Dark photon and scalar field for tabletop experiments

The axion's underdogs

Etienne SAVALLE

DPHP, CEA Saclay

30 Septembre 2024

Types of particles Occupation number (cf slide 24 Pierre's talk) :

$$n \propto \frac{h^3 \rho_{DM}}{m_{DM}^4 v_{max}^3} \simeq 10^{29} \left(\frac{\mu\text{eV}}{m}\right)^4 \gg 1$$

Pseudo-scalar

BASE **Axion** PV 200

Pokémon bosonique pseudo-scalar Taille : 0,0m Poids : 0,0kg

Cap.Spé. **Invisible Axion**

Axion can't be attacked by any Fighting-type or Electric-type moves.

Axionic Shield 50

Deflects all damage for one turn and absorbs 30 HP if the opponent uses a Psychic-type attack.

Faiblesse +20 Résistance −30

Axion bends light and manipulates energy fields, making it nearly invisible.

Retraite

©2012 Valenga.fr

Illus. Sébastien

Go back in time 40 minutes ago

Vector

BASE **Dark Photon** PV 50

Pokémon bosonique vectoriel Taille : 0,0m Poids : 0,0kg

Kinetic overload 30

If the opponent's Pokémon is Electric-type, this attack does an additional 50 damage due to Kinetic Mixing. In this case, shuffle one Energy card from your discard pile back into your deck.

Quantum shift

With Metal Energy attached, it transforms into a Photon and attacks first on the next turn. The transformation lasts as long as the Metal Energy is attached.

Faiblesse Résistance

The Dark Photon exploits its Kinetic Mixing with the standard photon to generate burst of kinetic energy.

Retraite

©2012 Valenga.fr

Illus. Sébastien

Underdog n°1

Scalar

BASE **Scalar field** PV 130

Pokémon bosonique pseudo-scalar Taille : 0,0m Poids : 0,0kg

Vacuum fluctuations 60

Shuffle your hand into your deck and draw 5 new cards. Also, remove any status effect from Scalar Field.

Symmetry break 90

If the opponent's Pokemon has more HP than Scalar Field deal an additional 40 damage.

Faiblesse +20 Résistance −10

Axion bends light and manipulates energy fields, making it nearly invisible.

Retraite

©2012 Valenga.fr

Illus. Sébastien

Underdog n°2

1 Dark Matter

2 Dark photon
- Properties
- Resonant experiments
- Broadband experiments

3 Scalar field
- Properties
- Colocated
- Space-time separated

BASE **Dark Photon** PV 50

Pokémon bosonique vectoriel Taille : 0,0m Poids : 0,0kg

Kinetic overload 30

If the opponent's Pokémon is Electric-type, this attack does an additional 50 damage due to Kinetic Mixing. In this case, shuffle one Energy card from your discard pile back into your deck.

Quantum shift

With Metal Energy attached, it transforms into a Photon and attacks first on the next turn. The transformation lasts as long as the Metal Energy is attached.

Faiblesse **Résistance**

Retraite

The Dark Photon exploits its Kinetic Mixing with the standard photon to generate burst of kinetic energy.

Illus. Sébastien

©2012 Valenga.fr

What is it ?

Hypothetical gauge boson, similar to the regular photon but associated with a hidden/dark sector.

Interaction

Kinetic mixing

Mass

Not necessarily massless as the photon

Detections strategies

Direct and indirect

Axion Lagrangian:

$$\mathcal{L}_{\text{axion}} = \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \frac{1}{2} m_\phi^2 \phi^2 - \frac{g_{\phi\gamma}}{4} \phi F_{\mu\nu} \tilde{F}^{\mu\nu} + \ldots$$

Dark Photon Lagrangian:

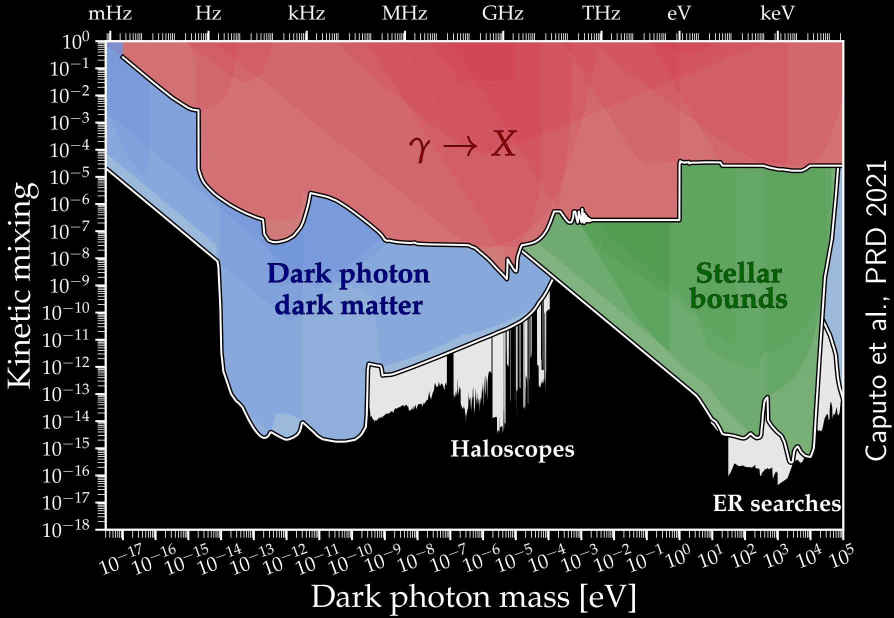
$$\mathcal{L}_{\text{dark photon}} = -\frac{1}{4} \phi_{\mu\nu} \phi^{\mu\nu} + \frac{1}{2} m_{\gamma'}^2 \phi_\mu \phi^\mu + \frac{\chi}{2} F_{\mu\nu} \phi^{\mu\nu}$$

Massless

- Photon of the hidden sector.
- Very weak kinetic mixing.
- Not a DM candidate.

Massive

- Different behavior at low/high energies.
- Kinetic mixing with photons.
- DM candidate.



Caputo et al., PRD 2021

Dark Photon Lagrangian:

$$\mathcal{L}_{\text{dark photon}} = -\frac{1}{4}\phi_{\mu\nu}\phi^{\mu\nu} + \frac{1}{2}m_{\gamma'}^{2}\phi_{\mu}\phi^{\mu} + \frac{\chi}{2}F_{\mu\nu}\phi^{\mu\nu}$$

Kinetic shift

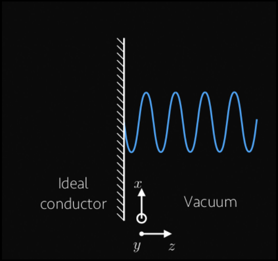
$$\phi^{\mu} \rightarrow \tilde{\phi}^{\mu} - \chi A^{\mu}$$

Modified Maxwell's equation

$$\vec{\nabla} \times \vec{H} - \dot{\vec{D}} = \chi\epsilon_0 \left(\dot{\vec{E}}_{DM} - c^2\vec{\nabla} \times \vec{B}_{DM} \right)$$

Additional electric field in vacuum

$$\vec{E}_{DM} = -\partial_t \vec{A} = \chi\omega_{\gamma'}\vec{\phi}_{DM} = i\chi\omega_{\gamma'}\phi_0 e^{i\omega_{\gamma'}t - ik_{\gamma'}x}\vec{e}$$



Dark photon in a mirror: Conversion to an "usual" electric field :

$$\vec{E}_{\text{out}} = -i\omega_{\gamma'}\phi_0\chi e^{-i\omega_{\gamma'}t - ik_{\gamma'}x}\vec{e}$$

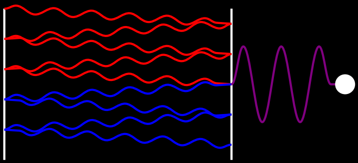
Thanks again Pierre !

Output Power: $\frac{\Pi}{\text{W}/\text{m}^2} = 1.44 \times 10^{-20}\left(\frac{\rho_{\text{DM}}}{\text{GeV}/\text{cm}^3}\right)\left(\frac{\chi}{10^{-12}}\right)^{-2}$

Emission: Normal to surface

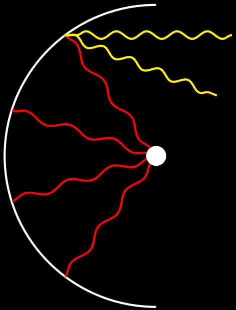
Resonant Search

- Narrow mass range
- High sensitivity
- Tuned detectors



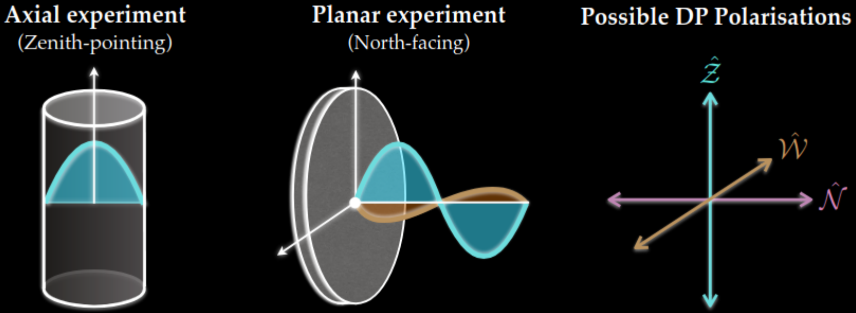
Broadband Search

- Wide mass range
- Moderate sensitivity
- Broad scan



Horns et al., JCAP 2013

Polarization: Big difference with the axion



Caputo et al., PRD 2021

Earth revolution creates a modulation

Sensitivity : Planar $>$ Axial and measurement timing optimizable

$$\mathrm{SNR}(f) \sim \frac{\Pi\, S\, Q\, \alpha}{k_B\left(T_{sys} + T_{ext}\right)}\sqrt{\frac{\tau}{\Delta f}}\delta(m - m_\varphi)$$

m_φ Monochromatic signal at the dark photon mass*

- Increase sensitivity with
  - S High surface area for broadband
  - Q High quality factor for resonant

α Optimally paced measurement method for polarization

T_{ext} External noise is already attenuated

- Out of focus for broadband
- Not enhanced by resonance

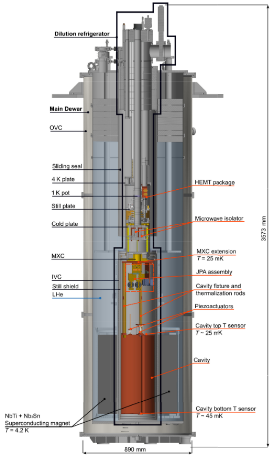
T_{sys} Limiting noise due to the measurement electronics temperature.

$\tau, \Delta f$ Can be tuned with duration and resolution

Center for Axion and Precision Physics :

- Resonant cavity : 1, 1.8, 2.5, 5 GHz
- Bandwidth : 150 MHz
- System noise : 0.4 K
- Sensitivity at the 10^{-14} level

Ahn et al., PRX 2024

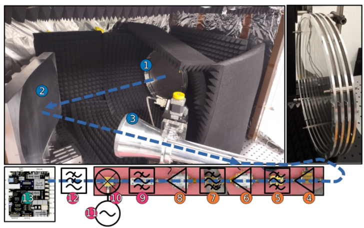


Other resonant experiments :

- Orpheus paper by Cervantes et al., PRD 2022
- Haystack paper by Backes et al., Nature 2021
- QUAX-LNF paper by Rettaroli et al., PRD 2024
- ORGAN paper by Mc Allister et al., ADP 2023

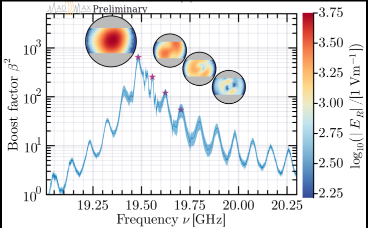
Magnetized Disc and Mirror Axion eXperiment:

- Broadband antenna
- Bandwidth : 19 – 20.4 GHz
- System noise : 240 K
- Sensitivity at the 10^{-12} level



Special features:

- Tunable resonance creating a sensitivity boost
- Experimental sentivity measurement



Egge et al., arXiv 2024

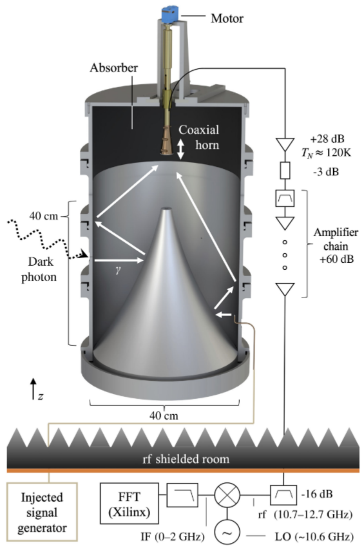
Broadband Reflector Experiment for Axion Detection

- Broadband antenna
- Bandwidth : 10.7 – 12.5 GHz
- System noise : 120 K
- Sensitivity at the 10^{-12} level

Special features:

- Hershey's kiss reflector

Knirck et al., PRL 2024



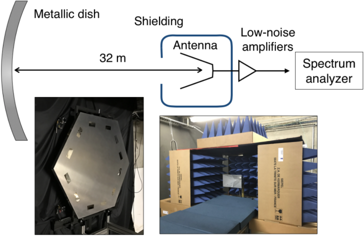
SearcH for U(1) darK matter with an Electromagnetic Telescope

- Broadband antenna
- Bandwidth : 5 – 7 GHz
- System noise : 554 K
- Sensitivity at the 10^{-10} level*

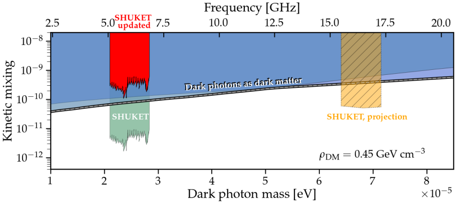
Special features:

- Lowest cost per PRL publication*

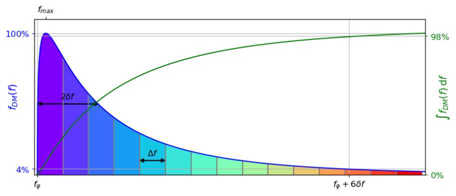
Brun et al., PRL 2019



SHUKET experiment



Sensitivity: Decrease due to diffraction and mismatch in the mode antenna Gué et al., PRD 2024

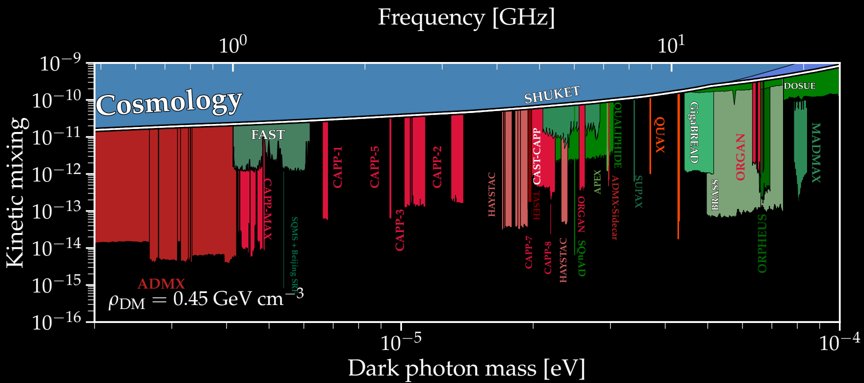


Data analysis: Improved software searching for non monochromatic shape

Upgrade: Improved electronic

$T_{sys} \searrow$ and $\tau \nearrow$

Stay tuned for revised constraints thanks to Jordan Gué's PHD work and Robin Signoret's future PHD work.



Caputo et al., PRD 2021

- Good training before an axion search
- Still some mass range to cover

1. Dark Matter

2. Dark photon
   - Properties
   - Resonant experiments
   - Broadband experiments

3. Scalar field
   - Properties
   - Colocated
   - Space-time separated

Scalar Field

Vacuum fluctuations 60

Shuffle your hand into your deck and draw 5 new cards. Also, remove any status effect from Scalar Field.

Symmetry break 90

If the opponent's Pokemon has more HP than Scalar Field deal an additional 40 damage.

Axion bends light and manipulates energy fields, making it nearly invisible.

What is it ?

A field represented by a scalar value at every point in space and time.

Interaction

Couples to other fields via Yukawa interactions or portal interactions.

Mass

From ultra-light to very heavy.

Detection strategies

Cosmic background, gravitational effects, precision experiments, and colliders.

Scalar field theory action

The theory relies on an action where φ is the massive scalar field :

$$S = \int d^4x \frac{\sqrt{-g}}{c} \frac{c^4}{16\pi G} \underbrace{\left[R - 2g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - V(\varphi)\right]}_{\text{General Relativity + scalar field}}$$

$$+ \int d^4x \frac{\sqrt{-g}}{c} \underbrace{\left[\mathcal{L}_{SM}[g_{\mu\nu}, \Psi_i] + \mathcal{L}_{int}[g_{\mu\nu}, \varphi, \Psi_i]\right]}_{\text{Standard Model + scalar field}}$$

General relativity part

1. Spatial dependance
2. Time dependance

Lagrangian part

1. Coupling SM-DM
2. Constants modulation

Lagrangien part

$$\mathcal{L}_{int}[g_{\mu\nu}, \varphi, \Psi] = \frac{\varphi^i}{i}\left[\frac{d_e^{(i)}}{4e^2}F_{\mu\nu}F^{\mu\nu} - \frac{d_g^{(i)}\beta_3}{2g_3}F^A_{\mu\nu}F_A^{\mu\nu} - \sum_{i=e,u,d}\left(d_{m_i}^{(i)} + \gamma_{m_i}d_g^{(i)}\right)m_i\bar{\psi}_i\bar{\psi}_i\right]$$

Damour and Donoghue, PRD 2010

i = 1 Linear coupling

i = 2 Quadratic coupling

Coupling parameter

d_e	Fine structure constant
d_{m_e}	Electron mass
$d_{m_{u,d}}$	Quark mass
d_g	Lambda QCD scale

General relativity action part

$$S = \int d^4x \frac{\sqrt{-g}}{c} \frac{c^4}{16\pi G} \underbrace{\left[R - 2g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - V(\varphi)\right]}_{\text{General Relativity + scalar field}}$$

How φ varies with space-time ? Appyling the least action principle we get the following scalar field equation :

Linear coupling

$$\Box\varphi + \left(\frac{m_\varphi c^2}{\hbar}\right)^2 \varphi = -\frac{4\pi G}{c^2}\alpha_A \rho_A$$

Quadratic coupling

$$\Box\varphi + \left(\frac{m_\varphi c^2}{\hbar} + \frac{4\pi G}{c^2}\alpha_A \rho_A\right)^2 \varphi = 0$$

Linear coupling

Classical phenomenology

$$\varphi_{(t,\vec{r})} = \varphi_0 \sin\left(\omega_\varphi t - \vec{k}_\varphi . \vec{r}\right) - s_A \frac{GM_A}{c^2 r} e^{-r/\lambda_\varphi}$$

Phenomenology

Time oscillation

Spatial dependance

Quadratic coupling

Richer phenomenology

$$\varphi_{(t,\vec{r})} = \varphi(r) \varphi_0 \sin\left(\omega_\varphi t - \vec{k}_\varphi . \vec{r}\right)$$

Phenomenology

Screening

Enhancement

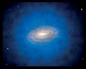
Energy-impulsion tensor and scalar field energy density

$$T^{\mu\nu}(\varphi) = \frac{2}{\sqrt{-g}}\frac{\delta\mathcal{L}}{\delta g_{\mu\nu}} \Rightarrow \langle\rho_\varphi\rangle = \frac{T_{00}}{c^2} = \langle\frac{1}{2\kappa c^2}\dot{\varphi}^2 + \frac{1}{2\kappa c^2}\omega_\varphi^2\varphi^2\rangle$$

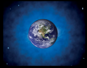
Energy density

$$\langle\rho_\varphi\rangle = \rho_{DM} \Rightarrow \varphi_0 = \frac{\sqrt{8\pi G\rho_{DM}}}{\omega_\varphi c}$$

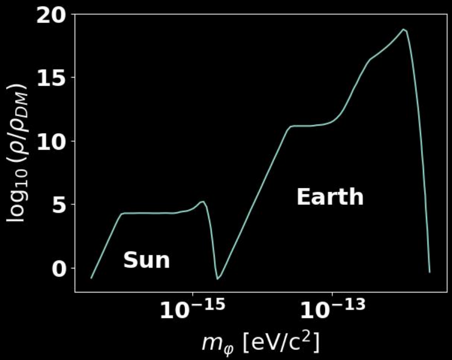
Density



Galactic halo



Earth halo



A. Banerjee et al., Nature Communications, (2020)

Fine structure constant variation

When considering only the electromagnetic effect, the effective lagrangien $\mathcal{L}_{int} + \mathcal{L}_{SM}$ leads to variation of the fine structure constant :

$$\mathcal{L}^{EM}_{eff} = \underbrace{-\frac{e^2 c}{16\pi\hbar\alpha}F^2}_{\text{Electromagnetism from Standard Model}} \underbrace{+d_e\varphi\frac{e^2 c}{16\pi\hbar\alpha}F^2}_{\text{Electromagnetism from scalar field}} \simeq \frac{-e^2 c}{16\pi\hbar\alpha\left(1+d_e\varphi\right)}F^2$$

Variation of the fine stucture constant

$$\alpha_{(t)} = \alpha\left(1 + d_e\sqrt{\frac{8\pi G\rho_{DM}}{\omega_\varphi c^2}}\cos(\omega_\varphi t)\right)$$

Other constants

$$m_j\left(\varphi\right) = m_j\left(1 + d^{(i)}_{m_j}\varphi^i\right)$$

for $j = e, u, d$

$$\Lambda_3\left(\varphi\right) = \Lambda_3\left(1 + d^{(i)}_{g}\varphi^i\right)$$

Colocated clocks

Comparison of different clocks at the same space and time :

$$\frac{\delta(\nu_A/\nu_C)}{(\nu_A/\nu_C)_0} = \left(d_e + \left(d_{m_e} - d_g\right)\right)\varphi$$

Dimensionless

$$m_x/\Lambda_3, \Rightarrow d_{m_x} - d_g.$$

vs

Space-time separated clocks

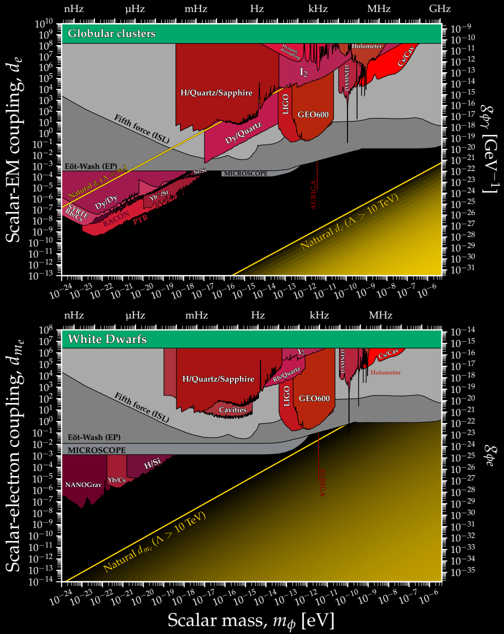
Comparison of the same clocks at different space and/or time :

$$\frac{\delta\left(\nu_{A_1}/\nu_{A_2}\right)}{\left(\nu_{A_1}/\nu_{A_2}\right)_0} = \left(2d_e + d_{m_e}\right)\varphi$$

Dimensional

$$m_x \Rightarrow d_{m_x}.$$

Existing constraints on linear coupling



Universality of free fall

Eot-Wash : Wagner et al., CQG 2012
MICROSCOPE : Bergé et al., PRL 2018

Colocated

SYRTE : Hees et al. PRL 2016
JILA : Kennedy et al., PRL 2020
BACON : Beloy et al., Nature, 2021
PTB : Filzinger et al., PRL 2023

Space-time separated

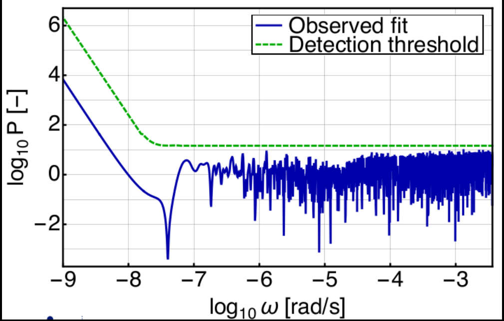
DAMNED : Savalle et al., PRL 2021
GEO600 : Vermeulen et al., Nature 2021
LIGO : Göttel et al., PRL 2024

Caputo et al., PRD 2021

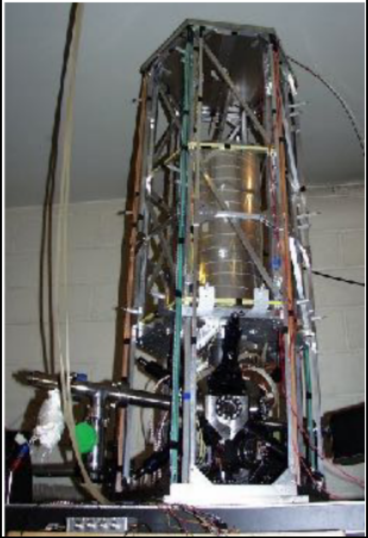
Clocks comparison:
Searching for a periodic signal in two clocks desynchronization

Sensitivity:

$$\frac{\delta(\nu_A/\nu_C)}{(\nu_A/\nu_C)_0} = d_e\varphi + \dots$$



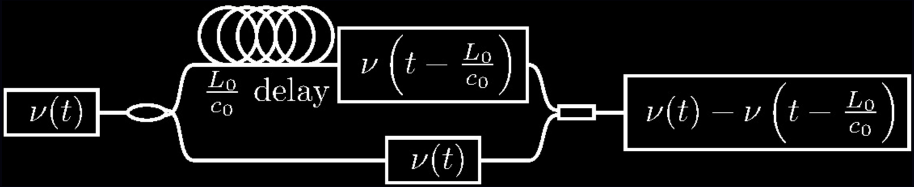
Hees et al., PRL 2016



SYRTE atomic clock

DArk Matter from Non Equal Delays

"DAMNED" allows to compare an ultrastable cavity to itself in the past.



$\nu(t)$

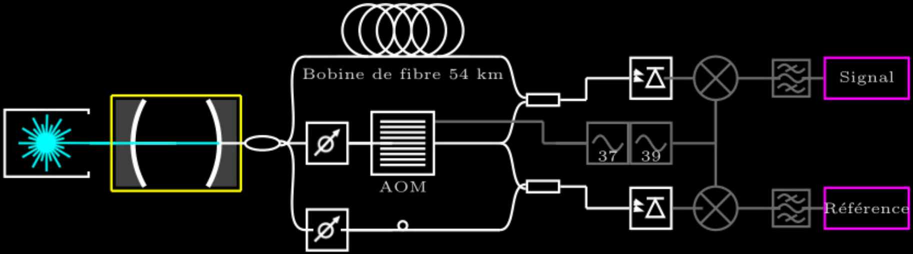
$\frac{L_0}{c_0}$ delay

$\nu\left(t - \frac{L_0}{c_0}\right)$

$\nu(t)$

$\nu(t) - \nu\left(t - \frac{L_0}{c_0}\right)$

Unequal-arm length Mach-Zender interferometer



Phase difference between the delayed and non delayed signals

$$\Delta\Phi(t) = \omega_0 T_0 + \omega_0 \int_{t-T_0}^{t} \left(\frac{\Delta T(t')}{T_0} + \frac{\Delta\omega(t')}{\omega_0}\right) \mathrm{d}t' + \omega_0 T_0 \left(\frac{\delta T}{T_0} + \frac{\delta\omega}{\omega_0}\right) \sin\left(\omega_\varphi t - \omega_\varphi \frac{T_0}{2}\right) \mathrm{sinc}\left(\omega_\varphi \frac{T_0}{2}\right)$$

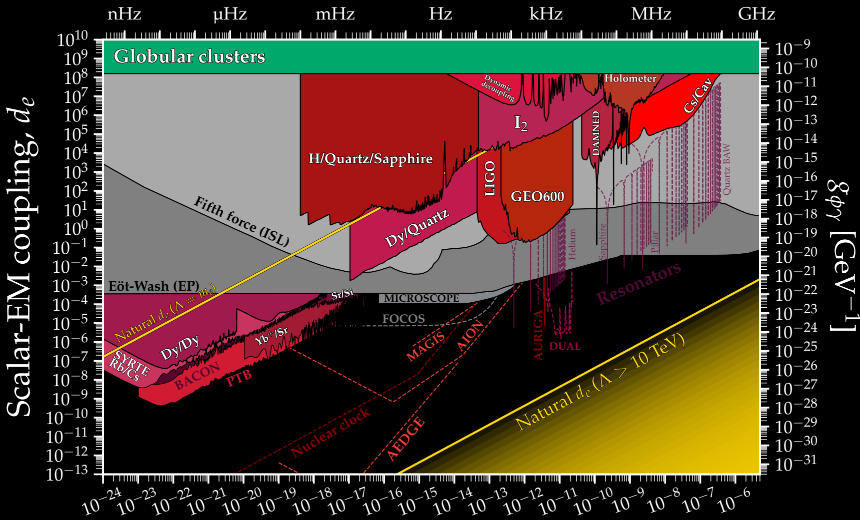
Color code

Nominal value

Noise

Dark matter effect

Scalar field conclusion



Caputo et al., PRD 2021

- Available with any stable/accurate metrology equipment
- Still some mass range to cover
- Same data analysis as an axion search