Searches for Dark Matter with Atoms and Optics: Varying Fundamental "Constants"

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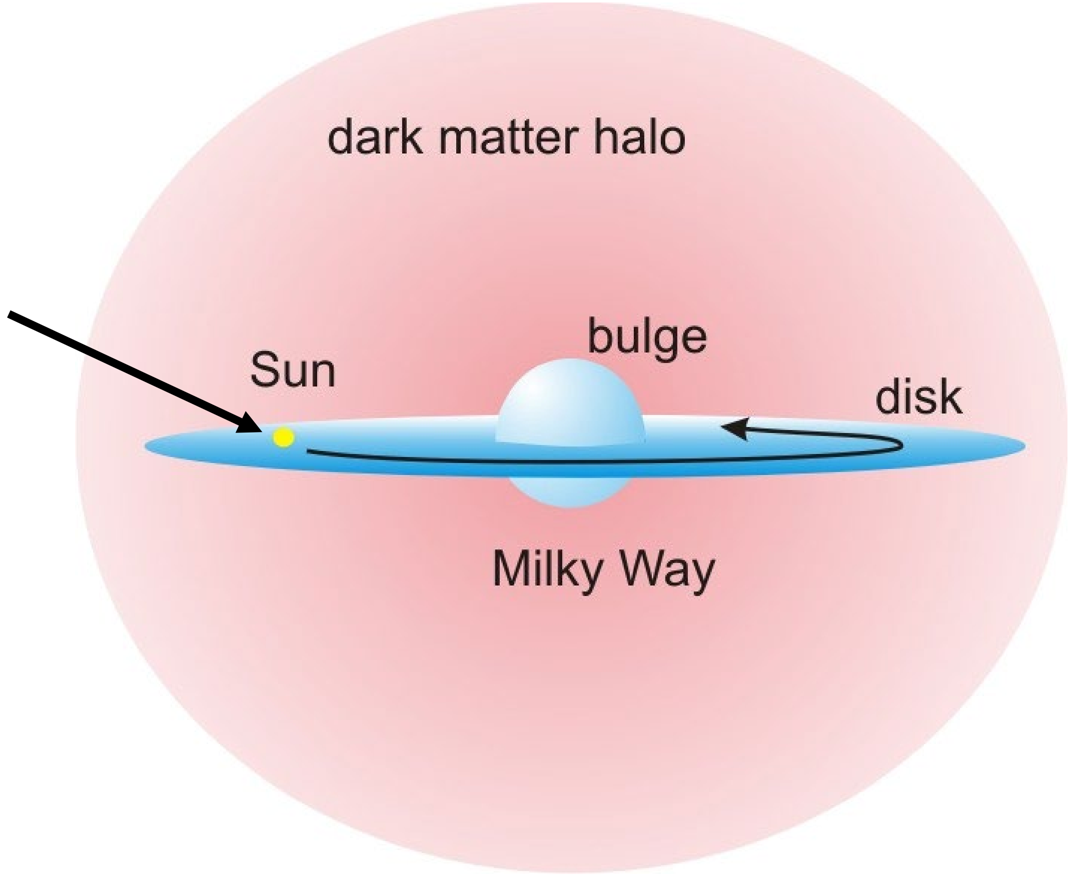
Dark Matter

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

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

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



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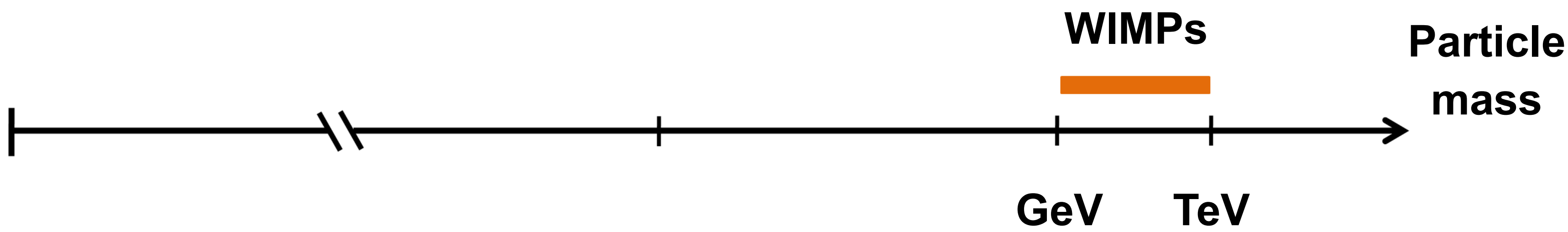

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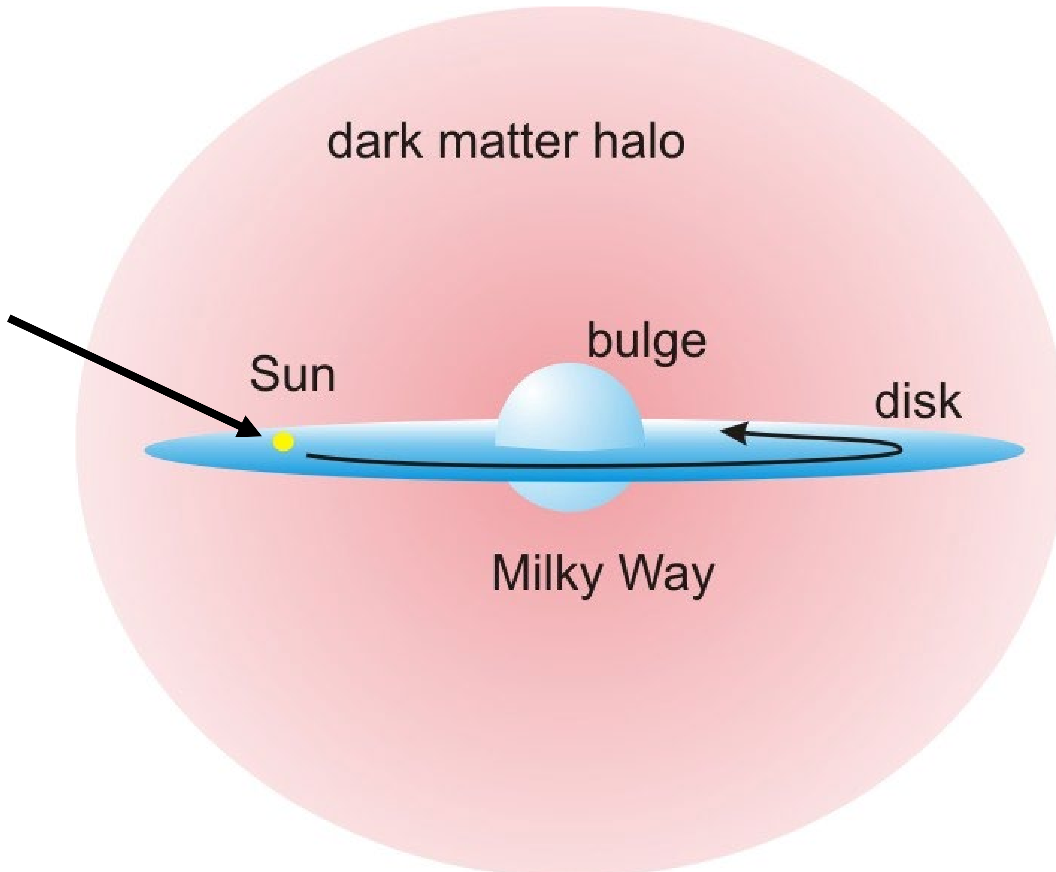

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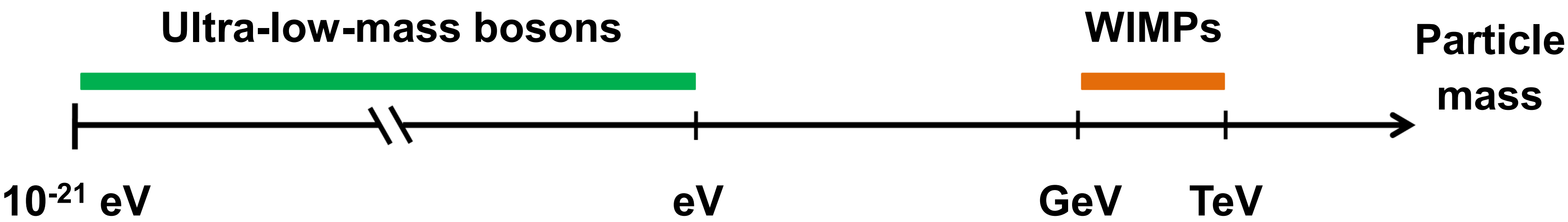

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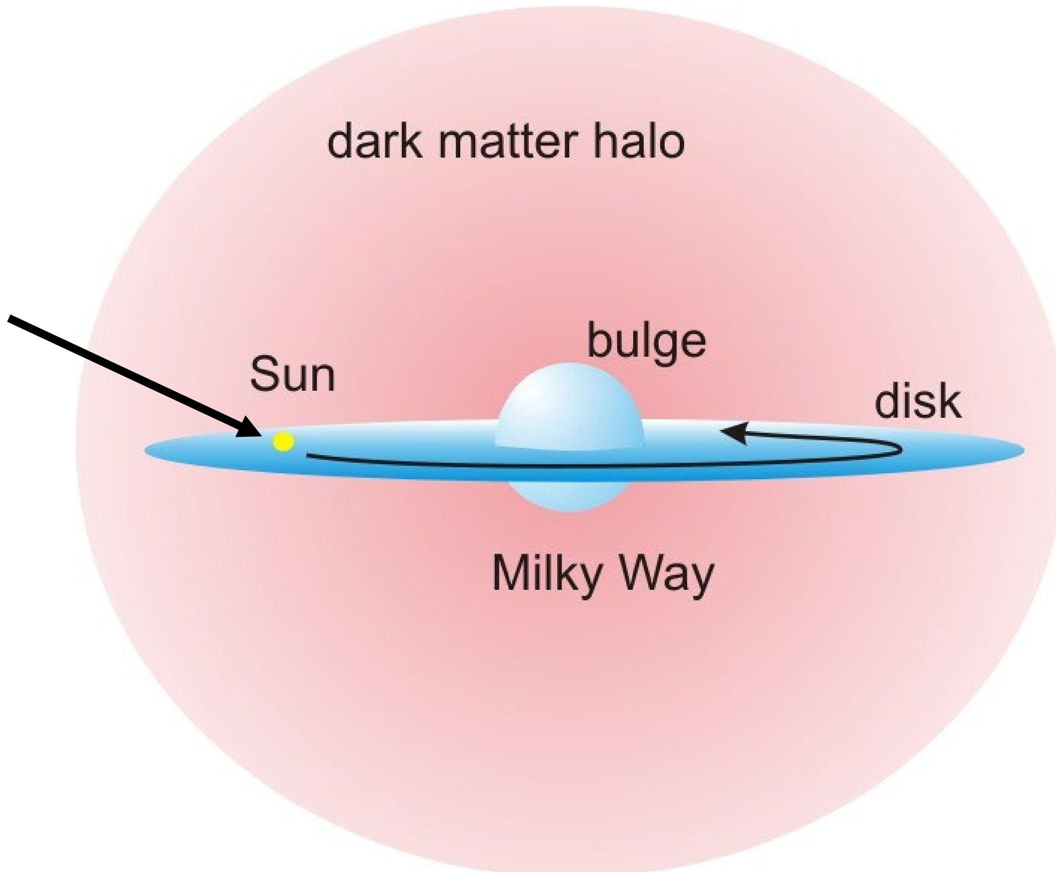
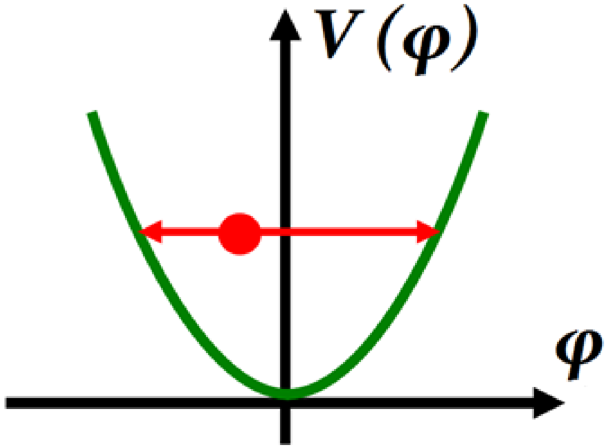


Low-mass Spin-0 Dark Matter

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



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

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

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Quality factor: $Q \sim 10^6$

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Ensemble of $N \gg 1$ particles:

$$\varphi(t) \propto \sum_{i=1}^{N} \cos\left[m_\varphi c^2 t/\hbar + m_\varphi v_i^2 t/(2\hbar) + \theta_i\right]$$

The particle velocities $\boldsymbol{v}_i$ are randomly distributed according to a Maxwell-Boltzmann-type distribution

On timescales $\Delta t \ll \tau_{\mathrm{coh}} \sim 2\pi/\left(m_\varphi \langle v_\varphi^2 \rangle\right)$, the accumulated random phases are $\ll 2\pi$

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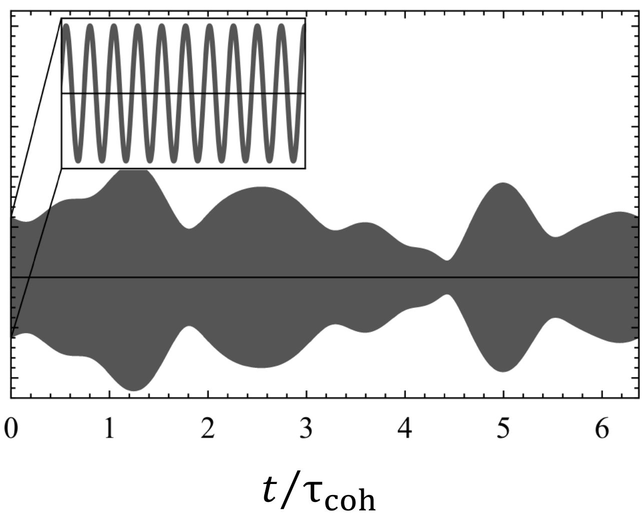
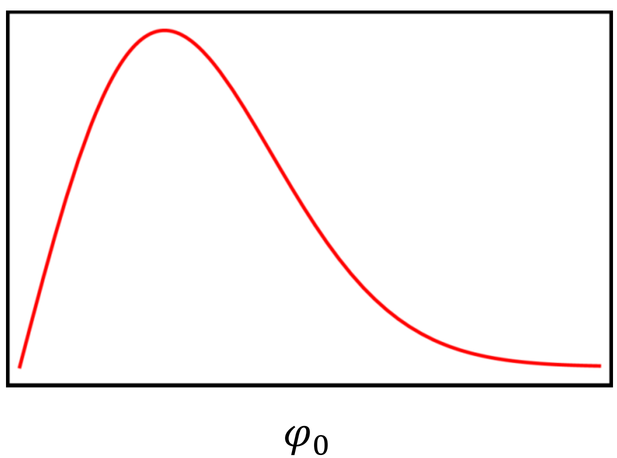
Evolution of φ_0 with time



Probability distribution function of φ_0 (Rayleigh distribution)



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

$T_{\mathrm{osc}} \sim 1\ \mathrm{month}$ 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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- *Wave-like* signatures [cf. *particle-like* signatures of WIMP DM]

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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Lab frame

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

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φ^2 interactions also exhibit the same oscillating-in-time signatures as above, as well as …

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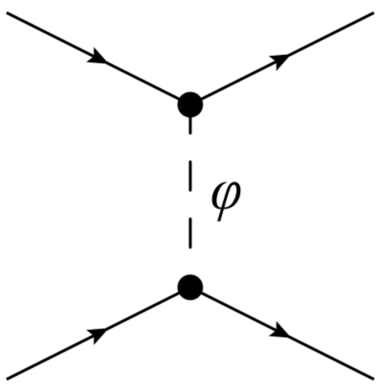
Fifth Forces: Linear vs Quadratic Couplings

[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**



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Profile outside of a spherical body

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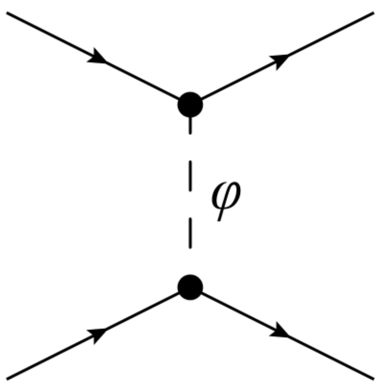

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Quadratic couplings ($\varphi^2 \bar{X} X$)

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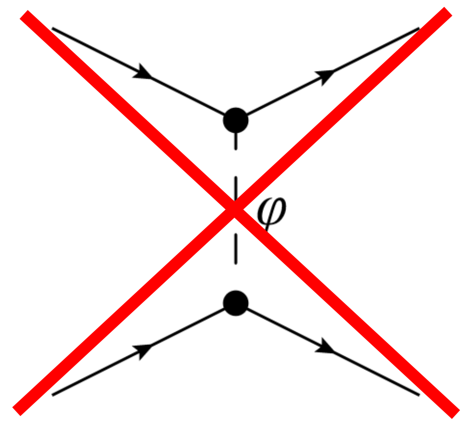

$$m_{\text{eff}}^2(\rho) = m_\varphi^2 \mp \kappa'\rho$$

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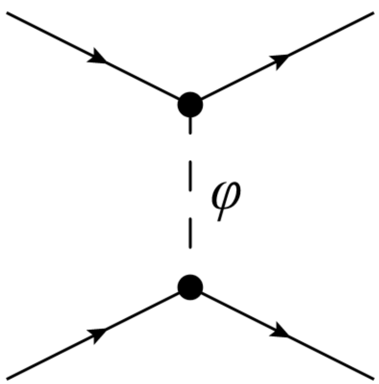

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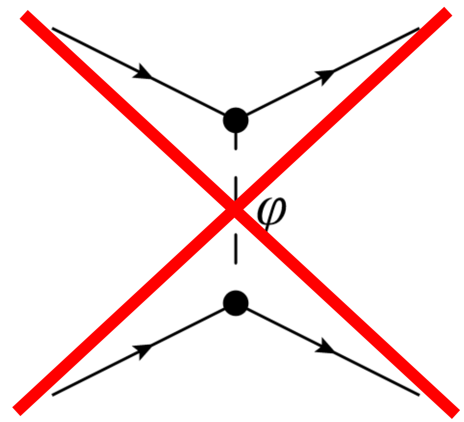

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Amplification/screening

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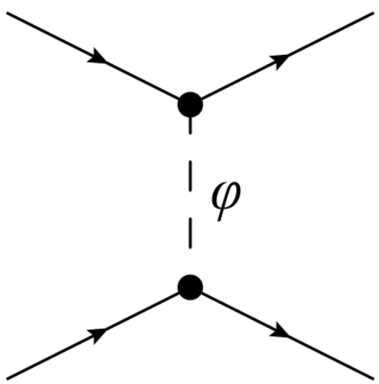

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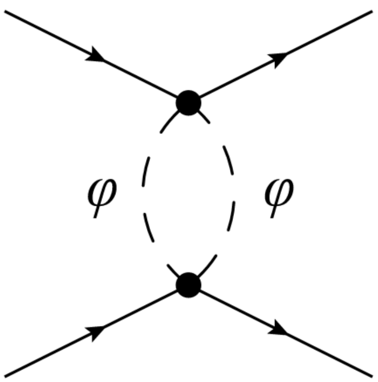

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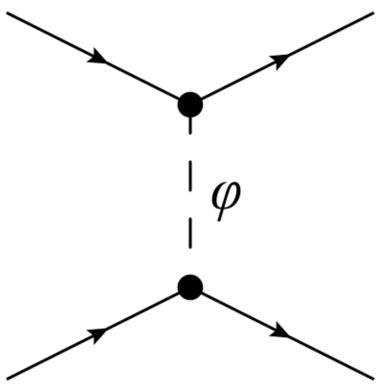

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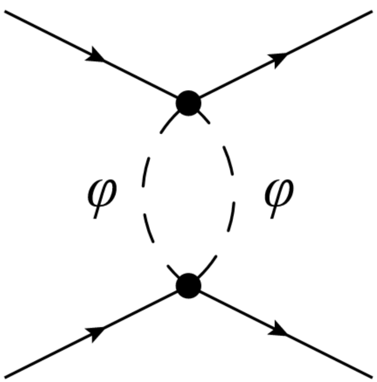

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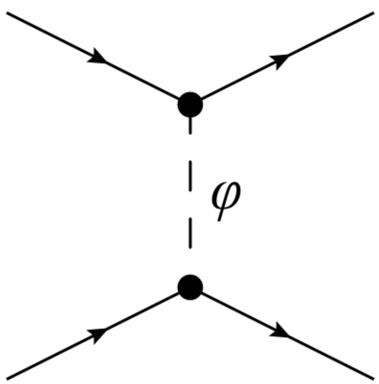

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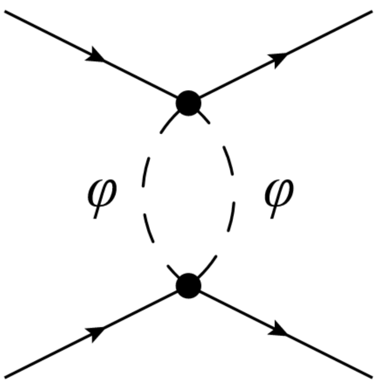

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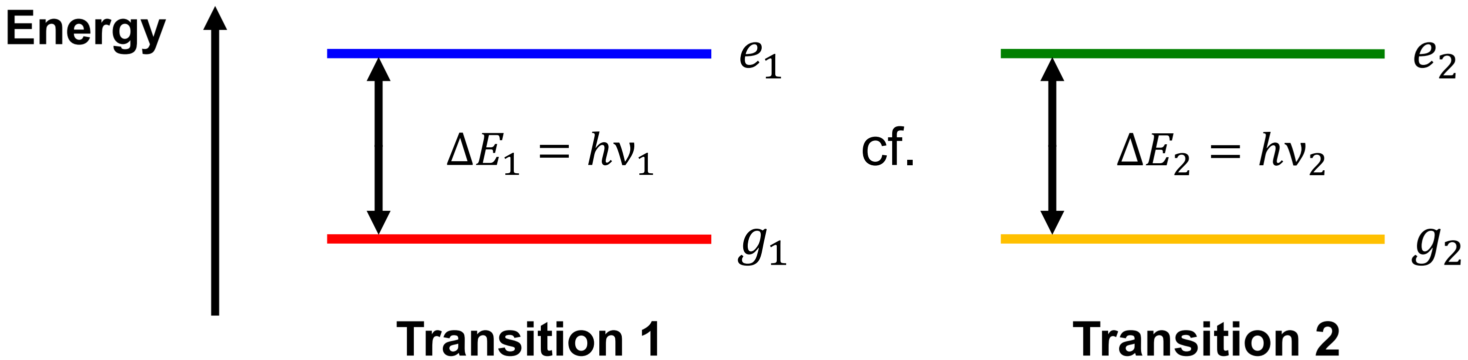
"Fifth-force" searches with accelerometers: torsion pendula, atom interferometry

Amplification/screening

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

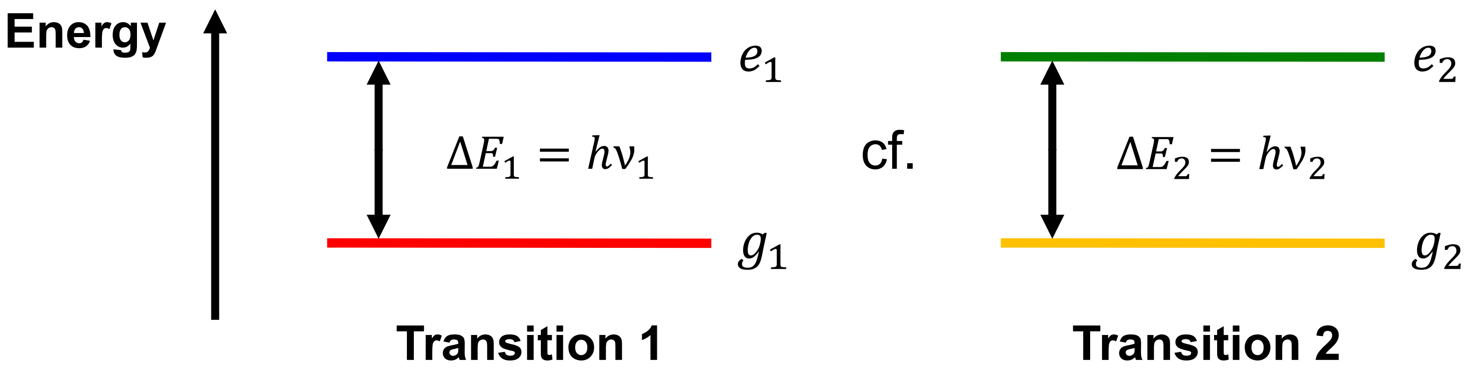
Overview: [Ludlow, Boyd, Ye, Peik, Schmidt, *Rev. Mod. Phys.* **87**, 637 (2015)]

"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)]



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

(lin.) (quad.)

- **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^+(E3)/Sr [PTB]:** [Huntemann, Peik *et al.*, Ongoing]

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)

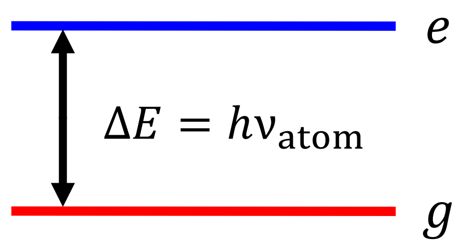
Cavity-Based Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter

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

Solid material

cf.

Electronic transition



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

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

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

- **Sr vs Glass cavity [Torun]:** [Wcislo *et al.*, *Nature Astronomy* **1**, 0009 (2016)]
- **Various combinations [Worldwide]:** [Wcislo *et al.*, *Science Advances* **4**, eaau4869 (2018)]
- **Cs vs Steel cavity [Mainz]:** [Antypas *et al.*, *PRL* **123**, 141102 (2019)]
- **Sr/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

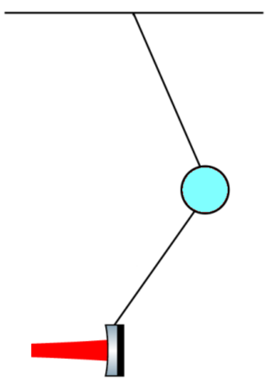
[Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRA* **93**, 063630 (2016)]

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.

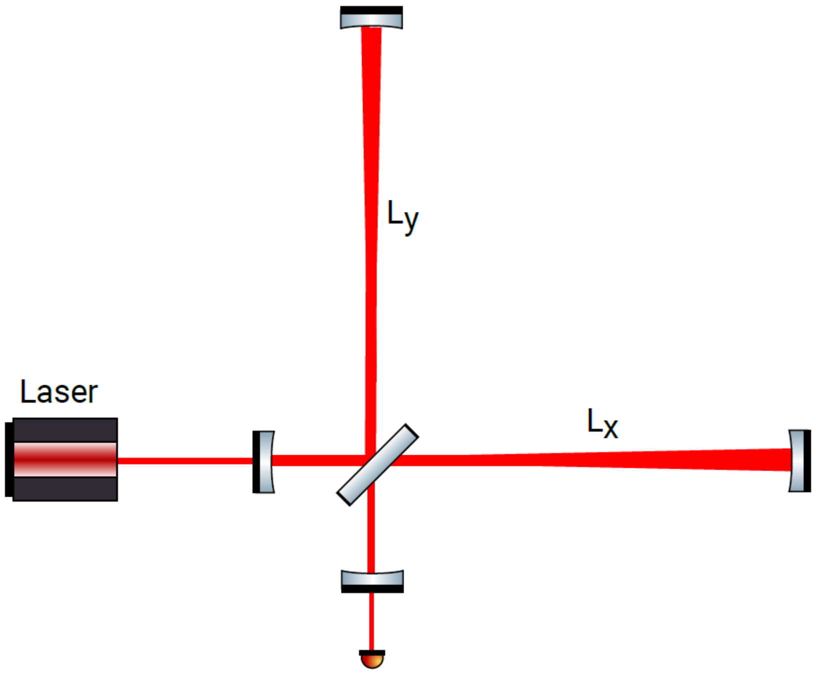
$$\frac{\nu_{\mathrm{atom}}}{\nu_{\mathrm{solid}}} \propto \alpha$$

Small-scale experiment currently under development at Northwestern University

[Geraci *et al.*, *Snowmass 2021 LOI #129 (CF2 section)*]

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

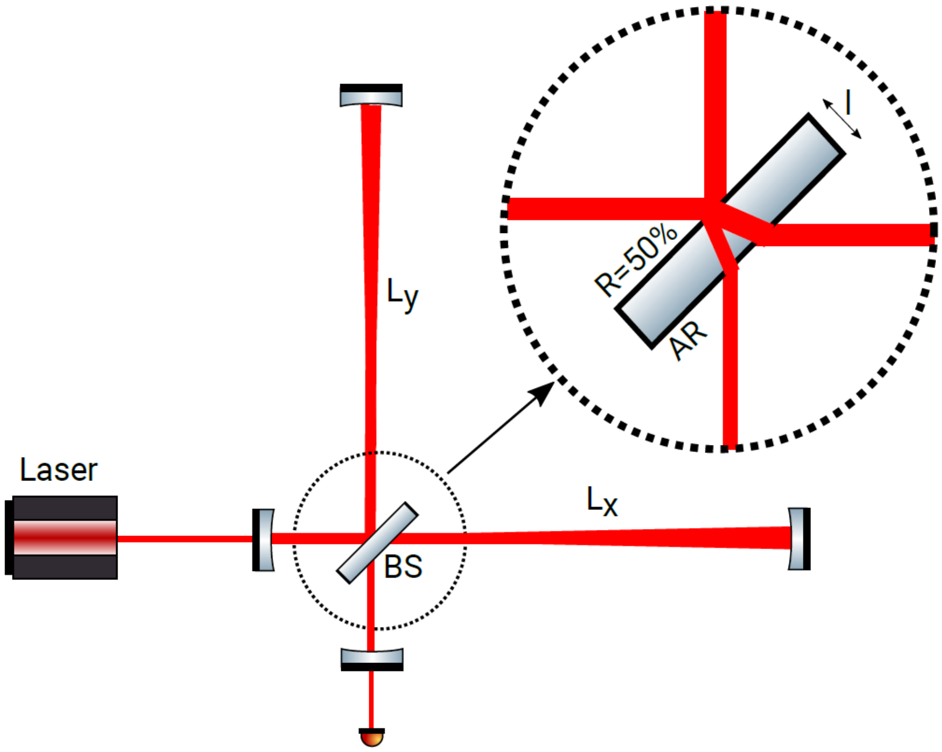
[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]



Michelson interferometer (GEO600)

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

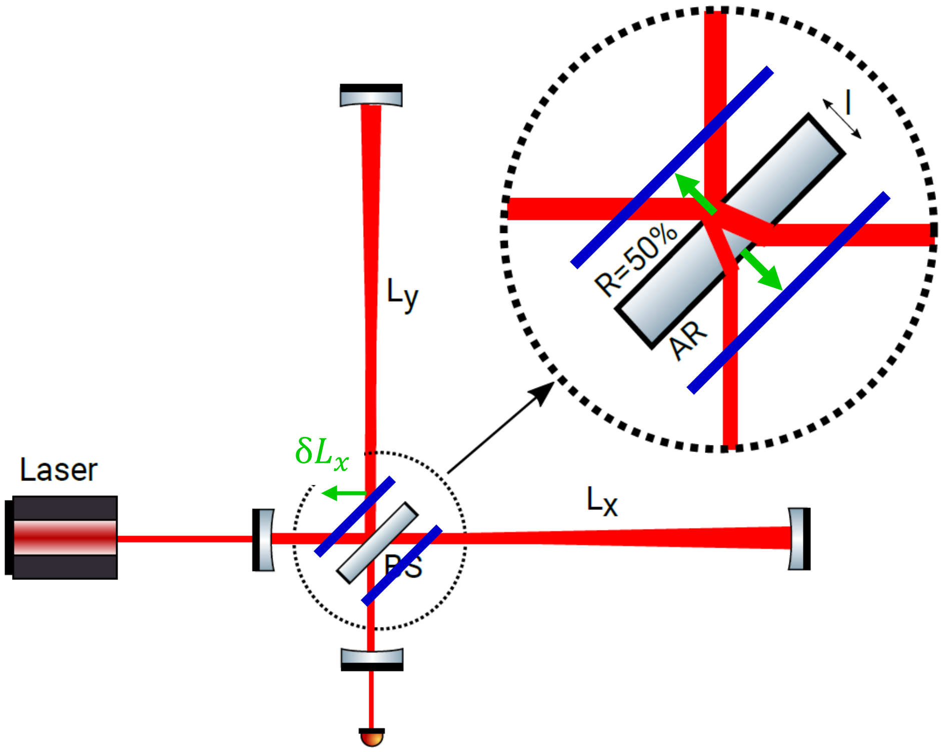
[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]



- Geometric asymmetry from beam-splitter

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

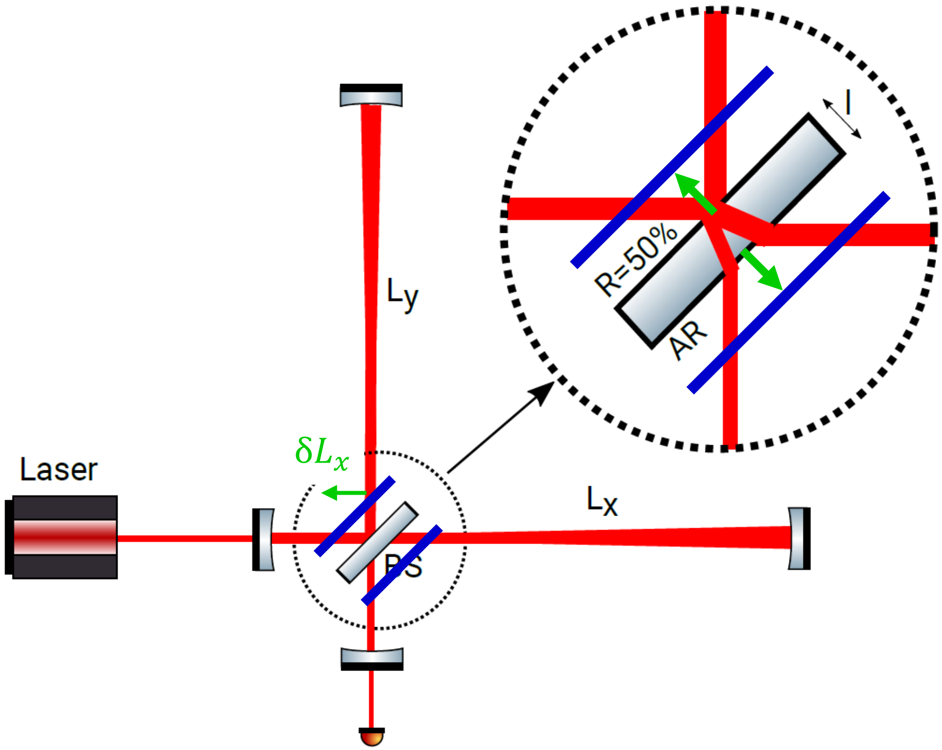
[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]



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

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

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



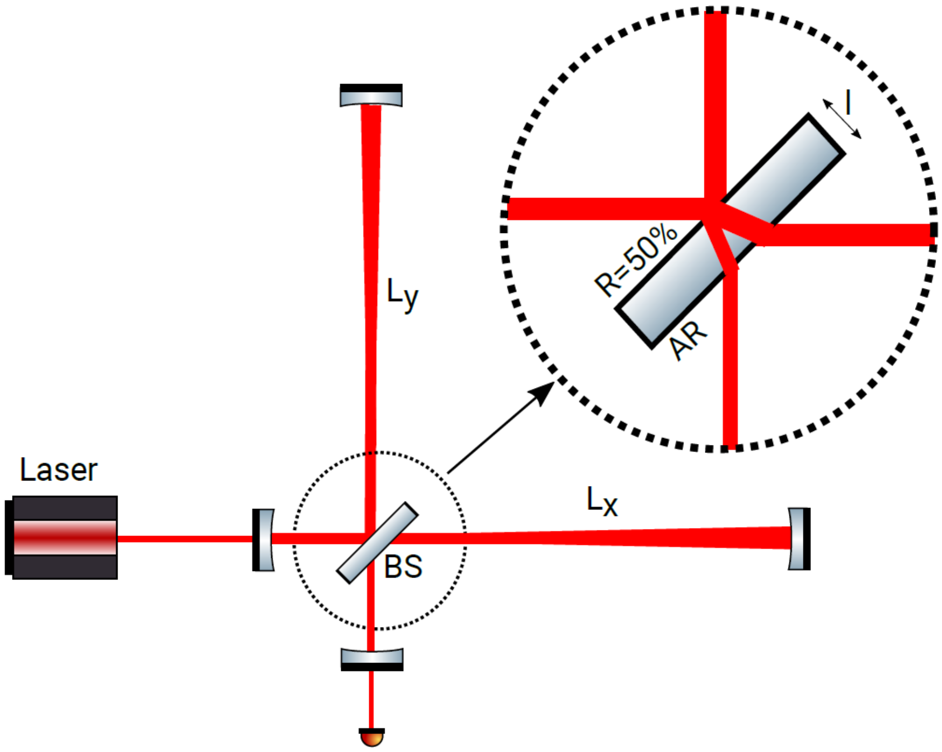
- Geometric asymmetry from beam-splitter: $\delta\left(L_x - L_y\right) \sim \delta(nl)$

First results recently reported using GEO600 and Fermilab holometer data:

[Vermeulen *et al.*, *Nature* **600**, 424 (2021)], [Aiello *et al.*, arXiv:2108.04746]

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

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



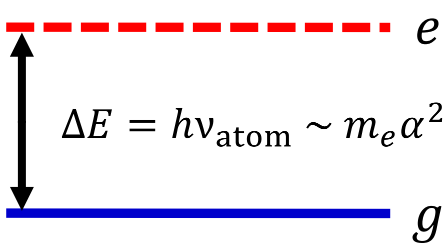
- Geometric asymmetry from beam-splitter: $\delta\left(L_x - L_y\right) \sim \delta(nl)$
- Both broadband and resonant narrowband searches possible:

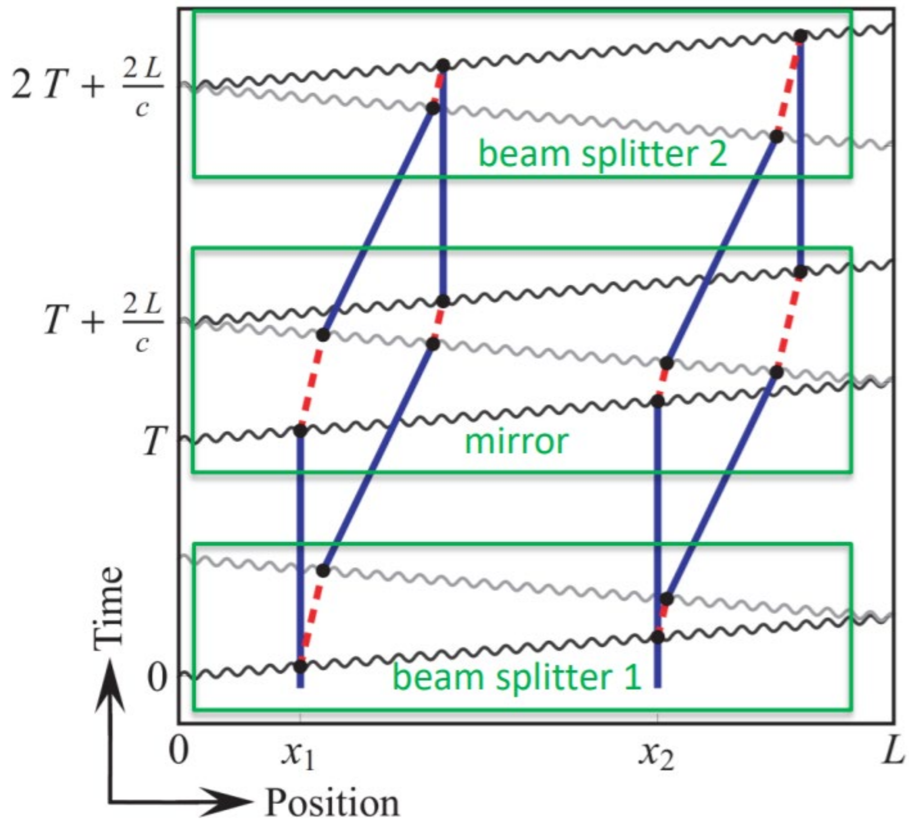
$$f_{\mathrm{DM}} \approx f_{\mathrm{vibr,BS}}(T) \sim v_{\mathrm{sound}}/l \;\; \Rightarrow \;\; Q \sim 10^6 \text{ enhancement}$$

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



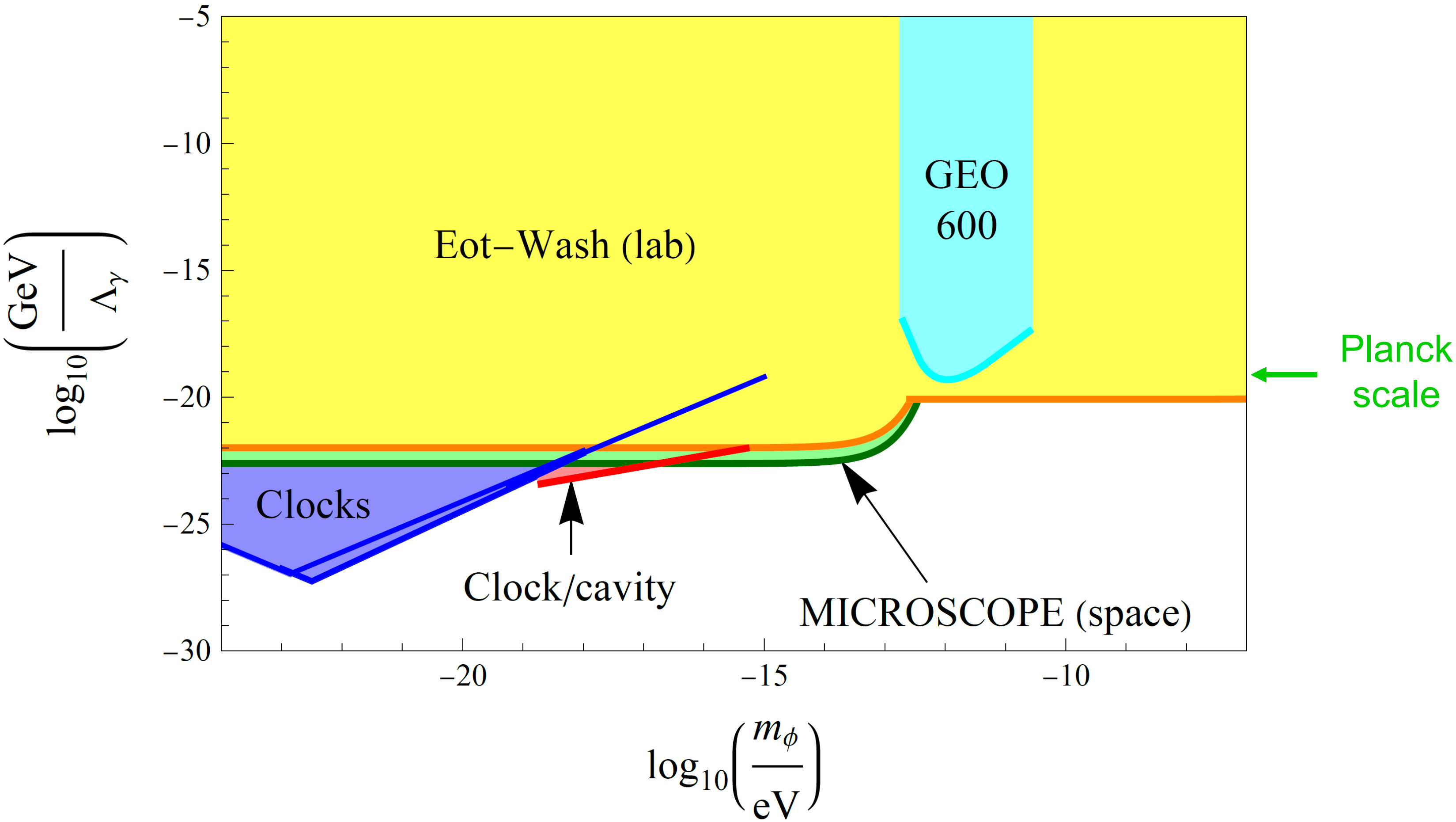


Phase shift between the two separated atom interferometers is maximised when $T_{\mathrm{osc}} \sim 2T$: $\delta(\Delta\Phi)_{\mathrm{max}} \sim \delta\nu_{\mathrm{atom}} \cdot T_{\mathrm{osc}}$

Constraints on Linear Interaction of Scalar Dark Matter with the Photon

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

4 orders of magnitude improvement!



Constraints on Linear Interaction of Scalar Dark Matter with the Photon

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

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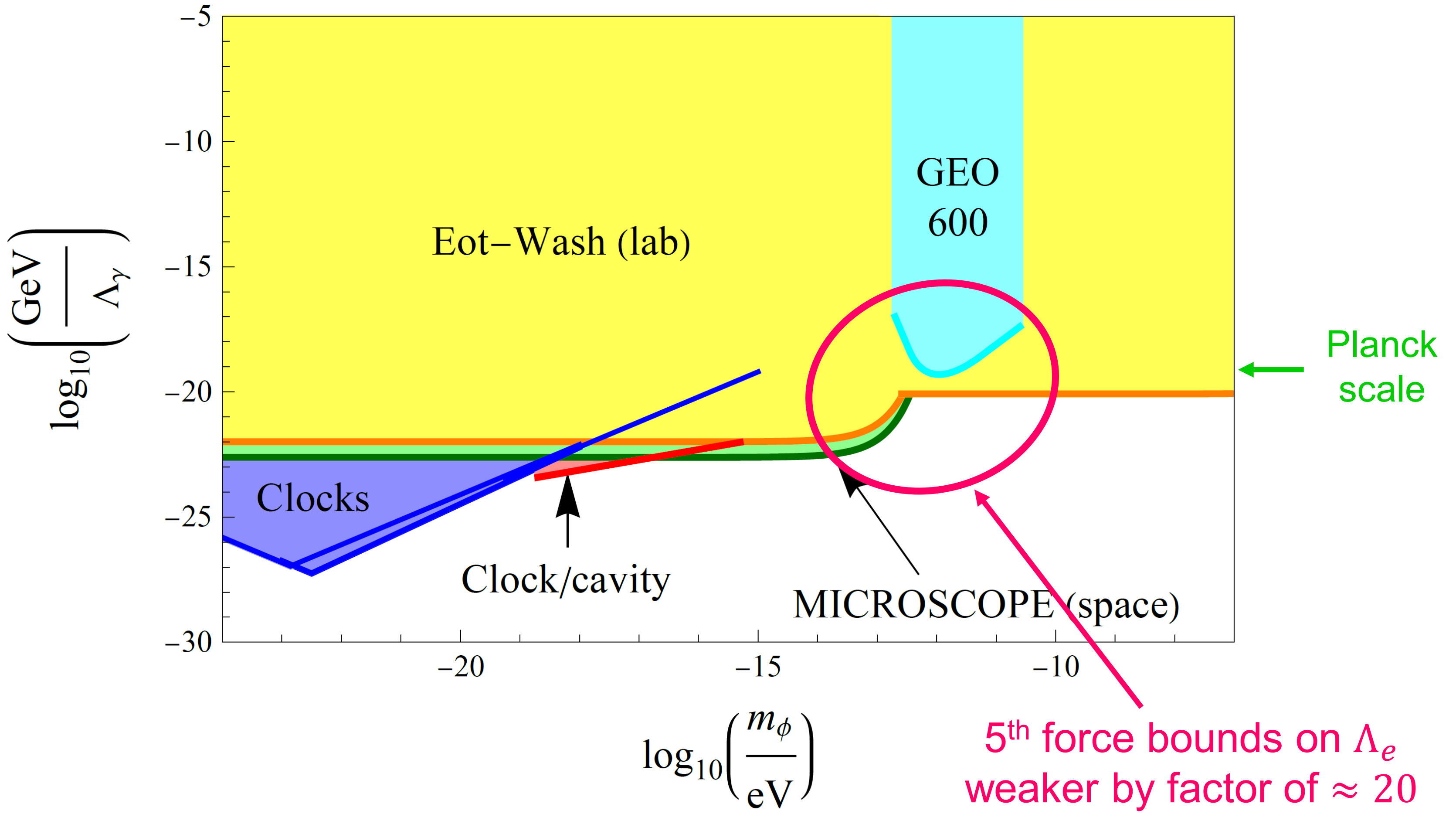
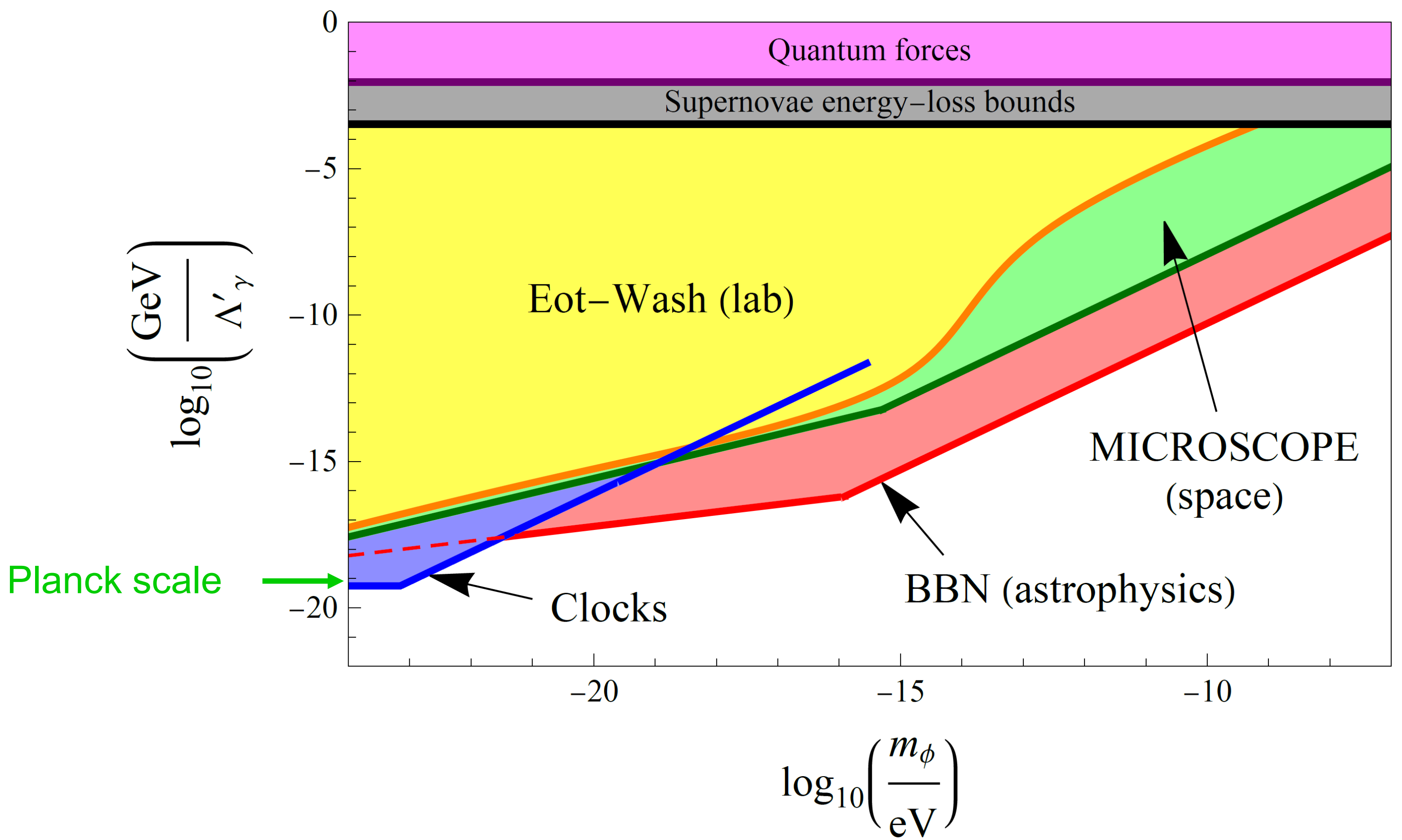


Constraints on Quadratic Interaction of Scalar Dark Matter with the Photon

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)]

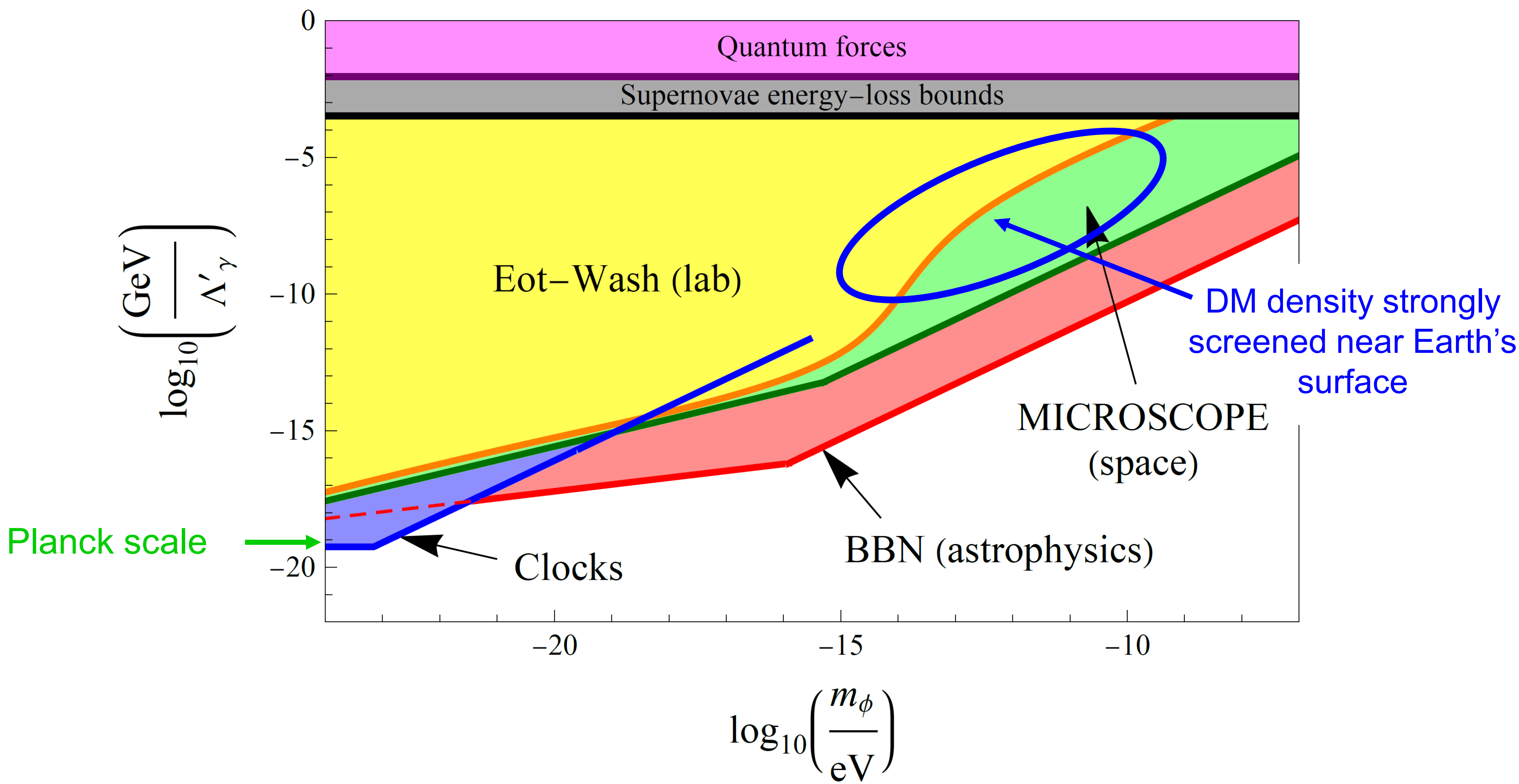
15 orders of magnitude improvement!



Constraints on Quadratic Interaction of Scalar Dark Matter with the Photon

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!



Summary

- Precision low-energy atomic and optical experiments provide powerful probes of dark matter via apparent variations of the fundamental “constants” of Nature
- We and other groups have improved the sensitivity to underlying interaction strengths between dark matter and ordinary matter by up to **15 orders of magnitude**
- Apparent variations of d_i, μ_i, g_i, can be induced by axionlike dark matter:
  - Ultracold neutrons (nEDM @ PSI) [*PRX* **7**, 041034 (2017)]
  - Trapped antiprotons (BASE @ CERN) [*Nature* **575**, 310 (2019)]
  - See also talks by Georg Bison and Joerg Jaeckel tomorrow

Back-Up Slides

Low-mass Spin-0 Dark Matter

Dark Matter

Scalars (Dilatons): $\varphi \xrightarrow{P} +\varphi$	**Pseudoscalars (Axions):** $\varphi \xrightarrow{P} -\varphi$
→ Time-varying fundamental constants	**→ Time-varying spin-dependent effects**
• Atomic clocks • Cavities and interferometers • Torsion pendula • Astrophysics (e.g., BBN)	• Co-magnetometers • Particle g-factors • Spin-polarised torsion pendula • Spin resonance (NMR, ESR)

Low-mass Spin-0 Dark Matter

Dark Matter

Scalars (Dilatons):

$\varphi \xrightarrow{P} +\varphi$

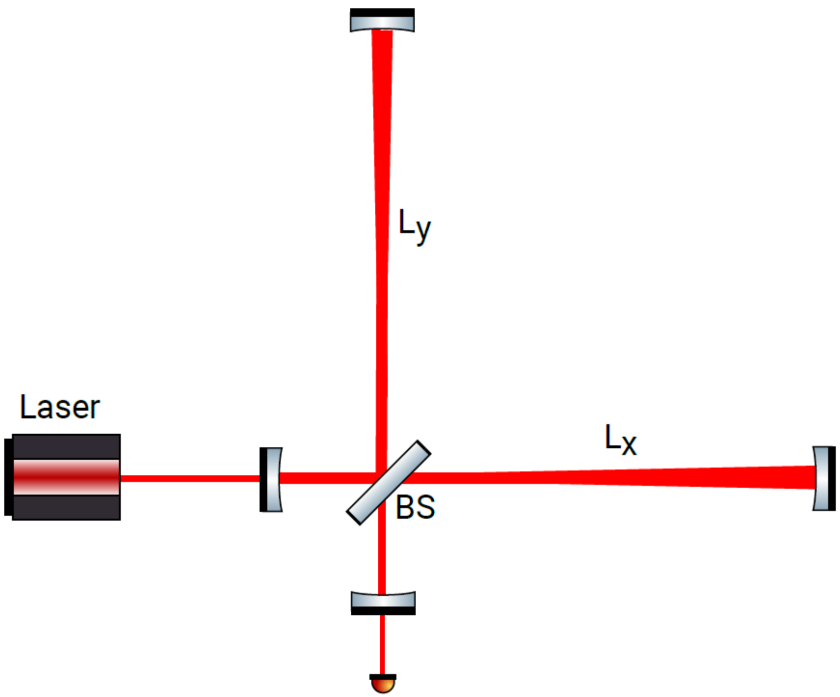
$\rightarrow$ **Time-varying fundamental constants**

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

Michelson vs Fabry-Perot-Michelson Interferometers

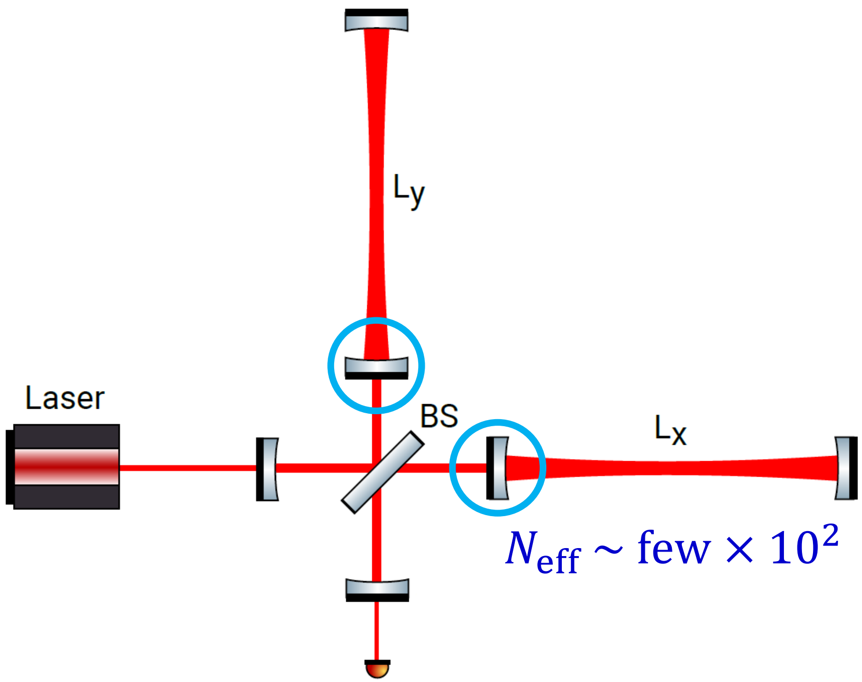
[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]

Michelson interferometer (GEO 600)



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

Fabry-Perot-Michelson interferometer (LIGO)

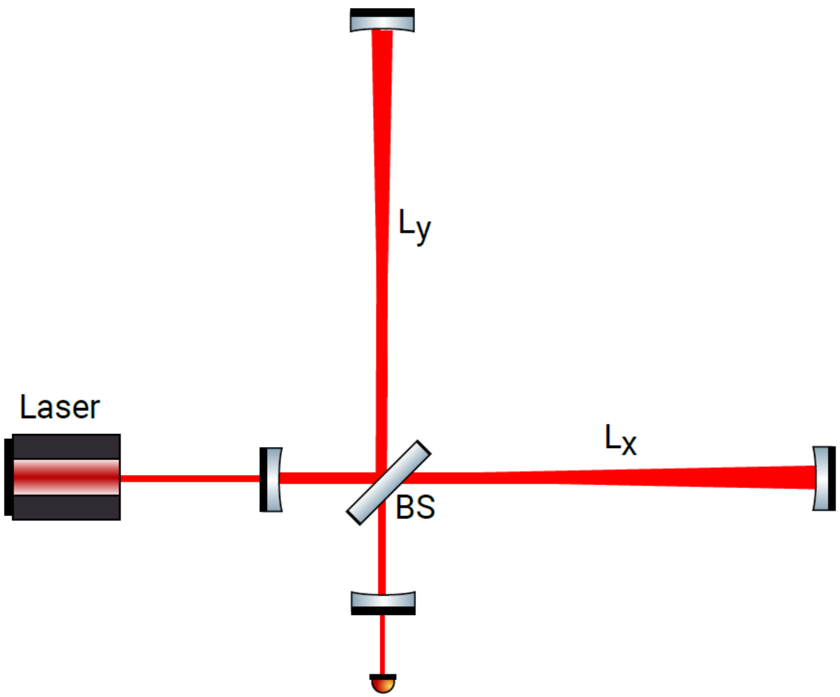


$$\delta(L_x - L_y)_{\text{BS}} \sim \delta(nl)/N_{\text{eff}}$$

Michelson vs Fabry-Perot-Michelson Interferometers

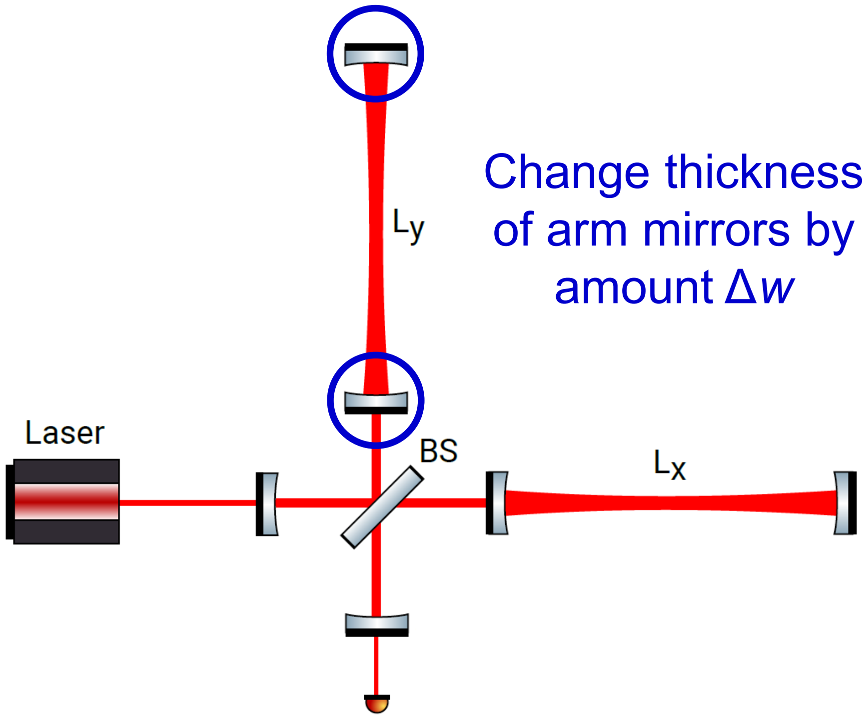
[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]

Michelson interferometer (GEO 600)



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

Fabry-Perot-Michelson interferometer (LIGO)



Change thickness of arm mirrors by amount Δw

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

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)

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

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

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

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

Low-mass Spin-0 Dark Matter

Dark Matter →

Pseudoscalars (Axions):

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

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

Here I focus on relatively new detection methods based on ***non-electromagnetic*** *couplings* →

Time-varying spin-dependent effects

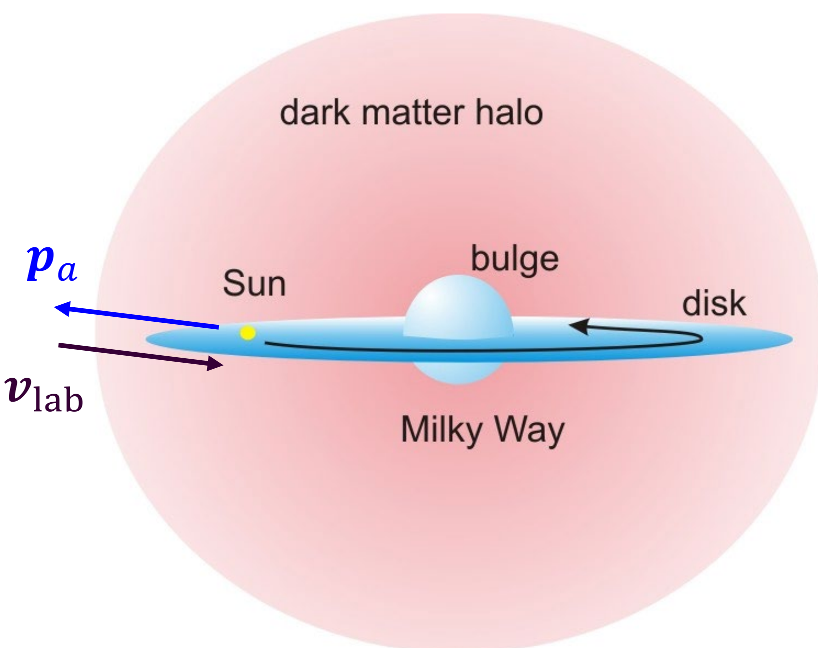
- Co-magnetometers
- Particle g-factors
- Spin-polarised torsion pendula
- Spin resonance (NMR, ESR)

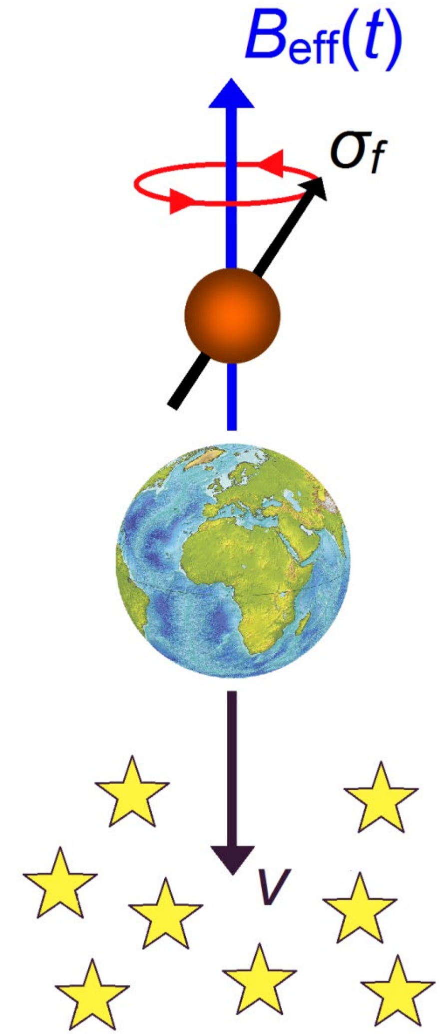
"Axion Wind" Spin-Precession Effect

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

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

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



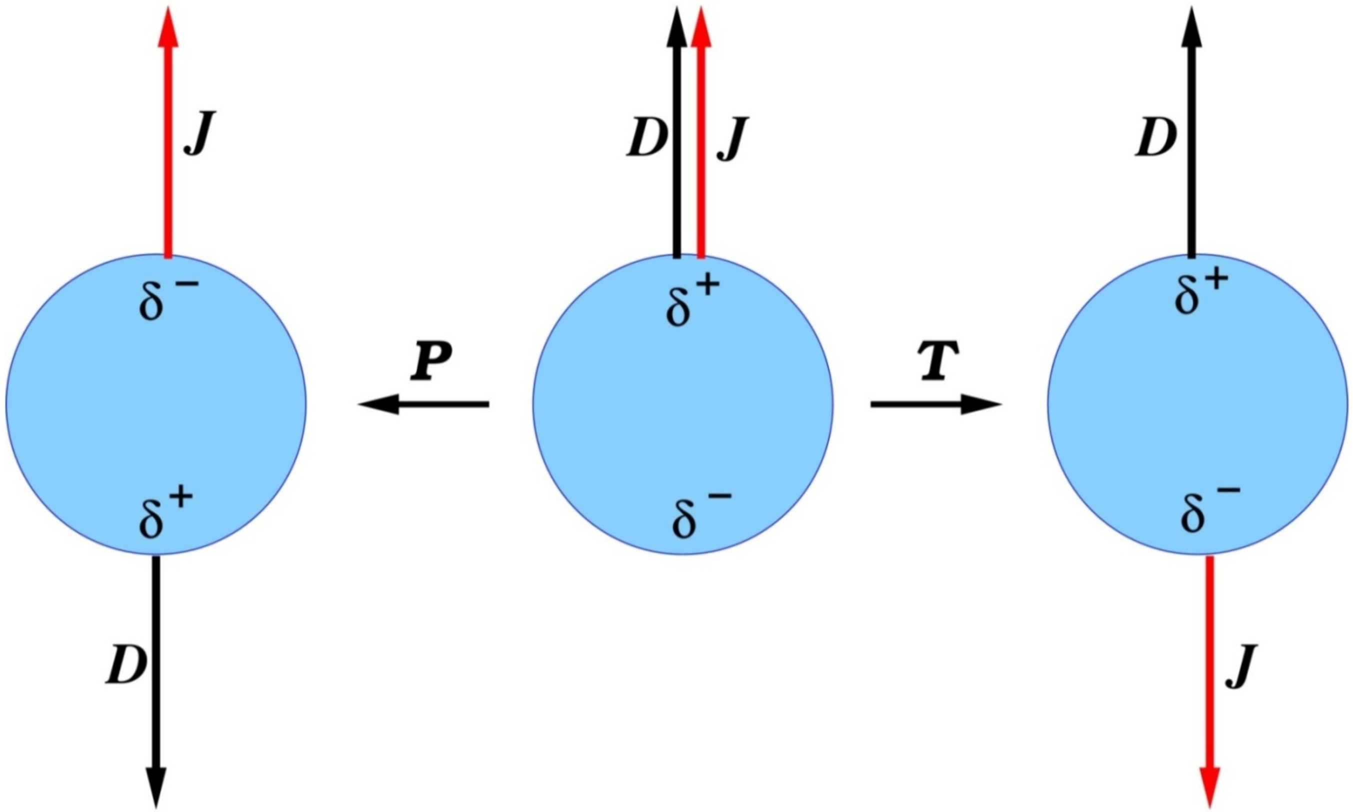


Oscillating Electric Dipole Moments

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



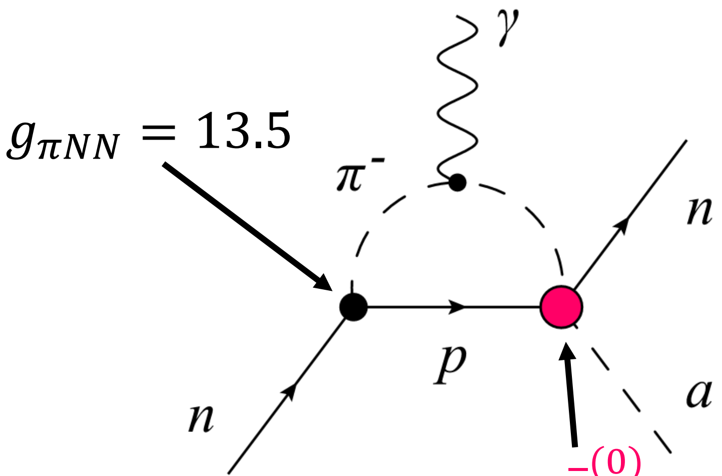
Oscillating Electric Dipole Moments

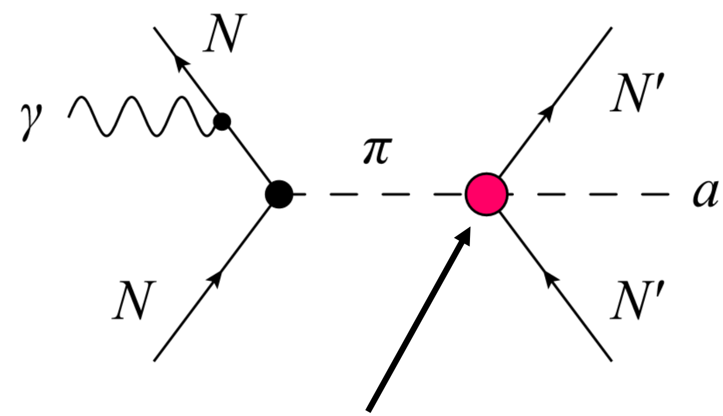
Nucleons: [Graham, Rajendran, *PRD* **84**, 055013 (2011)]

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

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

Nucleon EDMs | ***CP*-violating intranuclear forces**





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

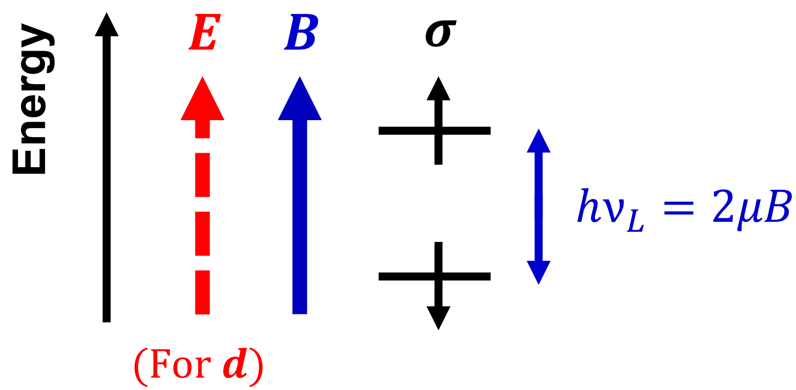
In nuclei, ***tree-level*** *CP*-violating intranuclear forces dominate over ***loop-induced*** nucleon EDMs [loop factor = $1/(8\pi^2)$].

Searching for Spin-Dependent Effects

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

Use spin-polarised sources: *Atomic magnetometers*, *cold/ultracold particles*, *torsion pendula*

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

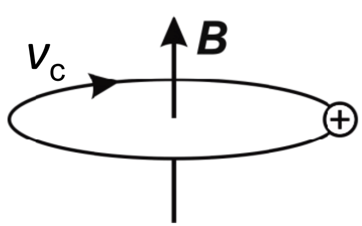


$$\frac{\nu_n}{\nu_{\mathrm{Hg}}} = \left|\frac{\mu_n B}{\mu_{\mathrm{Hg}} B}\right| + R(t)$$

B-field effect

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

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



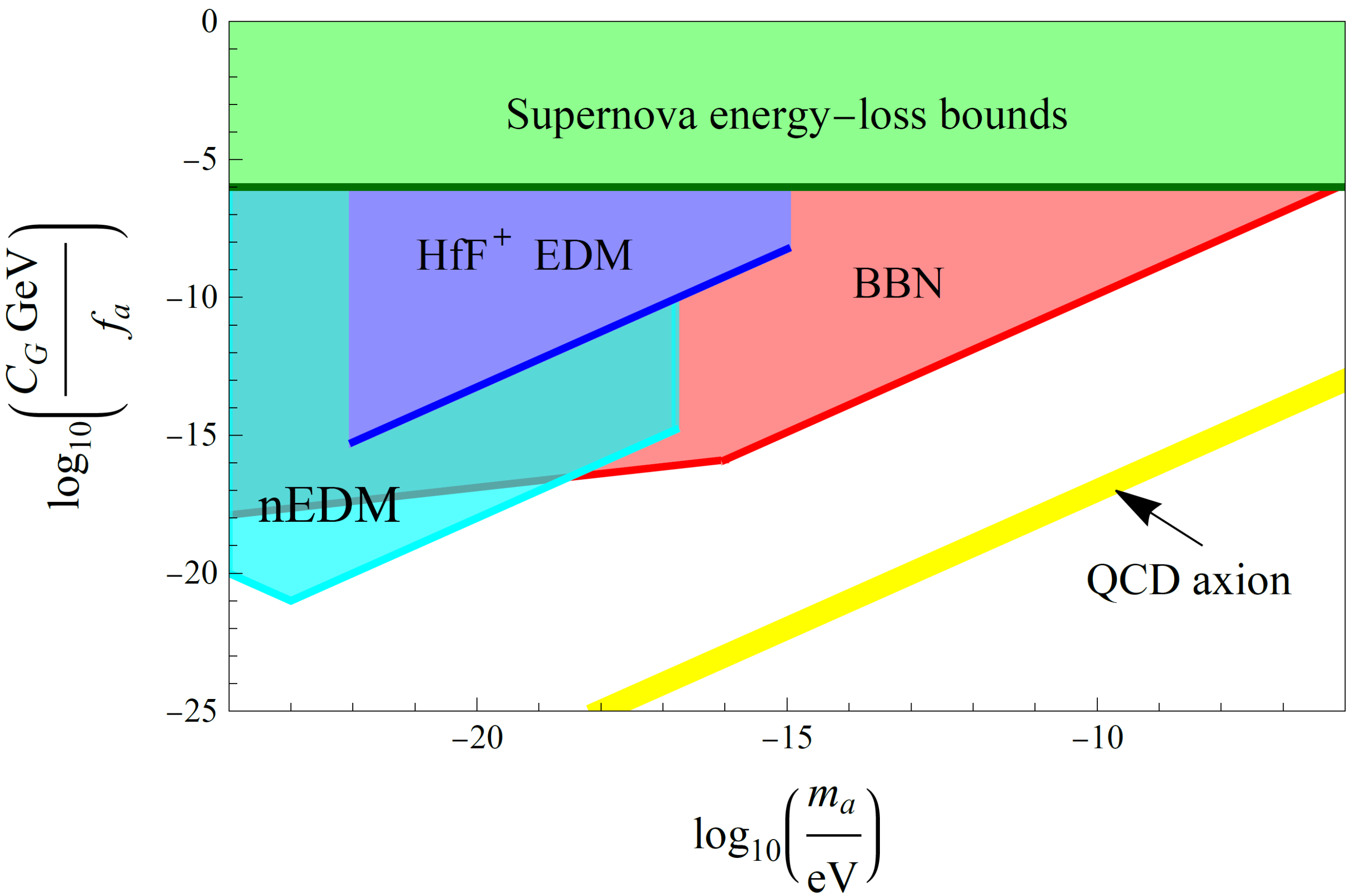
$$\left(\frac{\nu_L}{\nu_c}\right)_{\bar{p}} = \frac{|g_{\bar{p}}|}{2} + R(t)$$

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)]

3 orders of magnitude improvement!



Constraints on Interaction of Axion Dark Matter with the Antiproton

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

5 orders of magnitude improvement!