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Impact of Cavities on the Detection of Quadratically Coupled Ultra-Light Dark Matter

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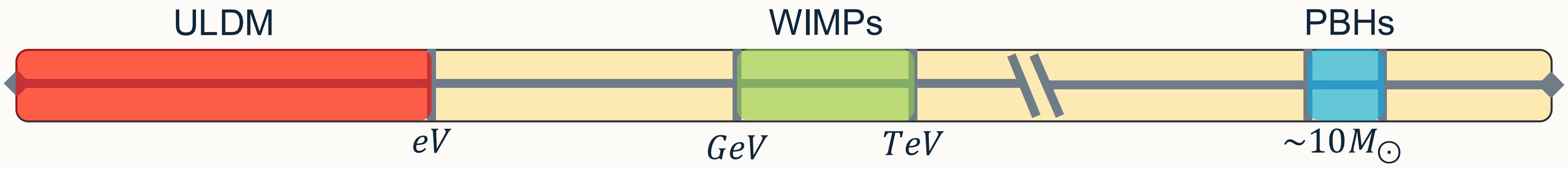
w/ Clare Burrage, Elisa Todarello, Michael Ross, Gray Rybka

Phys. Rev. D 113, 063505

arXiv:2605.28248

Background



ULDM Scalars

- Large number of possible candidates
- Treated as classical fields

$$\phi_H(t) = \phi_\infty \cos(mt + \delta)$$

$$\rho_{DM} = \frac{1}{2} m^2 \phi_\infty^2$$

Scalar Coupling To Matter

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

- Interactions induce shifts in fundamental constants:

$$\left.\begin{matrix} \alpha_{EM}\left(1+d_e\dfrac{(\kappa\phi)^2}{2}\right) \\[2em] m_f\left(1+d_{m_f}\dfrac{(\kappa\phi)^2}{2}\right) \\[2em] \Lambda_3\left(1+d_g\dfrac{(\kappa\phi)^2}{2}\right) \end{matrix}\right\} \quad m_A \to m_A\left(1+\alpha_A\frac{\phi^2}{2}\right)$$

Damour T, Donoghue JF. PRD. 2010 Oct 20;82(8).
Hees A, Minazzoli O, Savalle E, Stadnik YV, Wolf P. PRD. 2018 Sep 25;98(6)

Scalar Coupling To Matter

- Around non-relativistic matter:

$$S = \int d^4x \left[\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}(m^2 + \alpha\rho)\phi^2 \right] + \mathcal{L}_{SM}$$

- Matter provides local shift in effective mass

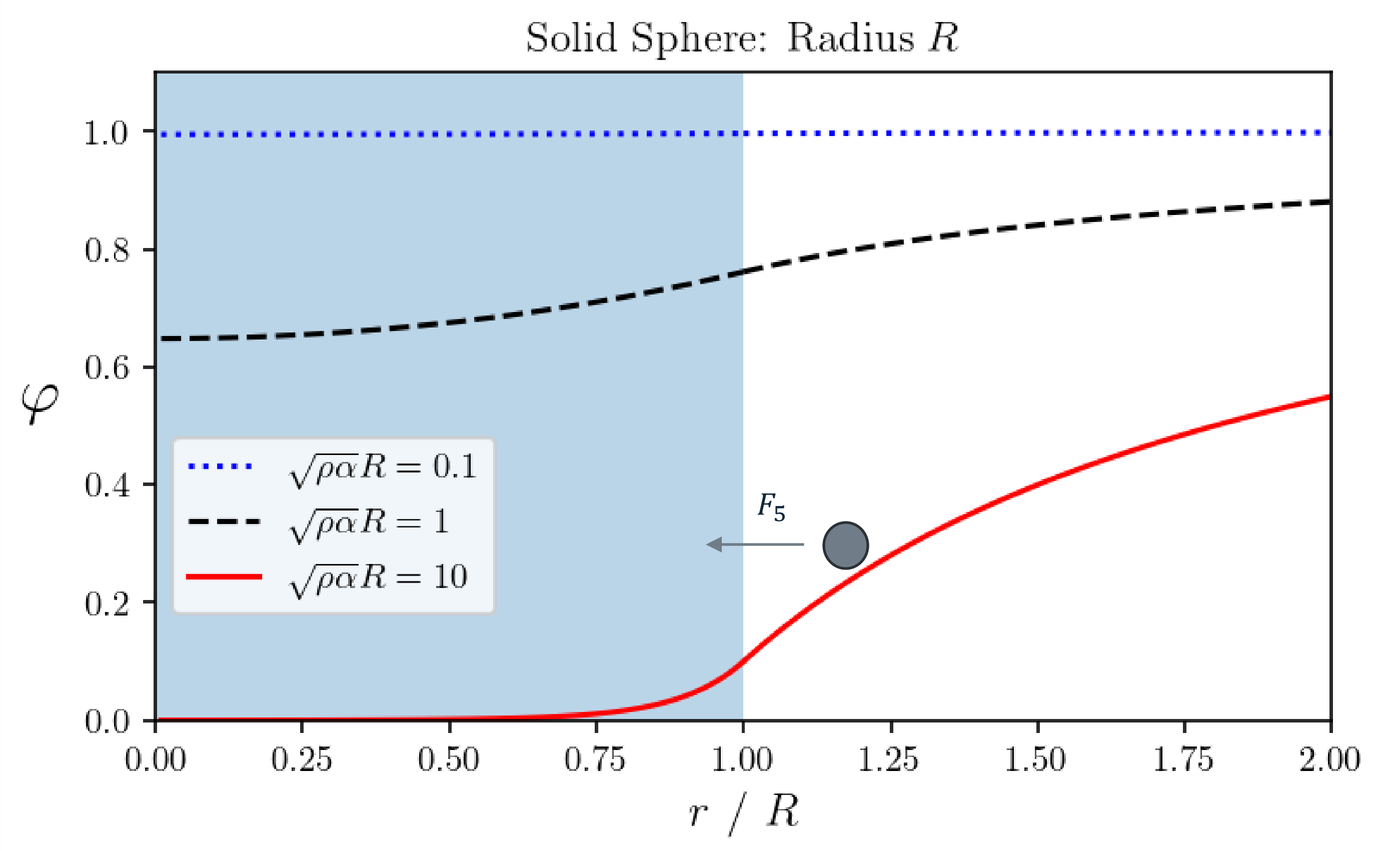
$$\Box\phi + (m^2 + \alpha\rho)\phi = 0$$

- Assume homogeneous solution away from matter

$$\phi = \phi_H(t)\varphi(x) \qquad\qquad |\alpha\phi^2| \ll 1$$

Matter Perturbs the Scalar Field

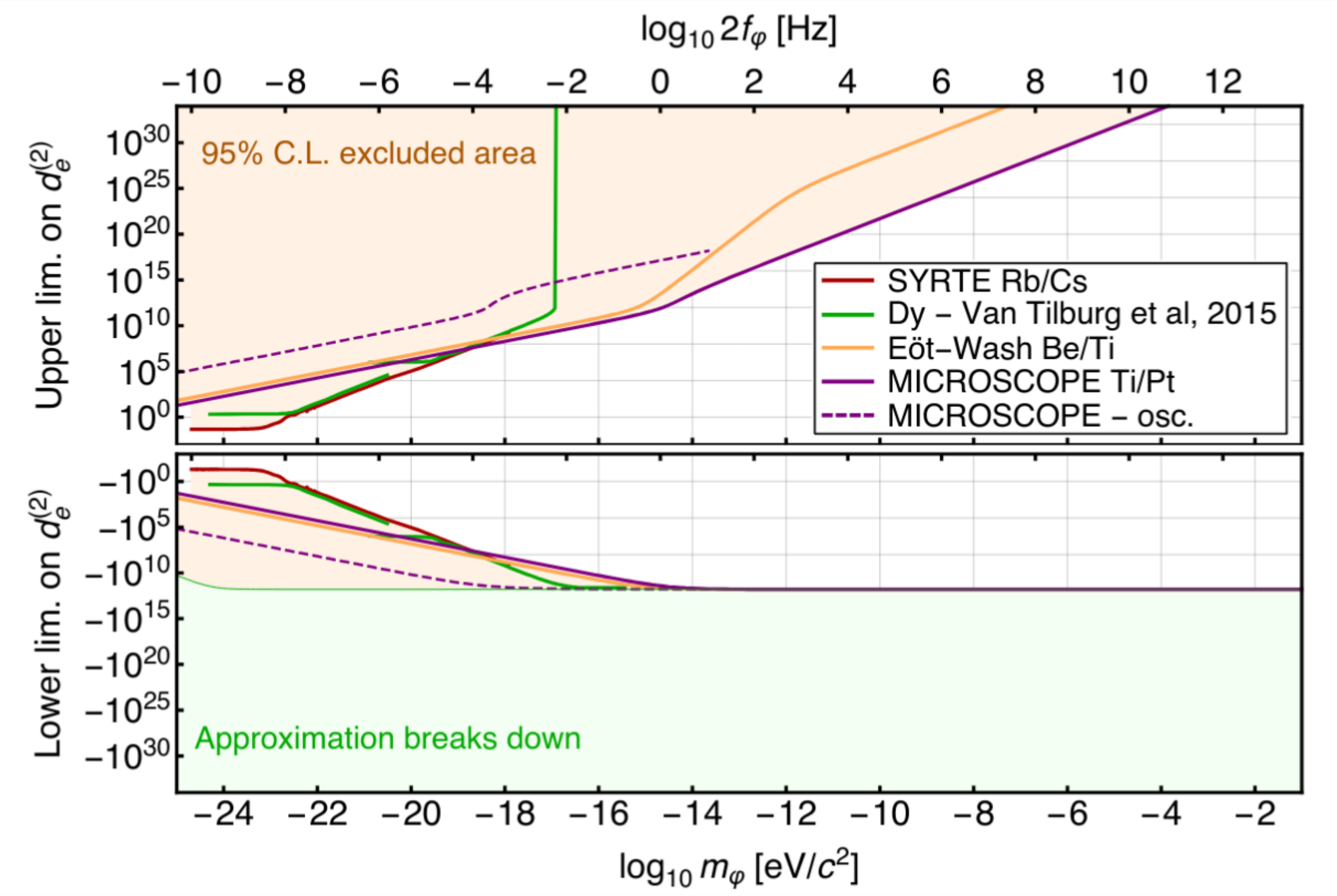
$$\rho_S(x) = \begin{cases} \rho, & r \leq R \\ 0, & r > R \end{cases}$$



Field gradients lead to fifth forces on test masses *T*:

$$F_5 = -\int d^3x \frac{\rho_T \alpha_T}{2} \nabla \phi^2$$

Existing Constraints



- Tabletop scale experiments
  - EP violation searches
  - Atomic Clocks
- Often assume idealised environments

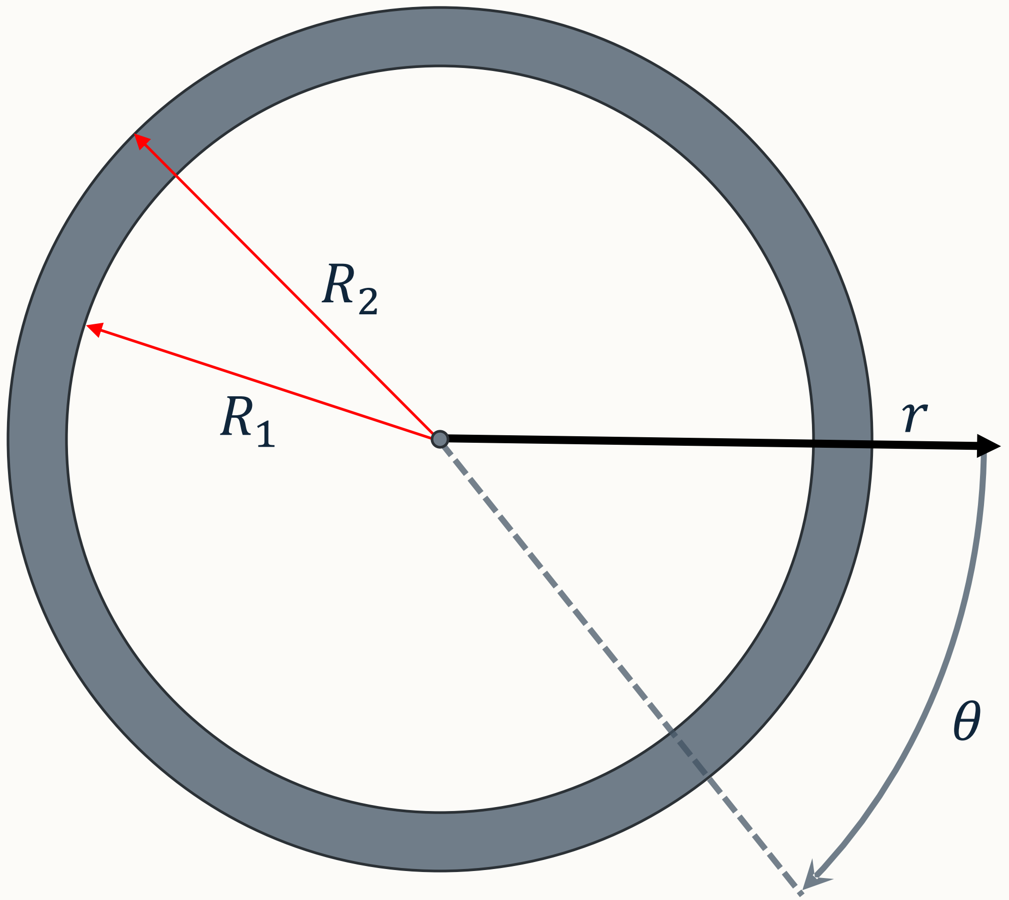
Hees A, Minazzoli O, Savalle E, Stadnik YV, Wolf P. Physical Review D. 2018 Sep 25;98(6)

Cavities to Model Enclosed Environments

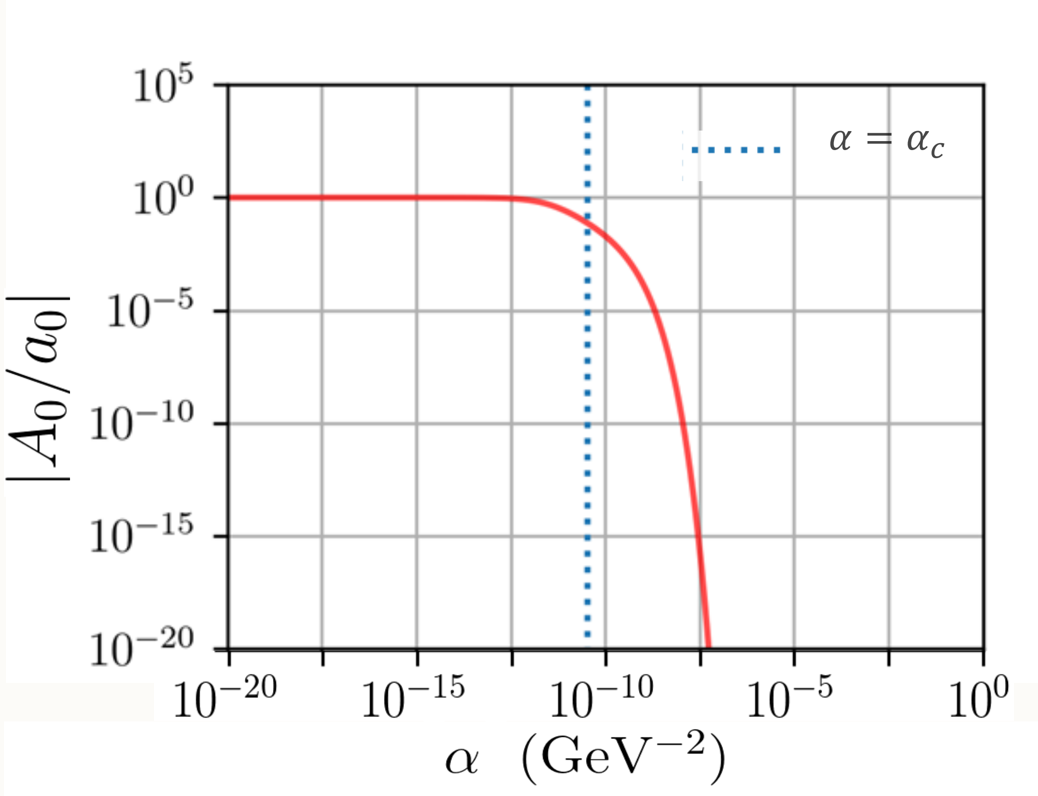
$$\rho(x) = \begin{cases} 0, & r \leq R_1 \\ \rho_C, & R_1 < r \leq R_2 \\ 0, & r > R_2 \end{cases}$$

Approximate description of:

- Vacuum Chamber
- Satellite Housing
- Laboratory Walls



Impact of Cavity



Aluminium Cavity:
- Internal Radius: 10 cm
- Thickness: 1cm

- Far from cavity, field has amplitude:

$$\varphi_o = a_0$$

- Inside cavity:

$$\varphi_i(r,\theta) = A_0$$

$$\alpha_C = \frac{1}{\rho_C (R_2 - R_1)^2}$$

- $\alpha > \alpha_c$: Field exponentially suppressed

Burrage C, A.M., Ross MP, Rybka G, Todarello E. Phys. Rev. D **113**, 063505

Example Rescaling of Constraints

Aluminium Cavity:

- Internal Radius: 10 cm
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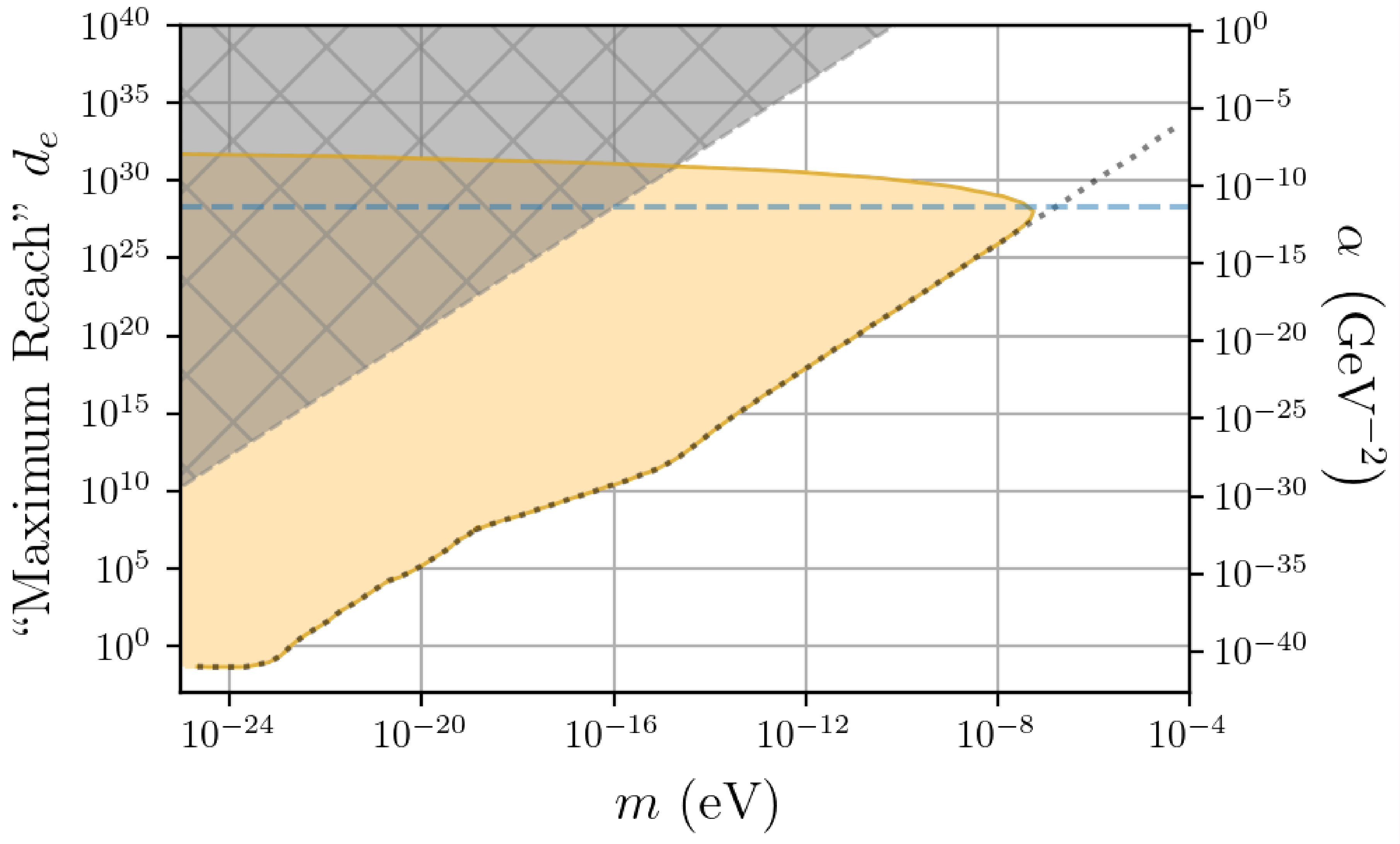

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LAGEOS-2

- ‘Disco ball’-like test mass:
  - Precise trajectory from laser ranging
  - Used to test GR

- Bounds placed on ‘anomalous’ pericentre precession:

Image Credit: NASA

$$\Delta\dot{\omega}_{an} \approx 3294.95 \times (-1.2 \times 10^{-4} \pm 2.10 \times 10^{-3} \pm 2.54 \times 10^{-2}) \text{ mas yr}^{-1}$$

Lucchesi M, Peron R, PRD. 2014 Apr 7;89(8)

Pericentre Precession

In orbit around earth LAGEOS-II Experiences a radial acceleration:

$$\ddot{r} = -\frac{GM_\oplus}{r^2} + \boxed{\frac{\delta^{(2)}}{r^2}} + \frac{l^2}{r^3} + \boxed{\frac{\delta^{(3)}}{r^3}}$$

Total Fifth Force

Contributes to Precession

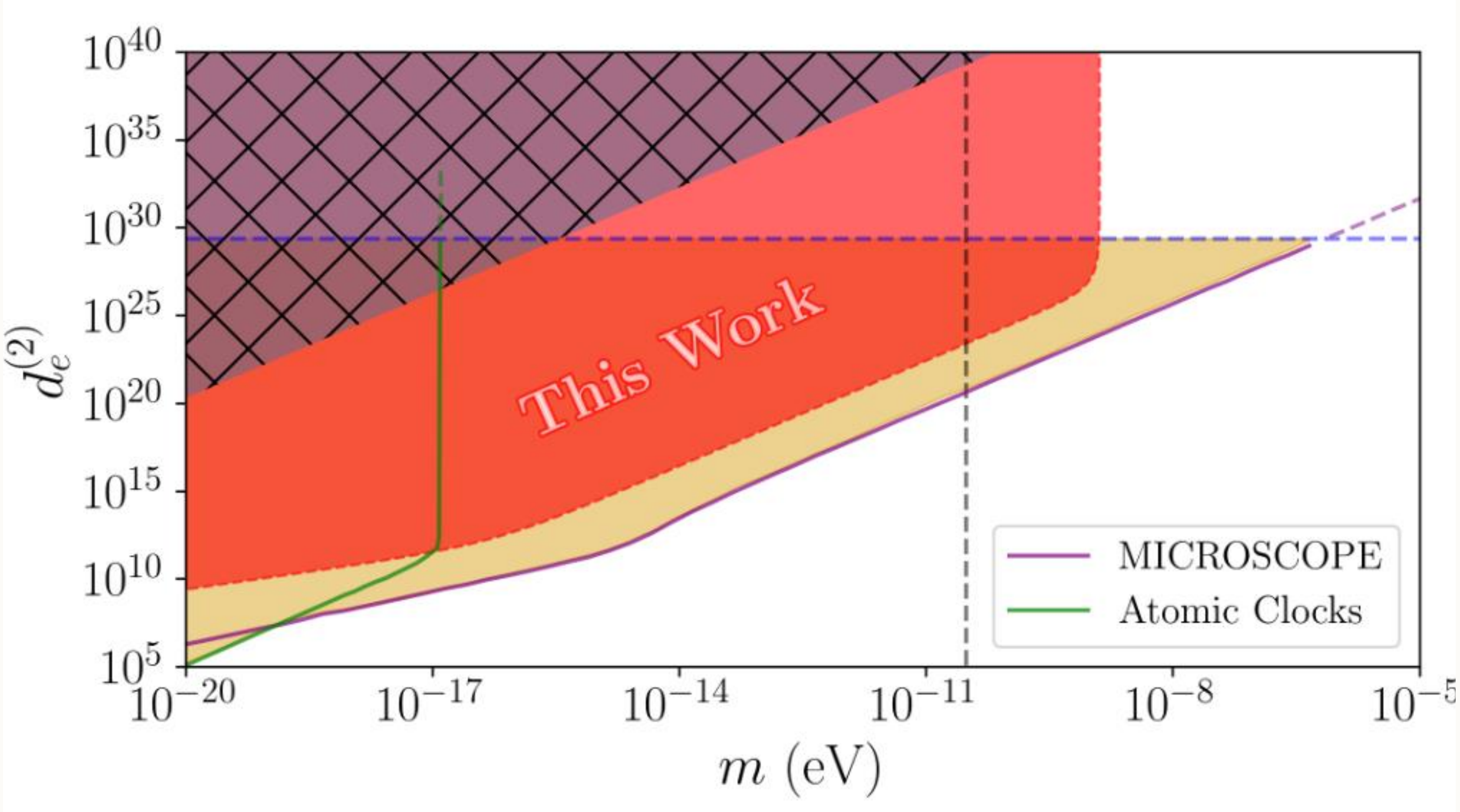
The correction to the motion of LAGEOS predicts a pericentre precession

$$\Delta\dot{\omega} \sim \frac{\rho_{DM}\tau_L R_L R_\oplus^2}{M_L m^2 r_L^4} \times f(\alpha)$$

Image Credit: NASA

Burrage C, A.M., Todarello E. Using the Pericentre Precession of LAGEOS II to Constrain Quadratically Coupled Ultralight Dark Matter

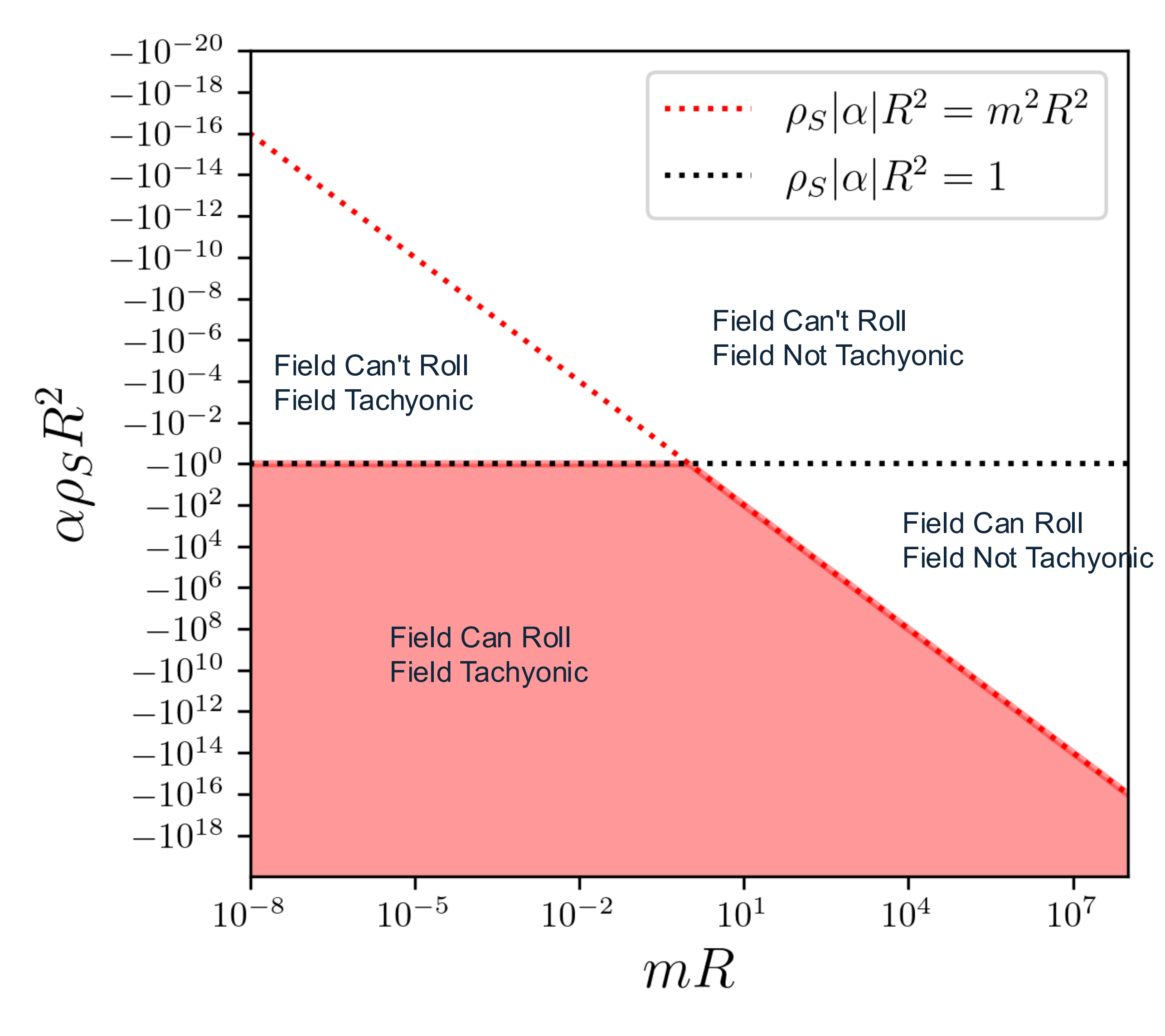
Constraints from LAGEOS-2



Burrage C, A.M., Todarello E. arXiv:2605.28248

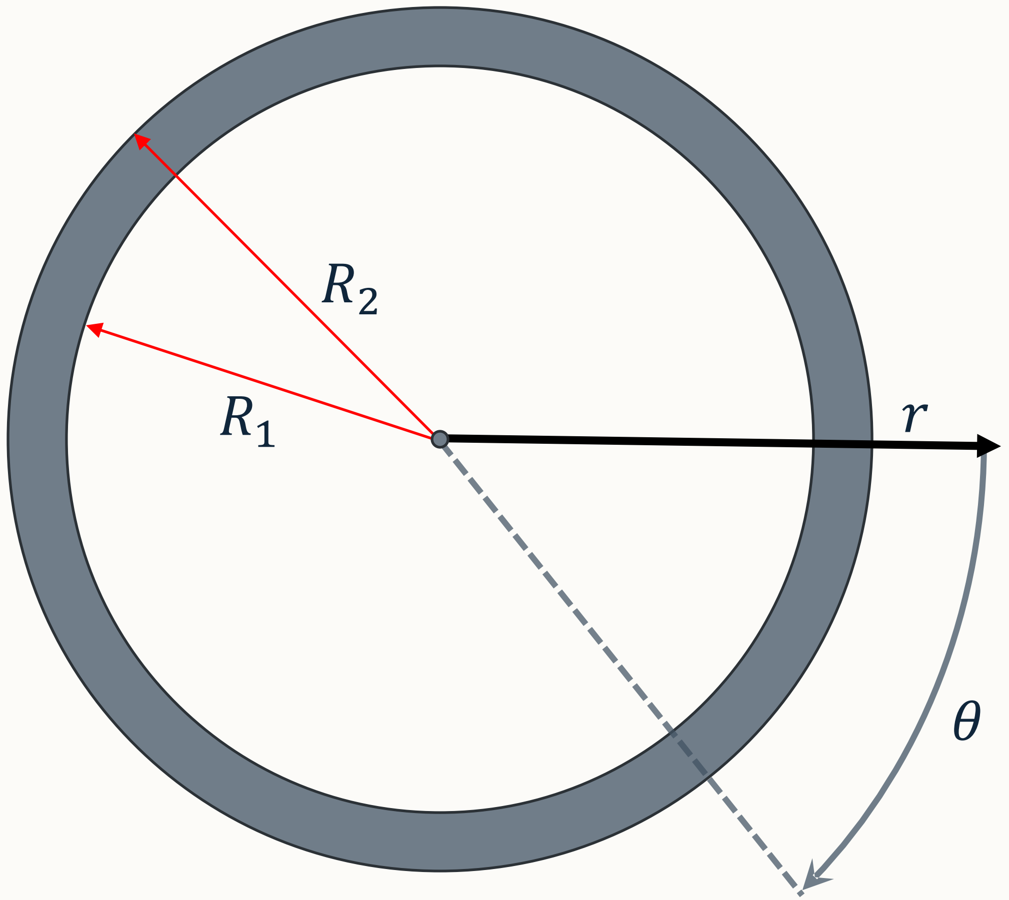
Summary

- Scalars featuring quadratic couplings to SM fields may constitute DM
- Properties of these scalars can be constrained by laboratory and satellite experiments
- Matter around experiments may weaken constraints at strong couplings
- Experiments such as LAGEOS-2 can still be used to place constraints at strong couplings


$\rho_S|\alpha|R^2 = m^2R^2$
$\rho_S|\alpha|R^2 = 1$
Field Can't Roll
Field Tachyonic
Field Can't Roll
Field Not Tachyonic
Field Can Roll
Field Not Tachyonic
Field Can Roll
Field Tachyonic
$\alpha\rho_S R^2$
mR

Cavities to Model Enclosed Environments

$$\rho(x) = \begin{cases} 0, & r \le R_1 \\ \rho_C, & R_1 < r \le R_2 \\ 0, & r > R_2 \end{cases}$$



- Without cavity/Background to cavity:

$$\varphi_o(r,\theta) = a_0 + a_1 r \cos\theta$$

- Inside cavity:

$$\varphi_i(r,\theta) = A_0 + A_1 r \cos\theta$$

Impact of Cavity

Aluminium Cavity:

- Internal Radius: 10 cm
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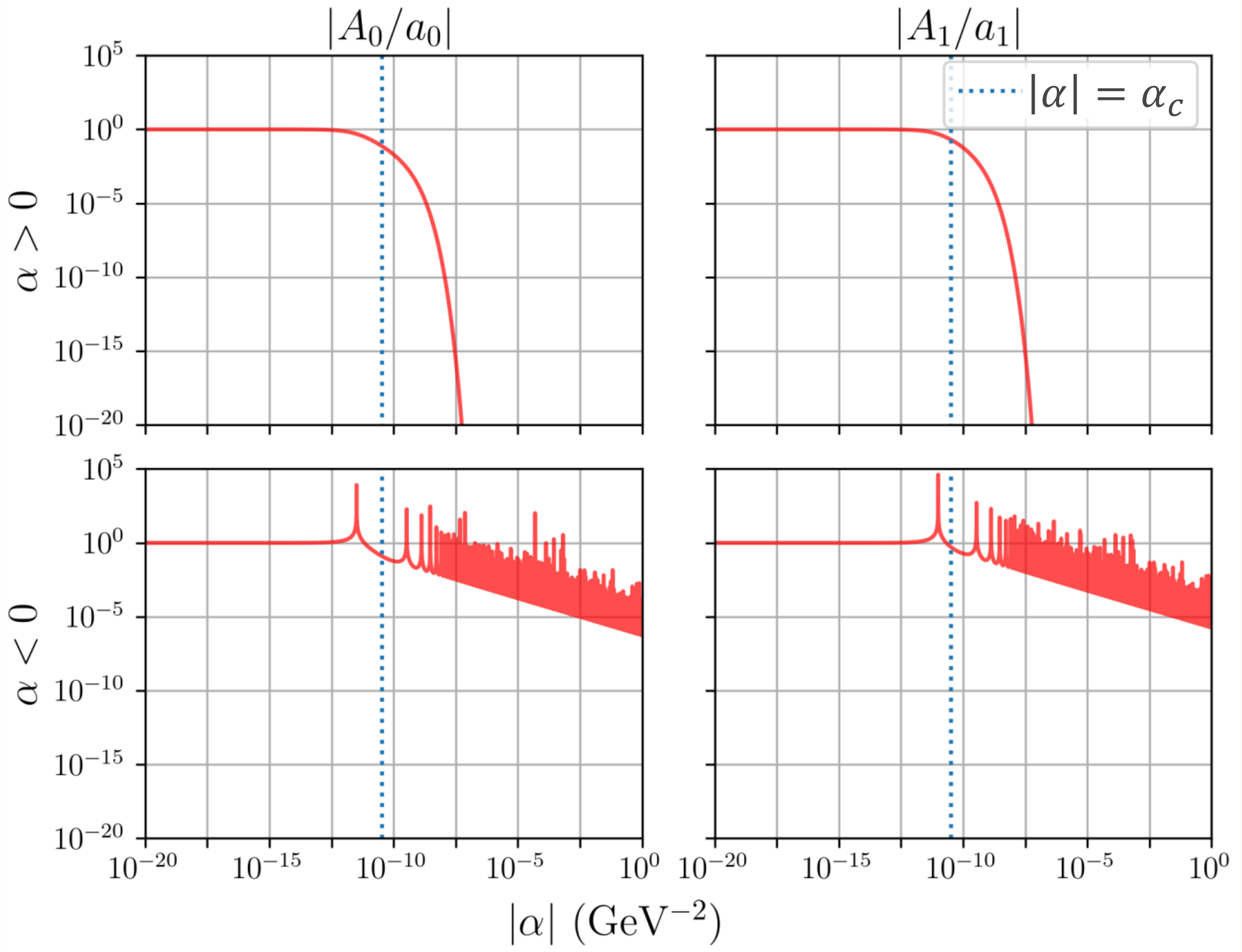

- Change in behaviour around:

$$\alpha_C = \frac{1}{\rho_C (R_2 - R_1)^2}$$

- $\alpha > 0$: Field exponentially suppressed

- $\alpha < 0$: Field suppressed as power law suppressed

Burrage C, A.M., Ross MP, Rybka G, Todarello E. Impact of cavities on the detection of quadratically coupled ultra-light dark matter