DPF-PHENO 2024

MagLev for Dark Matter

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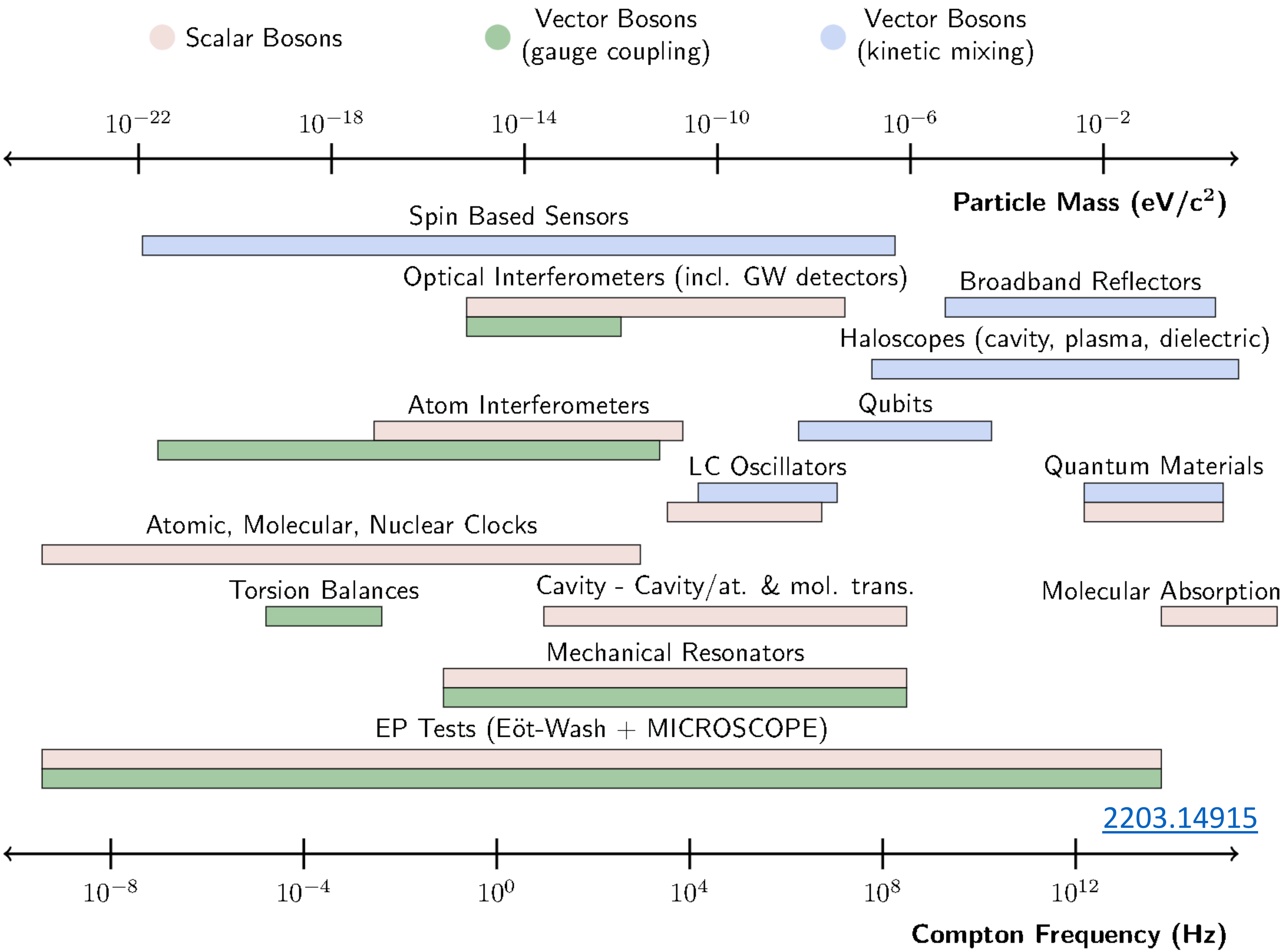
05/14/2024

with G. Higgins and Saarik Kalia

arXiv: 2310.18398

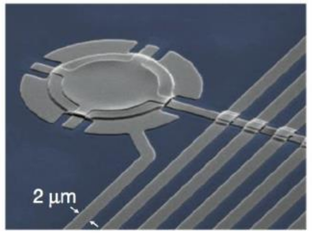
Active search program with opportunities



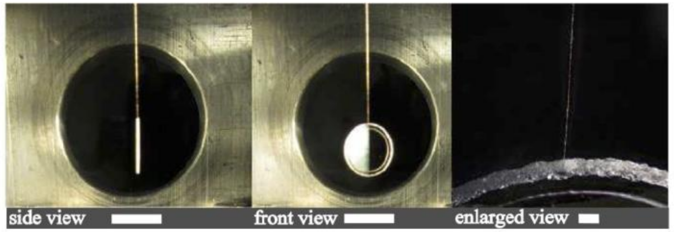
2203.14915

Active Field of Discovery Opportunities

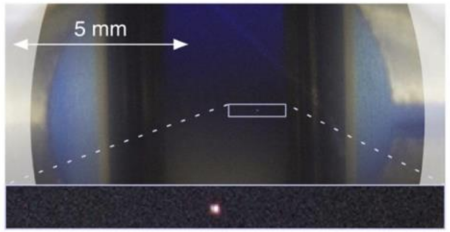
Mechanical Force Sensing for Dark Matter



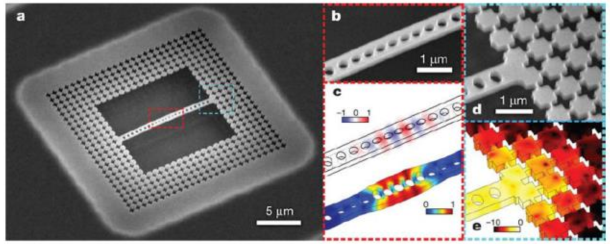
Teufel et al, Nature 2011



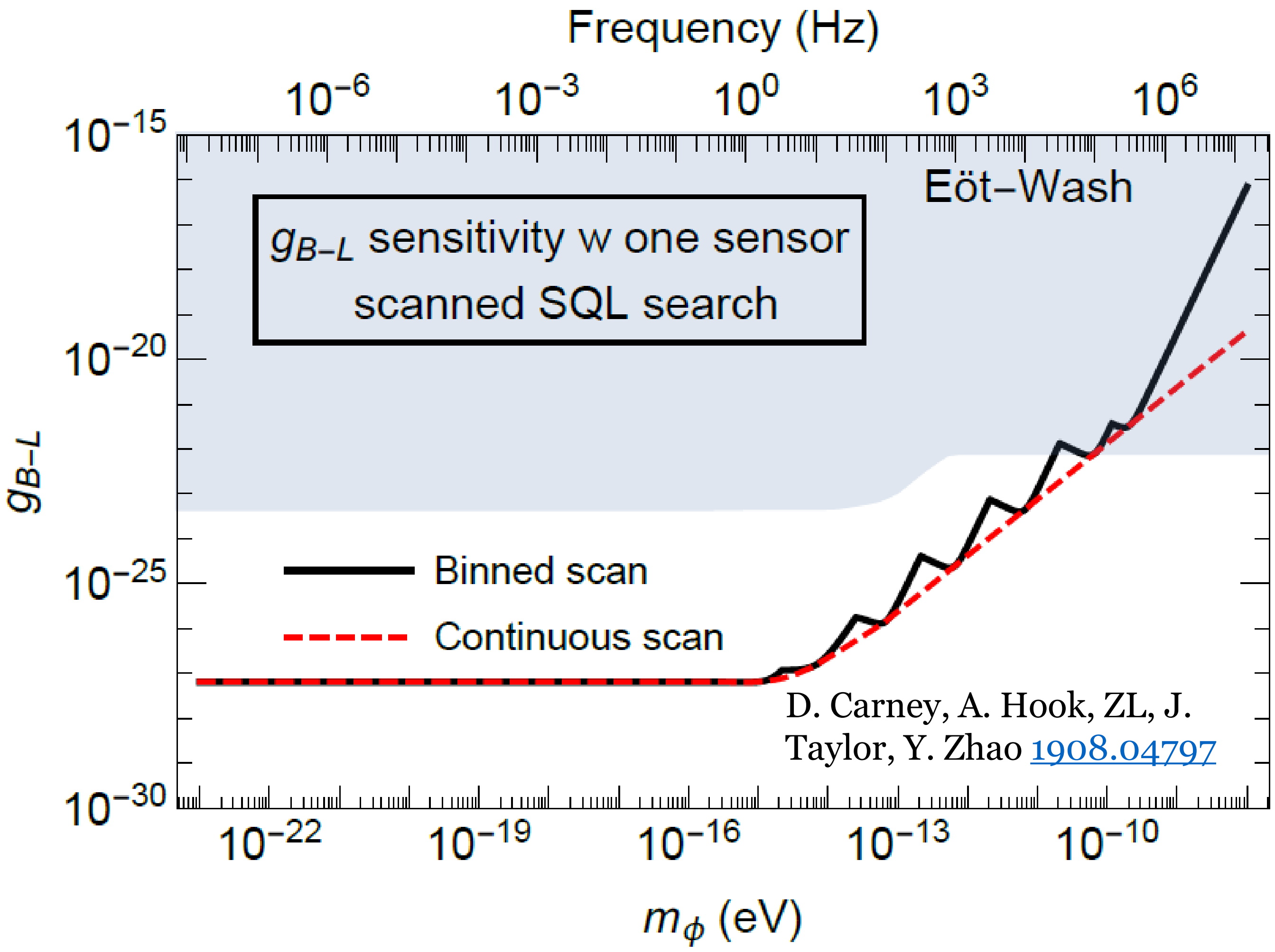
Matsumoto et al, PRA 2015



Aspelmeyer ICTP slides 2013



Painter et al, Nature 2011



D. Carney, A. Hook, ZL, J. Taylor, Y. Zhao [1908.04797](1908.04797)

Also see Graham, Kaplan, Mardon, Rajendran, [1512.06165](1512.06165)
and review papers: [2008.06074](2008.06074), [2203.14915](2203.14915)

All accelerometers are automatically a B-L DM sensor
What about other DM candidates?

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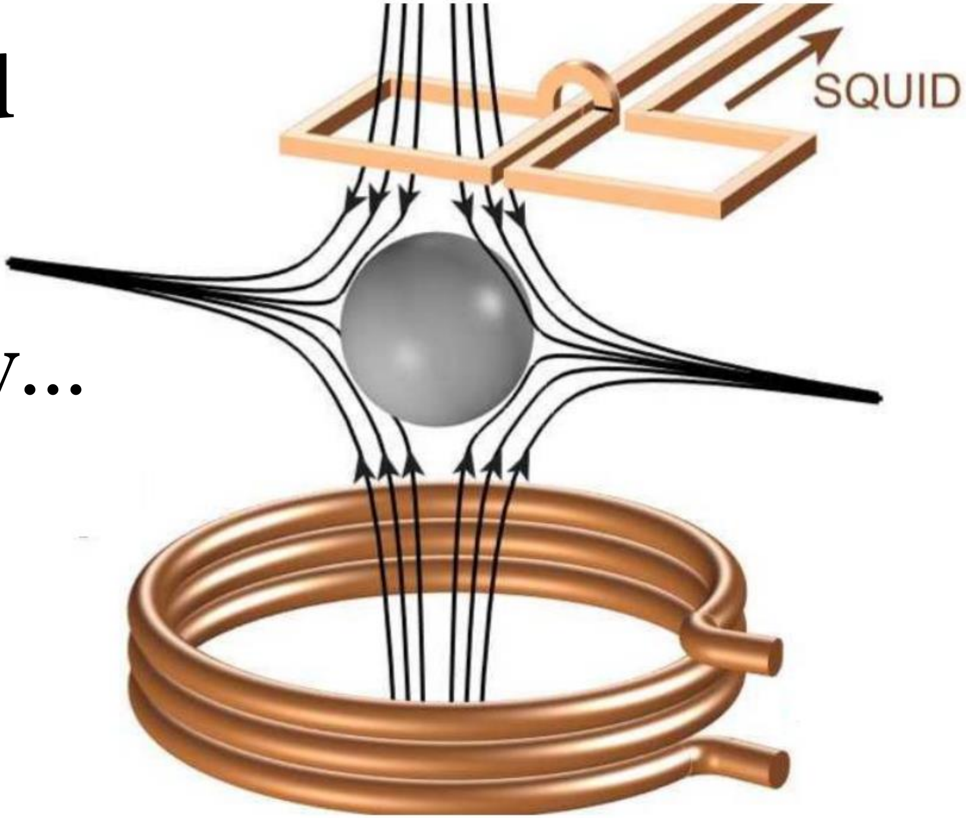
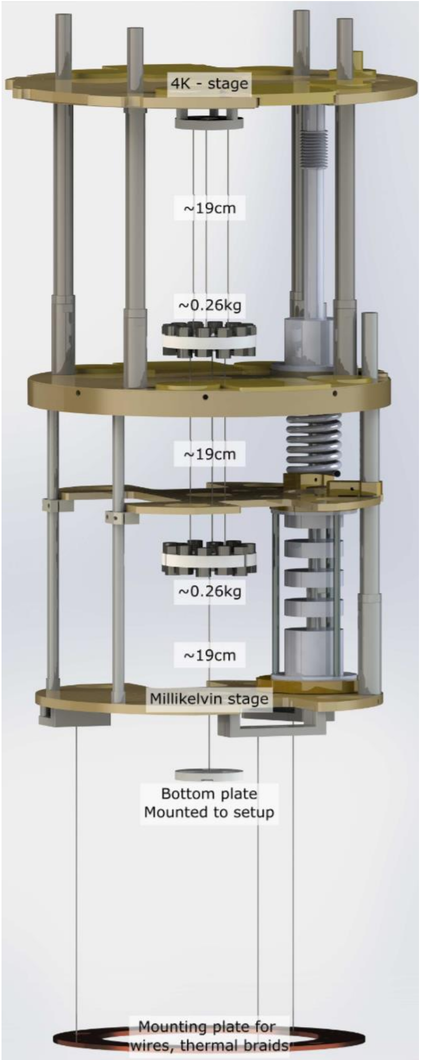
What about other DM candidates?

Unfortunately, generic accelerometers are "Neutral" (charge, spin, etc.) and insensitive to kinetically mixed dark photons and axions.

On the other hand:
Magnetically Levitated (MagLeV) System provides best acceleration sensitivity…



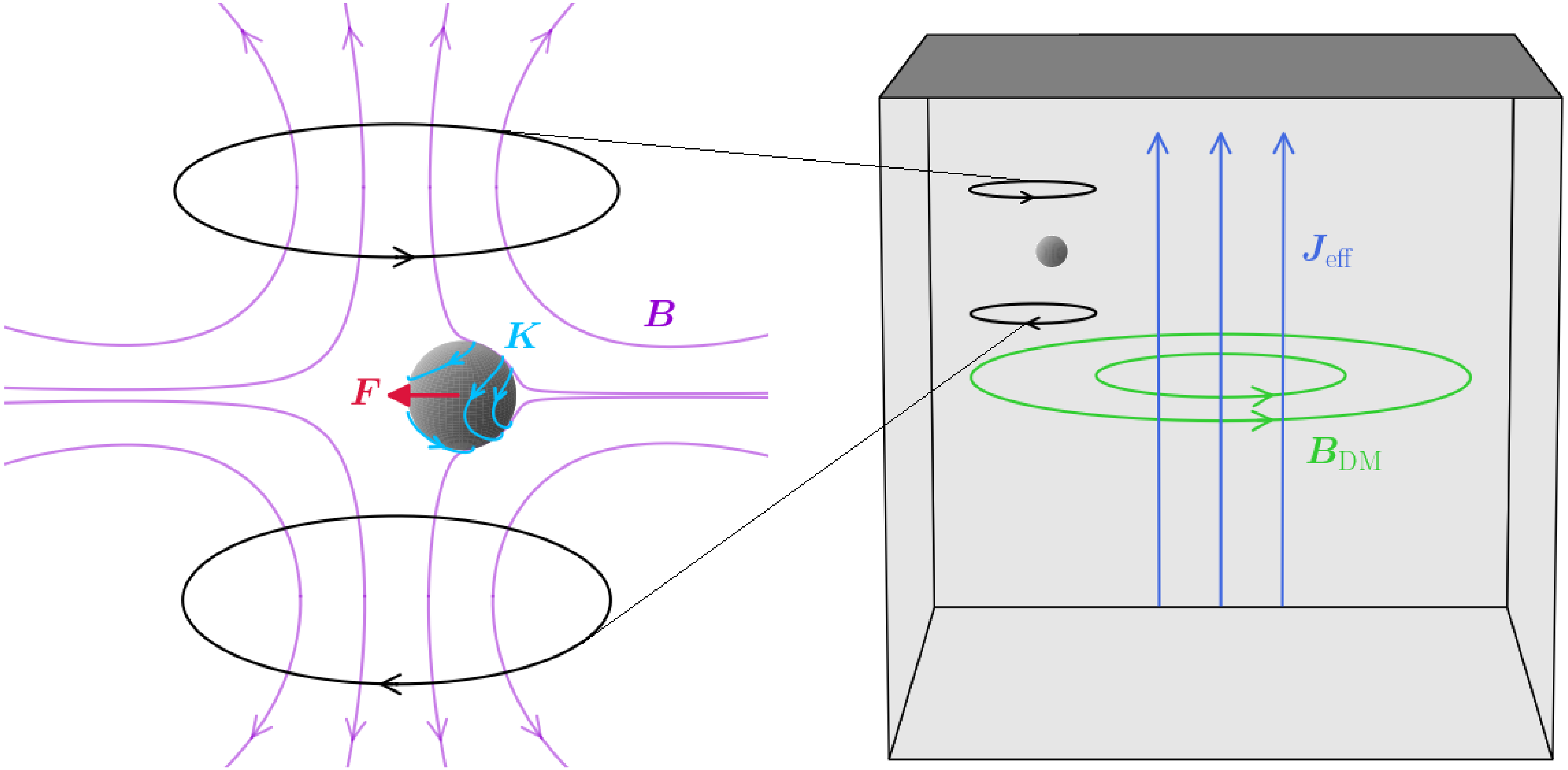
[Hofer et al., Phys. Rev. Lett. **131,** 043603 (2023)]



MagLev

- Magnetic field signal inside experimental apparatus
- Many experiments utilize EM resonances → $f_{DM} \geq kHz$ ($m_{DM} \geq 10^{-12}\ eV$)
- Can use mechanical resonance for lower frequencies
- Mechanical system + sensitive to magnetic fields → magnetic levitation

Our proposal



Kinetically mixed dark photon

$$L \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu - J_{EM}^\mu A_\mu$$

⬇

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu + \varepsilon m_{A'}^2 A'^\mu A_\mu - J_{\mathrm{EM}}^\mu A_\mu$$

- Two modes: “interacting” A, “sterile” A'
- Only A couples to charges/currents → observable field
- One massless and one massive state
- A and A' are not propagation states in vacuum!
  - Mixing (and all observable effects) are proportional to $m_{A'}$
  - A and A' *are* propagation states in conductor → mixing at boundary

Dark-photon effective current

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu + \varepsilon m_{A'}^2 A'^\mu A_\mu - J^\mu_{\rm EM} A_\mu$$

- When A' is DM and $\epsilon \ll 1$, then A' equivalent to $J^\mu_{\rm eff} = -\varepsilon m_{A'}^2 A'^\mu$
- Oscillates with frequency $\omega = m_{A'}$
- Just a single-photon EM problem with a background current!

Axionlike Particle

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{4}g_{a\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

- Allows axion to convert into photon in background B_0
- Trapping field acts as B_0 in our case!
- In non-relativistic limit,

$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = -g_{a\gamma}(\partial_t a)\mathbf{B}$$

- Also behaves as $\mathbf{J}_{\text{eff}} = i g_{a\gamma} m_a a \mathbf{B}_0$ (replace $\varepsilon m_{A'} \mathbf{A}' \to -i g_{a\gamma} a \mathbf{B}_0$)
- Note that direction set by B_0 not by DM!

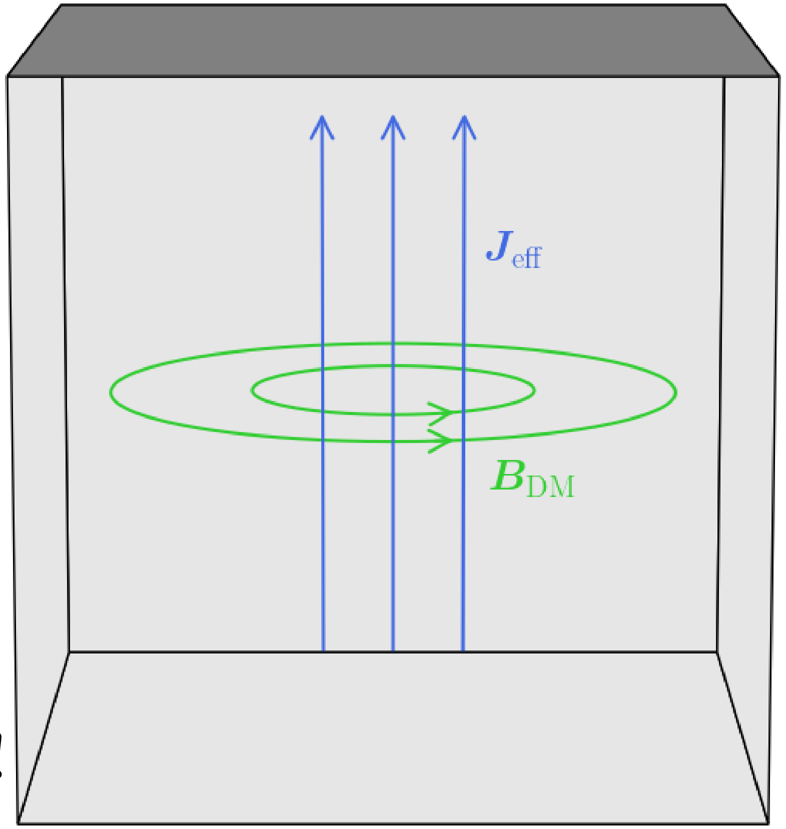
Dark-matter signal

- Dark-photon or axion DM can source EM fields

$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = \mathbf{J}_{\text{eff}}$$

- When λ_{DM} larger than apparatus, $\boldsymbol{E}$ negligible
  - $E_{||}$ vanishes at boundary
  - Can only grow on λ_{DM} length scales
  - Must be small in the interior

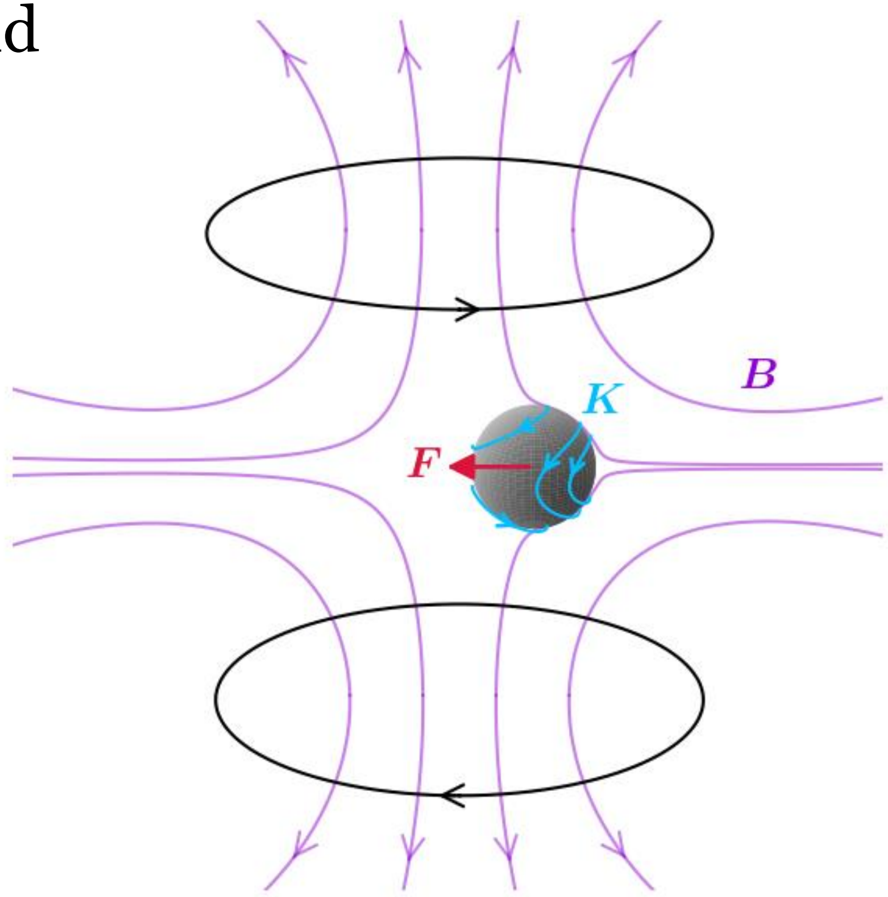
- Dominant signal of ultralight DM is (oscillating) $\boldsymbol{B}$!



Levitated superconductors

- Surface currents screen external magnetic field
- Magnetic field exerts force on currents
- Net restoring force $\mathbf{F} = -\frac{3}{2}V(\mathbf{B}\cdot\nabla)\mathbf{B}$
  - Depends on gradient!
- Alternatively, potential for superconductor

$$U \propto V|\mathbf{B}|^2$$

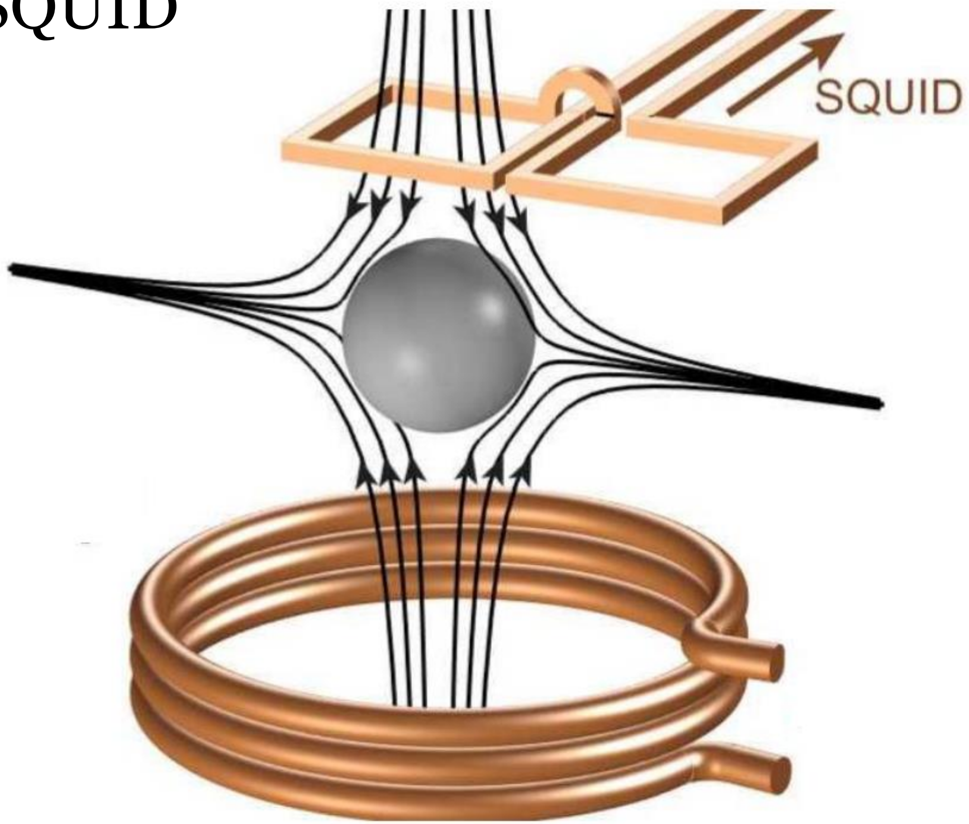


Response to DM signal

- Equilibrium position where $|\boldsymbol{B}|^2$ is minimized
- Harmonic oscillator w/ trapping frequency $f_0 \sim \partial B / \sqrt{\rho}$
  - Less dense superconductors are more strongly trapped!
- Time-oscillating $\boldsymbol{B}_{DM}$ will vary equilibrium position → oscillatory motion
- Resonant enhancement when $m_{DM} \approx 2\pi f_0$

Readout

- Can readout with pickup loop connected to SQUID
- Trapping field has flux through pickup loop
- As superconductor moves, flux changes
- Changes in flux measured by SQUID



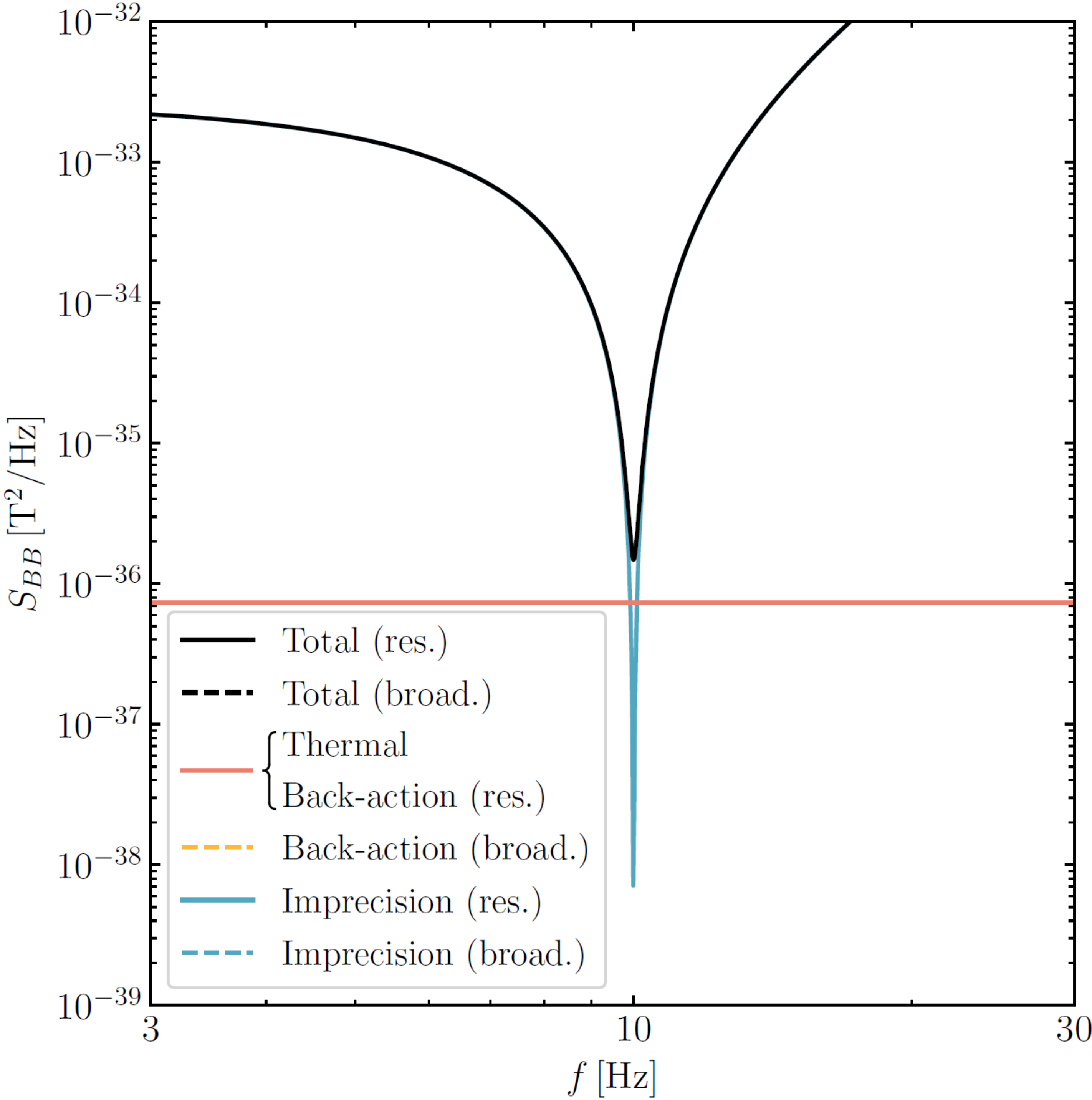
[Hofer et al., Phys. Rev. Lett. **131,** 043603 (2023)]

Noise sources

- Thermal: kicks from gas molecules
- Imprecision: flux noise → position
- Back-action: current noise → force
- Trade-off based on readout coupling
  - Resonant: back-action = thermal
  - Broadband: back-action = low-f imprecision

$$S_{BB}^{\text{imp}} = \frac{2\rho\kappa}{3m^2\omega_0^2} \cdot \tilde{\eta}^{-2} |\chi(\omega)|^{-2}$$

$$S_{BB}^{\text{back}} = \frac{2\rho\kappa}{3m^2\omega_0^2} \cdot \tilde{\eta}^{2}$$



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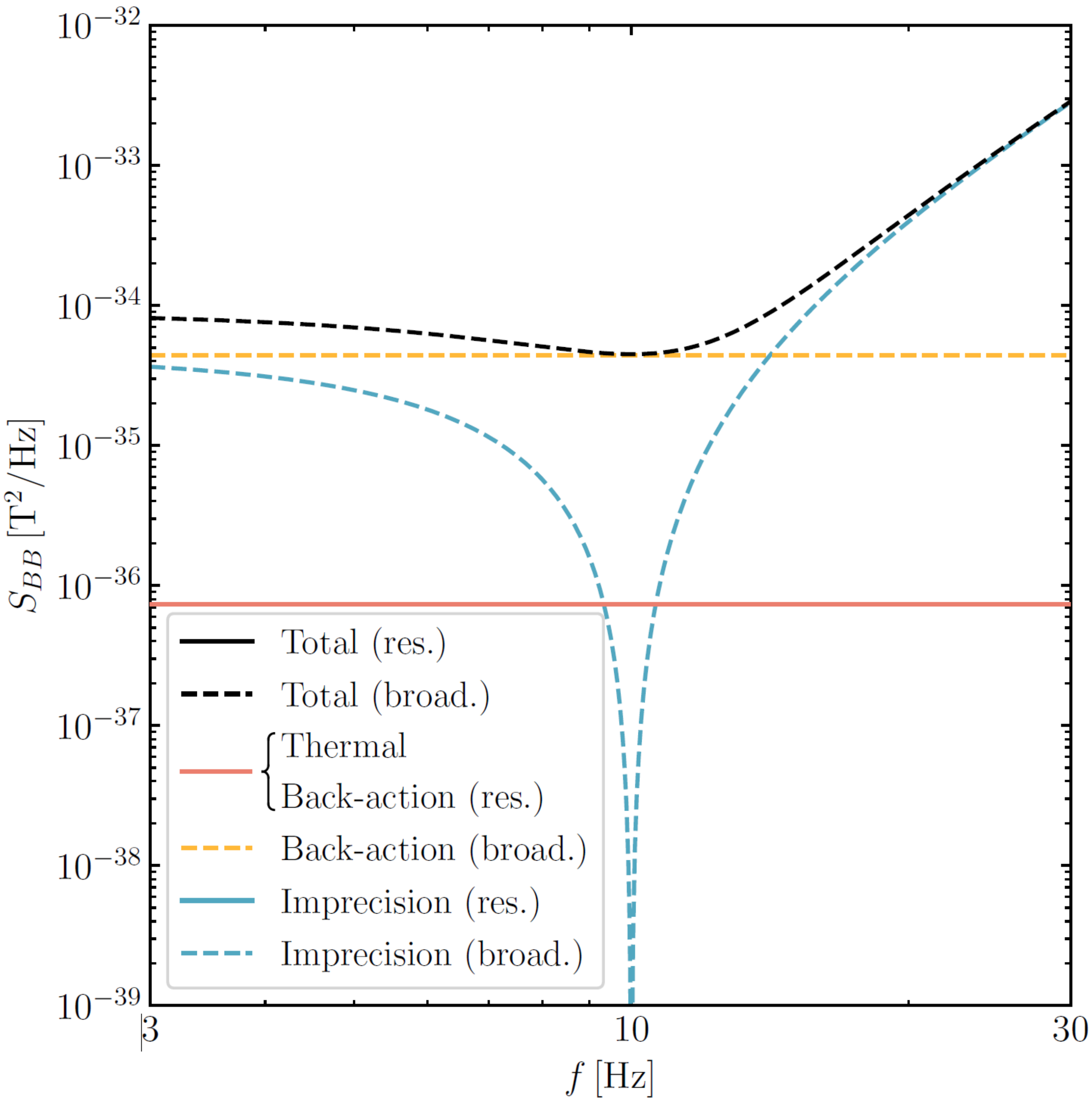

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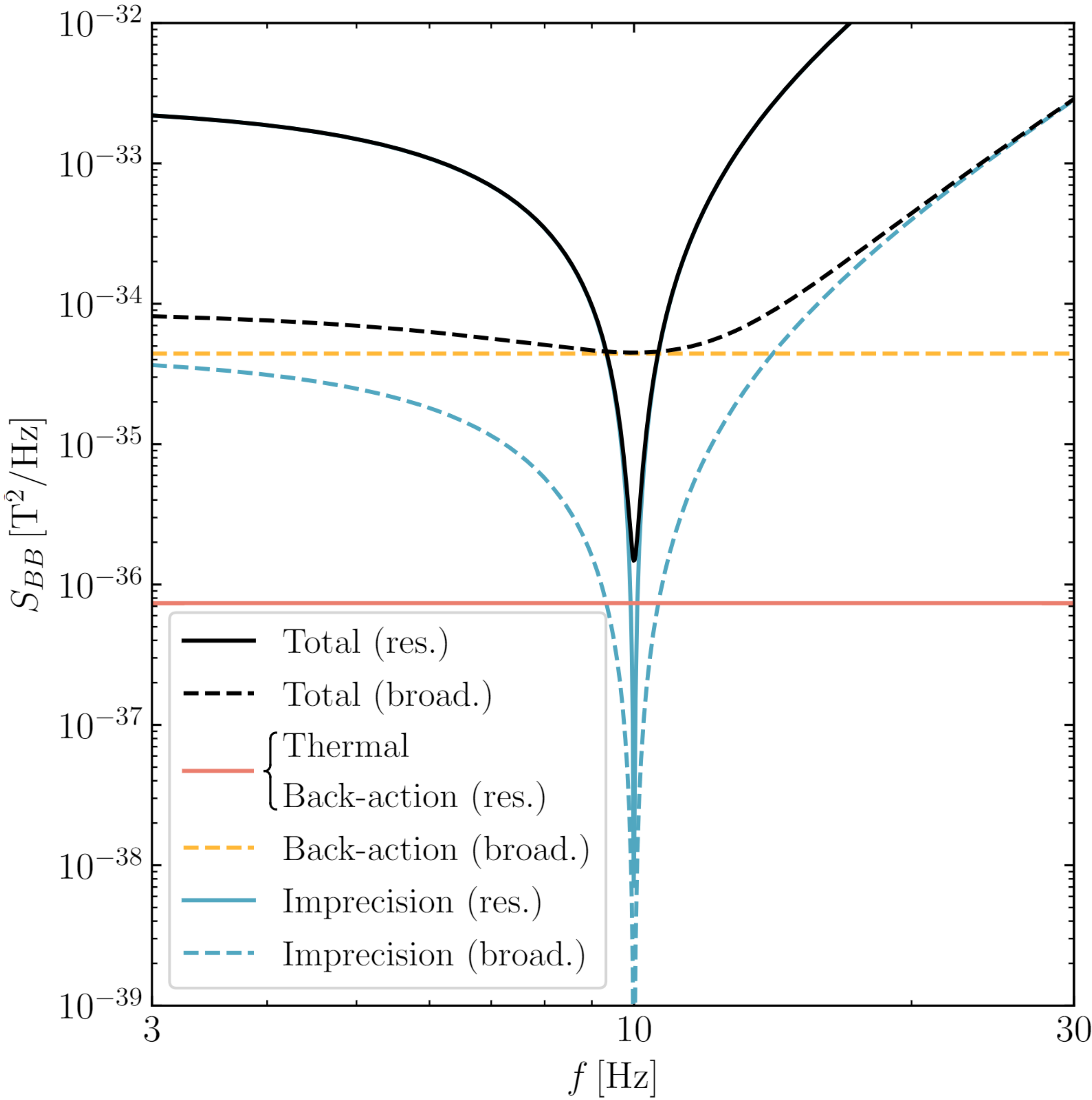
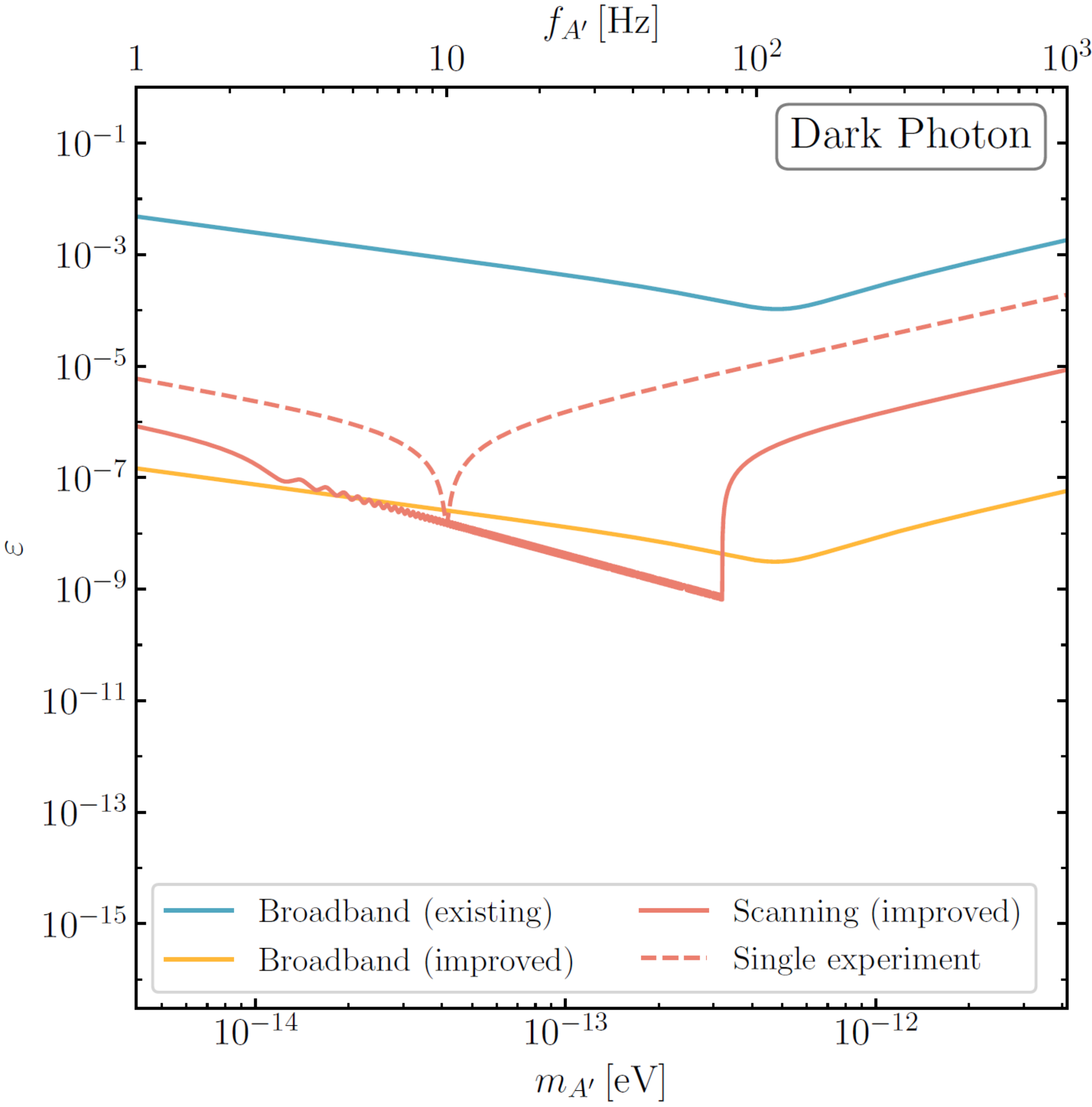


Dark photon sensitivity

Integration time: 1 yr

Temperature: 10 mK

	Existing	Improved
Mass	$10\,\mu$g	1 g
Density	$10\,\text{g/cm}^3$	$0.1\,\text{g/cm}^3$
Shield size	10 cm	1 m
Quality factor	10^7	10^{10}



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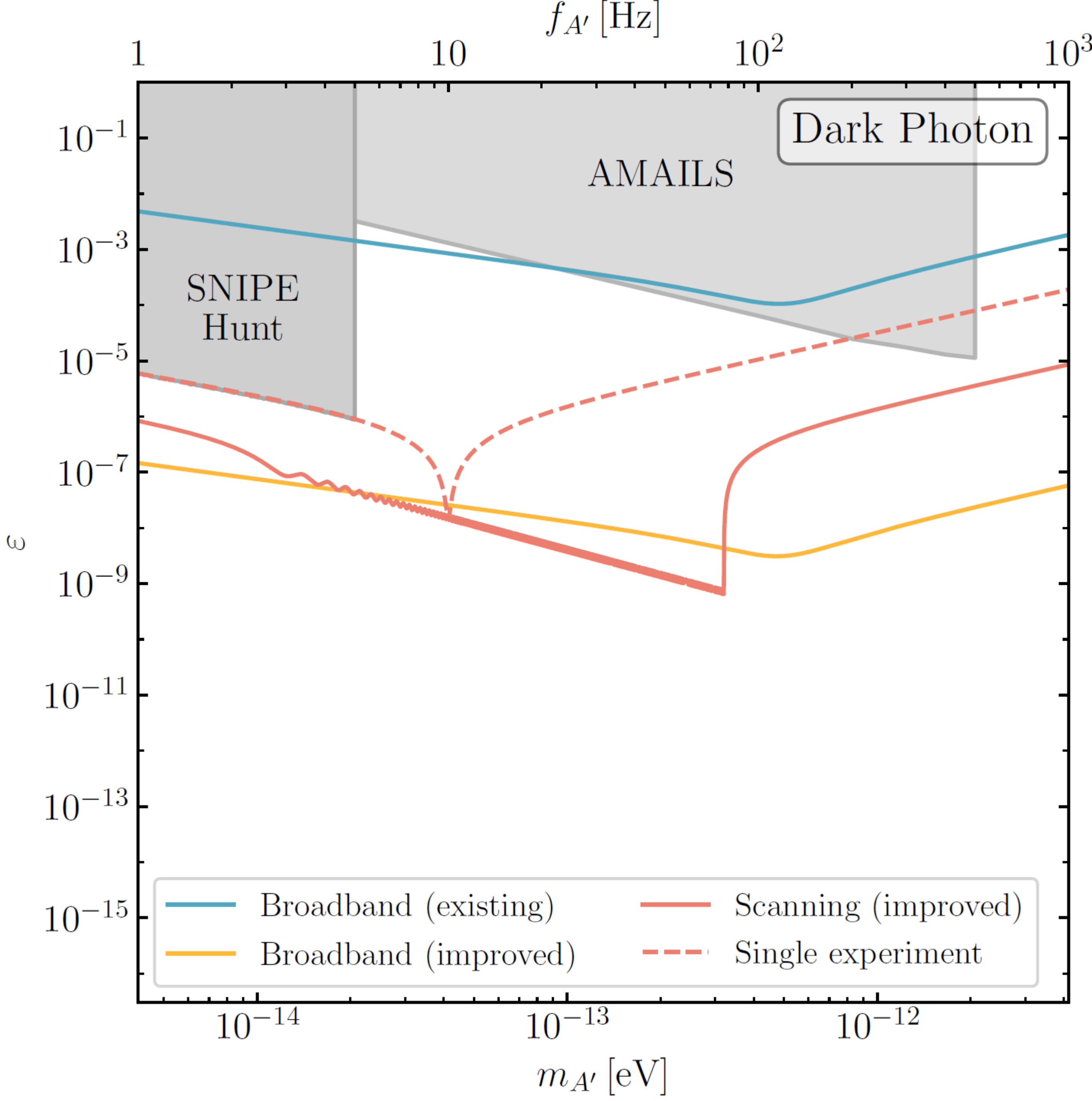

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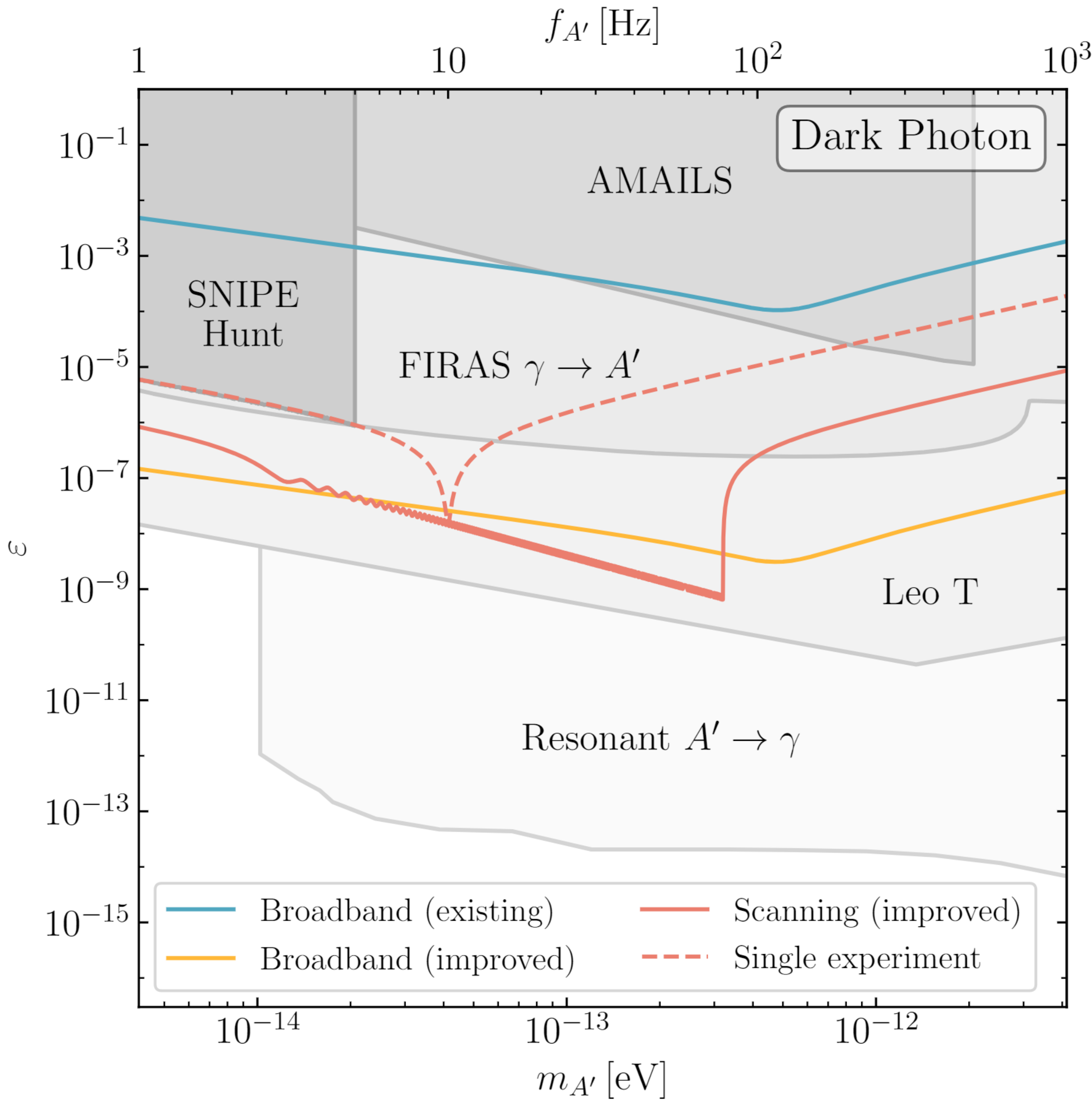

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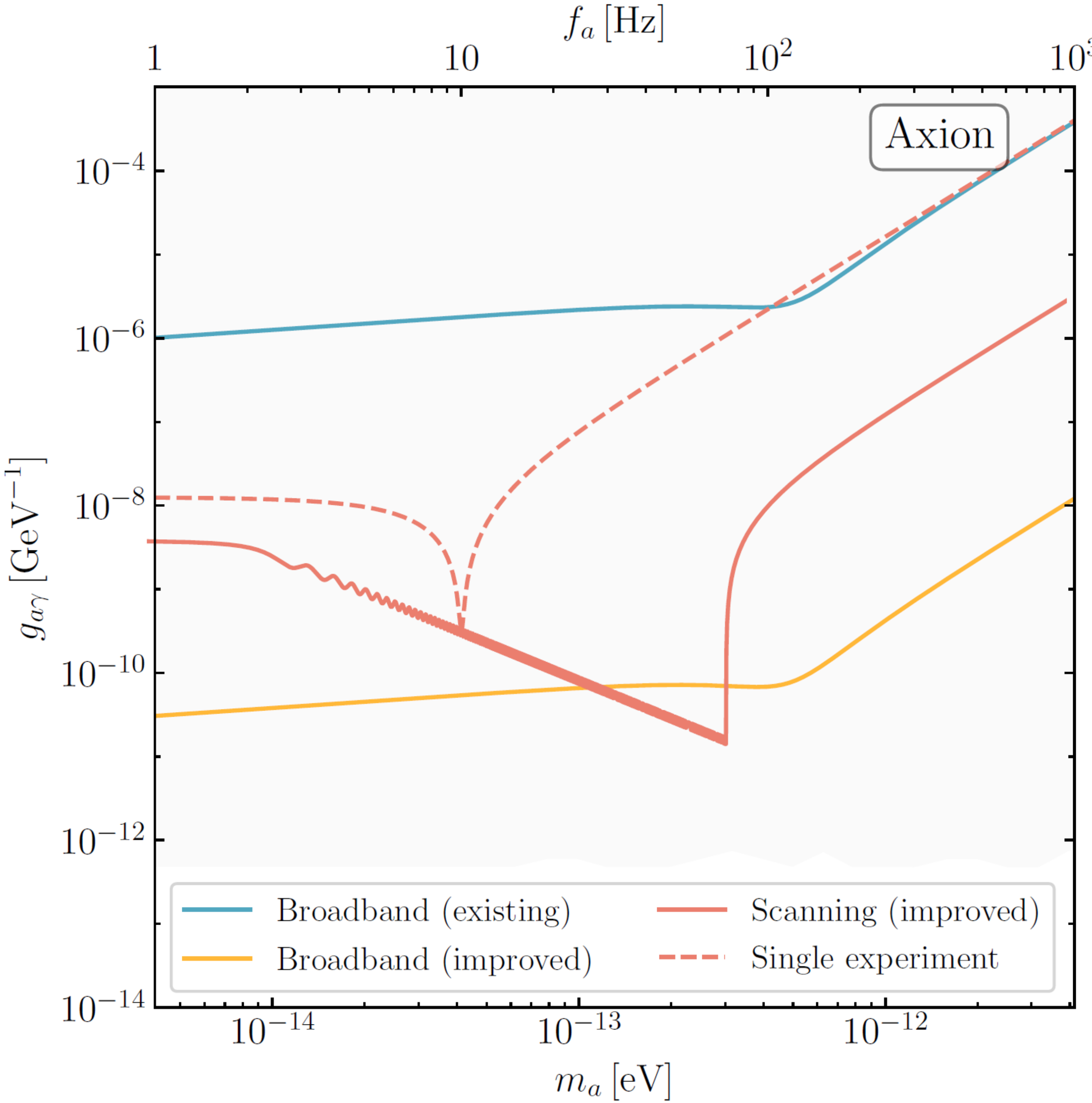

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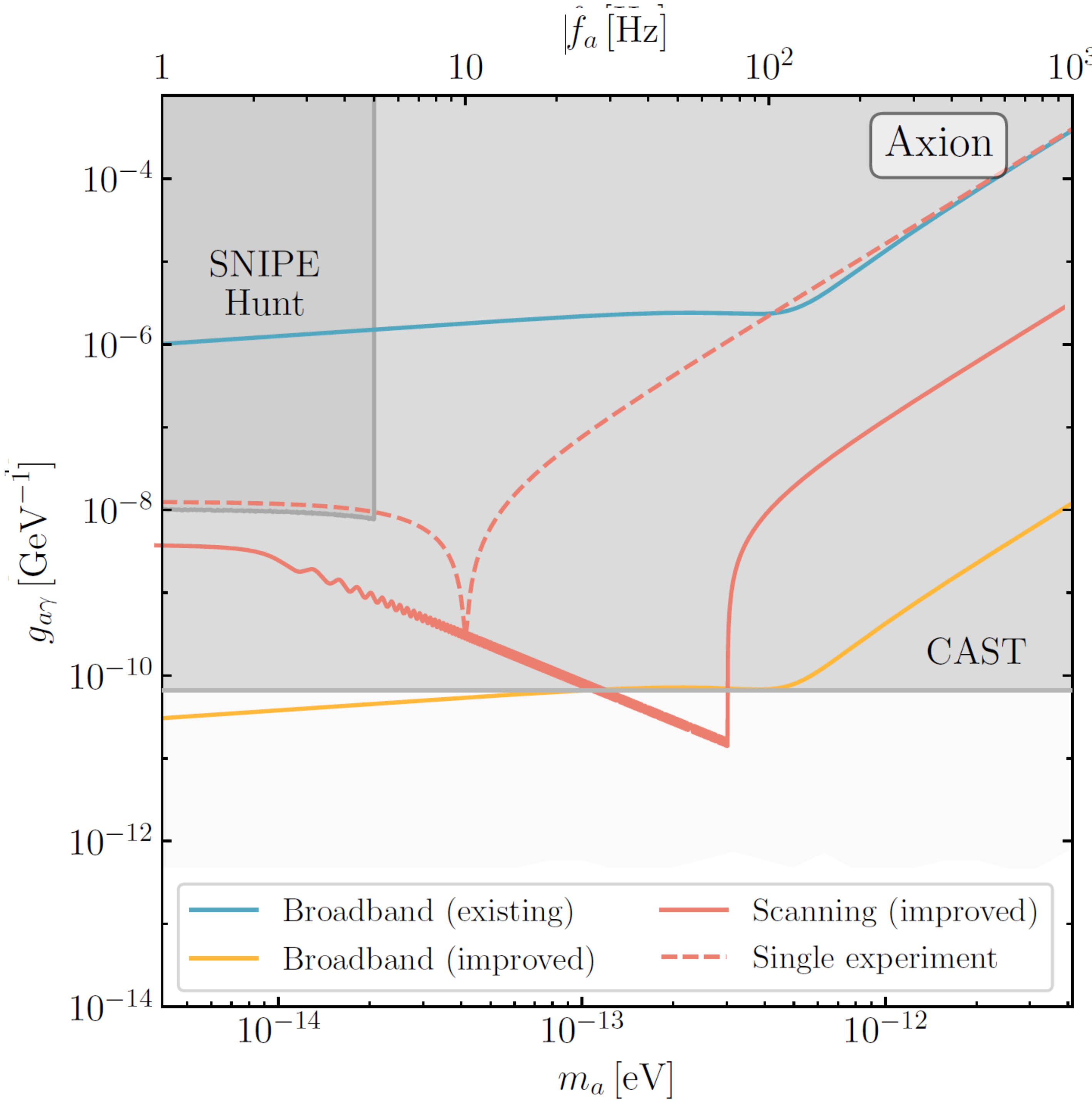

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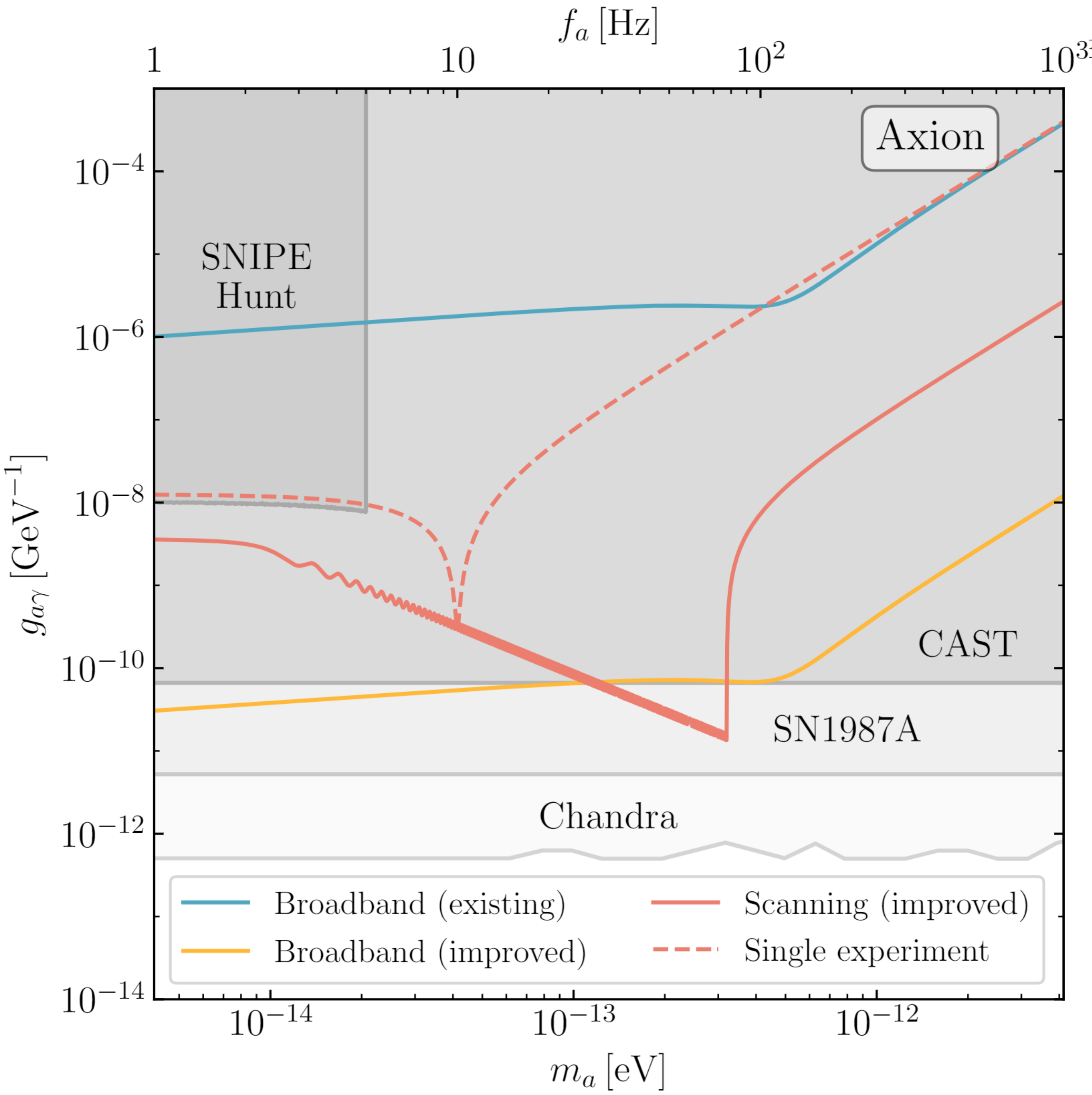

Conclusion

- Levitated superconductors can probe ultralight DM with $m_{DM} \leq 10^{-12}$ eV
- Superconductor settles at center of quadrupole trap
- Ultralight DM sources magnetic field → perturbs equilibrium
- Resonant and broadband schemes
- Existing setups already comparable to DPDM experiments
- Dedicated setup can be leading laboratory probe of ultralight DM