LABORATORY PROBES OF ULTRALIGHT DARK MATTER

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ULTRALIGHT SCALAR DARK MATTER

- Ultralight DM (m<0.1 eV) - large occupation number in the galaxy

$$N = n \cdot \lambda_{dB}^3 = \frac{\rho_{DM}}{m^4 v^3} \approx \left(\frac{\rho_{DM}}{0.3GeV/cm^3}\right)\left(\frac{0.1eV}{m}\right)^4$$

- Can be described as a classical field

$$\phi(t, \overrightarrow{x}) = A\cos(m_\phi\left(t - \overrightarrow{v}\cdot\overrightarrow{x} + \ldots\right))$$

- Energy density

$$\rho_{DM} = T_{00} \approx \frac{1}{2} m_\phi^2 A^2$$

- Ultralight scalar DM is the coherently oscillating as

$$\boxed{\langle\phi\left(t, \overrightarrow{x}\right)\rangle \simeq \frac{\sqrt{2\rho_{DM}}}{m_\phi}\cos(m_\phi\left(t - \overrightarrow{v}\cdot\overrightarrow{x} + \ldots\right)),}$$

A. Khmelnitskya and V. Rubakov, 1309.5888

ULTRALIGHT DM COUPLING TO THE SM

- If the DM field is coupled to photons and/or electrons

$$\mathcal{L}_{int} \supset \frac{g_{\phi\gamma}}{4}\phi F^{\mu\nu}F_{\mu\nu} - g_{\phi e} m_e \phi \bar{e} e$$

- e.g. Higgs-portal models, in which the scalar couples to the SM through its mixing with the Higgs $g_{\phi i} = g_{hi}\sin\theta$

$$g_{\phi e} = \frac{\sqrt{2}m_e}{v}\sin\theta\,, \qquad g_{\phi\gamma} = -\frac{\alpha_0 \sin\theta}{2\pi v}\left| A_W(\tau_W) + \sum_{\text{fermions}} N_{c,f} Q_f^2 A_F(\tau_f) \right| .$$

- **Temporal oscillations of $\alpha\,, m_e$ at frequency determined by the mass of the field.**
- **A mediator of a new fifth-force.**

TEMPORAL VARIATIONS OF FUNDAMENTAL CONSTANTS

- Oscillations of the DM field induce oscillations of $m_e\,, \alpha$

$$\boxed{\delta m_e = g_{\phi e} m_e \langle \phi(t, \vec{x}) \rangle\,, \qquad \delta\alpha = g_{\phi\gamma} \langle \phi(t, \vec{x}) \rangle \alpha^{SM} \qquad \langle \phi\left(t, \vec{x}\right) \rangle \simeq \frac{\sqrt{2\rho_{DM}}}{m_\phi} \cos(m_\phi t)\,,}$$

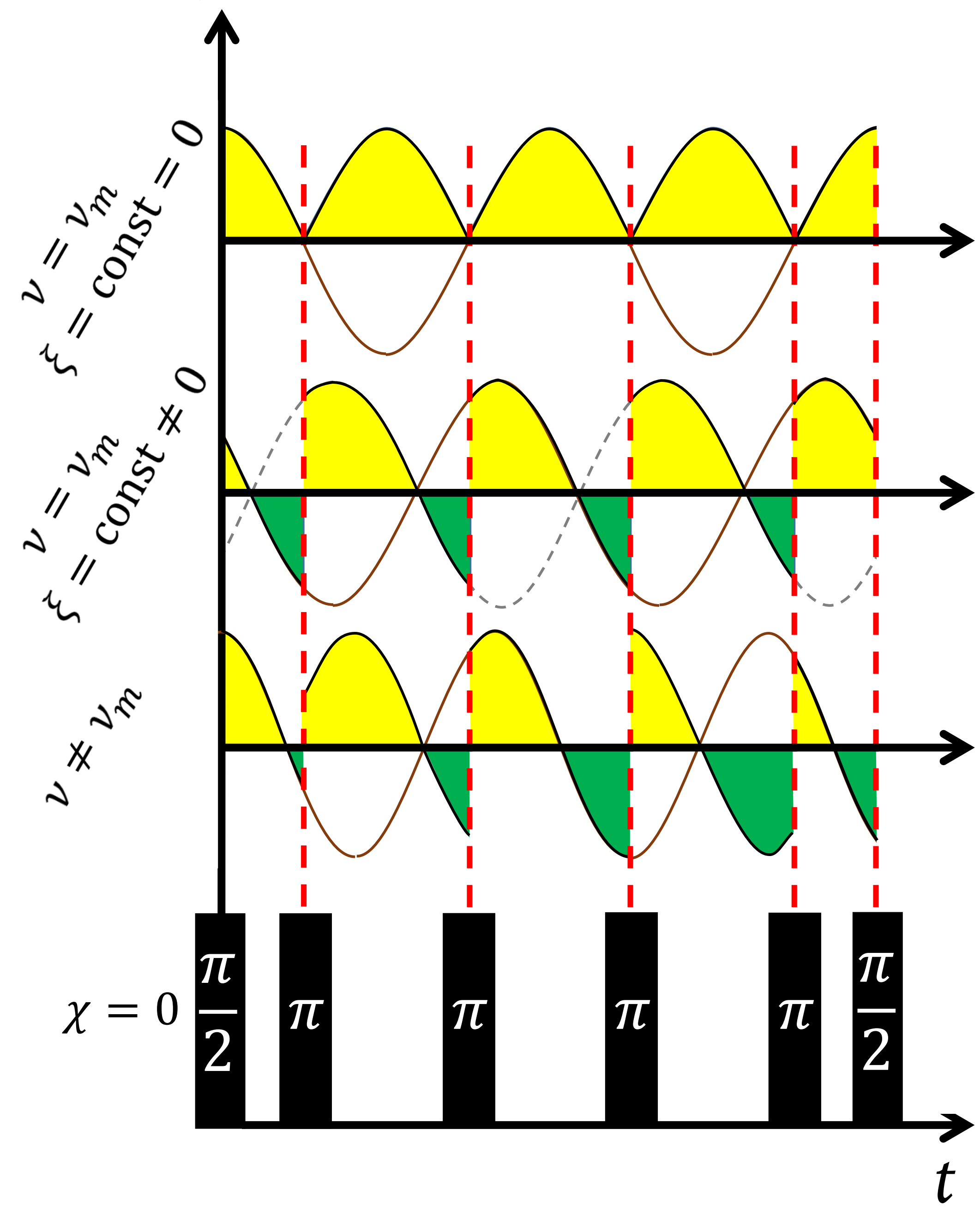
- **Temporal oscillations of atomic frequencies**
  - Rydberg energy levels $R_\infty \propto \alpha^2 m_e$
  - cavity modes frequencies $a_0 \propto (\alpha m_e)^{-1}$
  - H hyperfine transition $\omega_{HF} \propto \alpha^4 m_e^2$
- **Detectable by comparing two atomic probes that depend differently on $\boldsymbol{\alpha, m_e}$**

$$\Delta\Phi = \int \delta\omega_1(t) - \delta\omega_2(t) dt \approx \omega \int (n_{\alpha_2} - n_{\alpha_1}) \frac{\delta\alpha}{\alpha} + (n_{m_{e2}} - n_{m_{e1}}) \frac{\delta m_e}{m_e} dt$$

Y. V. Stadnik1 and V. V. Flambaum, PHYSICAL REVIEW A 93, 063630 (2016)

RAPIDALLY OSCILLATING DARK MATTER

- **"Heavy" ultralight DM** $m_\phi \gtrsim 10^{-12}\ \ eV, \nu_\phi \gtrsim 100\ \ Hz$
  - Theoretically motivated - relaxion DM.
  - **Blind spot** for atomic probes of temporal variations of fundamental constants due to rapid oscillations.
- **Dynamical Decoupling** - modulation - accumulating effects at a probe frequency, allows for long interrogation times.

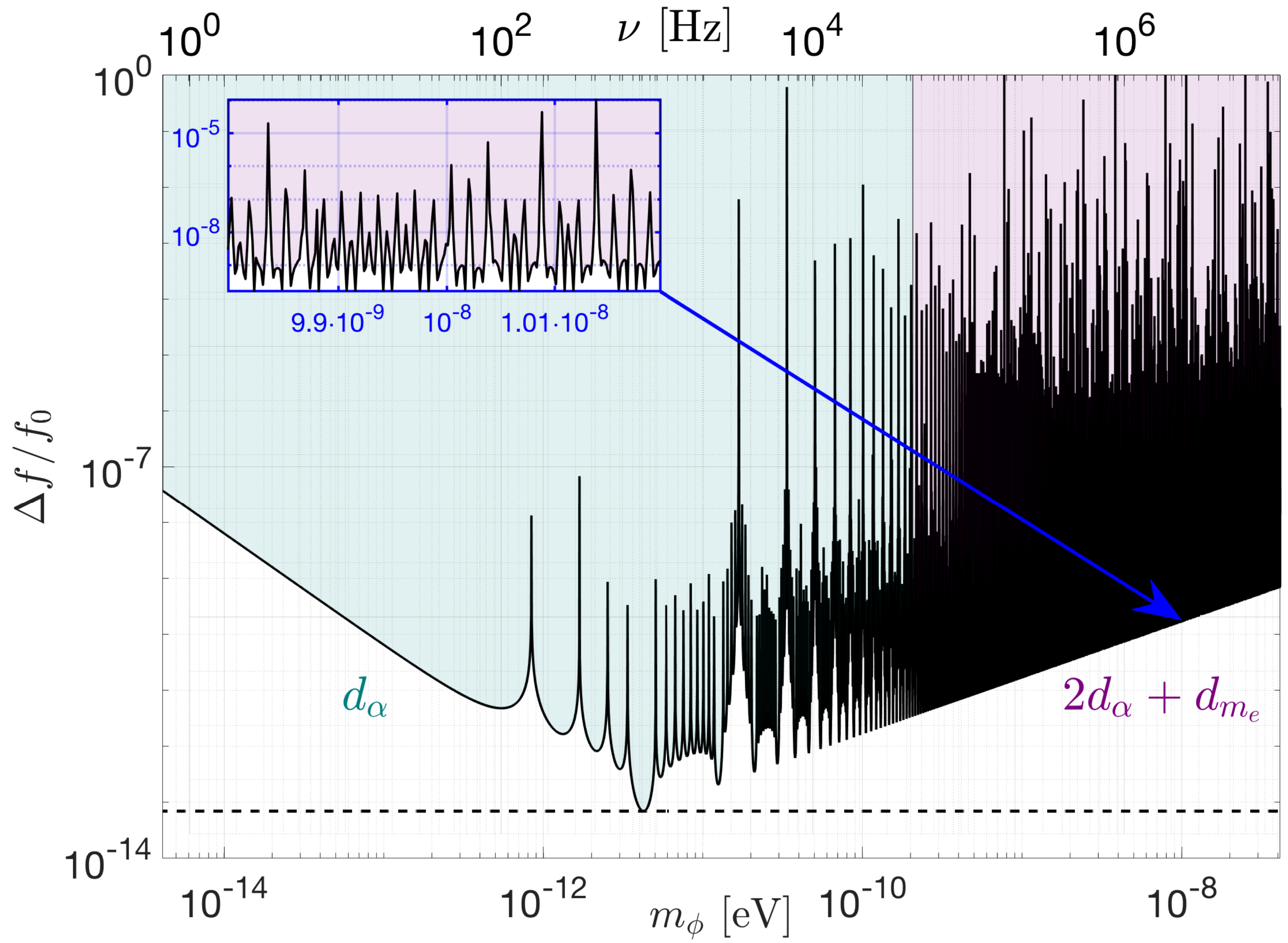


A. Banerjee et al., [1810.01889].

S. Aharony et al., [1902.02788].

PROBING RAPIDLY OSCILLATING DM USING DD

$$\frac{\Delta f(\nu)}{f_0} = \frac{\delta f_{\rm ion}(\nu) - \delta f_{\rm laser}(\nu)}{f_0} = \left(2 - F(\nu)\right)\frac{\delta\alpha}{\alpha} + \left(1 - F(\nu)\right)\frac{\delta m_e}{m_e}$$

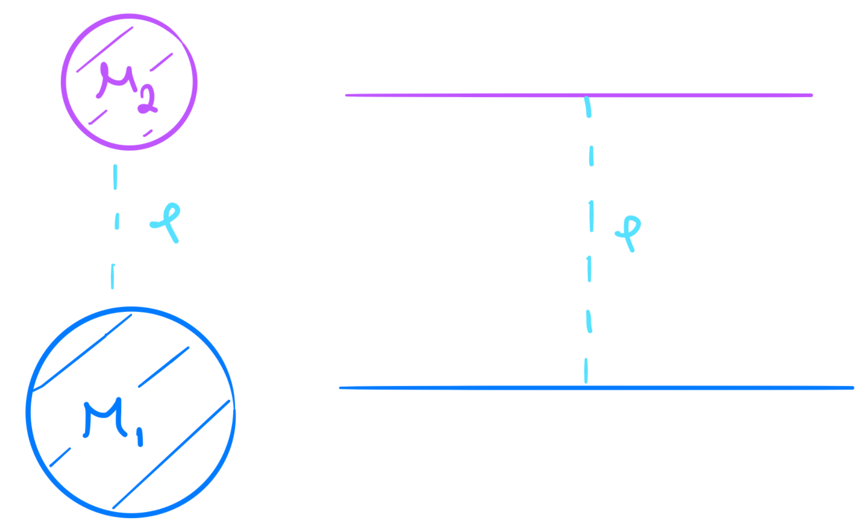


First model independent bounds on variations of α, m_e up to MHz frequencies.

S. Aharony et al., [1902.02788].

TESTS OF FIFTH-FORCE AND EP

- New scalar mediates a force (interaction) between neutral masses



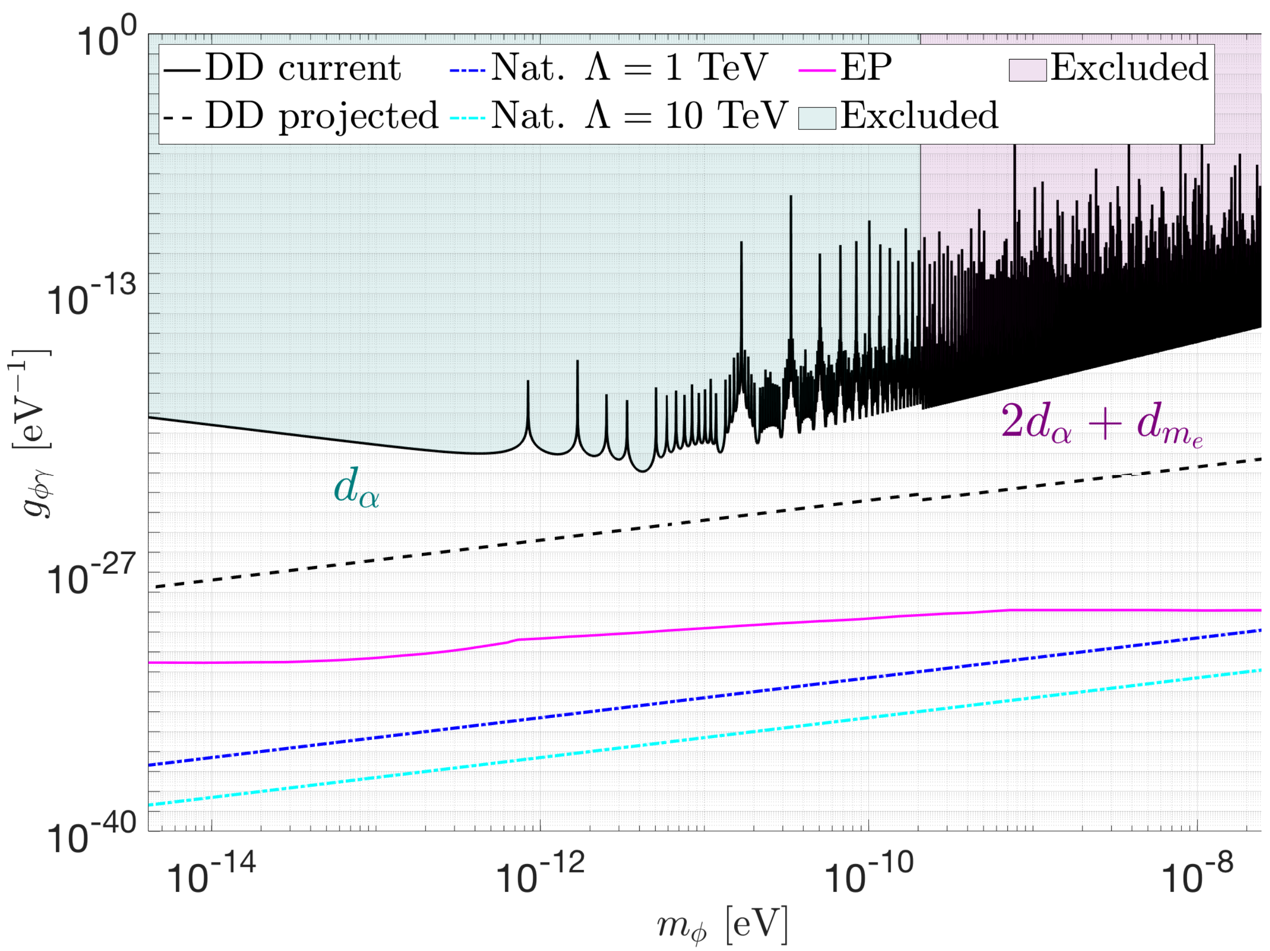
- **Searches for deviations from gravity**
  - massive force carrier - Yukawa potential

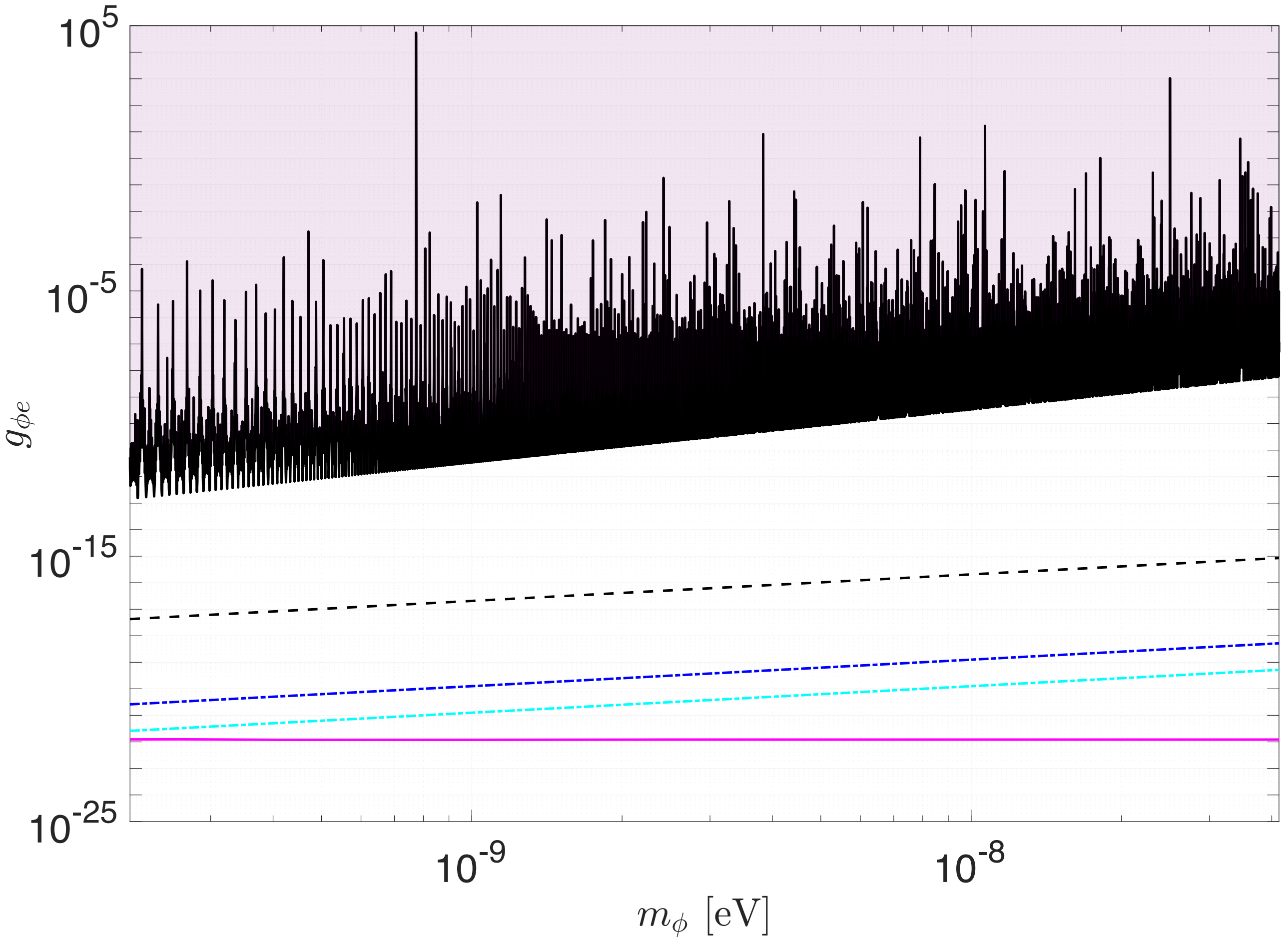
$$\boxed{V_\phi \propto \frac{e^{-m_\phi r}}{r}}$$

  - Non-universal couplings to masses of different compositions - **violation of the universality of free-fall** (Einstein's Equivalence Principle)

$$\boxed{\eta = \frac{a_A - a_B}{a_A + a_B} \propto \frac{1}{G}\left(g_{\phi e} Q^C_{m_e} + g_{\phi\gamma} Q^C_e\right)\left(g_{\phi e}\left(Q^A_{m_e} - Q^B_{m_e}\right) + g_{\phi\gamma}\left(Q^A_e - Q^B_e\right)\right)}$$

COMPARISON – FIFTH FORCE VS. FUND. CONSTANTS





QUADRATICALLY COUPLED DM

- Higher order interactions of the DM candidate with the SM

$$\mathscr{L} = g_{\phi^2 e}\phi^2 m_e \bar{e}e$$

- **Variations of** $\boldsymbol{m_e}$

$$\boxed{\frac{\delta m_e}{m_e} = g_{\phi^2 e}\frac{\rho_{DM}}{m_\phi^2}\cos(2m_\phi t)}$$

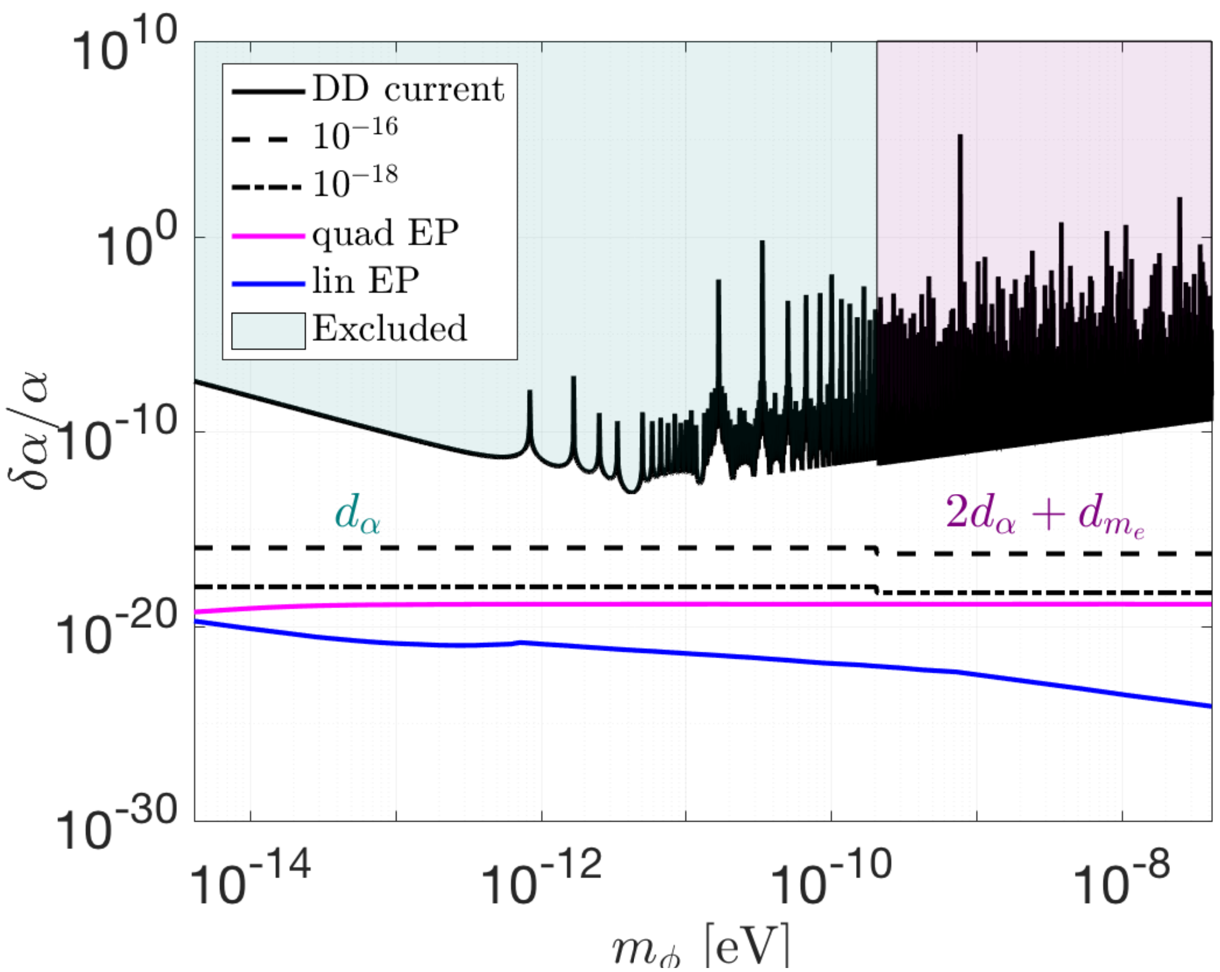
- **5F/EP -** gains DM density sensitivity, different r-dependance

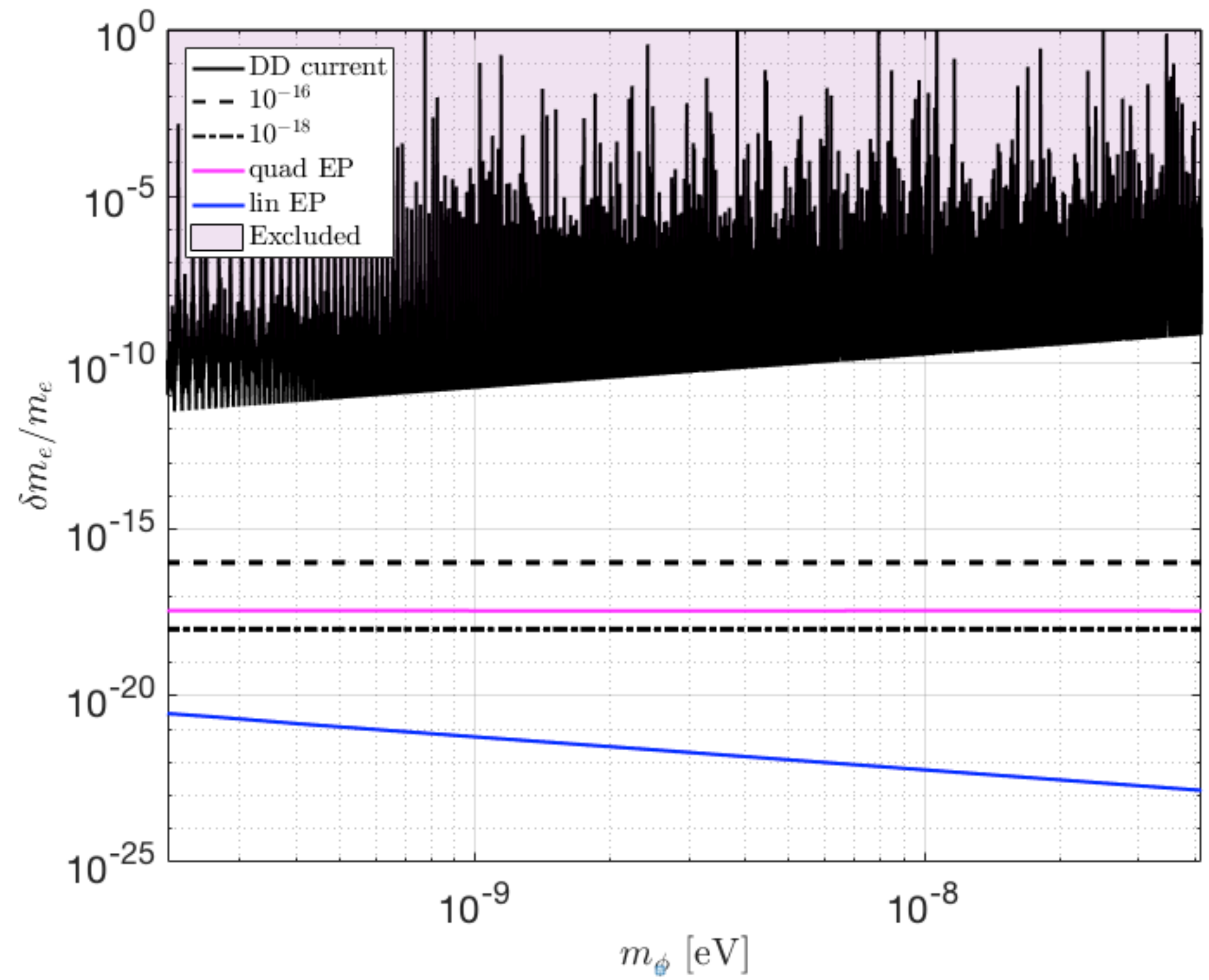
$$\boxed{V(r) \propto \phi^2 \sim \frac{\rho_{DM}}{m_\phi^2}\left(1 - s_A\frac{GM_A}{r}\right)^2}$$

$$\boxed{\eta = \frac{a_A - a_B}{a_A + a_B} \propto \frac{\rho_{DM}}{Gm_\phi^2}\left(g_{\phi^2 e}Q^C_{m_e} + g_{\phi^2\gamma}Q^C_e\right)\left(g_{\phi^2 e}\left(Q^A_{m_e} - Q^B_{m_e}\right) + g_{\phi^2\gamma}\left(Q^A_e - Q^B_e\right)\right)}$$

A. Hees et al, 1807.04512

COMPARISON - QUADRATICALLY COUPLED DM





OUTLOOK AND FUTURE WORK

- Ultralight DM could result in temporal oscillations of fundamental constants, and non-universal acceleration.
- Different couplings/density enhancement can make atomic probes more sensitive.
- Ongoing work - Model building for Natural theories with quadratically coupled DM.
- Future work - using tools from signal processing to increase the sensitivity to rapidly oscillating DM.

THANK YOU!

BACKUP SLIDES

DM HALOS CENTERED AROUND EARTH?

- Temporal variation probes are sensitive to the local DM density at the position of the experiment.
- What if the DM density is locally enhanced?
  - "SM" enhancement (?)
  - DM halos - earth's gravity as a source binding the star together.

RESULTS - DM HALOS AROUND EARTH