Searching for Ultralight Scalar Dark Matter with Muonium and Muonic Atoms

Yevgeny Stadnik

Australian Research Council DECRA Fellow

University of Sydney, Australia

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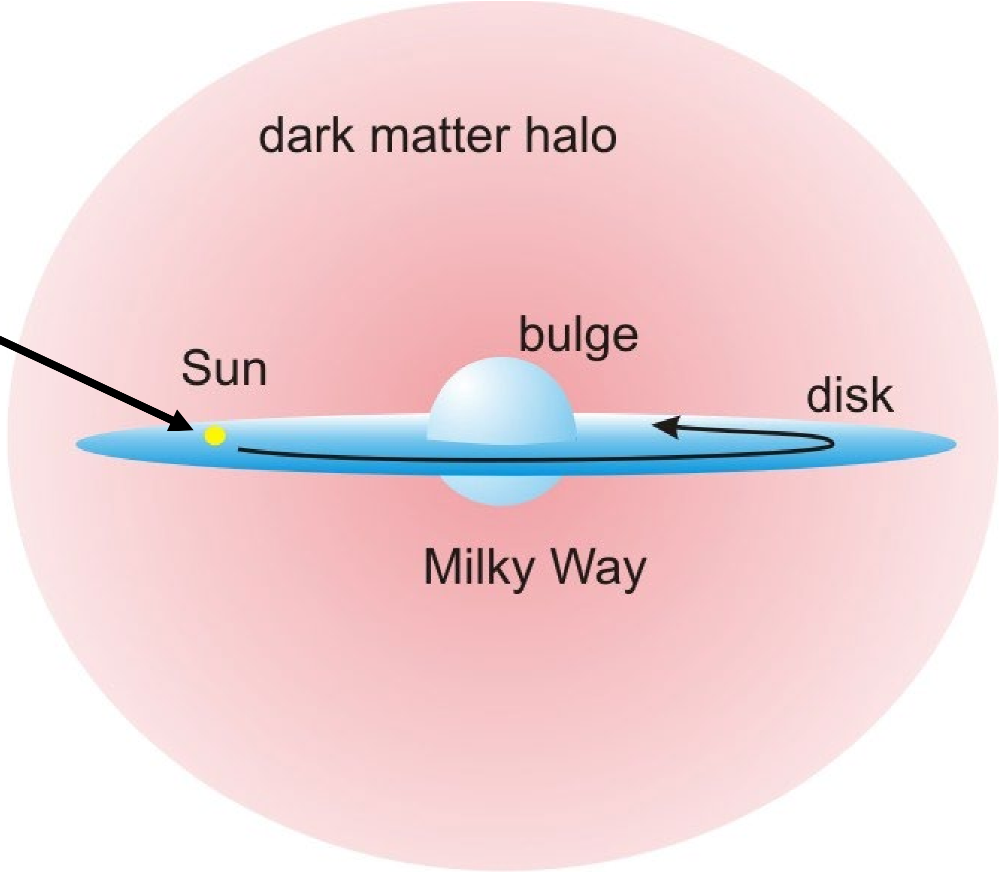
Dark Matter

Strong astrophysical evidence for existence of **dark matter** (~5 times more dark matter than ordinary matter)

$$\rho_{\mathrm{DM}} \approx 0.4\ \mathrm{GeV/cm^3}$$

$$v_{\mathrm{DM}} \sim 300\ \mathrm{km/s}$$



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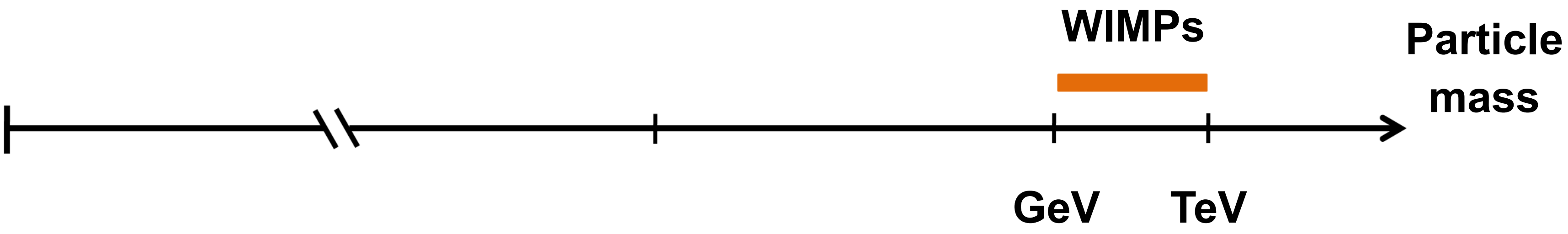

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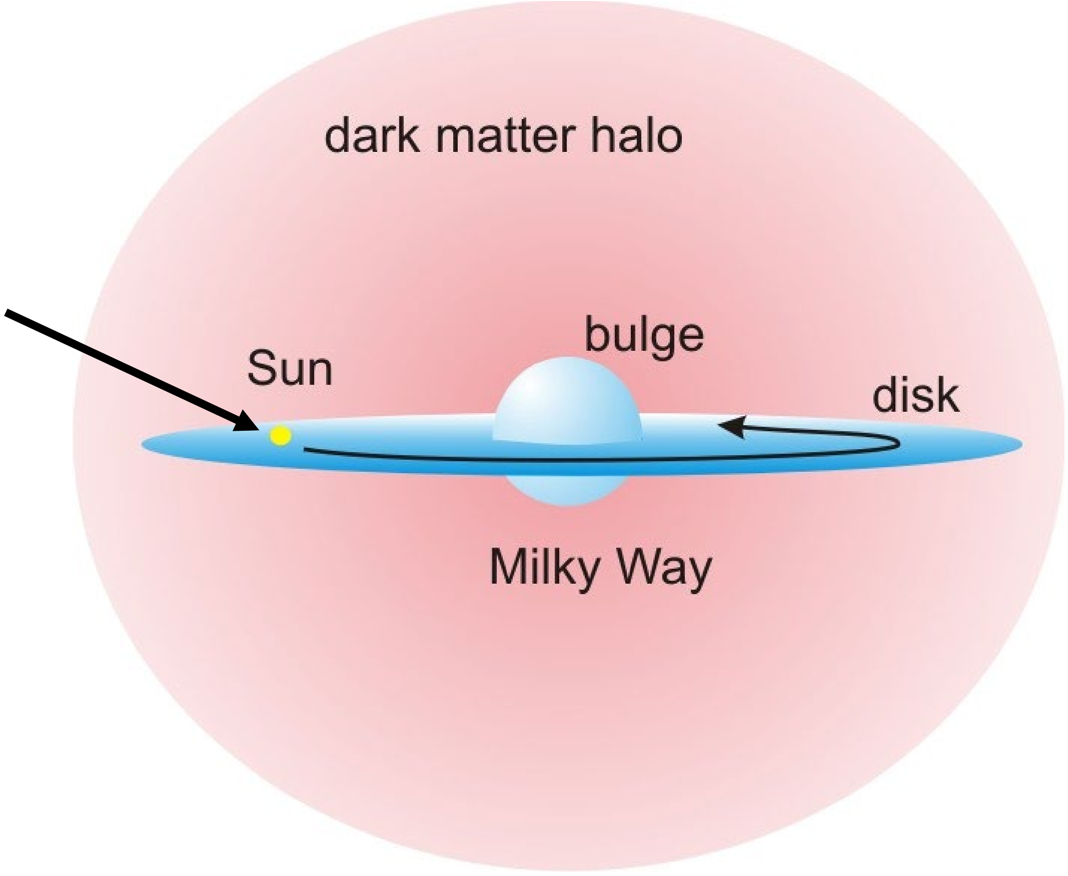

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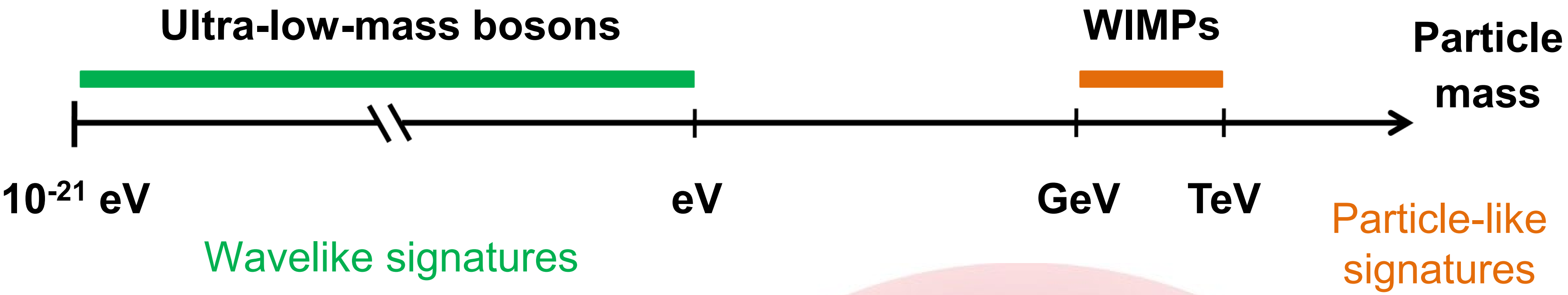

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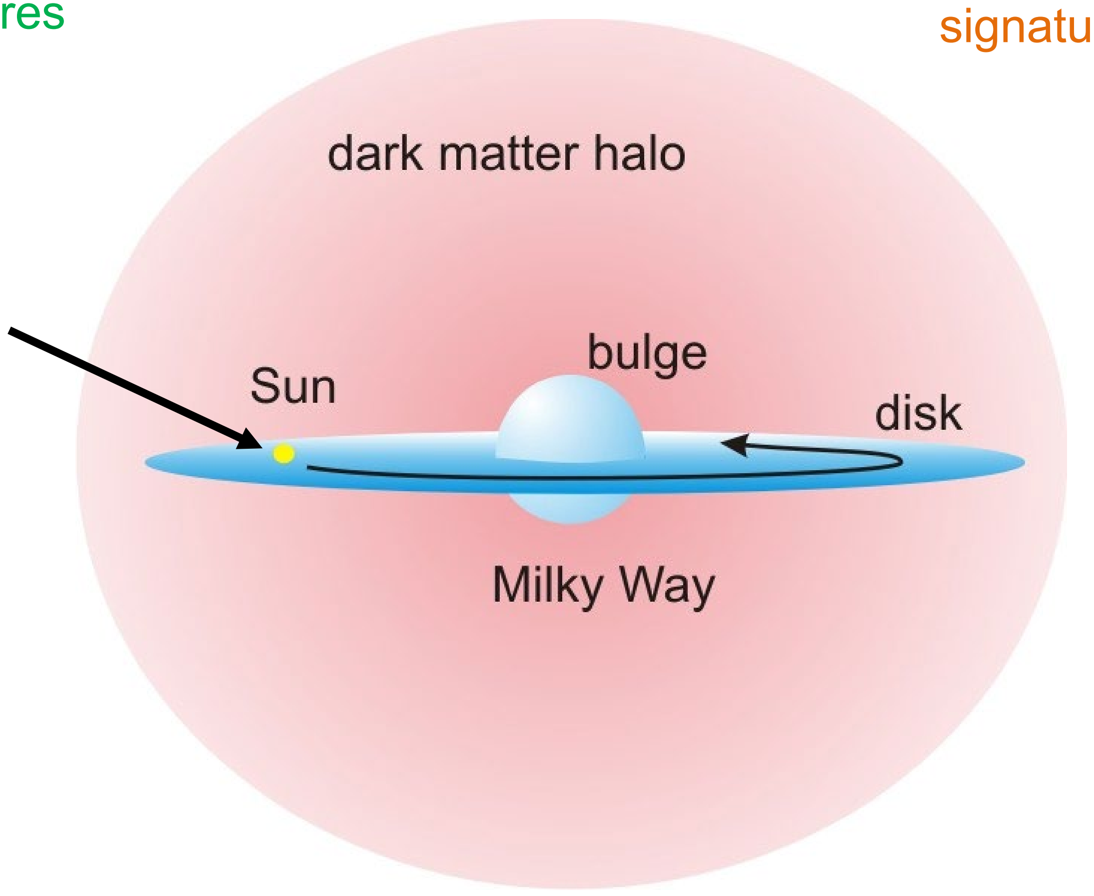
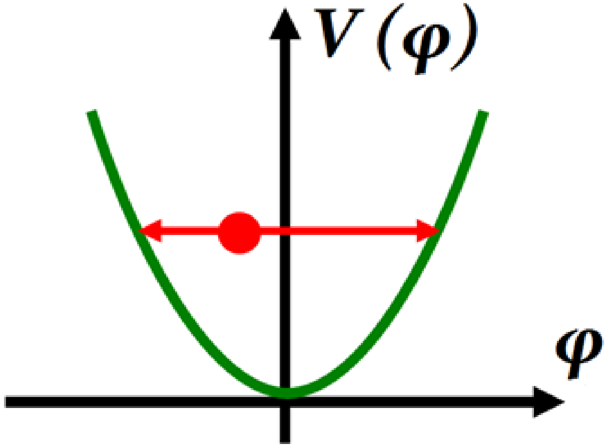


Low-mass Spin-0 Dark Matter

- Low-mass spin-0 particles form a coherently oscillating classical field $\varphi(t) \approx \varphi_0 \cos(m_\varphi c^2 t/\hbar)$, with energy density $\rho_\varphi \approx m_\varphi^2 \varphi_0^2/2 \;\; (\rho_{\mathrm{DM,local}} \approx 0.4\ \mathrm{GeV/cm^3})$



$$V(\varphi) = \frac{m_\varphi^2 \varphi^2}{2}$$

$$\ddot{\varphi} + m_\varphi^2 \varphi \approx 0$$

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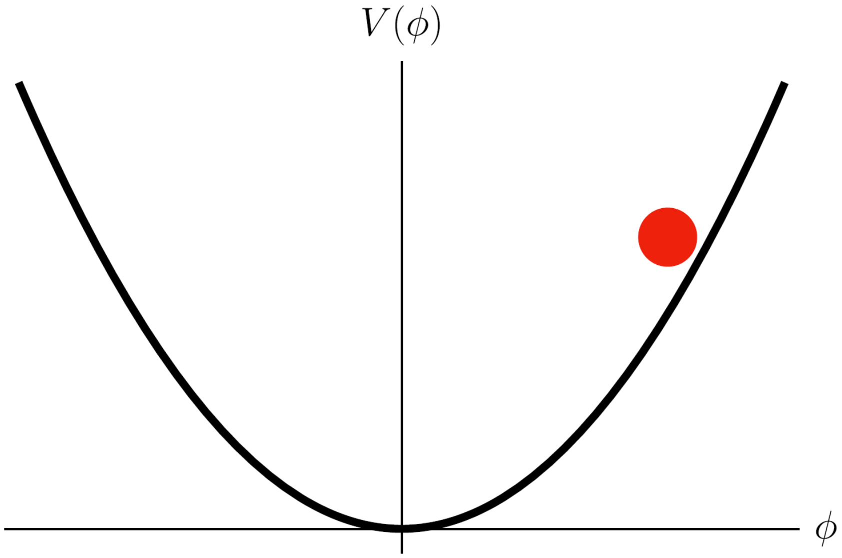

$$\ddot{\varphi} + 3H(t)\dot{\varphi} + m_\varphi^2 \varphi \approx 0$$ ←

$$H(t) = \dot{a}(t)/a(t)$$

Damped harmonic oscillator with a time-dependent frictional term

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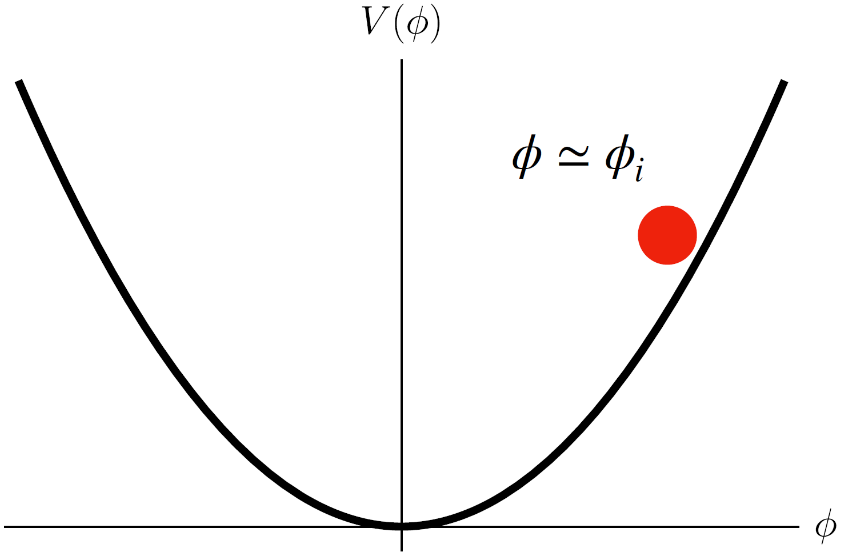

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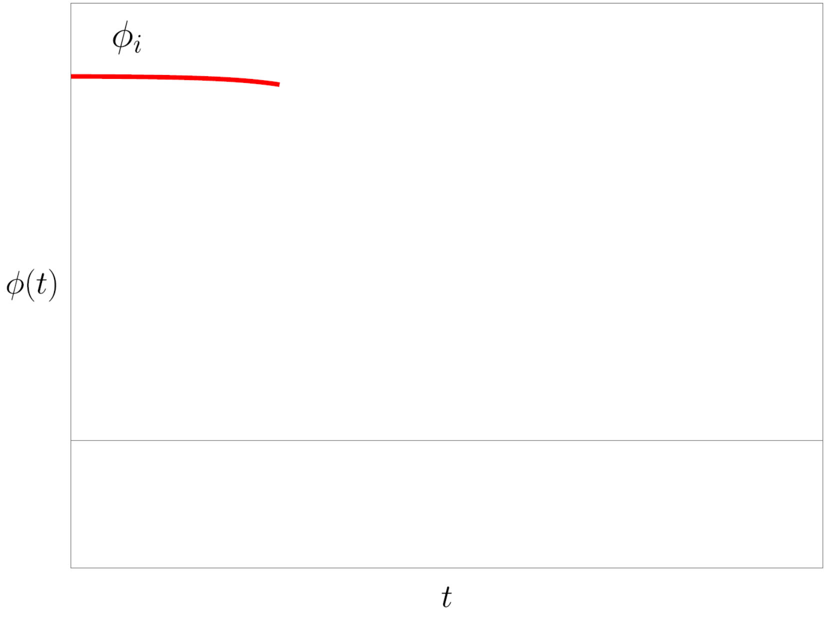

Overdamped regime

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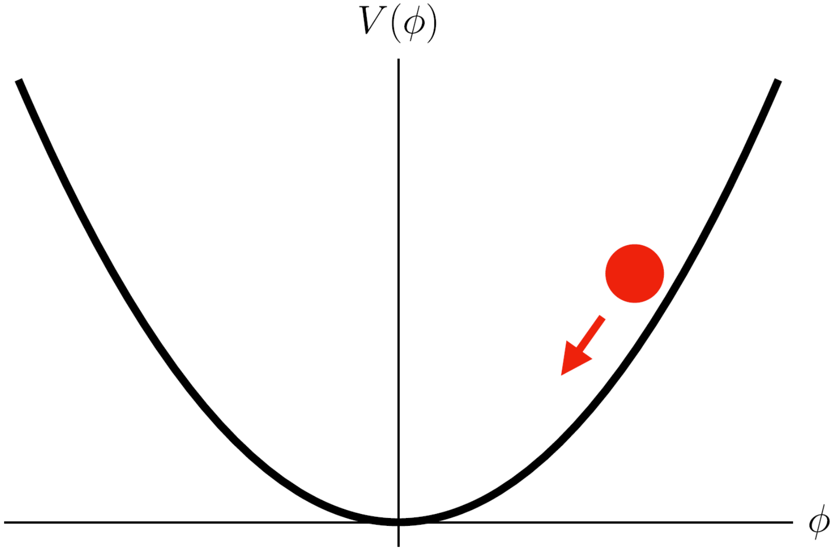

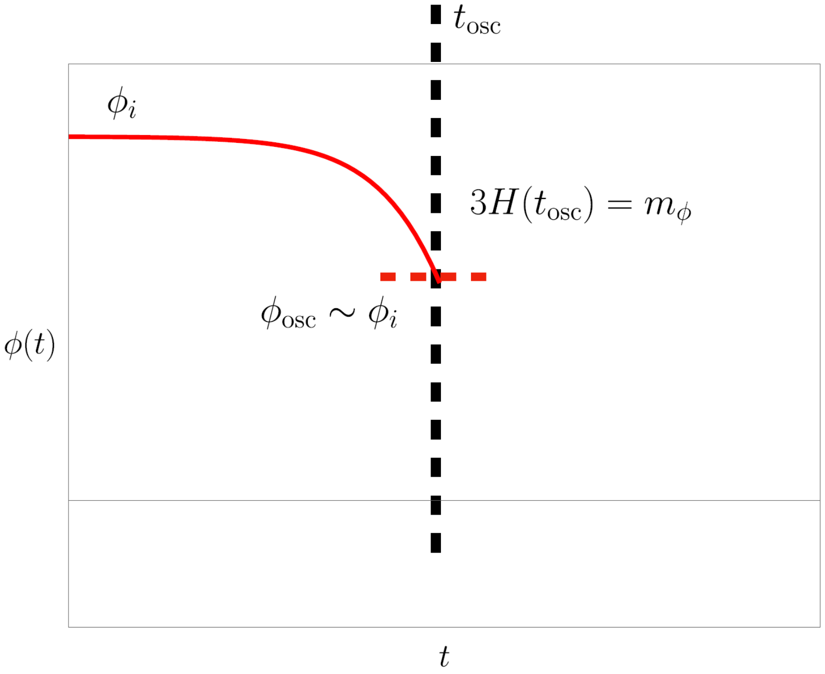

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Critically damped regime

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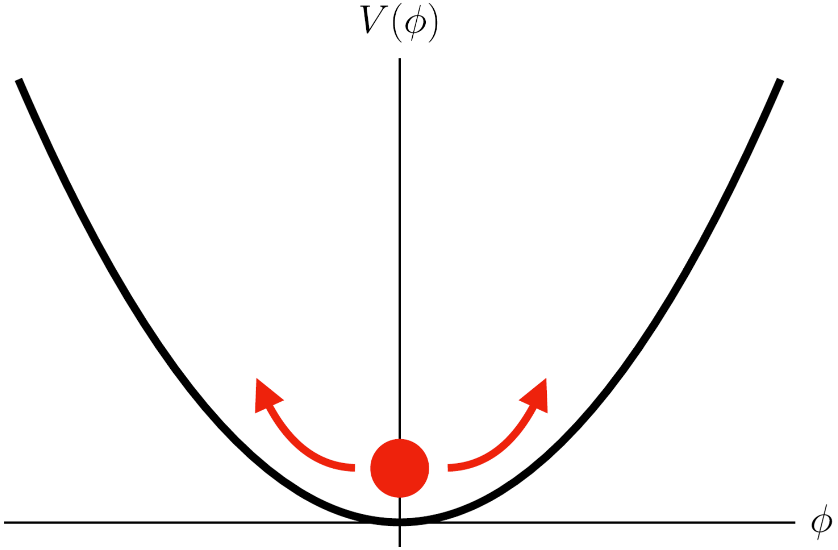

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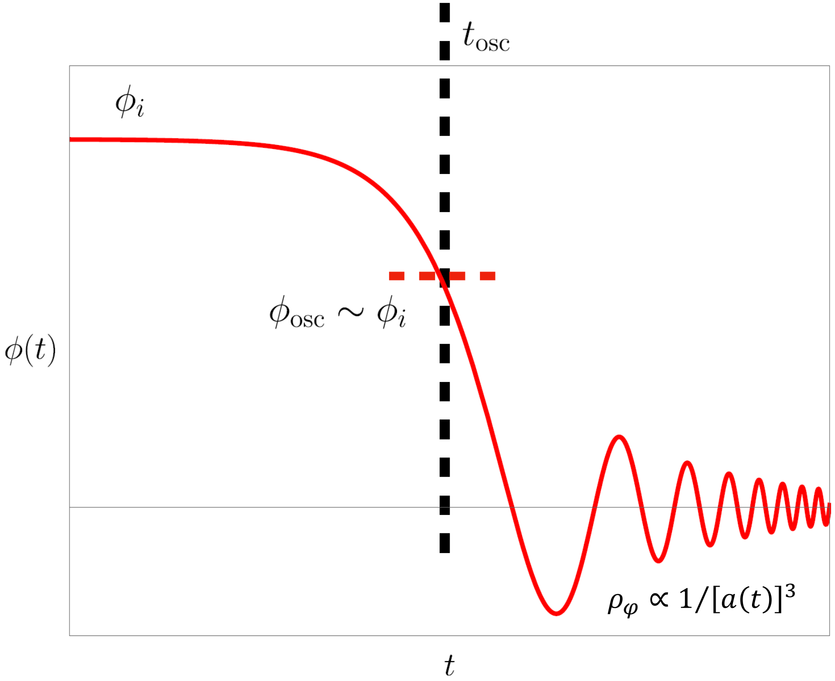

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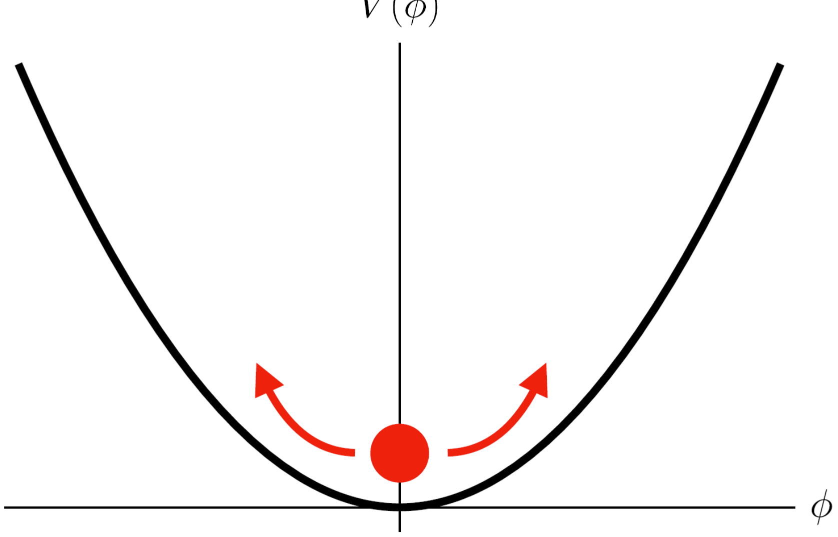

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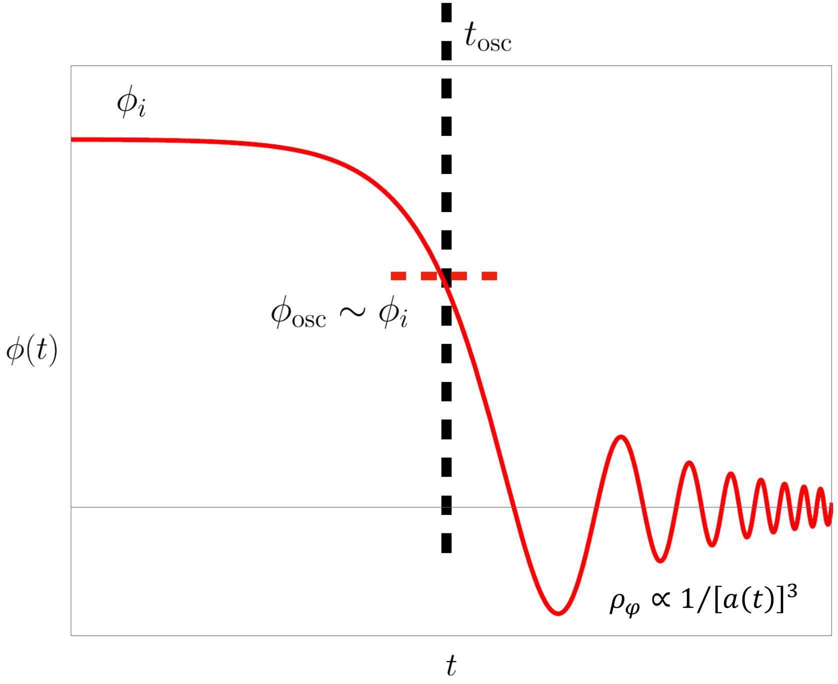

"Vacuum misalignment" mechanism – non-thermal production, ρ_φ governed by initial conditions (φ_i), redshifts as $\rho_\varphi \propto 1/[a(t)]^3$, with $\langle p_\varphi \rangle \ll \rho_\varphi$

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- $\Delta E_\varphi/E_\varphi \sim \langle v_\varphi^2\rangle/c^2 \underset{\substack{\big\uparrow \\ v_{\mathrm{DM}} \sim 300\ \mathrm{km/s}}}{\sim} 10^{-6} \quad \Rightarrow \quad \tau_{\mathrm{coh}} \sim 2\pi/\Delta E_\varphi \underset{\substack{\big\downarrow \\ Q_{\mathrm{DM}} \sim 10^6}}{\sim} 10^6 T_{\mathrm{osc}}$

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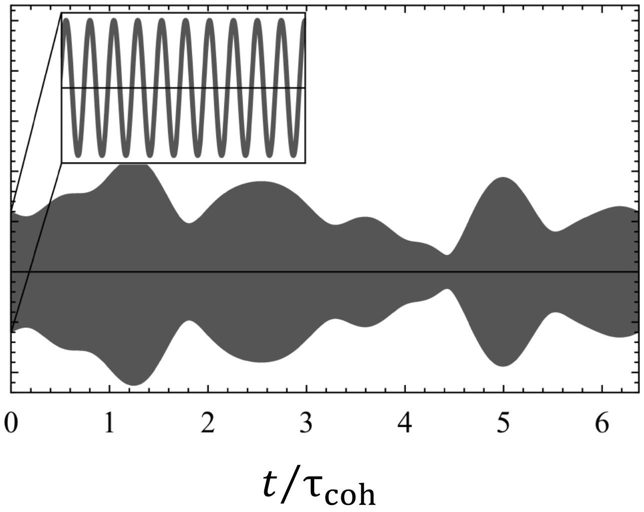
Evolution of φ_0 with time



$$\varphi(t) \sim \sum_{i=1}^{N} \frac{\varphi_0}{\sqrt{N}} \cos\left(m_\varphi t + \frac{m_\varphi v_i^2 t}{2} + \theta_i \right)$$

v_i follow quasi-Maxwell-Boltzmann distribution
(in the standard halo model)

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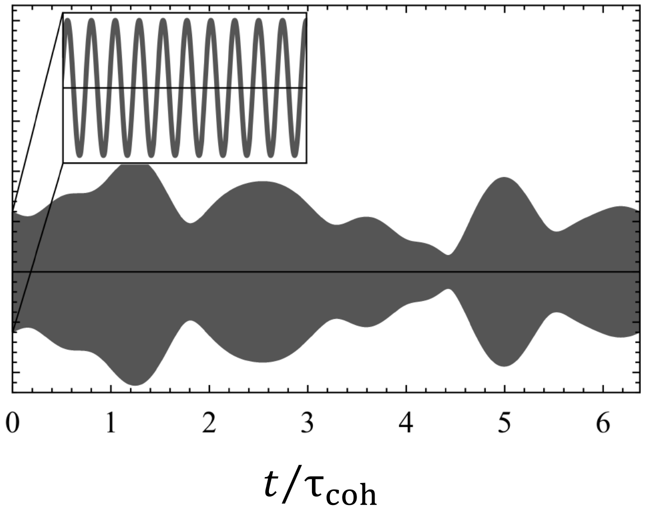
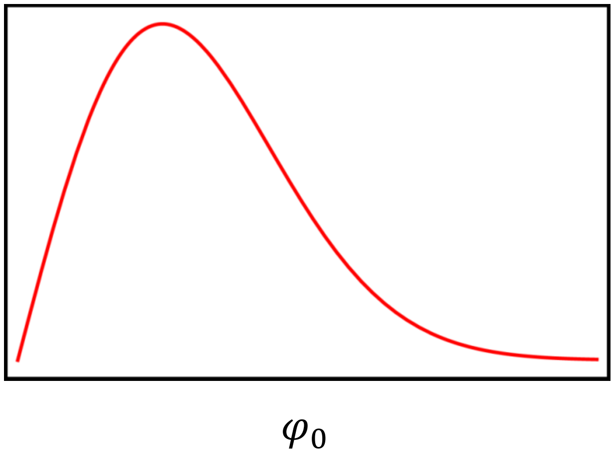


Probability distribution function of φ_0 (Rayleigh distribution)



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* Pauli exclusion principle rules out sub-eV *fermionic* dark matter

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↑

$T_{\mathrm{osc}} \sim 1\ \mathrm{month}$

IR frequencies

Lyman-α forest measurements [suppression of structures for $L \lesssim \mathcal{O}(\lambda_{\mathrm{dB},\varphi})$]

[Related figure-of-merit: $\lambda_{\mathrm{dB},\varphi}/2\pi \leq L_{\mathrm{dwarf\ galaxy}} \sim 100\ \mathrm{pc} \;\; \Rightarrow \;\; m_\varphi \gtrsim 10^{-21}\ \mathrm{eV}$]

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$\uparrow$

Lyman-α forest measurements [suppression of structures for $L \lesssim \mathcal{O}(\lambda_{\mathrm{dB},\varphi})$]

- *Wave-like* signatures [cf. *particle-like* signatures of WIMP DM]

Dark-Matter-Induced Variations of the Fundamental Constants

[Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRL* **115**, 201301 (2015)],

[Hees, Minazzoli, Savalle, Stadnik, Wolf, *PRD* **98**, 064051 (2018)]

$$\mathcal{L}_\gamma = \frac{\varphi}{\Lambda_\gamma}\frac{F_{\mu\nu}F^{\mu\nu}}{4} \approx \frac{\varphi_0\cos(m_\varphi t)}{\Lambda_\gamma}\frac{F_{\mu\nu}F^{\mu\nu}}{4} \quad\Rightarrow\quad \frac{\delta\alpha}{\alpha} \approx \frac{\varphi_0\cos(m_\varphi t)}{\Lambda_\gamma}$$

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φ^2 interactions also exhibit the same oscillating-in-time signatures as above, as well as …

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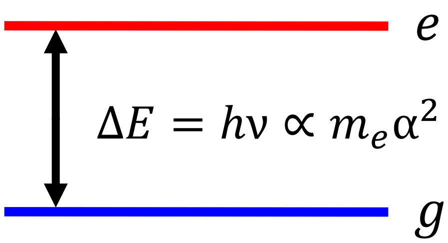
$$\Downarrow$$

Screening of φ field in and around matter if $\delta m_\varphi > 0$

Probes of Ultralight Scalar DM

Recent searches for ultralight scalar DM have focused on the electromagnetic (photon) and electron couplings

Atomic clocks

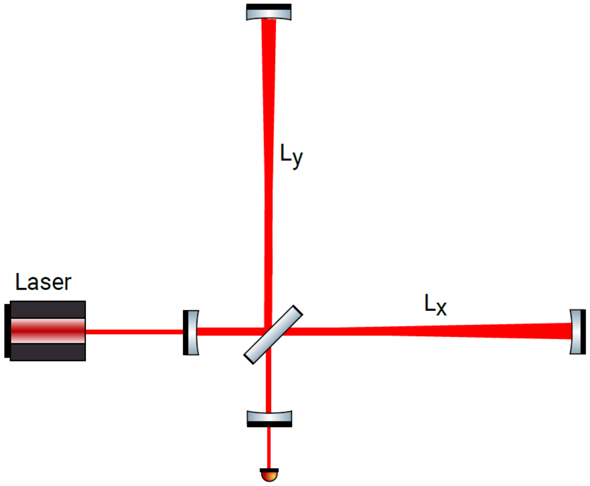


$$\Delta E = h\nu \propto m_e \alpha^2$$

Optical cavities

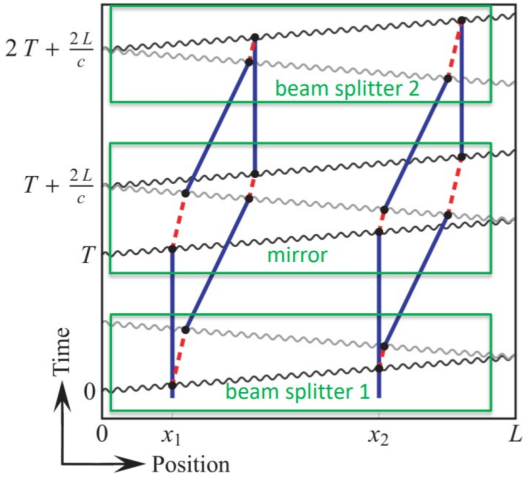
$$L_{\text{solid}} \propto a_{\text{B}} \propto 1/(m_e \alpha)$$

Laser interferometers



$$\Delta\Phi = \Phi_1 - \Phi_2$$

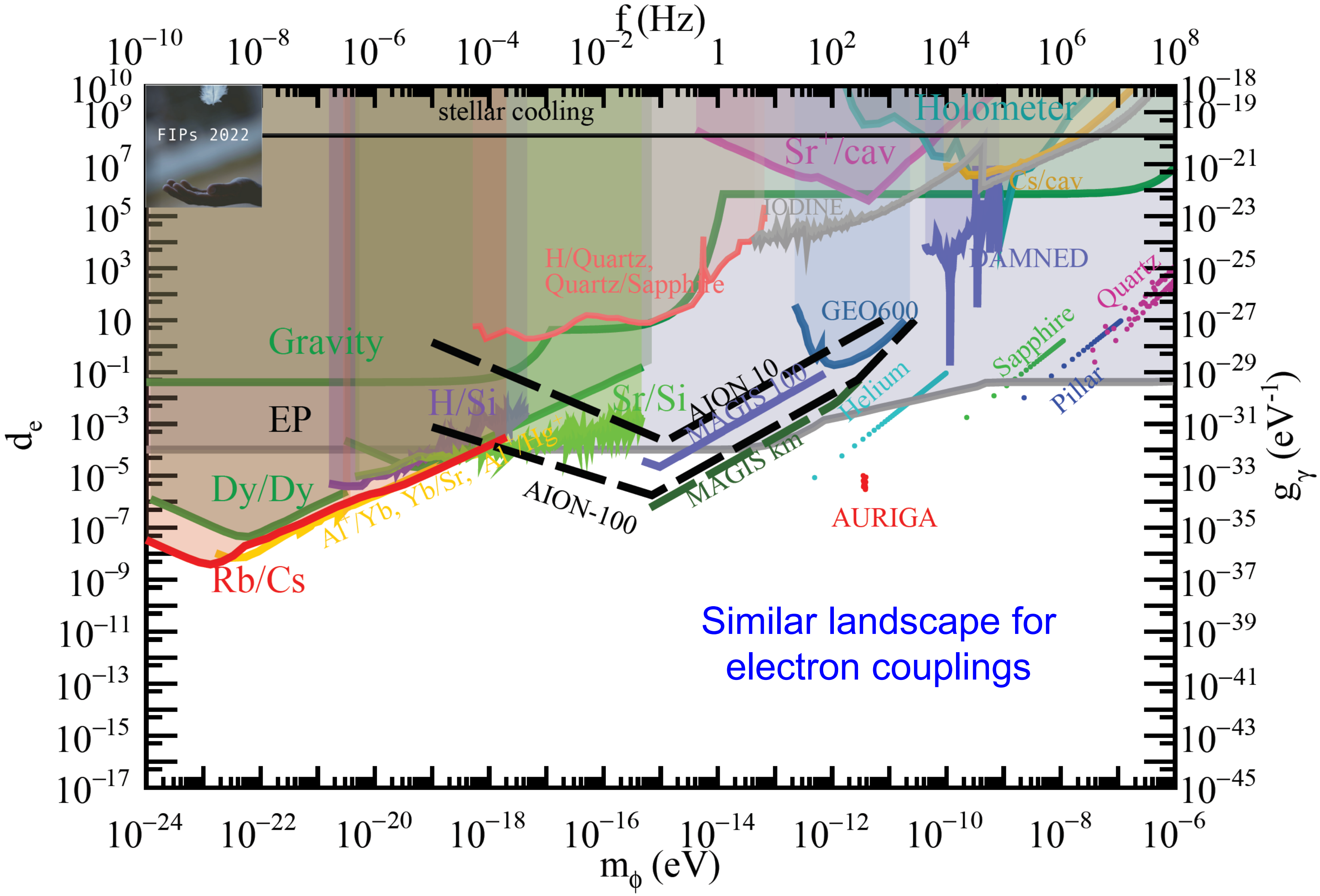
Atom interferometers *(proposed)*



For a recent overview, see e.g. [Antypas *et al.*, arXiv:2203.14915] and references therein

Constraints on Linear Scalar-Photon Coupling

Summary plot from FIPs 2022 workshop report: [Antel *et al.*, arXiv:2305.01715]



Similar landscape for electron couplings

Muonic Probes of Ultralight Scalar DM

- Possible flavour/generational dependence of scalar couplings in the lepton sector
- Extra motivation for muonic couplings from persistence of anomalies in muon physics, such as:
    - Proton radius puzzle
    - $(g-2)_\mu$ puzzle

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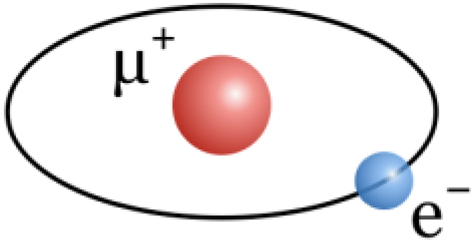
- Possible flavour/generational dependence of scalar couplings in the lepton sector
- Extra motivation for muonic couplings from persistence of anomalies in muon physics, such as:
  - Proton radius puzzle
  - $(g-2)_\mu$ puzzle
- No stable terrestrial sources of muons (unlike electrons), offering a qualitatively different phenomenology as compared to, e.g., scalar-electron couplings
- Scalar-muon coupling practically unconstrained by terrestrial EP tests (modulo possible loop effects)

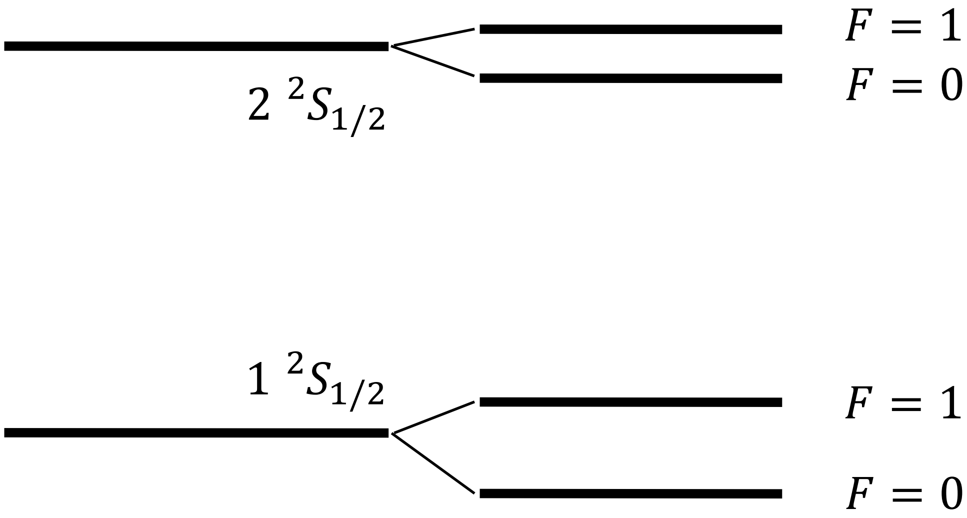
Probing Oscillations of m_μ with Muonium Spectroscopy

[Stadnik, *PRL* **131**, 011001 (2023)]

Muonium = $e^-\mu^+$ bound state, $m_r = \frac{m_e m_\mu}{m_e + m_\mu} \approx m_e(1 - m_e/m_\mu)$



$\tau_\mu \approx 2.2\ \mu\text{s}$



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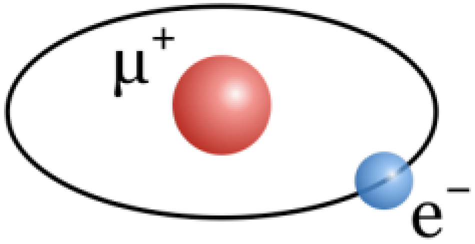
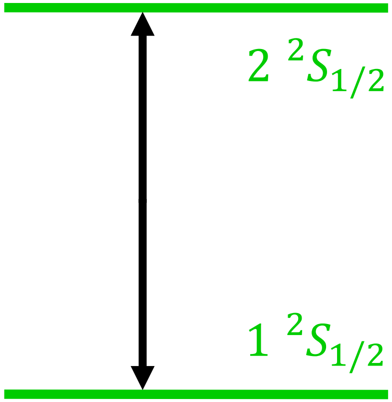


$\tau_\mu \approx 2.2$ μs

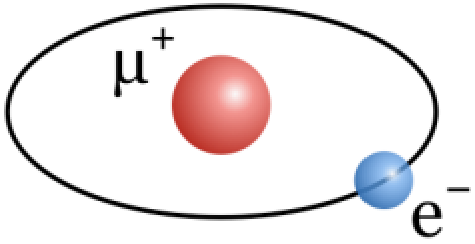


$$E_n^{\text{Rydberg}} = -\frac{m_r \alpha^2}{2n^2} \Rightarrow \frac{\Delta\nu_{1S-2S}}{\nu_{1S-2S}} \approx 2\frac{\Delta\alpha}{\alpha} + \frac{\Delta m_e}{m_e} + \frac{m_e}{m_\mu}\frac{\Delta m_\mu}{m_\mu}$$

Probing Oscillations of m_μ with Muonium Spectroscopy

[Stadnik, *PRL* **131**, 011001 (2023)]

Muonium = $e^-\mu^+$ bound state, $m_r = \frac{m_e m_\mu}{m_e + m_\mu} \approx m_e(1 - m_e/m_\mu)$



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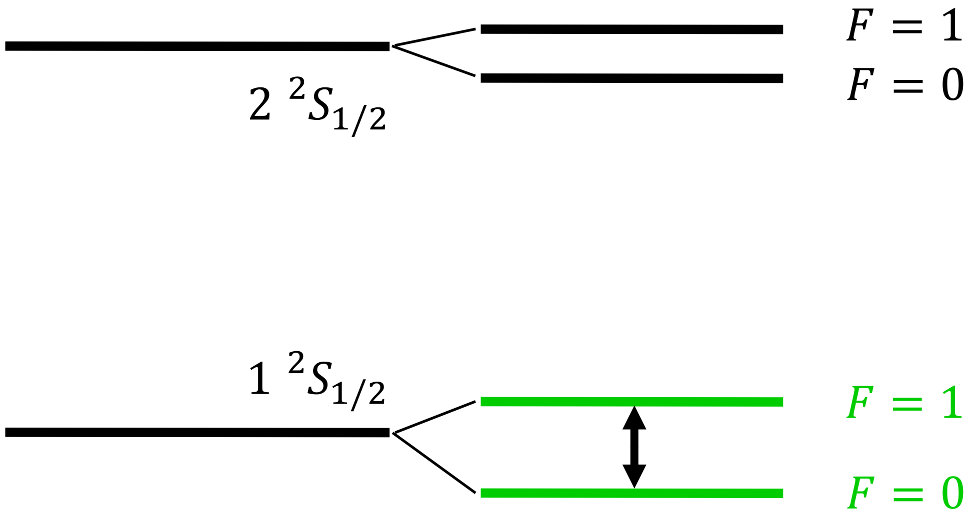


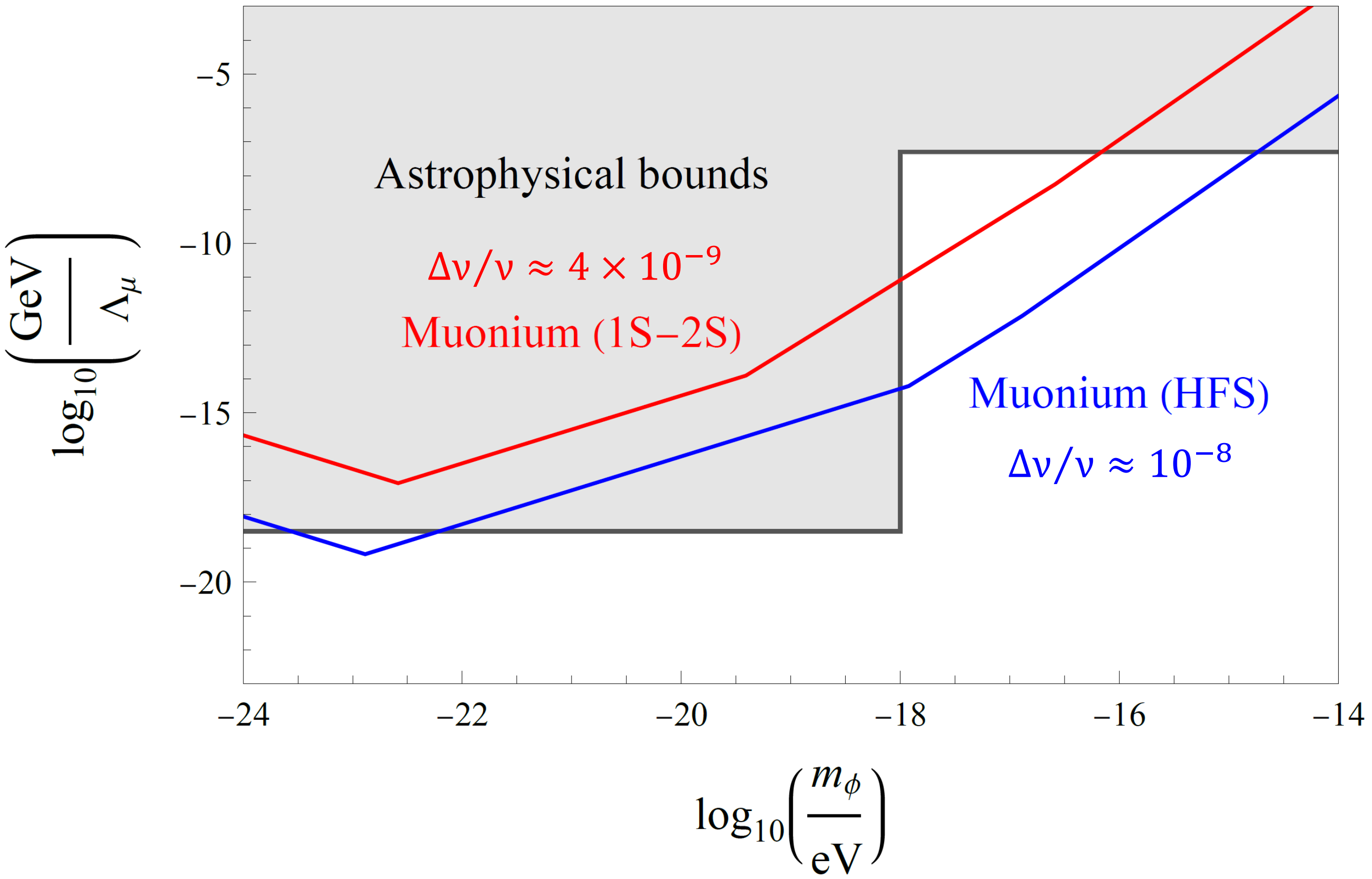
$$E_n^{\text{Rydberg}} = -\frac{m_r \alpha^2}{2n^2} \Rightarrow \frac{\Delta\nu_{1S-2S}}{\nu_{1S-2S}} \approx 2\frac{\Delta\alpha}{\alpha} + \frac{\Delta m_e}{m_e} + \frac{m_e}{m_\mu}\frac{\Delta m_\mu}{m_\mu}$$

$$\Delta E_{\text{Fermi}} = \frac{8 m_r^3 \alpha^4}{3 m_e m_\mu} \Rightarrow \frac{\Delta\nu_{\text{HFS}}}{\nu_{\text{HFS}}} \approx 4\frac{\Delta\alpha}{\alpha} + 2\frac{\Delta m_e}{m_e} - \frac{\Delta m_\mu}{m_\mu}$$

Estimated Sensitivities to Scalar Dark Matter with $\varphi\bar{\mu}\mu/\Lambda_\mu$ Coupling

[Stadnik, *PRL* **131**, 011001 (2023)]

Up to 7 orders of magnitude improvement possible with existing datasets!
(Best existing datasets from muonium experiments at LAMPF and RAL in 1990s)



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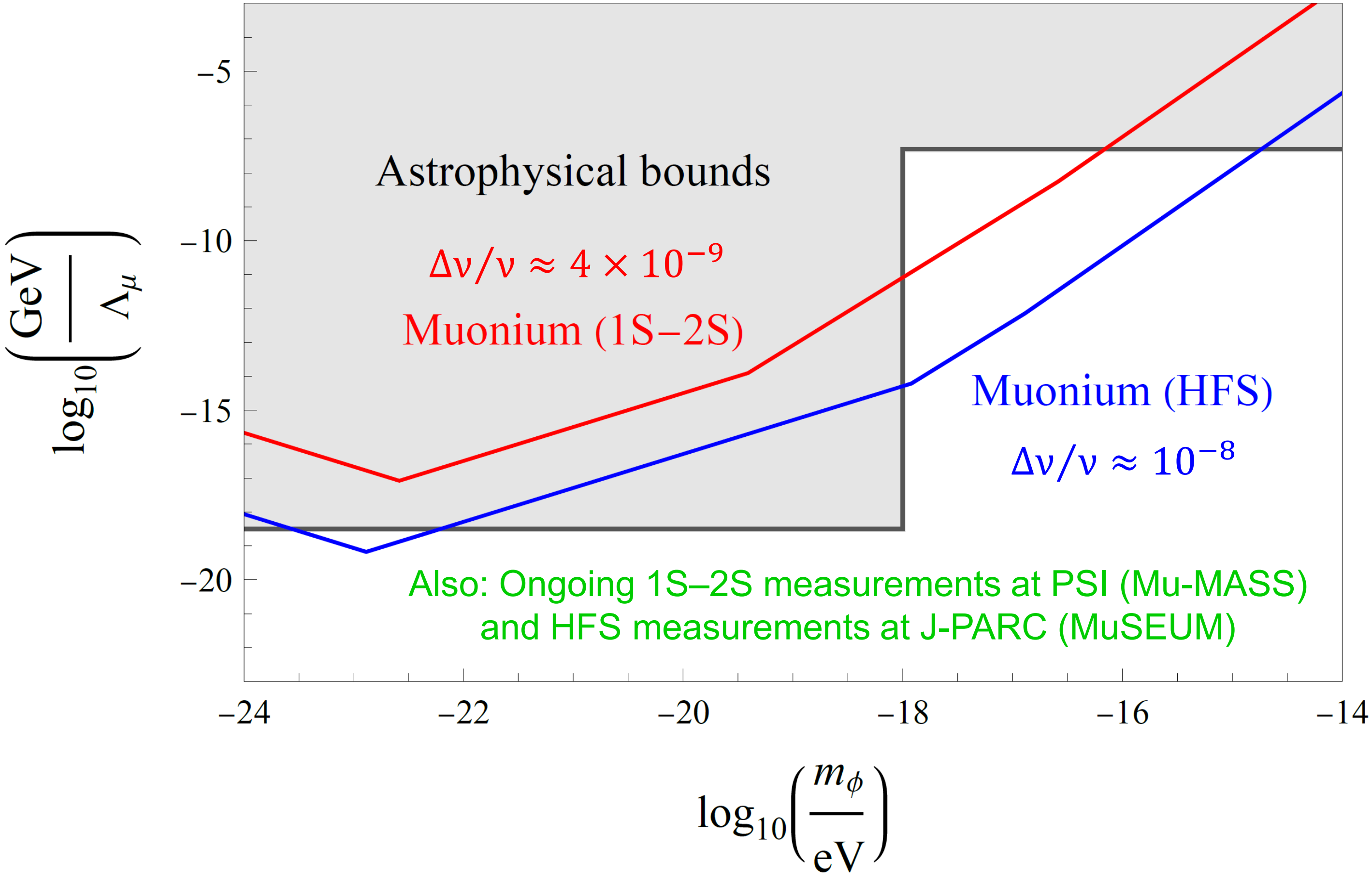
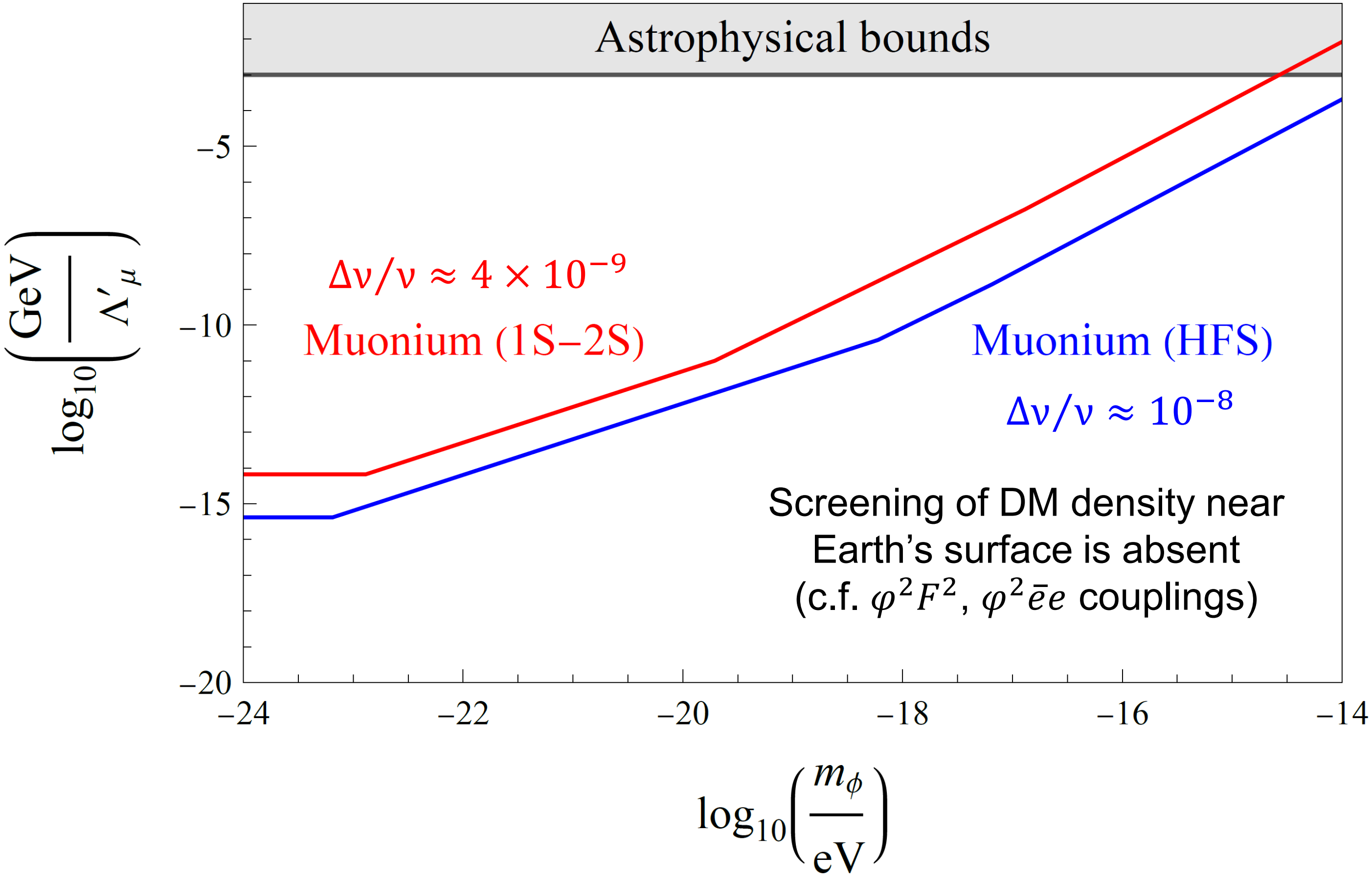


Also: Ongoing 1S–2S measurements at PSI (Mu-MASS) and HFS measurements at J-PARC (MuSEUM)

Estimated Sensitivities to Scalar Dark Matter with $\varphi^2\bar{\mu}\mu/(\Lambda'_\mu)^2$ Coupling

[Stadnik, *PRL* **131**, 011001 (2023)]

Up to 12 orders of magnitude improvement possible with existing datasets!
(Best existing datasets from muonium experiments at LAMPF and RAL in 1990s)

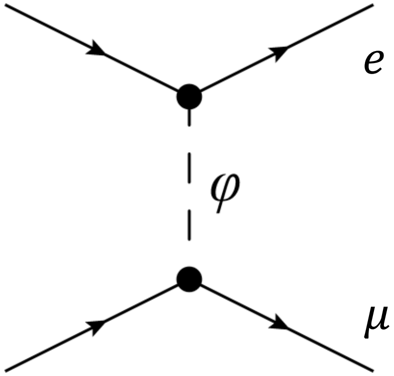


Screening of DM density near Earth's surface is absent (c.f. $\varphi^2 F^2$, $\varphi^2\bar{e}e$ couplings)

Probing Scalar-Muon Coupling with Muonium Free-fall

[Stadnik, *PRL* **131**, 011001 (2023)]

$$\mathcal{L}_{\mathrm{lin}} = -\frac{\varphi}{\Lambda_e} m_e \bar{e} e - \frac{\varphi}{\Lambda_\mu} m_\mu \bar{\mu} \mu \quad \Rightarrow \quad V_{e\mu}(r) \approx -\frac{m_e}{\Lambda_e} \frac{m_\mu}{\Lambda_\mu} \frac{e^{-m_\varphi r}}{4\pi r}$$



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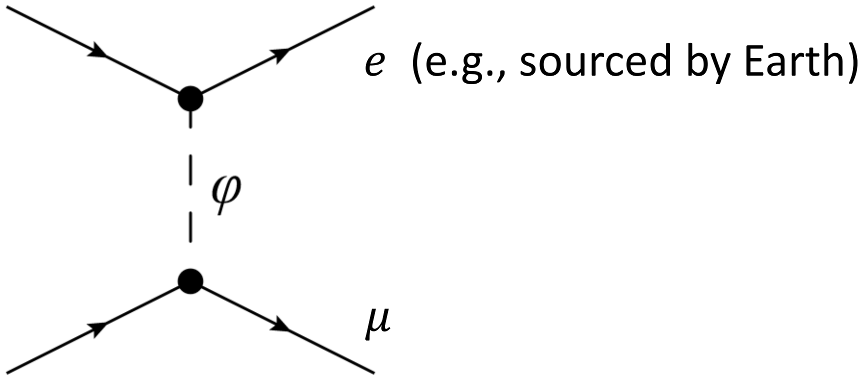

Local value of g measured in free-fall experiments using muonium would differ from experiments using non-muon-based test masses

Probing Scalar-Muon Coupling with Muonium Free-fall

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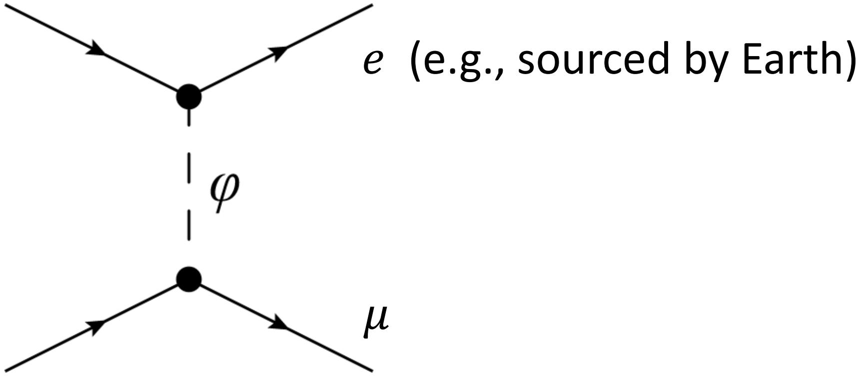


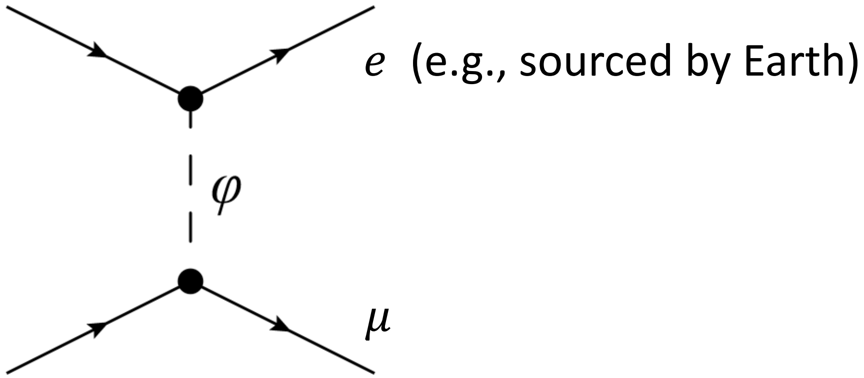
Local value of g measured in free-fall experiments using muonium would differ from experiments using non-muon-based test masses

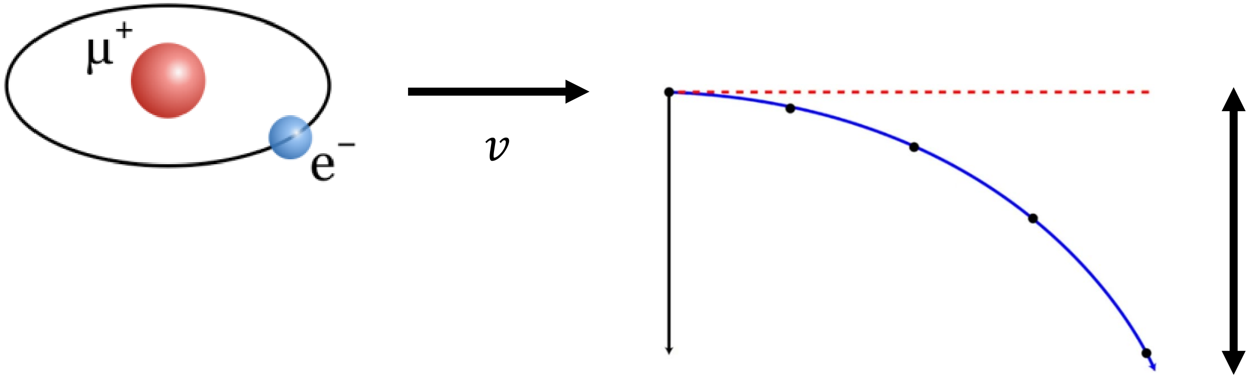
Recently started LEMING experiment at the Paul Scherrer Institute aims to measure g with a precision of $\Delta g / g \sim 0.1$ using muonium

Probing Scalar-Muon Coupling with Muonium Free-fall

[Stadnik, *PRL* **131**, 011001 (2023)]

$$\mathcal{L}_{\text{lin}} = -\frac{\varphi}{\Lambda_e} m_e \bar{e} e - \frac{\varphi}{\Lambda_\mu} m_\mu \bar{\mu}\mu \;\Rightarrow\; V_{e\mu}(r) \approx -\frac{m_e}{\Lambda_e}\frac{m_\mu}{\Lambda_\mu}\frac{e^{-m_\varphi r}}{4\pi r}$$



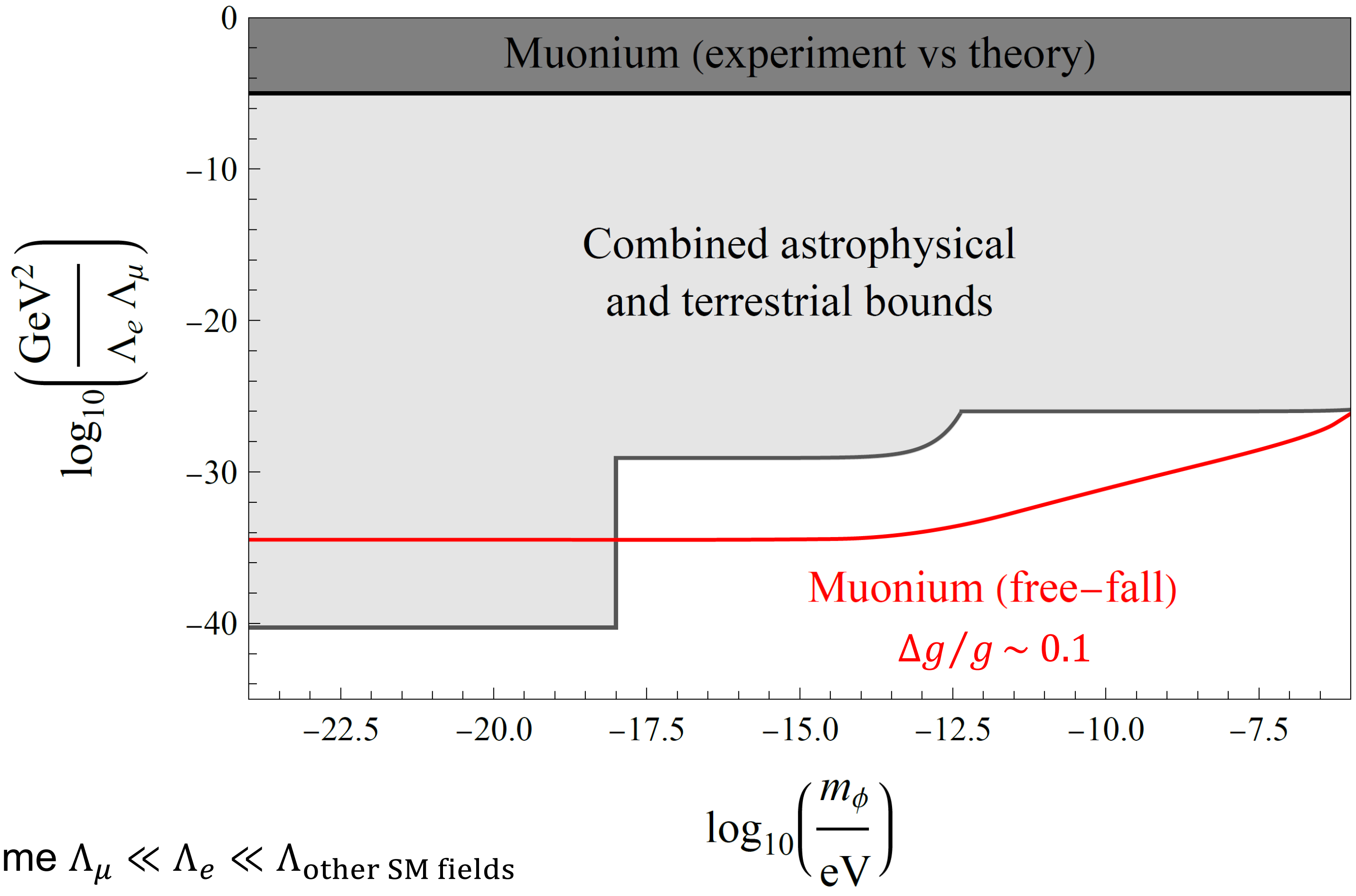


$$\Delta h \sim \frac{g\tau_\mu^2}{2} \approx 24\ \text{pm}$$

Probing Scalar-Muon Coupling with Muonium Free-fall

[Stadnik, *PRL* **131**, 011001 (2023)]

Up to 5 orders of magnitude improvement possible with ongoing measurements!
(Recently started LEMING experiment at PSI targets a precision of Δ*g*/*g* ~ 0.1)



Assume $\Lambda_\mu \ll \Lambda_e \ll \Lambda_{\text{other SM fields}}$

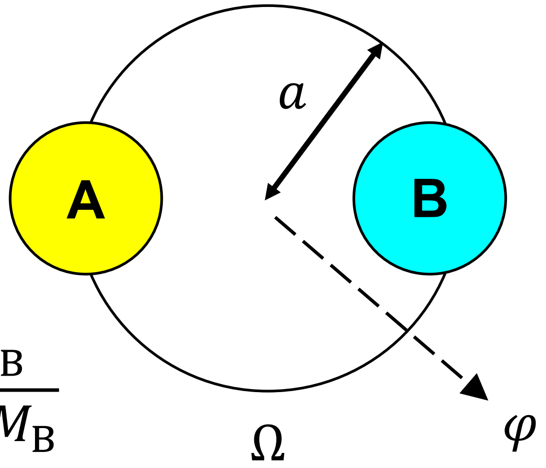
Summary

- Recent searches for ultralight scalar DM have focused on the electromagnetic (photon) and electron couplings
- Muonium spectroscopy offers a powerful probe of ultralight scalar dark matter via interactions with muons leading to apparent oscillations of muon mass
  – With existing datasets, up to $\sim 10^7$ improvement possible for $\varphi \bar{\mu} \mu$ coupling (up to $\sim 10^{12}$ for the $\varphi^2 \bar{\mu} \mu$ coupling over an even broader range of scalar DM masses)
- Ongoing muonium free-fall experiments to measure g offer up to $\sim 10^5$ improvement in sensitivity for the combination of $\varphi \bar{\mu} \mu$ and $\varphi \bar{e} e$ couplings by searching for φ-mediated forces

Back-Up Slides

Astrophysical Emission (Compact Binaries)

[Kumar Poddar *et al.*, *PRD* **100**, 123923 (2019)], [Dror *et al.*, *PRD* **102**, 023005 (2020)]



$$M = \frac{M_\mathrm{A} M_\mathrm{B}}{M_\mathrm{A} + M_\mathrm{B}}$$

$$\mathcal{L}_f = -\frac{\varphi}{\Lambda_f} m_f \bar{f} f$$

- Scalar Larmor radiation possible if $m_\varphi < \Omega$ (higher-order modes also possible for an elliptical orbit if $m_\varphi < n\Omega$, $n = 2, 3, \ldots$):

$$\frac{dE_\varphi}{dt} \sim \left(\frac{m_f}{\Lambda_f}\right)^2 (aM)^2 \Omega^4 \left(\frac{Q_\mathrm{A}}{M_\mathrm{A}} - \frac{Q_\mathrm{B}}{M_\mathrm{B}}\right)^2, \text{for } \Omega a \ll 1$$

- Dipole nature requires $Q_\mathrm{A}/M_\mathrm{A} \neq Q_\mathrm{B}/M_\mathrm{B}$, which is readily satisfied, e.g., for neutron-star/white-dwarf binary systems in the case of $f = n, e, \mu$

Fifth Forces: Linear vs Quadratic Couplings

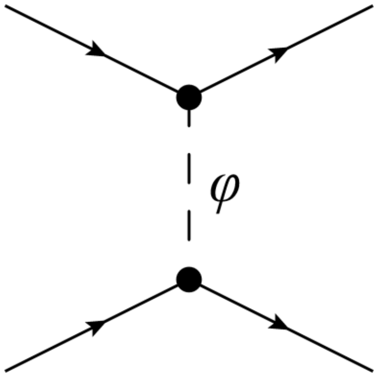
[Hees, Minazzoli, Savalle, Stadnik, Wolf, *PRD* **98**, 064051 (2018)]

Consider the effect of a massive body (e.g., Earth) on the scalar DM field

Linear couplings ($\varphi\bar{X}X$)

$$\Box\varphi + m_\varphi^2\varphi = \pm\kappa\rho$$

Source term



$$\varphi = \varphi_0\cos(m_\varphi t) \pm A\frac{e^{-m_\varphi r}}{r}$$

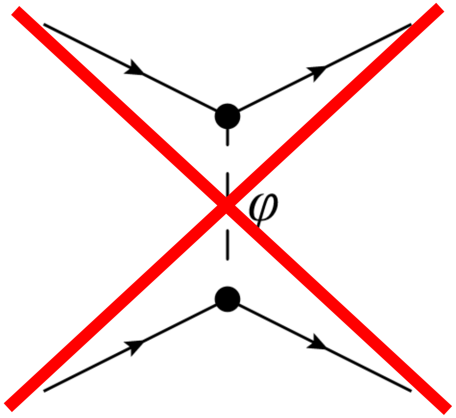
↑

Profile outside of a spherical body

Quadratic couplings ($\varphi^2\bar{X}X$)

$$\Box\varphi + m_\varphi^2\varphi = \pm\kappa'\rho\varphi$$

Effective mass



$$m_{\mathrm{eff}}^2(\rho) = m_\varphi^2 \mp \kappa'\rho$$

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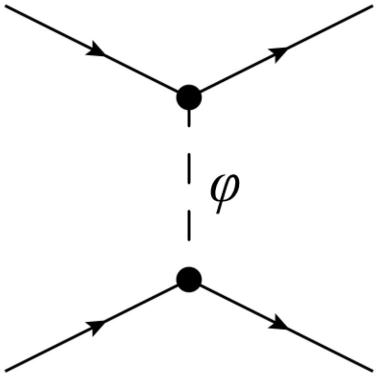
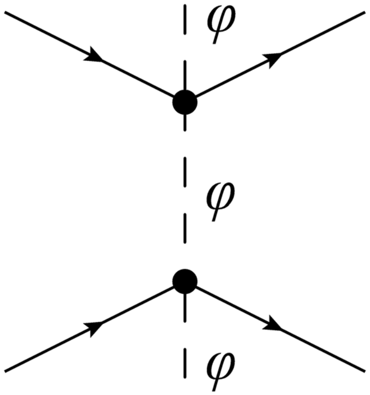


Quadratic couplings ($\varphi^2 \bar{X} X$)

$\Box\varphi + m_\varphi^2 \varphi = \pm\kappa'\rho\varphi$ **Effective mass**



$$\varphi = \varphi_0 \cos(m_\varphi t) \pm A \frac{e^{-m_\varphi r}}{r}$$

$$\varphi = \varphi_0 \cos(m_\varphi t)\left(1 \pm \frac{B}{r}\right)$$

Profile outside of a spherical body

Gradients + amplification/screening

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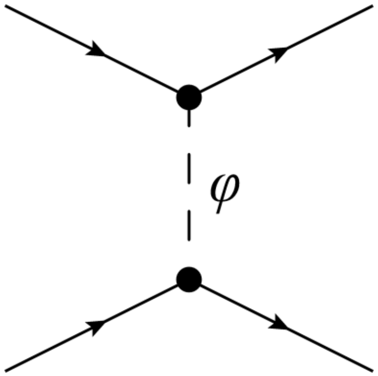

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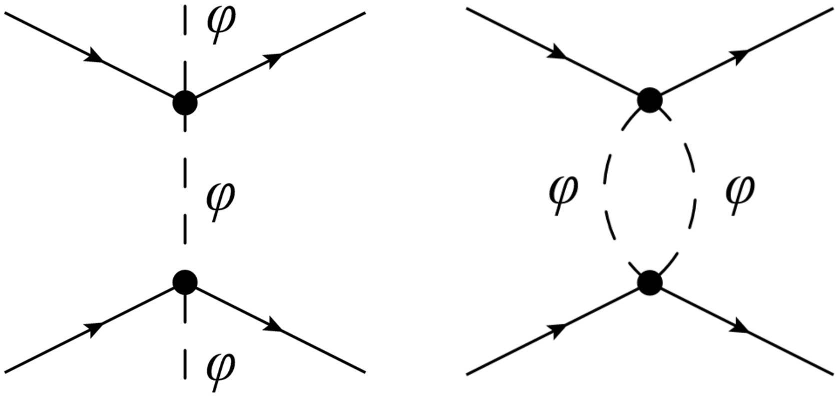
$\Box\varphi + m_\varphi^2\varphi = \pm\kappa'\rho\varphi$ **Effective mass**



$$\varphi = \underline{\varphi_0\cos(m_\varphi t)} \pm A\frac{e^{-m_\varphi r}}{r}$$

Motional gradients: $\varphi_0\cos(m_\varphi t - \boldsymbol{p}_\varphi\cdot\boldsymbol{x})$

“Fifth-force” experiments: torsion pendula, atom interferometry

$$\varphi = \underline{\varphi_0\cos(m_\varphi t)}\left(1 \pm \frac{B}{r}\right) - \hbar C\frac{e^{-2m_\varphi r}}{r^3}$$

$\downarrow$

Gradients + amplification/screening

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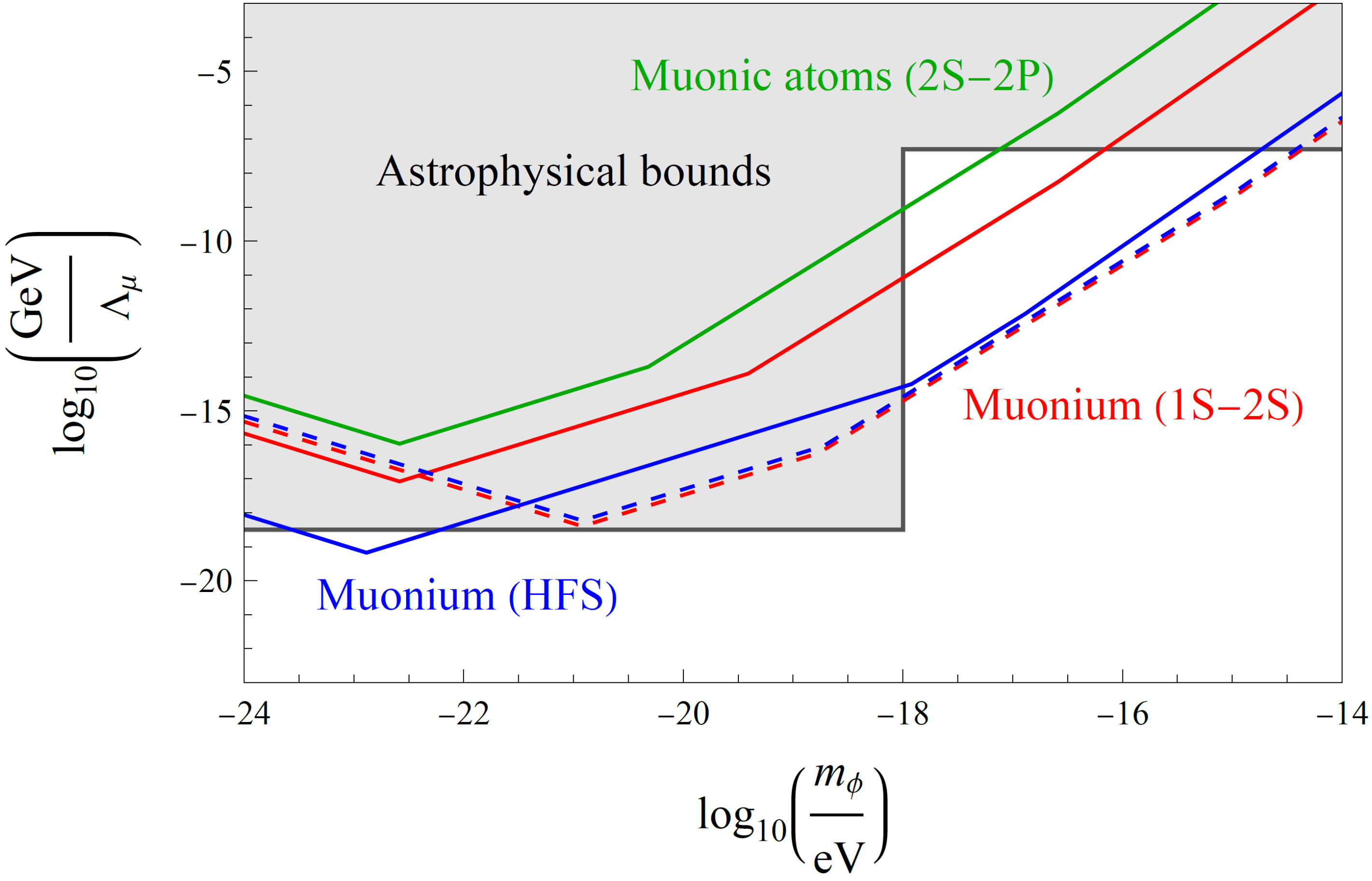

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