Dark photon searches with atomic transitions

C. Álvarez Luna   J. A. R. Cembranos

Departamento de Física Teórica
Universidad Complutense de Madrid
and IPARCOS

4th April 2019

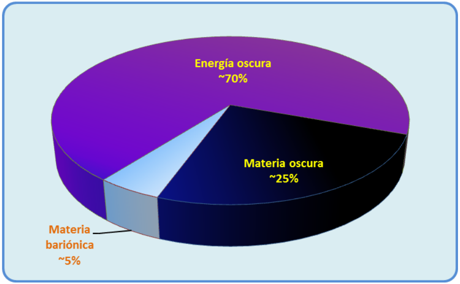
arXiv:1812.08501 [hep-ph]

c.a.luna@ucm.es

Contents

Introduction

- Dark matter



- Some posible candidates
  - WIMPs
  - Axions
  - WISPs $\rightarrow$ dark photons:

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U'(1)$$

Dark photons

Lagrangian for two $U(1)'s$: M, χ

$$\mathcal{L} = -\frac{1}{4}\left(F^{\mu\nu}F_{\mu\nu} + \phi^{\mu\nu}\phi_{\mu\nu} + 2\chi\phi^{\mu\nu}F_{\mu\nu}\right) - \frac{M^2}{2}\phi_\mu\phi^\mu - J_\mu A^\mu$$

Mass lagrangian: *massive* ans *massless* photons

$$A \to A - \chi\phi, \qquad \phi \to \phi + \mathcal{O}(\chi^2)$$

$$\mathcal{L} = -\frac{1}{4}\left(F^{\mu\nu}F_{\mu\nu} + \phi^{\mu\nu}\phi_{\mu\nu}\right) - \frac{M^2}{2}\phi_\mu\phi^\mu - J_\mu(A^\mu - \chi\phi^\mu)$$

Flavor lagrangian: *interacting* and *sterile* photons

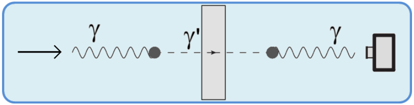
$$\tilde{A} = A - \chi\phi, \qquad \tilde{\phi} = \phi + \chi A$$

$$\mathcal{L} = -\frac{1}{4}\left(\tilde{F}^{\mu\nu}\tilde{F}_{\mu\nu} + \tilde{\phi}^{\mu\nu}\tilde{\phi}_{\mu\nu}\right) - \frac{M^2}{2}(\tilde{\phi}_\mu - \chi\tilde{A}_\mu)(\tilde{\phi}^\mu - \chi\tilde{A}^\mu) - J_\mu\tilde{A}^\mu$$

Current state of dark photon detection experiments

Photon - dark photon oscillation

- *Light shining through a wall*: $\rightarrow \chi \gtrsim 10^{-6}$
  - GammeV
  - BMW
  - LIPSS
  - ALPS



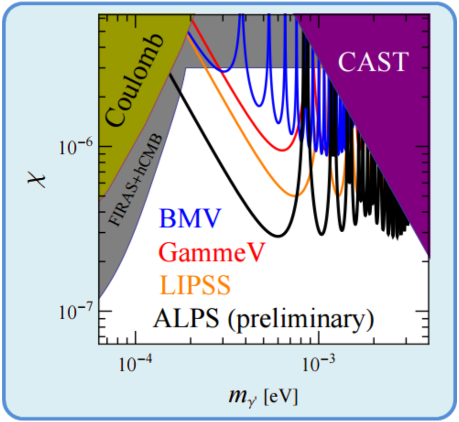
- Cavity experiments: ADMX $\rightarrow \chi \gtrsim 10^{-9}$
- Helioscopes $\rightarrow$ higher masses:
  - CAST (solar)
  - HB (horizontal branch stars)
  - Red Giant stars

etc.

Current state of dark photon detection experiments

Other bounds:

- Tests of the Coulomb $1/r^2$ law: $V(r) = \frac{\alpha}{r}\left(1 + \chi^2 e^{-Mr}\right)$
- Cosmic microwave background analyses (CMB): FIRAS



Jaeckel, Ringwald, arXiv:1002.0329v1 [hep-ph]

Dark photon - matter interaction

Coupling to fermions:

$$\mathcal{L}_{\gamma'\bar{\psi}\psi} = -q\chi\bar{\psi}\gamma^{\mu}A'_{\mu}\psi$$

Complete DP-matter interaction hamiltonian

$$H = -\frac{\nabla^2}{2m} + i\frac{q\chi}{2m}\left[\vec{\nabla}\cdot\vec{A}'(\vec{r},t) + \vec{A}'(\vec{r},t)\cdot\vec{\nabla}\right] + \frac{(q\chi)^2}{2m}\vec{A}'^2(\vec{r},t) - \chi\vec{\mu}\cdot\vec{B}'(\vec{r},t) + q\chi\phi'(\vec{r},t) + V(\vec{r})$$

We will focus on the coupling to the DP magnetic field. Study can be extended to other couplings.

Sikivie, arXiv:1409.2806v1 [hep-ph]

Yang, Di, arXiv:1606.01492v5 [hep-ph]

Atomic transitions induced by dark photons

DP-matter interaction hamiltonian

$$H = -\chi(\mu_e \vec{S} + \mu_N \vec{I}) \cdot \vec{B}'$$

$\vec{S}$: electron spin, $\vec{I}$: nuclear spin, μ_i: magnetic moments

Transition rate $|0\rangle \to |i\rangle$ on resonance

$$\mathcal{R}_i = \frac{2\chi^2}{M} \text{mín}(t, t_i, t') \cdot \int \mathrm{d}^3 p \frac{\mathrm{d}^3 n}{\mathrm{d} p^3}(\vec{p}) \sum_{\alpha=1}^{3} |\langle i| (\mu_e \vec{S} + \mu_N \vec{I}) \cdot (\vec{p} \times \vec{\xi}_\alpha) |0\rangle|^2$$

Resonance condition: $M = E_i - E_0$

t: measurement integration time

t_i: mean life of excited atomic state

$t'^{-1} = \delta E / 2\pi$: coherence time of DP signal

Atomic transitions induced by dark photons

Local DP energy density:

$$\rho = M \int \mathrm{d}^3 p \, \frac{\mathrm{d}^3 n}{\mathrm{d} p^3}(\vec{p})$$

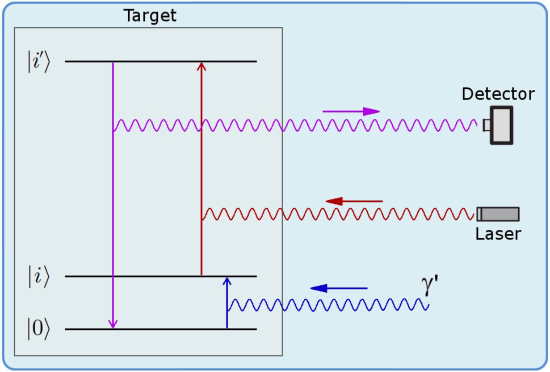
Effective coupling strength of the DP to the target

$$g_i^2 \bar{v}^2 M \rho \, \mu_B^2 \equiv \int \mathrm{d}^3 p \, \frac{\mathrm{d}^3 n}{\mathrm{d} p^3}(\vec{p}) \, |\vec{p}|^2 \, | \langle i | \left(\mu_e \vec{S} + \mu_N \vec{I} \right) |0\rangle \, |^2$$

$\Rightarrow$ transition rate per mole:

$$N_A \mathcal{R}_i = g_i^2 N_A \frac{4}{3} \chi^2 \bar{v}^2 \rho \mu_B^2 \, \text{mín}(t, t_i, t')$$

Experimental setup



Energy of $|i\rangle$ can be adjusted by Zeeman effect

Target temperature → target in ground ground state

$$N_A e^{-M/T} < 0.1 \quad \Rightarrow \quad T < 203 \text{ mK} \left(\frac{M}{\text{meV}} \right)$$

Experimental setup

Events per mole of target on resonance

$$\frac{\#\text{events}}{\text{mole}} = 0.5\ g_i^2 \left(\frac{\chi}{10^{-13}}\right)^2 \left(\frac{\text{meV}}{M}\right) \left(\frac{\rho}{\text{GeV}/\text{cm}^3}\right) \left(\frac{\bar{v^2}}{10^{-6}}\right)$$

Bound on the effective coupling ($N > 3/\epsilon$ for 95 % C.L.)

$$g_i > 2.5 \sqrt{\left(\frac{1}{\epsilon}\right) \left(\frac{A\ \text{g}}{M_{tar}}\right) \left(\frac{10^{-13}}{\chi}\right)^2 \left(\frac{M}{\text{meV}}\right) \left(\frac{\text{GeV}/\text{cm}^3}{\rho}\right) \left(\frac{10^{-6}}{\bar{v^2}}\right)}$$

$$\Rightarrow g_i > 0.09 \left(\frac{10^{-13}}{\chi}\right)$$

$$\epsilon = 0.6,\ \rho = 1\ \text{GeV}/\text{cm}^{-3},\ \bar{v^2} = 10^{-6},\ A \leq 150,\ M_{tar} = 10^3\ \text{g}\ (T/\text{mK})$$

Coupling of a DP to the target

Coupling to electrons ($\vec{S}$)

$$g_i = \frac{1}{\sqrt{2}} \left(\frac{\mu_e}{\mu_B} \right) = 0.708$$

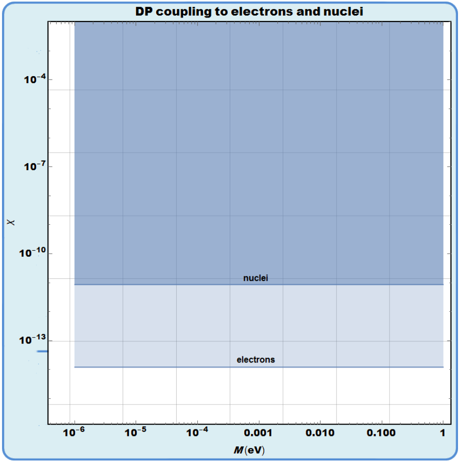
$$\Rightarrow \chi > 1.22 \cdot 10^{-14}$$

Coupling to nuclei ($\vec{I}$)

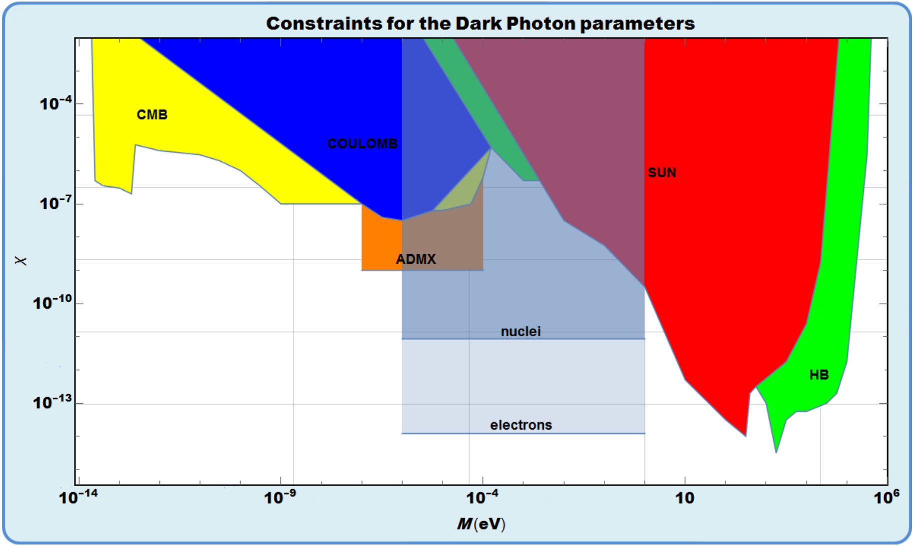
$$g_i = |\mathcal{M}| \left(\frac{\mu_N}{\mu_B} \right)$$

$$\chi > 0.09 \cdot 10^{-13} \left(\frac{\mu_B}{\mu_N} \right) \left(\frac{1}{|\mathcal{M}|} \right)$$

$$\Rightarrow \chi > 8.64 \cdot 10^{-12}$$



Comparison with other experiments



Conclusions

Summary:

- Dark photon: viable dark matter cadidate
- Possible interaction suppressed by $\chi \to$ detection
  - Photon-dark photon oscillation: LSTAW
  - Effective coupling to matter: atomic transitions induced on a target

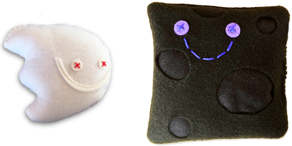
Results:

- Sensitivity for $M \sim \mathrm{meV}$: $\chi \sim 10^{-11} - 10^{-14}$
- Improvement of $7 - 8$ orders of magnitude with respect to previous experiments

Future insight:

- Study the effects of the setup components
- Choosing an appropriate material for the target
- Possible extension to different DM models

Thank you for your attention



arXiv:1812.08501 [hep-ph]

c.a.luna@ucm.es