Snowmass2021 - Letter of Interest

Gravitational Wave Observations as a Probe of Dissipative Dark matter

Thematic Areas: (check all that apply ☐/■)

■ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other) *[Please specify frontier/topical group]*

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Abstract: Gravitational-wave (GW) observations provide the first data that can treat dark matter on the same footing as the light-emitting matter of the standard model. As a result, they open a new direction in dark matter physics. In scenarios where dark matter can dissipate kinetic energy to form compact objects, dark matter may form black holes detectable by LIGO, VIRGO, and future gravitational wave observatories. If dark matter has a cosmologically relevant fermion heavier than the standard model proton, then dark matter may form sub-solar mass black holes. A detection of a sub-solar mass black hole would revolutionize dark matter physics. In the absence of a detection, constraints from GW wave observations provide constraints on dark-matter self-interactions in a new regime, distinct from but complementary to all current observations.

Dark matter with a particle spectrum more complex than that of a traditional WIMP may have dissipative interactions that allow for structure to be altered in an interesting way on small scales, while maintaining the halo structure observed on large scales[1]. For a simple model, atomic dark matter[2], estimates have shown that if even 0.01% of dark matter has collapsed into black holes, this population is accessible with current and near-future detectors[3]. Other works have explored black hole formation in other dissipative scenarios[4–6]. In addition, there are proposals for dark matter that collapse neutron stars into small black holes[7–10]. However, the theoretical effort in this direction has so far only scratched the surface.

GW observations have the potential to illuminate dark matter microphysics in at least two straightforward ways. First, the smallest mass of any detected black holes provides a lower limit on the mass of fundamental particles in the dark sector via the Chandrasekhar bound. Second, the formation of black holes from dark matter requires that the dark gas can cool to a low enough temperature for gravitational collapse to win over pressure. The detected mass of any dark black holes therefore bounds the cooling function, and the bound state energy levels (atomic or molecular) that enable cooling.

We identify four directions where advances in theory and analysis tools will allow the potential of GWs as a dark matter probe to be realized. These are (1) Analyze GW data to search for binary mergers involving sub-solar mass compact objects[11–13]; this direction will also improve constraints on primordial black holes[14–17] (2) Develop methods to model two different black hole populations, one of stellar origin and one related to dark matter, (3) Develop theory and simulation tools to understand compact object formation in dissipative dark matter models, and enable data to constrain the theory, and (4) Develop a framework to treat large-scale structure constraints on dissipation together with GW constraints.

This program may lead to significant advances in the coming decade, exploring a new and rich part of the possible dark matter parameter space.

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