Neutrino Spin Oscillations Catalyzed by the Fast Flavor Instability

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Abstract

Recent studies have shown that neutrinos in an anisotropic background can present coherent spin oscillations which depend directly on the absolute mass scale and Majorana phases. Neutrinos usually spend too little time in resonance to produce important effects in high energy astrophysical phenomena; however, we demonstrate that a fast flavor instability can substantially increase their characteristic energy, potentially making them relevant. We find several locations where the conditions for a fast flavor instability and for coherent spin oscillations are met simultaneously in the data from a neutron star merger simulation. We run a particle-in-cell simulation of the fast flavor instability at these locations and show the energy of spin oscillations along the direction of maximal neutrino flux is raised by 4 or more orders of magnitude. However, the oscillations are still too transient for all but the lowest energy neutrinos to experience significant spin-flip effects. We conclude nonlinear resonance is likely necessary for spin flip to have an important influence on supernova or merger dynamics.

Theory

Coherent Spin Oscillations

- Including Spin degrees of freedom in a derivation of the neutrino Quantum Kinetic Equations leads to a non-diagonal Hamiltonian in the helicity basis, expressible as

$$H = \begin{pmatrix} H_{RR} & H_{LR} \\ H_{LR}^{\dagger} & H_{LL} \end{pmatrix} \quad (1)$$

where each H_{ij} is a 3×3 matrix in flavor space (1).

- The off-diagonal component H_{LR} drives coherent helicity oscillations in anisotropic media, and is given by

$$H_{LR} = -\frac{1}{\vec{p}}\left(\Sigma_R^{+} m^{\dagger} - m^{\dagger}\Sigma_L^{-}\right) \quad (2)$$

where m is the mass matrix, $\vec{p}$ is the test neutrino momentum and $\Sigma_{L,R}^{\pm}$ are components of a chiral 4-potential that depend on the components of neutrino flux transverse to $\vec{p}$ (1).

- H_{LR} is linear in m, thus dependent on the absolute mass scale and Majorana phase (1).
- Spin oscillations only occur if the left and right handed diagonal elements of H of corresponding flavor are equal, leading to a resonance condition (5):

$$H_{RR} = H_{LL} \quad (3)$$

- In order for the resonance condition to be satisfied for long enough that significant spin oscillations arise, the neutrino distribution must evolve adiabatically relative to the timescale of H_{LR}. This is quantified by an adiabaticity parameter γ:

$$\gamma = \left(\frac{2|H_{LR}|^2}{\nabla H_{RR}}\right) \quad (4)$$

- when $\gamma > 1$, the diagonal components vary slowly compared to the spin oscillations induced by H_{LR}, leading to robust spin oscillations (5).

Fast Flavor Instability

- Triggered when there are equal numbers of neutrinos and antineutrinos propagating along some direction (4), causing the Electron-Lepton Number (ELN) to cross 0.
- Causes rapid transformations in flavor that shift the direction of the neutrino flux.
- Can therefore increase $\Sigma_{L,R}^{\pm}$ and H_{LR} by increasing the flux components transverse to the direction of neutrino flow.

Critical Points in Neutron Star Merger

- For a fast flavor instability to influence spin oscillations, the resonance condition (Eq. 1) and the ELN crossing condition must both be satisfied at the same location so that the two effects occur simultaneously.
- To test whether this is feasible we analyzed data from Foucart et al.'s neutron star merger simulation (3), finding several regions where both conditions were met:

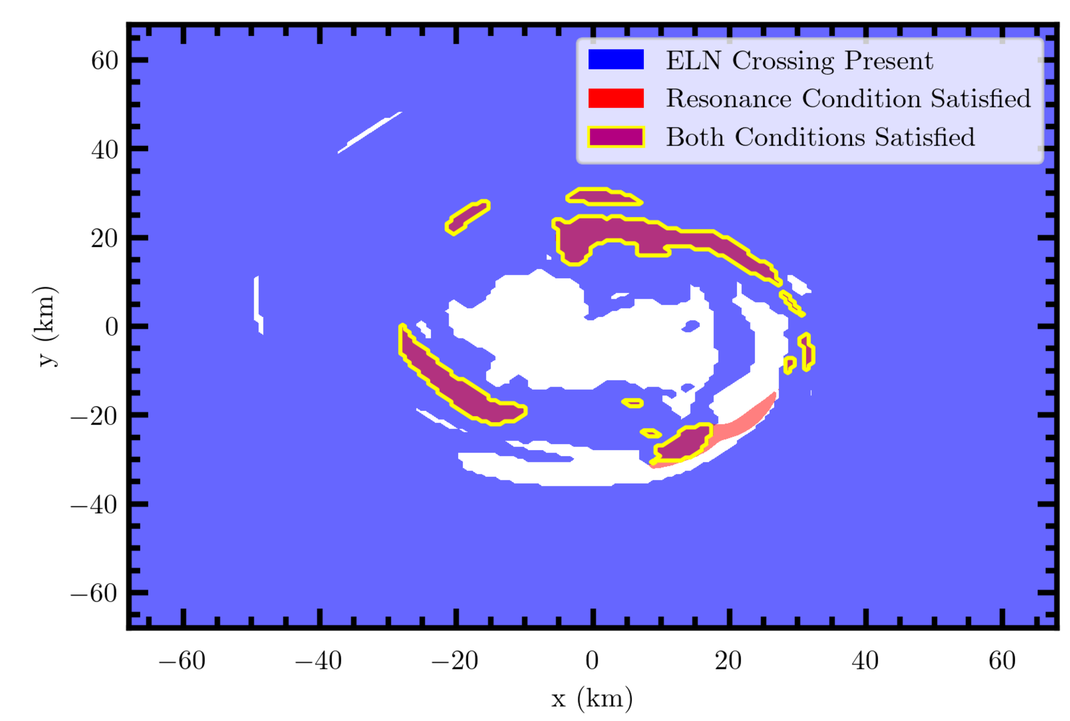

Fig. 1. Regions of interest plotted for a cross-section of a three dimensional neutron star merger simulation. Blue regions represent points where an ELN crossing is guaranteed along some direction, allowing for a fast flavor instability. Red regions are where the resonance condition for helicity oscillations is satisfied with some choice of basis. Outlined purple areas represent regions of interest where a fast flavor instability can magnify spin-flip effects.

- We simulated the fast flavor instability at several points within the regions of interest to see its effect on spin flip.
- Points with the highest initial value of the adiabaticity parameter (Eq. 4) along the direction perpendicular to the main neutrino flow were chosen in order to maximize the importance of the spin oscillations after the instability occurs. (A high value of γ in the transverse direction would result in a high γ in the principal flow direction after the instability causes the neutrino flux to shift.)

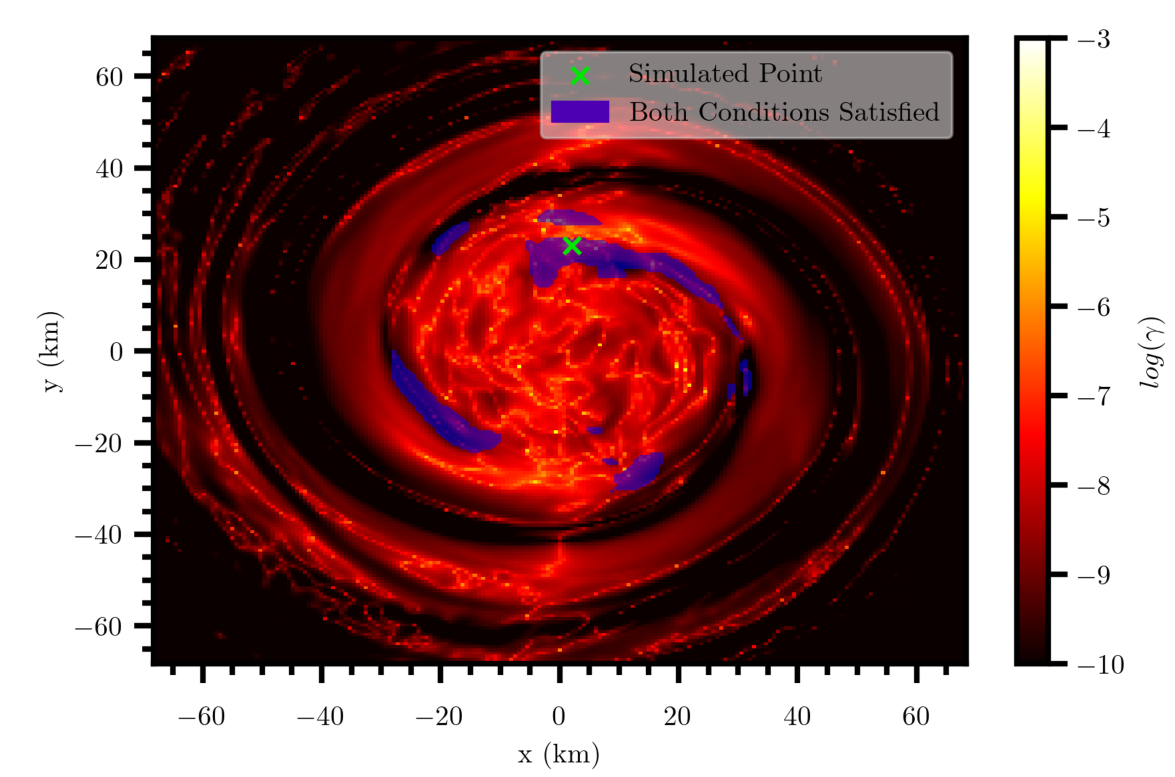

Fig. 2. Cross section of the merger simulation showing the values of the adiabaticity parameter. The basis is perpendicular to the direction of neutrino flow on a cross section of the merger simulation. The blue areas are regions of interest where the spin flip and fast flavor instability conditions are both satisfied. The green point is one we selected to simulate due to its high initial adiabaticity parameter.

Simulating the Fast Flavor Instability

- We ran a particle-in-cell simulation of the fast flavor instability designed by Richers et al. (4) using the neutrino and background matter configuration of the critical points as an initial condition.
- The instability increases the flux along directions transverse to the maximal neutrino flow, thus increasing H_{LR}:

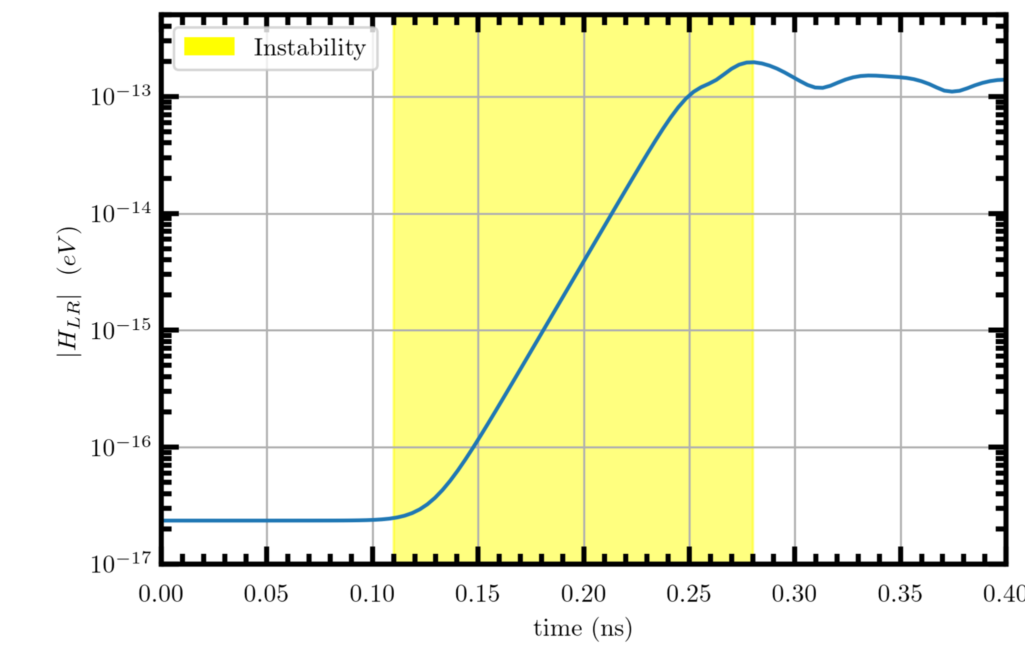

Fig. 3. The scalar magnitude of H_{LR} over time during a fast flavor instability simulation, with the momentum $\vec{p}$ along a direction near the maximal neutrino flow in the merger. The initial conditions were determined by the neutrino and background matter distribution at the critical point described in the previous section. The magnitude of H_{LR} was computed by projecting onto the Gell-Mann matrices and taking a squared sum. H_{LR} grows by 4 orders of magnitude during the simulation as the transverse components of neutrino flux are substantially increased by the instability.

- We see H_{LR} grow from 1.3×10^{-17} eV to 1.0×10^{-13} eV, thus substantially increasing γ.
- Nonetheless, even with this change the adiabaticity parameter is still too small to support important effects for neutrinos of typical energy 10MeV: $\gamma \sim 10^{-4}$ after the instability.
- Since H_{LR} is inversely proportional to $\vec{p}$, neutrinos of a lower energy would have a higher adiabaticity parameter and could still experience spin flip.
- After the instability neutrinos of energy 0.1MeV or lower could realistically experience spin oscillations, and recent results suggest that even if these oscillations occur at low energies they can then spread to higher energy neutrinos through nonlinear resonance (5).
- A full simulation including the spin-flip Hamiltonian terms would be required to observe this behavior.

Conclusions

The fast flavor instability presents the fascinating capacity to reorient the net neutrino flux away from the maximal direction of neutrino propagation. This allows the instability to substantially increase the energy of helicity oscillations in the direction most neutrinos are travelling by increasing the flux components transverse to that direction. While we observed that this effect did not make oscillations feasible for neutrinos of typical supernova energies, the instability did make adiabatic oscillations possible for low energy neutrinos, which could induce important effects through nonlinear resonance. In all our simulations the adiabaticity parameter increased significantly, so spin oscillations would be virtually impossible for neutrinos of any energy without being magnified by an effect like the fast flavor instability. A full simulation would be required to probe potential nonlinear effects with low energy neutrinos.

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