Manifestations of Low-Mass Dark Bosons

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Collaborators (Experiment):
CASPEr collaboration at Mainz
nEDM collaboration at PSI and Sussex
BASE collaboration at CERN and RIKEN

Beyond Standard Model: Where do we go from here?, Florence, September 2018

Motivation for Low-Mass Dark Bosons

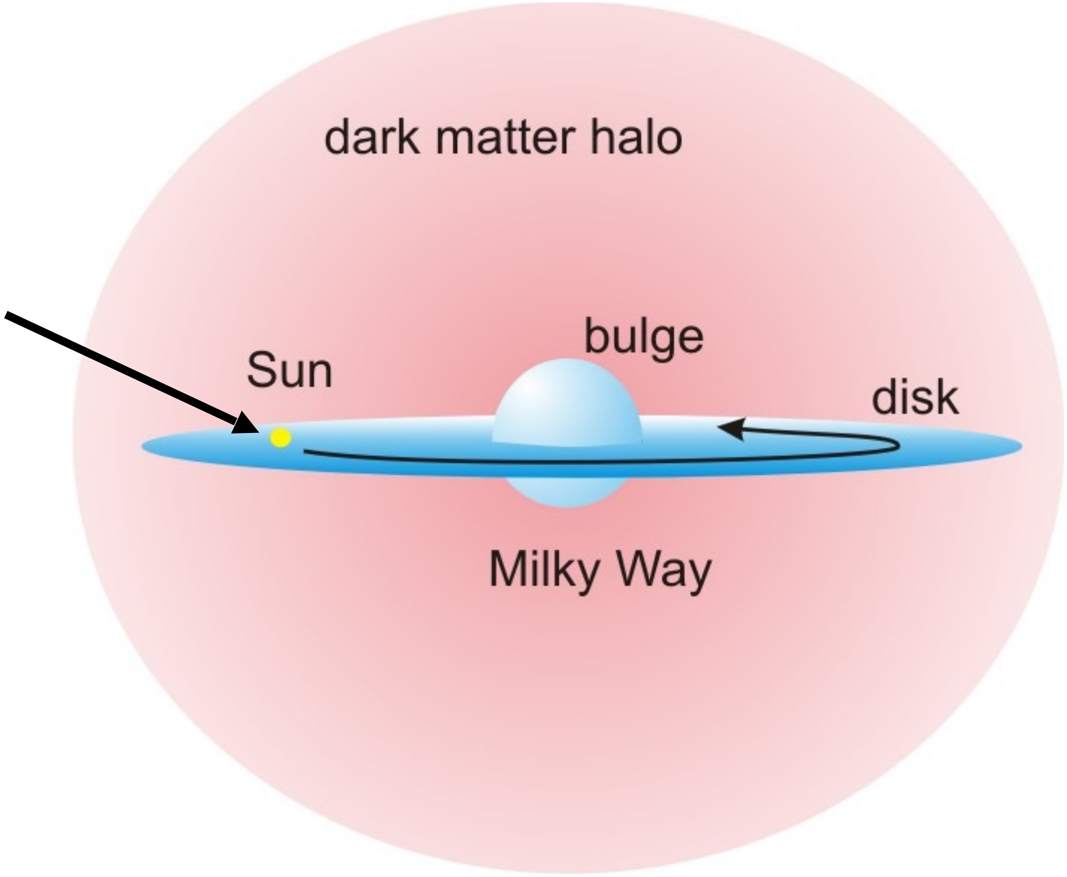
“Low-mass” ($m \ll 100$ GeV) dark bosons may explain several outstanding puzzles

Dark Matter

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

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

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



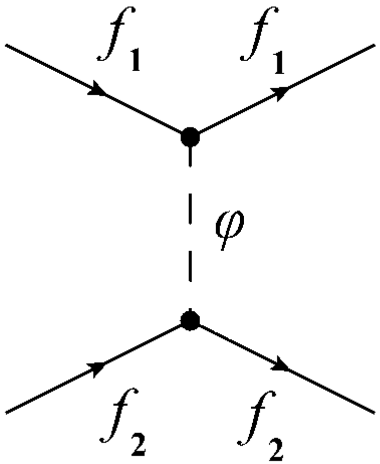
Motivation for Low-Mass Dark Bosons

“Low-mass” ($m << 100$ GeV) dark bosons may explain several outstanding puzzles:

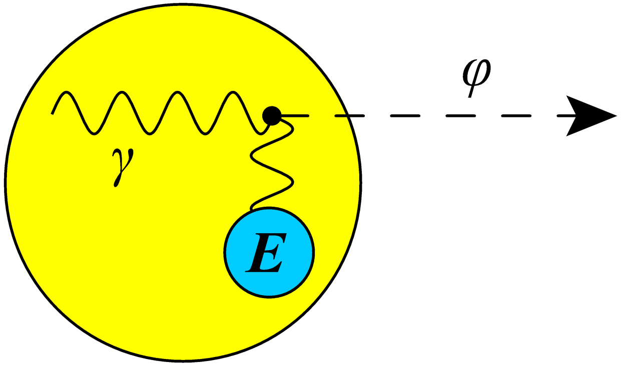
- Dark matter and dark energy
- Strong CP problem
- Hierachy problem
- ‘Hints’ of temporal and spatial variations of the electromagnetic fine-structure constant α at $z \sim 1$

$$\vdots$$

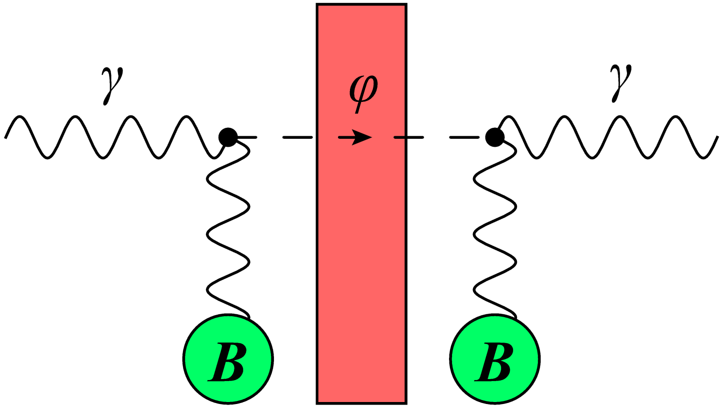
Manifestations of Dark Bosons



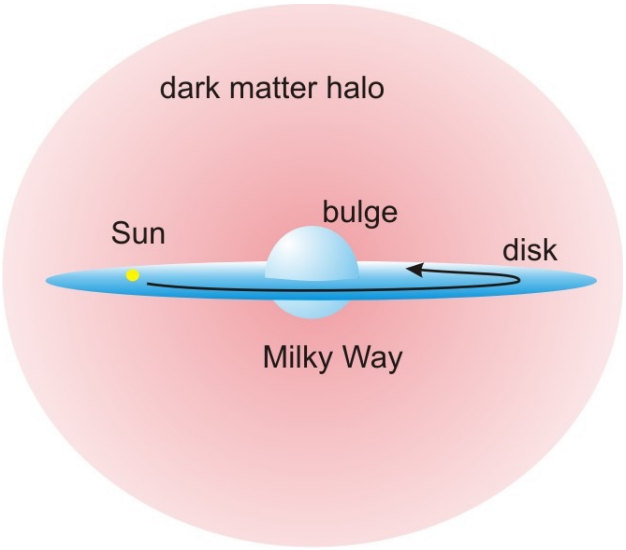
New forces



Stellar emission



Interconversion with
ordinary particles



Dark matter

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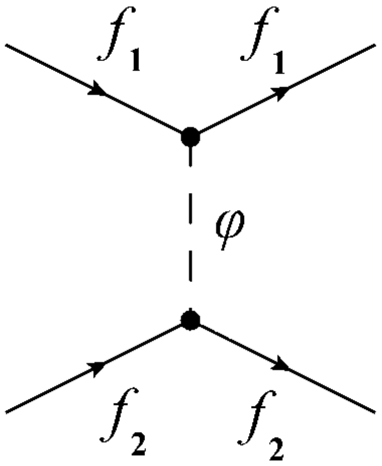

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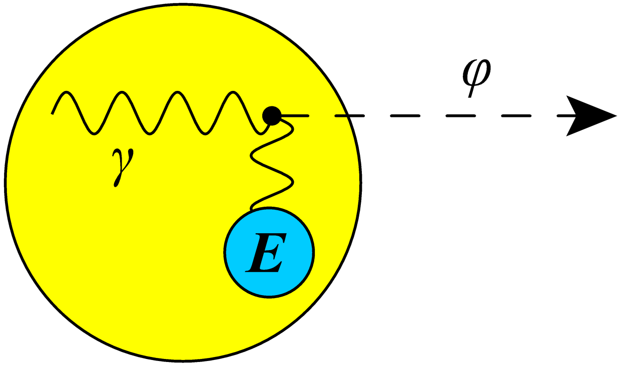

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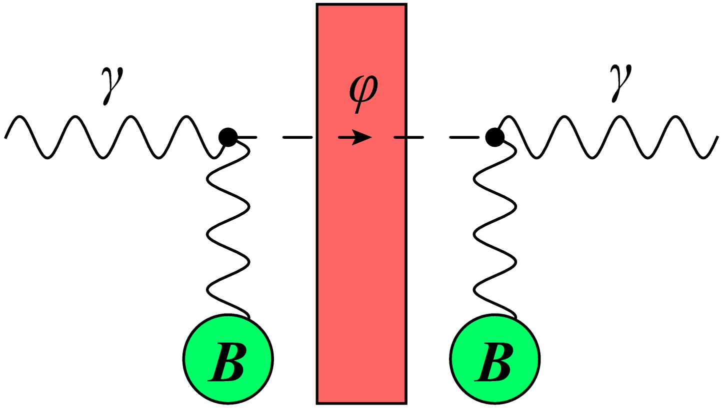

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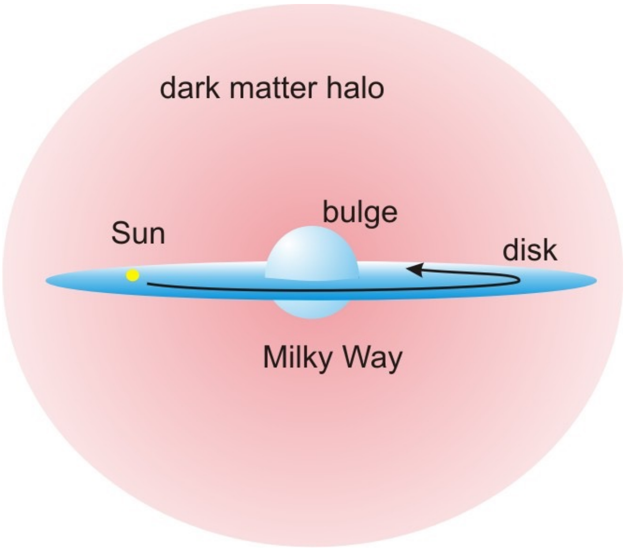

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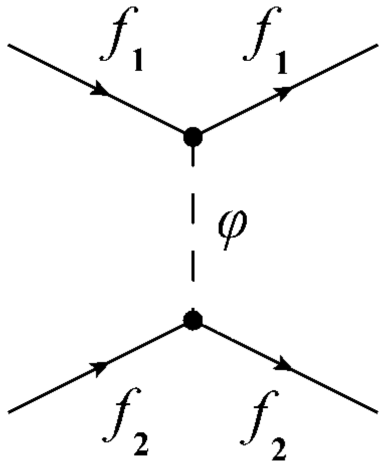

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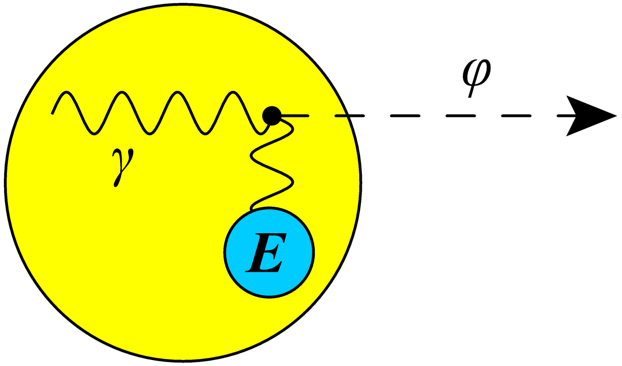

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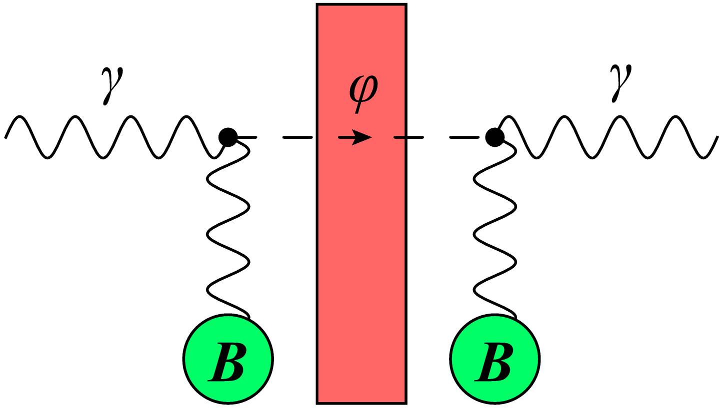

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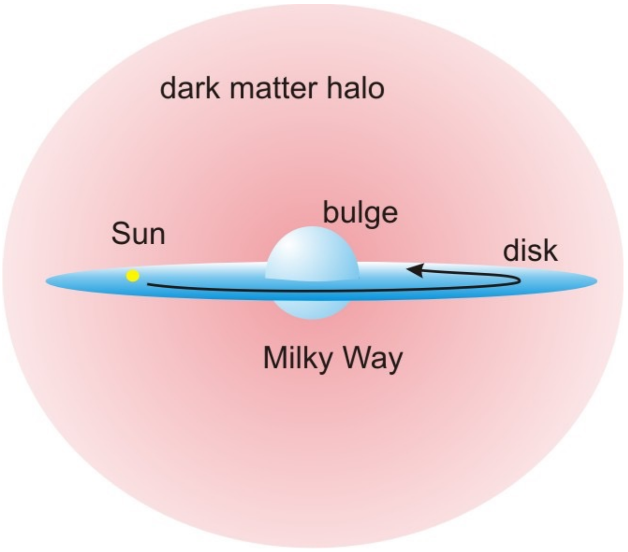
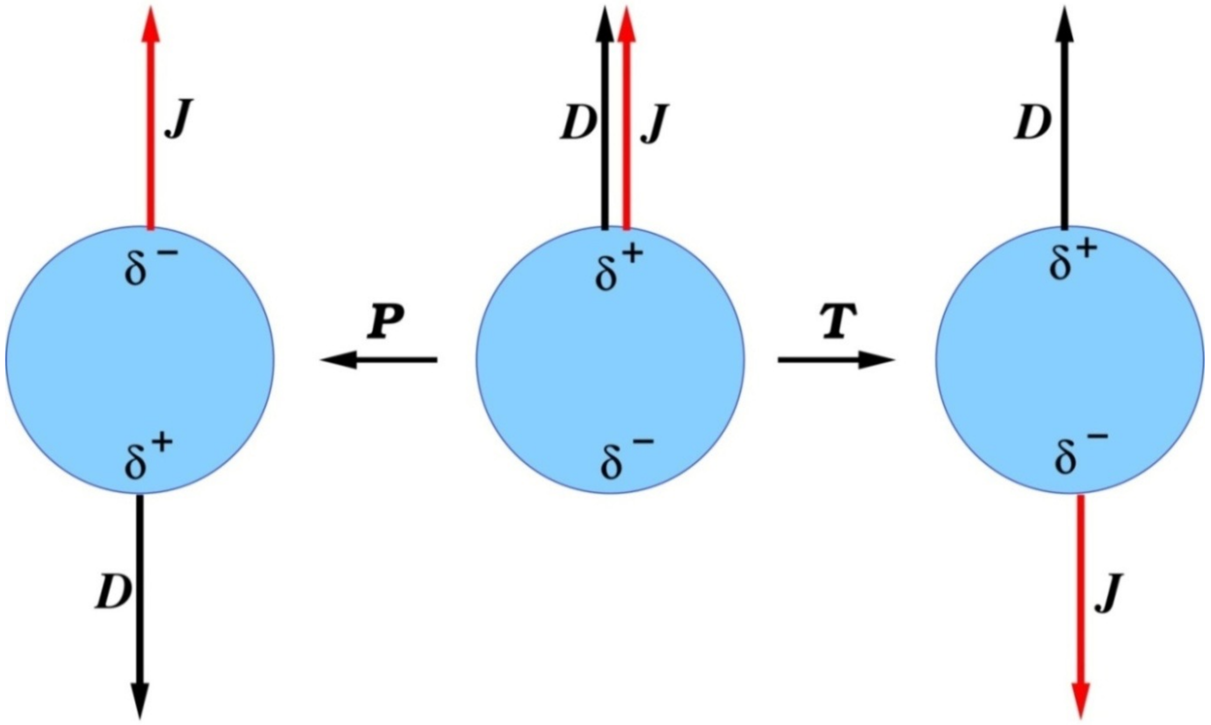


Dark matter

Basics of Atomic EDMs

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



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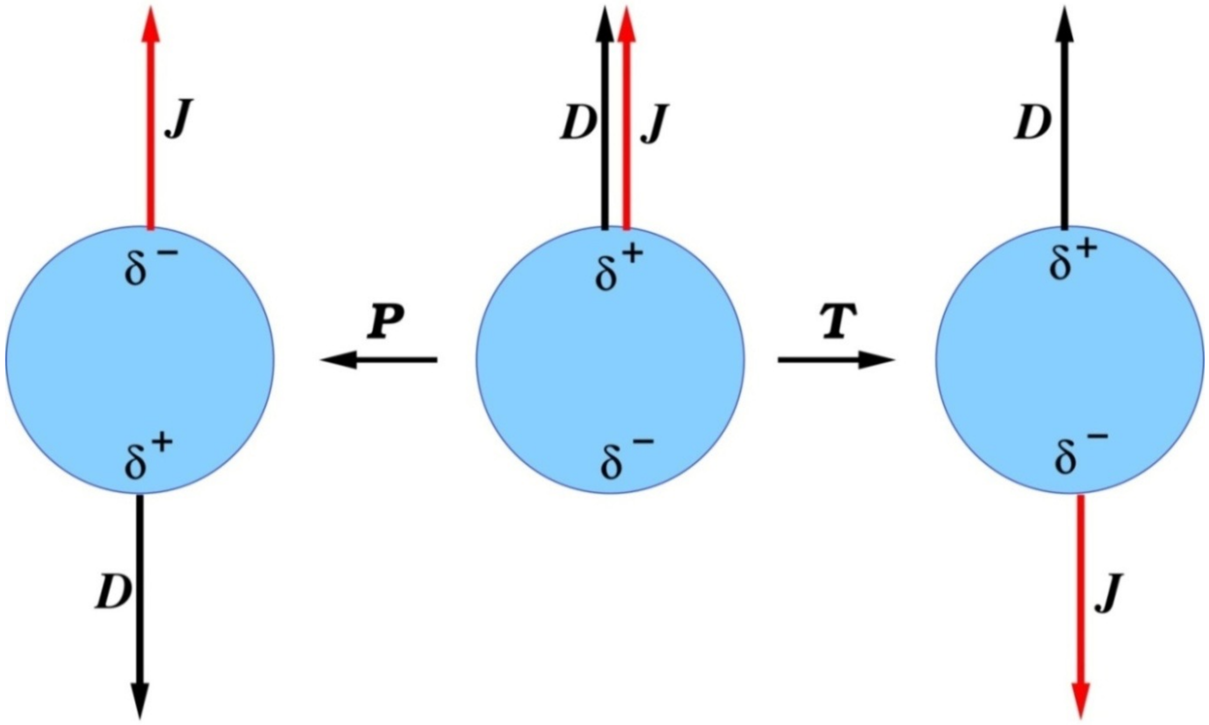

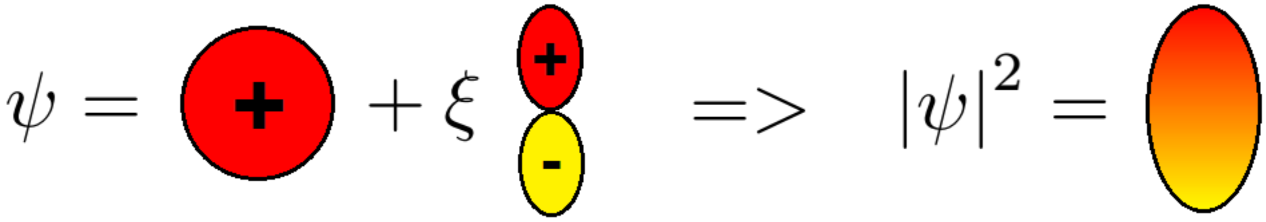

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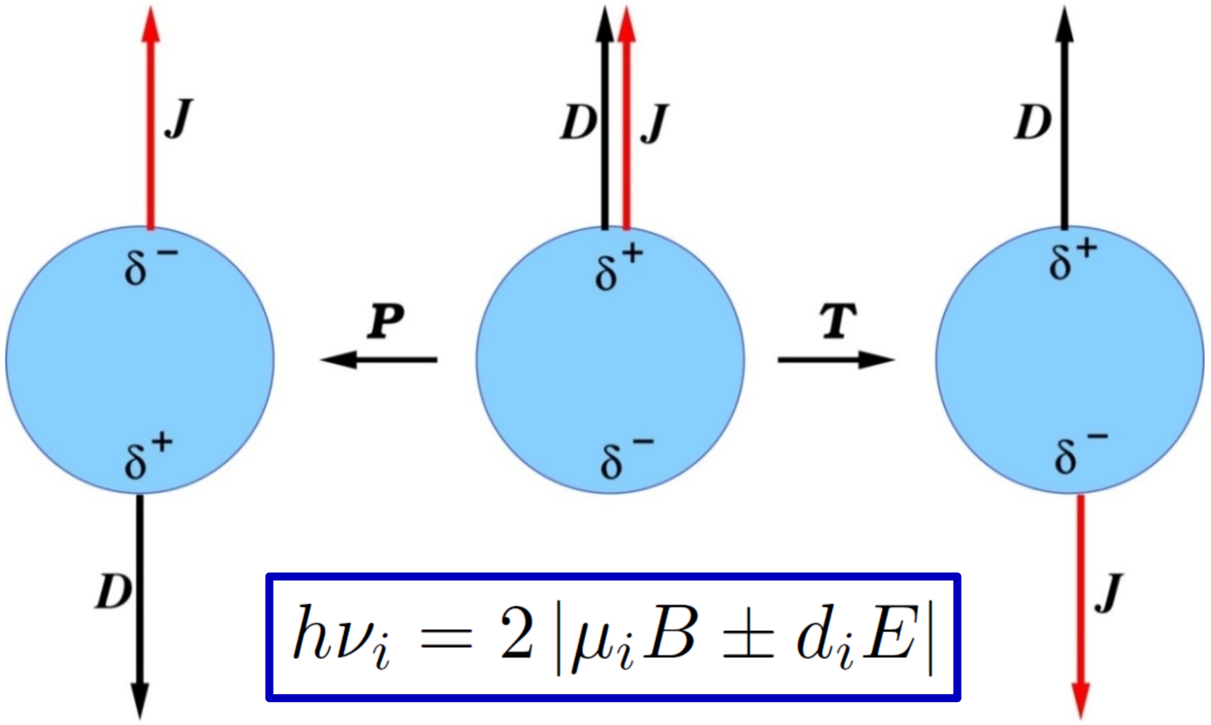
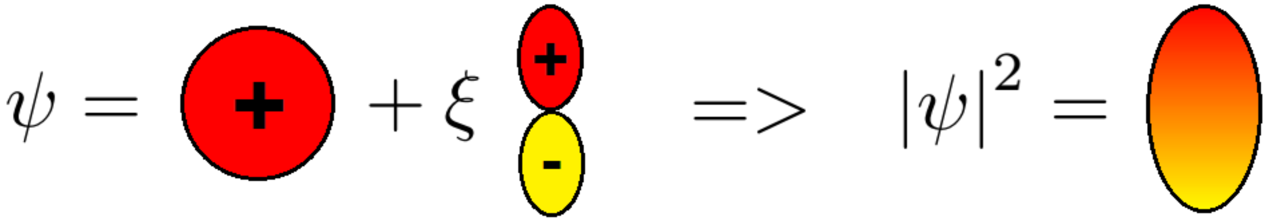


$$\boxed{h\nu_i = 2\,|\mu_i B \pm d_i E|}$$



Sensitivity of EDM Experiments

$|d_{\mathrm{Hg}}|$ limit ≈ $7*10^{-30}$ e cm

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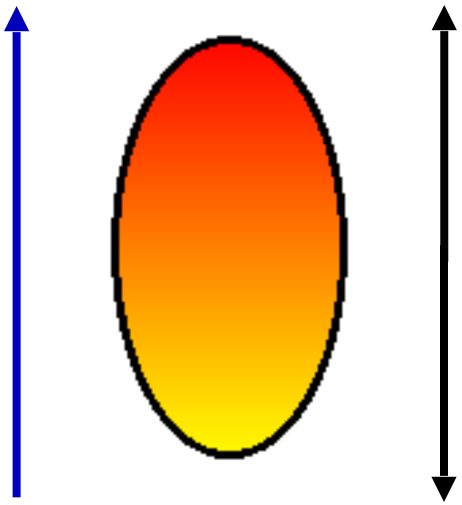

$+\delta Q$

$(d_{\mathrm{Hg}})_{\mathrm{classical}} = \delta Q \cdot L_{\mathrm{Hg}}$

$L_{\mathrm{Hg}} \approx 3*10^{-8}$ cm

$-\delta Q$

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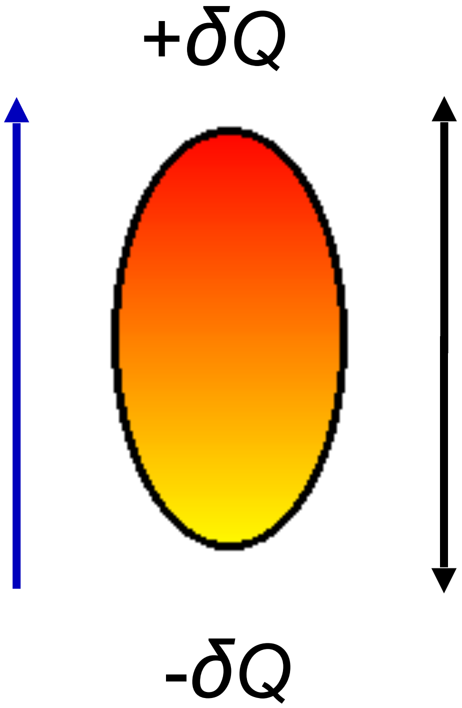


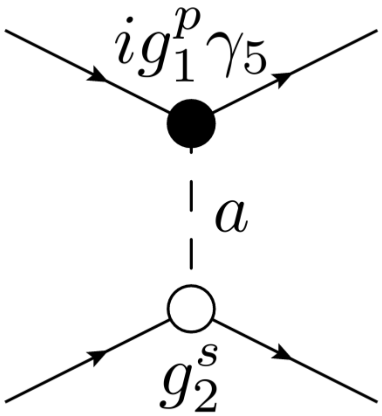
$(d_{Hg})_{\text{classical}} = \delta Q \cdot L_{Hg}$

$L_{Hg} \approx 3{*}10^{-8}$ cm

δQ sensitivity ~ 10^{-22} e (!)

Non-Cosmological Sources of Dark Bosons

[Stadnik, Dzuba, Flambaum, *PRL* 120, 013202 (2018)],
[Dzuba, Flambaum, Samsonov, Stadnik, *PRD* 98, 035048 (2018)]



$$\mathcal{L}_{\text{int}} = a\bar{f}\left(g_f^s + ig_f^p\gamma_5\right)f$$

$$V(r) \approx \frac{g_1^p g_2^s}{8\pi m_1}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{r}}\left(\frac{m_a}{r}+\frac{1}{r^2}\right)e^{-m_a r}$$

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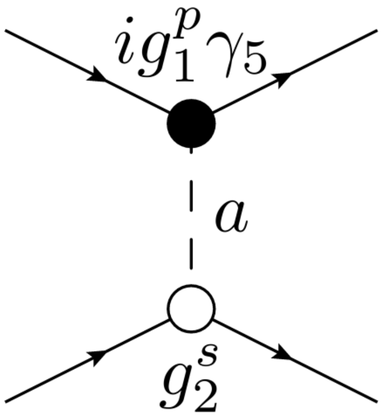

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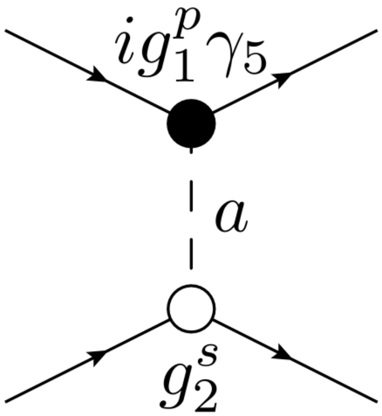

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P,*T*-violating forces => Atomic and Molecular EDMs

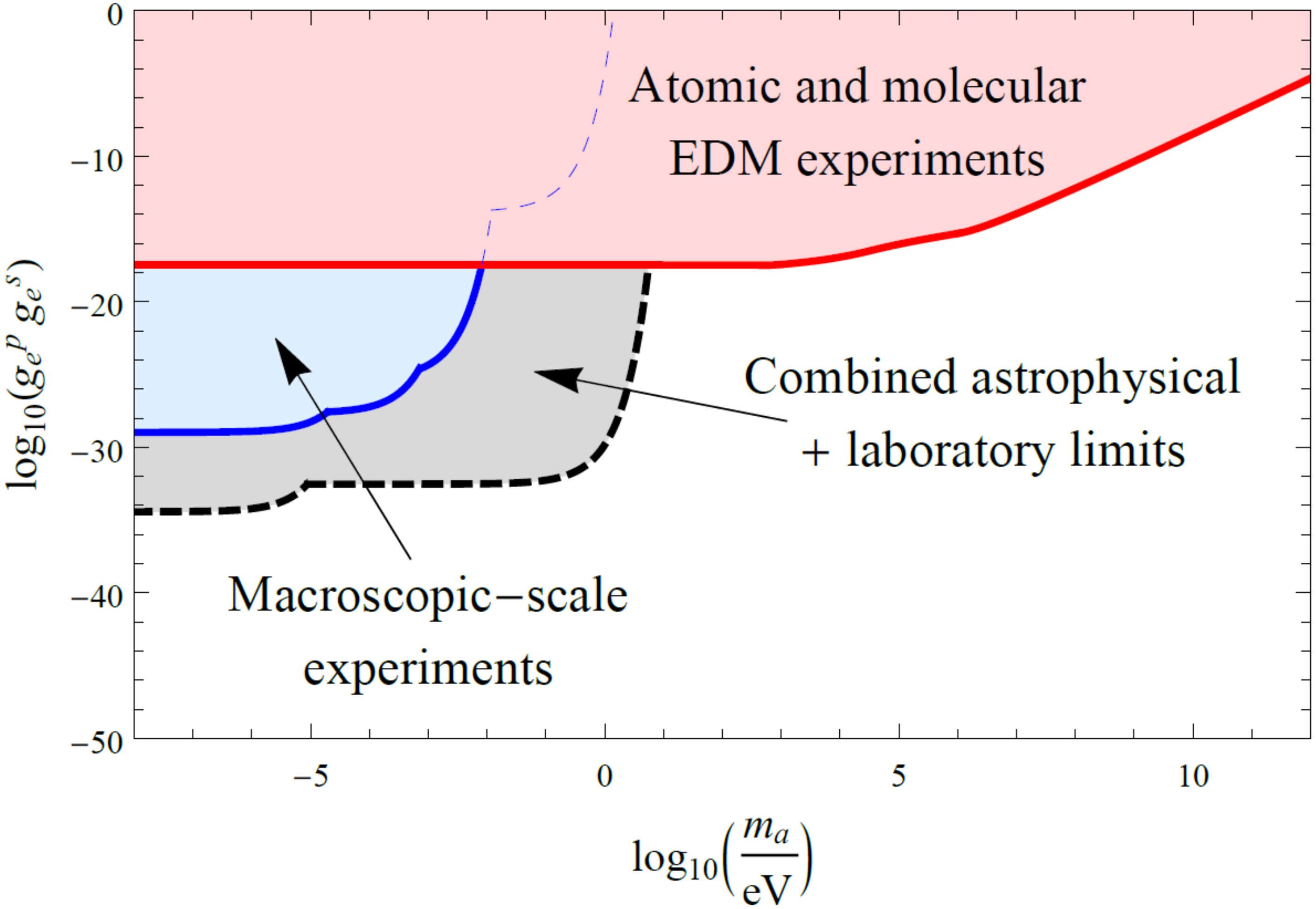
Atomic EDM experiments: Cs, Tl, Xe, Hg, Ra

Molecular EDM experiments: YbF, HfF$^+$, ThO

Constraints on Scalar-Pseudoscalar Electron-Electron Interaction

EDM constraints: [Stadnik, Dzuba, Flambaum, *PRL* 120, 013202 (2018)]

Many orders of magnitude improvement!



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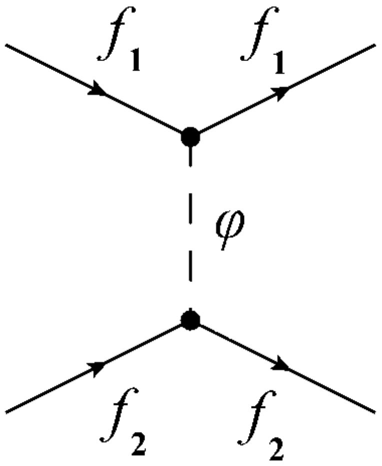

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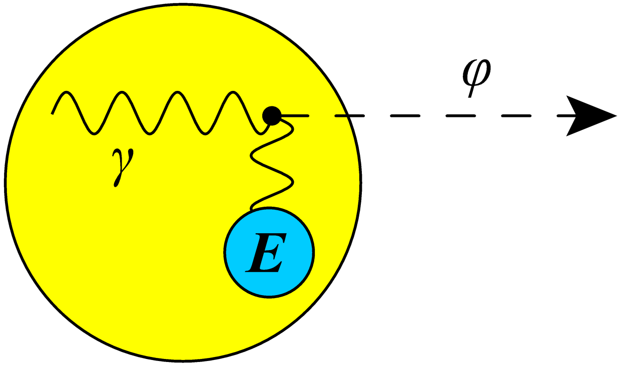

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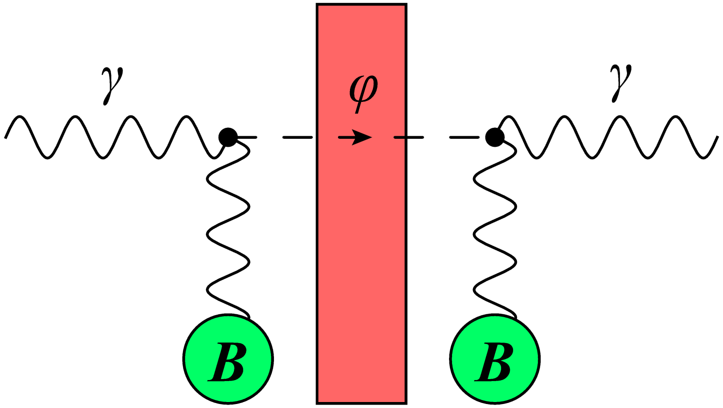

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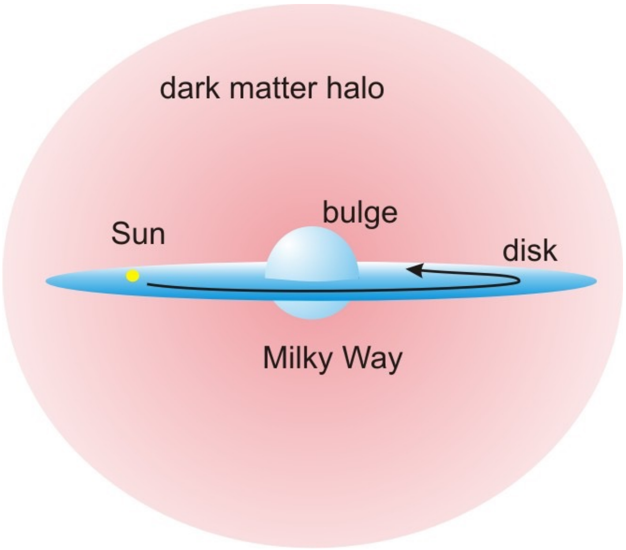
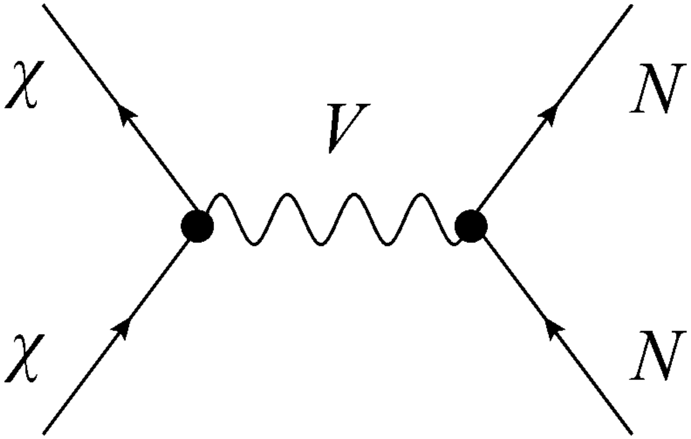


Dark matter

Motivation

Traditional "scattering-off-nuclei" searches for heavy WIMP dark matter particles (m_χ ~ GeV) have not yet produced a strong positive result.



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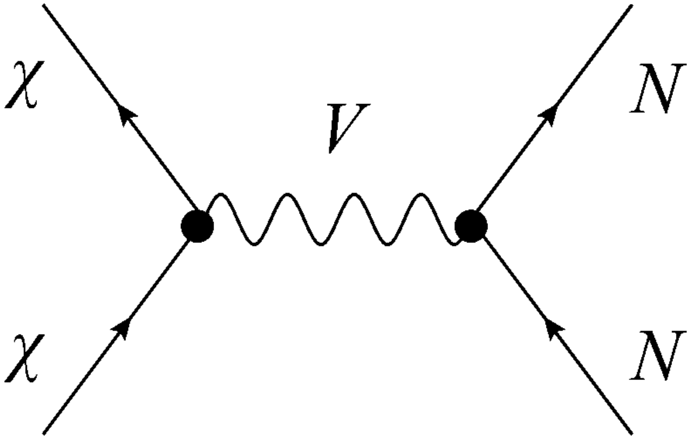

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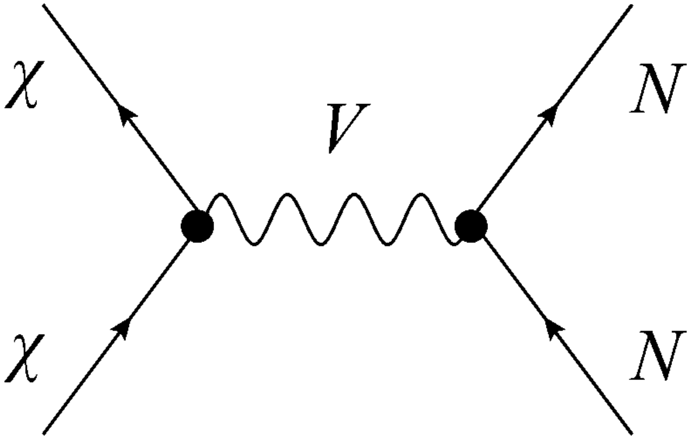

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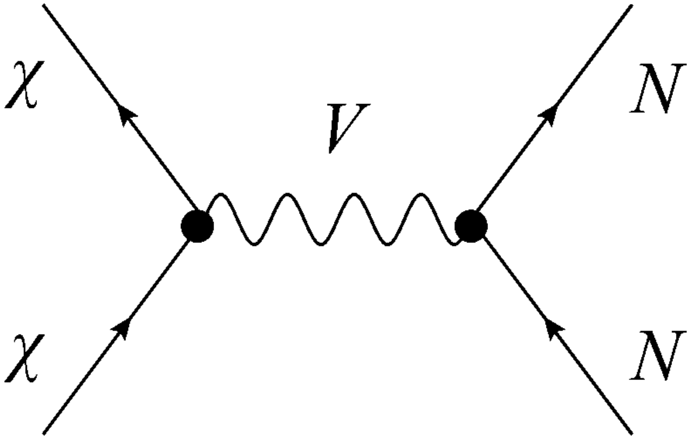

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Challenge: Observable is **fourth power** in a small interaction constant ($e' << 1$)!

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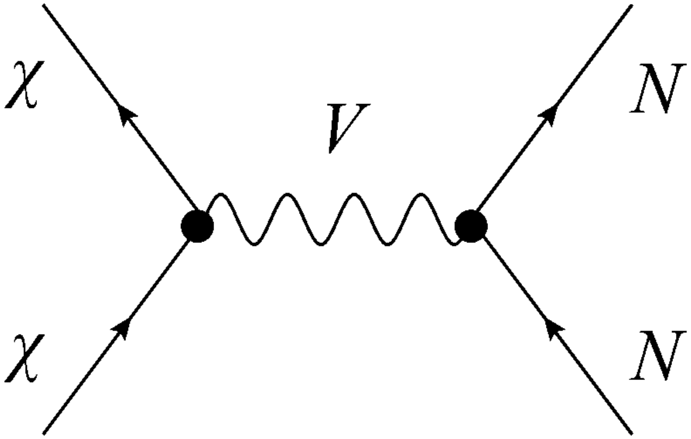

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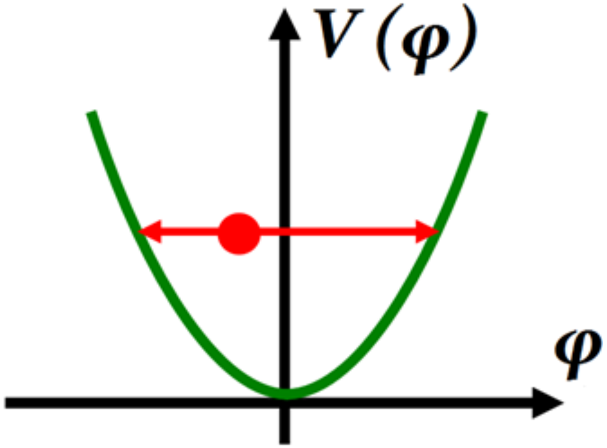
Question: *Can we instead look for effects of dark matter that are* ***first power*** *in the interaction constant?*

Low-mass Spin-0 Dark Matter

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



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

$$\tau_{\mathrm{coh}} \sim \frac{2\pi}{m_\phi \langle v_{\mathrm{DM}}^2 \rangle} \sim 10^6 T_{\mathrm{osc}}$$

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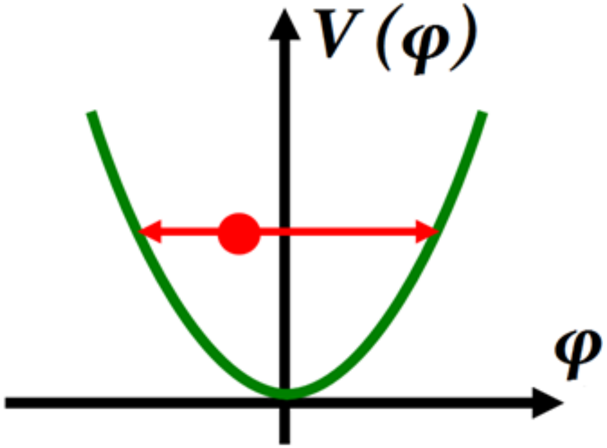

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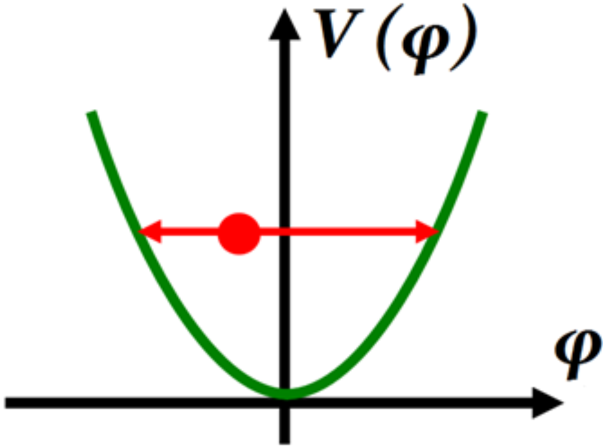

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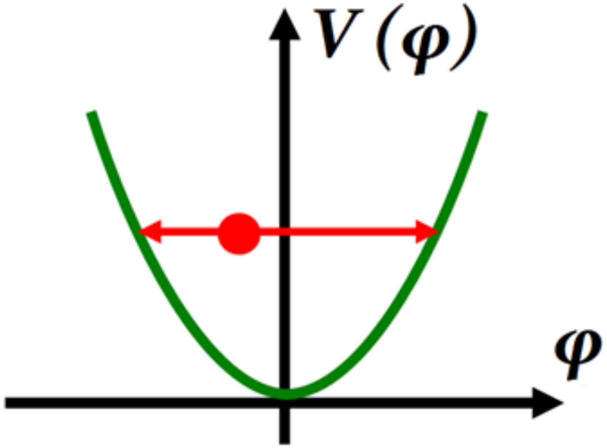

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$H << m_\varphi$: $\varphi \propto \cos(m_\varphi t)/t^{3/4}$ => $\rho \propto 1/V$ [Cold DM regime]

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Classical field

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- 10^{-22} eV $\lesssim m_\varphi << 1$ eV inaccessible to traditional "scattering-off-nuclei" searches, since $|p_\varphi| \sim 10^{-3} m_\varphi$ is extremely small => recoil effects of *individual particles* suppressed
- BUT can look for *coherent effects of a low-mass DM field* in low-energy atomic and astrophysical phenomena that are first power in the interaction constant κ:

$$\mathcal{L}_{\mathrm{eff}} = \kappa \phi^n X_{\mathrm{SM}} X_{\mathrm{SM}} \quad => \quad \mathcal{O} \propto \kappa$$

Low-mass Spin-0 Dark Matter

- *Low-mass spin-0 particles* form a *coherently oscillating classical* field $\varphi(t) = \varphi_0 \cos(m_\varphi c^2 t/\hbar)$, with energy density $<\rho_\varphi> \approx m_\varphi^2 \varphi_0^2/2$ ($\rho_{\mathrm{DM,local}} \approx 0.4$ GeV/cm^3)
- 10^{-22} eV $\lesssim m_\varphi << 1$ eV inaccessible to traditional "scattering-off-nuclei" searches, since $|p_\varphi| \sim 10^{-3} m_\varphi$ is extremely small => recoil effects of *individual particles* suppressed
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- First-power effects => Improved sensitivity to certain DM interactions by up to 15 orders of magnitude (!)

Low-mass Spin-0 Dark Matter

Dark Matter

Pseudoscalars

(Axions):

$\varphi \xrightarrow{P} -\varphi$

QCD axion resolves
strong CP problem

→ Time-varying spin-dependent effects

1000-fold improvement

"Axion Wind" Spin-Precession Effect

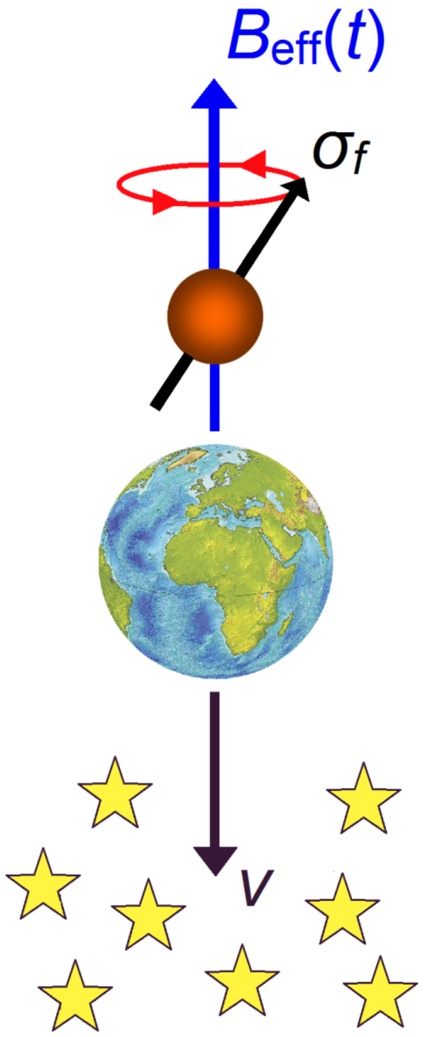
[Flambaum, talk at *Patras Workshop*, 2013], [Graham, Rajendran, *PRD* 88, 035023 (2013)], [Stadnik, Flambaum, *PRD* 89, 043522 (2014)]

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

$$=> \quad H_{\mathrm{eff}}(t) \simeq \boldsymbol{\sigma}_f\cdot\boldsymbol{B}_{\mathrm{eff}}\sin(m_a t)$$

Pseudo-magnetic field*

$$\boldsymbol{B}_{\mathrm{eff}} \propto \boldsymbol{v}$$



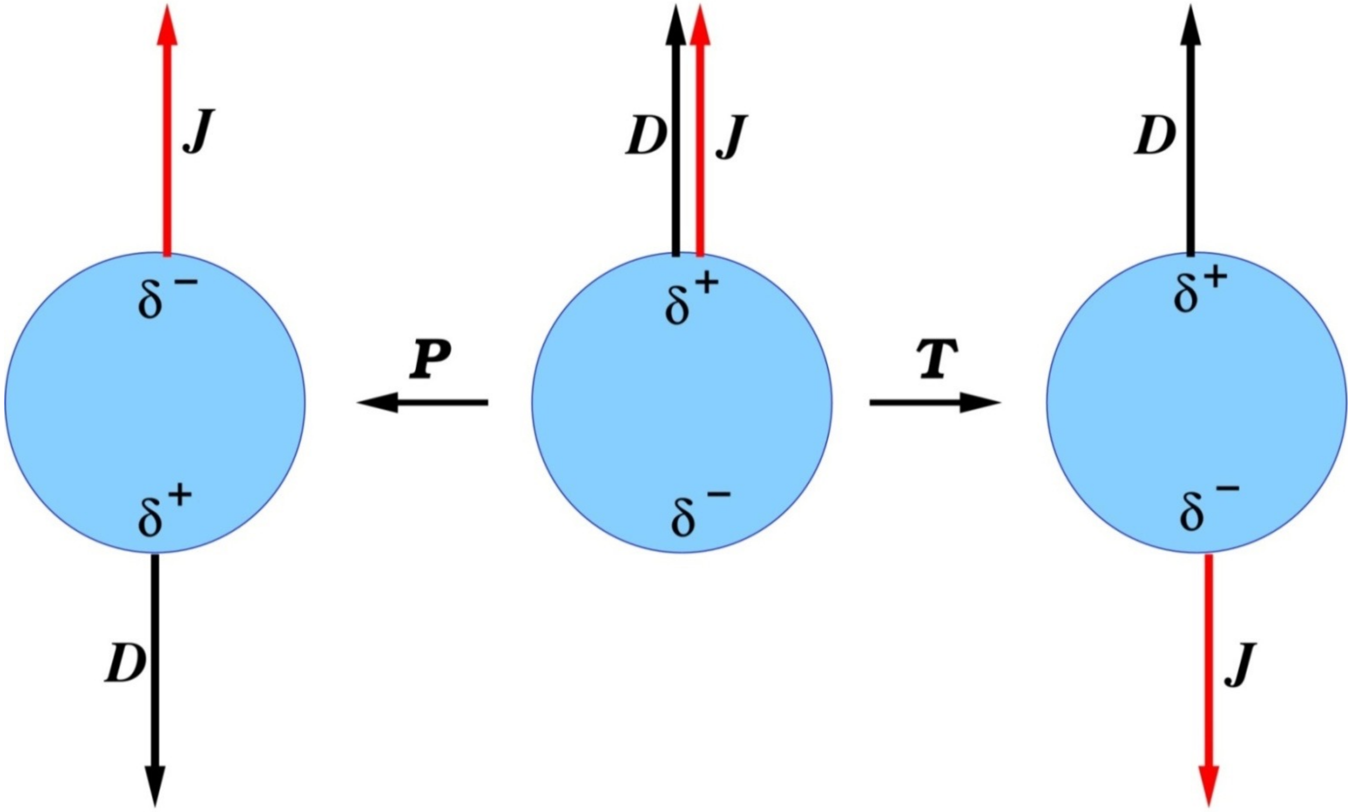
* Compare with usual magnetic field: $H = -\mu_f\cdot B$

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



Searching for Spin-Dependent Effects

Proposals: [Flambaum, talk at *Patras Workshop*, 2013; Stadnik, Flambaum, *PRD* 89, 043522 (2014); arXiv:1511.04098; Stadnik, PhD Thesis (2017)]

Use *spin-polarised sources*: Atomic magnetometers, ultracold neutrons, torsion pendula

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

$$\frac{\nu_n}{\nu_{\mathrm{Hg}}} = \underset{\substack{\Big\uparrow \\ \text{B-field} \\ \text{effect}}}{\left| \frac{\mu_n B}{\mu_{\mathrm{Hg}} B} \right|} + \underset{\substack{\Big\uparrow \\ \text{Axion DM} \\ \text{effect}}}{R(t)}$$

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B-field effect

Axion DM effect

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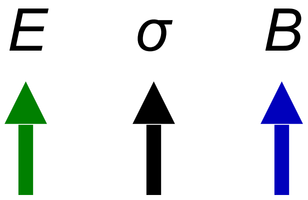
$$R_{\mathrm{EDM}}(t) \propto \cos(m_a t)$$



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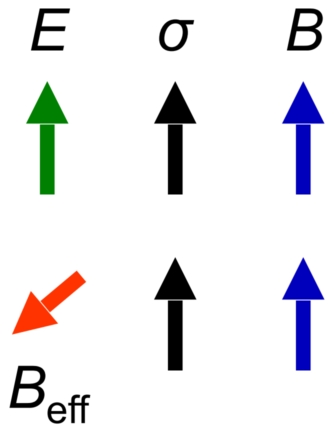
$$R_{\mathrm{wind}}(t) \propto \sum_{i=1,2,3} A_i \sin(\omega_i t)$$



$$\omega_1 = m_a, \;\; \omega_2 = m_a + \Omega_{\mathrm{sidereal}}, \;\; \omega_3 = |m_a - \Omega_{\mathrm{sidereal}}|$$

Earth's rotation

Searching for Spin-Dependent Effects

Proposals: [CASPEr collaboration, *Quantum Sci. Technol.* 3, 014008 (2018)]

Use *nuclear magnetic resonance* (“sidebands” technique)

Searching for Spin-Dependent Effects

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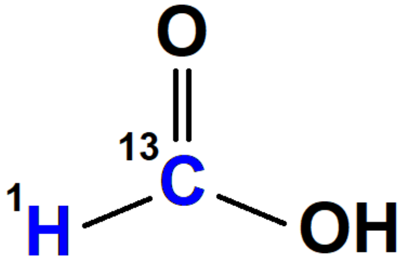

$H_J \sim J\, I_H \cdot I_C$

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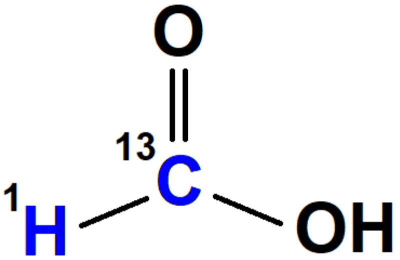

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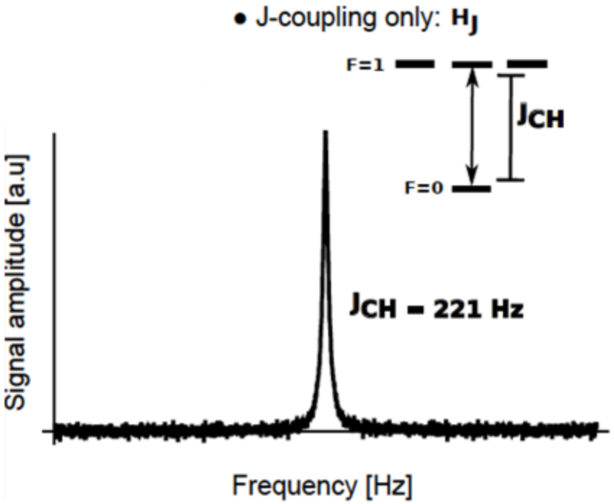

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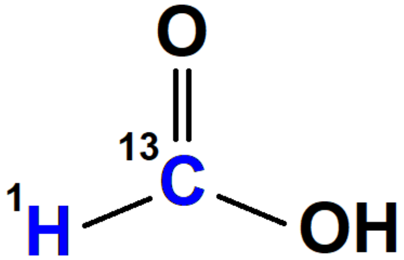

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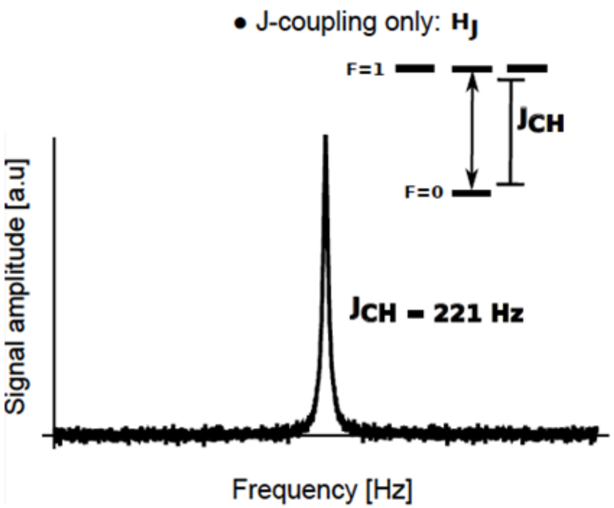

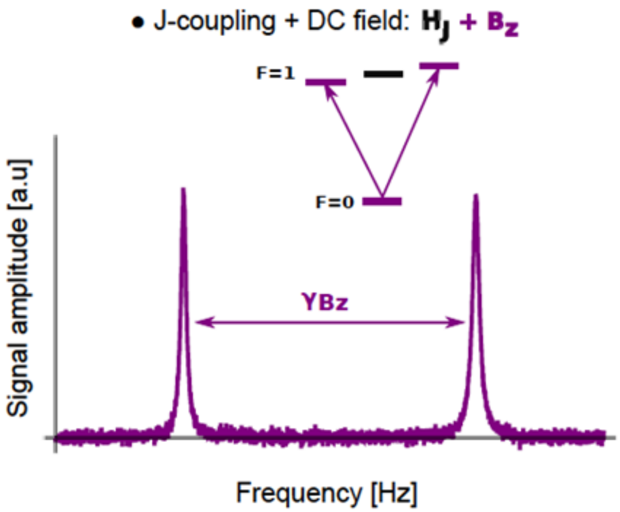

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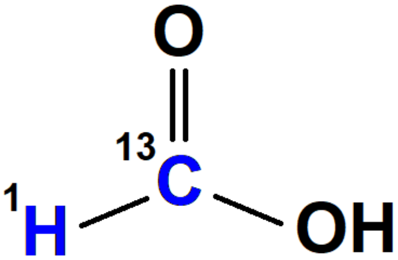
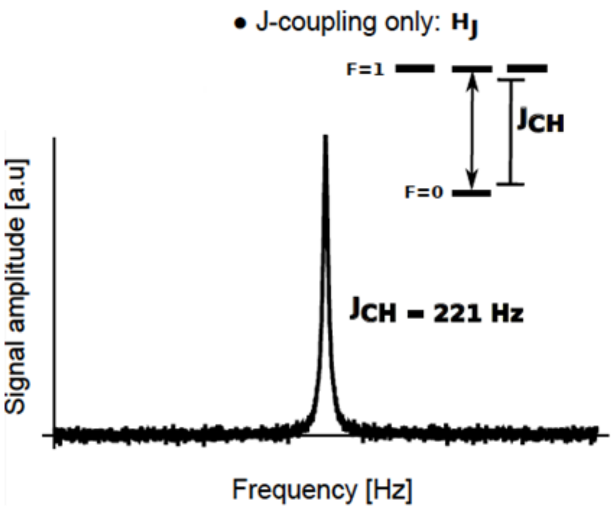
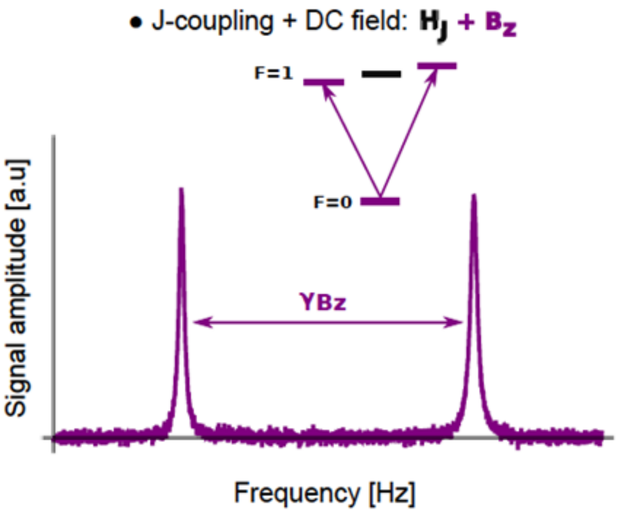
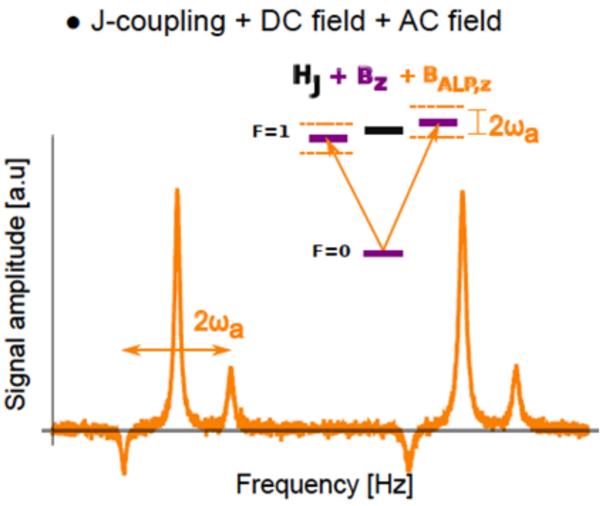


$$H_J \sim J\, I_H \cdot I_C$$


- J-coupling only: $\mathbf{H_J}$


- J-coupling + DC field: $\mathbf{H_J + B_z}$


- J-coupling + DC field + AC field

Searching for Spin-Dependent Effects

Proposals: [Budker, Graham, Ledbetter, Rajendran, A. O. Sushkov, *PRX* 4, 021030 (2014)]

Use *nuclear magnetic resonance*

Searching for Spin-Dependent Effects

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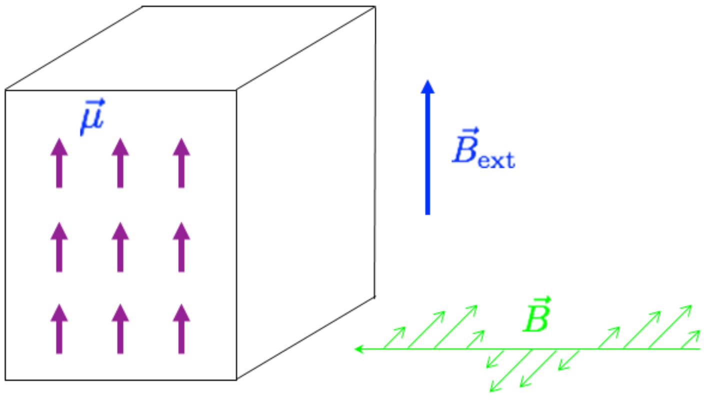
Use *nuclear magnetic resonance*

Traditional NMR



Resonance: $2\mu B_{ext} = \omega$

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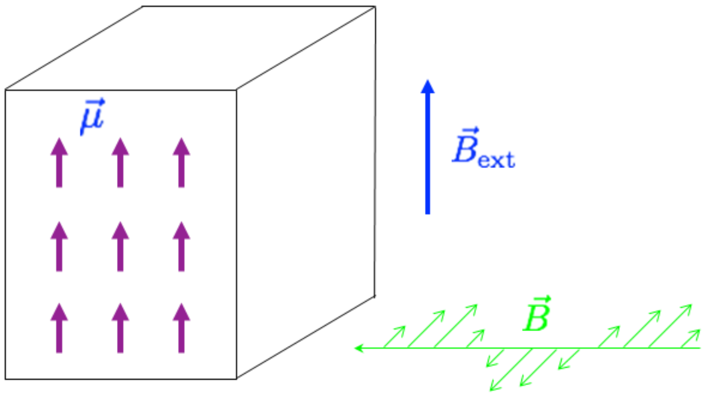
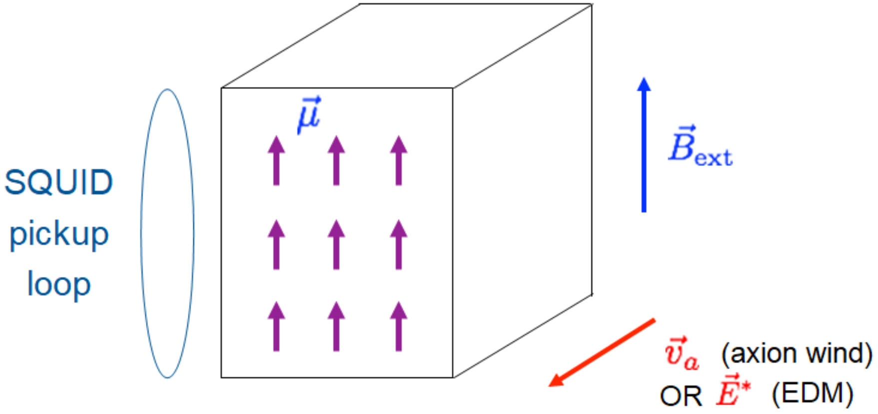


Resonance: $2\mu B_{\text{ext}} = \omega$

Dark-matter-driven NMR



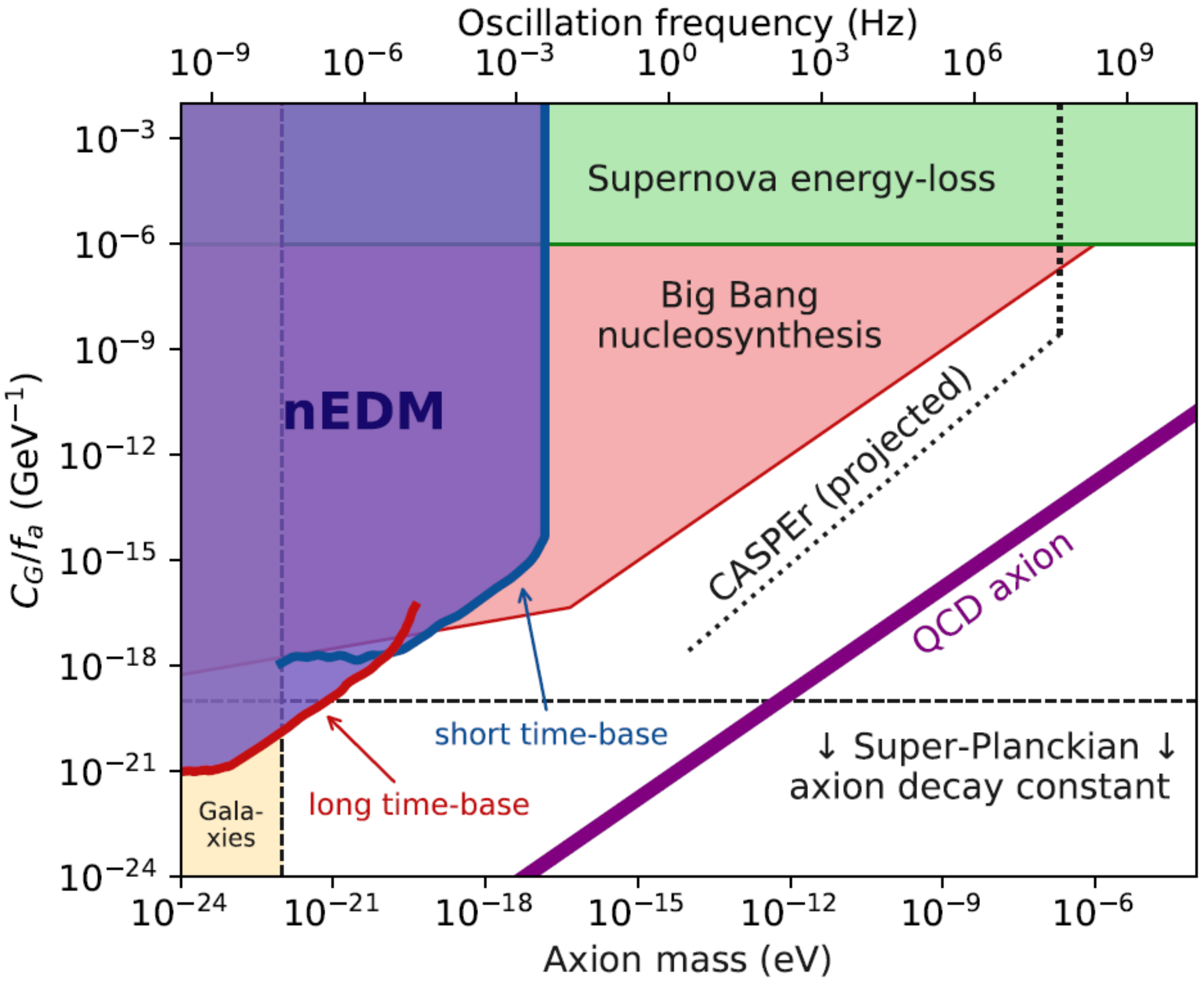
Resonance: $2\mu B_{\text{ext}} \approx m_a$

Measure transverse magnetisation

Constraints on Interaction of Axion Dark Matter with Gluons

nEDM constraints: [nEDM collaboration, *PRX* 7, 041034 (2017)]

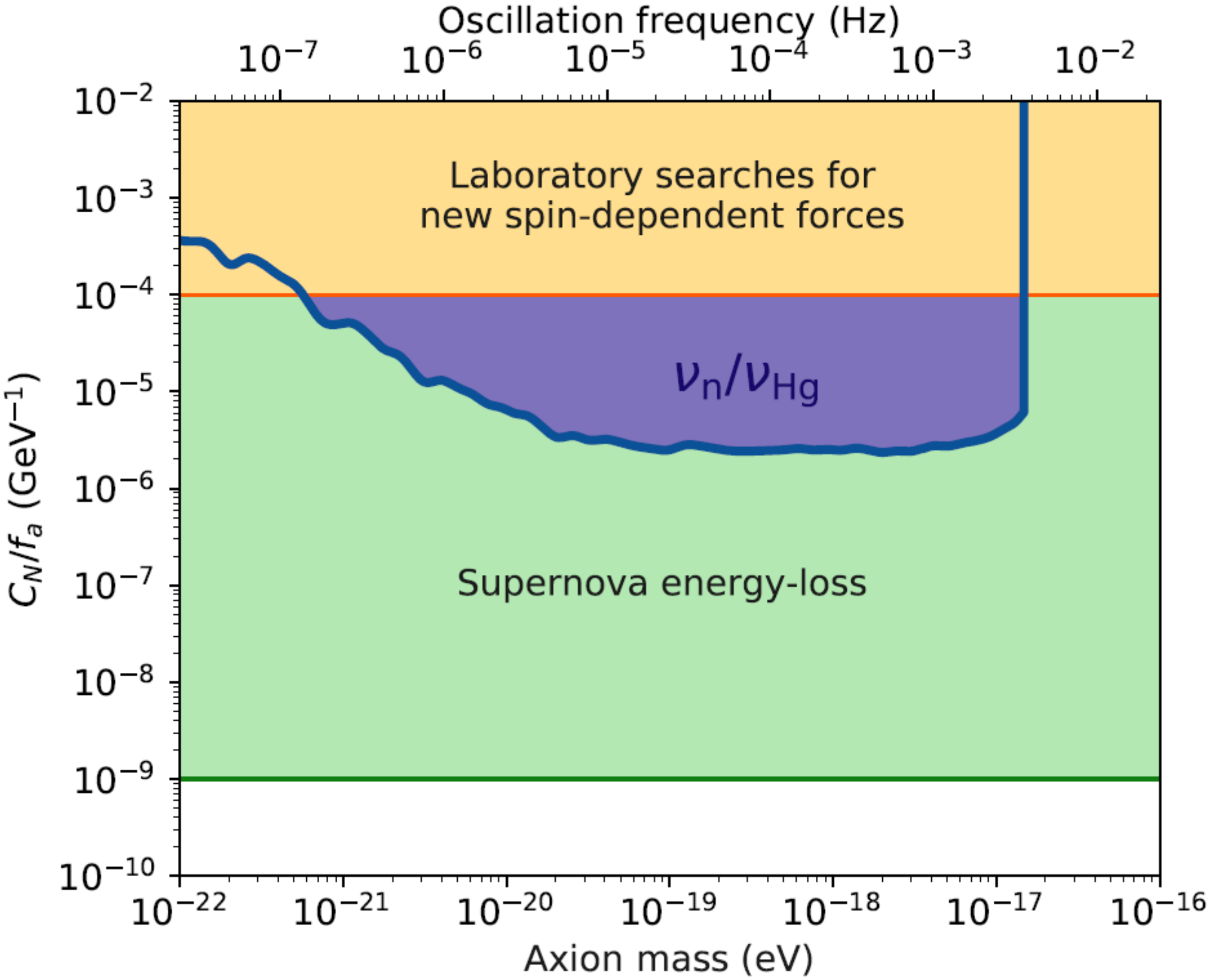
3 orders of magnitude improvement!



Constraints on Interaction of Axion Dark Matter with Nucleons

ν_n/ν_{Hg} constraints: [nEDM collaboration, *PRX* 7, 041034 (2017)]

40-fold improvement (laboratory bounds)!



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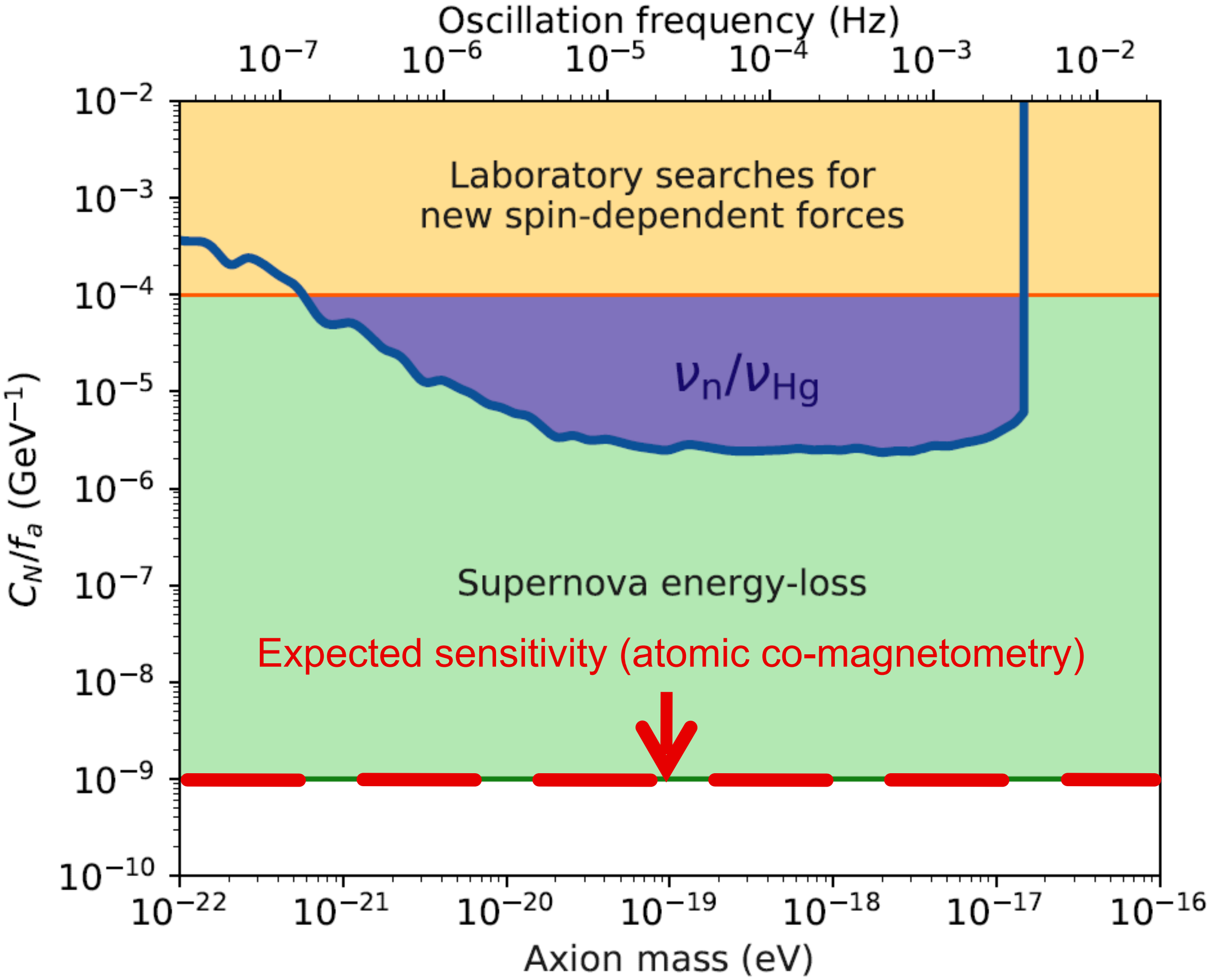
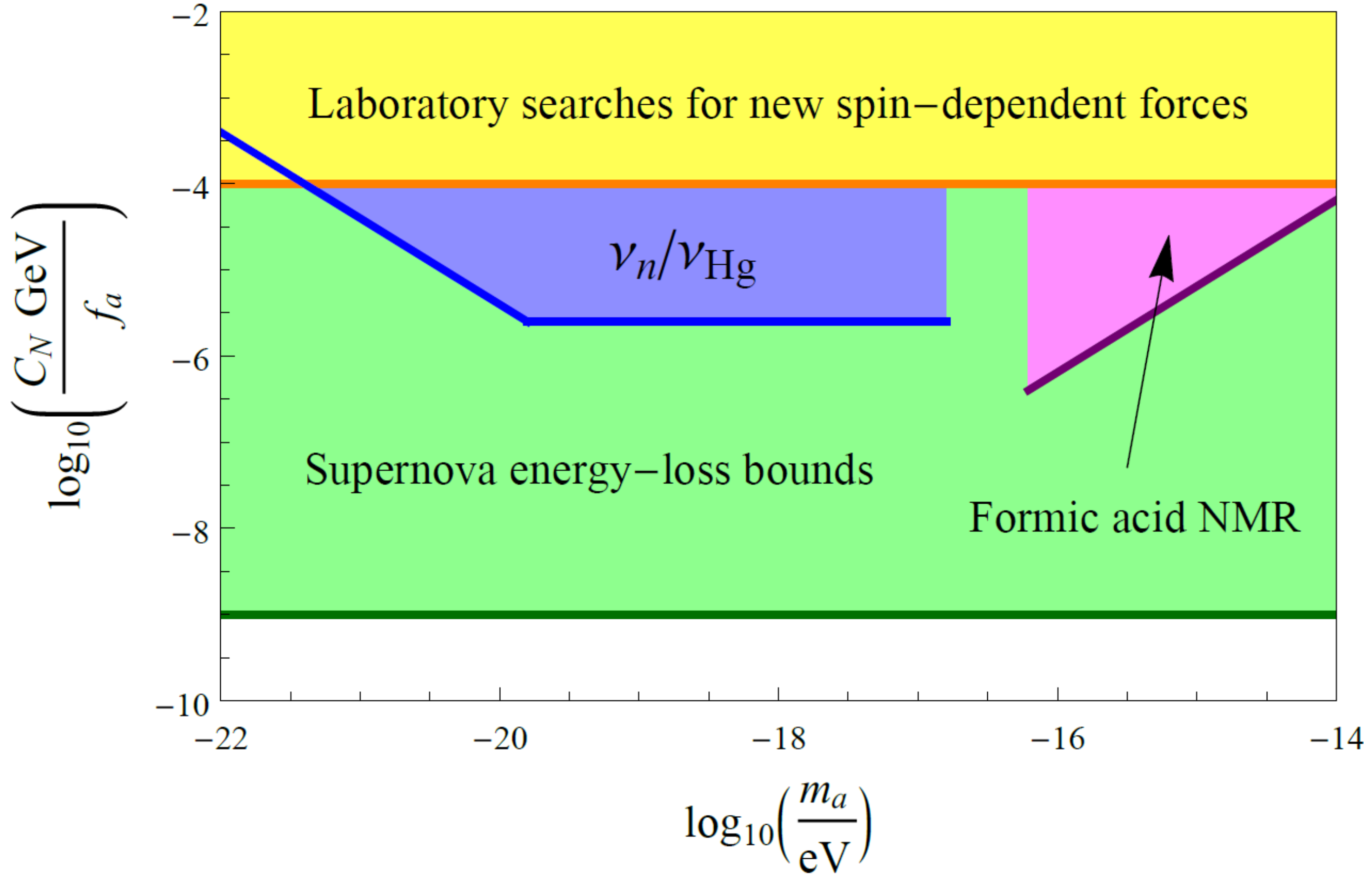


Constraints on Interaction of Axion Dark Matter with Nucleons

ν_n/ν_{Hg} constraints: [nEDM collaboration, *PRX* 7, 041034 (2017)]

Formic acid NMR constraints: [CASPEr collaboration, In preparation]

2 orders of magnitude improvement (laboratory bounds)!



Summary

- New classes of dark matter effects that are first power in the underlying interaction constant => Up to 15 orders of magnitude improvement

- Improved limits on dark bosons from atomic experiments (new forces, independent of ρ_{DM})

- More details in full slides (also on ResearchGate)