Novel Signatures of Dark Matter in Laser-Interferometric Gravitational-Wave Detectors

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東京大学
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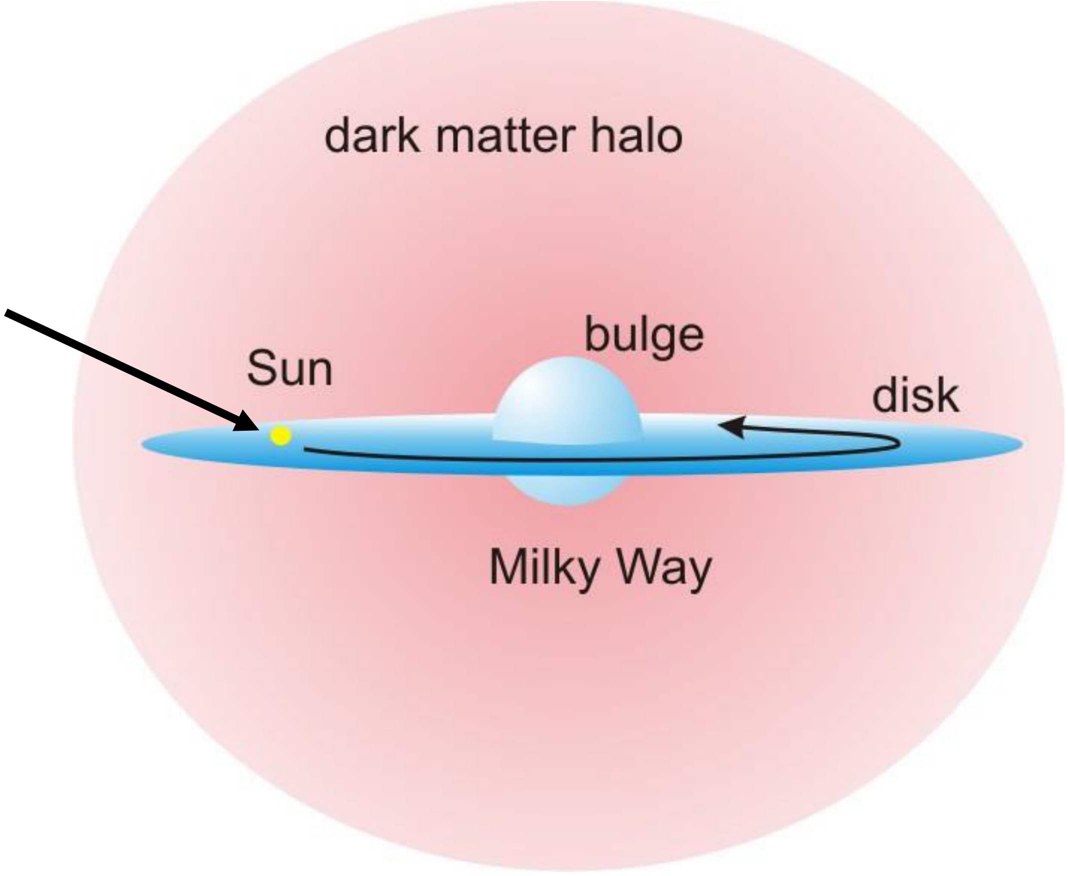
“Gravitational Wave Probes of Fundamental Physics”, Amsterdam, November 2019

Motivation

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

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

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



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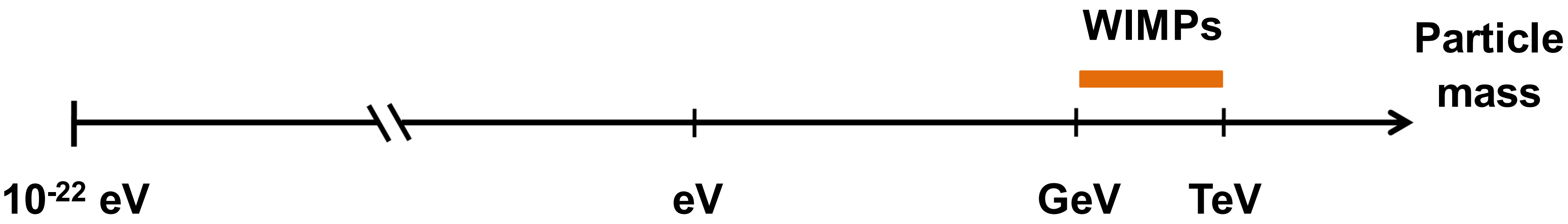

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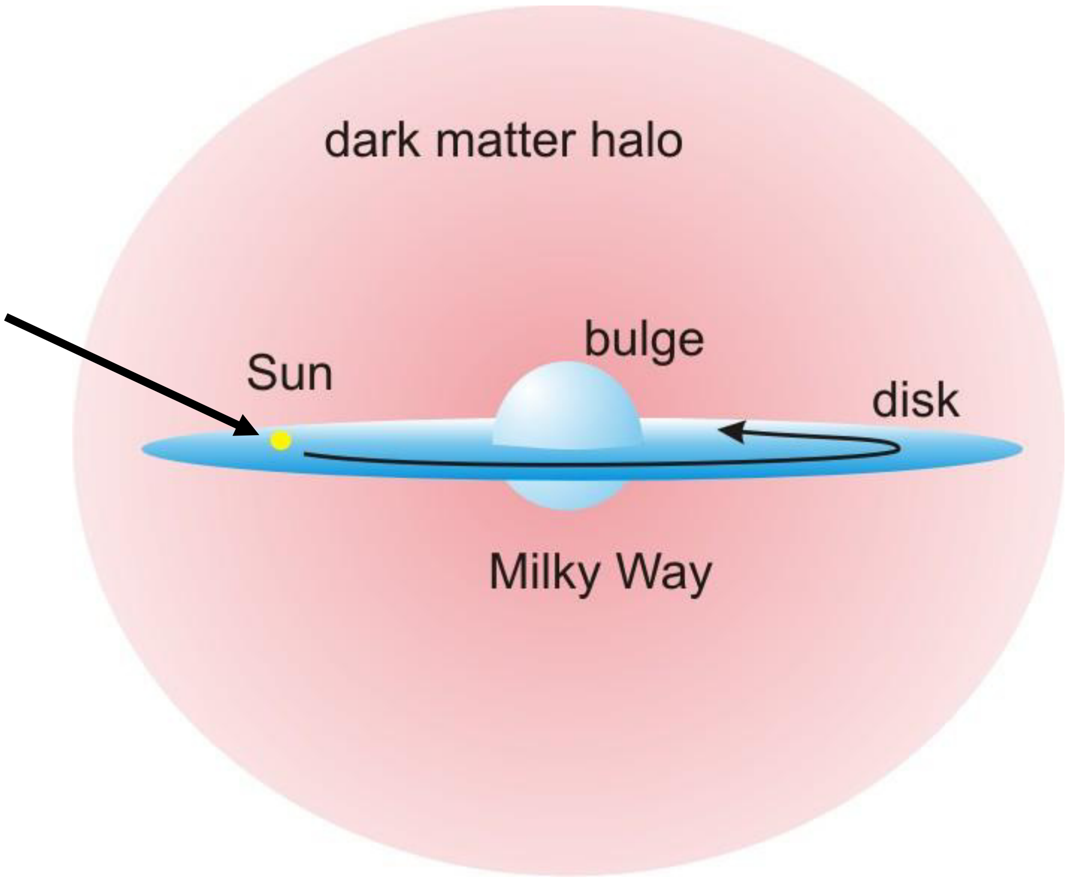

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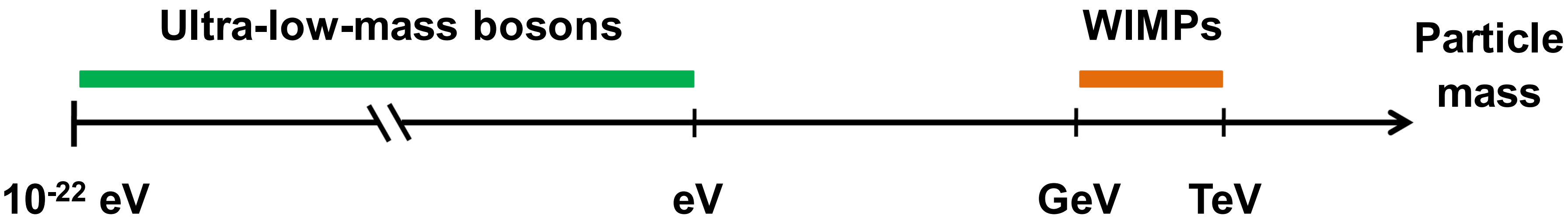

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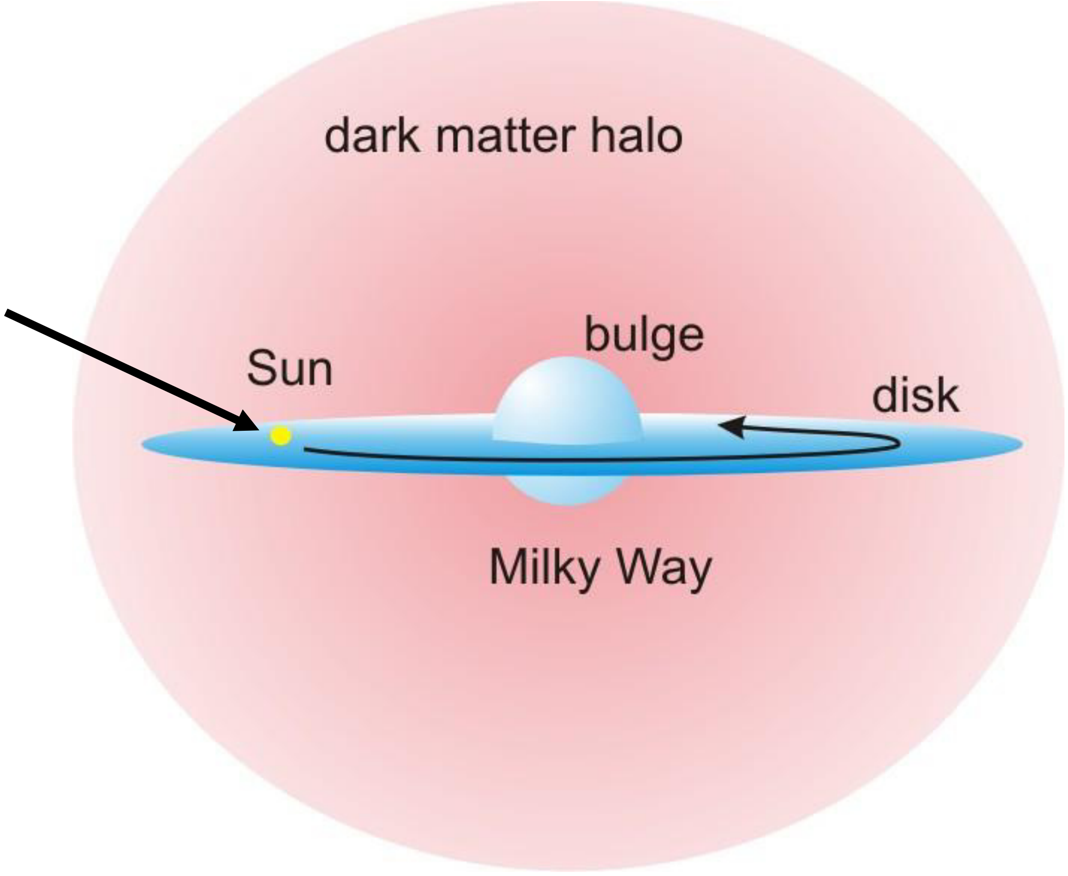
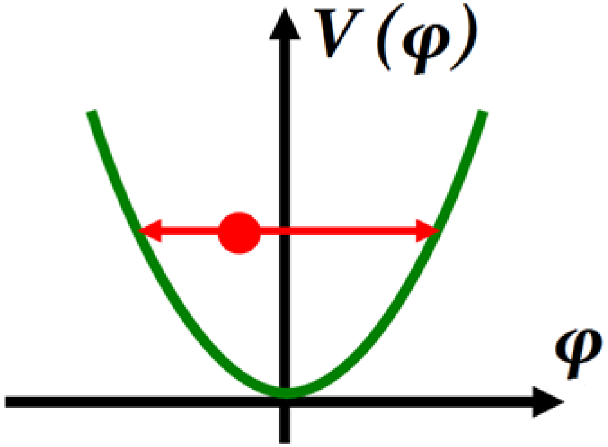


Low-mass Spin-0 Dark Matter

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



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

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

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- $10^{-22}\ \mathrm{eV} \lesssim m_\varphi \lesssim 1\ \mathrm{eV} \Leftrightarrow 10^{-8}\ \mathrm{Hz} \lesssim f \lesssim 10^{14}\ \mathrm{Hz}$

$\lambda_{\mathrm{dB},\varphi}/2\pi \leq L_{\text{dwarf galaxy}} \sim 1\ \mathrm{kpc}$

Classical field

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Classical field

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

Dark Matter-Induced Cosmological Evolution of the Fundamental Constants

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

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

$$\mathcal{L}_\gamma = \frac{\phi}{\Lambda_\gamma} \frac{F_{\mu\nu} F^{\mu\nu}}{4} \quad => \quad \frac{\delta\alpha}{\alpha} \approx \frac{\phi_0 \cos(m_\phi t)}{\Lambda_\gamma}$$

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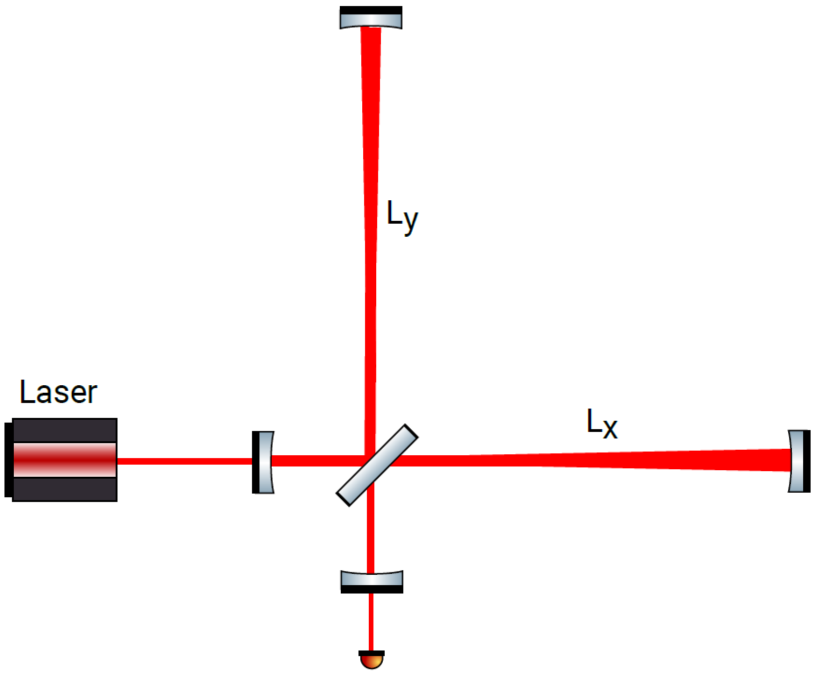
Solid material

$L \sim Na_B = N/(m_e\alpha)$

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

[Grote, Stadnik, arXiv:1906.06193]



Michelson interferometer (GEO 600)

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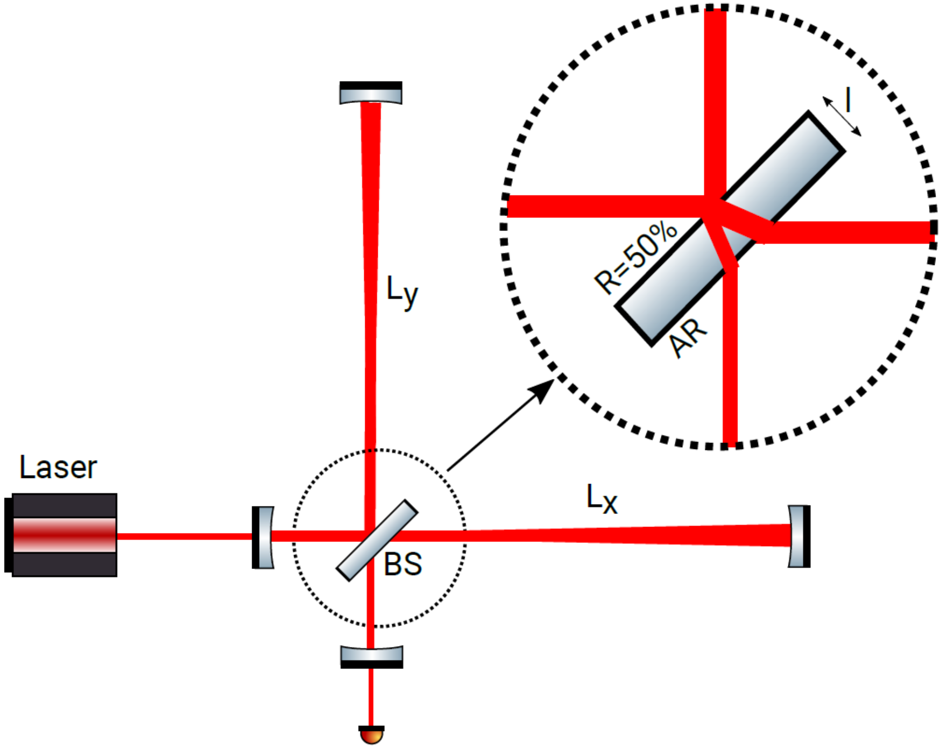

- Geometric asymmetry from beam-splitter: $\delta(L_x - L_y) \sim \delta(n l)$

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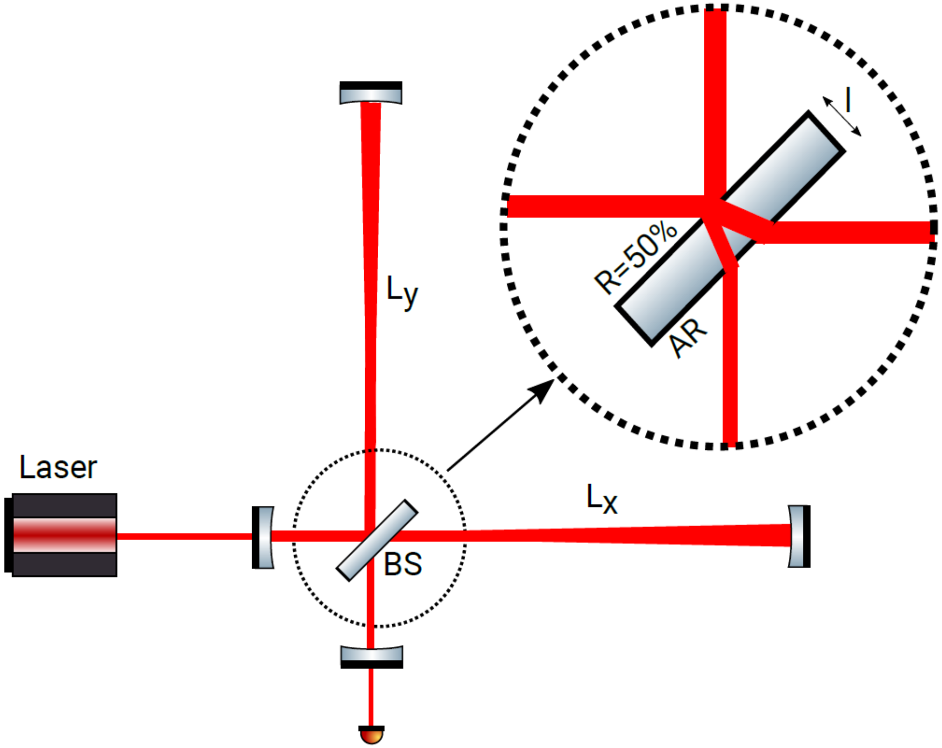
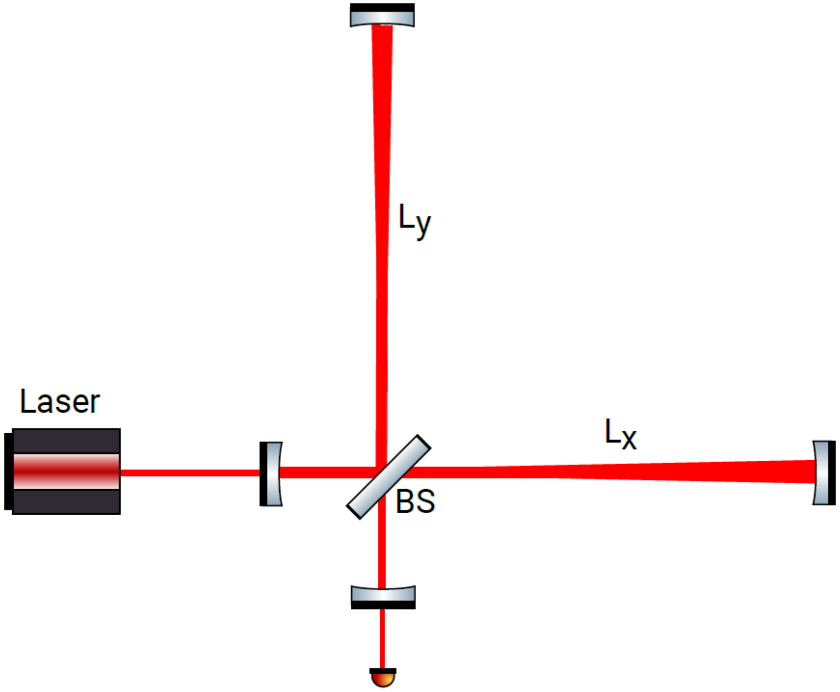


- Geometric asymmetry from beam-splitter: $\delta(L_x - L_y) \sim \delta(nl)$
- Both broadband and resonant narrowband searches possible: $f_{DM} \approx f_{vibr,BS} \sim v_{sound}/l$, $Q \sim 10^6$ enhancement

Michelson vs Fabry-Perot-Michelson Interferometers

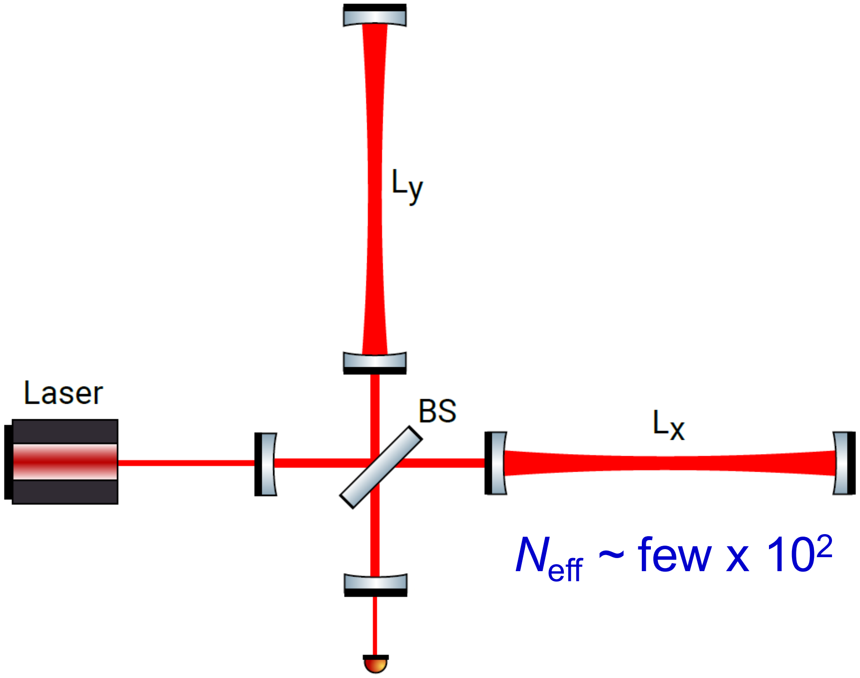
[Grote, Stadnik, arXiv:1906.06193]

Michelson interferometer
(GEO 600, Fermilab holometer)



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

Fabry-Perot-Michelson interferometer
(LIGO, VIRGO, KAGRA)



N_{eff} ~ few x 10^2

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

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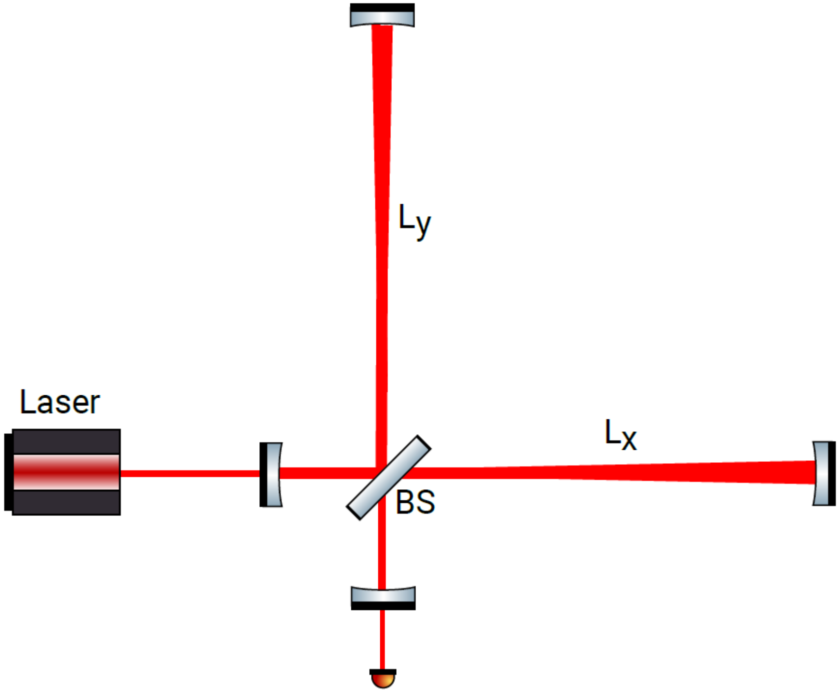

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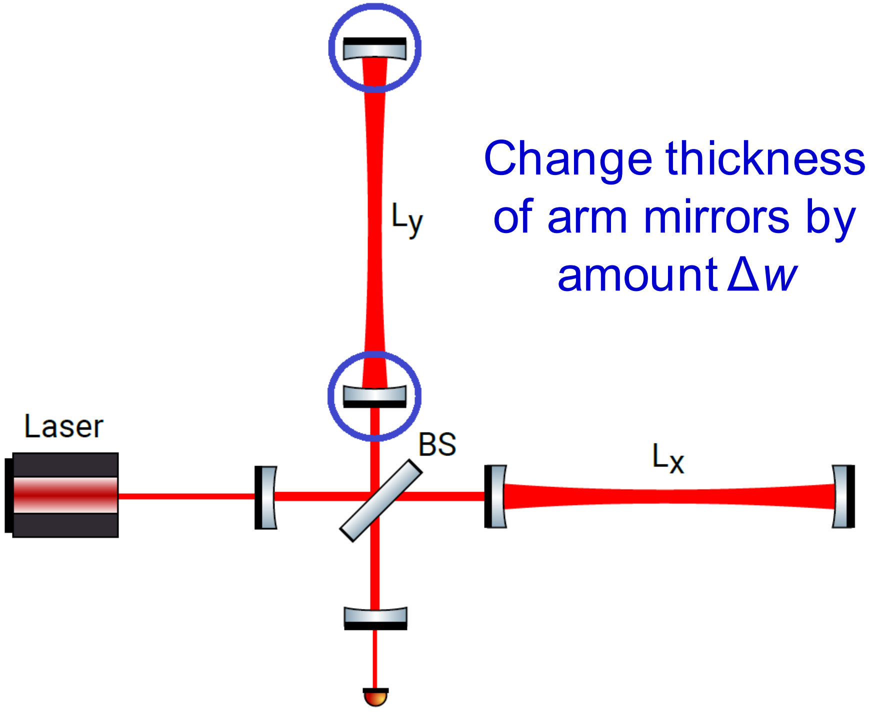
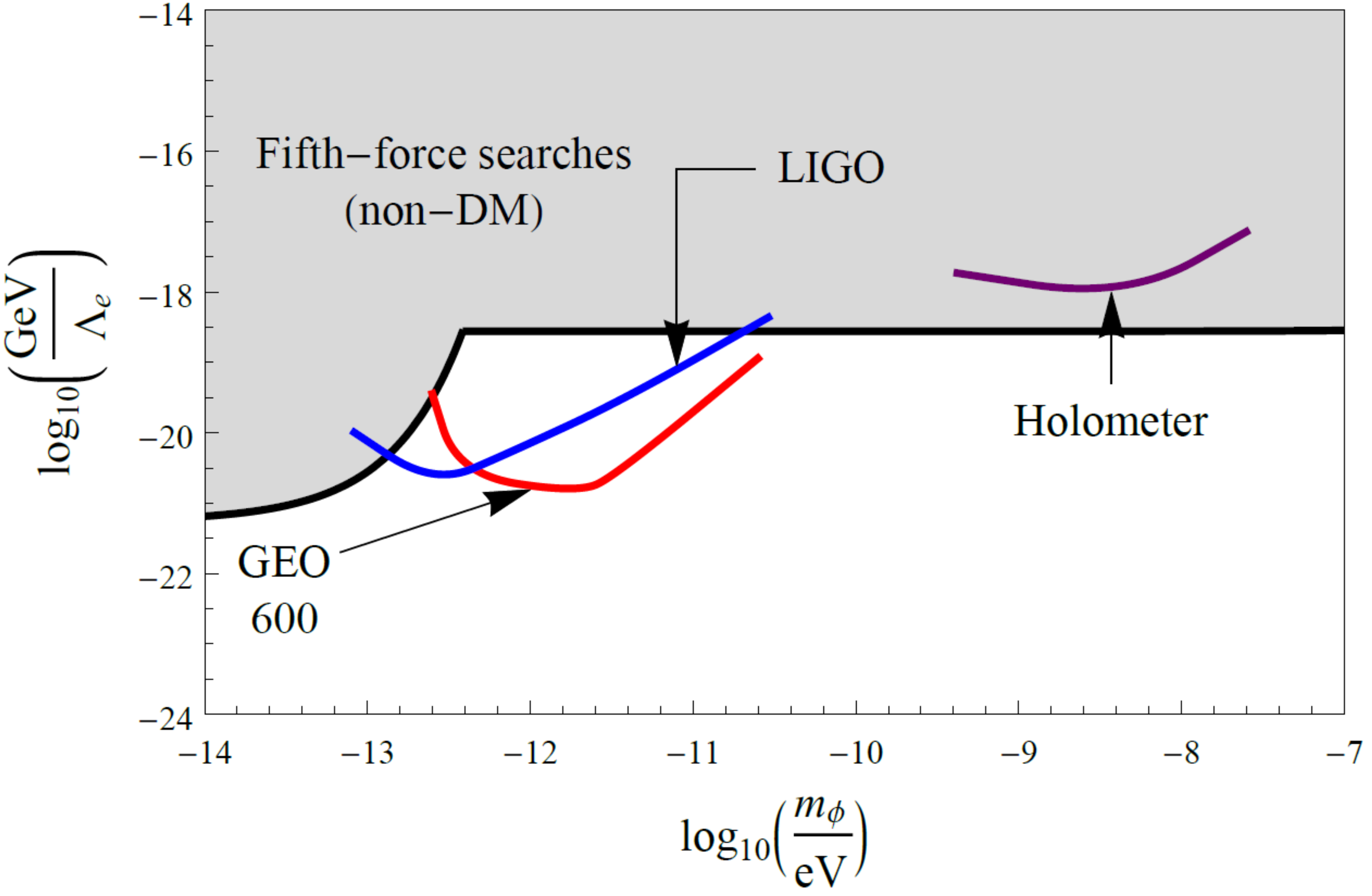


Change thickness of arm mirrors by amount Δw

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

Linear Interaction of Scalar Dark Matter with the Electron



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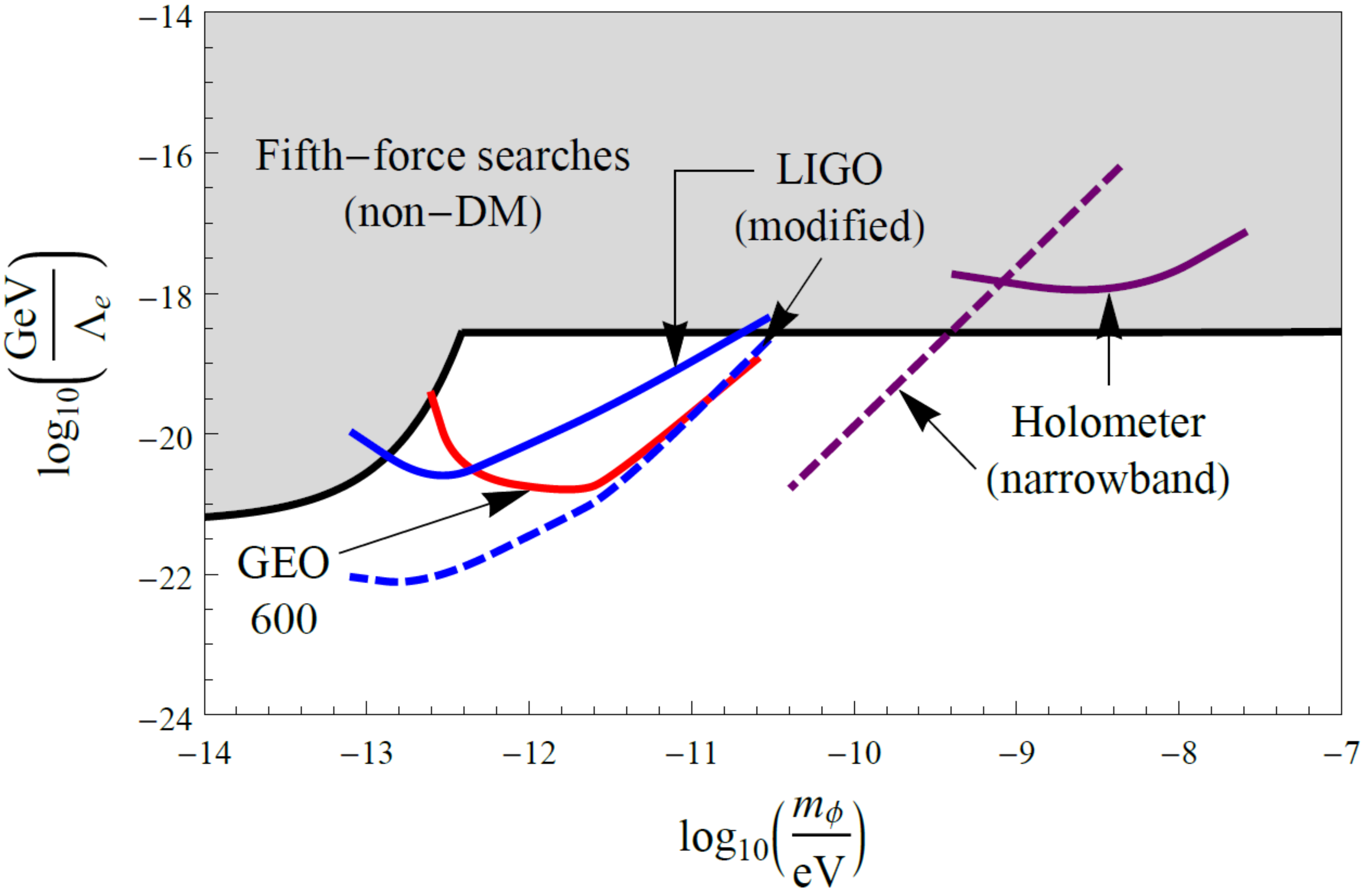

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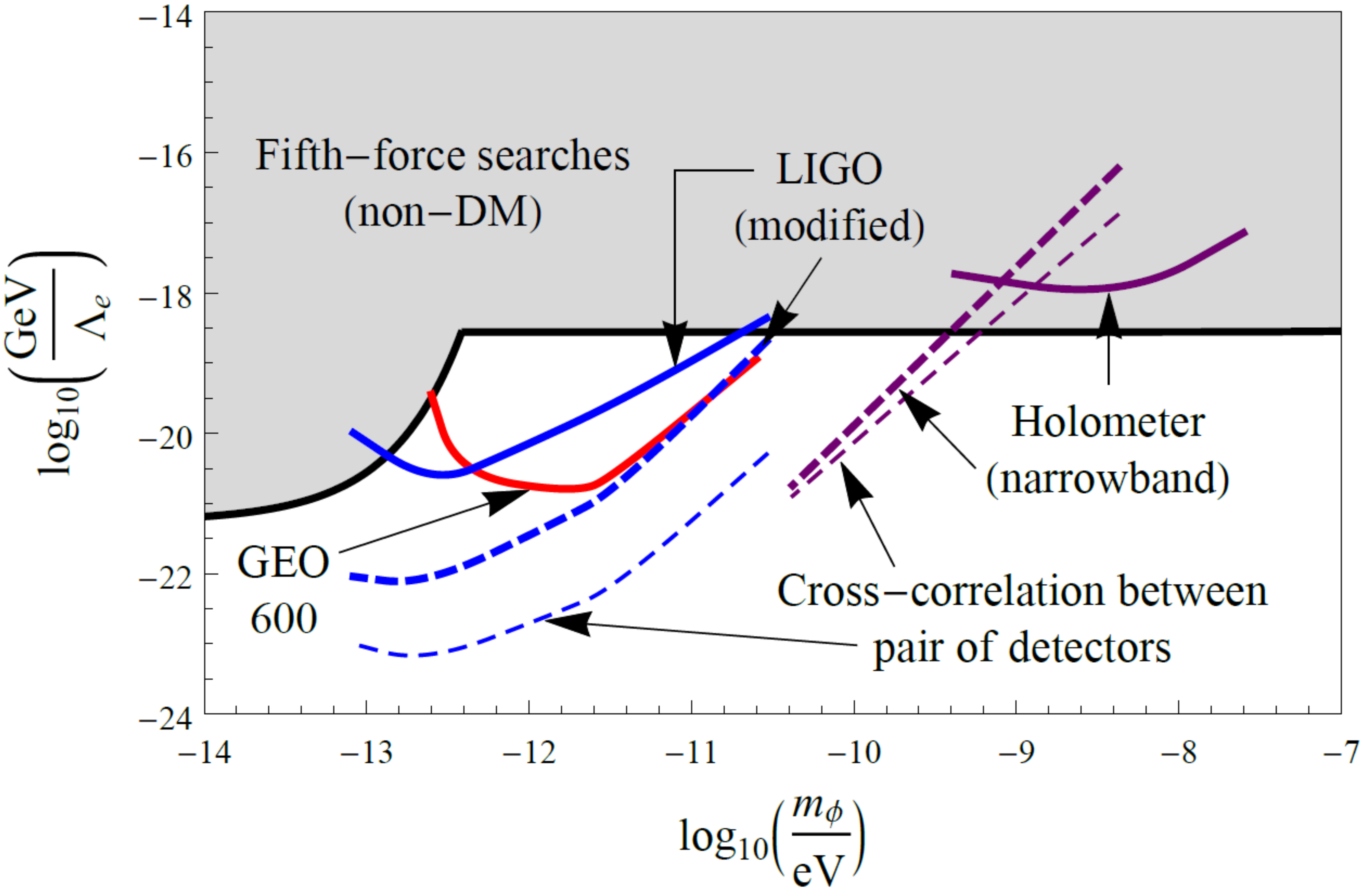


Summary

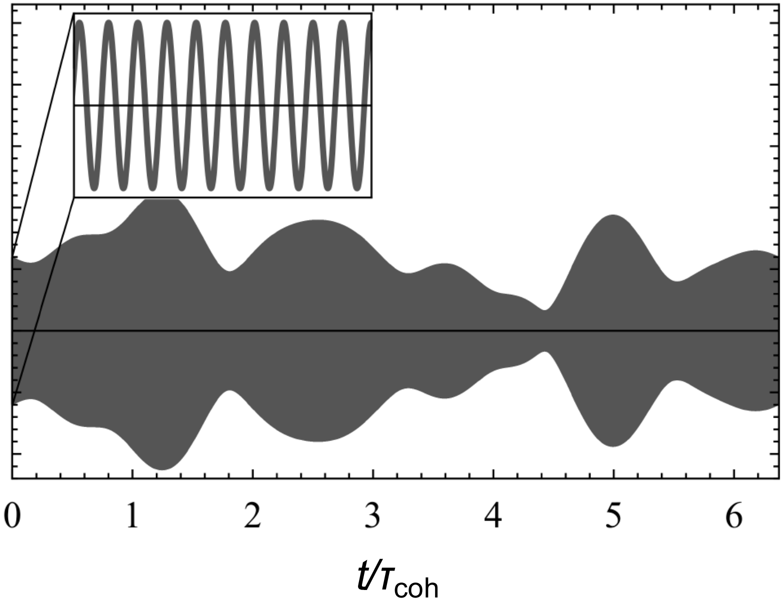
- Existing laser-interferometric gravitational-wave detectors are sensitive probes of scalar dark-matter fields oscillating at audio-band frequencies
- Changing arm mirror thicknesses by ~10% can greatly boost the sensitivity of Fabry-Perot-Michelson interferometers (LIGO, VIRGO, KAGRA) to dark matter
- (Small-scale) Interferometry experiments can be adapted to perform resonant narrowband searches
- Existing interferometers also sensitive to the passage of macroscopic dark-matter objects through detectors

Back-Up Slides

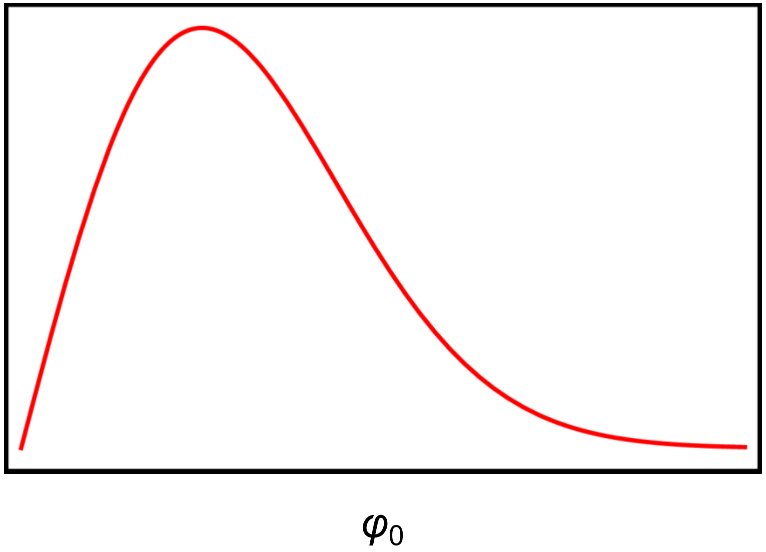
Temporal Coherence

- *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 $<\rho_\varphi> \approx m_\varphi{}^2\varphi_0{}^2/2$ ($\rho_{\mathrm{DM,local}} \approx 0.4\ \mathrm{GeV/cm^3}$)
- $\Delta E_\varphi / E_\varphi \sim <v_\varphi{}^2>/c^2 \sim 10^{-6}$ => $\tau_{\mathrm{coh}} \sim 2\pi/\Delta E_\varphi \sim 10^6 T_{\mathrm{osc}}$

Evolution of φ_0 with time



Probability distribution function of φ_0



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$$\phi = \phi_0 \cos(m_\phi t - \underline{\boldsymbol{p}_\phi \cdot \boldsymbol{x}}) \quad => \quad \underline{\boldsymbol{F} \propto \boldsymbol{p}_\phi \sin(m_\phi t)}$$

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

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Consider *quadratic couplings* of an oscillating classical *scalar* field, $\varphi(t) = \varphi_0 \cos(m_\varphi t)$, with SM fields.

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$$=> \frac{\delta m_f}{m_f} = \frac{\phi_0^2}{(\Lambda'_f)^2} \cos^2(m_\phi t) = \boxed{\frac{\phi_0^2}{2(\Lambda'_f)^2}} + \boxed{\frac{\phi_0^2}{2(\Lambda'_f)^2} \cos(2 m_\phi t)}$$

$$\rho_\phi = \frac{m_\phi^2 \phi_0^2}{2} \quad => \quad \phi_0^2 \propto \rho_\phi$$

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'Slow' drifts [Astrophysics (high ρ_{DM}): BBN, CMB]
+ Gradients [Fifth forces]

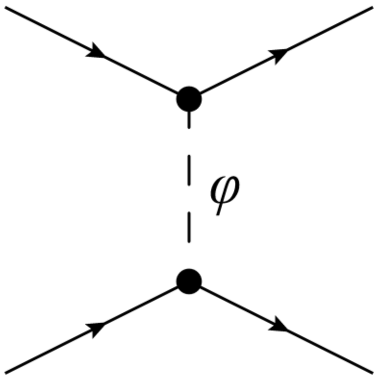
Oscillating variations
[Laboratory (high precision)]

Fifth Forces: Linear vs Quadratic Couplings

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

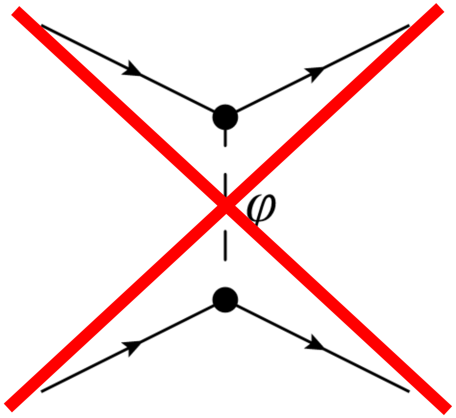
Consider the effect of a massive body (e.g., Earth) on the scalar DM field

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



$$\phi = \phi_0 \cos(m_\phi t) - A\frac{e^{-m_\phi r}}{r}$$

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



$$\phi = \phi_0 \cos(m_\phi t)\left(1 - \frac{B}{r}\right)$$

↓

Gradients + screening/amplification

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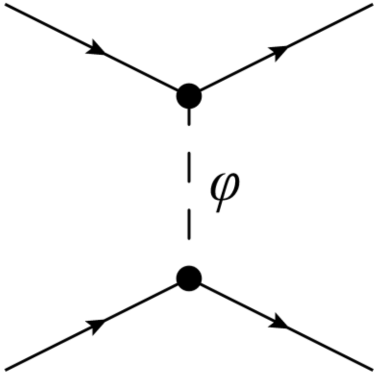

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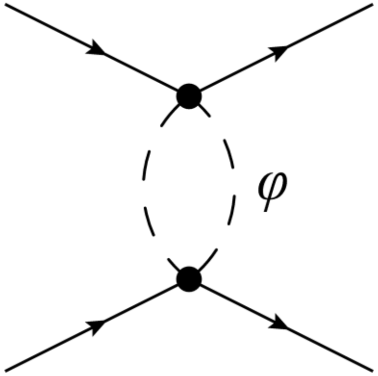

$$\phi = \phi_0 \cos(m_\phi t) \left(1 - \frac{B}{r}\right) - C \frac{e^{-2m_\phi r}}{r^3}$$

↓

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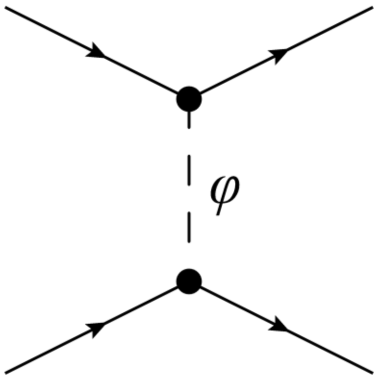

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Motional gradients: $\varphi_0 \cos(m_\varphi t - \boldsymbol{p}_\varphi \cdot \boldsymbol{x})$

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

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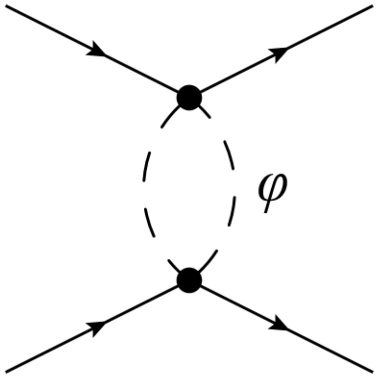

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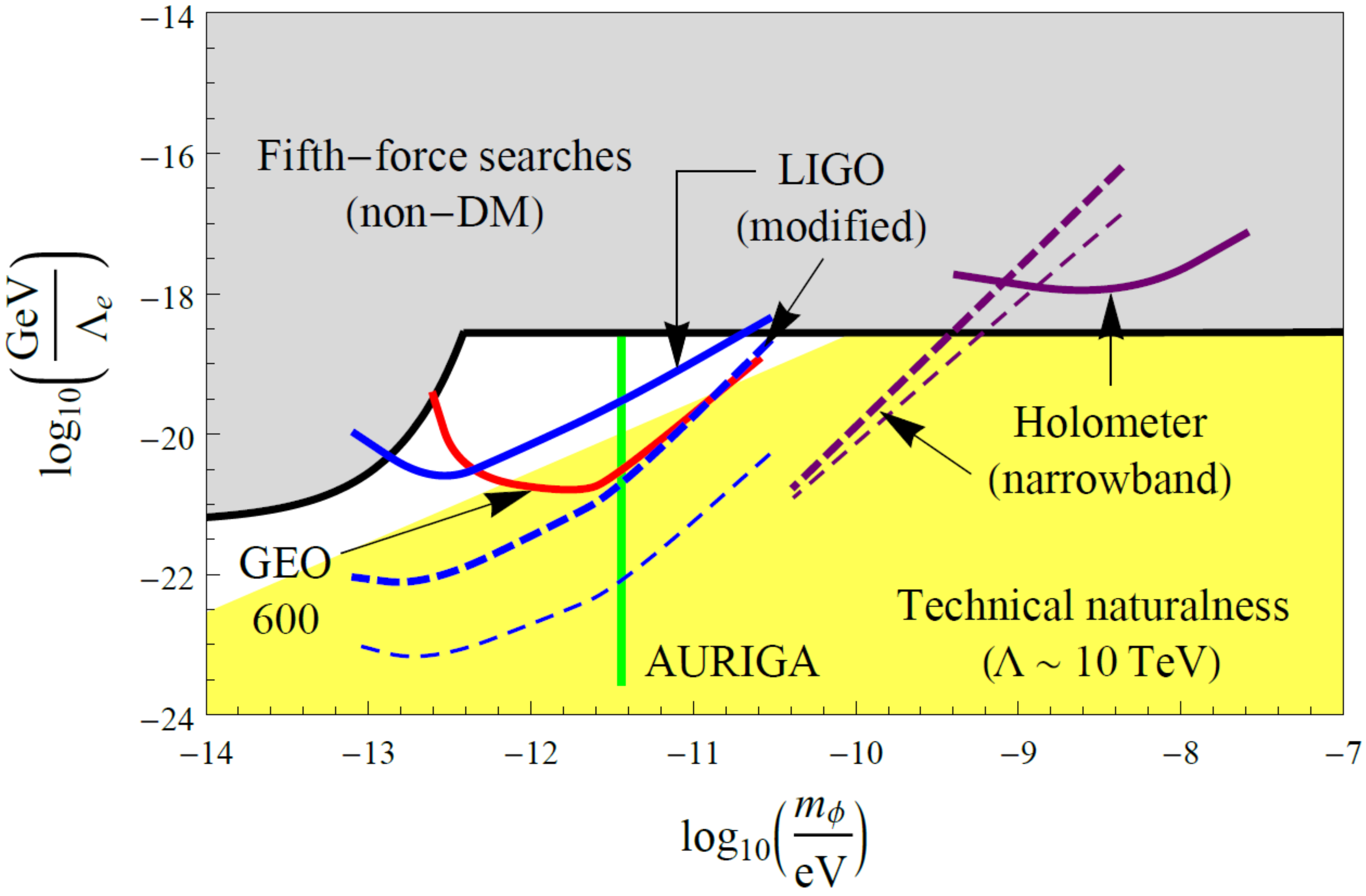
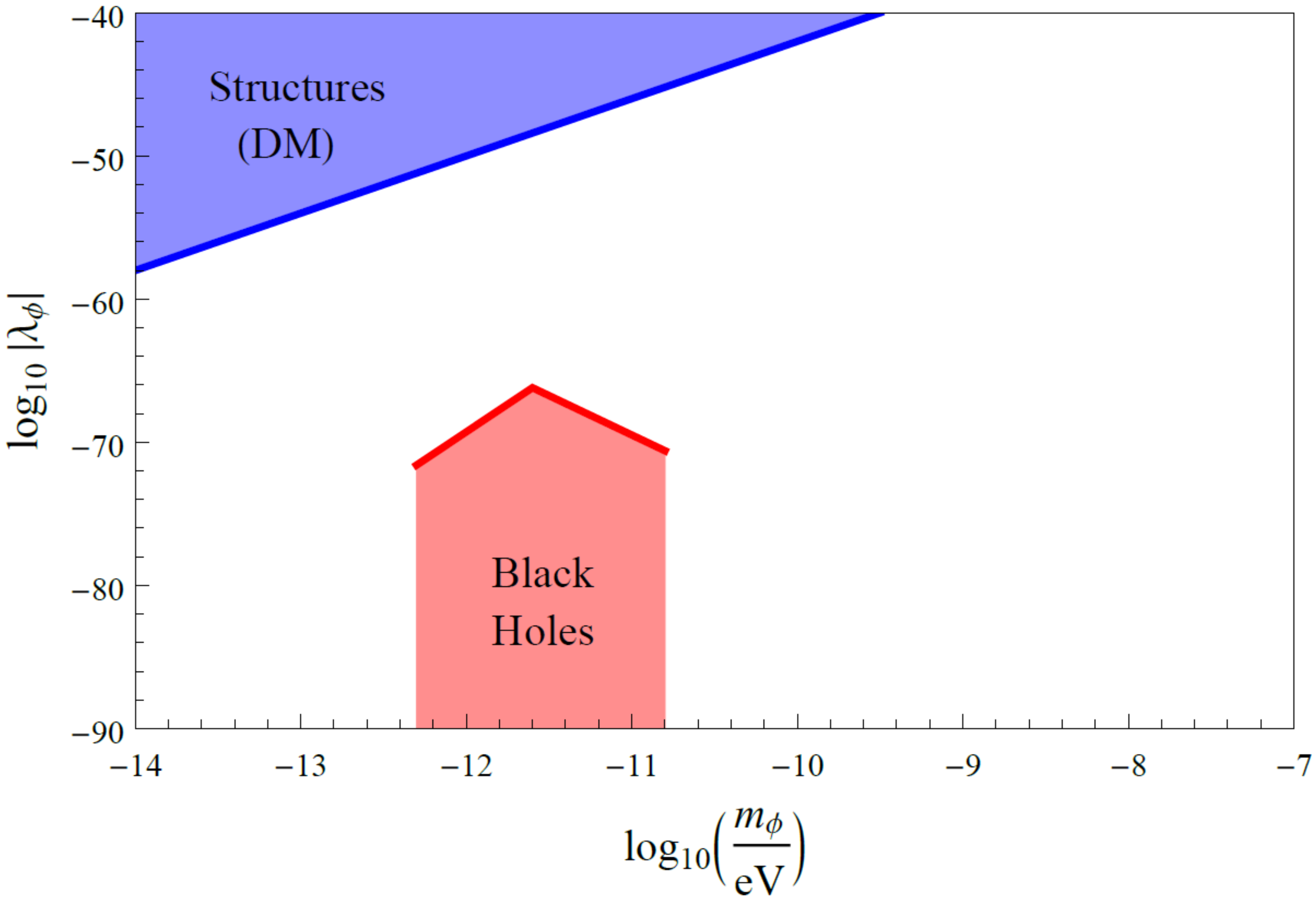
↓

Gradients + screening/amplification

Constraints on Linear Interaction of Scalar Dark Matter with the Electron



Quartic Self-Interaction of Scalar



Constraints on Linear Interaction of Scalar Dark Matter with the Higgs Boson

Rb/Cs constraints:

[Stadnik, Flambaum, *PRA* **94**, 022111 (2016)]

2 – 3 orders of magnitude improvement!