

Phenomenology of Ultralight Scalar Dark Matter

Yevgeny Stadnik

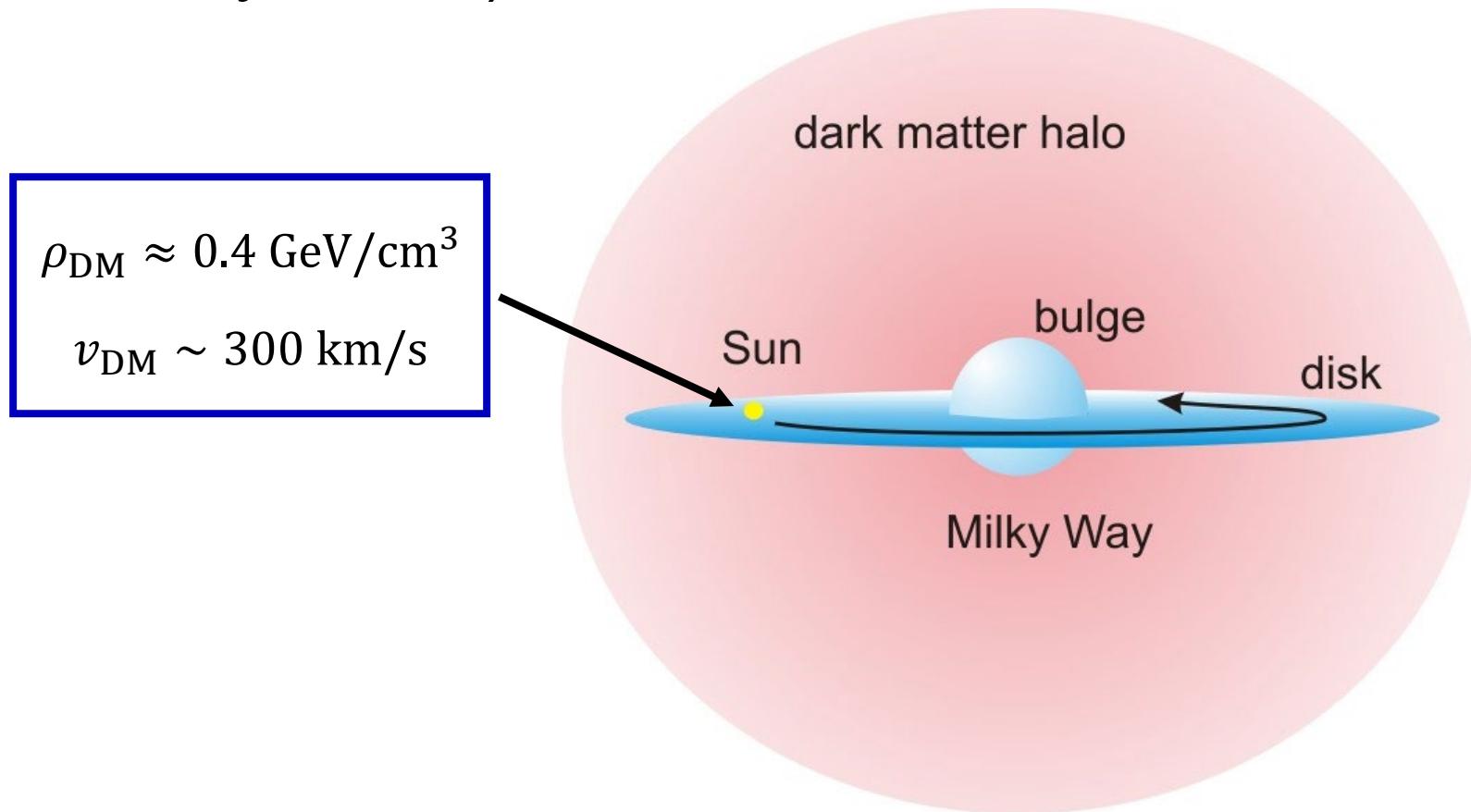
Australian Research Council DECRA Fellow

University of Sydney, Australia

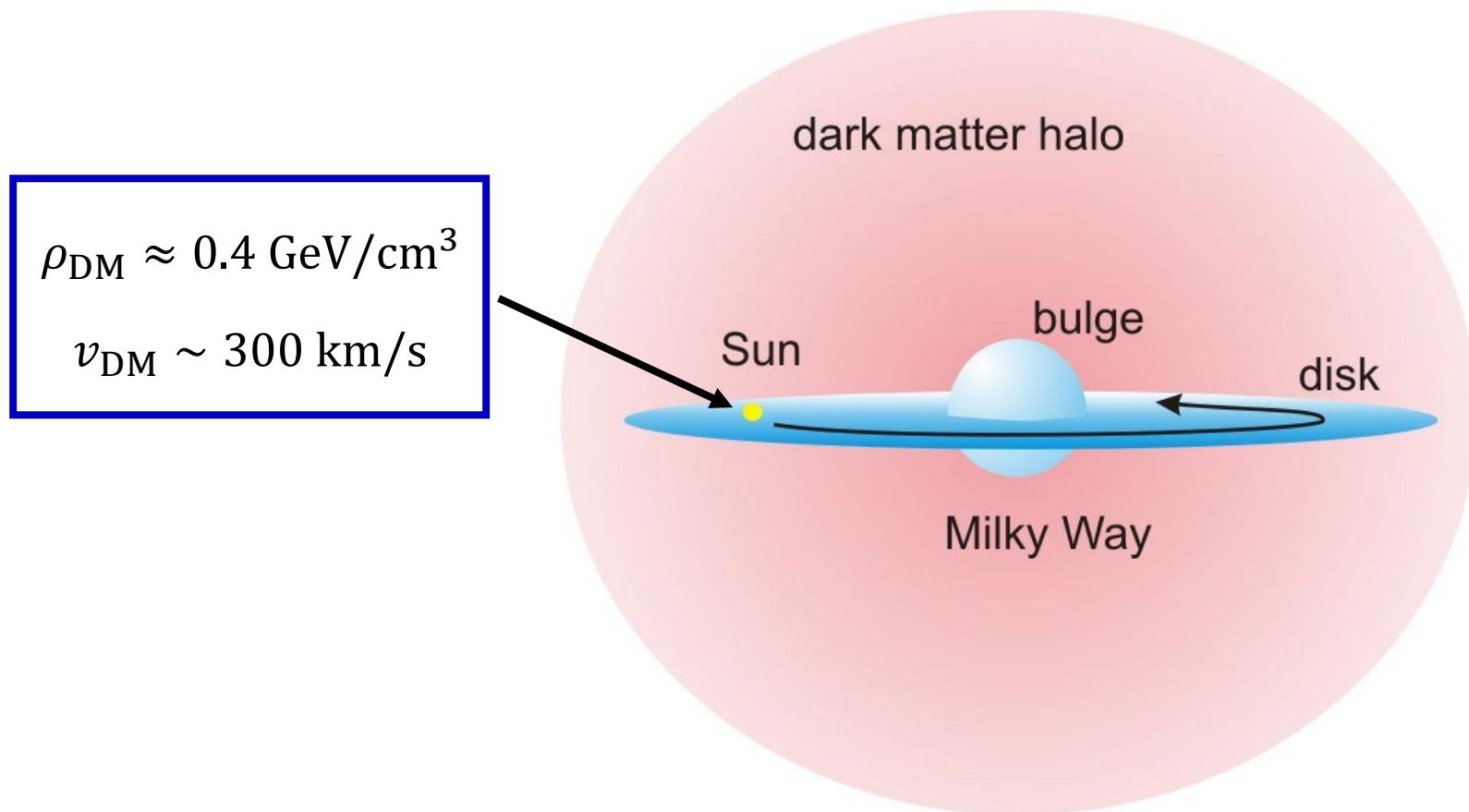
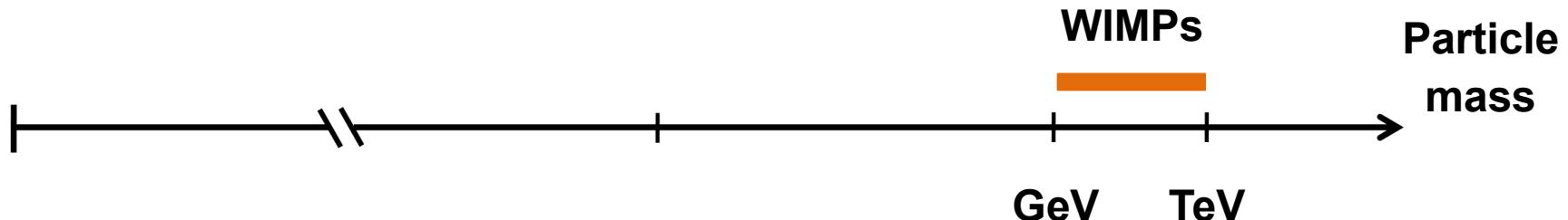
**Sydney Spring School of Particle Physics and Cosmology,
University of Sydney, Australia, 30th November – 2nd December 2022**

Dark Matter

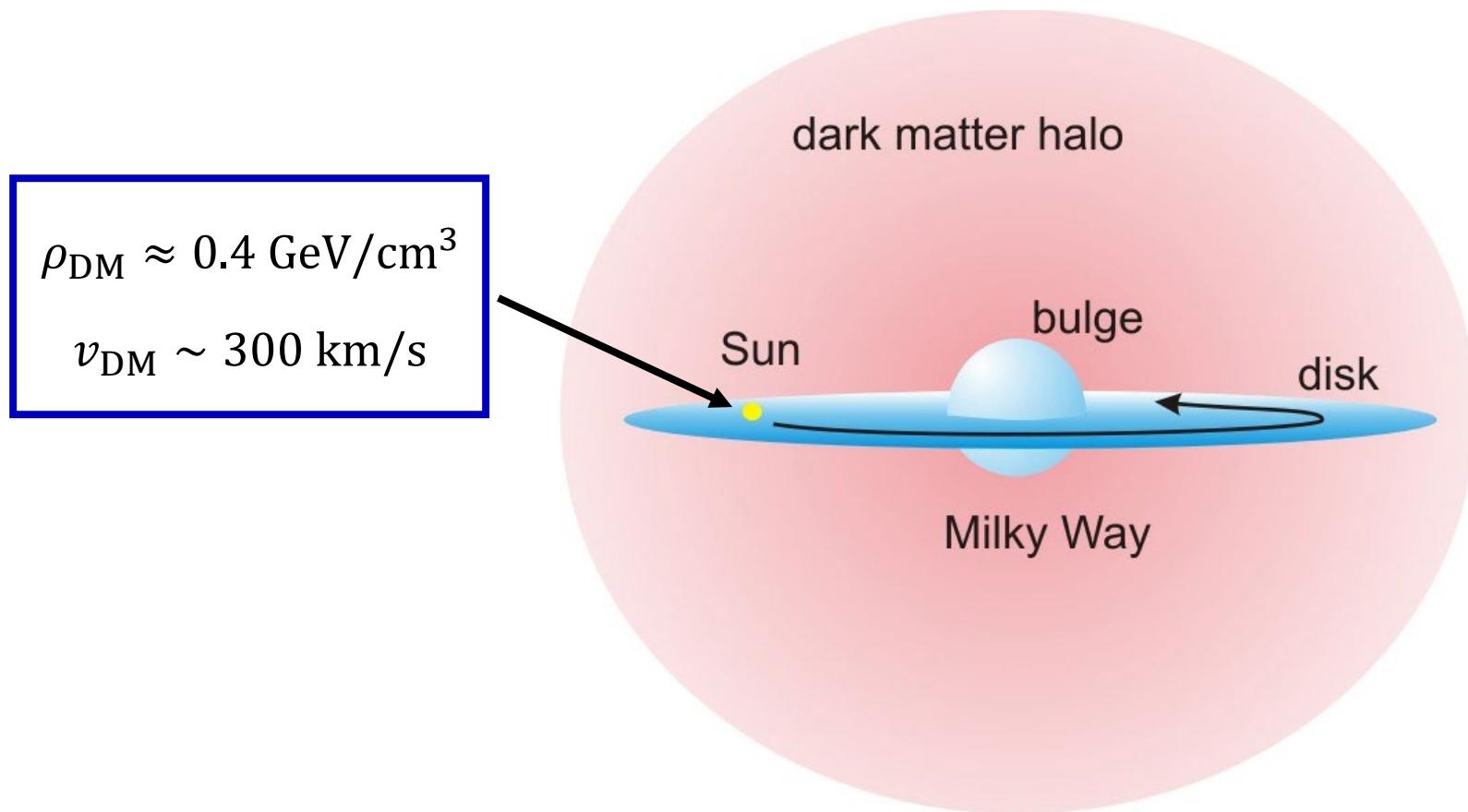
Strong astrophysical evidence for existence of **dark matter** (~5 times more dark matter than ordinary matter)



Dark Matter

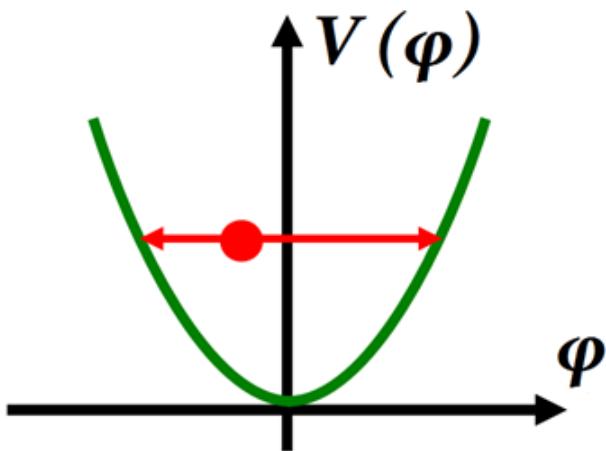


Dark Matter



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

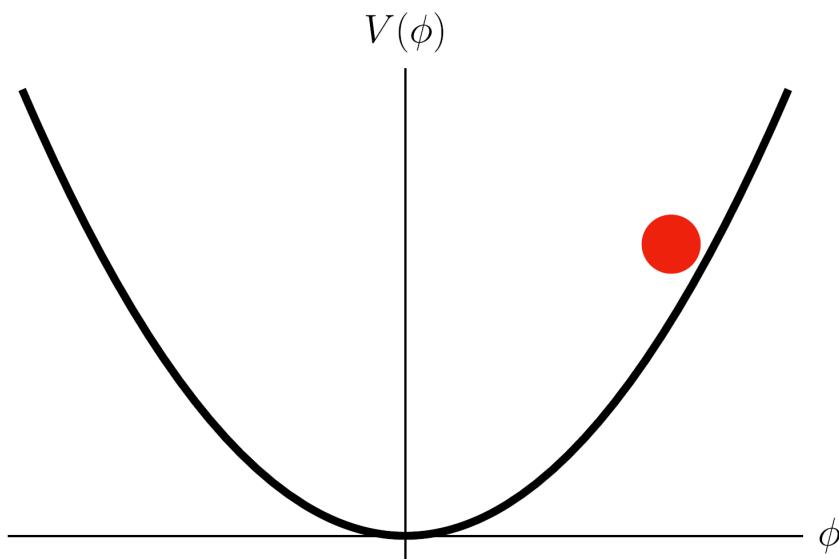


$$V(\varphi) = \frac{m_\varphi^2 \varphi^2}{2}$$

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

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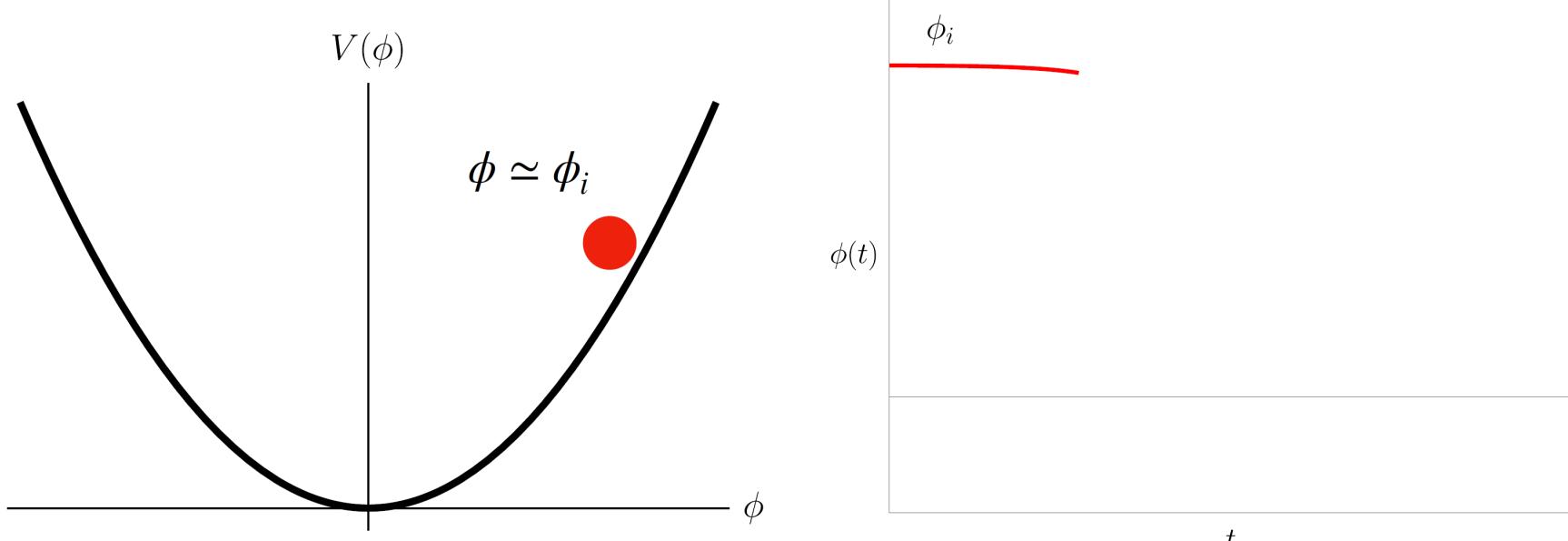


$$\ddot{\varphi} + 3H(t)\dot{\varphi} + m_\varphi^2 \varphi \approx 0$$

← Damped harmonic oscillator with a
time-dependent frictional term

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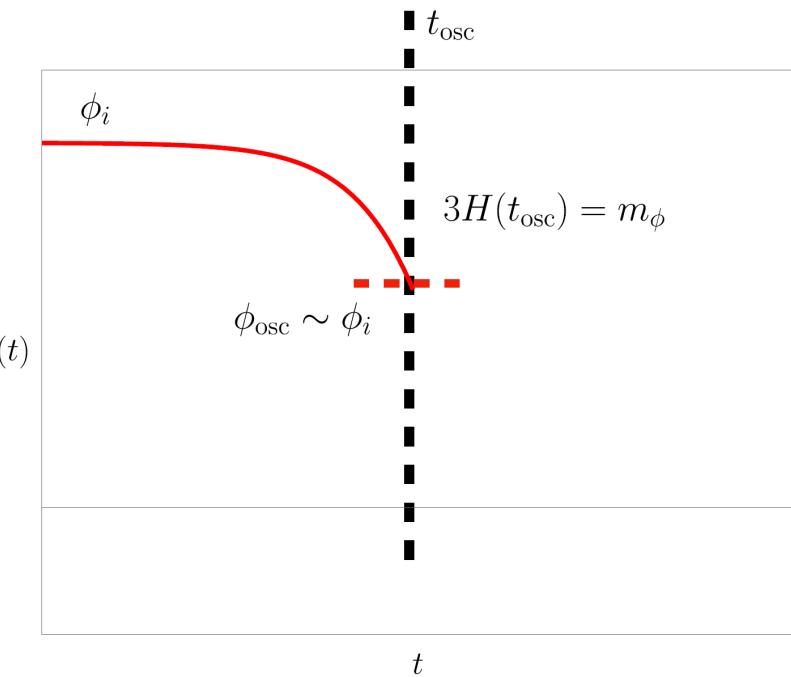
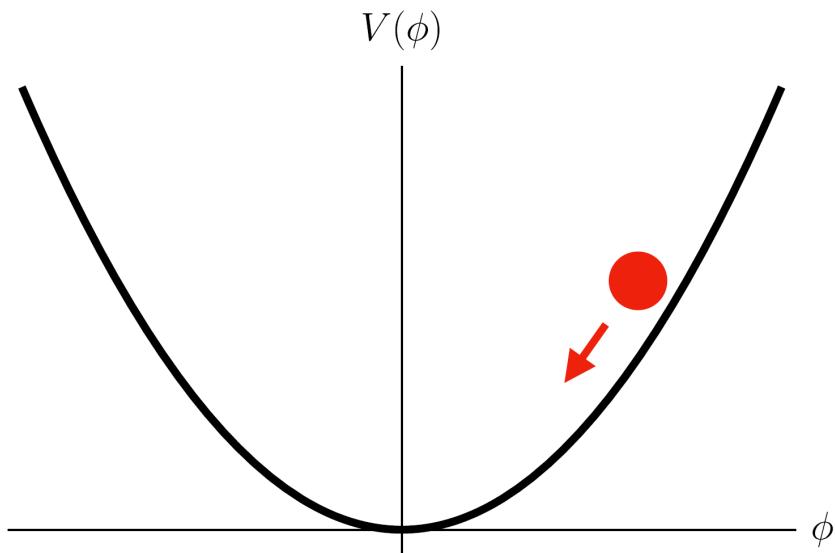


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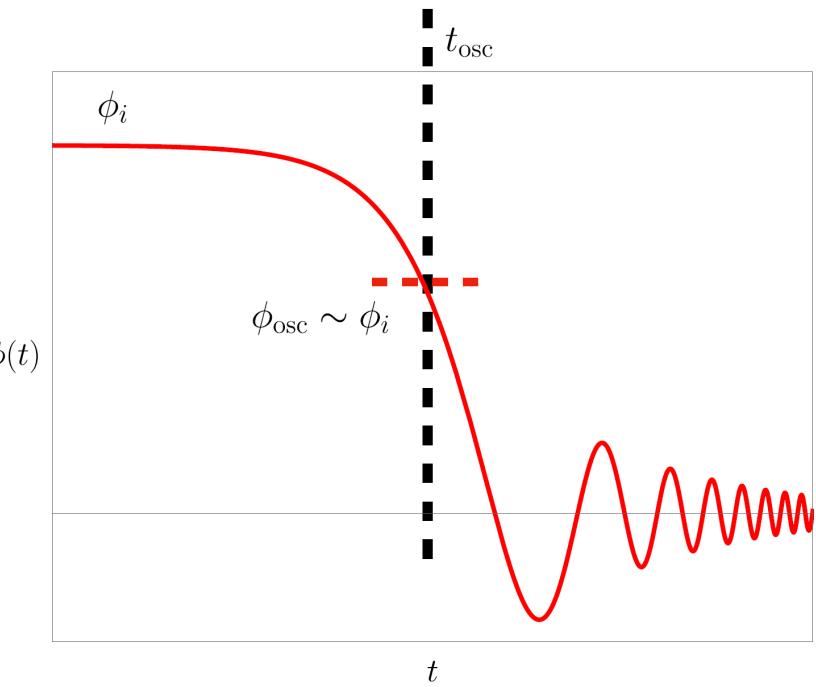
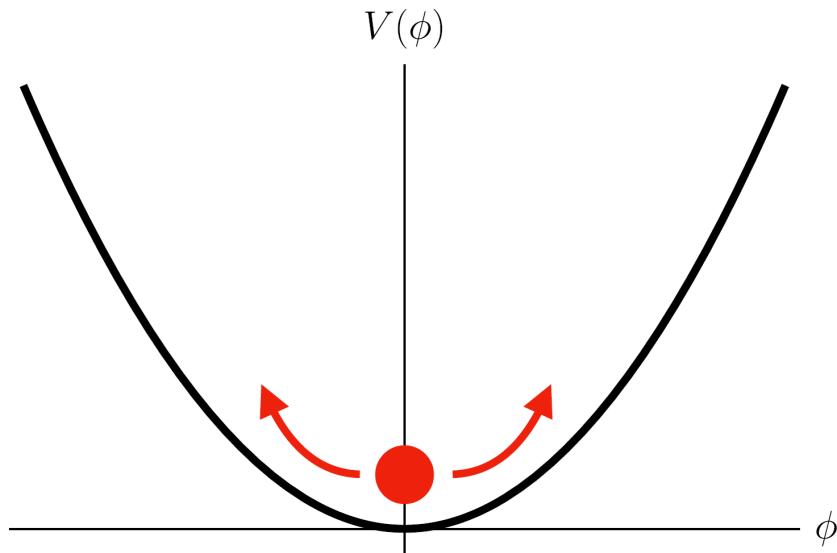


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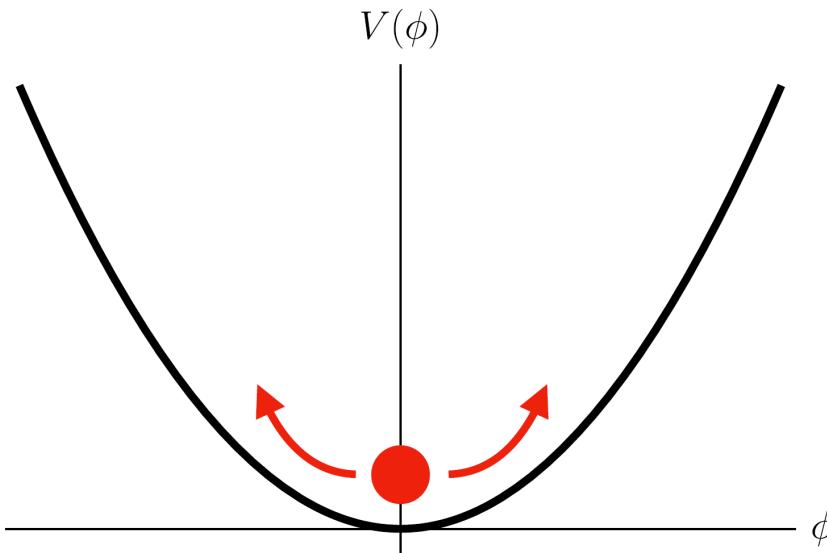


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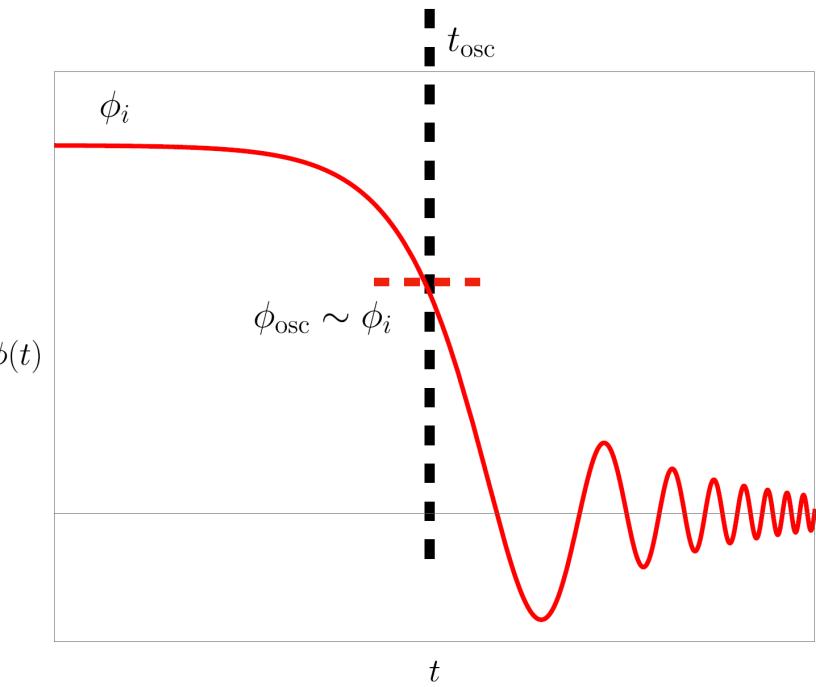
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“Vacuum misalignment” mechanism – non-thermal production, $\langle \rho_\varphi \rangle$ governed by initial conditions (ϕ_i), redshifts as $\langle \rho_\varphi \rangle \propto 1/[a(t)]^3$, with $\langle p_\varphi \rangle \ll \langle \rho_\varphi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

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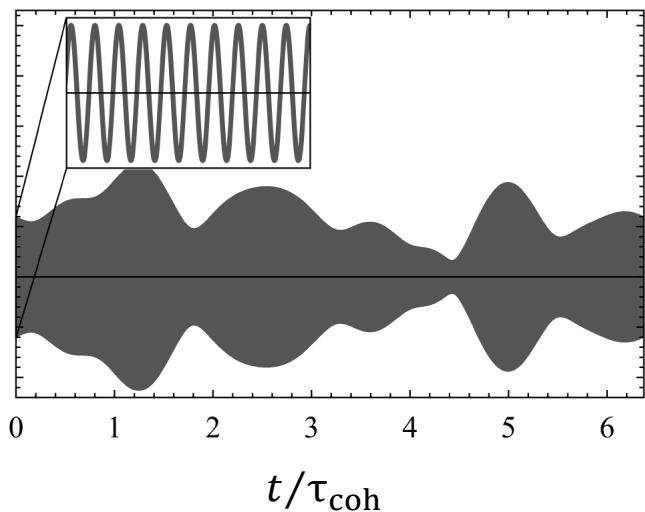
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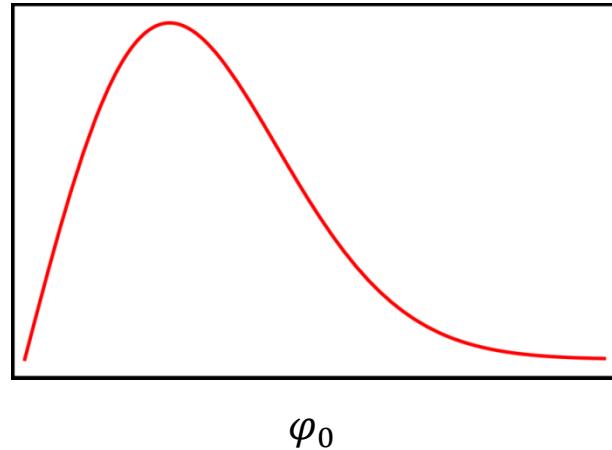

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Evolution of φ_0 with time



Probability distribution function of φ_0
(Rayleigh distribution)



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

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

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

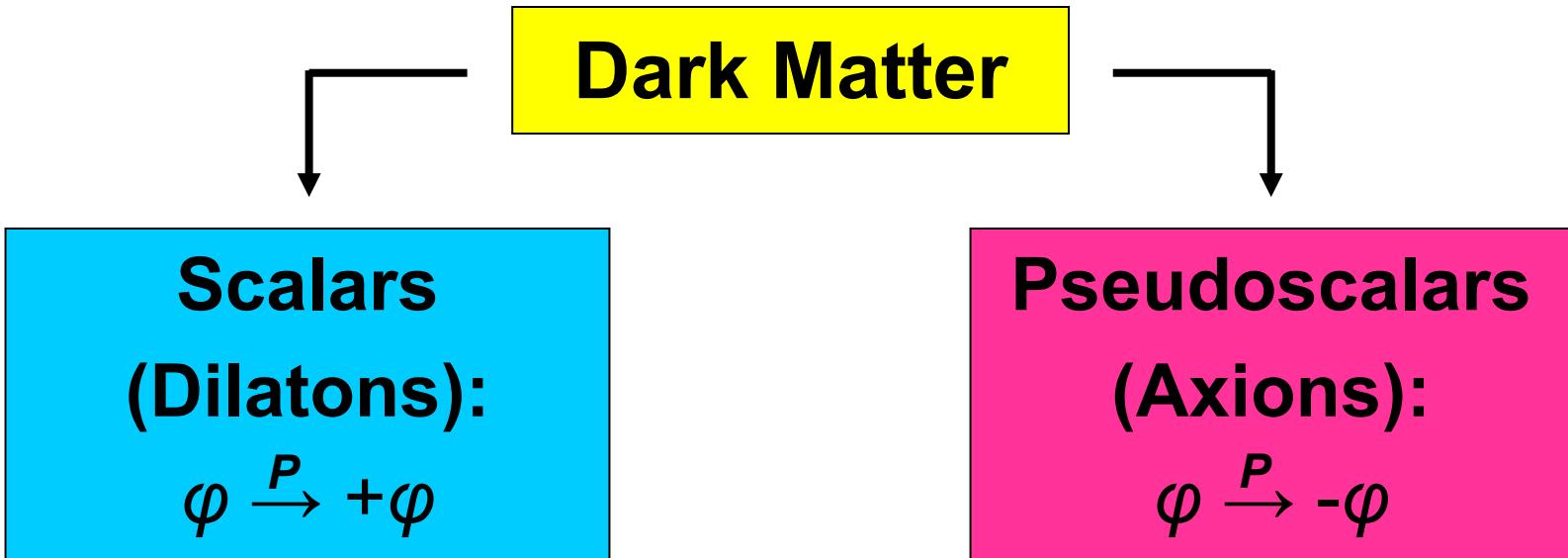
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- *Wave-like signatures* [cf. *particle-like* signatures of WIMP DM]

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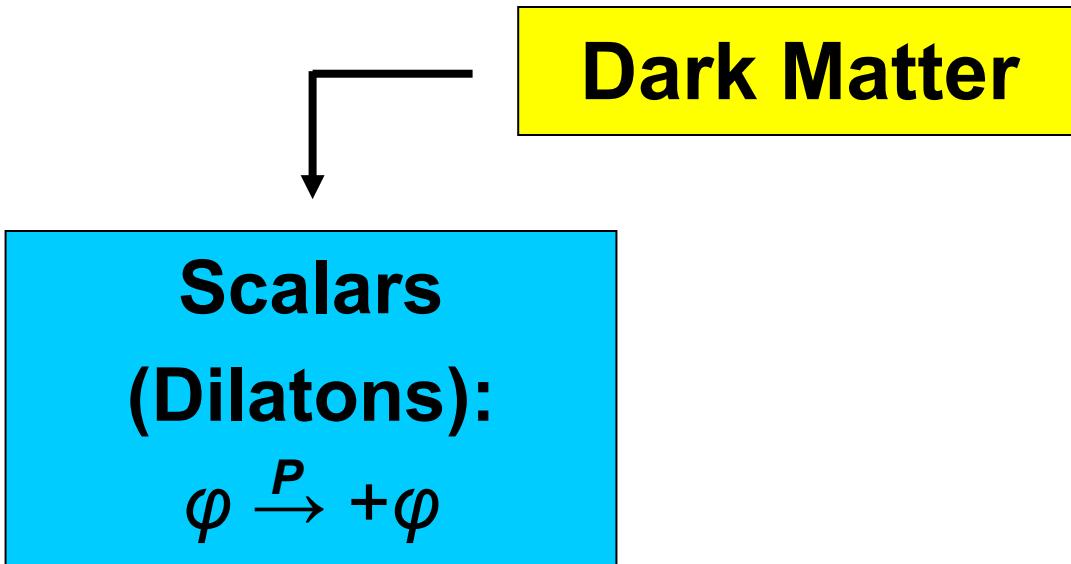
→ Spatio-temporal
variations of “constants”

- 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)

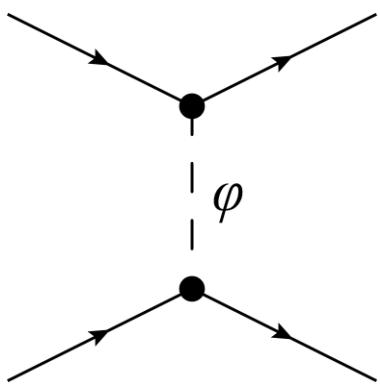
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Traditional Probes of Low-mass Scalars



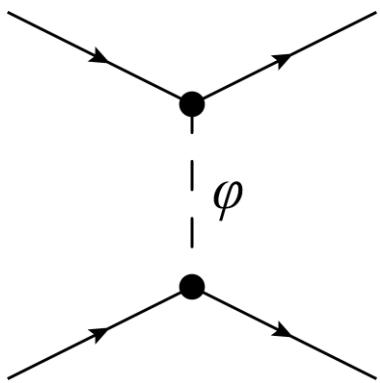
Particle exchange

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

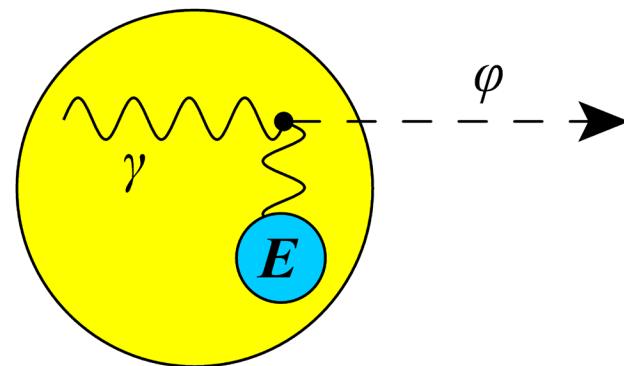
$$\Rightarrow V_\varphi(r) = -\frac{m_1 m_2 e^{-m_\varphi r}}{4\pi \Lambda_1 \Lambda_2 r}$$

→ Equivalence-principle-violating
“fifth-forces”

Traditional Probes of Low-mass Scalars



Particle exchange



Stellar emission

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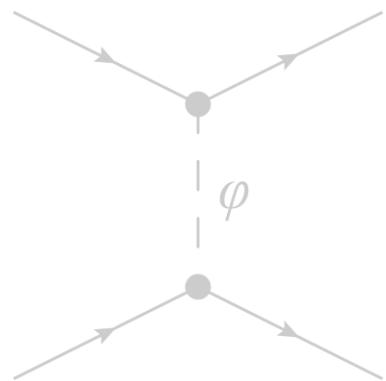
→ Equivalence-principle-violating
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$$\mathcal{L}_\gamma = \frac{\varphi}{\Lambda_\gamma} \frac{F_{\mu\nu} F^{\mu\nu}}{4}$$

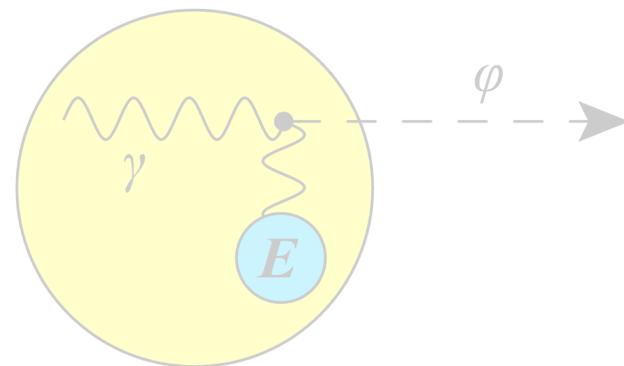
$$\Rightarrow \Gamma_\varphi \propto \frac{1}{\Lambda_\gamma^2}$$

→ Increased heating in active stars
(Increased cooling in “dead” stars)

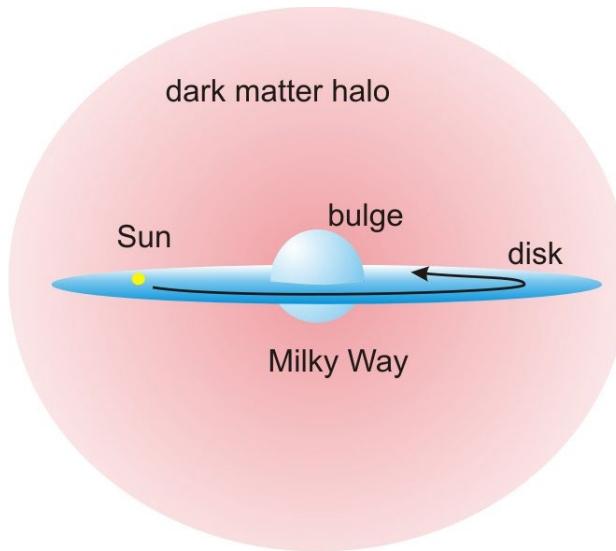
New Probes of Low-mass Scalars?



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)]

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

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

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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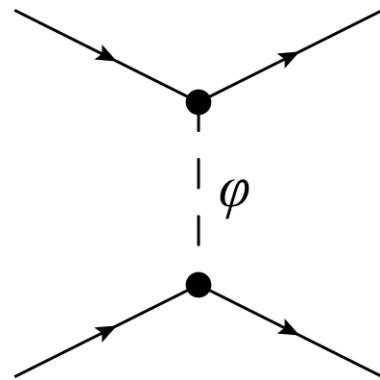
Fifth Forces: Linear vs Quadratic Couplings

[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

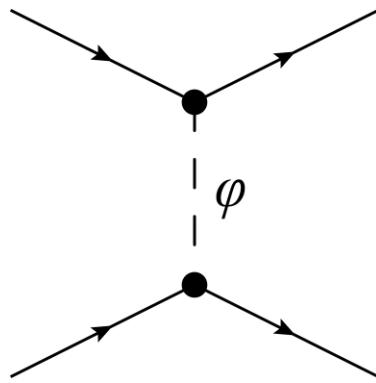
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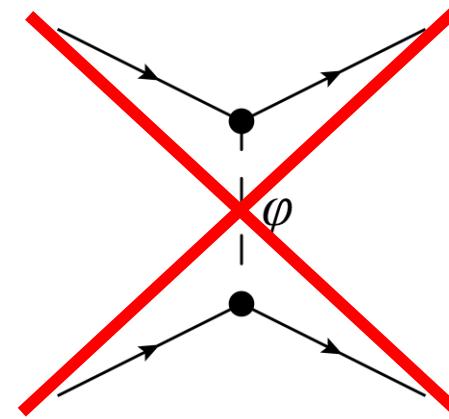
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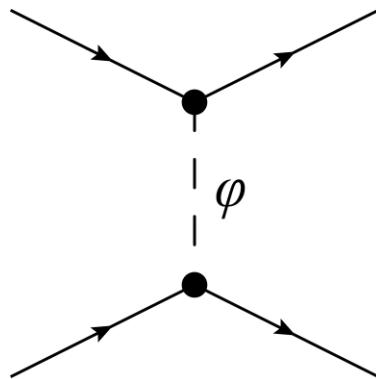
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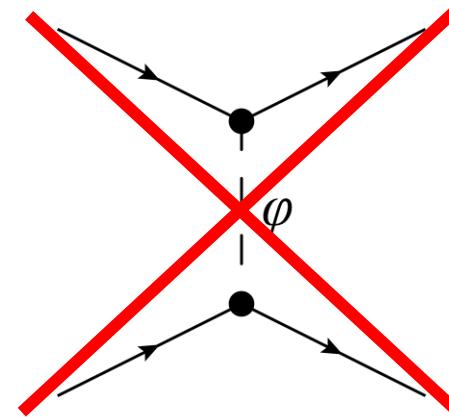
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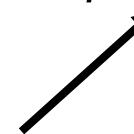


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Profile outside of a spherical body

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



Gradients + amplification/screening

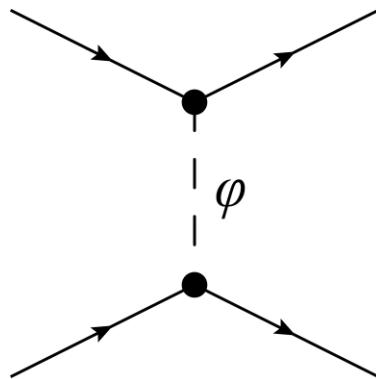
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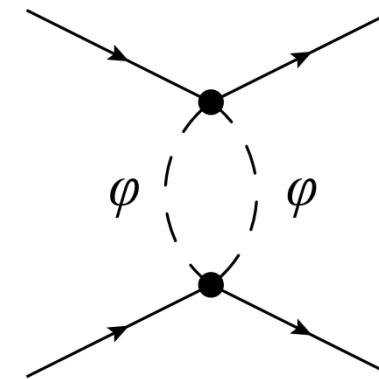
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$$\square\varphi + m_\varphi^2 \varphi = \pm \kappa \rho \quad \text{Source term}$$



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

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



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

Profile outside of a spherical body

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

Gradients + amplification/screening

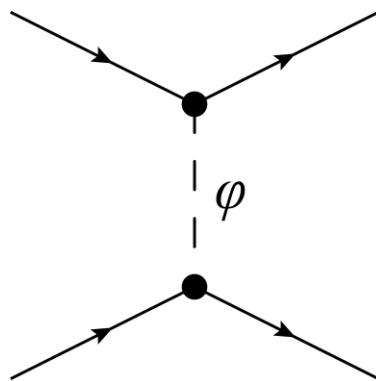
Fifth Forces: Linear vs Quadratic Couplings

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

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

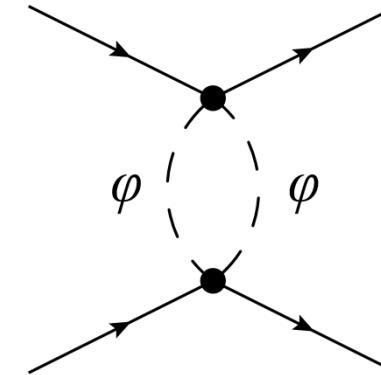
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$$\varphi = \frac{\varphi_0 \cos(m_\varphi t)}{\pm A} \frac{e^{-m_\varphi r}}{r}$$

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

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



Gradients + amplification/screening

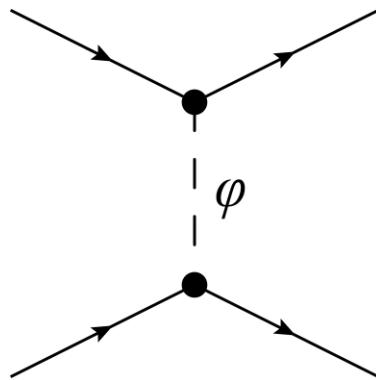
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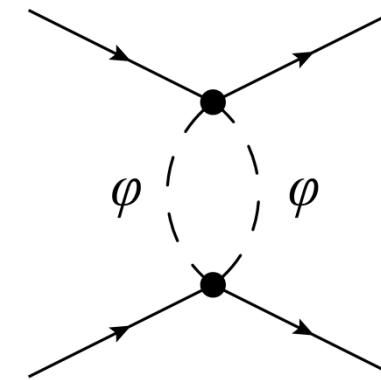
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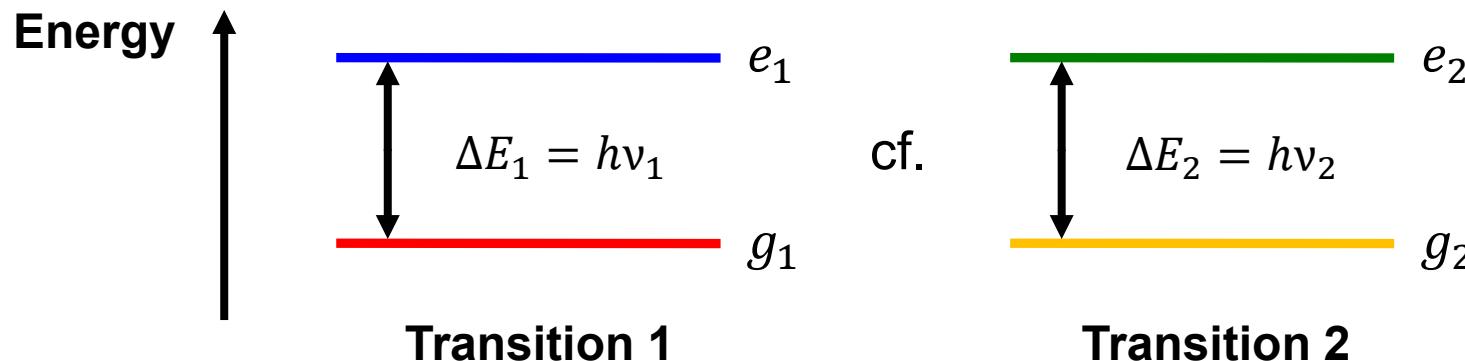
Motional gradients: $\varphi_0 \cos(m_\varphi t - \mathbf{p}_\varphi \cdot \mathbf{x})$

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

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

Gradients + amplification/screening

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



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

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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- Atomic optical transitions:

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

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



$$|p_e|_{\text{near nucleus}} \sim Z\alpha m_e c$$

Effects of Varying Fundamental Constants on Atomic Transitions

[Dzuba, Flambaum, Webb, *PRL* **82**, 888 (1999); *PRA* **59**, 230 (1999);
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Increasing Z

- Atomic hyperfine transitions:

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

Effects of Varying Fundamental Constants on Atomic Transitions

[Dzuba, Flambaum, Webb, *PRL* **82**, 888 (1999); *PRA* **59**, 230 (1999);
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$$K_\alpha(\text{H}) = 2.0, K_\alpha(\text{Rb}) = 2.3, K_\alpha(\text{Cs}) = 2.8$$



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[Dzuba, Flambaum, Webb, *PRL* **82**, 888 (1999); *PRA* **59**, 230 (1999);
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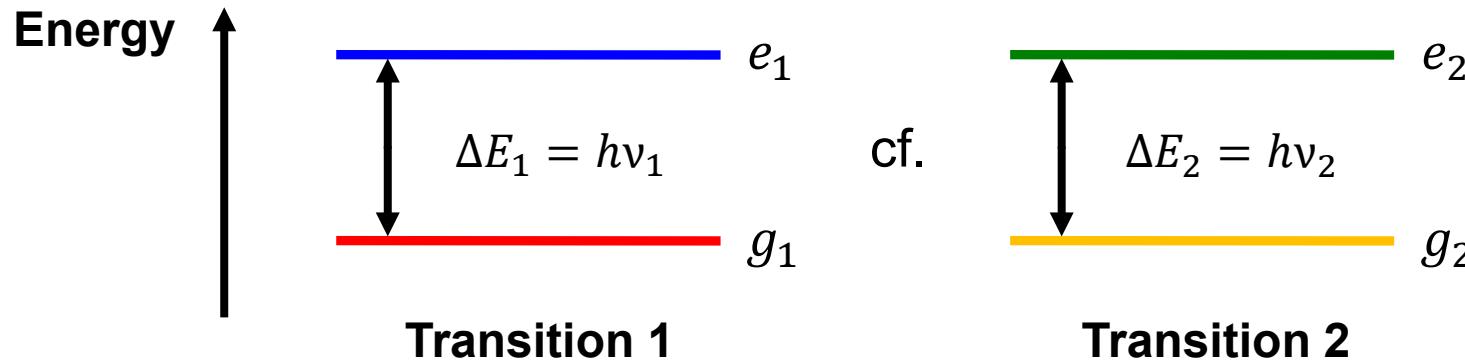
$K_{m_e/m_N} = 1$ $K_{m_q/\Lambda_{\text{QCD}}} \neq 0$

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



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)]



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

- **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^{+(E3)}/Sr [PTB]:** [Huntemann, Peik *et al.*, Ongoing]

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



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

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

(adiabatic regime)

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

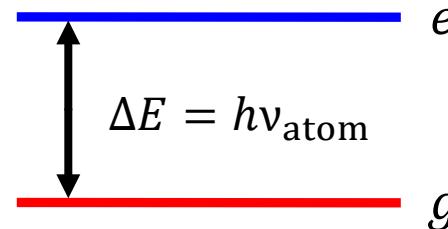
[Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRA* **93**, 063630 (2016)]

Solid material



cf.

Electronic transition



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

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

$$v_{\text{atom}} \propto Ry \propto m_e \alpha^2$$

$$\frac{v_{\text{atom}}}{v_{\text{solid}}} \propto \alpha$$

- **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 \(2021\)](#)]

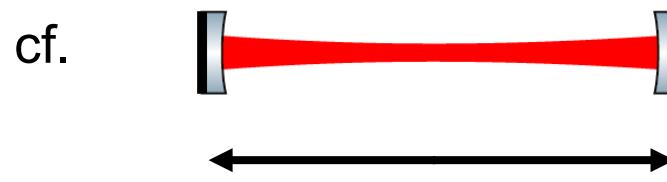
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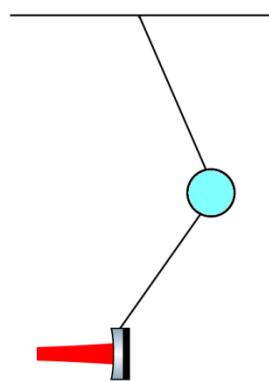
Solid material



Freely-suspended mirrors



Double-pendulum suspensions



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

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

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

$$\Rightarrow v_{\text{free}} \approx \text{constant}$$

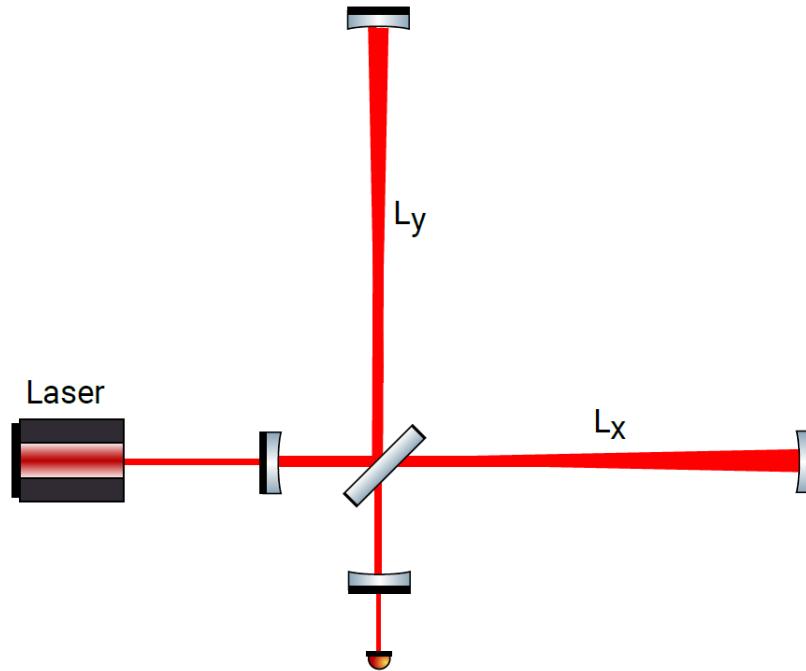
$$\frac{v_{\text{solid}}}{v_{\text{free}}} \propto m_e \alpha$$

$$\text{cf. } \frac{v_{\text{atom}}}{v_{\text{solid}}} \propto \alpha$$

Small-scale experiment currently under development at Northwestern University

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

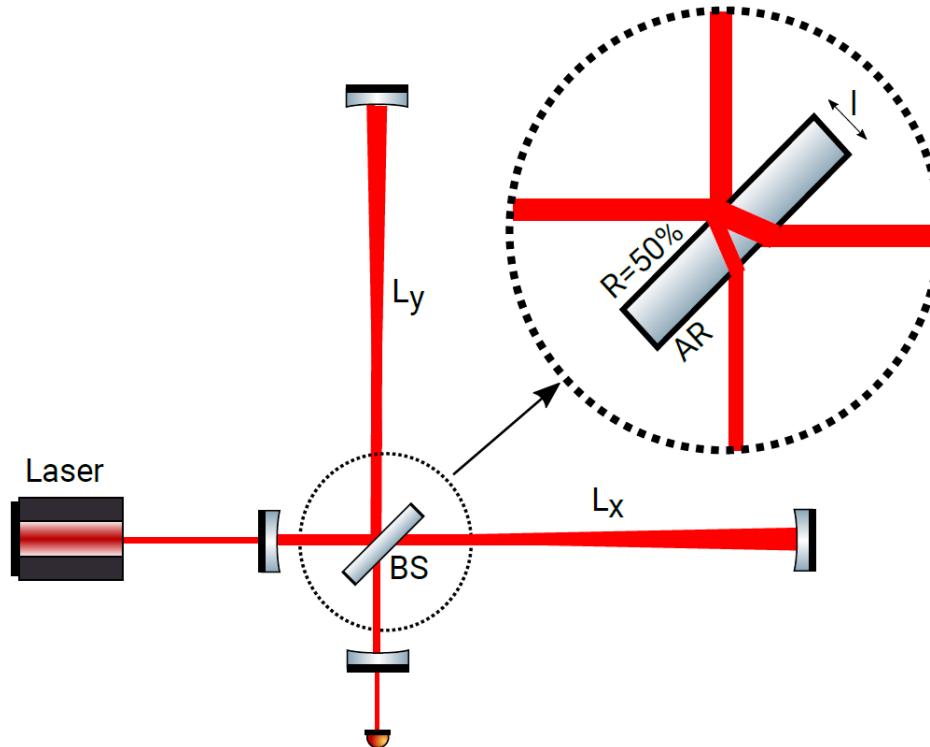
[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]



Michelson interferometer (GEO600)

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

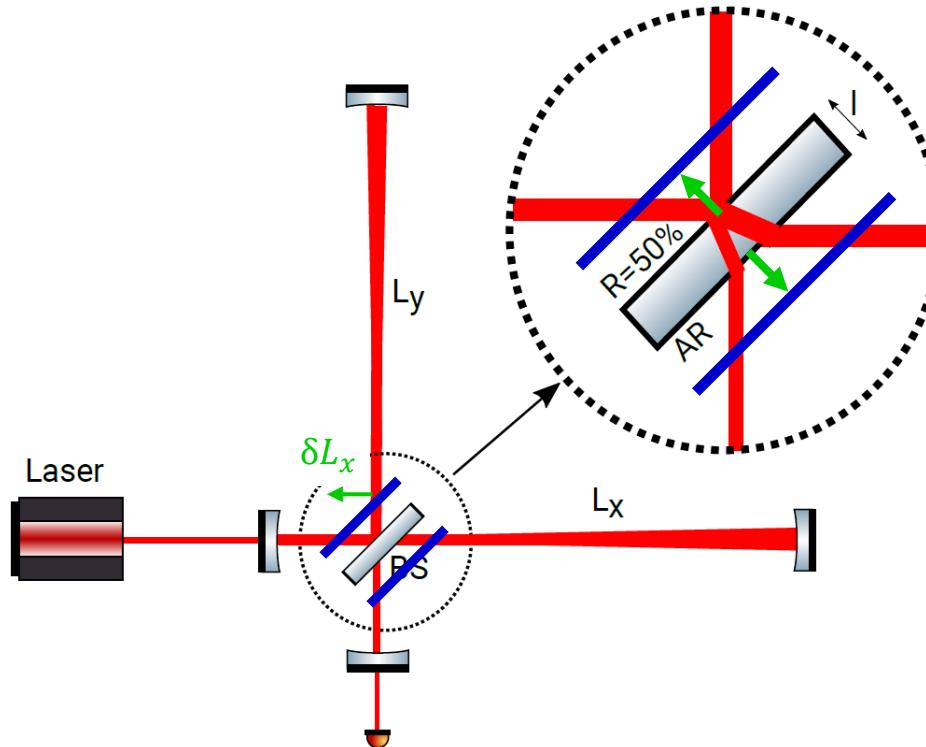
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- Geometric asymmetry from beam-splitter

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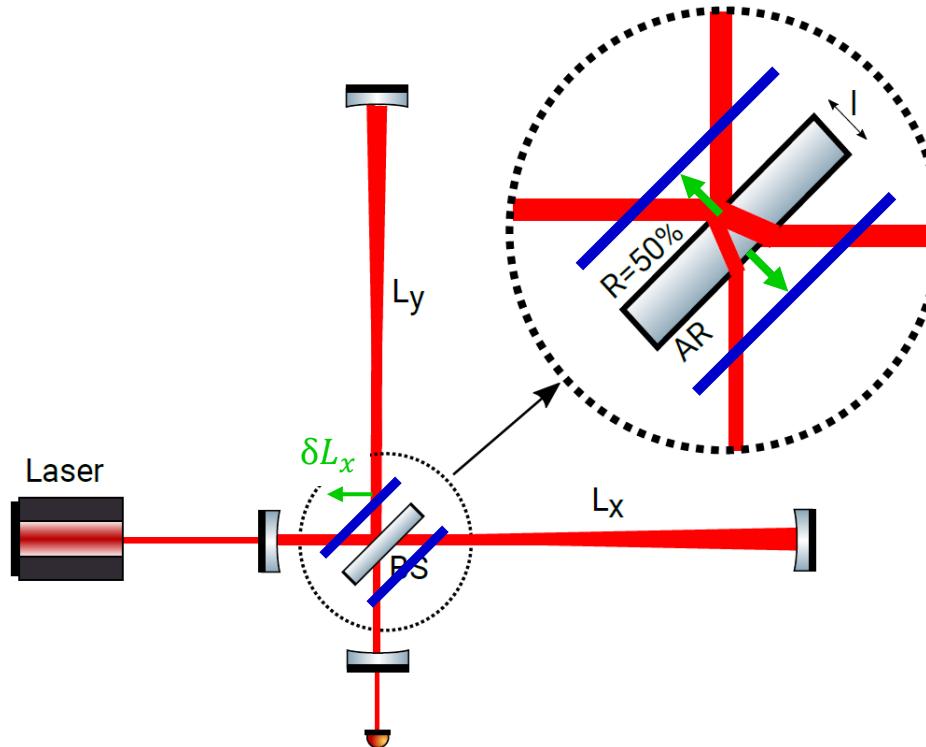
[Grote, Stadnik, *Phys. Rev. Research* 1, 033187 (2019)]



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

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

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



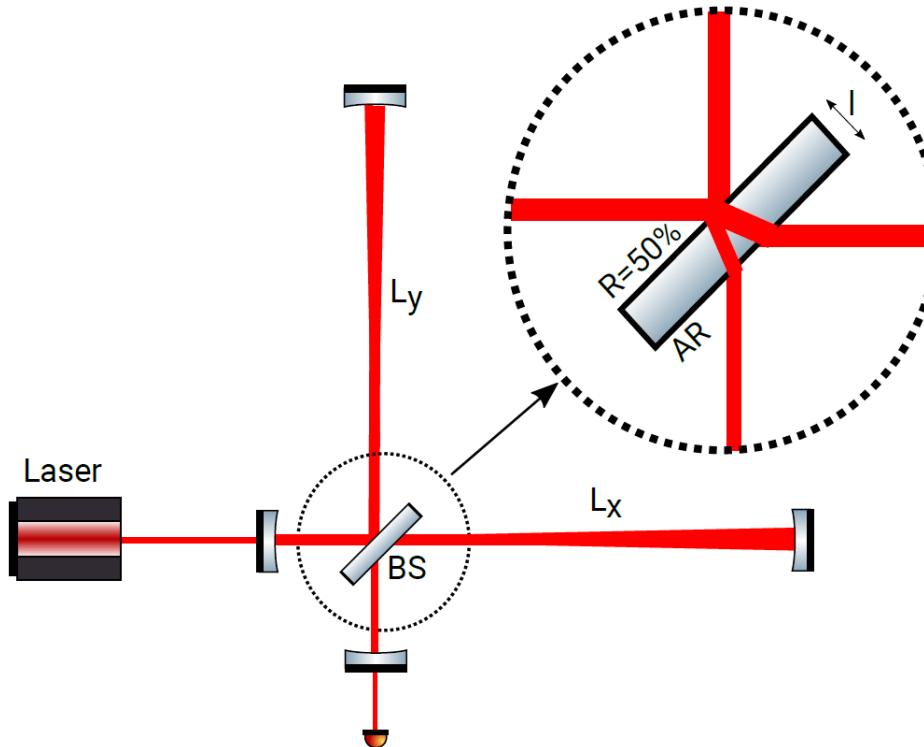
- Geometric asymmetry from beam-splitter: $\delta(L_x - L_y) \sim \delta(nl)$

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)]

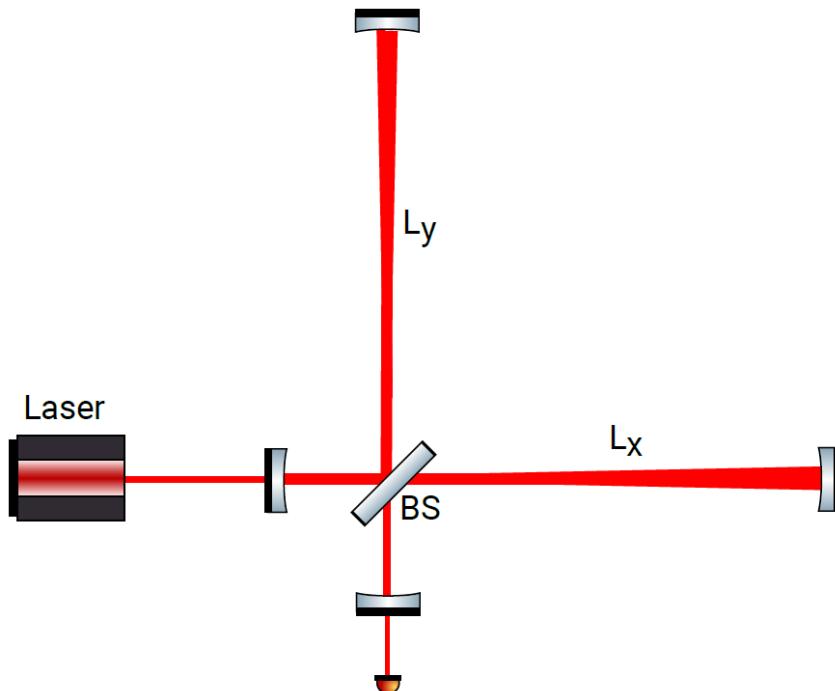


- Geometric asymmetry from beam-splitter: $\delta(L_x - L_y) \sim \delta(nl)$
- Both broadband and resonant narrowband searches possible:
$$f_{\text{DM}} \approx f_{\text{vibr,BS}}(T) \sim v_{\text{sound}}/l \Rightarrow Q \sim 10^6 \text{ enhancement}$$

Michelson vs Fabry-Perot-Michelson Interferometers

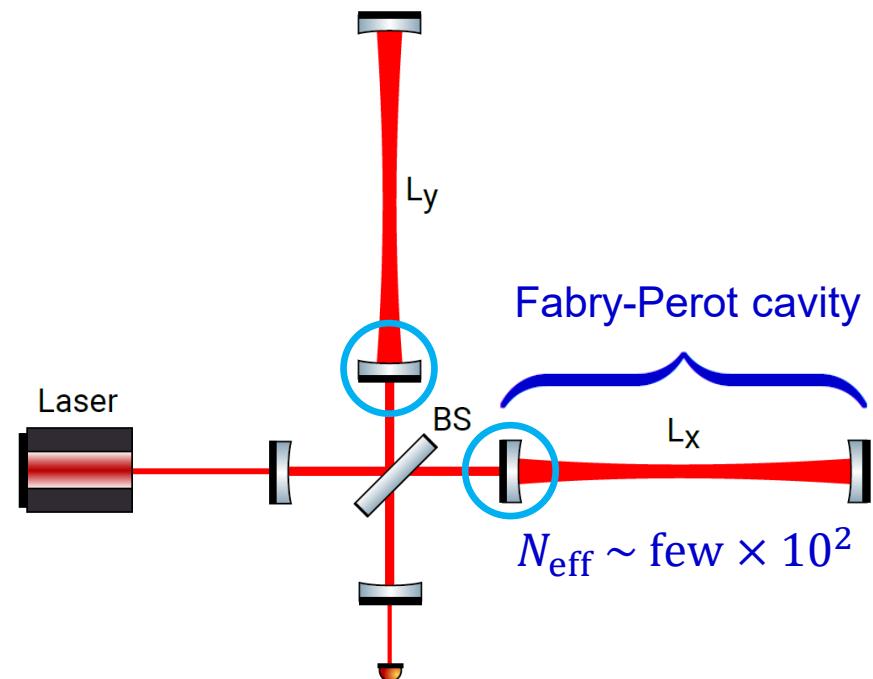
[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]

**Michelson interferometer
(GEO 600)**



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

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

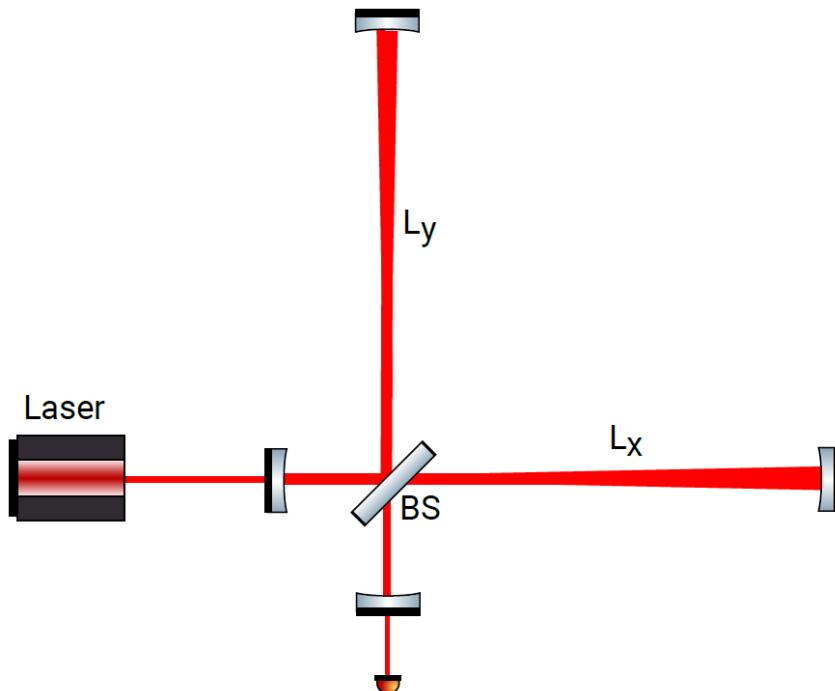


$$\delta(L_x - L_y)_{\text{BS}} \sim \delta(nl)/N_{\text{eff}}$$

Michelson vs Fabry-Perot-Michelson Interferometers

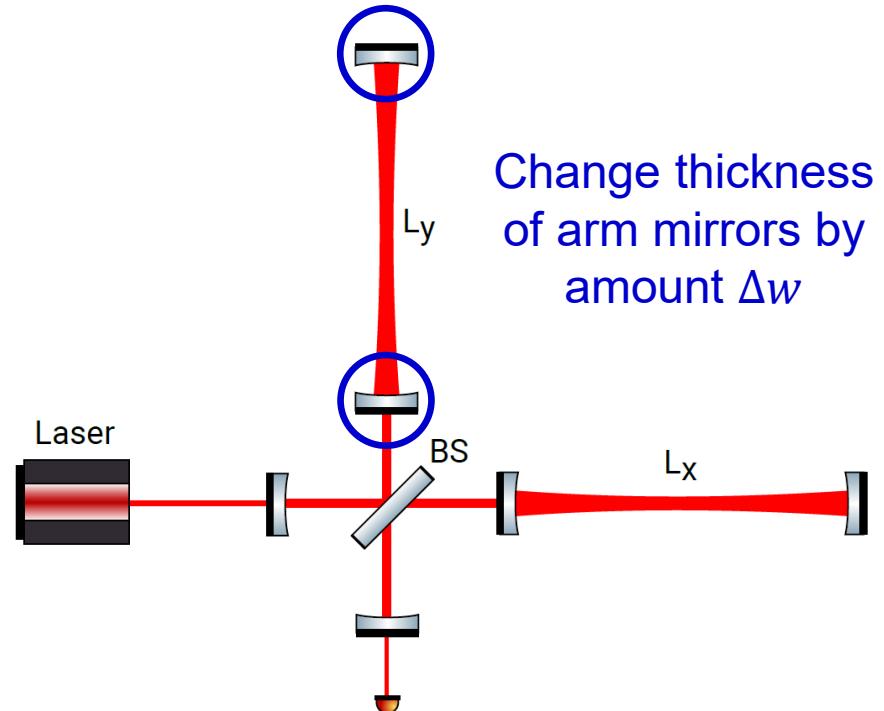
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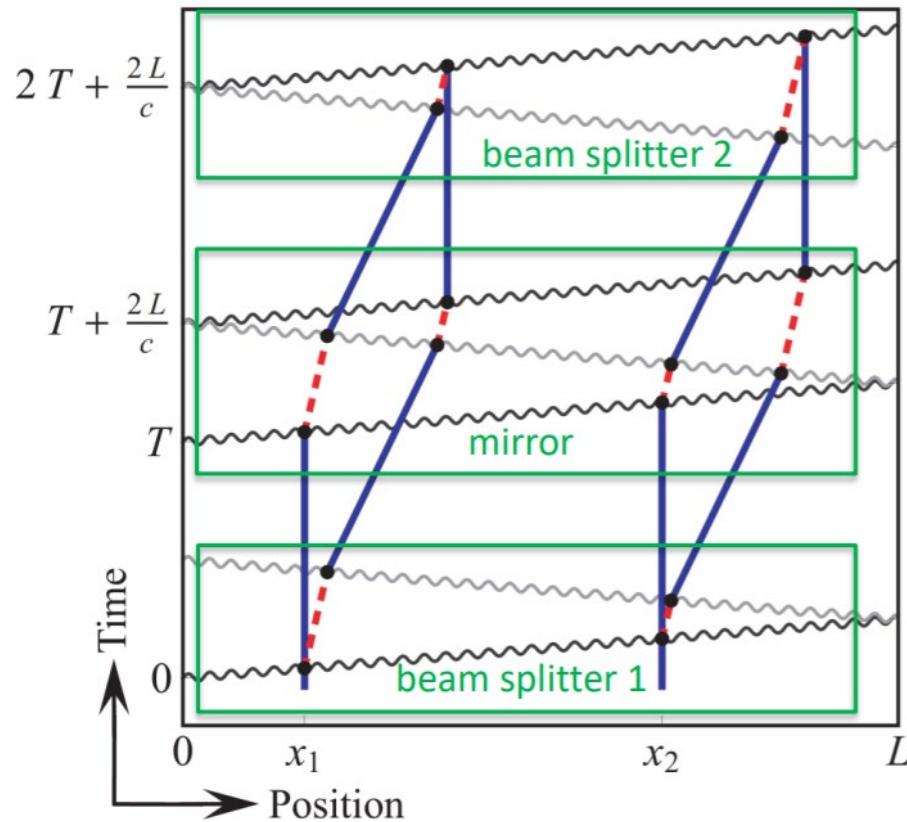
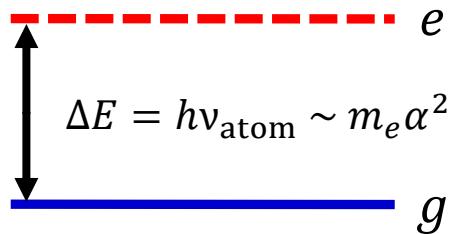


$$\delta(L_x - L_y) \approx \delta(\Delta w)$$

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

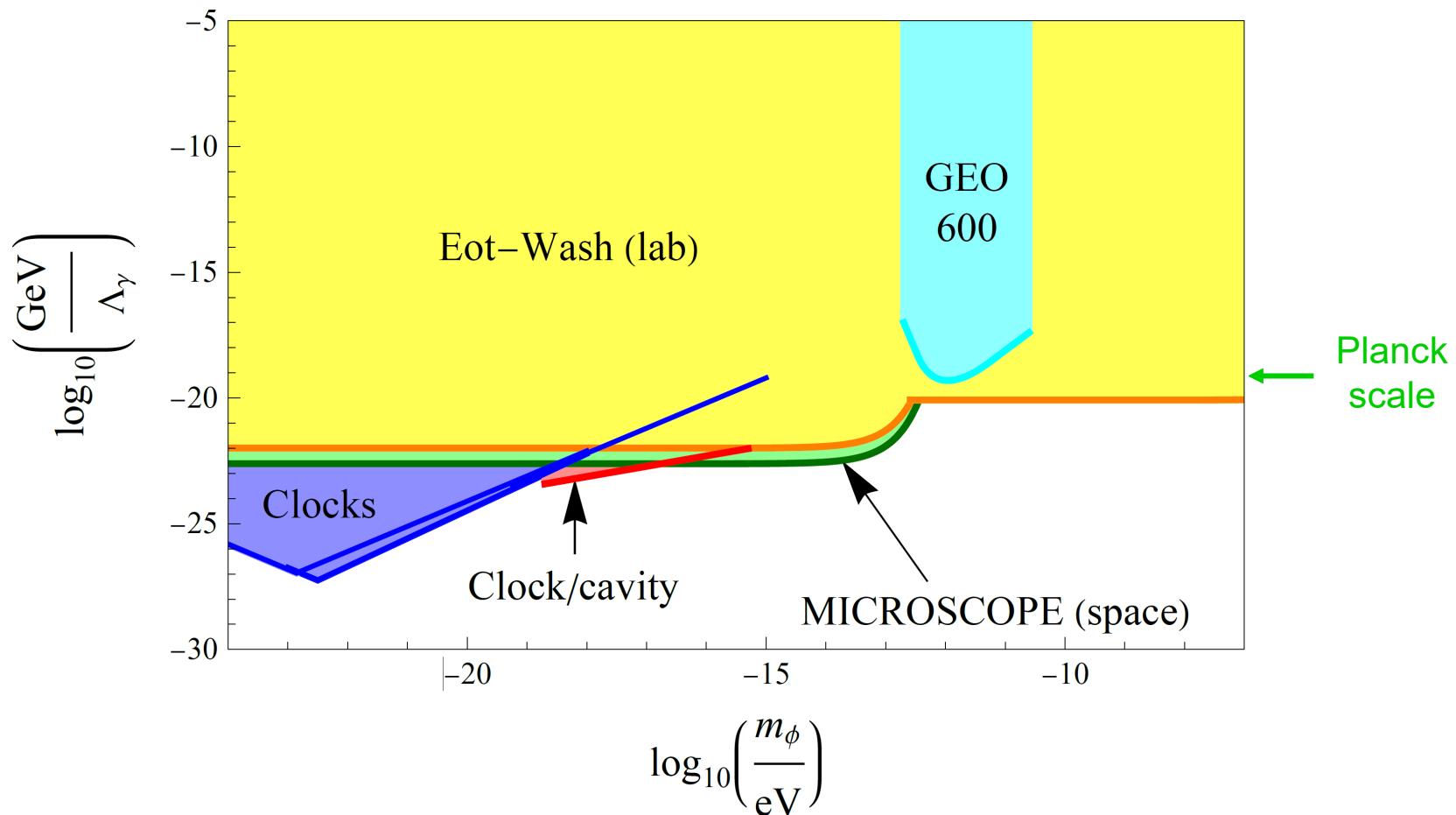


Phase shift between the two separated atom interferometers is maximised when $T_{\text{osc}} \sim 2T$: $\delta(\Delta\Phi)_{\text{max}} \sim \delta v_{\text{atom}} \cdot T_{\text{osc}}$

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!

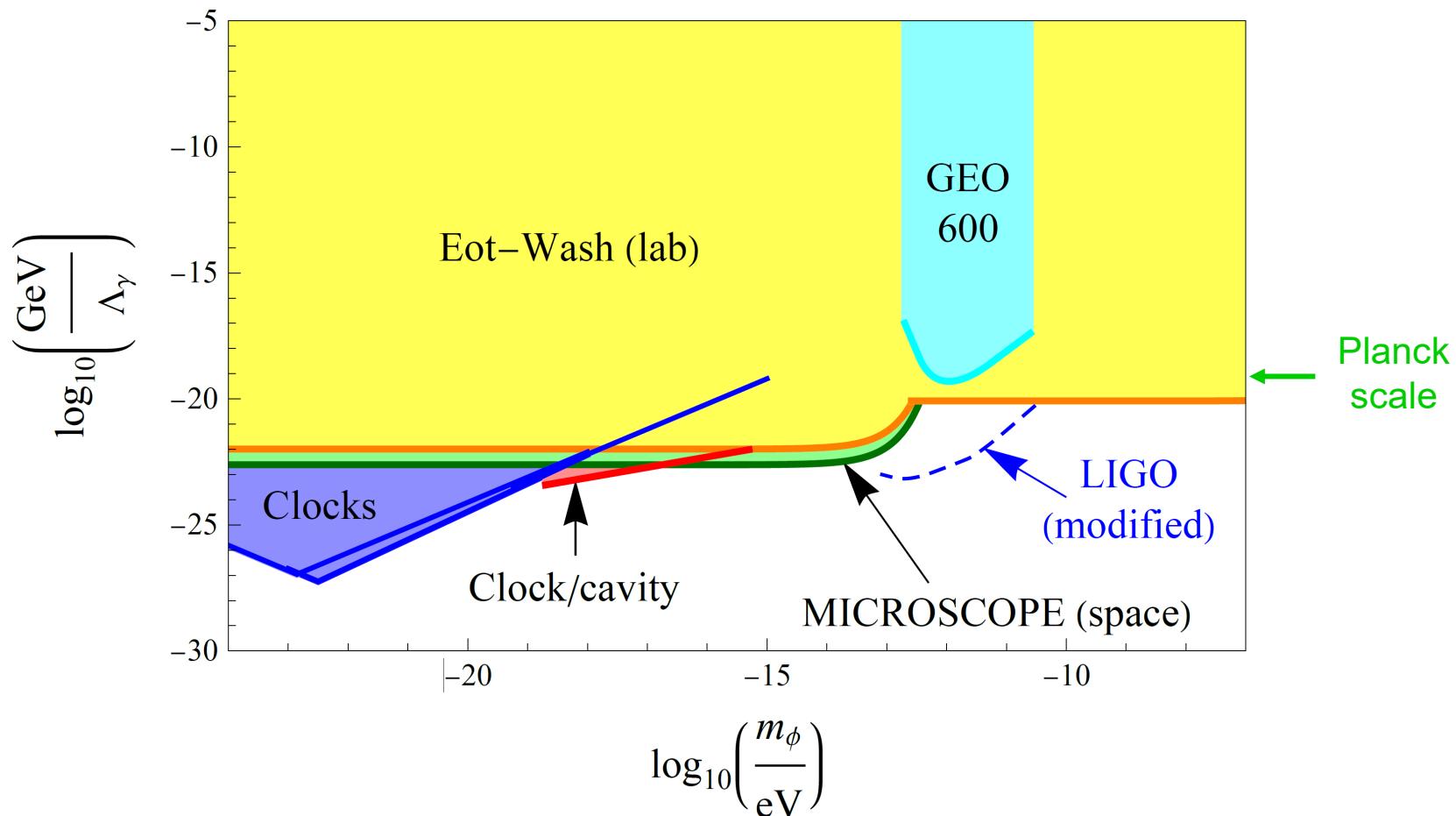


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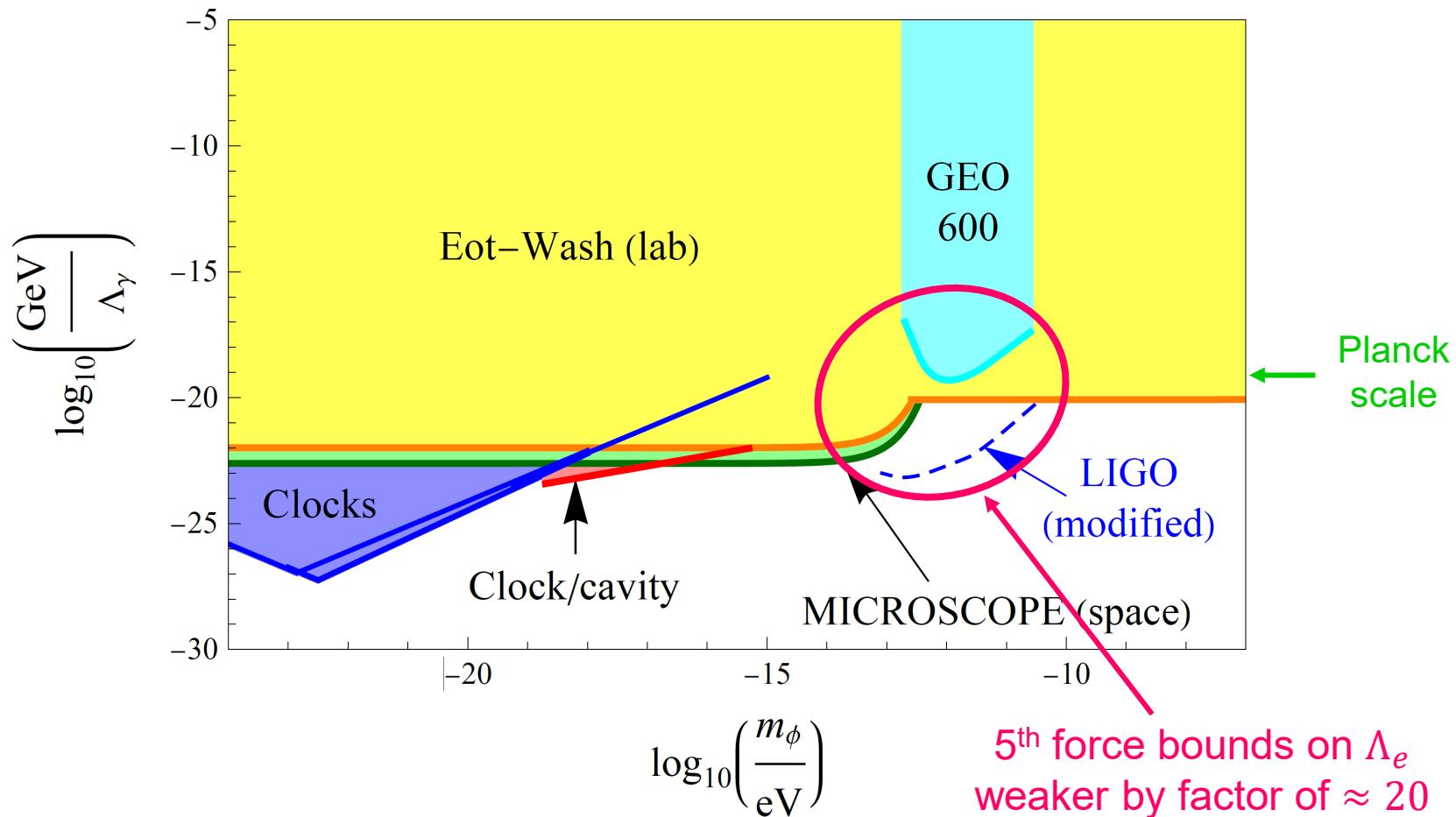
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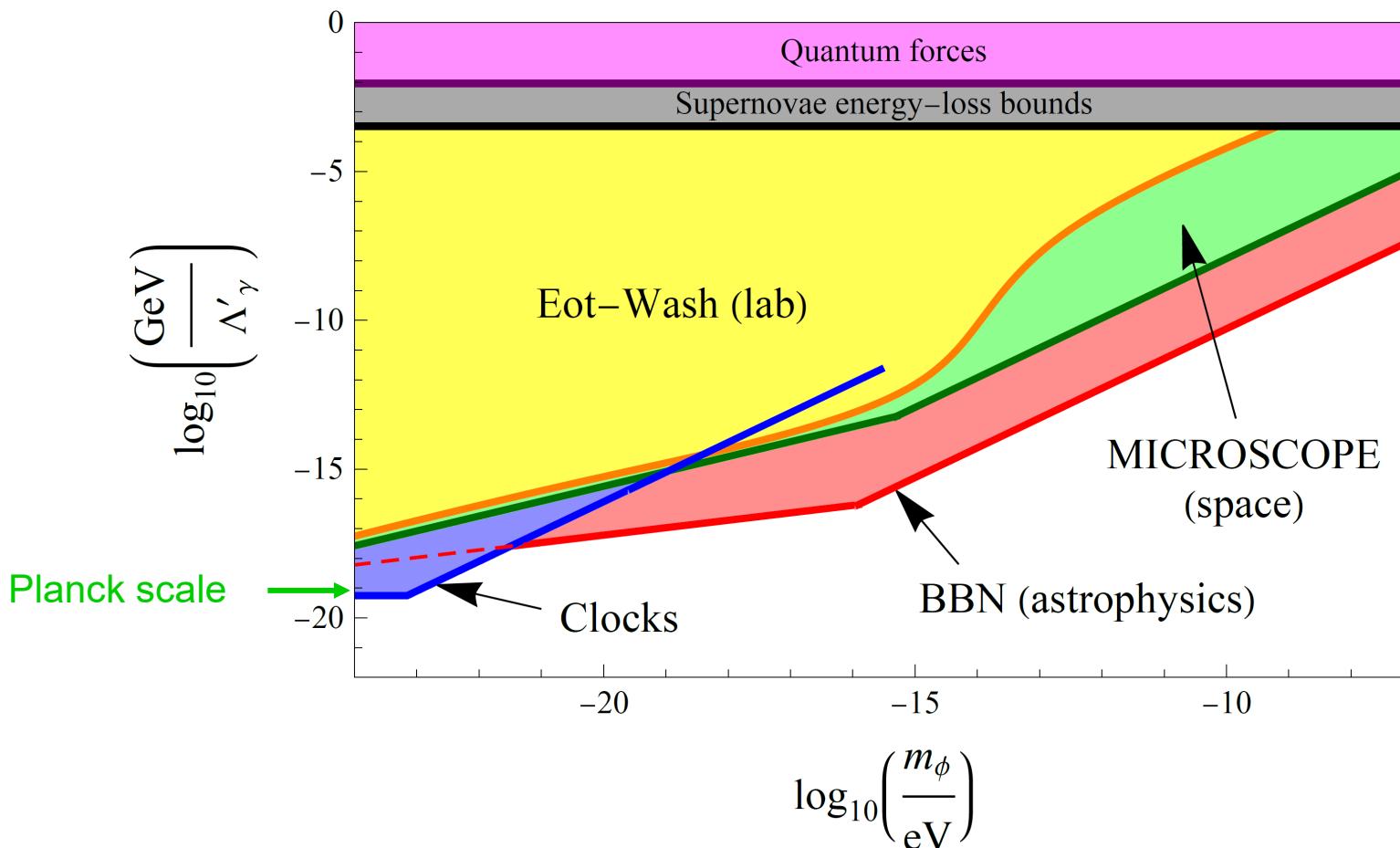
4 orders of magnitude improvement!



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)]

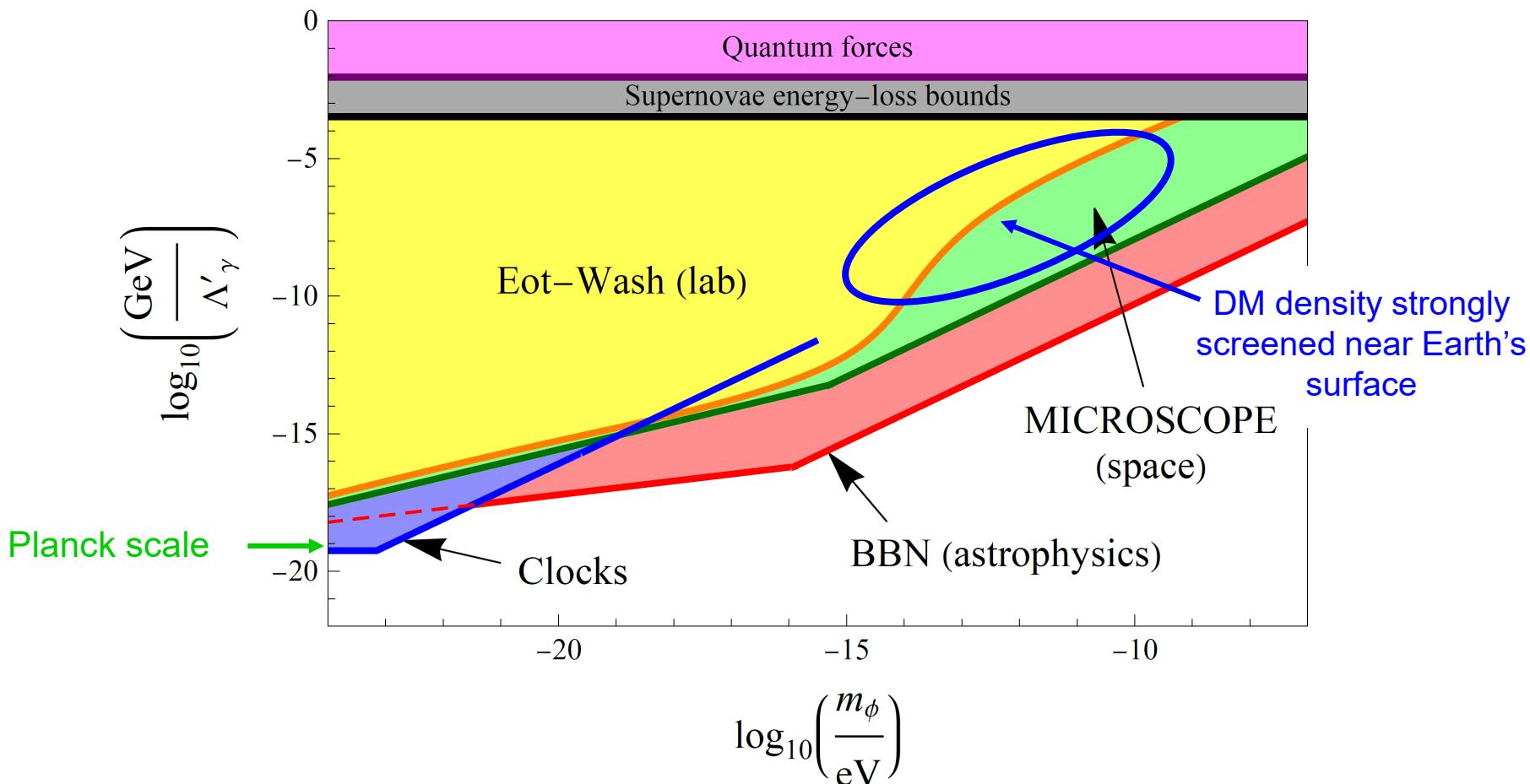
15 orders of magnitude improvement!



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15 orders of magnitude improvement!



Summary

- We have identified new signatures of ultralight scalar dark matter that have allowed us and other groups to improve the sensitivity to underlying interaction strengths by up to **15 orders of magnitude**
 - Novel approaches based on precision low-energy experiments (often “table-top scale”):
 - Atomic spectroscopy (clocks)
 - Optical cavities and interferometry
 - Torsion pendula and accelerometers
 - Muonium spectroscopy
- See my talk at DSU [Monday 4:10pm]
in the *Ultralight dark matter* session

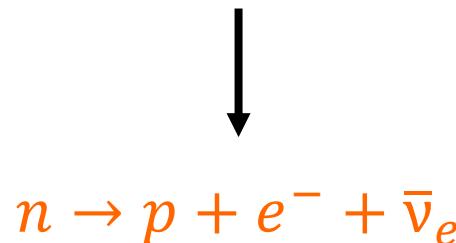
Back-Up Slides

BBN Constraints on ‘Slow’ Drifts in Fundamental Constants due to Dark Matter

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

- Largest effects of DM in early Universe (highest ρ_{DM})
- Big Bang nucleosynthesis ($t_{\text{weak}} \approx 1 \text{ s} - t_{\text{BBN}} \approx 3 \text{ min}$)
- Primordial ${}^4\text{He}$ abundance sensitive to n/p ratio
(almost all neutrons bound in ${}^4\text{He}$ after BBN)

$$\frac{\Delta Y_p({}^4\text{He})}{Y_p({}^4\text{He})} \approx \frac{\Delta(n/p)_{\text{weak}}}{(n/p)_{\text{weak}}} - \Delta \left[\int_{t_{\text{weak}}}^{t_{\text{BBN}}} \Gamma_n(t) dt \right]$$



Muon Probes of Scalar DM

- Most searches for ultralight scalar DM have focused on the electromagnetic (photon) and electron couplings
- *What about searching for ultralight scalar DM via its coupling to muons?*
- Possible flavour/generational dependence of scalar couplings in the lepton sector
- 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

Probing Oscillations of m_μ with Muonium Spectroscopy

[Stadnik, arXiv:2206.10808]

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

$$\mathcal{L}_{\text{quad}} = -\frac{\varphi^2}{(\Lambda'_\mu)^2} m_\mu \bar{\mu} \mu \Rightarrow \frac{\delta m_\mu}{m_\mu} \approx \frac{\varphi_0^2 \cos(m_\varphi t)}{(\Lambda'_\mu)^2}$$

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

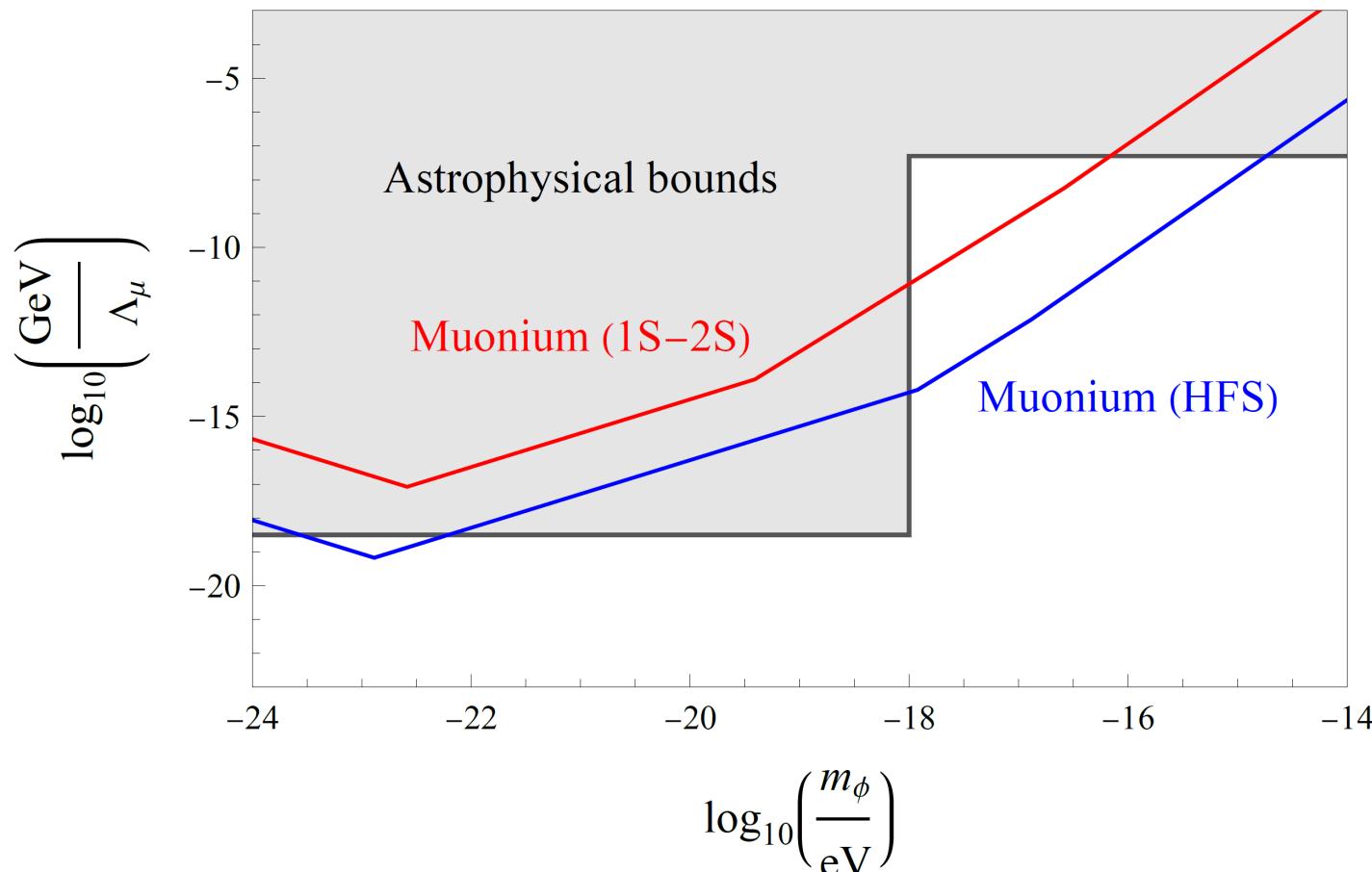
$$E_n^{\text{Rydberg}} = -\frac{m_r \alpha^2}{2n^2} \Rightarrow \frac{\Delta v_{1S-2S}}{v_{1S-2S}} \approx 2 \frac{\Delta \alpha}{\alpha} + \frac{\Delta m_e}{m_e} + \frac{m_e}{m_\mu} \frac{\Delta m_\mu}{m_\mu}$$

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

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

[Stadnik, arXiv:2206.10808]

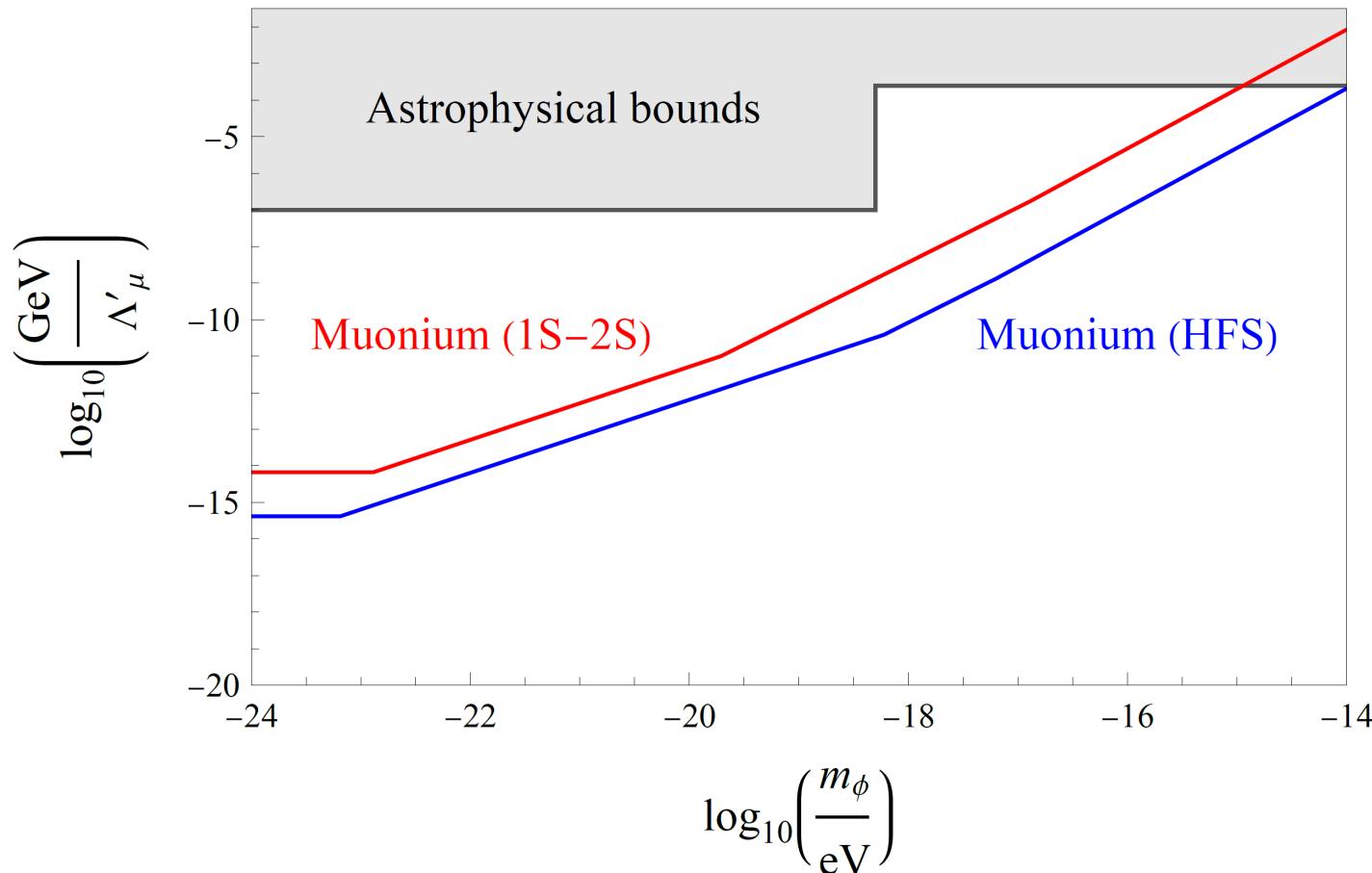
Up to 7 orders of magnitude improvement possible with existing datasets!



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

[Stadnik, arXiv:2206.10808]

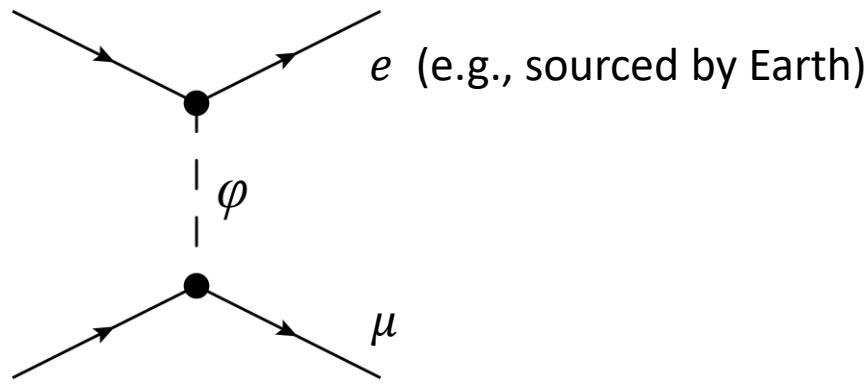
Up to 8 orders of magnitude improvement possible with existing datasets!



Probing Scalar-Muon Coupling with Muonium Free-fall

[Stadnik, arXiv:2206.10808]

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



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 PSI aims to measure g with a precision of $\Delta g/g \sim 0.1$

Probing Scalar-Muon Coupling with Muonium Free-fall

[Stadnik, arXiv:2206.10808]

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

