Non-Standard Interactions and Neutrino Oscillations in Core-Collapse Supernovae

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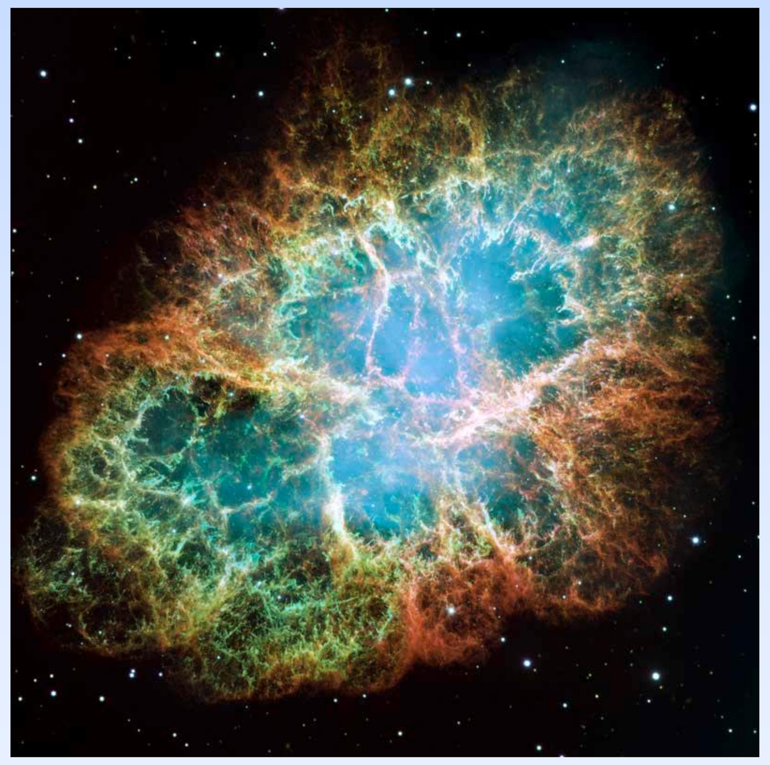
Neutrino Oscillations

- Neutrinos are very light (and hard to detect) fundamental particles (written as ν)
- Neutrinos come in three different flavors: $e,\ \mu,$ & τ. Flavor signifies the lepton which the neutrino interacts most with
- Over time, neutrinos can change flavor in a process known as neutrino oscillations
- A neutrino can only be observed to have one of the three flavors at a given time, but the quantum state of each flavor is unstable, leading to the flavor oscillation
- In a core-collapse supernova, enormous quantities of neutrinos are emitted from the core, and can be detected on Earth, presenting an ideal opportunity to study neutrino oscillations due to the high densities of matter and neutrinos in the supernova



- Neutrino oscillations can be described by the Schrodinger equation:

$$i\frac{dS}{dx} = HS$$

- S is a matrix representing the probabilities that a neutrino will have changed from one flavor to another at a specific distance from the core
- H is a matrix called the Hamiltonian, and it is made up of 3 components:

$$H = H_{vacuum} + H_{matter} + H_{\nu\nu}$$

- H_{vacuum} represents the instability of the flavor states. With no matter present, $H = H_{vacuum}$
- H_{matter} accounts for the effect of a neutrino's interactions with matter on its flavor
- $H_{\nu\nu}$ is the self-interaction Hamiltonian, accounting for interactions with the other neutrinos propagating through the supernova

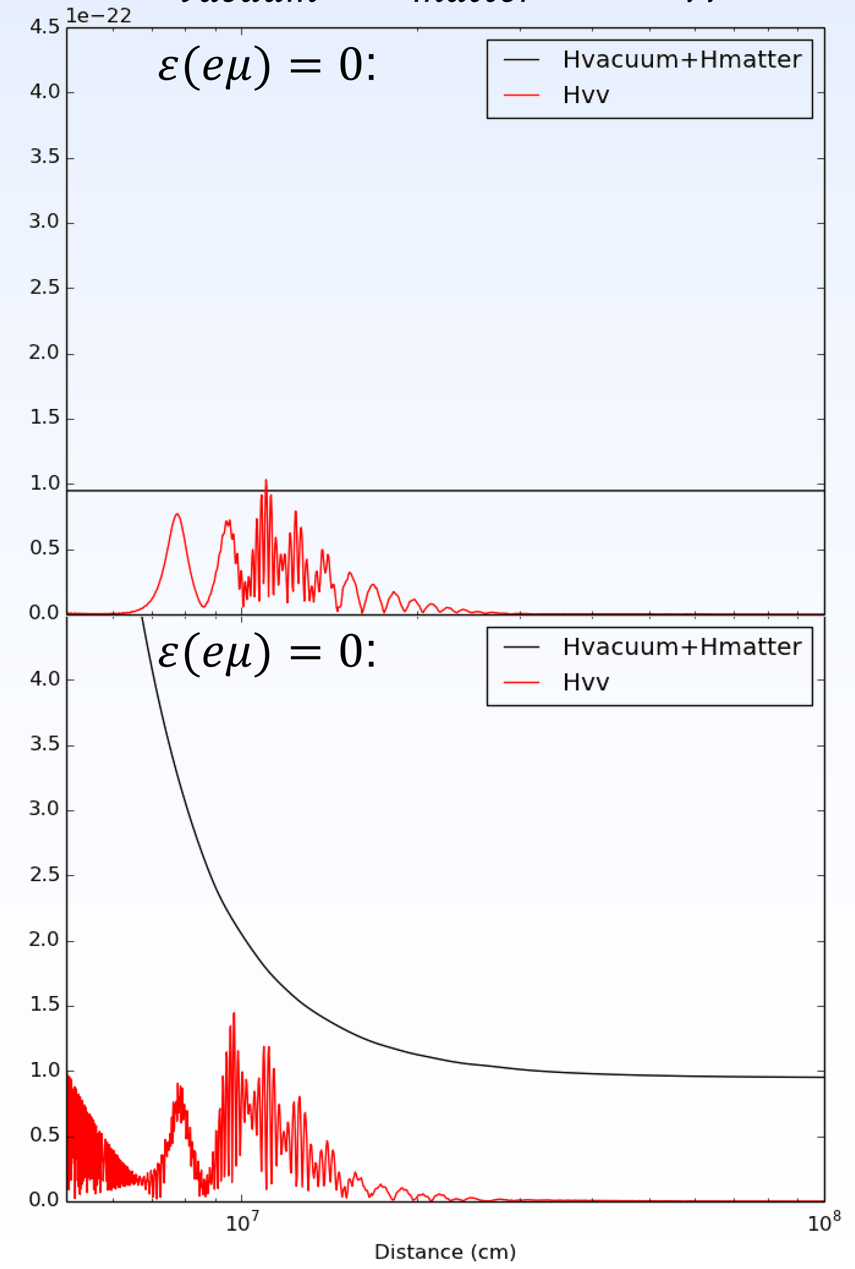
Non-Standard Interactions

- The standard model of particle physics presents a self-consistent description of the subatomic world
- However, there is evidence that the standard model is incomplete (i.e. dark matter, dark energy)
- Studying the effects of particle interactions outside standard model on neutrino oscillations could lead to detection of non-standard interactions (NSI) and give insight into the mysteries of the universe
- NSI with matter can be incorporated into the neutrino oscillation process as a matrix called ε
- The goal here is to identify the effects of NSI with matter on neutrino oscillations using 3 flavor neutrino oscillation simulation code Sqa
- Many different values for ε have been tested

Hamiltonian Evolution

- The probability of a neutrino changing from one flavor to another greatly increases when the component corresponding to those flavors in $H_{\nu\nu}$ grows bigger than that of $H_{vacuum} + H_{matter}$
- H_{vacuum} is constant with respect to distance, but is bigger at lower energies, so for some low energies, $H_{\nu\nu}$ never surpasses $H_{vacuum} + H_{matter}$
- The terms in H_{matter} corresponding to change in flavor are zero with no NSI, but increase with NSI

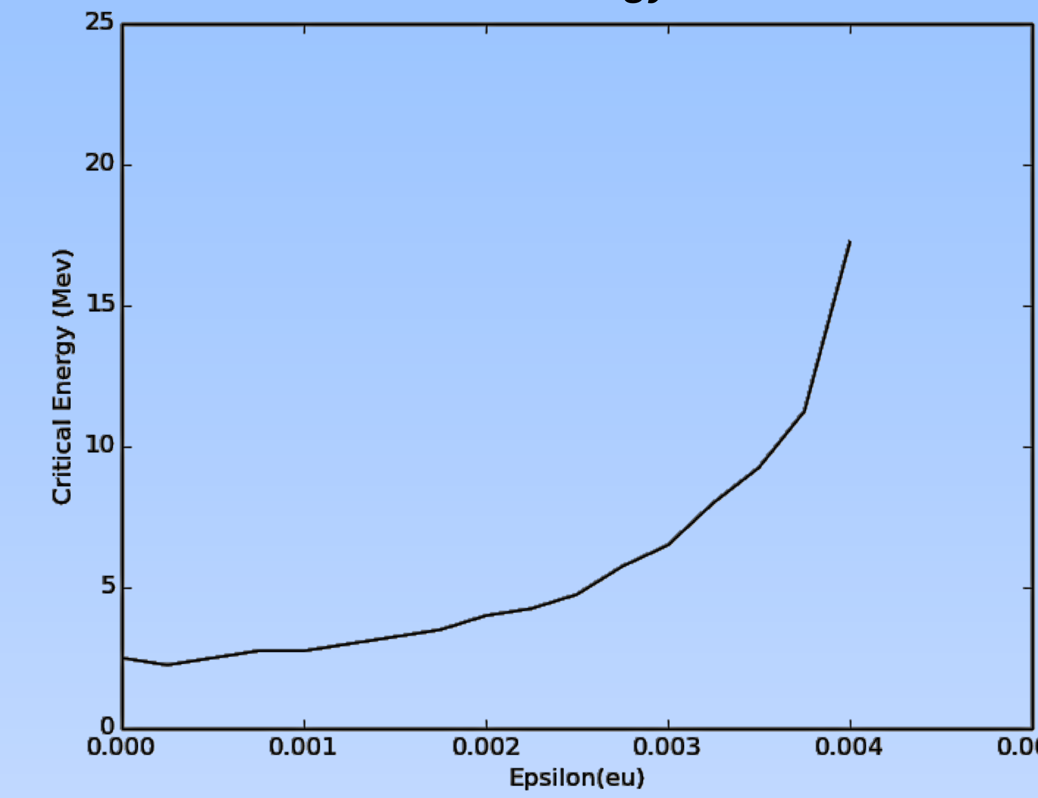
$e\mu$ Term of $H_{vacuum} + H_{matter}$ and $H_{\nu\nu}$ at 2.5 Mev



Critical Energies

- For each ε, the critical energy is the lowest energy at which $H_{\nu\nu}$ surpasses $H_{vacuum} + H_{matter}$

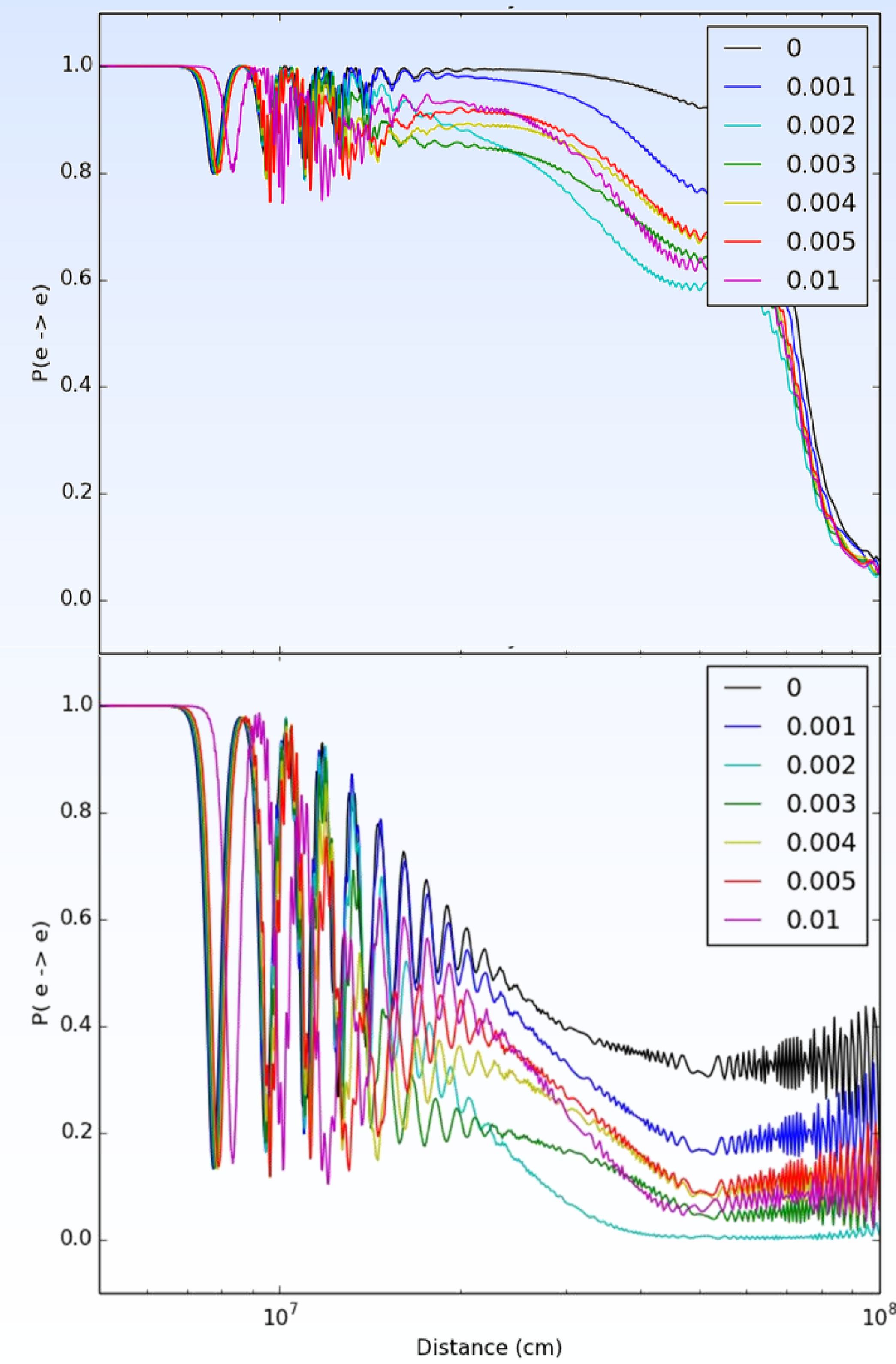
Critical Energy vs ε



Flavor Probabilities

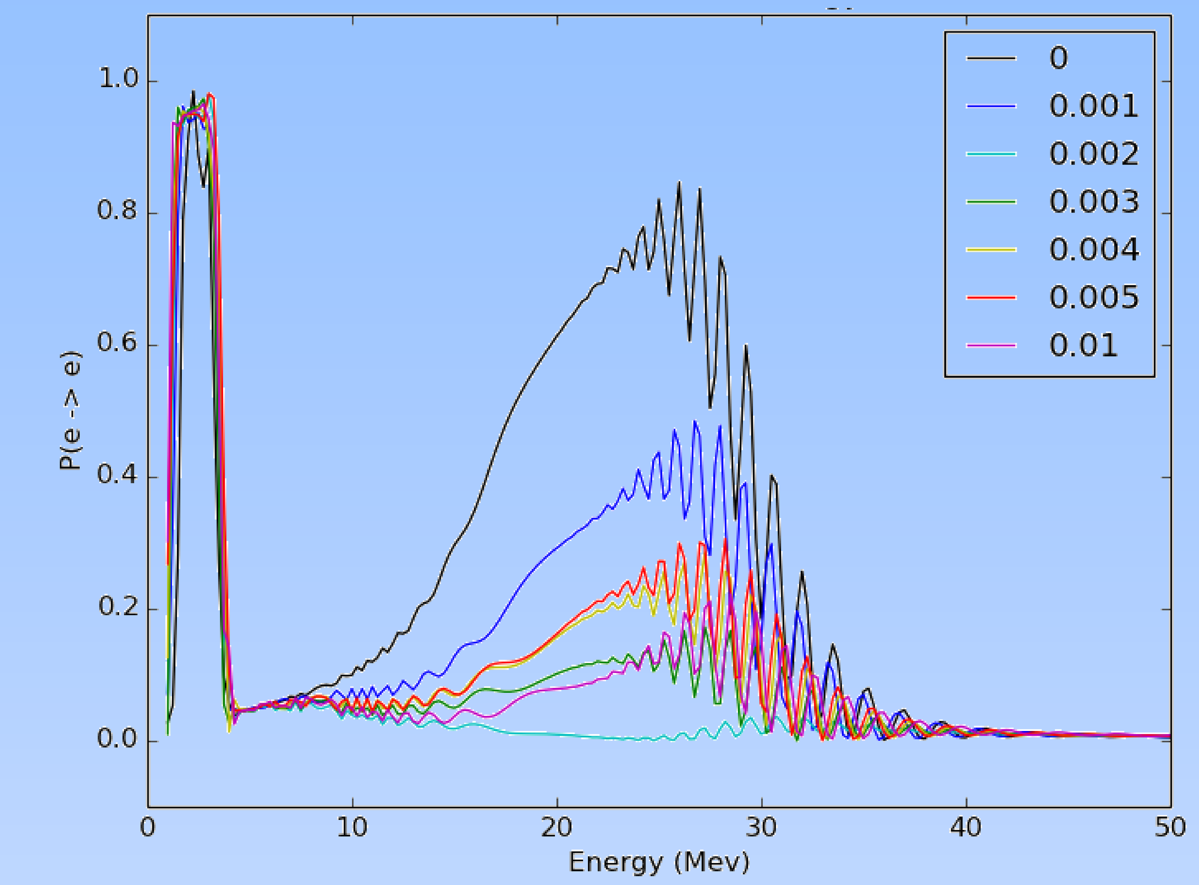
- Simulating neutrino oscillations in a supernova with different values of ε represent multiple possible strengths of NSI, and yield graphs that are similarly shaped but change with ε

$e \to e$ Probability vs Distance Over Multiple εs



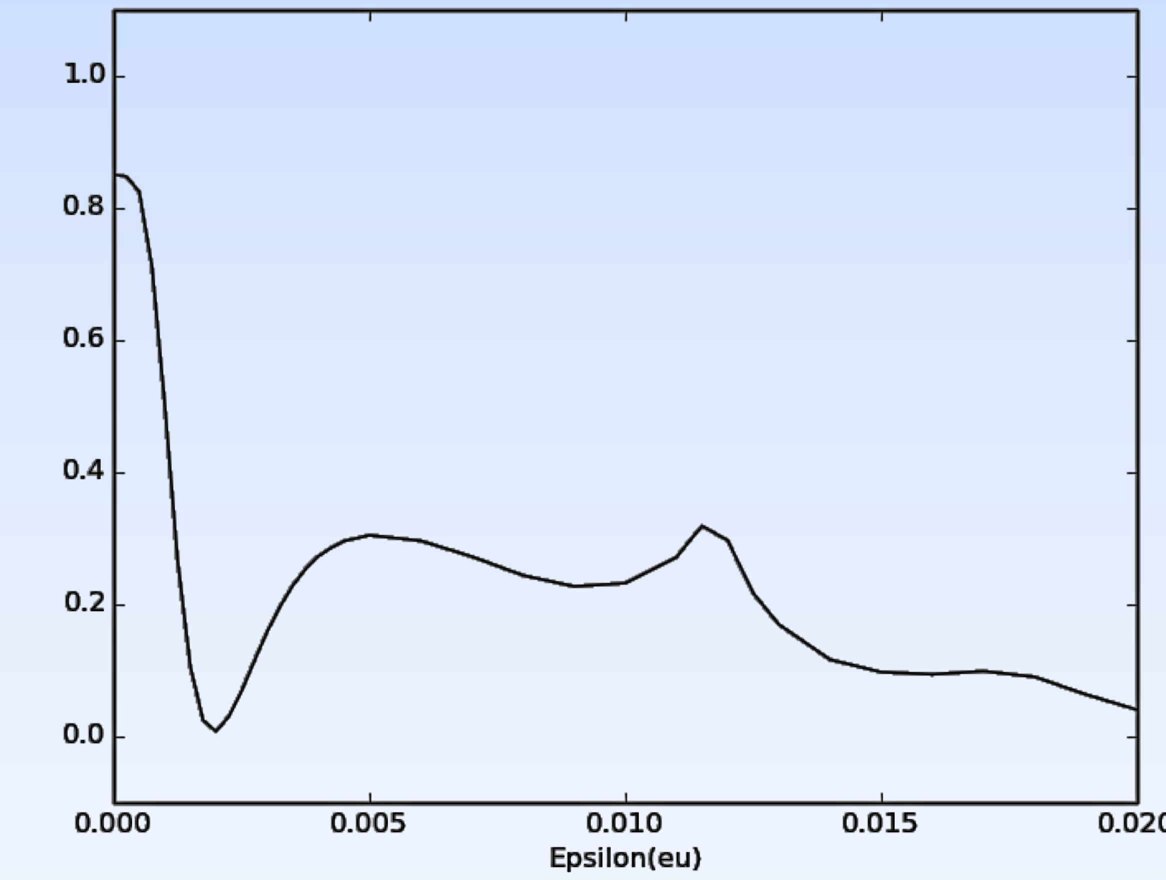
Final Probabilities

Final $e \to e$ Probability vs Energy Over Multiple εs



- In the graph above, the heights of the peaks near the middle of the energy spectrum do not correlate with the ε values

Peaks in Final Probability vs ε



- This lack of correlation is counterintuitive, but it is probably due to the fact that $H_{\nu\nu}$ is a non-linear term, so adding ε to H_{matter} has an effect on $H_{\nu\nu}$
- To further investigate these results, the next step is to modify Sqa to isolate the effects of NSI from the rest of the neutrino oscillation process

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Undergraduate Research in Computational Astrophysics