Dark Matter Equation of State in Neutron Stars: A Brief Report

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The incorporation of dark matter (DM) into neutron star (NS) models presents a fascinating frontier in astrophysics, potentially offering insights into both the nature of dense nuclear matter and dark matter properties. This report examines the equation of state (EOS) formulations for dark matter in neutron stars and analyzes how its presence affects stellar properties. We review theoretical models including fermionic, bosonic, and asymmetric dark matter, and discuss various approaches for implementing dark matter EOSs in neutron star simulations. The effects of dark matter on neutron star observables—including mass-radius relationships, tidal deformability, oscillation modes, and cooling characteristics—are examined alongside current observational constraints and future detection possibilities. Finally, we discuss challenges in the field and promising future directions for research at this intersection of nuclear astrophysics and dark matter physics.

I. INTRODUCTION

Neutron stars represent some of the most extreme environments in the universe, with core densities exceeding that of atomic nuclei. These ultradense objects serve as natural laboratories for studying matter under extreme conditions that cannot be reproduced in terrestrial experiments. Meanwhile, dark matter—a non-luminous component that comprises approximately 27% of the universe's mass-energy content—remains one of the most profound mysteries in modern physics. The intersection of these two domains opens fascinating possibilities for understanding fundamental physics.

The incorporation of dark matter into neutron star models has gained significant attention in recent years as researchers explore how the presence of dark matter might affect neutron star properties and whether these effects could be observed. This report provides a comprehensive analysis of the current understanding of dark matter equation of state (EOS) in neutron stars, the theoretical approaches used to model it, and its implications for neutron star observables.

II. THEORETICAL MODELS OF DARK MATTER IN NEUTRON STARS

A. Fermionic Dark Matter Models

Fermionic dark matter represents one of the most extensively studied models for dark matter in neutron stars. These models typically consider non-self-annihilating systems of spin-1/2 fermions, with the EOS often modeled as an ideal relativistic Fermi gas [15]. The dark matter parameters of interest include the particle mass (m_χ), Fermi momentum, and coupling constants that govern interactions.

When interactions are considered, relativistic mean field (RMF) approaches are employed to model self-interactions within the dark matter sector [4, 7]. These interactions significantly influence both the EOS and the resulting neutron star structure. For instance, a density-dependent EOS where fermionic dark matter interacts with nucleons via the Higgs portal has been proposed to study neutron star cooling properties [6].

B. Bosonic Dark Matter Models

Recent research has also explored bosonic dark matter models, particularly those involving self-interactions. The bosonic dark matter paradigm is characterized by anisotropic halos surrounding neutron stars, with specific mass ranges constrained by galactic cluster observations [2]. According to these studies, bosonic dark matter particle mass likely falls between 0.05-0.5 GeV with scattering lengths ranging from 0.9-3 fm [2].

The EOS for bosonic dark matter often assumes a Bose-Einstein condensate form, where particles can cluster into the same quantum state [16]. At low self-interaction strengths, this type of dark matter tends to form a core within neutron stars, while at higher interaction strengths, it forms a halo structure [16].

C. Asymmetric Dark Matter

Asymmetric dark matter (ADM) represents a specific class of dark matter models where particles and antiparticles are not produced in equal numbers, similar to the baryon asymmetry observed in the visible universe. Studies suggest that ADM can accumulate in neutron star interiors and significantly affect their global properties [10, 13].

Recent work has examined self-interacting, non-annihilating asymmetric fermionic dark matter that couples to neutron stars only through gravitational interaction [13]. This approach allows researchers to parame-

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terize the DM fraction inside neutron stars and explore how this fraction affects various stellar properties.

III. THEORETICAL APPROACHES TO DARK MATTER EOS

A. Two-Fluid vs. Single-Fluid Formalism

Two distinct approaches have emerged for modeling dark matter within neutron stars:

1. **Two-Fluid Approach**: In this framework, dark matter and nuclear matter interact solely through gravitational effects, with no direct coupling between the sectors [8, 15, 17, 19, 20]. The equilibrium configurations require solving a generalized version of the Tolman-Oppenheimer-Volkoff (TOV) equations for two perfect fluids interacting only through gravity [15]. This approach has been implemented using numerical methods such as the 4th-order Runge-Kutta algorithm with adaptive step size [17]. Das et al. [20] have employed this approach within a relativistic mean field theory framework to analyze the constraints from GW170817 on the nuclear equation of state in the presence of dark matter.

2. **Single-Fluid Approach**: This method introduces direct interactions between dark matter and nuclear matter components [7]. Though more complex, this approach can account for potential non-gravitational interactions between the sectors.

The mathematical formulation of the two-fluid system involves four coupled differential equations that simultaneously track the pressure and mass distributions of both ordinary and dark matter components [17]. These equations capture how the presence of dark matter indirectly affects the structure of the neutron star through gravitational coupling.

B. Nuclear Matter EOS Considerations

The effects of dark matter on neutron star properties depend significantly on the underlying nuclear matter EOS. Studies have used various models for the nuclear component, including:

- Relativistic mean field models with σ-ω-ρ meson interactions (FSU2R parameterization) [8]
- Chiral effective field theory-based EOSs [15]
- Density-dependent relativistic models [6, 7]
- QMC-RMF4 relativistic mean-field model with density-dependent magnetic fields [13]

The NITR and NITR-I energy density functionals have been specifically developed to reconcile observational constraints, including the mass limit of PSR J0952-0607 (2.35 ± 0.17 $M_\odot$), with theoretical predictions [1, 7].

IV. EFFECTS OF DARK MATTER ON NEUTRON STAR PROPERTIES

A. Mass-Radius Relationships

The introduction of dark matter typically softens the neutron star EOS, with significant consequences for the mass-radius relationship [6, 7]. Generally, dark matter cores reduce the maximum mass of neutron stars [3, 7, 16], though the specific effect depends on the dark matter particle properties:

- For heavier dark matter particles, the maximum gravitational mass decreases more significantly [13]
- For lighter dark matter particles, a transition from a dark core to a halo structure can occur, potentially increasing the maximum mass in some cases [13, 15]

These effects could be crucial for interpreting observational constraints. A DM core with a mass fraction as small as 5-10% could significantly affect how nuclear EOS models align with observations, potentially excluding some models based on the measured mass of PSR J0952-0607 while making others compatible with the LIGO/Virgo upper limit on tidal deformability [3].

B. Tidal Deformability

Tidal deformability—a measure of how easily a neutron star is deformed in an external gravitational field—is also affected by dark matter. Studies consistently show that dark matter reduces the dimensionless tidal deformability of neutron stars [1, 5].

A particularly interesting finding is that the dimensionless tidal deformability exhibits a sharp transition from behaving like a pure normal matter star to behaving like a pure dark matter star within a narrow range of intermediate dark matter mass fractions [5]. This characteristic could potentially be used to identify the presence of dark matter in neutron stars through gravitational wave observations.

C. Oscillation Modes

Non-radial f-mode oscillations (fundamental modes) of neutron stars provide another avenue for detecting the influence of dark matter. Research demonstrates that dark matter affects these oscillation patterns in ways that depend on the DM particle properties, DM self-interaction, and DM fraction [1, 9].

Studies have derived relations encoding the effect of dark matter on f-mode parameters and established universal relations for the DM fraction based on the total mass of the star and DM self-interaction strength [9]. These relationships could potentially be detected through future gravitational wave observations.

D. Cooling Properties

The presence of dark matter can significantly alter neutron star cooling processes [6]. As the DM mass and Fermi momentum increase, cooling becomes faster compared to standard neutron stars. This offers an opportunity to constrain dark matter properties through observations of neutron star thermal evolution.

Importantly, dark matter can have indirect effects on nuclear matter properties that influence cooling. For instance, in certain DM models, the proton fraction in the ordinary matter fluid changes, potentially decreasing the threshold gravitational mass required for direct URCA processes that enable fast stellar cooling [15].

V. OBSERVATIONAL CONSTRAINTS AND DETECTION POSSIBILITIES

A. Gravitational Wave Observations

Binary neutron star mergers observed through gravitational waves provide an important window into potential dark matter effects. The tidal signatures in these events could reveal the presence of dark matter in neutron stars, though current sensitivity is limited [5, 11].

Das et al. [21] have conducted pioneering work on dark matter admixed neutron star properties in light of gravitational wave observations, employing a two-fluid approach. Their research demonstrates how the presence of dark matter affects the tidal deformability of neutron stars and how these effects can be constrained using data from events like GW170817. This work represents an important step in using gravitational wave observations to probe the presence of dark matter in neutron stars.

Studies examining the potential of next-generation detectors like the Einstein Telescope (ET) and Cosmic Explorer (CE) suggest that even with these improved instruments, conclusively detecting dark matter in neutron stars will remain challenging due to degeneracies with the nuclear EOS and dark matter fraction [11]. Current models indicate that ET will likely not be able to definitively test the presence of DM in binary neutron star systems, even when combining many events and adding CE to the detector network [11].

B. Mass-Radius Measurements

Current neutron star mass-radius measurements can place some constraints on dark matter properties. Using Bayesian parameter estimation with available data, researchers have established that the lower bound of the ratio between dark matter effective self-repulsion strength (g_χ/m_ϕ) and particle mass (m_χ) can be constrained at the 68% credible level to $10^{-6.59}$ [10].

Improvements in measurement precision could enhance these constraints. If neutron star mass-radius measurement uncertainties are reduced to the 2% level, constraints on the lower bound of this ratio could improve to $10^{-6.5}$ at the 68% credible level [10].

C. Primordial Black Hole Interactions

A novel approach involves studying gravitational wave signals from primordial black holes inspiraling inside neutron stars. This phenomenon could potentially provide insights into the dense matter EOS, including effects from dark matter [14]. Calculations suggest that Advanced LIGO could detect the inspiraling of a 10^{-5} $M_\odot$ primordial black hole at a distance of 10 kpc, while next-generation detectors could extend this range significantly [14].

VI. CHALLENGES AND FUTURE DIRECTIONS

A. Model Degeneracies

A significant challenge in constraining dark matter properties using neutron star observations is the presence of degeneracies between various parameters. Current studies suggest that while some combinations of parameters (like the ratio of g_χ/m_ϕ to m_χ) can be constrained, other combinations, including the individual values of dark matter particle mass, coupling strength, and mass fraction, remain largely unconstrained [10].

These degeneracies make it difficult to conclusively identify the presence of dark matter in neutron stars using global properties alone, such as mass, radius, and tidal deformability [4]. Thakur et al. [19] have made important progress in this area by exploring robust correlations between fermionic dark matter model parameters and neutron star properties using a two-fluid perspective. Their work establishes several key relationships that could help break these degeneracies in future observations.

B. Recent Observational Tensions

Recent analyses indicate that neutron star models incorporating dark matter may be less favorable in light of current observational constraints [12, 18]. The Bayesian evidence for models with dark matter components is lower than for models without dark matter, suggesting that current observations do not strongly support the presence of significant dark matter in neutron stars [12].

Thakur et al. [18] have conducted a comprehensive analysis on the feasibility of dark matter admixed neutron stars based on recent observational constraints. Their work combines pulsar timing and gravitational wave observations to perform Bayesian inference on dark matter parameters, finding that current data somewhat disfavors significant dark matter components in neutron stars. However, these conclusions depend on the specific dark matter models and nuclear EOSs considered, and future observations with improved precision may provide clearer evidence.

VII. CONCLUSION

The investigation of dark matter EOSs in neutron stars represents a multifaceted approach to understanding both dark matter physics and dense nuclear matter. While current observational constraints do not strongly favor significant dark matter components in neutron stars, the theoretical models developed provide a framework for interpreting future observations.

The effects of dark matter on neutron star properties—including mass-radius relationships, tidal deformability, oscillation modes, and cooling characteristics—offer potential signatures that could be detected with next-generation instruments. These signatures depend crucially on the dark matter EOS, which in turn is governed by the particle properties and interaction mechanisms.

Continuing advances in gravitational wave astronomy, coupled with improved neutron star observations and refinements in nuclear physics constraints, promise to further illuminate this fascinating intersection of nuclear astrophysics and dark matter physics in the coming years.

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