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The relevance of Very Light Dark Matter

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Abstract. A concordant model of Dark Matter and Dark Energy is presented. Dark Energy arises out of magnetic condensation of very light fermions of micro-eV mass charged under an unbroken gauge group $U(1)_X$. The Dark Matter candidate is an oppositely charged fermionic species which is then shown to be naturally in the MeV to keV range.

1 The changing limits on DM mass

Dark Matter (DM) presents the tantalising possibility of revealing new symmetries in addition to of course identification of new particle species. The optimistic proposal is that of a weakly interacting massive particle WIMP , connected to the Electroweak sector, and its mass also linked to the electroweak scale, being the lightest species odd under a discrete symmetry present in an extension of the Standard Model (SM), such as the lightest supersymmetric particle. The other popular candidate for DM is the axion meant to explain the CP property of QCD vacuum.

Over the past few years direct search experiments have placed serious bounds on a TeV scale DM candidate, and LHC has not detected any supersymmetric sector, indeed the possible Higgs candidate has too high a mass. On the other hand several direct search experiments report an annual modulation effect, raising the possibility that the DM may not be the anticipated WIMP (see for example [1]). A variety of theoretically motivated ultra-light species are currently being sought experimentally [2]. While a substantial part of the light DM window is already ruled out, it is worth noting recent studies that indicate that the acceptable range for mass M_1 of a sterile neutrino is constrained to

$$2KeV \leq M_1 \leq 5KeV, \tag{1}$$

where the lower bound comes from structure formation constraint from Lyman α forest data while the upper bound comes from X-ray flux limits from decaying DM [3][4][5]. Further jsutification comes from N body simulations cum semi-analytic study of formation of dwarf galaxies [6]. Recently the possibility of keV scale sterile neutrino DM in a gauge extension of the Standard Model has also been considered [7]

Thus the possibility of low mass sterile fermions as Dark Matter remains open and consistent with observation. In our model to be discussed, the DM candidate is a fermion sterile under Standard Model but carries its own $U(1)_X$ charge.

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2 Towards a concordant explanation

A more puzzling discovery from the point of view of fundamental physics has been the Dark Energy component [8][9] of the cosmological energy density from direct observations, in accord with the WMAP precision data [10]. The extremely small value of the mass scale associated with this energy density makes it unnatural as Cosmological Constant[11], and therefore demands an unusual mechanism for relating it to the known physics of elementary particles. On the other hand a new window to the very low mass physics has been opened up by the discovery of the low mass scale of neutrinos [12], [13]. We may therefore exploit the presence of an ultra-light sector to explain the Dark Energy phenomenon autonomously at a low scale, without direct reference to its high scale connection with known physics.

In the following we report on a proposal wherein a gas of very light fermions enters a magnetised state based on a specific condensation mechanism. A domain structure occurs, separated by domain walls. It has been shown that such a medium satisfies an effective equation of state $p = (-2/3)\rho$. While negative pressure is obtained as expected for Dark energy, a further caveat is needed. The average domain size, determined by microscopic physics is so small that the wall gas, or the wall foam appears to be a homogeneous space filling medium on the scale of current Hubble radius. Thus the effective equation of state would indeed be $p = -\rho$.

These fermions need to be charged under a hitherto unobserved gauge group $U(1)_X$, and are shown to be ultra-light (nano to pico eV). The medium is then kept neutral under this new $U(1)_X$ due to presence of a heavier non-condensing species of opposite charge and equal abundance and turns out to have have a keV to MeV scale species as a partner to maintain a neutral medium. Thus the Dark Matter species emerges as a natural partner of an ultra-light scale particle whose condensation simulates the Dark Energy behaviour. Both the species carry equal and opposite charge of a hitherto unobserved $U(1)_X$. The connection of both these species to the SM can then be through kinetic mixing of the standard photon with the hidden photon. In the next few sections we discuss the Dark Energy proposal and in sec. 4 we discuss the emergence of naturally light Dark Matter.

3 Magnino condensation

The proposed model of condensation relies on magnetic condensation in a fermion gas. This unusual possibility is distiinct fromm the Heisenberg model of ferromagnetic exchange ineraction between electrons localised on thier respective lattice sites. Originally proposed by E C Stoner [14], the formulation assumes delocalised or *itinerant* fermions. Since long range abelian force is envisaged, but no such species are known to couple to Maxwell electromagnetism, we proceed by assuming the existence of a new fermionic species responding to a so far undetected abelian force $U(1)_X$. The mechanism relies on a mild repulsive force between the fermions. This repulsive energy is minimised provided the fermions are farther apart. The collective state which can ensures a larger characteristic separation is the one in which the spins are mutually parallel, thus relying on Fermi statistics. A balance between the mutual repulsive force and the requirements of fermi statitics can then result in the Stoner ferromagnetic state. The quantitative requirement is expressed by the Stoner criterion, eq. (2) below.

In a minimal model [15] it was proposed that the repulsive force is itself the dipolar magnetic repulsion between the magnetic moments. We dub this new species *magnino*. The name is justified by the fact that that predominant manifested property is magnetism. As to the magnetic moment, there are two possibilities. One is that the magnetic moment is induced, as was pursued in [15], and the fermion itself is not charged under the $U(1)_X$. The other possibility is that the magnetic moment is intrinsic. In the latter case, the magnino carries a charge, and there must be another species, equally abundant and oppositely charged for neutrality of the Universe. The second species can be a spectator without distrubing the condensation mechanism provided it is heavier. In this cse it is very tepting to think that it is a component of Dark Matter [16]. This is the model we pursue here.

The fermion gas in the cosmological setting has to be extremely rarefied. For example the microwave photon entropy is equivalent to 400 photons per cc, and the Big Bang Nucleosynthesis contraint leaves very little scope for additional light species. Subsequent to WMAP 7 year data [10], a window is reported to have opened up for accommodating the equivalent of one new relativistic degree of freedom [17].

In the past decade Stoner ansatz has received extensive theoretical attention in the context of surface phenomena and been verified in the 2-dimensional setting. In the 3-dimensional case, the dipolar model of [15] led to the calculations of [18] [19][20], which confirm the former at least in the non-relativistic setting. An experimental confirmation of the three dimensional Stoner mechanism has been reported in [21] for neutral ultra-cold gas of spinless atoms, where a Feshbach resonance is used for tuning the repulsion. These developments justify further pursuit of our original proposal, as done in a two component concordant model of [16].

An additional possibility in the mechanism is an explanation of the seeds required to produce the inter-galactic magnetic fields, provided the new $U(1)_X$ mixes with electromagnetism, as I discuss at the end. In the following I use the units $\hbar = c = 1$ and all dimensionful quantities are expressed in the units of eV.

3.1 The condensation mechanism

According to the Stoner ansatz [14] spontaneous ferromagnetism is a consequence of a shift in single particle energies, proportional to the difference between the spin up ($N_\uparrow$) and the spin down ($N_\downarrow$) populations. A parameter I is introduced to incorporate this, the single-particle energy spectrum being

$$E_{\uparrow,\downarrow}(\mathbf{k}) = E(\mathbf{k}) - I\frac{N_{\uparrow,\downarrow}}{N} \tag{2}$$

Using this it is shown [22][23] that the ferromagnetic susceptibility is

$$\chi = \frac{\chi_P}{1 - I\frac{\beta}{E_F}} \tag{3}$$

where β is a factor of order unity depending upon the geometry of the Fermi surface; for the spherical case having value $\frac{3}{4}$. The criterion for spontaneous magnetization is $\chi < 0$. A sufficient condition for the gas to be spontaneously magnetised at zero temperature is the Stoner criterion,

$$I > \frac{E_F}{\beta} \tag{4}$$

The origin of such a large energy shift is supposed to be a repulsive interaction among the fermions, which makes it favourable for them to enter the state of aligned spins, which in turn due to Pauli exclusion principle ensures large enough a separation among them so as to reduce the repulsive energy. An estimate of the size of this "exchange hole" [24][23] is given by the density deficit of same spin fermions in the vicinity of a given fermion, $\Delta n_M = -0.86 n_M$. Let the two-particle long range interaction energy be γ^2 which is repulsive. This energy reduction should be proportional to Δn_M. For the Stoner parameter I we may therefore stipulate the relation

$$I = \gamma^2 \frac{|\Delta n_M|}{n_M} \tag{5}$$

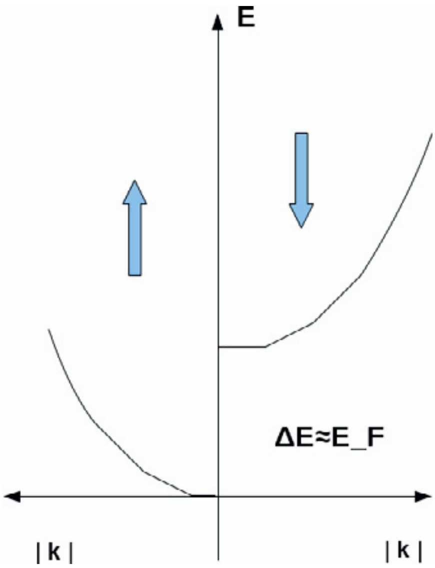

Figure 1. Stoner ansatz. Energy split between energies of up spin and down spin fermions is comparable to the Fermi energy

I now make the assumption that for the fermions under consideration, this coupling arises from magnetic dipole-dipole interaction, which is dominated by a repulsive contribution in an appropriate ferromagneic state. The resulting increase in single particle energy can be estimated on dimensional grounds as

$$\gamma^2 \;=\; \kappa_{JM}\mu_M^2|\Delta n_M| \tag{6}$$

where μ_M is the magnetic moment of the magnino.

The possibility of purely dipolar repulsive force resulting in Stoner state was explored using Hartree-Fock method in [19] where the favorable ferromagnetic state, dubbed "JM ansatz" there was found to be spheroidal. This ensures dominance of repulsion over attraction, and the related parameter κ_{JM} is a factor of order unity. Note that the interaction energy between non-relativistic dipoles goes as inverse third power of interparticle separation and hence consistent with scaling as $|\Delta n_M|$.

The magnetic moment introduced above is given by

$$\mu_M \equiv g_M \frac{e_X \hbar}{2m_M} \tag{7}$$

where e_X is the unit of charge of the new electromagnetism, and m_M is the mass of the magnino. At tree level, g_M has the Dirac value 2. Thus the Stoner criterion (4) becomes

$$\alpha_X n_M \left(\frac{g_M}{m_M}\right)^2 > \frac{4}{3}\left\{\left((3\pi^2 n_M)^{2/3} + m_M^2\right)^{1/2} - m_M\right\} \tag{8}$$

where $\alpha_X = e_X^2$ is the fine structure constant, and we have assumed $|\Delta n_M| \approx n_M$, and $\kappa = 1$ for simplicity.

3.2 Contributions to cosmic energy density

We proceed by assuming that in the condensed state, the spin degrees of freedom may be modelled by a Landau-Ginzberg lagrangian for the magnetisation **M**, a vector order parameter, with a symmetry breaking self-interaction $\lambda(\mathbf{M}\cdot\mathbf{M} - \sigma^2)^2$. Here σ determines the magnitude of the magnetization per unit volume, estimated to be $\mu_M|\Delta n_M|$ [23] upto a factor of order unity. From standard solitonic calculation [25] the domain walls have a width $w \sim (\sqrt{\lambda}\sigma)^{-1}$ and energy per unit area $\eta^3 \sim \sqrt{\lambda}\sigma^3$. The question to be addressed is whether these walls are stable on the cosmological time scale. The domain walls at hand form an intercconnected network and are expected to be classically stable due to an energy barrier involved. However they are quantum mechanically metastable because the vacuum manifold which is a 2 dimenional sphere allows for the wall to develop holes through tunneling [26]. The rate for such processes is however suppresed by a factor $\exp\{-B/\lambda\}$ where B is a factor of order unity. Thus the walls can be stable over the several billion years over which Dark Energy seems to have dominated the Universe, with values of the self-interaction parameter $\lambda \sim O(10^{-2})$. The mechanism thus predicts slow depletion of the DE density associated with domain wall decay.

According to the JM ansatz for the ferromagnetic state introduced in [19] the fermi surface of the condensate is spheroidal [20]. The condensed system would therefore form spheroidal domains of finite size, Being governed by the microscopic lagrangian, the size of the domains would be negligibly small compared to the Hubble radius of the late time Universe. The domain walls therefore fill the Universe in a foam like structure. The walls carry the disordered state at higher energy and therefore contribute to the total energy density as a homogeneous space filling medium. To make an estimate of the energy density contribution of the wall gas, we assume the average separation between the walls to be a length scale l, and assume the energy per unit area of walls to be smeared over the volume l^3. Thus

$$\rho_{WG} \approx \lambda\sigma^4 \left(\frac{w}{l}\right) \tag{9}$$

so that using the estimates we made in the previous para, we need

$$\rho_{WG} \approx \left(\frac{{g_M}^2\alpha_X}{m_M^2}\right) n_M^2 \left(\frac{w}{l}\right) \approx \rho_{DE} \tag{10}$$

If we assume the emergence of wall gas to have been not much earlier than when the equality $\rho_{WG} \approx \rho_m$ was reached, then using $g_M^2 \sim O(1)$, $\alpha_X \sim 10^{-2}$, and $(w/l) \lesssim 10$, we get a bound $m_M/\Upsilon \lesssim 10^{-8}$eV.

4 The partner "dark" component

Since the magnino is charged under the new $U(1)_X$, there must be a partner species of opposite value of the charge and the same abundance to ensure neutrality of the cosmological medium. The results derived so far remain unaffected if this partner is a heavier species, not participating in the magnetic condensation. In other words, the assumption is that the new unobserved sector is also asymmetric under charge conjugation like the observed sector. Let us designate this oppositely charged partner Y.

The third new component, the photons of the new electromagnetic force should also be present, with an entropy density in a ratio Υ_γ to the entropy density of the standard photons. From the observational bounds on the new effective relativistic degrees of freedom, it is necessary that $2\Upsilon + \Upsilon_\gamma < 1$. If we assume Y to be a massive non-relativistic species at present epoch, we can now obtain a bound on its mass. In order for this species to be a component of the Dark Matter, we need

$$\Omega_{DM} = \Upsilon m_Y n_\gamma < 0.27 \times 10^{-10} (eV)^4 \tag{11}$$

From which we get, $m_Y < (10/\Upsilon)$ eV. For $\Upsilon \sim O(1)$, this mass range is too light to act as Dark Matter to assist structure formation. Recent studies indicate that the lower bound on the Dark Matter candidate from Lyman-alpha data tends to be rather model dependent [27] [28]. Nevertheless it is reasonable to assume that the lower bound will be in the range of 2keV in order for the small scale structure to not be erased. If Υ is in the range of 10^{-3}, then m_Y can be sufficiently large to be acceptable Cold Dark Matter. The issues related to Dark Matter from hidden world have been discussed in [29].

Another interesting outcome of the magnetic nature of this condensation mechanism is that it may explain the existing inter-galactic magnetic fields. For this it is necessary that the two electromagnetisms mix through kinetic terms. Then over a large number of domains encompassing the scale of galactic clusters, the fluctuations from the average value zero of the net magnetic field may be large enough, that after mixing with standard electromagnetism it gives rise to the seeds required for generating the intergalactic magnetic fields [30][31]. These effects are the subject of ongoing work.

5 Conclusion

Several recent analyses permit keV scale Dark Matter consistent with current data. In the model presented here, a sterile fermionic species charged under hitherto unobserved new $U(1)_X$ acts as the keV scale Dark Matter. It is partner to another micro-eV mass fermionic species which undergoes condensation into a ferromagnetic phase. The model also holds the potential for explaining the origin of primordial intergalactic magnetic fields.

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