Axion Dark Matter (and Gravitational Wave) Detection in an SRF Cavity

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Axions:

hep-ph/2007.15656
A. Berlin, R. T. D'Agnolo, SARE, K. Zhou

JHEP 07 (2020) 088, hep-ph/1912.11048
A. Berlin, R. T. D'Agnolo, SARE, P. Schuster, N. Toro, C. Nantista, J. Neilson, S. Tantawi, K. Zhou

Gravitational Waves:

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

Hamburg, June 4, 2021

Outline

A lightning introduction to **axions**

Radio-Frequency **up-conversion** approach

Axion signal

Noise:

“Standard” haloscope considerations

SRF-specific noise sources & design

Discussion on **Gravitational Waves**

Outlook

A ⚡ introduction to Axions

QCD has a CP problem:

$$\mathcal{L} \supset \frac{\bar{\theta} g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{\mu\nu,a}$$

Term violates CP – leads to neutron EDM

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

Experimental limit:

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

$$\bar{\theta} \lesssim 10^{-10}$$

A ⚡ introduction to Axions

Solution: U(1)$_{PQ}$ symmetry anomalous under QCD:

pNGB after instanton breaking – QCD axion!

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

Peccei & Quinn (1977)
Weinberg (1978)
Wilczek (1978)

Potential for axion generated by confinement:

$$V = -m_\pi^2 f_\pi^2 \left(1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2 f_a} + \frac{\bar{\theta}}{2}\right)\right)^{1/2}$$

Minimised: $\langle a \rangle = -\bar{\theta} f_a$

Axion mass related to QCD scale: $m_a^2 f_a^2 \sim m_\pi^2 f_\pi^2$

A ⚡ introduction to Axions

Axion-like particles (ALPs)

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

Generic shift-symmetric P-odd scalar field w/ derivative couplings to SM fields

Mass unrelated to QCD scale: $\xcancel{m_a^2 f_a^2 \sim m_\pi^2 f_\pi^2}$

Motivations:

a) One of ~few concrete predictions from known String compactifications (string axiverse)

b) ALPs as Dark Matter from misalignment

c) Technology to search for ALPs exists

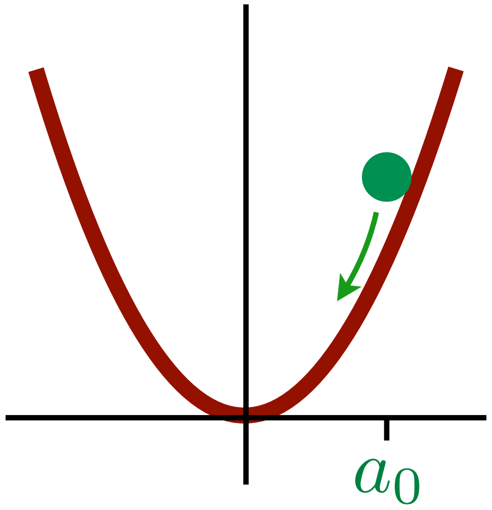
Svrček & Witten (2006)
Arvanitaki et al (2009)
Stott et al (2017)
Halverson & Langacker (2018)

ALPs as Dark Matter: Misalignment

Axion EoM in FRW Universe: $\ddot{a} + 3H\dot{a} + m_a^2 a = 0$

$$3H > m_a, \quad a = a_0$$

$$3H \lesssim m_a, \quad a \simeq a_0 \left(\frac{\alpha(H = 3m_a)}{\alpha(t)} \right)^{3/2} \cos(m_a t + \varphi)$$

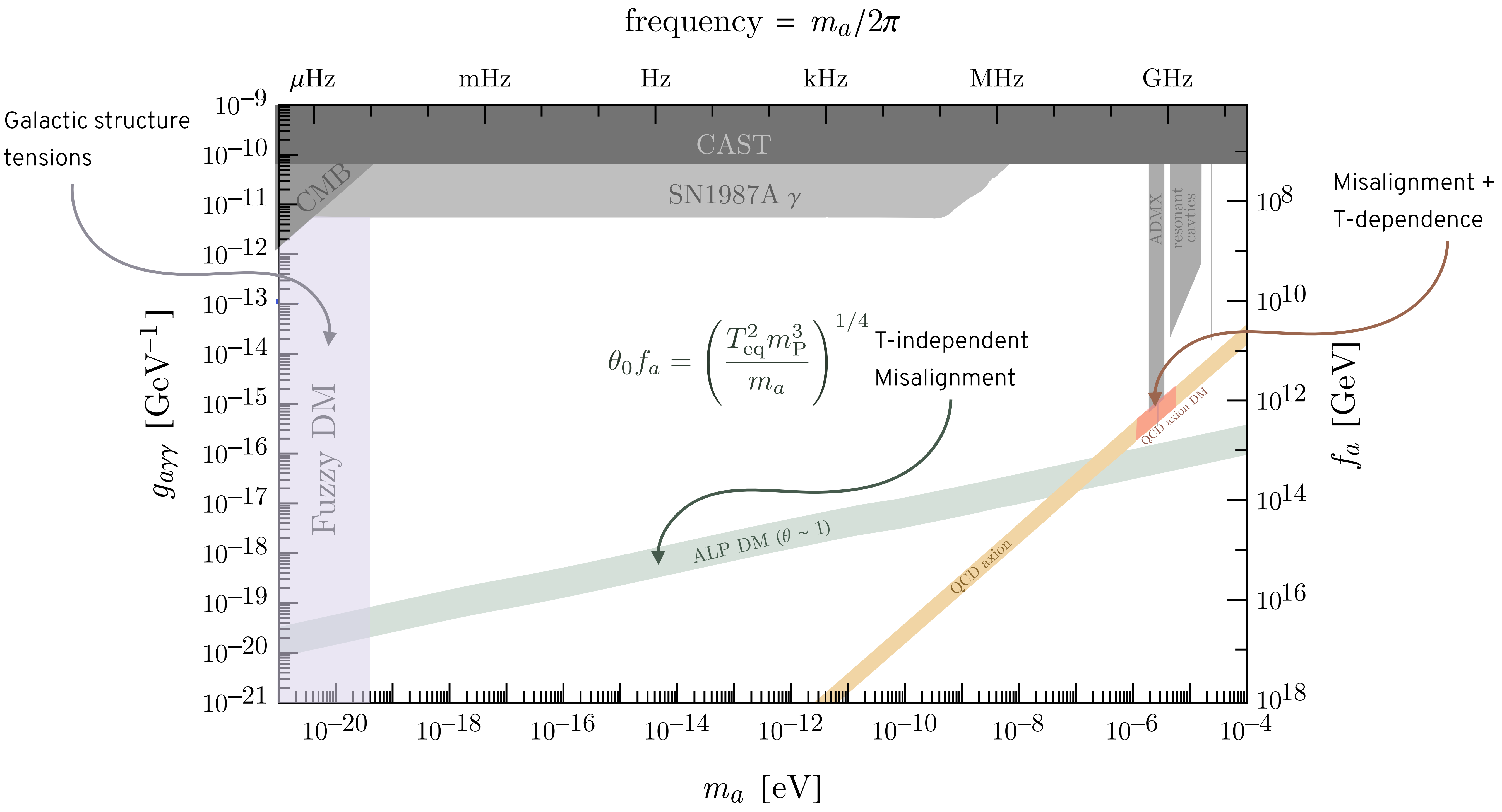


DM energy density: $\rho_{\rm DM} \sim T^3 T_{\rm eq}$

Recall: $\rho_a \sim m_a^2 a_0^2 \qquad T \sim (H^2 m_{\rm P}^2)^{1/4}$

Relic abundance: $a_0^2 = \left(\frac{T_{\rm eq}^2 m_{\rm P}^3}{m_a} \right)^{1/2}$ $\qquad a_0 = \theta_0 f_a$

Axions as Dark Matter: Targets



Galactic structure tensions

$$\theta_0 f_a = \left(\frac{T_{\rm eq}^2 m_{\rm P}^3}{m_a}\right)^{1/4}$$

T-independent Misalignment

Misalignment + T-dependence

Axion couplings to photons

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F \tilde{F}$$

QCD axion inevitably has such a coupling

$$g_{a\gamma\gamma}^{\text{QCD}} \simeq \frac{\alpha}{2\pi} \frac{1}{f_a} \left(\frac{E}{N} - 1.92 \right)$$

Anomaly coefficients

Mixing w/ pion

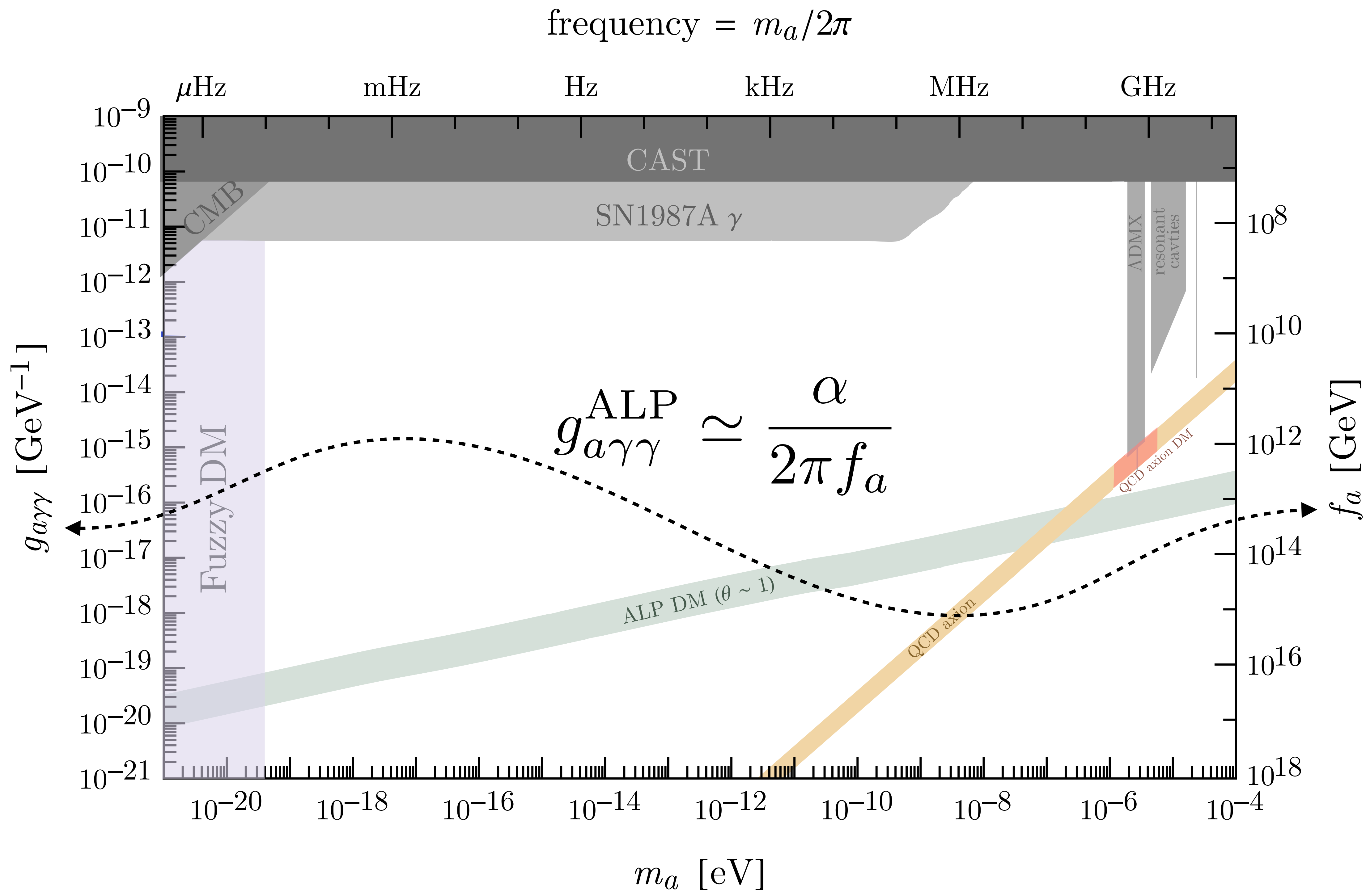
DFSZ: $\frac{E}{N} = \frac{8}{3}$

KSVZ: $\frac{E}{N} = \begin{cases} 0 & \text{neutral VLQs} \\ 2 & \pm 1 \text{ charged VLQs} \end{cases}$

ALP has coupling to photons introduced “by hand”

$$g_{a\gamma\gamma}^{\text{ALP}} \simeq \frac{\alpha}{2\pi f_a}$$

Axion couplings to photons



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

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

Resonant Axion Searches

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

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

$1/\tau_a \sim m_a\langle v^2\rangle$

$1/\tau_{\rm r} \sim \omega_{\rm sig}/Q_{\rm r}$

$Q_a \sim 1/\langle v^2\rangle$

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

⚠ **WARNING**

QUANTITIES OFTEN LINKED

Resonant Axion Searches

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

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

ADMX and other cavities: $\omega_{\rm sig} = m_a$ $B_a \sim J_{\rm eff}/\omega_{\rm sig}$ $\omega_{\rm sig} \sim V^{-1/3}$

Difficult to reach small axion masses – cavity has to be huge!

LC resonators: $\omega_{\rm sig} = m_a$ $B_a \sim J_{\rm eff} V^{1/3}$

Able to access small masses, but length-ratio suppressed

Different approach: Resonant Axion Searches

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

Heterodyne resonator: $\omega_{\mathrm{sig}} = \omega_0 \pm m_a$ $B_a \sim J_{\mathrm{eff}}/\omega_{\mathrm{sig}}$

Gain: $$\frac{\mathcal{E}_a^{(\mathrm{osc.})}}{\mathcal{E}_a^{(\mathrm{static})}} \sim \frac{\omega_0 \pm m_a}{m_a} \sim \frac{\omega_0}{m_a}$$

⚠ WARNING

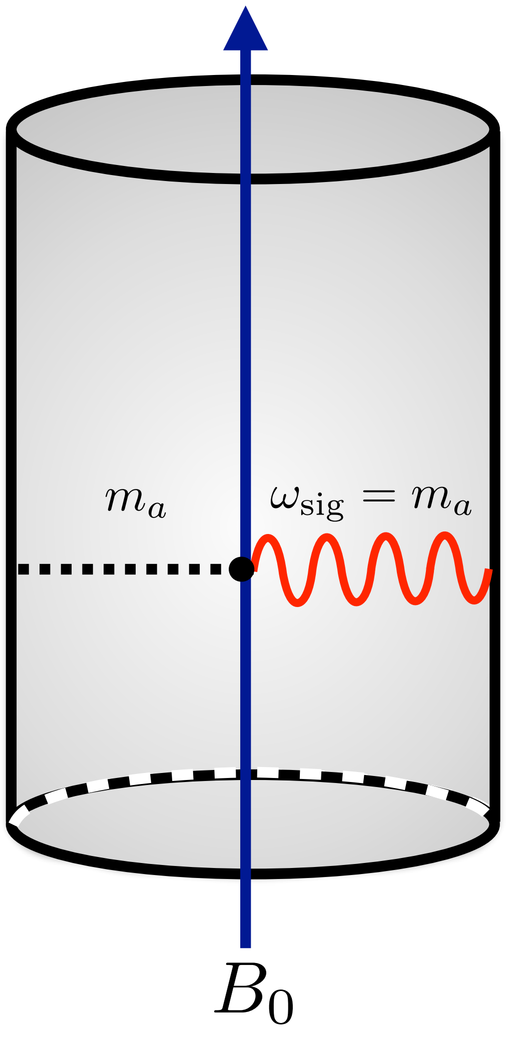
Noise & exp. parameters not discussed yet

Resonant Approaches

Static-field Haloscope:

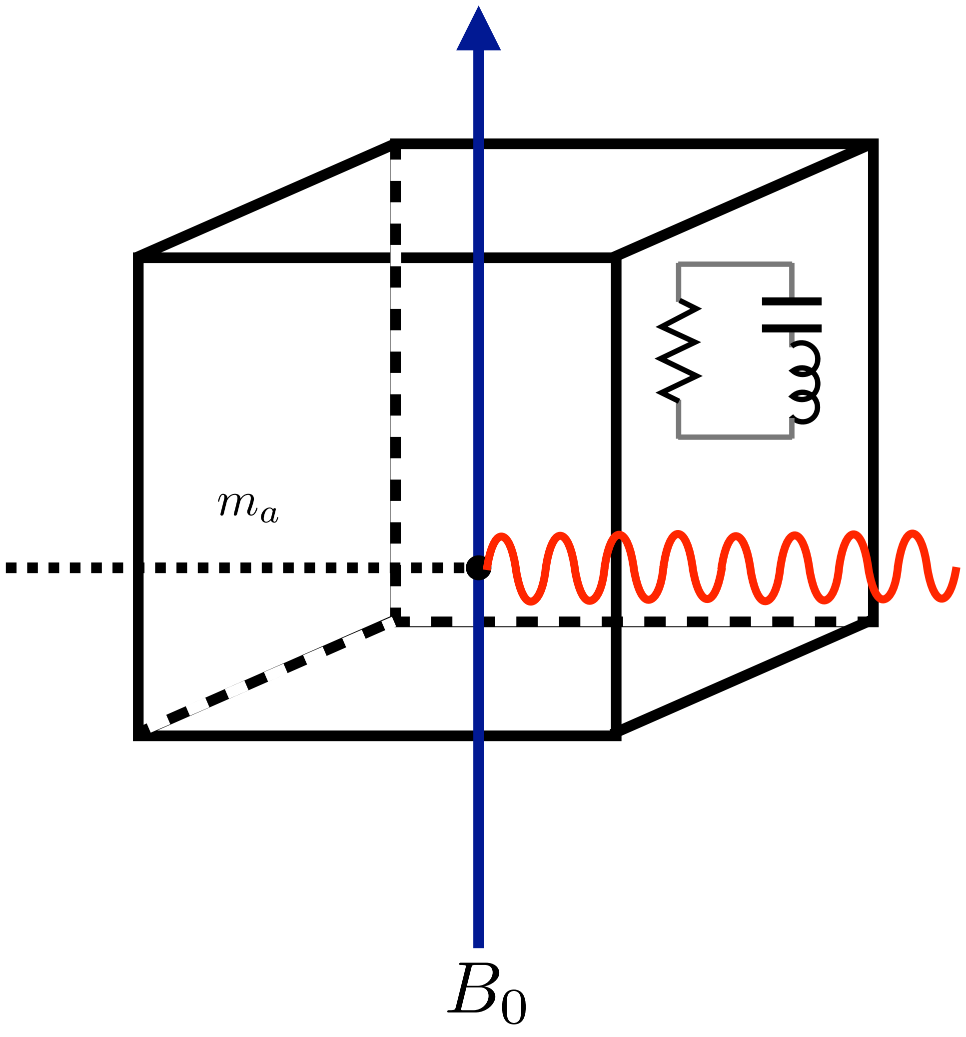
e.g. ADMX

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



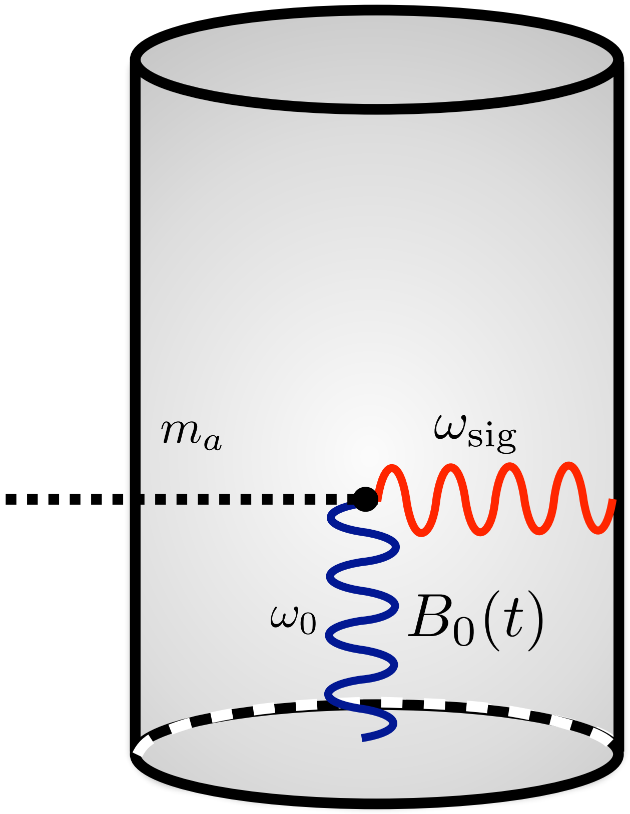
LC Resonator:

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



Heterodyne Resonator:

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



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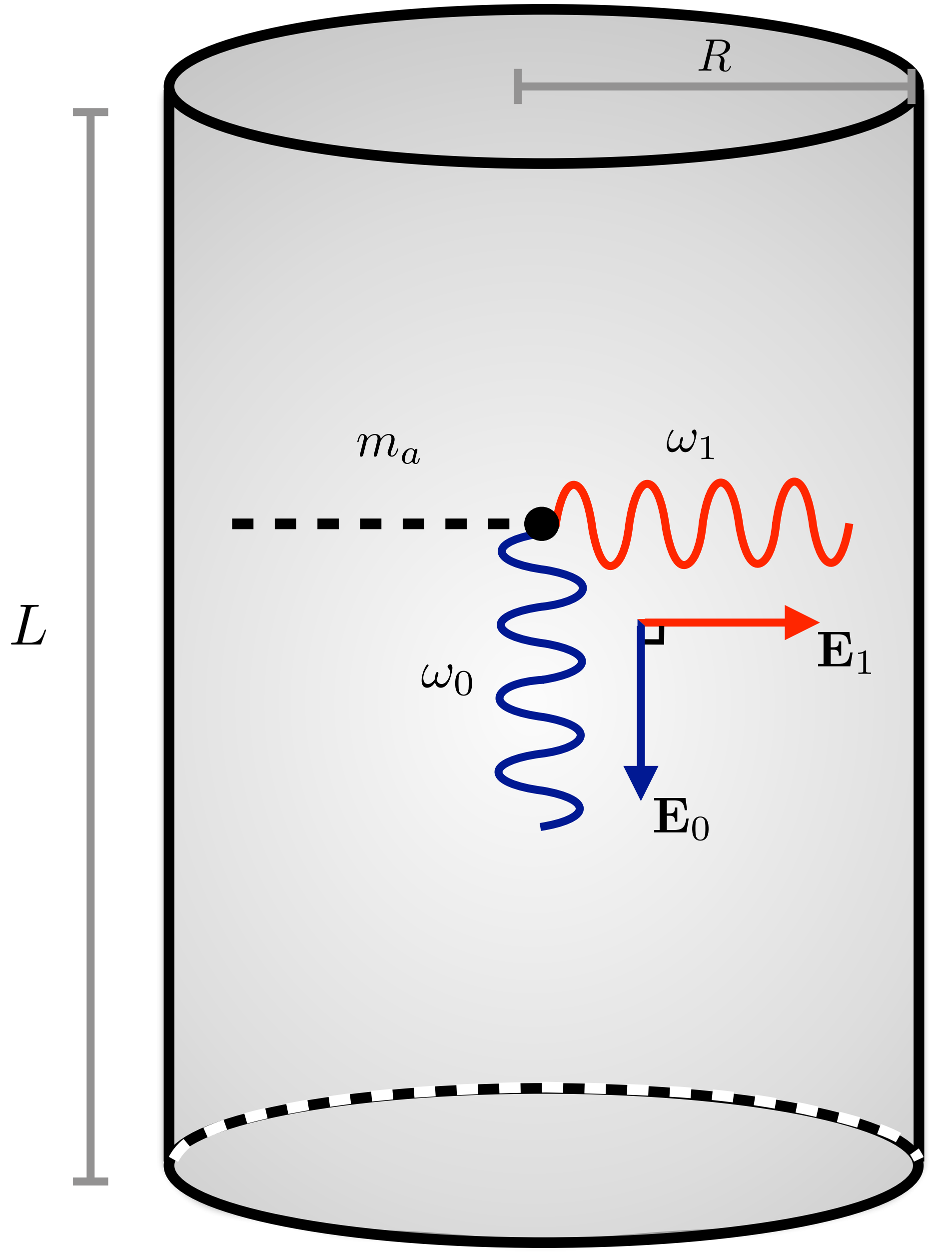
Also: R. Lasenby hep-ph/1912.11467

Allowed mode transitions



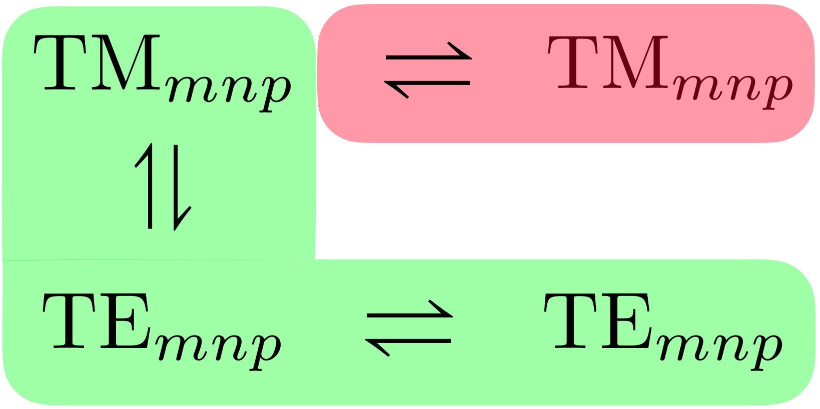
Cylindrical cavity modes: TM_{mnp} TE_{mnp}

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

MAXIMISE

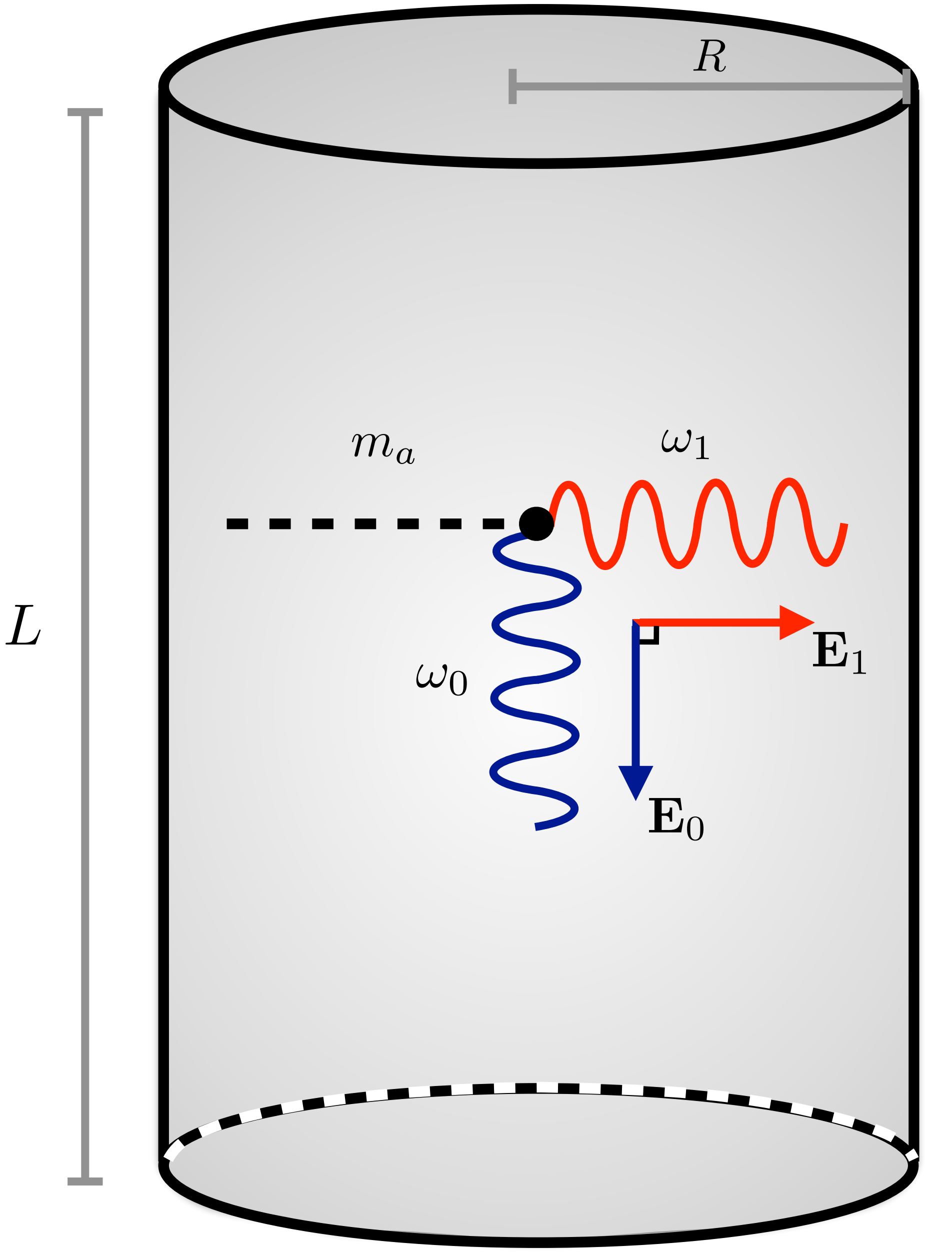
spin-0: $m_0 = m_1$

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



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

Broadband Axion Resonant Frequency Conversion



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Superconducting RF Cavity

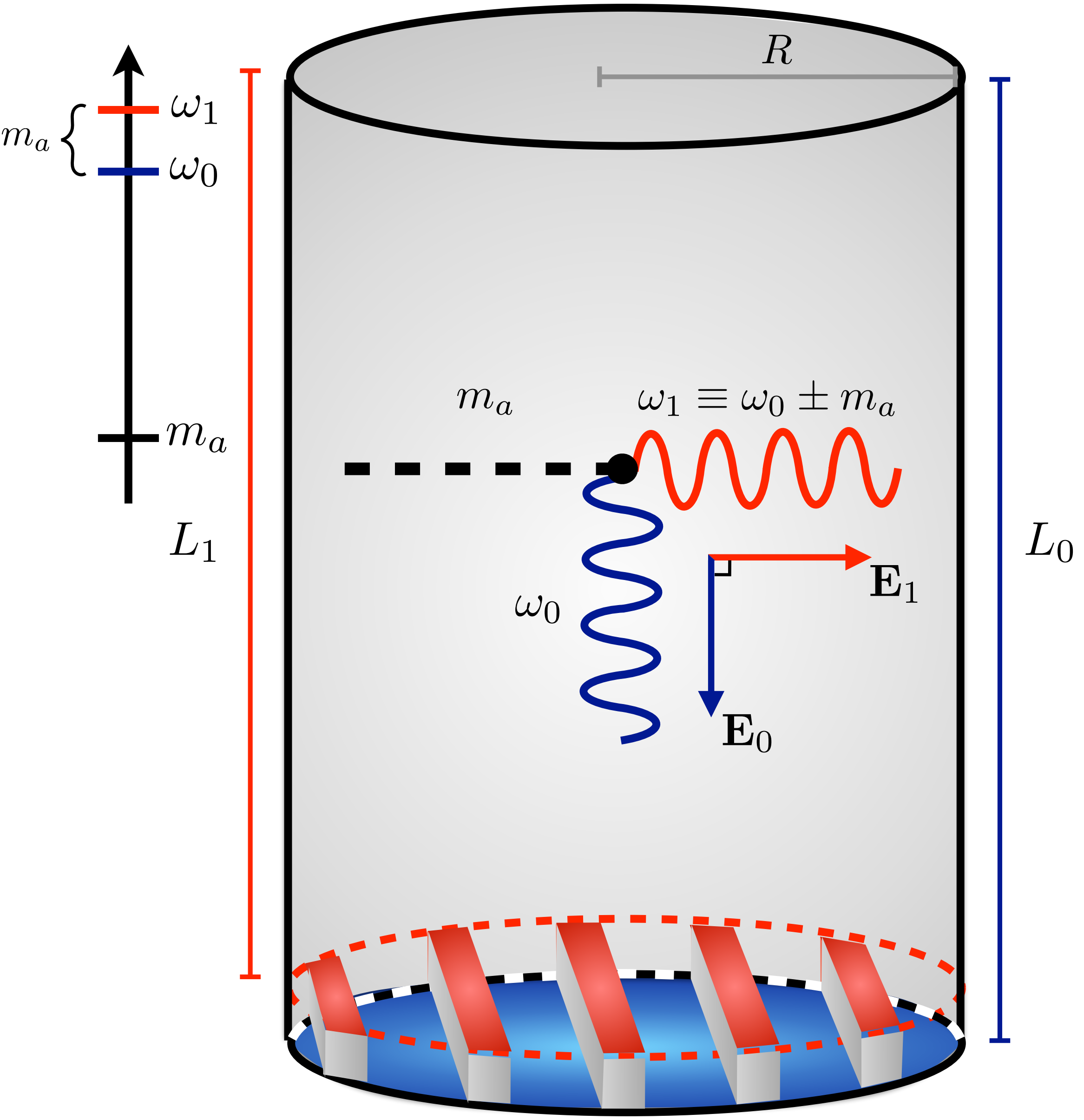
$$\omega_0 = \omega_1 \sim \text{GHz}$$

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

Requirement: $\delta\omega_i \lesssim \omega_i / Q_i^{\star}$

*Demonstrated by DarkSRF @ FNAL

Scanning Axion Resonant Frequency Conversion



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Superconducting RF Cavity

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

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

Tunability:

$\delta\omega \lesssim$ MHz piezos

$\delta\omega \gtrsim$ MHz fins

Degeneracy:

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

Broadband:

hep-ph/2007.15656

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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…

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

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

Axion Signal

Signal Power Spectral Density (PSD):

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

Signal Power (resonant):

$$P_{\rm sig} \simeq \frac{1}{4}\,(g_{a\gamma\gamma}\,\eta_{10}\,B_0)^2\;\rho_{\rm DM}\,V\times\begin{cases} Q_1/\omega_1 & \frac{m_a}{Q_a}\ll\frac{\omega_1}{Q_1}\\ \pi Q_a/m_a & \frac{m_a}{Q_a}\gg\frac{\omega_1}{Q_1}\,,\end{cases}$$

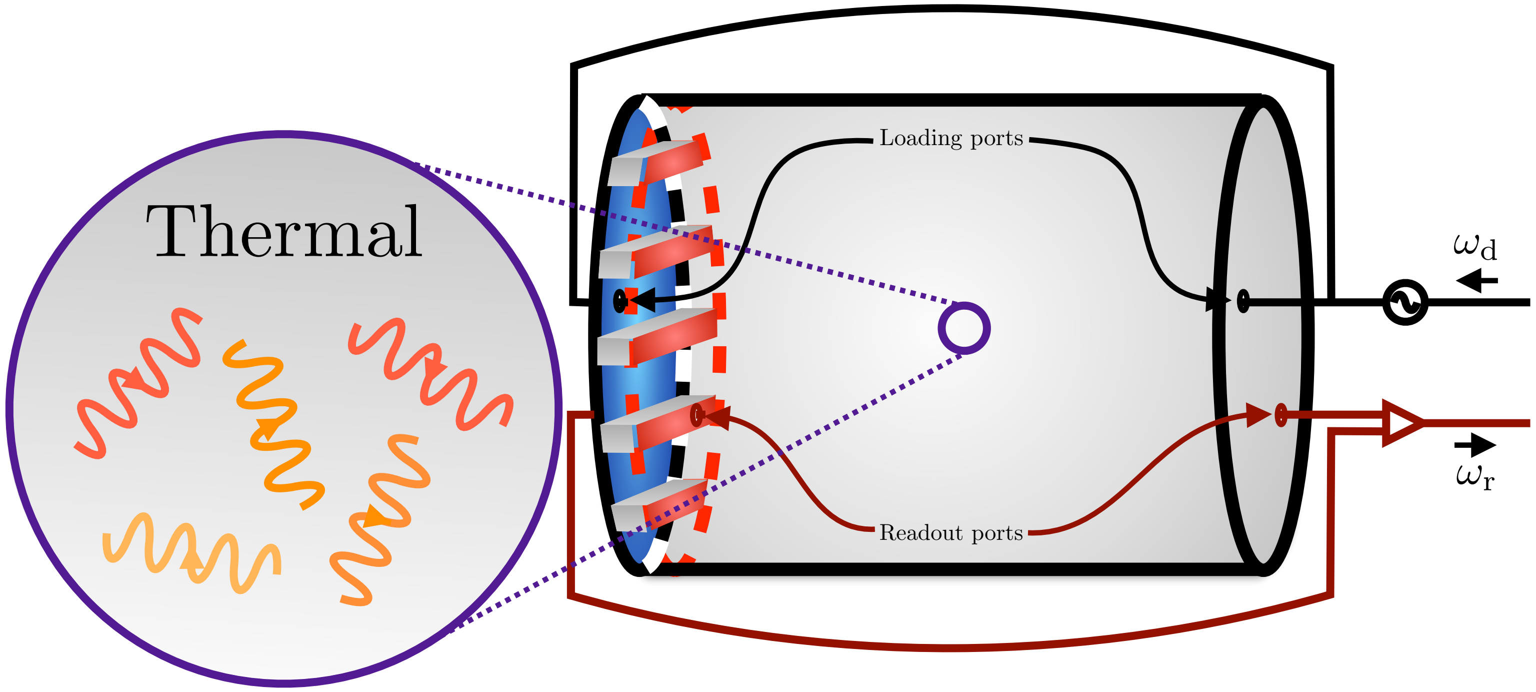
Widths: $\Delta\omega_a \sim m_a/Q_a$

$$\Delta\omega_r = \omega_1/Q_1$$

Standard Noise Sources: Thermal Noise

Power Spectral Density:

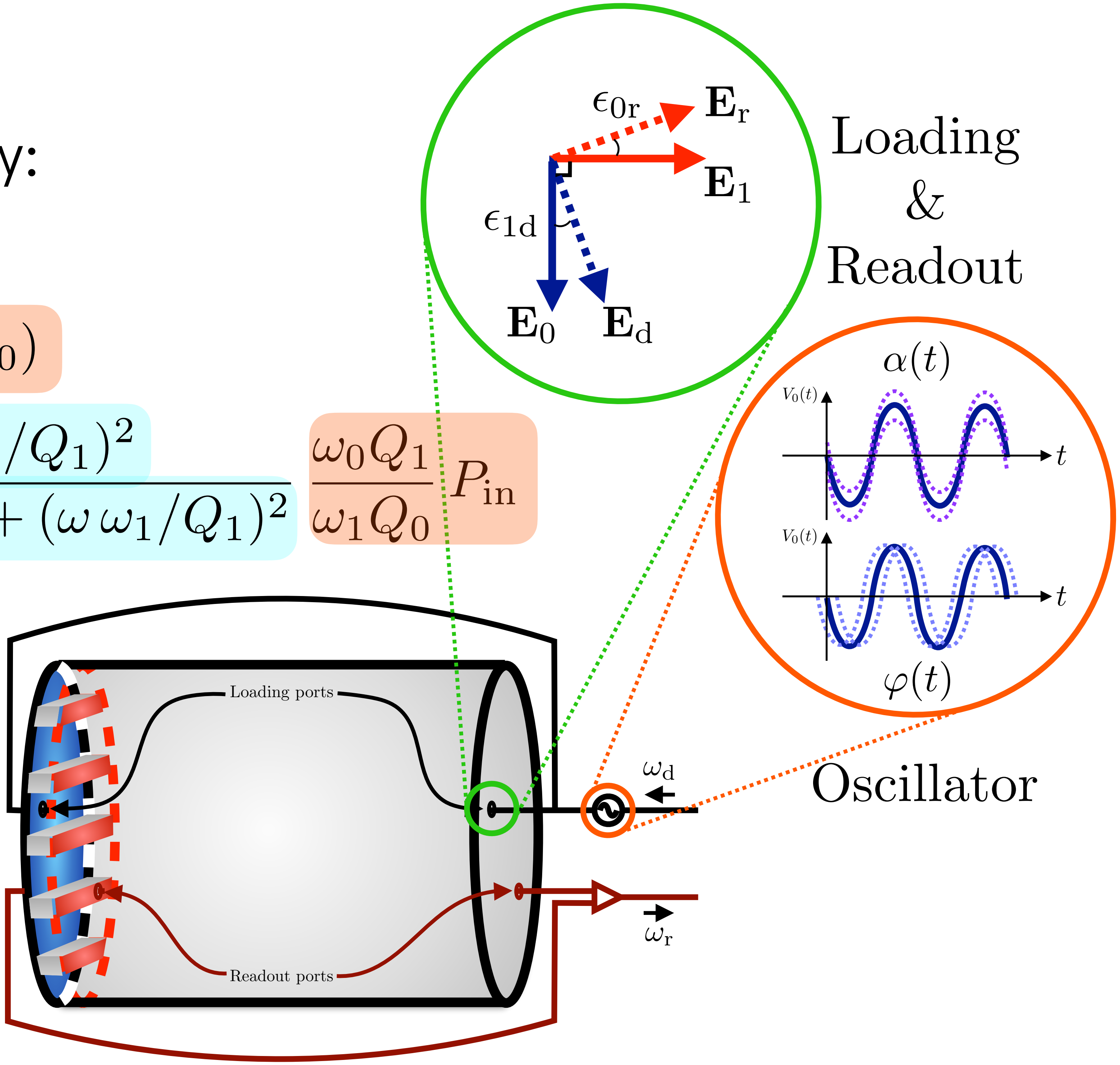
$$S_{\text{th}}(\omega) = \frac{Q_1}{Q_{\text{int}}} \frac{4\pi T \, (\omega\,\omega_1/Q_1)^2}{(\omega^2 - \omega_1^2)^2 + (\omega\,\omega_1/Q_1)^2}$$



Non-standard Noise Sources: Phase Noise

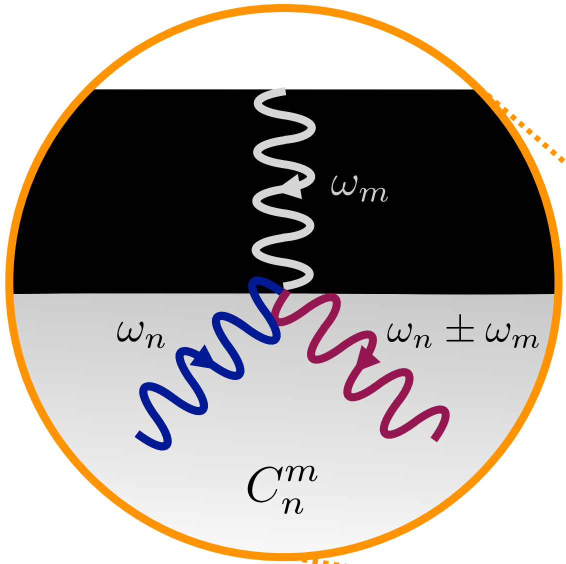
Power Spectral Density:

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



Non-standard Noise Sources: Wall Vibrations

Vibrations



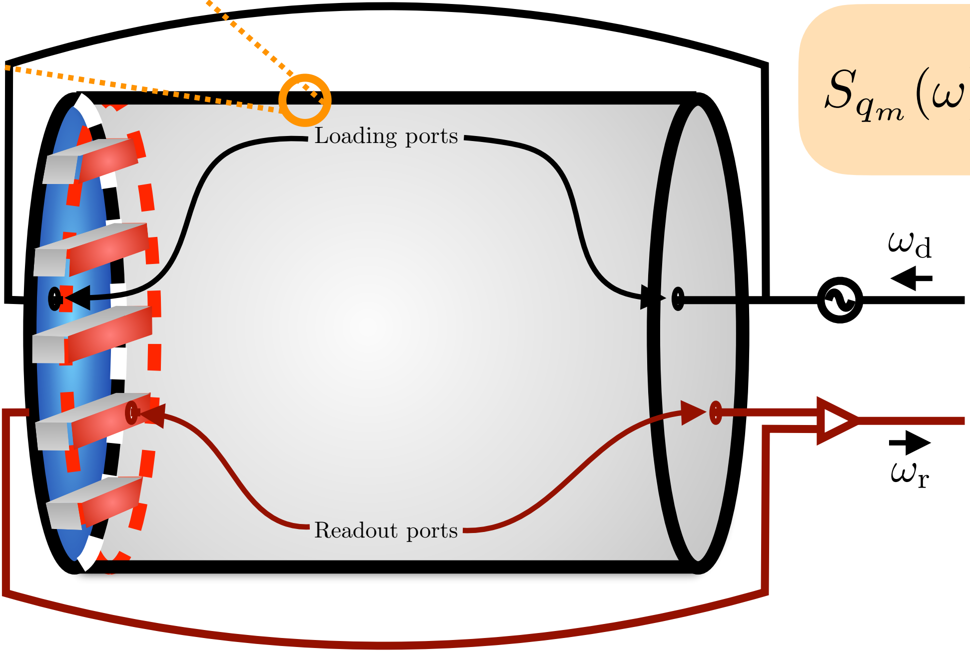
Power Spectral Density:

$$S_{\rm mech}(\omega) \simeq \frac{\epsilon_{1d}^2}{4} \frac{\omega_0}{Q_0} P_{\rm in} \times$$

$$\sum_{n=0,1} \frac{\left(S_{q_m}(\omega-\omega_0)/V^{2/3}\right)(\omega_n/Q_n)\,\omega_n^4\,\omega^2}{\left[(\omega^2-\omega_n^2)^2+(\omega\,\omega_n/Q_n)^2\right]\left[(\omega_0^2-\omega_n^2)^2+(\omega_0\,\omega_n/Q_n)^2\right]}$$

Displacement PSD:

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

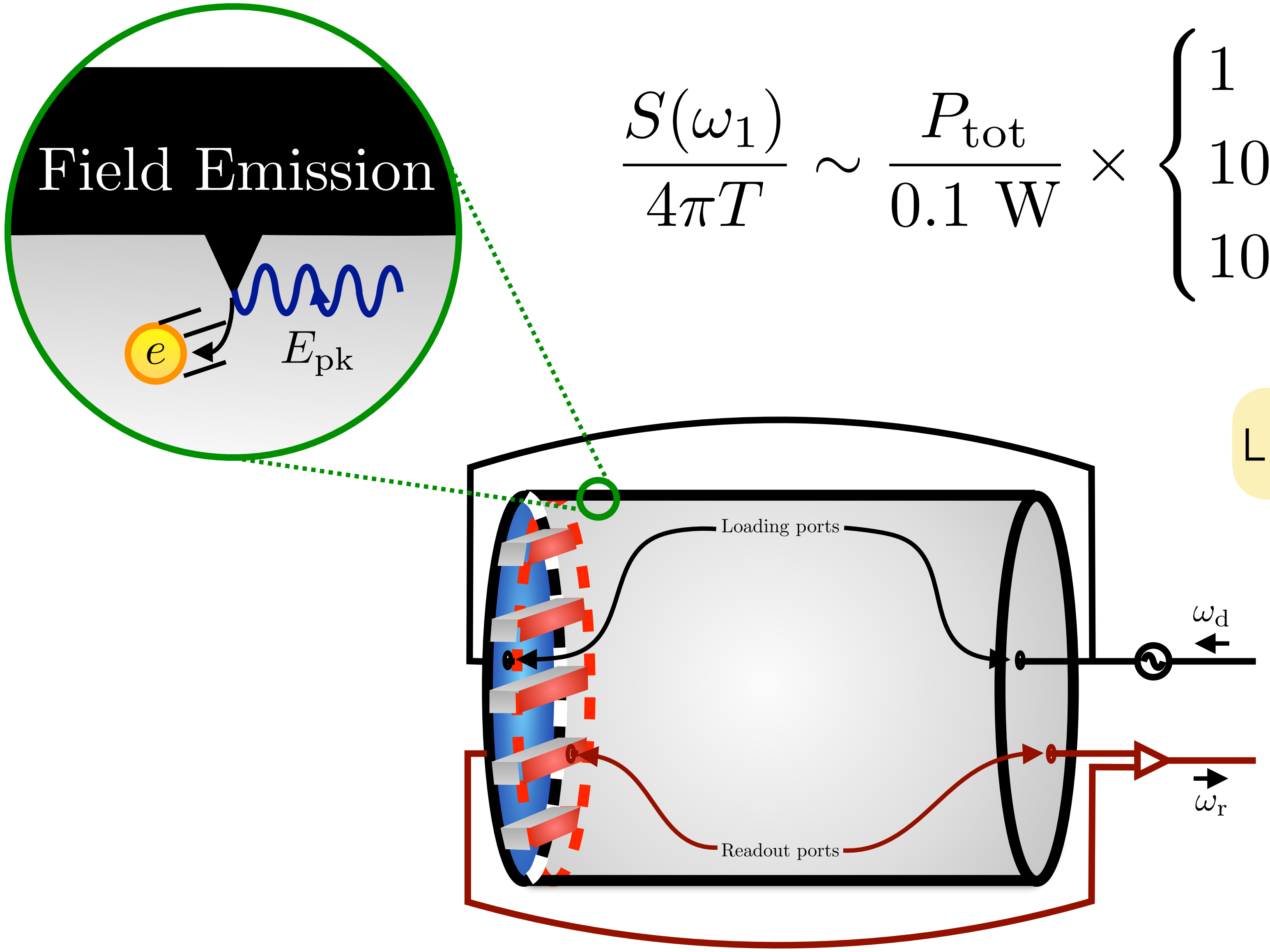


Non-standard Noise Sources: Field Emission

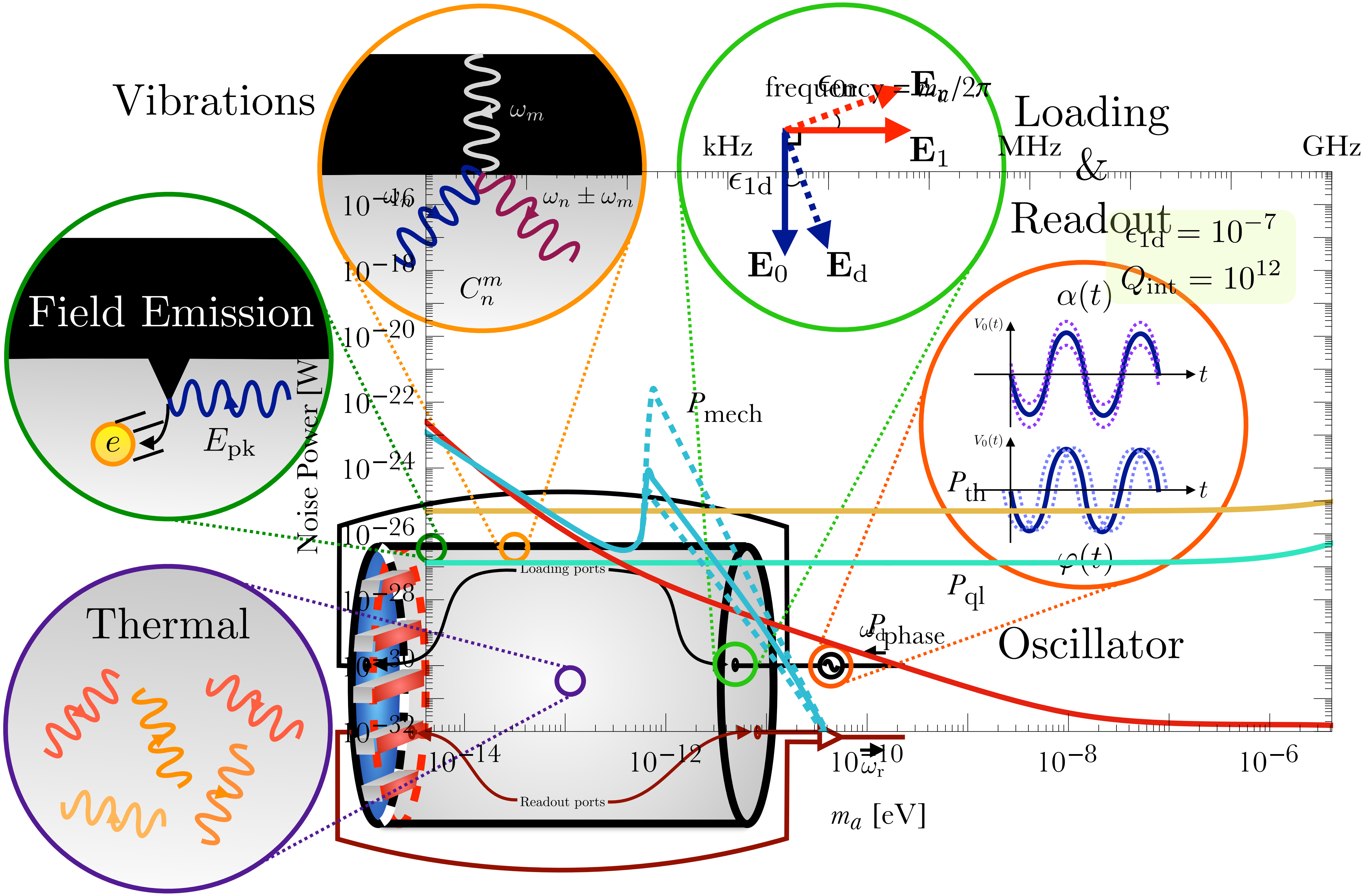
Power Spectral Density:

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

Limits max B-field ~ 0.2T



All Noise Sources



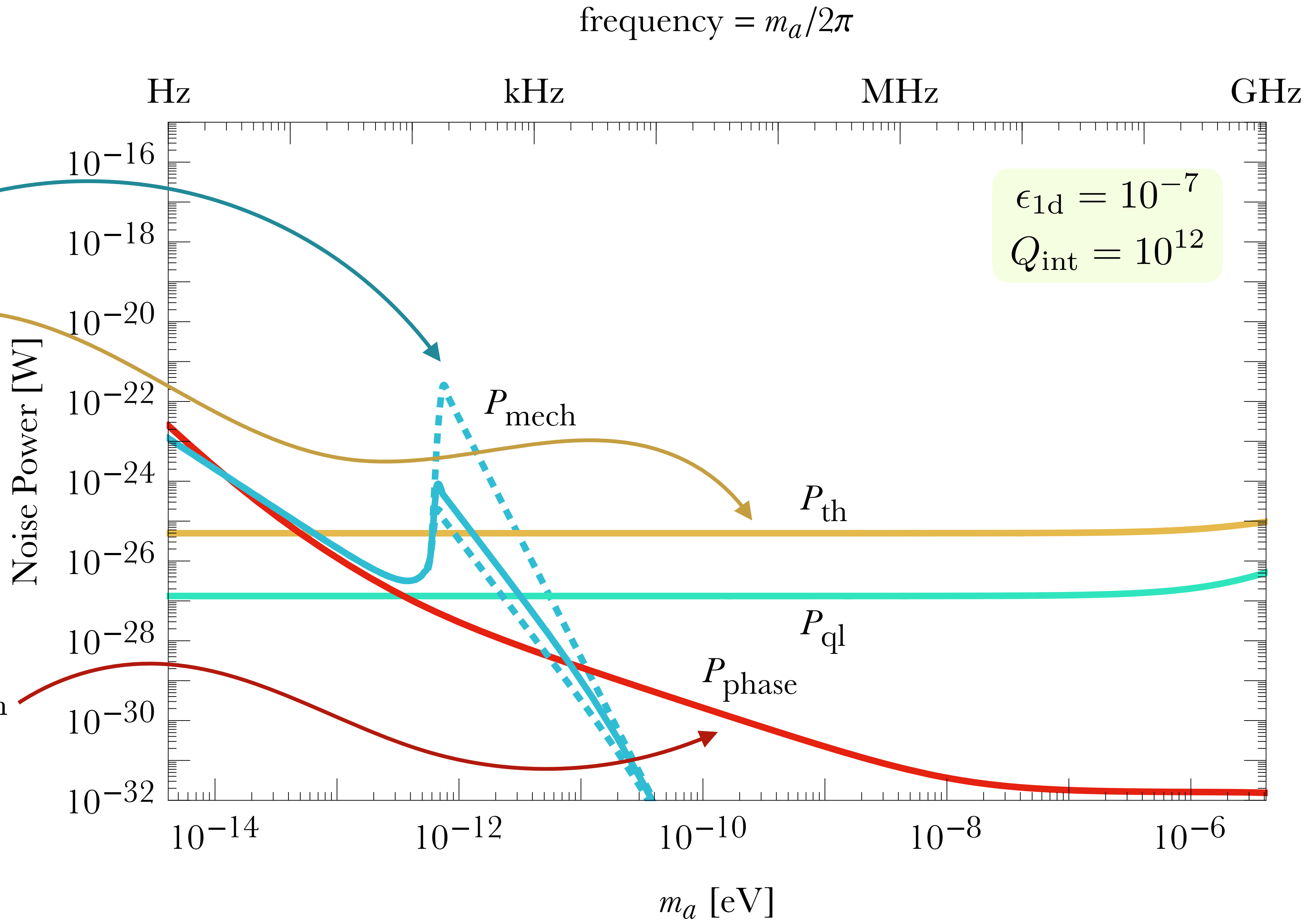
All Noise Sources

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

fractional wall disp. δ

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

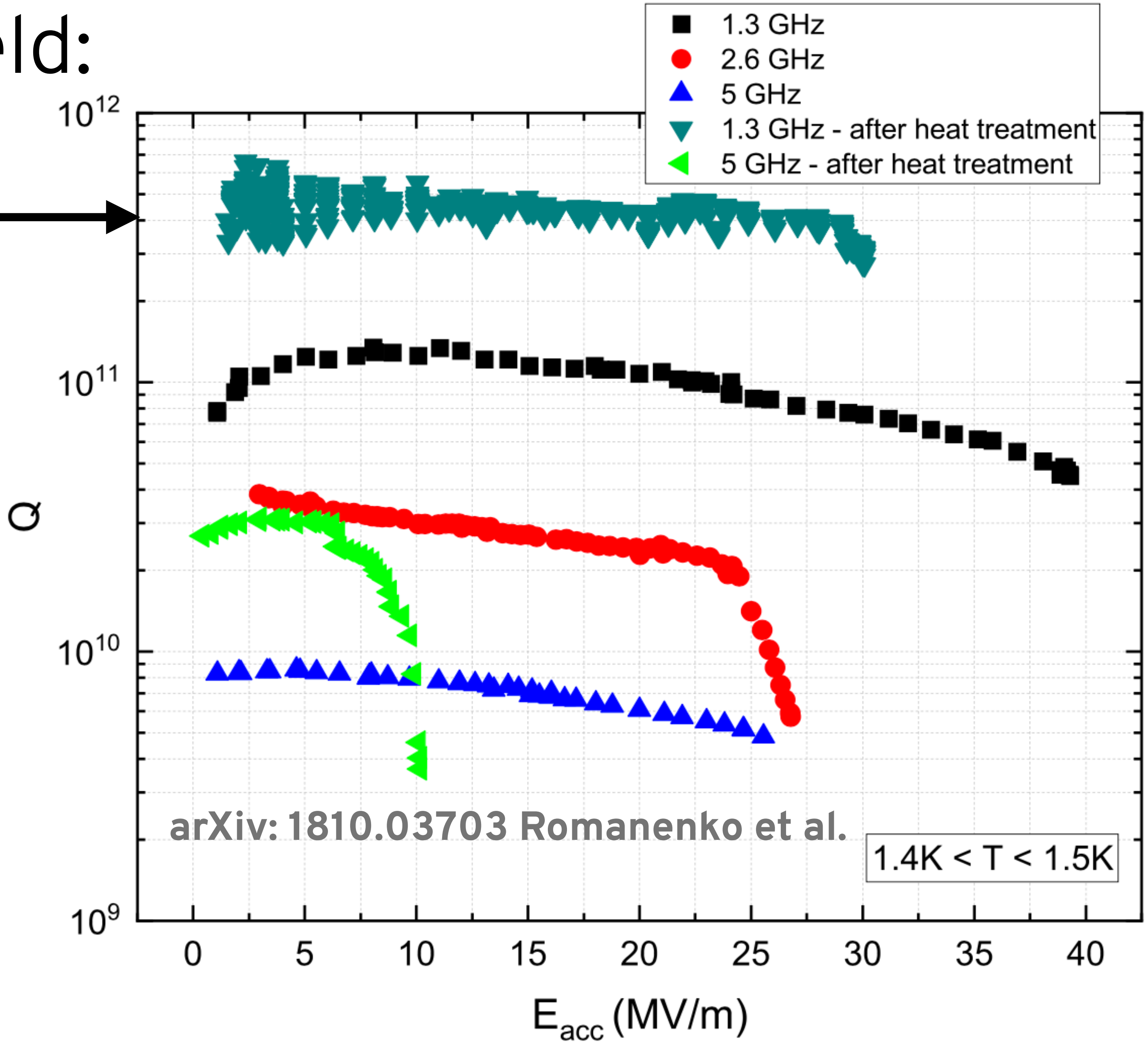
$$P_{\rm phase} \sim \epsilon_{\rm 1d}^2 S_\varphi(m_a) \frac{\omega_1}{Q_{\rm int}} P_{\rm in}$$



Experimental precedent

Q-factor & B-field:

Q~4x10^{11} @ B~0.1T



arXiv: 1810.03703 Romanenko et al.

Experimental precedent

Mode rejection:

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

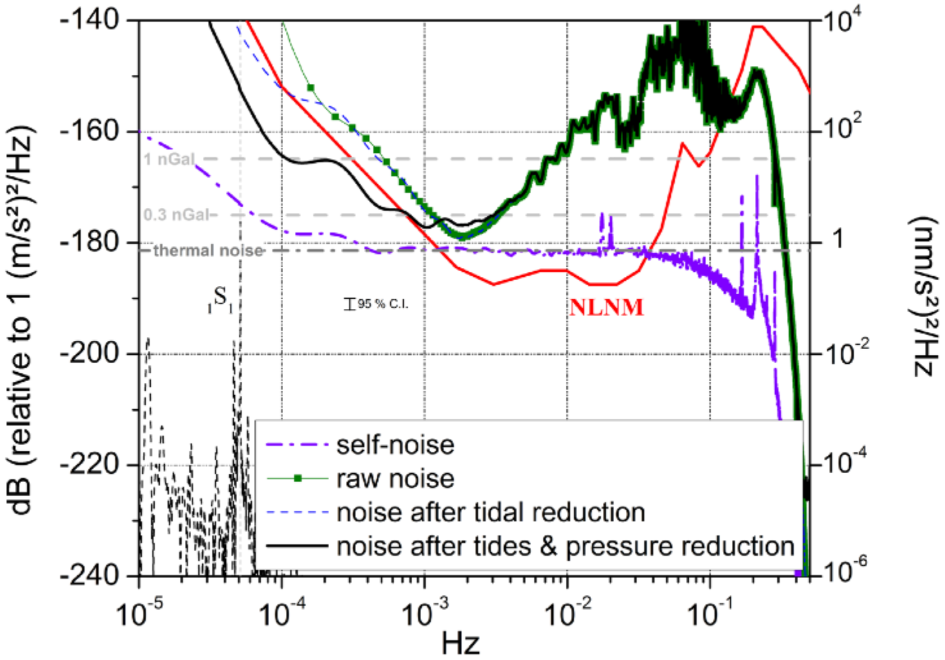
gr-qc/0502054 Ballantini et al.

physics/0004031 Bernard, Gemme, Parodi, Picasso

Low-frequency seismic noise:

$$\Delta\omega/\omega \sim \delta \sim 10^{-10}$$

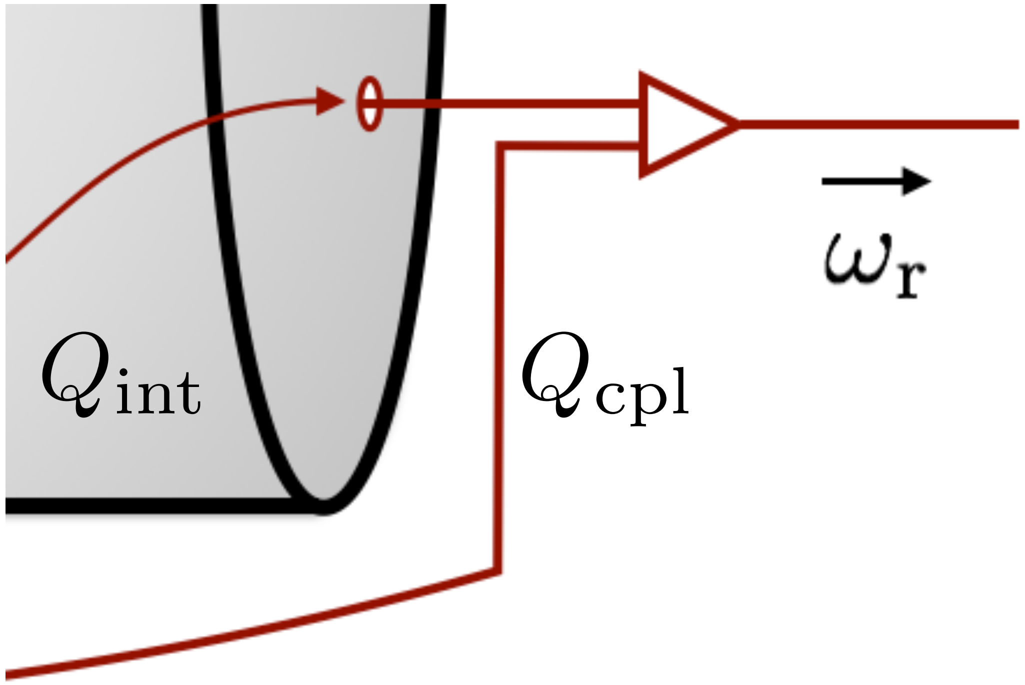
DarkSRF (2020)



Scientific Reports 8, 15324 (2018) Rosat & Hinderer

Signal to Noise: *readout & overcoupling*

Readout:



$$Q_1 = \frac{Q_\text{int} Q_\text{cpl}}{Q_\text{int} + Q_\text{cpl}}$$

Signal:

$$S_\text{sig}(\omega) \to \frac{Q_1}{Q_\text{cpl}} S_\text{sig}(\omega)$$

Noise:

$$S_\text{noise}(\omega) = S_\text{ql}(\omega) + \frac{Q_1}{Q_\text{cpl}} \left(S_\text{th}(\omega) + S_\text{phase}(\omega) + S^{(1)}_\text{mech}(\omega) \right) + \frac{Q_0}{Q_\text{cpl}} S^{(0)}_\text{mech}(\omega)$$

Signal to Noise

Roughly:

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

Thermal noise dominated:

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

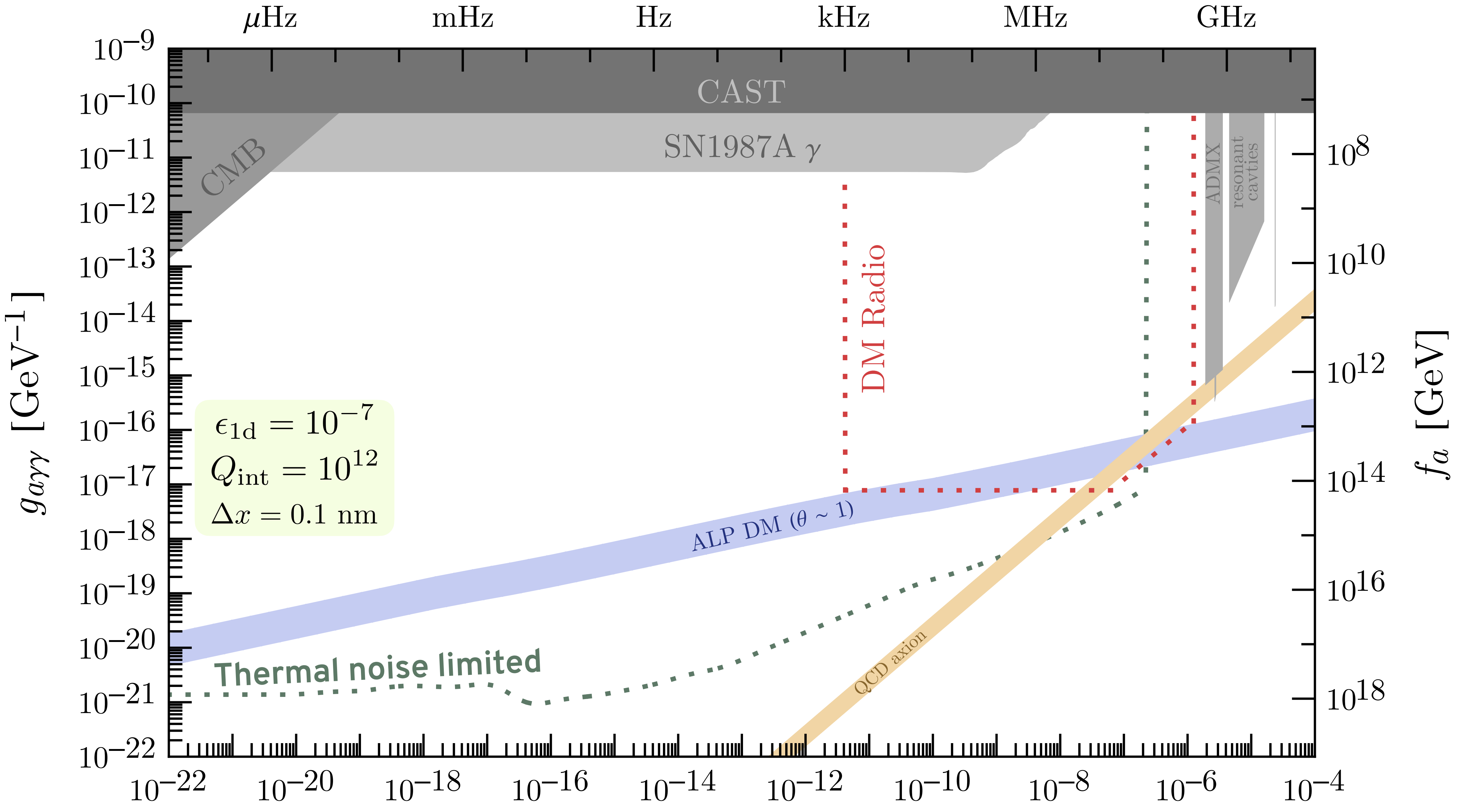
Comparison with LC resonator:

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

Resonant Axion Resonant Frequency Conversion

B = 0.2 T, *T* = 2K, ω₀ = 1 GHz

frequency $= m_a/2\pi$



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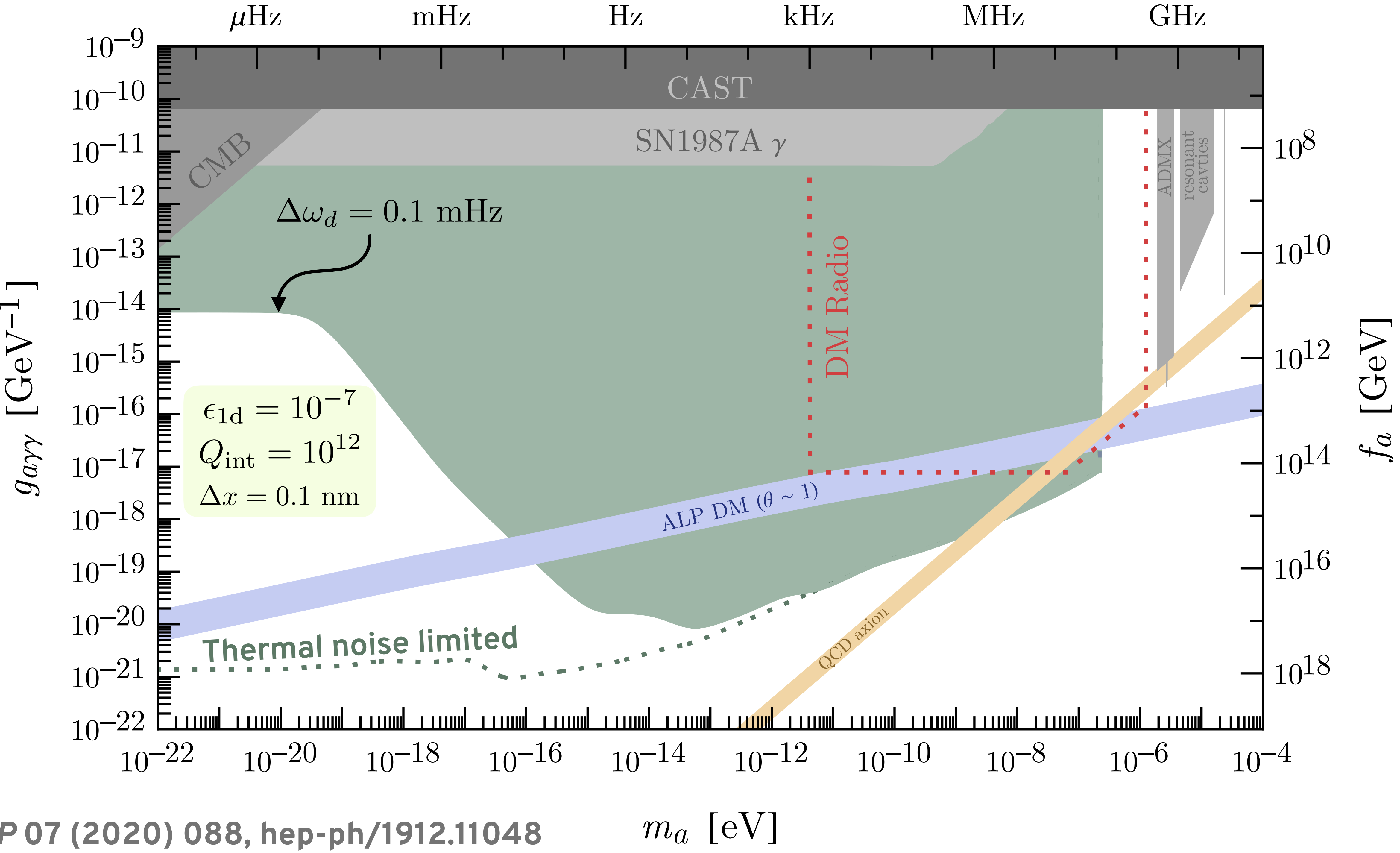

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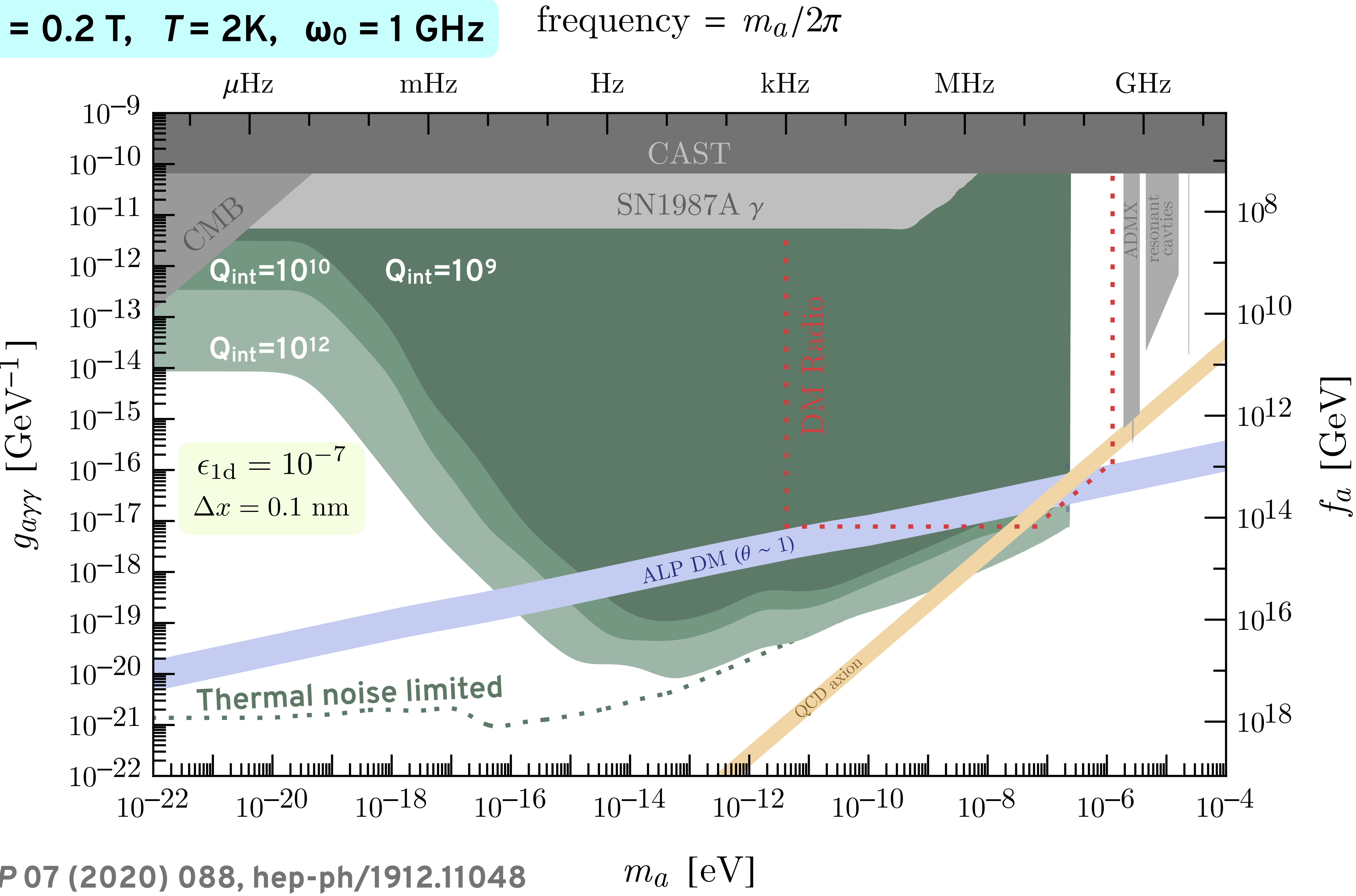
Resonant parameter variations: *Q-factor*

B = 0.2 T, *T* = 2K, ω_0 = 1 GHz



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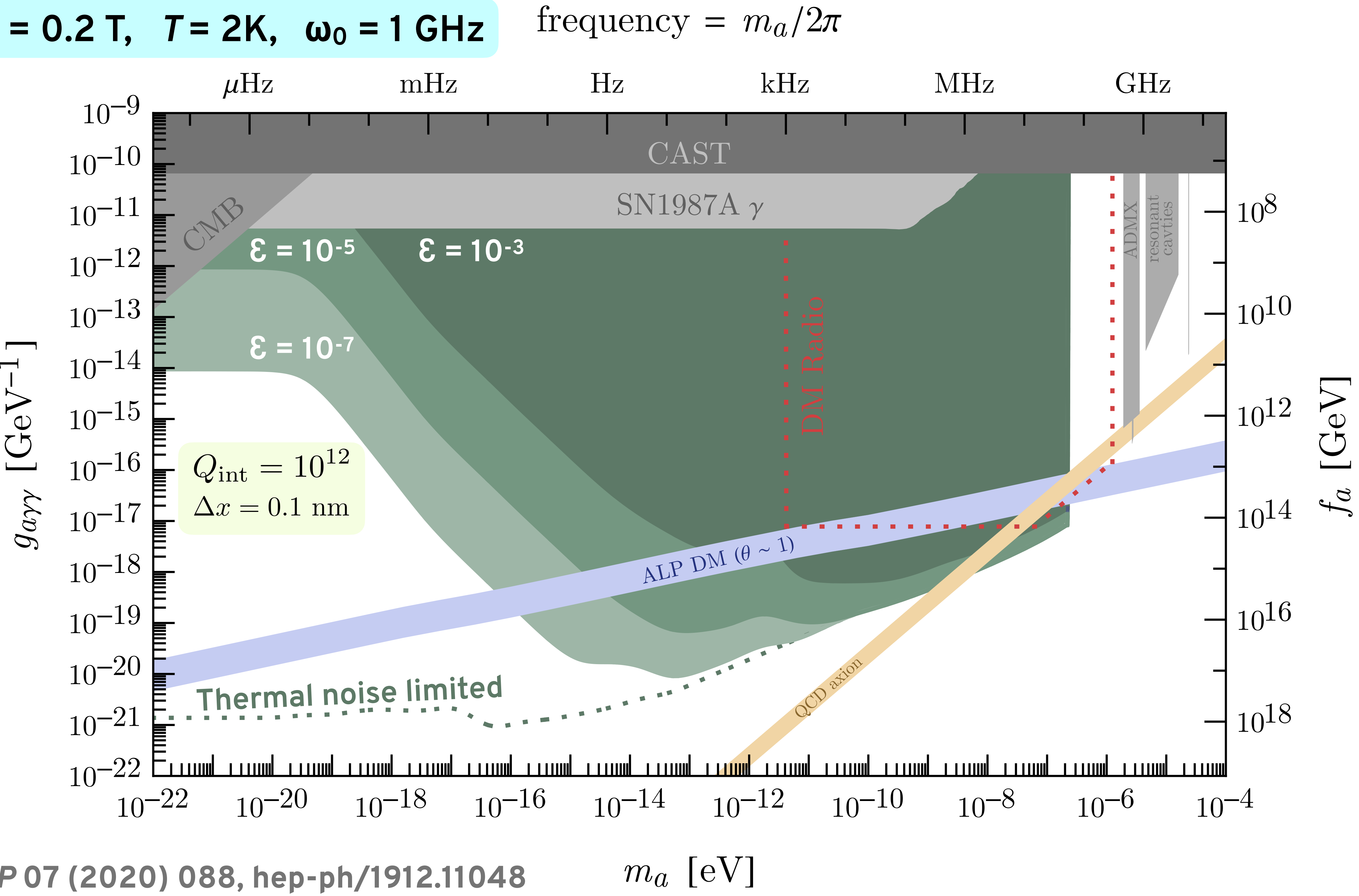
Resonant parameter variations: *mode rejection*

B = 0.2 T, T = 2K, ω_0 = 1 GHz



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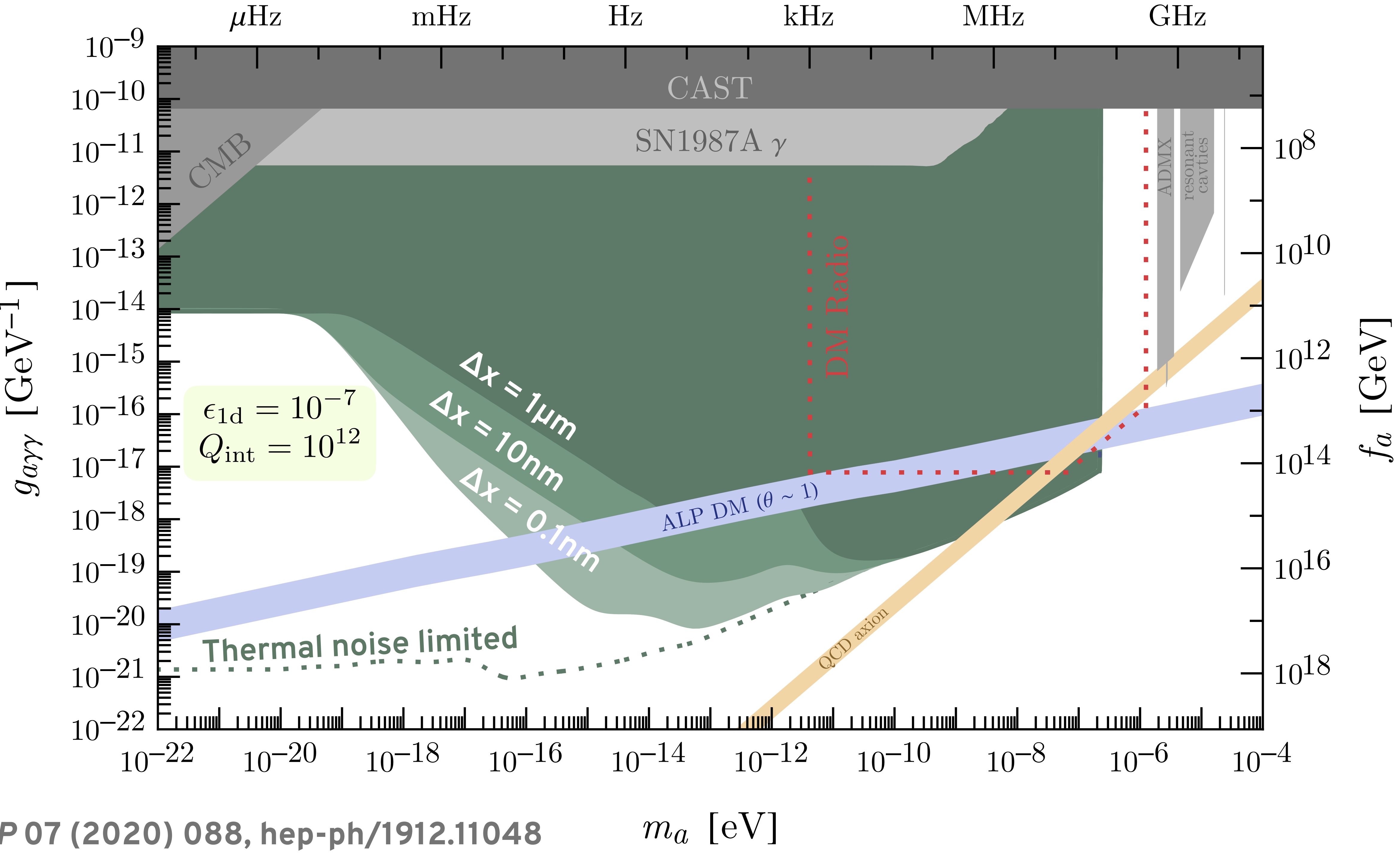

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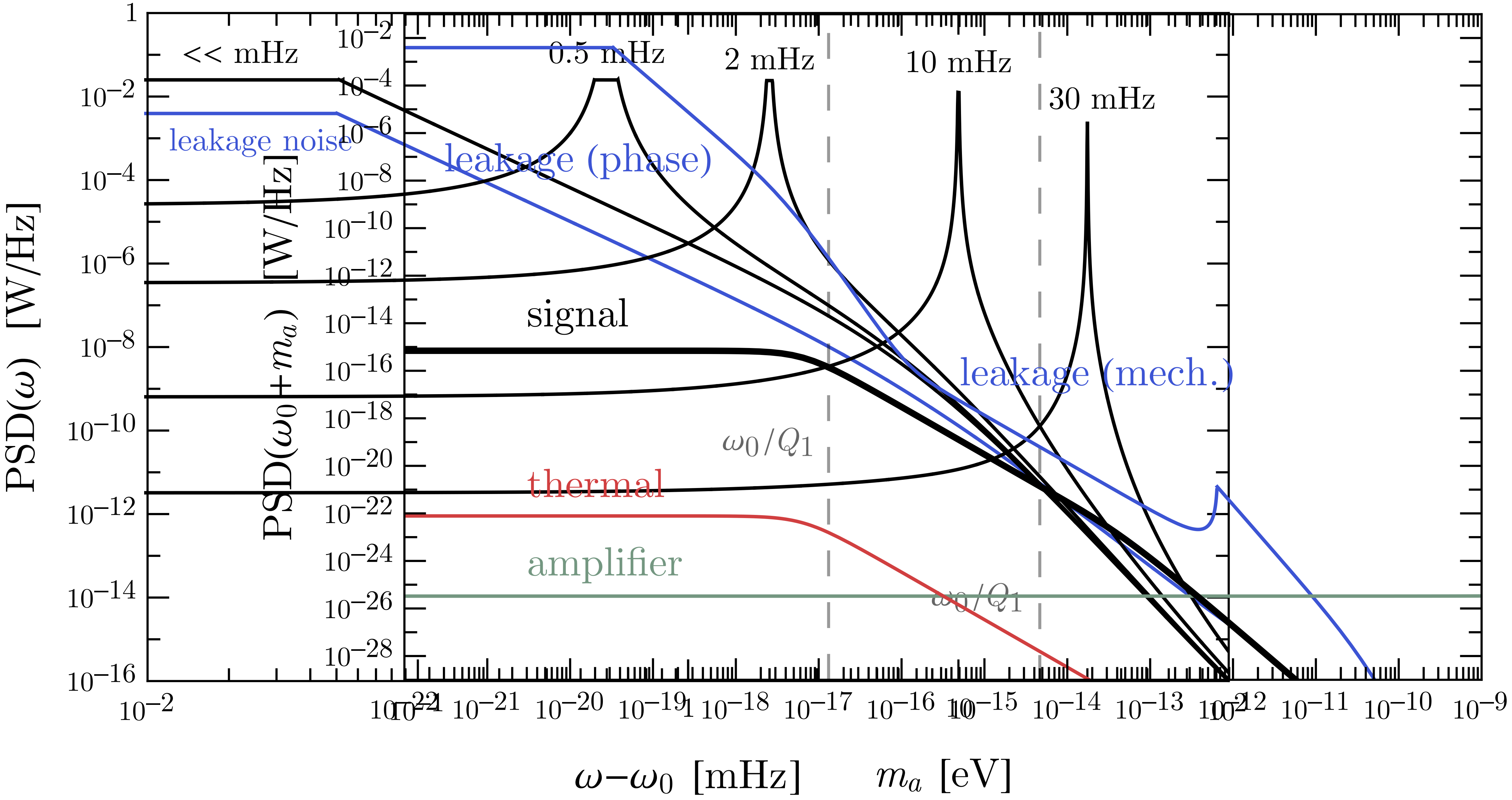
Noise Sources: Broadband search

Leveraging non-zero excitement of signal mode off-resonance



hep-ph/2007.15656

A. Berlin, R. T. D'Agnolo, SARE, K. Zhou

Broadband Signal to Noise

Roughly:

$$\boxed{\mathrm{SNR} \sim \frac{P_{\mathrm{sig}}}{S_n(\omega_{\mathrm{sig}})} \sqrt{\frac{t_{\mathrm{int}}}{\Delta\omega_{\mathrm{sig}}}}}$$

$$\Delta\omega_{\mathrm{sig}} = \max(\Delta\omega_d, \Delta\omega_a)$$

(external oscillator has finite width)

Low masses:

$$\mathrm{SNR} \sim \rho_{\mathrm{DM}} \left(\frac{g_{a\gamma\gamma}\, Q_{\mathrm{int}}}{\omega_0\, \epsilon} \right)^2 \sqrt{t_{\mathrm{int}}\, \Delta\omega_d}$$

High masses:

$$\mathrm{SNR} \sim \rho_{\mathrm{DM}} V_{\mathrm{cav}} \frac{\Delta\omega_r}{S_{\mathrm{amp}}(\omega_{\mathrm{sig}})} \left(\frac{g_{a\gamma\gamma}\, B_0}{m_a} \right)^2 \sqrt{\frac{t_{\mathrm{int}}}{\Delta\omega_a}}$$

Intermediate masses:

$$S_{\mathrm{leak}}(\omega_{\mathrm{sig}}) \sim \epsilon^2\, P_{\mathrm{in}} \left(\frac{\Delta\omega_r}{m_a} \right)^2 S_\varphi(m_a)$$

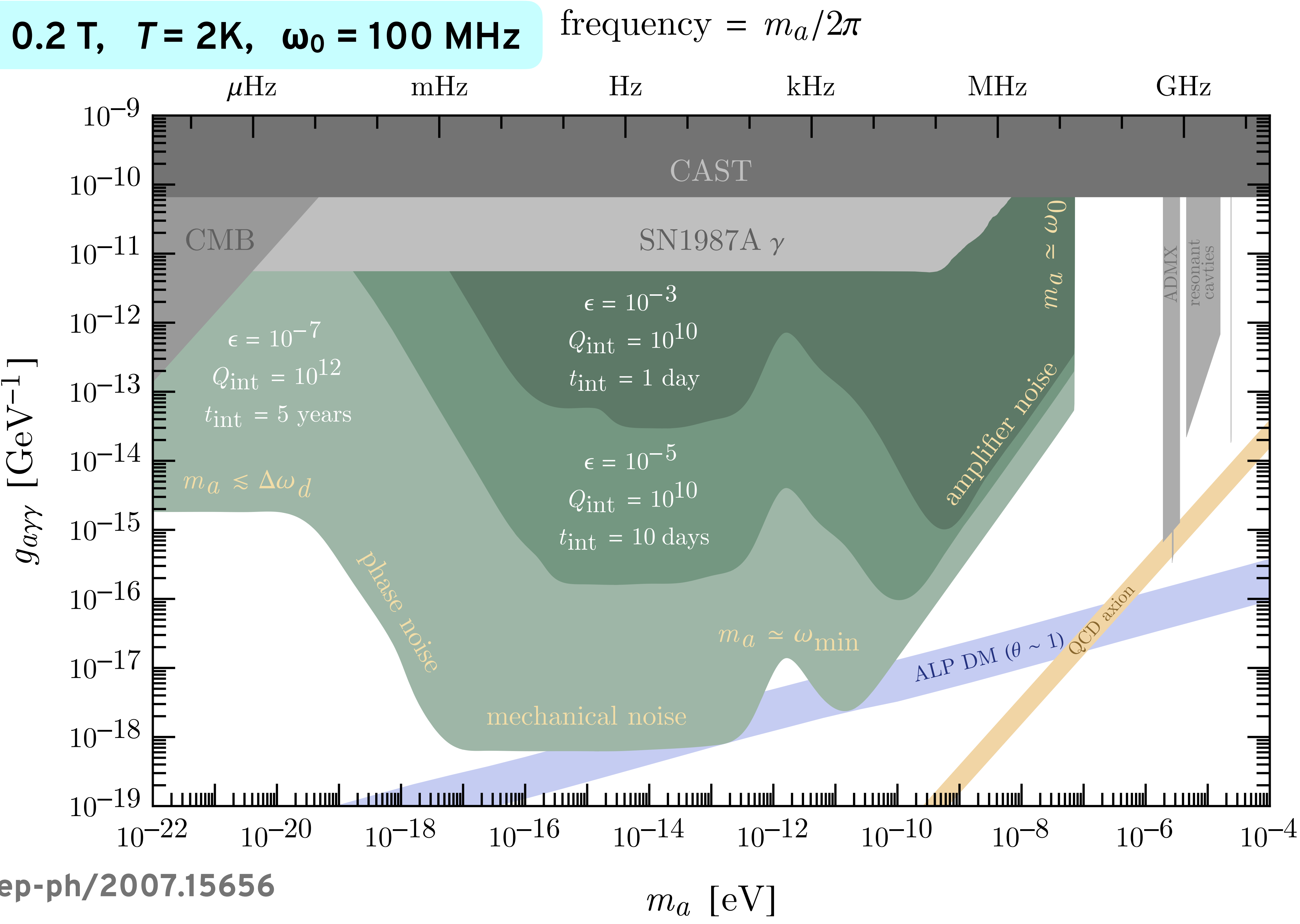
phase-dominated

$$S_{\mathrm{leak}}(\omega_{\mathrm{sig}}) \sim \epsilon^2\, P_{\mathrm{in}} \left(\frac{\Delta\omega_r}{m_a} \right)^2 \frac{\delta^2\, Q_{\mathrm{int}}^2}{\omega_{\mathrm{min}}\, Q_m}$$

mechanical-dominated

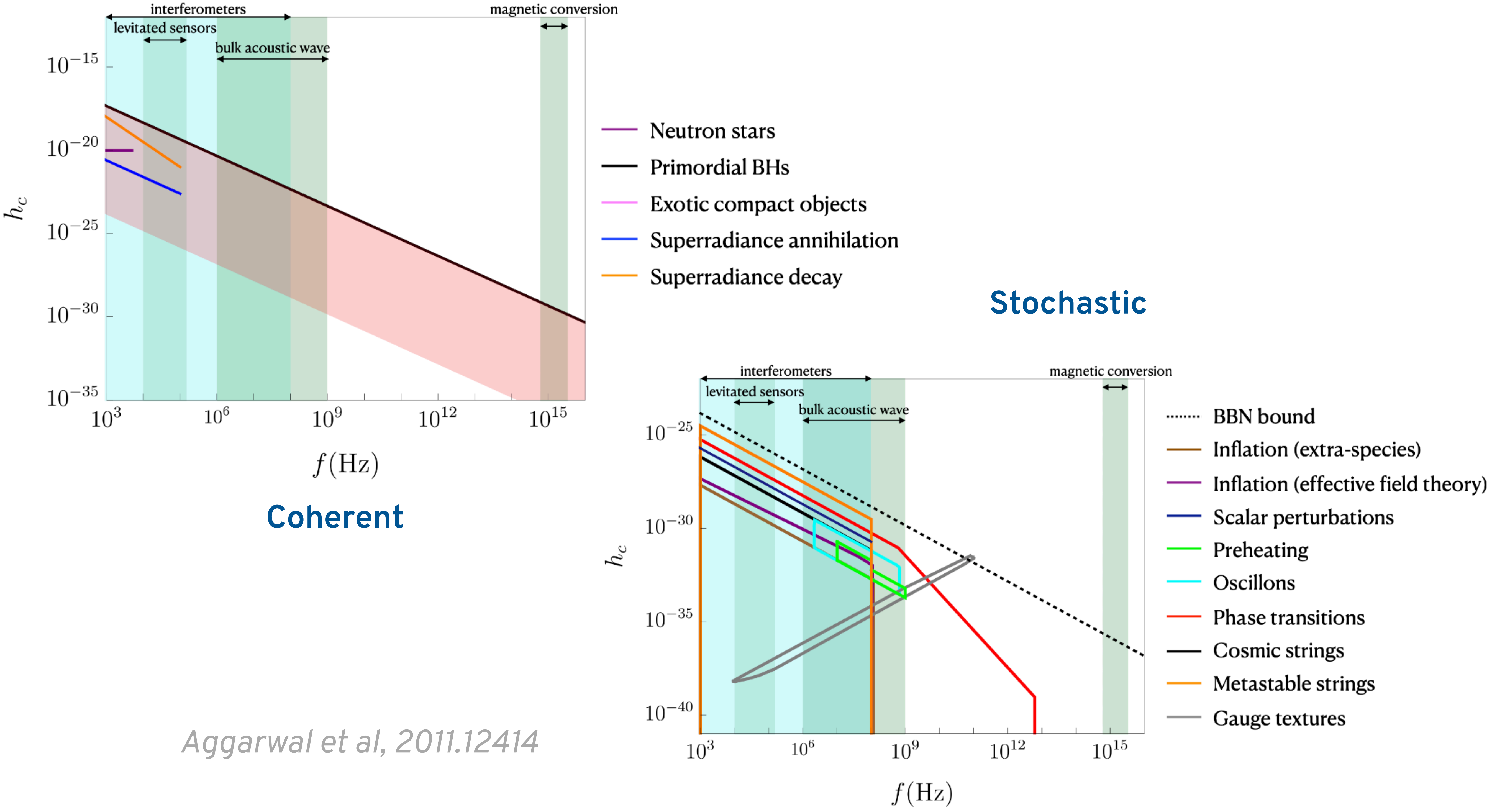
Broadband Axion Resonant Frequency Conversion

B = 0.2 T, T = 2K, ω_0 = 100 MHz



hep-ph/2007.15656

Gravitational Waves?



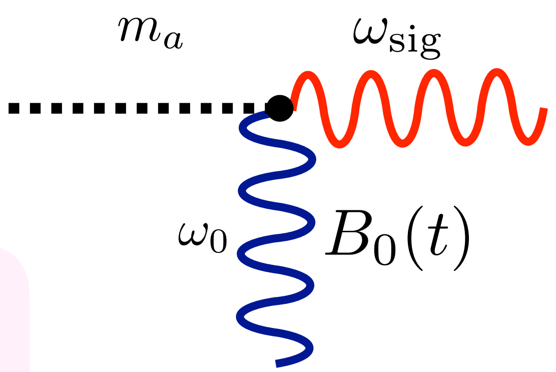
Coherent

Stochastic

Aggarwal et al, 2011.12414

Comparing with Axion

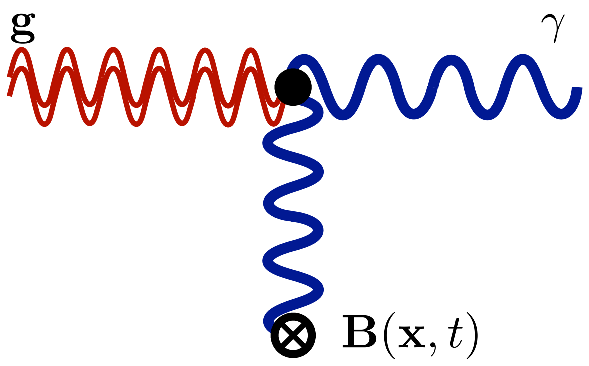
Axion electrodynamics: $\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4}\, a\, F\tilde{F} = -g_{a\gamma\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$



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

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

GW – photon mixing (Gertsenshtein effect)



$$\partial_\mu F^{\mu\nu} = -J^\nu_{\rm SM}\left(1+\frac{1}{2}h\right) + h_\alpha{}^\nu J^\alpha_{\rm SM} - \partial_\mu\left[\frac{1}{2}hF^{\mu\nu} - h_\alpha{}^\mu F^{\alpha\nu} + h_\alpha{}^\nu F^{\alpha\mu}\right]$$

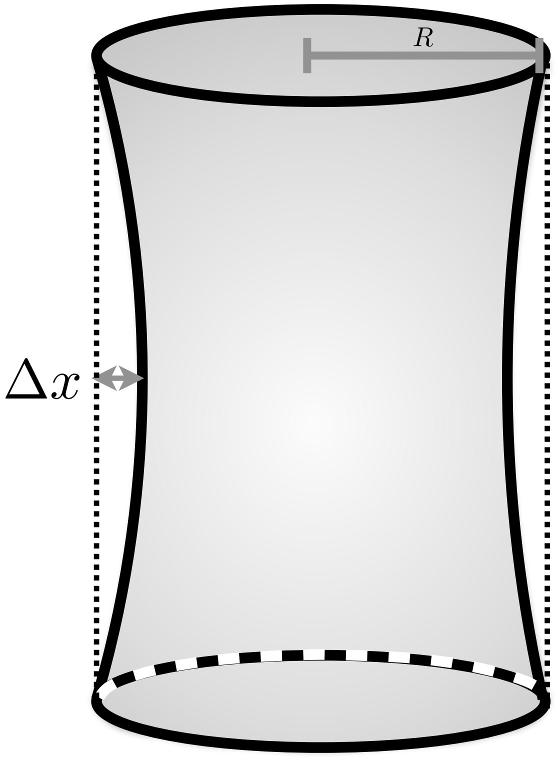
Maxwell's new and improved Equations

GW interaction w/ Cavity Walls

Indirect effect: GWs perturb cavity walls Δx

Cavity modes dependent on geometry

Small perturbations: $\omega_c \rightarrow \omega_c(1 + f(\Delta x))$



Proper detector frame, effect of GW is that of Newtonian force on a test mass:

$$F_i \simeq \frac{m}{2}\ddot{h}_{ij}^{\mathrm{TT}} x^j$$

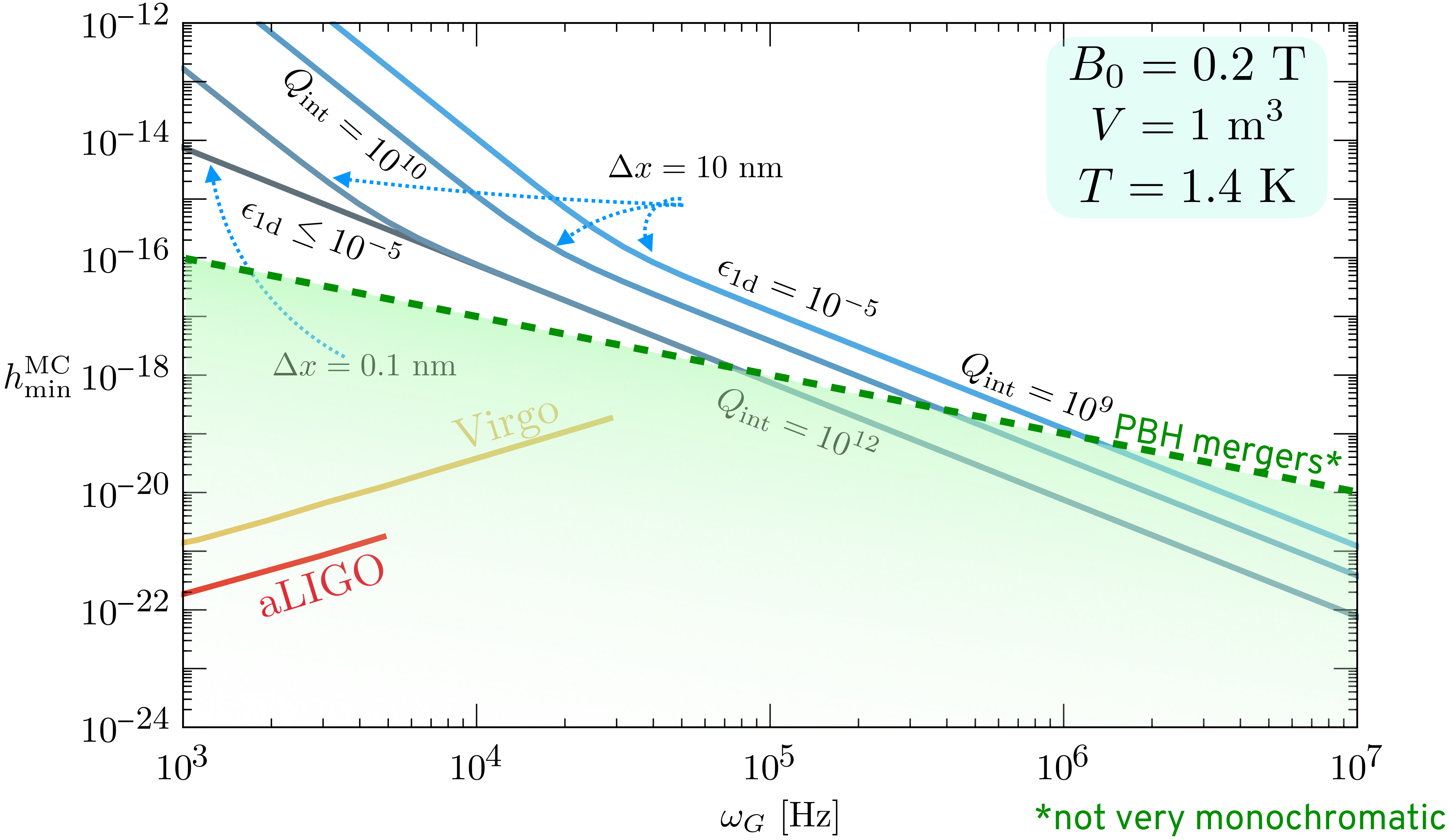
Passing gravitational wave will move walls, spreading power in frequency space

Focus of MAGO collaboration @ CERN in early 2000s – *e.g. gr-qc/0502054*

Reach — Monochromatic source**

***ultra-preliminary*

$$h_{\rm min}^{\rm MC} \sim \frac{1}{\omega_G^2}\left(\frac{T}{\omega_1 Q_1}\right)^{1/2}\left(\frac{\delta\omega}{t_{\rm int}}\right)^{1/4}\frac{1}{E_0 V^{7/6}} \sim 10^{-22}\left(\frac{10^7\ {\rm Hz}}{\omega_G}\right)^2$$



*not very monochromatic

Outlook

Radio-Frequency **up-conversion** approach

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

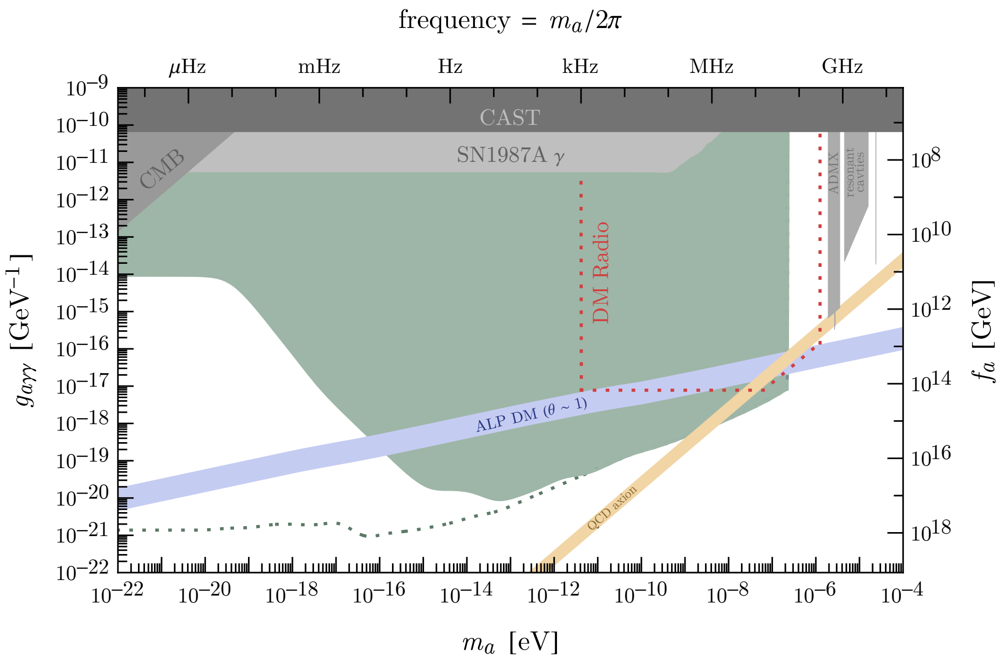
Parametric gain for small axion masses vs. LC Resonator

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

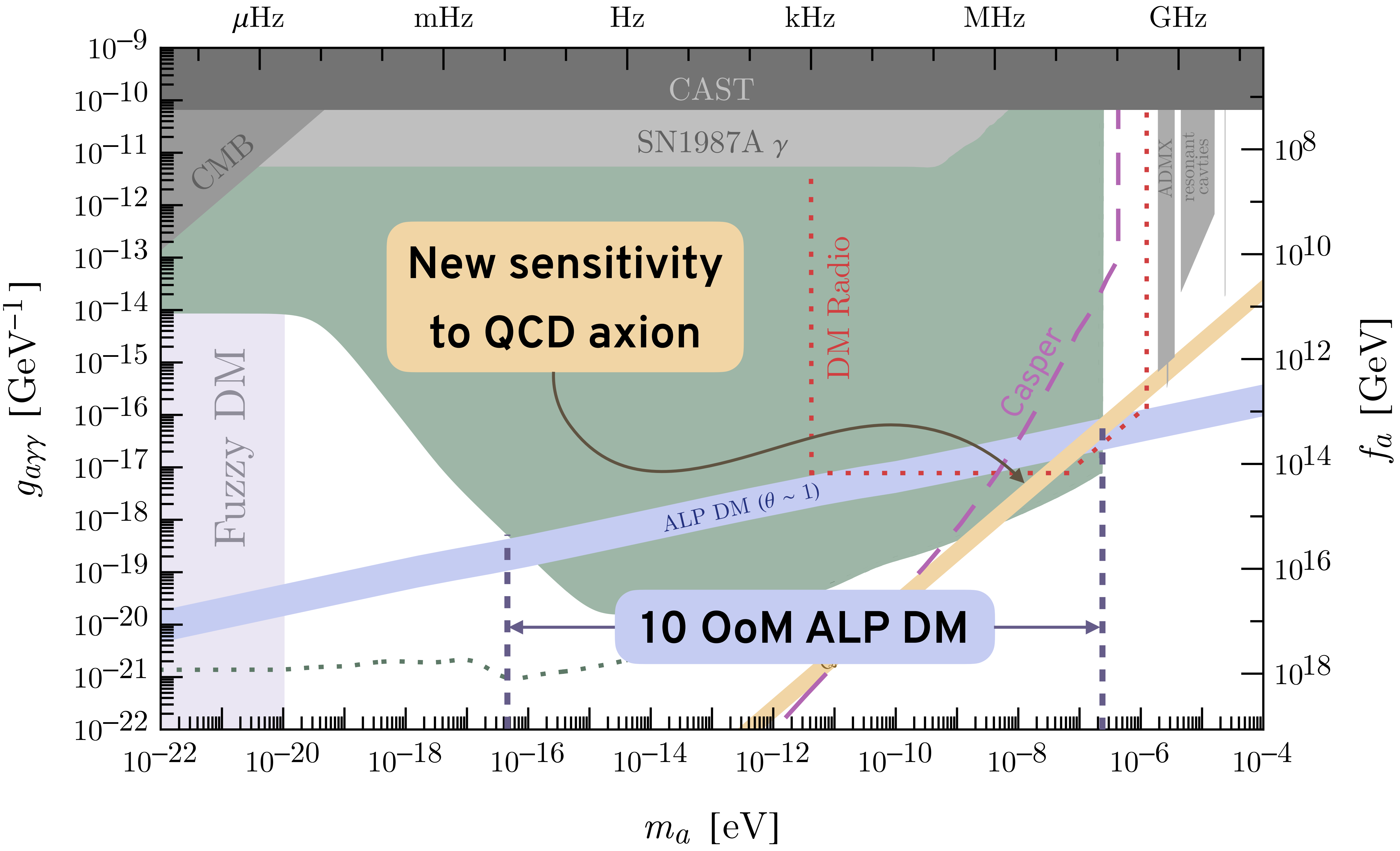
SLAC group seeking internal funding

SRF group @ CERN interested in making preliminary noise measurements

Snowmass LOI *CF2* & *AF5*



Outlook



New sensitivity to QCD axion

10 OoM ALP DM

Backup

Power comparison with static LC resonator

Power for monochromatic background field:

$$P_{\rm sig} \simeq \frac{1}{4} \left(g_{a\gamma\gamma}\, \eta_{10}\, B_0\right)^2 \rho_{\rm DM}\, V \times \begin{cases} Q_1/\omega_1 & \frac{m_a}{Q_a} \ll \frac{\omega_1}{Q_1} \\ \pi Q_a/m_a & \frac{m_a}{Q_a} \gg \frac{\omega_1}{Q_1} \end{cases} ,$$

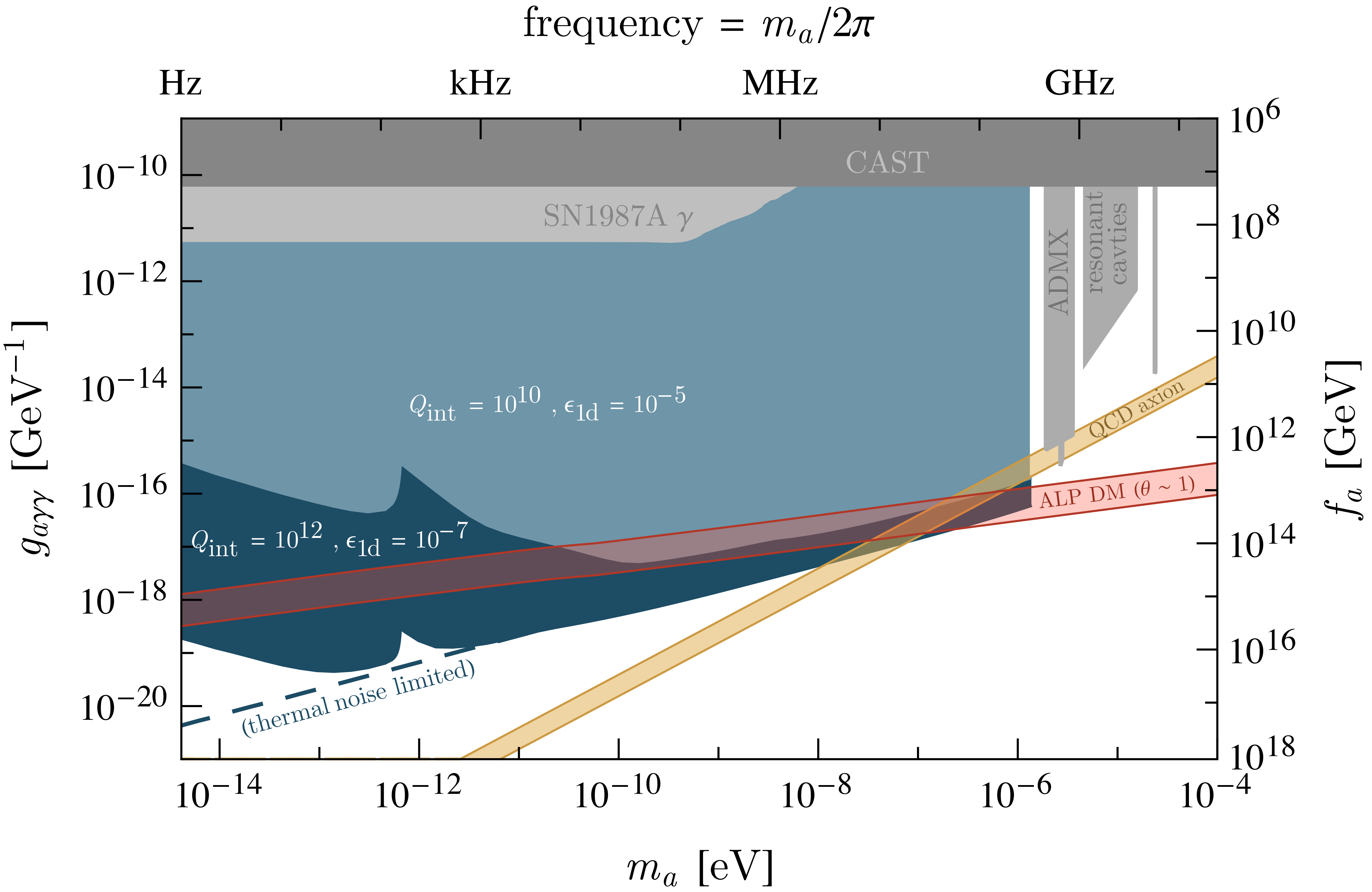
Power for LC resonator:

$$P_{\rm sig}^{\rm (LC)} \sim \left(g_{a\gamma\gamma} B_{\rm LC}\right)^2 \rho_{\rm DM}\, V^{5/3} \min(Q_{\rm LC}, Q_a)\, m_a$$

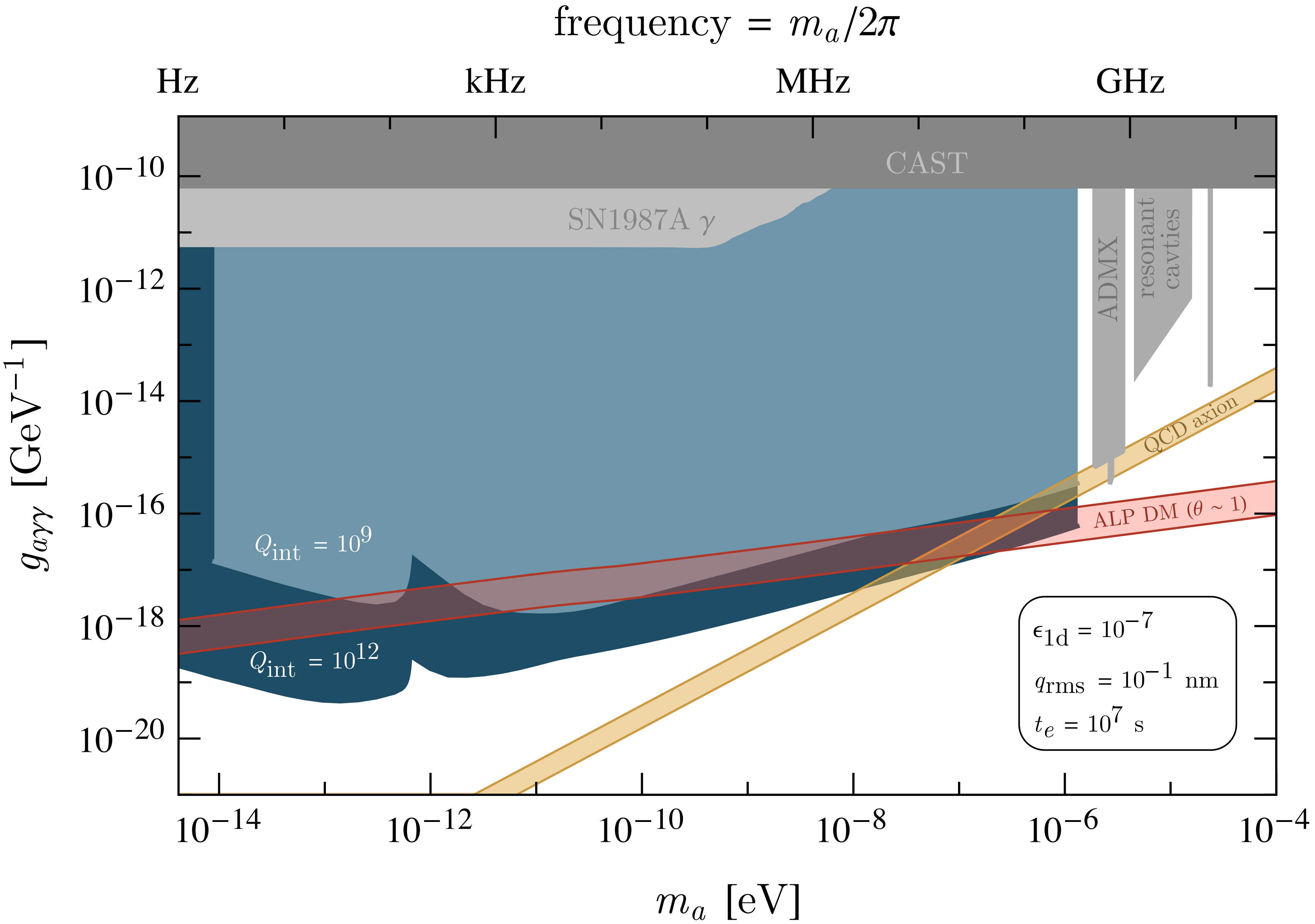
Ratio:

$$\frac{P_{\rm sig}}{P_{\rm sig}^{\rm (LC)}} \sim \left(\frac{0.2\ \rm T}{4\ \rm T}\right)^2 \times \begin{cases} (Q_1/Q_a)^2\, \frac{(\omega_1/Q_1)}{(m_a/Q_a)} & \frac{m_a}{Q_a} \ll \frac{\omega_1}{Q_1} \\ (\omega_1/m_a)^2 & \frac{m_a}{Q_a} \gg \frac{\omega_1}{Q_1} \end{cases}$$

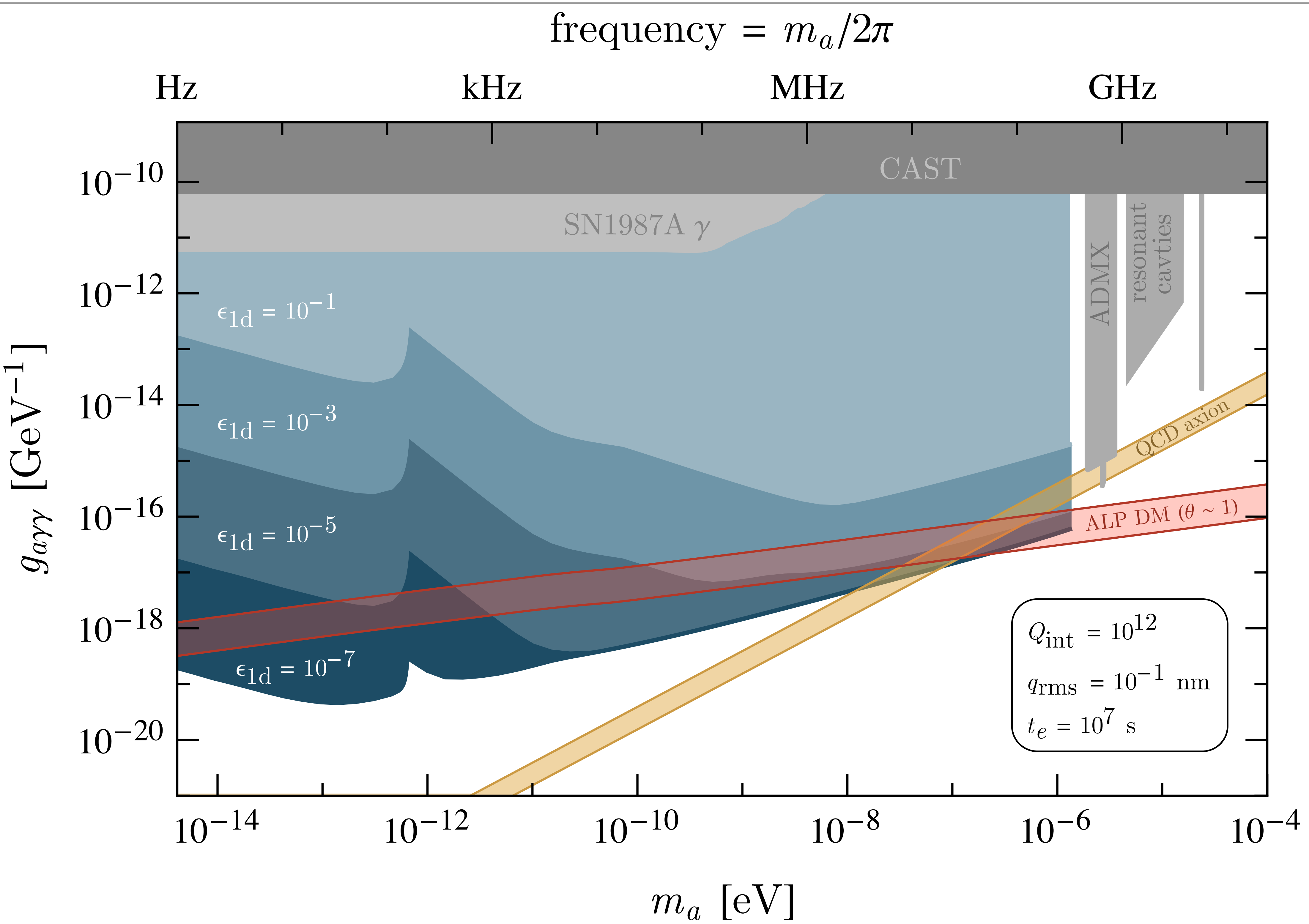
Potential Sensitivity



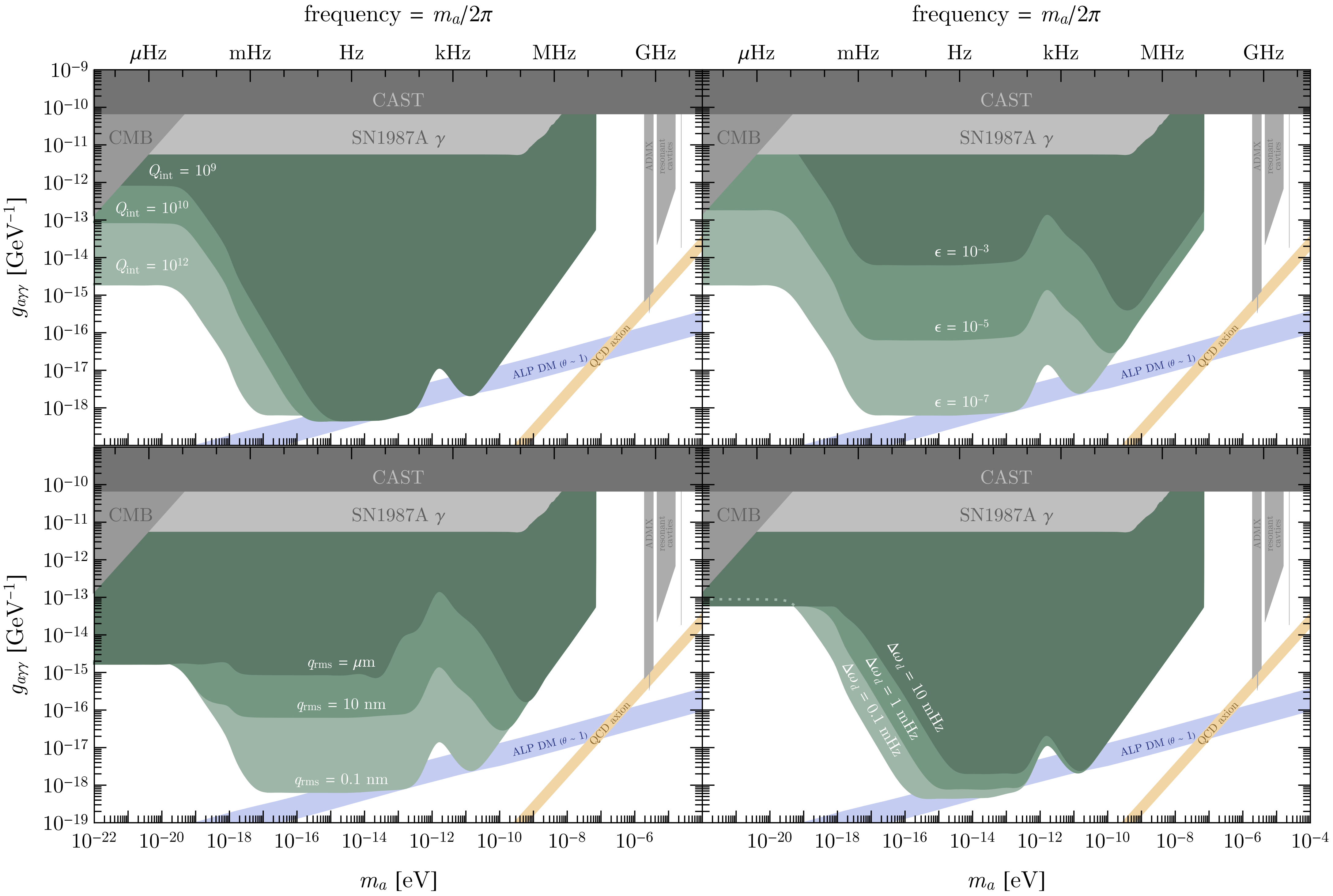
Potential Sensitivity dependences – $Q_{\rm int}$



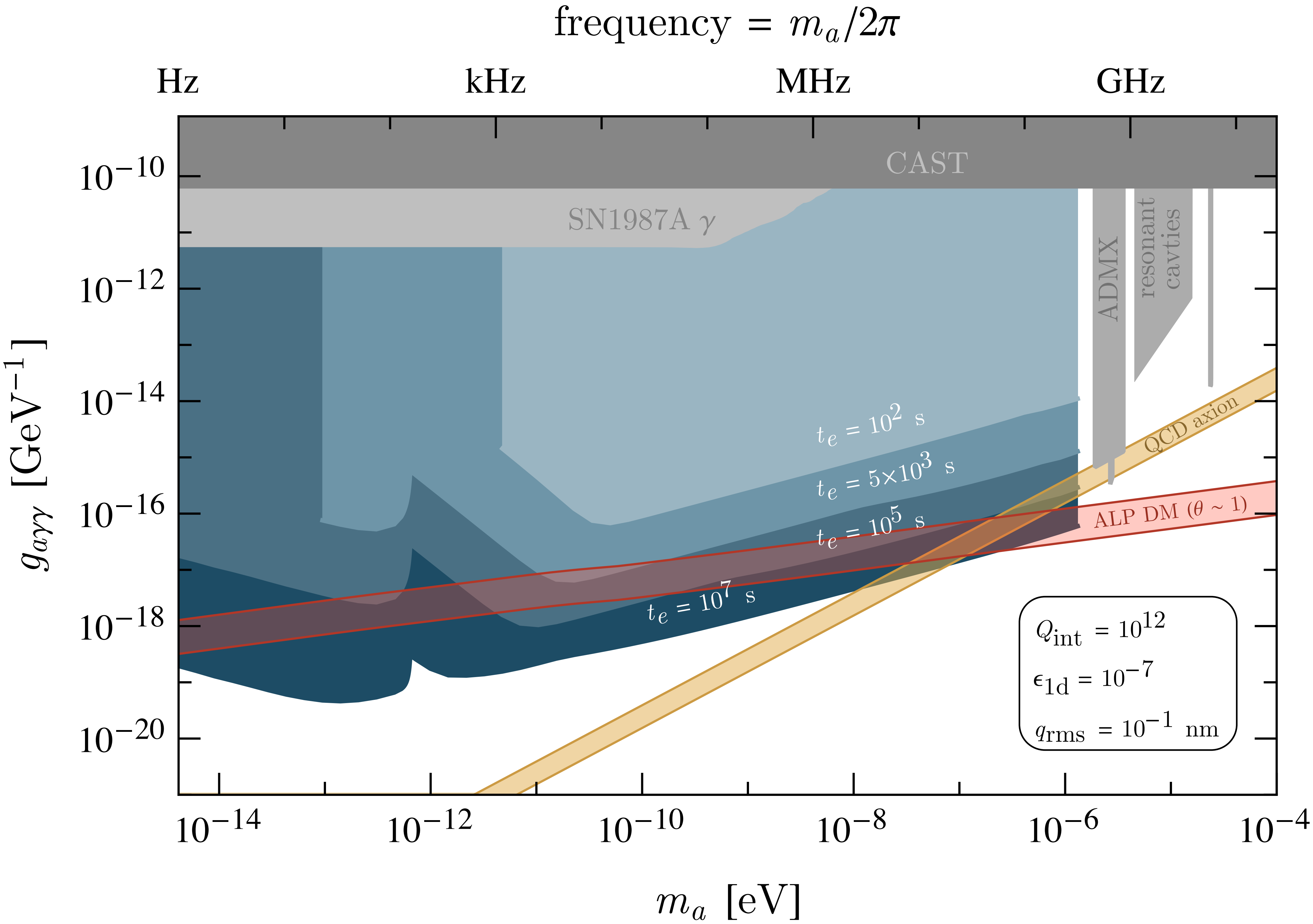
Potential Sensitivity dependences — geom. factor



Broadband Axion Resonant Frequency Conversion



Potential Sensitivity dependences — e-fold time



Statistical treatment

Both signal and noise exponentially distributed:

$$L[\tilde{d}] = \prod_i \frac{e^{-|\tilde{d}_i|^2/(S_s(\omega_i)+S_n(\omega_i))}}{\pi(S_s(\omega_i)+S_n(\omega_i))}$$

Test statistic:

$$q(g_{a\gamma\gamma}) = -2\,\log\left(\frac{L(g_{a\gamma\gamma},\hat{\hat{\theta}}_s,\hat{\hat{\theta}}_n)}{L(\hat{g}_{a\gamma\gamma},\hat{\theta}_s,\hat{\theta}_n)}\right)\Theta(g_{a\gamma\gamma}^2-\hat{g}_{a\gamma\gamma}^2)$$

For $t_{\rm int} \gg \tau_a$ Wilks' theorem implies

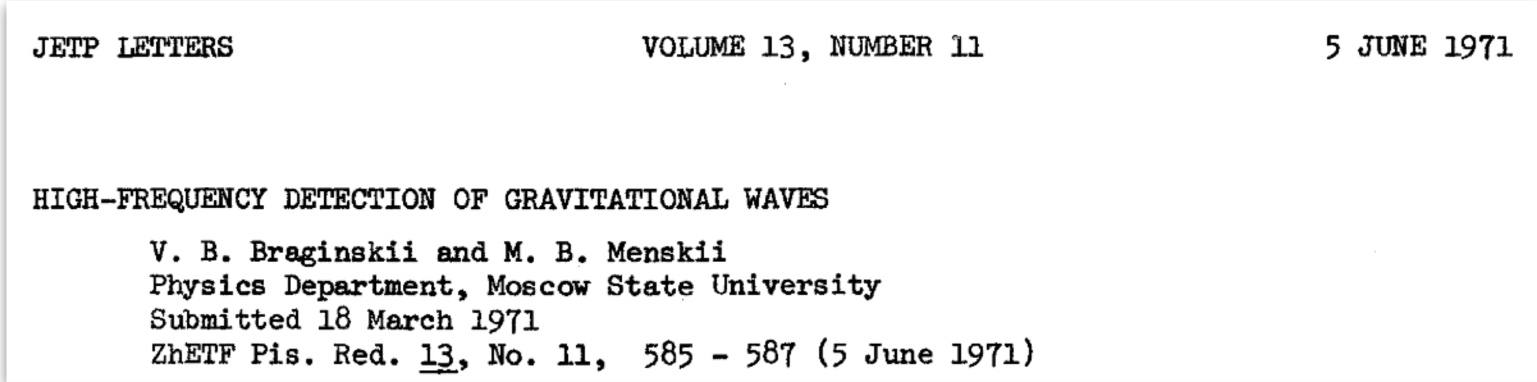
$$q(g_{a\gamma\gamma}) \simeq \sum_i \left(\frac{g_{a\gamma\gamma}^2\,\lambda_{s,i}(\hat{\hat{\theta}}_s)}{\lambda_{n,i}(\hat{\hat{\theta}}_n)}\right)^2 \simeq \frac{t_{\rm int}}{2\pi}\int_0^\infty d\omega\,\left(\frac{S_s(\omega)}{S_n(\omega)}\right)^2 \qquad \mathrm{SNR}(t_{\rm int}\gg\tau_a) \gtrsim \begin{cases} 1.3 & 90\%\ \mathrm{C.L.} \\ 1.6 & 95\%\ \mathrm{C.L.}\ , \end{cases}$$

For $t_{\rm int} \ll \tau_a$ axion signal in single DFT bin

$$q(g_{a\gamma\gamma}^2,S) = 2\times\begin{cases} 0 & g_{a\gamma\gamma}^2\,\lambda_s+\lambda_n < S \\ \frac{S}{g_{a\gamma\gamma}^2\,\lambda_s+\lambda_n} - 1 + \log\frac{g_{a\gamma\gamma}^2\,\lambda_s+\lambda_n}{S} & \lambda_n \le S \le g_{a\gamma\gamma}^2\,\lambda_s+\lambda_n \\ \frac{S}{g_{a\gamma\gamma}^2\,\lambda_s+\lambda_n} - \frac{S}{\lambda_n} + \log\frac{g_{a\gamma\gamma}^2\,\lambda_s+\lambda_n}{\lambda_n} & S < \lambda_n \end{cases} \qquad \mathrm{SNR}(t_{\rm int}\ll\tau_a) \gtrsim \begin{cases} 5.6 & 90\%\ \mathrm{C.L.} \\ 12.5 & 95\%\ \mathrm{C.L.} \end{cases}$$

GW interaction w/ EM strategy: venerable history

Braginskii & Menskii, 1971

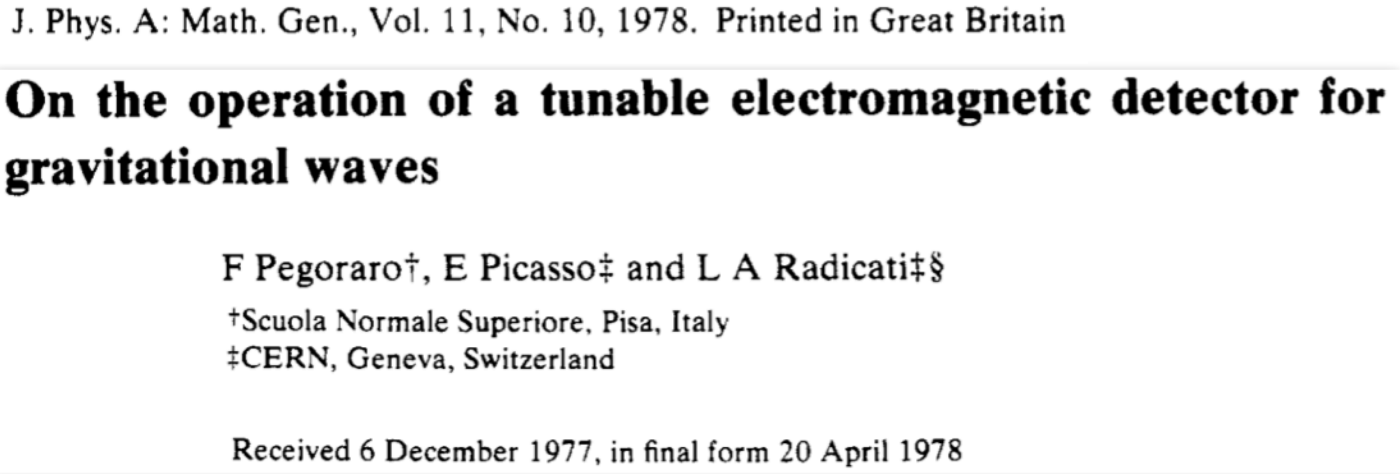


JETP LETTERS VOLUME 13, NUMBER 11 5 JUNE 1971

HIGH-FREQUENCY DETECTION OF GRAVITATIONAL WAVES

V. B. Braginskii and M. B. Menskii
Physics Department, Moscow State University
Submitted 18 March 1971
ZhETF Pis. Red. 13, No. 11, 585 - 587 (5 June 1971)

Pegoraro, Picasso & Radicati, 1978



J. Phys. A: Math. Gen., Vol. 11, No. 10, 1978. Printed in Great Britain

On the operation of a tunable electromagnetic detector for gravitational waves

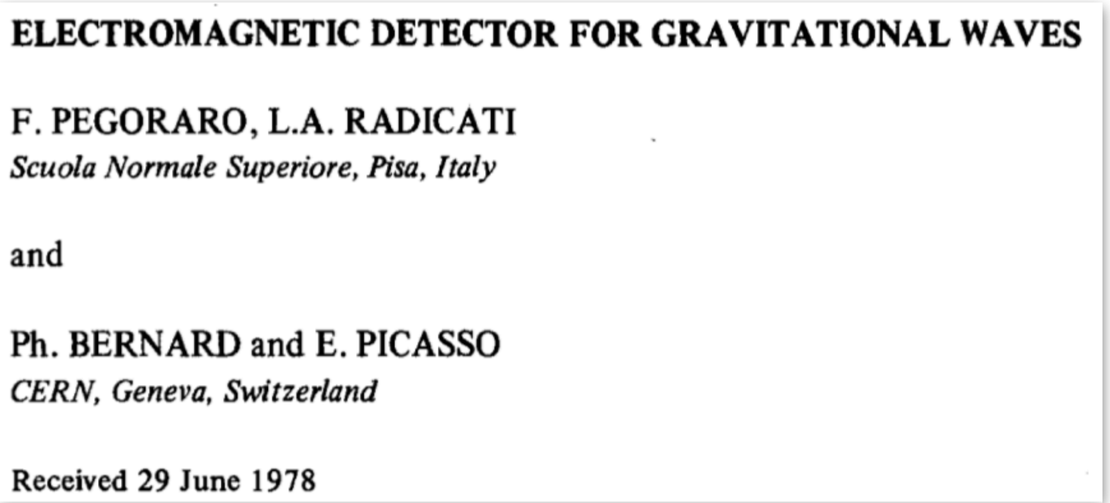
F Pegoraro†, E Picasso‡ and L A Radicati‡§
†Scuola Normale Superiore, Pisa, Italy
‡CERN, Geneva, Switzerland

Received 6 December 1977, in final form 20 April 1978

Pegoraro, Radicati, Bernard & Picasso, 1978

Led to MAGO collaboration @ CERN

early 2000's



ELECTROMAGNETIC DETECTOR FOR GRAVITATIONAL WAVES

F. PEGORARO, L.A. RADICATI
Scuola Normale Superiore, Pisa, Italy

and

Ph. BERNARD and E. PICASSO
CERN, Geneva, Switzerland

Received 29 June 1978

See also Caves 1979, Reece, Reiner & Melissinos 1982, 1984

Framing the question

Proper detector frame

$$ds^2 \simeq -\, dt^2 \left(1 + \overset{\textit{inert. acc.}}{2\mathbf{a}\cdot\mathbf{x}} + \overset{\textit{grav. redshift}}{(\mathbf{a}\cdot\mathbf{x})^2} - \overset{\textit{rotation t-dilate}}{(\boldsymbol{\Omega}\times\mathbf{x})^2} + \boxed{R_{0i0j}x^i x^j}\right)$$
$$+\, 2dt\,dx^i \left(\overset{\textit{Sagnac effect}}{\epsilon_{ijk}\Omega^j x^k} - \frac{2}{3}R_{0jik}x^j x^k\right) + dx^i dx^j \left(\delta_{ij} - \frac{1}{3}R_{ikjl}x^k x^l\right)$$

Gravitational wave in TT gauge

$$\partial_\mu h^{\mu\nu} = 0, \quad h_\mu{}^\mu = 0, \quad h_{00} = h_{0i} = 0$$

Riemann takes simple form

$$\boxed{R_{0i0j} = -\frac{1}{2}\ddot{h}^{\mathrm{TT}}_{ij}}$$

Framing the question

Proper detector frame

$$ds^2 \simeq -dt^2\left(1 - \frac{1}{2}\ddot{h}_{ij}^{\mathrm{TT}} x^i x^j\right) + dx^i dx^i$$

Maxwell’s new and improved equations, roughly:

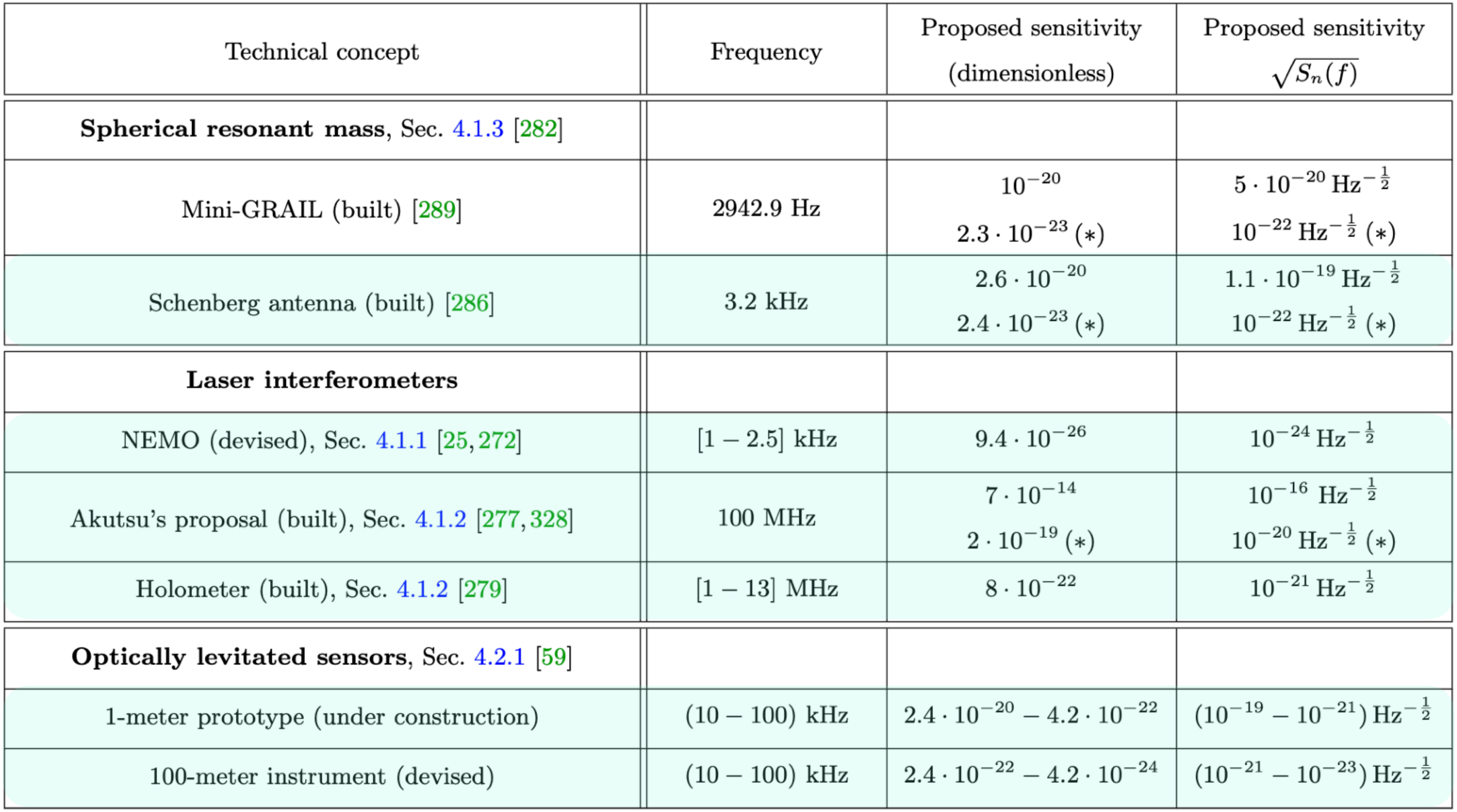
$$\nabla \cdot \mathbf{E} = \rho(1 - h_{00}) + \nabla h_{00} \cdot \mathbf{E}$$

$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = \mathbf{J} + \partial_t(h_{00}\mathbf{E})$$

Generation of EM wave from GW and background field:

$$\Box \mathbf{E} = -\partial_t^2(h_{00}\mathbf{E}_0)$$

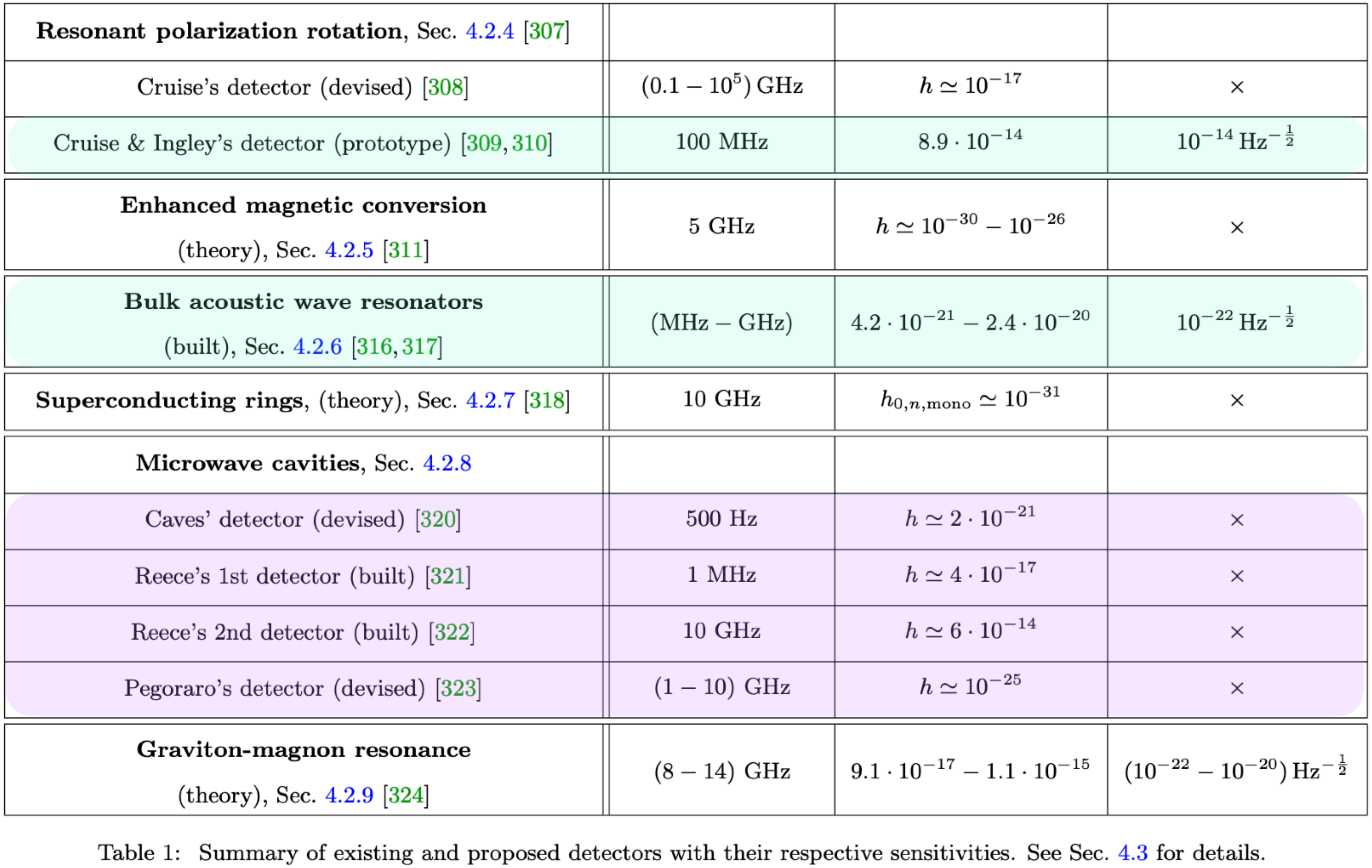
Experimental context



Technical concept	Frequency	Proposed sensitivity (dimensionless)	Proposed sensitivity $\sqrt{S_n(f)}$
Spherical resonant mass, Sec. 4.1.3 [282]			
Mini-GRAIL (built) [289]	2942.9 Hz	10^{-20} $2.3 \cdot 10^{-23}$ $(*)$	$5 \cdot 10^{-20}\,\mathrm{Hz}^{-\frac{1}{2}}$ $10^{-22}\,\mathrm{Hz}^{-\frac{1}{2}}$ $(*)$
Schenberg antenna (built) [286]	3.2 kHz	$2.6 \cdot 10^{-20}$ $2.4 \cdot 10^{-23}$ $(*)$	$1.1 \cdot 10^{-19}\,\mathrm{Hz}^{-\frac{1}{2}}$ $10^{-22}\,\mathrm{Hz}^{-\frac{1}{2}}$ $(*)$
Laser interferometers			
NEMO (devised), Sec. 4.1.1 [25,272]	$[1 - 2.5]$ kHz	$9.4 \cdot 10^{-26}$	$10^{-24}\,\mathrm{Hz}^{-\frac{1}{2}}$
Akutsu's proposal (built), Sec. 4.1.2 [277,328]	100 MHz	$7 \cdot 10^{-14}$ $2 \cdot 10^{-19}$ $(*)$	$10^{-16}\,\mathrm{Hz}^{-\frac{1}{2}}$ $10^{-20}\,\mathrm{Hz}^{-\frac{1}{2}}$ $(*)$
Holometer (built), Sec. 4.1.2 [279]	$[1 - 13]$ MHz	$8 \cdot 10^{-22}$	$10^{-21}\,\mathrm{Hz}^{-\frac{1}{2}}$
Optically levitated sensors, Sec. 4.2.1 [59]			
1-meter prototype (under construction)	$(10 - 100)$ kHz	$2.4 \cdot 10^{-20} - 4.2 \cdot 10^{-22}$	$(10^{-19} - 10^{-21})\,\mathrm{Hz}^{-\frac{1}{2}}$
100-meter instrument (devised)	$(10 - 100)$ kHz	$2.4 \cdot 10^{-22} - 4.2 \cdot 10^{-24}$	$(10^{-21} - 10^{-23})\,\mathrm{Hz}^{-\frac{1}{2}}$

Aggarwal et al, 2011.12414

Experimental context



Resonant polarization rotation, Sec. 4.2.4 [307]			
Cruise's detector (devised) [308]	$(0.1 - 10^5)$ GHz	$h \simeq 10^{-17}$	×
Cruise & Ingley's detector (prototype) [309, 310]	100 MHz	$8.9 \cdot 10^{-14}$	$10^{-14}\,\mathrm{Hz}^{-\frac{1}{2}}$
Enhanced magnetic conversion (theory), Sec. 4.2.5 [311]	5 GHz	$h \simeq 10^{-30} - 10^{-26}$	×
Bulk acoustic wave resonators (built), Sec. 4.2.6 [316, 317]	(MHz – GHz)	$4.2 \cdot 10^{-21} - 2.4 \cdot 10^{-20}$	$10^{-22}\,\mathrm{Hz}^{-\frac{1}{2}}$
Superconducting rings, (theory), Sec. 4.2.7 [318]	10 GHz	$h_{0,n,\mathrm{mono}} \simeq 10^{-31}$	×
Microwave cavities, Sec. 4.2.8			
Caves' detector (devised) [320]	500 Hz	$h \simeq 2 \cdot 10^{-21}$	×
Reece's 1st detector (built) [321]	1 MHz	$h \simeq 4 \cdot 10^{-17}$	×
Reece's 2nd detector (built) [322]	10 GHz	$h \simeq 6 \cdot 10^{-14}$	×
Pegoraro's detector (devised) [323]	$(1 - 10)$ GHz	$h \simeq 10^{-25}$	×
Graviton-magnon resonance (theory), Sec. 4.2.9 [324]	$(8 - 14)$ GHz	$9.1 \cdot 10^{-17} - 1.1 \cdot 10^{-15}$	$(10^{-22} - 10^{-20})\,\mathrm{Hz}^{-\frac{1}{2}}$

Table 1: Summary of existing and proposed detectors with their respective sensitivities. See Sec. 4.3 for details.

Aggarwal et al, 2011.12414

Signal to Noise GWs

Roughly:

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

Monochromatic:

$$S^{\rm MC}_{\rm sig}(\omega) = \frac{\omega_{\rm sig}}{Q_{\rm sig}} \frac{\omega^4 (\eta E_0 h_0)^2 V}{(\omega^2_{\rm sig} - \omega^2)^2 + (\omega \omega_{\rm sig}/Q_{\rm sig})^2} S_{e_0}(\omega - \omega_G)$$

$$h_0 \sim \omega_G^2 V^{2/3} h$$

Flat:

$$S^{\rm Flat}_{\rm sig}(\omega) = \frac{\omega_{\rm sig}}{Q_{\rm sig}} \frac{\omega^4 (\eta E_0)^2 V}{(\omega^2_{\rm sig} - \omega^2)^2 + (\omega \omega_{\rm sig}/Q_{\rm sig})^2} \frac{3H_0^2}{8} \left(\frac{\Omega_{\rm GW}(\omega - \omega_0)}{(\omega - \omega_0)^3} + \frac{\Omega_{\rm GW}(\omega + \omega_0)}{(\omega + \omega_0)^3} \right)$$

$$\Omega_{\rm GW} \sim \frac{1}{3H_0^2} \omega^2 h^2_{\rm sto}$$

Design params:

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

$$h^{\rm MC}_{\rm min} \sim \frac{1}{\omega_G^2} \left(\frac{T}{\omega_1 Q_1} \right)^{1/2} \left(\frac{\delta\omega}{t_{\rm int}} \right)^{1/4} \frac{1}{E_0 V^{7/6}} \sim 10^{-22} \left(\frac{10^7\ \mathrm{Hz}}{\omega_G} \right)^2$$