Searching for Ultralight Scalar Dark Matter with Muonium and Muonic Atoms

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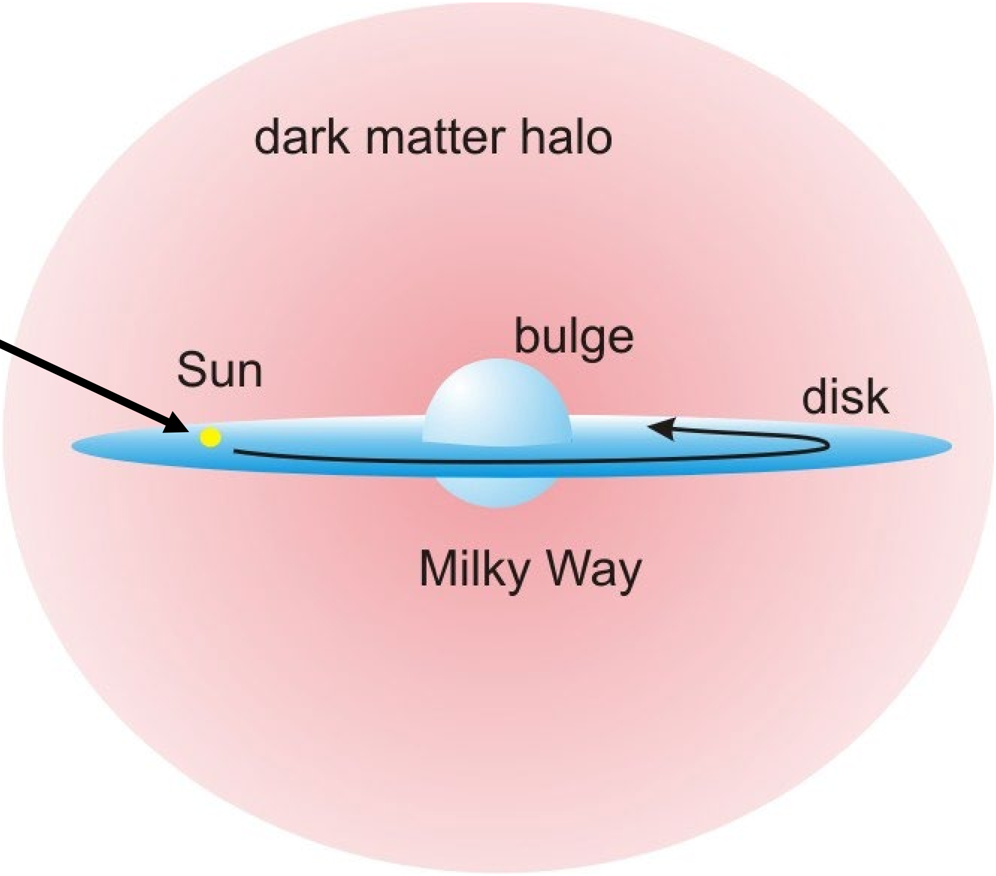
Dark Matter

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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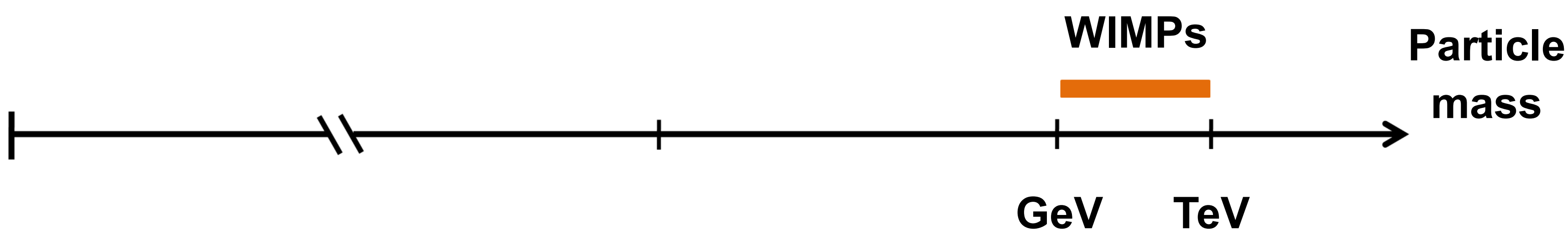

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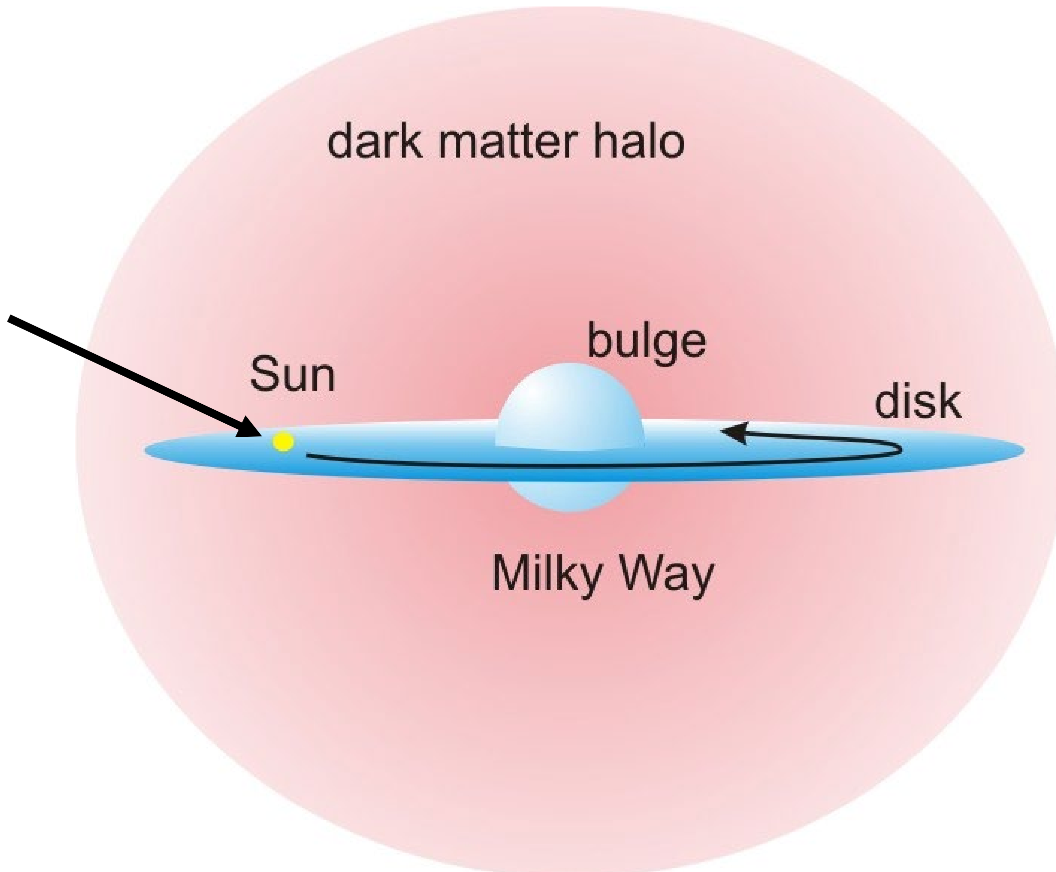

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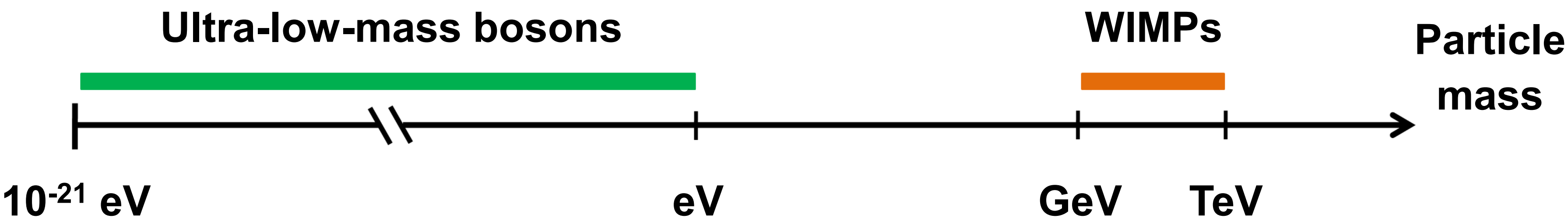

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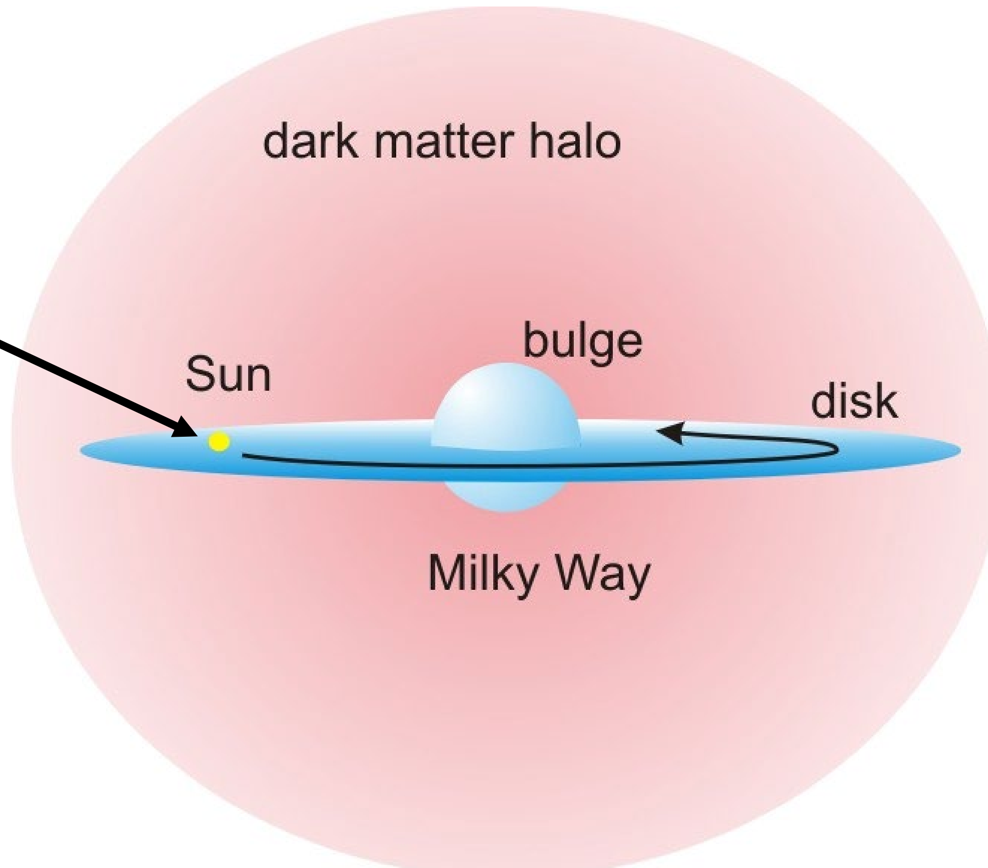
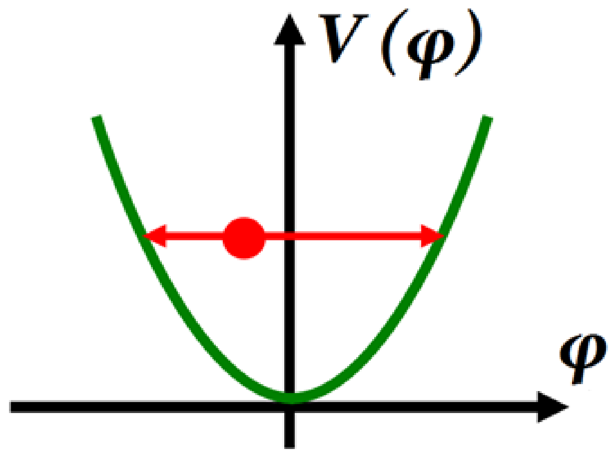


Low-mass Spin-0 Dark Matter

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



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

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

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

$Q_{\mathrm{DM}} \sim 10^6$ (↓)

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- $10^{-21}\ \mathrm{eV} \lesssim m_\varphi \lesssim 1\ \mathrm{eV} \;\; \Leftrightarrow \;\; 10^{-7}\ \mathrm{Hz} \lesssim f_{\mathrm{DM}} \lesssim 10^{14}\ \mathrm{Hz}$

$T_{\mathrm{osc}} \sim 1\ \mathrm{month}$ 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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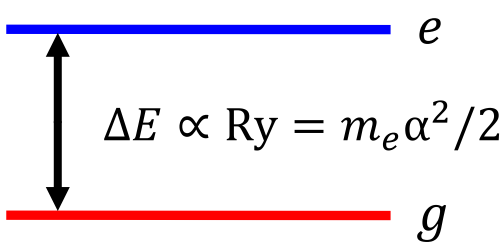
- *Wave-like* signatures [cf. *particle-like* signatures of WIMP DM]

Probes of Ultralight Scalar DM

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

Atomic clocks



Optical cavities

$L \propto a_\mathrm{B} = 1/(m_e \alpha)$

see, e.g., [Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRL* **115**, 201301 (2015)] for details

Muonic Probes of Ultralight Scalar DM

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    - Proton radius puzzle
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- Extra motivation from persistence of various anomalies in muon physics, such as:
  - Proton radius puzzle
  - $(g-2)_\mu$ puzzle
- No stable terrestrial sources of muons (unlike electrons)

Probing Oscillations of m_μ with Muonium Spectroscopy

[Stadnik, arXiv:2206.10808]

$$\mathcal{L}_{\text{lin}} = -\frac{\varphi}{\Lambda_\mu} m_\mu \bar{\mu}\mu \approx -\frac{\varphi_0 \cos(m_\varphi t)}{\Lambda_\mu} m_\mu \bar{\mu}\mu \quad \Rightarrow \quad \frac{\delta m_\mu}{m_\mu} \approx \frac{\varphi_0 \cos(m_\varphi t)}{\Lambda_\mu}$$

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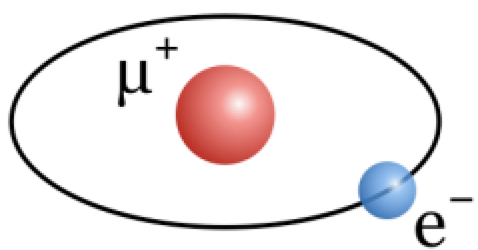
Muonium = $e^-\mu^+$ bound state, $m_r = \frac{m_e m_\mu}{m_e + m_\mu} \approx m_e(1 - m_e/m_\mu)$



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

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

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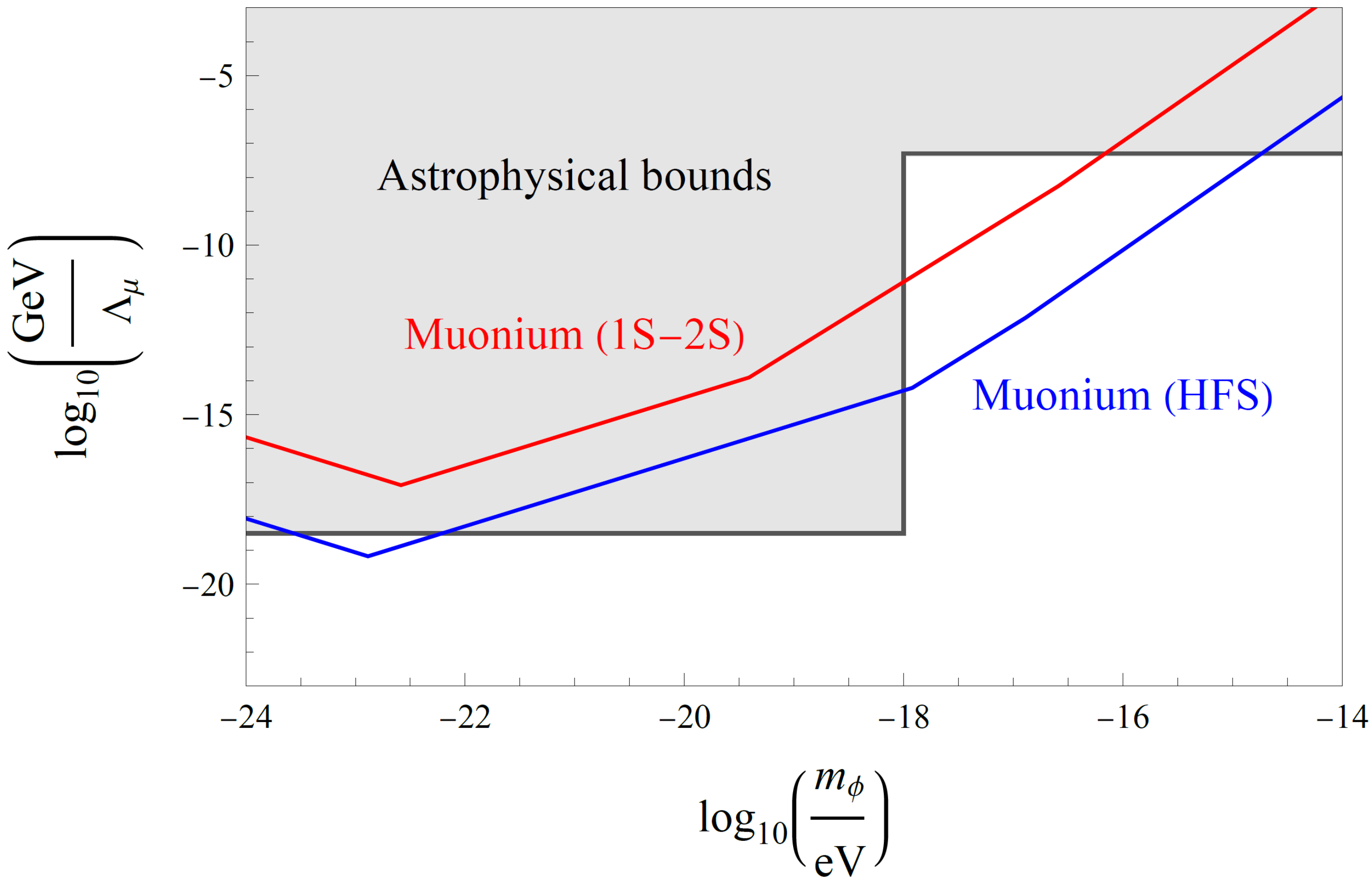
$$\Delta E_{\text{Fermi}} = \frac{8 m_r^3 \alpha^4}{3 m_e m_\mu} \quad \Rightarrow \quad \frac{\Delta \nu_{\text{HFS}}}{\nu_{\text{HFS}}} \approx 4\frac{\Delta\alpha}{\alpha} + 2\frac{\Delta m_e}{m_e} - \frac{\Delta m_\mu}{m_\mu}$$

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

[Stadnik, arXiv:2206.10808]

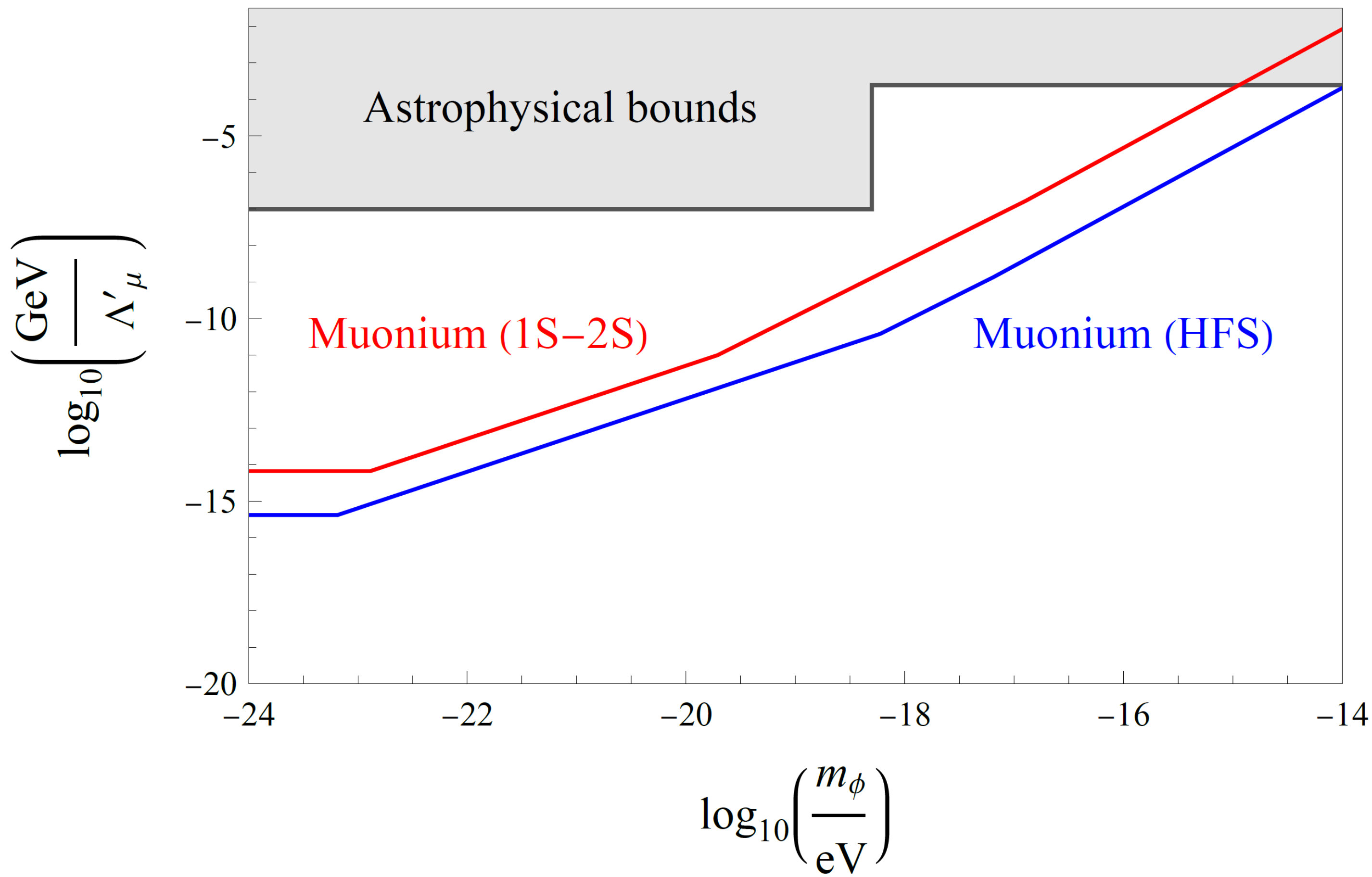
Up to 7 orders of magnitude improvement possible with existing datasets!



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

[Stadnik, arXiv:2206.10808]

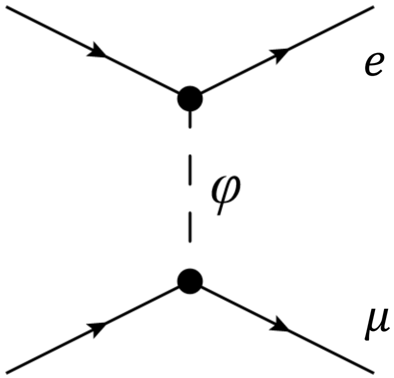
Up to 8 orders of magnitude improvement possible with existing datasets!



Probing Scalar-Muon Coupling with Muonium Free-fall

[Stadnik, arXiv:2206.10808]

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



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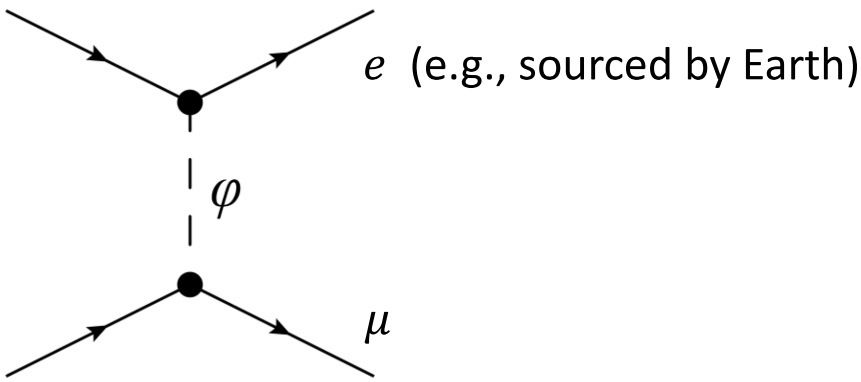

Local value of g measured in free-fall experiments using muonium would differ from experiments using non-muon-based test masses

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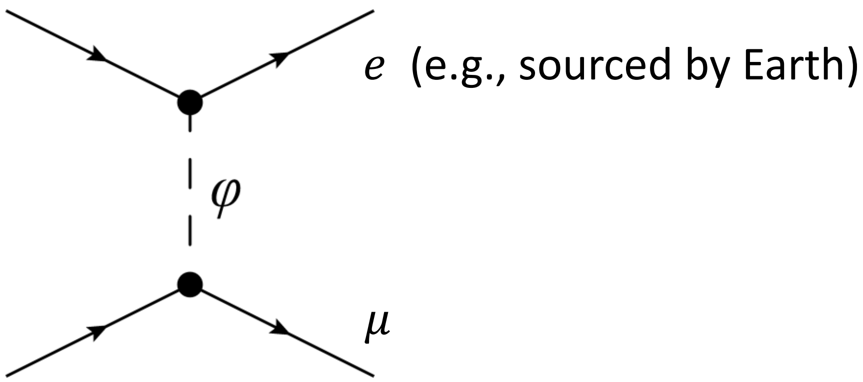

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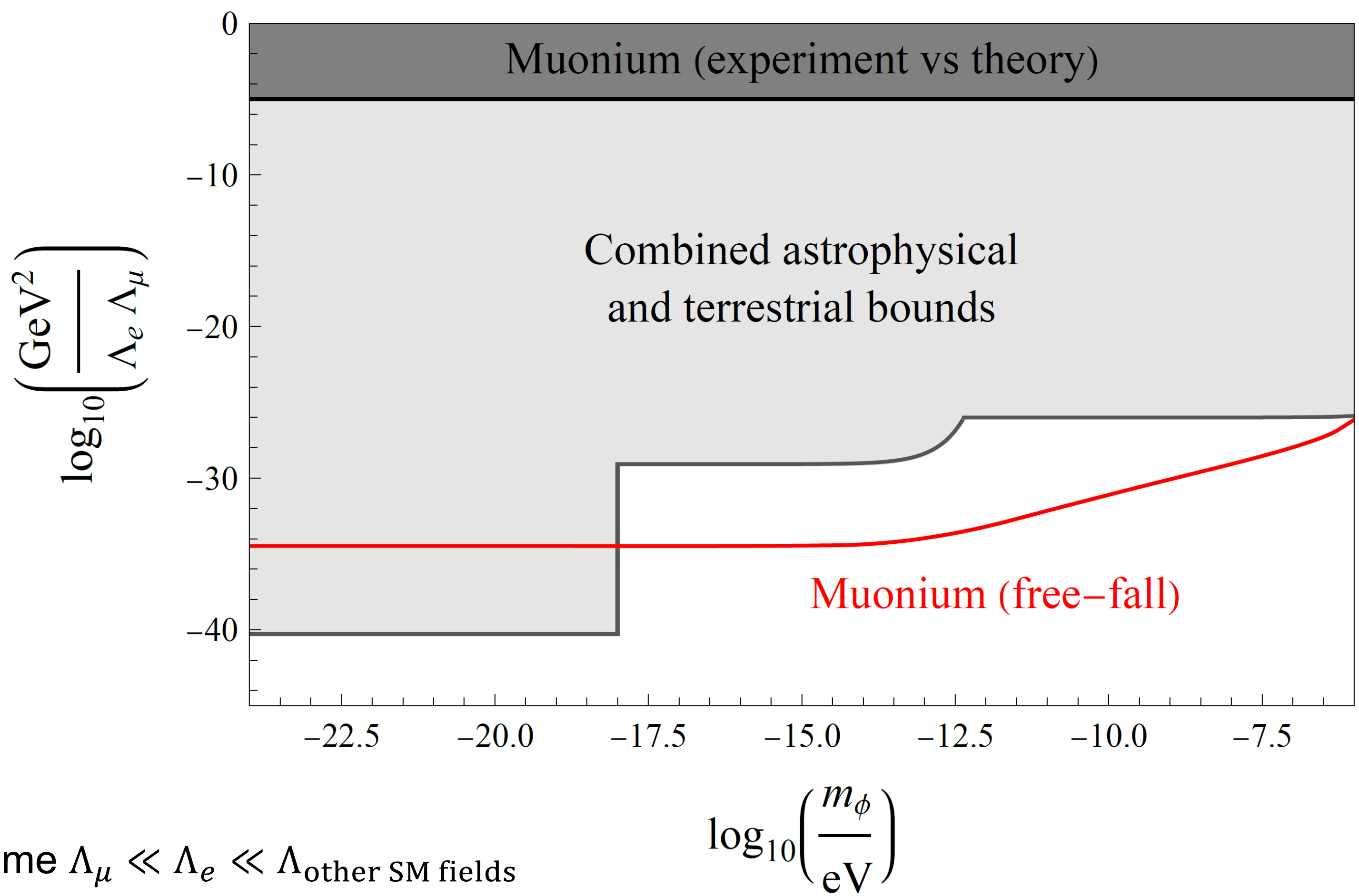
Recently started LEMING experiment at the Paul Scherrer Institute aims to measure g with a precision of $\Delta g / g \sim 0.1$ using muonium

Probing Scalar-Muon Coupling with Muonium Free-fall

[Stadnik, arXiv:2206.10808]

Up to 5 orders of magnitude improvement possible with ongoing measurements!



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 $\sim 10^8$ 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

Low-mass Spin-0 Dark Matter

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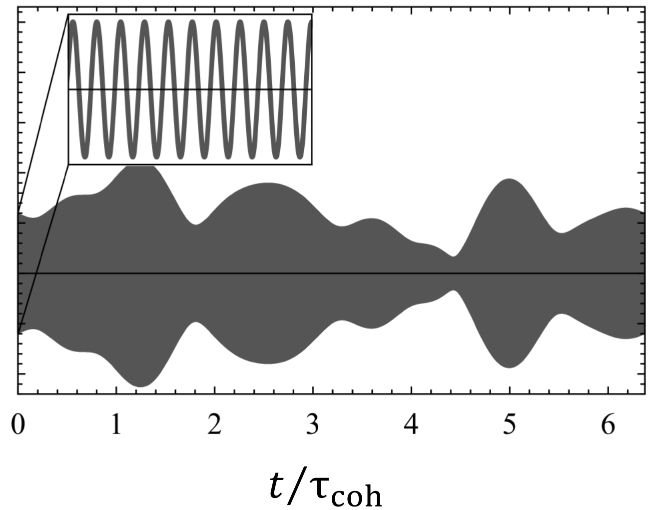
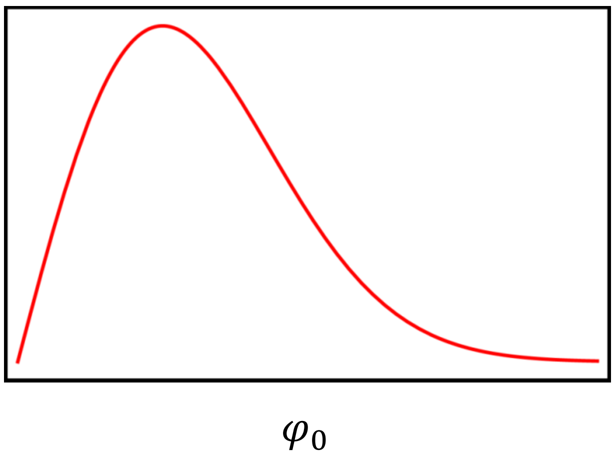
Evolution of φ_0 with time



Probability distribution function of φ_0 (e.g., Rayleigh distribution)



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)]

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

$$\mathcal{L}_f = -\frac{\varphi}{\Lambda_f} m_f \bar{f} f \approx -\frac{\varphi_0\cos(m_\varphi t)}{\Lambda_f} m_f \bar{f} f \Rightarrow \frac{\delta m_f}{m_f} \approx \frac{\varphi_0\cos(m_\varphi t)}{\Lambda_f}$$

$$\varphi = \varphi_0\cos(m_\varphi t - \boldsymbol{p}_\varphi \cdot \boldsymbol{x}) \Rightarrow \boldsymbol{F} \propto \boldsymbol{p}_\varphi \sin(m_\varphi t)$$

$$\left.\begin{aligned} \mathcal{L}'_\gamma &= \frac{\varphi^2}{(\Lambda'_\gamma)^2}\frac{F_{\mu\nu}F^{\mu\nu}}{4} \\ \mathcal{L}'_f &= -\frac{\varphi^2}{(\Lambda'_f)^2} m_f \bar{f} f \end{aligned}\right\} \Rightarrow \left\{\begin{aligned} &\frac{\delta\alpha}{\alpha} \propto \frac{\delta m_f}{m_f} \propto \Delta\rho_\varphi \\ &\boldsymbol{F} \propto \boldsymbol{\nabla}\rho_\varphi \end{aligned}\right.$$

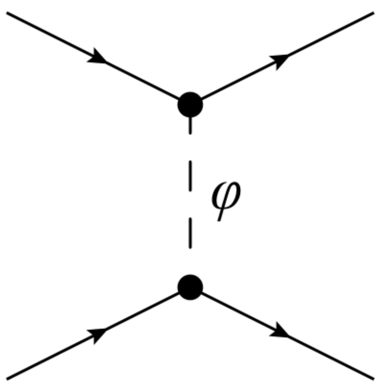
Fifth Forces: Linear vs Quadratic Couplings

[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 ($\varphi^2 \bar{X} X$)

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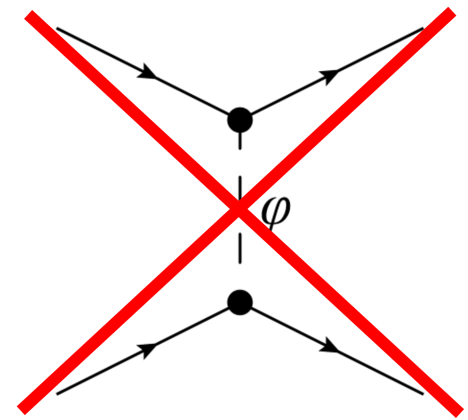

$$m_{\text{eff}}^2(\rho) = m_\varphi^2 \mp \kappa' \rho$$

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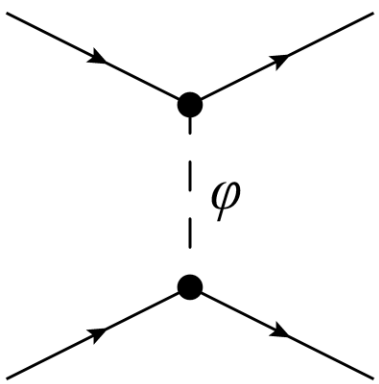

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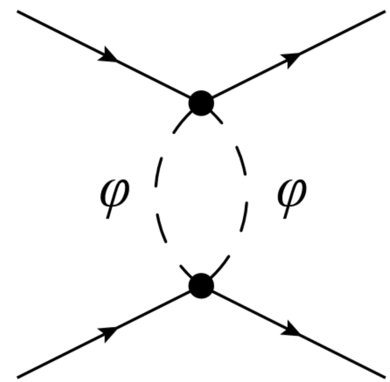

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$$\varphi = \underline{\varphi_0 \cos(m_\varphi t)} \left(1 \pm \frac{B}{r}\right) - \hbar C \frac{e^{-2m_\varphi r}}{r^3}$$

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

"Fifth-force" experiments: torsion pendula, atom interferometry

Gradients + amplification/screening