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AGENCIA
ESTATAL DE
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Violation of the equivalence principle induced by oscillating rest mass and transition frequency, and its detection in atom interferometers

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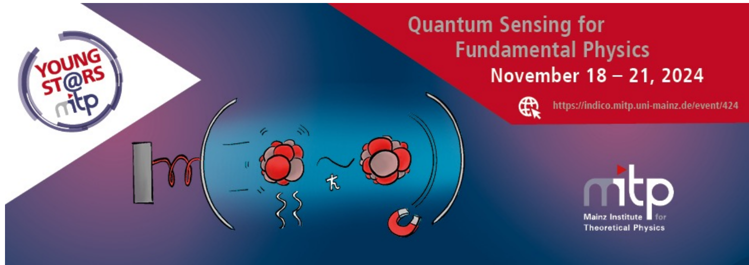


*Based on JG et al. PRD **110,** 035005 (2024)*

Ultralight dark matter (ULDM) characteristics

Occupation number
in phase space →

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

$\sim 0.4\ GeV/cm^3$

$\sim 10^{-3}c$

$< 10\ eV$

P. Tourrenc et al., arXiv:0407187
M. Cirelli et al., arXiv:2406.01705
...

→ULDM with $mc^2 < 10\ eV$ must be <u>bosonic</u>

→ When $\boldsymbol{mc^2 \ll eV}$ $\rightarrow \frac{n}{n_k} \gg 1$ and a generic scalar DM field φ can be treated **classically**

$|\vec{k}| = \omega v/c^2$, with v velocity of DM wave
In Earth's inertial frame, $v \equiv v_{DM} = 10^{-3}c$

$$\boldsymbol{\varphi = \varphi_0 \cos\left(\omega t - \vec{k}.\vec{x}\right)}$$

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

$\hbar\omega = mc^2$ in DM rest frame

Dilaton, axion and oscillating mass and frequency

couplings

couplings

Fermions fields

$$\mathcal{L} = \mathcal{L}_0(\alpha, m_e, \ldots) + \phi\left(\frac{d_e}{4\mu_0}F^{\mu\nu}F_{\mu\nu} \qquad \frac{d_g\beta_3}{2g_s}G^{\mu\nu}G_{\mu\nu} \qquad \sum_{i=e,u,d}\left(d_{m_i}+\gamma_{m_i}d_g\right)m_i\bar{\psi}_i\psi_i\right)$$

Dilaton field

QCD stress energy tensor

*T. Damour and T. Donoghue, PRD **82** (2010)*

Interaction Lagrangian leads to variations of $\theta \;= \{\alpha, m_e, \hat{m}_q, \delta m_q, \Lambda_{QCD}\}$

$$\boxed{\boldsymbol{\theta_i \rightarrow \theta_i(1 + d_i\phi(t,\vec{x}))}}$$

(remember $\phi(t,\vec{x}) = \phi_0\cos(\omega t - \vec{k}.\vec{x})$)

Rest mass and transition frequency of atoms depend on θ

$f(d_i, A, Z)$

$$\boldsymbol{m_A(\phi(t,\vec{x})) = m_A^0\left(1 + \phi_0[Q_M^A]_\phi\cos(\omega t - \vec{k}.\vec{x})\right)}$$

$$\boldsymbol{\omega_A(\phi(t,\vec{x})) = \omega_A^0\left(1 + \phi_0[Q_\omega^A]_\phi\cos(\omega t - \vec{k}.\vec{x})\right)}$$

$g(d_i, A, Z)$

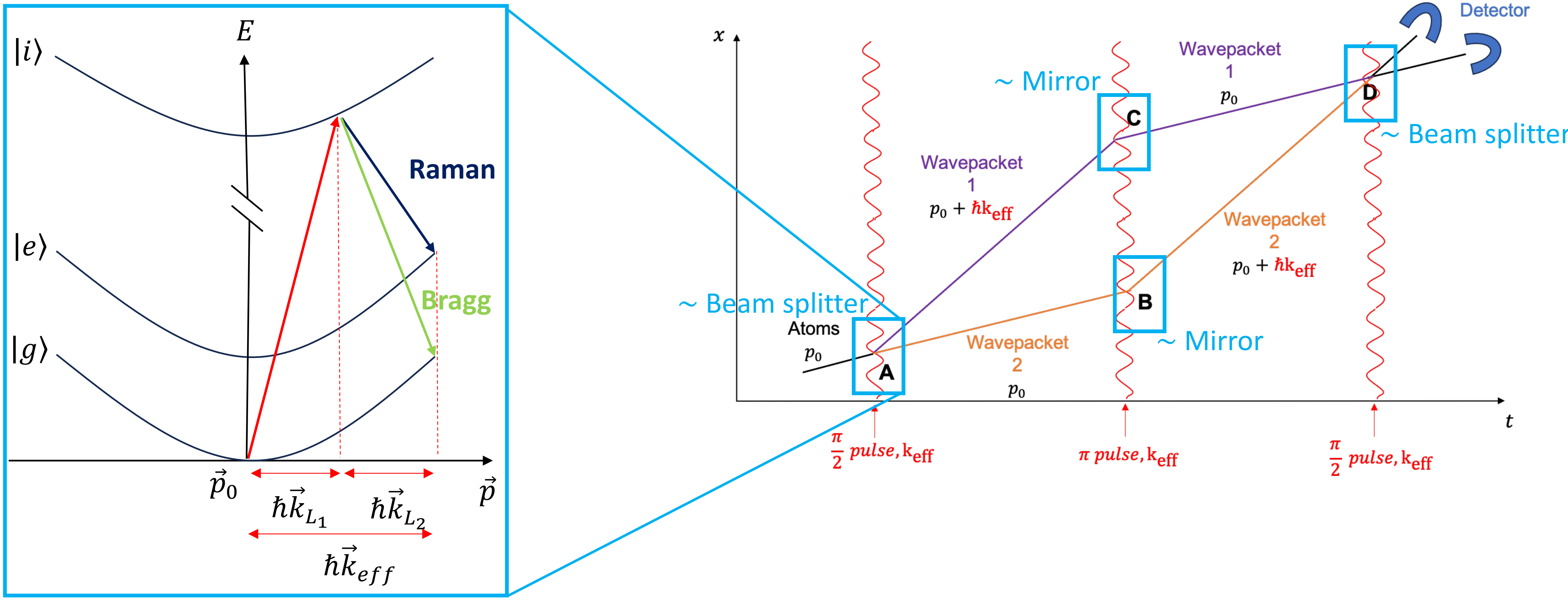
Similar oscillations arise through the axion-gluon coupling $1/f_a$

*H. Kim and G. Perez, PRD **109** (2024)*

→ Leads to $\boldsymbol{\vec{a}_A \propto -\vec{k}c^2[Q_M^A]_\phi\, sin(\omega t - \vec{k}.\vec{x})}$ **which is atom dependent**

→ Differential acceleration measurable in **classical tests of the UFF** and **atom interferometry**

Principle of atom interferometry



At the detection step, check for state population $\int dS_{det}\,|\Psi_I(T_d,\vec{x}_d)+\Psi_{II}(T_d,\vec{x}_d)|^2$

$$\propto 1+\cos(\Phi_I-\Phi_{II})$$

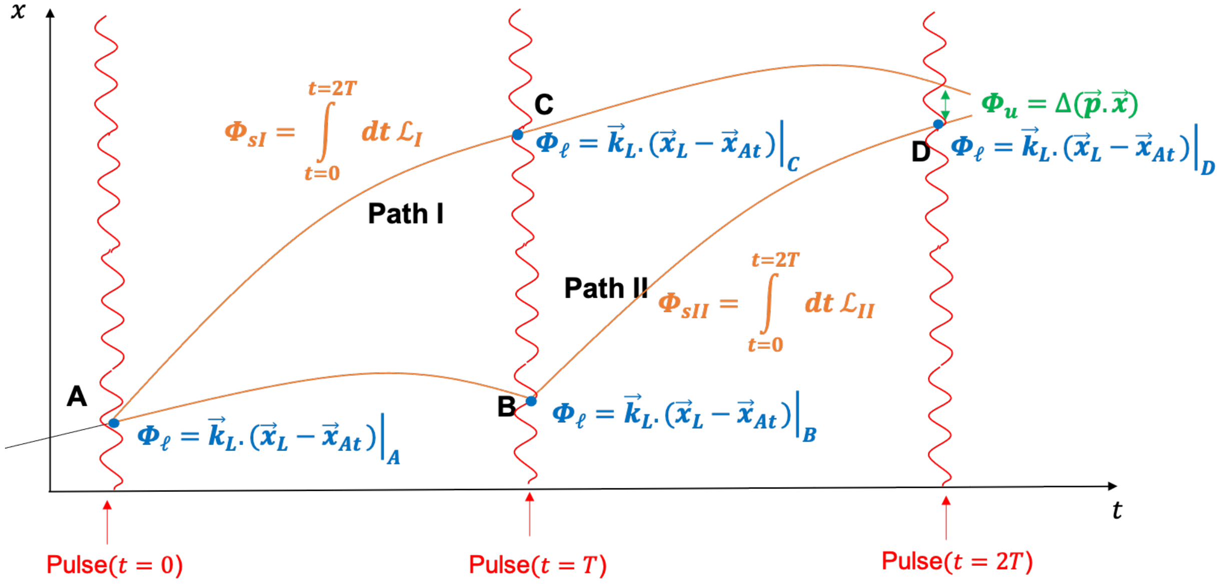
$$= 1+\cos\Delta\Phi$$

Phase contributions

Feynman path integral to compute $\Delta\Phi$ (works only for lagrangians at most quadratic in $(\vec{x}, \vec{p})$)

P. Storey and C. Cohen-Tannoudji, JP2 ***4*** *11 (1994)*

- Φ_s : phase accumulated by wavepackets along the trajectory
- Φ_ℓ : phase factors of laser
- Φ_u : spatial incoincidence between wavepackets



Scalar DM fields impact

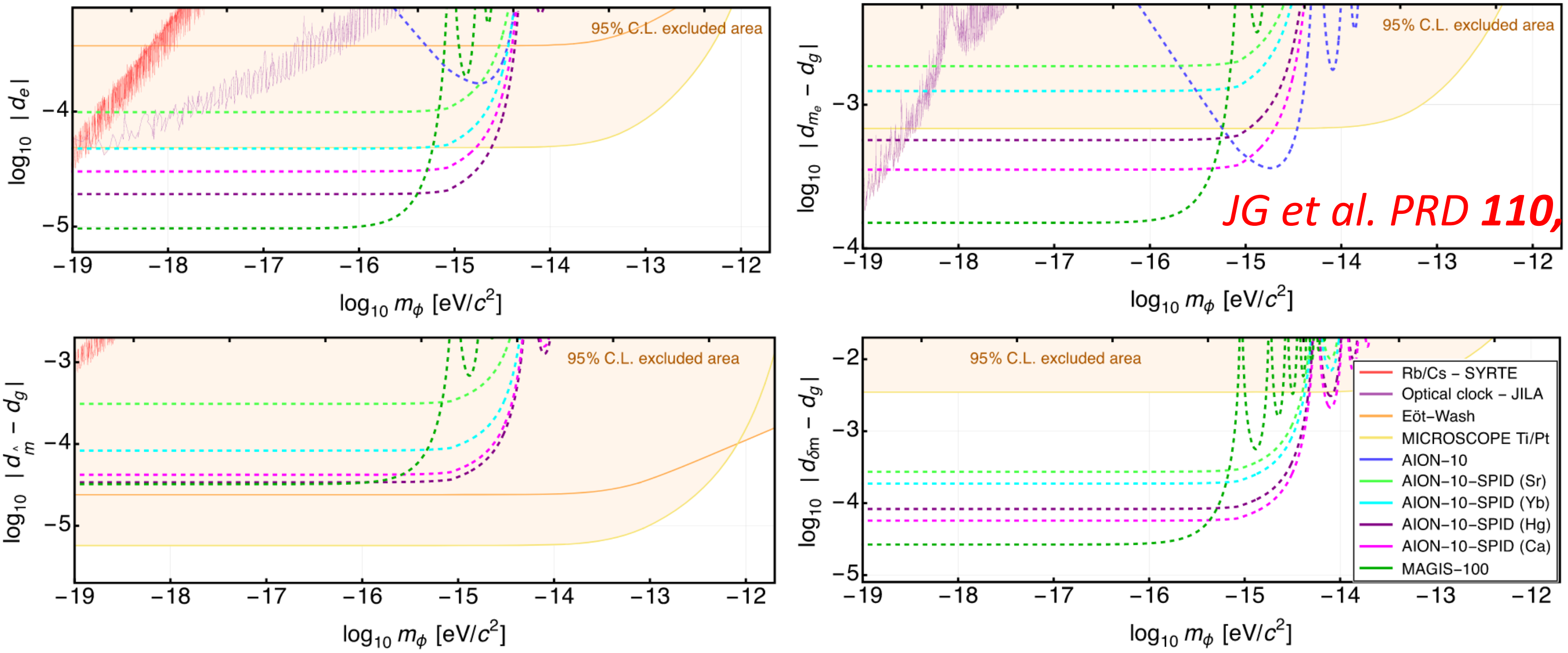
- Classical trajectories of atoms
- Recoil velocity kick
- Laser reference and frequency

A. Geraci and A. Derevianko, PRL ***117*** *(2016)*
P. Graham et al., PRD ***93*** *(2016)*
L. Badurina et al., PRD ***105*** *(2022)*

→ Extends previous calculations

→ Complete picture of scalar DM signals in AI (through oscillating mass and frequency)

AI sensitivities to dilaton and axion couplings



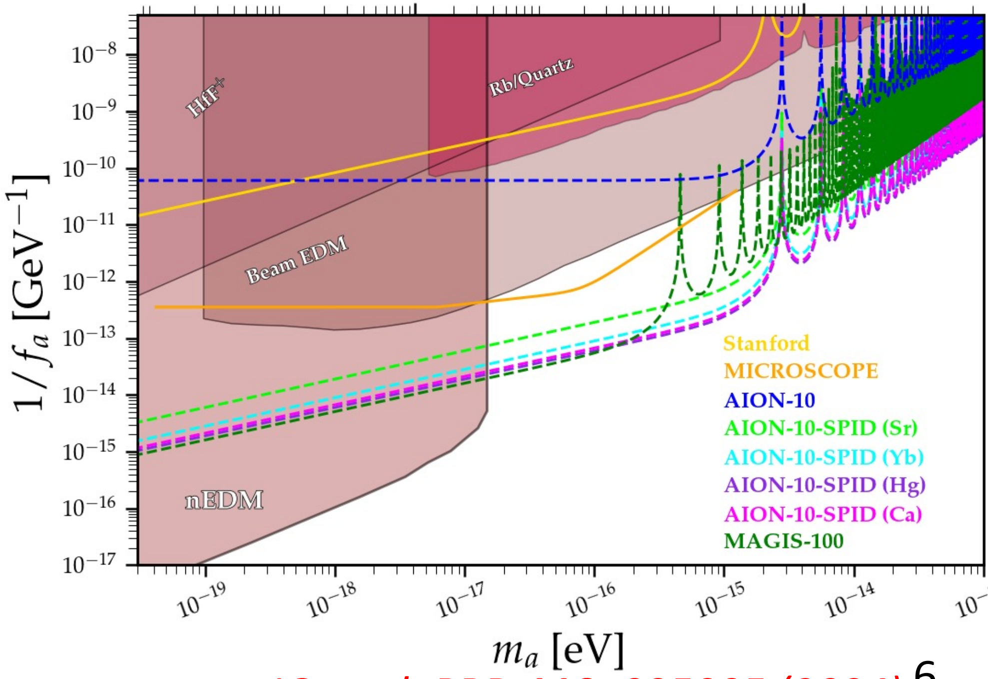
*JG et al. PRD **110,** 035005 (2024)*

Which setup is the most sensitive to scalar DM ?

- Bragg differential (Stanford Tower) ?
- Gradiometers (AION-10) ?
- Single Photon Isotope Differential (MAGIS-100) ?

→ SPID is much more sensitive to DM than gradiometers, even with same experimental parameters

(From cajohare.github.io/AxionLimits/)



*JG et al. PRD **110,** 035005 (2024)*

Conclusion

- ULDM scalar candidates can produce EP violating accelerations
- Those accelerations can be probed in classical tests of the UFF and AI
- Taking into account as most DM effects as possible (atoms' classical trajectories, laser frequency, recoil velocity kick), we provide analysis of expected signals in AI
- We find that setups with two colocated AI employing isotopes are much more sensitive to ULDM couplings, compared to gradiometers
- In the future, AI will be able to probe large unconstrained regions of the parameter space