Neutrino Flavor Evolution in Dense Media: Fast modes and Flavor Equilibrium

NBIA-LANL Neutrino Quantum Kinetics in Dense Environments
NBI, Copenhagen, August 26-30, 2019

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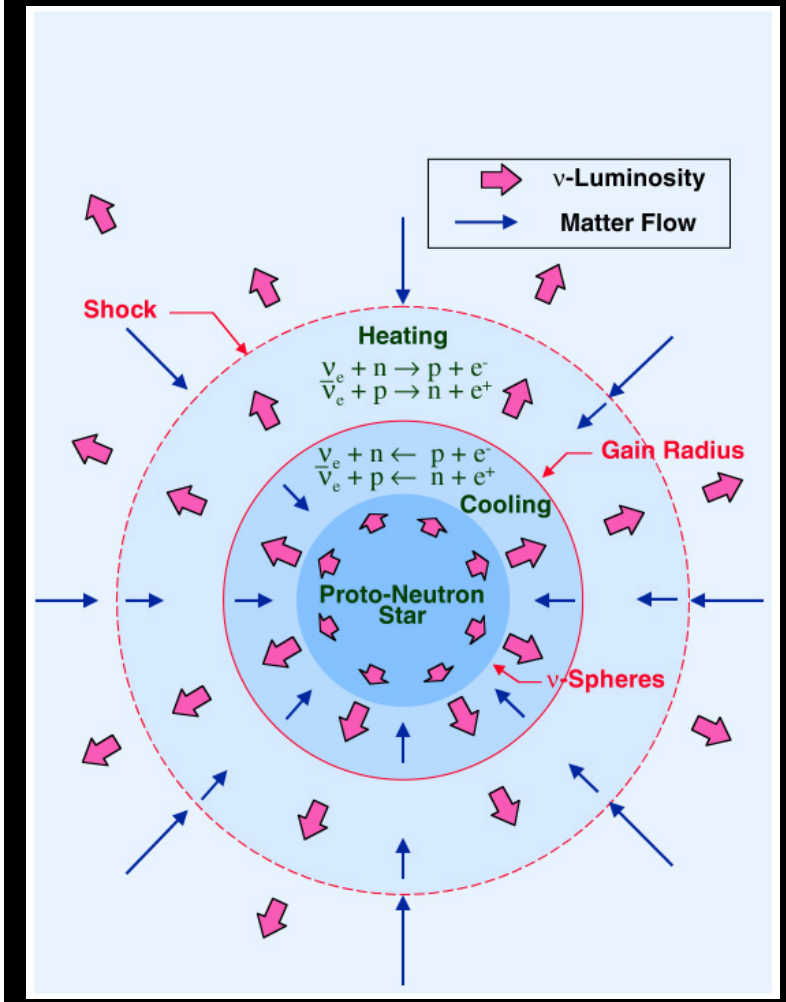
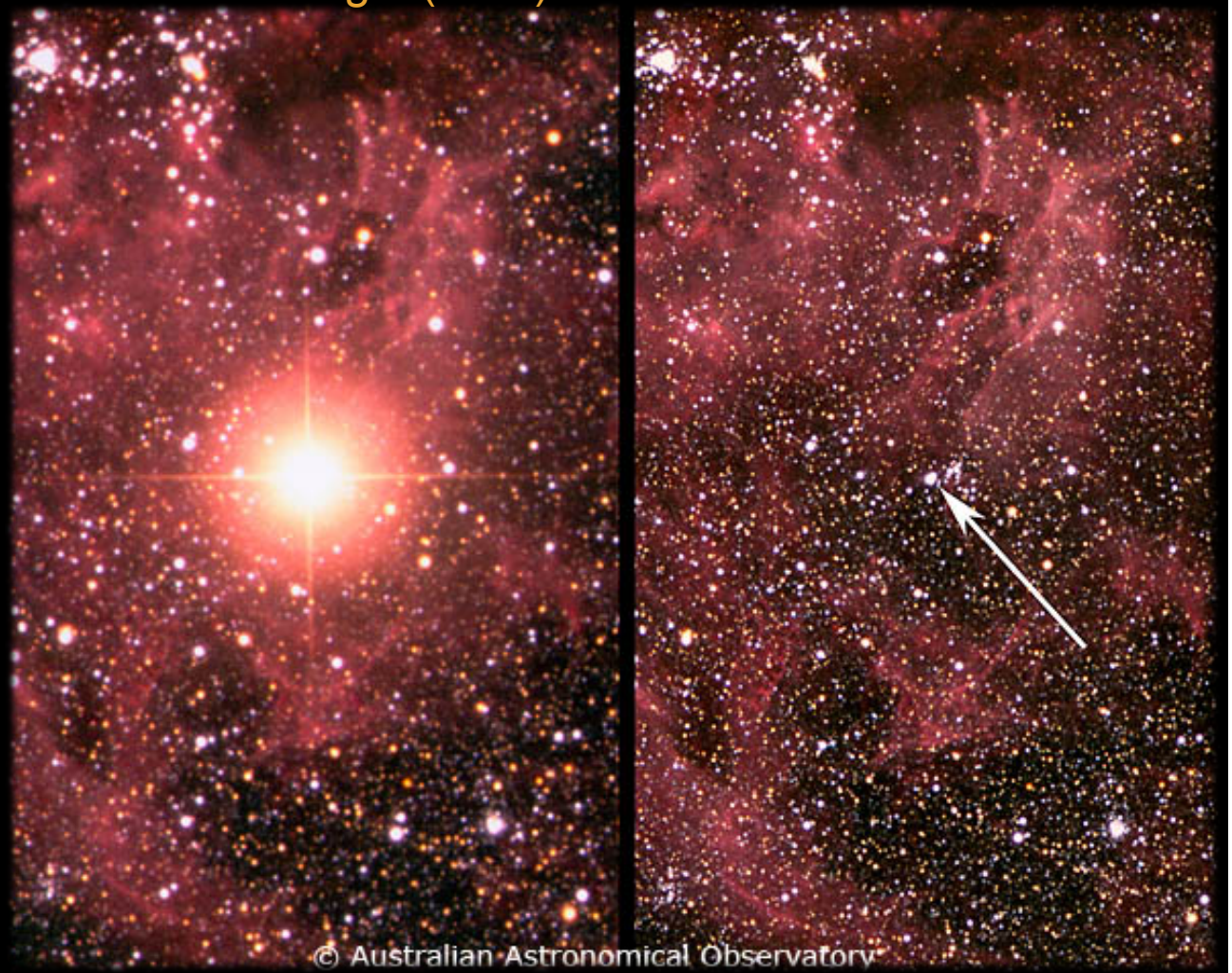
Astro-Particule et Cosmologie (APC)





Core-Collapse Supernovae

- A huge amount of energy (~10^{53} ergs (10^{46} joule), 99% of the total released energy) is released in the form of neutrinos of all flavors.

- Neutrinos could experience flavor oscillations which could have important consequences for the matter composition, the SN dynamics and the observed spectra on earth

Neutrino Oscillations in Dense Media

- Neutrino evolution in dense neutrino media is very different from the one in vacuum and matter

$$i(\partial_t + \mathbf{v}\cdot\nabla)\rho = [H, \rho]$$

$$H = \frac{1}{2}\begin{bmatrix} -\omega\cos 2\theta + \sqrt{2}G_{\rm F}n_e & \omega\sin 2\theta \\ \omega\sin 2\theta & \omega\cos 2\theta - \sqrt{2}G_{\rm F}n_e \end{bmatrix} + H_{\nu\nu}$$

$$\sqrt{2}G_{\rm F}\int \underbrace{d^3q}_{\text{coupling}}(1 - \mathbf{v_P}\cdot\mathbf{v_q})(\underbrace{\rho_\nu}_{\text{nonlinearity}} - \rho_{\bar\nu})$$

Neutrino Bulb Model

- We have a 7-D problem!

$$\rho(t; \underbrace{r, \Theta, \Phi}_{\text{space}}; \underbrace{E, \theta, \phi}_{\text{Momentum}})$$

time translation symmetry

$$\rho(\cancel{t}; r, \Theta, \Phi; E, \theta, \phi)$$

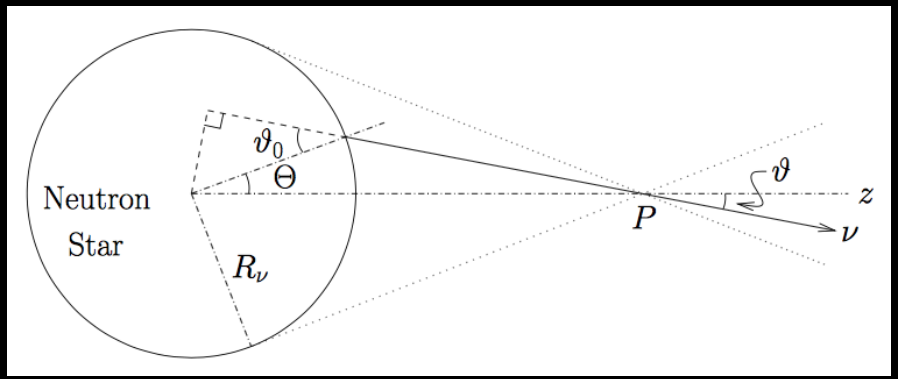
spherical symmetry & axial symmetry around radial direction

$$\rho(\cancel{t}; r, \cancel{\Theta}, \cancel{\Phi}; E, \theta, \cancel{\phi})$$

- *Neutrino Bulb Model:*

  neutrinos are emitted isotropically from the surface of porto-neutron star

$$\rho(r; E, \theta)$$



Duan et al., PRD 74, (2006) 105014

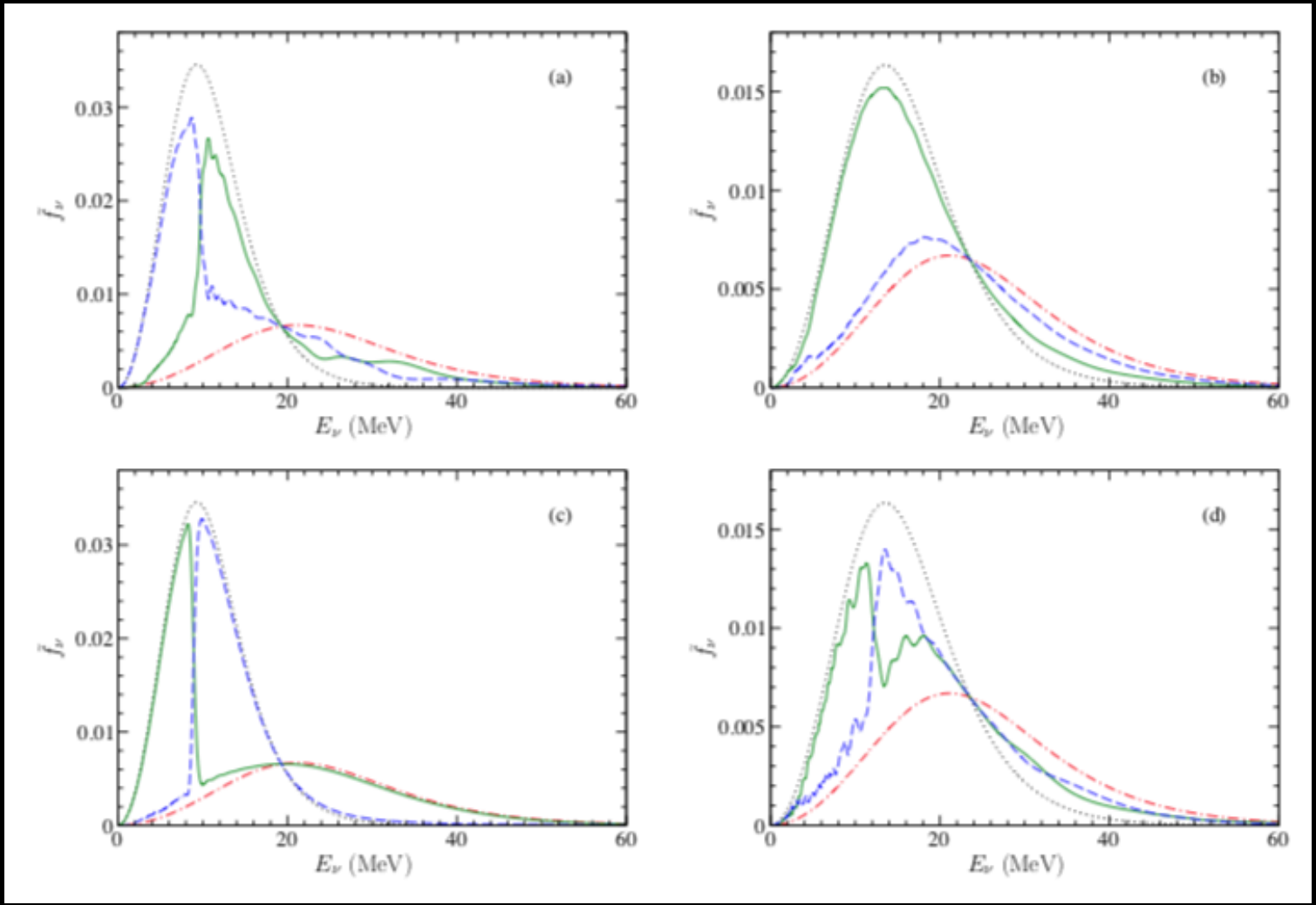
Neutrino Bulb Model

- Even for this simple model, we have to solve ~10^6 nonlinear differential equations simultaneously
- The most remarkable feature is the presence of spectral swapping

ν $\bar{\nu}$

NH

IH



Duan, Fuller, Carlson and Qian; Phys.Rev. D74 (2006) 105014
see also Dasgupta, Dighe, Raffelt and Smirnov; Phys.Rev.Lett.103:051105,2009

Too Simplistic Model ?!

- Our simplistic calculations are based on two important assumptions:
  - Neutrinos are emitted isotropically

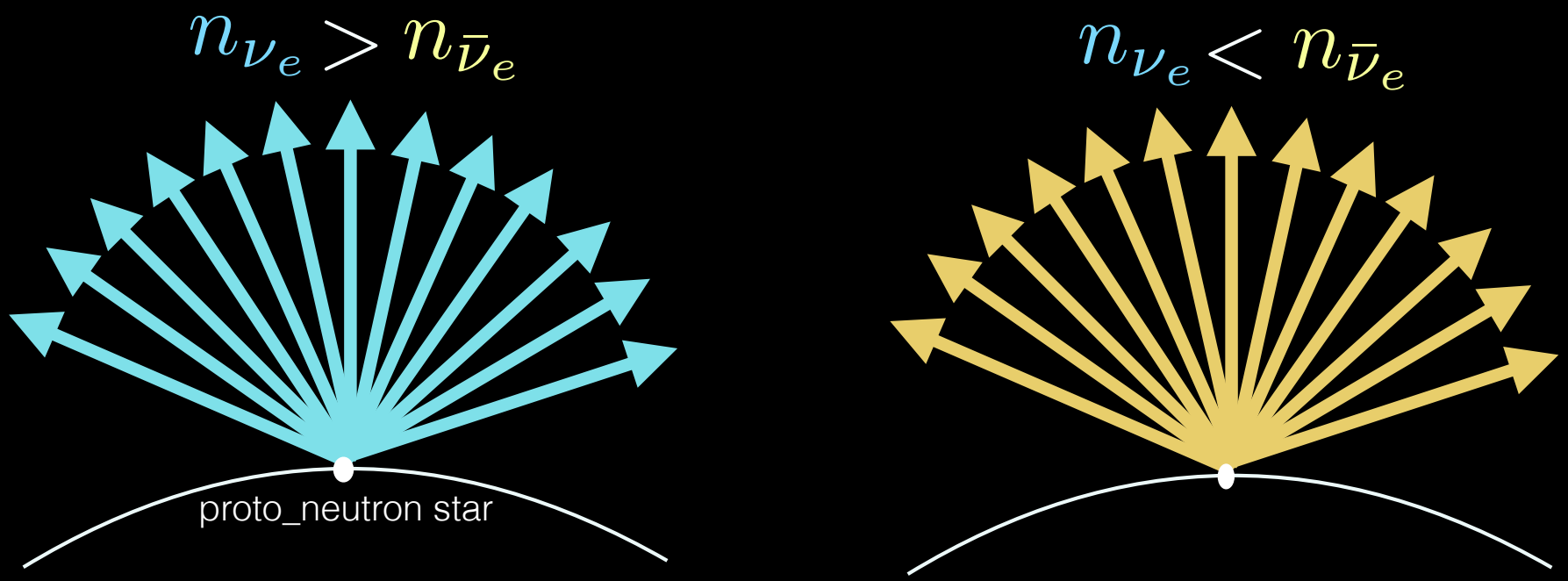
    R. Sawyer, Phys.Rev.Lett. 116 (2016)
    S. Chakraborty, R. Hansen, I. Izaguirre, G. Raffelt, JCAP 1603 (2016)
    I. Izaguirre, G. Raffelt, I. Tamborra, PRL 118(2017)
    M. R. Wu & I. Tamborra, PRD 95, 103007 (2017)
    Capozzi, Dasgupta, Lisi, Marrone, Mirizzi, PRD 96 (2017)
    S. Abbar & H. Duan, Phys.Rev. D98 (2018)
    F. Capozzi, B. Dasgupta, A. Mirizzi, M. Sen, G. Sigl, Phys.Rev.Lett. 122 (2019)
    S. A. Richers, G. McLaughlin, J. Kneller, A. Vlasenko, PRD99 (2019)
    ….
    …

  - Neutrino gas posses time/special symmetries

    G. Raffelt, S. Sarikas, D. S. Seixas, PRL 111, 091101 (2013)
    H. Duan & S. Shalgar, PLB 747, 2015
    A. Mirizzi, G. Mangano & N. Saviano, PRD 92, 021702 (2015)
    S. Chakraborty, R. .S. Hansen, I. Izaguirre and G. G. Raffelt, JCAP 1601 (2016)
    S. Abbar & H. Duan, PLB 751, 2015H. Duan & S. Shalgar, PLB 747, 2015
    B. Dasgupta and A. Mirizzi, Phys.Rev. D92 (2015)

Fast Flavor Conversion Modes

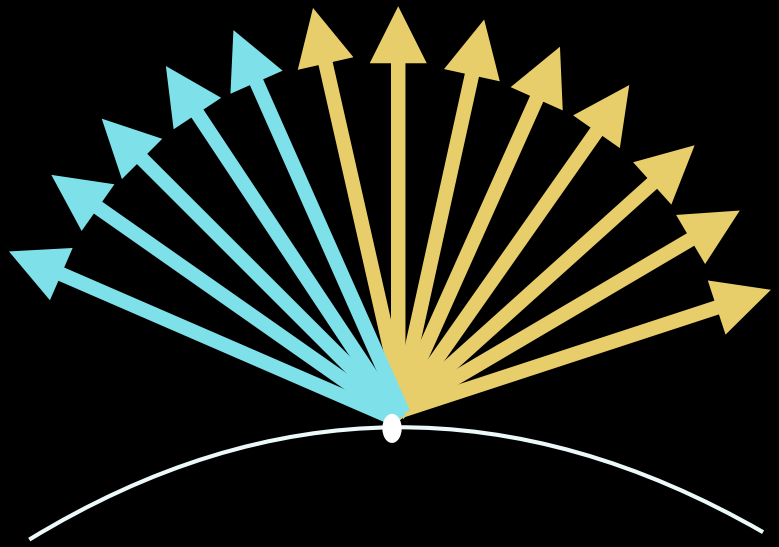
- We assumed that neutrinos and antineutrinos are emitted isotropically from the surface of the neutrino source
- $f_{\nu_e}(\theta) - f_{\bar{\nu}_e}(\theta)$ is either always positive or negative



- This implies that the scales on which flavor conversion could occur is determined by vacuum frequency $\Delta m^2/2E \sim 1\ \mathrm{km}^{-1}$
- At vary large matter densities, collective oscillations could be irrelevant since collisions occur on much smaller scales!

Fast Flavor Conversion Modes

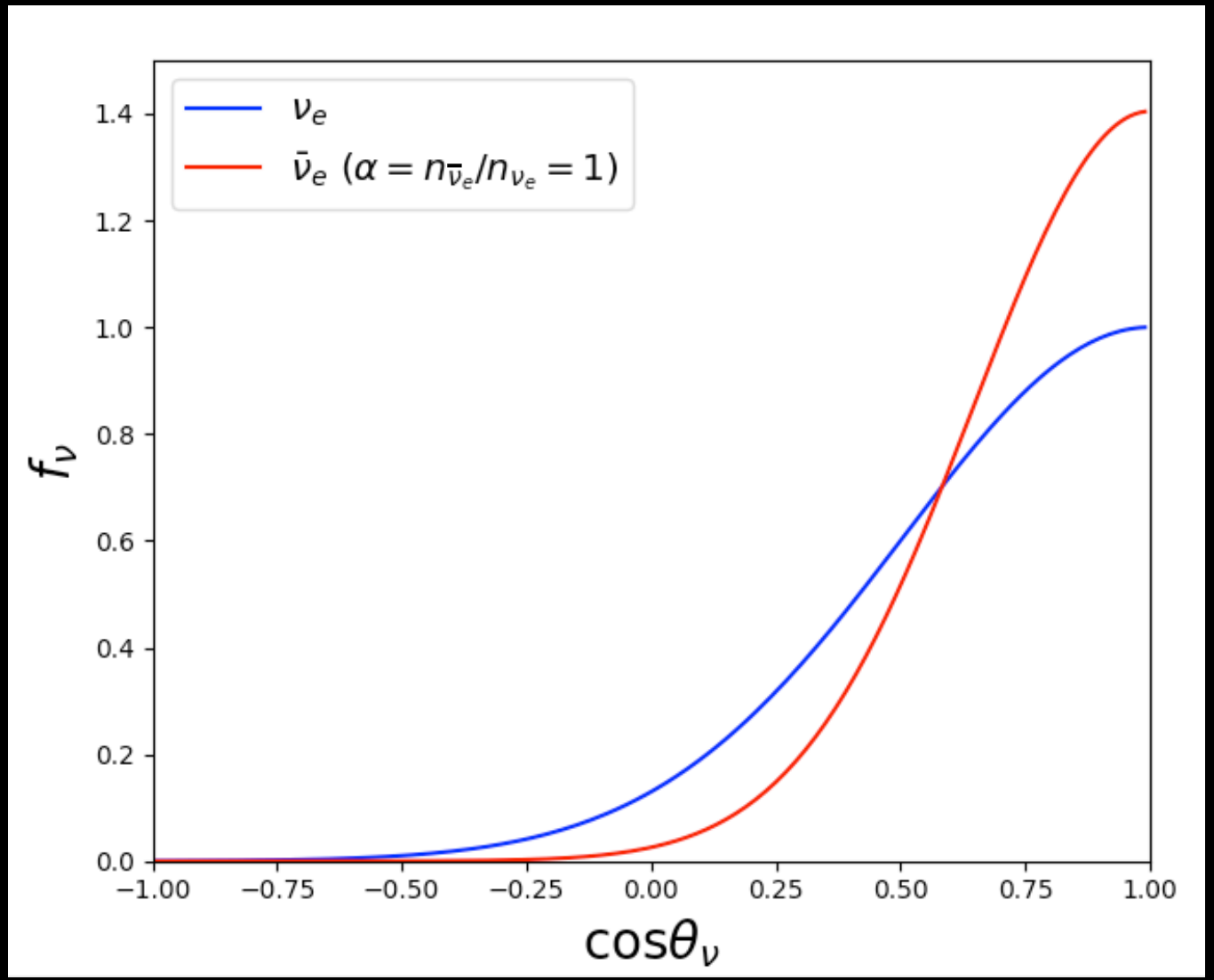
- Fast modes could occur when there is crossing in $f_{\nu_e}(\theta) - f_{\bar{\nu}_e}(\theta)$



- Scales on which flavor conversion can occur is now proportional to n_ν and could be < 10 cm on the surface of proto-neutron star
- Neutrino oscillations could now occur at densities that had been long thought to be the realm of collisional and scattering processes

Occurrence of fast modes in CCSNe

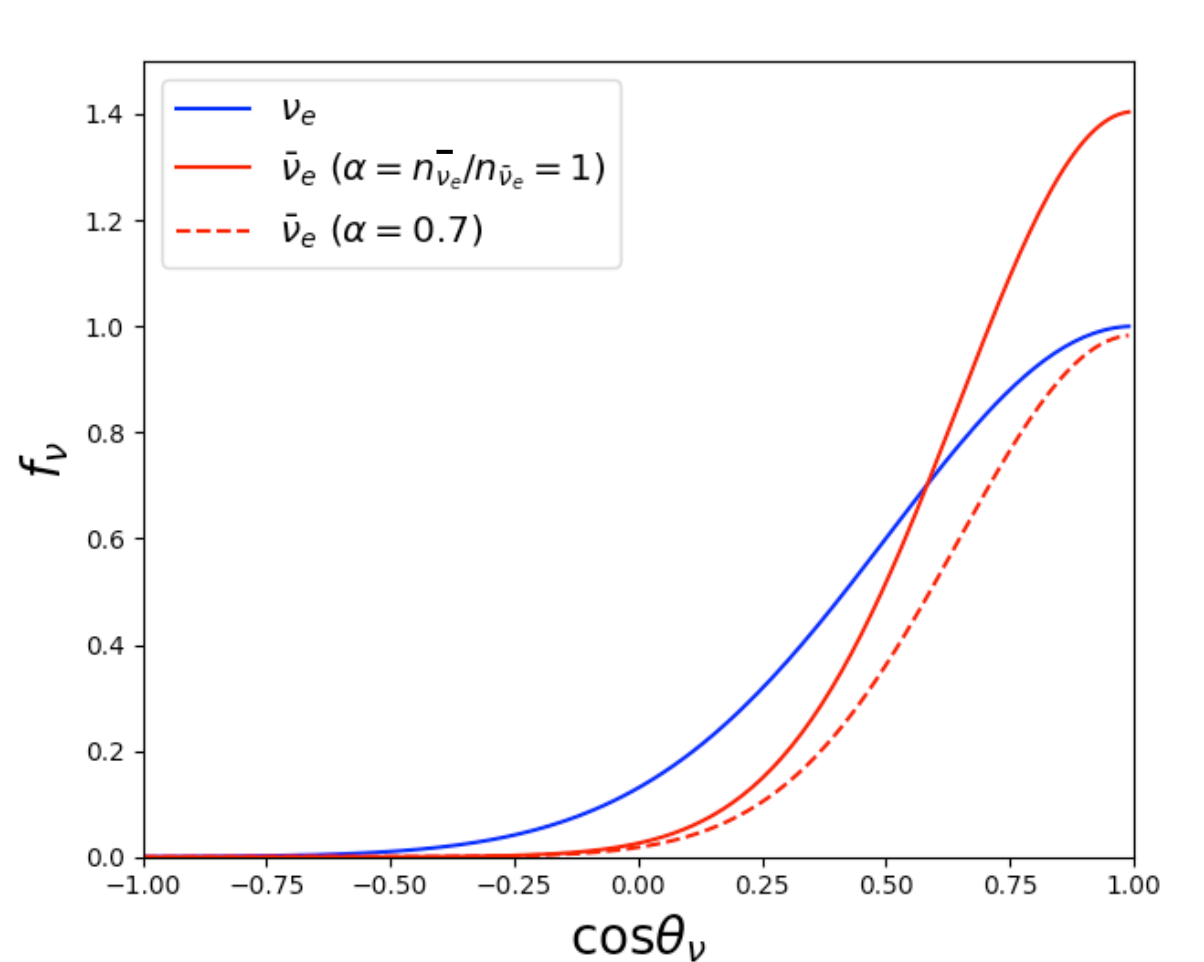
- One might naively expect to observe angular crossings in SN environment since ν_e and $\bar{\nu}_e$ decouple at different radii



Occurrence of fast modes in CCSNe

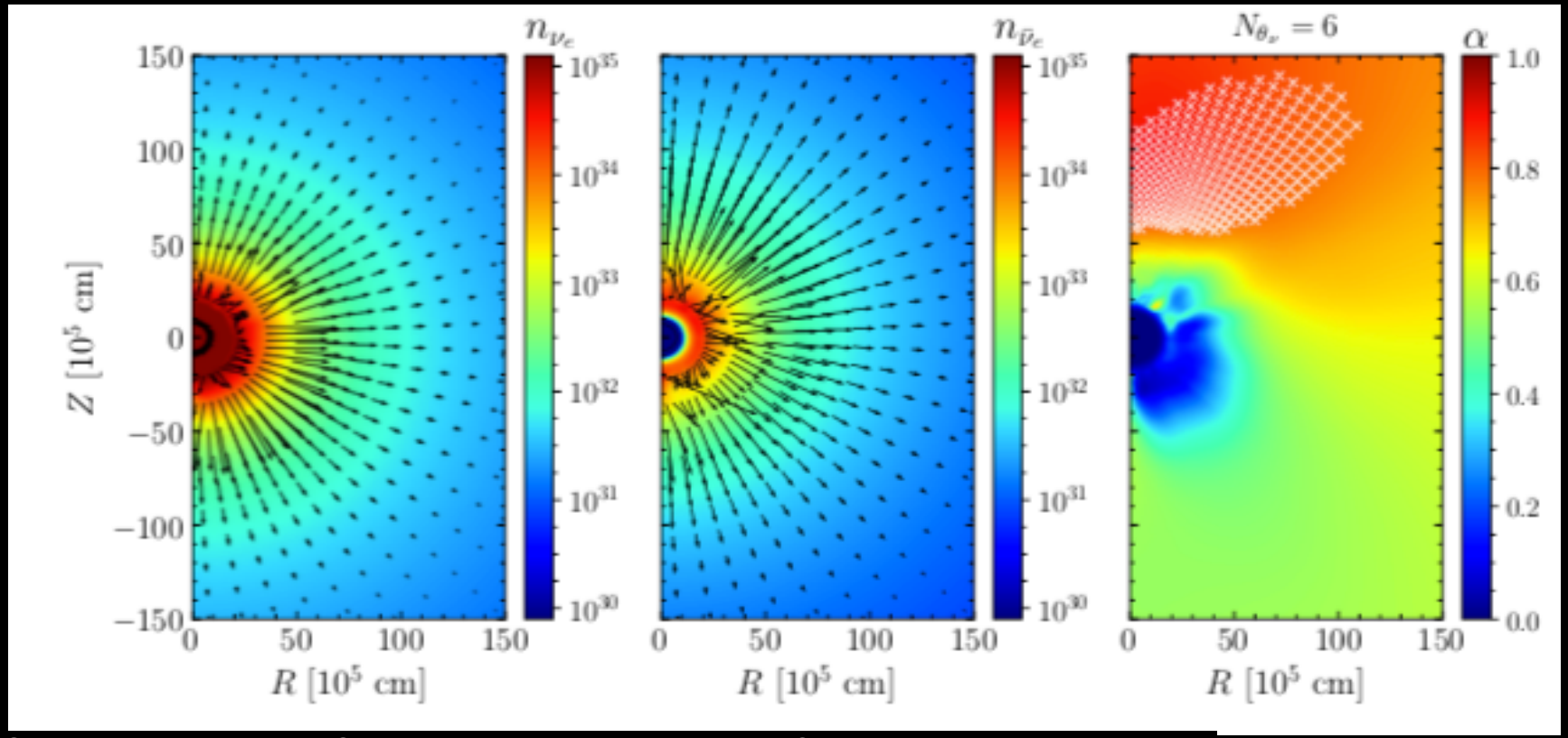
- BUT it is not that easy …
- $\bar{\nu}_e$ are much less abundant during the early stages of a CCSN which hinders the occurrence of crossings
- **No** crossings were observed in 1D SN models

I. Tamborra, L. Huedepohl, G. Raffelt, H. T. Janka, Astrophys.J. 839 (2017)
S. Shalgar, I. Tamborra, arXiv:1904.07236



Occurrence of fast modes in CCSNe

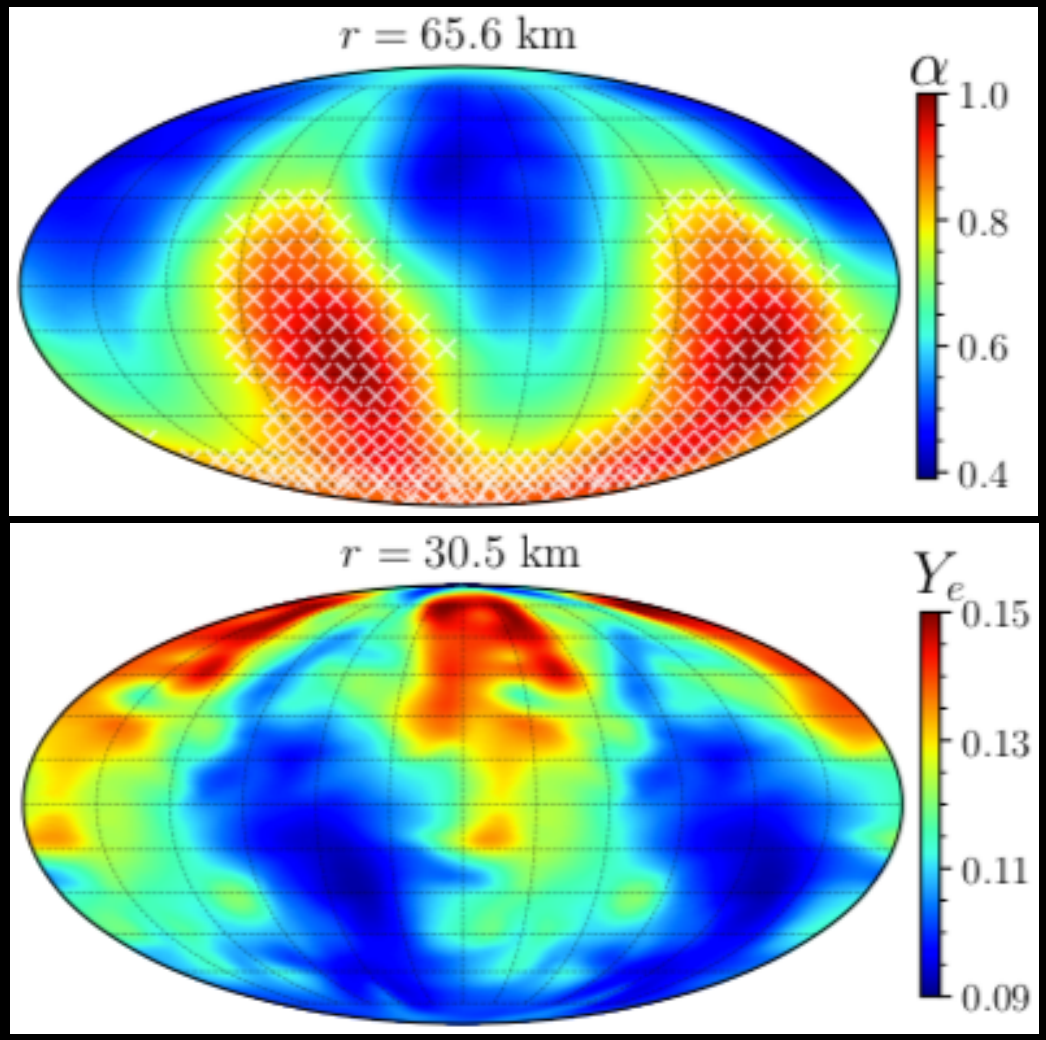
- But this could change in MD SN models
- The neutrino emission could be asymmetric as in LESA (see Tamborra et. al., Astrophys.J. 792, 96)
- So there could exist regions with large values of $\alpha = n_{\bar{\nu}_e}/n_{\nu_e}$ in spite of its small average value
- We examined neutrino distributions obtained by solving the Boltzmann equation for some fixed profiles of MD SN simulations



S. Abbar, H. Duan, K. Sumiyoshi, T, Takiwaki and M. C. Volpe, arXiv:1904.08877

Occurrence of fast modes in CCSNe

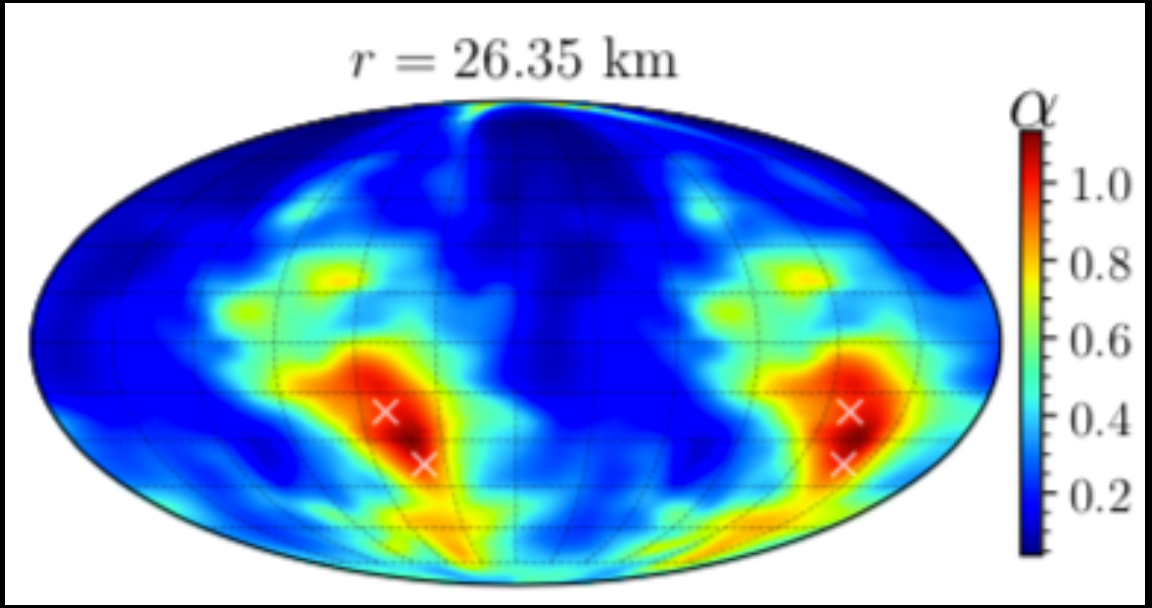
- The pattern in α is correlated with a similar pattern in $Y_e = n_p/(n_p + n_n)$ which forms very deep inside the PNS



S. Abbar, H. Duan, K. Sumiyoshi, T, Takiwaki and M. C. Volpe, arXiv:1904.08877

Occurrence of fast modes in CCSNe

- Crossings could also occur very deep inside the PNS where alpha is very close to 1.



S. Abbar, H. Duan, K. Sumiyoshi, T, Takiwaki and M. C. Volpe, in preparation

Occurrence of fast modes in CCSNe

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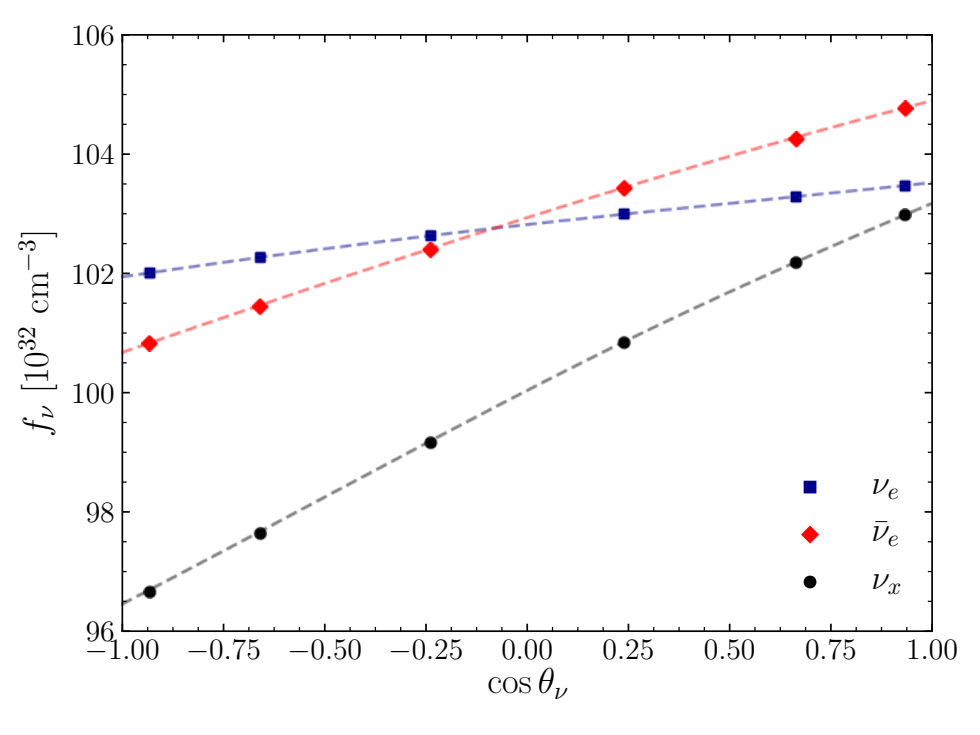


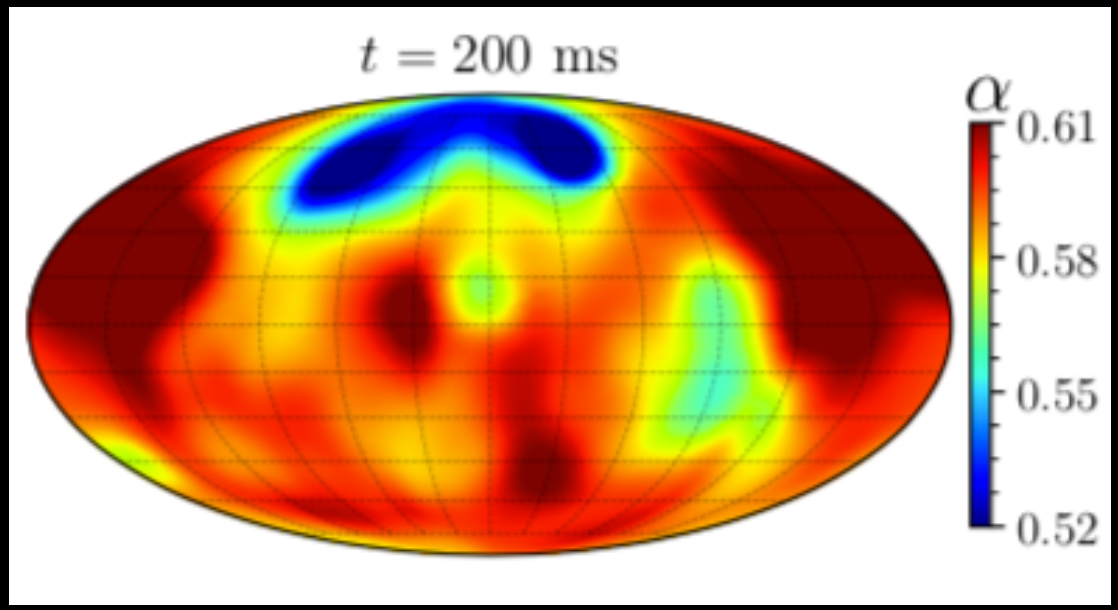
S. Abbar, H. Duan, K. Sumiyoshi, T, Takiwaki and M. C. Volpe, in preparation

fast modes inside the PNS

- Although it is surprising, its physical implication and importance is not clear!
  - Such short scale flavor conversion modes are not unique to fast modes. Since $\alpha \simeq 1$, the neutrino gas is almost always unstable even without crossing and the flavor conversion scales is proportional to $\sqrt{n_\nu}$
  - If the neutrino gas is totally degenerate, what do we expect from neutrino oscillations?

Occurrence of fast modes in CCSNe

- No crossings were found for 27M⊙ progenitor model.

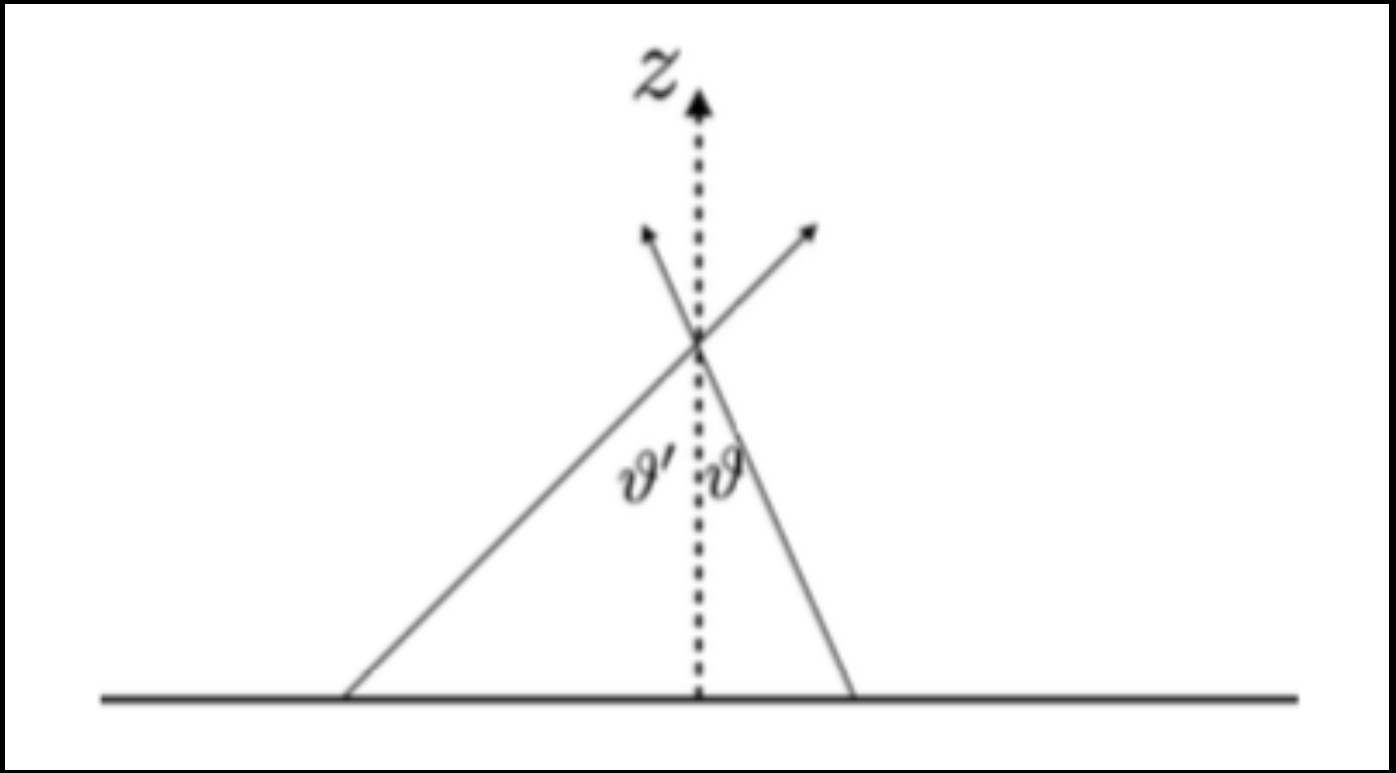


S. Abbar, H. Duan, K. Sumiyoshi, T, Takiwaki and M. C. Volpe, in preparation

- Azari et. al. (2019) did not find any crossings in a self-consistent simulation: much less convective activity

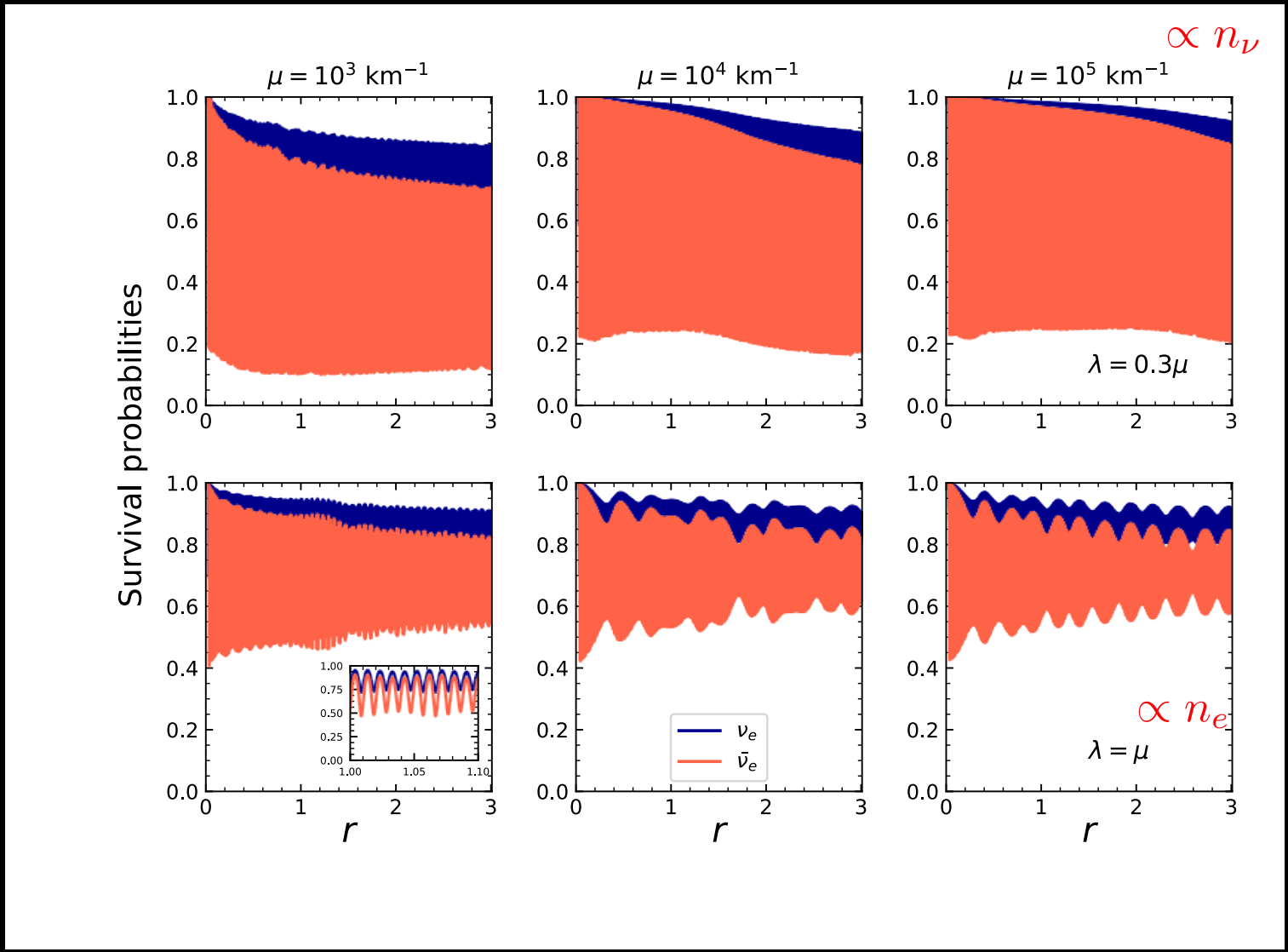
Fast modes in the nonlinear regime

- It was speculated that fast modes could lead to flavor equipartition
- We studied fast modes in a 1D model



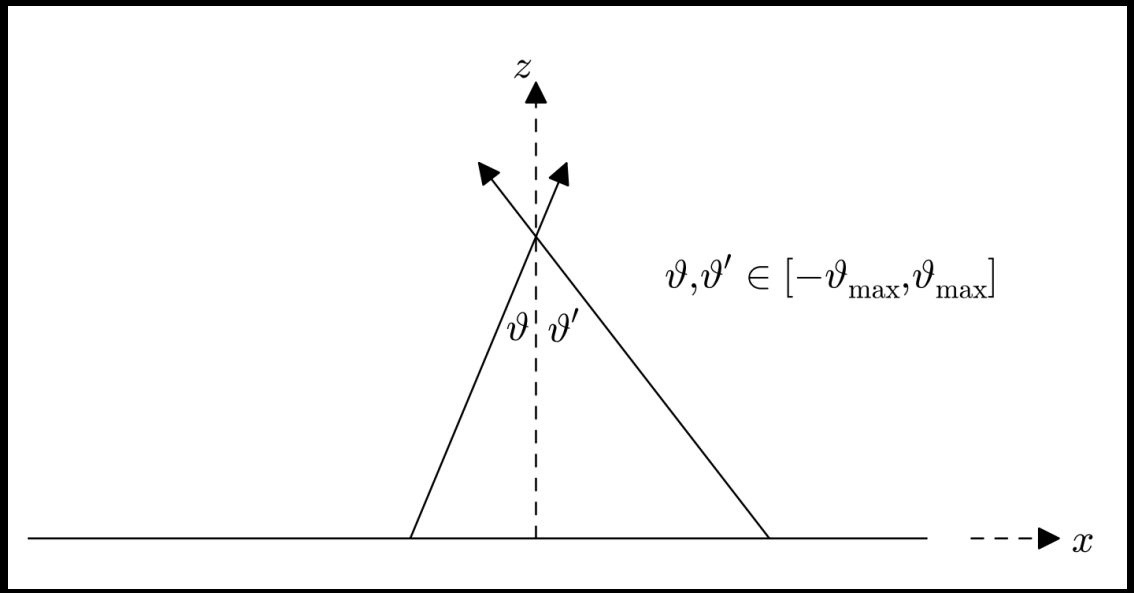
Fast modes in the nonlinear regime

- In this 1D model, fast modes DO NOT lead to flavor equilibrium
- One has the usual collective modes but on very small scales



Neutrino evolution in a 2D model

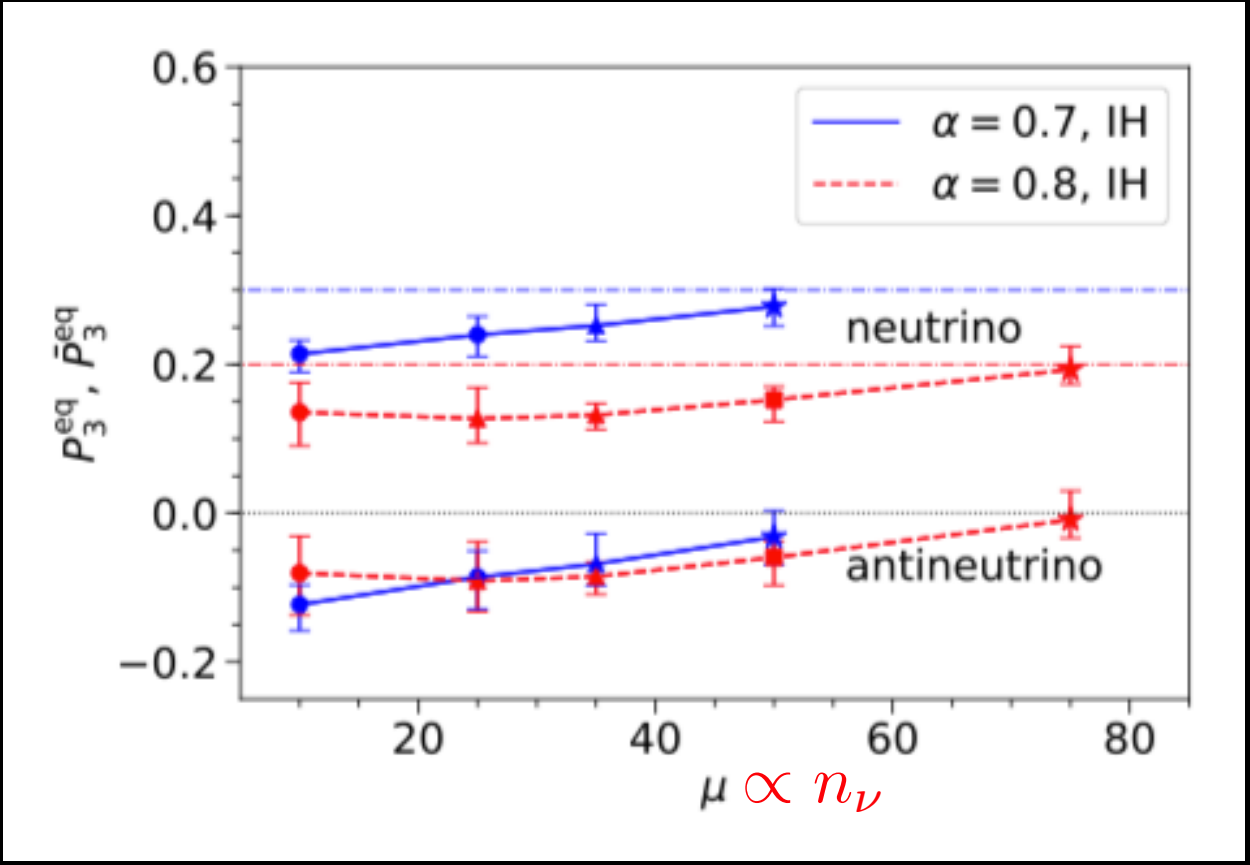
- we have an **infinite line** that emits neutrinos
- We also assume that we have periodic boundary condition along the line



S. Abbar, H. Duan and S. Shalgar; PRD 92, (2015) 065019

Neutrino evolution in a 2D model

- Neutrinos could reach some sort of flavor equilibrium if the neutrino number density is large enough



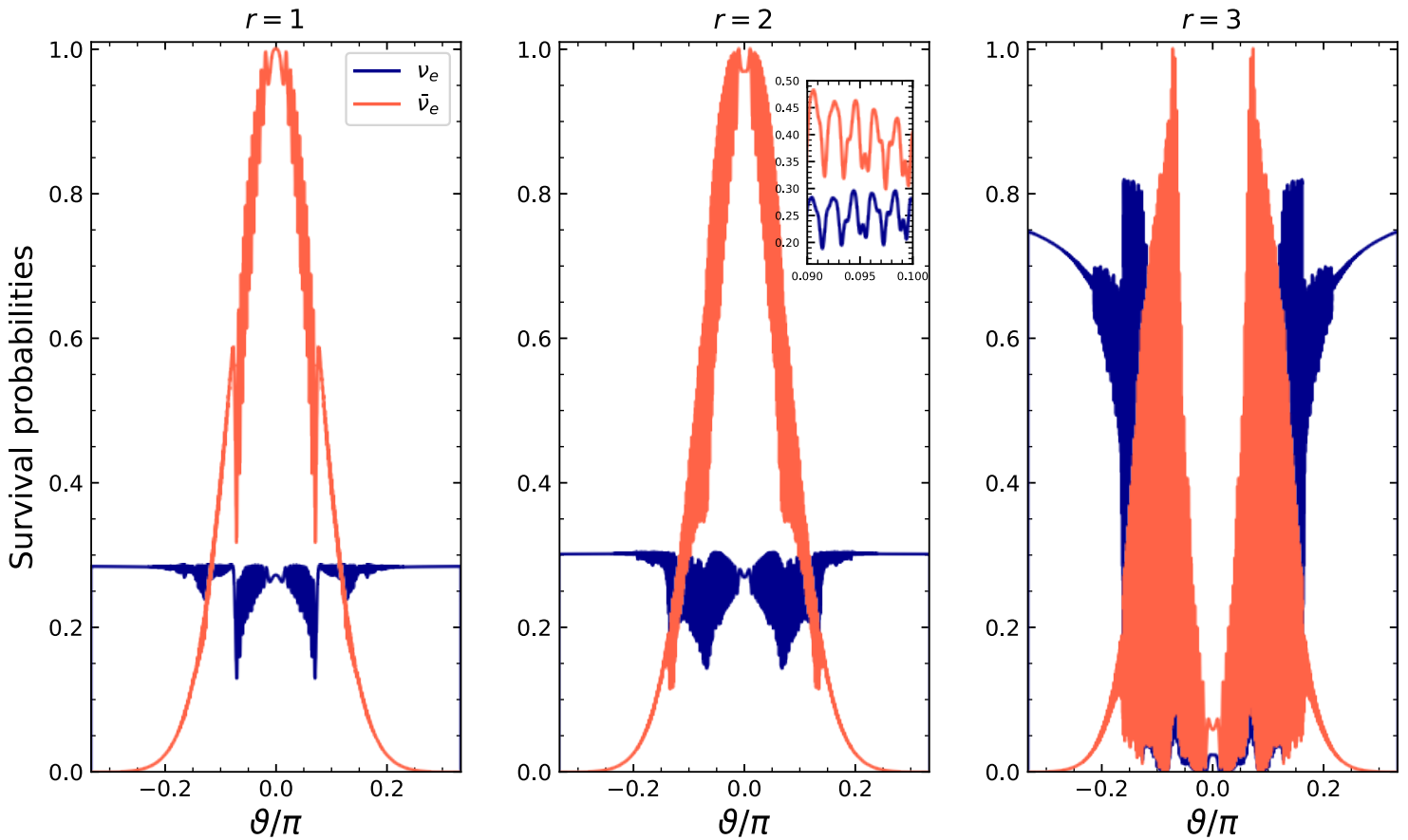
J. D. Martins, S. Abbar and H. Duan, arXiv:1904.08877

Open Questions

- Do fast modes exist in the SN environment?
- Is there any generic flavor equilibrium in dense neutrino media?
- If there is such a flavor equilibrium, how does it affect the physics of CCSNe?

Fast modes in the nonlinear regime

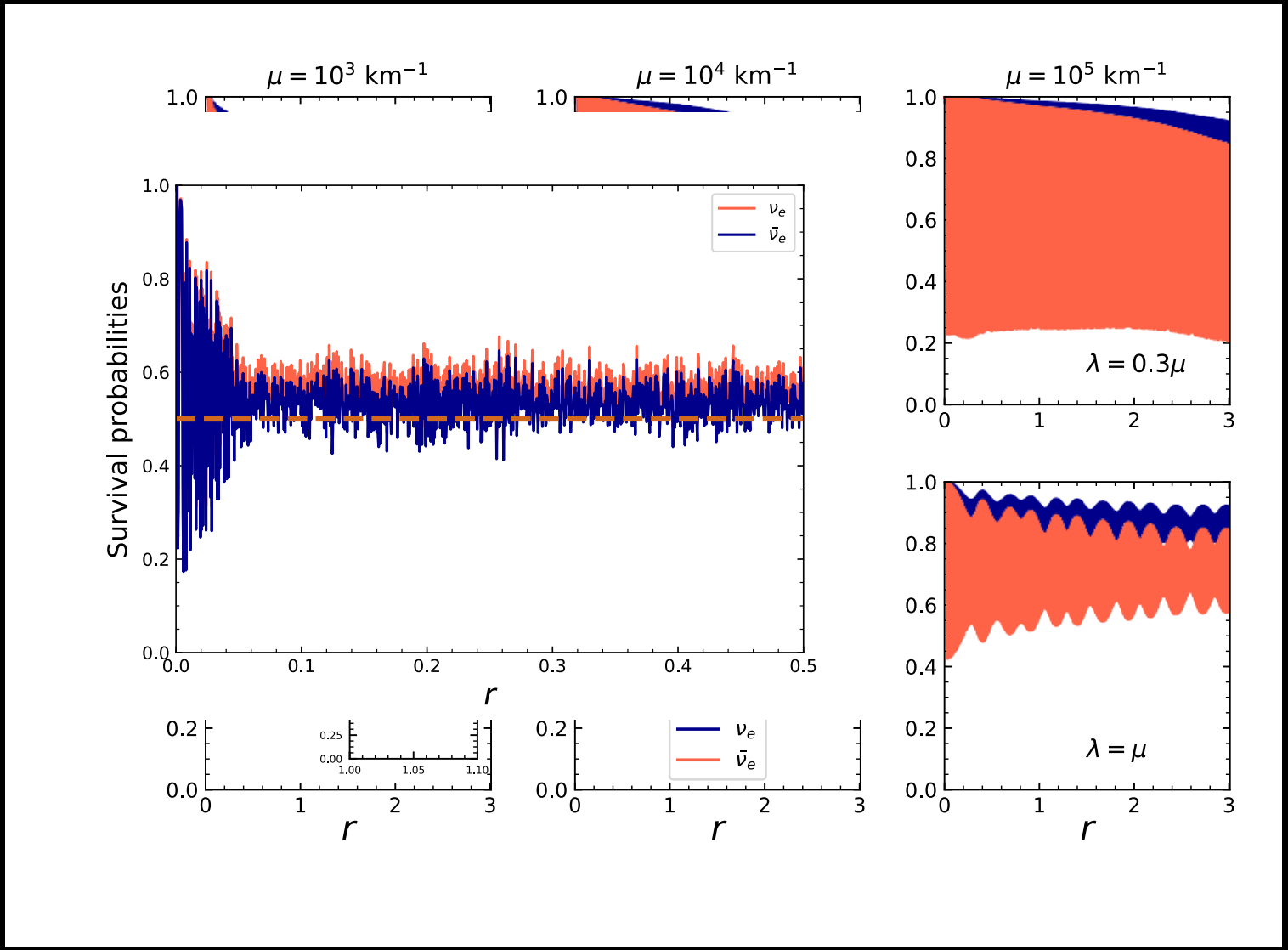
- The neutrino angular distribution could be extremely uneven



S. Abbar and M. C. Volpe, Phys.Lett. B790 (2019)

Fast modes in the nonlinear regime

- The neutrino angular distribution could be extremely uneven
- Having small angular resolution could lead to a sort of artificial flavor equilibrium

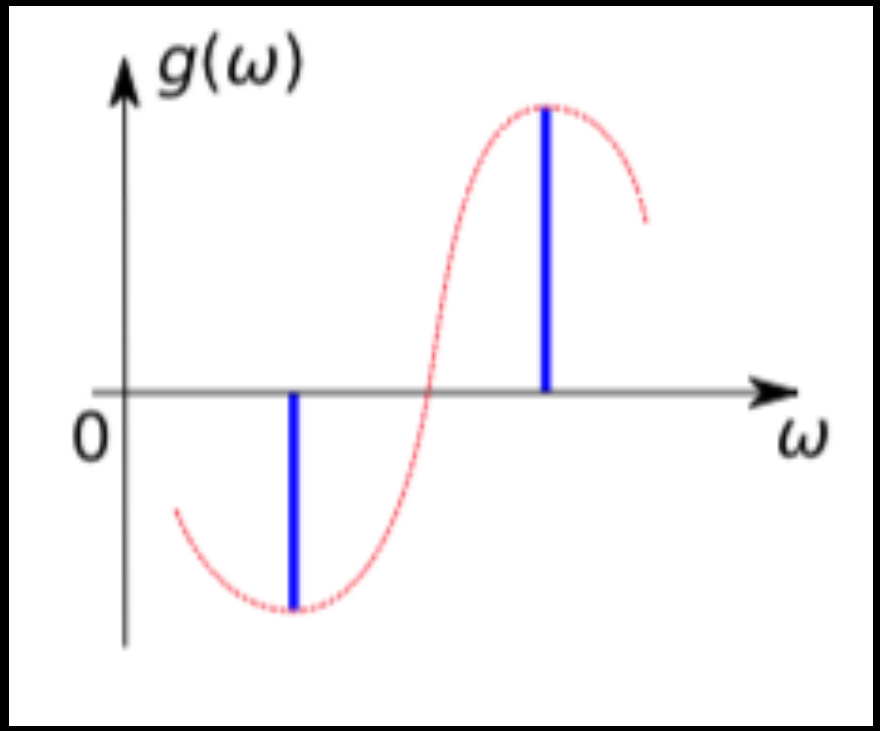


S. Abbar and M. C. Volpe, Phys.Lett. B790 (2019)

Fast modes in the nonlinear regime

- The bipolar model describes a homogeneous and isotropic neutrino gas initially consisting of mono-energetic ν_e and $\bar{\nu}_e$

S. Abbar & H. Duan, Phys.Rev. D98 (2018)



$\propto n_e$ $\propto n_{\nu_e}$

$$i\begin{bmatrix}\dot{\epsilon}_1\\ \dot{\epsilon}_2\end{bmatrix} = \begin{bmatrix}-\omega_1 + \lambda + \mu g_2 & -\mu g_2\\ -\mu g_1 & -\omega_2 + \lambda + \mu g_1\end{bmatrix}\begin{bmatrix}\epsilon_1\\ \epsilon_2\end{bmatrix}$$

$g_1 g_2 < 0$ → Instability

$\kappa \sim \omega$

- Existence of crossing is necessary to have instability
- Growth rate is proportional to vacuum frequency

Fast modes in the nonlinear regime

- The bipolar model

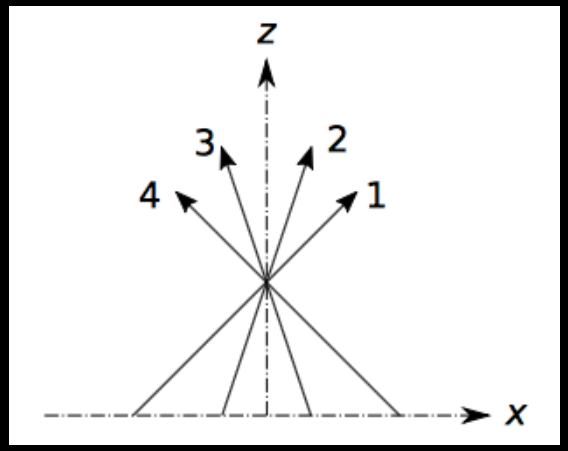
$\propto n_e$ $\propto n_{\nu_e}$

$$i\begin{bmatrix}\dot{\epsilon}_1\\ \dot{\epsilon}_2\end{bmatrix} = \begin{bmatrix}-\omega_1 + \lambda + \mu g_2 & -\mu g_2\\ -\mu g_1 & -\omega_2 + \lambda + \mu g_1\end{bmatrix}\begin{bmatrix}\epsilon_1\\ \epsilon_2\end{bmatrix}$$

$g_1 g_2 < 0$ → Instability

$\kappa \sim \omega$

- Anisotropic neutrino medium



$$\frac{\omega_1 - \lambda - 2\mu(\Gamma_{14} g_1 - \gamma_{13} g_2)}{\cos\theta_1}$$

$$i\frac{d}{dz}\begin{bmatrix}\epsilon_{1+}\\ \epsilon_{2+}\end{bmatrix} = \begin{bmatrix}-\tilde{\omega}_{1+} + \tilde{\mu}_+\tilde{g}_{2+} & -\tilde{\mu}_+\tilde{g}_{2+}\\ -\tilde{\mu}_+\tilde{g}_{1+} & -\tilde{\omega}_{2+} + \tilde{\mu}_+\tilde{g}_{1+}\end{bmatrix}\begin{bmatrix}\epsilon_{1+}\\ \epsilon_{2+}\end{bmatrix}$$

S. Abbar & H. Duan, Phys.Rev. D98 (2018)

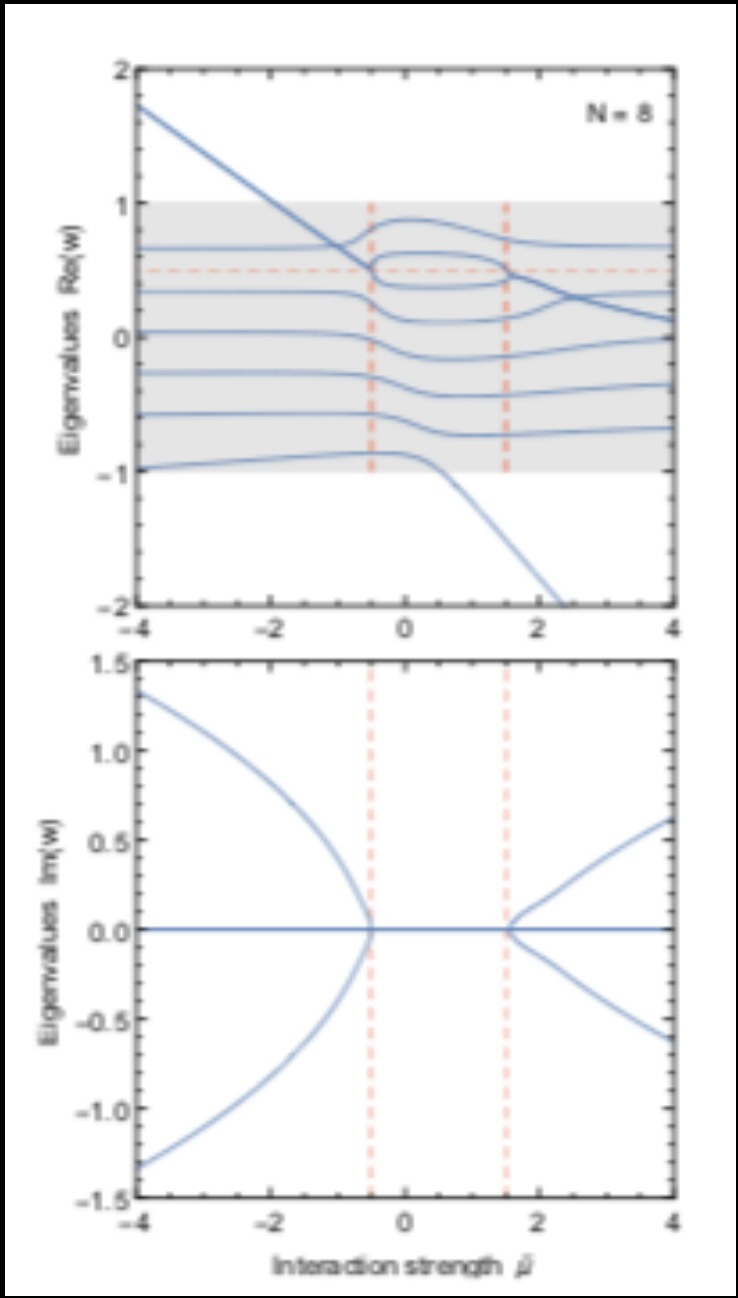
$$\tilde{g}_{1-} = -\frac{g_1}{v_{2z}},$$
$$\tilde{g}_{2-} = -\frac{g_2}{v_{1z}},$$

$\kappa \sim \tilde{\omega}$

- Everything is determined by effective quantities

Fast modes in the nonlinear regime

- Tow non-collective modes can merge and make a collective mode



Capozzi, Raffelt, Stirner; arXiv: 1906:08794