Heterodyne Detection of Axions & GWs in SRF Cavities

The Cavity Variations

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Université de Genève

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A. Berlin, R. T. D'Agnolo, **SARE,** P. Schuster, N. Toro, C. Nantista, J. Neilson, S. Tantawi, K. Zhou

***PRD* 104 (2021) 11, L111701, hep-ph/2007.15656**

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

PRD 108 8, 084058 hep-ph/2303.01518

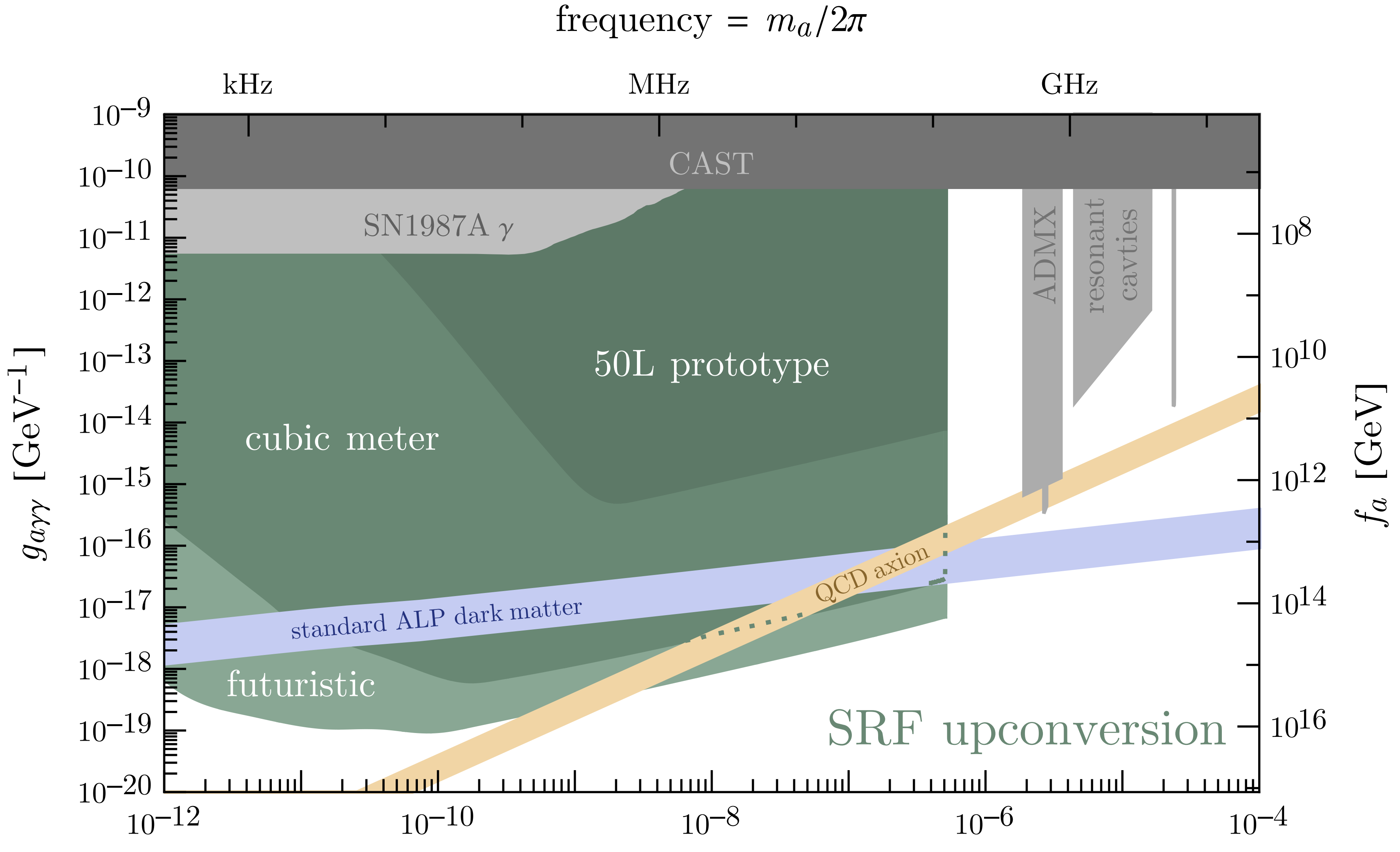
A. Berlin, D. Blas, R. T. D'Agnolo, **SARE,** R. Harnik, Y. Kahn, J. Schütte-Engel, M. Wentzel

High-level Summary

Search for weakly-coupled signals in a *loaded* SRF cavity

Oscillating background B-field: **heterodyne up-conversion approach decouples input ω_{in} from V_{det}**

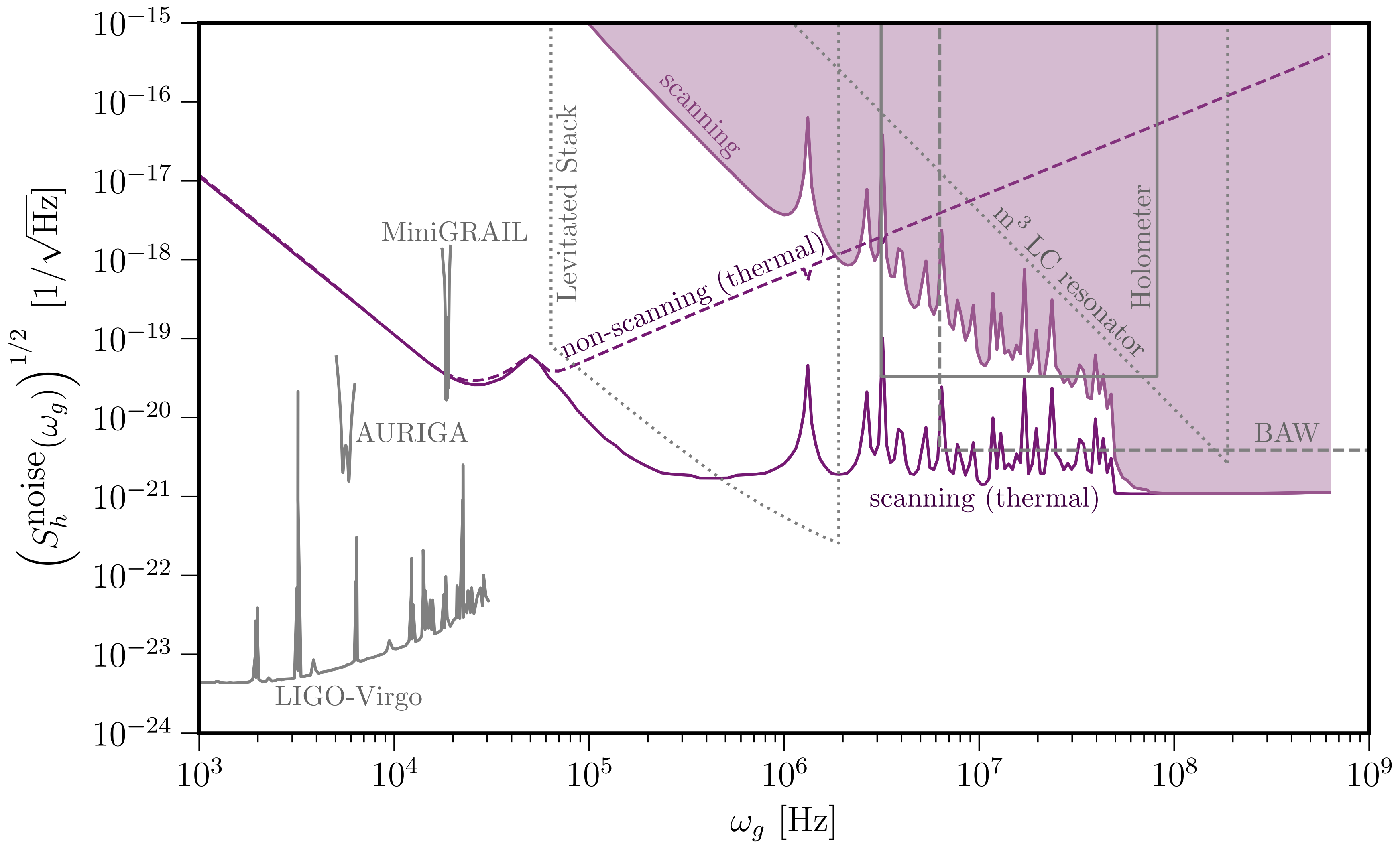
Axion Dark Matter



$$\mathcal{L}_{\text{in}} \sim -g_{a\gamma\gamma} a F \tilde{F}$$

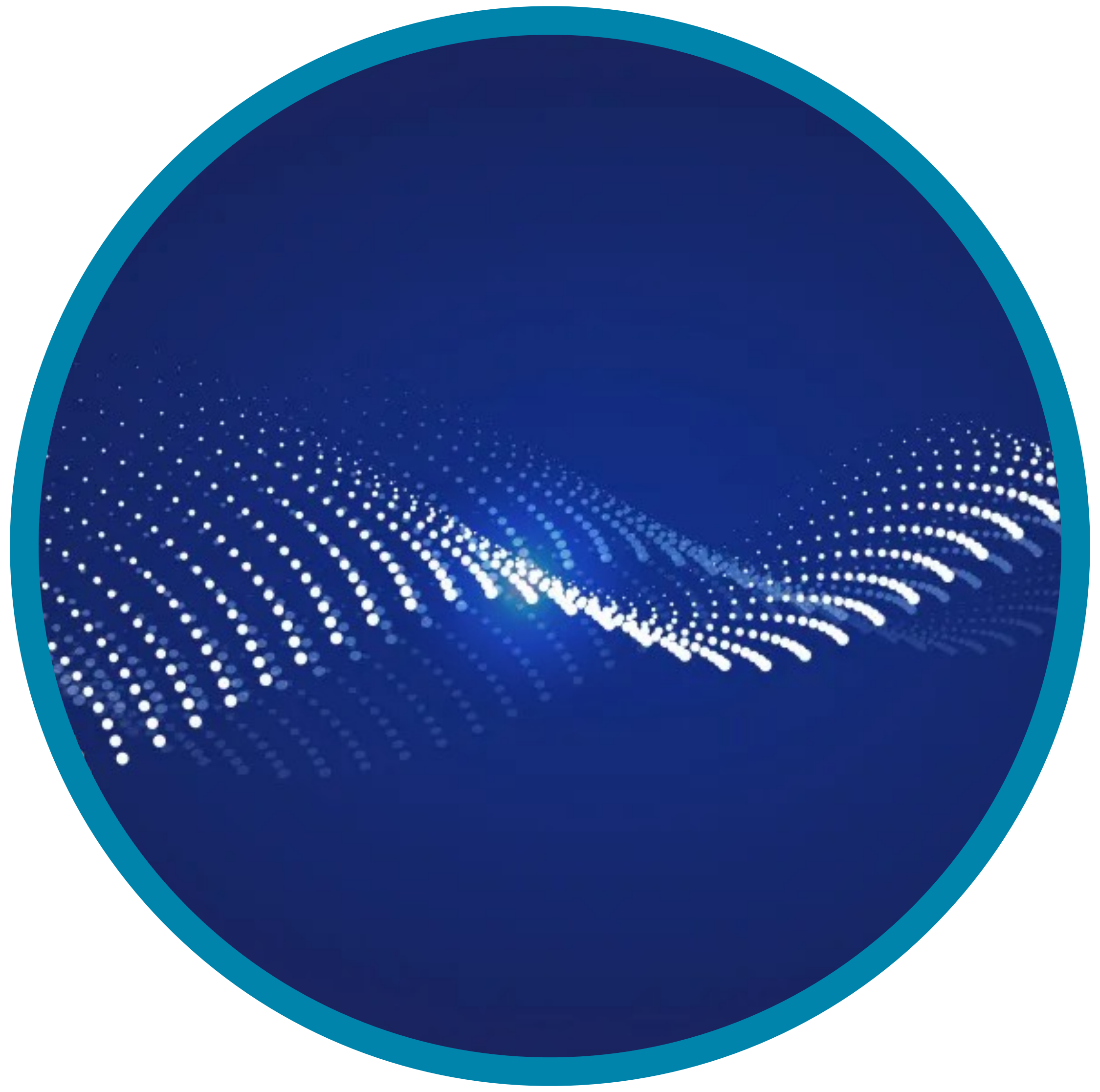
$$\omega_{\text{sig}} = \omega_0 \pm \omega_{\text{in}}$$

Gravitational Waves



$$\mathcal{L}_{\text{in}} \sim h_{\mu\nu} T^{\mu\nu}$$

Axion Dark Matter



Axion, ALPs and Axion Electrodynamics

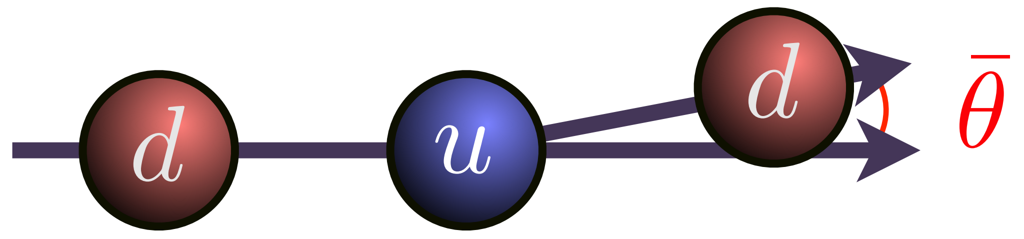
Axion introduced to solve strong CP problem

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

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

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

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



Mixing w/ pion or from full theory:

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

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

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

Maxwell's new and improved Equations

Axions and Cavities

FoM:

$$P_{\rm sig} \sim \omega_{\rm sig}^2 B_a^2 V \min\left(\frac{1}{\Delta\omega_r}, \frac{1}{\Delta\omega_a}\right)$$

and/or $$\mathcal{R} \sim \frac{\Delta\omega_r}{t_{\rm int}}\mathrm{SNR}^2$$

Axions and Cavities

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

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Minimise: $P_{\rm n}$

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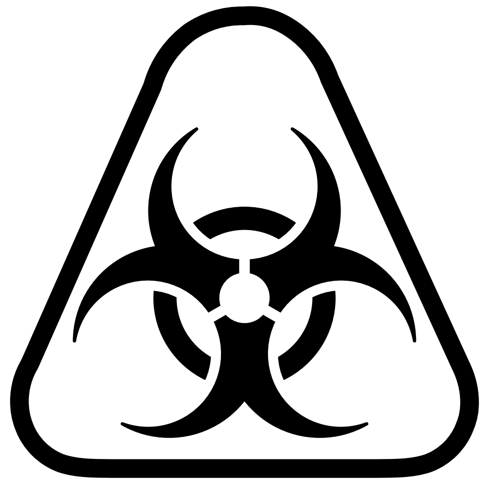


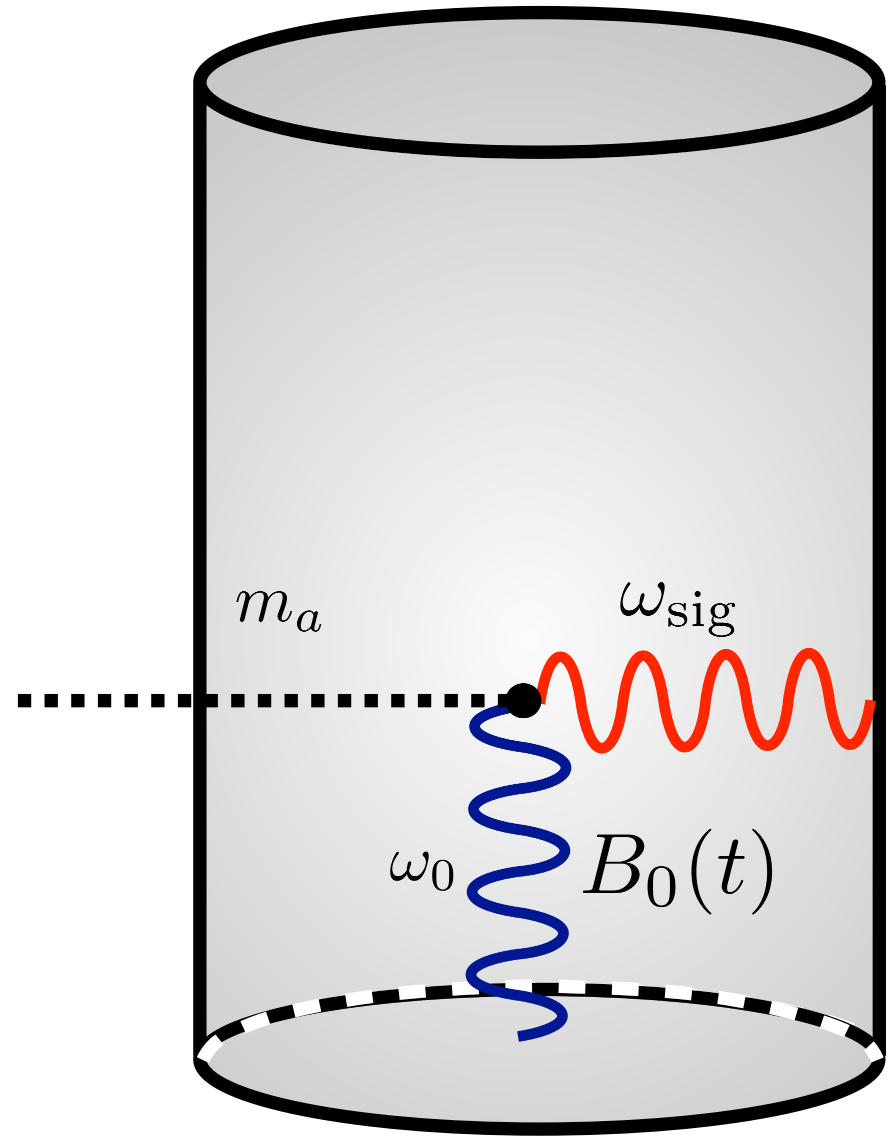
Maximise: $\omega_{\rm sig}$, B_a, V

Minimise: $P_{\rm n}$

New Approach

Heterodyne Superconducting Radio-Frequency Resonator:

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



Enhances $\omega_{\rm sig}$

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Decouples axion mass from detector volume

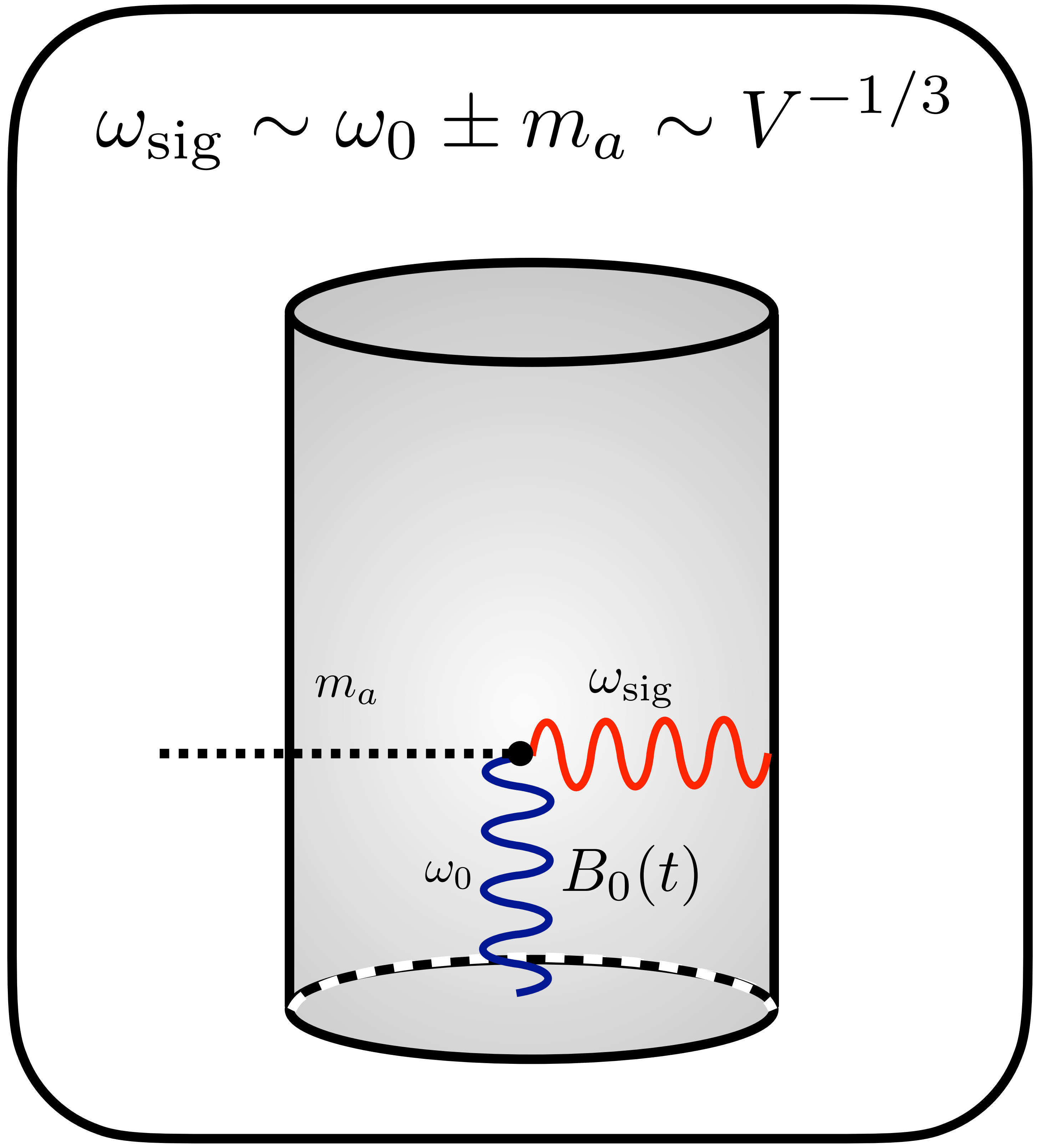
New Approach

Heterodyne Superconducting Radio-Frequency Resonator:

Q-factor $\gtrsim 10^{10}$

Applications elsewhere,
e.g. Quantum Computing:
see e.g. quant-ph/2304.09345

Enhances B_a



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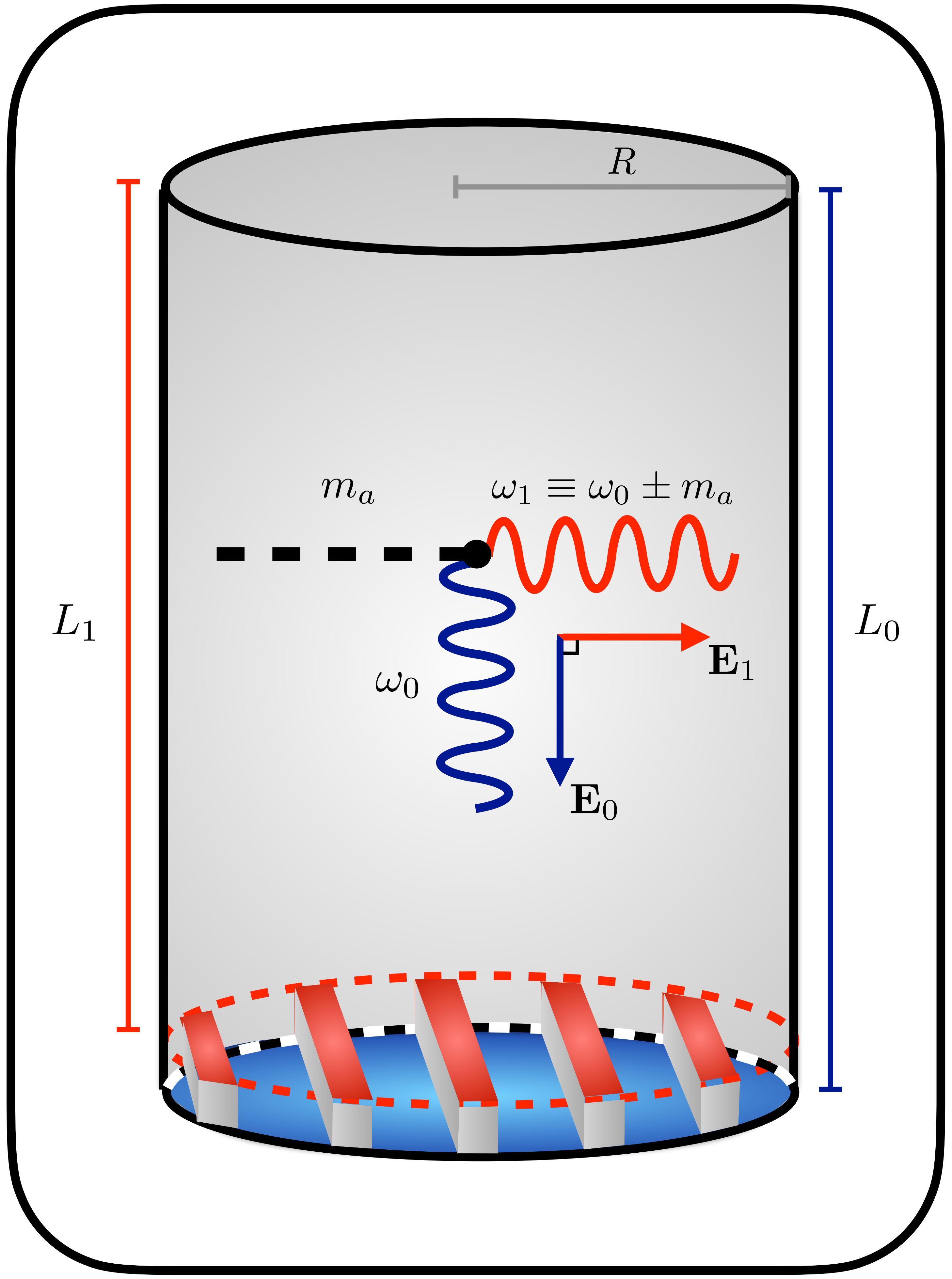
Heterodyne Resonator

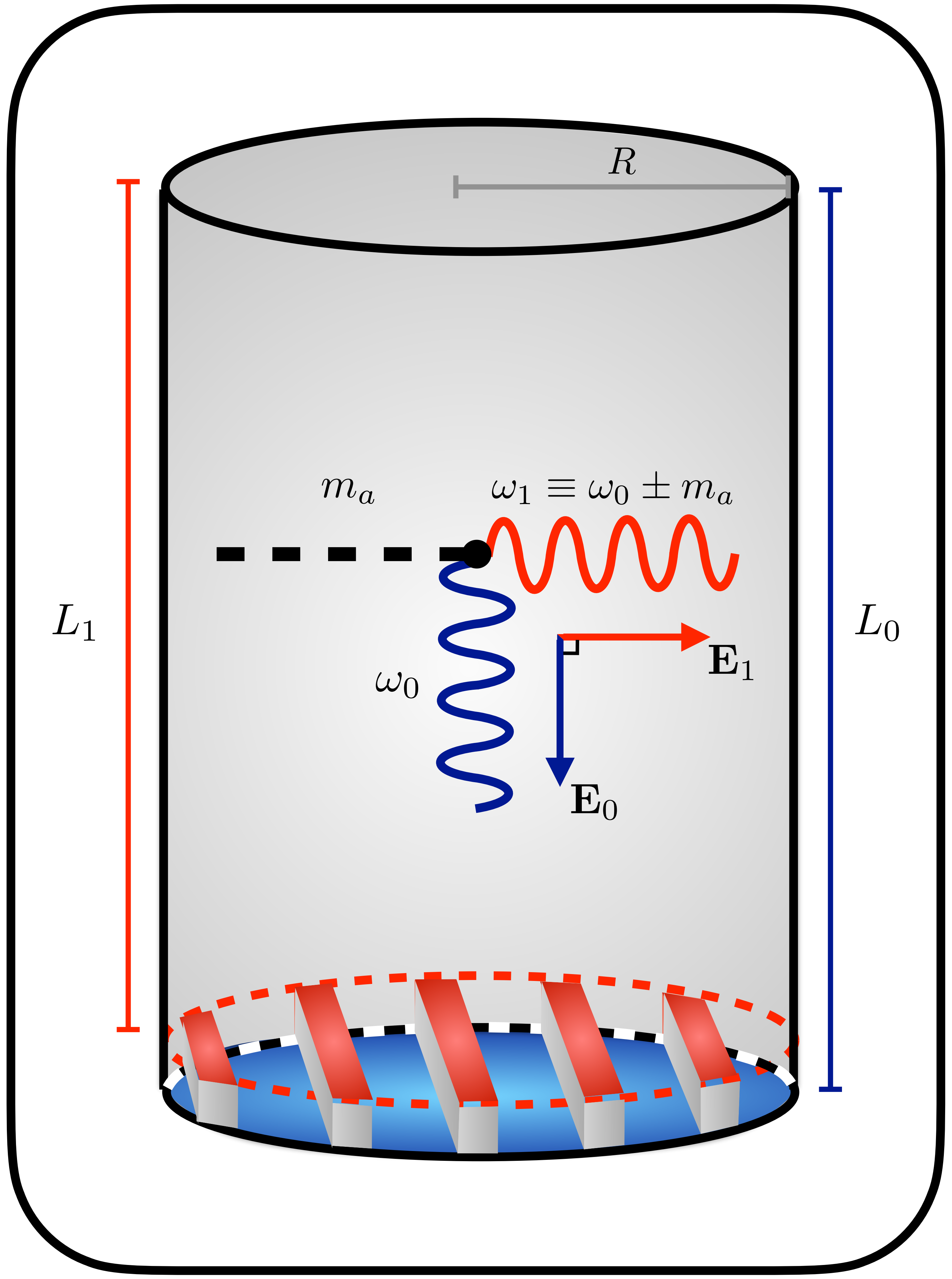


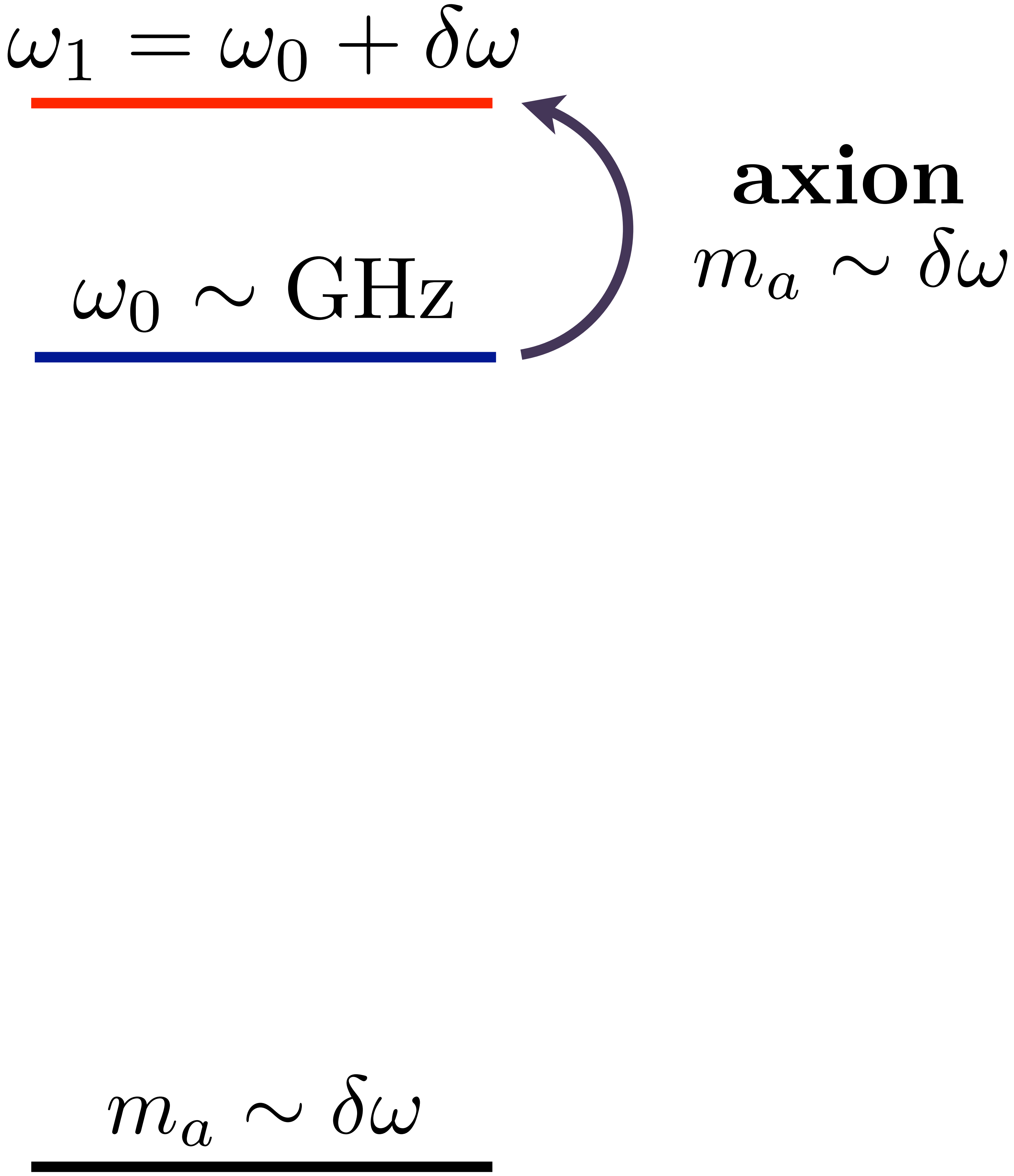
$$\omega_1 = \omega_0 + \delta\omega$$

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

$$m_a \sim \delta\omega$$

Heterodyne Resonator





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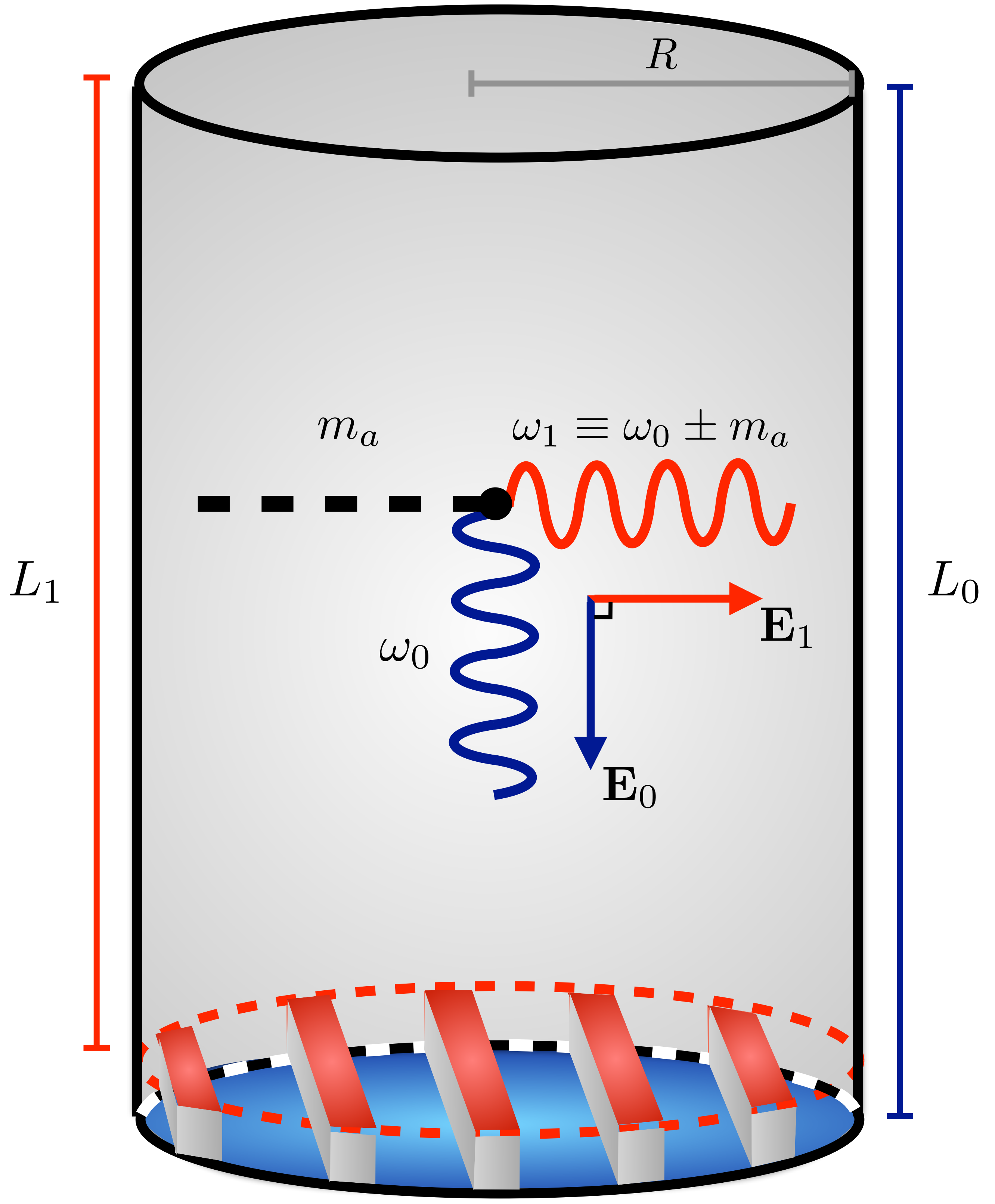


$\omega_1 = \omega_0 + \delta\omega$

$\omega_0 \sim \mathrm{GHz}$

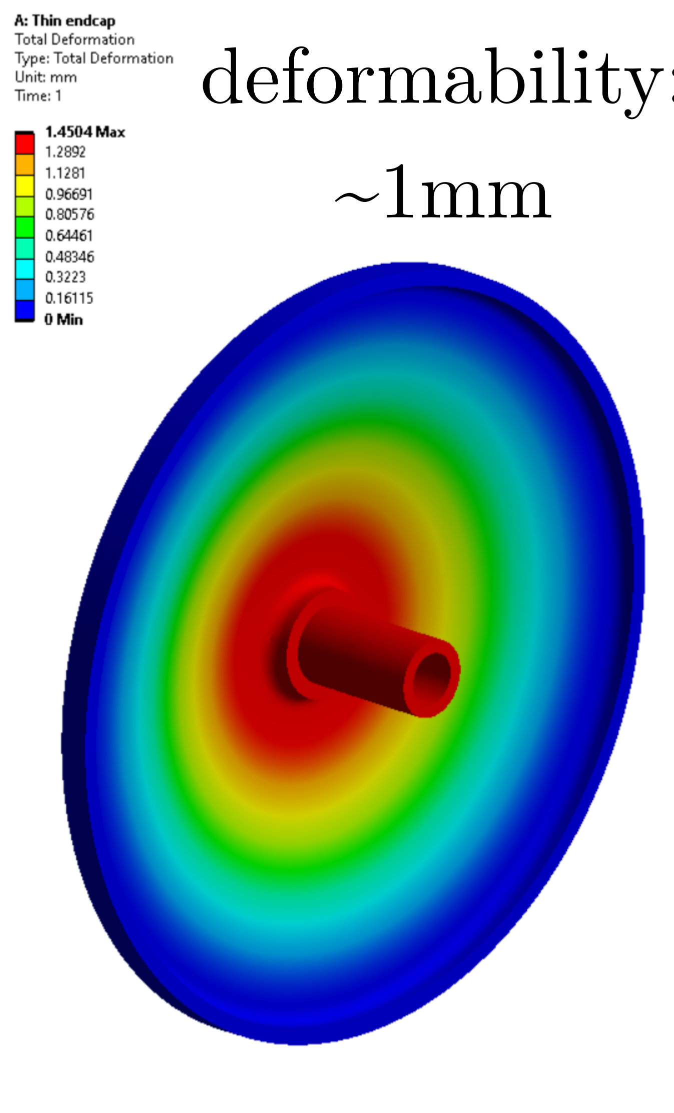
axion
$m_a \sim \delta\omega$

$m_a \sim \delta\omega$

Tunability

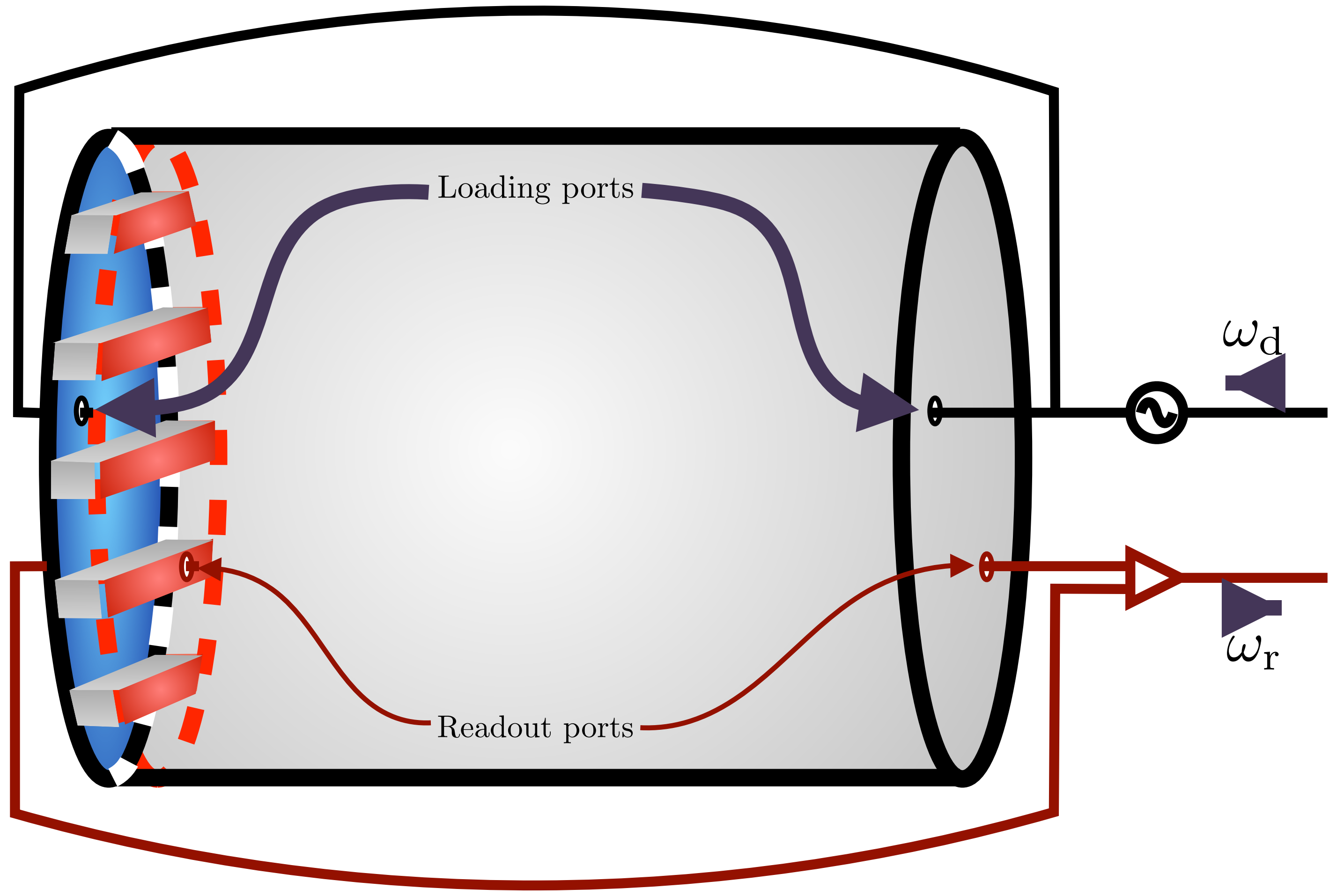
$\delta\omega \ll \mathrm{GHz}$

deformability:
$\sim$1mm



Courtesy: Marco Oriunno (SLAC)

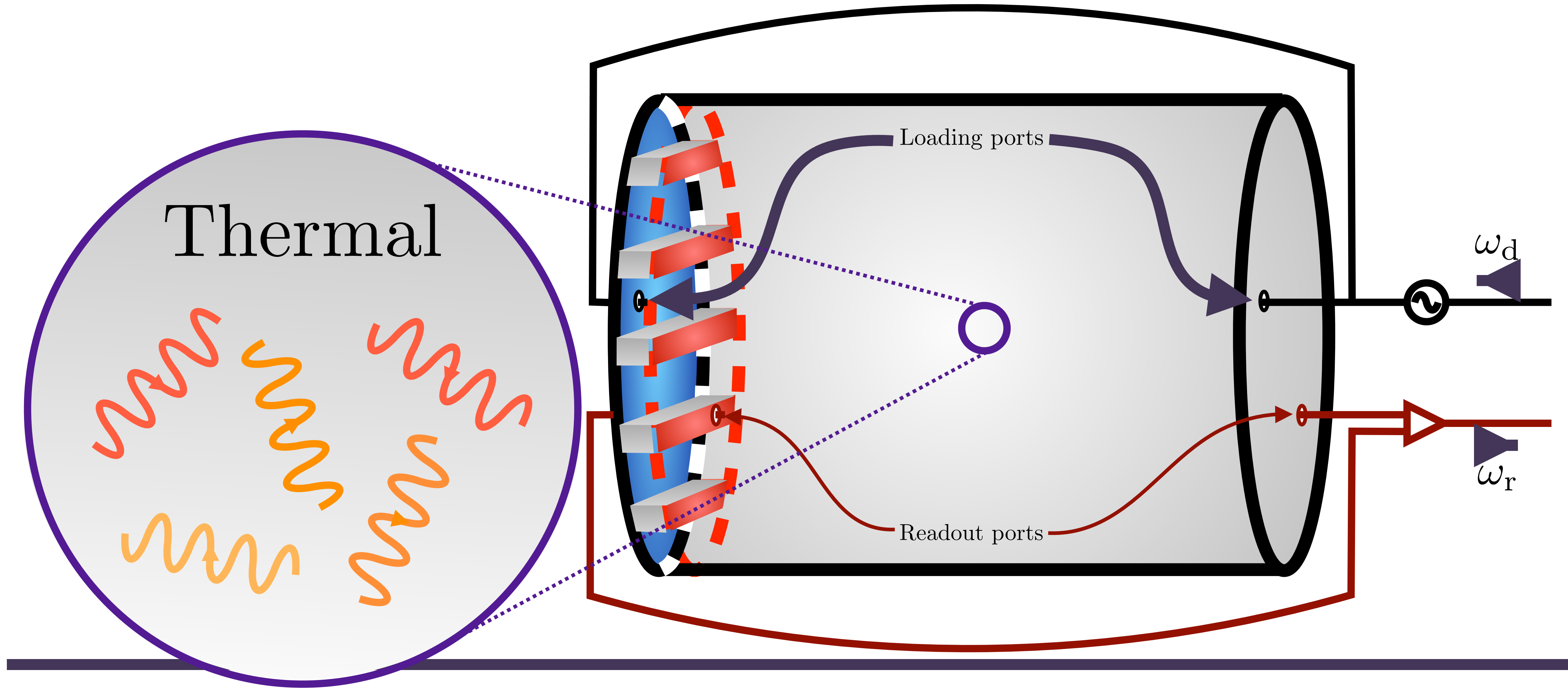
All Noise Sources



See backup for details on each noise source

All Noise Sources

- ***Thermal noise***: requires cryo



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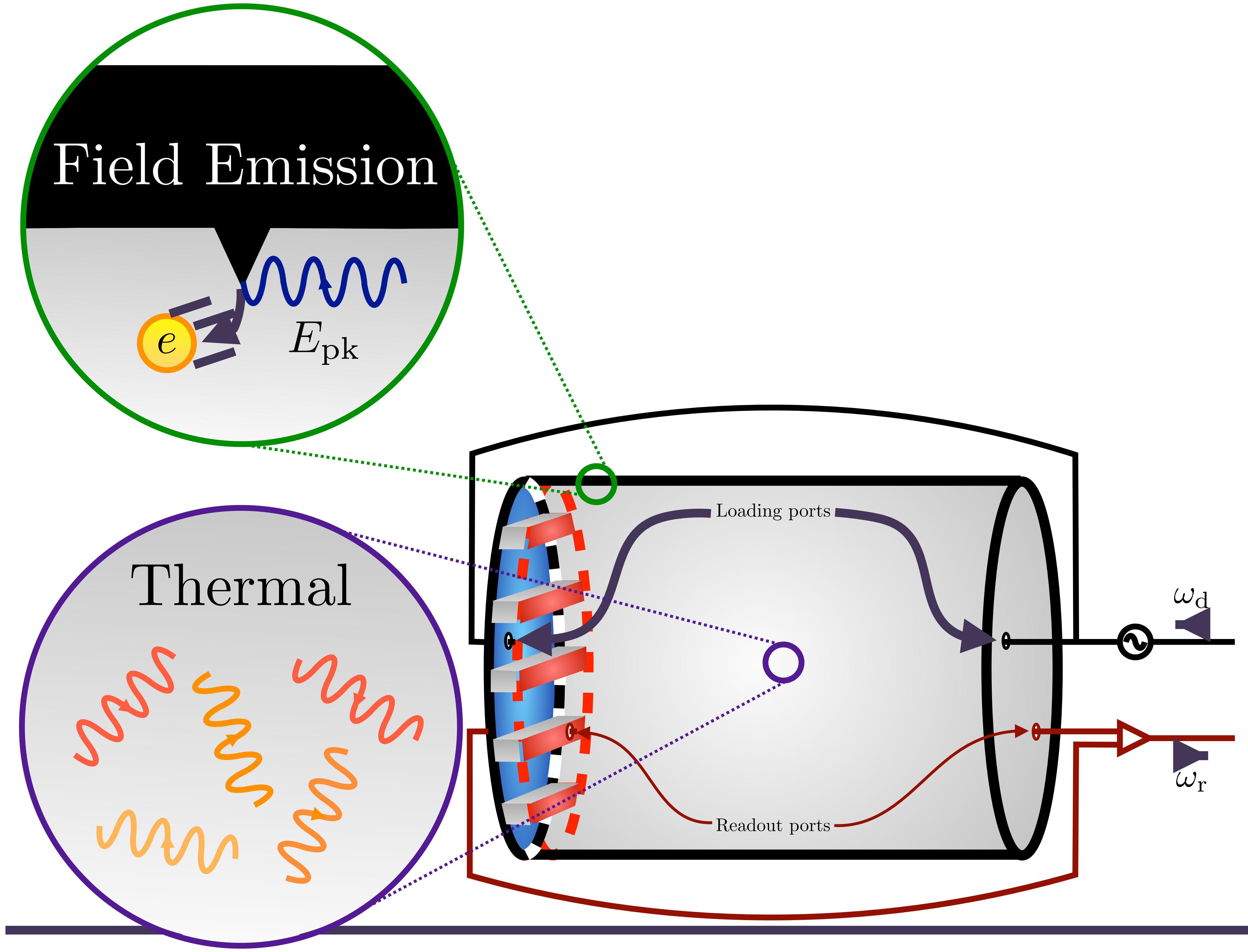

- ***Thermal noise***: requires cryo
- ***Field Emission***: careful design & limits peak B-field

See backup for details on each noise source

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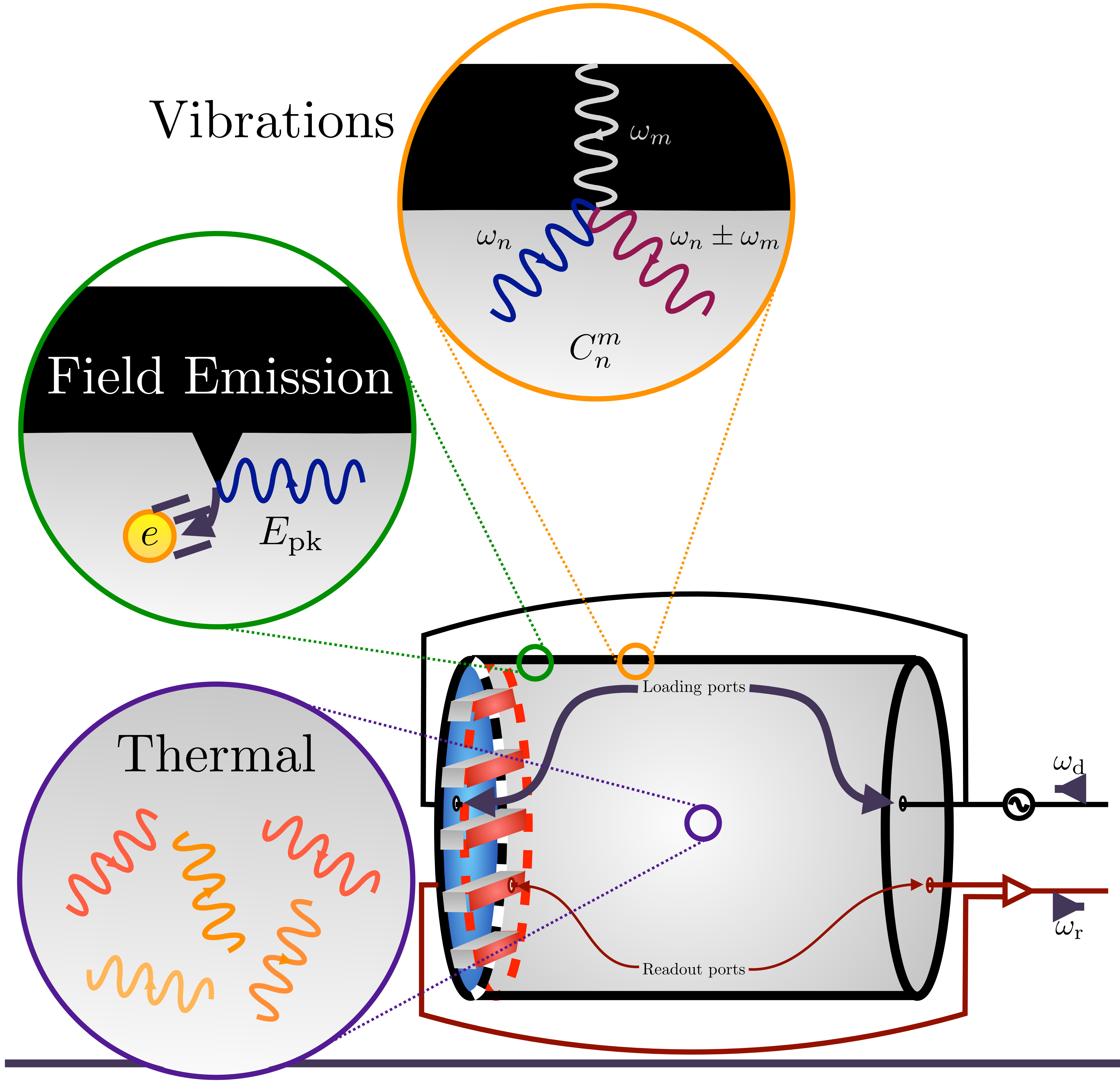

- ***Thermal noise***: requires cryo
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- ***Vibrations***: design to reduce microphonics, isolation, cryo

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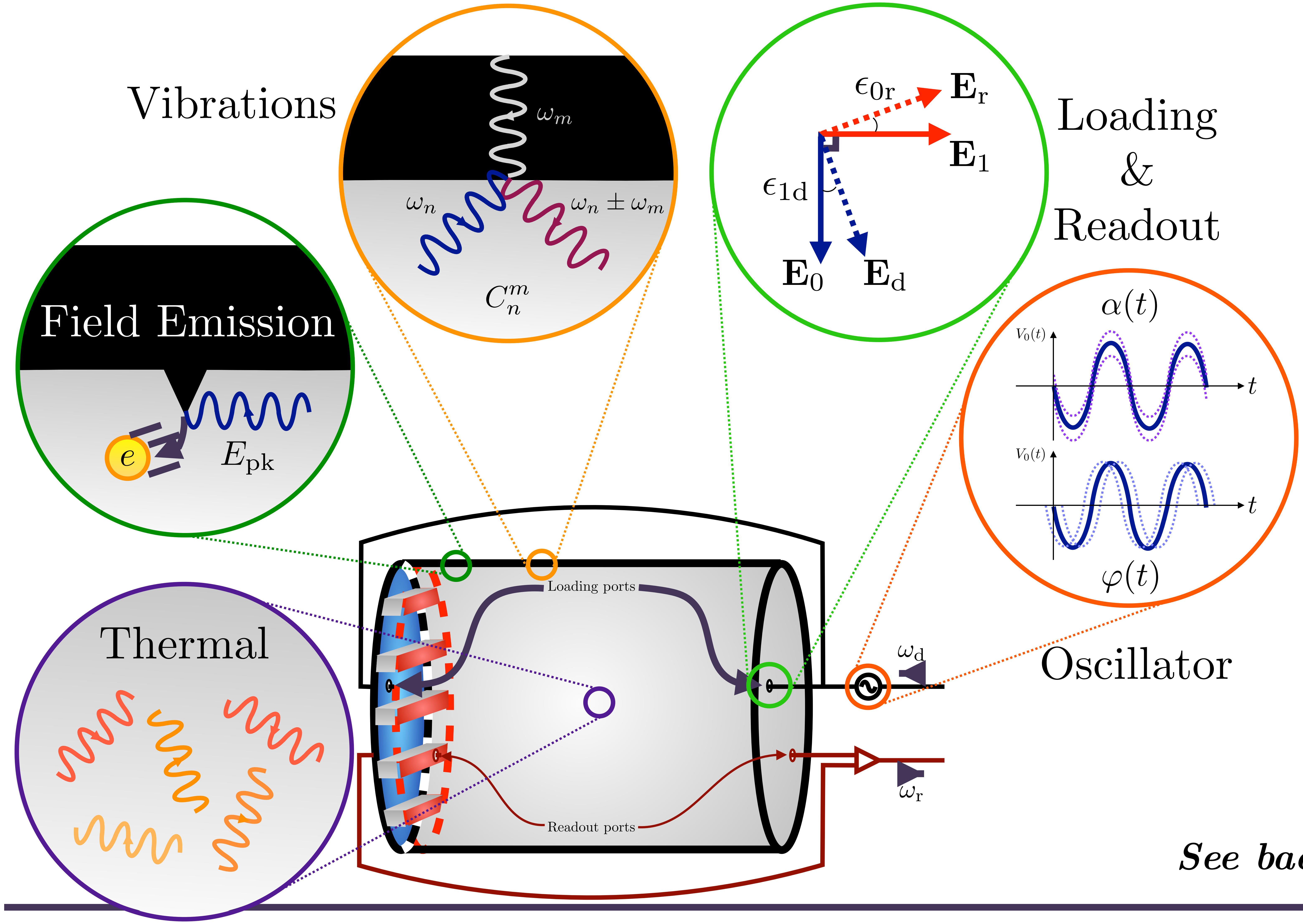

- ***Thermal noise***: requires cryo
- ***Field Emission***: careful design & limits peak B-field
- ***Vibrations***: design to reduce microphonics, isolation, cryo
- ***Loading/Readout & Phase***: design to improve coupling to pump & signal modes. Low phase-noise pump & readout electronics

See backup for details on each noise source

Signal to Noise

Signal to Noise

Thermal noise dominated:

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

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Comparison with LC resonator:

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

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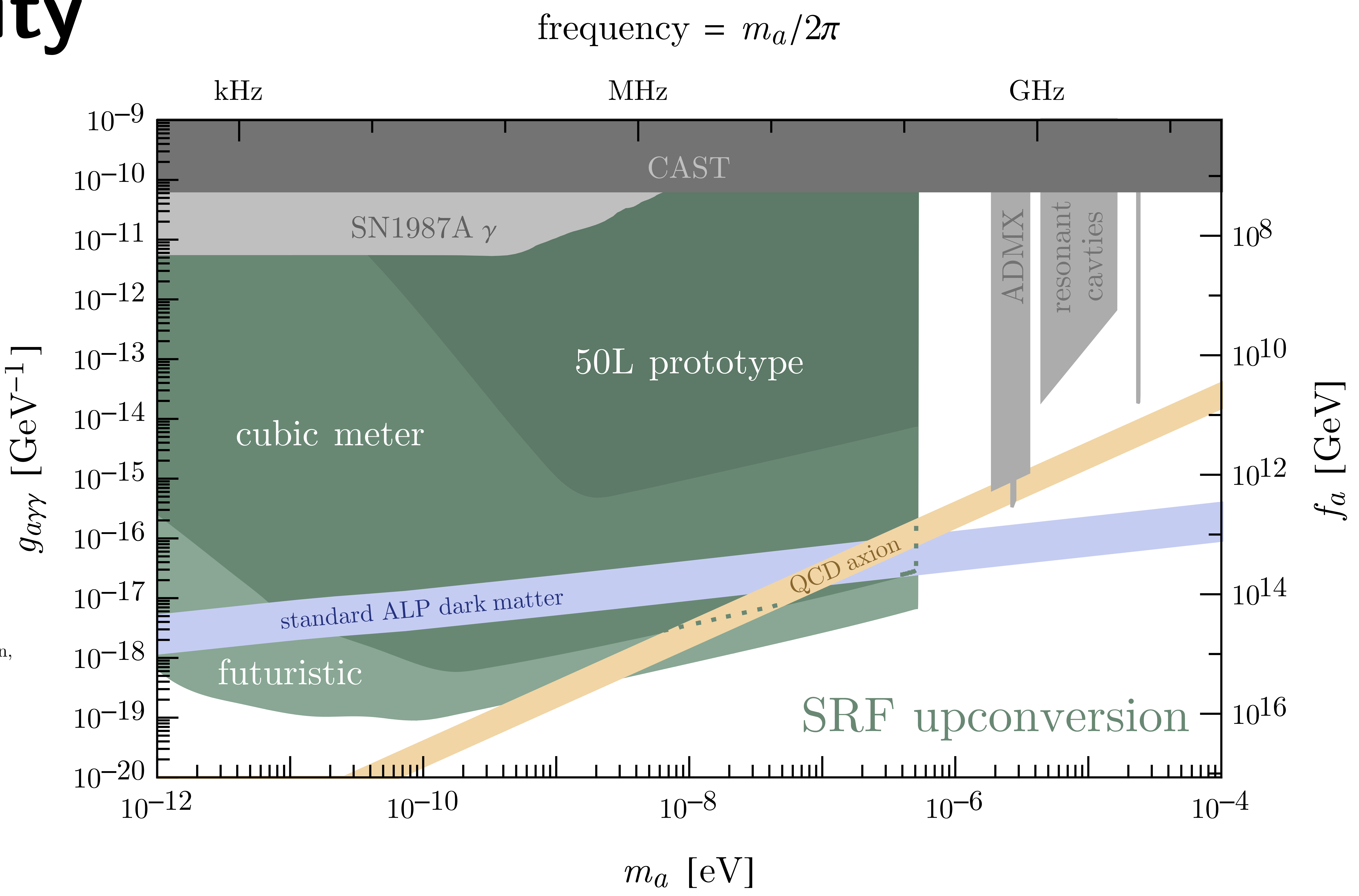
Sensitivity



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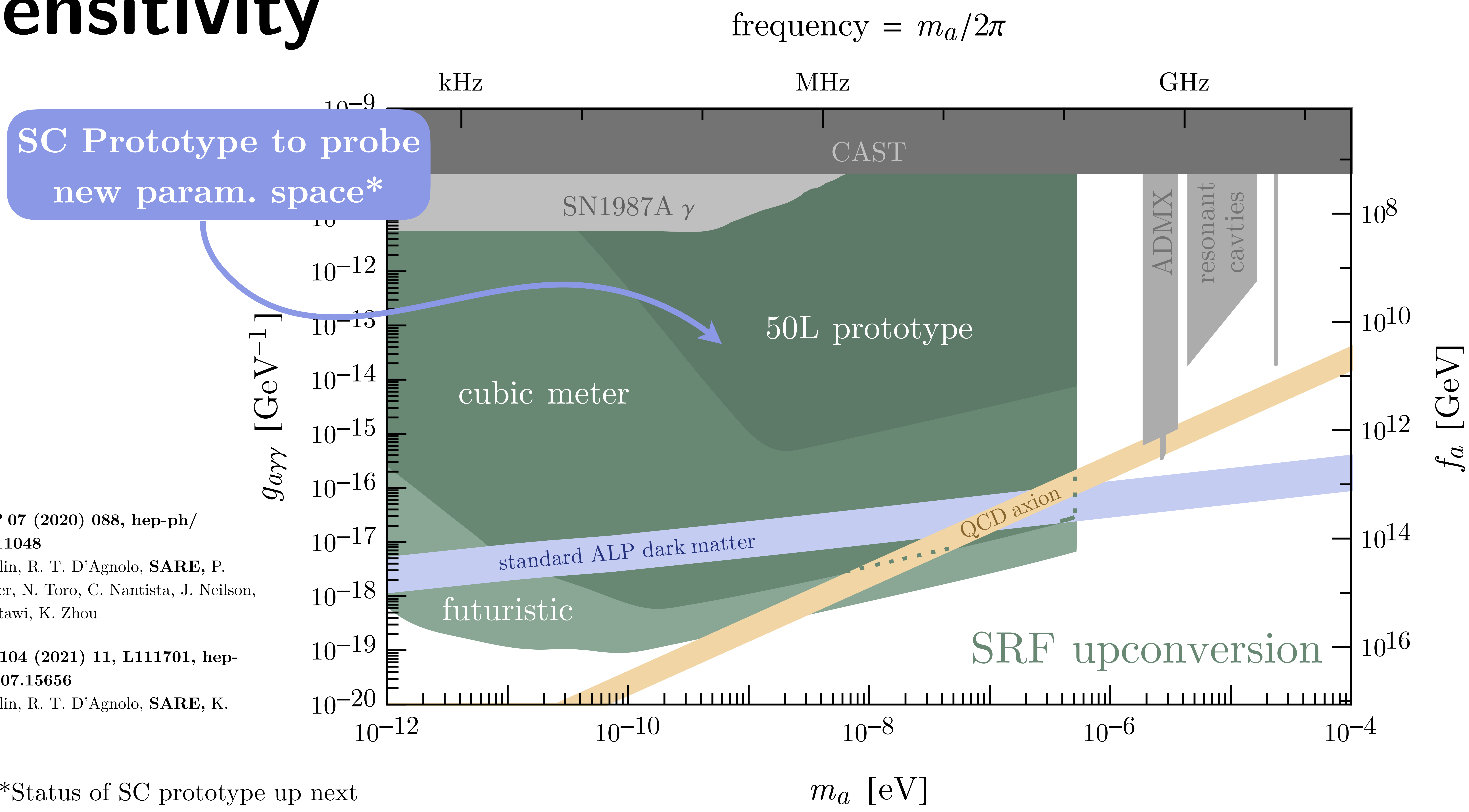

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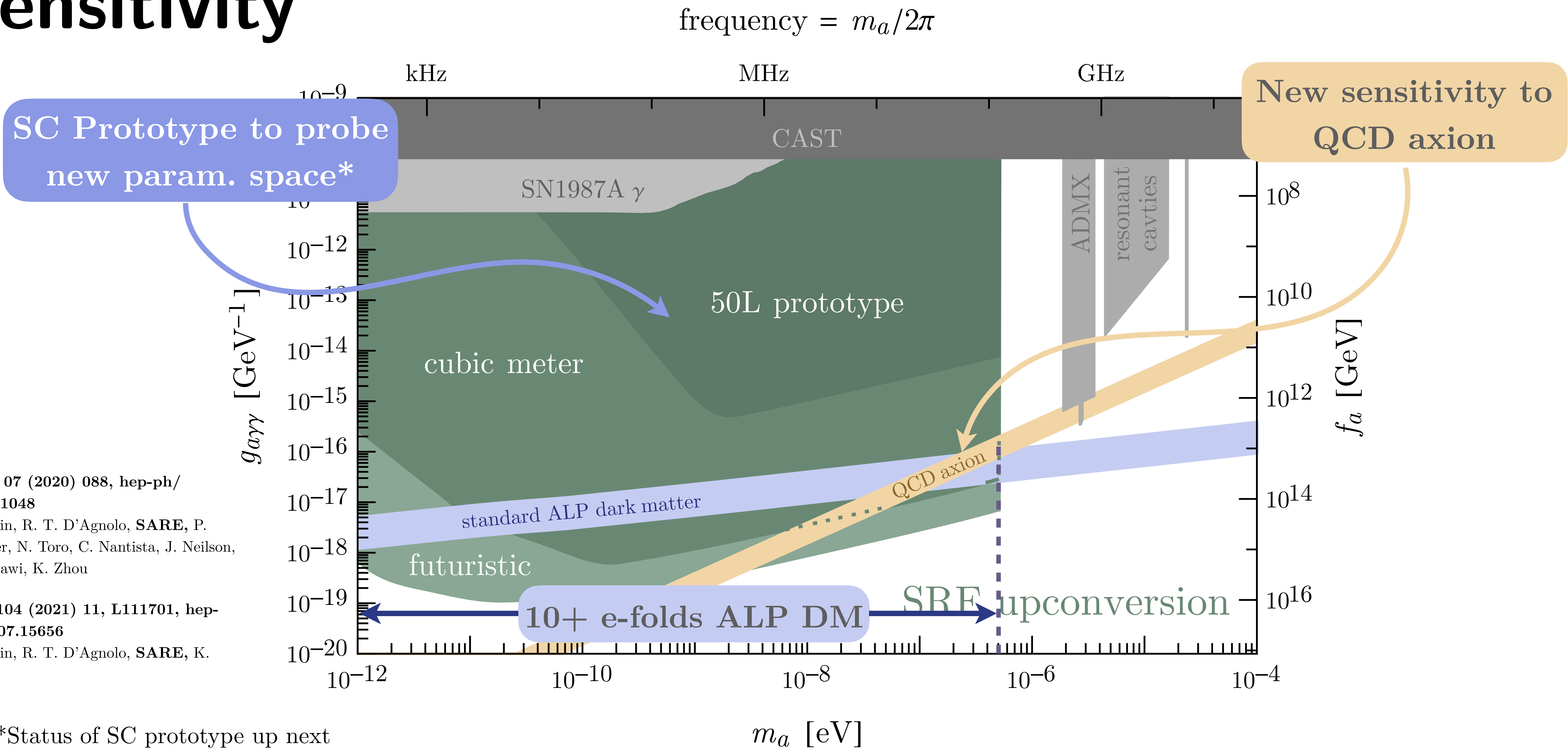
*Status of SC prototype up next

Sensitivity



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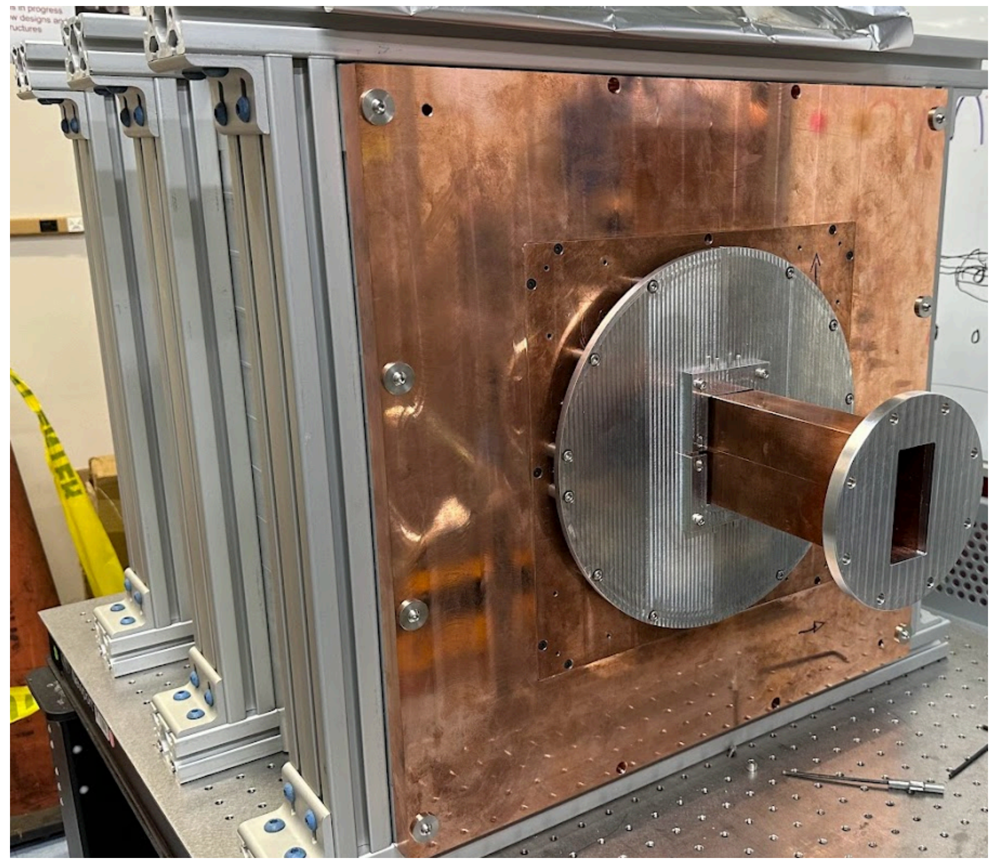
Current Status

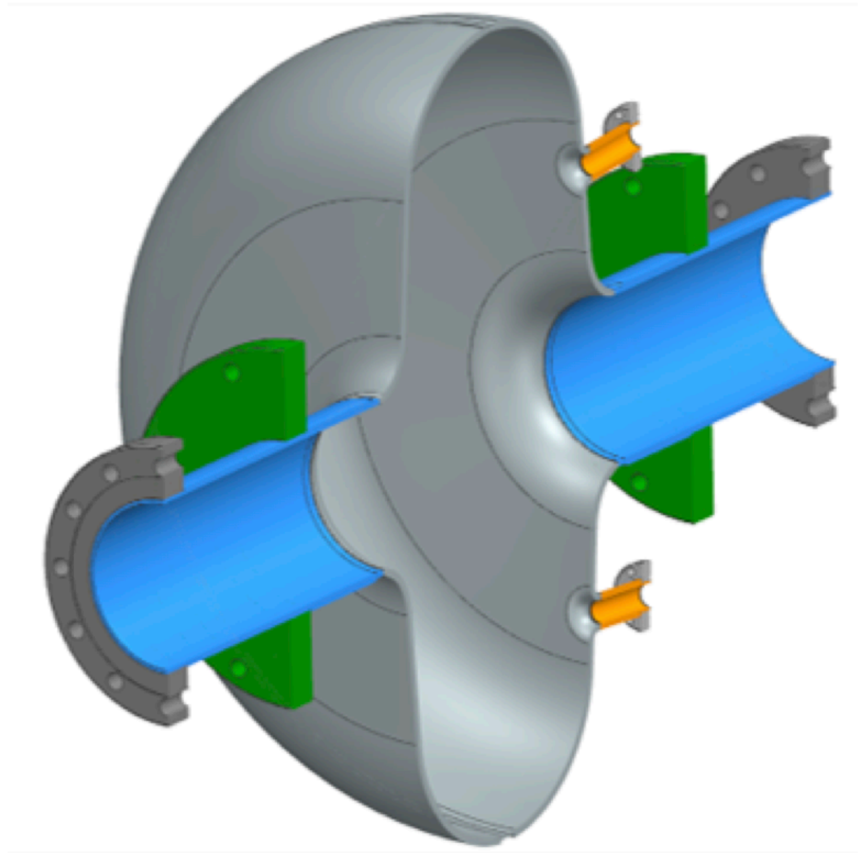
SLAC



LDRD led by S. Tantawi

- Copper prototype
- Input from PBC

FNAL



Giaccone et al [hep-ex/2207.11346]

- Single-cell SRF

CERN

SARE contact w/ A.MacP since 2019

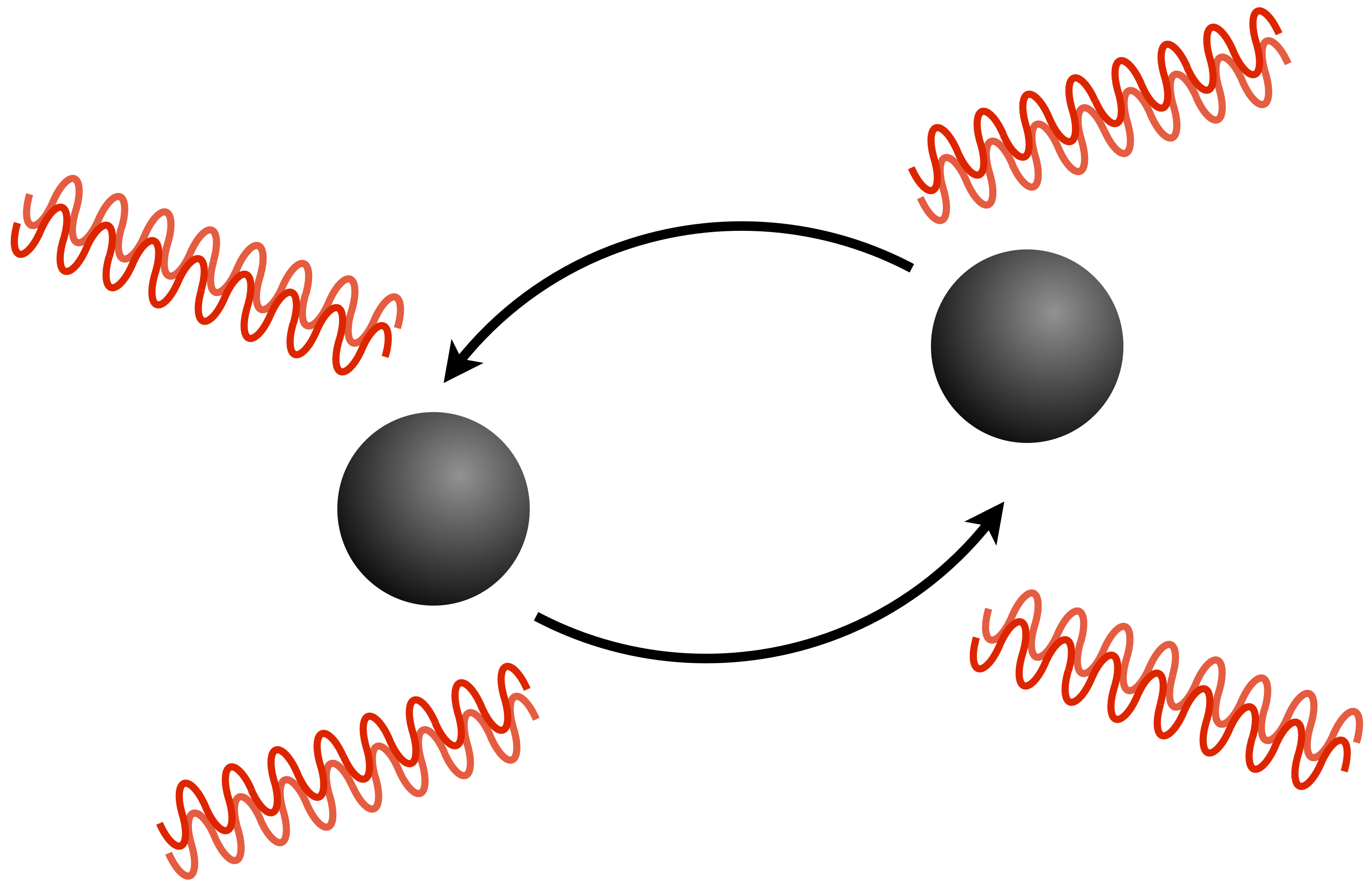
- PBC since ~2021
- QTI since Jan. 2024

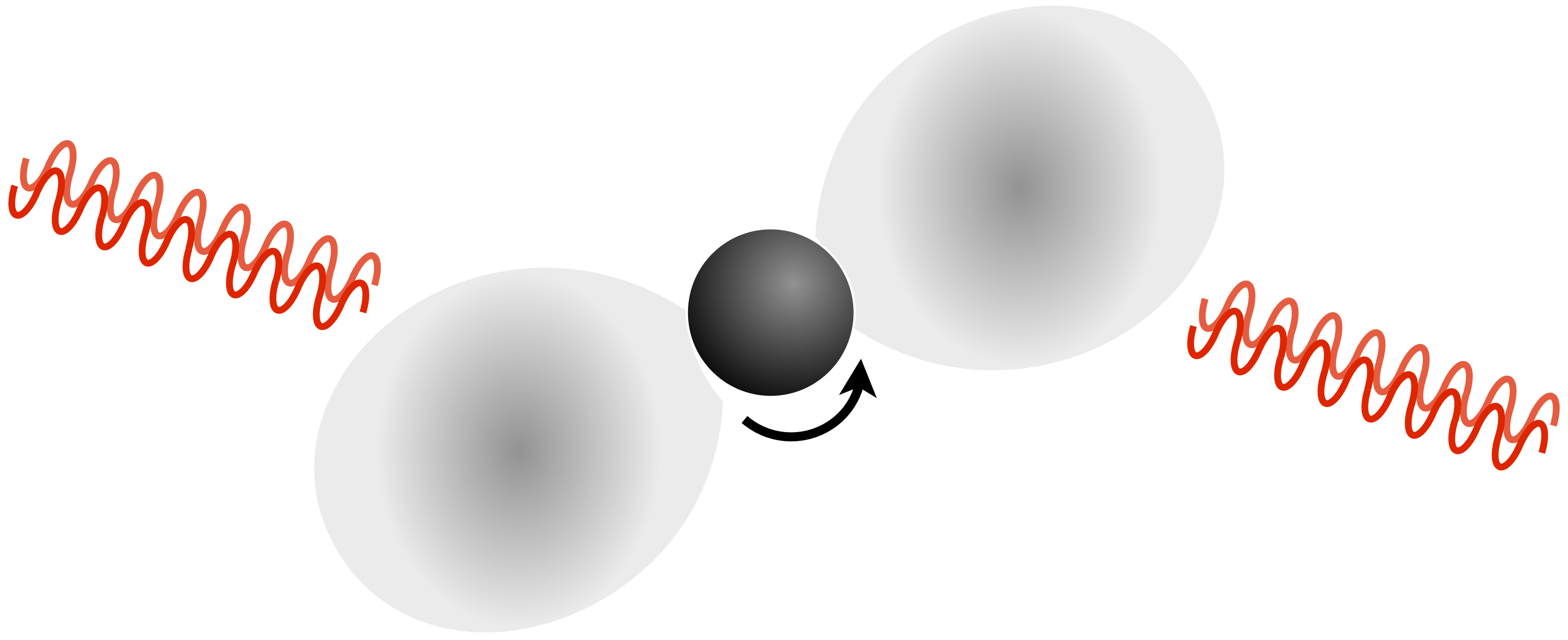
See Bianca's talk

Axion Summary

- **Axion: good DM candidate & can solve strong CP**
- **Heterodyne detector enables low-mass searches**
  Ongoing efforts at SLAC, SQMS @FNAL & CERN QTI
- **Noise level above Standard Quantum Limit**
- **Quantum techniques promise to improve scan rate**

Gravitational Waves





High-Frequency Gravitational Waves

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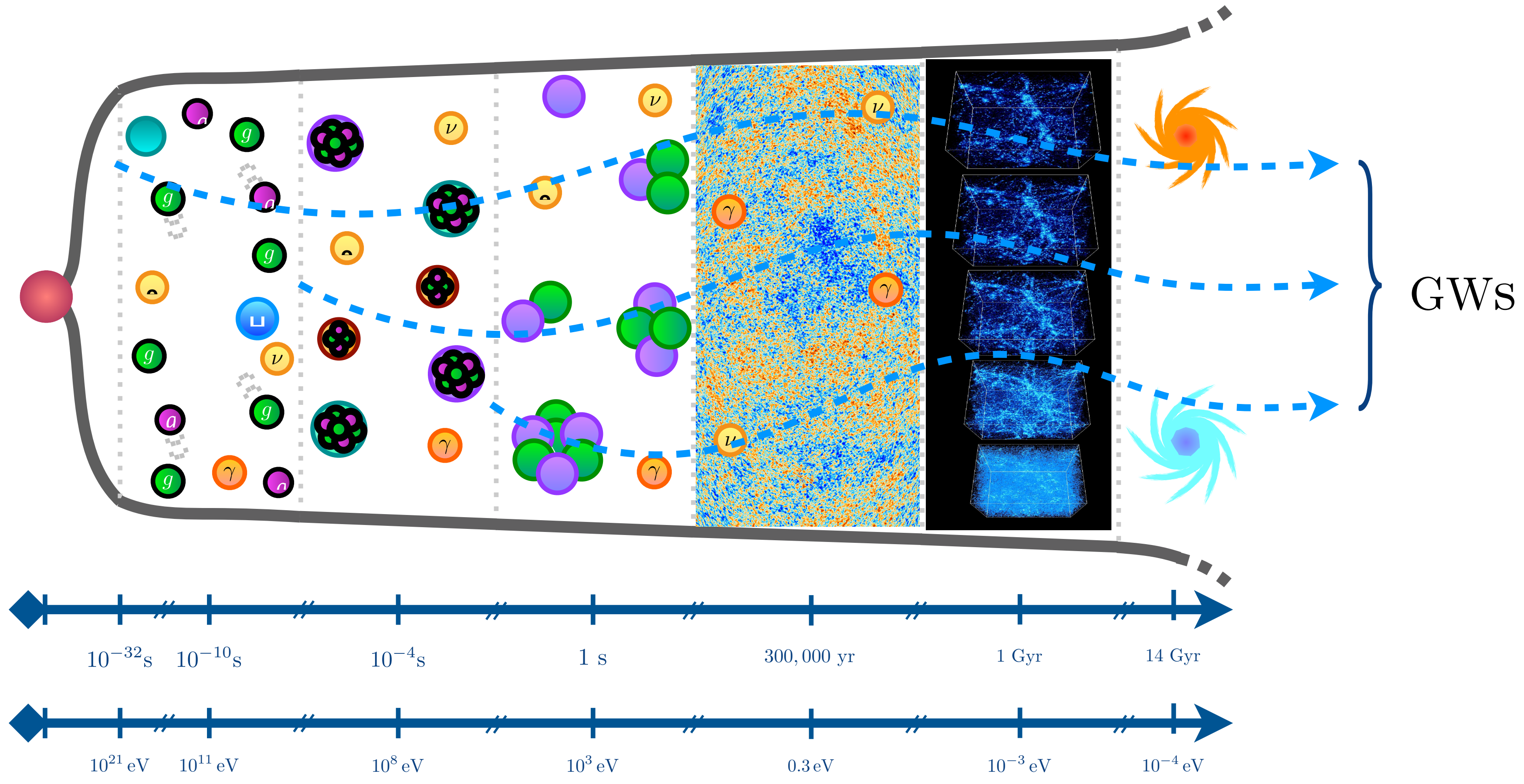
Cosmological GWs

$$\omega_g \Leftrightarrow T_{\rm origin}$$



High-Frequency Gravitational Waves

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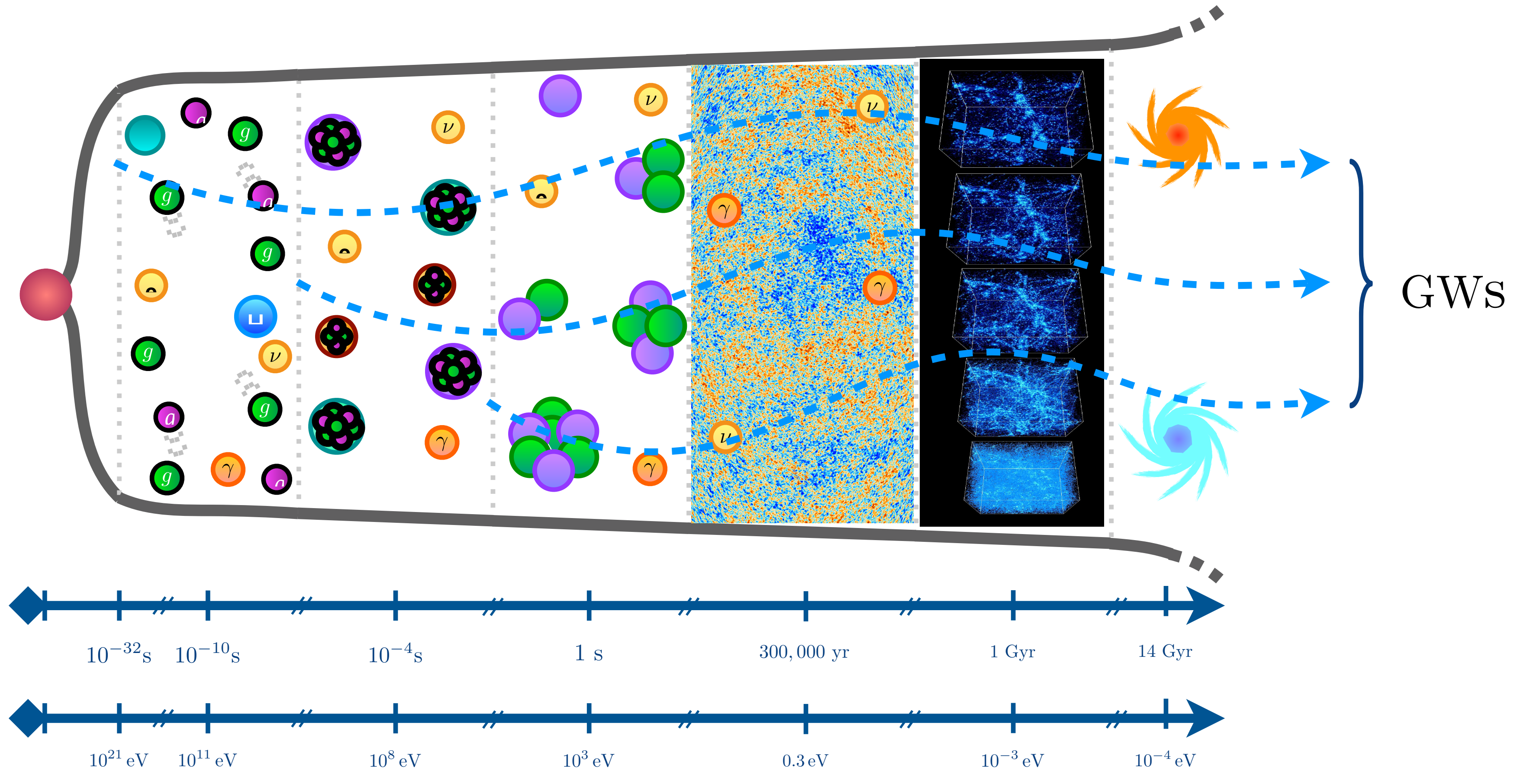

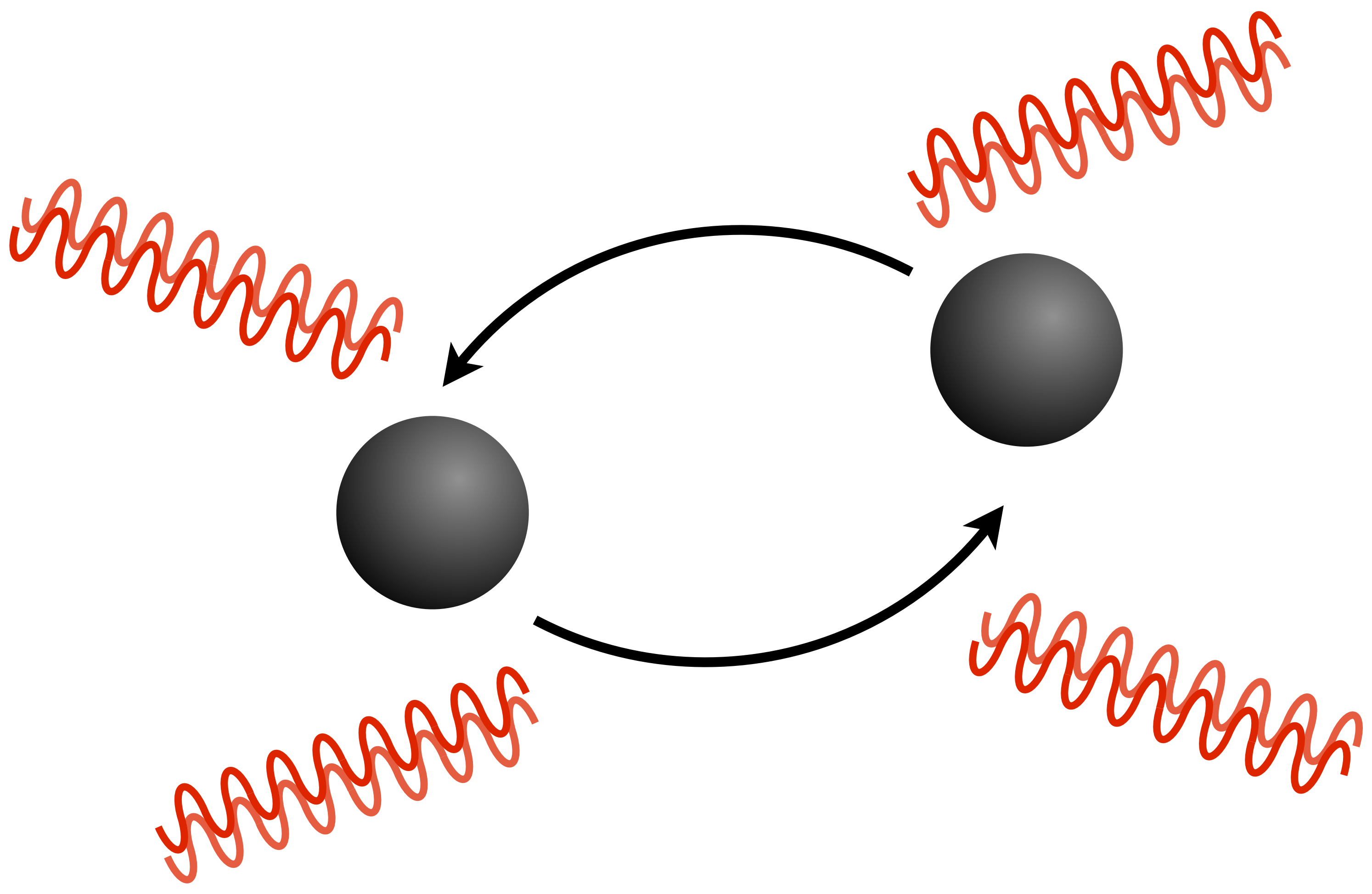

Astrophysical GWs

$$\omega_g \Leftrightarrow \Lambda_{\text{origin}}$$

MAGO 2.0

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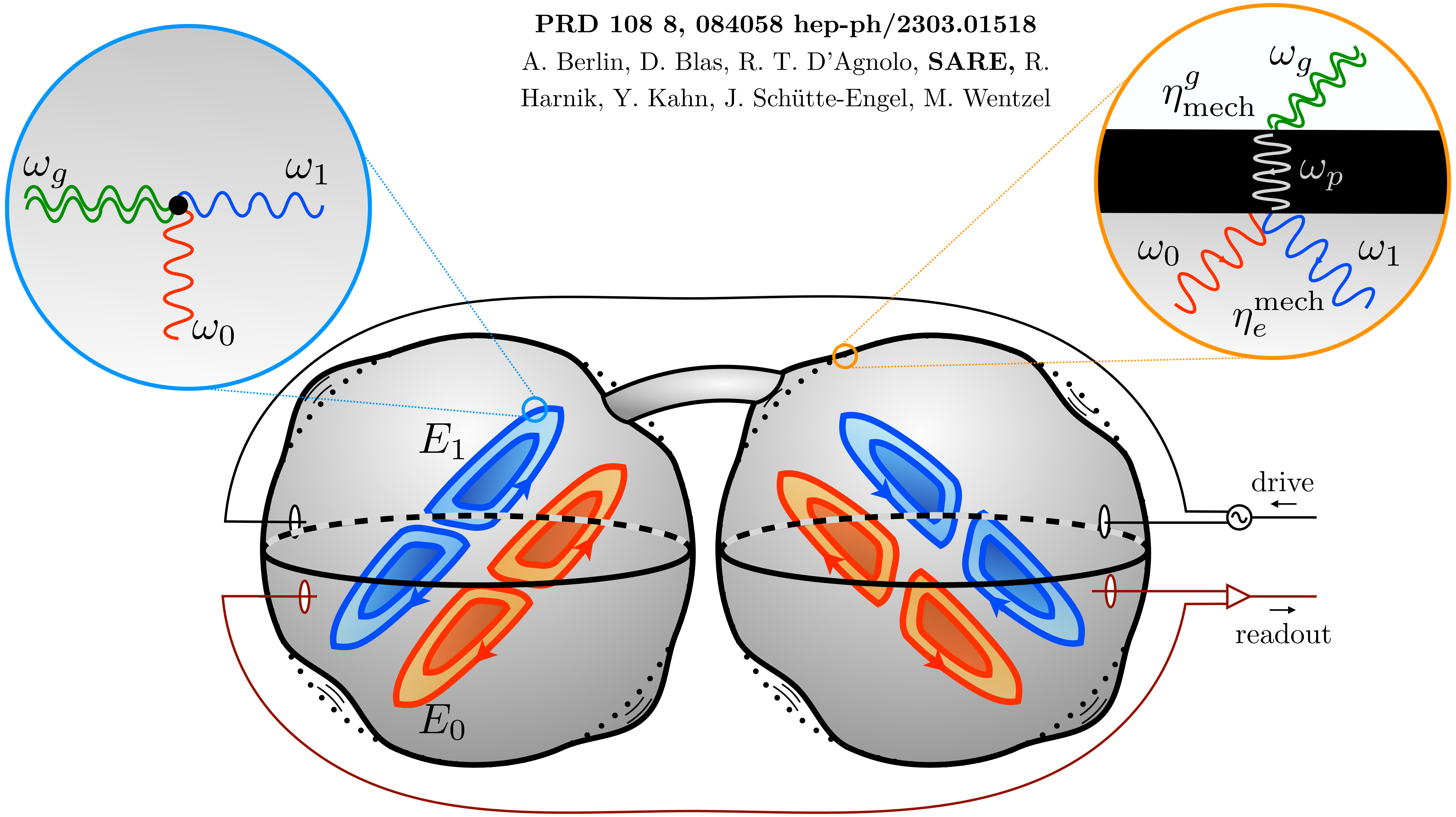
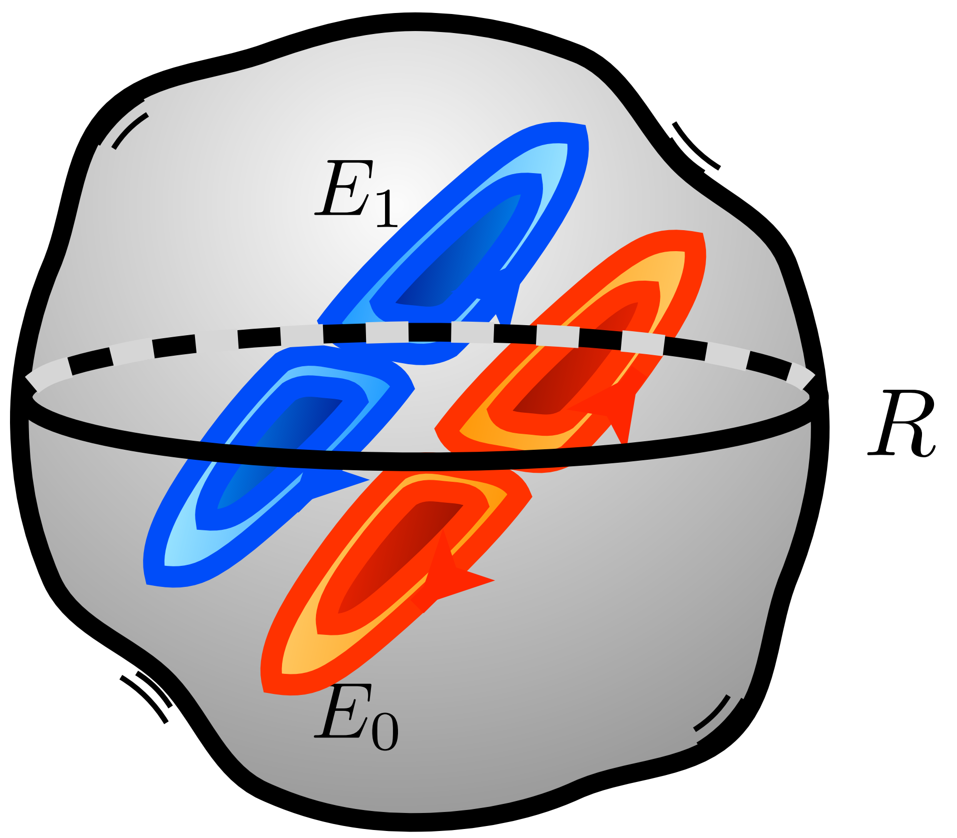
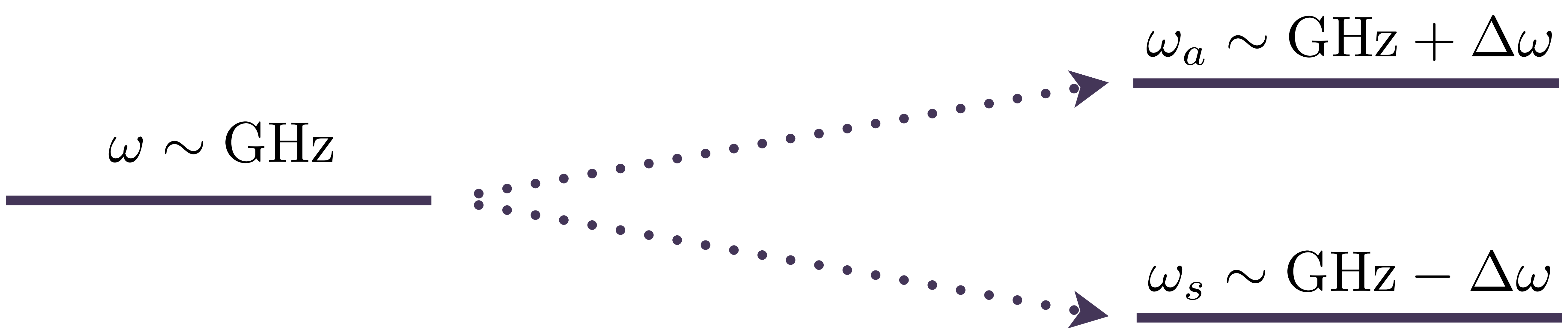


MAGO 2.0

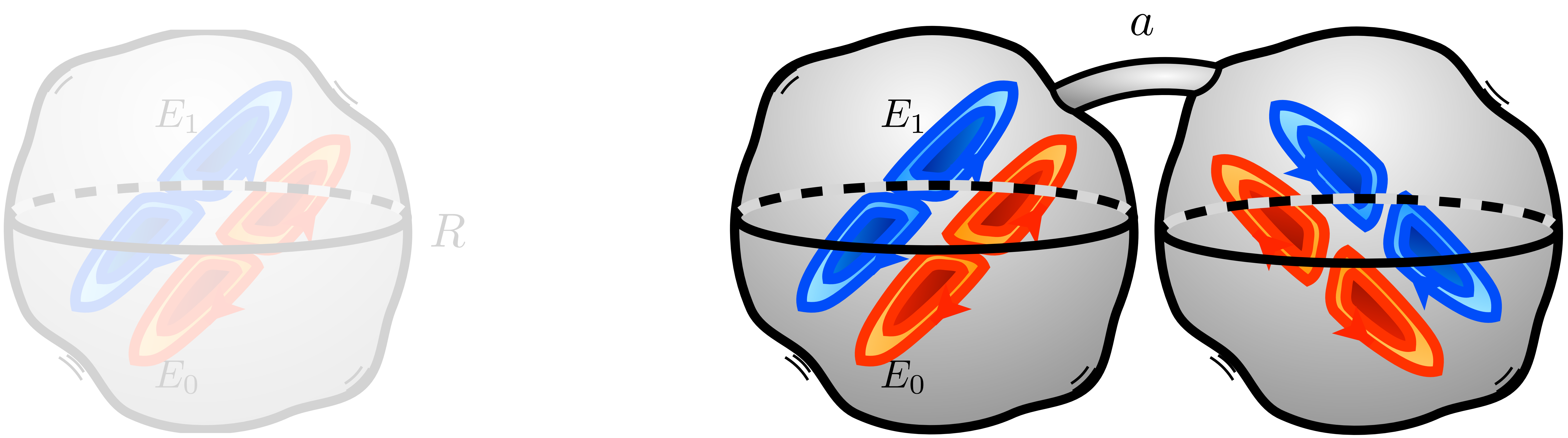
$\omega \sim \text{GHz}$



MAGO 2.0



$\Delta\omega \sim (a/R)^3$



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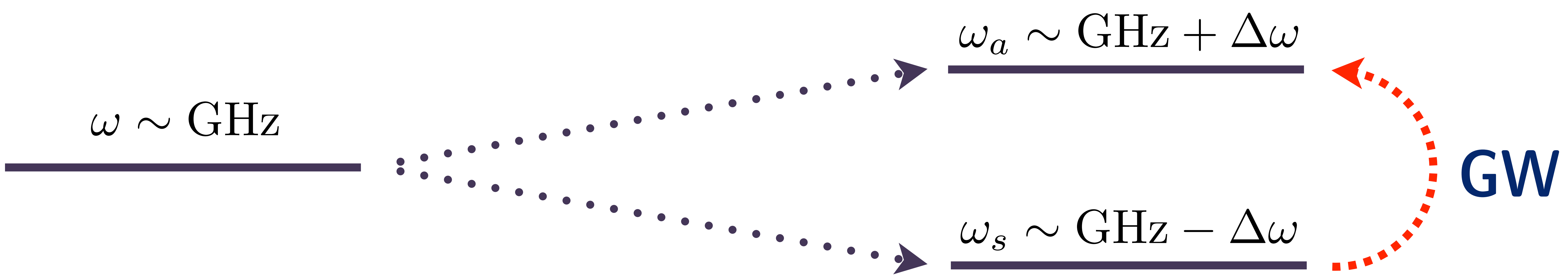

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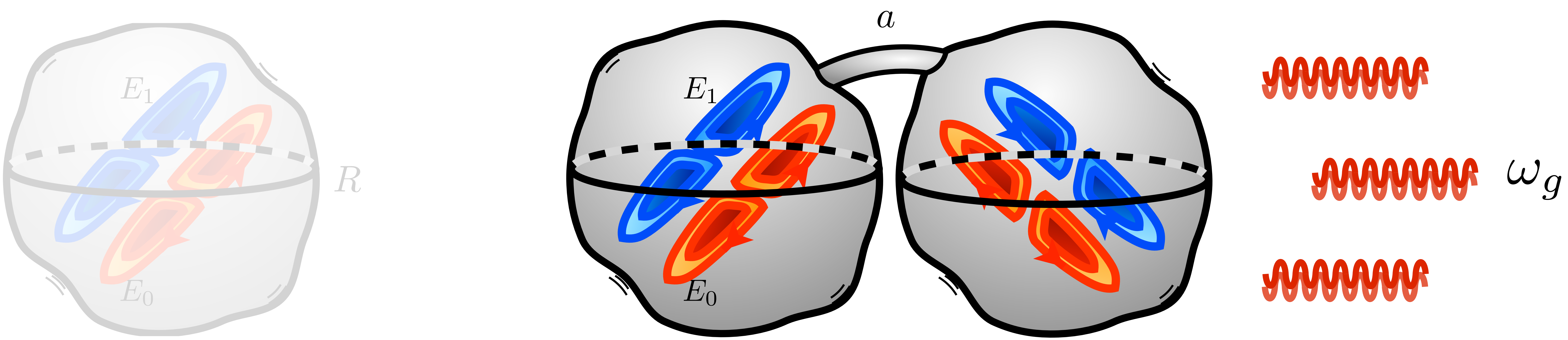
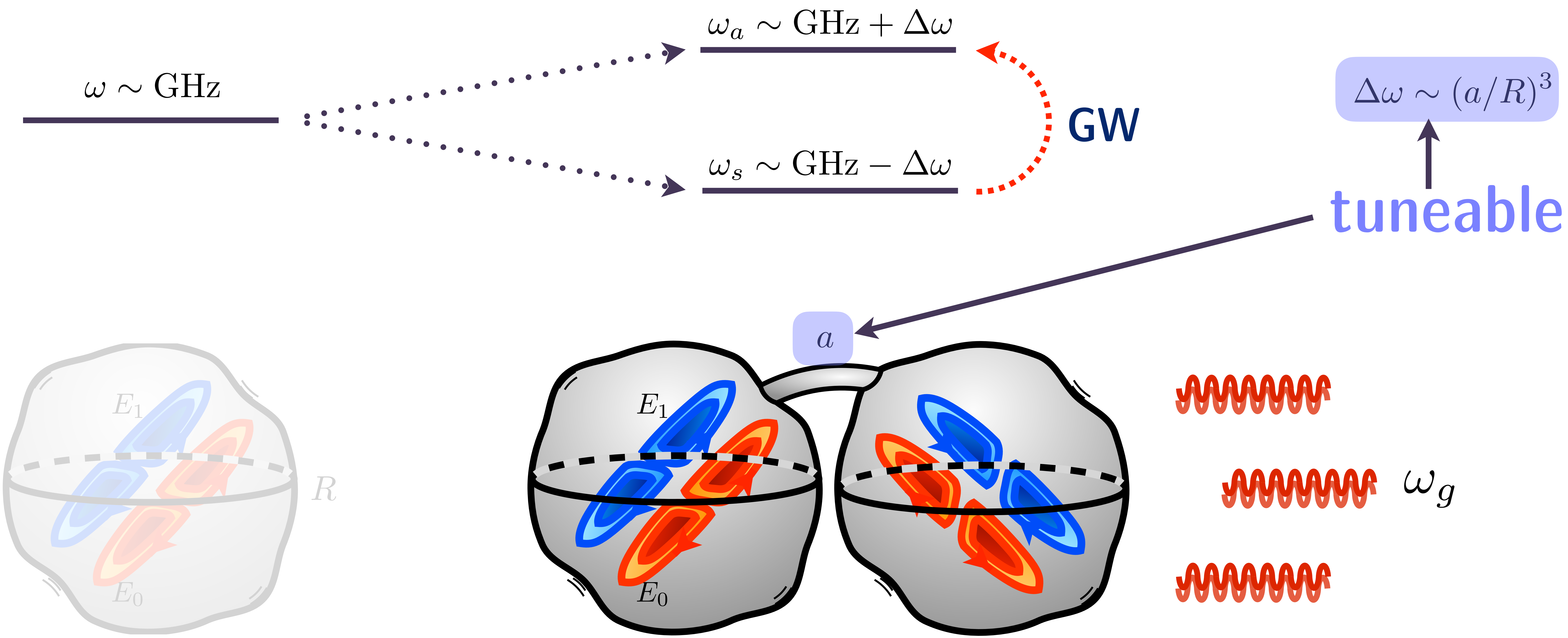
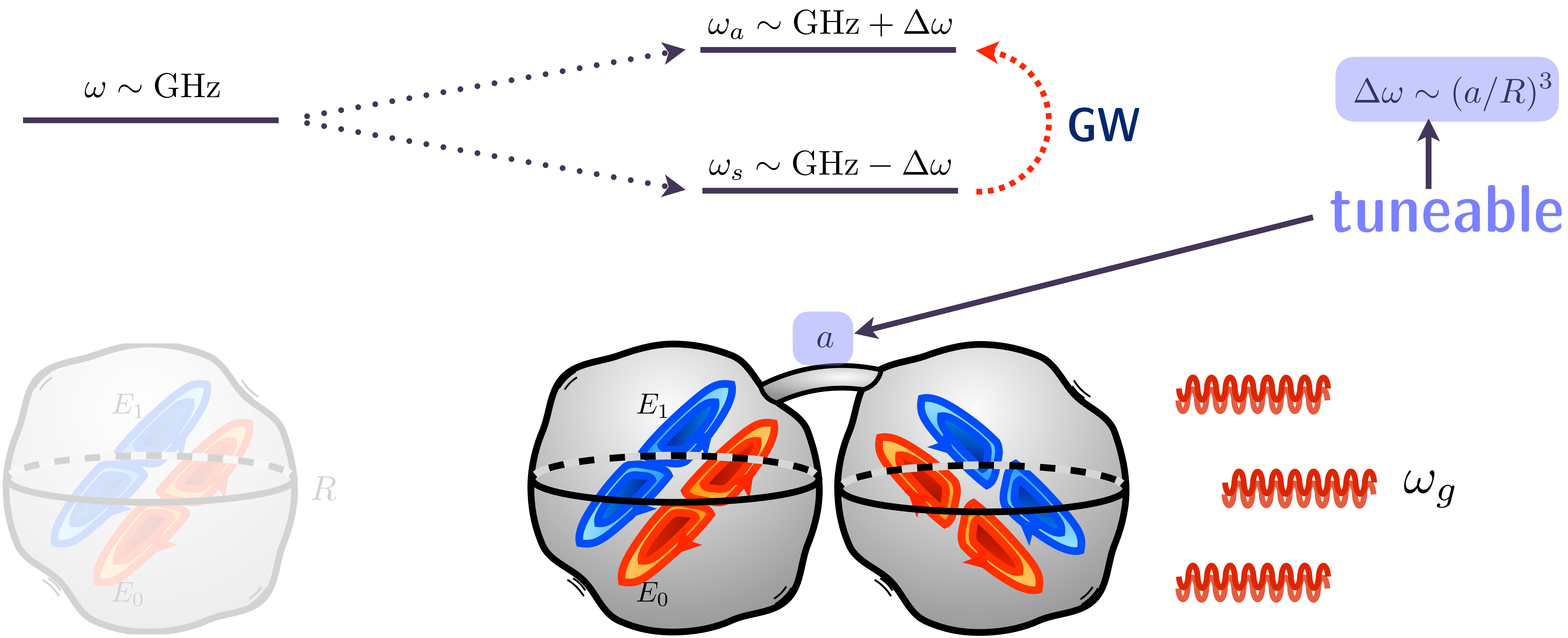


MAGO 2.0



$\omega_a \sim \mathrm{GHz} + \Delta\omega$
$\omega \sim \mathrm{GHz}$
GW
$\Delta\omega \sim (a/R)^3$
$\omega_s \sim \mathrm{GHz} - \Delta\omega$
tuneable
a
E_1
R
E_0
E_1
ω_g
E_0

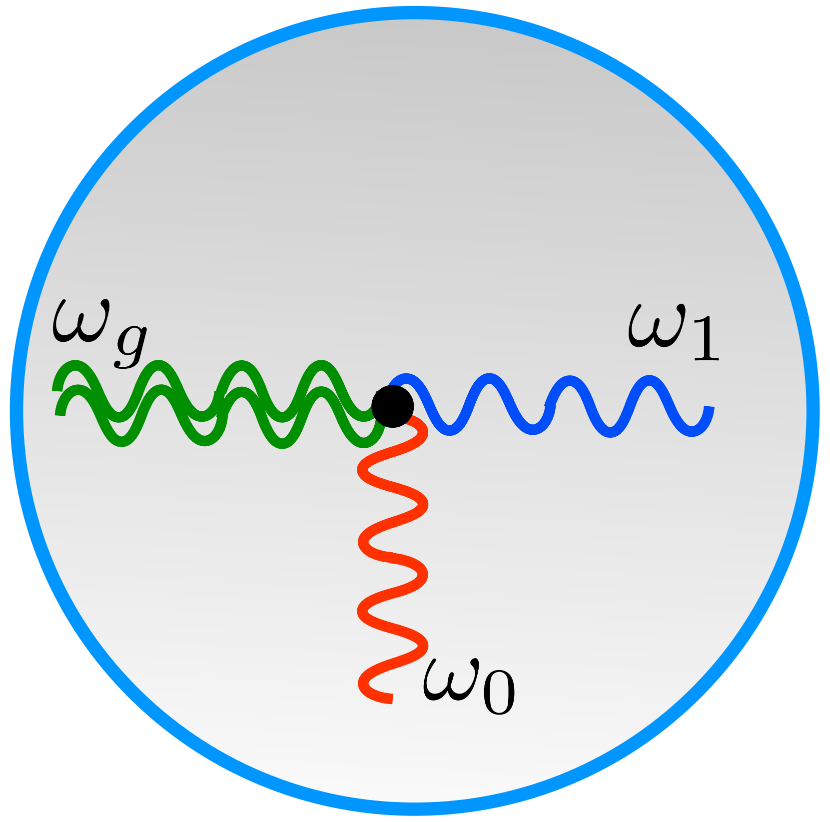
MAGO 2.0



2. Resonant with *beat frequency* ✅

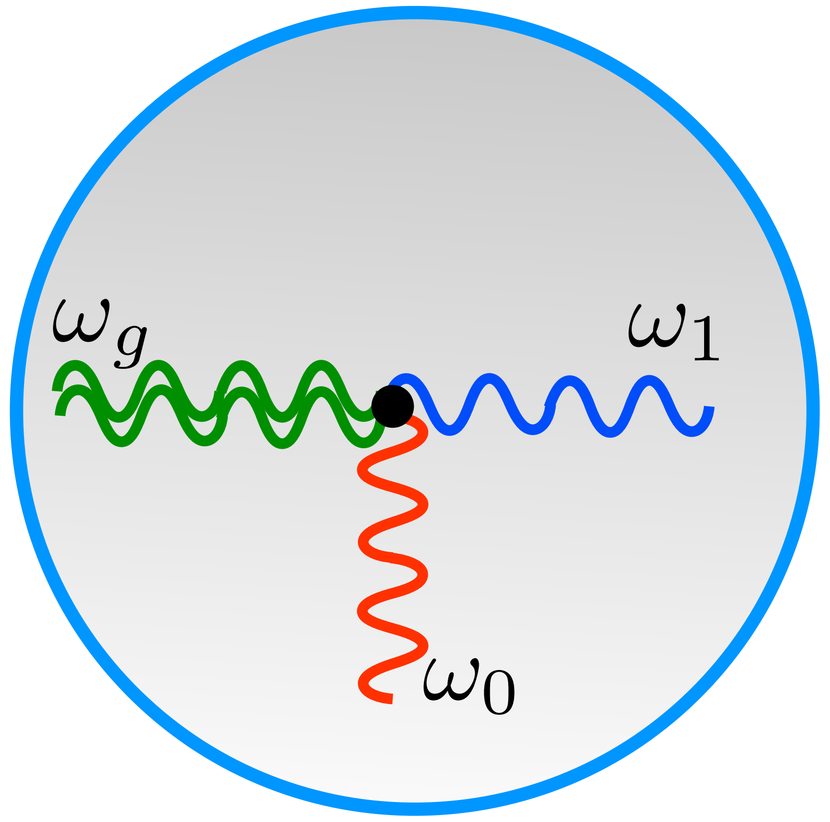
EM and Mechanical signals

EM and Mechanical signals



Parametrics of the EM signal: $E_{\rm sig}^{\rm (EM)} \sim Q_{\rm em}\,(\omega_g\,L_{\rm cav})^2\,h^{\rm TT}\,E_0$

EM and Mechanical signals



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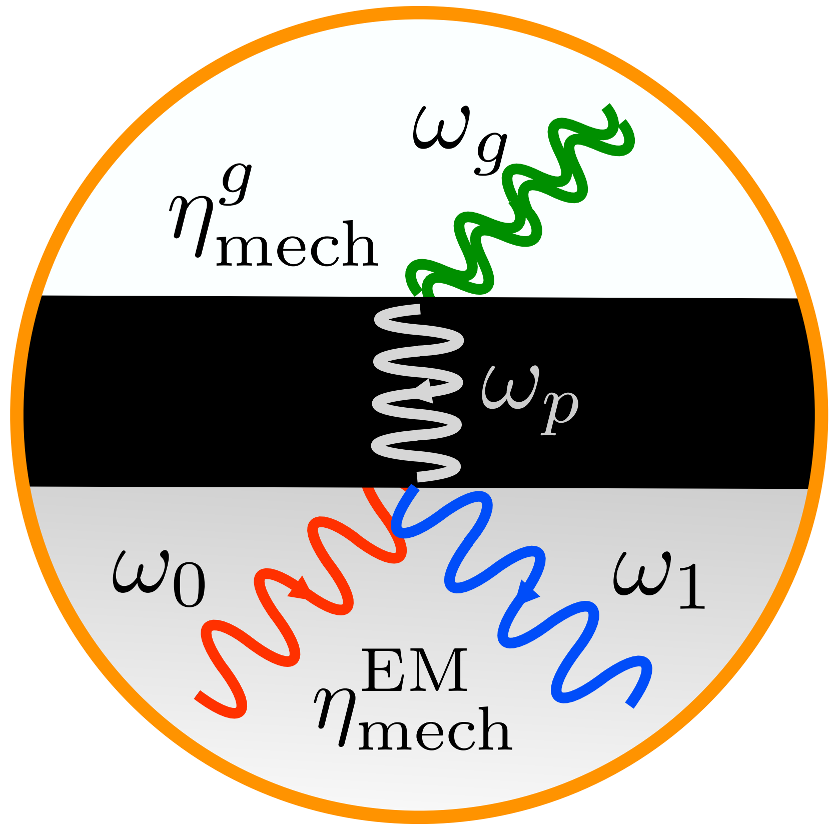
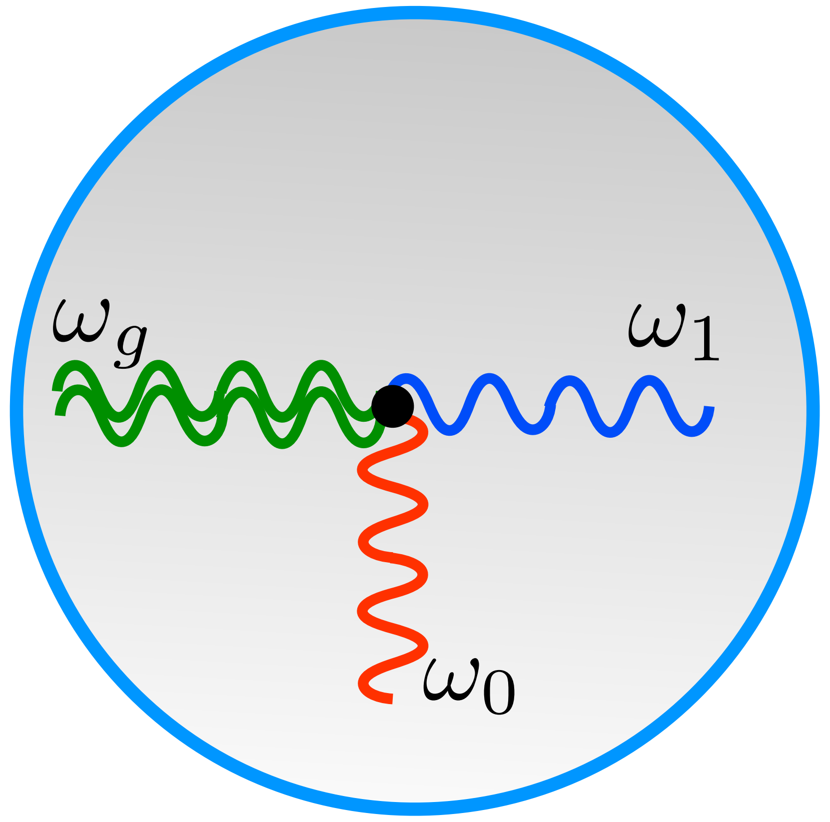
Mechanical signal: $$E_{\rm sig}^{\rm (mech)} \sim Q_{\rm em}\,h^{\rm TT}\,E_0\,\min\left(1\,,\,\frac{\omega_g\,L_{\rm cav}}{c_s}\right)^2$$



EM and Mechanical signals



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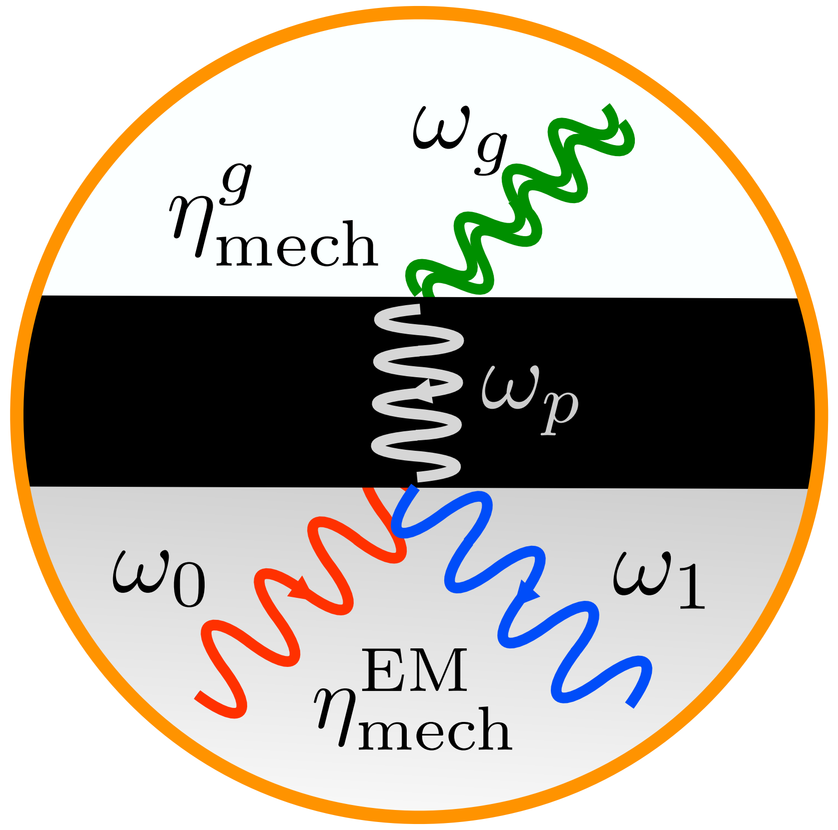
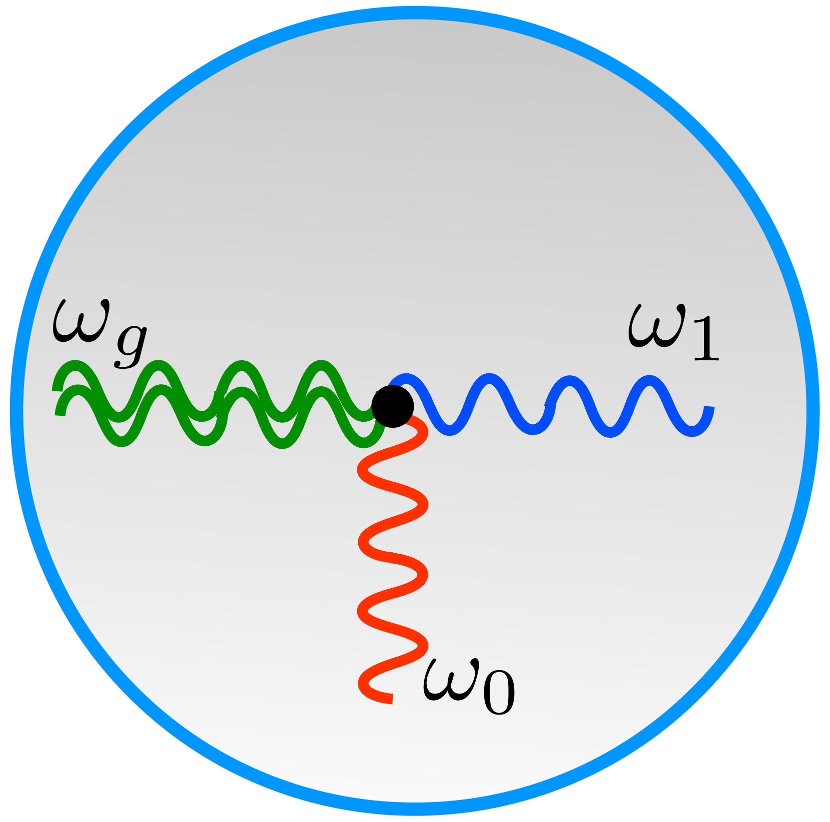
Enhanced by $1/c_s^2 \gg 1$ *(!)*

Mechanical signal: $E_{\rm sig}^{\rm (mech)} \sim Q_{\rm em}\,h^{\rm TT}\,E_0\,\min\left(1\,,\,\frac{\omega_g\,L_{\rm cav}}{c_s}\right)^2$



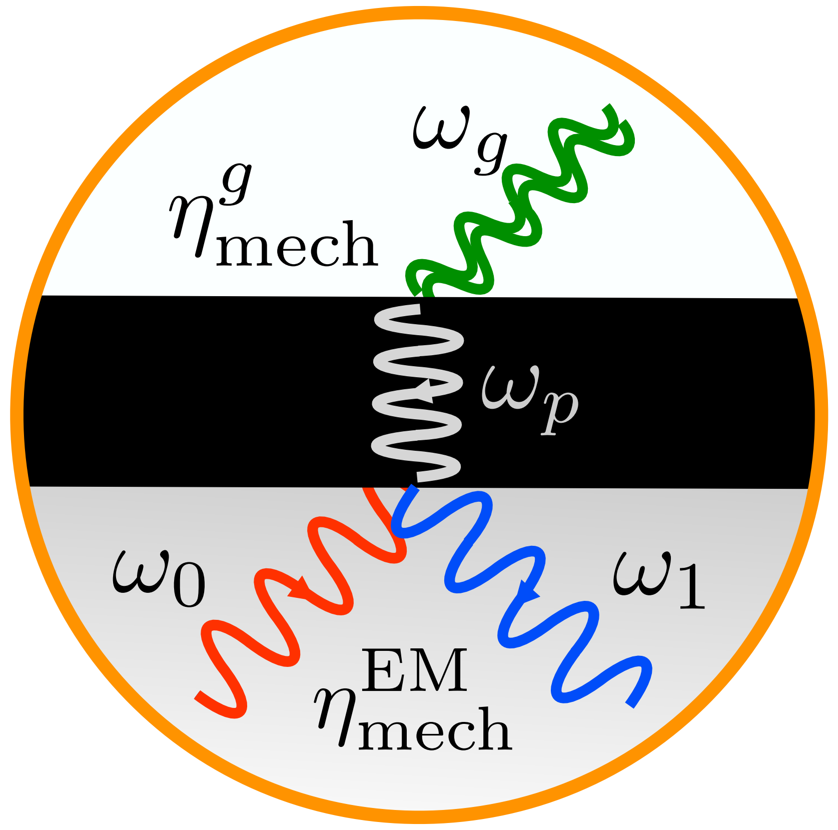
EM and Mechanical signals



Parametrics of the EM signal: $E_{\rm sig}^{\rm (EM)} \sim Q_{\rm em}\,(\omega_g\,L_{\rm cav})^2\,h^{\rm TT}\,E_0$

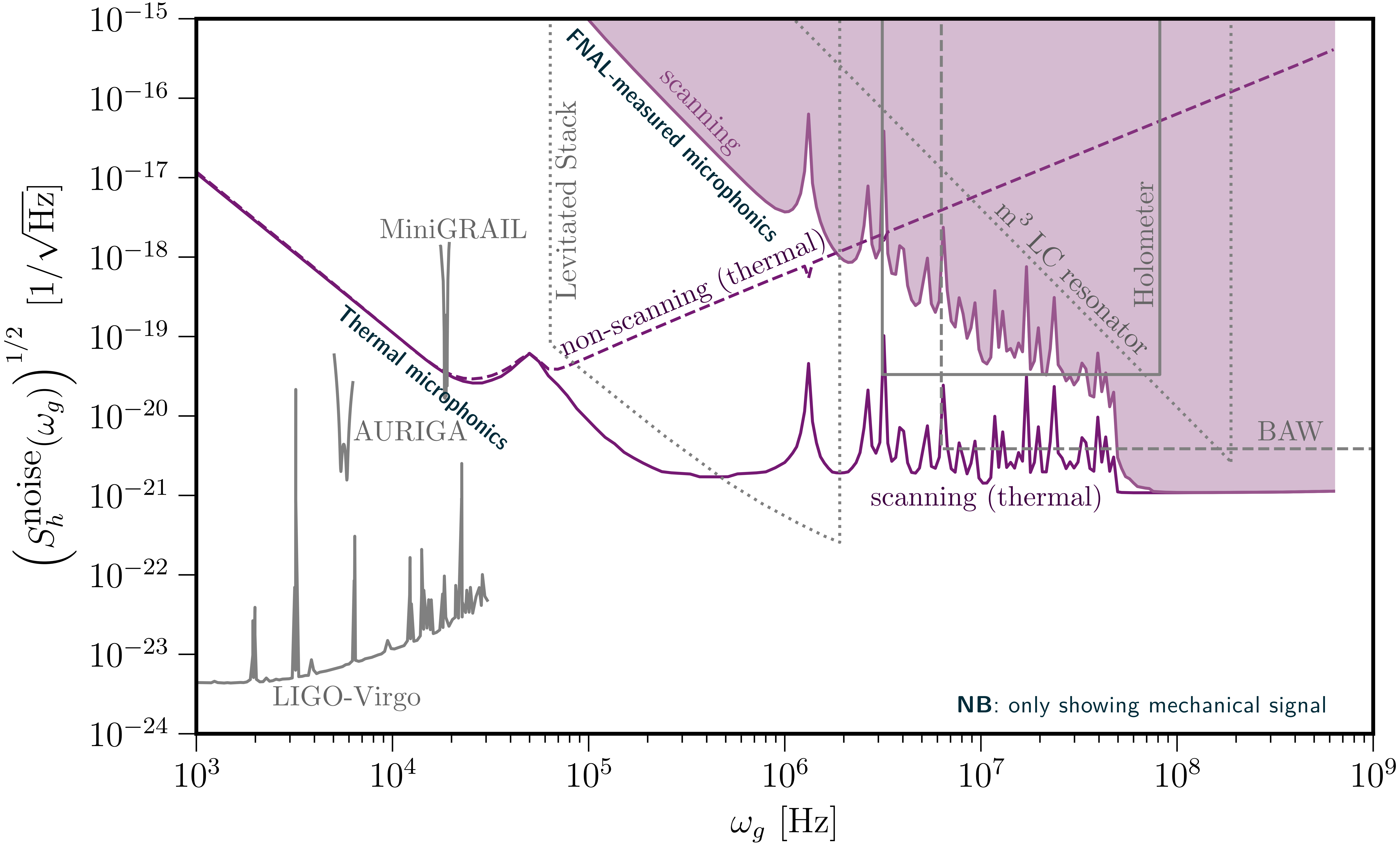
Enhanced by $1/c_s^2 \gg 1$ (!)

Mechanical signal: $E_{\rm sig}^{\rm (mech)} \sim Q_{\rm em}\,h^{\rm TT}\,E_0\,\min\left(1\,,\,\frac{\omega_g\,L_{\rm cav}}{c_s}\right)^2$

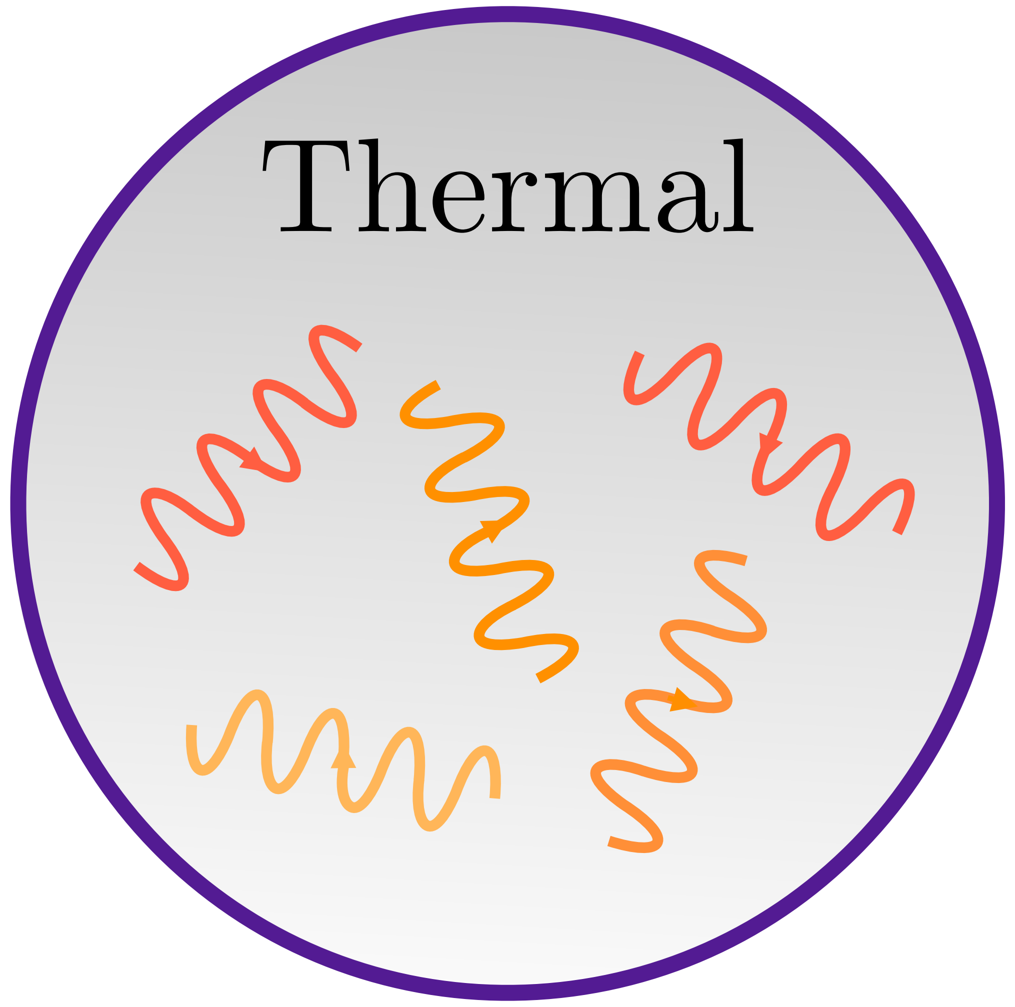


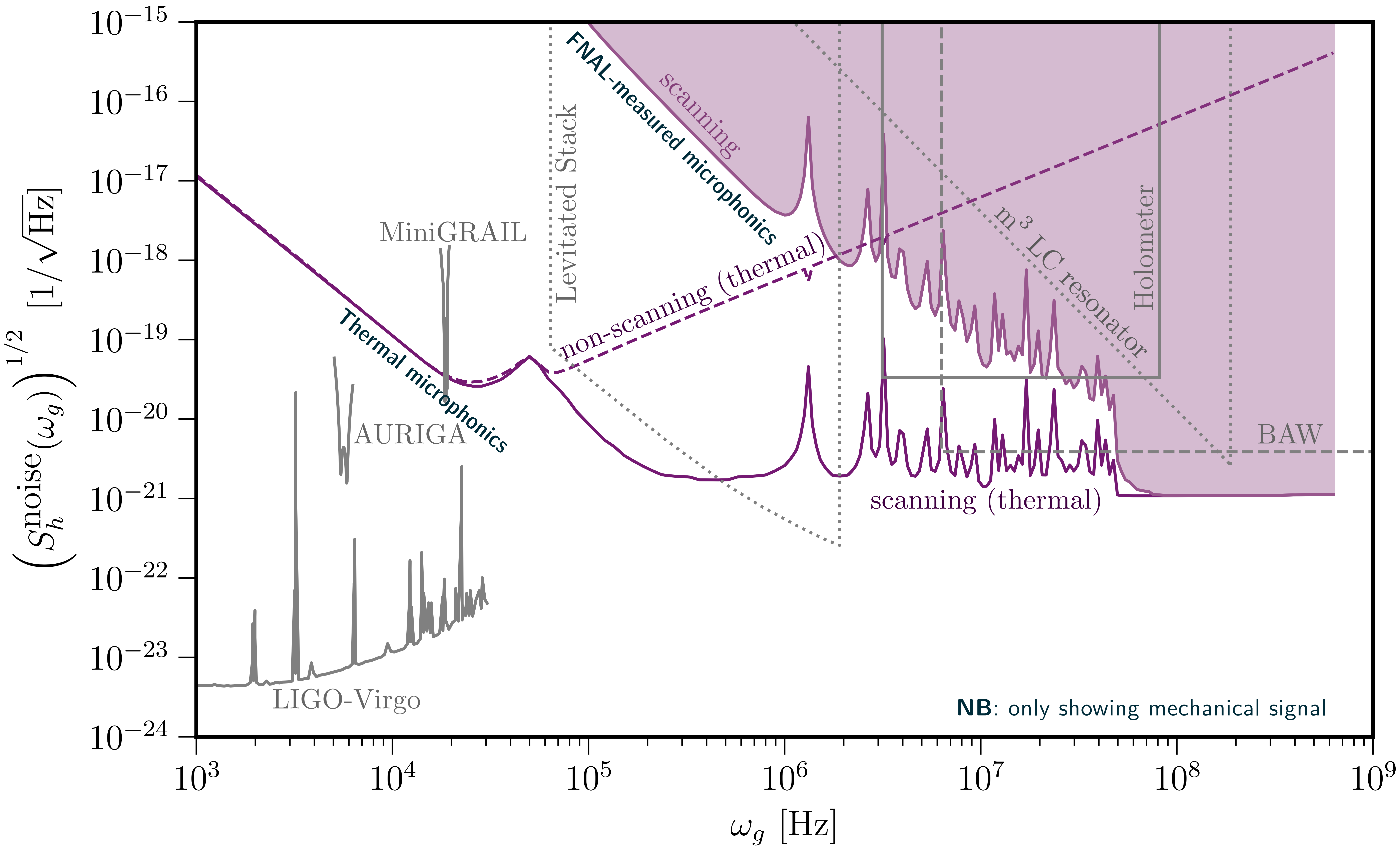
Mechanical modes less "rigid" than EM modes

Noise in MAGO 2.0

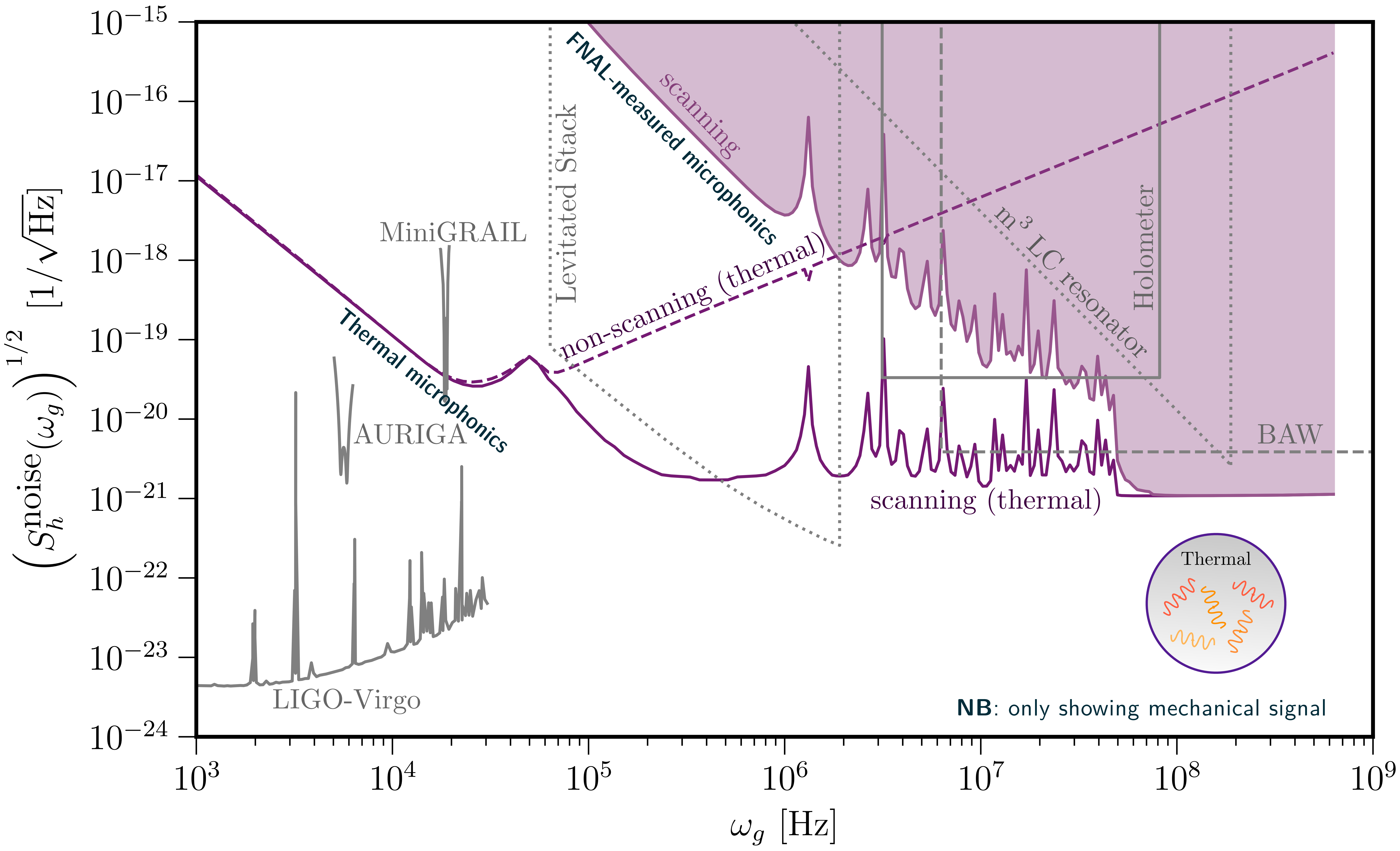


Noise in MAGO 2.0

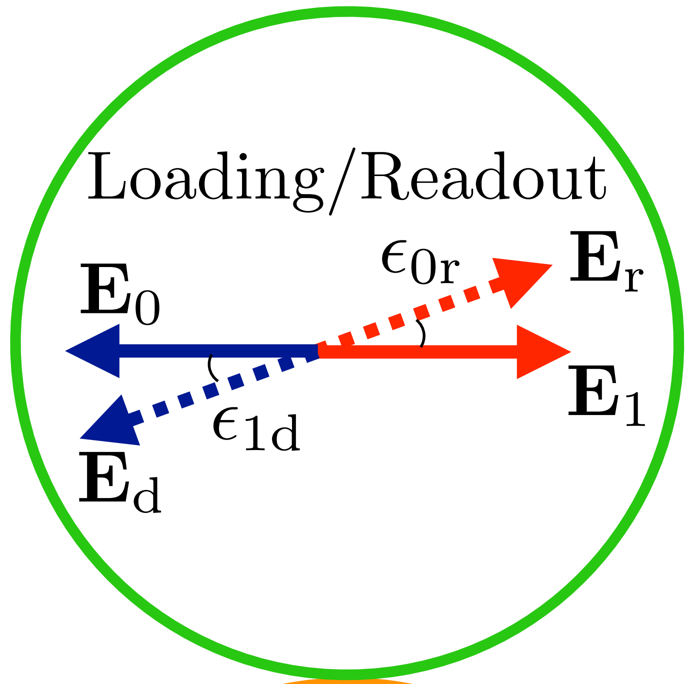


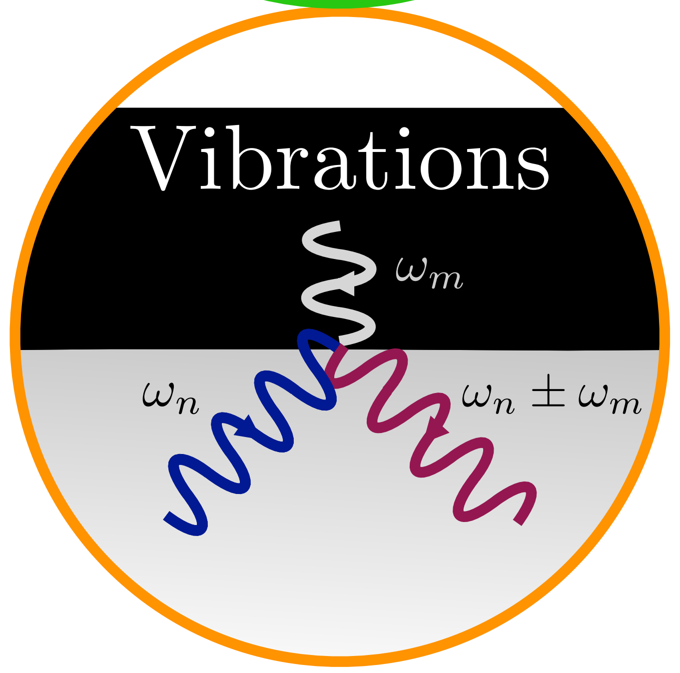


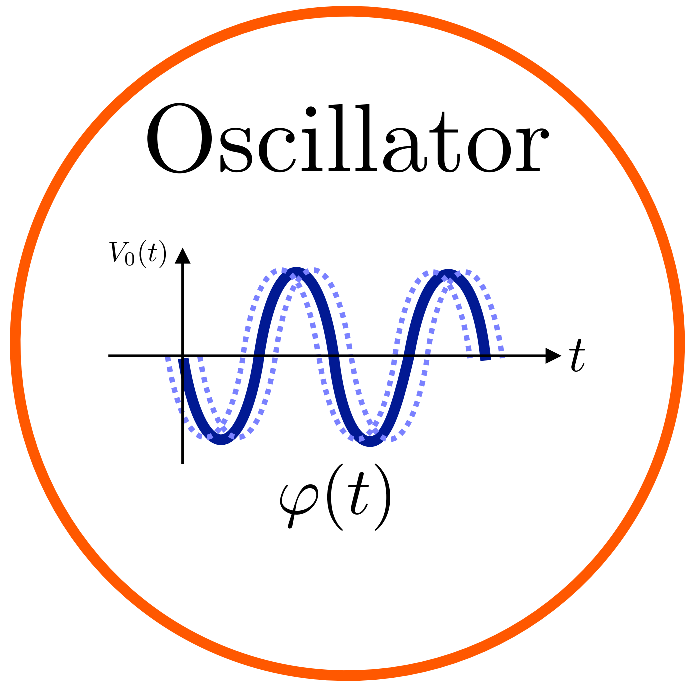
Noise in MAGO 2.0

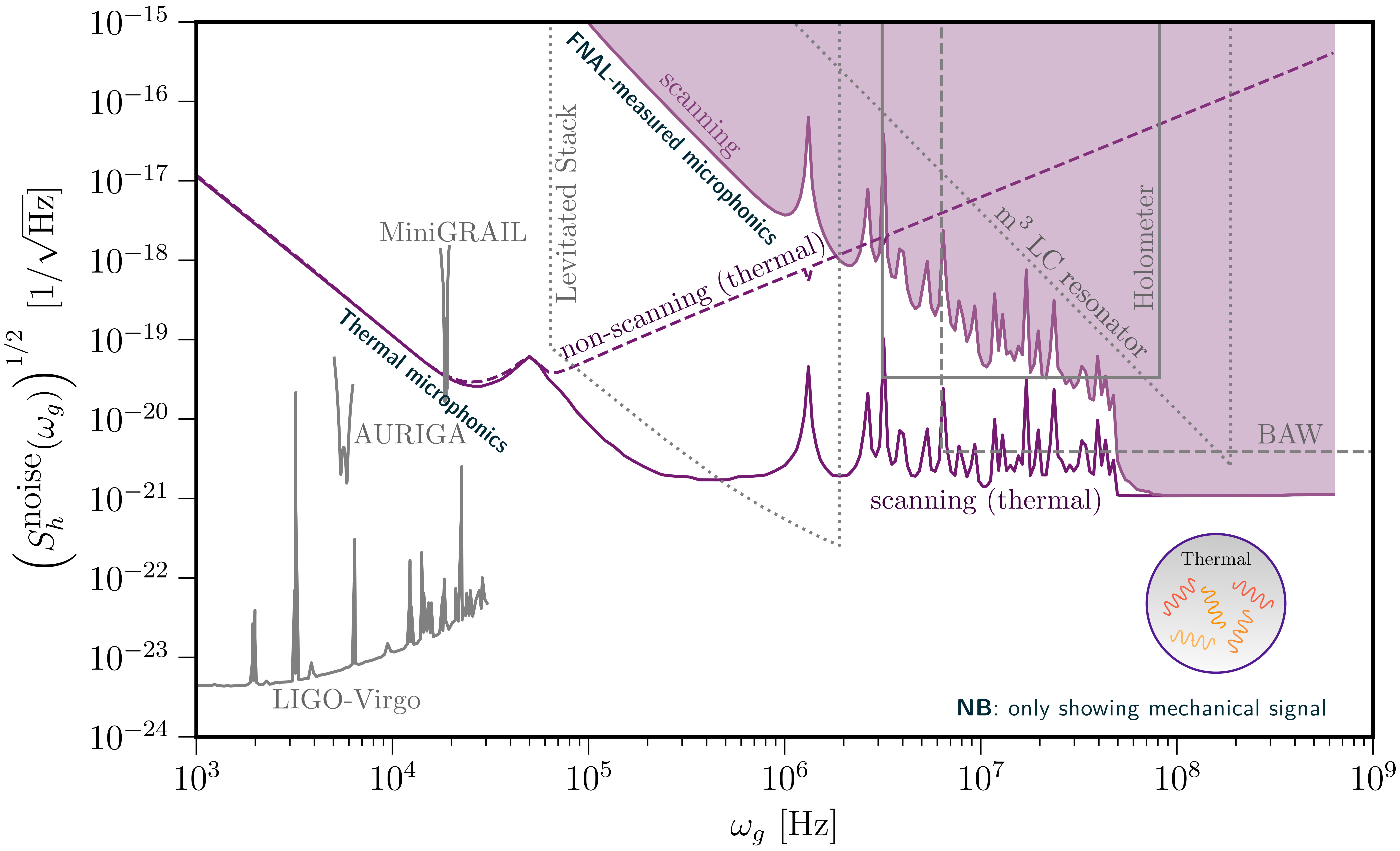


Noise in MAGO 2.0

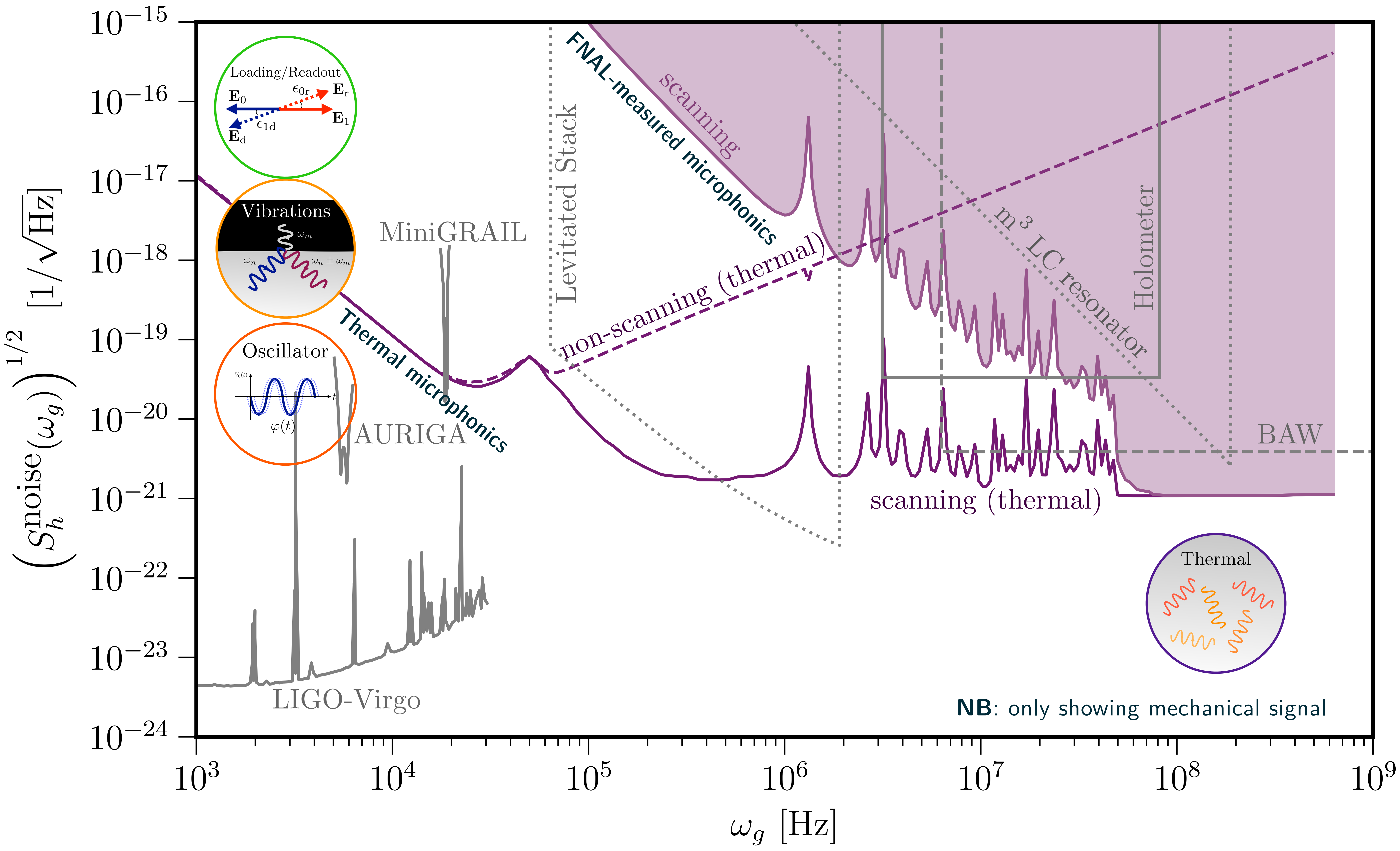




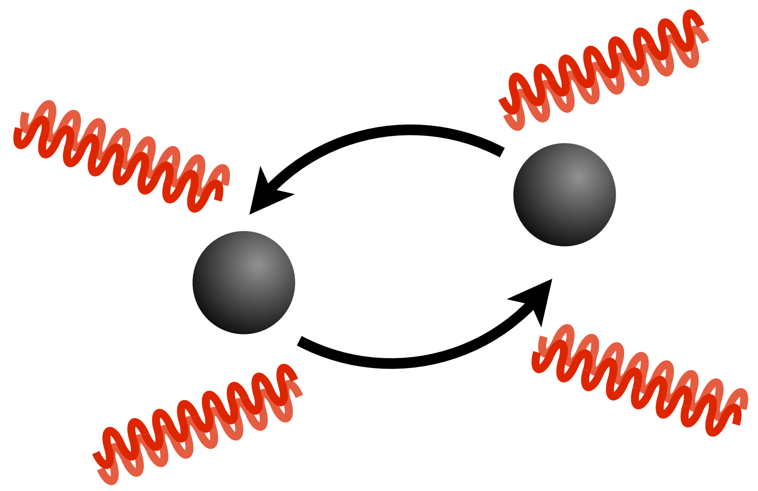




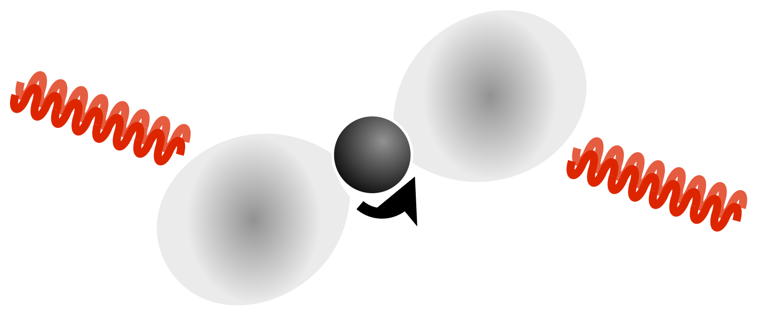
Noise in MAGO 2.0



Gravitational Waves

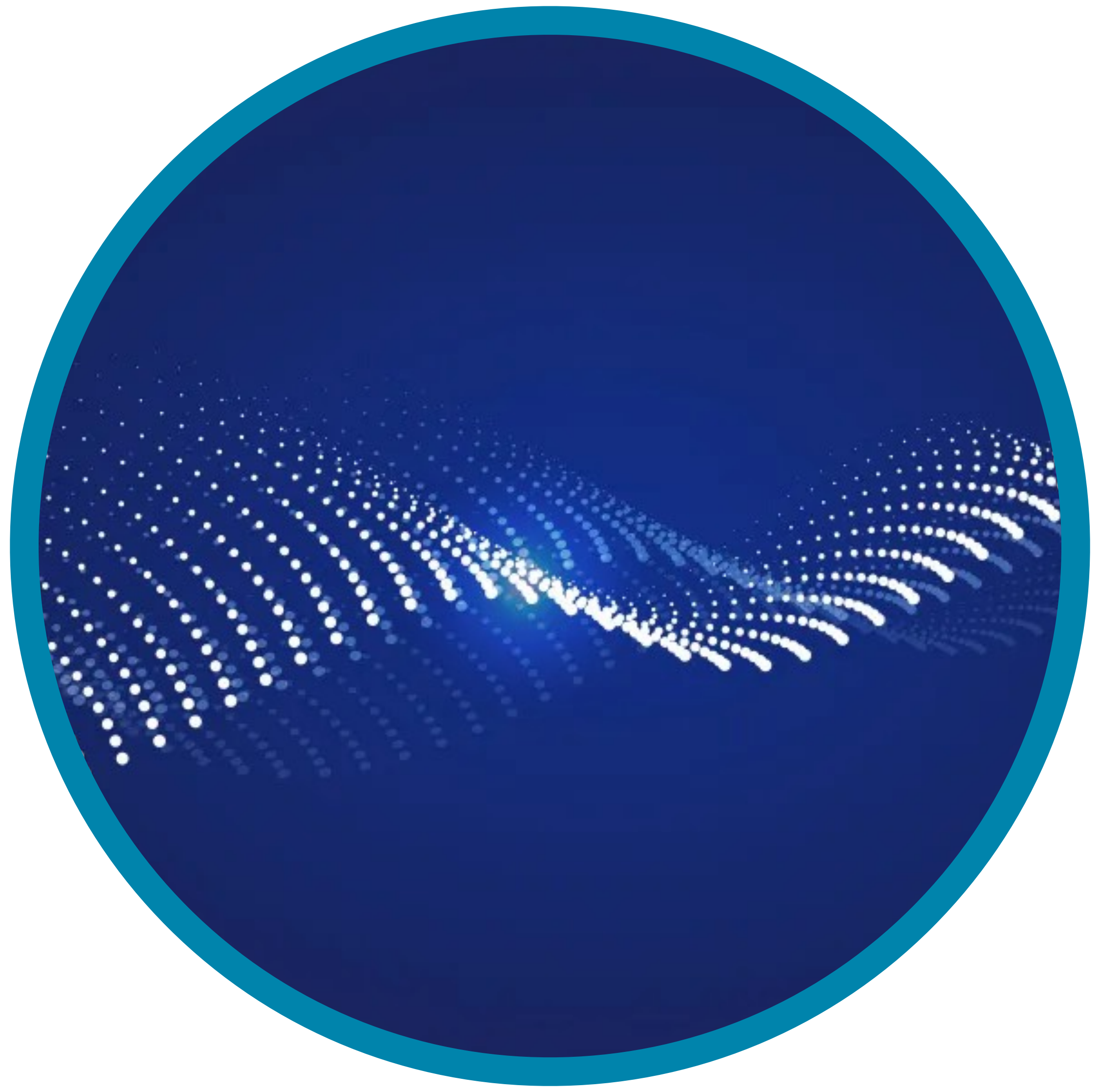


- **HFGWs provide insight into early universe/BSM**
- **Reaching anticipated stochastic sources difficult**
- **Broadband sensitivity of MAGO 2.0:**
  ongoing collaboration w/ DESY & SQMS @FNAL
  See Bianca's talk
- **Improve scan rate for resonant searches w/ Quantum techniques**



BACKUP

Axion Dark Matter BACKUP



Comparison of approaches

	Static-field Haloscope	LC Resonator	RF Frequency Conversion
$J_{\rm eff}$	$\propto B_0^{\rm static}\cos(m_a t)$	$\propto B_0^{\rm static}\cos(m_a t)$	$\propto B_0^{\rm RF}\cos(\omega_0 \pm m_a)t$
$\mathcal{E}_a$	$\propto m_a/\omega_{\rm sig} \sim 1$	$\propto m_a V^{1/3} \lesssim 1$	$\propto (\omega_0 \pm m_a)/\omega_{\rm sig} \sim 1$
$P_{\rm sig}$	$J_{\rm eff}^2 V \min\left(\frac{Q_{\rm r}}{m_a}, \frac{Q_a}{m_a}\right)$	$J_{\rm eff}^2 m_a^2 V^{5/3} \min\left(\frac{Q_{\rm LC}}{m_a}, \frac{Q_a}{m_a}\right)$	$J_{\rm eff}^2 V \min\left(\frac{Q_{\rm SRF}}{\omega_0 \pm m_a}, \frac{Q_a}{m_a}\right)$

Axion Signal

Signal Power Spectral Density (PSD):

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

Axion PSD: $\langle a(t)^2\rangle = \frac{1}{(2\pi)^2}\int d\omega\ S_a(\omega) = \frac{\rho_{\text{DM}}}{m_a^2}$

Background magnetic field PSD:

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

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

Axion Signal

Signal Power Spectral Density (PSD):

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

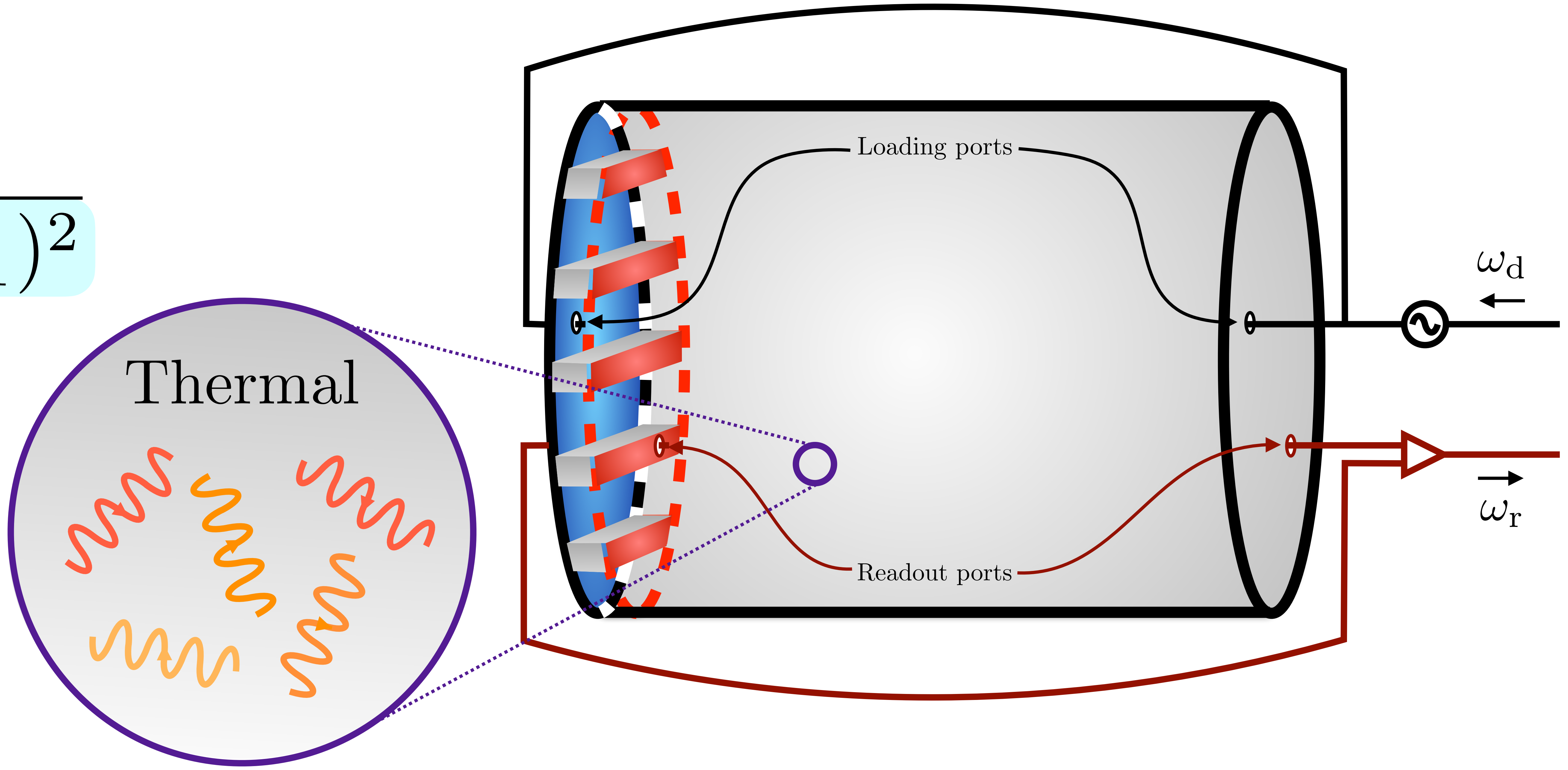
Signal Power (resonant):

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

Standard Noise Sources: Thermal Noise

Power Spectral Density:

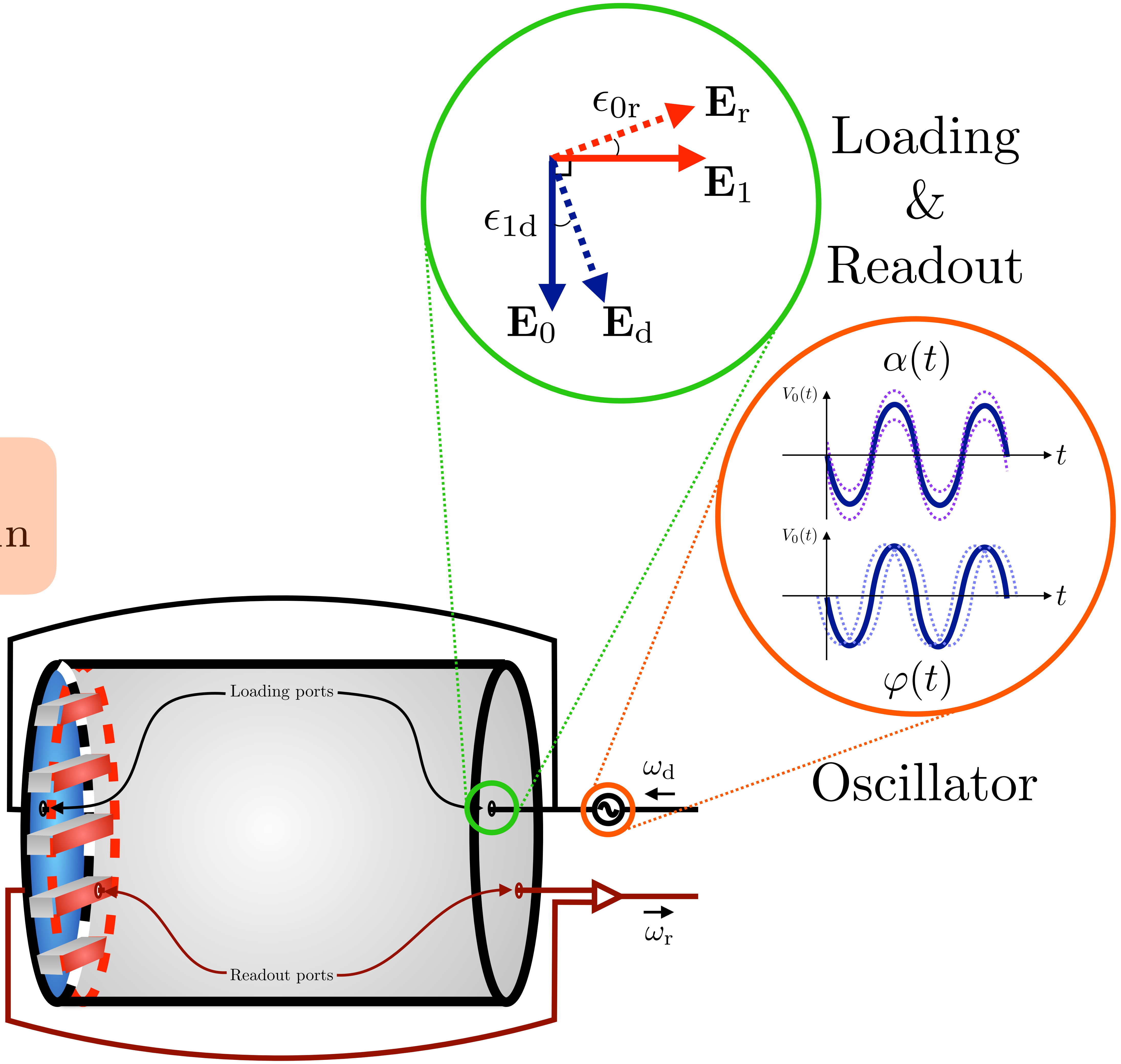
$$S_{\rm th}(\omega) = \frac{Q_1}{Q_{\rm int}} \frac{4\pi T\,(\omega\,\omega_1/Q_1)^2}{(\omega^2-\omega_1^2)^2 + (\omega\,\omega_1/Q_1)^2}$$



Non-standard Noise Sources: Phase Noise

Power Spectral Density:

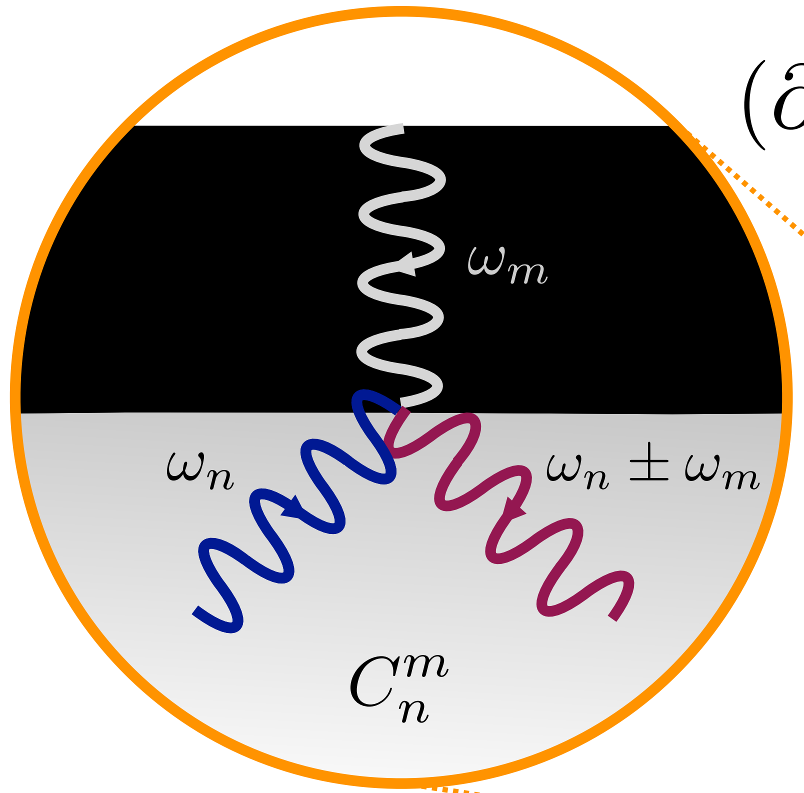
$$S_{\text{phase}}(\omega) \simeq \frac{1}{2}\,\epsilon_{1\text{d}}^2\, S_\varphi(\omega-\omega_0) \times \frac{(\omega\,\omega_1/Q_1)^2}{(\omega^2-\omega_1^2)^2+(\omega\,\omega_1/Q_1)^2}\,\frac{\omega_0 Q_1}{\omega_1 Q_0}\,P_{\text{in}}$$



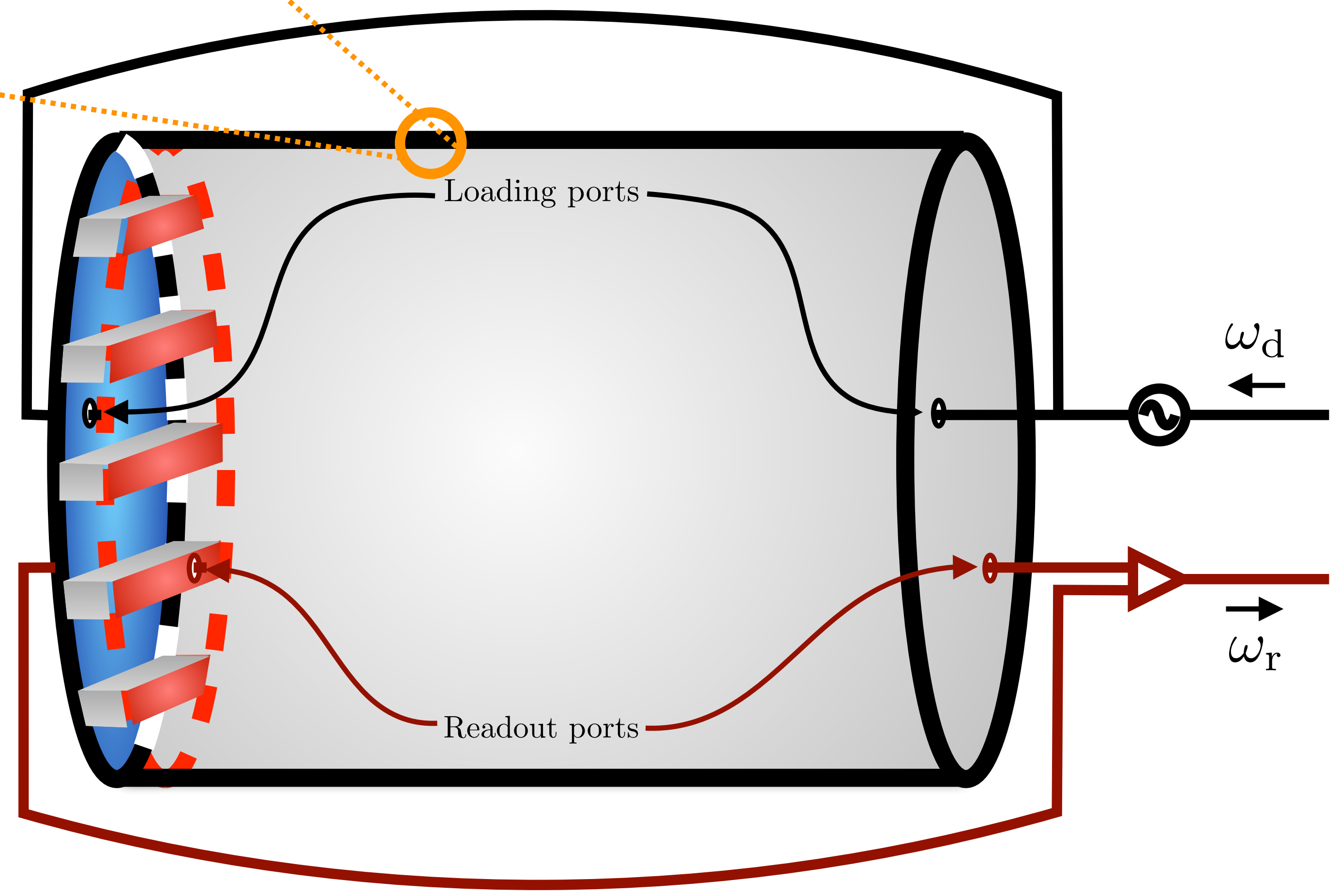
Non-standard Noise Sources: Vibrations

Vibrations

$$(\partial_t^2 + \omega_n^2)\, e_n \simeq \frac{2}{U_n} \sum_m e_m \begin{cases} \int_{\Delta V} d^3\mathbf{x} \left[\omega_n\,\omega_m\,\mathbf{B}_m \cdot \mathbf{B}_n^* - \frac{1}{2}\,(\omega_n^2 + \omega_m^2)\,\mathbf{E}_m \cdot \mathbf{E}_n^*\right] + \mathcal{O}(\Delta V^2) & (V' \subset V) \\ \int_{\Delta V} d^3\mathbf{x} \left[\omega_n\,\omega_m\,\mathbf{B}_m \cdot \mathbf{B}_n^* - \omega_n^2\,\mathbf{E}_m \cdot \mathbf{E}_n^*\right] + \mathcal{O}(\Delta V^2) & (V \subset V') \end{cases}$$

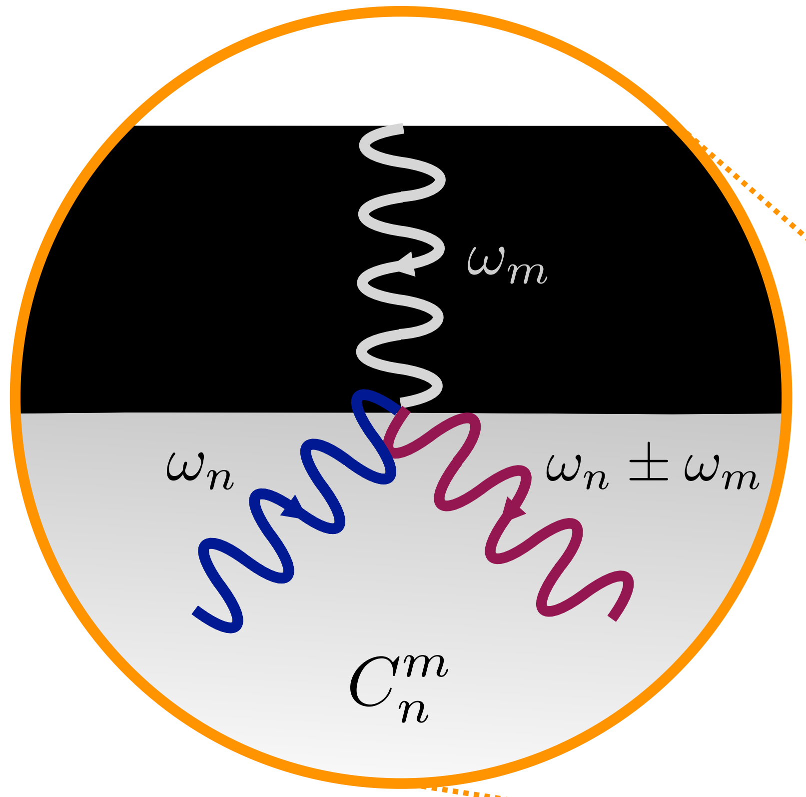


Cavity perturbation theory, see e.g. Meidlinger (2009), Pozar, etc.



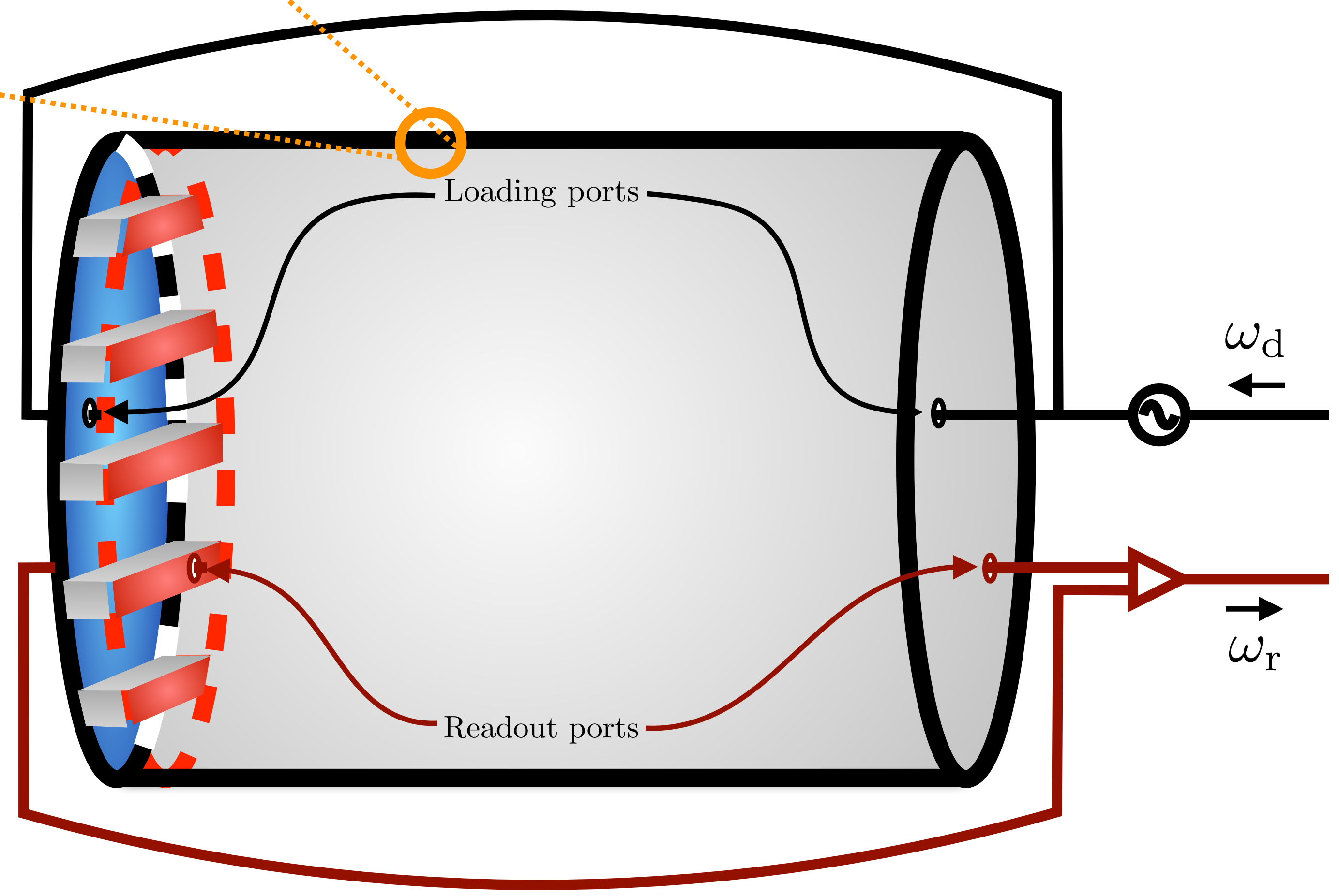
Non-standard Noise Sources: Vibrations

Vibrations



Power Spectral Density:

$$S_{\rm mix} = \frac{\epsilon_{01}^2}{4} P_{\rm in} \sum_{i=0,1} \frac{\omega_i^4}{(\omega_0^2 - \omega_i^2)^2 + (\omega_0\omega_i/Q_i)^2} \frac{(\omega\omega_i)^2}{(\omega^2 - \omega_i^2)^2 + (\omega\omega_i/Q_i)^2} |C_i^m|^2 S_{q_m}(\omega - \omega_0)$$

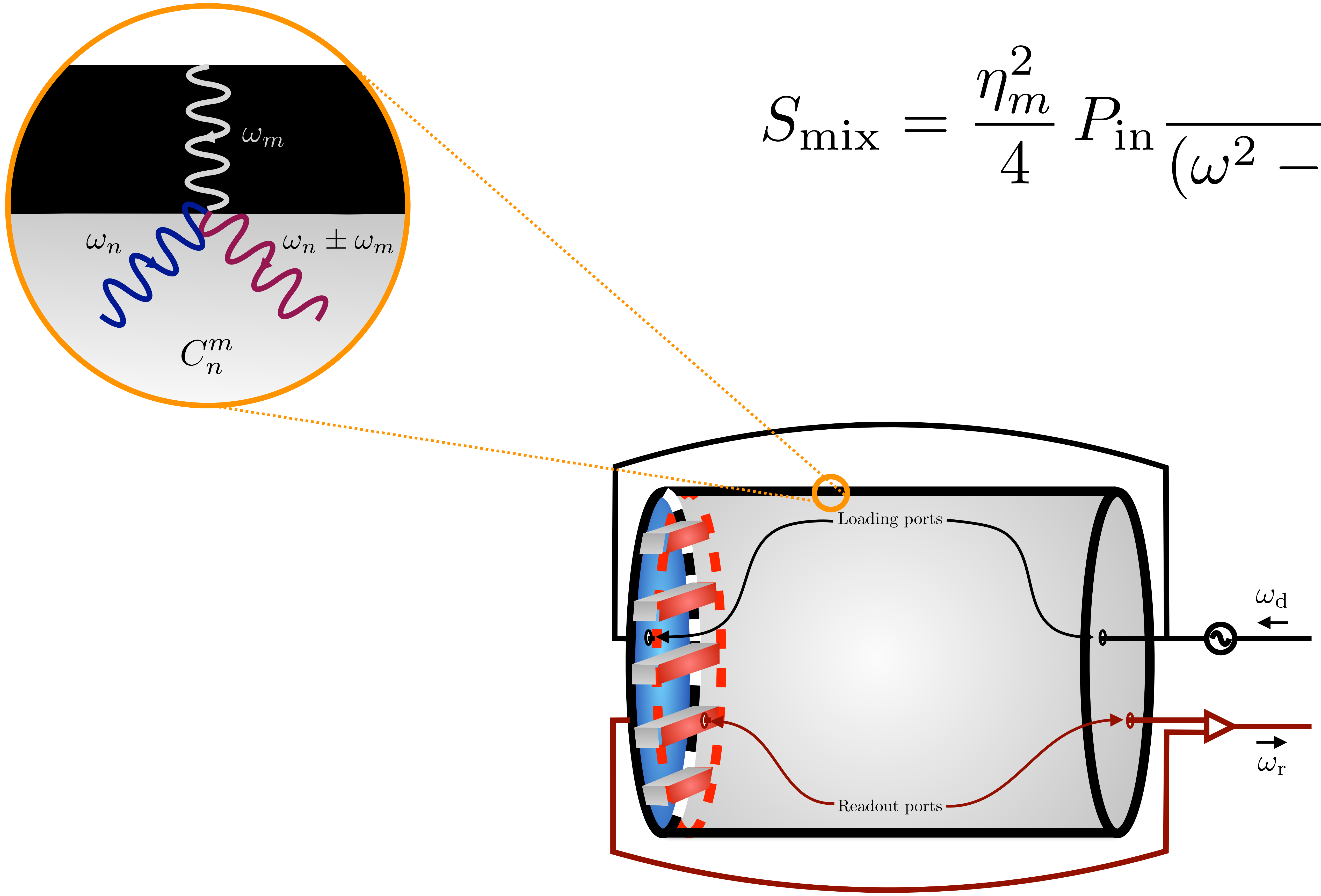


Displacement PSD:

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

Non-standard Noise Sources: Vibrations mixing

Vibrations



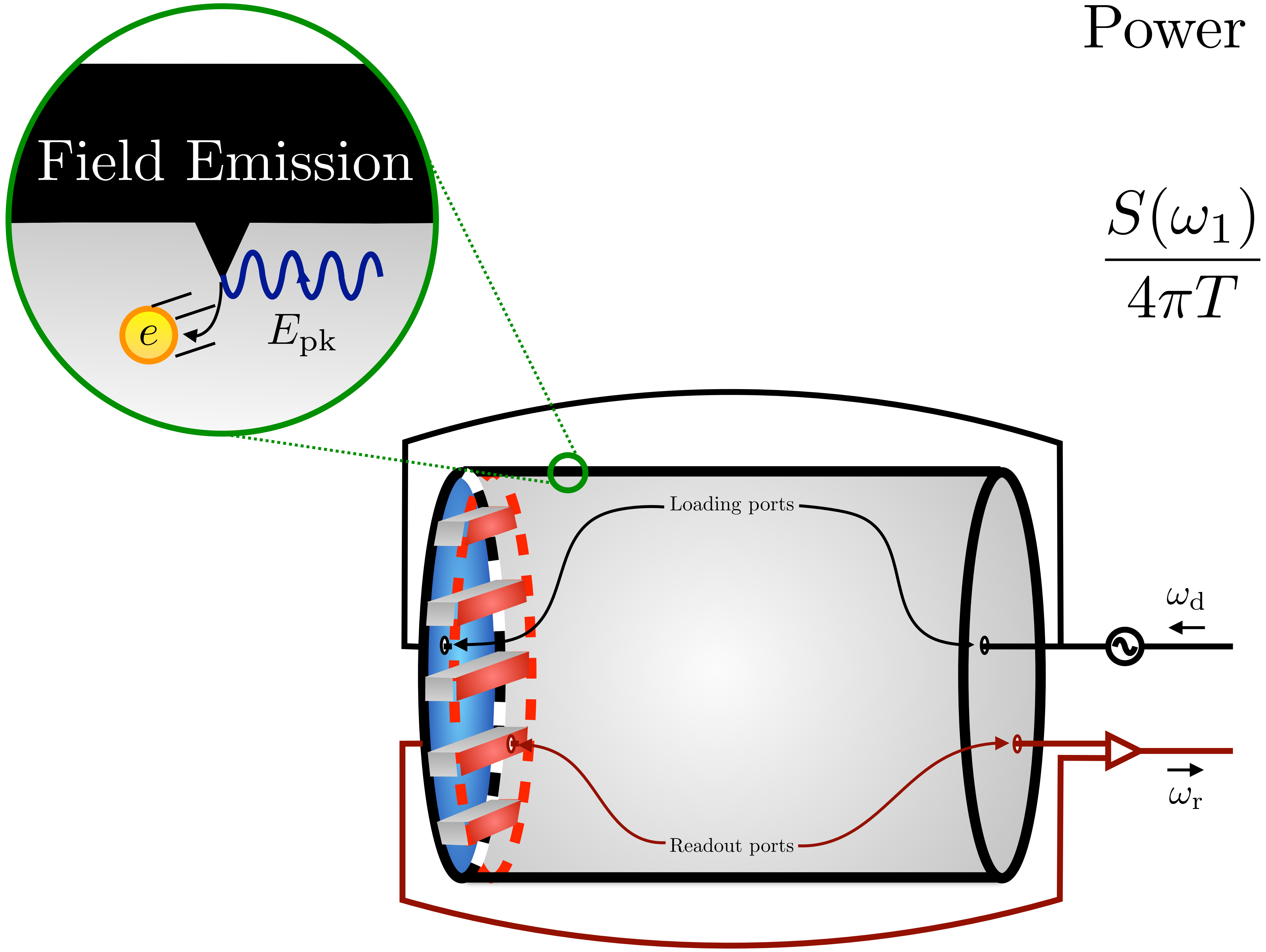
Power Spectral Density:

$$S_{\rm mix} = \frac{\eta_m^2}{4} P_{\rm in} \frac{\omega_0^4}{(\omega^2 - \omega_1^2)^2 + (\omega\omega_1/Q_1)^2} |C_1^m|^2 S_{q_m}(\omega - \omega_0)$$

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 ~ 0.2 T

All Noise Sources

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

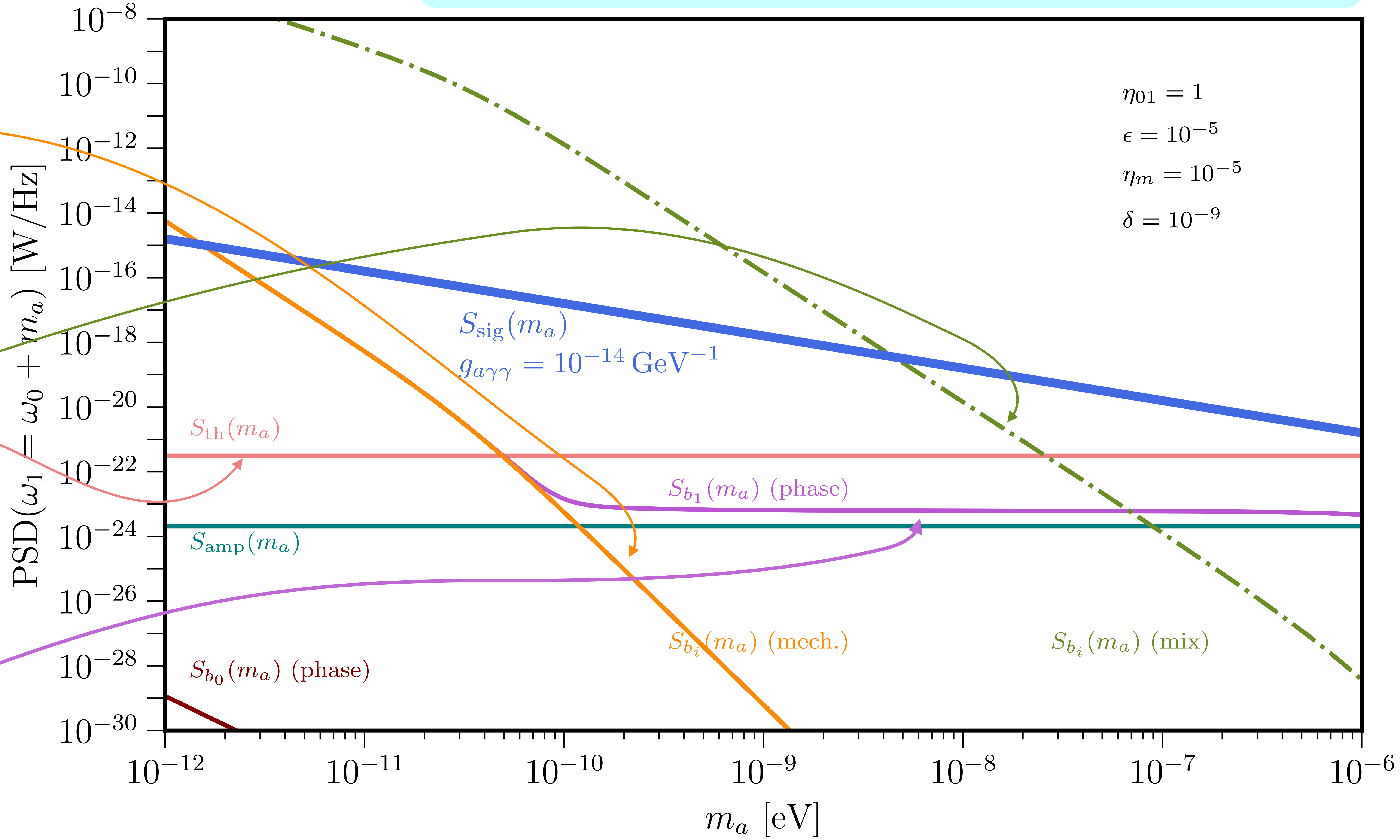
fractional wall disp. δ

$$P_{\rm mix} \sim \eta_m^2 \delta^2 \frac{Q_1 Q_m \omega_1 \omega_{\rm min}^3}{m_a^4} P_{\rm in}$$

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

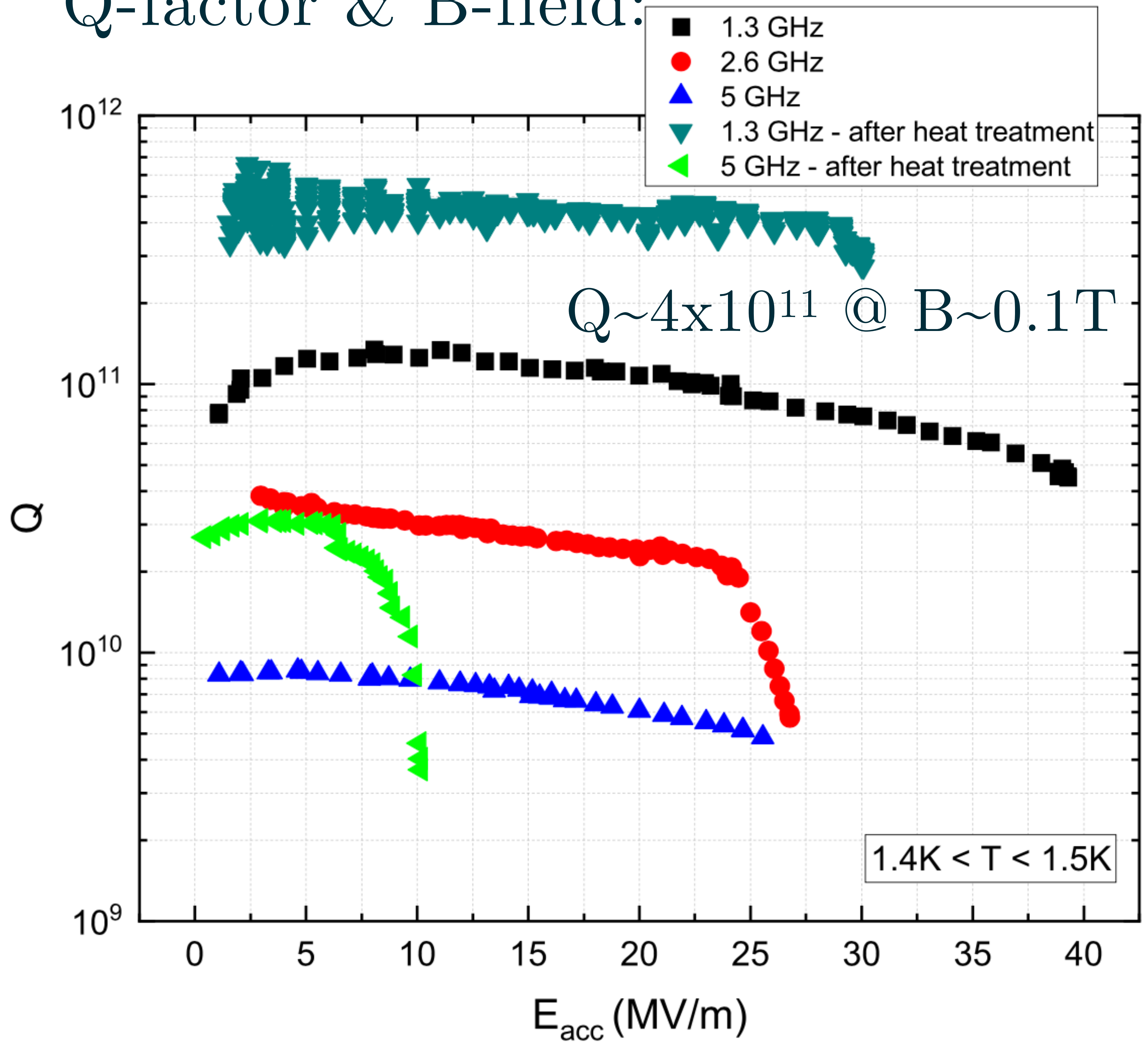
$$P_{\rm phase} \sim \epsilon_{\rm 1d}^2 S_\varphi(m_a) \frac{\omega_1}{Q_{\rm int}} P_{\rm in}$$

B = 0.1 T, T = 2K, $\omega_0 = 2\pi$ GHz, V = 0.05 m³



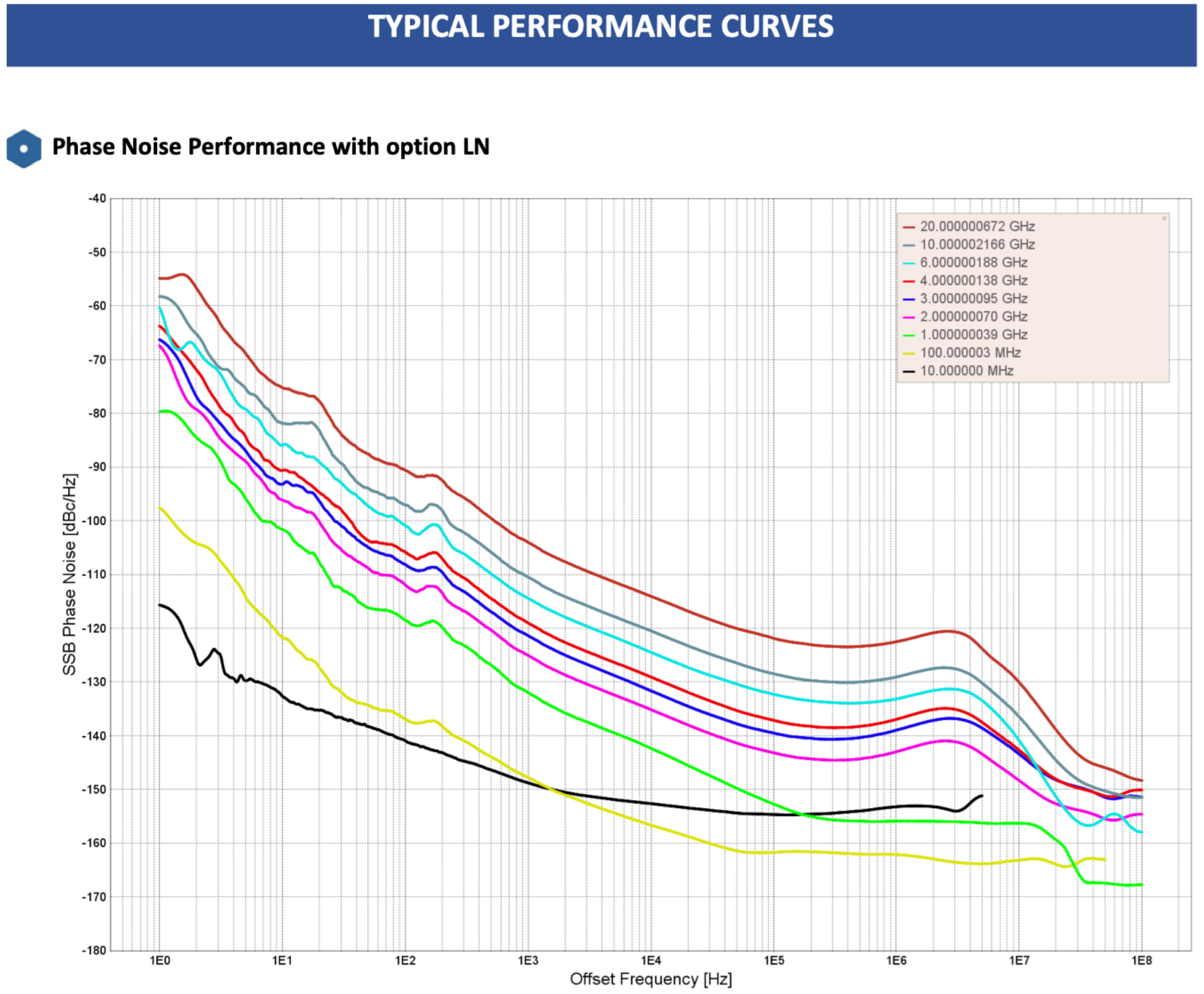
Technology Requirements

Q-factor & B-field:



arXiv: 1810.03703 Romanenko et al.

Phase noise: *e.g.* BN865-M



In total need ~ -240 dB/Hz @ GHz to reach thermal noise floor

Technology Requirements

Mode rejection:

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

gr-qc/0502054 Ballantini, ..., Calatroni et al
physics/0004031 Bernard, Gemme, Parodi, Picasso

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Original MAGO collaboration

gr-qc/0502054 Ballantini, ..., Calatroni et al

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Technology Requirements

Mode rejection:

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

Original MAGO collaboration

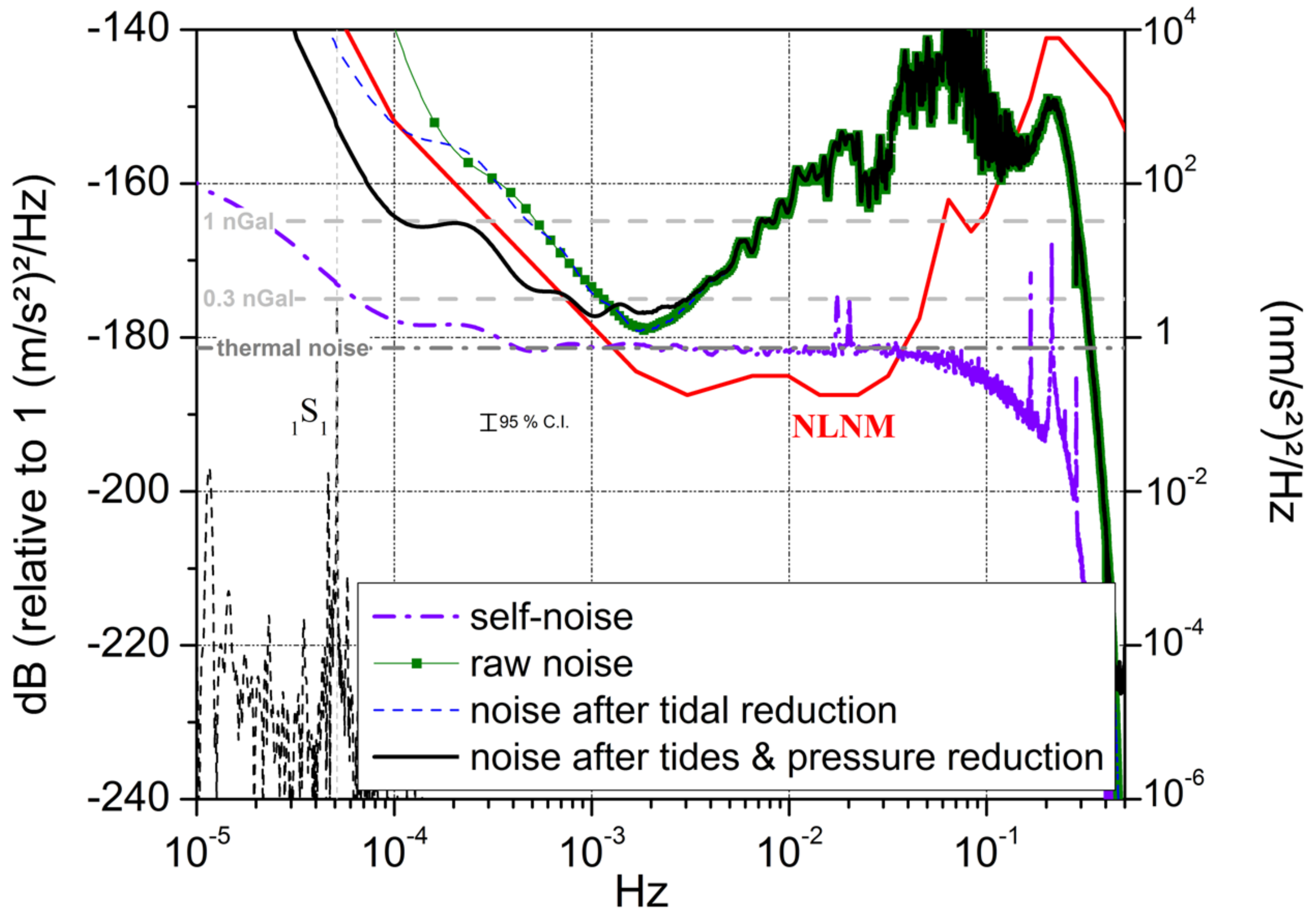
gr-qc/0502054 Ballantini, ..., Calatroni et al

physics/0004031 Bernard, Gemme, Parodi, Picasso

Low-frequency seismic noise:

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

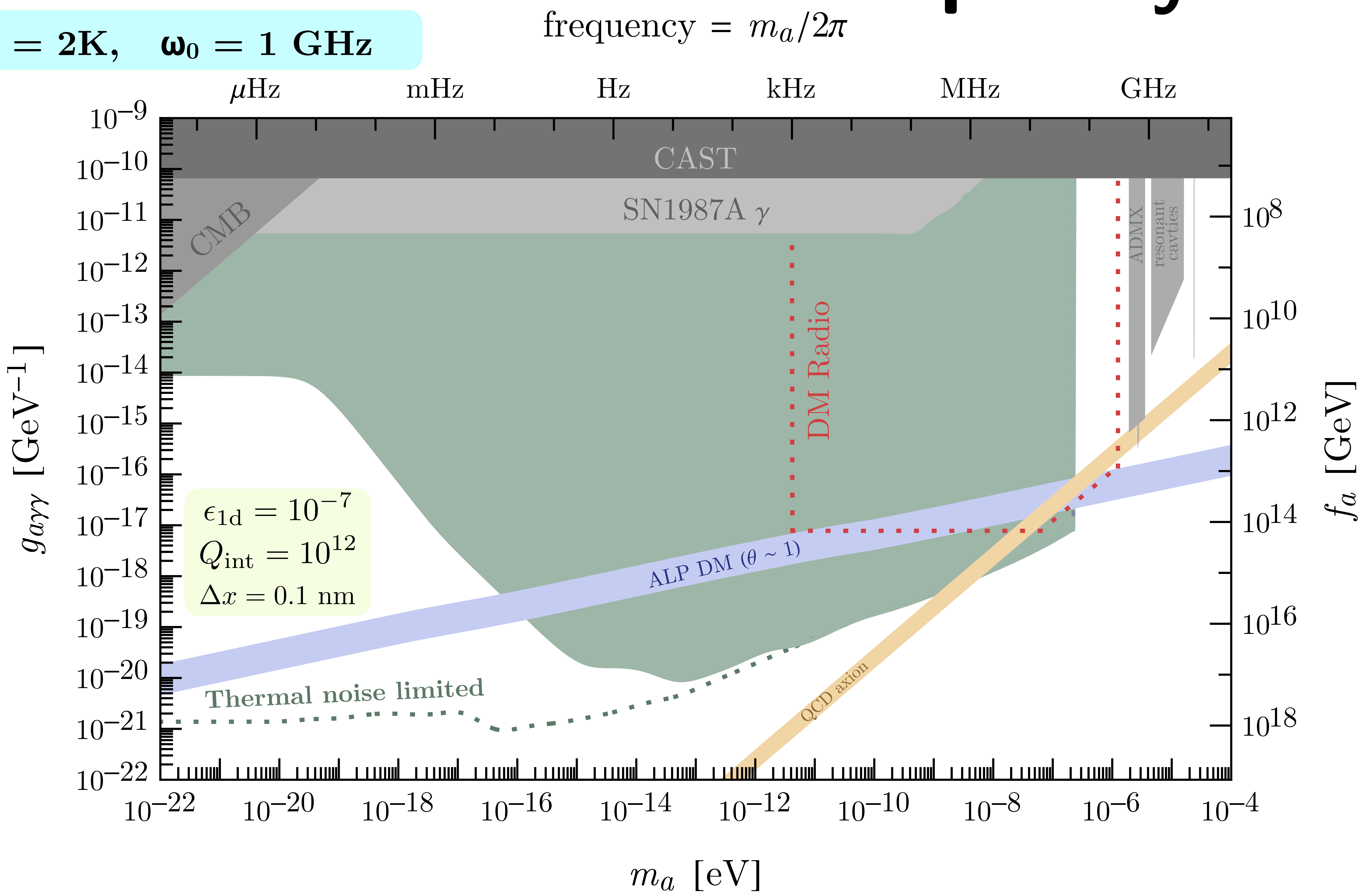
DarkSRF (2020)



Scientific Reports 8, 15324 (2018) Rosat & Hinderer

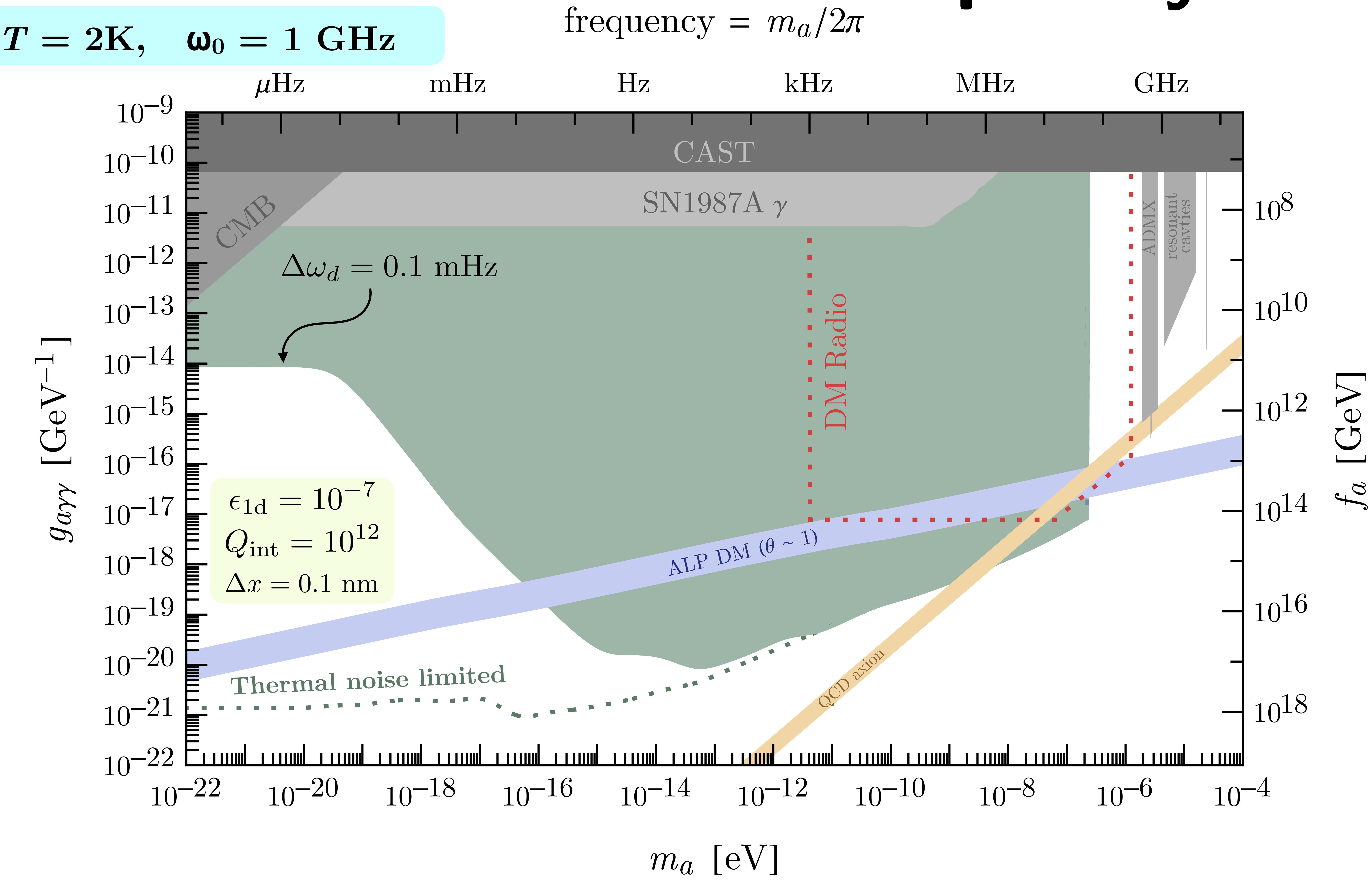
Resonant Axion Resonant Frequency Conversion

B = 0.2 T, T = 2K, ω_0 = 1 GHz



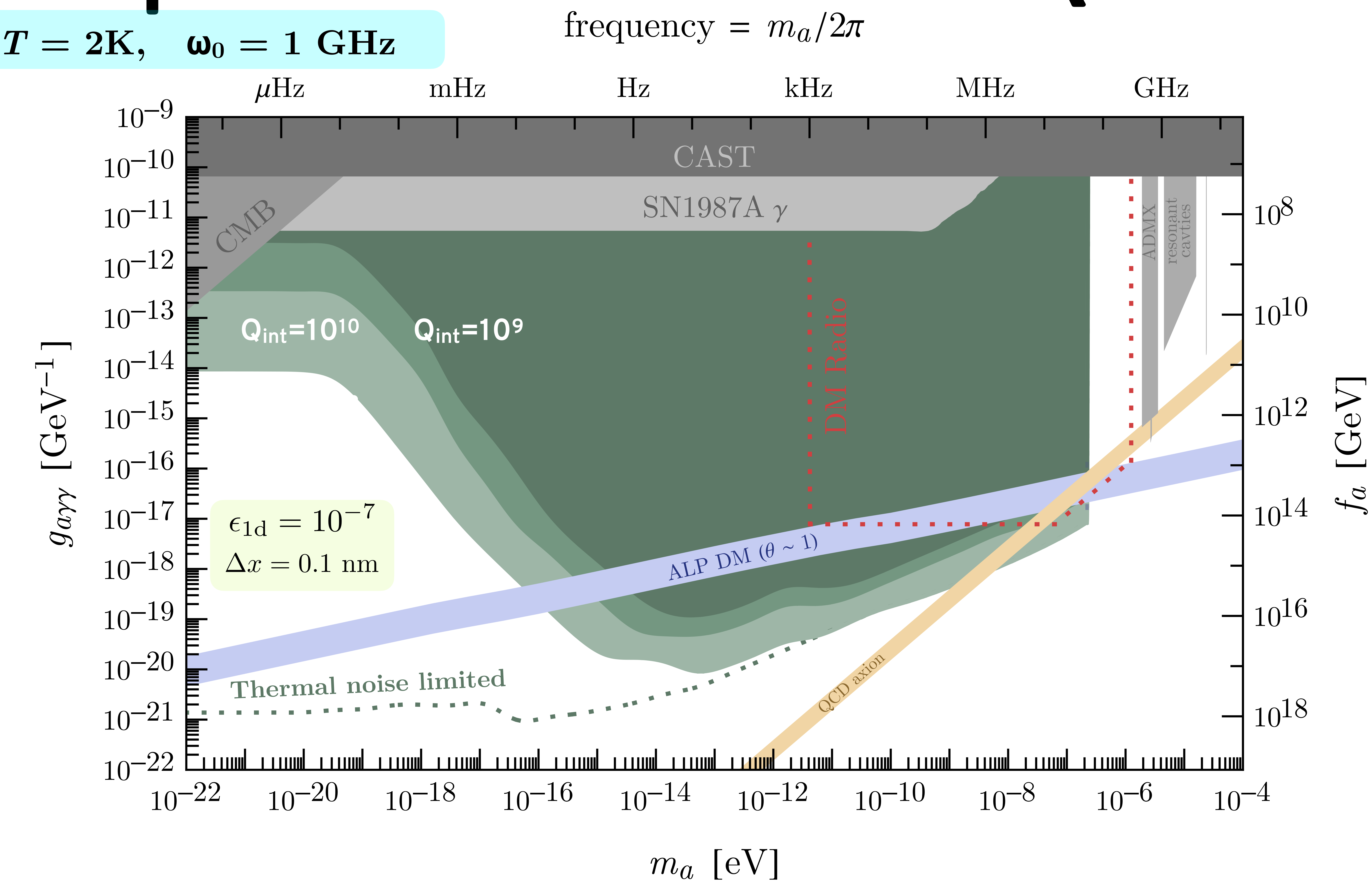
Resonant Axion Resonant Frequency Conversion

$\mathbf{B = 0.2\ T}, \quad \boldsymbol{T = 2K}, \quad \boldsymbol{\omega_0} = \mathbf{1\ GHz}$



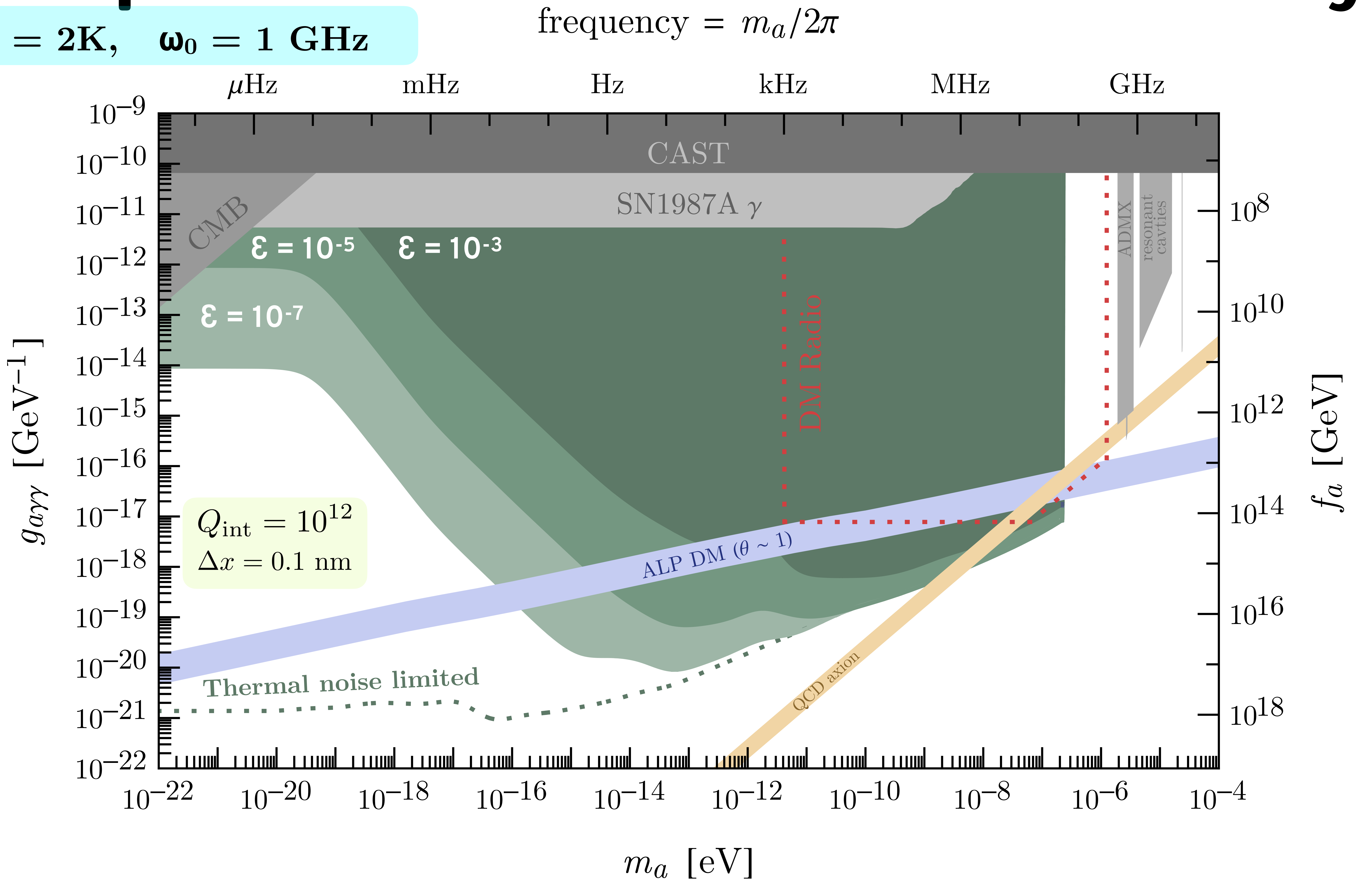
Resonant parameter variations: *Q-factor*

$B = 0.2$ T, $T = 2$K, $\omega_0 = 1$ GHz



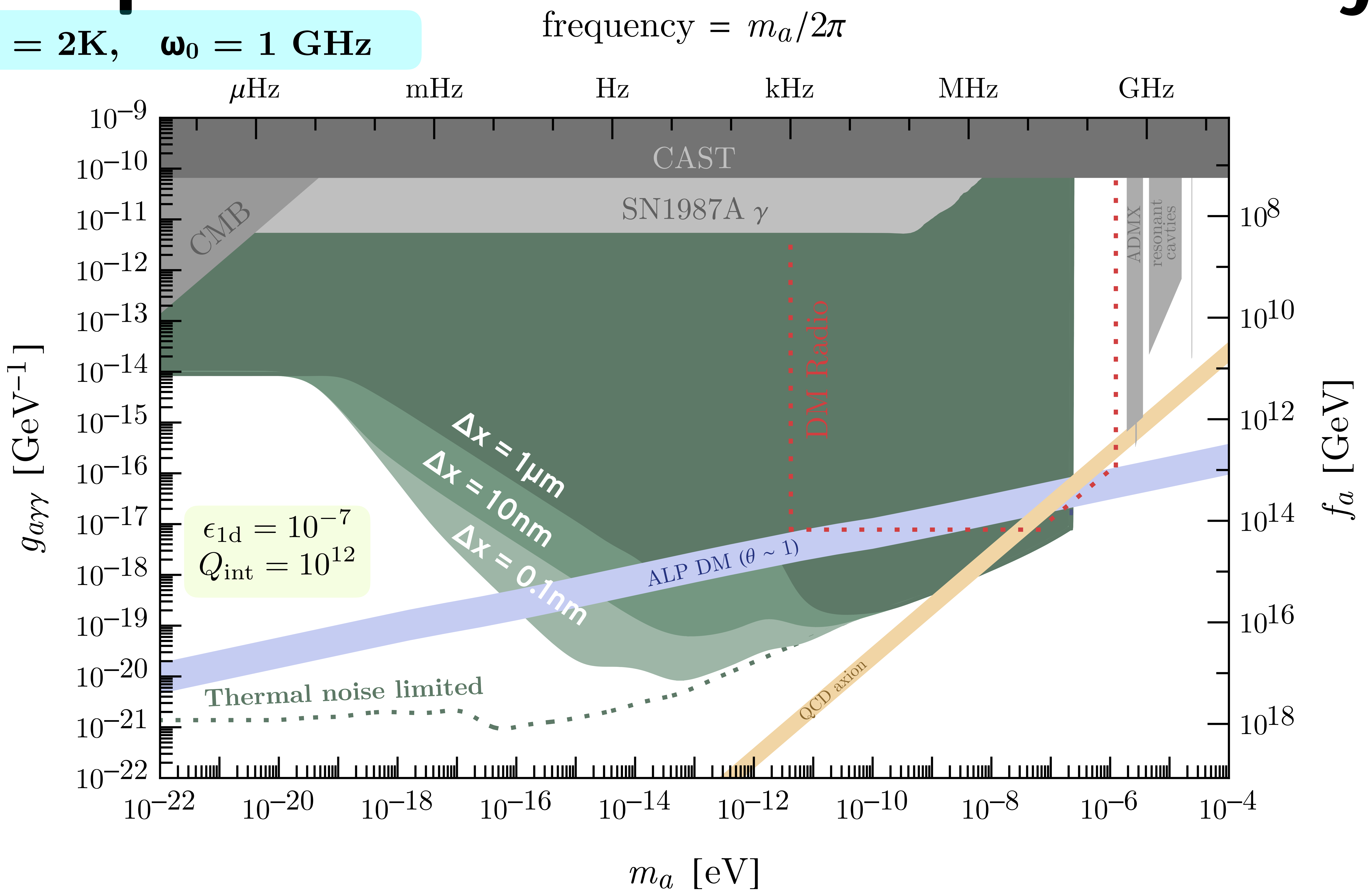
Resonant parameter variations: *mode rejection*

$B = 0.2$ T, $T = 2$K, $\omega_0 = 1$ GHz

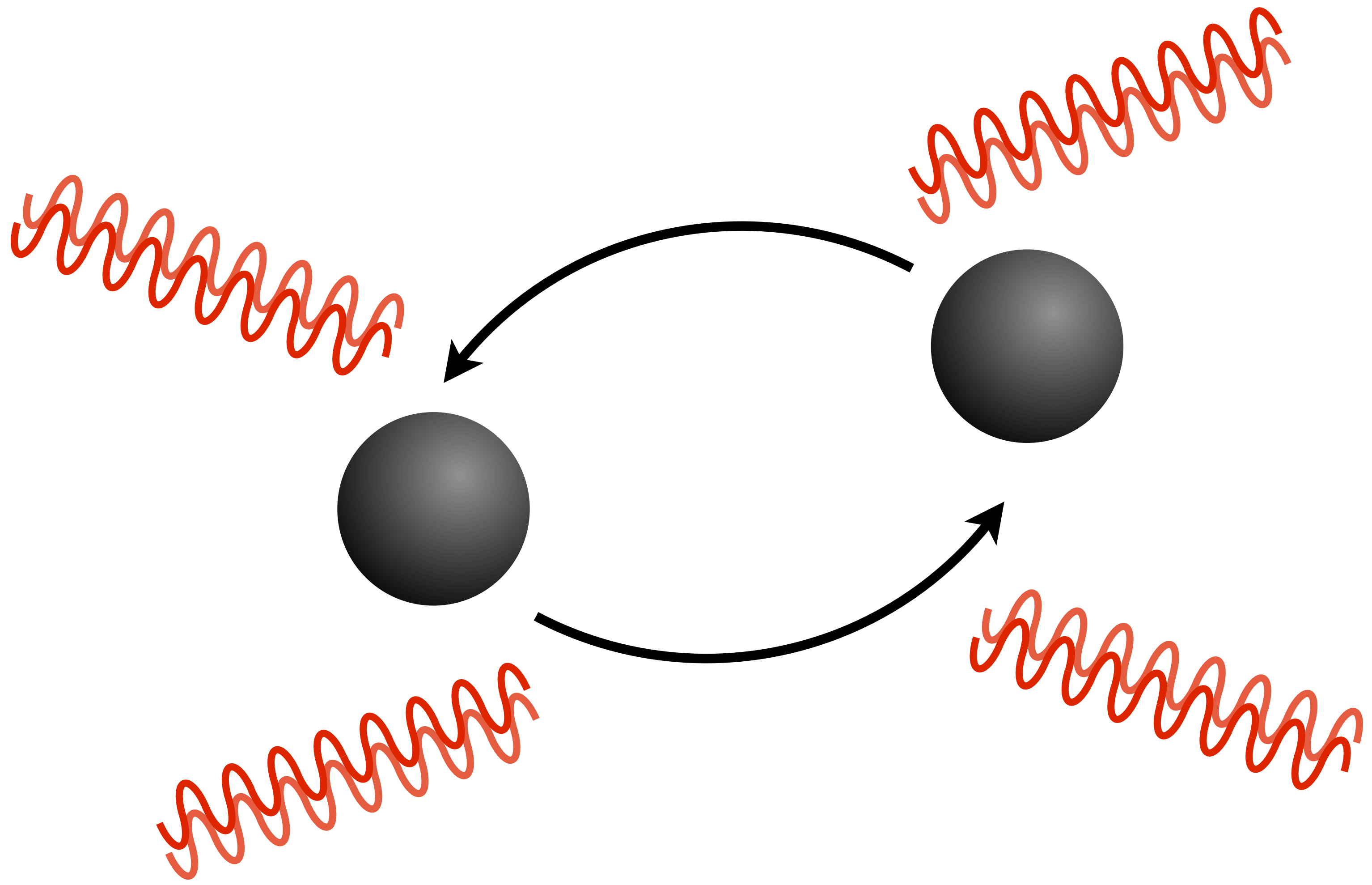


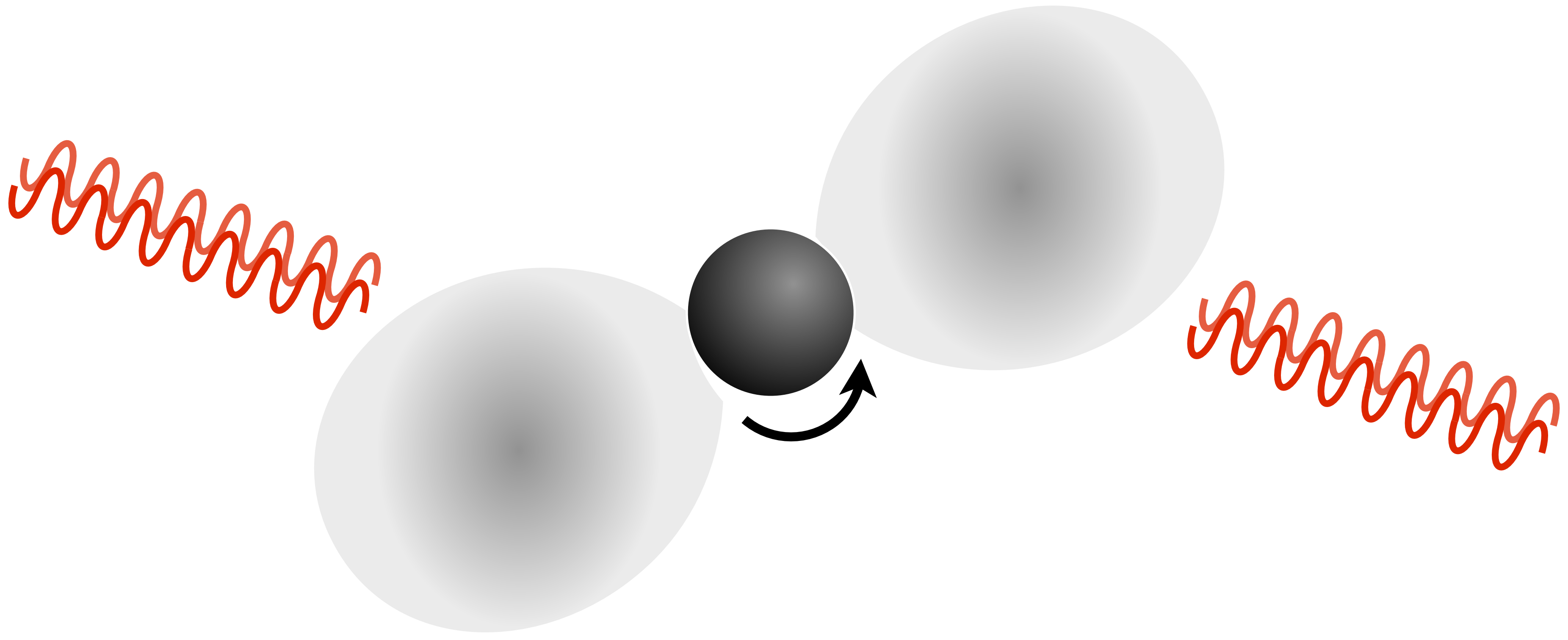
Resonant parameter variations: *mode rejection*

$\mathbf{B = 0.2\ T}, \quad T = \mathbf{2K}, \quad \boldsymbol{\omega_0} = \mathbf{1\ GHz}$

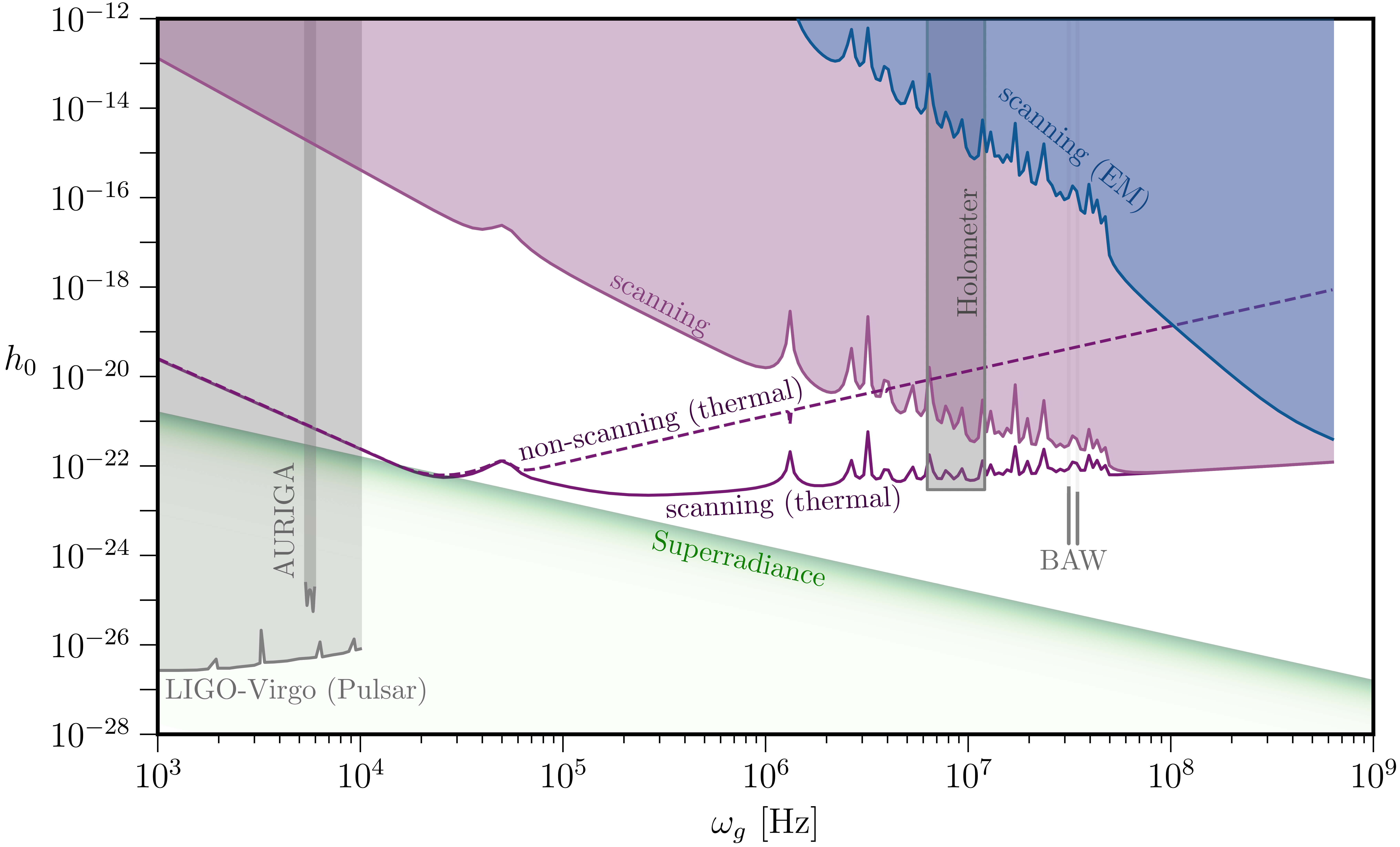


Gravitational Waves BACKUP





MAGO 2.0 sensitivity to coherent GWs



Why SRF Cavity as a Weber Bar?

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Thermal mechanical noise smaller for larger mass $S_{\text{noise}}^{(\text{mech.})} \propto \frac{4T\omega_p}{Q_p M}$

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Thermal EM noise-limited reach scales as $$S_h^{\rm (EM)} \propto \frac{1}{Q}\frac{T}{\omega_0 U_0}$$

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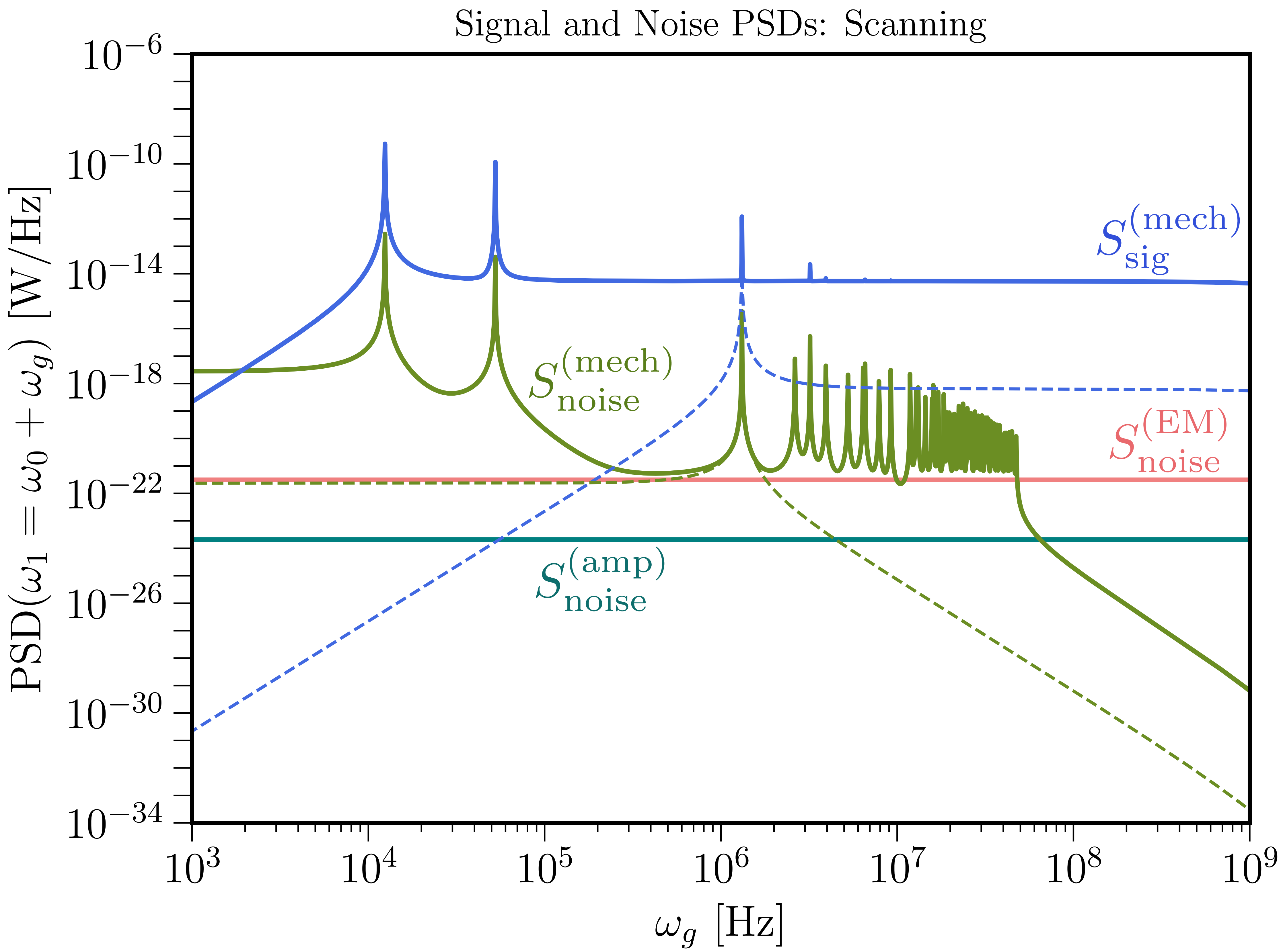
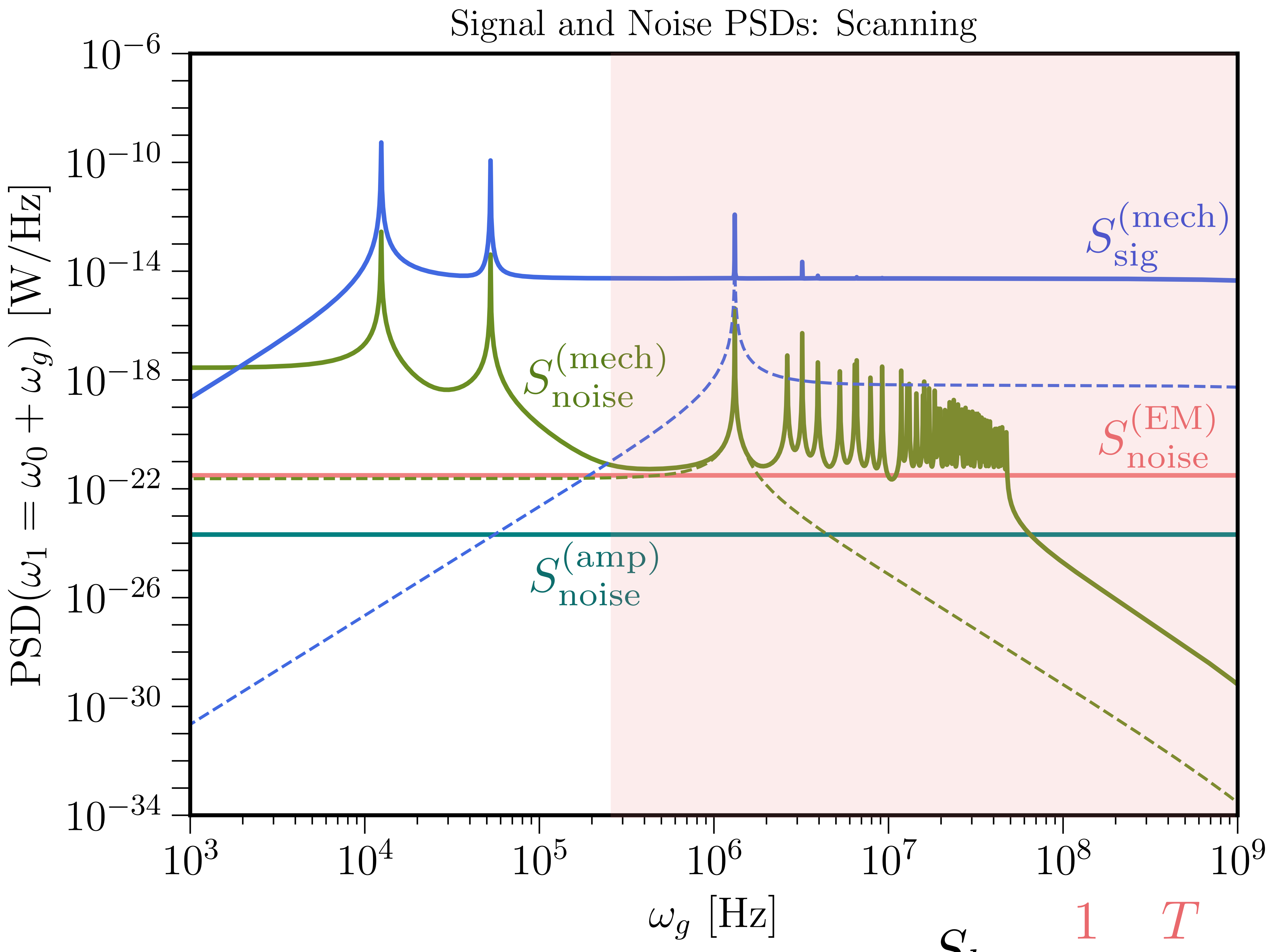
Thermal EM noise-limited reach scales as $S_h^{(\text{EM})} \propto \frac{1}{Q} \frac{T}{\omega_0 U_0}$

SRF Cavity w/ Q~10^{10} means better sensitivity

Noise in MAGO 2.0



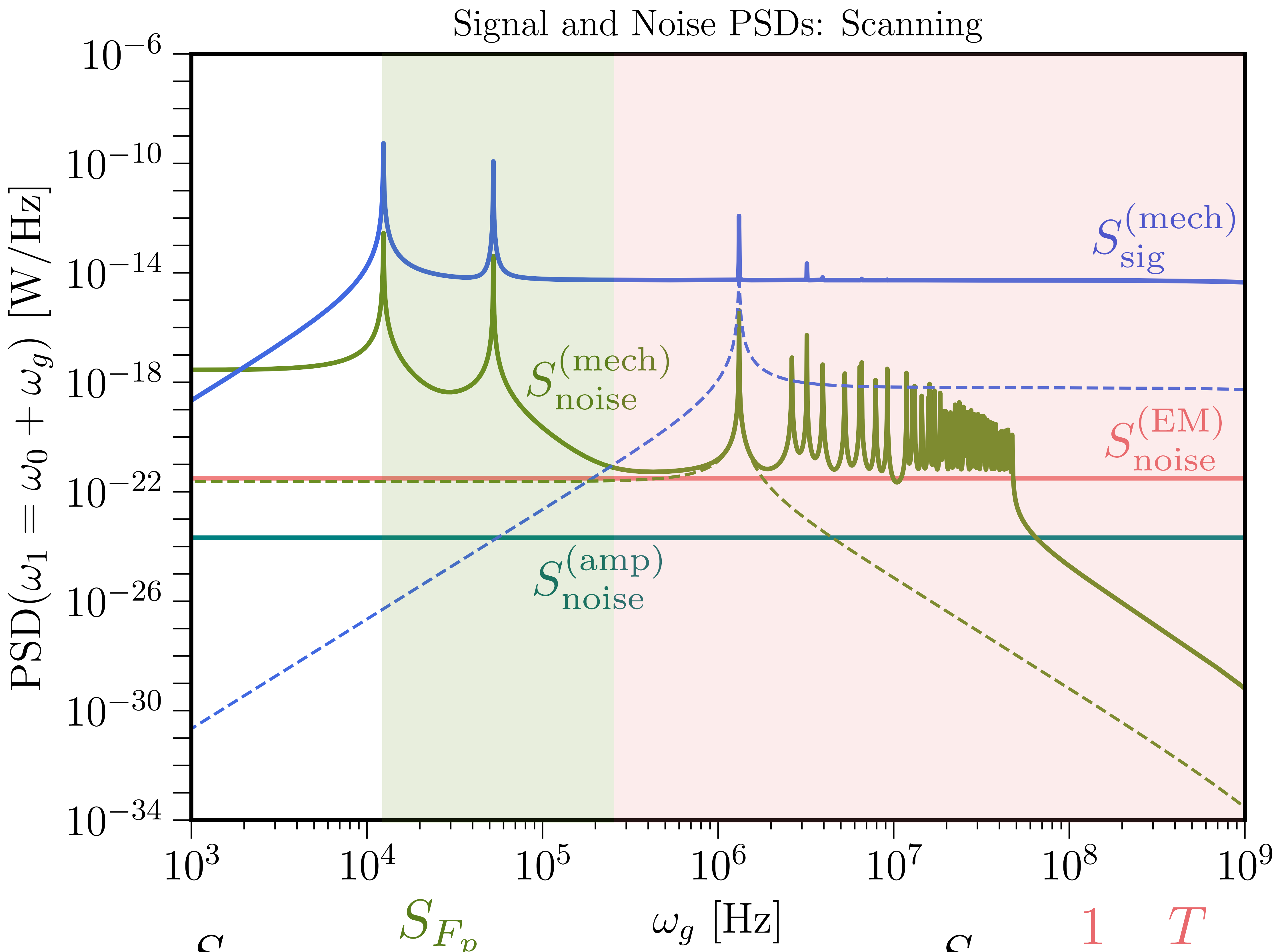
Noise in MAGO 2.0



$$S_h \sim \frac{1}{Q}\frac{T}{\omega_0 U_0}$$

EM Th. > MHz

Noise in MAGO 2.0



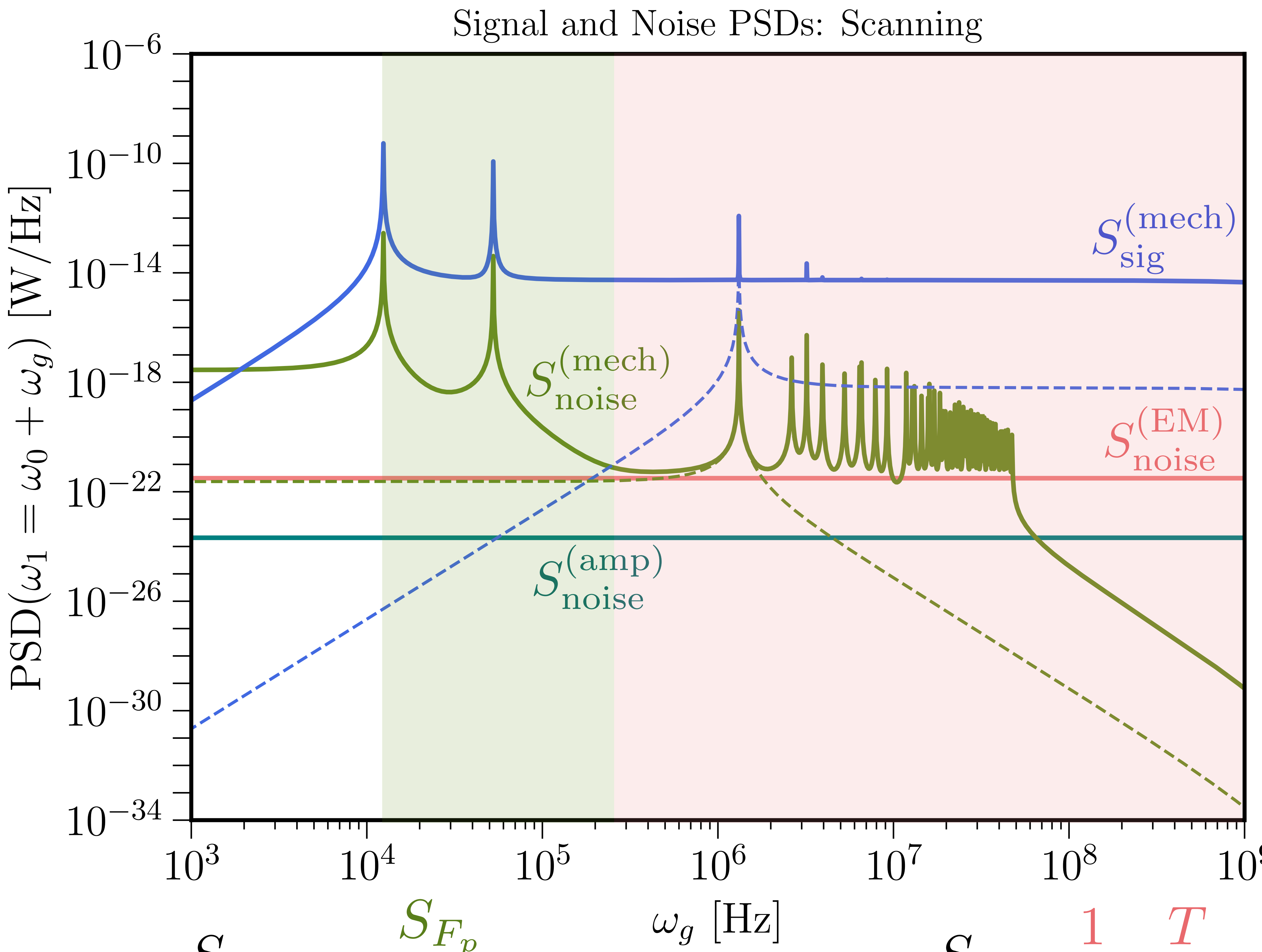
$$S_h \sim \frac{S_{F_p}}{\omega_g^4 (ML)^2}$$

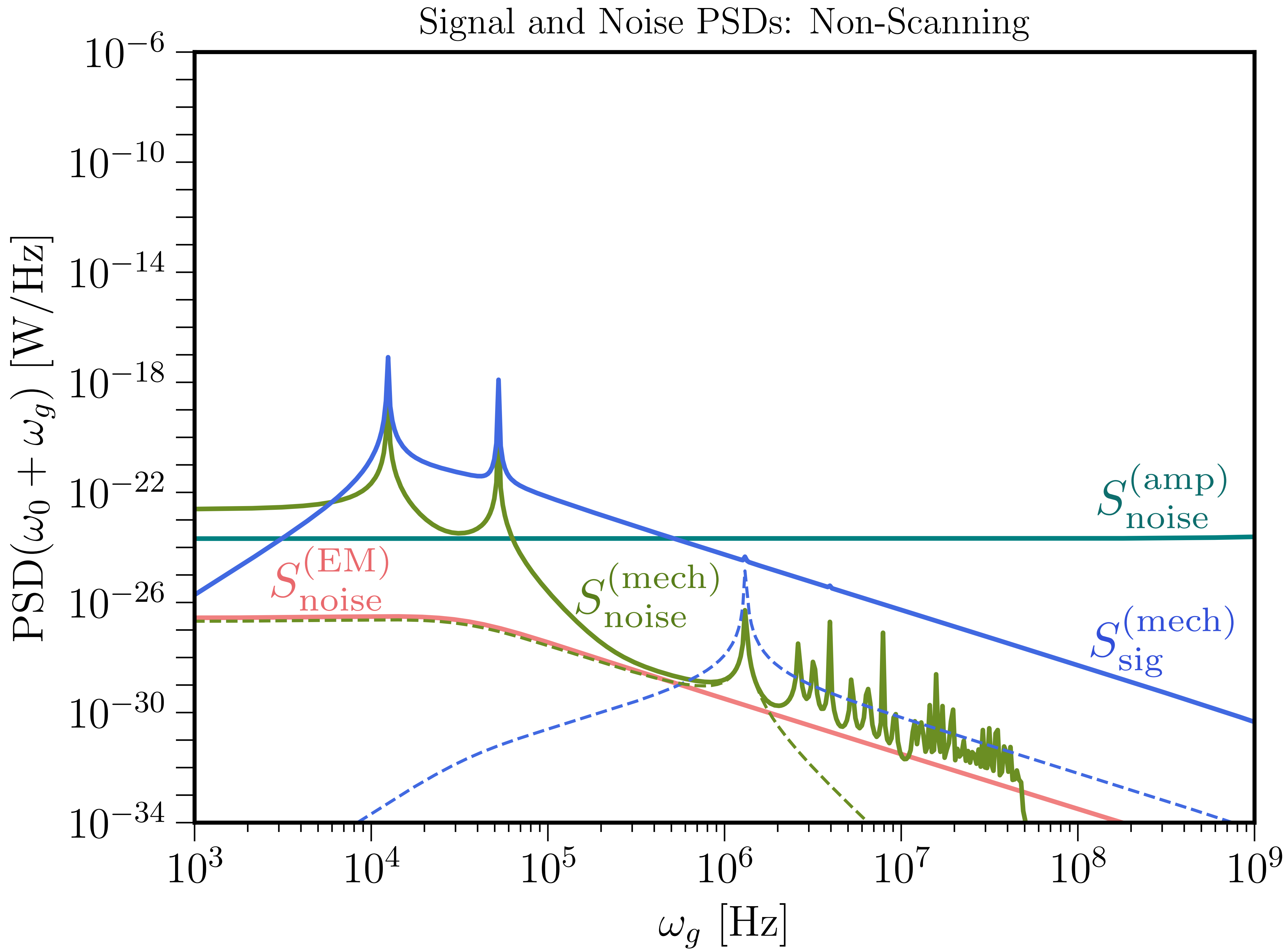
Mech < MHz

$$S_h \sim \frac{1}{Q} \frac{T}{\omega_0 U_0}$$

EM Th. > MHz

Noise in MAGO 2.0





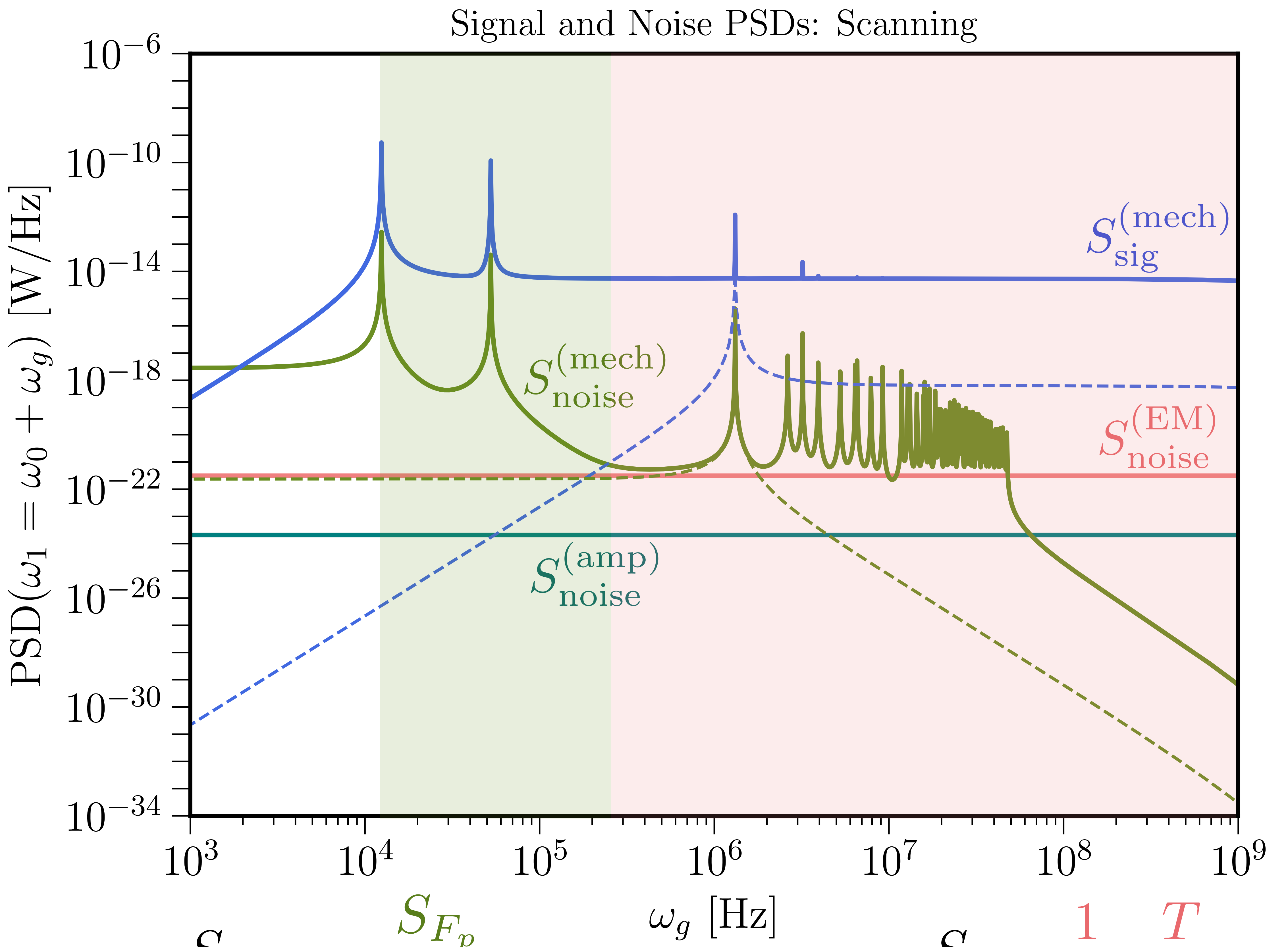
$$S_h \sim \frac{S_{F_p}}{\omega_g^4 (ML)^2}$$

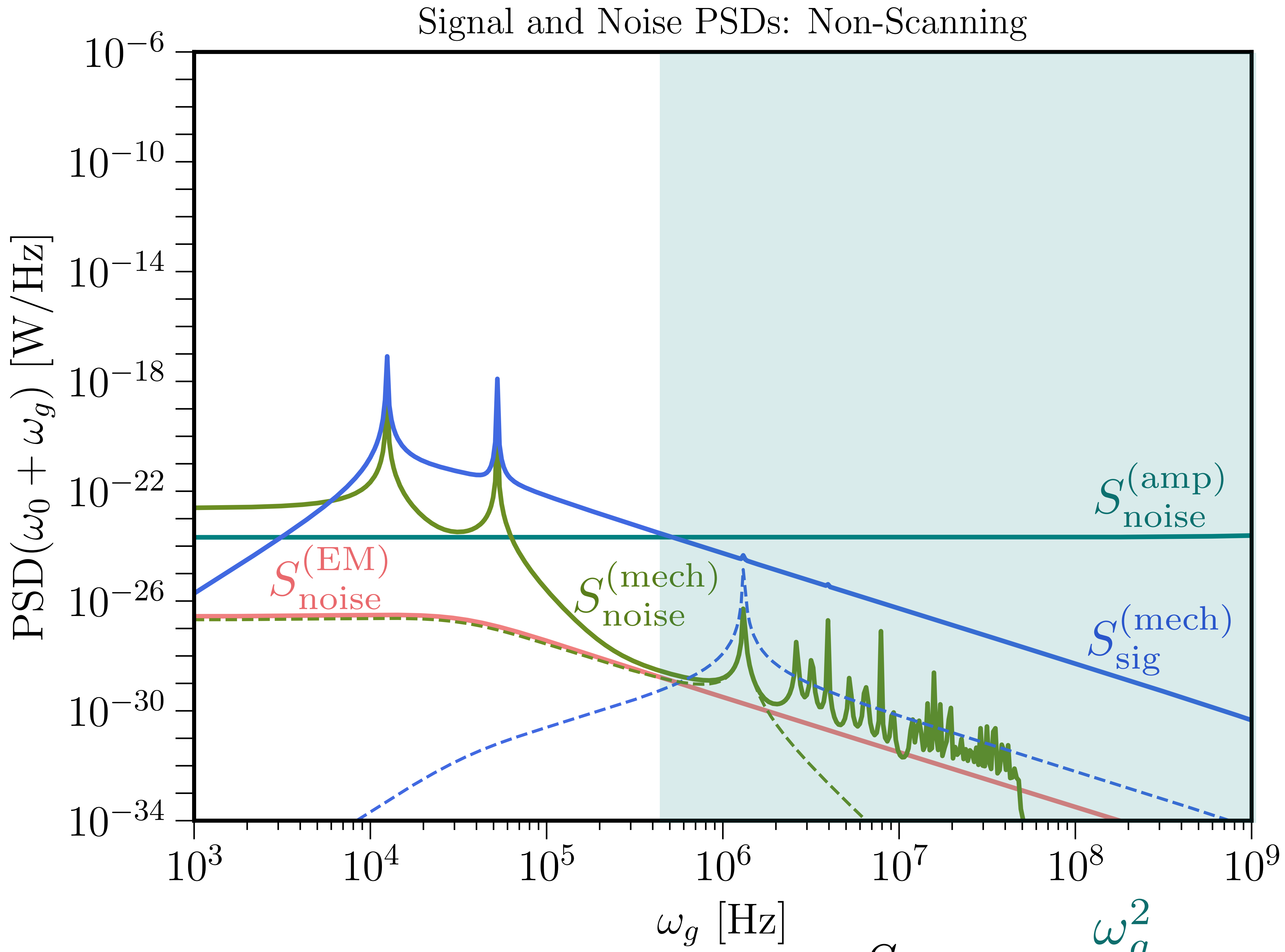
Mech $<$ MHz

$$S_h \sim \frac{1}{Q} \frac{T}{\omega_0 U_0}$$

EM Th. $>$ MHz

Noise in MAGO 2.0





$$S_h \sim \frac{S_{F_p}}{\omega_g^4 (ML)^2}$$

Mech $<$ MHz

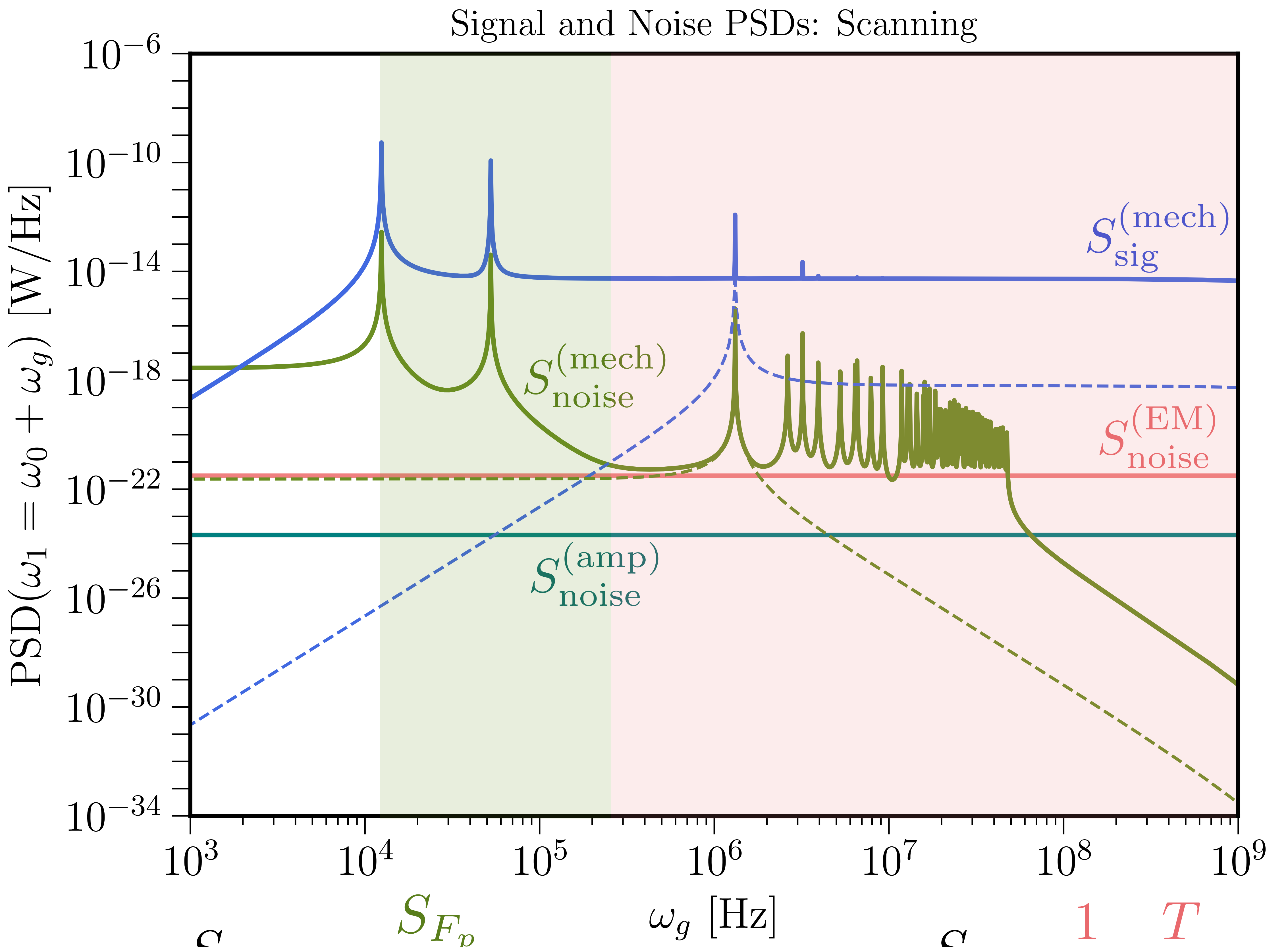
$$S_h \sim \frac{1}{Q}\frac{T}{\omega_0 U_0}$$

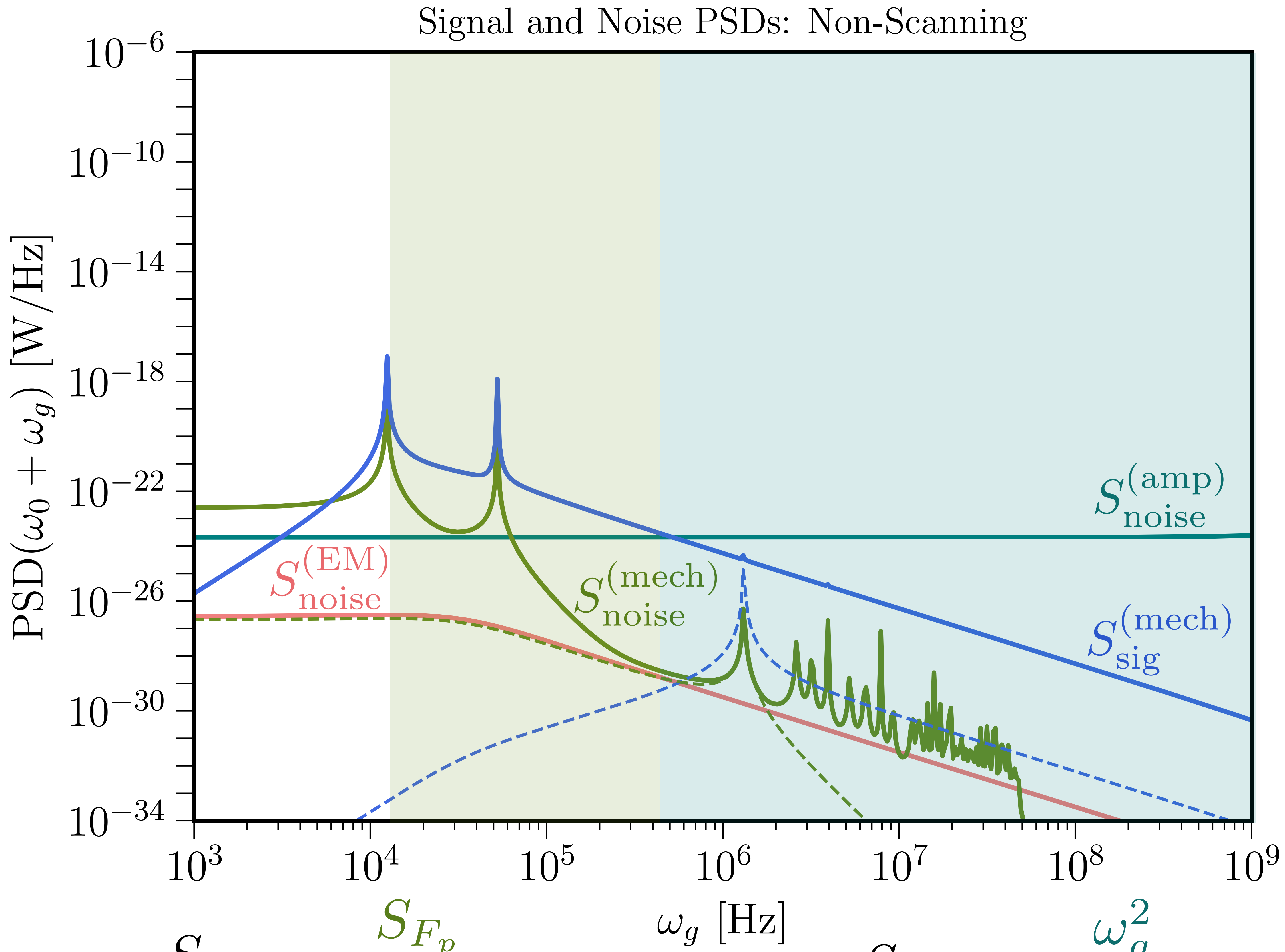
EM Th. $>$ MHz

$$S_h \sim \frac{\omega_g^2}{\hbar\omega_0(\omega_0 U_0)}$$

Amp $>$ MHz

Noise in MAGO 2.0





$$S_h \sim \frac{S_{F_p}}{\omega_g^4 (ML)^2}$$

Mech < MHz

$$S_h \sim \frac{1}{Q} \frac{T}{\omega_0 U_0}$$

EM Th. > MHz

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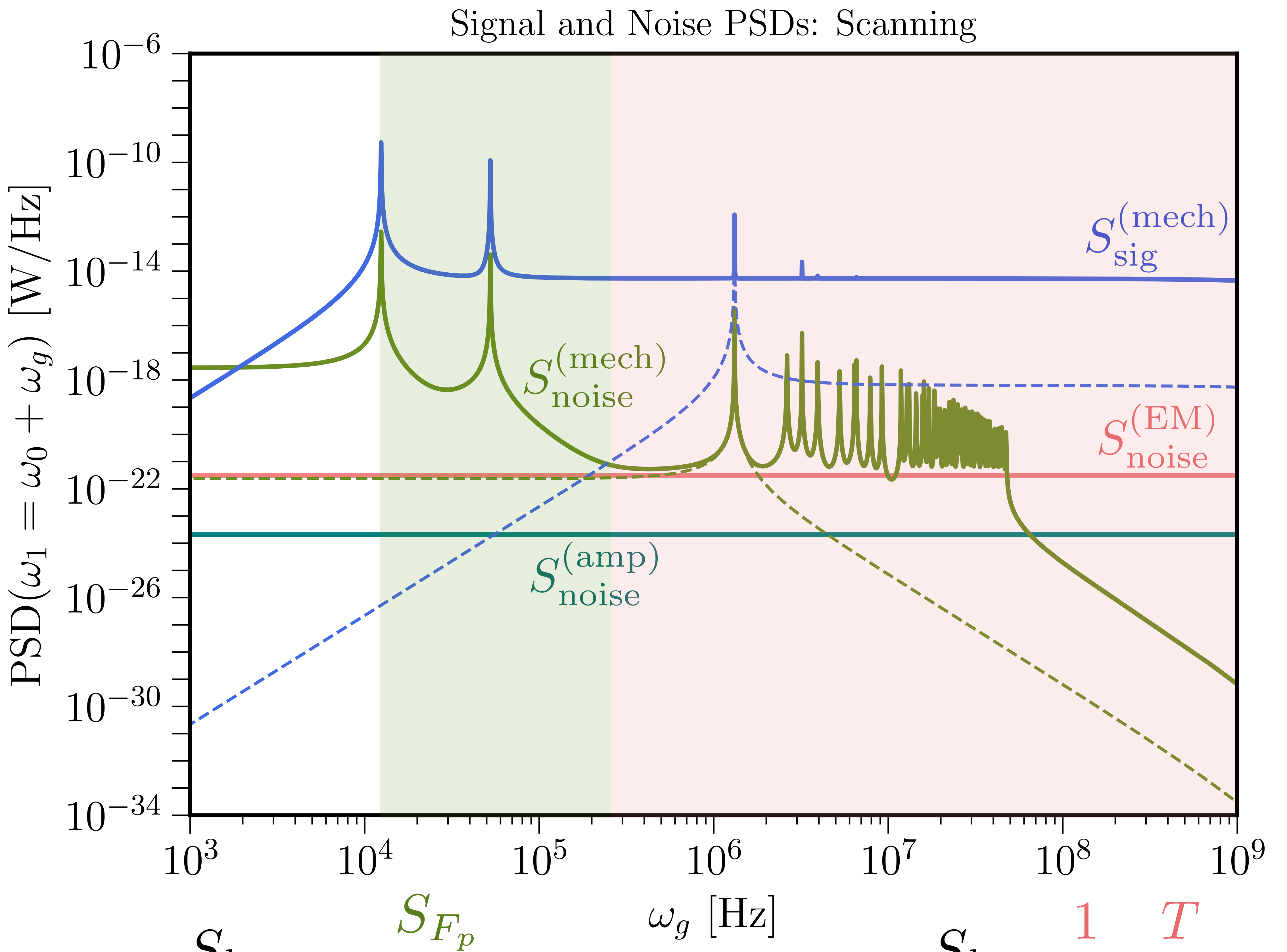
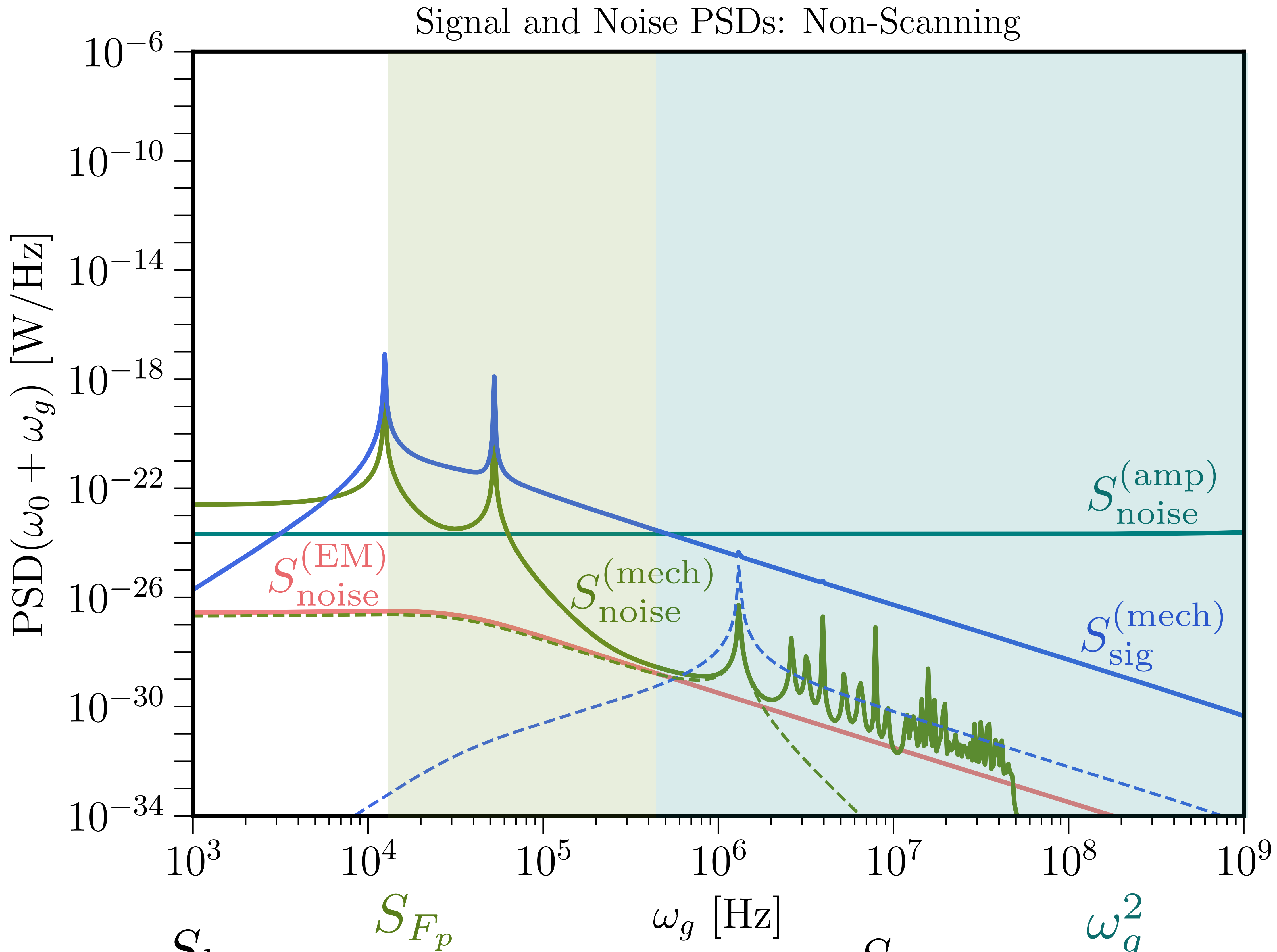
Amp > MHz

Noise in MAGO 2.0





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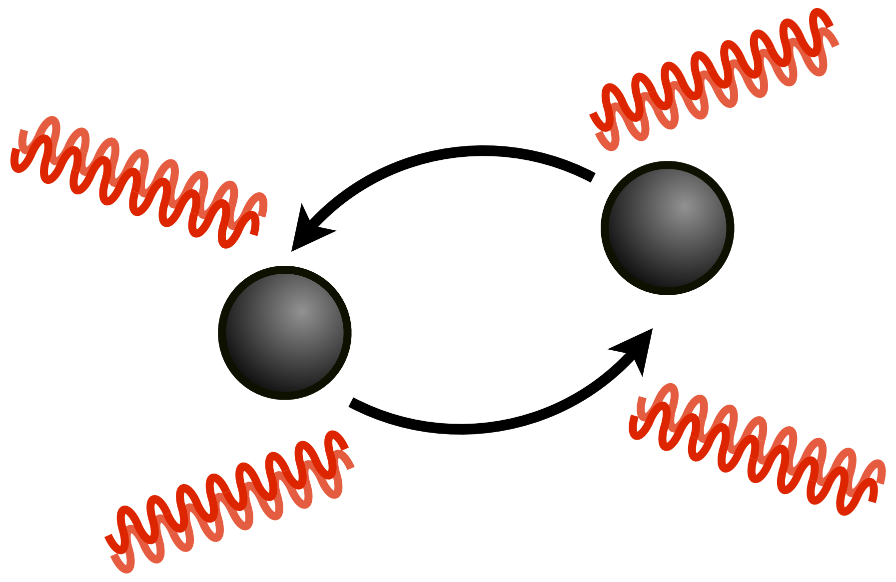
NB: missing radiation damping effect studied in *Löwenberg, Moortgat-Pick: 2307.14379*

Is this good enough to see BSM sources?

Primordial Black Hole binary inspirals



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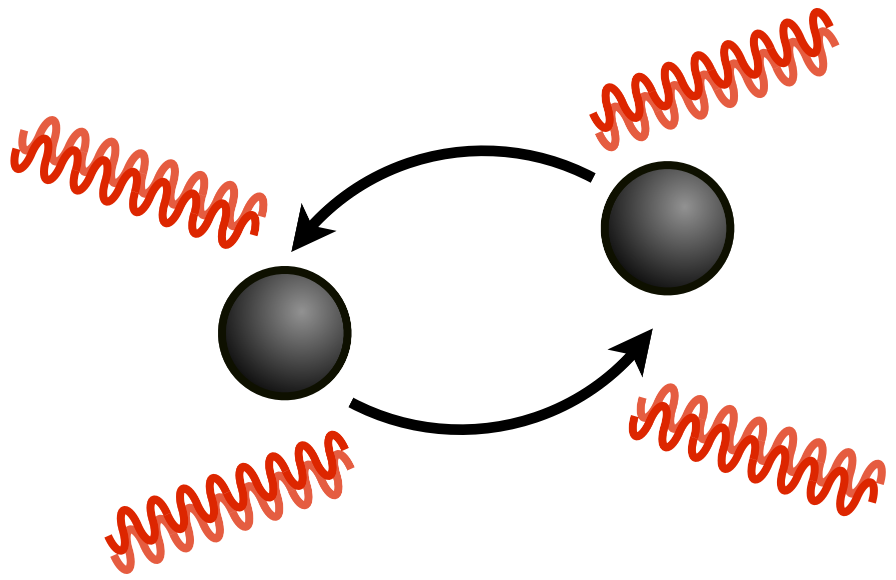

$$\omega_g \simeq 14 \text{ GHz} \times (10^{-6}\, M_\odot/M_b)\,(r_{\rm ISCO}/r_b)^{3/2}$$

$$d\omega_g/dt \propto (M_b/r_b)^{11/6}$$

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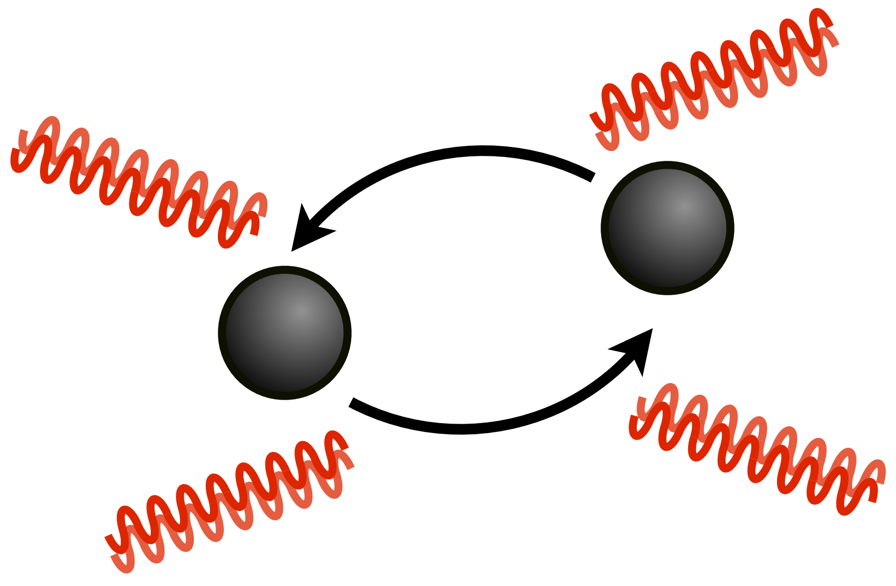

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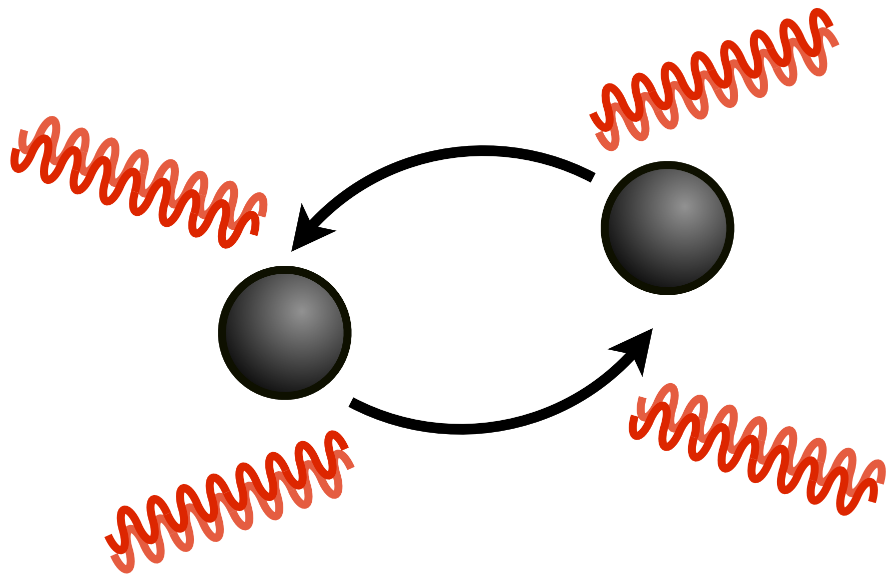

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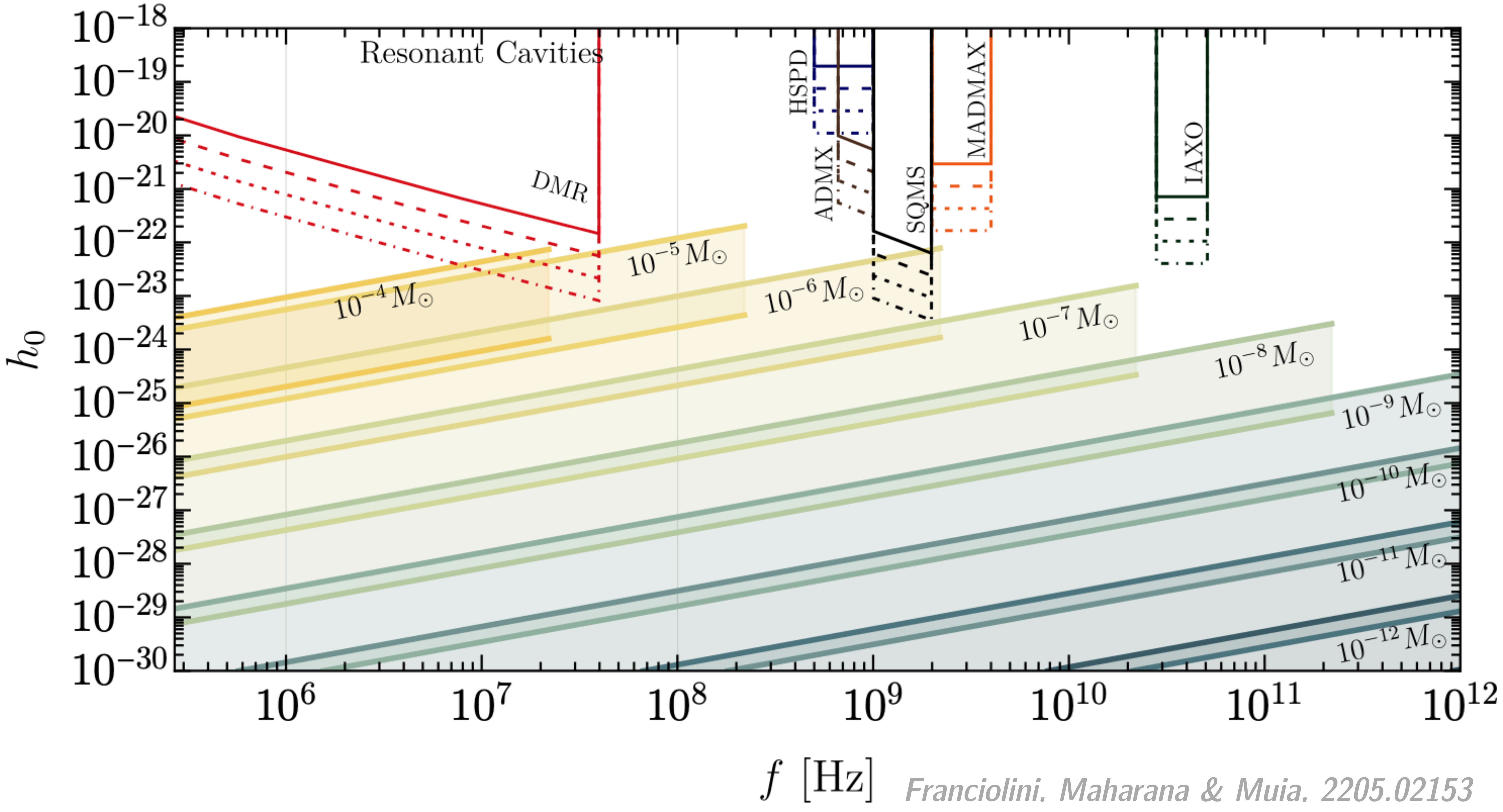

Franciolini, Maharana & Muia, 2205.02153

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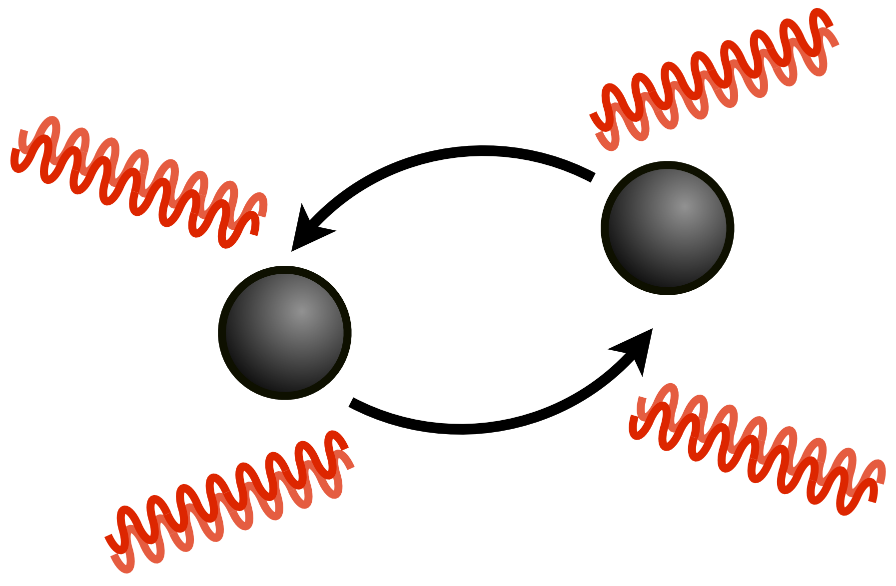

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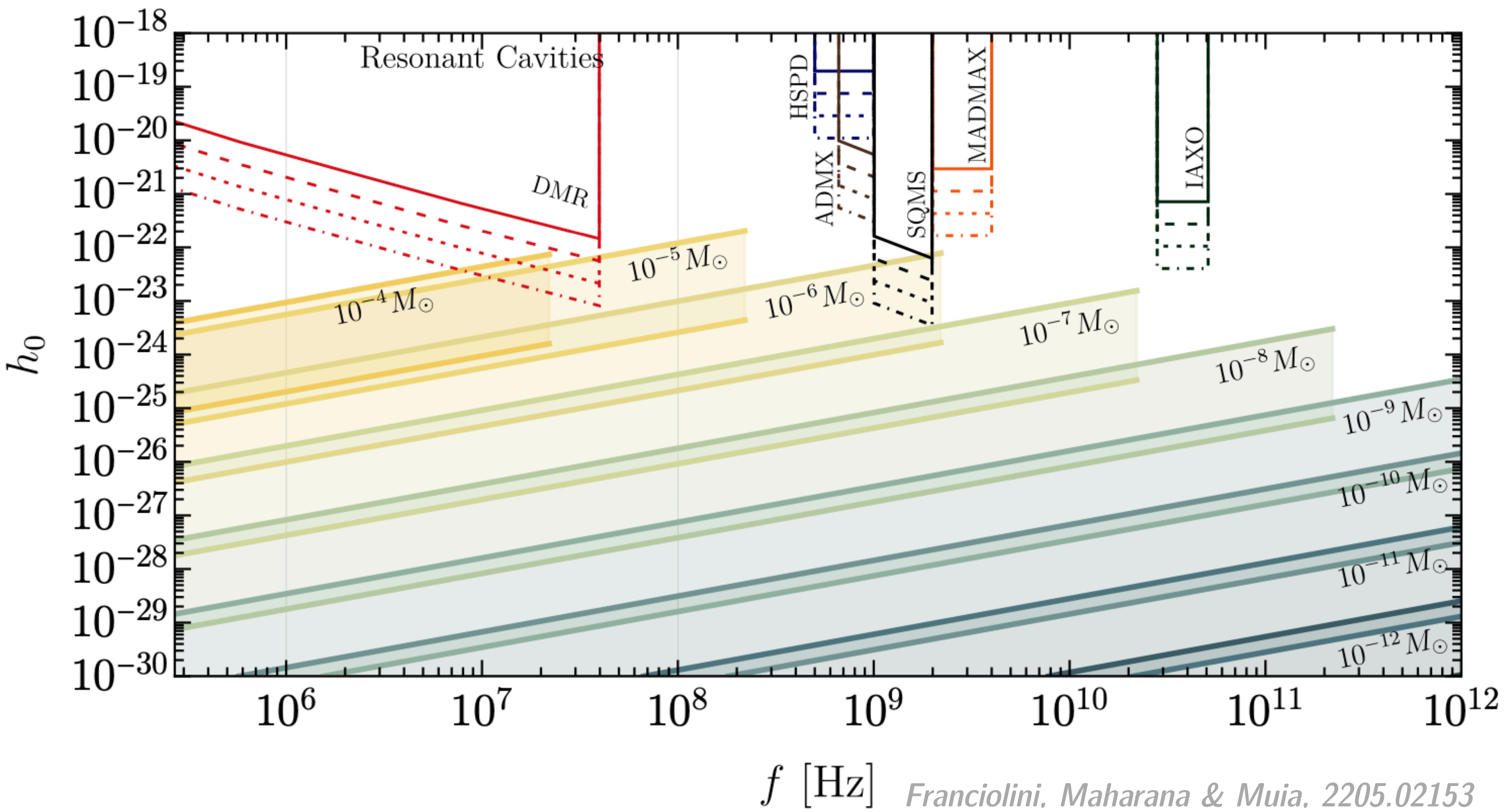

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difficult at GHz, plausible at kHz

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Superradiance (BSM^2)

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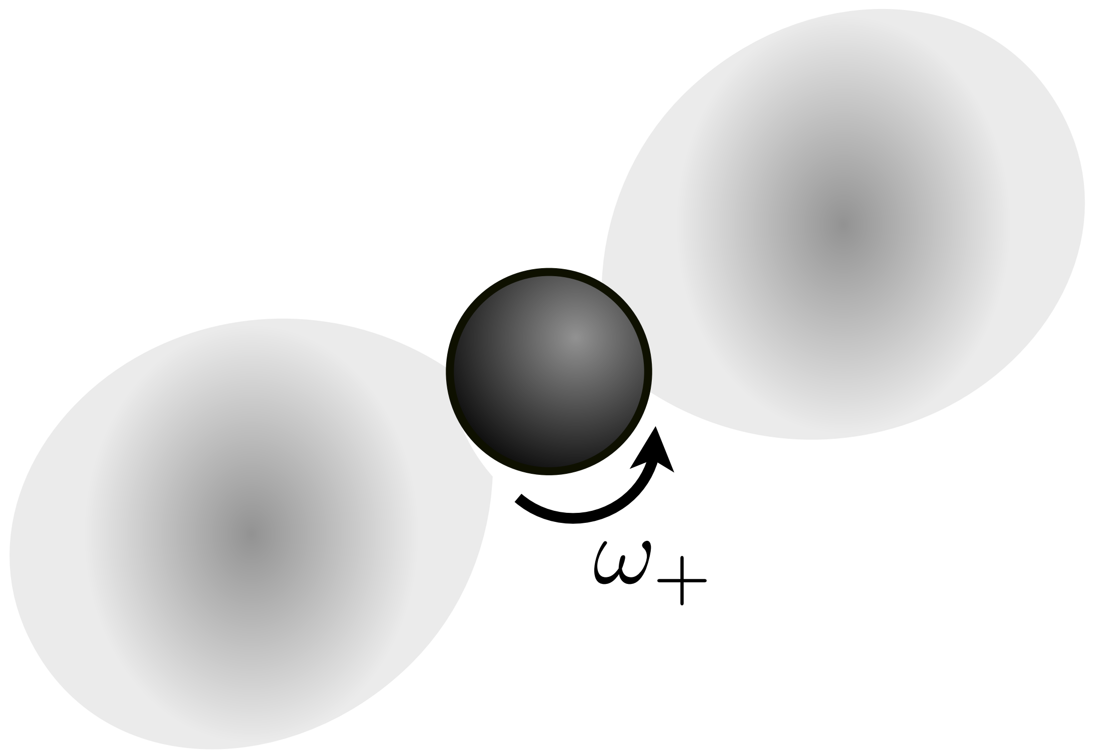
Superradiance (BSM²)



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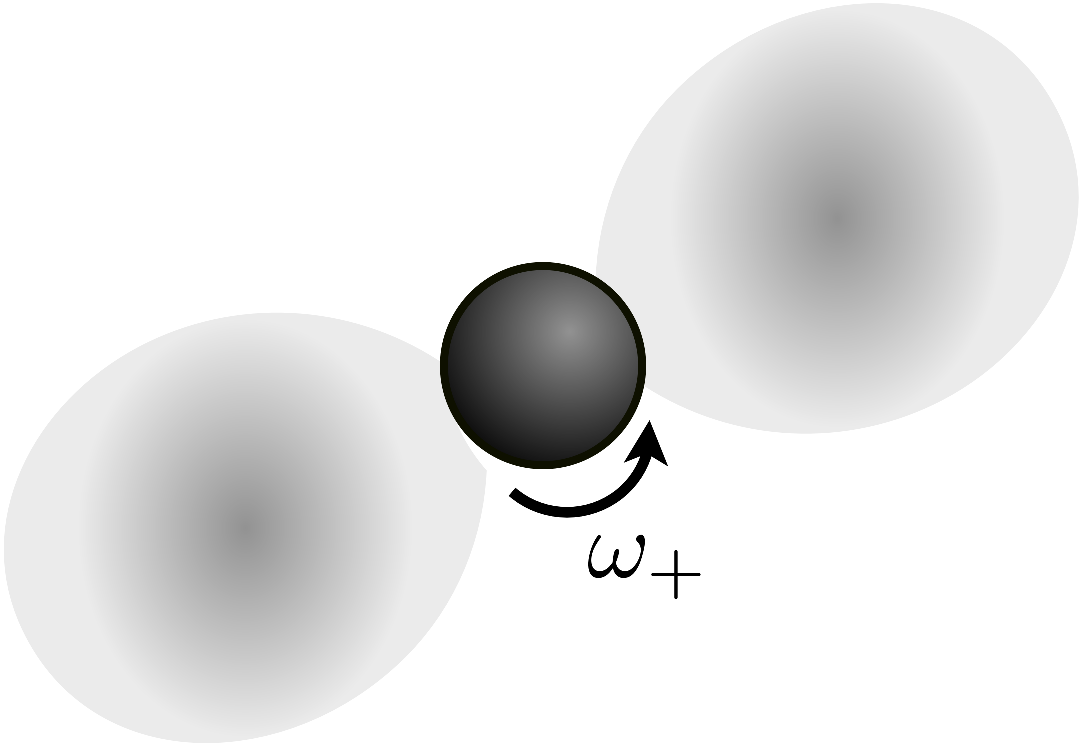

Ternov et al (1978)
Zouros & Eardley (1979)
Arvanitaki et al (2009)
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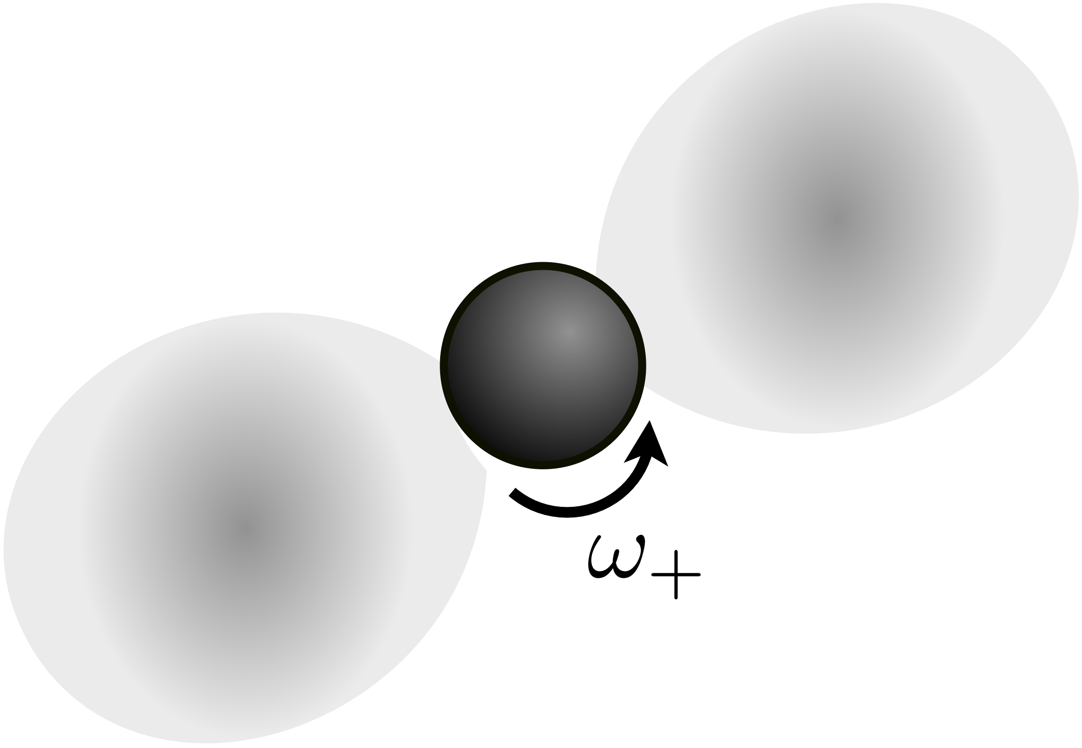

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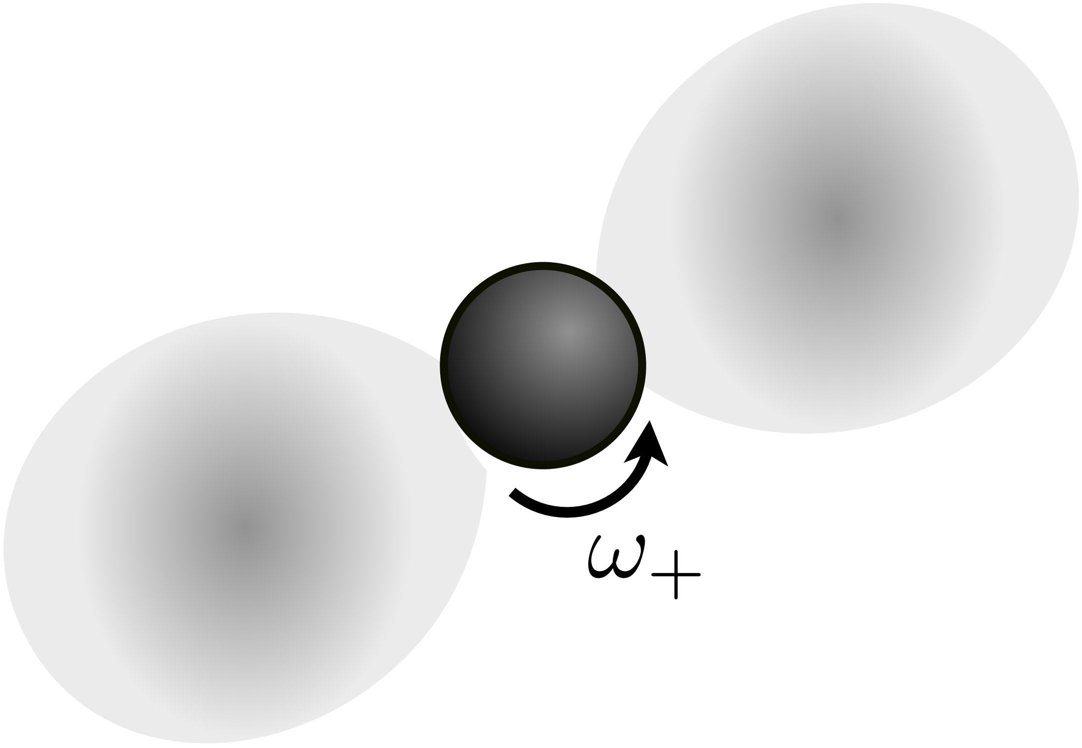

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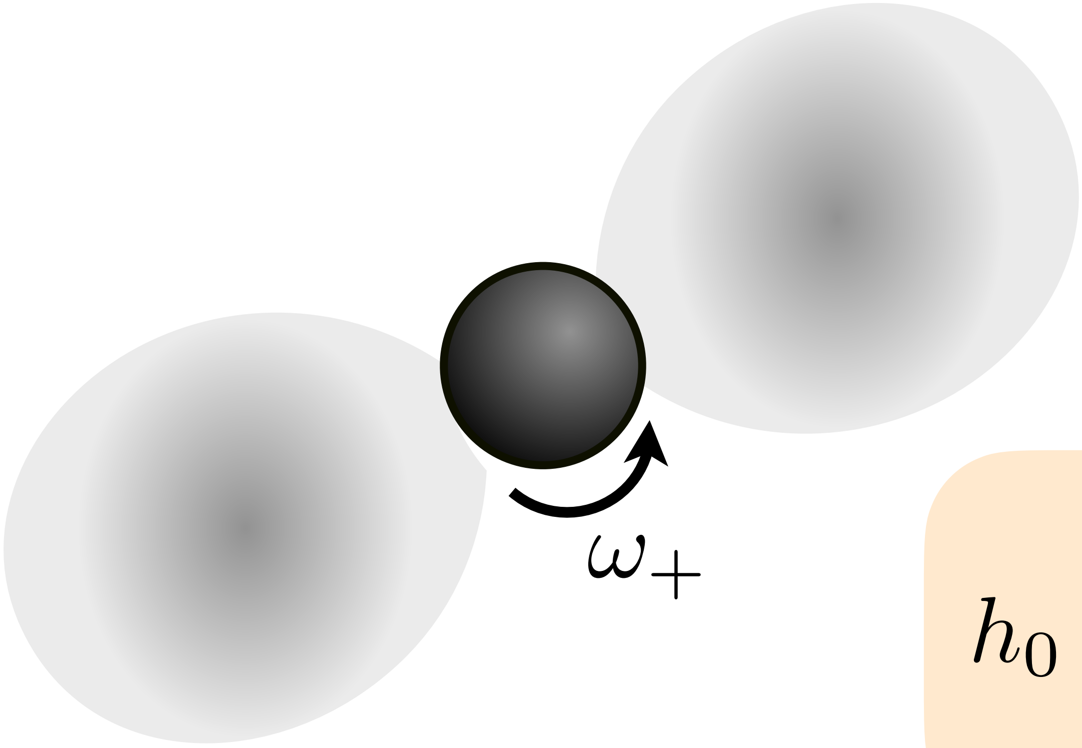

$$h_0 \sim 10^{-27} \times \left(\frac{10\ {\rm kpc}}{D}\right)\left(\frac{M_{\rm PBH}}{10^{-4}\ M_\odot}\right)$$

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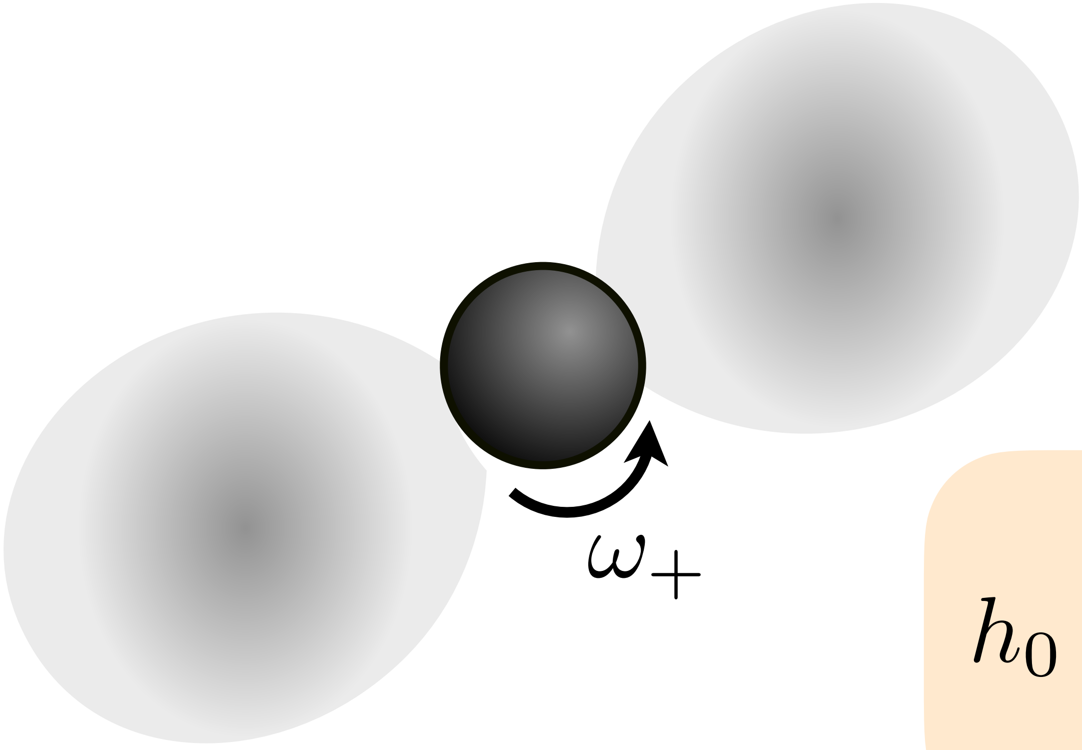

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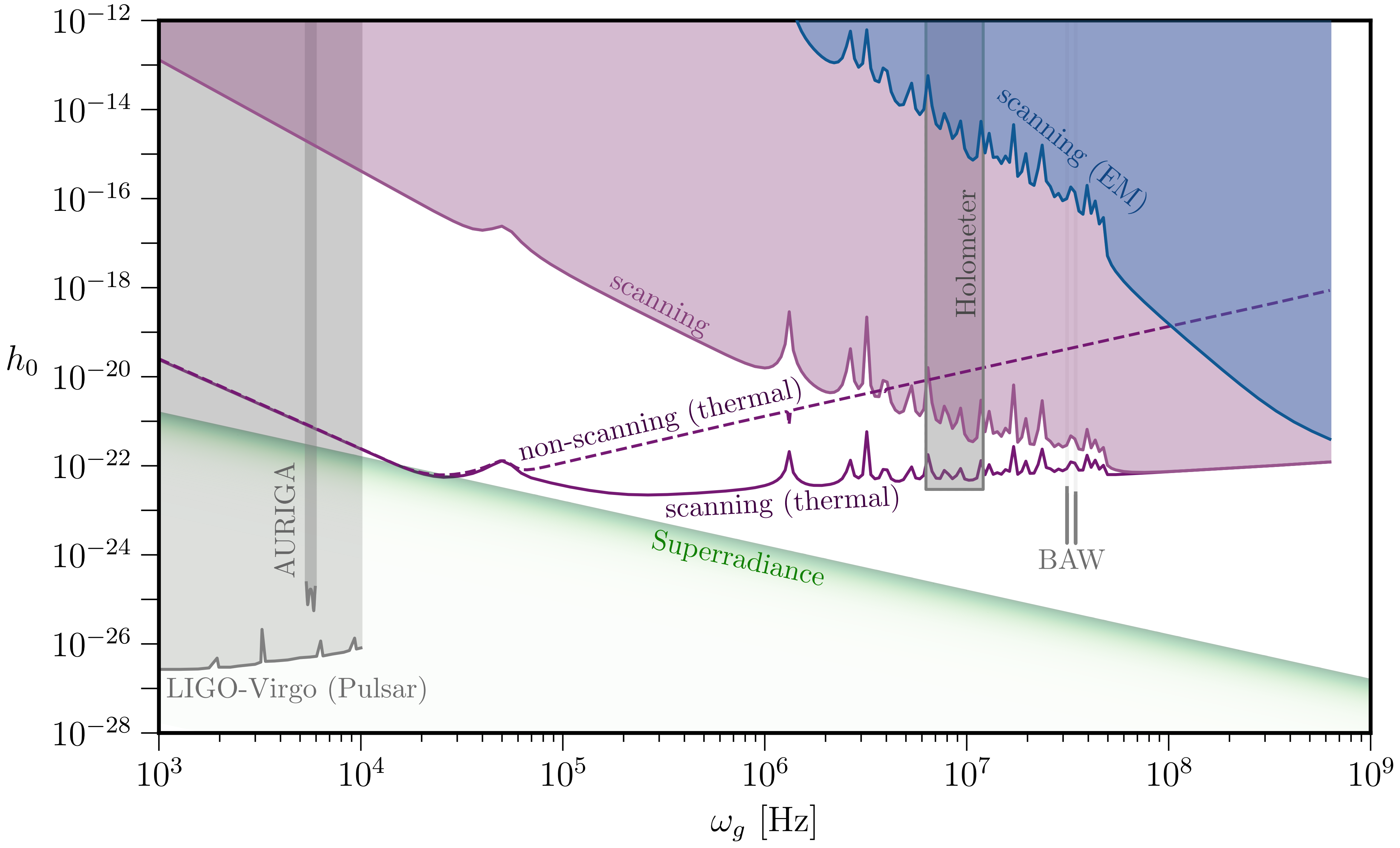

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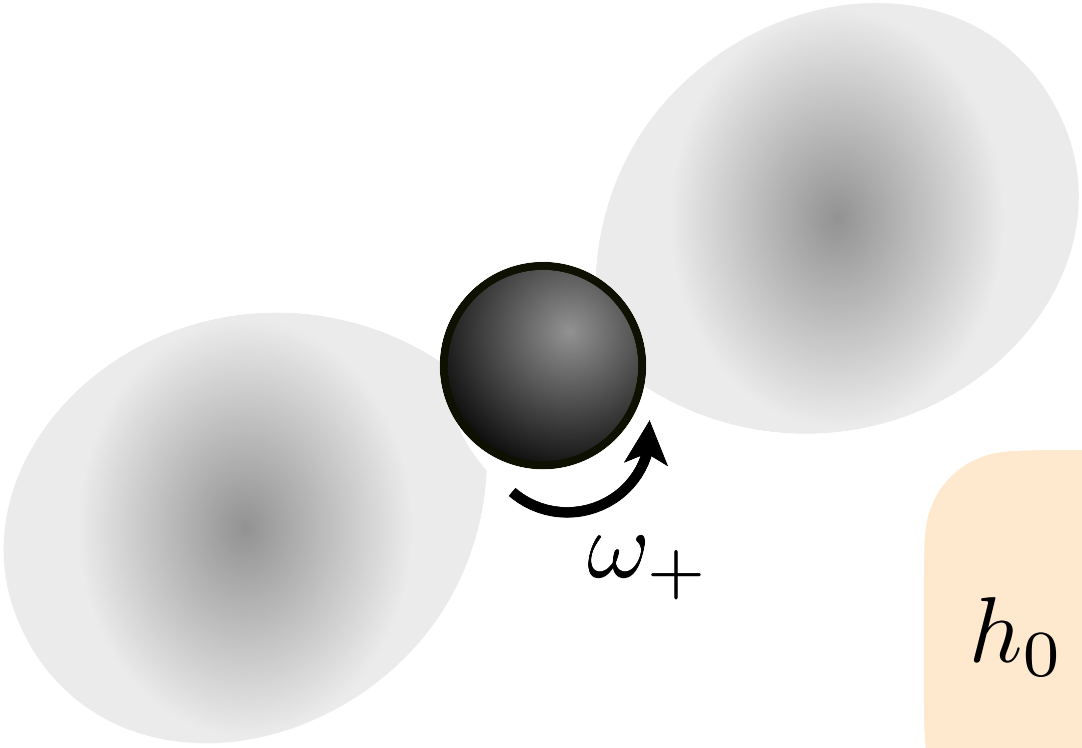

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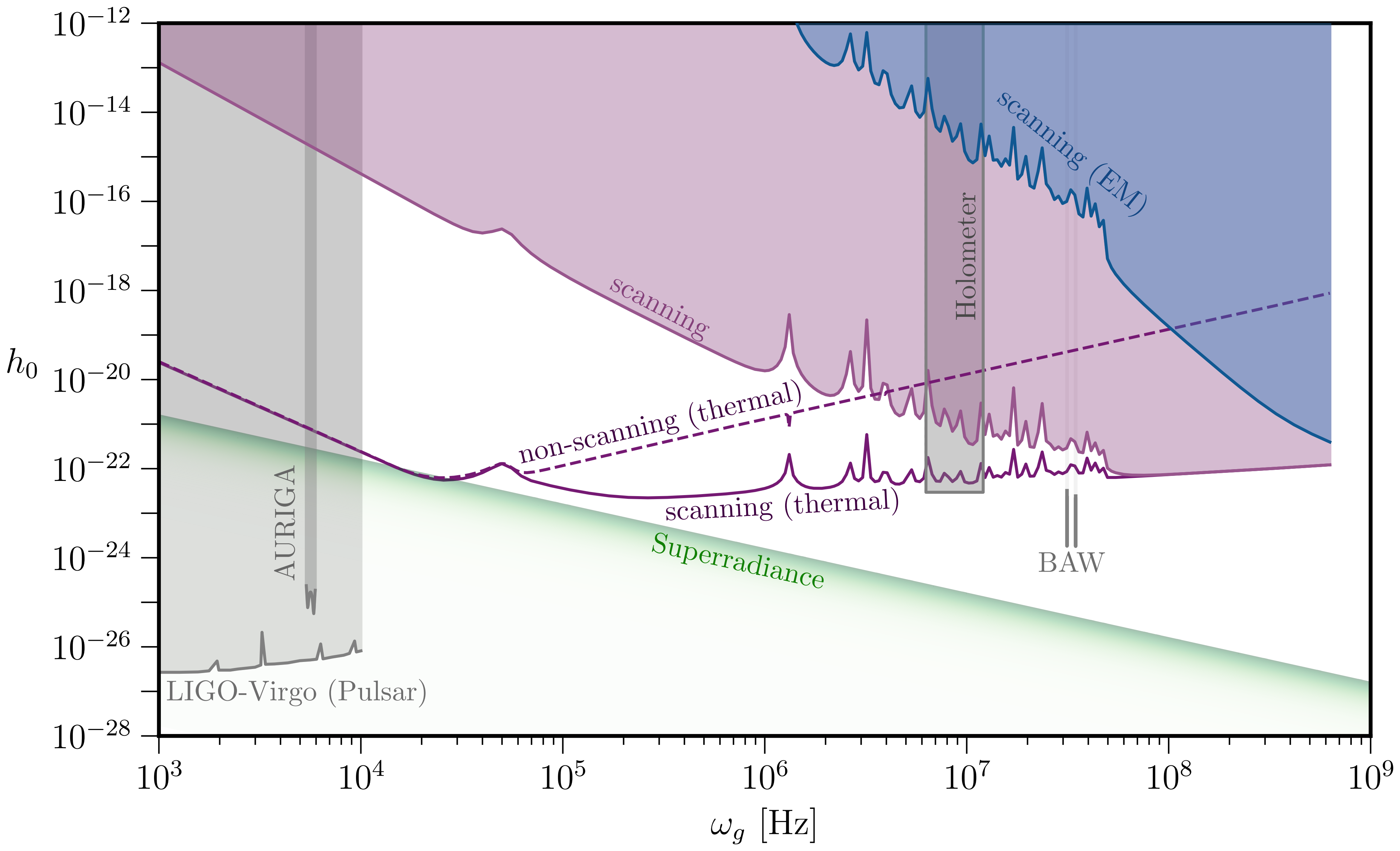

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