Fast neutrino flavor conversion at late time

Soumya Bhattacharyya
Department Of Theoretical Physics, TIFR
soumyaquanta@gmail.com

Background and Objectives

- High neutrino density inside supernovae allows self-interaction of strength μ >> λ (matter potential), ω (vacuum scale)
- Such conditions favor fast flavor conversions (FFC) : 1) Rapid and occurs at a rate μ 2) Can give rise to complete flavor conversion 3) System gets coupled and also nonlinear
- Linear stability analysis [1] was done in previous literatures : Helpful to understand if or when FFC occurs but fails to study the impact of FFC on the observable neutrino fuxes or explosion mechanism
- Our motivation **:** Understanding the nonlinear mechanism of FFC both numerically and analytically considering a system of inhomogeneous and non-stationary dense neutrino gas with 1 (space) +1 (momentum)+1 (time) phase space dimensionality

Equation of Motion for FFC in 1+1+1 D [2, 3]

$$\left(\partial_t + v\partial_x\right)\mathbf{P}_v(x,t) = \mu \underbrace{\left(\mathbf{M}_0(x,t) - v\mathbf{M}_1(x,t)\right)}_{\mathbf{H}_v} \times \mathbf{P}_v(x,t)$$

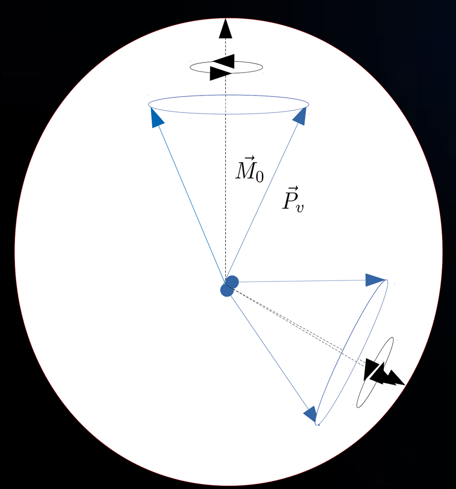
$$\mathbf{M}_n = \int_{-1}^{1} L_n(v)\mathbf{P}_v \, dv$$

- Developed our own faster numerical strategy to solve the EOM.
- Discretized in space for each velocity v to solve a set of couped nonlinear O.D.E as a function of t.
- Method **:** B.D.F Boundary Condition **:** Periodic in space
- Solver **:** Zvode and scipy.fftpack.diff in python

Results

- System becomes approximately stationary in time allowing us to drop the time index from the quantities in the EOM.
- In the stationary limit the polaization vectors for each velocity mode show a precession in space around a common axis , $\mathbf{M}_0$, in some rotated frame. **"~"** sign denotes the quantities in that frame
- In the same frame $\mathbf{M}_0$ has a spatial motion equivalent to the motion of a pendulum [4, 5] in a inhomogeneous magnetic field **B** with fixed spin (σ), fixed energy (E) and fixed length M_0

1) Pendulum Motion :

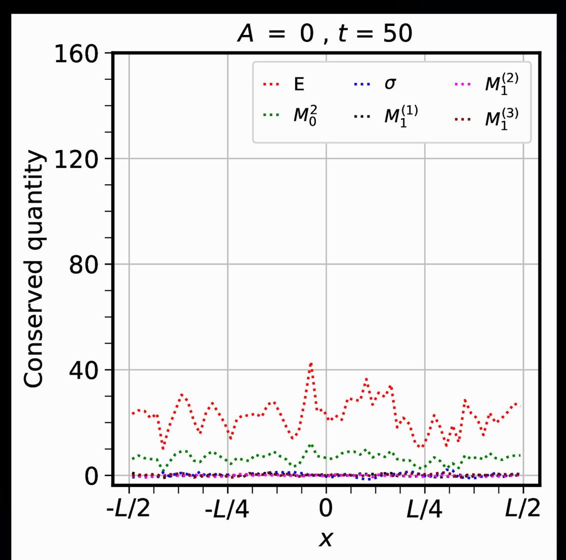


$$\widetilde{\mathbf{P}}_v : \frac{d}{dx}\widetilde{\mathbf{P}}_v(x) = \frac{\widetilde{\mathbf{M}}_0(x)}{v} \times \widetilde{\mathbf{P}}_v(x)$$

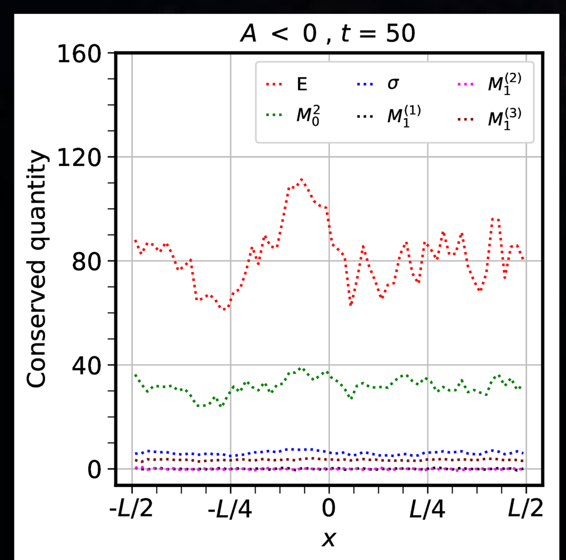
$$\widetilde{\mathbf{M}}_0 : \widetilde{\mathbf{M}}_0 \times \frac{d^2}{dx^2}\widetilde{\mathbf{M}}_0 + \sigma\left|\widetilde{\mathbf{M}}_0\right|\frac{d}{dx}\widetilde{\mathbf{M}}_0 = \left|\widetilde{\mathbf{M}}_0\right|^2 \widetilde{\mathbf{B}} \times \widetilde{\mathbf{M}}_0$$

$$E = \widetilde{\mathbf{B}}.\widetilde{\mathbf{M}}_0 + \frac{1}{2}\widetilde{\mathbf{D}}.\widetilde{\mathbf{D}} \qquad \sigma = \widetilde{\mathbf{D}}.\widetilde{\mathbf{M}}_0 \qquad \left|\widetilde{\mathbf{M}}_0\right| = \mathbf{const}$$

$$\widetilde{\mathbf{D}} = \sum_{n=odd} \alpha_n \widetilde{\mathbf{M}}_n, \ \widetilde{\mathbf{B}} = \sum_{n=even} \beta_n \widetilde{\mathbf{M}}_n$$

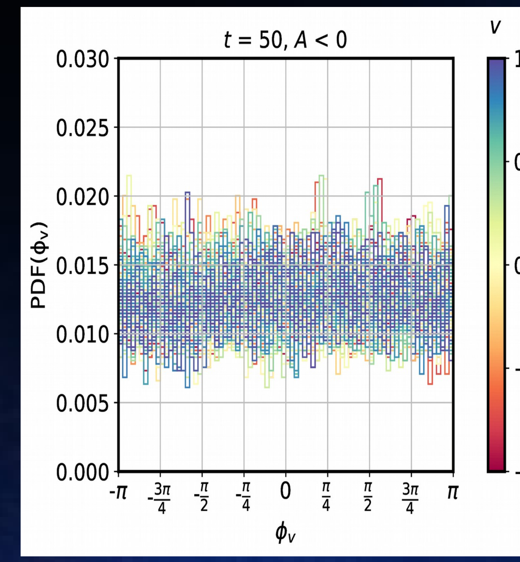


One can see the Energy is not exactly constant which has to do with our stationary approximation

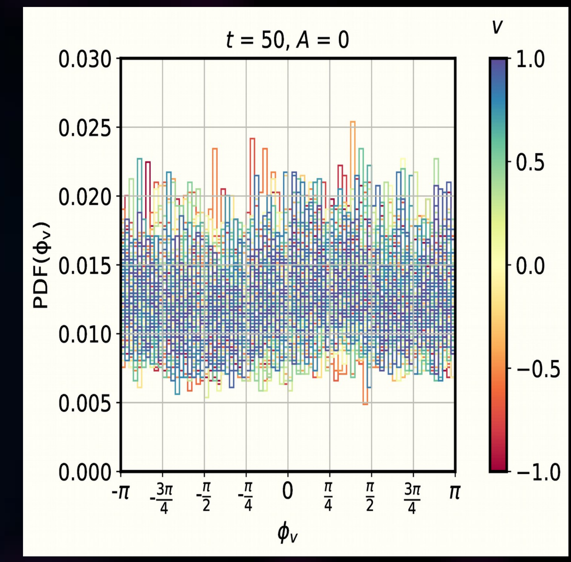


2) Phase Randomization :

- The phase relationship between the transverse components of the polarization vector in the $e^1 - e^2$ plane behaves like a uniform random distribution in space between [-π, π] at late times [9]
- This is true for any specific velocity mode and any value of the lepton asymmetry A.



This plot shows the approximate stationarity In time

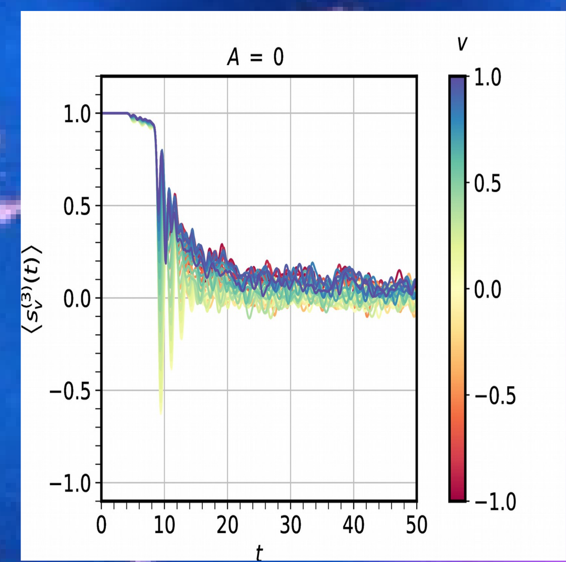


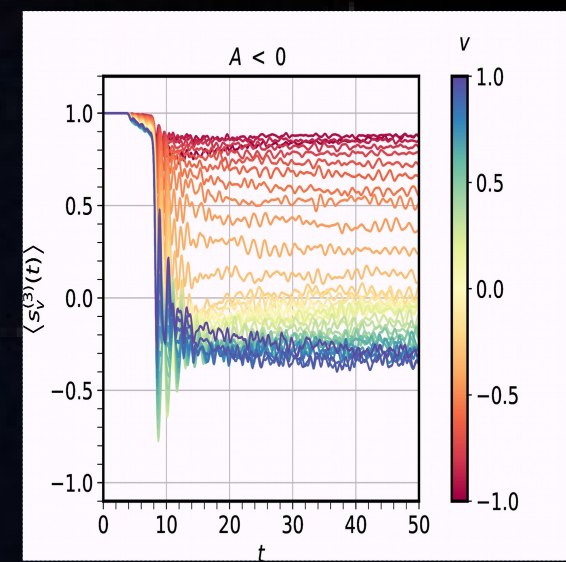
3) Depolarization in velocity space :

- The spatially avergeed (⟨....⟩) polarization vectors exhibit complete (partial) decoherence for zero (non zero) lepton asymmetry at late times. [6, 7]
- For partial decoherence the vanishing range of velocity modes loosely depends on the occurrence of the sign-fip of the e^3 component of the corotating Hamiltonian. The condition for the sign flip for a specific v **:** [9]

$$\Big(\alpha(t_{ini})A + vB(t_{ini})\Big)\Big(\alpha(t_{fin})A + vB(t_{fin})\Big) < 0 \qquad A = \int_{-1}^{1} \left\langle P_v^{(3)} \right\rangle\Big|_{t=0} dv \qquad \left\langle \mathbf{M}_1^{(3)} \right\rangle = B(t)$$

- α(t) is the component of $\langle H_v^3 \rangle$ parallel to $\langle M_0^3 \rangle$ in the corotating frame.
- This kinematic decoherence stems from randomization of the transverse components of the polarization vectors.



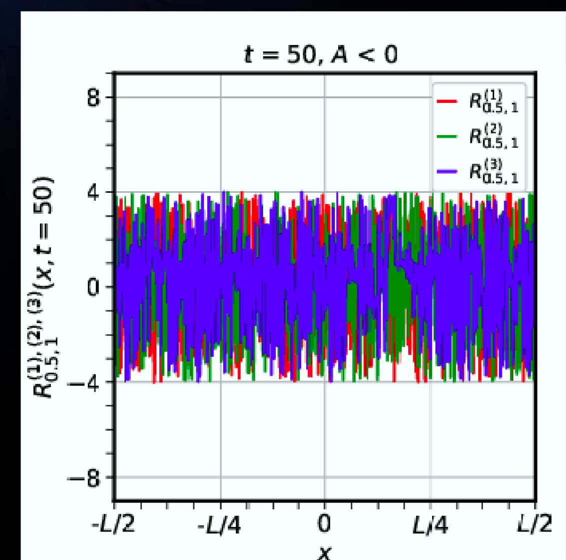


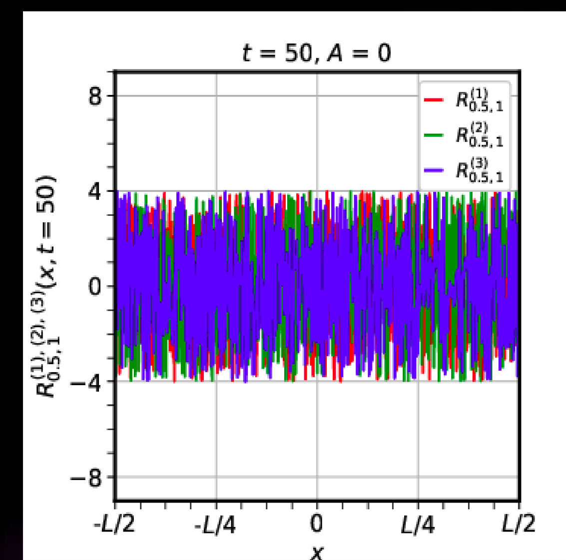
4) Non-separable solution in x & v :

- The stationary solution of the late time EOM is non-separable in x & v implying a non-collective behaviour [8] for FFC at late time.
- This can be checked numerically through a qaauntity defined as :

$$R^i_{v_1,v_2}(x) = \frac{P^i_{v_1}(x)}{P^i_{v_2}(x)}\Big|_{t=50} \qquad i = 1,2,3$$

- Separable solution in x & v in the stationary limit will imply no spatial dependence for the above quantity . But the numerical simulation shows a large variation in space for the above quantity implying a non-separable solution in x & v. This is true for any velocity pair with any value of A at late time





[1] PhysRevD.84.053013 (2011)
[2] JCAP 03, 042 (2016)
[3] JCAP 02, 019 (2017)
[4] Phys. Rev.D 74, 105010 (2006)
[5] Phys. Rev. D 101,043009 (2020)
[6] Phys. Rev. D 75, 083002 (2007)
[7] Phys. Rev. D 76, 125018 (2007)
[8] PhysRevD.78.125015
[9] arXiv: 2005.00459