Snowmass2021 Letter of Interest:
Effective Field Theories for Phases of Matter and sub-GeV Dark Matter Detection

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Letter of Interest

In recent years, new synergies between condensed matter and high energy theory have emerged with the development of relativistic effective field theories (EFTs) for different phases of matter (see e.g. [1–5] and references therein). This approach has already found successful in diverse applications that range from hydrodynamics (see e.g. [6, 7]), to the fractional quantum Hall effect [8], and even to cosmology [9, 10].

The main idea behind the above techniques is that every condensed matter system (or indeed the Universe) spontaneously breaks at least part of the spacetime Poincarè group, and possibly other internal symmetries. The Goldstone bosons associated to this spontaneous breaking are collective excitations of the system at hand. It is well known that the dynamics of Goldstone bosons is dictated by symmetry breaking patterns—powerful constraints that determine low energy EFTs of the condensed matter systems. Such an approach to condensed matter is formulated in a relativistic quantum field theory language, and falls under a framework much more familiar to high energy physicists.

In concurrence with the above theoretical developments, a new and rapidly developing field in the experimental search for dark matter has set its sights on dark matter with mass in the keV to MeV range (see e.g. the proposals [11–34]). While massive enough to be treated as particles, dark matter in this mass range is not heavy enough to release sizable energy to a detector via standard recoil processes. Unable to resolve individual atoms or molecules, it must instead interact with low energy (meV to eV) collective excitations of a detector material. Reliable descriptions of the dark matter interaction with the collective excitations of the medium are then necessary to estimate rates and elucidate finer details of dark matter properties.

This Letter of Interest concerns the development of the above described EFT techniques, and their application to keV-MeV dark matter direct detection.

The main idea behind the construction of such EFTs is as follows:

1. Given a condensed matter system, identify which spacetime and internal symmetries are broken, and identify the corresponding Goldstone bosons (collective excitations);
2. Write the most general Lagrangian invariant under the full symmetry group;
3. Organize the Lagrangian in a derivative expansion, valid at small momenta up to a certain cutoff.

The above can be applied to a condensed matter system that is proposed as a dark matter detector. Once this is done, and given the symmetries of the dark sector under consideration, it is simple to couple the dark matter field to the Goldstone field(s). This allows for the study of emission and/or scattering processes of the dark matter particle off the collective excitations of the medium. In particular, one can take advantage of well known and well tested tools from high energy physics (amplitude analysis, Monte Carlo generators, etc.).

The approach described above has already been employed in [16–18] to study the response of a possible detector based on superfluid ^{4}He to the passage of sub-MeV dark matter. The EFT for an s-wave superfluid is arguably the simplest one, being describable in terms of only a single scalar, $\psi(x) = \mu t + \pi(x)$, with π the phonon field, and a lowest order Lagrangian given just by $\mathcal{L} = P\left(\sqrt{\partial_\mu\psi\partial^\mu\psi}\right)$, with P the pressure of the superfluid [1]. The use of this technique has been successful both in confirming the results obtained with more standard techniques [14, 15, 19] from an independent viewpoint and in providing new understanding, for example, of the role of different collective excitations (phonons vs rotons) [17], and the underlying reason for some observed suppression of the emission rate [35].

The above EFT techniques constitute a broad theoretical framework through which to analyse light dark matter detection that is applicable to different models of the dark sector and different materials and collective excitations. A recent example is an EFT for the description of of gapped phonons in solids in the limit of small gap (the so-called "pseudo-acoustic" phonons) [36]. This could provide complementary insight into the response of crystal based detectors (see e.g. [21]), identify new signatures, as well as provide a new understanding of (and avoiding suppression effects in) the emission rate of optical phonons, as highlighted in [32].

With this Letter of Interest we encourage discussion on the above mentioned theoretical techniques, and the synergy of this proposal with those dedicated to low-threshold dark matter direct detection.

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