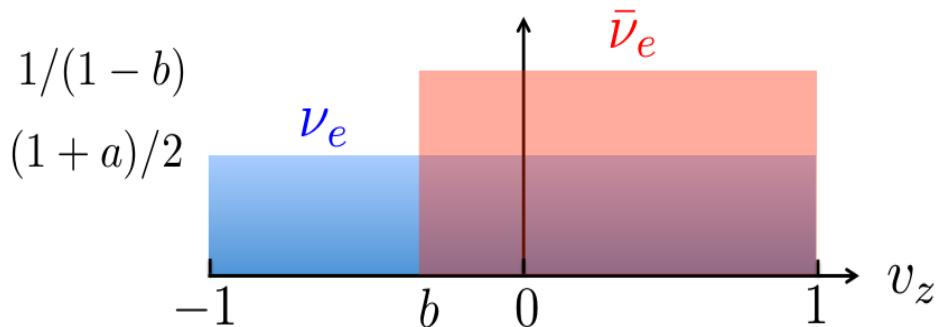


# FAST OSCILLATIONS

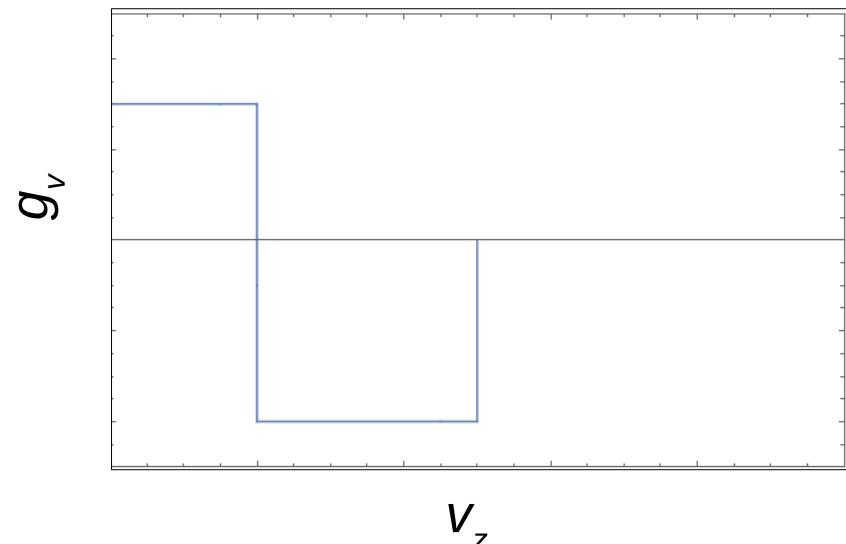
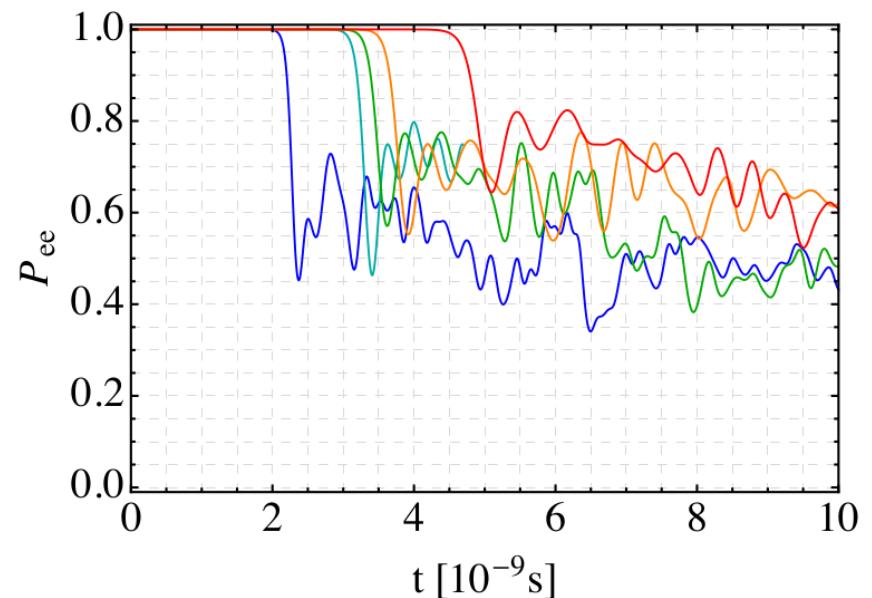
- *Driven by neutrino density  $\mu$*

$$\mu \sim \sqrt{2} G_F n_\nu \sim O(10^5 \text{ km}^{-1})$$

- *May occur just above the neutrinosphere*
- *Growth Rate  $\sim \mu$*
- *Spectrum dependent on angular distribution*



B. Dasgupta et al arXiv:1609.00528



R. F. Sawyer Phys. Rev. D 72, 045003 (2005)

Chakraborty et al, arXiv:1602.00698

# PLAN OF TALK

- *Introduction*
- **Fast Oscillations**
- *Nonlinear Analysis*
- *Conclusion*

# TWO FLAVOR CASE

$$iv^\beta \partial_\beta \rho_{\mathbf{p}}^{e\mu} = \left[ \frac{m_1^2 - m_2^2}{2E} + v_\beta (\lambda_e^\beta - \lambda_\mu^\beta) \right] \rho_{\mathbf{p}}^{e\mu} - \sqrt{2} G_F (\rho_{\mathbf{p}}^{ee} - \rho_{\mathbf{p}}^{\mu\mu}) v^\beta \int d\mathbf{p}' v'_\beta (\rho_{\mathbf{p}'}^{e\mu} - \bar{\rho}_{\mathbf{p}'}^{e\mu})$$

$$\rho_{\mathbf{p}} = \frac{f_{\nu_e, \mathbf{p}} + f_{\nu_\mu, \mathbf{p}}}{2} \mathbb{1} + \frac{f_{\nu_e, \mathbf{p}} - f_{\nu_\mu, \mathbf{p}}}{2} \begin{pmatrix} s_{\mathbf{p}} & S_{\mathbf{p}} \\ S_{\mathbf{p}}^* & -s_{\mathbf{p}} \end{pmatrix}$$

$$iv^\beta \partial_\beta S_{E,v} = (\omega + v^\beta \lambda_\beta) S_{E,v} - \sqrt{2} G_F v^\beta \int d\Gamma' v'_\beta (f_{v_e, v'} - f_{\bar{v}_e, v'}) S_{E', v'}$$

$$\int d\Gamma' = \int_{-\infty}^{\infty} dE' \int_0^1 du' \int_0^{2\pi} d\phi'$$

# FAST OSCILLATIONS

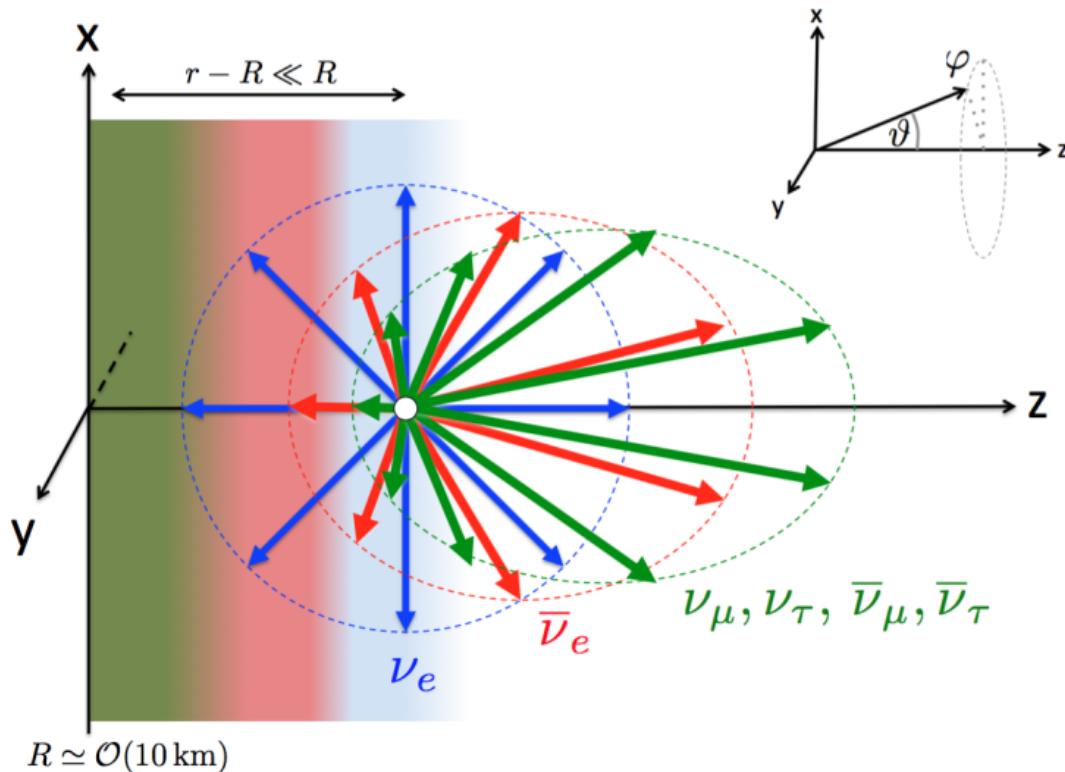
$$iv^\beta \partial_\beta S_{E,v} = (\omega + v^\beta \lambda_\beta) S_{E,v} - \sqrt{2} G_F v^\beta \int d\Gamma' v'_\beta (f_{v_e, v'} - f_{\bar{v}_e, v'}) S_{E', v'}$$

- $M^2=0$  i.e.  $\omega_j \rightarrow 0$
- Growth Rate  $\sim \mu$
- Spectrum dependent on angular distribution
- Crossing in the spectrum important

$$iv^\beta \partial_\beta S_v = (v^\beta \lambda_\beta) S_v - v^\beta \int d\Gamma' v'_\beta G_v S_{v'}$$

## *Fast oscillations study – Angular distributions*

*Different Flavors – Different angular distributions*



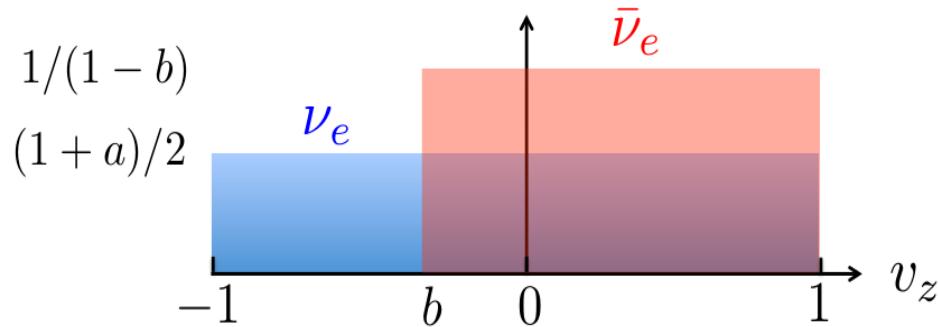
*Flavor dependent  
zenith angle distributions  
of neutrino fluxes*

# FAST OSCILLATIONS : TWO FLAVOR

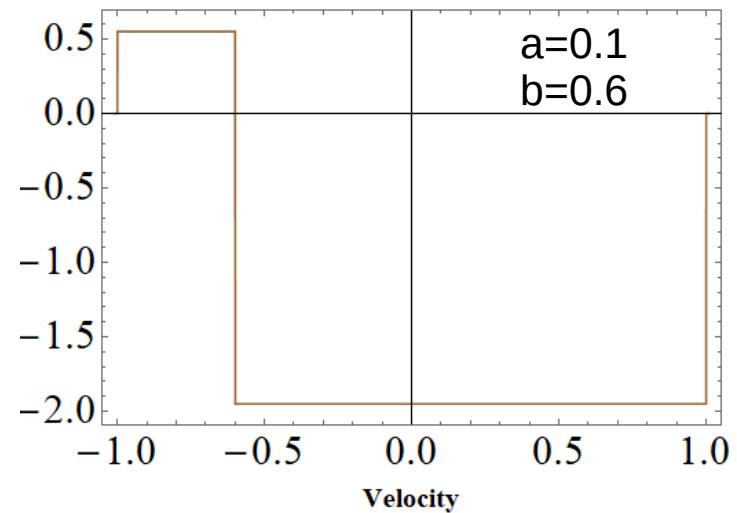
*ELN is given by:*

$$G_v = \int_{-\infty}^{+\infty} \frac{E^2 dE}{2\pi^2} g_{E,v} = \sqrt{2} G_F \int_0^{\infty} \frac{E^2 dE}{2\pi^2} (f_{\nu_e, p} - f_{\bar{\nu}_e, p})$$

*Zero Crossing in  $G_v$*



*Necessary condition for fast flavor conversions*



# THREE FLAVOR CASE

$$iv^\beta \partial_\beta \rho_{\mathbf{p}}^{e\mu} = \left[ \frac{m_1^2 - m_2^2}{2E} + v_\beta (\lambda_e^\beta - \lambda_\mu^\beta) \right] \rho_{\mathbf{p}}^{e\mu} - \sqrt{2} G_F (\rho_{\mathbf{p}}^{ee} - \rho_{\mathbf{p}}^{\mu\mu}) v^\beta \int d\mathbf{p}' v'_\beta (\rho_{\mathbf{p}'}^{e\mu} - \bar{\rho}_{\mathbf{p}'}^{e\mu})$$

*Similar equations for e- $\tau$  and  $\mu-\tau$*

$$\begin{aligned} \rho_{\mathbf{p}} = & \frac{f_{\nu_e, \mathbf{p}} + f_{\nu_\mu, \mathbf{p}} + f_{\nu_\tau, \mathbf{p}}}{3} \mathbb{1} + \frac{f_{\nu_e, \mathbf{p}} - f_{\nu_\mu, \mathbf{p}}}{3} \begin{pmatrix} s_{\mathbf{p}} & S_{1\mathbf{p}} & 0 \\ S_{1\mathbf{p}}^* & -s_{\mathbf{p}} & 0 \\ 0 & 0 & 0 \end{pmatrix} \\ & + \frac{f_{\nu_e, \mathbf{p}} - f_{\nu_\tau, \mathbf{p}}}{3} \begin{pmatrix} s_{\mathbf{p}} & 0 & S_{2\mathbf{p}} \\ 0 & 0 & 0 \\ S_{2\mathbf{p}}^* & 0 & -s_{\mathbf{p}} \end{pmatrix} + \frac{f_{\nu_\mu, \mathbf{p}} - f_{\nu_\tau, \mathbf{p}}}{3} \begin{pmatrix} 0 & 0 & 0 \\ 0 & s_{\mathbf{p}} & S_{3\mathbf{p}} \\ 0 & S_{3\mathbf{p}}^* & -s_{\mathbf{p}} \end{pmatrix} \end{aligned}$$

$$iv^\beta \partial_\beta S_{jE, v} = (\omega_j + v^\beta \lambda_{j\beta}) S_{jE, v} - \sqrt{2} G_F v^\beta \int d\Gamma_j' v'_\beta g_{jE', v'} S_{jE', v'} \quad j=1,2,3$$

$$\int d\Gamma' = \int_{-\infty}^{\infty} dE' \int_0^1 du' \int_0^{2\pi} d\phi'$$

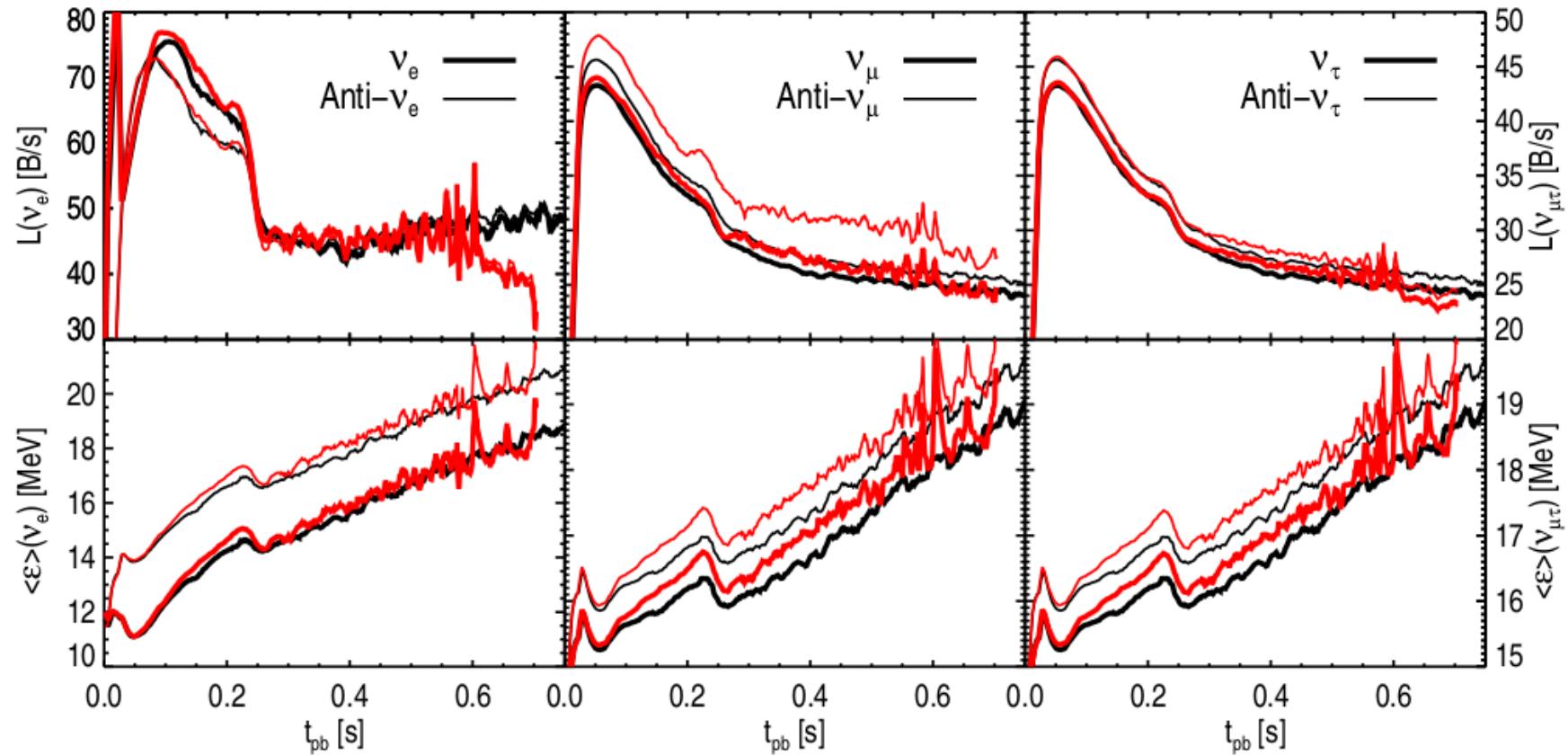
# ANGULAR SPECTRUM

*In Fast flavor limit,*

$$G_{1,\mathbf{v}} = \int_{-\infty}^{+\infty} \frac{E^2 dE}{2\pi^2} g_{1,E,\mathbf{v}} = \sqrt{2} G_F \int_0^{\infty} \frac{E^2 dE}{2\pi^2} (f_{\nu_e,\mathbf{p}} - f_{\bar{\nu}_e,\mathbf{p}} - f_{\nu_\mu,\mathbf{p}} + f_{\bar{\nu}_\mu,\mathbf{p}})$$
$$G_{2,\mathbf{v}} = \int_{-\infty}^{+\infty} \frac{E^2 dE}{2\pi^2} g_{2,E,\mathbf{v}} = \sqrt{2} G_F \int_0^{\infty} \frac{E^2 dE}{2\pi^2} (f_{\nu_e,\mathbf{p}} - f_{\bar{\nu}_e,\mathbf{p}} - f_{\nu_\tau,\mathbf{p}} + f_{\bar{\nu}_\tau,\mathbf{p}})$$
$$G_{3,\mathbf{v}} = \int_{-\infty}^{+\infty} \frac{E^2 dE}{2\pi^2} g_{3,E,\mathbf{v}} = \sqrt{2} G_F \int_0^{\infty} \frac{E^2 dE}{2\pi^2} (f_{\nu_\mu,\mathbf{p}} - f_{\bar{\nu}_\mu,\mathbf{p}} - f_{\nu_\tau,\mathbf{p}} + f_{\bar{\nu}_\tau,\mathbf{p}})$$

- *MuLN and TauLN in addition to ELN*
- *In Case of two flavor,  $f_{\nu_\mu} = f_{\bar{\nu}_\mu}$ ,  $f_{\nu_\tau} = f_{\bar{\nu}_\tau}$*
- *The spectrum reduces to only ELN*

# EFFECT OF PRESENCE OF MUONS



Obtained from 2D simulations([R. Bollig et al, arXiv:1706.04630](#))

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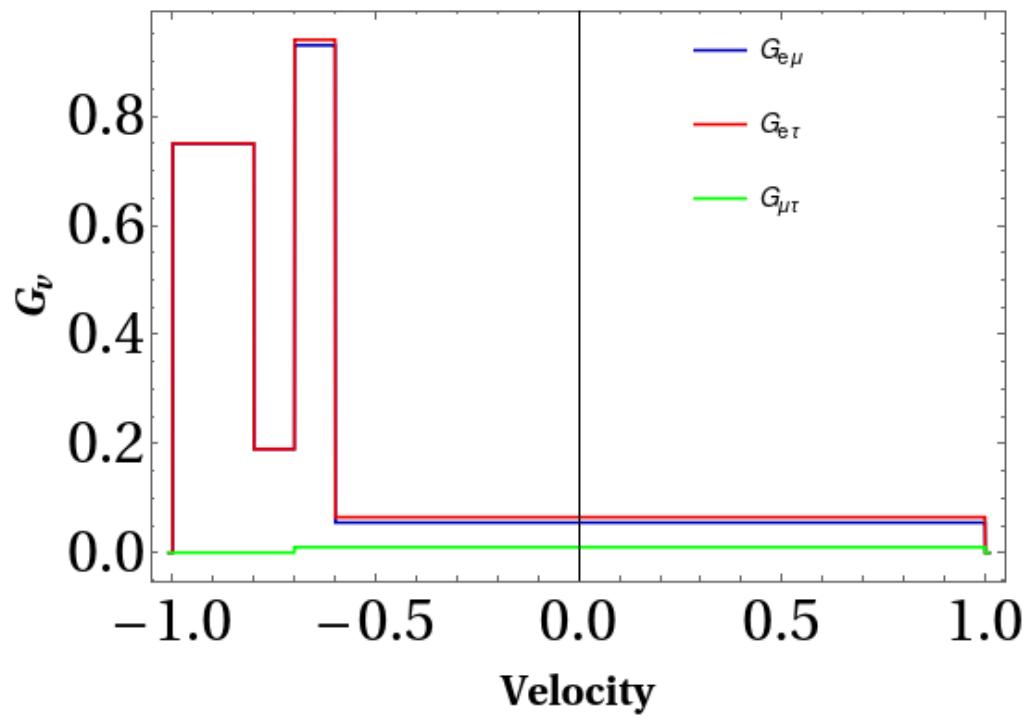
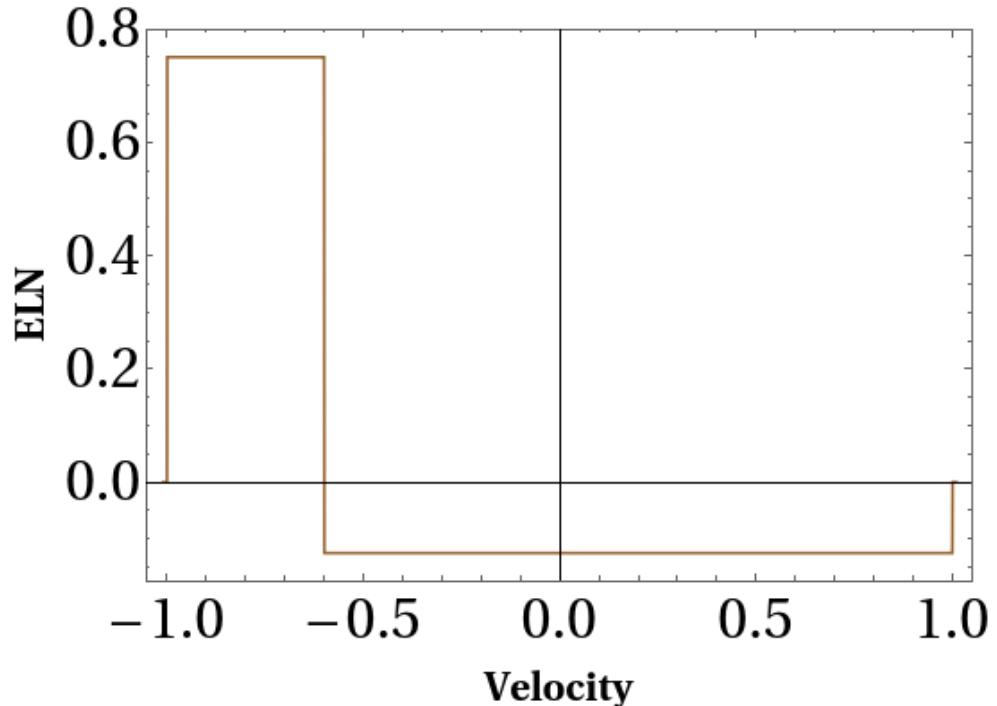
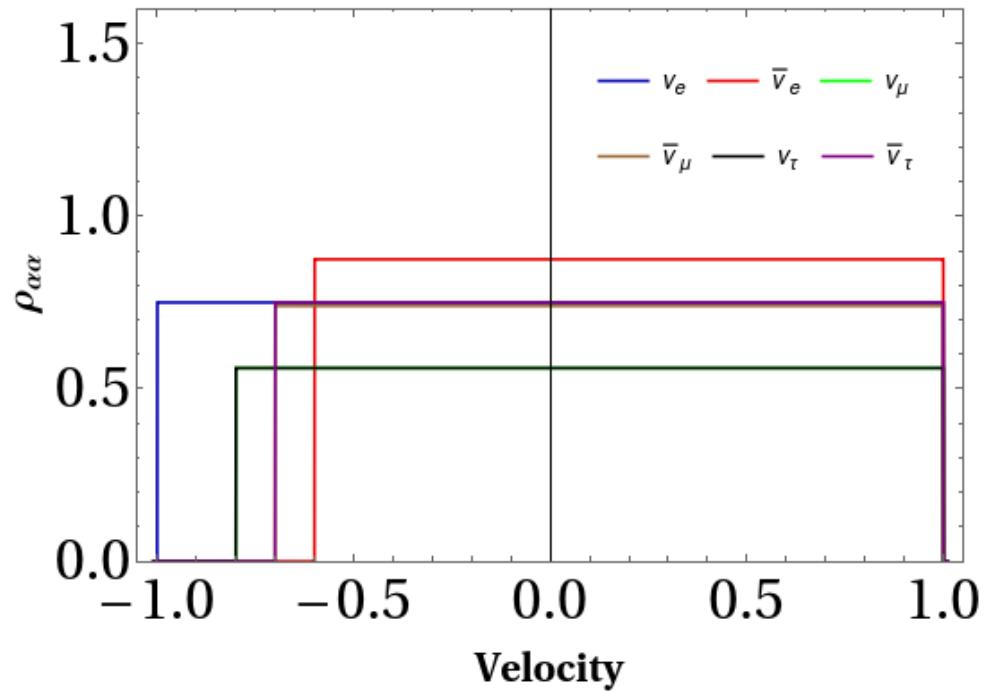
# FAST OSCILLATIONS : THREE FLAVOR

*Based on PRL 125,251801 (2020)*

*Authors : Francesco Capozzi, Madhurima Chakraborty, Sovan Chakraborty  
and Manibrata Sen*

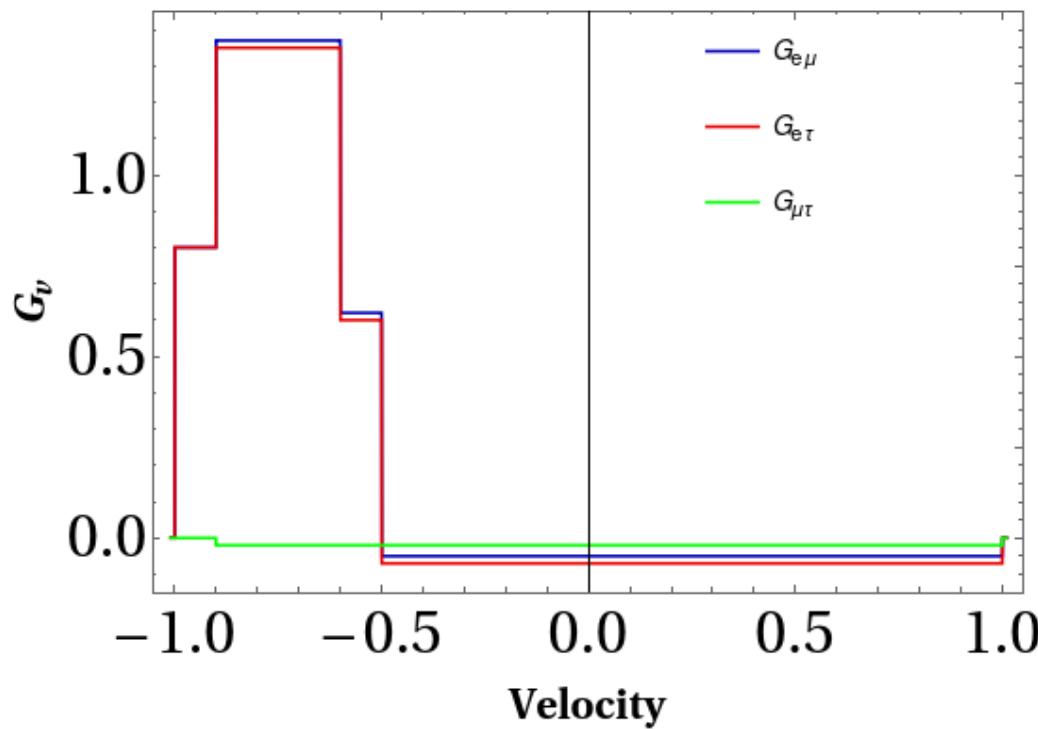
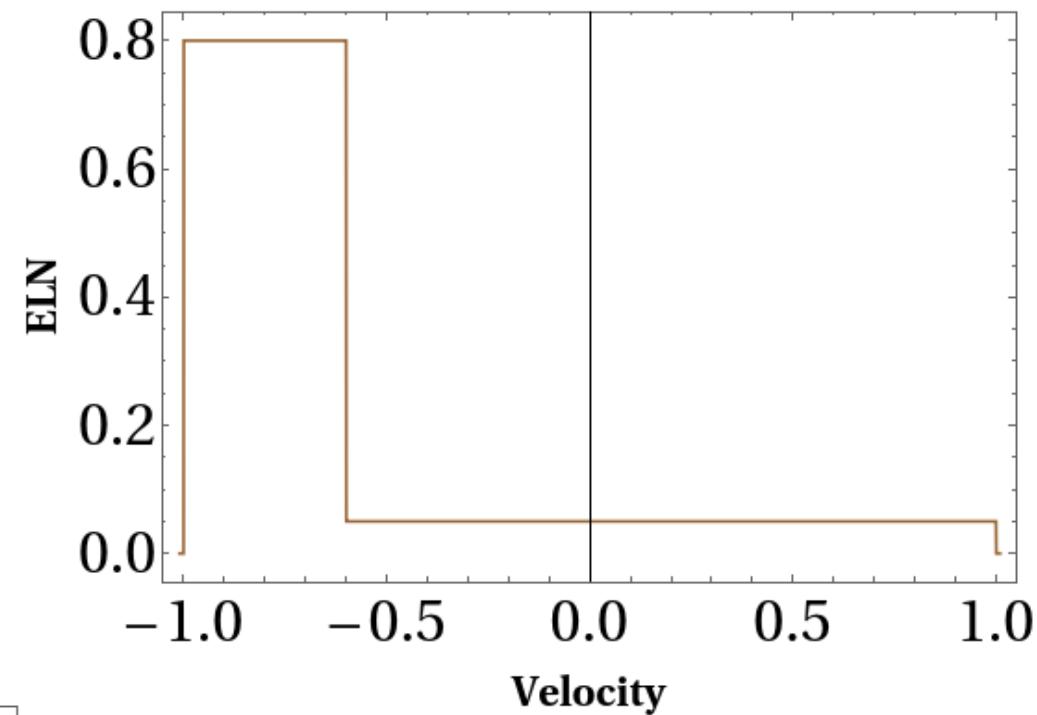
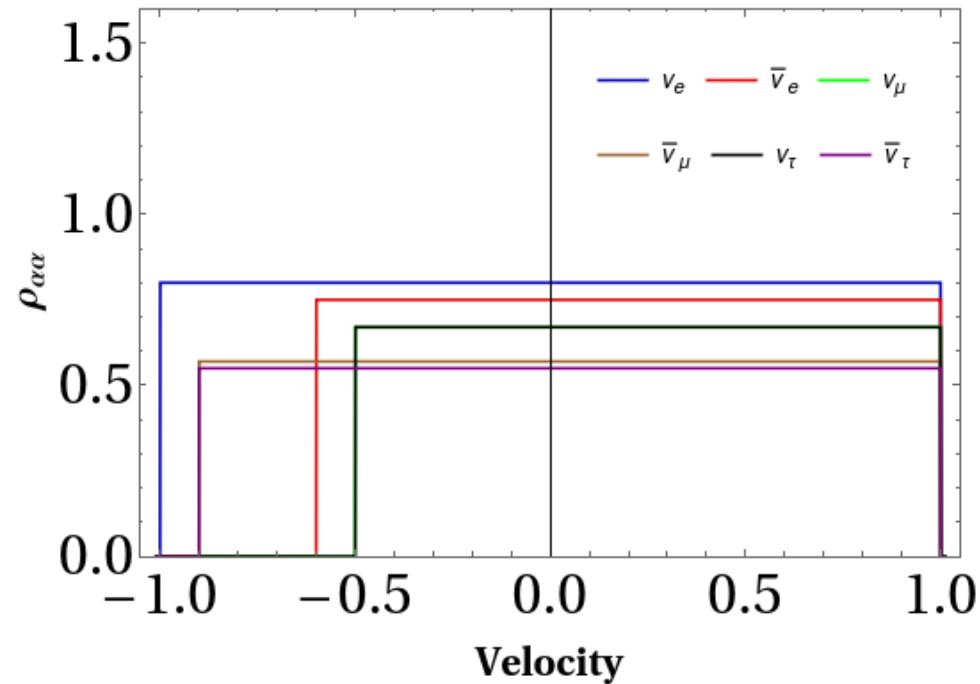
- *Muons may be present in early accretion phase*  
*(R. Bollig et al, arXiv:1706.04630)*
- *Increases the luminosities and average energies  
of other two flavors*
- *Study of fast oscillations in non linear picture*
- *Effect of addition of third flavor*

# CASE 1



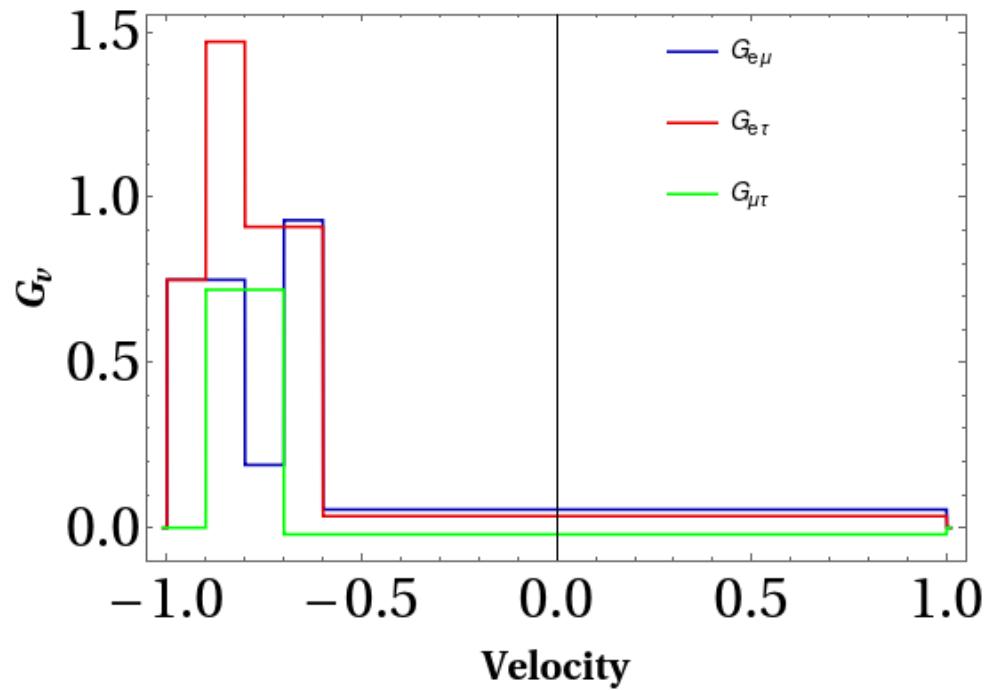
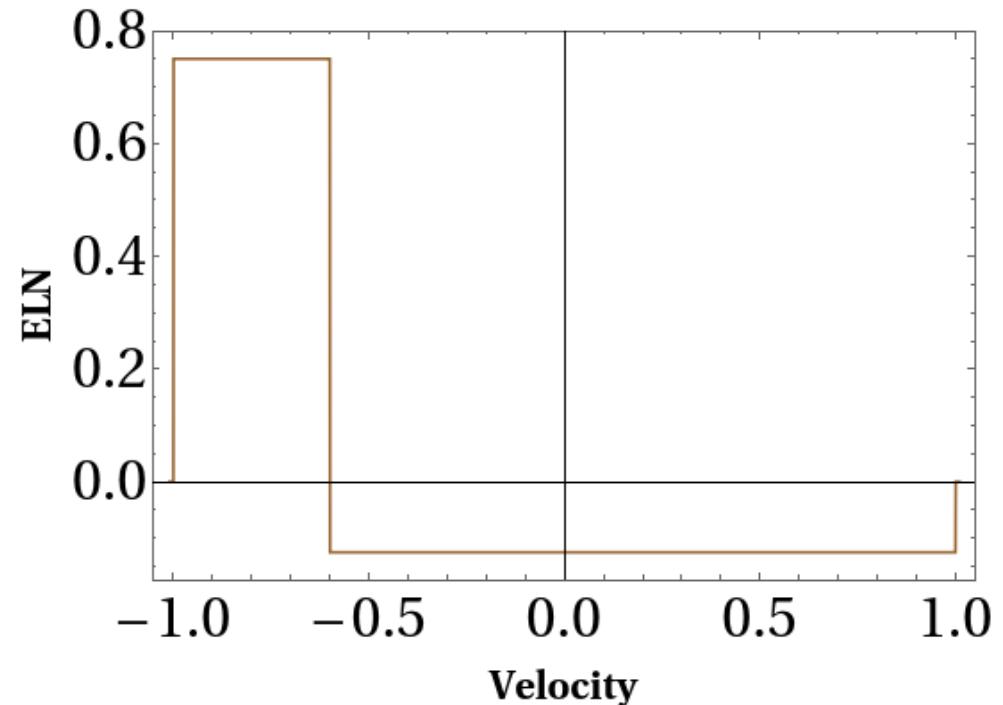
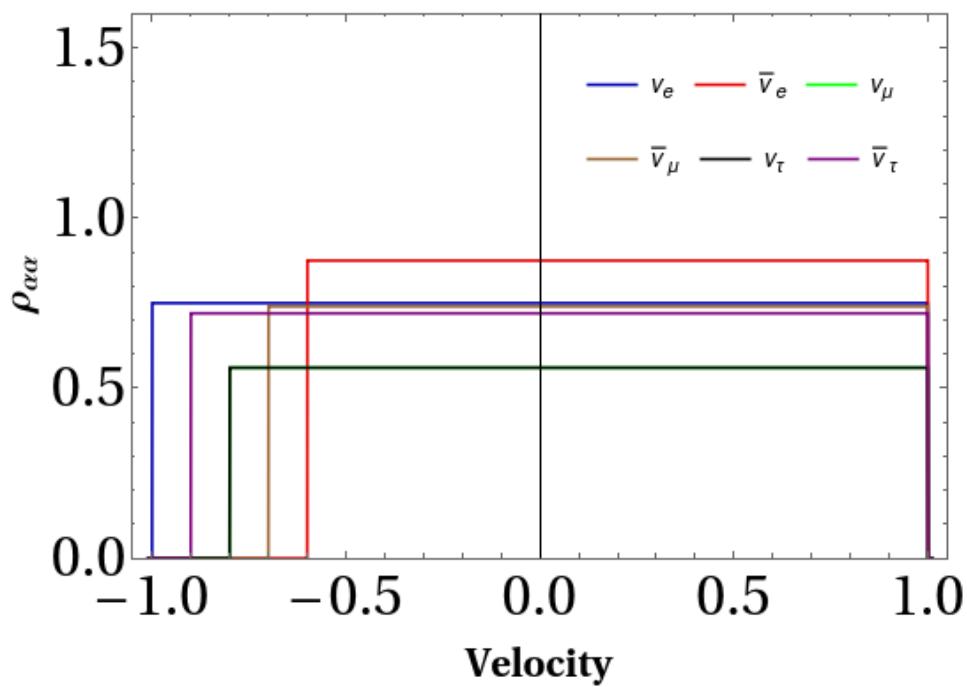
No instability in any sector  
from linear stability analysis

# CASE 2



Sector	$\kappa/\mu$
e-μ	0.017
e-τ	0.025
μ-τ	No Instability

# CASE 3



Sector	$\kappa/\mu$
e- $\mu$	No Instability
e- $\tau$	No Instability
$\mu$ - $\tau$	0.006

# NON-LINEAR ANALYSIS : 3 FLAVOR

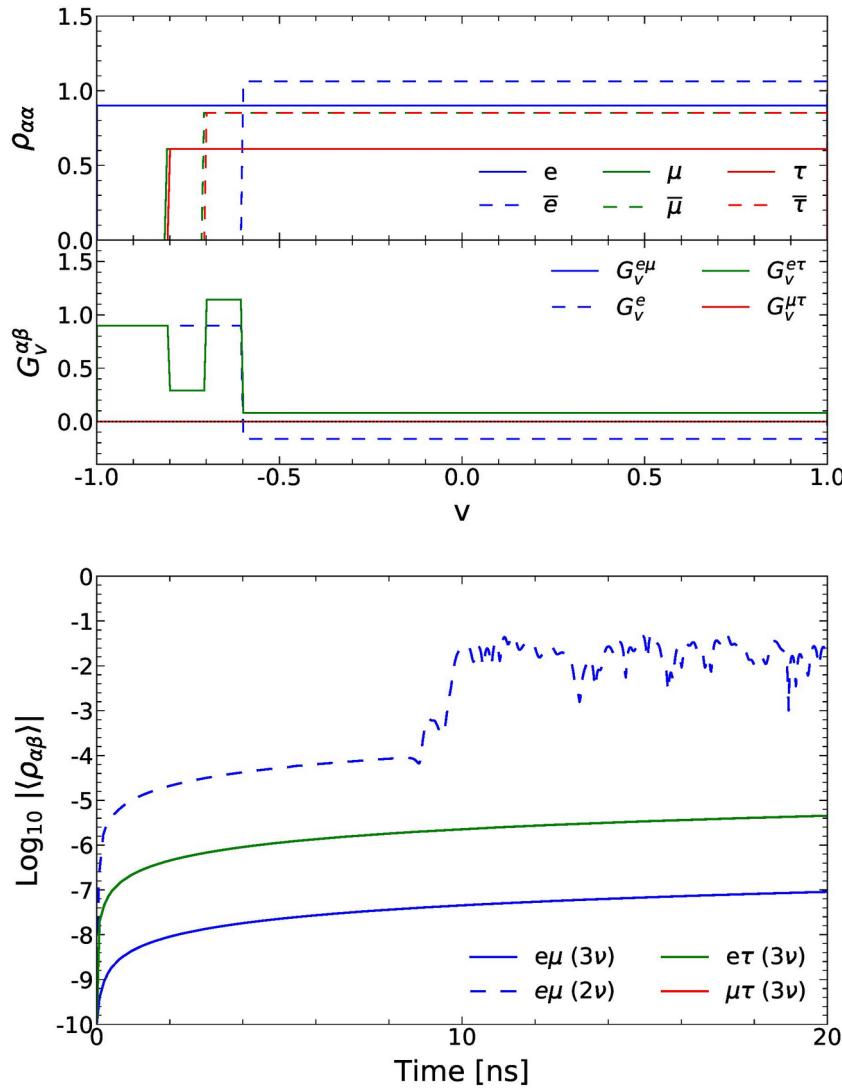
$$i (\partial_t + \mathbf{v}_p \cdot \nabla_x) \rho_{p,x,t} = [\Omega_{p,x,t}, \rho_{p,x,t}]$$



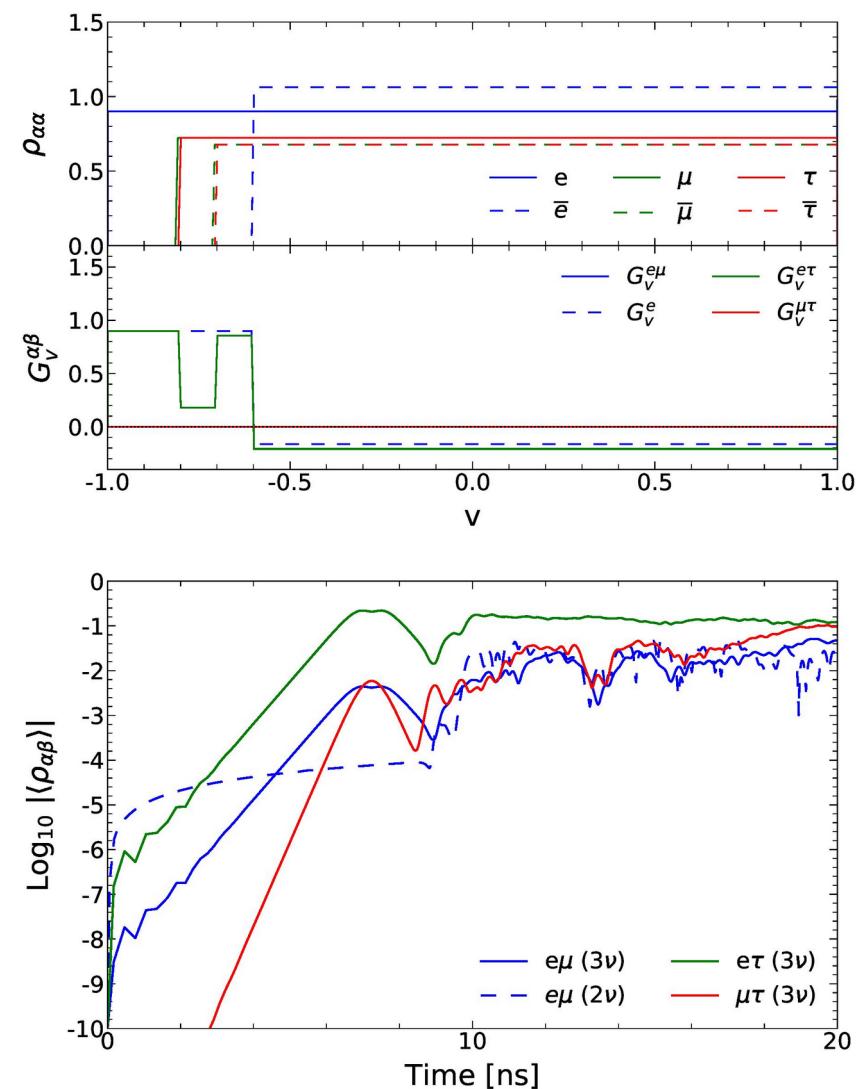
Vacc.+matter+ $\nu\nu$  interaction

- ▶ *Fast Oscillation - Vacuum term acts as seed*
- ▶ *Only temporal evolution considered*
- ▶ *Matter terms neglected*
- ▶ *Dynamics of the system governed by nonlinear terms  
( $\nu\nu$  interaction)*

# NON-LINEAR ANALYSIS : NUMERICAL EXAMPLES

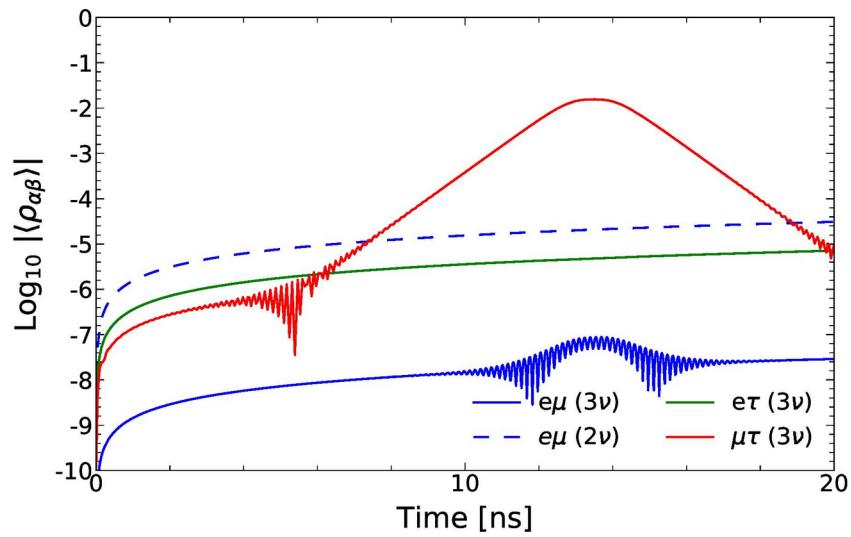
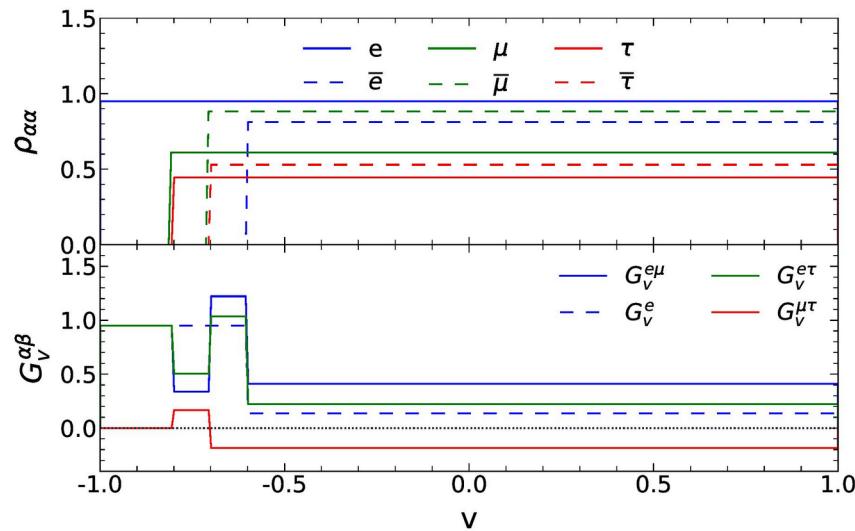


Case 1

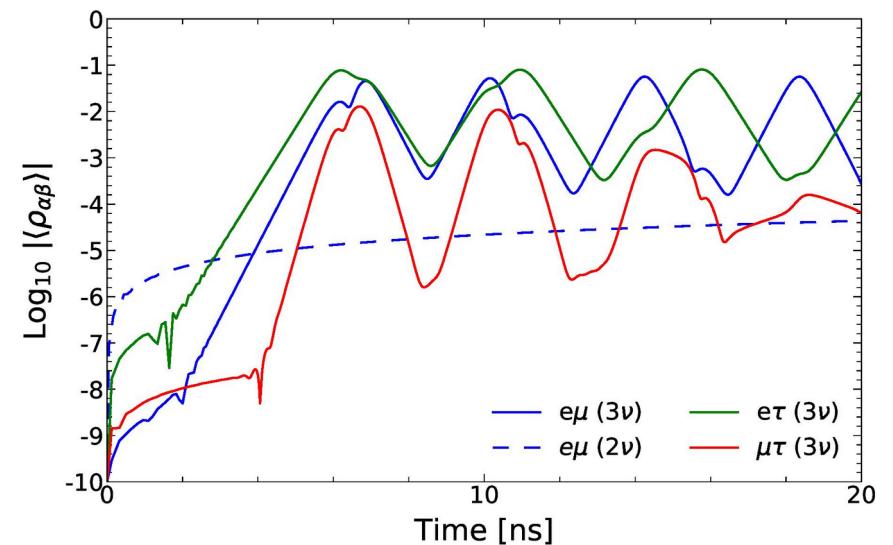
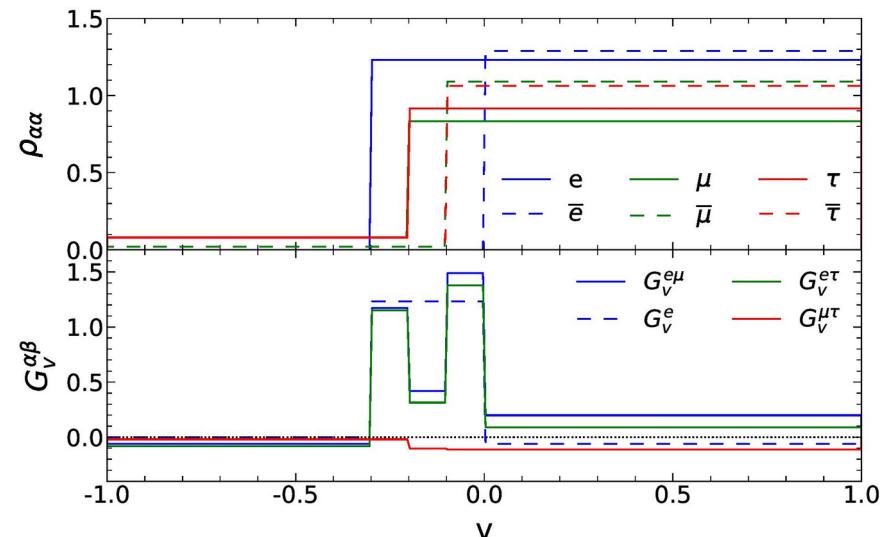


Case 2

# NON-LINEAR ANALYSIS : NUMERICAL EXAMPLES



Case 3



Case 4

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# CONCLUSION

- *Non-negligible MuLN and TauLN can enhance or suppress the crossings in ELN*
- *Effect on Fast flavor conversions*
- *Nonlinear analysis done*
- *Simple toy examples considered*
- *Explain the importance of need of detailed 3 flavor analysis*
- *Future muon simulations will further explain the effect in case of realistic situations*

**THANK YOU**