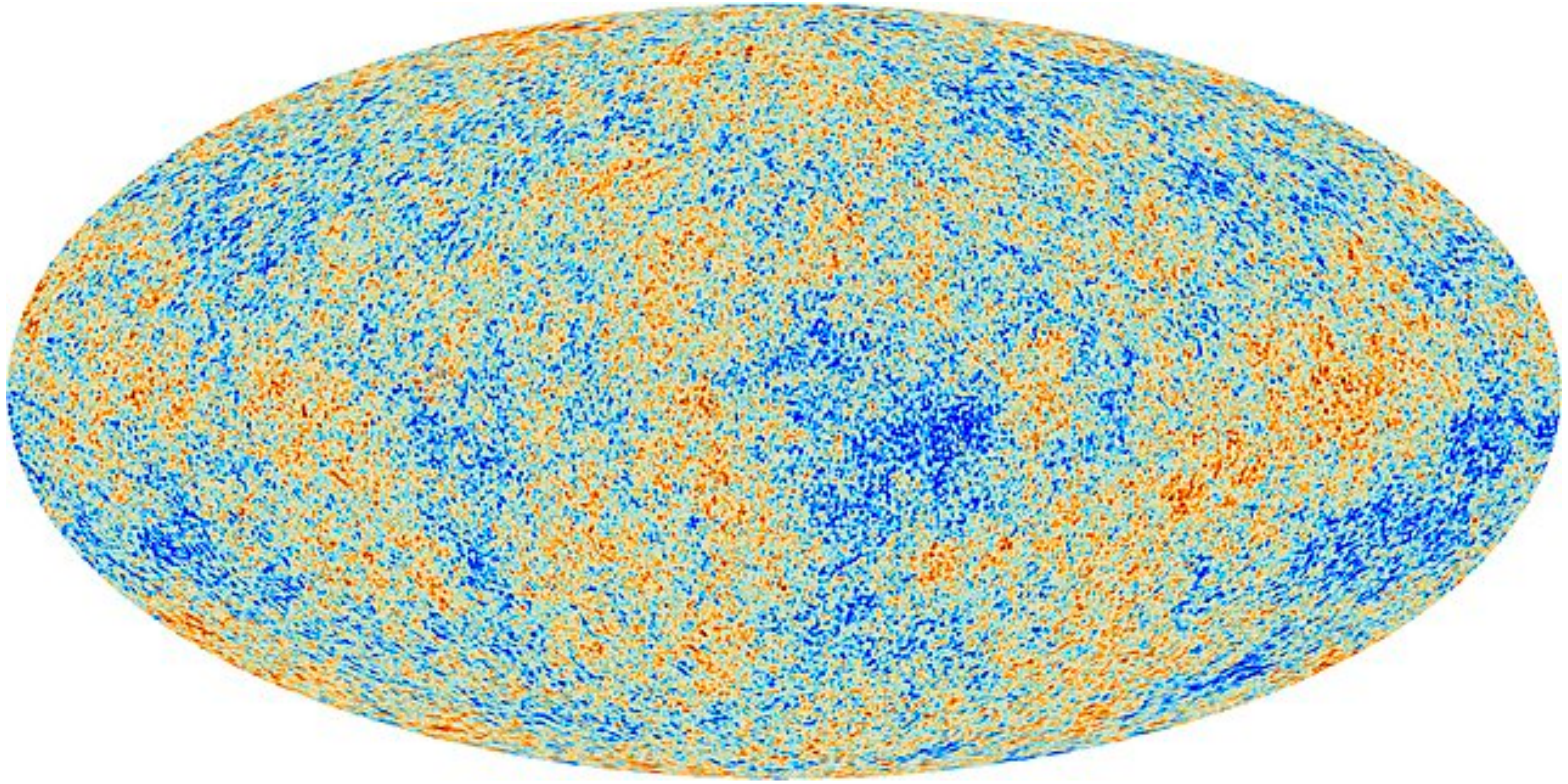
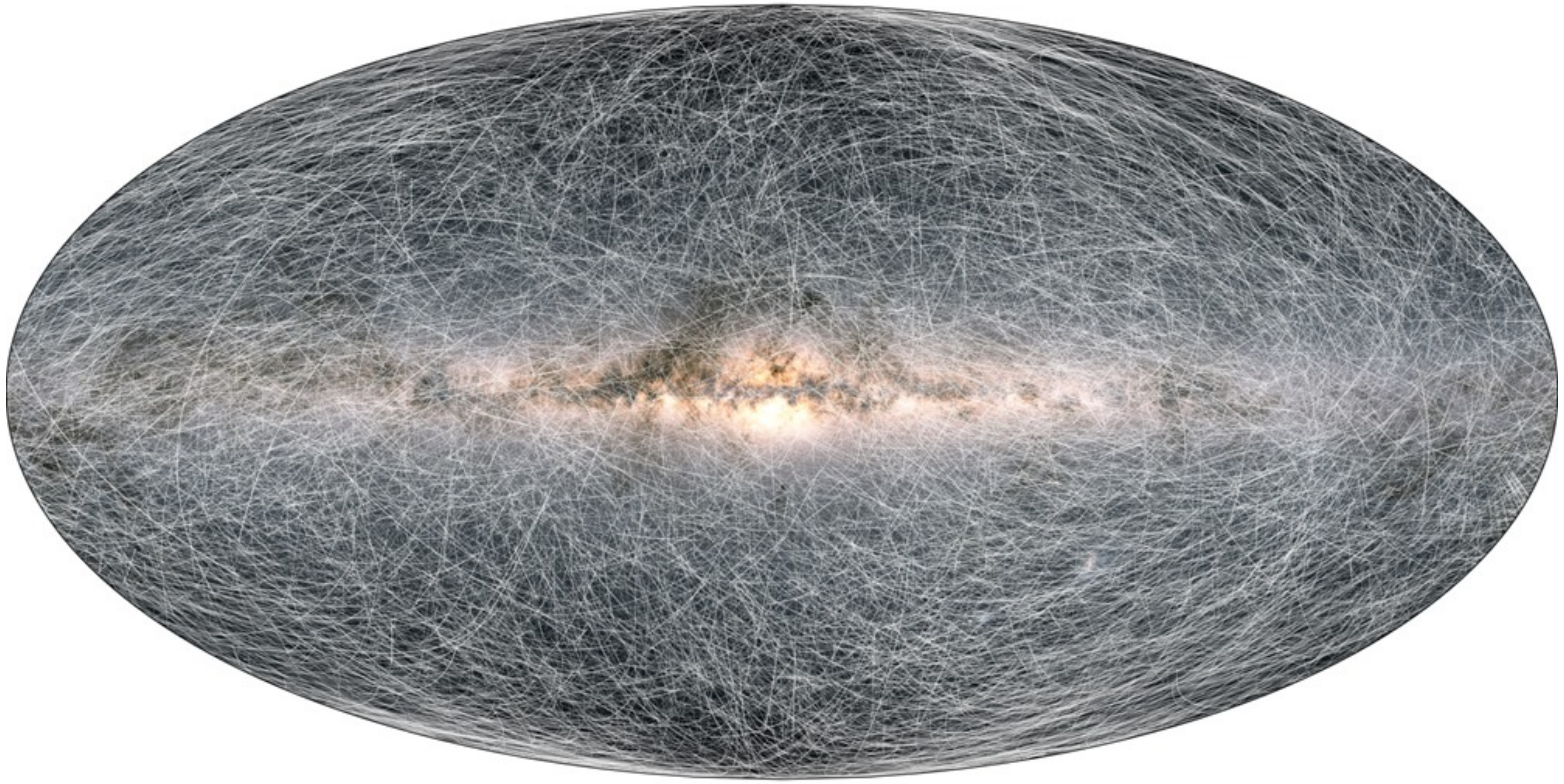
HETERODYNE DETECTION OF AXION DARK MATTER

Raffaele Tito D’Agnolo - CEA IPhT Saclay and ENS Paris





DARK MATTER MASS

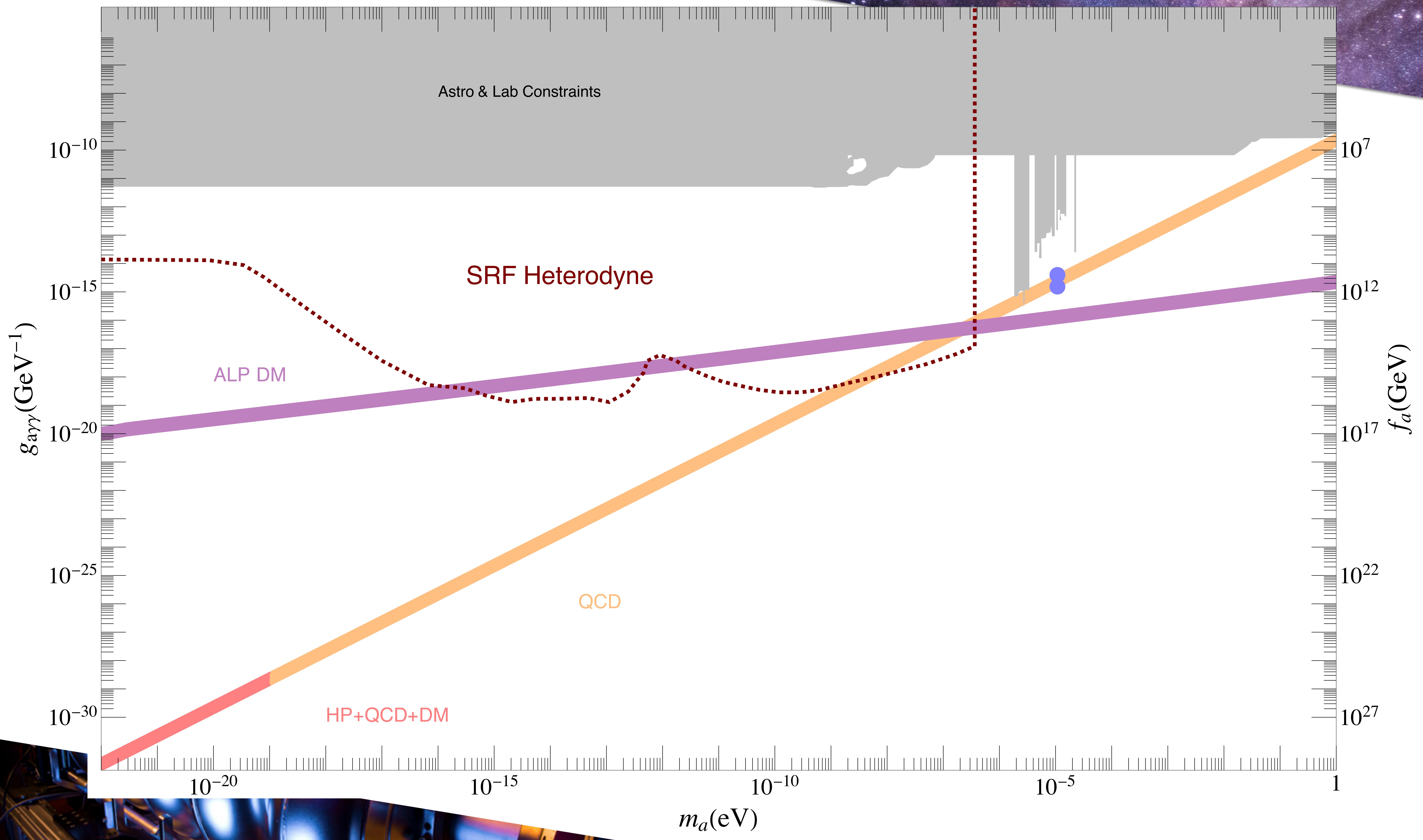

Self-coupling
50 O.M.
Mass
50 O.M.
80 O.M.
Couplings to ordinary matter

DARK MATTER MASS

Theory Spotlight

AXIONS

- Minimal Extension of what we know to exist
- Simple and predictive cosmology
- Solve another big problem in particle physics
- Ubiquitous in string theory



Astro & Lab Constraints
SRF Heterodyne
ALP DM
QCD
HP+QCD+DM
$g_{a\gamma\gamma}(\mathrm{GeV}^{-1})$
$f_a(\mathrm{GeV})$
$m_a(\mathrm{eV})$
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
10^{7}
10^{12}
10^{17}
10^{22}
10^{27}
10^{-20}
10^{-15}
10^{-10}
10^{-5}
1

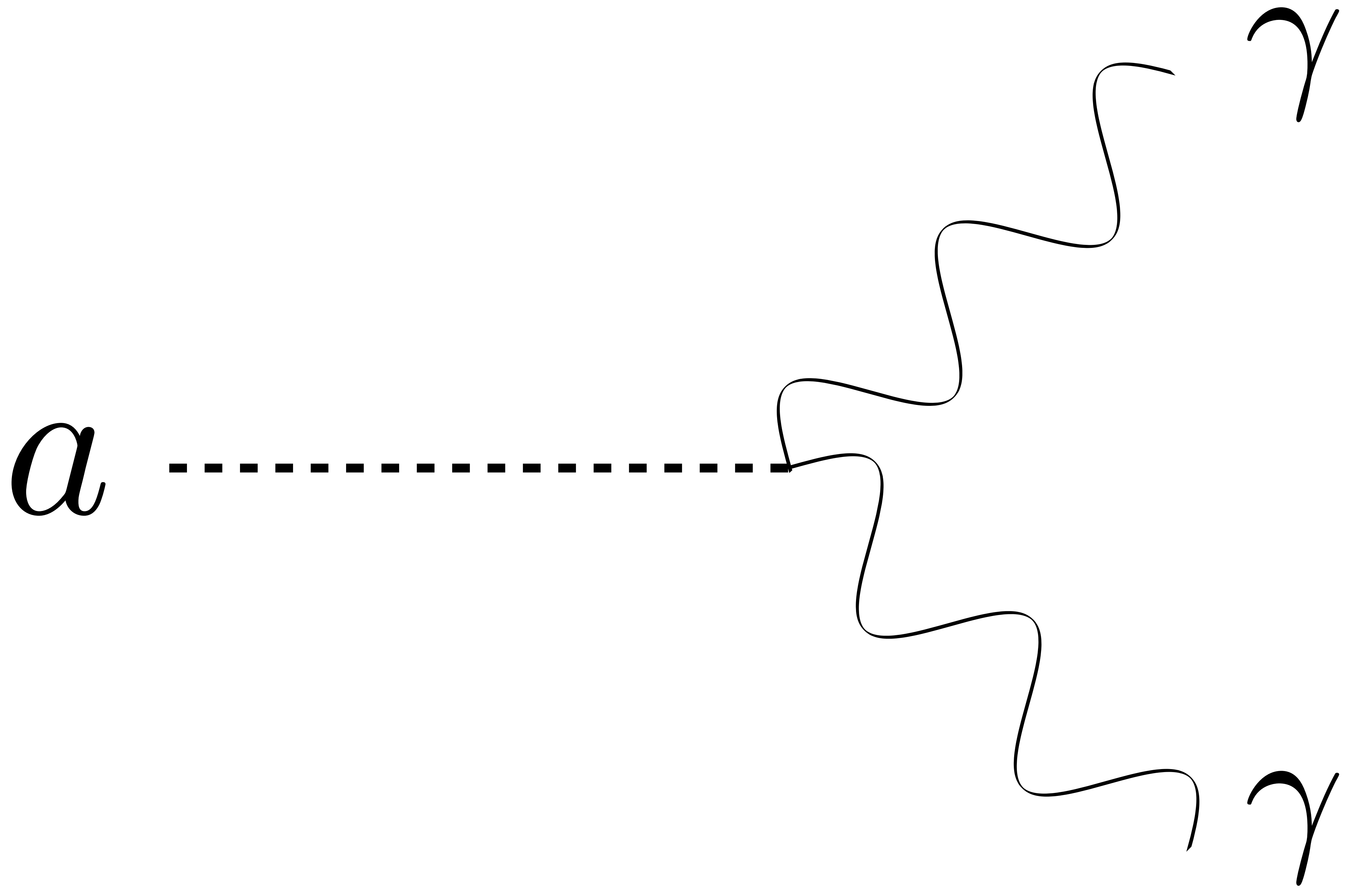
ALPS DETECTION

ALP DARK MATTER IN THE LAB

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

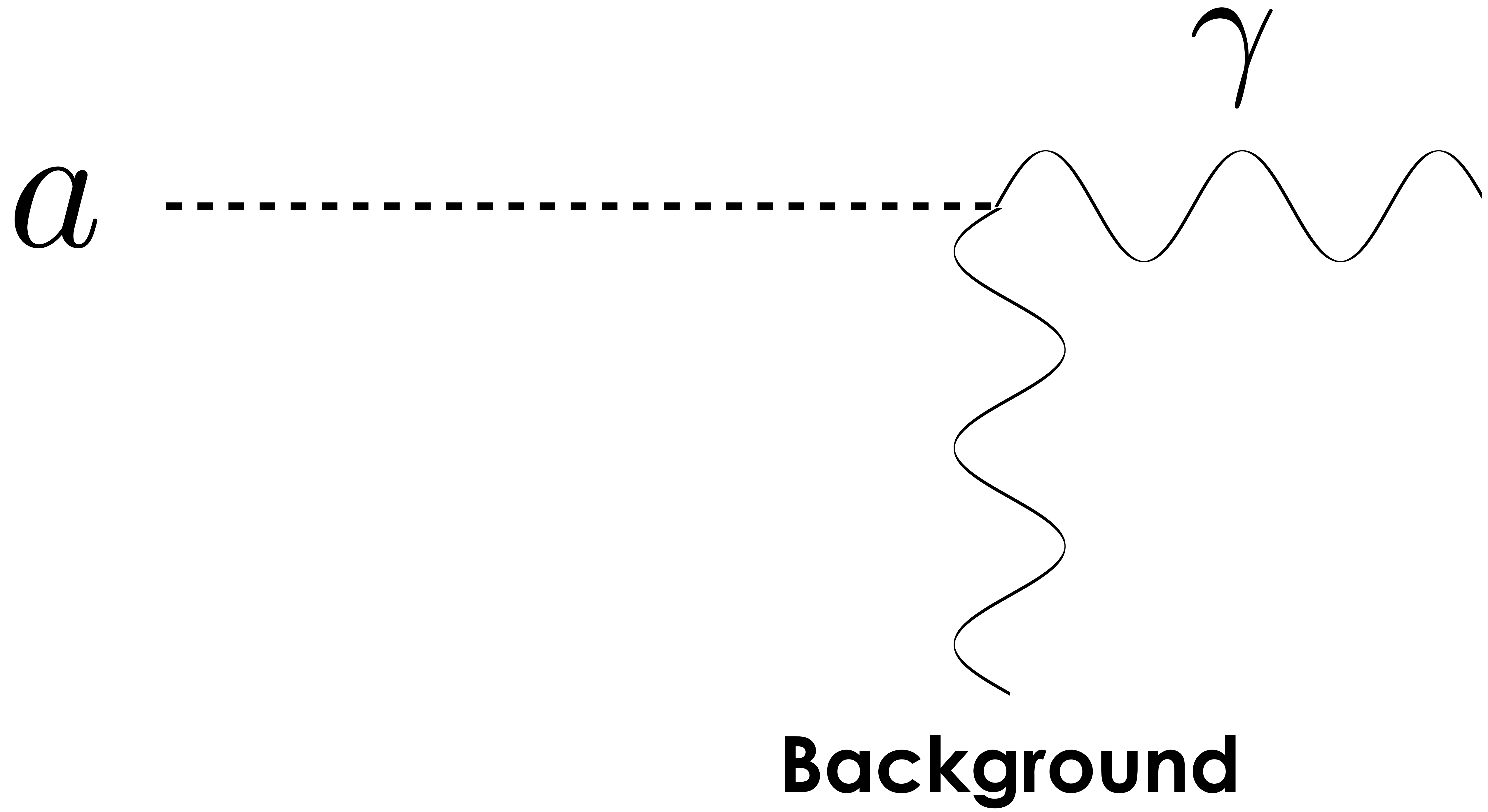
$$\Delta t \lesssim \frac{10^6}{m_a}$$

ALP DARK MATTER DETECTION




Astro & Lab Constraints
SRF Heterodyne
ALP DM
QCD
HP+QCD+DM
$\frac{a}{f_a} \simeq 10^{-21}$
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
$g_{a\gamma\gamma}(\mathrm{GeV}^{-1})$
10^{7}
10^{12}
10^{17}
10^{22}
10^{27}
$f_a(\mathrm{GeV})$
10^{-20}
10^{-15}
10^{-10}
10^{-5}
1
$m_a(\mathrm{eV})$

ALP DARK MATTER DETECTION

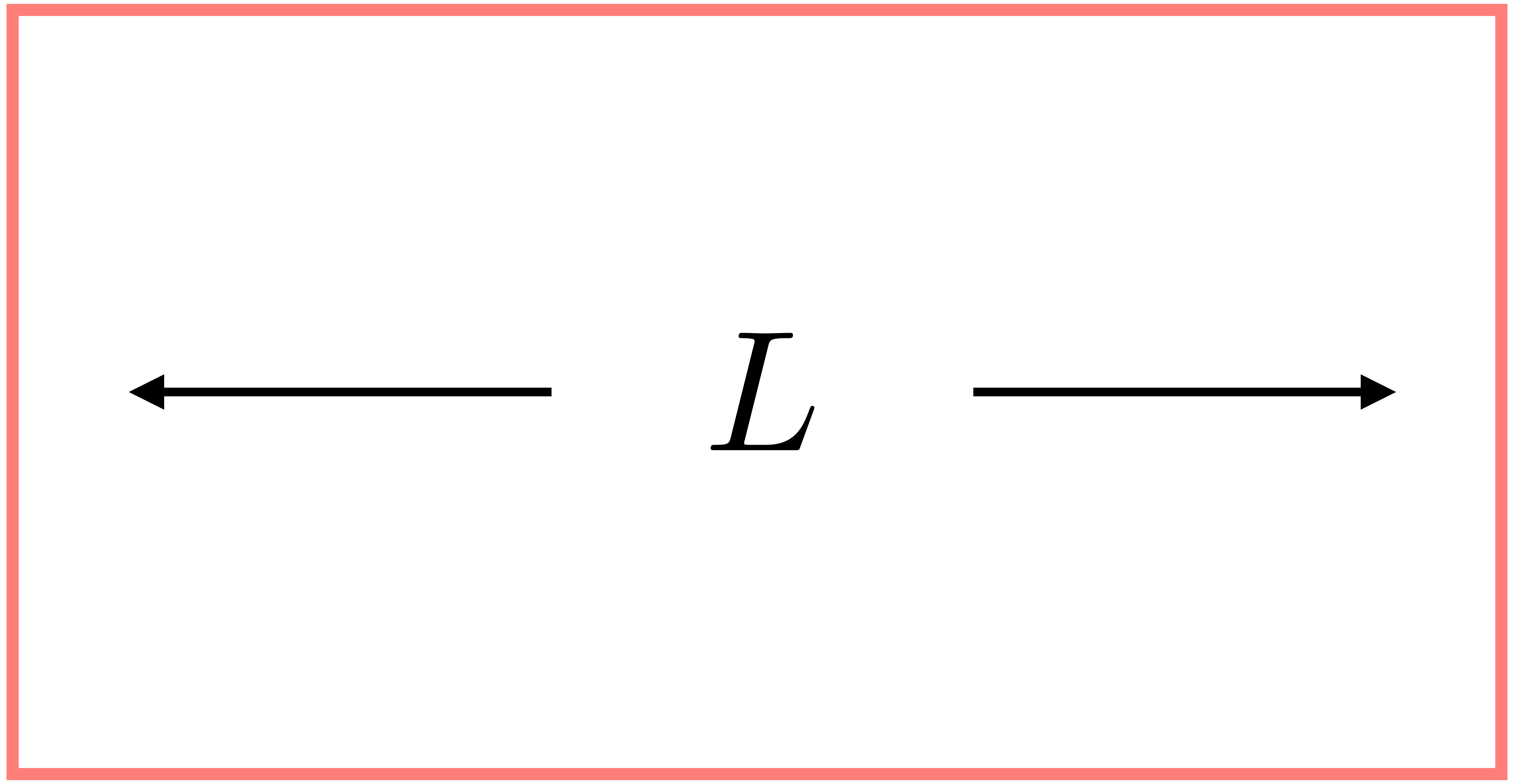


$$\sim \frac{a}{f_a} E_{\mathrm{bkg}} \simeq \boxed{10^{-21} E_{\mathrm{bkg}}}$$

but you know exactly the waveform
and the signal is always there

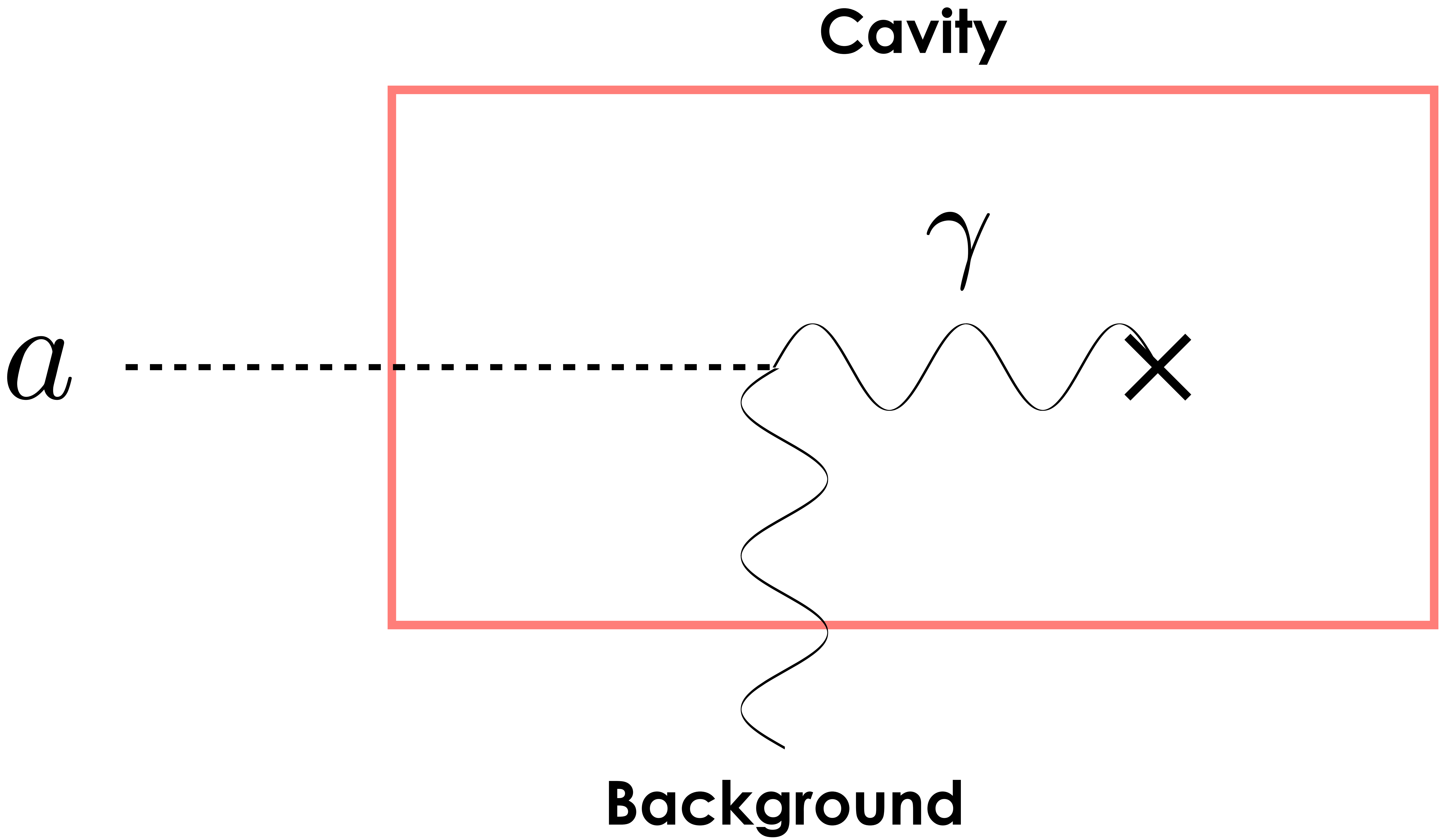
AXION DARK MATTER DETECTION

Cavity



$$m_\gamma \simeq \frac{1}{L}$$

AXION DARK MATTER DETECTION



Resonance

$$m_a \simeq \frac{1}{L}$$

Astro & Lab Constraints
Axion DM
ALP DM
QCD
HP+QCD+DM
$g_{a\gamma\gamma}(\mathrm{GeV}^{-1})$
$f_a(\mathrm{GeV})$
$m_a(\mathrm{eV})$
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
10^{7}
10^{12}
10^{17}
10^{22}
10^{27}
10^{-20}
10^{-15}
10^{-10}
10^{-5}
1

Cavity:

$$\sum_n \left(\partial_t^2 + \frac{\omega_n}{Q_n} \partial_t + \omega_n^2 \right) \mathbf{E}_n = g_{a\gamma\gamma} \partial_t (\mathbf{B} \partial_t a)$$

Cavity:

$$\sum_n \left(\partial_t^2 + \frac{\omega_n}{Q_n} \partial_t + \omega_n^2 \right) \mathbf{E}_n = g_{a\gamma\gamma} \partial_t (\mathbf{B} \partial_t a)$$

$$\omega_1 \simeq m_a \qquad \partial_t(\mathbf{B}) \simeq 0$$

AXION DETECTION

Cavity:

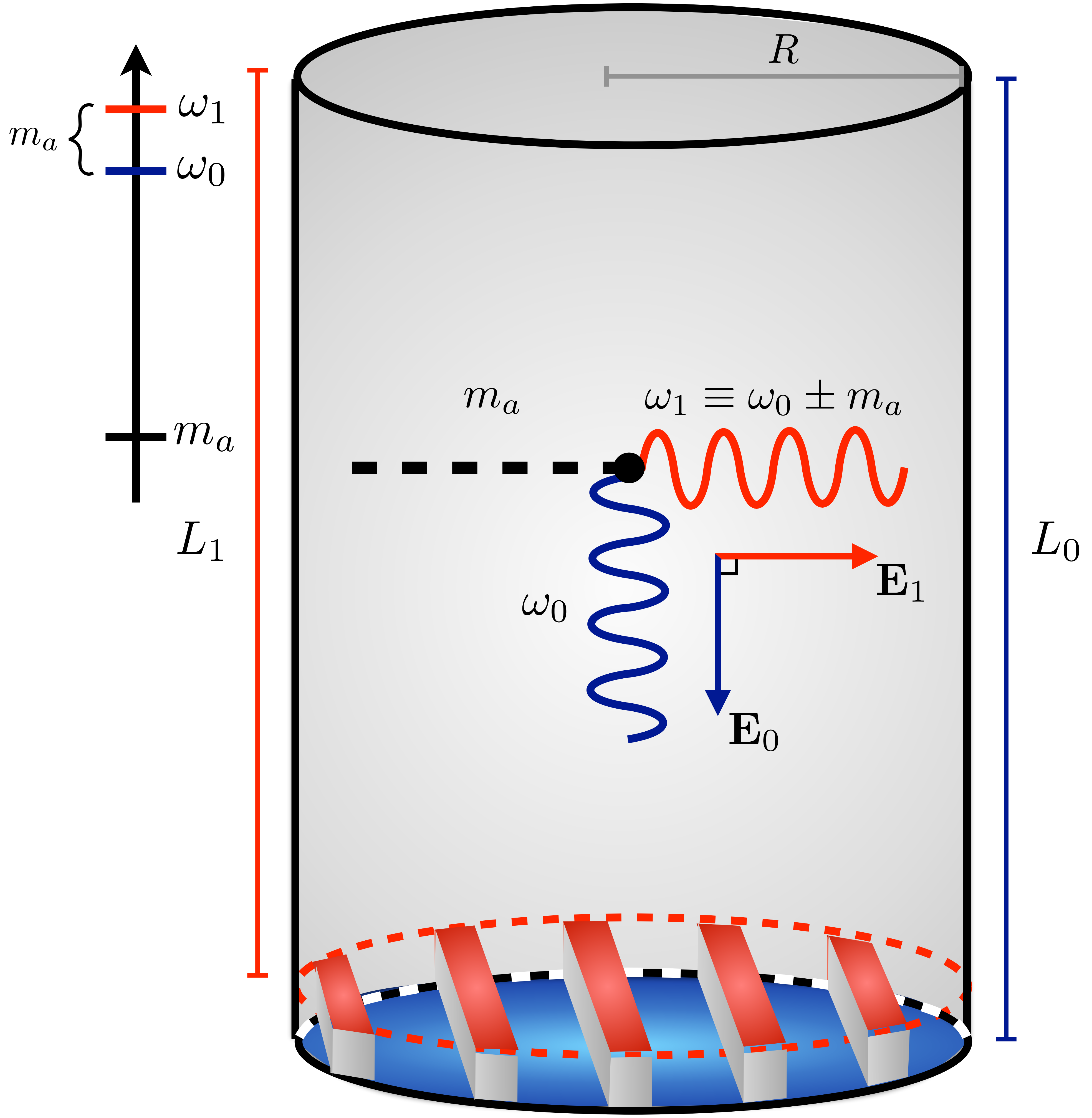
$$\sum_n \left(\partial_t^2 + \frac{\omega_n}{Q_n}\partial_t + \omega_n^2 \right) \mathbf{E}_n = g_{a\gamma\gamma}\partial_t(\mathbf{B}\partial_t a)$$

$$\omega_1 \simeq m_a \qquad \partial_t(\mathbf{B}) \simeq 0$$

$$\left(\partial_t^2 + \frac{m_a}{Q_1}\partial_t + m_a^2 \right) \mathbf{E}_1 = \boxed{g_{a\gamma\gamma}\mathbf{B}\sqrt{\rho_{\mathrm{DM}}}m_a \cos m_a t}$$

HETERODYNE DETECTION

[Berlin, RTD, S. Ellis, C. Nantista, J. Nielson, P. Schuster, S. Tantawi, N. Toro, K. Zhou'19]



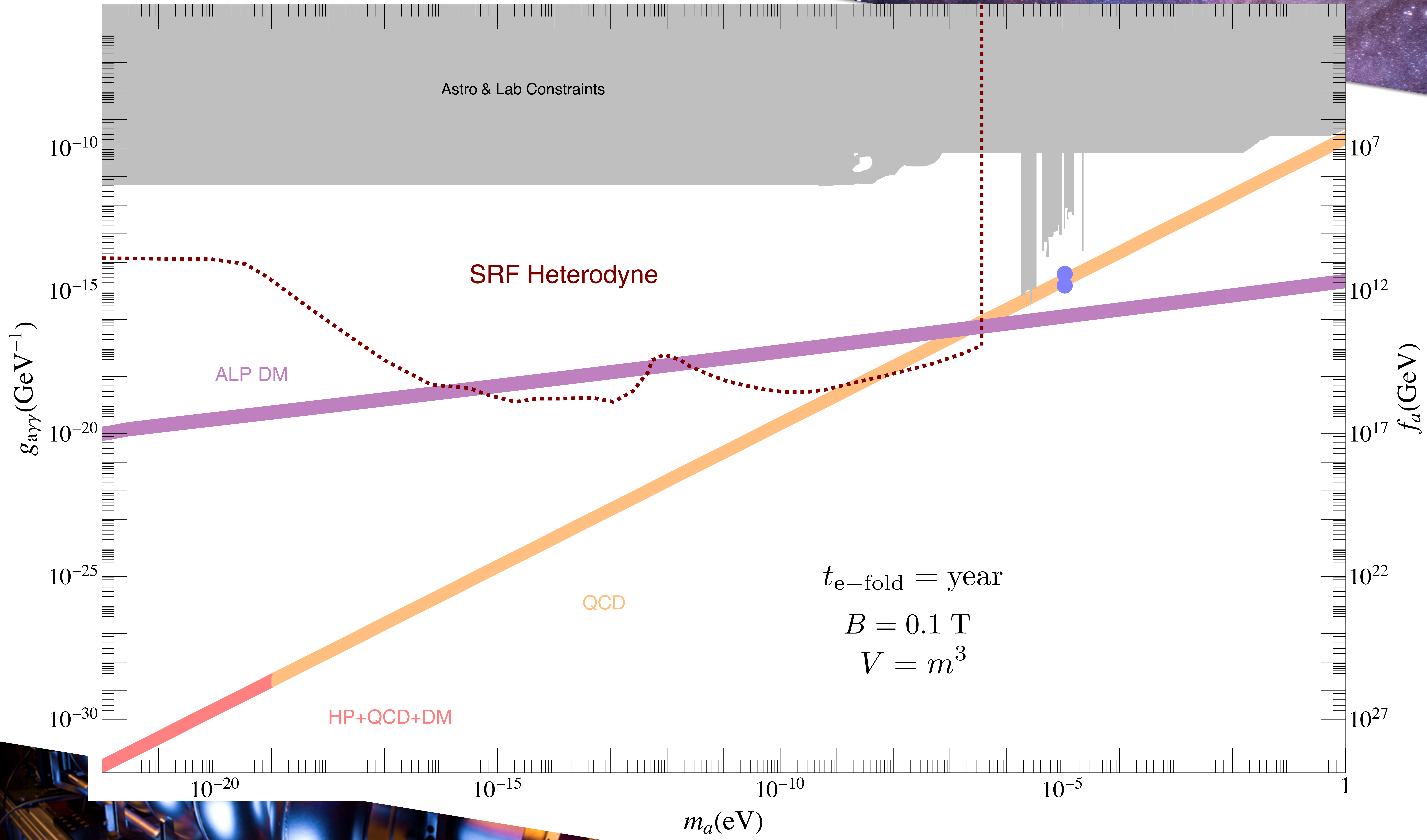
HETERODYNE DETECTION

[Berlin, RTD, S. Ellis, C. Nantista, J. Nielson, P. Schuster, S. Tantawi, N. Toro, K. Zhou'19]

$$\sum_n \left(\partial_t^2 + \frac{\omega_n}{Q_n} \partial_t + \omega_n^2 \right) \mathbf{E}_n = g_{a\gamma\gamma} \partial_t (\mathbf{B} \partial_t a)$$

$$\partial_t(\mathbf{B}) \simeq i\omega_0 \mathbf{B} \qquad \omega_1 \simeq \omega_0 + m_a$$

$$\partial_t J_{\text{eff}} = g_{a\gamma\gamma} \partial_t (\mathbf{B} \partial_t a) \propto \omega_0 m_a \gg m_a^2$$



Astro & Lab Constraints
SRF Heterodyne
ALP DM
QCD
HP+QCD+DM
$t_{\text{e-fold}} = \text{year}$
$B = 0.1$ T
$V = m^3$
$g_{a\gamma\gamma}(\text{GeV}^{-1})$
$f_a(\text{GeV})$
$m_a(\text{eV})$
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
10^{7}
10^{12}
10^{17}
10^{22}
10^{27}
10^{-5}
1

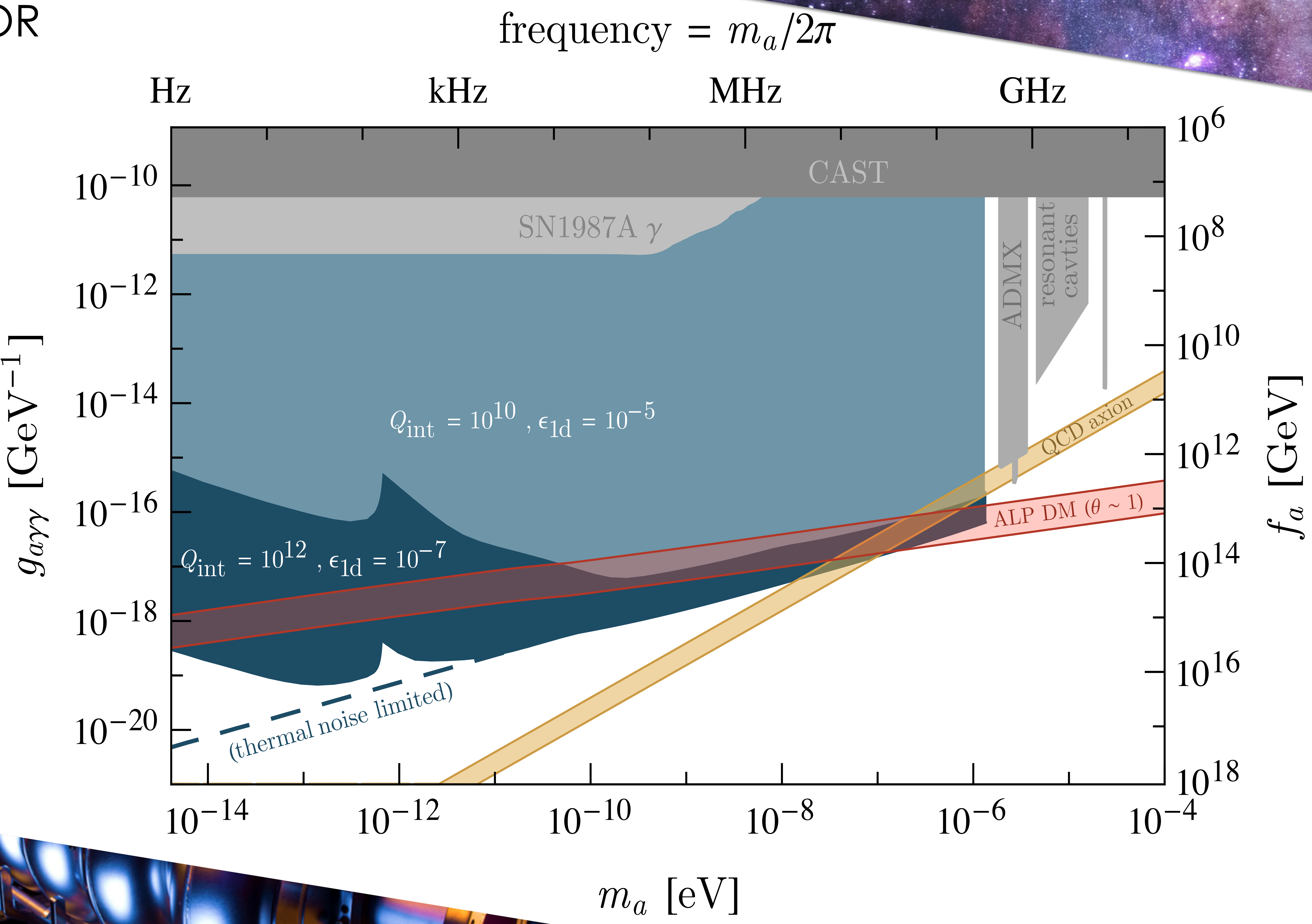
CRUCIAL INGREDIENTS

- Large Q (cryogenics)
- Good mode separation (clever geometry)
- Tunability

IMPORTANT INGREDIENTS

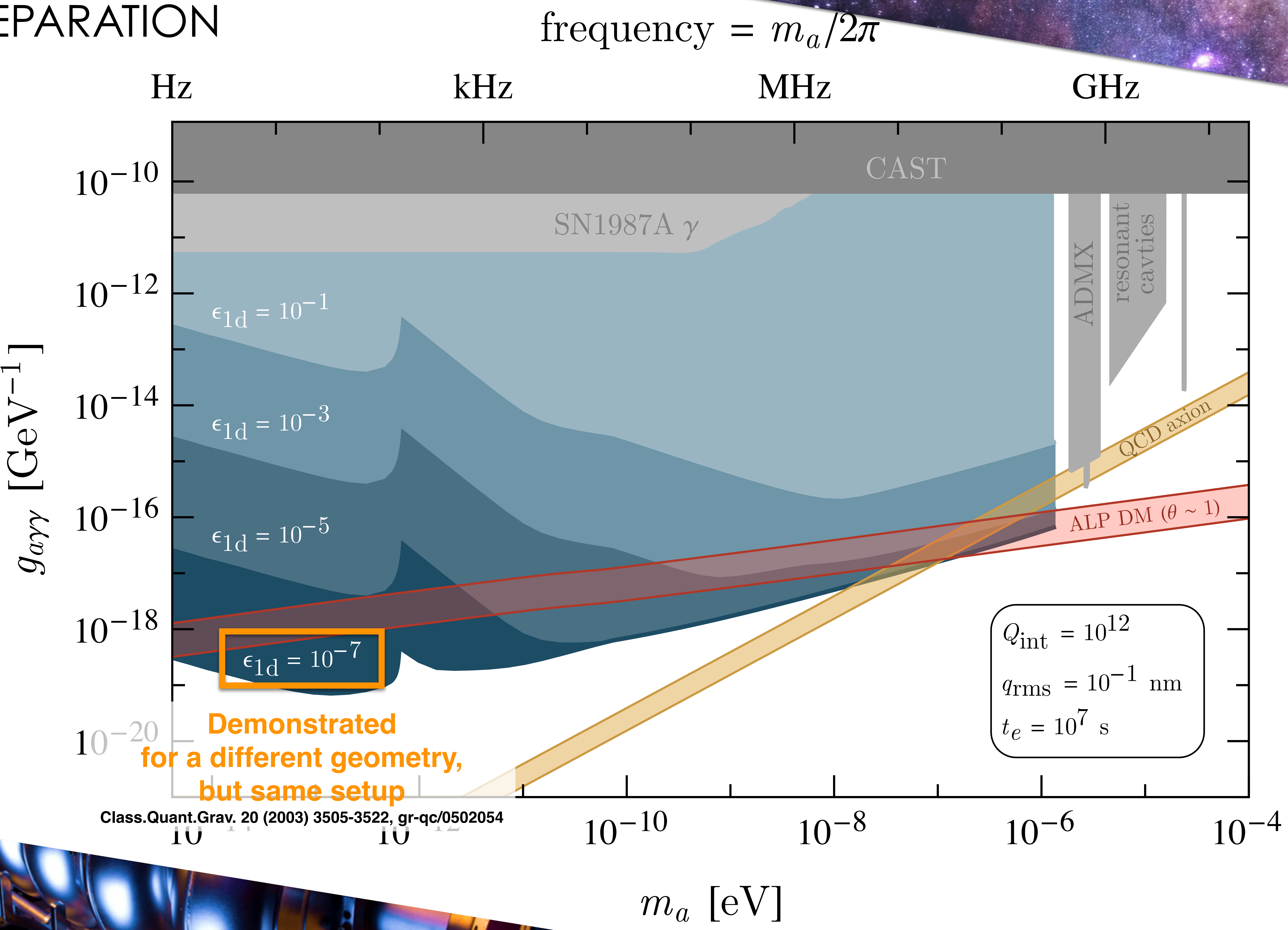
- Isolation from vibrations
- Integration time (for axion masses above kHz)

Q-FACTOR



frequency = $m_a/2\pi$
Hz
kHz
MHz
GHz
CAST
SN1987A γ
ADMX
resonant cavties
$Q_{\rm int} = 10^{10}$, $\epsilon_{\rm 1d} = 10^{-5}$
$Q_{\rm int} = 10^{12}$, $\epsilon_{\rm 1d} = 10^{-7}$
(thermal noise limited)
QCD axion
ALP DM ($\theta \sim 1$)
$g_{a\gamma\gamma}$ [GeV^{-1}]
f_a [GeV]
m_a [eV]
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{6}
10^{8}
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}

MODE SEPARATION



Demonstrated for a different geometry, but same setup

Class.Quant.Grav. 20 (2003) 3505-3522, gr-qc/0502054

PROTOTYPES

THREE PROTOTYPES

SLAC NATIONAL ACCELERATOR LABORATORY

Fermilab

CERN

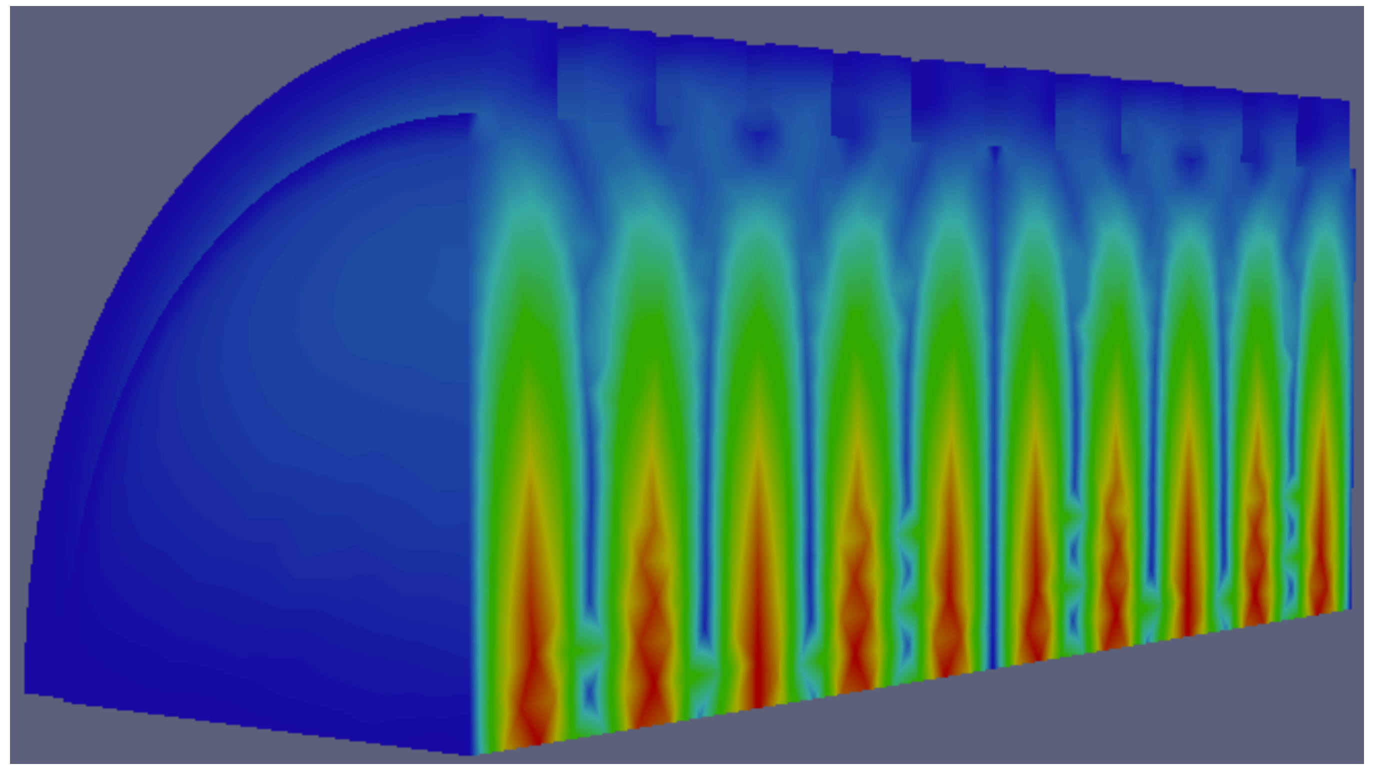
Exp: S. Calatroni, Z. Li, C. Nantista, J. Nielson, M. Oriunno, S. Tantawi
Th: R.T. D'Agnolo, S. Ellis, P. Schuster, N. Toro, K. Zhou

All slides from: Z. Li and M. Oriunno

Exp: S. Calatroni, Z. Li, C. Nantista, J. Nielson, M. Oriunno, S. Tantawi
Th: R.T. D'Agnolo, S. Ellis, P. Schuster, N. Toro, K. Zhou

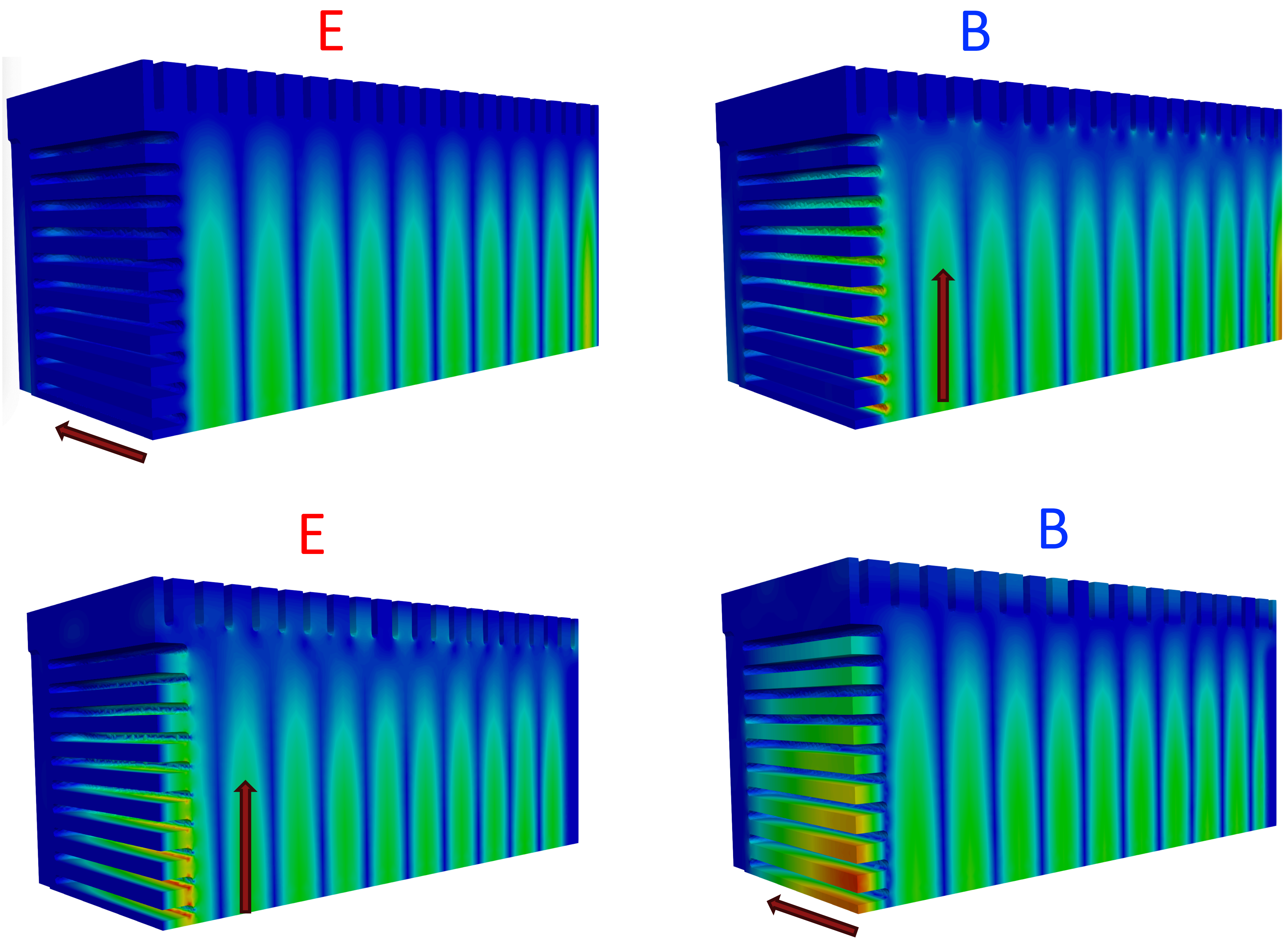
HE11 mode

- Corrugated wave guide
- Both E and B field transverse to the direction of propagation
- Both E and B field concentrated around the center of the cavity
- High Q
  - Very low field on the outer wall
  - Most of EM loss on the ends

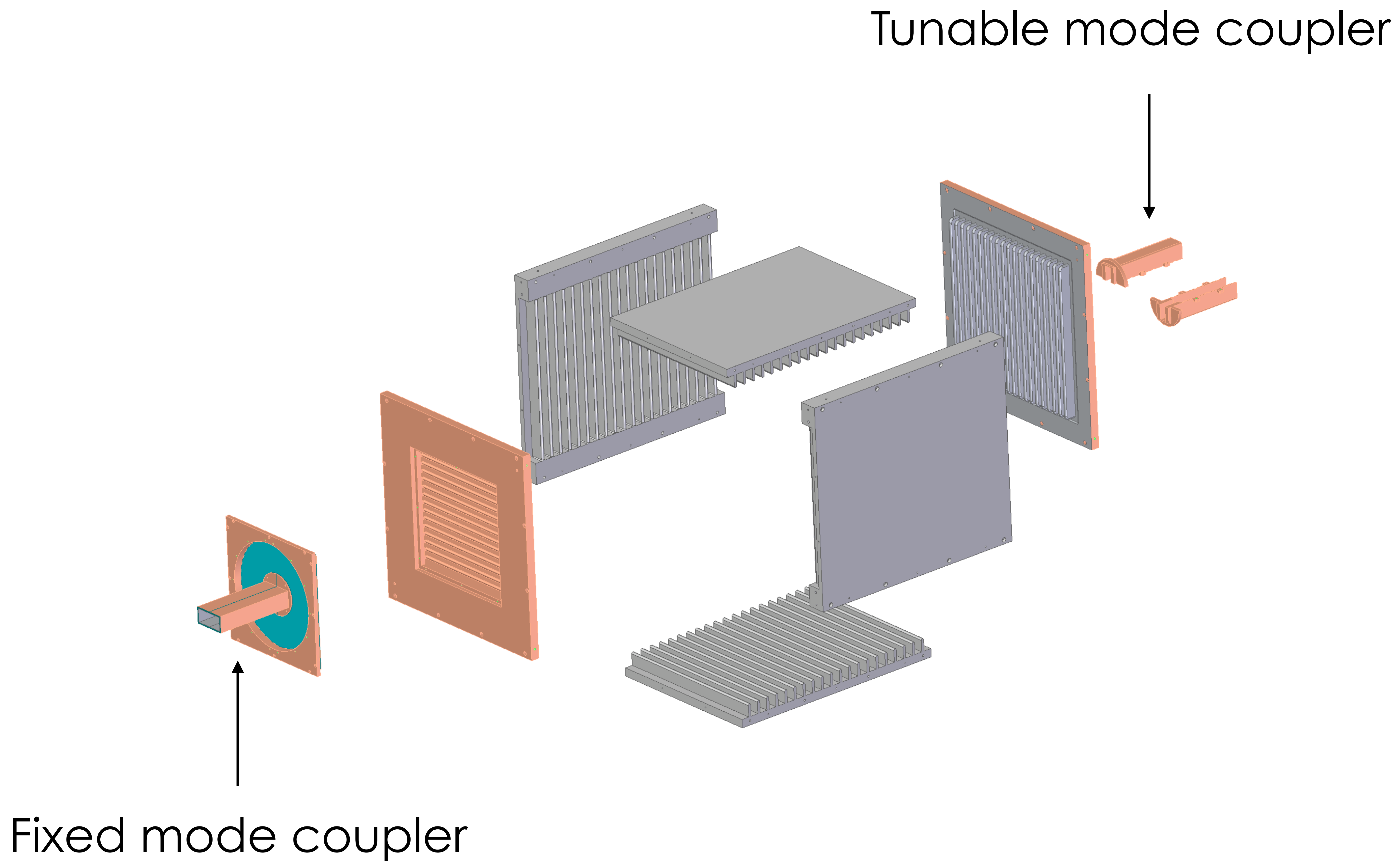


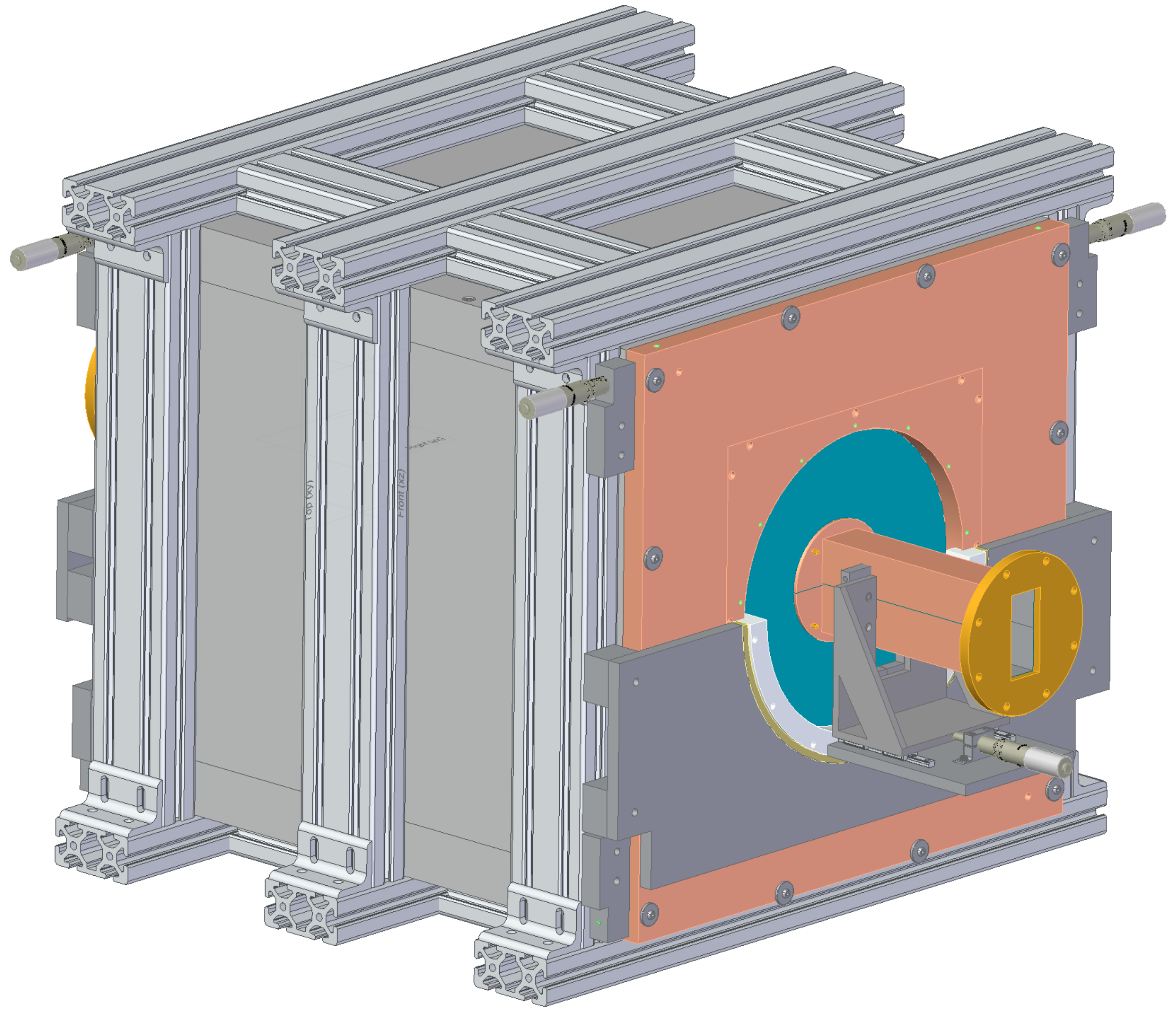
1/4 wavelength fins on the endplates

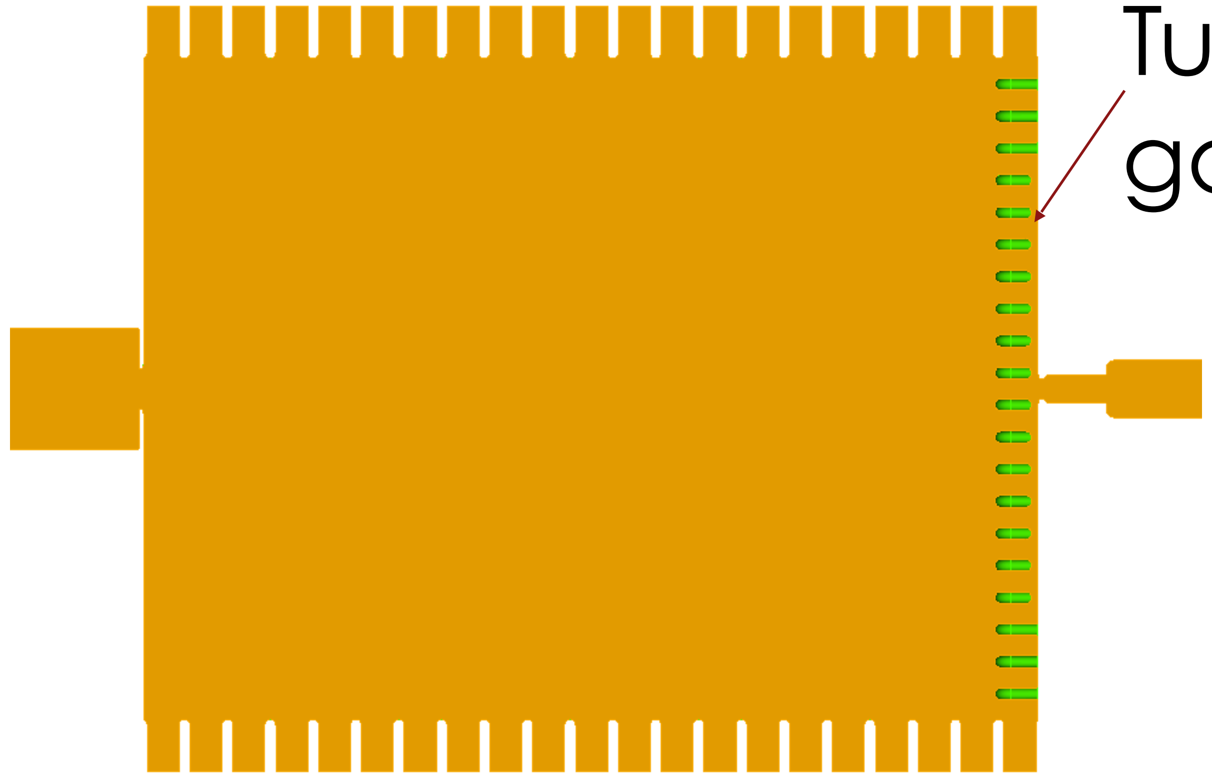
X-polarization



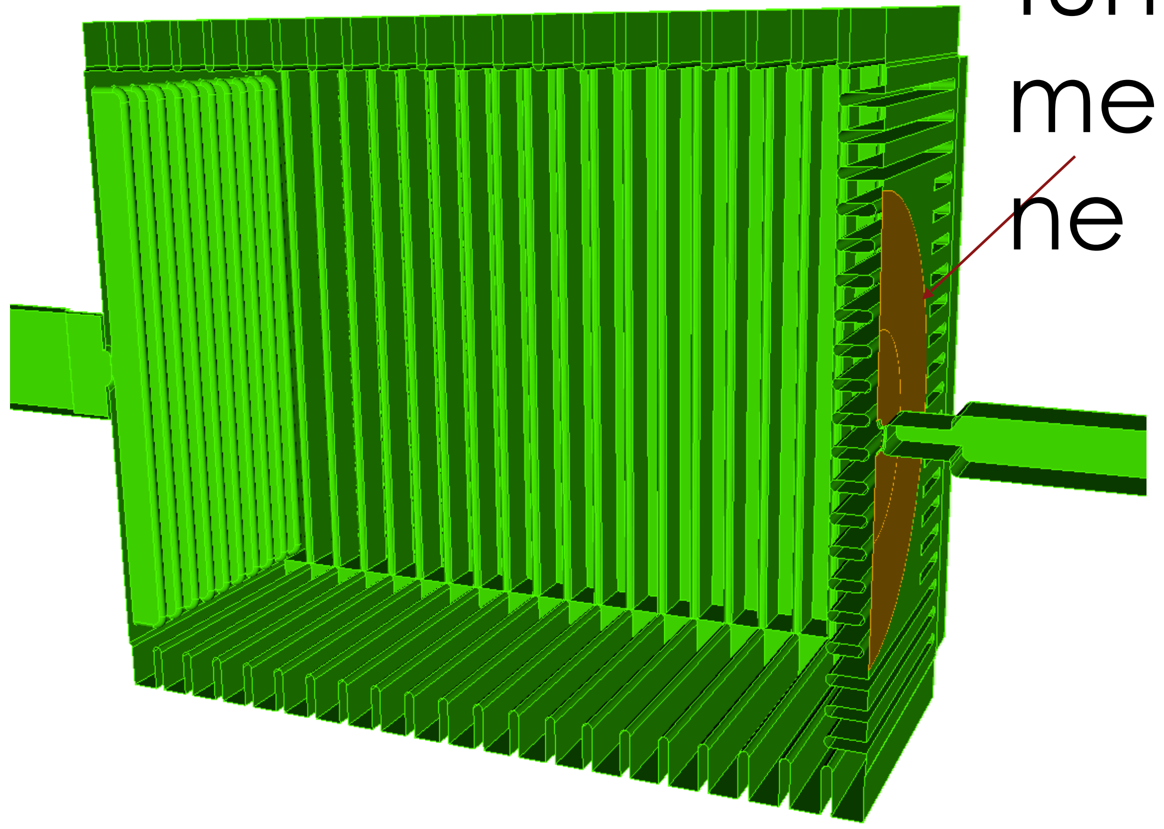
Y-polarization


Tunable mode coupler
Fixed mode coupler

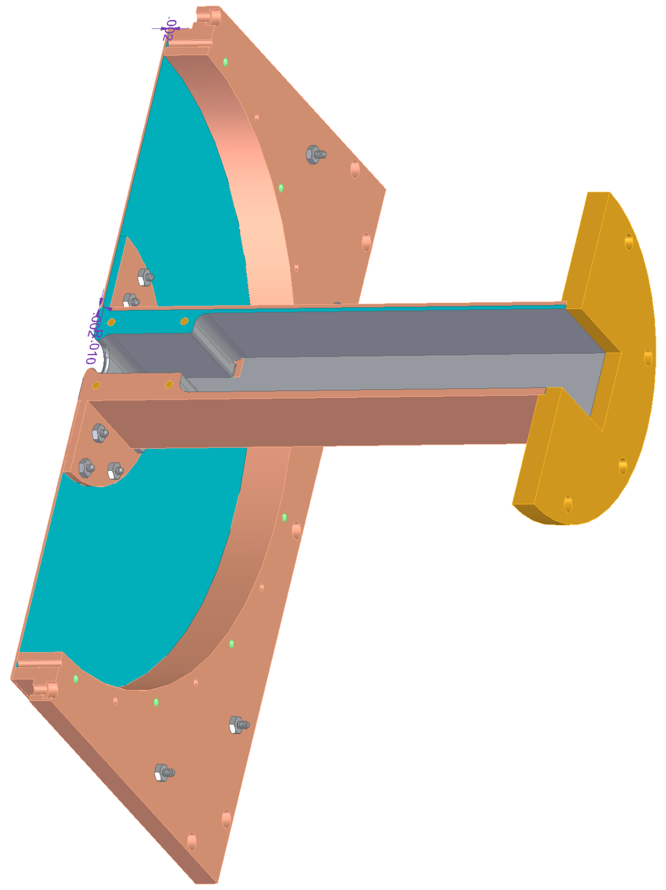


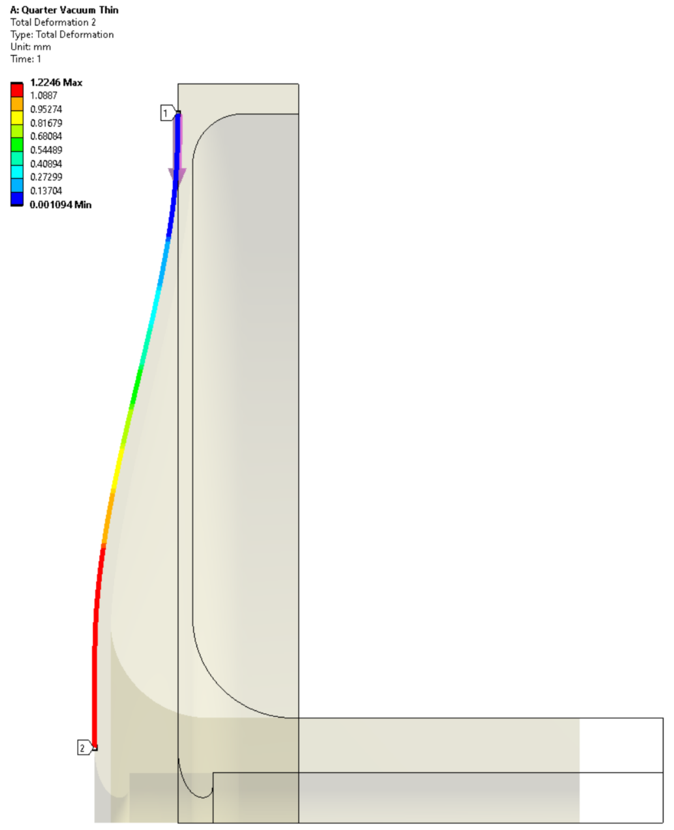


Tuner gap

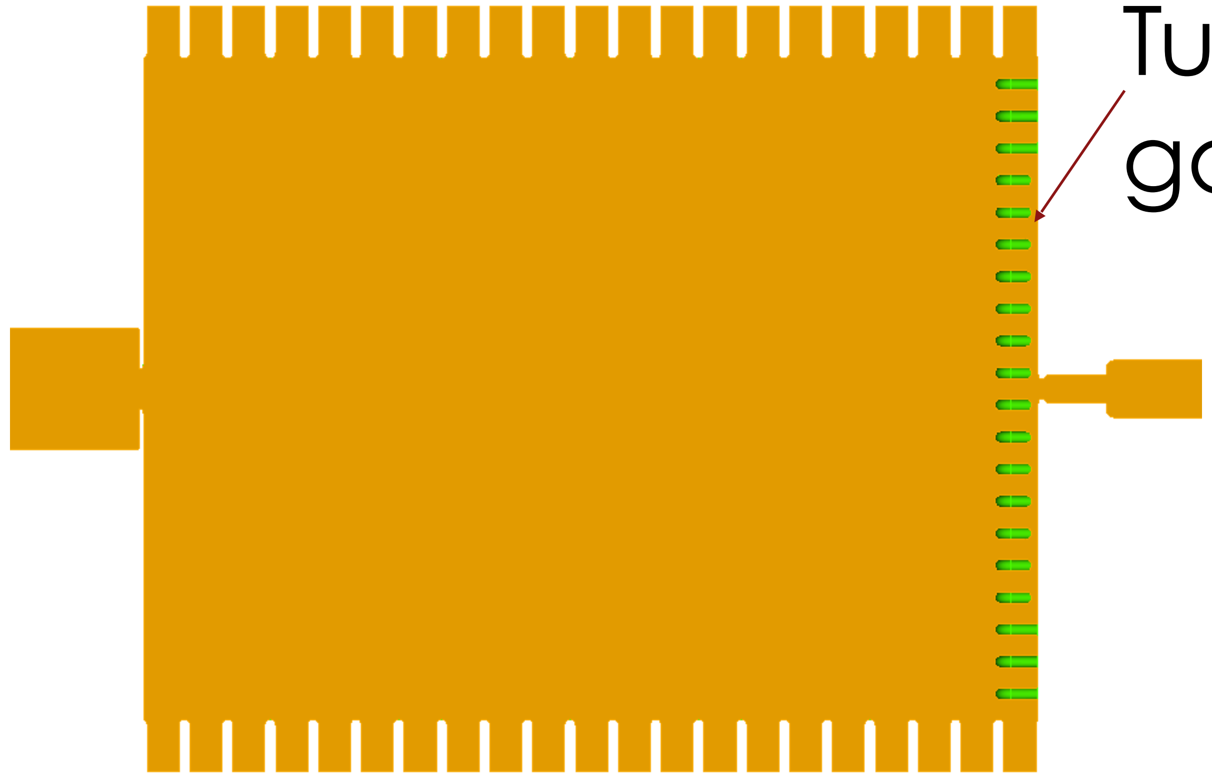


Tuner membra ne

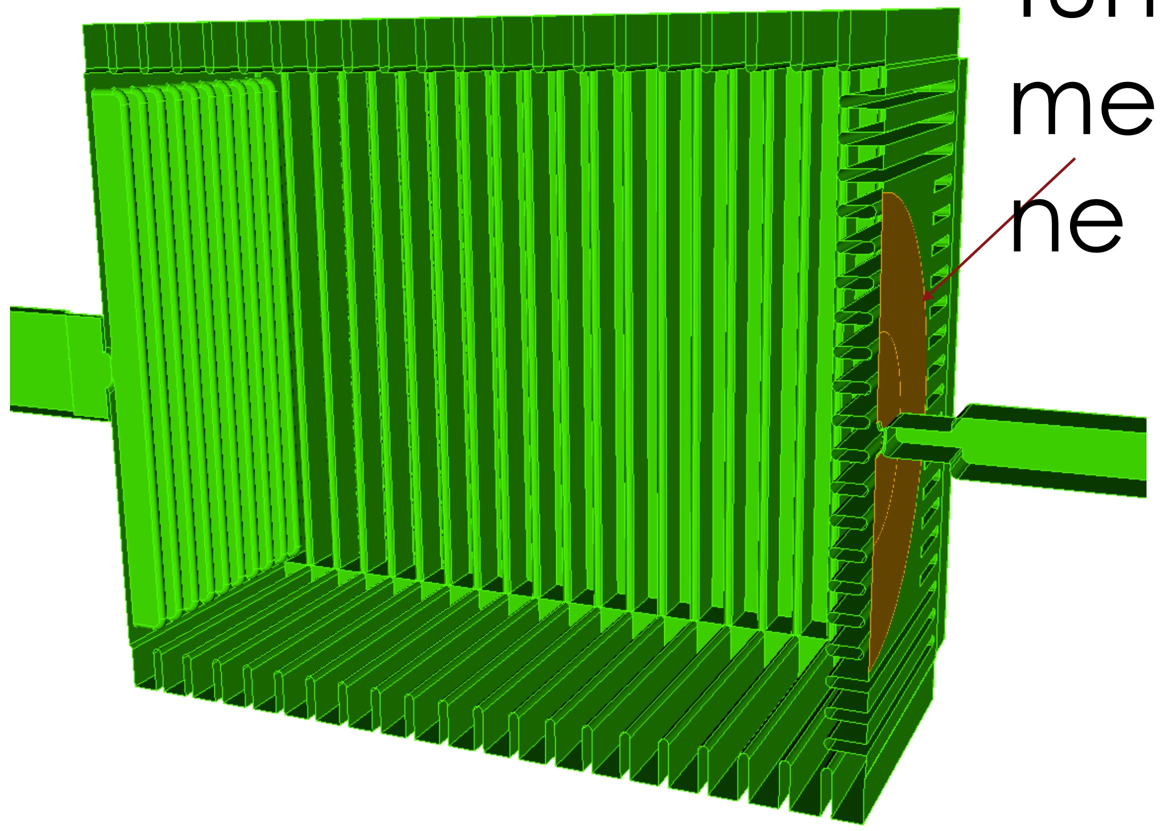




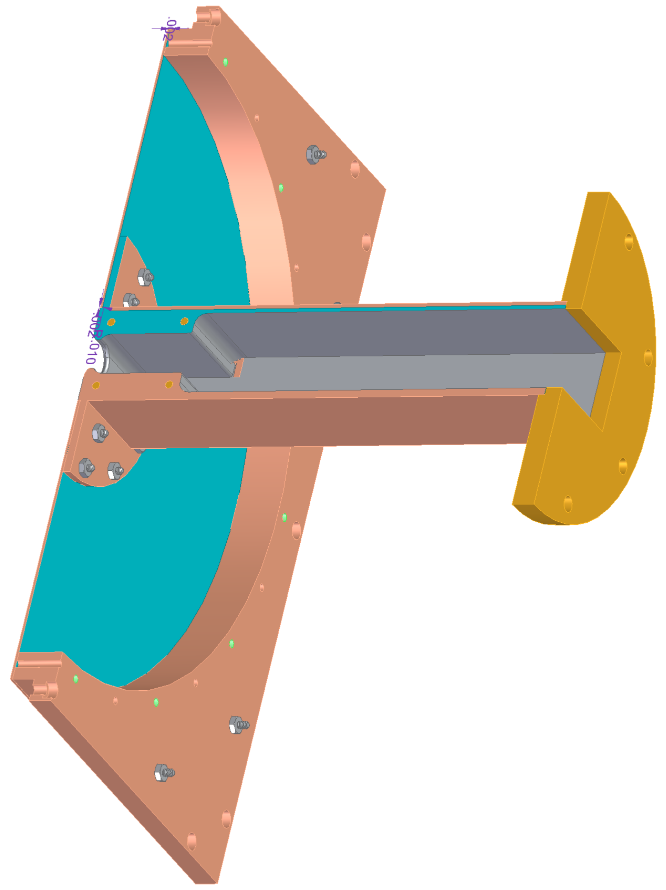
Membrane deformation

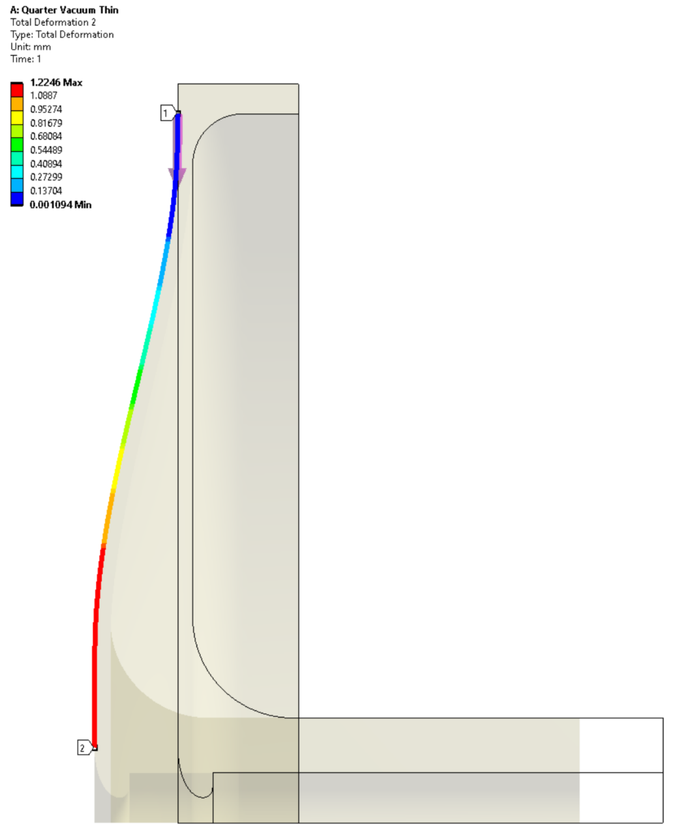


Tuner gap

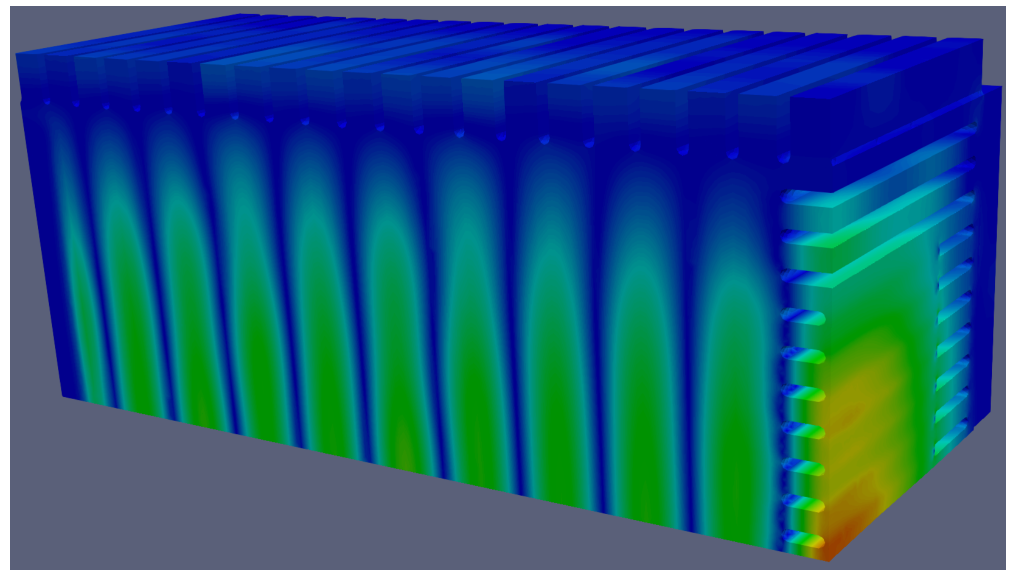


Tuner membrane

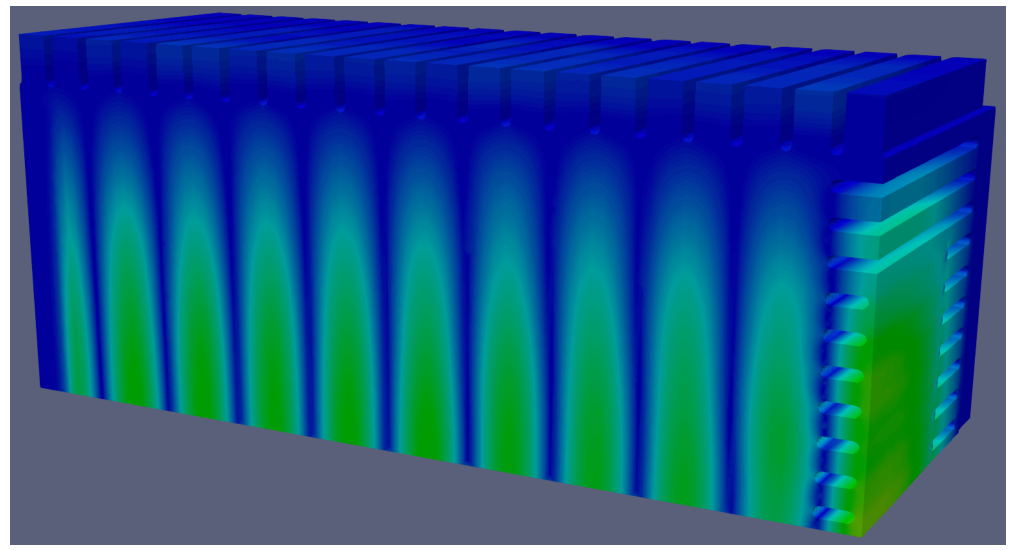




Membrane deformation



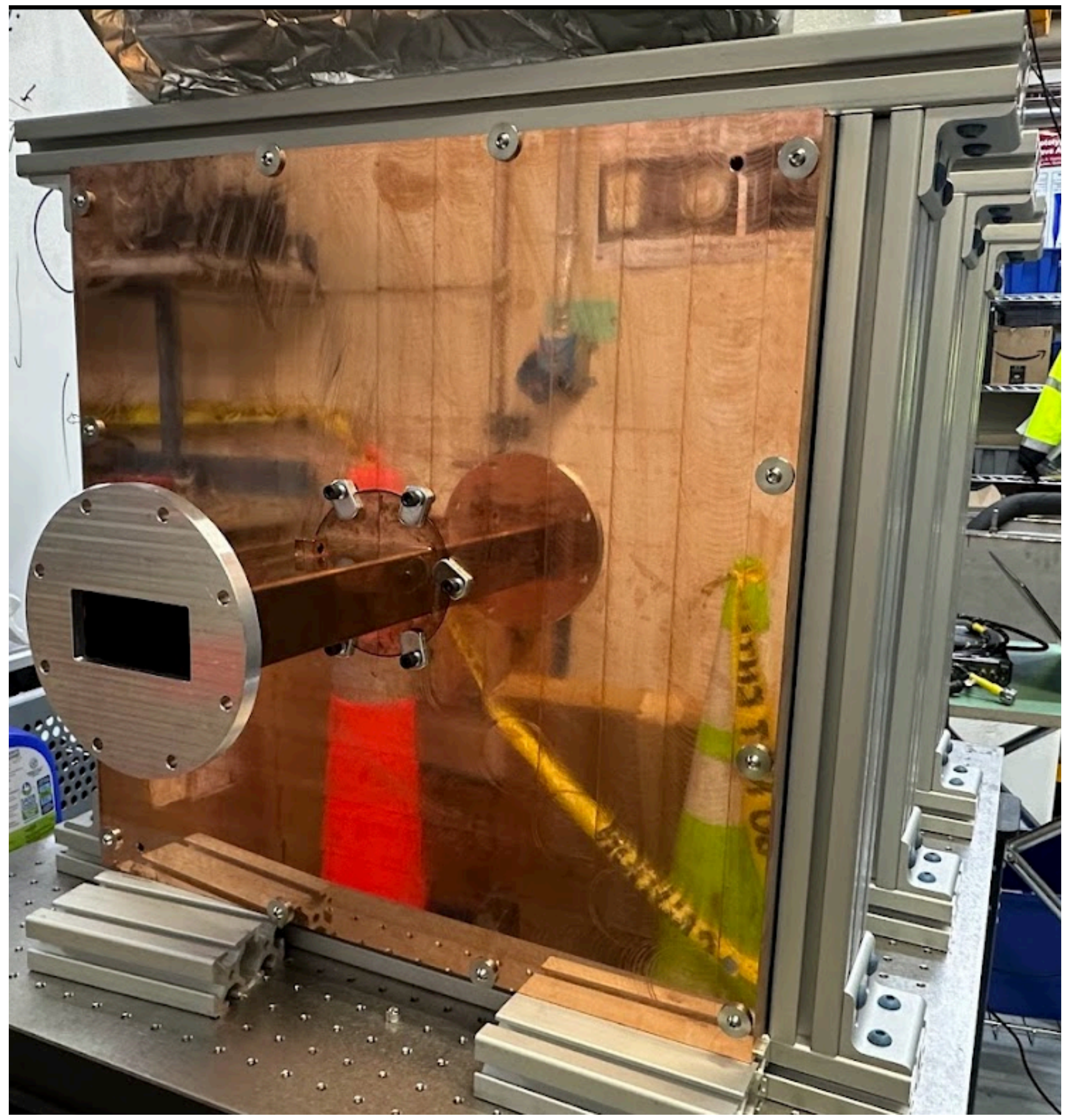
gap = -1mm
f ~ 2.8564 GHz



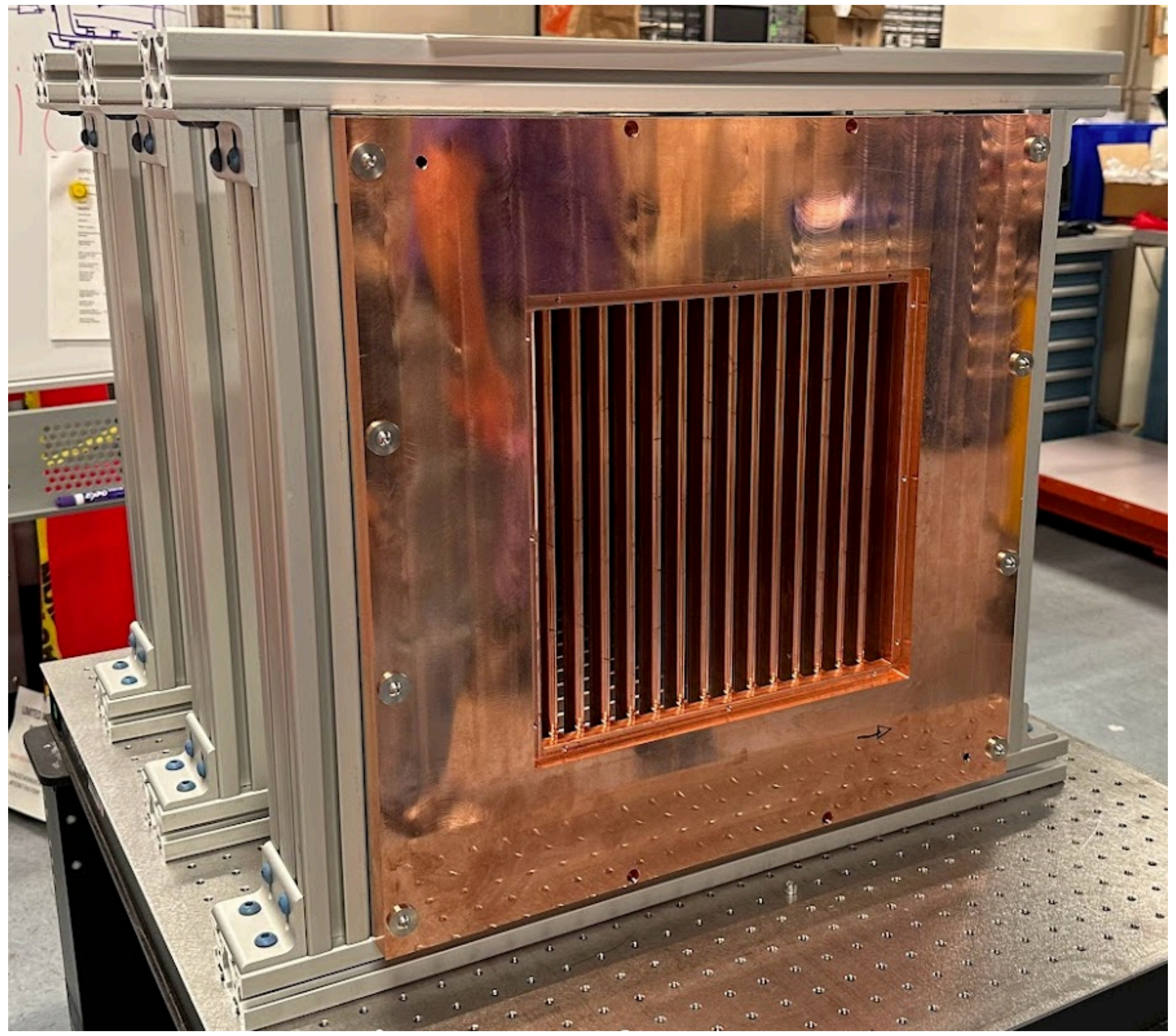
gap = +1mm
f ~ 2.8445 GHz

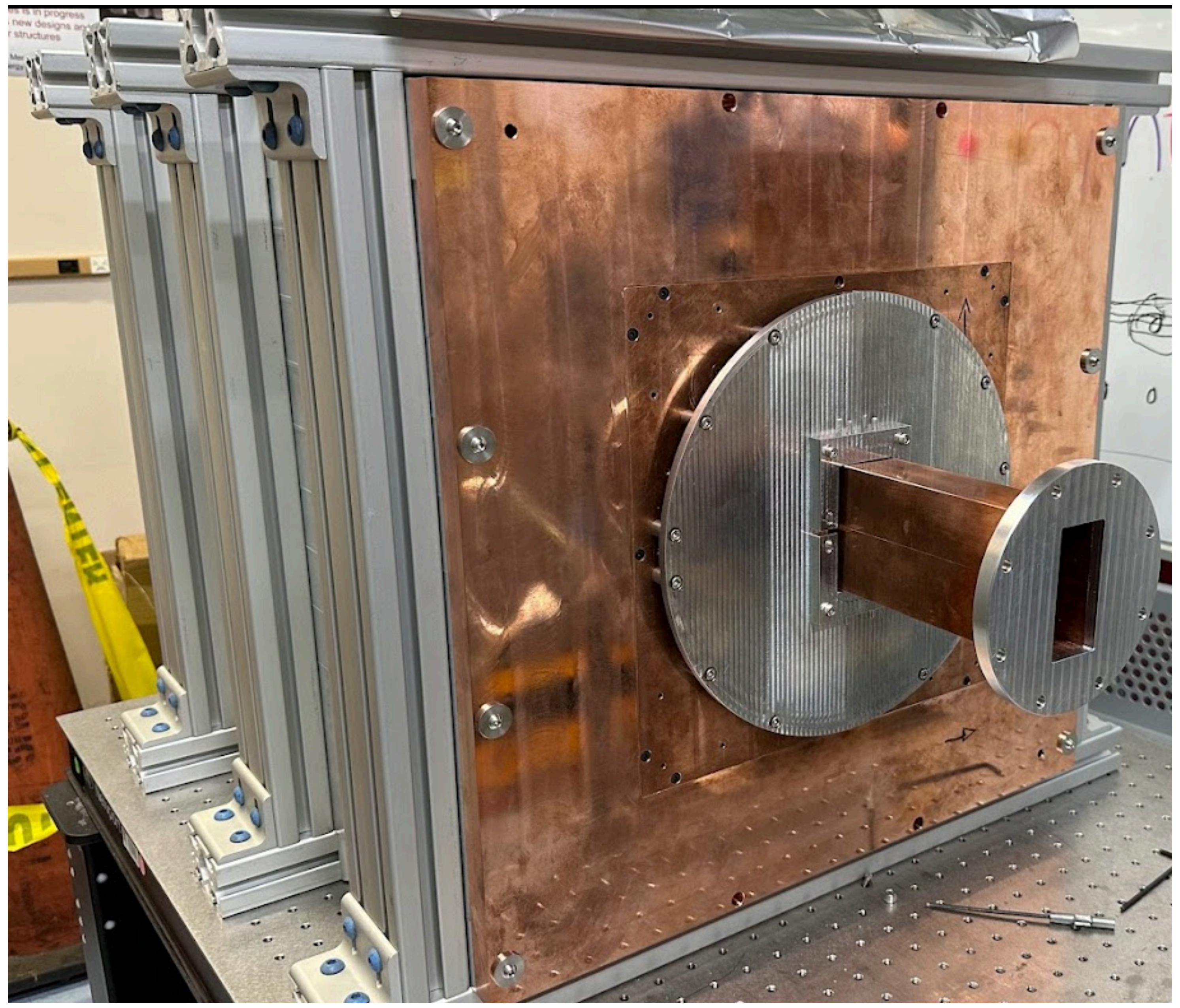
NATIONAL
ACCELERATOR
LABORATORY

Coupler of fixed frequency mode



Coupler and tuner of tunable mode





SLAC NATIONAL ACCELERATOR LABORATORY

(*) loaded non-tunable mode

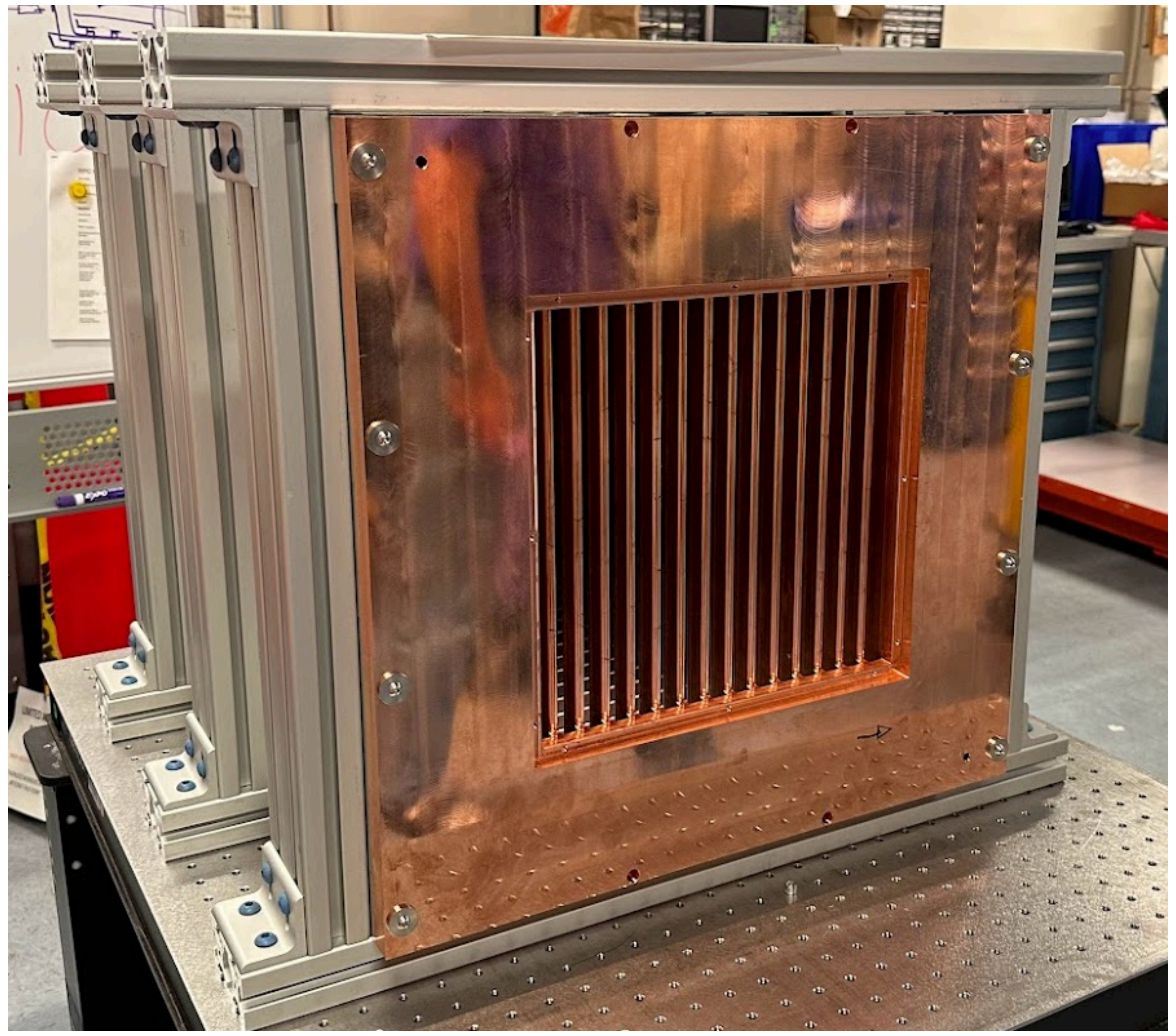
(*) $Q \simeq 3.5 \times 10^4$

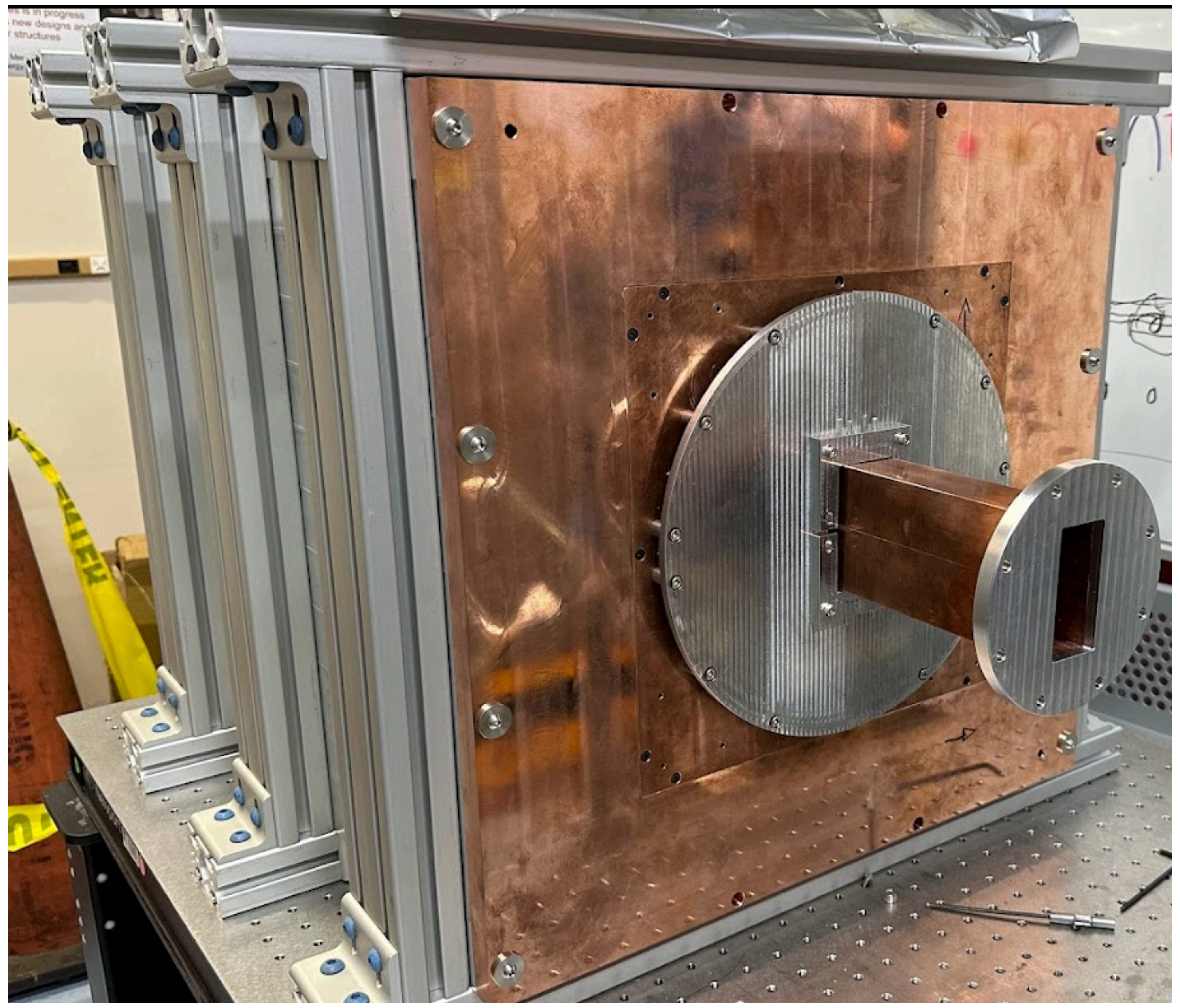
$V \simeq (0.48 \times 0.46 \times 0.46)\,\mathrm{m}^3$

$T \simeq 300\,\mathrm{K}$

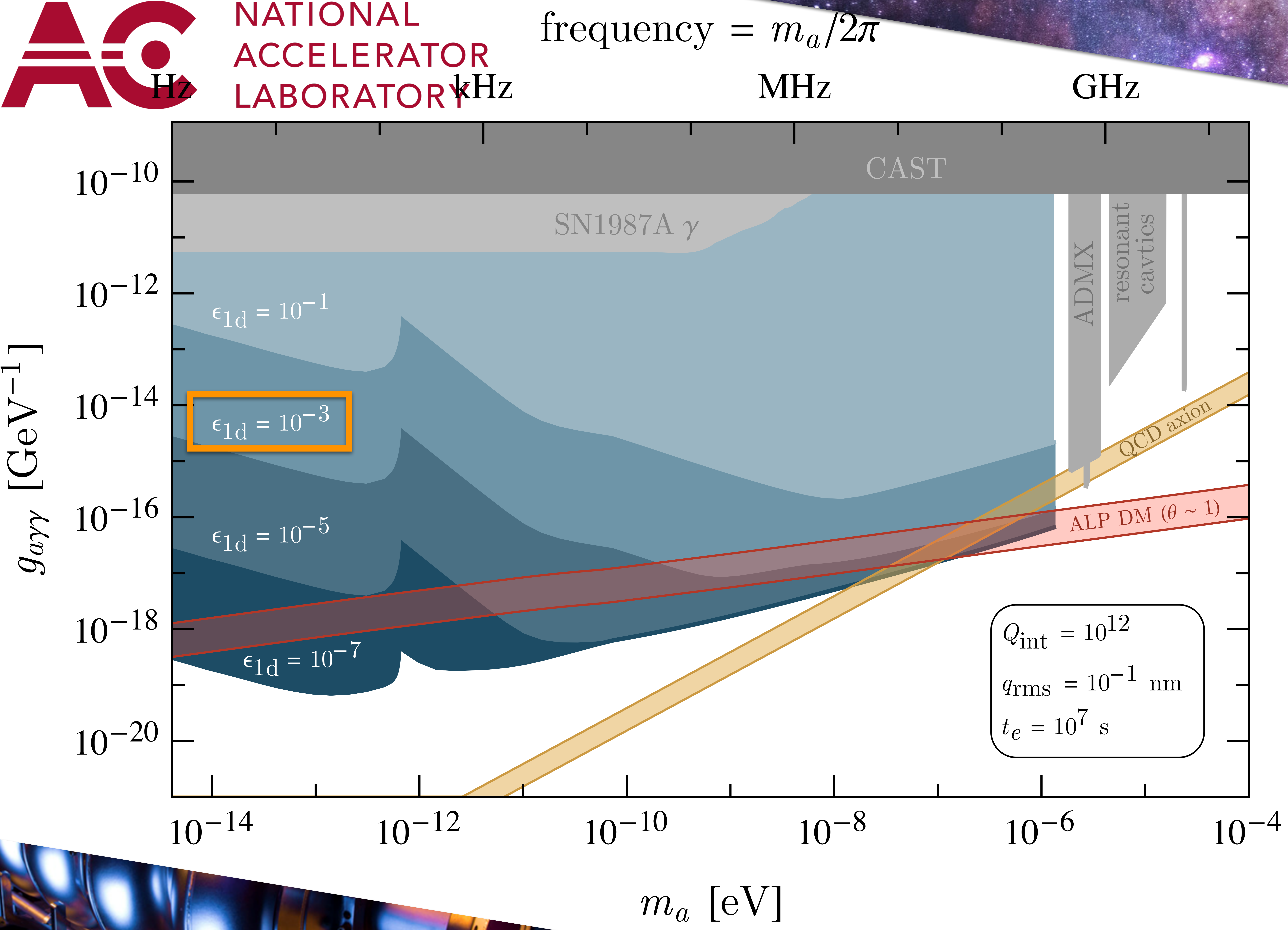
$\epsilon_{1d} \simeq 10^{-3}$

$\omega \simeq 3\,\mathrm{GHz}$





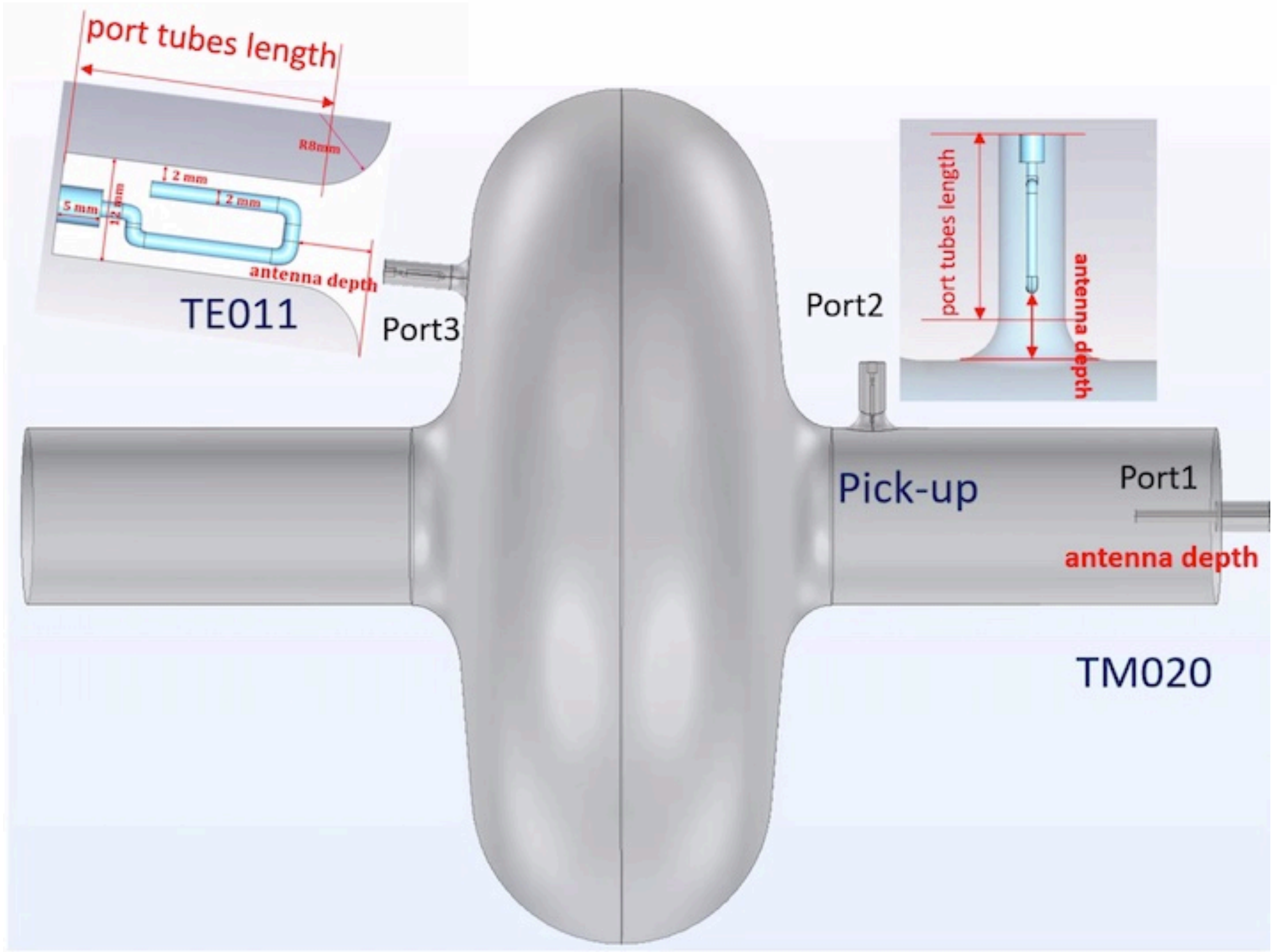
SLAC NATIONAL ACCELERATOR LABORATORY



SQMS Team

Parameters based on informal conversations

VERY PRELIMINARY!



$Q \simeq 10^{10}$ (loaded)

$V \simeq 10\ \mathrm{L}$

$\omega_0 \gtrsim \mathrm{GHz}$

$T \simeq 4\ \mathrm{K}$

$\epsilon_d \simeq ?$

The potential sensitivity is beyond current bounds

Small Collaboration (to be confirmed)

Exp: A. Grudiev, J. Bremer, S. Calatroni, A. Castilla, A. MacPherson + 1 Fellow from PBC

Th: R.T. D'Agnolo, S. Ellis

Material Budget: 450 kCHF/3 years from QTI

Design to be confirmed

Superconducting cavity operated at cryogenic temperatures

CONCLUSION

- A powerful theoretical idea with the potential of exploring the biggest region of unexplored axion parameter space, including two orders of magnitude on the QCD line
- Still much to do on the experimental side (join us!)
- The first prototype to take data (SLAC) is giving very encouraging results

BACKUP

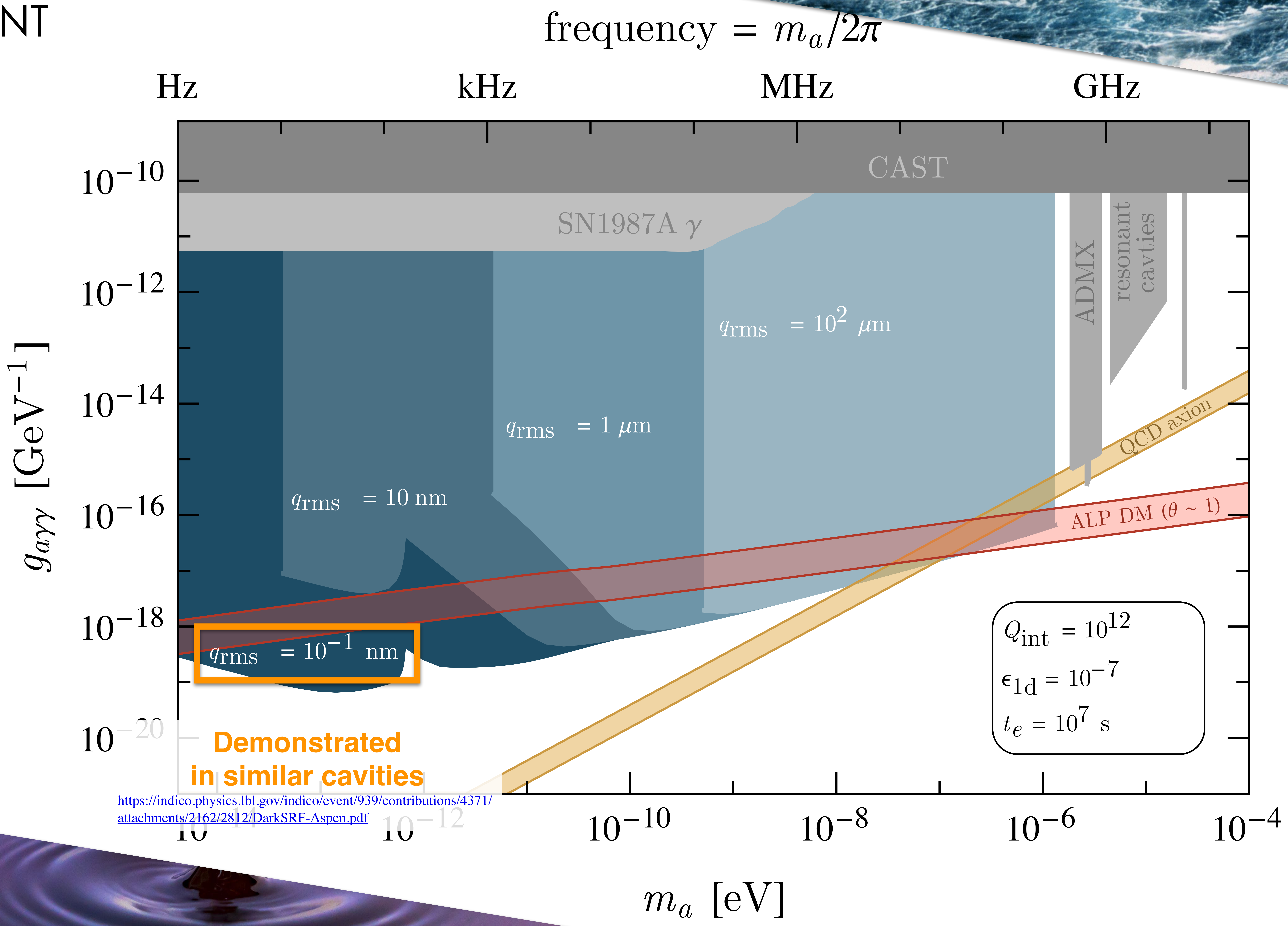
$$E_\phi = -\frac{k_0}{k_\perp}\left(m\frac{k_z}{k_0}\frac{J_m(k_\perp r)}{k_\perp r} + \Lambda J_m'(k_\perp r)\right)\sin m\phi$$

$$E_r = \frac{k_0}{k_\perp}\left(\frac{k_z}{k_0}J_m'(k_\perp r) + m\Lambda\frac{J_m(k_\perp r)}{k_\perp r}\right)\cos m\phi$$

$$H_\phi = \frac{k_0}{\eta_0 k_\perp}\left(J_m'(k_\perp r) + m\frac{k_z}{k_0}\Lambda\frac{J_m(k_\perp r)}{k_\perp r}\right)\cos m\phi\,,$$

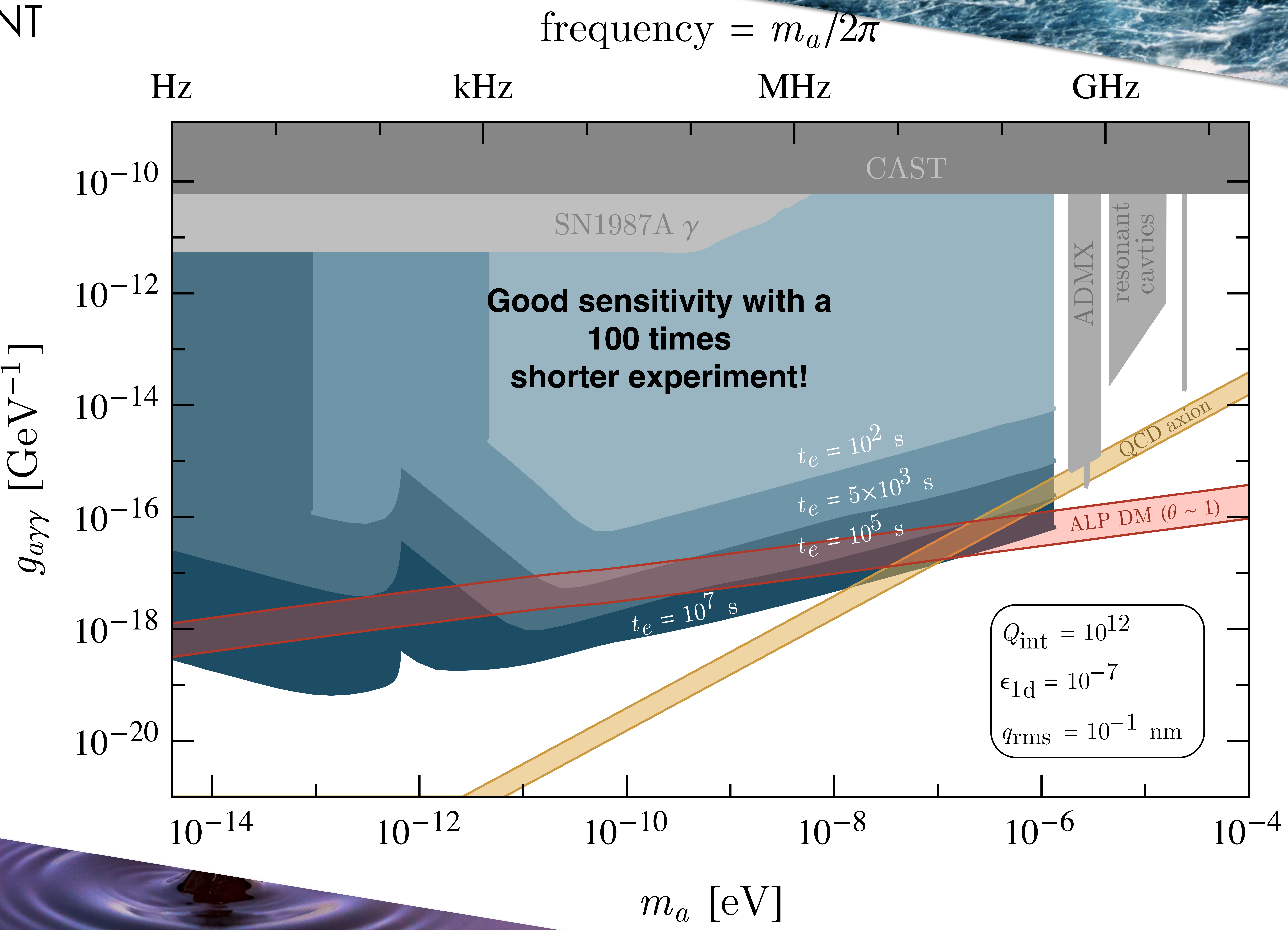
$$H_r = \frac{k_0}{\eta_0 k_\perp}\left(m\frac{J_m(k_\perp r)}{k_\perp r} + \frac{k_z}{k_0}\Lambda J_m'(k_\perp r)\right)\sin m\phi$$

RESONANT



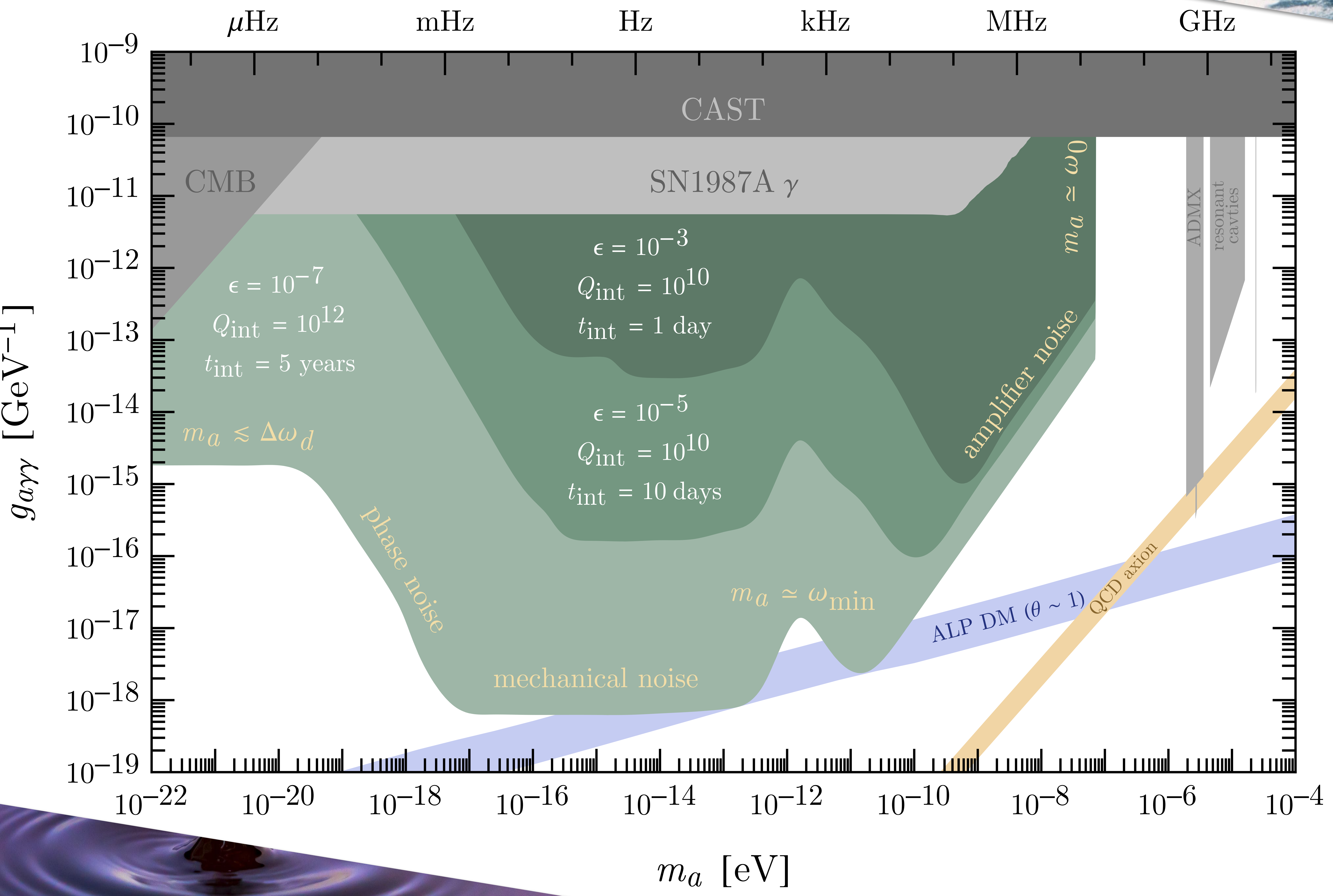
https://indico.physics.lbl.gov/indico/event/939/contributions/4371/attachments/2162/2812/DarkSRF-Aspen.pdf

RESONANT

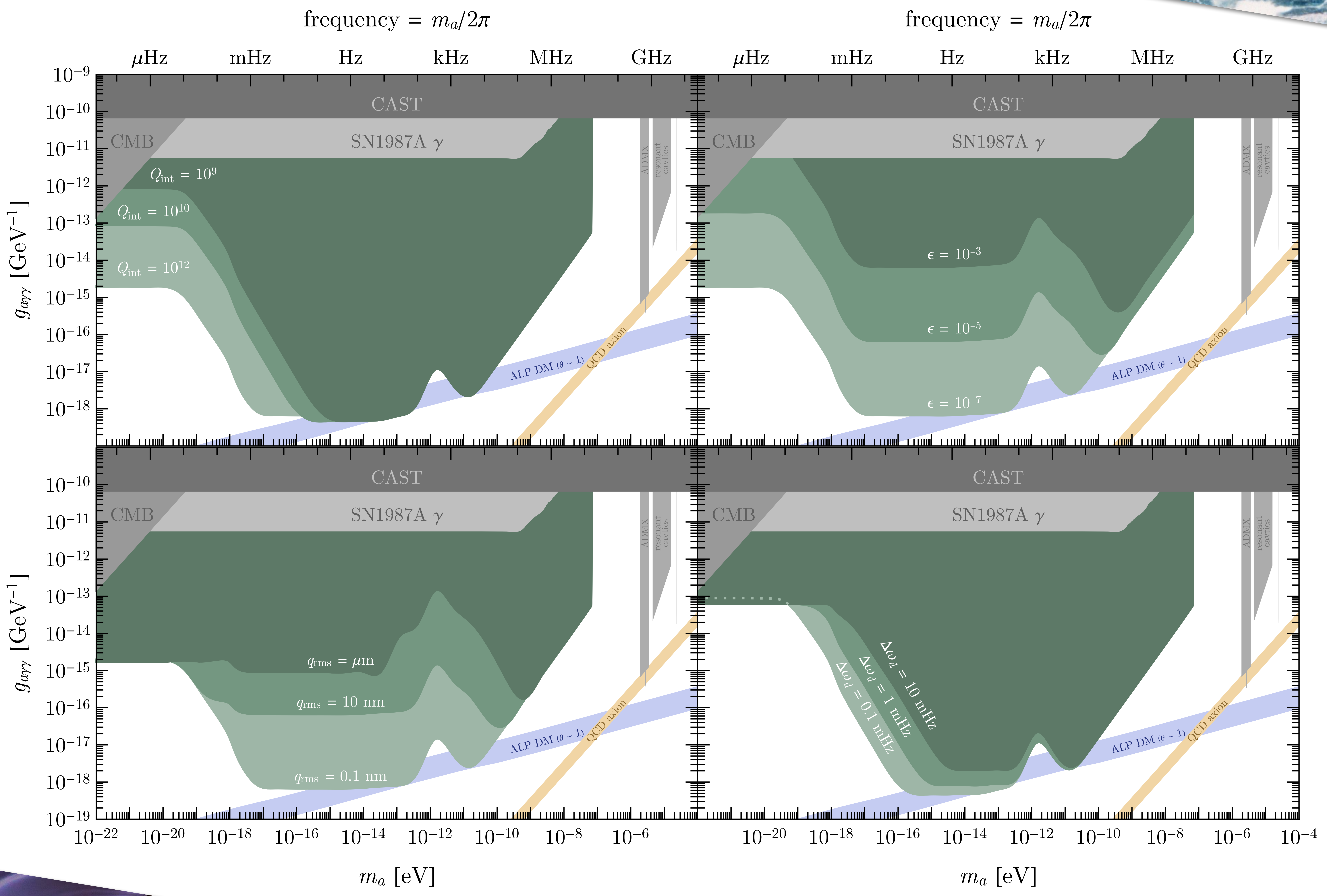


frequency = $m_a/2\pi$
Hz
kHz
MHz
GHz
CAST
SN1987A γ
ADMX
resonant cavties
Good sensitivity with a 100 times shorter experiment!
$t_e = 10^2$ s
$t_e = 5\times10^3$ s
$t_e = 10^5$ s
$t_e = 10^7$ s
QCD axion
ALP DM ($\theta \sim 1$)
$Q_{\rm int} = 10^{12}$
$\epsilon_{\rm 1d} = 10^{-7}$
$q_{\rm rms} = 10^{-1}$ nm
$g_{a\gamma\gamma}$ [GeV^{-1}]
m_a [eV]
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}

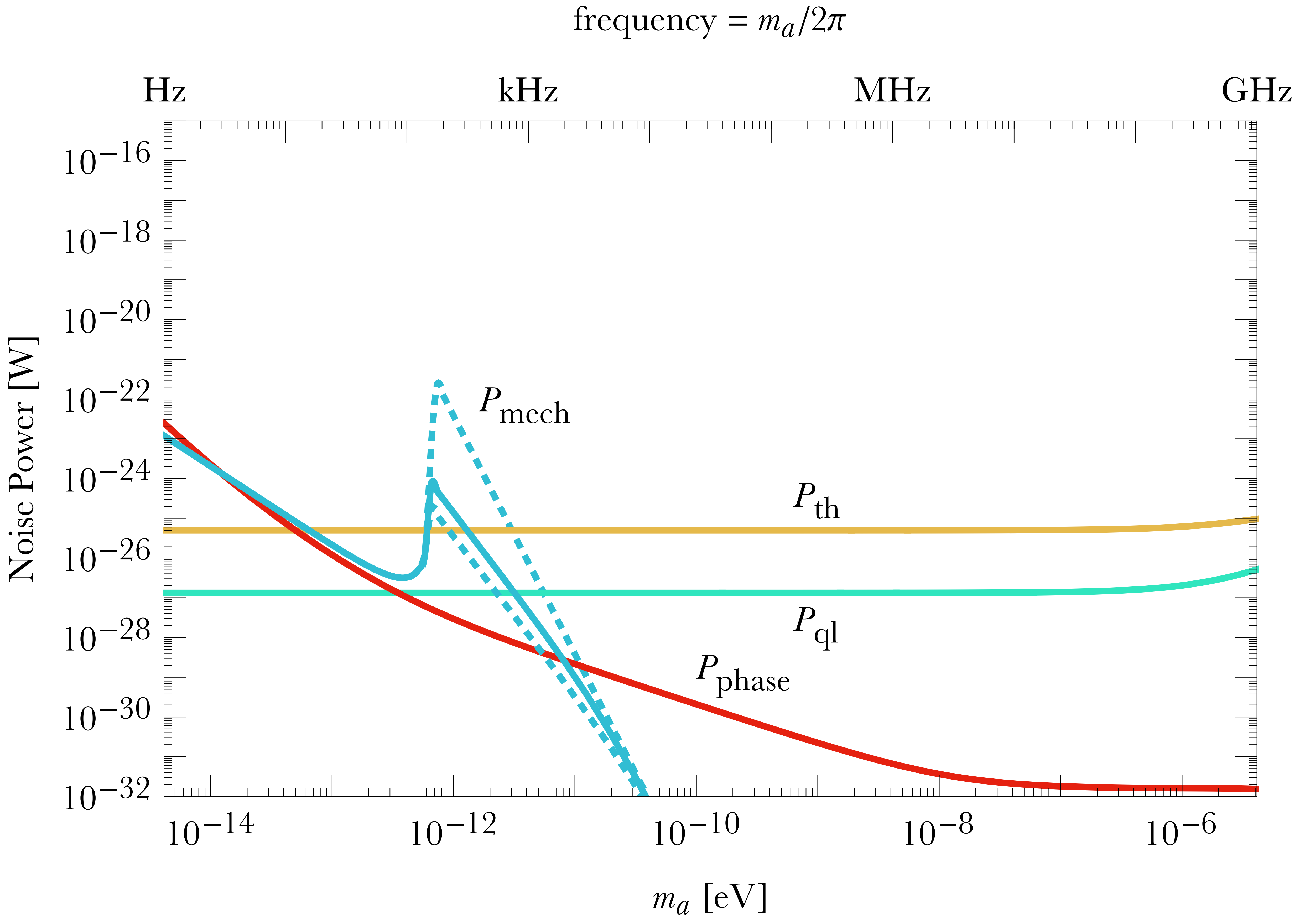
A.Berlin, RTD, S. Ellis, K. Zhou 2007.15656

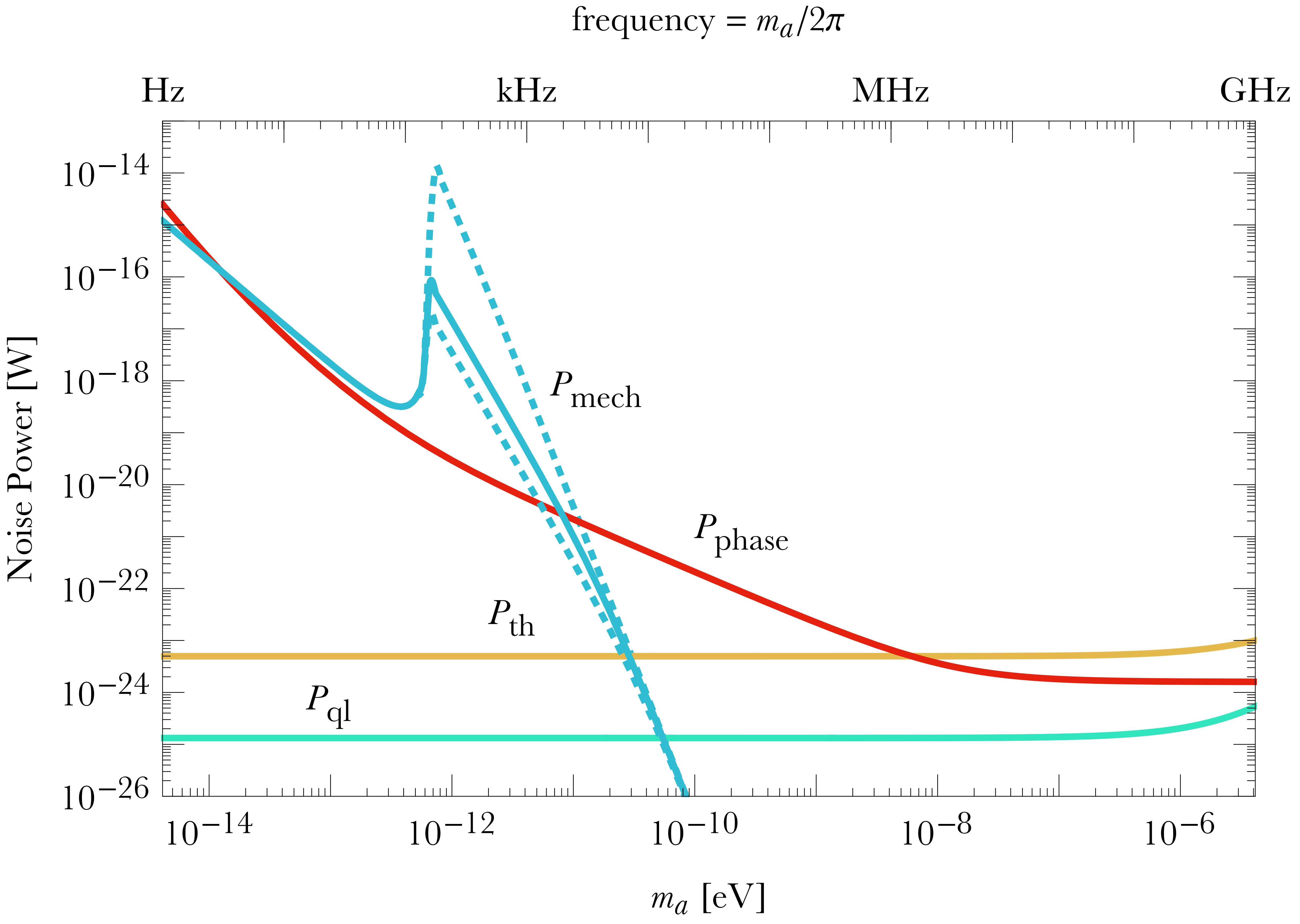


A.Berlin, RTD, S. Ellis, K. Zhou 2007.15656



NOISE PSDs



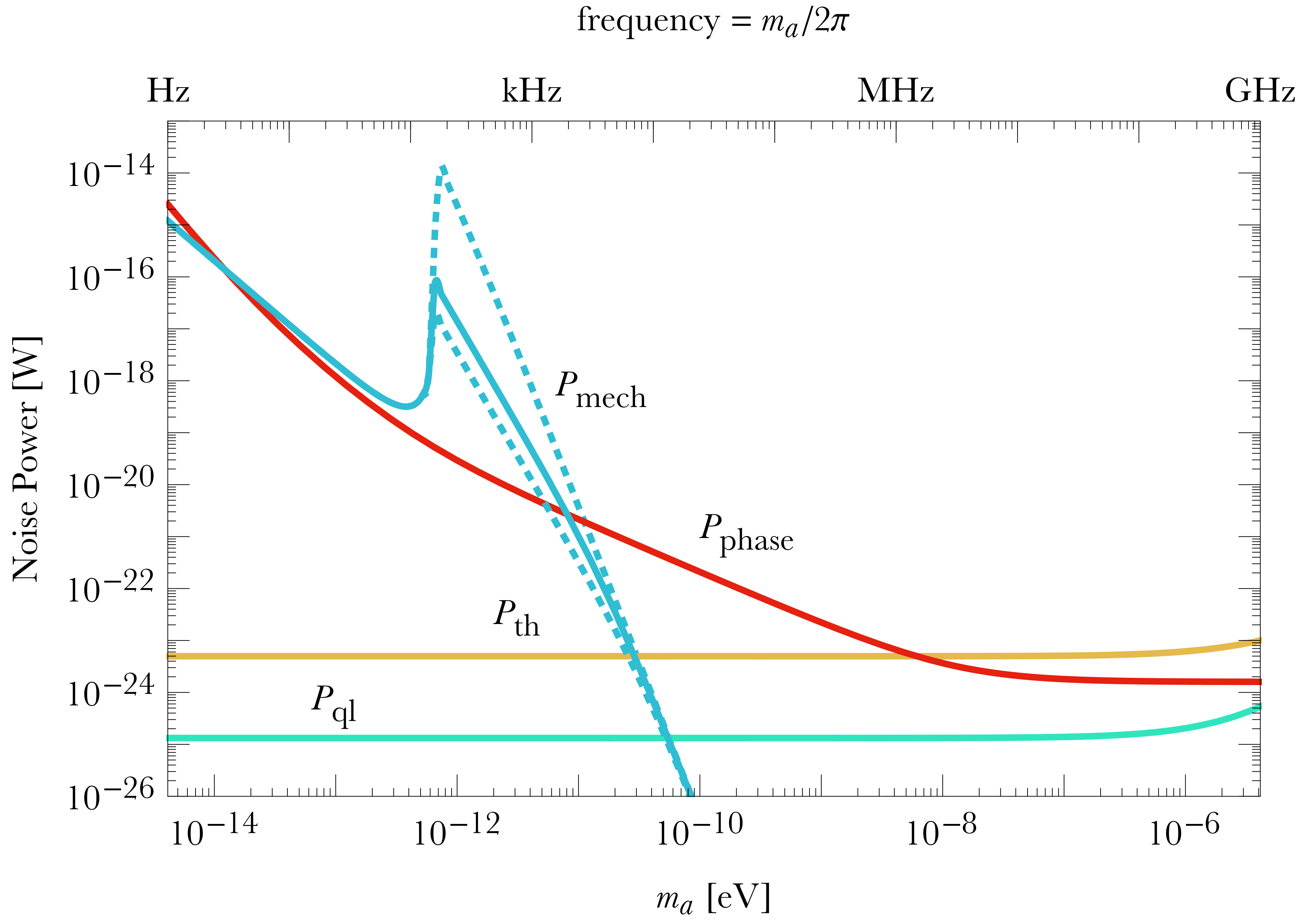


$$\epsilon_{1d} = 10^{-7}, \quad Q = 10^{12}$$

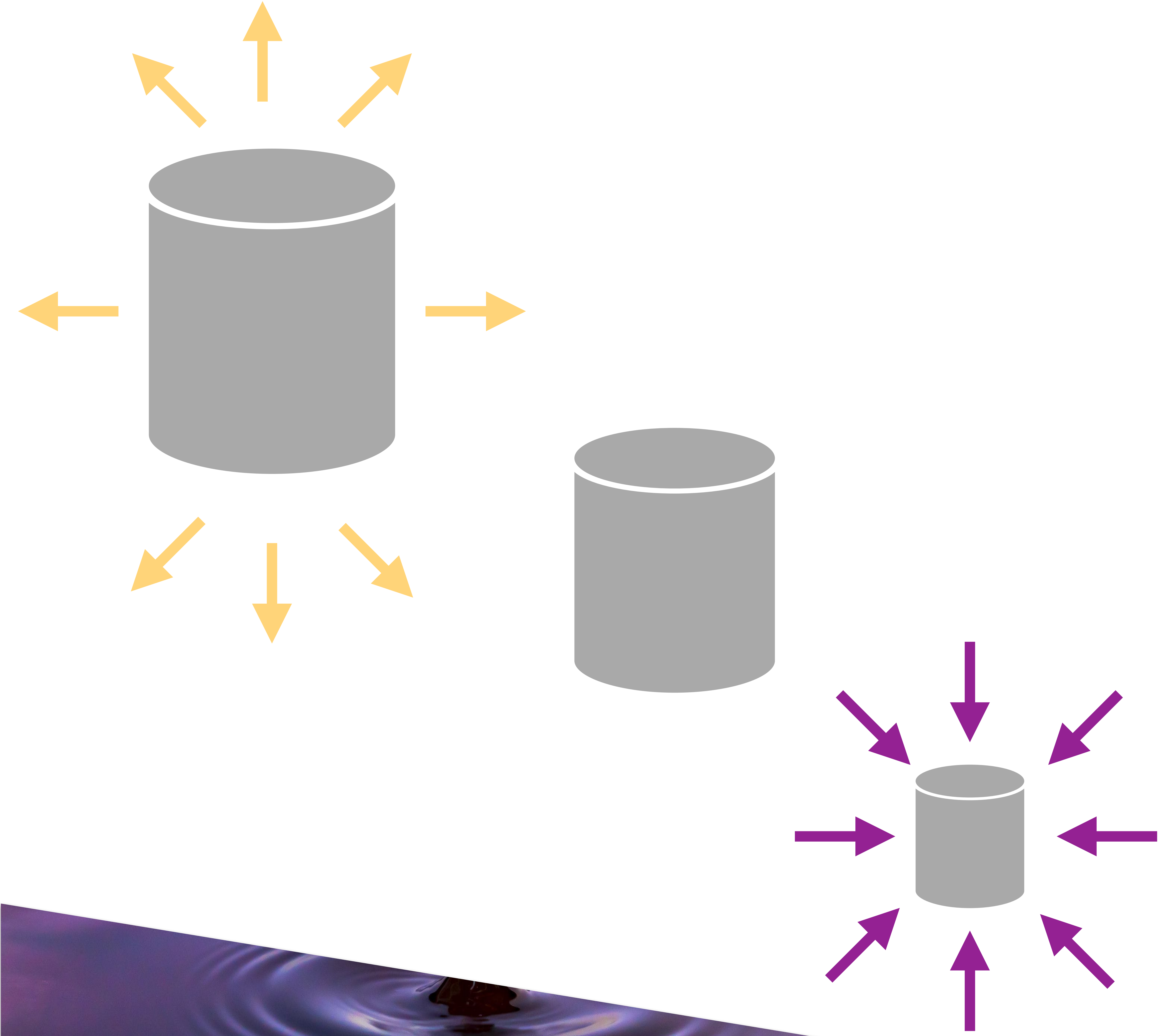
$$\epsilon_{1d} = 10^{-5}, \quad Q = 10^{10}$$

NOISE PSDs

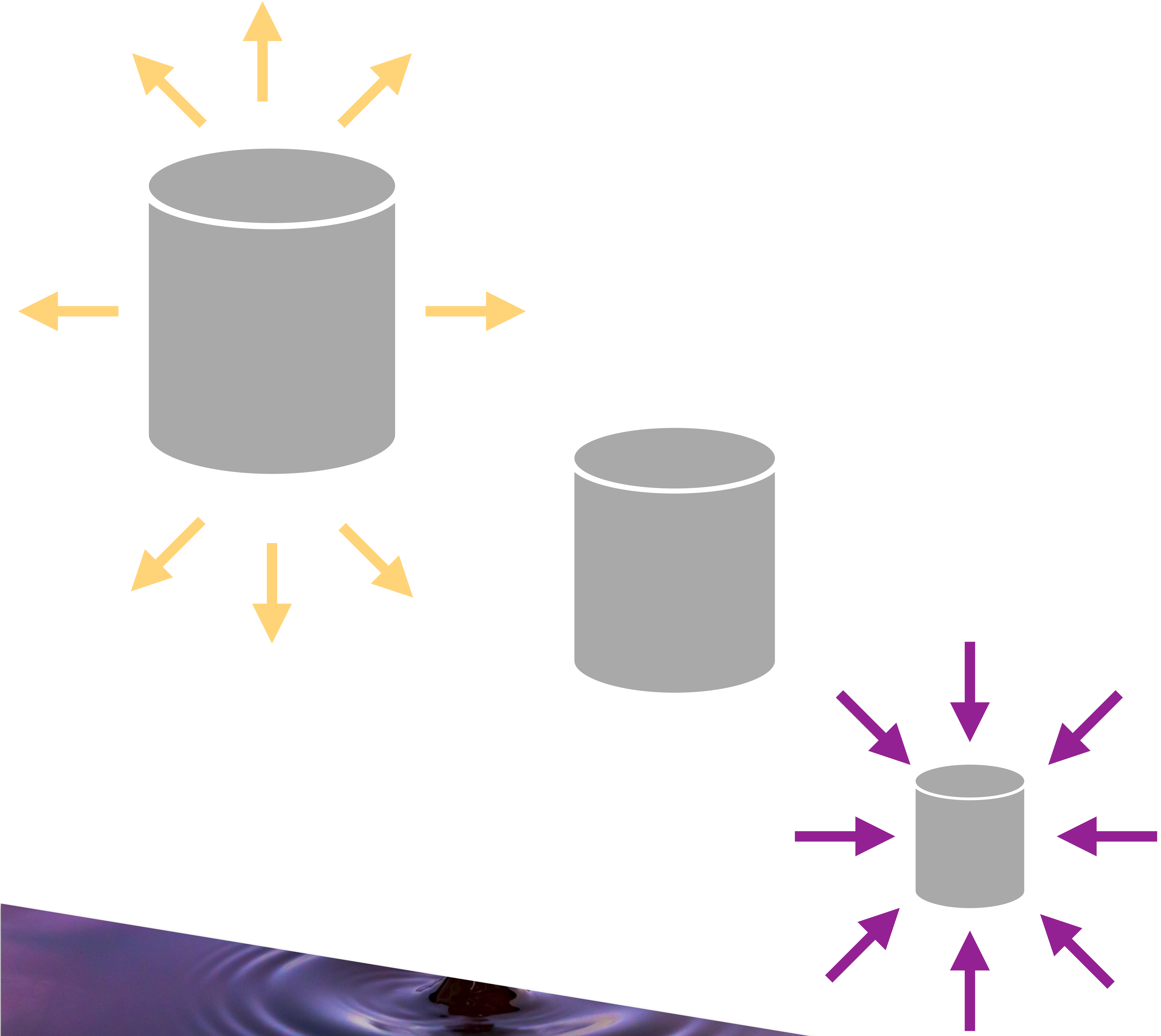
We bound the total power in mechanical noise for by considering two cases: where the axion mass is situated at or near a local maximum of the noise PSD or at a local minimum (ma at the midpoint between two adjacent resonances, i.e., assuming a typical separation of ~ 100 Hz between mechanical resonances, at 50 Hz separation from each). The total mechanical noise powers obtained in these two extreme cases, illustrated by dashed curves, define an envelope for the mechanical noise power at each scan step. The noise power only approaches the upper envelope in narrow regions of size Δωm about each resonance



$$\epsilon_{1d} = 10^{-5}, \quad Q = 10^{10}$$

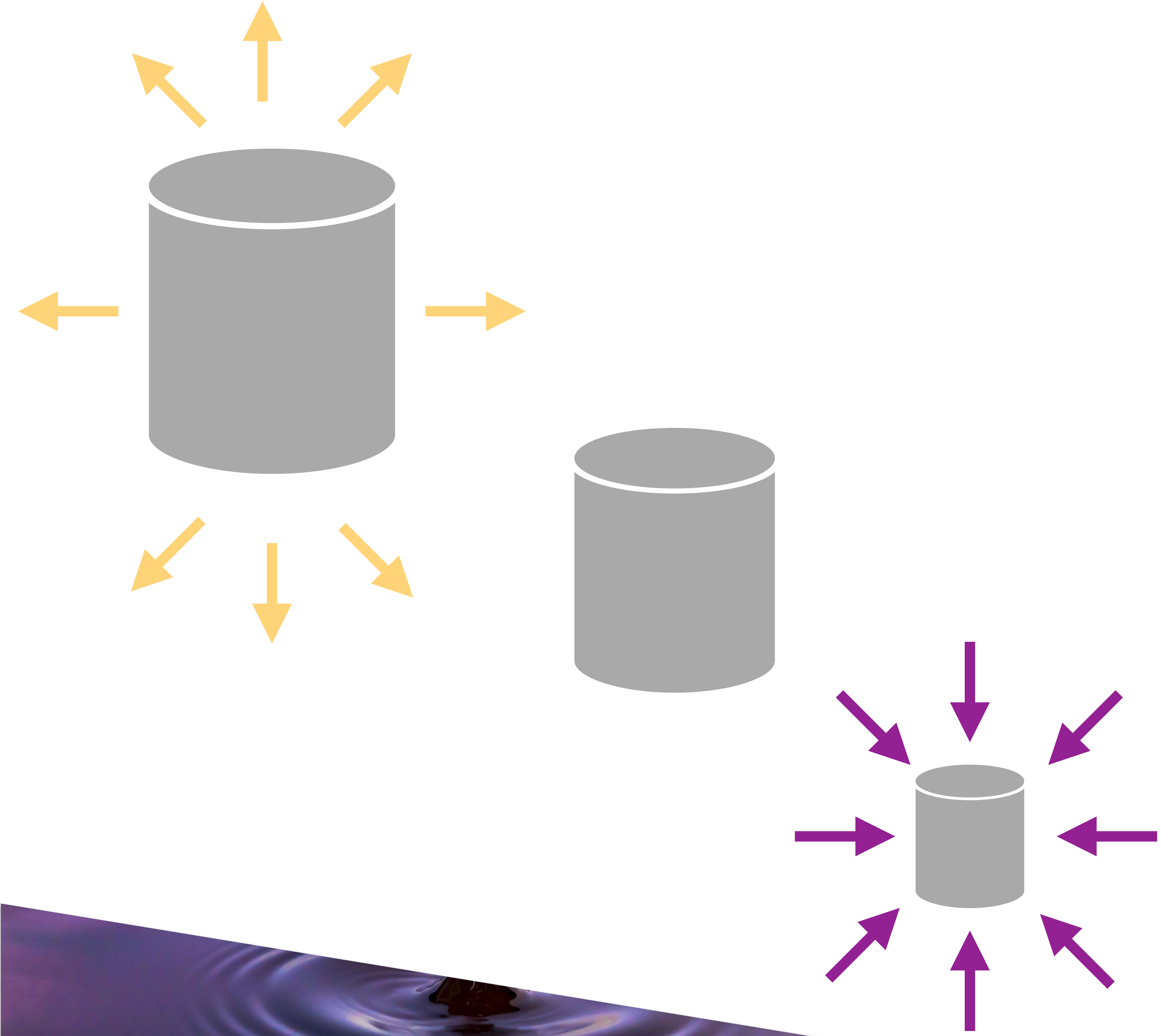


$$\delta\omega_n \simeq -\frac{1}{2} q_m C_n^m \omega_n$$



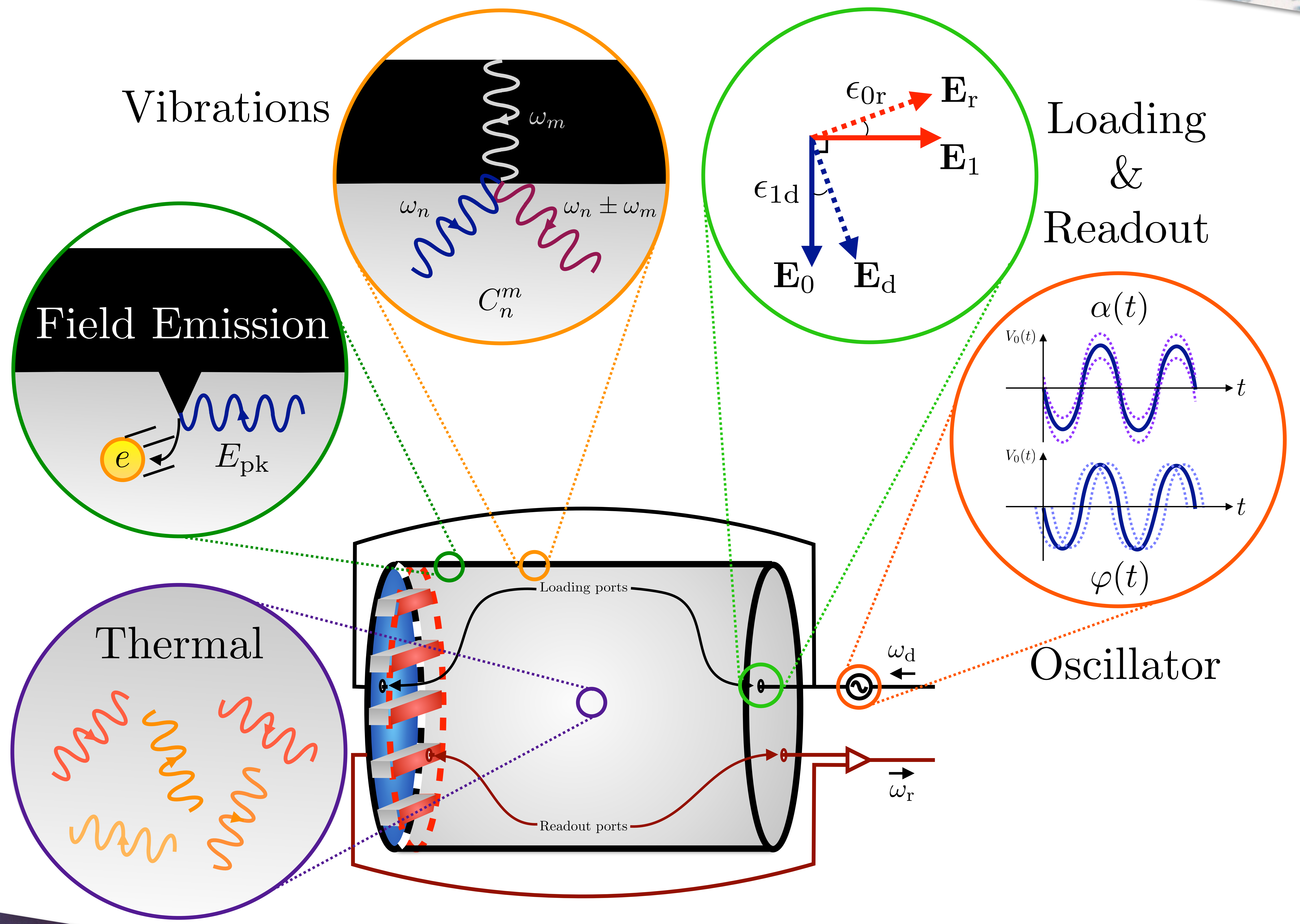
$$\delta\omega_n \simeq -\frac{1}{2} q_m C_n^m \omega_n$$

$$\langle q_m^2 \rangle \simeq \frac{S_{f_m}(\omega_m) Q_m}{4\pi M \omega_m^3}$$



MAGO
Measured the force PSD around kHz
We conservatively took it flat up to GHz

$$\langle q_m^2 \rangle \simeq \frac{S_{f_m}(\omega_m) Q_m}{4\pi M \omega_m^3}$$

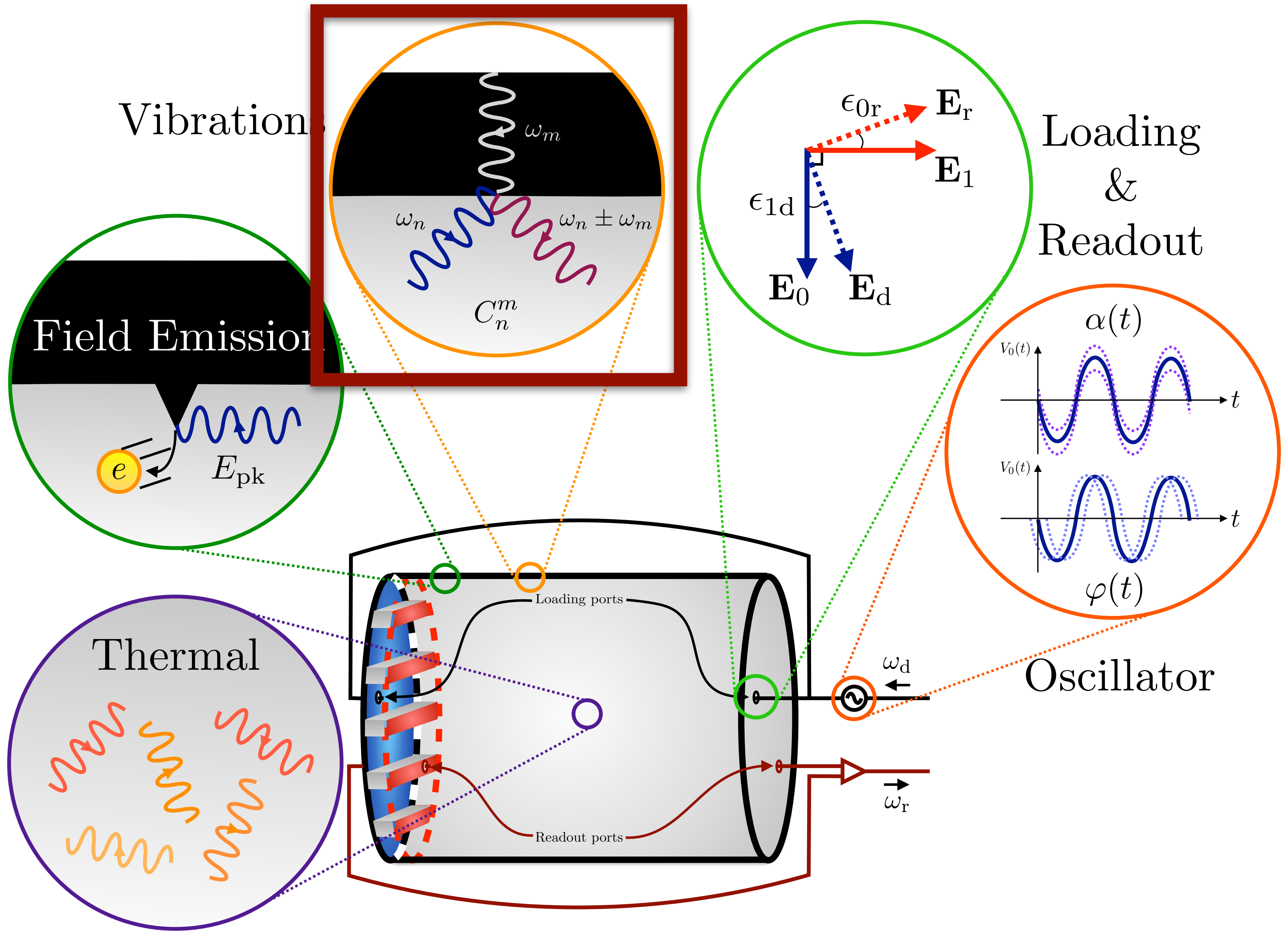


Vibrations
ω_m
ω_n
$\omega_n \pm \omega_m$
C_n^m
ϵ_{0r}
$\mathbf{E}_r$
$\mathbf{E}_1$
ϵ_{1d}
$\mathbf{E}_0$
$\mathbf{E}_d$
Loading
&
Readout
Field Emission
e
E_{pk}
$\alpha(t)$
$V_0(t)$
t
$\varphi(t)$
Thermal
Loading ports
Readout ports
ω_d
ω_r
Oscillator

VIBRATIONAL NOISE

Wall Displacement

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



External Force

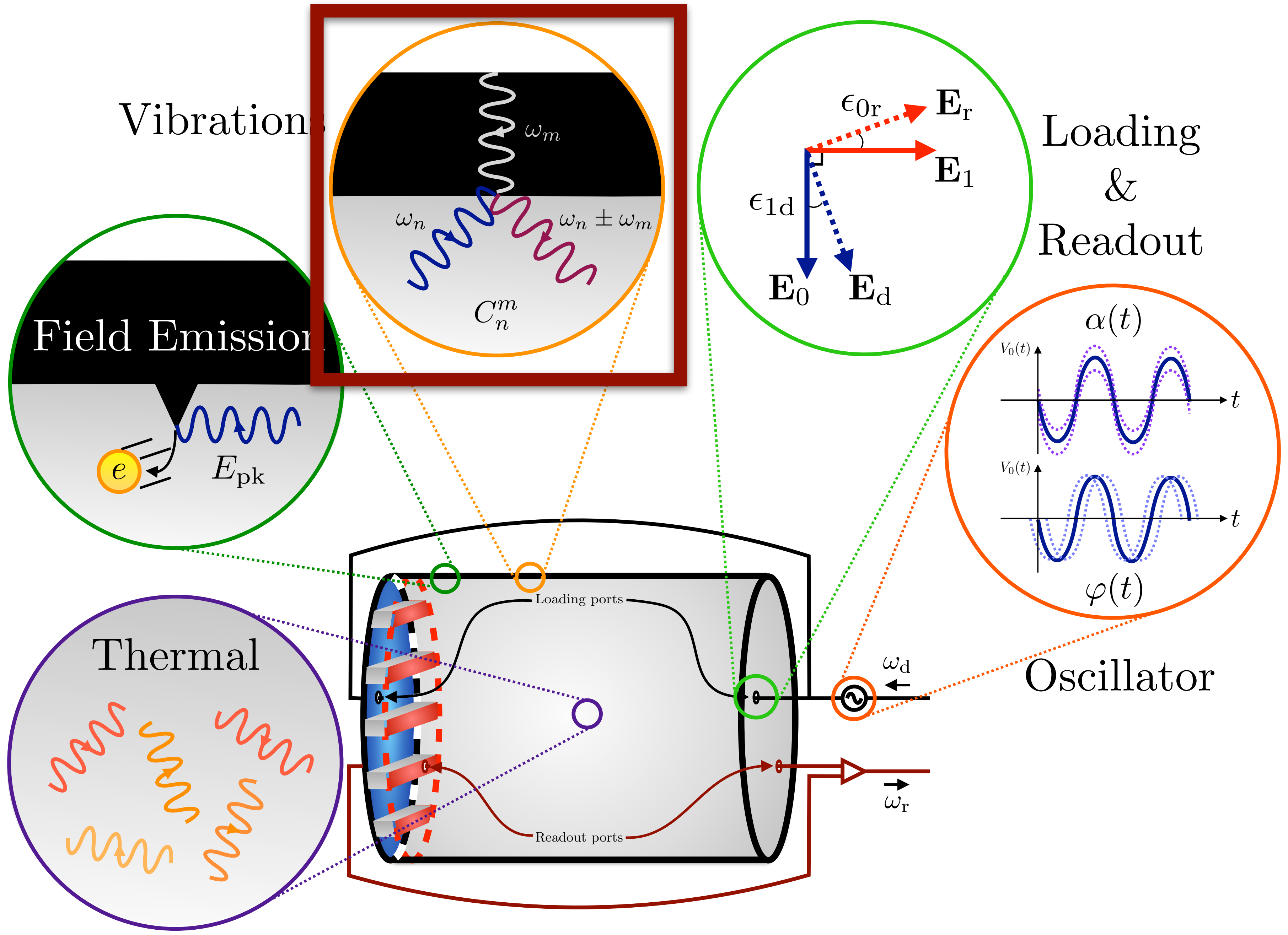
$$S_{q_m}(\omega) \simeq \frac{1}{M^2}\frac{S_{f_m}(\omega)}{(\omega^2-\omega_m^2)^2+(\omega_m\omega/Q_m)^2}$$

$$\omega_m^{\rm min} \simeq {\rm kHz}$$

Class.Quant.Grav. 20 (2003) 3505-3522, gr-qc/0502054

VIBRATIONAL NOISE

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



External Force

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

We assumed that for every axion mass > kHz there is a corresponding resonant mechanical mode that is maximally coupled to the electromagnetic properties of the cavity. An OVERLY PESSIMISTIC assumption.

LEAKAGE NOISE

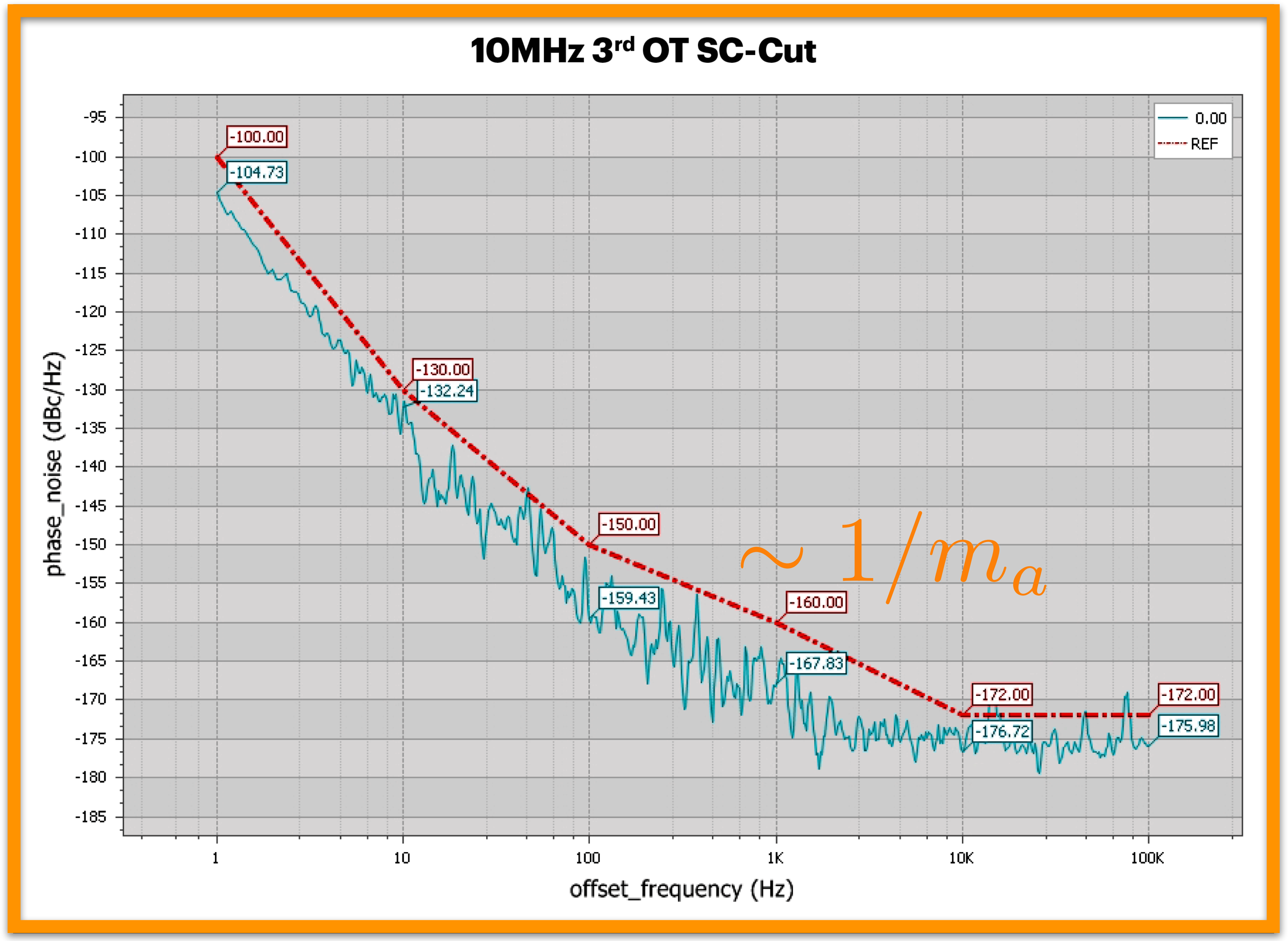
$$S_{\text{phase}}(\omega) \simeq \frac{1}{2}\,\epsilon_{1\text{d}}^2\,S_\phi(\omega-\omega_0)\,\boxed{\frac{(\omega\,\omega_1/Q_1)^2}{(\omega^2-\omega_1^2)^2+(\omega\,\omega_1/Q_1)^2}}\,\frac{\omega_0 Q_1}{\omega_0 Q_0}\,P_{\text{in}}$$

Cavity Response

LEAKAGE NOISE

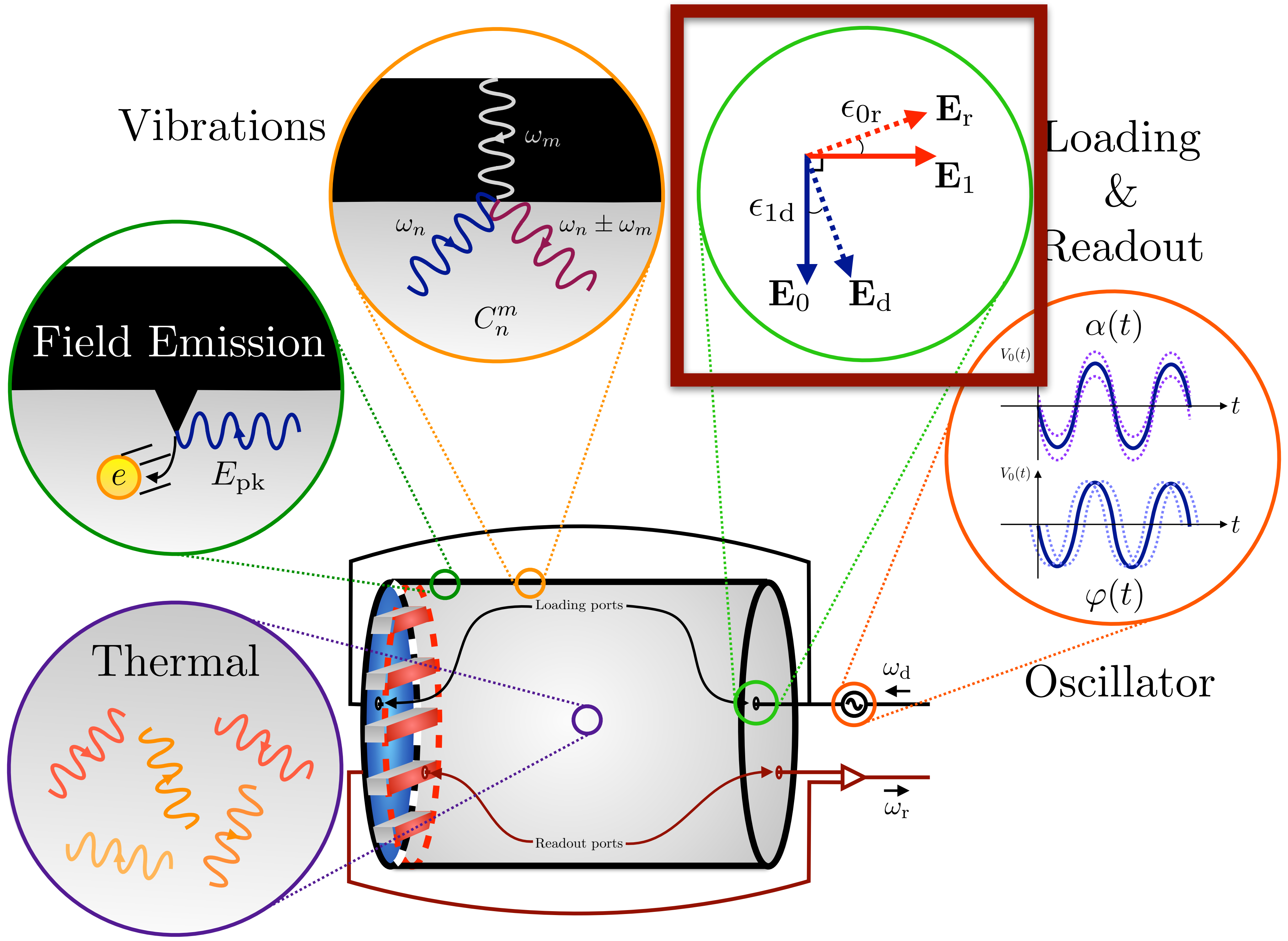
$$S_{\text{phase}}(\omega) \simeq \frac{1}{2}\,\epsilon_{1\text{d}}^2\, \boxed{S_\phi(\omega-\omega_0)}\, \frac{(\omega\,\omega_1/Q_1)^2}{(\omega^2-\omega_1^2)^2+(\omega\,\omega_1/Q_1)^2}\, \frac{\omega_0 Q_1}{\omega_0 Q_0}\, P_{\text{in}}$$

$\sim 1/m_a$



LEAKAGE NOISE

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



From MAGO
and other similar cavities

OVERCOUPLING

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

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

Overcoupling can enlarge the scan step, keeping the SNR fixed

EXISTING PROTOTYPE

MAGO '05

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INFN and Scuola Normale Superiore, Pisa, Italy and CERN, Geneva, Switzerland

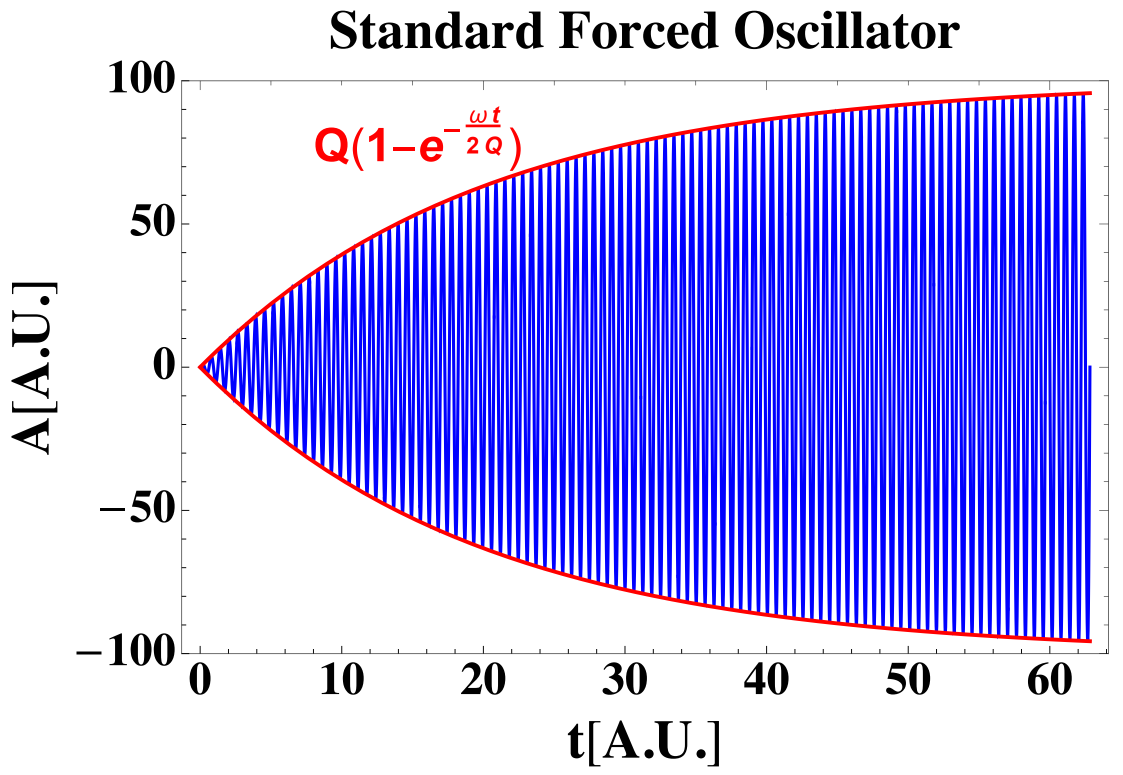
Power = Energy/Time

Time

$$\min[\tau_a, \tau_r] = \min\left[\frac{Q_a}{m_a}, \frac{Q_1}{\omega_1}\right]$$

$$t = \tau_a = \frac{Q_a}{m_a}$$ **Axion stops being monochromatic**

$$t = \tau_r = \frac{Q_1}{\omega_1}$$ **Steady State**



Power = Energy/Time

Energy

$$\omega_1^2 B_a^2 V \min\left[\frac{Q_a^2}{m_a^2}, \frac{Q_1^2}{\omega_1^2}\right]$$

Time

$$\min[\tau_a, \tau_r] = \min\left[\frac{Q_a}{m_a}, \frac{Q_1}{\omega_1}\right]$$

Static: $\omega_1 \simeq m_a$

$$P \simeq m_a B_a^2 V \min[Q_a, Q_1]$$

Naively no reason to build resonators with Q > 10^6

Power = Energy/Time

Energy

$$\omega_1^2 B_a^2 V \min\left[\frac{Q_a^2}{m_a^2}, \frac{Q^2}{\omega_1^2}\right]$$

Time

$$\min[\tau_a, \tau_r] = \min\left[\frac{Q_a}{m_a}, \frac{Q_1}{\omega_1}\right]$$

Oscillating: $\omega_1 > m_a$

$$P \simeq \omega_1 B_a^2 V \min[Q_a(\omega_1/m_a), Q_1]$$

Great advantage of high-Q resonators at low m_a

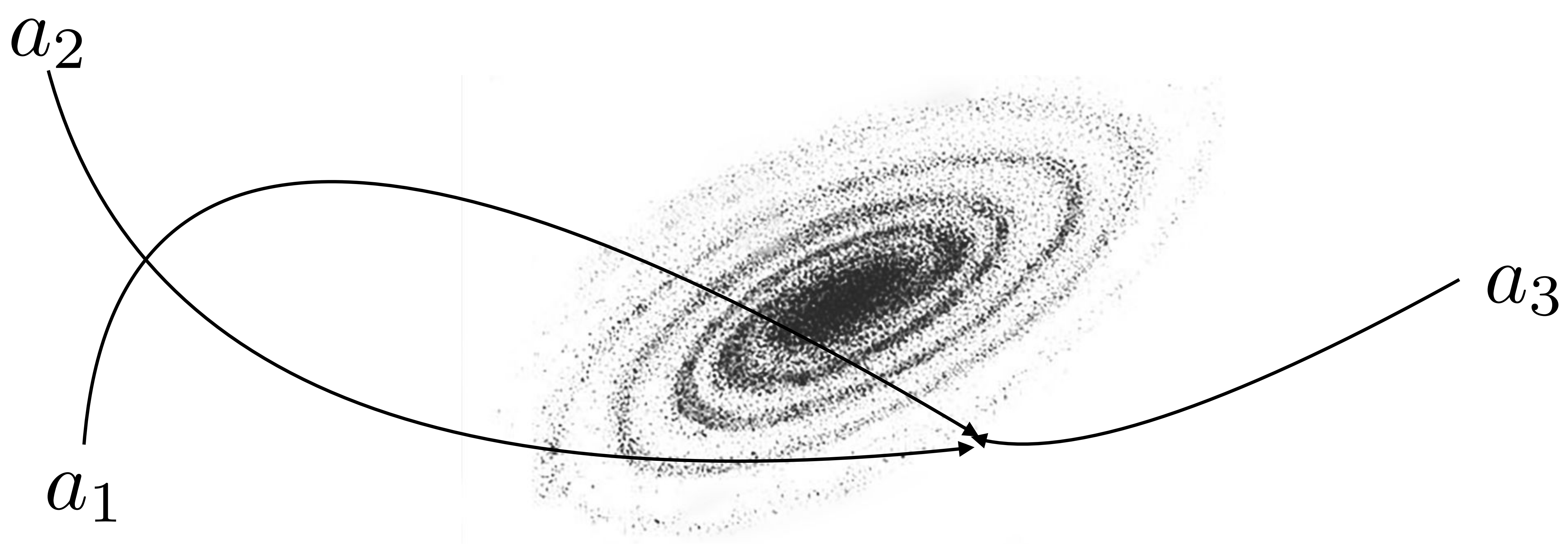
Dark Matter Particles in a de Broglie Volume **Today**

Galaxy: $$N_{\rm DM} \simeq 10^{3} \left(\frac{\rm eV}{m_{\rm DM}}\right)$$

Universe: $$N_{\rm DM} \simeq 10^{-3} \left(\frac{\rm eV}{m_{\rm DM}}\right)$$

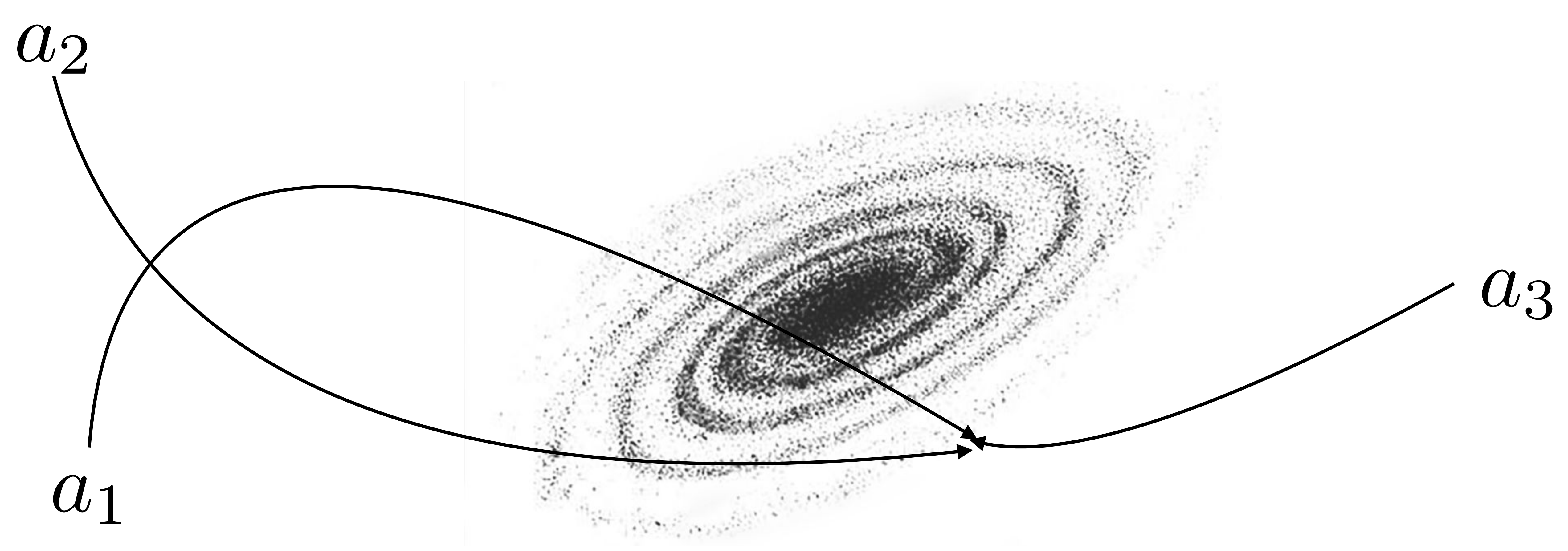
ALP DARK MATTER IN THE LAB

In each experimental bin we are summing over a multitude of plane waves with different phases



ALP DARK MATTER IN THE LAB

In each experimental bin we are summing over a multitude of plane waves with different phases



$$a(t) = a_0 \left[\cos\left(m_a \left(1 + \frac{v_1^2}{2}\right) t + \phi_1 \right) + \cos\left(m_a \left(1 + \frac{v_2^2}{2}\right) t + \phi_2 \right) + \ldots \right]$$

$$\simeq a_0 \cos(m_a t + \phi) \left[\cos(\delta\omega_a t + \phi') + \ldots \right]$$

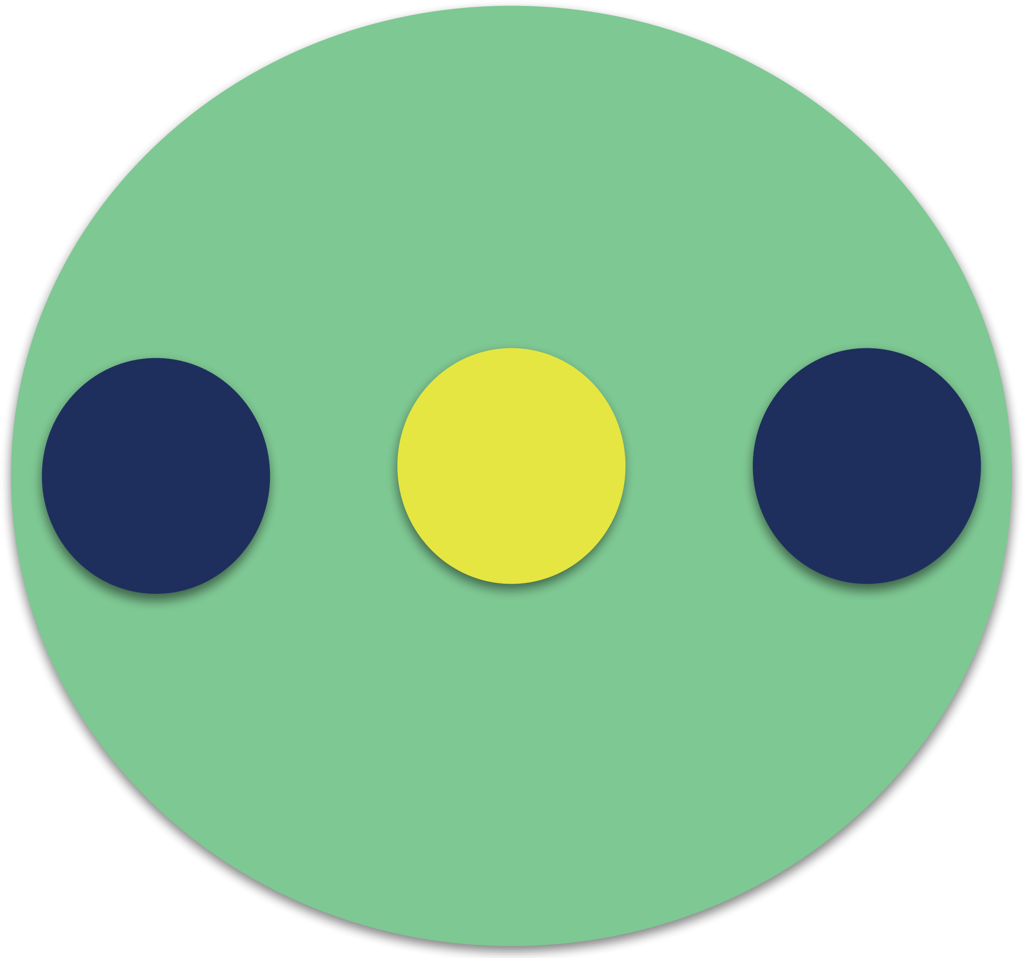
$$\delta\omega_a \simeq \frac{1}{m_a \langle v_{\mathrm{DM}}^2 \rangle} \simeq \frac{10^6}{m_a}$$

Effectively: very **slow modulation of** an approximately **monochromatic field**

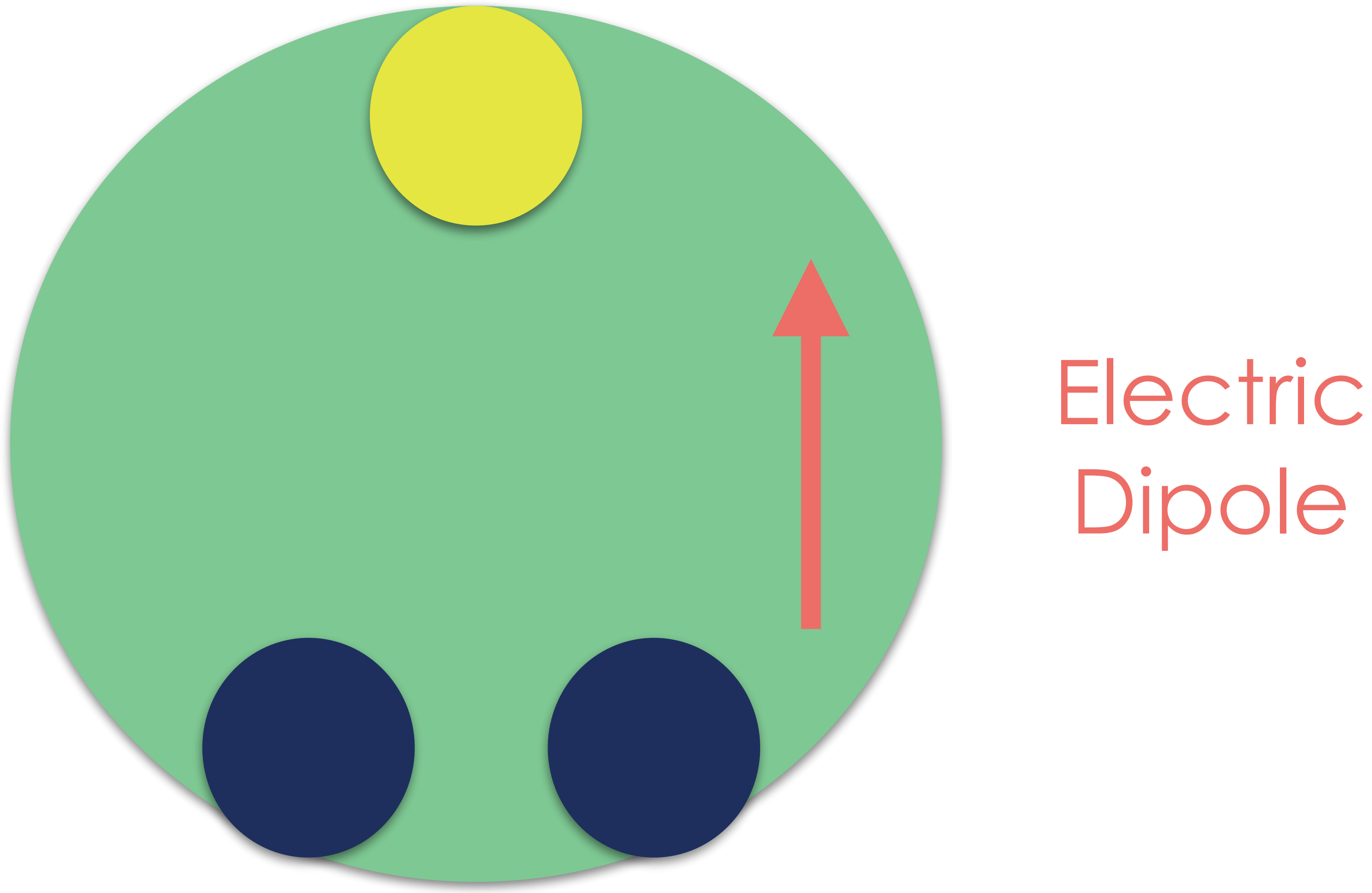
ULTRALIGHT AXION-LIKE DARK MATTER

$$\theta G\tilde{G}$$

Neutron $\theta = 0$



Neutron $\theta \neq 0$



$$|\theta| \lesssim 10^{-10}$$ **Experimentally**

Introduce a new **global symmetry at fa**

$$\theta G\tilde{G} \longrightarrow \left(\theta + \frac{a}{f_a}\right) G\tilde{G}$$

At the minimum

$$\langle a \rangle = -\theta f_a$$

QCD Phase Transition

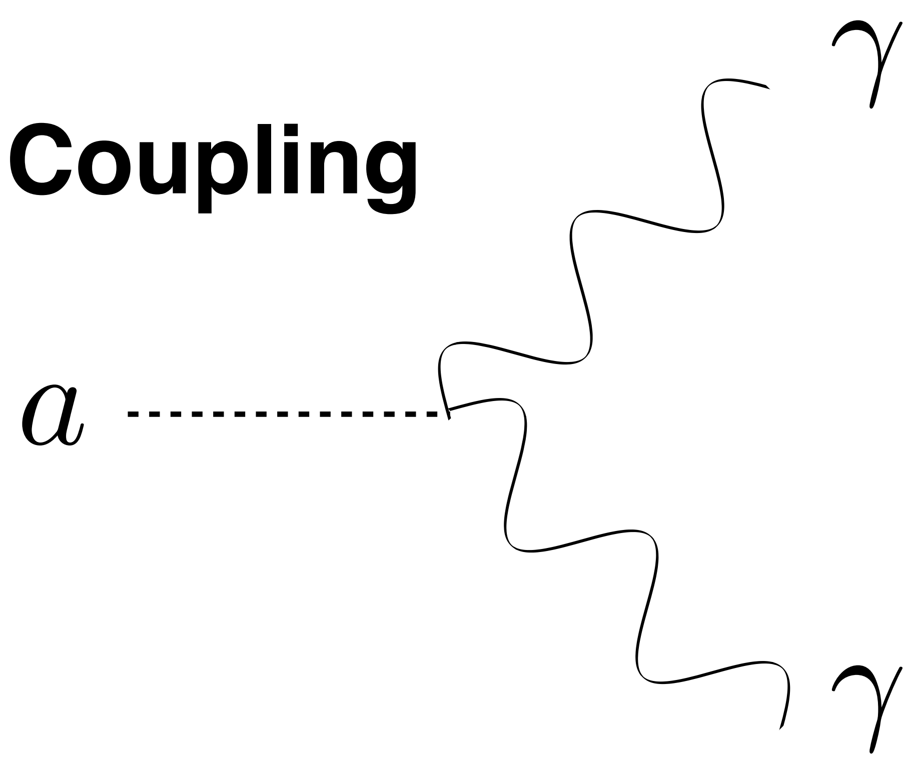
$$\frac{a}{f_a} G\tilde{G} \longrightarrow \frac{a}{f_a}\frac{\pi}{f_\pi} + \ldots$$

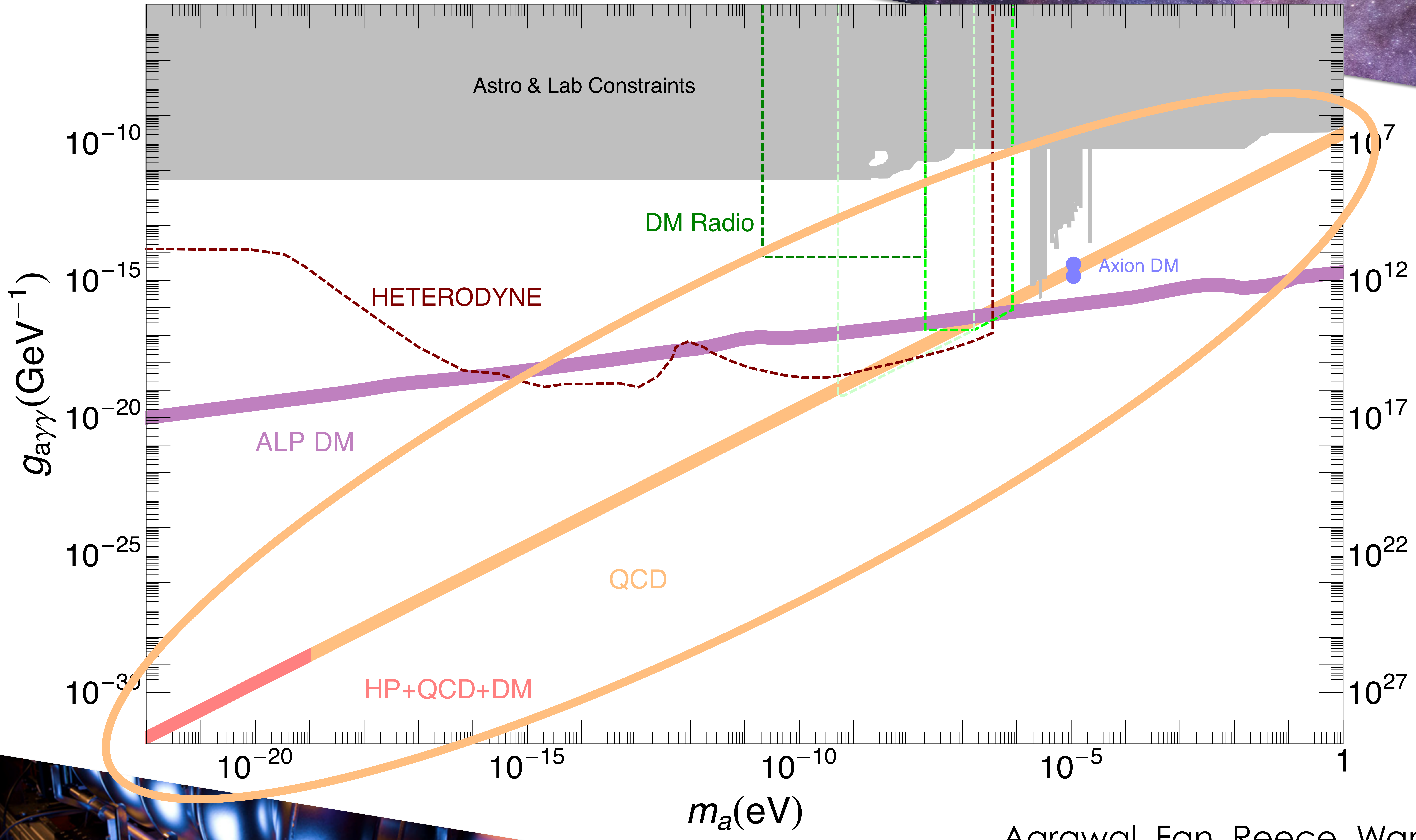
Mass

$$m_a \sim \frac{m_\pi^2}{f_a} \sim 10^{-2}\ \mathrm{eV}\ \frac{10^9\ \mathrm{GeV}}{f_a}$$

Relevant Coupling

$$\frac{a}{f_a}\mathbf{E}\cdot\mathbf{B}$$





Agrawal, Fan, Reece, Wang '18