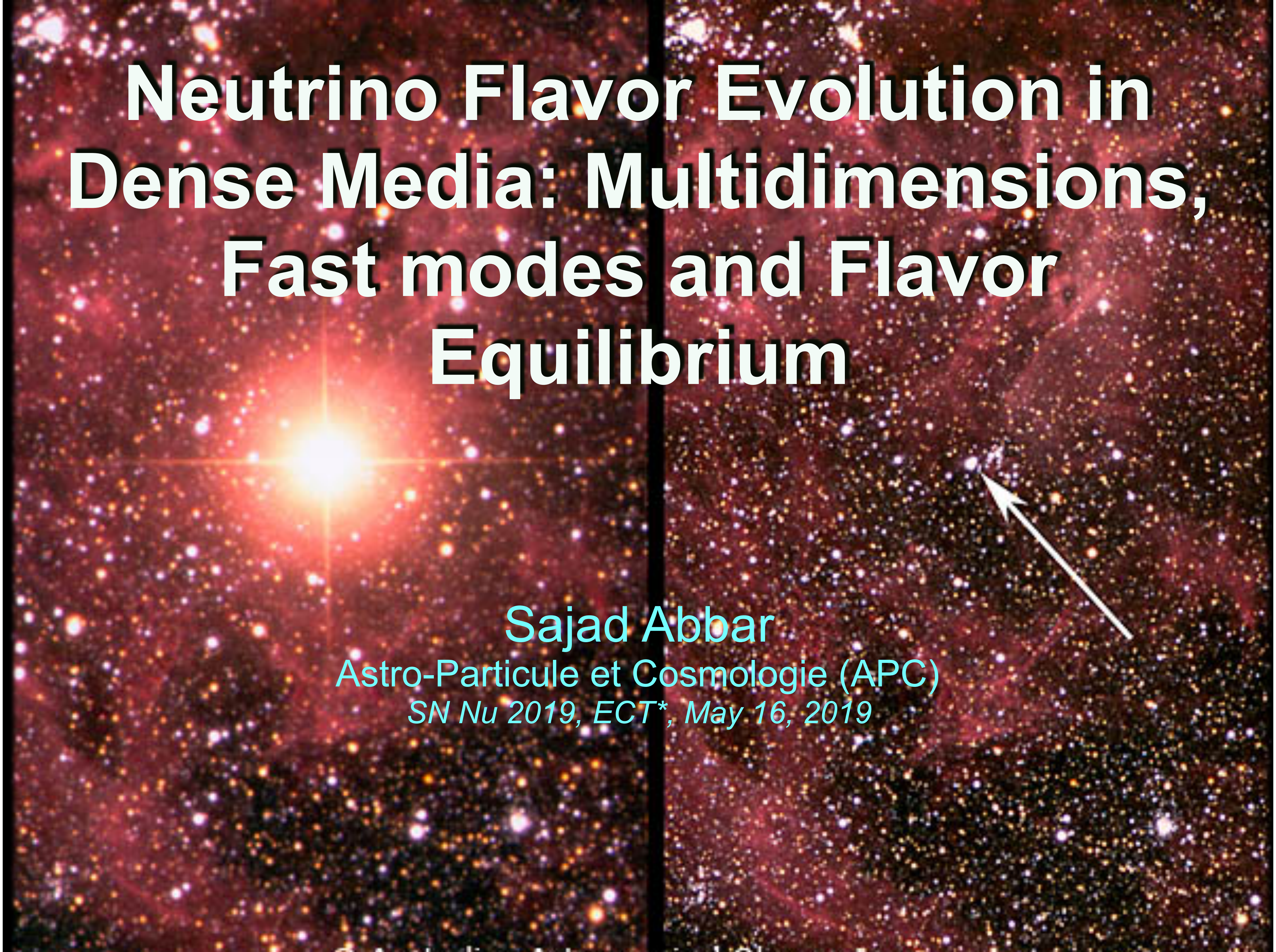
Neutrino Flavor Evolution in Dense Media: Multidimensions, Fast modes and Flavor Equilibrium



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SN Nu 2019, ECT, May 16, 2019*

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

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

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

$$\sqrt{2}G_{\mathrm{F}}\int \underset{\substack{\downarrow \\ \text{coupling}}}{\underline{d^3}}q(1-\mathbf{v}_{\mathbf{P}}\cdot\mathbf{v}_{\mathbf{q}})(\underset{\substack{\downarrow \\ \text{nonlinearity}}}{\underline{\rho_\nu}}-\rho_{\bar{\nu}})$$

Neutrino Bulb Model

- We have a 7-D problem!

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

time translation symmetry

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

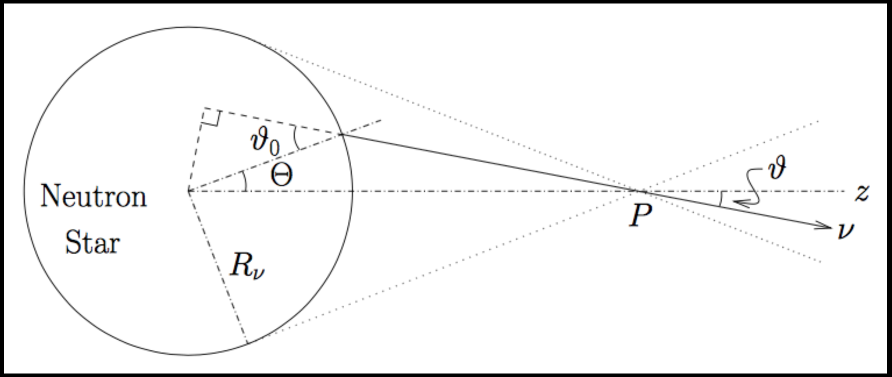
spherical symmetry & axial symmetry around radial direction

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

- *Neutrino Bulb Model:*

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

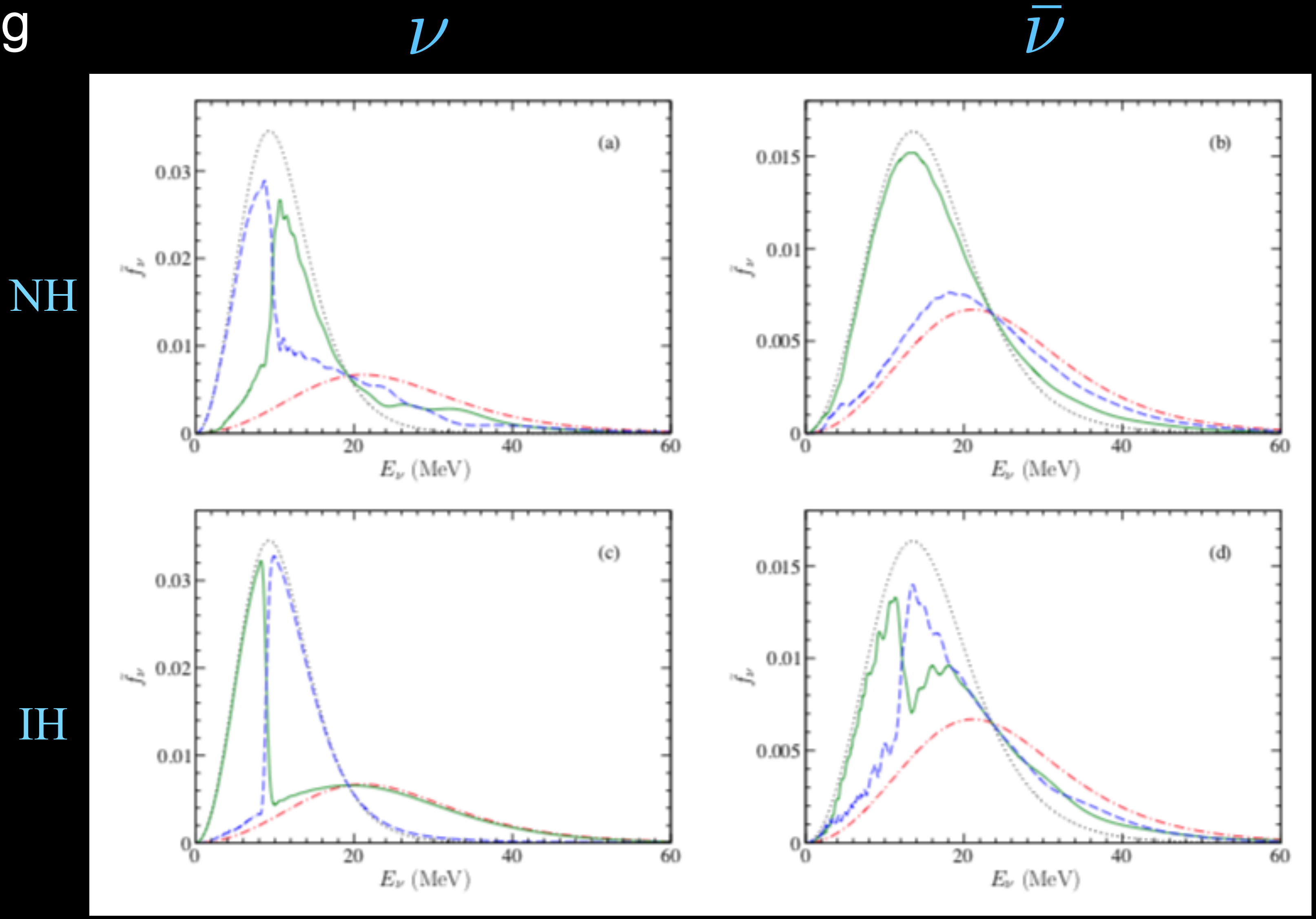
$$\rho(r; E, \theta)$$



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



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 Models ?!

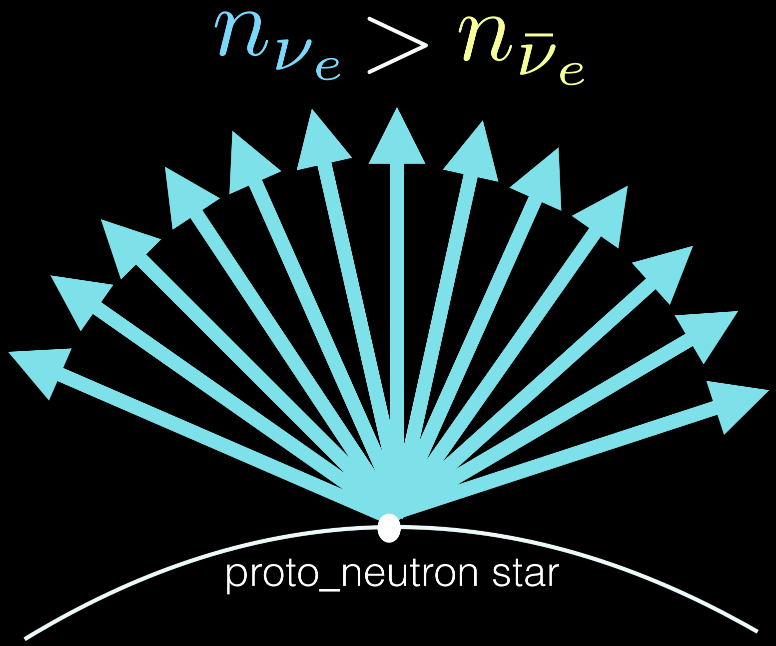
- Our simplistic calculations are based on two important assumptions:
  - Neutrino evolution has time/special symmetries

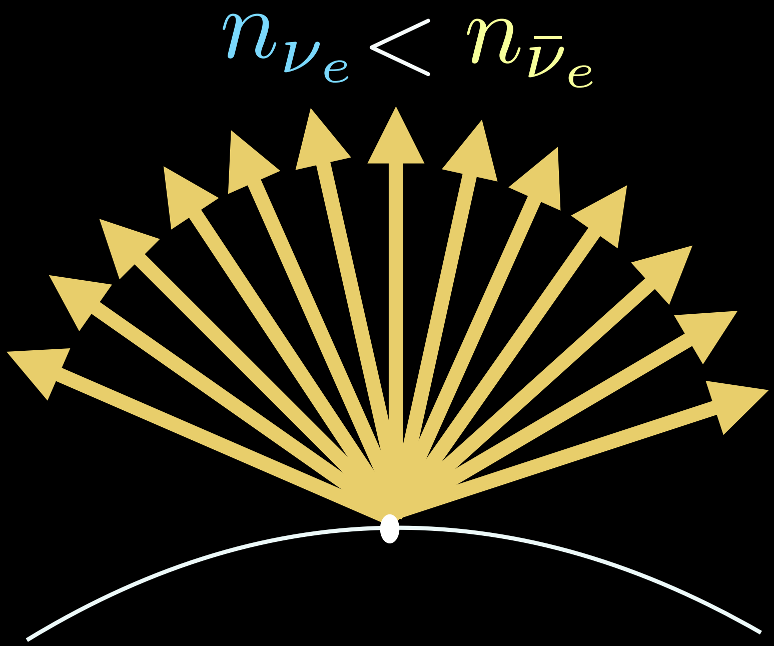
    G. Raffelt, S. Sarikas, D. S. Seixas, PRL 111, 091101 (2013)
    H. Duan & S. Shalgar, PLB 747, 2015
    A. Mirizzi, G. Mangano & N. Saviano, PRD 92, 021702 (2015)
    S. Chakraborty, R. .S. Hansen, I. Izaguirre and G. G. Raffelt, JCAP 1601 (2016)
    S. Abbar & H. Duan, PLB 751, 2015H. Duan & S. Shalgar,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

  - Neutrinos are emitted isotropically

Anisotropic Neutrino Emission

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

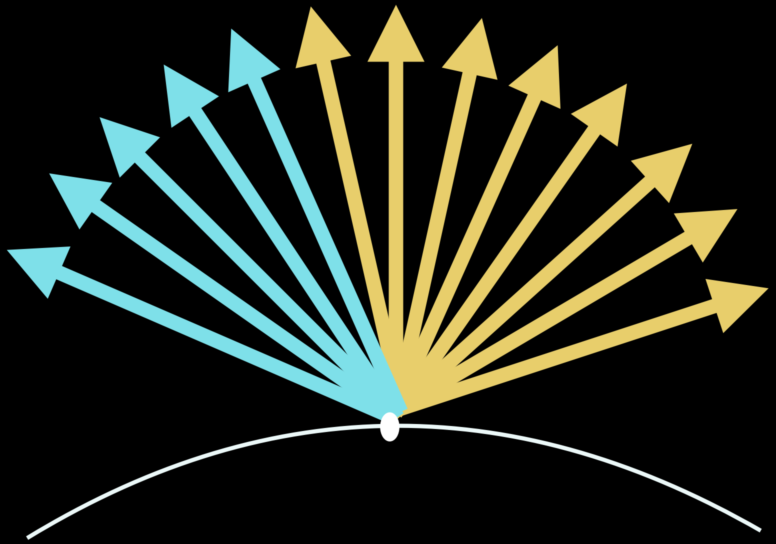




- This implies that the scales on which flavor conversion could occur is determined by vacuum frequency $\Delta m^2/2E \sim 1\ \mathrm{km}^{-1}$
- At vary large matter densities, collective oscillations is irrelevant since collisions occur on much smaller scales!

Anisotropic Neutrino Emission

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

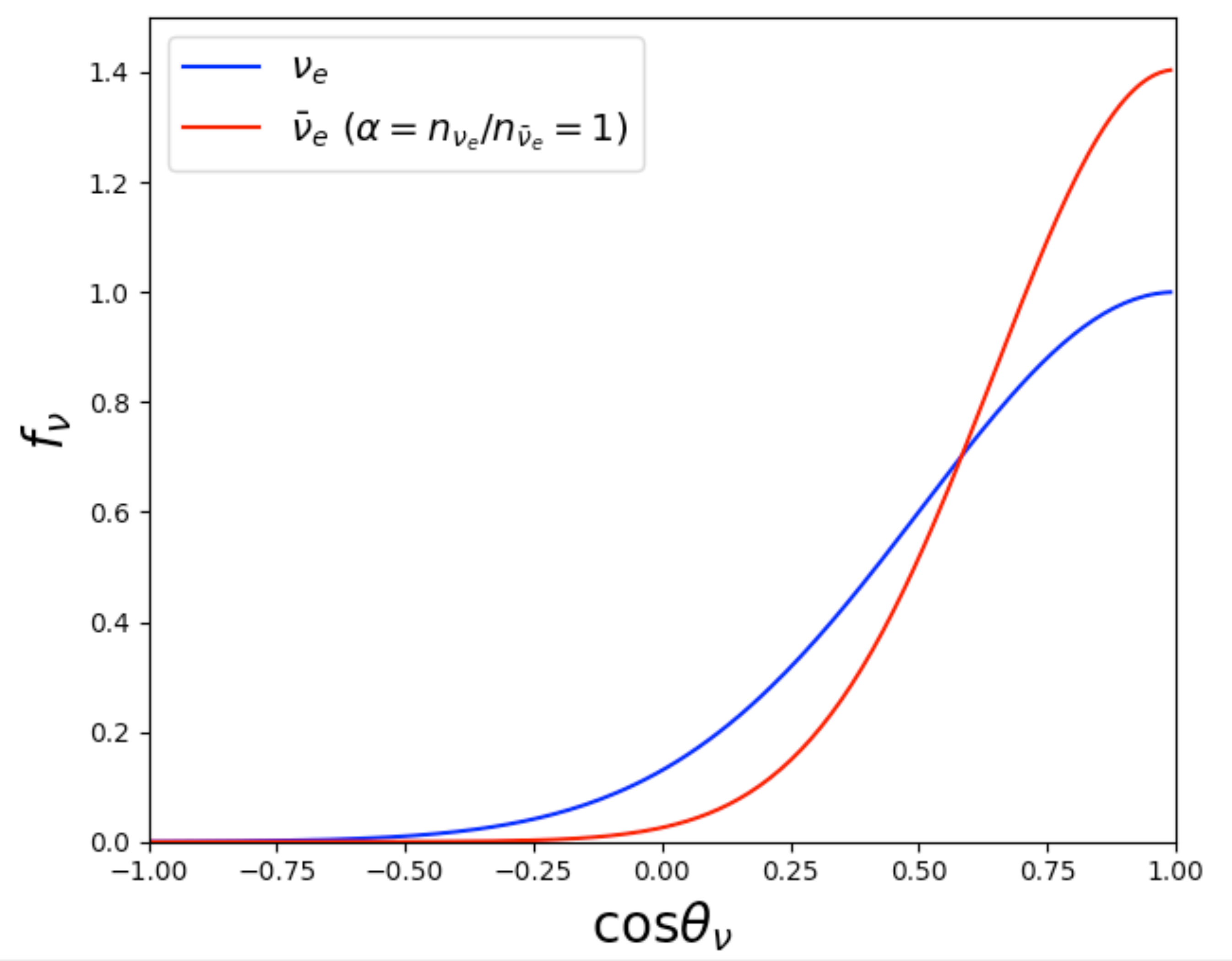


- Scales on which flavor conversion could occur is now determined by n_{ν_e} (n_e) and could be < 10 cm on the surface of proto-neutron star
- Neutrino oscillations could now occur at densities that had been long thought to be the realm of collisional and scattering processes

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)
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)
….
…

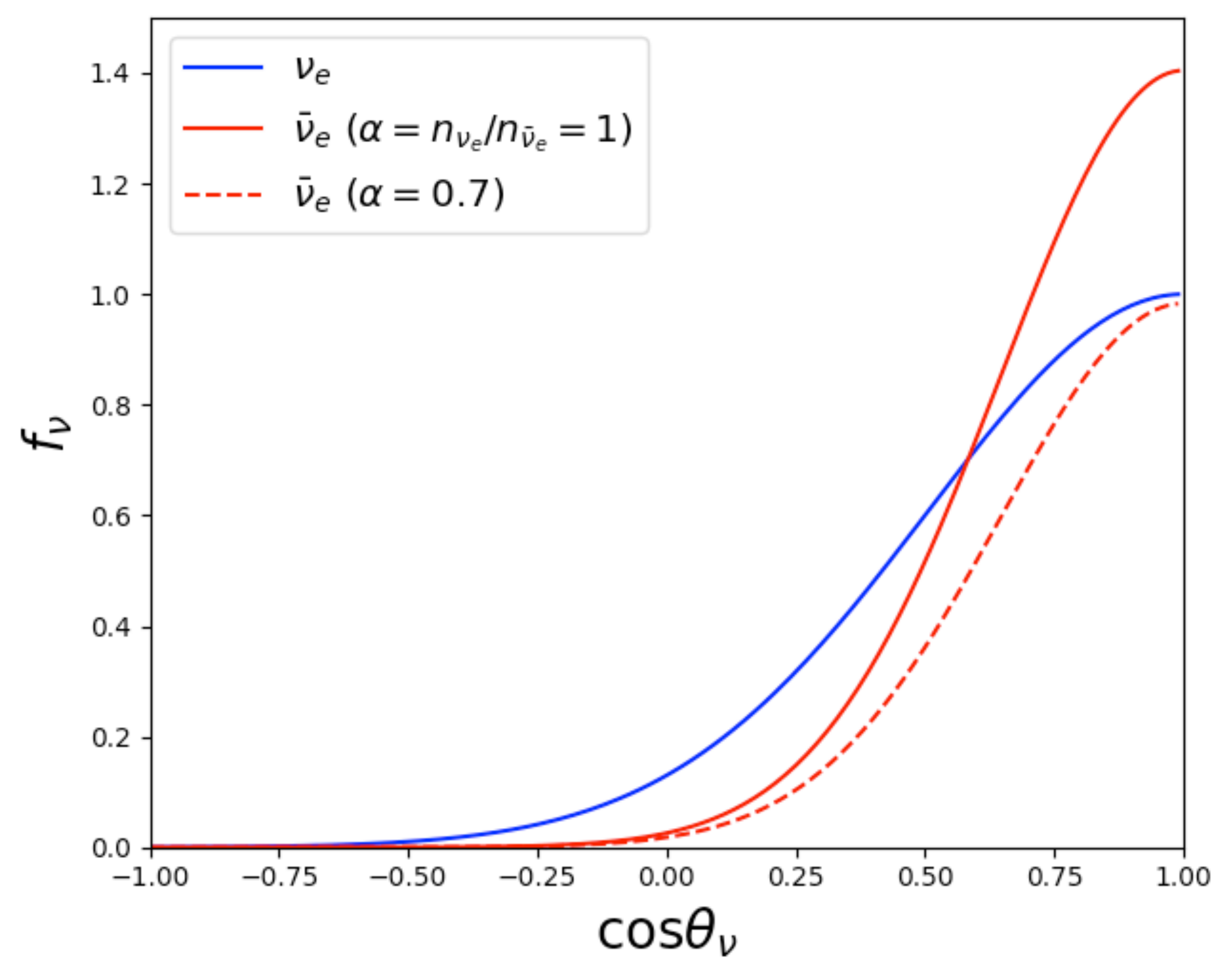
Occurrence of fast modes in CCSNe

- One might naively expect to observe angular crossings in SN environment



Occurrence of fast modes in CCSNe

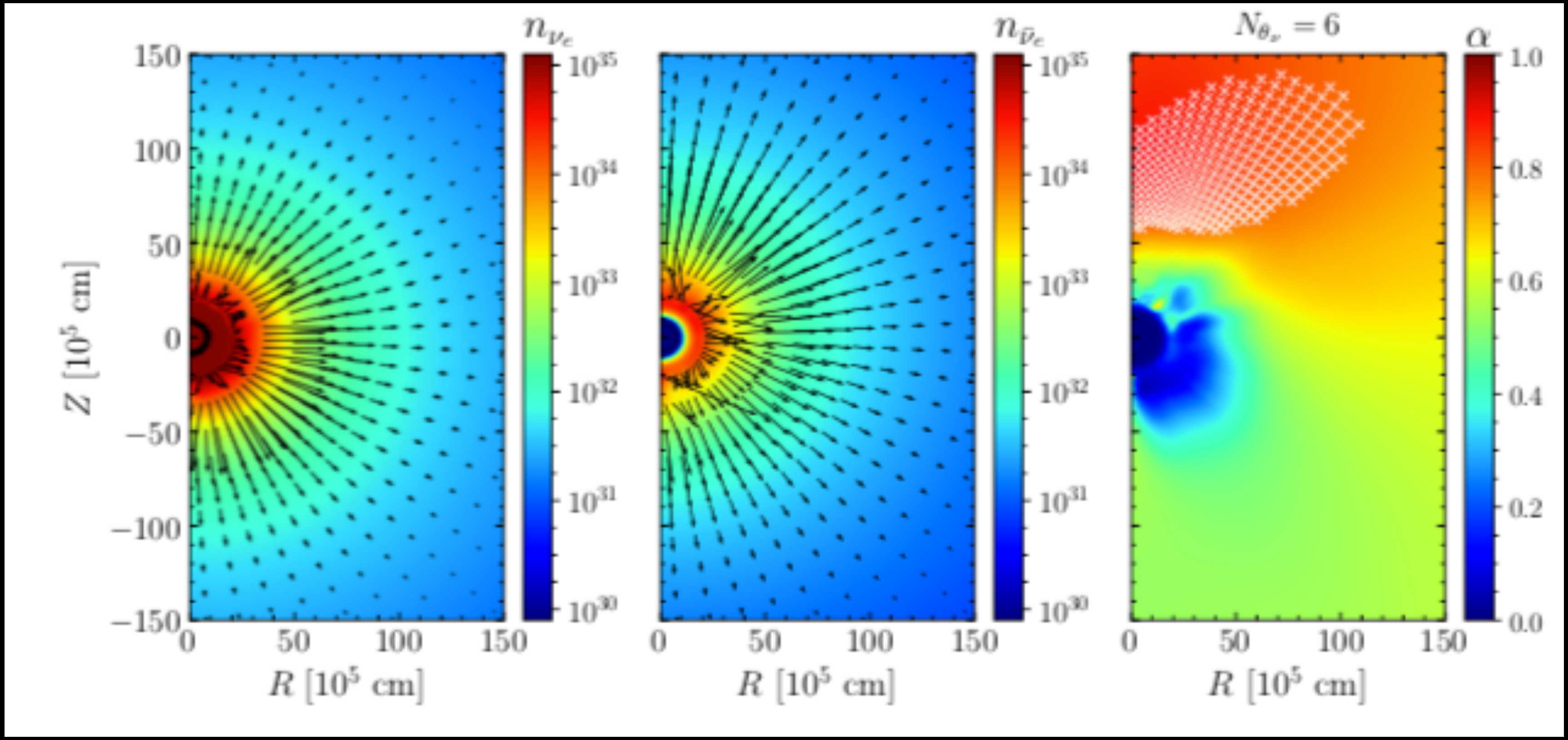
- BUT it is not that easy …



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

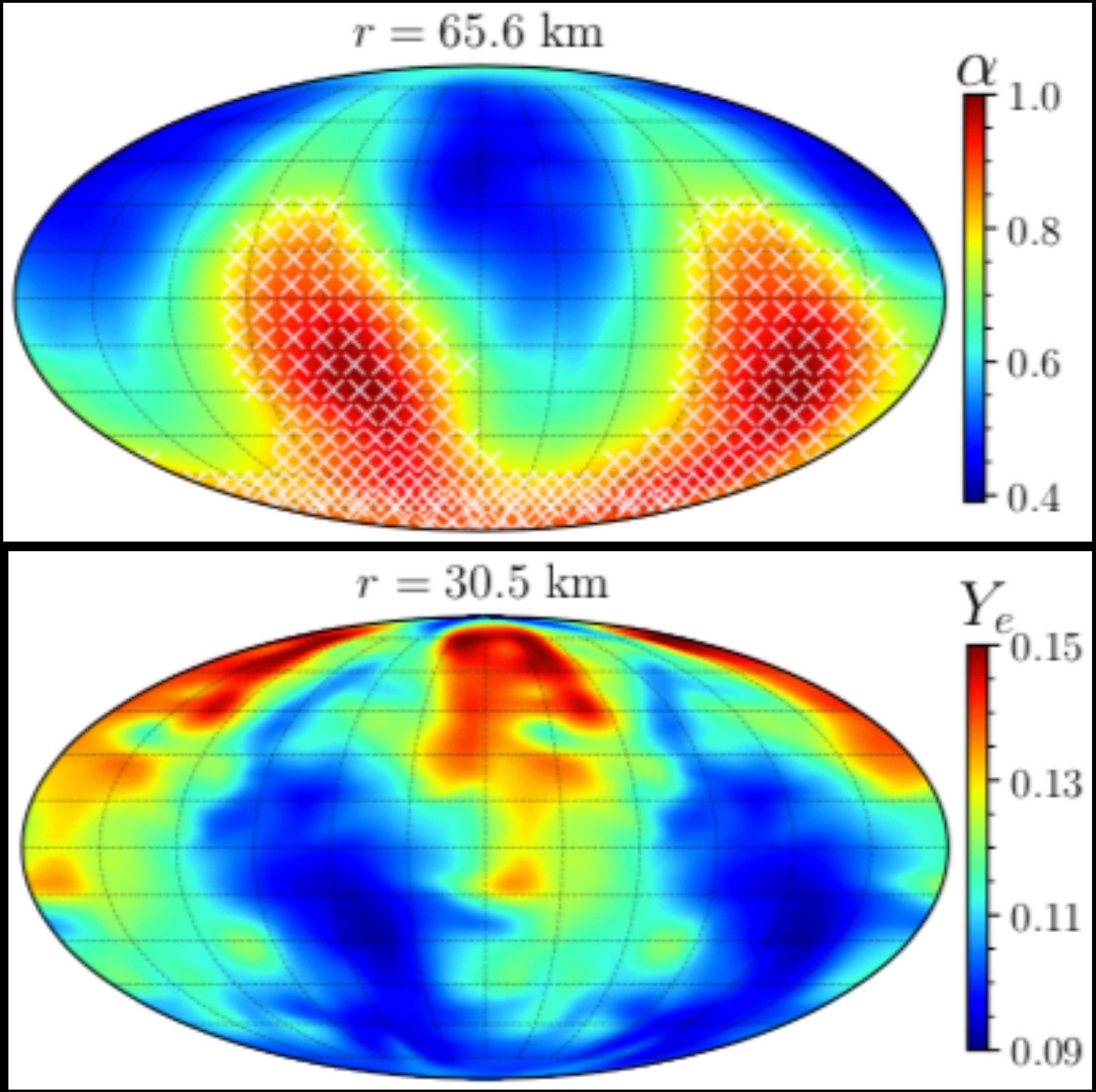
Occurrence of fast modes in CCSNe

- We examined the neutrino distributions obtained by solving the Boltzmann transport equation for several fixed profiles which are representative snapshots taken from separate 2D and 3D supernova simulations with an 11.2M⊙ progenitor model.



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

Occurrence of fast modes in CCSNe



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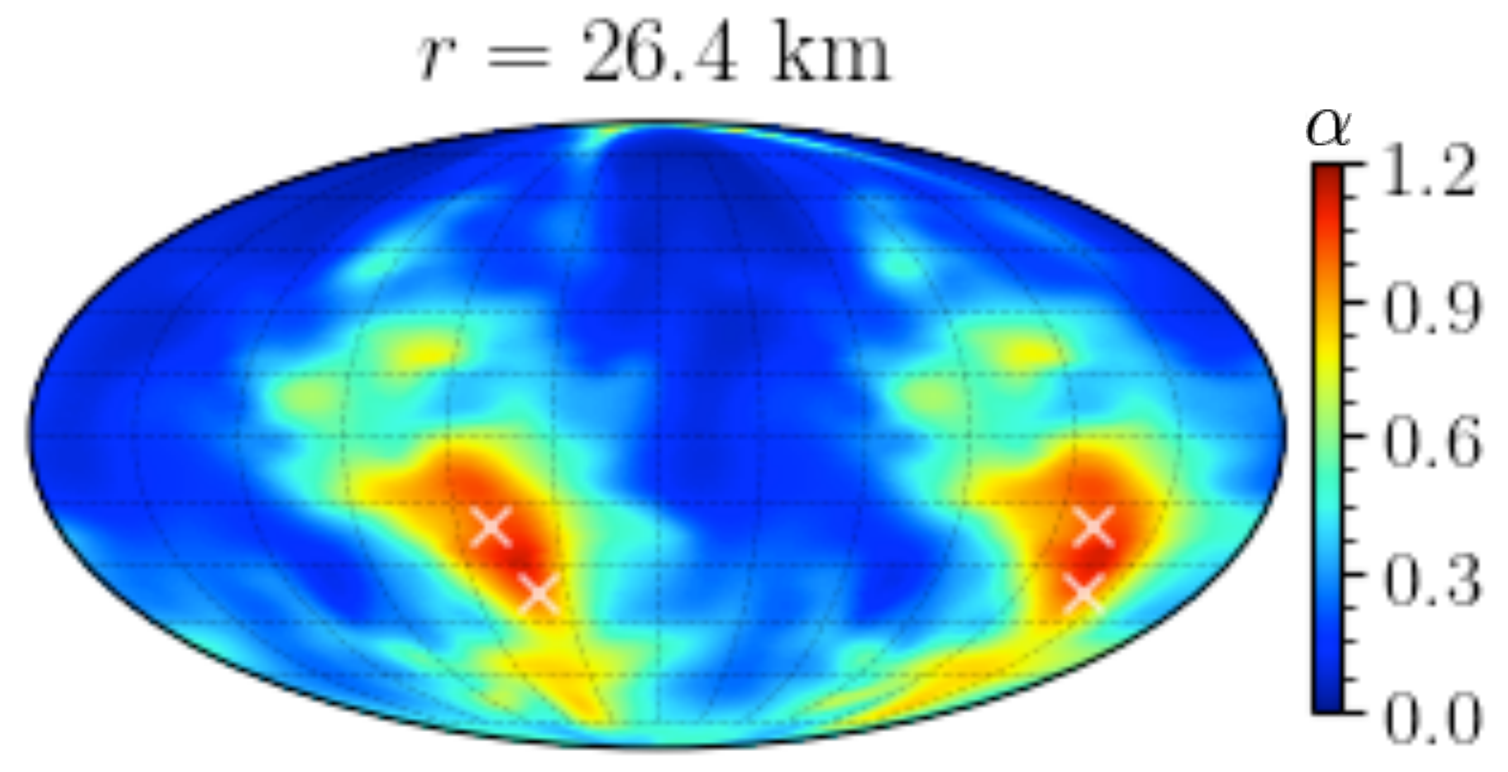
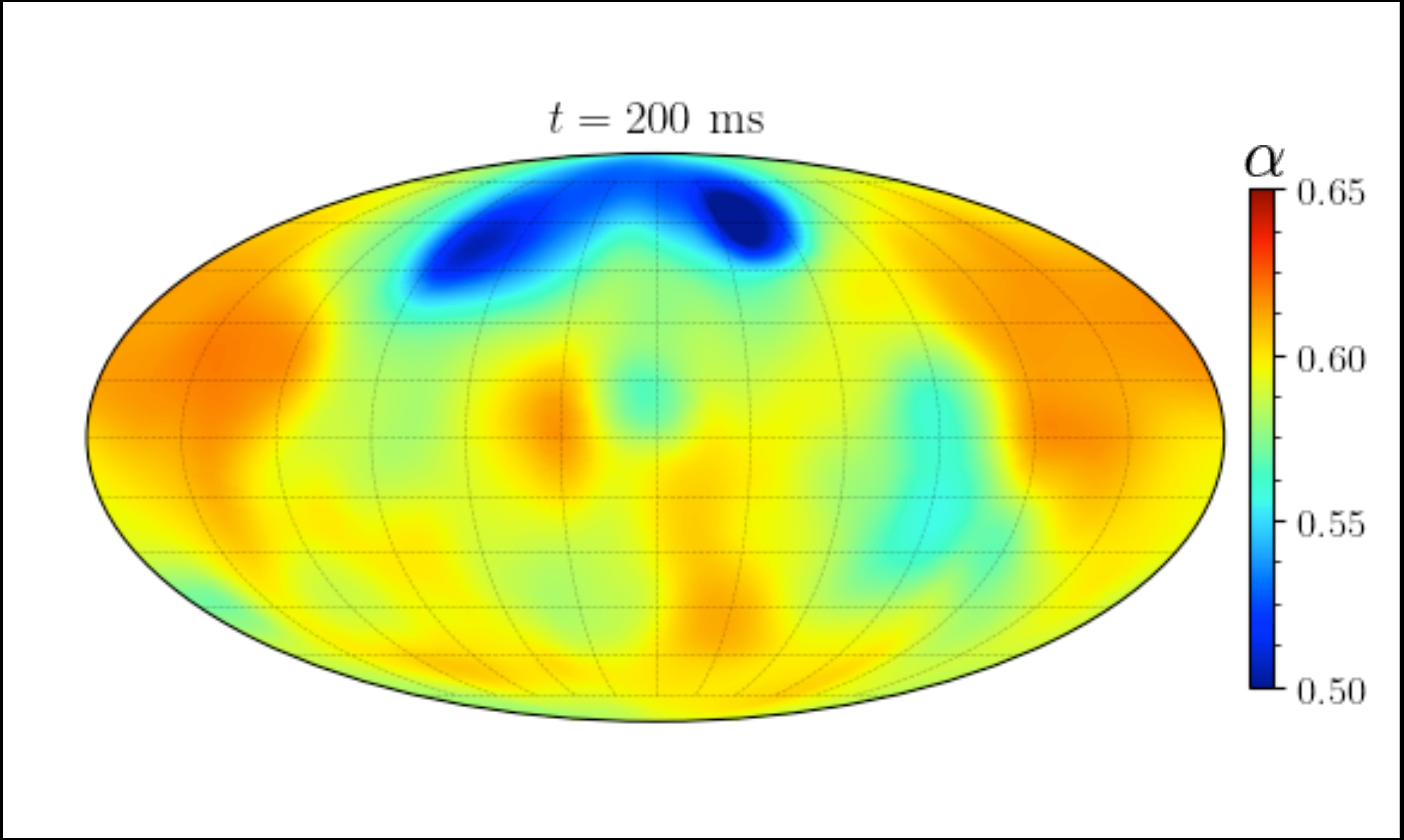
Occurrence of fast modes in CCSNe

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



Occurrence of fast modes in CCSNe

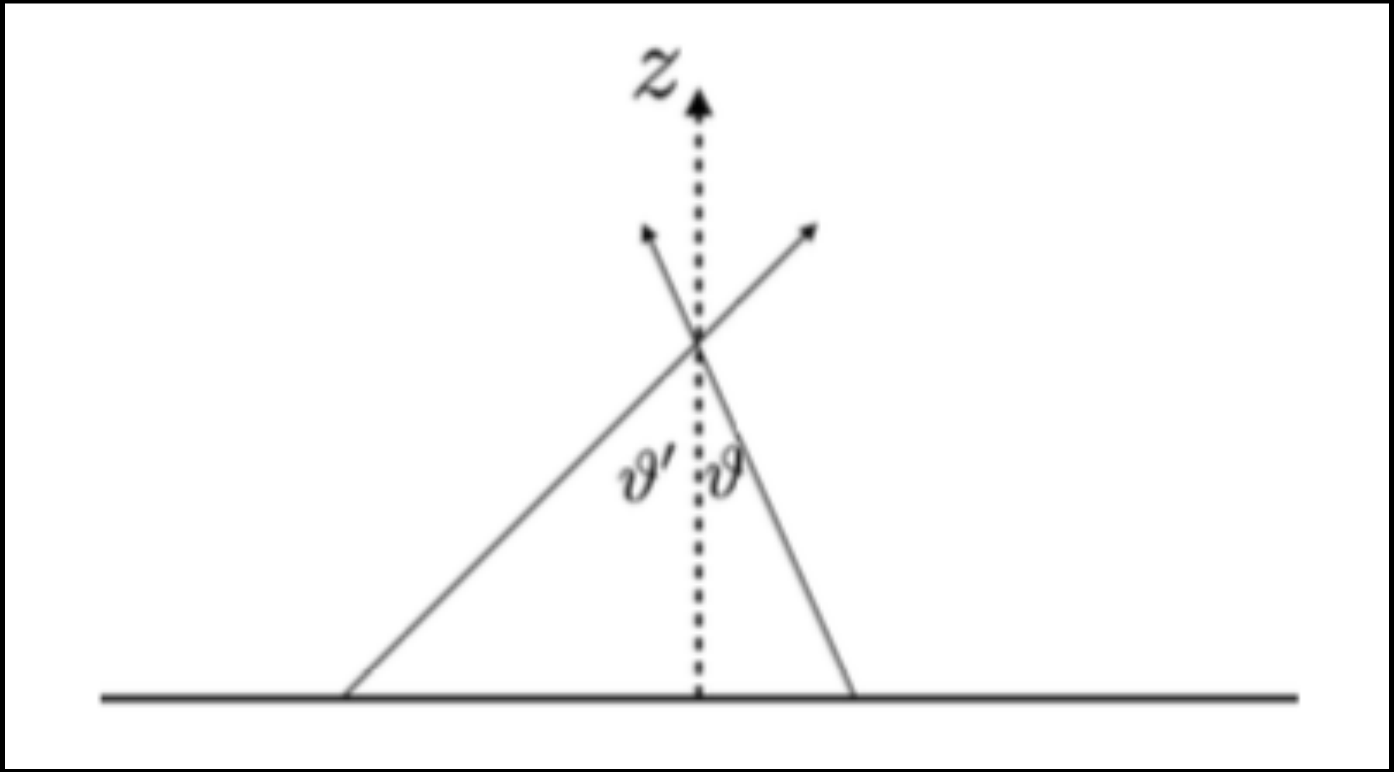
- No crossings were found for 27M⊙ progenitor model.



- Azari et. al. did not find any crossings in a self-consistent calculations: much less convective activity

Fast modes in the nonlinear regime

- It was speculated that fast modes could lead to flavor equipartition



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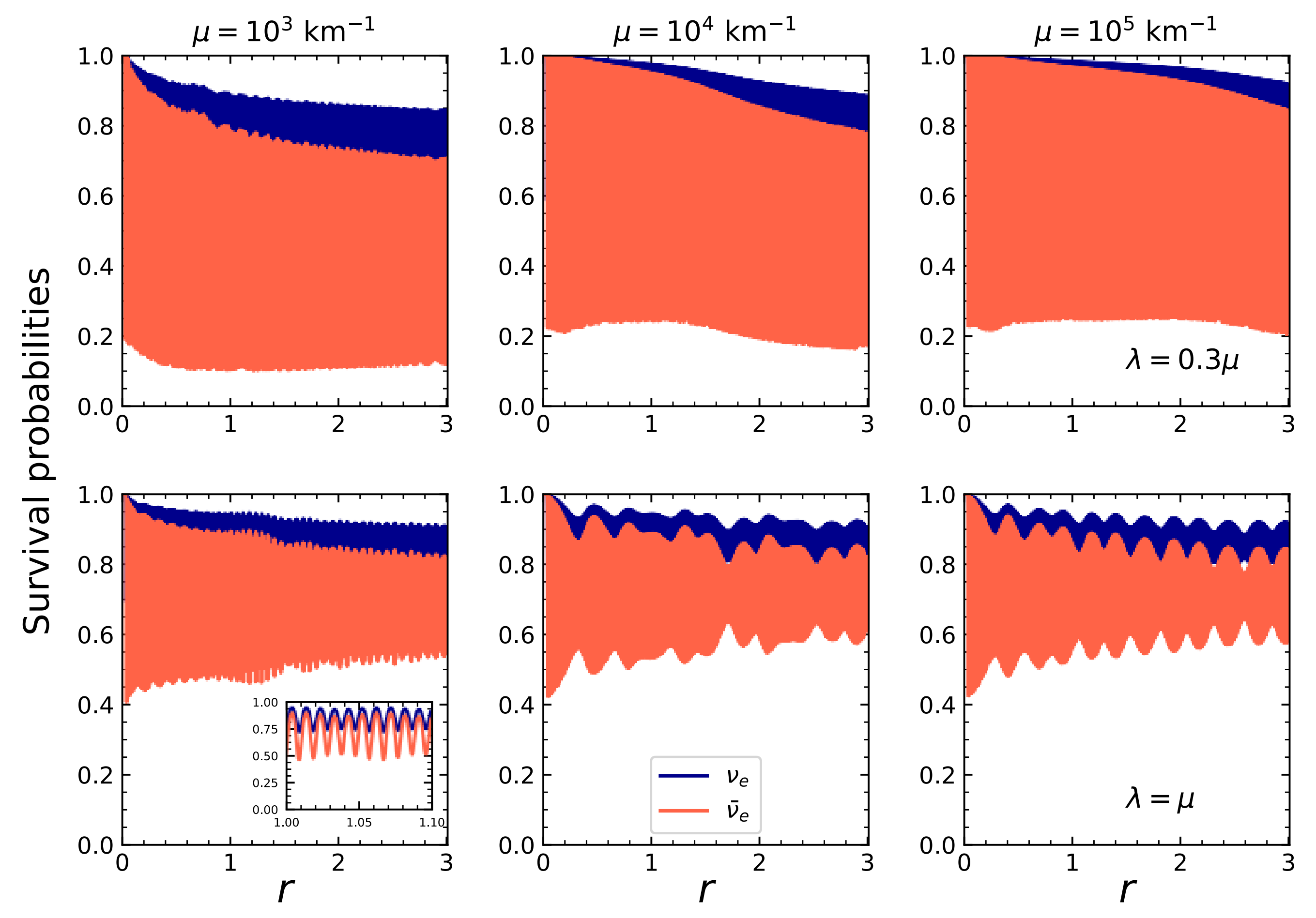

S. Abbar and M. C. Volpe, Phys.Lett. B790 (2019)

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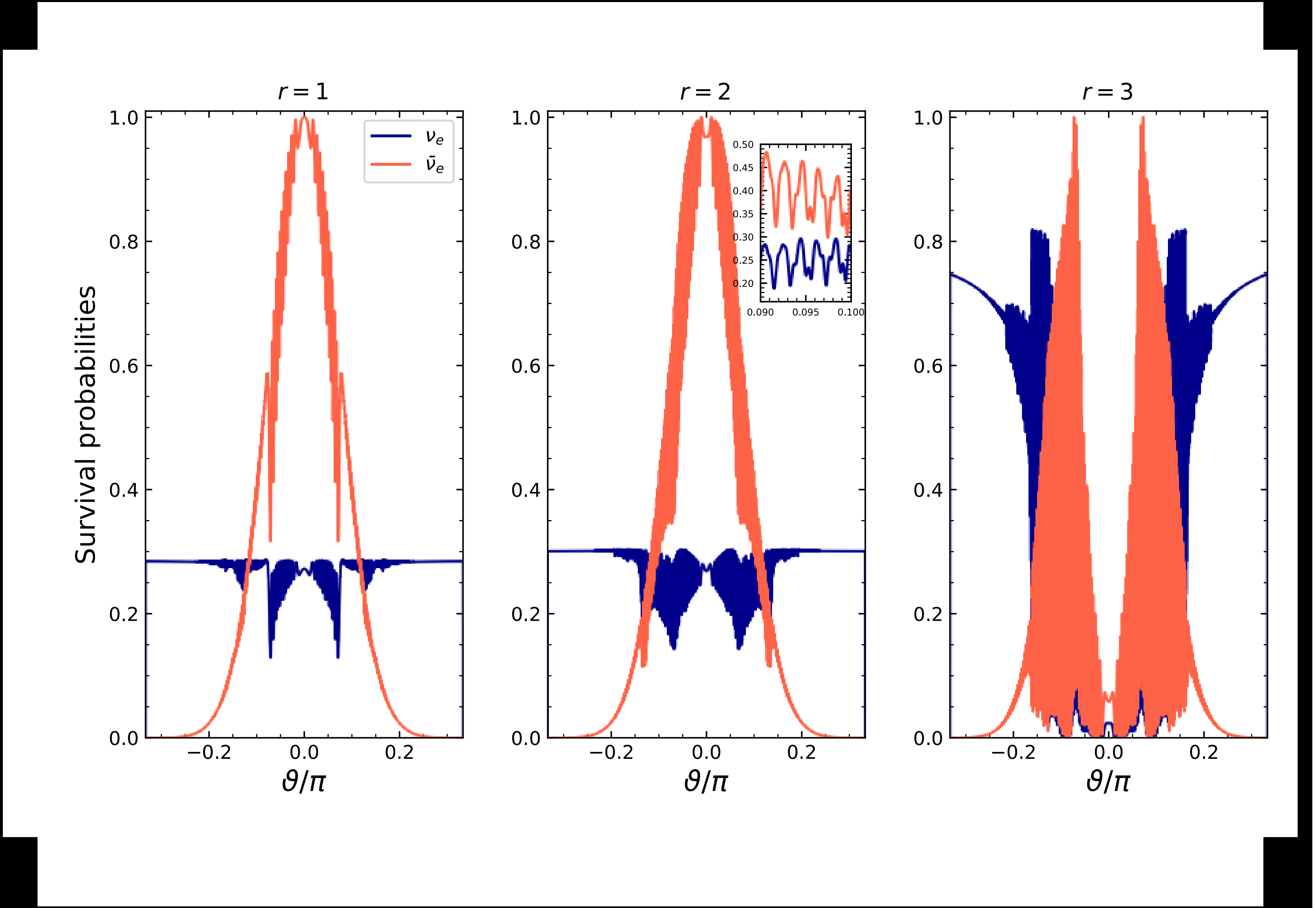

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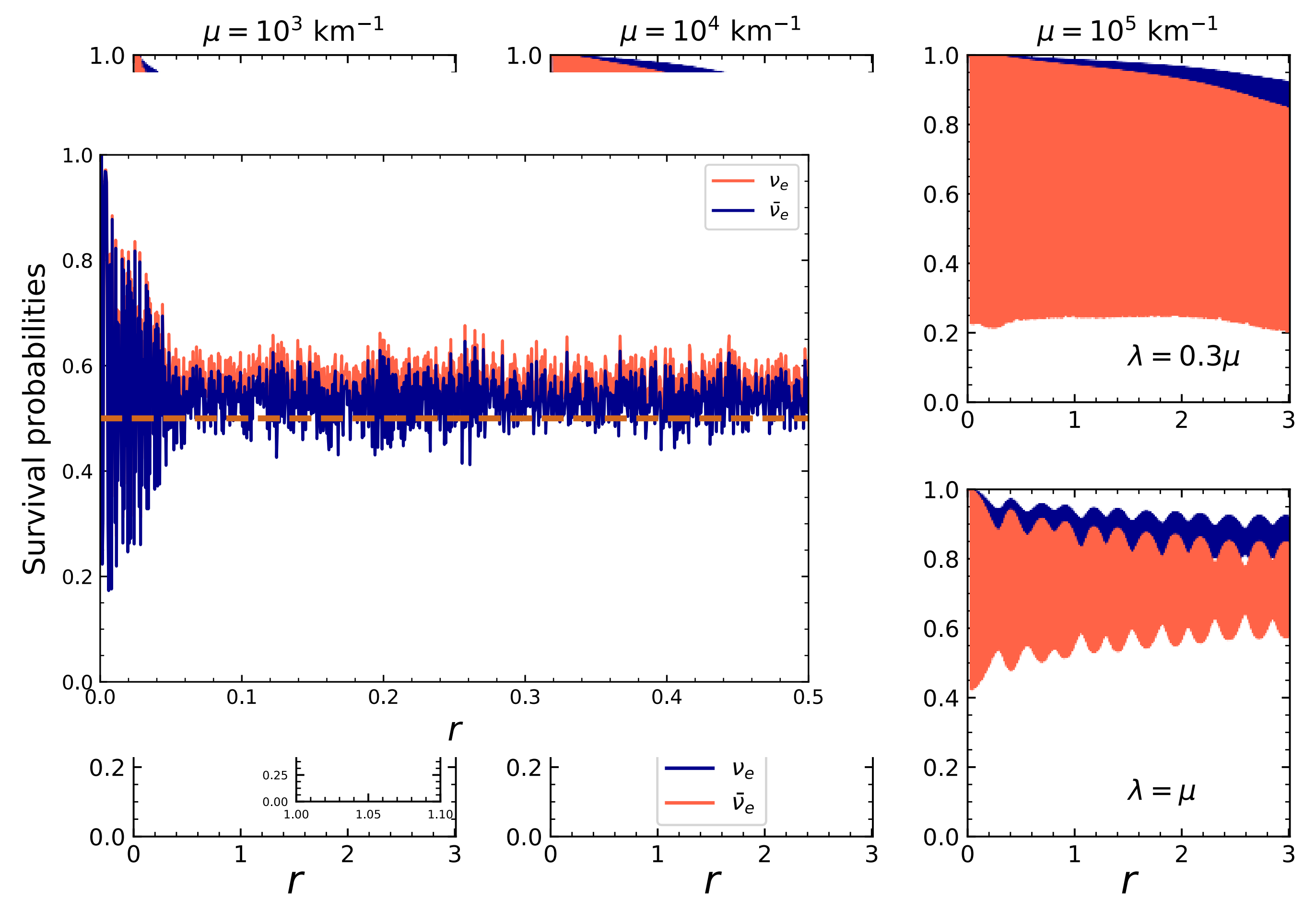
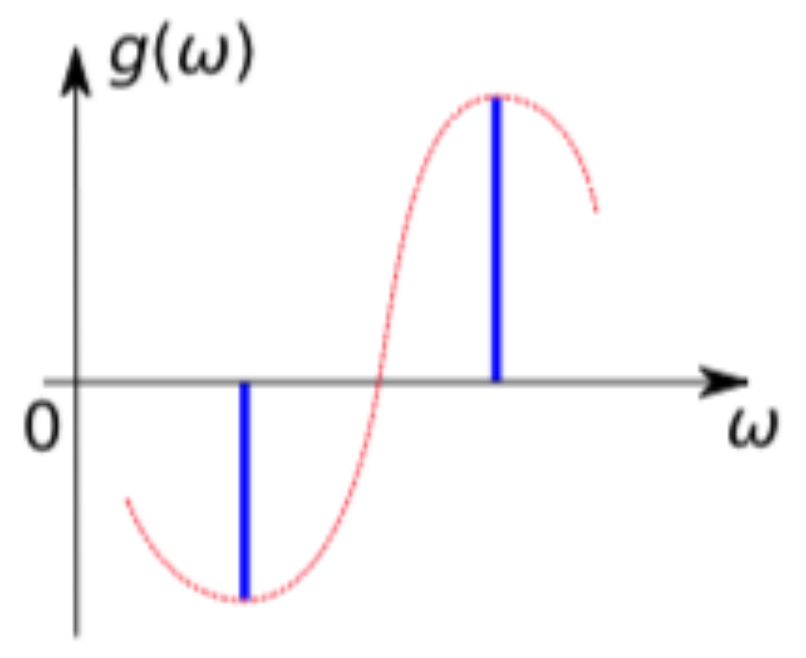


S. Abbar and M. C. Volpe, Phys.Lett. B790 (2019)

Fast modes in the nonlinear regime

- The bipolar model describes a homogeneous and isotropic neutrino gas initially consisting of mono-energetic νe and ν¯e

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



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

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

$g_1 g_2 < 0$ ➡ Instability

$\kappa \sim \omega$

Fast modes in the nonlinear regime

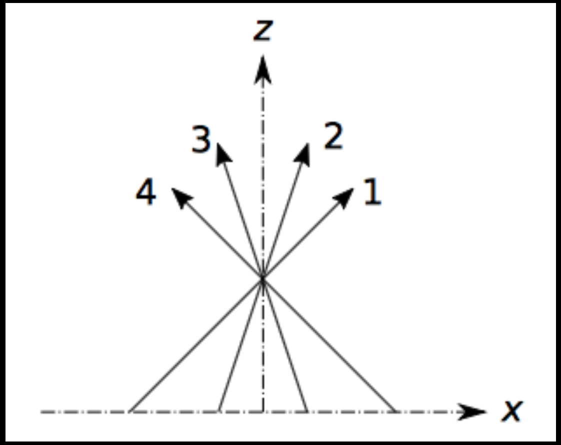
- The bipolar model

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

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

$g_1 g_2 < 0$ → Instability

- Anisotropic neutrino medium



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

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

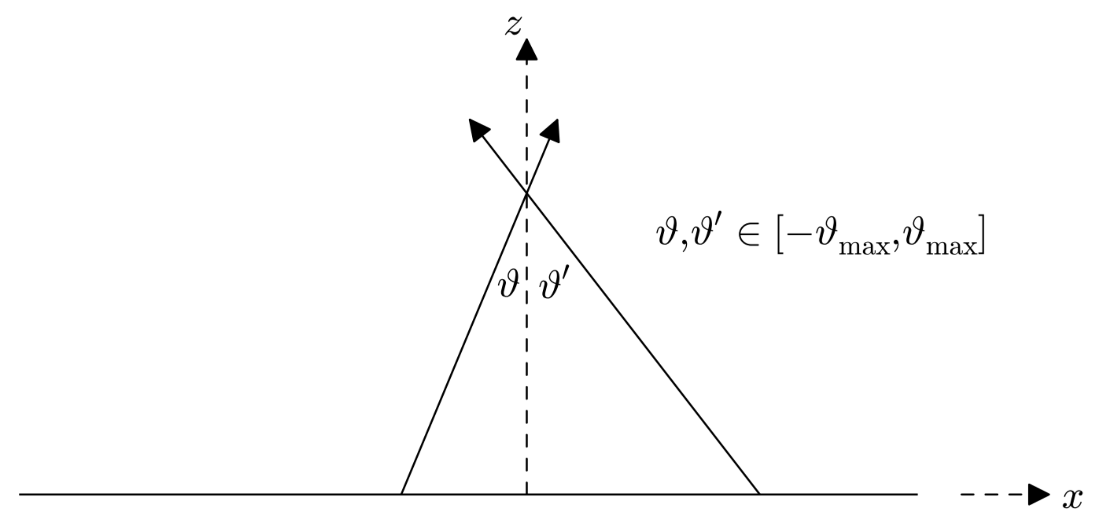
S. Abbar & H. Duan, Phys.Rev. D98 (2018)

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

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

Neutrino evolution in a 2D model

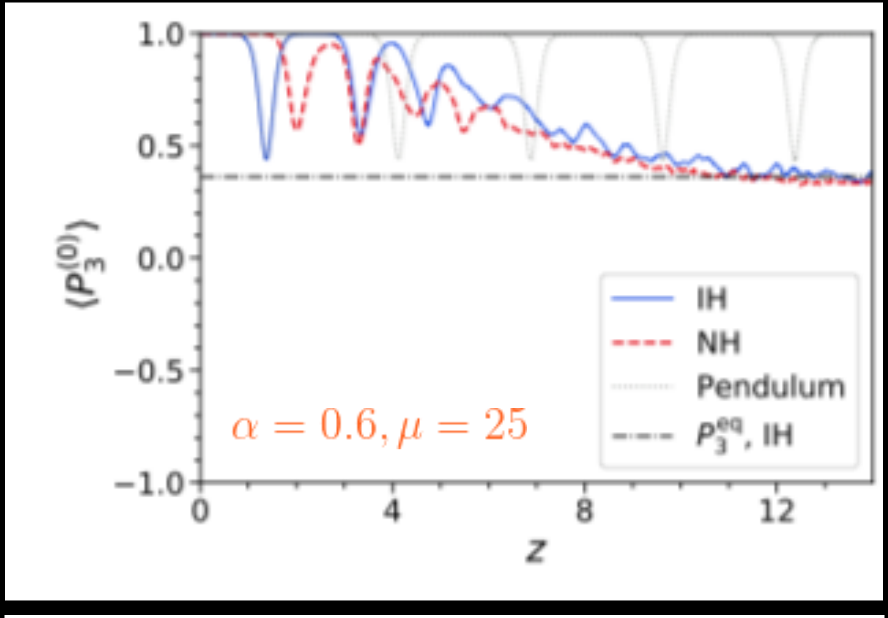
- In this toy model, we have an **infinite line** that emits neutrinos and antineutrinos from all the points on the line. We also assume that we have periodic boundary condition along the line with the period of **L**

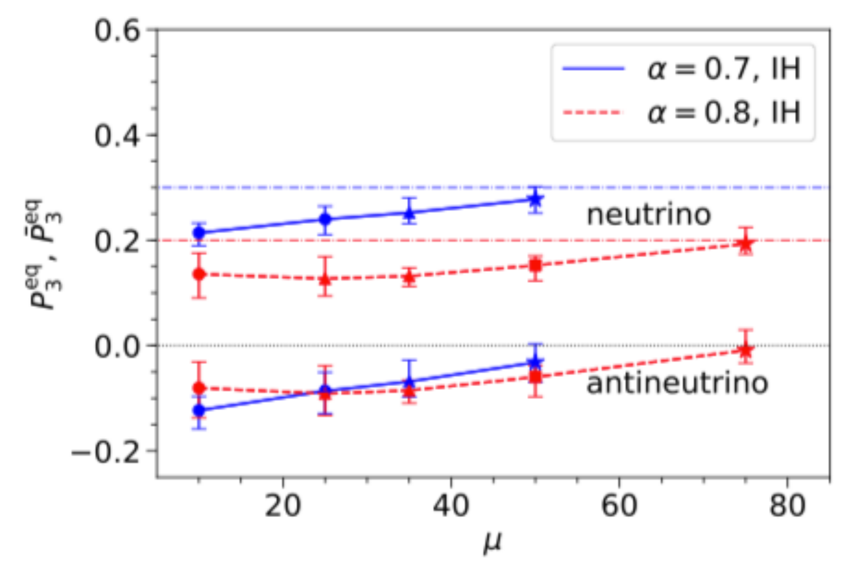


S. Abbar, H. Duan and S. Shalgar; PRD 92, (2015) 065019

Neutrino evolution in a 2D model

- Neutrinos could reach some sort of flavor equilibrium at large neutrino number densities





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

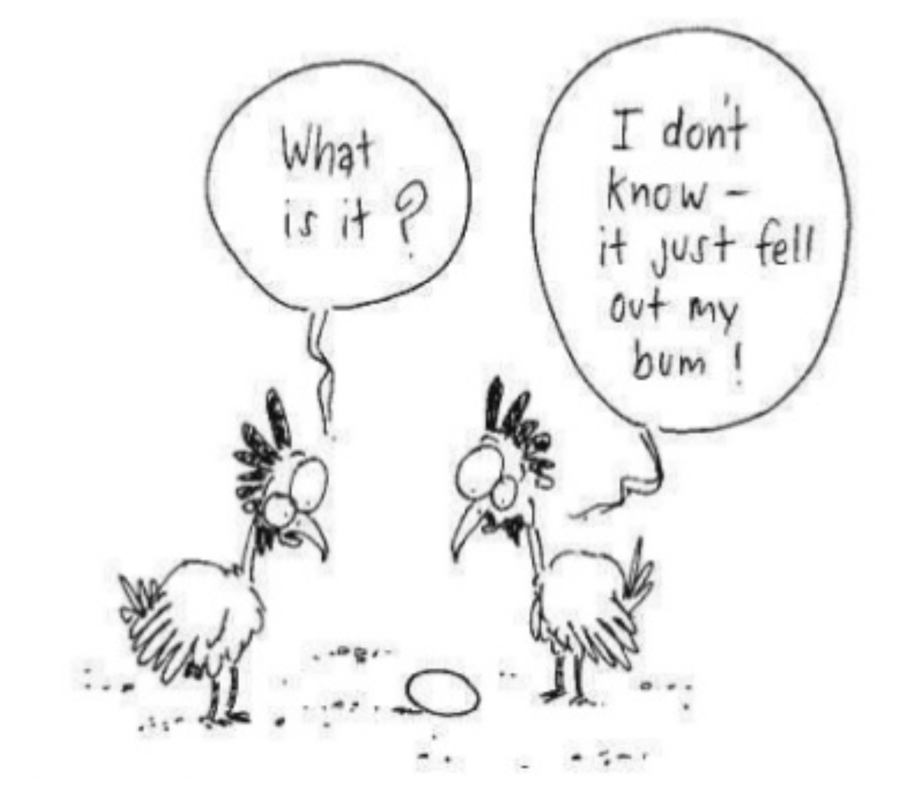
Conclusion

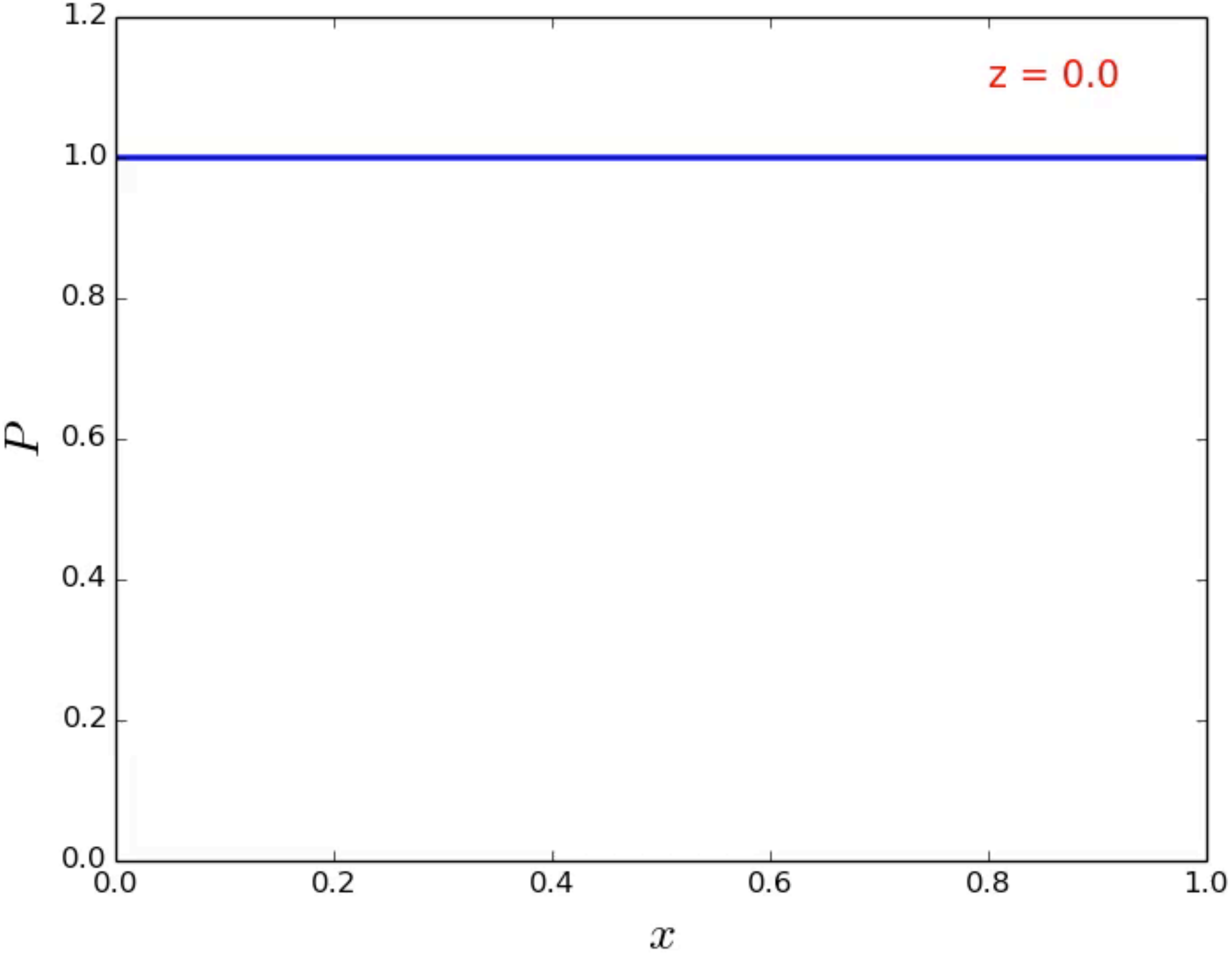
- Fast modes could occur in the during the early stages of a CCSN if there is a strong LESA (or multiple structure)

- Fast modes does not necessarily result in flavor equilibrium

- Some sort of flavor equilibrium might arise in MD models

THANK YOU




z = 0.0
P
x
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0.6
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1.0
1.2
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0.2
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0.6
0.8
1.0