# "Once-in-a-lifetime encounter" (OILE) models for neutrino media: A path from coherent mean-field oscillations to quantum decoherence


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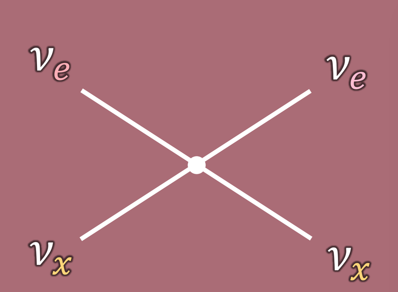
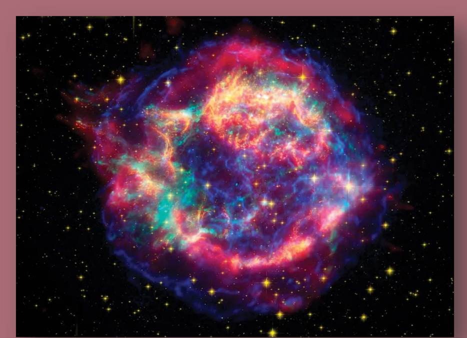
## Neutrinos in supernovae & more

A core-collapse supernova releases $10^{58}$ neutrinos in *seconds*. In such **extreme, neutrino-dense astrophysical environments**, neutrinos interact with each other and exchange their **flavor**. (This also occurs during collisions of neutron stars and in the early universe.)

To get a complete picture of these interesting environments, we have to understand how the neutrinos interact and exchange flavor.



We study collective neutrino oscillations in order to understand...

- Supernova explosions
- The origin of the universe's atoms (r-process nucleosynthesis)
- Many-body quantum phenomena

## Once-in-a-lifetime encounters

An open question, currently under debate:
*Do neutrinos get entangled with each other as they interact, and how does this affect them?*

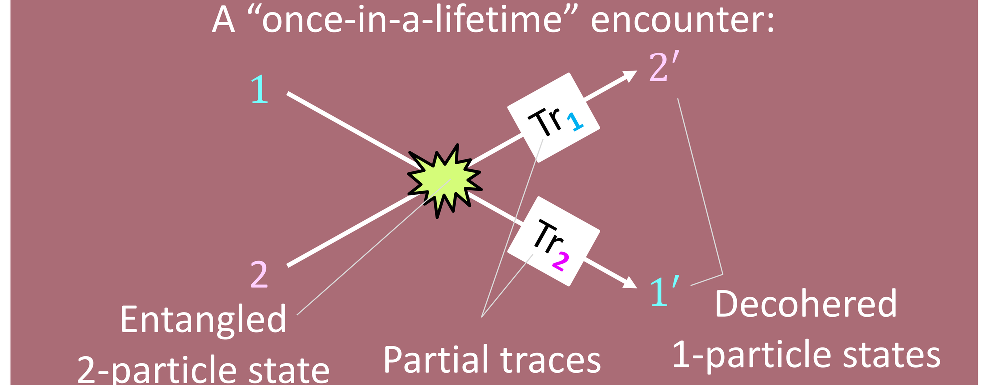
Different approaches to collective neutrino oscillations:

| Mean-field | OILE models | Many-body models |
|---|---|---|
| None | Some (see below) | All |

(Amount of entanglement)

In real neutrino-dense environments, neutrinos are point-like particles (small wave packets). They interact often, but any pair collide at most once in their lifetimes. Inspired by this, OILE models keep track of 1-particle states as they collide, get entangled, and decohere.

A "once-in-a-lifetime" encounter:



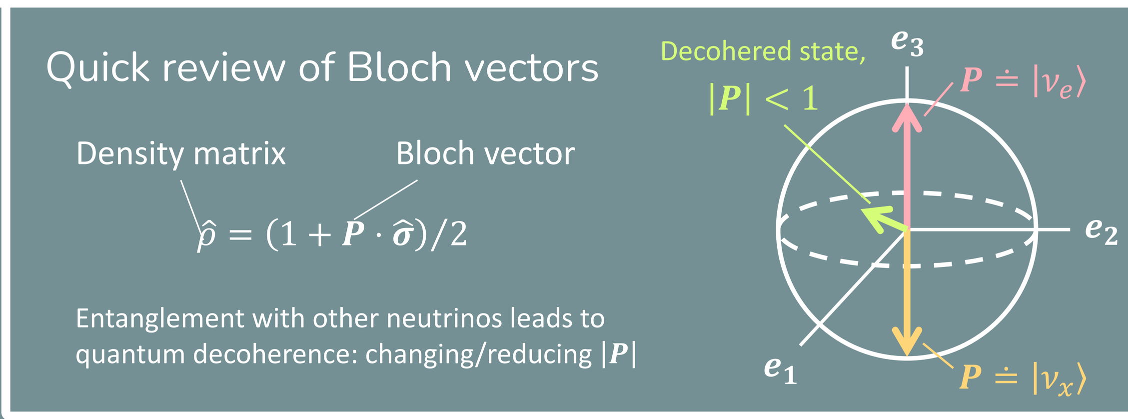

$$\hat\rho_1' = \mathrm{Tr}_2\left[\hat U^{\rm int}(\hat\rho_1\otimes\hat\rho_2)(\hat U^{\rm int})^\dagger\right]$$

## Numerical experiments with OILE models in simple situations

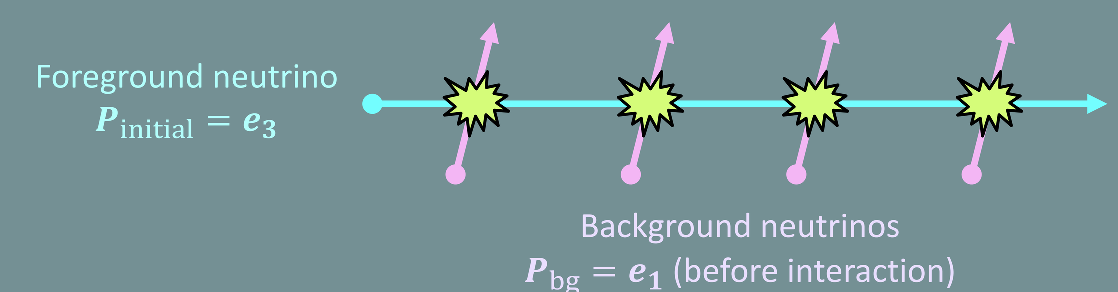
Neutrino-neutrino interactions:

- Neutrinos have two possible flavor states, labeled "e" and "x", and exchange flavor according to:
- The 2-neutrino interaction Hamiltonian: $\hat H_{ij}^{\rm int} = \mu(1-\vec v_i\cdot\vec v_j)\begin{pmatrix}1&&&\\&&1&\\&1&&\\&&&1\end{pmatrix}$ (rows/columns: ee, ex, xe, xx)
- Interaction strength (inverse timescale): $\mu\sim G_F/V_{\rm wavepacket}$
- Time-evolution operator for an interaction: $\hat U_{ij}^{\rm int} = \exp[-i\,\mu t^{\rm int}(\cdots)]$
- "**Impact parameter**": $\gamma\equiv\mu t^{\rm int}$ — $t^{\rm int}$: Interaction duration

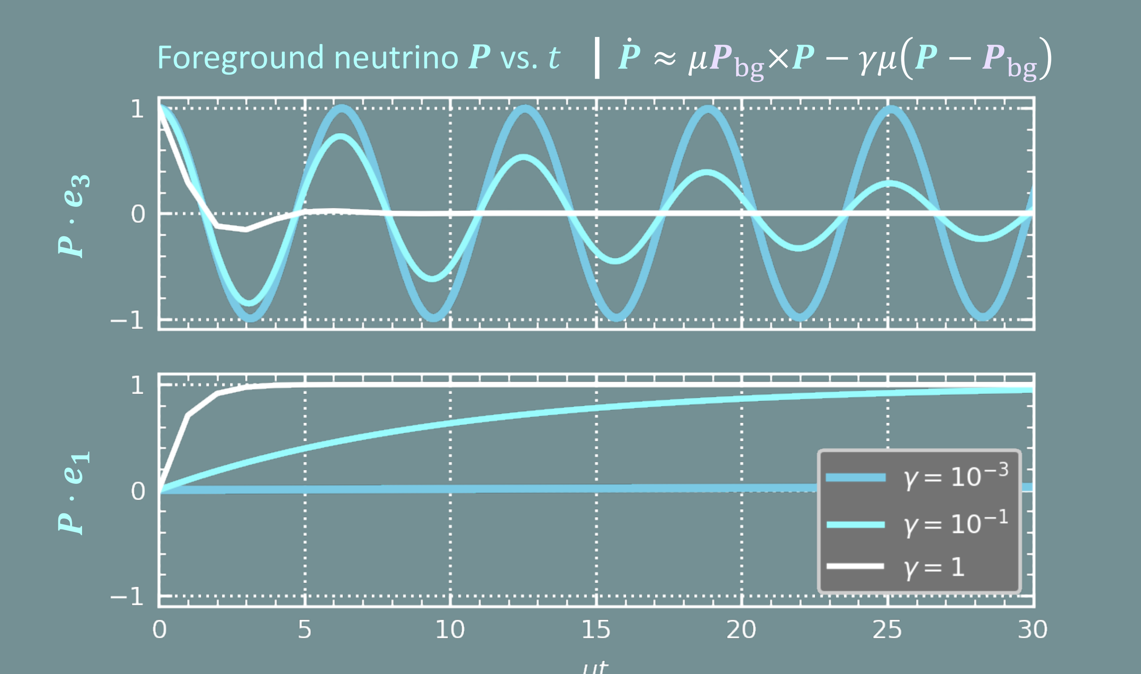
### Quick review of Bloch vectors




### Simple situation 1: Foreground neutrino in a uniform neutrino background




In this first simple model, a foreground neutrino interacts with different background neutrinos in succession. The background neutrinos all begin in the same initial state. The evolution of the foreground neutrino over time is shown on the right (in terms of its Bloch vector, $\boldsymbol P$).

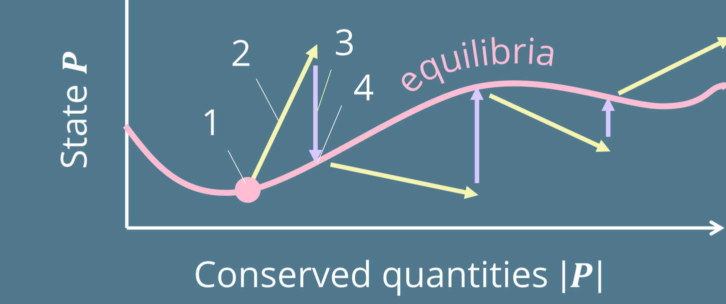



$\gamma=0$ → Large $\gamma$

Mean-field limit: coherent oscillation (From very many, very weak interactions) — Decoherence from entanglement ($\boldsymbol P\to\boldsymbol P_{\rm bg}$)

## Miscidynamics: Paths along equilibria

Decoherence from entanglement can be viewed as a series of small "kicks" to the system that push it away from mean-field equilibrium.

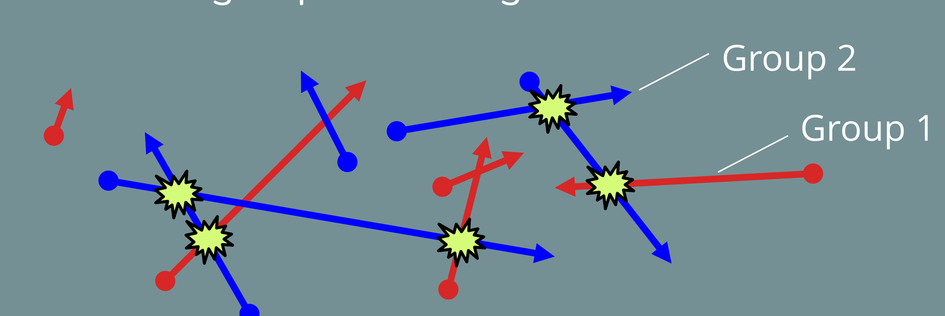



Miscidynamics — How to predict the path along equilibria:

1. Start in an equilibrium, parameterized by $|\boldsymbol P|$ (conserved in the mean-field limit).
2. Imagine a small "kick" that changes $|\boldsymbol P|$.
3. Find the new equilibrium with the new $|\boldsymbol P|$.
4. Repeat steps 1 to 3.

Miscidynamics separates slow time scales (decoherence from entanglement) from fast ones (equilibration). The fast time scales are too short to simulate with brute force, but separation of time scales brings the inclusion of neutrinos in astrophysical simulations within reach.

### Simple situation 2: Two-group neutrino gas

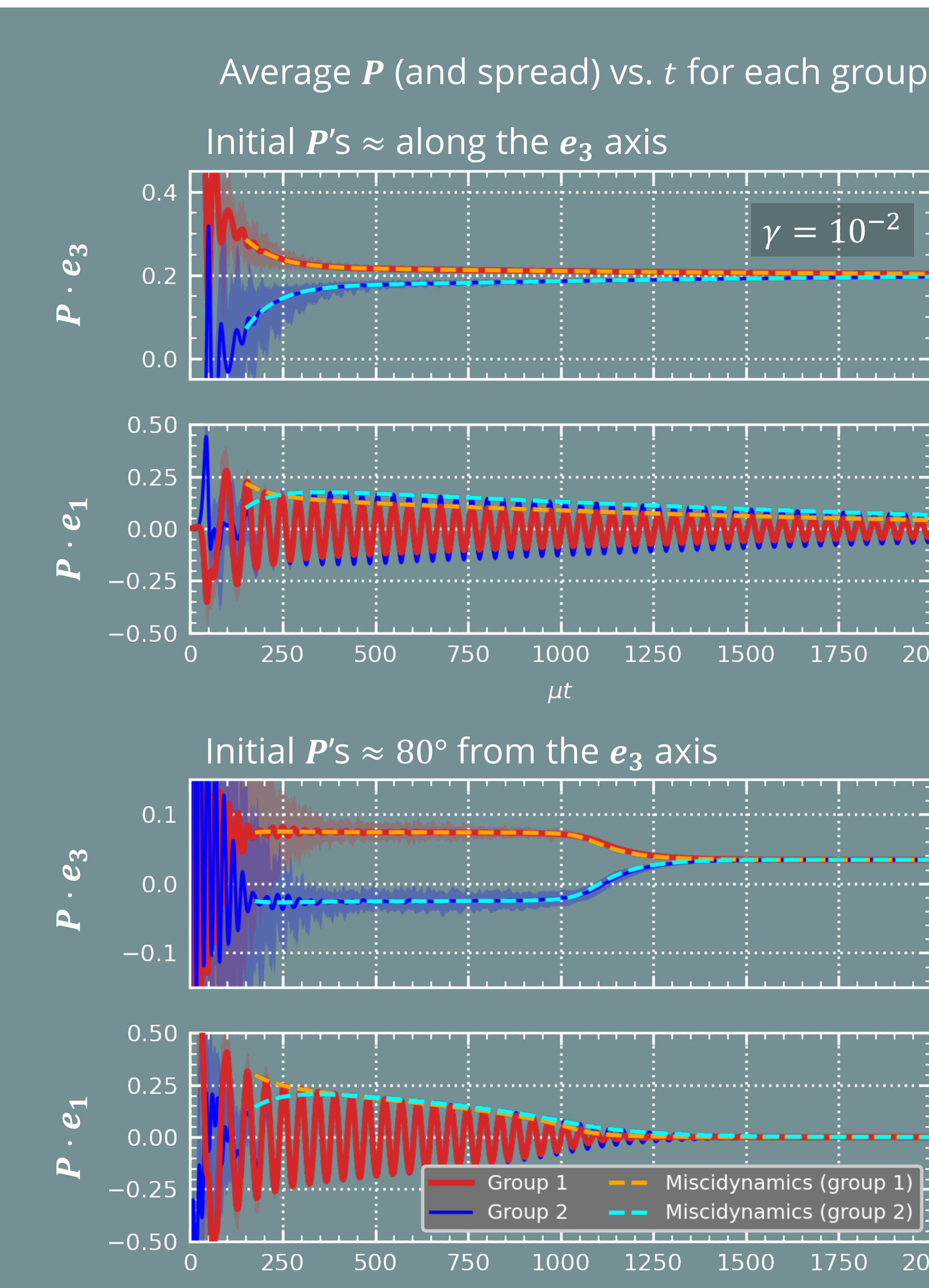



In this model, all neutrinos interact and are kept track of (but otherwise, things are similar to the model above). All neutrinos interact with each other in different random pairs. The "gas" is made up of two groups of neutrinos, differentiated by their initial states and intrinsic (vacuum) oscillation frequencies. $\gamma=10^{-2}$ for all cases shown.

The evolution of the average state of each group of neutrinos is shown on the right (the spread within a group is lightly shaded). *Eventually*, all neutrinos get entangled and decohere ($\boldsymbol P\to\approx\boldsymbol 0$). But, what happens along the way?

| $\gamma\mu t=0$ | $\gamma\mu t\gtrsim1$ | $\gamma\mu t\to\infty$ |
|---|---|---|
| Mean-field limit | Path along equilibria (Miscidynamics) | Maximum decoherence from entanglement |

After the initial period of equilibration, entanglement drives the gas along a path of different mean-field equilibria (when $\gamma\mu t\gtrsim1$). The final asymptotic state agrees with predictions of many-body models. The path taken along the way is described by the **theory of miscidynamics** (dashed curves).




## Conclusions

- OILE models provide an intuitive picture of the way entanglement builds up in successive neutrino-neutrino collisions
  - In the simple cases shown, the "impact parameter" $\gamma$ describes the amount of entanglement that builds up in each collision
- In OILE models, this entanglement drives a neutrino gas along a path of mean-field equilibria, and the path is predicted by miscidynamics
  - Miscidynamics may allow inclusion of neutrino dynamics in simulations of supernovae & more

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### References


- *Once-in-a-lifetime encounter models for neutrino media: From coherent oscillations to flavor equilibration*. Kost, Johns, Duan (2024). arXiv:2402.05022
- *Once-in-a-lifetime encounter models for neutrino media II: Quasi-steady states and miscidynamic flavor evolution*. Kost, Johns, Duan (2025). arXiv:2508.14331
- *Subgrid modeling of neutrino oscillations in astrophysics*. Johns (2025). arXiv:2401.15247