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"New Ideas for the Dark Sector and the Early Universe"

PI: Justin Khoury, Associate Professor of Physics and Astronomy

Institution: University of Pennsylvania
Mailing address: 209 South 33rd Street, Philadelphia, PA 19104
Phone: (215) 573-7152
Email: jkhoury@sas.upenn.edu
Administrative Contact: Maureen Miller, mpmiller@sas.upenn.edu, (215) 898-8182

"New Ideas for the Dark Sector and the Early Universe"

1 Major Project Goals

1. Develop a novel framework for dark matter (DM), based on the rich physics of superfluidity.
2. Seek deeper understanding of the symmetries and associated Ward identities underlying inflation.

2 Goals Accomplishments

2.1 Phenomenology of Dark Matter Superfluidity

In a series of papers [1,2] a few years ago, Khoury and Dr. L. Berezhiani (MPA, Munich) proposed a novel theory of DM superfluidity, inspired by recent developments in condensed matter physics. In this approach, the DM and MOND components represent different phases of a single underlying substance, unified through the rich physics of superfluidity. The MOND phenomenon emerges from the superfluid phase of DM.

The proposal assumes DM particles, which behave as a cold, collisionless fluid on large scales. As non-linear structures form, the increase in DM density triggers a phase transition to a superfluid phase. The model requires DM to be light ($m \lesssim 2\,\mathrm{eV}$) and to interact sufficiently strongly, such that it can reach thermal equilibrium and Bose-Einstein condense in the central regions of galaxies. Superfluidity (and along with it MOND) only occurs in sufficiently low-mass halos, in which the DM temperature (set by the DM velocity dispersion) is below critical. Massive galaxy clusters are above critical temperature, and DM is in the normal phase. Thus the framework successfully distinguishes galaxies (where MOND is successful) from galaxy clusters (where MOND is not).

The superfluid nature of DM dramatically changes its macroscopic behavior in galaxies. Instead of behaving as individual particles, the DM is more aptly described as collective excitations, in particular phonons. The DM phonons couple to ordinary matter, thereby mediating an additional force (beyond Newtonian gravity) between baryons. For a particular choice of the superfluid equation of state, the resulting dynamics is similar to MOND, such that the DM superfluid reproduces the MOND empirical success in galaxies.

In a recent preprint [3], Khoury, Berezhiani and Dr. Benoit Famaey (Strasbourg) developed in detail some of the main phenomenological consequences of such a formalism, by revisiting the expected dark matter halo profile in the presence of an extended baryon distribution. In particular, they showed how rotation curves of both high and low surface brightness galaxies can be reproduced, with a slightly rising rotation curve at large radii in massive high surface brightness galaxies, thus subtly different from Milgrom's law. They pointed out other expected differences with Milgrom's law, in particular in dwarf spheroidal satellite galaxies, tidal dwarf galaxies, and globular clusters, whose Milgromian or Newtonian behavior depends on the position with respect to the superfluid core of the host galaxy.

2.2 Emergent MOND from Particle Interactions

Over the last year, together with Penn postdoc Dr. Riccardo Penco and Dr. Famaey (Strasbourg), Khoury has developed a novel mechanism that instead relies on DM-baryon *particle* interactions, without any additional long-range force other than (Newtonian) gravity. Indeed, the most straightforward interpretation of the Mass Discrepancy Acceleration Relation (MDAR) is that, given the baryonic mass profile $M_{\rm b}(r)$ in a galaxy, the DM profile $M(r)$ can be uniquely predicted.

In a recent paper [4], Khoury and collaborators have discovered that the desired DM profile can naturally emerge as an equilibrium configuration arising from particle interactions between DM and baryons.

Specifically, using the hydrostatic equilibrium and heat transport equations, they have found that this can occur quite generically as long as the following three conditions are satisfied:

1. The typical relaxation time of DM particles is comparable to the dynamical time $t_{\rm dyn}$, *i.e.*, the time it takes for a DM particle to "sample" an appreciable fraction of the galaxy. In the ideal gas parlance this is known as *Knudsen regime*, and in spiral galaxies it is attained if DM particles relax predominantly by interacting with baryons in the galactic disk. As a corollary, this requirement places an upper bound on the strength of DM self-interactions.

2. DM particles cool down as a result of their interaction with baryons. Simple kinematic arguments show that this occurs as long as DM particles are much heavier (lighter) than baryons and interactions are predominately elastic (inelastic). Thus, this requirement correlates the mass DM-baryon mass hierarchy to the nature of DM-baryon interactions.

3. The product of the DM-baryon interaction cross section $\sigma_{\rm int}$ and the typical energy ϵ exchanged in a collision is inversely proportional to the local DM number density n,

$$\sigma_{\rm int}\epsilon \sim 1/n\,. \tag{1}$$

   This behavior, while at first sight unusual, can be realized quite easily in particle physics models, for instance as a result of *Debye screening*. Indeed, the cross section resulting from screened interactions is $\sigma_{\rm int} \sim \lambda_{\rm D}^2$, where the Debye screening length is $\lambda_{\rm D} \sim 1/\sqrt{n}$.

Under these assumptions, Khoury has shown that rotationally-supported systems (*i.e.*, disk galaxies) satisfy the MDAR. Specifically, in regions dominated by DM, the framework predicts the deep-MOND force law $a \simeq \sqrt{a_0 a_{\rm b}}$, where $a_{\rm b}$ is the Newtonian acceleration due to baryons alone. In regions where the potential is dominated by baryons, it predicts a nearly constant DM 'surface brightness' in good agreement with observations.

2.3 Symmetries of the Early Universe

Precision observations of the CMB have established that the large scale structure originated from primordial density perturbations with nearly scale-invariant and Gaussian statistics. The leading paradigm for the origin of these perturbations is inflation, a burst of exponential expansion shortly after the big bang. In the last decade it has become increasingly clear that viewing inflation as a process of spontaneous symmetry breaking is an extremely powerful approach. Instead of focusing on specific inflationary models, one studies the general consequences of the symmetries underlying inflation.

In a series of papers Khoury and collaborators have shown that Maldacena's original consistency relation and the conformal consistency relation follow respectively from the Ward identities for broken spatial dilations and special conformation transformations. Maldacena's consistency relation is one of the most powerful probes of early universe physics. It states that the 3-point function of ζ in the "squeezed" or soft limit is determined by the scale transformation of the 2-point function.

By including tensor perturbations, Khoury and collaborators have shown that, remarkably, cosmological perturbations enjoy an *infinite* number of non-linearly realized global symmetries. These are residual diffeomorphisms mapping field configurations which fall off at infinity into those which do not. Certain linear combinations of these transformations can be smoothly extended to physical configurations which do fall off at infinity, and as such constitute adiabatic modes.

In a recent paper [5] with former student Dr. A. Joyce (Columbia) and Prof. K. Hinterbichler (Case Western) Khoury studied the consistency relations of inflation in 2+1 dimensions. Gravity in 2+1 dimensions is simpler primarily because it has no local degrees of freedom, nevertheless it is far from trivial because of global and boundary degrees of freedom, *e.g.*, BTZ black hole. This makes 2+1 dimensions an ideal simplified testing ground.

In 2+1-dimensional inflation, the relevant group of symmetries is the infinite-dimensional conformal group of $\mathbb{R}^2$. This is the familiar Virasoro group from two dimensional conformal field theory. Khoury and collaborators have shown that the Virasoro symmetries induce a profile for ζ to all orders in the coordinates. Specifically, at each order in n, the holomorphic and anti-holomorphic generators can be arranged into a symmetric, traceless n-index tensor, which acts as $\delta_{i_1\cdots i_n}\zeta \;\propto\; x^{(i_1}\cdots x^{i_n)_{\rm T}}$. Furthermore, the same transformation can be derived starting from the conformal transformations of spatial slices and applying Weinberg's adiabatic mode construction. In other words, the infinite set of adiabatic modes for ζ is in one-to-one correspondence with the asymptotic symmetries of dS_3, so that either can be derived from the other.

Khoury and collaborators have derived an infinite set of consistency relations that derive from the Virasoro symmetries. (A key difference from the infinite set of consistency relations (**??**) in 3+1 dimensions is that the latter necessarily involve tensor modes for $n \geq 2$, whereas the 2+1-dimensional identities constrain scalar perturbations only.) In momentum space they relate the symmetric, traceless part of the correlation function at each order q^n in the soft momentum to a symmetry transformation on a lower-point function. Khoury has performed a number of non-trivial checks of these identities by applying the EFT of inflation to 2+1 dimensions.

Products

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[3] L. Berezhiani, B. Famaey and J. Khoury, "Phenomenological consequences of superfluid dark matter with baryon-phonon coupling," arXiv:1711.05748 [astro-ph.CO], to appear in JCAP.

[4] B. Famaey, J. Khoury and R. Penco, "Emergence of the mass discrepancy-acceleration relation from dark matter-baryon interactions," JCAP **1803**, no. 03, 038 (2018) doi:10.1088/1475-7516/2018/03/038 [arXiv:1712.01316 [astro-ph.CO]].

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