Hidden Photon Dark Matter Interacting via ALPs

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A theory of Dark Matter particle

Light particles with feeble coupling with Standard Model, such as axion-like particle(ALP) or hidden photon (HP), are excellent candidates to solve the Dark Matter (DM) problem [1]. These candidates can be created in early times by means of a **non-thermal process** like misalignment mechanism or inflationary vectorial fluctuations and, in addition, have a very rich phenomenology to be tested. So far, the null result of the searches suggest that the experimental investigation and astrophysical observation need to be improved in order to examine smaller masses or weaken coupling.
In this work we propose a alternative explanation. We suggest that the dark sector is more complex than usually thought. Concretely, in this model, the hidden photon (the DM particle in our model) interacts with the visible sector (photon) by means of an ALP that serves as a mediator between the two particles. Many variants of the model has been consider in the literature, see for example [2]. In order to establish our model we propose the following lagrangian

$$\mathcal{L} = \mathcal{L}_\gamma + \mathcal{L}_\phi + \mathcal{L}_{\gamma'} - \frac{1}{4} g_{\phi\gamma\gamma'} \phi F_{\mu\nu} \tilde{X}^{\mu\nu} \tag{1}$$

We impose a Z_2-symmetry in the dark sectors that forbid any other interaction between the visible and invisible sectors, then all the effects come from the coupling $g_{\phi\gamma\gamma'}$. The aim of the present work is to study the viability of this theory mainly through the cosmological stability and phenomenological effects in laboratories as well as astrophysical observations. For the sake of brevity we show the results assuming a massless ALP, however a broad range of masses has been considered in the original work [3] as well as other bounds no discussed here.

Cosmological stability

From the well-established ΛCDM paradigm the DM has been present from early times to nowadays. Then, a basic examination of the model is that the hidden photons DM must be long-lived to agree with the cosmological theory.
The **depletion** of the DM background can mainly happen through the process $\gamma' \to \gamma + \phi$. There are three different ways: spontaneous decay, Bose-enhanced and stimulated decay because of a photon background. In the former case the requirement is that the life-time must be at least the age of the universe

$$\Gamma_{\gamma' - \phi\gamma} = \frac{g^2_{\phi\gamma\gamma'}}{96\pi} \left(1 - \frac{m^2_\phi}{m^2_{\gamma'}}\right)^3 < \frac{1}{\tau_{uni}} \tag{2}$$

This bound is showed in the orange region of the summary plot.
On the other hand, the stimulated decay occurs because the HP DM background serves as an external "hidden" electric field that oscillates with frequency $m_{\gamma'}$

$$\mathbf{X} = \mathbf{X_0} \cos(m_{\gamma'}\, t), \tag{3}$$

then a **parametric resonance** regimen is possible when a external photon with momentum

$$k = \frac{(m^2_{\gamma'} - m^2_\phi)}{2 m_{\gamma'}} \tag{4}$$

is coming. If this resonance is reached the DM is depleted quickly and the photon number grows exponentially. Furthermore the contribution of Bose-enhanced decay increase the depletion process. Imposing the condition for the energy densities $\rho_\gamma < \rho_{dm}$ at every cosmological epoch we found the exclusion area where this model is unstable and then is not a DM model. Additionally, we look **CMB distortions** including the annihilation process $\gamma' + \gamma \to \phi$. By using FIRAS data we found the exclusion area CMB.

Stellar energy loss

The inner structure of a star can be modify due to non-standard interaction involving photons as our model incorporate. We focus on the **plasmons decay** process $\gamma^* \to \gamma' + \phi$ with decay rate

$$\Gamma_{\gamma^* \to \gamma'\phi} = \frac{g^2_{\phi\gamma\gamma'}}{96\pi} \frac{\omega^4_{pl}}{\omega}, \tag{5}$$

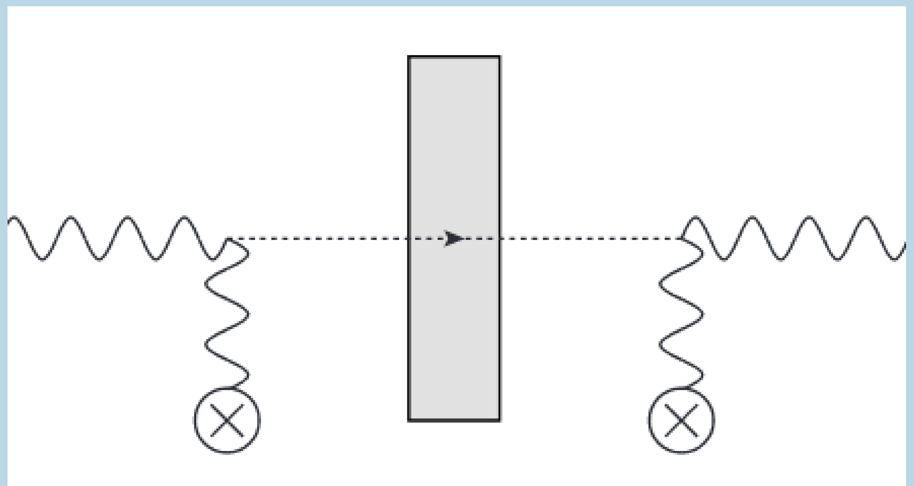
where ω_{pl} is the plasma mass that is a function of the star radius, then we have computed the anomalous energy loss rate

$$Q_{\gamma'\phi} = \frac{g^2_{\phi\gamma\gamma'}}{48\pi^3} \zeta_3 \omega^4_{pl} T^3, \tag{6}$$

The solar luminosity (volumetric integration of $Q_{\gamma'\phi}$) is currently constrained $L_{\gamma'\phi} < 0.1 L_\odot$ while for HB stars is customary to consider that dark emission per unit mass at the core can account for $\varepsilon_{\gamma'\phi} < 10$ erg s^{-1} gr^{-1}. We show these bounds in the blue region of the plot.

Laboratory bounds

Light Shining through Wall



Schematic representation of LSW experiment

The local DM halo act as a "hidden" electrical field given by (3). This external field allows that an incoming photon to have chances to undergo processes like: oscillation, "decay", and stimulate the decay of the DM. The probability to observe photons after the wall goes

$$P_{\gamma\gamma} \sim g^4_{\phi\gamma\gamma'} \rho^2_{dm} L^4. \tag{7}$$

The most stringent version of this experiment, the ALPS collaboration, gives an upper bound $P_{\gamma\gamma} \lesssim 10^{-25}$. The first version ALPS-I as well as the current running version ALPS-IIc can be found in the plot.

Helioscope
The ALP emission from plasmon decay in the Sun can also be constrained by earth-based experiment. Starting from the decay rate (5) we have computed the total flux of ALP arriving at the earth, that is given by

$$\Phi(\omega) = \frac{1}{4\pi d^2} \int_{Sun} dV \frac{2\omega}{\pi^2} \frac{\Gamma_{\gamma^* \to \gamma'\phi}}{e^{\omega/T} - 1}. \tag{8}$$

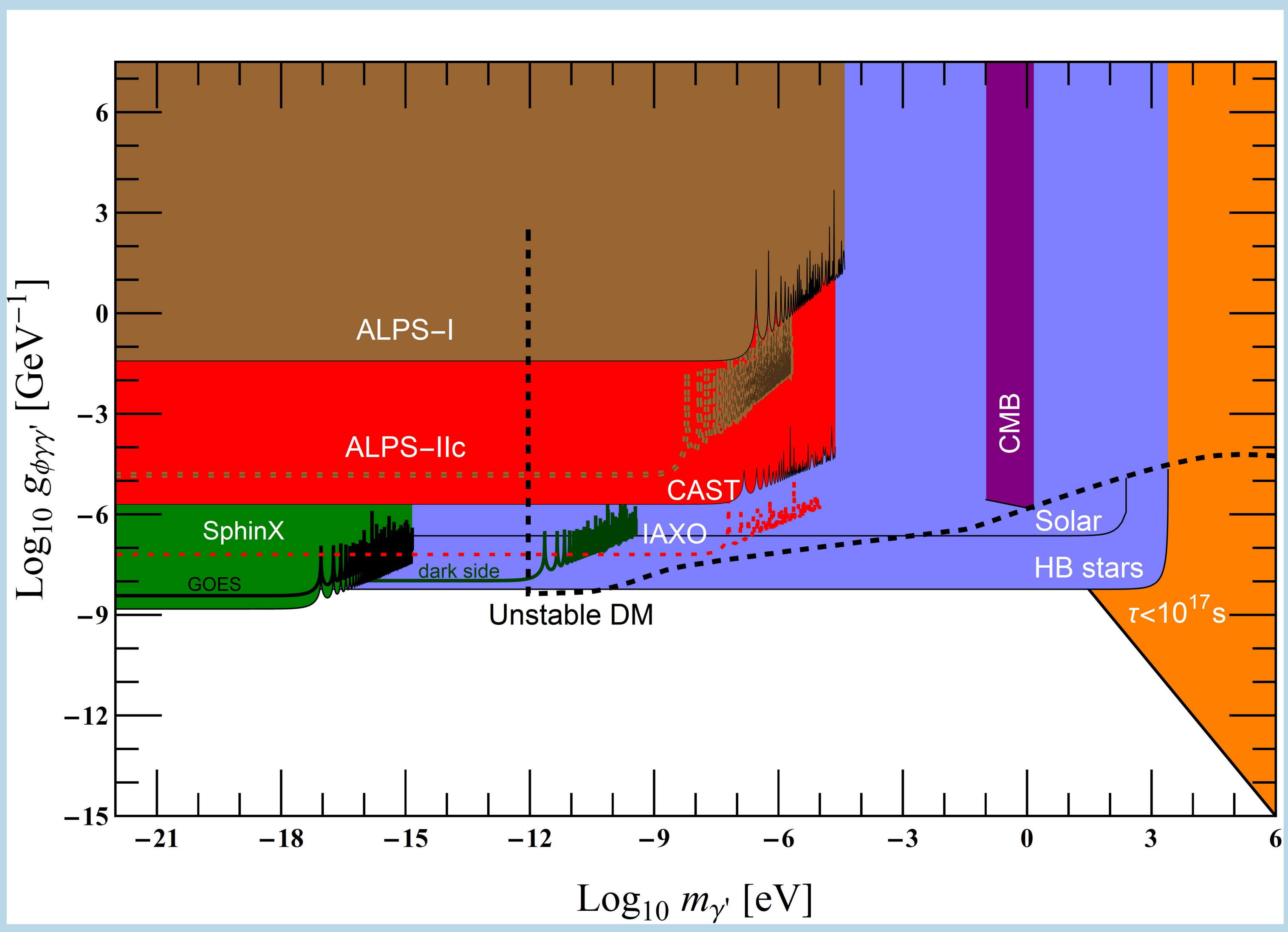
In addition, the ALP-photon conversion goes

$$P_{\phi\gamma} \sim g^2_{\phi\gamma\gamma'} \rho_{dm} L^2. \tag{9}$$

We have applied this result in the experiment CAST as can be seen in the red region of the exclusion plot. Moreover we include the parameter range that can potentially be cover by IAXO in future searches. See dashed red line in plot.

Exclusion plot

Extensive summary of several tests cosidering massless ALP. Extended version can be foun in [3].



References

[1] P. Arias, D. Cadamuro, M. Goodsell, J. Jaeckel, J. Redondo and A. Ringwald, "WISPy Cold Dark Matter," JCAP **06** (2012)
[2] P. Agrawal, N. Kitajima, M. Reece, T. Sekiguchi and F. Takahashi, Phys. Lett. B **801** (2020) [arXiv:1810.07188 [hep-ph]].
[3] P. Arias, A. Arza, J. Jaeckel and D. Vargas-Arancibia, [arXiv:2007.12585 [hep-ph]].