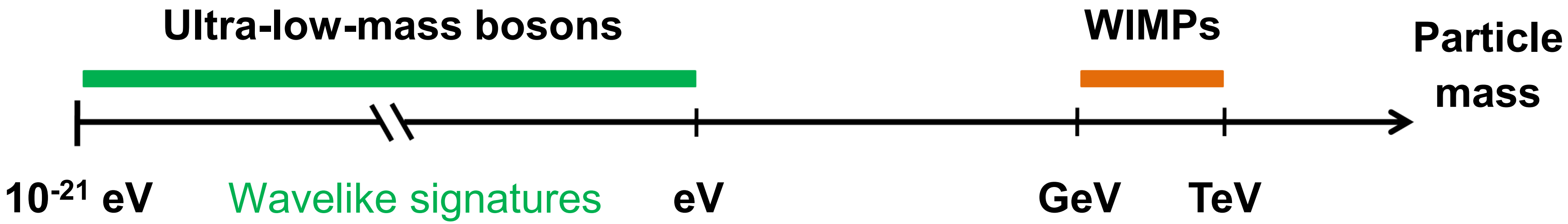
Probing Ultralight Dark Matter with Precision Atomic and Optical Experiments

Yevgeny Stadnik

High Precision Experiments for Light Dark Matter,
IPPP, Durham, UK, 7-9 September 2026

Dark Matter

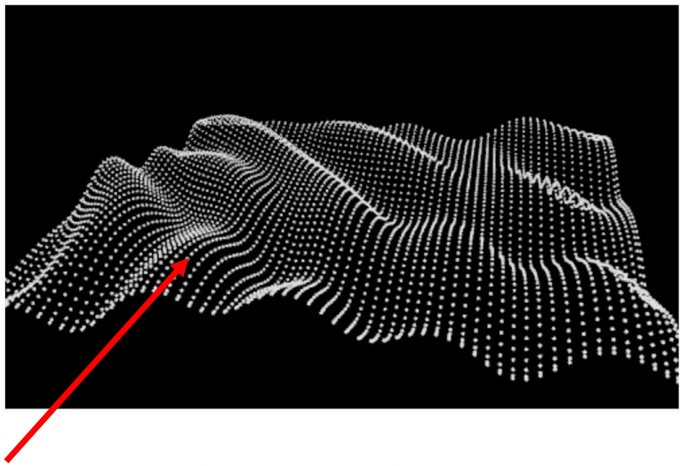


Ultra-low-mass bosons

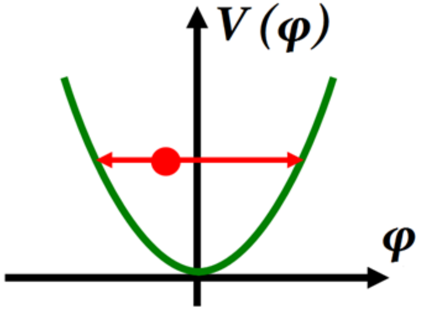
WIMPs

Particle mass

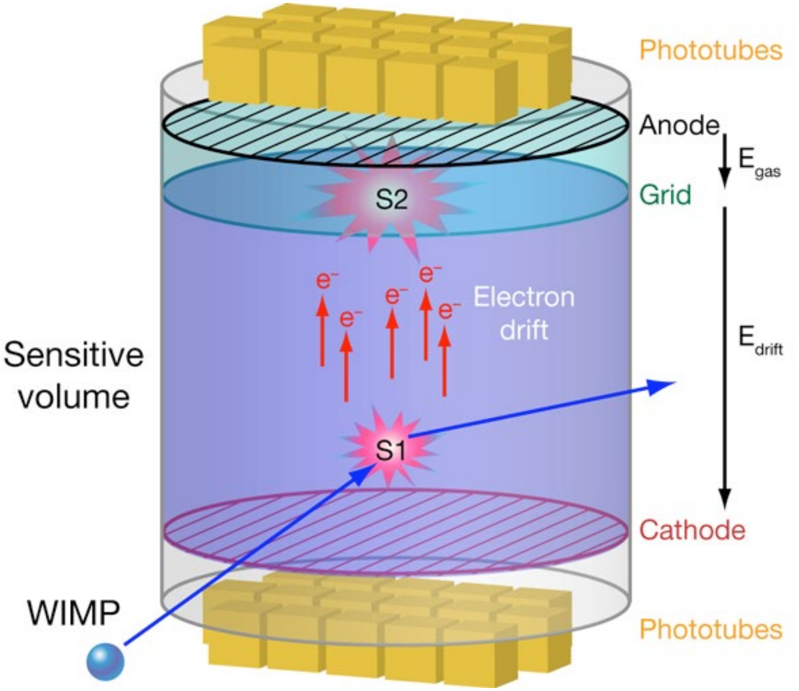
10^{-21} eV Wavelike signatures **eV** **GeV** **TeV**



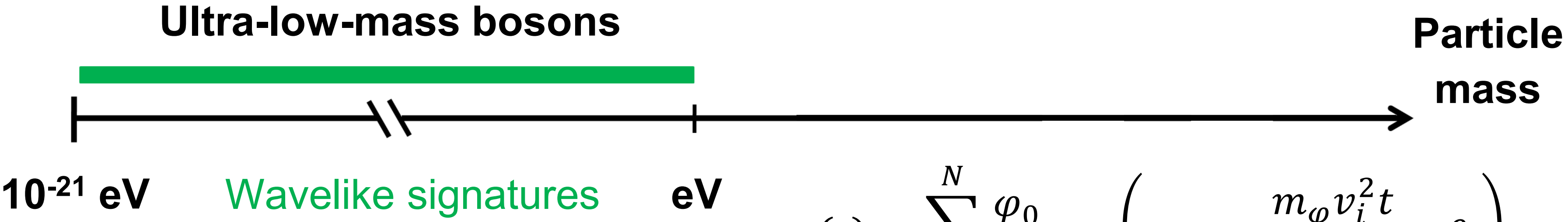
$$\varphi(t) \sim \varphi_0 \cos\left(m_\varphi c^2 t/\hbar\right),\ \varphi_0 \sim \sqrt{\rho_{\mathrm{DM}}}/m_\varphi$$



Particle-like signatures



Dark Matter

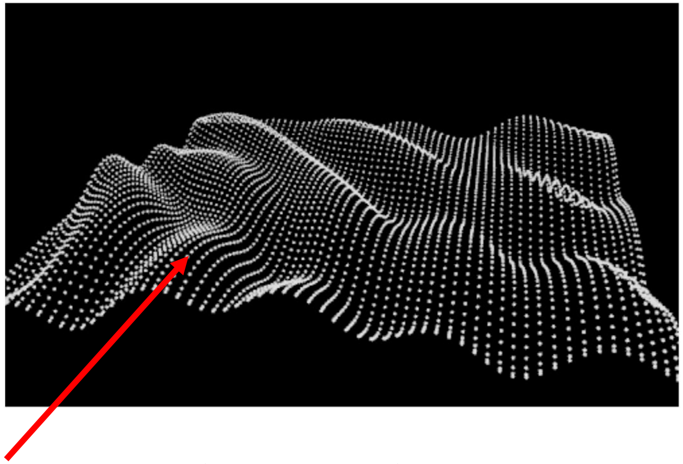


Ultra-low-mass bosons

Particle mass

10^{-21} eV Wavelike signatures **eV**

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



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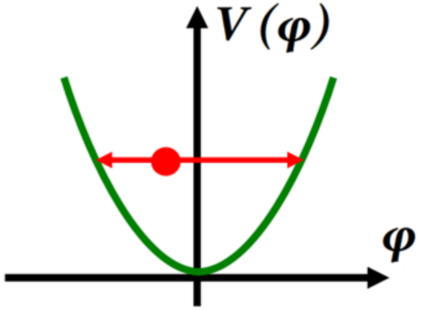
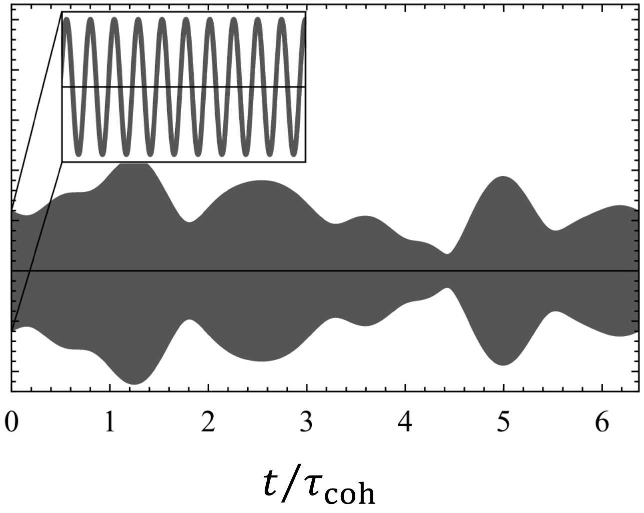


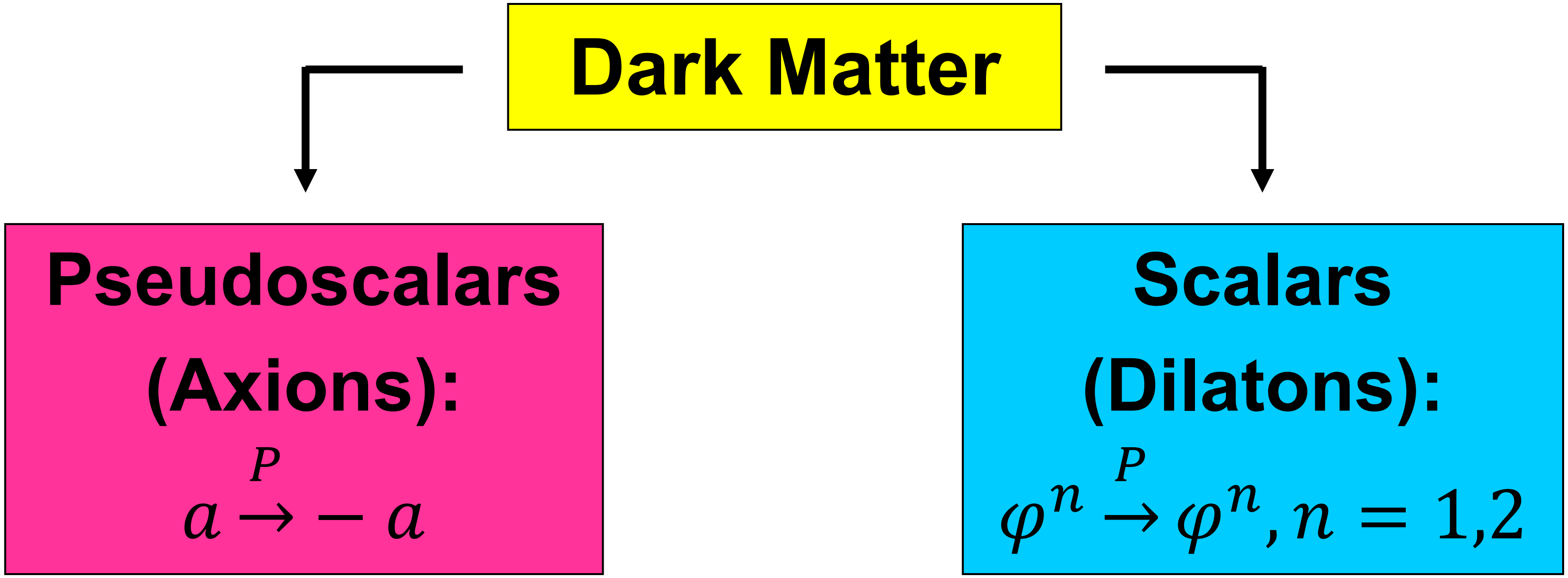
Evolution of φ_0 with time



$$\Delta E_\varphi / E_\varphi \sim \Delta v_\varphi^2 / c^2 \sim 10^{-6}$$

$$\Rightarrow\ \tau_{\mathrm{coh}} \sim 2\pi/\Delta E_\varphi \sim 10^6 T_{\mathrm{osc}}$$

Low-mass Spin-0 Dark Matter



Dark Matter

Pseudoscalars (Axions):

$$a \xrightarrow{P} -a$$

Scalars (Dilatons):

$$\varphi^n \xrightarrow{P} \varphi^n, n = 1,2$$

Time-varying EDMs and spin-precession effects

Spatio-temporal variations of "constants"

Effects scale to the first power in an underlying interaction constant!
(e.g., energy shifts, phase shifts, accelerations or torques)

Traditional dark matter effects have a second or fourth power scaling
(e.g., collisions with, absorption by or interconversion with ordinary matter)

Low-mass Spin-0 Dark Matter

Dark Matter

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Scalars (Dilatons):

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Time-varying EDMs and spin-precession effects

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

Spatio-temporal variations of "constants"

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

Low-mass Spin-0 Dark Matter

Dark Matter

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More traditional axion dark matter detection methods tend to focus on the ***electromagnetic*** *coupling*

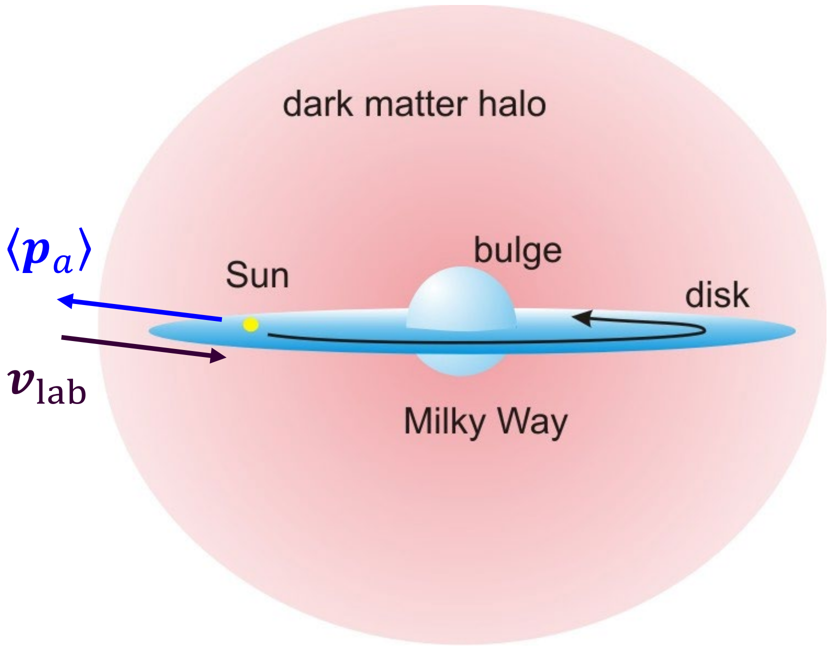
Here I focus on relatively new detection methods based on ***non-electromagnetic*** *couplings leading to spin-based signatures*

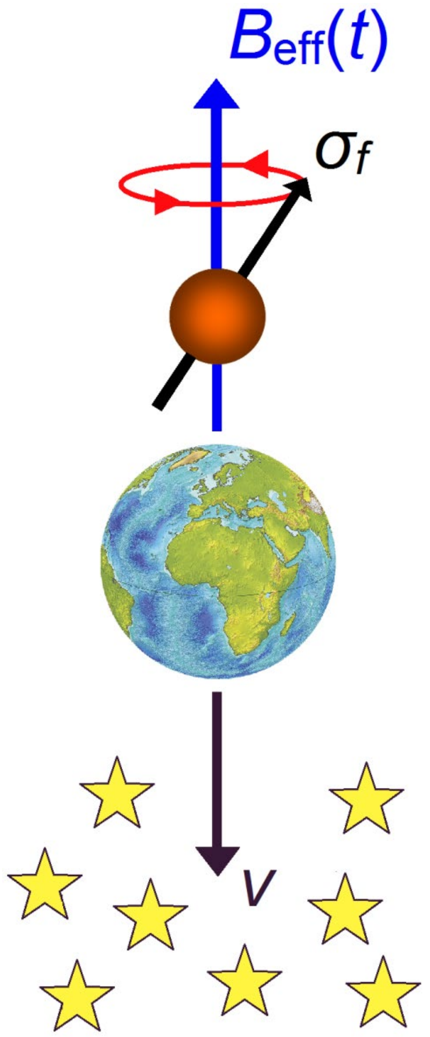
"Axion Wind" Spin-Precession Effect

[Flambaum, talk at *Patras Workshop*, 2013], [Stadnik, Flambaum, *PRD* **89**, 043522 (2014)]

$$\mathcal{L}_f = -\frac{C_f}{2f_a}\,\partial_i[a_0\cos(m_a t - \boldsymbol{p}_a\cdot\boldsymbol{x})]\,\bar{f}\gamma^i\gamma^5 f$$

$$\Rightarrow\quad H_{\mathrm{wind}}(t) = \boldsymbol{\sigma}_f\cdot\boldsymbol{B}_{\mathrm{eff}}(t) \propto \boldsymbol{\sigma}_f\cdot\boldsymbol{p}_a\sin(m_a t)$$



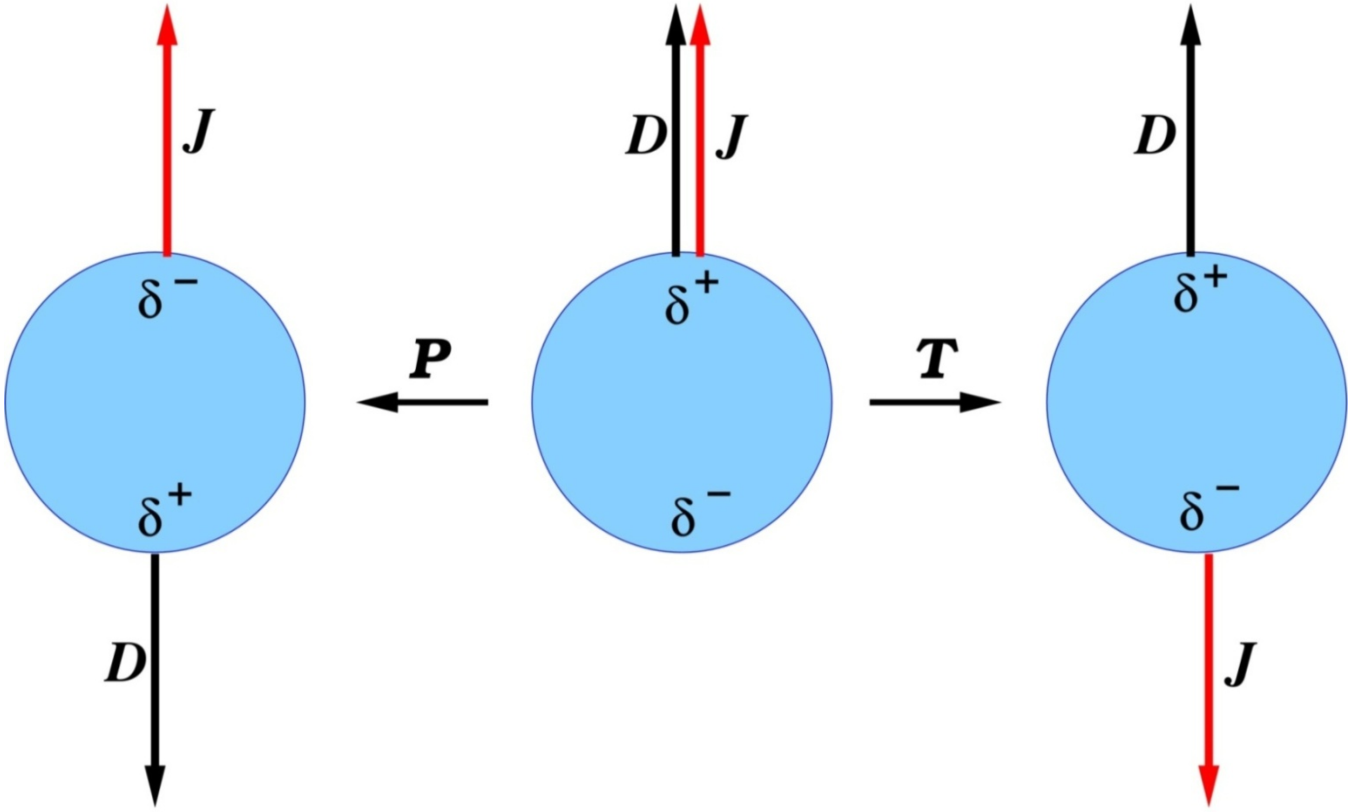


Oscillating Electric Dipole Moments

Nucleons: [Graham, Rajendran, *PRD* **84**, 055013 (2011)]

Atoms and molecules: [Stadnik, Flambaum, *PRD* **89**, 043522 (2014)]

Electric Dipole Moment (EDM) = parity (P) and time-reversal-invariance (T) violating electric moment



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$$\mathcal{L} = \frac{g_s^2}{32\pi^2}\frac{C_G}{f_a}a_0\cos(m_a t)G\tilde{G} \quad \Rightarrow \quad \begin{array}{c} \boldsymbol{d}(t) \propto \boldsymbol{J}\cos(m_a t), \\ H_{\mathrm{EDM}}(t) = \boldsymbol{d}(t)\cdot\boldsymbol{E} \end{array}$$

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$$\text{cf. } \mathcal{L} = \frac{g_s^2}{32\pi^2}\theta G\tilde{G} \quad \Rightarrow \quad \theta \leftrightarrow \frac{C_G}{f_a}a_0\cos(m_a t)$$

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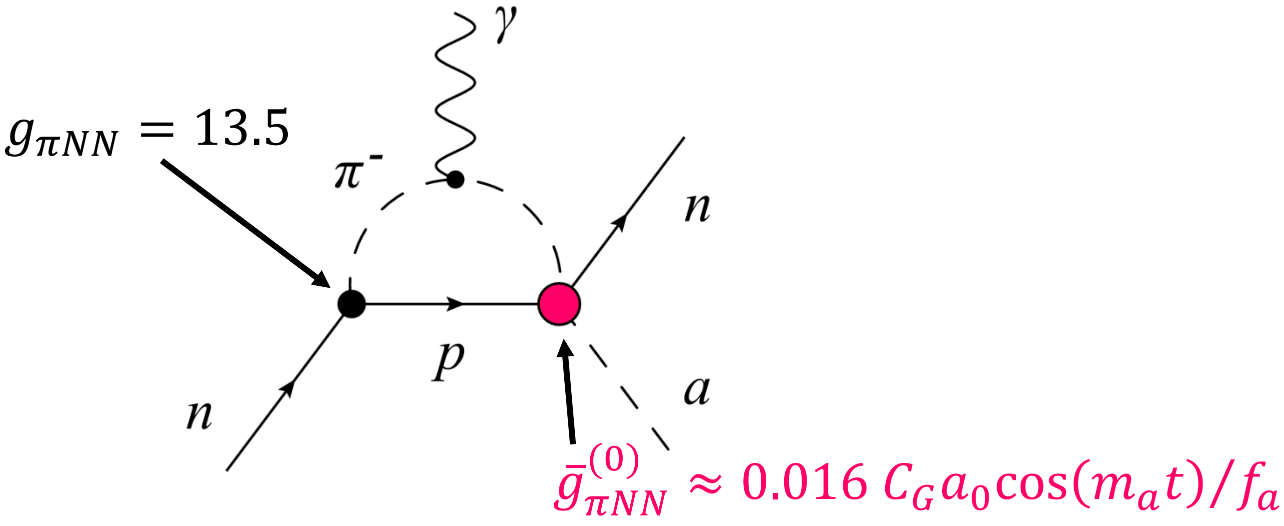
Nucleon EDMs (e.g., d_n)



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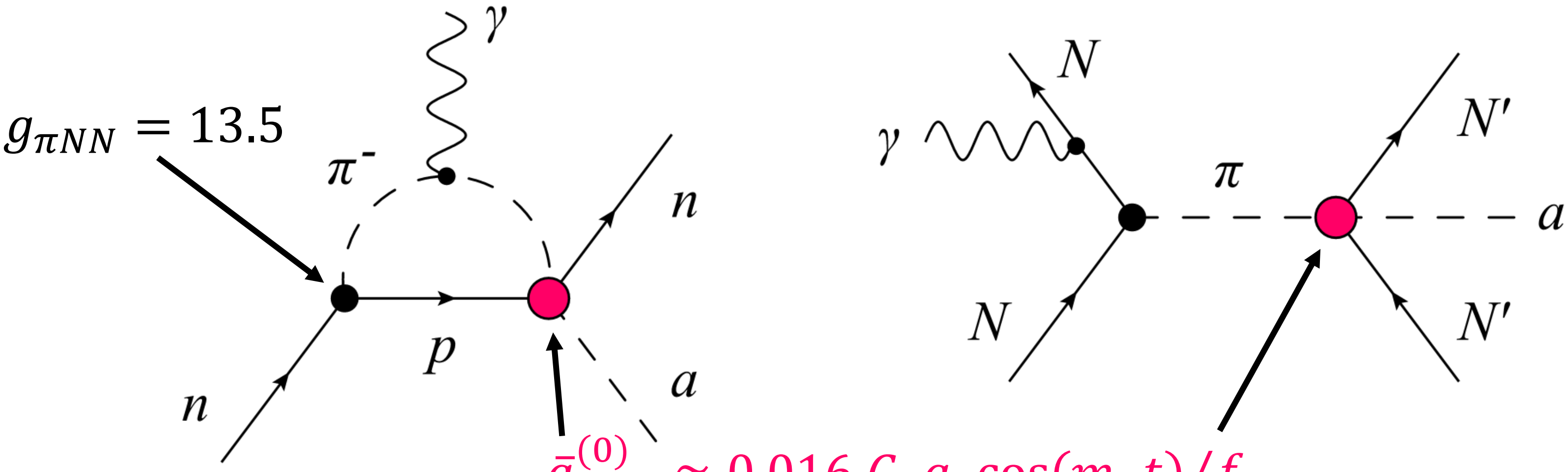
Nucleon EDMs (e.g., d_n) **CP-violating intranuclear forces**



$\bar{g}_{\pi NN}^{(0)} \approx 0.016\, C_G a_0 \cos(m_a t)/f_a$

In nuclei, ***tree-level*** CP-violating intranuclear forces dominate over ***loop-induced*** nucleon EDMs [loop factor = $1/(8\pi^2)$].

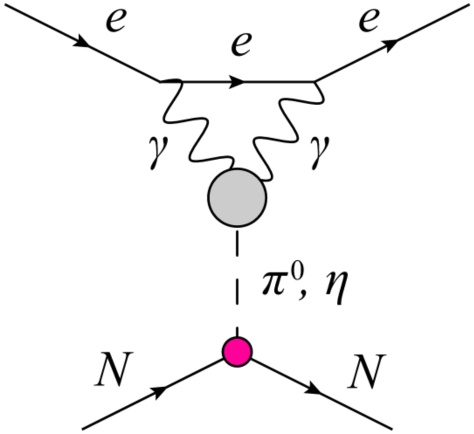
Paramagnetic Atoms and Molecules

[Flambaum, Pospelov, Ritz, Stadnik, *PRD* **102**, 035001 (2020)]

CP-odd nuclear scalar polarisability arises at 2-loop level, $\mathcal{O}(A)$ enhanced

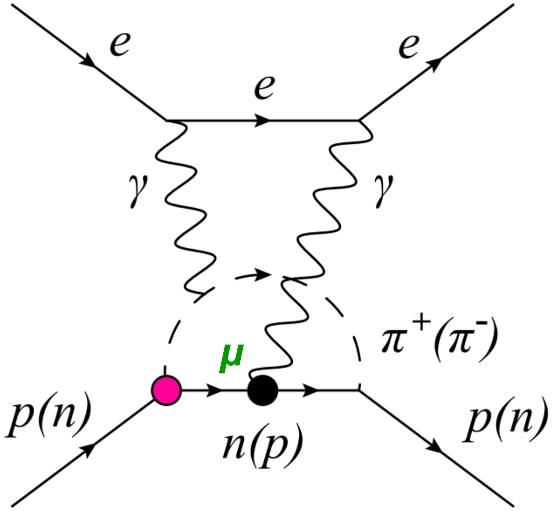
Interaction of one of photons with nucleus is *magnetic* ⇒ no Schiff screening

LO: $\mathcal{O}\left(m_\pi^{-2}\right)$



CP-odd nucleon polarisabilities $(\propto \boldsymbol{E}\cdot\boldsymbol{B})$

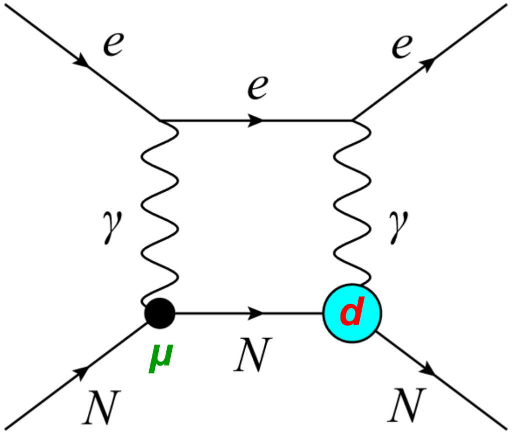
NLO: $\mathcal{O}\left(m_\pi^{-1}\right)$



CP-odd nucleon polarisabilities $(\propto \boldsymbol{E}\cdot\boldsymbol{B})$

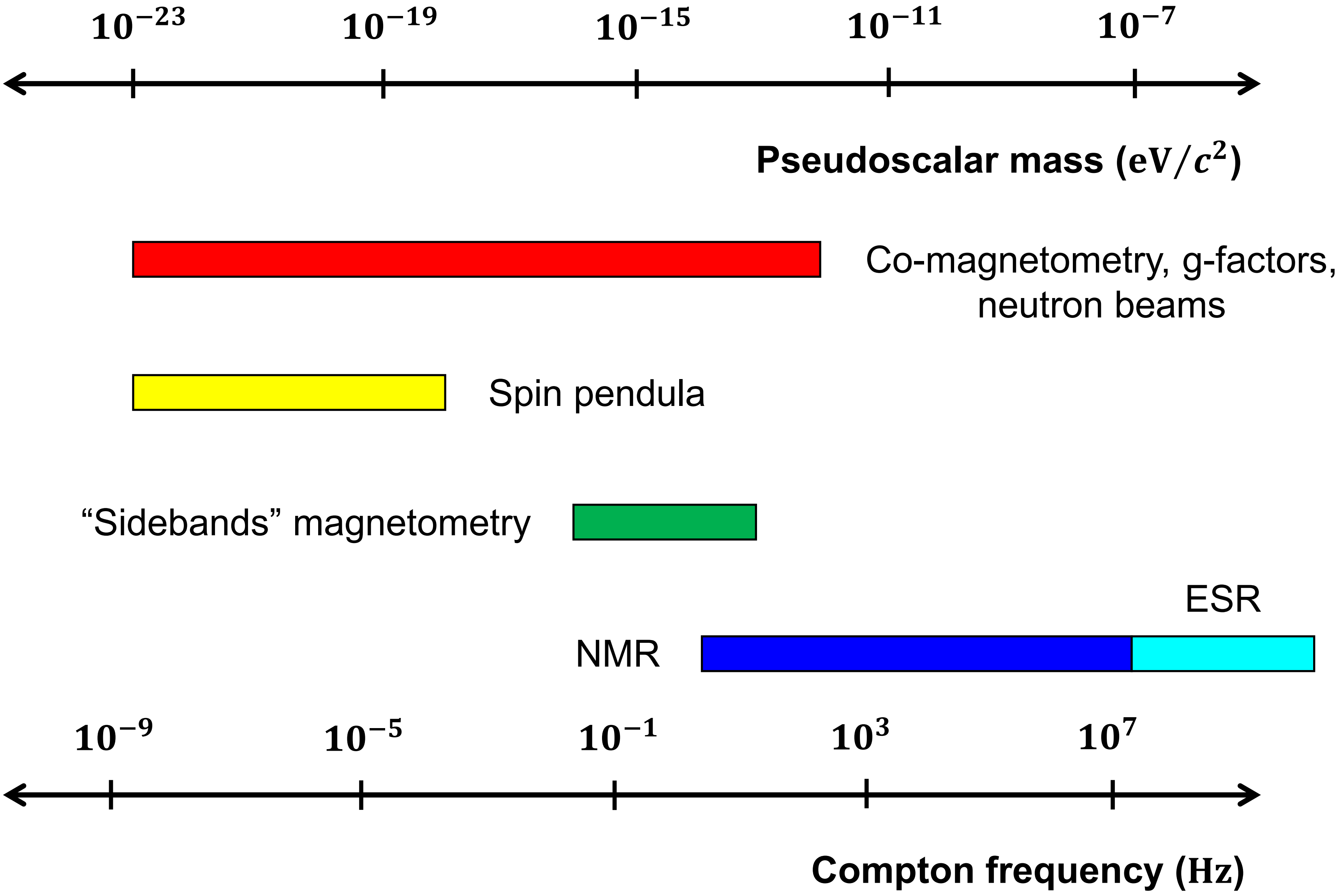
$\boldsymbol{\mu}-\boldsymbol{d}$: $\mathcal{O}[\ln(A)/p_\mathrm{F}]$

[Fermi-gas model]



Internal nuclear excitations

Probes of Time-Varying EDMs and Spin-Precession Effects



Broadband Searches, $a\bar{N}N/aG\tilde{G}/a\bar{e}e$, $10^{-23}\mathrm{eV} \le m_a \le 10^{-16}\mathrm{eV}$

Proposals: [Flambaum, talk at *Patras Workshop*, 2013;
Stadnik, Flambaum, *PRD* **89**, 043522 (2014); Stadnik, thesis (Springer, 2017)]

Lorentz-invariance-violation-type searches:
Magnetometers, *cold/ultracold particles*, *spin pendula*

Similar to previous searches for Lorentz-invariance violation using spin-polarised sources

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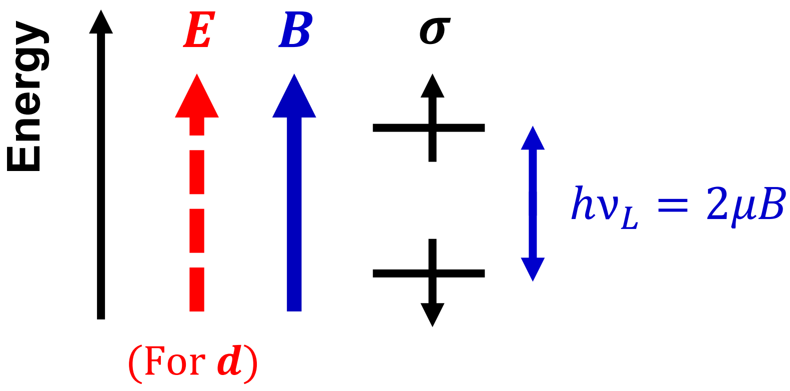
Experiment at PSI ($n/^{199}\mathrm{Hg}$): [nEDM collaboration, *PRX* **7**, 041034 (2017)]



“Spin clock”

$$\boxed{\frac{\nu_n}{\nu_{\mathrm{Hg}}} = \left|\frac{\mu_n B}{\mu_{\mathrm{Hg}} B}\right|}$$

↑

***B*-field effect**

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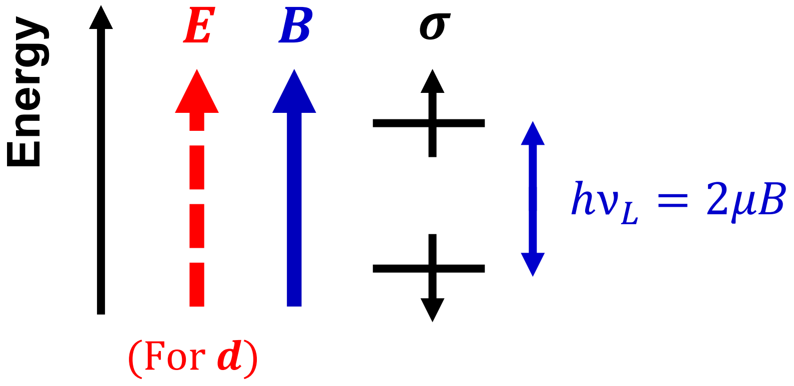

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$$\frac{\nu_n}{\nu_{\mathrm{Hg}}} = \left|\frac{\mu_n \cancel{B}}{\mu_{\mathrm{Hg}} \cancel{B}}\right|$$

$\boldsymbol{B}$-field
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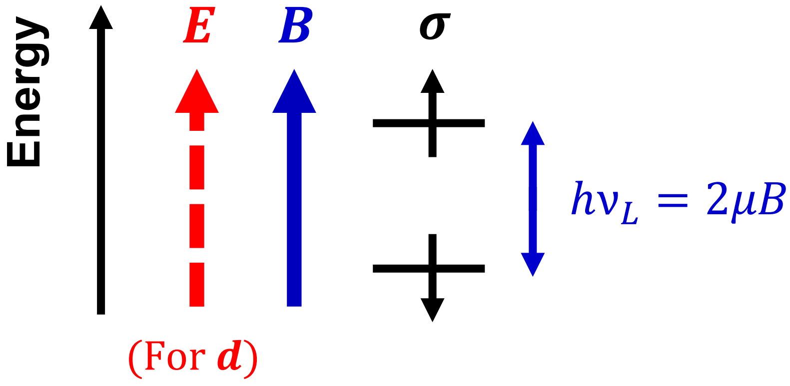

"Spin clock"

$$\boxed{\frac{\nu_n}{\nu_{\text{Hg}}} = \left|\frac{\mu_n \cancel{B}}{\mu_{\text{Hg}} \cancel{B}}\right| + R(t)}$$

B-field effect

DM effect (*non-magnetic* coupling to σ or d)

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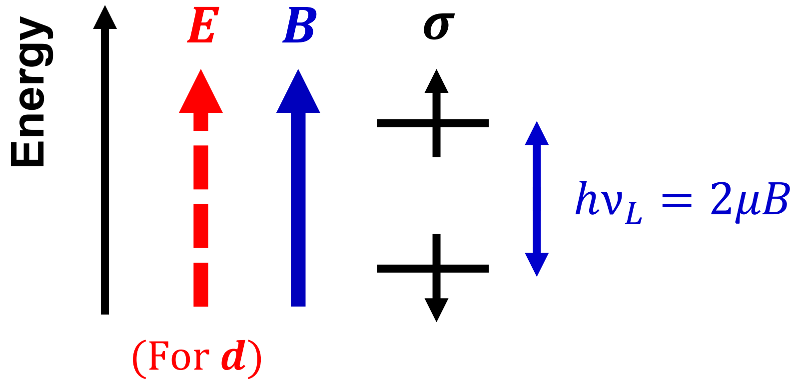

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***B*-field effect**

DM effect (*non-magnetic* coupling to $\boldsymbol{\sigma}$ or $\boldsymbol{d}$)

- **$n/^{199}$Hg [PSI]:** [nEDM collaboration, *PRX* **7**, 041034 (2017)]
- **^{13}CH$_3$CN [Mainz]:** [Wu *et al.*, *PRL* **122**, 191302 (2019)]
- **^{3}He/K [Princeton]:** [Bloch *et al.*, *JHEP* **2020**, 167 (2020)], [Lee *et al.*, *PRX* **13**, 011050 (2023)]
- **^{3}He/^{39}K [NASDUCK (Israel-US)]:** [Bloch *et al.*, *Nature Comm.* **14**, 5784 (2023)]
- **^{21}Ne-Rb-K [Beijing-Mainz]:** [Wei *et al.*, *Rep. Prog. Phys.* **88**, 057801 (2025)], [Xu *et al.*, *Comm. Phys.* **7**, 226 (2024)]
- **K-^{87}Rb-^{3}He [Mainz-Krakow]:** [Gavilan-Martin *et al.*, *Nature Comm.* **16**, 4953 (2025)]
- **^{3}He/^{129}Xe [Mainz]:** [Zhang, Wu, Yan, *PRL* **135**, 131001 (2025)]

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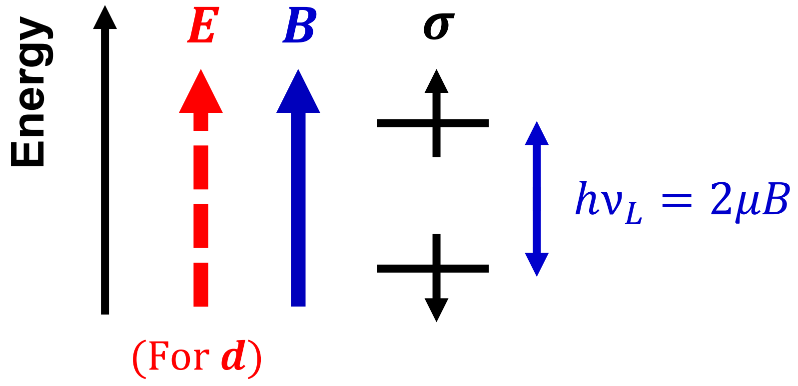
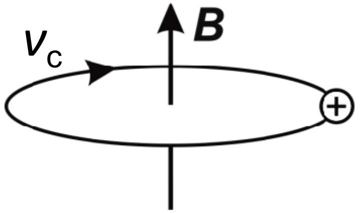


$$\boxed{\frac{\nu_n}{\nu_{\mathrm{Hg}}} = \left|\frac{\mu_n \cancel{B}}{\mu_{\mathrm{Hg}} \cancel{B}}\right| + R(t)}$$

***B*-field effect**

DM effect (*non-magnetic* coupling to $\boldsymbol{\sigma}$ or $\boldsymbol{d}$)

Proposal + Experiment at CERN ($\bar{p}$): [BASE collaboration, *Nature* **575**, 310 (2019)]



$$\boxed{\left(\frac{\nu_L}{\nu_c}\right)_{\bar{p}} = \frac{|g_{\bar{p}}|}{2} + R(t)}$$

Broadband Searches, $a\bar{N}N/aG\tilde{G}/a\bar{e}e$, $10^{-23}\text{eV} \leq m_a \leq 10^{-16}\text{eV}$

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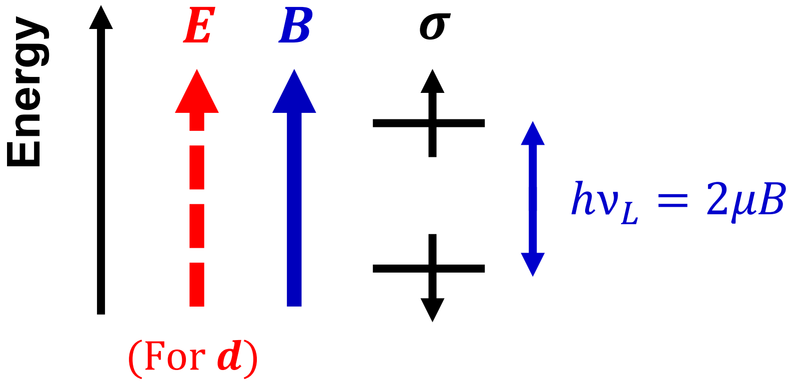

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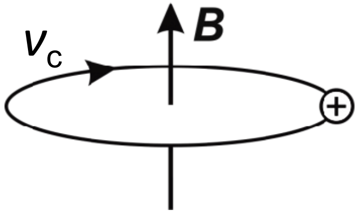


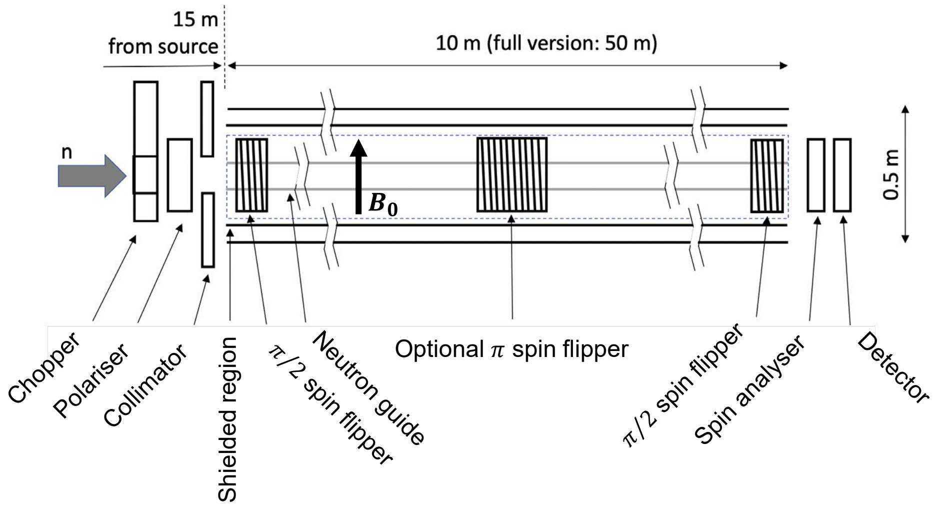
$$\boxed{\left(\frac{\nu_L}{\nu_c}\right)_{\bar{p}} = \frac{|g_{\bar{p}}|}{2} + R(t)}$$

Antimatter probe!

Broadband Searches, $a\bar{n}n/aG\tilde{G}$, $10^{-22}\text{eV} \leq m_a \leq 10^{-13}\text{eV}$

Besides stored or trapped particles, can also use particle beams:

Proposal at ESS (n beam): [Fierlinger, Holl, Milstead, Santoro, Snow, Stadnik, *PRL* **133**, 181001 (2024)]



$$\text{SNR} \propto \sqrt{N\tau T}$$

Total measurement time

Number of neutrons

Precession time

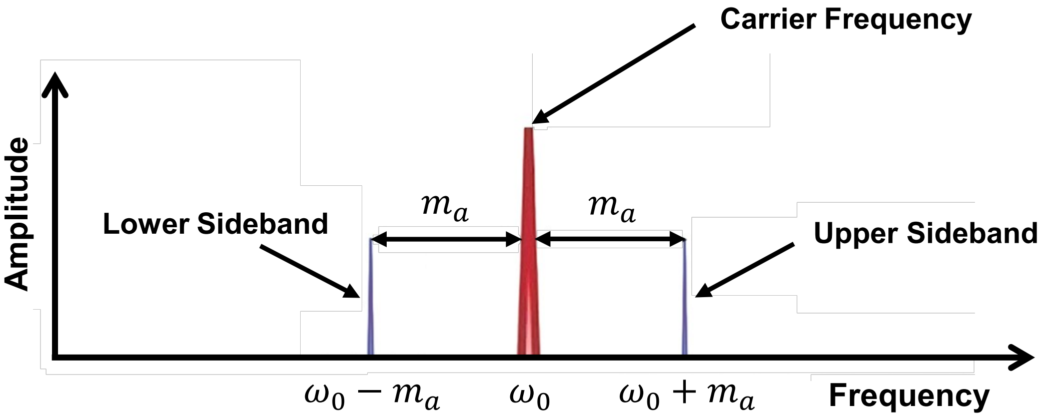
System	Stored ultracold neutrons (nEDM at PSI)	Cold neutron beam (HIBEAM at ESS)
Neutron number	$\sim 10^5$	$\sim 10^{11}$ (per shot, 10Hz rate)
Precession time	$\sim 100 - 200$ s	$\sim 0.01 - 0.1$ s
Neutron speed	$\lesssim 10$ m/s	≈ 1 km/s

Broadband Searches, $a\bar{N}N$, $10^{-16}\mathrm{eV} \leq m_a \leq 10^{-13}\mathrm{eV}$

Proposal: [Garcon *et al.*, *Quantum Sci. Technol.* **3**, 014008 (2018)]

"Sidebands" magnetometry technique –

In the presence of a weak AC (pseudo)magnetic field, sideband features develop around the carrier frequency

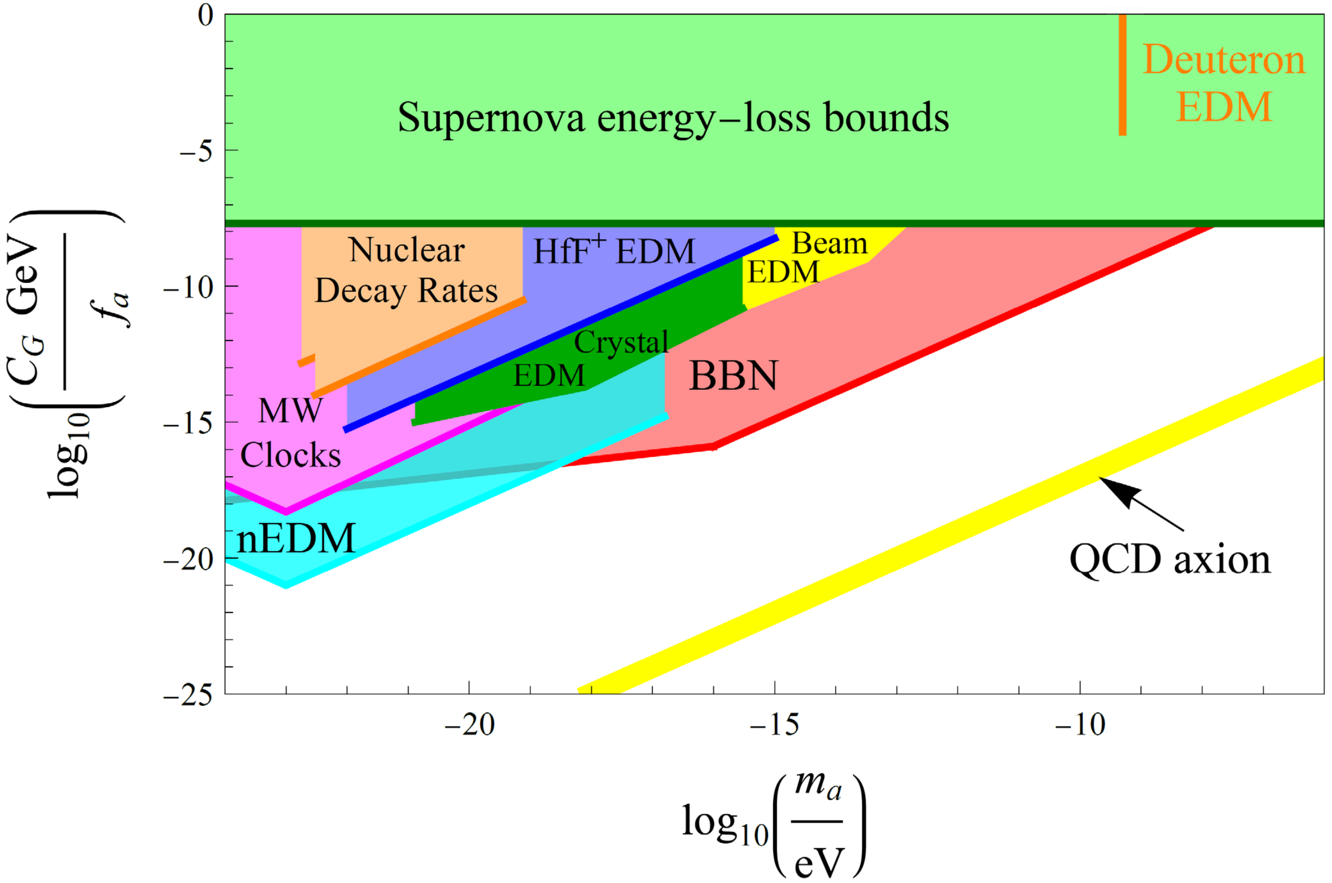


Experiment at Mainz (Formic acid NMR): [Garcon *et al.*, *Sci. Adv.* **5**, eaax4539 (2019)]

Experiment at PSI (Hg): [nEDM collaboration, *SciPost Phys.* **15**, 058 (2023)]

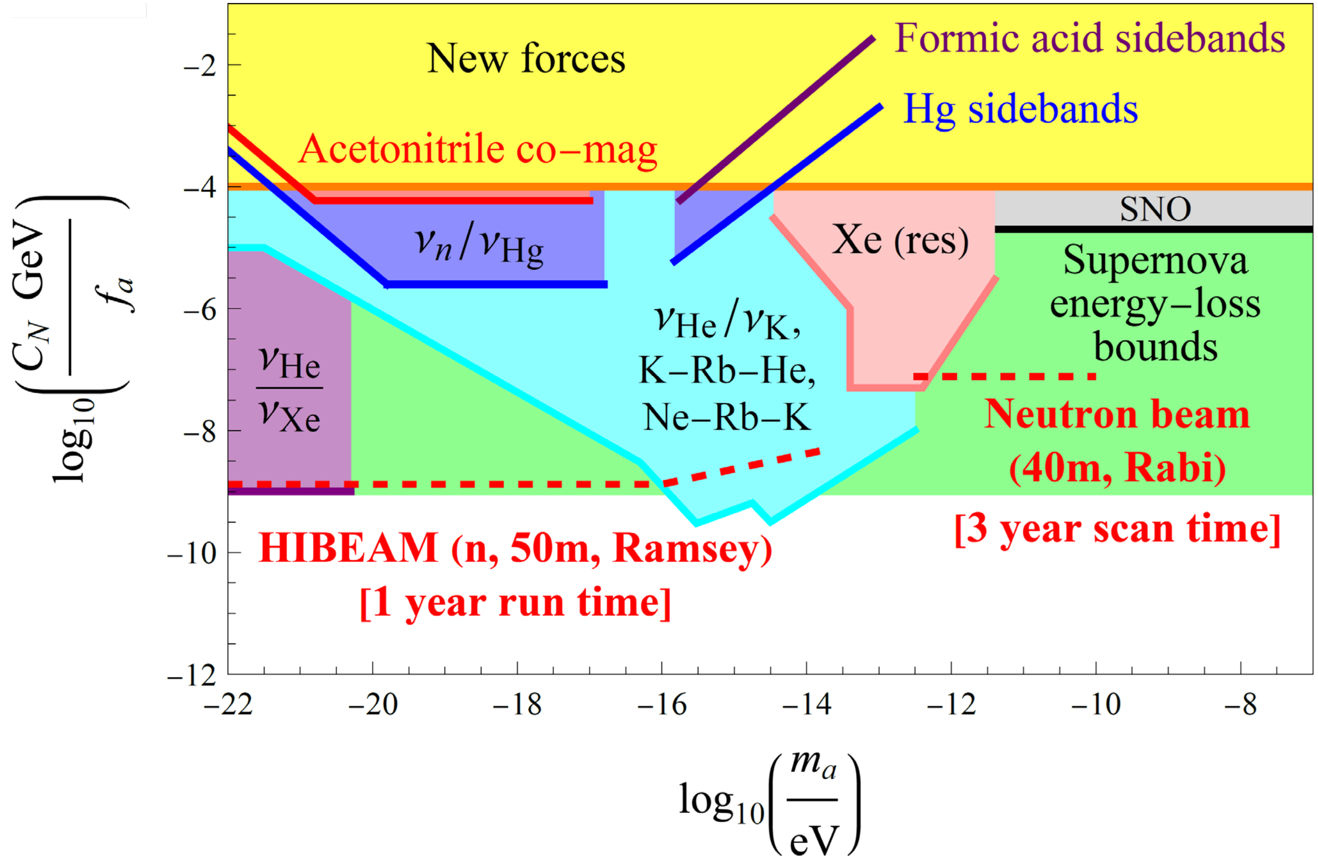
Constraints on Axion Dark Matter with $C_G a G_{\mu\nu}\tilde{G}^{\mu\nu}/f_a$ Coupling

nEDM constraints (PSI): [nEDM collaboration, *PRX* **7**, 041034 (2017)]
HfF⁺ EDM constraints (JILA): [Roussy *et al*., *PRL* **126**, 171301 (2021)]
Beam EDM constraints (ILL): [Schulthess *et al*., *PRL* **129**, 191801 (2022)]
Deuteron EDM constraints (Jülich): [Karanth *et al*., *PRX* **13**, 031004 (2023)]
Crystal EDM constraints (Toronto): [Fan *et al*., *PRL* **136**, 121802 (2026)]



Sensitivity to Axion Dark Matter with $C_N(\partial_\mu a)\bar{N}\gamma^\mu\gamma^5 N/2f_a$ Coupling

ν_n/ν_{Hg} constraints (PSI): [nEDM collaboration, *PRX* **7**, 041034 (2017)]
Acetonitrile constraints (Mainz): [Wu *et al*., *PRL* **122**, 191302 (2019)]
Formic acid constraints (Mainz): [Garcon *et al*., *Sci. Adv.* **5**, eaax4539 (2019)]
Hg sidebands constraints (PSI): [nEDM collaboration, *SciPost Phys.* **15**, 058 (2023)]
Neutron beam projections (ESS): [Fierlinger *et al*., *PRL* **133**, 181001 (2024); arXiv:2412.10832]



Sensitivity to Axion Dark Matter with $C_N(\partial_\mu a)\bar{N}\gamma^\mu\gamma^5 N/2f_a$ Coupling

ν_n/ν_{Hg} constraints (PSI): [nEDM collaboration, *PRX* **7**, 041034 (2017)]
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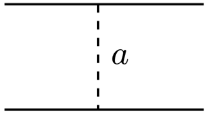
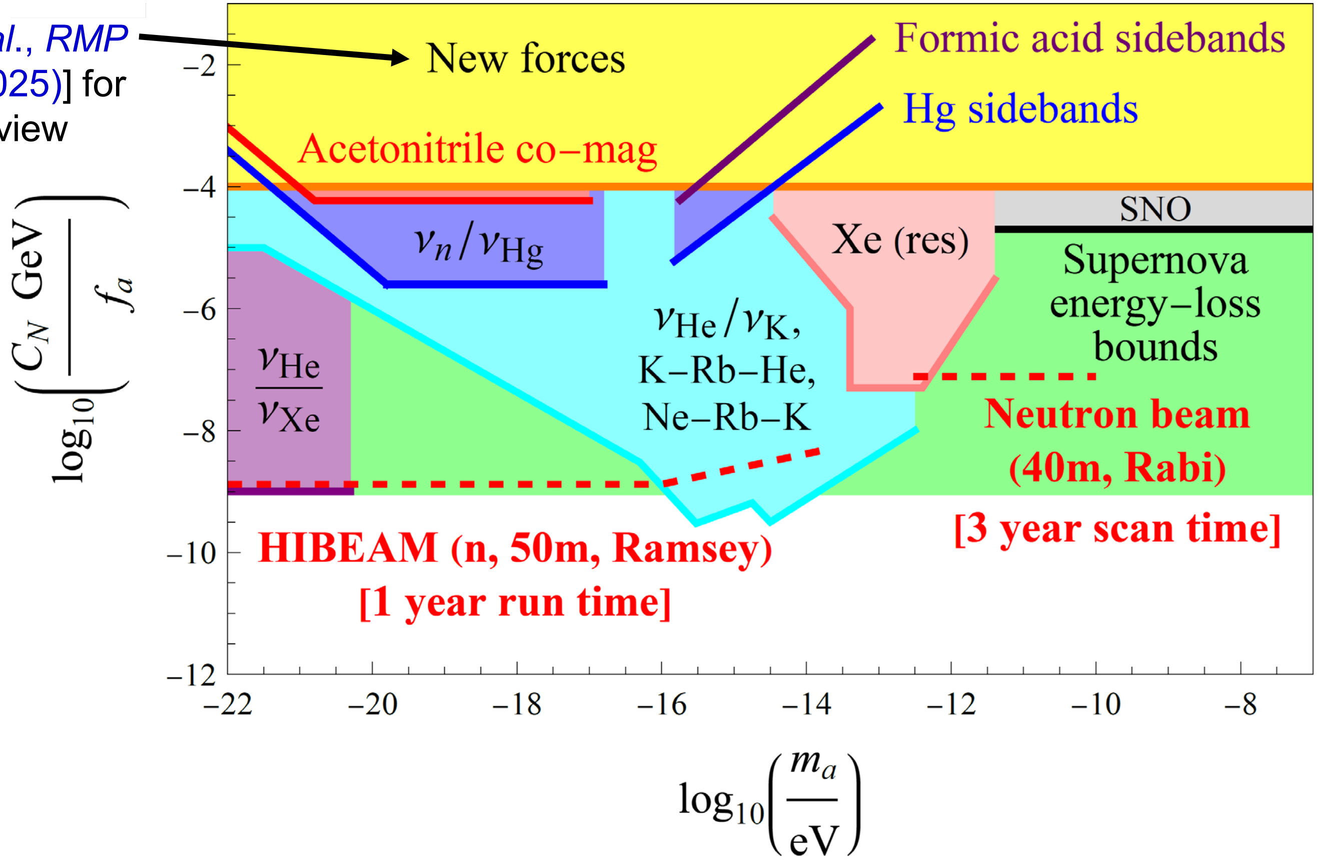
See [Cong *et al*., *RMP* **97**, 025005 (2025)] for a recent review





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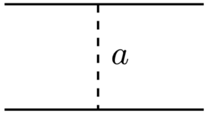

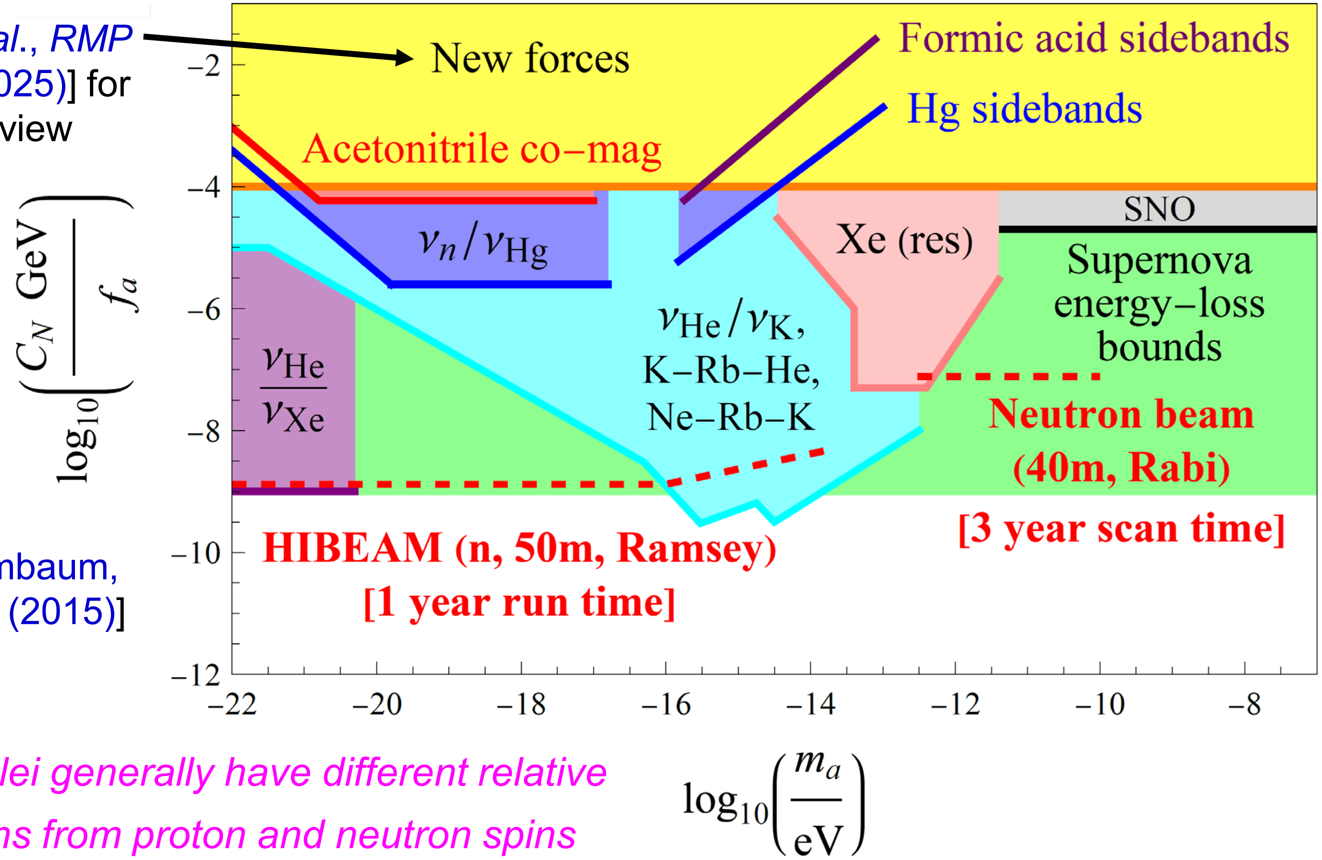

[Stadnik, Flambaum, *EPJC* **75**, 110 (2015)]

Different nuclei generally have different relative contributions from proton and neutron spins

Low-mass Spin-0 Dark Matter

Dark Matter

Scalars (Dilatons):

$$\varphi^n \xrightarrow{P} \varphi^n, n = 1,2$$

Spatio-temporal variations of “constants”

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

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)]

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

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$$\mathcal{L}_f = -\frac{\varphi}{\Lambda_f}m_f\bar{f}f \approx -\frac{\varphi_0\cos(m_\varphi t)}{\Lambda_f}m_f\bar{f}f \quad\Rightarrow\quad \frac{\delta m_f}{m_f} \approx \frac{\varphi_0\cos(m_\varphi t)}{\Lambda_f}$$

Dark-Matter-Induced Variations of the Fundamental Constants

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

φ^2 interactions also exhibit the same oscillating-in-time signatures as above (except at frequency $2m_\varphi$), as well as …

* φ^2 interactions may arise in models with a Z_2 symmetry ($\varphi \to -\varphi$)

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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Dark-Matter-Induced Variations of the Fundamental Constants

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

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

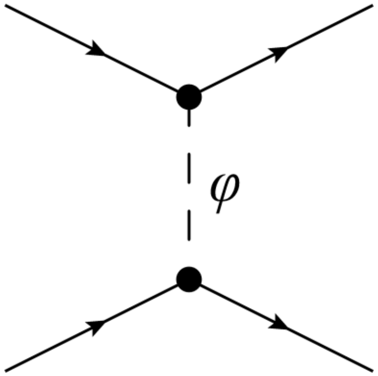
Fifth Forces: Linear vs Quadratic Couplings

[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

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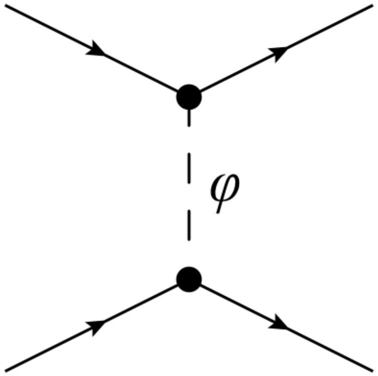


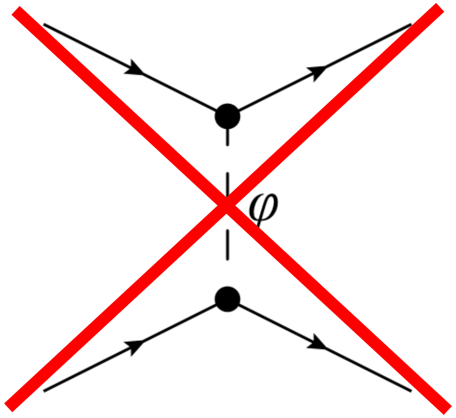
$$\varphi = \varphi_0\cos(m_\varphi t) \pm A\frac{e^{-m_\varphi r}}{r}$$

↑

Profile outside of a spherical body

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

$\Box\varphi + m_\varphi^2\varphi = \pm\kappa'\rho\varphi$ **Effective mass**



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

Fifth Forces: Linear vs Quadratic Couplings

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

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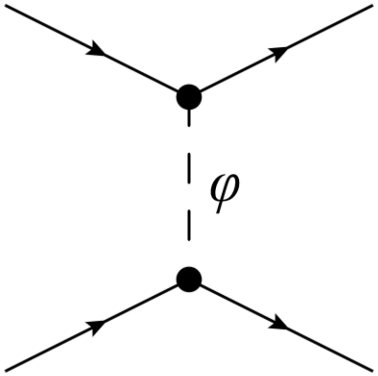

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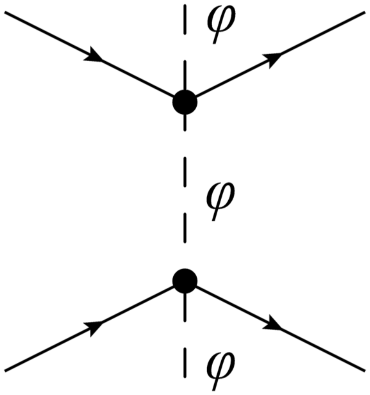
Effective mass



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

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

Force range:
$\lambda_{\mathrm{coh}} \gg \lambda_{\mathrm{Comp}}$

Profile outside of a spherical body

Gradients + amplification/screening

Fifth Forces: Linear vs Quadratic Couplings

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

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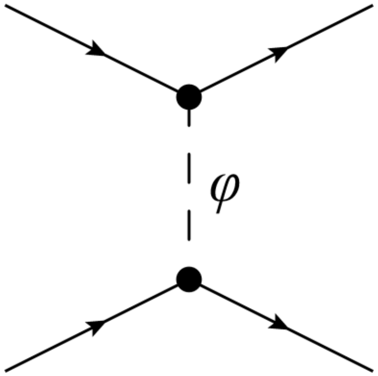

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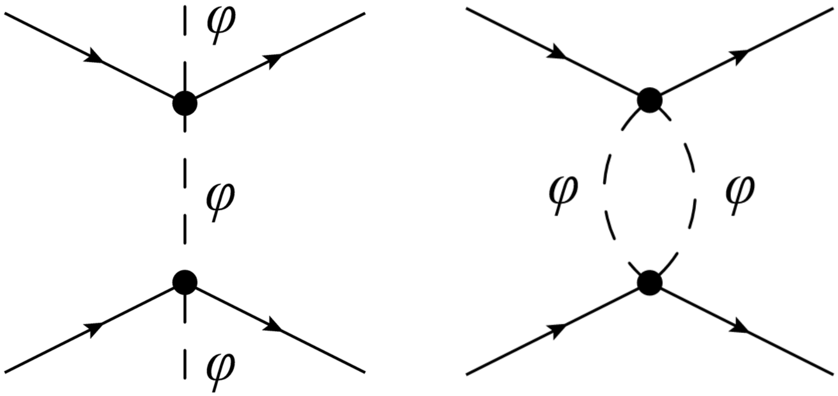
Effective mass



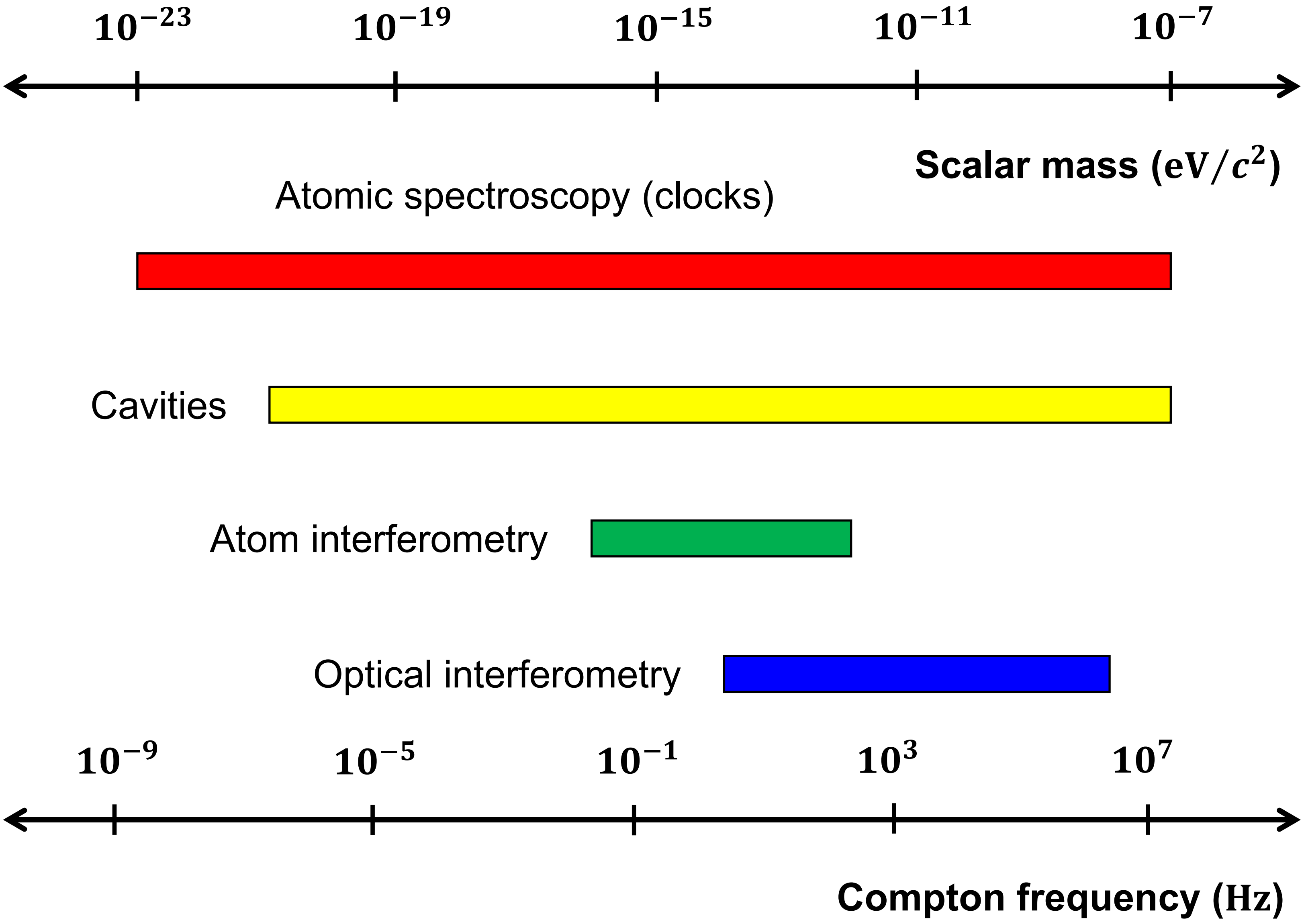
$$\varphi = \varphi_0 \cos(m_\varphi t) \pm A \frac{e^{-m_\varphi r}}{r}$$

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

Profile outside of a spherical body

Gradients + amplification/screening

Probes of Oscillating Fundamental Constants



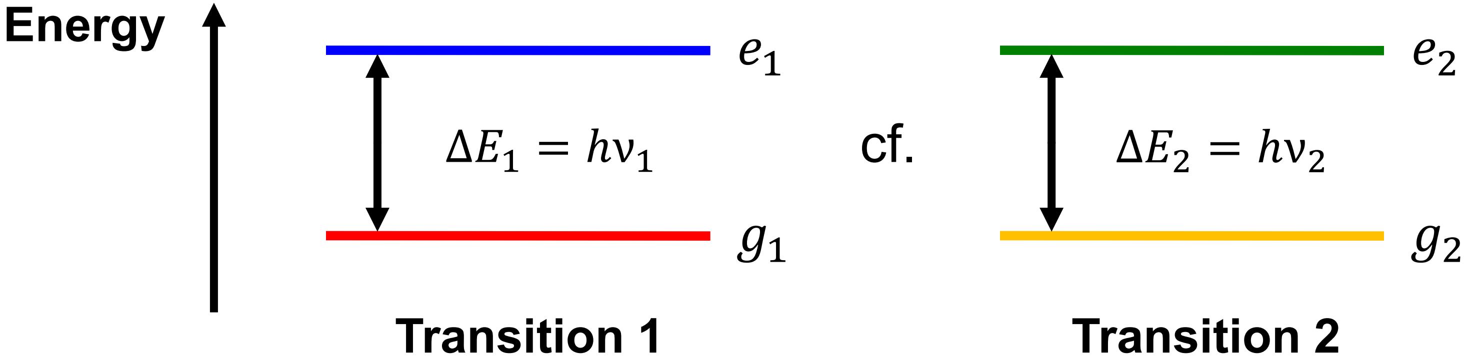
Atomic spectroscopy (clocks)

Cavities

Atom interferometry

Optical interferometry

Atomic Spectroscopy Searches for Variations of Fundamental Constants



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

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

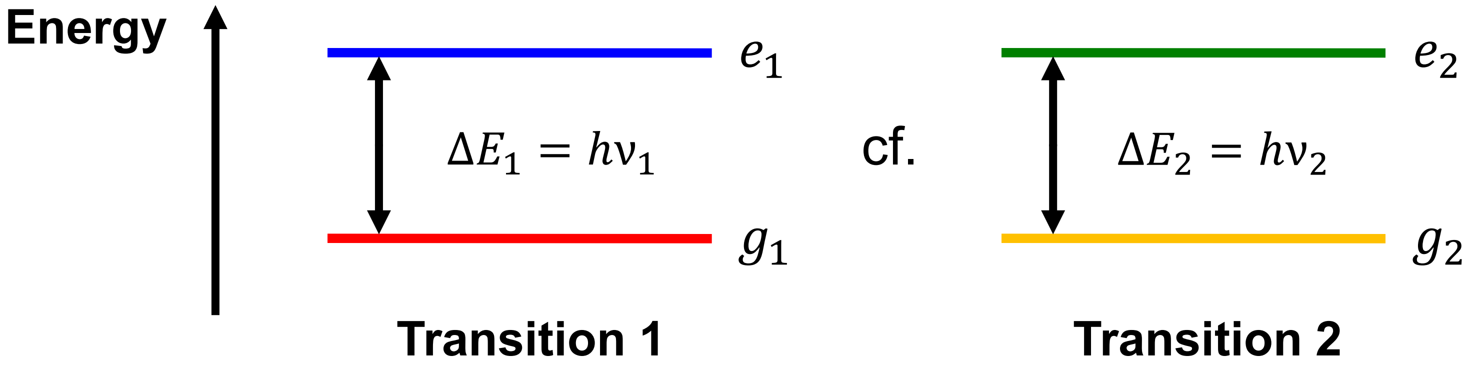
Recent overview: [Ludlow, Boyd, Ye, Peik, Schmidt, *Rev. Mod. Phys.* **87**, 637 (2015)]

“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)]

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)]



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

- **^{162}Dy/^{164}Dy [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.*, *PRL* **130**, 253001 (2023)]
- **Yb$^+$(E3)/Sr, Sr/Cs [NPL]:** [Sherrill *et al.*, *New J. Phys.* **25**, 093012 (2023)]
- **Muonium and muonic atoms (proposal):** [Stadnik, *PRL* **131**, 011001 (2023)]

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

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

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

(slow variations)

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

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

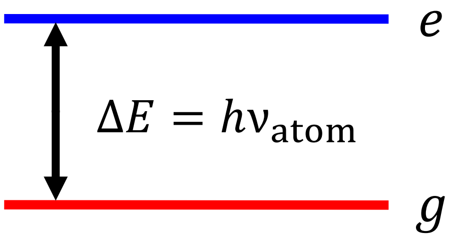
Solid material

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

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

cf.

Electronic transition



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

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

- **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); *PRL* **129**, 031301 (2022)]
- **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

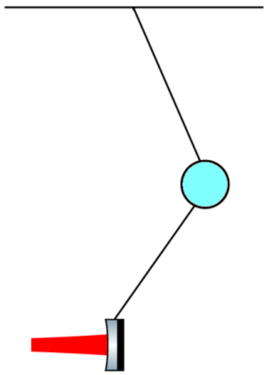
[Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRA* **93**, 063630 (2016)]

Solid material

cf.

Freely-suspended mirrors

Double-pendulum suspensions



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

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

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

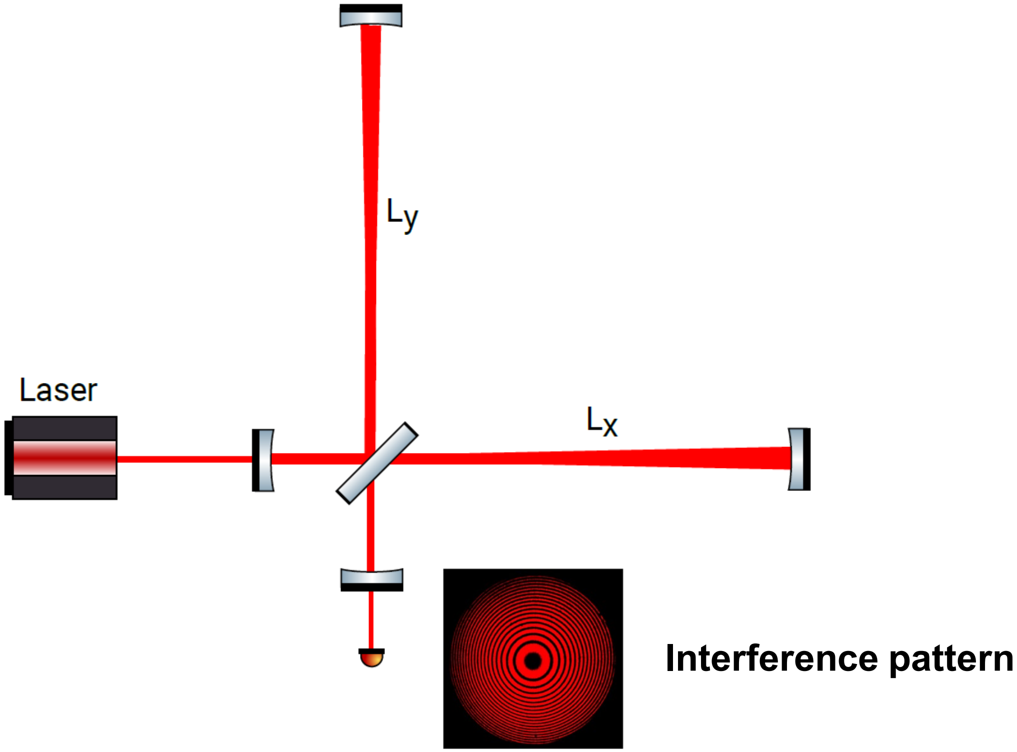
$$\Rightarrow \ \nu_{\mathrm{free}} \approx \mathrm{constant}$$

$$\boxed{\frac{\nu_{\mathrm{solid}}}{\nu_{\mathrm{free}}} \propto m_e \alpha} \quad \mathrm{cf.} \quad \frac{\nu_{\mathrm{atom}}}{\nu_{\mathrm{solid}}} \propto \alpha$$

First results from small-scale experiment at Northwestern University based on a similar idea have recently been reported: [Deshpande *et al.*, *PRL* **135**, 261001 (2025)]

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

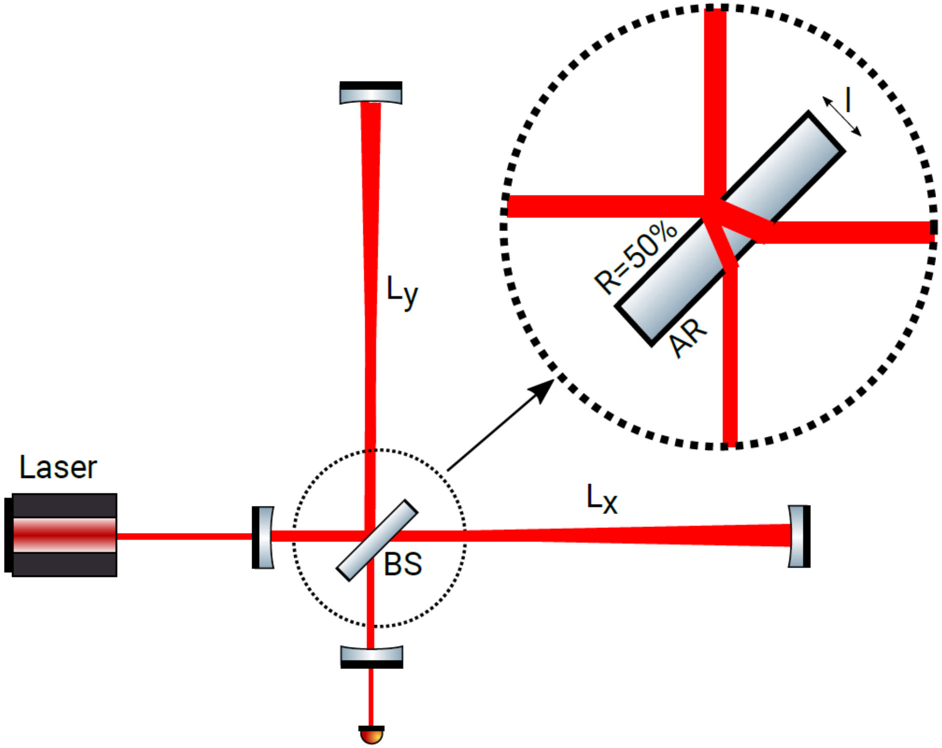
[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]



Michelson interferometer (e.g., GEO600)

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

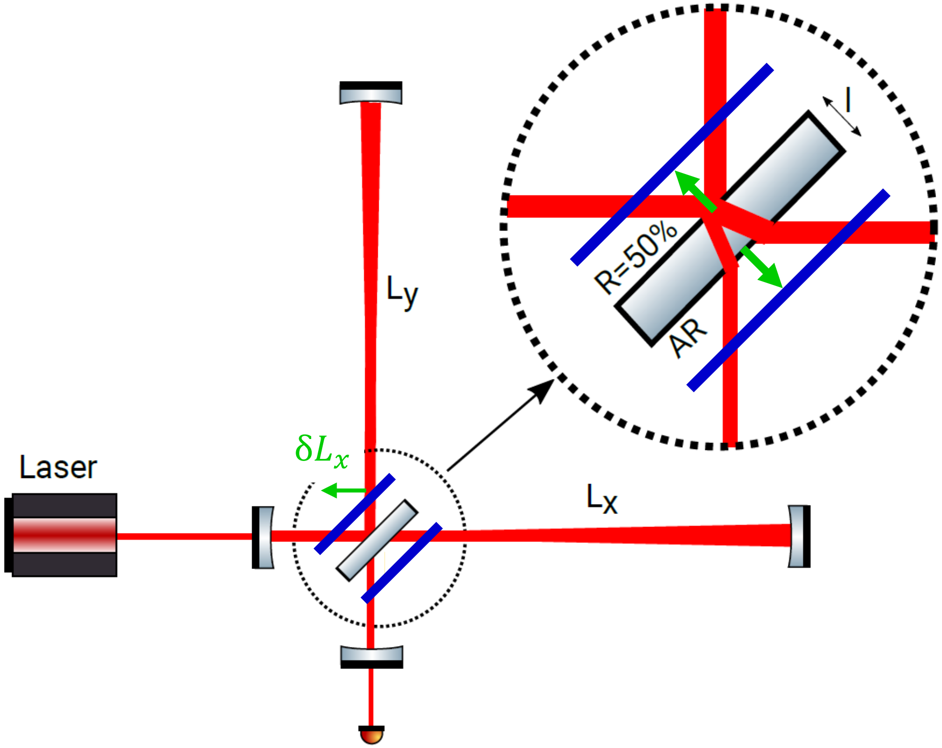
[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]



- Geometric asymmetry from beam-splitter

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

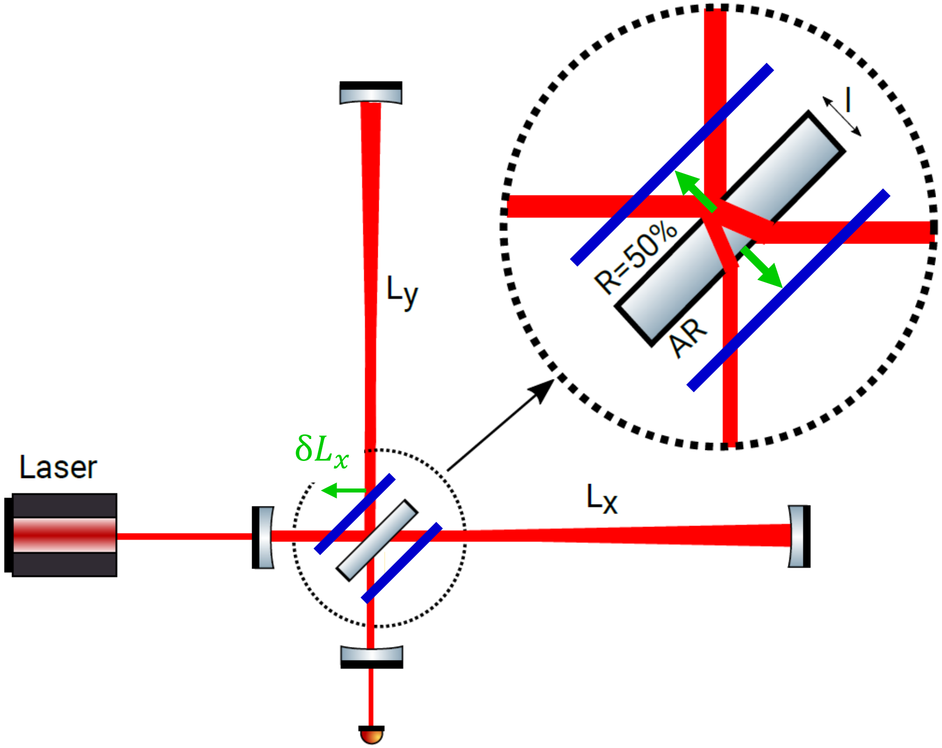
[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]



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

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: $\boxed{\delta(L_x - L_y) \sim \delta(nl)}$

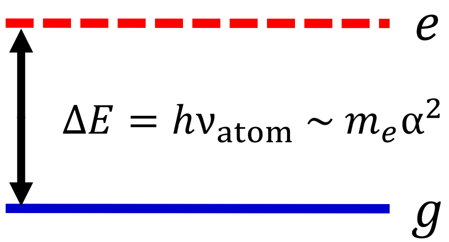
First search results reported using GEO600 and Fermilab holometer data:
[Vermeulen *et al.*, *Nature* **600**, 424 (2021)], [Aiello *et al.*, *PRL* **128**, 121101 (2022)]

More recent search using LIGO (O3) data: [Göttel *et al.*, *PRL* **133**, 101001 (2024)]

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

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

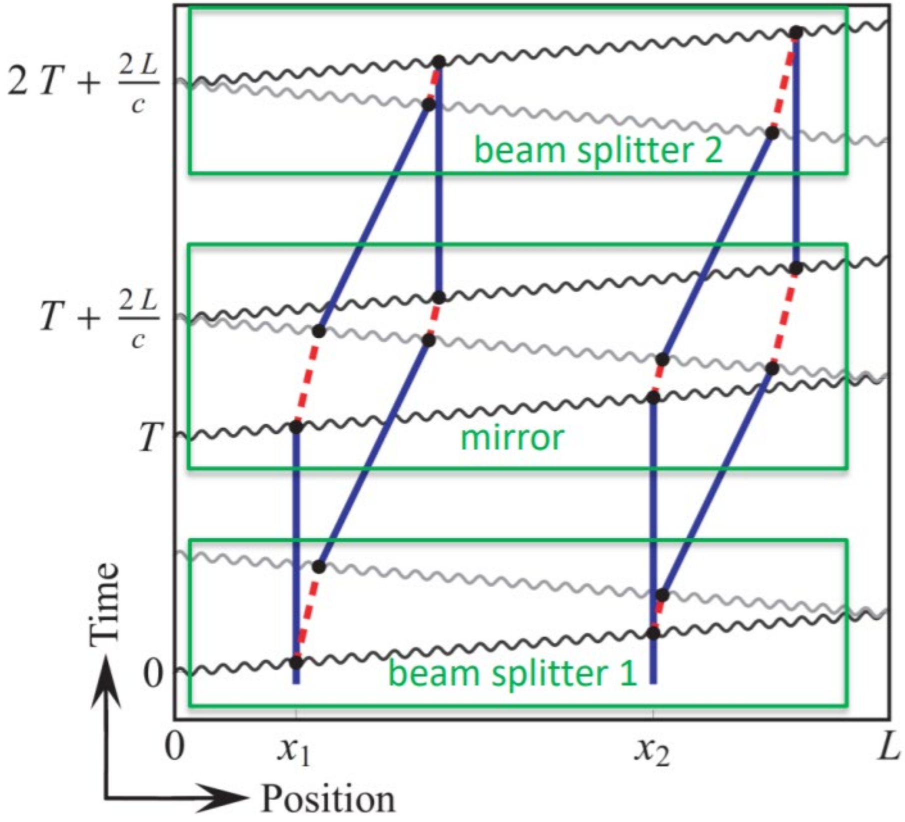
Electronic transition



$$\Delta E = h\nu_{\text{atom}} \sim m_e \alpha^2$$

When $T_{\text{osc}} \sim 2T$:

$$\delta(\Delta\Phi)_{\max} \sim T_{\text{osc}}\,\delta\nu_{\text{atom}}$$

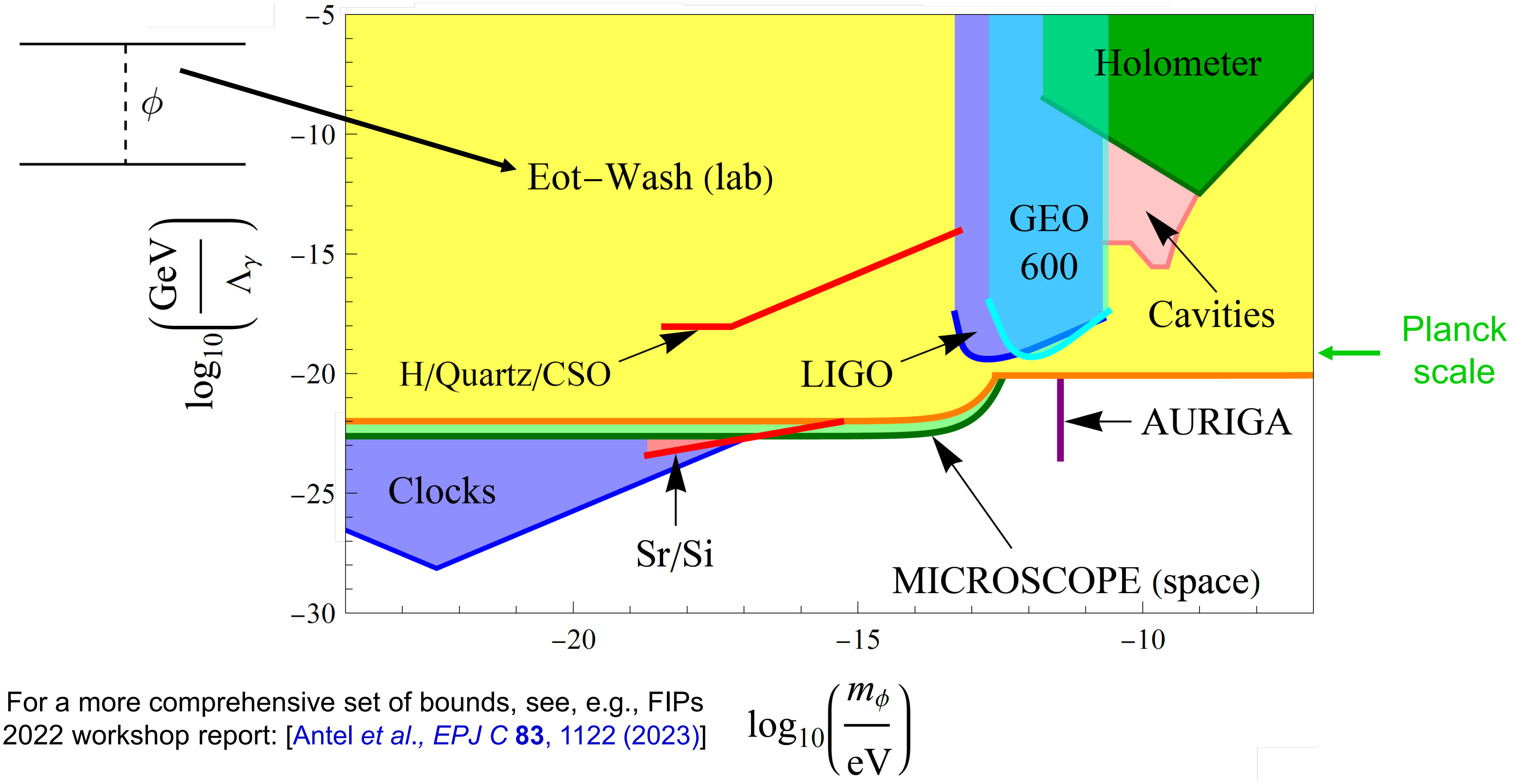


AION-10 experiment under construction at Oxford: [Badurina *et al.*, *JCAP* **05** (2020) 011]

MAGIS-100 experiment under construction at Fermilab: [Abe *et al.*, *QST* **6**, 044003 (2021)]

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

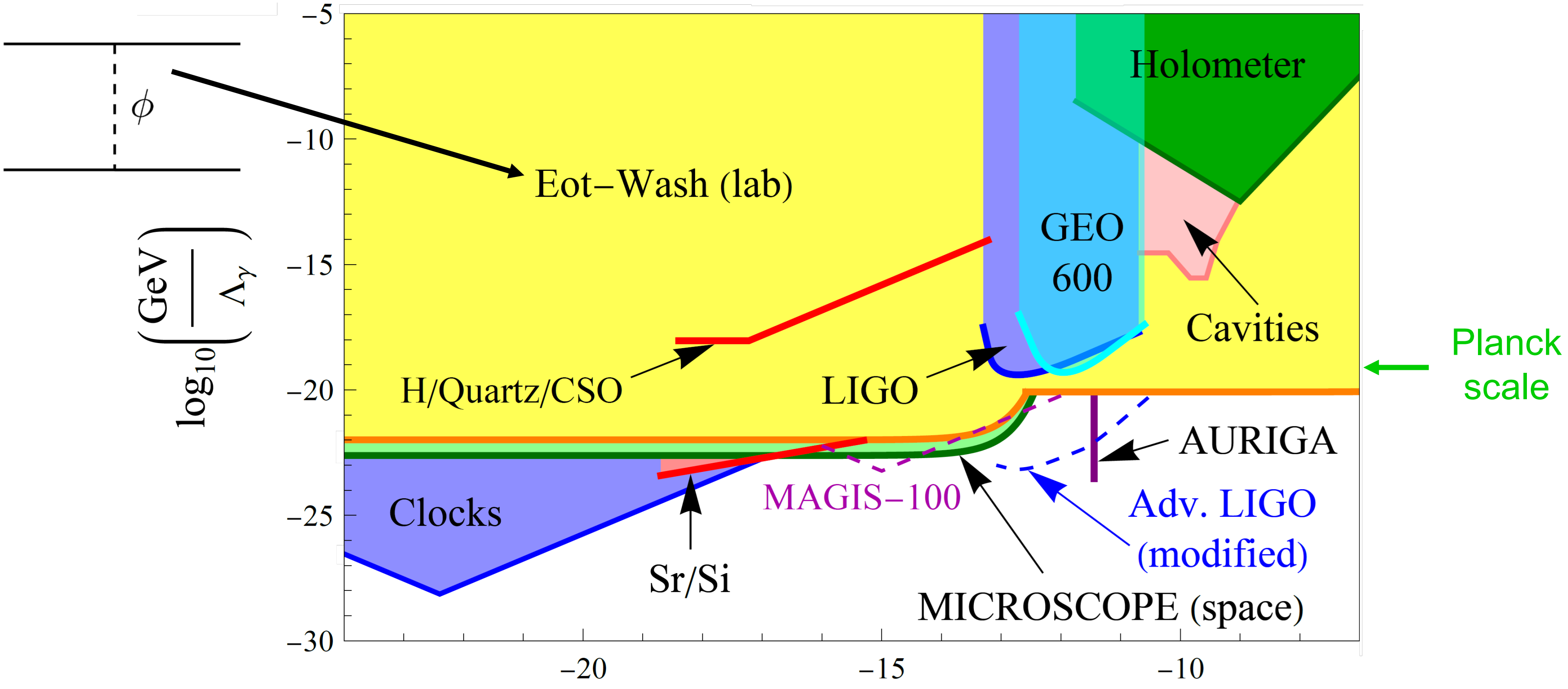
Clock comparisons: [*PRL* **115**, 011802 (2015)], [*PRL* **117**, 061301 (2016)], [*Nature* **591**, 564 (2021)], [*PRL* **130**, 253001 (2023)]; **Sr/Si:** [*PRL* **125**, 201302 (2020)]; **H/Quartz/CSO:** [*PRL* **126**, 071301 (2021)]; **GEO600:** [*Nature* **600**, 424 (2021)]; **LIGO:** [*PRL* **133**, 101001 (2024)]; **AURIGA:** [*PRL* **118**, 021302 (2017)]; **Cavities:** [*PRL* **126**, 051301 (2021)], [*PRL* **135**, 261001 (2025)]; **Fermilab holometer:** [*PRL* **128**, 121101 (2022)]



For a more comprehensive set of bounds, see, e.g., FIPs 2022 workshop report: [Antel *et al.*, *EPJ C* **83**, 1122 (2023)]

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

Clock comparisons: [*PRL* **115**, 011802 (2015)], [*PRL* **117**, 061301 (2016)], [*Nature* **591**, 564 (2021)], [*PRL* **130**, 253001 (2023)]; **Sr/Si:** [*PRL* **125**, 201302 (2020)]; **H/Quartz/CSO:** [*PRL* **126**, 071301 (2021)]; **GEO600:** [*Nature* **600**, 424 (2021)]; **LIGO:** [*PRL* **133**, 101001 (2024)]; **AURIGA:** [*PRL* **118**, 021302 (2017)]; **Cavities:** [*PRL* **126**, 051301 (2021)], [*PRL* **135**, 261001 (2025)]; **Fermilab holometer:** [*PRL* **128**, 121101 (2022)]

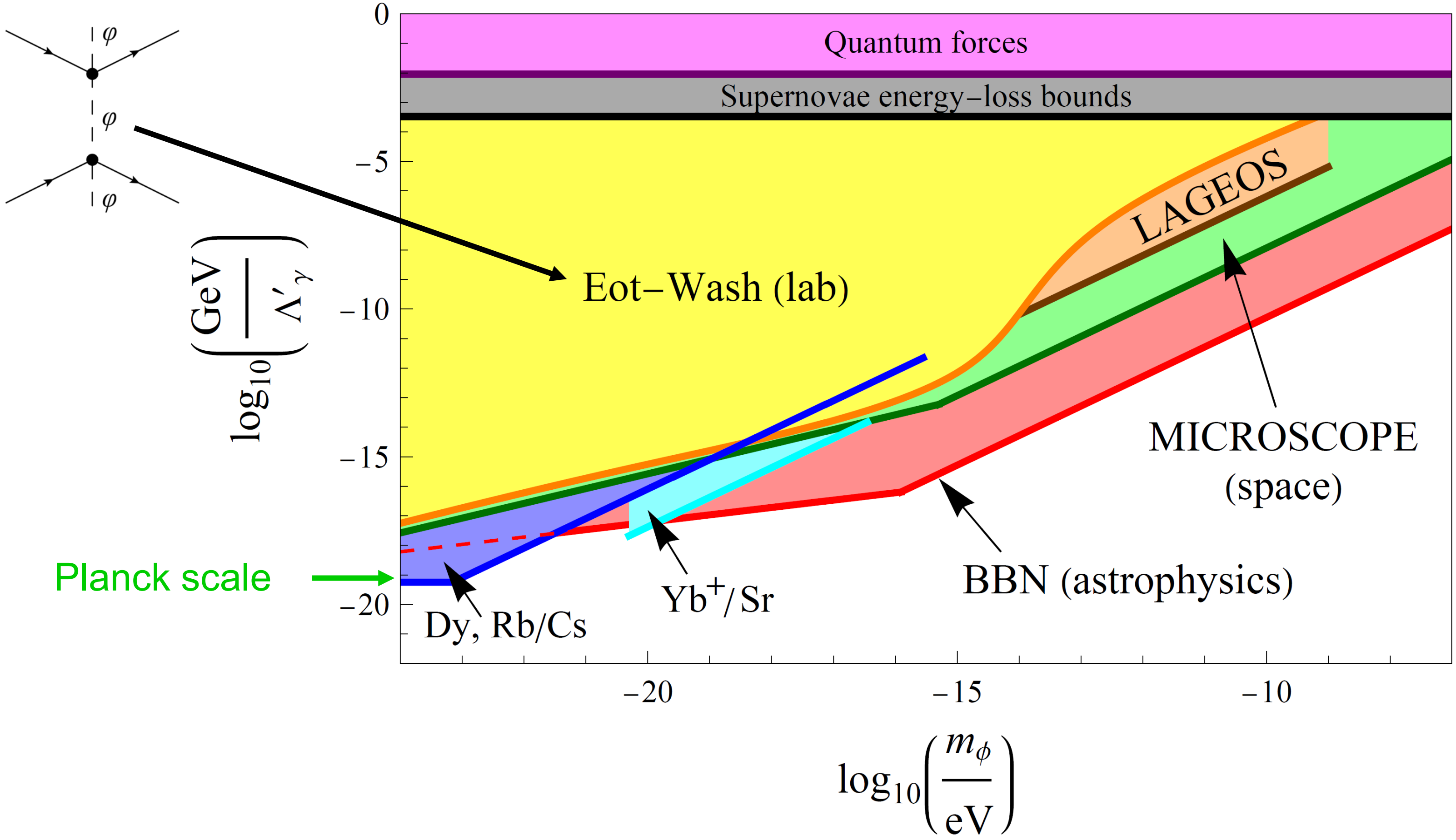


For a more comprehensive set of bounds, see, e.g., FIPs 2022 workshop report: [Antel *et al.*, *EPJ C* **83**, 1122 (2023)]

$\log_{10}\left(\frac{m_\phi}{\text{eV}}\right)$

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

^{162}Dy/^{164}Dy, Rb/Cs: [Stadnik, Flambaum, *PRL* **115**, 201301 (2015); *PRA* **94**, 022111 (2016)]
BBN: [Stadnik, Flambaum, *PRL* **115**, 201301 (2015)], [Bouley, Sorensen, Yu, *JHEP* **03** (2023) 104]
MICROSCOPE + Eöt-Wash: [Hees *et al.*, *PRD* **98**, 064051 (2018)]
Yb$^+$(E3)/Sr: [Sherrill *et al.*, *New J. Phys.* **25**, 093012 (2023)]; **LAGEOS:** [Burrage *et al.*, arXiv:2605.28248]



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

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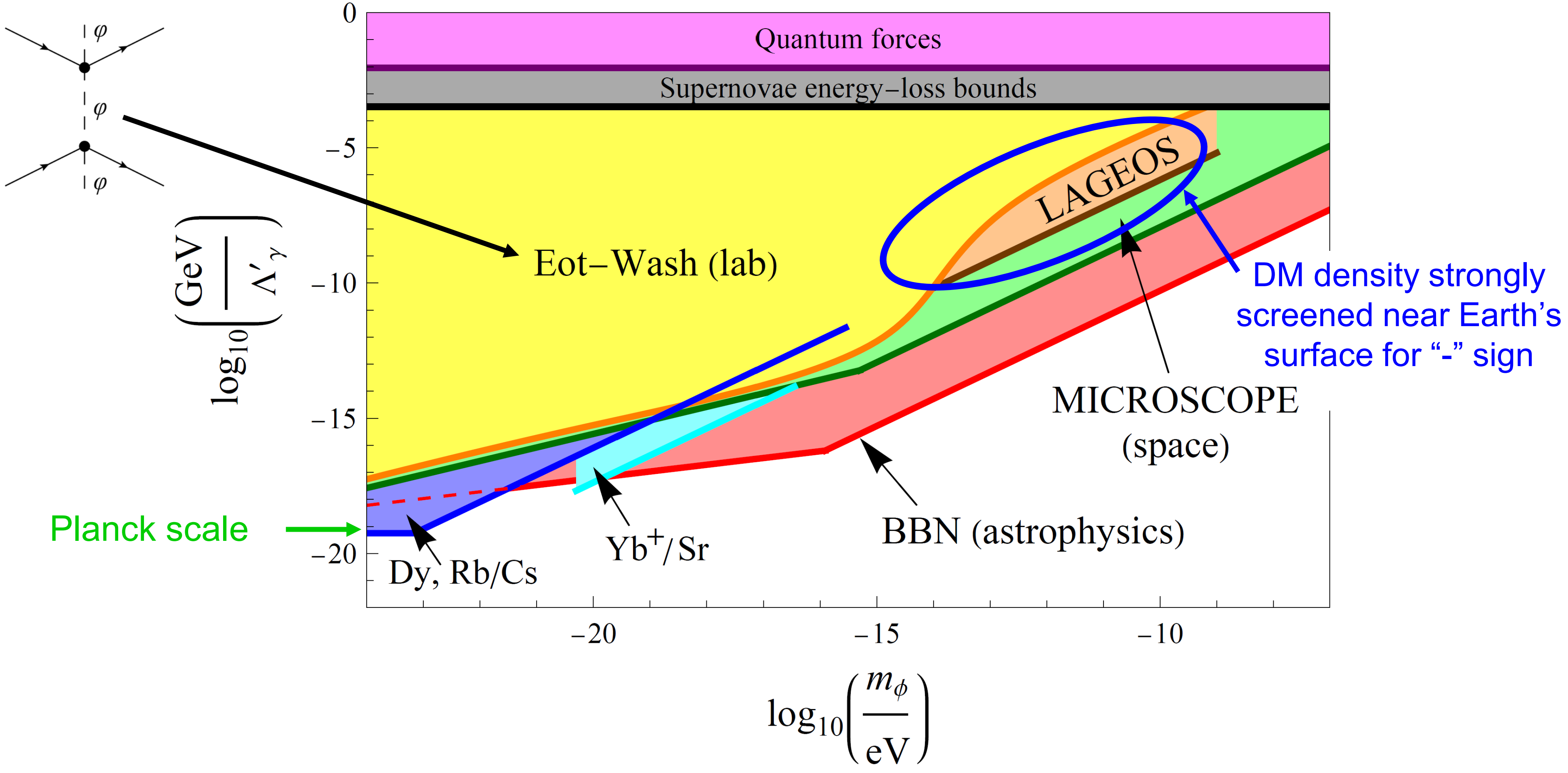


Planck scale

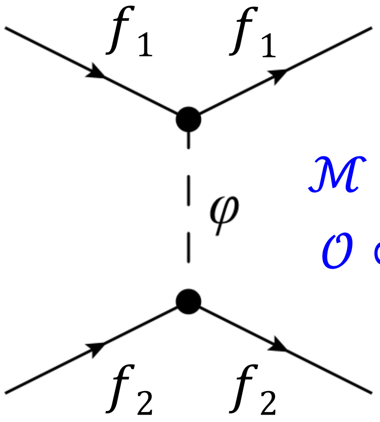
DM density strongly screened near Earth's surface for "-" sign

Summary

- Precision atomic and optical experiments provide sensitive probes of ultra-low-mass bosonic dark matter:
  - Atomic spectroscopy (clocks, exotic atoms) [Scalars]
  - Optical cavities and interferometry [Scalars, Vectors]
  - Magnetometry and *g*-factors [Pseudoscalars, Vectors]
  - Torsion pendula [Scalars, Pseudoscalars, Vectors]
- Demonstrated improved sensitivity to underlying interaction strengths by up to **15 orders of magnitude**
- Effects of screening (or anti-screening) can be important in certain models of dark matter (e.g., with φ^2 couplings)

Back-Up Slides

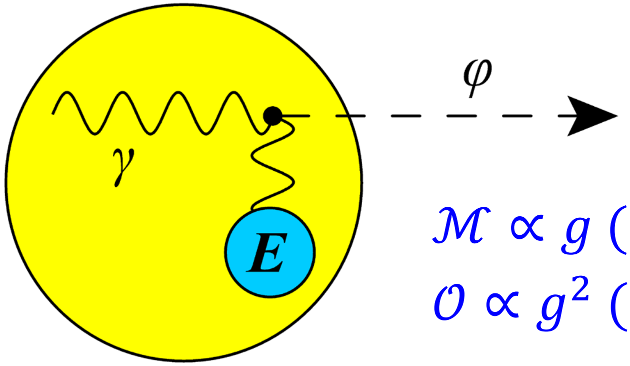
Complementary Probes of Low-mass Scalars



$\mathcal{M} \propto g^2$

$\mathcal{O} \propto g^2$

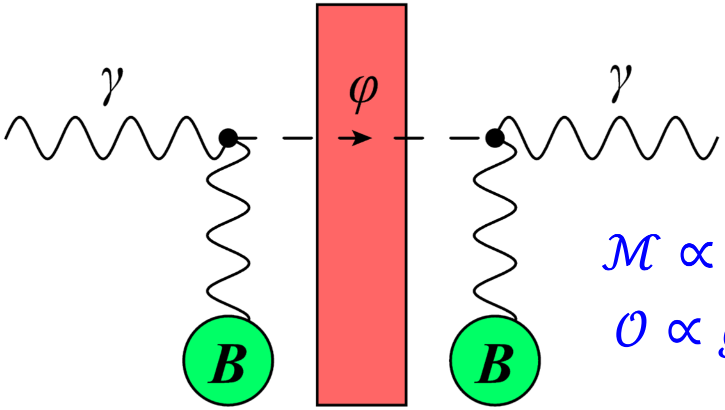
New forces



$\mathcal{M} \propto g$ (or g^2)

$\mathcal{O} \propto g^2$ (or g^4)

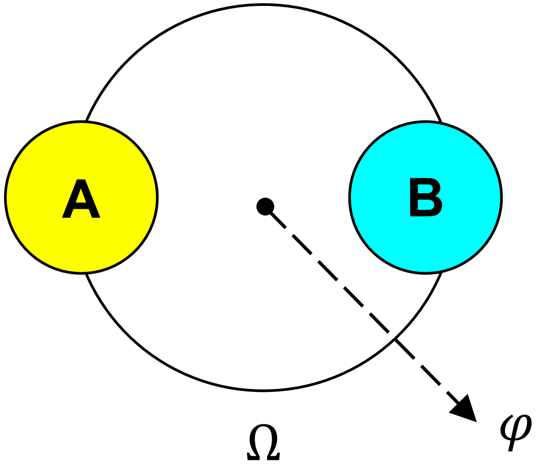
Stellar emission



$\mathcal{M} \propto g^2$

$\mathcal{O} \propto g^4$

Interconversion with ordinary particles

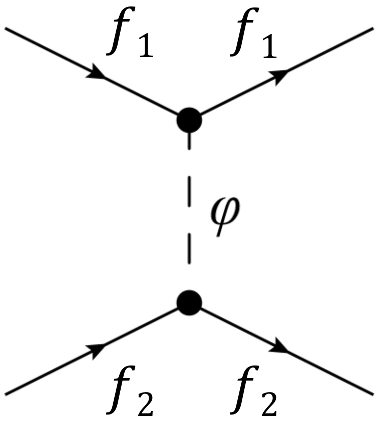


$\mathcal{M} \propto g$

$\mathcal{O} \propto g^2$

Larmor radiation

Equivalence-Principle-Violating Forces



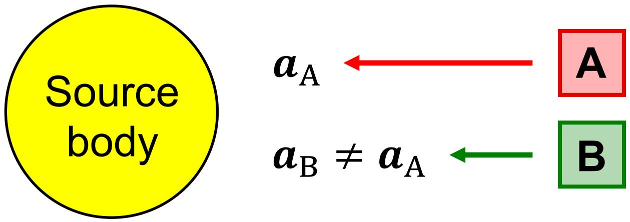
$$\mathcal{L}_f = -\frac{\varphi}{\Lambda_f} m_f \bar{f} f$$

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

- Different mass-energy components of an atom generally scale differently with proton number Z and atomic number $A = Z + N$:

$$M_{\mathrm{atom}} \approx (A - Z)m_n + Zm_p + Zm_e + 100Z(Z-1)\alpha/A^{1/3}\ \mathrm{MeV} + \cdots$$

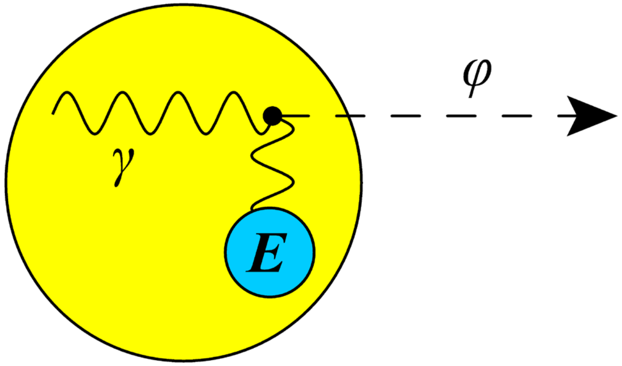
- Different atoms and isotopes would generally experience different accelerations, implying violation of the equivalence principle



Eötvös ratio: $\eta_{\mathrm{AB}} = 2\frac{|\boldsymbol{a}_{\mathrm{A}} - \boldsymbol{a}_{\mathrm{B}}|}{|\boldsymbol{a}_{\mathrm{A}} + \boldsymbol{a}_{\mathrm{B}}|}$

Astrophysical Emission (Hot Media)

[Raffelt, *Phys. Rept.* **198**, 1 (1990)]

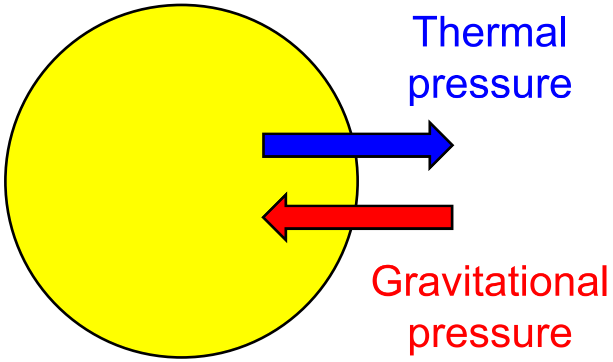


Primakoff-type conversion

$$\mathcal{L}_\gamma = \frac{\varphi}{\Lambda_\gamma}\frac{F_{\mu\nu}F^{\mu\nu}}{4} \quad \Rightarrow \quad \varepsilon_{\gamma\gamma\to\varphi} \sim \frac{T^7}{\Lambda_\gamma^2}$$

Emission possible for $m_\varphi \lesssim \mathcal{O}(T)$

Excessive energy loss via additional channels would contradict stellar models and observations



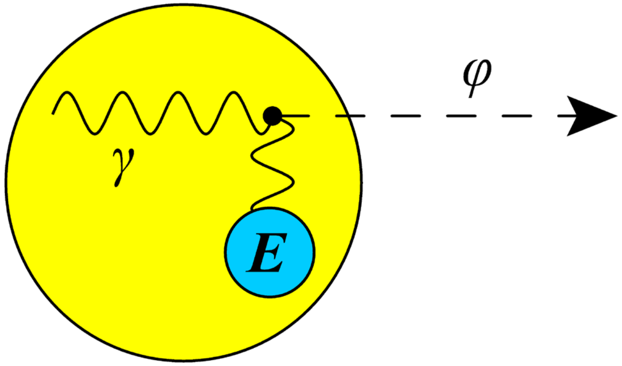
Increased heating in active stars (e.g., Sun and main sequence stars, HB stars, red giants)

$$\langle E_{\text{mech}}\rangle = \langle E_{\text{kin}}\rangle + \langle E_{\text{grav}}\rangle = \langle E_{\text{grav}}\rangle/2 < 0$$

$$\langle E_{\text{mech}}\rangle \downarrow \;\Rightarrow\; -\langle E_{\text{grav}}\rangle/2 = \langle E_{\text{kin}}\rangle \uparrow$$

Astrophysical Emission (Hot Media)

[Raffelt, *Phys. Rept.* **198**, 1 (1990)]

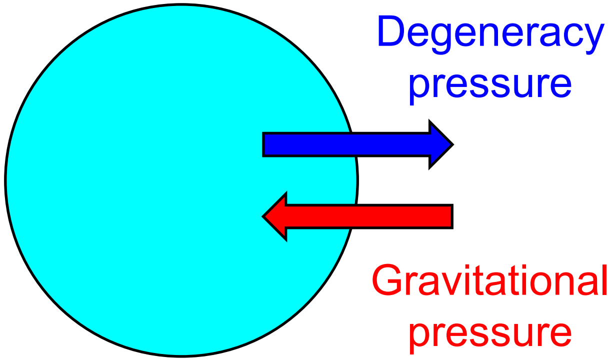


Primakoff-type conversion

$$\mathcal{L}_\gamma = \frac{\varphi}{\Lambda_\gamma} \frac{F_{\mu\nu}F^{\mu\nu}}{4} \Rightarrow \varepsilon_{\gamma\gamma\to\varphi} \sim \frac{T^7}{\Lambda_\gamma^2}$$

Emission possible for $m_\varphi \lesssim \mathcal{O}(T)$

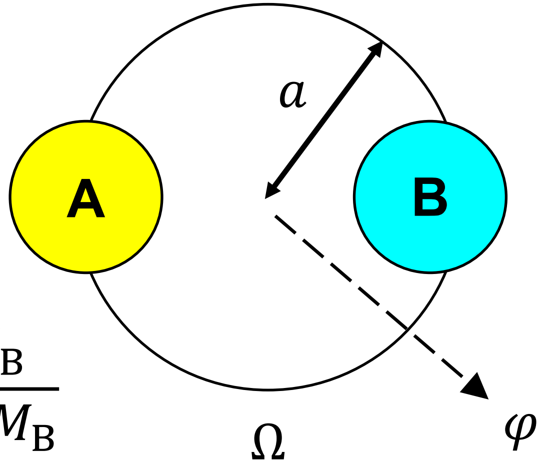
Excessive energy loss via additional channels would contradict stellar models and observations



Increased cooling in dead stars
(e.g., white dwarves, neutron stars)

Astrophysical Emission (Compact Binaries)

[Kumar Poddar *et al.*, *PRD* **100**, 123923 (2019)], [Dror *et al.*, *PRD* **102**, 023005 (2020)]



$$M = \frac{M_{\mathrm{A}} M_{\mathrm{B}}}{M_{\mathrm{A}} + M_{\mathrm{B}}}$$

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

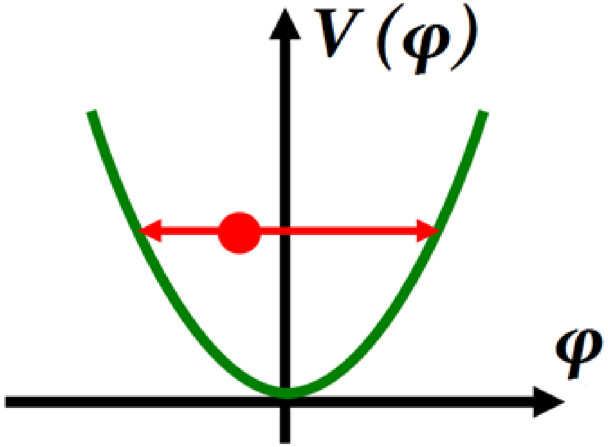
- Scalar Larmor radiation possible if $m_\varphi < \Omega$ (higher-order modes also possible for an elliptical orbit if $m_\varphi < n\Omega$, $n = 2, 3, \ldots$):

$$\frac{dE_\varphi}{dt} \sim \left(\frac{m_f}{\Lambda_f}\right)^2 (aM)^2 \Omega^4 \left(\frac{Q_{\mathrm{A}}}{M_{\mathrm{A}}} - \frac{Q_{\mathrm{B}}}{M_{\mathrm{B}}}\right)^2, \text{for } \Omega a \ll 1$$

- Dipole nature requires $Q_{\mathrm{A}}/M_{\mathrm{A}} \neq Q_{\mathrm{B}}/M_{\mathrm{B}}$, which is readily satisfied, e.g., for neutron-star/white-dwarf binary systems in the case of $f = n, e, \mu$

Low-mass Spin-0 Dark Matter

- Low-mass spin-0 particles form a coherently oscillating classical field $\varphi(t) \approx \varphi_0 \cos(m_\varphi c^2 t/\hbar)$, with energy density $\rho_\varphi \approx m_\varphi^2 \varphi_0^2/2$ $(\rho_{\mathrm{DM,local}} \approx 0.4\ \mathrm{GeV/cm^3})$



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

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

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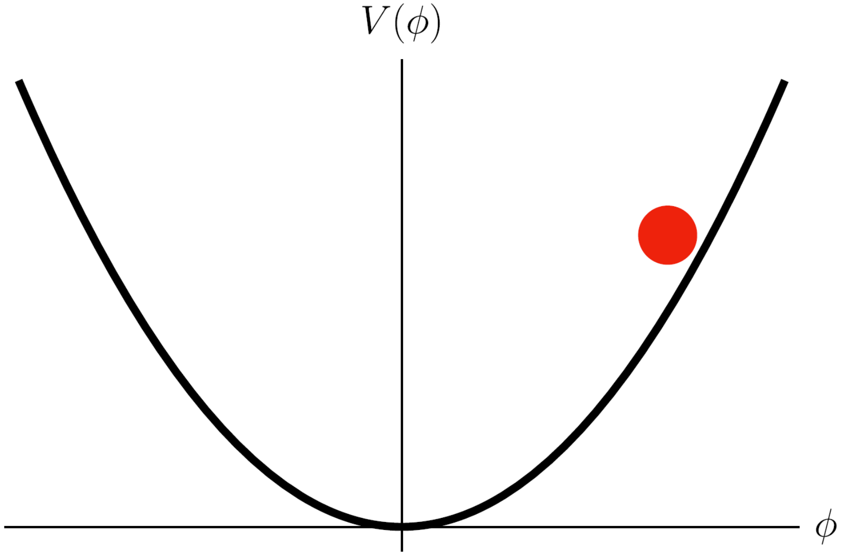

$$\ddot{\varphi} + 3H(t)\dot{\varphi} + m_\varphi^2 \varphi \approx 0 \longleftarrow$$

$$H(t) = \dot{a}(t)/a(t)$$

Damped harmonic oscillator with a time-dependent frictional term

$(H = \text{Hubble parameter},\ a = \text{scale factor})$

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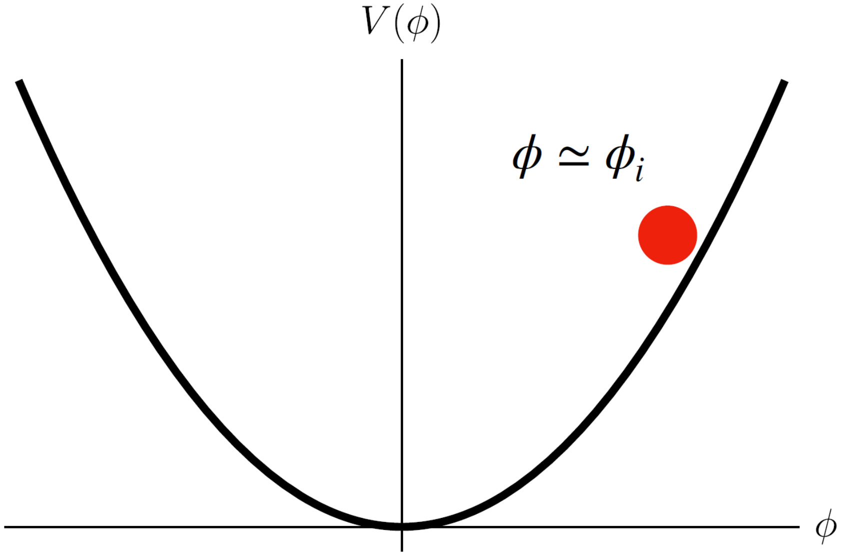
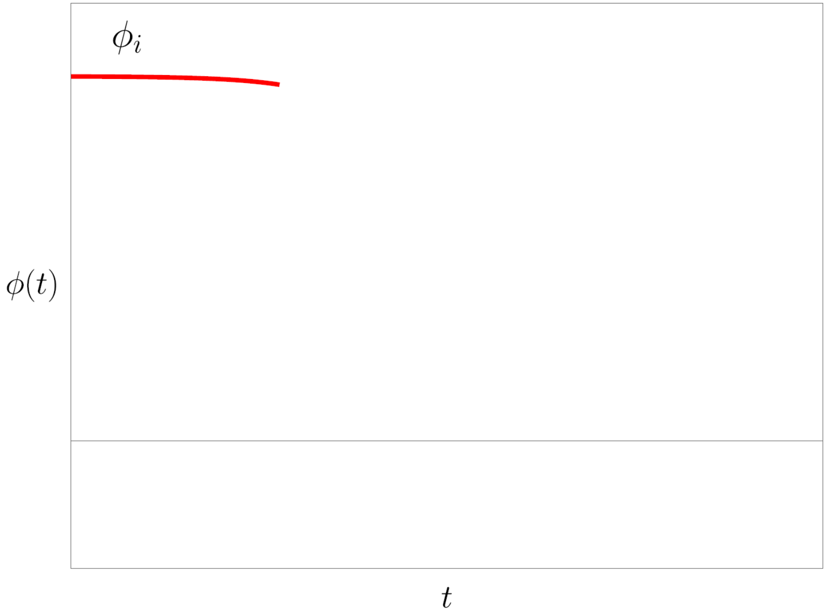


$$\ddot{\varphi} + 3H(t)\dot{\varphi} + m_\varphi^2 \varphi \approx 0$$

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



Overdamped regime

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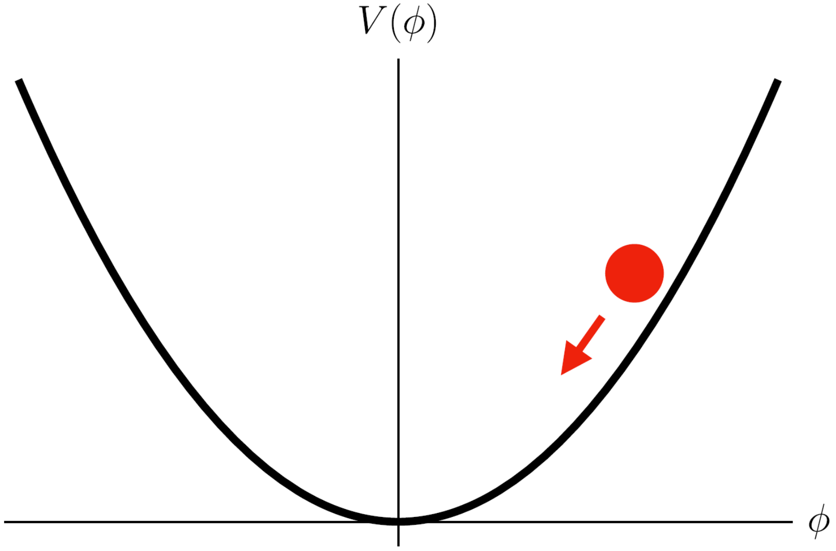
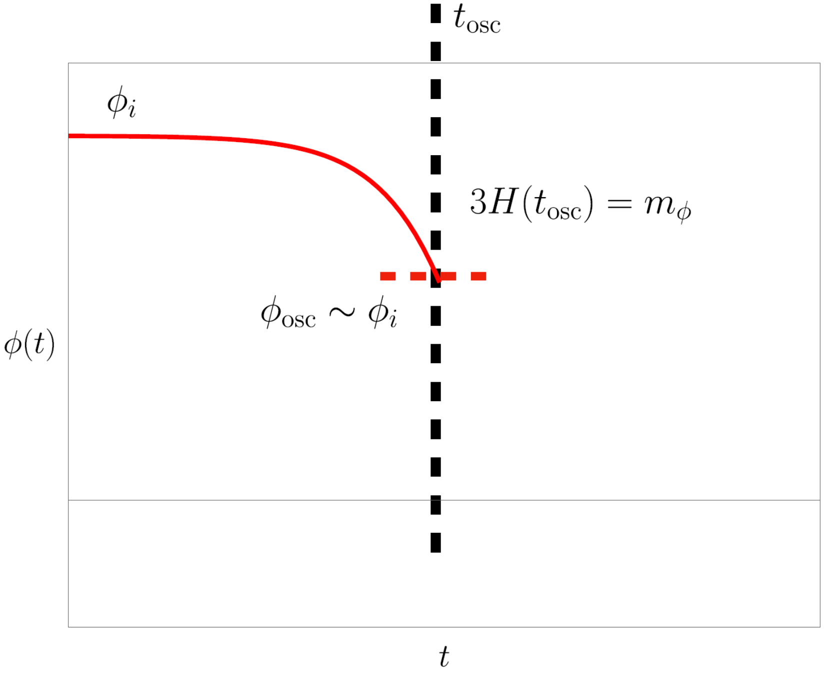


$$\ddot{\varphi} + 3H(t)\dot{\varphi} + m_\varphi^2 \varphi \approx 0$$

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



Critically damped regime

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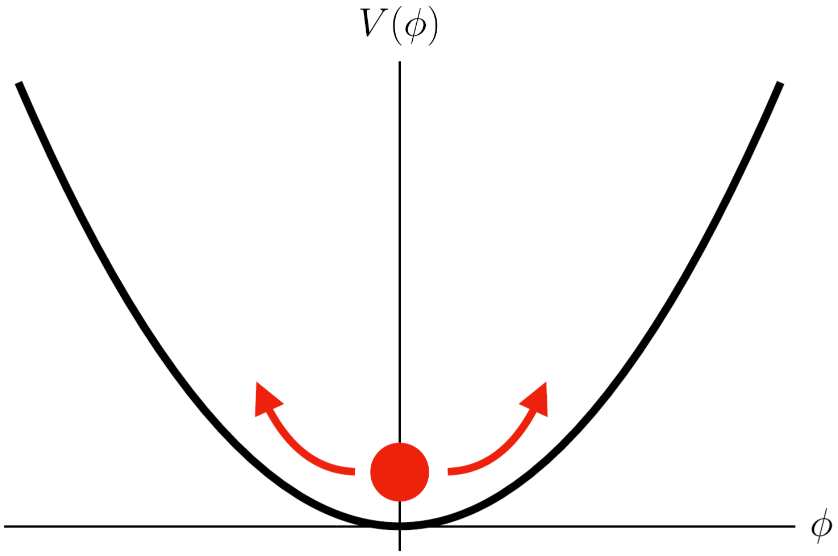
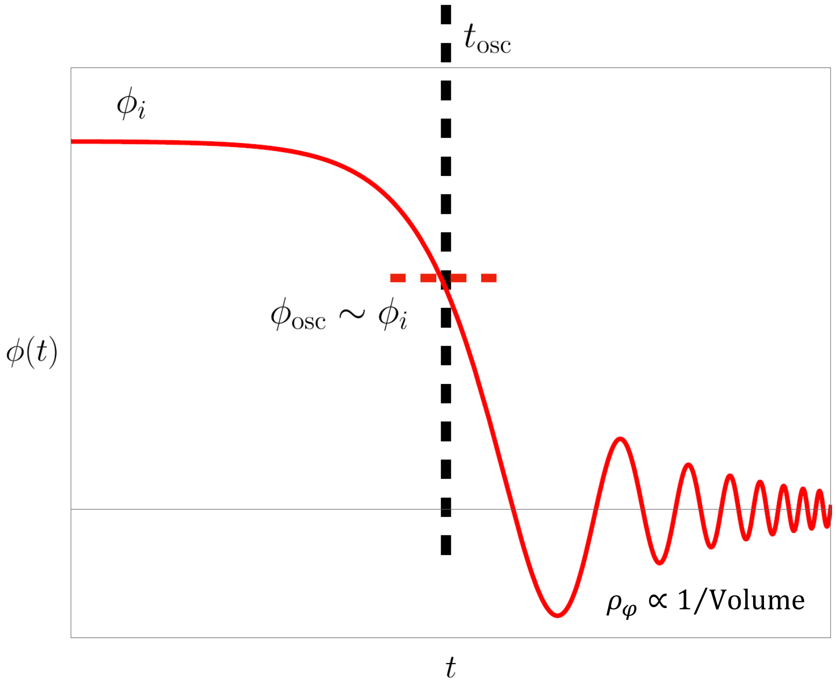


$$\ddot{\varphi} + 3H(t)\dot{\varphi} + m_\varphi^2 \varphi \approx 0$$

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



Underdamped regime

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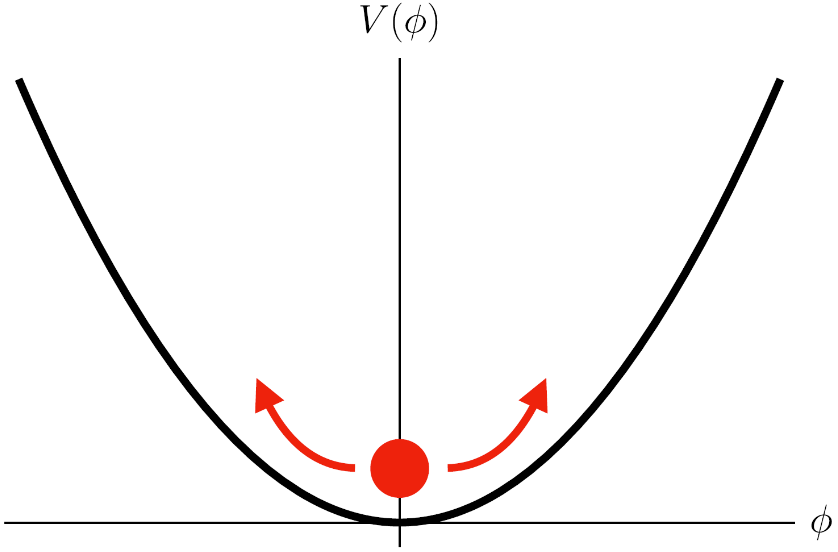

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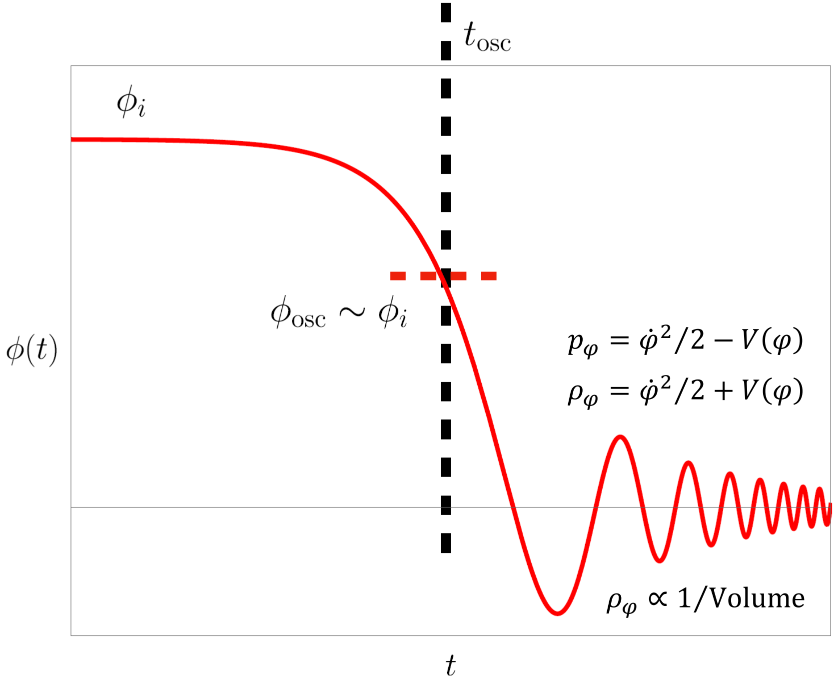

"Vacuum misalignment" mechanism – non-thermal production, ρ_φ governed by initial conditions (φ_i), redshifts as $\rho_\varphi \propto 1/\mathrm{Volume}$, with $\langle p_\varphi \rangle \ll \rho_\varphi$

Low-mass Spin-0 Dark Matter

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- *Coherently* oscillating field, since *cold* $\left(E_\varphi \approx m_\varphi c^2\right)$
- $\Delta E_\varphi / E_\varphi \sim \left\langle v_\varphi^2 \right\rangle / c^2 \underset{\substack{\uparrow \\ v_{\mathrm{DM}} \sim 300\ \mathrm{km/s}}}{\sim} 10^{-6} \quad \Rightarrow \quad \tau_{\mathrm{coh}} \sim 2\pi / \Delta E_\varphi \underset{\substack{\downarrow \\ Q_{\mathrm{DM}} \sim 10^6}}{\sim} 10^6 T_{\mathrm{osc}}$

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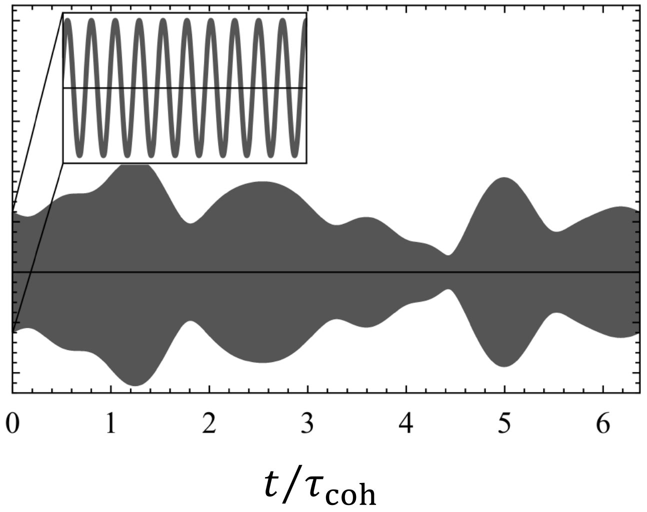
Evolution of φ_0 with time



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

$\boldsymbol{v}_i$ follow quasi-Maxwell-Boltzmann distribution (in the standard halo model)

Low-mass Spin-0 Dark Matter

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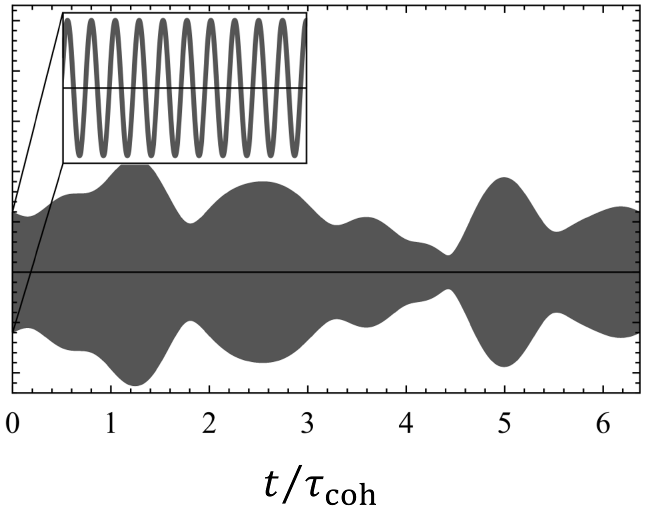
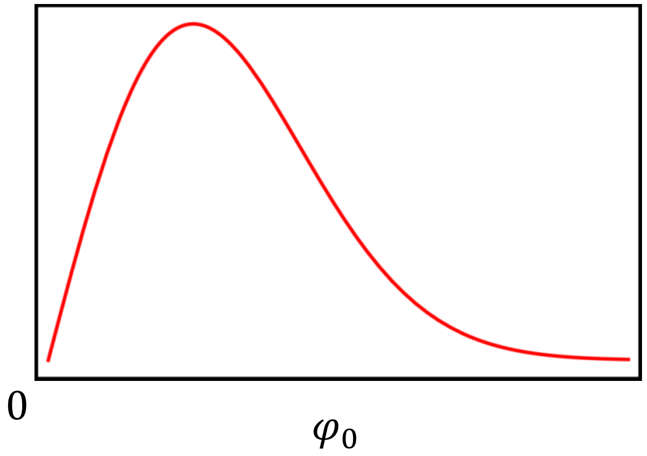


Probability distribution function of φ_0 (Rayleigh distribution)



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

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

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

$\uparrow$

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

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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↑

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

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

Low-mass Spin-0 Dark Matter

Dark Matter

Pseudoscalars (Axions):

$$a \xrightarrow{P} -a$$

QCD axion resolves strong CP problem

Time-varying EDMs and spin-precession effects

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

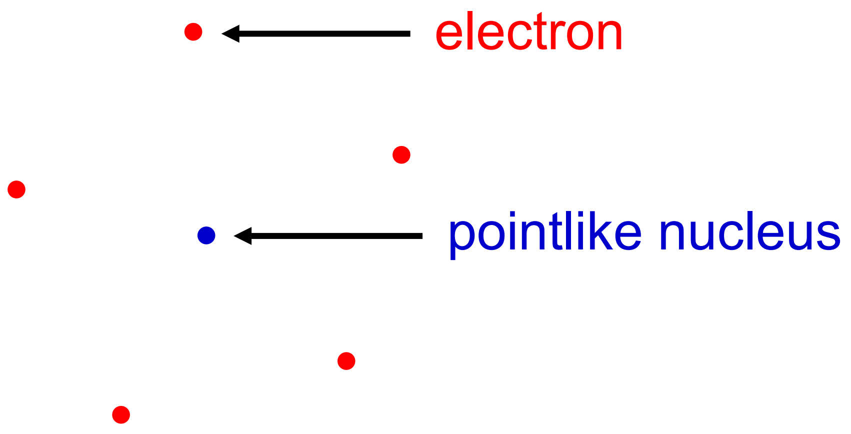
*More traditional axion dark matter detection methods tend to focus on the **electromagnetic** coupling*

*Here I focus on relatively new detection methods based on **non-electromagnetic** couplings leading to spin-based signatures*

Schiff's Theorem

[Schiff, *Phys. Rev.* **132**, 2194 (1963)]

Schiff's Theorem: "In a neutral atom made up of point-like non-relativistic charged particles (interacting only electrostatically), the constituent EDMs are screened from an external electric field."



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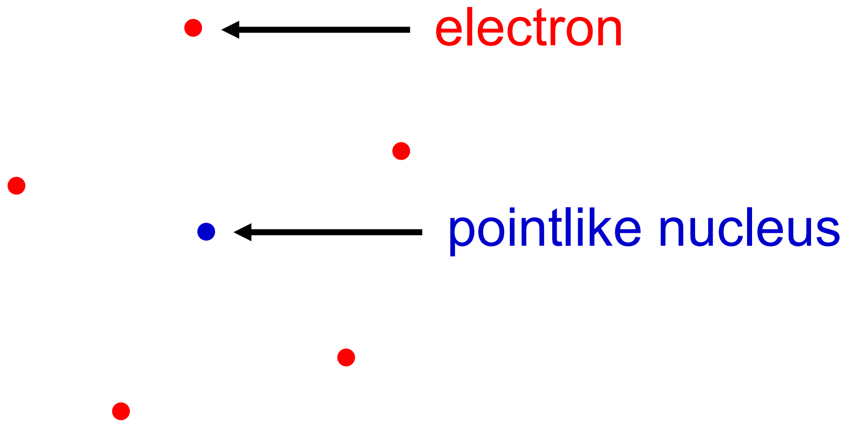

Classical explanation for nuclear EDM: A neutral atom does not accelerate in an external electric field!

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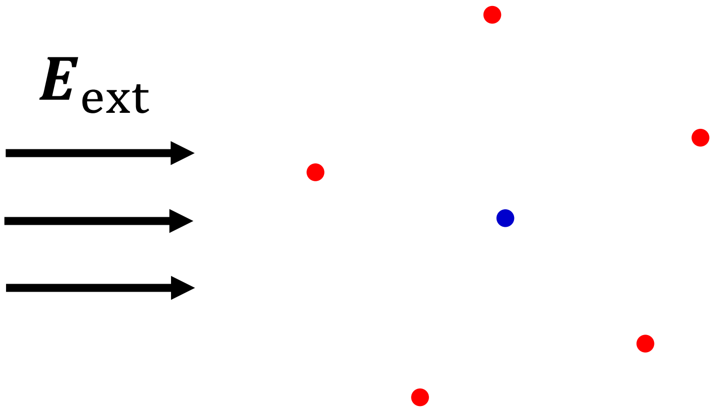

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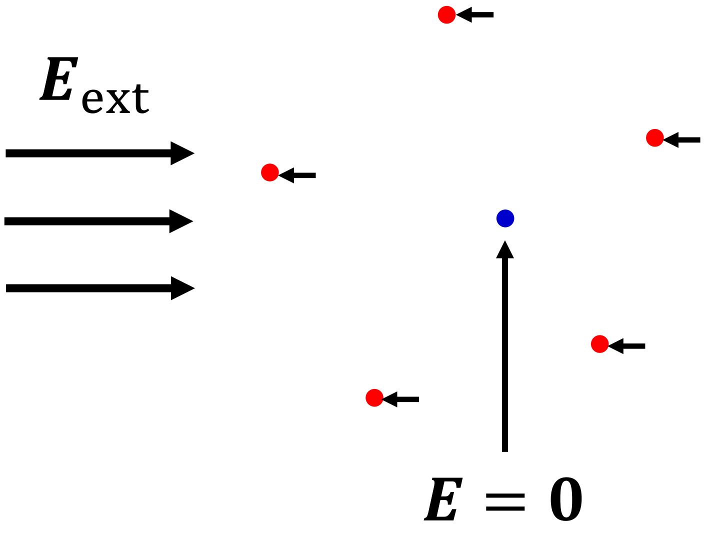


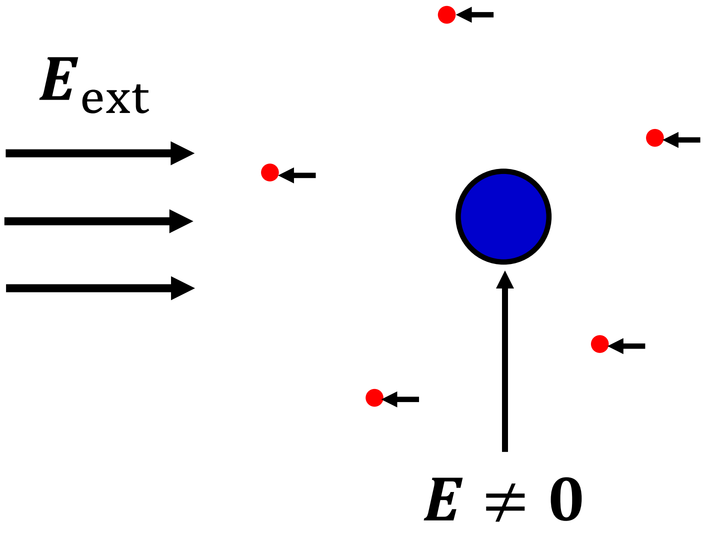
Classical explanation for nuclear EDM: A neutral atom does not accelerate in an external electric field!

Lifting of Schiff’s Theorem

[Sandars, *PRL* **19**, 1396 (1967)],

[O. Sushkov, Flambaum, Khriplovich, *JETP* **60**, 873 (1984)]

In real (heavy) atoms: Incomplete screening of external electric field due to finite nuclear size, parametrised by *nuclear Schiff moment*.

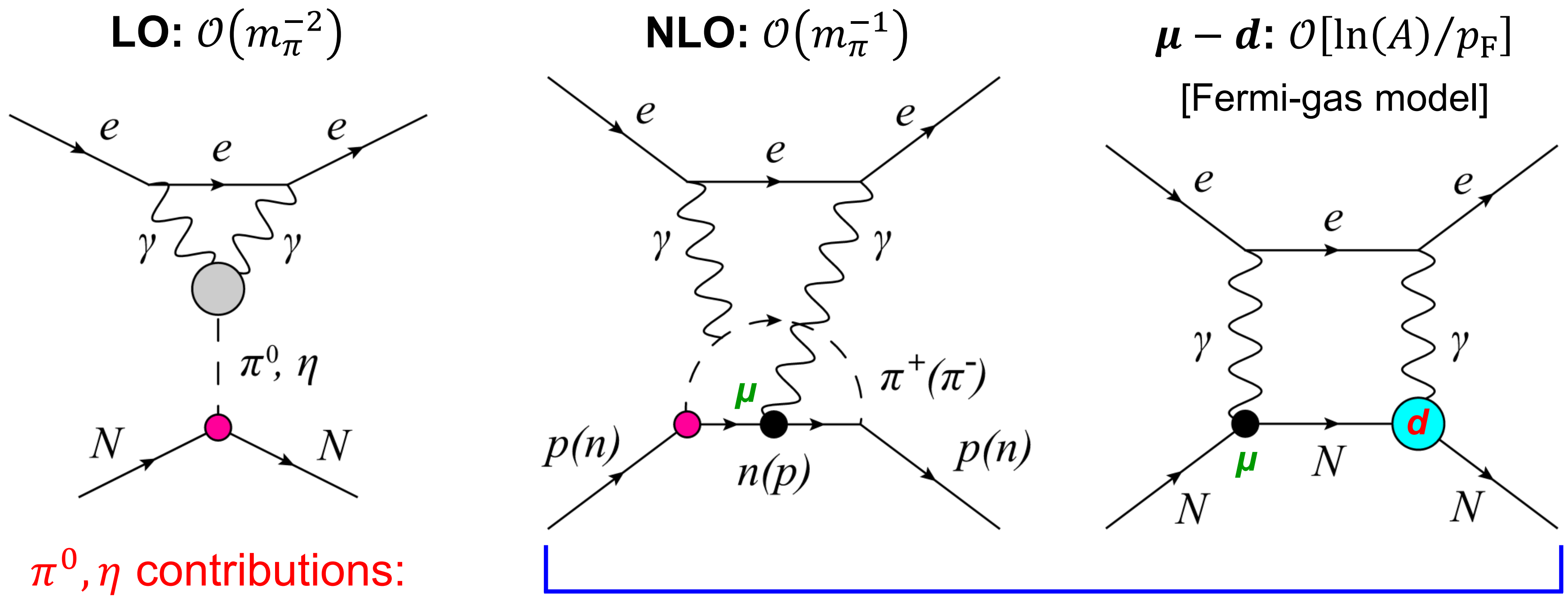


Paramagnetic Atoms and Molecules

[Flambaum, Pospelov, Ritz, Stadnik, *PRD* **102**, 035001 (2020)]

CP-odd nuclear scalar polarisability arises at 2-loop level, $\mathcal{O}(A)$ enhanced

Interaction of one of photons with nucleus is *magnetic* ⇒ no Schiff screening



LO: $\mathcal{O}\left(m_\pi^{-2}\right)$

NLO: $\mathcal{O}\left(m_\pi^{-1}\right)$

$\boldsymbol{\mu - d}$: $\mathcal{O}[\ln(A)/p_\mathrm{F}]$

[Fermi-gas model]

π^0, η contributions: ***opposite*** sign

p, n contributions: ***same*** sign

For $Z \sim 80$ & $A \sim 200$: $C_\mathrm{SP}(\theta) \approx \left[0.1_\mathrm{LO} + 1.0_\mathrm{NLO} + 1.7_{(\mu-d)}\right] \times 10^{-2}\theta \approx 0.03\theta$

$$\mathcal{L}_\mathrm{contact} = -G_F C_\mathrm{SP} \bar{N} N \bar{e} i \gamma_5 e/\sqrt{2}, \qquad \theta \leftrightarrow C_G a_0 \cos(m_a t)/f_a$$

Second-Order, CP-Even Effects

$$\mathcal{L} = \frac{g_s^2}{32\pi^2}\theta G\tilde{G}, \qquad \theta \leftrightarrow \frac{C_G}{f_a} a_0 \cos(m_a t)$$

θ-term may be absorbed into the quark mass matrix

$\Rightarrow$ Pion and nucleon masses depend on θ^2

$$\mathcal{L} \supset \frac{f_\pi \bar{g}_{\pi NN}^{(0)}}{2} \frac{m_d - m_u}{m_d + m_u} \theta^2 \bar{N} \tau^3 N \;\Rightarrow\; \delta(m_n - m_p) \approx 0.37\theta^2 \text{ MeV}$$

$\Swarrow$ $\Downarrow$ δm_p

Nuclear decay rates [Zhang *et al.*, *PRD* **108**, L071101 (2023)], [Broggini *et al.*, *PLB* **855**, 138836 (2024)]

BBN

[Blum *et al.*, *PLB* **737**, 30 (2014)]

$\Uparrow$

$$m_\pi^2(\theta) = B\sqrt{m_u^2 + m_d^2 + 2m_u m_d \cos(\theta)}, \qquad B = -\frac{\langle \bar{q}q \rangle_0}{f_\pi^2} \approx 2 \text{ GeV}$$

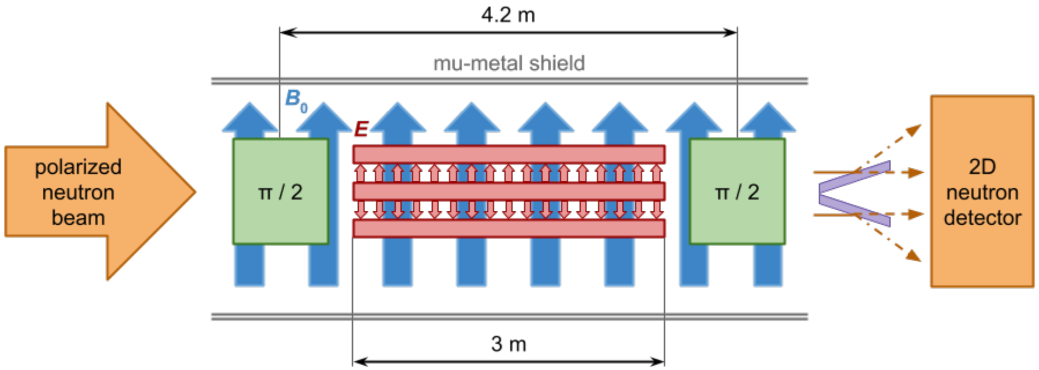
$$\Rightarrow \left.\frac{\delta m_\pi}{m_\pi}\right|_{\theta \approx 0} \approx -\frac{m_u m_d}{4(m_u + m_d)^2}\theta^2 \;\Rightarrow\; g_{\text{nucl}}(m_\pi) \;\Rightarrow$$ **Microwave clocks**

[Kim, Perez, *PRD* **109**, 015005 (2024)]

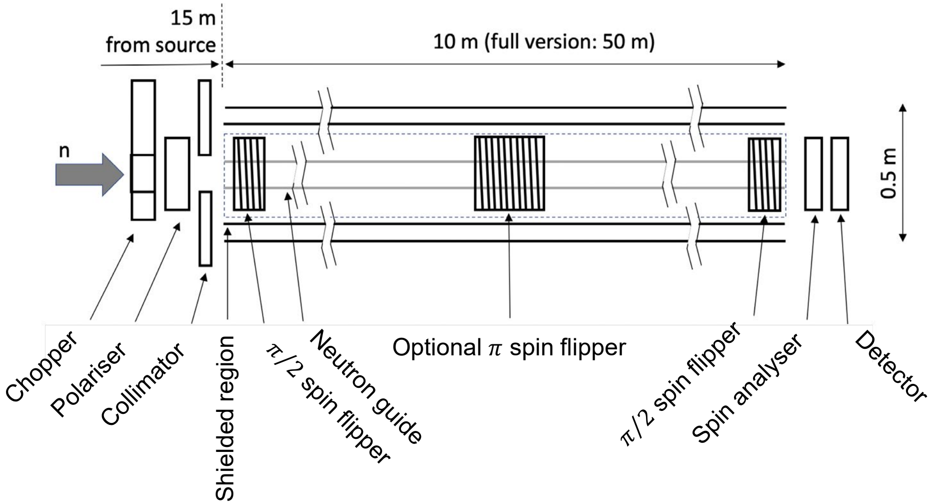
Broadband Searches, $a\bar{n}n/aG\tilde{G}$, $10^{-22}\text{eV} \leq m_a \leq 10^{-13}\text{eV}$

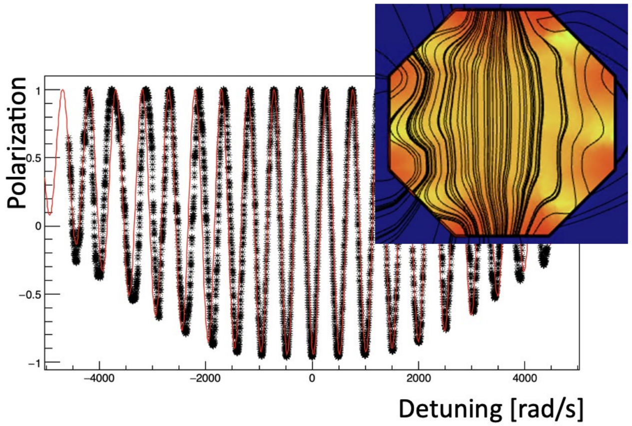
Besides stored or trapped particles, can also use particle beams:

Experiment at ILL (n beam, EDM): [Schulthess *et al*., *PRL* **129**, 191801 (2022)]



Proposal at ESS (n beam): [Fierlinger, Holl, Milstead, Santoro, Snow, Stadnik, *PRL* **133**, 181001 (2024)]





Ramsey fringes

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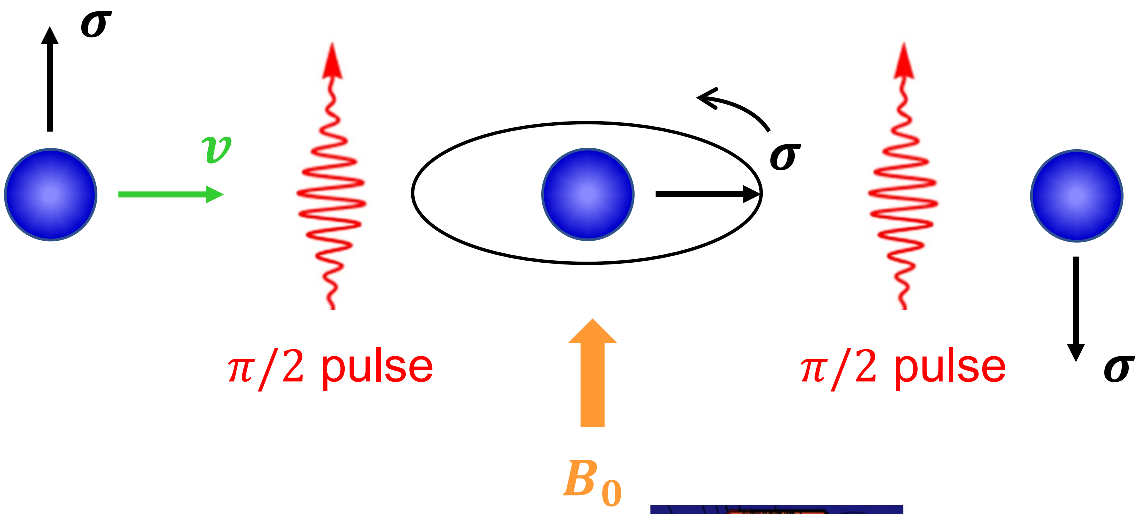

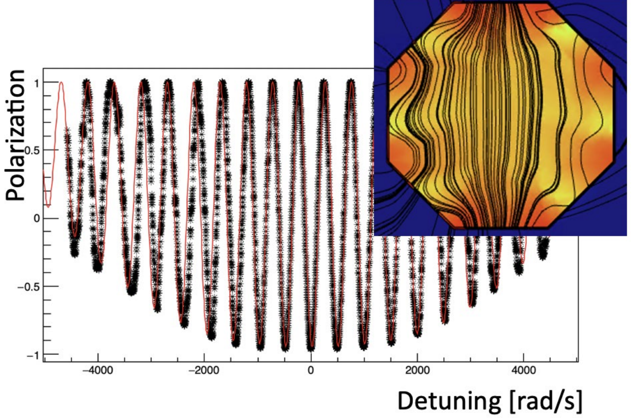

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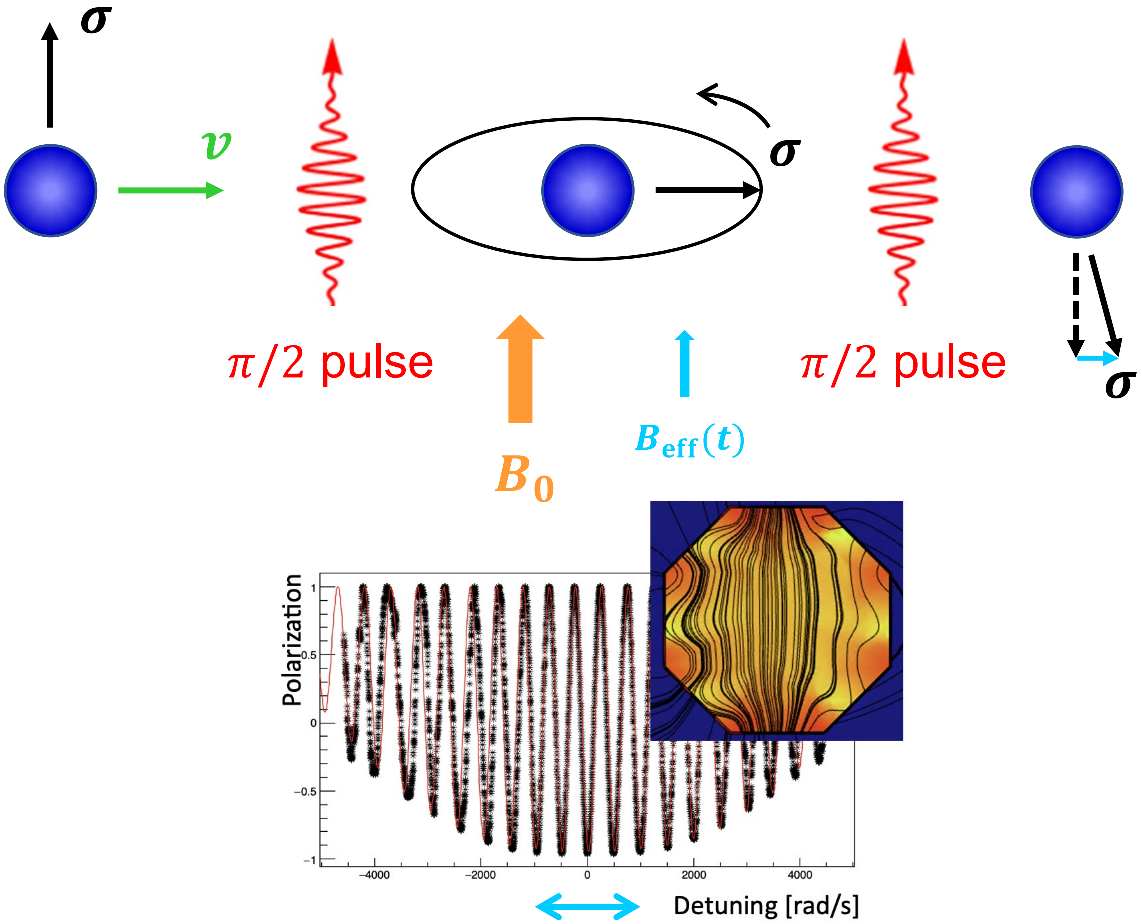
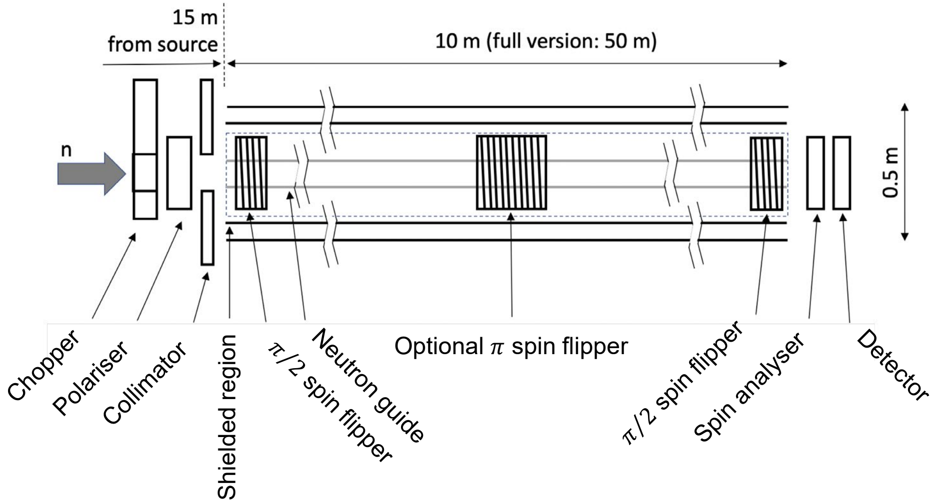


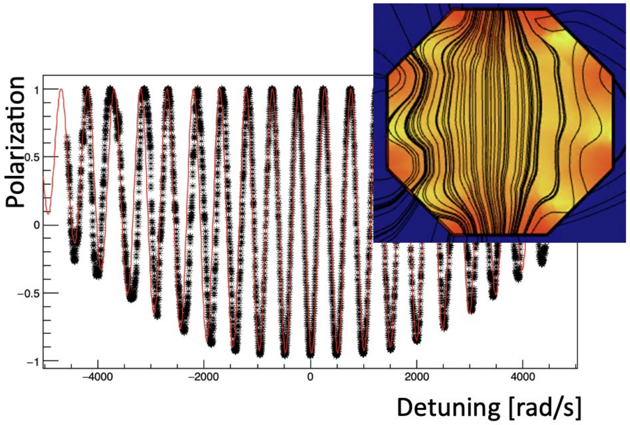
Temporal shifts in Ramsey fringe pattern

What About Using Particle Beams?

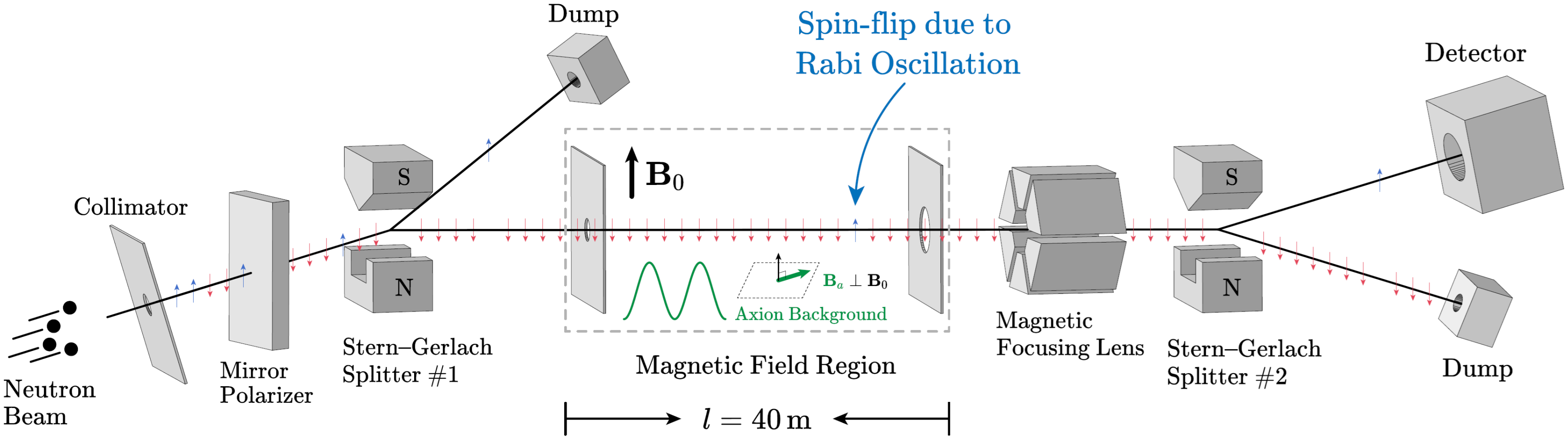
HIBEAM Proposal at ESS (Ramsey, 10^{-22} eV – 10^{-13} eV):

[Fierlinger, Holl, Milstead, Santoro, Snow, Stadnik, *PRL* **133**, 181001 (2024)]



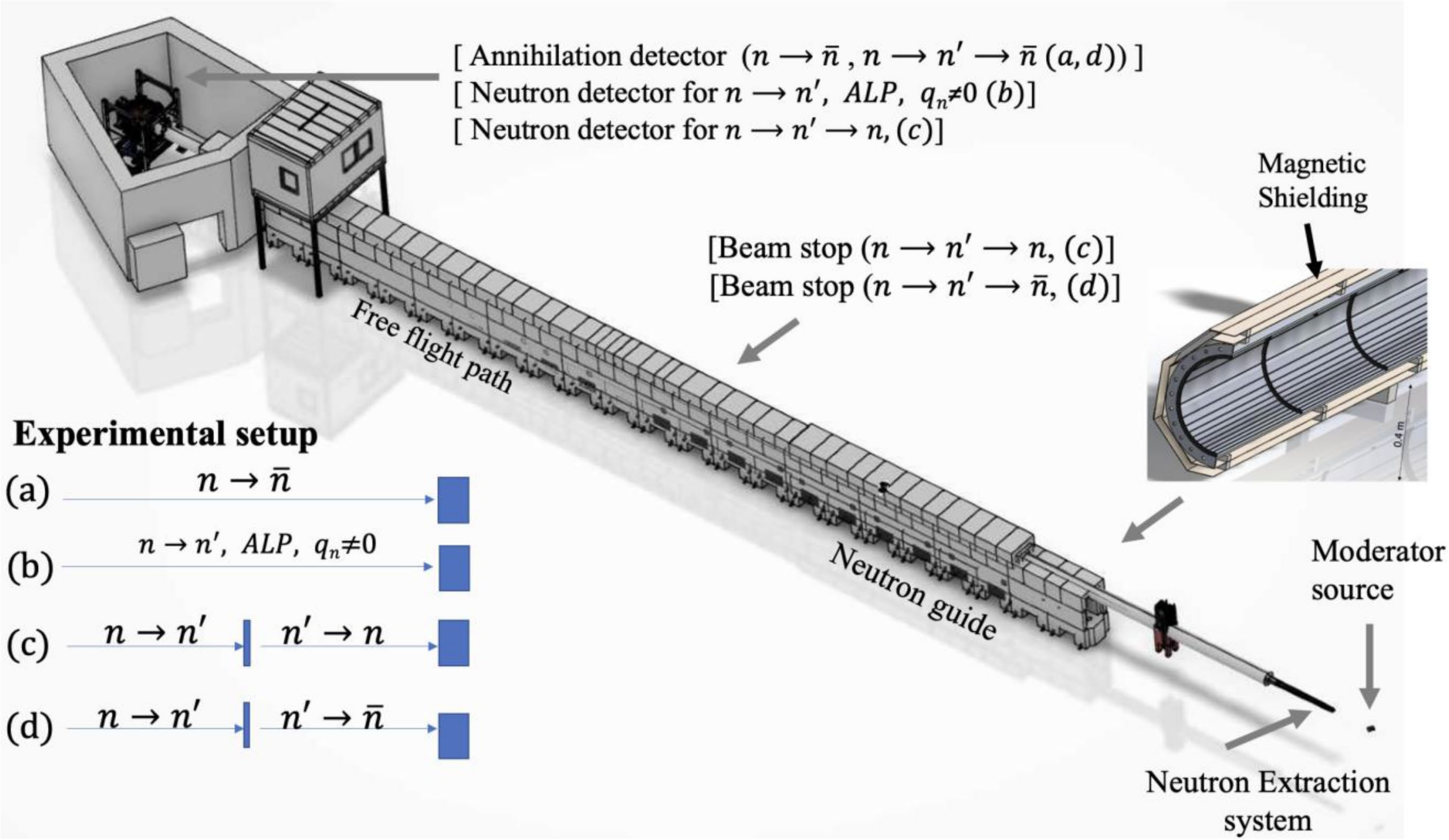


Proposal at ESS (Rabi, 10^{-13} eV – 10^{-10} eV): [Fierlinger, Sheng, Stadnik, Xing, arXiv:2412.10832]



HIBEAM Experimental Setups

Courtesy of slides by David Milstead and Valentina Santoro of the HIBEAM Collaboration



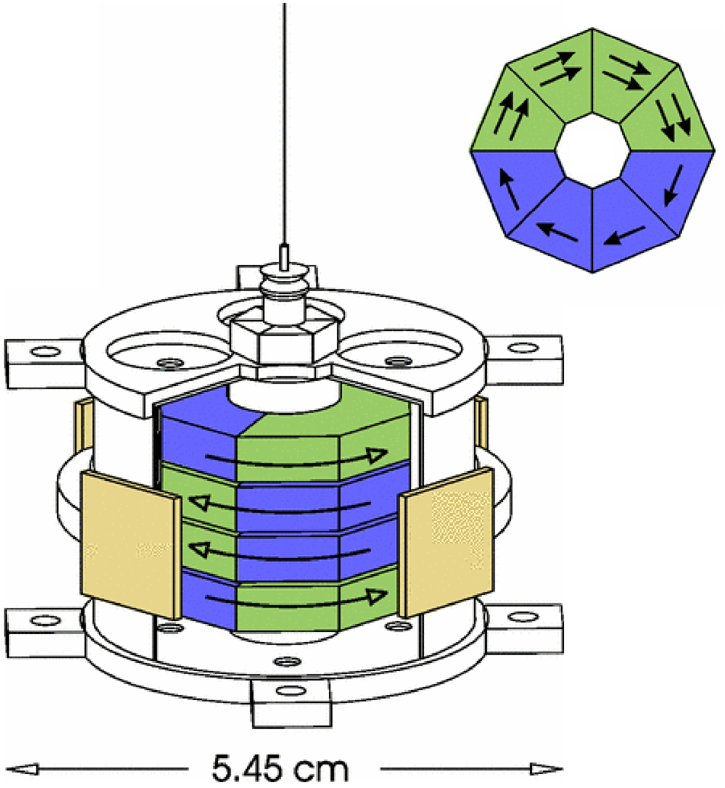
Broadband Searches, $a\bar{e}e$, $10^{-23}\mathrm{eV} \leq m_a \leq 10^{-18}\mathrm{eV}$

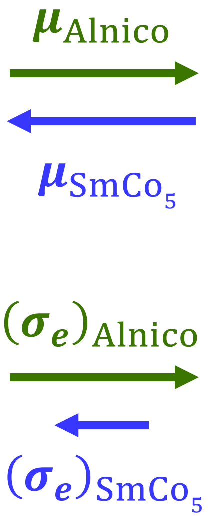
Proposals: [Flambaum, talk at *Patras Workshop*, 2013; Stadnik, Flambaum, *PRD* **89**, 043522 (2014); Stadnik, thesis (Springer, 2017)]

Lorentz-invariance-violation-type searches:

Magnetometers, cold/ultracold particles, *spin pendula*

Seattle Experiment (Alnico/SmCo$_5$): [Terrano *et al.*, *PRL* **122**, 231301 (2019)]





$\boldsymbol{\mu}_{\mathrm{Alnico}}$

$\boldsymbol{\mu}_{\mathrm{SmCo}_5}$

$$\boldsymbol{\mu}_{\mathrm{pendulum}} \approx \mathbf{0}$$

$(\boldsymbol{\sigma}_e)_{\mathrm{Alnico}}$

$(\boldsymbol{\sigma}_e)_{\mathrm{SmCo}_5}$

$$(\boldsymbol{\sigma}_e)_{\mathrm{pendulum}} \neq \mathbf{0}$$

$$\boxed{\boldsymbol{\tau}(t) \propto (\boldsymbol{\sigma}_e)_{\mathrm{pendulum}} \times \boldsymbol{B}_{\mathrm{eff}}(t)}$$

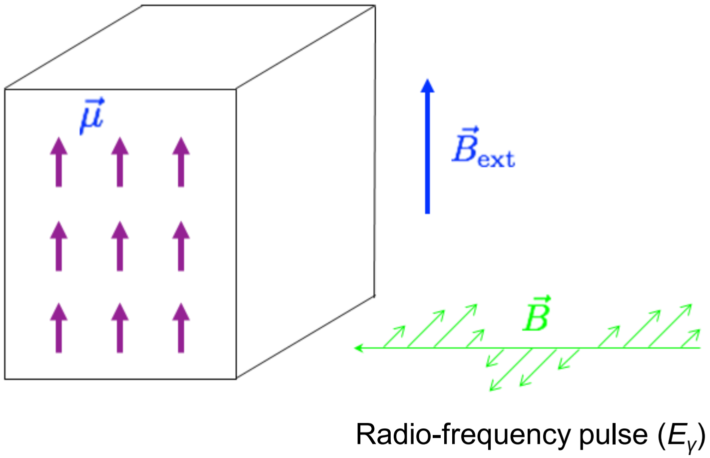
Resonant Searches, $a\bar{N}N/aG\tilde{G}$, $10^{-14}\mathrm{eV} \leq m_a \leq 10^{-7}\mathrm{eV}$

In resonant-type searches, the DM-induced signal may be enhanced by up to $Q_{\mathrm{DM}} \sim 10^6$

Proposal (liquid Xe, solid-state $PbTiO_3$): [Budker *et al.*, *PRX* **4**, 021030 (2014)]

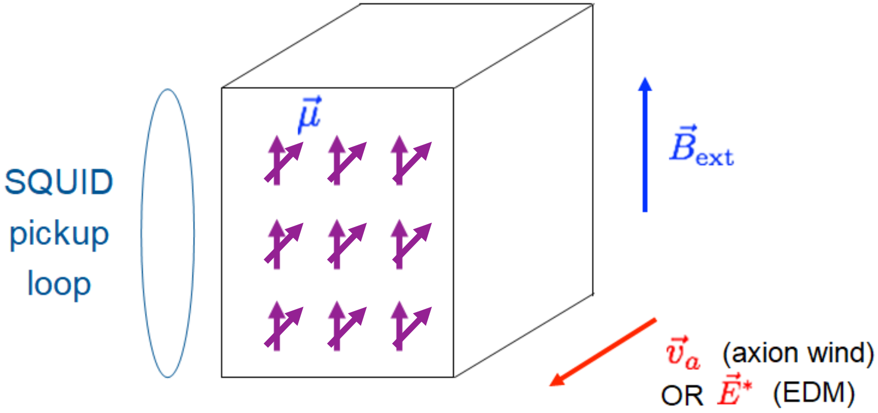
Experiment (Xe vapour): [Jiang *et al.*, *Nature Phys.* **17**, 1402 (2021)],
[Bloch *et al.*, *Sci. Adv.* **8**, eabl8919 (2022)]

Traditional NMR



Resonance: $2\mu B_{\mathrm{ext}} = E_\gamma$

Dark-matter-driven NMR



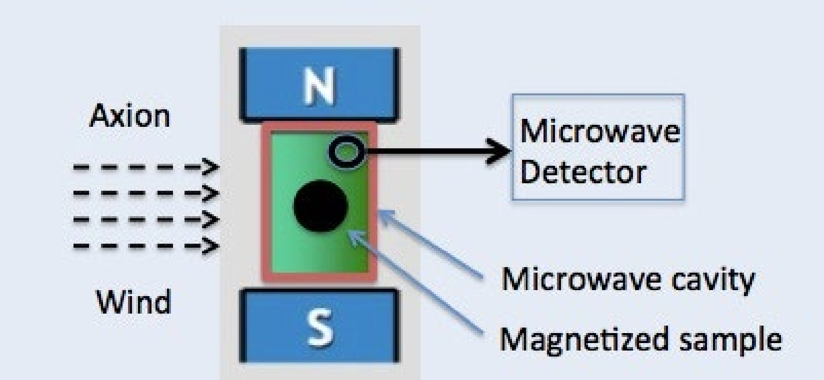
Resonance: $2\mu B_{\mathrm{ext}} \approx m_a$

Measure transverse magnetisation

Resonant Searches, $a\bar{e}e$, $10^{-7}\mathrm{eV} \leq m_a \leq 10^{-4}\mathrm{eV}$

In resonant-type searches, the DM-induced signal may be enhanced by up to $Q_{\mathrm{DM}} \sim 10^6$

Proposals (ESR): [Krauss, Moody, Wilczek, Morris, HUTP-85/A006 (1985)], [Raffelt, MPI-PAE/PTh 86/85 (1985)], [Barbieri, Cerdonio, Fiorentini, Vitale, *PLB* **226**, 357 (1989)], [Caspers, Semertzidis, *Proceedings of the Workshop on Cosmic Axions*, 1990], [Kakhidze, Kolokolov, *Sov. Phys. JETP* **72**, 598 (1991); Vorob'ev, Kakhidze, Kolokolov, *Phys. Atom. Nuclei* **58**, 959 (1995)], [Barbieri *et al*., *Phys. Dark Universe* **15**, 135 (2017)]



Resonance: $2\mu B_{\mathrm{ext}} \approx E_{\mathrm{res,cav}} \approx E_{\pm} \approx m_a$

Measure photons resulting from axion-to-polariton conversion (hybridised cavity-magnon mode)

INFN Experiment (YIG): [Crescini *et al*., *EPJ C* **78**, 703 (2018); *PRL* **124**, 171801 (2020)]

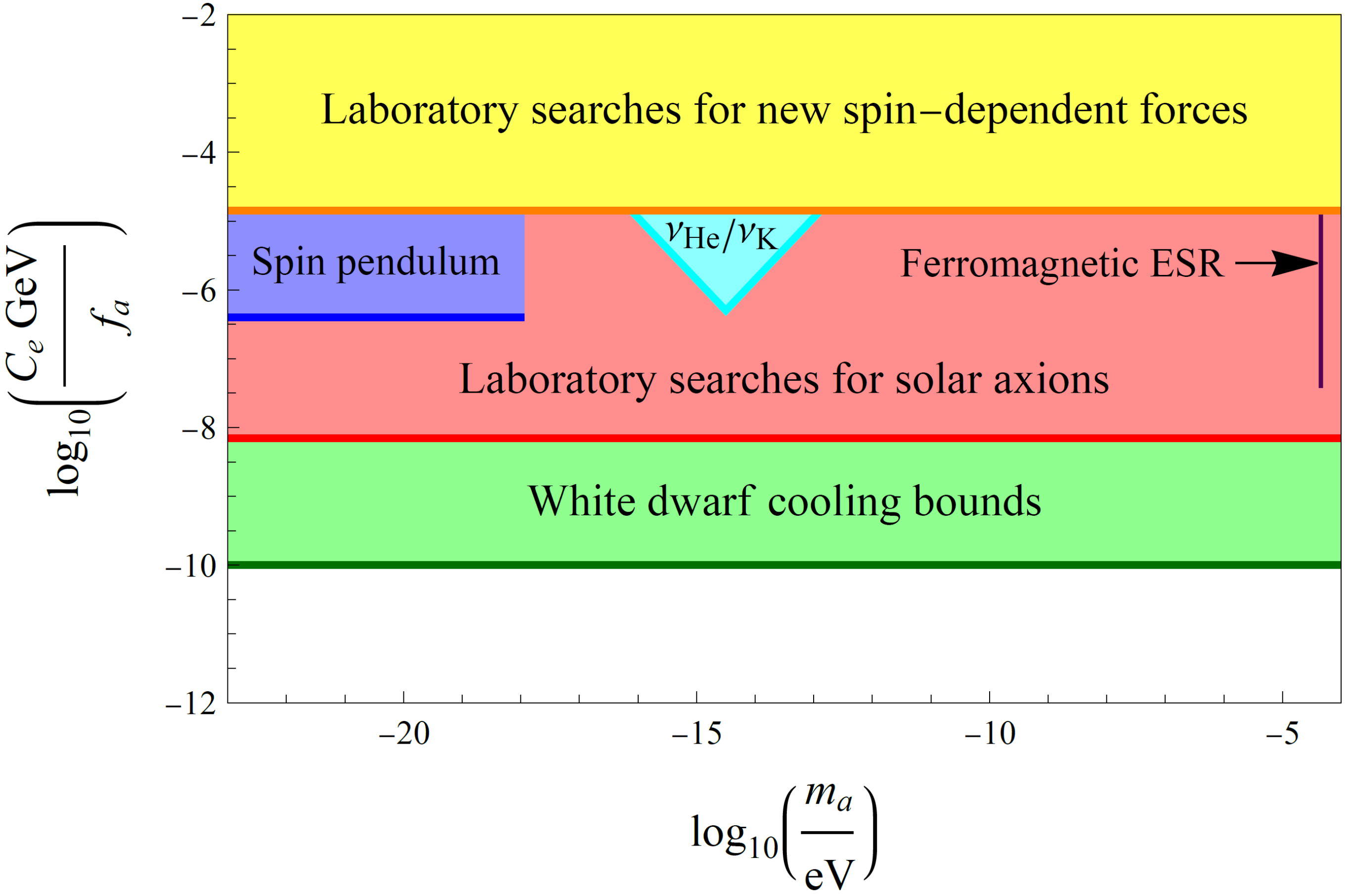
UWA Experiment (YIG): [Flower, Bourhill, Goryachev, Tobar, *Phys. Dark Universe* **25**, 100306 (2019)]

Constraints on Axion Dark Matter with $C_e(\partial_\mu a)\bar{e}\gamma^\mu\gamma^5 e/2f_a$ Coupling

Spin-polarised torsion pendulum (Seattle): [Terrano *et al.*, *PRL* **122**, 231301 (2019)]

Ferromagnetic ESR (INFN): [Crescini *et al.*, *EPJ C* **78**, 703 (2018); *PRL* **124**, 171801 (2020)]

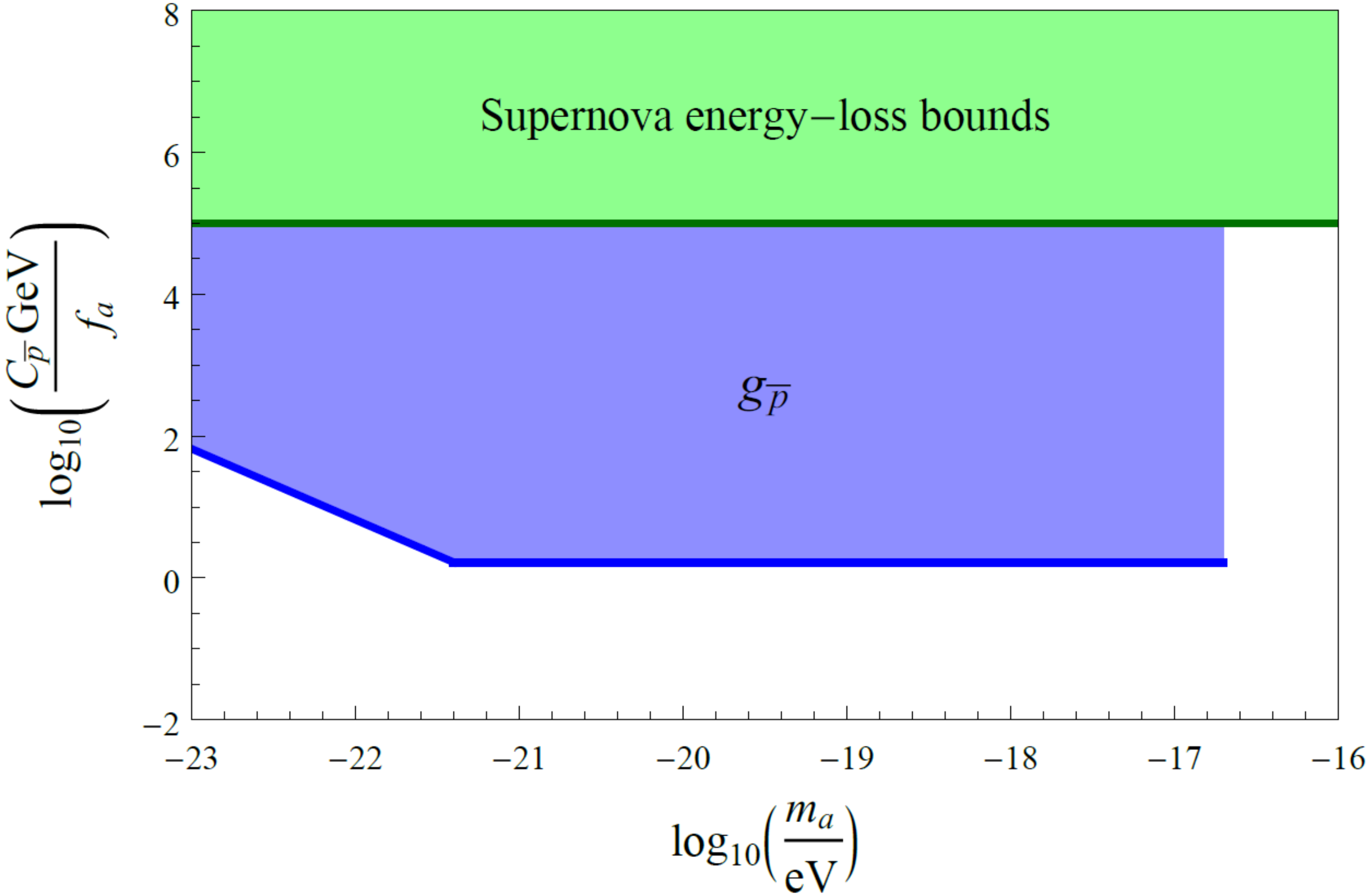
Ferromagnetic ESR (UWA): [Flower, Bourhill, Goryachev, Tobar, *Phys. Dark Universe* **25**, 100306 (2019)]



Constraints on Interaction of Axion Dark Matter with the Antiproton

Antiproton constraints: [BASE collaboration, *Nature* **575**, 310 (2019)]

5 orders of magnitude improvement!



Low-mass Spin-0 Dark Matter

Dark Matter

Scalars (Dilatons):

$$\varphi^n \xrightarrow{P} \varphi^n, n = 1,2$$

Spatio-temporal variations of “constants”

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

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)]

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

$$\mathcal{L}_f = -\frac{\varphi}{\Lambda_f} m_f \bar{f} f \approx -\frac{\varphi_0\cos(m_\varphi t)}{\Lambda_f} m_f \bar{f} f \quad\Rightarrow\quad \frac{\delta m_f}{m_f} \approx \frac{\varphi_0\cos(m_\varphi t)}{\Lambda_f}$$

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

Lab frame

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

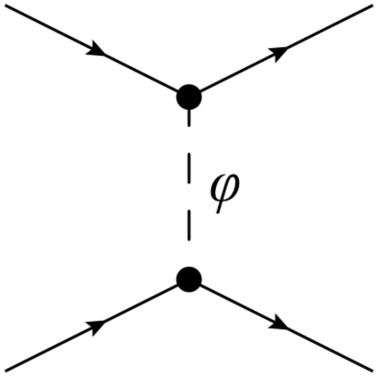
Fifth Forces: Linear vs Quadratic Couplings

[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**



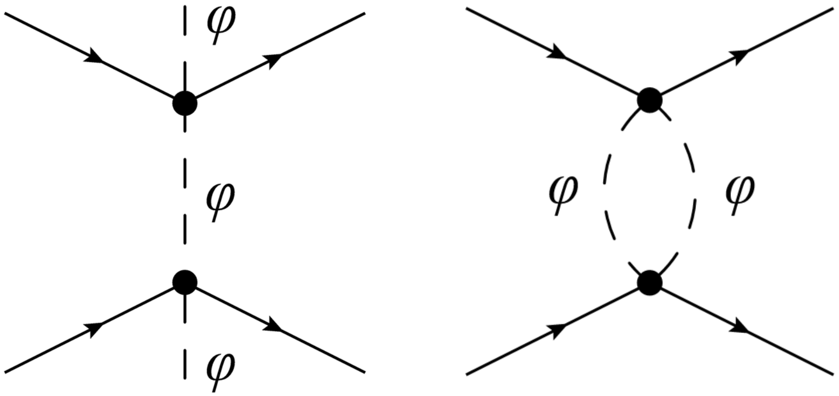
$$\varphi = \underline{\varphi_0\cos(m_\varphi t)} \pm A\frac{e^{-m_\varphi r}}{r}$$

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

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

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

$\Box\varphi + m_\varphi^2\varphi = \pm\kappa'\rho\varphi$ **Effective mass**



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

↓

Gradients + amplification/screening

Quadratic Couplings: Boundary Conditions

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

B.C. Choice 1:

$$\lim_{r\to\infty} p_\varphi = 0$$

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

[Banerjee, Perez, Safronova, Savoray, Shalit, *JHEP* **10**, 042 (2023)];

[Bauer, Chakraborti, *PRD* **112**, 103019 (2025)];

[Burrage, Elder, Garcia, Jaeckel, *PRD* **111**, 103526 (2025)]

- *Screening* for – sign
- *Amplification* (*anti-screening*) for + sign

B.C. Choice 2:

$$\lim_{r\to\infty} p_\varphi \neq 0$$

[Stadnik, *Nature Astronomy* **8**, 434 (2024)];

[Day, Liu, Luty, Zhao, *JHEP* **7**, 136 (2024)];

[Tilburg, *PRD* **109**, 096036 (2024)];

[Banerjee, Bloch, Bonnefoy, Ellis, Perez, Savoray, Springmann, Stadnik, *JHEP* **06** (2026) 039];

[Garcia, Hammett, Jaeckel, *JCAP* **10** (2025) 022];

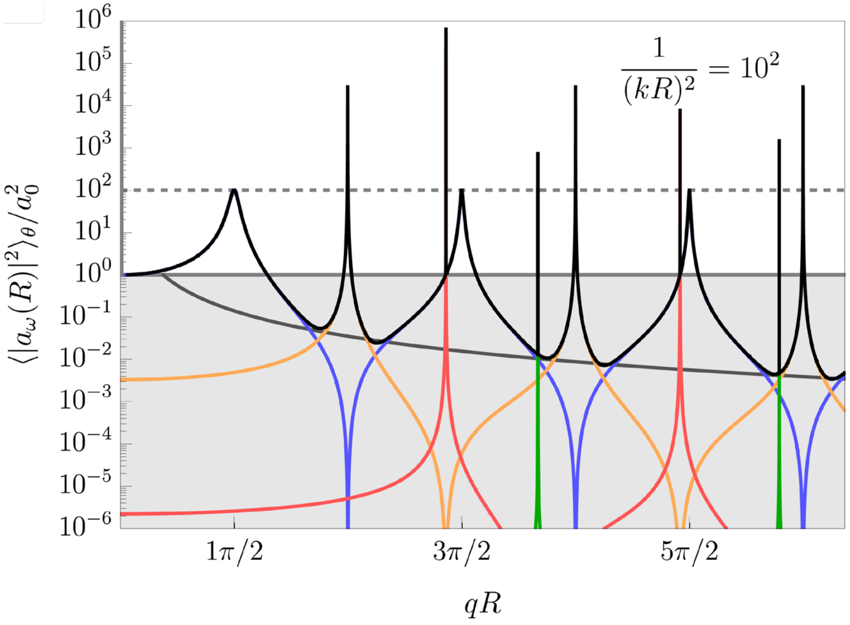
[arXiv:2601.16259], [arXiv:2605.28248], [arXiv:2606.28481], [arXiv:2606.28491], …

- *Screening* for – sign
- For + sign, *amplification* only on resonance (at poles of S-matrix)

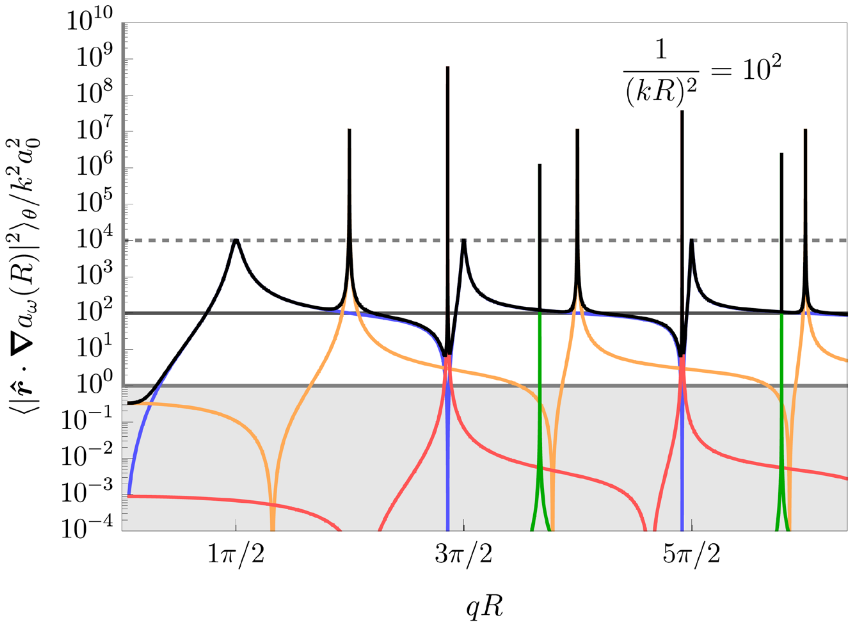
Field Amplitude vs Gradient Behaviour Near Surface of Source Body: $\lim_{r\to\infty} p_\varphi \neq 0$

[Banerjee, Bloch, Bonnefoy, Ellis, Perez, Savoray, Springmann, Stadnik, *JHEP* **06** (2026) 039]

$$\Box\varphi + m_\varphi^2\varphi = +\kappa'\rho\varphi$$



Field amplitude generally suppressed, except near resonances



Radial field gradient generally enhanced

Our findings apply to models of scalars and axions with quadratic couplings

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:

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

Non-relativistic atomic unit of frequency

Relativistic factor

Effects of Varying Fundamental Constants on Atomic Transitions

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

$$\frac{\nu_{\mathrm{opt},1}}{\nu_{\mathrm{opt},2}} \propto \frac{\left(m_e e^4/\hbar^3\right) F_{\mathrm{rel},1}^{\mathrm{opt}}(Z\alpha)}{\left(m_e e^4/\hbar^3\right) F_{\mathrm{rel},2}^{\mathrm{opt}}(Z\alpha)}$$

Effects of Varying Fundamental Constants on Atomic Transitions

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- Atomic optical transitions:

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

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

Increasing *Z*

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

Effects of Varying Fundamental Constants on Atomic Transitions

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

- Atomic optical transitions:

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

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

Increasing *Z*

For transitions between closely spaced energy levels that arise due to the near cancellation of contributions of different nature, the K_α sensitivity coefficients can be greatly enhanced, e.g.:

- $\left|K_\alpha\left(\mathrm{Cf}^{15+}\right)\right| \approx 50$ [Dzuba *et al*., *PRA* **92**, 060502(R) (2015)]
- $\left|K_\alpha\left({}^{229}\mathrm{Th}\right)\right| \sim 10^4$ [Flambaum, *PRL* **97**, 092502 (2006)]

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

- Atomic hyperfine transitions:

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

Effects of Varying Fundamental Constants on Atomic Transitions

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

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

- Atomic hyperfine transitions:

$K_{m_e/m_N} = 1$

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

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

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

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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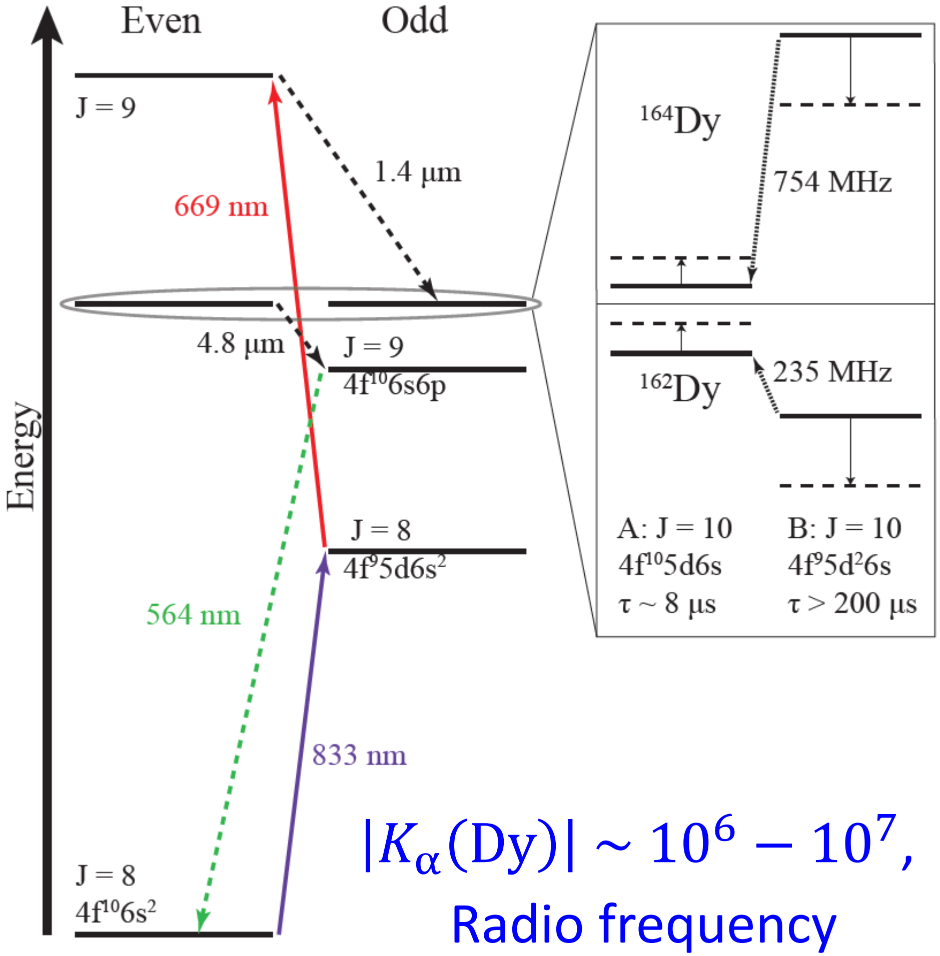

$|K_\alpha(\mathrm{Dy})| \sim 10^6 - 10^7$,

Radio frequency

Enhanced Effects of Varying Fundamental Constants on Atomic and Other Transitions

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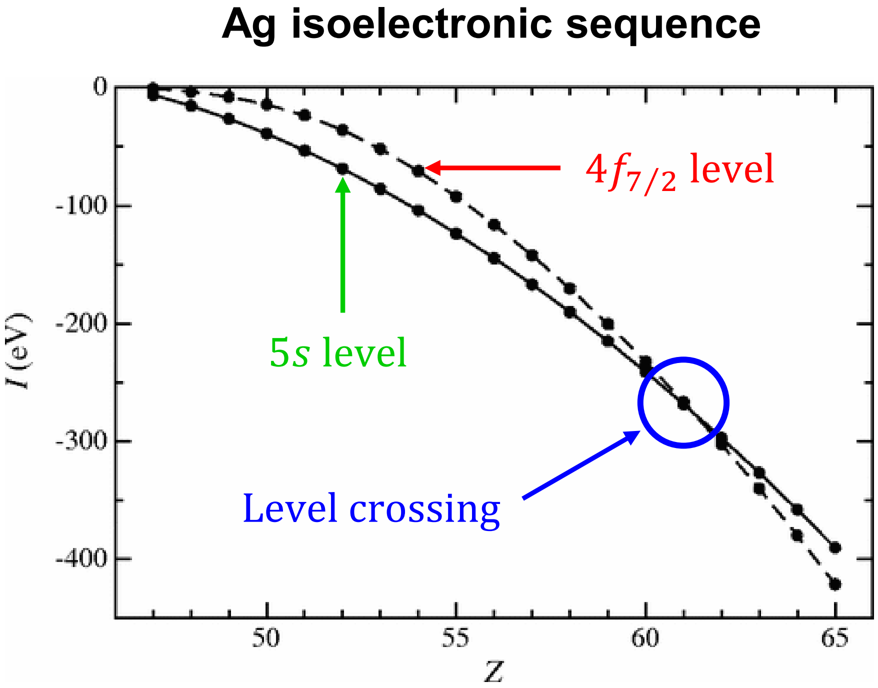

e.g., $\left|K_\alpha\left(\mathrm{Cf}^{15+}\right)\right| \approx 50$,

Optical frequency

(Bi isoelectronic sequence)

Enhanced Effects of Varying Fundamental Constants on Atomic and Other Transitions

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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

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- Sensitivity coefficients may be greatly enhanced for transitions between nearly degenerate levels in:
  - Atoms
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There exists a low-energy ($\approx 8\ \mathrm{eV}$) isomeric transition between the ground and first-excited states of ^{229}Th, due to fortuitous cancellation between the electromagnetic and strong force intervals

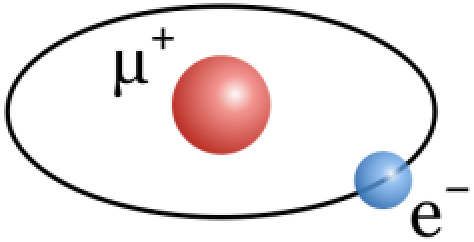
$$|K_\alpha(\mathrm{Th})| \sim 10^4,$$

Ultraviolet frequency

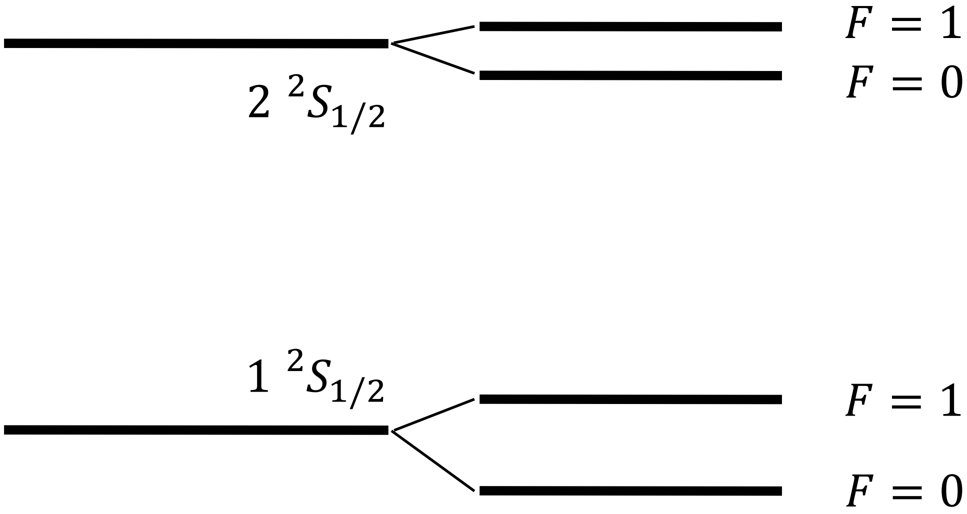
Transitions in Exotic Atoms

[Stadnik, *PRL* **131**, 011001 (2023)]

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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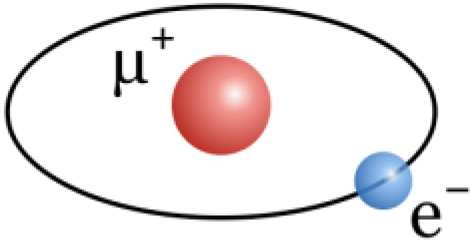

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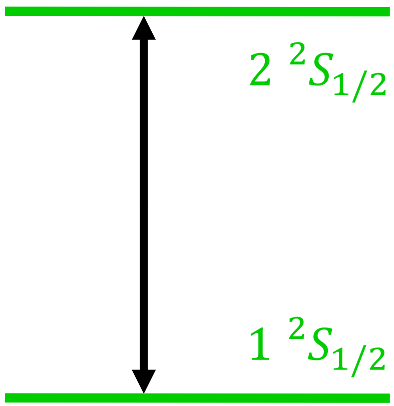

$$E_n^{\text{Rydberg}} = -\frac{m_r \alpha^2}{2n^2} \Rightarrow \frac{\Delta\nu_{1S-2S}}{\nu_{1S-2S}} \approx 2\frac{\Delta\alpha}{\alpha} + \frac{\Delta m_e}{m_e} + \frac{m_e}{m_\mu}\frac{\Delta m_\mu}{m_\mu}$$

Transitions in Exotic Atoms

[Stadnik, *PRL* **131**, 011001 (2023)]

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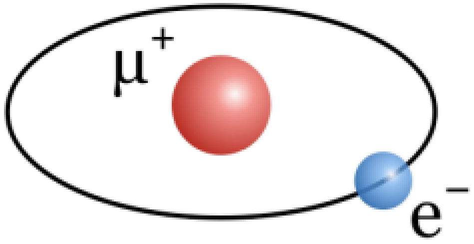
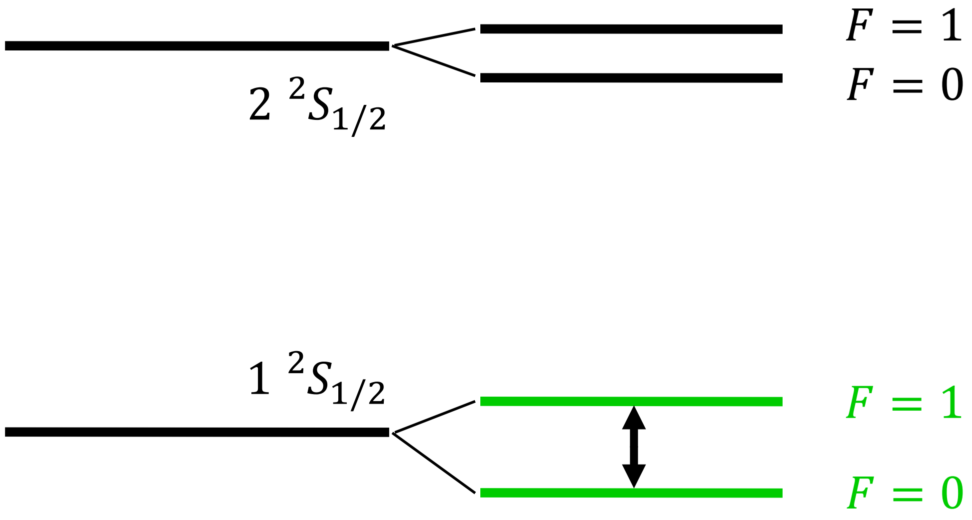


$\tau_\mu \approx 2.2$ μs



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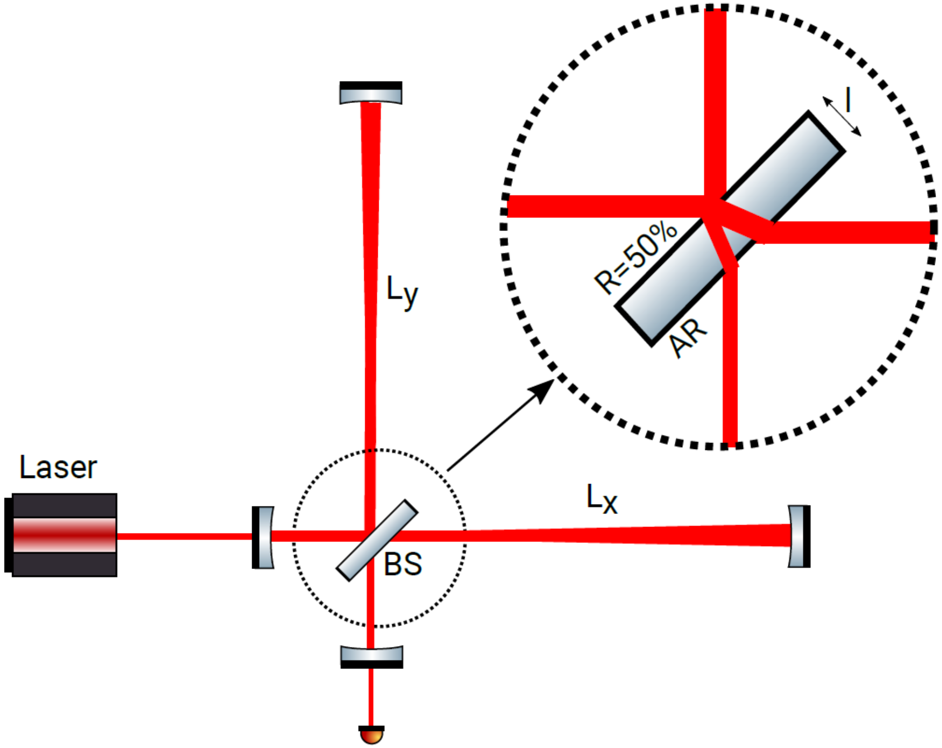
$$\Delta E_{\mathrm{Fermi}} = \frac{8 m_r^3 \alpha^4}{3 m_e m_\mu} \Rightarrow \frac{\Delta\nu_{\mathrm{HFS}}}{\nu_{\mathrm{HFS}}} \approx 4\frac{\Delta\alpha}{\alpha} + 2\frac{\Delta m_e}{m_e} - \frac{\Delta m_\mu}{m_\mu}$$

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

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



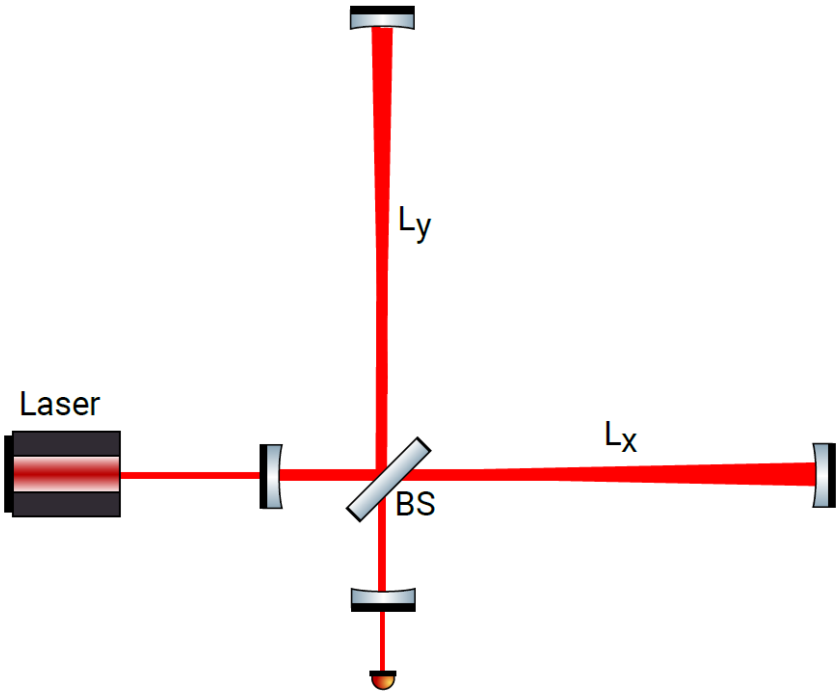
- Geometric asymmetry from beam-splitter: $\boxed{\delta\left(L_x - L_y\right) \sim \delta(nl)}$
- Both broadband and resonant narrowband searches possible:

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

Michelson vs Fabry-Perot-Michelson Interferometers

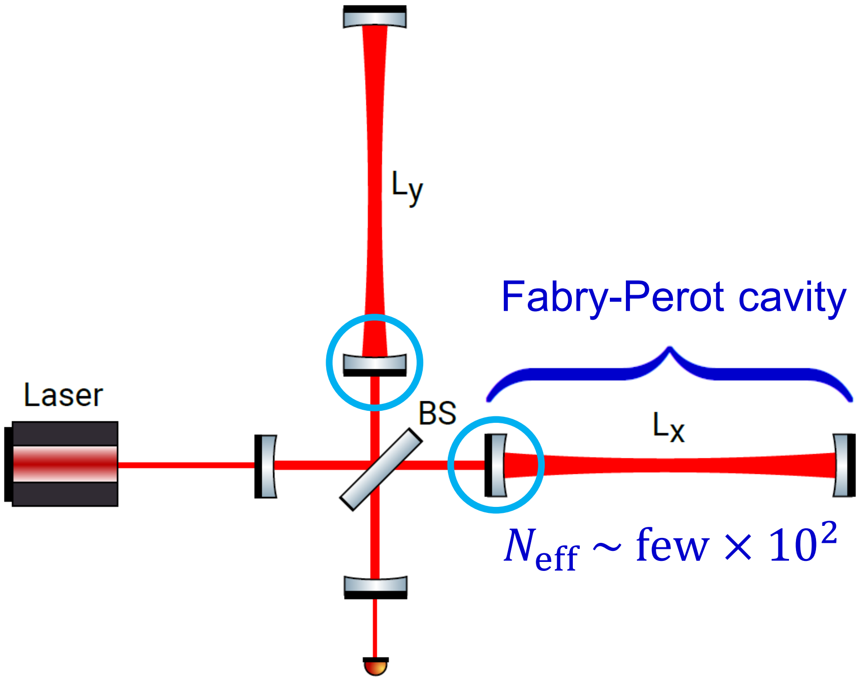
[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]

Michelson interferometer (GEO 600)



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

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



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

Michelson vs Fabry-Perot-Michelson Interferometers

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

Michelson interferometer
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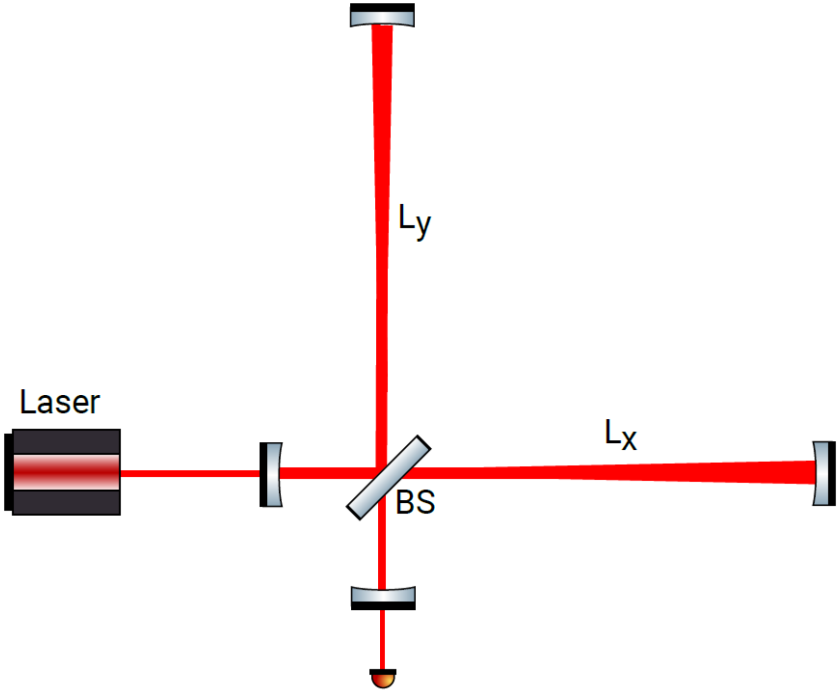

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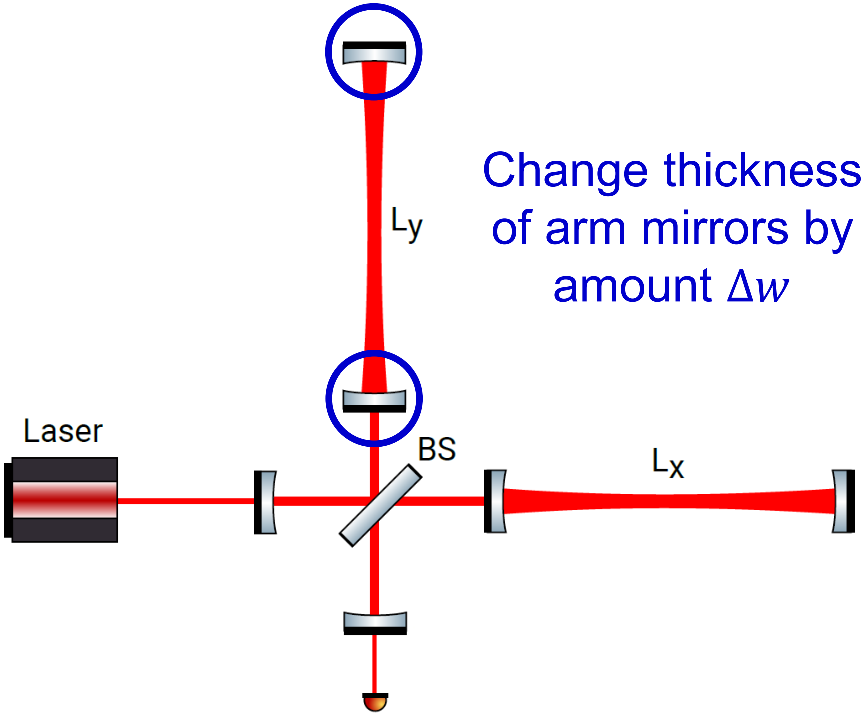
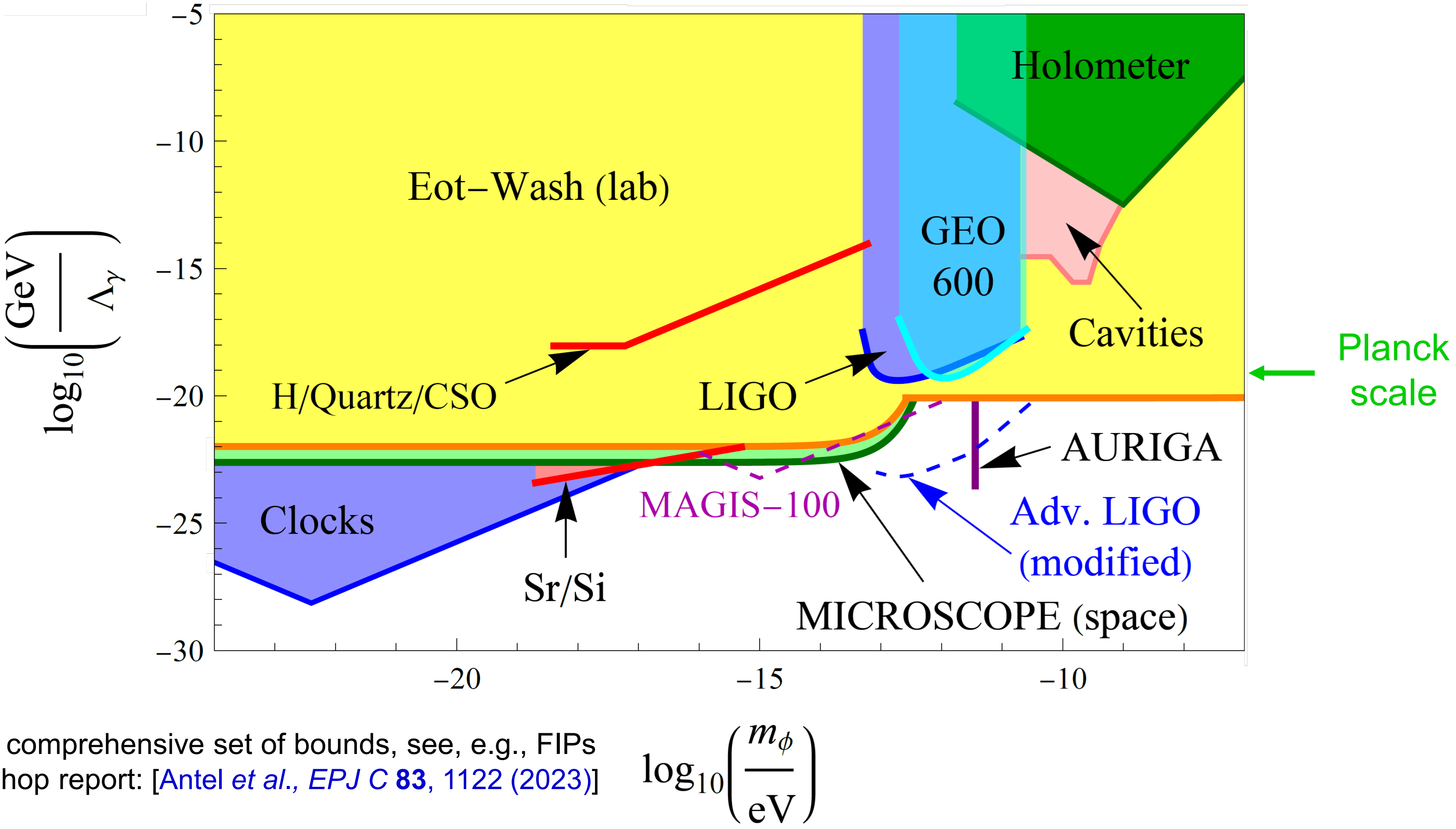


Change thickness of arm mirrors by amount Δw

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

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

Clock comparisons: [*PRL* **115**, 011802 (2015)], [*PRL* **117**, 061301 (2016)], [*Nature* **591**, 564 (2021)], [*PRL* **130**, 253001 (2023)]; **Sr/Si:** [*PRL* **125**, 201302 (2020)]; **H/Quartz/CSO:** [*PRL* **126**, 071301 (2021)]; **GEO600:** [*Nature* **600**, 424 (2021)]; **LIGO:** [*PRL* **133**, 101001 (2024)]; **AURIGA:** [*PRL* **118**, 021302 (2017)]; **Cavities:** [*PRL* **126**, 051301 (2021)], [*PRL* **135**, 261001 (2025)]; **Fermilab holometer:** [*PRL* **128**, 121101 (2022)]



For a more comprehensive set of bounds, see, e.g., FIPs 2022 workshop report: [Antel *et al.*, *EPJ C* **83**, 1122 (2023)]

Constraints on Scalar Dark Matter with $m_e \varphi \bar{e} e / 4\Lambda_e$ Coupling

Yb/Cs: [*PRL* **129**, 241301 (2022)]; **Sr/Cs:** [*New J. Phys.* **25**, 093012 (2023)];
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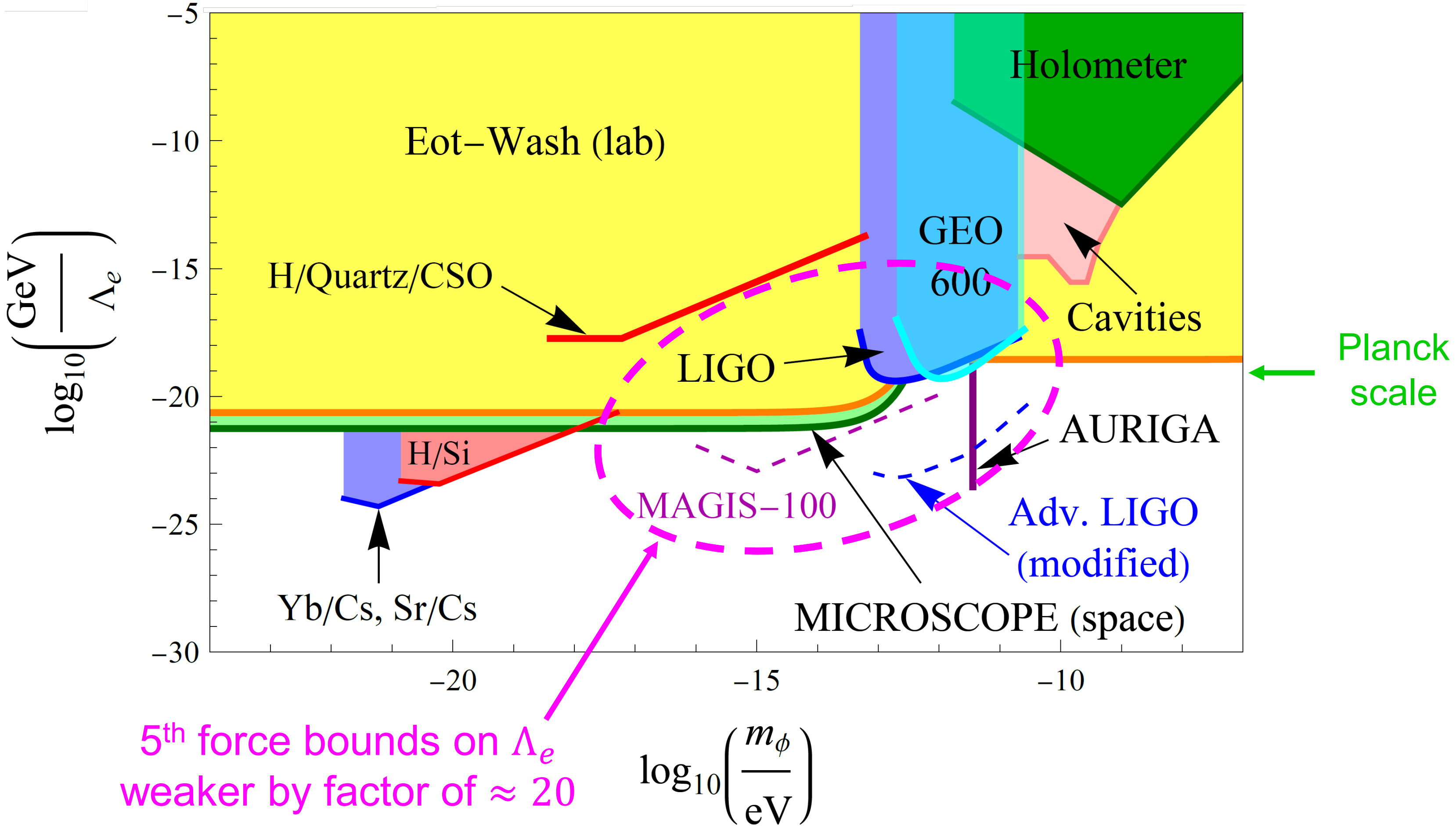

5th force bounds on Λ_e weaker by factor of ≈ 20

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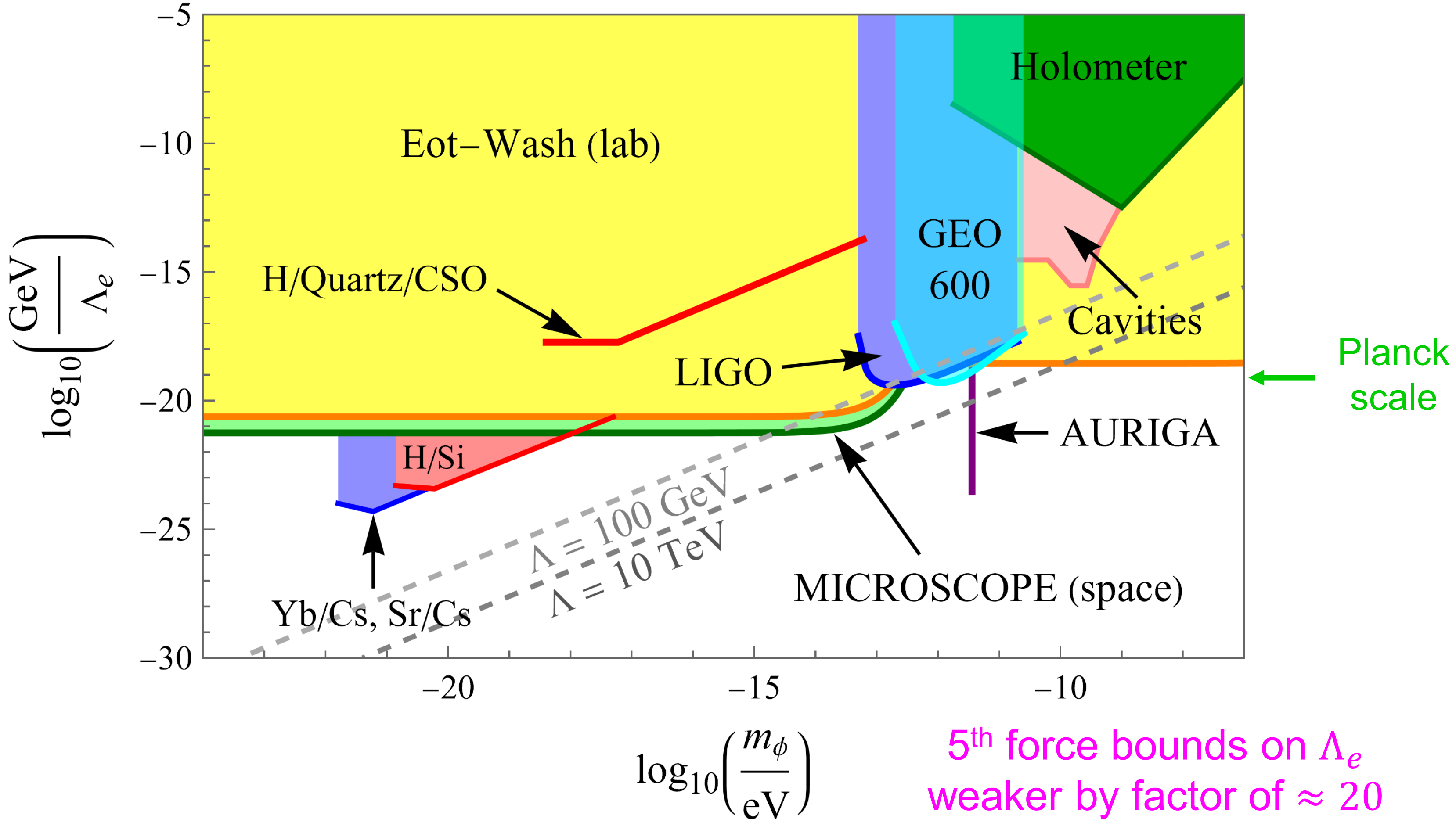

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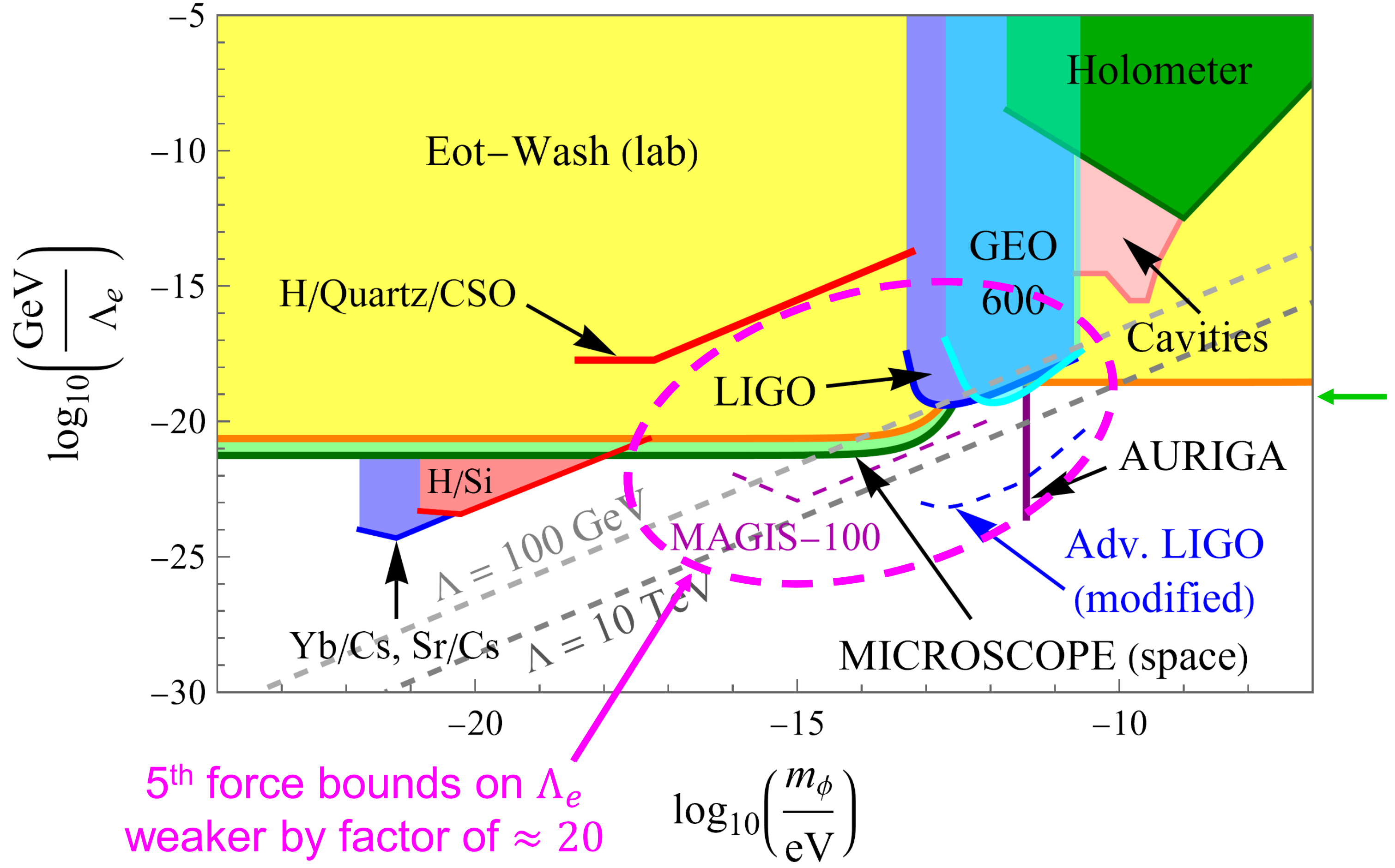
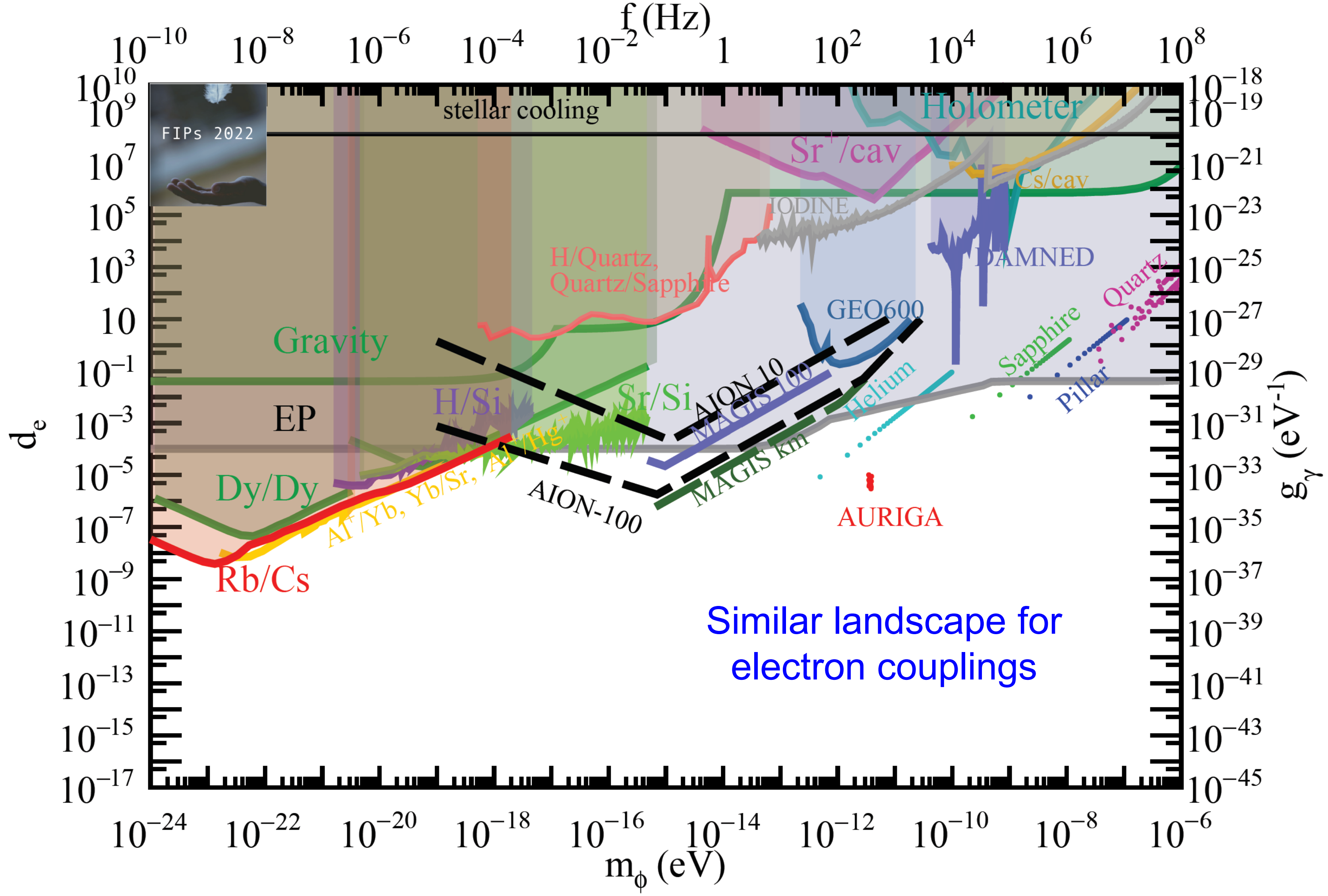


Planck scale

5th force bounds on Λ_e weaker by factor of ≈ 20

Constraints on Linear Scalar-Photon Coupling

Summary plot from FIPs 2022 workshop report: [Antel *et al.*, *EPJ C* **83**, 1122 (2023)]



Similar landscape for electron couplings

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 ($t_{\mathrm{weak}} \approx 1\ \mathrm{s} - t_{\mathrm{BBN}} \approx 3\ \mathrm{min}$)
- Primordial ^{4}He abundance sensitive to n/p ratio

(almost all neutrons bound in ^{4}He after BBN)

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

$$p + e^- \rightleftharpoons n + \nu_e$$

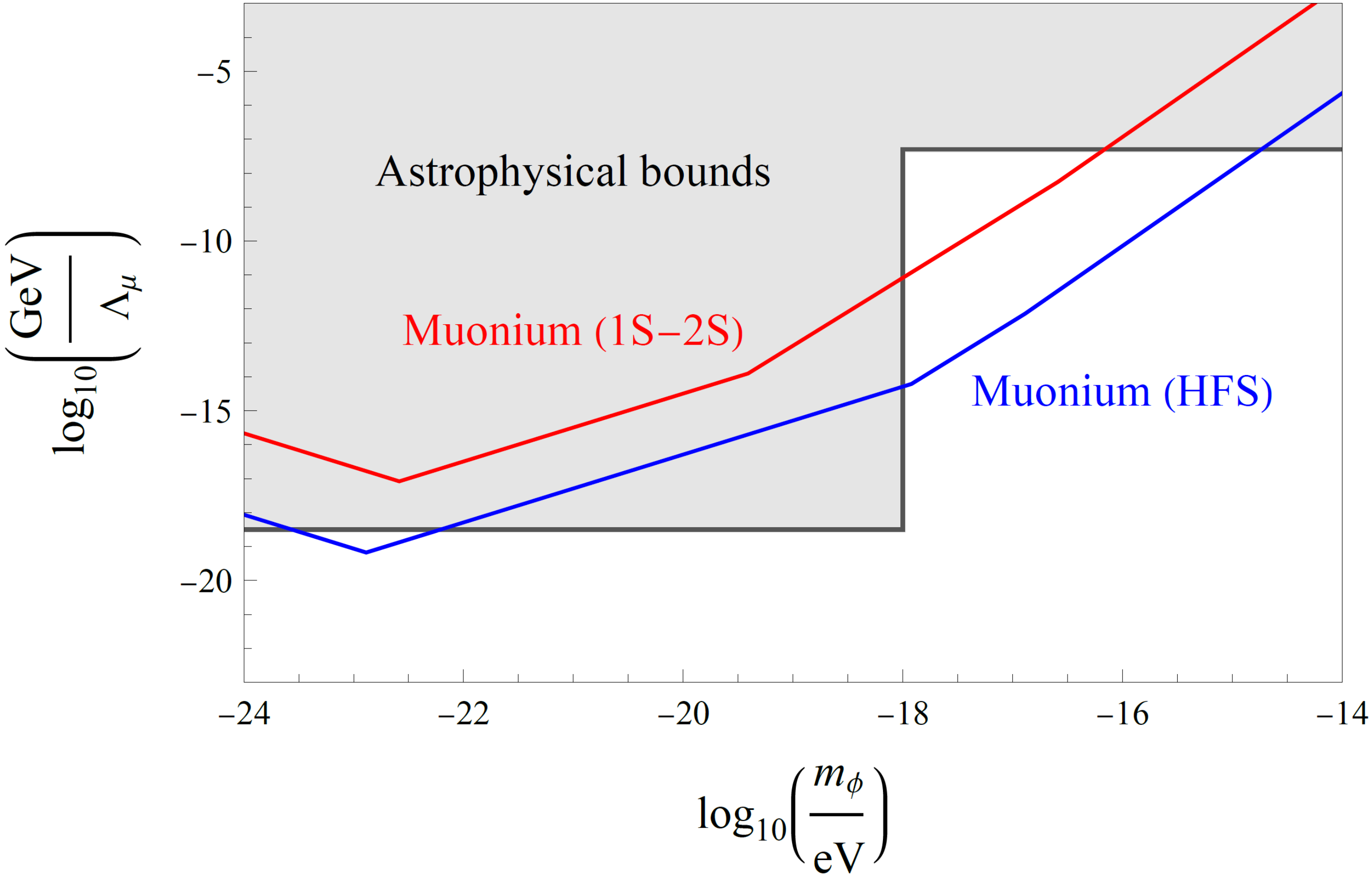
$$n + e^+ \rightleftharpoons p + \bar{\nu}_e$$

$$n \rightarrow p + e^- + \bar{\nu}_e$$

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

[Stadnik, *PRL* **131**, 011001 (2023)]

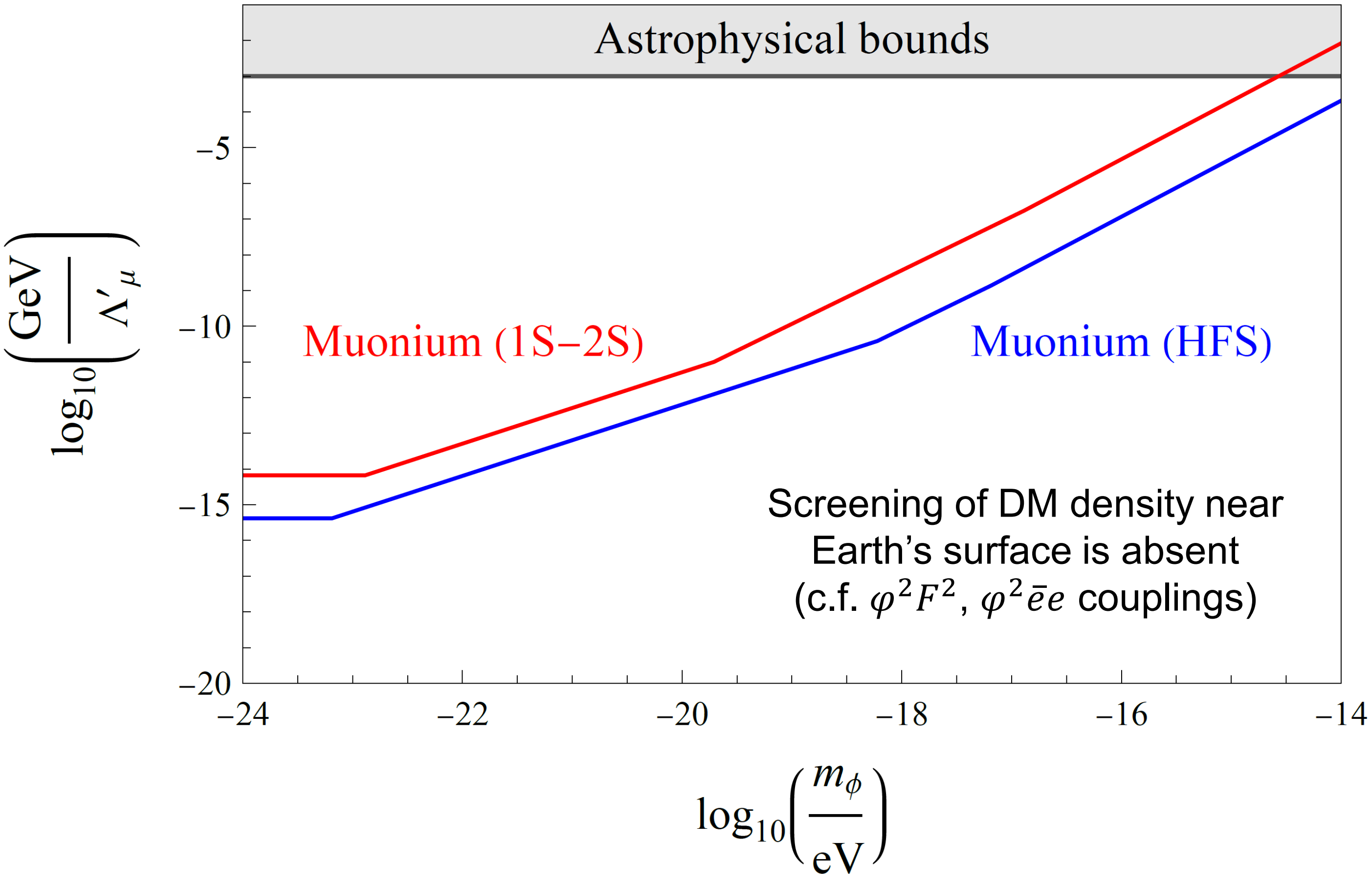
Up to 7 orders of magnitude improvement possible with existing datasets!
(Best existing datasets from muonium experiments at LAMPF and RAL in 1990s)



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

[Stadnik, *PRL* **131**, 011001 (2023)]

Up to 12 orders of magnitude improvement possible with existing datasets!
(Best existing datasets from muonium experiments at LAMPF and RAL in 1990s)

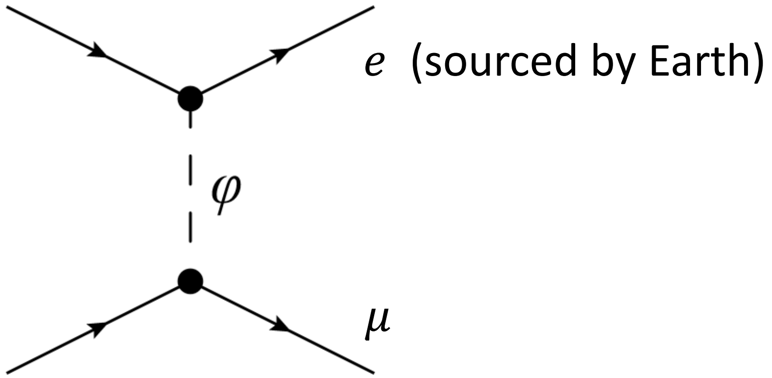


Screening of DM density near Earth's surface is absent (c.f. $\varphi^2 F^2$, $\varphi^2 \bar{e}e$ couplings)

Probing Scalar-Muon Coupling with Muonium Free-fall

[Stadnik, *PRL* **131**, 011001 (2023)]

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



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

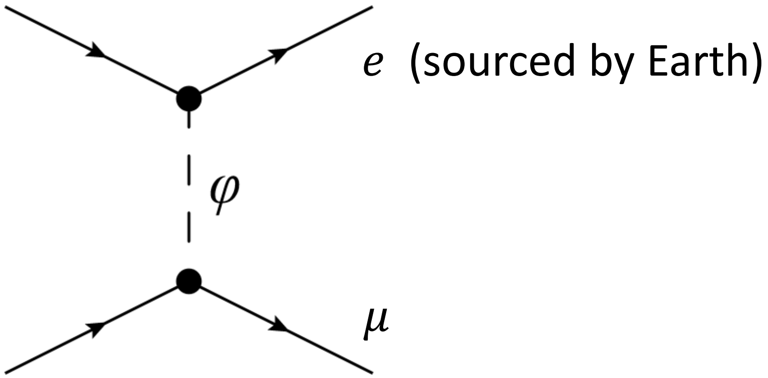
Weak equivalence principle violation

(lepton flavour dependent)

Probing Scalar-Muon Coupling with Muonium Free-fall

[Stadnik, *PRL* **131**, 011001 (2023)]

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



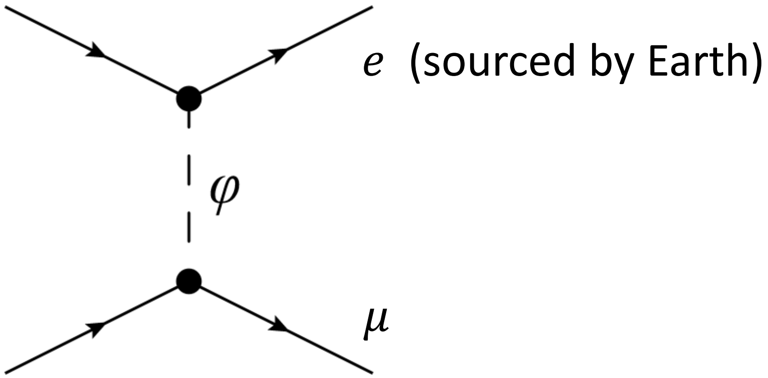
Local value of g measured in free-fall experiments using muonium would differ from experiments using non-muon-based test masses

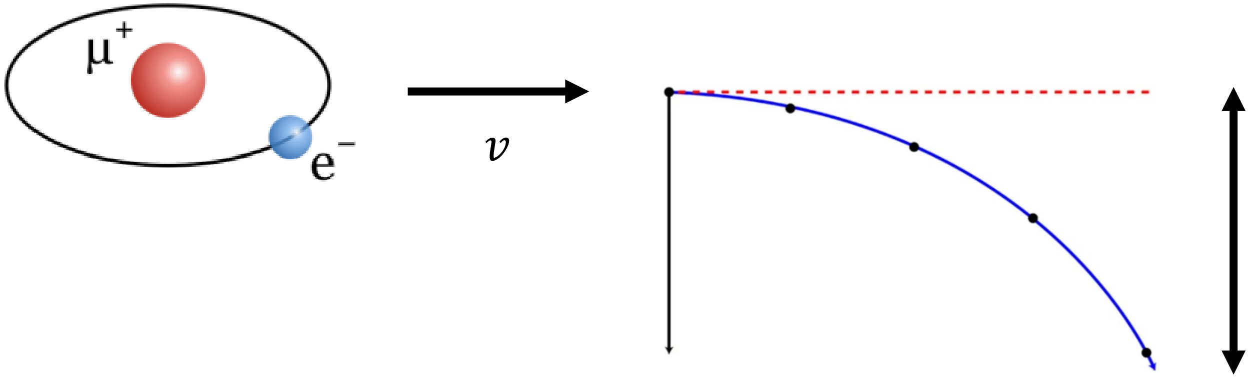
Recently started LEMING experiment at PSI aims to measure g with a precision of $\Delta g/g \sim 10^{-2} - 10^{-1}$ using muonium

Probing Scalar-Muon Coupling with Muonium Free-fall

[Stadnik, *PRL* **131**, 011001 (2023)]

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



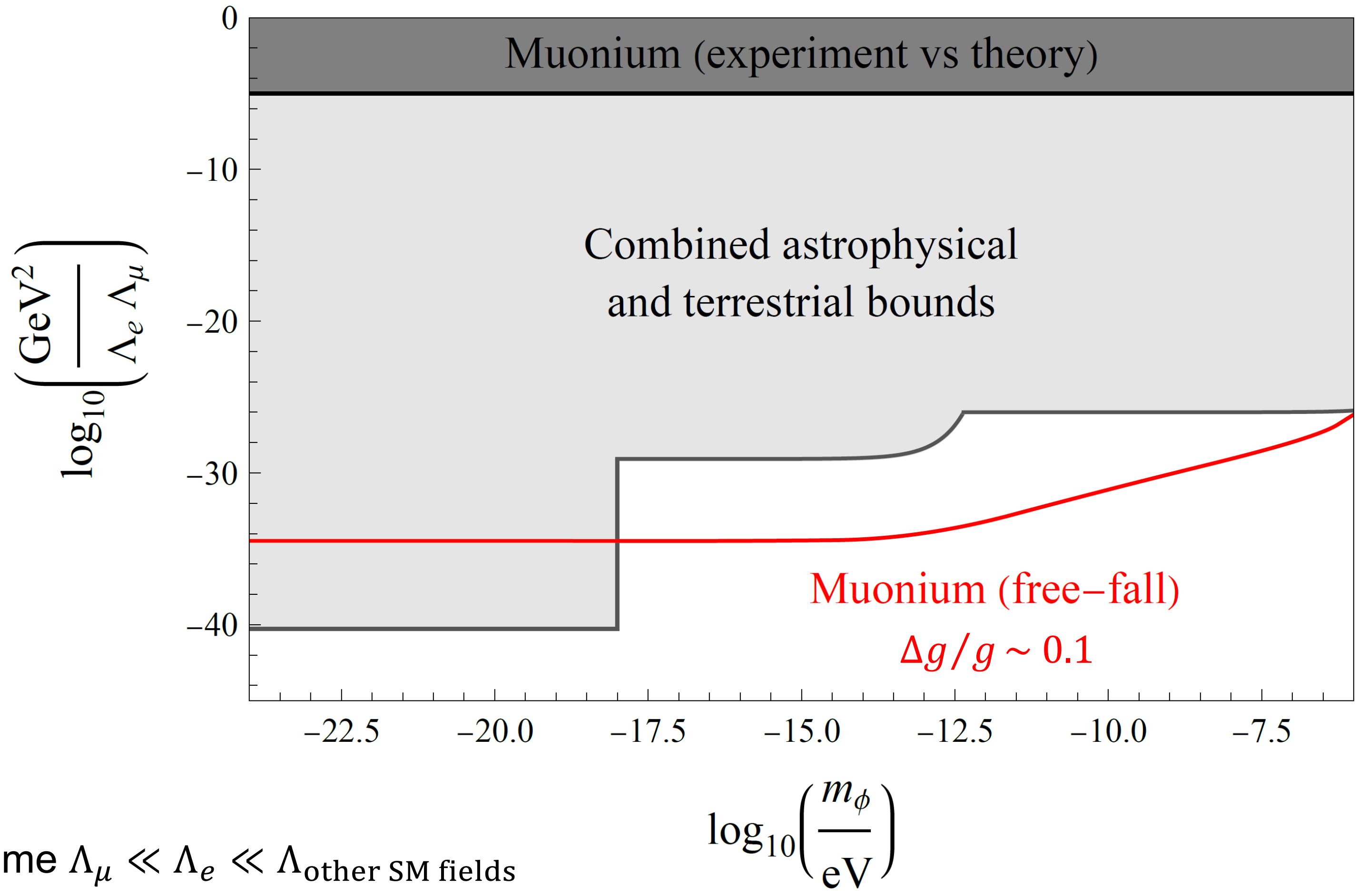


$$\Delta h \sim \frac{g \tau_\mu^2}{2} \approx 24 \text{ pm}$$

Probing Scalar-Muon Coupling with Muonium Free-fall

[Stadnik, *PRL* **131**, 011001 (2023)]

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