The DAMNED Experiment

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Outline

1. Introduction
   - Dark matter
   - Ultralight dark matter scalar field theory
   - Co-located vs Space-time separated experiment

2. The DAMNED experiment
   - Experimental setup
   - Sensitivity to dark matter
   - Simulation
   - Preliminary results
   - Estimated constraints
Dark Matter search - What we know about it?

Dark matter gravitational evidences
- Galaxy rotation curves
- Gravitational lensing
- Cosmic Microwave Background
- Structure formation

Dark matter characteristics
- Cold ($v \ll c$)
- Forms a galactic halo
- Virialized in the galaxy
- Typical density $\rho_{DM} = 0.4 \text{GeV/cm}^3$

Dark matter hopes
- DM interacts with standard model fields
- It will be detected and new physics will arise.

E. Savalle (SYRTE)
ACES Workshop 2019
Dark Matter search - Where are we looking?

Dark Sector Candidates, Anomalies, and Search Techniques

- Ultralight Dark Matter
- Pre-Inflationary Axion
- Post-Inflationary Axion
- QCD Axion
- WIMPs
- Hidden Sector Dark Matter
- Hidden Thermal Relics / WIMPLESS DM
- Asymmetric DM
- Freeze-In DM
- SIMPs / ELDERS
- Beryllium-8
- Muon $g-2$
- Small-Scale Structure

Small Experiments: Coherent Field Searches, Direct Detection, Nuclear and Atomic Physics, Accelerators

arXiv:1707.04591
Scalar field theory - Effect on the fundamental constant

**Fine structure constant variation**

With a scalar field $\varphi(\vec{r},t)$, the lagrangien of electromagnetism is modified:

$$\mathcal{L}_{EM}^{eff} = -\frac{e^2 c}{16\pi \hbar \alpha_0} F^2 + d_e \varphi(\vec{r},t) \frac{e^2 c}{16\pi \hbar \alpha_0} F^2 \approx \frac{-e^2 c}{16\pi \hbar \alpha_0} F^2 \frac{\alpha_0}{\alpha_0 \left(1 + d_e \varphi(\vec{r},t)\right)}$$

Electromagnetism - Standard Model

Electromagnetism - scalar field

Fine structure constant oscillation

References:

T. Damour et al. PRD 82,084033, A. Arvanitaki et al. PRD 91,015015 and Y.V. Stadnik et al. PRL 115,201301

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- **Electromagnetism - Standard Model**
- **Electromagnetism - scalar field**
- **Fine structure constant oscillation**

### Time-only variation of the fundamental constants

A fundamental constant $X$ varies with $\varphi(\mathbf{r}, t)$ through a coupling constant $d_X$

$$X(t) = X_0 \left(1 + d_X \frac{\sqrt{8\pi G\hbar\rho_{DM}}}{m_\varphi c^3} \sin(\omega_m t)\right)$$

- the fine structure constant $\{\alpha, d_e\}$,
- the electron mass $\{m_e, d_{m_e}\}$ and average quark mass $\{m_q, d_{m_q}\}$,
- the QCD mass scale $\{\Lambda_3, d_g\}$.

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T. Damour et al. PRD 82,084033, A. Arvanitaki et al. PRD 91,015015 and Y.V. Stadnik et al. PRL 115,201301

E. Savalle (SYRTE) | ACES Workshop 2019 | 4 / 13 | October 28, 2019 | 4 / 13
Bohr radius oscillation

\[ a_0 = \frac{\hbar}{m_e c \alpha} \quad \Rightarrow \quad \frac{\delta a_0}{a_0} = -\frac{\delta \alpha}{\alpha} - \frac{\delta m_e}{m_e} = -(d_e + d_{m_e}) \varphi(\vec{r},t) \]

Anything made of atom will see its length oscillate in time.
Co-located vs Space-time separated experiment

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**Colocated clocks**

Comparison of different clocks at the same space and time:

\[ \frac{\delta (\nu_A/\nu_C)}{(\nu_A/\nu_C)_0} = (d_e + (d_{m_e} - d_g)) \varphi(\vec{r},t) \]
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Space-time separated clocks

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

\[ \frac{\delta (\nu_{A_1}/\nu_{A_2})}{(\nu_{A_1}/\nu_{A_2})_0} = (2d_e + d_{m_e}) \varphi(\vec{r},t) \]
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Dark matter effect on the setup

Fiber delay $T = nL/c$

C. Braxmaier et al. PRD 64,042001
Dark matter effect on the setup

Fiber delay $T = nL/c$

- Fiber length oscillation
  $$L \propto a_0 \propto (\alpha + m_e)^{-1}$$

- Fiber refractive index
  $$n \propto (\alpha + m_e/m_N)$$

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**Fiber delay**  \( T = nL/c \)

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- Longer fiber  ✓ Better sensitivity to dark matter  × Less optical signal

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**Cavity output frequency** \( \omega \propto L^{-1}_{\text{cavity}} \)

B. Canuel et al. arXiv:1703.02490

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#### Cavity output frequency \( \omega \propto L_{cavity}^{-1} \)

\[
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≃ The photons lifetime in the cavity is highly extended by the cavity finesse \( \mathcal{F} \simeq 8 \times 10^5 \). It has almost no effect on the cavity frequency.

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#### Cavity output frequency $\omega \propto L_{cavity}^{-1}$

| $\omega \propto a_0^{-1} \propto (\alpha + m_e)$ | ✓ The spacer could be oscillating at mechanical resonance. It enhances ($Q = 6 \times 10^4$) the sensitivity at the harmonics frequencies. |

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Cavity frequency oscillation

\[ \omega(t) = \omega_0 + \Delta \omega(t) + \delta \omega \sin(\omega_m t) \]

Color code

Nominal value
Dark matter effect on the setup

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\[ \omega(t) = \omega_0 + \Delta \omega(t) + \delta \omega \sin(\omega_m t) \sin(\omega_m T_0^2) \text{sinc}(\omega_m T_0^2) \]

Color code

Nominal value
Noise

Phase difference between the delayed and non-delayed signals

\[ \Delta \Phi(t) = \omega_0 T_0 + \omega_0 \int_{t-T_0}^t \left( \Delta T(t') \frac{T_0}{T_0} + \Delta \omega(t') \omega_0 \right) \, dt' + \omega_0 T_0 \left( \delta T \frac{T_0}{T_0} + \delta \omega \omega_0 \right) \sin(\omega_m t - \omega_m T_0^2) \text{sinc}(\omega_m T_0^2) \]
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Fiber delay oscillation

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Signal simulation

What are we expecting with/without dark matter on the experiment?
First experimental results

Desynchronization

Signal - 50km
Reference - 1m

$S_{\Delta \phi}$ [rad^2/Hz]

$F$ [Hz]

$10^{-6}$

$10^{-7}$

$10^{-8}$

$10^{-9}$
First experimental results

Desynchronisation
Signal - 50km
Reference - 1m

- Fiber noise decreases with fiber length
- Shot noise limited

Fiber noise
Zone of interest
Cavity noise

$S_{\Delta\phi}$ [rad^2/Hz]

$f$[Hz]
Estimated constraints not actual constraints
## Conclusion

### Ongoing work

- Perform a FFT on 4TB of data.
- Improve the noise floor of the cavity.
- Search for the stochastic nature of the scalar field (A. Derevianko’s presentation)

---

There is no evidence for dark matter with this experiment (yet?). It will allow us to decorrelate the damping constant. It should be close to constraints of the torsion balance experiments. It will improve constraints by one or two orders of magnitude at the cavity resonance frequency.

Thank you for your attention!
Conclusion

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DAMNED experiment

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Thank you for your attention
Scalar field theory - General discussion

Scalar field theory action

The theory relies on an action where $\varphi(\vec{r}, t)$ is the massive scalar field:

$$S = \int d^4 x \frac{\sqrt{-g}}{c} \left[ \frac{R}{2\kappa} - \frac{2g^{\mu\nu} \partial_\mu \varphi(\vec{r}, t) \partial_\nu \varphi(\vec{r}, t) + V(\varphi(\vec{r}, t))}{2\kappa} + \mathcal{L}_{SM}[g_{\mu\nu}, \Psi_i] + \mathcal{L}_{int}[g_{\mu\nu}, \varphi(\vec{r}, t)] \right]$$

General relativity + Scalar field

Standard Model

Field interaction with Standard Model

Lagrangian of the scalar field interaction with Standard Model

$$\mathcal{L}_{int} = \varphi(\vec{r}, t) \left[ d_e \frac{e^2 c}{16\pi \hbar \alpha} F^2 - d_g \frac{\beta g_3}{2g_3} (F^A)^2 - c^2 \sum_{k=e,u,d} \left( d_{m_k} + \gamma_{m_k} d_g \right) m_k \psi_k \psi_k \right]$$

The constants $d_x$ characterize the interaction between the scalar field $\varphi(\vec{r}, t)$ and the different Standard Model sectors.

T. Damour et al. PRD 82,084033, A. Arvanitaki et al. PRD 91,015015 and Y. V. Stadnik et al. PRL 115,201301

E. Savalle (SYRTE)
Scalar field theory - Oscillating scalar field

How $\varphi(\vec{r},t)$ varies with space-time?

Deriving the field equation from the scalar field action with a quadratic potential, we get:

$$\Box \varphi(\vec{r},t) + \left(\frac{m_\varphi c}{\hbar}\right)^2 \varphi(\vec{r},t) = 0$$

Full $\varphi(\vec{r},t)$ solution

$$\varphi(t,\vec{r}) = \frac{\sqrt{8\pi G\hbar \rho_{DM}}}{m_\varphi c^3} \sin \left(\omega_m t - \vec{k}_m \cdot \vec{r}\right) - s_A \frac{GM_A}{c^2 r} e^{-r/\lambda_\varphi}$$

For more details and quadratic scalar field see: A. Hees et al. PRD 98,064051

Time varying $\varphi(t)$

$$\varphi(t) = \varphi_0 \sin(2\pi f_m t)$$
Cavity acoustic resonance induced by dark matter

Cavity resonance
With the cavity length oscillation, one mirror is a mass on a spring.

Dampened driven parametric harmonic oscillator
With $\delta D$ the displacement induced by the resonant effect,

\[
\frac{d^2 \delta D(t)}{dt^2} + \omega_0^2 \delta D(t) + \frac{\omega_0}{Q_0} \frac{d \delta D(t)}{dt} = \frac{\delta L}{L_0} L_0 \omega_m^2 \sin(\omega_m t)
\]

Harmonic oscillator
Damping
Parametric driving force

Solution
\[
\delta D(t) = \frac{\delta L \omega_m^2}{(\omega_0^2 - \omega_m^2)^2 + \frac{\omega_0^2}{Q_0^2}} \left[ \left( \frac{\omega_0^2}{\omega_m^2} - 1 \right) \sin(\omega_m t) - \frac{\omega_0}{\omega_m Q_0} \cos(\omega_m t) \right]
\]
Cavity finesse

Phase in the cavity

\[
\frac{\delta \omega}{\omega_0} = \frac{2 \omega_m l_0 / cr^2 (1 + r^2) \sin(\omega_m l_0 / c)}{r^4 - 2 r^2 \cos(2 \omega_m l_0 / c) + 1}
\]
DAMNED noise

Desynchronisation
- Signal - 25km
- Blue cavity - 25km
  from Xie et al.

Cavity lock shifted due to thermal instabilities in the lab in June 2018

Cavity instabilities seen through the DAMNED transfer function

\[ S_c^*(f) = (1 - \cos^2 \left( \frac{2nf_0}{c_0} \right))S_c \]