Heterodyne Detection of Axion Dark Matter in an RF Cavity

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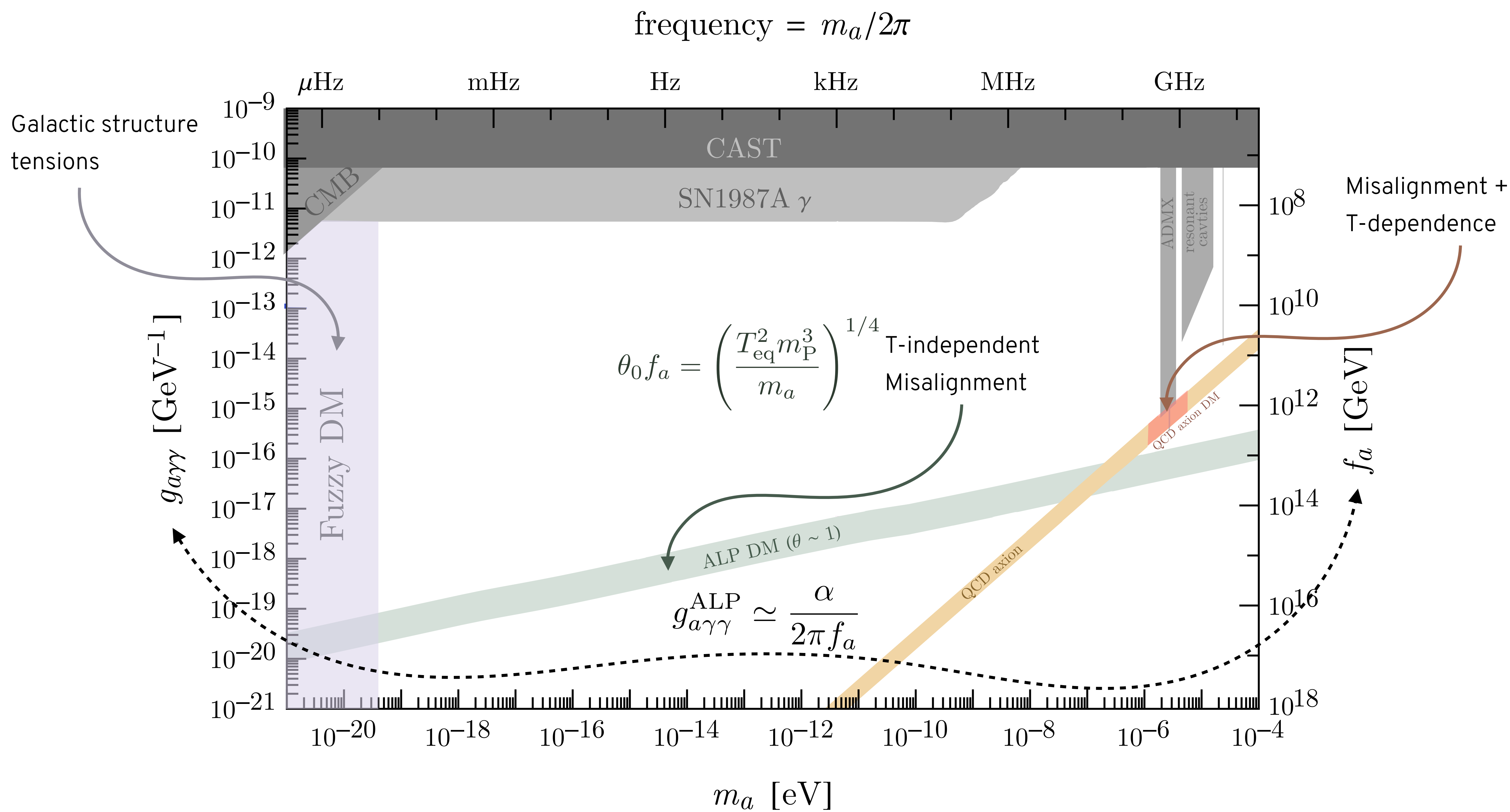
Axions as Dark Matter: Targets



Resonant Axion Searches

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

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

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

Maxwell's new and improved Equations

Axion dark matter: $a(t) \simeq \frac{\sqrt{2\rho_{\rm DM}}}{m_a}\cos(m_a t + \varphi)$

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

Resonant Axion Searches

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

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

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

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

WARNING

QUANTITIES OFTEN LINKED

Cavities, LC: $B_a \sim J_{\rm eff} V^{1/3}$

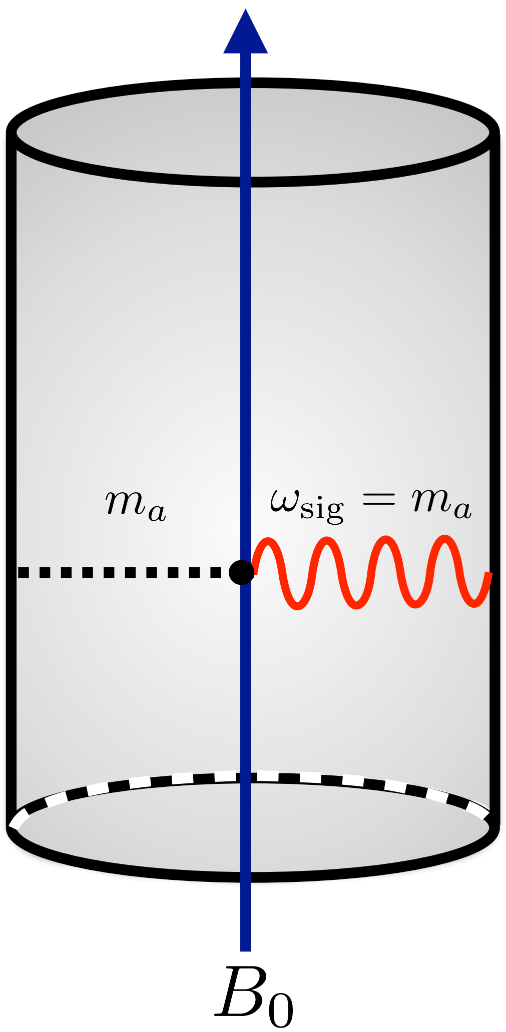
Cavities: $\omega_{\rm sig} \sim V^{-1/3}$

Resonant Approaches

Static-field Haloscope:

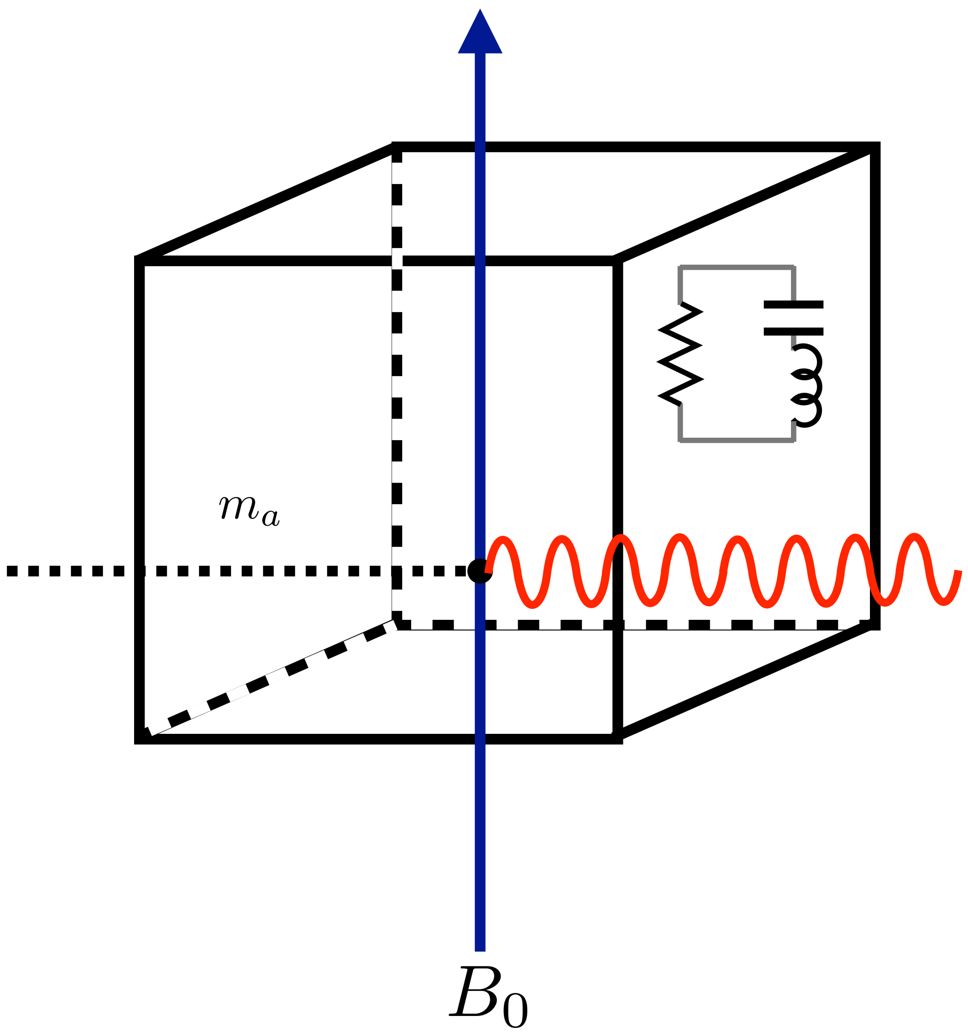
e.g. ADMX

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



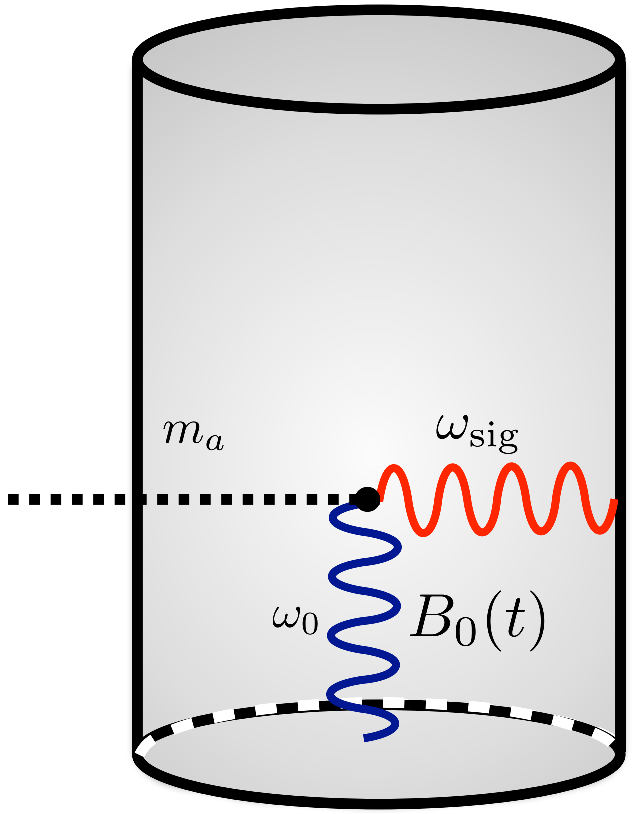
LC Resonator:

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



Heterodyne Resonator:

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



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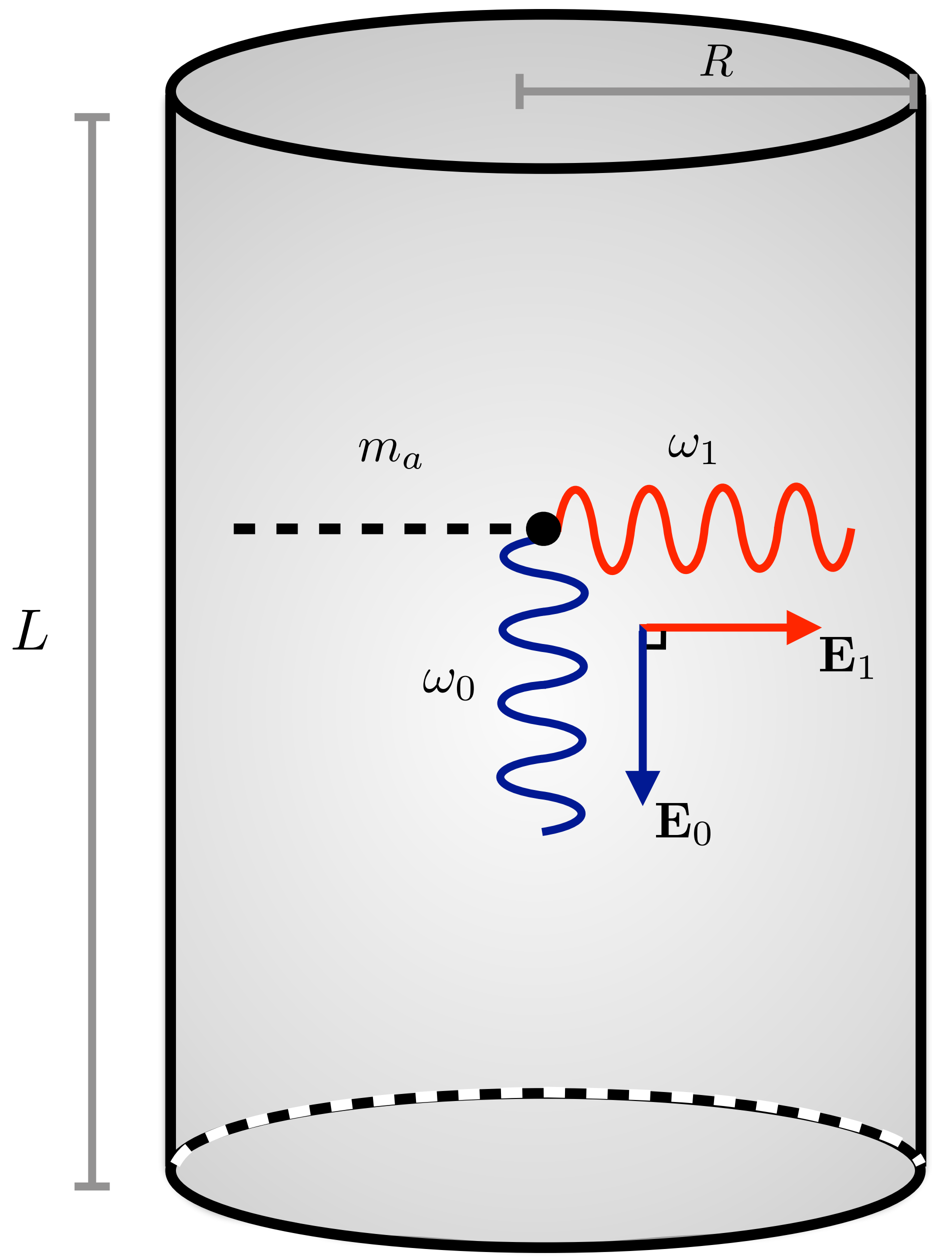
Also: R. Lasenby hep-ph/1912.11467

Allowed mode transitions



Cylindrical cavity modes: TM_{mnp} TE_{mnp}

Axion allowed transitions: $\eta \propto \int_V \mathbf{E}_1^* \cdot \mathbf{B}_0 \neq 0$

MAXIMISE

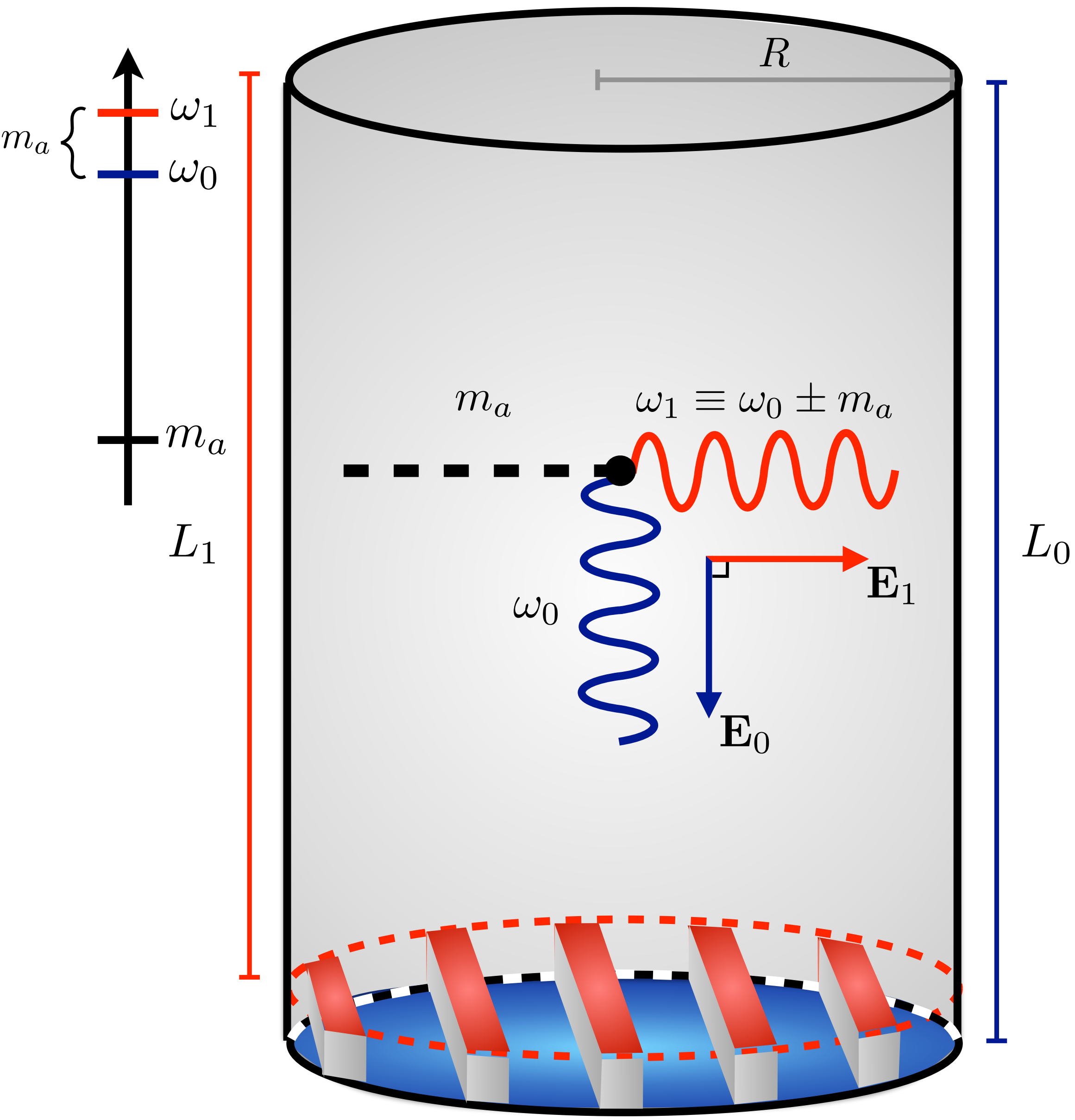
spin-0: $m_0 = m_1$

pseudoscalar: $p_0 + p_1 = \mathrm{odd}$

TM_{mnp}	$\rightleftharpoons$	TM_{mnp}
$\upharpoonleft\downharpoonright$		
TE_{mnp}	$\rightleftharpoons$	TE_{mnp}

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

Scanning Axion Resonant Frequency Conversion



Superconducting RF Cavity

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

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

Tunability:

$\delta\omega \lesssim$ MHz piezos

$\delta\omega \gtrsim$ MHz fins

Degeneracy:

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

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Broadband:
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Axion Signal

Signal Power Spectral Density (PSD):

$$S_{\rm sig}(\omega) = \frac{\omega_1}{Q_1}\,(g_{a\gamma\gamma}\,\eta_{10}\,B_0)^2\,V\,\frac{\omega^2}{(\omega^2-\omega_1^2)^2+(\omega\,\omega_1/Q_1)^2}\int\frac{d\omega'}{(2\pi)^2}\,(\omega'-\omega)^2\,S_{b_0}(\omega')\,S_a(\omega-\omega')$$

Axion PSD:

$$\langle a(t)^2\rangle = \frac{1}{(2\pi)^2}\int d\omega\;S_a(\omega) = \frac{\rho_{\rm DM}}{m_a^2}$$

Background magnetic field PSD: To be discussed further...

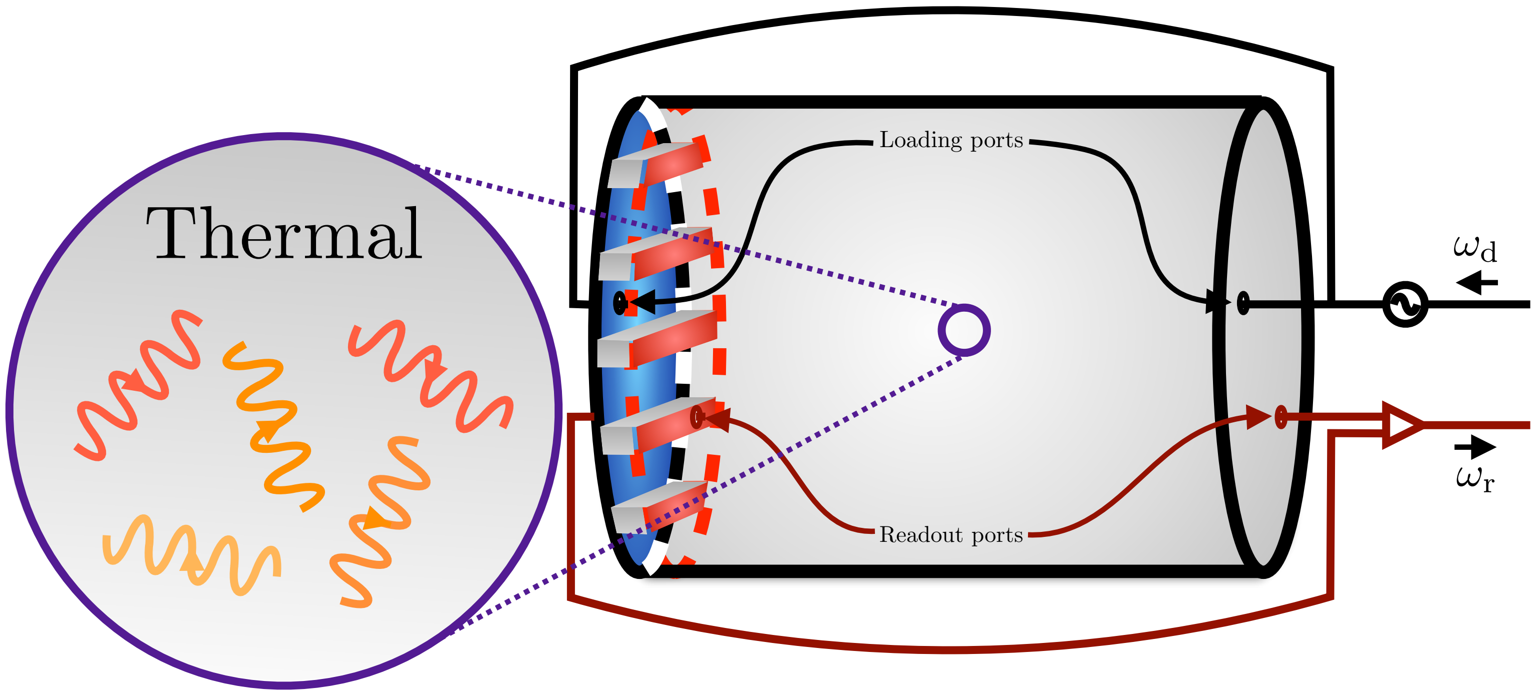
$$S_{b_i}(\omega) = \pi^2\Big(\delta(\omega-\omega_i)+\delta(\omega+\omega_i)\Big) + S_{b_i}^{(\rm phase)} + S_{b_i}^{(\rm mech)}$$

NB: $B_i \equiv \sqrt{\frac{1}{V_{\rm cav}}\int_{V_{\rm cav}}|\mathbf{B}_i(x)|^2}$ $\qquad \mathbf{B}_i(x,t) = \mathbf{B}_i(x)\,b_i(t)$

Standard Noise Sources: Thermal Noise

Power Spectral Density:

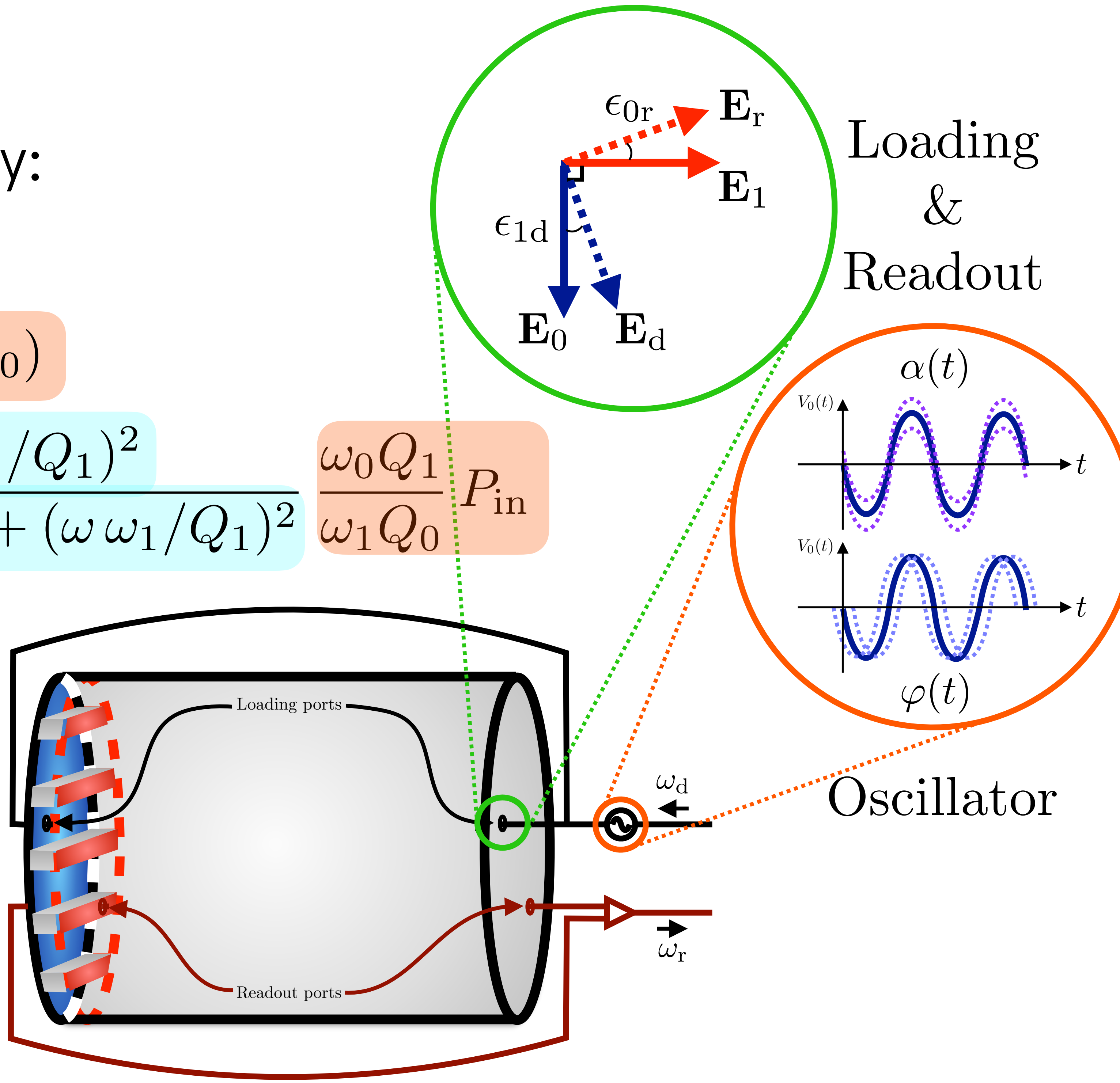
$$S_{\rm th}(\omega) = \frac{Q_1}{Q_{\rm int}} \frac{4\pi T \, (\omega\,\omega_1/Q_1)^2}{(\omega^2-\omega_1^2)^2 + (\omega\,\omega_1/Q_1)^2}$$



Non-standard Noise Sources: Phase Noise

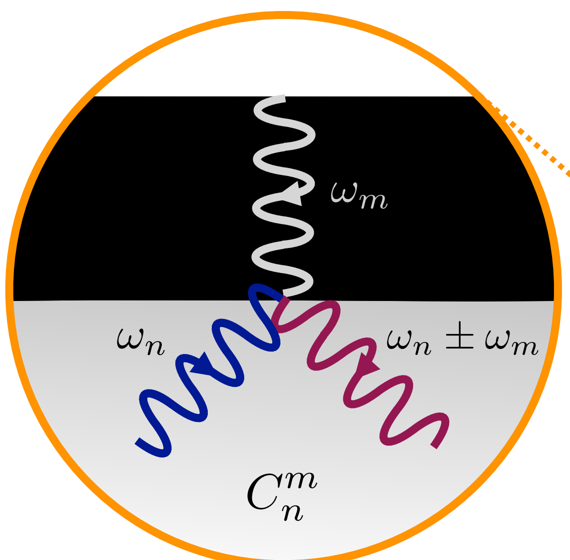
Power Spectral Density:

$$S_{\rm phase}(\omega) \simeq \frac{1}{2}\,\epsilon_{\rm 1d}^2\, S_\varphi(\omega-\omega_0) \times \frac{(\omega\,\omega_1/Q_1)^2}{(\omega^2-\omega_1^2)^2+(\omega\,\omega_1/Q_1)^2}\,\frac{\omega_0 Q_1}{\omega_1 Q_0} P_{\rm in}$$



Non-standard Noise Sources: Wall Vibrations

Vibrations

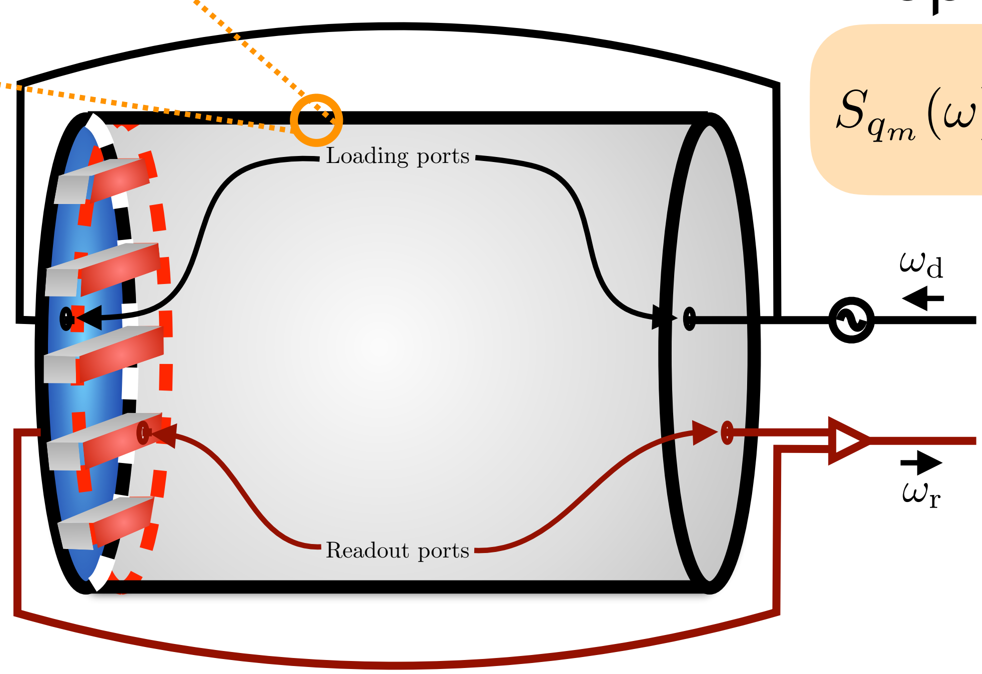


Power Spectral Density:

$$S_{\rm mech}(\omega) \simeq \frac{\epsilon_{1d}^2}{4} \frac{\omega_0}{Q_0} P_{\rm in} \times \sum_{n=0,1} \frac{\left(S_{q_m}(\omega-\omega_0)/V^{2/3}\right)(\omega_n/Q_n)\,\omega_n^4\,\omega^2}{\left[(\omega^2-\omega_n^2)^2+(\omega\,\omega_n/Q_n)^2\right]\left[(\omega_0^2-\omega_n^2)^2+(\omega_0\,\omega_n/Q_n)^2\right]}$$

Displacement PSD:

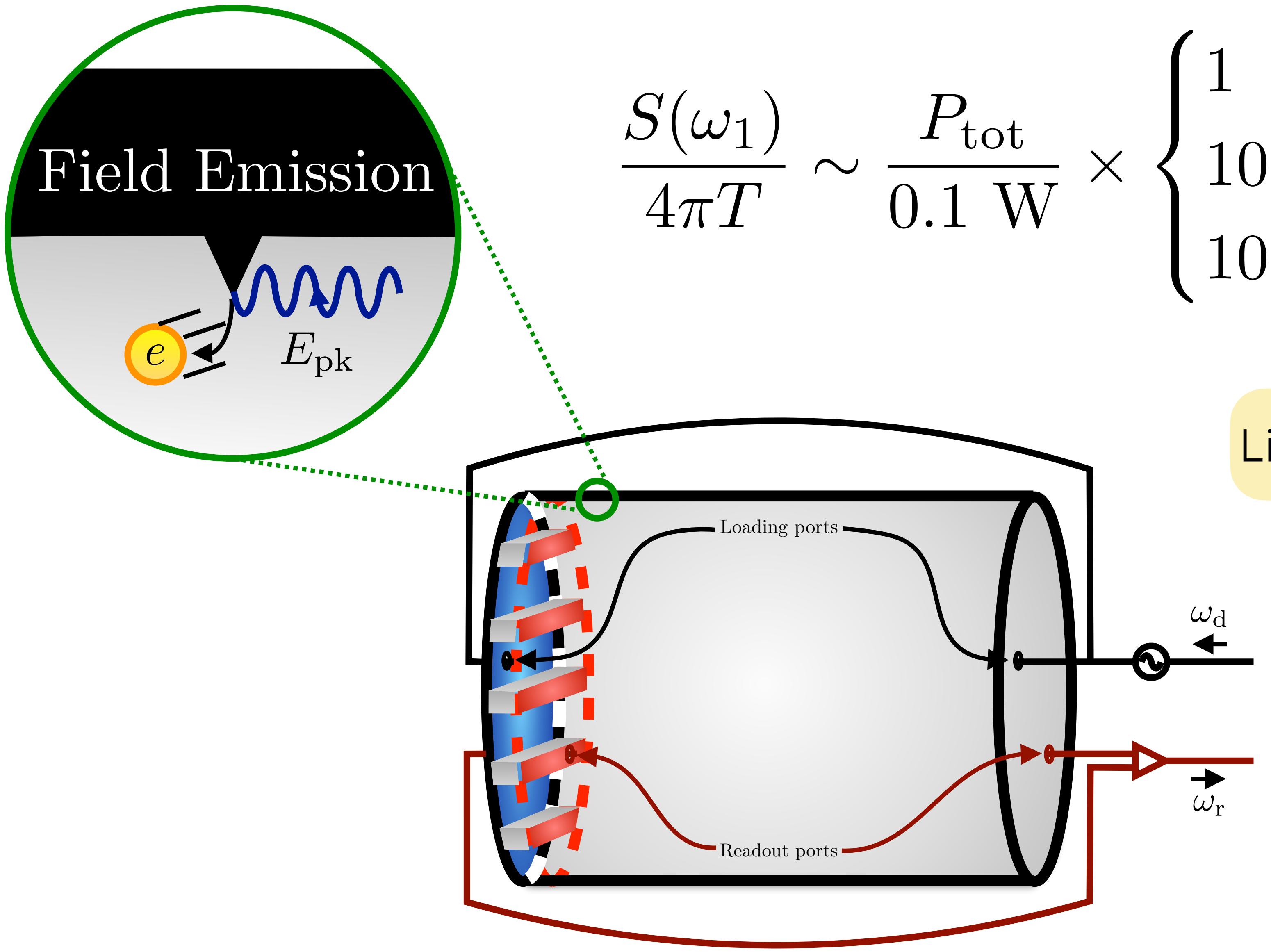
$$S_{q_m}(\omega) \simeq \frac{1}{M^2} \frac{S_{f_m}(\omega)}{(\omega^2-\omega_m^2)^2+(\omega_m\omega/Q_m)^2}$$



Non-standard Noise Sources: Field Emission

Power Spectral Density:

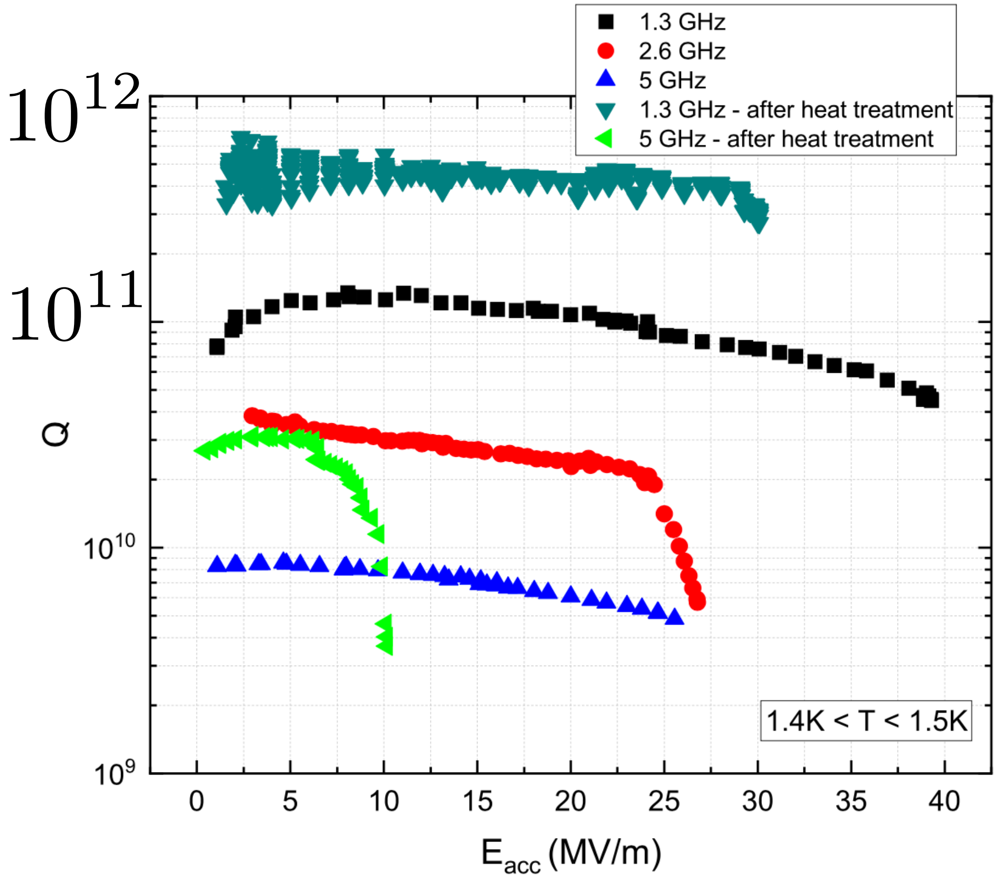
$$\frac{S(\omega_1)}{4\pi T} \sim \frac{P_{\rm tot}}{0.1\ \rm W} \times \begin{cases} 1 & \text{synchrotron} \\ 10^{-6} & \text{transition} \\ 10^{-5} & \text{Bremsstrahlung}\,, \end{cases}$$



Limits max B-field ~ 0.2T

Experimental precedent

Q-factor & B-field:



arXiv: 1810.03703 Romanenko et al.

Mode rejection:

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)

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:

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

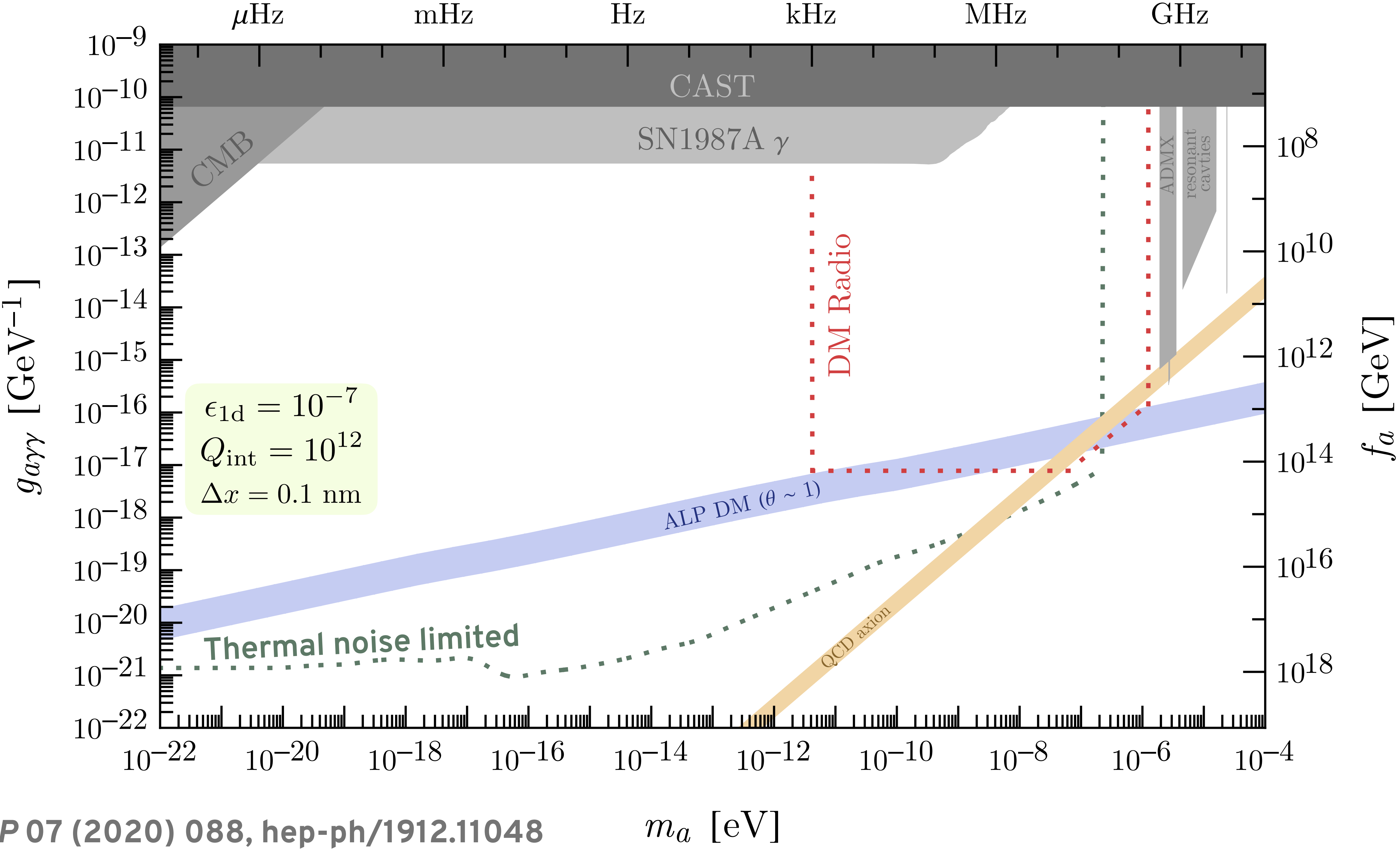
Comparison with LC resonator:

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

Resonant Axion Resonant Frequency Conversion

B = 0.2 T, T = 2K, ω_0 = 1 GHz

frequency $= m_a/2\pi$



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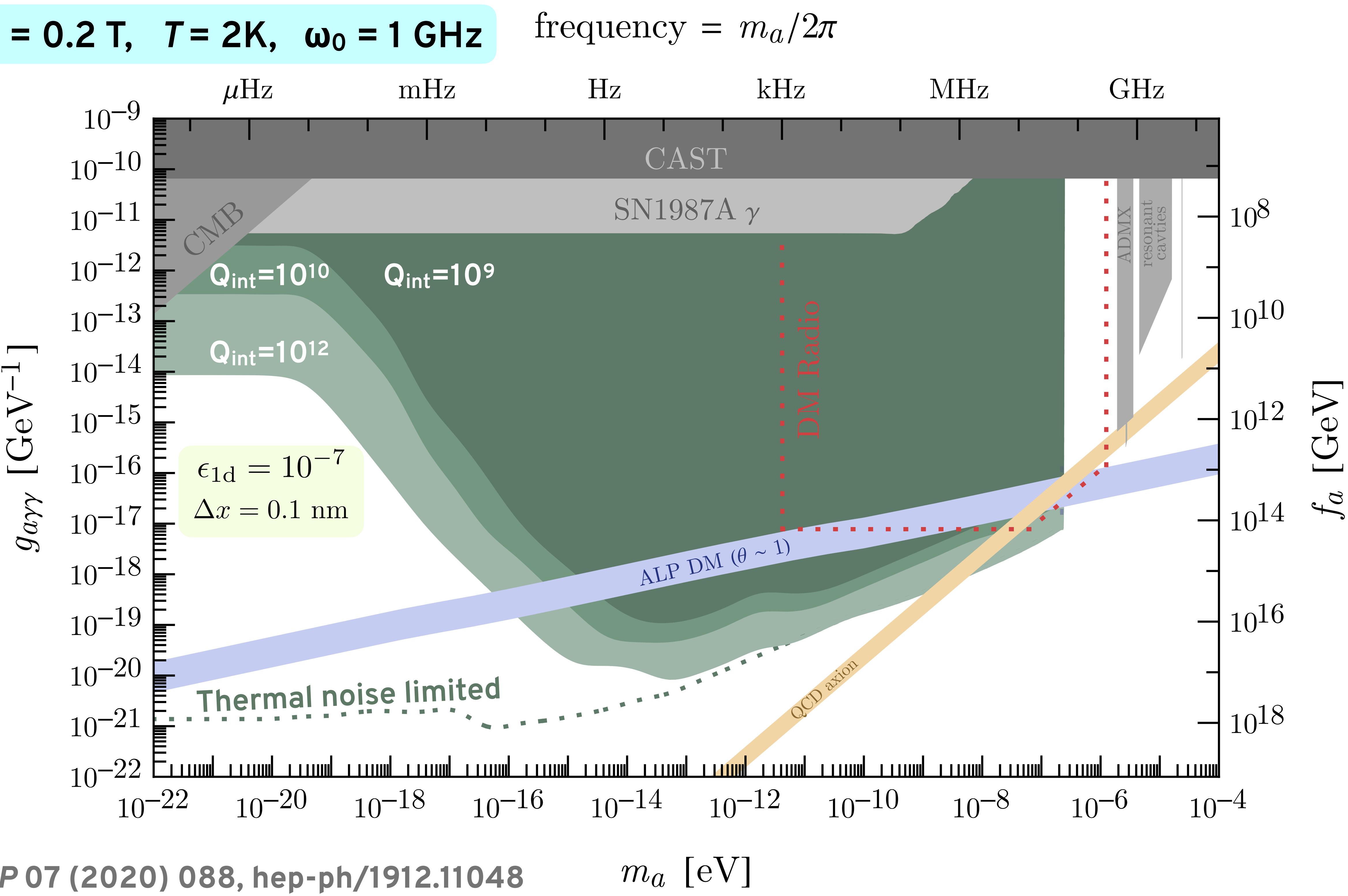
Resonant parameter variations: *Q-factor*

B = 0.2 T, T = 2K, ω_0 = 1 GHz



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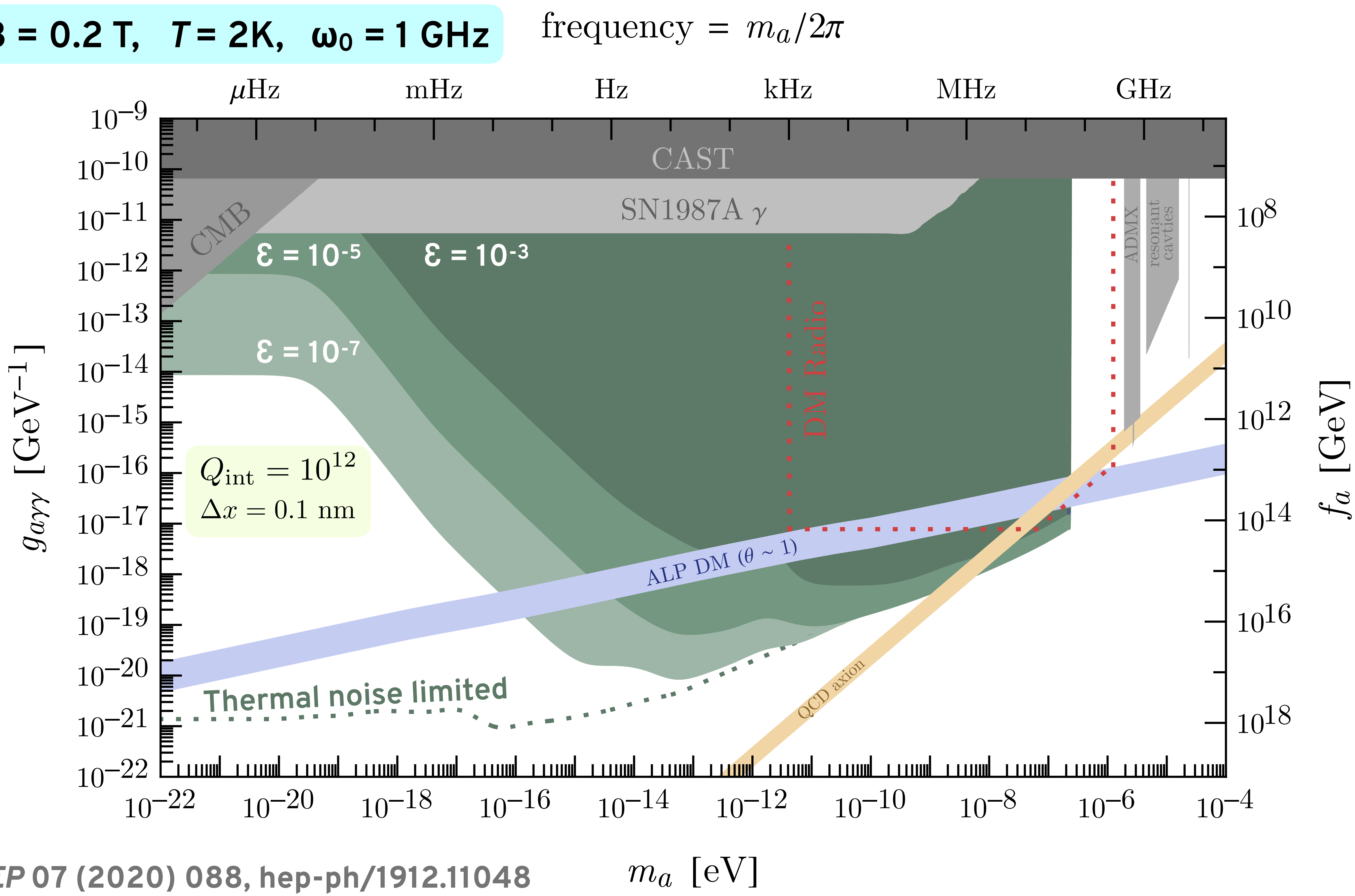
Resonant parameter variations: *mode rejection*

B = 0.2 T, T = 2K, ω_0 = 1 GHz



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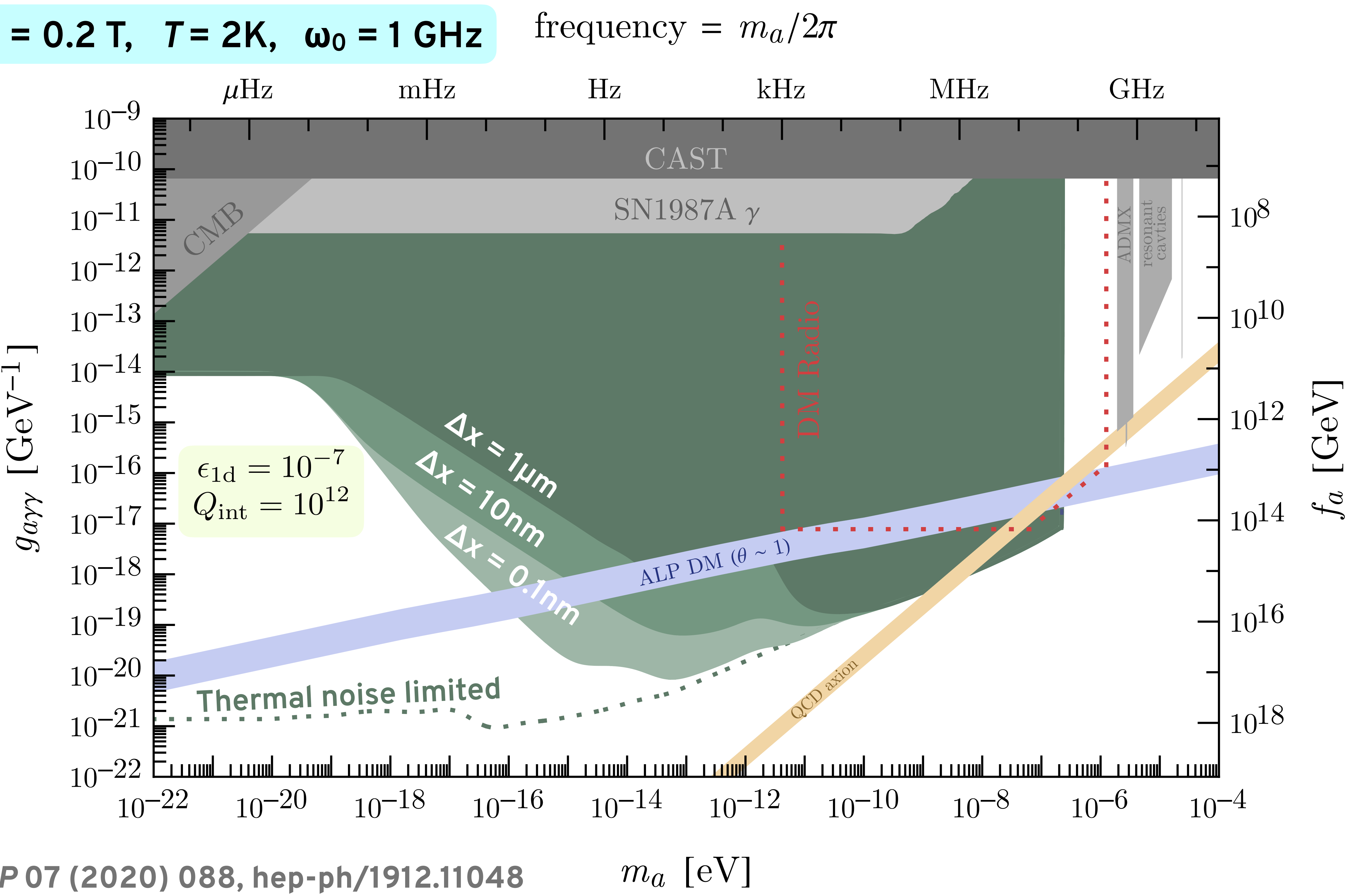
Resonant parameter variations: *mode rejection*

B = 0.2 T, *T* = 2K, ω_0 = 1 GHz



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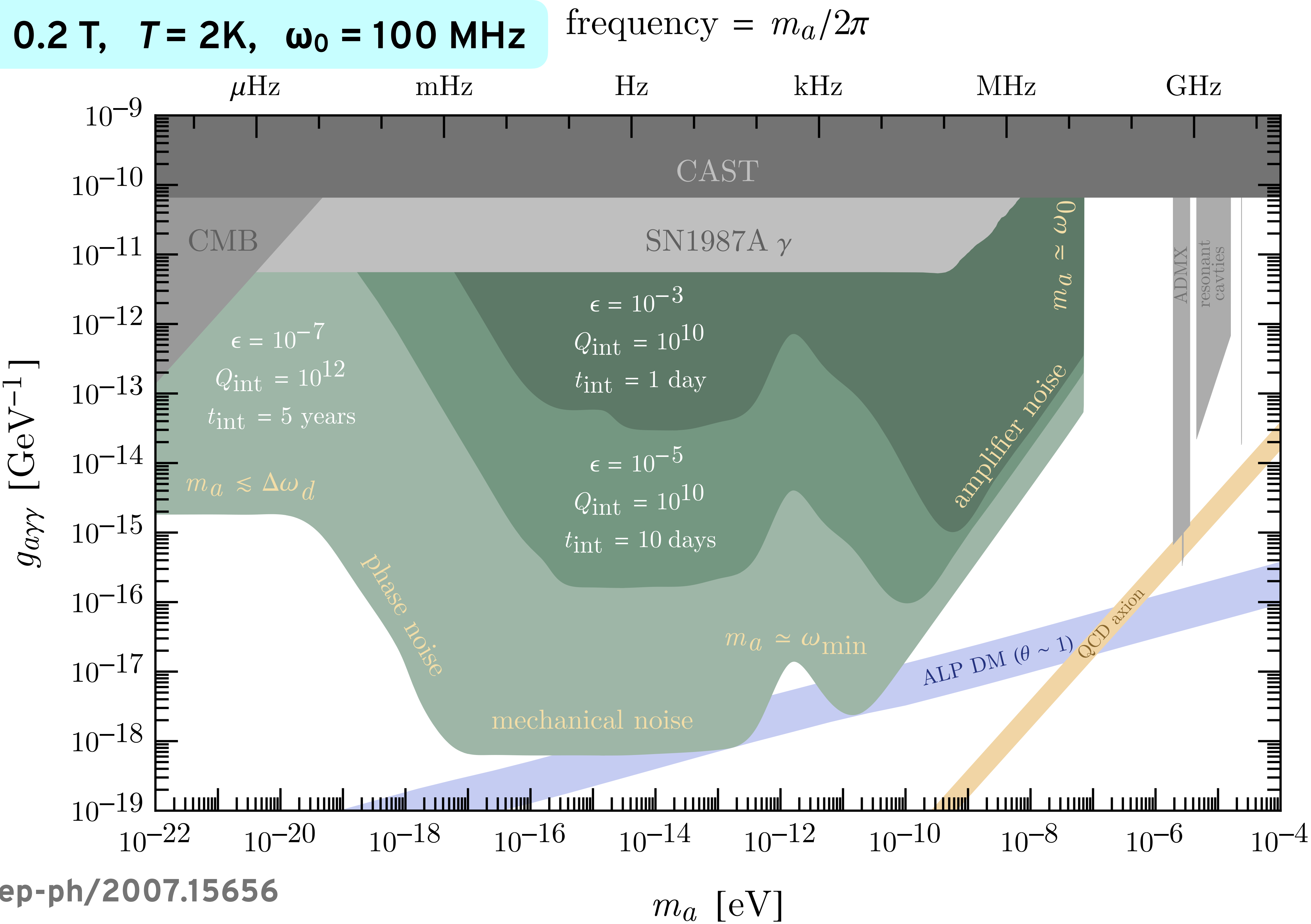
Broadband Axion Resonant Frequency Conversion

B = 0.2 T, T = 2K, ω_0 = 100 MHz



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Outlook

Radio-Frequency **up-conversion** approach

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

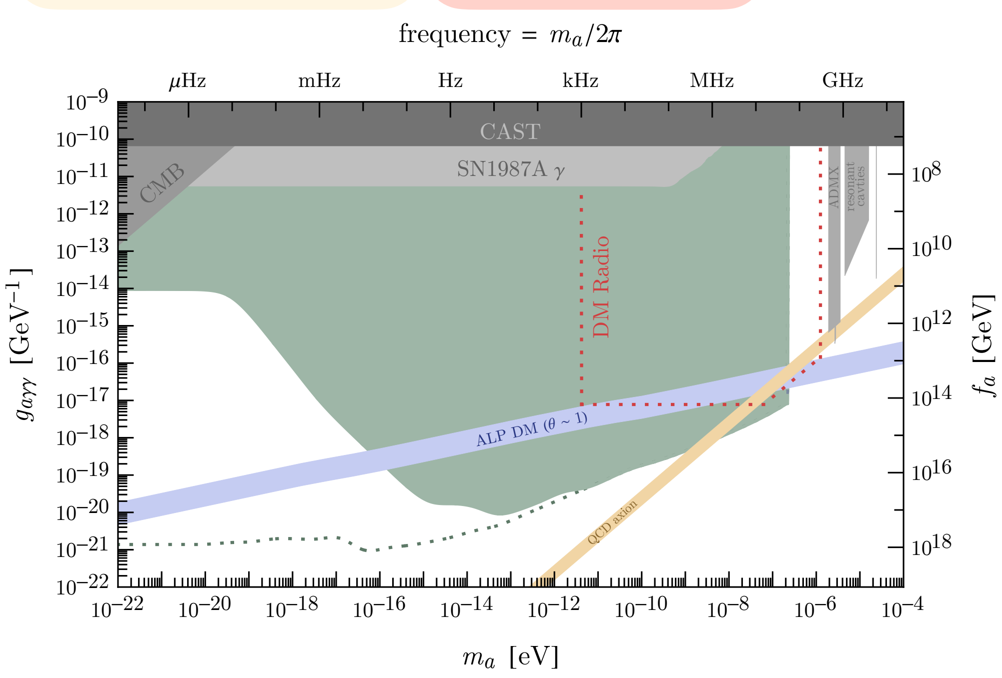
Parametric gain for small axion masses vs. LC Resonator

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

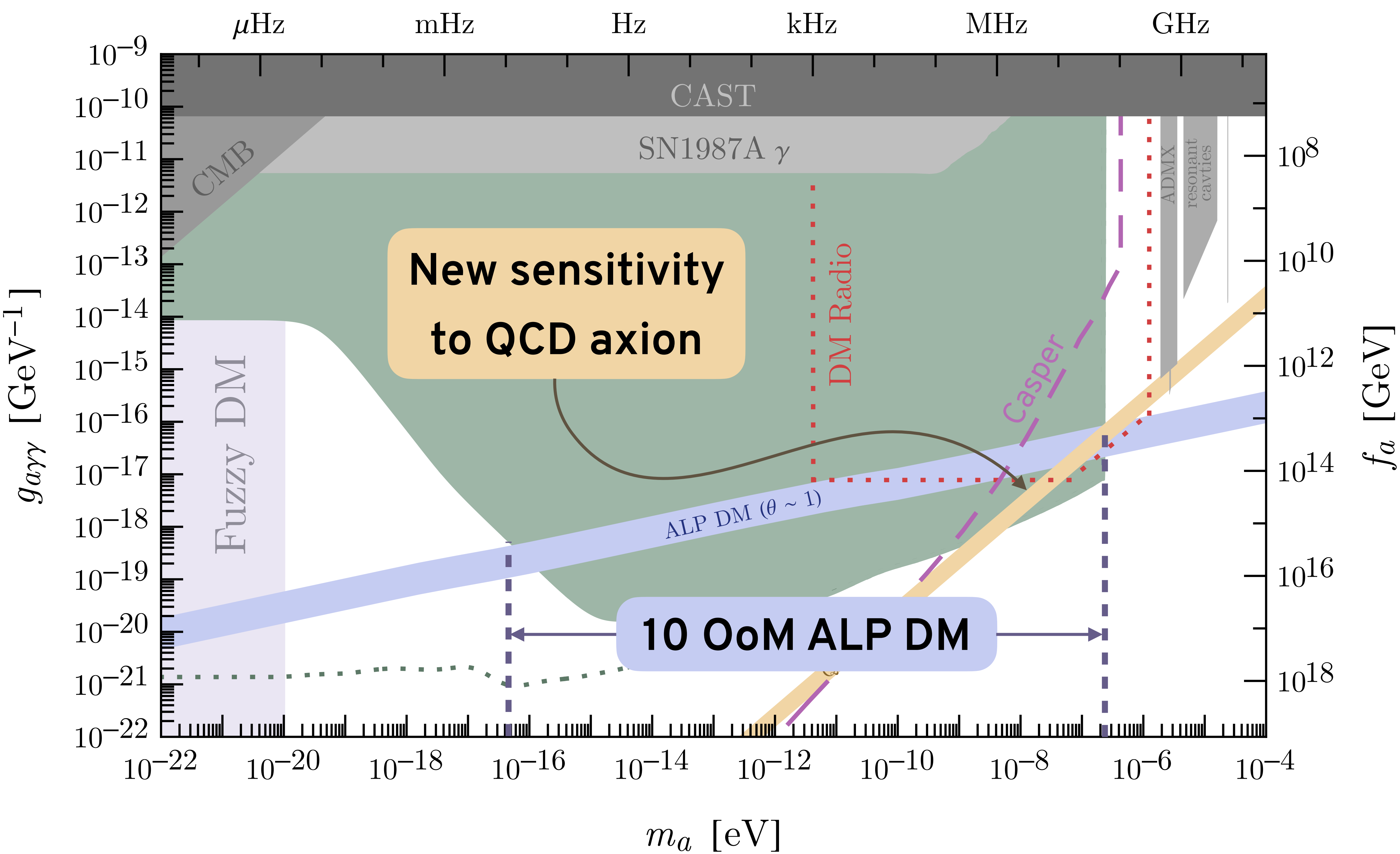
SLAC group seeking internal funding

In discussions for Physics Beyond Colliders @ CERN

Snowmass LOI *CF2* & *AF5*



Outlook



μHz
mHz
Hz
kHz
MHz
GHz
CAST
CMB
SN1987A γ
DM Radio
ADMX
resonant cavties
Casper
New sensitivity to QCD axion
Fuzzy DM
ALP DM (θ ~ 1)
10 OoM ALP DM
$g_{a\gamma\gamma}$ [GeV^{-1}]
f_a [GeV]
m_a [eV]
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