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

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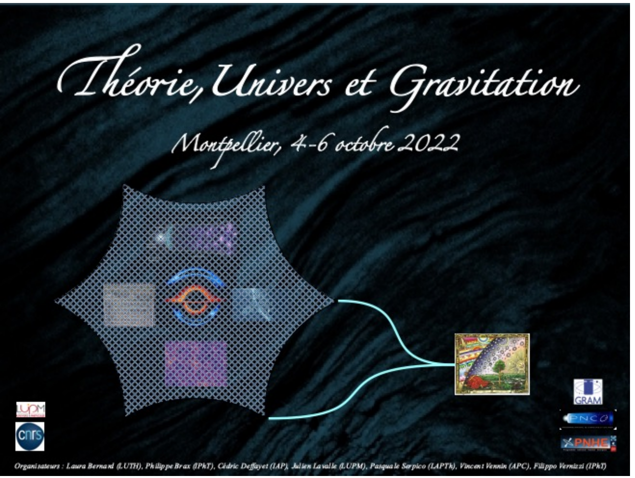
SYRTE

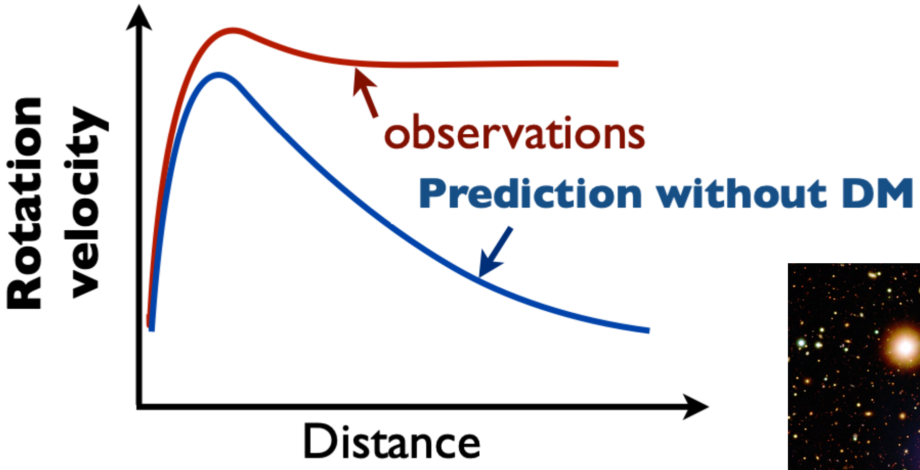
SYstèmes Références Temps-Espace, CNRS, Observatoire de Paris, Université PSL, Sorbonne Université, LNE



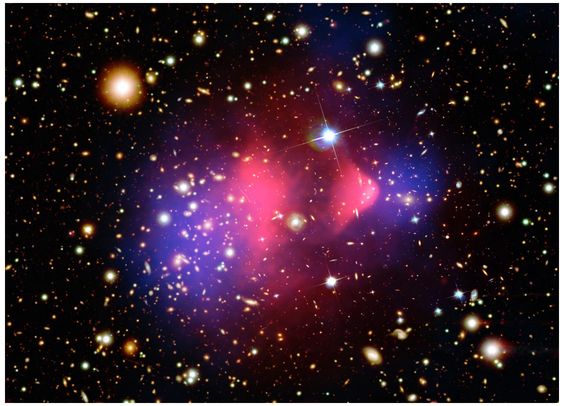
Théories Univers et Gravitation, Montpellier
October 6th 2022

Why do we need Dark Matter ?

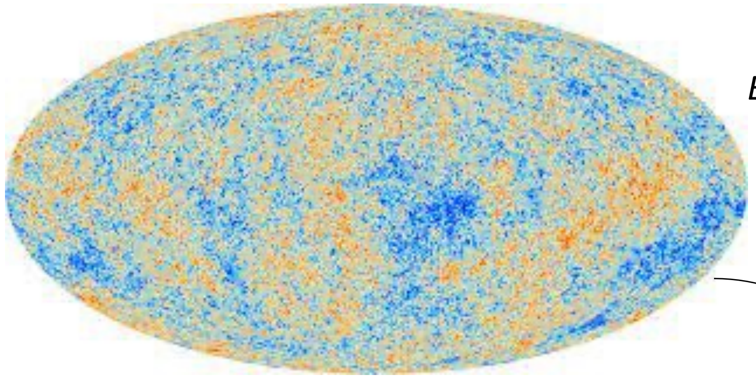
Explains astrophysical observations at different scales :

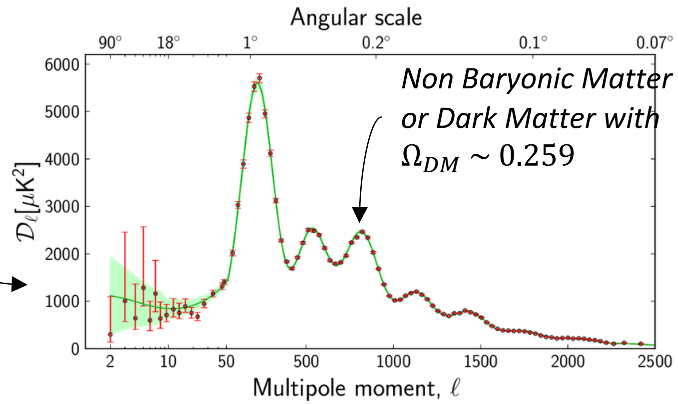


- **Galactic scale**
(velocity rotation curves, weak lensing,…)



- **Galactic cluster scale**
(bullet cluster, strong lensing,…)

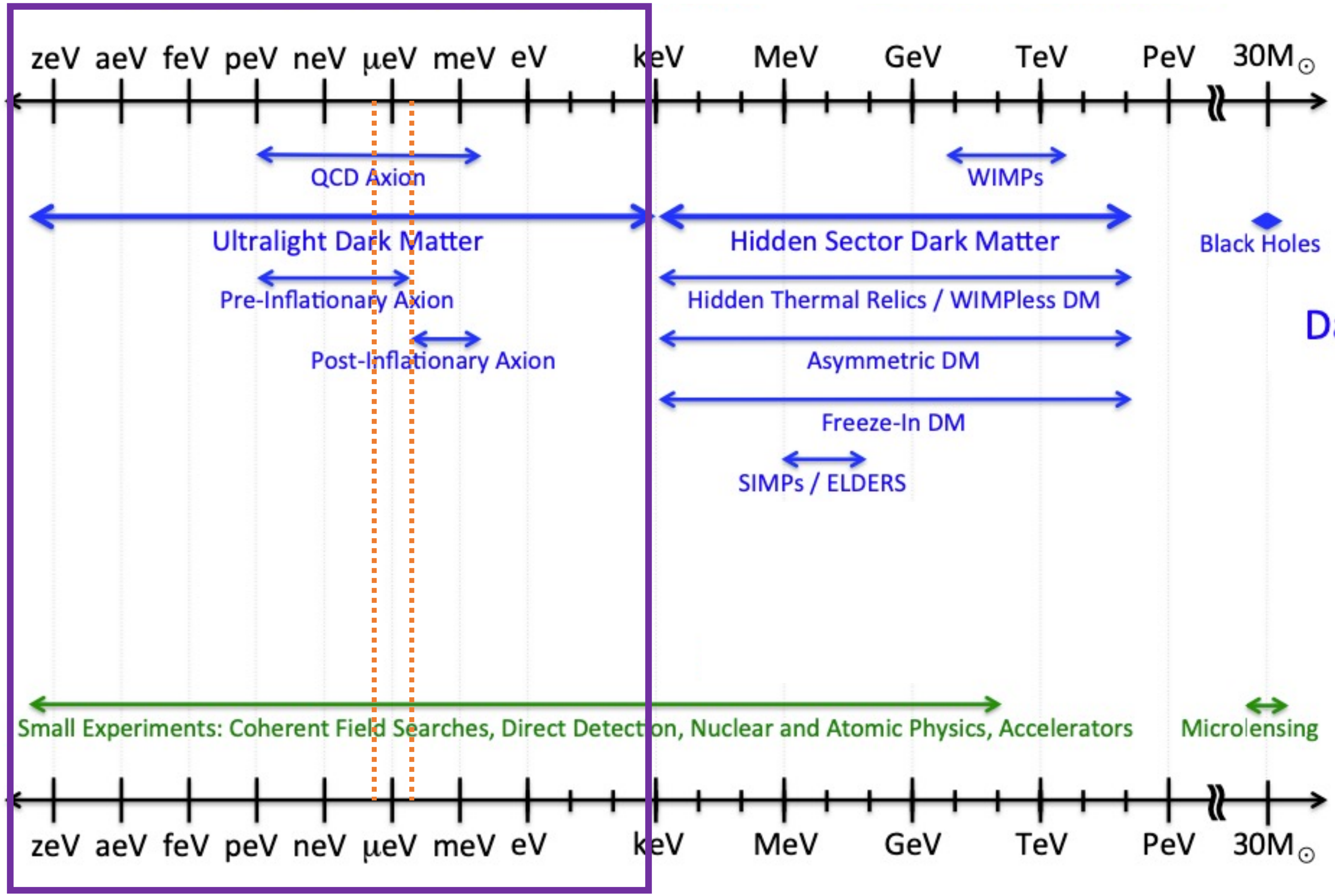




- **Cosmological scale**
(CMB, structure formation,…)

Classes of DM

ULDM mass interval



Dark Sector Candidates

Search Techniques

Fig. 1 from US cosmic vision : new idea for Dark Matter 2017, Arxiv:1707:04951

Ultralight Dark Matter (ULDM) models

Occupation number in phase space →

$$\frac{n}{n_k} \sim \frac{6\pi^2\hbar^3}{c^2}\frac{\rho_{DM}}{m^4 v_{max}^3} > \mathbf{1}$$

ρ_{DM}: $\sim 0.3\ GeV/cm^3$; v_{max}: $\sim 10^{-3}c$; m: $< 10\ eV$

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

→ULDM (with $m < 10\ eV$) has to be <u>bosonic</u> (Pauli exclusion principle)

- When $\boldsymbol{m \ll eV}$ → $\frac{n}{n_k} \gg 1$ → 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),...)**

Does DP induce oscillating electric field ?

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

EM field

EM strength tensor

DP strength tensor

DP field

Kinetic mixing coupling

Horns et al. JCAP, 2013

- Cosmologically, DP field oscillates at its Compton frequency $\vec{\phi} = \vec{\phi}_0 \cos \omega t$

$\omega = m \; (\mathrm{k} = 0)$

- This mixing 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 χ 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 ($\mathcal{O}(GHz)$)

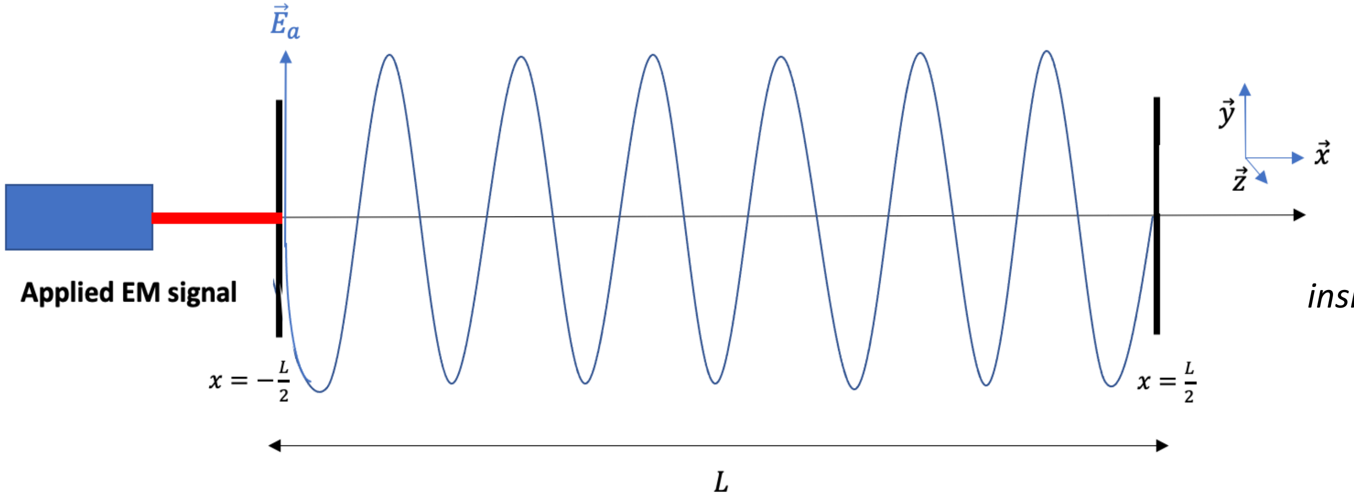


Fig. 2 : Signal applied inside a microwave cavity, with the appropriate frequency such that a resonance occurs.

- 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
→ **Q is the amplitude amplification factor**

- In the context of DP, $\vec{E}_{DP}$ acts as another initial wave which might enter in resonance.

The experiment : Setup using microwave signal

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We can **either** measure the DM electric field directly…

$$\vec{E}_T \propto \underbrace{\vec{X}_{DM} e^{-i\omega_{DM} t}}_{\text{DM field contrib. (small)}}$$

→ Oscillate too fast ($\mathcal{O}(GHz)$)
→ Amplitude too small ($\mathcal{O}(\chi)$)

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

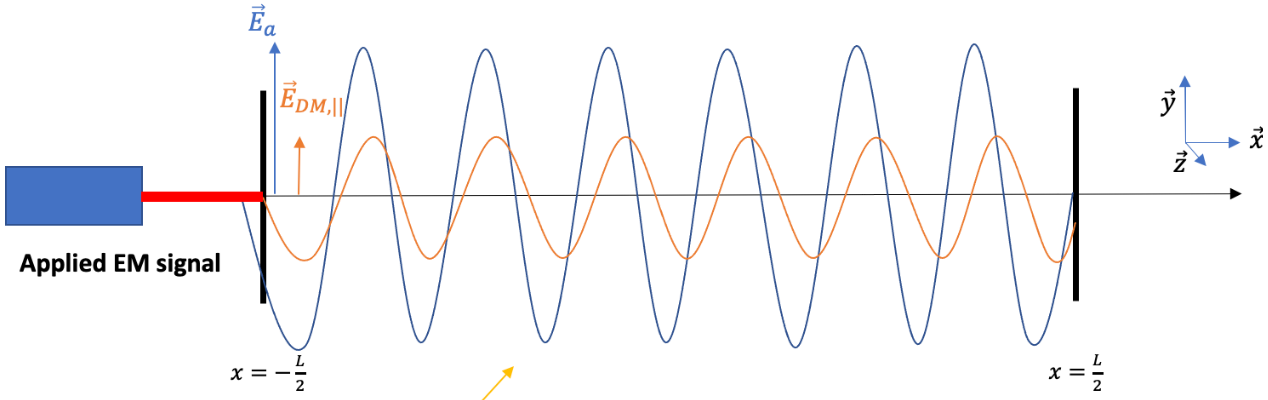

Fig. 3 : A microwave signal sent inside a resonant cavity, with a frequency close to the one of the hypothetical DP.

$\omega_a - \omega_{DM}$ $\quad$ $\vec{E}_{DM}$ $\quad$ $\omega_a + \omega_{DM}$

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

✓

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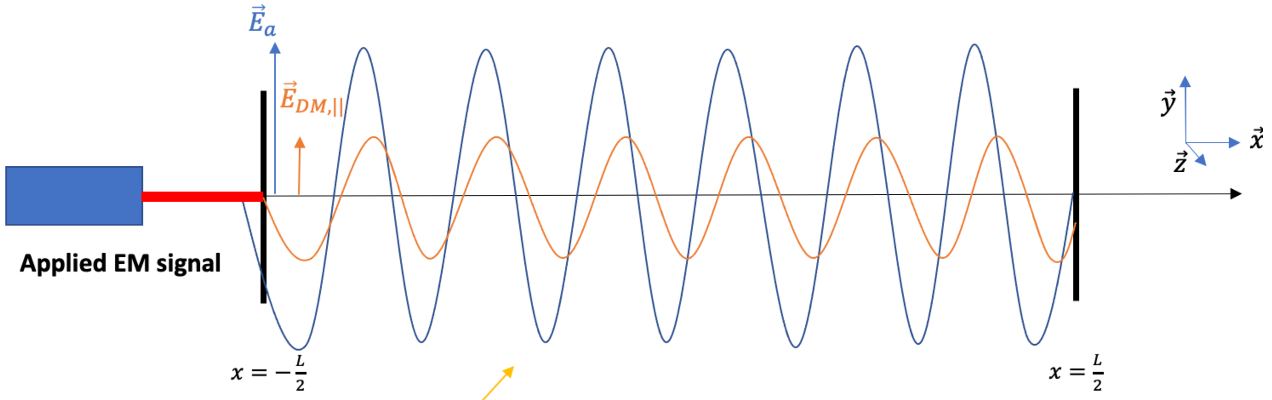

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$\Delta\omega = \omega_a - \omega_{DM}$ ✓ ; $\Sigma\omega = \omega_a + \omega_{DM}$

Oscillation too fast/Amplitude too small

→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**

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

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

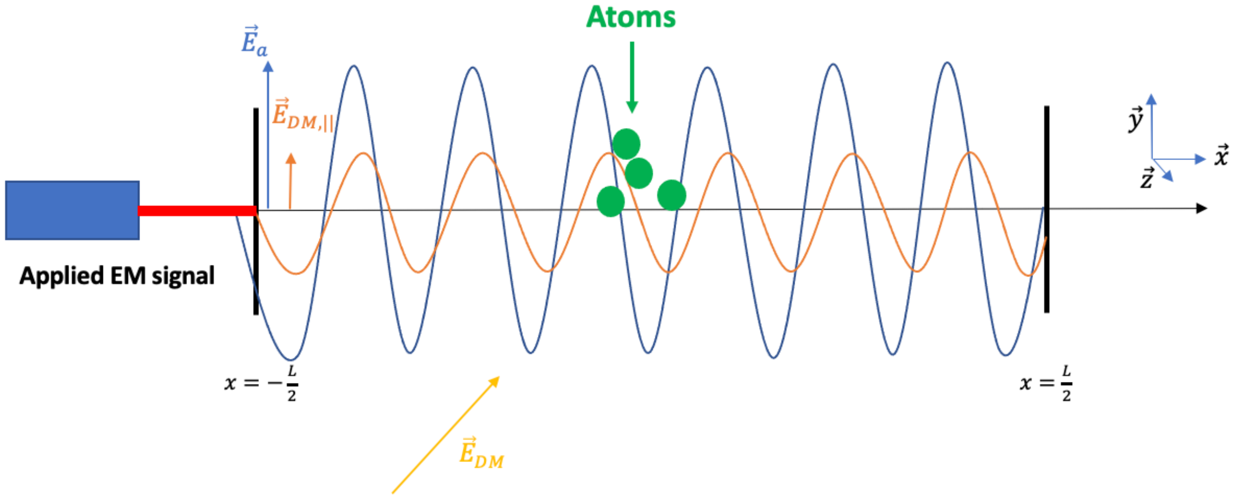


Fig. 4 : Atoms at the center of the cavity to measure the Stark effect induced by $\langle \boldsymbol{E_T}\rangle^2$

With **Rydberg atoms** :

- High accuracy on $\boldsymbol{\Delta\nu}$ from $\langle \boldsymbol{E}\rangle^2$
- Large polarizability $\Delta\boldsymbol{\alpha}$
- Good resolution on $\langle \boldsymbol{E}\rangle^2$ (with small T_{obs})

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

The experiment : Experimental methodology

1) Apply electric field with initial frequency ω_a during T_{obs}
   → scan possible DM signals with $\Delta\omega < f_s$

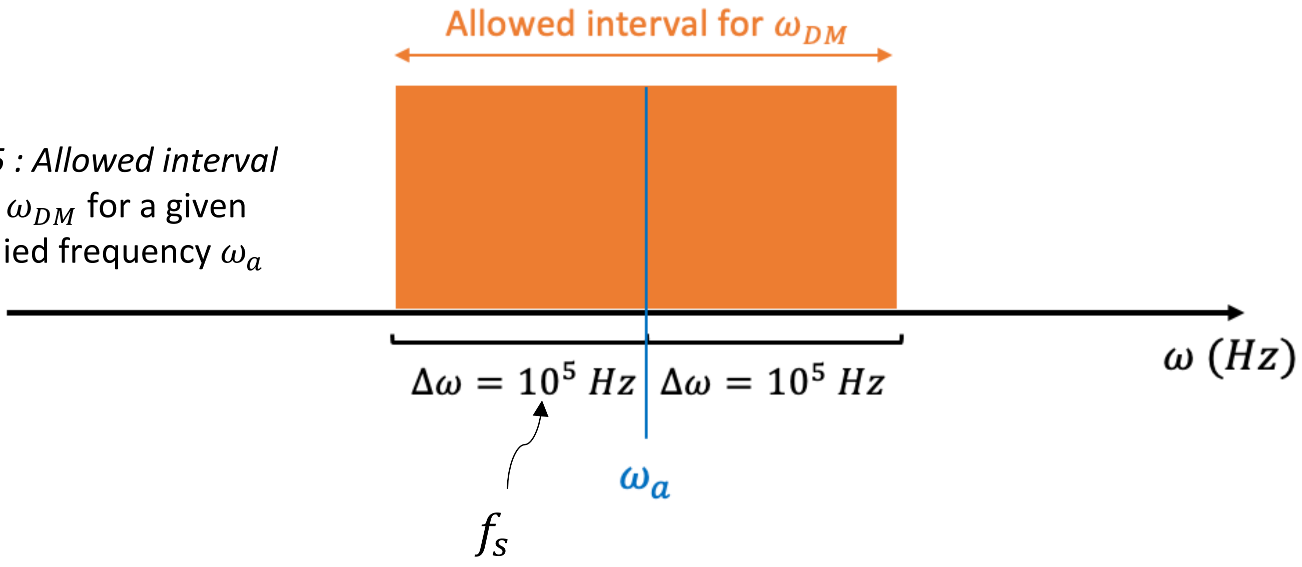
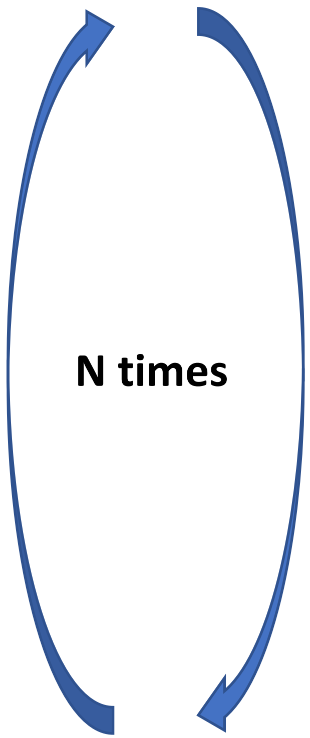


Fig. 5 : Allowed interval for ω_{DM} for a given applied frequency ω_a



2) Shift applied frequency by 2×10^5 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 $\langle E_{min} \rangle^2 = 1\ (\mathrm{V/m})^2$

→ $\chi(\omega_{DM}) = f(Q, X_a, X_{DM}, \ldots)$

	Microwave cavity
Quality factor Q	10^4
Cavity length	10 cm
Injected power	1 W
Effective mode radius	$\mathcal{O}(cm)$
$\langle E_{min} \rangle^2$	$1\ (\mathrm{V/m})^2$
Number of atoms N_a	10^4
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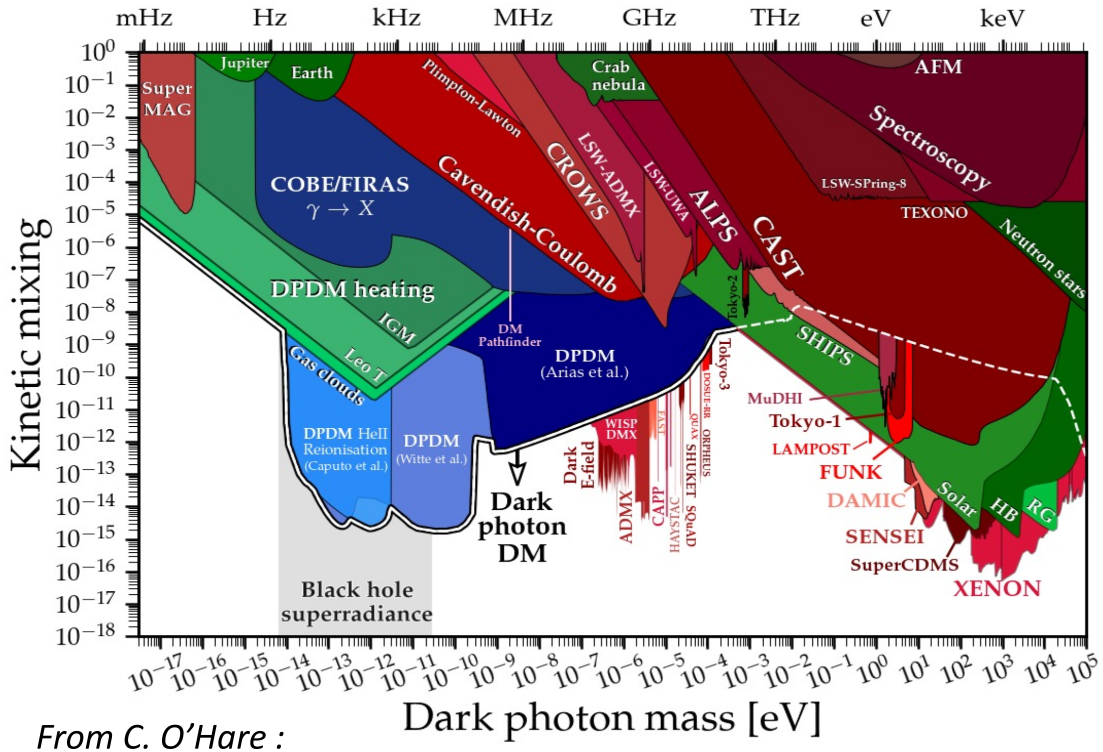

From C. O'Hare :
https://github.com/cajohare

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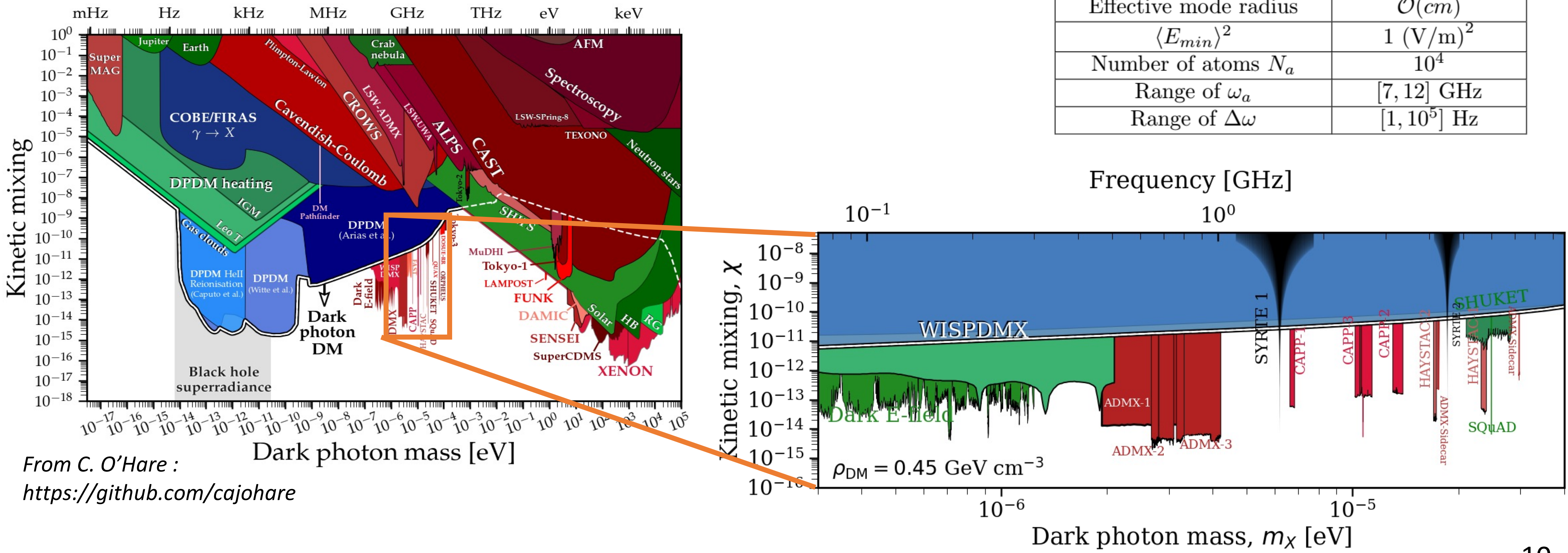

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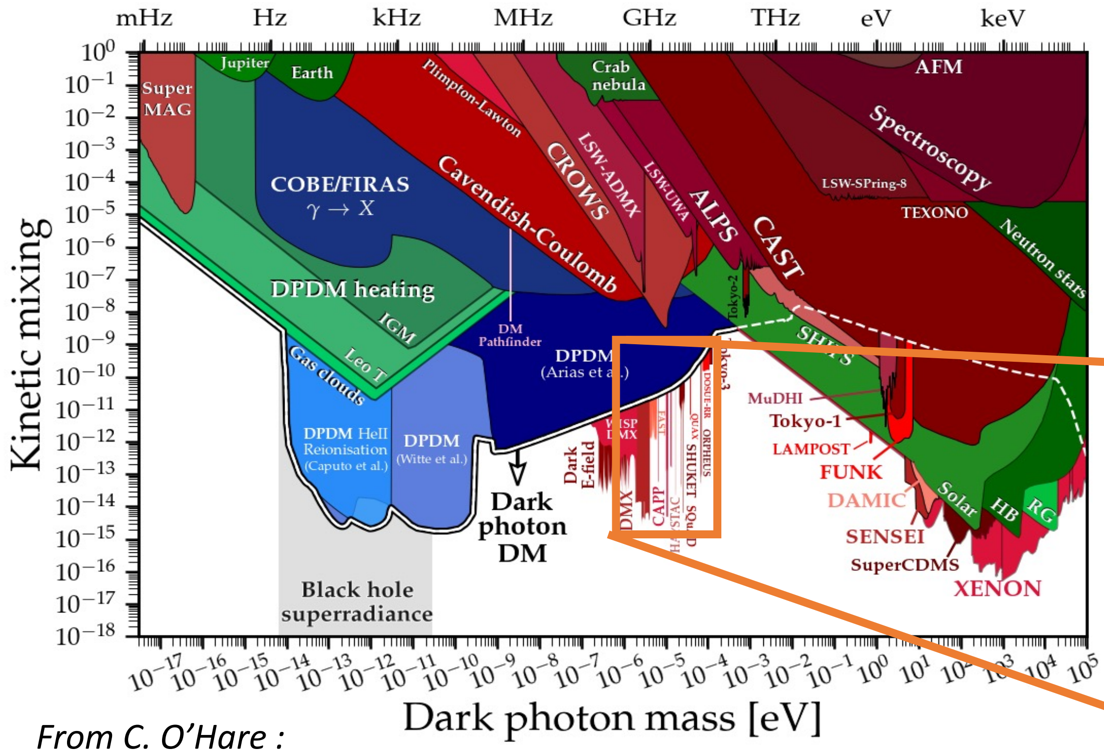

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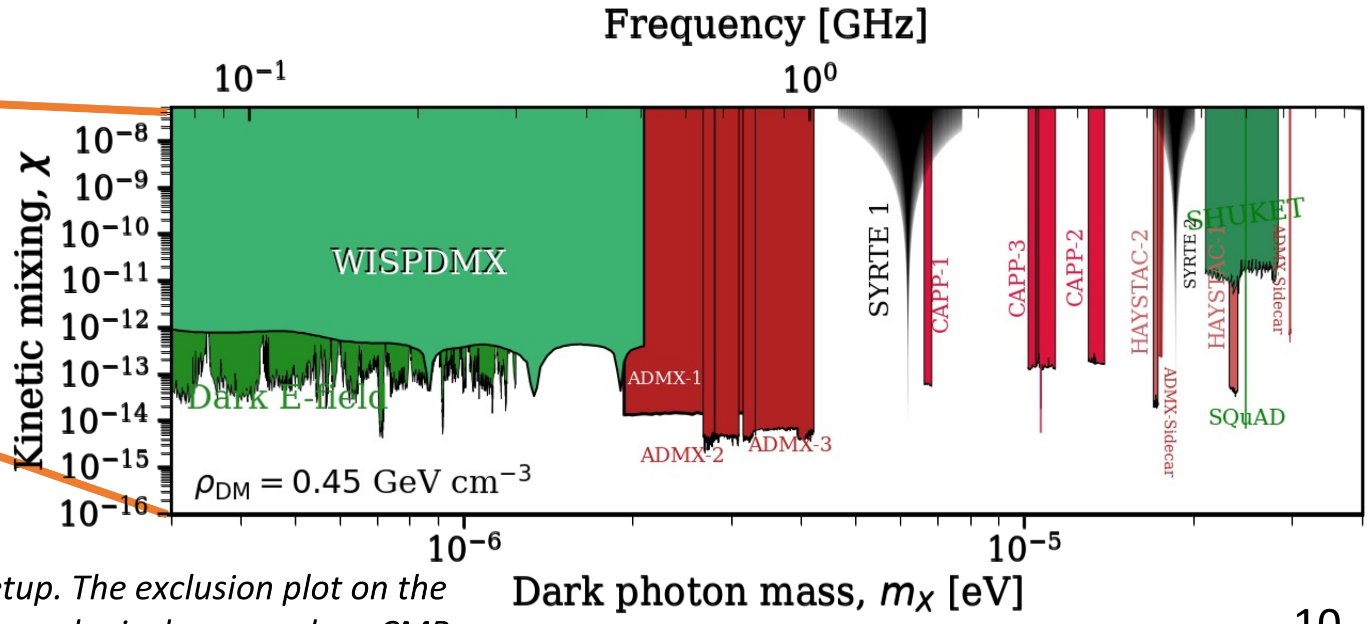

Fig. 6 : Constraint on χ obtained with this setup. The exclusion plot on the right shows only lab experiments and omit cosmological ones such as CMB.

Rough estimation of the experiment's sensitivity

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

→ $\vec{E}_T = A(\vec{X}_{DM}, \omega_{DM})e^{-i\omega_{DM}t} + B(\vec{X}_a, \omega_a)e^{-i\omega_a t}$ + **syst. noise** ← $\propto \Delta\vec{X}_a$

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

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

$\Rightarrow \searrow S_{RIN}$ **or** $\nearrow T_{obs} \Longrightarrow$ **Better constraint on** χ

Rough estimation of the experiment’s sensitivity

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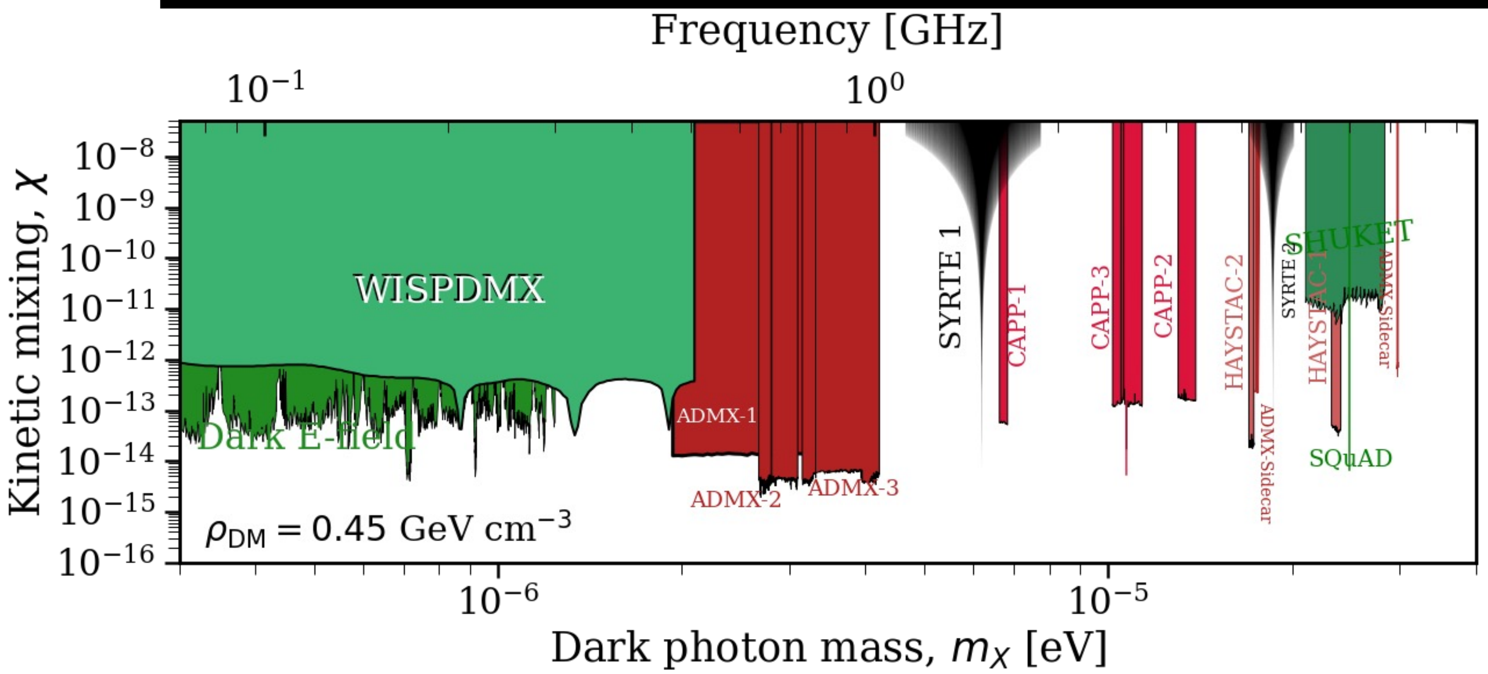

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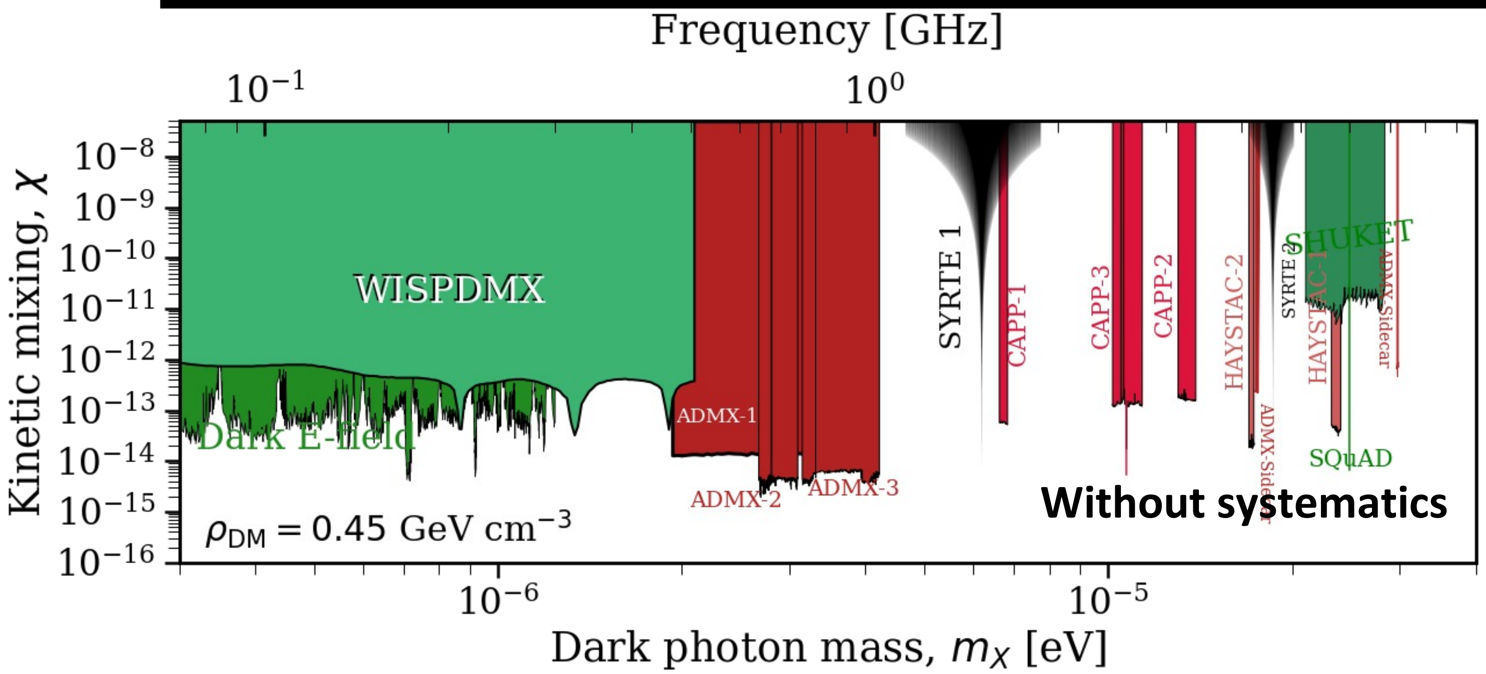

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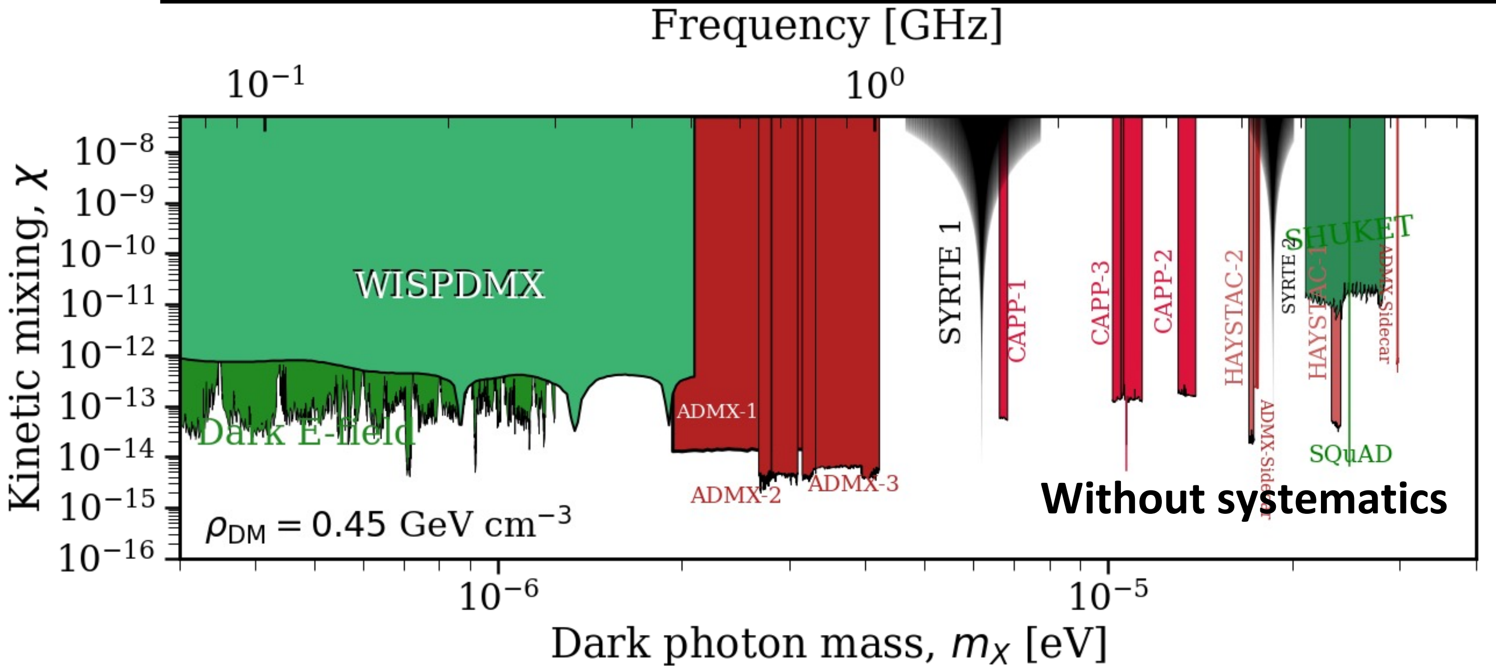

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Number of atoms N_a	10^4
Range of ω_a	$[7, 12]$ GHz
Range of $\Delta\omega$	$[1, 10^5]$ Hz
T_{obs}	600 s
S_{RIN} (best case scenario)	$10^{-9}/\sqrt{Hz}$

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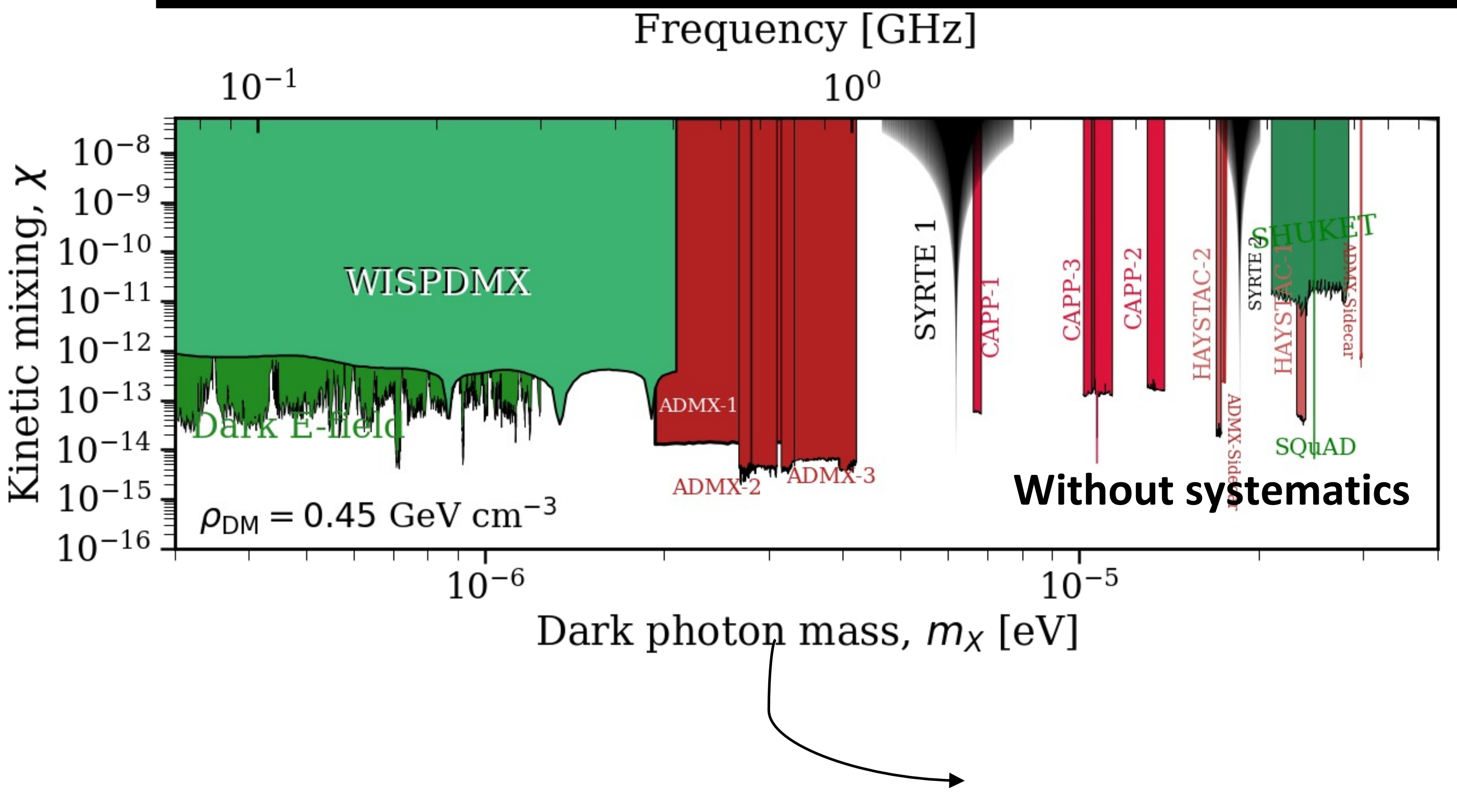

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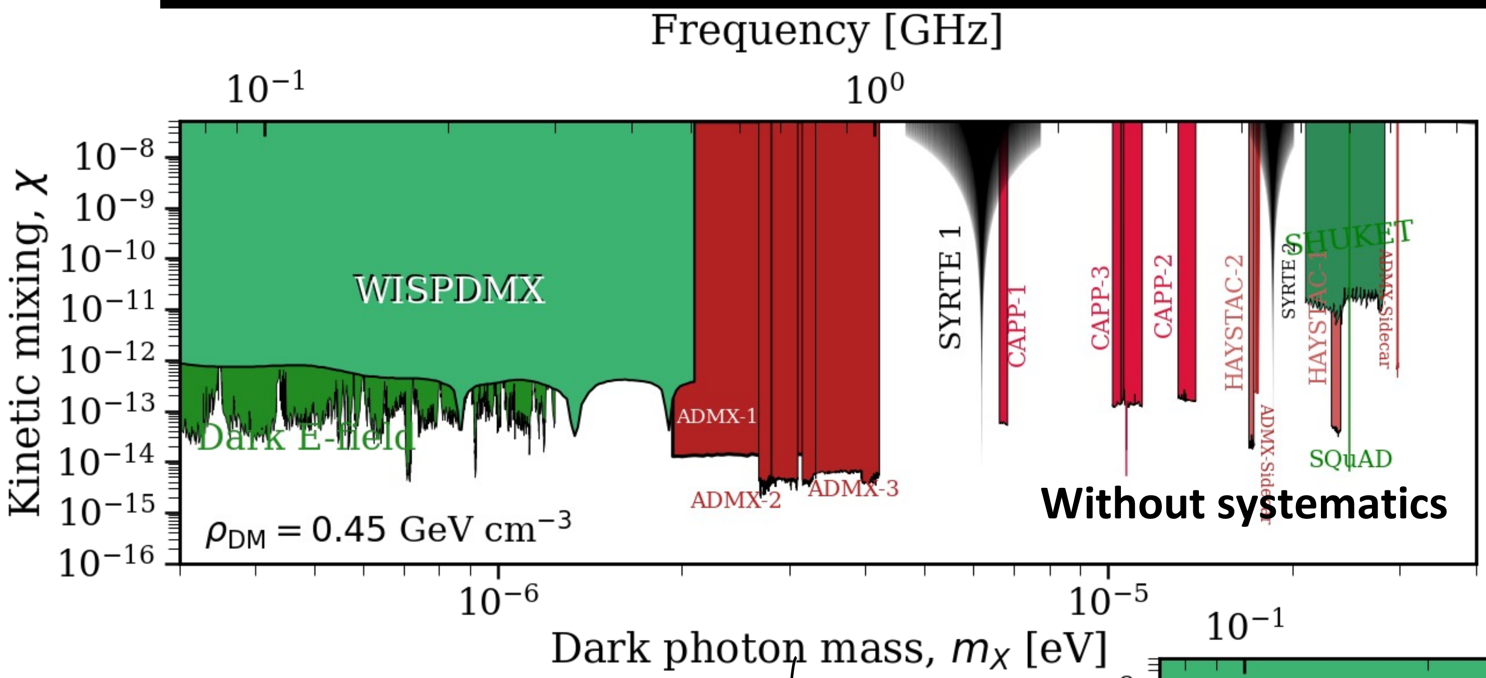

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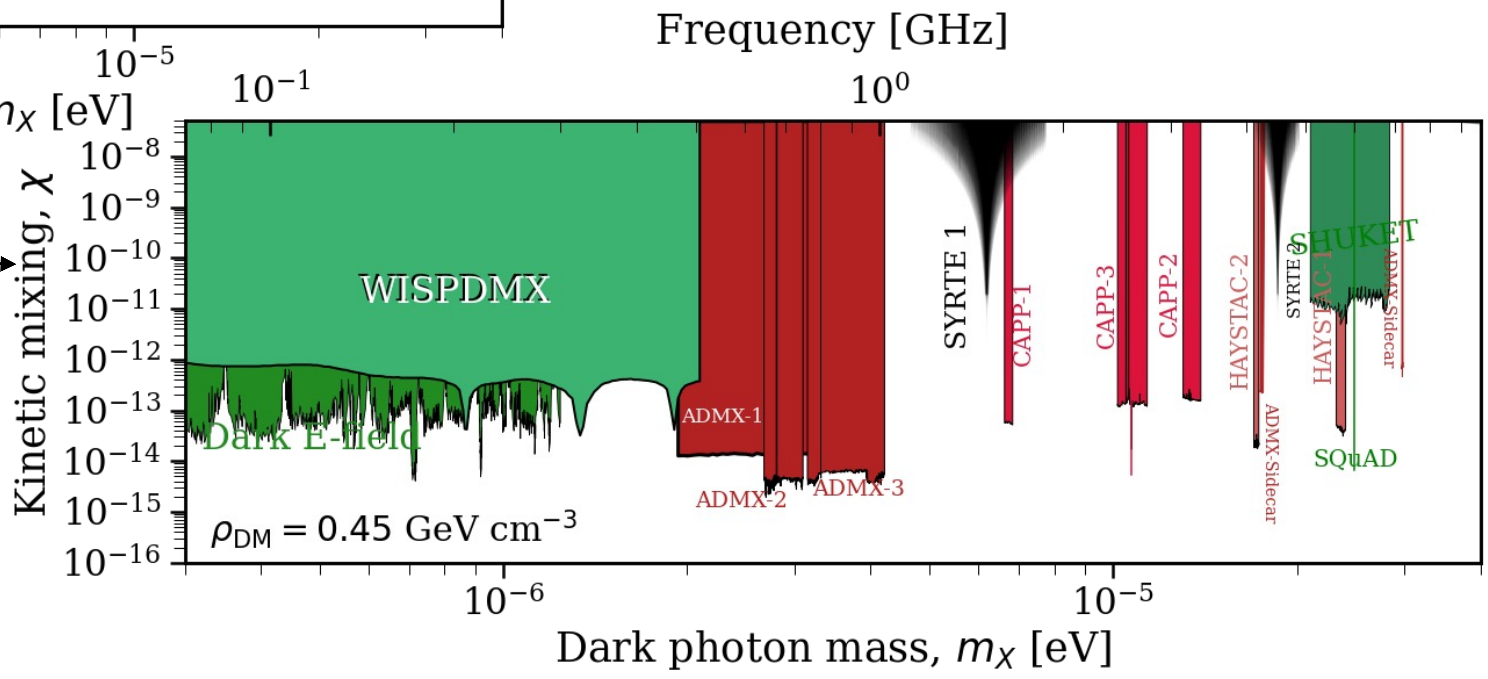

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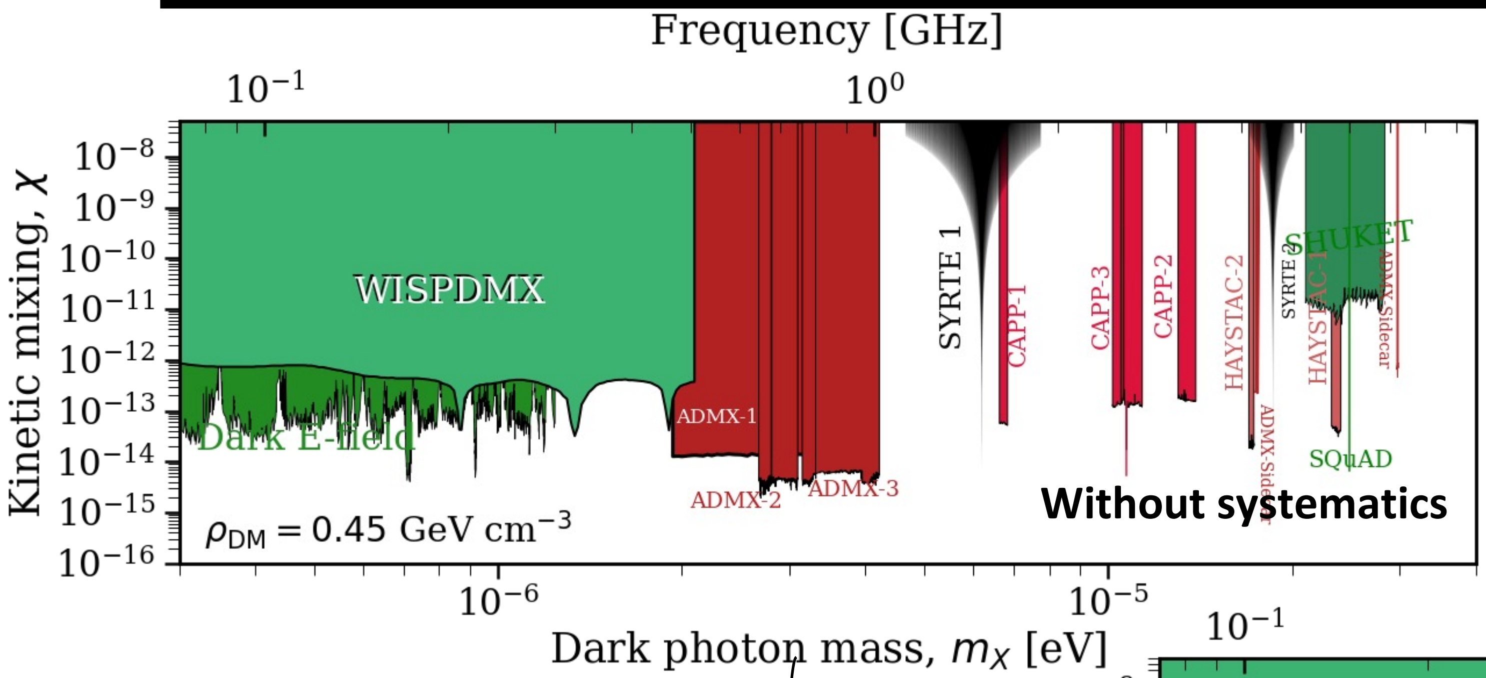

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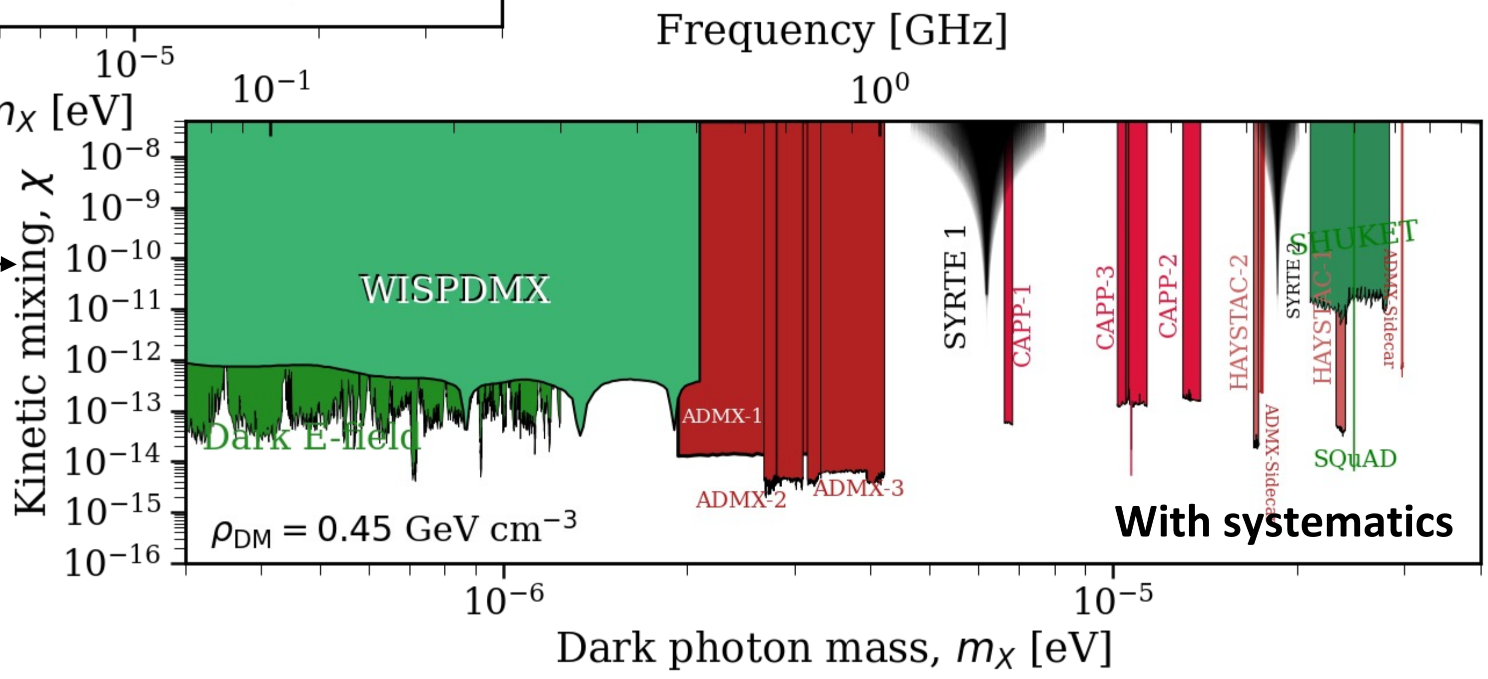

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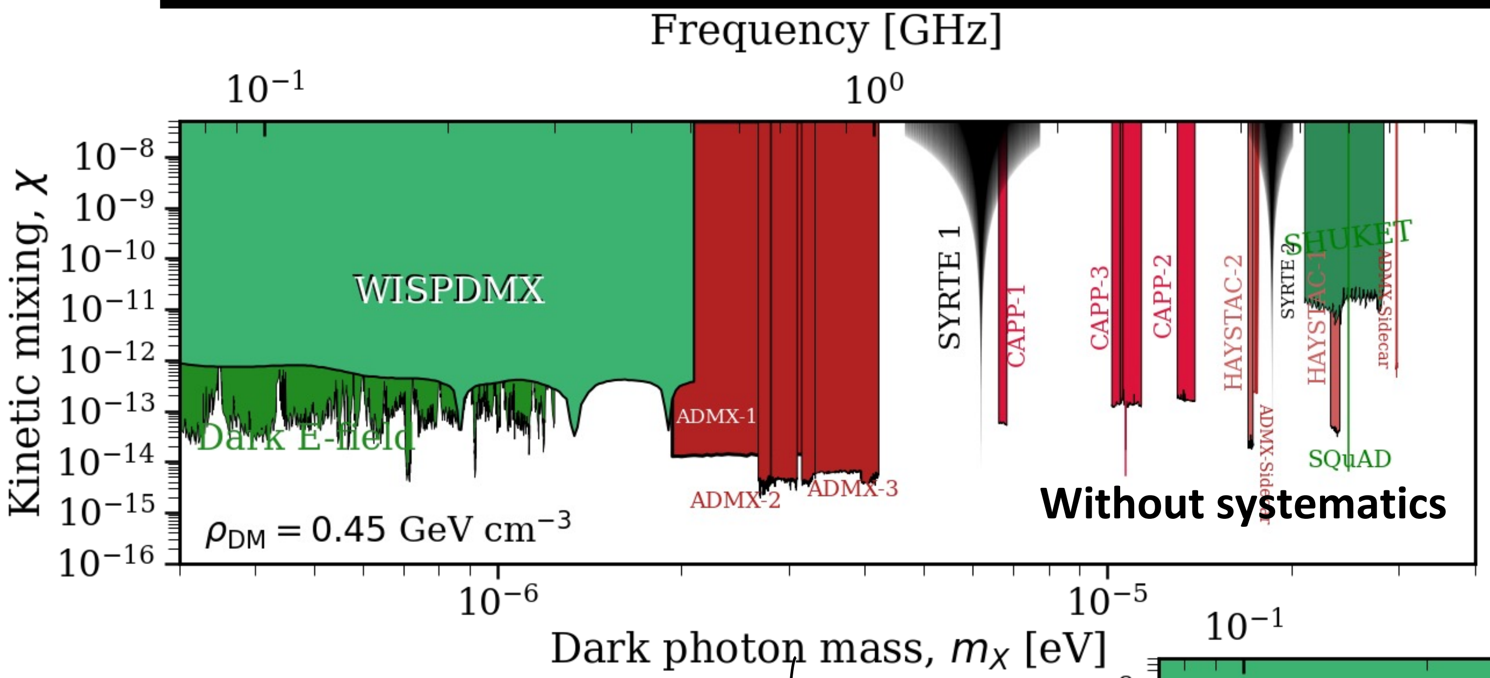

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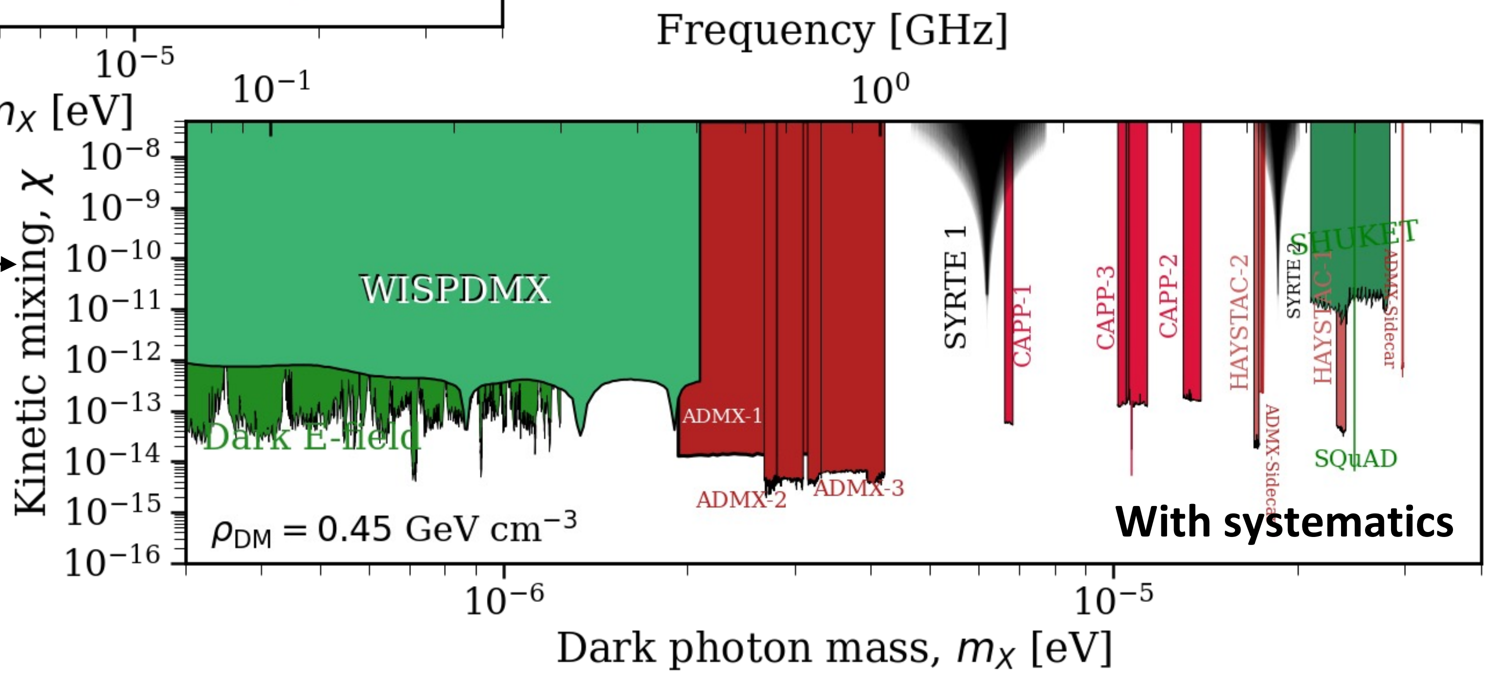

Fig. 7 : Constraint on χ obtained with this setup for T_{obs}= 600 s , $S_{RIN} = 10^{-9}/\sqrt{Hz}$

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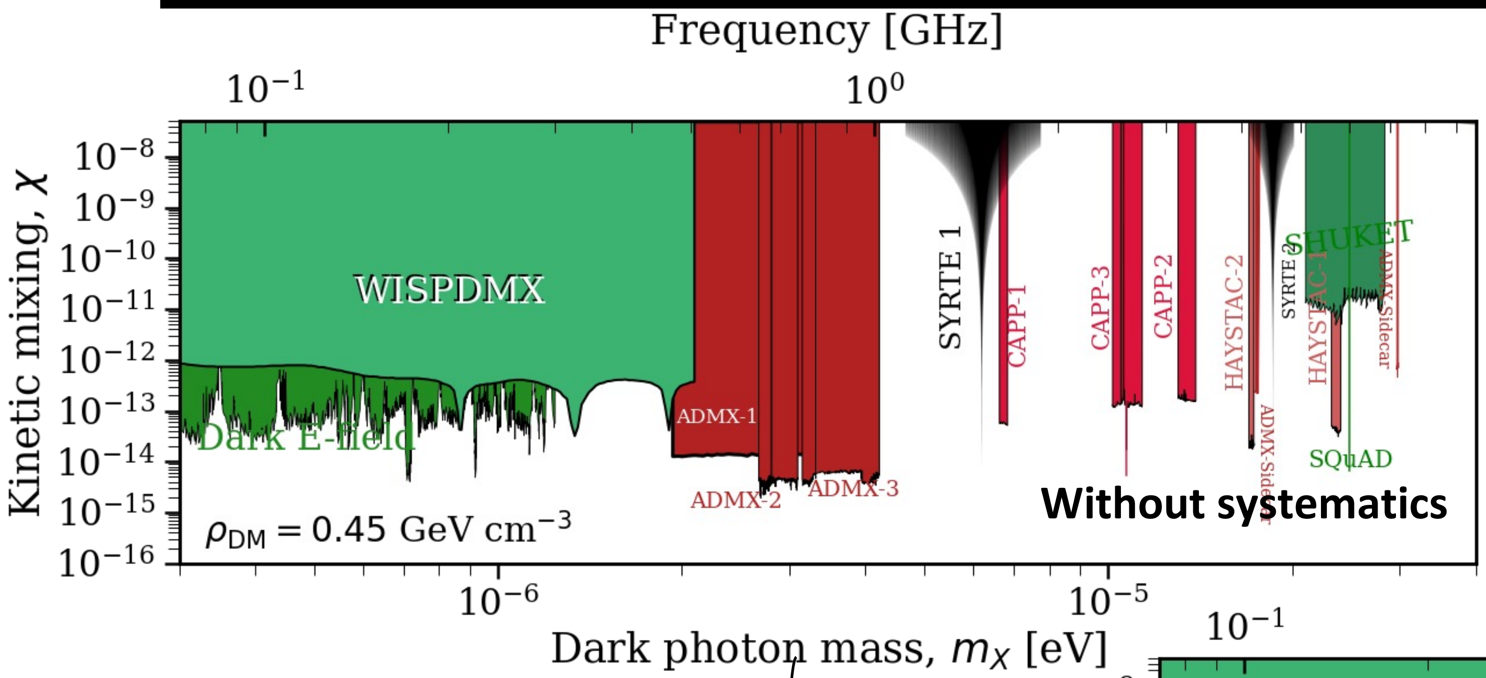

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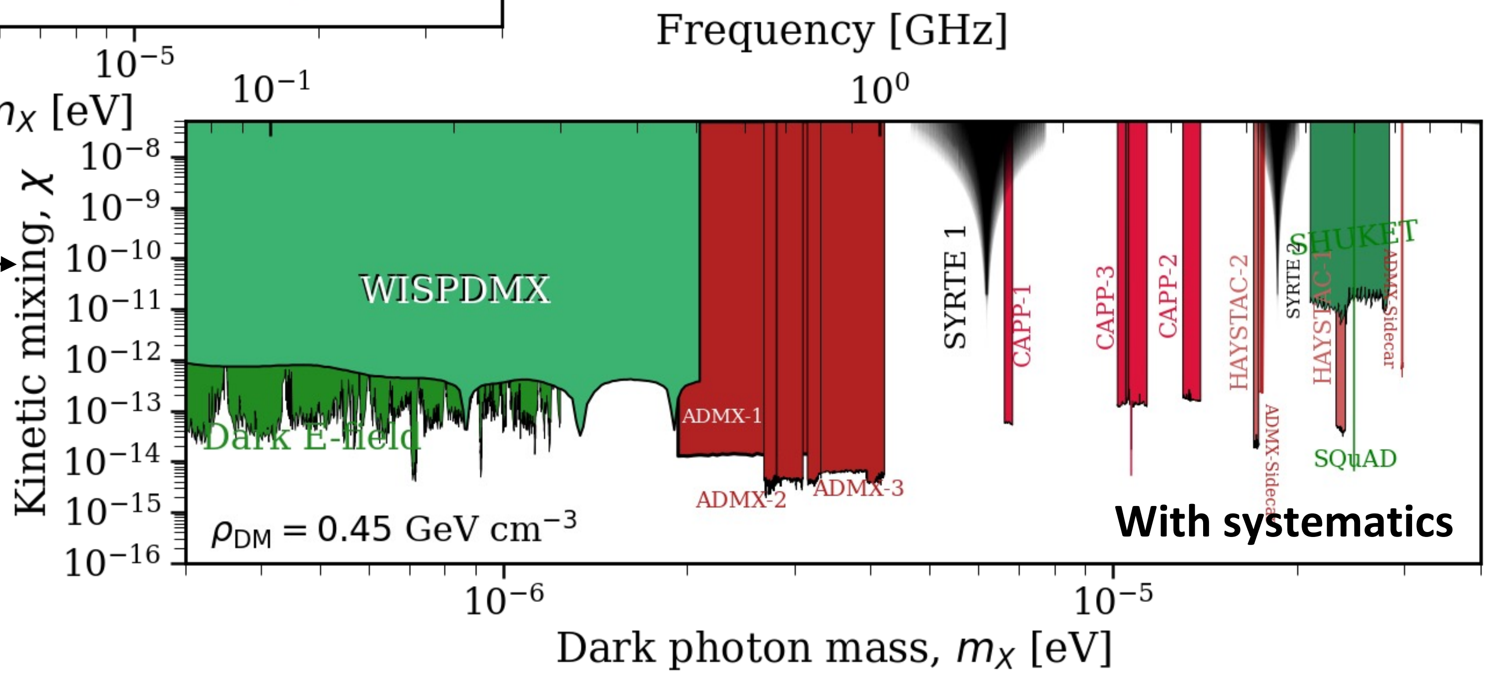
→ Need to consider $\boldsymbol{T_{obs} = 600}$ **s**



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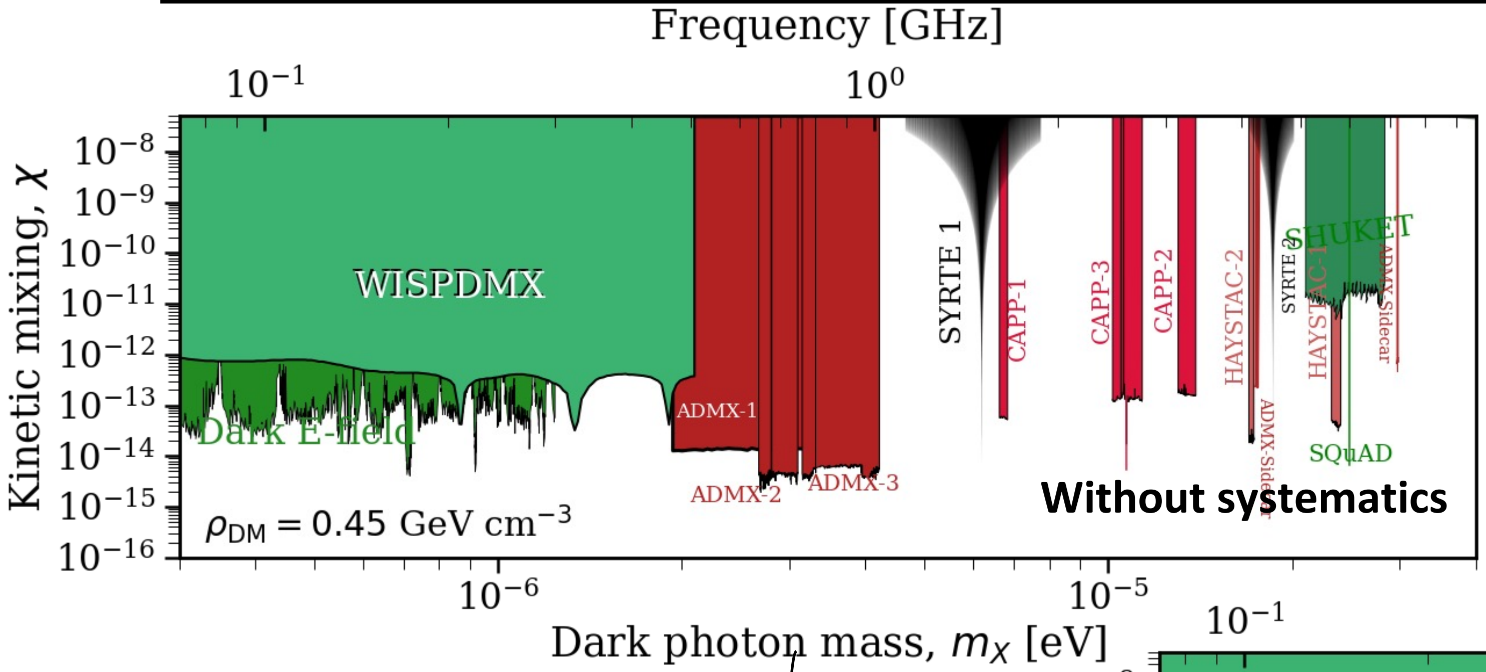

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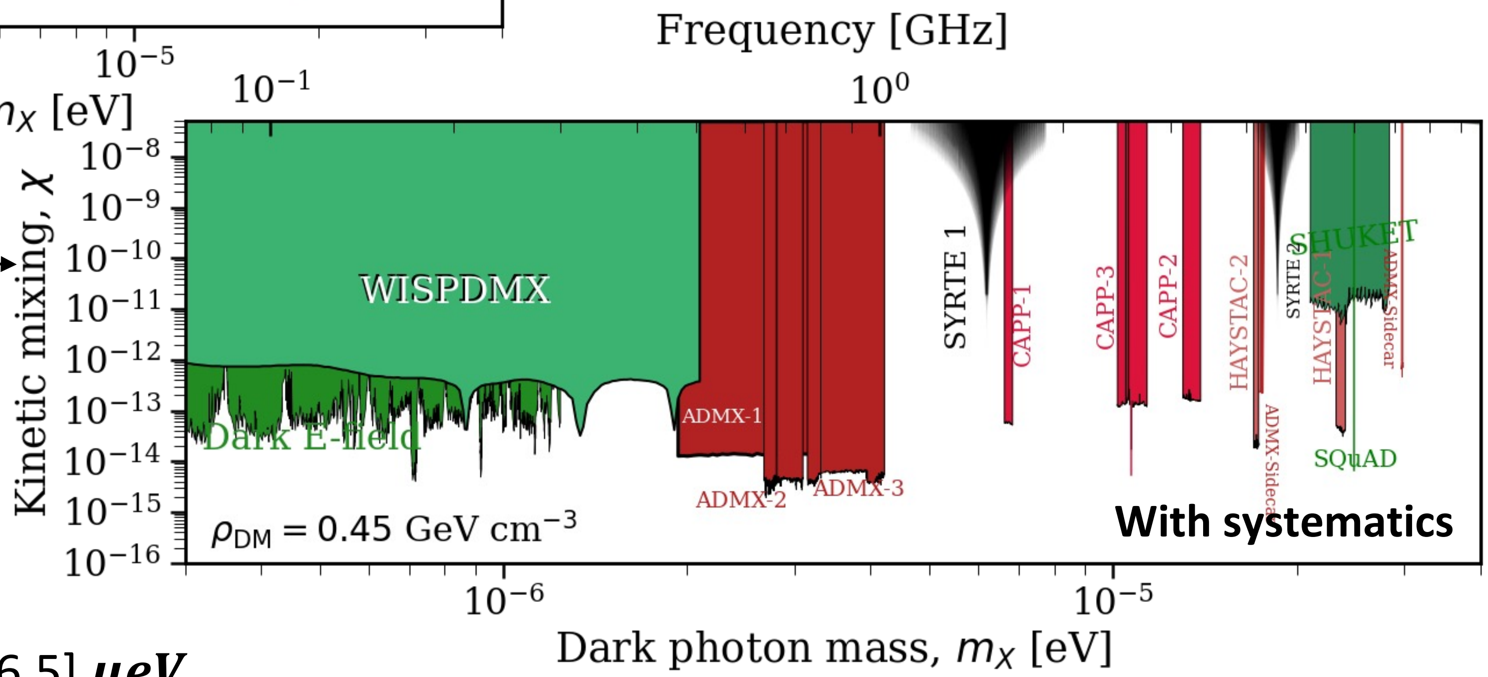

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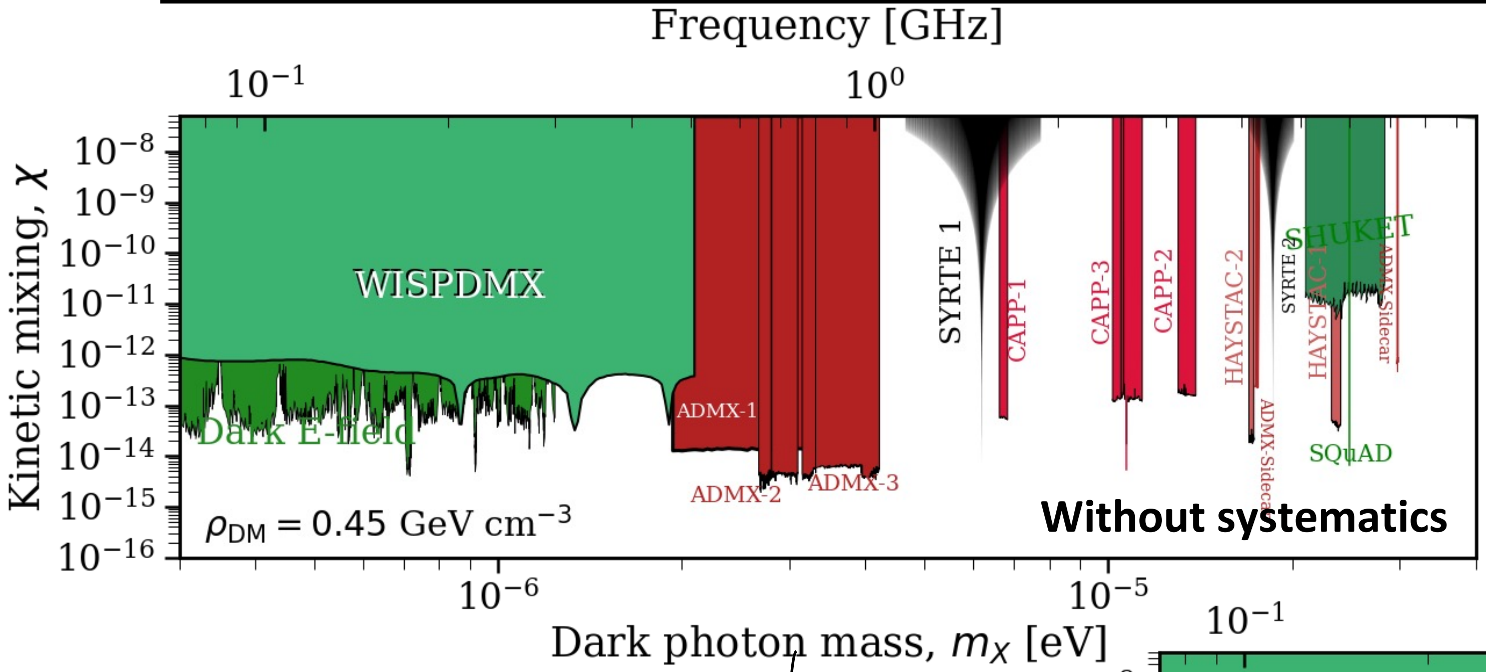
Nb of times we switch ω_a

Total experiment time $T_{tot} = NT_{obs}$

$T_{tot} \sim$ 1 month ≡ scan DM masses ∈ [5.9 ; 6.5] μeV

Rough estimation of the experiment's sensitivity



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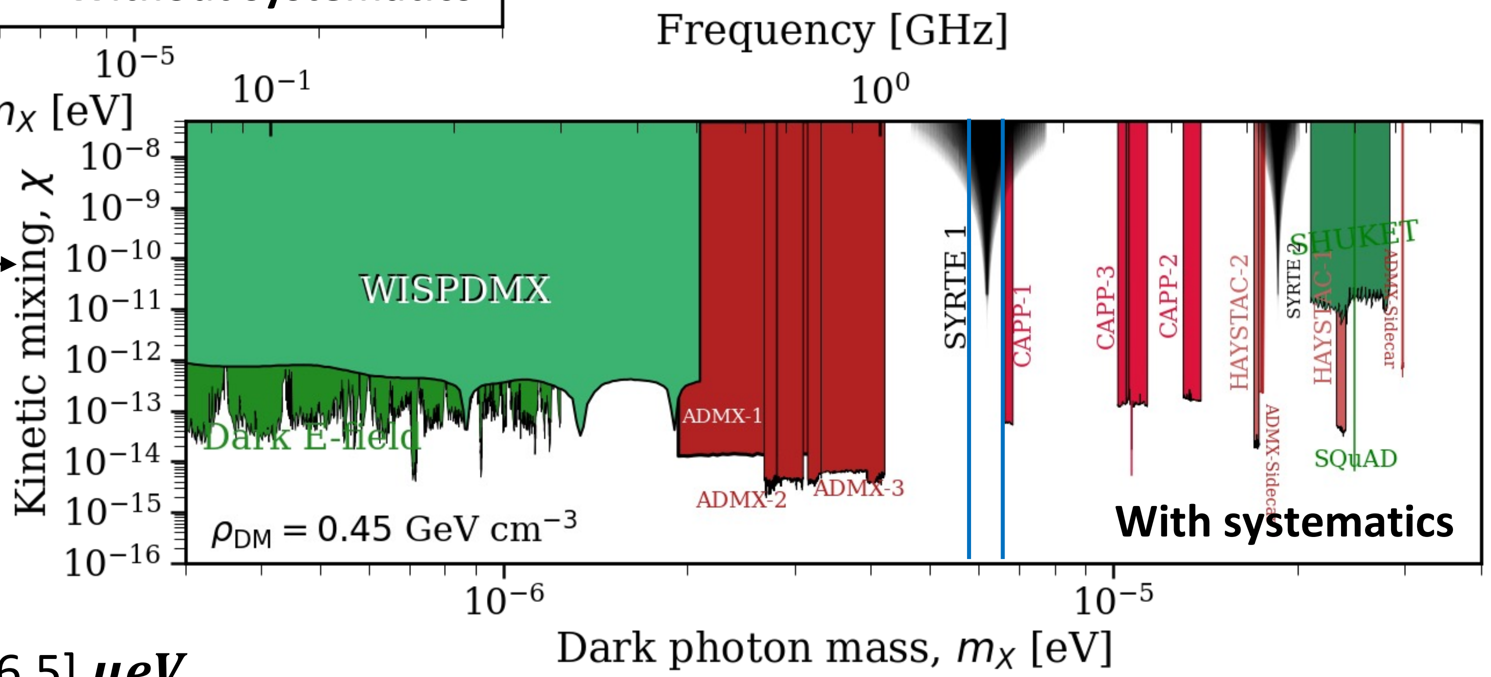

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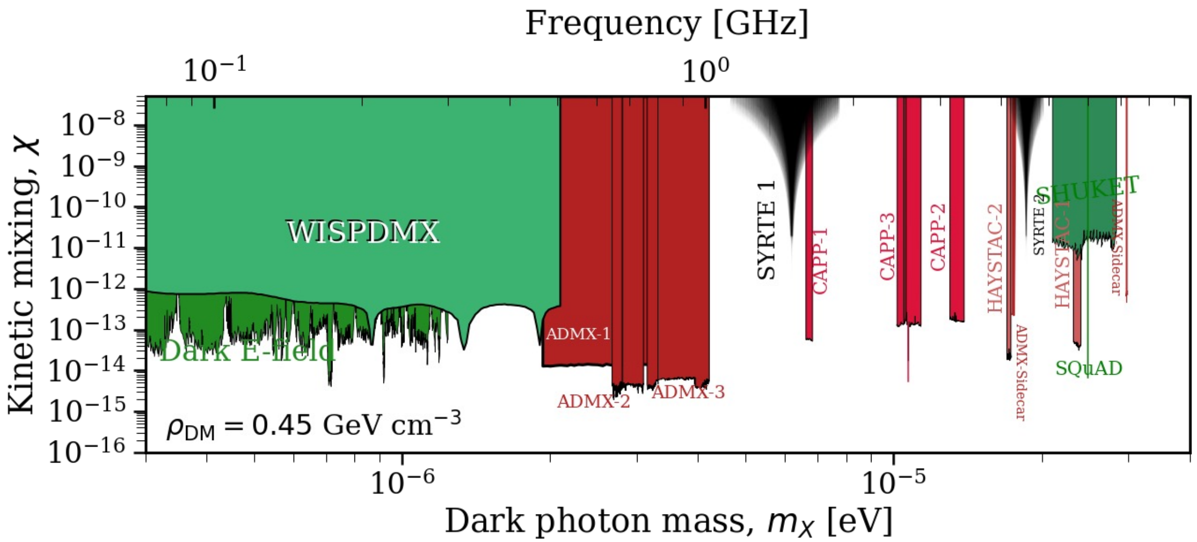
Conclusion

- 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 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 → we require n odd (antinode at the center)

- Reflectivity coeff of mirrors r is related to quality factor as

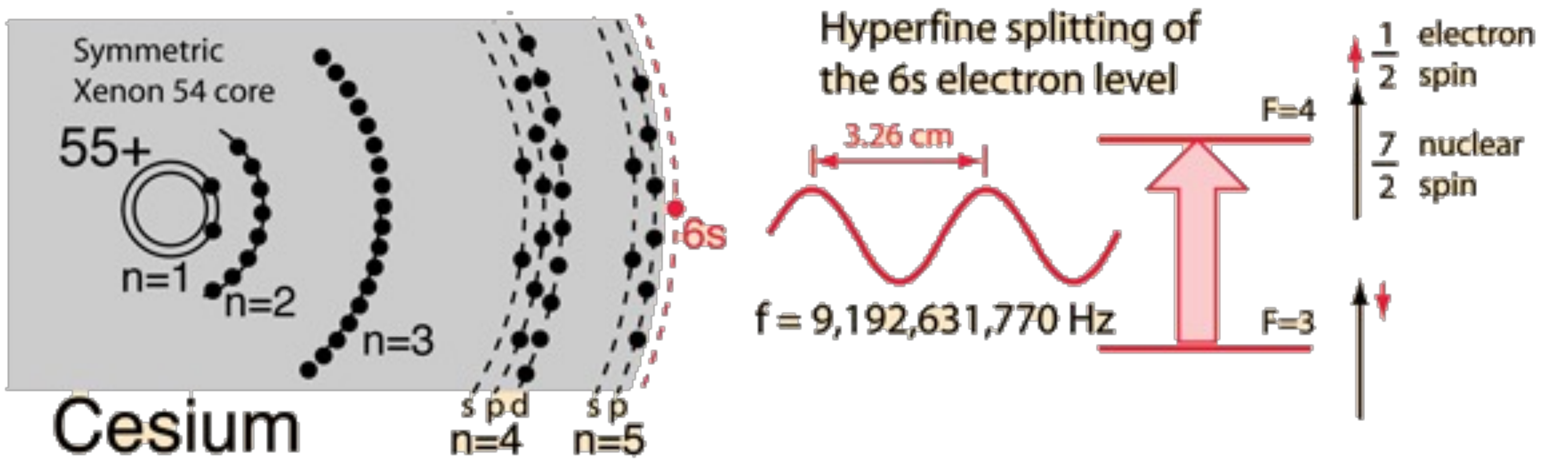
$$Q = \frac{2\pi}{\lambda(1 - r^2)}$$

This relation is valid only around resonances.

- Finesse of a cavity defined as

$$\mathcal{F} = 2\pi N_e \rightarrow \mathcal{F} \approx Q$$

Back-up : Atomic clock



From http://hyperphysics.phy-astr.gsu.edu

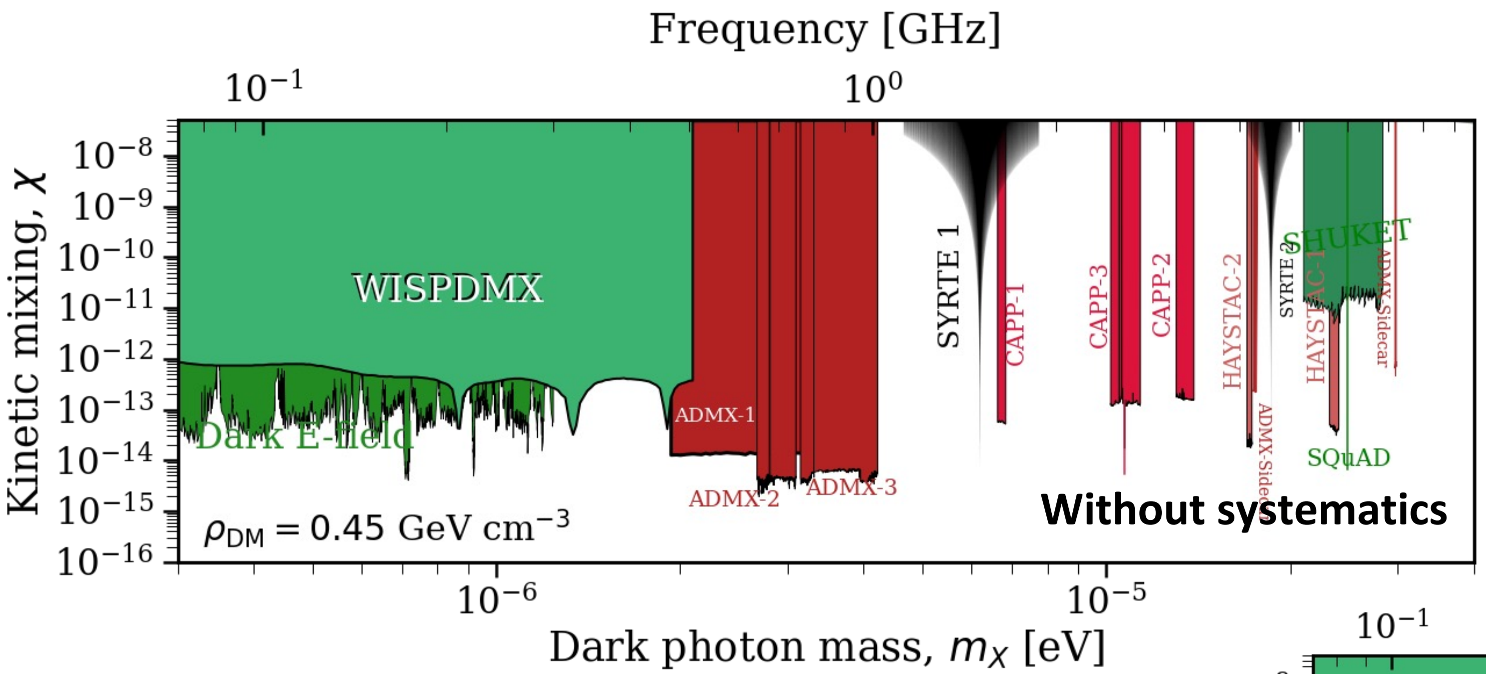
Atoms inside a cavity, excited by a laser.

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.

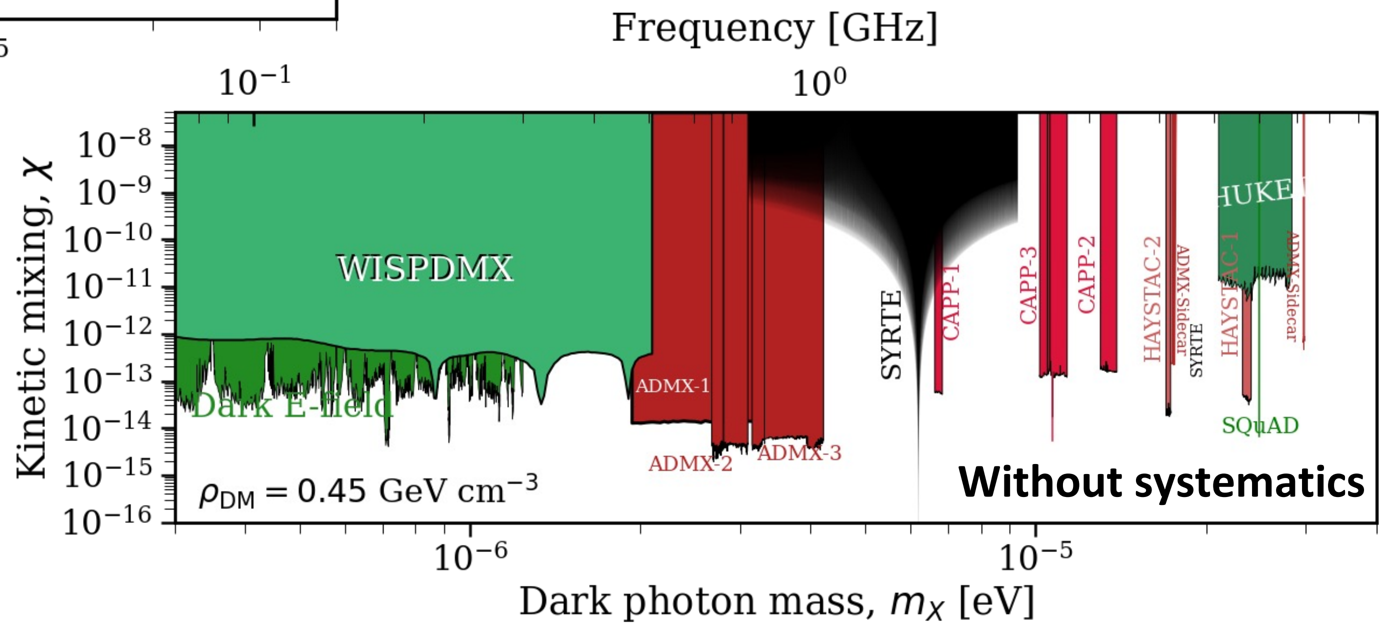
→ Wave with appropriate frequency and need to count oscillations to give time

Back-up : How does Q impacts the sensitivity ?



$Q = 10^4$

$Q = 10^6$



Back-up : why microwave cavity and not optical ?

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

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

2. Optical frequency ≡ eV mass
   → QFT required for DP field

Back-up :DP cosmo evolution + field equations

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

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

Nelson, Scholtz, PRD, 2011

whose solution is oscillatory.

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

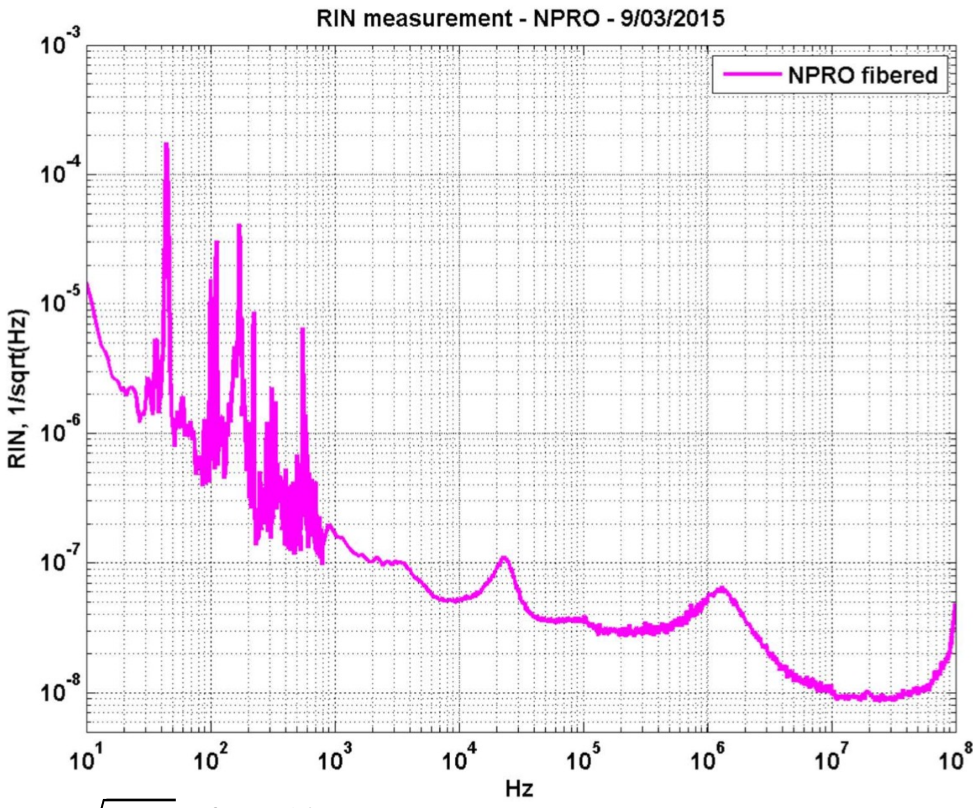
- In the **microwave regime** and considering $\boldsymbol{v_{DM} \sim 10^{-3}}$ in Earth's frame, the DP field can be approximated by a standing wave in a cavity of length $L \sim 10$ cm. Then,

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

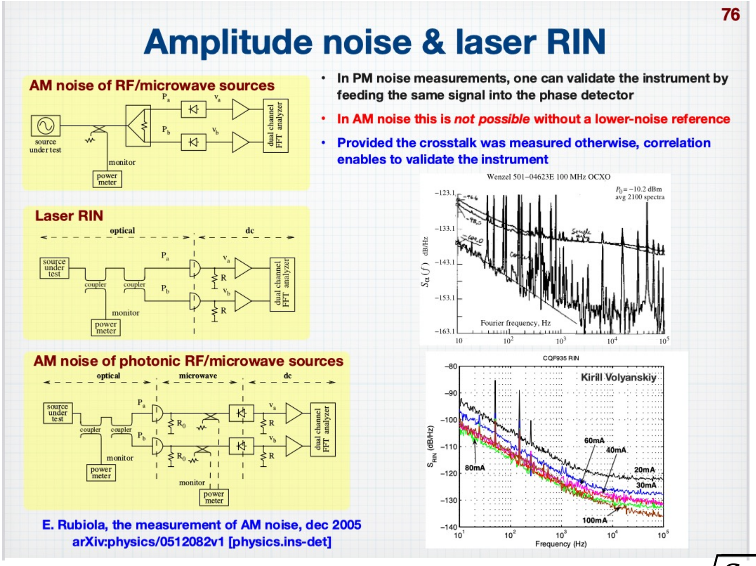
- The DP mixes with the SM photon as

$$\partial_\mu \partial^\mu A^\nu = -\chi \phi^\nu$$
$$(\partial_\mu \partial^\mu + m^2)\phi^\nu = -\chi \partial_\mu \partial^\mu A^\nu$$

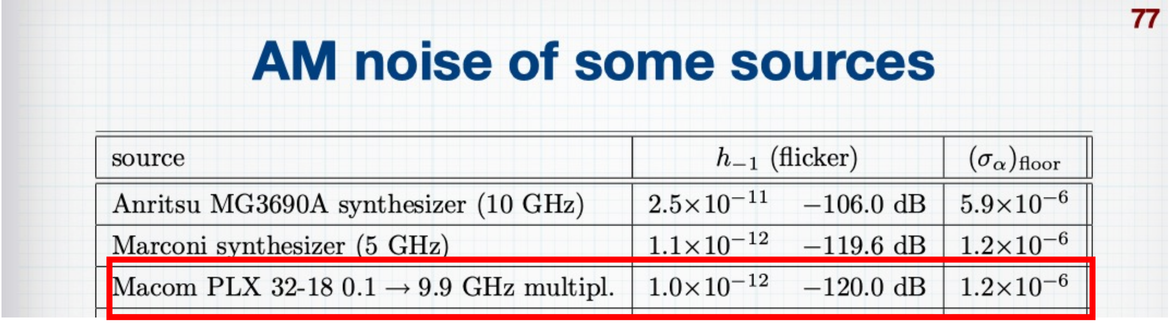
Back-up : Systematic noise and Data analysis



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



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



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AM noise of some sources

source	h_{-1} (flicker)		$(\sigma_\alpha)_{\text{floor}}$
Anritsu MG3690A synthesizer (10 GHz)	2.5×10^{-11}	-106.0 dB	5.9×10^{-6}
Marconi synthesizer (5 GHz)	1.1×10^{-12}	-119.6 dB	1.2×10^{-6}
Macom PLX 32-18 0.1 → 9.9 GHz multipl.	1.0×10^{-12}	-120.0 dB	1.2×10^{-6}

With RIN noise $\propto f^{-1}$, the $S_{RIN} = 10^{-9}/\sqrt{Hz}$ works at frequencies $f \sim 10^4 - 10^5$ Hz