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

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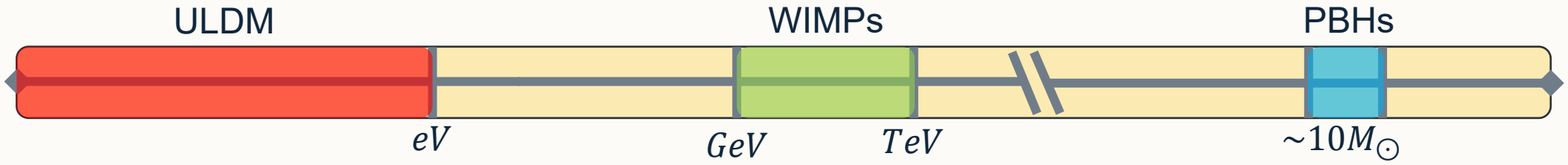
Based on arXiv:2507.16526 w/ Clare Burrage, Elisa Todarello, Michael Ross, Gray Rybka

Background

- DM candidates exist over broad mass range



ULDM Scalars

- Predicted in physics beyond the SM
- 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:

$$\left.\begin{array}{l} \alpha_{EM}\left(1 + d_e\frac{(\kappa\phi)^2}{2}\right) \\ m_f\left(1 + d_{m_f}\frac{(\kappa\phi)^2}{2}\right) \\ \Lambda_3\left(1 + d_g\frac{(\kappa\phi)^2}{2}\right) \end{array}\right\} \quad m_A \rightarrow m_A\left(1 + \alpha_A\frac{\phi^2}{2}\right)$$

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

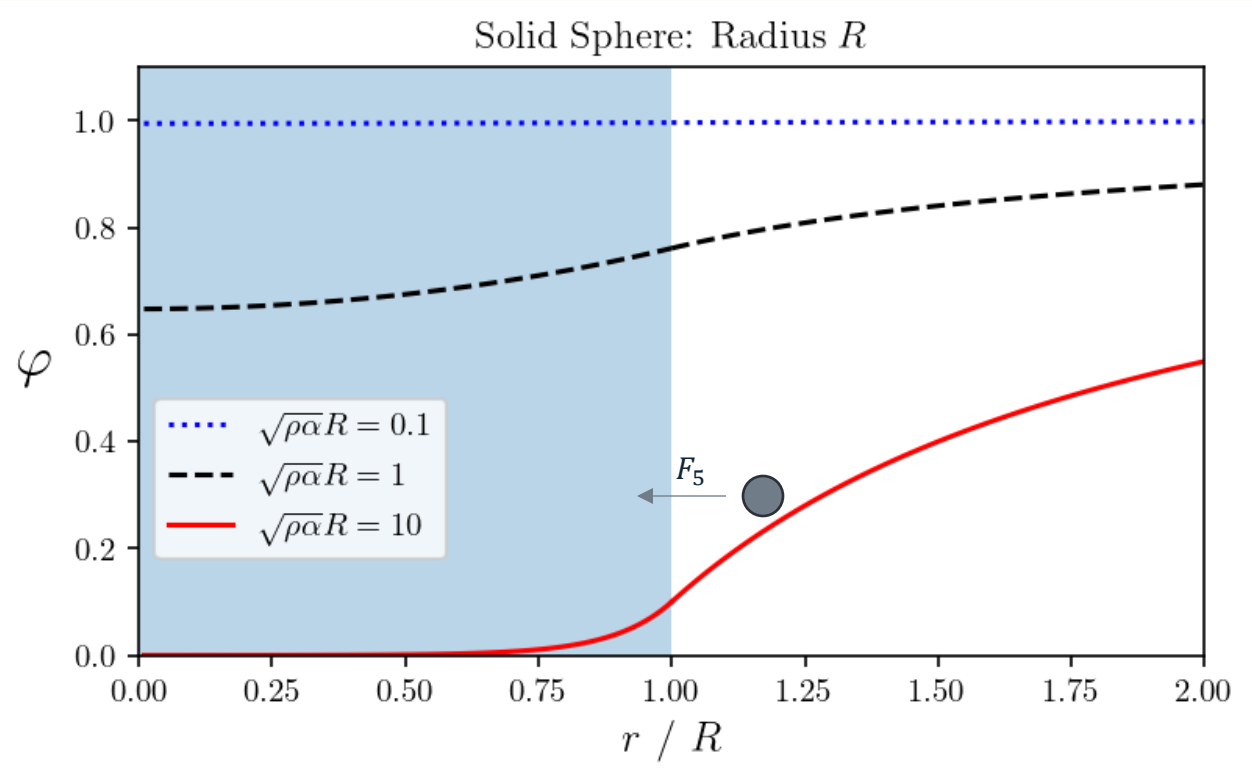
$$\Box\phi + (m^2 + \alpha\rho)\phi = 0$$

- Assume homogeneous solution away from matter

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

Matter Perturbs the Scalar Field

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

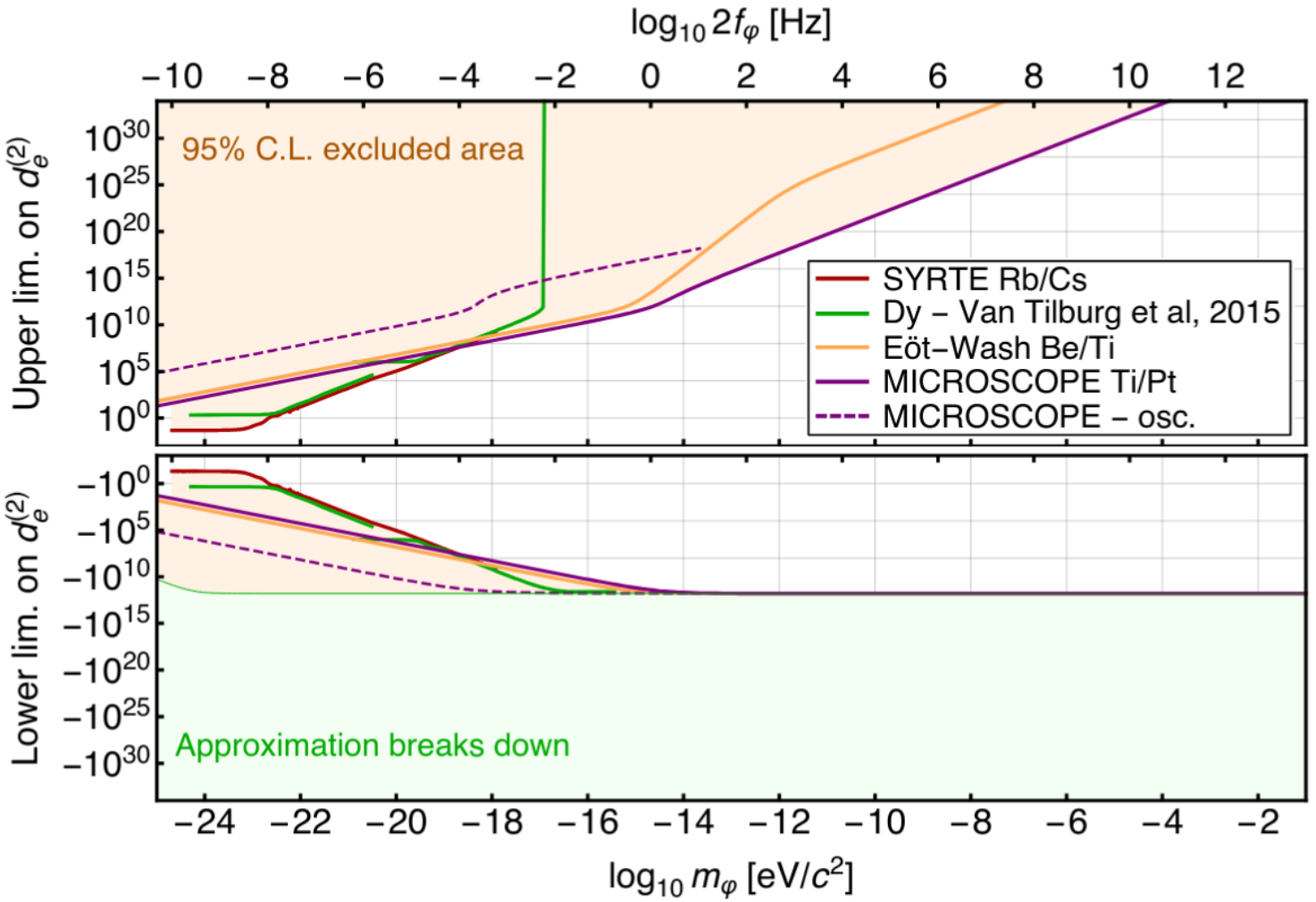


- Field gradients lead to fifth forces:

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

- Negative α result in more complicated behaviour

Existing Constraints

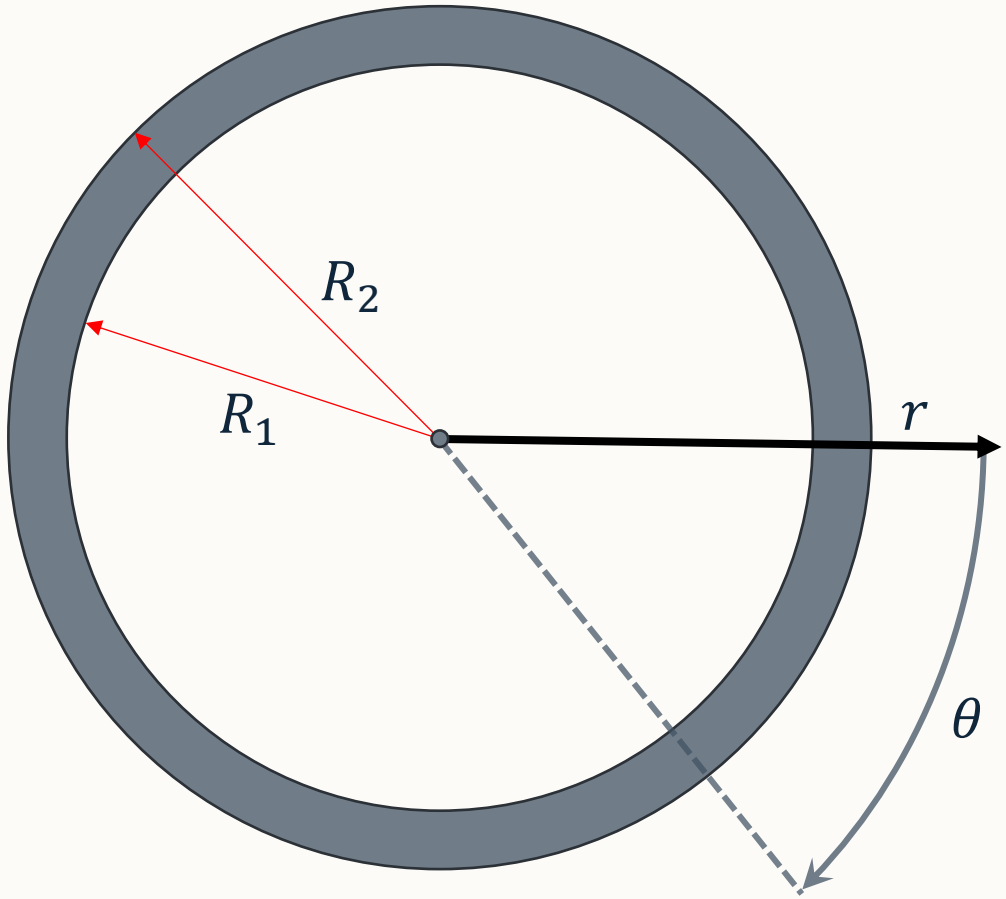


- Tabletop scale experiments
  - EP violation searches
  - Atomic Clocks
- Often assume idealised environments

Hees A, Minazzoli O, Savalle E, Stadnik YV, Wolf P. Violation of the equivalence principle from light scalar dark matter. Physical Review D. 2018 Sep 25;98(6)

Cavities to Model Enclosed Environments

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



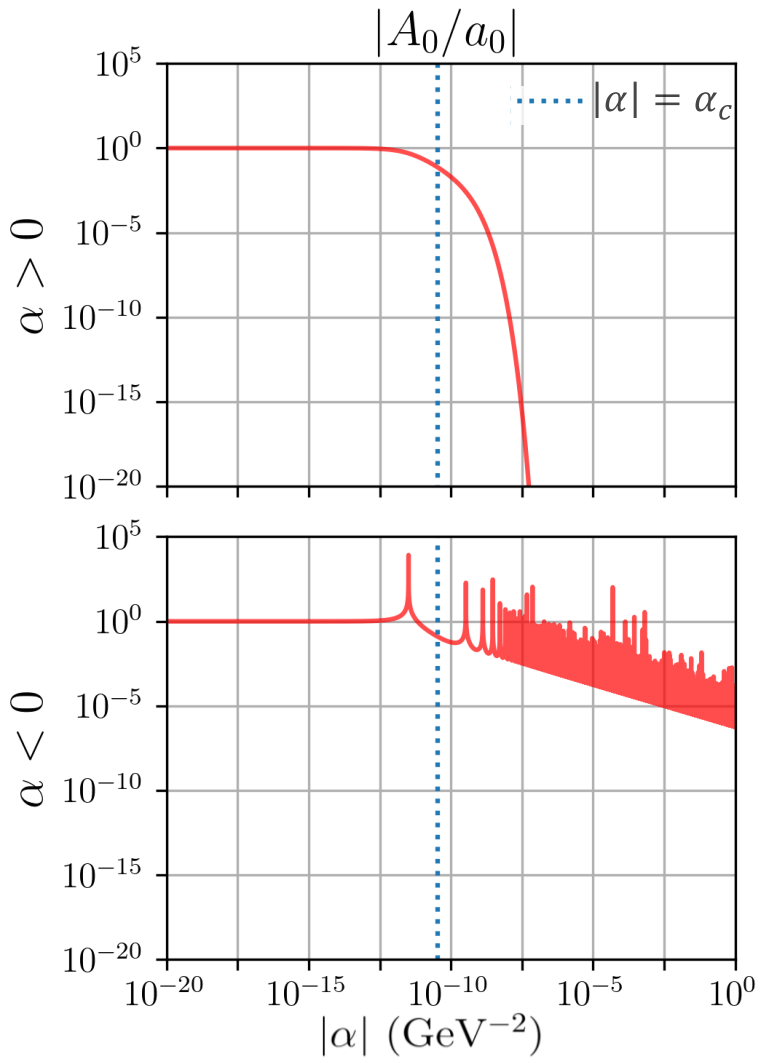
- Without cavity/Background to cavity:

$$\varphi_o(r, \theta) = a_0$$

- Inside cavity:

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

Impact of Cavity



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

- 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

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Example Rescaling of Constraints

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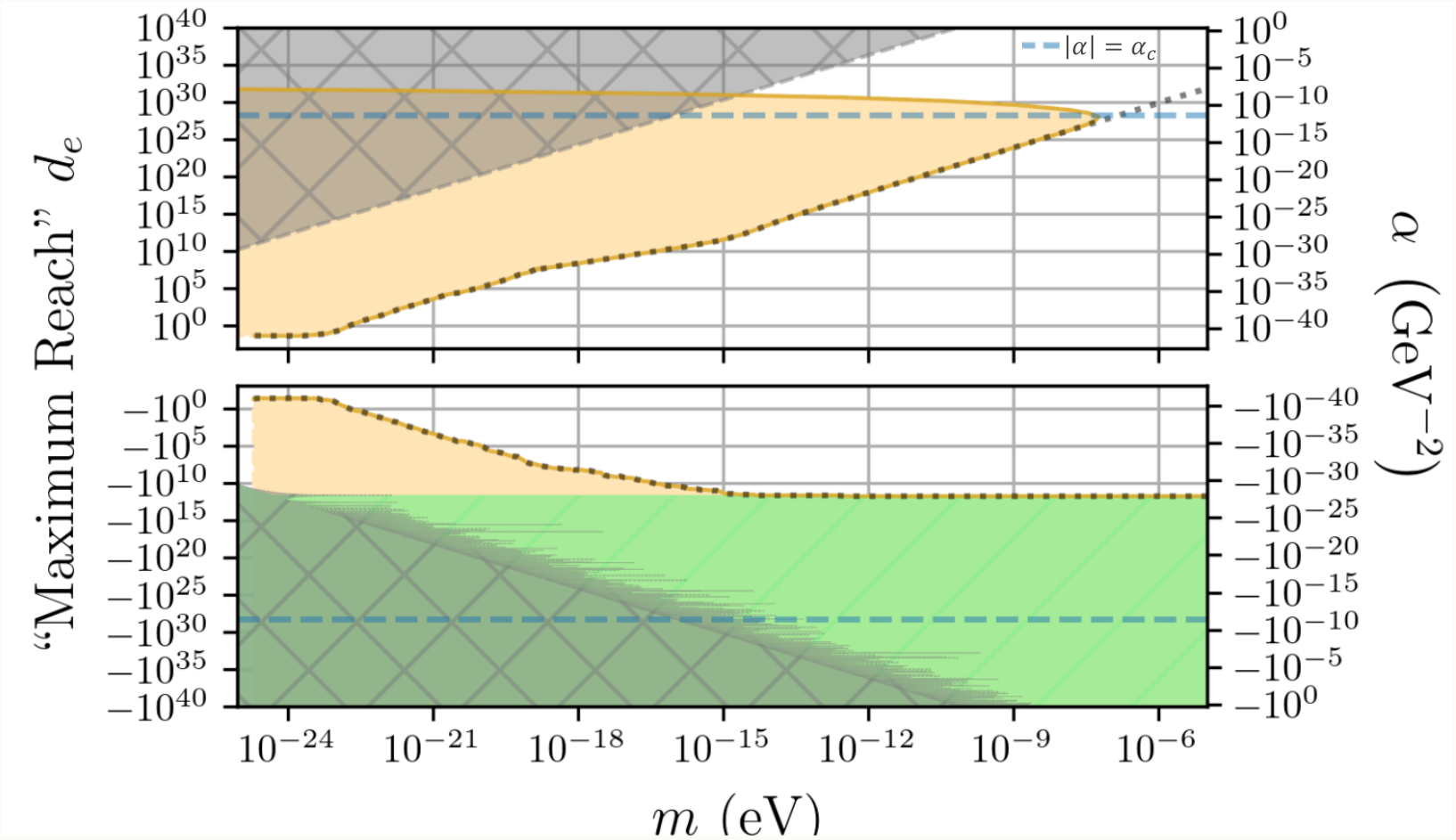

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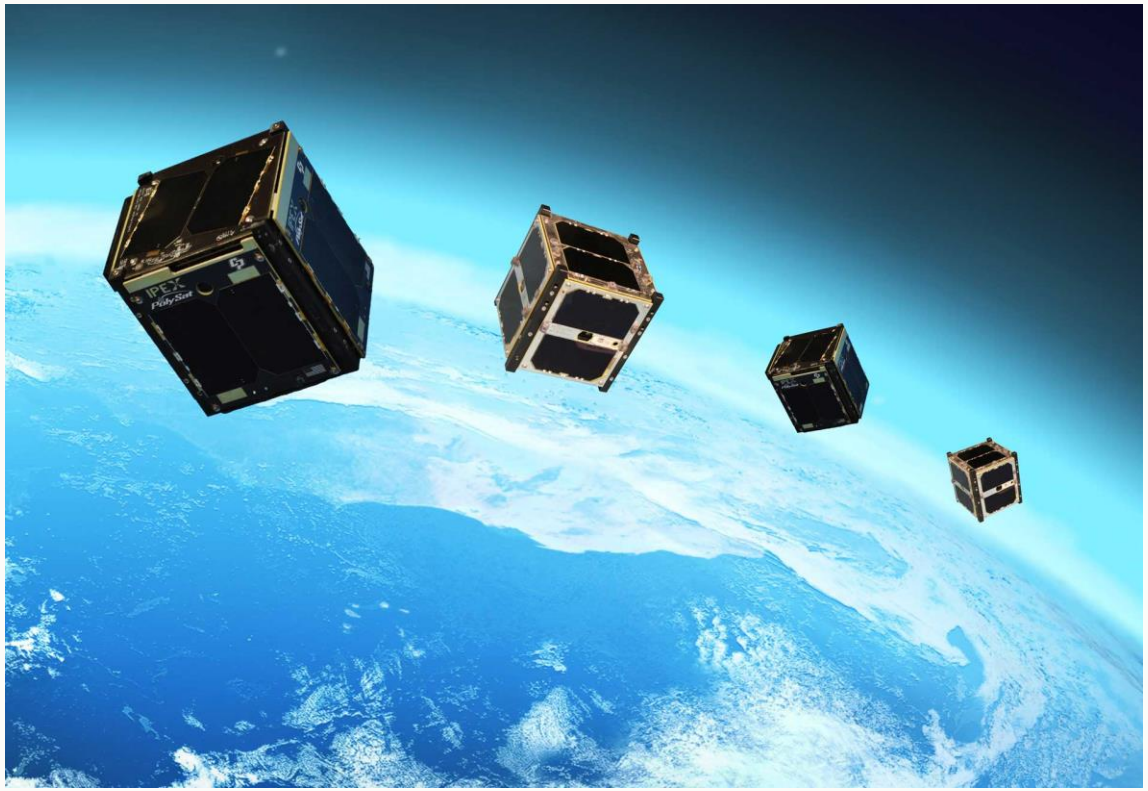
Mitigating Environmental Effects

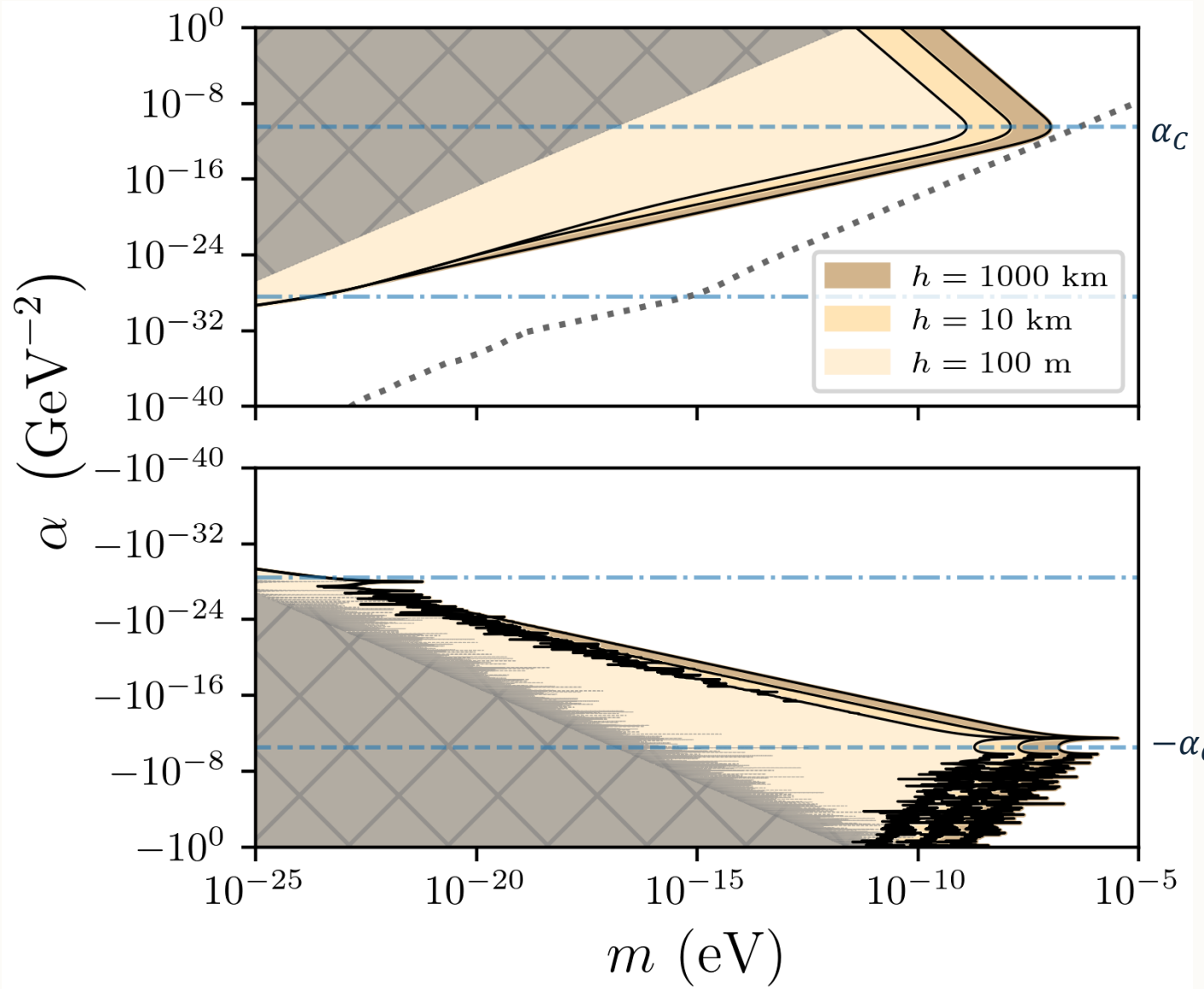
- CubeSats – minimise experimental environment



- Use (differential) acceleration to constrain scalar properties

Image Credit: JPL

Differential Force on Cavities



Cavities:
- Equal Mass: (~4 kg)
- Internal Radius: 10 cm, 9cm
- Thickness: 1cm , 2cm

Constraint forecast assuming:
- Satellites described as Cavities
- No signal observed up to sensitivity: 100 fN
- Differential satellite-Earth 5th force constrained
- Universal α

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Summary

- Scalars featuring quadratic couplings to SM fields may constitute DM
- Properties of these scalars can be constrained by laboratory scale experiments
- Matter environments suppresses effects at strong couplings
- Experiments may be designed to mitigate environmental effects

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:

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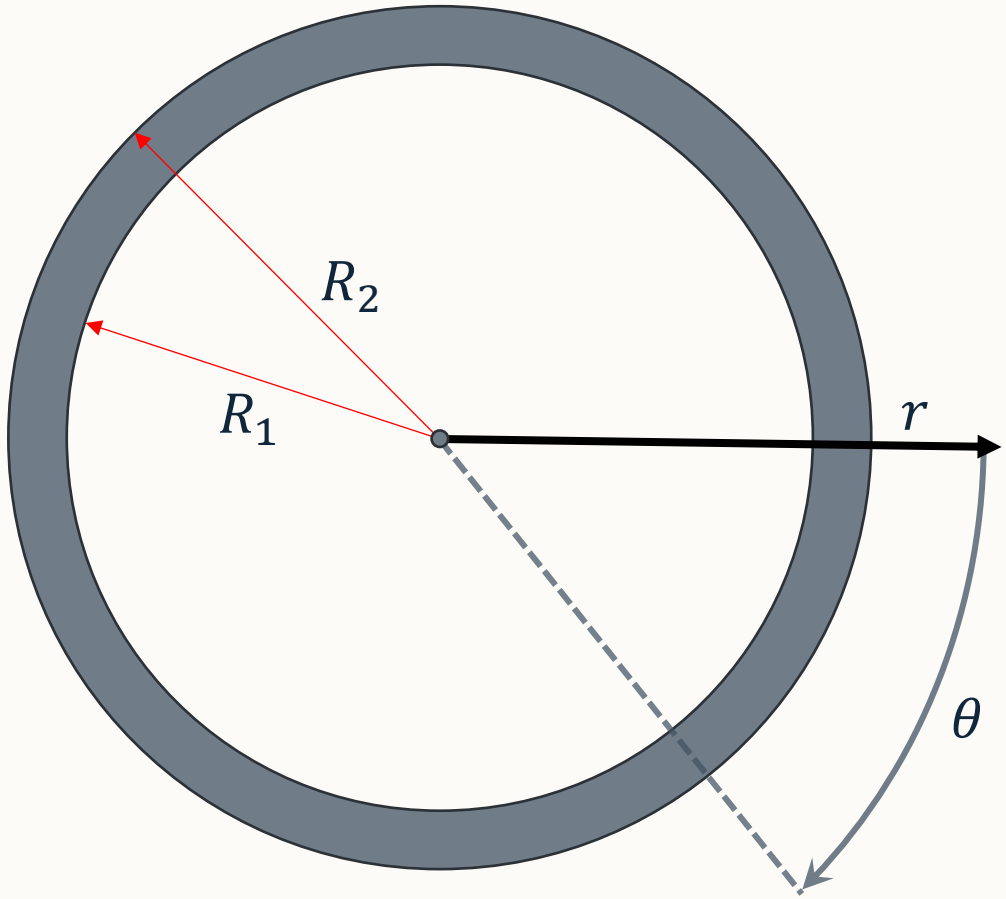

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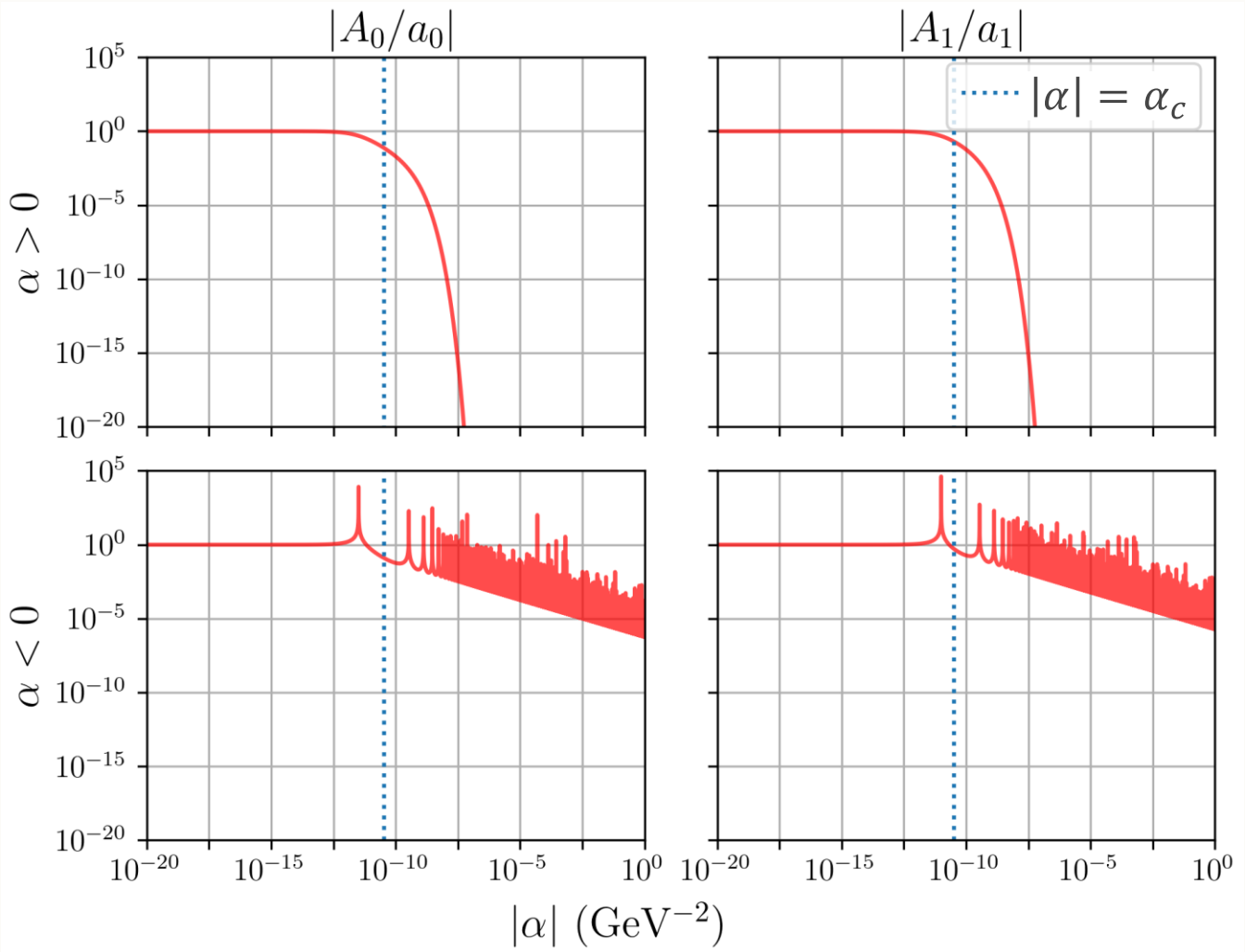

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