Search for vector dark matter in microwave cavities with Rydberg atoms

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Based on JG et al. Phys. Rev. D 108 035042 (2023)

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COSMIC WISPers, DESY
February 1st 2024

COSMIC WISPERS CA21106

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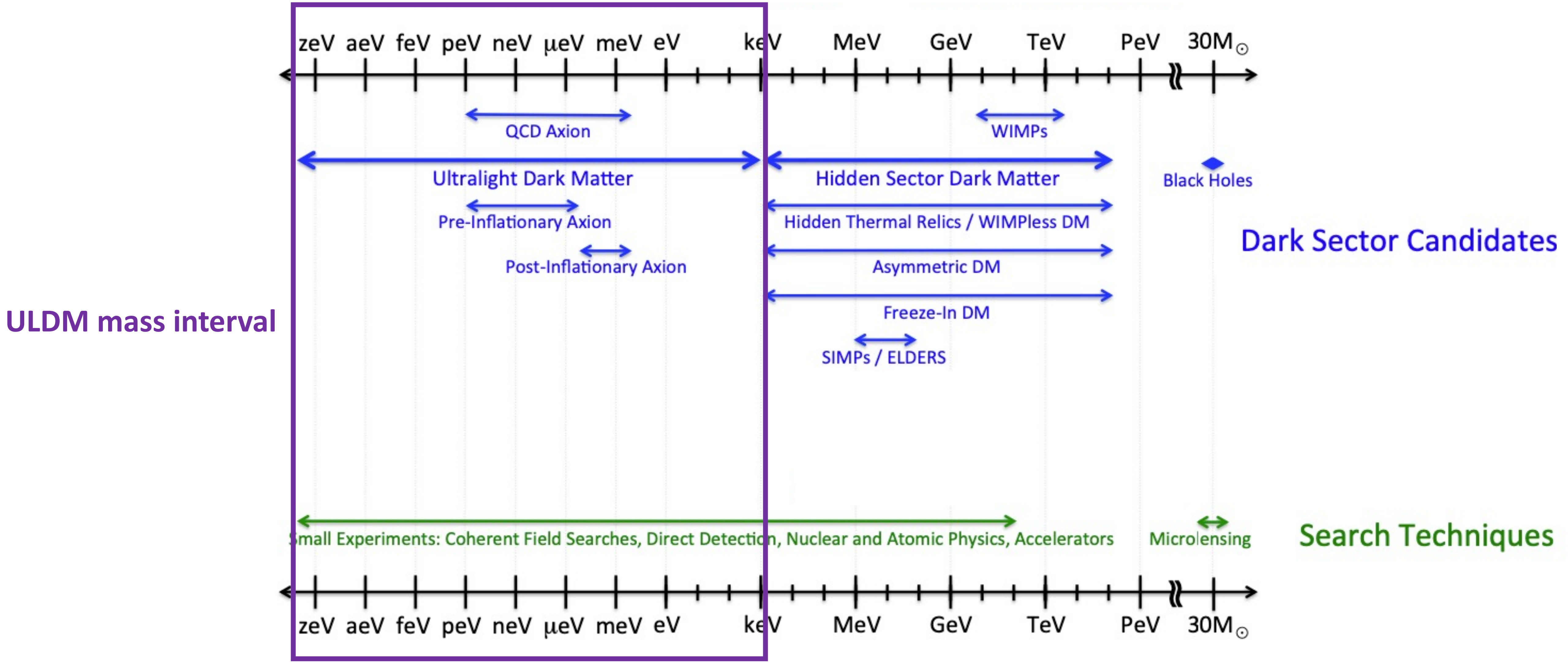
cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Funded by the European Union

Classes of Dark Matter



From US cosmic vision : new idea for Dark Matter 2017, Arxiv:1707:04951

Ultra Light Dark Matter (ULDM) models

Occupation number in phase space

$$\frac{n}{n_k} \sim \frac{\rho_{DM}}{(mc^2)^4 v_{max}^3} > \mathbf{1}$$

$\sim 0.4\ GeV/cm^3$

$\sim 10^{-3} c$

$< 10\ eV$

Inspired from P. Tourrenc et al, Arxiv:quantum-ph/0407187, 2004

→ULDM with $mc^2 < 10\ eV$ must be bosonic (Pauli exclusion principle)

- Various bosonic ULDM candidates
  - Scalar fields (Dilatons,...)
  - Pseudo-scalar fields (Axions,...)
  - Vector fields (Dark photons,...)

- When $\boldsymbol{mc^2 \ll eV}$ $\rightarrow n/n_k \gg 1 \rightarrow$ a generic vector field $\vec{\phi}$ can be treated **classically**, i.e as oscillating solution of the Klein Gordon equation in FRLW expanding universe,

$$\vec{\boldsymbol{\phi}} = \vec{\boldsymbol{\phi}}_0 \cos(\boldsymbol{\omega_{DM} t})$$

$\hbar\omega_{DM} = m_{DM}c^2$ in DM rest frame

$\propto \sqrt{\rho_{DM}}$, local DM energy density

Dark Photon (DP) phenomenology

DP can couple to matter through B-L current → leads to violation of UFF *P. Fayet, Phys. Rev. D **99** (2019)*

Here, we are interested in its coupling with electromagnetism

Kinetic mixing coupling

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + j^{\mu}A_{\mu} - \frac{1}{4}\phi^{\mu\nu}\phi_{\mu\nu} - \frac{1}{2}m^2\phi_{\mu}\phi^{\mu} - \boxed{\frac{\chi}{2}F^{\mu\nu}\phi_{\mu\nu}}$$

DP strength tensor

DP field

*B. Holdom, Phys. Lett. **166B**, 196 (1986)*

The photon-DP mixing generates a standard electric field **filling the whole space**

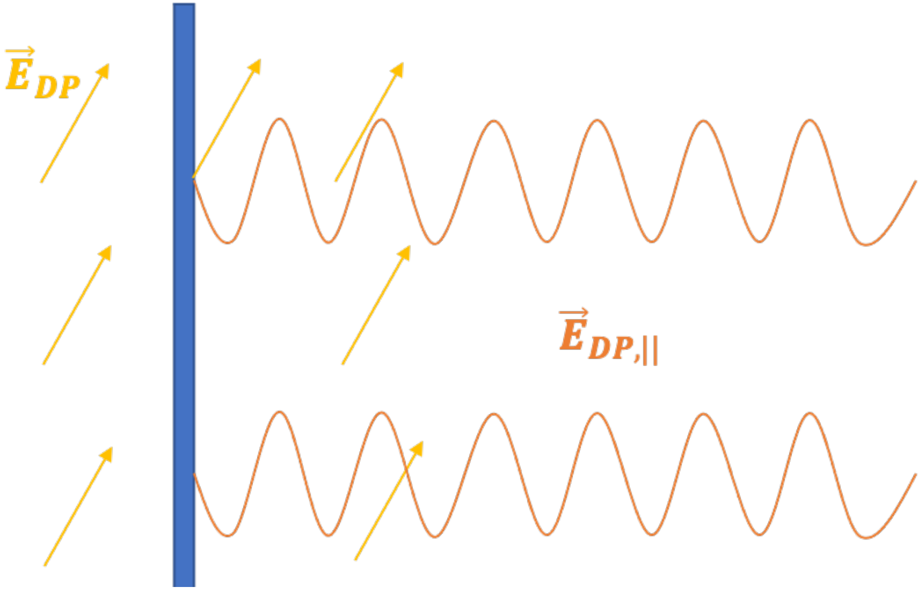
$$\vec{E}_{DP} \approx -\chi\omega\vec{\phi}_0\cos(\omega_{DM}t)$$

$\equiv \vec{\phi}$

which is the observable we aim at detecting!

Resonant cavity to amplify $\vec{E}_{DP}$

Use of metallic plate to create classical propagating EM field by boundary conditions



At GHz freq., mainly 2 types experiments to detect $\vec{E}_{DP}$

1) Cavities (haloscopes) *P. Arias et al., JCAP 06 (2012)*
→ Detection of EM power inside the cavity $\propto \chi^2$

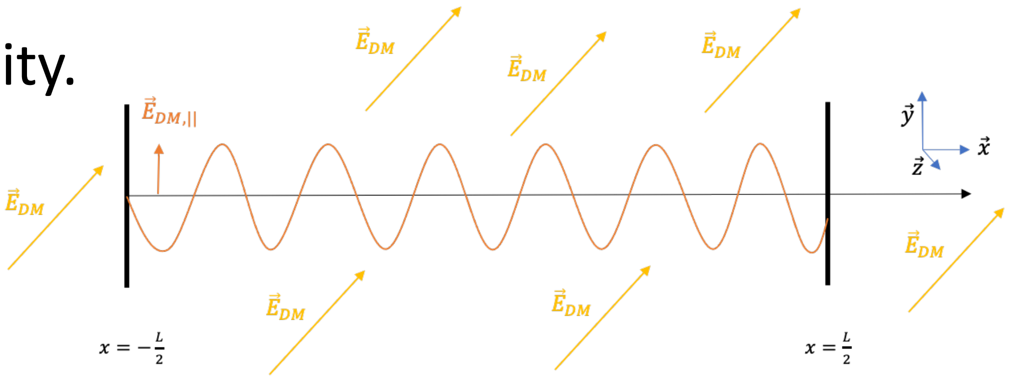
2) Dish antennas *D. Horns et al., JCAP 04 (2013)*
→ Detection of EM power focused by curvature of dish $\propto \chi^2$

In **JG et al. PRD (2023)**, we propose a new way of detecting $\vec{E}_{DP}$ using microwave cavity and atoms **whose signal is $\propto \chi$**

The experiment : Setup using microwave signal

We work in 1D with a microwave cavity.

$$X_{DM,||} \propto \chi\sqrt{\rho_{DM}}\cos(\omega_{DM} t)$$



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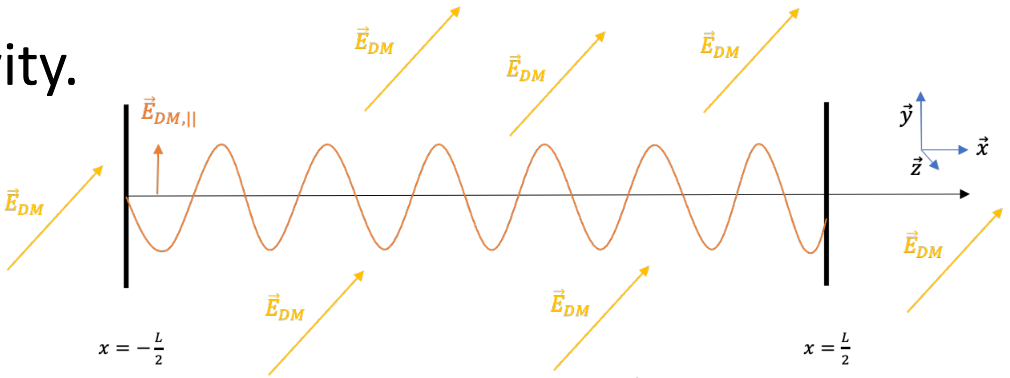
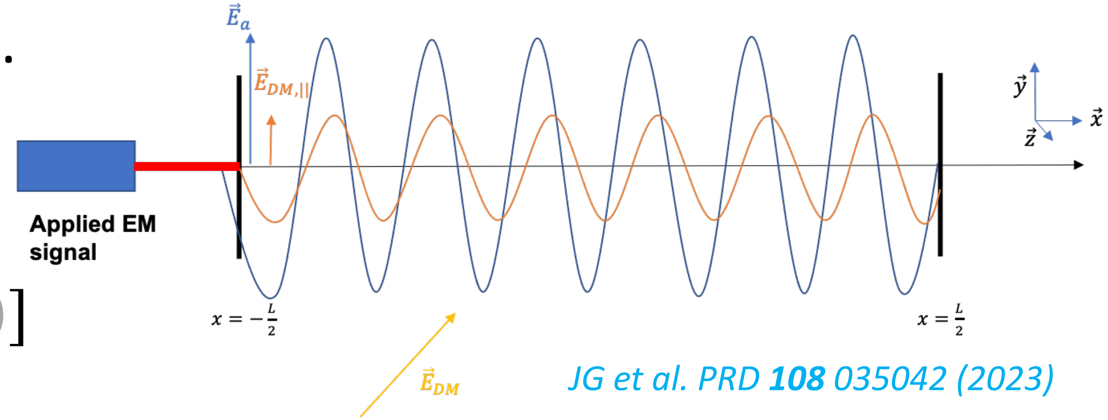


→ Apply an external field $\vec{E}_a \propto \vec{X}_a \cos(\omega_a t + \phi_a)$…

…and look at the total E field squared



JG et al. PRD ***108*** *035042 (2023)*

$\omega_a - \omega_{DM}$ ✓

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

Oscillating too fast and/or amplitude too small

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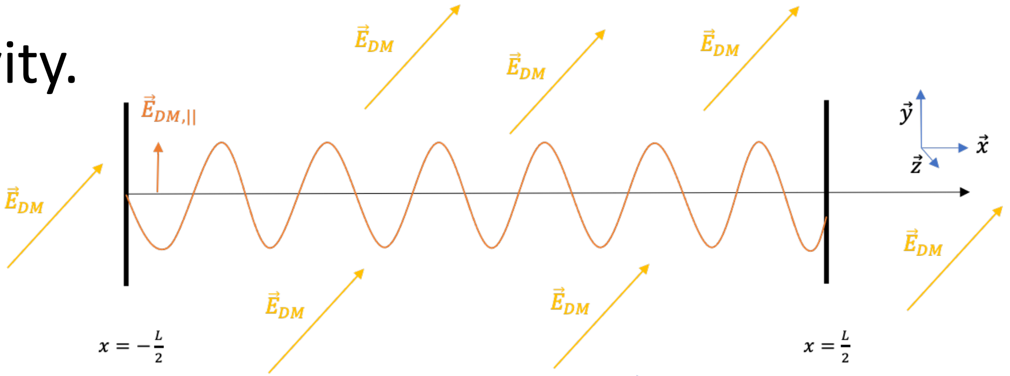
$X_{DM,||} \propto \chi \sqrt{\rho_{DM}} \cos(\omega_{DM} t)$



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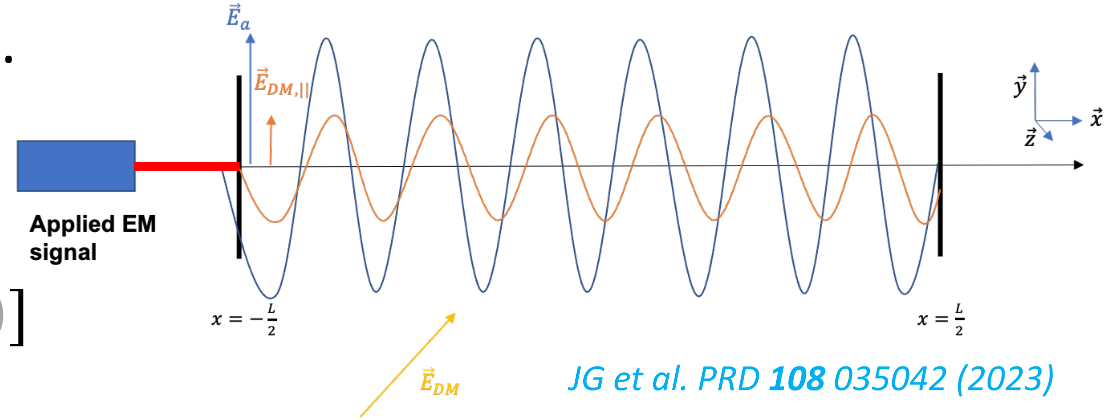


*JG et al. PRD **108** 035042 (2023)*

$\omega_a - \omega_{DM}$ ✓

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

Oscillating too fast and/or amplitude too small

→ **Slowly oscillating signal $\propto \chi$**

→ **We are sensitive to ω_{DM} such that $\Delta\omega < \pi f_s$**

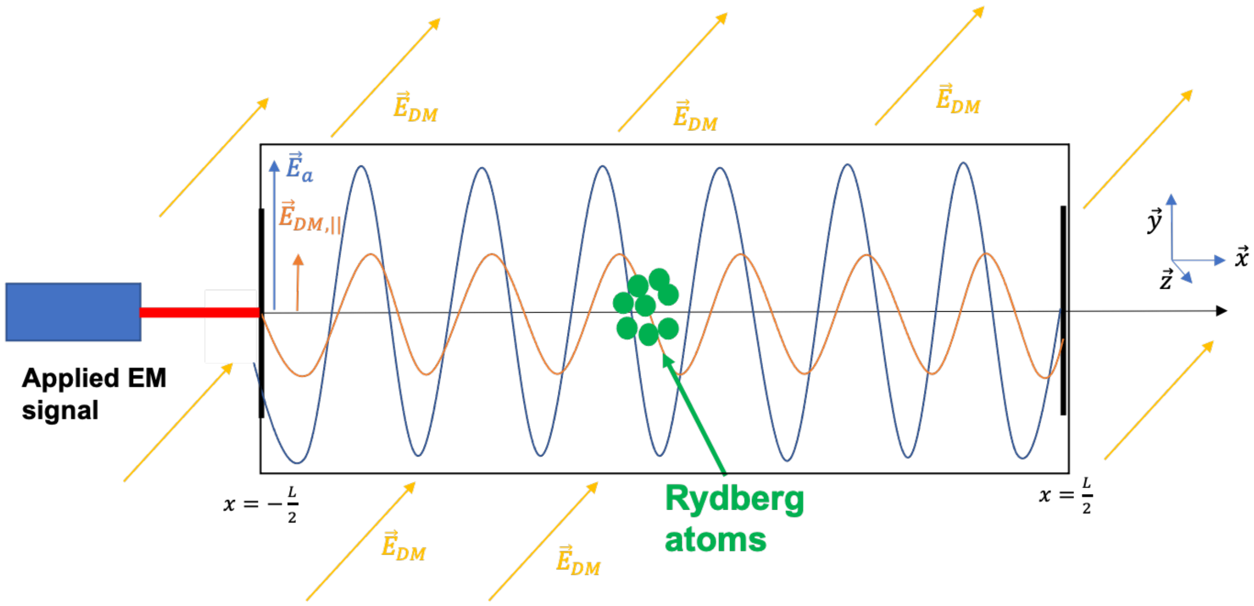
→ **We use the applied field to amplify the weak DM field (through $\vec{X}_a$)**

The experiment : Detection using Rydberg atoms

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

$$\boldsymbol{\Delta\nu} = \frac{\mathbf{1}}{\mathbf{2h}}\Delta\boldsymbol{\alpha}\langle \boldsymbol{E}\rangle^{2}$$

→Measurement of transition frequency of an atom and look for $\nu(t) = \nu_0 + \boldsymbol{\Delta\nu}\,\mathbf{cos}(\boldsymbol{\Delta\omega t} + \boldsymbol{\phi_a})$



With **Rydberg atoms** :

-High accuracy on $\boldsymbol{\Delta\nu}$ from $\langle \boldsymbol{E}\rangle^{2}$

-Large polarizability $\Delta\boldsymbol{\alpha}$

-Good resolution on $\langle \boldsymbol{E}\rangle^{2}$

→ **Better sensitivity on $\langle \boldsymbol{E}\rangle^{2}$**

-Short lifetime ($\sim\mu$s)

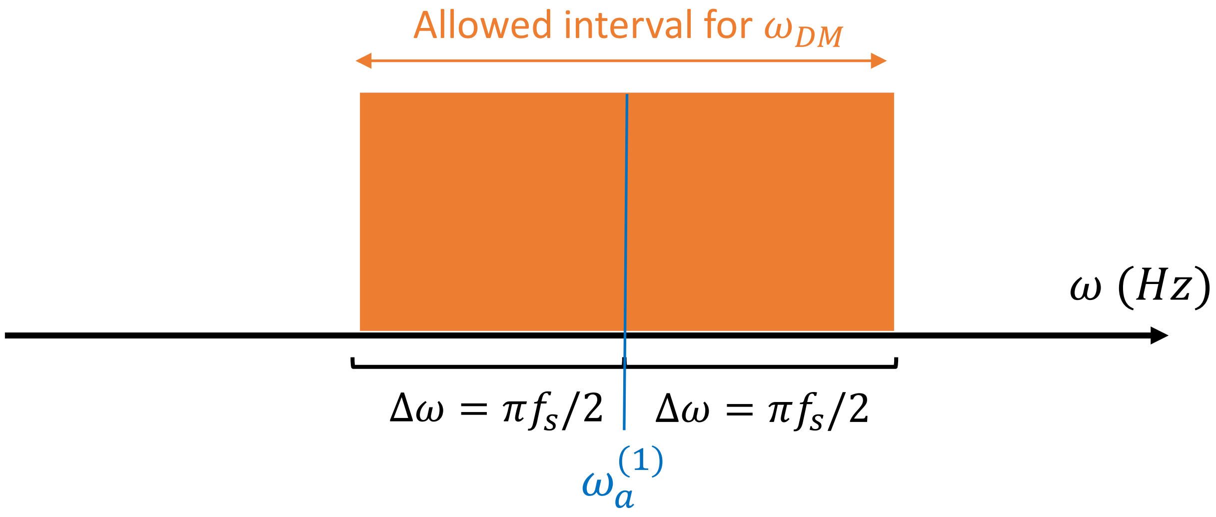
-Non-destructive measurement

→ **High sampling frequency possible**

Experimental methodology

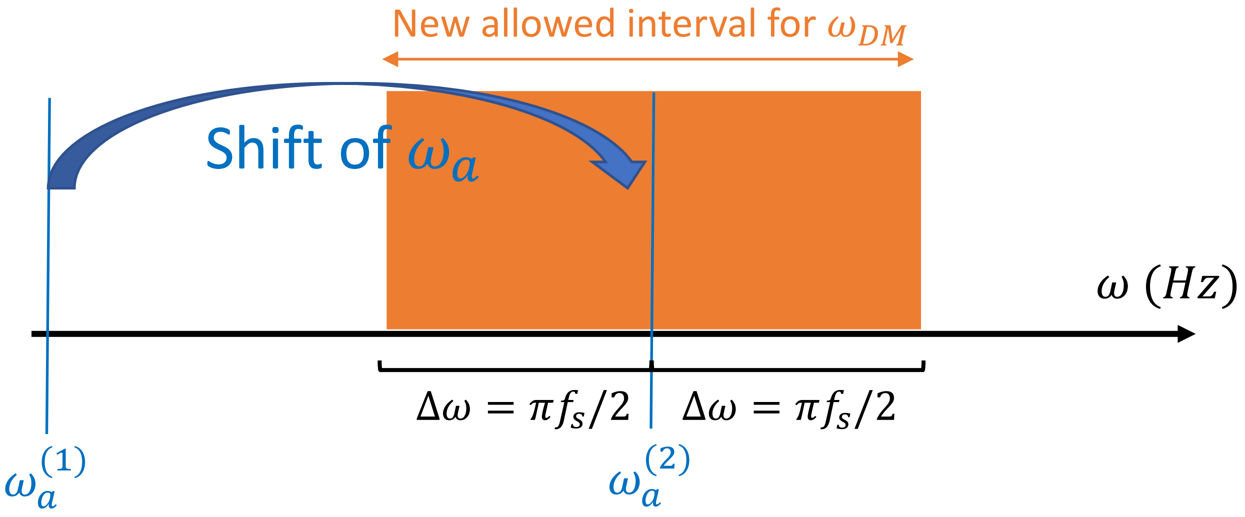
1) Apply electric field with frequency ω_a for T_{obs}

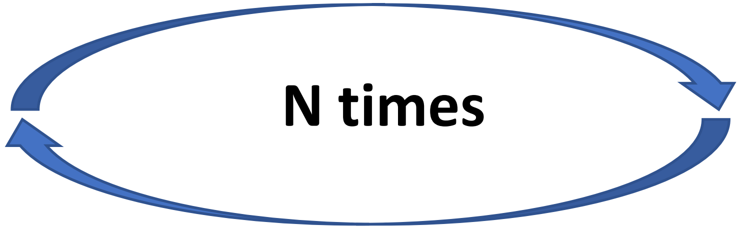
→ scan DM signals with $\frac{2\pi}{T_{obs}} < |\Delta\omega| < \frac{\pi f_s}{2}$



2) Shift applied frequency by πf_s for T_{obs}

→ scan new DM signals with $\frac{2\pi}{T_{obs}} < |\Delta\omega| < \frac{\pi f_s}{2}$





→ **Large window of DM frequencies scanable** $(= Nf_s)$

Rough estimation of the experiment sensitivity

1st source of noise : Statistical noise

→ Measurement uncertainty on the frequency shift of atoms…

Frequency shift noise PSD

$$\sigma_{\Delta\nu}^2 = \frac{S_{\Delta\nu} f_s}{2}$$

Frequency shift variance

…induces a measurement uncertainty on the electric field squared

$$S_{\Delta\nu} = \left(\frac{\Delta\alpha}{2h}\right)^2 S_{E^2}$$

Electric field squared noise PSD

Rough estimation of the experiment sensitivity

2nd source of noise : Systematic effect

→ Amplitude fluctuation of the applied field, characterized by the RIN of the signal generator

$$X_a \rightarrow X_a\left(1 + \int d\omega_0 \frac{\Delta X_a(\omega_0)}{X_a}\cos(\omega_0 t + \phi_0)\right)$$

The RIN PSD $S_{RIN}(\omega_0)$ is given by

$$\frac{\Delta X_a(\omega_0)}{X_a} = \sqrt{\frac{S_{RIN}(\omega_0)}{2T_{obs}}}$$

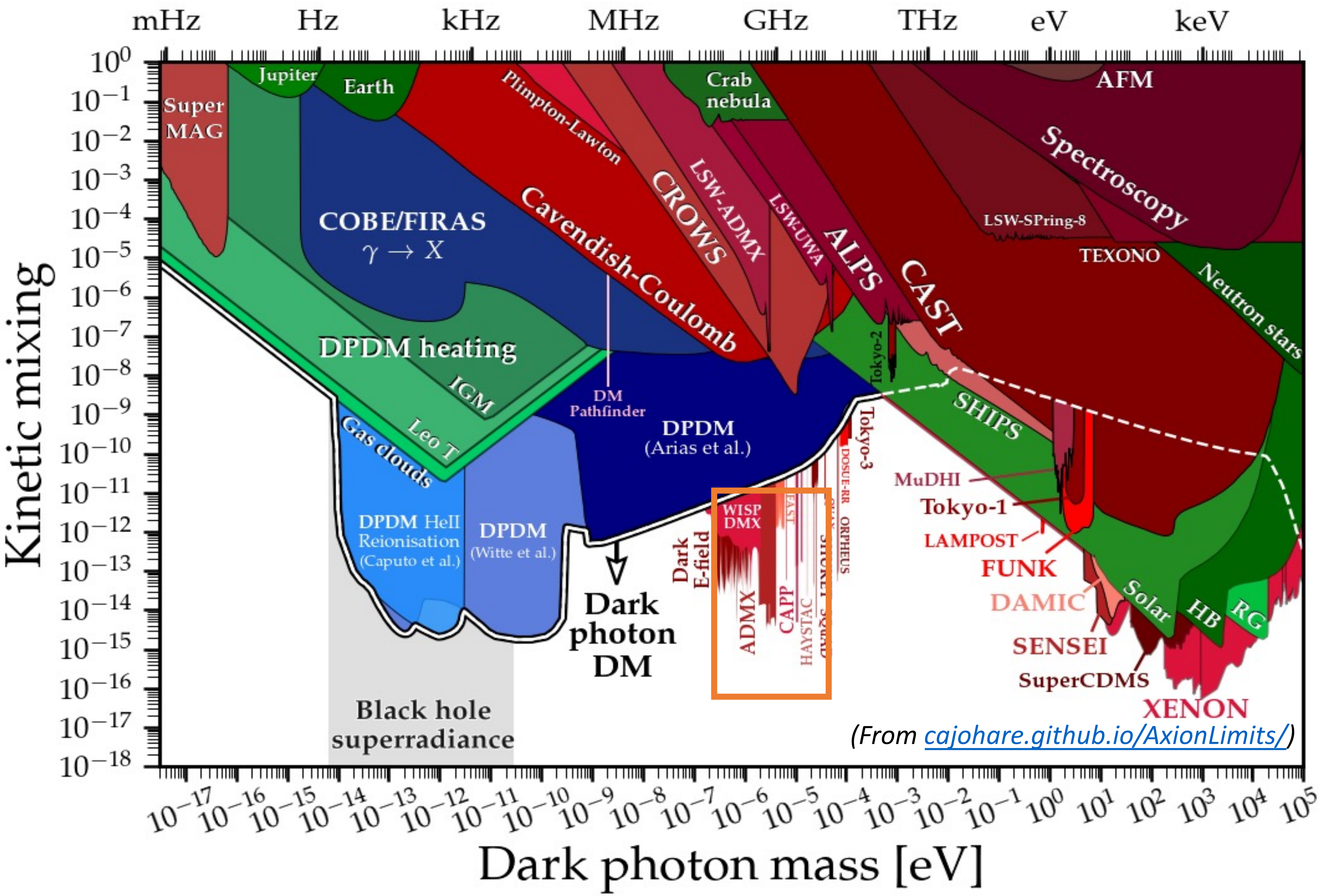
$$S_{RIN}(\omega) = \frac{P_{RIN}}{\omega}$$

(Flicker type noise)

The main amplitude fluctuation (mimicking a signal at $\Delta\omega$) is at frequency $\omega_0 = \Delta\omega$. Then

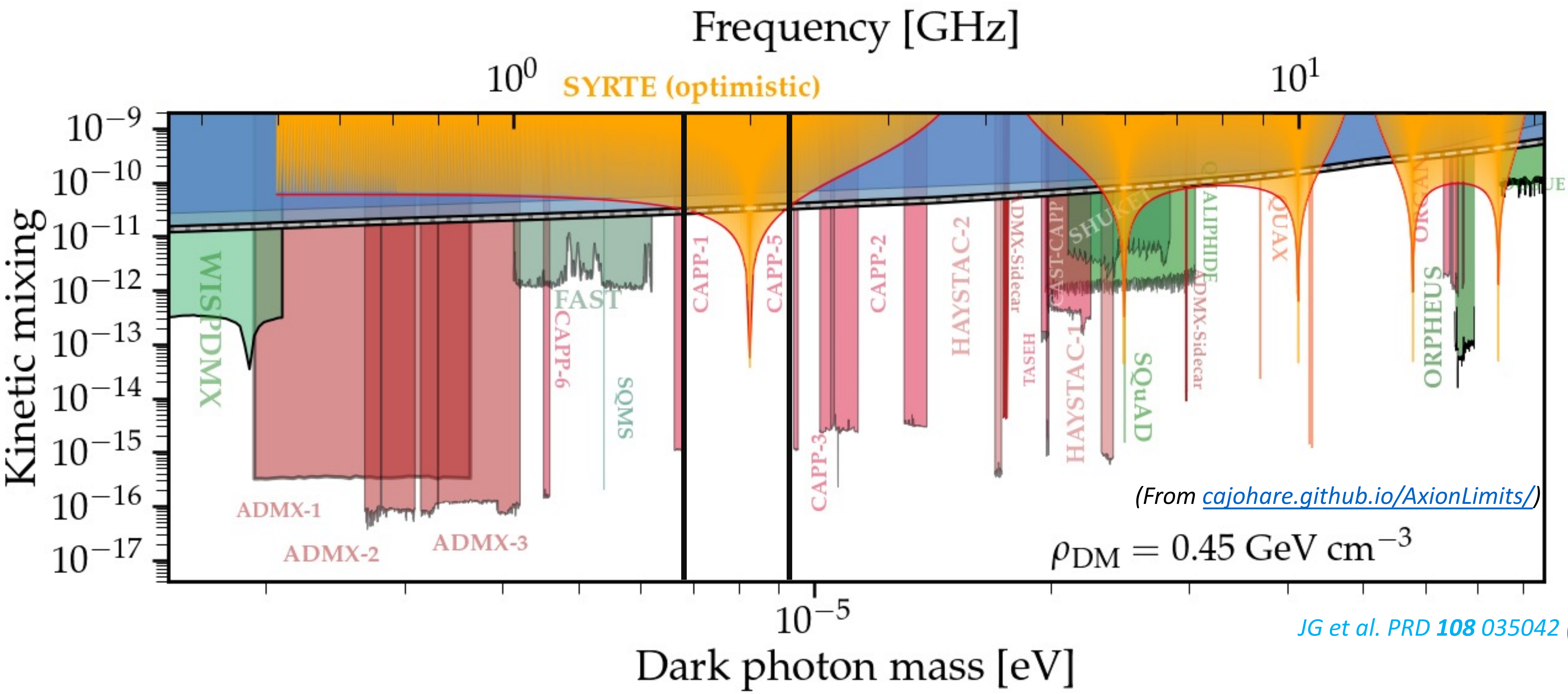
$$X_a \rightarrow X_a + \Delta X_a(\Delta\omega)\cos(\Delta\omega t + \phi_0)$$

Rough estimation of the experiment sensitivity



(From cajohare.github.io/AxionLimits/)

Rough estimation of the experiment sensitivity

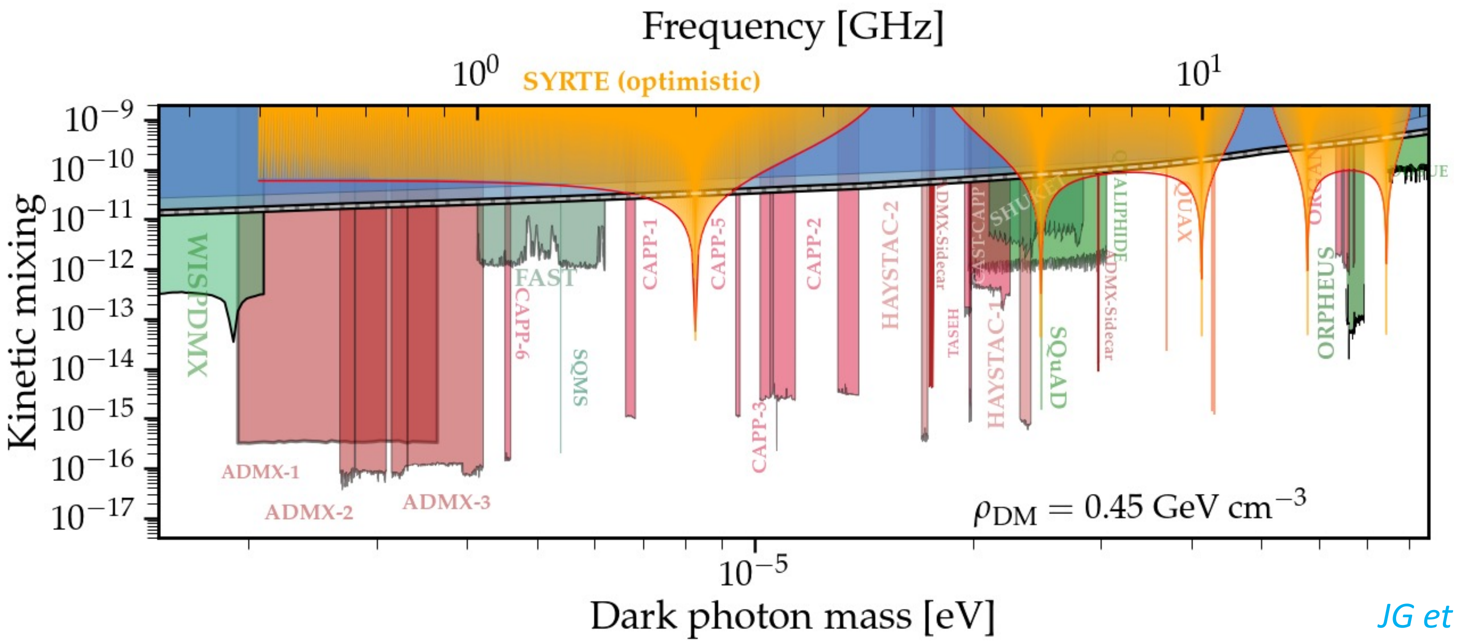


*JG et al. PRD **108** 035042 (2023)*

With realistic experimental parameters, $\sim$5 days of data-taking could constrain **the black region**

Conclusion

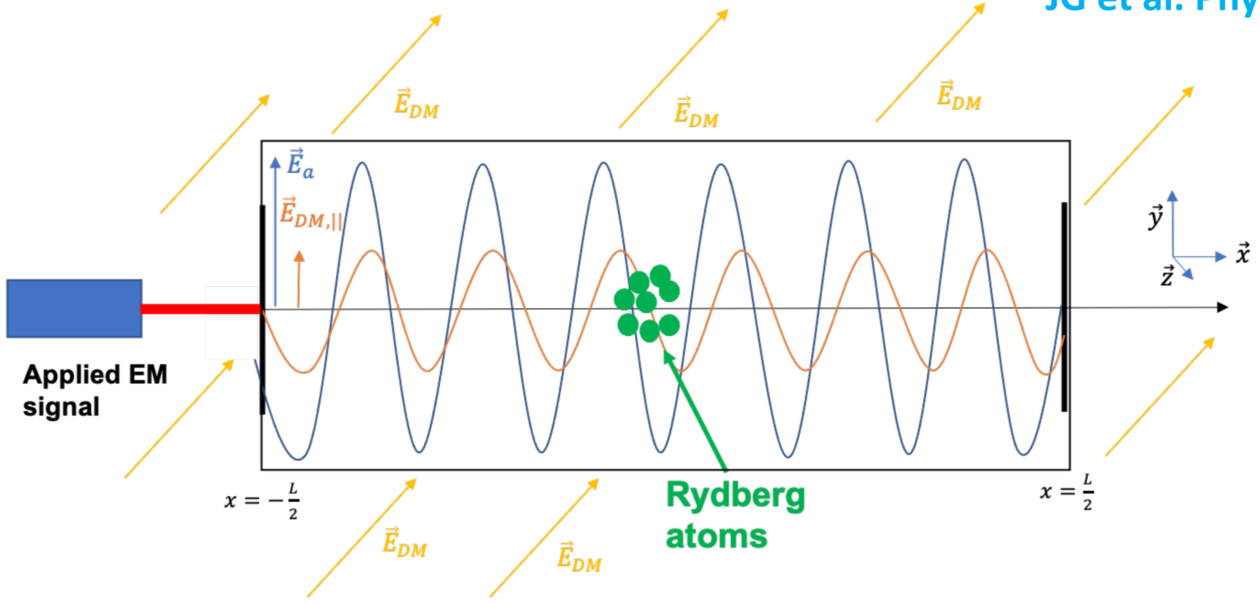
- DP is a serious DM candidate → numerous lab experiments trying to detect it.
- **Proposal of a new kind of experiment looking for DP using atoms inside a microwave cavity**. As a resonant device, it acts as a narrow band DM detector.
- With the current technology in quantum optics, **competitive constraints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



*JG et al. PRD **108** 035042 (2023)*

- Experiment could be feasible in the near future using Sr or Hg clocks e.g @SYRTE

JG et al. Phys. Rev. D 108 035042 (2023)



Thank you for your attention !

I am looking for postdoctoral position starting next year in COSMIC WISPers working group related areas (direct dark matter detection with quantum sensors) so please, let me know if you propose opportunities !

This work was supported by the Programme National GRAM of CNRS/INSU with INP and IN2P3 co-funded by CNES.

GRAM

Back-up : propagation of DP field in lab

- Free Klein-Gordon equation of each DP space component A^i

$$\ddot{\phi}^i + 3H\dot{\phi}^i + \omega^2\phi^i \approx 0$$

whose solution is oscillatory when $\omega \gg H$

- Treating DP field as a classical **massive** field, we have (in its rest frame)

$$\omega = \frac{mc^2}{\hbar}$$

$$\vec{\phi} = \vec{\phi}_0 \cos(\omega t)$$

Now, considering the DP field makes the whole DM local density, it passes through lab with $\vec{v}_{DM}$

$\mathcal{O}(10^{-3}\text{c})$

$$\vec{k} = \frac{m\vec{v}_{DM}}{\hbar} \rightarrow \lambda \gg L\text{, size of cavity experiment considered}$$

$\mathcal{O}(10^{-6}\text{ eV})$ $\mathcal{O}(300\text{ m})$

→ **propagation neglected in the lab frame**

Back-up : Experimental parameters

TABLE I: Assumed experimental parameters

Parameters	Numerical values	
Quality factor Q [47]	10^4	
Mirrors reflectivity r	$\approx 1 - 2 \times 10^{-4}$	*J. Guena et al., IEEE TUFFC **59,** 391 (2012)*
Cavity length L	7.5 cm	
Injected field strength $X_a(\omega)$	$[18.1, 1.70 \times 10^5]$ V/m	
Sampling frequency f_s	10^2 ; 10^3 Hz	
Individual measurement time $T_{\rm obs}$	60 s	*Bridge et al. Opt. Express **24,** 2281 (2016)*
Range of $f_a = \omega_a/2\pi$	$[0.5, 20.5]$ GHz	
Range of $\Delta\omega$	$[2\pi/T_{\rm obs}, \pi f_s]$ rad/s	
Statistical noise PSD S_{E^2}	$10^{-4}/f_s$ $({\rm V/m})^4/{\rm Hz}$	*Millen et al. Journal of Physics **44**, 184001 (2011)*
Systematic effect PSD $S_{\rm RIN}(\omega)$	$10^{-13}/\omega$; $10^{-15}/\omega$	*Rubiola, Arxiv:physics/0512082 (2005)*

Back-up : modest/optimistic sensitivities