Delayed Supernova Neutrinos from Neutrino-Dark Matter Scattering

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This paper compiles research on dark matter and neutrino scattering to produce bounds for a future experiment to test. Dark matter is a particle that has no known interactions. Assuming dark matter behaves like a fermion and interacts through the weak force, it is possible through interactions with neutrinos to find its mass and other useful information. To do so, highly energetic neutrinos are required. This paper focuses on highly energetic neutrino created through a supernova. This paper relates the dark matter mass, the mediator mass, and the dark matter and neutrino interaction to each other. Code was created to simulate the many unknowns in this interaction using supernova SN1987a as a baseline. Supernova neutrinos are energetic enough to potentially interact with dark matter and still have energy left to be detected. This makes supernova neutrinos very important for detecting the relatively slow and weakly interacting dark matter. Based on the analysis, the results of a future neutrino detection experiment on a supernova should be able to determine the properties of dark matter.

I. INTRODUCTION

The standard model correctly predicts many interactions in the universe, yet, there are still gaps in the knowledge that is out of its reach. This paper describes the relationship between two mysteries: neutrinos and dark matter. Dark matter is a substance whose only known property is that it interacts with normal mass through gravity. Nothing about dark matter can be described through the standard model. Another particle, the neutrino, does interact with other particles, but its mass cannot be described through the standard model. The natural conclusion is that understanding these two particles will fill in the gaps of the standard model.

II. TAU

Tau is an estimate of the amount of scattering between neutrinos and dark matter. The greater the Tau, the fewer neutrinos reach a designated distance. The greater the distance, the more chances for a neutrino to scatter. Over an incredibly large distance, two very weakly interacting particles can produce noticeable effects. Experiments want to find these noticeable effects with the maximum amount of scattering without scattering all possible neutrinos from reaching Earth.

$$\tau = (\rho_{DM}/m_X)\sigma D \tag{1}$$

Tau is a value that can be directly acquired from the experiment. It is possible to estimate the amount of neutrinos that can hit earth from a supernova. By comparing that value to the amount of neutrinos a detector should be able to detect, the amount of neutrinos that doesn't make it to Earth is calculated. This calculated tau value describes the unknown of the equation, the cross section. The distance and density are known experimental constants. The cross section is an unknown for this interaction and tau is a way to determine what it can be.

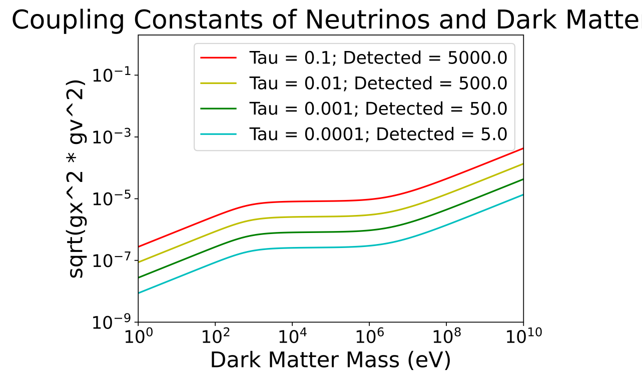

FIG. 1. The possible coupling constants for a certain number of detected neutrinos using a $10 MeV$ mediator mass.

The cross section of a particle is the area where another particle can interact with it. The larger the cross section, the more likely it is for a particle to enter its range and interact with it. Due to the small range of the weak force, the cross section for the neutrino-dark matter interaction is really small.

The coupling constant between dark matter and neutrinos can be found from the cross section. The range and force created is determined by a mediator particle which is described though the coupling constant. Tau allows a value to be found for the coupling constant. This constant is not the constant for each particle but is unique to this interaction. Each particle has its own coupling constant which multiplies with the particle it interacts with. Tau is capable of finding the product of the interaction. Although this experiment does not describe each interaction separately, a future experiment will have values to test to find each individual constant.

The NFW profile [1] is a function that outputs the dark matter density at a certain distance from the center of the Milky Way Galaxy. For other galaxies, estimates can be made for their parameters. Using the NFW profile, it is possible to find the average dark matter density be-

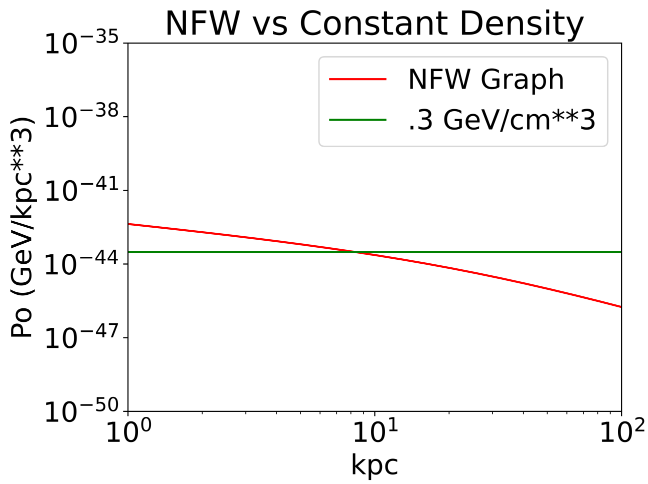

FIG. 2. A constant dark matter density vs an integrated version using the NFW profile. In total, the NFW integration produces a slightly lower dark matter density for SN1987a than the constant $.3GeV/cm^3$ assumption at Earth.

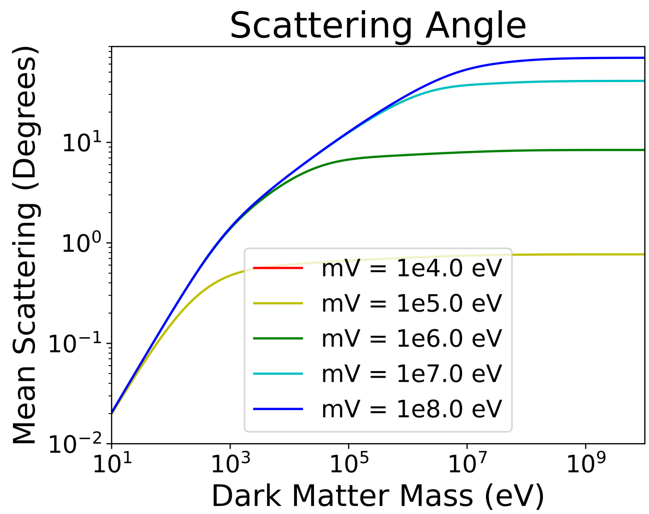

FIG. 3. The average angle in degrees where scattering occurs due to different mediator masses

tween two points, even if those two points are in different galaxies. The equation is:

$$\rho(r) = \frac{\rho_0}{(r/r_0)(1 + (r/r_0))^2} \tag{2}$$

where for the Milky Way Galaxy, $\rho_0 = (8.18 \pm 2.67) \times 10^6\ M_\odot\ \text{kpc}^{-3}$ and $r_0 = 9.04 \pm 2.43$ using kpc in Ref [1]. Converting $M_\odot$ into GeV and kpc into cm^3 produces a value of $0.3GeV/cm^3$.

Using the NFW profile, a energy density at a distance from the center of the galaxy can be found. This energy density is determined by the discrepancy in speeds of stars in galaxies versus the known mass in the galaxy. This difference in speed can only be the result of galaxies having more mass than they appear. In the equation the mass of the dark matter particle is unknown. Without the dark matter mass, only an estimate can be made. However, an experiment may be able to find the dark matter mass and confirm estimates using Tau.

A. Scattering

Neutrino scattering must happen rarely enough for some neutrinos to make it to Earth without scattering. Neutrino events from supernova in the past appeared from a single direction. This assumption becomes that neutrinos on the path from a supernova to Earth realistically only scatters once. [2] The average angle of all possible scattering locations where the neutrino scatters once is taken to provide an estimate for the new distance scattered neutrinos must travel and therefore a time delay. The time delay for scattered neutrinos is important because the delay alone can produce the dark matter mass. Different dark matter masses produce different angles and even cross sections. As the mass increases, the neutrino will scatter with a much steeper angle. If the mass is big enough, dark matter particles can act similar to a wall and completely deflect a neutrino. At every mass, there's a different maximum angle. There's another contributor to the angle of scattering.

The interaction between two particles produce a mediator particle to transfer the energy. For the dark matter and neutrino interaction, this particle has mass. This mass of the particle decreases the range of the interaction and increases its strength. A heavy mediator mass can deflect neutrinos at a greater angle at the cost of a lower interaction range.

Estimating the mediator mass for this interaction is also important and also possible. Since the mediator mass is one of the biggest contributors to the scattering angle, finding data about the scattering angle can find data about the mediator mass. Due to current resolution technology of neutrino detectors, directly finding the angle of incoming neutrinos is difficult. It has room for a lot of error. However, a better way of determining the angle is by finding its time delay.

III. TIME DELAY

As stated before, time delay is due to the extra distance traveled due to scattering. Time delay is one piece of observable data that can be found in the experiment. The other is the amount of neutrinos that arrive. The time delay is all that is required to determine scattering angles. For each dark matter mass, there is a corresponding average angle at a certain mediator mass. Since neutrinos are estimated to move at a constant speed, the distance traveled can be directly converted to a time value. The

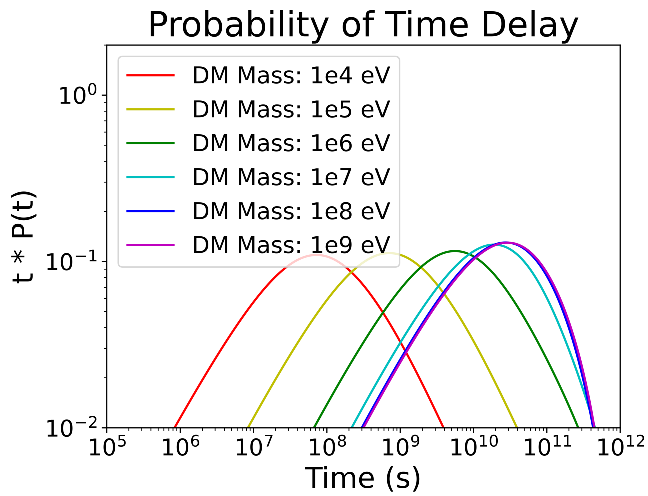

FIG. 4. The time distribution of neutrinos for specific dark matter masses using a $10MeV$ mediator mass at 10kpc.

scattered path compared to the normal path creates a triangle. There are many points where the neutrino can collide with dark matter, but all those points will create a path that is equal to the time delay.

The path created at all possible points of impact create an ellipse. The average angle of all points on the ellipse determine the mean scattering angle. The mean scattering angle provides the possible mediator masses for each dark matter mass.

Each dark matter mass also has an associated time delay for it. The scattering angle is determined by the dark matter mass. A lot of the interaction between neutrinos and dark matter is due to its masses and how the momentum is conserved after a collision. The scattering angle is very dependent on the mass of the dark matter so with the time delay the dark matter mass can be found.

This graph uses an equation in [3]

$$P(t) \approx \int \frac{d\varphi}{t + (D\varphi^2/2)} \frac{1}{\sigma_\nu} \left(\frac{d\sigma_\nu}{d\theta} \right)_{\theta = \varphi + 2t/(D\varphi)}, \qquad (3)$$

where the geometric constraint should be imposed for φ to satisfy $\theta_{\min} \leqq \theta \approx \varphi + 2t/(D\varphi) \leqq \theta_{\max}$, where $\theta_{\min} = 2\sqrt{2t/D}$ and $\theta_{\max} = \pi$

and solves it over multiple time intervals using multiple different dark matter masses. All possible φ are summed to produce a φ value to use. The distance used is a constant 10kpc due to 10kpc being around the distance where its large magnitude begins to neutralize the very small cross sections of the neutrino-dark matter interaction.

IV. FUTURE WORK

These values assume the integrated dark matter density between a supernova and Earth is constant between the two locations. In reality, depending on the location neutrinos may scatter much closer to that supernova than expected. This issue can be taken account for but it is too time consuming for the time constraints on this research.

Many equations used for this research use the small angle limit. This is due to the distance neutrinos must travel from supernova to reach Earth, the angles are most likely to be very small. This may not be the case where scattering can occur much farther than originally thought. Finding values without this simplification can improve results.

This experiment assumes neutrino interactions bounce with sharp angles. There is a possibility for the cross sections to be large with very weak interactions between the two. This allows for a smoother curve between the bouncing between multiple dark matter particles instead of one. The scattering angle will no longer become a simple Pythagorean distance but more rounded and much harder to predict.

V. CONCLUSION

The tau and time delay of a future experiment is very likely to discover new information about dark matter. This experiment will require that a supernova occurs nearby; it must be far enough for ample amounts of scattering to occur but close enough for many of the neutrinos to be able to reach earth. A failed experiment where neutrinos are not detected to scatter still provides new and stronger constraints for the nature of dark matter and neutrinos.

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