Snowmass2021 - Letter of Interest

Illuminating the Dark Sector in Neutron Star Mergers

Bhupal Dev[a], Jean-Francois Fortin[b], Huaike Guo[c], Steven P. Harris[d,e], Kuver Sinha[c], and Yongchao Zhang[a]

[a]Department of Physics and McDonnell Center for the Space Sciences, Washington University, St. Louis, MO 63130, USA
[b]Département de Physique, de Génie Physique et d'Optique, Université Laval, Québec, QC G1V 0A6, Canada
[c]Department of Physics and Astronomy, University of Oklahoma, Norman, OK 73019, USA
[d]Department of Physics and McDonnell Center for the Space Sciences, Washington University, St. Louis, MO 63130, USA
[e]Institute for Nuclear Theory and Department of Physics, University of Washington, Seattle, WA 98195

- ■ (TF09) Astro-particle physics & cosmology
- ■ (CF1) Dark Matter: Particle Like
- ■ (CF2) Dark Matter: Wavelike
- ■ (CF3) Dark Matter: Cosmic Probes
- ■ (CF7) Cosmic Probes of Fundamental Physics

* **Corresponding author:** Kuver Sinha (kuver.sinha@ou.edu)

Abstract: This Letter of Interest discusses the possibility of using neutron star (NS) mergers as a new tool to constrain beyond the Standard Model (BSM) physics, specifically light particles belonging to the dark or sterile sector. We will examine the impact such particles would have on NS merger dynamics, considering both the possibilities that they can free-stream through the dense nuclear matter and the case where they are trapped. We will calculate the decay and mean free path of these BSM species in realistic merger conditions. Our results may be regarded as a first step aimed at understanding how the BSM physics affects merger simulations and potentially interfaces with observations. We will also discuss possible multi-messenger signatures of these scenarios.

Over the past few decades, supernovae and cooling neutron stars (NSs) have served as a laboratory for studying beyond the Standard Model (BSM) particles, most notably, the axion or axion-like particle (ALP) [1–8]. Now, with the observation of both gravitational wave [9] and electromagnetic signal [10, 11] from GW170817, NS mergers provide a novel environment to study dark-sector particles, as mergers are the only place in the universe where nuclear matter at NS densities is heated up to tens of MeV. Mergers contain very diverse thermodynamic conditions, including regions where the nuclear matter is strongly degenerate, but also regions where it is non-degenerate [12].

The role of axions in NS mergers was initiated in [13]. Axions (a) could be produced via the nuclear bremsstrahlung process $N + N \to N + N + a$ (with N representing nucleons) in the nuclear matter which makes up the merging NSs. We calculated the mean free path (MFP) of axions in hot, dense nuclear matter and found that the MFP is always comparable to or longer than the size of the merger region. As a result, axions escape from the merger, taking energy from the system which cools it. Within current laboratory, astrophysical and cosmological constraints on the axion-nucleon coupling (see e.g. Refs. [14, 15] for a review), the cooling due to axion emission can occur in NS mergers on timescales as fast as a few milliseconds, which means that it could have an impact on the dynamics of a NS merger, whose remnant typically lives for tens of milliseconds [16].

With this LOI, we wish to study the impact of other dark-sector particles on NS mergers, and also determine what NS merger observations might be able to tell us about these dark-sector particles. In particular, we are currently studying the impact of a light CP-even scalar S on NS mergers, which is expected to be different from the CP-odd axion case, just as in the case of supernovae [17] (see Refs. [18, 19] for comparison). The scalar particle could be produced via the same production channel as the axion, i.e. $N + N \to N + N + S$; here the single and multi-pion exchange contributions could play an important role. We plan to calculate the MFP and decay of S as functions of NS density, temperature, nucleon-scalar coupling, and the scalar mass to map out the conditions under which the scalar S would be trapped or would free-stream through the merger. If the scalar has a large MFP compared to the NS size, then it will carry energy away from the merger and cool it down. In contrast to the axion case, it may be possible that there exists some allowed parameter space where the scalar is trapped within the merger. If this is the case, then the scalar particle may contribute to heat conduction within the merger, altering the dramatic temperature gradients that simulations indicate exist in mergers.

In future upcoming work, we plan to study the role of other particles, including dark photons, Majorons, light fermionic dark matter particles, and sterile neutrinos in NS mergers. Our overarching program is to investigate BSM physics in NS mergers, in the spirit of what has been achieved for BSM physics in supernovae over the last few decades. NS merger simulations may also be used to set limits on the non-standard interactions (NSIs) of the active neutrinos, which will be highly relevant in the context of multi-messenger detection of neutrinos from NS mergers at large-scale neutrino detectors like DUNE and Hyper-K [20–22].

Understanding the temperature evolution of the merger remnant is important, because high temperatures lead to a large thermal pressure, which allows the remnant to stave off collapse for a period of time. In addition, if the temperature becomes sufficiently high, the nuclear matter will deconfine into quark matter. Finally, many transport properties depend strongly on the temperature [23], making it vital that we understand the temperature evolution of the merger, including the possible impact of BSM particles.

In conclusion, the NS mergers provide an unprecedented window of opportunity for probing BSM physics in the coming decades. With the advent of multi-messenger astronomy with NS mergers, this is expected to be an important endeavor.

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