Challenges and opportunities in searching for quadratically coupled dark matter

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Outline:

Scalar dark matter with quadratic couplings

Dark matter production and 'kicks'

Local tests and environmental screening

University of Nottingham
UK | CHINA | MALAYSIA

Ultra-Light Scalar Dark Matter

Light and feebly interacting bosons can be dark matter

A scalar field oscillating in a quadratic potential

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

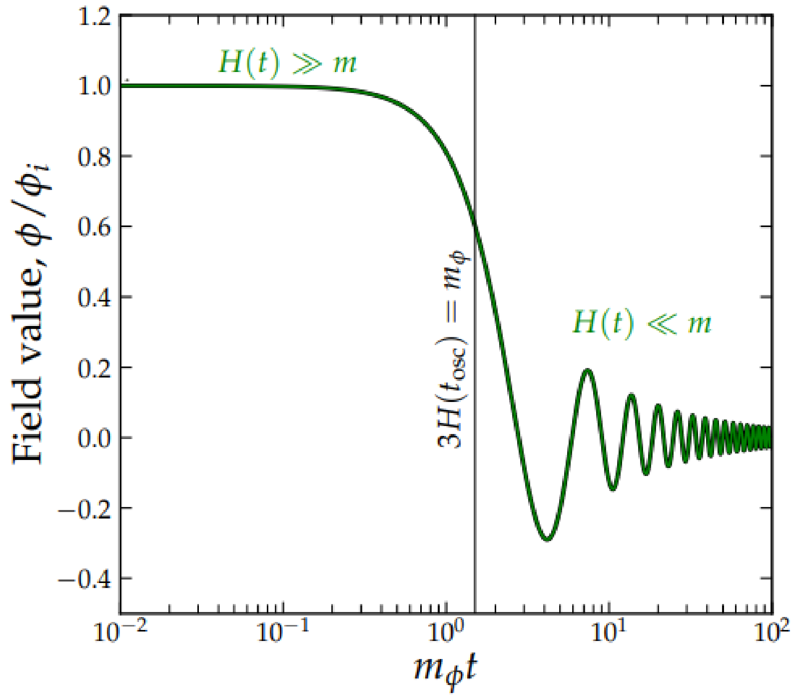
Gives zero pressure and dark matter energy density

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

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

Light and feebly interacting bosons can be dark matter



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

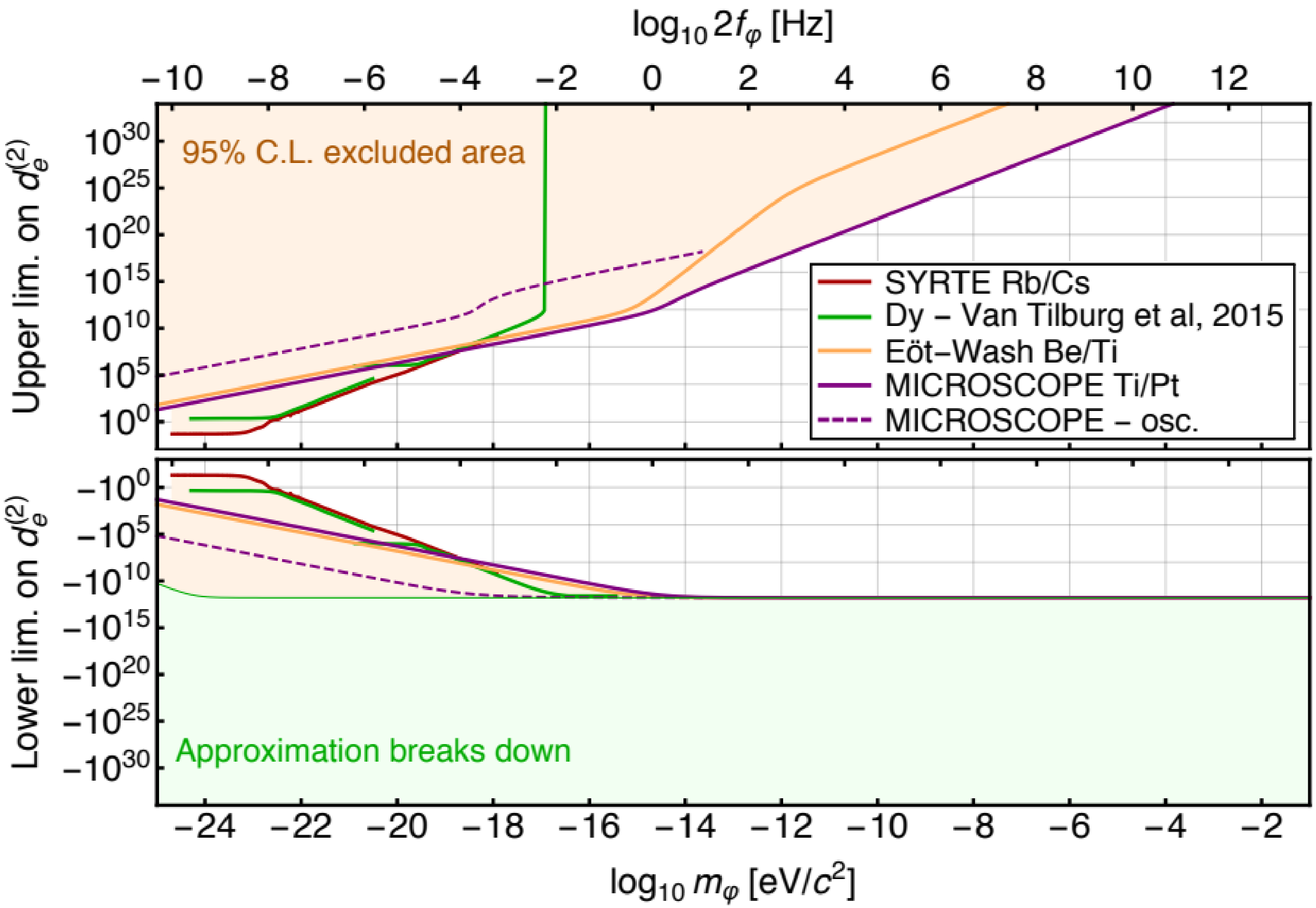
$$\mathcal{L}_{int} = \frac{(\kappa\phi)^2}{2}\left[\frac{d_e}{4}F_{\mu\nu}F^{\mu\nu} - \frac{d_g\beta_3}{2g_3}F^A_{\mu\nu}F^{A\ \mu\nu} - \sum_{i=u,d,e}(d_{m_i} + \gamma_{m_i}d_g)m_i\bar{\psi}_i\psi_i\right]$$

Leading to: Varying fundamental 'constants'

Macroscopic couplings to non-relativistic energy density

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

Ultra-Light Scalar Dark Matter - Constraints



Hees, Minazzoli, Savalle, Stadnik, Wolf. Phys. Rev. D 98 no. 6, (2018) 064051
See also: Banerjee, Perez, Safronova, Savoray. JHEP 10 (2023) 042
Bartnick, Springmann, Stelzl, Weiler. arxiv:2509.25305
Bauer, Chakraborti, Rostagni, JHEP 05 (2025) 023

EVOLUTION DURING RADIATION DOMINATION

Quadratic Couplings in Cosmology

$$\mathcal{L} \supset \frac{1}{2}(\nabla\phi)^2 - V(\phi) + i\bar{\psi}_i \nabla\!\!\!/ \psi_i - m_i(1 + A(\phi))\bar{\psi}_i\psi_i$$

Homogeneous cosmological equation of motion for the scalar:

$$\begin{aligned}\ddot{\phi} + 3H\dot{\phi} &= -V_{,\phi}(\phi) + A_{,\phi}(\phi) T^{\mu}_{\mu_i}, \\ &\approx -V_{,\phi}(\phi) - A_{,\phi}(\phi)\rho_R \Sigma_i\end{aligned}$$

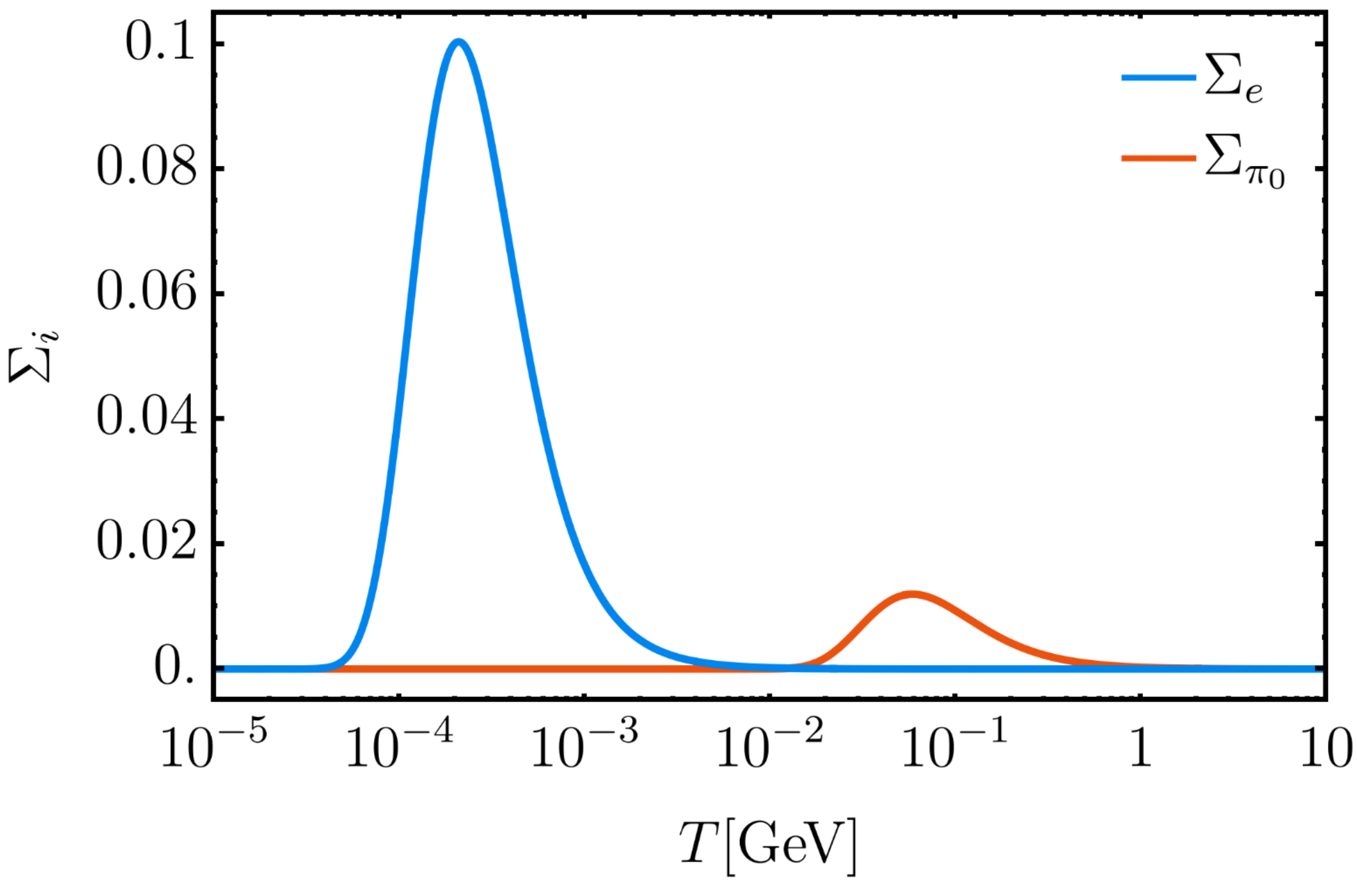
where

$$\Sigma_i = (\rho_i - 3P_i)/\rho_R$$

CB, Sevillano Muñoz. Phys.Rev.D 114 (2026) 4, 043541

Kicking function

$$\Sigma_i(T) = \frac{15}{\pi^4}\frac{g_i}{g_*(T)}\left(\frac{m_i^2}{T^2}\right)\int_{m_i/T}^{\infty}\frac{\sqrt{u^2-(m_i/T)^2}}{e^u \pm 1}\mathrm{d}u,$$



CB, Sevillano Muñoz. Phys.Rev.D 114 (2026) 4, 043541

Effects of the 'Kick'

Assuming quadratic coupling

$$A(\phi) = \frac{\beta}{2M_{\rm Pl}^2}\phi^2 + \cdots$$

and that the scalar energy density is subdominant

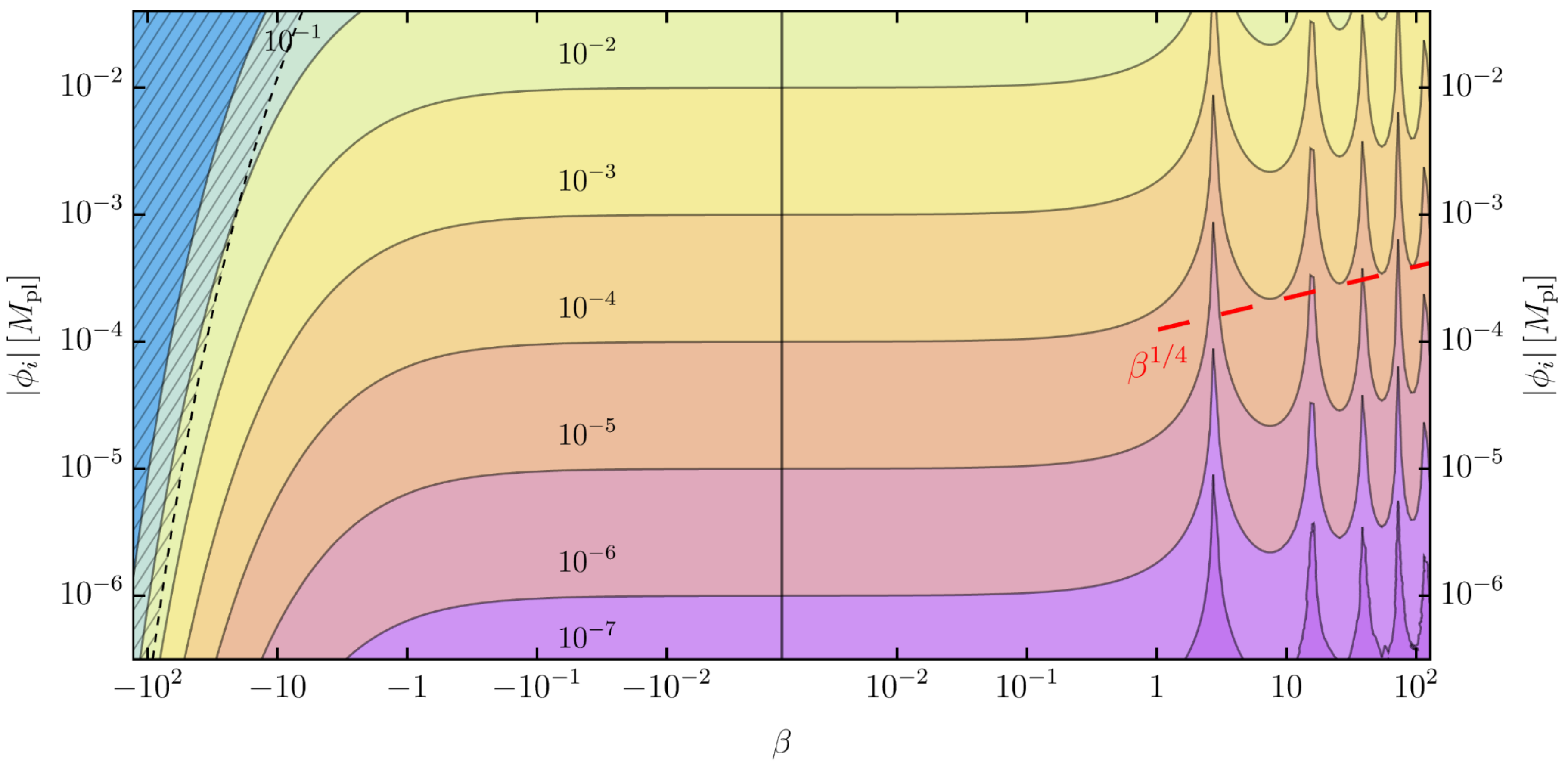
$$\phi'' + \phi' \approx -\frac{\mu^2\phi}{H^2} - 3\beta\phi\Sigma(T_i)$$

If the kick occurs while the field is frozen

- Field may start to oscillate
- For negative coupling, field could be destabilised

CB, Sevillano Muñoz. Phys.Rev.D 114 (2026) 4, 043541

Effects of the 'Kick'



CB, Sevillano Muñoz. Phys.Rev.D 114 (2026) 4, 043541

Effects of the 'Kick'

Effect on final dark matter density

$$\langle \rho_f \rangle \propto \begin{cases} \beta^{-1/2} & \text{for } \beta \gg 1 \\ \exp\left(-\beta \bar{\Sigma}\right) & \text{for } |\beta| < 1 \\ \exp\left(\sqrt{-\beta \bar{\bar{\Sigma}}}\right) & \text{for } \beta \ll -1, \end{cases}$$

Oscillations cause reduction in dark matter density due to redshifting

- despite injection of potential / kinetic energy

CB, Sevillano Muñoz. Phys.Rev.D 114 (2026) 4, 043541

Dark QCD Axion

Bare axion potential

$$V(a) = -\Lambda^4 \sqrt{1 - \xi \sin^2\left(\frac{a}{2f}\right)},$$

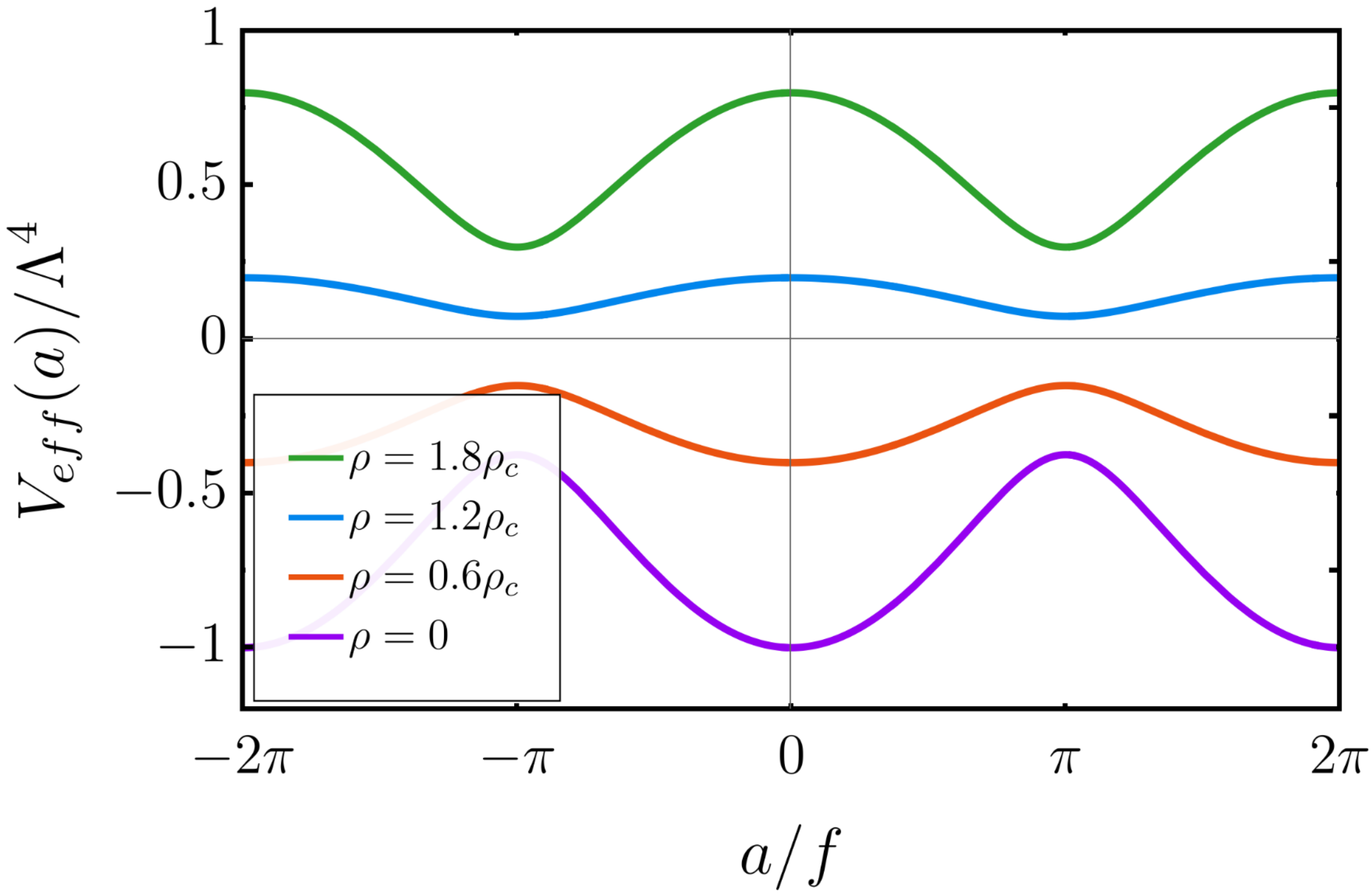
Coupling to density of dark baryons

$$V_b(a) = +2\alpha \sqrt{1 - \xi \sin^2\left(\frac{a}{2f}\right)} T_\mu^{\mu\,(b)}$$

Gives rise to negative coupling strengths

Grilli di Cortona, Hardy, Pardo Vega, Villadoro. JHEP 01 (2016) 034.
Hook, Huang. JHEP 06 (2018) 036. Garani, Redi, Tesi JHEP 12 (2021) 139.
Tsai, McGehee, Murayama, Phys. Rev. Lett. 128 (2022) 17 172001.
Khoury, Lin, Trodden. Phys. Rev. Lett. 135 (2025) 18 181001.

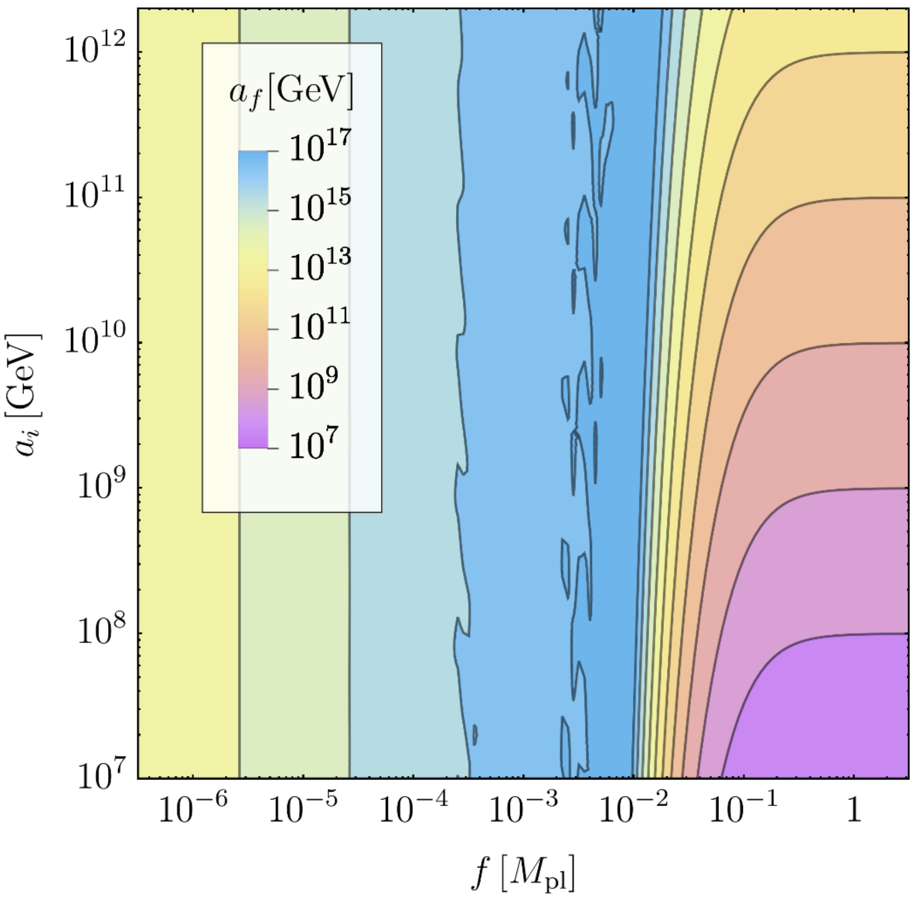
Dark QCD Axion



CB, Sevillano Muñoz. Phys.Rev.D 114 (2026) 4, 043541

Effect of a dark pion kick

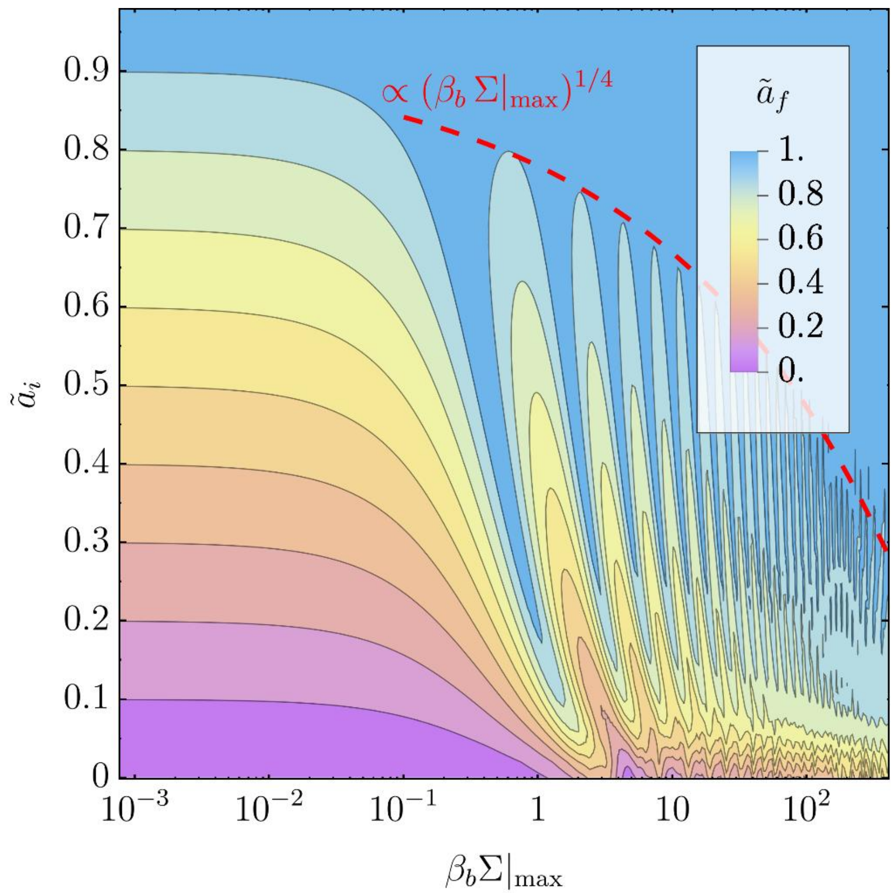
Fixing alpha =1/2



CB, Sevillano Muñoz. Phys.Rev.D 114 (2026) 4, 043541

Effect of a dark pion kick

Allowing coupling to vary and rescaling by the decay constant

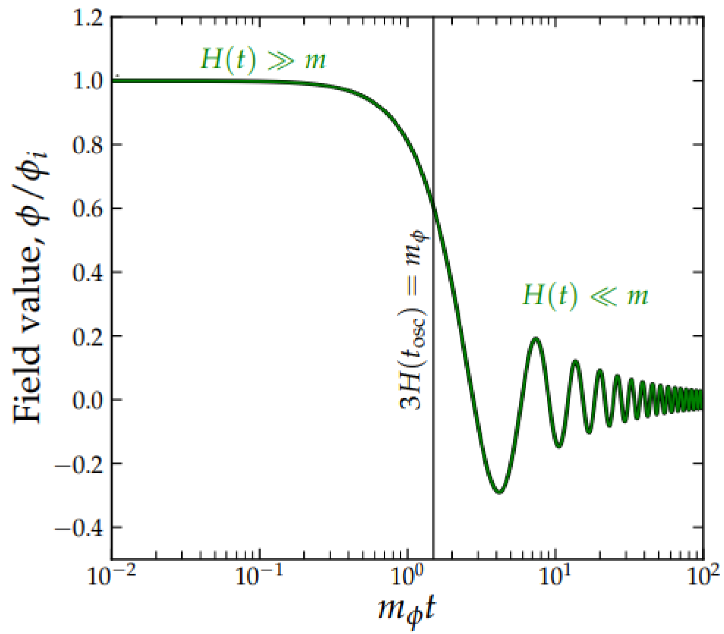


CB, Sevillano Muñoz. Phys.Rev.D 114 (2026) 4, 043541

SEARCHING FOR QUADRATICALLY COUPLED ULDM

Searching for ULDM

Homogeneous background evolution



Can we sense the time evolution of the background field?

Can we see scalar mediated forces?

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

TIME VARIATION

Atomic Clocks

Interactions with matter

$$\mathcal{L} = (\kappa\phi)^n \left(d_\gamma^{(n)} \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - d_{m_e}^{(n)} m_e \bar{\psi}_e \psi_e \right)$$

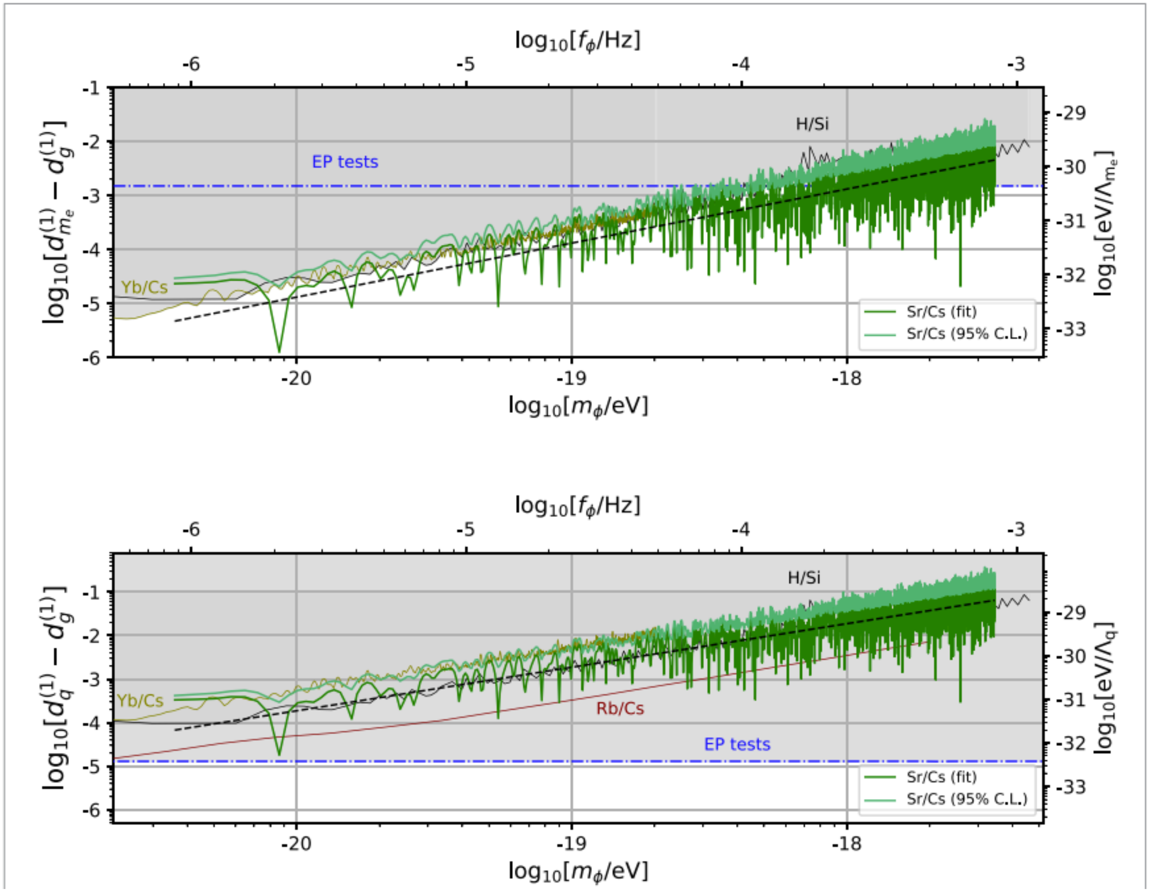
Lead to variations in fundamental constants

$$\frac{\delta\alpha}{\alpha} \equiv d_\gamma^{(n)} (\kappa\phi)^n \qquad \frac{\delta m_f}{m_f} \equiv d_{m_f}^{(n)} (\kappa\phi)^n \qquad \frac{\delta\Lambda_{\mathrm{QCD}}}{\Lambda_{\mathrm{QCD}}} \equiv d_g^{(n)} (\kappa\phi)^n$$

Sherrill et al, New J. Phys. 25 093012 (2023)

Atomic Clocks – Constraints on ULDM

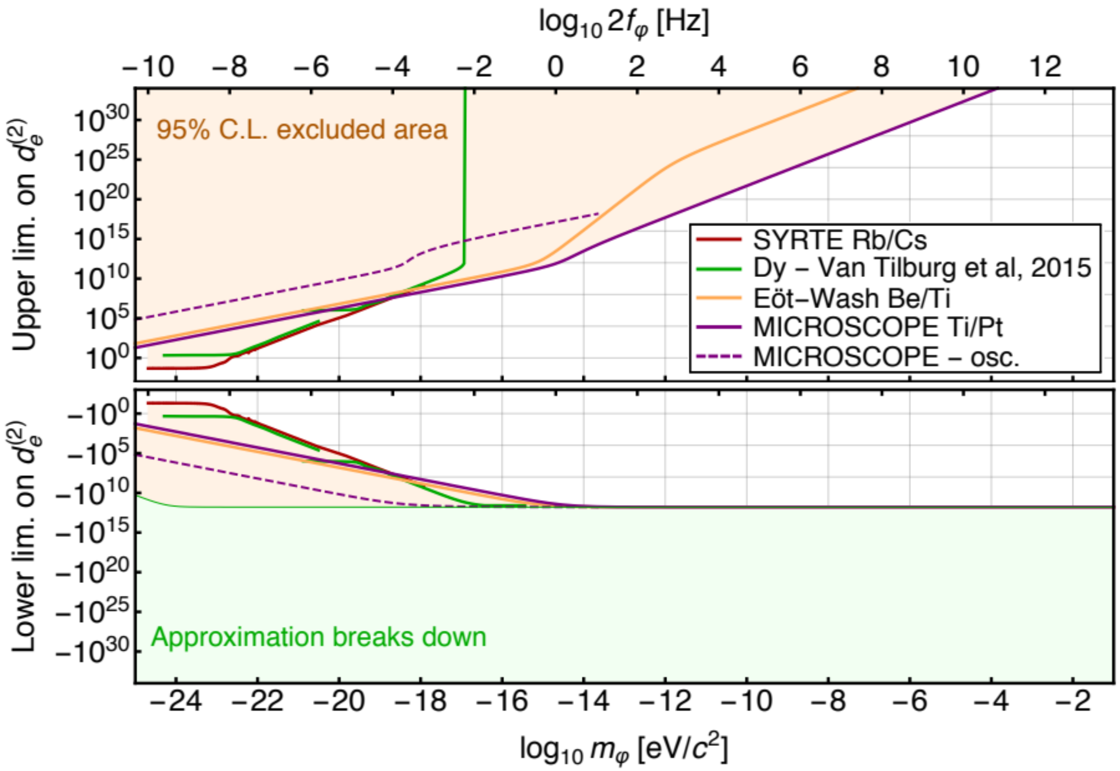
$$\phi_{\text{homog}}(t) = \phi_\infty \cos(mt + \delta)$$



Sherrill et al, New J. Phys. 25 093012 (2023)

Ultra-Light Scalar Dark Matter - Constraints

Assuming cosmological time-variation translates to local time-variation, and quadratic couplings to matter



Hees, Minazzoli, Savalle, Stadnik, Wolf. Phys. Rev. D 98 no. 6, (2018) 064051

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Bartnick, Springmann, Stelzl, Weiler. arxiv:2509.25305

Bauer, Chakraborti, Rostagni, JHEP 05 (2025) 023

FIFTH FORCES

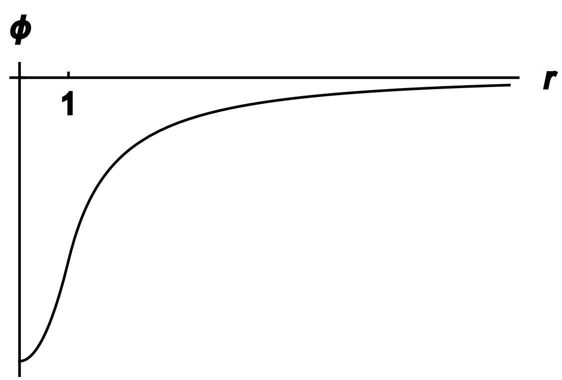
Yukawa Forces

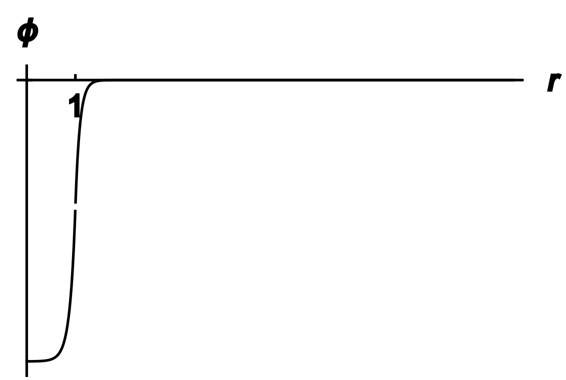
Static Klein-Gordon equation

$$\nabla^2\phi - m^2\phi = \frac{\rho(\vec{x})}{M^2}$$

Spherical object of constant density ρ and radius R

$$\phi(r) = -\frac{\rho}{M^2 m^2}\begin{cases} 1 - \frac{1+Rm}{\cosh mR + \sinh mR}\,\frac{\sinh mr}{mr} & r \le R\ , \\ \frac{e^{m(R-r)}}{mr}\left(\frac{Rm\cosh mR - \sinh mR}{\cosh mR + \sinh mR}\right) & r > R\ . \end{cases}$$

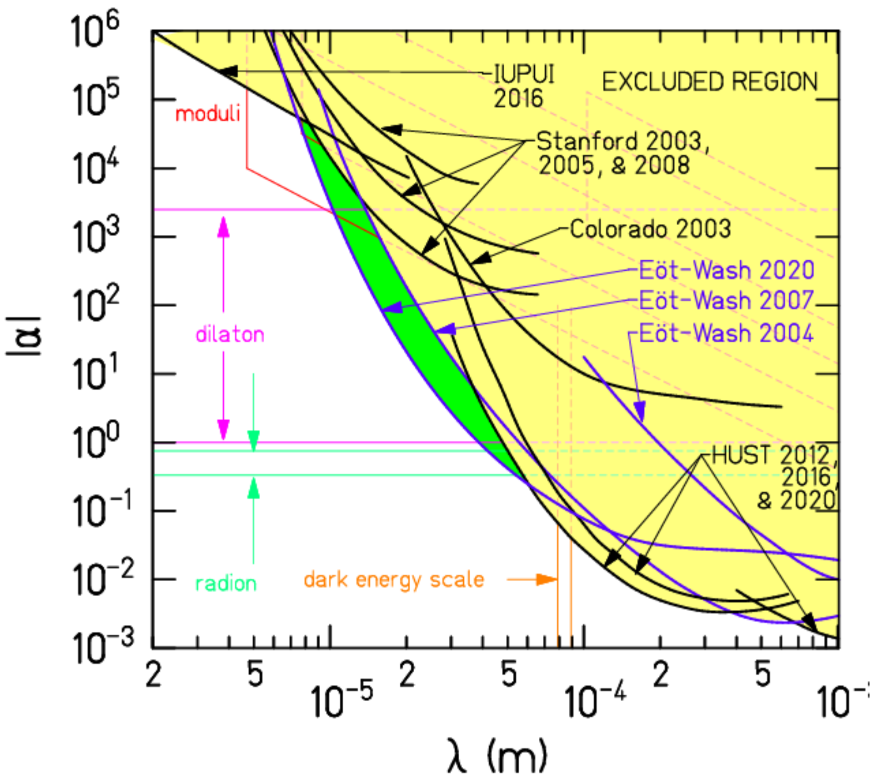


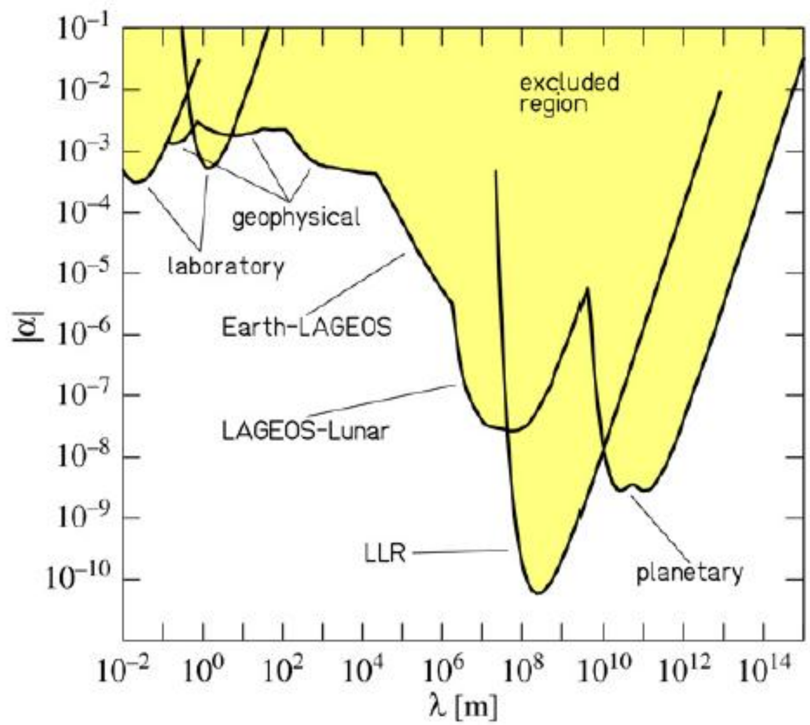


Yukawa Fifth Forces

A long-range Yukawa fifth force is excluded to a high degree of precision in the solar system

$$V(r) = -\frac{G\alpha m_1 m_2}{r} e^{-m_\phi r}$$





Adelberger et al. Prog. Part. Nucl. Phys. 62 (2009) 102. Lee et al. PRL 124 (2020) 10, 101101.

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'

Macroscopic couplings to non-relativistic energy density

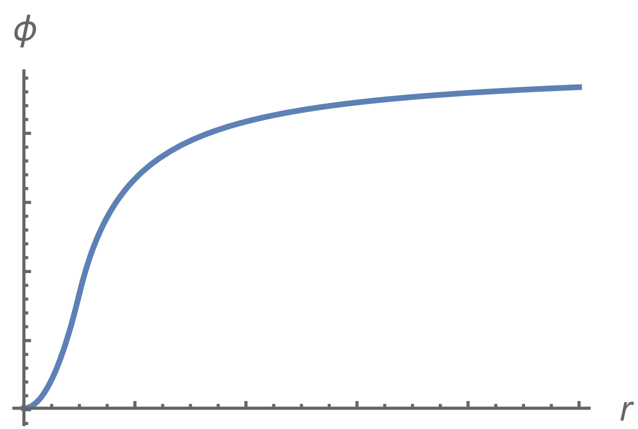
$$S = \int d^4x \left(\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{1}{2}\rho\alpha\phi^2\right)$$

Quadratically Coupled U-L Scalar Dark Matter

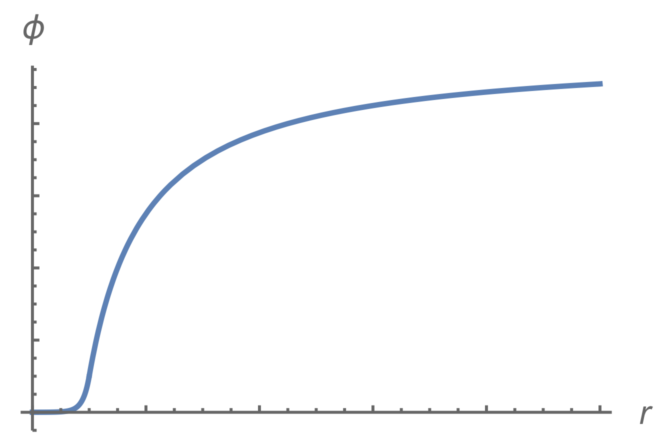
In the presence of a static, spherical dense object

$$\phi_{\rm st}(r,t) = \phi_\infty \cos(mt+\delta) \times \begin{cases} \frac{\operatorname{sech}(\alpha m R)\sinh(\alpha m r)}{(\alpha m r)} & r \leq R \\ 1 - \frac{(\alpha m R) - \tanh(\alpha m R)}{(\alpha m r)} & r > R \end{cases}$$

$$\alpha m R = \frac{\sqrt{\rho} R}{M}$$



Small αmR



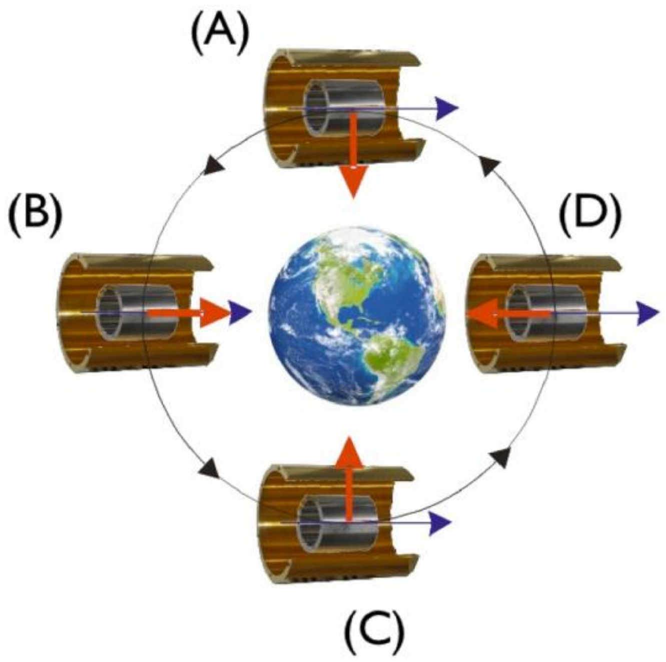
Large αmR

Hees, Minazzoli, Savalle, Stadnik, Wolf. Phys. Rev. D 98 no. 6, (2018) 064051
Bauer, Rostagni. Phys. Rev. Lett. 132 (2024) 10 101802. Bauer, Chakraborti. Phys. Rev. D 112 (2025) 10, 103019. CB, Elder, Garcia del Castillo, Jaeckel. Phys.Rev.D 111 (2025) 10, 103526

MICROSCOPE

Eötvös parameter

$$\eta_{\mathrm{A,B}} = 2\frac{a_{\mathrm{A}} - a_{\mathrm{B}}}{a_{\mathrm{A}} + a_{\mathrm{B}}}$$



$\eta(\mathrm{Ti};\mathrm{Pt}) = [-1.5 \pm 2.3 \pm 1.5] \times 10^{-15}$

Touboul et al. Phys. Rev. Lett. 129, 121102 (2022), Class. Quantum Grav. 39 204009 (2022)

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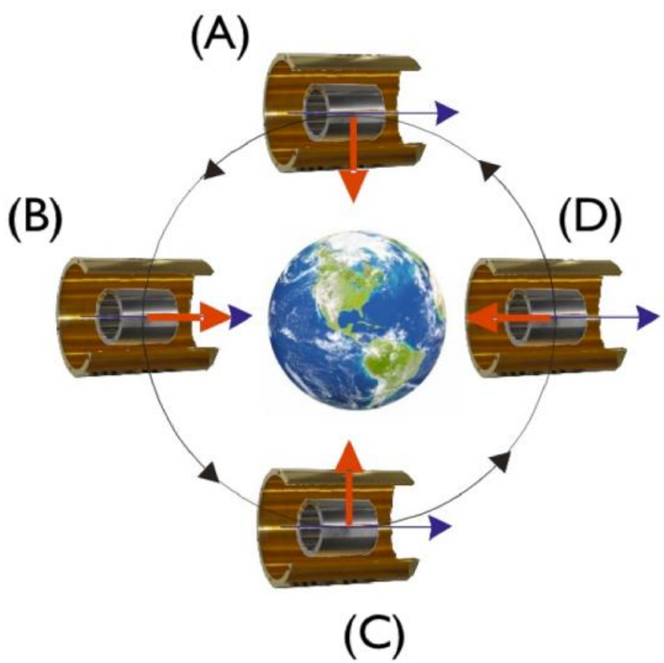
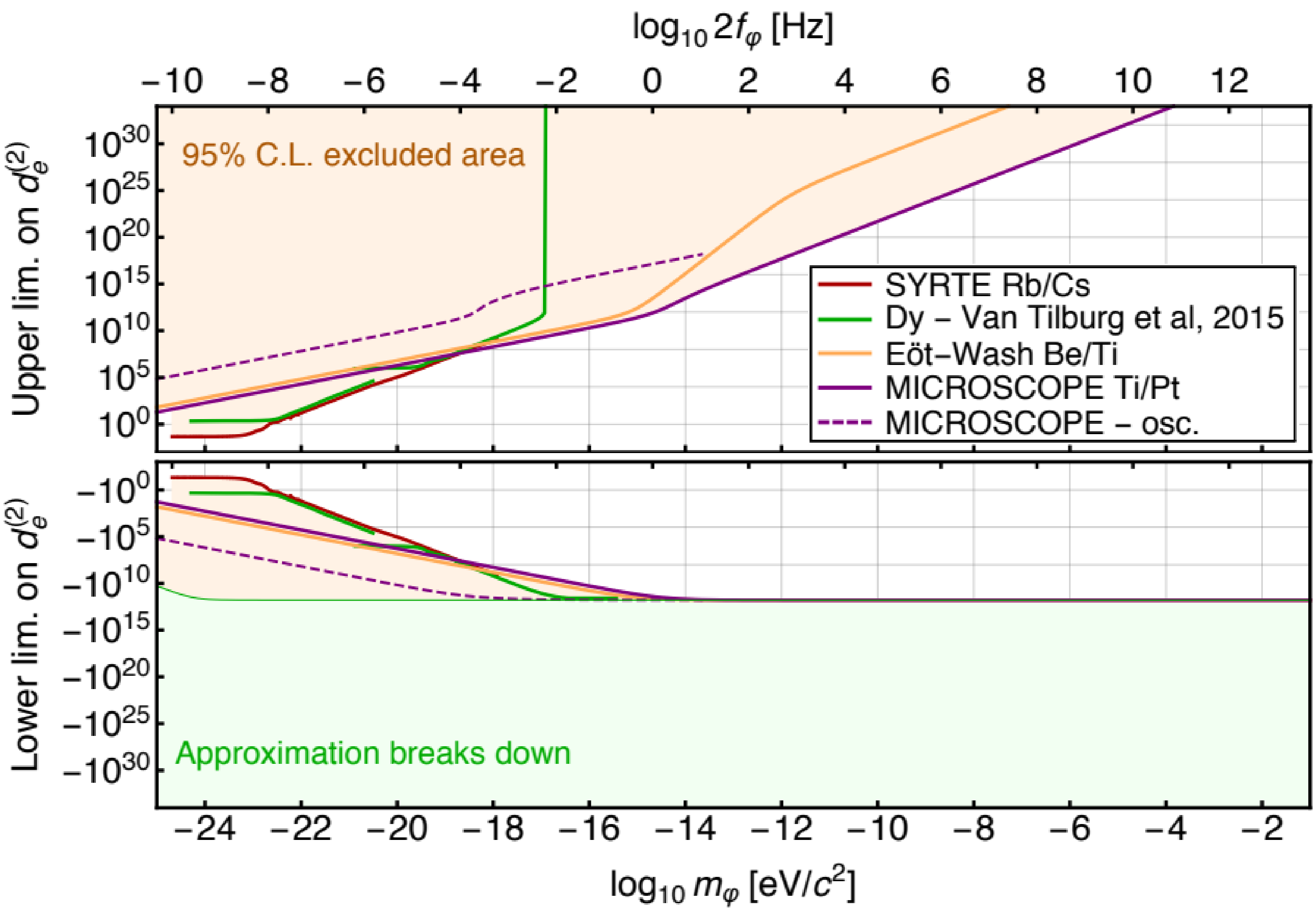


Future improvements possible with STEIN

Touboul et al. Phys. Rev. Lett. 129, 121102 (2022), Class. Quantum Grav. 39 204009 (2022)

Current Constraints



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Ultra-Light Scalar Dark Matter

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

Density dependent effective mass, can lead to short Compton wavelengths

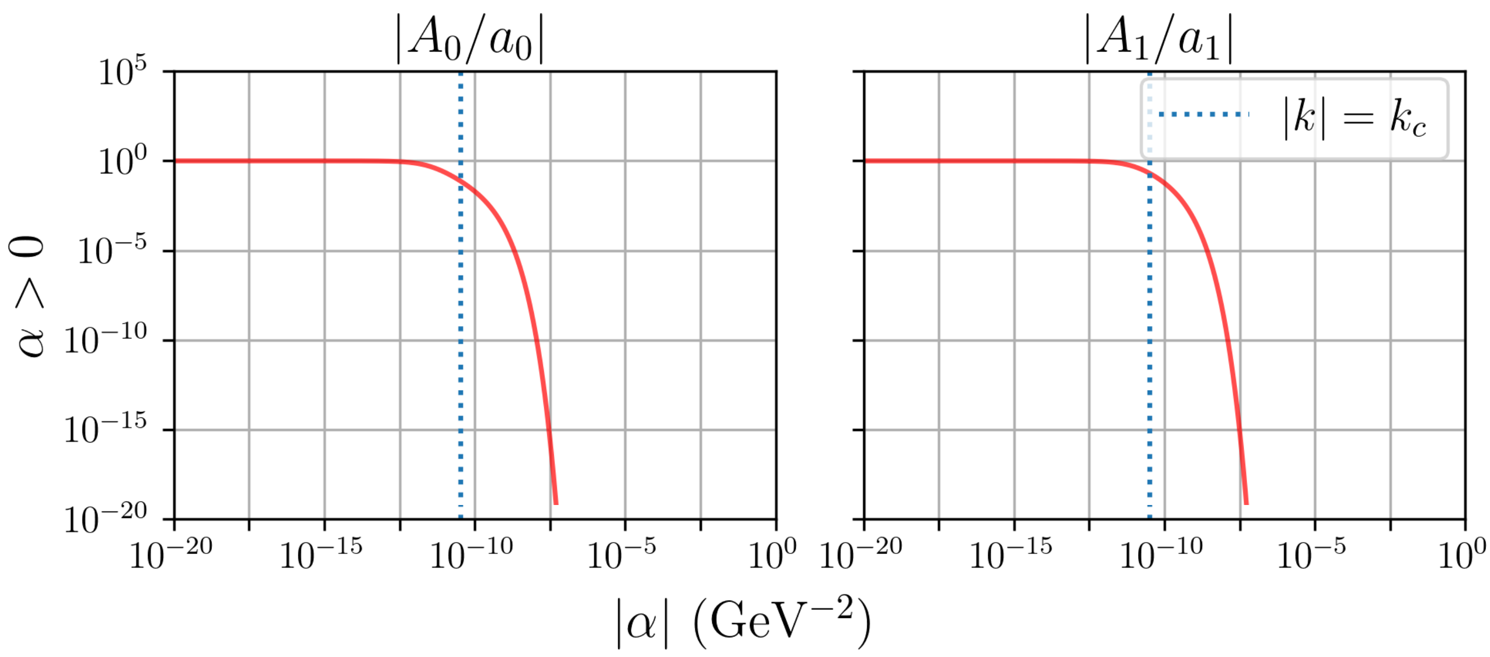
$$\lambda_C = \frac{h}{m_{\text{eff}}c} \approx 10^{-5} \left(\frac{\text{GeV}^{-2}}{\alpha} \right)^{1/2} \left(\frac{\text{g/cm}^3}{\rho} \right)^{1/2} \text{cm}$$

Scalar cavity can suppress the amplitude of dark matter oscillations

CB, MacDonald, Ross, Rybka, Todarello. Phys.Rev.D 113 (2026) 063505

Ultra-Light Scalar Dark Matter

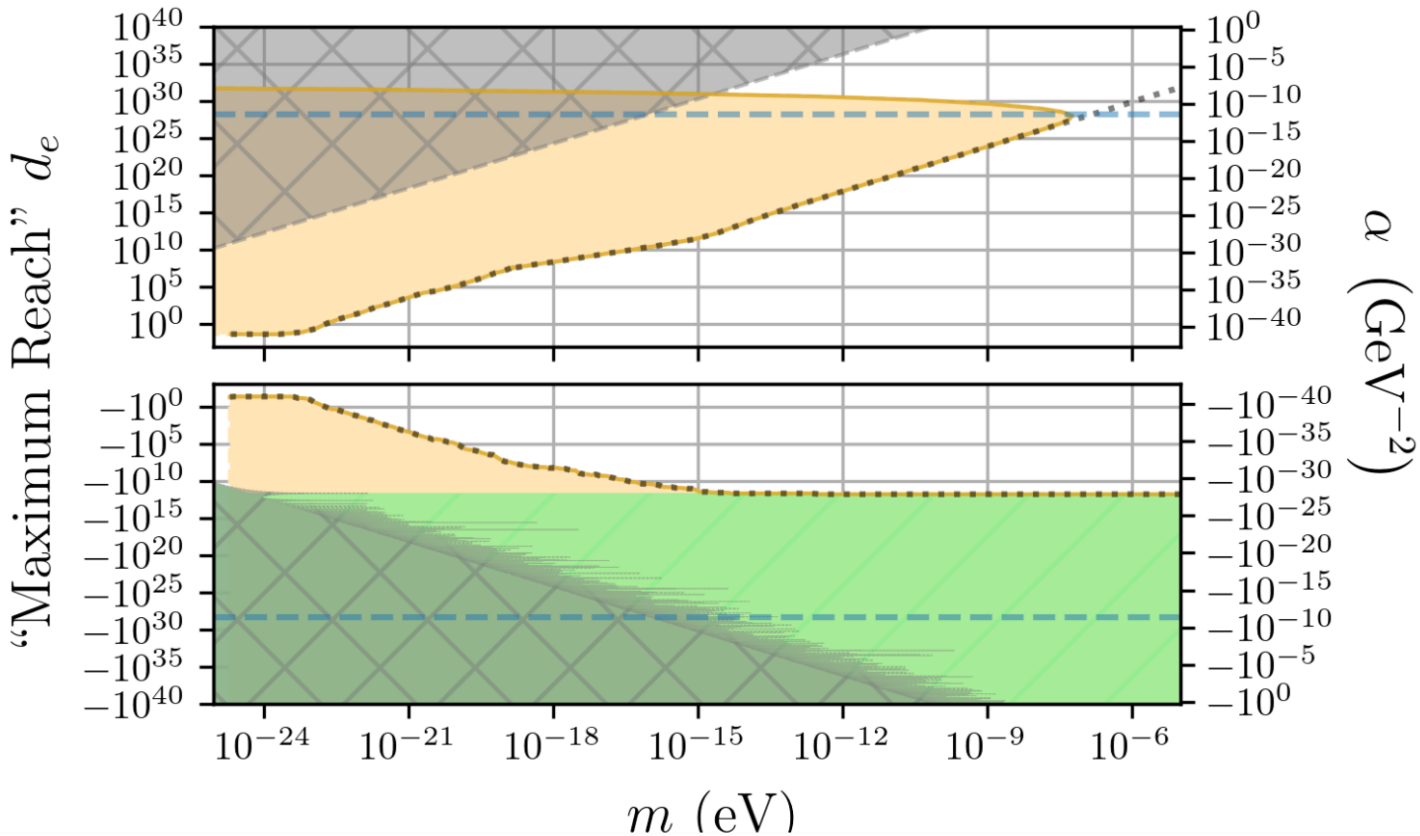
Scalar cavity can suppress the amplitude of dark matter oscillations



CB, MacDonald, Ross, Rybka, Todarello. Phys.Rev.D 113 (2026) 063505

Effects of a Spherical Cavity

Naive rescaling weakens constraints at strong coupling



New opportunities for space-based searches?

CB, MacDonald, Ross, Rybka, Todarello. Phys.Rev.D 113 (2026) 063505

Pericentre precession of LAGEOS II

Laser Geodynamic Satellite II - high-density passive laser reflector in a stable medium Earth orbit

Anomalous pericentre precession constrained to be

$$\Delta\dot{\omega}_\phi \lesssim -181 \text{ mas yr}^{-1}$$

Lucchesi, Peron. Phys. Rev. D, 89(8):082002, (2014). Image credit: NASA

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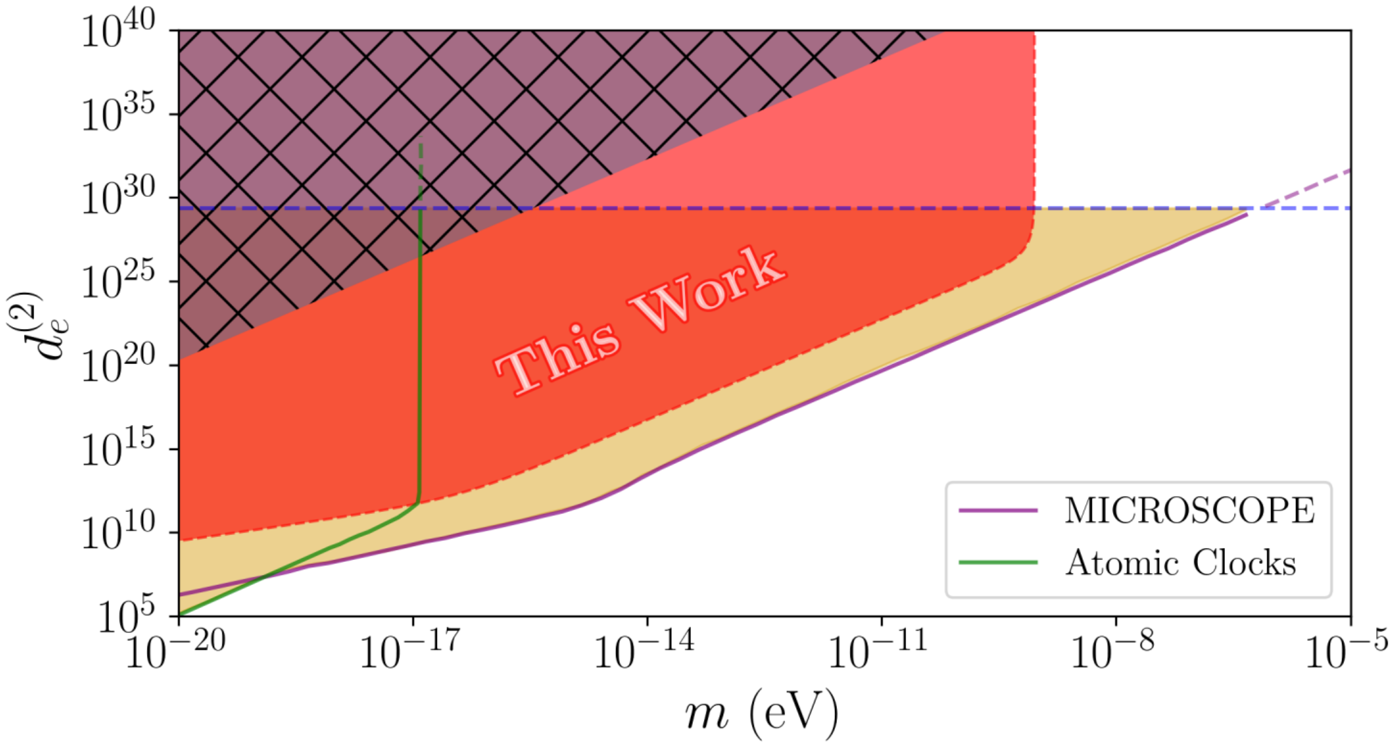


CB, Macdonald, Todarello. arXiv:2605.28248

Approximations

Neglecting the internal structure of the satellite and the Earth

Treating the Earth as a spherical source

Assuming the scalar profile due to the Earth can be linearised over the size of the satellite

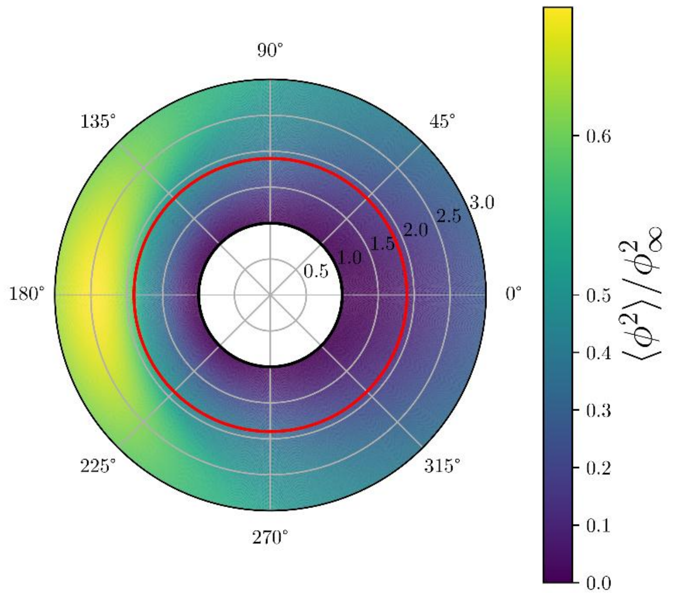
Neglecting the effects of the Sun and the Moon

CB, Macdonald, Todarello. arXiv:2605.28248

Neglecting the dark matter wind?

Modelling the wind as an incoherent ensemble of field modes

$$\phi_w = \phi_\infty \int d^3\vec{p}\sqrt{f(\vec{p};\vec{p}_0)}\ \mathrm{Re}\left[\varphi_w(\vec{r},\vec{p})e^{i\left(\omega(p)t+\chi_{\vec{p}}\right)}\right]$$



CB, Macdonald, Todarello. arXiv:2605.28248.
See also: Gan, Liu, Liu, Luo, Yu. JHEP 02 (2026) 043

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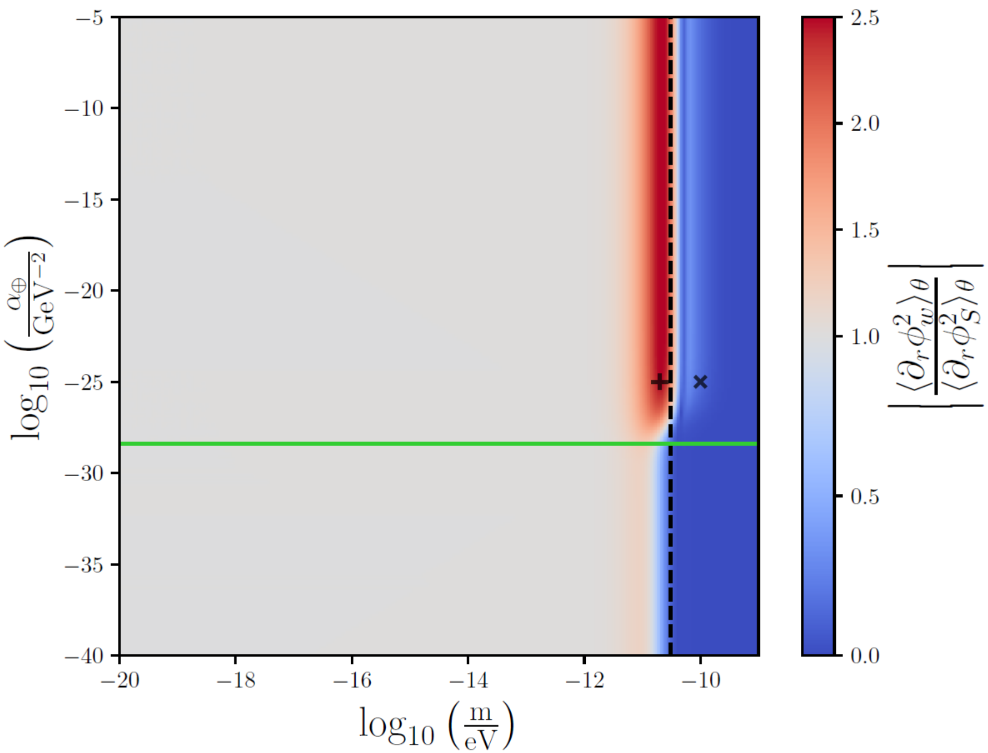

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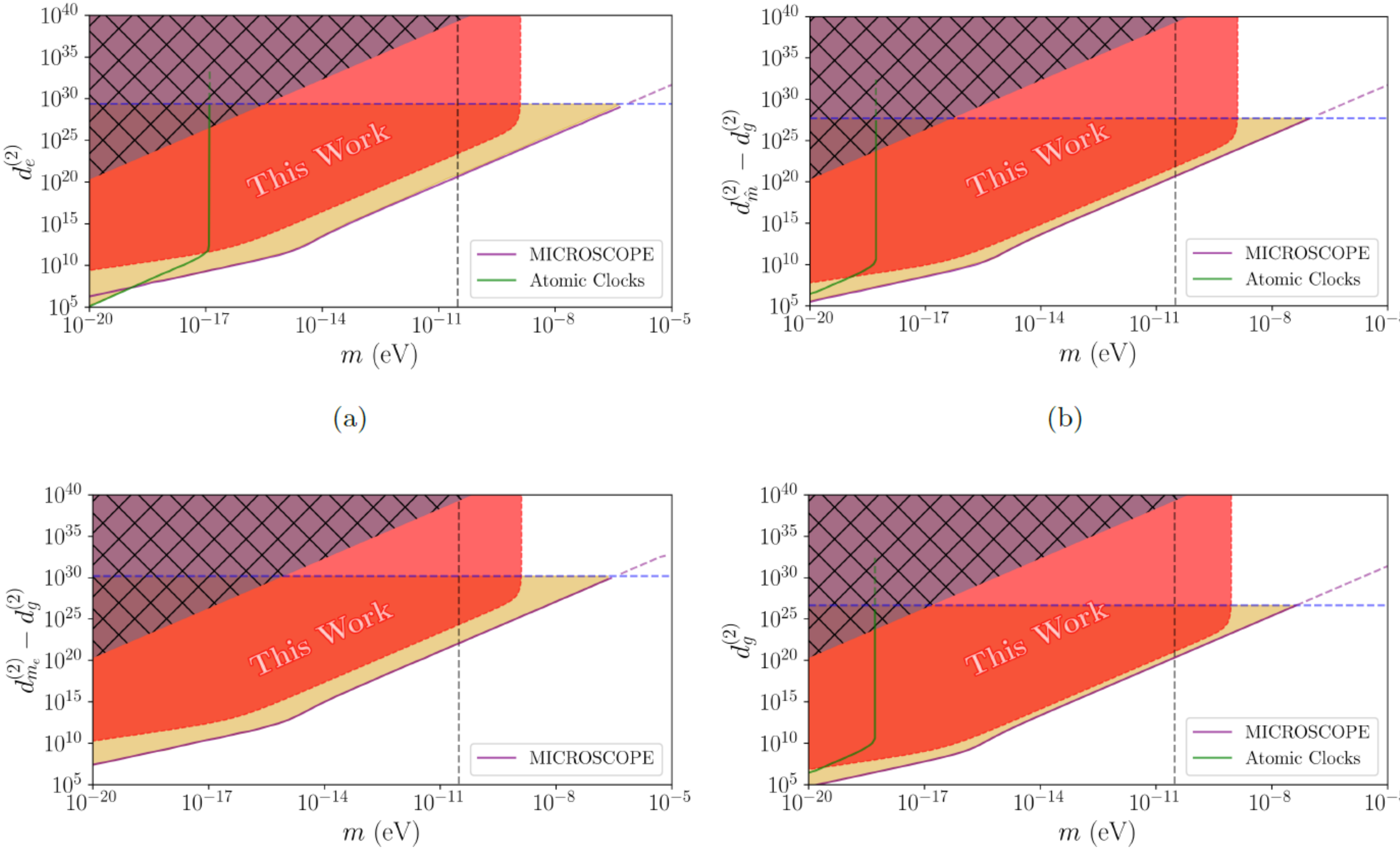
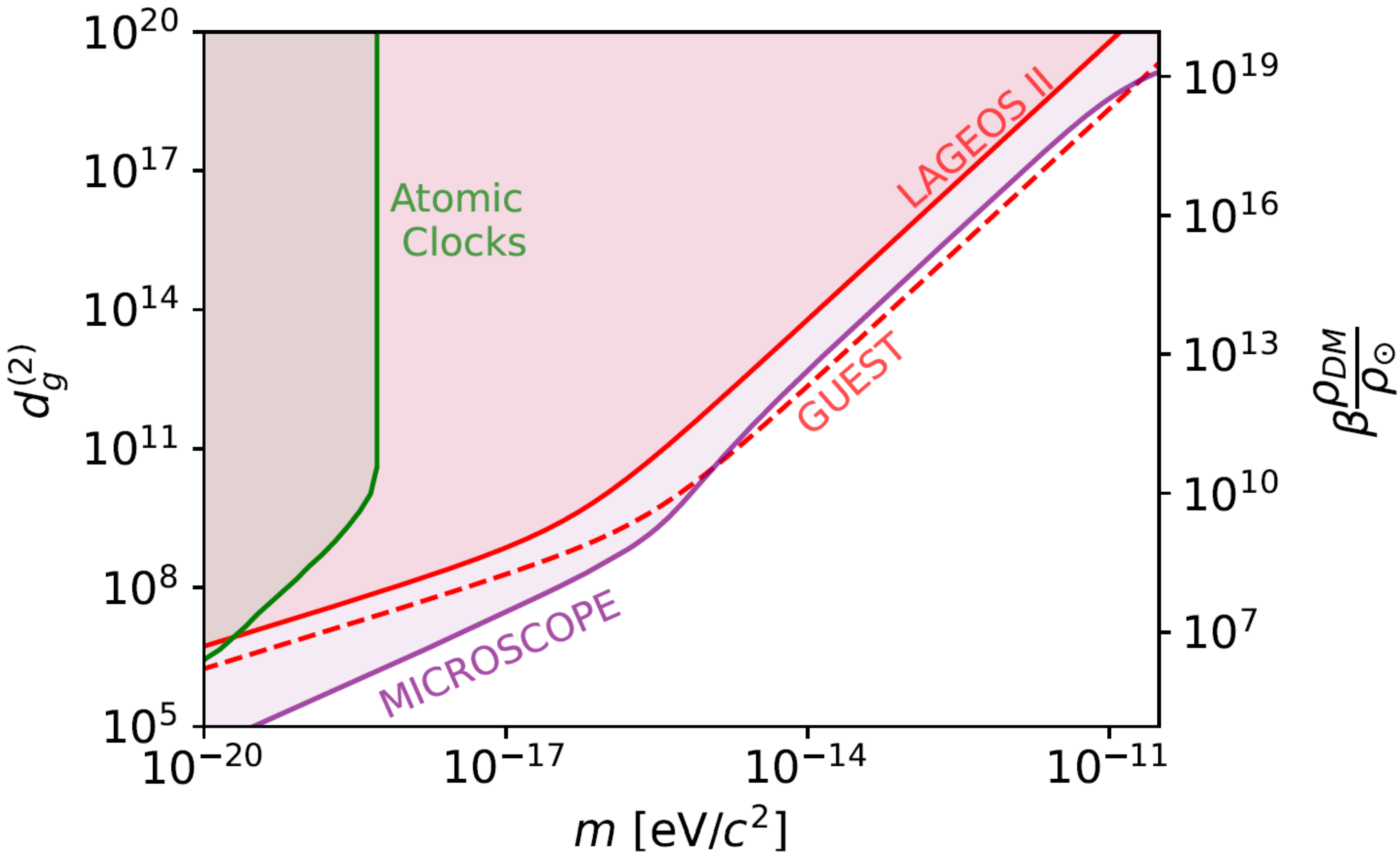


CB, Macdonald, Todarello. arXiv:2605.28248

Future Improvements with GUEST



Blas et al. arXiv:2607.18390

Summary

Ultra-light scalar fields are a possible dark matter candidate

When particle species become non-relativistic in the early universe this kicks the dynamics of the scalar field

Changes expected scalar value and dark matter abundance

Environmental dependence can suppress signatures of strongly coupled models in some experiments

But leave opportunities open for others

Compactness

In GR compactness is defined as: $\mathcal{C} = \frac{GM_*}{R} = \frac{\rho R^2}{6M_{\rm Pl}^2}$

Object	Compactness		
Black hole	~1		
Neutron star	0.6		
White dwarf	4×10^{-4}		
Sun	4×10^{-6}		
Milky Way	3×10^{-6}		
Earth	1×10^{-9}		
Asteroid	1×10^{-11}		
ISS	7×10^{-25}		
Apple	4×10^{-27}		
Silica Microsphere	1×10^{-36}		
Atomic Nucleus	1×10^{-40}		

Compactness

Choosing a different normalisation scale: $\tilde{C} = \frac{\rho R^2}{M^2}$

Object	Compactness	10^{10} GeV	10^{5} GeV
Black hole	~1	3×10^{16}	3×10^{26}
Neutron star	0.6	2×10^{16}	2×10^{26}
White dwarf	4×10^{-4}	1×10^{13}	1×10^{23}
Sun	4×10^{-6}	1×10^{11}	1×10^{21}
Milky Way	3×10^{-6}	9×10^{10}	9×10^{20}
Earth	1×10^{-9}	4×10^{7}	4×10^{17}
Asteroid	1×10^{-11}	4×10^{5}	4×10^{15}
ISS	7×10^{-25}	2×10^{-8}	200
Apple	4×10^{-27}	1×10^{-10}	1
Silica Microsphere	1×10^{-36}	3×10^{-20}	3×10^{-10}
Atomic Nucleus	1×10^{-40}	3×10^{-24}	3×10^{-14}