Directly Probing Ultra-Low-Mass Scalar-Field Dark Matter with Gravitational-Wave Detectors

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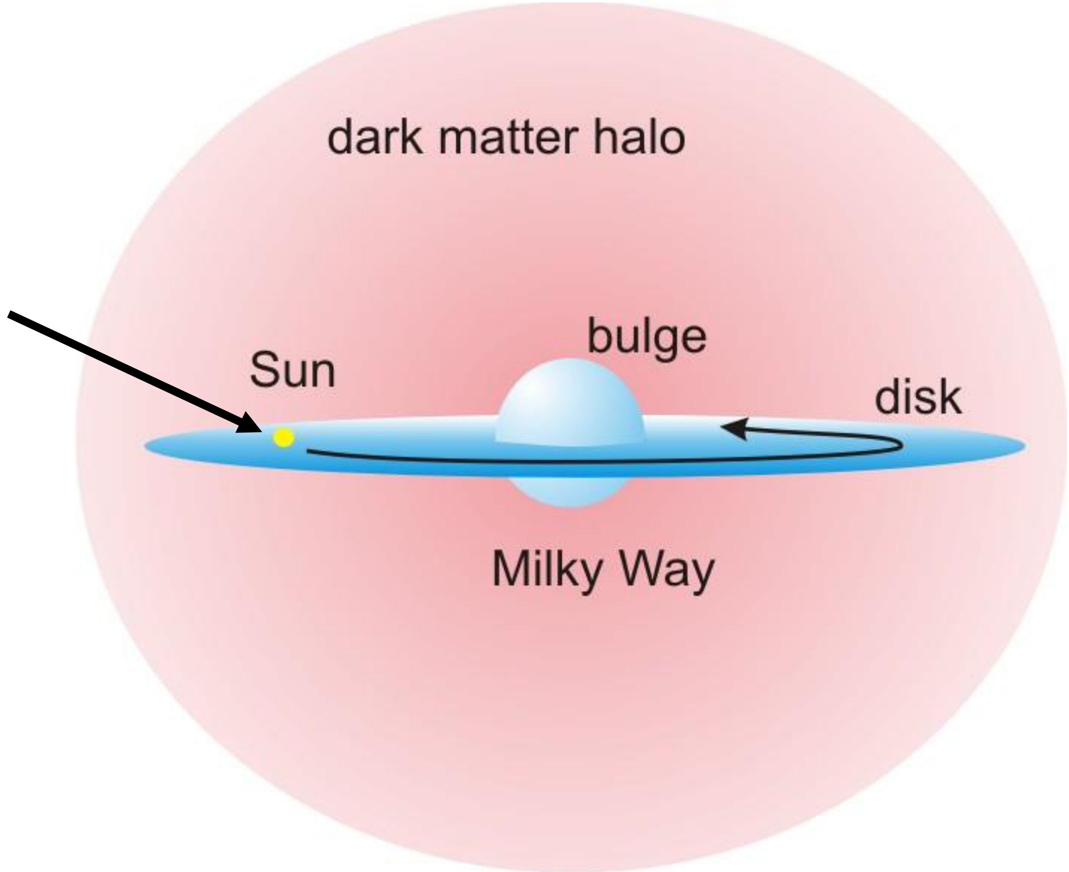
Dark Matter

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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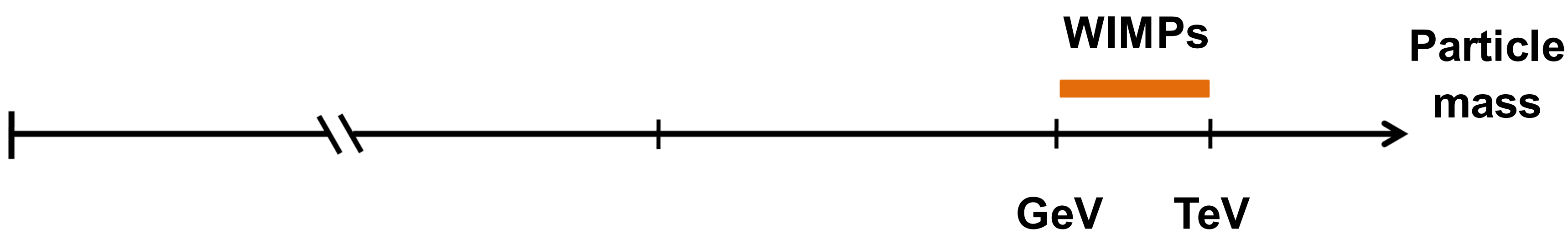

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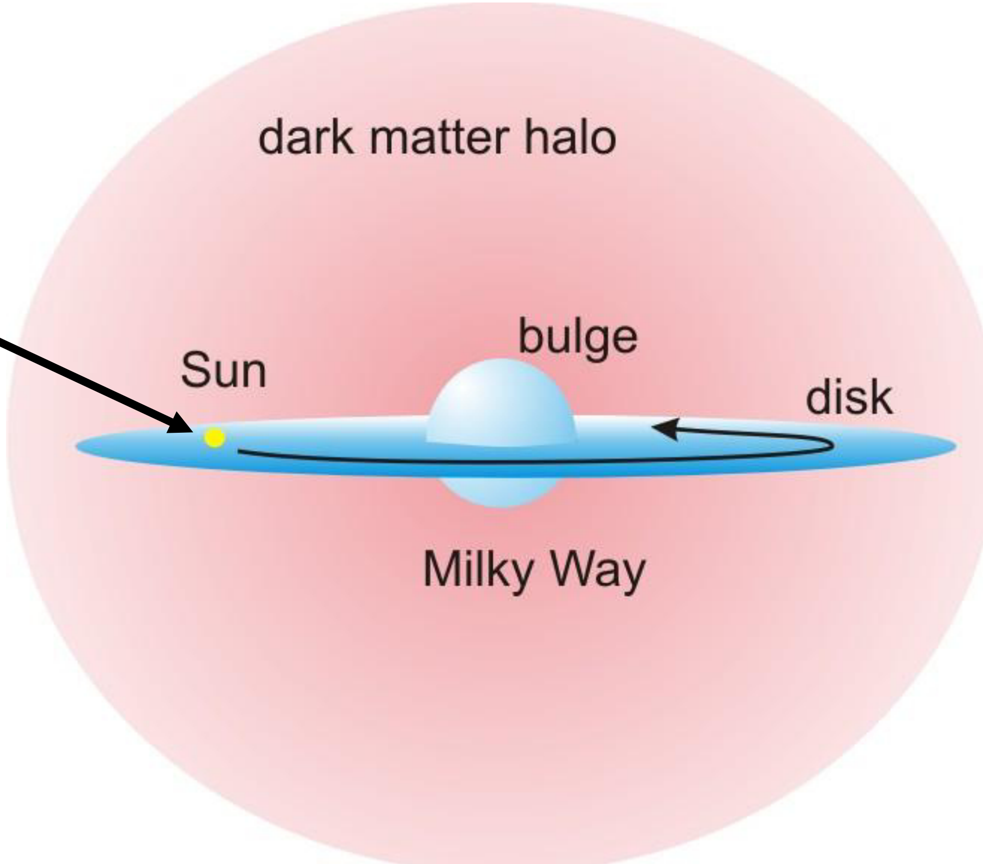

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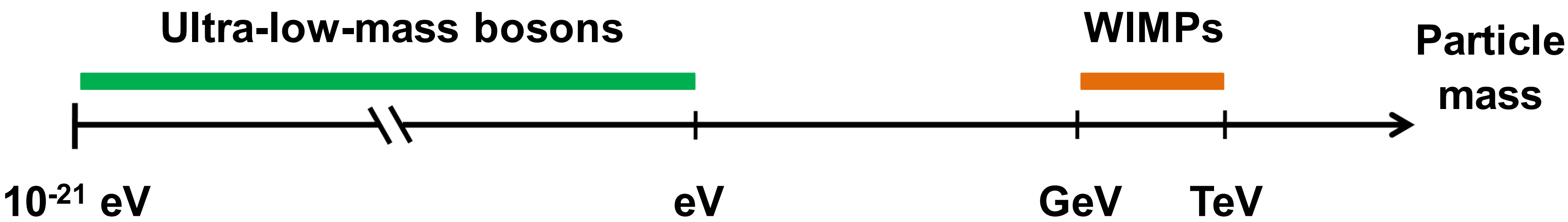

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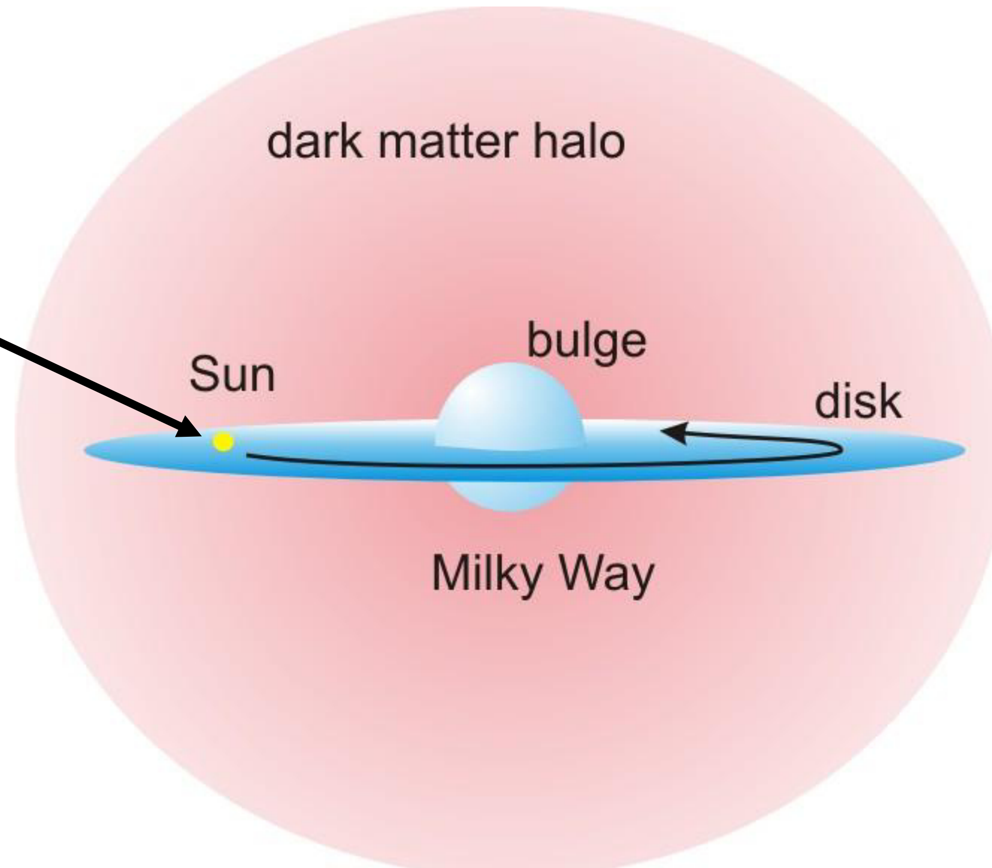
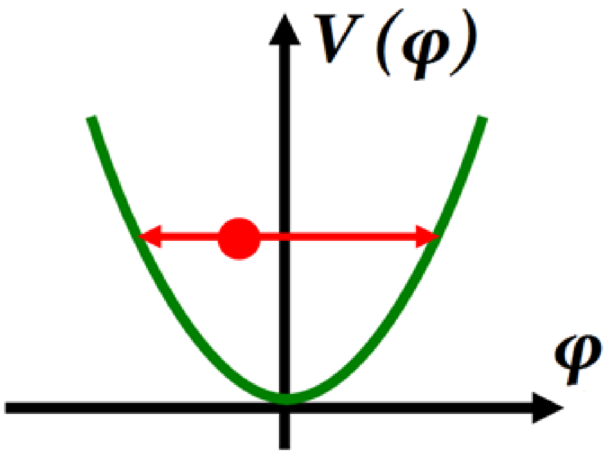


Low-mass Spin-0 Dark Matter

- Low-mass spin-0 particles form a coherently oscillating classical field $\varphi(t) = \varphi_0 \cos\left(m_\varphi c^2 t/\hbar\right)$, 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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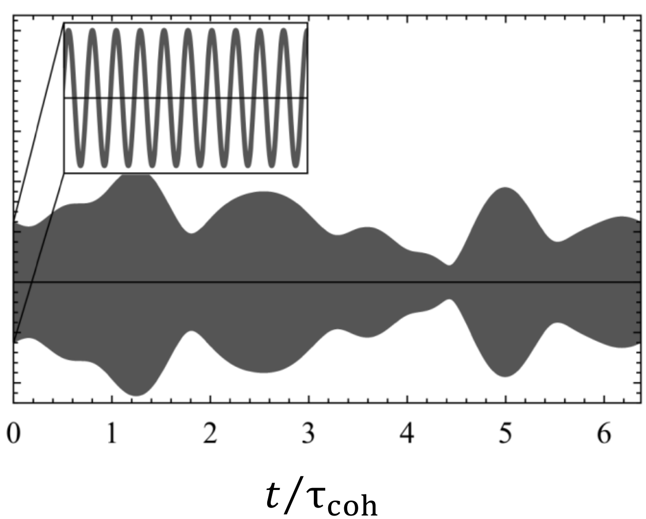
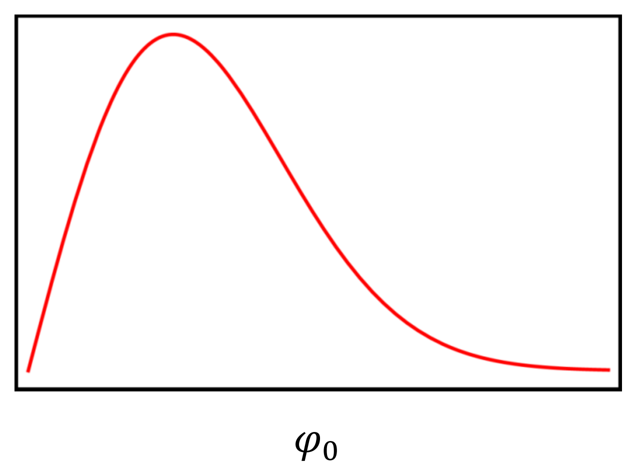
Evolution of φ_0 with time



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



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

$T_{\mathrm{osc}} \sim 1\ \mathrm{month}$ 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]

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)]

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

Solid material

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

$$\frac{\delta L(t)}{L} \approx -\frac{\delta\alpha(t)}{\alpha} - \frac{\delta m_e(t)}{m_e}$$

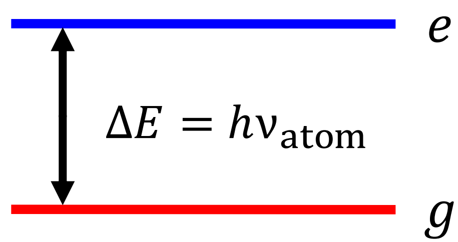
Cavity-Based Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter

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

Solid material

cf.

Electronic transition



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

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

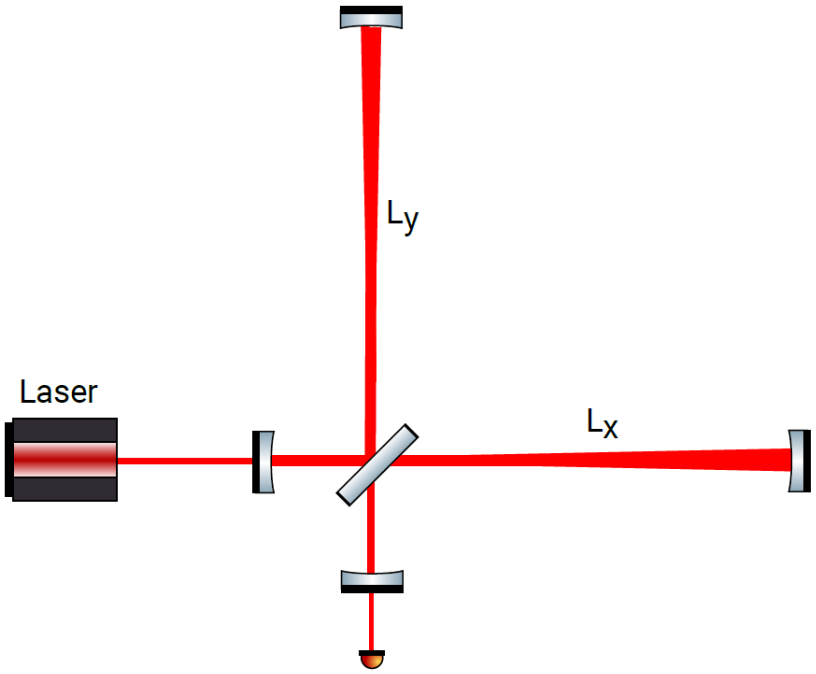
$\nu_{\text{atom}} \propto \text{Ry} \propto m_e \alpha^2$

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

- **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^+ vs Glass cavity [Weizmann]:** [Aharony *et al*., arXiv:1902.02788]
- **Sr/H vs Silicon cavity [JILA + PTB]:** [Kennedy *et al*., *PRL* **125**, 201302 (2020)]
- **H vs Sapphire/Quartz cavities [UWA]:** [Campbell *et al*., arXiv:2010.08107]

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

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



Michelson interferometer (GEO 600)

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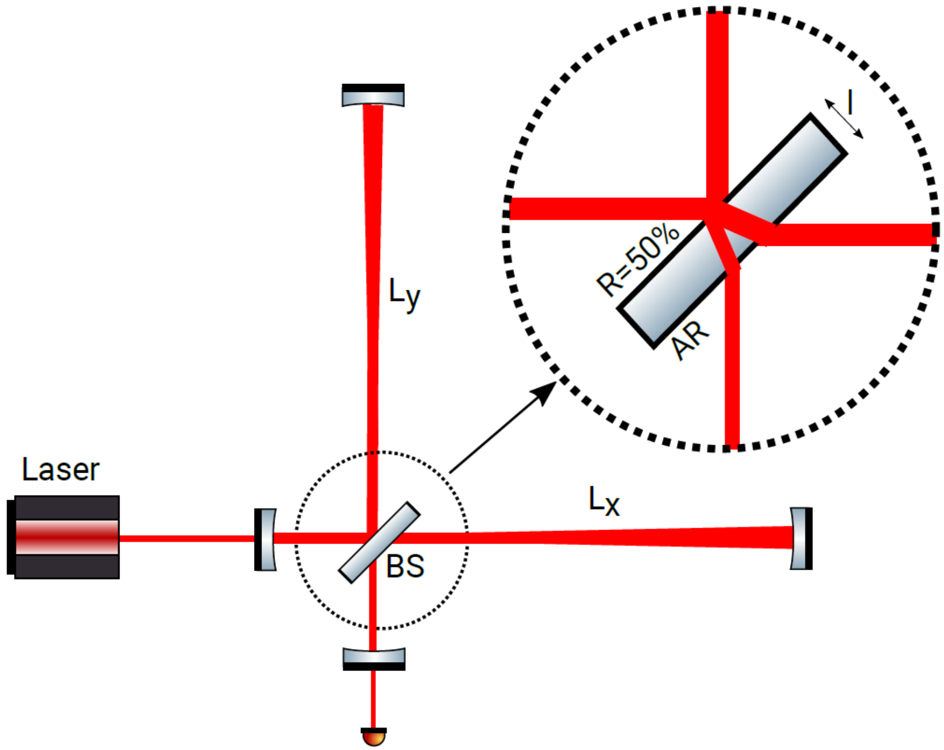

- Geometric asymmetry from beam-splitter

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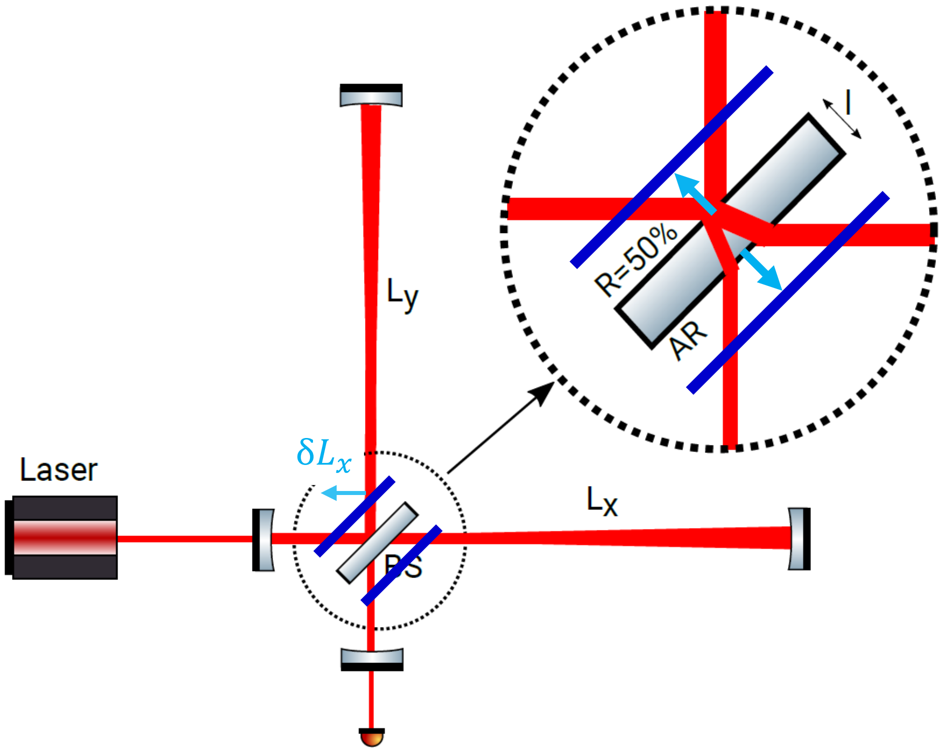

- Geometric asymmetry from beam-splitter: $\delta(L_x - L_y) \sim \delta(nl)$

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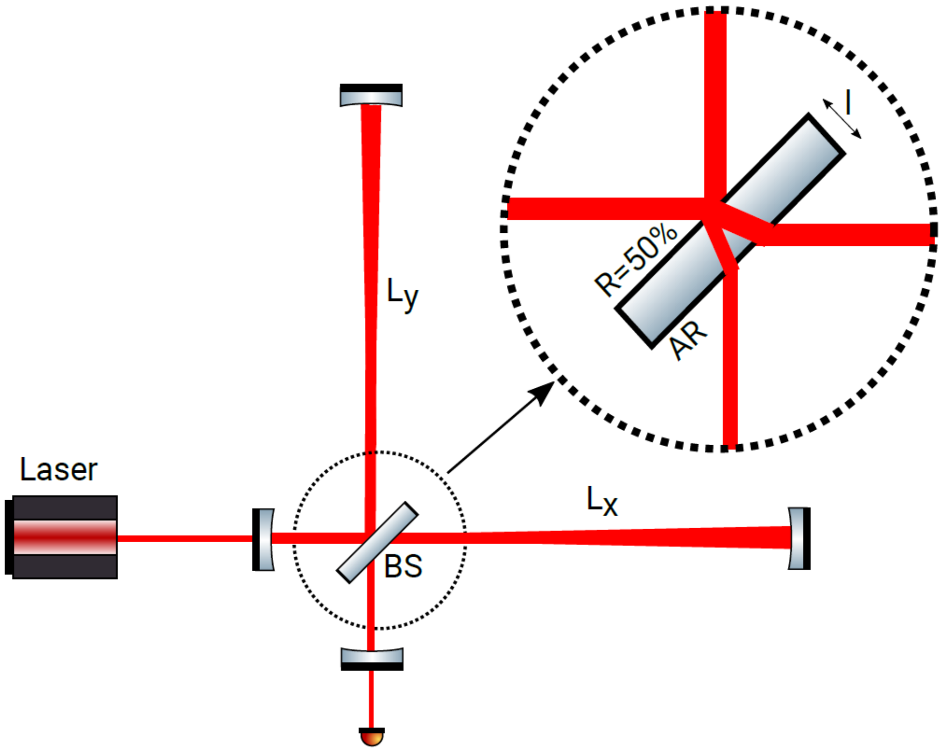


- Geometric asymmetry from beam-splitter: $\delta\left(L_x - L_y\right) \sim \delta(nl)$
- Both broadband and resonant narrowband searches possible:

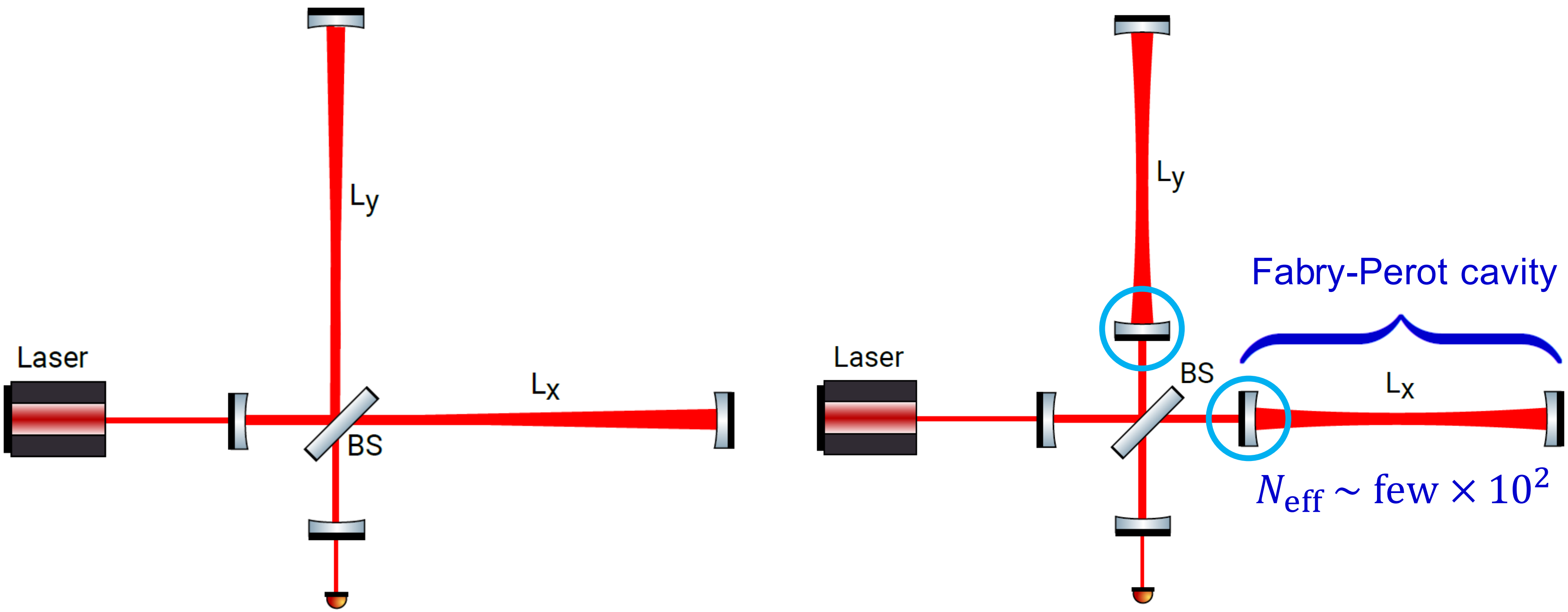
$$f_{\mathrm{DM}} \approx f_{\mathrm{vibr,BS}}(T) \sim v_{\mathrm{sound}}/l \;\Rightarrow\; Q \sim 10^6 \text{ enhancement}$$

Michelson vs Fabry-Perot-Michelson Interferometers

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

Michelson interferometer (GEO 600)

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



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

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

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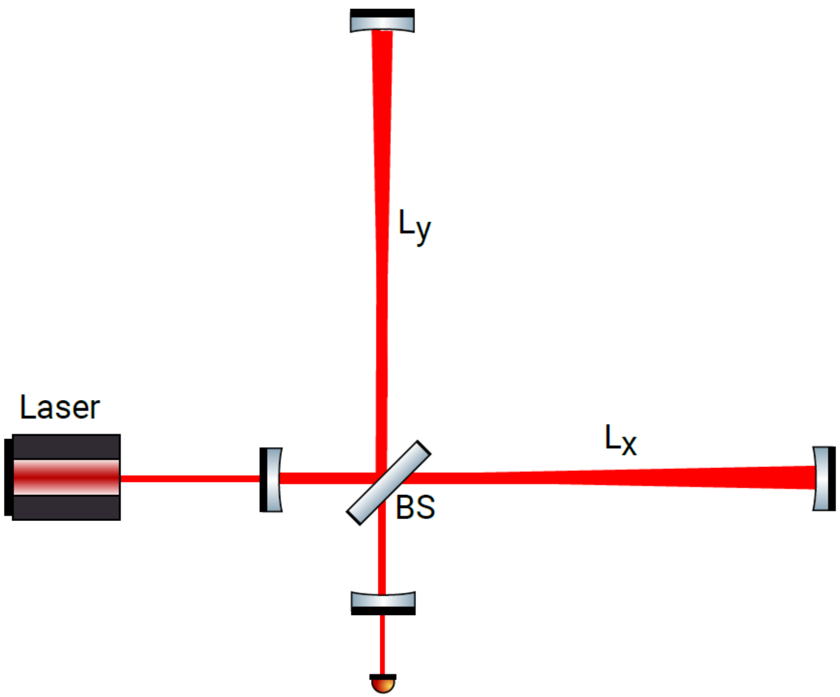

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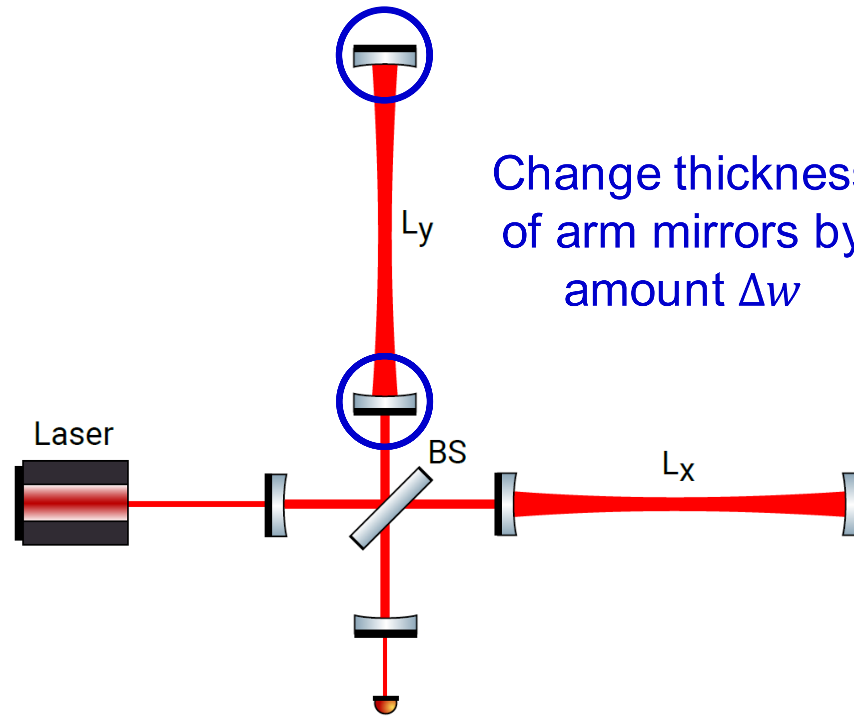
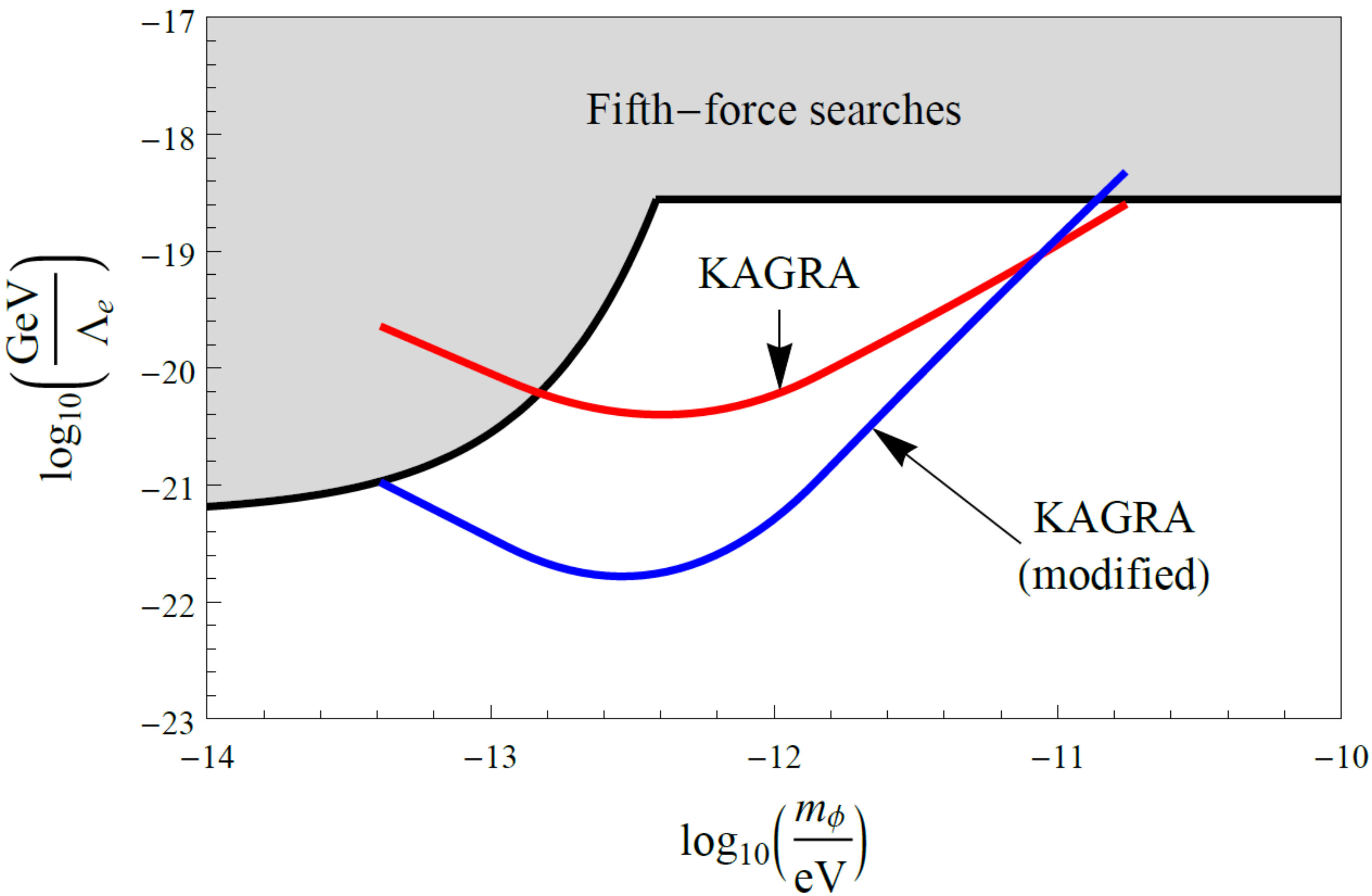
Fabry-Perot-Michelson IFO (LIGO/VIRGO/KAGRA)



Change thickness of arm mirrors by amount Δw

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

Sensitivity of KAGRA to Interaction of Scalar Dark Matter with the Electron



* Sensitivity estimate assumes total integration time of 1 year at KAGRA design sensitivity

† Modified configuration assumes 10% FP mirror thickness difference between two arms

Summary

- Laser-interferometric gravitational-wave detectors can be used as **sensitive direct probes** of ultra-low-mass scalar-field dark matter
- KAGRA (at design sensitivity) can improve sensitivity to the interaction of scalar-field dark matter with the electron by up to a **factor of ~100**
- With minor modifications, an additional improvement in sensitivity by **another factor of ~30** is possible
- Related ongoing search for scalar dark matter by the GEO600 collaboration (Michelson interferometer)

Back-Up Slides

Dark-Matter-Induced Variations of the Fundamental Constants

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

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

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

$$\mathcal{L}_f = -\frac{\phi^2}{(\Lambda'_f)^2} m_f \bar{f} f \quad \text{c.f.} \quad \mathcal{L}_f^{\text{SM}} = -m_f \bar{f} f \quad => \quad m_f \rightarrow m_f \left[1 + \frac{\phi^2}{(\Lambda'_f)^2} \right]$$

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

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

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

Oscillating variations
[Laboratory (high precision)]

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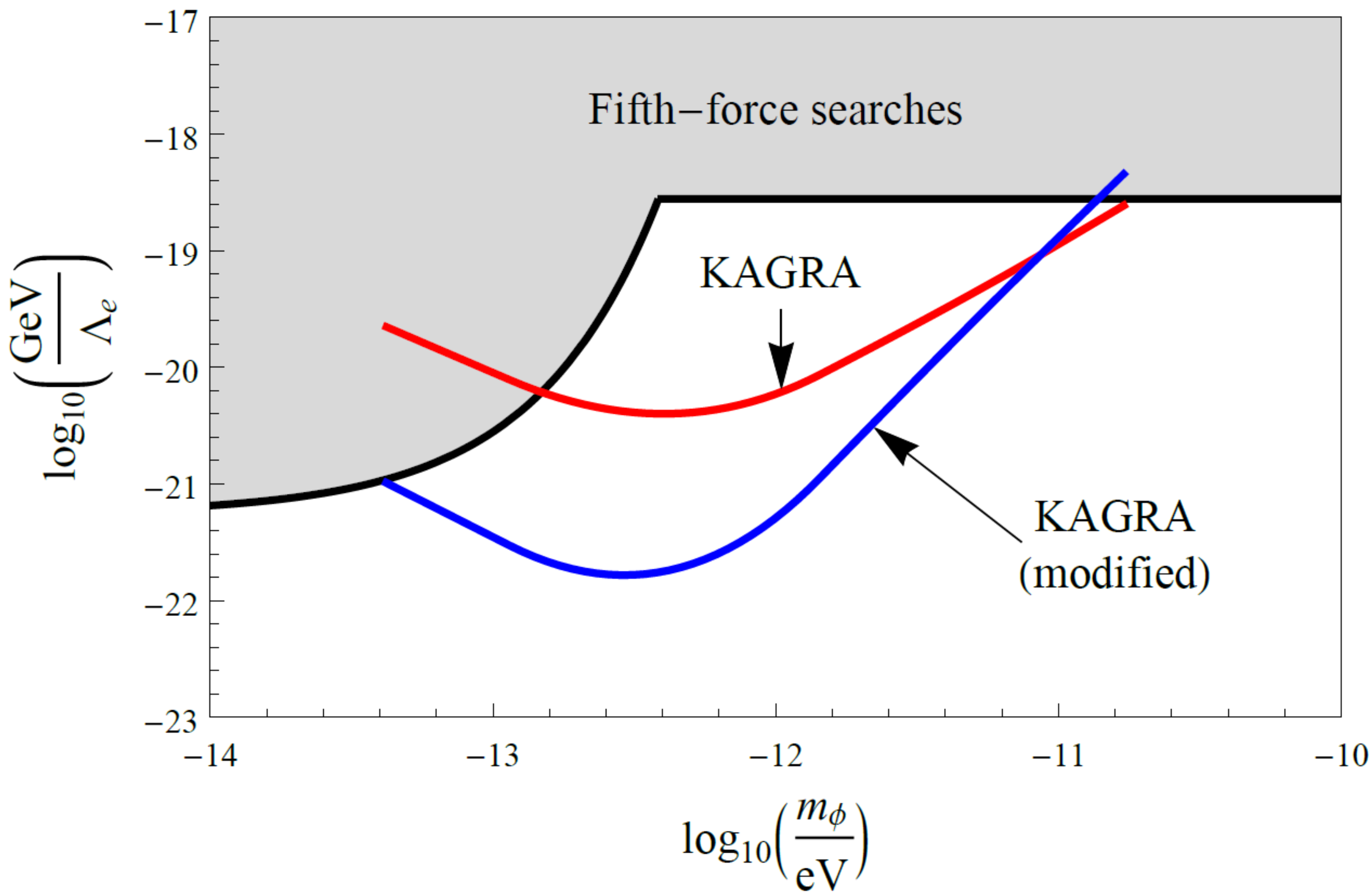

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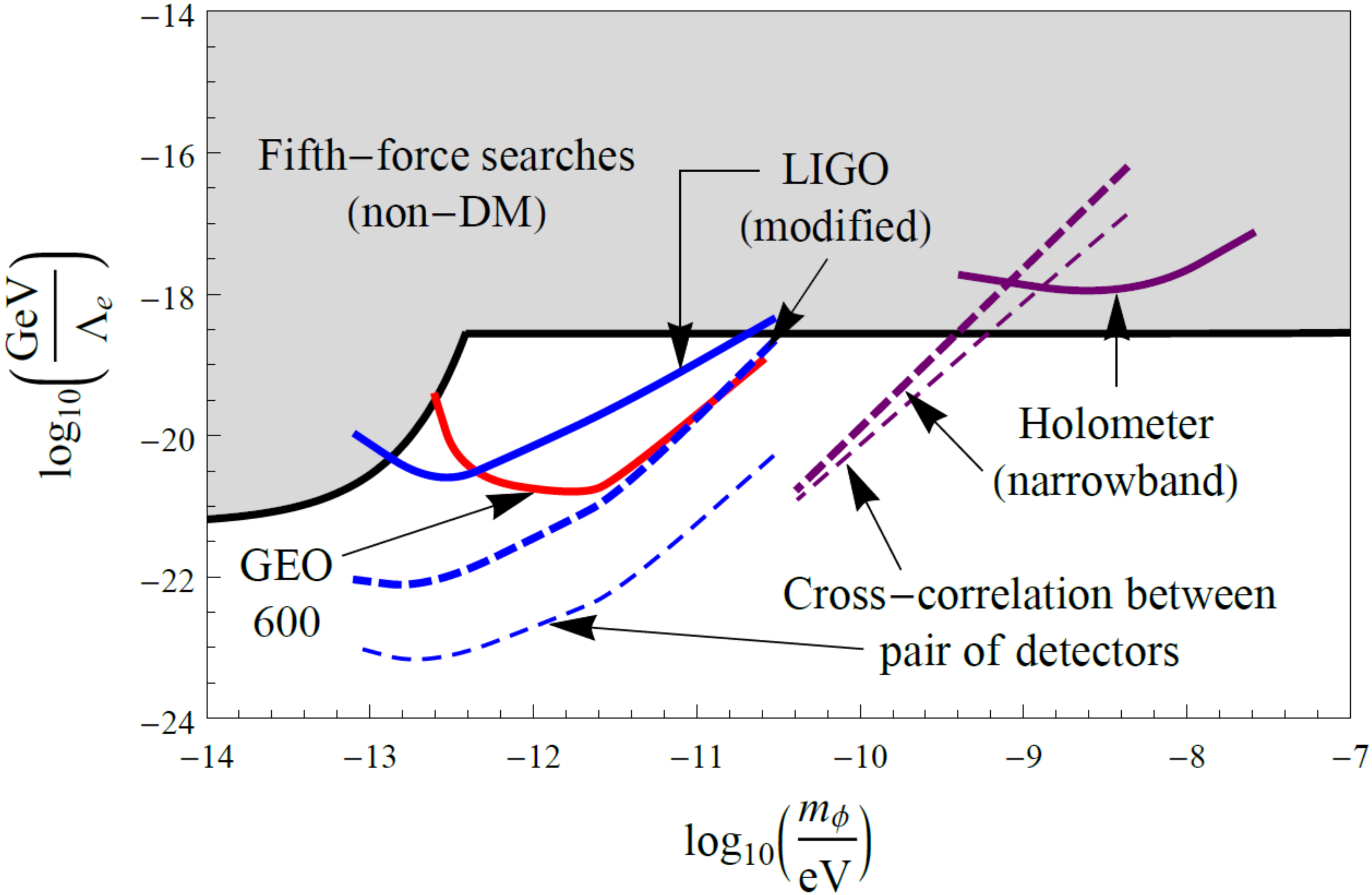
Linear Interaction of Scalar Dark Matter with the Electron



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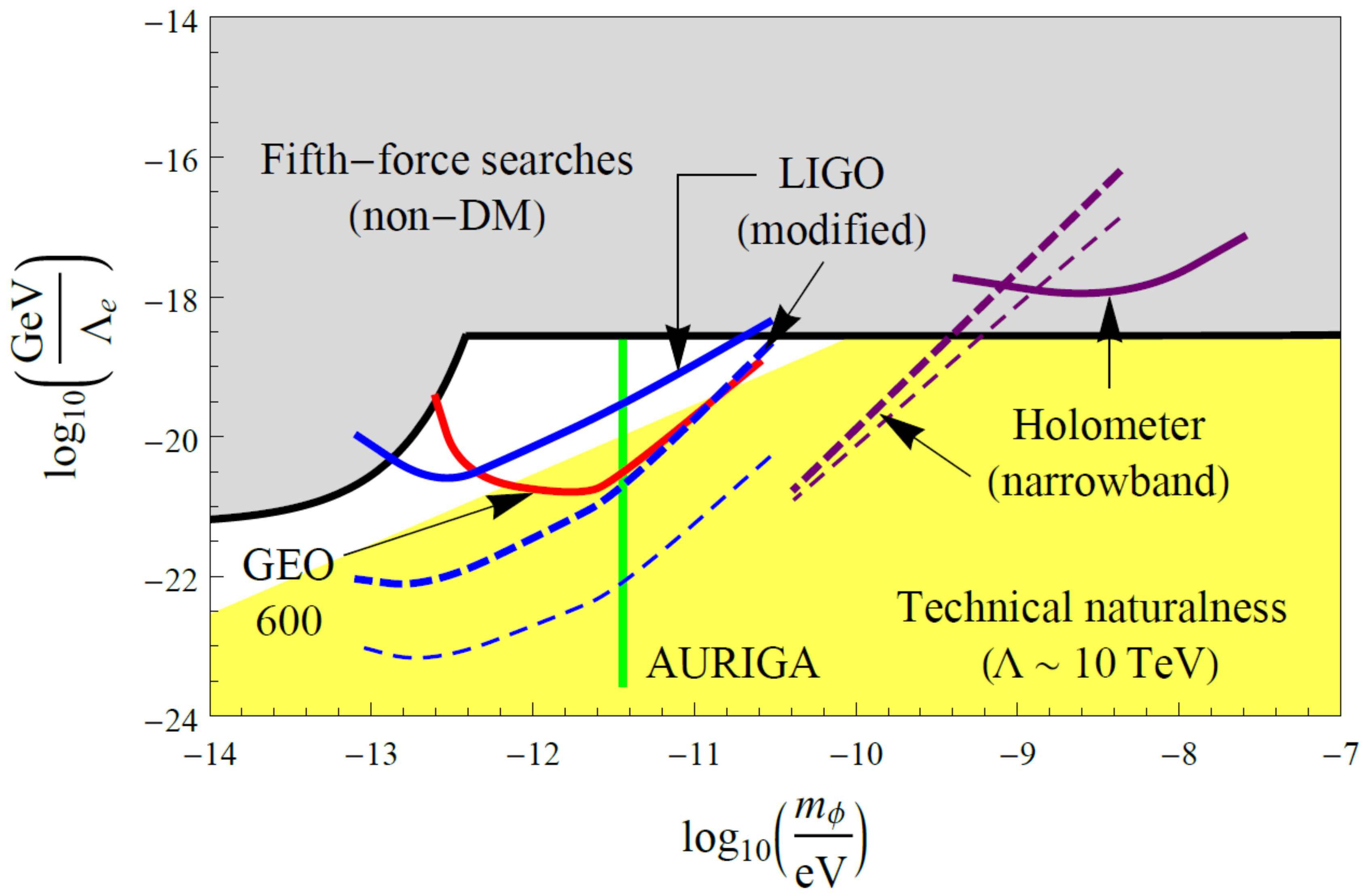

Quartic Self-Interaction of Scalar