Searching for Ultralight Scalar Dark Matter with Muonium and Muonic Atoms

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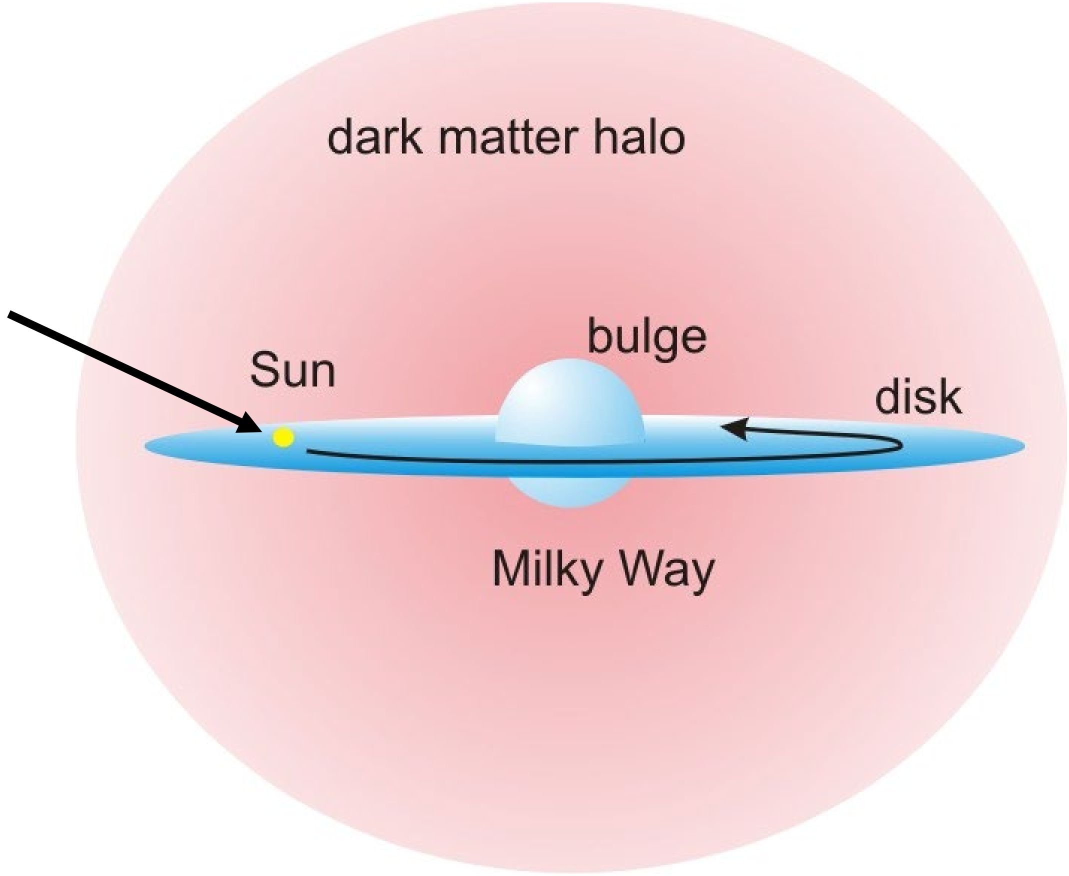
Dark Matter

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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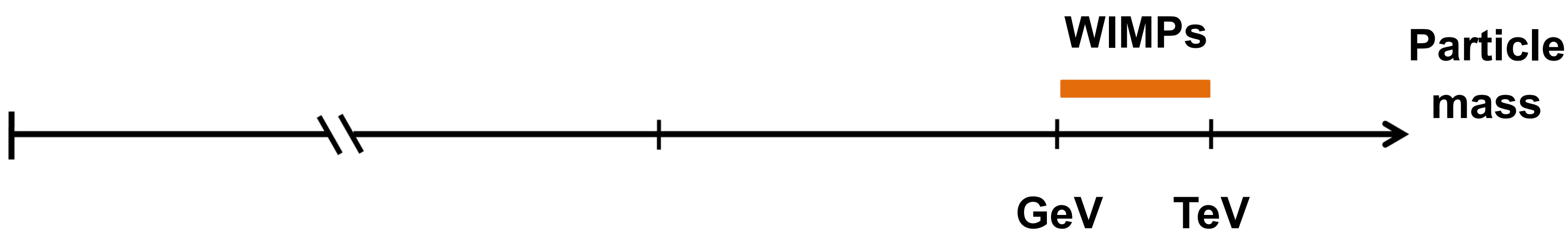

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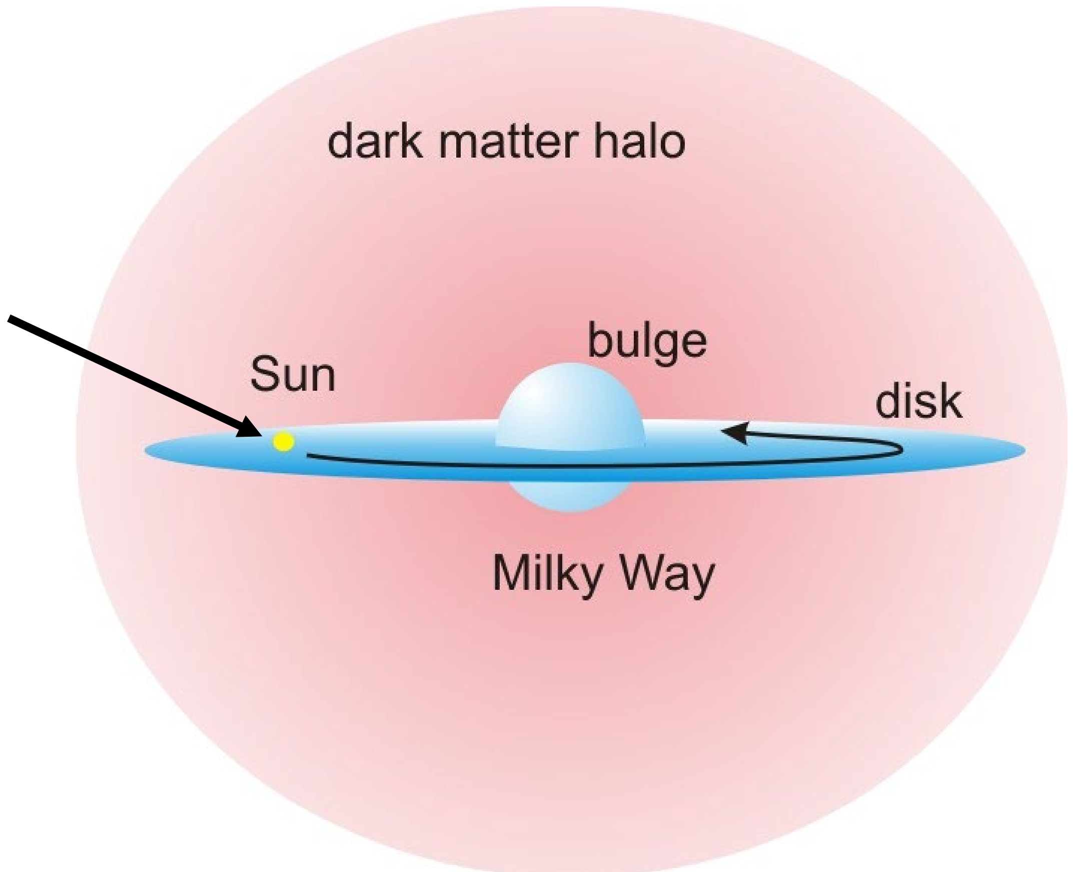

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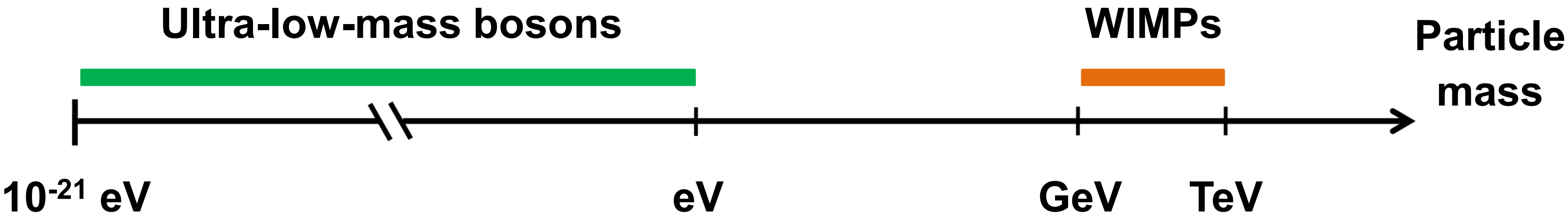

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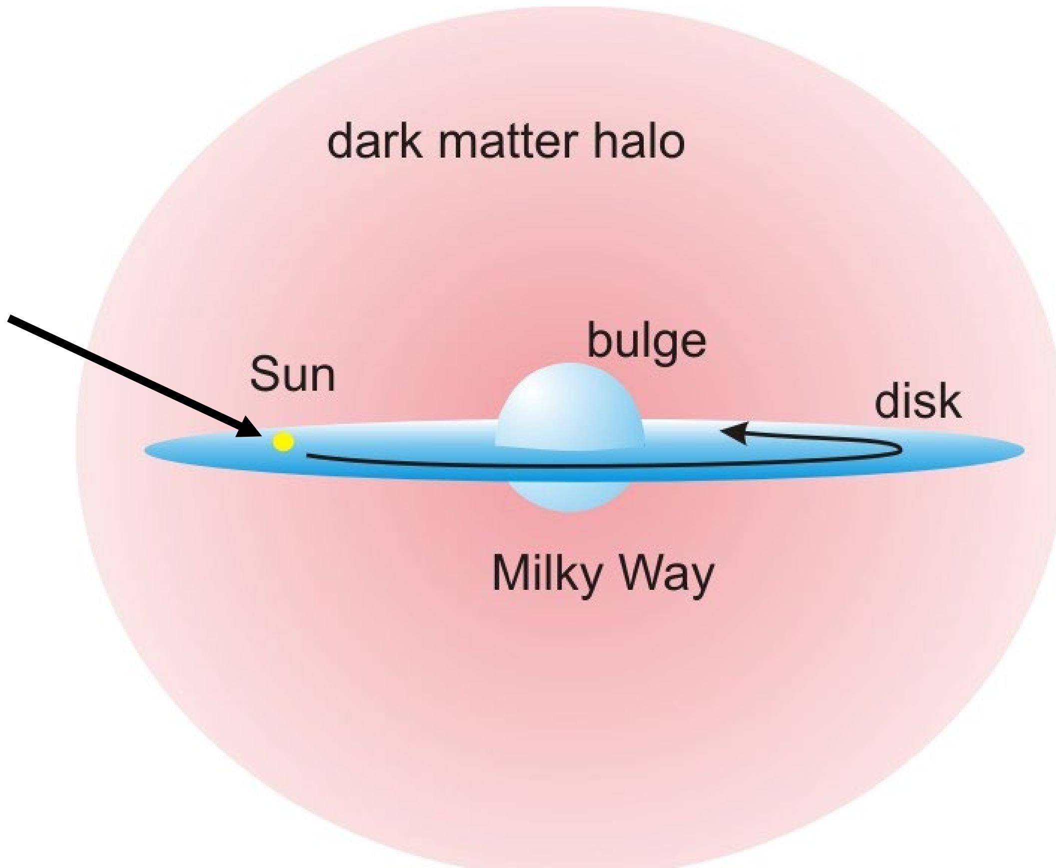
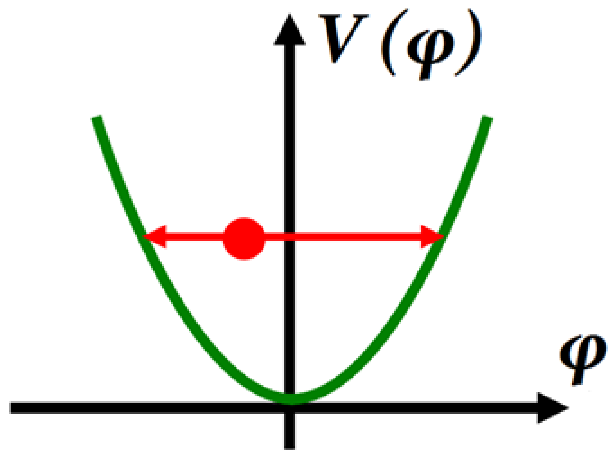


Low-mass Spin-0 Dark Matter

- 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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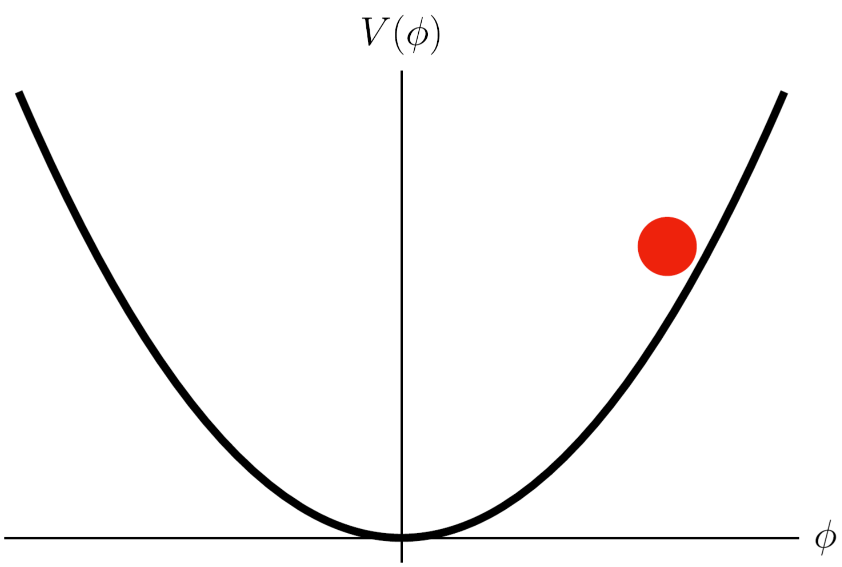

$\ddot{\varphi} + 3H(t)\dot{\varphi} + m_\varphi^2 \varphi \approx 0$ ⟵ Damped harmonic oscillator with a time-dependent frictional term

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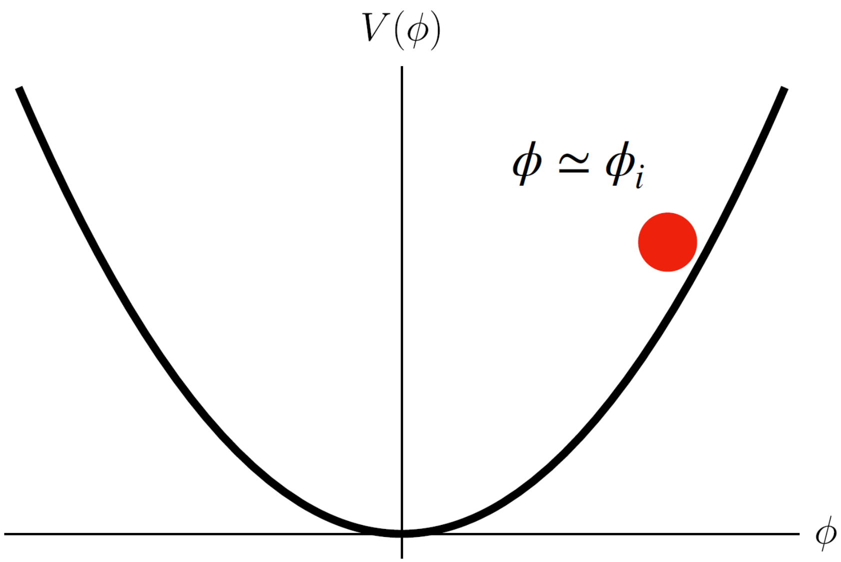

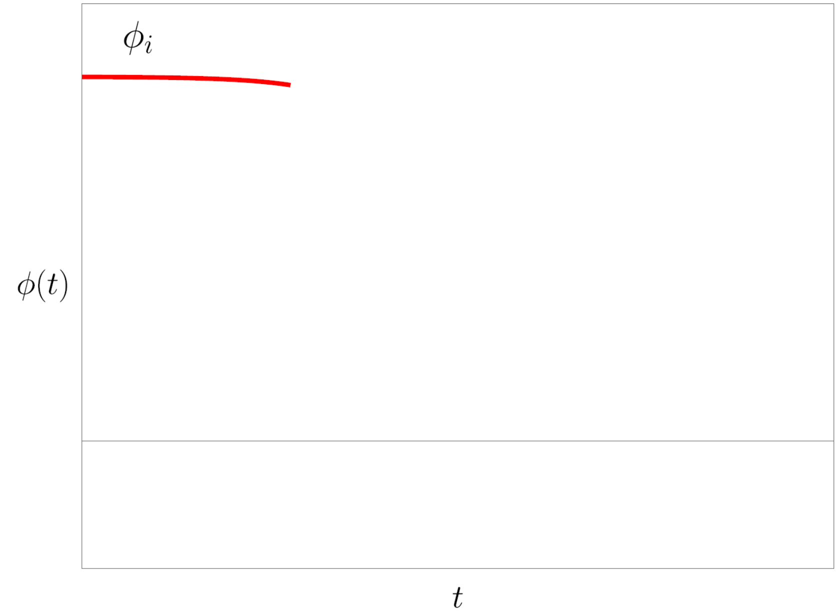

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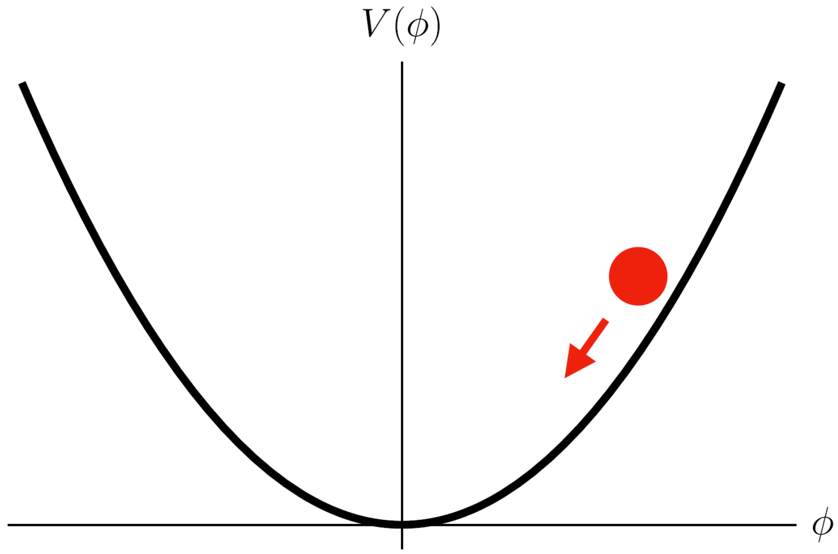

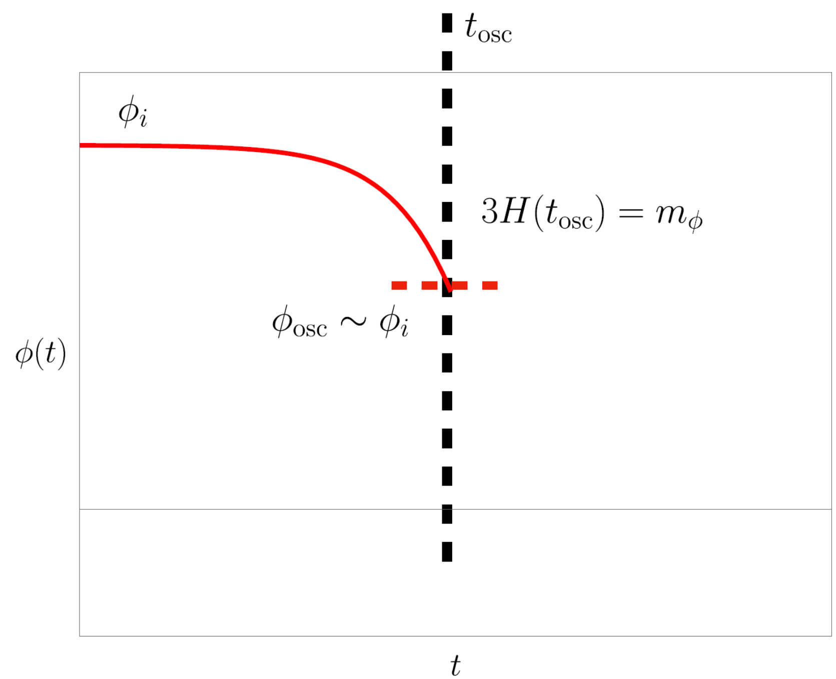

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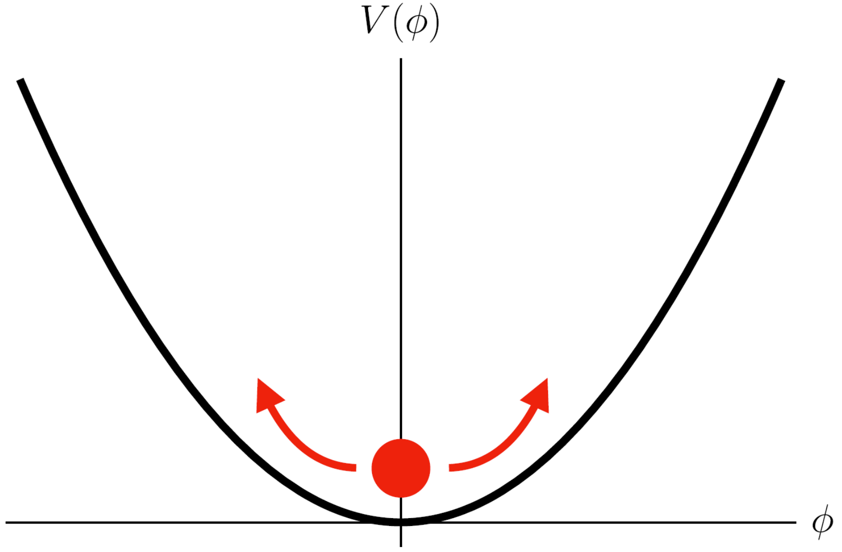

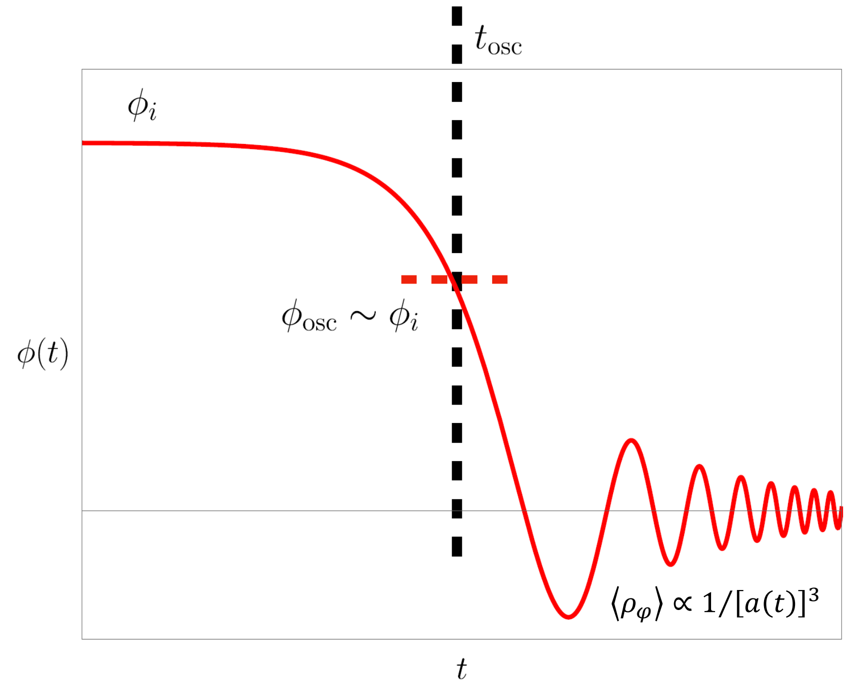

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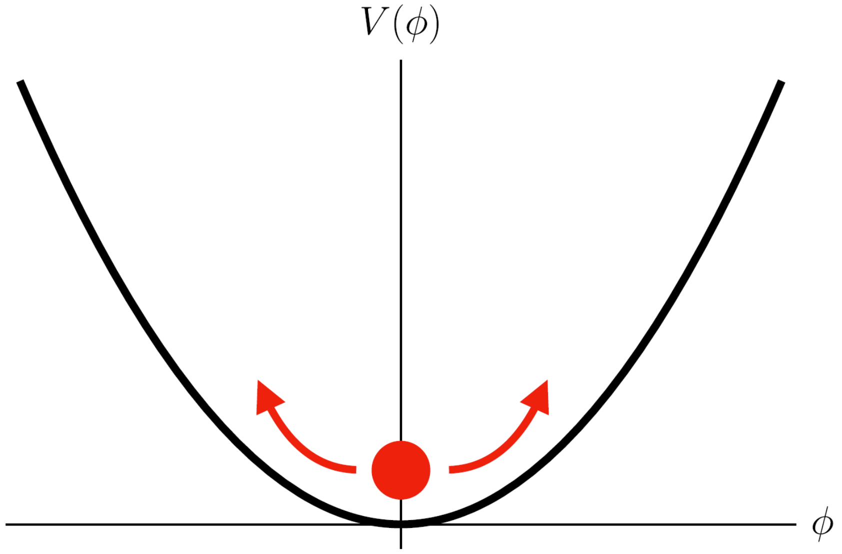

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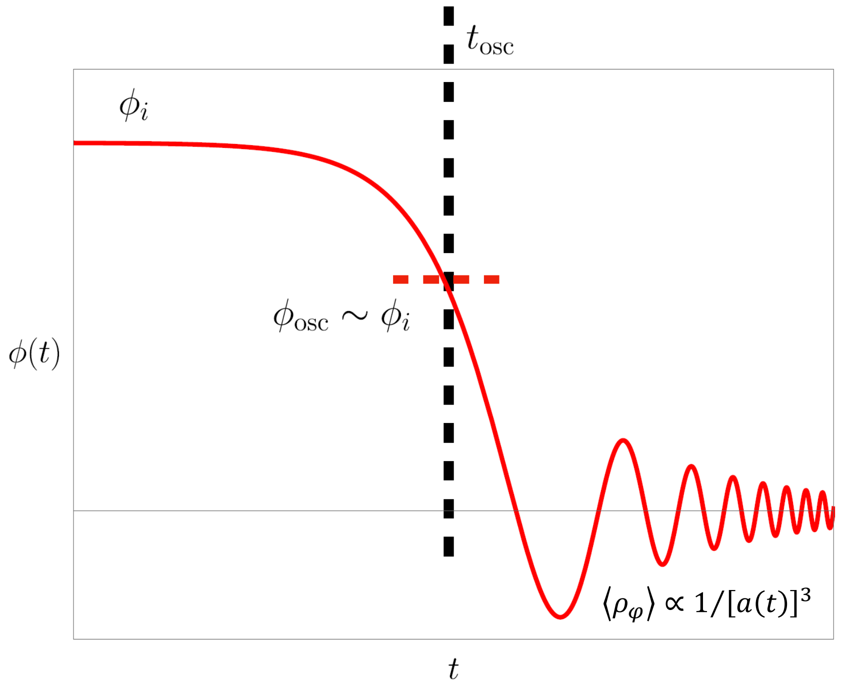

"Vacuum misalignment" mechanism – non-thermal production, $\langle\rho_\varphi\rangle$ governed by initial conditions (φ_i), redshifts as $\langle\rho_\varphi\rangle \propto 1/[a(t)]^3$, with $\langle p_\varphi\rangle \ll \langle\rho_\varphi\rangle$

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$Q_{\mathrm{DM}} \sim 10^6$

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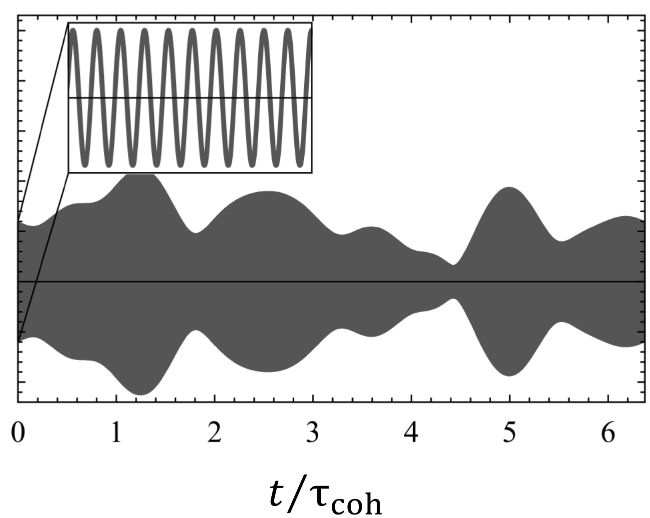
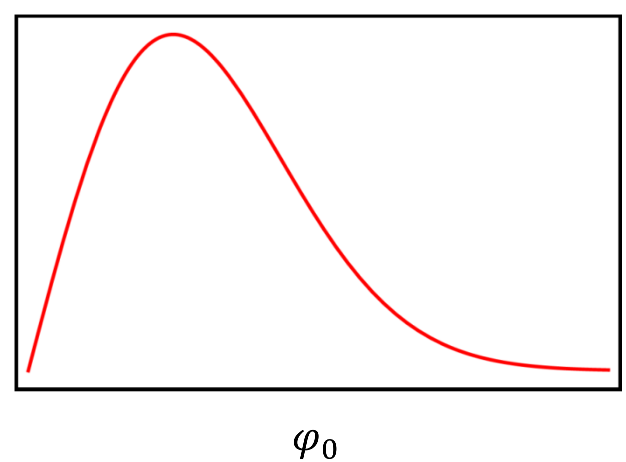
Evolution of φ_0 with time



Probability distribution function of φ_0 (Rayleigh distribution)



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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]

Low-mass Spin-0 Dark Matter

Dark Matter

Scalars (Dilatons):
$\varphi \xrightarrow{P} +\varphi$

Pseudoscalars (Axions):
$\varphi \xrightarrow{P} -\varphi$

→ Spatio-temporal variations of "constants"

- Atomic spectroscopy (clocks)
- Cavities and interferometers
- Torsion pendula (accelerometers)
- Astrophysics (e.g., BBN)

→ Time-varying spin-dependent effects

- Co-magnetometers
- Particle *g*-factors
- Spin-polarised torsion pendula
- Spin resonance (NMR, ESR)

Low-mass Spin-0 Dark Matter

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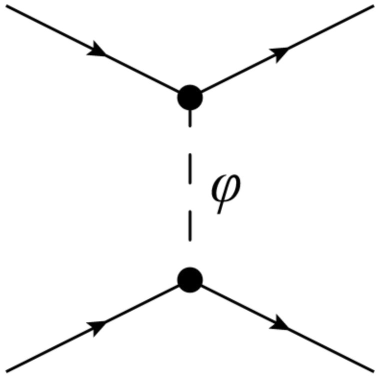
Traditional Probes of Low-mass Scalars



Particle exchange

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

$$\Rightarrow\ V_\varphi(r) = -\frac{m_1}{\Lambda_1}\frac{m_2}{\Lambda_2}\frac{e^{-m_\varphi r}}{4\pi r}$$

→ Equivalence-principle-violating "fifth-forces"

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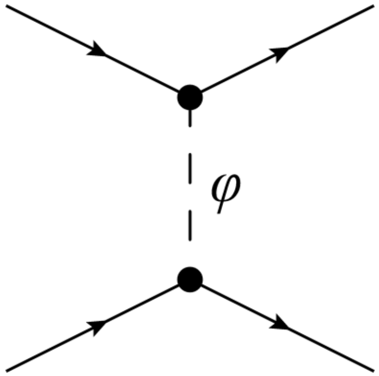

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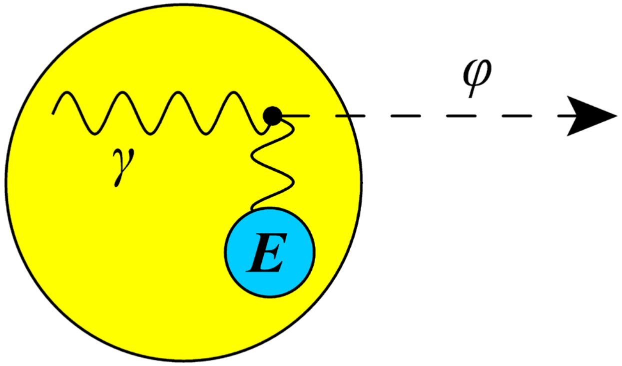

Stellar emission

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→ Equivalence-principle-violating "fifth-forces"

$$\mathcal{L}_\gamma = \frac{\varphi}{\Lambda_\gamma}\frac{F_{\mu\nu}F^{\mu\nu}}{4}$$

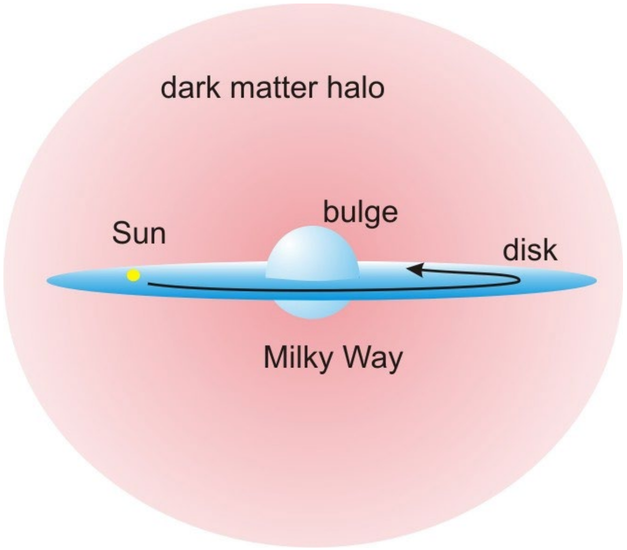
$$\Rightarrow \; \Gamma_\varphi \propto \frac{1}{\Lambda_\gamma^2}$$

→ Increased heating in active stars (Increased cooling in "dead" stars)

New Probes of Low-mass Scalars?

Particle exchange

Stellar emission



Dark matter

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)]

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

Lab frame

Solar System (and lab) move through stationary dark matter halo

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

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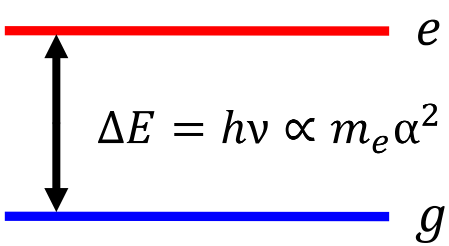
Probes of Low-mass Scalar DM

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

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

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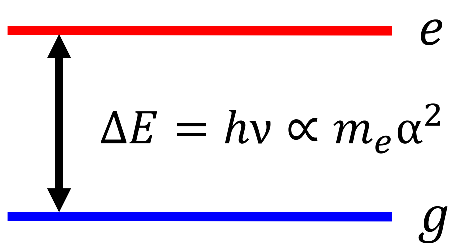

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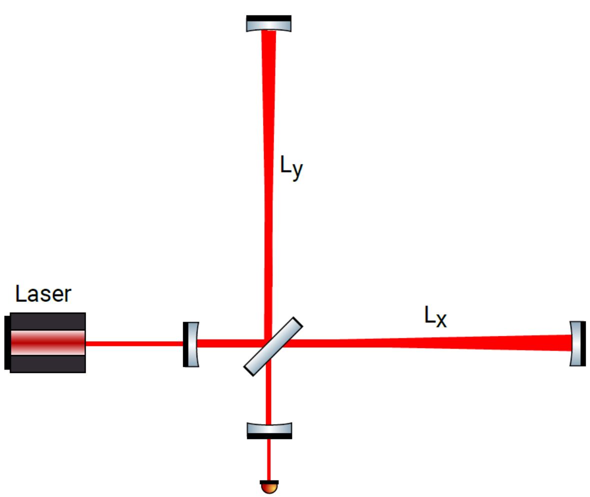
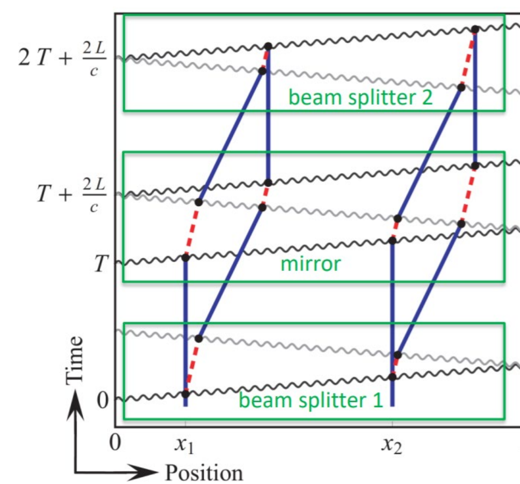
Laser interferometers



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

Atom interferometers *(proposed)*

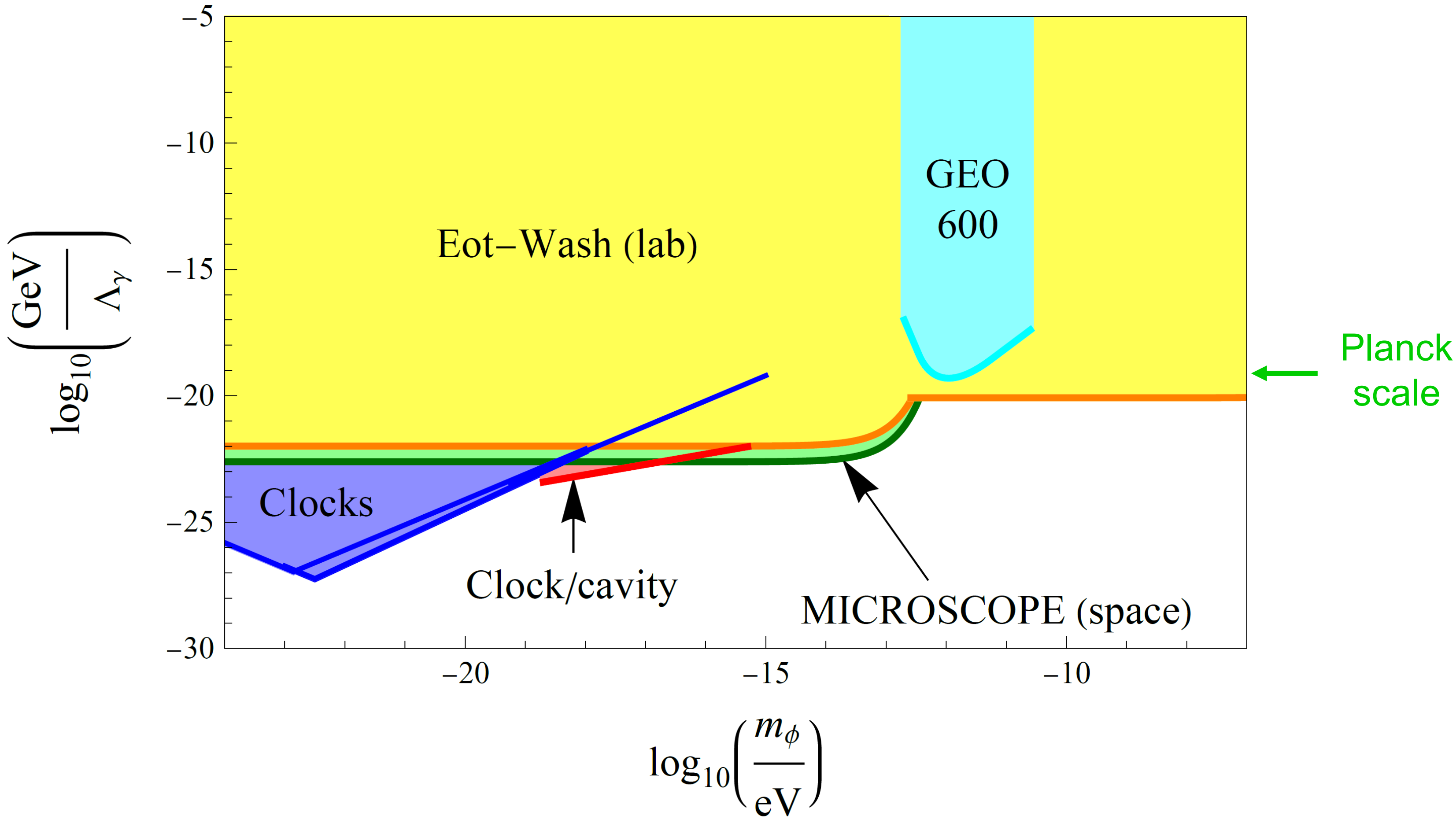


For a recent overview, see e.g. [Antypas *et al.*, arXiv:2203.14915] and references therein

Constraints on Scalar Dark Matter with $\varphi F_{\mu\nu}F^{\mu\nu}/4\Lambda_\gamma$ Coupling

Clock/clock: [*PRL* **115**, 011802 (2015)], [*PRL* **117**, 061301 (2016)], [*Nature* **591**, 564 (2021)];
Clock/cavity: [*PRL* **125**, 201302 (2020)]; **GEO600:** [*Nature* **600**, 424 (2021)]

4 orders of magnitude improvement!



Constraints on Scalar Dark Matter with $\varphi F_{\mu\nu} F^{\mu\nu}/4\Lambda_\gamma$ Coupling

Clock/clock: [*PRL* **115**, 011802 (2015)], [*PRL* **117**, 061301 (2016)], [*Nature* **591**, 564 (2021)];
Clock/cavity: [*PRL* **125**, 201302 (2020)]; **GEO600:** [*Nature* **600**, 424 (2021)]

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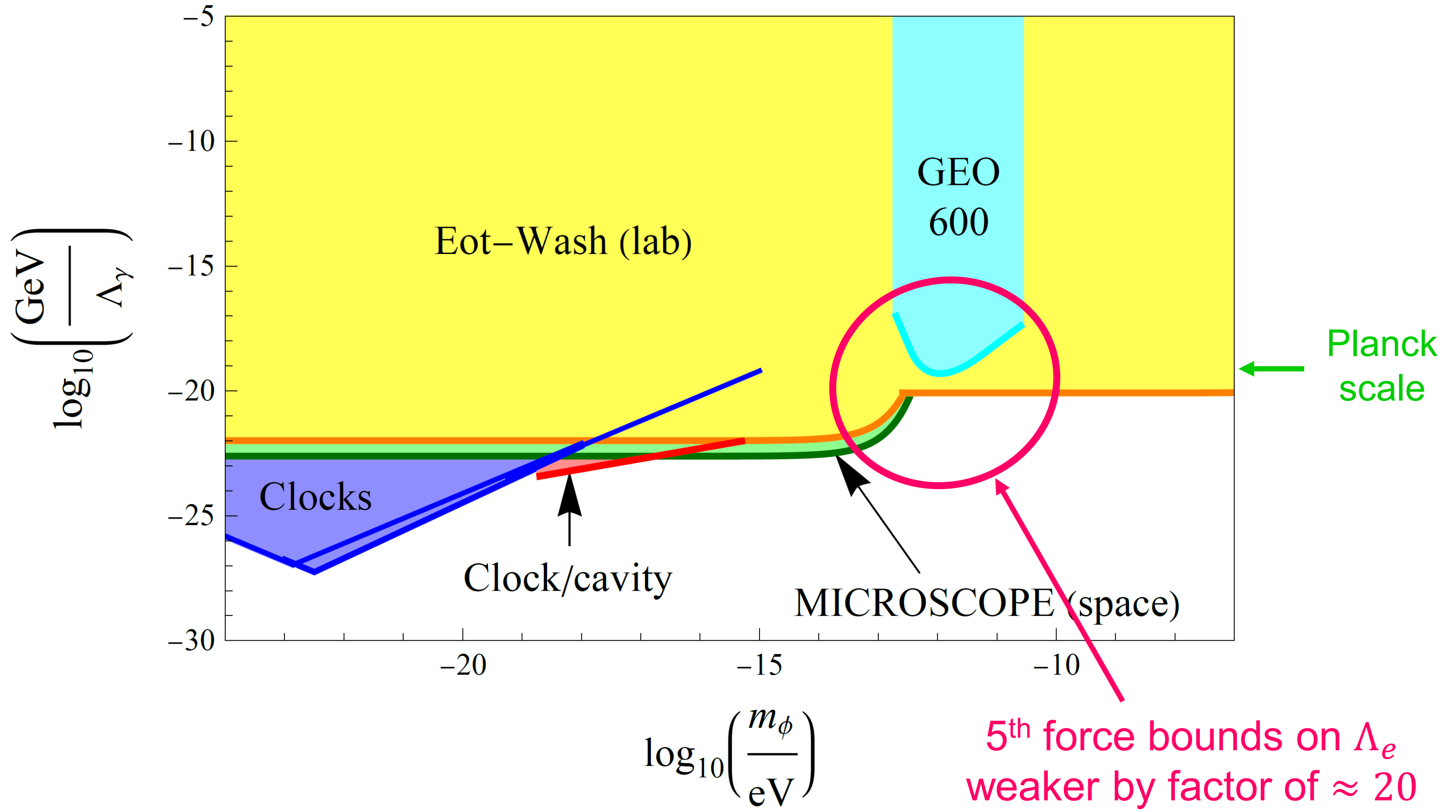
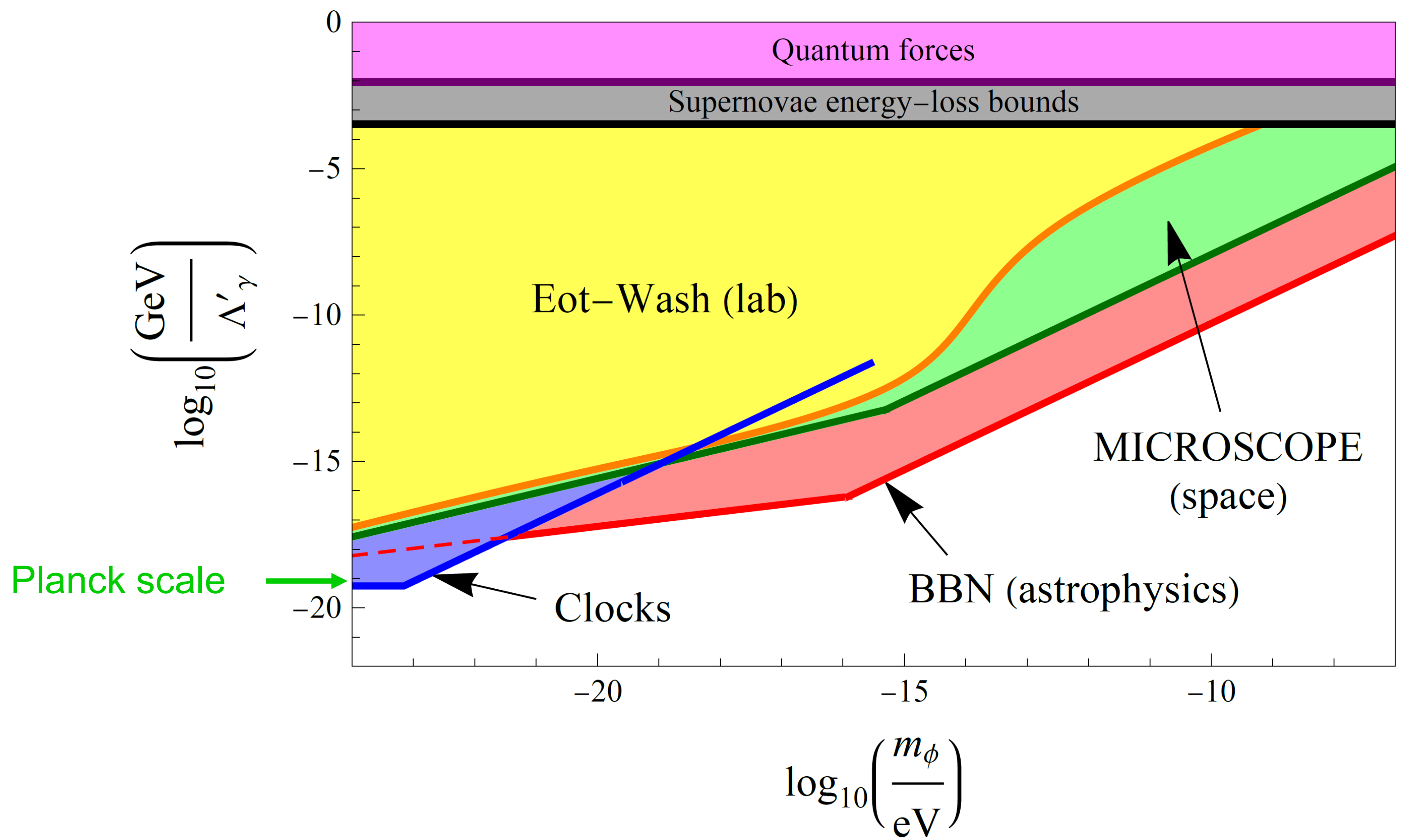


Constraints on Scalar Dark Matter with $\varphi^2 F_{\mu\nu}F^{\mu\nu}/4(\Lambda'_\gamma)^2$ Coupling

Clock/clock + BBN constraints: [Stadnik, Flambaum, *PRL* **115**, 201301 (2015); *PRA* **94**, 022111 (2016)]; **MICROSCOPE + Eöt-Wash constraints:** [Hees *et al.*, *PRD* **98**, 064051 (2018)]

15 orders of magnitude improvement!



Muonic Probes of Ultralight Scalar DM

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  - Proton radius puzzle
  - $(g-2)_\mu$ puzzle

Muonic Probes of Ultralight Scalar DM

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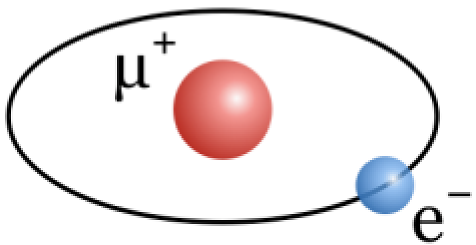
- Possible flavour/generational dependence of scalar couplings in the lepton sector
- Extra motivation from persistence of anomalies in muon physics, such as:
  - Proton radius puzzle
  - $(g-2)_\mu$ puzzle
- No stable terrestrial sources of muons (unlike electrons), leading to a qualitative different phenomenology as compared to, e.g., scalar-electron couplings

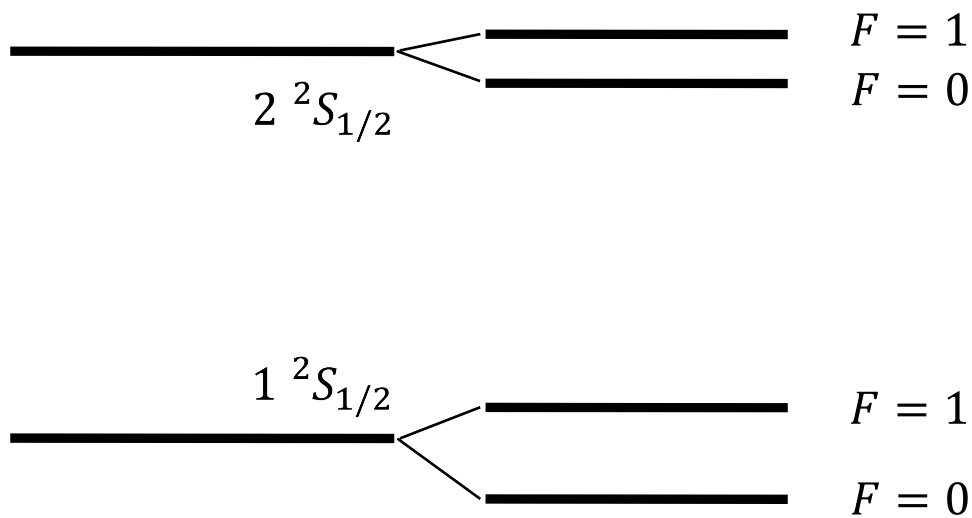
Probing Oscillations of m_μ with Muonium Spectroscopy

[Stadnik, arXiv:2206.10808]

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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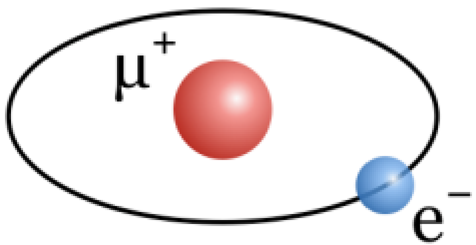

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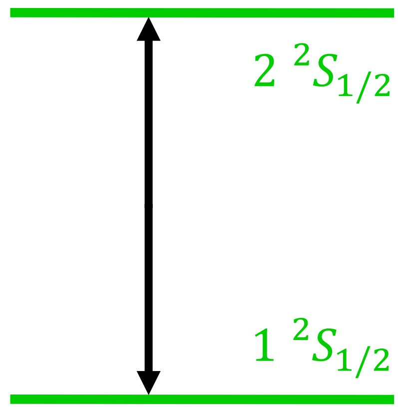

$$E_n^{\text{Rydberg}} = -\frac{m_r \alpha^2}{2n^2} \Rightarrow \frac{\Delta\nu_{1S-2S}}{\nu_{1S-2S}} \approx 2\frac{\Delta\alpha}{\alpha} + \frac{\Delta m_e}{m_e} + \frac{m_e}{m_\mu}\frac{\Delta m_\mu}{m_\mu}$$

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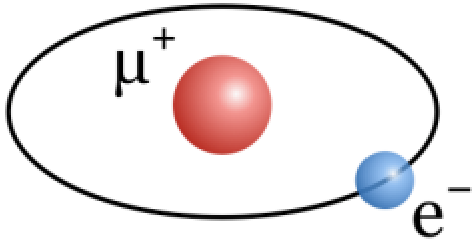

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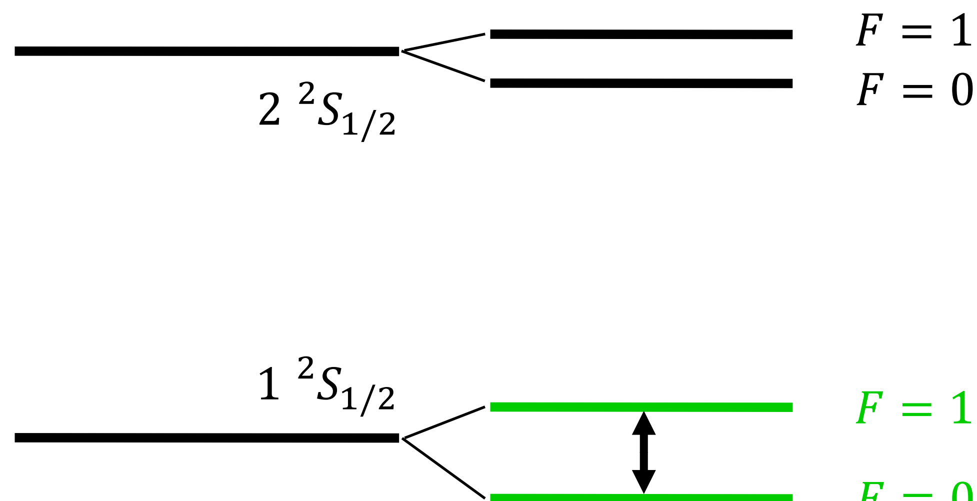

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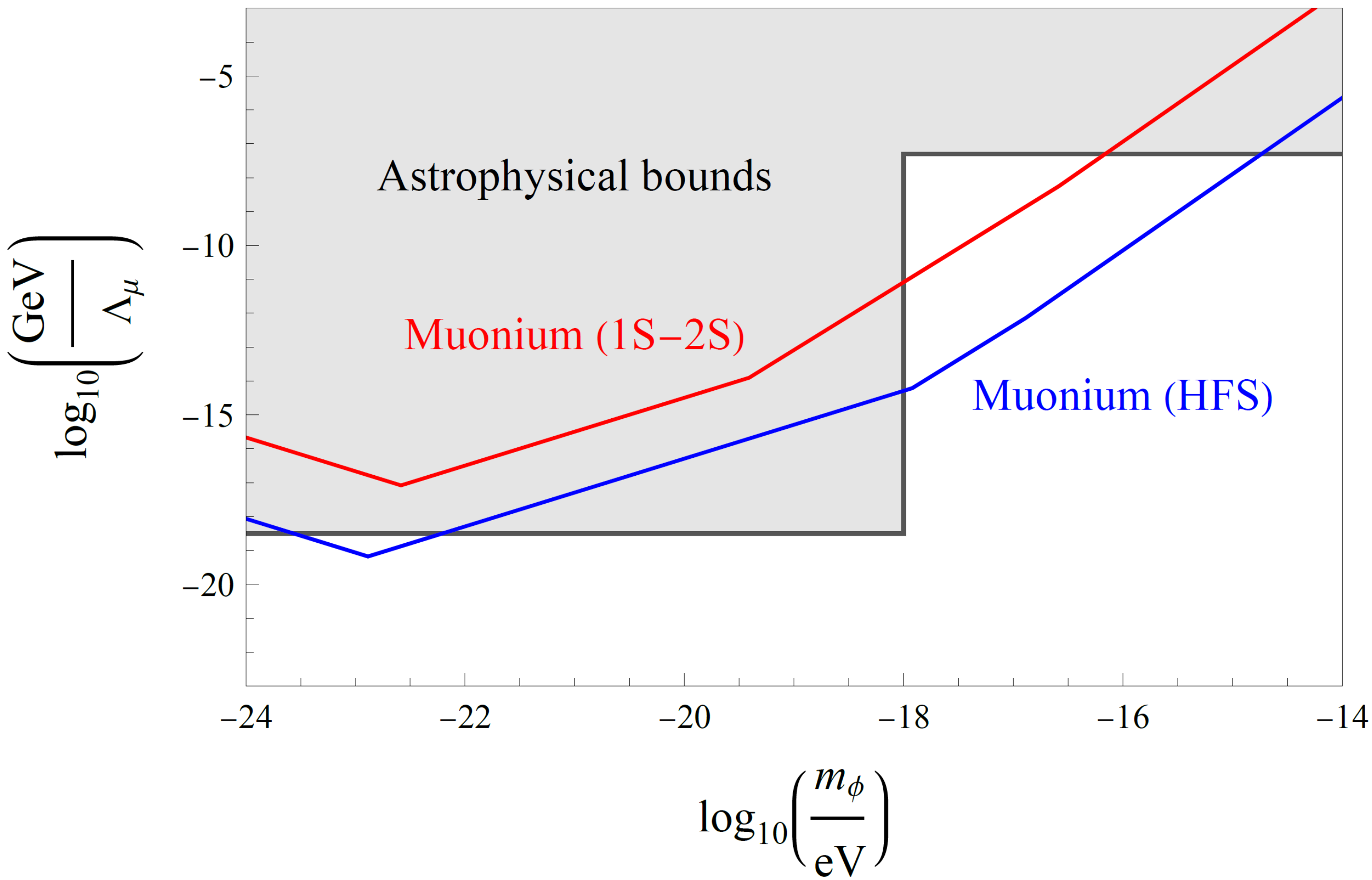
$$\Delta E_{\mathrm{Fermi}} = \frac{8 m_r^3 \alpha^4}{3 m_e m_\mu} \Rightarrow \frac{\Delta\nu_{\mathrm{HFS}}}{\nu_{\mathrm{HFS}}} \approx 4\frac{\Delta\alpha}{\alpha} + 2\frac{\Delta m_e}{m_e} - \frac{\Delta m_\mu}{m_\mu}$$

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

[Stadnik, arXiv:2206.10808]

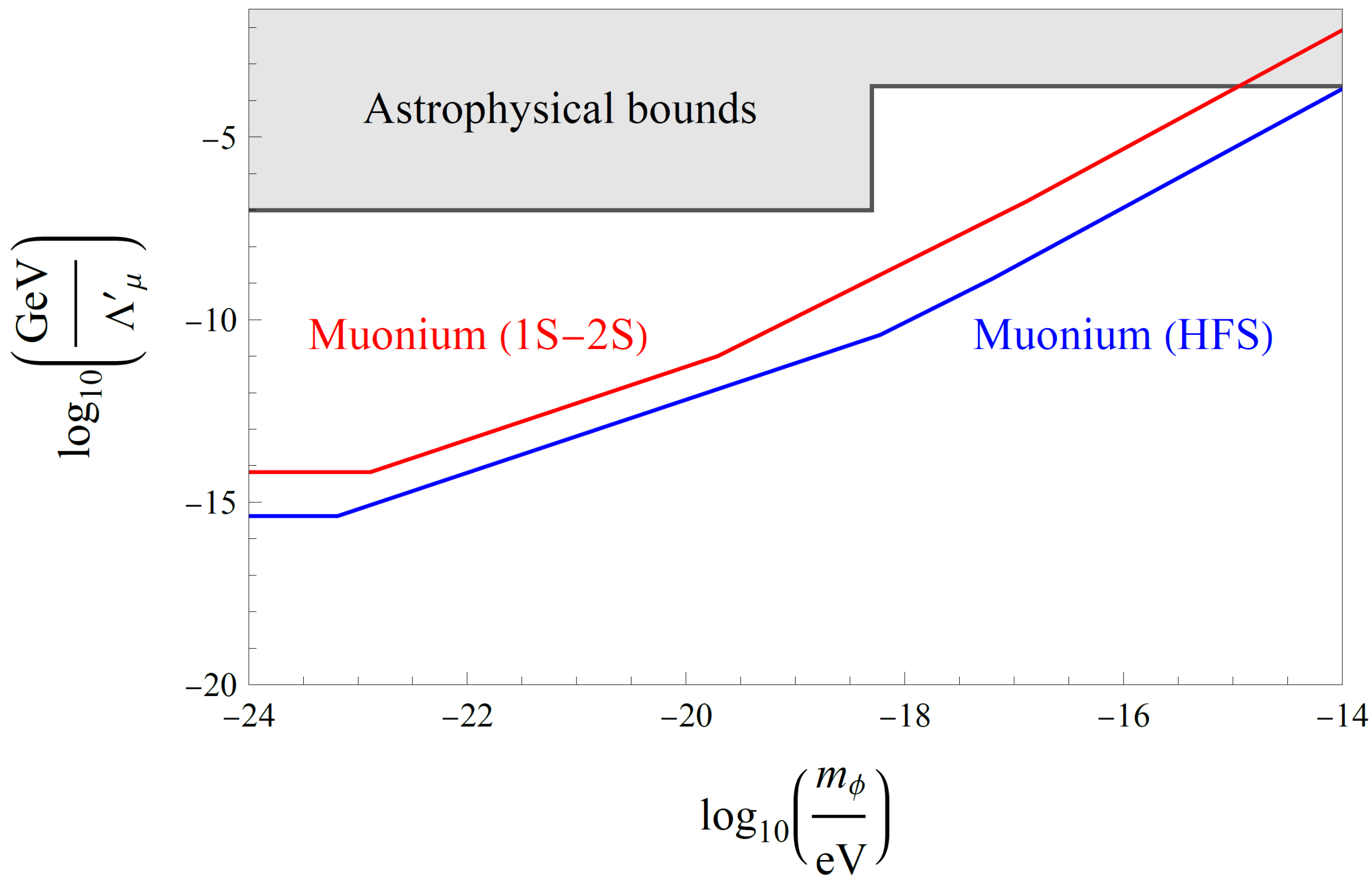
Up to 7 orders of magnitude improvement possible with existing datasets!
(Best existing datasets from muonium experiments at LAMPF in 1990s)



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

[Stadnik, arXiv:2206.10808]

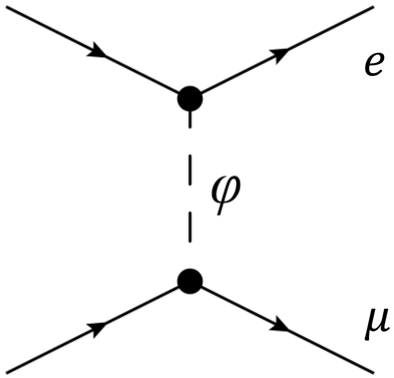
Up to 8 orders of magnitude improvement possible with existing datasets!
(Best existing datasets from muonium experiments at LAMPF in 1990s)



Probing Scalar-Muon Coupling with Muonium Free-fall

[Stadnik, arXiv:2206.10808]

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



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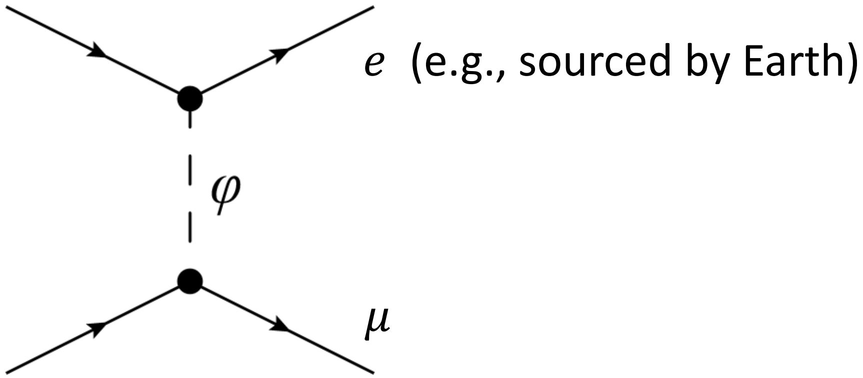

Local value of g measured in free-fall experiments using muonium would differ from experiments using non-muon-based test masses

Probing Scalar-Muon Coupling with Muonium Free-fall

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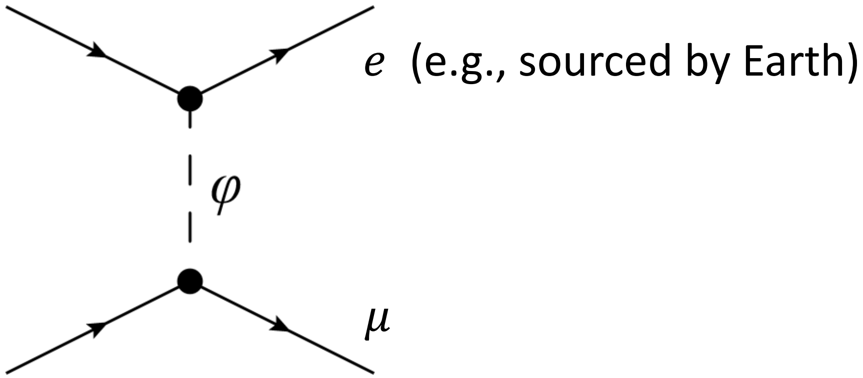


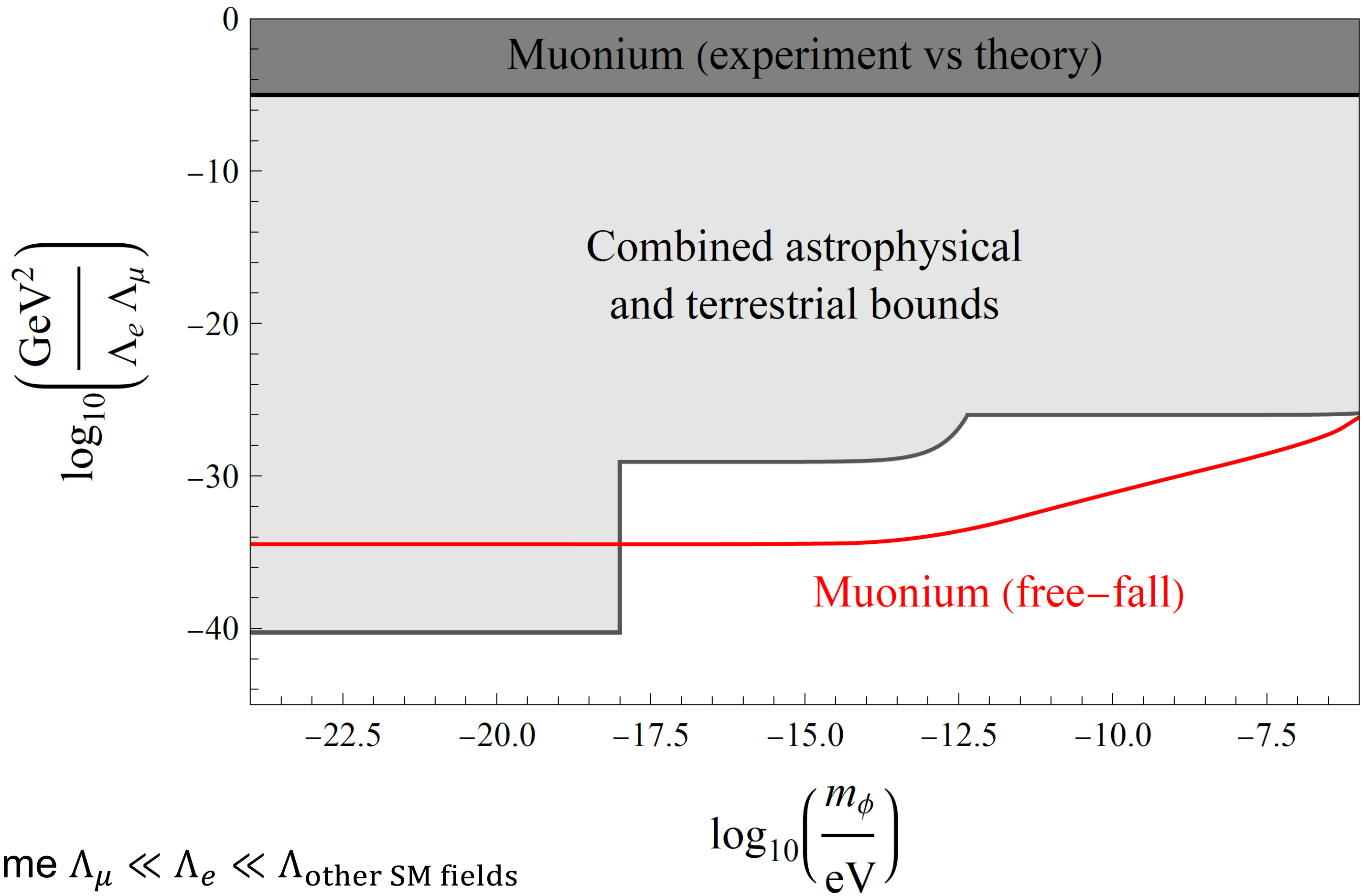
Local value of g measured in free-fall experiments using muonium would differ from experiments using non-muon-based test masses

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, arXiv:2206.10808]

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 $\sim 10^8$ 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

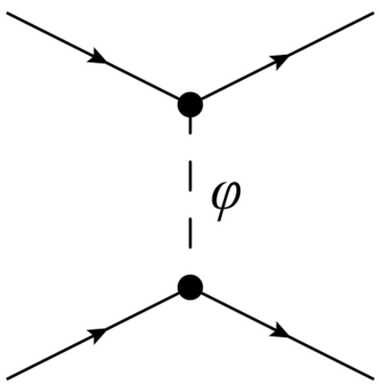
Fifth Forces: Linear vs Quadratic Couplings

[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**

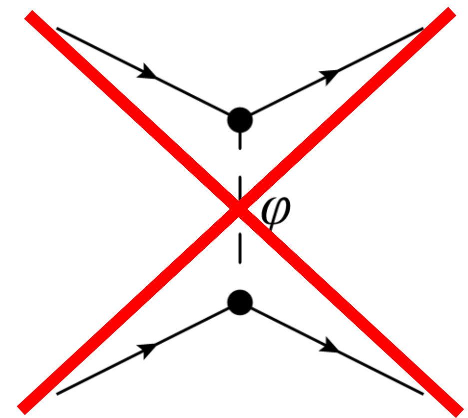


$$\varphi = \varphi_0 \cos(m_\varphi t) \pm A \frac{e^{-m_\varphi r}}{r}$$

Profile outside of a spherical body

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

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



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

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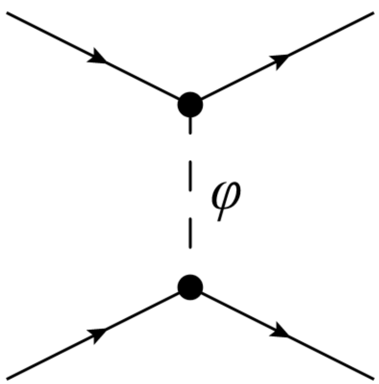

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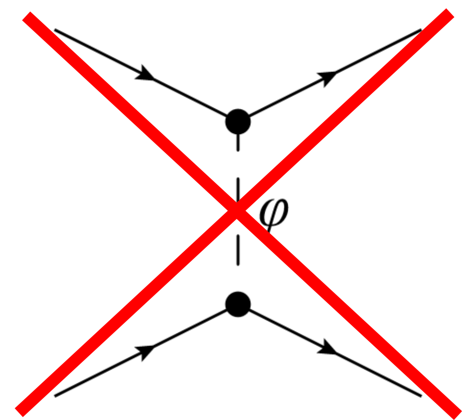

$$\varphi = \varphi_0 \cos(m_\varphi t)\left(1 \pm \frac{B}{r}\right)$$

Profile outside of a spherical body

Gradients + amplification/screening

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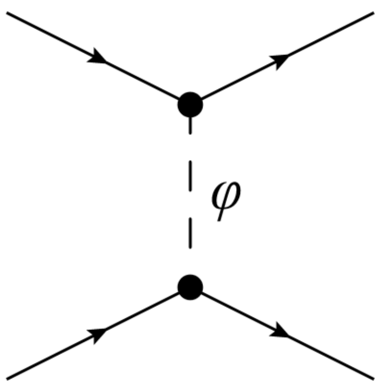

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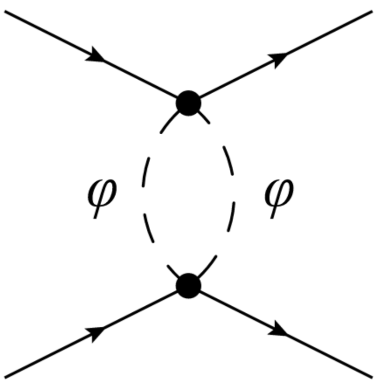

$$\varphi = \varphi_0 \cos(m_\varphi t) \left(1 \pm \frac{B}{r}\right) - \hbar C \frac{e^{-2m_\varphi r}}{r^3}$$

Profile outside of a spherical body

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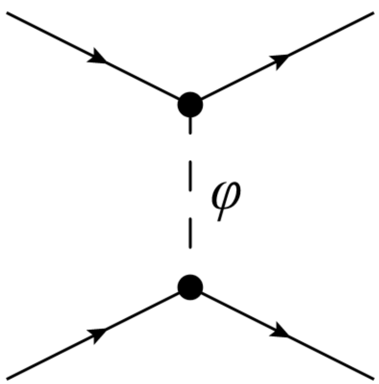

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Motional gradients: $\varphi_0 \cos(m_\varphi t - \boldsymbol{p}_\varphi \cdot \boldsymbol{x})$

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

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

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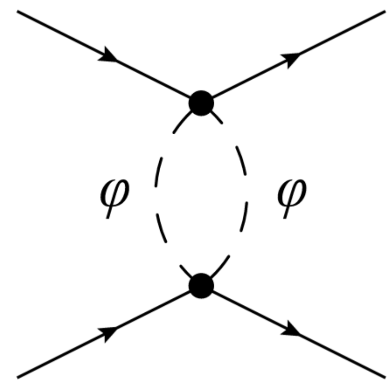

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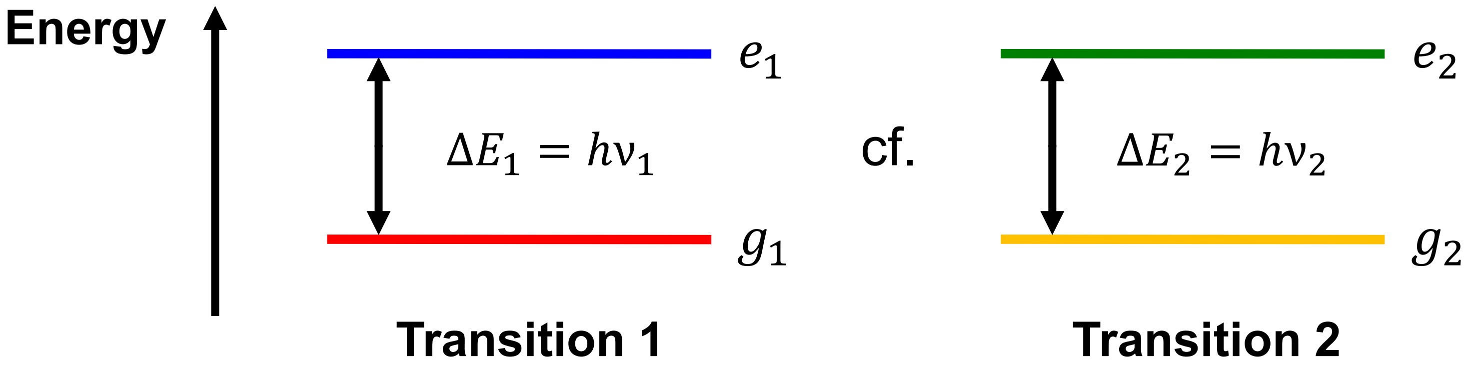
Gradients + amplification/screening

Atomic Spectroscopy Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter



$$\frac{\delta(\nu_1/\nu_2)}{\nu_1/\nu_2} = \left(K_{X,1} - K_{X,2}\right)\frac{\delta X}{X} \; ; \; X = \alpha, m_e/m_N , \ldots$$

Atomic spectroscopy (including clocks) has been used for decades to search for "slow drifts" in fundamental constants

Recent overview: [Ludlow, Boyd, Ye, Peik, Schmidt, *Rev. Mod. Phys.* **87**, 637 (2015)]

"Sensitivity coefficients" K_X required for the interpretation of experimental data have been calculated extensively by Flambaum group

Reviews: [Flambaum, Dzuba, *Can. J. Phys.* **87**, 25 (2009); *Hyperfine Interac.* **236**, 79 (2015)]

Effects of Varying Fundamental Constants on Atomic Transitions

[Dzuba, Flambaum, Webb, *PRL* **82**, 888 (1999); *PRA* **59**, 230 (1999); Dzuba, Flambaum, Marchenko, *PRA* **68**, 022506 (2003); Angstmann, Dzuba, Flambaum, *PRA* **70**, 014102 (2004); Dzuba, Flambaum, *PRA* **77**, 012515 (2008)]

- Atomic optical transitions:

$$\nu_{\text{opt}} \propto \left(\frac{m_e e^4}{\hbar^3}\right) F_{\text{rel}}^{\text{opt}}(Z\alpha)$$

Non-relativistic atomic unit of frequency

Relativistic factor

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$$K_\alpha(\mathrm{Sr}) = 0.06, K_\alpha(\mathrm{Yb}) = 0.3, K_\alpha(\mathrm{Hg}) = 0.8$$

Increasing *Z*

$$|\boldsymbol{p}_e|_{\mathrm{near\ nucleus}} \sim Z\alpha m_e c$$

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$$\nu_{\mathrm{hf}} \propto \left(\frac{m_e e^4}{\hbar^3}\right)\left[\alpha^2 F_{\mathrm{rel}}^{\mathrm{hf}}(Z\alpha)\right]\left(\frac{m_e}{m_N}\right)\mu$$

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$$K_\alpha(\mathrm{H}) = 2.0, K_\alpha(\mathrm{Rb}) = 2.3, K_\alpha(\mathrm{Cs}) = 2.8$$

Increasing *Z*

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Increasing *Z*

- Atomic hyperfine transitions:

$K_{m_e/m_N} = 1$

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Increasing *Z*

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Increasing *Z*

- Atomic hyperfine transitions:

$$K_{m_e/m_N} = 1$$

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$$K_{m_q/\Lambda_{\mathrm{QCD}}} \neq 0$$

$$K_\alpha(\mathrm{H}) = 2.0, K_\alpha(\mathrm{Rb}) = 2.3, K_\alpha(\mathrm{Cs}) = 2.8$$

Increasing *Z*

Enhanced Effects of Varying Fundamental Constants on Atomic and Other Transitions

[Dzuba, Flambaum, Webb, *PRL* **82**, 888 (1999); Flambaum, *PRL* **97**, 092502 (2006); *PRA* **73**, 034101 (2006); Berengut, Dzuba, Flambaum, *PRL* **105**, 120801 (2010)]

- Sensitivity coefficients may be greatly enhanced for transitions between nearly degenerate levels in:
  - Atoms
  - Highly-charged ions
  - Molecules
  - Nuclei

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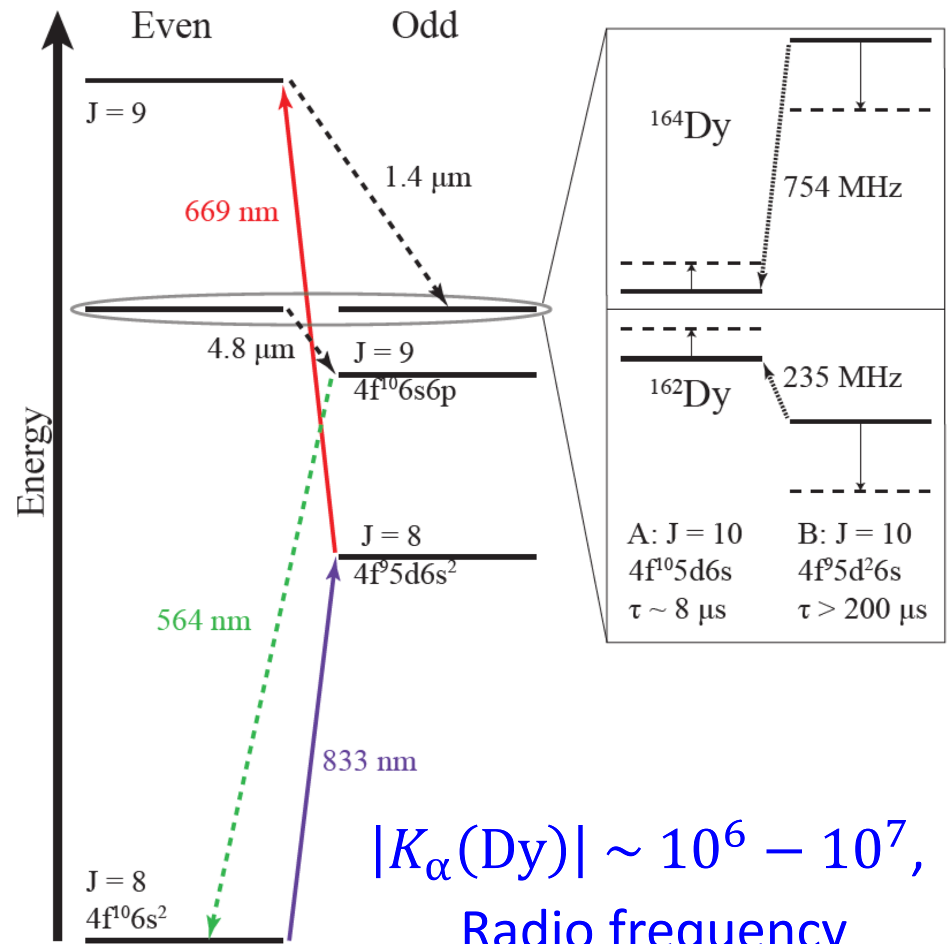

$|K_\alpha(\mathrm{Dy})| \sim 10^6 - 10^7$,

Radio frequency

Enhanced Effects of Varying Fundamental Constants on Atomic and Other Transitions

[Dzuba, Flambaum, Webb, *PRL* **82**, 888 (1999); Flambaum, *PRL* **97**, 092502 (2006); *PRA* **73**, 034101 (2006); Berengut, Dzuba, Flambaum, *PRL* **105**, 120801 (2010)]

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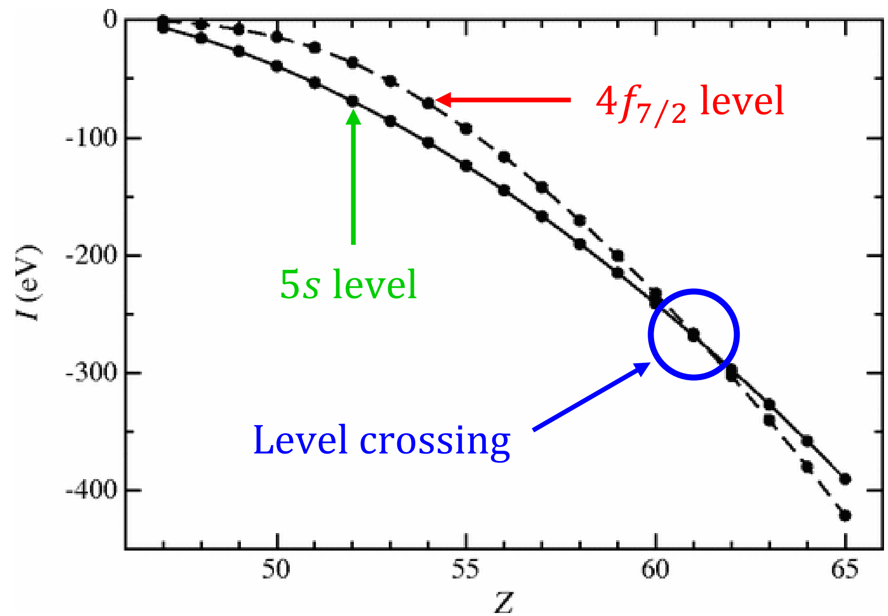
  - Nuclei

Ag isoelectronic sequence



e.g., $\left|K_\alpha\left(\mathrm{Cf}^{15+}\right)\right| \approx 50$,

Optical frequency

(Bi isoelectronic sequence)

Enhanced Effects of Varying Fundamental Constants on Atomic and Other Transitions

[Dzuba, Flambaum, Webb, *PRL* **82**, 888 (1999); Flambaum, *PRL* **97**, 092502 (2006); *PRA* **73**, 034101 (2006); Berengut, Dzuba, Flambaum, *PRL* **105**, 120801 (2010)]

- Sensitivity coefficients may be greatly enhanced for transitions between nearly degenerate levels in:
  - Atoms
  - Highly-charged ions
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  - Nuclei

Much richer energy level structure possible in molecules than in atoms, and can include contributions from various types of energy intervals:

- Fine-structure
- Hyperfine magnetic
- Rotational
- Vibrational
- Ω-doubling

e.g., $|K_\alpha(\mathrm{HfF}^+)| \approx 2000$,

$\left|K_{m_e/m_N}(\mathrm{HfF}^+)\right| \approx 80$,

Far-infrared frequency

Enhanced Effects of Varying Fundamental Constants on Atomic and Other Transitions

[Dzuba, Flambaum, Webb, *PRL* **82**, 888 (1999); Flambaum, *PRL* **97**, 092502 (2006); *PRA* **73**, 034101 (2006); Berengut, Dzuba, Flambaum, *PRL* **105**, 120801 (2010)]

- Sensitivity coefficients may be greatly enhanced for transitions between nearly degenerate levels in:
  - Atoms
  - Highly-charged ions
  - Molecules
  - Nuclei

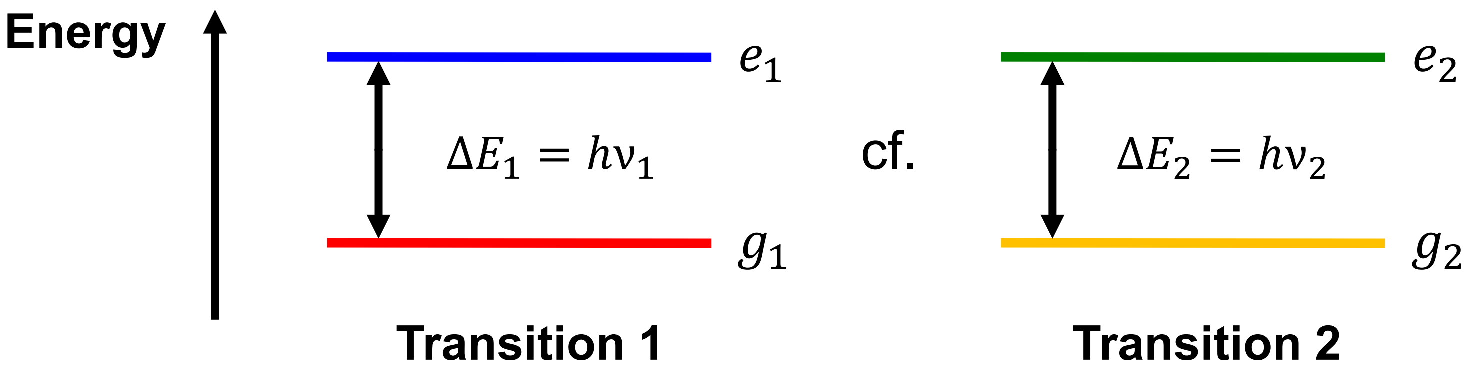
There exists a low-energy (≈ 8 eV) isomeric transition between the ground and first-excited states of ^{229}Th, due to fortuitous cancellation between the electromagnetic and strong force intervals

$$|K_\alpha(\mathrm{Th})| \sim 10^4,$$

Ultraviolet frequency

Atomic Spectroscopy Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter

[Arvanitaki, Huang, Van Tilburg, *PRD* **91**, 015015 (2015)], [Stadnik, Flambaum, *PRL* **114**, 161301 (2015)]



$$\frac{\delta(\nu_1/\nu_2)}{\nu_1/\nu_2} \propto \sum_{X=\alpha, m_e/m_N, \ldots} \left(K_{X,1} - K_{X,2}\right) \cos(2\pi f_{\mathrm{DM}} t)\ ;\ 2\pi f_{\mathrm{DM}} = m_\varphi \text{ or } 2m_\varphi$$

- **Dy/Cs [Mainz]:** [Van Tilburg *et al.*, *PRL* **115**, 011802 (2015)], [Stadnik, Flambaum, *PRL* **115**, 201301 (2015)]
- **Rb/Cs [SYRTE]:** [Hees *et al.*, *PRL* **117**, 061301 (2016)], [Stadnik, Flambaum, *PRA* **94**, 022111 (2016)]
- **Al^+/Yb, Yb/Sr, Al^+/Hg^+ [NIST + JILA]:** [BACON Collaboration, *Nature* **591**, 564 (2021)]
- **Yb/Cs [NMIJ]:** [Kobayashi *et al.*, *PRL* **129**, 241301 (2022)]
- **Yb^+(E3)/Sr [PTB]:** [Filzinger *et al.*, arXiv:2301.03433]

Cavity-Based Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter

[Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRA* **93**, 063630 (2016)]

Solid material

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

$$\Rightarrow \nu_{\text{solid}} \propto 1/L_{\text{solid}} \propto m_e \alpha$$

(adiabatic regime)

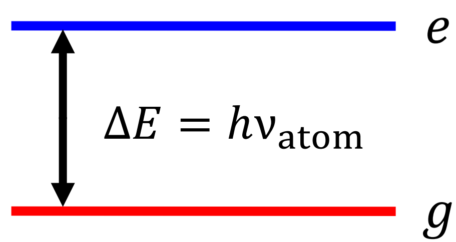
Cavity-Based Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter

[Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRA* **93**, 063630 (2016)]

Solid material

cf.

Electronic transition



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

$$\Rightarrow \nu_{\mathrm{solid}} \propto 1/L_{\mathrm{solid}} \propto m_e \alpha$$

$$\nu_{\mathrm{atom}} \propto \mathrm{Ry} \propto m_e \alpha^2$$

$$\frac{\nu_{\mathrm{atom}}}{\nu_{\mathrm{solid}}} \propto \alpha$$

- **Sr vs Glass cavity [Torun]:** [Wcislo *et al.*, *Nature Astronomy* **1**, 0009 (2016)]
- **Various combinations [Worldwide]:** [Wcislo *et al.*, *Science Advances* **4**, eaau4869 (2018)]
- **Cs vs Steel cavity [Mainz]:** [Antypas *et al.*, *PRL* **123**, 141102 (2019)]
- **Sr/H vs Silicon cavity [JILA + PTB]:** [Kennedy *et al.*, *PRL* **125**, 201302 (2020)]
- **Sr^+ vs Glass cavity [Weizmann]:** [Aharony *et al.*, *PRD* **103**, 075017 (2021)]
- **H vs Sapphire/Quartz cavities [UWA]:** [Campbell *et al.*, *PRL* **126**, 071301 (2021)]

Cavity-Based Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter

[Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRA* **93**, 063630 (2016)]

Solid material

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

$\Rightarrow \nu_{\mathrm{solid}} \propto 1/L_{\mathrm{solid}} \propto m_e \alpha$

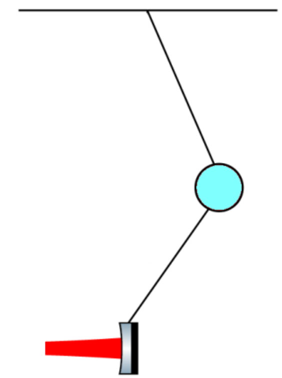
cf.

Freely-suspended mirrors

$L_{\mathrm{free}} \approx \mathrm{const.}$ for $f_{\mathrm{DM}} > f_{\mathrm{natural}}$

$\Rightarrow \nu_{\mathrm{free}} \approx$ constant

Double-pendulum suspensions



$$\frac{\nu_{\mathrm{solid}}}{\nu_{\mathrm{free}}} \propto m_e \alpha$$

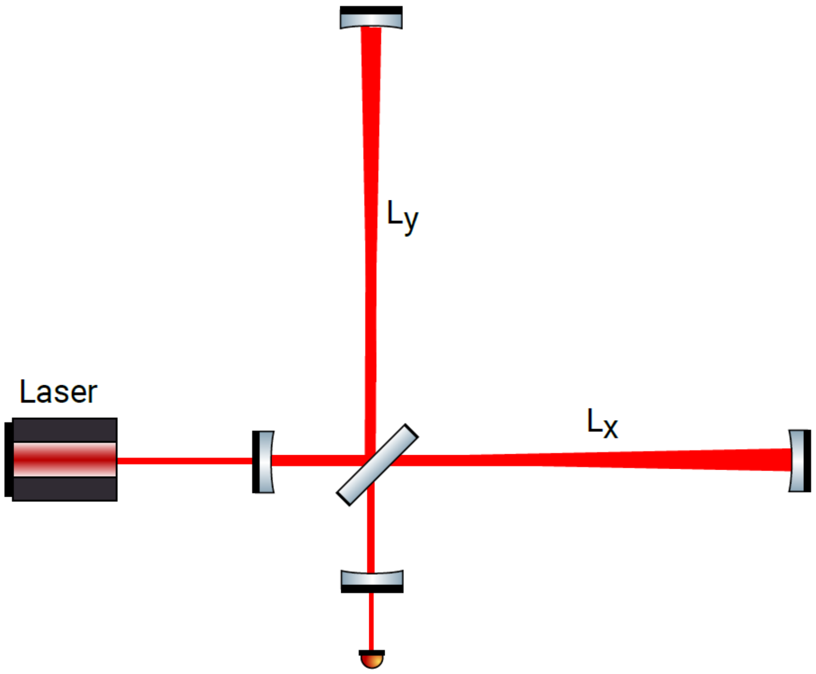
cf.

$$\frac{\nu_{\mathrm{atom}}}{\nu_{\mathrm{solid}}} \propto \alpha$$

Small-scale experiment currently under development at Northwestern University

Laser Interferometry Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter

[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]



Michelson interferometer (GEO600)

Laser Interferometry Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter

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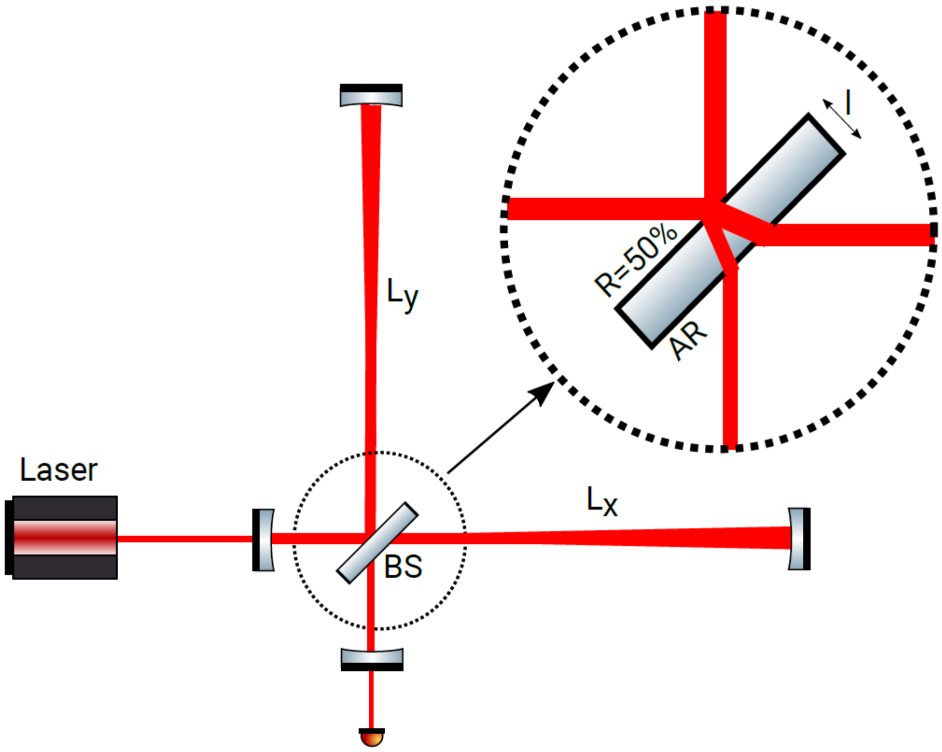

- Geometric asymmetry from beam-splitter

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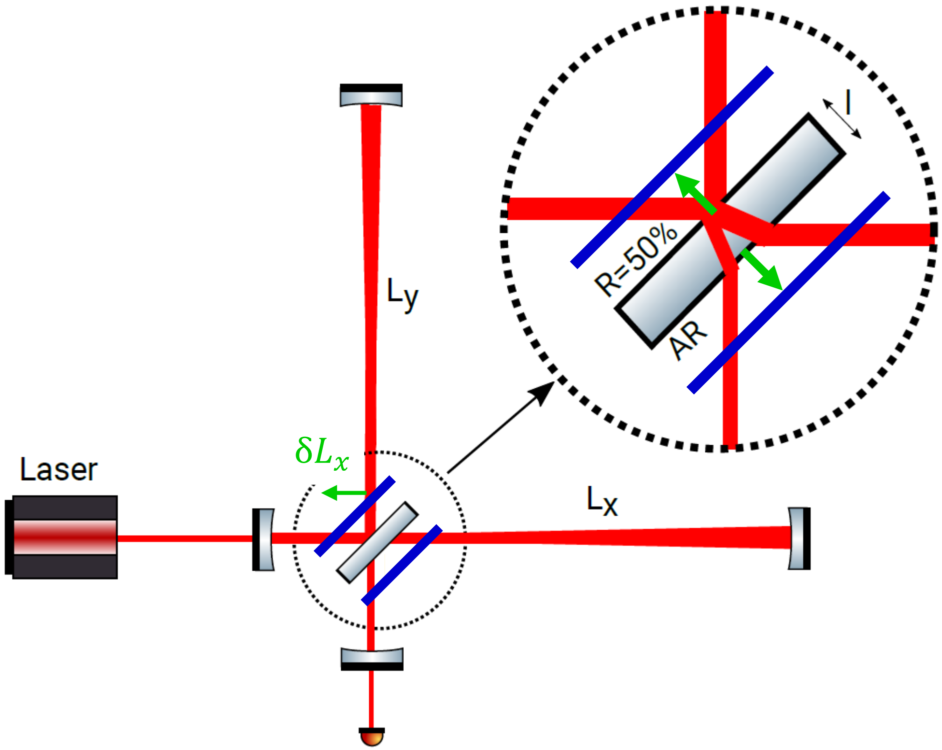


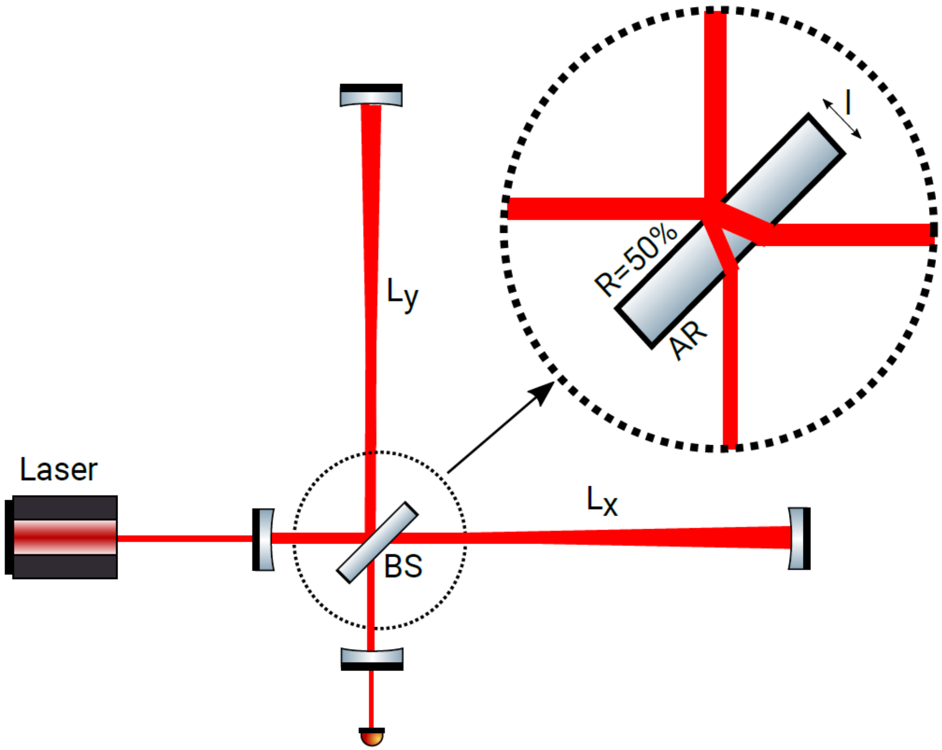
- Geometric asymmetry from beam-splitter: $\delta(L_x - L_y) \sim \delta(nl)$

First results recently reported using GEO600 and Fermilab holometer data:

[Vermeulen *et al.*, *Nature* **600**, 424 (2021)], [Aiello *et al.*, *PRL* **128**, 121101 (2022)]

Laser Interferometry Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter

[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]



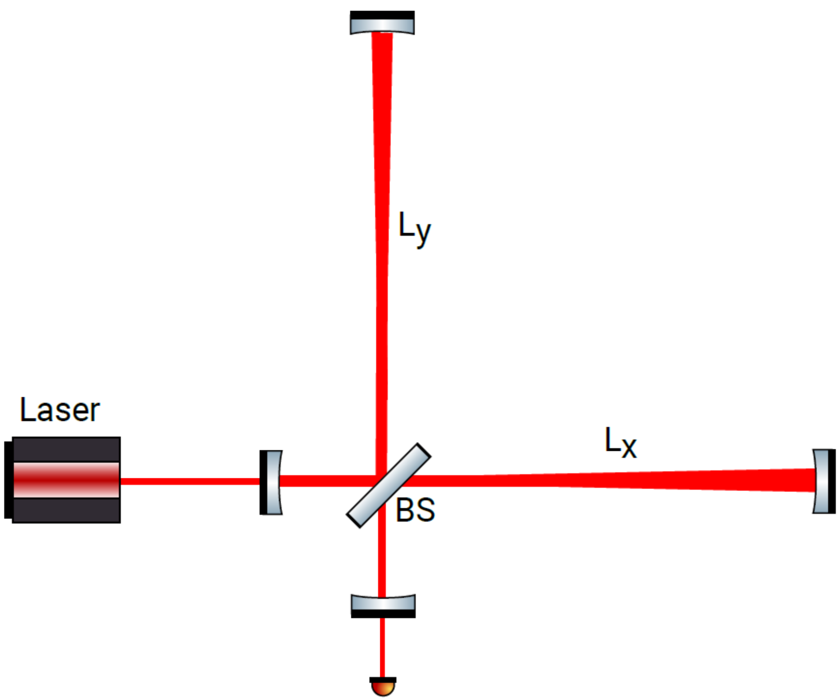
- Geometric asymmetry from beam-splitter: $\delta(L_x - L_y) \sim \delta(nl)$
- Both broadband and resonant narrowband searches possible:

$$f_{\mathrm{DM}} \approx f_{\mathrm{vibr,BS}}(T) \sim v_{\mathrm{sound}}/l \;\; \Rightarrow \;\; Q \sim 10^6 \text{ enhancement}$$

Michelson vs Fabry-Perot-Michelson Interferometers

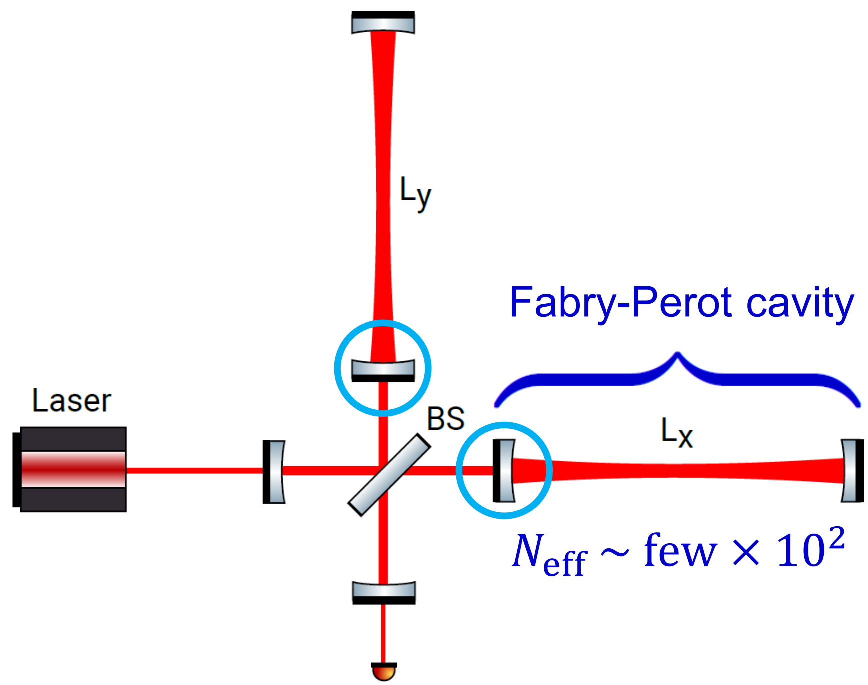
[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]

Michelson interferometer (GEO 600)



$$\delta\left(L_x - L_y\right)_{\text{BS}} \sim \delta(nl)$$

Fabry-Perot-Michelson IFO (LIGO/VIRGO/KAGRA)



$$\delta\left(L_x - L_y\right)_{\text{BS}} \sim \delta(nl)/N_{\text{eff}}$$

Michelson vs Fabry-Perot-Michelson Interferometers

[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]

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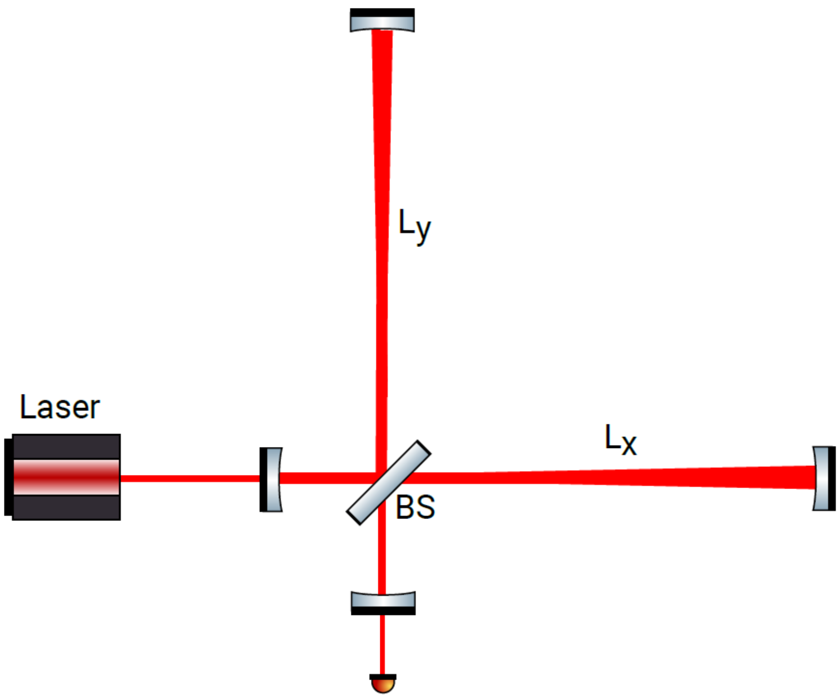
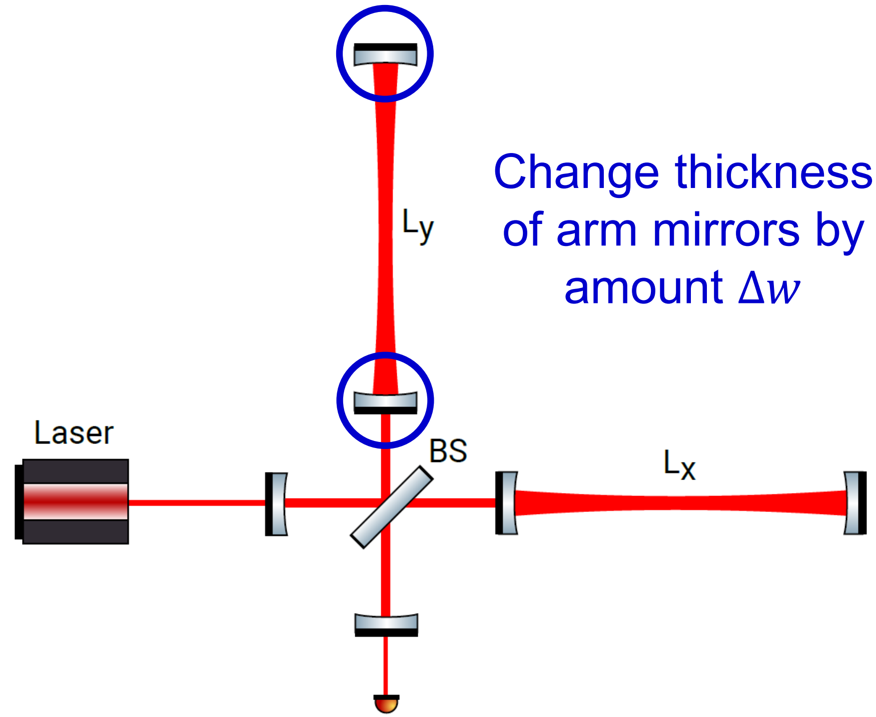


$$\delta\left(L_x - L_y\right)_{\mathrm{BS}} \sim \delta(nl)$$

Fabry-Perot-Michelson IFO (LIGO/VIRGO/KAGRA)

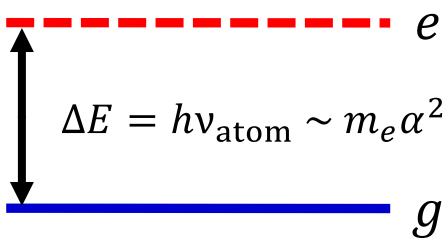


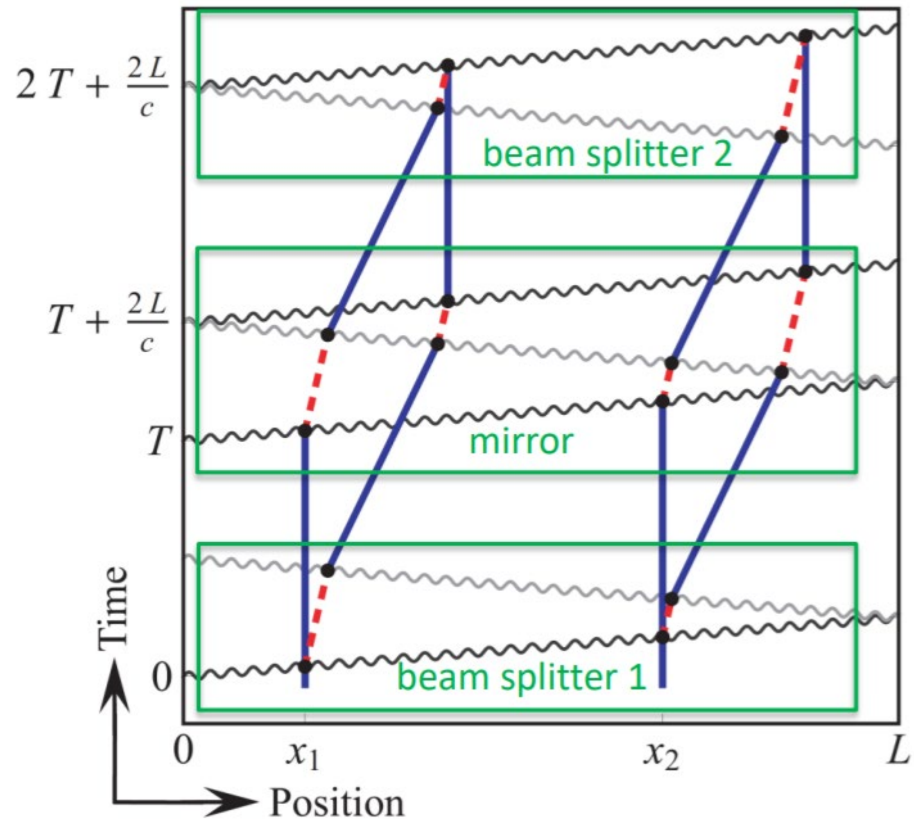
$$\delta\left(L_x - L_y\right) \approx \delta(\Delta w)$$

Atom Interferometry Searches for Oscillating Variations in Fundamental Constants due to Dark Matter

[Arvanitaki, Graham, Hogan, Rajendran, Van Tilburg, *PRD* **97**, 075020 (2018)]

Electronic transition



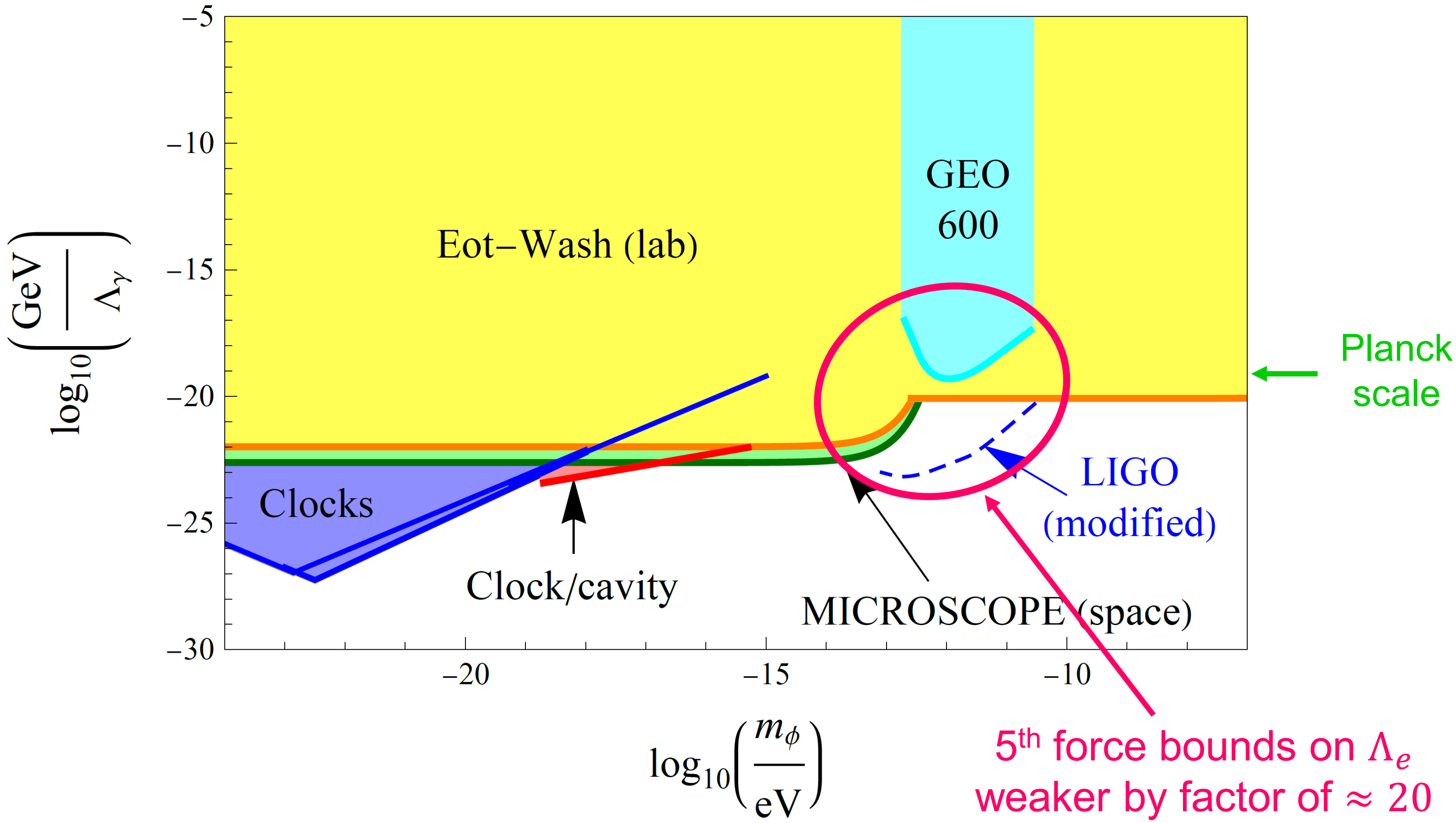


Phase shift between the two separated atom interferometers is maximised when $T_{\text{osc}} \sim 2T$: $\delta(\Delta\Phi)_{\text{max}} \sim \delta\nu_{\text{atom}} \cdot T_{\text{osc}}$

Constraints on Scalar Dark Matter with $\varphi F_{\mu\nu}F^{\mu\nu}/4\Lambda_\gamma$ Coupling

Clock/clock: [*PRL* **115**, 011802 (2015)], [*PRL* **117**, 061301 (2016)], [*Nature* **591**, 564 (2021)];
Clock/cavity: [*PRL* **125**, 201302 (2020)]; **GEO600:** [*Nature* **600**, 424 (2021)]

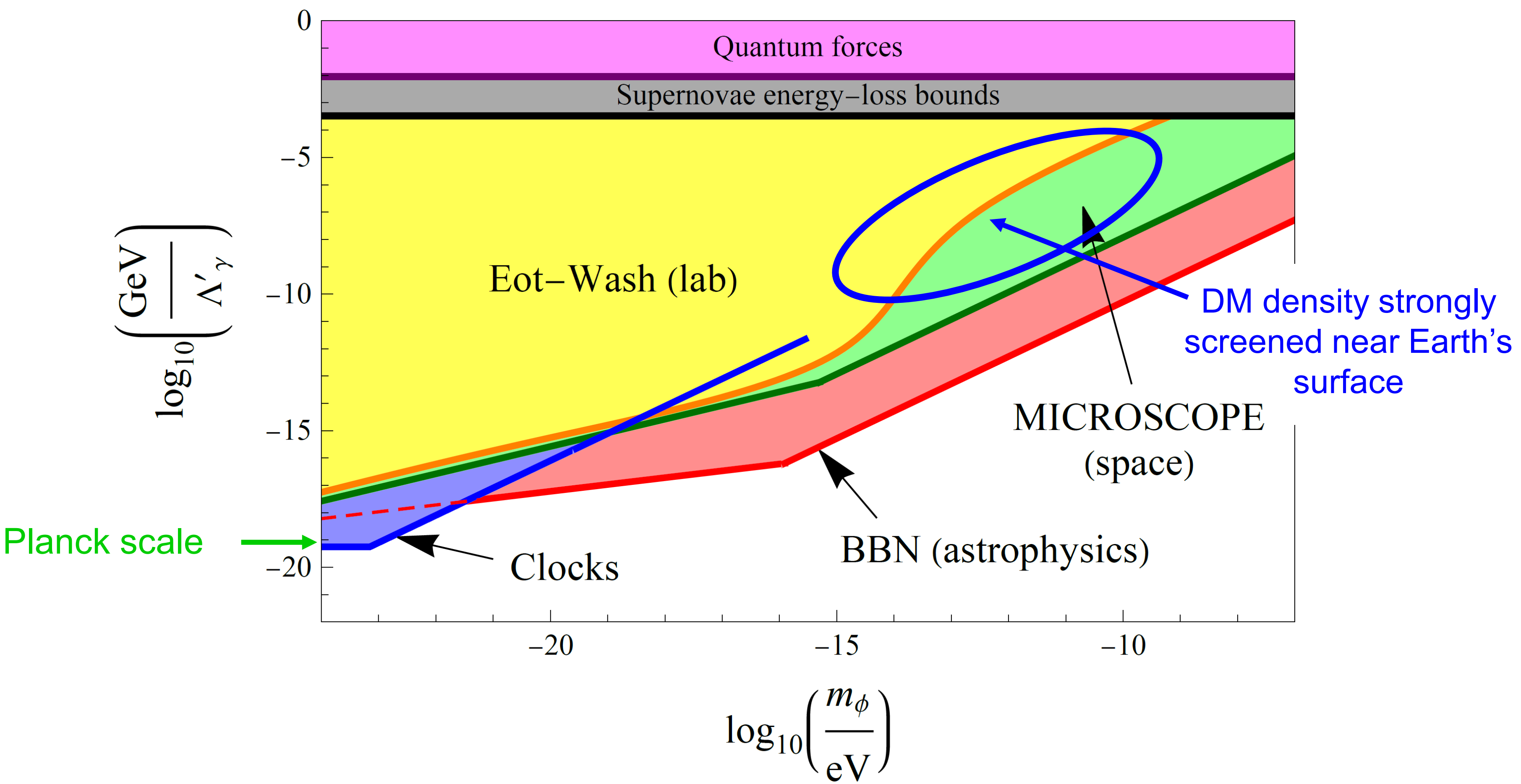
4 orders of magnitude improvement!



Constraints on Scalar Dark Matter with $\varphi^2 F_{\mu\nu}F^{\mu\nu}/4(\Lambda'_\gamma)^2$ Coupling

Clock/clock + BBN constraints: [Stadnik, Flambaum, *PRL* **115**, 201301 (2015); *PRA* **94**, 022111 (2016)]; **MICROSCOPE + Eöt-Wash constraints:** [Hees *et al.*, *PRD* **98**, 064051 (2018)]

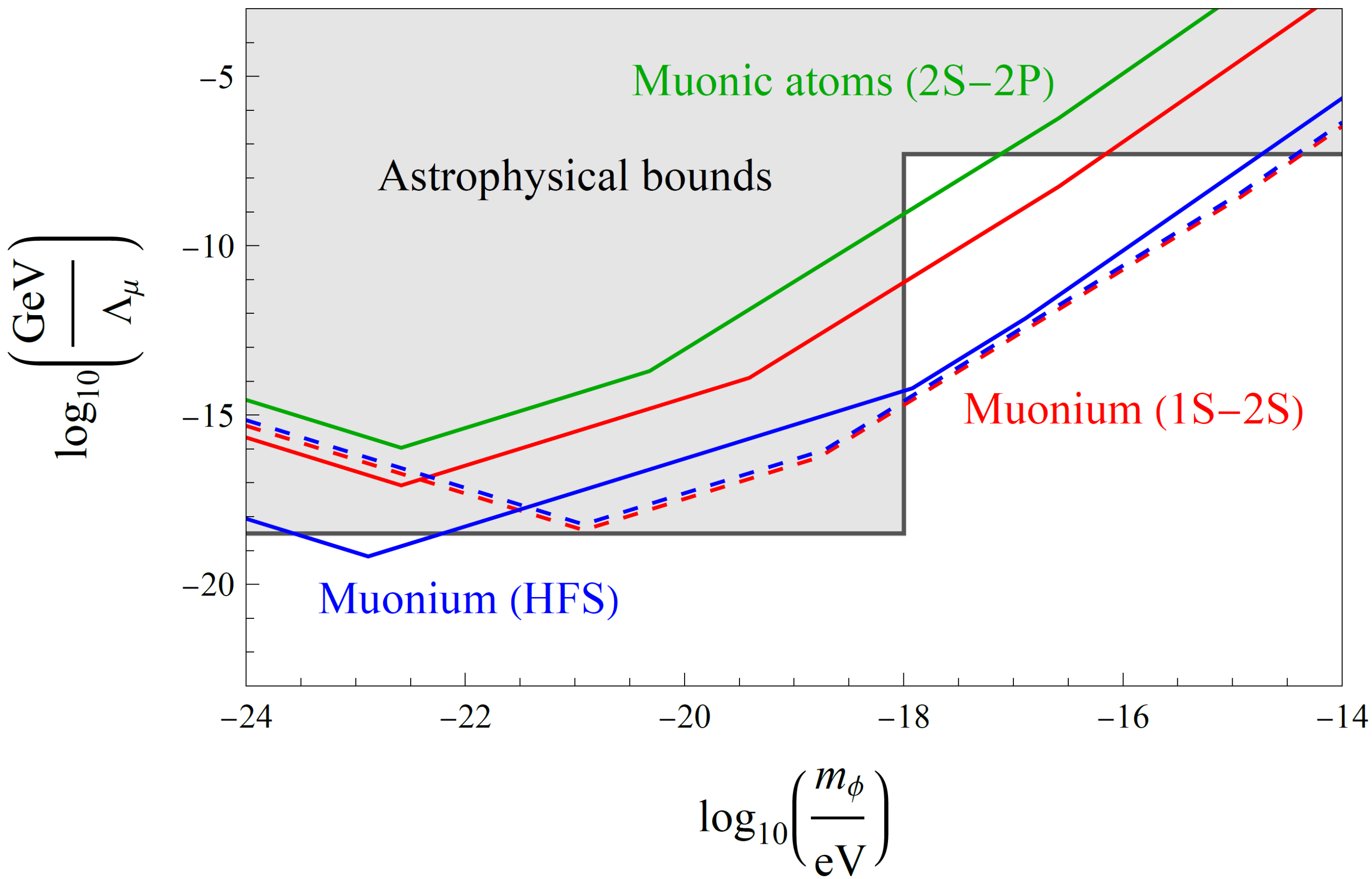
15 orders of magnitude improvement!



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!
(Best existing datasets from muonium experiments at LAMPF in 1990s)



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!
(Best existing datasets from muonium experiments at LAMPF in 1990s)