The relevance of Very Light Dark Matter : *in the context of a concordant Dark Energy model*

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Outline

- Cosmic magnino : DE and DM in one model
- Observational evidence turning around (Ly α, Dwarf galaxy spectrum)

Proposal in a nutshell

- A condensation mechanism using known physics of abelian gauge force
- A mechanism operating autonomously at the low scale at which it is observed

Features :

- A species of light fermions condenses into a ferromagnetic state
- Network of Domain walls stores excess energy and simulates Dark Energy
- Need an unbroken $U(1)_{\rm Hidden}$ to achieve this
- Hence also need oppositely charged species, heavier, non-condensing

Salient features of the proposal

- A new $U(1)$ is proposed, along with its own "photon", "electron" and "proton".
- The "electron" needs to have a huge magnetic moment to enter the collective non-perturbative state – hence named "magnino"
- The condensation mechanism dates from 1934, Stoner ferromagnetism
- Setting the intrinsic "cosmological constant" to zero (!!??),
  - the requirement Condensate Energy = Dark Energy fixes the mass of the magnino
- The requirment of Dark Matter fixes the heavy component mass

Cons and pros of Domain Wall Dark Energy

- Wrong equation of state; Generically $p_{DW} = -\frac{2}{3}\rho_{DW}$
  Observations strongly support $w = -1$
- Inhomogeneous imprints on CMB
- Tying up the low scale with particle physics

Responses/Pros :

- Domain Wall network exists on a scale far smaller than H^{-1}; hence almost continuum and hence effectively $p = -\rho$
- SN Ia data leave open the possibility of evolving w
  Sahni, Shafieloo, Starobinsky (2009); Jassal, Bagla and Padmanabhan (2004), (2010).
- Most phenomenological models involve a scalar field with bizarre properties
- Sterile neutrinos may be an indication of a hidden sector with low mass scales.

The "pros" who have made such proposals :
Battye, Bucher, Spergel (1999)
Friedland, Murayama, Perelstein (2002)
Conversi, Melchiorri, Mersini, Silk (2004)

The condensation mechanism

Unlike the Heisenberg ferromagnetism for localised fermions, Stoner mechanism also called "band ferromagnetism" operates for delocalised fermions

Pauli paramagnetism of a gas of free spin1/2 fermions

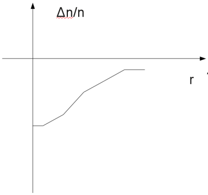
$$\chi_P = \mu_M^2 D(E_F) = \mu_M^2 \frac{3}{2} \frac{n_M}{E_F}$$

Here $D(E_F)$ is the density of states at the fermi surface.

Ferromagnetism occurs in a strongly coupled system, where magnetism persists in the absence of external field.

Same spin density deficit

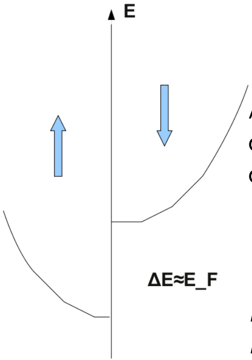
For an 2-fermion antisymmetrized plane wave function with momenta $\mathbf{k_1}$ and $\mathbf{k_2}$ we can estimate the "exchange hole" or the deficiency of same spin fermions in the neighborhood of a given fermion by averaging over the Fermi sphere and integrating over the relative positions



$$\begin{aligned}\Delta n_F &= n_F \left\{ 1 - \frac{9}{2} \int_0^1 4\pi u^2 \, du \, \frac{(\sin u - u \cos u)^2}{u^6} \right\} \\ &= -0.86 n_F\end{aligned}$$

[Ibach and Lüth]

The Stoner ansatz (1934)



A shift in single particle energies, proportional to the difference between the spin up $(N_\uparrow)$ and the spin down $(N_\downarrow)$ populations.

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

I assumed independent of $\mathbf{k}$ is the Stoner Parameter.
I is a single particle quantity of dimension of energy.

The ferromagnetic susceptibility is

$$\chi = \frac{\chi_P}{1 - I\frac{D(E_F)}{2n_M}} = \frac{\chi_P}{1 - I\frac{3}{4E_F}}$$

The condition for spontaneous magnetization is negative χ, which is ensured provided the second term in the denominator dominates. A sufficient condition for the occurrence of ferromagnetism is the Stoner criterion,

$$I > \frac{4}{3}E_F$$

Magnino hypothesis

Magninos!

UAY ArXiv:astro-ph 2005; APS Proceedings of PASCOS 2005; ArXiv:astro-ph 2011

Dirac fermions light enough and dilute enough that their magnetic interaction dominates over their Coulomb interaction.

$$\frac{\mu_{_M}^2}{r^3} > \frac{e_{_M}^2}{r};\ \frac{\alpha_{_M}}{m_{_M}^2} n_{_M}^{2/3} \gg \alpha_{_M}$$

For such itinerant fermions, the mass $m_{_M}$ and the cosmological parameter $n_{_M}$ are sufficient to charactarise the ferromagnetic state.

Stoner parameter for magninos

Dipolar replusion energy [UAY APS proceedings PASCOS 2005; ArXiv:astro-ph 2005]

$$I = \mu_M^2 \, |\Delta n_M| \, \kappa_{JM}$$

Δn_M is local number density deficit due to Pauli principle, and κ_{JM} is a geometric factor computed by Jha and Mohanti [JPhys 2006, PRE 2009] Fregoso and Fradkin [PRL 2009]

Contributions to cosmic energy density

$$\rho_{\text{ground state}} = \rho_{gas} + \rho_{magnetic} < \rho_{gas}$$

At the site of the defects (walls) $\rho_{magnetic}$ is absent.

Thus $\left|\rho_{magnetic}\right|$ is the contribution of the defects to the vacuum energy.
We propose

$$\rho_{DE} \approx \rho_{wallgas}$$

i.e., the above mentioned contribution averaged over domains bounded by the walls, and under the assumption that gravity ignores ground state vacuum energy.

Finally, we shall take energy density stored in walls to be

$$\sigma^3 = In_{_M} \approx \left(\mu_{_M}^2 n_{_M}^2\right)^{3/4}$$

Here $In_{_M}$ = (Single particle Stoner energy)x(number density)

Conjecturing the magnino sector

Let us parameterise the abundance $n_{_M} = \Upsilon n_\gamma$.
Standard value $n_\gamma \approx 3.2 \times 10^{-12}\,({}_{eV})^3$. Putting above conditions and using the proposed dipolar estimate for Stoner parameter I, we get the constraint

$$\frac{m_{_M}}{\Upsilon}\left(\frac{R_{_0}}{R_{_2}}\right)^{1/2} \lesssim 10^{-8}{}_{eV}$$

where R_0 is the scale factor today and R_2 is its value at the epoch of formation of the walls.

The partner "dark" component

For neutrality, we need the oppositely charged particle, X
Assume this to be heavier, and not condensing.

- Can these be DM candidates?
- Opposing requirements : Υ should large enough to allow the magninos to condense,
- But too large ($\Upsilon \sim 1$) would force m_X to be too small.
- Assume smallest allowed $m_{DM} \gtrsim$ 2keV. (Boyarsky, Lesgourgues, Ruchaysky et al)
- Then with $\Upsilon \approx 10^{-3}$, the X particles can be the ultra-light Dark Matter without overclosing the Universe.

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Sterile neutrino Dark Matter

(de Vega et al 2011)

$$\mathcal{L}_{yuk} = h\bar{\nu}_L \langle \Phi \rangle \nu_R$$

- gives rise to the usual see-saw relation $m_\nu \simeq m_D^2/M$.
- With M =1keV and $m_D = hv = 0.1$eV, we get $m_\nu \simeq 10^{-5}$eV
- The mixing $\zeta = m_D/M \sim 10^{-4}$ is adequate to produce the sterile neutrinos is sufficient quantity in early Universe.

Experiments : MARE with Rhenium 187; KATRIN, to determine some of the parameters.

Dark Matter in νMSM + $U(1)_{B-L}$

Non-gauged proposal
Asaka, Shaposhnikov, Blanchet (2005)

- See-saw can be achieved with TeV scale heavy neutrinos
- One neutrino can be keV scale if Dirac Yukawa coupling $h_1 \sim 10^{-13}$
- Small coupling makes it stable against decay during age of the Universe
- Attempts to implement this in the contxt of gauged $B - L$ not successful
  (Sahu, UAY (2006))

Observational evidence turning around

The mass of N_1 is constrained to

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

- The lower bound comes from structure formation constraint from Lyman α forest data.
  (Viel, Lesgourgues, Haehnelt, Matarrese and Riotto (2005))
- Upper bound comes from X-ray flux limits from decaying DM. (Abazajian, Fuller and Tucker, (2001)
- Further jsutification comes from N body simulations cum semi-analytic study of formation of dwarf galaxies (Maccio and Fontanot, MNRAS 2010)

keV neutrino DM in gauged model

- Recently Berzukov, Hettsmansperger and Lindner (2010) have considered the possibility of keV scale sterile neutrino DM.
- Required see-saw can be achieved exploiting the scales introduced by the Higgs required to break the gauge symmetries
- evade the M_{B-L} and overclosure constraint by allowing the next heavier neutrnio to decay after N_1 thermally produced goes out of equilibrium, producing large entropy.

Reliability of Lyman *alpha* constraint

- Note however a reassessment, Boyarsky, Lesgourgues, Ruchayskiy and Viel (2009)
  which claims that Lyman α data are too indirect – need to assume dynamics of structure formation – and lower bounds on DM mass are model dependent;
- It is claimed that technically no lower bound is yet implied.

Thus the possibility of low mass neutrinos as Dark Matter remains open and consistent with theoretical models.

Open questions

- At what energy scale does this sector tie up with SM?
  - Kinetic mixing $\epsilon F^{(1)\mu\nu} F^{(2)}_{\mu\nu}$, $\epsilon < 10^{-9}$
  - Does this cause loss of energy especially near neutron stars with strong Maxwell fields?
  - While most of $U(1)_{hidden}$ magnetic field is trapped in domains, some long range flux statistically remains. Can the kinetic mixing provide the seeds for intergalactic magnetic fields?
- At what temperature did the ferromagnetic phase transition occur? Did it leave any imprint on the WMAP?

Conclusions

- The clasic 100GeV WIMP may not be the solution
- Detailed simulations and models based on observational evidence permit keV scale Dark Matter
- We have a specific proposal for Dark Energy, where Very Light Dark Matter arises naturally

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