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Dark matter superfluidity and galactic dynamics

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ABSTRACT

We propose a unified framework that reconciles the stunning success of MOND on galactic scales with the triumph of the ΛCDM model on cosmological scales. This is achieved through the physics of superfluidity. Dark matter consists of self-interacting axion-like particles that thermalize and condense to form a superfluid in galaxies, with ∼mK critical temperature. The superfluid phonons mediate a MOND acceleration on baryonic matter. Our framework naturally distinguishes between galaxies (where MOND is successful) and galaxy clusters (where MOND is not): dark matter has a higher temperature in clusters, and hence is in a mixture of superfluid and normal phase. The rich and well-studied physics of superfluidity leads to a number of striking observational signatures.

The standard Λ Cold Dark Matter (ΛCDM) model does very well at fitting large scale observables. On galactic scales, however, a number of challenges have emerged. Disc galaxies display a tight correlation between total baryonic mass and asymptotic velocity, $M_{\rm b} \sim v_{\rm c}^4$, known as the Baryonic Tully–Fisher Relation (BTFR) [1,2]. Hydrodynamical simulations can reproduce the BTFR by tuning baryonic feedback processes, but their stochastic nature naturally results in a much larger scatter [3]. Furthermore, the mass [4,5] and phase-space [6–9] distributions of dwarf satellites in the Local Group are puzzling.

A radical alternative is MOdified Newtonian Dynamics (MOND) [10], which replaces dark matter (DM) with a modification of gravity at low acceleration: $a \simeq a_{\rm N}$ ($a_{\rm N} \gg a_0$); $a \simeq \sqrt{a_{\rm N} a_0}$ ($a_{\rm N} \ll a_0$), with best-fit value $a_0 \simeq 1.2 \times 10^{-8}$ cm/s^2. This empirical force law has been remarkably successful at explaining a wide range of galactic phenomena [11]. In the MOND regime, a test particle orbits an isolated source according to $v^2/r = \sqrt{G_{\rm N} M_{\rm b} a_0}/r^2$. This gives a constant asymptotic velocity, $v_{\rm c}^2 = \sqrt{G_{\rm N} M_{\rm b} a_0}$, which in turn implies the BTFR.

The empirical success of MOND, however, is limited to galaxies. The predicted temperature profile in galaxy clusters conflicts with observations [12]. The Tensor–Vector–Scalar (TeVeS) relativistic extension [13] fails to reproduce the CMB and matter spectra [14, 15]. The lensing features of merging clusters [16,17] are problematic [18]. This has motivated various hybrid proposals that include both DM and MOND, *e.g.*, [19–23].

In this Letter, together with a longer companion paper [24], we propose a novel framework that unifies the DM and MOND phenomena through the physics of superfluidity. There are two central ideas underlying our work, which must be carefully distinguished. The first is the very general idea that DM forms a superfluid inside galaxies, with a coherence length of order the size of galaxies. The critical temperature is ∼mK, which intriguingly is comparable to Bose–Einstein condensation (BEC) critical temperatures for cold atom gases. Indeed, in many ways our DM behaves like cold dark atoms. The generic idea of DM superfluidity leads to a number of remarkable observational consequences. The superfluid nature of DM dramatically changes its macroscopic behavior in galaxies. Instead of evolving as independent particles, DM is more aptly described as collective excitations. The second central idea is the postulate that superfluid phonons mediate a MOND-like force between baryons. Since superfluidity only occurs at low temperature, our framework naturally distinguishes between galaxies (where MOND is successful) and galaxy clusters (where MOND is not). Due to the larger velocity dispersion in clusters, DM has a higher temperature and hence is in a mixture of superfluid and normal phases [25–27].

The superfluid interpretation makes the non-analytic nature of the MOND scalar action more palatable. The Unitary Fermi Gas, which has attracted much excitement in cold atom physics [28], is also governed by a non-analytic kinetic term [29]. Our equation of state $P \sim \rho^3$ suggests that the DM superfluid arises through three-body interactions. It would be fascinating to find precise cold atom systems with the same equation of state, as this would give important insights on the microphysical interactions underlying

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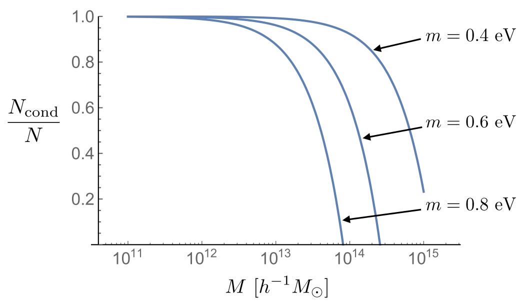

Fig. 1. Fraction of DM particles in the condensate.

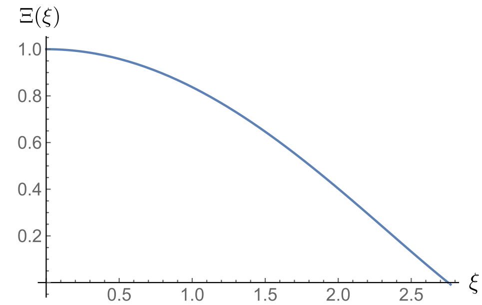

Fig. 2. Numerical solution of Lane–Emden equation.

our superfluid. Tantalizingly, this might allow laboratory simulations of galactic dynamics.

The idea of DM BEC has been studied before [30–34], with important differences from our work. In BEC DM galactic dynamics are caused by the condensate density profile; in our case phonons play a key role in explaining the BTFR. Moreover, BEC DM has $P \sim \rho^2$ instead of $\sim\rho^3$. This implies a much lower sound speed, which puts BEC DM in tension with observations [35].

DM condensation: In order for DM particles to condense in galaxies, their de Broglie wavelength $\lambda_{\rm dB} \sim (mv)^{-1}$ must be larger than the interparticle separation $\ell \sim (m/\rho_{\rm vir})^{1/3}$. From standard collapse theory, the density at virialization is $\rho_{\rm vir} \simeq (1+z_{\rm vir})^3\ 5.4 \times 10^{-28}$ g/cm^3, while the virial velocity is $v = 113\, M_{12}^{1/3}\sqrt{1+z_{\rm vir}}$ km/s, where $M_{12} \equiv M/10^{12}M_\odot$. Thus $\lambda_{\rm dB} \gtrsim \ell$ implies

$$m \lesssim 2.3\,(1+z_{\rm vir})^{3/8}\ M_{12}^{-1/4}\ {\rm eV}\,. \qquad (1)$$

We work in $\hbar = 1$ units.

The second condition is that DM thermalizes, with temperature set by the virial velocity v. The interaction rate is $\Gamma \sim \mathcal{N} v \rho_{\rm vir} \frac{\sigma}{m}$, where $\mathcal{N} \sim \frac{\rho_{\rm vir}}{m}\frac{(2\pi)^3}{\frac{4\pi}{3}(mv)^3}$ is the Bose enhancement factor. The rate should be larger than the inverse dynamical time $t_{\rm dyn} \sim \frac{1}{\sqrt{G_{\rm N}\rho_{\rm vir}}}$, such that the coherence length will span the halo. This translates into a bound on the cross section (with $m_{\rm eV} \equiv m/{\rm eV}$):

$$\sigma/m \gtrsim (1+z_{\rm vir})^{-7/2}\, m_{\rm eV}^4 M_{12}^{2/3}\ 52\ {\rm cm}^2/{\rm g}\,. \qquad (2)$$

Later on, we will adopt $m = 0.6$ eV as a fiducial value. For $M_{12} = 1$ and $z_{\rm vir} = 2$, the inequality becomes $\sigma/m \gtrsim 0.1$ cm^2/g. The lower end is consistent with current constraints [36–38] on σ/m for self-interacting dark matter (SIDM) [39], though these constraints must be carefully revisited in the superfluid context.

The critical temperature, obtained by equipartition $k_{\rm B}T_{\rm c} = \frac{1}{3}mv_{\rm c}^2$, is in the mK range:

$$T_{\rm c} = 6.5\, m_{\rm eV}^{-5/3}(1+z_{\rm vir})^2\ {\rm mK}\,. \qquad (3)$$

For $0 < T < T_{\rm c}$, the system is a mixture of condensate and normal components. The fraction of condensed particles, $1-(T/T_{\rm c})^{3/2}$ [40], is shown in Fig. 1 as a function of halo mass assuming $z_{\rm vir} = 0$. For $m \lesssim$ eV, galaxies are almost completely condensed while massive clusters have a significant normal component. Also, since T_c depends on redshift, halos at higher redshift tend to have more superfluid than the ones formed more recently.

Superfluid phase: The relevant low-energy degrees of freedom of a superfluid are phonons, described by a scalar field θ. In the presence of a gravitational potential Φ, the non-relativistic effective action is $\mathcal{L} = P(X)$, where $X = \dot\theta - m\Phi - (\vec\nabla\theta)^2/2m$ [29]. The nature of the superfluid (*i.e.*, its equation of state) is encoded in the choice of P. Up to this point, the discussion has been very general. However, in order to endow our superfluid with MOND-like phenomenology, we conjecture that DM superfluid phonons are governed by the MOND action [41]

$$\mathcal{L} = \tfrac{2}{3}\Lambda(2m)^{3/2}X\sqrt{|X|} - \alpha\frac{\Lambda}{M_{\rm Pl}}\theta\rho_{\rm b}\,, \qquad (4)$$

where Λ is a mass scale, $\rho_{\rm b}$ is the baryonic matter density, and α is a dimensionless constant. This action should only be trusted *away from* $X = 0$, as we will see later. The matter coupling breaks the shift symmetry at the $1/M_{\rm Pl}$ level and is thus technically natural. Remarkably (4) is strikingly reminiscent of the Unitary Fermi Gas, $\mathcal{L}_{\rm UFG}(X) \sim X^{5/2}$, which is also non-analytic [29].

The phonon action (4) uniquely fixes the properties of the condensate through standard thermodynamics. At finite chemical potential, $\theta = \mu t$, and ignoring Φ, the pressure is given by the Lagrangian density:

$$P(\mu) = \tfrac{2}{3}\Lambda(2m\mu)^{3/2}\,. \qquad (5)$$

This is the grand canonical equation of state $P = P(\mu)$ for the condensate. The number density, $n = \partial P/\partial\mu$, is

$$n = \Lambda(2m)^{3/2}\mu^{1/2}\,. \qquad (6)$$

Combining these expressions with $\rho = mn$, we obtain

$$P = \frac{\rho^3}{12\Lambda^2 m^6}\,. \qquad (7)$$

This is a polytropic equation of state $P \sim \rho^{1+1/n}$ with index $n = 1/2$. In comparison, BEC DM has $P \sim \rho^2$ [32].

Including phonons excitations $\theta = \mu t + \phi$, the quadratic action for ϕ is $\mathcal{L}_{\rm quad} = \frac{\Lambda(2m)^{3/2}}{4\mu^{1/2}}\left(\dot\phi^2 - \frac{2\mu}{m}(\vec\nabla\phi)^2\right)$. The sound speed can be immediately read off:

$$c_s = \sqrt{2\mu/m}\,. \qquad (8)$$

Using (7), we compute the static, spherically-symmetric density profile of the DM condensate halo. Introducing dimensionless variables $\rho = \rho_0\Xi$ and $r = \sqrt{\frac{\rho_0}{32\pi G_{\rm N}\Lambda^2 m^6}}\,\xi$, with ρ_0 denoting the central density, hydrostatic equilibrium implies the Lane–Emden equation, $\left(\xi^2\Xi'\right)' = -\xi^2\Xi^{1/2}$, with boundary conditions $\Xi(0) = 1$ and $\Xi'(0) = 0$. The numerical solution is shown in Fig. 2. It vanishes at $\xi_1 \simeq 2.75$, which defines the halo size: $R = \sqrt{\frac{\rho_0}{32\pi G_{\rm N}\Lambda^2 m^6}}\,\xi_1$. Meanwhile the central density is related to the halo mass as [42] $\rho_0 = \frac{3M}{4\pi R^3}\frac{\xi_1}{|\Xi'(\xi_1)|}$, with $\Xi'(\xi_1) \simeq -0.5$. Combining these results, we obtain:

$$\rho_0 \simeq M_{12}^{2/5} m_{\rm eV}^{18/5}\Lambda_{\rm meV}^{6/5}\ 7\times 10^{-25}\ {\rm g/cm}^3\,;$$
$$R \simeq M_{12}^{1/5} m_{\rm eV}^{-6/5}\Lambda_{\rm meV}^{-2/5}\ 36\ {\rm kpc}\,, \qquad (9)$$