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

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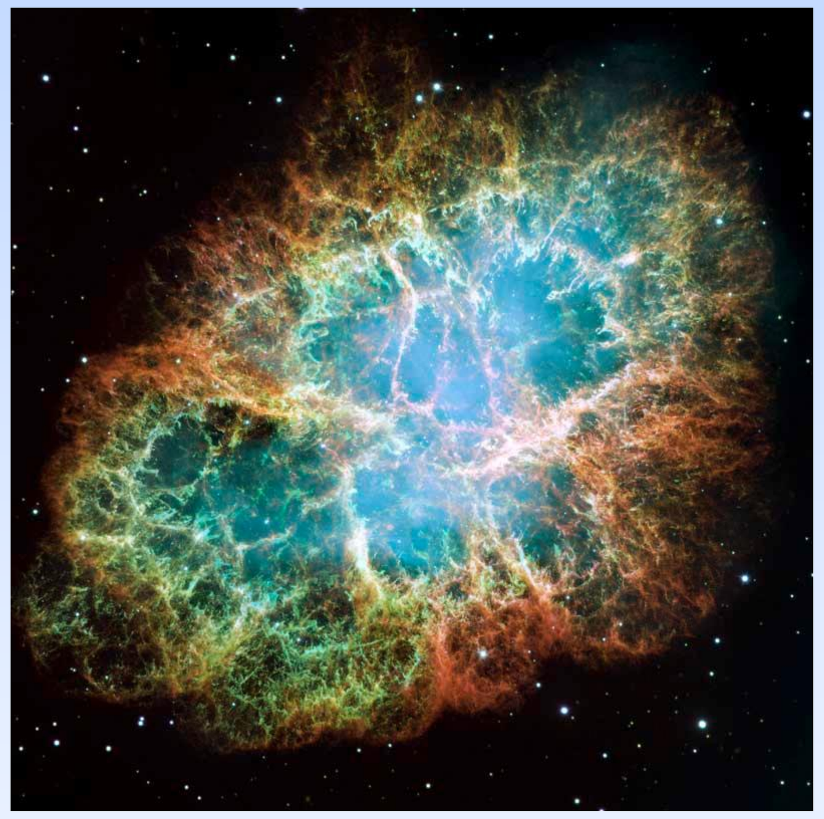
Neutrino Oscillations

- Neutrinos are very light (and hard to detect) fundamental particles (written as ν)
- Neutrinos come in three different flavors: e, μ, & 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 probability that a neutrino will have a given flavor can oscillate over time
- 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 at high densities



- 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

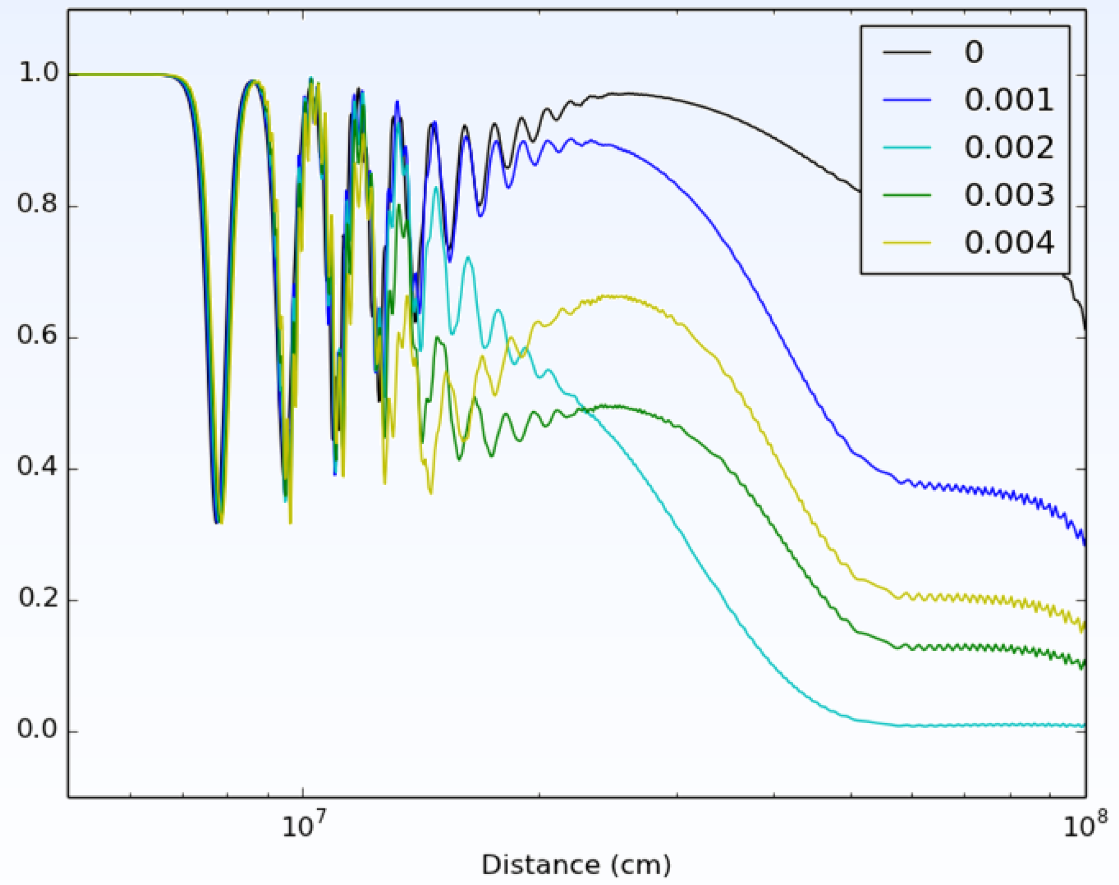
Non-Standard Interactions

- The standard model of particle physics presents a self-consistent description of the subatomic world
- However, there is evidence, such as dark matter, dark energy, and even gravity, that the standard model is incomplete
- Because we know so little about what lies beyond the standard model, it is entirely possible that there are non-standard interactions (NSI) between particles that could influence neutrino oscillations
- Studying the effects of NSI on neutrino oscillations could lead to detection of 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, added to H_{matter} in the Hamiltonian equation
- The goal here is to identify the effects of NSI with matter on neutrino oscillations using 3 flavor neutrino oscillation simulation code Sqa
- A range of values for ε were tested to determine exactly how the oscillations depend on ε

Flavor Probabilities

- The simulation tracks the probability that a neutrino of any one flavor will have changed to another flavor as the neutrino moves out from the core through a supernova density profile

$e \rightarrow e$ Probability vs Distance at 20 MeV for Multiple ε Values

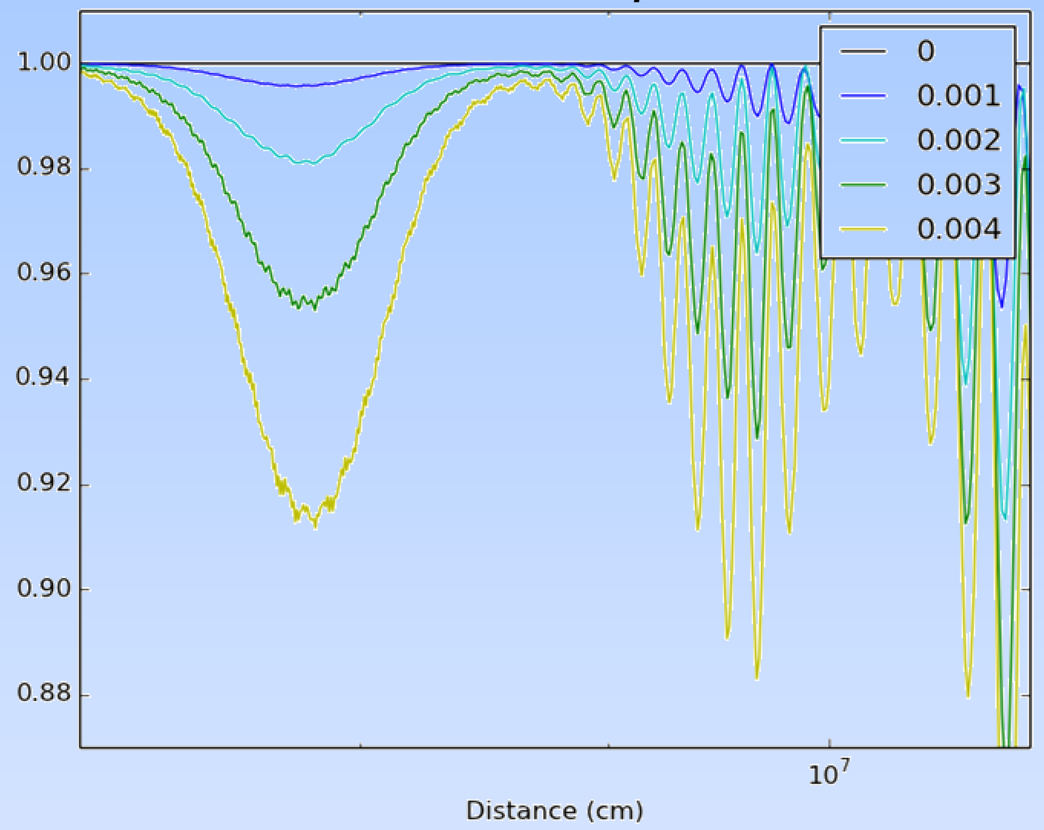


- The probability curves for different ε values are similarly shaped, especially early on, but more drastic differences are found at further distances

Early ε Dependence

- At distances close to the core, before significant self-interaction effects occur, the effects on the probabilities relate quadratically to ε
- This can be seen in the perturbation caused by ε on the no-NSI solution, found by factoring out the probability without NSI from the total probability

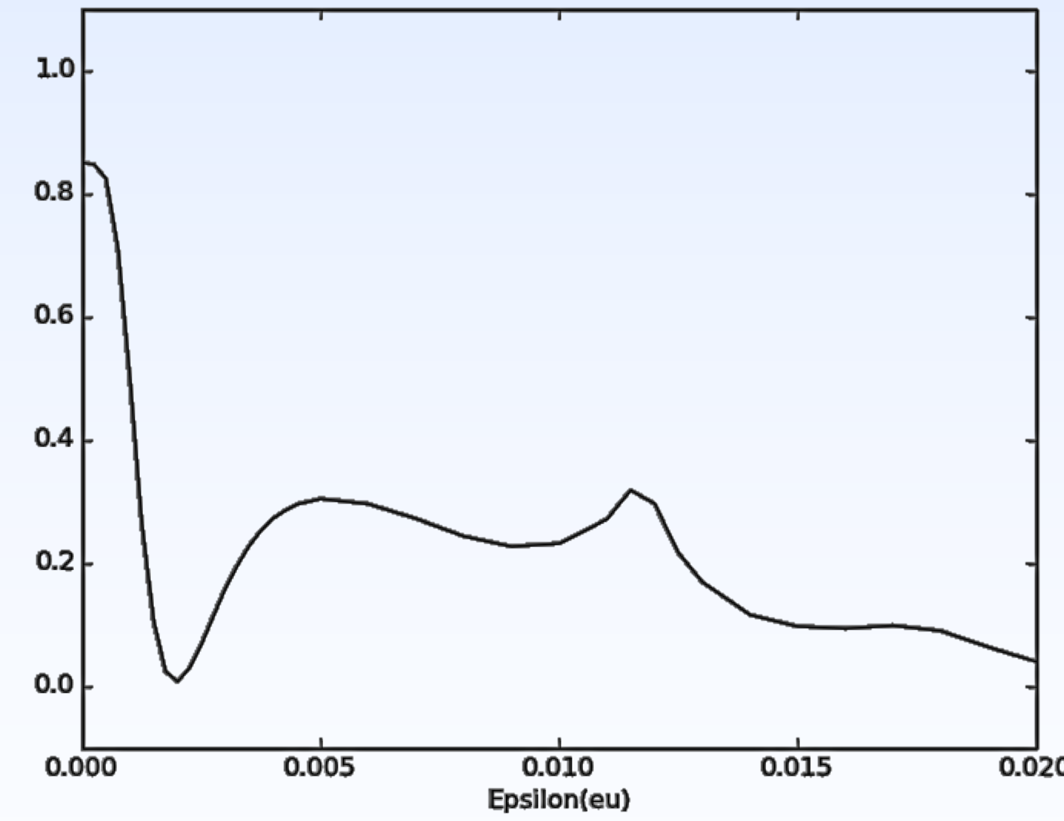
NSI Probability Perturbation vs Distance at 20 MeV for Multiple ε values



Nonlinearity

- At further distances, the perturbation from NSI no longer has a simple dependence on the value of ε

Final $e \rightarrow e$ Probability vs ε

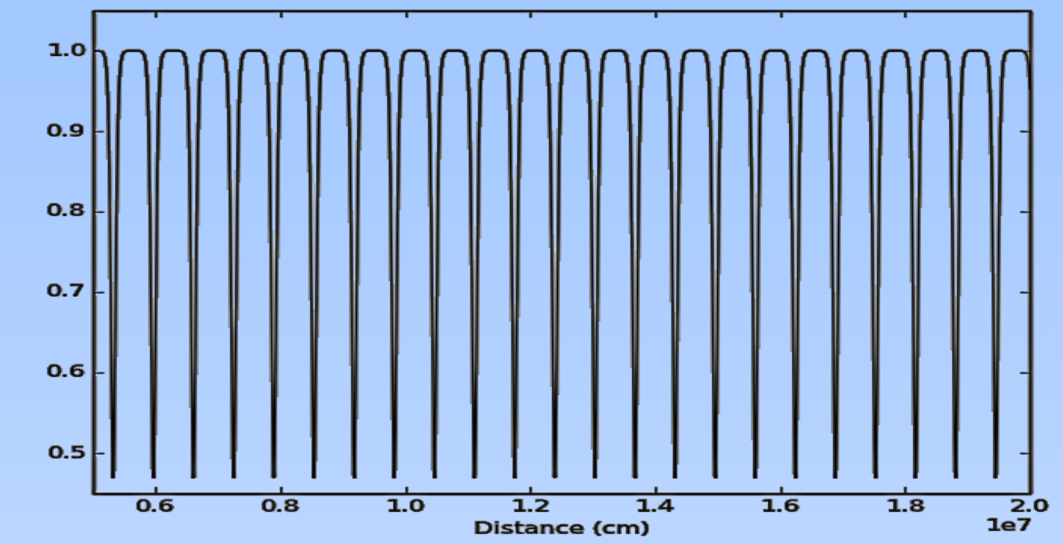


- This is because $H_{\nu\nu}$ depends on S, resulting in a nonlinear matrix differential equation
- As ε affects how S evolves, it also changes $H_{\nu\nu}$, which then leads to complicated effects on S
- Nonlinear matrix differential equations are very difficult to solve and can have strange behavior

Simplified Case

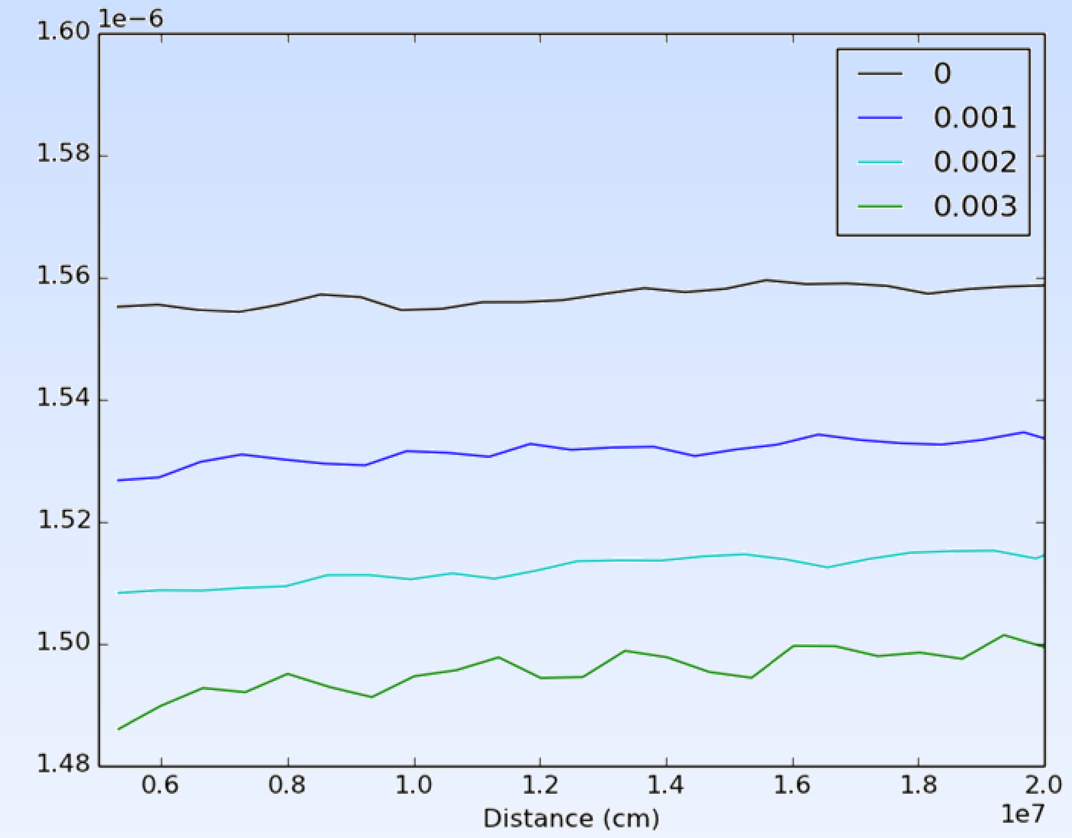
- As NSI can have significant effects on oscillations in the supernova context, the simulation was run at constant density and a single energy to study how the NSI effects interact with the nonlinearity

$e \rightarrow e$ Probability vs Distance at 20 MeV



- In this case, different ε values only affect the frequency of the drops in probability

Probability Oscillation Frequency vs Distance for Multiple ε Values



- Frequency appears to decrease with ε
- A general relation between the frequency and ε could be applied to the more complicated case of a supernova density profile with multiple energies
- This could lead to the detection of the strength of NSI and thereby a deeper understanding of the intricacies of the universe

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