Searching for Quadratically Coupled Ultra-Light Dark Matter

Clare Burrage

University of Nottingham

Outline:

Ultra-light dark matter

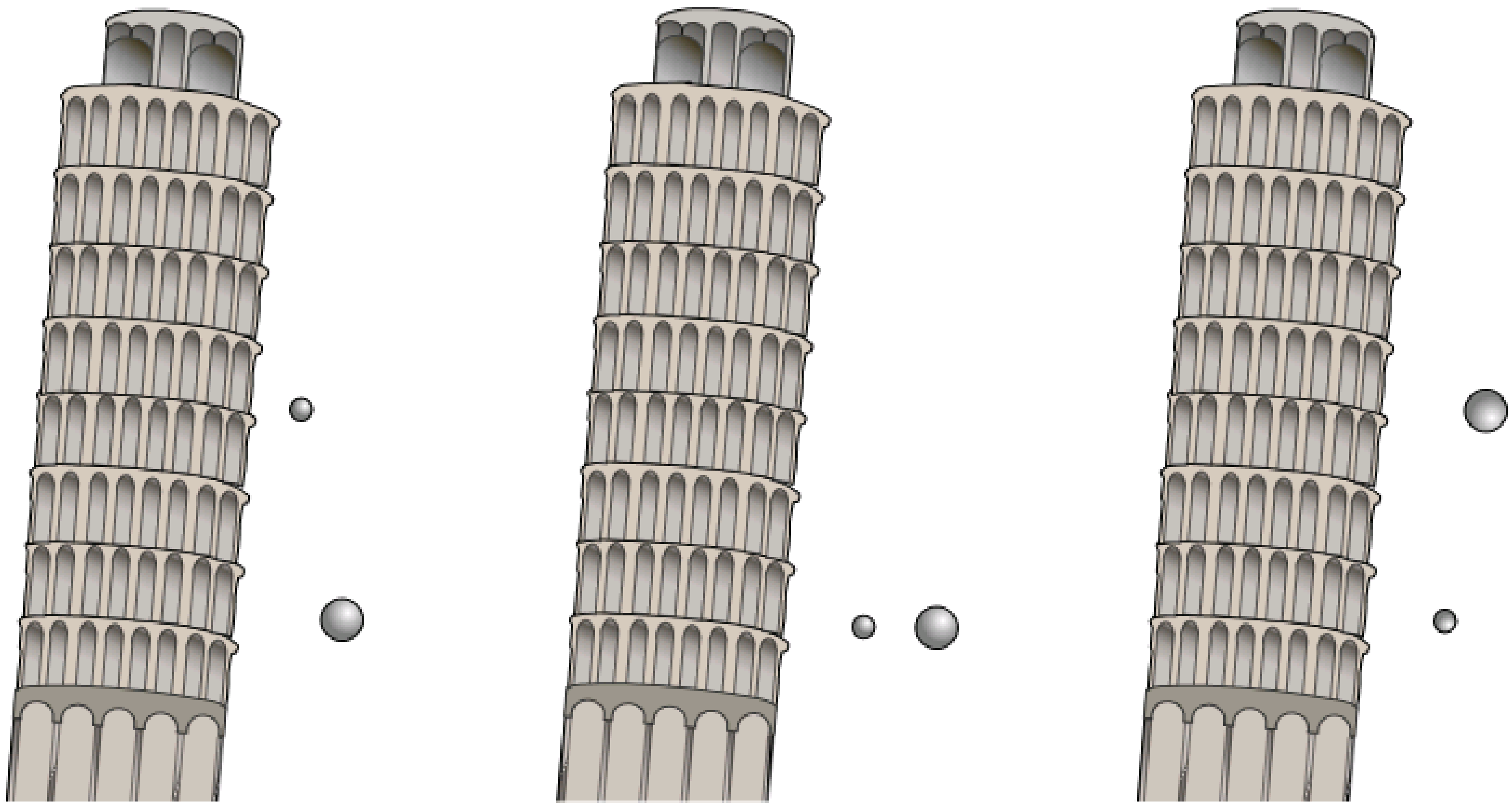
Quadratic couplings to matter

Density dependent masses

Searches and constraints

Outline

Do all objects fall at the same rate?



Old idea | Galileo | Dark Matter fifth force?

Image credit: Theresa Knott

Ultra-Light Scalar Dark Matter

Light and feebly interacting bosons can be dark matter

A scalar field oscillating in a quadratic potential

$$\phi_{\rm homog}(t) = \phi_\infty \cos(mt + \delta)$$

Gives zero pressure and dark matter energy density

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

Preskill, Wise, Wilczek. Phys. Lett.B 120 (1983) 127–132. Abbott, Sikivie. Phys. Lett.B 120 (1983) 133–136. Dine, Fischler, Phys. Lett. B 120 (1983)137–141.
For a review see e.g. Ferreira. Astron. Astrophys. Rev. 29 (2021) 1, 7

Ultra-Light Scalar Dark Matter

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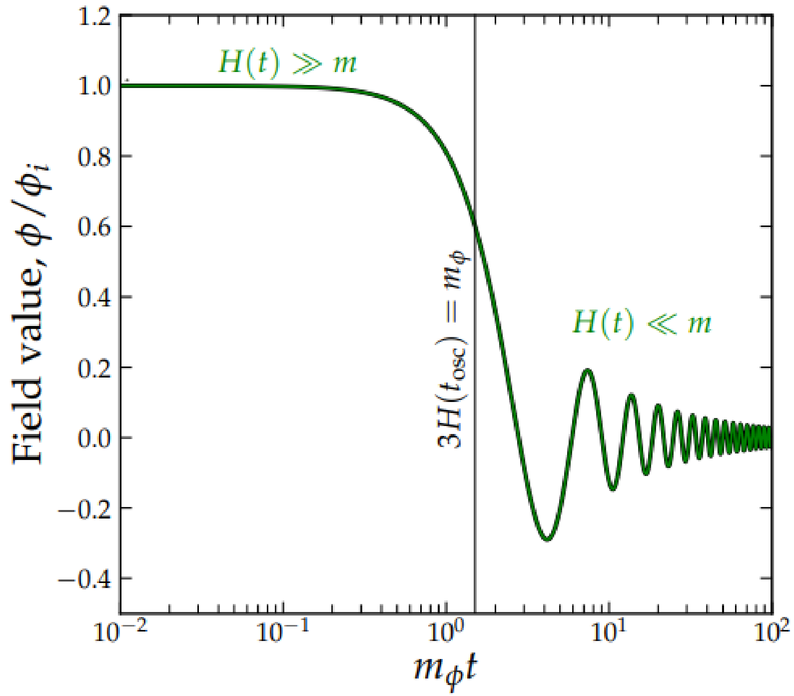

High occupation numbers mean they can be described as classical fields exhibiting a wave-like behaviour

Figure from lecture notes by O'Hare. Arxiv:2403.17697

Ultra-Light Scalar Dark Matter

Quadratic interactions from

e.g. symmetric Higgs portals, axion models

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

Leading to varying fundamental 'constants'

$$\alpha_{EM}(\phi) = \alpha_{EM}\left(1 + d_e\frac{(\kappa\phi)^2}{2}\right)$$

$$m_i(\phi) = m_i\left(1 + d_{m_i}\frac{(\kappa\phi)^2}{2}\right)$$

$$\Lambda_3(\phi) = \Lambda_3\left(1 + d_g\frac{(\kappa\phi)^2}{2}\right)$$

Damour, Donoghue. PRD (2010) 8 084033, CQG (2010) 20 202001,

Ultra-Light Scalar Dark Matter

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Leading to macroscopic couplings to non-relativistic energy density

$$S = \int d^4x \left(\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{1}{2}\rho\alpha\phi^2\right)$$

And a density dependent effective mass

$$\Box\phi = -\left(m^2 + \rho\alpha\right)\phi$$

Damour, Donoghue. PRD (2010) 8 084033, CQG (2010) 20 202001,

Ultra-Light Scalar Dark Matter

Scalar equation of motion

$$\Box\phi = -\left(m^2 + \rho\alpha\right)\phi$$

Density dependent effective mass, can lead to short Compton wavelengths

$$\lambda_C = \frac{h}{m_{\rm eff}c} \approx 10^{-5}\left(\frac{\rm GeV^{-2}}{\alpha}\right)^{1/2}\left(\frac{\rm g/cm^3}{\rho}\right)^{1/2}\ {\rm cm}$$

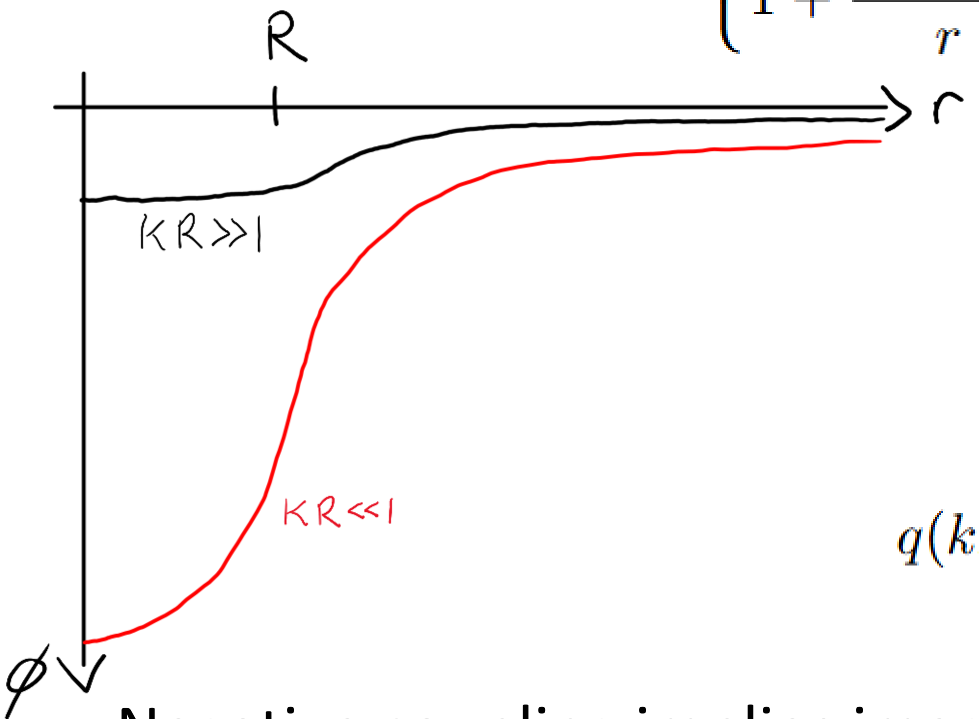
In the presence of a static, spherical dense object

$$\phi = \phi_H(t)\varphi_S(r)$$

$$\nabla^2\varphi_S(r) = \alpha\rho(r)\varphi_S(r)$$

Quadratically Coupled U-L Scalar Dark Matter

$$\varphi_S(r) = \begin{cases} \operatorname{sech}(kR)\dfrac{\sinh(kr)}{kr} & r < R \\ 1 + \dfrac{q(kR)R}{r} & r > R \end{cases}$$



$$k = \sqrt{\rho_S \alpha}$$

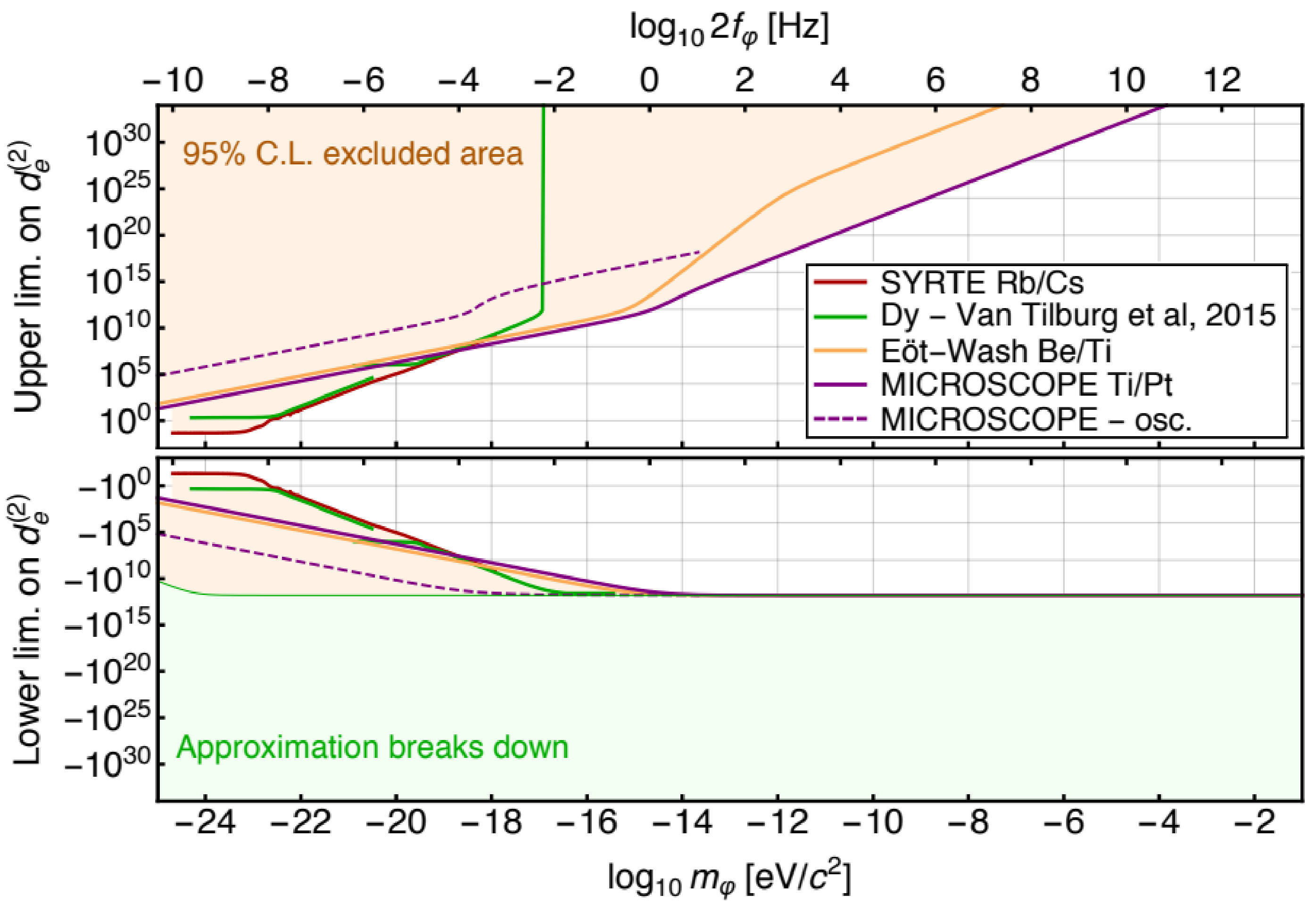
$$q(kR) = \frac{\tanh(kR) - kR}{kR}$$

$$q(kR) \approx \begin{cases} -\frac{1}{3}(kR)^2 & |kR| \ll 1 \\ -1 & |kR| \gg 1 \end{cases}$$

Negative coupling implies imaginary k and divergences for specific sources

Hees, Minazzoli, Savalle, Stadnik, Wolf. Phys. Rev. D 98 no. 6, (2018)064051
CB, Elder, Garcia del Castillo, Jaeckel. Phys. Rev. D 111 (2025) 10, 103526

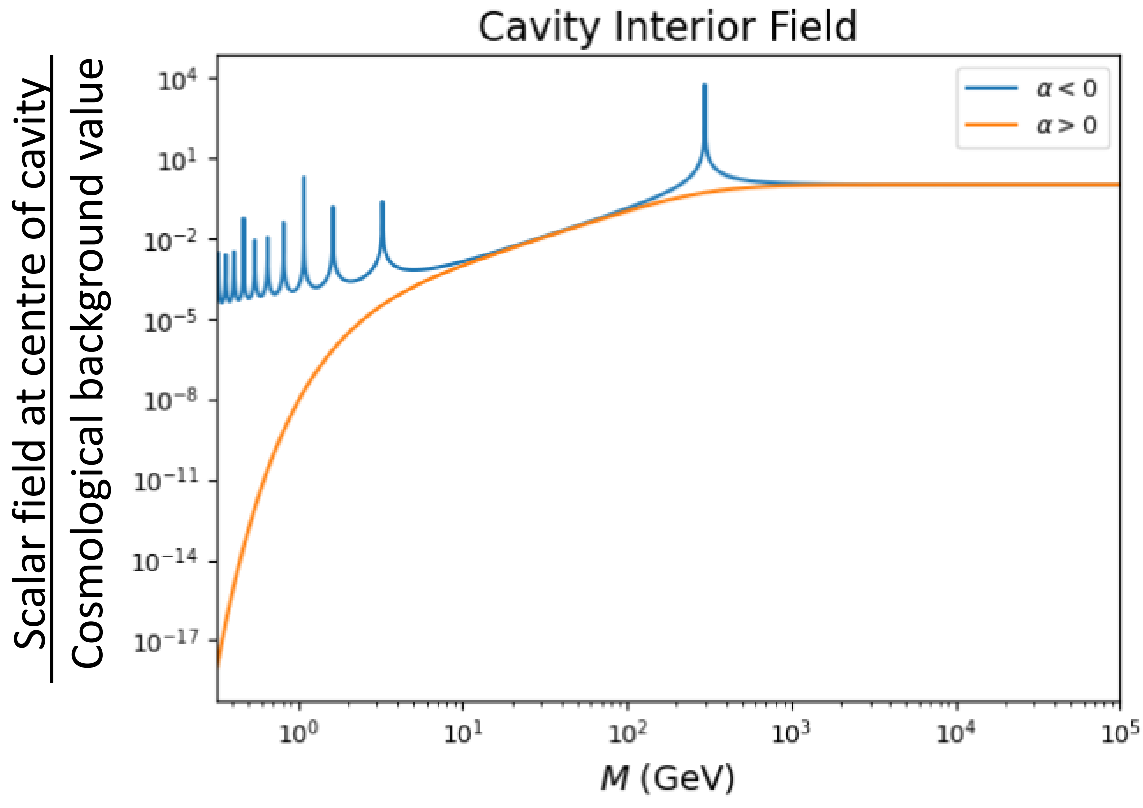
Ultra-Light Scalar Dark Matter - Constraints



Hees, Minazzoli, Savalle, Stadnik, Wolf. Phys. Rev. D 98 no. 6, (2018) 064051
Banerjee, Perez, Safronova, Savoray. JHEP 10 (2023) 042

Effects of a Spherical Cavity

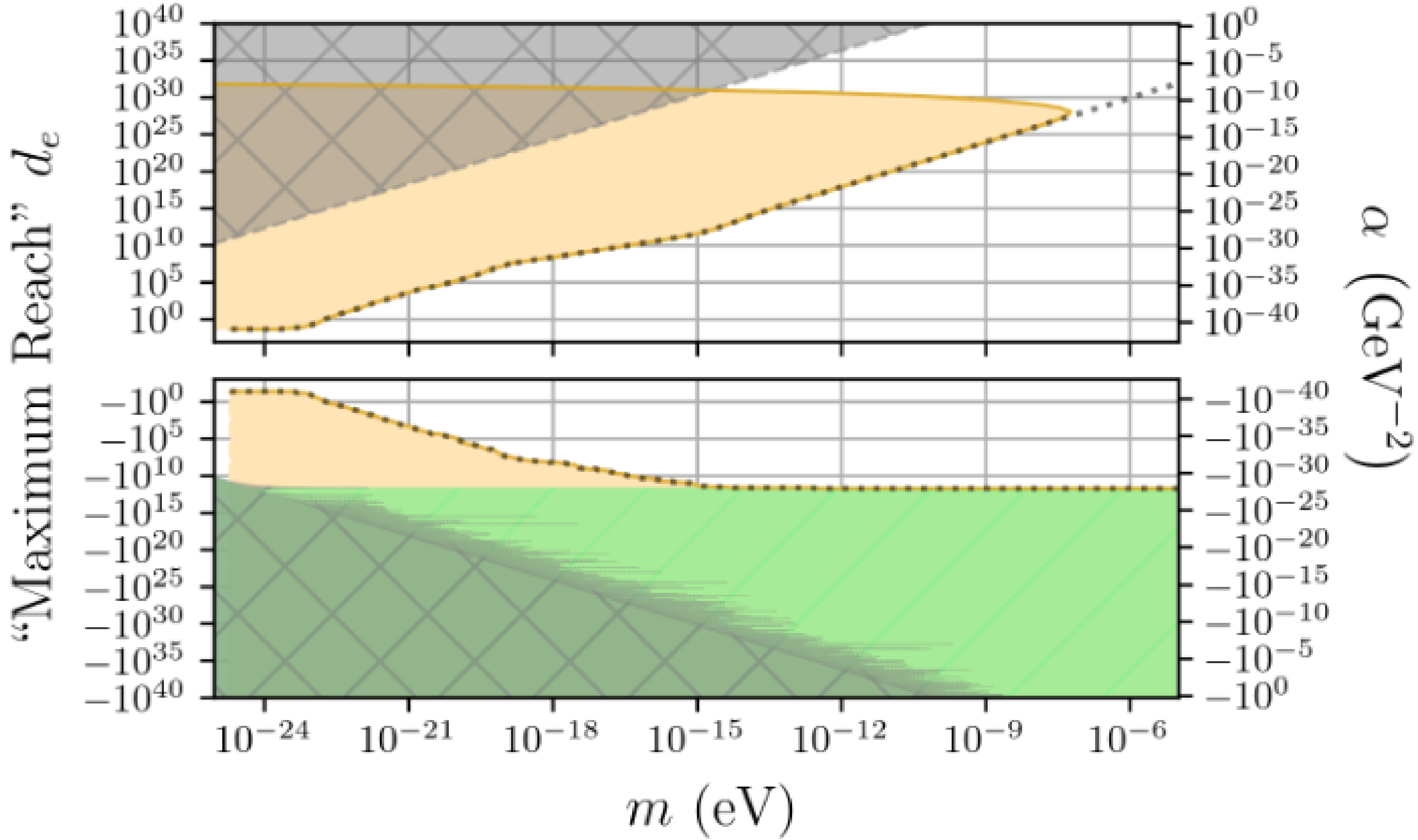
Aluminium cavity. 10 cm internal radius, 1 cm thick walls



CB, MacDonald, Ross, Rybka, Todarello. arXiv:2507.16526

Effects of a Spherical Cavity

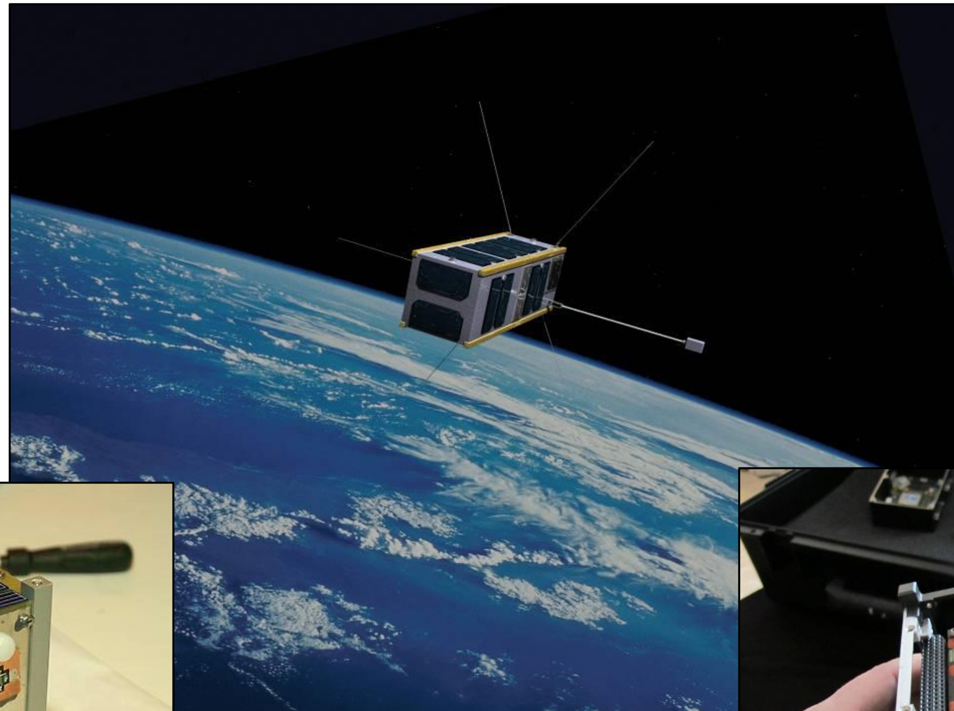
Naive rescaling weakens constraints at strong coupling



CB, MacDonald, Ross, Rybka, Todarello. arXiv:2507.16526

CubeSats

Small, off-the-shelf commercial satellites



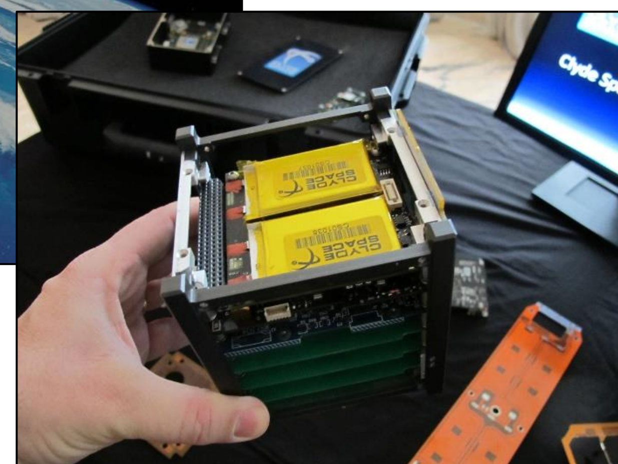
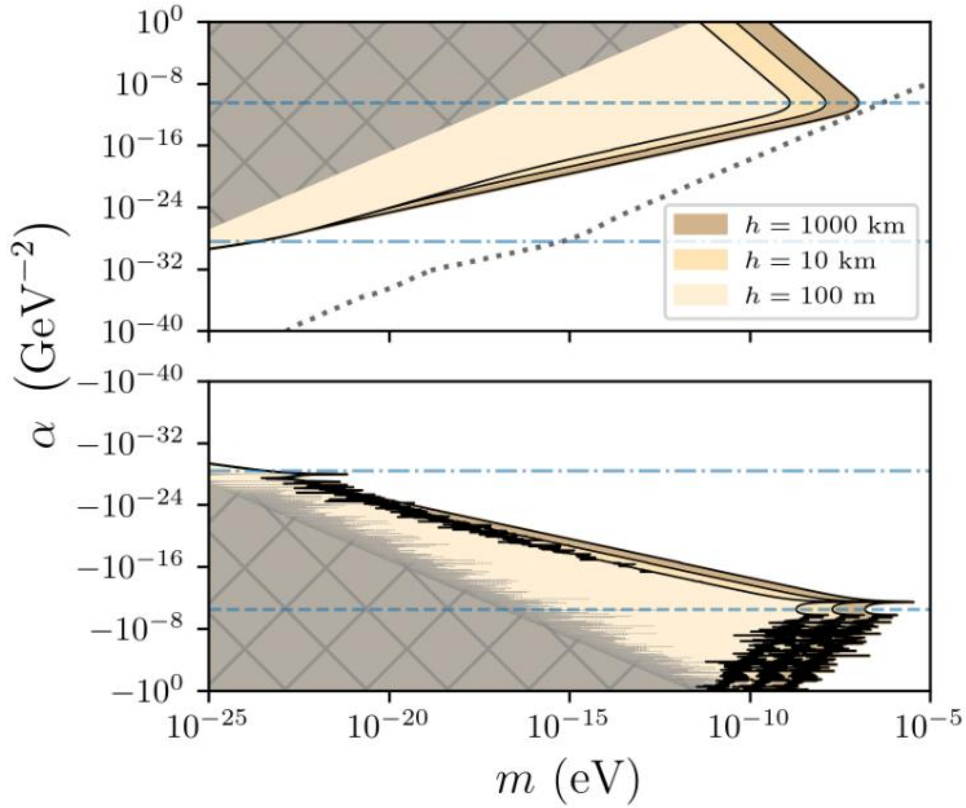


Image credits: Bjørn Pedersen, Svobodat, Clyde Space

Differential Force

Forecast constraints on universal coupling

Two cavities, same mass and external dimension, different internal radii. Sensitivity ~100 fN



CB, MacDonald, Ross, Rybka, Todarello. arXiv:2507.16526

Summary

Ultra-light scalar fields can be Dark Matter

Leading order interactions with Standard Model may be quadratic in the scalar, leading to density dependent effective masses

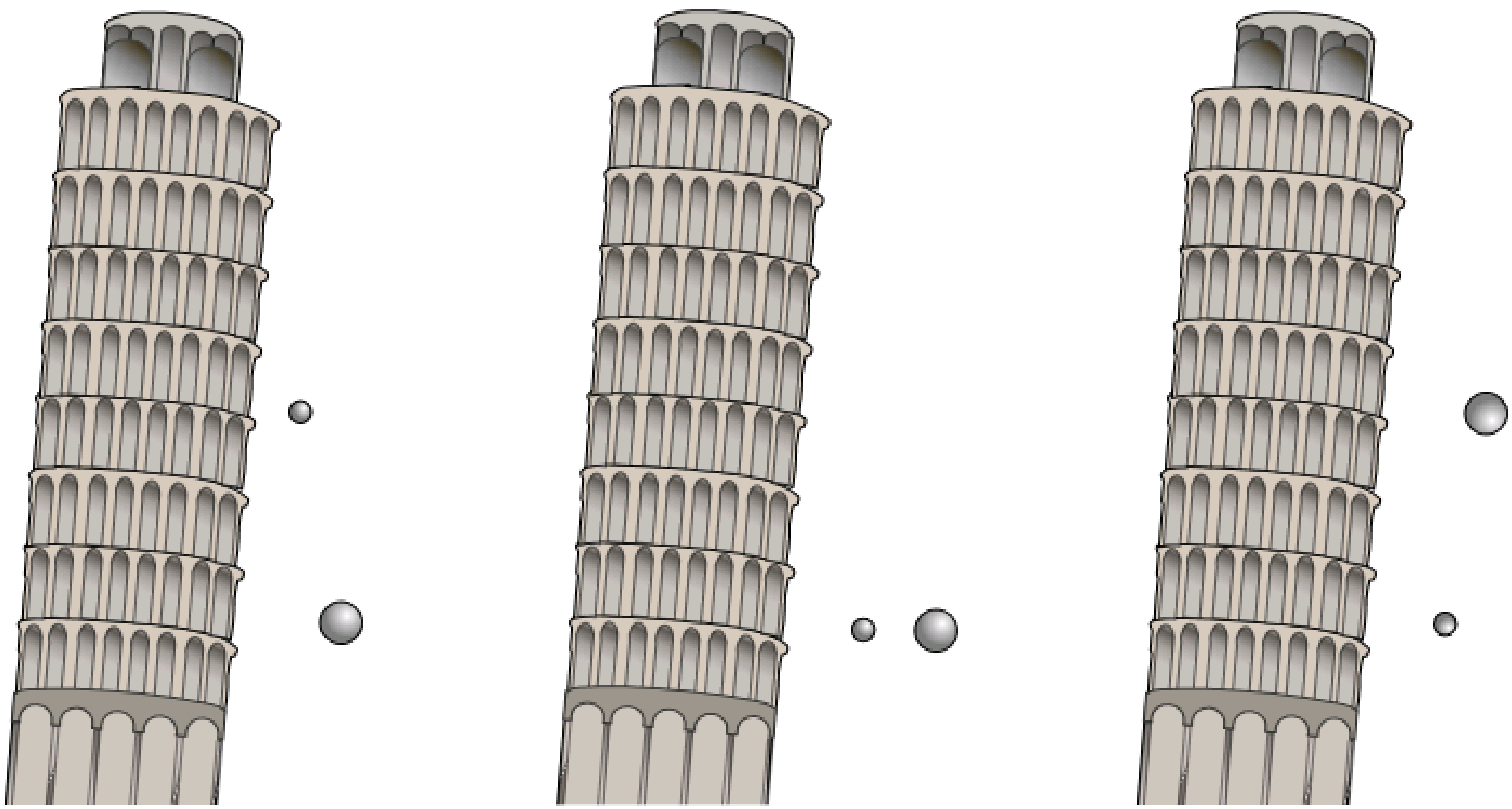
Corresponding long range forces and time varying constants are not seen

Experimental environments may hide these forces from fifth force searches

Can still be detected in suitably designed experiments and observations

Testing the Equivalence Principle

Do compact objects and diffuse objects fall at the same rate?



Old idea | Galileo | Dark Universe fifth force?

Image credit: Theresa Knott