Search for dark matter through Stark effect measurement with Rydberg atoms in microwave cavities

J. Gué, A. Hees, R. Le Targat, J. Lodewyck, P. Wolf

SYRTE
SYstèmes Références Temps-Espace, CNRS, Observatoire de Paris, Université PSL, Sorbonne Université, LNE

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Why do we need Dark Matter?

Explains astrophysical observations at different scales:

- **Galactic scale** (velocity rotation curves, weak lensing, ...)
- **Galactic cluster scale** (bullet cluster, strong lensing, ...)
- **Cosmological scale** (CMB, structure formation, ...)

Equation: $\Omega_M \approx 0.259$
Classes of DM

Fig. 1 from US cosmic vision: new idea for Dark Matter 2017, Arxiv:1707:04951
Ultralight Dark Matter (ULDM) models

\[
\frac{n}{n_k} \sim \frac{6\pi^2 \hbar^3}{c^2 m^4 \nu_{\text{max}}^3} \rho_{\text{DM}} \sim \frac{0.3 \text{ GeV/cm}^3}{10^{-3}c}
\]

\[< 10 \text{ eV}\]

\[\Rightarrow \text{ULDM (with } m < 10 \text{ eV) has to be bosonic (Pauli exclusion principle)} \]

• When \(m \ll eV \rightarrow \frac{n}{n_k} \gg 1 \rightarrow \text{the field can be treated classically.}\)

• We classify the different ULDM models from their nature
  
  ➢ Scalar field (Dilatons,...)
  ➢ Pseudo-scalar field (Axions,...)
  ➢ Vector field (Dark photons (DP),...)

Inspired from Tourrenc et al, Arxiv:quantum-ph/0407187, 2004
Does DP induce oscillating electric field?

- Cosmologically, DP field oscillates at its Compton frequency $\phi = \phi_0 \cos \omega t$
  \[ \omega = m (k = 0) \]

- DP lagrangian given by
  \[ \mathcal{L} = -\frac{1}{4} \phi^{\mu\nu} \phi_{\mu\nu} - \frac{1}{2} m^2 \phi_{\mu} \phi^{\mu} - \frac{\chi}{2} F_{\mu\nu} \phi^{\mu\nu} \]

- The mixing term generates a standard electric field filling the whole space
  \[ \vec{E}_{DP} \approx -i \chi \omega \vec{\phi} e^{-i\omega t} \]
  which we would like to detect! Or, constrain $\chi$ on a given range of DP masses.

- Additionally, if DP field accounts for the whole DM, $|\vec{E}_{DP}| = \chi \sqrt{2 \rho_{DM}}$
Resonant cavity and why using it in this context?

- Microwave cavity: Resonator confining EM signal with frequencies in the microwave range \( \mathcal{O}(\text{GHz}) \)

- In real cavities, loss of energy characterized by **quality factor, Q**. The larger Q is, the higher electric field amplitude will be inside the cavity.

- In the context of DP, \( \vec{E}_{DP} \) acts as another initial wave which might enter in resonance.
The experiment: Setup using microwave signal
We can **either** measure the DM electric field directly...

\[ \vec{E}_T \propto \vec{X}_{DM} e^{-i\omega_{DM} t} \]

- Oscillate too fast \((\mathcal{O}(GHz))\)
- Amplitude too small \((\mathcal{O}(\chi))\)
We can either measure the DM electric field directly...

\[ \vec{E}_T \propto X_{DM} e^{-i\omega_{DM} t} \]

→ Oscillate too fast \((\mathcal{O}(GHz))\)

→ Amplitude too small \((\mathcal{O}(\chi))\)

...or apply an external field and measure the square of the total electric field

\[ |\vec{E}_T|^2 \propto X_a X_{DM}[\cos(\Delta \omega t + \phi_a) + \cos(\Sigma \omega t + \phi_a)] + X_{DM}^2 \cos(2\omega_{DM} t) + X_a^2 \cos(2\omega_a t + \phi_a) \]

Oscillation too fast/Amplitude too small
The experiment: Setup using microwave signal

We can either measure the DM electric field directly...

\[ \vec{E}_T \propto \vec{X}_{DM} e^{-i\omega_{DM} t} \]

→ Oscillate too fast (\(O(GHz)\))
→ Amplitude too small (\(O(\chi)\))

...or apply an external field and measure the square of the total electric field

The DM frequency we look for is such that \(\Delta \omega < f_s\), sampling frequency of the apparatus

In addition, we take advantage of the possible high injected power contained in \(\vec{X}_{a}\)
The experiment: Detection using Rydberg atoms

Best way of measuring the square of the electric field strength is through Stark effect

\[ \Delta v = \frac{1}{2h} \Delta \alpha \langle E \rangle^2 \]

- Measurement of transition frequency of an atom and look for
  \[ \nu(t) = \nu_0 + \Delta v \cos(\Delta \omega t + \phi_a) \]

With Rydberg atoms:
- High accuracy on \( \Delta \nu \) from \( \langle E \rangle^2 \)
- Large polarizability \( \Delta \alpha \)
- Good resolution on \( \langle E \rangle^2 \) (with small \( T_{\text{obs}} \))

\[ \rightarrow \text{Better sensitivity to} \ \langle E \rangle^2 \]

Fig. 4: Atoms at the center of the cavity to measure the Stark effect induced by \( \langle E_T \rangle^2 \)
The experiment : Experimental methodology

1) Apply electric field with initial frequency $\omega_a$ during $T_{obs}$

→ scan possible DM signals with $\Delta \omega < f_s$

2) Shift applied frequency by $2 \times 10^5$ Hz for another $T_{obs}$

→ Large window of DM masses scanable ($= 2Nf_s$)
**Rough estimation of the experiment’s sensitivity**

**Statistical noise:** Measurement uncertainty of the electric field squared from the atoms.

- Minimal detectable field power $\langle E_{\text{min}} \rangle^2 = 1 \, (\text{V/m})^2$
- $\chi(\omega_{DM}) = f(Q, X_a, X_{DM}, ...)$

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From C. O’Hare : https://github.com/cajohare
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**Fig. 6:** Constraint on $\chi$ obtained with this setup. The exclusion plot on the right shows only lab experiments and omit cosmological ones such as CMB.
Rough estimation of the experiment’s sensitivity

**Systematic noise:** RIN (Relative Intensity Noise) of a signal describes the fluctuation of its power.

\[ \Delta \dot{X}_B X_B = RIN = \sqrt{\frac{2S_{RIN}}{T_{obs}}} \]

Close to resonances, the applied field amplitude is enhanced a lot (with its fluctuation)

\[ \Rightarrow \] The experimental limit becomes the systematic effect and

\[ \chi \approx \frac{\Delta X_a}{X_a} \]

No dependence on Q or any other cavity parameters.

\[ \Rightarrow \downarrow S_{RIN} \text{ or } \uparrow T_{obs} \Rightarrow \text{Better constraint on } \chi \]
Rough estimation of the experiment’s sensitivity
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Rough estimation of the experiment’s sensitivity

$\rho_{DM} = 0.45 \text{ GeV cm}^{-3}$

Dark photon mass, $m_X$ [eV]
Rough estimation of the experiment’s sensitivity

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Rough estimation of the experiment’s sensitivity

Without systematics

\[ \rho_{DM} = 0.45 \text{ GeV cm}^{-3} \]

Kinetic mixing, \( \chi \)

Dark E-field

Frequency [GHz]

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Dark photon mass, \( m_X \) [eV]

Kinetic mixing, \( \chi \)

\[ \rho_{DM} = 0.45 \text{ GeV cm}^{-3} \]

Frequency [GHz]

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Rough estimation of the experiment’s sensitivity

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**Graph:**

- Frequency [GHz]
- Kinetic mixing, $\chi$
- Dark photon mass, $m_X$ [eV]
- Dark E-field
- $\rho_{\text{DM}} = 0.45 \text{ GeV cm}^{-3}$
Rough estimation of the experiment’s sensitivity

**Fig. 7**: Constraint on \( \chi \) obtained with this setup for \( T_{\text{obs}} = 600 \) s, \( S_{\text{RIN}} = 10^{-13}/\omega \)

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Rough estimation of the experiment’s sensitivity

→ Not dramatic change in sensitivity
→ Need to consider $T_{\text{obs}} = 600$ s

**Fig. 7**: Constraint on $\chi$ obtained with this setup for $T_{\text{obs}} = 600$ s, $S_{RIN} = 10^{-13}/\omega$
Rough estimation of the experiment’s sensitivity

Not dramatic change in sensitivity
Need to consider $T_{\text{obs}} = 600$ s

$\text{Nb of times we switch } \omega_a$

Total experiment time $T_{\text{tot}} = NT_{\text{obs}}$
$T_{\text{tot}} \sim 1 \text{ month} \equiv \text{scan DM masses } \in [5.9; 6.5] \mu eV$

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Fig. 7: Constraint on $\chi$ obtained with this setup for $T_{\text{obs}} = 600$ s, $S_{RIN} = 10^{-13}/\omega$
Rough estimation of the experiment’s sensitivity

\[ \rho_{DM} = 0.45 \text{ GeV cm}^{-3} \]

\[ \omega_a \]

\[ m_X \text{ [eV]} \]

\[ N \text{ [times]} \]

\[ T_{obs} = 600 \text{ s} \]

\[ T_{tot} \sim 1 \text{ month} \equiv \text{scan DM masses } \in [5.9; 6.5] \text{ } \mu \text{eV} \]

Total experiment time \( T_{tot} = NT_{obs} \)

Quality factor \( Q \)

Cavity length \( 10^4 \) cm

Injected power \( 1 \text{ W} \)

Effective mode radius \( O(\text{cm}) \)

\( (E_{\text{min}})^2 \text{ [V/m]}^2 \)

Range of \( \omega_a \) [7, 12] GHz

Range of \( \Delta \omega \) [1, 10^5] Hz

\( T_{obs} = 600 \text{ s} \)

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Fig. 7: Constraint on \( \chi \) obtained with this setup for \( T_{obs} = 600 \text{ s} \), \( S_{RIN} = 10^{-13}/\omega \)
Conclusion

- **DP is a serious DM candidate → numerous lab experiments trying to detect it.**
- **Proposal of a new kind of experiment looking for DP using atoms inside a microwave cavity.** As a resonant device, it acts as a narrow band DM detector.
- With the current technology in quantum optics, **competitive constraints on the coupling constant \( \chi \)** compared to other lab experiments.

Next step: How to mitigate the experimental limiting factor, the systematic effect?
Thank you for your attention!
Back-up: Cavity parameters

- Resonance conditions: \( \lambda = \frac{2L}{n} \) or \( kL = n\pi \)

- Detection at the center from atoms \( \rightarrow \) we require \( n \) odd (antinode at the center)

- Reflectivity coeff of mirrors \( r \) is related to quality factor as
  \[ Q = \frac{2\pi}{\lambda(1 - r^2)} \]

  This relation is valid only around resonances.

- Finesse of a cavity defined as
  \[ F = 2\pi N_e \rightarrow F \approx Q \]
Atoms inside a cavity, excited by a laser.
The closer the frequency of the laser is to the energy difference between the 2 levels, the more excited atoms there will be

→ Assessment of the frequency of the laser to be closest possible to the energy difference.
→ Wave with appropriate frequency and need to count oscillations to give time
Back-up: How does $Q$ impact the sensitivity?

\[ Q = 10^6 \]

\[ Q = 10^4 \]

\[ \rho_{DM} = 0.45 \text{ GeV cm}^{-3} \]

Frequency [GHz]

Without systematics

Kinetic mixing, $\chi$

Dark photon mass, $m_X$ [eV]
Back-up: why microwave cavity and not optical?

1. $\vec{E}_{DP} \approx -i\chi\omega \phi e^{-i\omega t}$ valid if we neglect $k$.

To do so, we require $L \ll \lambda$ ($L$, size of experiment considered (< 10 cm))
$\rightarrow$ ok in microwave range
$\rightarrow$ in optical range, $k \sim 10^6$ m$^{-1} \gg \frac{2\pi}{\lambda}$

2. Optical frequency $\equiv$ eV mass
$\rightarrow$ QFT required for DP field
Back-up : DP cosmo evolution + field equations

• Free Klein-Gordon equation (in expanding universe) of each DP space component $\phi^i$

\[
\ddot{\phi}^i + 3H\dot{\phi}^i + m^2 \phi^i \approx 0
\]

whose solution is oscillatory.

Nelson, Scholtz, PRD, 2011

• Additionally, $p_{ij} \sim \langle T_{ij} \rangle = 0$ and the field behaves as pressureless fluid or CDM

• In the microwave regime and considering $\nu_{DM} \sim 10^{-3}$ in Earth’s frame, the DP field can be approximated by a standing wave in a cavity of length $L \sim 10$ cm. Then,

$$\omega = m; \phi^0 = 0$$

• The DP mixes with the SM photon as

$$\partial_\mu \partial^\mu A^\nu = -\chi \phi^\nu$$

$$(\partial_\mu \partial^\mu + m^2) \phi^\nu = -\chi \partial_\mu \partial^\mu A^\nu$$
Back-up: Systematic noise and Data analysis

$\sqrt{S_{RIN}}$ of a Nd laser, measurement provided by Artemis lab.

$\sqrt{S_{RIN}}$ of different sources (arXiv: Rubiola, 2005)

### AM noise of some sources

<table>
<thead>
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<th>source</th>
<th>$I_{h-1}$ (flicker)</th>
<th>$[\sigma_{\alpha}]_{\text{floor}}$</th>
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<tr>
<td>Anritsu MG3690A synthesizer (10 GHz)</td>
<td>$2.5 \times 10^{-11}$</td>
<td>$-106.0$ dB</td>
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<tr>
<td>Marconi synthesizer (5 GHz)</td>
<td>$1.1 \times 10^{-12}$</td>
<td>$-119.6$ dB</td>
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<td>Macom PLX 32-18 0.1 $\rightarrow$ 9.9 GHz multipl.</td>
<td>$1.0 \times 10^{-12}$</td>
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