Dark pion dark matter : WIMP vs. SIMP

Pyungwon Ko[1]

School of Physics, Korea Institute for Advanced Study,
Seoul 02455, Korea

Abstract

Dark pions from strongly interacting hidden sector can be a good dark matter candidate, either weakly interacting massive particle (WIMP) or strongly interacting massive particle (SIMP), depending on parameters such as dark pion mass and its couplings to the SM fields as well as among themselves. In this talk I discuss both scenarios.

1 Introduction

One of the most pressing questions in particle physics at the moment is to understand dark matter of the universe. So far the existence of DM was confirmed through astrophysical and cosmological observations where only gravitational force plays an important role. Let us first list the relevant questions we have to answer for better understanding of DM from the viewpoint of particle physics described by quantum field theory:

- How many species of DM are there in the universe ?
- What are their masses and spins ?
- Are they absolutely stable or very long-lived ?
- How do they interact among themselves and with the SM particles ?
- Where do their masses come from ?

In order to answer (some of) these questions, we have to observe its signals through nongravitational observations such as colliders and/or various (in)direct detection experiments. There are various ongoing experiments searching for DM particles.

There are many candidates for nonbaryonic dark matter in particle physics: e.g. axion and its supersymmetric partners, sterile neutrinos, gravitino, weakly interacting massive particles (WIMP) [such as the lightest supersymmetric particle (LSP) or the lightest Kaluza-Klein particle (LKP)], and strongly interacting particle (SIMP). And the universe may be filled with cocktails of different species of DM particles.

In this talk, I will concentrate on DM from strongly interacting hidden sector, the so-called hidden (or dark) QCD models (see Fig. 1). In this class of models, flavor and baryon numbers in the hidden sector are accidental symmetries of renormalizable hidden QCD Lagrangian. Then the lightest mesons (let me call it dark pion) and baryons in the hidden sector make DM. Their lifetime could be much longer than the age of the universe because their decays are triggered by dim-5 and dim-6 operators, respectively. Note that dim-5 operators that induce DM decay is dangerous in principle, and we shall assume that its coefficient is small enough to suppress the dark pion decay.

[1] pko@kias.re.kr

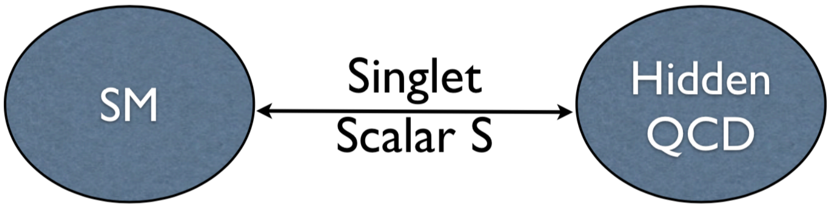

Figure 1: Schematic view of the hidden (dark) QCD model

2 EWSB and CDM from Strongly Interacting Hidden Sector : WIMP scenario

Another nicety of models with strongly interacting hidden sector is that one can construct a model where all the masses of the SM particles and DM are generated by dimensional transmutation in the strongly interacting hidden sector [1, 2, 3, 4]. Basically the light hadron masses such as proton or ρ meson come from confinement, which is derived from massless QCD through dimensional transmutation. One can ask if all the masses of observed particles can be generated by quantum mechanics, in a similar manner with the proton mass in the massless QCD. The most common way to address this question is to employ the Coleman-Weinberg mechanism for radiative symmetry breaking. Here I present a new model based on nonpertubative dynamics like technicolor or chiral symmetry breaking in ordinary QCD (Fig. 1).

Let us consider a scale-invariant extension of the SM with a strongly interacting hidden sector [1, 2, 3, 4]:

$$\begin{aligned} \mathcal{L} &= \mathcal{L}_{\rm SM,kin} + \mathcal{L}_{\rm SM,Yukawa} - \frac{\lambda_H}{4}(H^\dagger H)^2 - \frac{\lambda_{SH}}{2}\, S^2 H^\dagger H - \frac{\lambda_S}{4} S^4 \\ &- \frac{1}{4}\mathcal{G}^a_{\mu\nu}\mathcal{G}^{a\mu\nu} + \sum_{k=1,...,f} \overline{\mathcal{Q}}_k \left[iD\cdot\gamma - \lambda_k S \right] \mathcal{Q}_k . \end{aligned} \quad (1)$$

Here $\mathcal{Q}_k$ and $\mathcal{G}^a_{\mu\nu}$ are the hidden sector quarks and gluons, and and the index k is the flavor index in the hidden sector QCD. We introduced a real singlet scalar S and replaces all the mass parameters by S field in order to respect classical scale symmetry. In this model, we have assumed that the hidden sector strong interaction is vectorlike and confining like the ordinary QCD. Then we can use the known aspects of QCD dynamics to the hidden sector QCD.

In this model, dimensional transmutation will take place in the hidden sector and generate the hidden QCD scale and chiral symmetry breaking with nonzero $\langle \bar{\mathcal{Q}}_k \mathcal{Q}_k \rangle$. Once a nonzero $\langle \bar{\mathcal{Q}}_k \mathcal{Q}_k \rangle$ is developed, the $\lambda_k S$ term generate the linear potential for the real singlet S, which

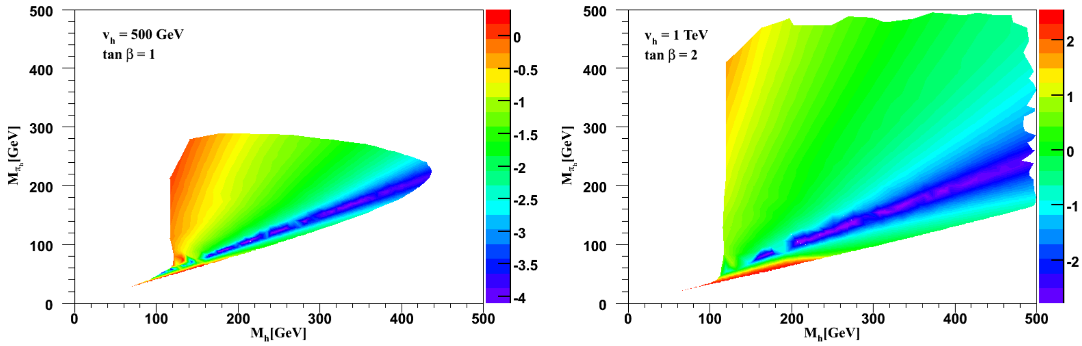

Figure 2: $\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for (a) $v_h = 500$ GeV and $\tan\beta = 1$, and (b) $v_h = 1$ TeV and $\tan\beta = 2$.

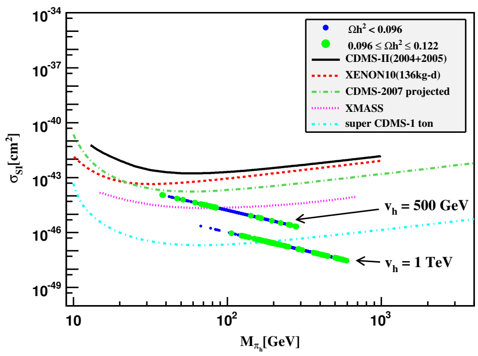

Figure 3: $\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h}. The upper one is for $v_h = 500$ GeV and $\tan\beta = 1$, and the lower one is for $v_h = 1$ TeV and $\tan\beta = 2$.

in turn results in the nonzero $\langle S \rangle$. Then the hidden sector current quark masses are induced through λ_k terms, and the EWSB can be triggered through λ_{SH} term if it has a correct sign. Then the Nambu-Goldstone boson in the hidden sector, hidden pion or dark pion π_h, will get nonzero masses, and becomes a good CDM candidate. Their dynamics at low energy can be described by chiral Lagrangian method. Also hidden sector baryons $\mathcal{B}_h$ will be formed, the lightest of which would be long lived due to the accidental h-baryon number conservation. Here we consider only the hidden sector pion as dark matter, since dynamics of h-baryons are more difficult to describe in a theoretically systematical way.

Thermail relic denstiy and the spin-independent DM-nucleon scattering cross section relevant for direct detection of DM can be estimated by constructing the chiral Lagrangian for dark pion, including the interactions between dark pions and the SM fields. The results are shown in Figs. 2 and 3, which show that dark pions can be good candidates for WIMP. See Ref. [3, 4] for more details.

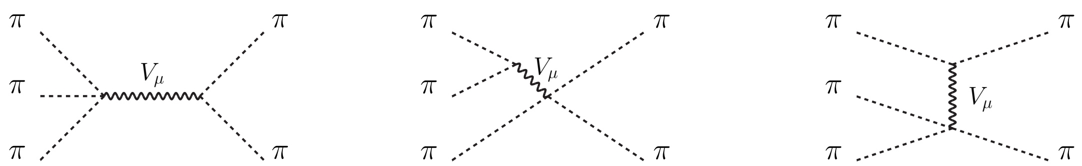

Figure 4: Feynman diagrams contributing to $3 \to 2$ processes for the dark pions with the vector meson interactions.

3 Strongly interacting massive particle (SIMP) scenario within the hidden QCD model

In the original models by Ko *et al.* [1, 2, 3, 4], the Wess-Zumino-Witten (WZW) interaction was not considered. If one includes the WZW term, then the DM number changing processes, $3 \to 2$, becomes possible and one may be able to achieve the correct relic density from this. Also $2 \to 2$ DM self-scattering can be large enough ($\sigma_{\rm self}/m_{\rm DM} \sim O(1)$ barn/GeV) to solve some of the vanilla ΛCDM paradigm, such as the core-cusp puzzle [5]. This new way to achieve both the relic density and the large self scattering cross section is often called Strongly Interacting Massive Particle (SIMP) scenario [6]. However, it turns out that the original proposal by Hochberg et al. for dark pion DM [7] is unlikely to be compatible with the validity of chiral perturbation theory, since one has to have $m_\pi / f_\pi \sim O(4\pi)$.

In Ref. [8], the present author showed that this problem can be significantly relieved if one includes the dark vector mesons (analogy of ρ and ω in the ordinary QCD) because of new $3 \to 2$ diagrams shown in Fig. 4. Also light dark vector mesons make additional contirbutions to the dark pion self scattering through s, t and u-channel exchanges of dark vector mesons. Including these new contributions to the dark pion DM $3 \to 2$ and $2 \to 2$ scatterings from light dark vector mesons and assuming narrow width approximation for them, we find that the phenomenologically viable parameter space is about $m_\pi / f_\pi \sim$ a few (Fig. 5), which is well below 2π, the validity region of the chiral perturbation theory. It is also much smaller than the original proposal $\sim 4\pi f_\pi$ [7].

4 Summary

Summarizing my talk, dark pion DM from strongly interacting hidden sector remains a good DM candidate, whose longevity is due to the accidental flavor symmetry of dark QCD. Depending on the parameter space, one can achieve either WIMP or SIMP scenario.

Acknowledgement The author is grateful to Professor Takuya Morozumi and Professor Yusuke Shimizu for organizing the PPAP2018 in a plesant manner and inviting him with great hospitality. PPAP2018 is sponsored by JSPS Grant-in Aid for Scientific Research (C) Grant Number JP17K05418 and Core of Research for the Energetic Universe (Core-U) of Hiroshima University.

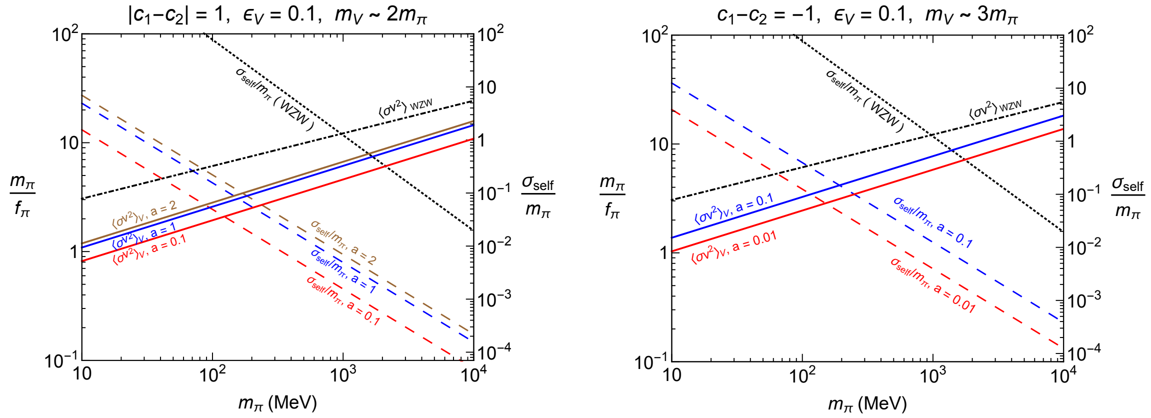

Figure 5: Contours of relic density ($\Omega h^2 \approx 0.119$) for m_π and m_π/f_π and self-scattering cross section per DM mass in cm^2/g as a function of m_π. The case without and with vector mesons are shown in black lines and colored lines respectively. We have imposed the relic density condition for obtaining the contours of self-scattering cross section. Vector meson masses are taken near the resonances with $m_V \approx 2m_\pi$ ($m_V \approx 3m_\pi$) on left (right) plots. In both plots, $c_1 - c_2 = -1$ and $\epsilon_V = 0.1$ are taken. See Ref. [8] for the definitions of these parameters.

References

[1] T. Hur, D. W. Jung, P. Ko and J. Y. Lee, Phys. Lett. B **696**, 262 (2011)

[2] P. Ko, Int. J. Mod. Phys. A **23**, 3348 (2008)

[3] T. Hur and P. Ko, Phys. Rev. Lett. **106**, 141802 (2011)

[4] H. Hatanaka, D. W. Jung and P. Ko, JHEP **1608**, 094 (2016)

[5] S. Tulin and H. B. Yu, Phys. Rept. **730**, 1 (2018)

[6] Y. Hochberg, E. Kuflik, T. Volansky and J. G. Wacker, Phys. Rev. Lett. **113**, 171301 (2014)

[7] Y. Hochberg, E. Kuflik, H. Murayama, T. Volansky and J. G. Wacker, Phys. Rev. Lett. **115**, no. 2, 021301 (2015)

[8] S. M. Choi, H. M. Lee, P. Ko and A. Natale, arXiv:1801.07726 [hep-ph].