Heterodyne Detection of Axion Dark Matter in SRF Cavities

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SLAC LDRD Technical Document

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

Swiss National Science Foundation

High-level Summary

Radio-Frequency **up-conversion** approach

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

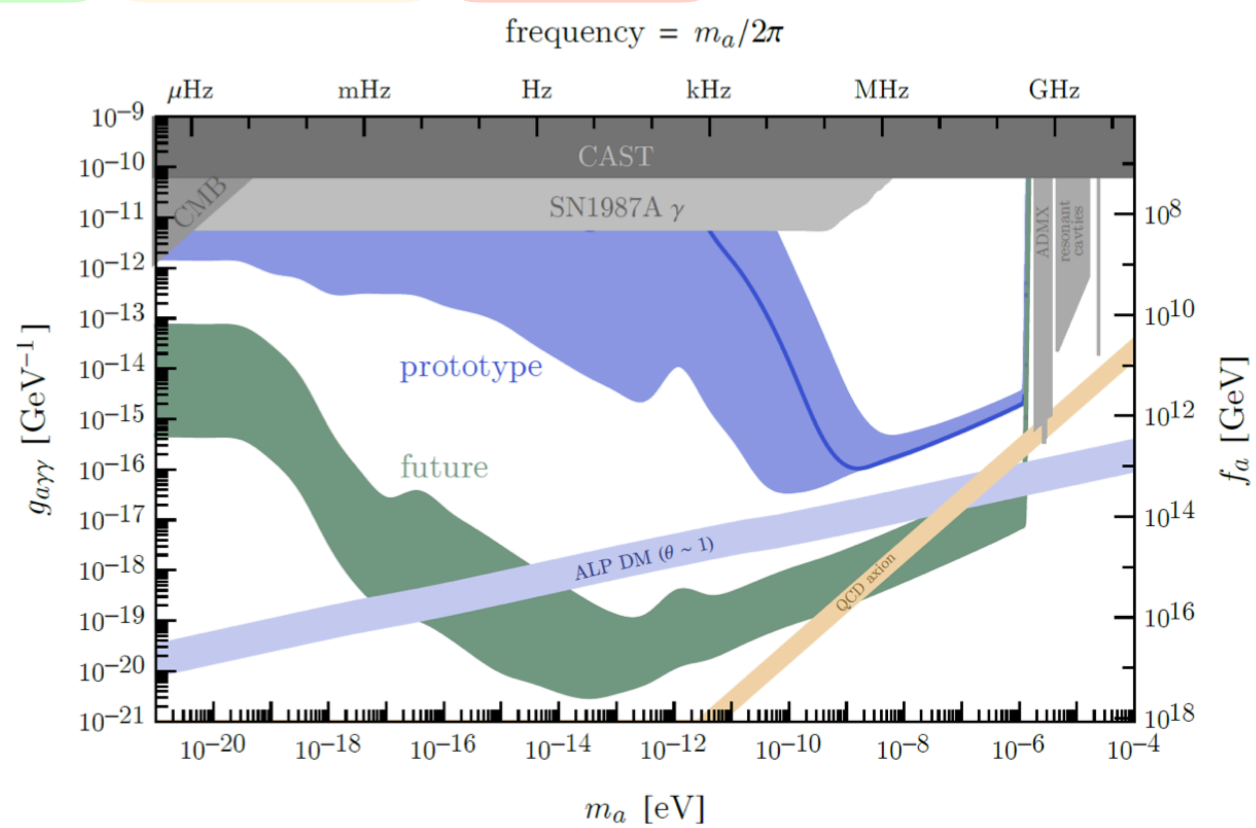
Parametric gain for small axion masses vs. static searches

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

Prototype design underway @ SLAC

Discussions ongoing w/ PBC @ CERN

Discussions ongoing w/ FNAL SQMS



Resonant Axion Searches

Presence of axion dark matter ~ effective current

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

Axion-induced magnetic field induces an E.M.F.: $\mathcal{E}_a \sim V^{2/3}\, \partial_t B_a$

$$P_{\rm sig}^{(\rm r)} \sim \frac{\mathcal{E}_a^2}{R}\, \min\left(1, \frac{\tau_a}{\tau_{\rm r}}\right) \sim \omega_{\rm sig}^2\, B_a^2 V\, \min\left(\frac{Q_{\rm r}}{\omega_{\rm sig}}, \frac{Q_a}{m_a}\right)$$

$1/\tau_a \sim m_a \langle v^2 \rangle$ $\qquad$ $1/\tau_{\rm r} \sim \omega_{\rm sig}/Q_{\rm r}$ $\qquad$ $Q_a \sim 1/\langle v^2 \rangle$

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

WARNING

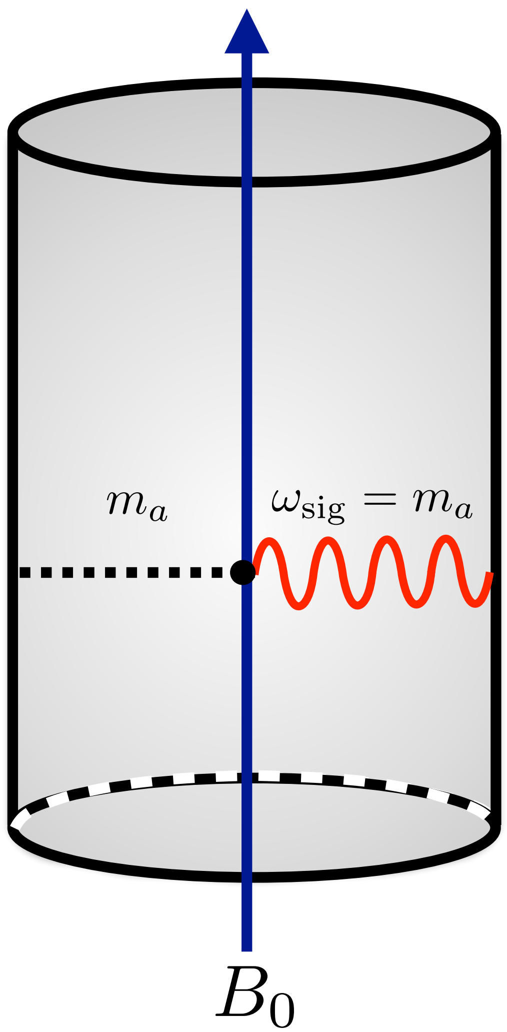
QUANTITIES OFTEN LINKED

Resonant Approaches

Static-field Haloscope:

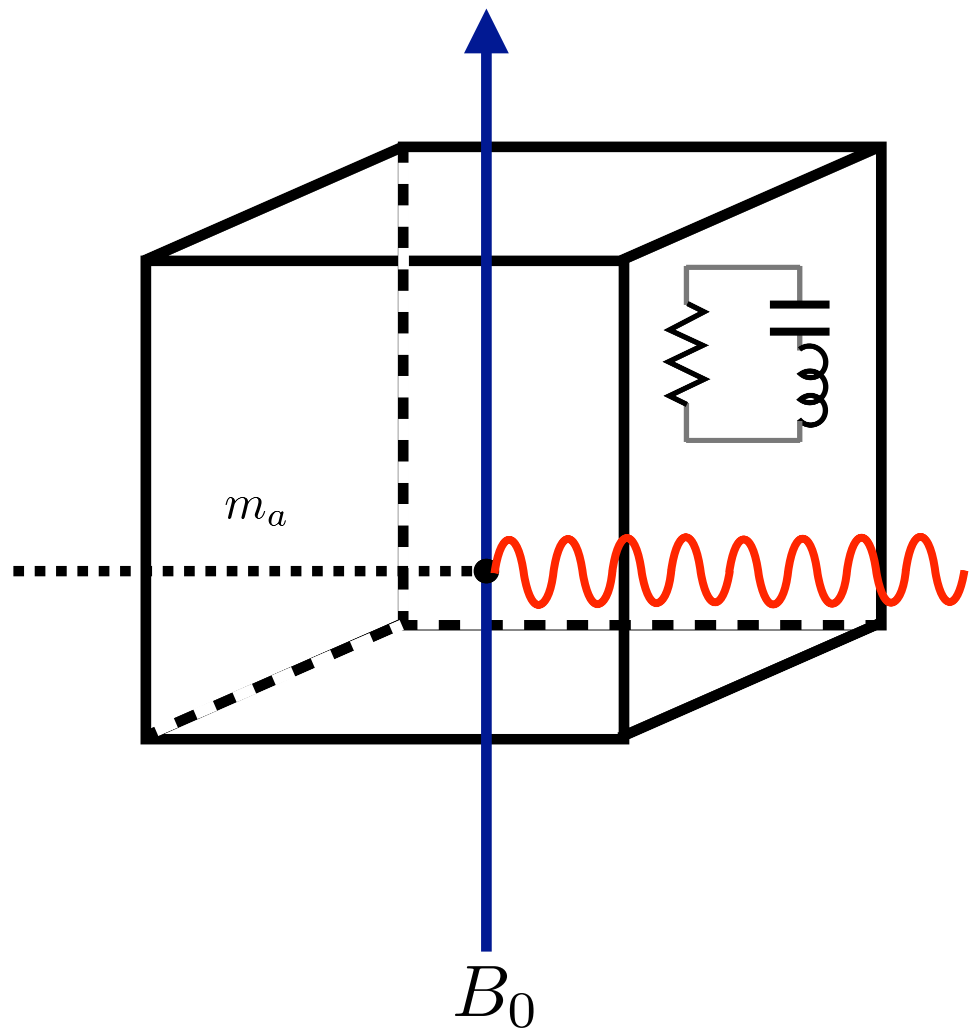
e.g. ADMX

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



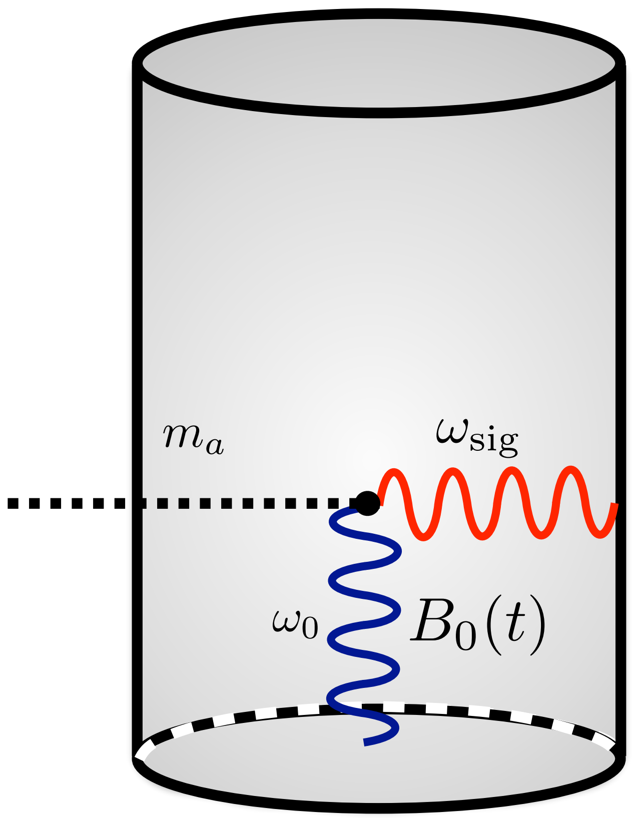
LC Resonator:

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



Heterodyne Resonator:

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



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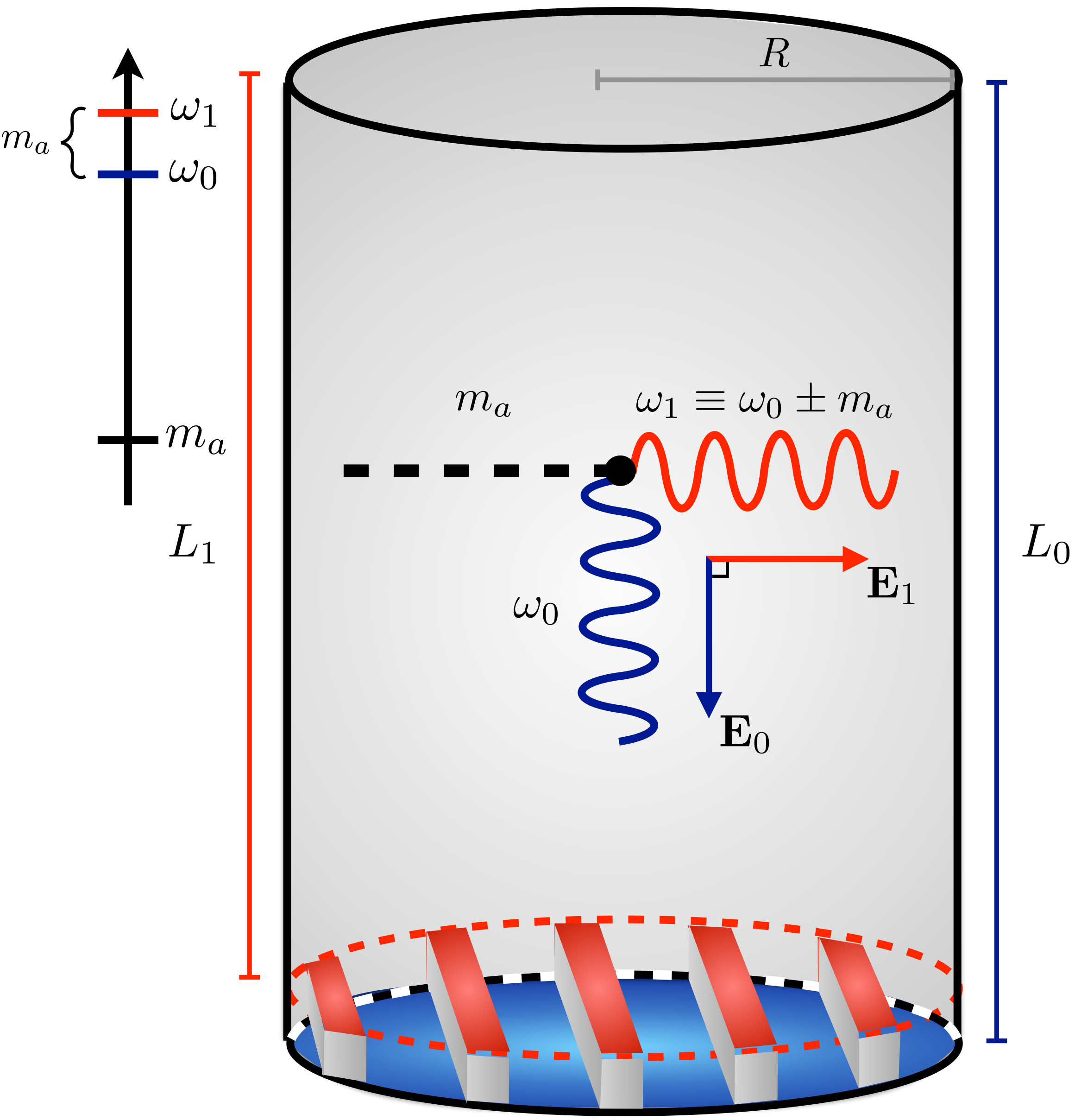
Also: R. Lasenby hep-ph/1912.11467

Axion Resonant Frequency Conversion



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Superconducting RF Cavity

$$\omega_0 = \omega_1 \sim \mathrm{GHz}$$

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

Tunability:

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

$\delta\omega \gtrsim \mathrm{MHz}$ fins

Degeneracy:

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

Broadband:
hep-ph/2007.15656
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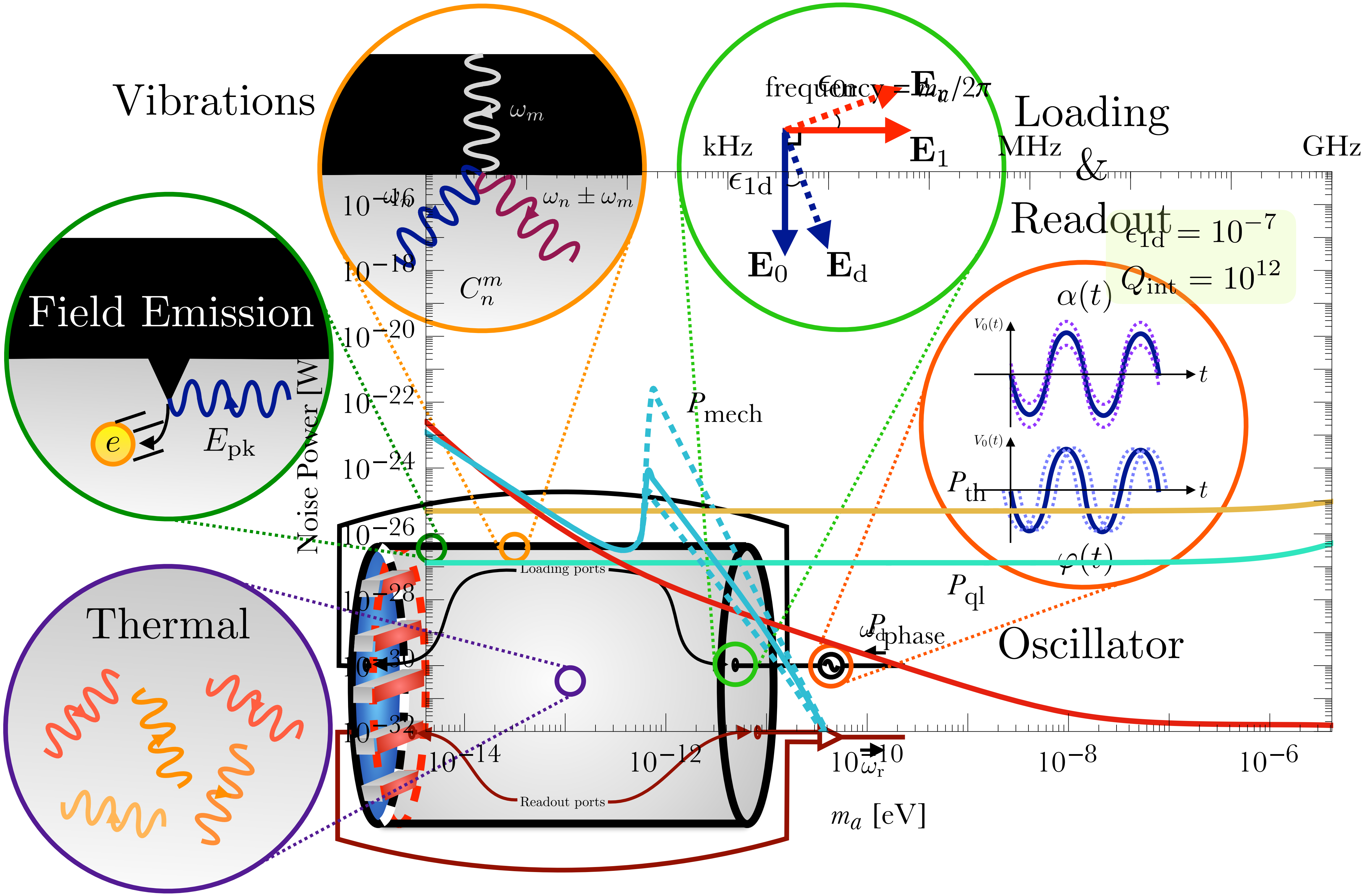
All Noise Sources



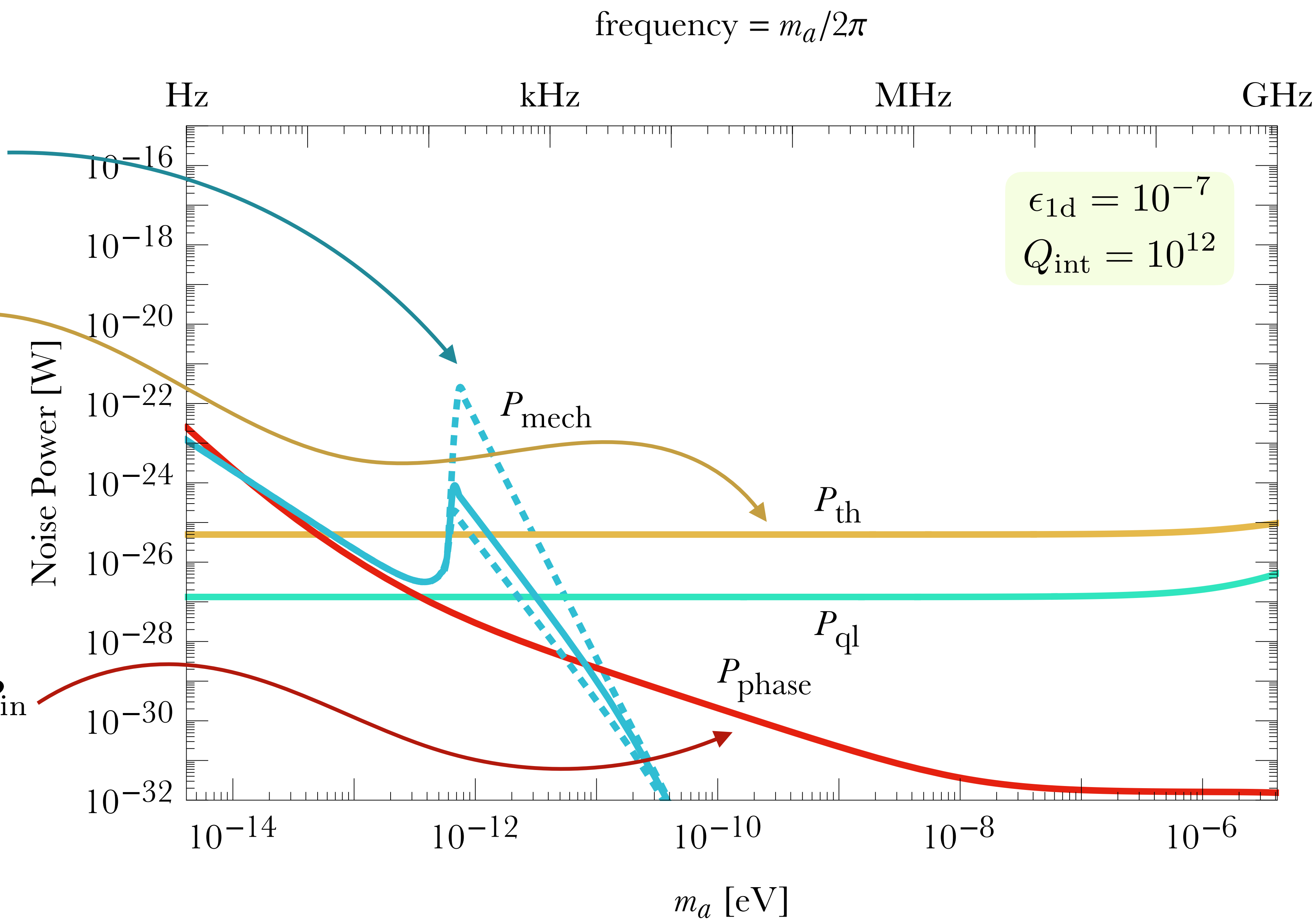
All Noise Sources

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

fractional wall disp. δ

$$P_{\rm th} \sim T \frac{\omega_1}{Q_{\rm int}}$$

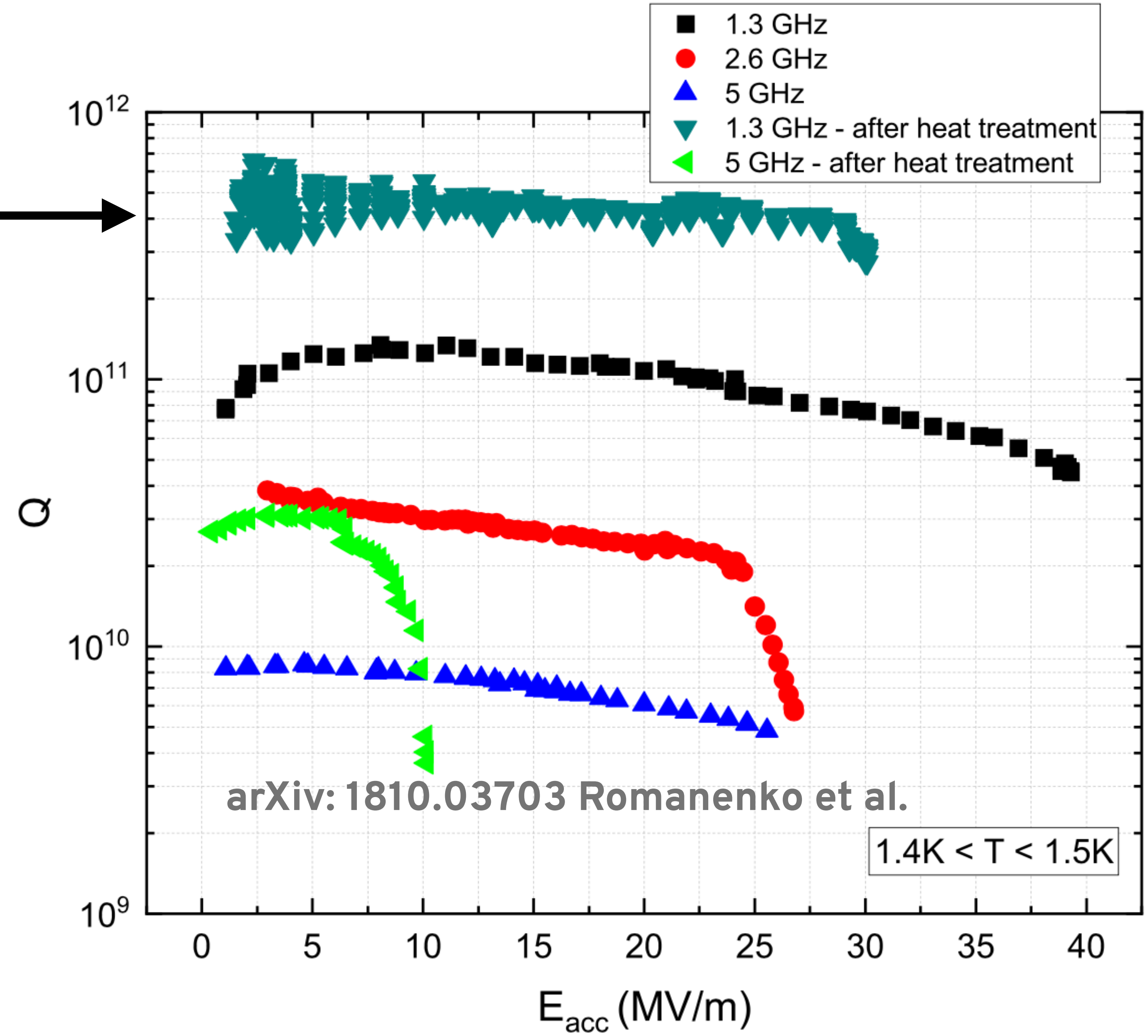
$$P_{\rm phase} \sim \epsilon_{\rm 1d}^2 S_\varphi(m_a) \frac{\omega_1}{Q_{\rm int}} P_{\rm in}$$



Experimental precedent

Q-factor & B-field:

Q~4x10[11] @ B~0.1T →



Experimental precedent

Mode rejection:

$\mathcal{E} = 10^{-7}$ achieved

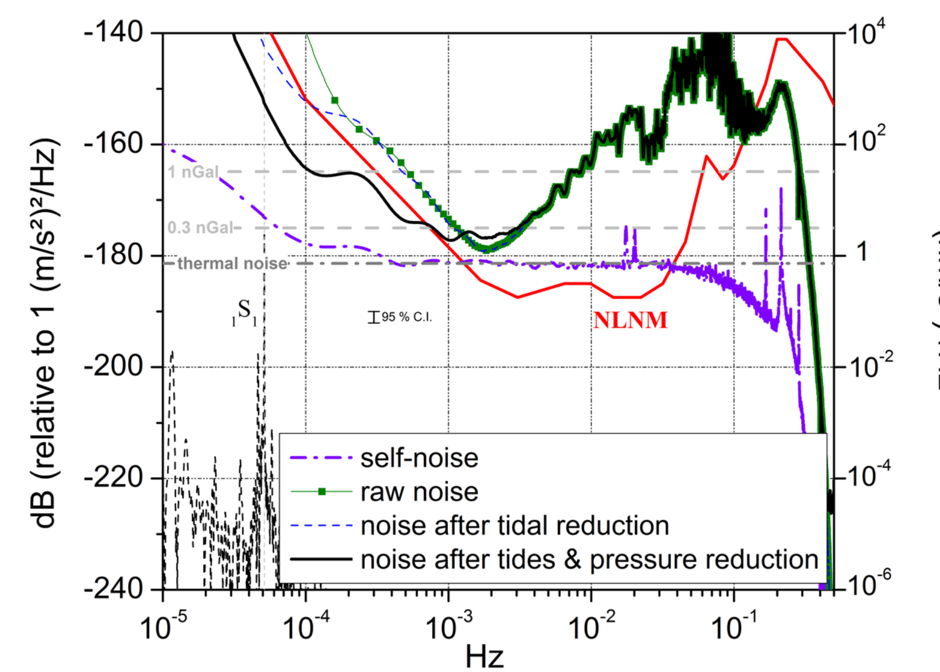
gr-qc/0502054 Ballantini et al.

physics/0004031 Bernard, Gemme, Parodi, Picasso

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:

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

Thermal noise dominated:

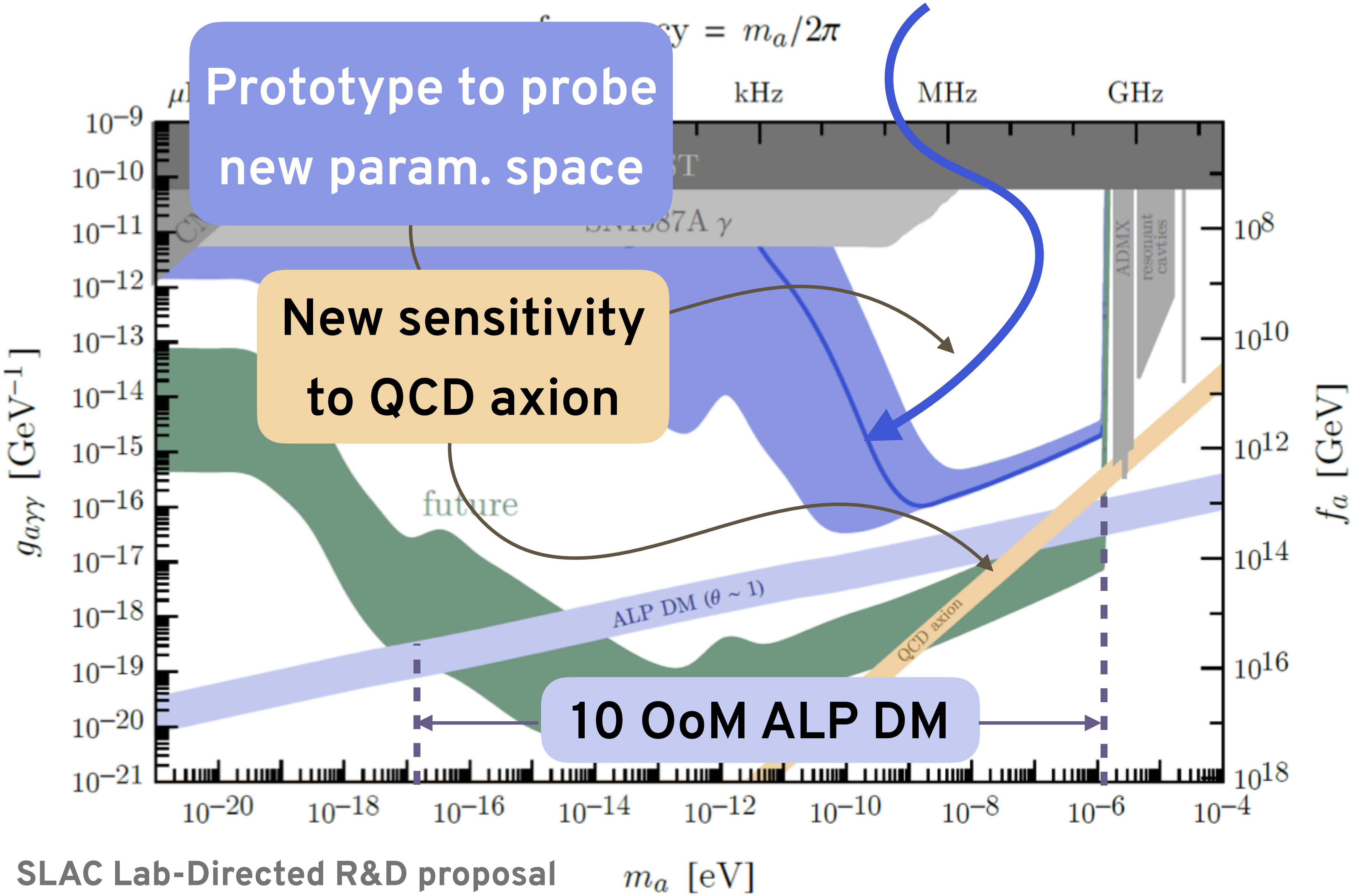
$$\mathrm{SNR} \sim \frac{\rho_{\rm DM}\, V}{m_a\, \omega_1} \left(g_{a\gamma\gamma}\, \eta_{10}\, B_0\right)^2 \left(\frac{Q_a\, Q_{\rm int}\, t_e}{T} \right)^{1/2}$$

Comparison with LC resonator:

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

Prototype R&D **FUNDED** at SLAC

$$L = 50\,\mathrm{cm},\ \ R = 14.7\,\mathrm{cm},\ \ Q_{\mathrm{int}} = 7\times10^{10},\ \ U = 72\,\mathrm{J}$$



SLAC Lab-Directed R&D proposal

Outlook

Radio-Frequency **up-conversion** approach

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

Parametric gain for small axion masses vs. LC Resonator

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

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