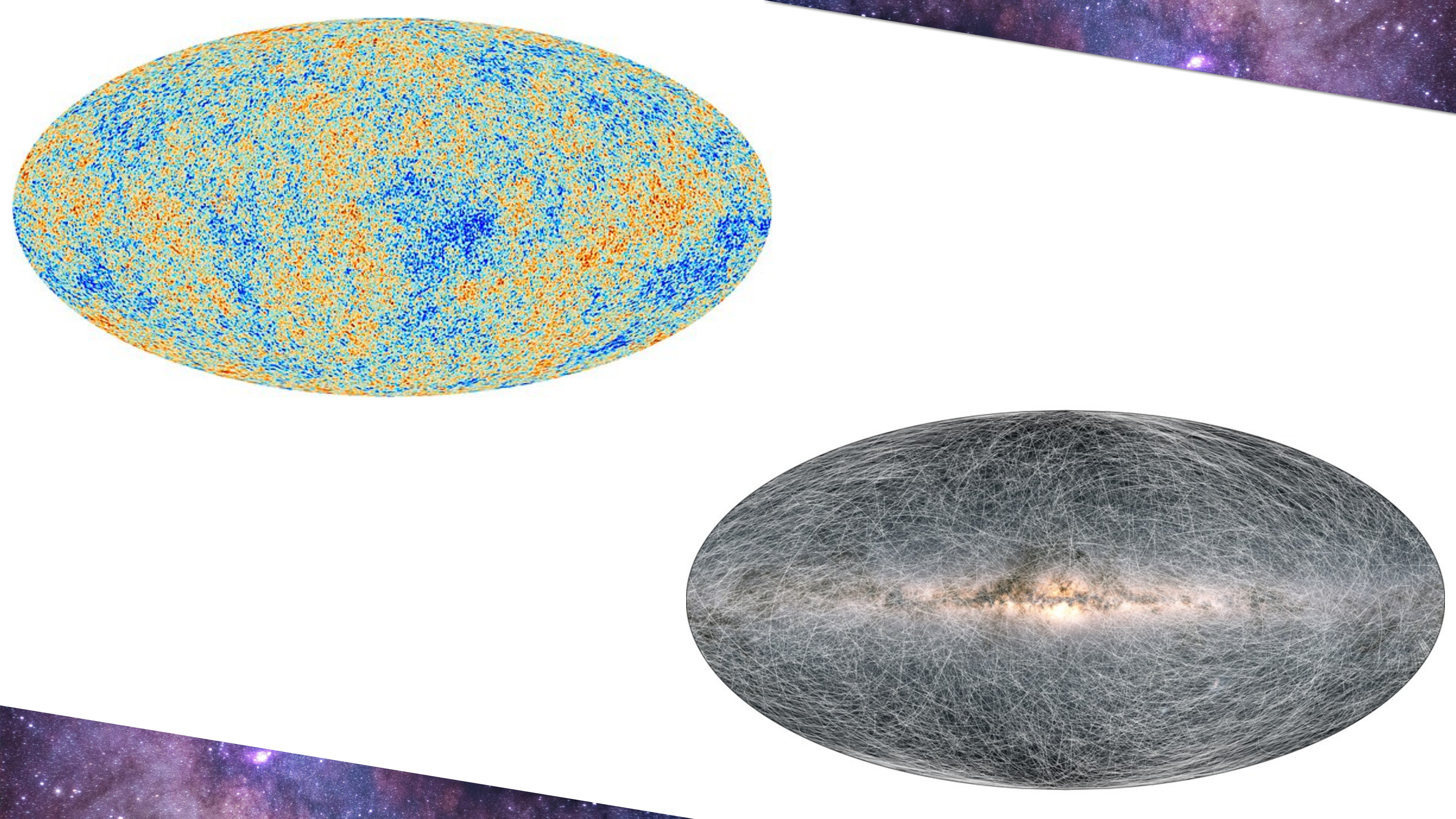


WAVES IN A BOX: RESONANT CAVITIES FOR AXION AND GW DETECTION



Raffaele Tito D'Agnolo - CEA IPhT Saclay

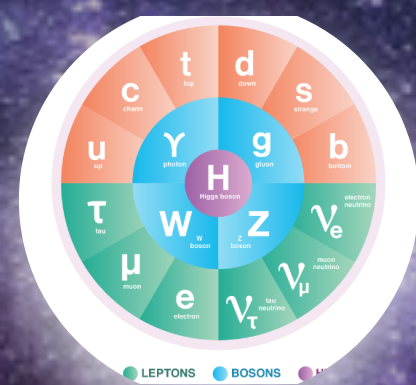


DARK MATTER MASS

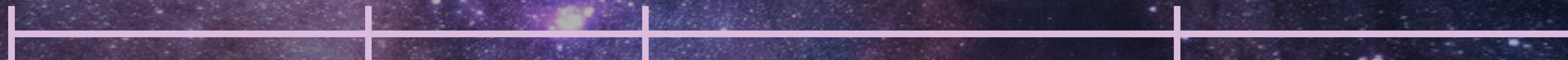
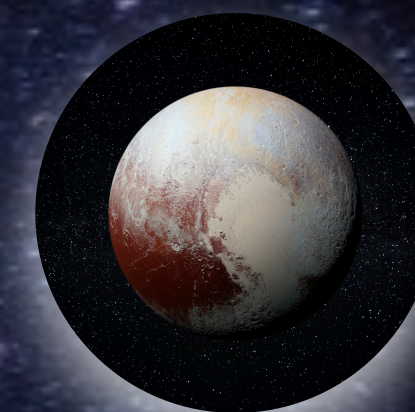


one order of magnitude

DARK MATTER MASS



Person



Neutrino

Higgs



Pluto

Self-coupling

50 O.M.

Mass

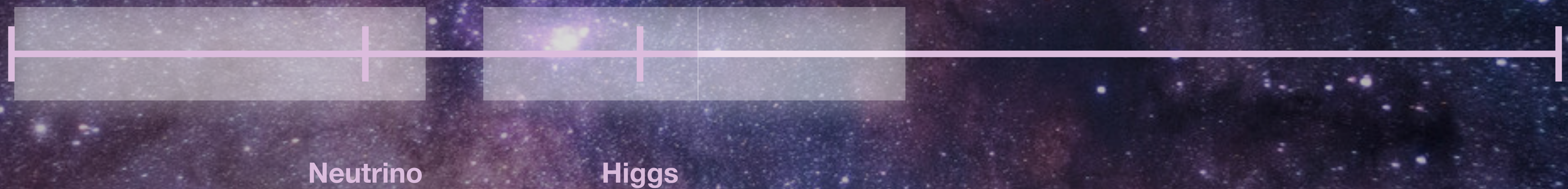
50 O.M.

80 O.M.

Couplings to ordinary matter



DARK MATTER MASS

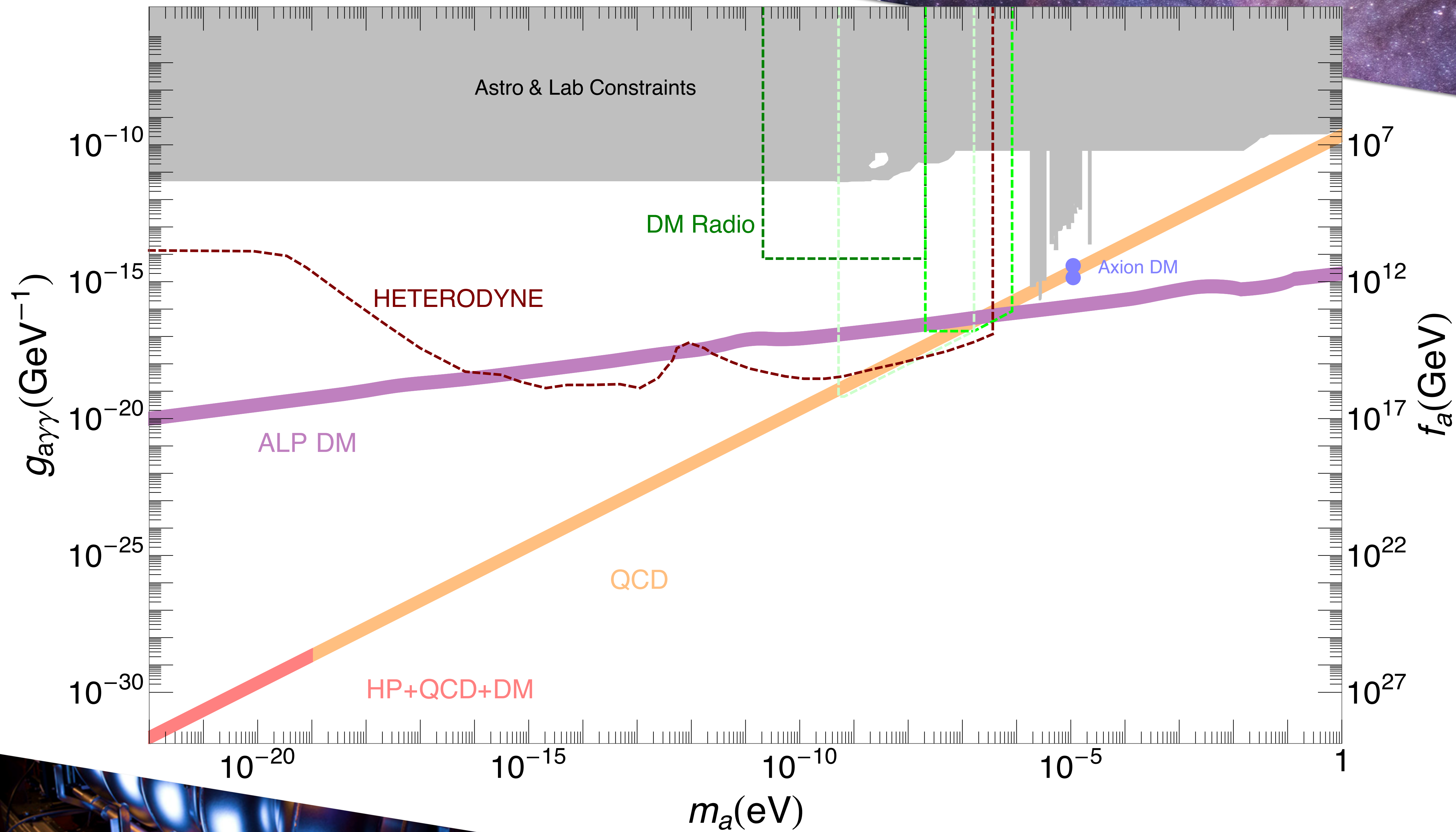


Theory Spotlight

DARK MATTER MASS



Theory Spotlight





ω_g

10 Hz

kHz

LIGO-VIRGO



ω_g

nHz

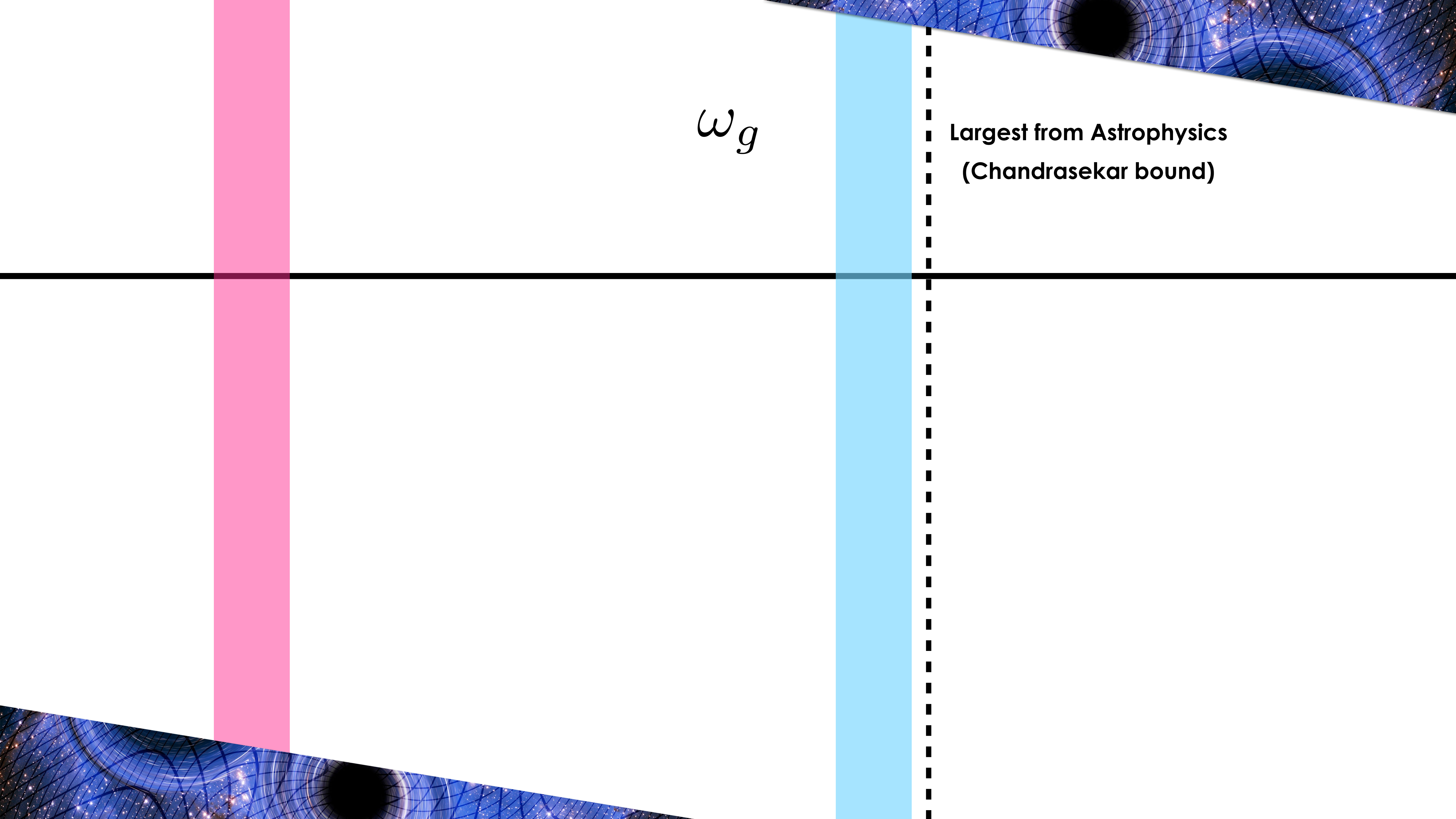
μ Hz

10 Hz

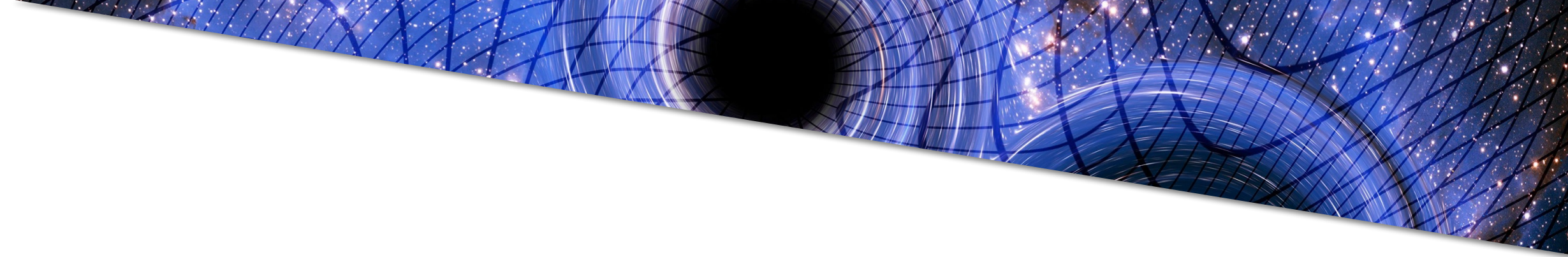
kHz

PULSAR TIMING

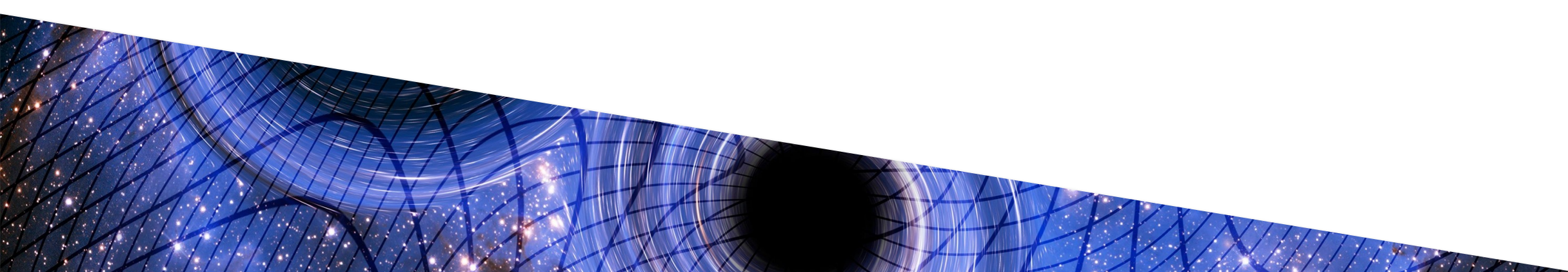
LIGO-VIRGO

A diagram illustrating spacetime curvature around a black hole. A central black circle represents the event horizon. Blue grid lines represent the fabric of spacetime, which is distorted and curved by the gravity of the black hole. The grid lines are denser and more curved near the black hole, indicating stronger gravity. The background is a dark blue space filled with stars.
$$\omega_g$$

**Largest from Astrophysics
(Chandrasekar bound)**

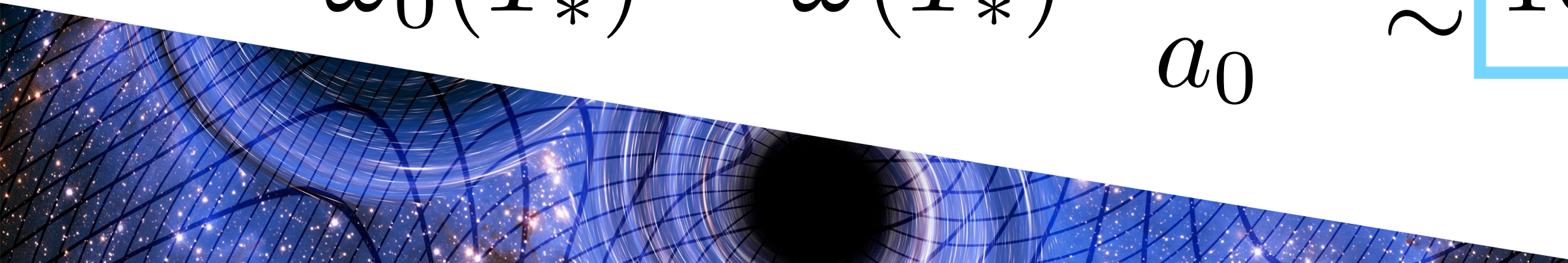

$$\omega_g$$

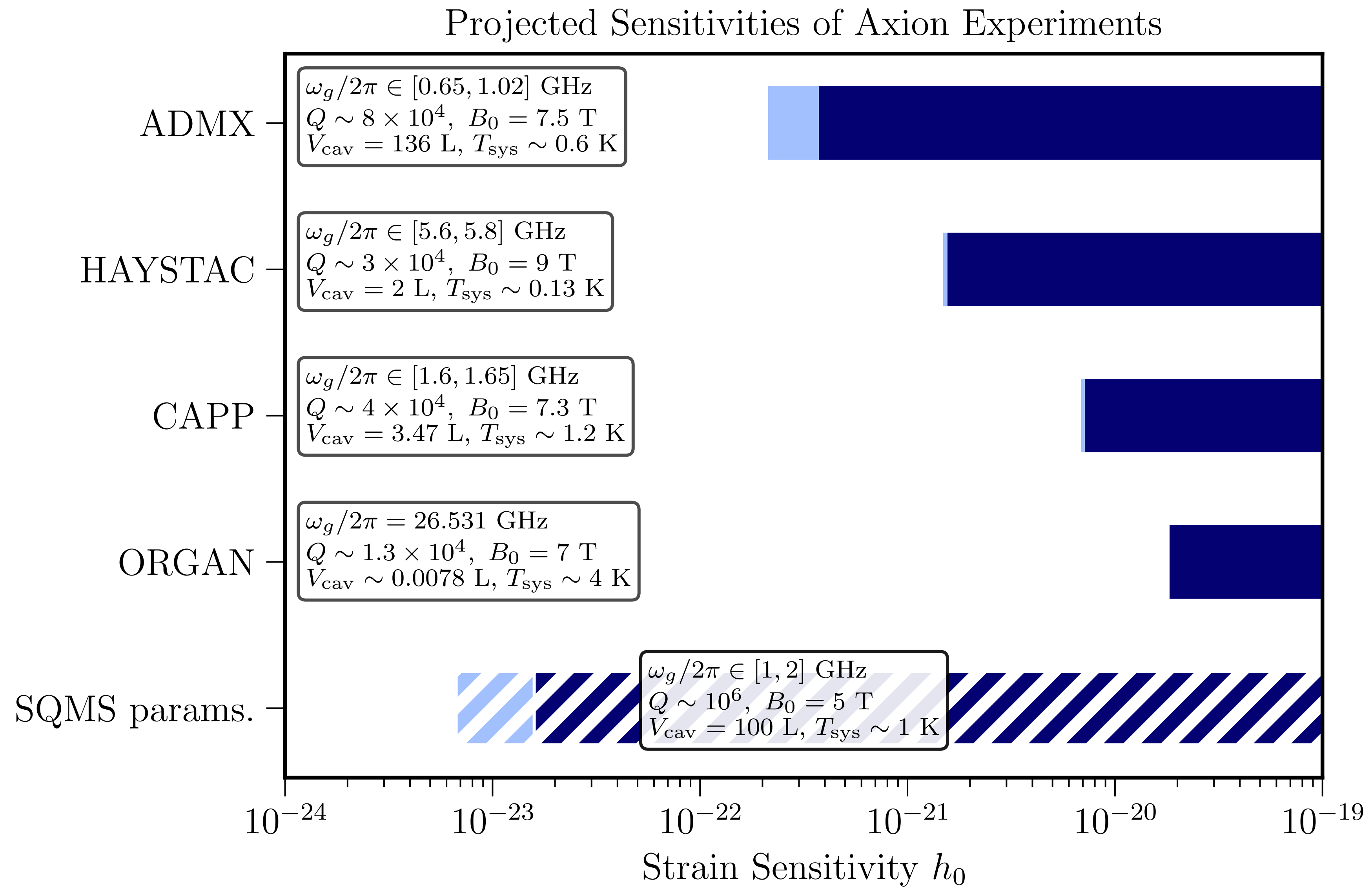
$$\lambda(T_*) < \frac{1}{H(T_*)} \quad \text{Causality}$$

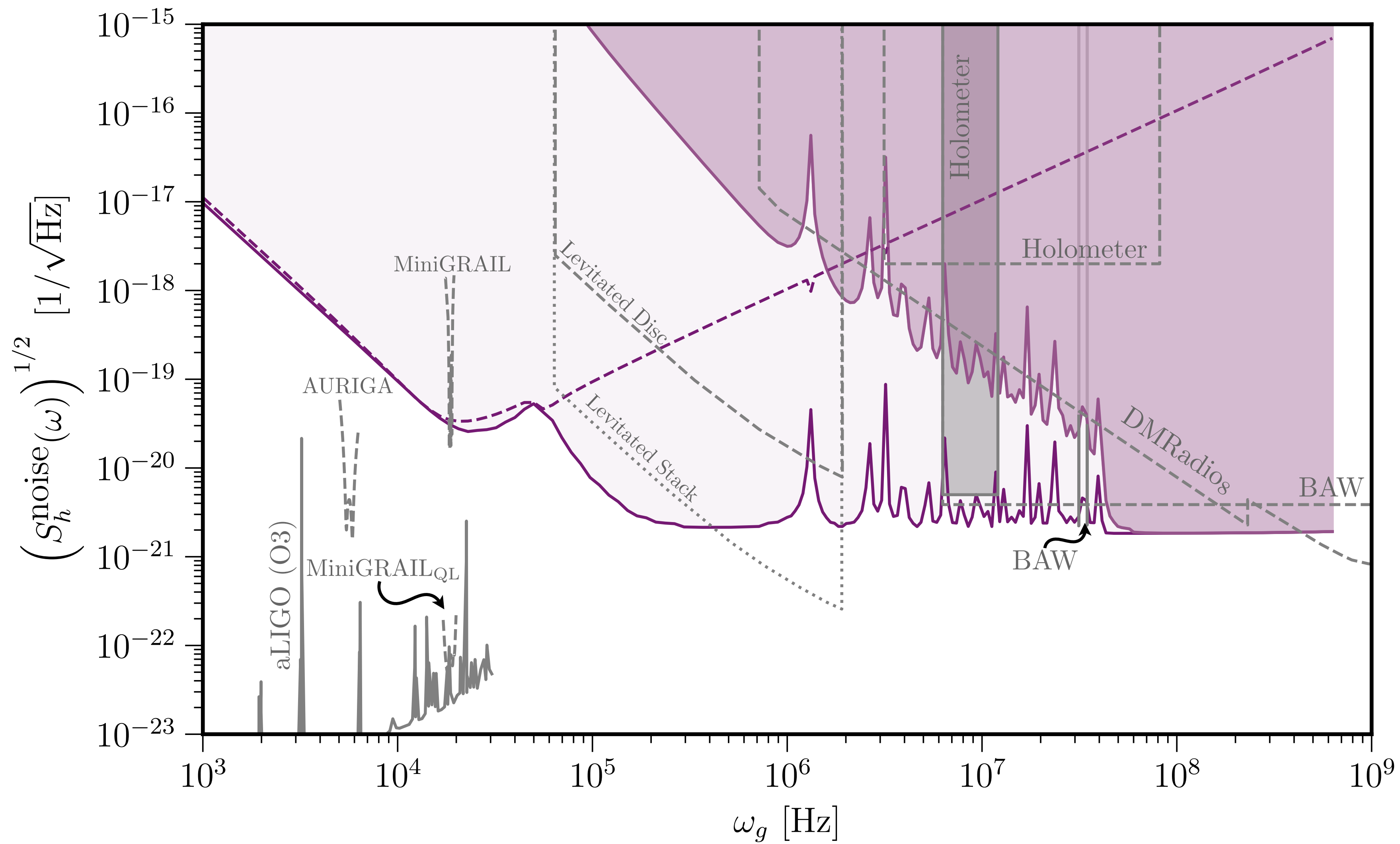



$$\omega_g$$

$$\lambda(T_*) < \frac{1}{H(T_*)} \quad \text{Causality}$$

$$\omega_0(T_*) = \omega(T_*) \frac{a(T_*)}{a_0} \gtrsim \boxed{100 \text{ MHz}} \left(\frac{T_*}{10^{15} \text{ GeV}} \right) \left(\frac{g_*(T_*)}{100} \right)^{1/6}$$


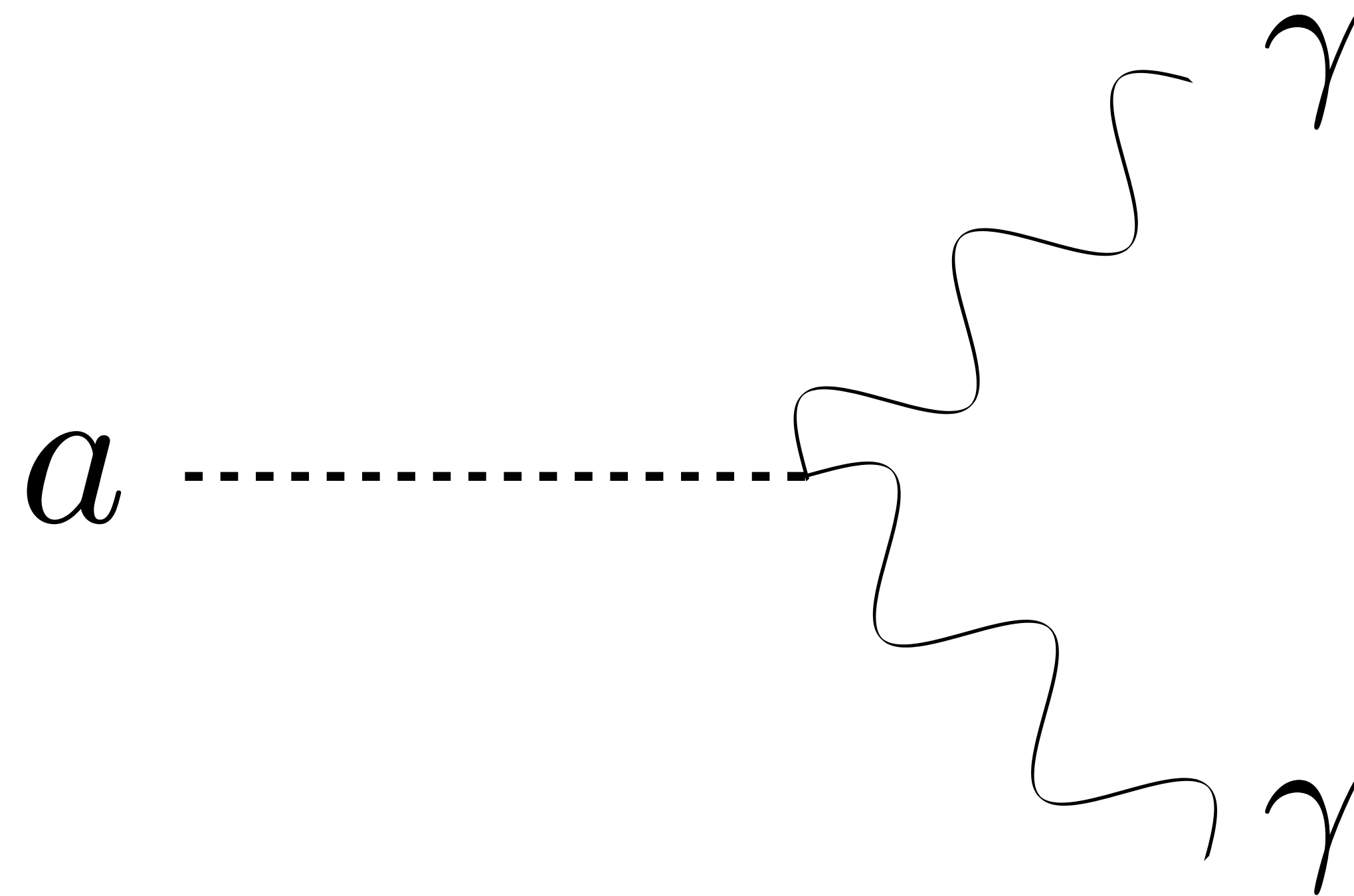
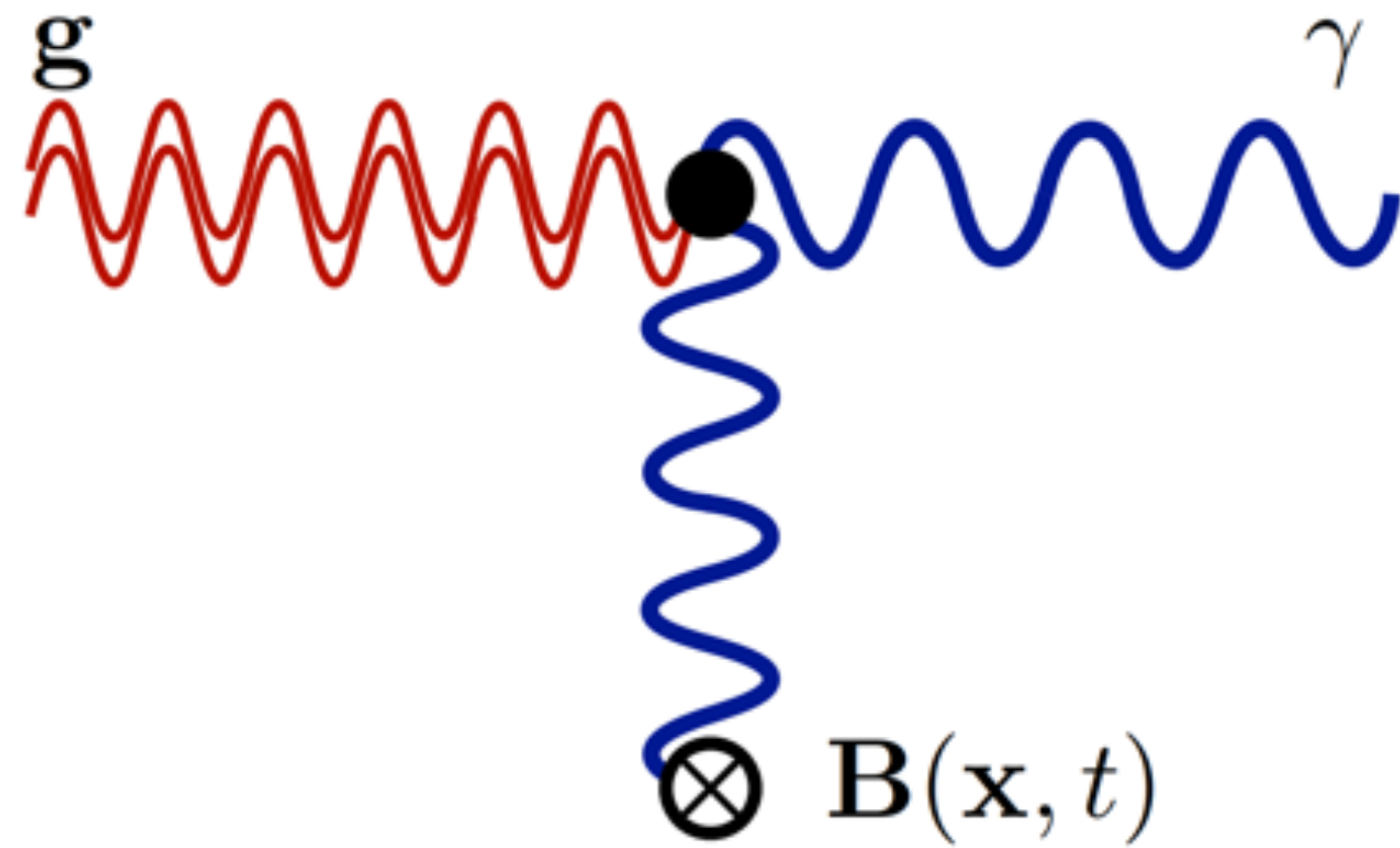




Berlin, Blas, D'Agnolo, Ellis, Harnik, Kahn, Schutte-Engel, Wentzel

ANALOGY

The image is a composite background. The upper right portion shows a clear view of the Milky Way galaxy, with its characteristic band of stars and reddish-pink interstellar dust stretching across the dark blue and purple of space. The lower left portion is a blue-tinted graphic showing a grid of lines that warp and curve into concentric circles, representing the gravitational wells of black holes. The word 'ANALOGY' is centered horizontally across the middle of the image, where it overlaps both the starry sky and the warped grid.

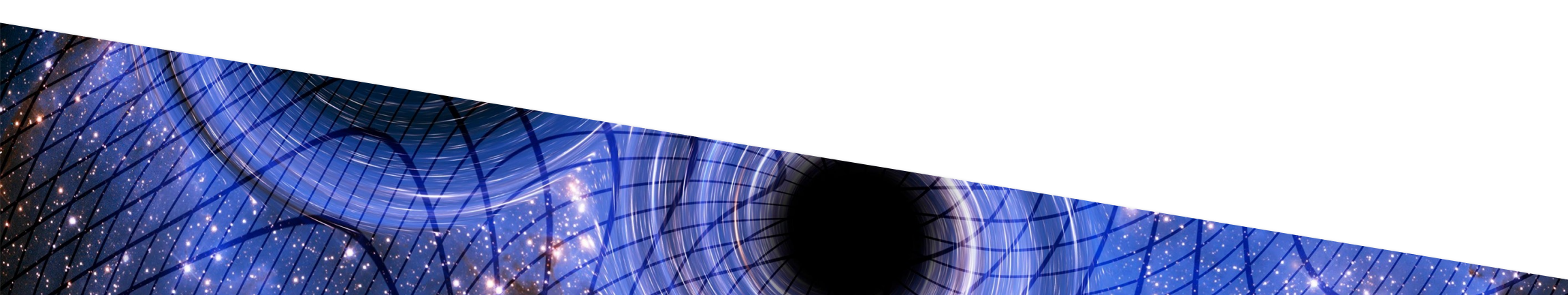




Dark Matter Particles in a de Broglie Volume **Today**

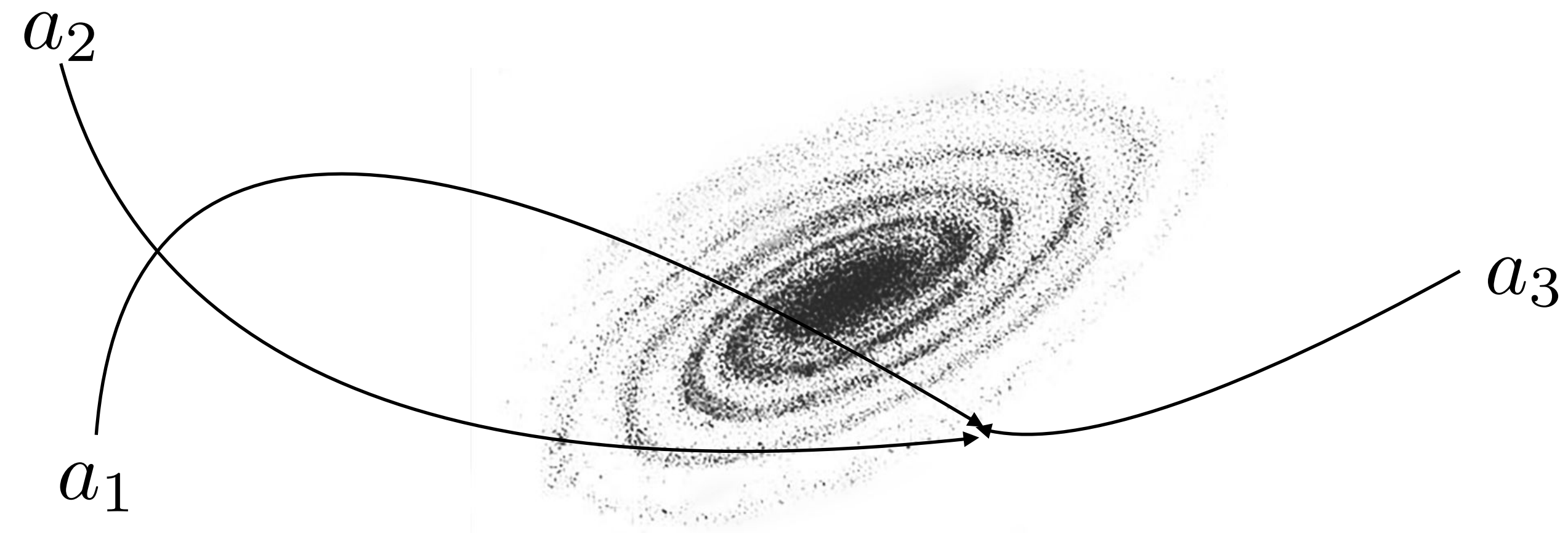
Galaxy: $N_{\text{DM}} \simeq 10^3 \left(\frac{\text{eV}}{m_{\text{DM}}} \right)$

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

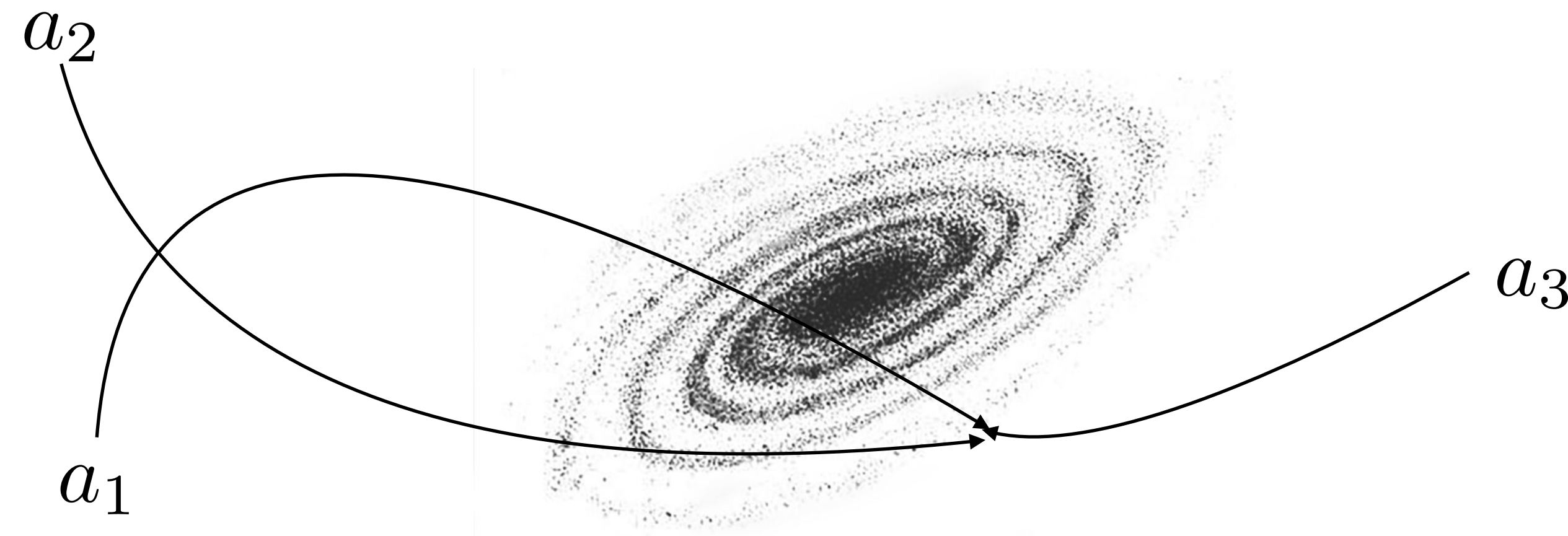


ALP DARK MATTER IN THE LAB

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



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



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

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

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

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

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

ULTRALIGHT
AXION-LIKE
DARK MATTER

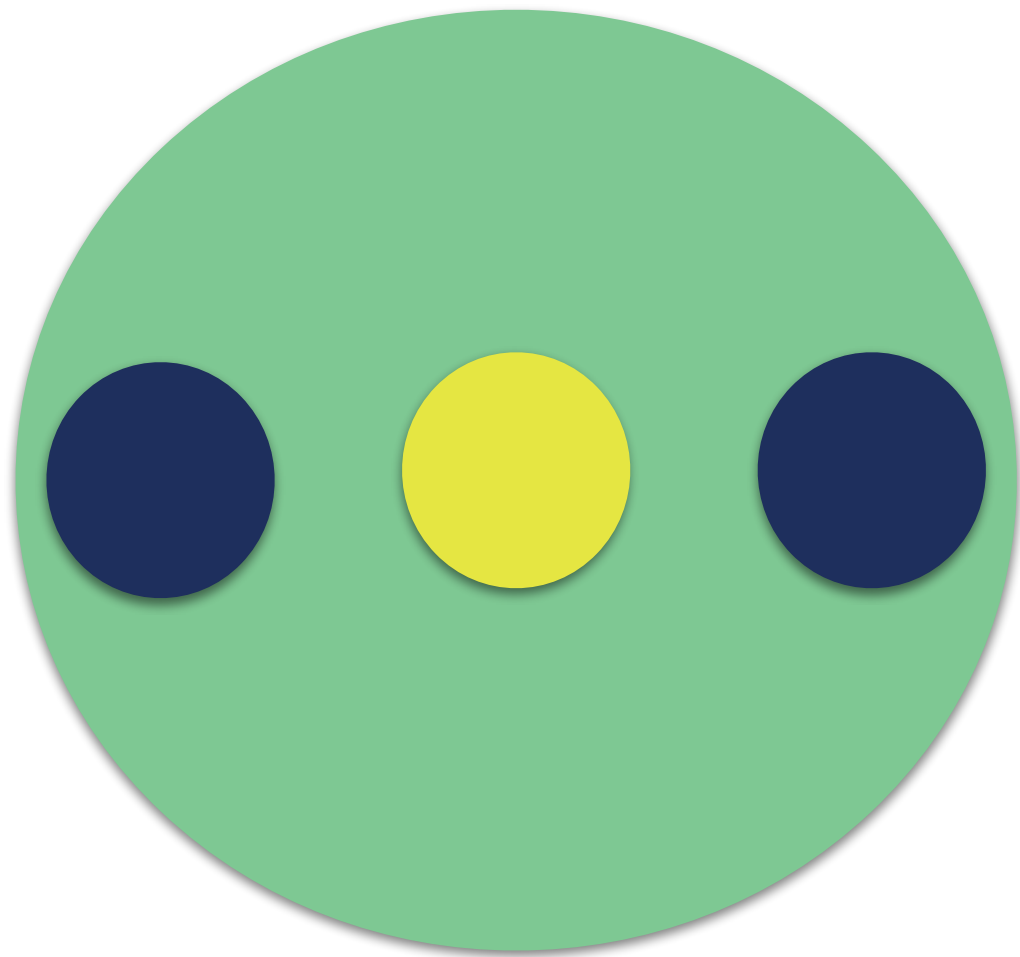


ULTRALIGHT

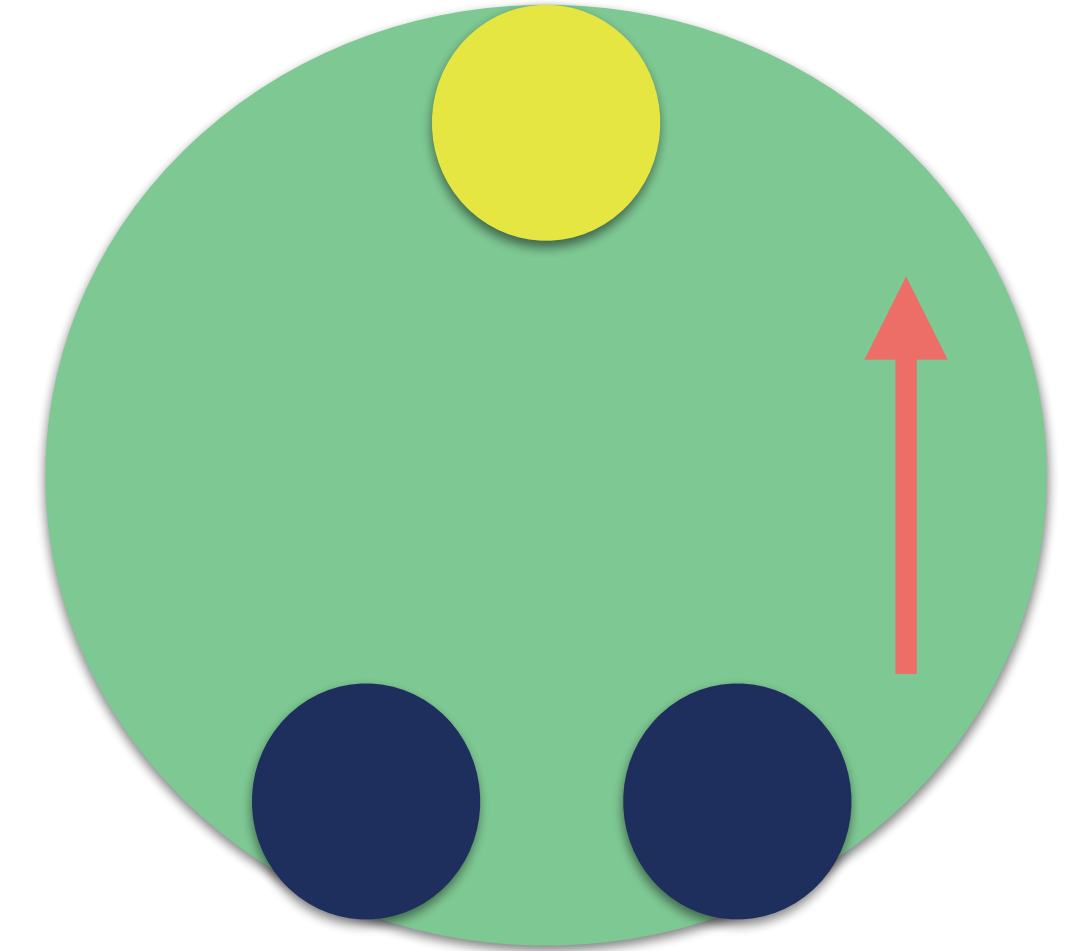
- Minimal Extension of what we know to exist
 - Simple and predictive cosmology
 - Solve another big problem in particle physics
- 

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

Neutron $\theta = 0$



Neutron $\theta \neq 0$



Electric
Dipole

$$|\theta| \lesssim 10^{-10} \quad \text{Experimentally}$$

Introduce a new **global symmetry** at f_a

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

At the minimum

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

QCD Phase Transition

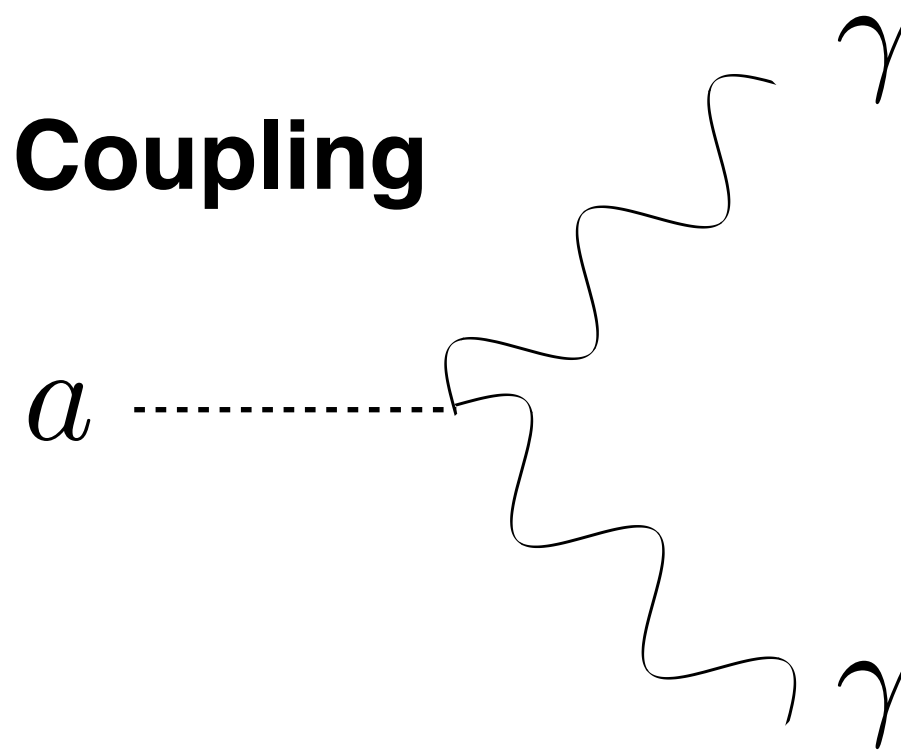
$$\frac{a}{f_a} G \tilde{G} \longrightarrow \frac{a}{f_a} \frac{\pi}{f_\pi} + \dots$$

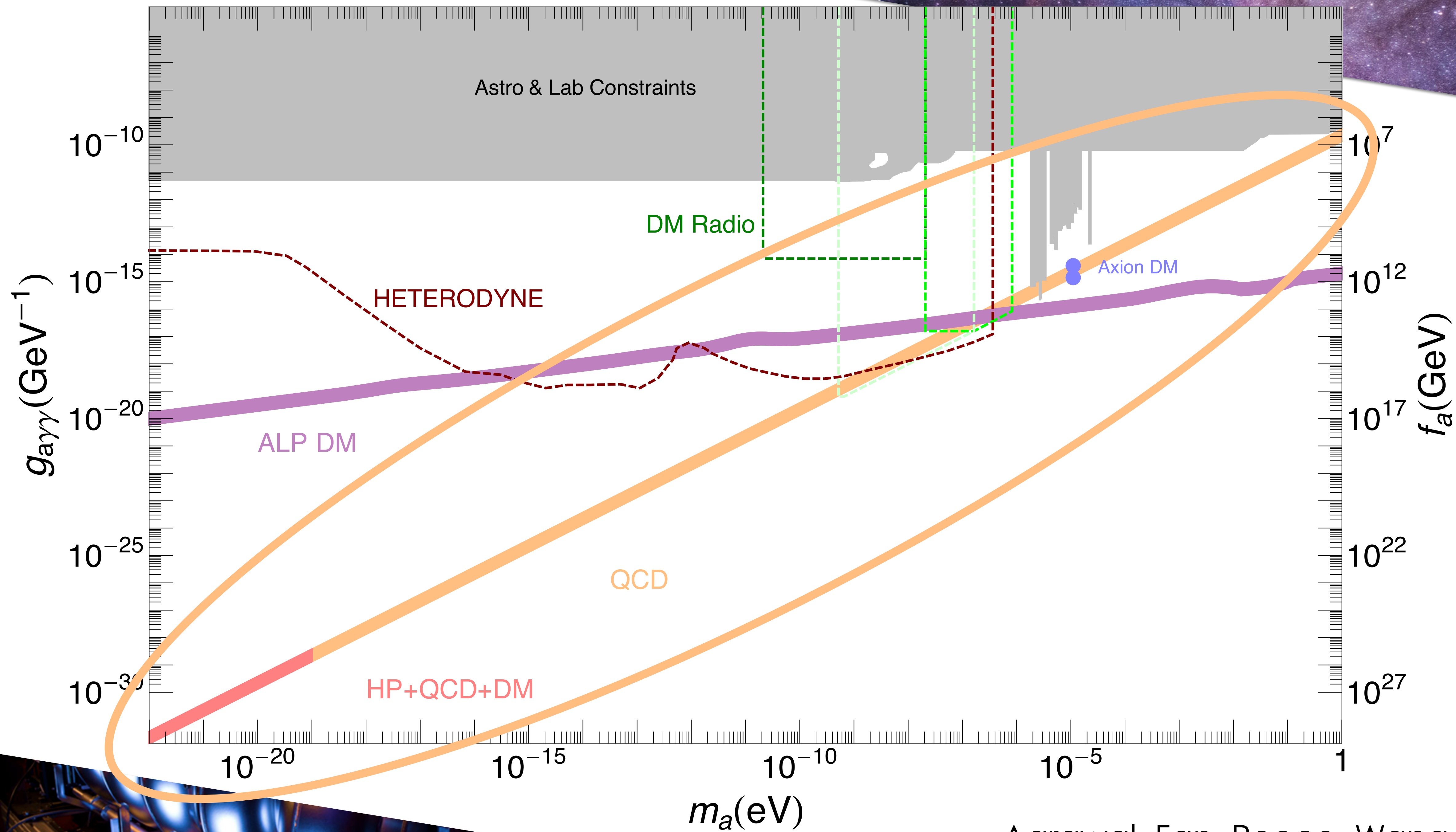
Mass

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

Relevant Coupling

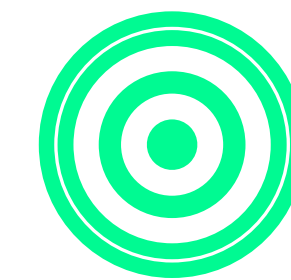
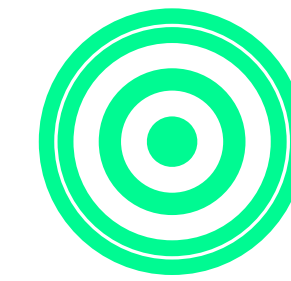
$$\frac{a}{f_a} \mathbf{E} \cdot \mathbf{B}$$





ULTRALIGHT

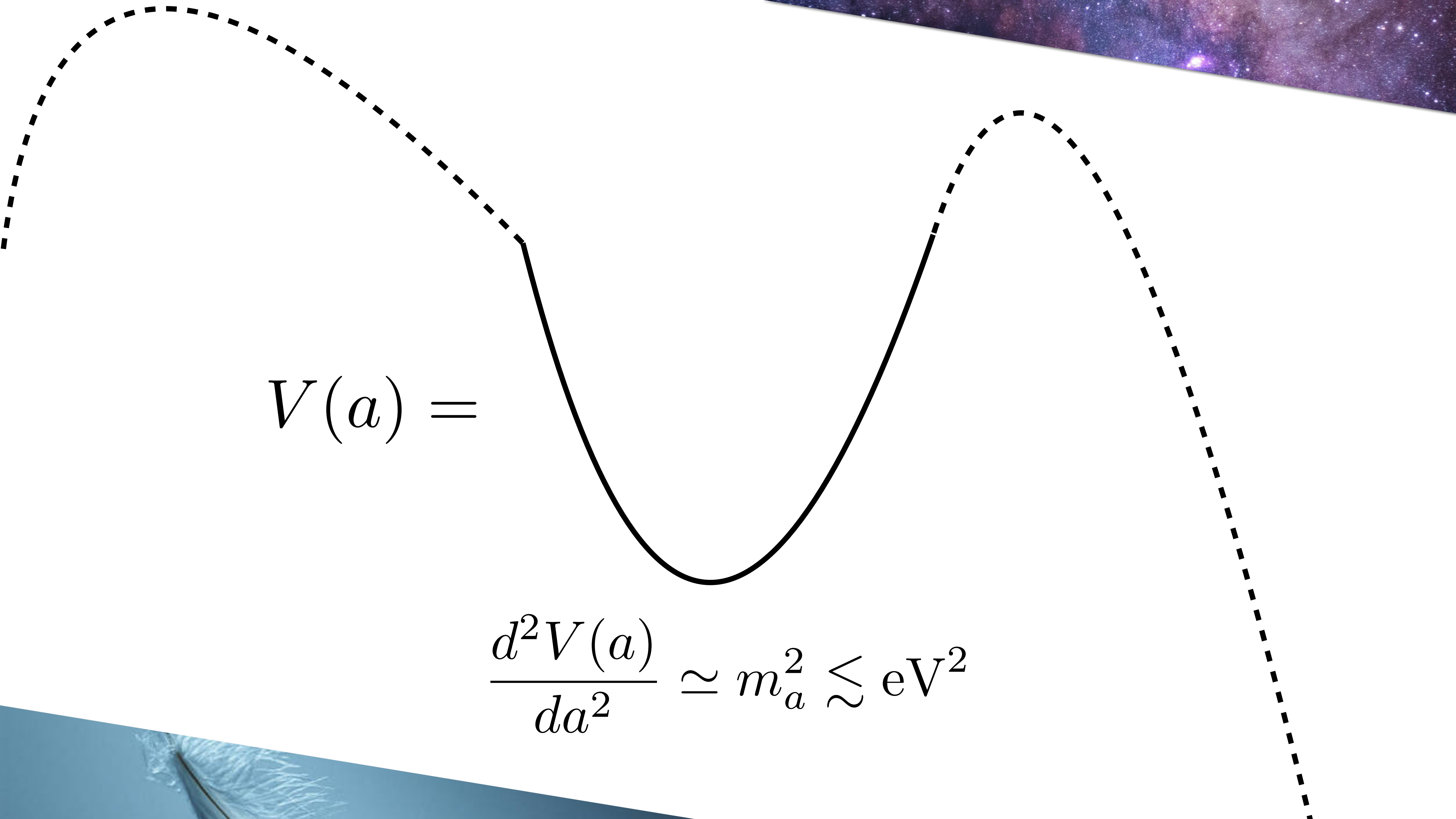
- Minimal Extension of what we know to exist
- Simple and predictive cosmology
- Solve another big problem in particle physics



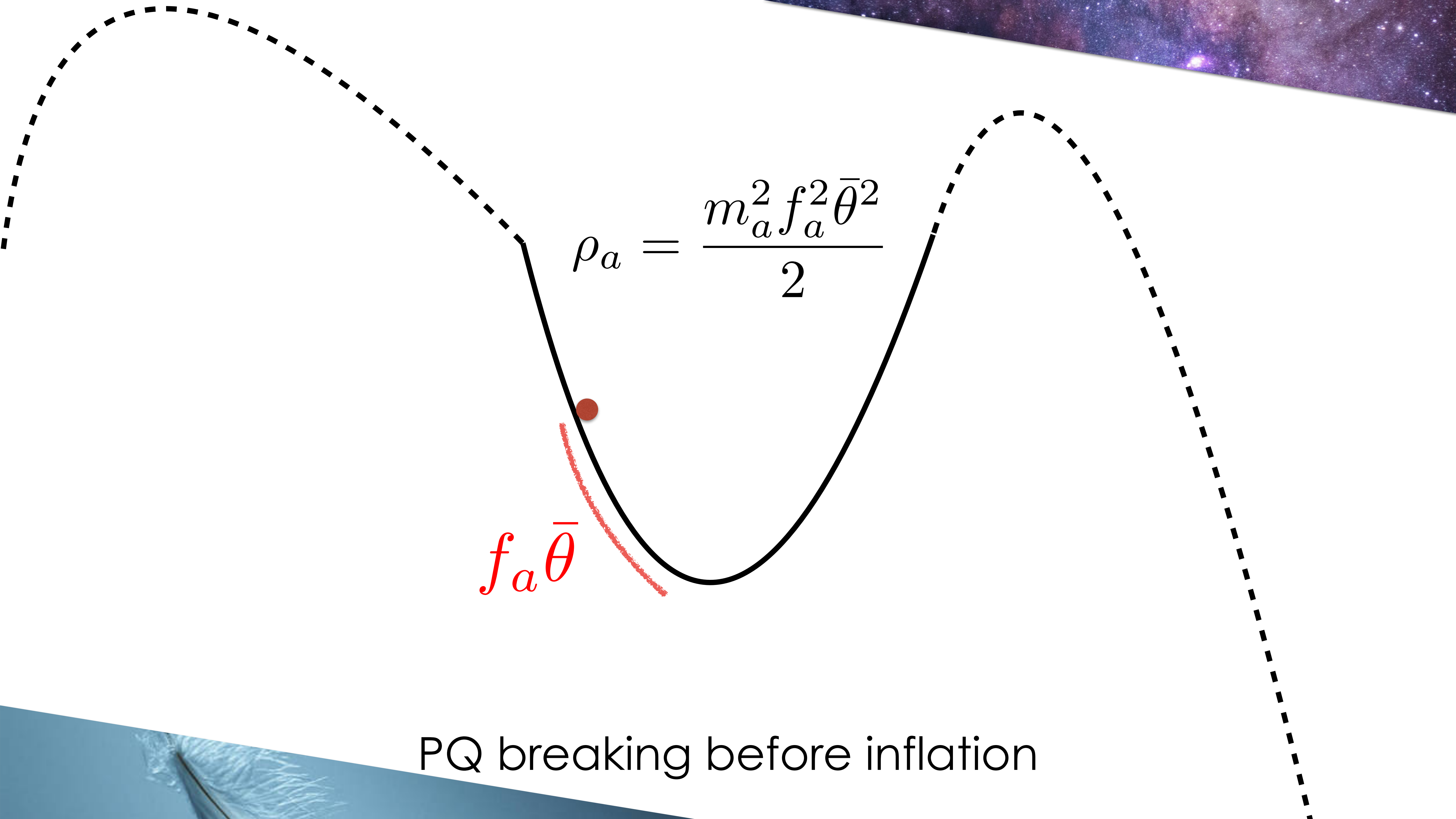
Dark Matter Particles in a de Broglie Volume **Today**

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

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

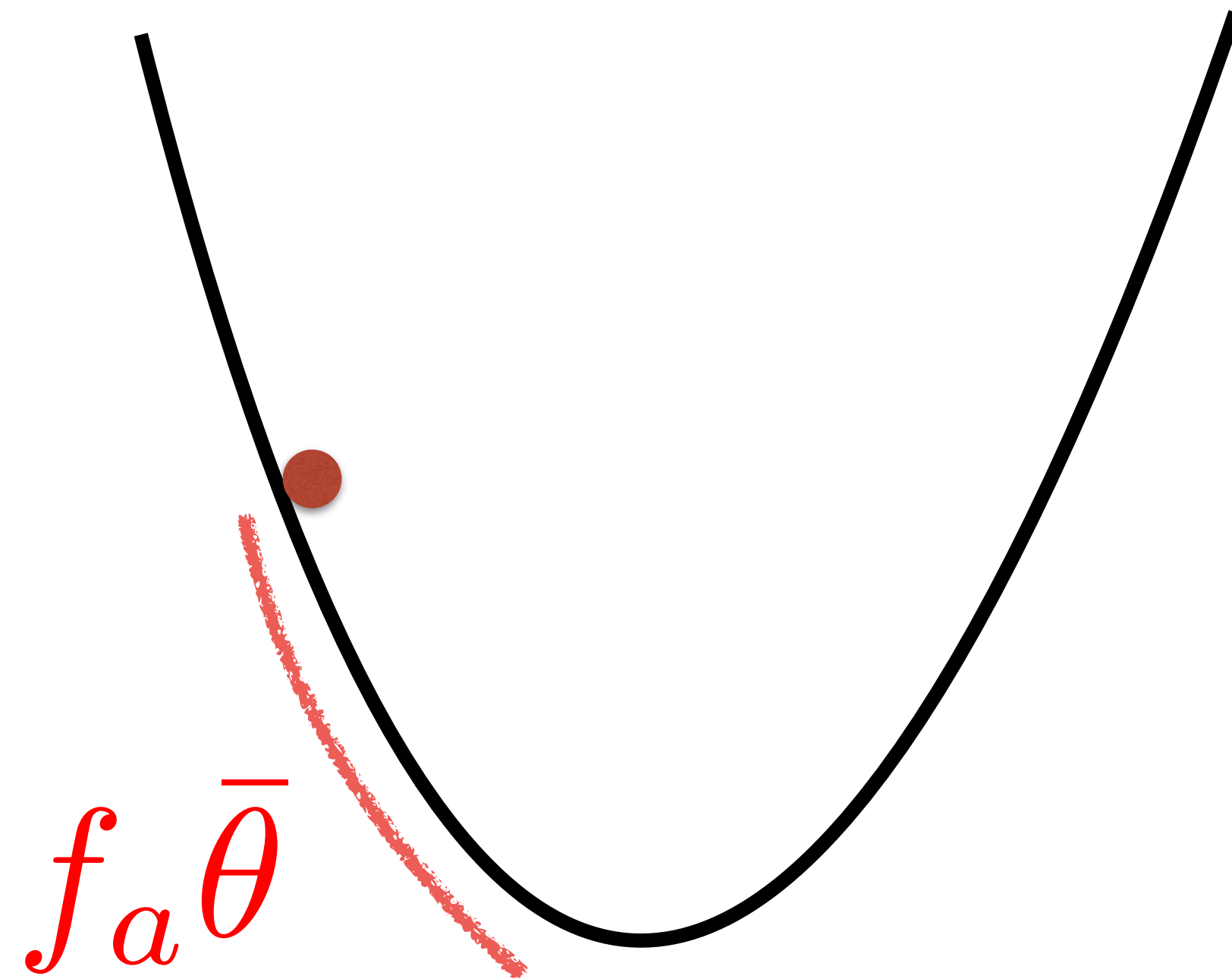
The image shows a potential energy curve V(a) on a white background. The curve consists of a solid black parabolic segment with its minimum at the bottom center, and two dashed black segments that extend from the ends of the solid segment, curving upwards and outwards. The text 'V(a) =' is positioned to the left of the solid segment. At the bottom of the image, there are decorative borders: a blue textured strip on the left and a purple starry space strip on the right.
$$V(a) =$$

$$\frac{d^2 V(a)}{da^2} \simeq m_a^2 \lesssim \text{eV}^2$$



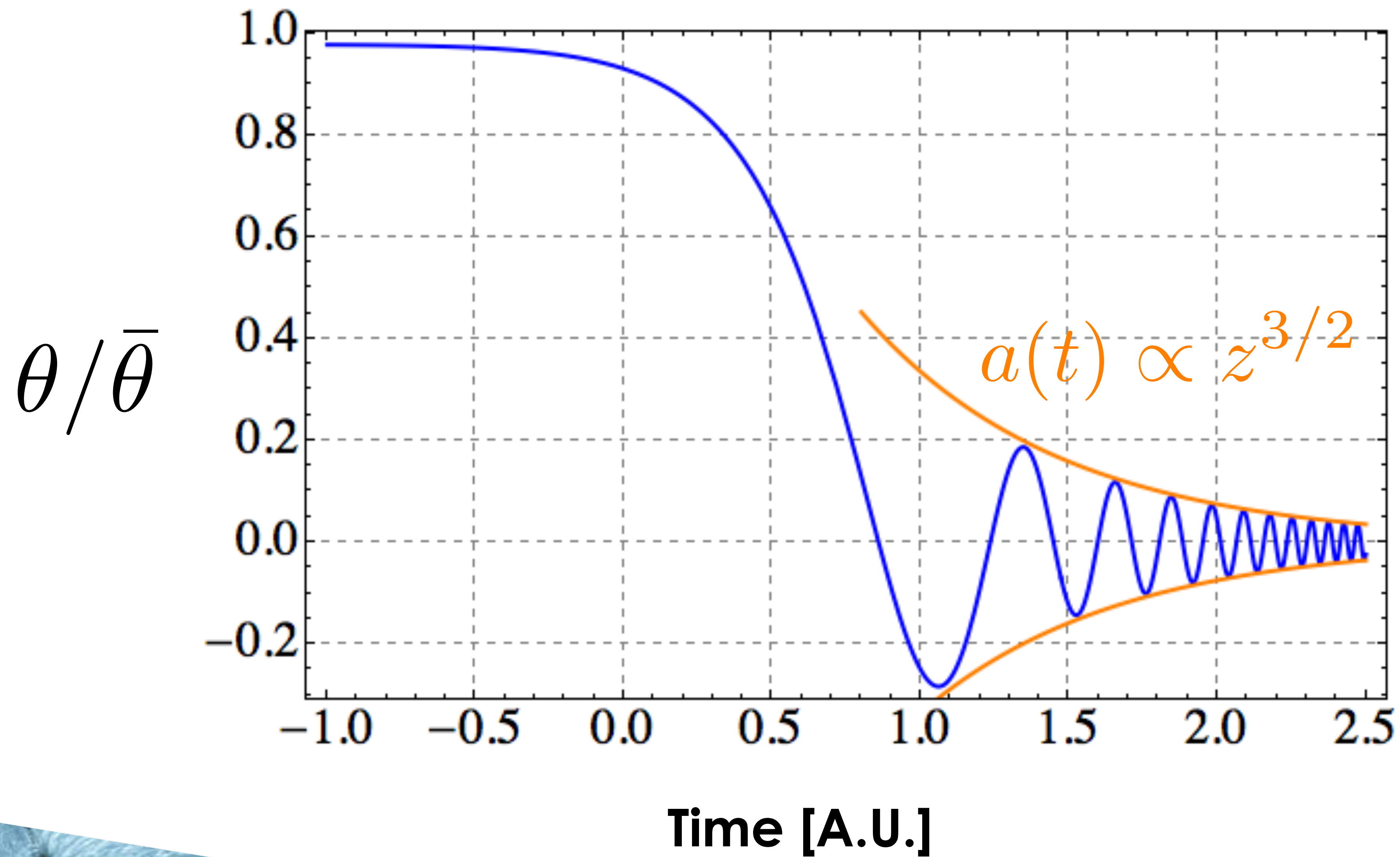
PQ breaking before inflation

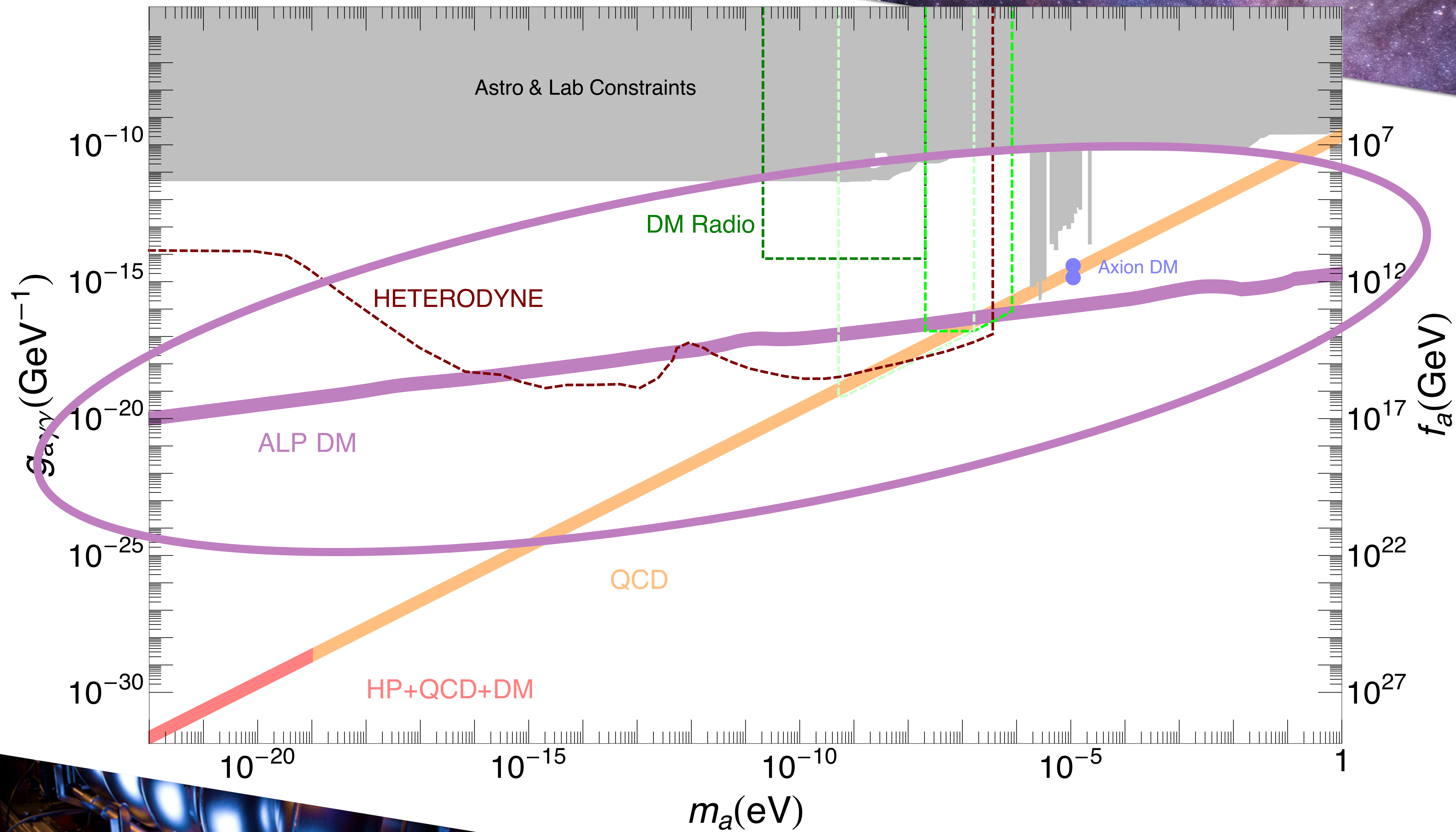
Classical Equation of Motion



$$\ddot{\theta} + 3H\dot{\theta} + m_a^2(T)\theta = 0$$

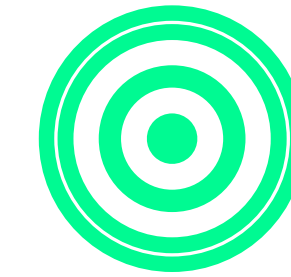
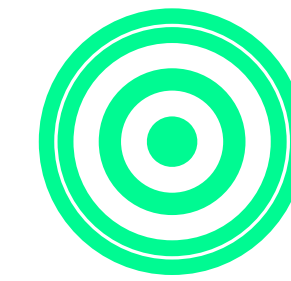
$$\ddot{\theta} + 3H\dot{\theta} + m_a^2(T)\theta = 0$$





ULTRALIGHT

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

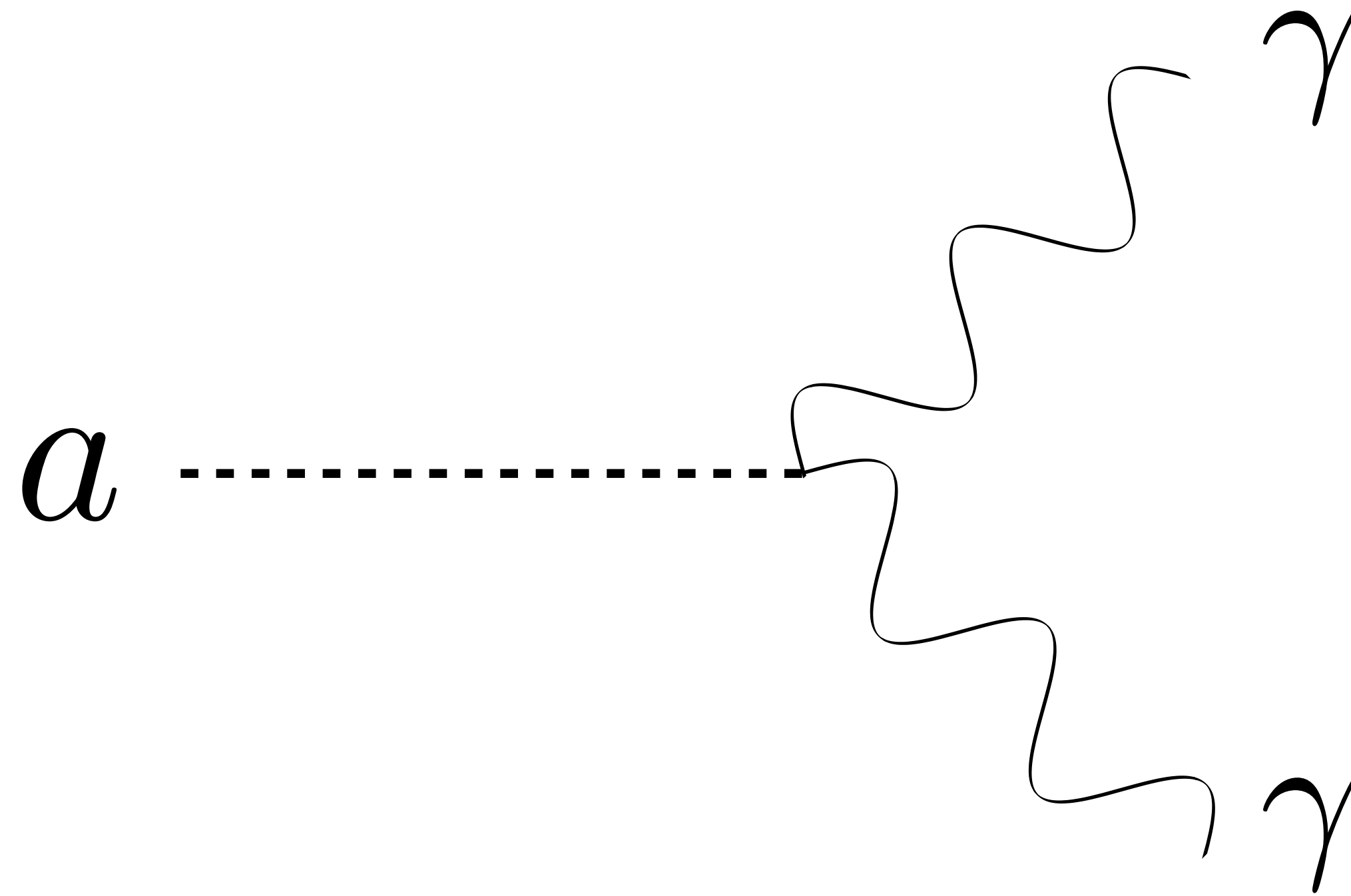


The background of the slide is a composite image. The left side shows a close-up of the ALPS (Advanced Large Photon Spectrometer) detector, featuring several large, polished, metallic hemispherical components arranged in a row. The right side of the image transitions into a deep space view of the Milky Way galaxy, showing a dense field of stars and the characteristic reddish-pink dust lanes of the galactic core.

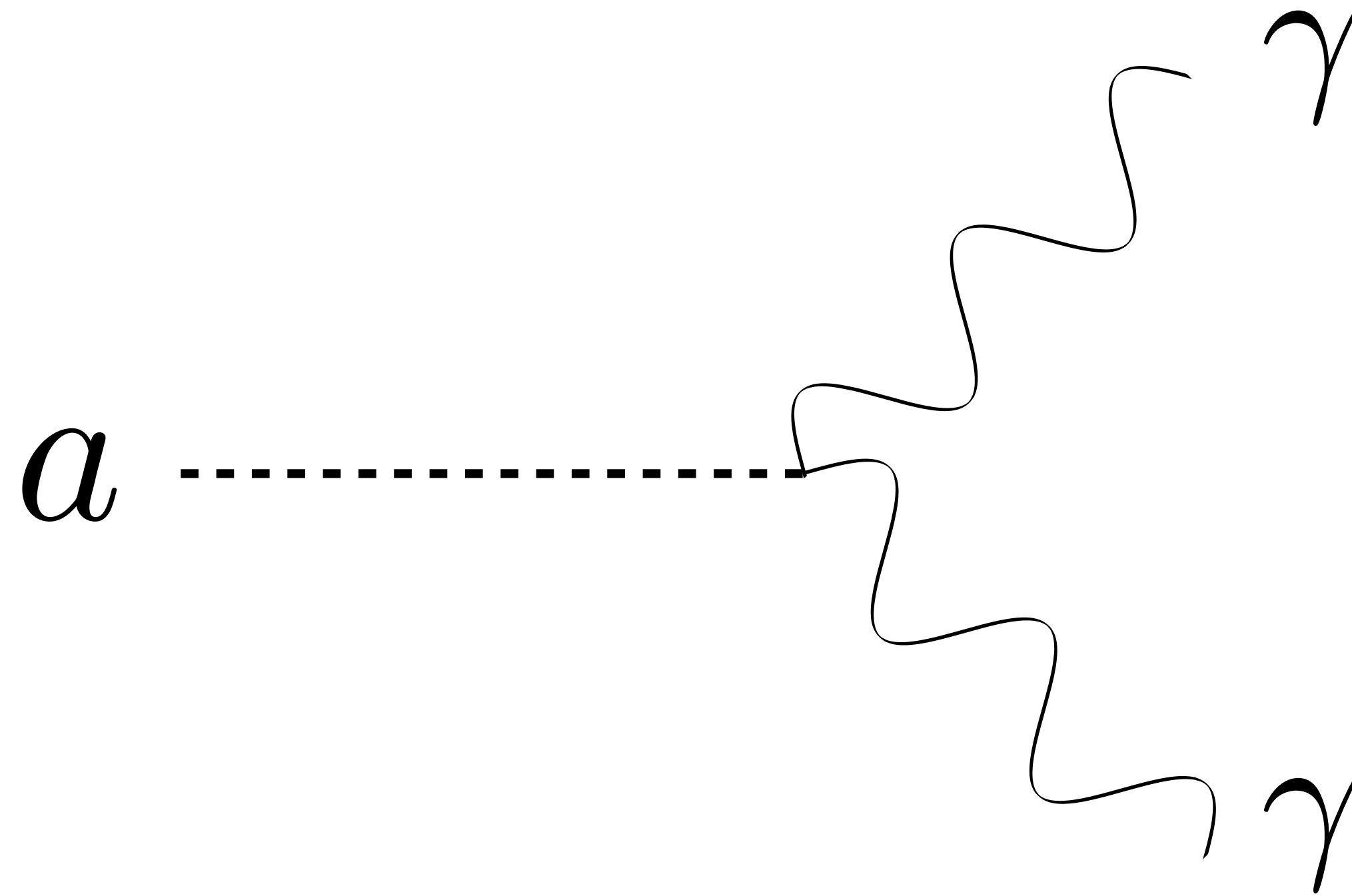
ALPS DETECTION

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

ALP DARK MATTER DETECTION

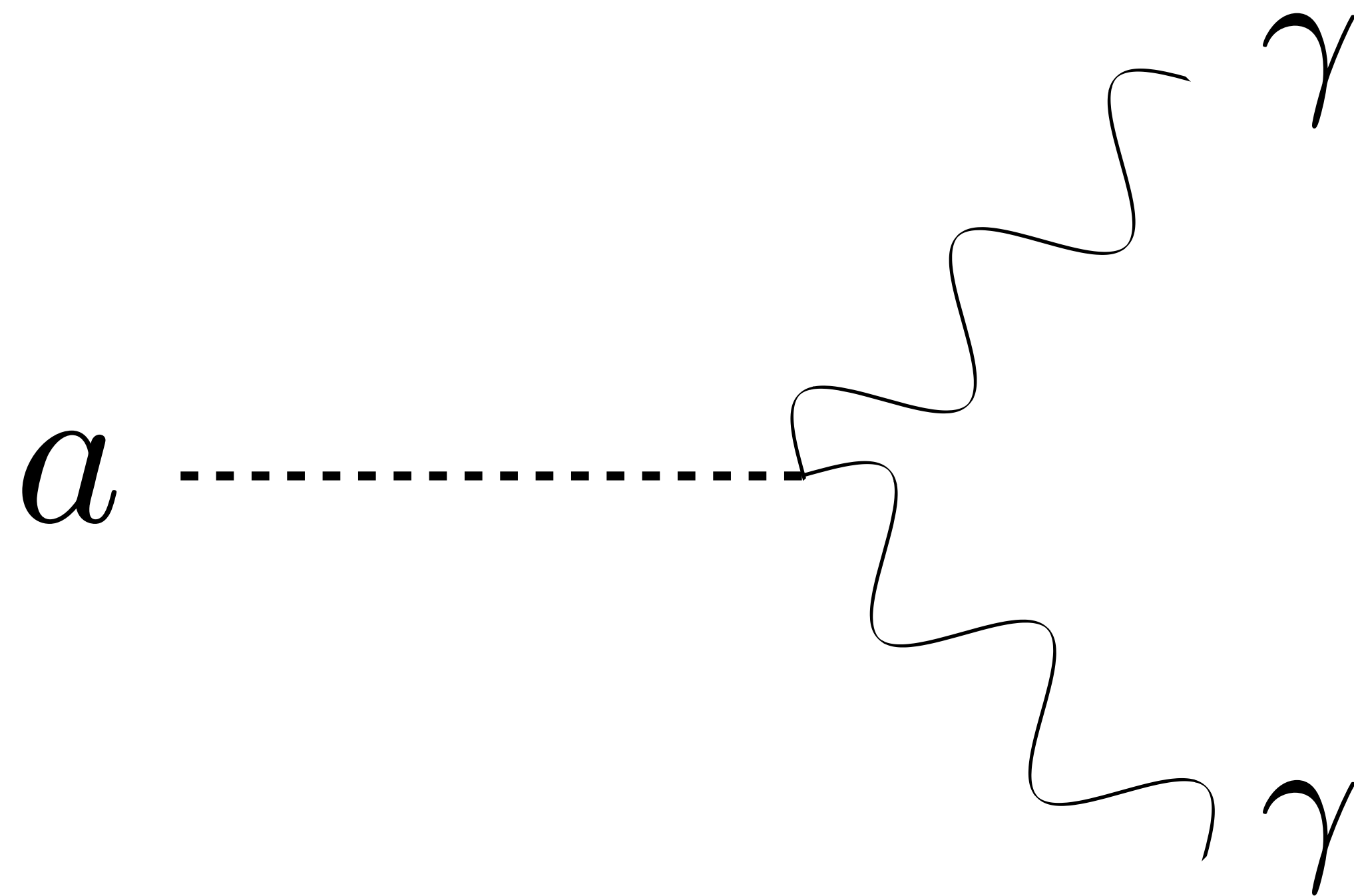


ALP DARK MATTER DETECTION



$$\nabla \times \mathbf{B} \simeq \partial_t \mathbf{E} + \mathbf{J} + \underline{g_{a\gamma\gamma} \mathbf{B} \partial_t a}$$

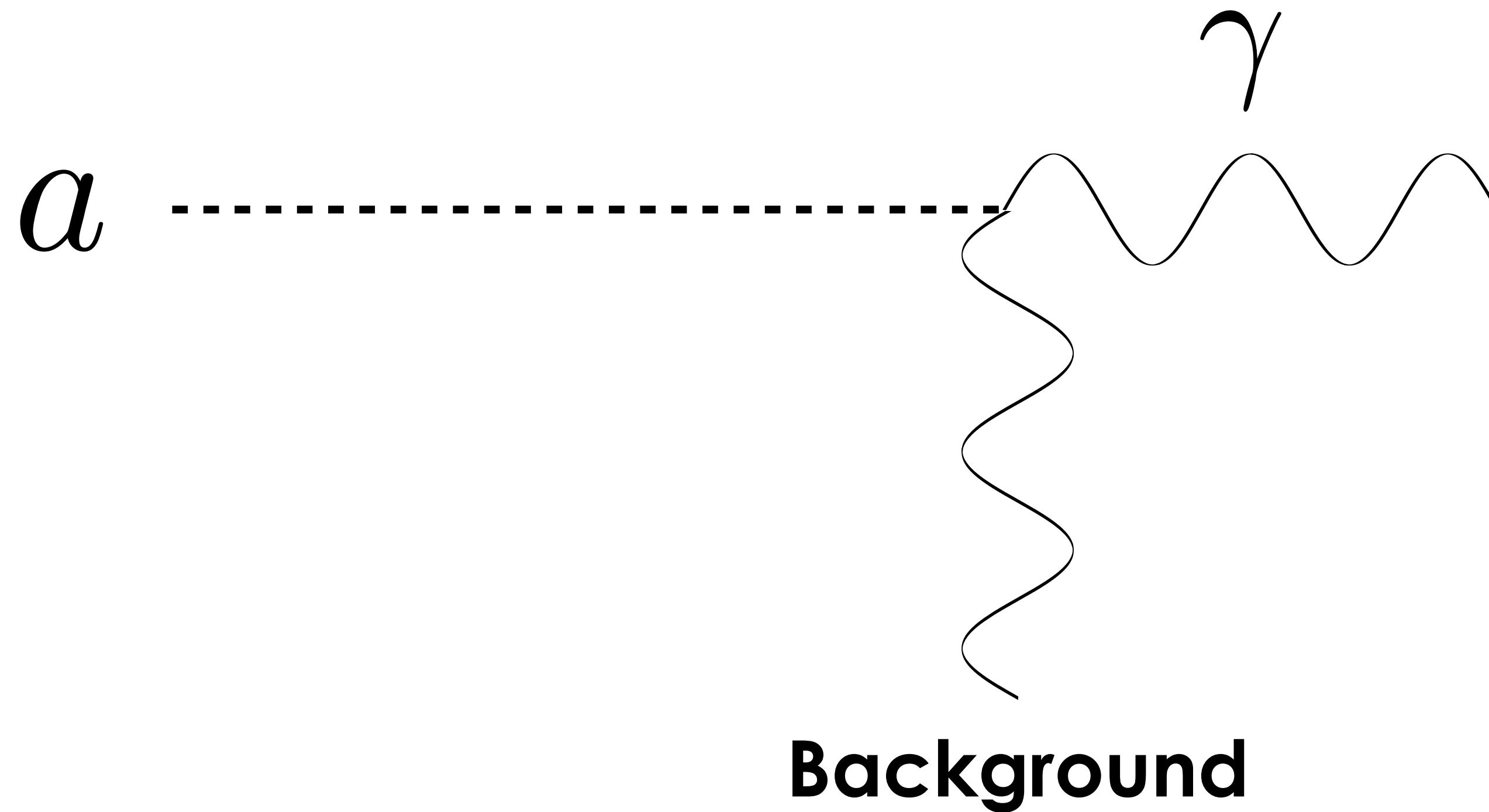
ALP DARK MATTER DETECTION



$$\nabla \times \mathbf{B} \simeq \partial_t \mathbf{E} + \mathbf{J} + \underline{g_{a\gamma\gamma} \mathbf{B} \partial_t a}$$

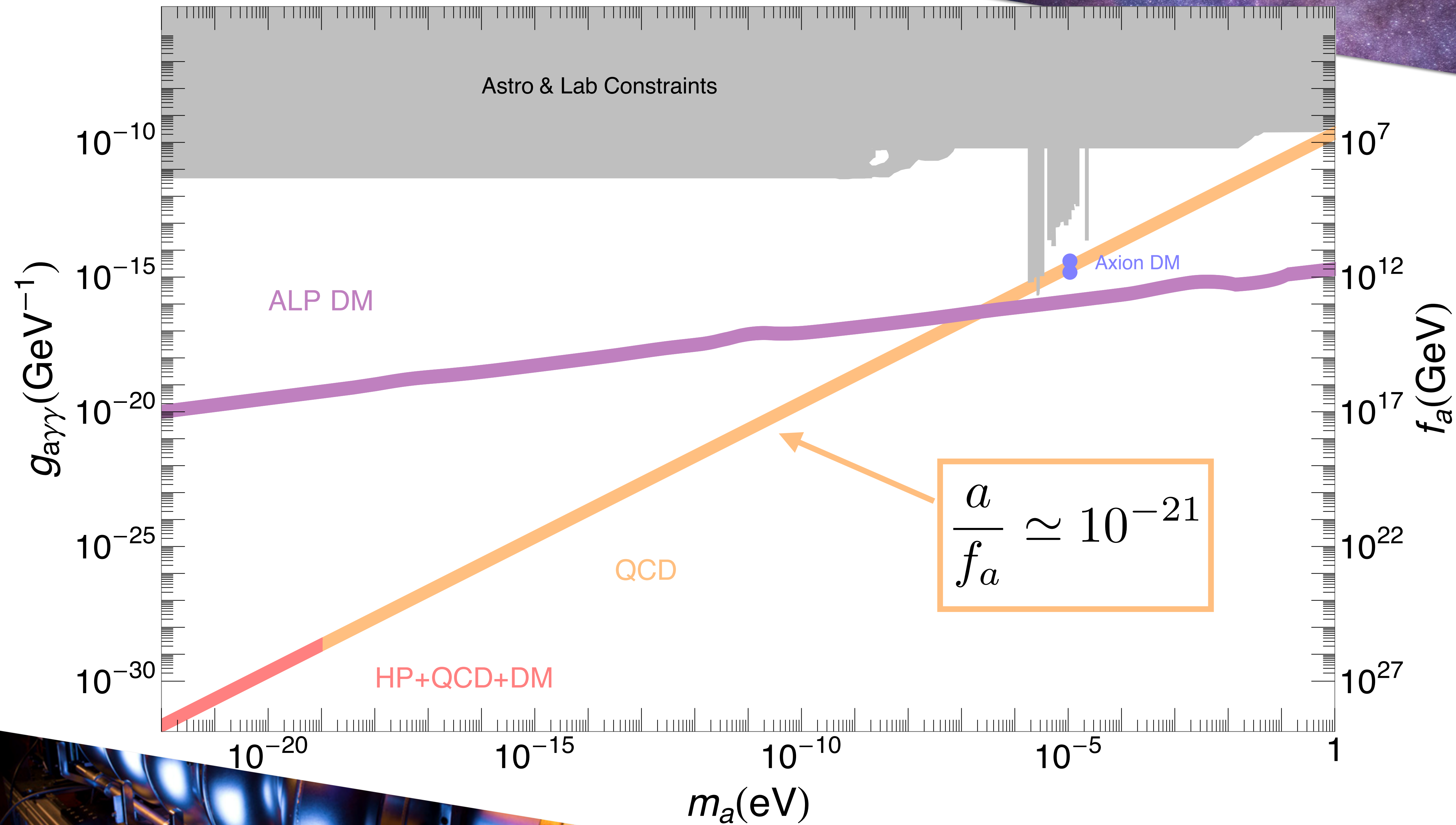
$$J_{\text{eff}}(t) \sim g_{a\gamma\gamma} B_0(t) \sqrt{\rho_{\text{DM}}} \cos m_a t$$

ALP DARK MATTER DETECTION



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

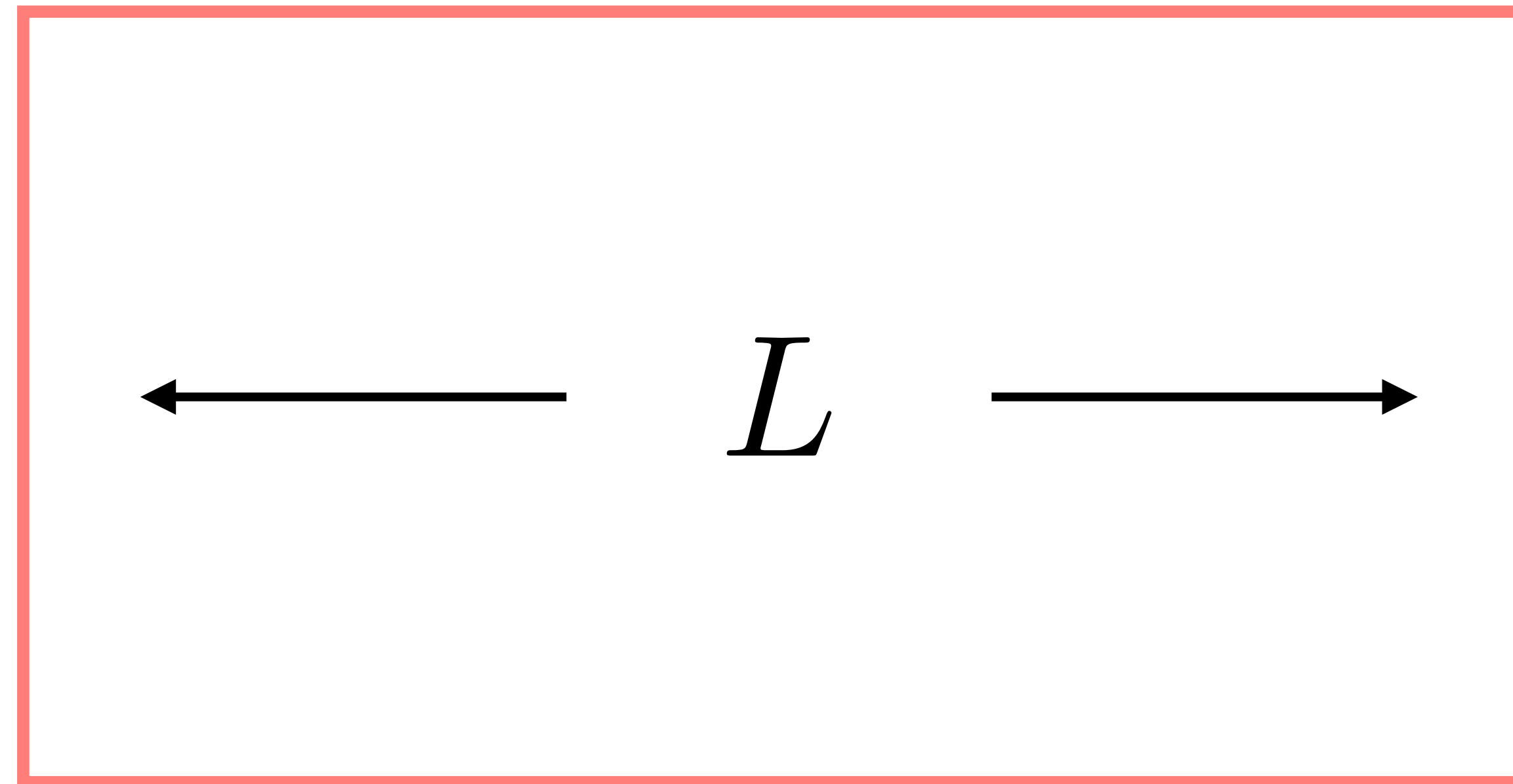
but you know exactly the waveform
and the signal is always there



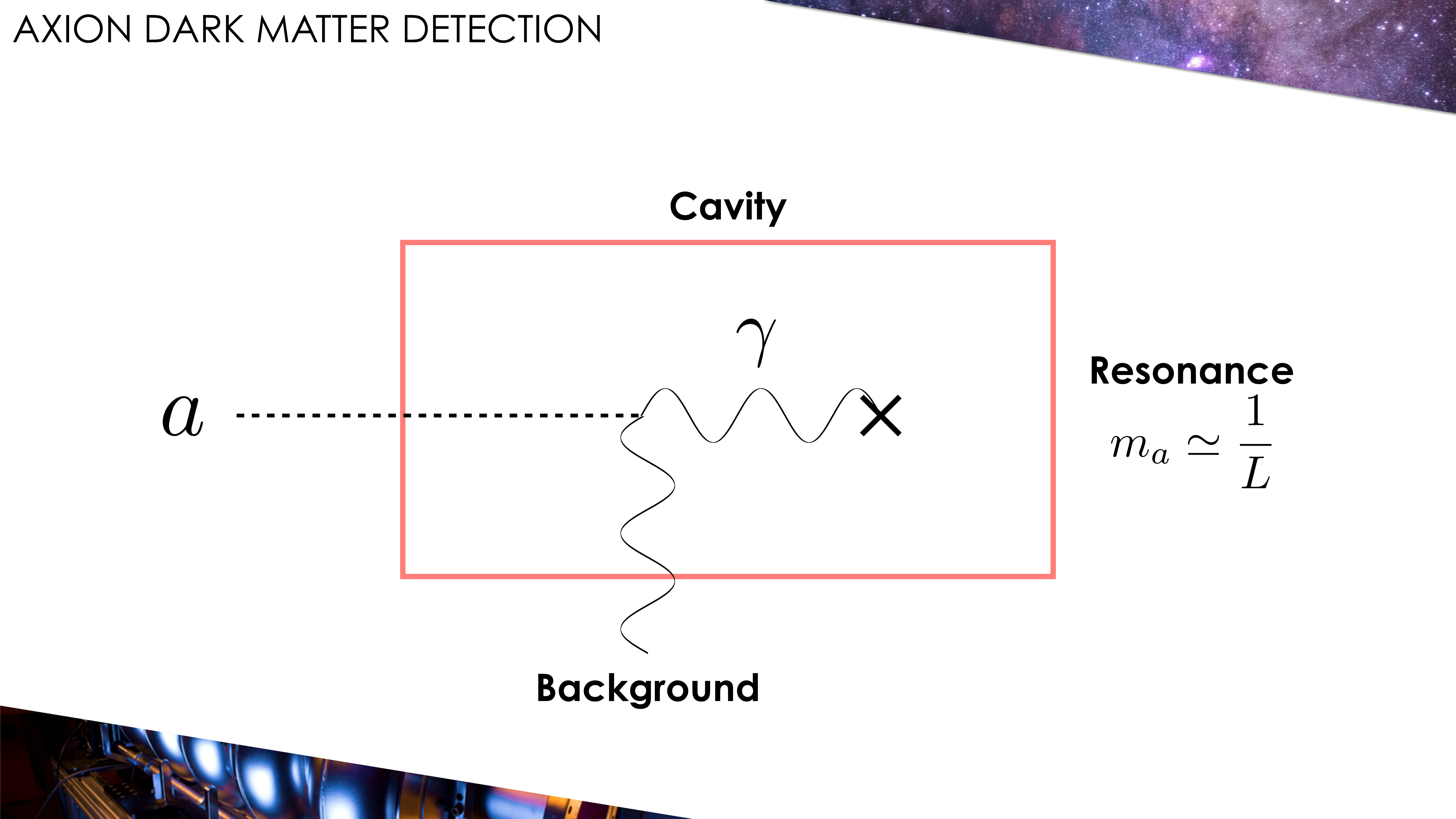
My personal rule of thumb

$$\frac{\Delta O_{\text{exp}}}{O_{\text{exp}}} \gtrsim 10^{-9}$$

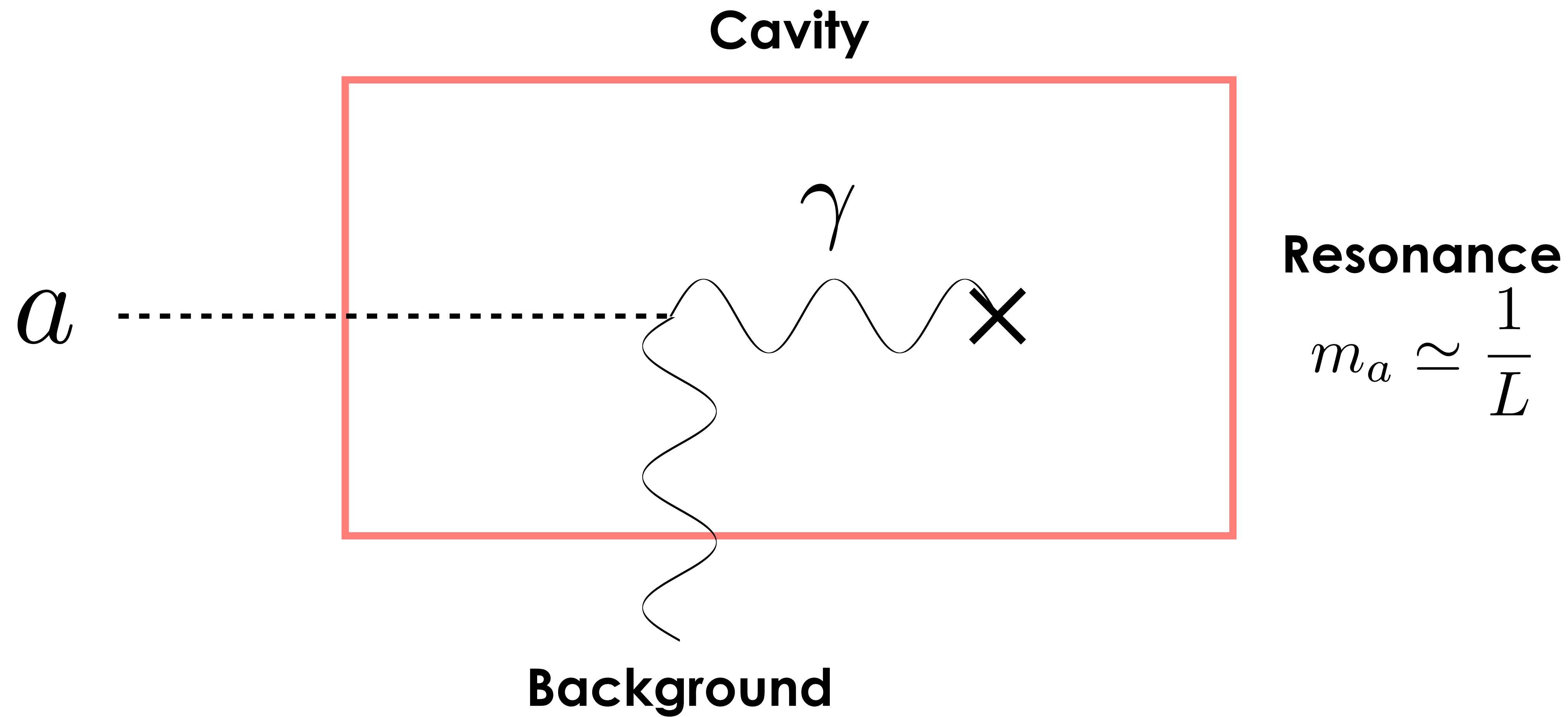
Cavity

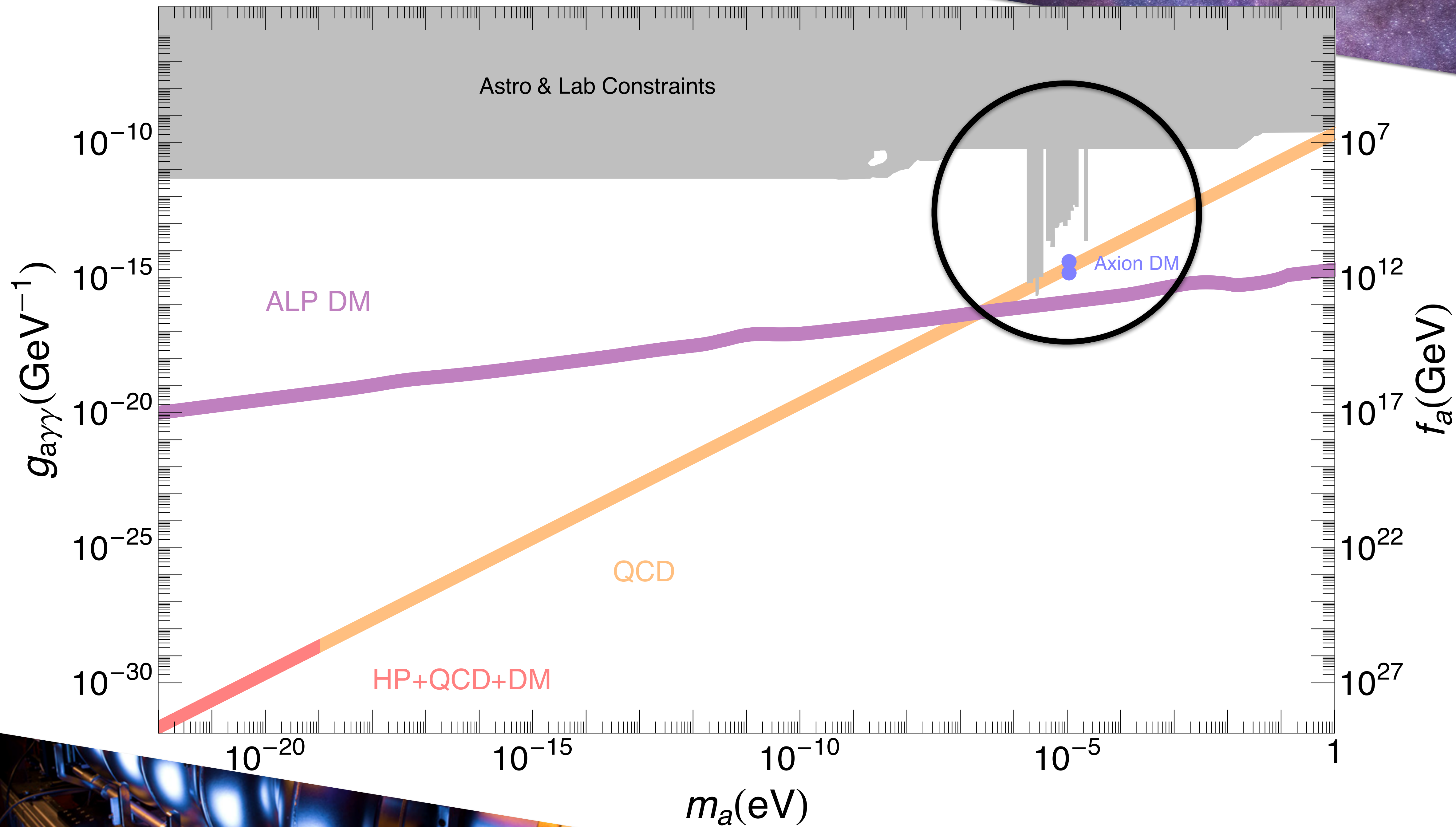


$$m_\gamma \simeq \frac{1}{L}$$



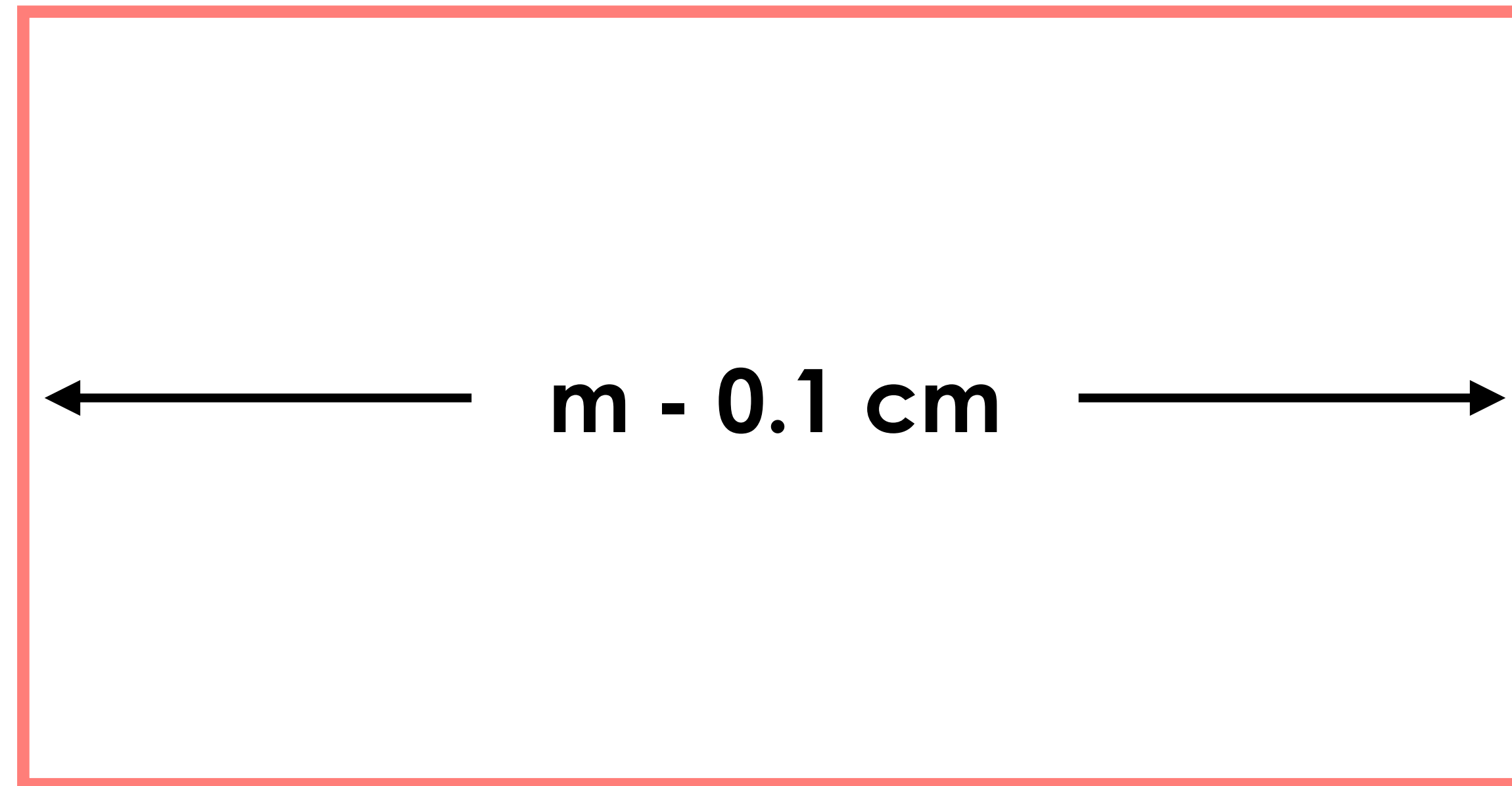
AXION DARK MATTER DETECTION



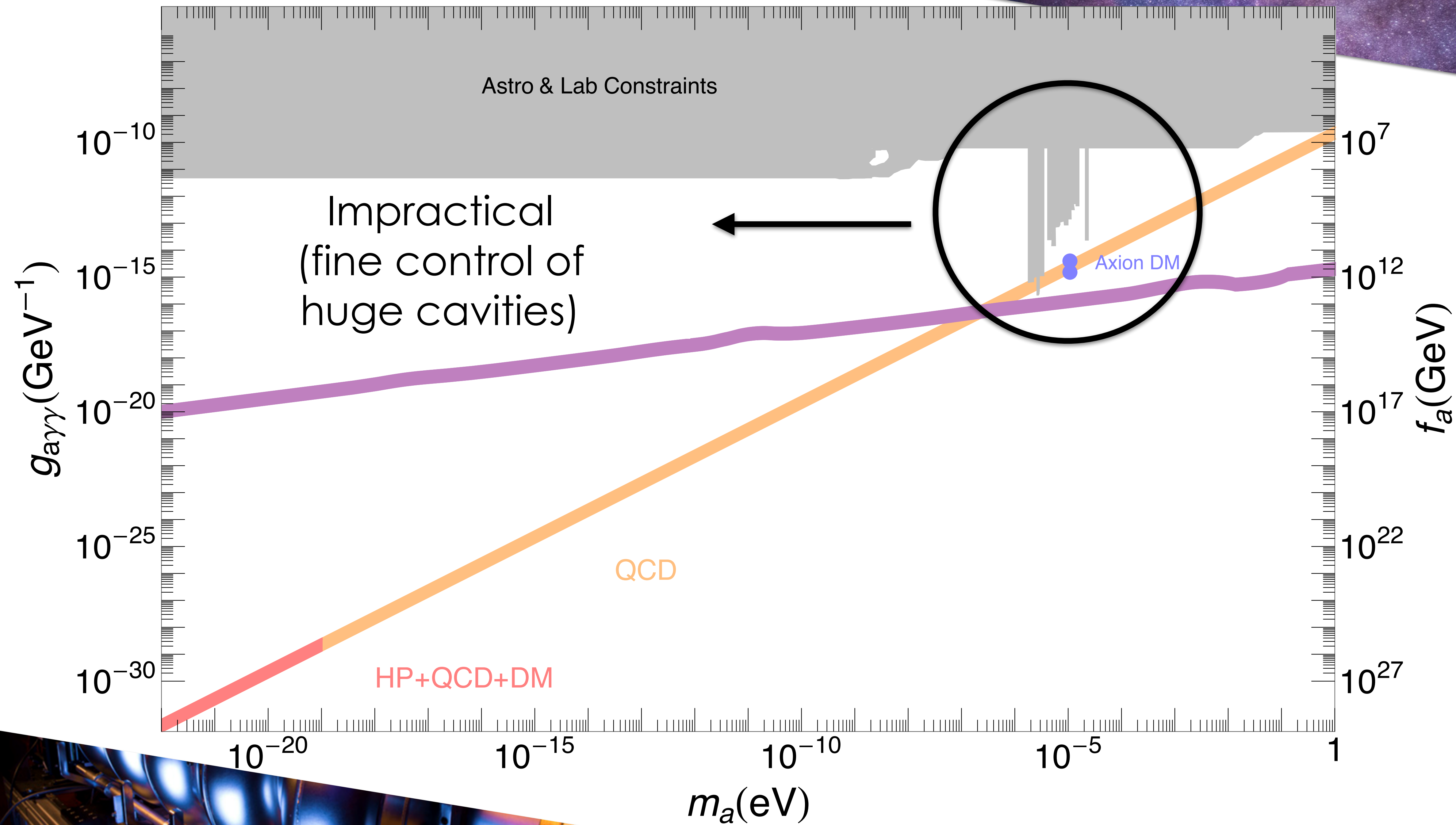


AXION DETECTION

Cavity



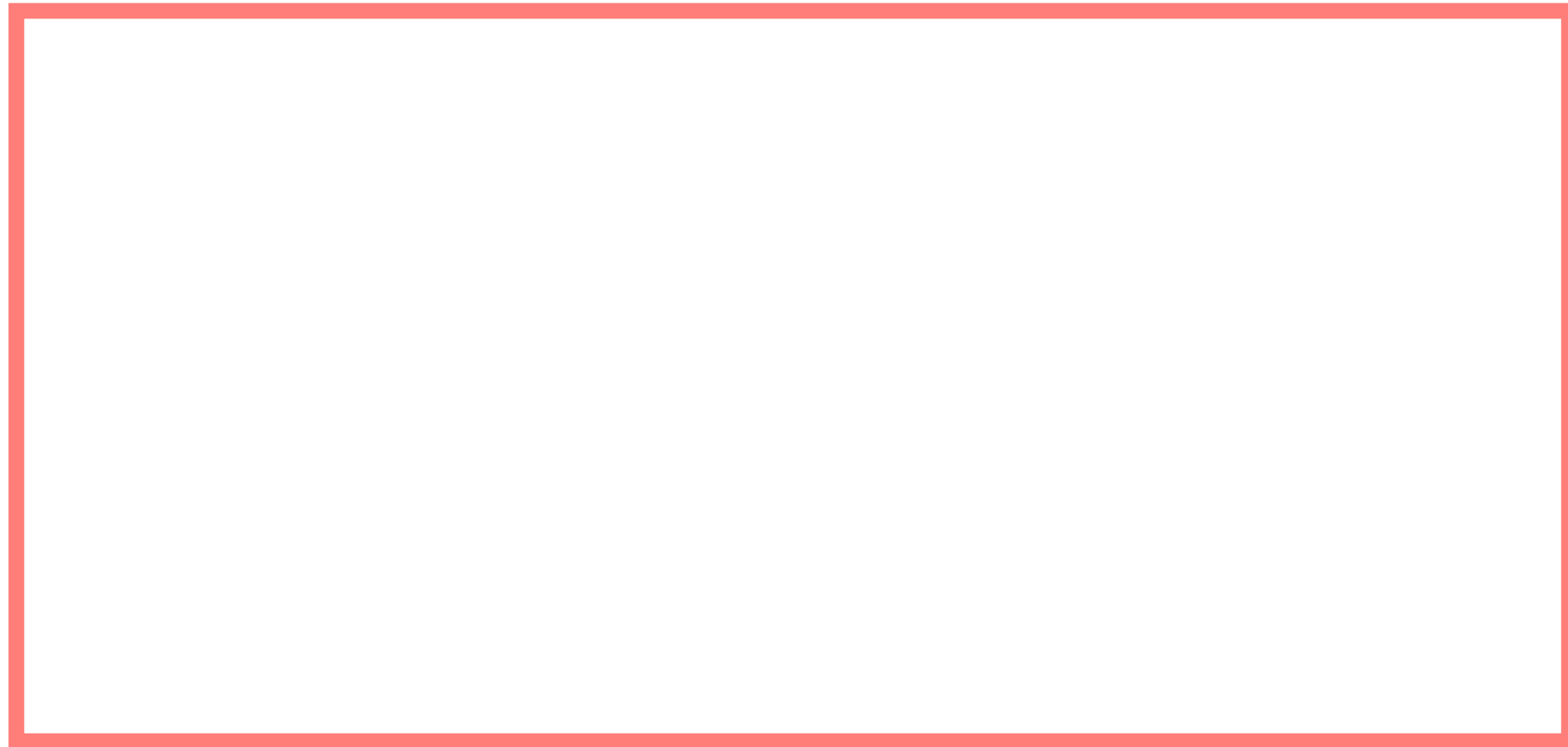
Low noise electronics
High quality factors



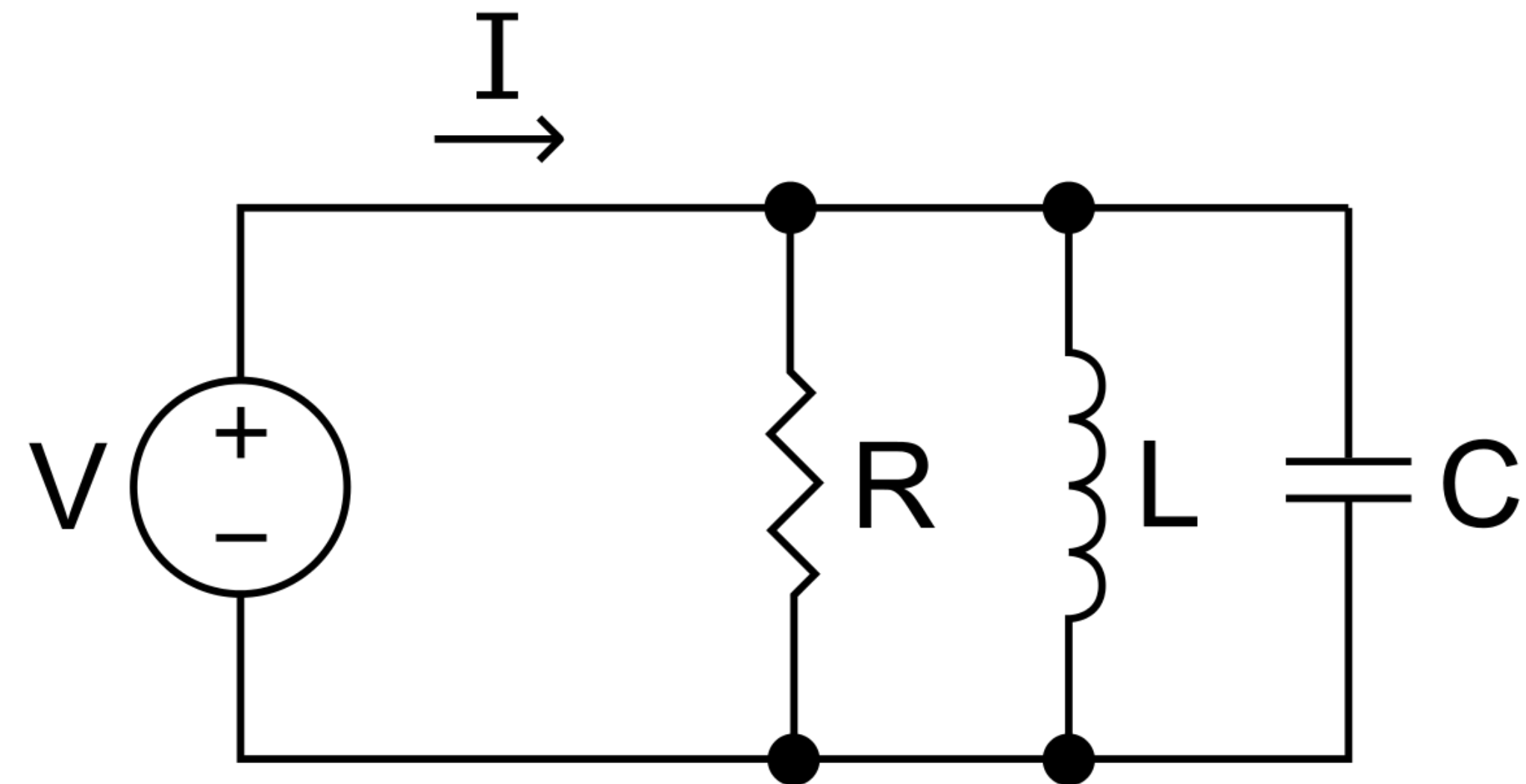
DM RADIO AND ABRACADABRA

[Kahn, Safdi, Tahler '16][Chauduri, Irwin, Graham, Mardon '18-'19]

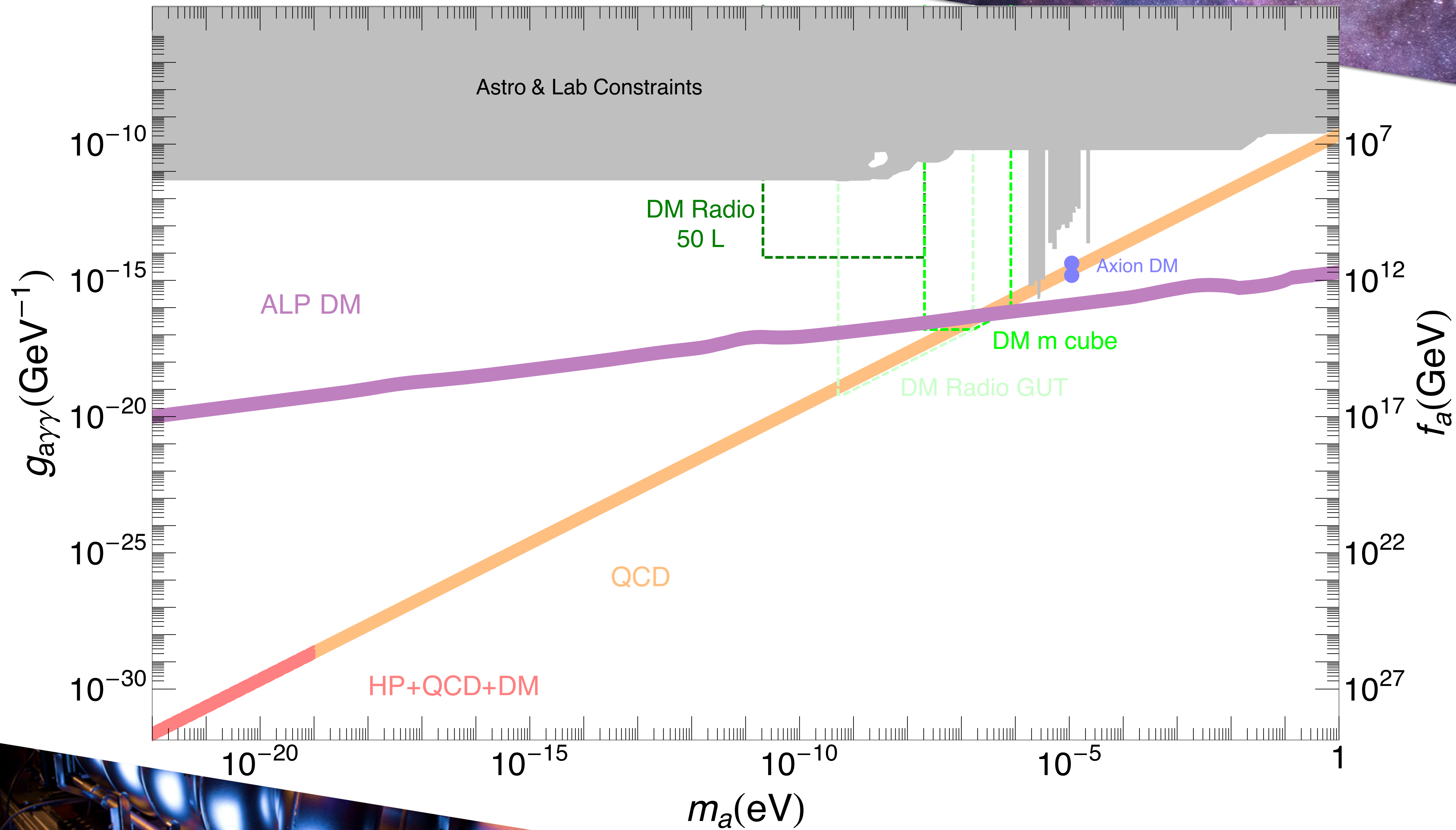
Cavity



RLC Circuit



$$\omega = \frac{1}{\sqrt{LC}}$$



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:

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

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

Cavity:

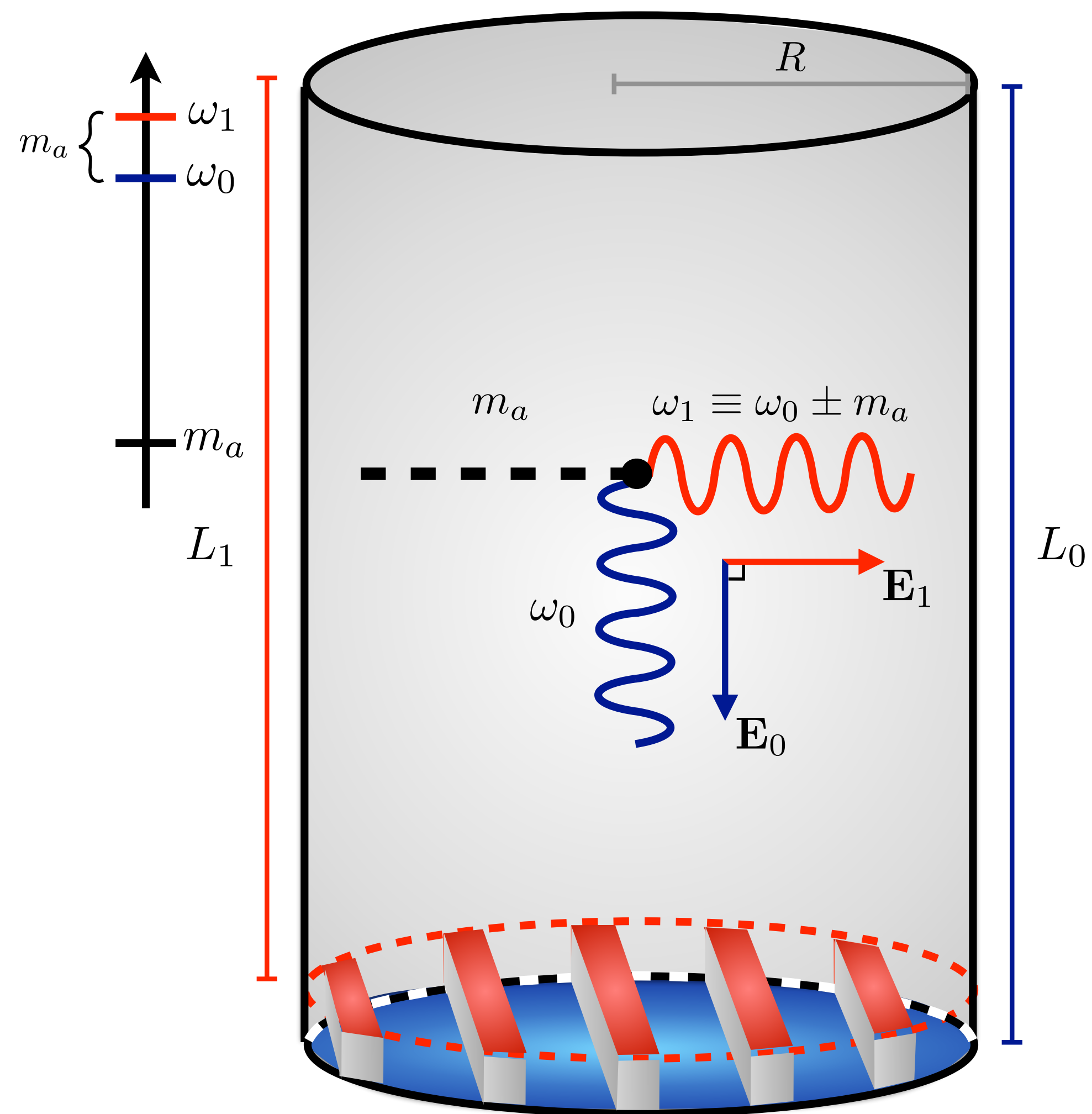
$$\sum_n \left(\partial_t^2 + \frac{\omega_n}{Q_n} \partial_t + \omega_n^2 \right) \mathbf{E}_n = g_{a\gamma\gamma} \partial_t (\mathbf{B} \partial_t a)$$

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

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

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]

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

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

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



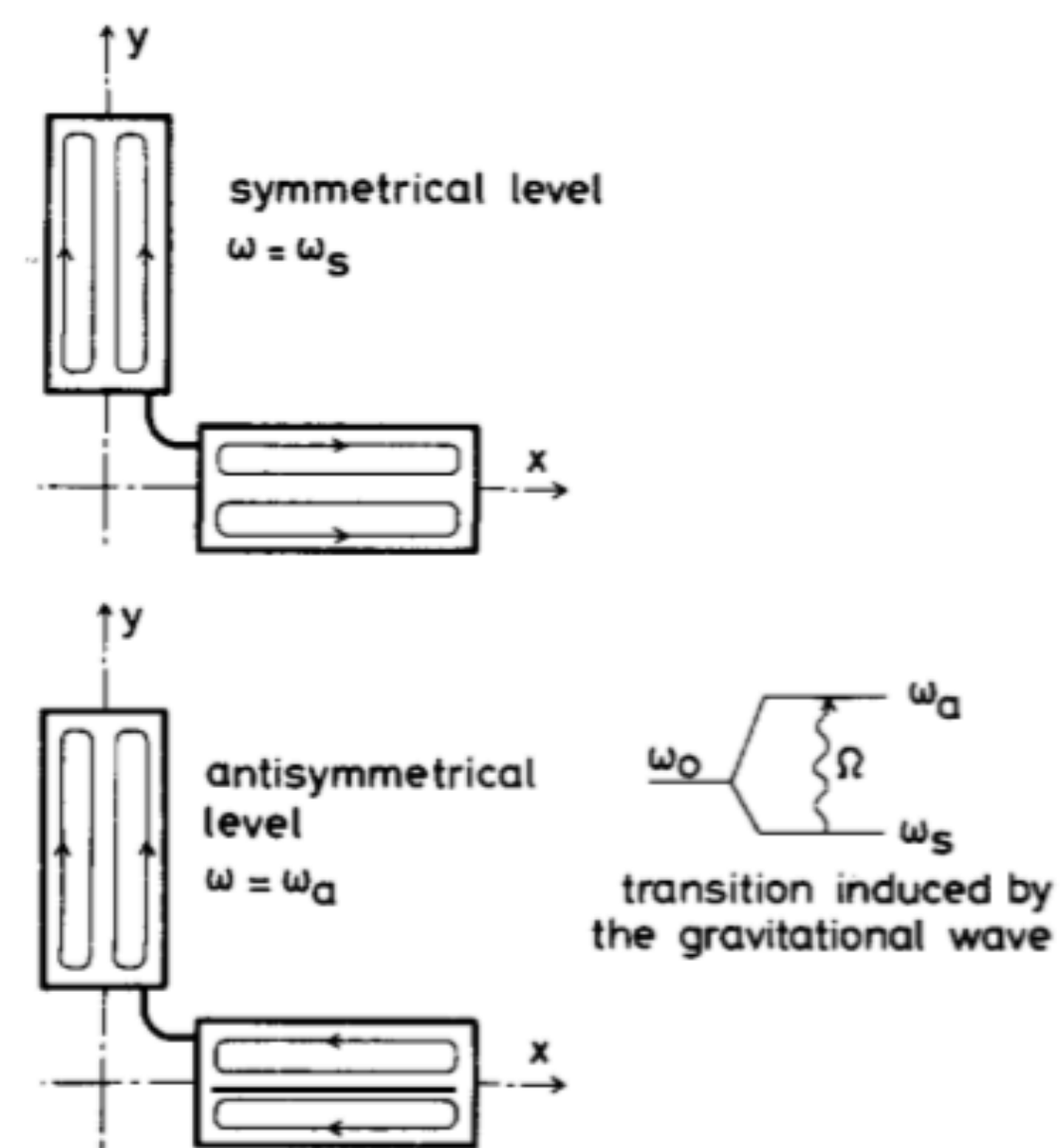
NOISE AND SENSITIVITY

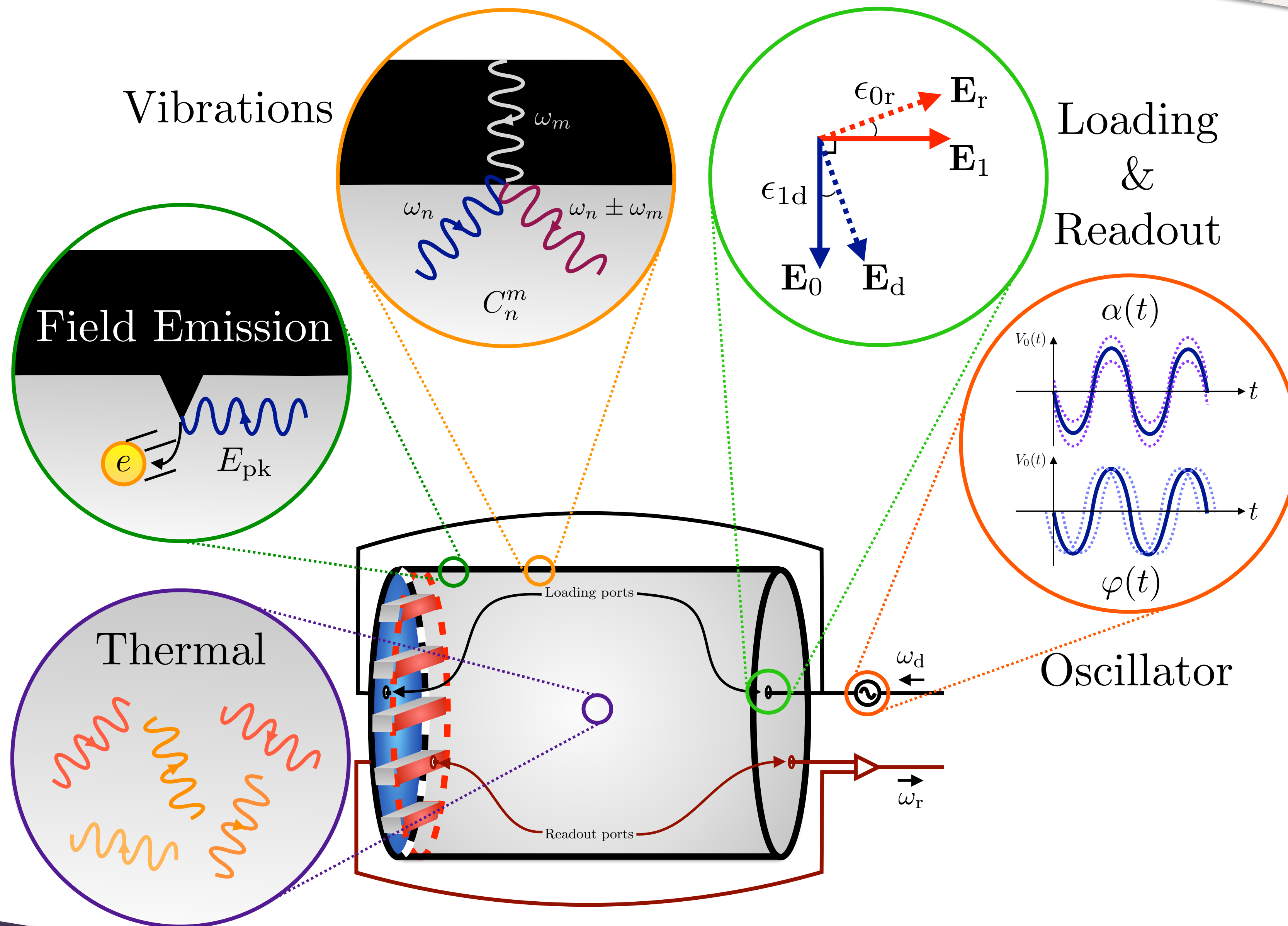
With a different geometry,
viable also for gravitational waves!

Radicati, Pegoraro, Picasso '78



MAGO '05





LEAKAGE NOISE

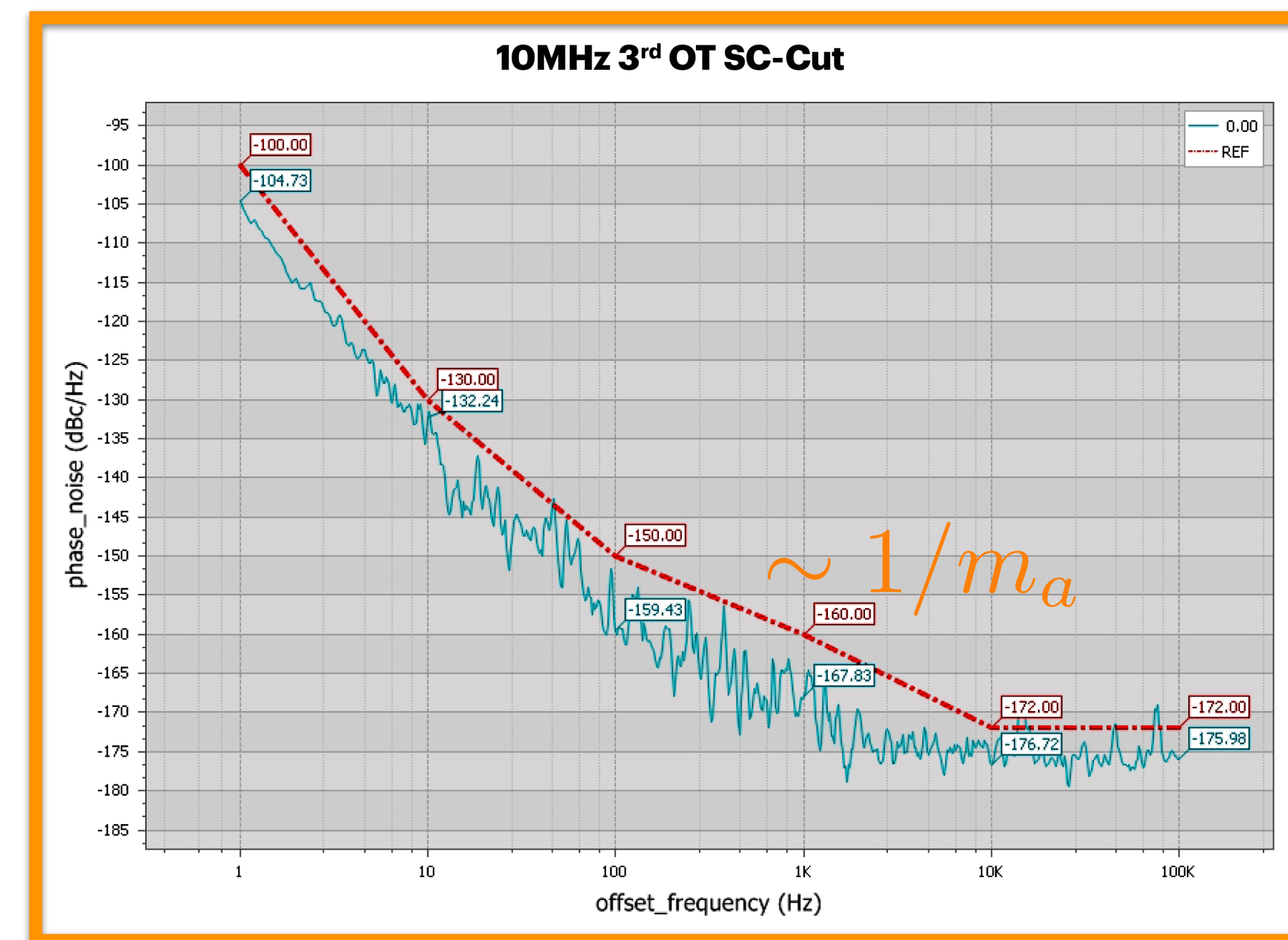
$$S_{\text{phase}}(\omega) \simeq \frac{1}{2} \epsilon_{1d}^2 S_{\phi}(\omega - \omega_0) \boxed{\frac{(\omega \omega_1 / Q_1)^2}{(\omega^2 - \omega_1^2)^2 + (\omega \omega_1 / Q_1)^2}} \frac{\omega_0 Q_1}{\omega_0 Q_0} P_{\text{in}}$$

Cavity Response

LEAKAGE NOISE

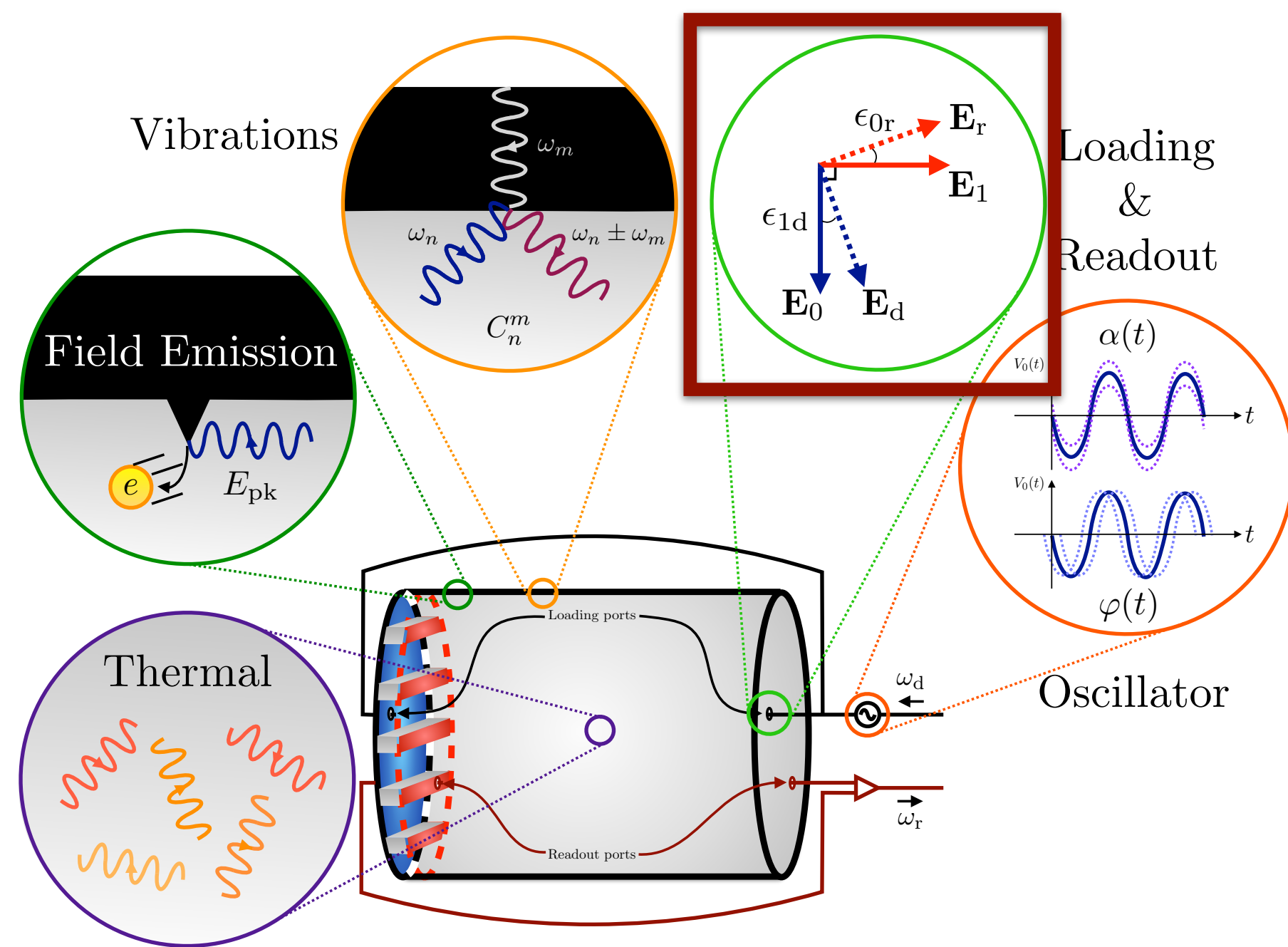
$$S_{\text{phase}}(\omega) \simeq \frac{1}{2} \epsilon_{1d}^2 \boxed{S_{\phi}(\omega - \omega_0)} \frac{(\omega \omega_1 / Q_1)^2}{(\omega^2 - \omega_1^2)^2 + (\omega \omega_1 / Q_1)^2} \frac{\omega_0 Q_1}{\omega_0 Q_0} P_{\text{in}}$$

$\sim 1/m_a$

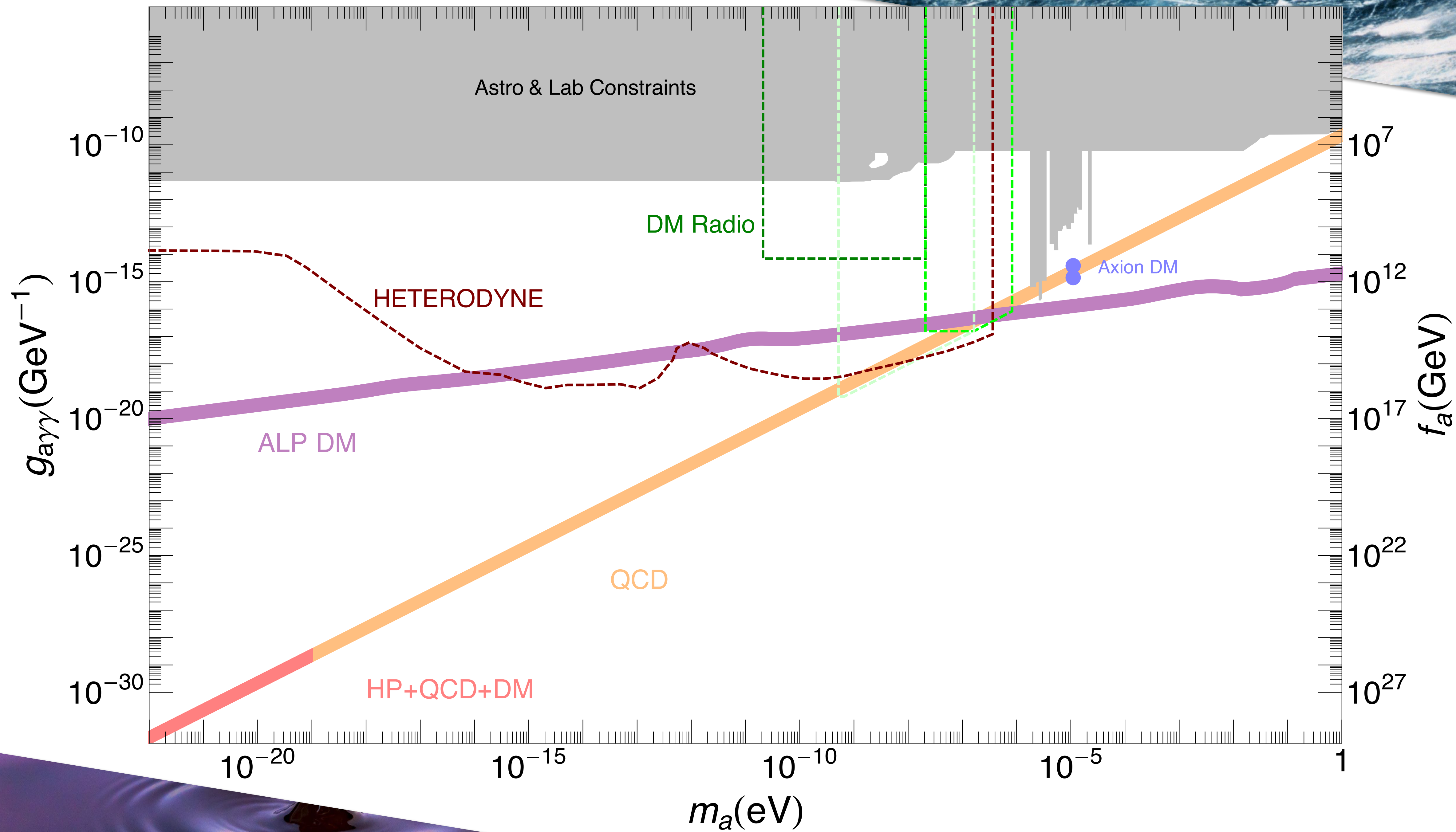


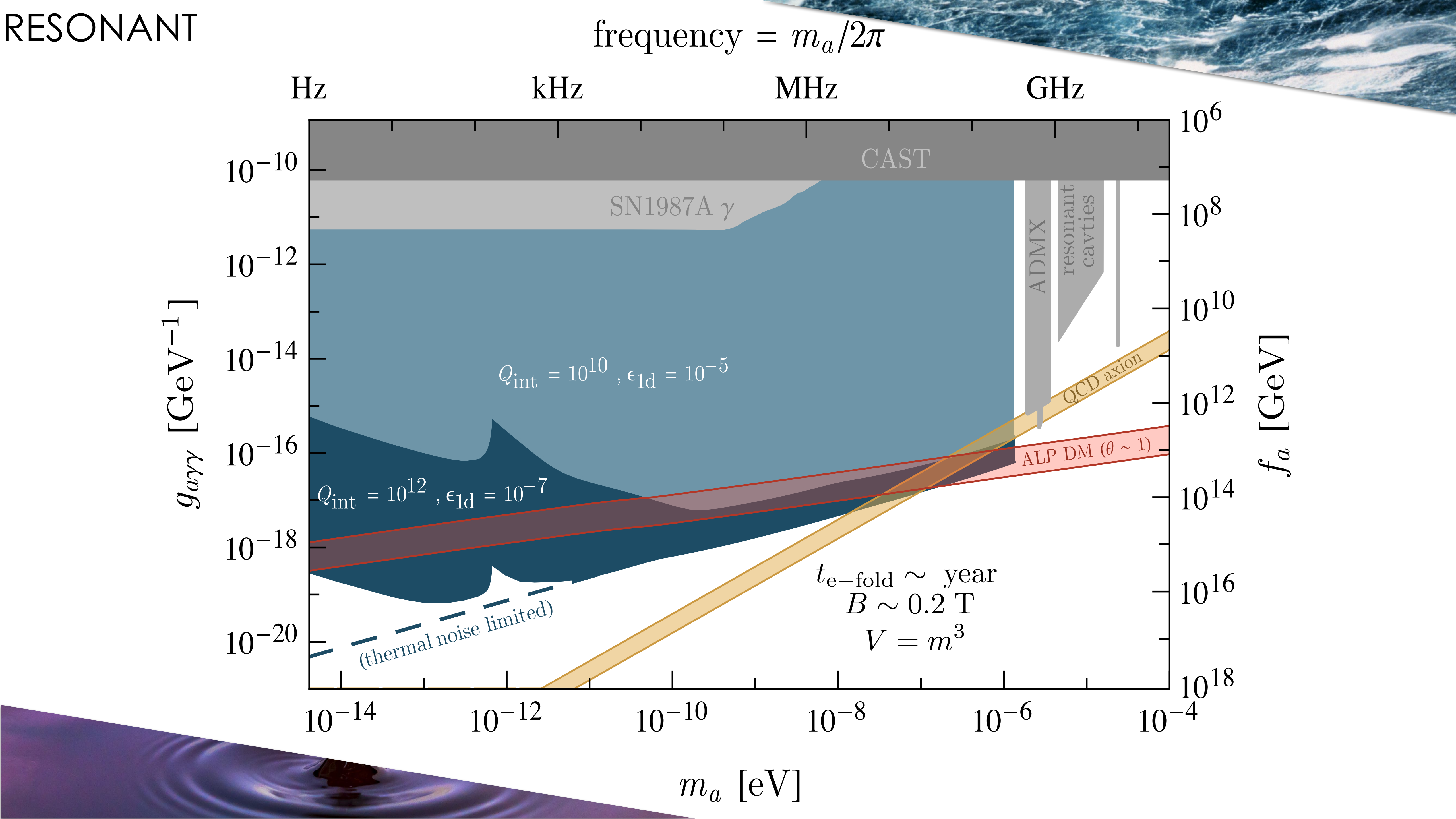
LEAKAGE NOISE

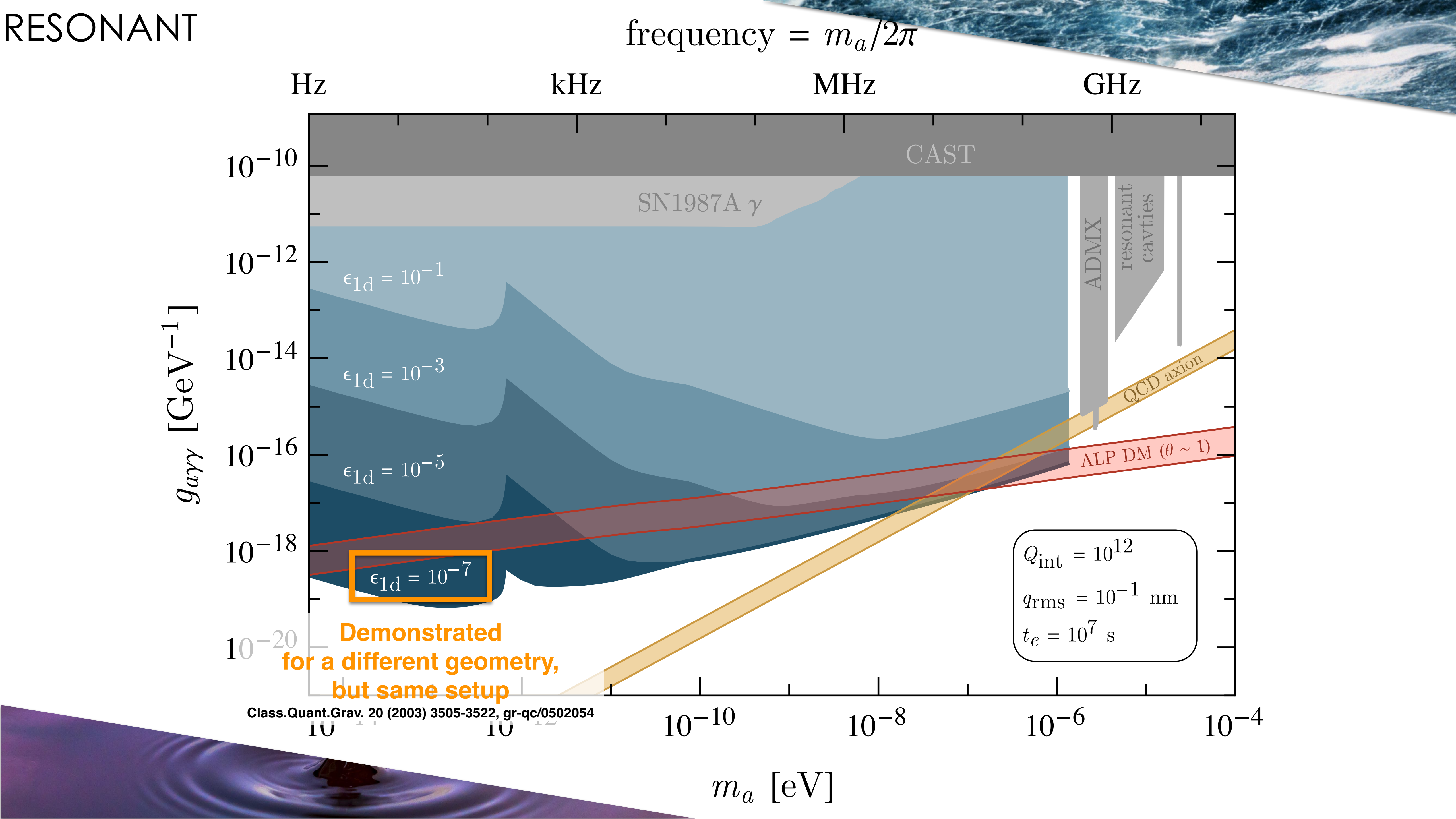
$$S_{\text{phase}}(\omega) \simeq \frac{1}{2} \epsilon_{1d}^2 S_{\phi}(\omega - \omega_0) \frac{(\omega \omega_1 / Q_1)^2}{(\omega^2 - \omega_1^2)^2 + (\omega \omega_1 / Q_1)^2} \frac{\omega_0 Q_1}{\omega_0 Q_0} P_{\text{in}}$$

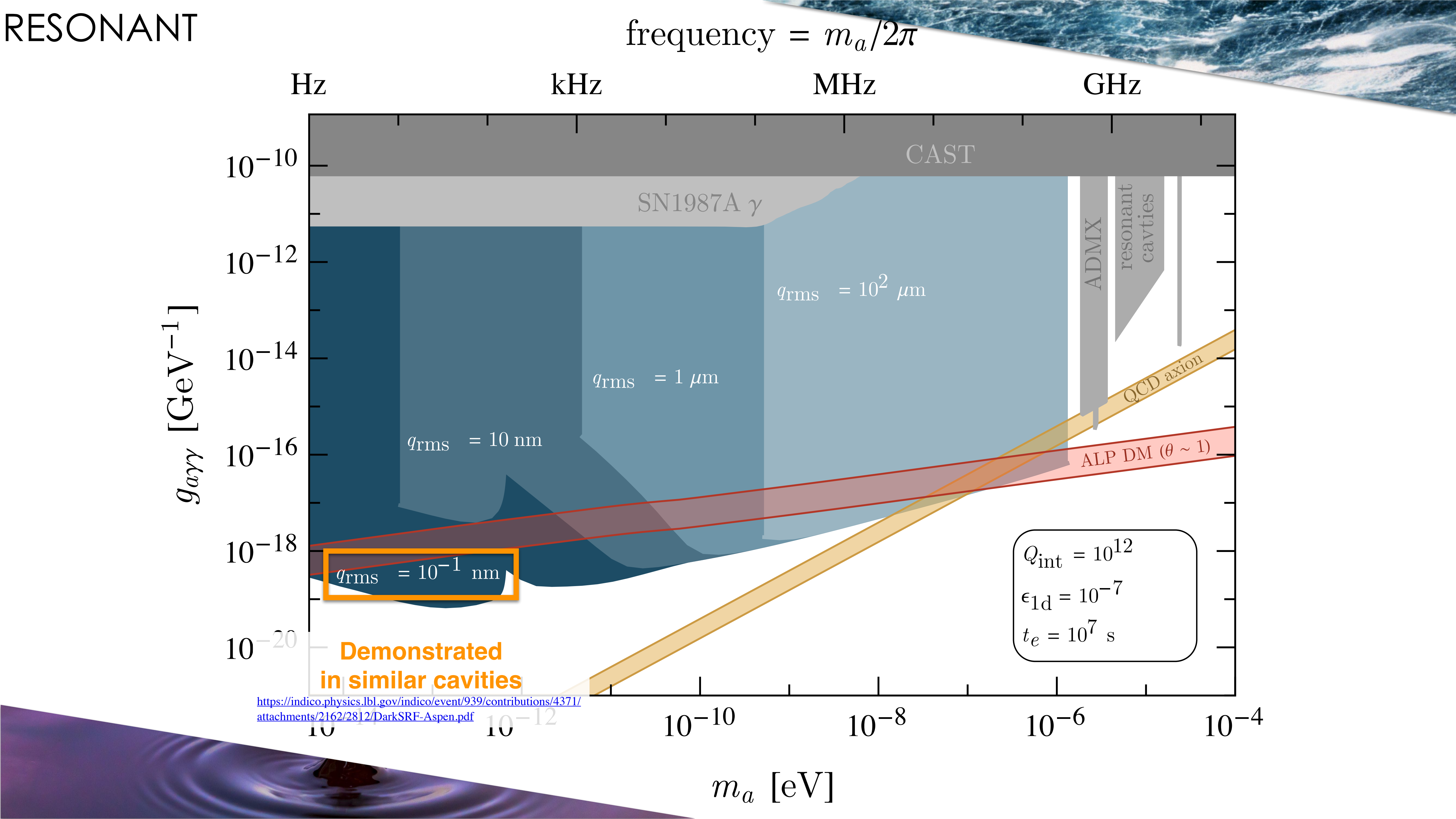


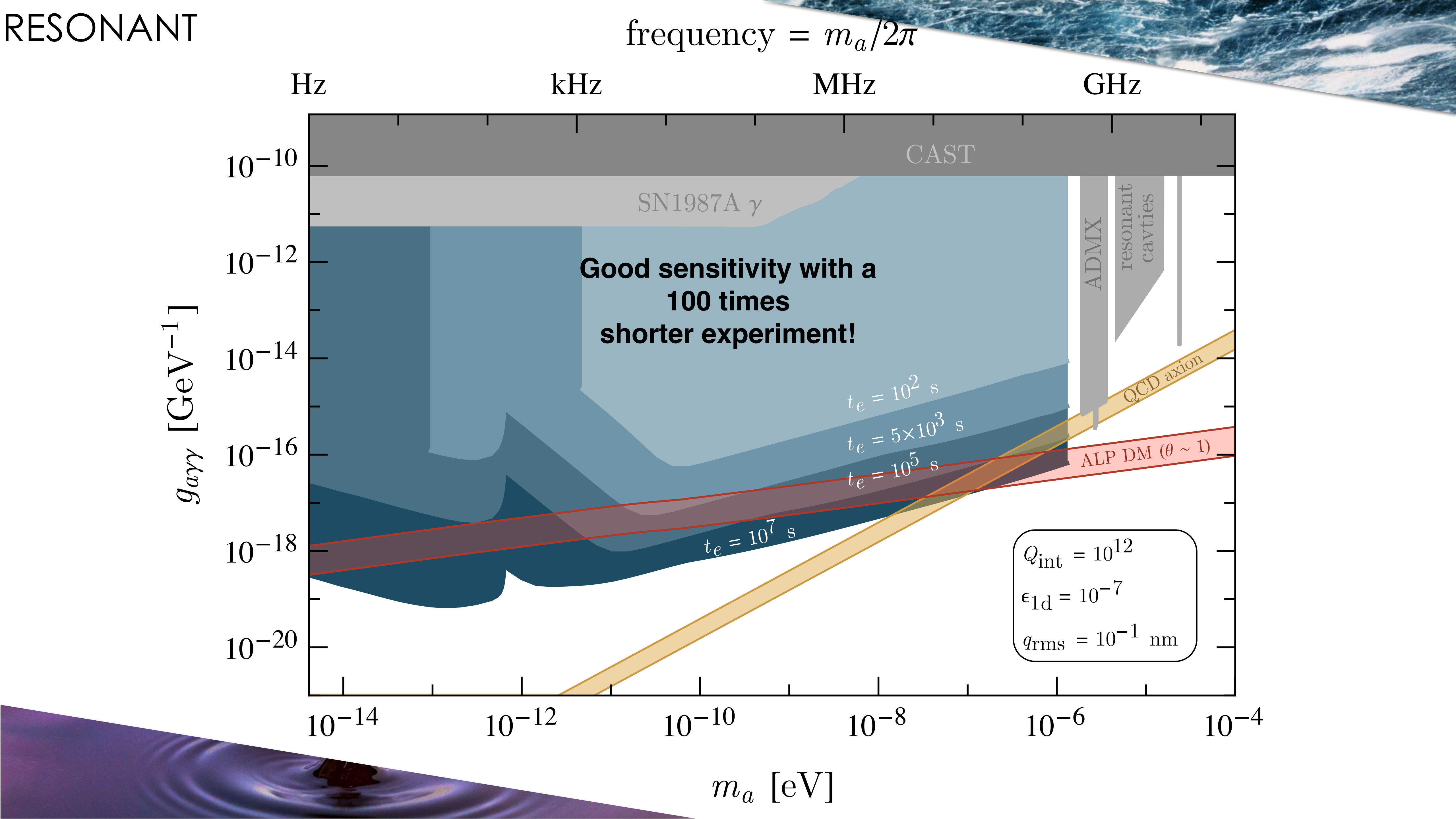
**From MAGO
and other similar cavities**

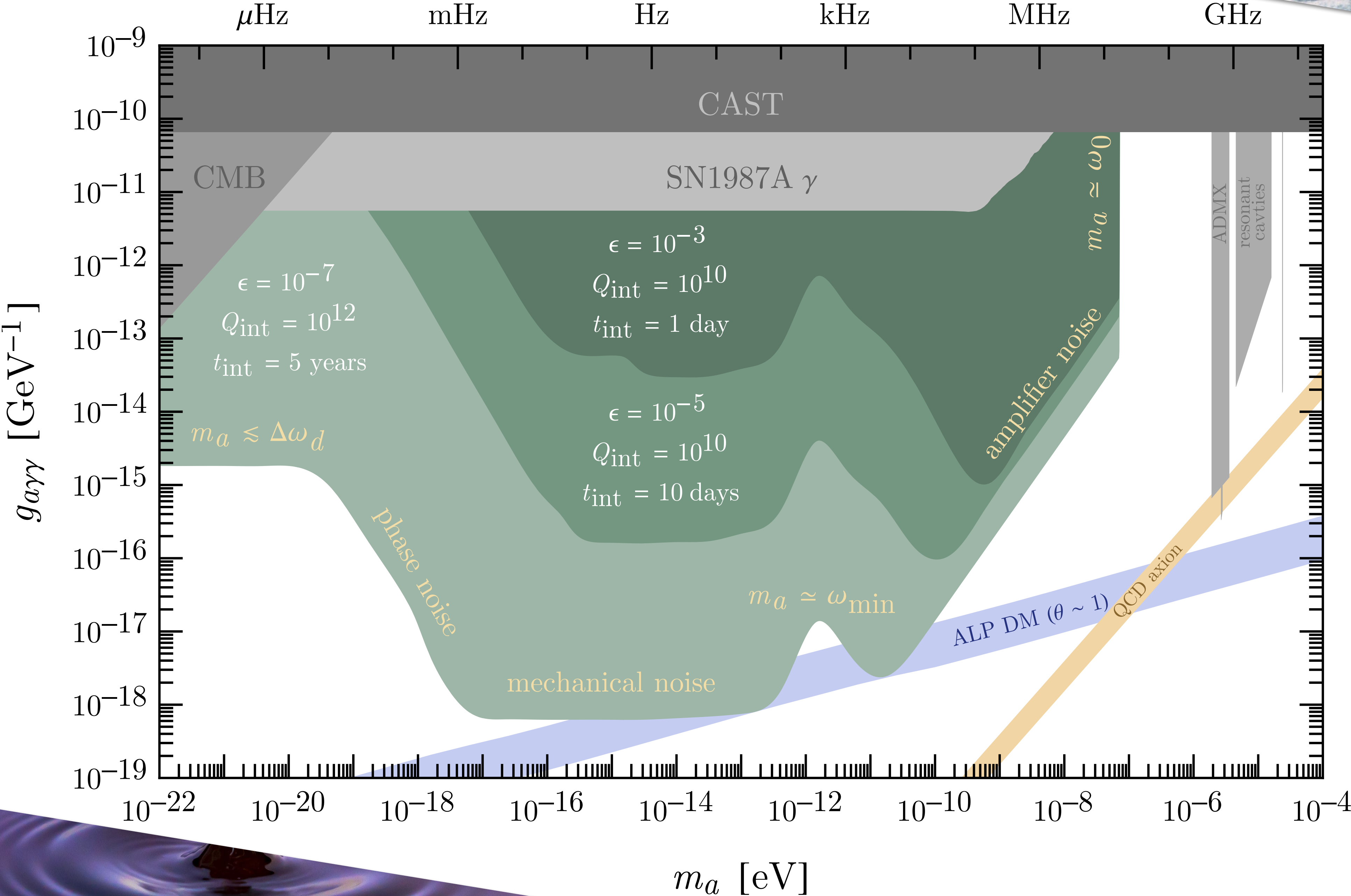










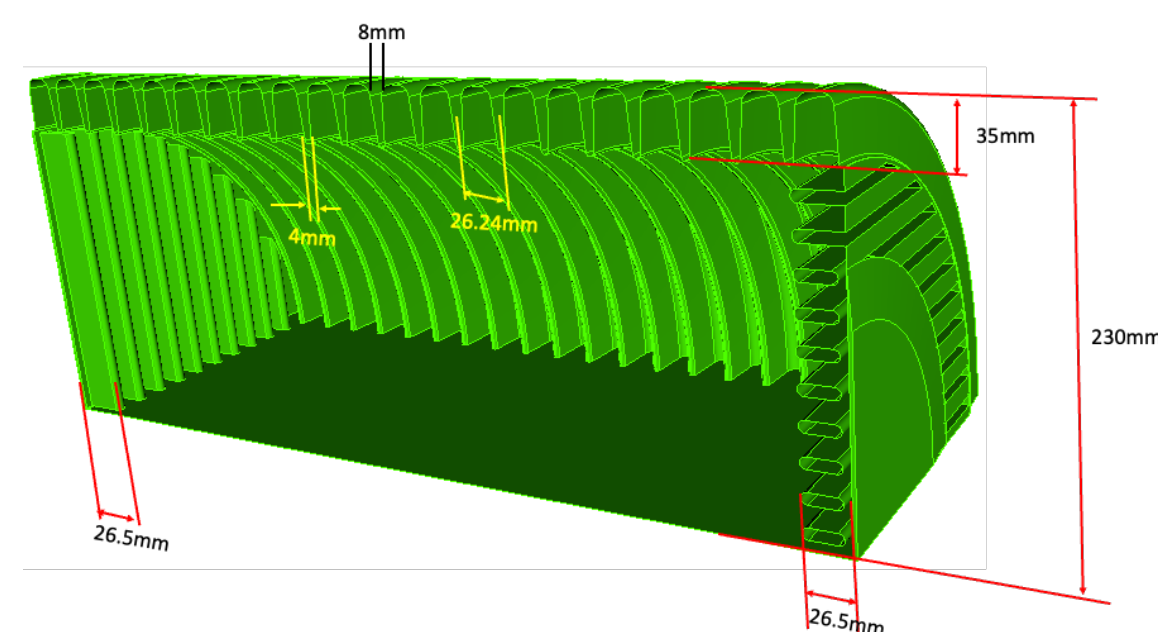


THREE PROTOTYPES [~ 1 YEAR]

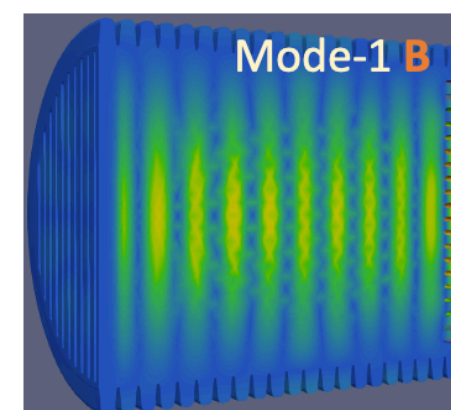
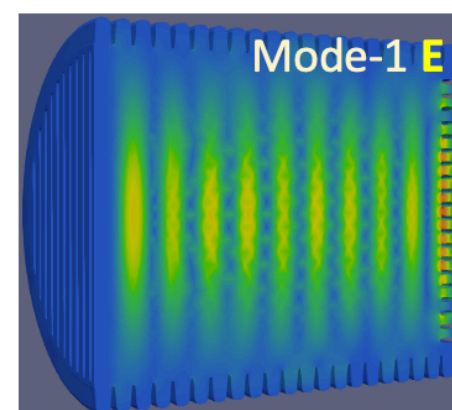


2507.07173

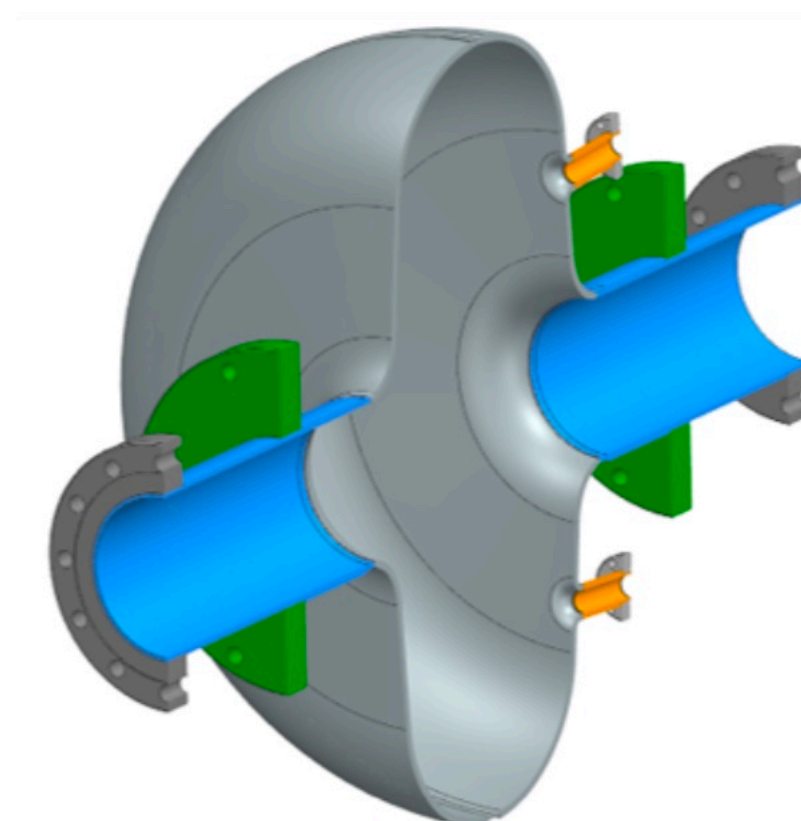
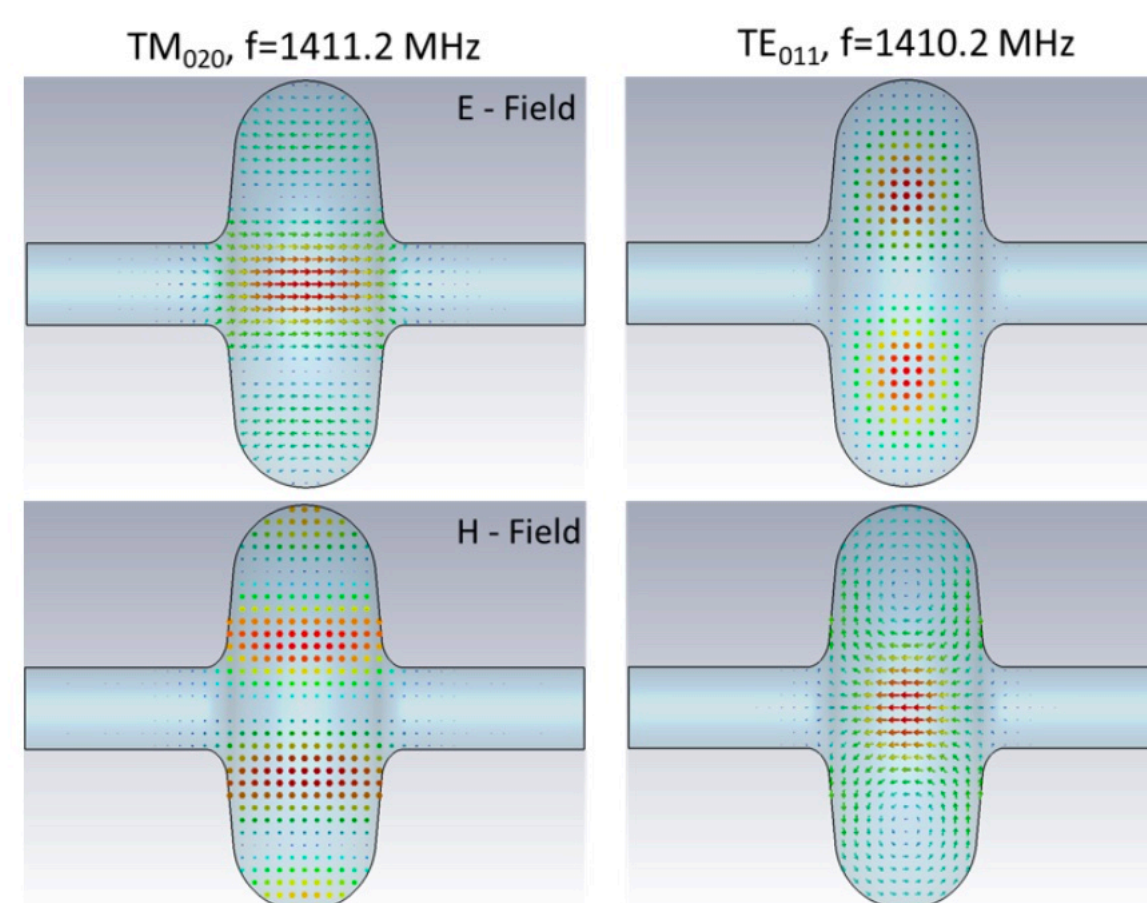
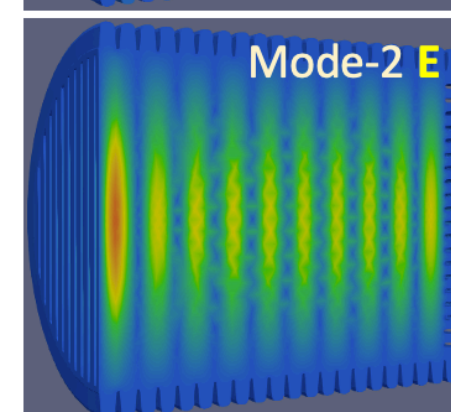
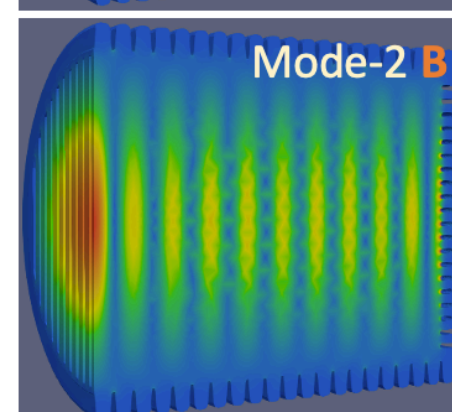
arXiv:2207.11346



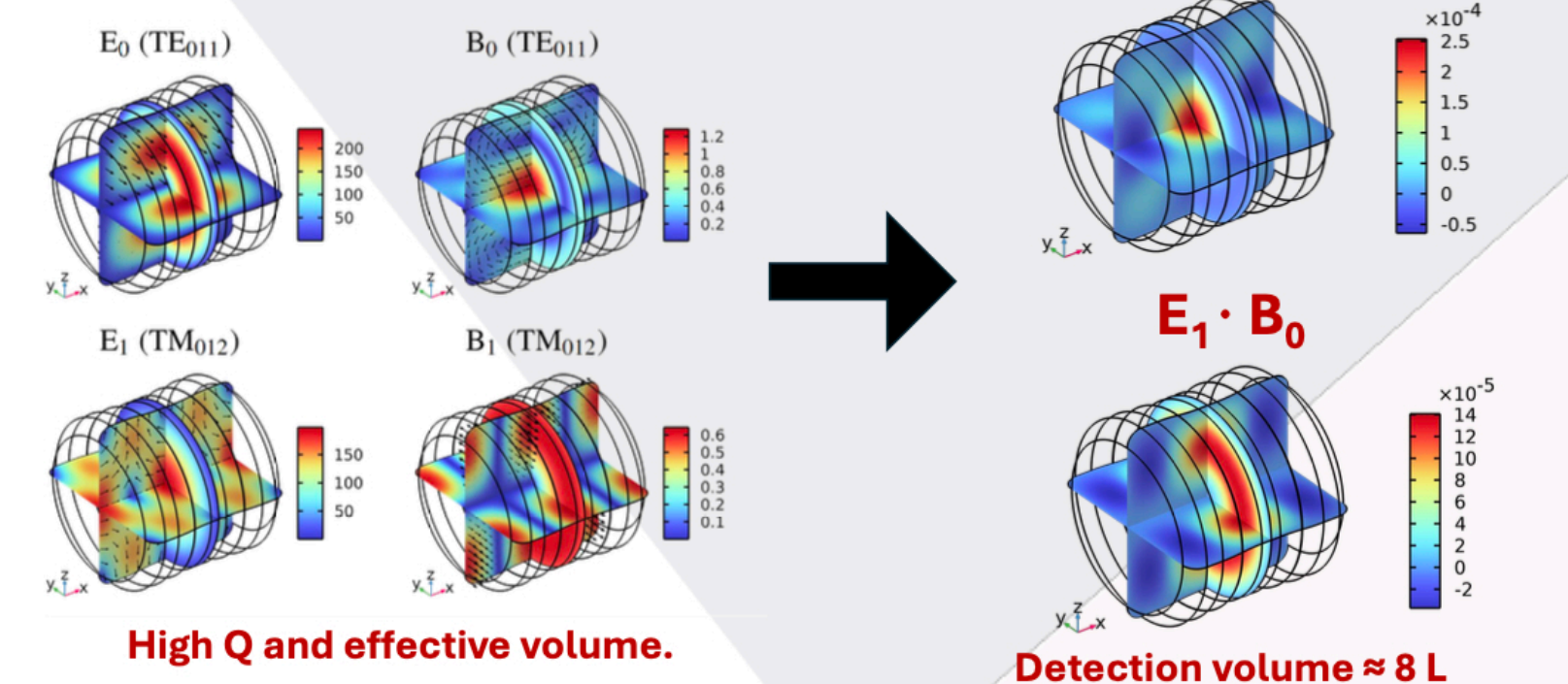
HE11
polatization-1 (E,B)



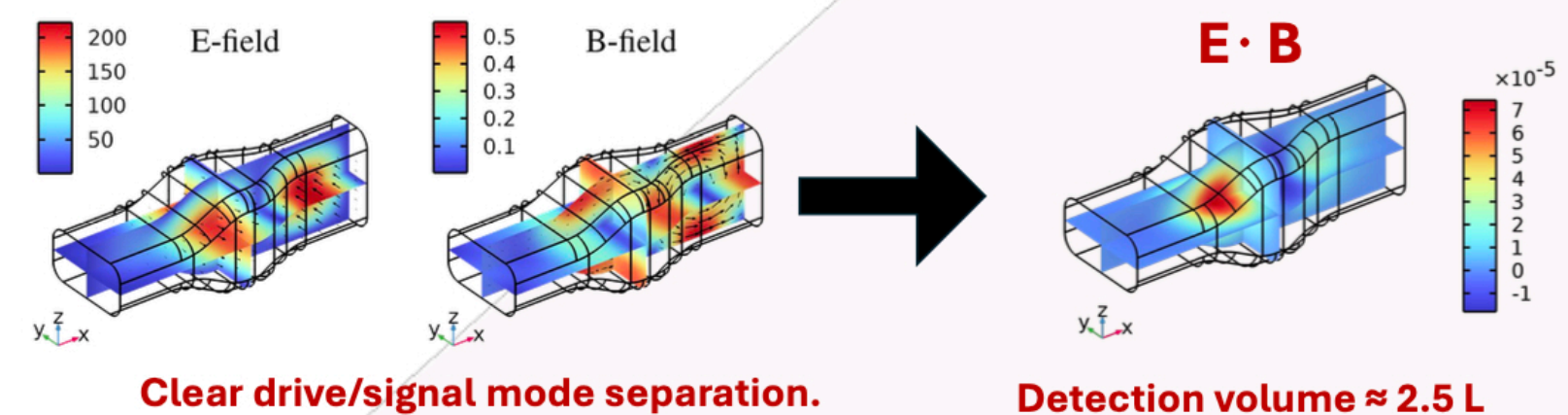
HE11
polatization-2 (B,E)



Cylindrical Concept



Guide-Based Concept



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

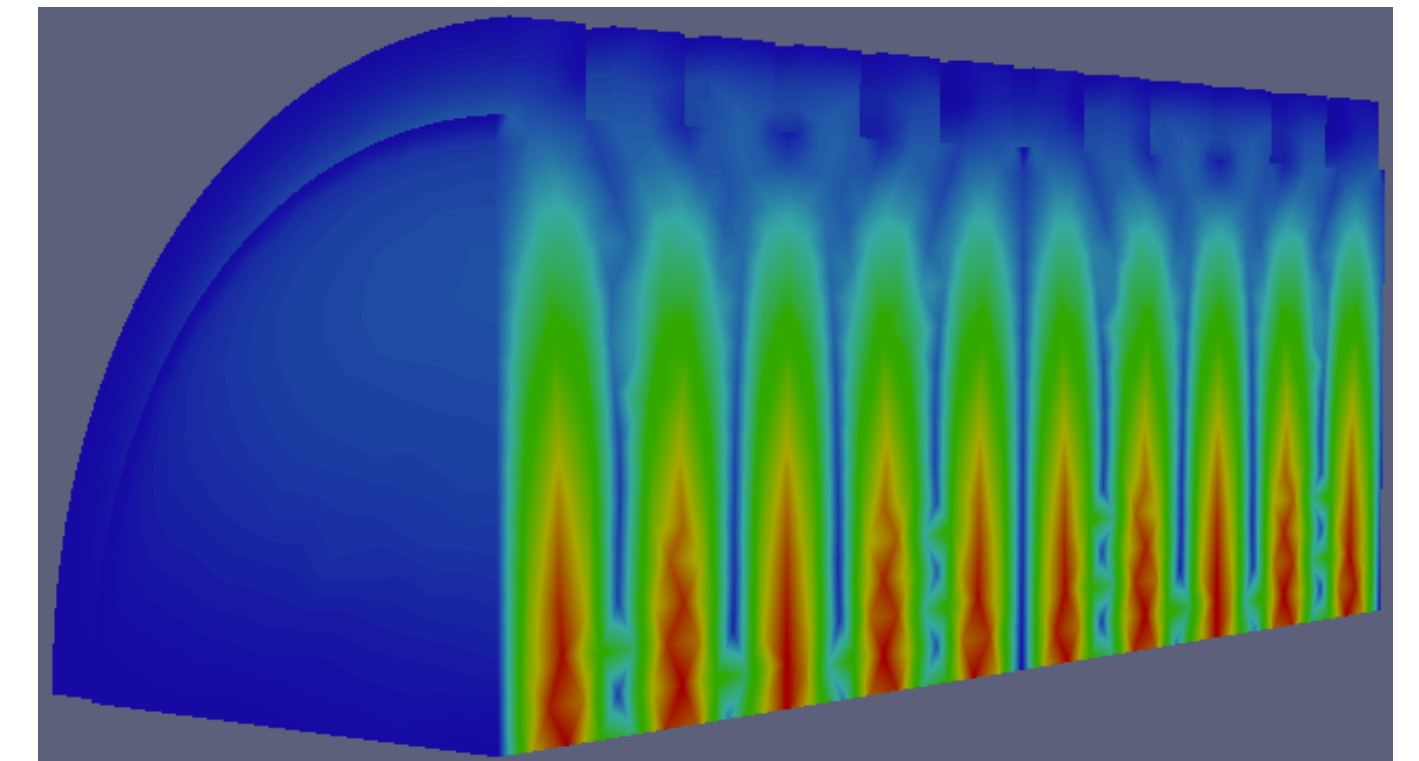
All slides from: Z. Li and M. Oriunno



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

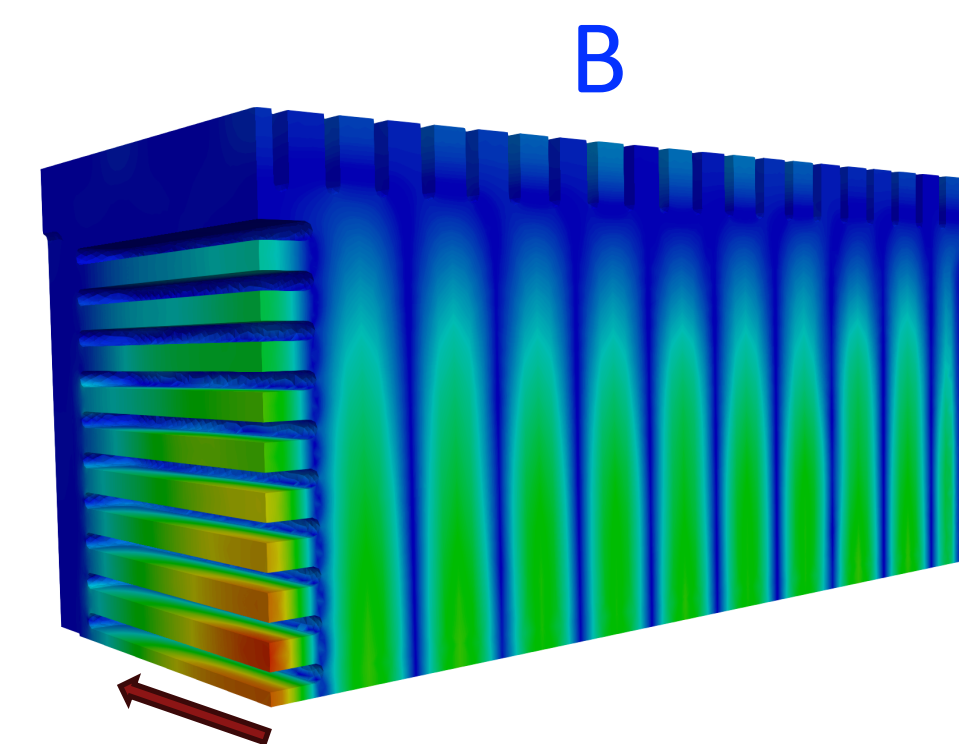
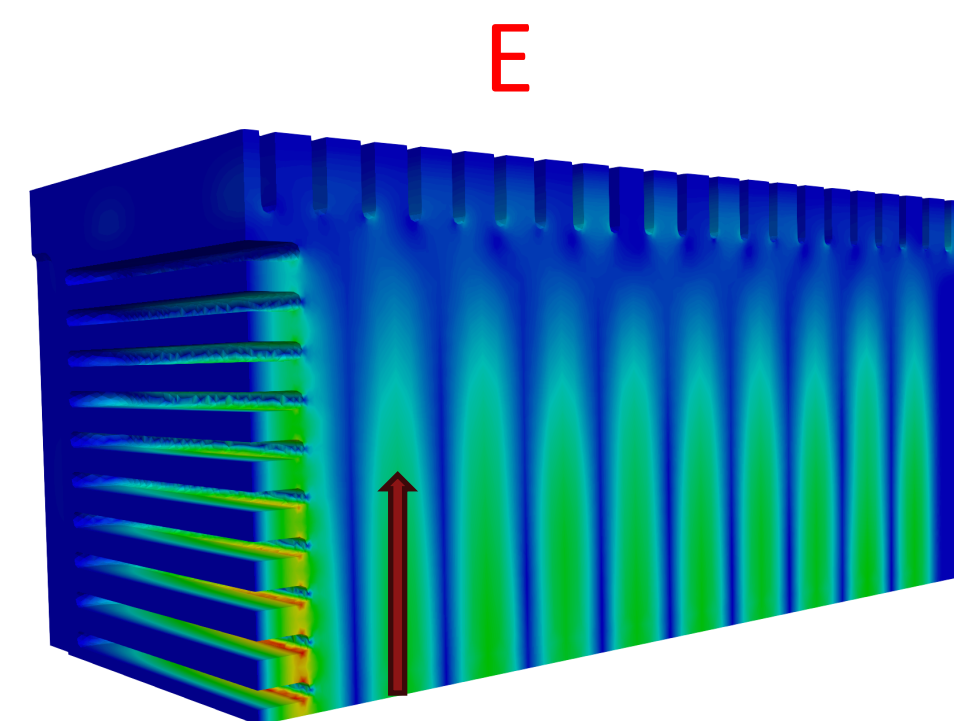
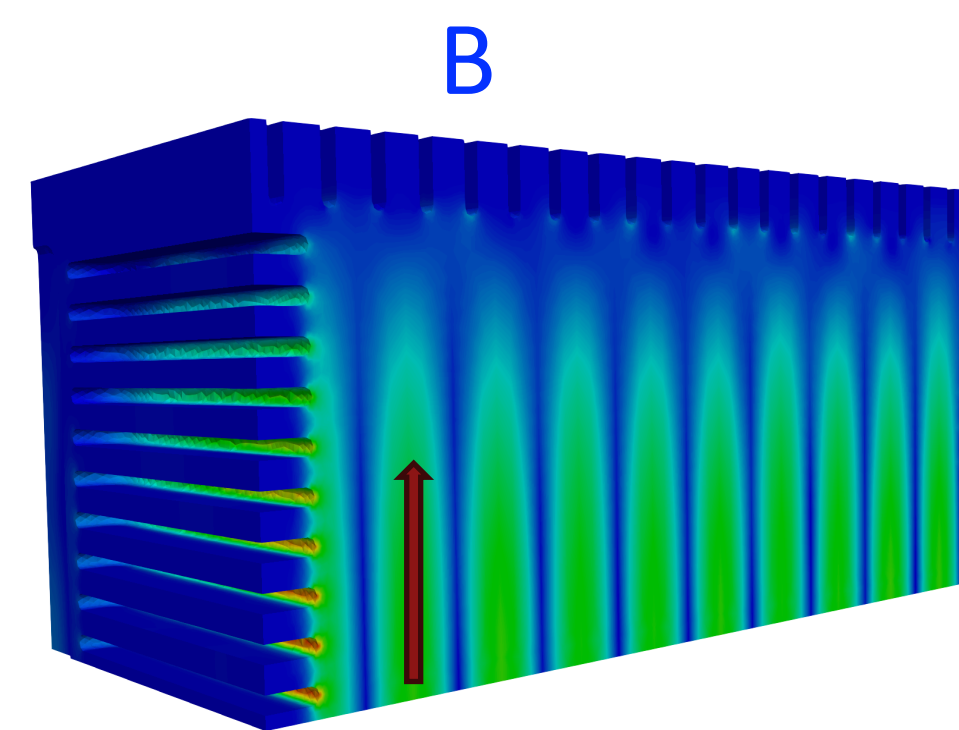
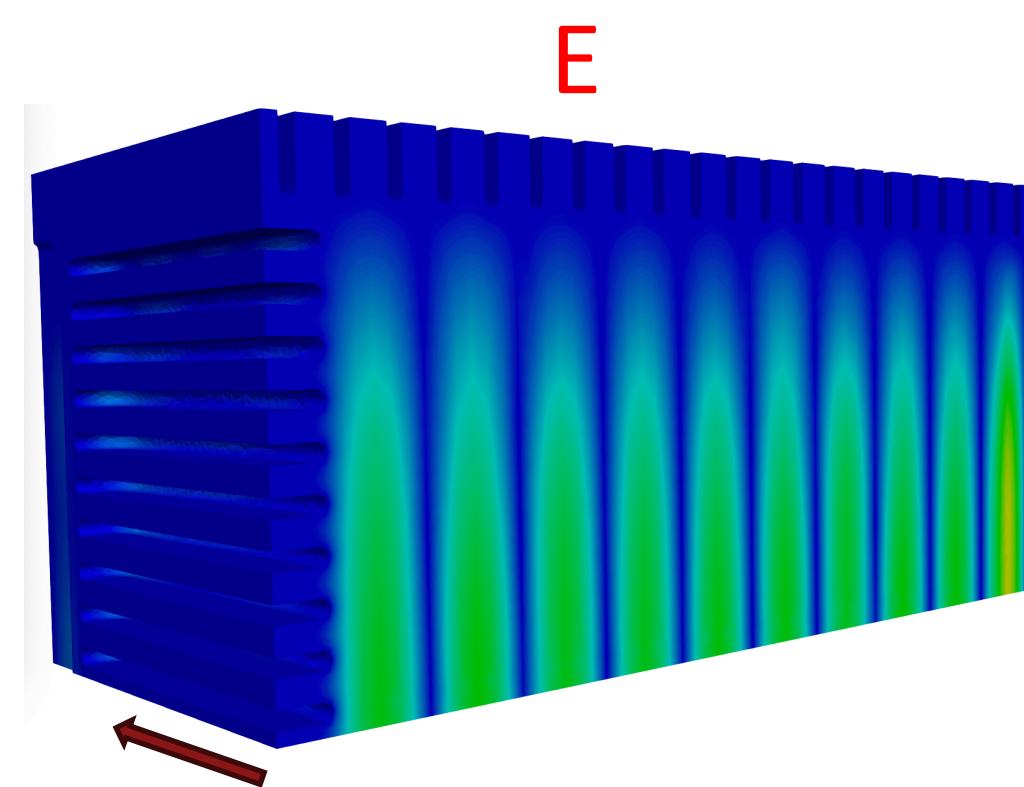
HE11 mode

- 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



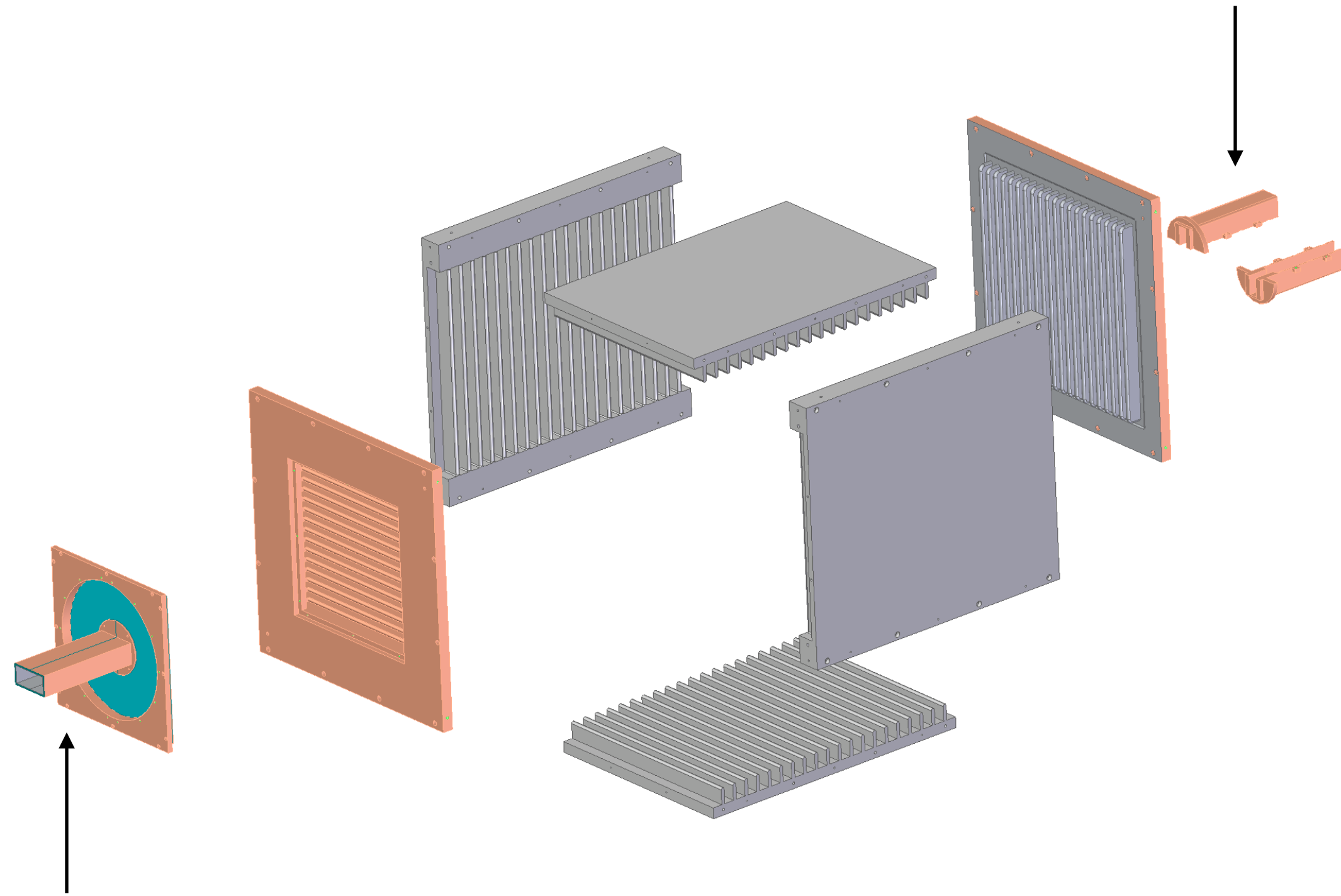
1/4 wavelength fins on the endplates

X-polarization

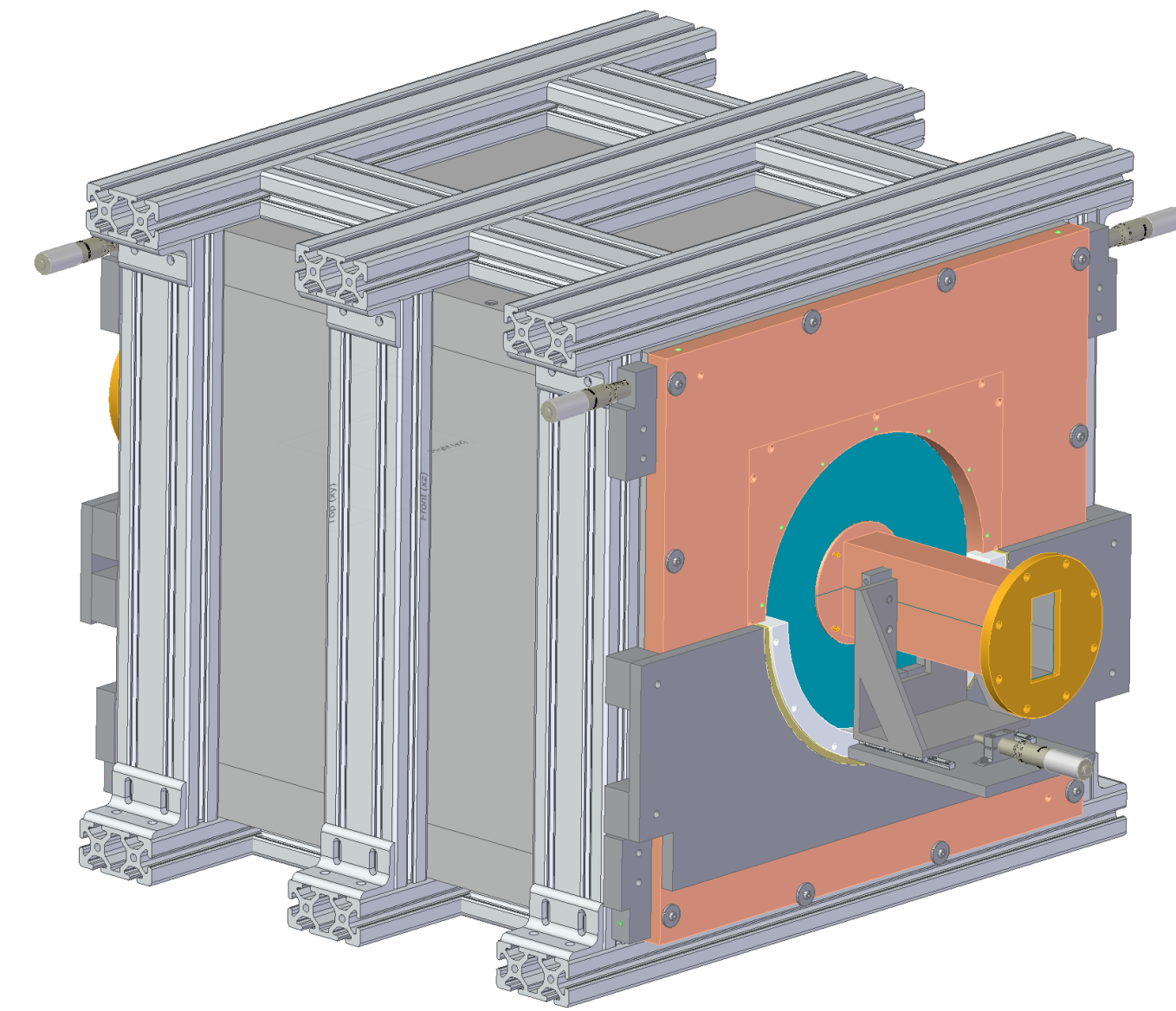


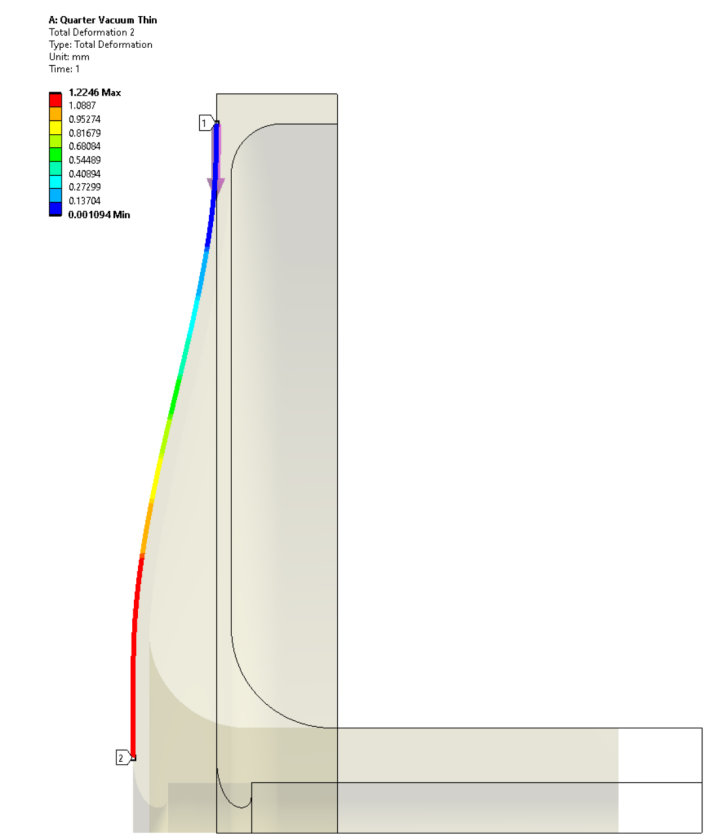
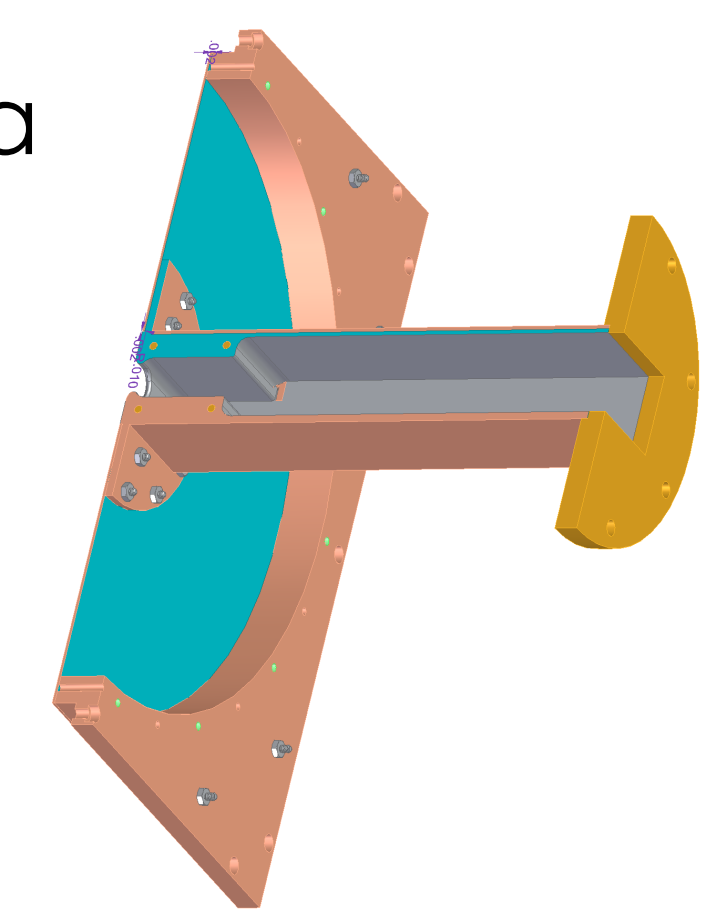
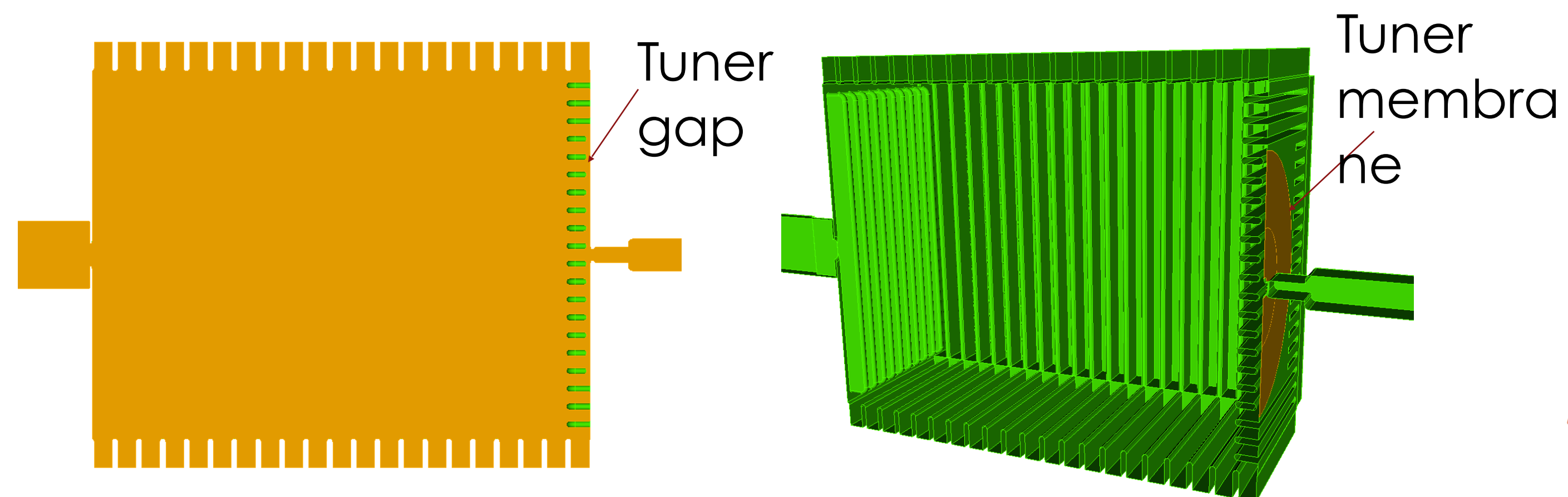
Y-polarization

Tunable mode coupler



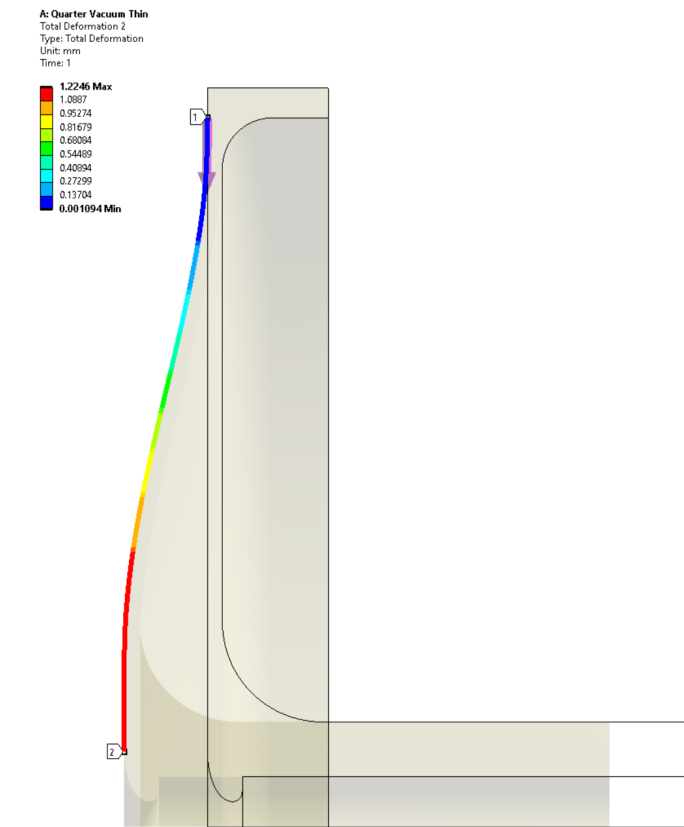
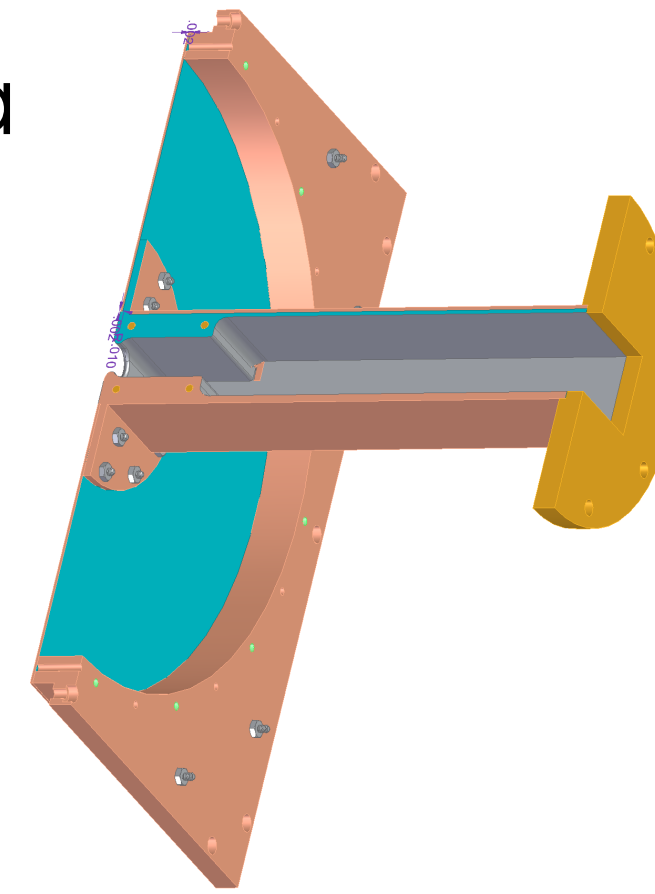
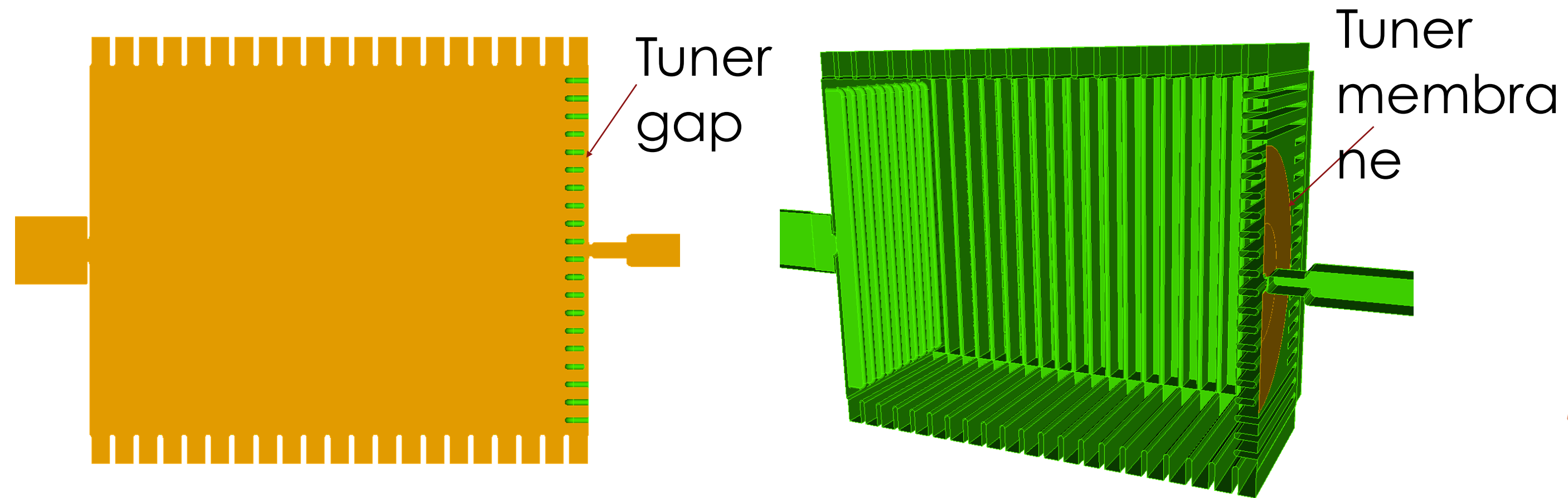
Fixed mode coupler



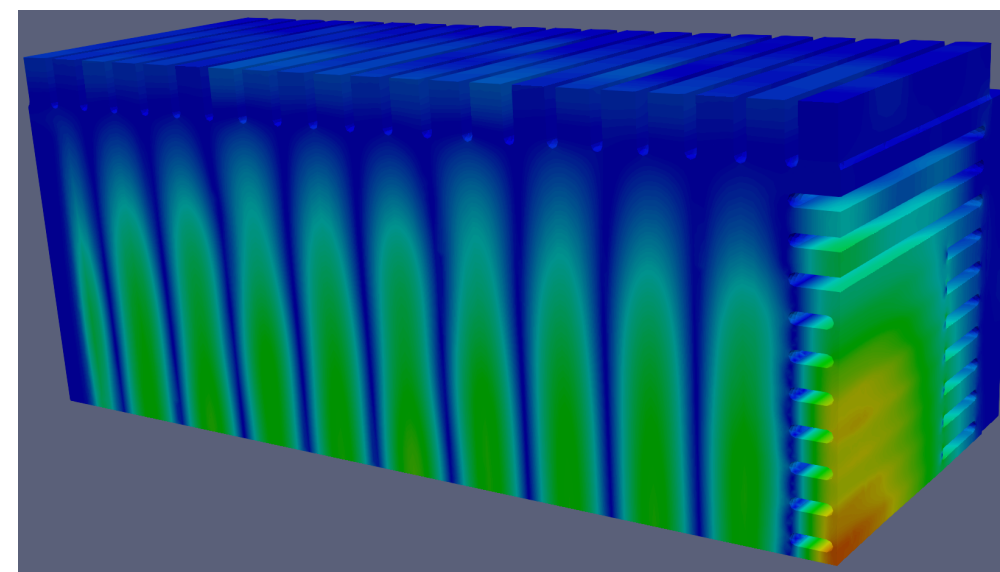


Membrane deformation

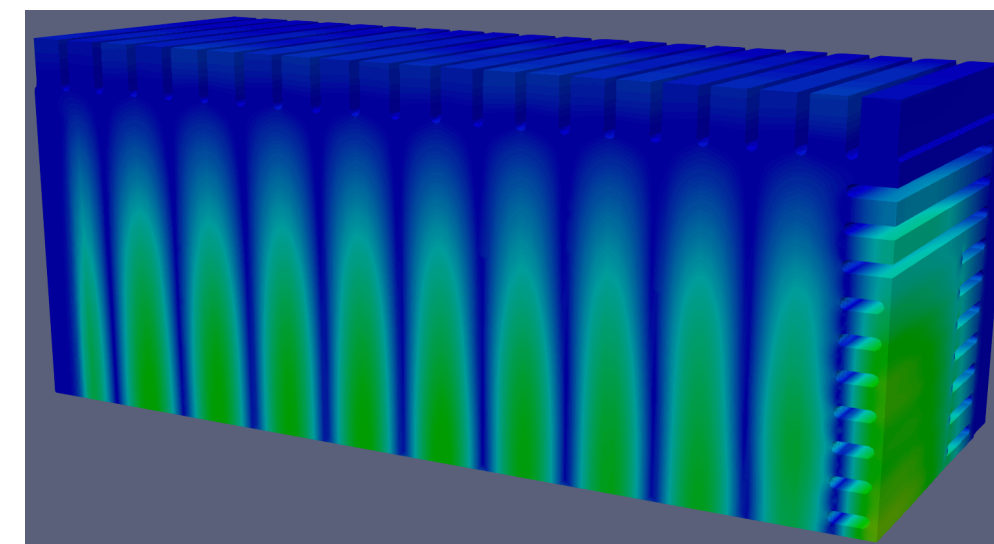




Membrane deformation



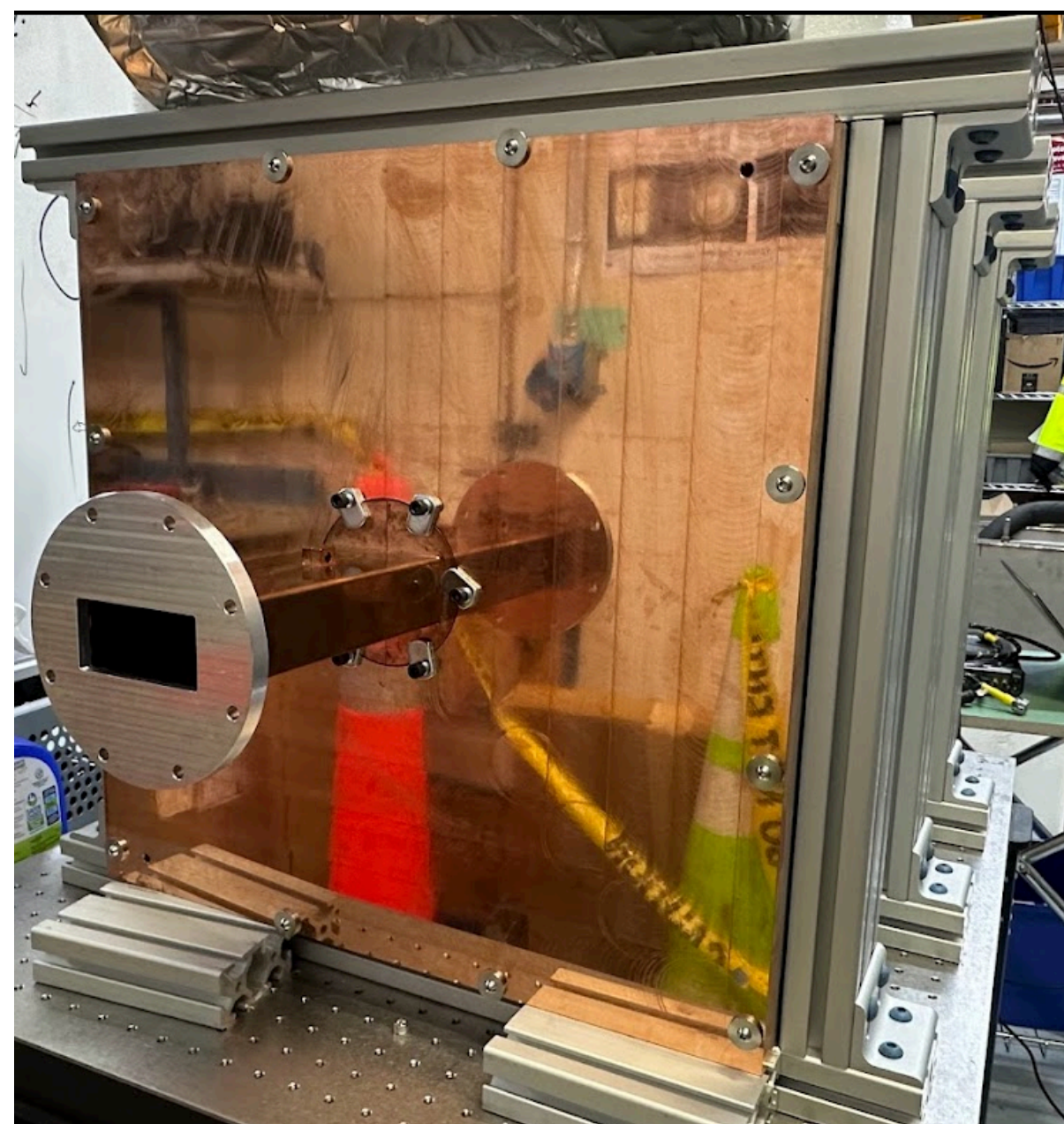
gap = -1mm
 $f \sim 2.8564$ GHz



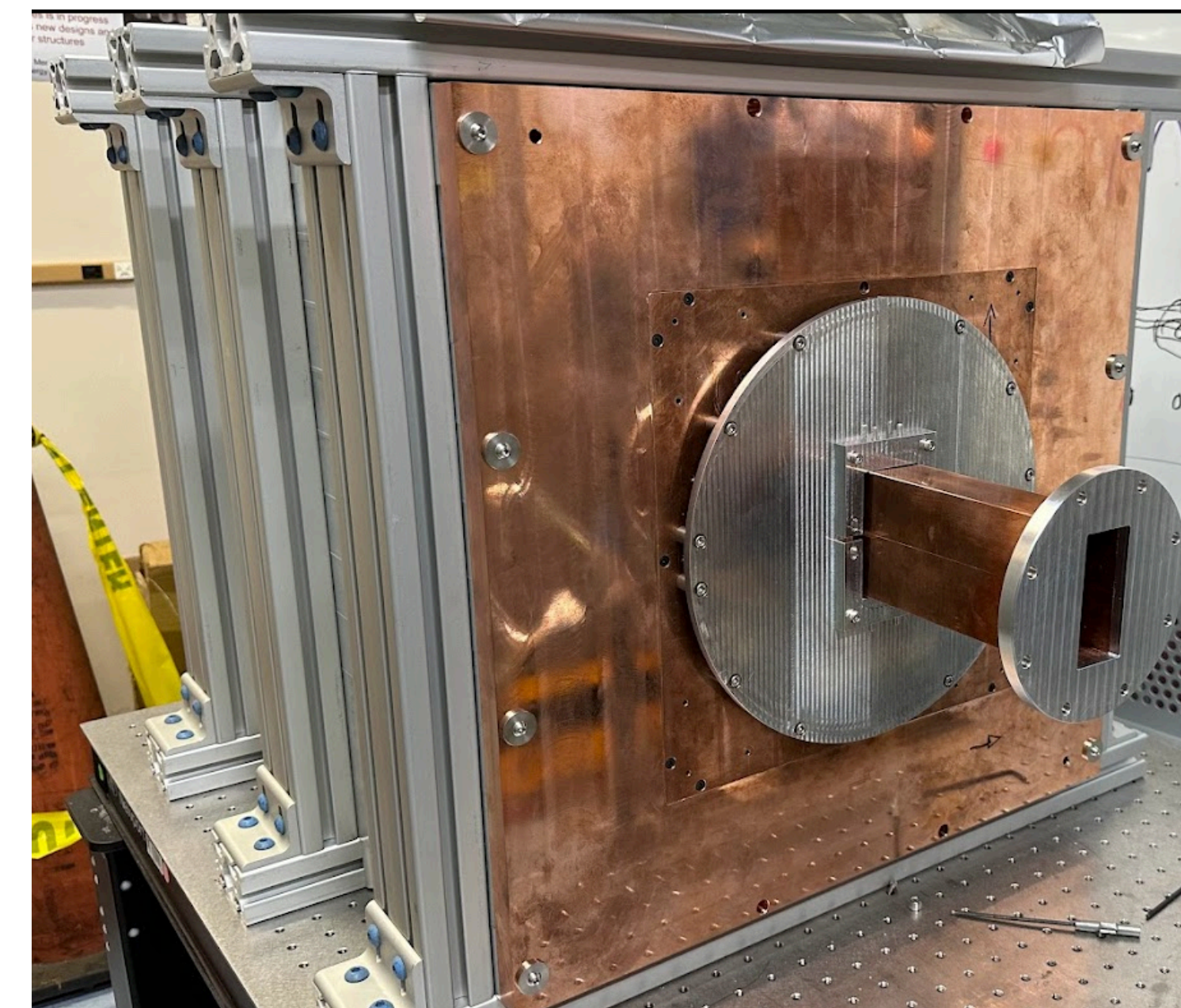
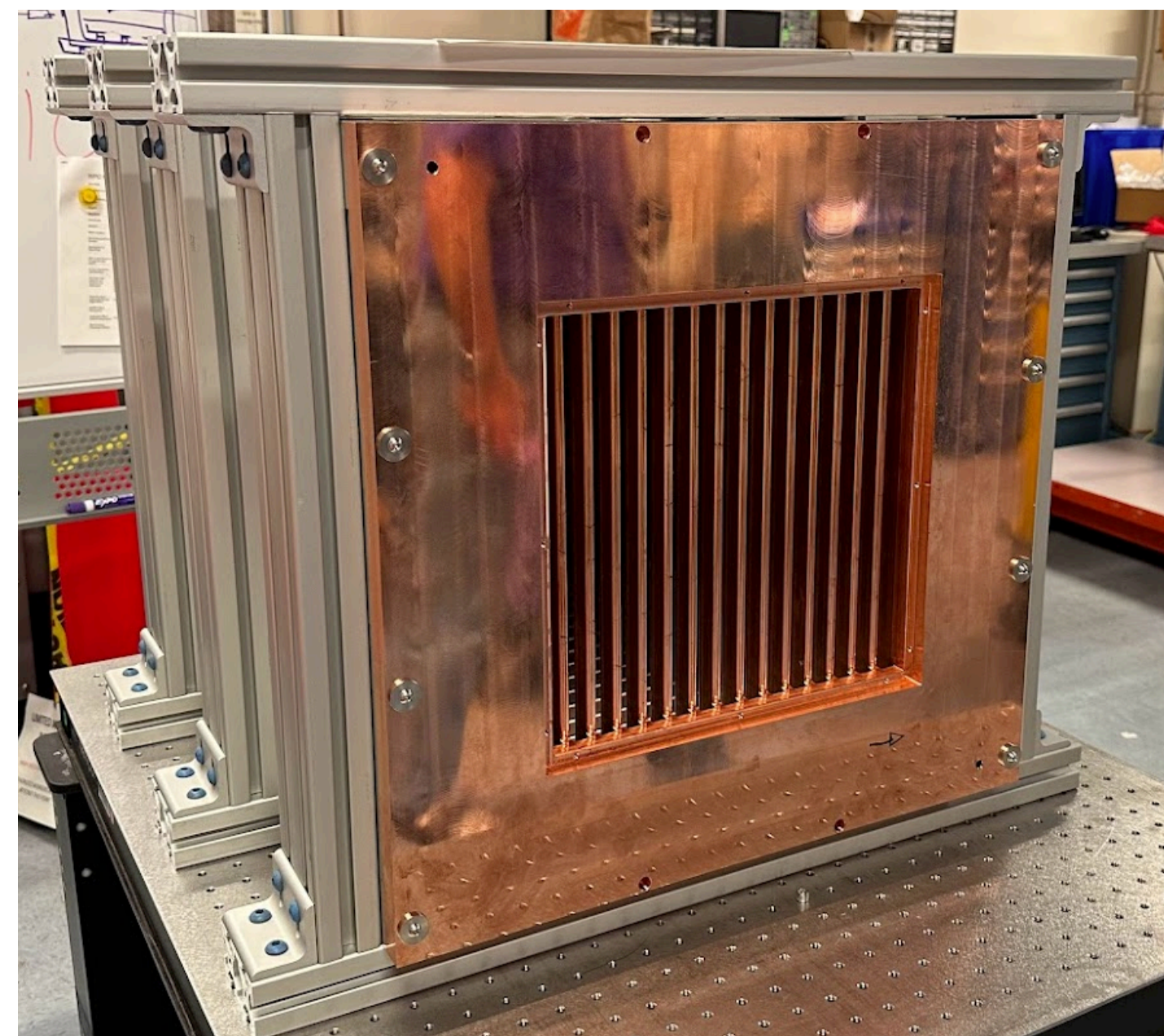
gap = +1mm
 $f \sim 2.8445$ GHz



Coupler of fixed frequency mode



Coupler and tuner of tunable mode



(*) loaded non-tunable mode

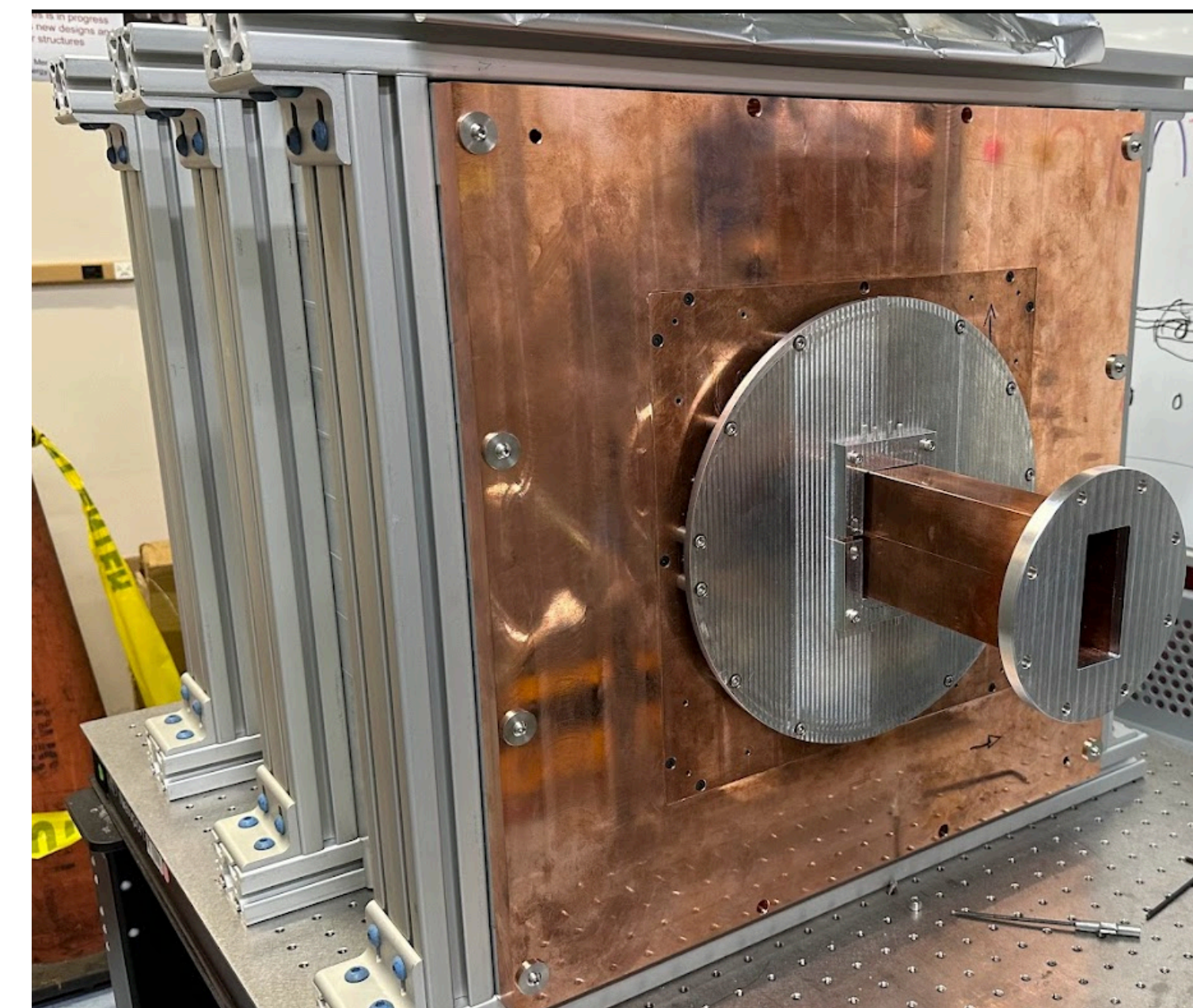
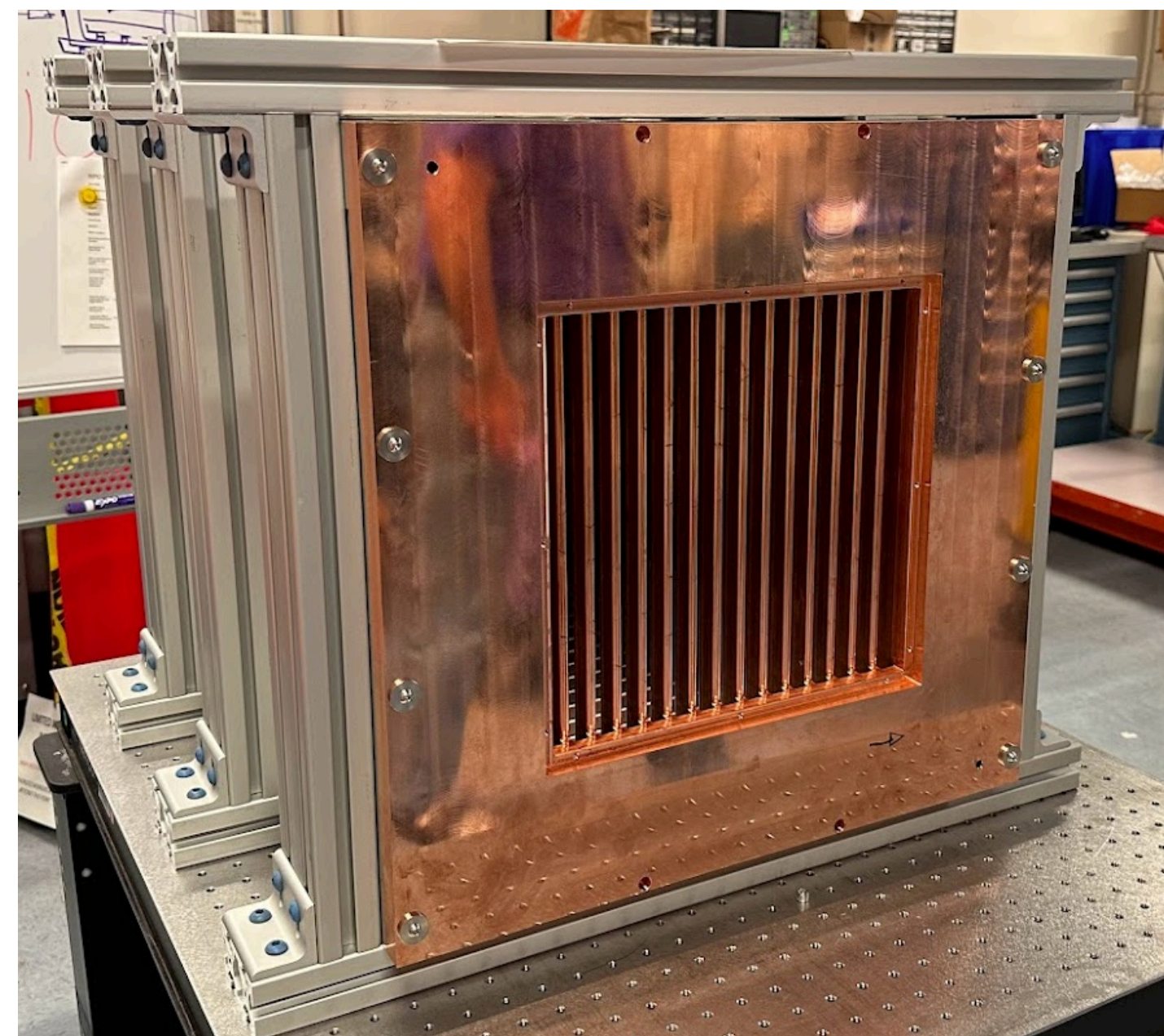
$$(*) \quad Q \simeq 3.5 \times 10^4$$

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

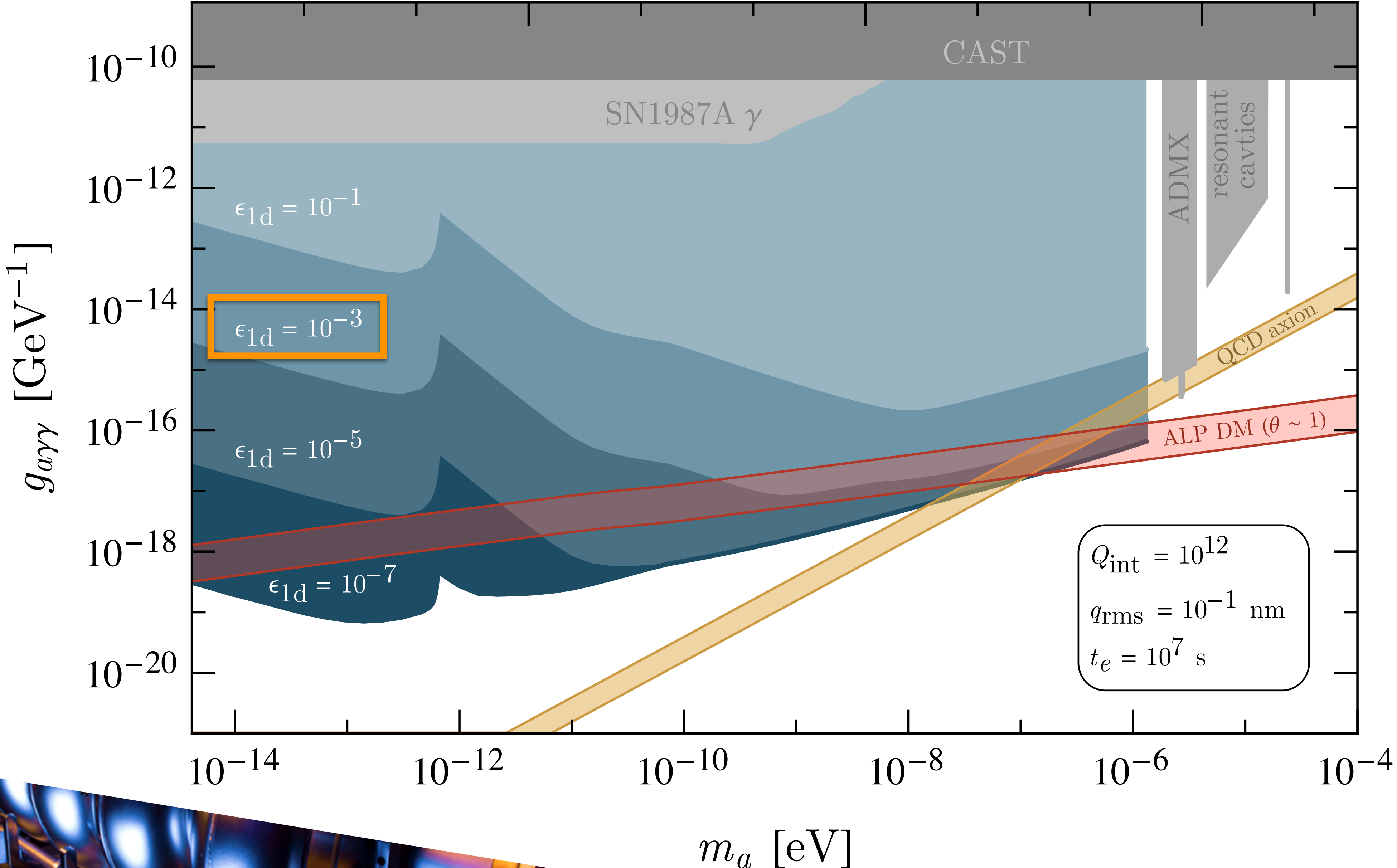
$$T \simeq 300 \text{ K}$$

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

$$\omega \simeq 3 \text{ GHz}$$

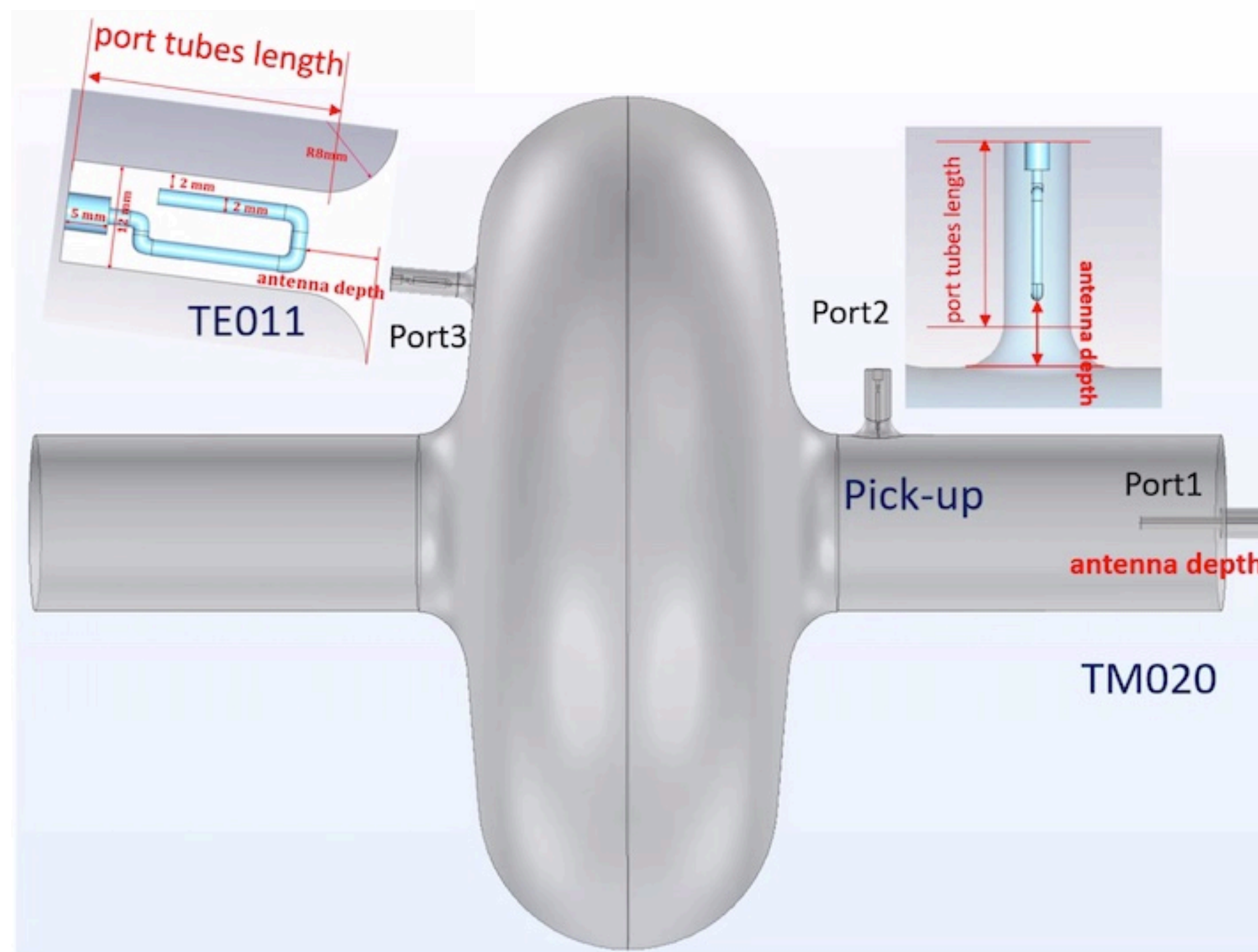


frequency = $m_a/2\pi$



SQMS Team

Parameters based on informal conversations
VERY PRELIMINARY!



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

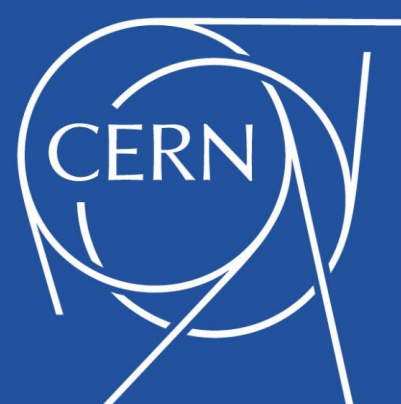
$$V \simeq 10 \text{ L}$$

$$\omega_0 \gtrsim \text{GHz}$$

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

$$\epsilon_d \simeq ?$$

The potential sensitivity is beyond current bounds



W. L. Millar, L. Balocchi, D. Barrientos, J. Bremer, S. Calatroni, S. A. R. Ellis, R.T. D'Agnolo, A. Grudiev, T. Koettig, N. Koss, A. Macpherson, S. Valleccorsa

Slides from: W. L. Millar

3. Cryogenic Stages

A staged upgrade of the cryogenic system is planned to support the programme, with the ultimate target, a set of week-long sub-Kelvin data-taking runs throughout 2028.

Phase A: Facility Check

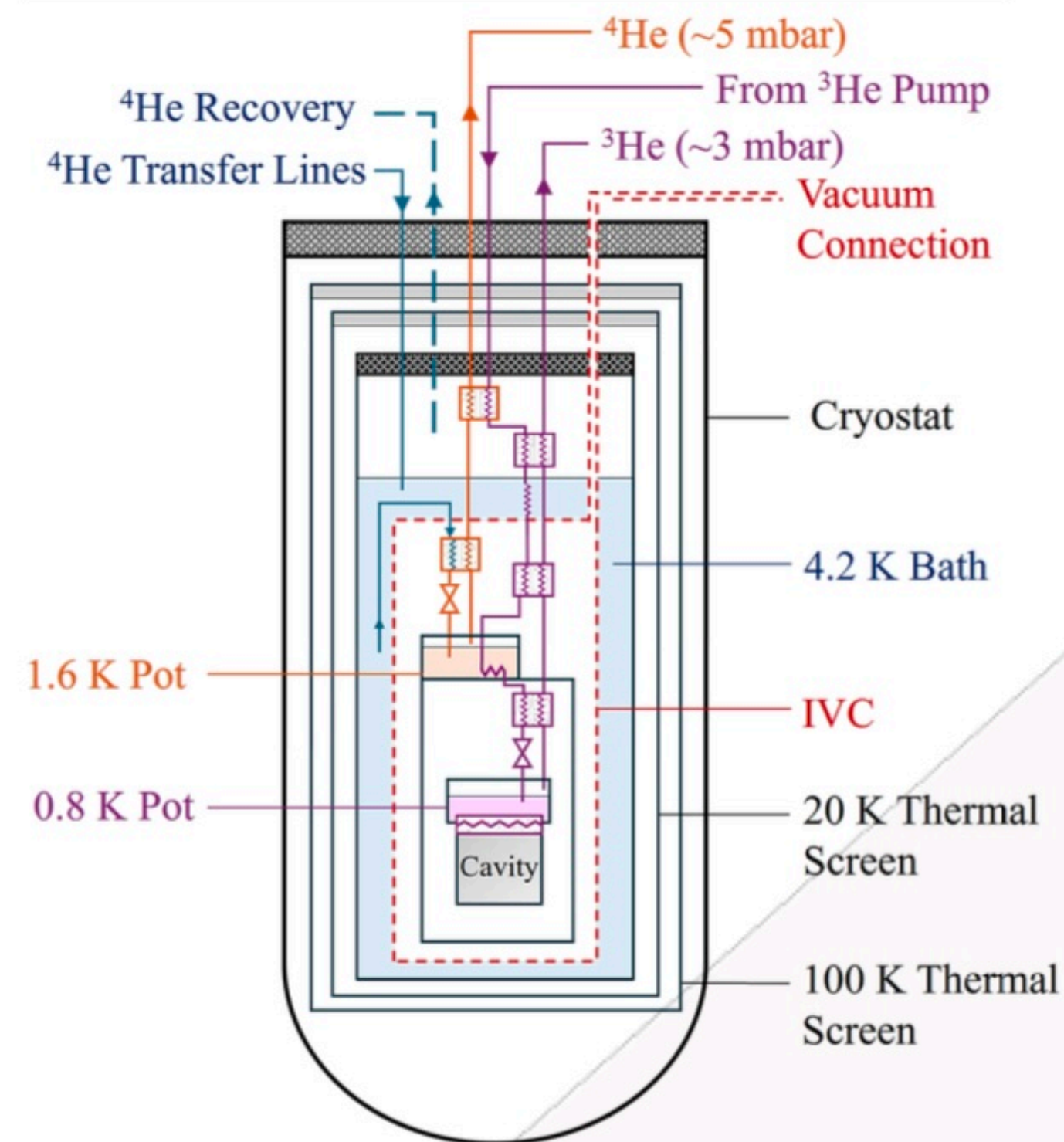
- ❖ Helium-4 bath at 1.5 K—for standard submerged measurements.
- ❖ Control/acquisition cross-checks over a six-month period from January 2026.

Phase B: Prototype Run

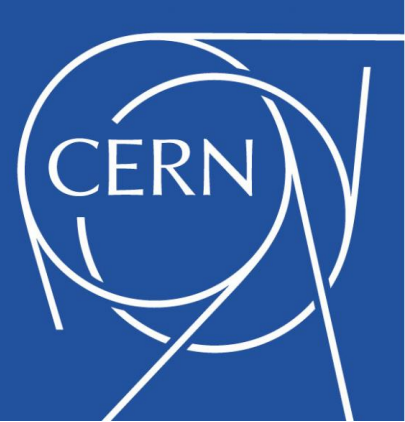
- ❖ Cavity maintained at ~1.55 K in an inner vacuum chamber (IVC).
- ❖ Estimation of heat loads (1 W RF target).
- ❖ Targeting Q1 2027.

Phase C (shown right): Data Taking Run

- ❖ ³He pot (condensed) in an inner vacuum chamber with thermal links.
- ❖ Full readout chain and tuning scheme in place → final commissioning of DAQ.
- ❖ **Target: 800 mK operation through 2028.**



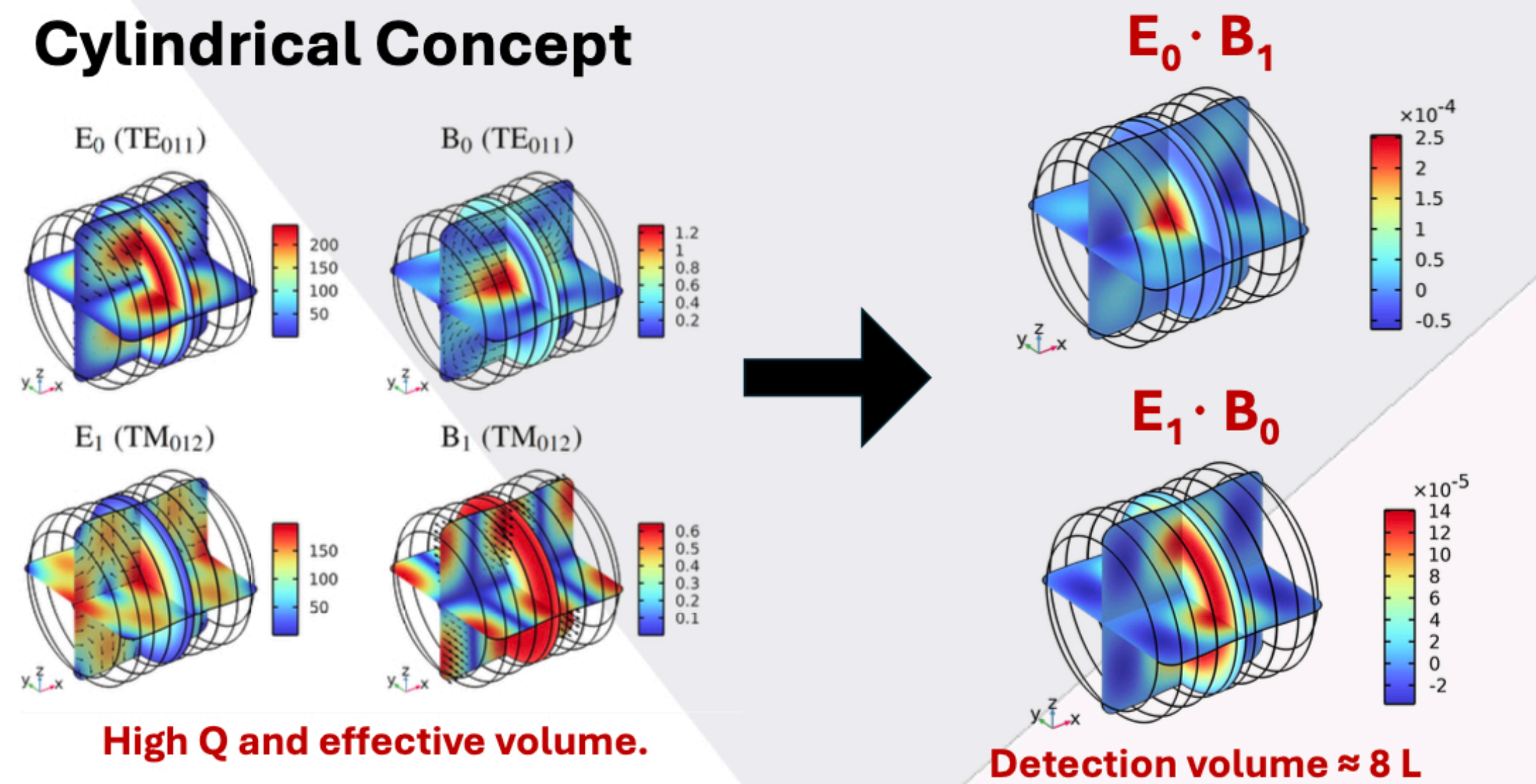
- **Mitigate thermal noise ($P = k_B \cdot T \cdot \Delta f$)**
- **High-Q operation → enhanced sensitivity.**
- **Integration of low-noise amplification stage.**



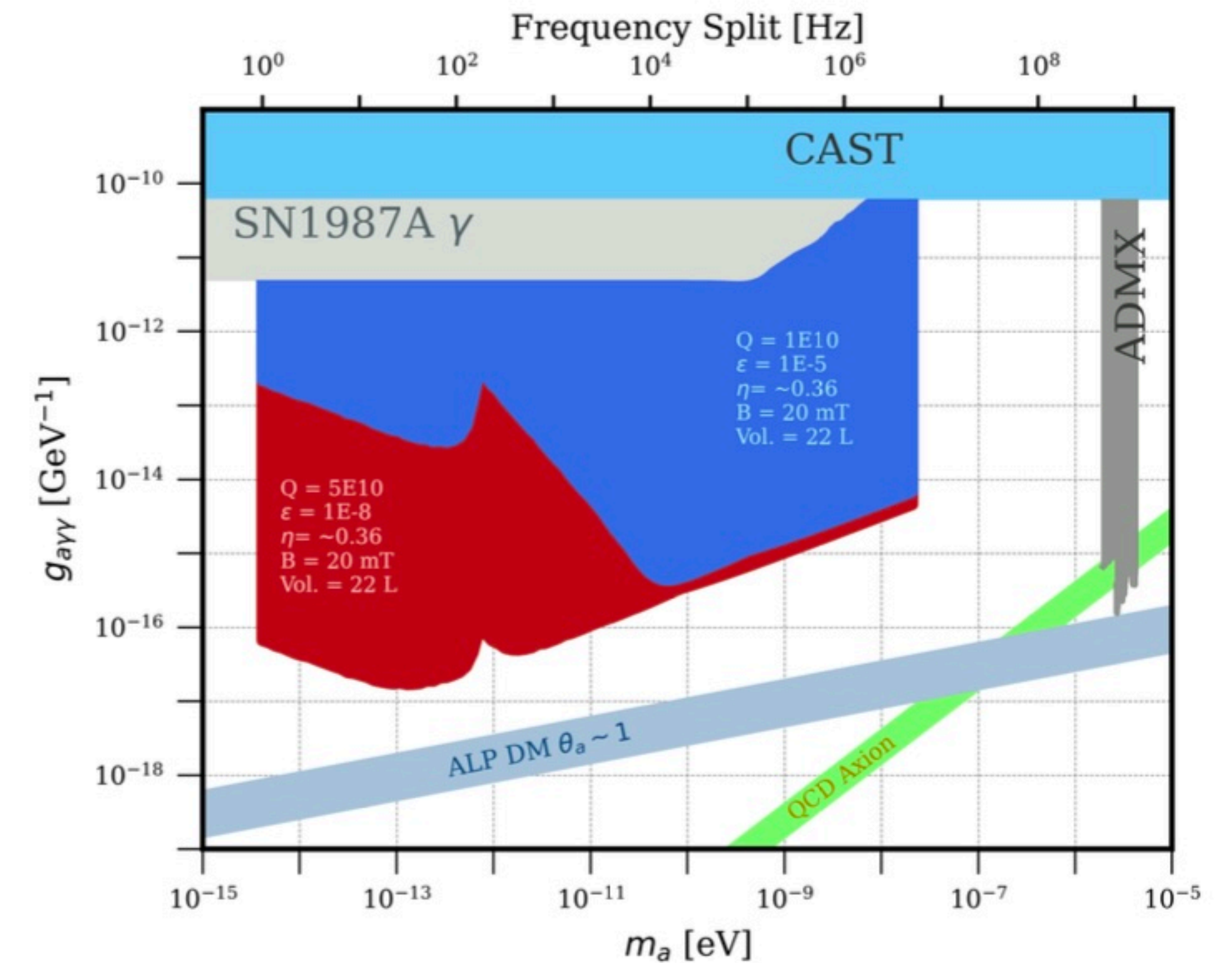
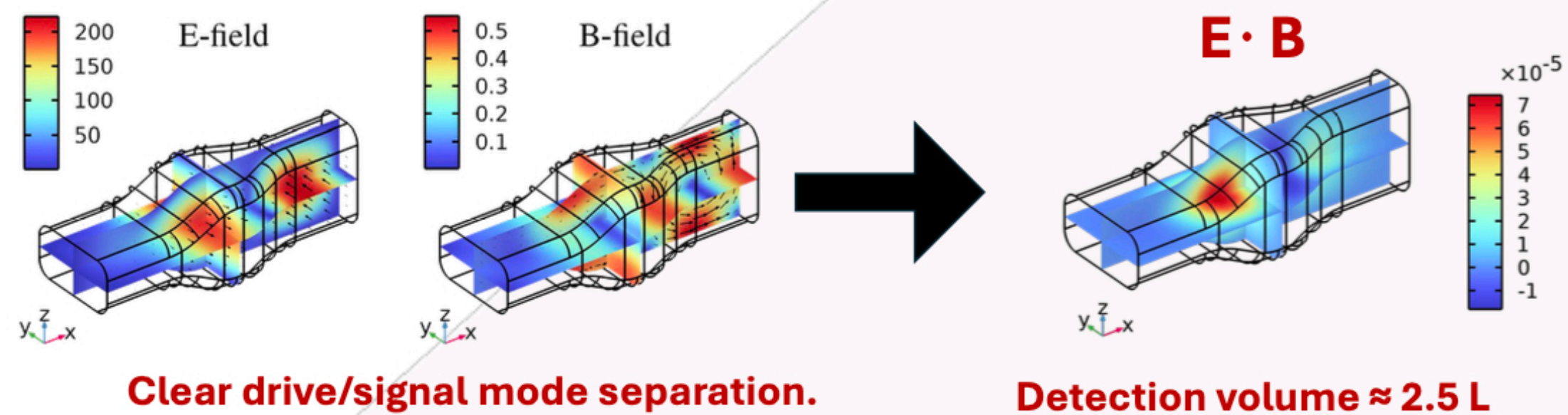
W. L. Millar, L. Balocchi, D. Barrientos, J. Bremer, S. Calatroni, S. A. R. Ellis,
R.T. D'Agnolo, A. Grudiev, T. Koettig, N. Koss, A. Macpherson, S. Vallecorsa

Slides from: W. L. Millar

Cylindrical Concept



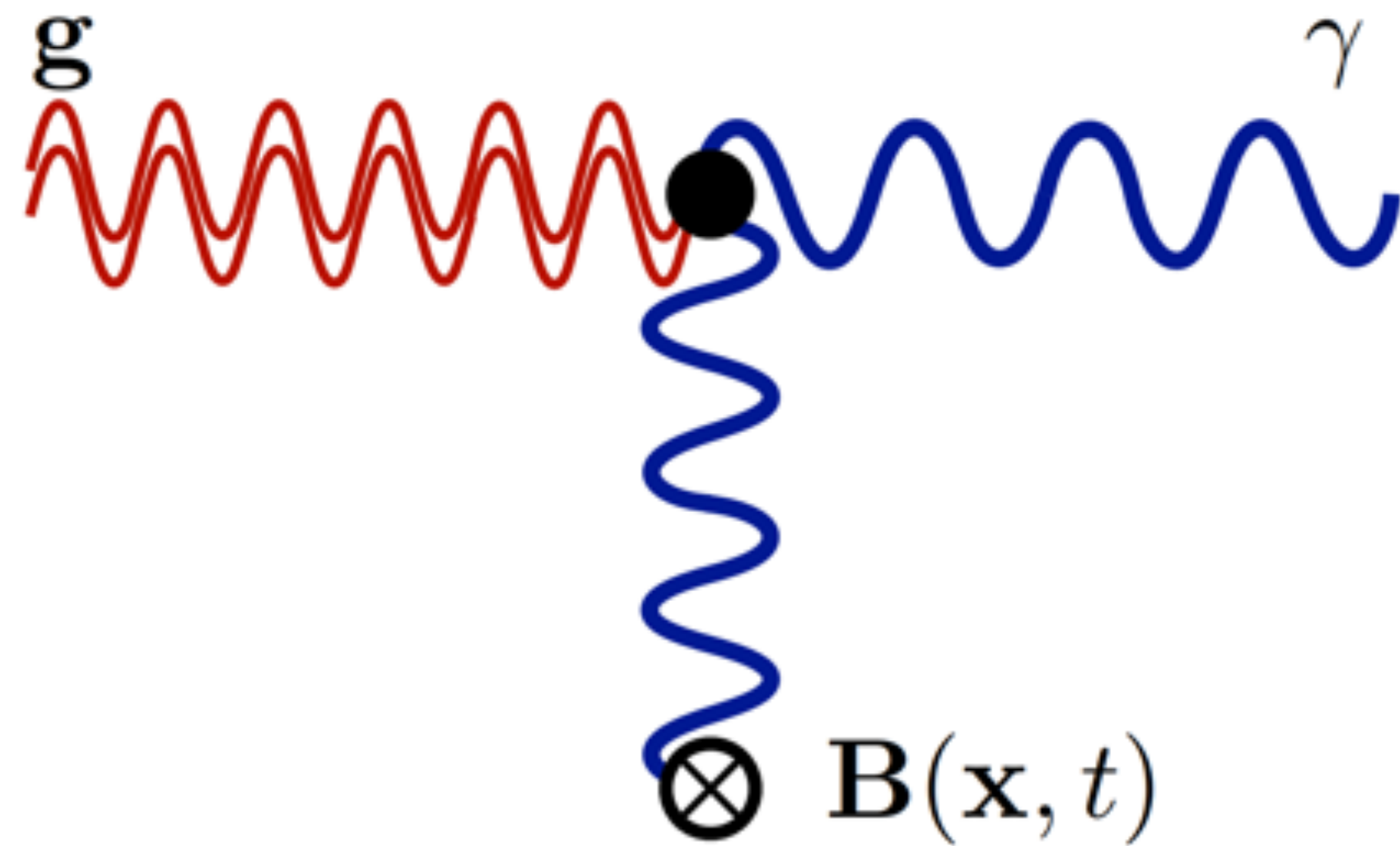
Guide-Based Concept



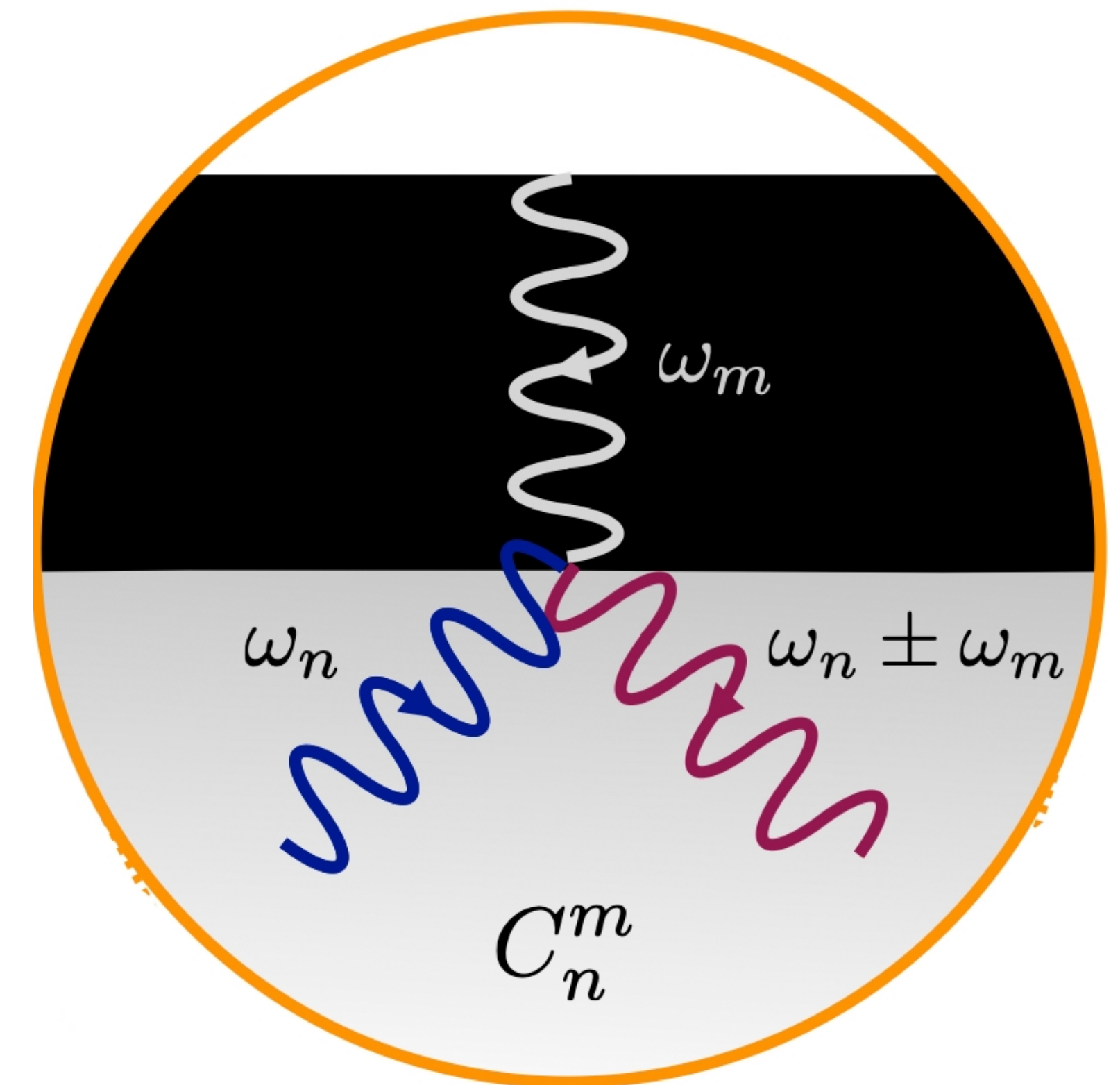
The background is a composite image. The left side shows a close-up of the LIGO interferometer's mirrors and optical components, which are highly reflective and metallic. The right side features a visualization of gravitational waves as concentric, glowing blue and white ripples against a dark blue space filled with numerous small, distant stars. The text is centered across the middle of the image, spanning both the mechanical and cosmic parts of the background.

GRAVITATIONAL WAVES DETECTION

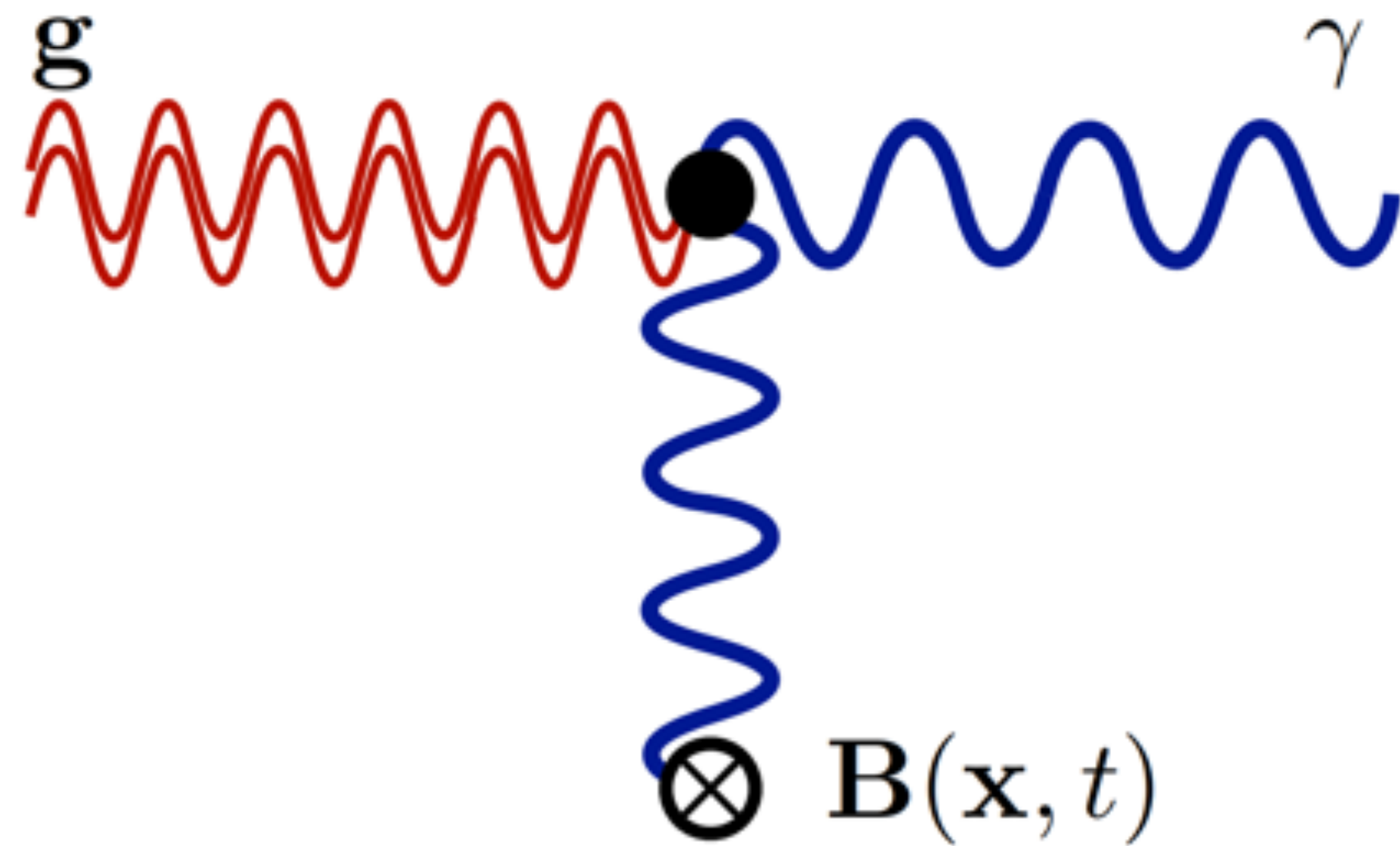
ELECTROMAGNETIC



MECHANICAL



ELECTROMAGNETIC




$$S \supset -\frac{1}{2} \int d^4x \, j_{\text{eff}}^\mu A_\mu$$

GW

$$\underline{j_{\text{eff}}^\mu} = \partial_\nu \left(\frac{1}{2} h F^{\mu\nu} + h^\nu{}_\alpha F^{\alpha\mu} - h^\mu{}_\alpha F^{\alpha\nu} \right)$$

Axion

$$\underline{j_{\text{eff}}^\mu} = \epsilon^{\mu\nu\rho\sigma} \partial_\nu (a F_{\rho\sigma})$$

Not a covariant vector



Proper Detector Frame (PDF) Vs Transverse Traceless (TT) Frame
(Fermi Normal Coordinates)





TT gauge = comoving with the wave
 $(t_{\text{TT}}, x_{\text{TT}}, y_{\text{TT}}, z_{\text{TT}})$

$$\begin{aligned} t_{\text{TT}} &\simeq t - \frac{i}{4} \omega_g (x^2 - y^2) h_+ e^{i\omega_g t}, & x_{\text{TT}} &\simeq x - \frac{1}{2} x (1 - i\omega_g z) h_+ e^{i\omega_g t} \\ y_{\text{TT}} &\simeq y + \frac{1}{2} y (1 - i\omega_g z) h_+ e^{i\omega_g t}, & z_{\text{TT}} &\simeq z - \frac{i}{4} \omega_g (x^2 - y^2) h_+ e^{i\omega_g t} \end{aligned}$$

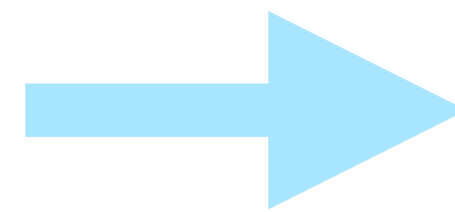




TT gauge = comoving with the wave
 $(t_{\text{TT}}, x_{\text{TT}}, y_{\text{TT}}, z_{\text{TT}})$

Wrong Conclusion

Theorem: $j_{\text{eff},\text{TT}}^{\mu} = 0$

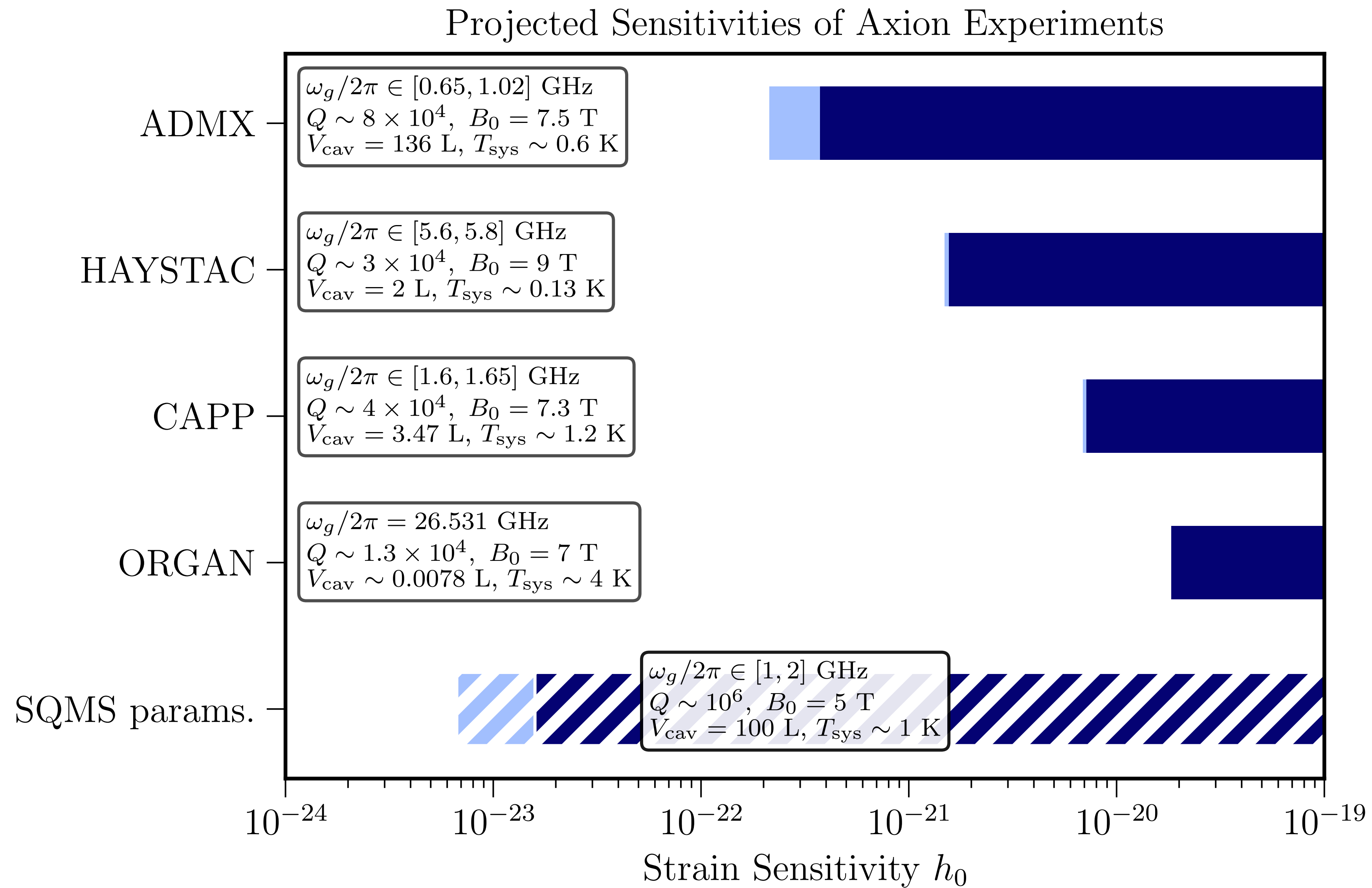


No signal

Doubly Wrong:

1. Impossible to prepare a uniform B-field in the TT frame
2. Even if you could do it, there would still be a signal (wire moving)



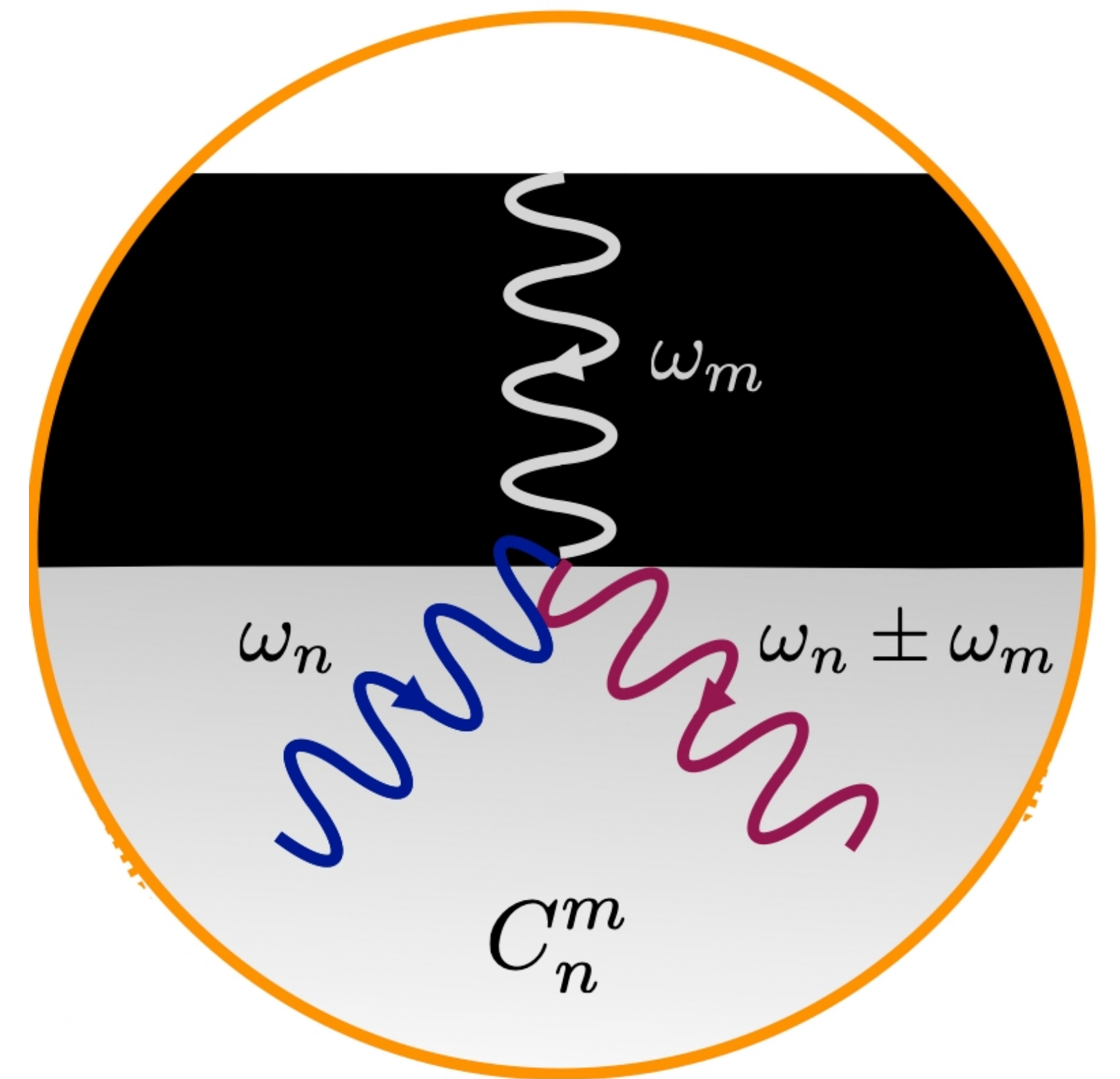


Mechanical Mode

$$\left(\partial_t^2 + \frac{\omega_m}{Q} \partial_t + \omega_m^2 \right) \underline{u_m} = \frac{F_m}{M_{\text{cav}}}$$

$$F_m \sim \text{Riemann}$$

MECHANICAL



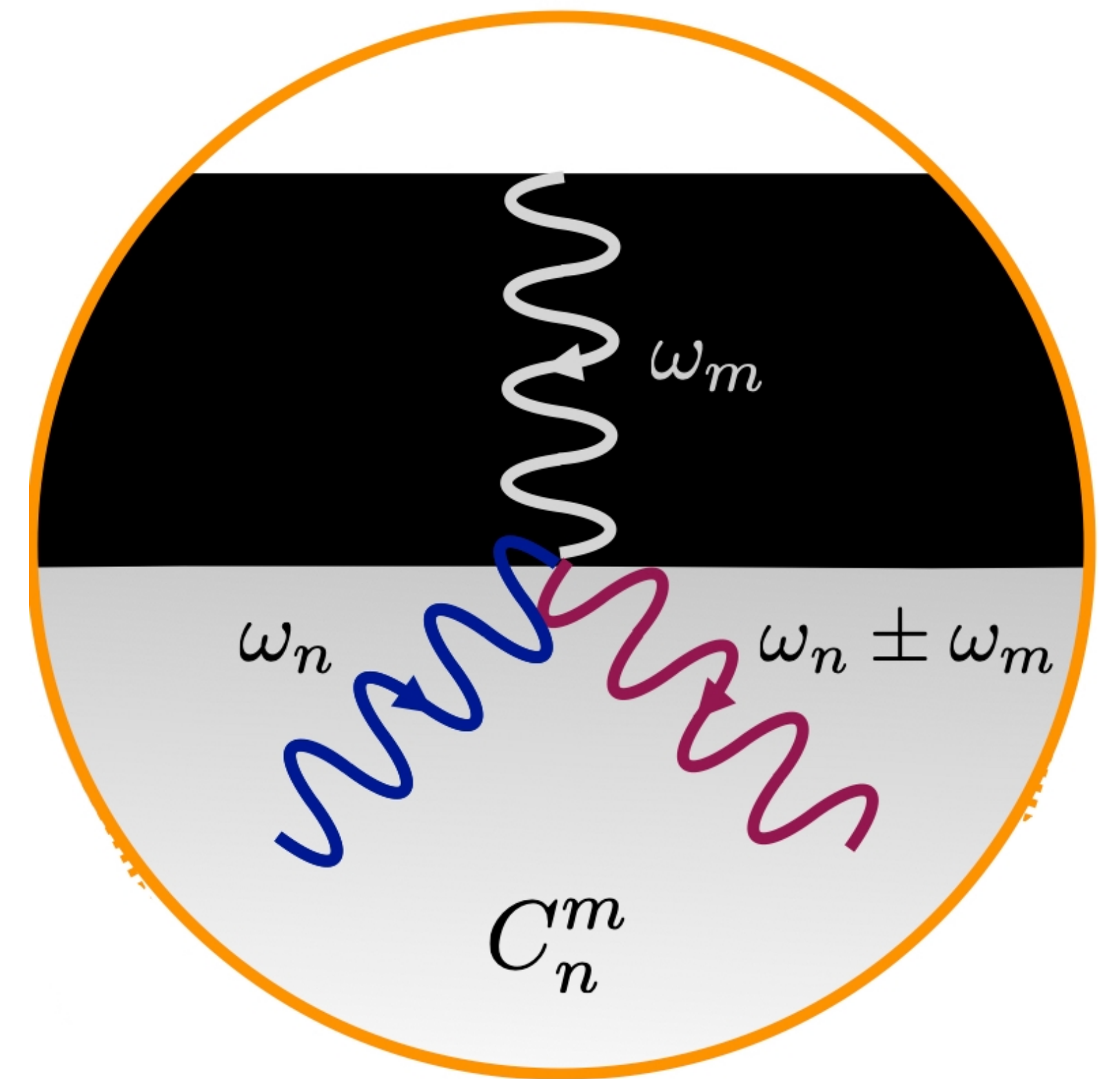
Mechanical Mode

$$\left(\partial_t^2 + \frac{\omega_m}{Q} \partial_t + \omega_m^2 \right) \underline{u_m} = \frac{F_m}{M_{\text{cav}}}$$

$$F_m \sim \text{Riemann}$$

$$u_m \sim Q \frac{\omega_g^2}{\omega_m^2} (h L_{\text{cav}})$$

MECHANICAL



Mechanical Mode

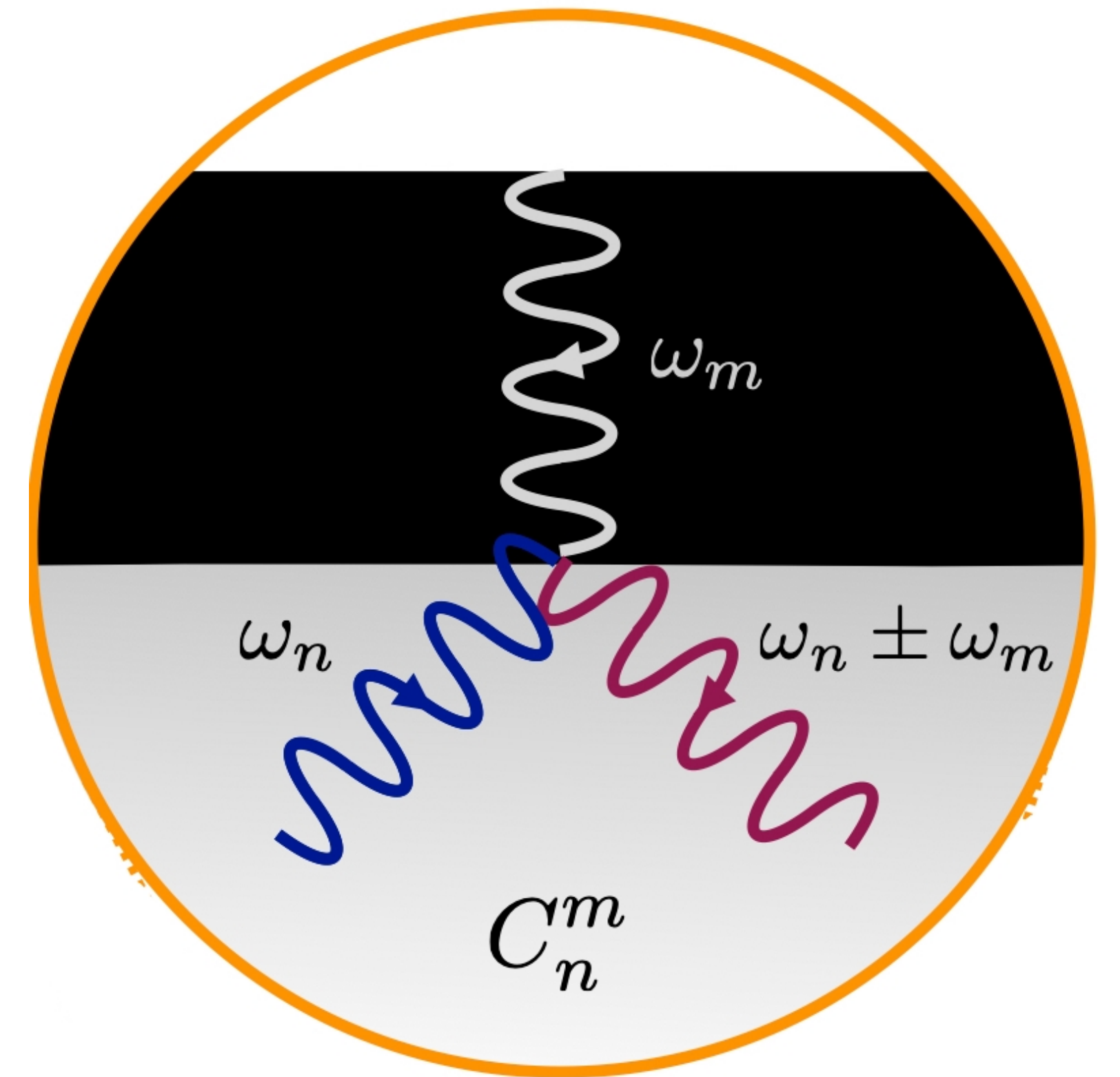
$$\omega_m \sim \frac{c_s}{L_{\text{cav}}} < 1/L$$

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

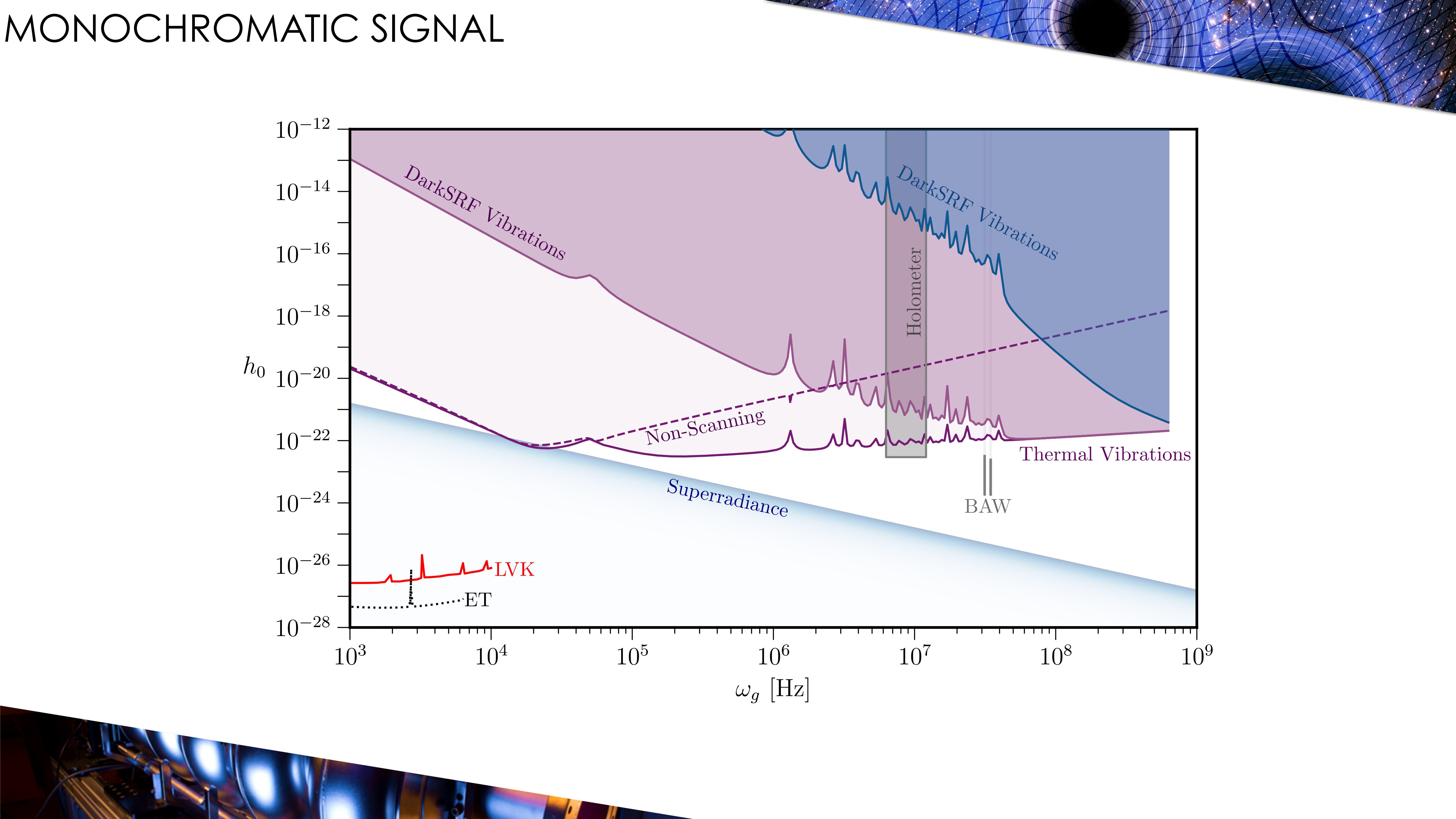
Niobium ~0.5 m cavity

$$u_m \sim Q \frac{\omega_g^2}{\omega_m^2} (h L_{\text{cav}})$$

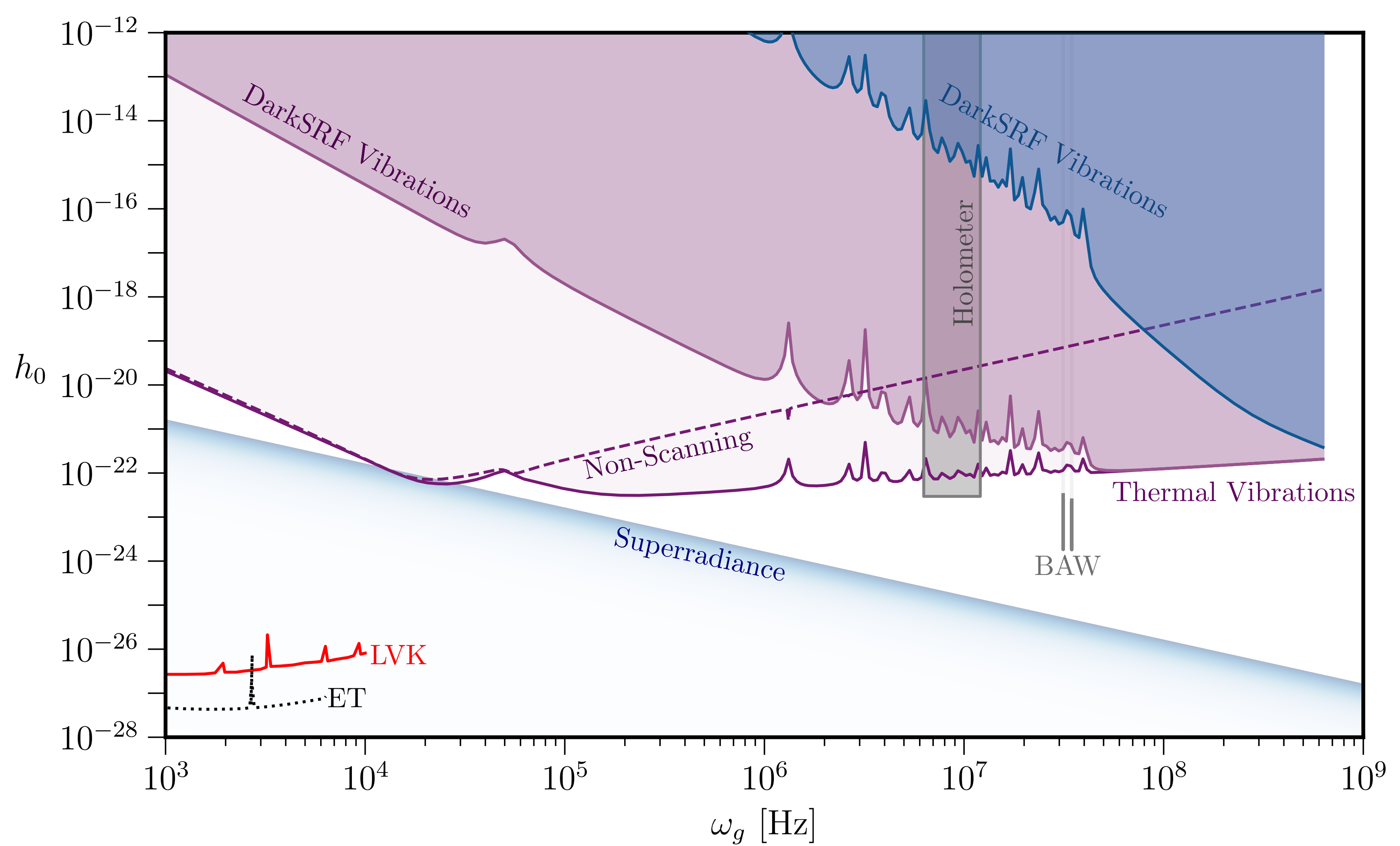
MECHANICAL

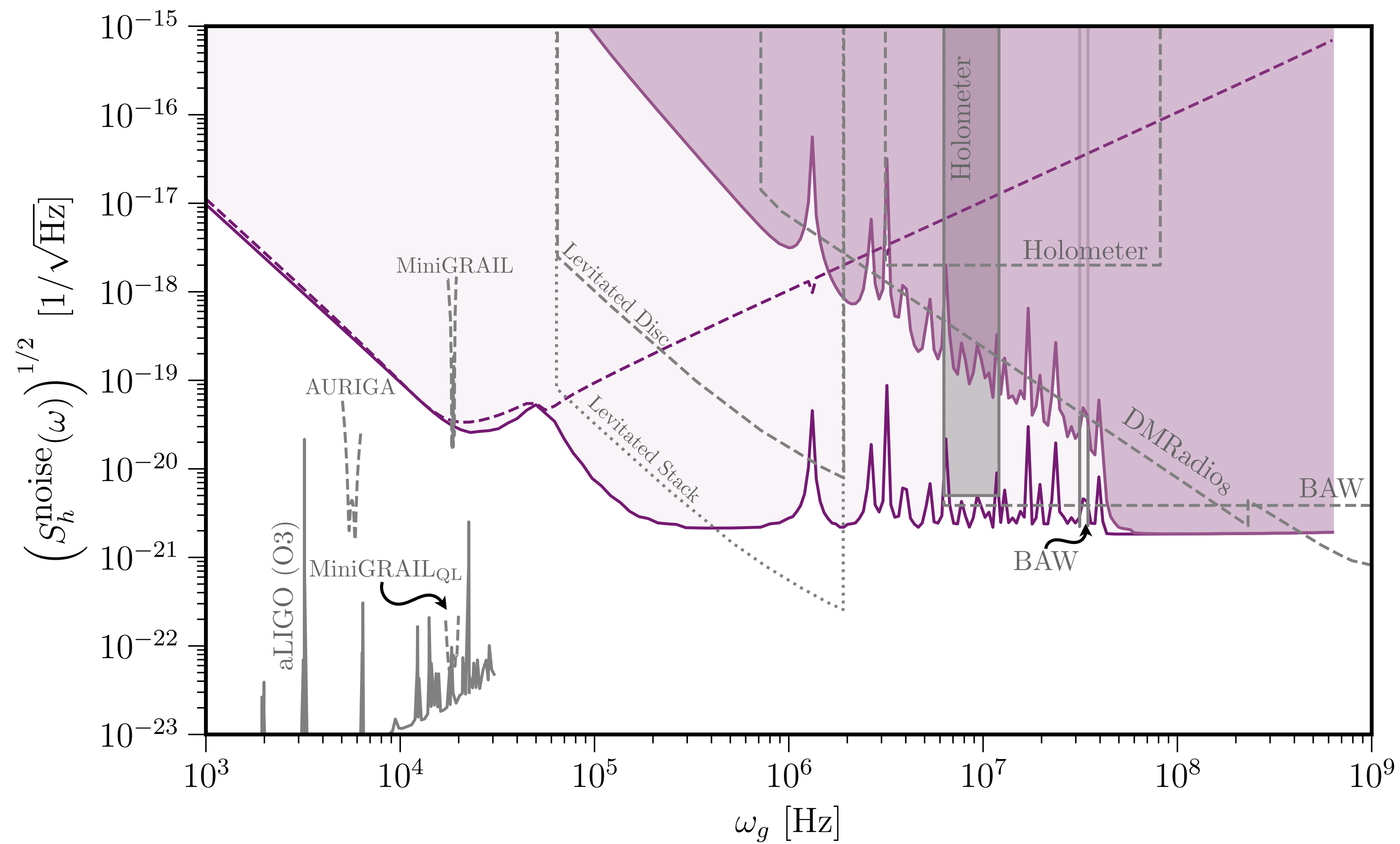


[Caves '78], [Radicati, Pegoraro, Picasso '78]



MONOCHROMATIC SIGNAL





EXISTING PROTOTYPE



MAGO '05

R. Ballantini, A. Chincarini, S. Cuneo, G. Gemme,* R. Parodi, A. Podest`a, and R. Vaccarone

INFN and Universita` degli Studi di Genova, Genova, Italy

Ph. Bernard, S. Calatroni, E. Chiaveri, and R. Losito

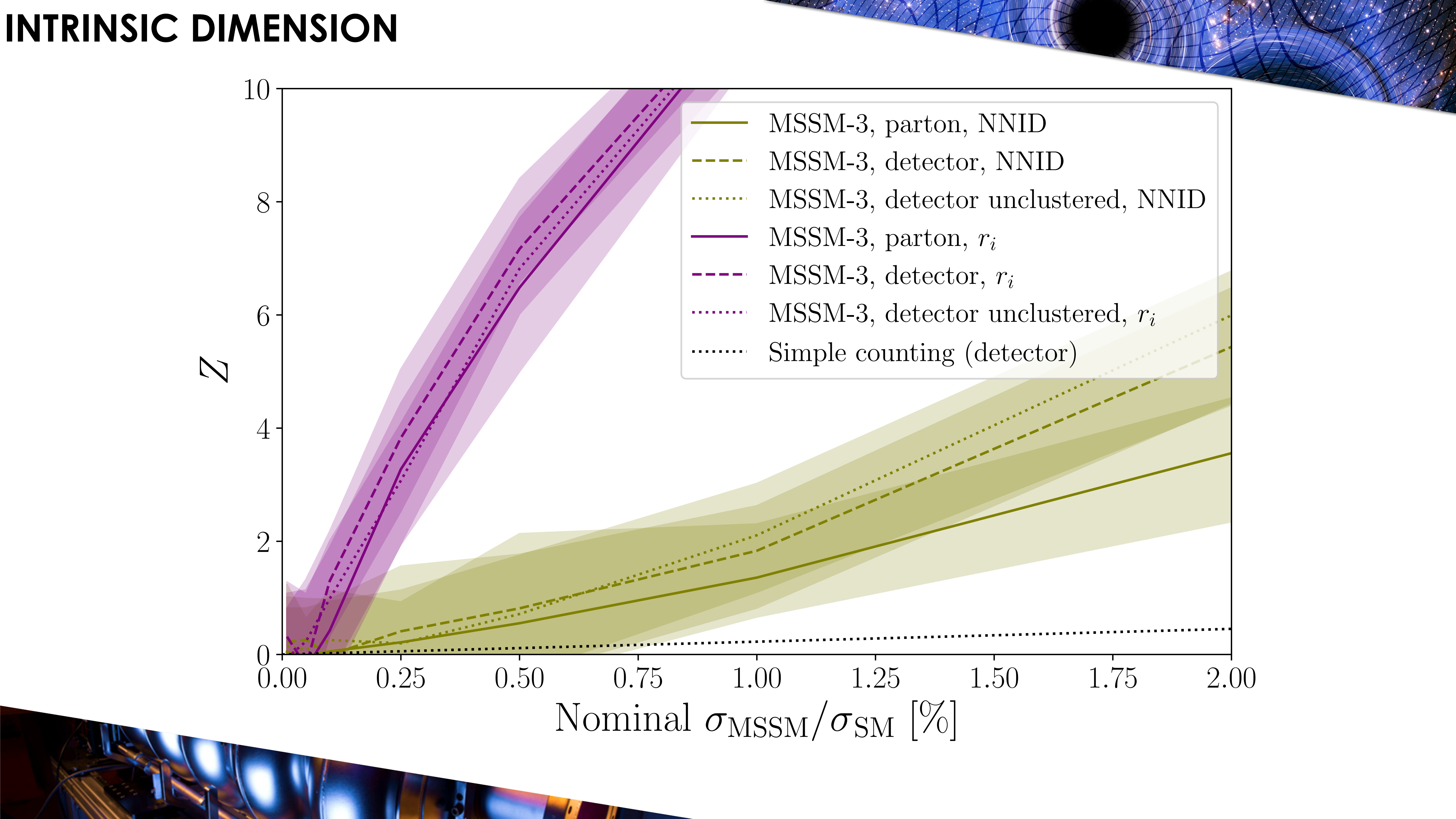
CERN, Geneva, Switzerland

R.P. Croce, V. Galdi, V. Pierro, and I.M. Pinto

INFN, Napoli, and Universita` degli Studi del Sannio, Benevento, Italy

E. Picasso

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



BACKUP

SUPERRADIANCE

$$\omega_g \simeq 2m_a \simeq \text{GHz} \left(\frac{10^{-4} M_\odot}{M_{\text{BH}}} \right)$$

$$h = 10^{-24} \left(\frac{\Delta a_*}{0.1} \right) \left(\frac{1 \text{ kpc}}{D} \right) \left(\frac{M_b}{10^{-1} M_\odot} \right) \left(\frac{\alpha}{0.2} \right)^7$$

Signal from: [Arvanitaki, Geraci '12]

$$\frac{N_{\text{cycles}}}{Q} \simeq \left(\frac{\text{GHz}}{f_g} \right)^{5/3} \left(\frac{10^{-9} M_{\odot}}{m_{\text{PBH}}} \right)^{5/3} \quad Q = 10^6$$

$$h \simeq 10^{-26} \left(\frac{1 \text{ pc}}{D} \right) \left(\frac{m_{\text{PBH}}}{10^{-9} M_{\odot}} \right)^{5/3} \left(\frac{\omega_g}{\text{GHz}} \right)^{2/3}$$

If they are DM and are all in binaries (1 year)

$$D \simeq 10^{-3} \text{ pc}$$

If they are DM

$$D \simeq 10 \text{ pc} \left(\frac{m_{\text{PBH}}}{10^{-9} M_{\odot}} \right)$$

Power

$$\frac{dP}{dE} \sim \text{const.}$$

$$\frac{d\Gamma}{dE} \sim \frac{1}{E}$$

Number of
gravitons

$$\Gamma \sim \exp[B \log(E/\Lambda)], \quad B \ll 1$$

POWER FROM THE SUN

Signal

$$P_{\text{tot}} \simeq 6 \times 10^{14} \frac{\text{erg}}{\text{s}} \simeq 10^{11} \text{ eV}^2$$

$$P_{\text{exp}} \simeq 10^{-12} \text{ eV}^2$$

Total emitted power (in gravitons)

Power reaching a m-sized
experiment on Earth (in gravitons)

Signal from:[Weinberg '65]

POWER FROM THE SUN

Signal

$$P_{\text{tot}} \simeq 6 \times 10^{14} \frac{\text{erg}}{\text{s}} \simeq 10^{11} \text{ eV}^2$$

Total emitted power (in gravitons)

$$P_{\text{exp}} \simeq 10^{-12} \text{ eV}^2$$

Power reaching a m-sized experiment on Earth (in gravitons)

Noise

$$P_{\text{th}} \simeq T \Delta\omega \simeq \text{eV}^2 \left(\frac{T}{\text{K}} \right)$$

Thermal Noise in the bandwidth of the signal (in photons)

Signal from:[Weinberg '65]

High Mass

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

Low Mass

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

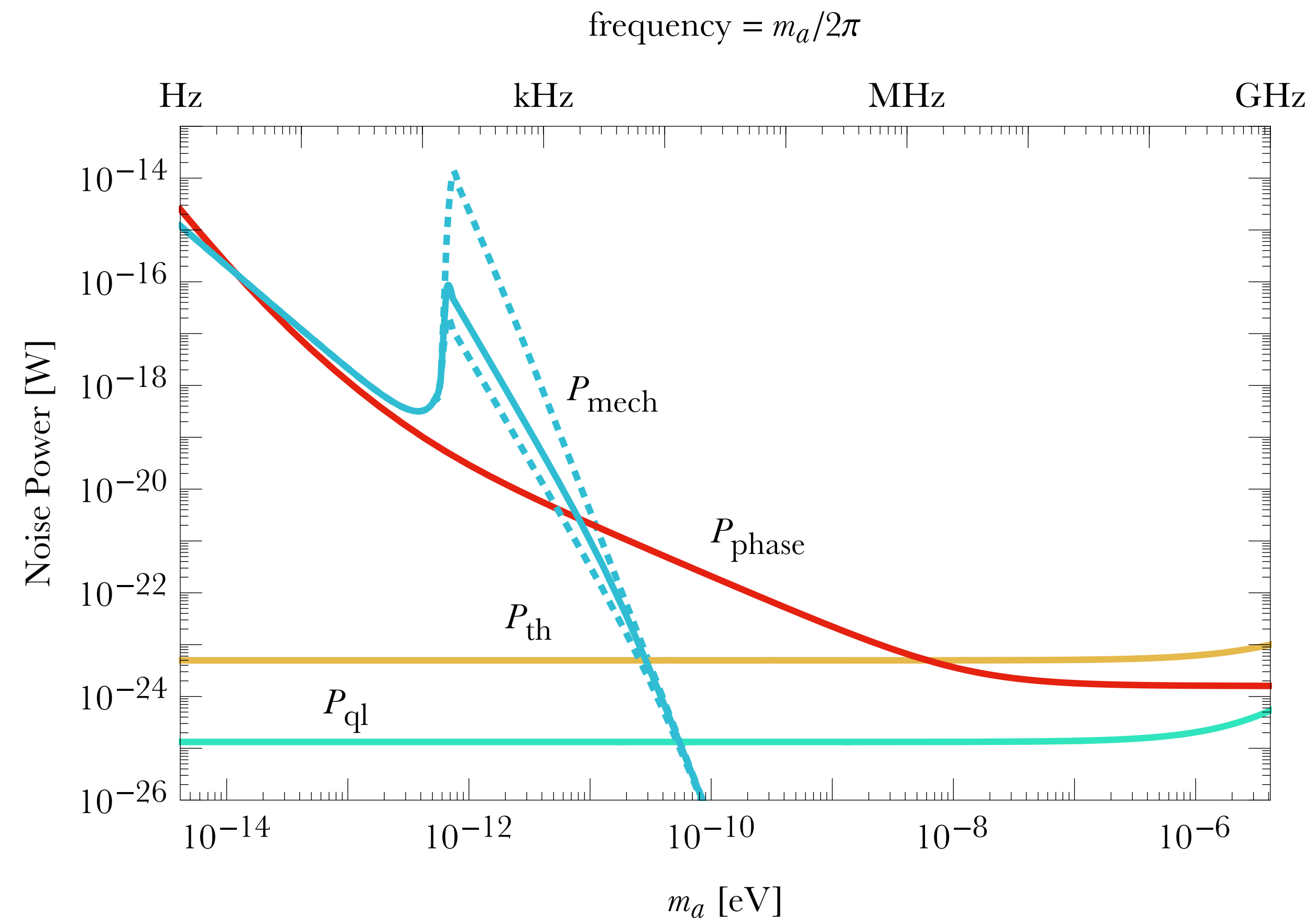
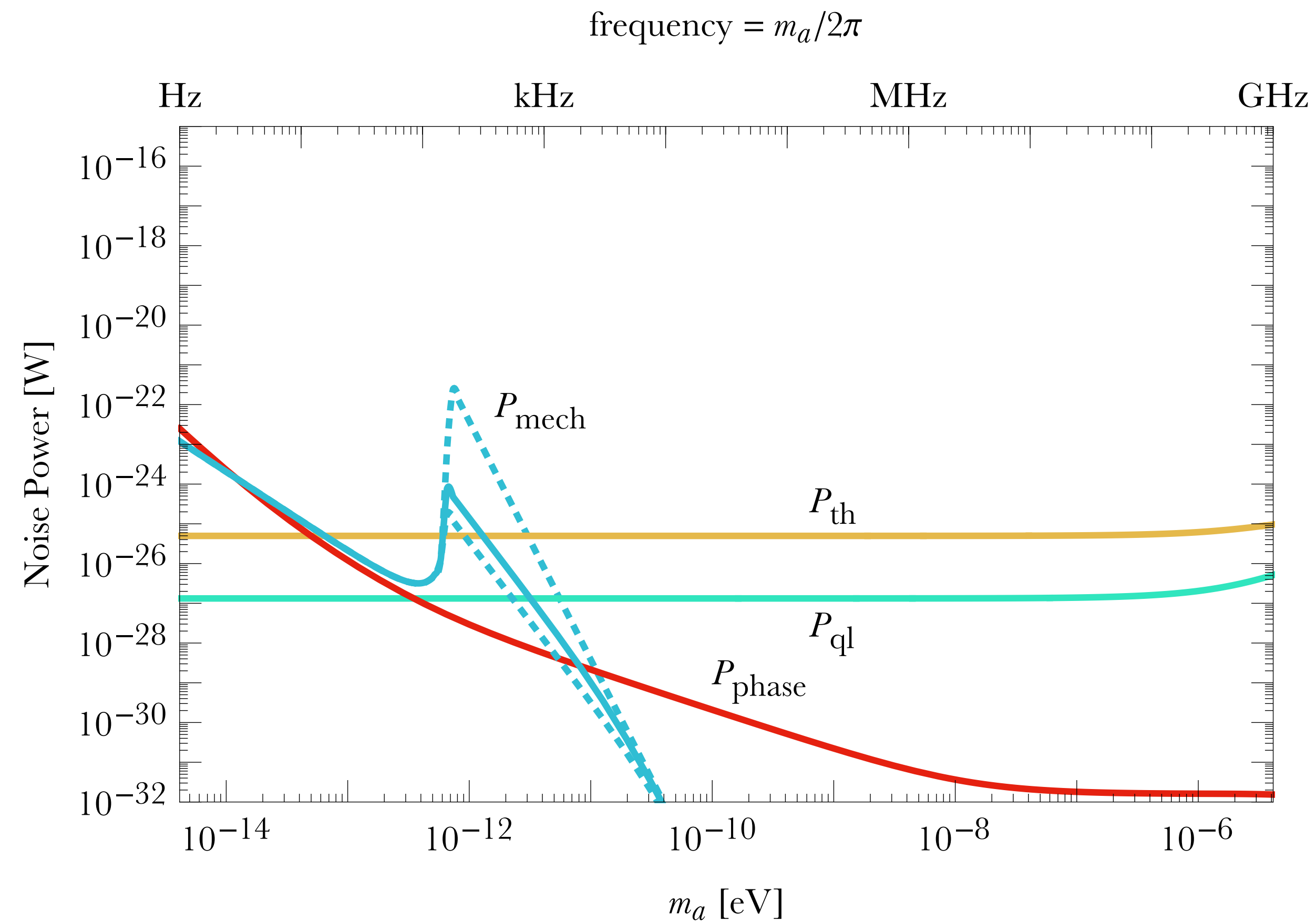
High Mass

$$\text{SNR}_{\text{mech noise}} \simeq \frac{1}{4} \sqrt{\frac{\pi^3 t_{\text{int}}}{2 \Delta \omega_{\text{osc}}}} |\eta_{\text{mech}}^g(\omega_p^{\text{sig}})|^2 \frac{|\eta_{\text{mech}}^{\text{EM}}(\omega_p^{\text{sig}})|^2}{|\eta_{\text{mech}}^{\text{EM}}(\omega_p^{\text{noise}})|^2} \frac{M_{\text{cav}}^2 V_{\text{cav}}^{2/3}}{S_{F_p}(\omega_g)} h_0^2 \omega_g^4 \times \begin{cases} 1 & , \omega_g \neq \omega_p^{\text{noise}} \\ 1/(Q_p^{\text{noise}})^2 & , \omega_g \simeq \omega_p^{\text{noise}} \end{cases}$$

Low Mass

$$\text{SNR}_{\text{EM noise}} \simeq \frac{1}{16} \sqrt{\frac{\pi t_{\text{int}}}{2 \Delta \omega_{\text{osc}}}} Q_{\text{int}}^2 |\eta_{\text{mech}}^g|^2 |\eta_{\text{mech}}^{\text{EM}}|^2 \frac{P_{\text{in}}}{T} h_0^2$$

NOISE PSDs

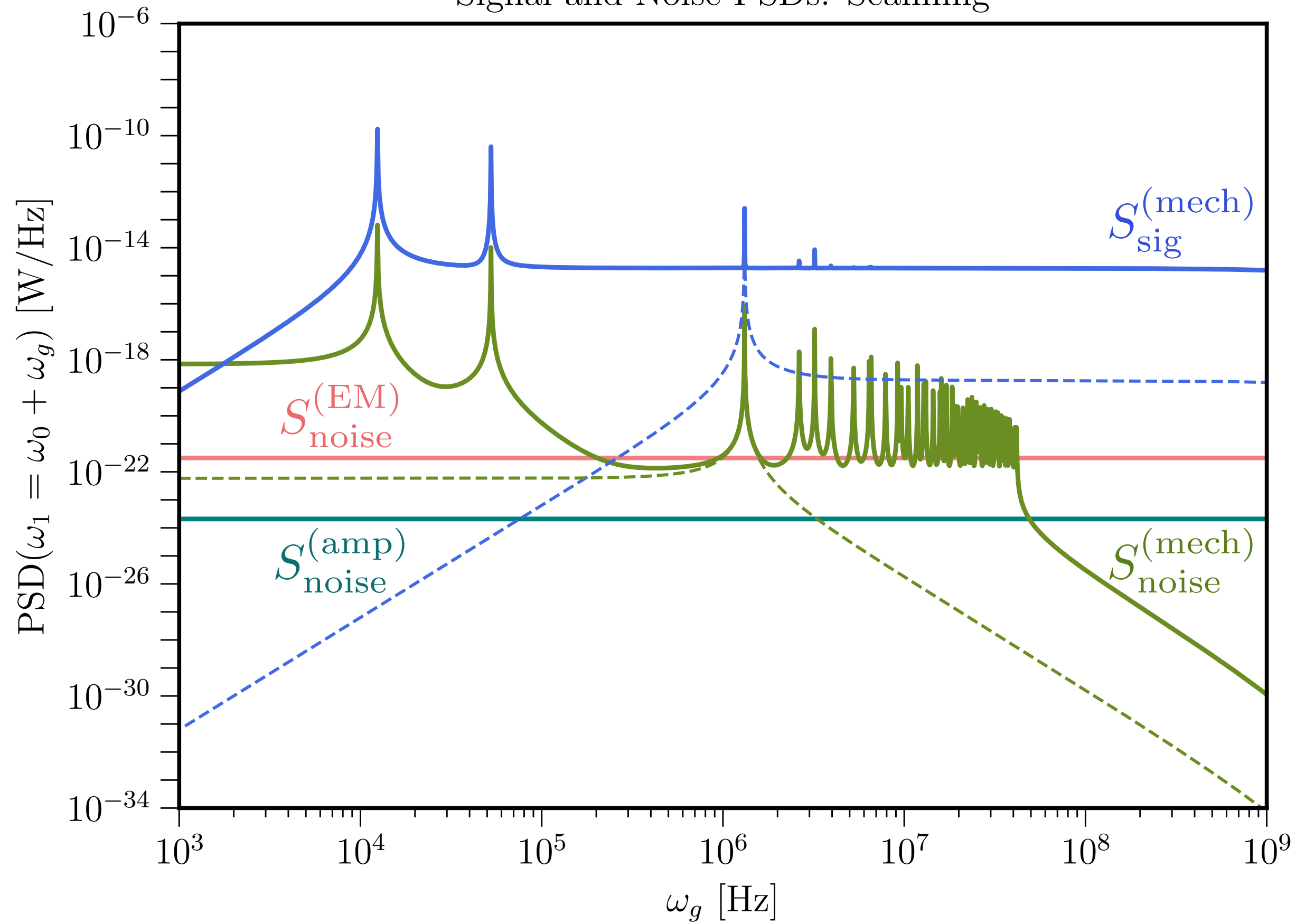


$$\epsilon_{1d} = 10^{-7}, \quad Q = 10^{12}$$

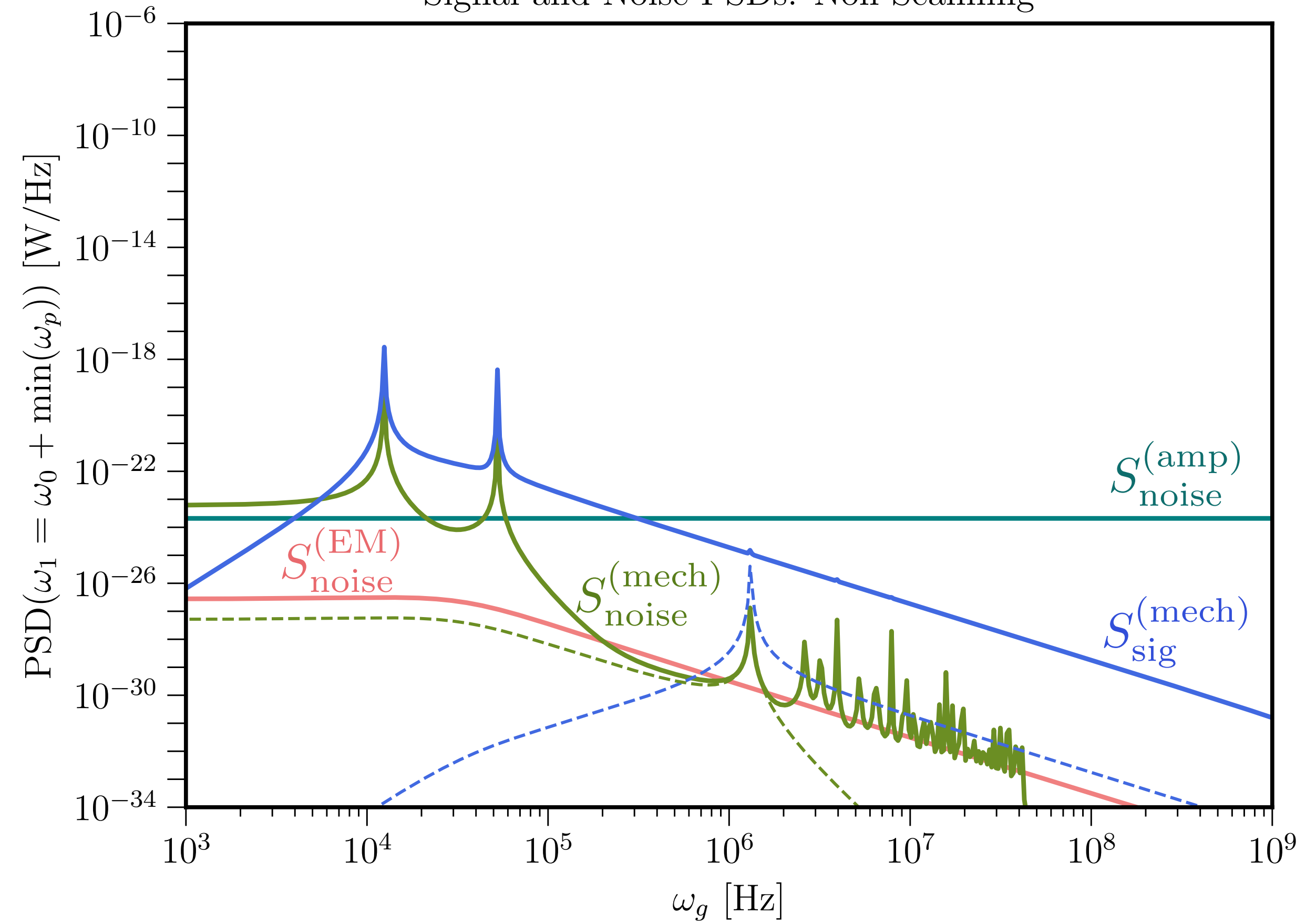
$$\epsilon_{1d} = 10^{-5}, \quad Q = 10^{10}$$

NOISE PSDs GWs

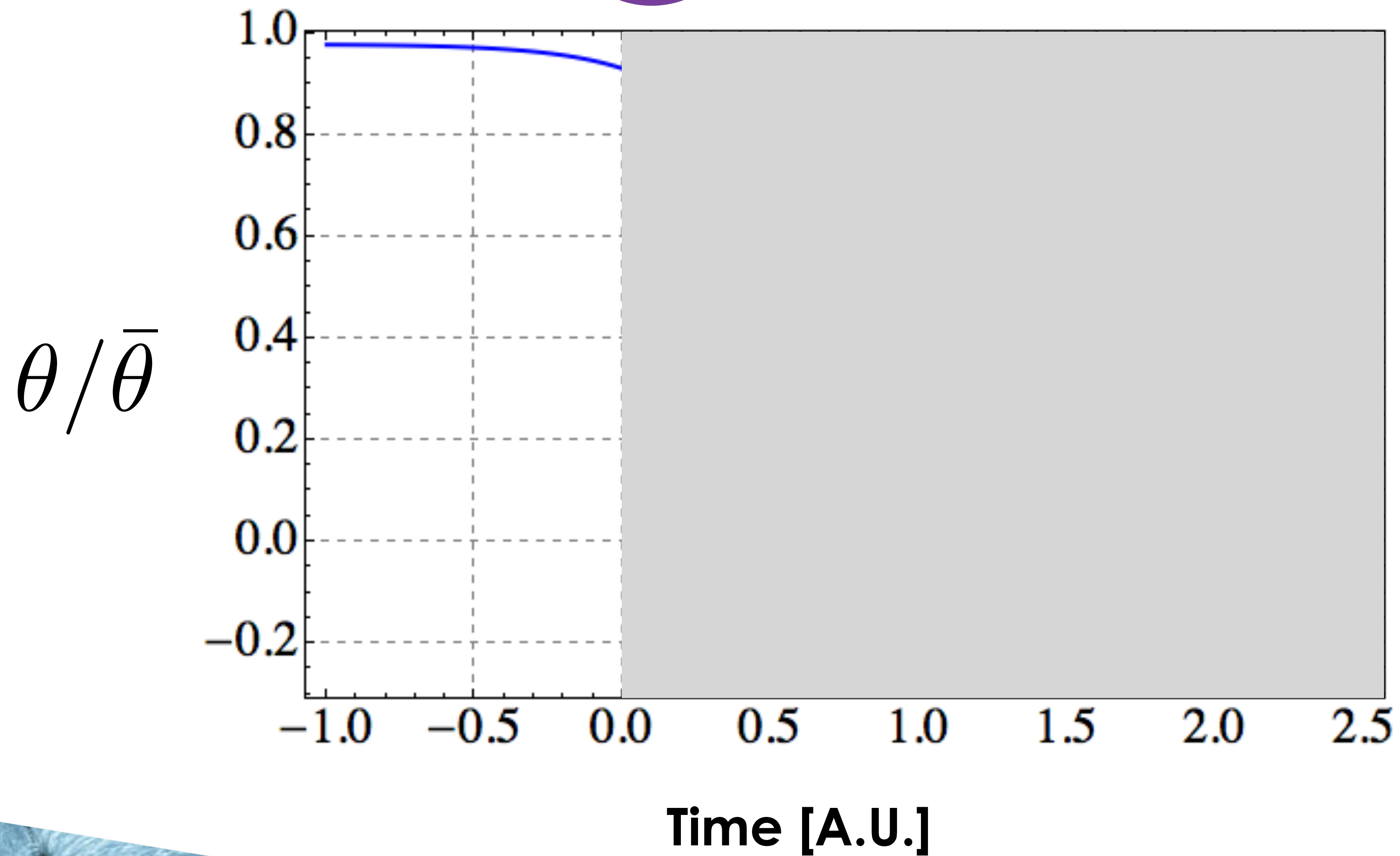
Signal and Noise PSDs: Scanning



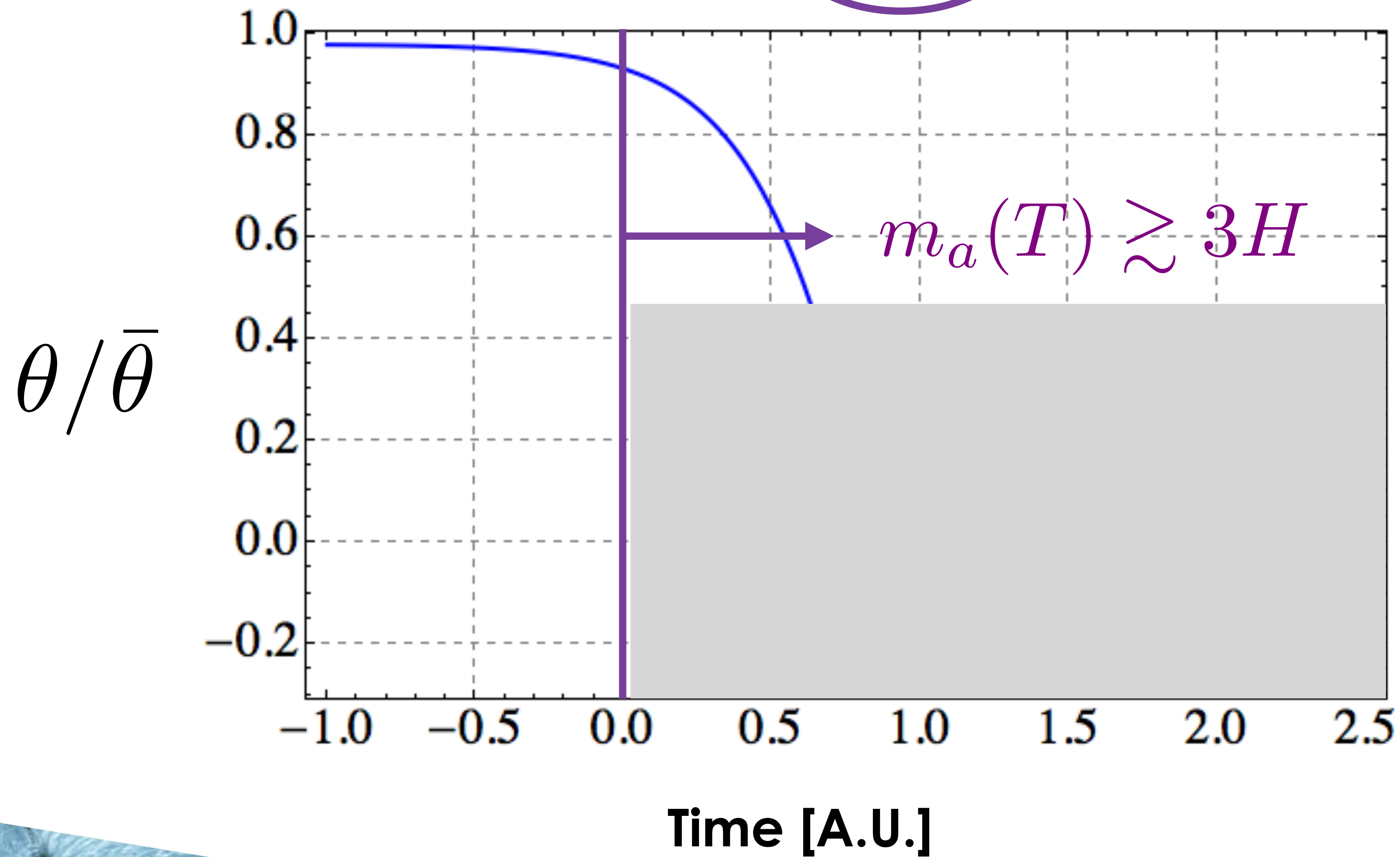
Signal and Noise PSDs: Non-Scanning



$$\ddot{\theta} + 3H\dot{\theta} + m_a^2(T)\theta = 0$$

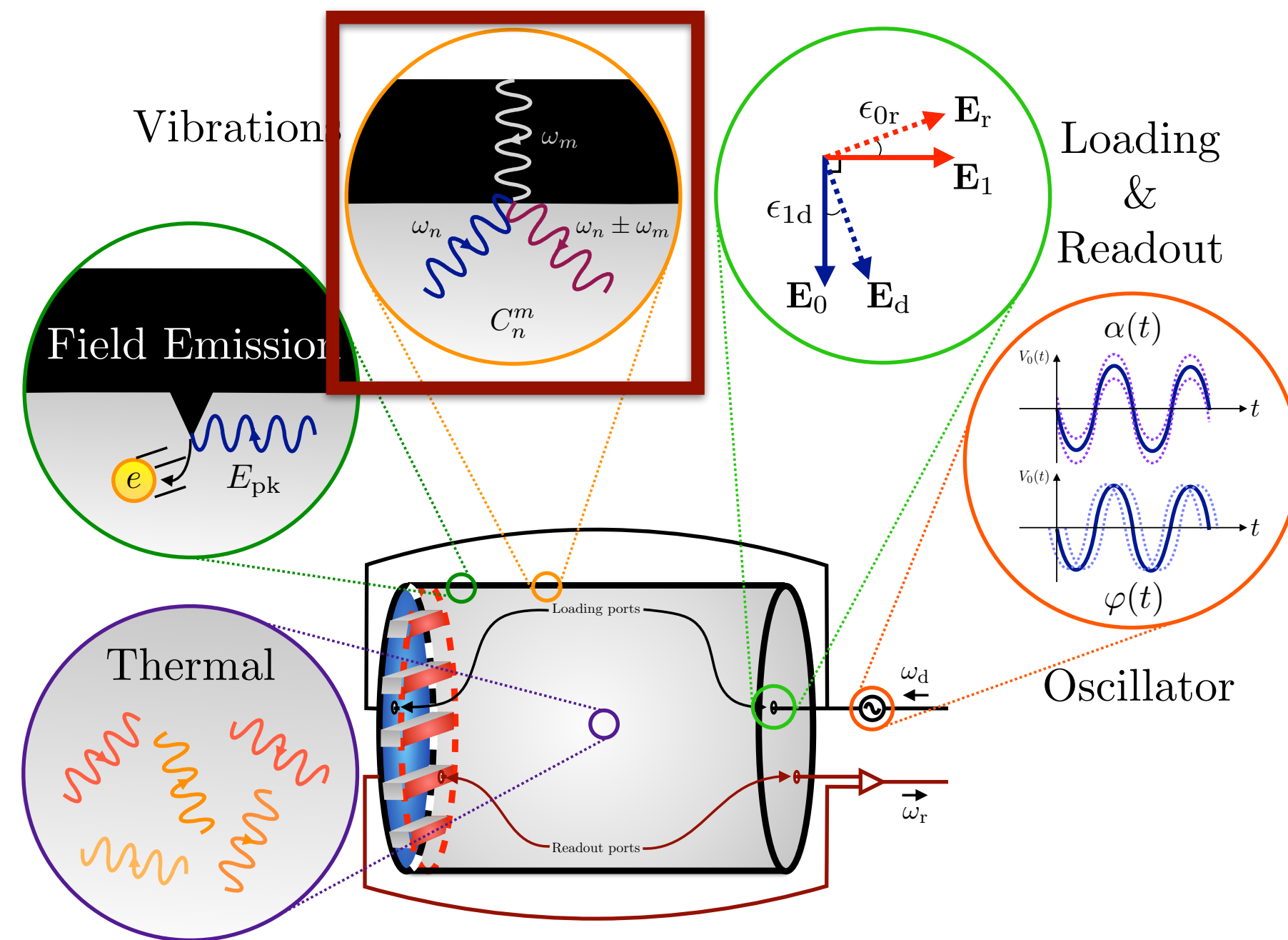


$$\ddot{\theta} + 3H\dot{\theta} + m_a^2(T)\theta = 0$$



Wall Displacement

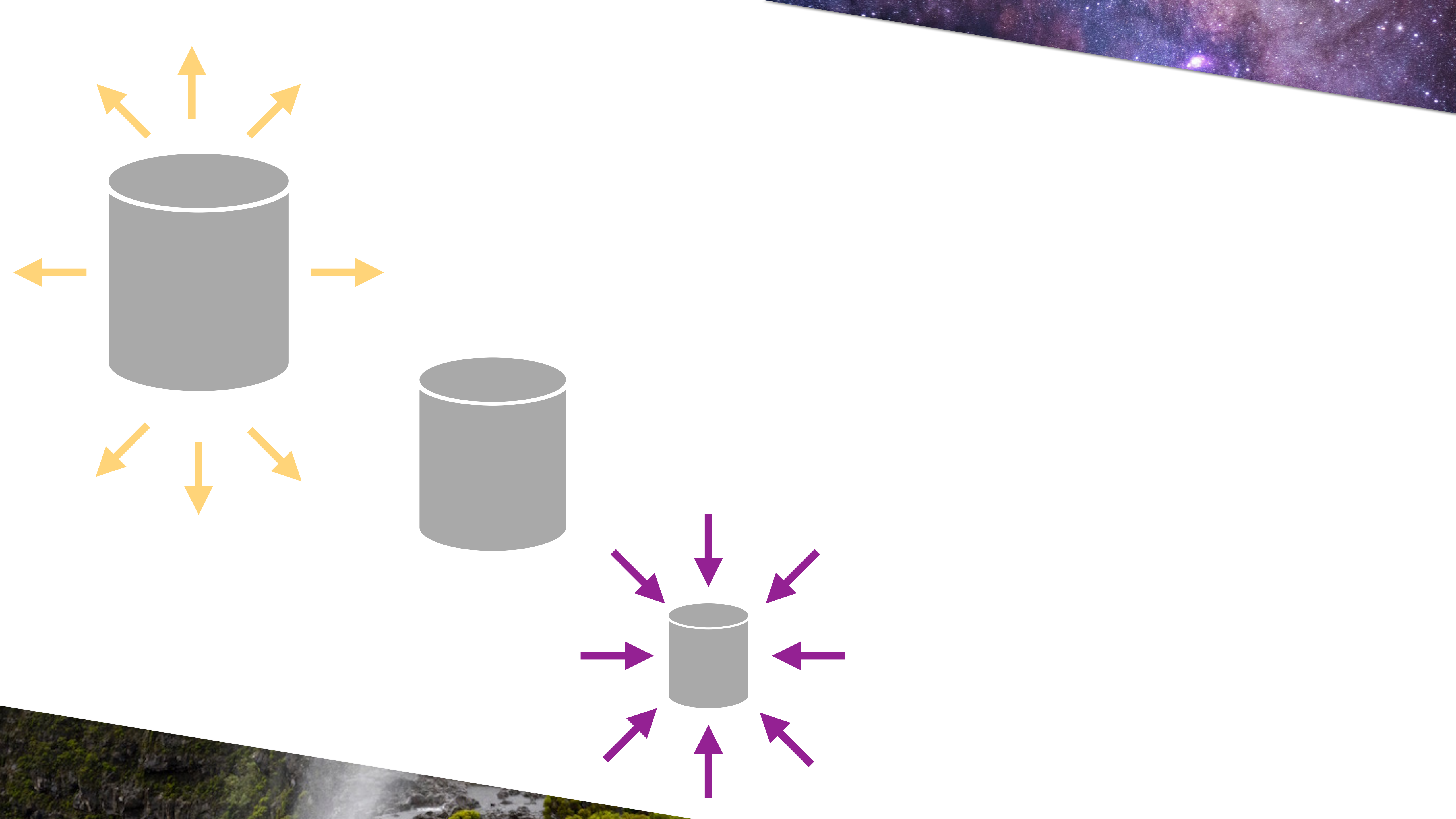
$$S_{\text{mech}}(\omega) = \sum_{n=0,1} S_{\text{mech}}^{(n)}(\omega) \simeq \frac{\epsilon_{1d}^2}{4} \frac{\omega_0}{Q_0} P_{\text{in}} \sum_{n=0,1} \frac{S_{q_m}(\omega - \omega_0) / V^{2/3} (\omega_n / Q_n) \omega_n^4 \omega^2}{[(\omega^2 - \omega_n^2)^2 + (\omega \omega_n / Q_n)^2] [(\omega_0^2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

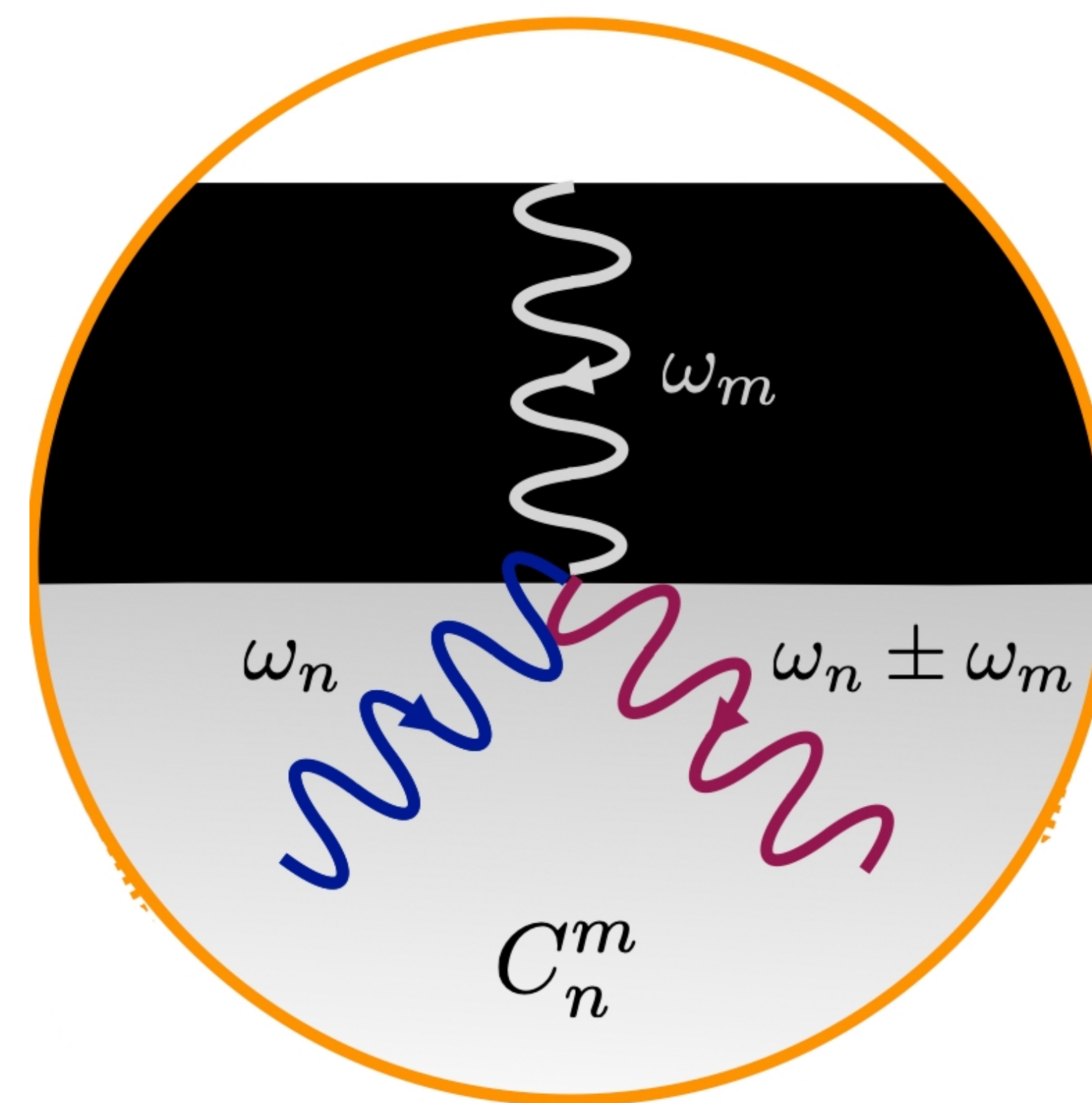
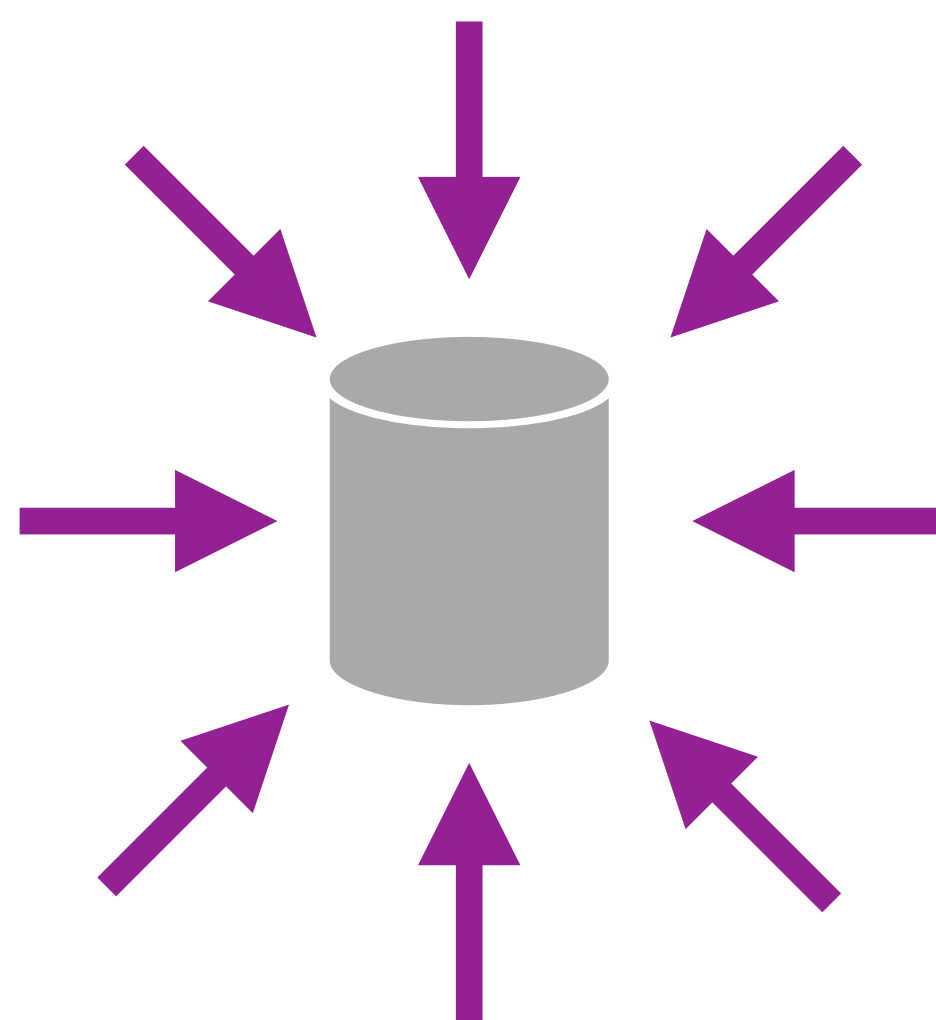
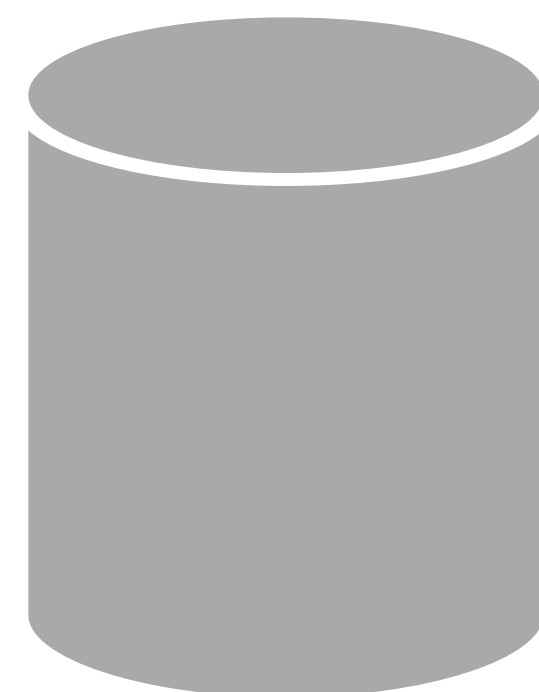
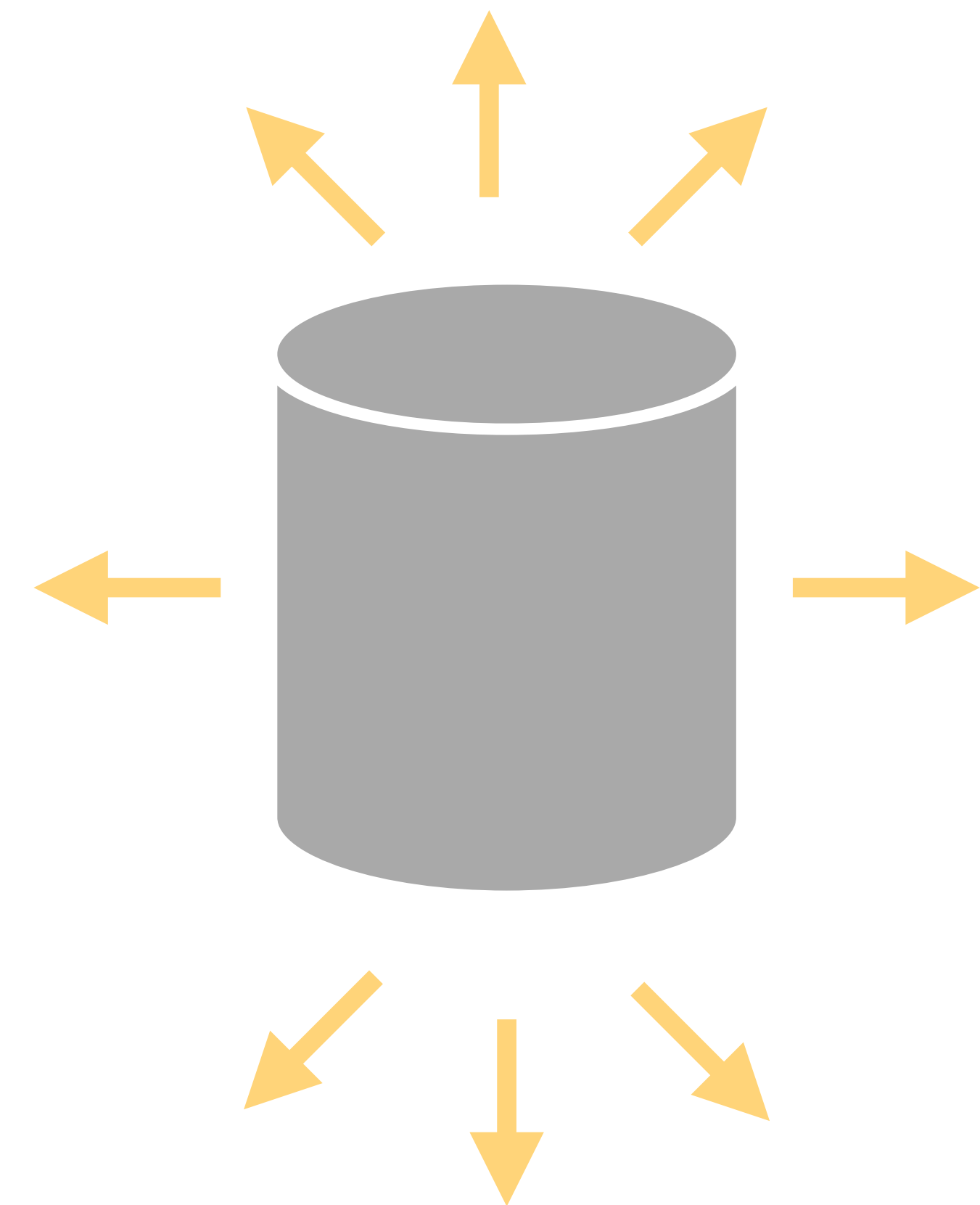


External Force

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

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

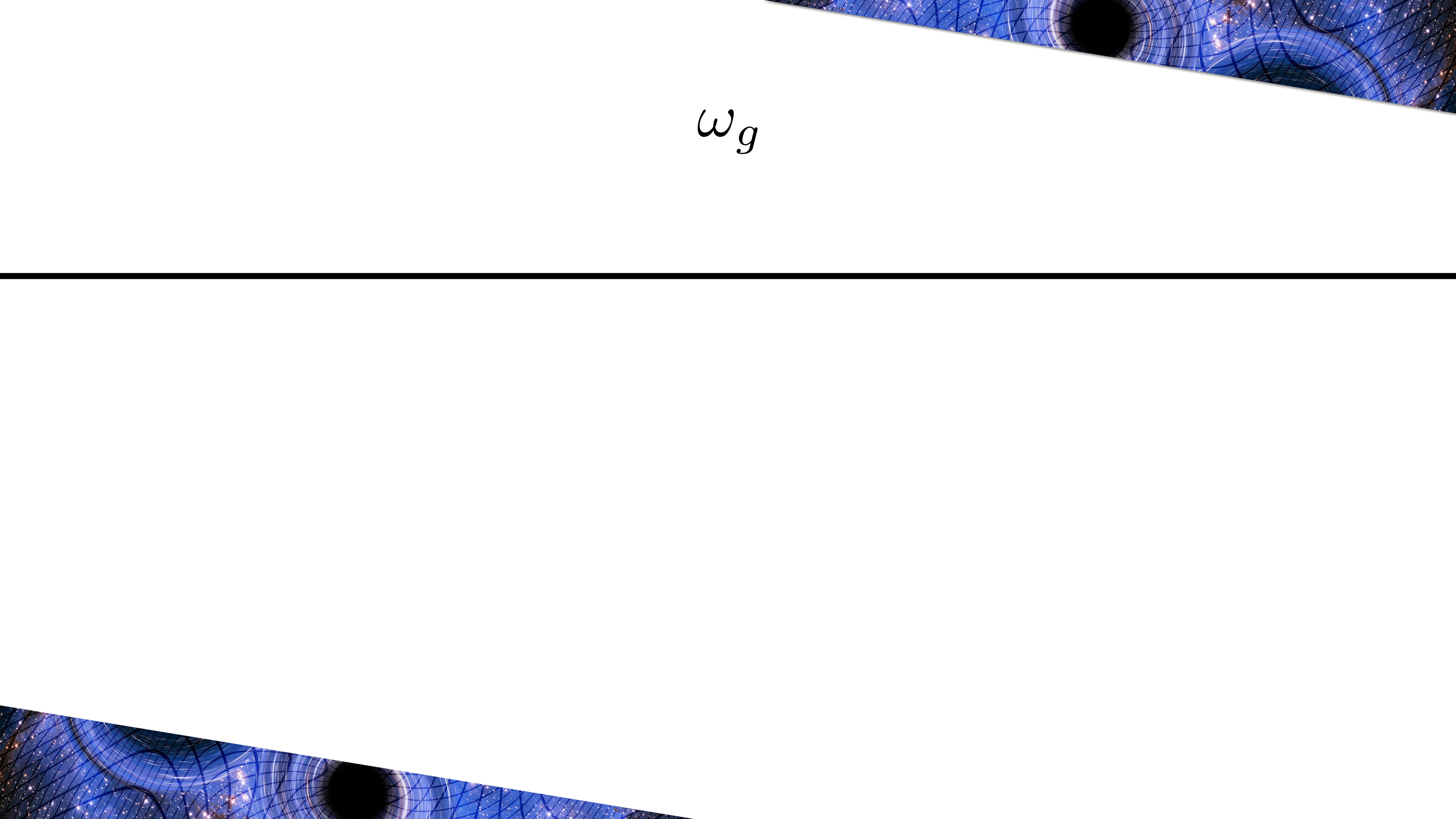




MAGO CAVITY



MAGO '05


$$\omega_g$$

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

Frequency: $\omega_a \simeq \text{GHz} \frac{m_a}{10^{-6} \text{ eV}}$

Coherence: $\tau_a \simeq \text{ms} \frac{10^{-6} \text{ eV}}{m_a}$

Max Exp. Size: $\lambda_a \simeq 200 \text{ m} \frac{10^{-6} \text{ eV}}{m_a}$

Produced Colder than the SM (even if not via misalignment)

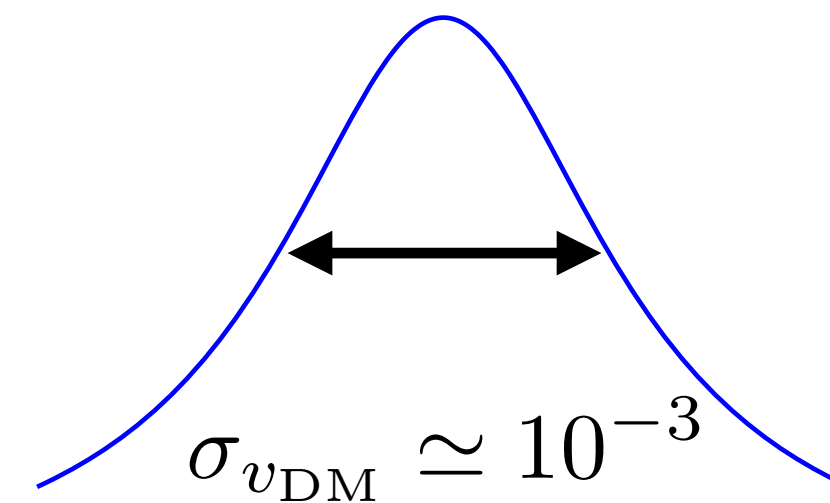
$$E_a \approx m_a$$

Produced Colder than the SM (even if not via misalignment)

$$E_a \approx m_a$$

It acquires a **small velocity dispersion** from virialization **in the Milky Way**

$$E_a \simeq m_a \left(1 + \frac{v_{\text{DM}}^2}{2} \right)$$

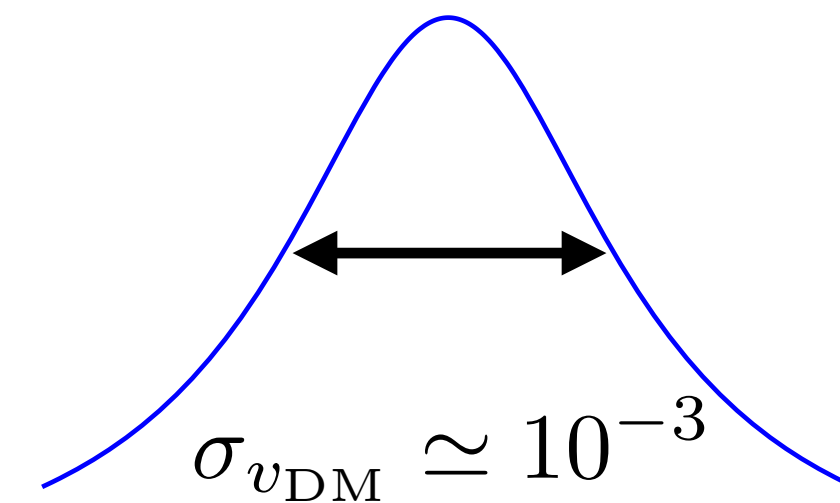


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Lots of axions in each frequency bin that we can resolve
(even more in a De Broglie volume):

$$\Delta N_a \simeq \frac{\rho_{\text{DM}} V}{m_a^2 t_{\text{int}} v_{\text{DM}}^2} \simeq 10^{24} \left(\frac{10^{-14} \text{ eV}}{m_a} \right)^2 \left(\frac{\text{year}}{t_{\text{int}}} \right) \left(\frac{V}{\text{m}^3} \right)$$

MADMAX and LAMPOST

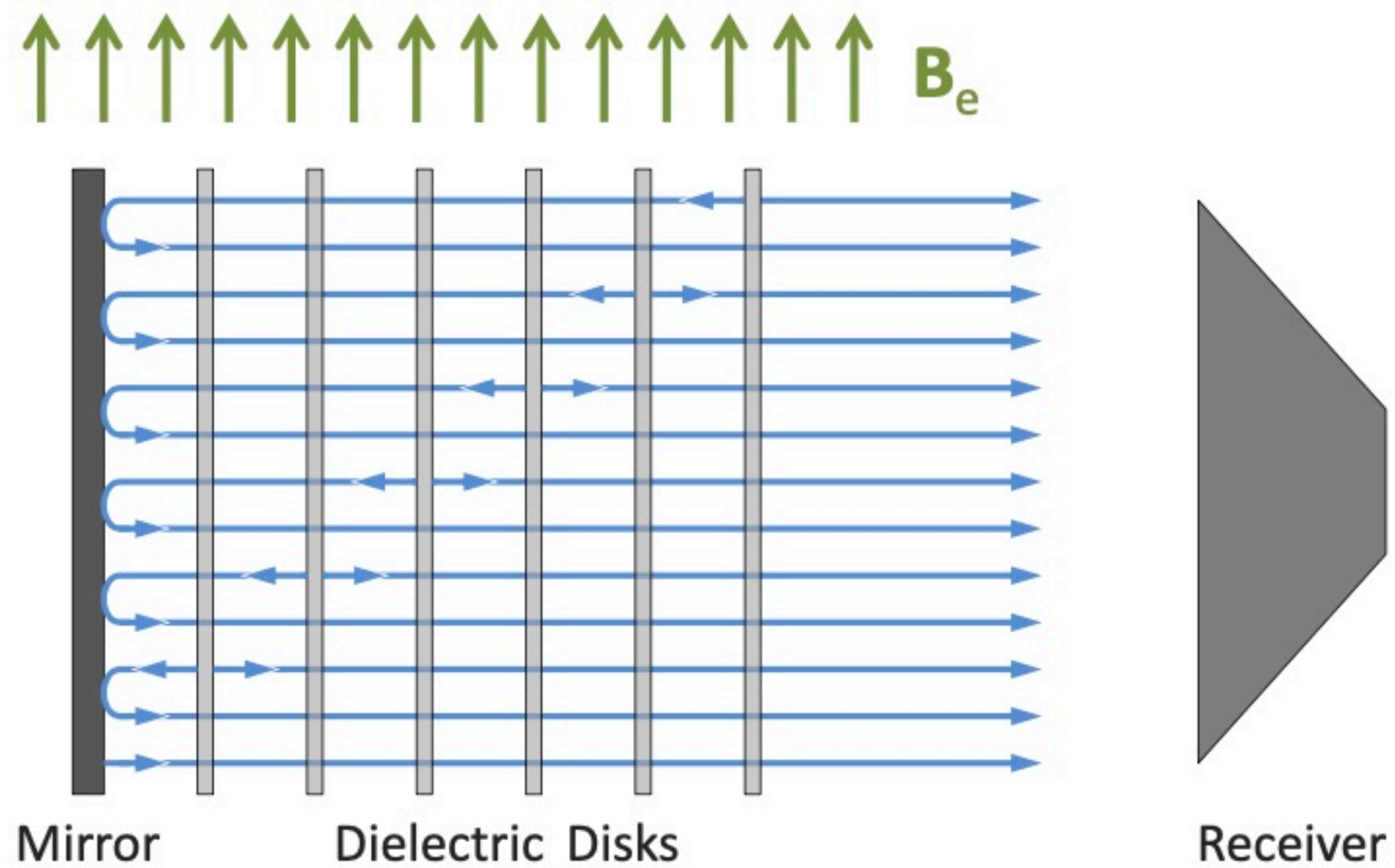
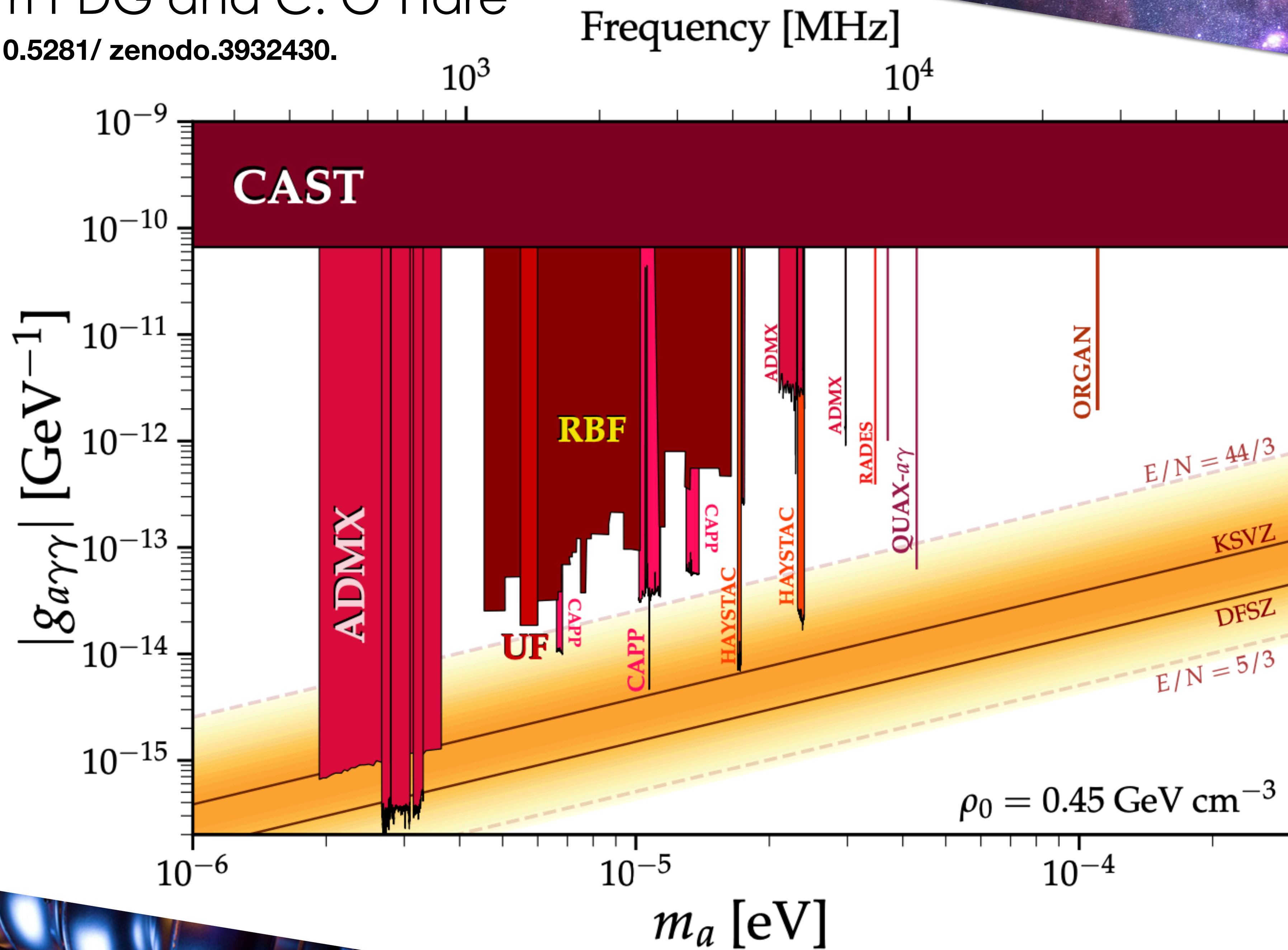


Figure from PDG and C. O'Hare
<https://doi.org/10.5281/zenodo.3932430>.



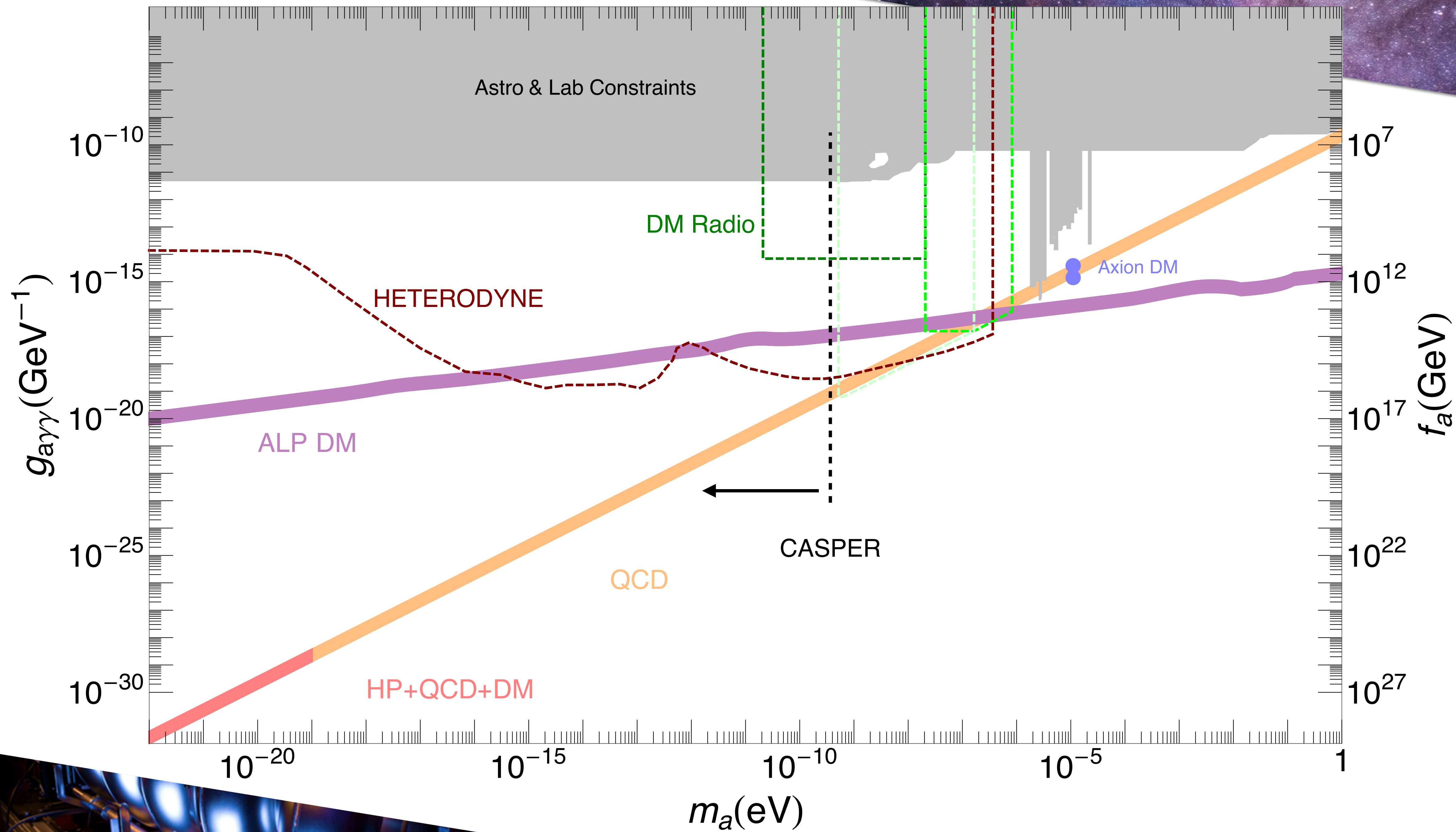
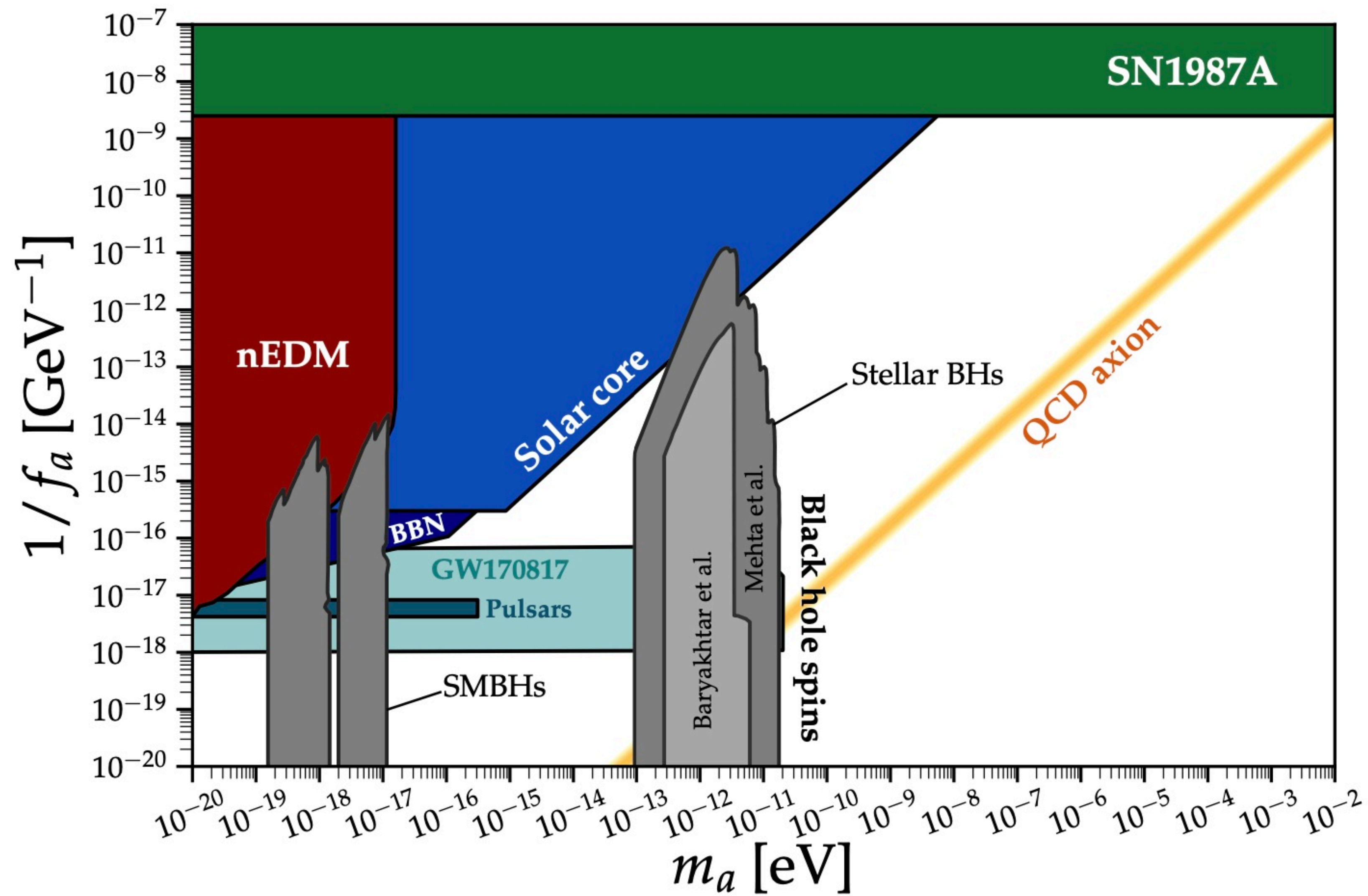


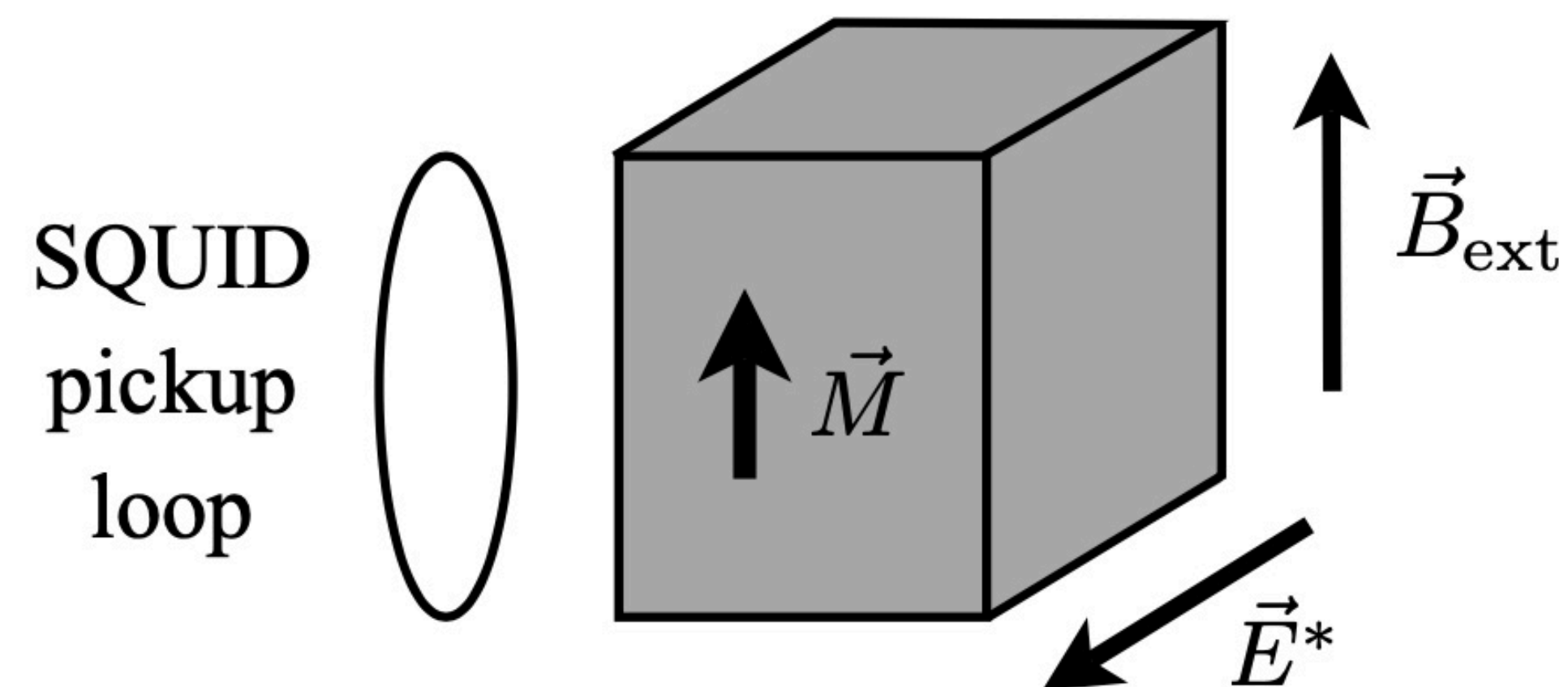
Figure from PDG and C. O'Hare

<https://doi.org/10.5281/zenodo.3932430>.



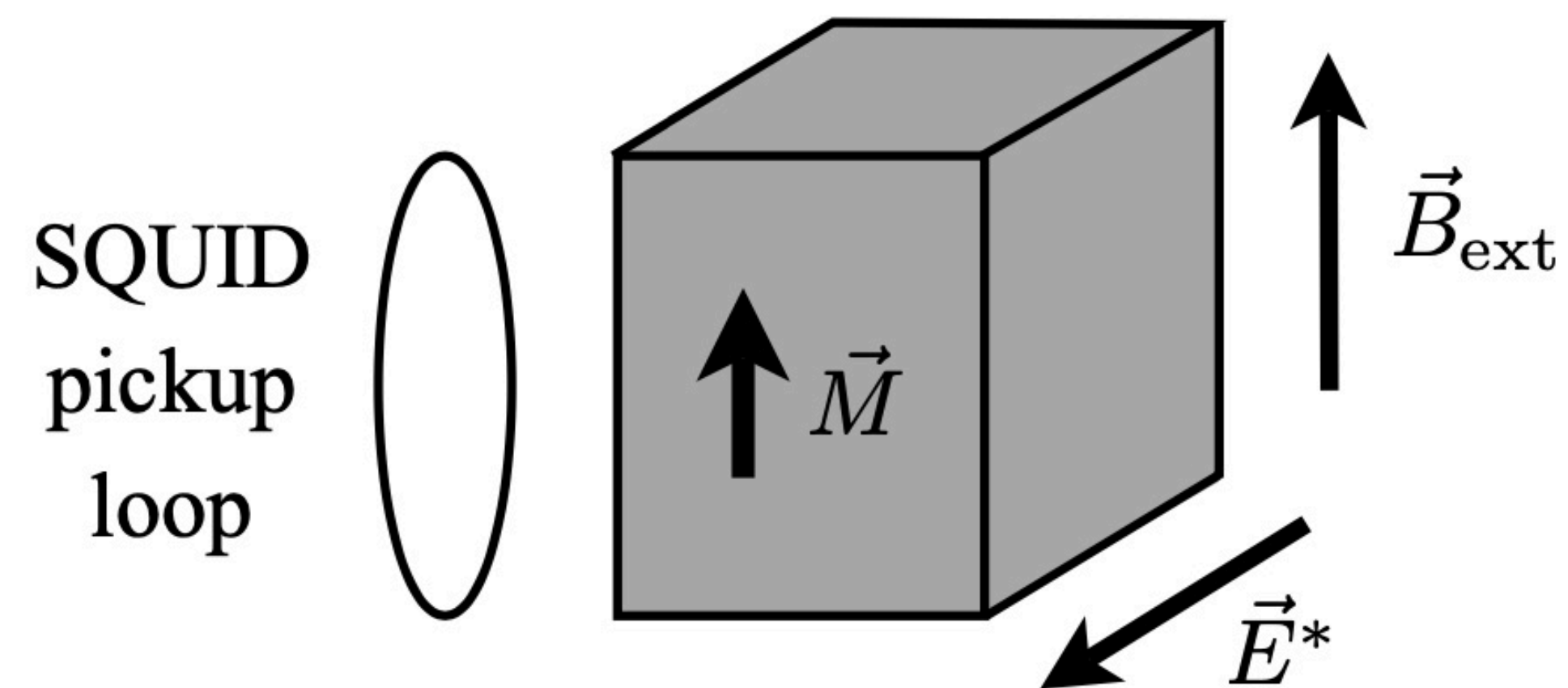
Valid for QCD Axion!

$$H \simeq \frac{a}{m_N f_a} \vec{\sigma} \cdot \vec{E}$$

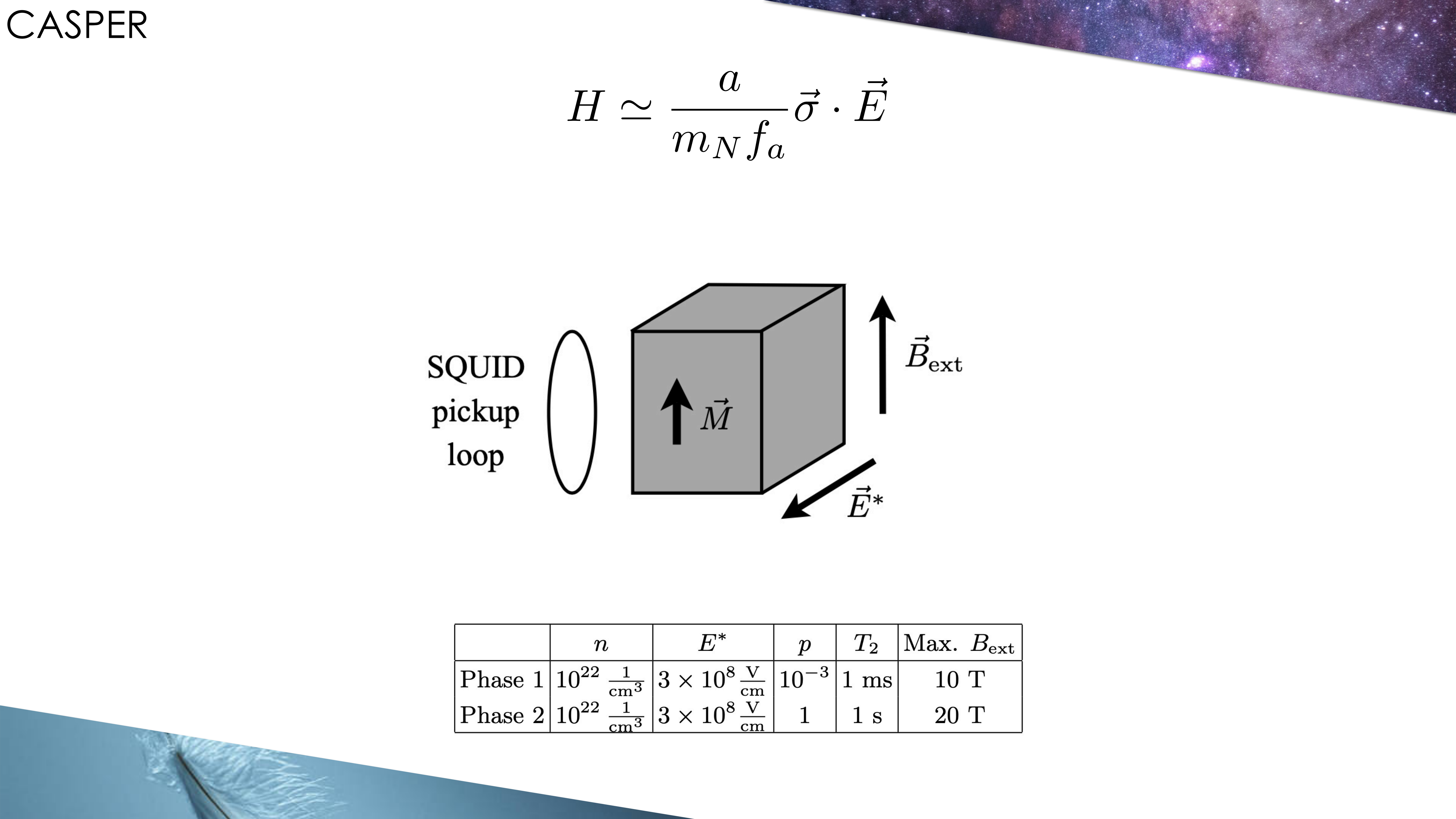


Without the axion you have a magnetisation component precessing around B (Larmor frequency)

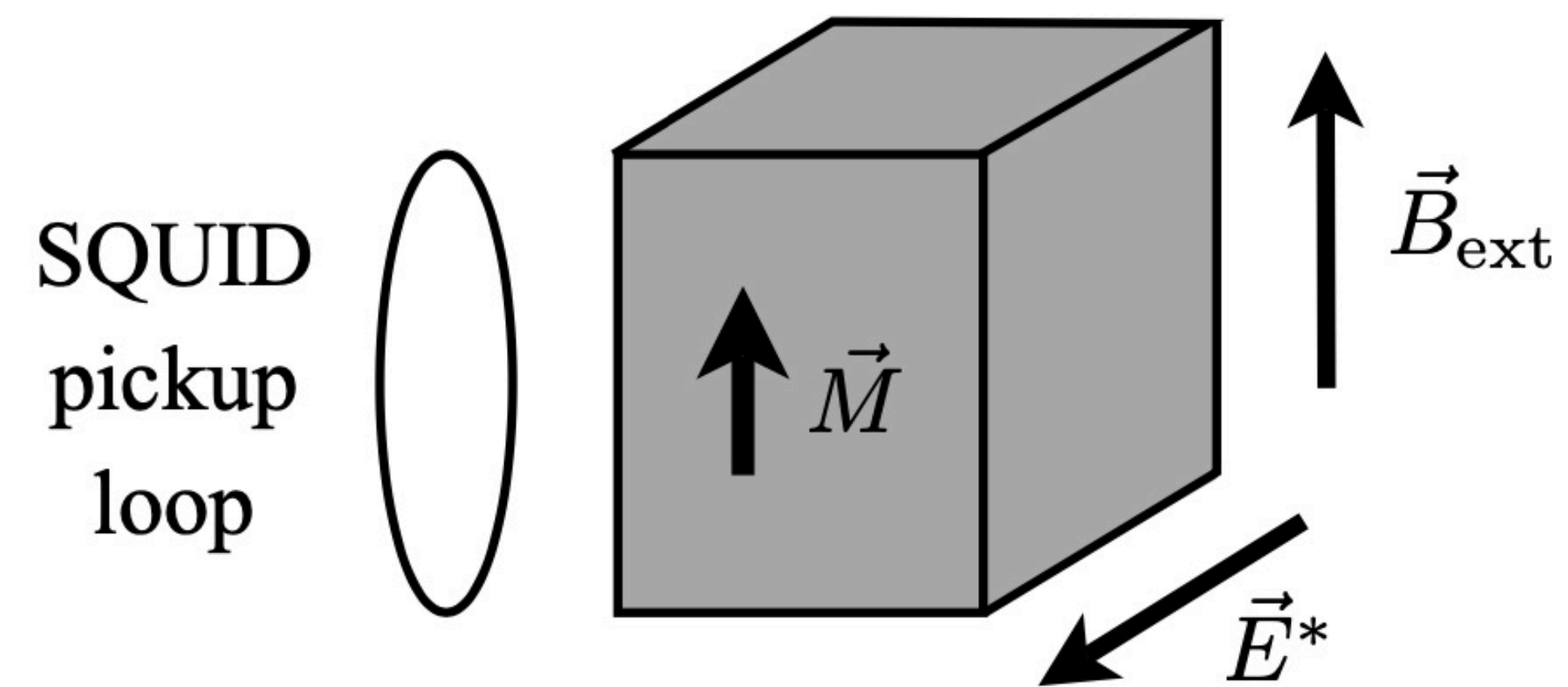
$$H \simeq \frac{a}{m_N f_a} \vec{\sigma} \cdot \vec{E}$$



$$M(t) \approx np\mu E^* \epsilon_S d_n \frac{\sin \left[\left(\frac{2\mu B_{\text{ext}} - m_a c^2}{\hbar} \right) t \right]}{\frac{2\mu B_{\text{ext}} - m_a c^2}{\hbar}} \sin (2\mu B_{\text{ext}} t)$$



$$H \simeq \frac{a}{m_N f_a} \vec{\sigma} \cdot \vec{E}$$



	n	E^*	p	T_2	Max. B_{ext}
Phase 1	$10^{22} \frac{1}{\text{cm}^3}$	$3 \times 10^8 \frac{\text{V}}{\text{cm}}$	10^{-3}	1 ms	10 T
Phase 2	$10^{22} \frac{1}{\text{cm}^3}$	$3 \times 10^8 \frac{\text{V}}{\text{cm}}$	1	1 s	20 T

DANCE

Obata, Fujita, Michimura, '18

