Two particle hidden sector

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Talk based on recent work with Paola Arias, Carlos Maldonado: arXiv:1710.08740 [hep-ph], and collaboration with string-pheno group lead by J. Conlon (Oxford U.).

Outline of the talk

- Motivation
- ALPs
- Hidden photons

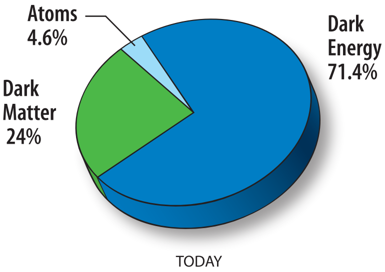
Our work:

- Two particle model for the hidden sector

DM is with us

Universe content: Λ CDM

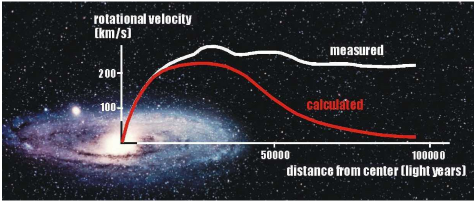
- CMB
- large-scale structure formation
- abundances of elements (H,He,Li)
- accelerating expansion of the universe



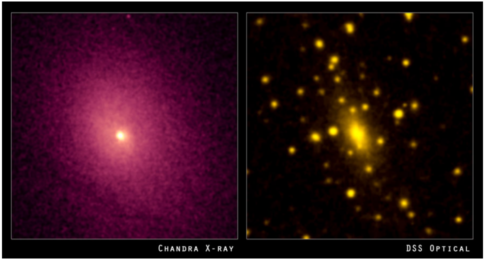
Credit: Courtesy of NASA

Evidence for dark matter

- Galaxies in clusters 30's, Zwicky
- Galaxy rotation velocity measurements 50's, Vera Rubin

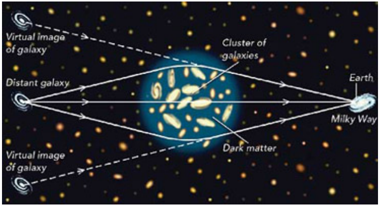


- Hot gas distribution in Hydra A

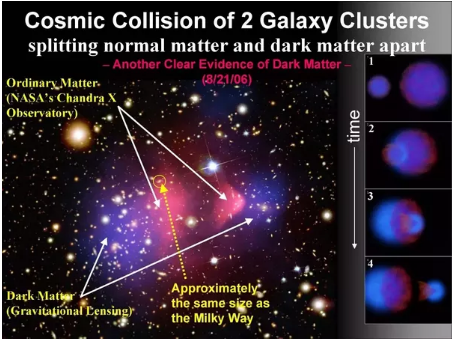


Evidence for dark matter

- Strong lensing



- Collisions of galaxy clusters, Bullet cluster



- Other effects: velocities of stars in dwarft galaxies, galaxy interactions, weak lensing

DM Candidates

Theoretically well motivated:

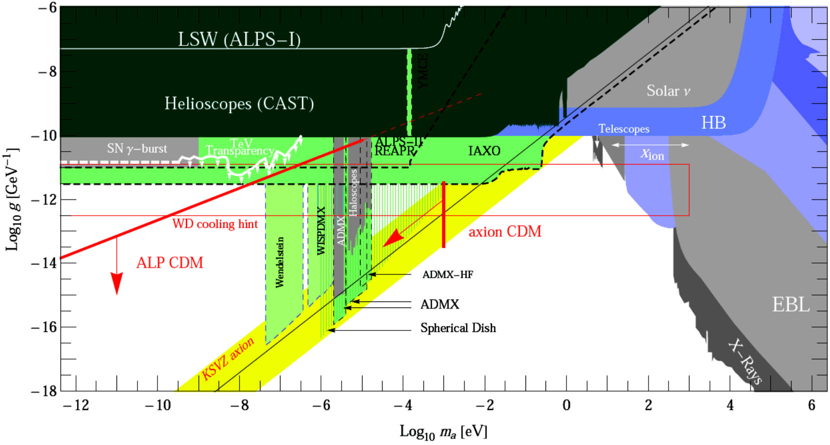
1. Neutralino, gravitino (susy$\rightarrow$hierarchy problem and cosmological constant problem)
2. sterile neutrinos (neutrino masses, baryon asymmetry if Majorana)
3. Axion and ALPs in the Peccei-Quinn extended SM (Strong CP problem, $U(1)$ extensions of the SM). For recent review, Ringwald arXiv:1612.08933v1 [hep-ph].

Extra hidden $U(1)$ (local) symmetry also motivates the introduction of hidden photons. Goodsell and Ringwald, arXiv:1002.1840v1 [hep-th].

$\rightarrow$ $U(1)$ extensions of the SM are a common feature in string theory motivated models. Very nice review: Quevedo's lectures at ICTP 2002.

List of searches (not complete)

- Stellar cooling
- Light shining through walls
- Helioscopes
- Axiondark matter searches (Haloscopes)
- Polarization experiments



Photon - ALP mixing: brief review

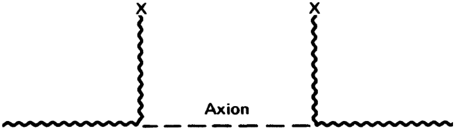
ALP - photon Lagrangian

$$\mathcal{L}_{a\gamma} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4M}aF_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\partial_\mu a\partial^\mu a - \frac{1}{2}m_a^2 a^2\,, \tag{1}$$

For general ALPs the coupling, $M = g_{a\gamma\gamma}^{-1}$ and the mass m_a are unspecified.
The coupling takes the form

$$\frac{1}{M}a\mathbf{E}\cdot\mathbf{B}\,. \tag{2}$$

$\rightarrow$ the ALP mixes with the photon by means of a transverse magnetic field.



$\rightarrow$ parameters m_a and M capture the low energy phenomenology.

Photon - ALP mixing: brief review

In the linearized field approximation, the propation of the system $\gamma - a$ reduces to a Schrödinger-like equation Raffelt, Stodolsky '87

$$\left[\omega + \begin{pmatrix} \Delta_\gamma & \Delta_{\rm F} & \Delta_{\gamma ay} \\ \Delta_{\rm F} & \Delta_\gamma & \Delta_{\gamma az} \\ \Delta_{\gamma ay} & \Delta_{\gamma az} & \Delta_a \end{pmatrix} - i\partial_x\right]\psi(x) = 0\,, \quad \psi(x) = \begin{pmatrix} A_y \\ A_z \\ a \end{pmatrix}\,, \tag{3}$$

where the refractive index and the plasma frequency are

$$\Delta_\gamma = -\frac{\omega_{\rm pl}^2}{2\omega}\,, \quad \omega{\rm pl} = \sqrt{\frac{4\pi\alpha n_e}{m_e}}\,, \tag{4}$$

n_e is the free electron density. We also neglect Faraday rotation terms $\Delta_{\rm F} \sim 0$. The mass of the axion appears in

$$\Delta_a = -\frac{m_a^2}{2\omega}\,, \tag{5}$$

and the axion-photon mixing is

$$(\Delta_{\gamma a})_i = \frac{B_i}{2M}\,. \tag{6}$$

Photon - ALP mixing: brief review

The propagation from of propagating from $x = x_0$ to $x = L/2$ as

$$\psi_f(x_0) = \mathcal{T}_x \left[\exp \left(-i\omega L \; - i \int_{x_0}^{L/2} \mathcal{M}(x) \mathrm{d}x \right) \right] \psi_i \,, \tag{7}$$

where

$$\mathcal{M}(x) = \left(\begin{array}{ccc} \Delta_\gamma(x) & 0 & \Delta_{\gamma ay}(x) \\ 0 & \Delta_\gamma(x) & \Delta_{\gamma az}(x) \\ \Delta_{\gamma ay}(x) & \Delta_{\gamma az}(x) & \Delta_a(x) \end{array} \right) . \tag{8}$$

Here, $\mathcal{T}_x$ denotes the 'x-ordering' operator.
For an initially pure ALP state $\psi_i = (0, 0, 1)$ at $x = x_0$, the $a \to \gamma$ conversion is then given by

$$P_{a \to \gamma}(x_0) = |\psi_{Ax}^\dagger \psi_f(x_0)|^2 + |\psi_{Ay}^\dagger \psi_f(x_0)|^2 \,, \tag{9}$$

Single domain result:

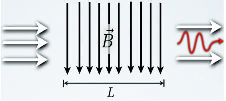
$$P(\gamma \to a) = \sin^2(2\theta)\sin^2\left(\frac{\Delta}{\cos 2\theta}\right), \tag{10}$$

with (for negligible m_a)

$$\theta \sim \frac{B_\perp \omega}{M n_e}, \quad \Delta \sim \frac{n_e L}{\omega}. \tag{11}$$

Small angle approximation:

$$P(a \to \gamma) \sim \frac{B_\perp^2 L^2}{4M^2}, \tag{12}$$

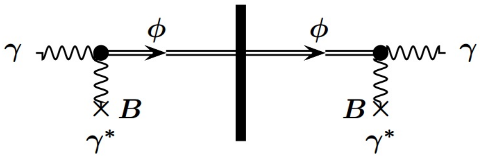


Conversion main features:

- Grows with $B_\perp^2$ $\to$ big fields.
- Grows with L^2 $\to$ B must be coherent over large distances.
- Drops off with M^2 $\to$ suppressed by weak couplings.

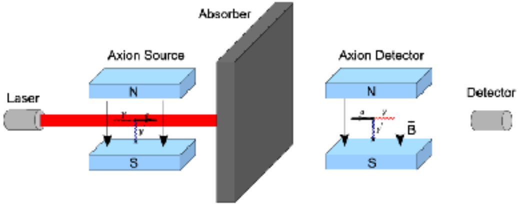
Light shining trough a wall (ALP case)

LSW setup (picture taken from ALPS - DESY website)



Remark: A M^{-4} suppression factor in light shining trough a wall and solar axion production.

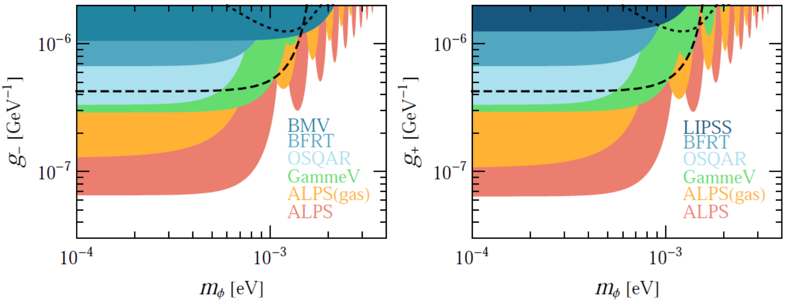
ALPS-I arXiv:1004.1313 [hep-ex]: $B \sim 5$T, $L \sim 10$ m, $\omega \sim 2.33$ eV, Power$\sim$ 1kW



$P \sim 10^{-25}$

Light shining trough a wall (LSW) (ALP case)

Exclusion limits (95% C.L.) for pseudoscalar (left) and scalar (right) axion-like-particles



Photon - HP mixing

Low energy effective Lagrangian:

$$\mathcal{L} \supset -\frac{1}{4g_a^2} F_{\mu\nu}^{(a)} F_{(a)}^{\mu\nu} - \frac{1}{4g_b^2} F_{\mu\nu}^{(b)} F_{(b)}^{\mu\nu} + \frac{\chi_{ab}}{2g_a g_b} F_{\mu\nu}^{(a)} F^{(b)\mu\nu} + m_{ab}^2 A_\mu^{(a)} A^{(b)\mu}, \tag{13}$$

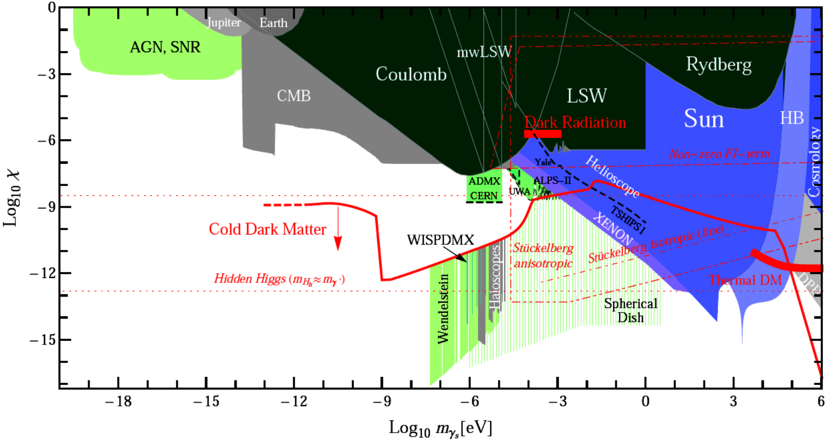
$\rightarrow$ dimensionless kinetic mixing parameter χ_{ab} is generated at an arbitrarily large scale, it does not suffer mass suppression $\Rightarrow$ fantastic window to high energy physics!

$\rightarrow$ mass mixing term comes from Stückelberg mechanism in string theory.

Review Abel, Goodsell, Jaeckel, Khoze, Ringwald 2008.
The conversion probability in vacuum is given by

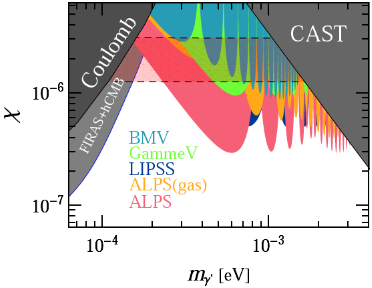
$$P(\gamma \rightarrow \gamma') = 4\chi^2 \sin^2\left(\frac{m_\gamma'^2 L}{4\omega}\right) \tag{14}$$

Exclusion limits for hidden photons



Light shining trough a wall (LSW) (HP case)

Exclusion limits (95% C.L.) for hidden photons



Model with two particles in the hidden sector

PA, Arias P., Maldonado, C., arXiv:1710.08740 [hep-ph]
Let us consider the effective Lagrangian for the model

$$\mathcal{L} = -\frac{1}{4} f_{\mu\nu} f^{\mu\nu} - \frac{1}{4} x_{\mu\nu} x^{\mu\nu} + \frac{1}{2} \partial_\mu \phi \partial^\mu \phi + \frac{1}{2} \sin\chi f_{\mu\nu} x^{\mu\nu} + \frac{1}{4} g \phi x_{\mu\nu} \tilde{x}^{\mu\nu} - \frac{m_\phi^2}{2} \phi^2 + \frac{m_{\gamma'}^2 \cos^2\chi}{2} x_\mu x^\mu, \tag{15}$$

introduced in 2014 Jaeckel et al. (motivated by the 3.5 keV line).
Interactions between the ALP field and the photon will emerge via hidden photon mixing

$$X_\mu = x_\mu - \sin\chi a_\mu \tag{16}$$

$$A_\mu = a_\mu \cos\chi. \tag{17}$$

And the Lagrangian in this new basis reveals the interaction states

$$\begin{aligned} \mathcal{L}' = & - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} + \frac{1}{2} \partial_\mu \phi \partial^\mu \phi + \frac{1}{4} g \phi X_{\mu\nu} \tilde{X}^{\mu\nu} + \frac{g}{2} \tan\chi \phi X_{\mu\nu} \tilde{F}^{\mu\nu} \\ & + \frac{g}{4} \tan^2\chi \phi F_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{m_\phi^2}{2} \phi^2 + \frac{m_{\gamma'}^2 \cos^2\chi}{2} \left(X_\mu X^\mu + 2\tan\chi X_\mu A^\mu + \tan^2\chi A_\mu A^\mu \right). \end{aligned} \tag{18}$$

Linearized equations

Following Raffelt 1987, we can obtain a linearized set of equations. We will assume:

- a coherent source of frequency ω propagating into the $\hat{z}$ direction.
- spatial extent of the photon beam transverse to $\hat{z}$ is much bigger than the wavelength
- presence of an external homogeneous magnetic field $\vec{B}$, oriented in the $\hat{x}$ direction
- no external hidden field is present
- external electromagnetic field is much stronger than the photon source $|\vec{A}_{\rm ext}| \gg |\vec{A}|$, and that terms of the form $\phi|\vec{A}|$, $|\vec{A}||\vec{X}|$, $\phi|\vec{X}|$ can be neglected.
- The gauge $\partial_i A_i = 0$ and $A_0 = X_0 = 0$.

EOM:

$$-({\partial_t}^2 - \vec{\nabla}^2)\vec{A} - g\tan^2\chi\,\partial_t\phi\vec{B} = m^2_{\gamma'}(\sin^2\chi\,\vec{A} + \cos\chi\sin\chi\,\vec{X}) \tag{19}$$

$$({\partial_t}^2 - \vec{\nabla}^2)\phi + m^2_\phi = g\tan\chi\,\partial_t\vec{X}\cdot\vec{B} + g\tan^2\chi\,\partial_t\vec{A}\cdot\vec{B} \tag{20}$$

$$-({\partial_t}^2 - \vec{\nabla}^2)\vec{X} - g\tan\chi\partial_t\phi\vec{B} = m^2_{\gamma'}\cos^2\chi\left(\vec{X} + \tan\chi\,\vec{A}\right). \tag{21}$$

Schrödinger-like equation

Plane wave approximation is a good one:

$$\vec{A}(z,t) = e^{i\omega t}\vec{A}(z), \quad \phi(z,t) = e^{i\omega t}\phi(z), \quad \vec{X}(z,t) = e^{i\omega t}\vec{X}(z) \tag{22}$$

Taking the expansion[1] $(\omega^2 + \partial_z{}^2) \approx 2\omega(\omega - i\partial_z)$, we finally find:

$$\left(\omega - i\partial_z - \frac{m^2_{\gamma'}}{2\omega}\begin{pmatrix} \sin^2\chi & \sin\chi\cos\chi \\ \sin\chi\cos\chi & \cos^2\chi \end{pmatrix}\right)\begin{pmatrix} A_\perp \\ X_\perp \end{pmatrix} = 0, \tag{23}$$

$$\left(\omega - i\partial_z - \frac{1}{2\omega}\begin{pmatrix} m^2_{\gamma'}\sin^2\chi & m^2_{\gamma'}\sin\chi\cos\chi & gB\omega\,\tan^2\chi \\ m^2_{\gamma'}\sin\chi\cos\chi & m^2_{\gamma'}\cos^2\chi & gB\omega\,\tan\chi \\ gB\omega\,\tan^2\chi & gB\omega\,\tan\chi & m^2_\phi \end{pmatrix}\right)\begin{pmatrix} A_\parallel \\ X_\parallel \\ \phi \end{pmatrix} = 0. \tag{24}$$

With the linearisation we obtain a first order differential equation of Schroedinger-type,

$$i\partial_z\psi(z) = H\psi(z)$$

where

$$\psi(z) = \left\{A_\parallel(z), X_\parallel(z), \phi(z)\right\}\ .$$

[1] Valid if the variation of the external field is negligible compared to photon wavelength and further the relativistic approximation $\omega + k \sim 2\omega$.

Oscillations: mixing angles

Let us introduce a 3×3 rotation matrix, such that

$$\begin{pmatrix} A_{\parallel} \\ X_{\parallel} \\ \phi \end{pmatrix} = R \begin{pmatrix} A'_{\parallel} \\ X'_{\parallel} \\ \phi' \end{pmatrix}; \qquad R^T R = I, \quad \det(R)^2 = 1. \tag{25}$$

the primed states in the equation above are propagation (mass) eigenstates, whose dispersion relation is given by

$$\begin{aligned} \omega_1 &= \omega = k, & (26) \\ \omega_2 &= \omega - \Omega - \Delta & (27) \\ \omega_3 &= \omega - \Omega + \Delta. & (28) \end{aligned}$$

Where the functions Ω and Δ are defined respectively as

$$\Omega \equiv \frac{m_{\gamma'}^2 + m_\phi^2}{4\omega}, \qquad \Delta \equiv \frac{gB}{2\cos^2\chi}\sqrt{\sin^2\chi + x^2\cos^4\chi}, \qquad x \equiv \frac{m_{\gamma'}^2 - m_\phi^2}{2gB\omega}. \tag{29}$$

A convenient parametrisation of this matrix is given in terms of two angles, θ, χ

$$R = \begin{pmatrix} \cos\chi & \cos\theta\sin\chi & -\sin\theta\sin\chi \\ -\sin\chi & \cos\theta\cos\chi & -\cos\chi\sin\theta \\ 0 & \sin\theta & \cos\theta. \end{pmatrix} \tag{30}$$

Where,

$$\sin\theta = \frac{\sin\chi}{\sqrt{\mathcal{F}^2 + \sin^2\chi}}, \qquad \mathcal{F} = \left(x + \frac{2\Delta}{Bg}\right)\cos^2\chi. \tag{31}$$

Conversion probabilities single domain

The probability that after traveling a distance z from the source, a photon will convert into an ALP, HP or remain a photon, is given respectively by

$$P_{\gamma_\parallel \to \gamma'_\parallel} = 4\cos^2\chi \sin^2\chi \left(\cos^2\theta \sin^2\left(\frac{\delta_1+\delta_2}{2}\right) + \sin^2\theta \sin^2\left(\frac{\delta_1-\delta_2}{2}\right) - \cos^2\theta \sin^2\theta \sin^2\delta_1 \right) , \quad (32)$$

$$P_{\gamma \to \phi} = 4\sin^2\chi \cos^2\theta \sin^2\theta \sin^2\delta_1 \, . \quad (33)$$

and $P_{\gamma_\parallel \to \gamma_\parallel}(z) = 1 - P_{\gamma_\parallel \to \gamma'_\parallel} - P_{\gamma_\parallel \to \phi}$. In (32) and (33) we have defined the oscillation angles by

$$\delta_1 = \Delta z \, , \qquad \delta_2 = \Omega z \, . \quad (34)$$

For the perpendicular component of the beam, the probability of oscillation to hidden photons it is known, but we write it by completeness

$$P_{\gamma_\perp \to \gamma'_\perp} = 4\sin^2\chi \cos^2\chi \sin^2\left(\frac{m^2_{\gamma'} z}{4\omega}\right) . \quad (35)$$

Limiting cases

- Strong mixing regime: $|x| \ll \sin\chi \ll 1 \Rightarrow \theta \sim \pi/4$
- Weak mixing regime: $\sin\chi \ll |x| \ll 1 \Rightarrow \theta \sim 0, \pi/2$
- Very-weak mixing regime: $\sin\chi \ll 1 \ll |x| \Rightarrow \theta \sim 0, \pi/2$ (total decoupling of the ALP to the other particles)

Oscillation angles

For benchmark values such as $B = 5\,\mathrm{T}$, $z \sim 10\,\mathrm{m}$ and $\omega = 2.33\,\mathrm{eV}$, we get the following approximate expressions for the oscillation angles

$$\delta_1 \approx 2\pi \left(\frac{z}{10\,\mathrm{m}}\right) \begin{cases} \left(\frac{B}{5\,\mathrm{T}}\right) \left(\frac{g\chi}{3\times 10^{-10}\,\mathrm{eV}^{-1}}\right), & \text{if} \quad |x| < \sin\chi \\ \left(\frac{2.33\,\mathrm{eV}}{\omega}\right) \frac{m_{\gamma'}^2 - m_\phi^2}{(10^{-3}\,\mathrm{eV})^2}, & \text{if} \quad |x| > \sin\chi \end{cases} \tag{36}$$

$$\delta_2 \approx 2\pi \left(\frac{z}{10\,\mathrm{m}}\right) \left(\frac{2.33\,\mathrm{eV}}{\omega}\right) \frac{m_{\gamma'}^2 + m_\phi^2}{(10^{-3}\,\mathrm{eV})^2} \tag{37}$$

$\rightarrow$ small δ_1-angle regime for sufficiently small couplings, $g \sin\chi < 3 \times 10^{-10}\,\mathrm{eV}^{-1}$, in case (I) ($|x| < \sin\chi$) or when $|m_{\gamma'}^2 - m_\phi^2| < (10^{-3}\,\mathrm{eV})^2$, in case (II) or (III) ($|x| > \sin\chi$). The latter occurs when either both masses are smaller than meV or when we have fine tuning of the masses.

$\rightarrow$ small δ_2-angle regime occurs for $|m_{\gamma'}^2 + m_\phi^2| < (10^{-3}\,\mathrm{eV})^2$

$\rightarrow$ In the small-angles regime we do not need to worry about conversion probabilities arriving at a minima at the detector.

LSW probabilities

It can be easily check that $P_{\gamma_\parallel \to \mathcal{W} \to \gamma_\parallel} = |P_{\gamma_\parallel \to \phi}(L) + P_{\gamma_\parallel \to \gamma'_\parallel}(L)|^2$, the explicit expression is given by

$$P_{\gamma_\parallel \to \mathcal{W} \to \gamma_\parallel} = \quad 16 \sin^4 \chi \left(\cos^2 \chi \left(\sin^2 \theta \sin^2 \left(\frac{\delta_1 - \delta_2}{2} \right) + \cos^2 \theta \sin^2 \left(\frac{\delta_1 + \delta_2}{2} \right) \right) \right. \\ \left. + \sin^2 \chi \sin^2 \theta \cos^2 \theta \sin^2 \delta_1 \right)^2 , \tag{38}$$

The perpendicular component, $P_{\gamma_\perp \to \mathcal{W} \to \gamma_\perp} = P_{\gamma_\perp \to \gamma'_\perp}(L)^2$, is given by

$$P_{\gamma_\perp \to \gamma'_\perp}(L) = 16 \sin^4 \chi \cos^4 \chi \sin^4 \left(\frac{m^2_{\gamma'}, L}{4\omega} \right) \tag{39}$$

The total probability for photon regeneration has to include both parallel and perpendicular components with appropriate weights in order to take into account the polarization of the beam,

$$P_{\mathrm{LSW}} = w_\parallel P_{\gamma_\parallel \to \mathcal{W} \to \gamma_\parallel} + w_\perp P_{\gamma_\perp \to \mathcal{W} \to \gamma_\perp} . \tag{40}$$

LSW probabilities, limiting cases

Case (I), $|x| \ll \sin\chi$*:*

$$P_{\gamma_\parallel \to \mathcal{W} \to \gamma_\parallel} \approx 4\chi^4 (1 - \cos\delta_1 \cos\delta_2)^2 \,, \tag{41}$$

Oscillation can be suppressed when either one of the following conditions holds

$$\delta_1 \approx 2n\pi \quad \text{and} \quad \delta_2 \approx 2m\pi \,, \quad m, n \in \mathbb{Z} \,, \tag{42}$$

or

$$\delta_1 \approx (2n+1)\pi \quad \text{and} \quad \delta_2 \approx (2m+1)\pi \,, \quad m, n \in \mathbb{Z} \,. \tag{43}$$

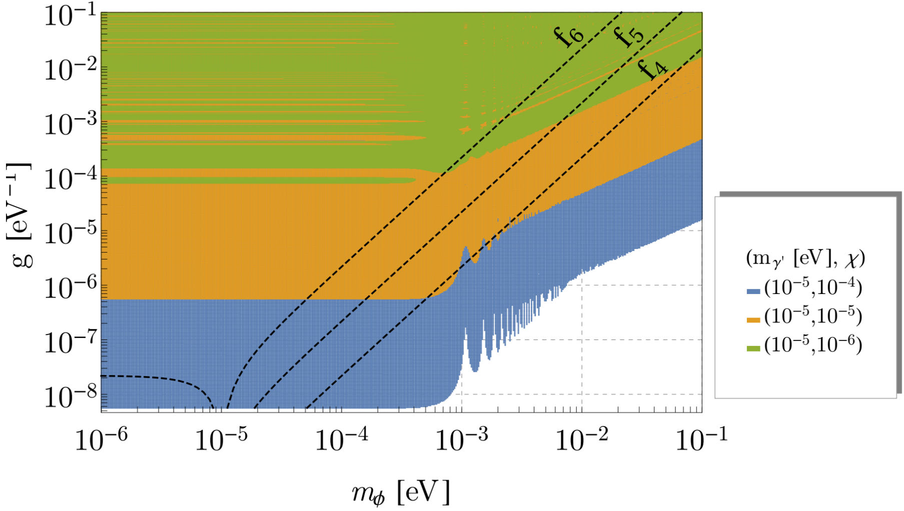
Cases (II) and (III), $\sin\chi \ll |x|$*:*

$$P_{\gamma_\parallel \to \mathcal{W} \to \gamma_\parallel} \approx 16\chi^4 \sin^4\left(\frac{m_{\gamma'}^2 L}{4\omega}\right) + O(\chi^6/x^2) \,. \tag{44}$$

There is effectively a single oscillation angle that depends on the mass of the hidden photon only. We can have suppression in the probability when $\frac{m_{\gamma'}^2 L}{4\omega} \approx \pi n$ (n an integer), in which case we need to consider the subleading term

$$O(\chi^6/x^2) = \frac{8\chi^6}{x^2} \sin\delta_1 \sin^2\left(\frac{m_{\gamma'}^2 L}{4\omega}\right) \left(\mp \sin\delta_2 + \sin\delta_1 \chi^2\right) \,. \tag{45}$$

The subleading term would restore a dependence in m_ϕ of the probability.



10^{-1}
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10^{-8}
g [eV^{-1}]
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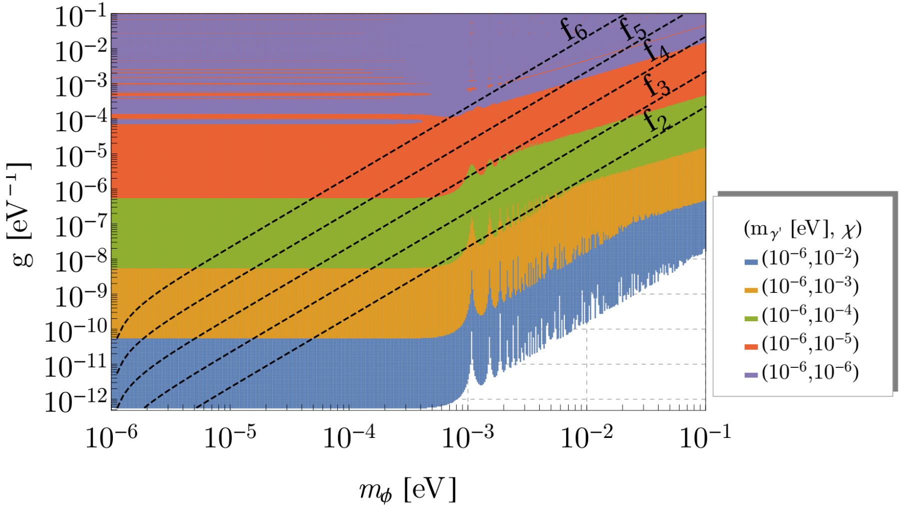
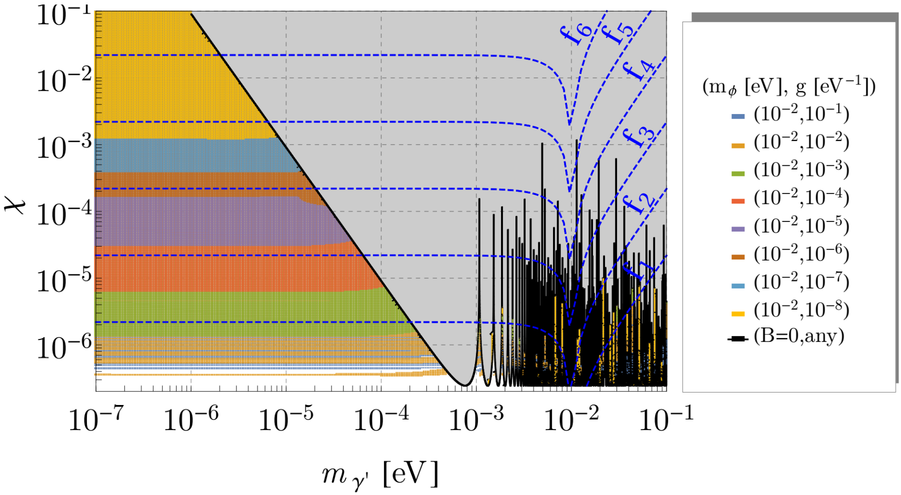
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
m_ϕ [eV]
($m_{\gamma'}$ [eV], χ)
(10^{-5},10^{-4})
(10^{-5},10^{-5})
(10^{-5},10^{-6})

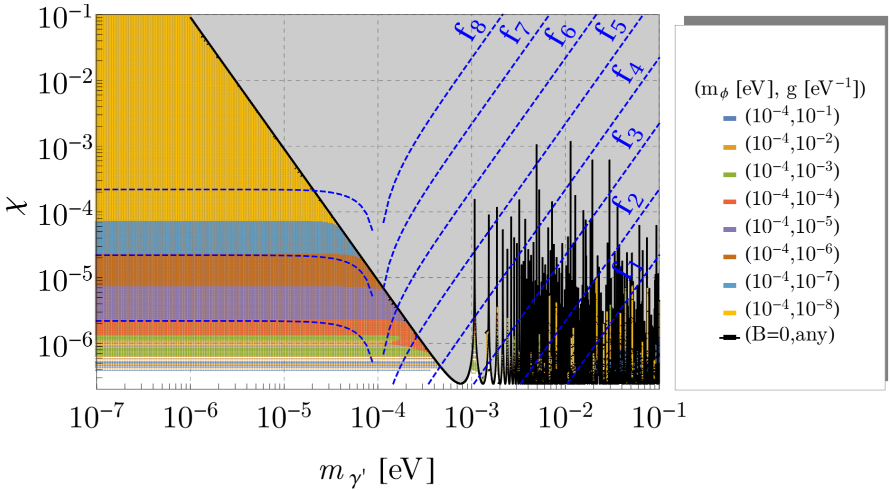
Exclusion plots using ALPS-I



Exclusion plots using ALPS-I



Exclusion plots using ALPS-I



Concluding remarks

- If DM is not detected we will have to face the challenges of models with more than one particle in the hidden sector.
- In case of positive detection we need to determine the features that would allow us to distinguish single particle models and models with more than one particle in the hidden sector.

Present task: determine unique signatures of a two particle model in astronomical setups or cosmological setups ω_{pl}, $B(x)$, problem is more difficult.

Thank you for your attention and happy birthday Marcelo!