Loss of flavor coherence in a dense neutrino gas

Joshua D. Martin

3/17/2023

LA-UR-23-22543

Neutrino flavor evolution

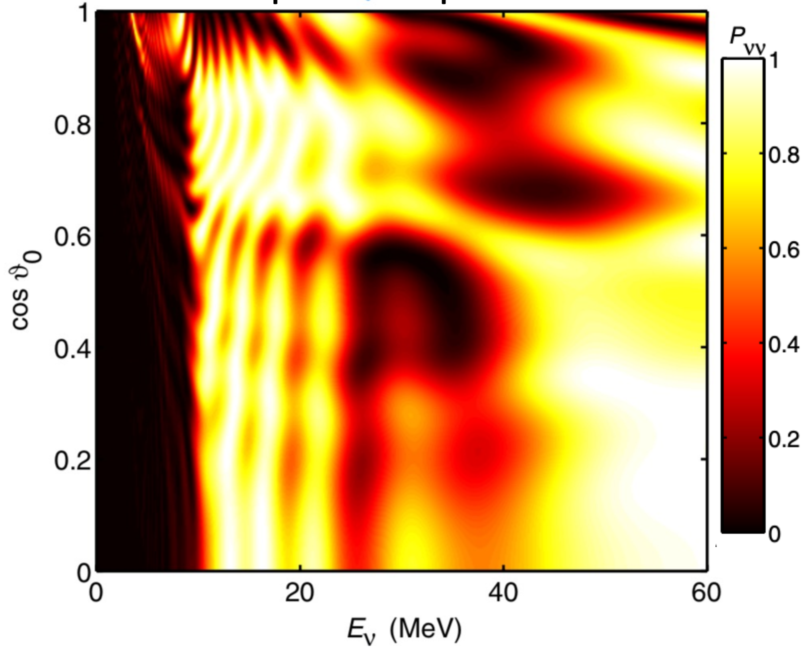
- In the MF approximation a rich set of phenomena is observed.
  - Collective oscillations
  - Spectral splits/swaps
    - Predictable in the spectrum
  - Extremely rapid flavor oscillations
    - Leads to average flavor scrambling/equipartition?
- Recent work in few neutrino many-body problem reveals substantial MB entanglement.

Patwardhan, Cervia, Balantekin *Phys.Rev.D* 100 (2019) 8, 083001

Illa, Savage arXiv:2210.08656

$$\mu \to 0$$

Spectral Split



H. Duan, G. M. Fuller, J. Carlson, and Y.-Z. Qian. *Phys. Rev.*, D74:105014, 2006.

Neutrino many body problem

- Two flavor approximation
- Need to retain ~2^N amplitudes for N neutrinos for quantum many body (MB) evolution
- Only need 3N real numbers for N polarization vectors in the mean-field (MF)
- If MF works, lets do that!
  - No entanglement

$$\omega_i \approx \mathcal{O}(10)\ \mathrm{km}^{-1}$$

$$H = \sum_i \boxed{\frac{\omega_i}{2}\mathbf{B}\cdot\boldsymbol{\sigma}_i}$$

Vacuum Oscillations

$$+$$

$$\frac{\mu}{2N}\sum_{i<j}(1-\vec{v}_i\cdot\vec{v}_j)\boxed{\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j}$$

Flavor Exchange

$$\boxed{100 < \frac{\mu(t)}{\omega_0} < 0}$$

$$\mathrm{U.C.} \implies \vec{v}_i = 0$$

$$\mathrm{R.C.} \implies \vec{v}_i \neq 0$$

Y. Pehlivan, A. B. Balantekin, Toshitaka Kajino, and Takashi Yoshida *Phys. Rev. D* 84, 065008 (2011).

Conserved quantities

$$H_{\mathrm{vac}} = \sum_i \frac{\omega_i}{2} \mathbf{B} \cdot \boldsymbol{\sigma}_i$$

$$H_{\nu\nu} = \frac{\mu}{2N} \sum_{i<j} (1 - \vec{v}_i \cdot \vec{v}_j) \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j$$

- The uniform coupling case is integrable. There are as many conserved charges as there are dimensions of the Hilbert space.

$$\mathbf{J} = \frac{1}{2} \sum_i \boldsymbol{\sigma}_i$$

$$[H_{\mathrm{vac}}, \mathbf{B} \cdot \mathbf{J}] = 0$$

$$[H_{\nu\nu}, J_\alpha] = 0 \qquad [H_{\nu\nu}, J^2] = 0$$

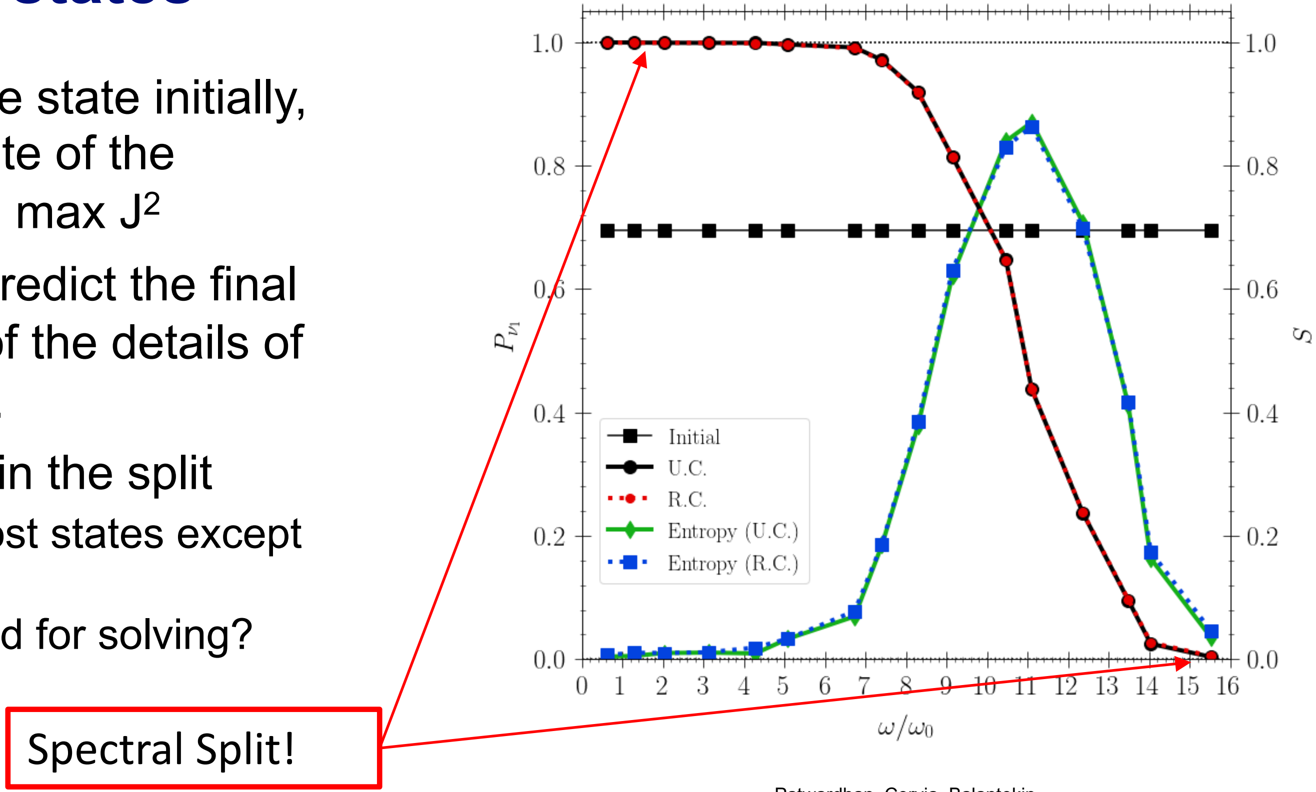
$$[H_{\mathrm{vac}} + H_{\nu\nu}, \mathbf{B} \cdot \mathbf{J}] = 0$$

$$\left[H_{\mathrm{vac}} + H_{\nu\nu}^{(\mathrm{U.C.})}, R_m\right] = 0$$

Initially all equal states

- If all spins in the same state initially, this is an extreme state of the Hamiltonian – lives in max J^2
- If adiabatic, we can predict the final state independently of the details of the 2-body couplings.
- Entropy is only large in the split
  - Does MF work for most states except those near the split?
  - Hybrid MB/MF method for solving?

$$|\Psi_i\rangle = |\nu_e\rangle^{\otimes N}$$



Patwardhan, Cervia, Balantekin
Phys. Rev. D 104, 123035 (2021)

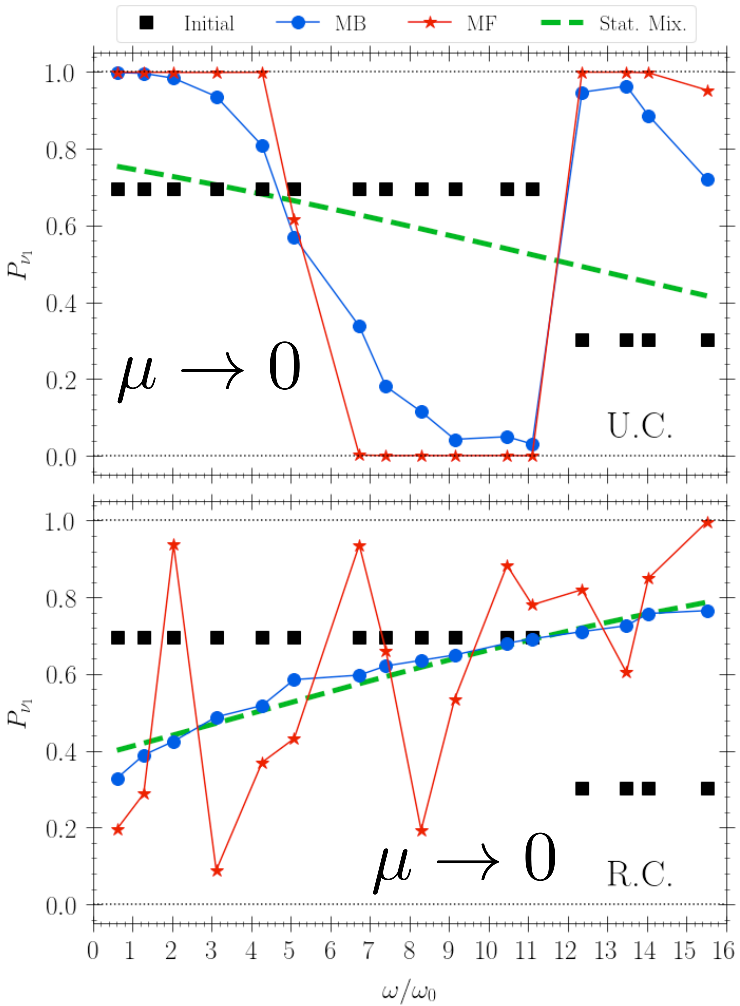
JDM, A. Roggero, H. Duan, J. Carlson
arXiv:2301.07049

Mixed flavor initial state

- The detailed evolution of more general states is sensitive to the choice of 2-body couplings for both formalisms
- Uniform 2-body couplings still show spectral split

Patwardhan, Cervia, Balantekin
Phys. Rev. D 104, 123035 (2021)

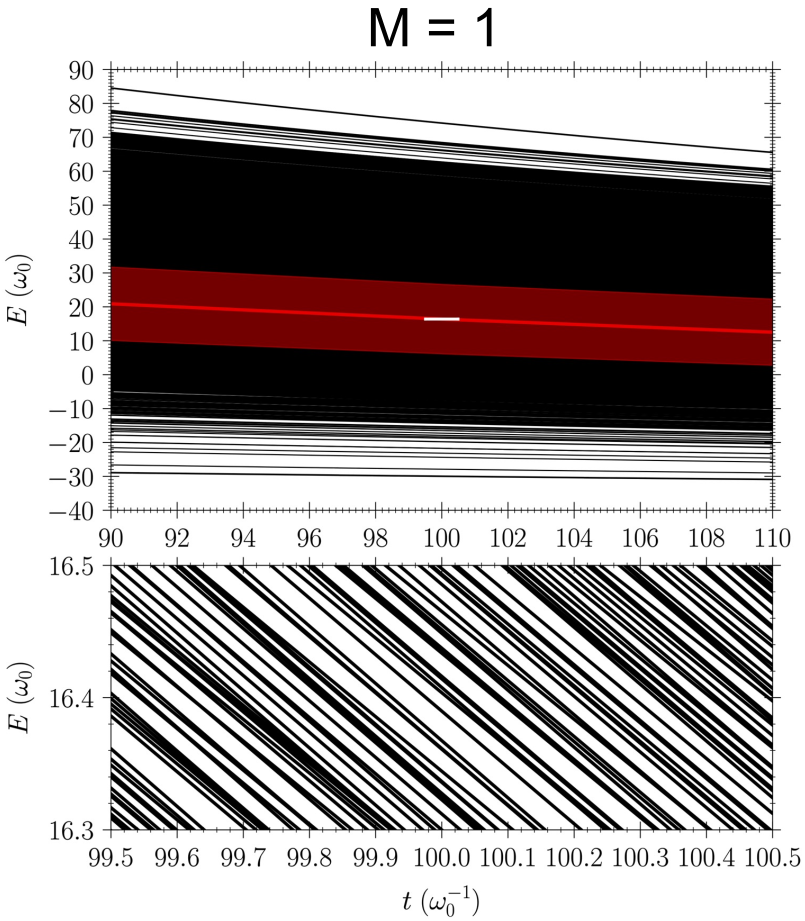
- Random couplings show poor agreement between MB and MF.



JDM, A. Roggero, H. Duan, J. Carlson
arXiv:2301.07049

Distribution in the spectrum

- J_z is conserved, so each m subspace evolves independently.
- Initial state has overlap with lots of intermediate energy states
- States evolve in time – subsequently lots of avoided level crossings.
- Results in state having support on many more energy states than the initial state.
- Unless symmetry protected, trace reduced subsystems will likely display decoherence

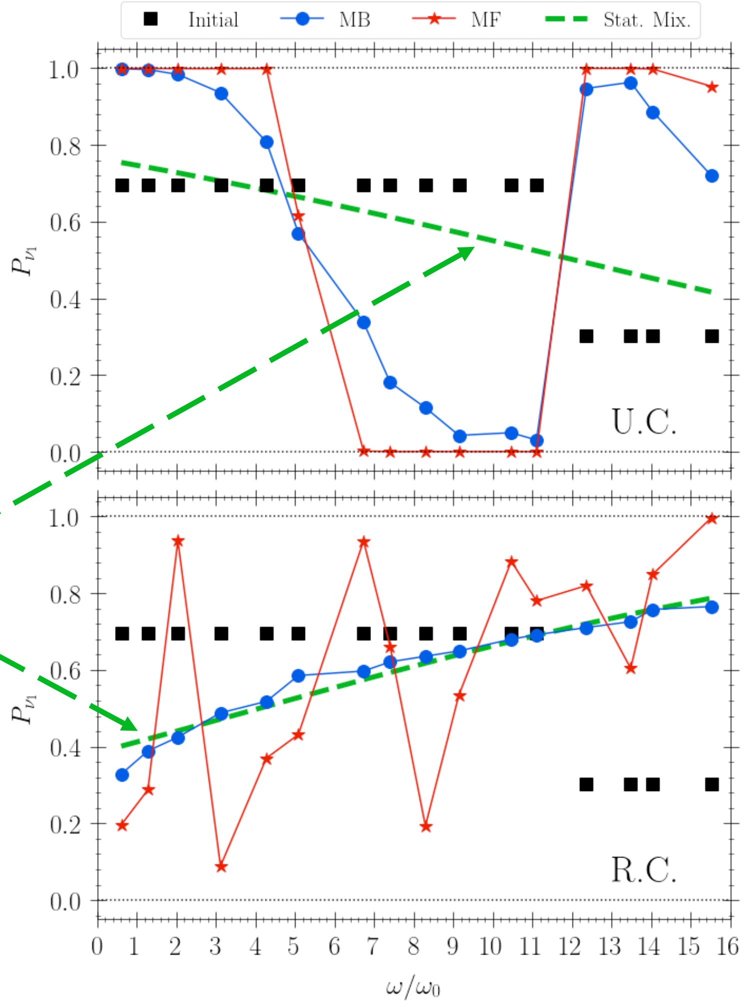


JDM, A. Roggero, H. Duan, J. Carlson
arXiv:2301.07049

Mixed flavor initial state

- R.C.: Entanglement ends up in many-spin partitions of the system.
  - Few body subsystems look like statistical mixtures.
- Invites treatment as a classical statistical mixture with some temperature β
- Stat. Mixture gives better agreement than MF
  - Obtaining this requires solving the MB system

$$\mathcal{P}_{\nu_1} \propto e^{-\beta(\omega-\mu)}$$



JDM, A. Roggero, H. Duan, J. Carlson
arXiv:2301.07049

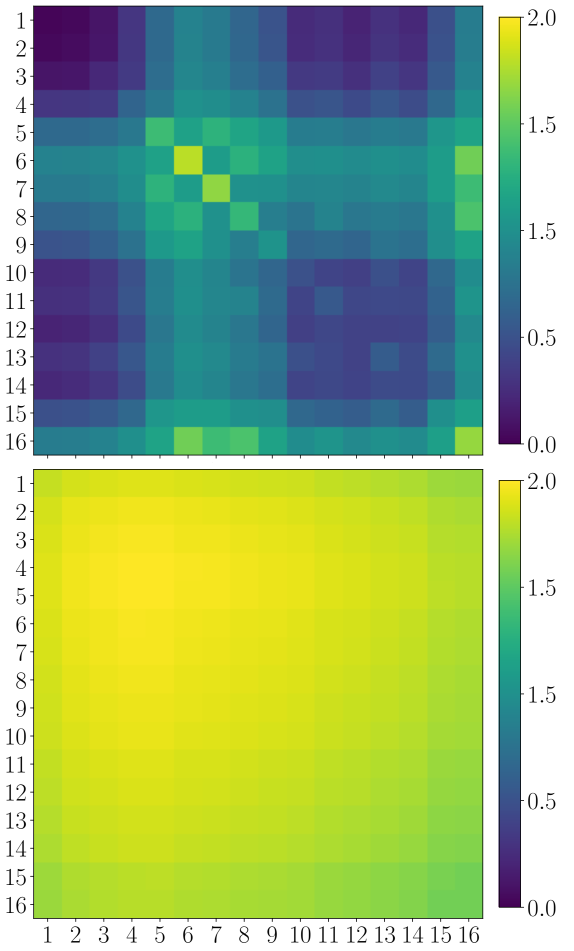
Two body entanglement

- Symmetry protects against development of significant entanglement for the uniform coupling case.
  - Entropy largest in the spectral split as seen by Patwardhan, Cervia, & Balantekin
- Nearly maximal entanglement in both one- and two-body RDMs

$$\text{U.C.} \implies \vec{v}_i = 0$$

$$\text{R.C.} \implies \vec{v}_i \neq 0$$

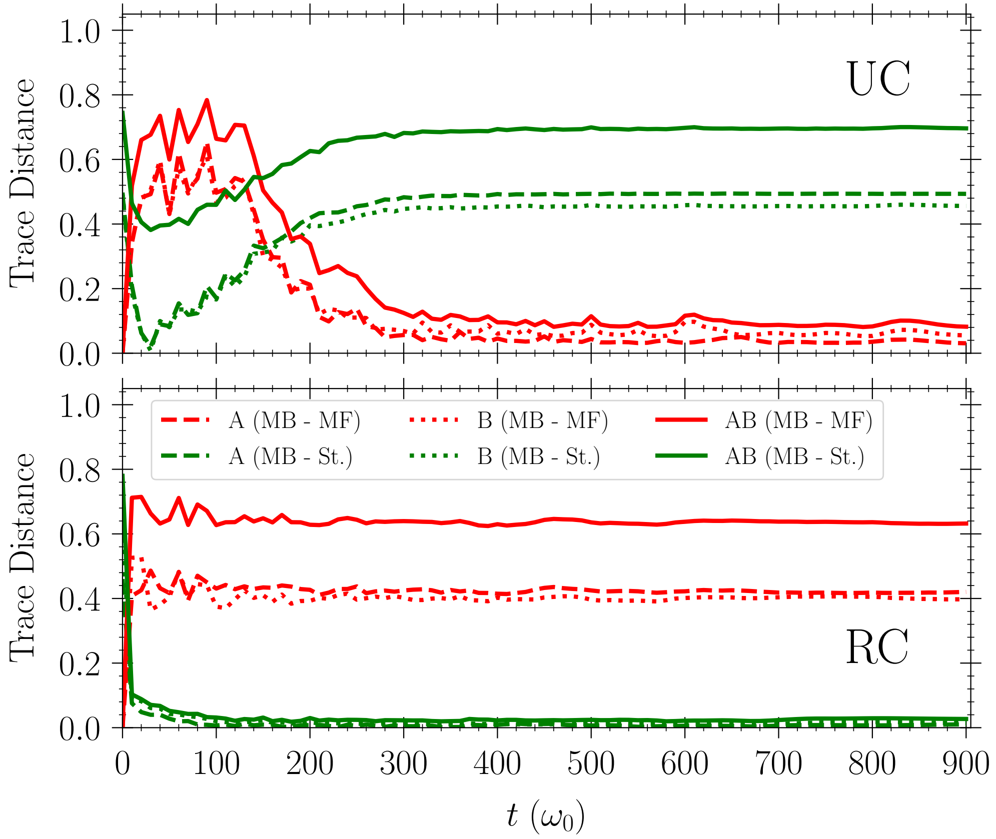
$$S_{ij} = -\text{Tr}\left[\rho_{ij} \log_2\left(\rho_{ij}\right)\right]$$



Loss of Coherence

- Trace distance characterizes how distinguishable two quantum states (RDM's ρ,ρ') are.
- A = neutrino 12
- B = neutrino 13

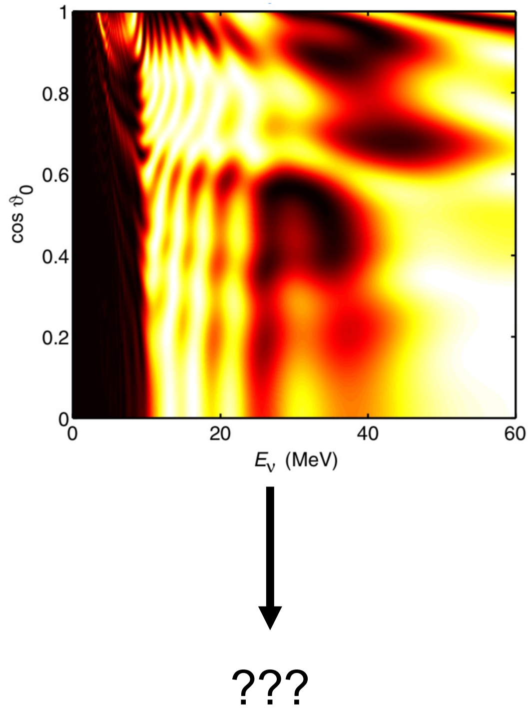
$$T(\rho, \rho') = \frac{1}{2}\mathrm{Tr}\left[\sqrt{(\rho - \rho')^\dagger (\rho - \rho')}\right]$$



JDM, A. Roggero, H. Duan, J. Carlson
arXiv:2301.07049

Some next thoughts

- Is it possible to predict stat. params. without doing MB calculation?
- We probably can do upwards of 30 flavor-spins on HPC platforms. Can we find how these decohered one-body states depend on Hamiltonian parameters?
- What can we learn from quantum computing?



Thanks!

- Collaborators:
  - Joe Carlson, Huaiyu Duan, Alessandro Roggero, Duff Neill
- You!

U.S. DEPARTMENT OF ENERGY | Office of Science

Los Alamos NATIONAL LABORATORY EST. 1943