Time-Varying Electric Dipole Moments and Spin-Precession Effects Induced by Axion Dark Matter

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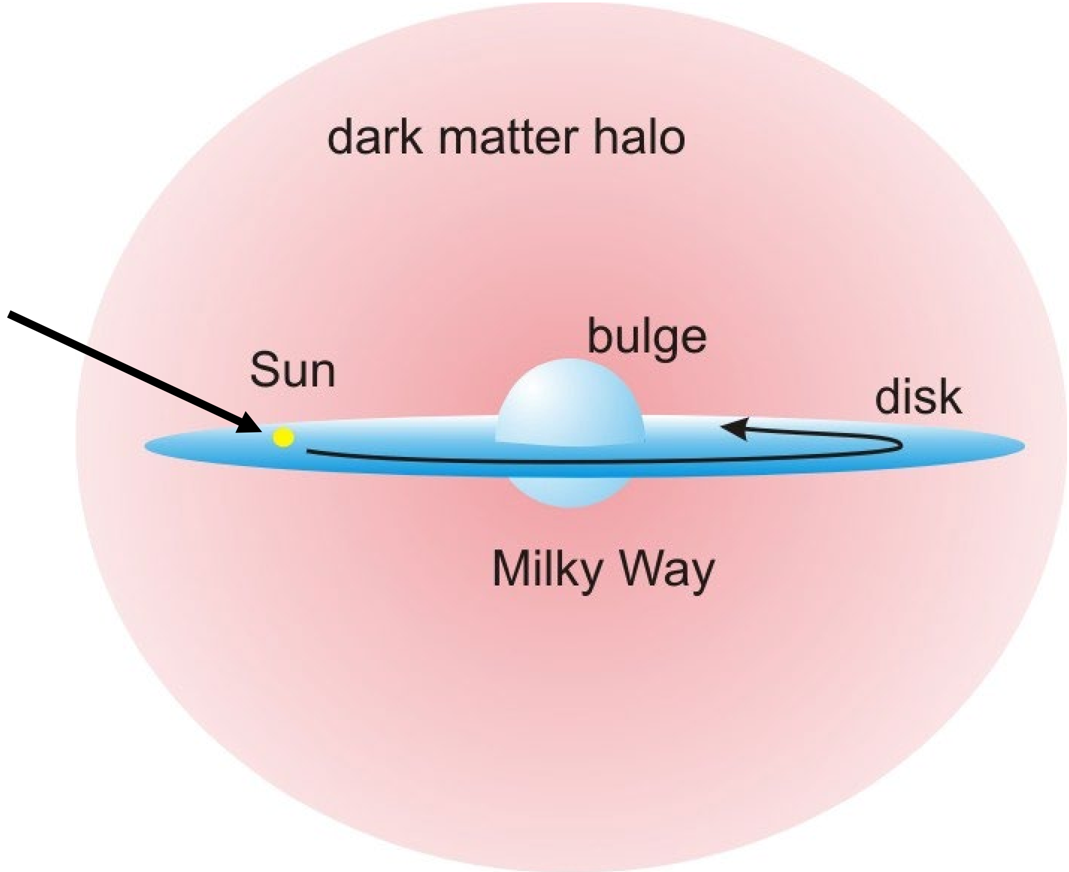
ICISE, Quy Nhon, Vietnam, 4-10 August 2024

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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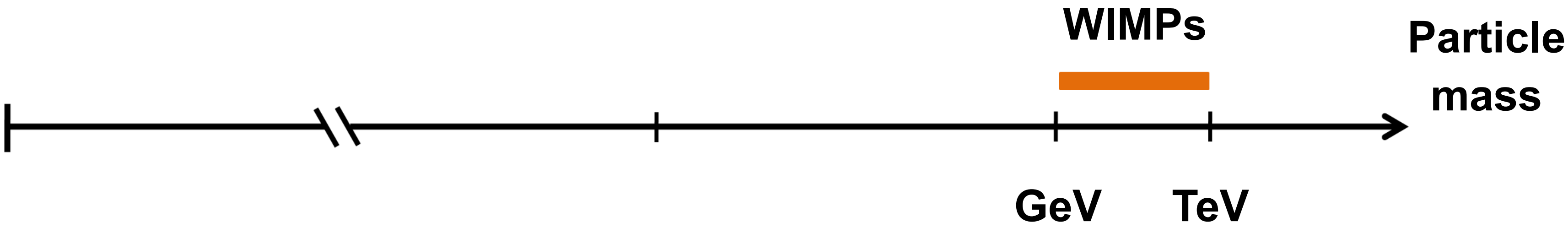

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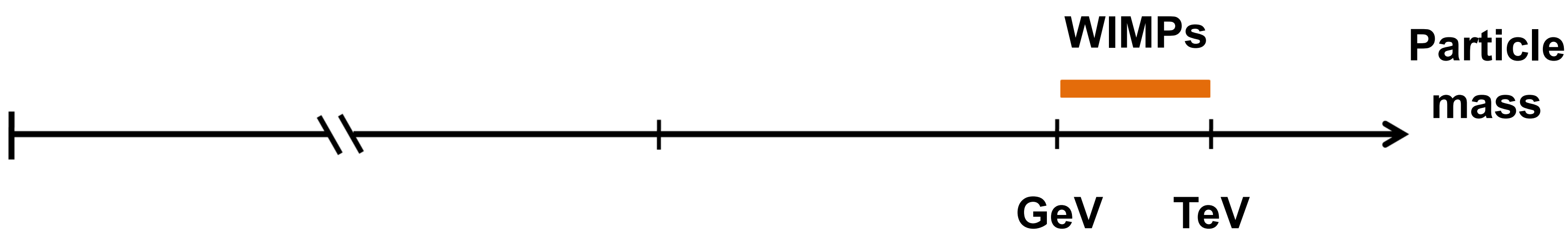
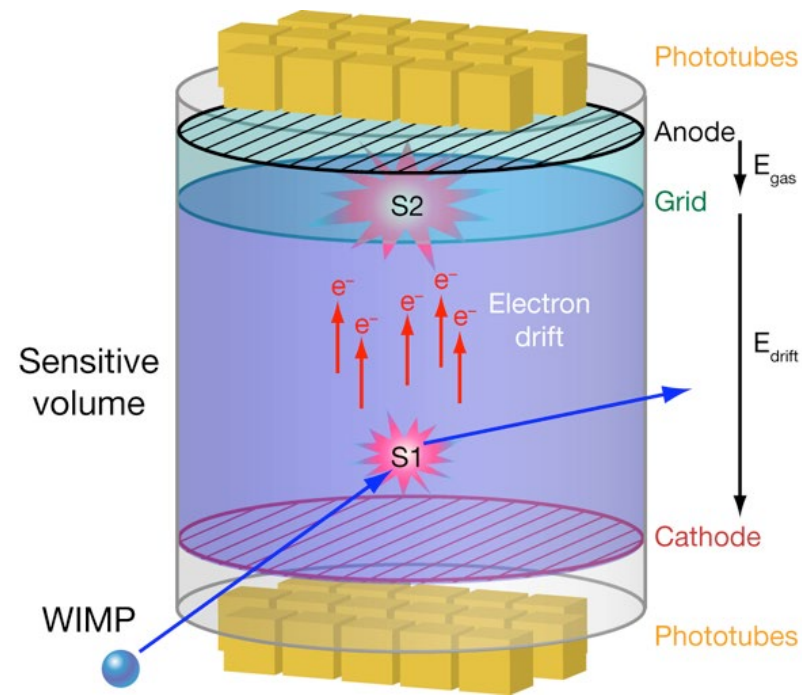


Particle-like signatures



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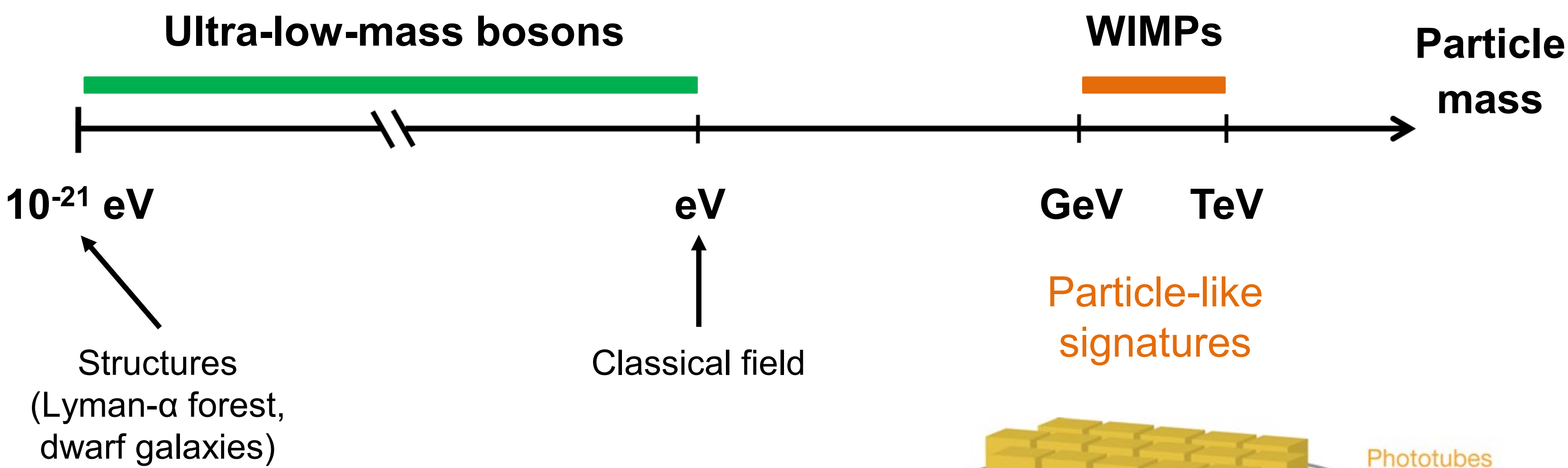
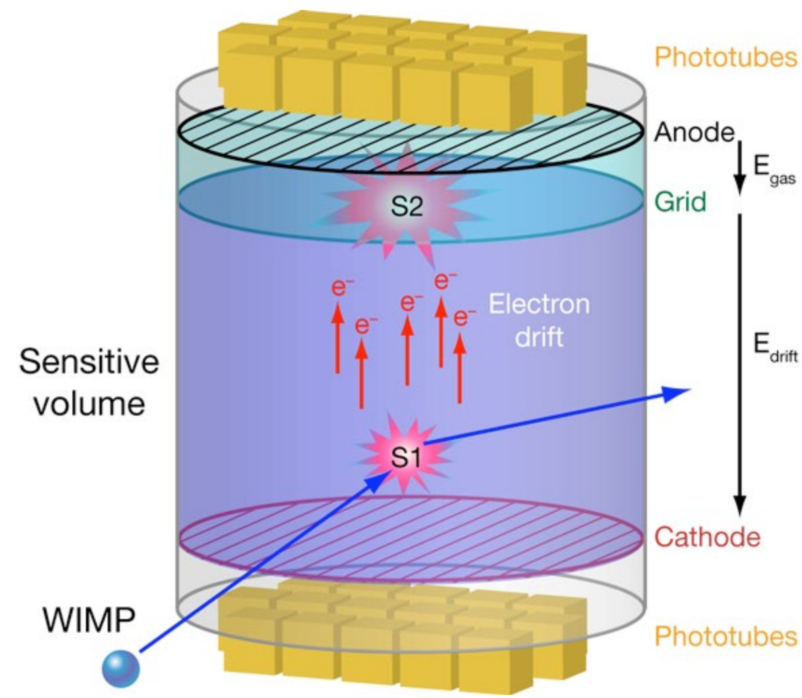
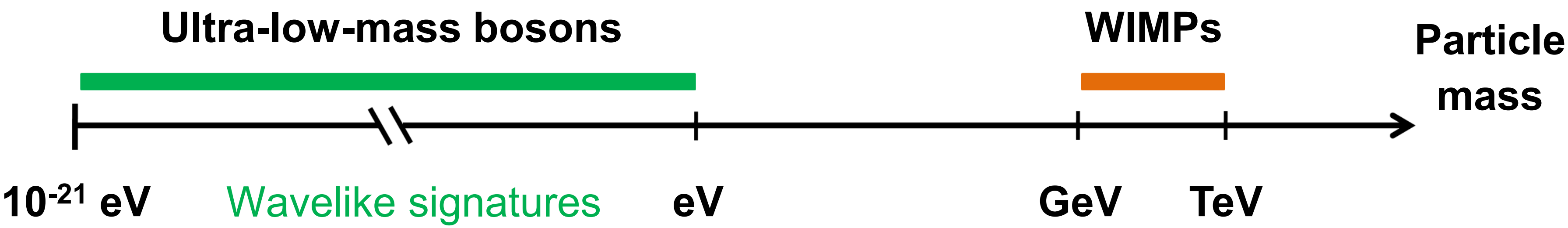

Ultra-low-mass bosons
WIMPs
Particle mass
10^{-21} eV
eV
GeV
TeV
Particle-like signatures
Structures (Lyman-α forest, dwarf galaxies)
Classical field


Phototubes
Anode
E_{gas}
Grid
S2
e^-
Electron drift
E_{drift}
Sensitive volume
S1
Cathode
WIMP
Phototubes

Dark Matter



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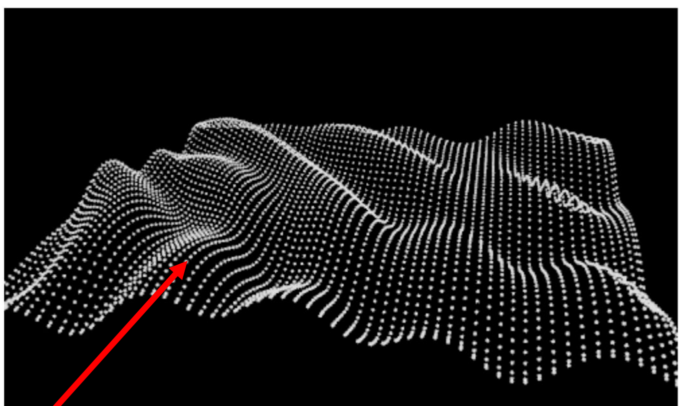
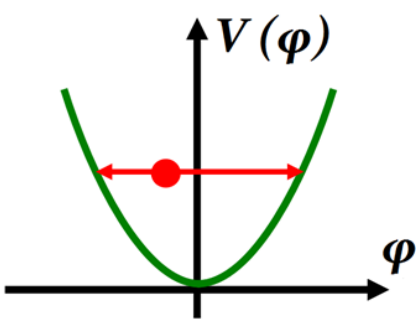
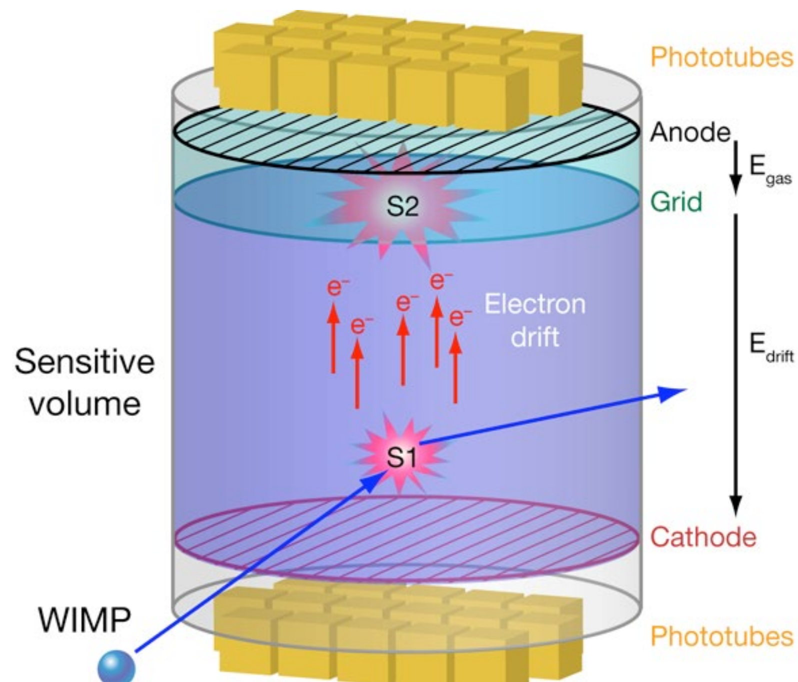


$$\varphi(t) \sim \varphi_0 \cos\left(m_\varphi c^2 t/\hbar\right),\ \varphi_0 \sim \sqrt{\rho_{\mathrm{DM}}}/m_\varphi$$





Dark Matter

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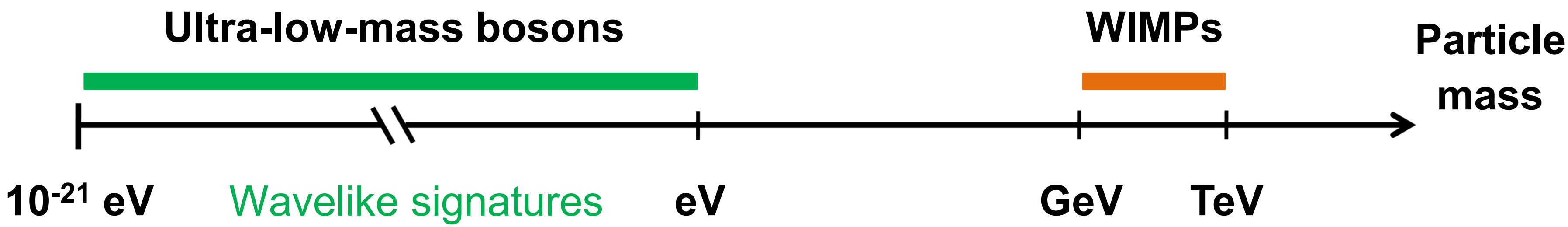

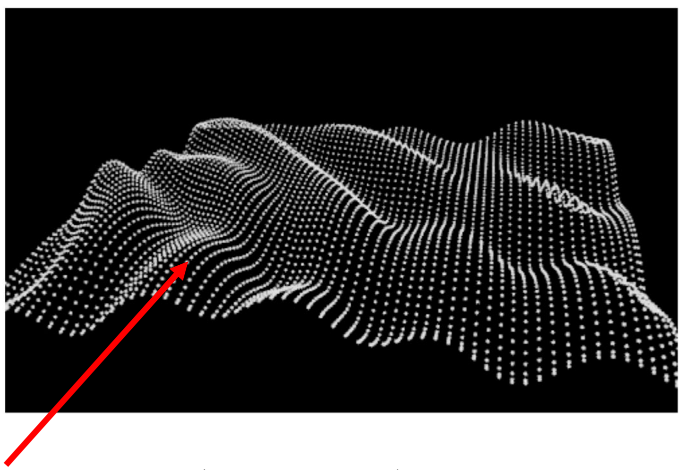

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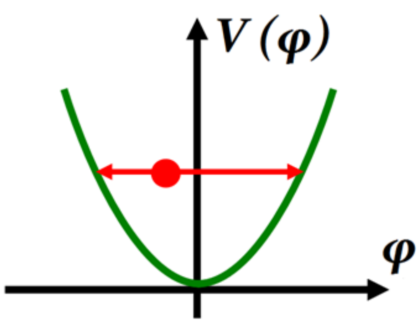
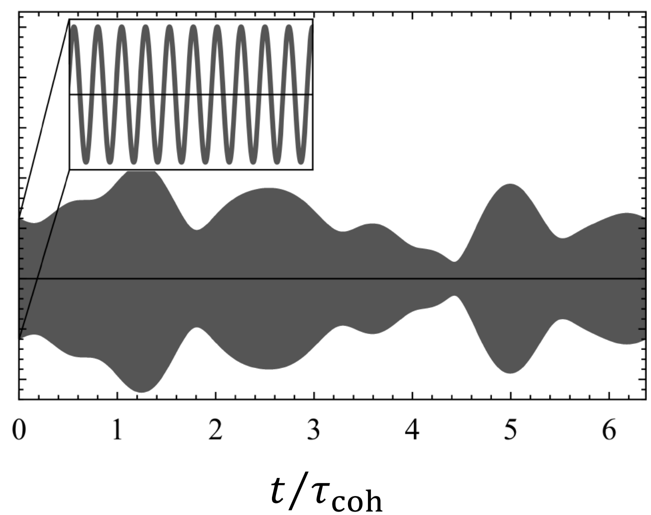


$$\Delta E_\varphi / E_\varphi \sim \Delta v_\varphi^2 / c^2 \sim 10^{-6}$$

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

Evolution of φ_0 with time



Low-mass Spin-0 Dark Matter

Dark Matter

Pseudoscalars (Axions):

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

Time-varying EDMs and spin-precession effects

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

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)

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*

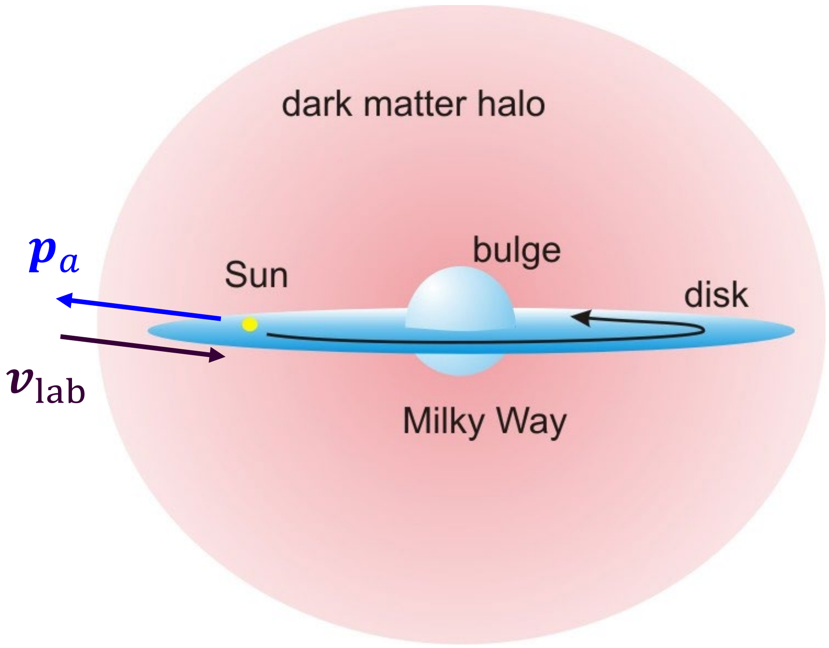
Here I focus on relatively new detection methods based on ***non-electromagnetic*** *couplings leading to spin-based signatures*

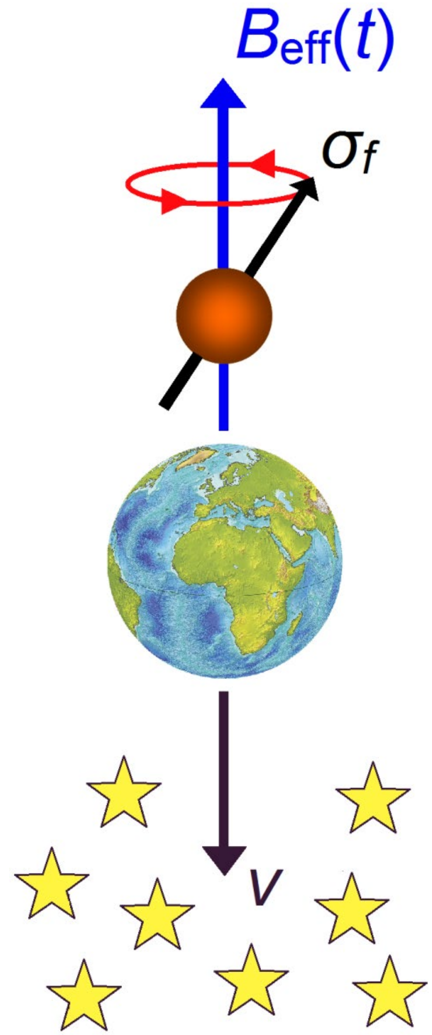
"Axion Wind" Spin-Precession Effect

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

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

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





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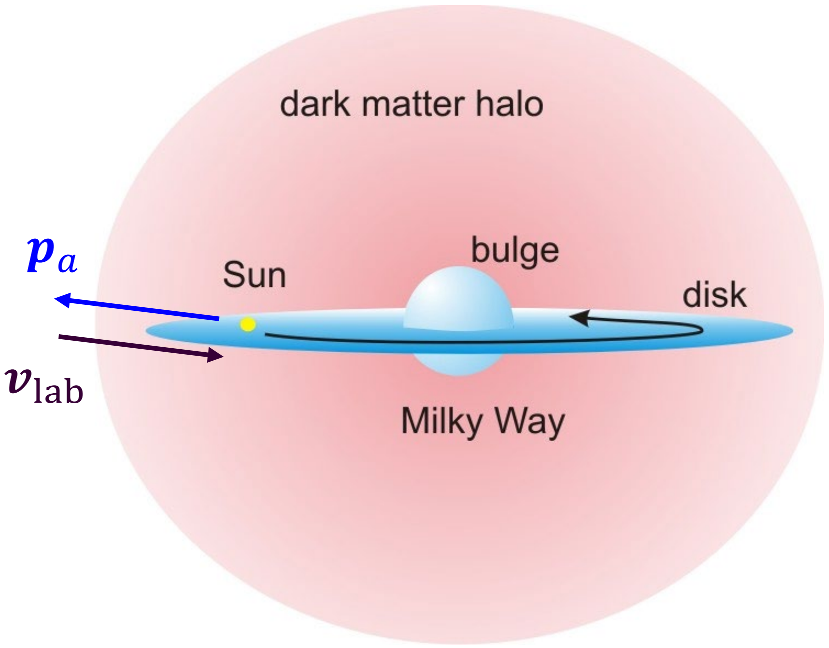

- *In lab frame, apparent direction of $\boldsymbol{p}_a$ changes over the course of a day due to Earth's rotation*

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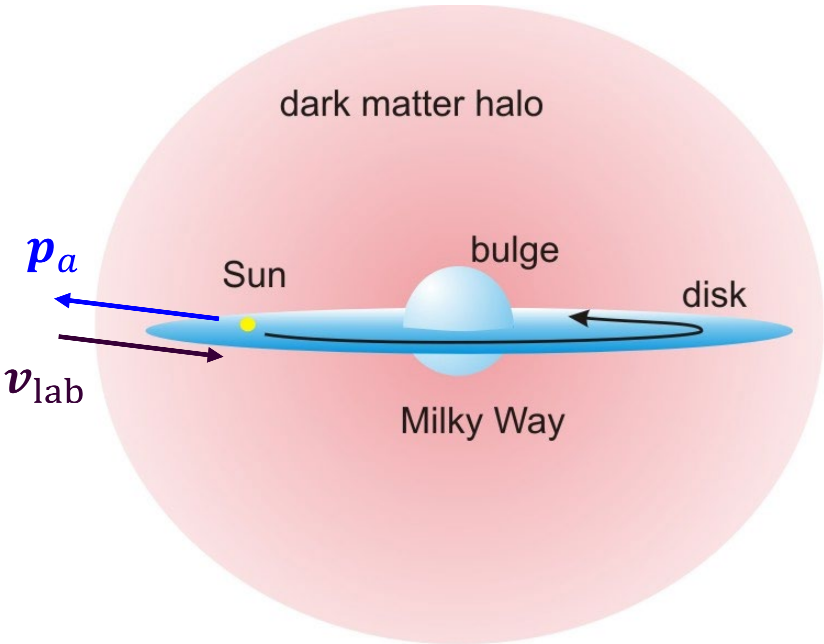


- *In lab frame, apparent direction of $\boldsymbol{p}_a$ changes over the course of a day due to Earth's rotation*
- $\langle \boldsymbol{p}_a \rangle \propto -\boldsymbol{v}_{\rm lab}$ *on long timescales, but on shorter timescales the direction of $\boldsymbol{p}_a$ may differ from $\langle \boldsymbol{p}_a \rangle$ due to random nature of $\boldsymbol{v}_{\rm DM}$ (Maxwell-Boltzmann distributed)*

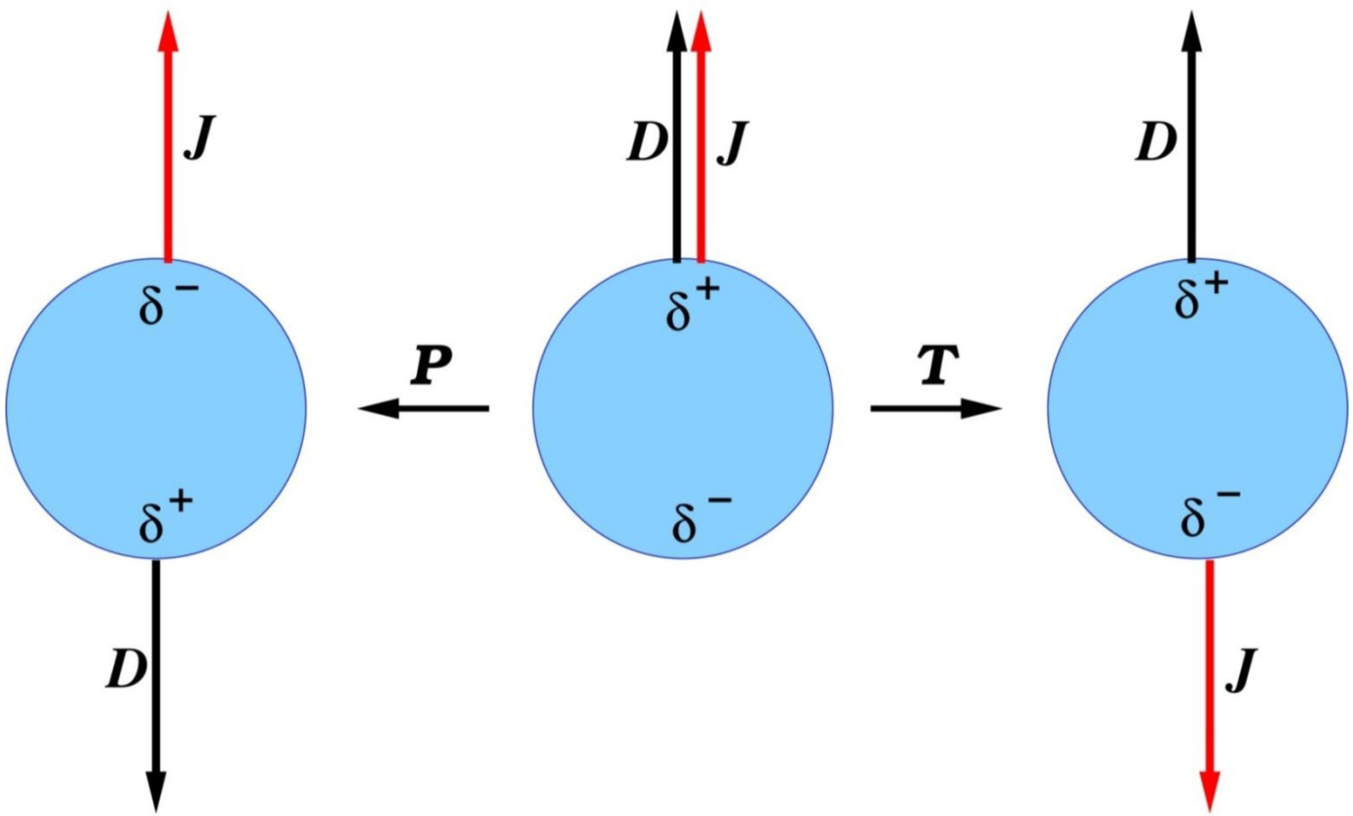
[Centers *et al*., *Nature Comm.* **12**, 7321 (2021)], [Lisanti *et al*., *PRD* **104**, 055037 (2021)]

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

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

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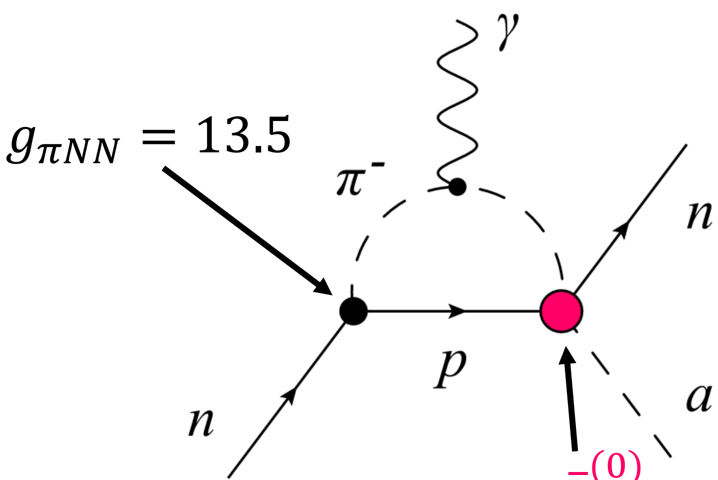
Nucleon EDMs



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

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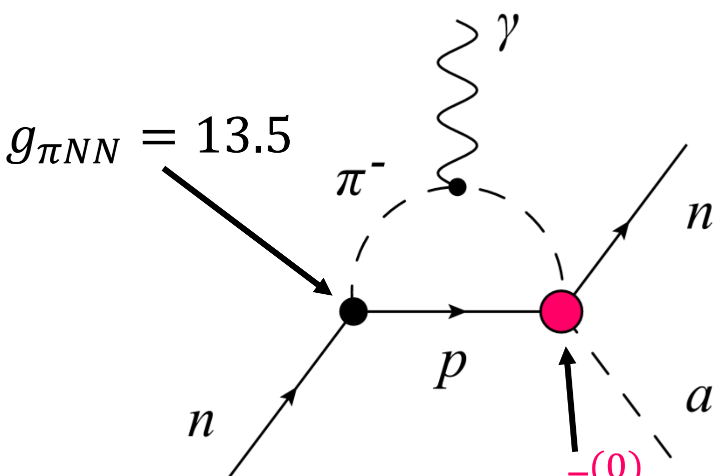
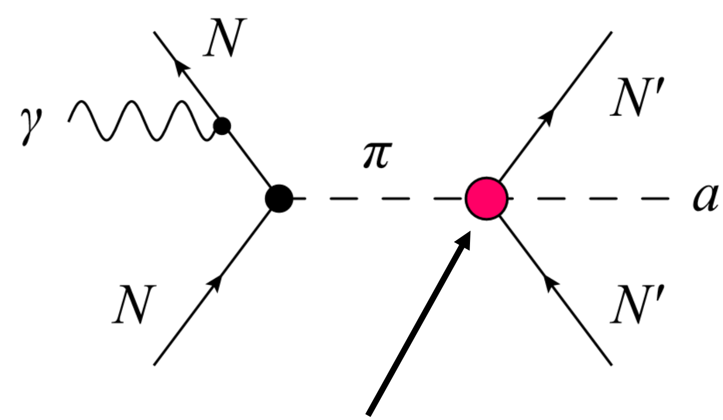
Nucleon EDMs

_CP_-violating intranuclear forces





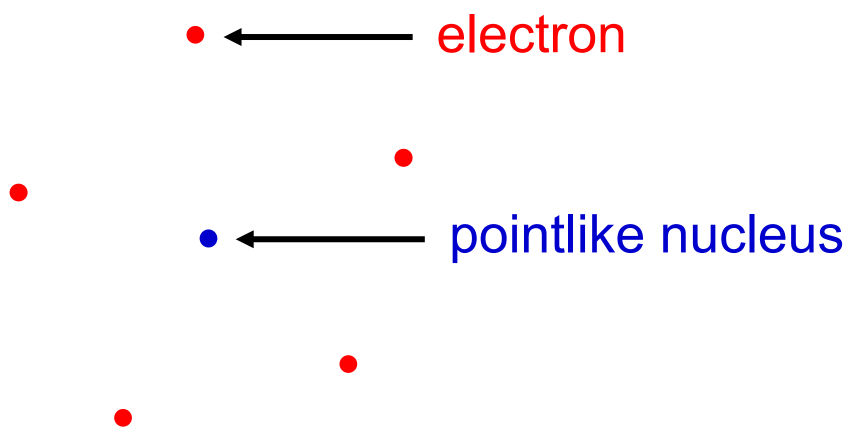
$\bar{g}_{\pi NN}^{(0)} \approx 0.016\, C_G a_0 \cos(m_a t)/f_a$

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

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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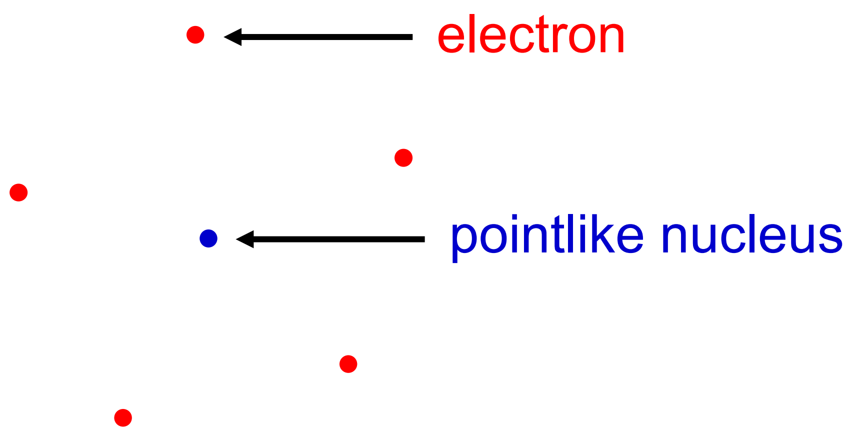

Classical explanation for nuclear EDM: A neutral atom does not accelerate in an external electric field!

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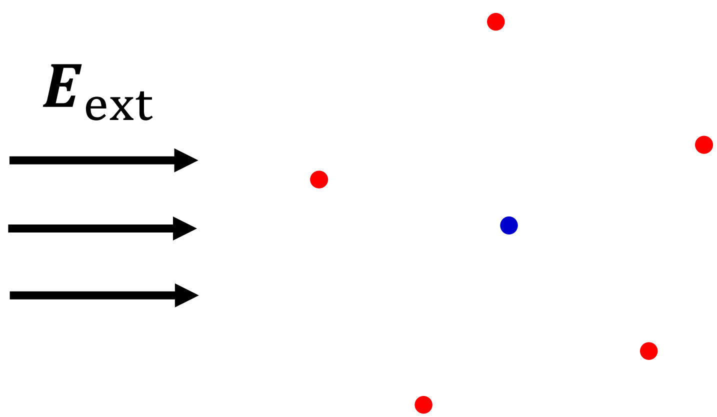

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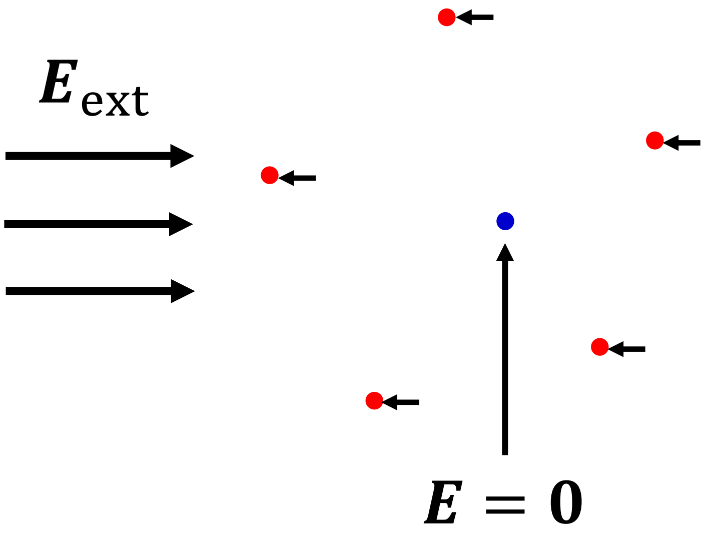

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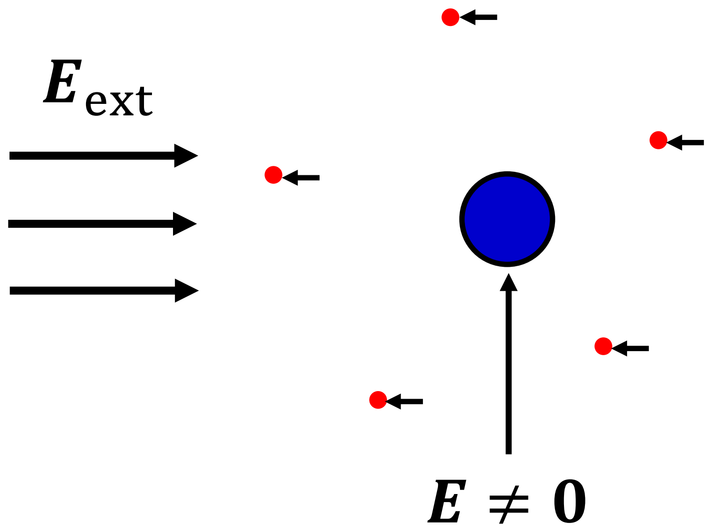
Lifting of Schiff's Theorem

[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*.



$$|\boldsymbol{S}_{\text{nucl}}| \sim |\boldsymbol{d}_{\text{nucl}}| \times R_{\text{nucl}}^2$$

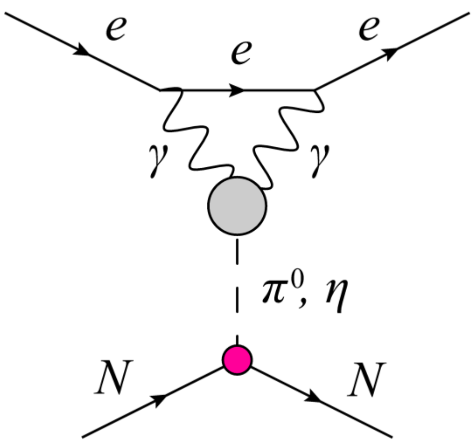
Paramagnetic Atoms and Molecules

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

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

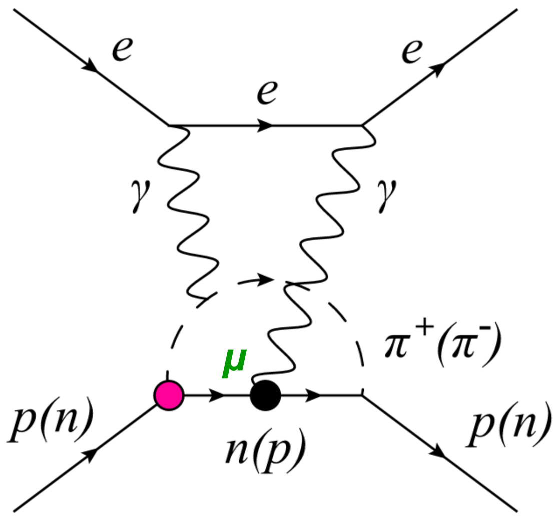
Interaction of one of photons with nucleus is *magnetic* $\Rightarrow$ no Schiff screening

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



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

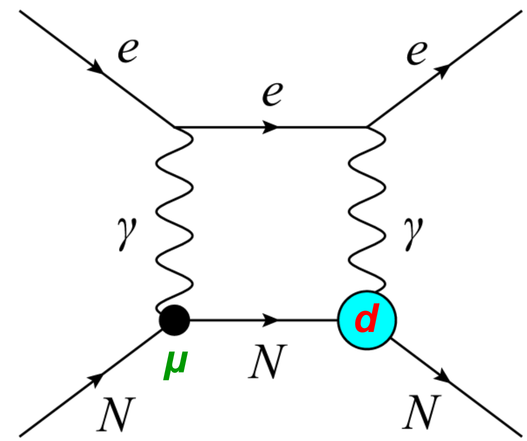
NLO: $\mathcal{O}\left(m_\pi^{-1}\right)$



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

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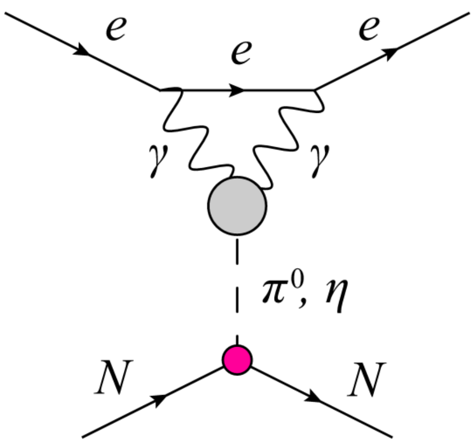

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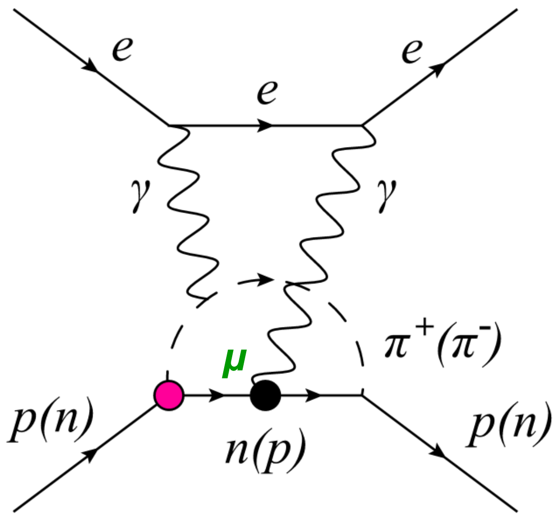

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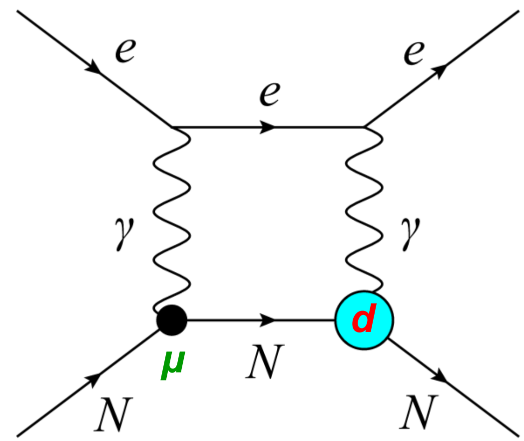


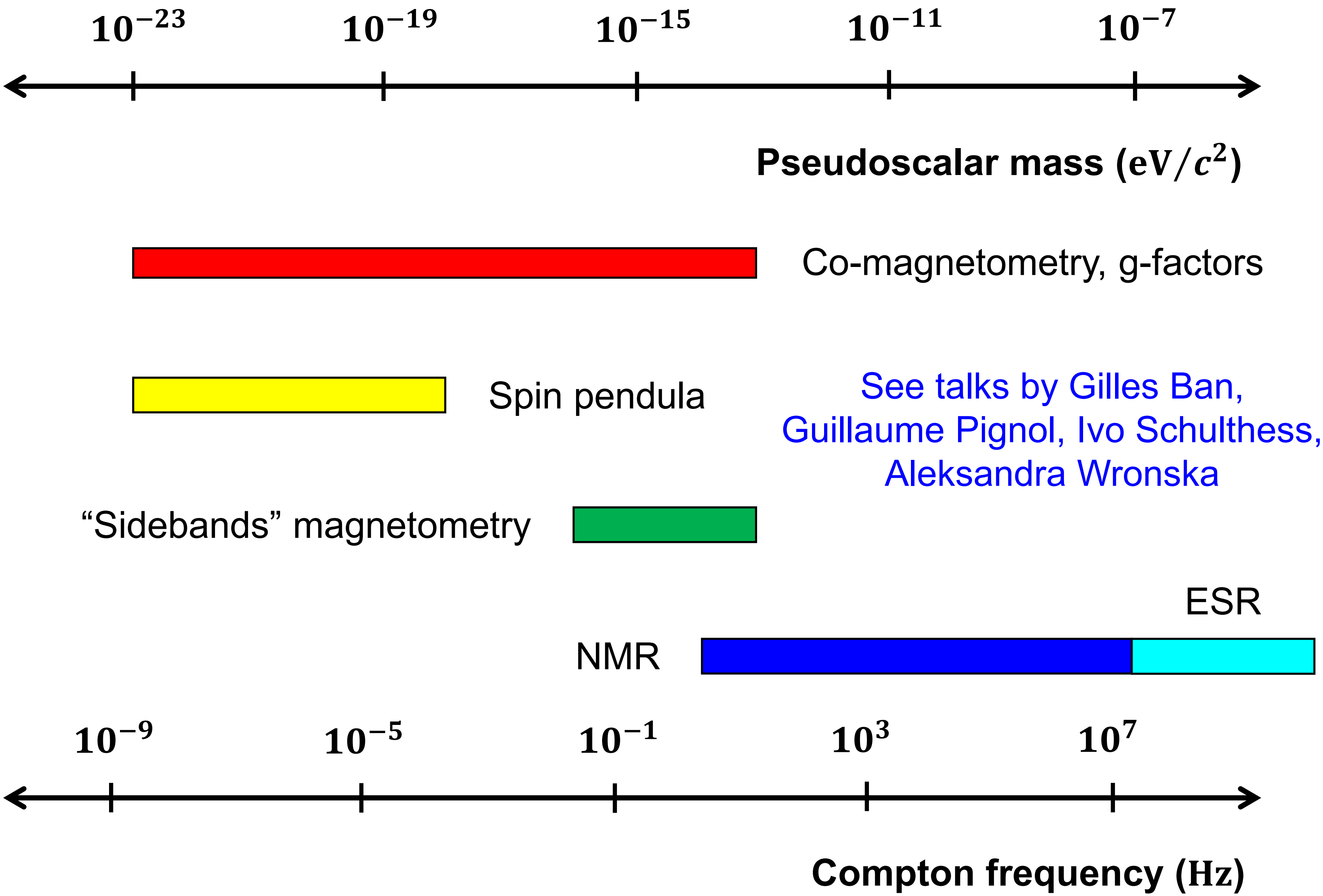
π^0, η contributions: ***opposite*** sign

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

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

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

Probes of Time-Varying EDMs and Spin-Precession Effects



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

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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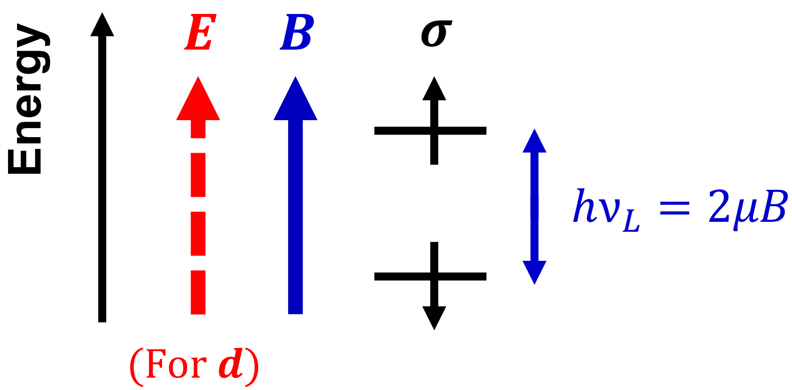
Experiment (n/Hg): [nEDM collaboration, *PRX* **7**, 041034 (2017)]



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

↑ B-field effect

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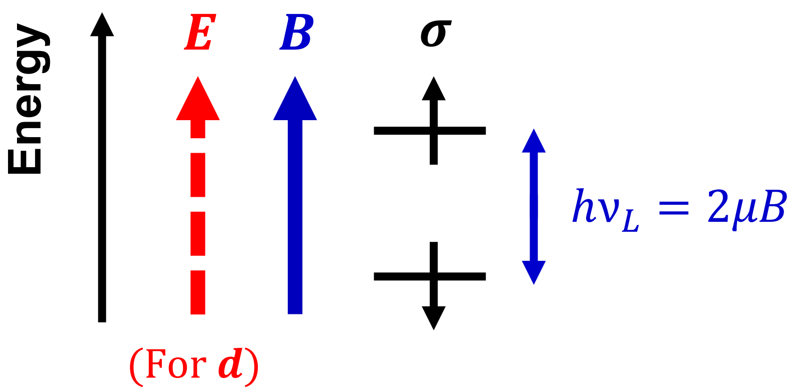

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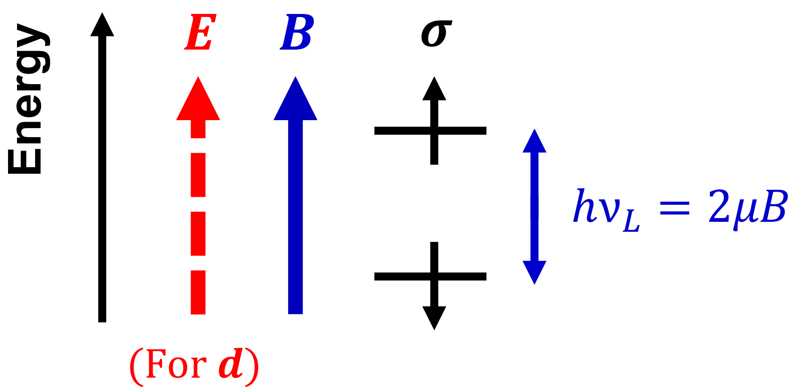

$$\frac{\nu_n}{\nu_{\text{Hg}}} = \left|\frac{\mu_n \cancel{B}}{\mu_{\text{Hg}} \cancel{B}}\right| + R(t)$$

***B*-field effect**

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

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

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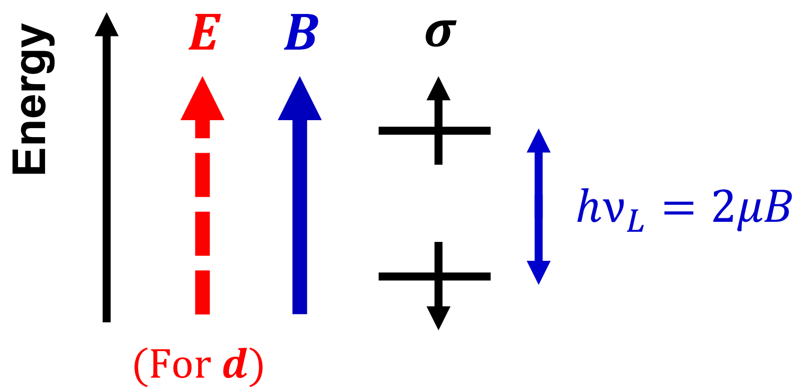
Lorentz-invariance-violation-type searches:

Magnetometers, *cold/ultracold particles*, *spin pendula*

Experiment (n/Hg): [nEDM collaboration, *PRX* **7**, 041034 (2017)]

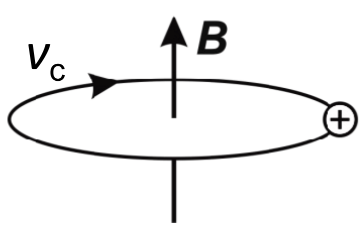


$$\frac{\nu_n}{\nu_{\mathrm{Hg}}} = \left|\frac{\mu_n B}{\mu_{\mathrm{Hg}} B}\right| + R(t)$$

B-field effect

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

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



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

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

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

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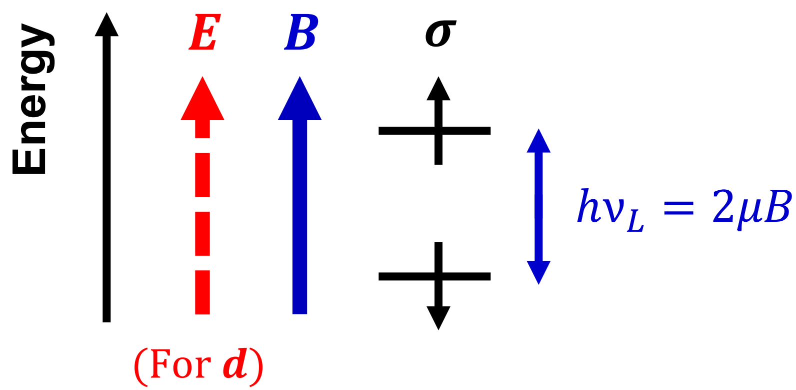

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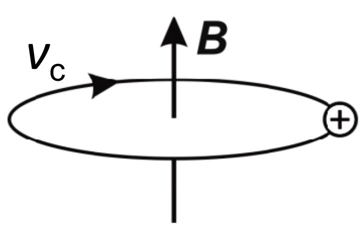


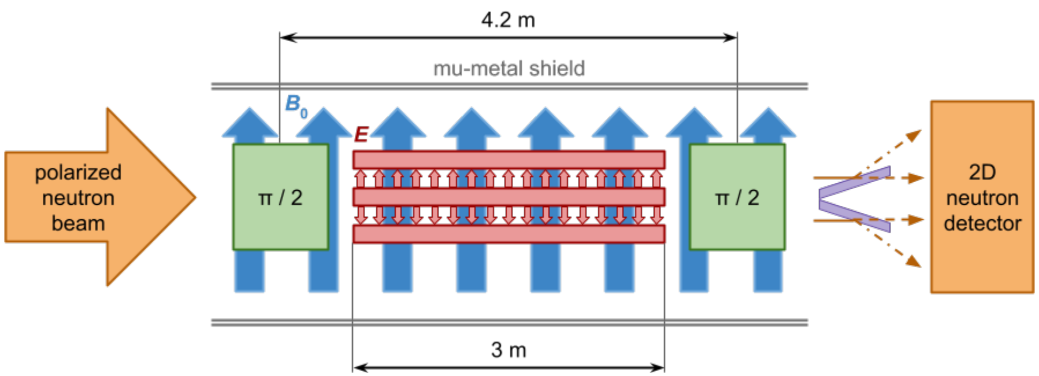
$$\left(\frac{\nu_L}{\nu_c}\right)_{\bar{p}} = \frac{|g_{\bar{p}}|}{2} + R(t)$$

Antimatter probe!

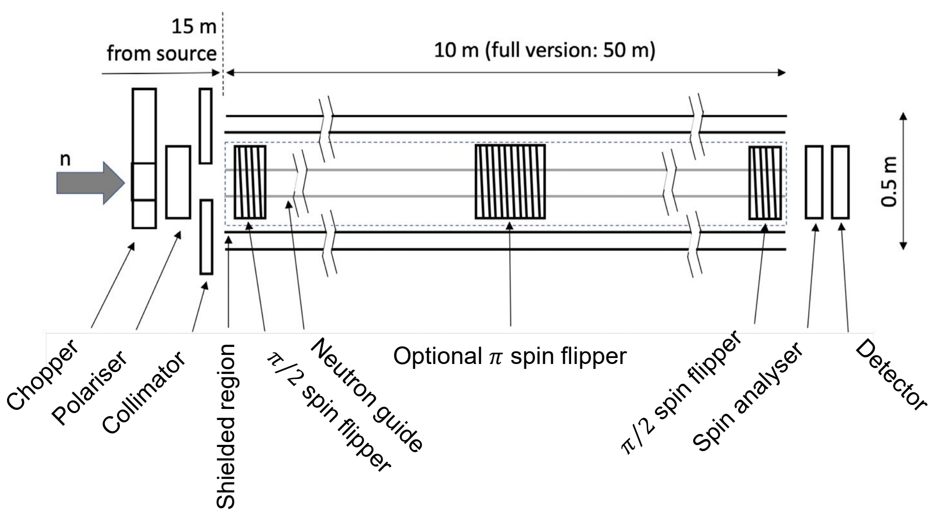
Broadband Searches, $a\bar{n}n/aG\tilde{G}$, $10^{-22}\mathrm{eV} \leq m_a \leq 10^{-13}\mathrm{eV}$

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

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



Proposal at ESS (n beam): [Fierlinger, Holl, Milstead, Santoro, Snow, Stadnik, arXiv:2404.15521]

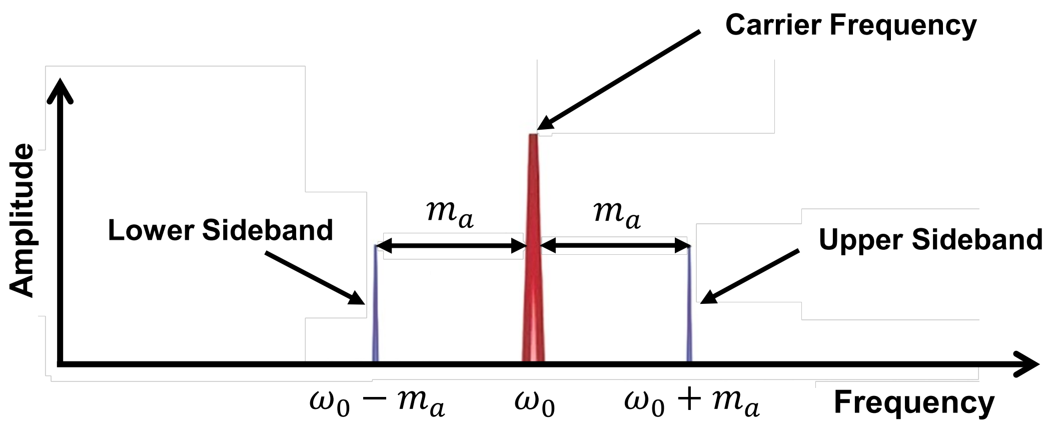


Broadband Searches, $a\bar{N}N$, $10^{-16}\mathrm{eV} \leq m_a \leq 10^{-13}\mathrm{eV}$

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

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

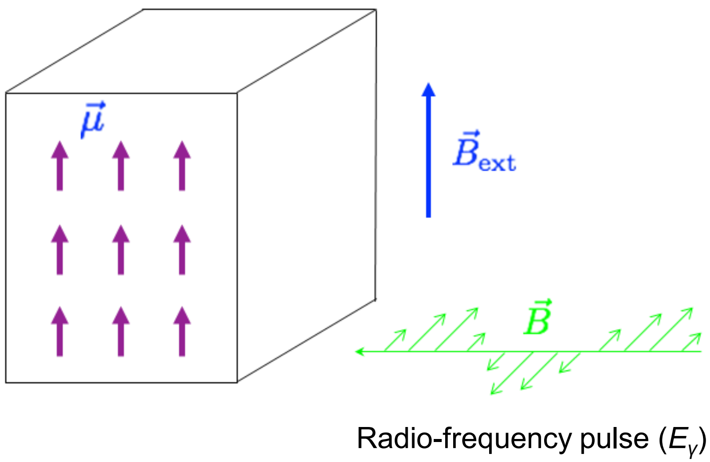
Resonant Searches, $a\bar{N}N/aG\tilde{G}$, $10^{-14}\text{eV} \leq m_a \leq 10^{-7}\text{eV}$

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

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

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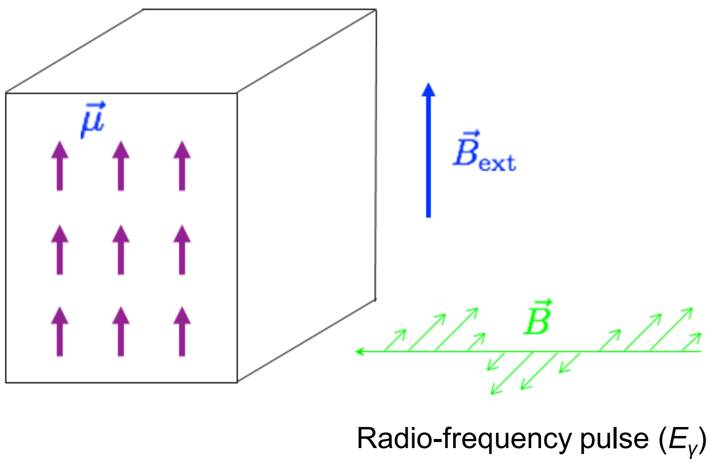

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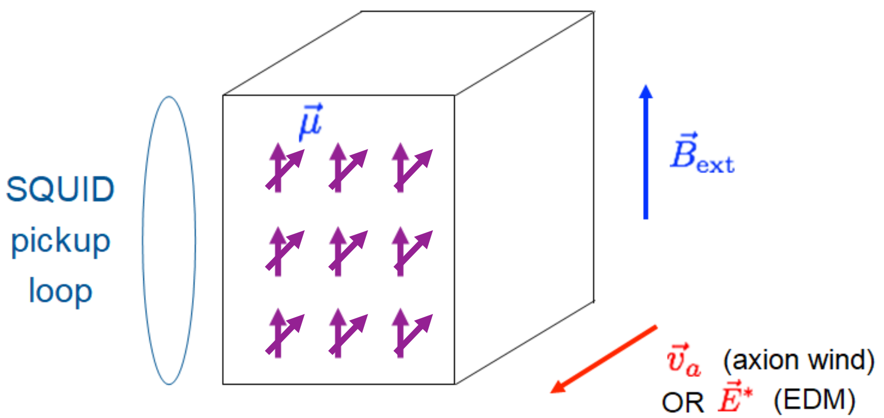
Dark-matter-driven NMR



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

Measure transverse magnetisation

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

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

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$\Downarrow$

BBN

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

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

$$\Rightarrow \frac{\delta m_\pi}{m_\pi}\bigg|_{\theta \approx 0} \approx -\frac{m_u m_d}{4(m_u + m_d)^2}\theta^2$$

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δm_p

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

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

Second-Order, CP-Even Effects

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θ-term may be absorbed into the quark mass matrix

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$\Downarrow$ **BBN** [Blum *et al.*, *PLB* **737**, 30 (2014)]

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

$\Uparrow$

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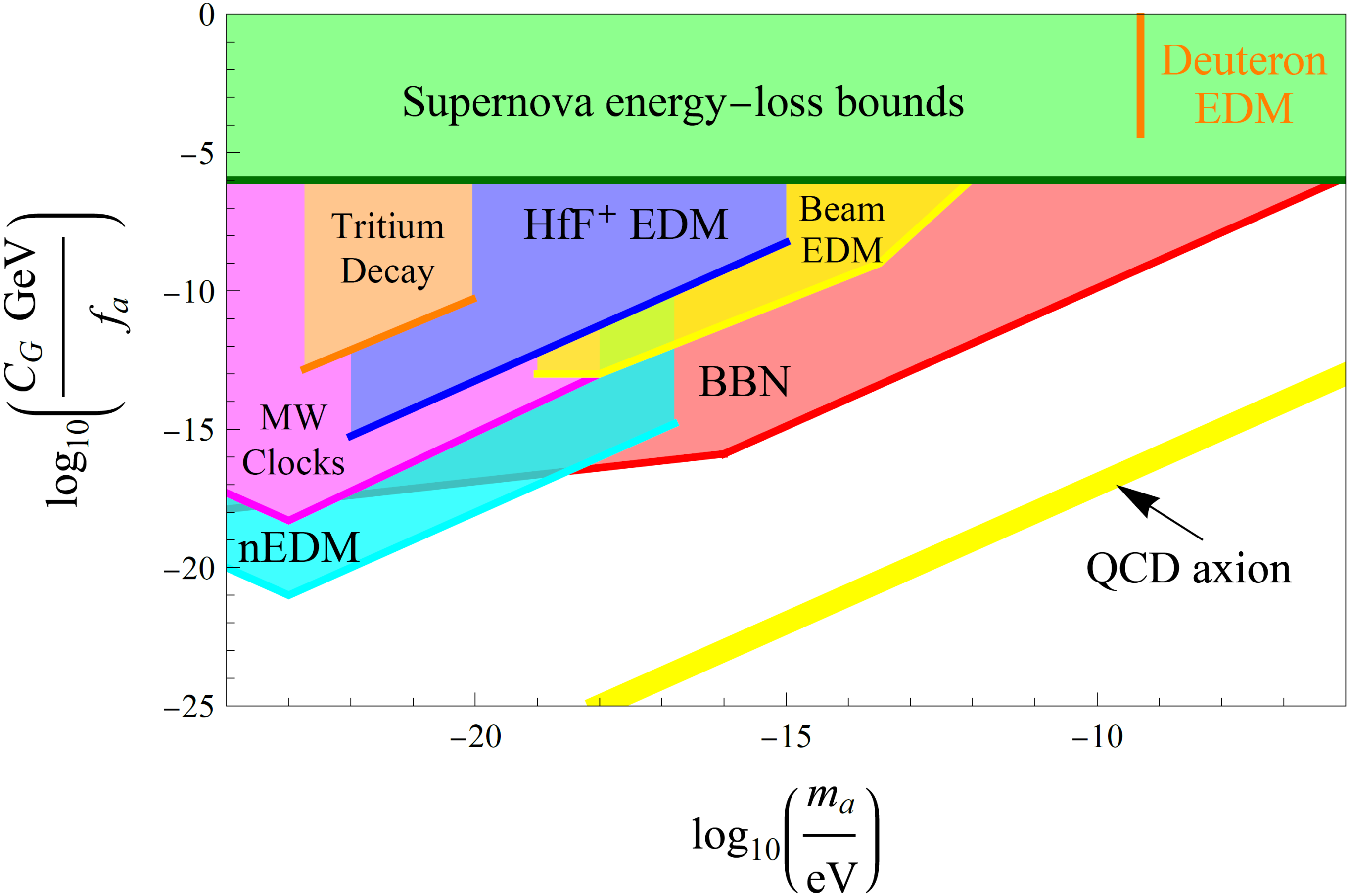
δm_p $\Rightarrow$ **Microwave clocks**

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

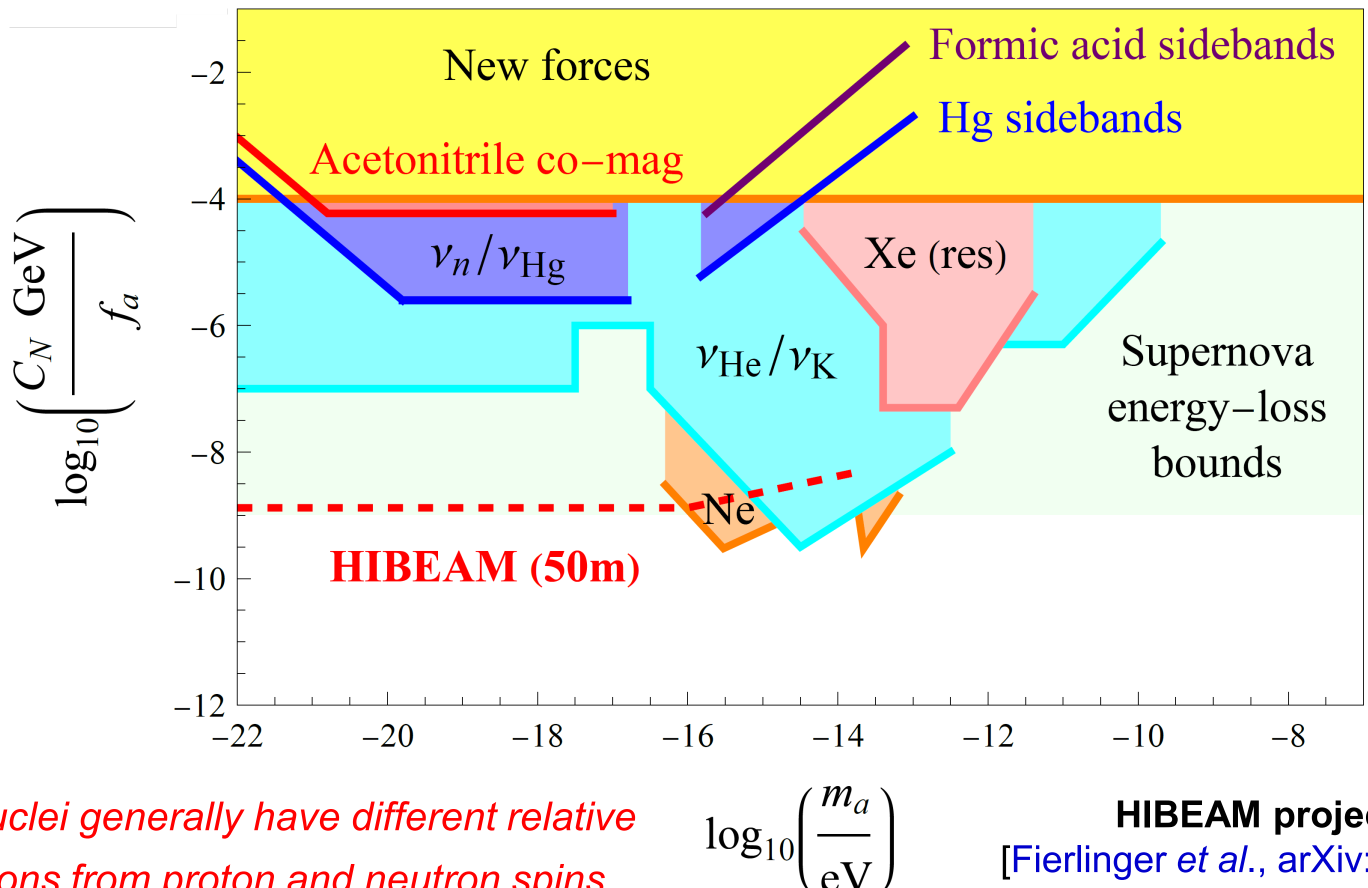
Constraints on Interaction of Axion Dark Matter with Gluons

nEDM constraints: [nEDM collaboration, *PRX* **7**, 041034 (2017)]
HfF⁺ EDM constraints: [Roussy *et al*., *PRL* **126**, 171301 (2021)]
Beam EDM constraints: [Schulthess *et al*., *PRL* **129**, 191801 (2022)]
Deuteron EDM constraints: [Karanth *et al*., *PRX* **13**, 031004 (2023)]



Constraints on Interaction of Axion Dark Matter with Nucleons

ν_n/ν_{Hg} constraints: [nEDM collaboration, *PRX* **7**, 041034 (2017)]
ν_{He}/ν_K constraints: [Bloch *et al*., *JHEP* **2020**, 167 (2020); *Nature Comm*. **14**, 5784 (2023)]
Xe (res) constraints: [Jiang *et al*., *Nature Phys*. **17**, 1402 (2021)], [Bloch *et al*., *Sci. Adv*. **8**, eabl8919 (2022)]
Hg sidebands constraints: [nEDM collaboration, *SciPost Phys*. **15**, 058 (2023)]



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

HIBEAM projection:
[Fierlinger *et al*., arXiv:2404.15521]

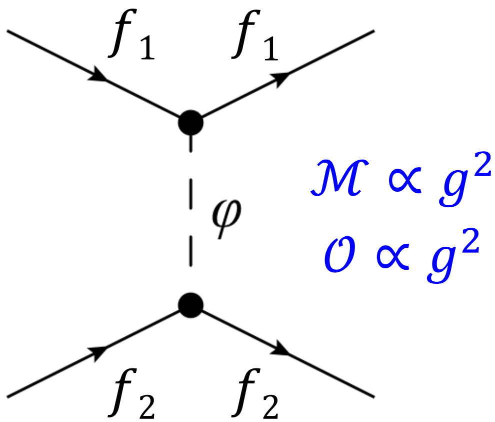
Summary

- We have identified new signatures of axion(like) dark matter that have allowed us and other groups to improve the sensitivity to underlying interaction strengths compared with previous methods

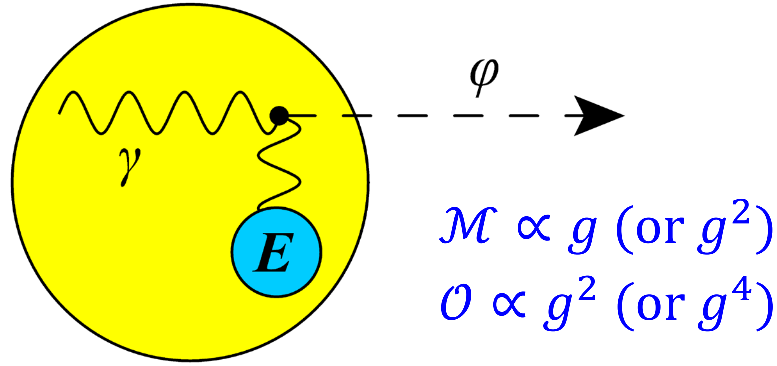
- Novel approaches based on precision low-energy experiments (often "table-top" scale) searching for:
    - Time-varying electric dipole moments
    - Time-varying spin-precession effects
    - Varying fundamental "constants" of Nature

Back-Up Slides

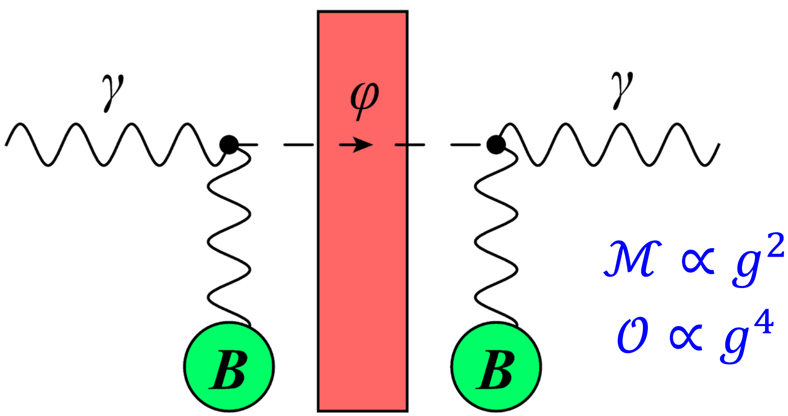
Complementary Probes of Low-mass Scalars



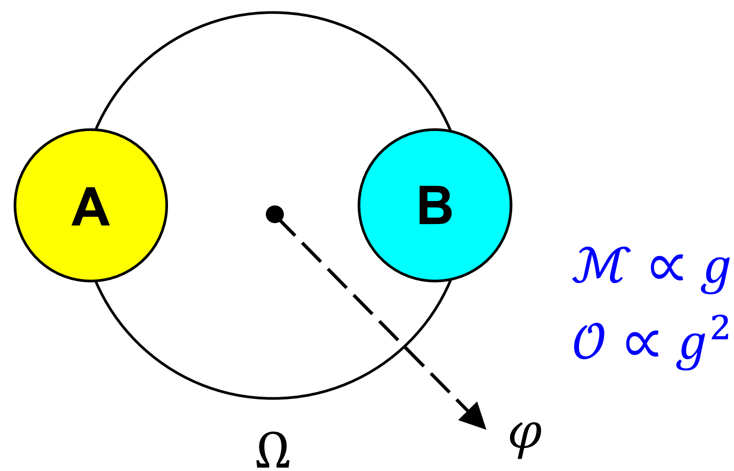
New forces



Stellar emission

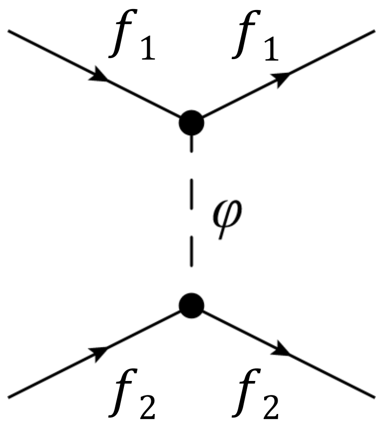


Interconversion with ordinary particles



Larmor radiation

Equivalence-Principle-Violating Forces



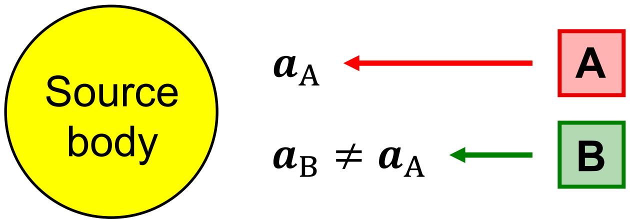
$$\mathcal{L}_f = -\frac{\varphi}{\Lambda_f} m_f \bar{f} f$$

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

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

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

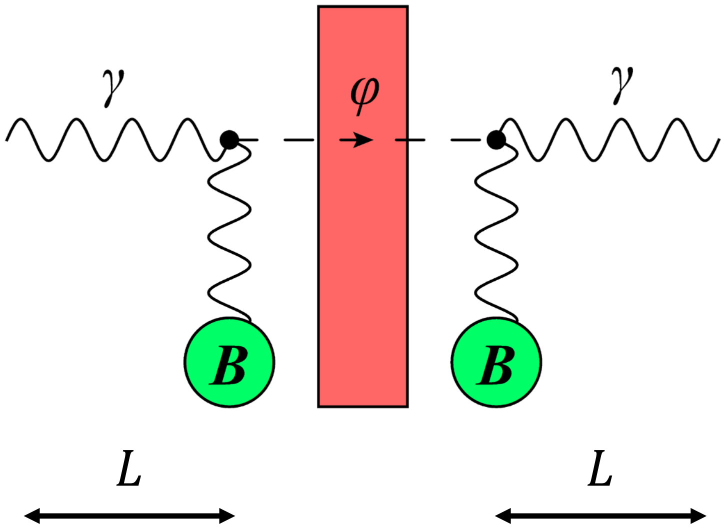
- Different atoms and isotopes would generally experience different accelerations, implying violation of the equivalence principle



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

Light-shining-through-a-wall Experiments

[ALPS Collaboration, *PLB* **689**, 149 (2010)], [OSQAR Collaboration, *PRD* **92**, 092002 (2015)]



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

$$\Rightarrow\ p_{\gamma\to\varphi\to\gamma} = \left(\frac{B}{\Lambda_\gamma}\right)^4 \left[\frac{1}{q}\sin\left(\frac{qL}{2}\right)\right]^4$$

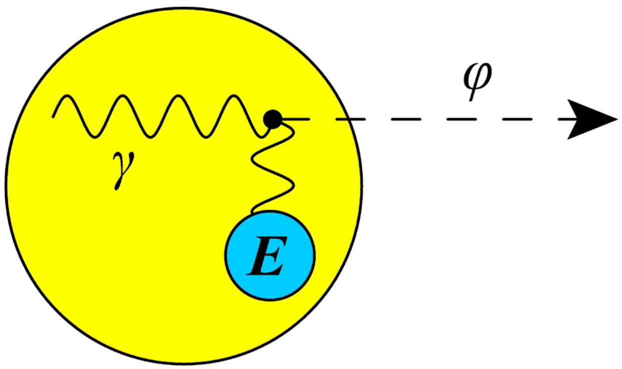
$q = |\boldsymbol{k}_\gamma - \boldsymbol{k}_\varphi|$ is the momentum transfer during interconversion

$\mathcal{L}_{\rm scalar} \propto \varphi F_{\mu\nu}F^{\mu\nu} \propto \varphi\left(\boldsymbol{B}^2 - \boldsymbol{E}^2\right) \Rightarrow$ Need $\boldsymbol{E}_\gamma^{\rm lin} \perp \boldsymbol{B}$

$\mathcal{L}_{\rm pseudoscalar} \propto \varphi F_{\mu\nu}\tilde{F}^{\mu\nu} \propto \varphi \boldsymbol{E}\cdot\boldsymbol{B} \Rightarrow$ Need $\boldsymbol{E}_\gamma^{\rm lin} \parallel \boldsymbol{B}$

Astrophysical Emission (Hot Media)

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

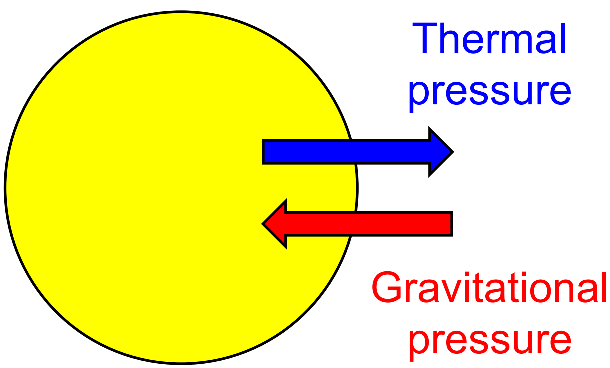


$$\mathcal{L}_\gamma = \frac{\varphi}{\Lambda_\gamma}\frac{F_{\mu\nu}F^{\mu\nu}}{4} \Rightarrow \varepsilon_{\gamma\gamma\to\varphi} \sim \frac{T^7}{\Lambda_\gamma^2}$$

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

Primakoff-type conversion

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)

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

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

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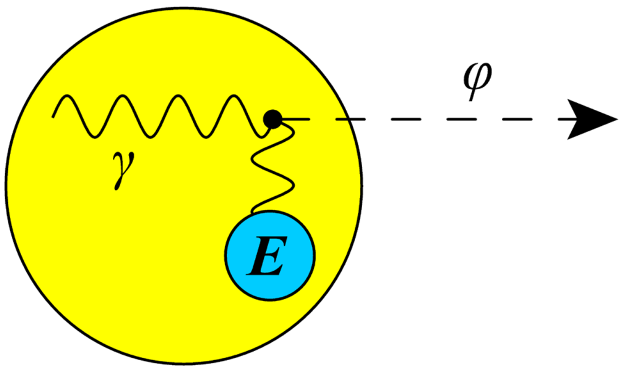
[Raffelt, *Phys. Rept.* **198**, 1 (1990)]



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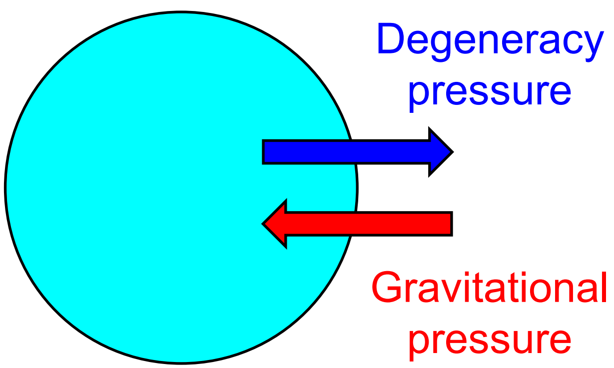
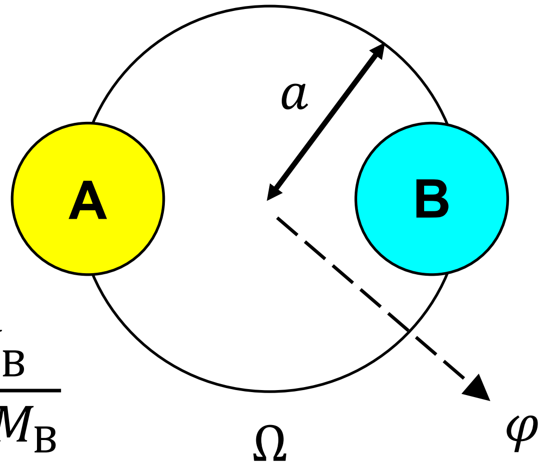


Increased cooling in dead stars (e.g., white dwarves, neutron stars)

Astrophysical Emission (Compact Binaries)

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



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

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

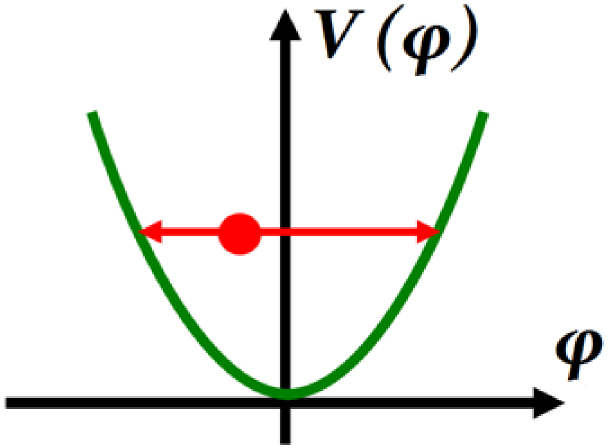
- Scalar Larmor radiation possible if $m_\varphi < \Omega$ (higher-order modes also possible for an elliptical orbit if $m_\varphi < n\Omega$, $n = 2, 3, \ldots$):

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

- 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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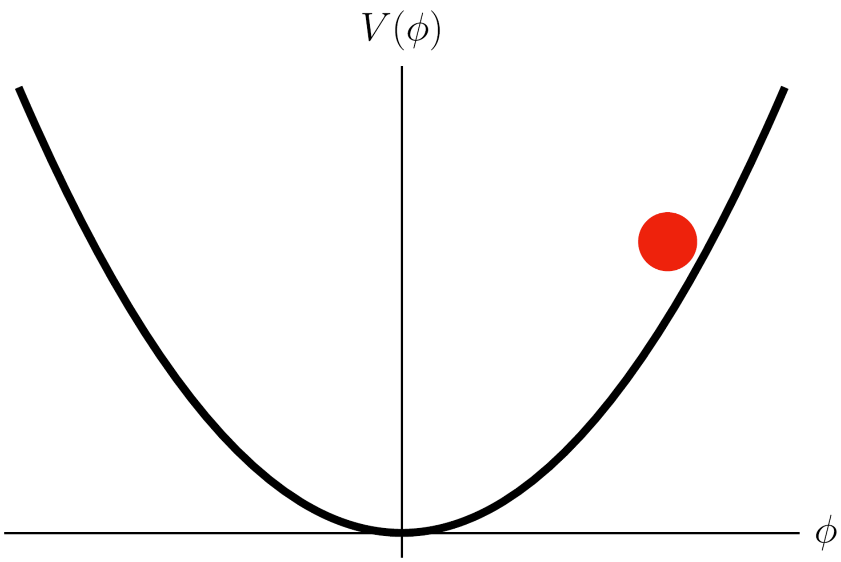

$$\ddot{\varphi} + 3H(t)\dot{\varphi} + m_\varphi^2 \varphi \approx 0$$
$$H(t) = \dot{a}(t)/a(t)$$

⟵ Damped harmonic oscillator with a time-dependent frictional term

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

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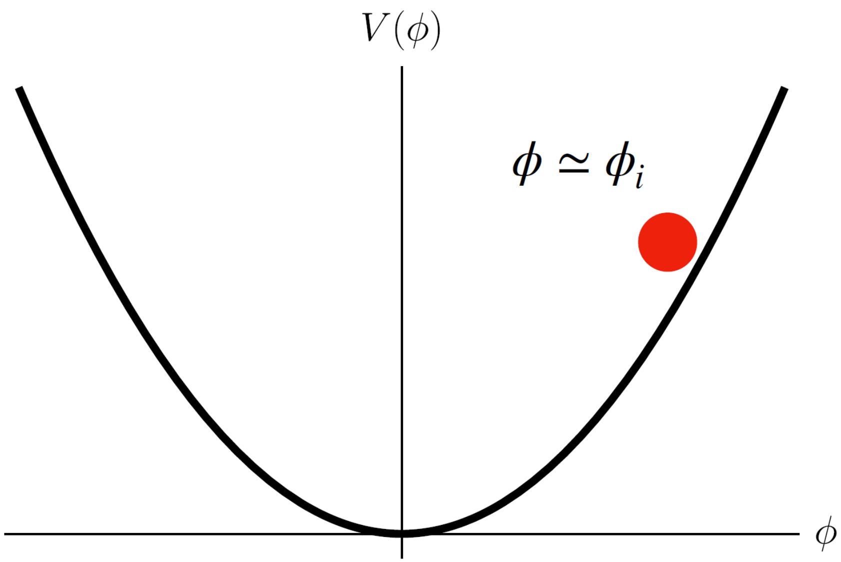
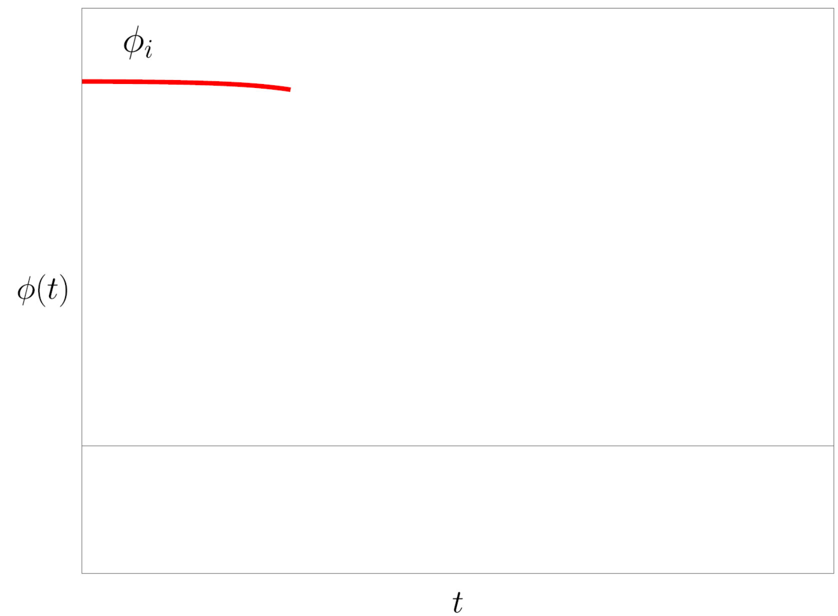


$$\ddot{\varphi} + 3H(t)\dot{\varphi} + m_\varphi^2 \varphi \approx 0$$

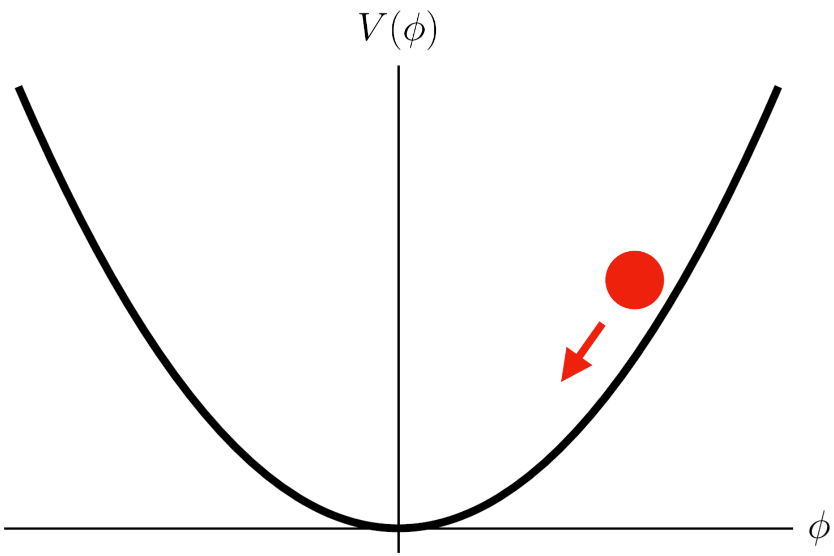
$$m_\varphi \ll 3H(t) \sim 1/t$$



Overdamped regime

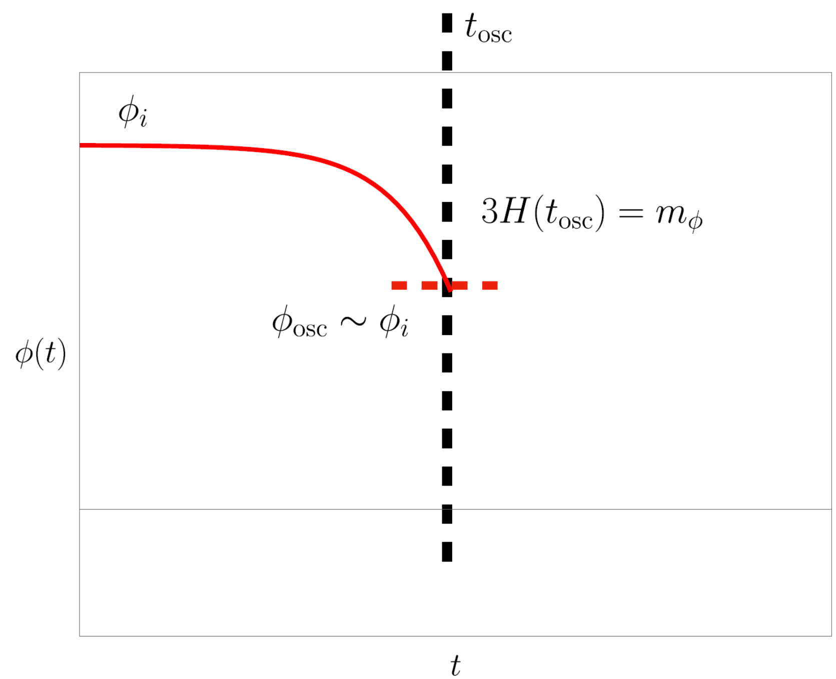
Low-mass Spin-0 Dark Matter

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



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

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



Critically damped regime

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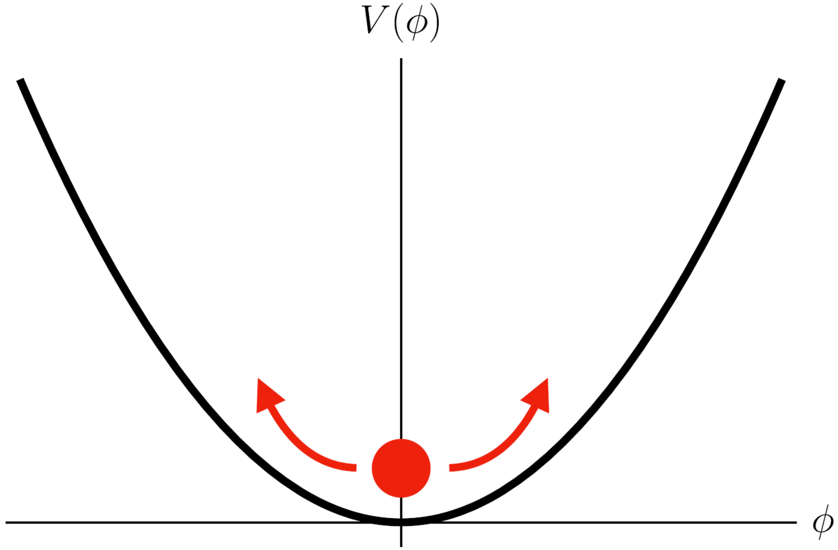
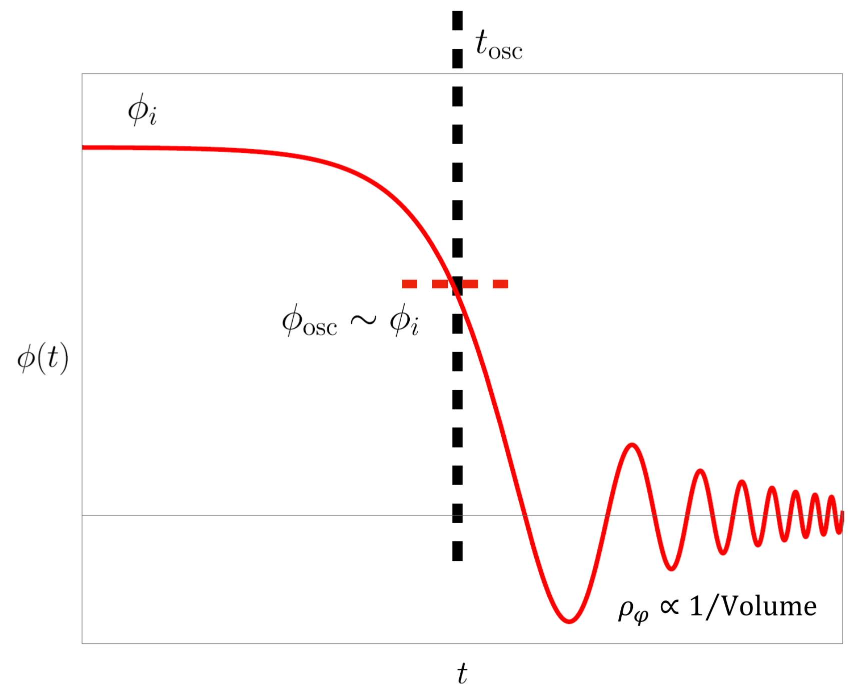


$$\ddot{\varphi} + 3H(t)\dot{\varphi} + m_\varphi^2 \varphi \approx 0$$

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



Underdamped regime

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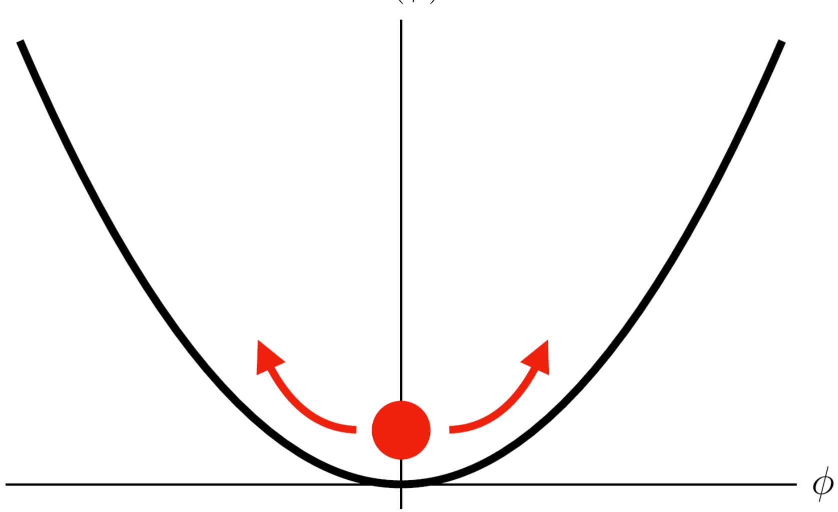

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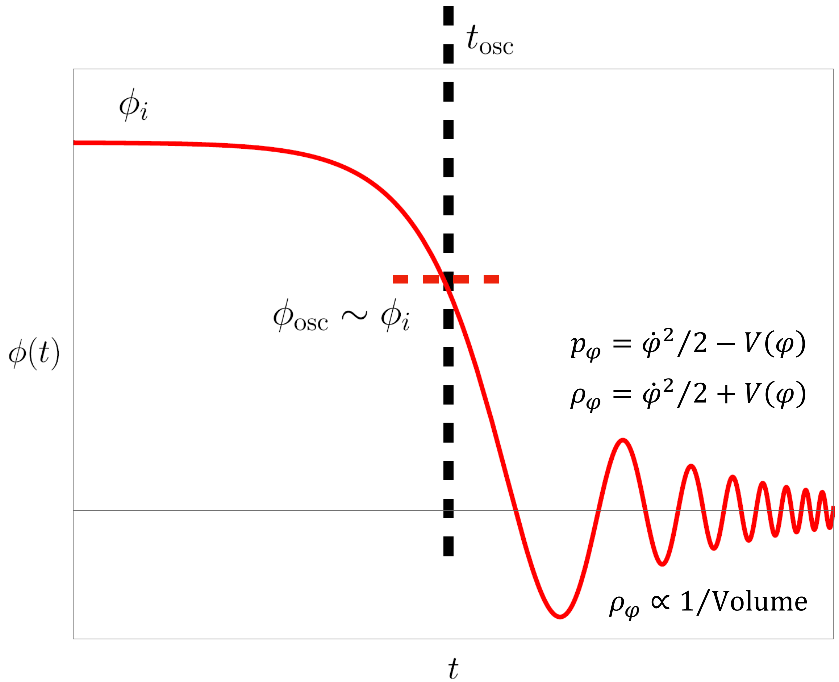

"Vacuum misalignment" mechanism – non-thermal production, ρ_φ governed by initial conditions (φ_i), redshifts as $\rho_\varphi \propto 1/\mathrm{Volume}$, with $\langle p_\varphi \rangle \ll \rho_\varphi$

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$v_{\mathrm{DM}} \sim 300\ \mathrm{km/s}$ (↑ points to $\langle v_\varphi^2 \rangle / c^2 \sim 10^{-6}$)

$Q_{\mathrm{DM}} \sim 10^6$ (↓ from $\tau_{\mathrm{coh}} \sim 10^6 T_{\mathrm{osc}}$)

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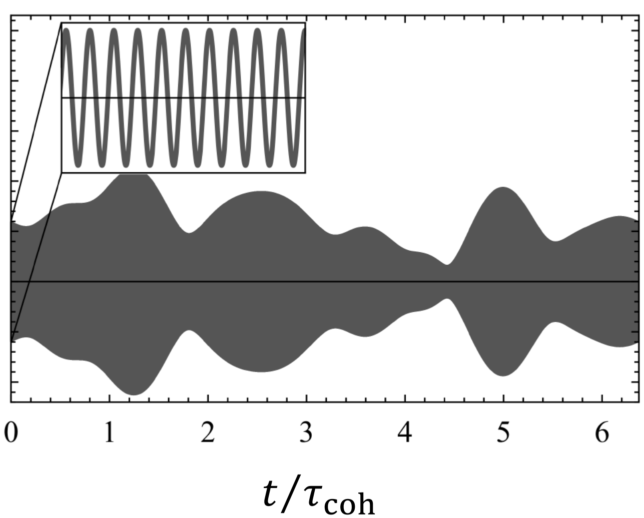
Evolution of φ_0 with time



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

v_i follow quasi-Maxwell-Boltzmann distribution (in the standard halo model)

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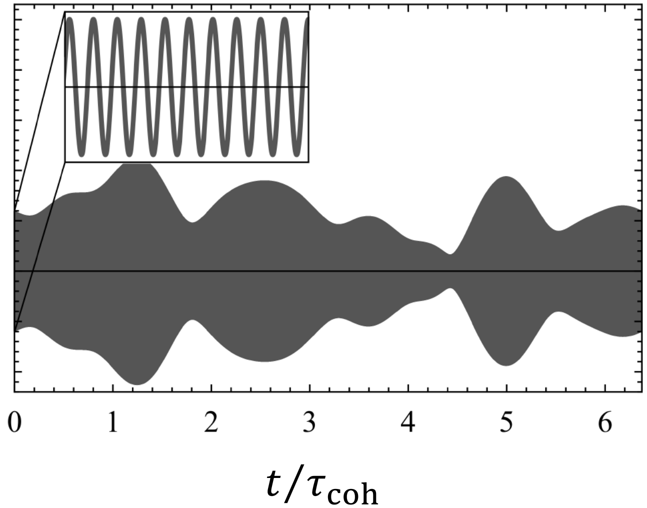
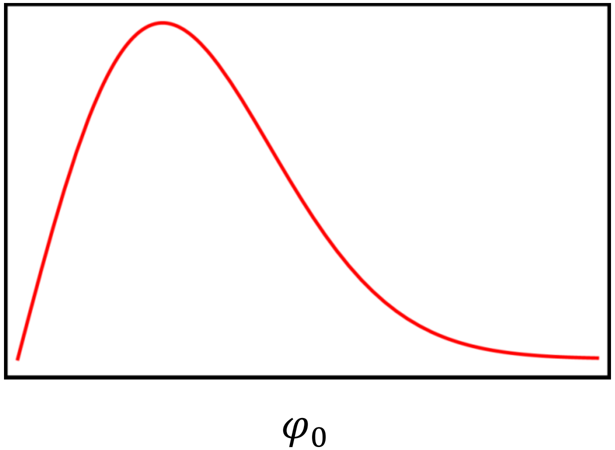


Probability distribution function of φ_0 (Rayleigh distribution)



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

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

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

$T_{\mathrm{osc}} \sim 1\ \mathrm{month}$ 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):	**Scalars (Dilatons):**
$a \xrightarrow{P} -a$	$\varphi^n \xrightarrow{P} \varphi^n, n = 1,2$

Time-varying EDMs and spin-precession effects

- Co-magnetometers
- Particle *g*-factors
- 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

Pseudoscalars (Axions):

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

QCD axion resolves strong CP problem

Time-varying EDMs and spin-precession effects

- Co-magnetometers
- Particle *g*-factors
- Spin-polarised torsion pendula
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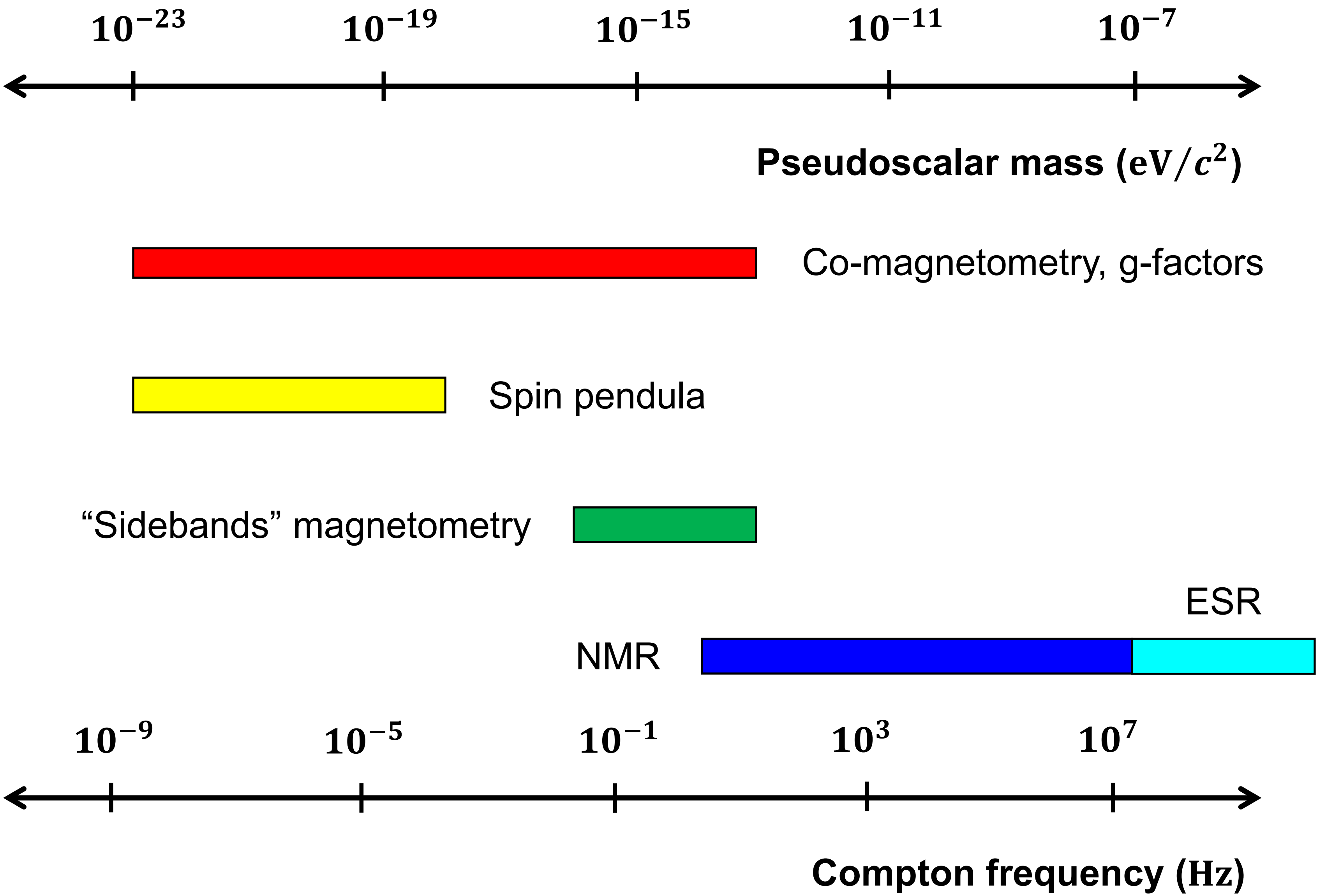
*More traditional axion dark matter detection methods tend to focus on the **electromagnetic** coupling*

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

Probes of Time-Varying EDMs and Spin-Precession Effects



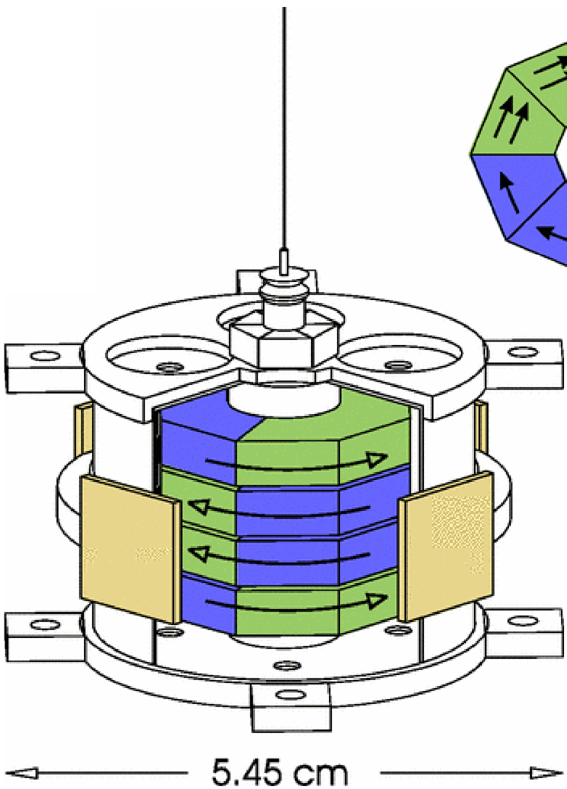
Broadband Searches, $a\bar{e}e$, $10^{-23}\mathrm{eV} \leq m_a \leq 10^{-18}\mathrm{eV}$

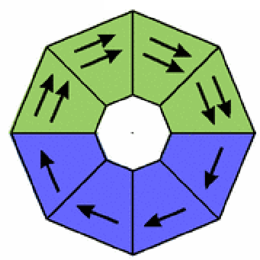
Proposals: [Flambaum, talk at *Patras Workshop*, 2013;
Stadnik, Flambaum, *PRD* **89**, 043522 (2014); Stadnik, thesis (Springer, 2017)]

Lorentz-invariance-violation-type searches:

Magnetometers, cold/ultracold particles, <u>*spin pendula*</u>

Experiment (Alnico/$\mathbf{SmCo_5}$): [Terrano *et al.*, *PRL* **122**, 231301 (2019)]





$\boldsymbol{\mu}_{\mathrm{Alnico}}$ → ← $\boldsymbol{\mu}_{\mathrm{SmCo_5}}$

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

$(\boldsymbol{\sigma}_e)_{\mathrm{Alnico}}$ → ← $(\boldsymbol{\sigma}_e)_{\mathrm{SmCo_5}}$

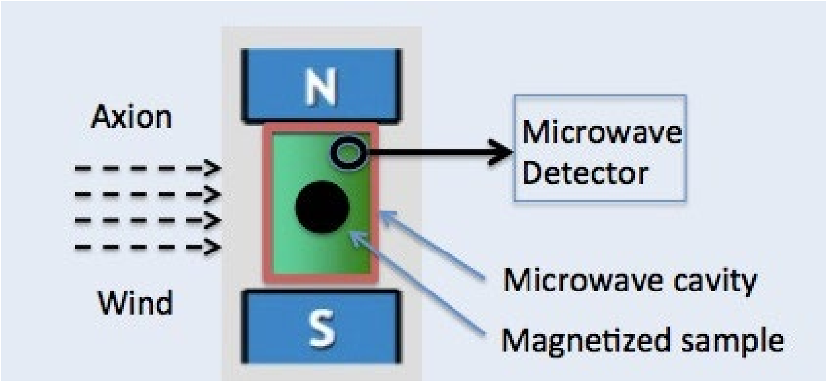
$$(\boldsymbol{\sigma}_e)_{\mathrm{pendulum}} \neq \mathbf{0}$$

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

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)

- **YIG [INFN]:** [Crescini *et al.*, *EPJ C* **78**, 703 (2018); *PRL* **124**, 171801 (2020)]
- **YIG [UWA]:** [Flower, Bourhill, Goryachev, Tobar, *Phys. Dark Universe* **25**, 100306 (2019)]

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

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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 ($\varphi \rightarrow -\varphi$)

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$$\Downarrow$$

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

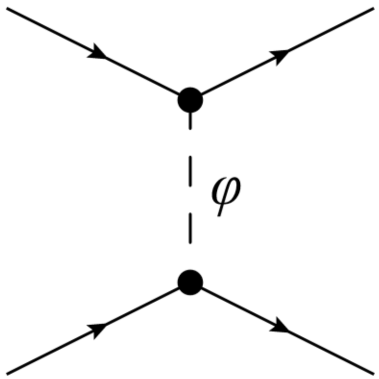
Fifth Forces: Linear vs Quadratic Couplings

[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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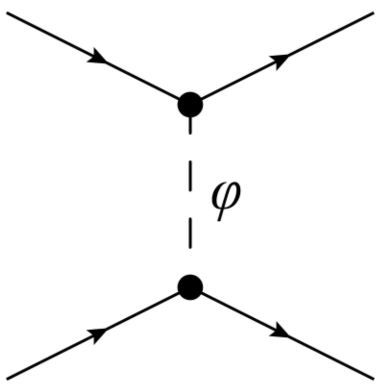

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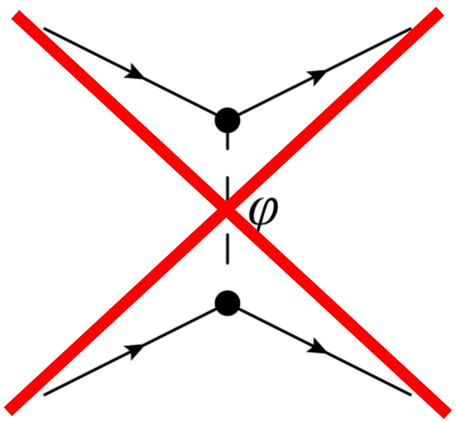
Profile outside of a spherical body

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

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



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

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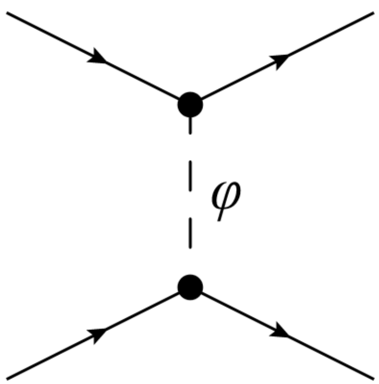

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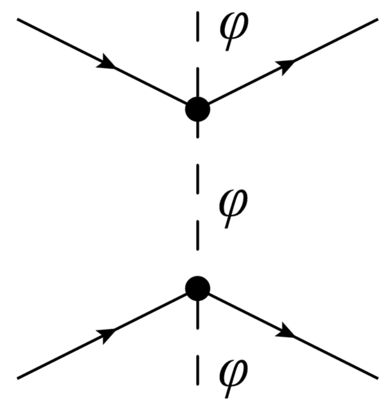

$$\varphi = \varphi_0 \cos(m_\varphi t) \left(1 \pm \frac{B}{r}\right)$$

Profile outside of a spherical body

Gradients + amplification/screening

Fifth Forces: Linear vs Quadratic Couplings

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

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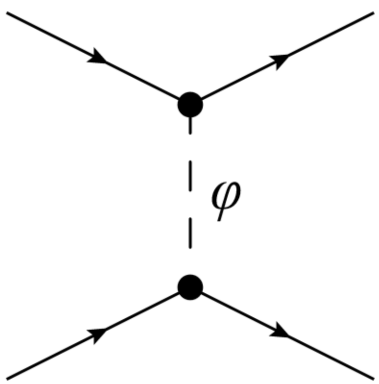

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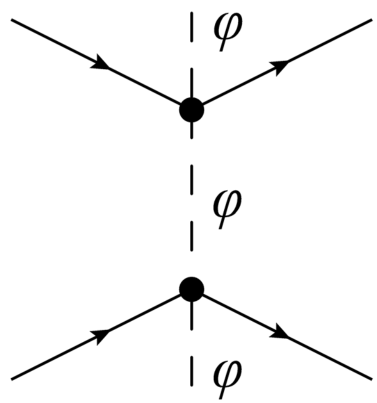
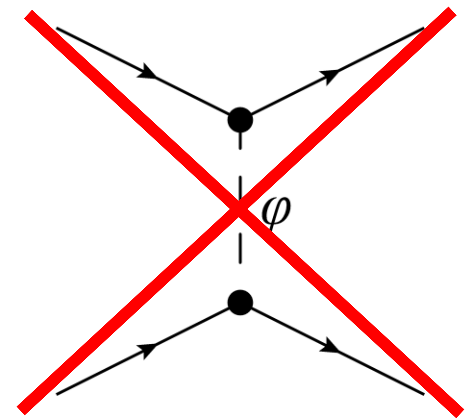
Quadratic couplings ($\varphi^2 \bar{X} X$)

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





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

Profile outside of a spherical body

Gradients + amplification/screening

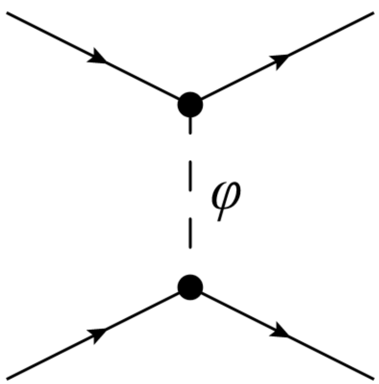
Fifth Forces: Linear vs Quadratic Couplings

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

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

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

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



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

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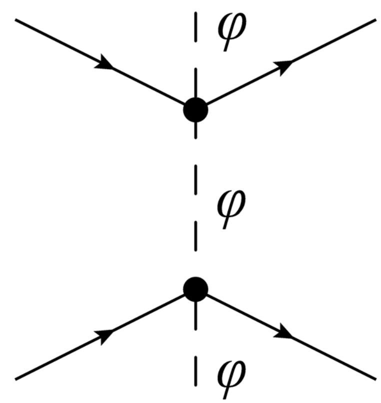

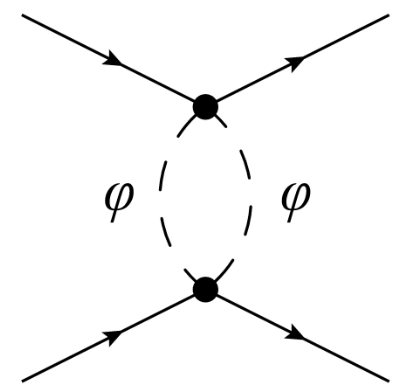

$$\varphi = \varphi_0\cos(m_\varphi t)\left(1 \pm \frac{B}{r}\right) - \hbar C\,\frac{e^{-2m_\varphi r}}{r^3}$$

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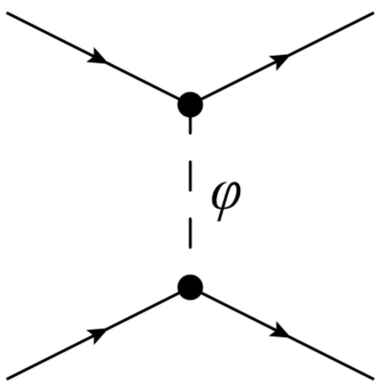

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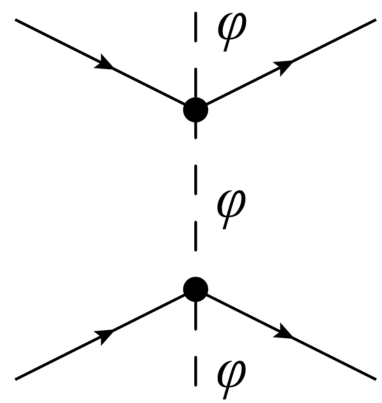

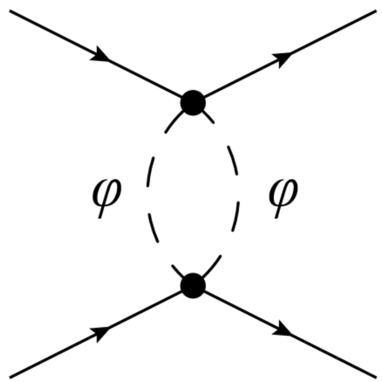

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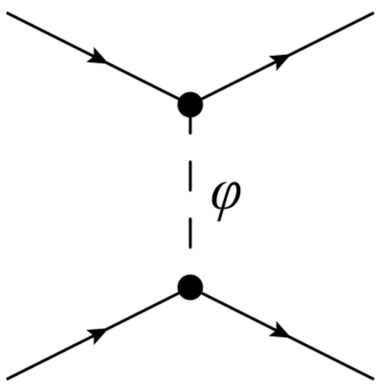

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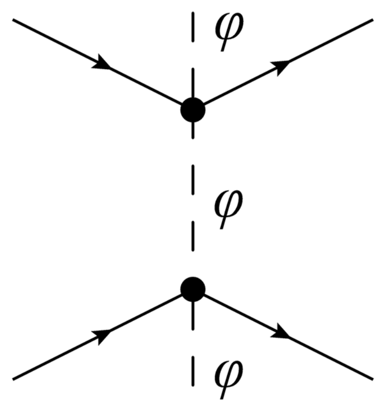
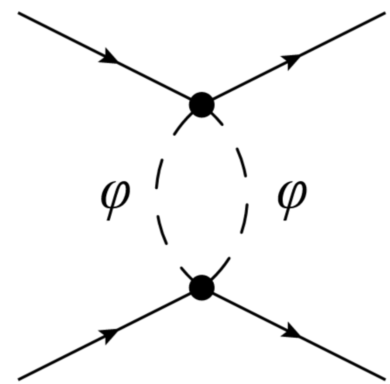
"Fifth-force" experiments: torsion pendula, atom interferometry

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

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





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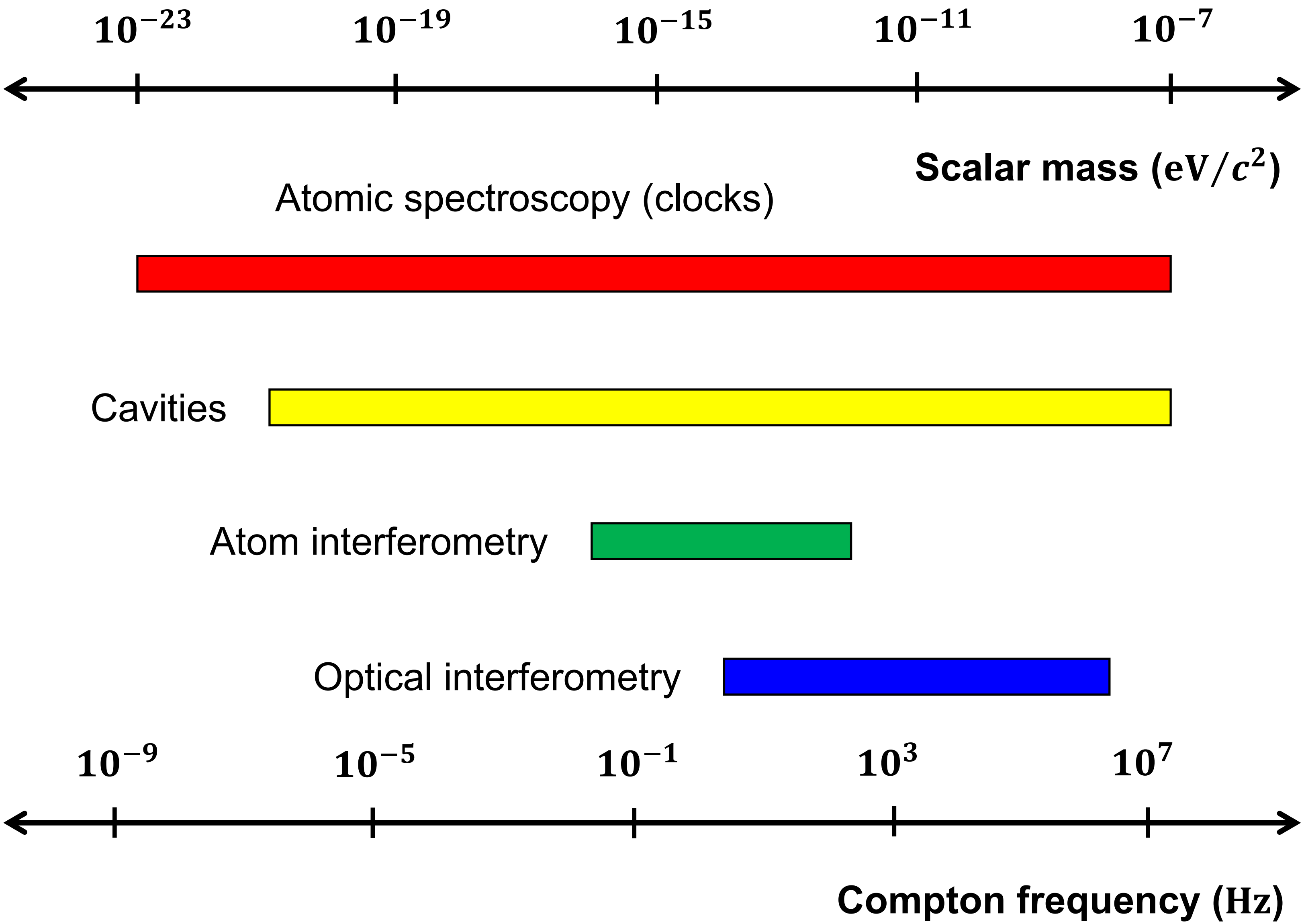
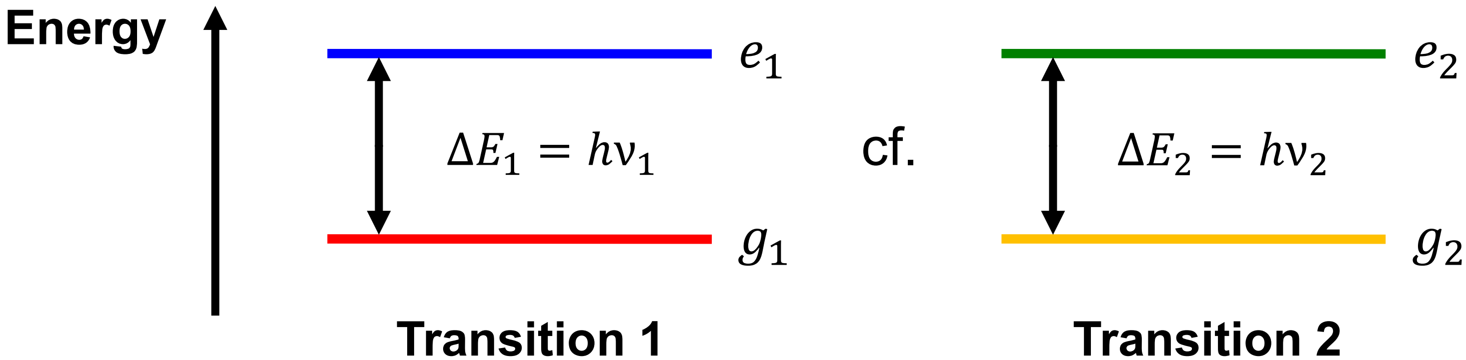
Gradients + amplification/screening

Probes of Oscillating Fundamental Constants



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



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

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

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

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

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

Effects of Varying Fundamental Constants on Atomic Transitions

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

- Atomic optical transitions:

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

Non-relativistic atomic unit of frequency

Relativistic factor

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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*

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

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[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)]

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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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→ **Increasing *Z***

- Atomic hyperfine transitions:

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

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

Increasing *Z*

Effects of Varying Fundamental Constants on Atomic Transitions

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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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Increasing *Z*

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Increasing *Z*

- Atomic hyperfine transitions:

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

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

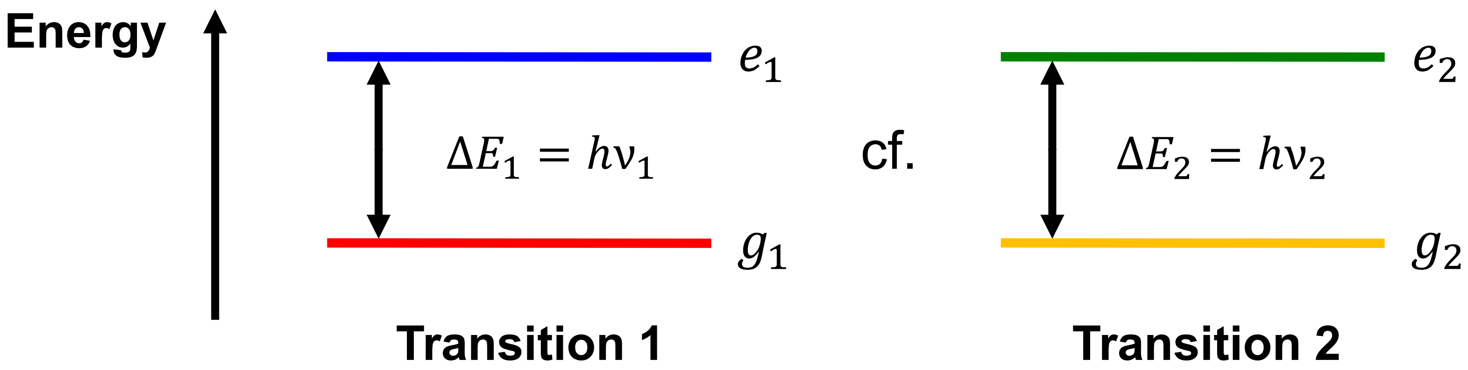
$$K_{m_q/\Lambda_{\mathrm{QCD}}} \neq 0$$

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

Increasing *Z*

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

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



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

- **Dy/Cs [Mainz]:** [Van Tilburg *et al.*, *PRL* **115**, 011802 (2015)], [Stadnik, Flambaum, *PRL* **115**, 201301 (2015)]
- **Rb/Cs [SYRTE]:** [Hees *et al.*, *PRL* **117**, 061301 (2016)], [Stadnik, Flambaum, *PRA* **94**, 022111 (2016)]
- **Al^+/Yb, Yb/Sr, Al^+/Hg^+ [NIST + JILA]:** [BACON Collaboration, *Nature* **591**, 564 (2021)]
- **Yb/Cs [NMIJ]:** [Kobayashi *et al.*, *PRL* **129**, 241301 (2022)]
- **Yb^+(E3)/Sr [PTB]:** [Filzinger *et al.*, *PRL* **130**, 253001 (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

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

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

(adiabatic regime)

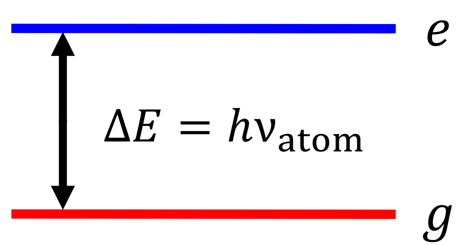
Cavity-Based Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter

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

Solid material

cf.

Electronic transition



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

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

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

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

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

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

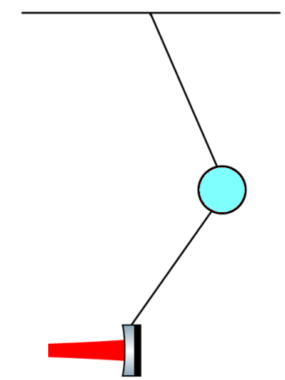
[Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRA* **93**, 063630 (2016)]

Solid material

cf.

Freely-suspended mirrors

Double-pendulum suspensions



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

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

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

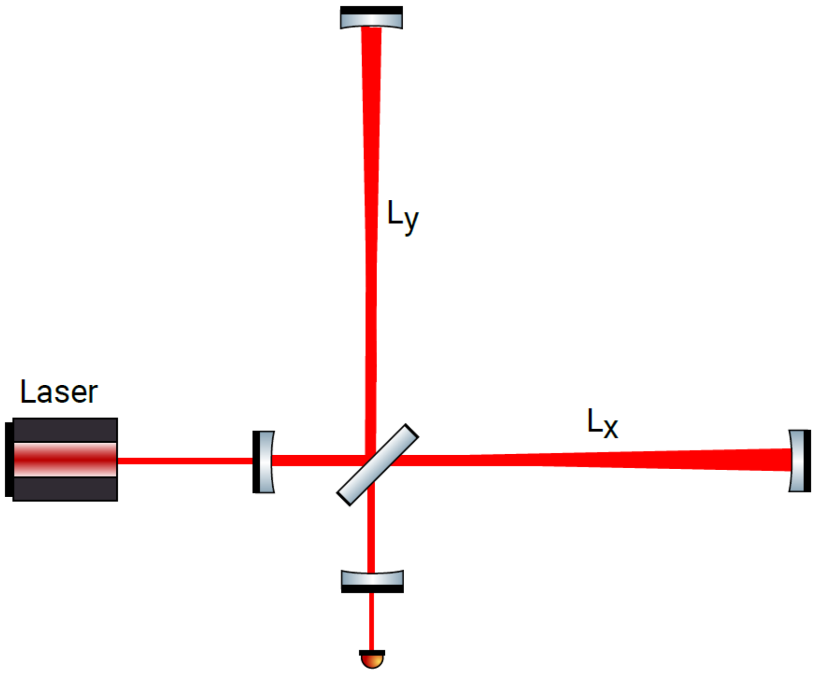
cf.

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

Small-scale experiment currently under development at Northwestern University

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

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



Michelson interferometer (GEO600)

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

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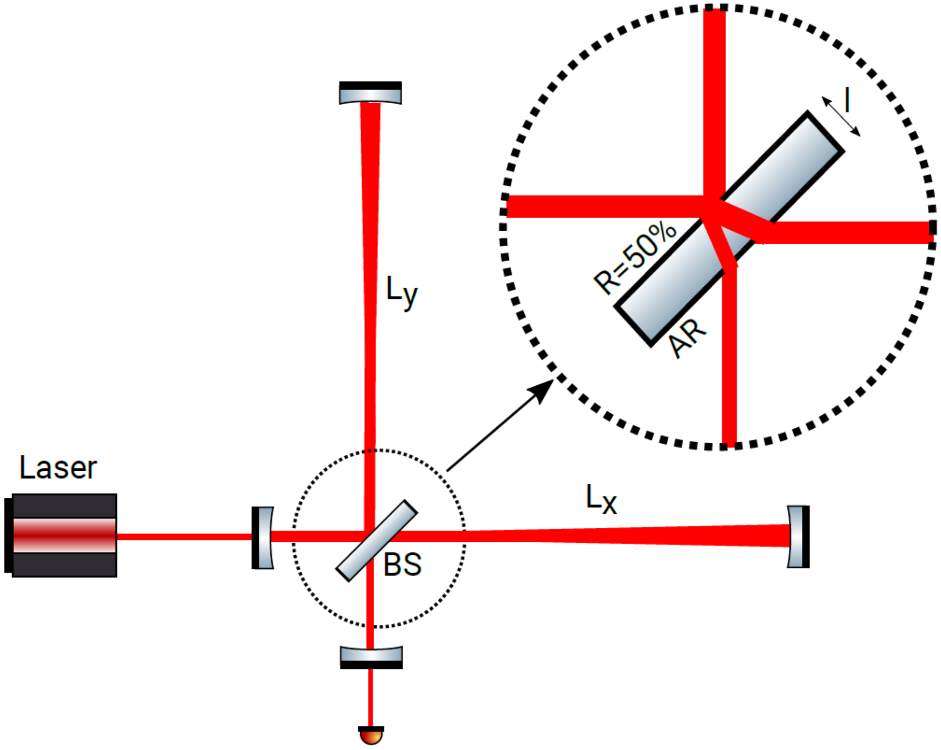

- Geometric asymmetry from beam-splitter

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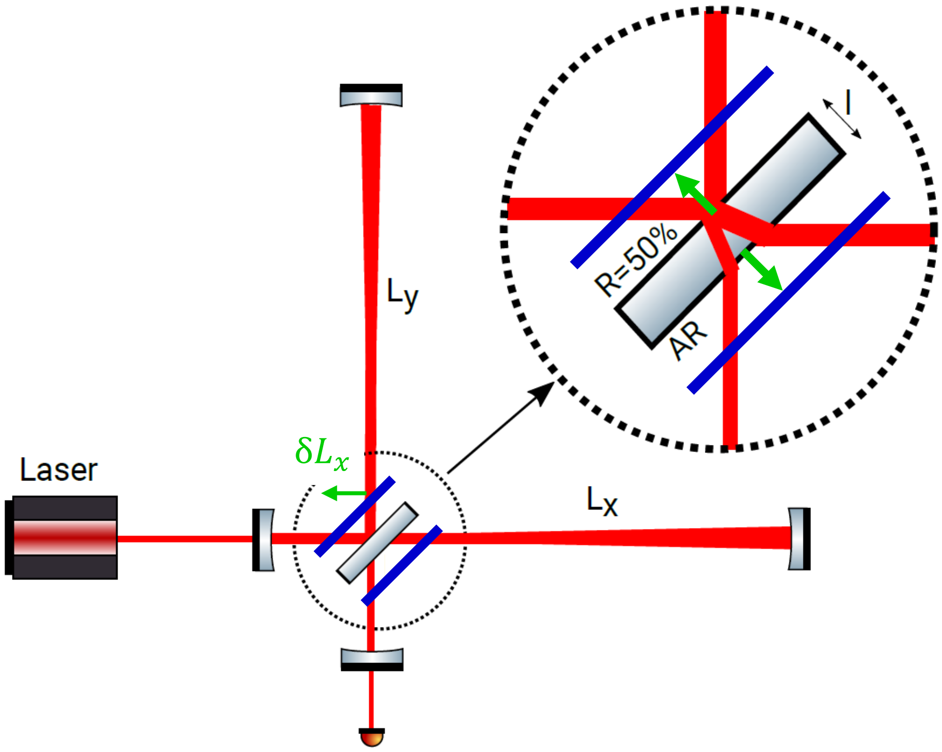

- Geometric asymmetry from beam-splitter: $\delta(L_x - L_y) \sim \delta(nl)$

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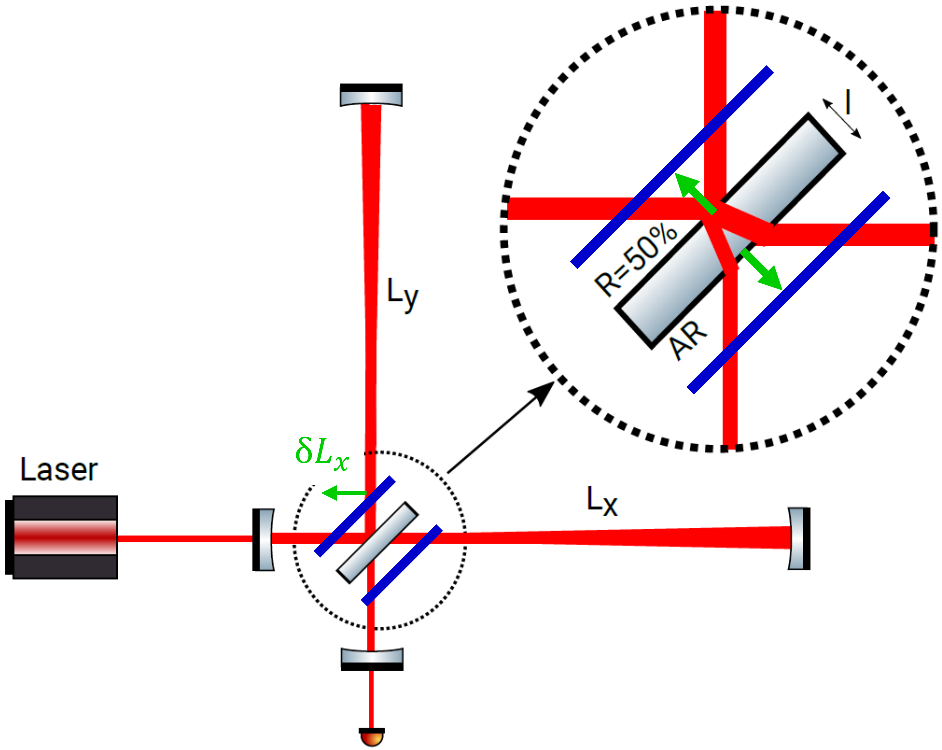

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First results recently reported using GEO600 and Fermilab holometer data:

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

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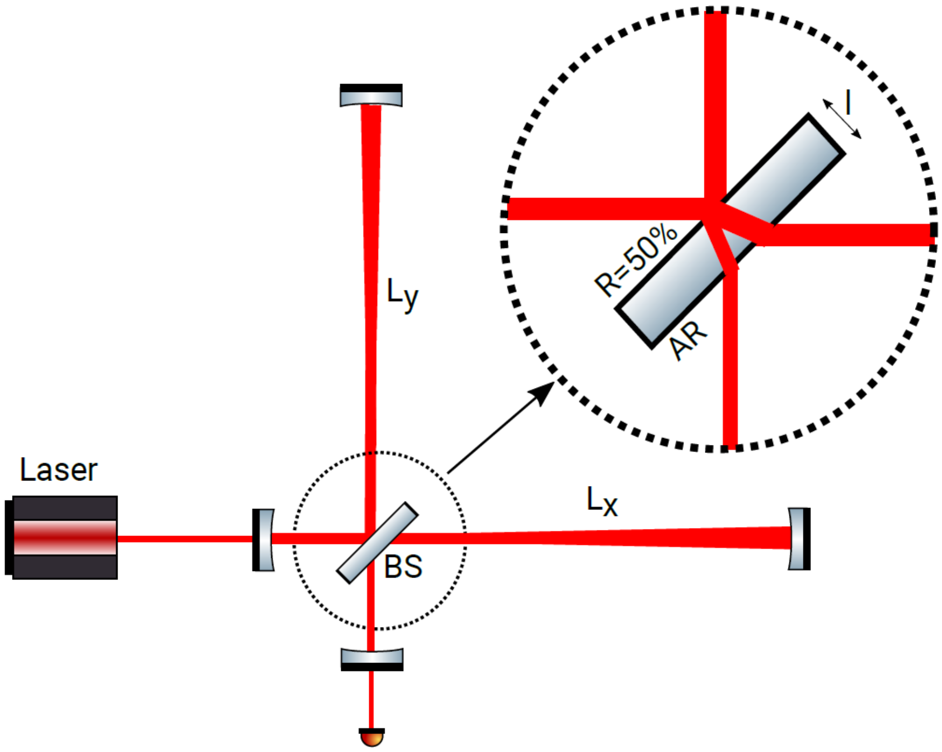


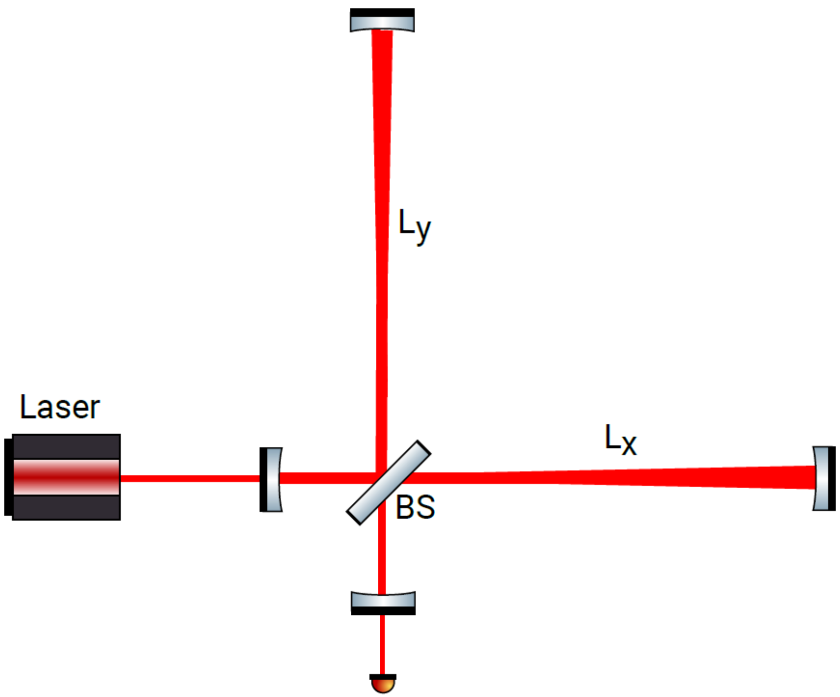
- Geometric asymmetry from beam-splitter: $\delta(L_x - L_y) \sim \delta(nl)$
- Both broadband and resonant narrowband searches possible:

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

Michelson vs Fabry-Perot-Michelson Interferometers

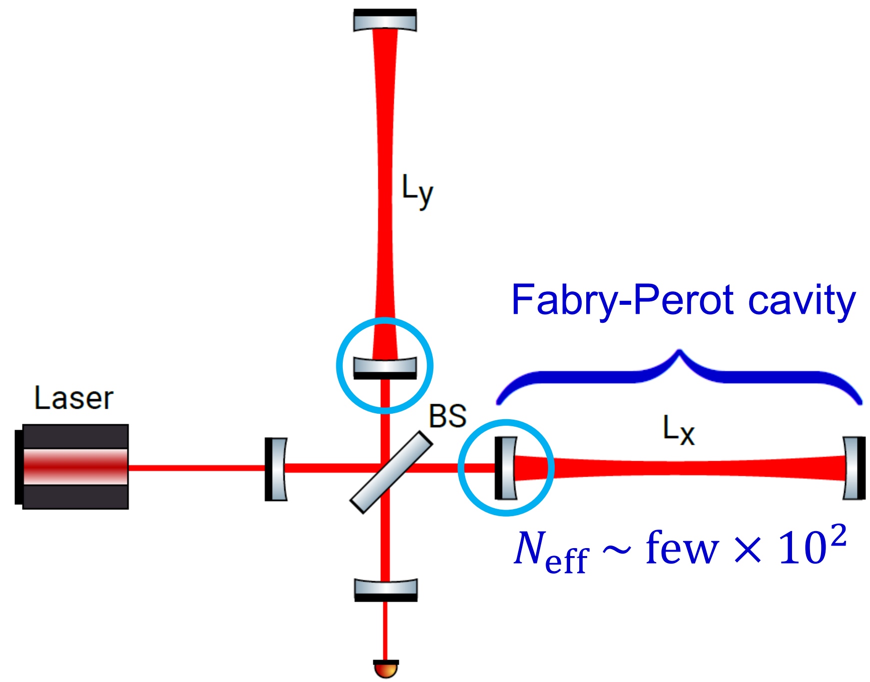
[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]

Michelson interferometer (GEO 600)



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

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

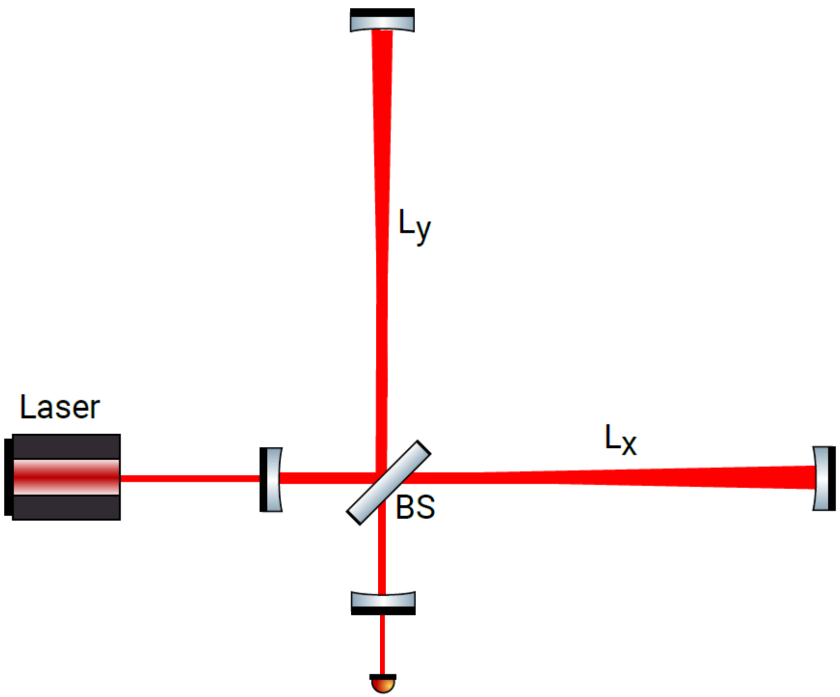


$$\delta\left(L_x - L_y\right)_{\mathrm{BS}} \sim \delta(nl)/N_{\mathrm{eff}}$$

Michelson vs Fabry-Perot-Michelson Interferometers

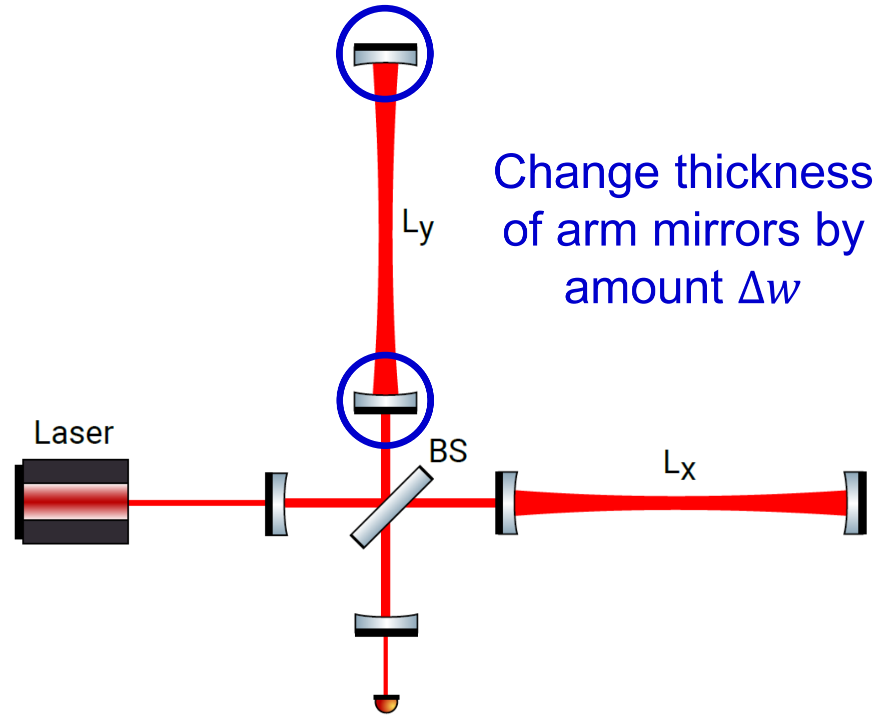
[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]

Michelson interferometer (GEO 600)



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

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



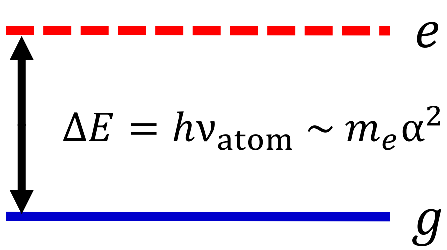
Change thickness of arm mirrors by amount Δw

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

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

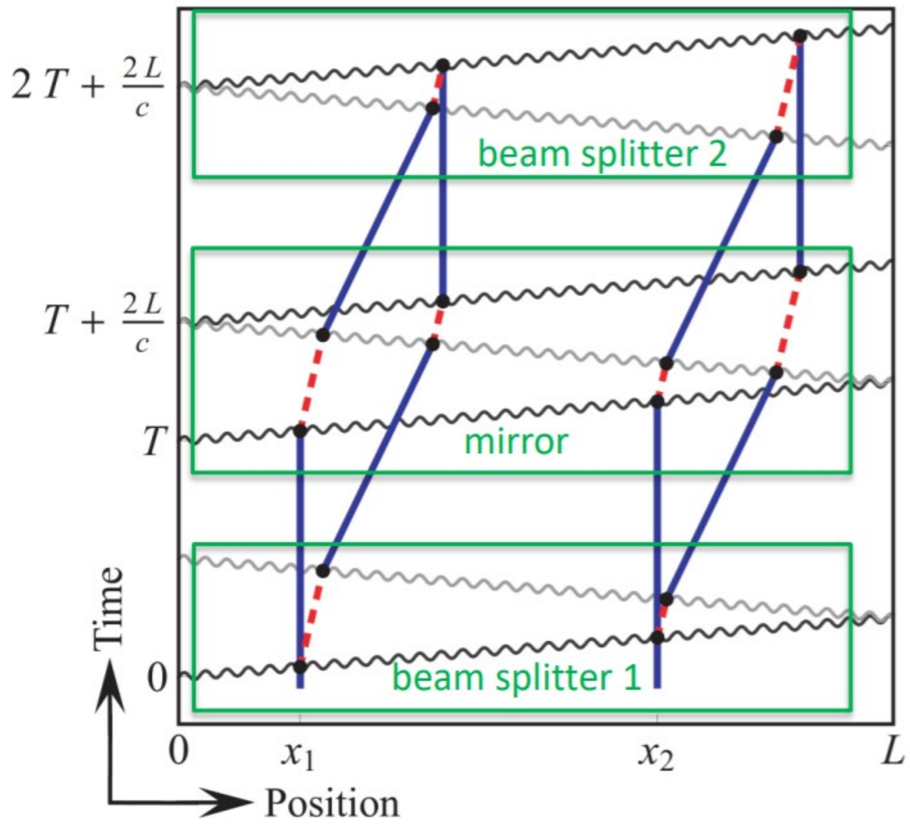
[Arvanitaki, Graham, Hogan, Rajendran, Van Tilburg, *PRD* **97**, 075020 (2018)]

Electronic transition



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

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



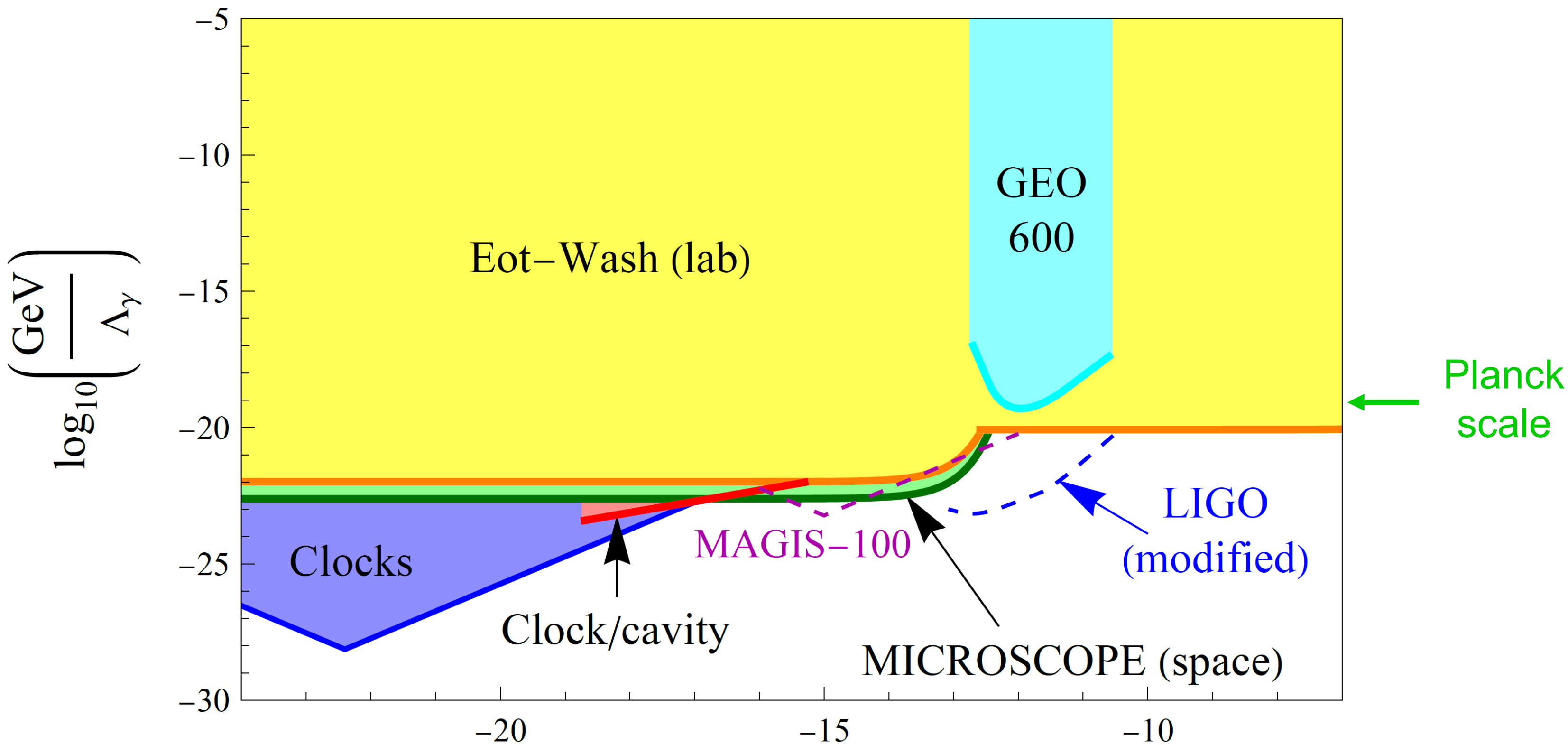
AION-10 experiment under construction at Oxford [Badurina *et al.*, *JCAP* **05** (2020) 011]

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/clock: [*PRL* **115**, 011802 (2015)], [*PRL* **117**, 061301 (2016)], [*Nature* **591**, 564 (2021)], [*PRL* **130**, 253001 (2023)]; **Clock/cavity:** [*PRL* **125**, 201302 (2020)]; **GEO600:** [*Nature* **600**, 424 (2021)]

5 orders of magnitude improvement!



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

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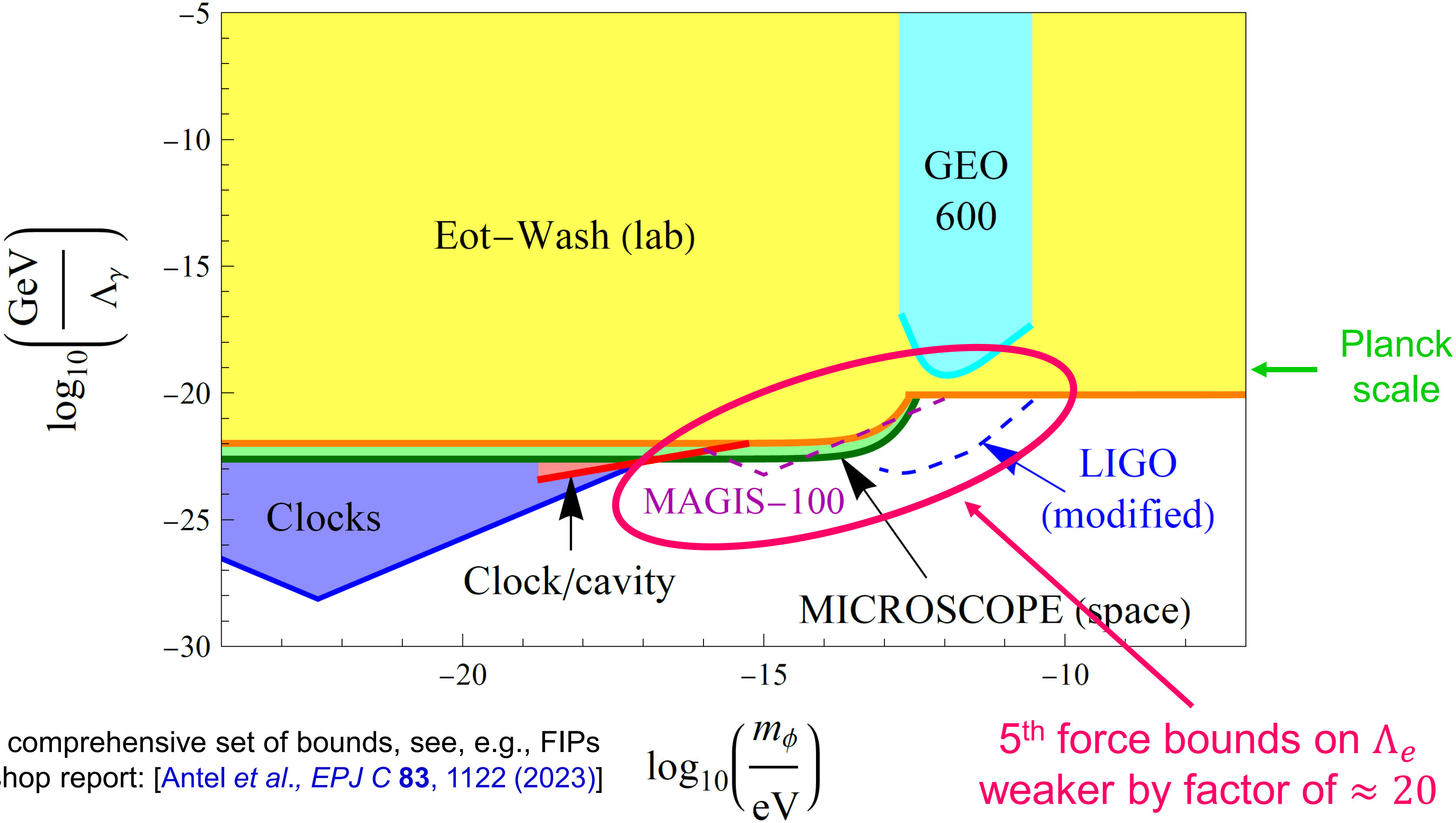

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BBN Constraints on 'Slow' Drifts in Fundamental Constants due to Dark Matter

[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)

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

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

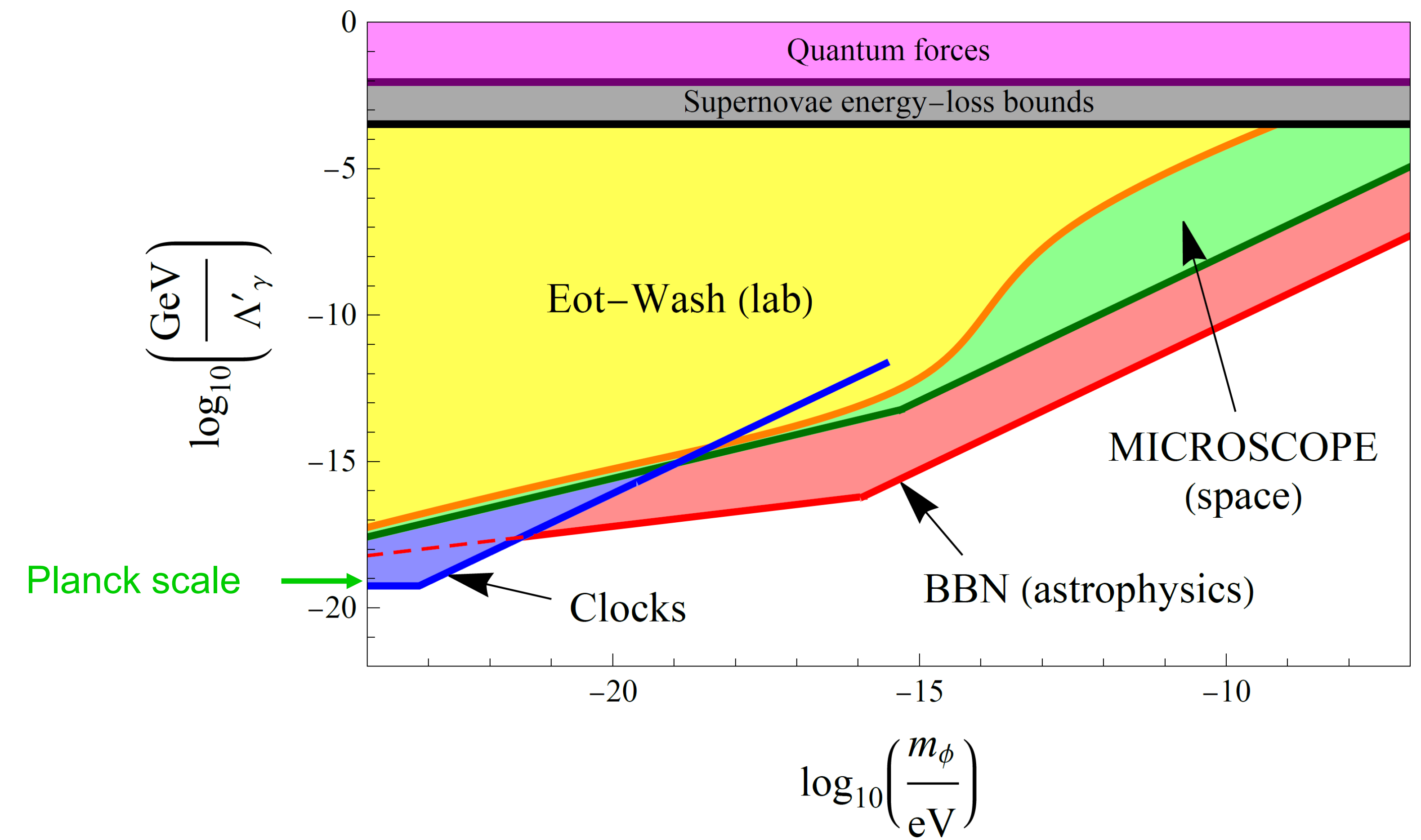
$$n + e^+ \rightleftharpoons p + \bar{\nu}_e$$

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

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

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

15 orders of magnitude improvement!



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

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

15 orders of magnitude improvement!