

Searching for Ultralight Scalar Dark Matter with Muonium and Muonic Atoms

Yevgeny Stadnik

Australian Research Council DECRA Fellow

University of Sydney, Australia

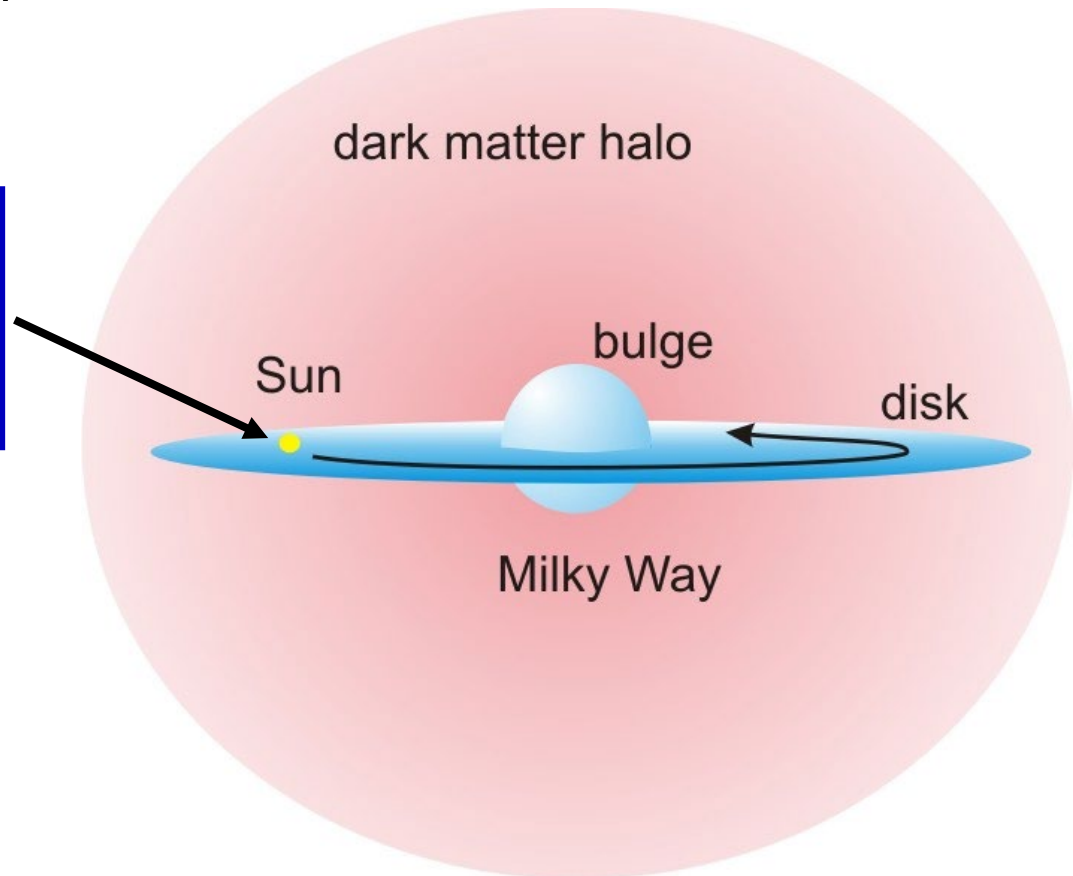
[arXiv:2206.10808](https://arxiv.org/abs/2206.10808), PRL (In press)

5th NPKEI Workshop, Busan, South Korea, 4 – 9 June 2023

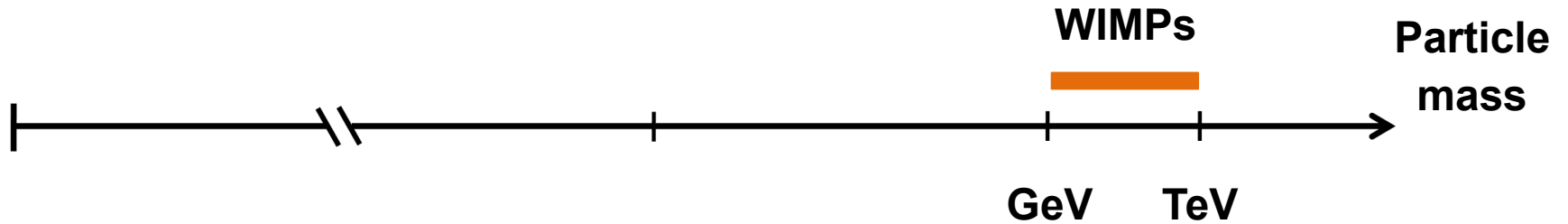
Dark Matter

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

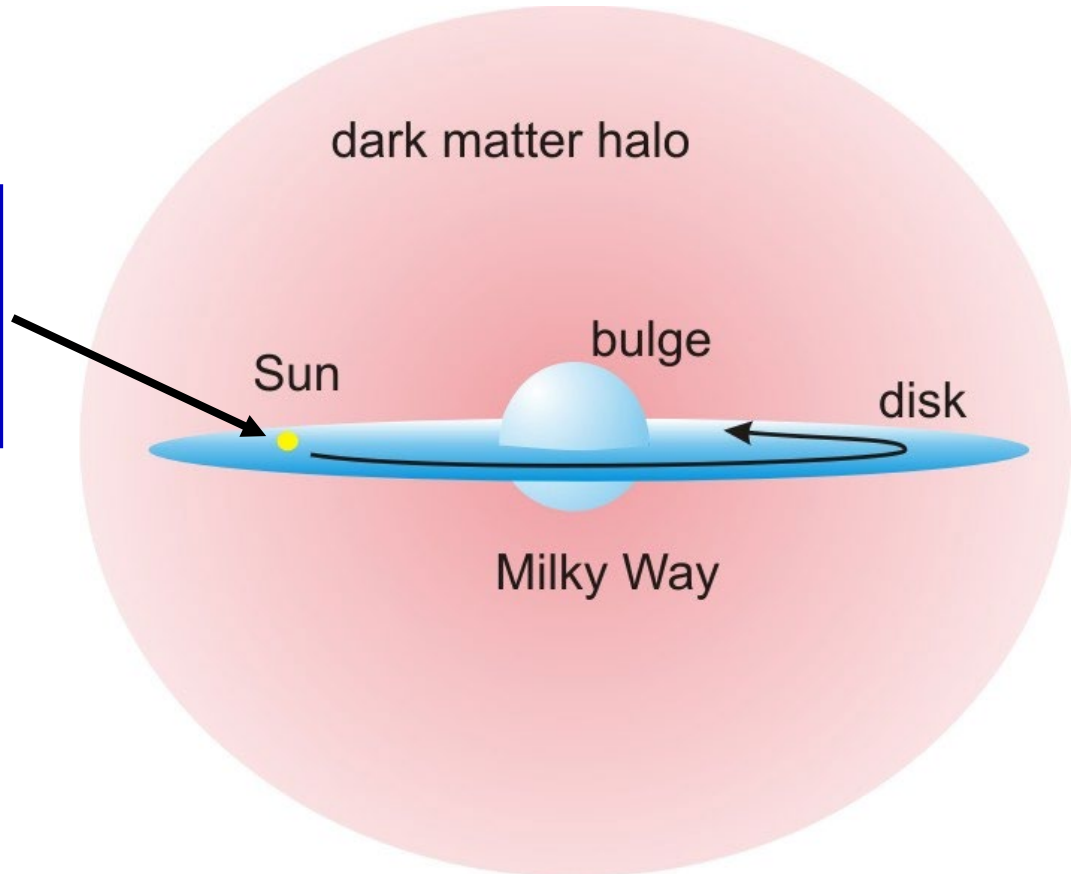
$$\rho_{\text{DM}} \approx 0.4 \text{ GeV/cm}^3$$
$$v_{\text{DM}} \sim 300 \text{ km/s}$$



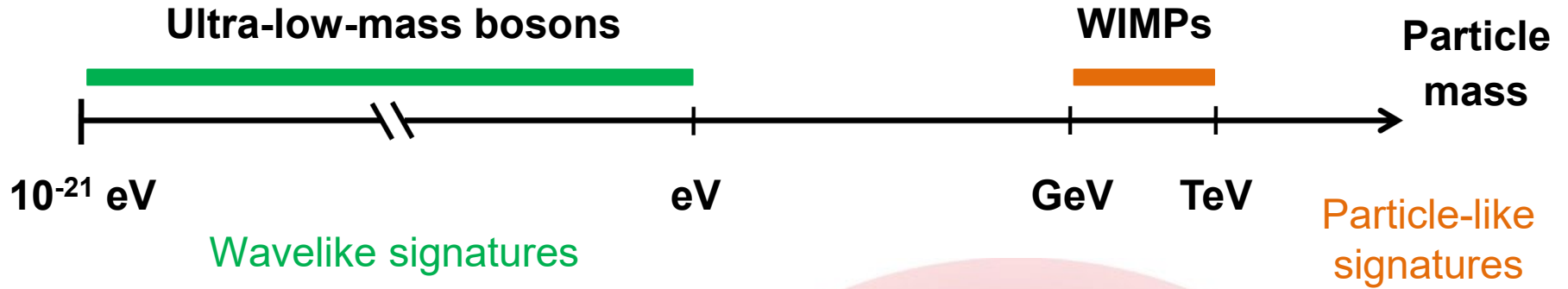
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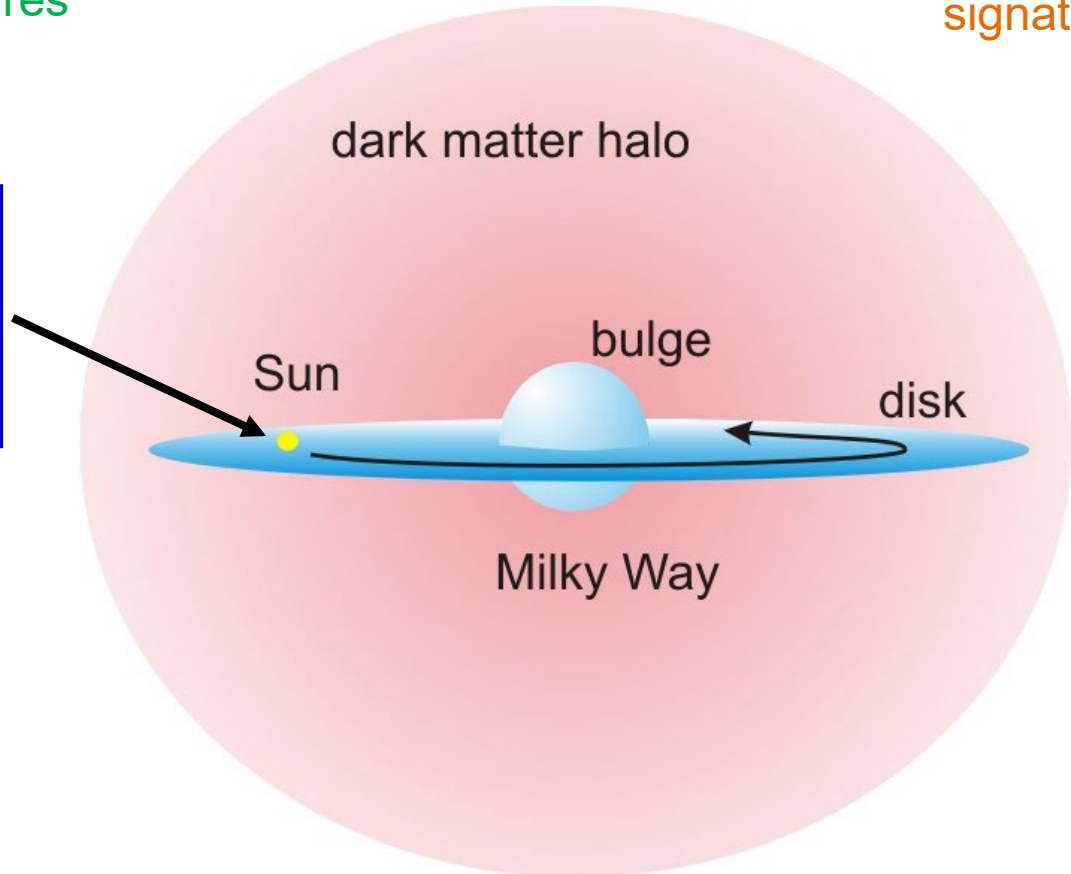


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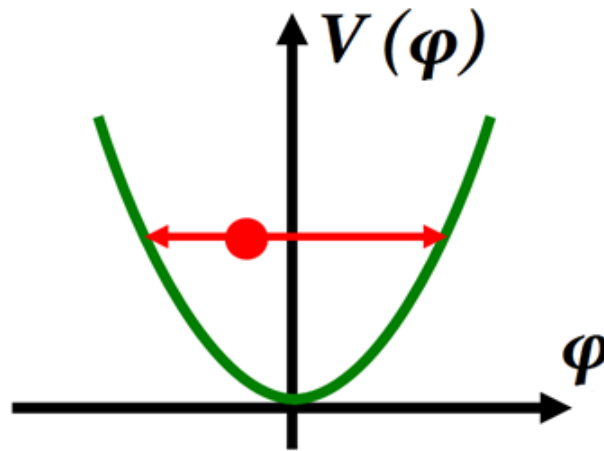
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Low-mass Spin-0 Dark Matter

- 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 $\rho_\varphi \approx m_\varphi^2 \varphi_0^2 / 2$ ($\rho_{\text{DM,local}} \approx 0.4 \text{ GeV/cm}^3$)

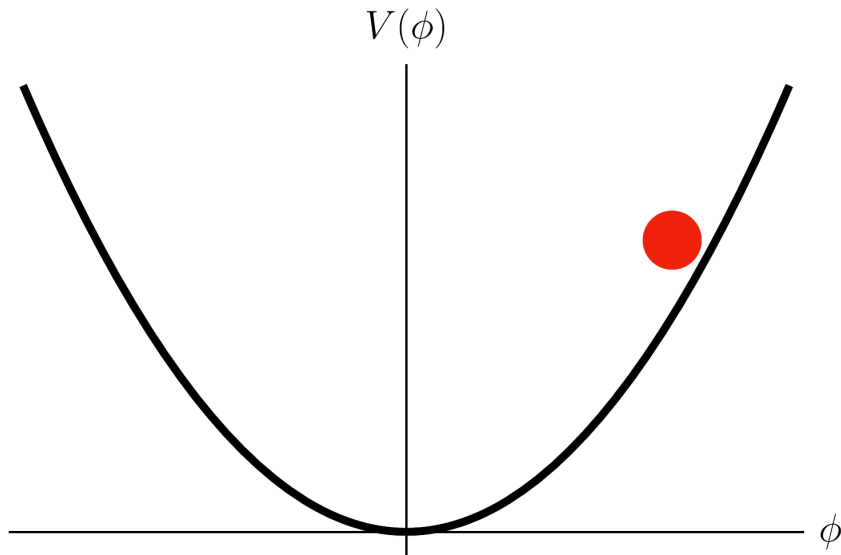


$$V(\varphi) = \frac{m_\varphi^2 \varphi^2}{2}$$

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

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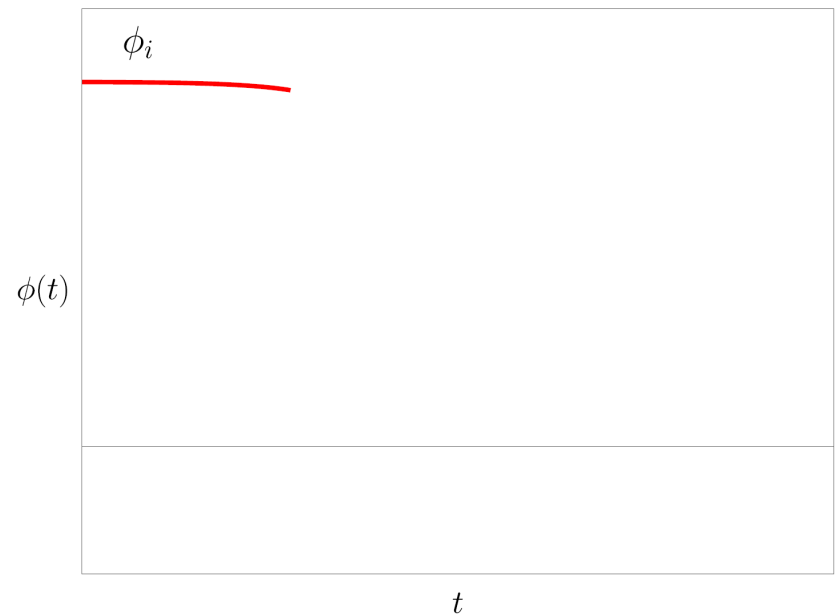
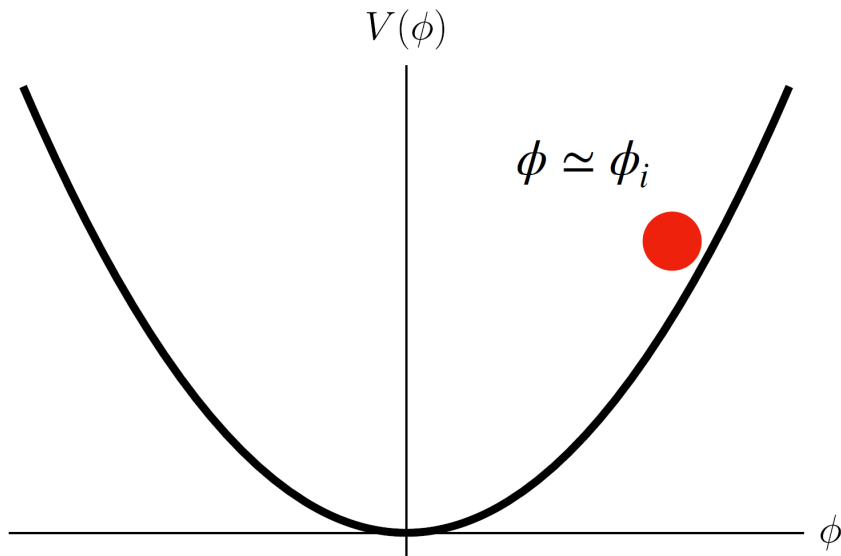


$$\ddot{\phi} + 3H(t)\dot{\phi} + m_\varphi^2\phi \approx 0$$
$$H(t) = \dot{a}(t)/a(t)$$

← Damped harmonic oscillator with a time-dependent frictional term

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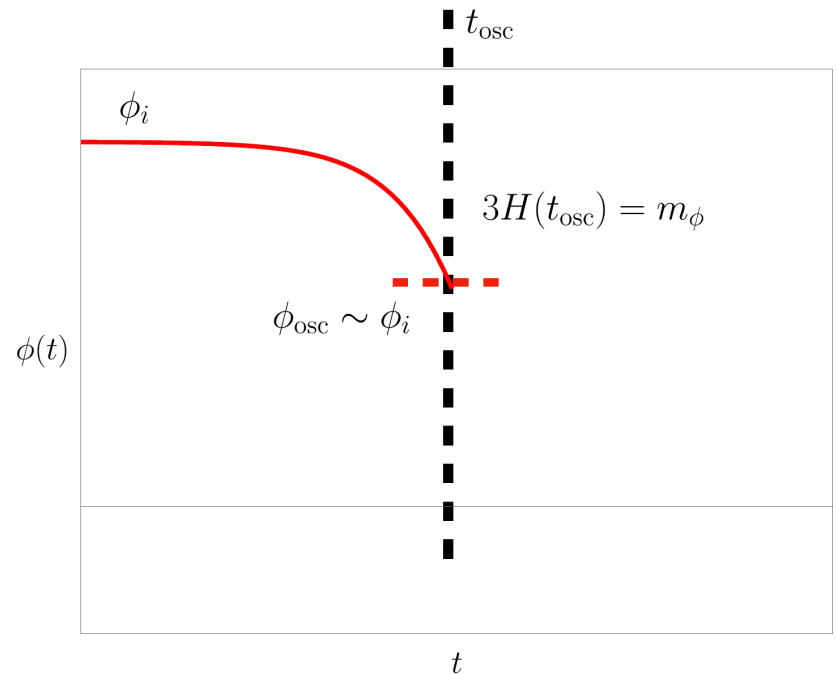
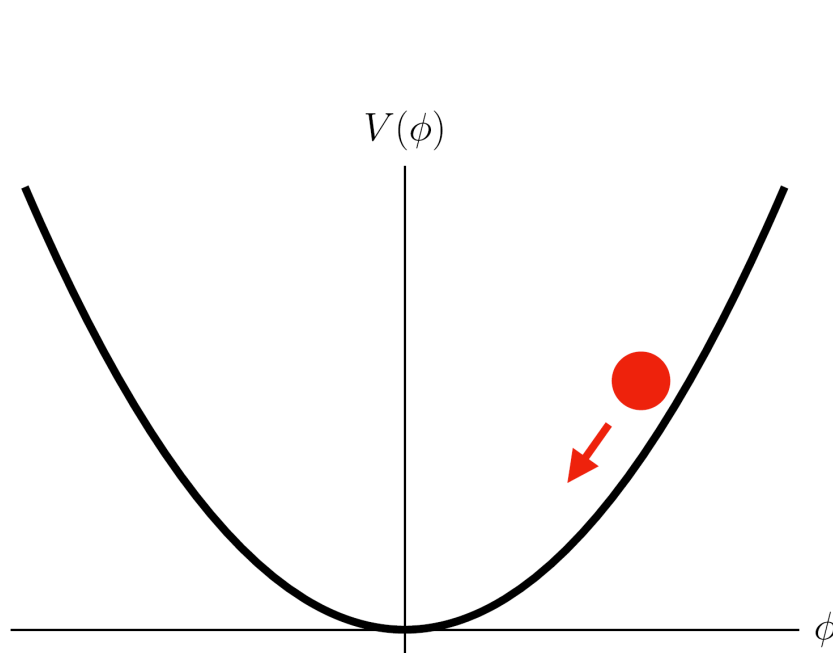
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$$m_\varphi \ll 3H(t) \sim 1/t$$

Overdamped regime

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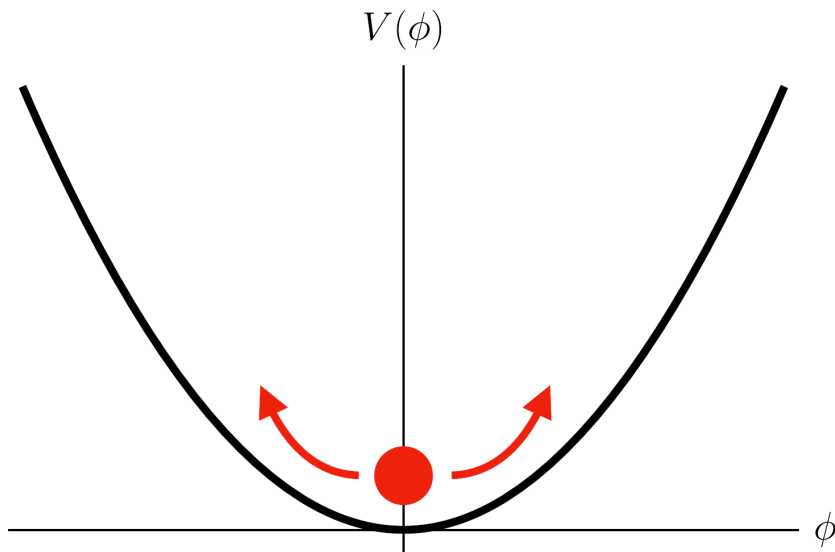
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Critically damped regime

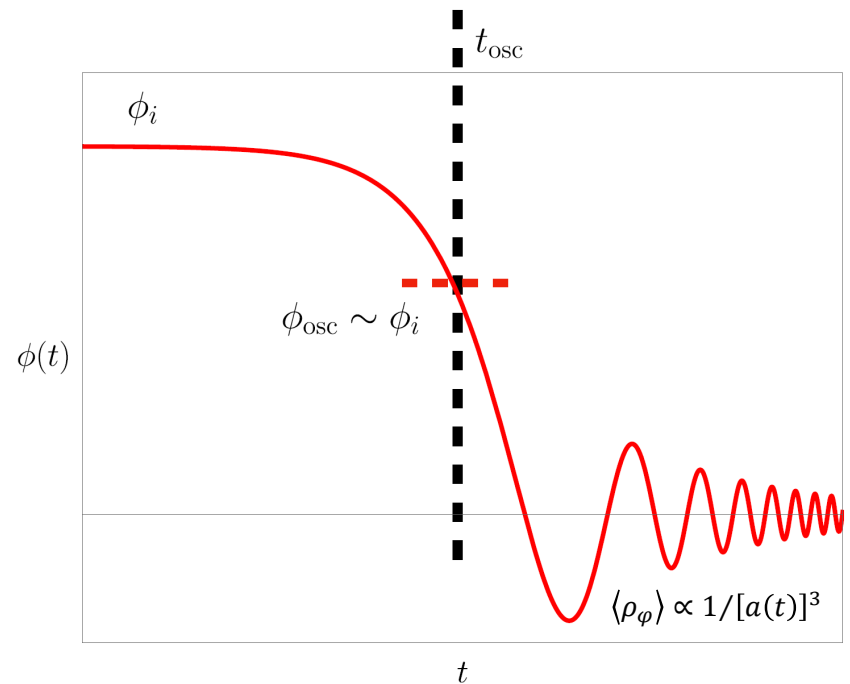
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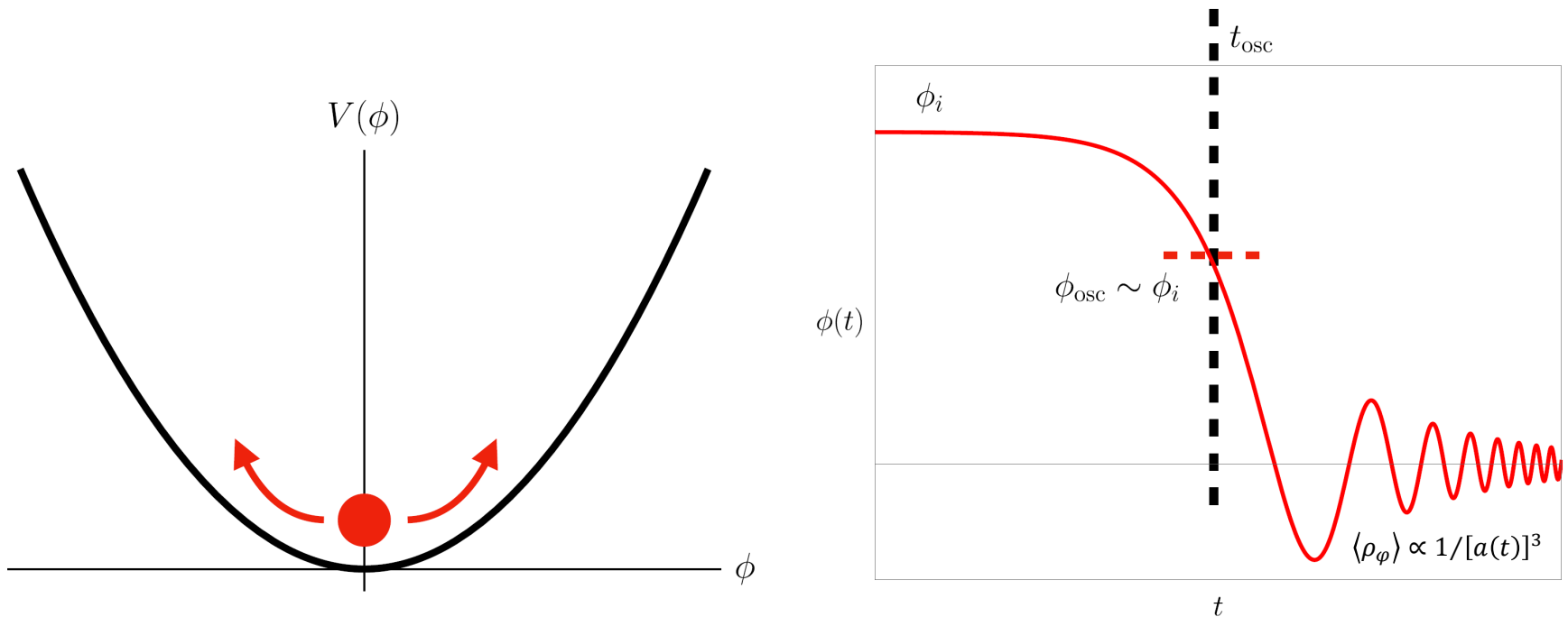
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“Vacuum misalignment” mechanism – non-thermal production, ρ_φ governed by initial conditions (φ_i), redshifts as $\rho_\varphi \propto 1/[a(t)]^3$, with $\langle p_\varphi \rangle \ll \rho_\varphi$

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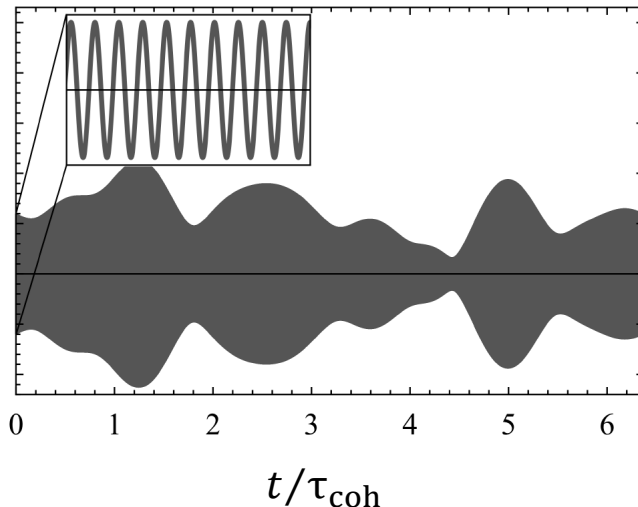
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 $v_{\text{DM}} \sim 300 \text{ km/s}$ $Q_{\text{DM}} \sim 10^6$

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Evolution of φ_0 with time



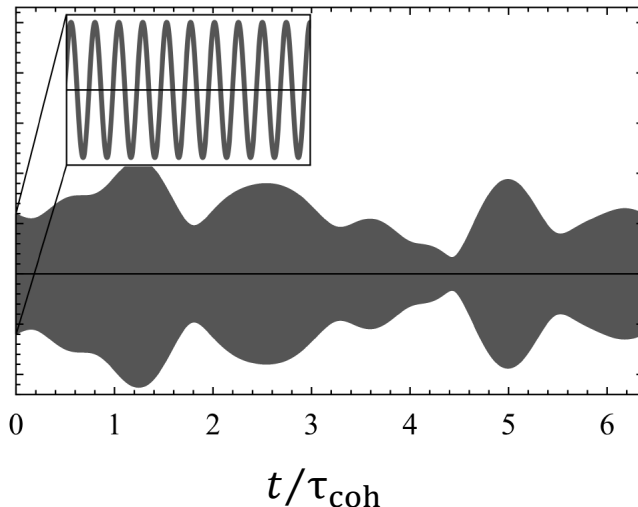
$$\varphi(t) \sim \sum_{i=1}^N \frac{\varphi_0}{\sqrt{N}} \cos\left(m_\varphi t + \frac{m_\varphi v_i^2 t}{2} + \theta_i\right)$$

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

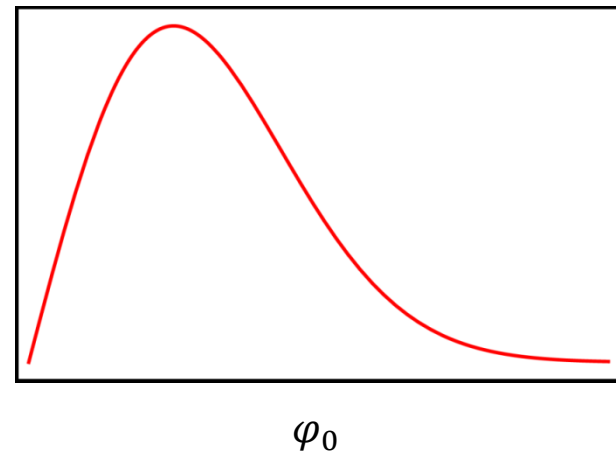
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Evolution of φ_0 with time



Probability distribution function of φ_0
(Rayleigh distribution)



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- *Classical* field for $m_\varphi \lesssim 1 \text{ eV}$, since $n_\varphi (\lambda_{\text{dB},\varphi} / 2\pi)^3 \gg 1$

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

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- $10^{-21} \text{ eV} \lesssim m_\varphi \lesssim 1 \text{ eV} \Leftrightarrow 10^{-7} \text{ Hz} \lesssim f_{\text{DM}} \lesssim 10^{14} \text{ Hz}$
 \uparrow $T_{\text{osc}} \sim 1 \text{ month}$ **IR frequencies**

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

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

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

- **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)]

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

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

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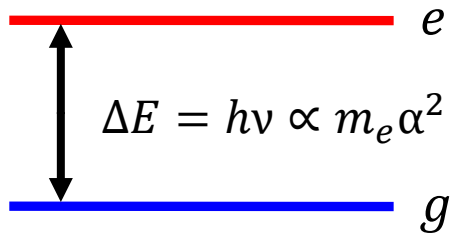
⇓

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

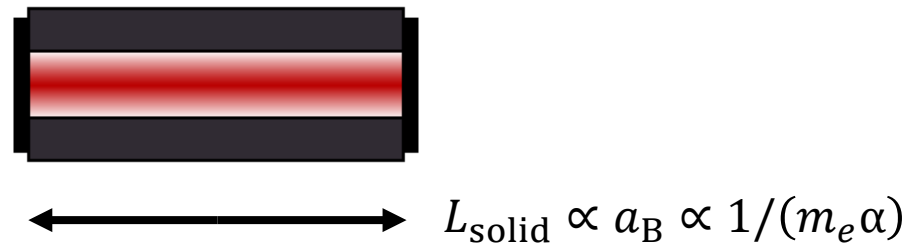
Probes of Ultralight Scalar DM

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

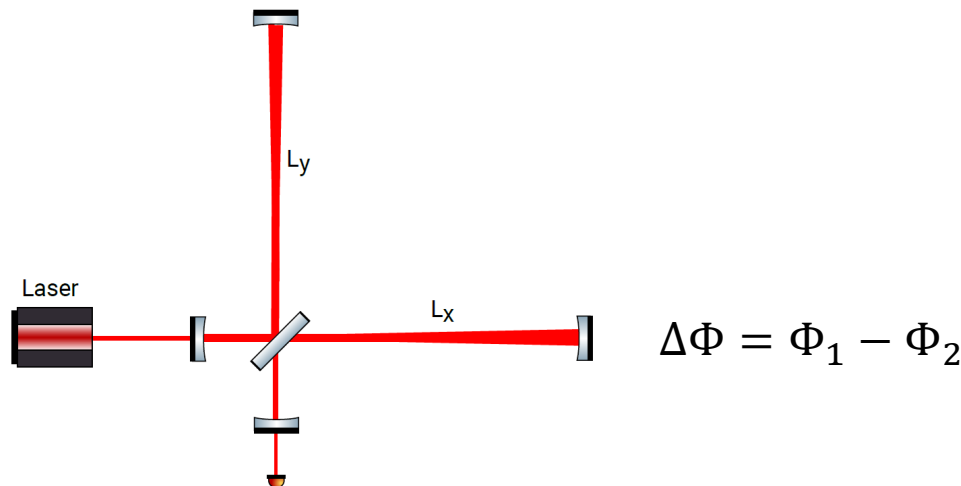
Atomic clocks



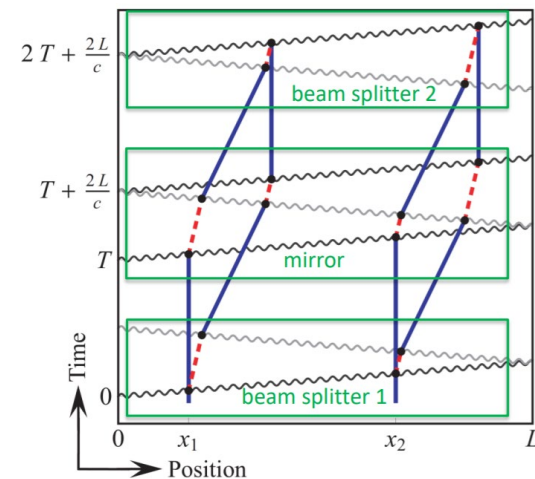
Optical cavities



Laser interferometers



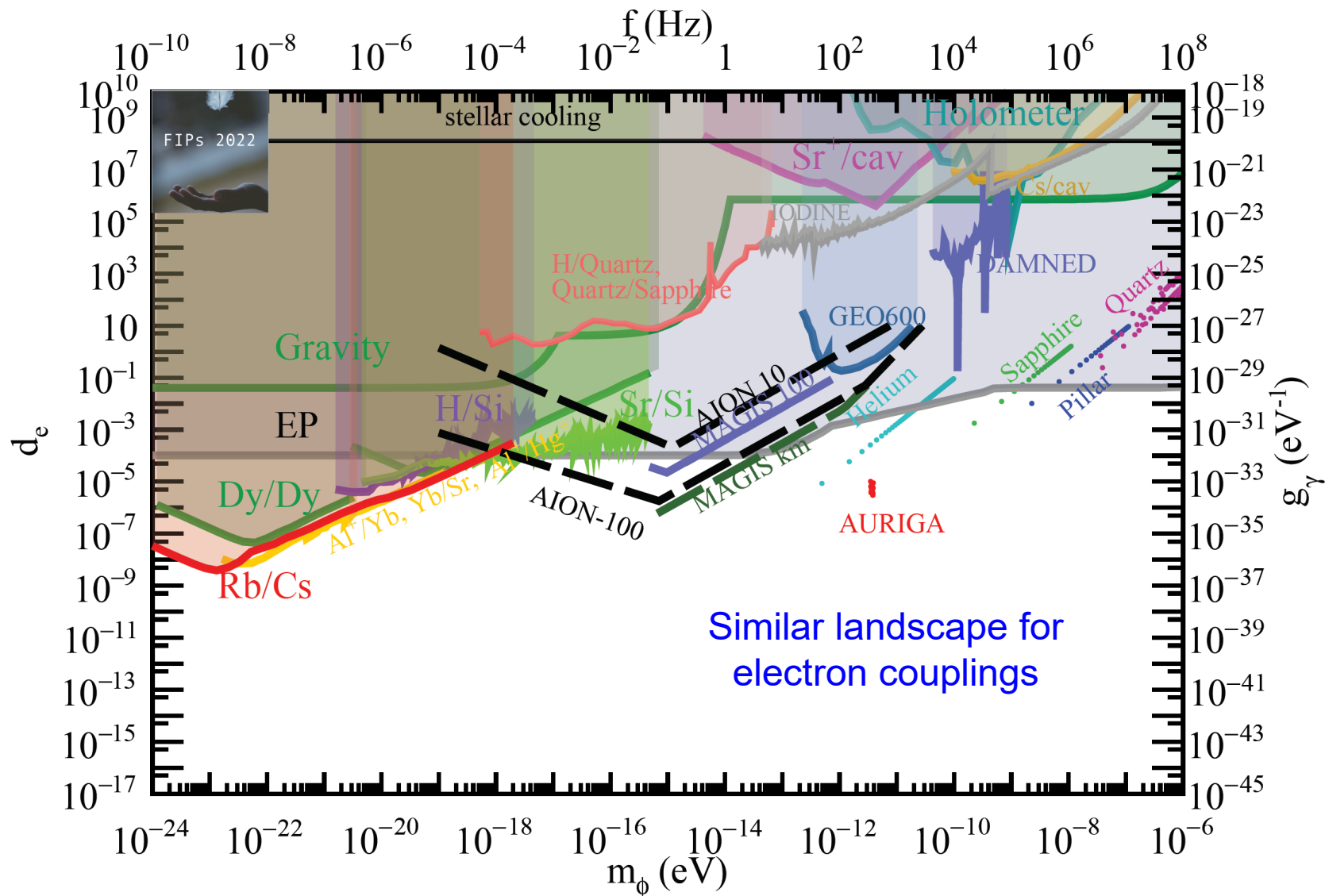
Atom interferometers (proposed)



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]



Muonic Probes of Ultralight Scalar DM

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- Extra motivation for muonic couplings from persistence of anomalies in muon physics, such as:
 - Proton radius puzzle
 - $(g - 2)_\mu$ puzzle

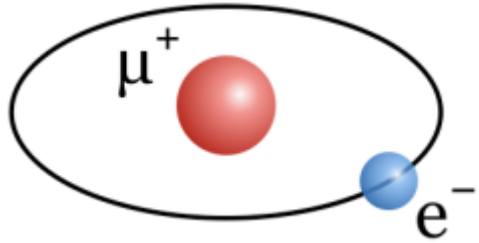
Muonic Probes of Ultralight Scalar DM

- 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
- 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)

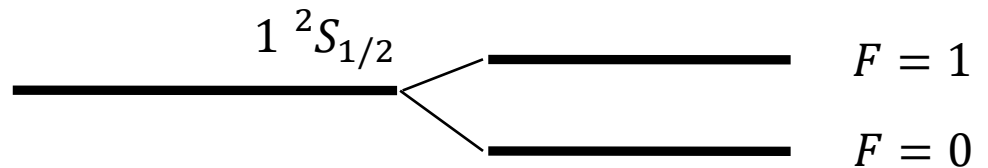
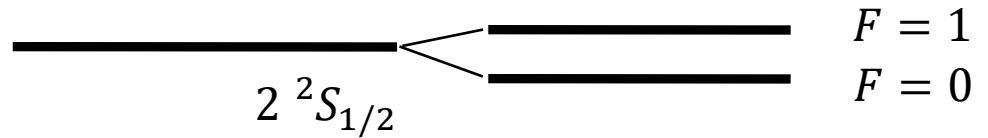
Probing Oscillations of m_μ with Muonium Spectroscopy

[Stadnik, arXiv:2206.10808; *PRL* (In press)]

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



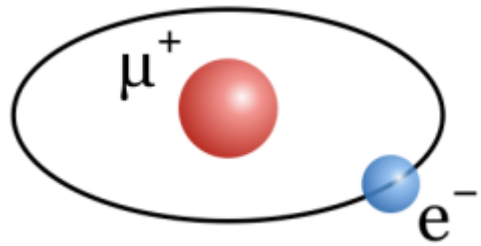
$$\tau_\mu \approx 2.2 \mu\text{s}$$



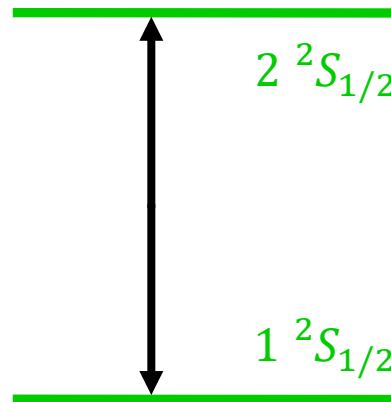
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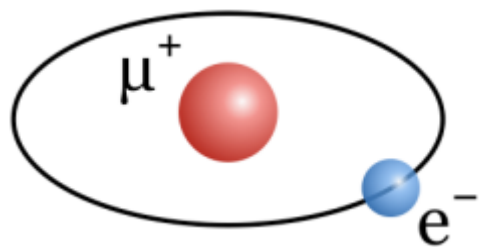


$$E_n^{\text{Rydberg}} = -\frac{m_r \alpha^2}{2n^2} \Rightarrow \frac{\Delta v_{1S-2S}}{v_{1S-2S}} \approx 2 \frac{\Delta \alpha}{\alpha} + \frac{\Delta m_e}{m_e} + \frac{m_e}{m_\mu} \frac{\Delta m_\mu}{m_\mu}$$

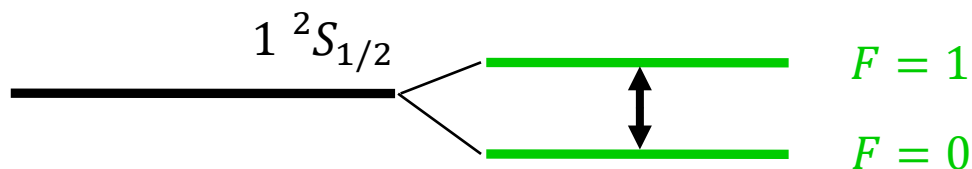
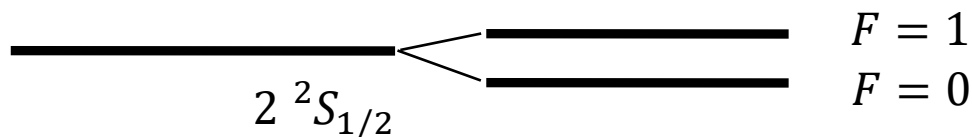
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$\tau_\mu \approx 2.2 \mu\text{s}$



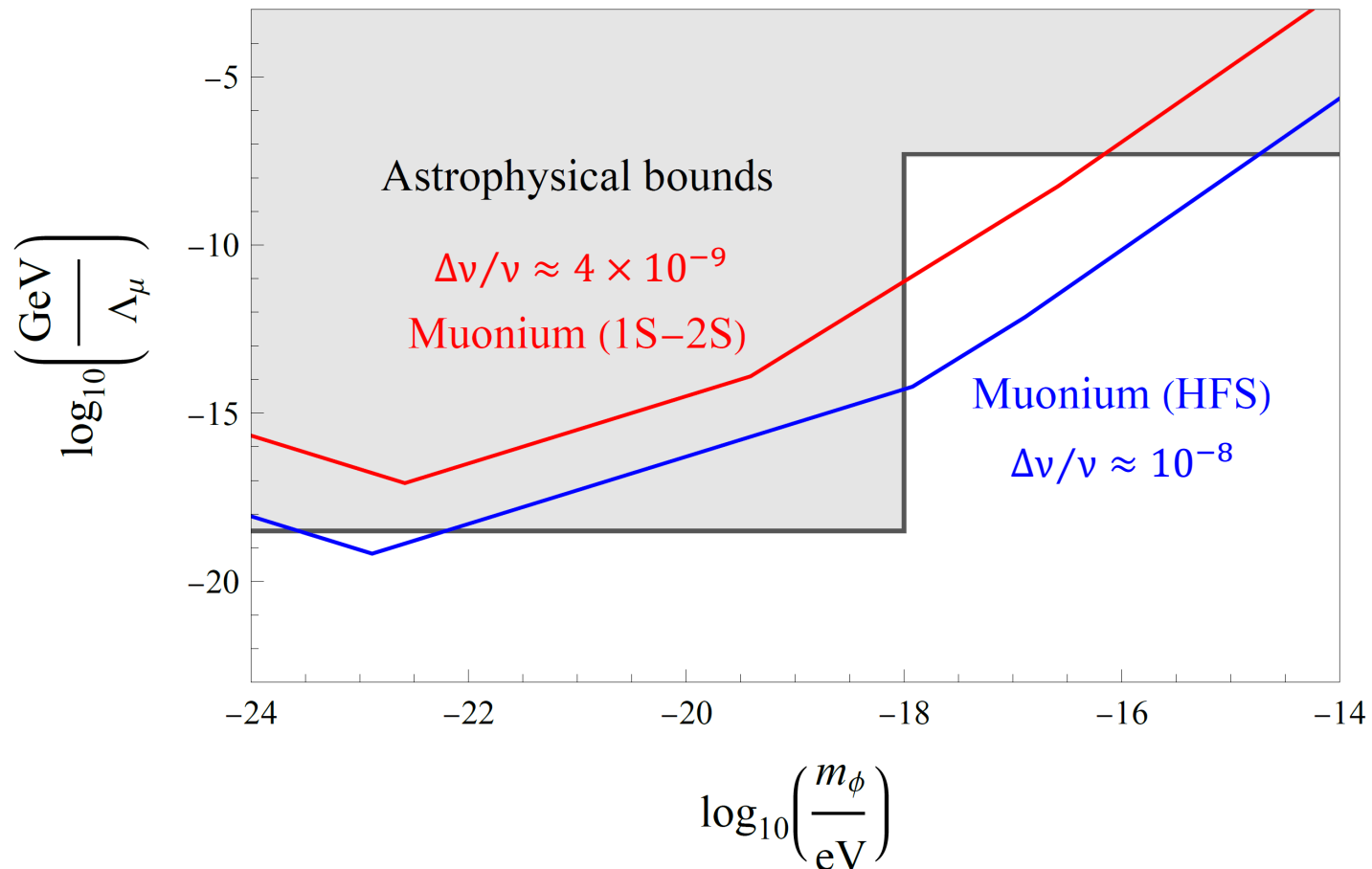
$$E_n^{\text{Rydberg}} = -\frac{m_r \alpha^2}{2n^2} \Rightarrow \frac{\Delta v_{1S-2S}}{v_{1S-2S}} \approx 2 \frac{\Delta \alpha}{\alpha} + \frac{\Delta m_e}{m_e} + \frac{m_e}{m_\mu} \frac{\Delta m_\mu}{m_\mu}$$

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

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

[Stadnik, arXiv:2206.10808; *PRL* (In press)]

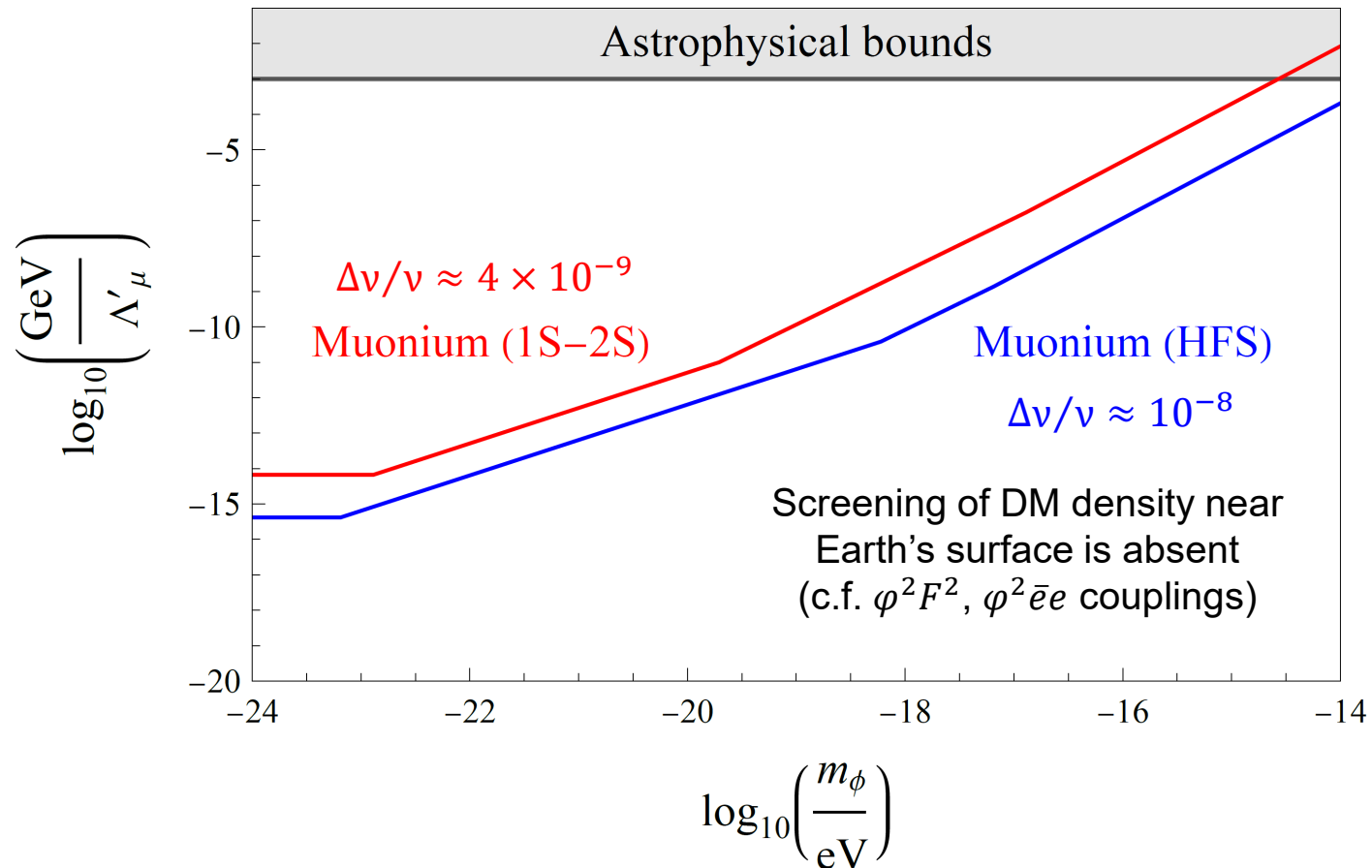
**Up to 7 orders of magnitude improvement possible with existing datasets!
(Best existing datasets from muonium experiments at LAMPF and RAL in 1990s)**



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

[Stadnik, arXiv:2206.10808; *PRL* (In press)]

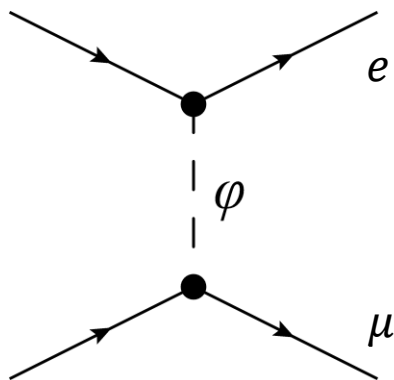
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Probing Scalar-Muon Coupling with Muonium Free-fall

[Stadnik, arXiv:2206.10808; *PRL* (In press)]

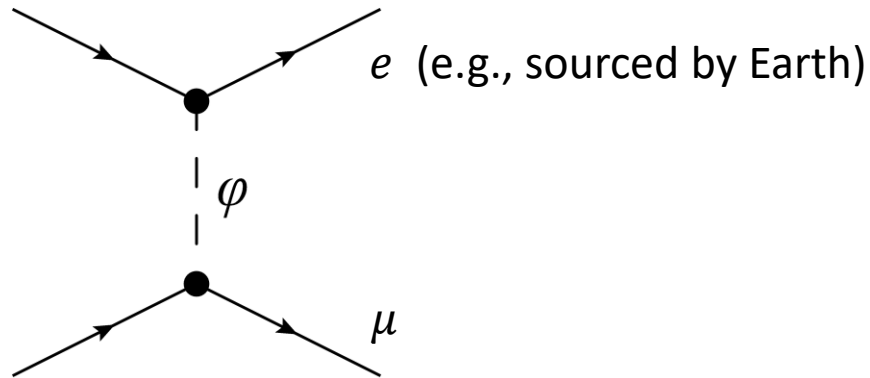
$$\mathcal{L}_{\text{lin}} = -\frac{\varphi}{\Lambda_e} m_e \bar{e}e - \frac{\varphi}{\Lambda_\mu} m_\mu \bar{\mu}\mu \Rightarrow V_{e\mu}(r) \approx -\frac{m_e m_\mu e^{-m_\varphi r}}{\Lambda_e \Lambda_\mu 4\pi r}$$



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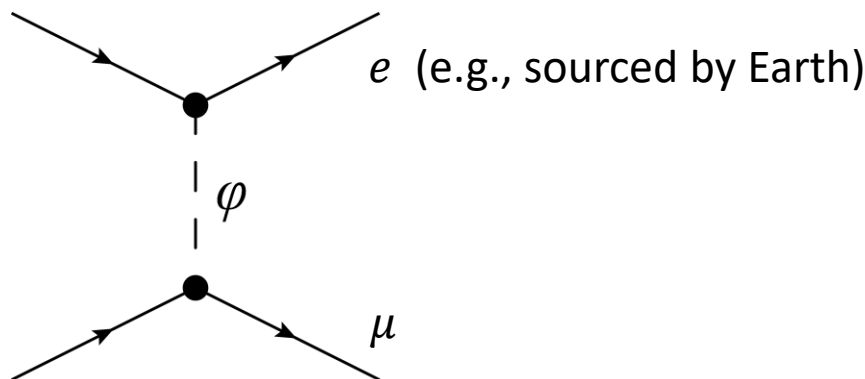


Local value of g measured in free-fall experiments using muonium would differ from experiments using non-muon-based test masses

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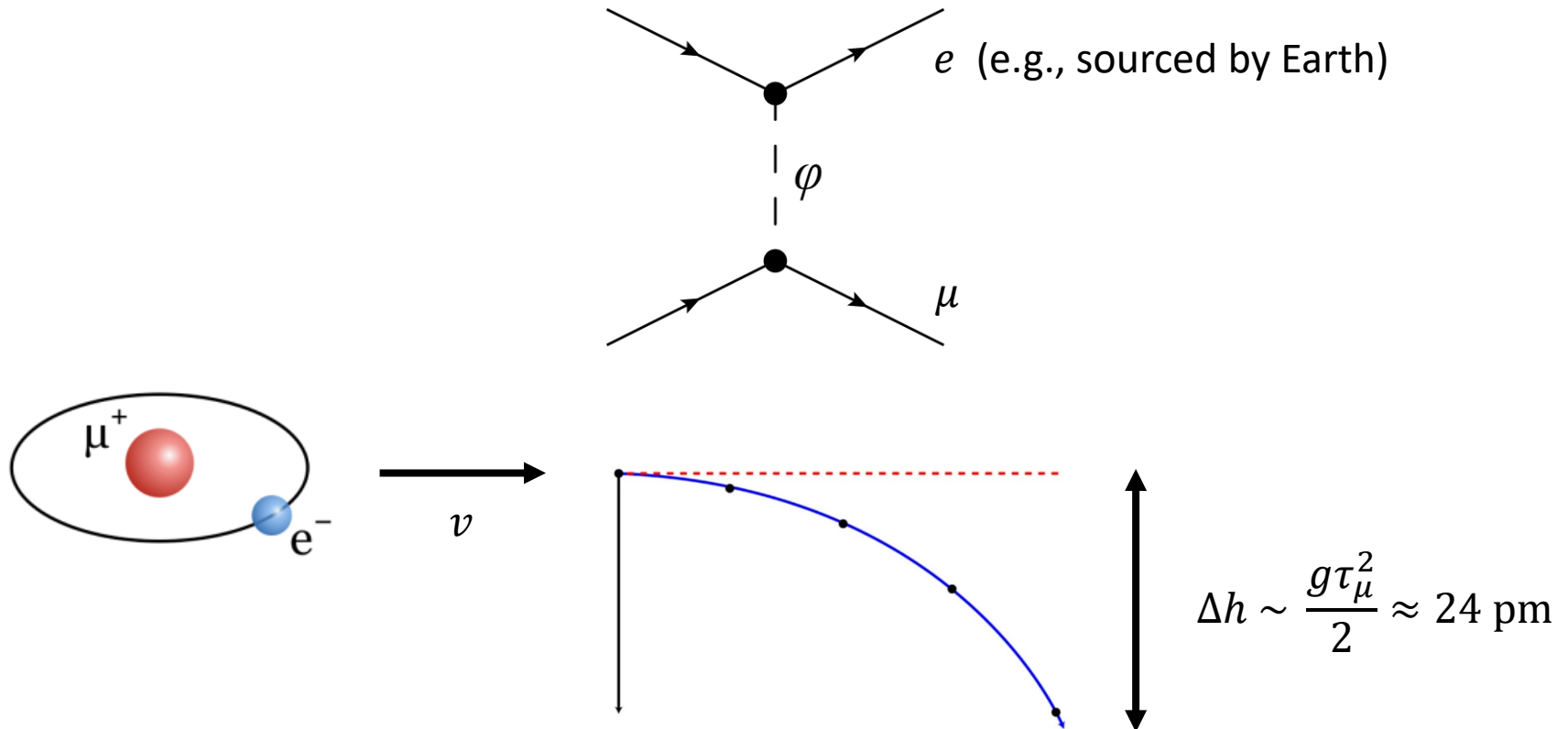
Local value of g measured in free-fall experiments using muonium would differ from experiments using non-muon-based test masses

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

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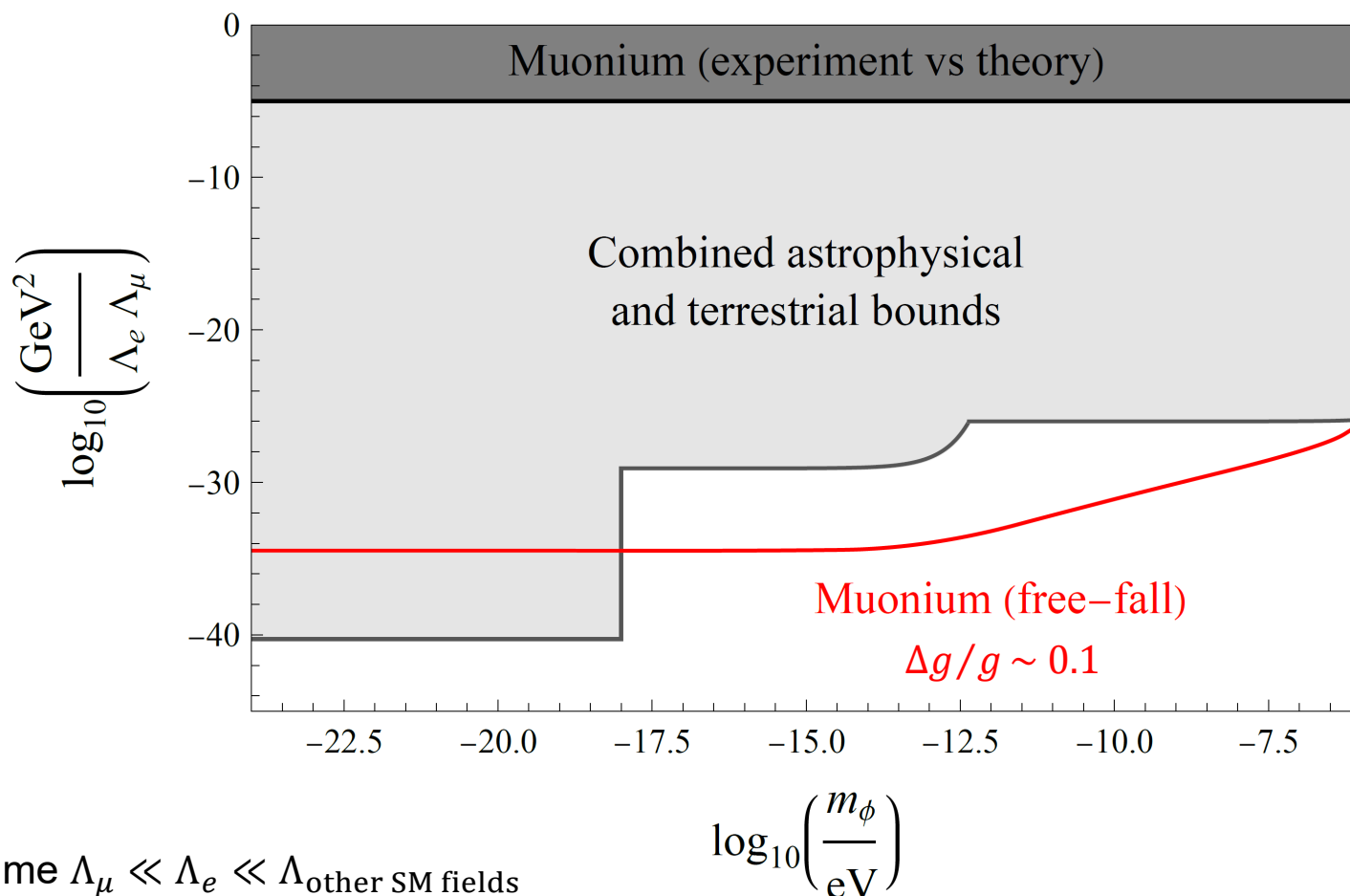
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Probing Scalar-Muon Coupling with Muonium Free-fall

[Stadnik, arXiv:2206.10808; *PRL* (In press)]

Up to 5 orders of magnitude improvement possible with ongoing measurements!
(New LEMING experiment at PSI targets a precision of $\Delta g/g \sim 0.1$)



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

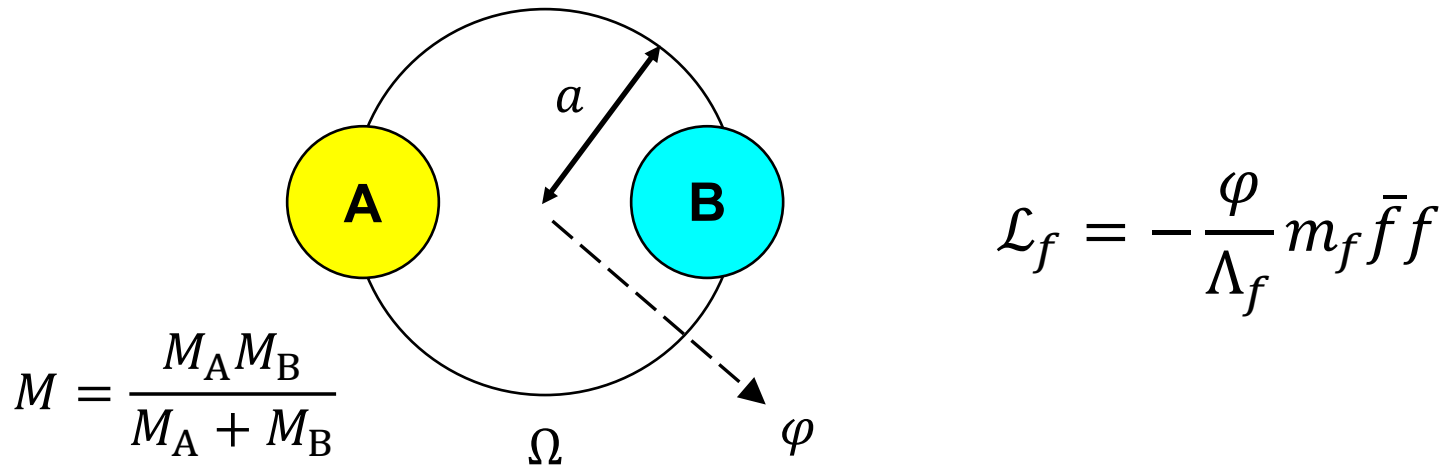
Summary

- 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)]



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

$$\frac{dE_\varphi}{dt} \sim \left(\frac{m_f}{\Lambda_f}\right)^2 (aM)^2 \Omega^4 \left(\frac{Q_A}{M_A} - \frac{Q_B}{M_B}\right)^2, \text{ for } \Omega a \ll 1$$

- Dipole nature requires $Q_A/M_A \neq Q_B/M_B$, which is readily satisfied, e.g., for neutron-star/white-dwarf binary systems in the case of $f = n, e, \mu$

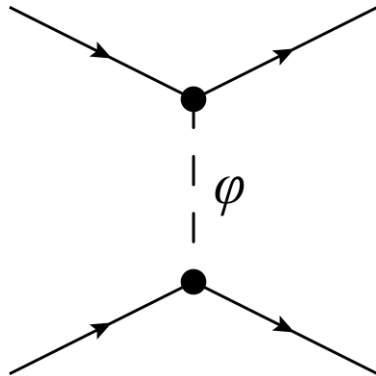
Fifth Forces: Linear vs Quadratic Couplings

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

$$\square\varphi + m_\varphi^2\varphi = \pm\kappa\rho \quad \text{Source term}$$



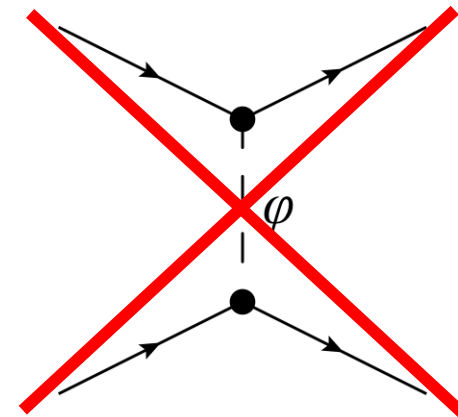
$$\varphi = \varphi_0 \cos(m_\varphi t) \pm A \frac{e^{-m_\varphi r}}{r}$$



Profile outside of a spherical body

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

$$\square\varphi + m_\varphi^2\varphi = \pm\kappa'\rho\varphi \quad \text{Effective mass}$$



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

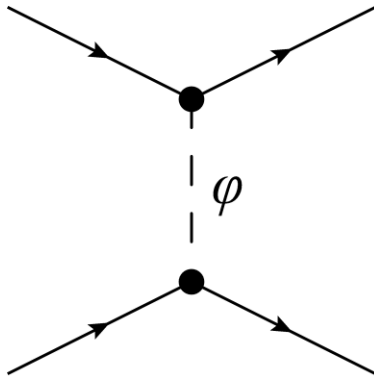
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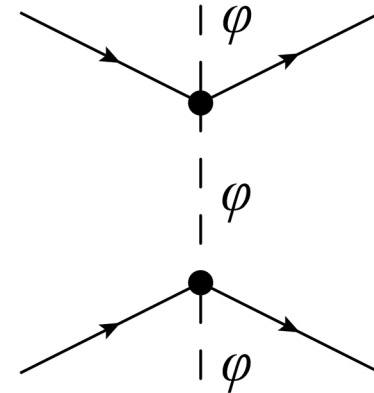


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↑
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↓
Gradients + amplification/screening

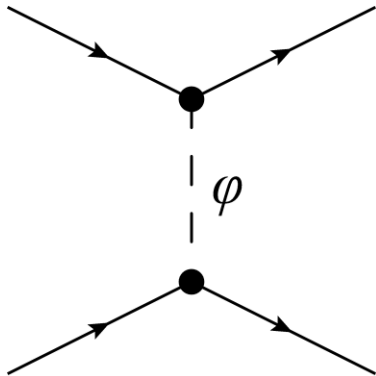
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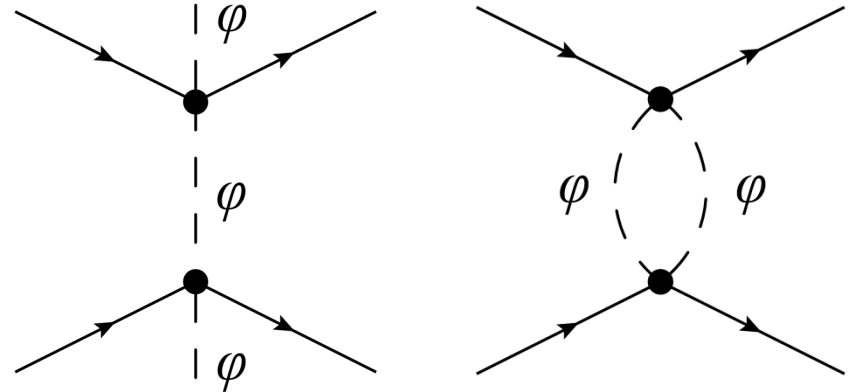
$$\varphi = \underline{\varphi_0 \cos(m_\varphi t)} \pm A \frac{e^{-m_\varphi r}}{r}$$

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

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

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

$$\square\varphi + m_\varphi^2\varphi = \pm\kappa'\rho\varphi \quad \text{Effective mass}$$



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

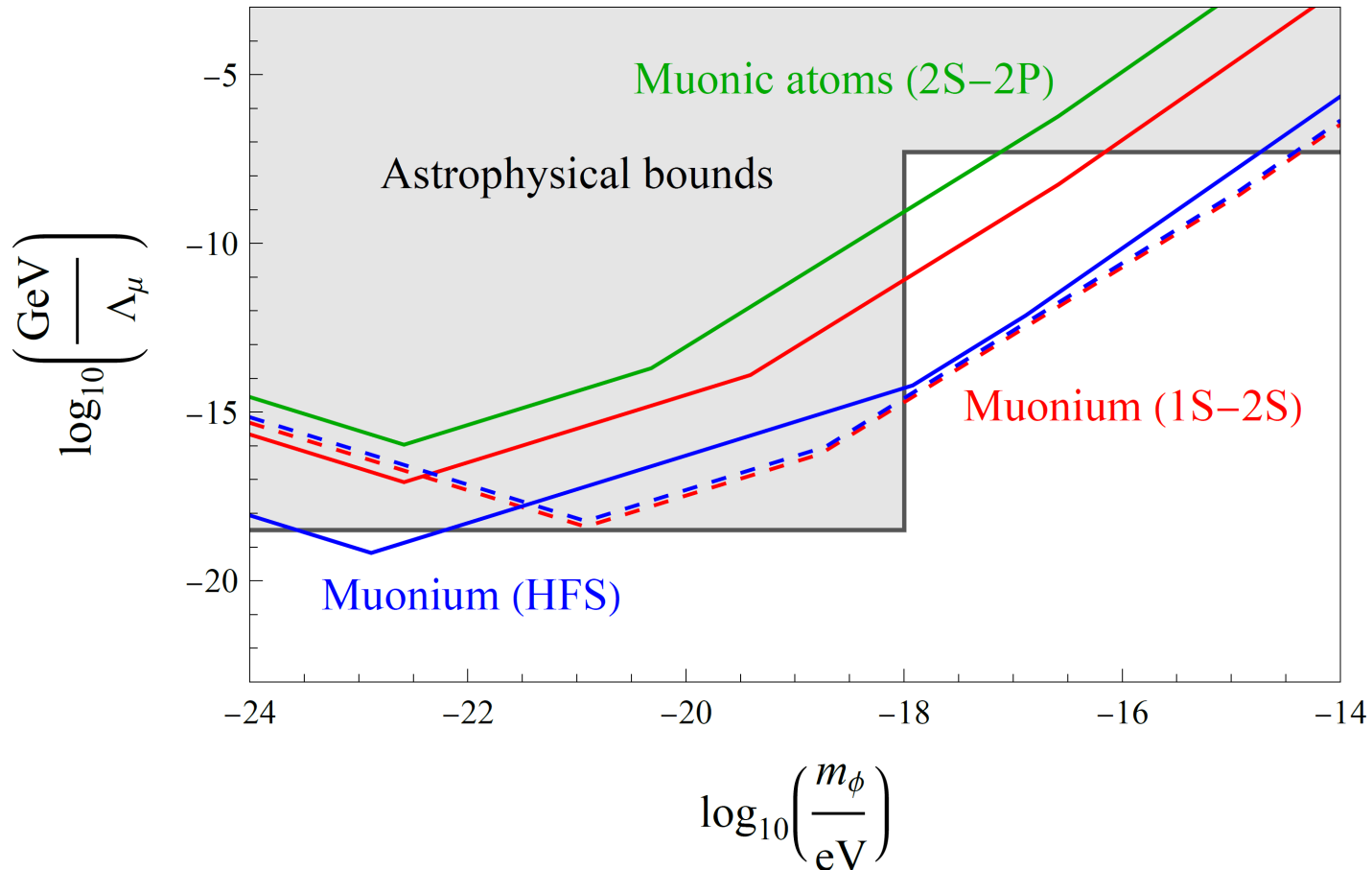


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