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Pion-like dark matter

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Abstract

We introduce the model of the light dark matter particles emerging as the pseudo-Goldstone bosons of spontaneously broken $G_{\rm DM} = SU(N) \otimes SU(N)$ to the unbroken $H_{DM} = SU(N)$ group. The associated fields transform linearly under H_{DM}, but non-linearly under G_{DM}/H_{DM} and their number is equal to the number of broken generators of G/H group according to the Coleman-Wess-Zumino theorem. Those massless fields which acquire $H_{\rm DM}$ breaking degenerate masses we call "dark mater pions" (DMP). We investigate the thermal history of DMP and solve the Boltzmann equations. We compare the results with the WMAP and PLANCK data as well as with the direct detection experiment results and constrain the model parameters.

Keywords: dark matter, cosmology, theories beyond Standard Model

1. Dark Matter Pions

Dark matter (DM) is hypothesized matter which can account for the observed astrophysical and cosmological observations as a result of the invisible mass. The main evidences include the measurements of structure formation, the anisotropy of the Cosmic Microwave Background (CMB), observation of the rotation curves of spiral galaxies and mass-to-light ratio of cluster galaxies. For review see [1].

The observations tell us also some of the properties of the dark matter: it should be electrically neutral (in order to be non-luminous), massive (since we observe gravitational lensing), should be non-baryonic (in order to preserve baryon/photon ratio needed for primordial nucleosynthesis), should be cold, i.e non-relativistic (which is indicated by the structure formation) and since it escapes our direct detection experiments till now, it should be weak-interacting with the ordinary matter. In the Standard Model (SM) of particle physics there is no such a candidate particle and therefore we are forced to search for a new matter.

We suggest a phenomenological model for DM based on the analogy with the QCD and nonlinear realization of the spontaneously broken chiral symmetry, similar to the non-linear σ-model with added mass term for DMP. Therefore we call these dark matter particles emerging in our model "dark matter pions" (DMP).

The effective Lagrangian of DM and DM-SM interactions is constructed by considering the lowest-dimensional SM gauge invariant operators for the specific case $G_{DM} = SU(N) \otimes SU[N)$ and $H_{DM} = SU(N)$. In addition, we require that SM particles are singlets under H_{DM} and that DMP are singlets under SM symmetries. This brings us to the following Lagrangian [2]:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm DM} + \mathcal{L}_{\rm DM-SM} \tag{1}$$

$$\begin{aligned}
\mathcal{L}_{\rm DM} &= f^2\,{\rm tr}\left\{\partial_\mu\Sigma^\dagger\,\partial^\mu\Sigma\right\} + \frac{1}{2}f^2\left(M^2{\rm tr}\Sigma + {\rm H.c.}\right),\\
\mathcal{L}_{\rm DM-SM} &= \frac{1}{2}\lambda_h\left(|\phi|^2 - v^2\right){\rm tr}\left\{\partial_\mu\Sigma^\dagger\,\partial^\mu\Sigma\right\}\\
&\quad + \frac{1}{2}f^2\lambda_h'\left(|\phi|^2 - v^2\right)({\rm tr}\Sigma + {\rm H.c.})\\
&\quad + B^{\mu\nu}\left(\lambda_V{\rm tr}\left\{\Sigma^\dagger\partial_\mu\Sigma\,\partial_\nu\Sigma^\dagger\right\} + {\rm H.c.}\right)
\end{aligned} \tag{2}$$

where $B^{\mu\nu}$ is the SM $U(1)_Y$ gauge field containing γ and Z bosons, $\Sigma = \exp(i\pi_a T^a/f)$ is $SU(N)$ unitary filed containing DM pion fields π_a, and $v = \langle\phi\rangle \simeq 174$GeV. In

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analogy with QCD we call f the DMP decay constant. The first term is $SU(N) \otimes SU(N)$ invariant, the remaining terms are only invariant under the diagonal subgroup $SU(N)$ under which the π^a transform according to the adjoint representation.

For a specific illustrative case with $N = 2$ considered here, we have 3 mass degenerate DM pions, π_o, π_+, π_-. In the model there are then 4 parameters (mass of the DMP M, strength of interaction of DMP with the photon and the Z boson λ_V, strength of interaction of DMP with the Higgs λ_h and the DMP decay constant f; the Higgs portal interactions $\lambda'_h = 0$ since they are excluded in this simplified model) with the following constraints: (i) $\lambda_h < 1$ (assuming the perturbativity of the model); (ii) $4\pi f \ll M$ (consistency of the chiral model); (iii) $f \geq \{\max\{4\pi\lambda_V, 1\}\}^{1/2} M/(4\pi)$ (asking that NLO corrections are less than LO). In addition we take $\lambda_V = 0.63$ (this parameter can change freely since its change can be compensated by the change of other parameters in the calculated scattering amplitudes).

2. Dark Matter Pion Thermal History

Dark matter decouples from SM particles in the very early Universe. If DM is a thermal relic its interactions controls its abundance at the Universe. When the Hubble constant $H > \Gamma_{\rm DM}$ it comes to the freeze out of DM and DM is decoupled from the rest of the particles at the temperature $T \sim M$. By defining $Y = n/s$ and $Y^{\rm eq} = n^{\rm eq}/s$, where s is the entropy density [3]:

$$s = \frac{2\pi^2}{45} g_s(T) T^3 \,; g_s(T) = \sum_k r_k g_k \left(\frac{T_k}{T}\right)^3 \theta(T - m_k) \quad (3)$$

the process of changing the number density n of the DM particles due to the collisions and the expansion Universe is described by the Boltzmann equations as

$$\frac{dY}{dt} + 3HY = -\frac{\langle\sigma v\rangle s}{Hx}\left(Y^2 - (Y^{\rm eq})^2\right). \quad (4)$$

The distribution for massive particles in equilibrium is given by

$$n^{\rm eq} = gz \int \frac{d^3\mathbf{p}}{(2\pi)^3} e^{-E/T} = \frac{zgm^3}{2\pi^2}\frac{K_2(x)}{x}\,,\ x = \frac{m}{T} \quad (5)$$

where $z = e^{\mu/T}$ is fugacity (z(SM particles) $= 1$) and μ is the chemical potential. In above $\langle\sigma v\rangle$ is thermally averaged cross section which requires calculation of all DMP self-interactions and DMP interactions with the SM particles. All expressions can be found in [2].

In our model there is a conserved charge q and therefore $\mu_{\pi_+} = -\mu_{\pi_-}$ and $\mu_{\pi_o} = 0$, and $q = Y_- - Y_+$. Hence there are *only two* coupled Boltzmann equations for $Y_{+,o}$ of the type (4) which has to solved numerically with the boundary conditions $Y \to Y^{\rm eq}$ as $x \to 1$ to obtain the DMP densities and the freeze out temperatures. For $q = 0$ there will be only one Boltzmann equation to solve since then $Y_o = Y_+ = Y_-$.

The relic abundance is obtained from the following expression

$$\Omega_{\rm DM} h^2 = 2.7711 \times 10^8 (M/{\rm GeV})(Y_o + Y_+ + Y_-)_{x=\infty} \quad (6)$$

For the total DMP abundance $Y_t = Y_o + Y_+ + Y_-$ the following inequality is valid: $Y_t(q \neq 0) > Y_t(q = 0)$ (at least for small q and with the other parameters fixed), it follows that

$$\Omega_{\rm DM}(f, M, \lambda_h, \lambda_V; q = 0) < \Omega_{\rm DM}(f, M, \lambda_h, \lambda_V; q \neq 0) \quad (7)$$

implying that the region in parameter space that can satisfy the experimental DM constraints is determined by $\Omega_{DM}(f, M, \lambda_h, \lambda_V; q = 0) < \Omega_{\rm DM_{exp}}$. If this inequality is satisfied for some parameters $\{f,\ M,\ \lambda_h,\ \lambda_V\}$, then there will be a non-zero q such that $\Omega_{\rm DM}(f, M, \lambda_h, \lambda_V; q) = \Omega_{\rm DM_{exp}}$. That is, if the predicted abundance falls below the observations when $q = 0$, one can always fulfill the experimental constraints

$$\begin{aligned} 0.094 \leq \Omega_{\rm DM_{WMAP}} h^2 \leq 0.130\,, \\ 0.112 \leq \Omega_{\rm DM_{PLANCK}} h^2 \leq 0.128\,, \end{aligned} \quad (8)$$

by introducing an appropriate q (at least when the difference is small).

3. Constraints from the WMAP/PLANCK data and direct detection experiments

We restrict the parameters of the model by using the data from the measurements of the cosmic background radiation by the WMAP and PLANCK experiments [4], and also consider constraints from the direct detection experiments LUX [5], XENON and XENON1T [6]. Scanning the parameter space (M, f, λ_h) in the range $50\,{\rm GeV} \leq M \leq 2\,{\rm TeV}$, $50\,{\rm GeV} \leq f \leq 1.5\,{\rm TeV}$, $10^{-4} \leq |\lambda_h| \leq 1$ respectively, and using $q = 0$ and $\lambda_V = 0.63$ we obtain the parametric space shown in Fig.1. Considering carefully various limits and dependencies in the parametric space, together with the WMAP/PLANCK constraints from (8) and combining them (Fig. 1) to a single equation we get:

$$\begin{aligned} 4.04 \times 10^{-7} \leq \left(\frac{\lambda_h M}{f^2}\right)^2 + 0.93\left(\frac{\lambda_V M^2}{f^3}\right)^2 \\ \leq 5.59 \times 10^{-7} \delta_{q0}\,, \end{aligned} \quad (9)$$

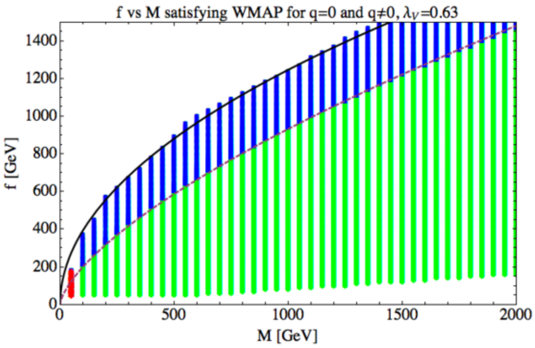

Figure 1: Region in the $f-M$ plane allowed by the CDM constraint (blue); the region corresponding to DM under-abundance (green); and the region excluded by the Higgs decay constraint (10) (red). The solid and dashed black line correspond to the analytic approximations (9), see [2].

with (M, f in GeV) and where δ_{q0} vanishes when $q \neq 0$ so that there is no upper limit in (9) in this case. Additional constraint comes from the Higgs decay $h \to \pi\pi$ (for $M < 62.5$ [GeV])) [2]:

$$f > 5.9|\lambda_h|^{1/2}|7812.5 - M^2|^{1/2}\left[1-\left(\frac{M}{62.5}\right)^2\right]^{1/8}. \quad (10)$$

From the direct detection LUX experiment [5] we have

$$f > 10^3\,|\lambda_h|^{1/2}. \quad (11)$$

The resulting allowed regions including all constraints are shown in Fig.2 for $\lambda_V = 0.0023$. This is the smallest value for λ_V according to the naive dimensional analysis, when $\lambda_V \simeq g'/(4\pi)^2$ (g' is the $U(1)_Y$ SM gauge coupling), which provides the upper limit on allowed M. By enhancing λ_V the allowed values for M become lower, see Fig.1.

It can be concluded that our model of DMP satisfy WMAP/PLANCK and direct detection experiment results in a large region of the parametric space, indicating that for each value of M the decay constant f is constrained to a range approximately 200 GeV wide. When the coupling to the Higgs is not not to small, current data force DMP masses to be larger than 100 GeV, while XENON1T [6] would push M above 2 TeV since f^2/λ_h is large.

Collider signals will be hard to see since the process to be detected is essentially jets with the missing energy. It is interesting to note that in our model DM couples only to the γ, Z and h SM particles and therefore there is no mechanism to suppress the effects of DMP at XENON experiments and to enhance them at DAMA/LIBRA [7].

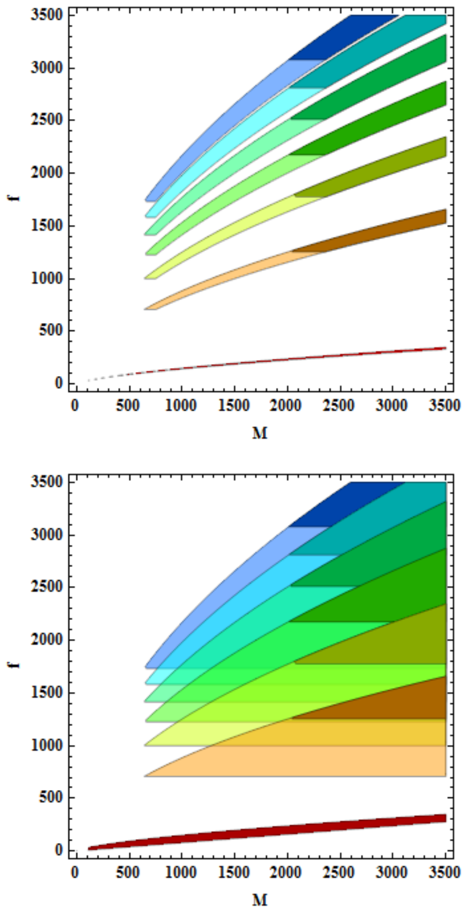

Figure 2: The colored areas denote parameter regions allowed by all constraints for $\lambda_V = 0.0023$ and $\lambda_h = 0, 0.5, 1.0, 1.5, 2.0, 2.5, 3$ (from the bottom up); the top (bottom) panel corresponds to $q = 0$ ($q \neq 0$). The darker colored regions correspond to the limits expected from the proposed XENON1T [6] experiment. For $q \neq 0$ the allowed region do not have a lower bound because of (7).

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