Dark photon searches with atomic transitions

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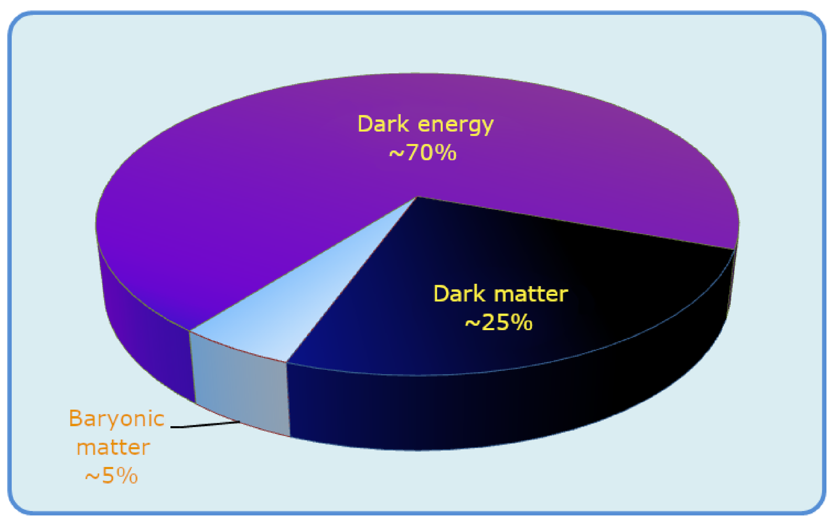
1. Introduction



Motivation: dark matter problem $\rightarrow$ candidates:

- WIMPs
- Axions
- WISPs $\rightarrow$ dark photons (DP):

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

Lagrangian for describing two $U(1)s$: parameters 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

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

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

Flavor lagrangian: *interacting* and *sterile* photons

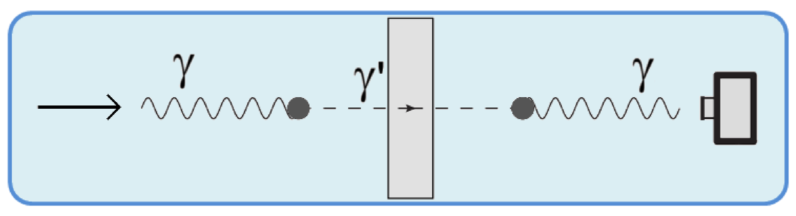
$$\tilde{A} = A - \chi\phi, \qquad \tilde{\phi} = \phi + \chi A$$

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

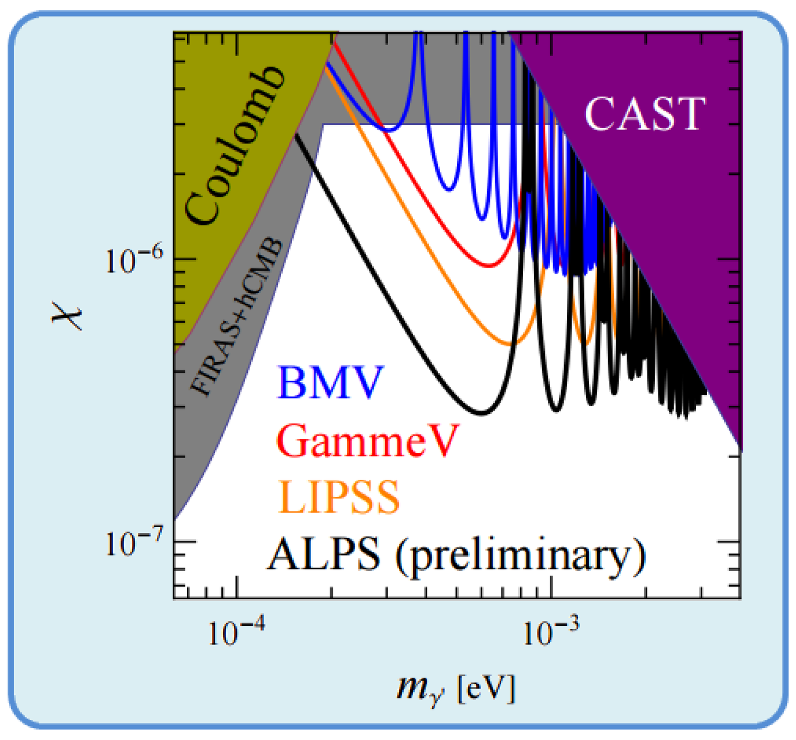
2. Current state of DP detection experiments

Experiments based on photon - DP oscillation

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

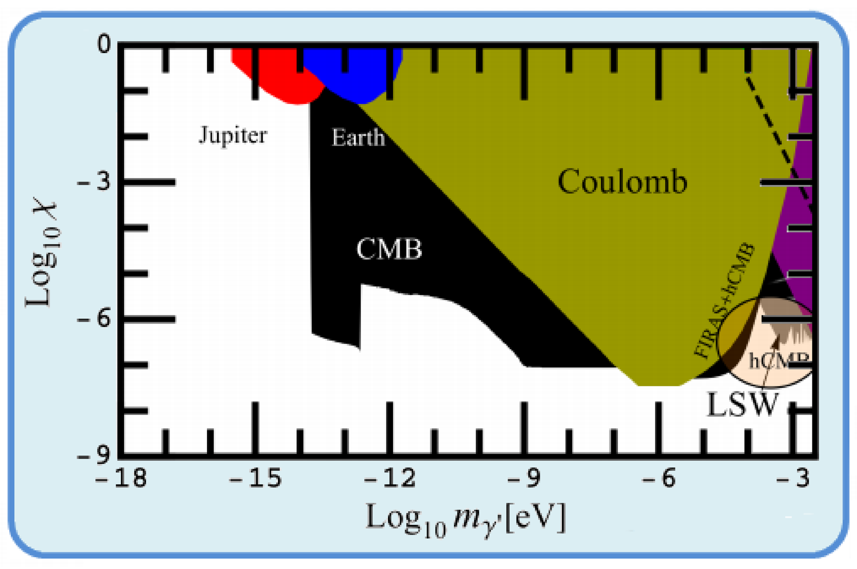


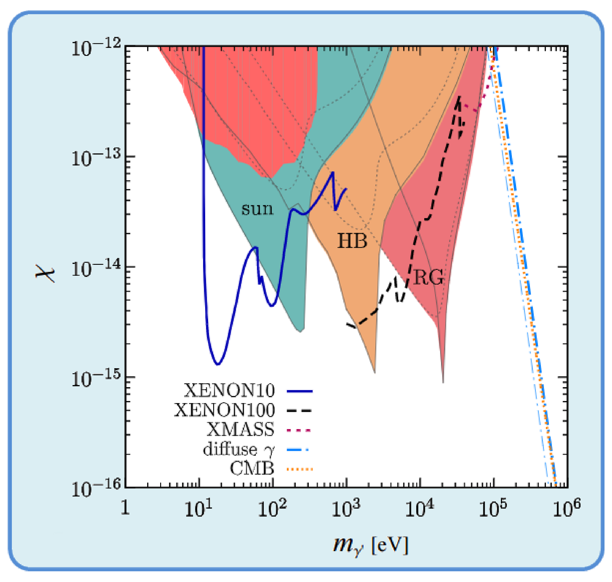
- Haloscope microwave cavity experiments: ADMX $\rightarrow \chi 10^{-9}$
- Helioscopes $\rightarrow$ higher masses:
  - solar: CAST and future IAXO
  - horizontal branch stars (HB)
  - Red Giant stars (RG)



Other experimental tests

- 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





3. Atomic transitions induced by DPs

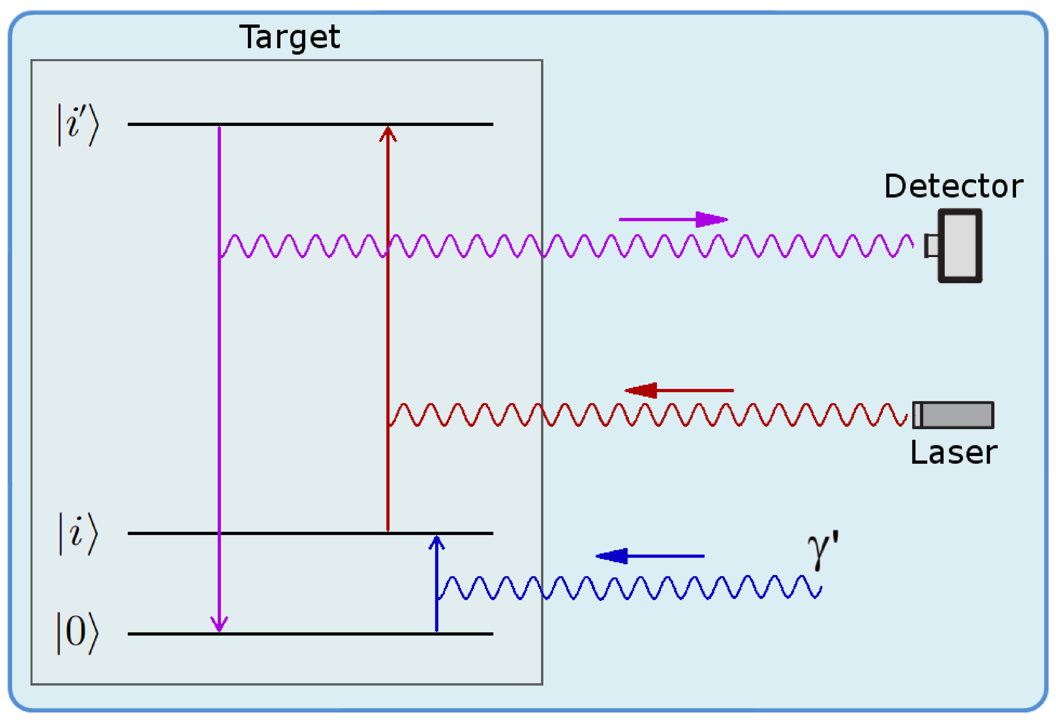
DP - matter interaction hamiltonian: χ suppression

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

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

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

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



Resonance condition:

$$M = E_i - E_0$$

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

Temperature: target in ground state

$$T < 203 \text{ mK}\left(\frac{M}{\text{meV}}\right)$$

Effective coupling strength of the DP to the target: g_i (dimensionless)

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

Events per mole of target on resonance $\sim tN_A\mathcal{R}_i$:

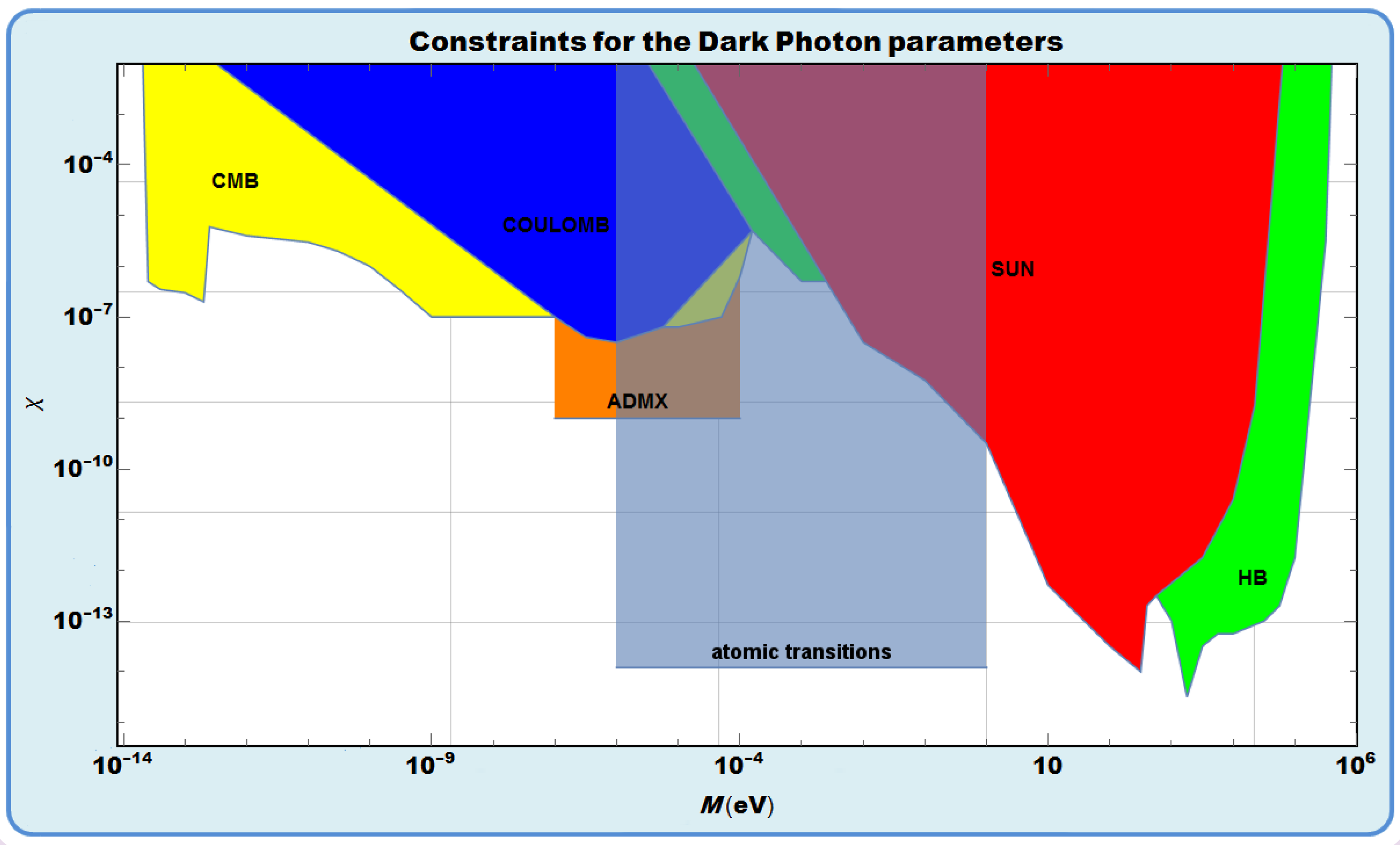
$$\frac{\#\text{events}}{\text{mole}} = 0.5\, g_i^2 \left(\frac{\chi}{10^{-13}}\right)^2 \left(\frac{\text{meV}}{M}\right)\left(\frac{\rho}{\text{GeV/cm}^3}\right)\left(\frac{\bar{v}^2}{10^{-6}}\right)$$

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

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

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

Coupling to electrons ($\vec{S}$): $g_i = \frac{1}{\sqrt{2}}\left(\frac{\mu_e}{\mu_B}\right) = 0.71 \Rightarrow \boldsymbol{\chi > 1.22 \cdot 10^{-14}}$



4. Conclusions and future work

- dark photon: viable dark matter candidate
- possible interaction with matter suppressed by $\chi \rightarrow$ detection
- atomic transitions: sensitivity of $\chi \sim 10^{-14}$ for M $\sim$ meV, improvement!

⋆ further study of the effects of the setup components
⋆ choosing appropriate target (e.g. transition metal & rare earth ions crystals)
⋆ same technique can be used for different dark matter candidates

References

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