

Heterodyne Detection of Axion Dark Matter in SRF Cavities

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JHEP 07 (2020) 088, [hep-ph/1912.11048](#)

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Phys.Rev.D 104 (2021) 11, L111701,

[hep-ph/2007.15656](#)

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SLAC LDRD Technical Document: PI Sami Tantawi

Gravitational Waves:

220X.XXXXXX

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and Gravitational Waves

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High-level Summary

- Signal *Oscillating background B-field: Radio-Frequency up-conversion approach*

$$\omega_{\text{sig}} = \omega_0 \pm m_a$$

Parametric gain for small axion masses vs. static searches

$$\frac{\text{SNR}}{\text{SNR}^{\text{LC}}} \sim \frac{\omega_0 \pm m_a}{m_a} \left(\frac{Q_{\text{int}}}{Q_{\text{LC}}} \right)^{1/2} \left(\frac{T_{\text{LC}}}{T} \right)^{1/2} \left(\frac{B_0}{B_{\text{LC}}} \right)^2$$

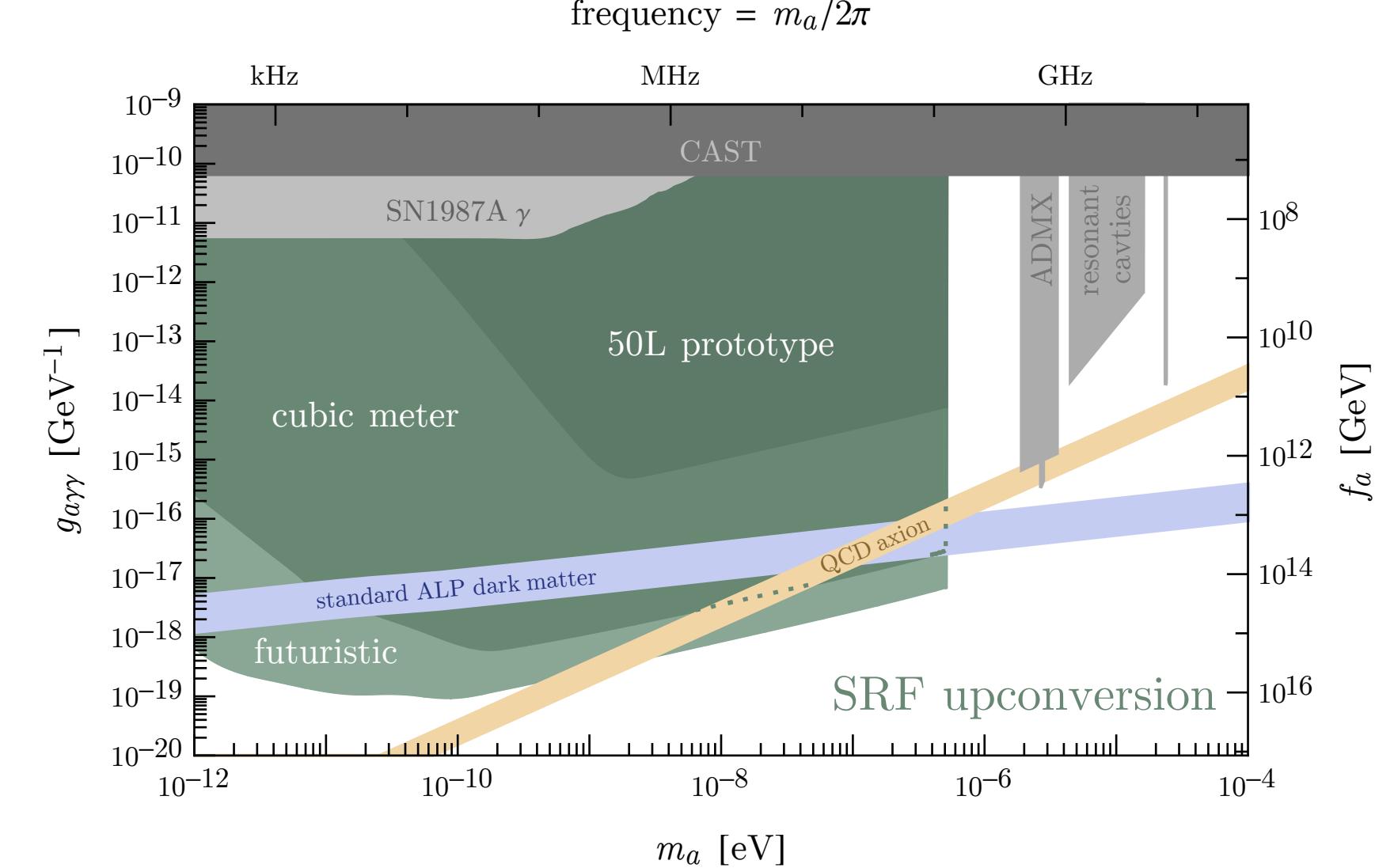
frequency = $m_a/2\pi$

- Outlook

Prototype design underway @ SLAC

Discussions ongoing w/ PBC @ CERN

Discussions ongoing w/ FNAL SQMS



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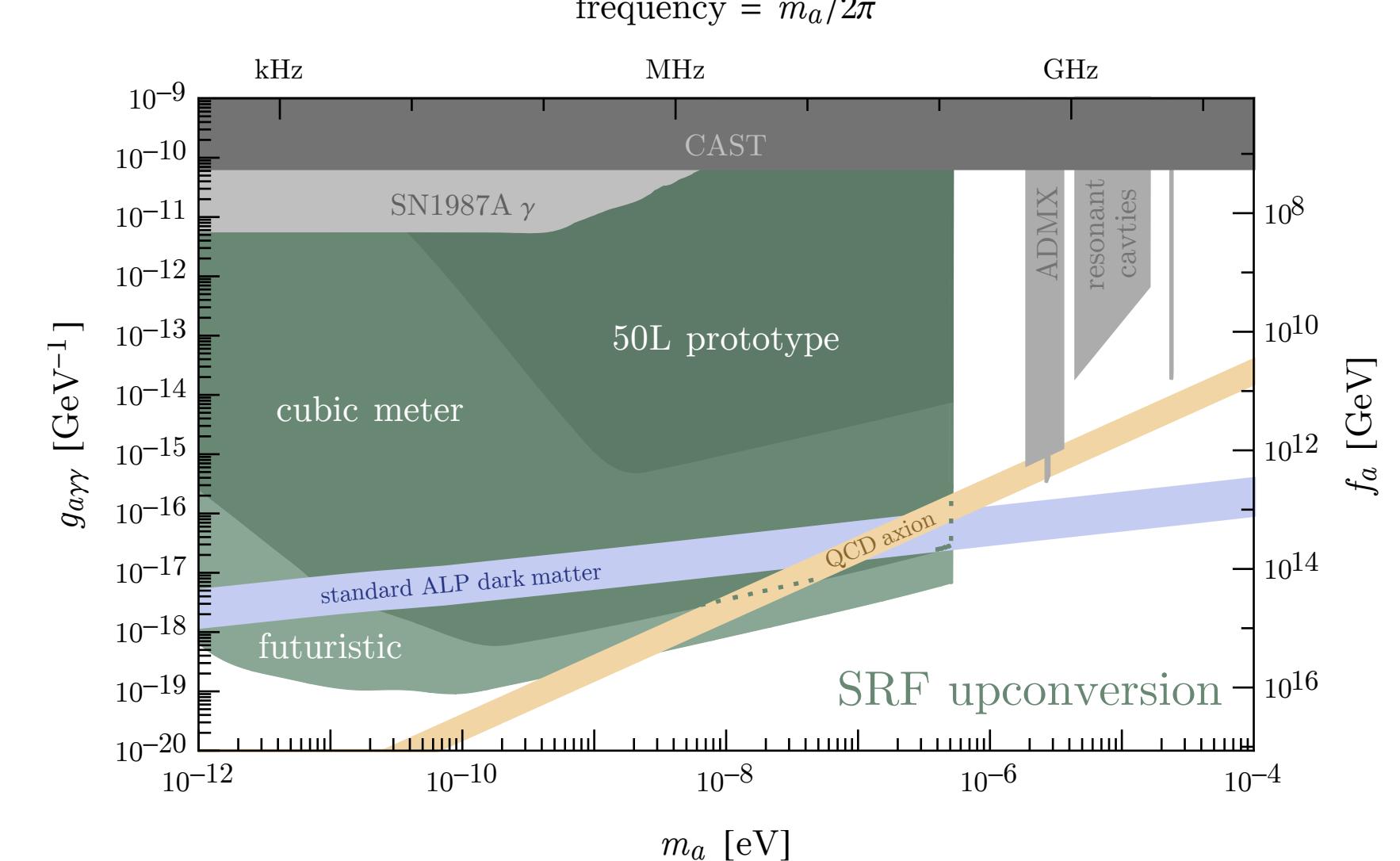
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Works for Gravitational Waves



Axion, ALPs and Axion Electrodynamics

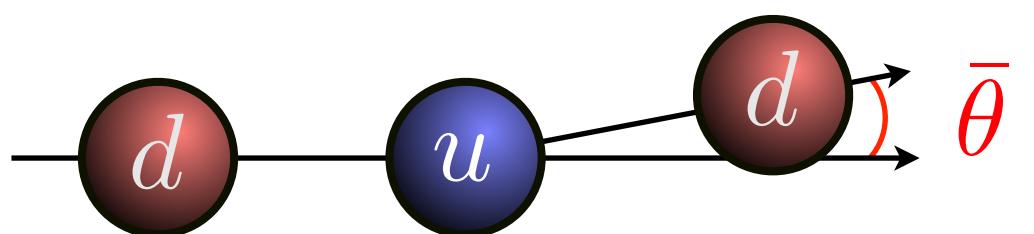
Axion introduced to solve strong CP problem

Axion, ALPs and Axion Electrodynamics

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$$d_n \sim 10^{-16} \bar{\theta} \text{ e cm}$$

$$d_n^{\text{exp}} \lesssim 10^{-26} \text{ e cm}$$



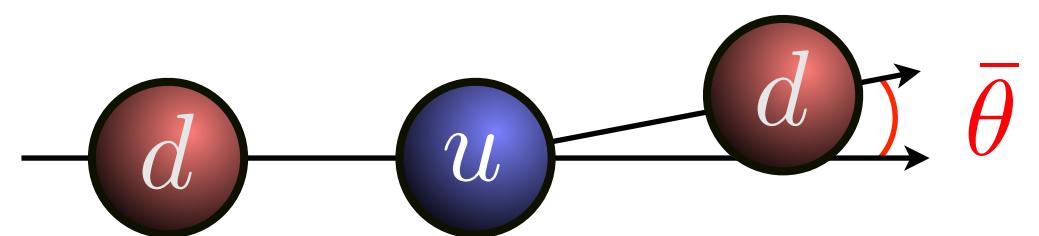
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$$\mathcal{L} \supset \left(\frac{a}{f_a} + \bar{\theta} \right) \frac{g_s^2}{32\pi^2} G_{\mu\nu}^a \tilde{G}^{\mu\nu,a}$$

Peccei & Quinn (1977)
Weinberg (1978)
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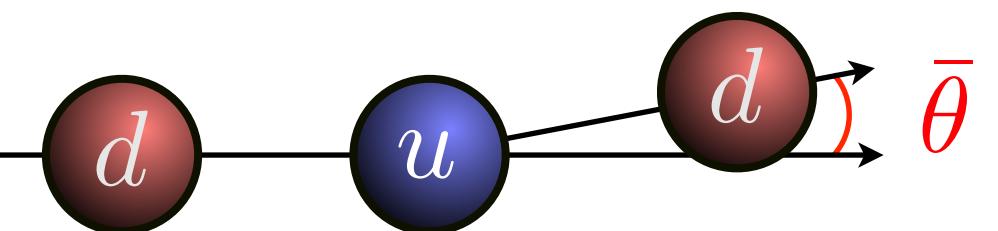


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Axion-like particles (ALPs): generic shift-symmetric CP -odd scalar

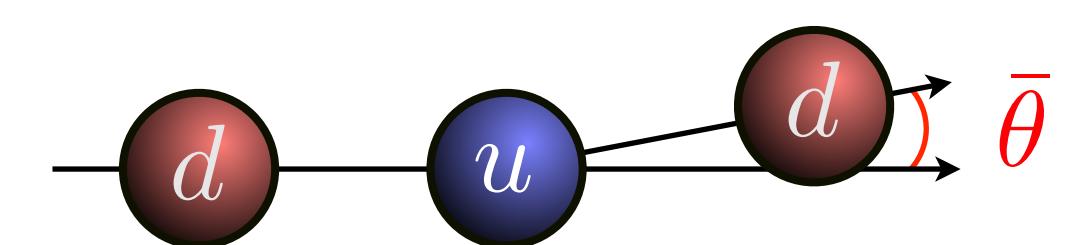
$$\mathcal{L}_{\text{ALP}} \supset \frac{1}{2} m_a^2 a^2 + \mathcal{L}_{\text{int}}$$

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- Motivations:**
- a) One of \sim few concrete predictions from known String compactifications (string axiverse)
 - b) ALPs as Dark Matter from misalignment
 - c) Technology to search for ALPs exists

Svrček & Witten (2006)
Arvanitaki et al (2009)
Stott et al (2017)
Halverson & Langacker (2018)

Axion, ALPs and Axion Electrodynamics

Axion electrodynamics:

$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F \tilde{F} = -g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

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$$\nabla \cdot \mathbf{E} = \rho - g_{a\gamma\gamma} \mathbf{B} \cdot \nabla a$$

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

Maxwell's new and improved Equations

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Axion dark matter:

$$a(t) \simeq \frac{\sqrt{2\rho_{\text{DM}}}}{m_a} \cos(m_a t + \varphi)$$

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$$J_{\text{eff}}(t) \sim g_{a\gamma\gamma} B_0(t) \sqrt{\rho_{\text{DM}}} \cos m_a t \Rightarrow B_a(t) \propto J_{\text{eff}}(t)$$

Resonant Axion Searches

Presence of axion dark matter \sim effective current

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Maximise: $\omega_{\text{sig}}, B_a, V$

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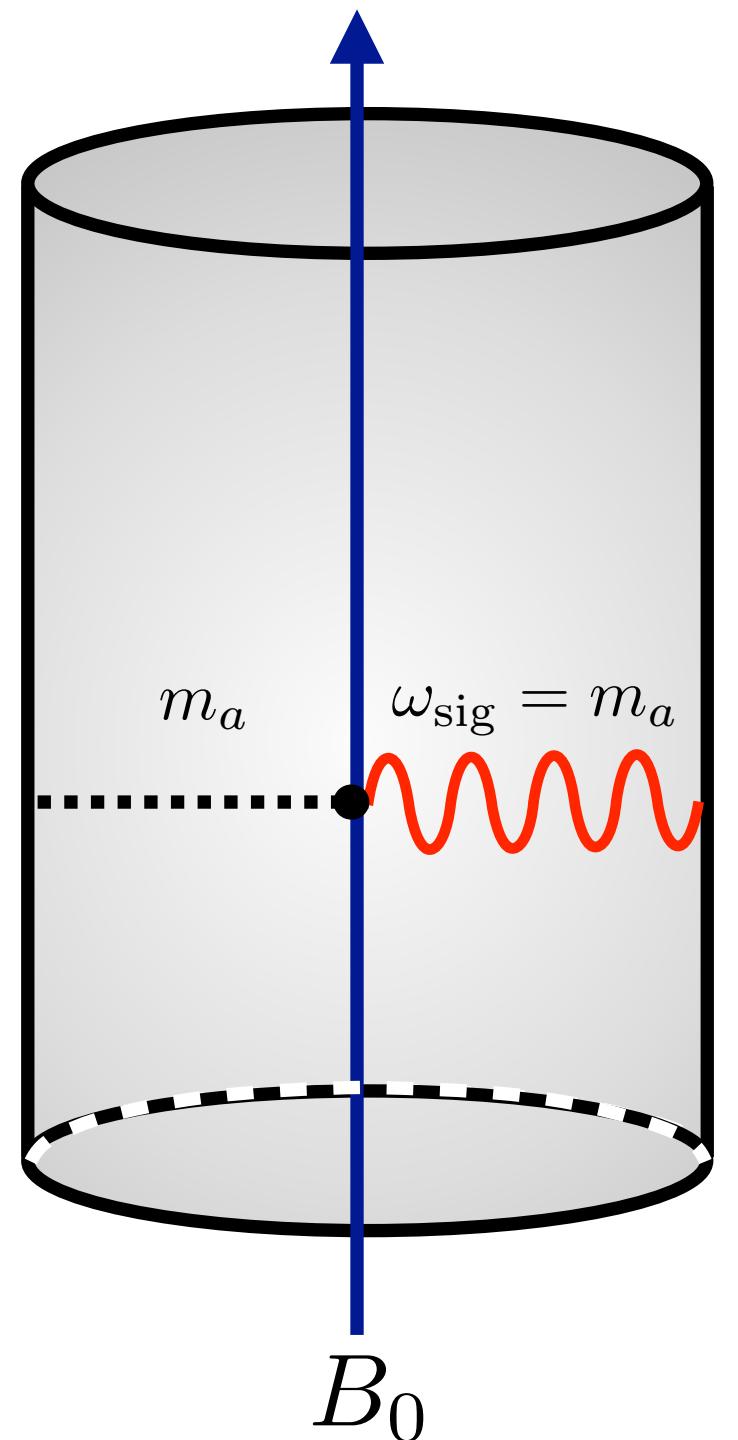
Resonant Approaches

Resonant Approaches

Static-field Haloscope:

e.g. ADMX

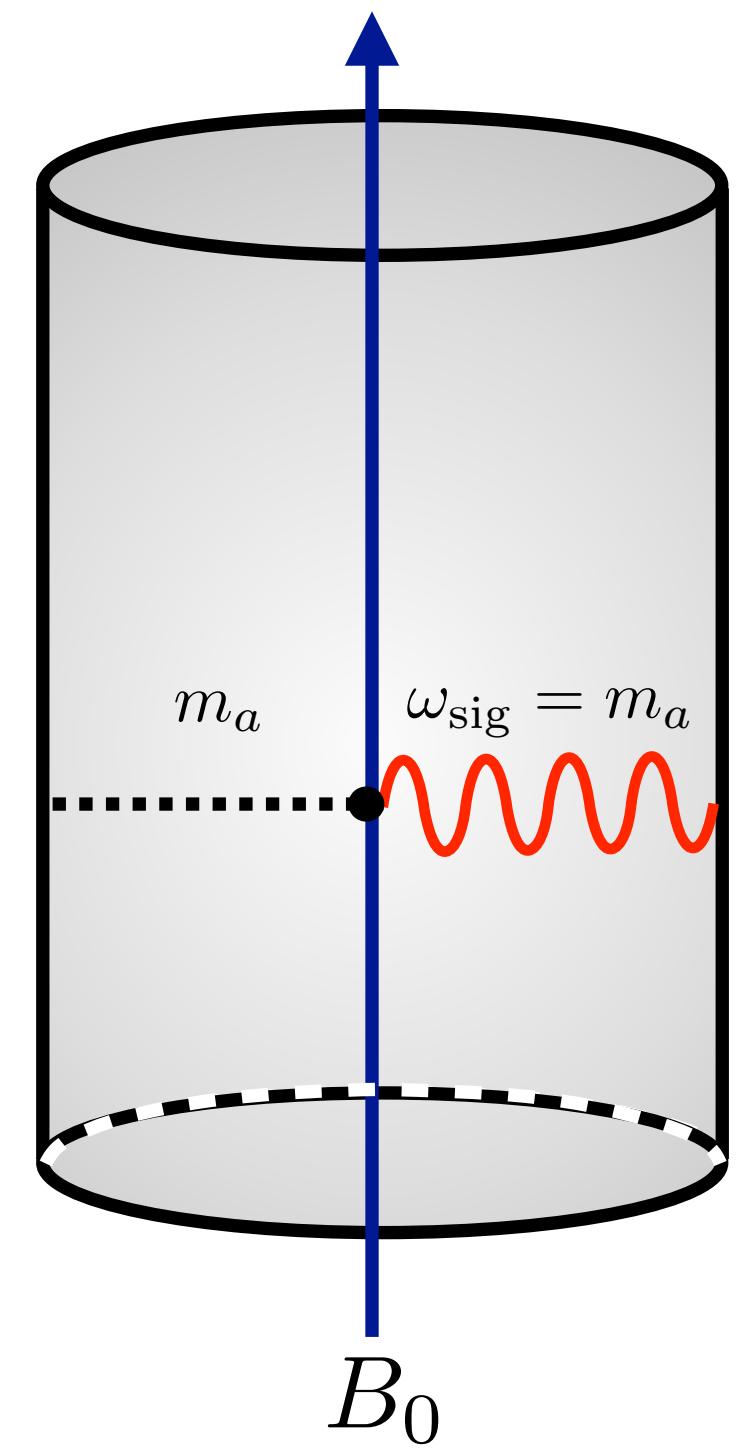
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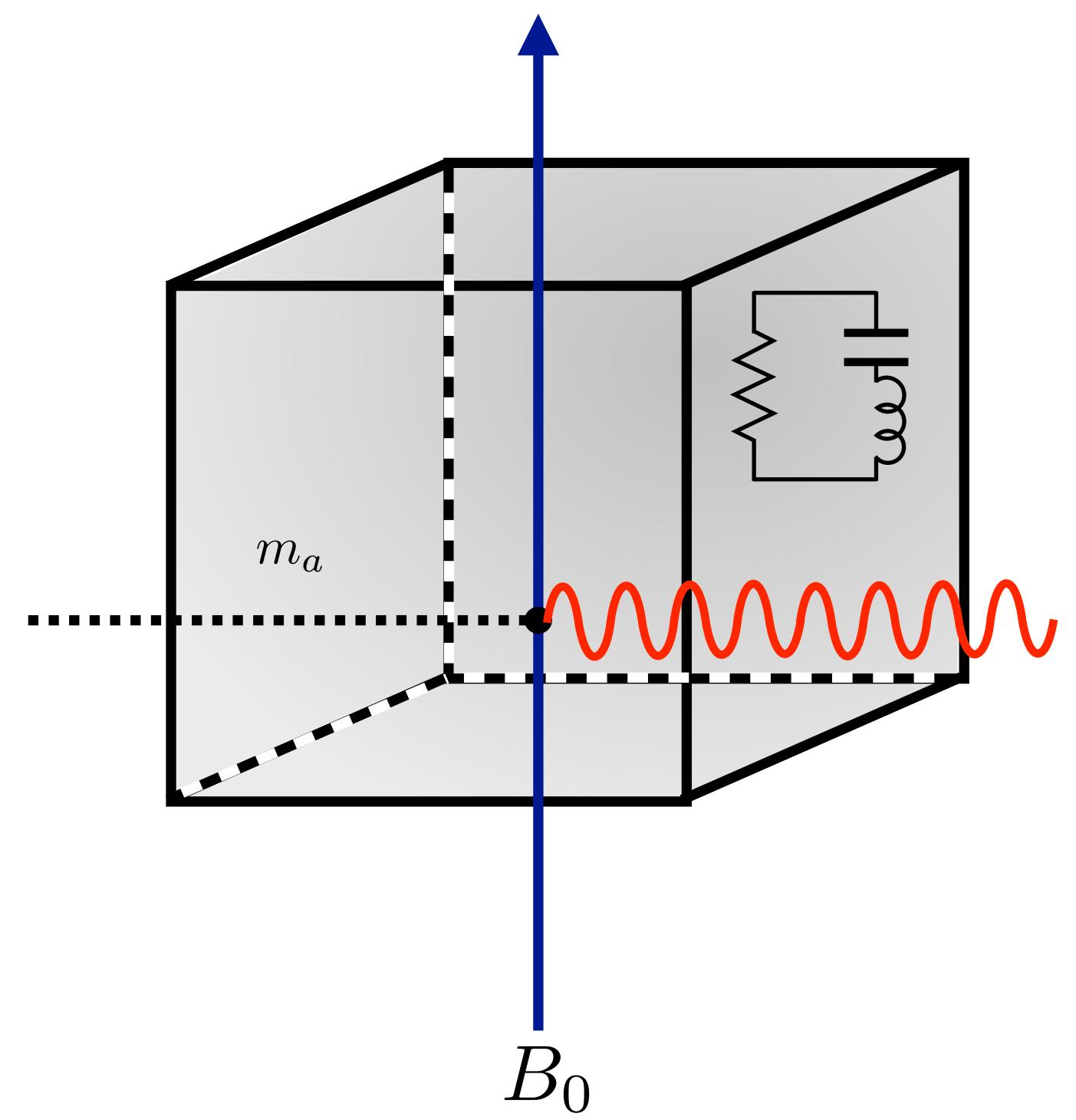
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LC Resonator:
e.g. DM Radio

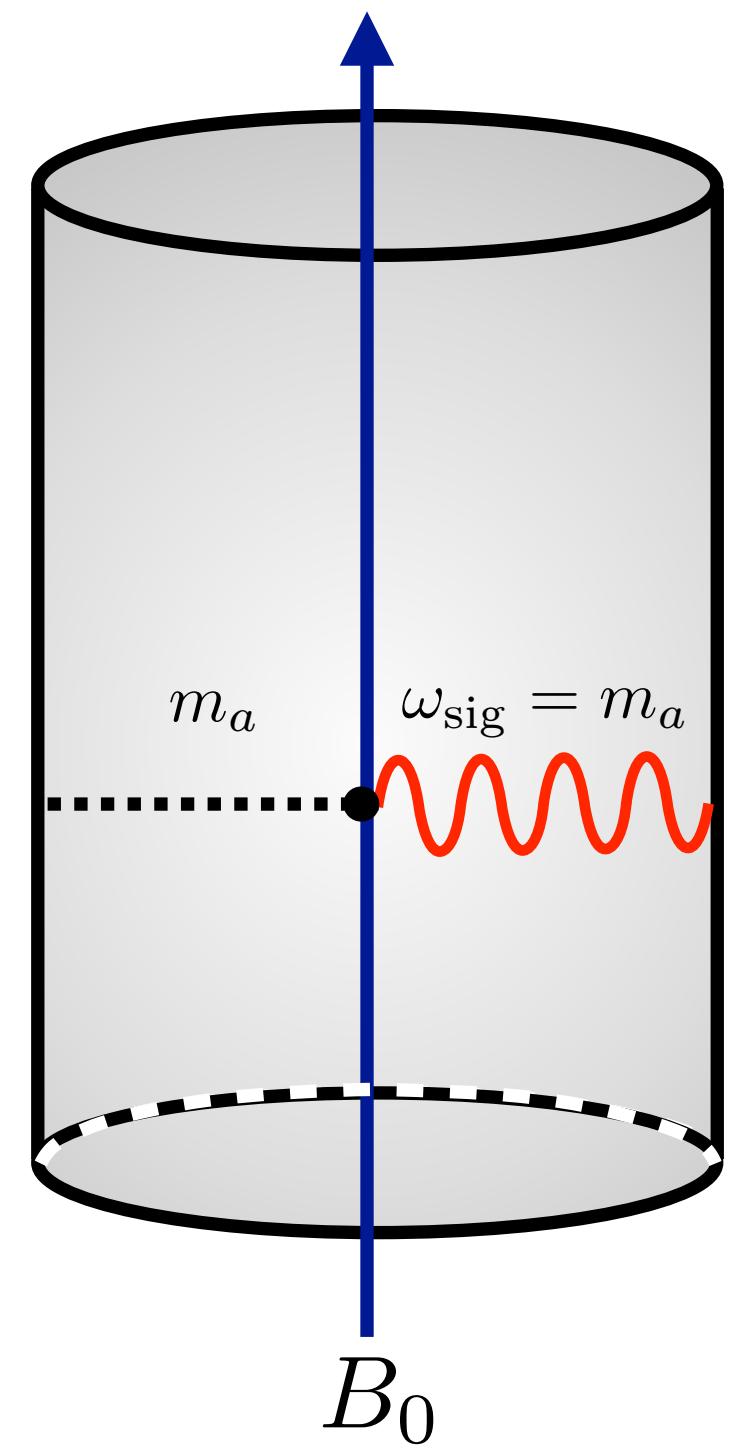
$$\omega_{\text{sig}} = m_a = \omega_{\text{LC}}$$



Resonant Approaches

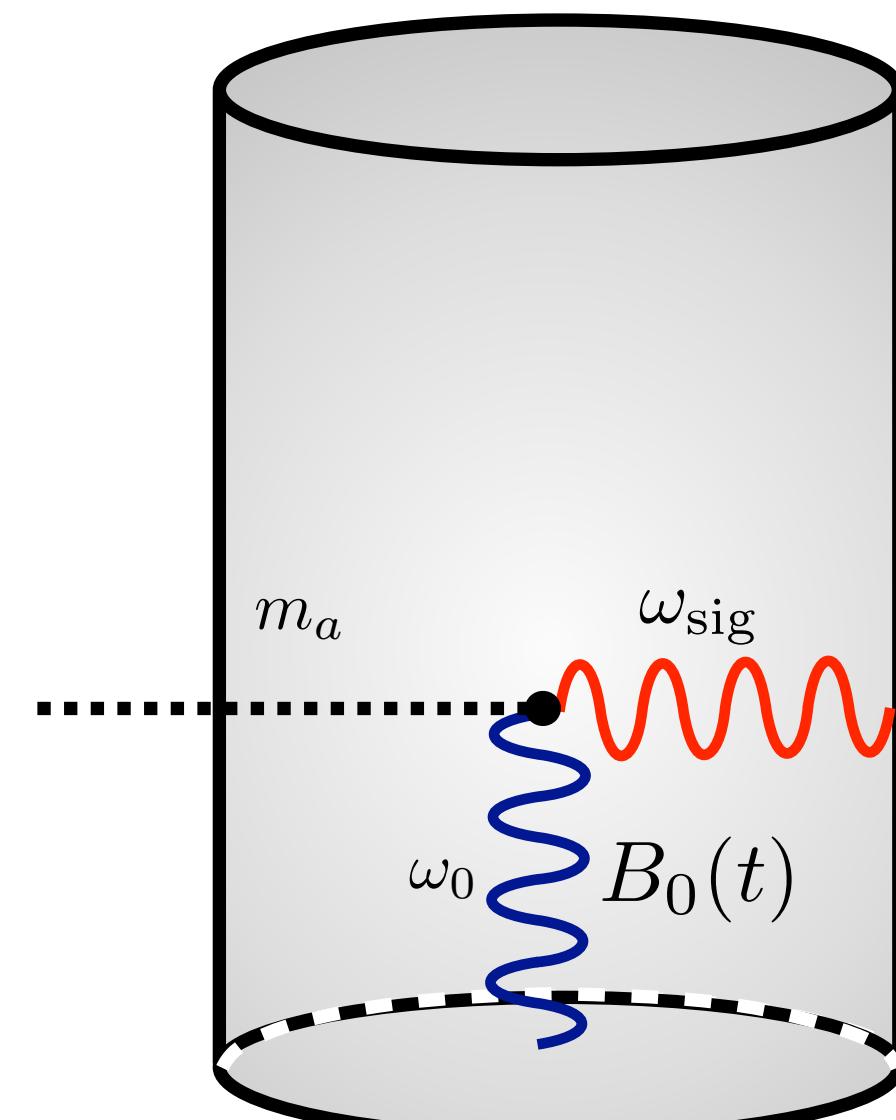
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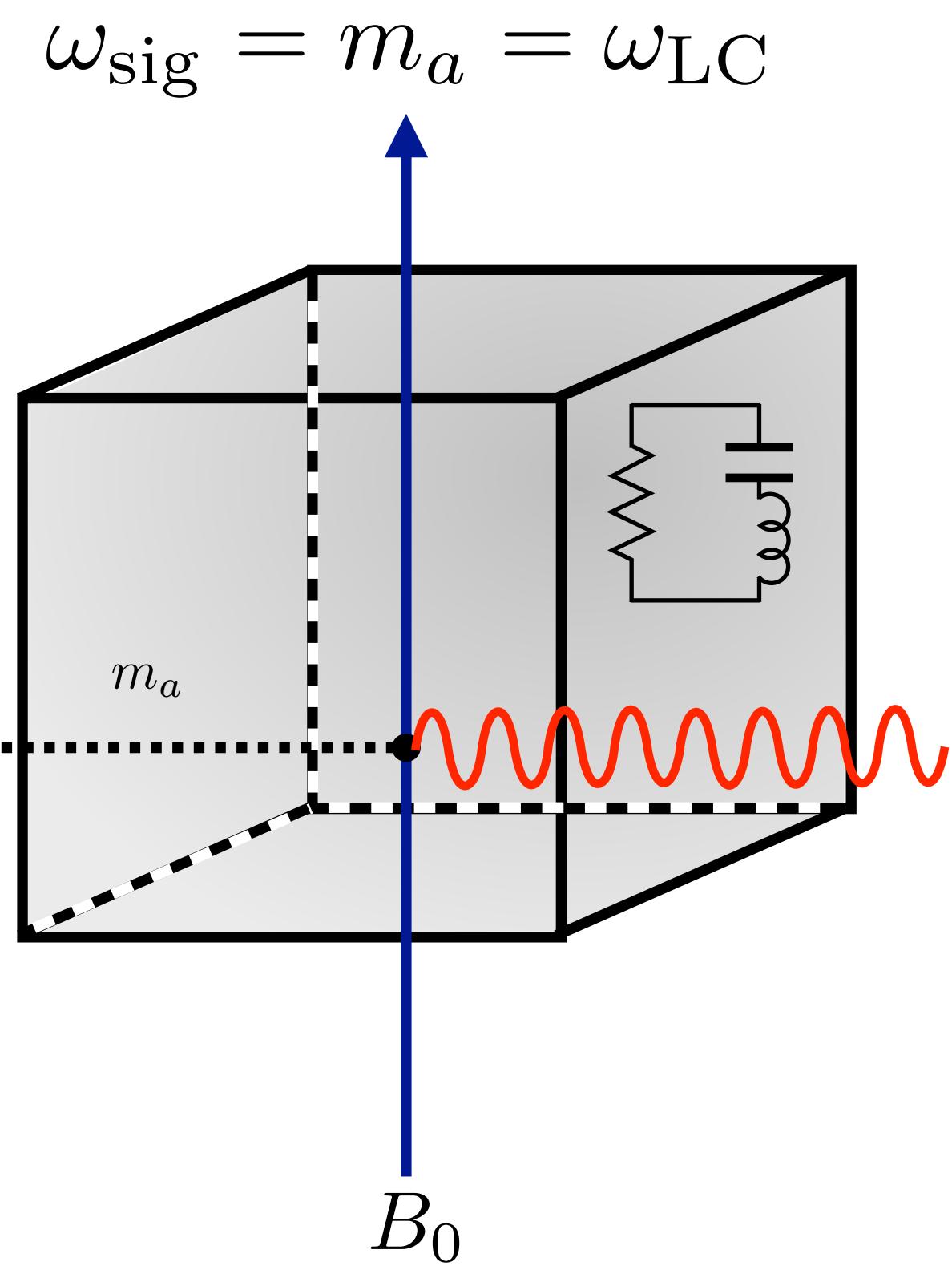
Heterodyne Resonator:

$$\omega_{\text{sig}} \sim \omega_0 \pm m_a \sim V^{-1/3}$$



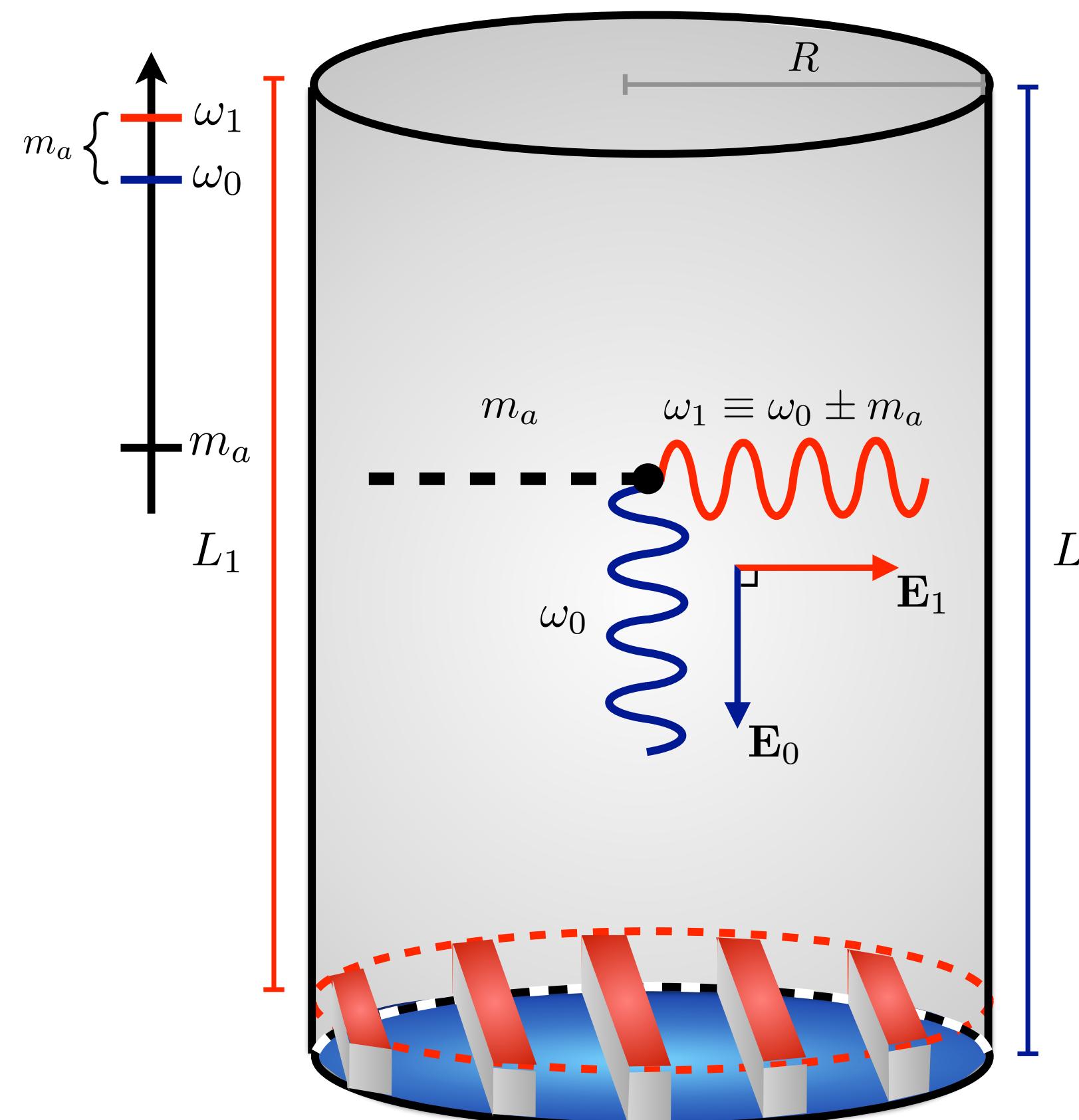
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Also: R. Lasenby hep-ph/1912.11467

Axion Resonant Frequency Conversion



Superconducting RF Cavity

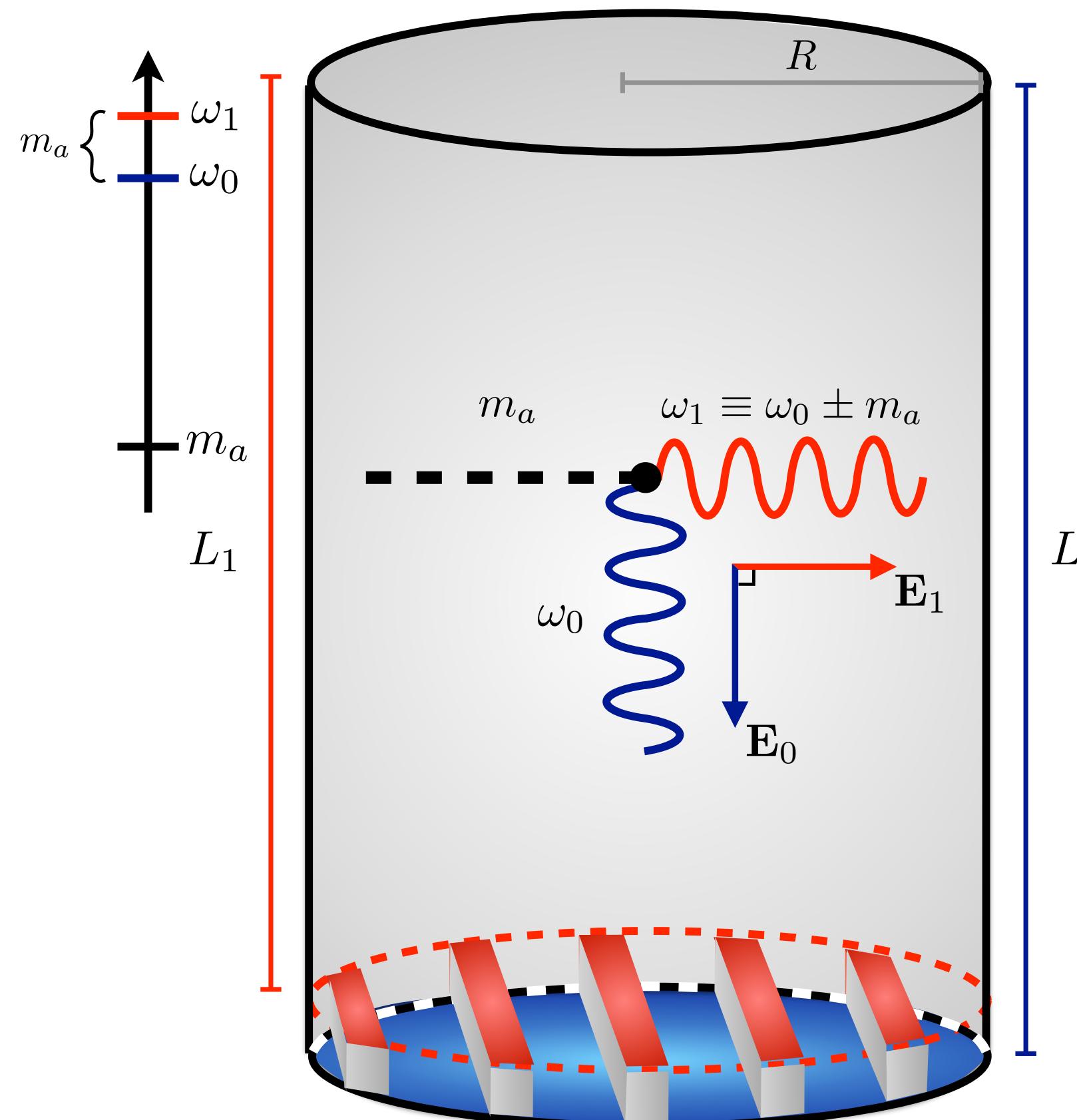
$$\omega_0 \sim \omega_1 \sim \text{GHz}$$

$$Q_{\text{int}} \sim 10^9 \div 10^{13}$$

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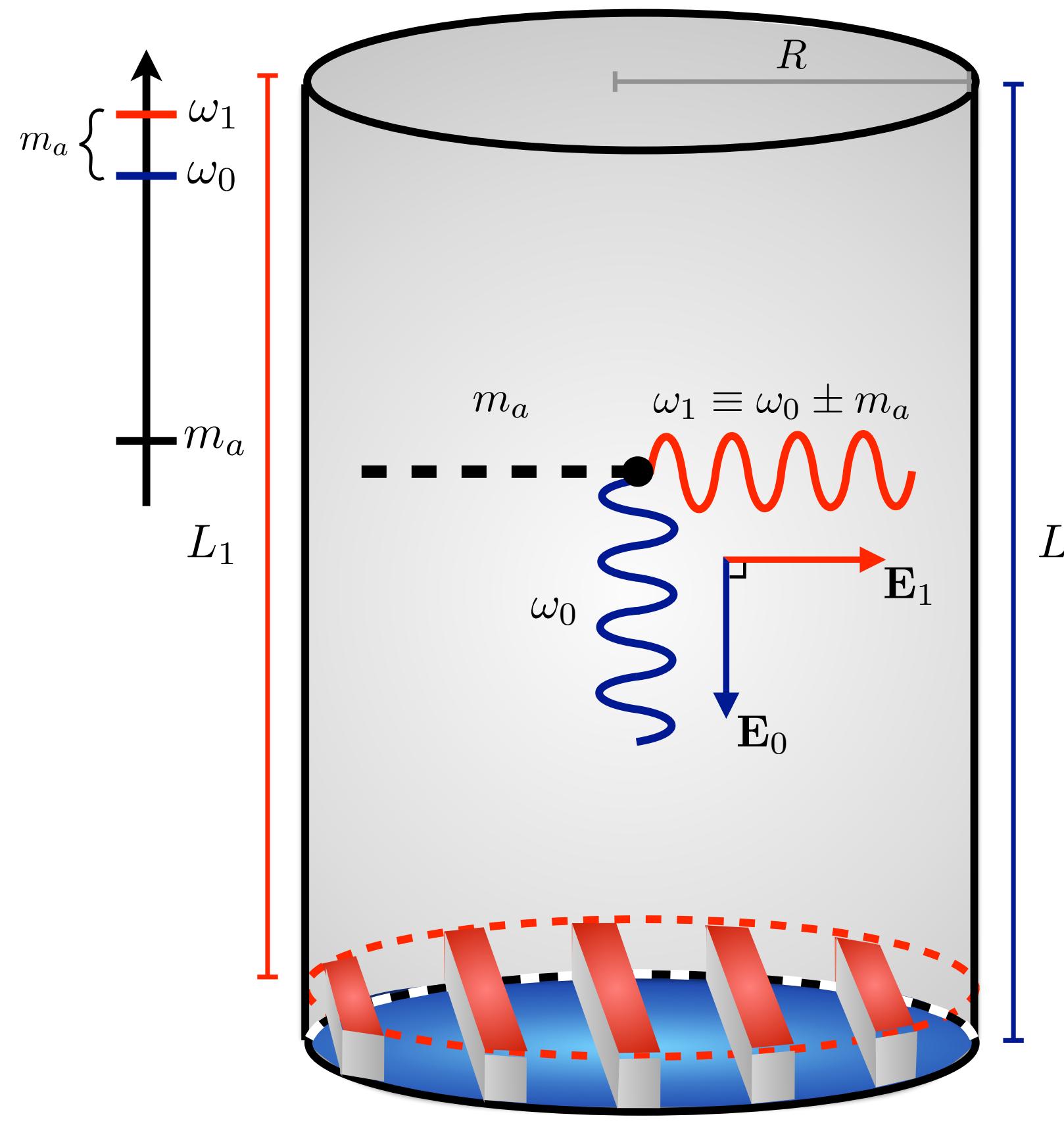
$\delta\omega \lesssim \text{MHz}$ piezos

$\delta\omega \gtrsim \text{MHz}$ ‘plunger’

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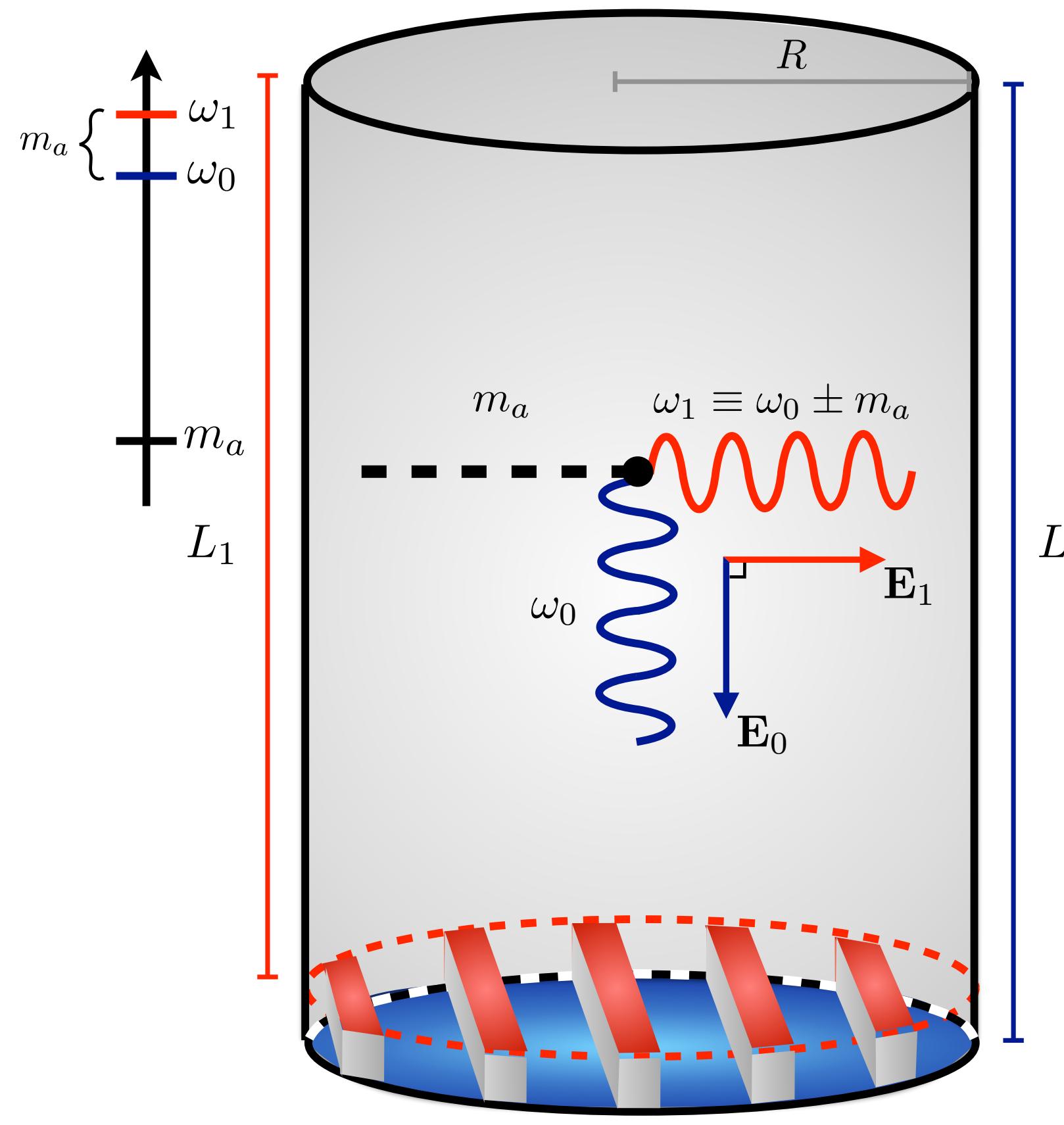
Degeneracy:

$$\frac{L}{R} = \left(\frac{\pi(p_1^2 - p_0^2)}{x_{mn_0}^2 - x'_{mn_1}^2} \right)^{1/2}$$

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Broadband:

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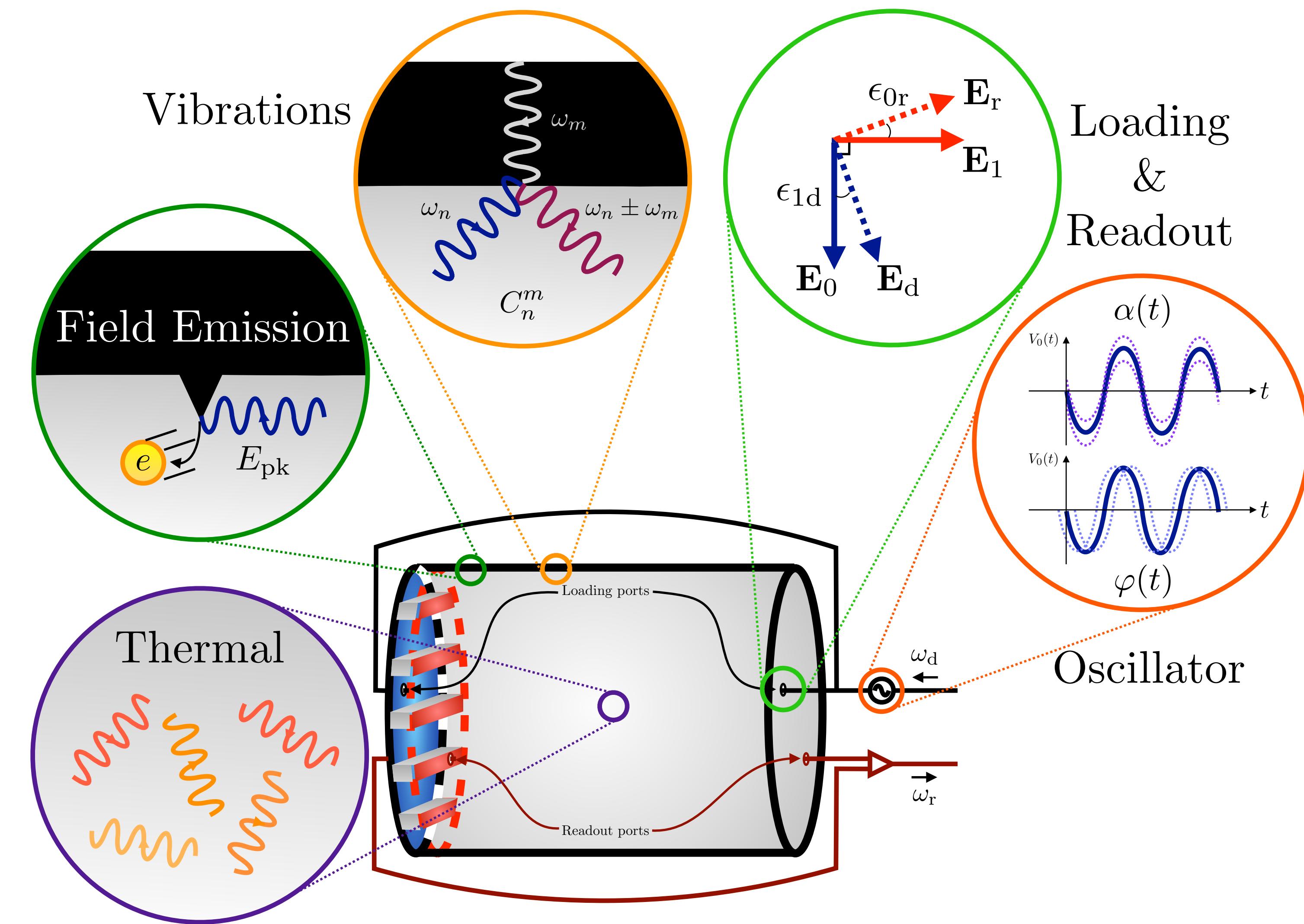
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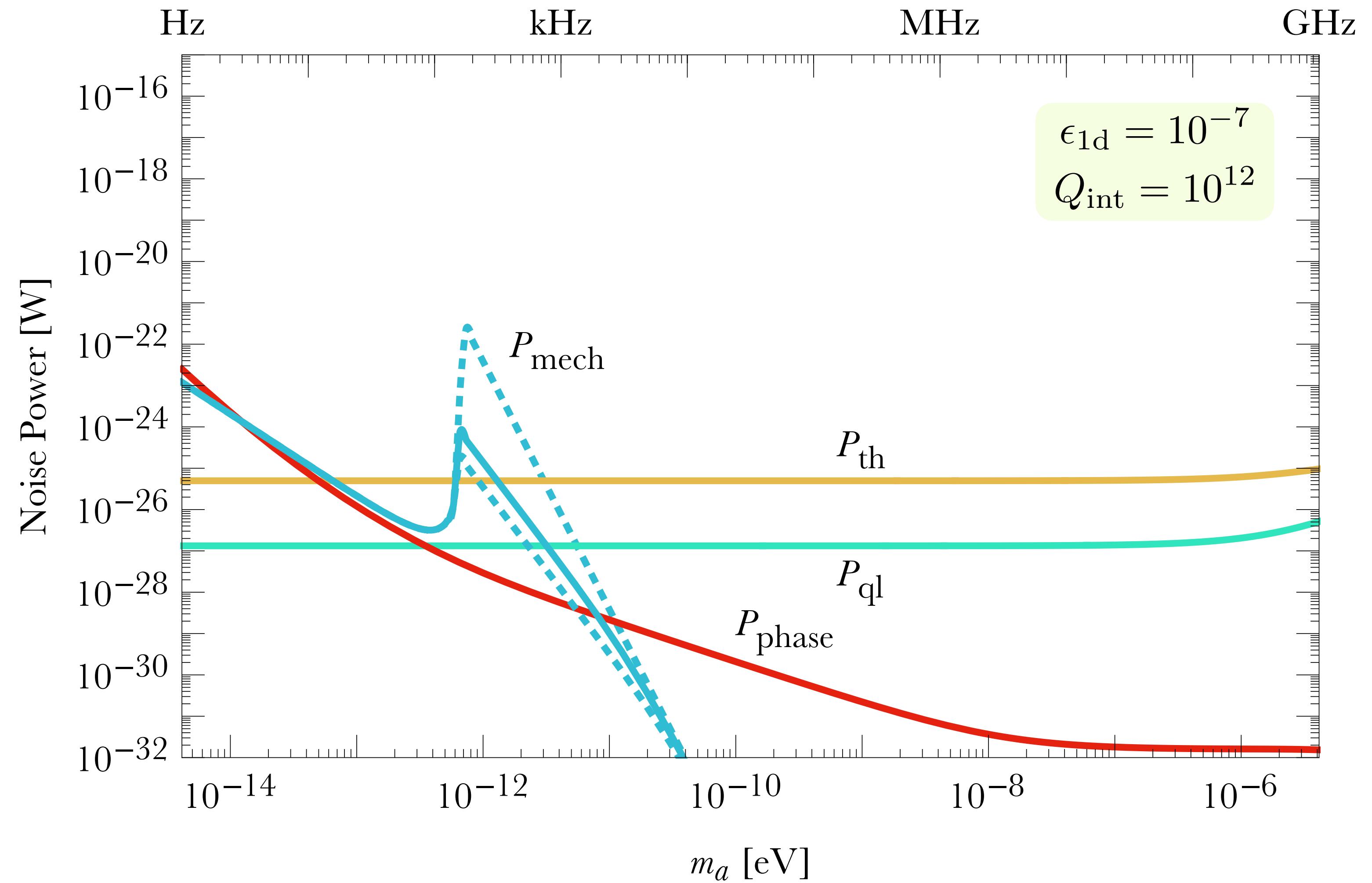
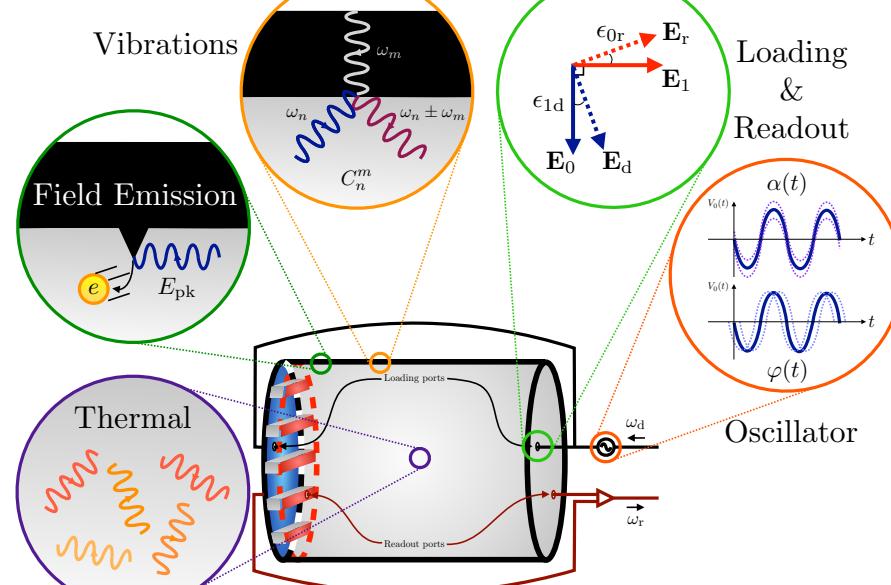
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All Noise Sources

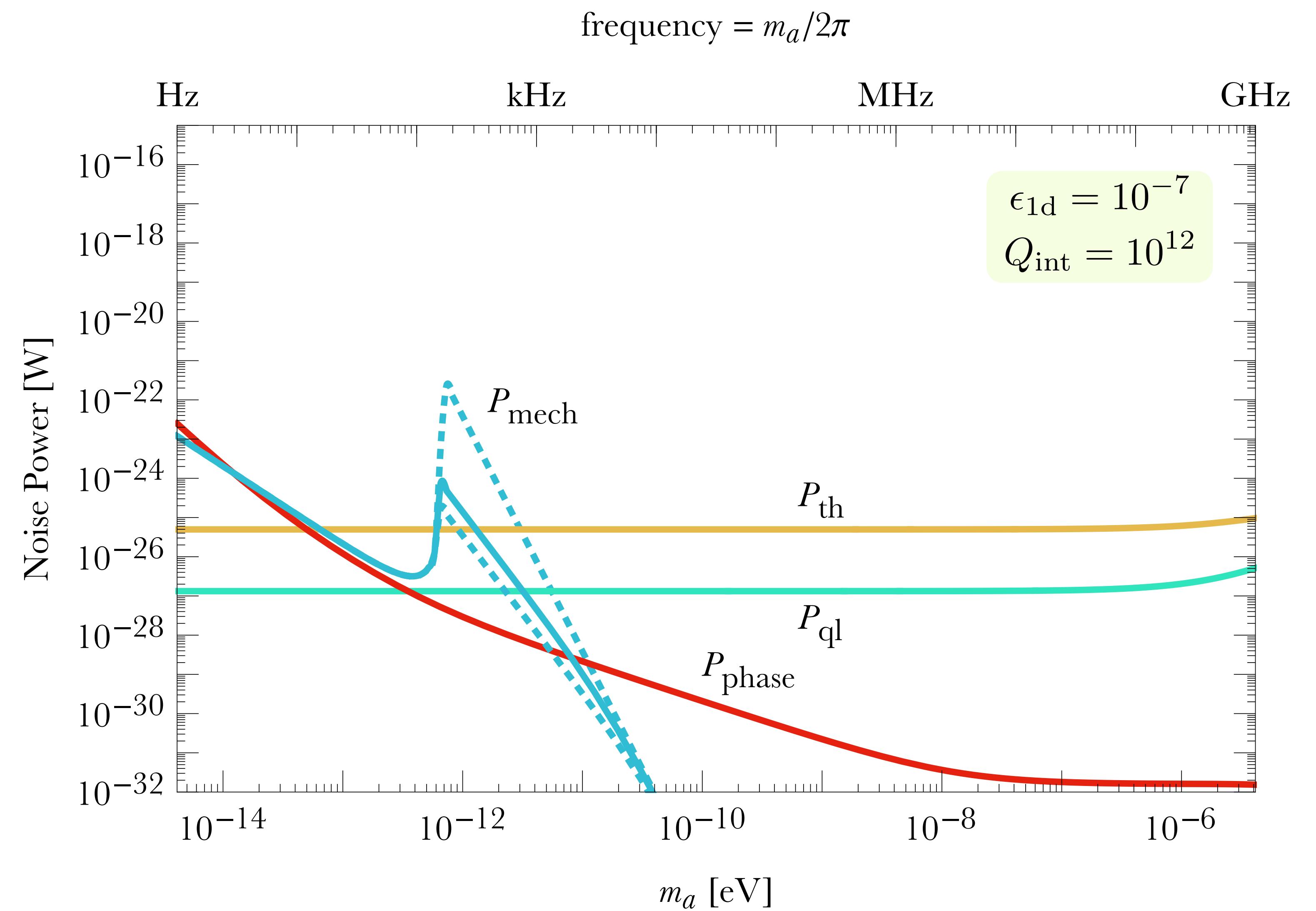


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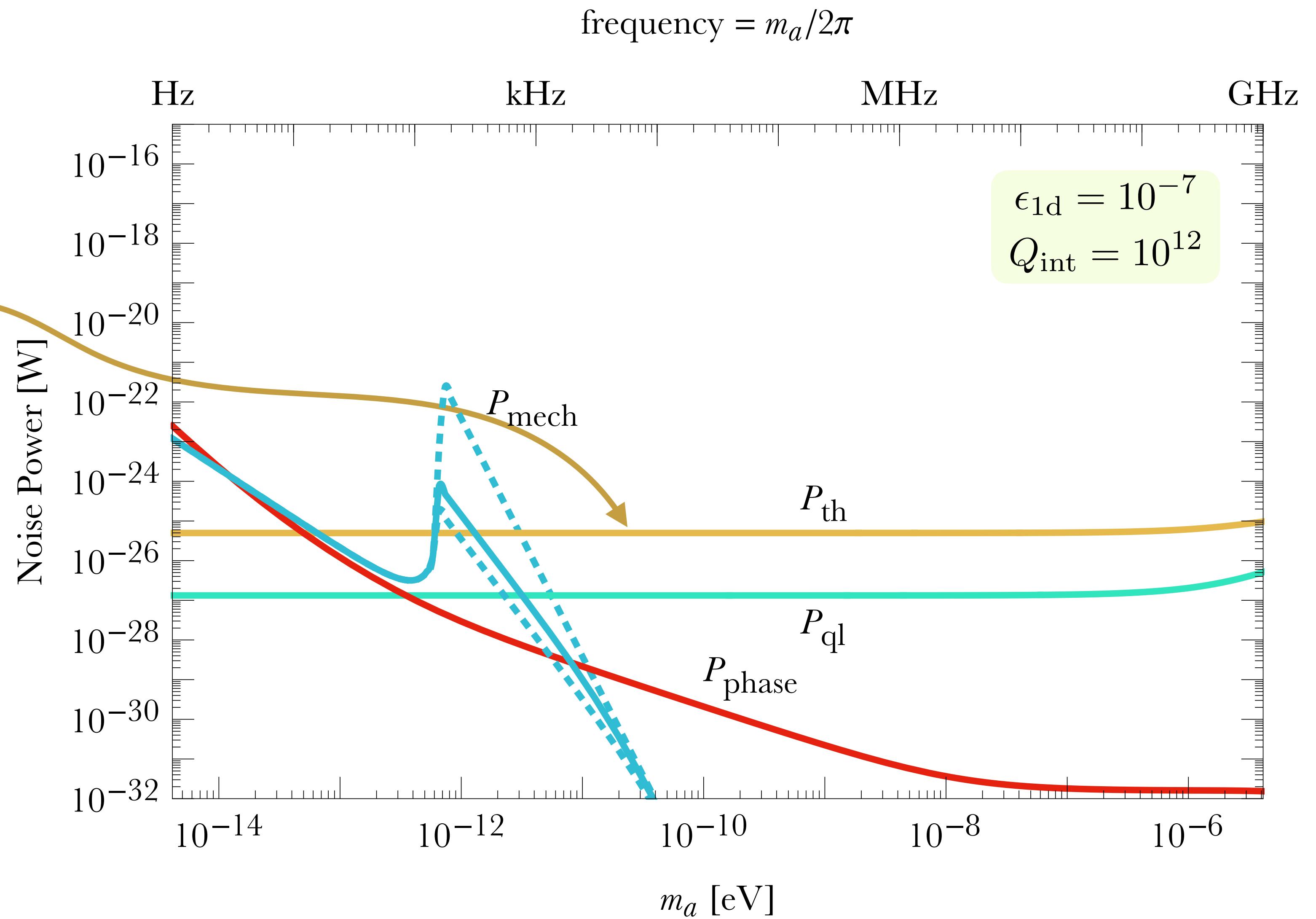


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All Noise Sources

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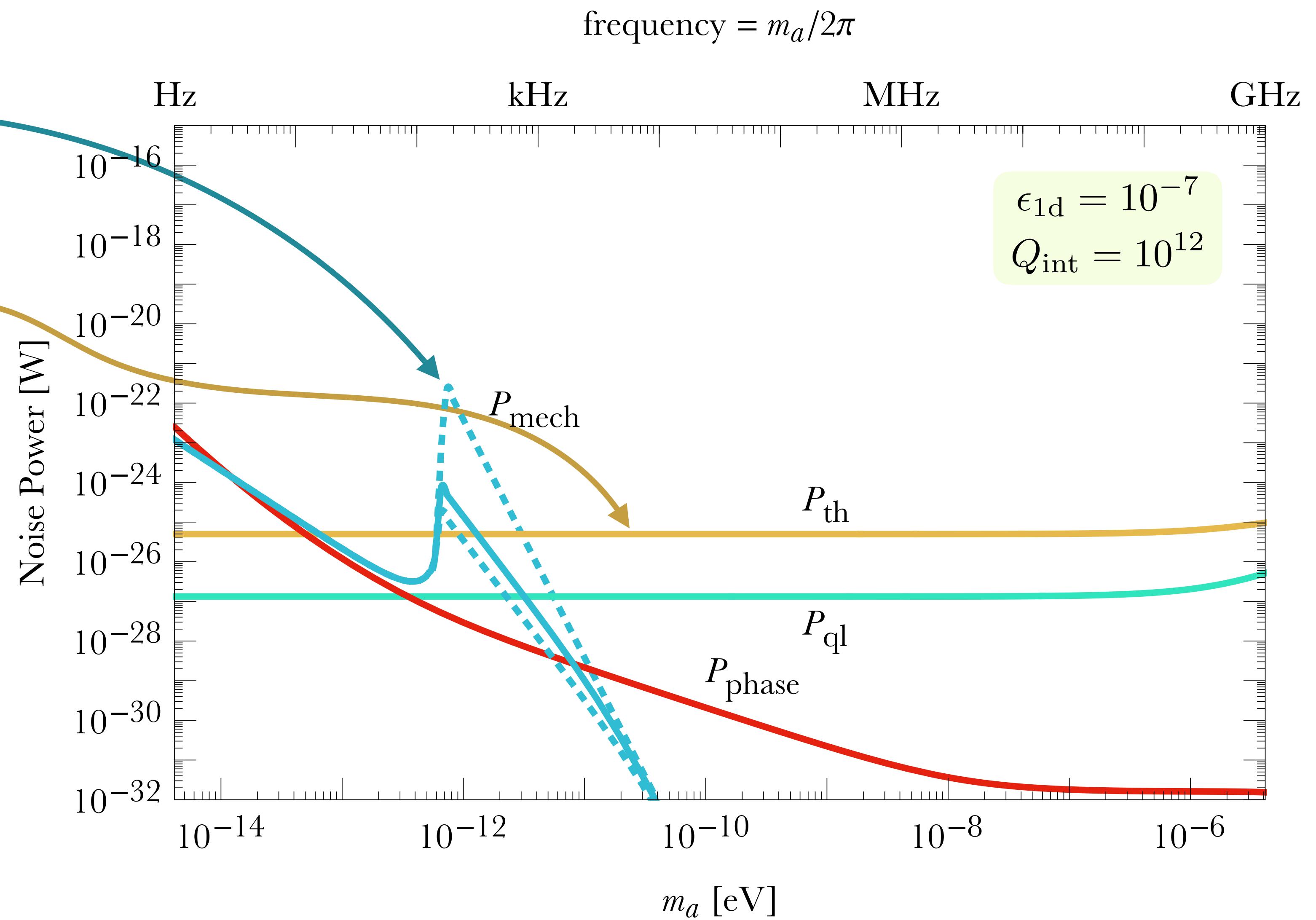


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$$P_{\text{mech}} \sim \epsilon_{1d}^2 \delta^2 \frac{\omega_0^2 \omega_{\min}^3}{m_a^5} P_{\text{in}}$$

fractional wall disp. δ

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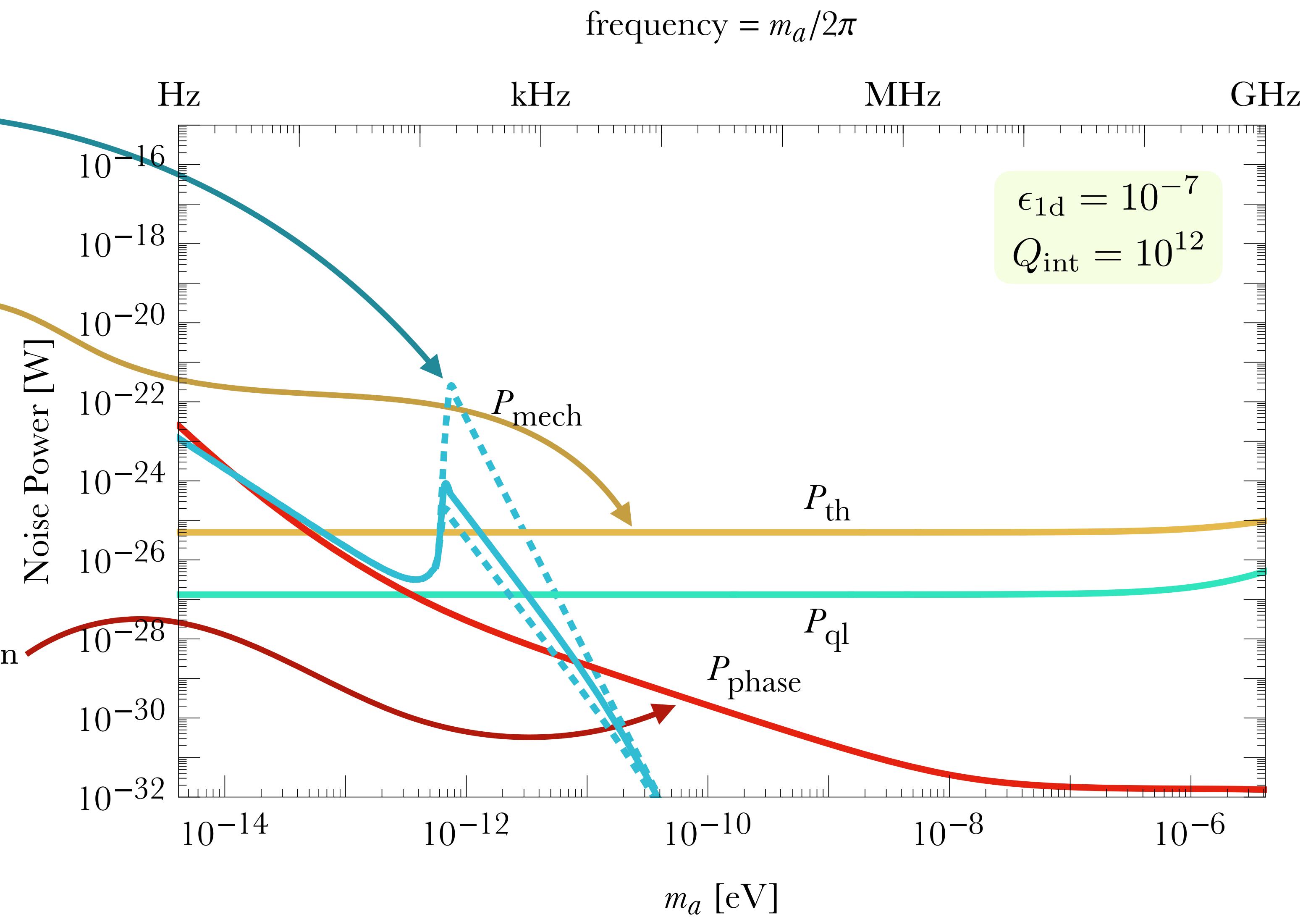
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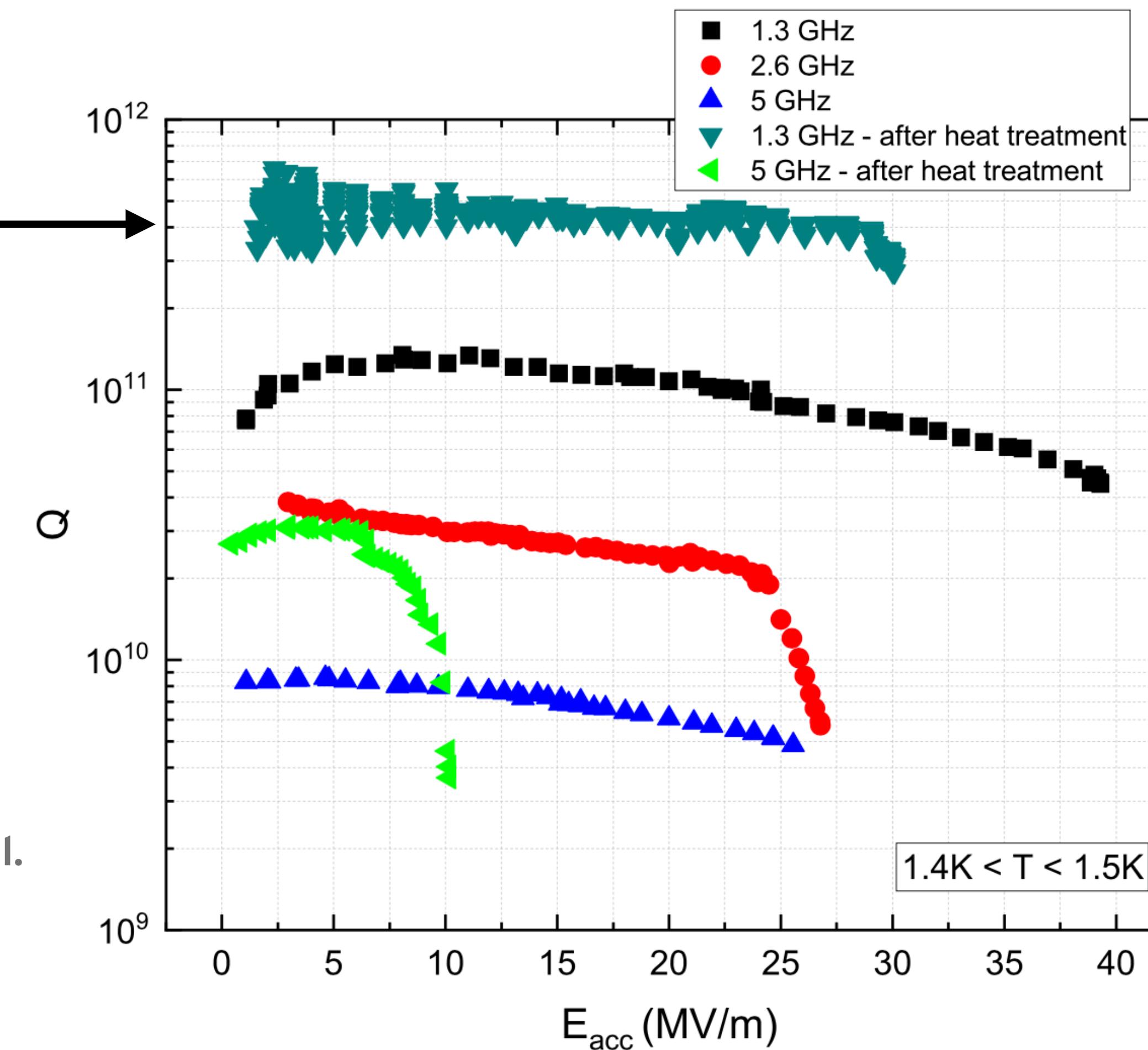


Experimental precedent

Q-factor & B-field:

$Q \sim 4 \times 10^{11} @ B \sim 0.1T$

arXiv: 1810.03703 Romanenko et al.



Experimental precedent

Mode rejection:

$\varepsilon = 10^{-7}$ achieved



[gr-qc/0502054](https://arxiv.org/abs/gr-qc/0502054) Ballantini et al.
[physics/0004031](https://arxiv.org/abs/physics/0004031) Bernard, Gemme, Parodi, Picasso

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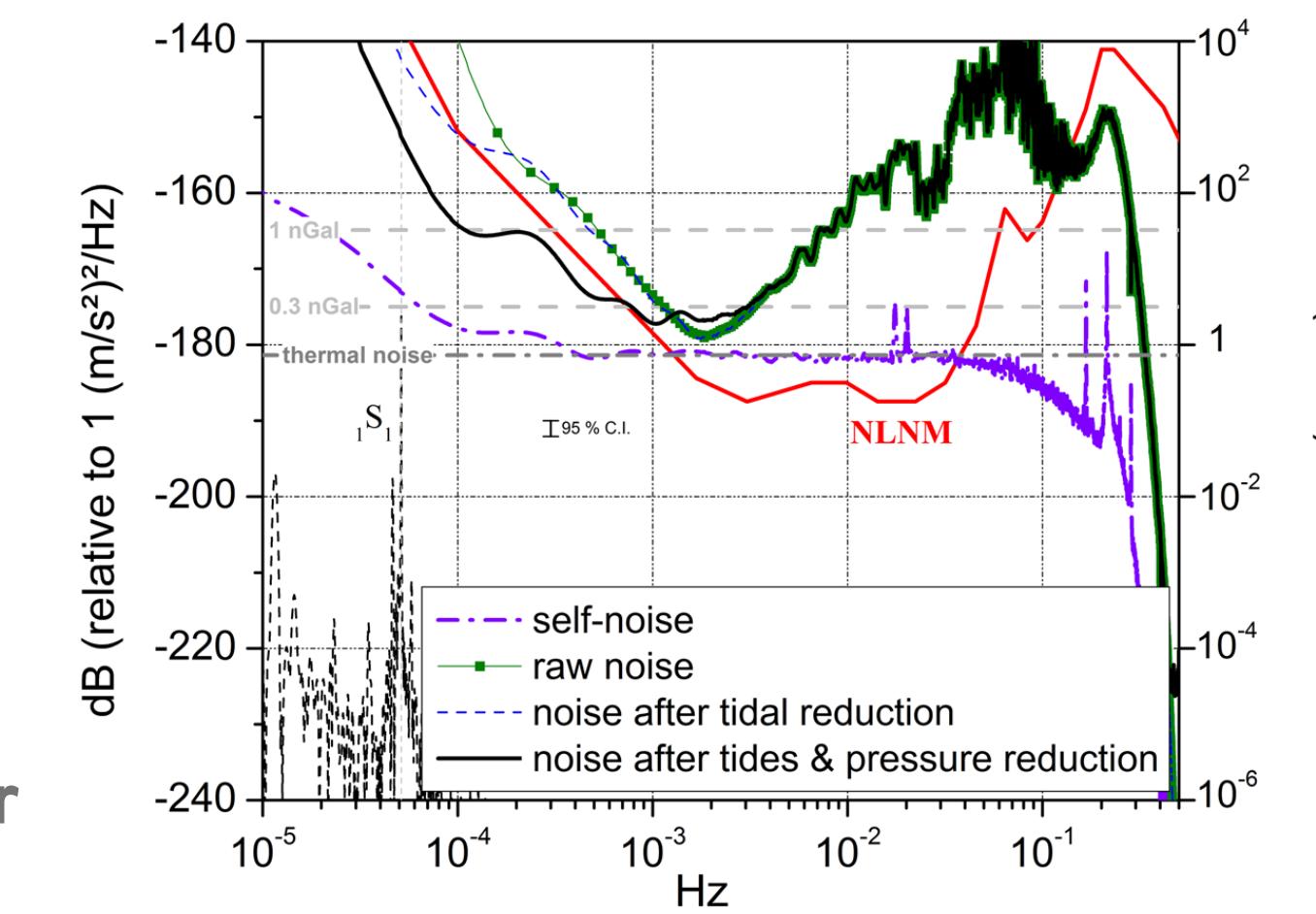
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Low-frequency
seismic noise:

$\Delta\omega/\omega \sim \delta \sim 10^{-10}$
DarkSRF (2020)

Scientific Reports 8, 15324 (2018) Rosat & Hinderer



Signal to Noise

Roughly:

$$(\text{SNR})^2 \simeq t_{\text{int}} \int_0^\infty d\omega \left(\frac{S_{\text{sig}}(\omega)}{S_{\text{noise}}(\omega)} \right)^2$$

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Comparison with LC resonator:

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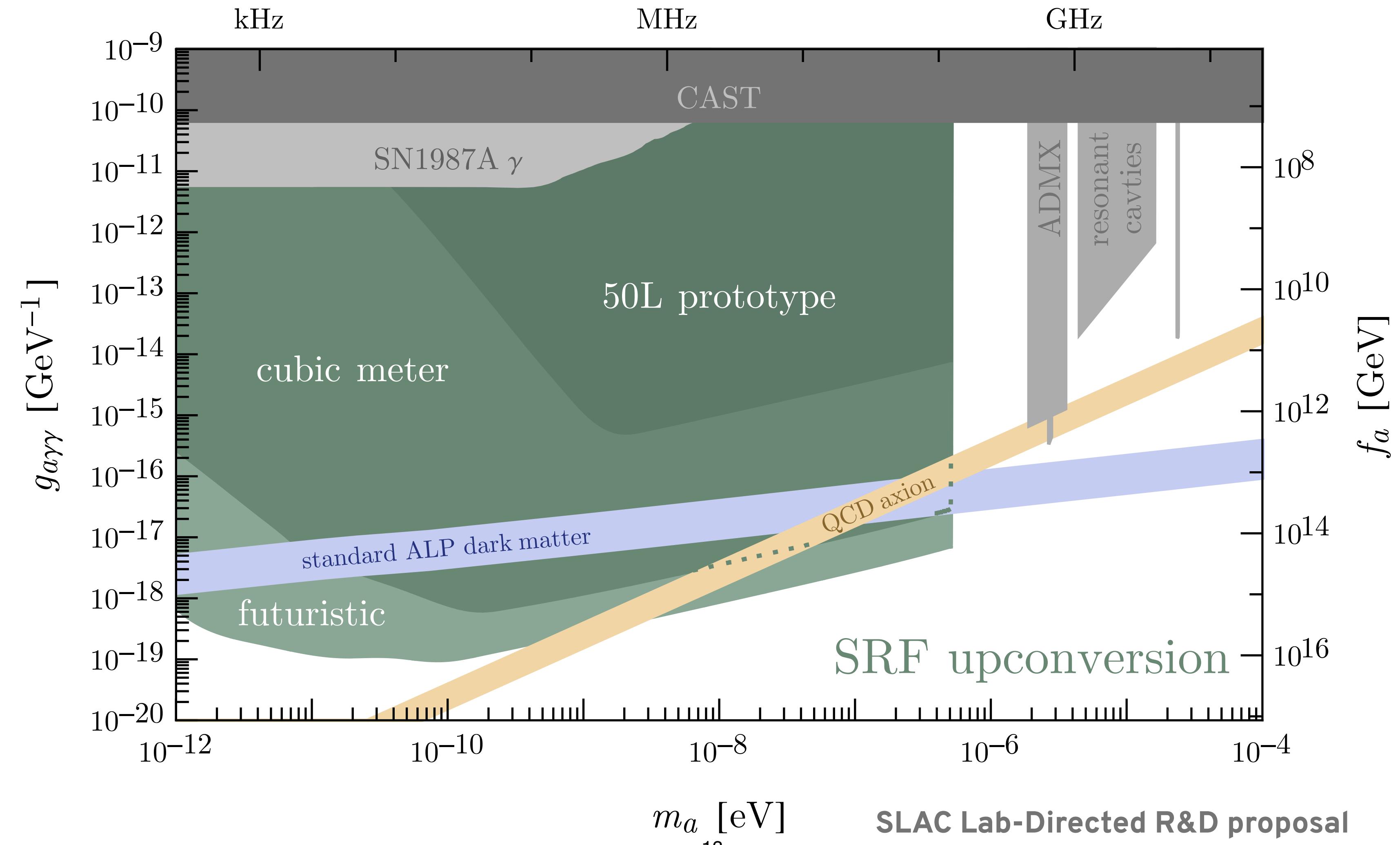
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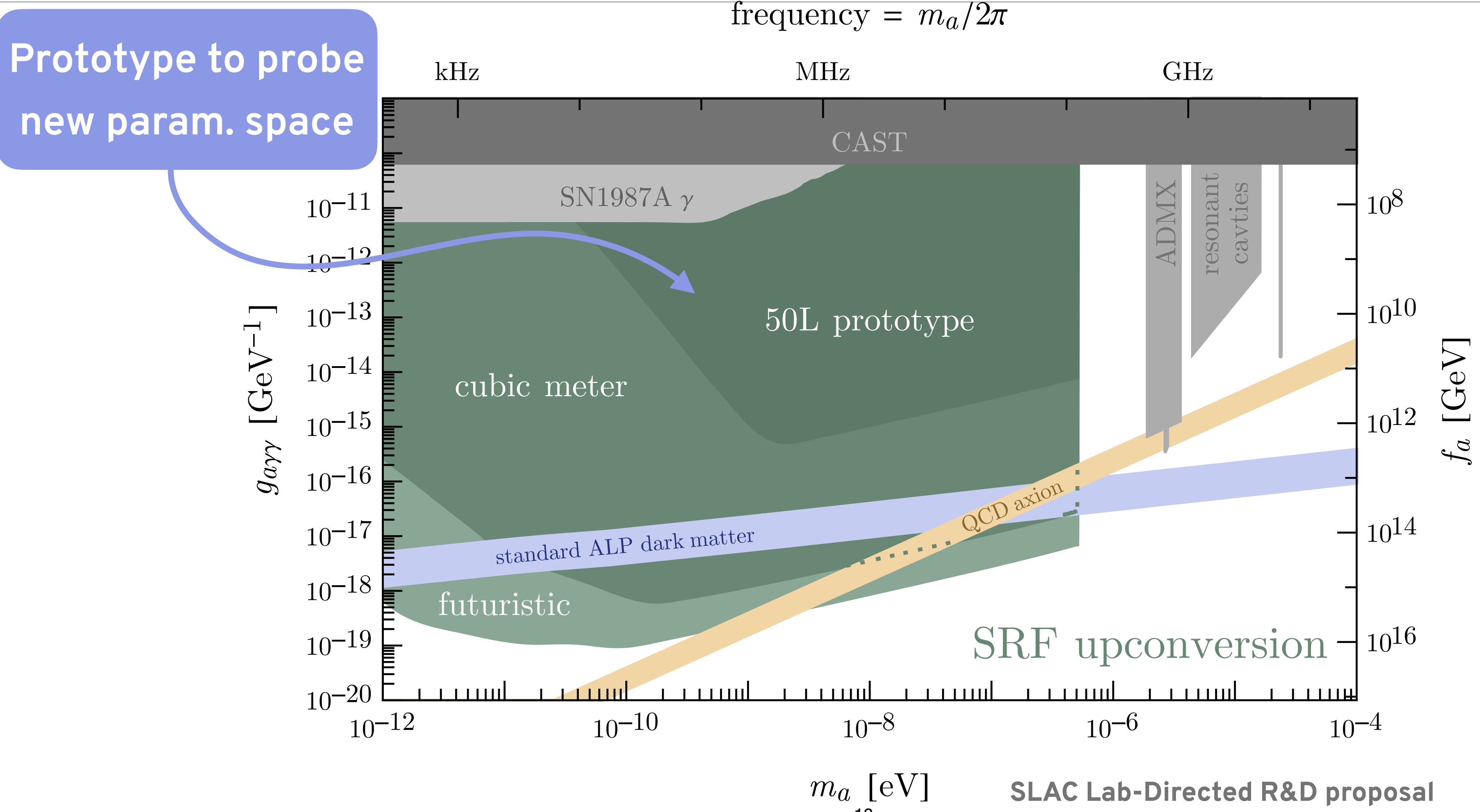
Prototype R&D FUNDED at SLAC



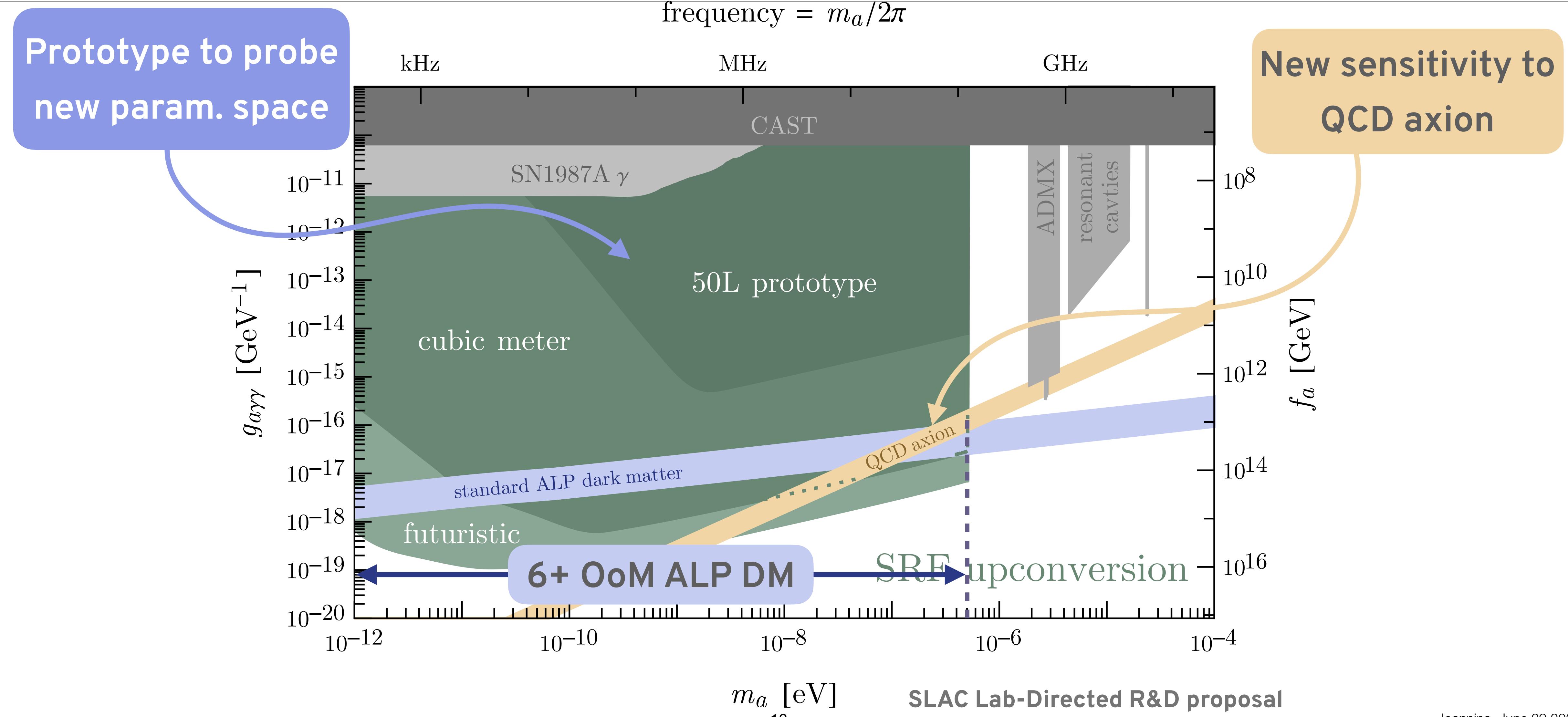
frequency = $m_a/2\pi$



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Prototype R&D FUNDED at SLAC



What about GWs?

Gravitational interaction with Electromagnetism:

$$S_{\text{EM}} = \int d^4x \sqrt{-g} \left(-\frac{1}{4} g^{\mu\alpha} g^{\nu\beta} F_{\mu\nu} F_{\alpha\beta} + g^{\mu\nu} J_\mu A_\nu \right)$$

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Raffelt & Stodolsky (1988)

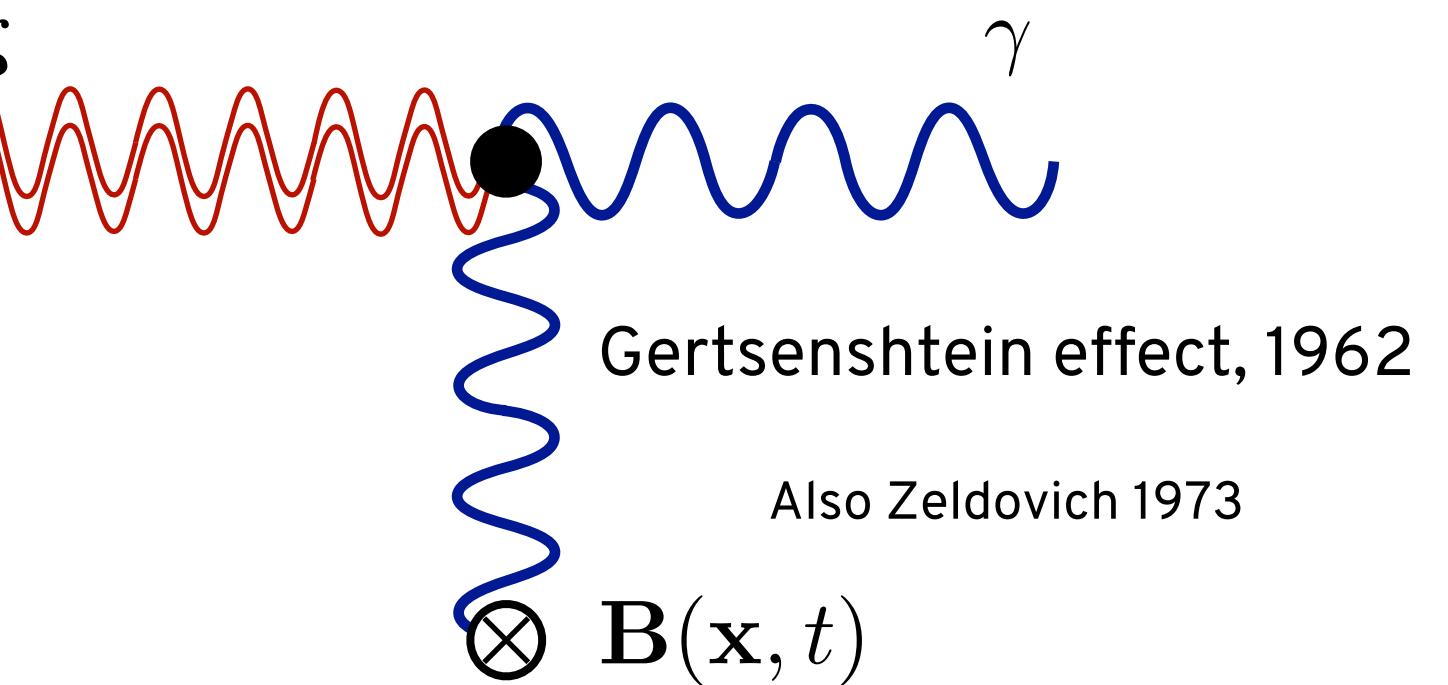
See also: Domcke, Gracia-Cely, Rodd, 2202.00695

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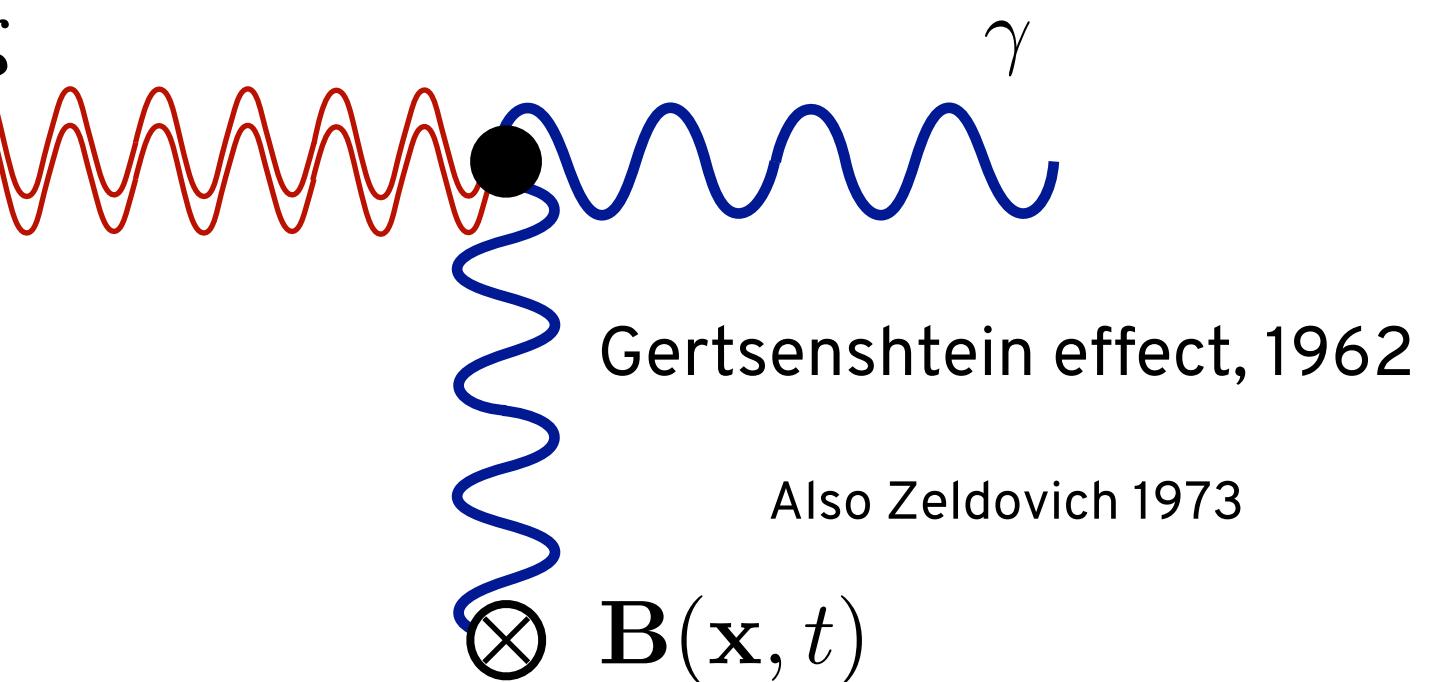
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Maxwell's equations:

See also: Domcke, Gracia-Cely, Rodd, 2202.00695

$$\nabla_\mu F^{\mu\nu} = -J^\nu, \quad \nabla_{[\mu} F_{\nu\alpha]} = 0$$

$$\partial_\mu F^{\mu\nu} = -J_{\text{SM}}^\nu \left(1 + \frac{1}{2} h \right) + h_\alpha{}^\nu J_{\text{SM}}^\alpha - \partial_\mu \left[\frac{1}{2} h F^{\mu\nu} - h_\alpha{}^\mu F^{\alpha\nu} - h_\beta{}^\nu F^{\mu\beta} \right]$$

J_{eff}^ν

Static Haloscope Reach – Monochromatic source

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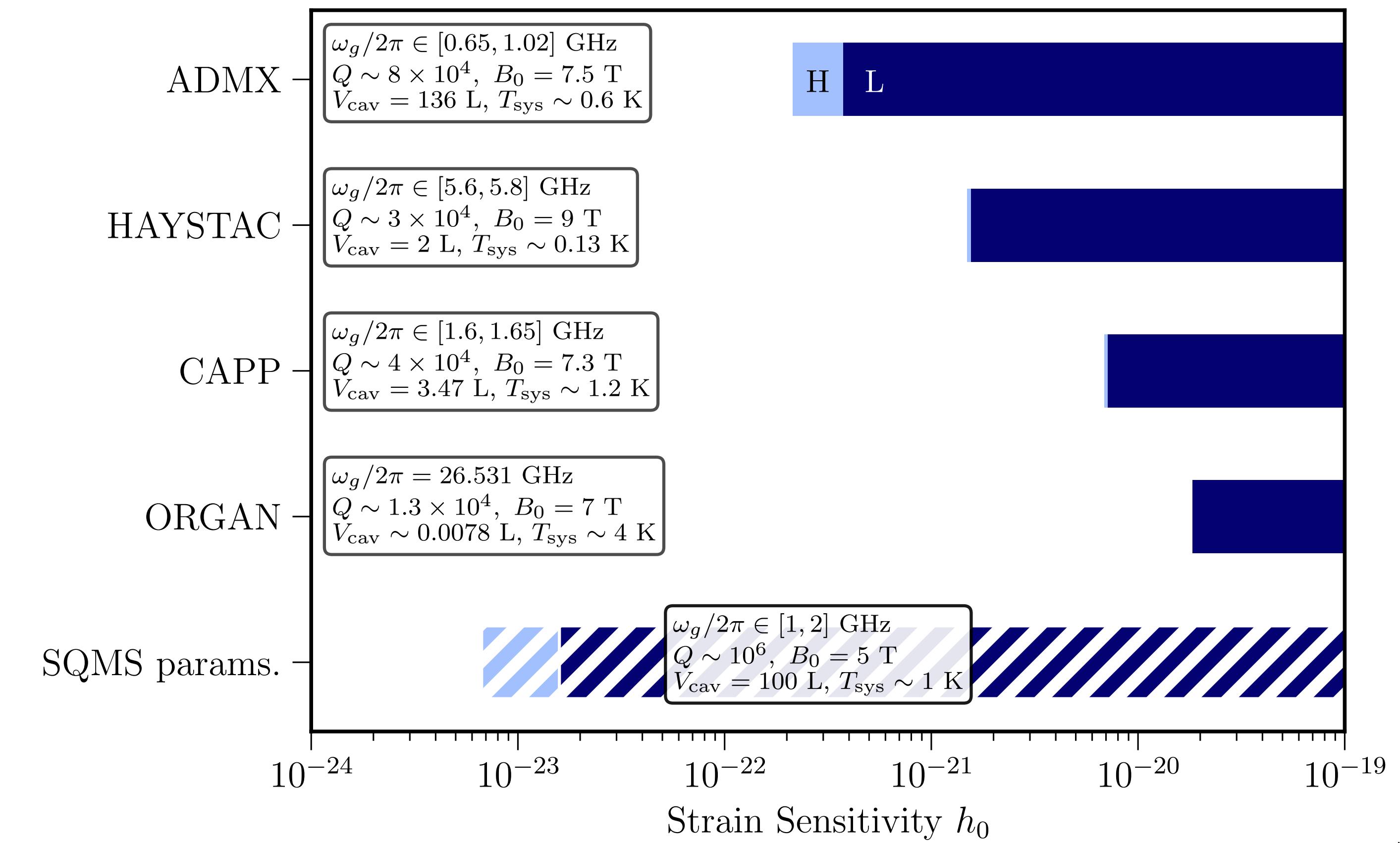
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Phys. Rev. D 105, 116011

hep-ph/2112.11465

**A. Berlin, D. Blas, R. T. D'Agnolo, SARE,
R. Harnik, Y. Kahn, J. Schütte-Engel**

Projected Sensitivities of Axion Experiments



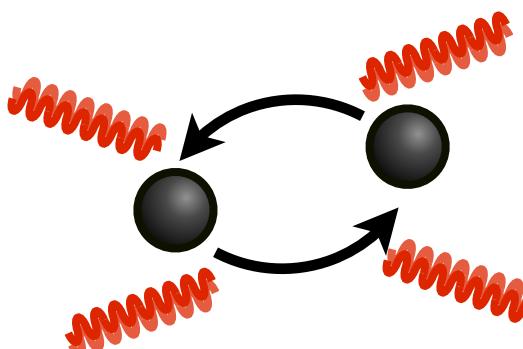
Static Haloscope Reach – Monochromatic source

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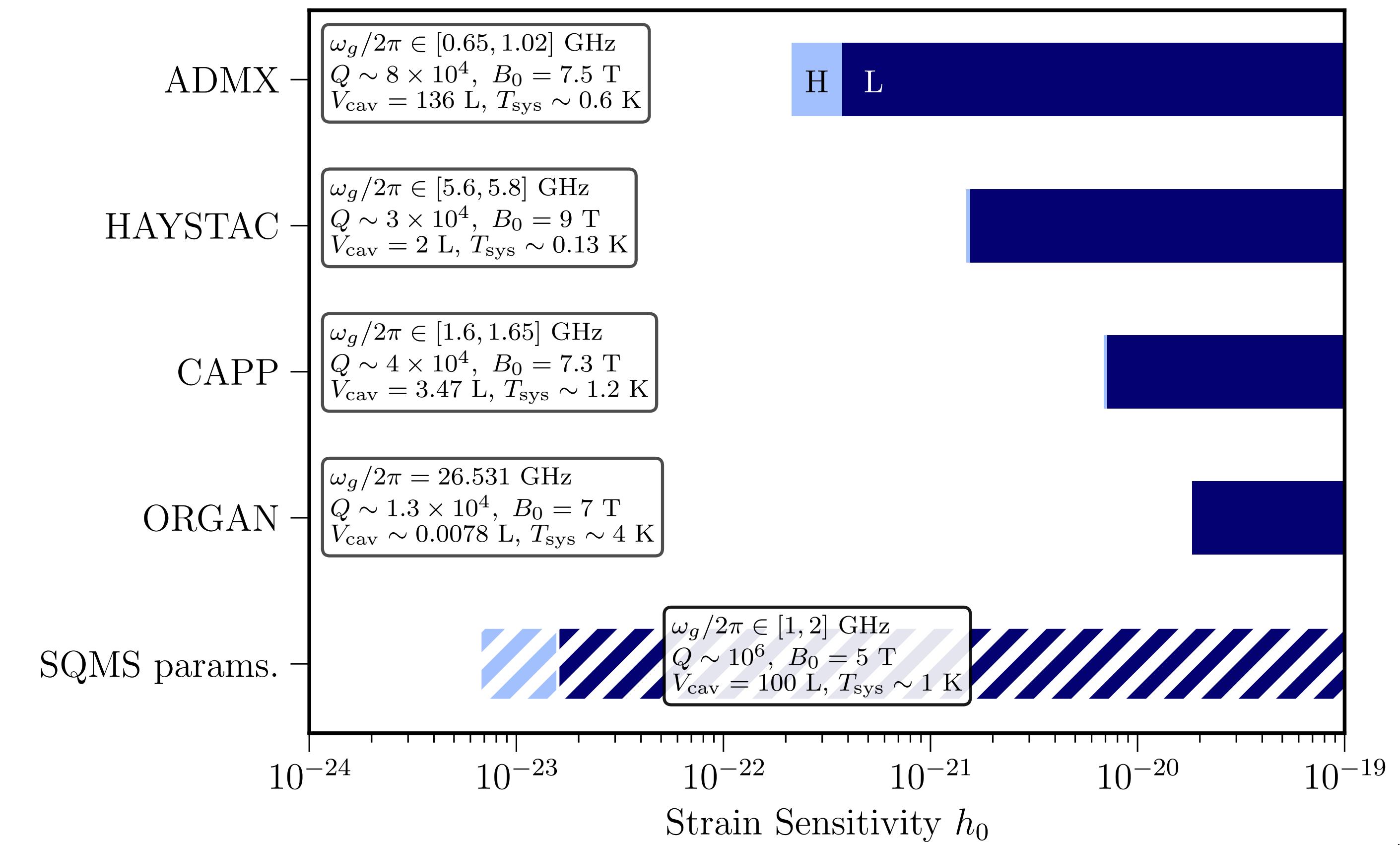
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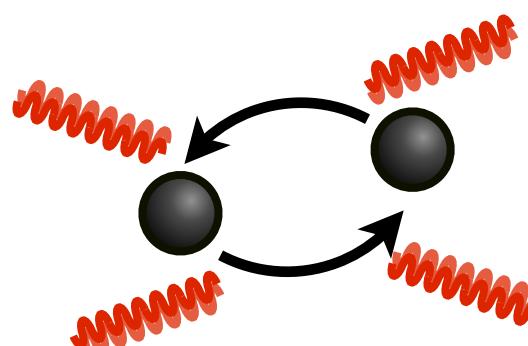
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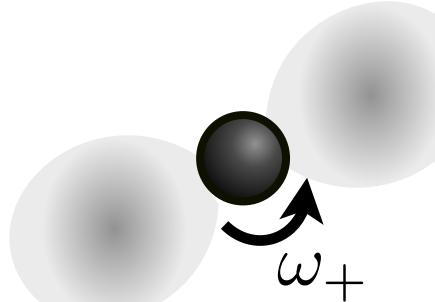
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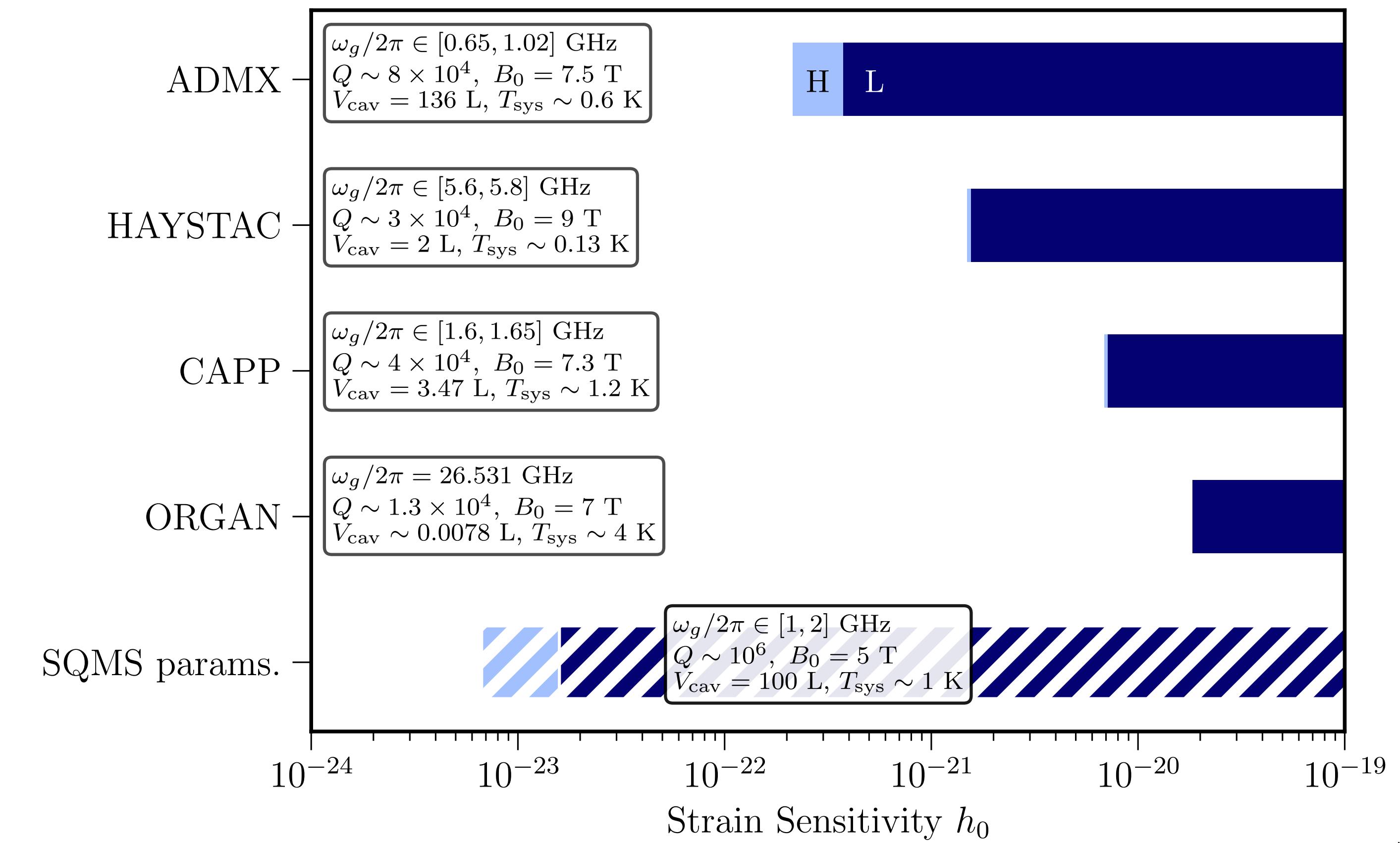


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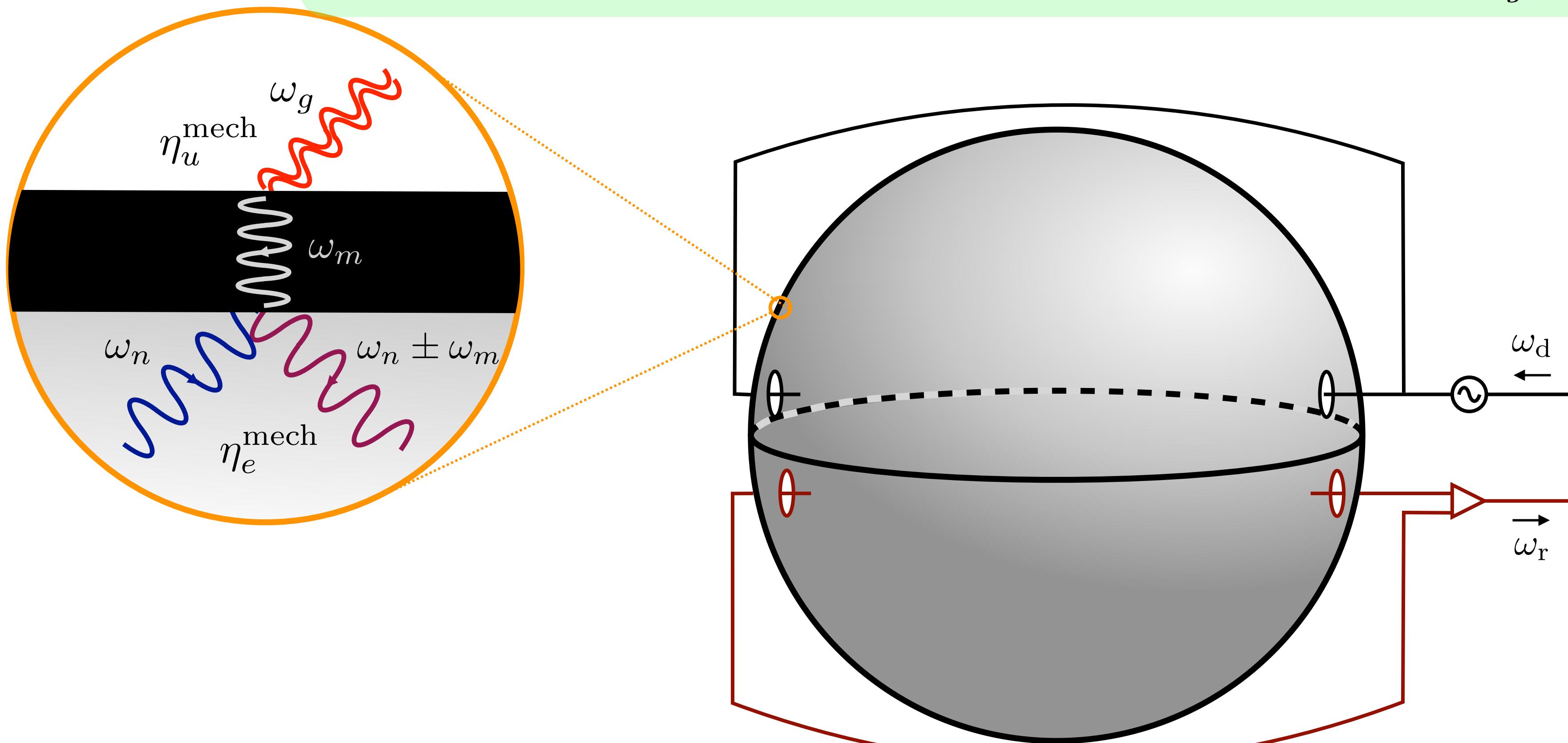
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Projected Sensitivities of Axion Experiments



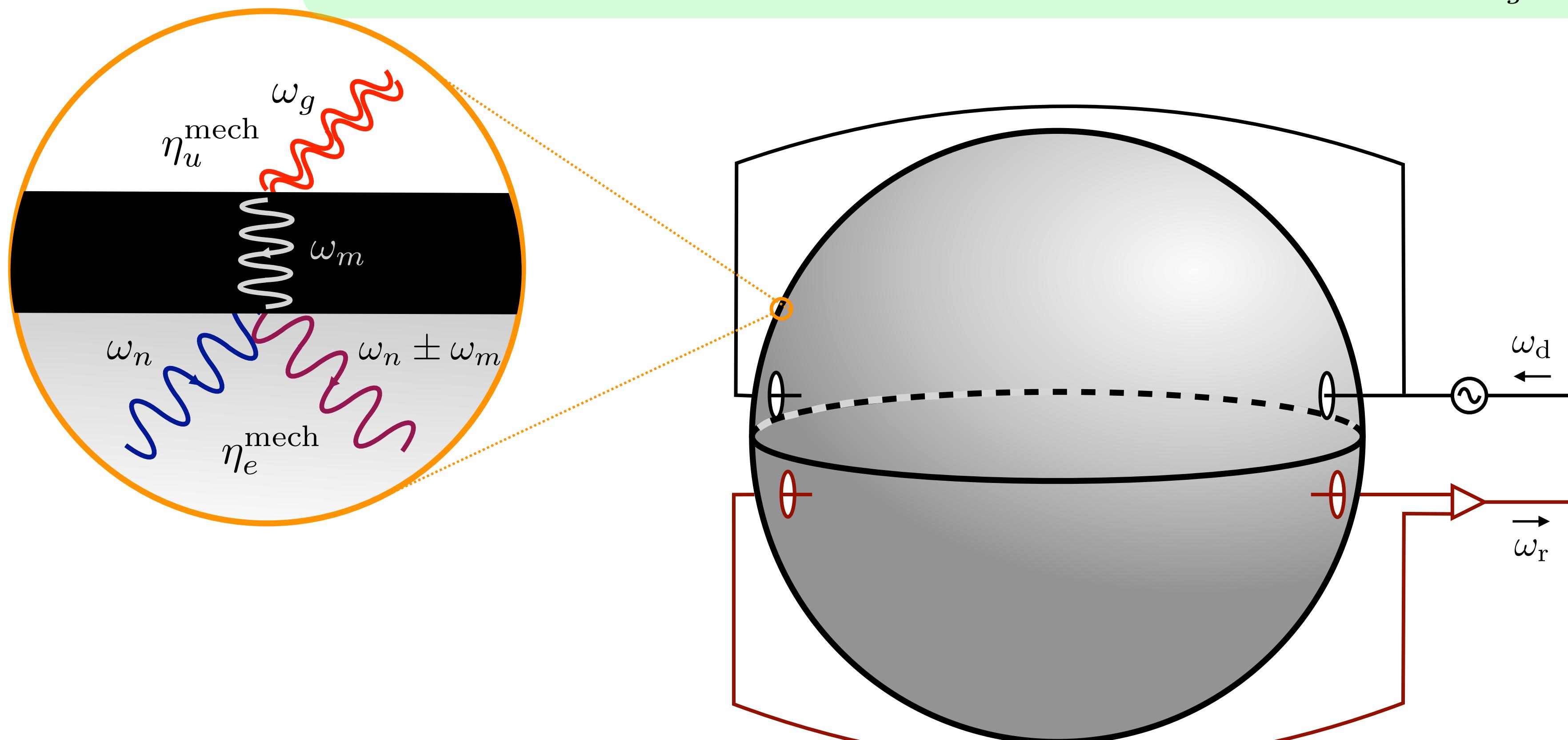
Heterodyne Gravitational Wave Signal: Mechanical

$$P_{\text{sig}} \simeq \frac{1}{16} Q_1 \omega_1 (|\eta_u^{\text{mech}}| |\eta_e^{\text{mech}}| h_0 E_0)^2 V_{\text{cav}} \times \begin{cases} Q_m^2 & \omega_g^2 - \omega_m^2 \ll \frac{\omega_m \omega_g}{Q_m} \\ \frac{\omega_g^4}{(\omega_g^2 - \omega_m^2)^2} & \omega_g^2 - \omega_m^2 \gg \frac{\omega_m \omega_g}{Q_m} \end{cases}$$



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If* thermal noise dominant

$$h_0^{\text{res}} \lesssim 10^{-27}$$

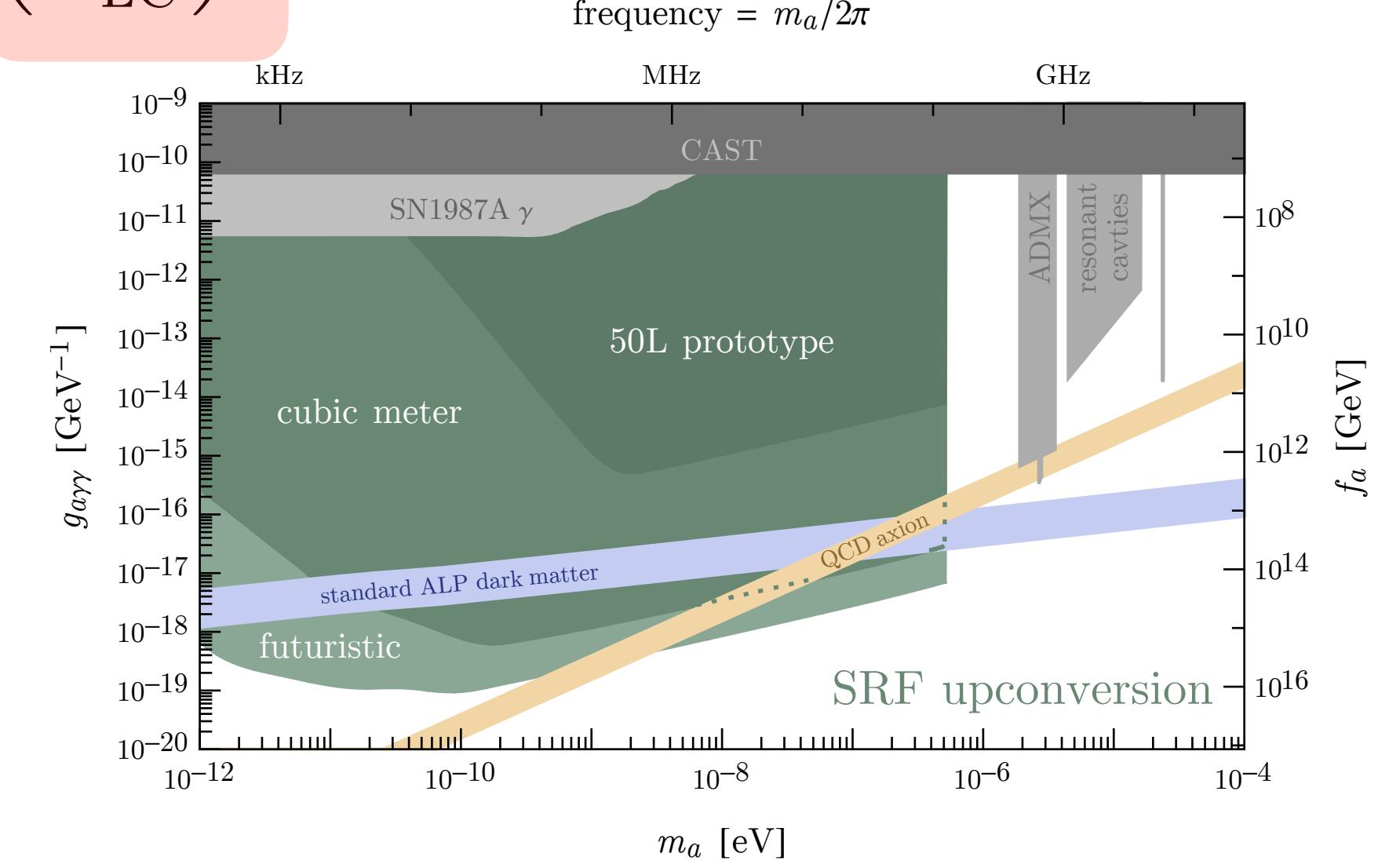
Outlook

- Signal *Oscillating background B-field: Radio-Frequency up-conversion approach*

$$\omega_{\text{sig}} = \omega_0 \pm m_a$$

Parametric gain for small axion masses vs. static searches

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- Outlook

Prototype design underway @ SLAC

Discussions ongoing w/ PBC @ CERN

Discussions ongoing w/ FNAL SQMS

Similar setup for Gravitational Waves – stay tuned