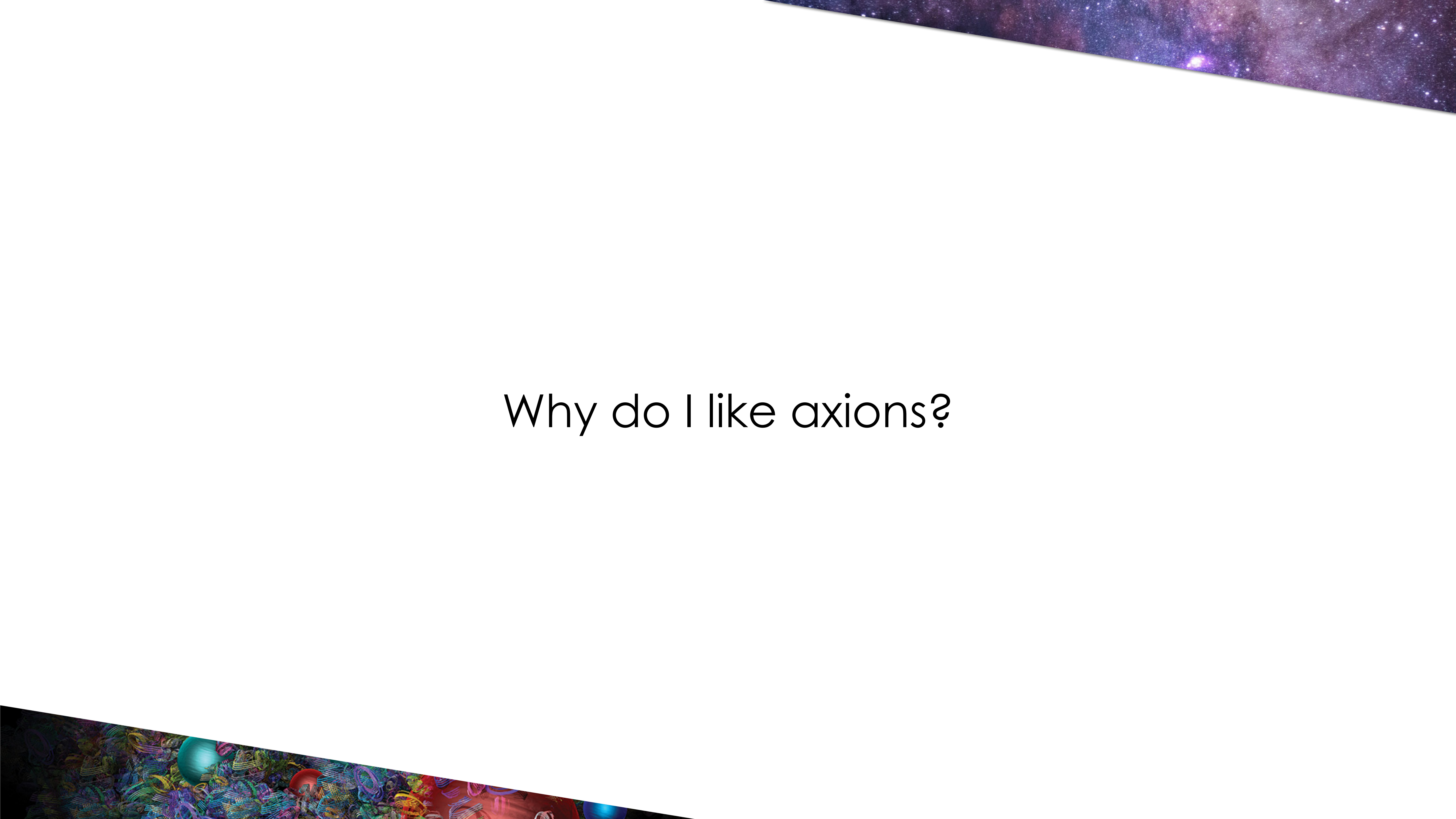


AXION DARK MATTER DETECTION

Raffaele Tito D'Agnolo - IPhT Saclay and ENS Paris

The image features a white background with a diagonal split. The top-right corner shows a deep space scene with a purple and blue galaxy. The bottom-left corner shows a complex, colorful visualization of particle physics, likely a particle detector or simulation, with various colored tracks and spheres. Centered on the white background is the text "Why do I like axions?".

Why do I like axions?

WHY DO I LIKE AXIONS?

1. A good dark matter candidate



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

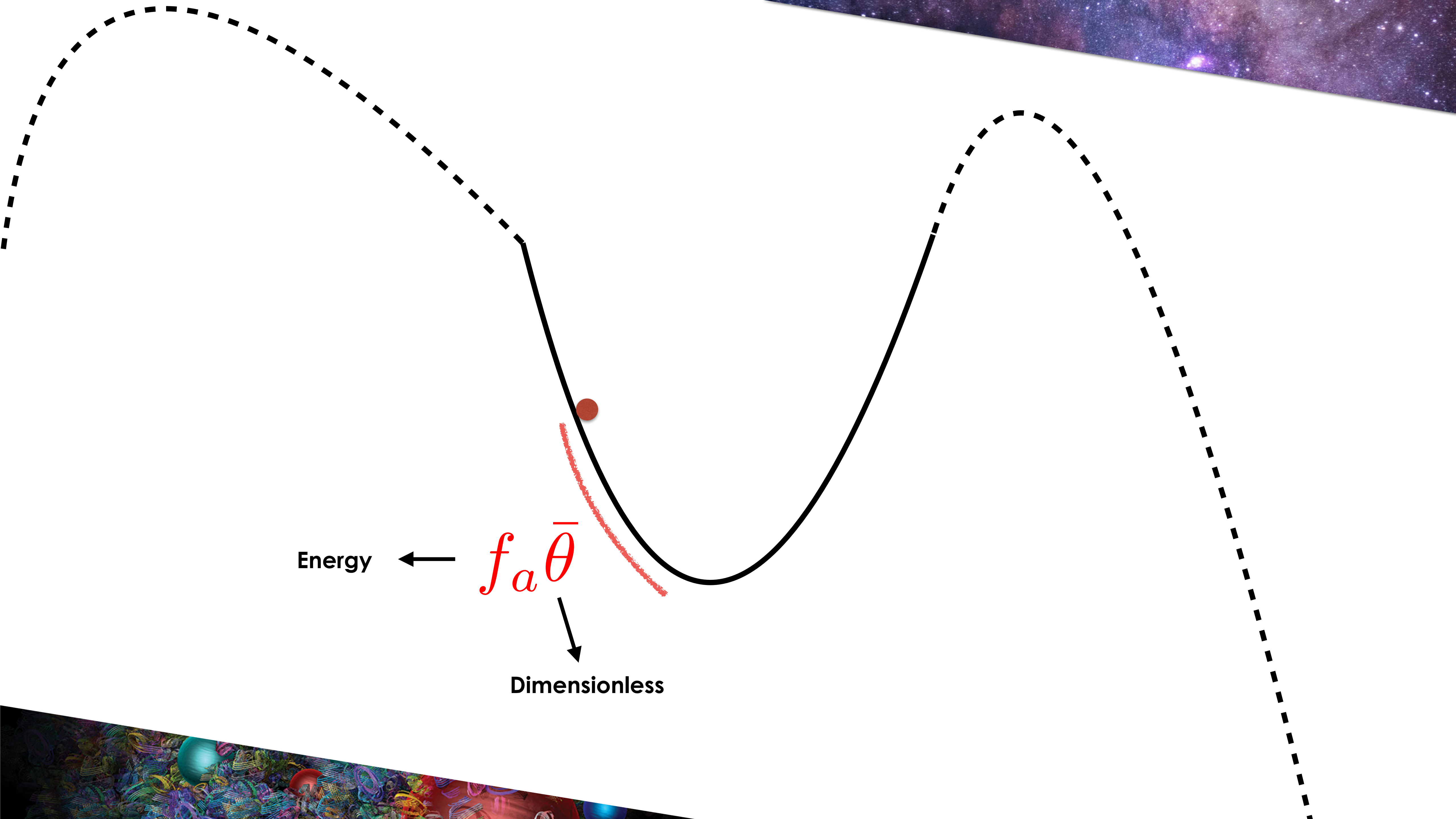
Galaxy: $N_{\text{DM}} \simeq 10^3 \left(\frac{\text{eV}}{m_{\text{DM}}} \right)$

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

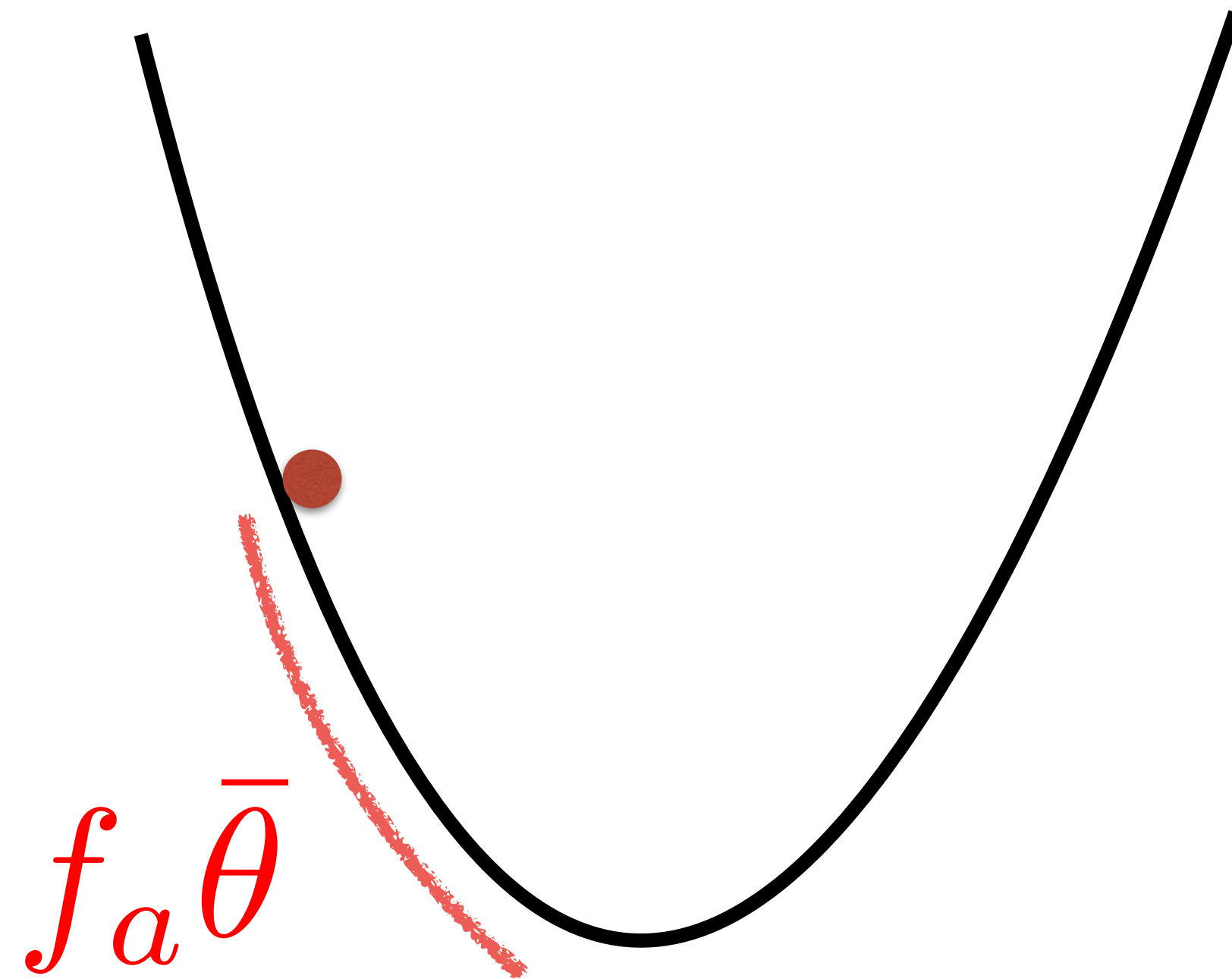



$$V(a) =$$

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

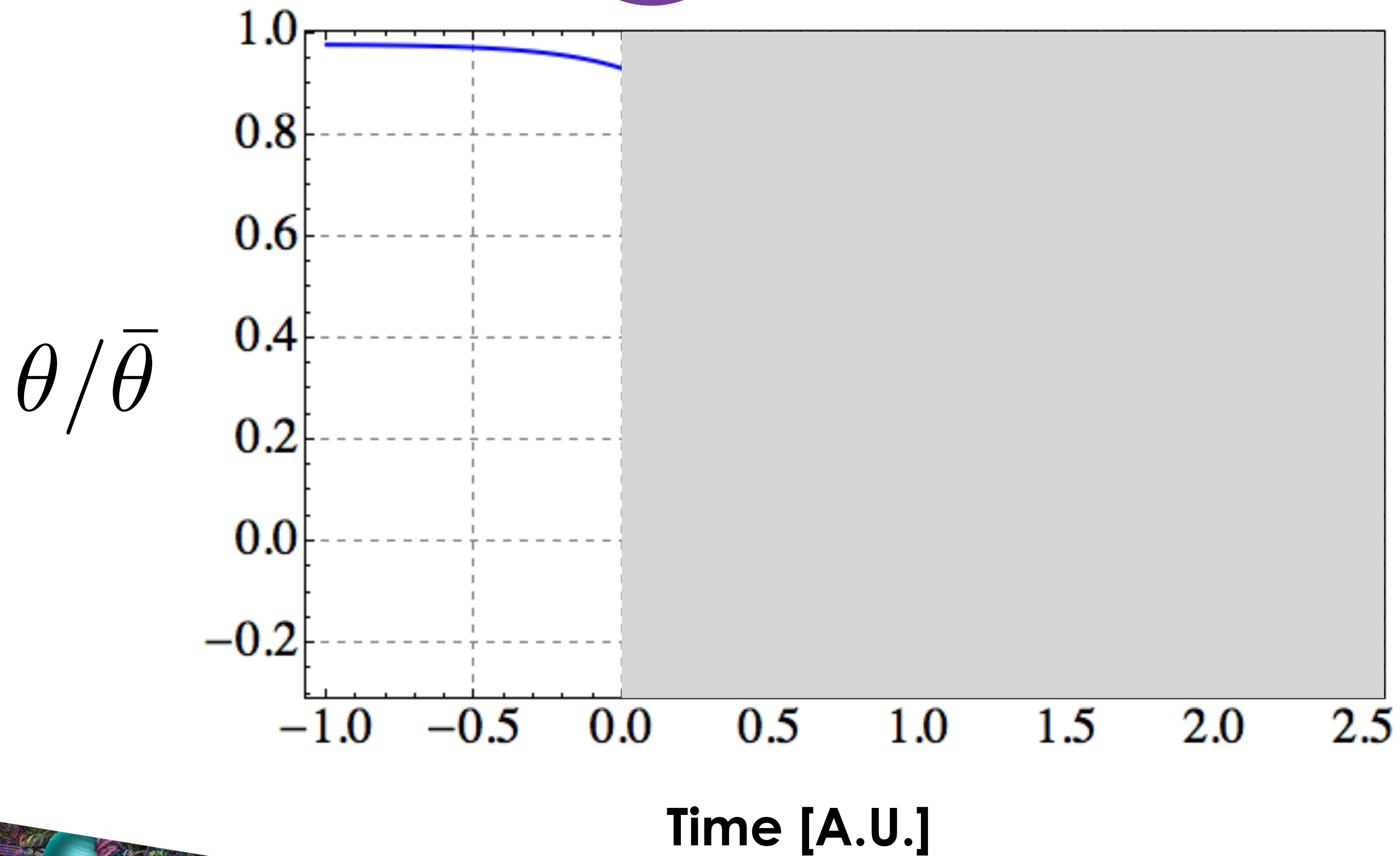


Classical Equation of Motion

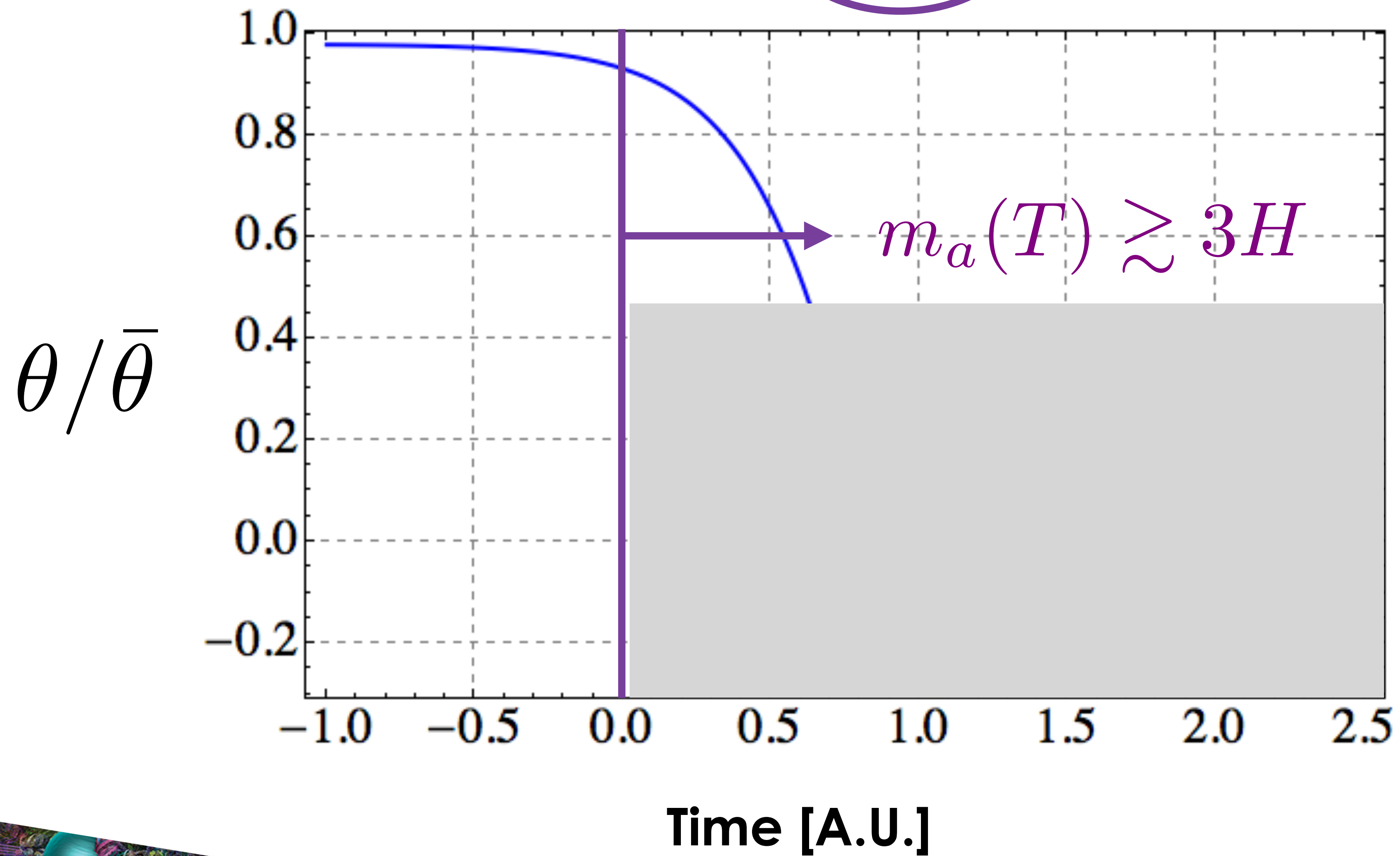


$$\ddot{\theta} + 3H\dot{\theta} + m_a^2(T)\theta = 0$$

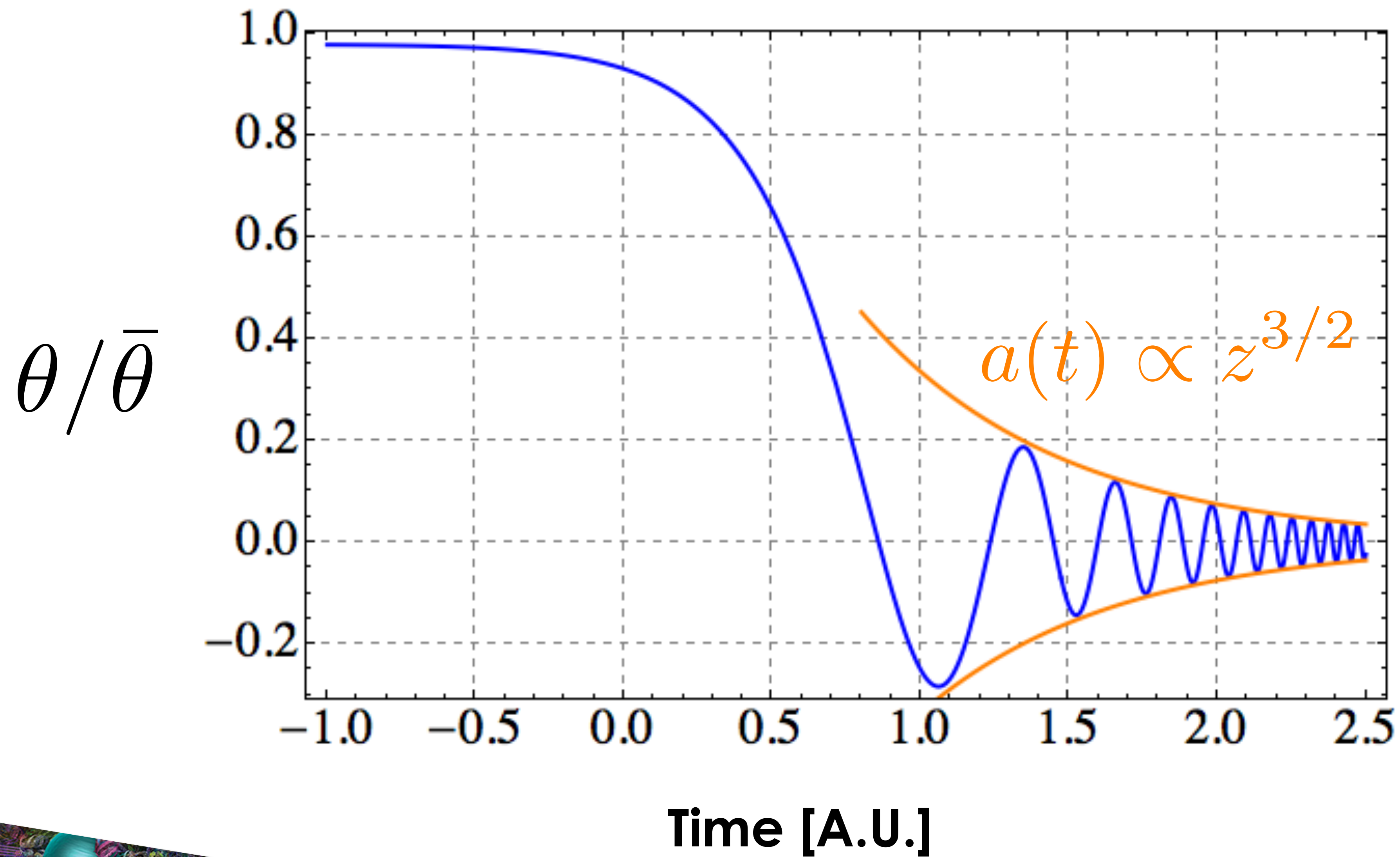
$$\ddot{\theta} + 3H\dot{\theta} + m_a^2(T)\theta = 0$$



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

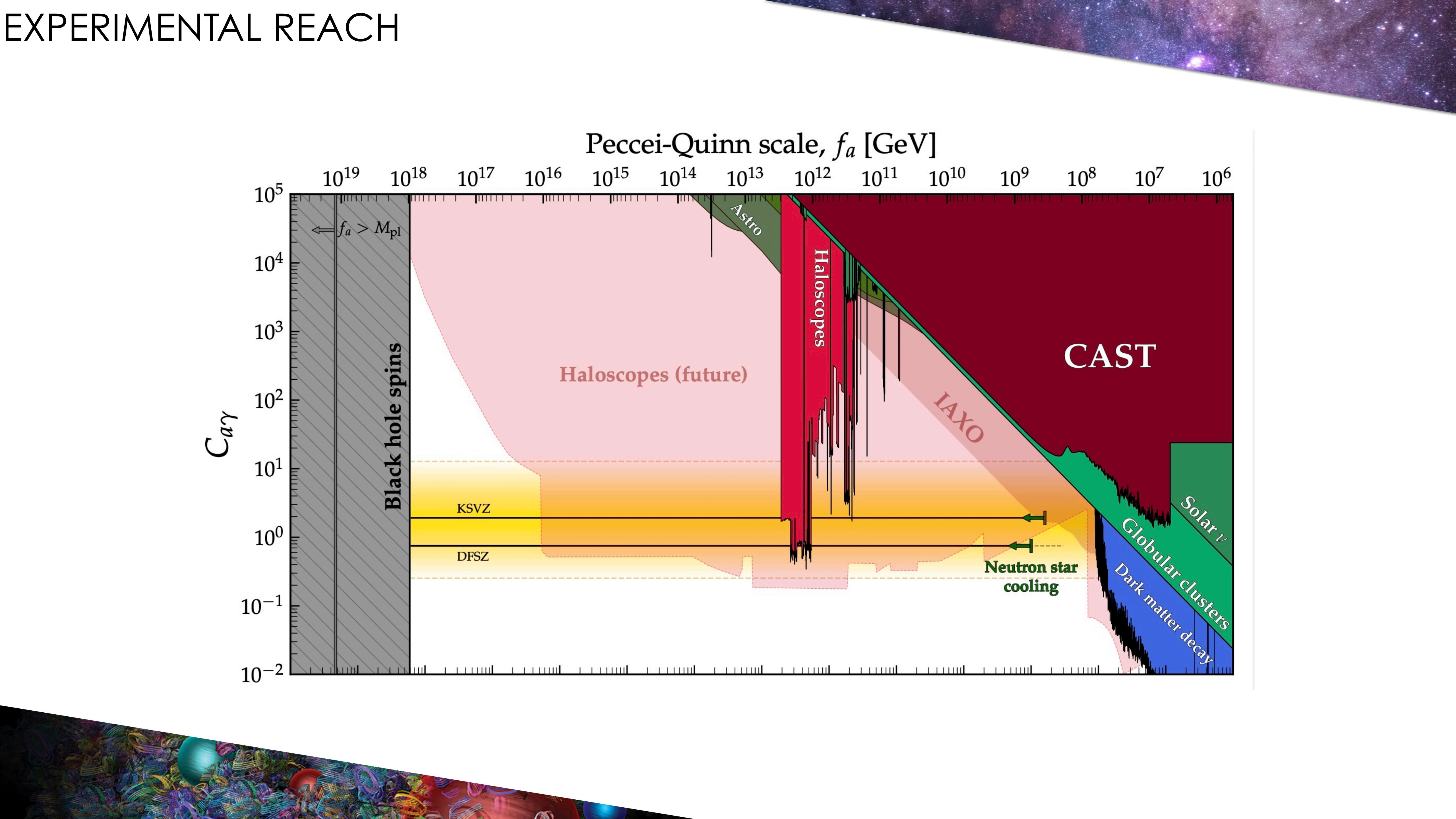


$$\ddot{\theta} + 3H\dot{\theta} + m_a^2(T)\theta = 0$$

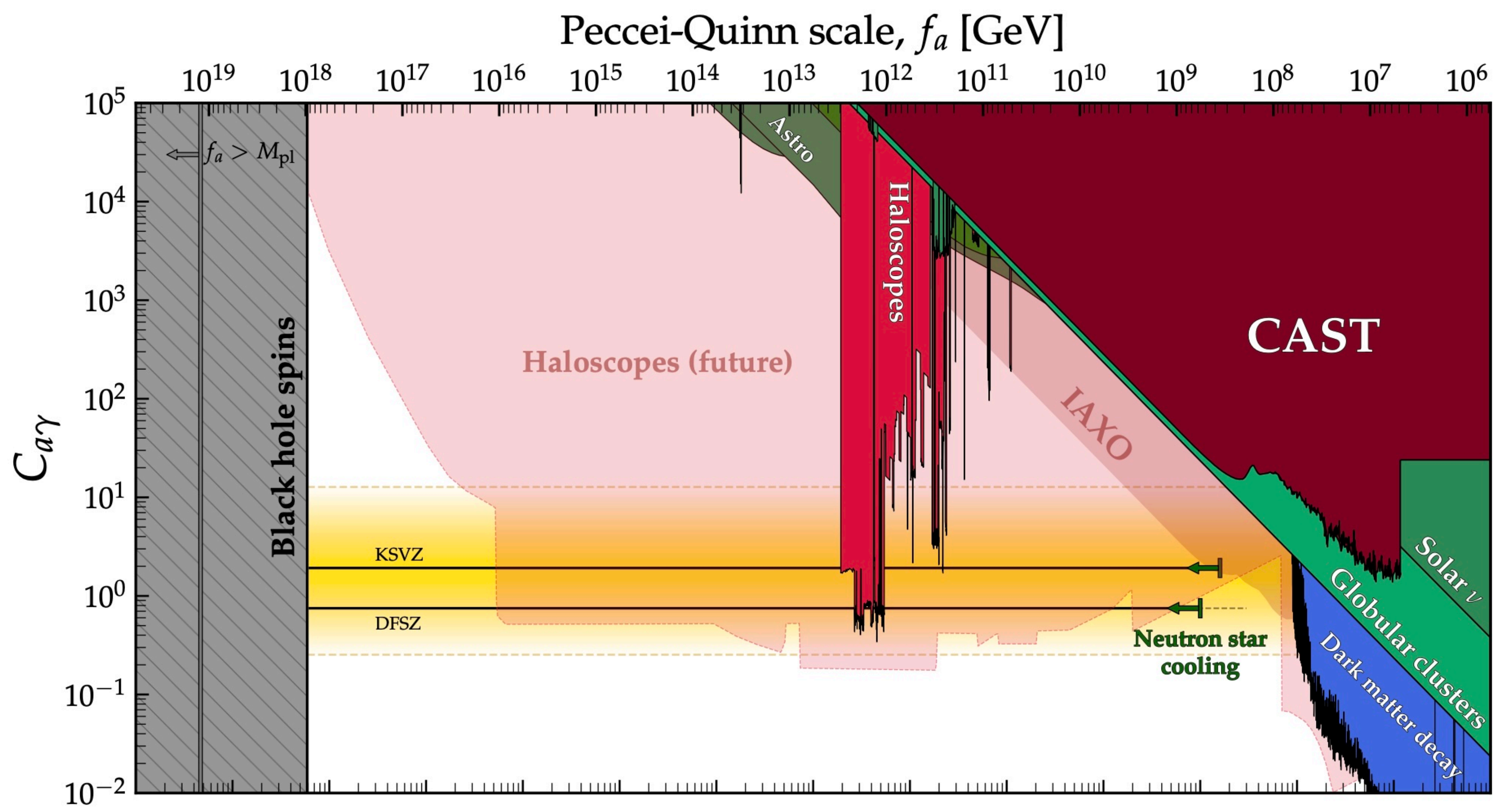


WHY DO I LIKE AXIONS?

2. It is a very good time to look for them



EXPERIMENTAL REACH



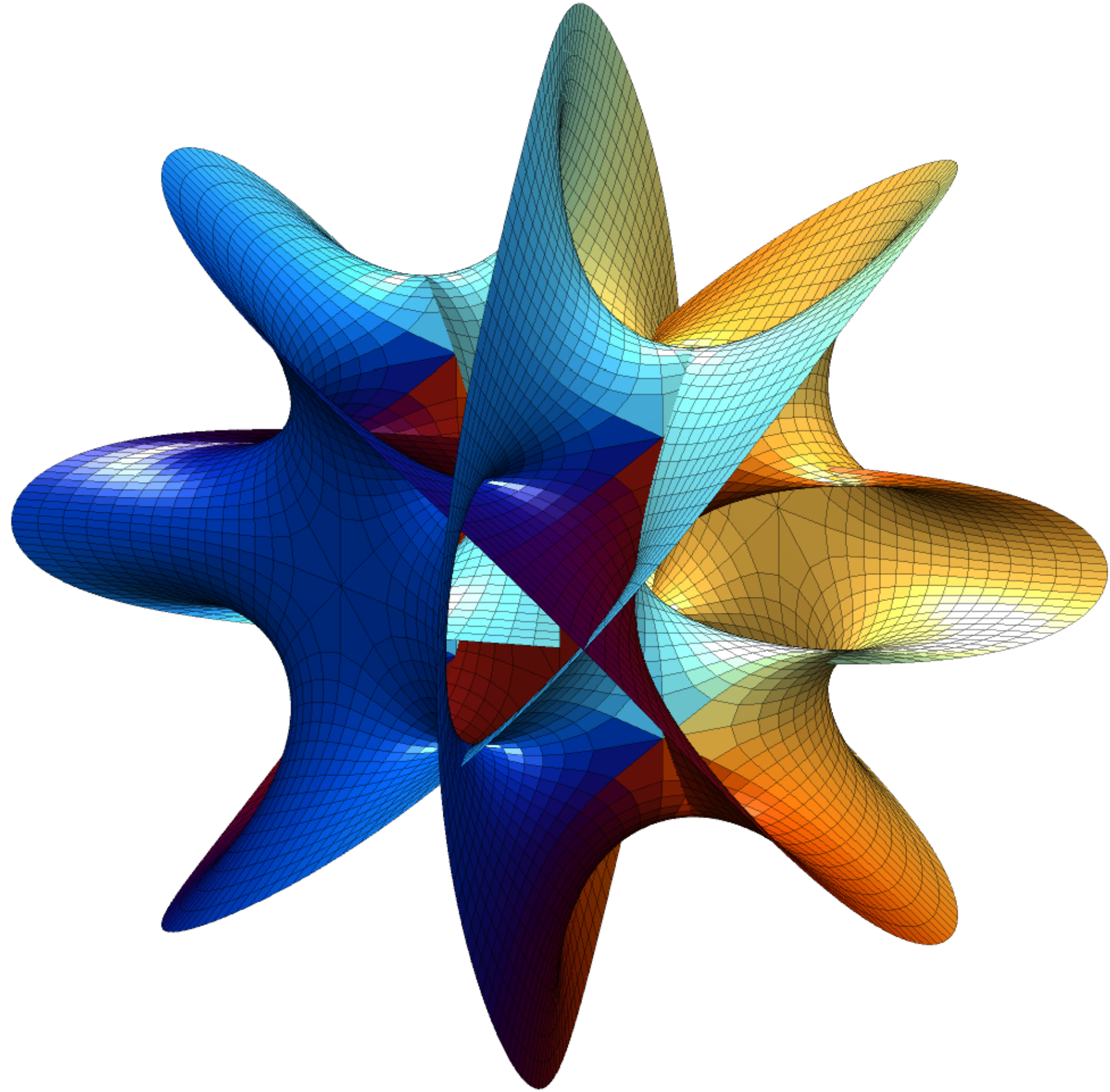
3. A clean probe of high energies

$$\mathcal{A} \frac{\alpha_s}{2\pi} \frac{a}{f_a} G \tilde{G}$$

$$A_{\text{UV}} = A_{\text{IR}}$$

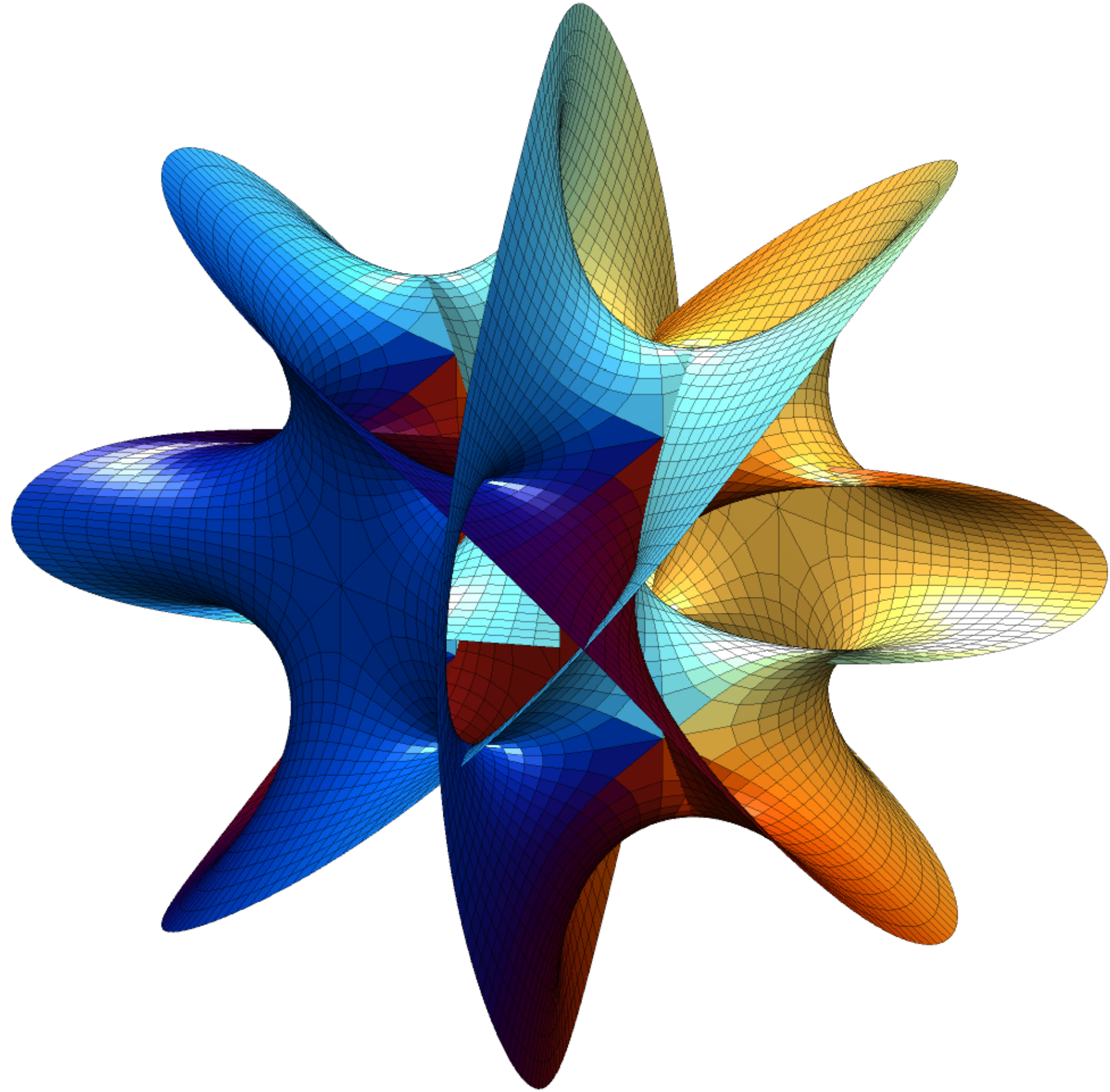
4. Generically predicted in string theory

GENERIC UV PREDICTION



$$S = \int d^d x \sqrt{-G} \left(M_*^{d-2} R + \mathcal{L} \right)$$

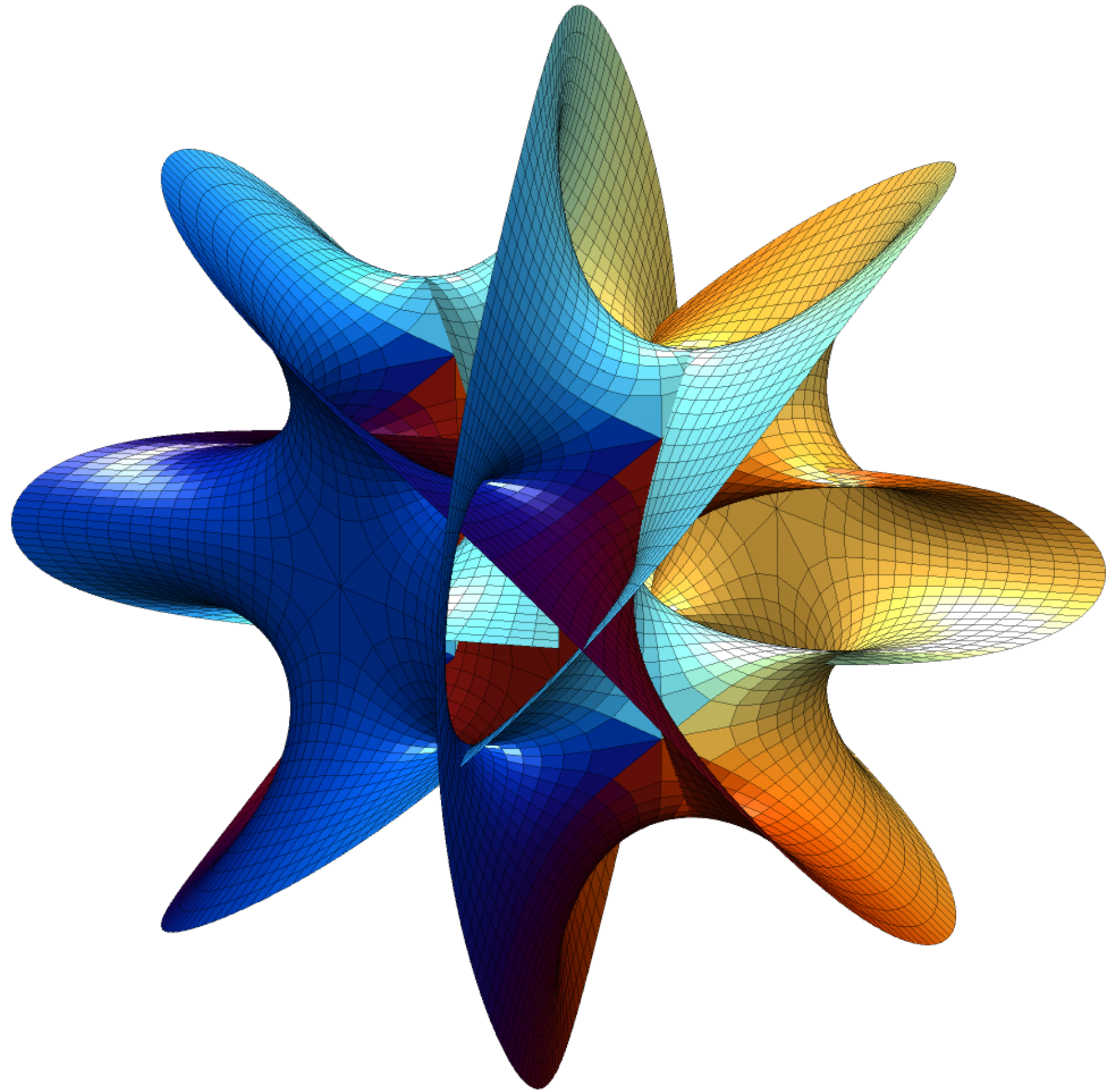
GENERIC UV PREDICTION



$$S = \int d^d x \sqrt{-G} \left(M_*^{d-2} R + \mathcal{L} \right)$$

$$= \int d^4 x \sqrt{-g} \left(M_{\text{Pl}}^2 R + \mathcal{L}' \right)$$

GENERIC UV PREDICTION



$$S = \int d^d x \sqrt{-G} \left(M_*^{d-2} R + \mathcal{L} \right)$$

$$= \int d^4 x \sqrt{-g} \left(M_{\text{Pl}}^2 R + \mathcal{L}' \right)$$

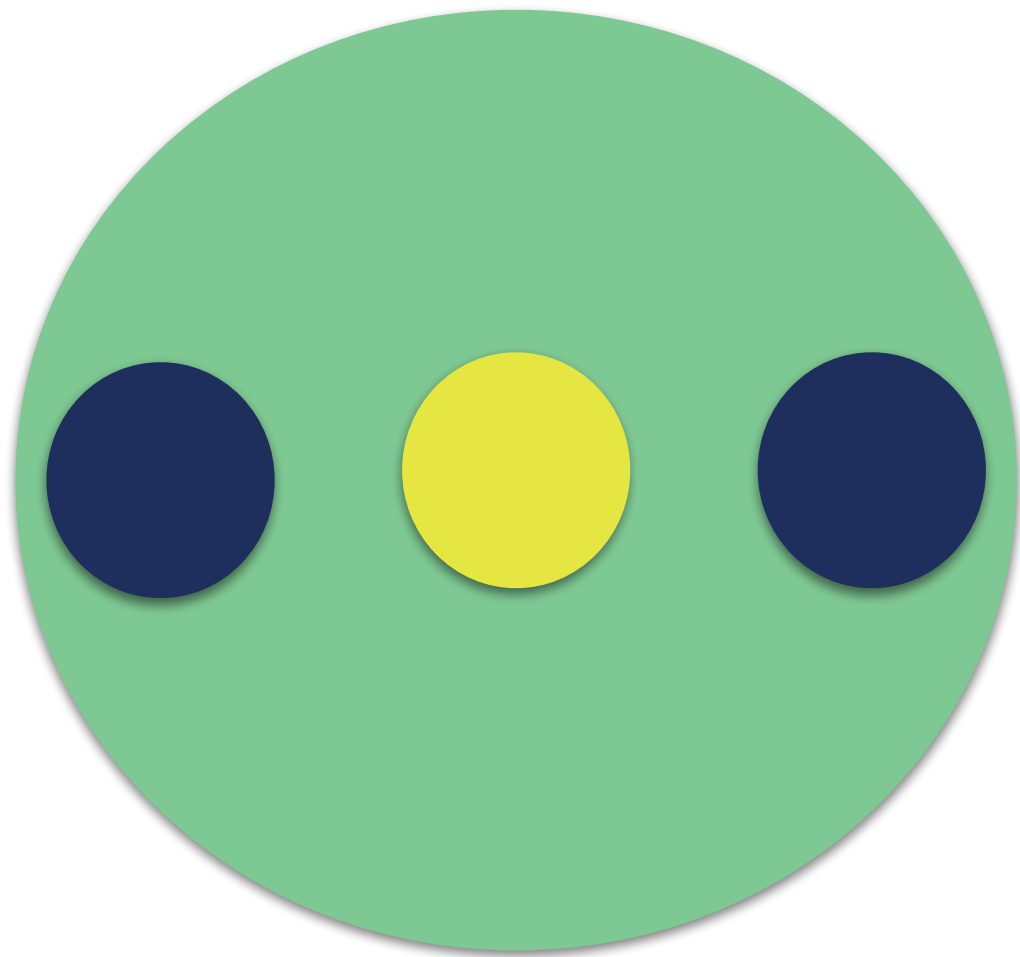
$$A \rightarrow A + d\Lambda$$

$$a = \int_C A$$

5. They solve a puzzle of the Standard Model

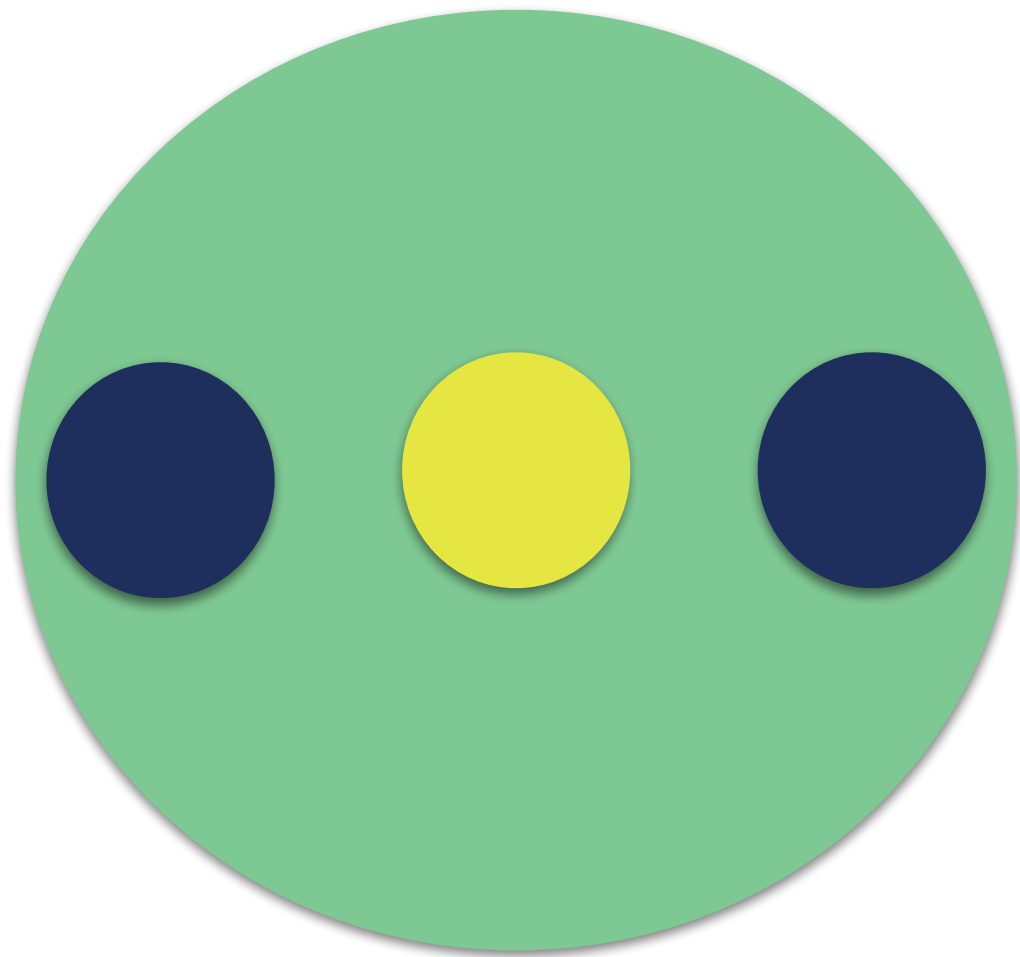
$$\theta G \tilde{G}$$

Neutron $\theta = 0$

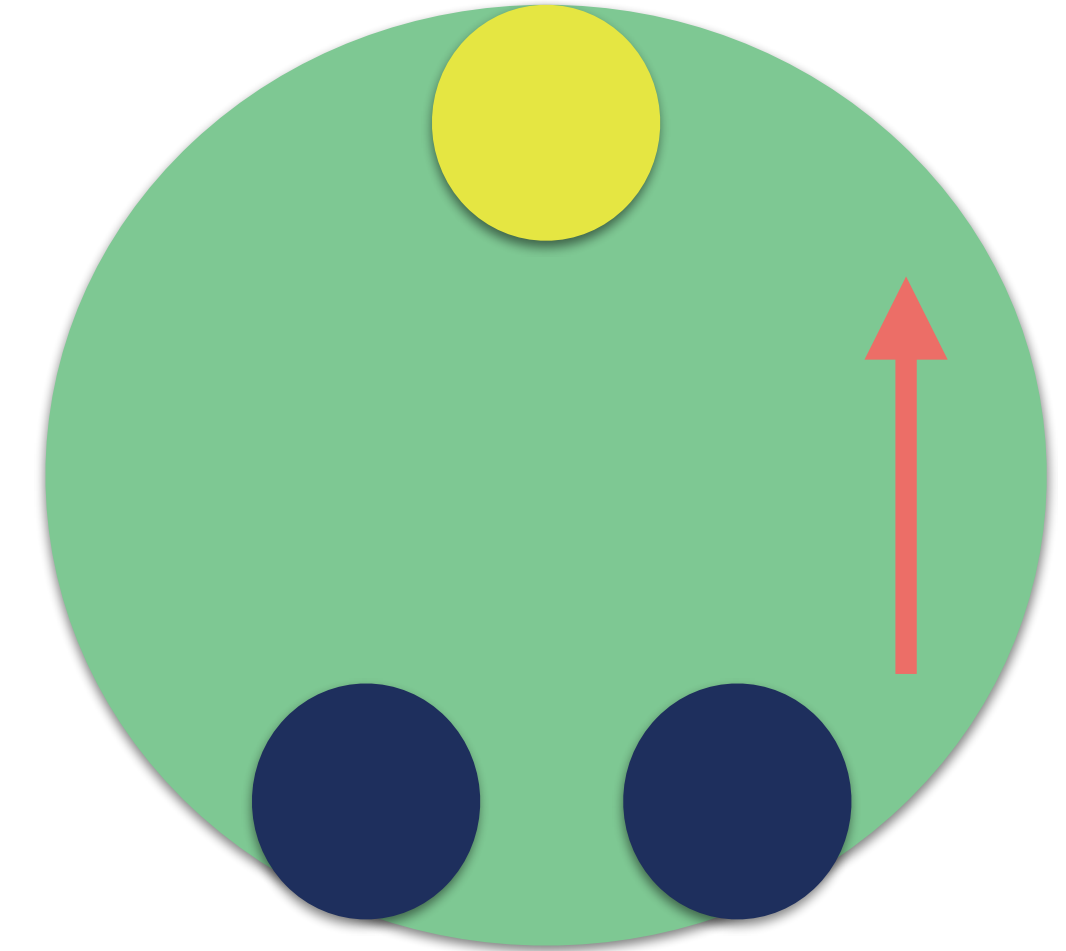


$$\theta G \tilde{G}$$

Neutron $\theta = 0$



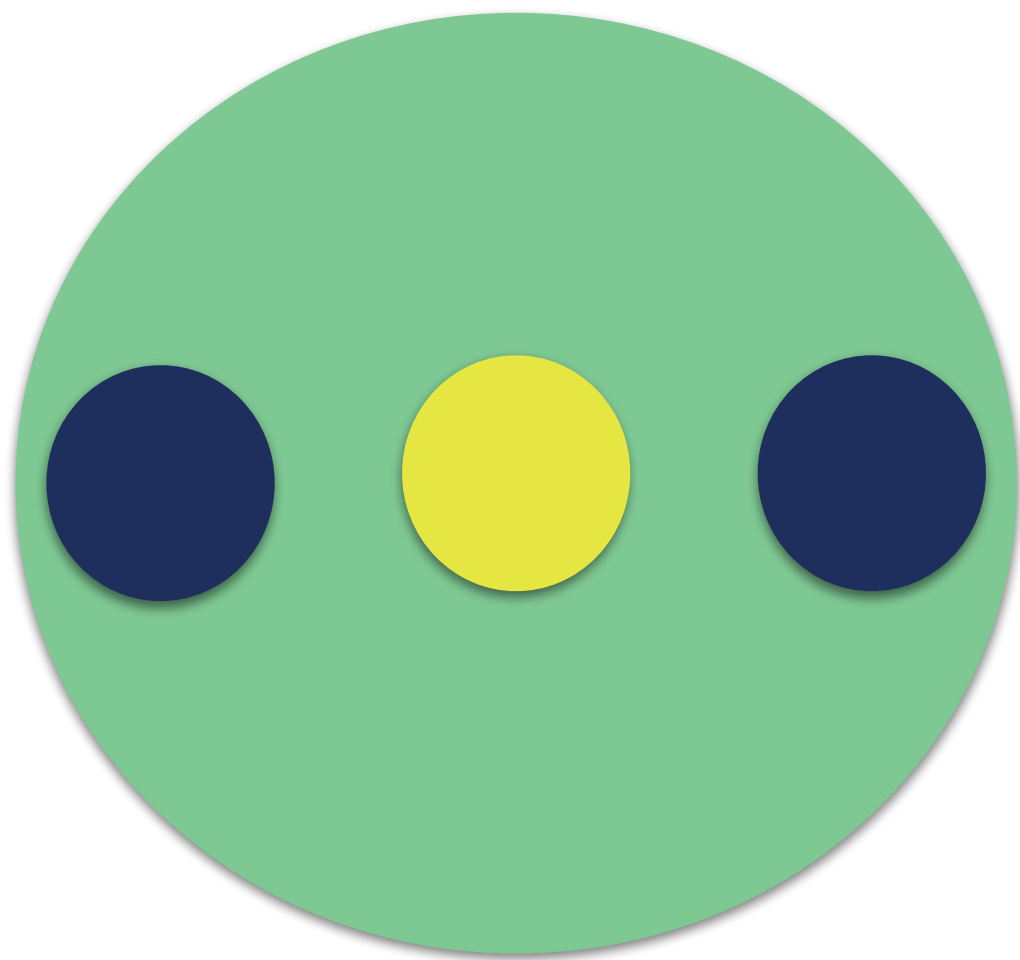
Neutron $\theta \neq 0$



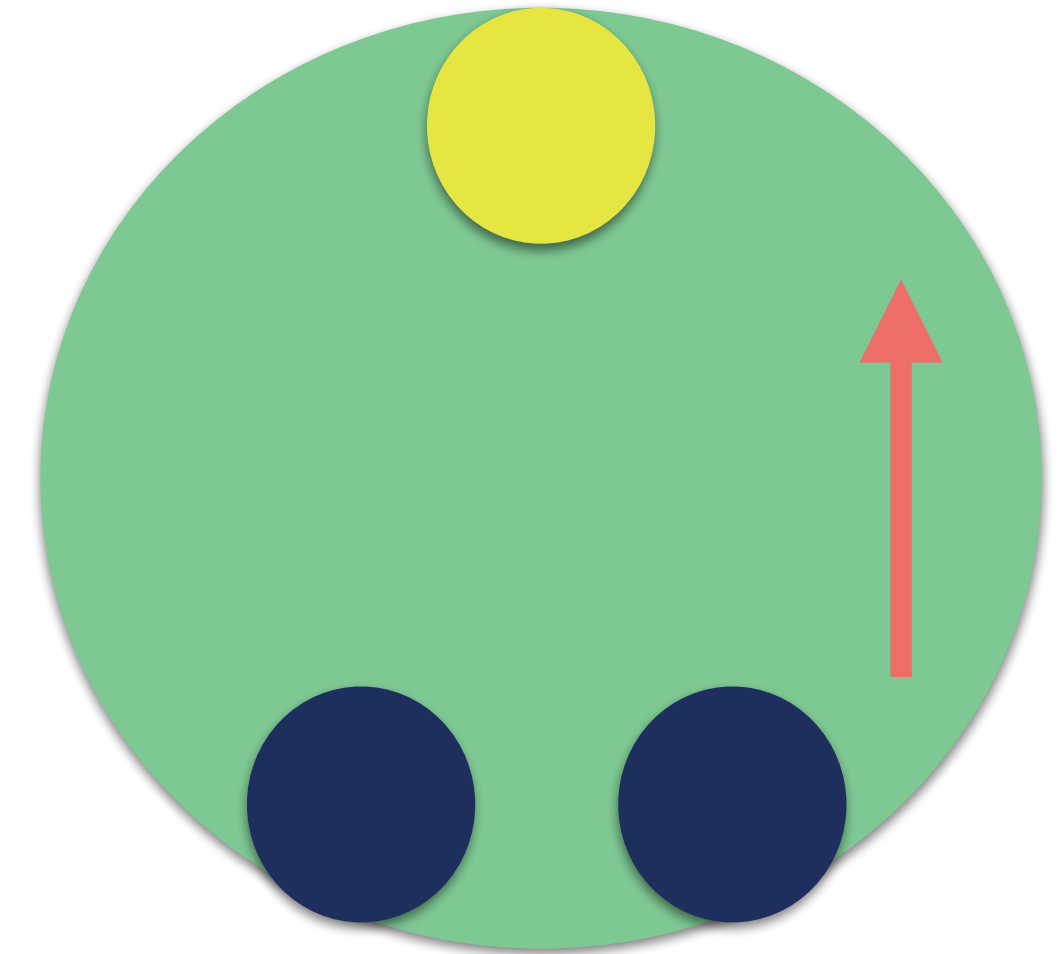
Electric
Dipole

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

Neutron $\theta = 0$



Neutron $\theta \neq 0$



Electric
Dipole

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

Introduce a new **global symmetry** at fa

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

At the minimum

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

WHY DO I LIKE AXIONS?

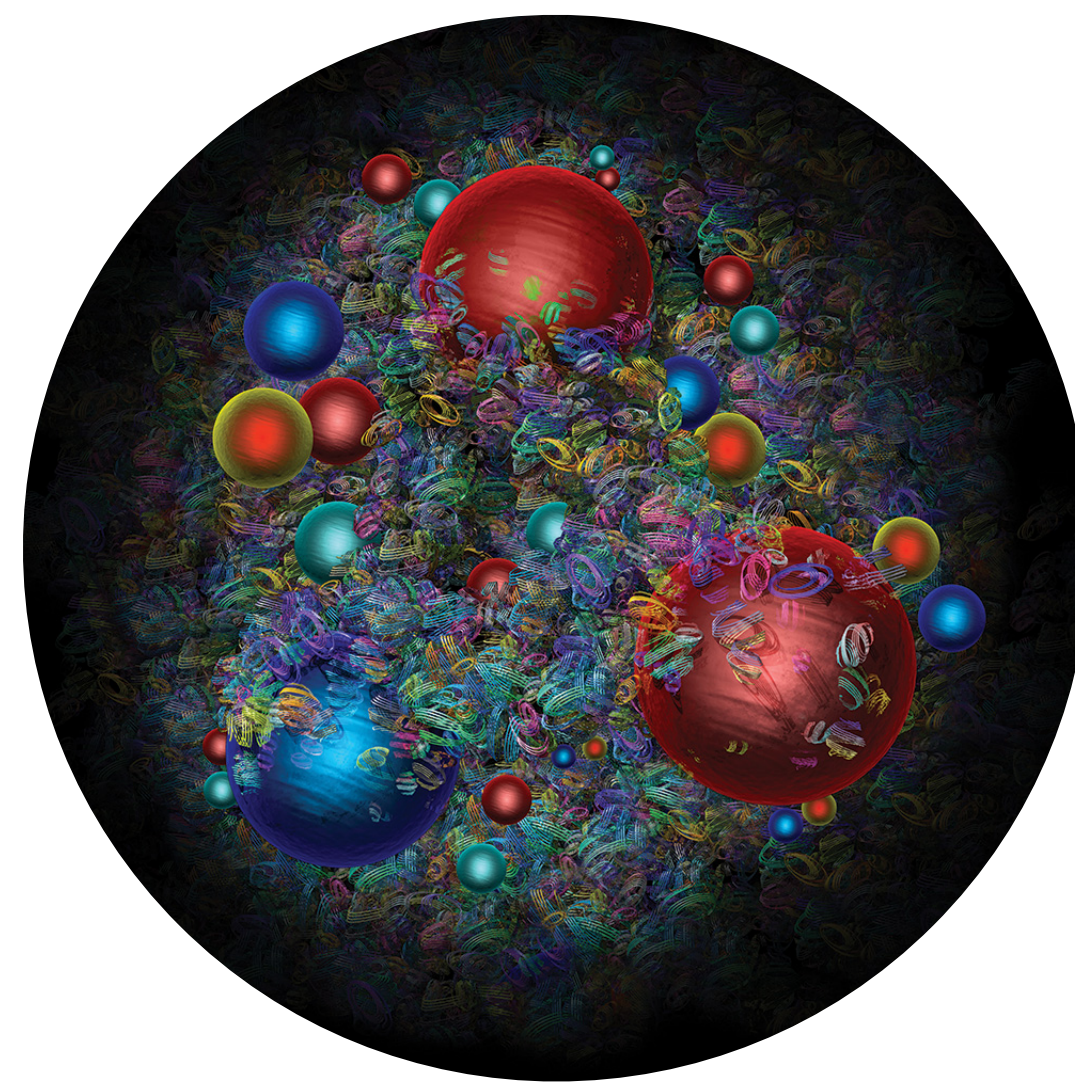
1. A good dark matter candidate
2. A clean probe of high energies
3. Generically predicted in string theory
4. Solves a puzzle of the Standard Model
5. We can discover them if they are dark matter
6. They can also explain the Higgs mass

$$aF\tilde{F}$$

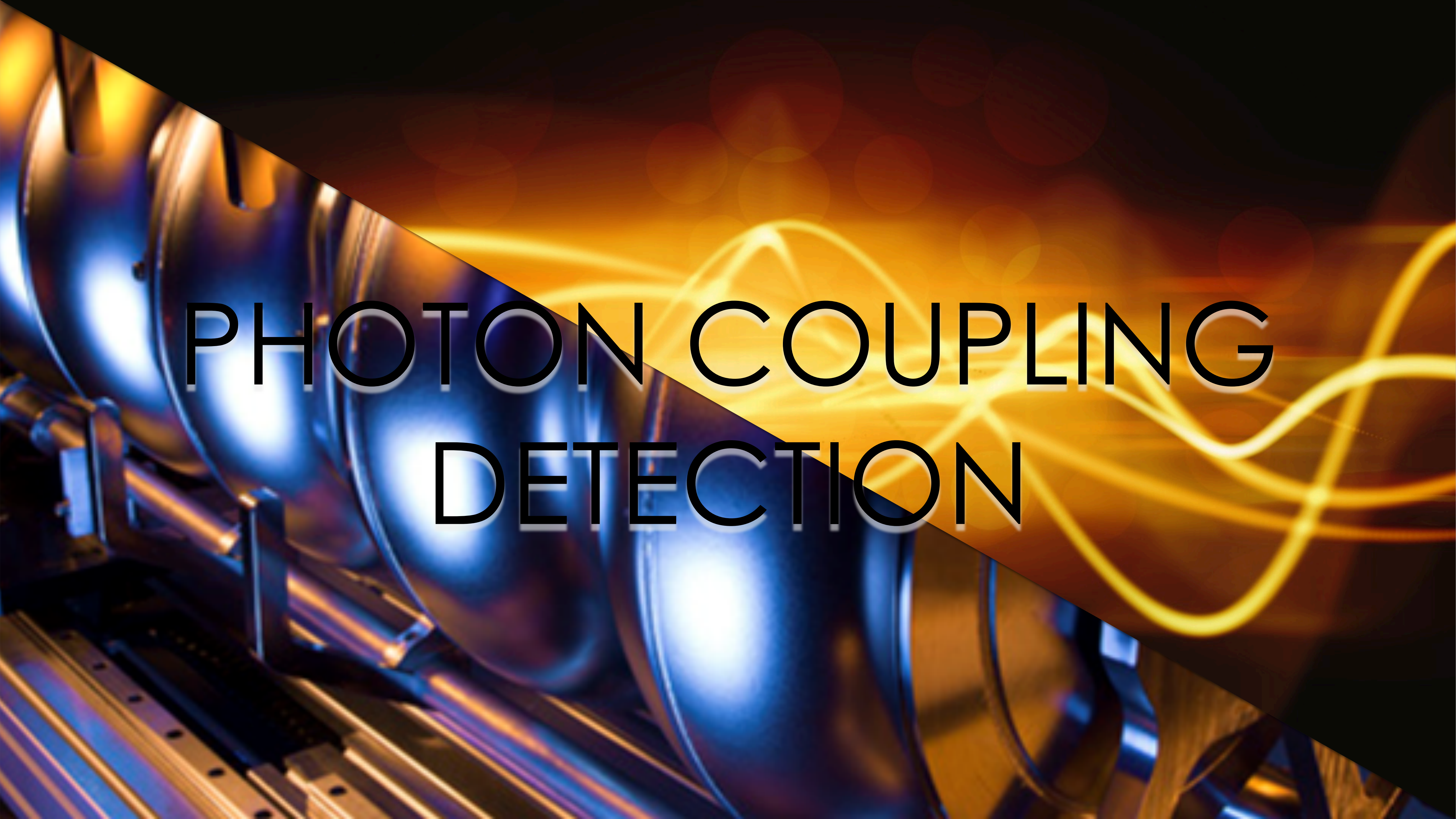


Photons

$$aG\tilde{G}$$

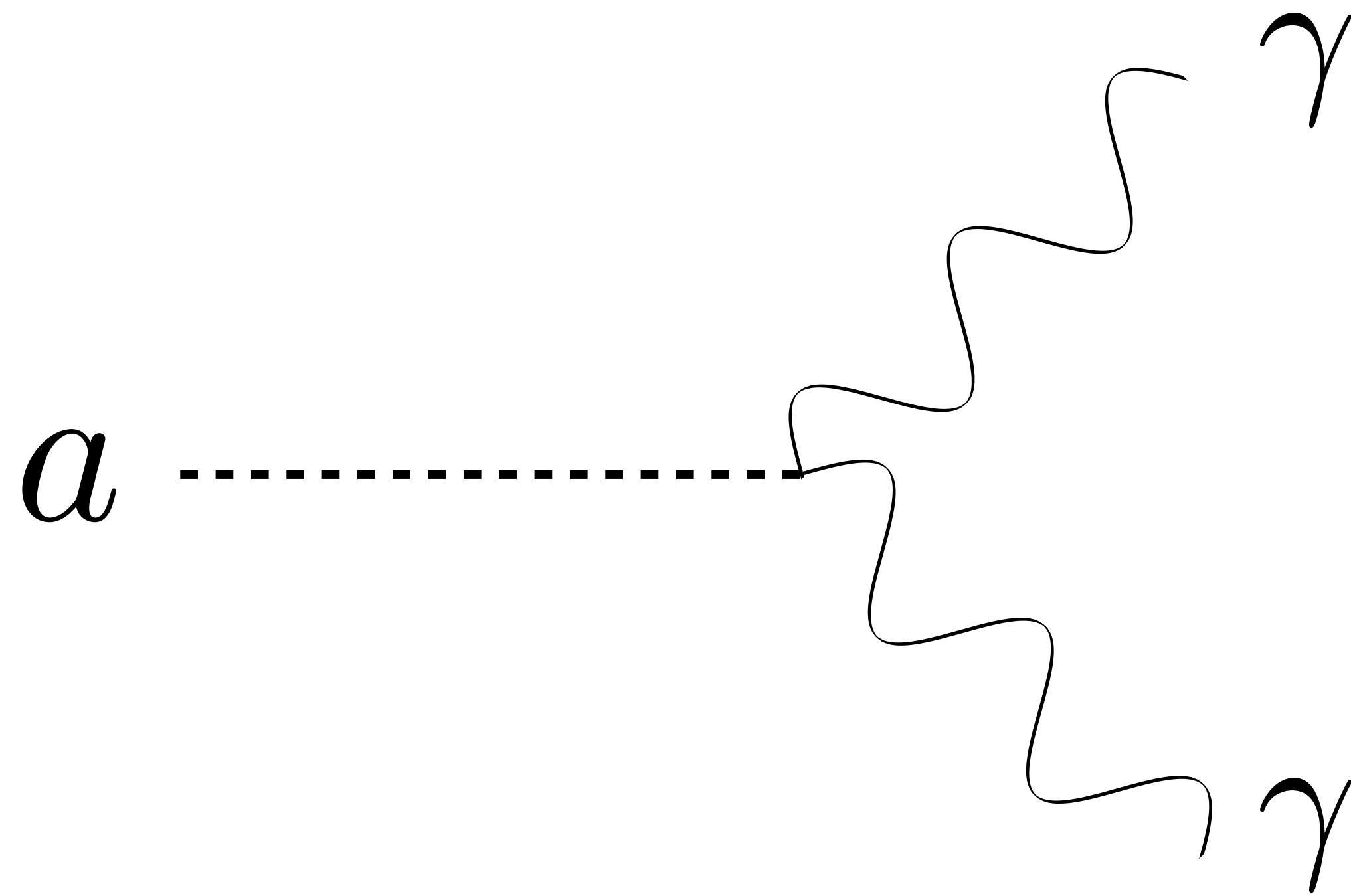


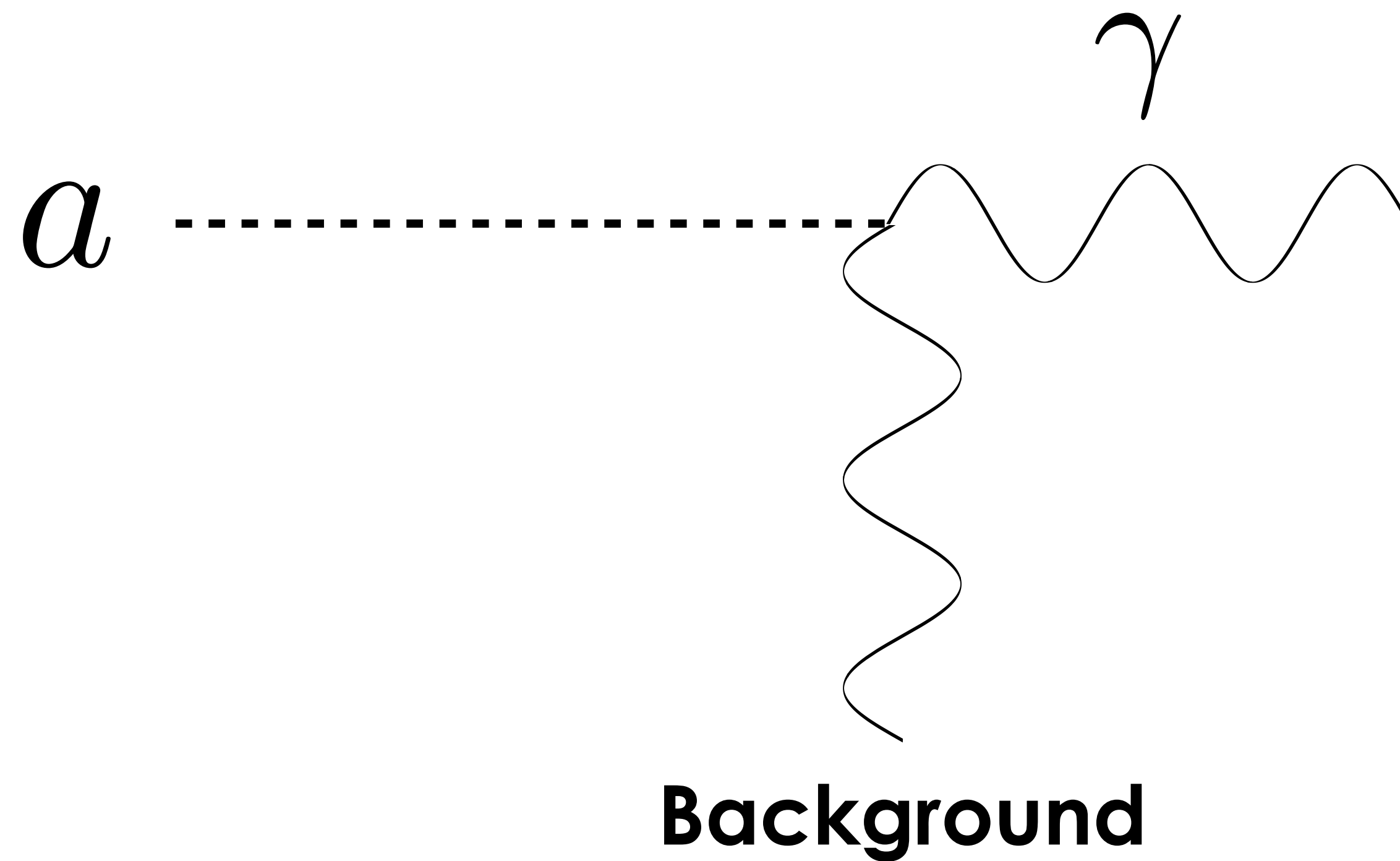
Gluons

The background is a complex abstract composition. The left side features a series of overlapping, semi-transparent blue spheres or lenses, creating a sense of depth and reflection. The right side is dominated by bright, glowing yellow and orange light trails that form intricate, swirling patterns. A sharp diagonal line runs from the top-left corner towards the bottom-right, separating the blue-toned left half from the warmer, yellow-toned right half. The overall effect is one of high-tech, scientific, or futuristic energy.

PHOTON COUPLING DETECTION

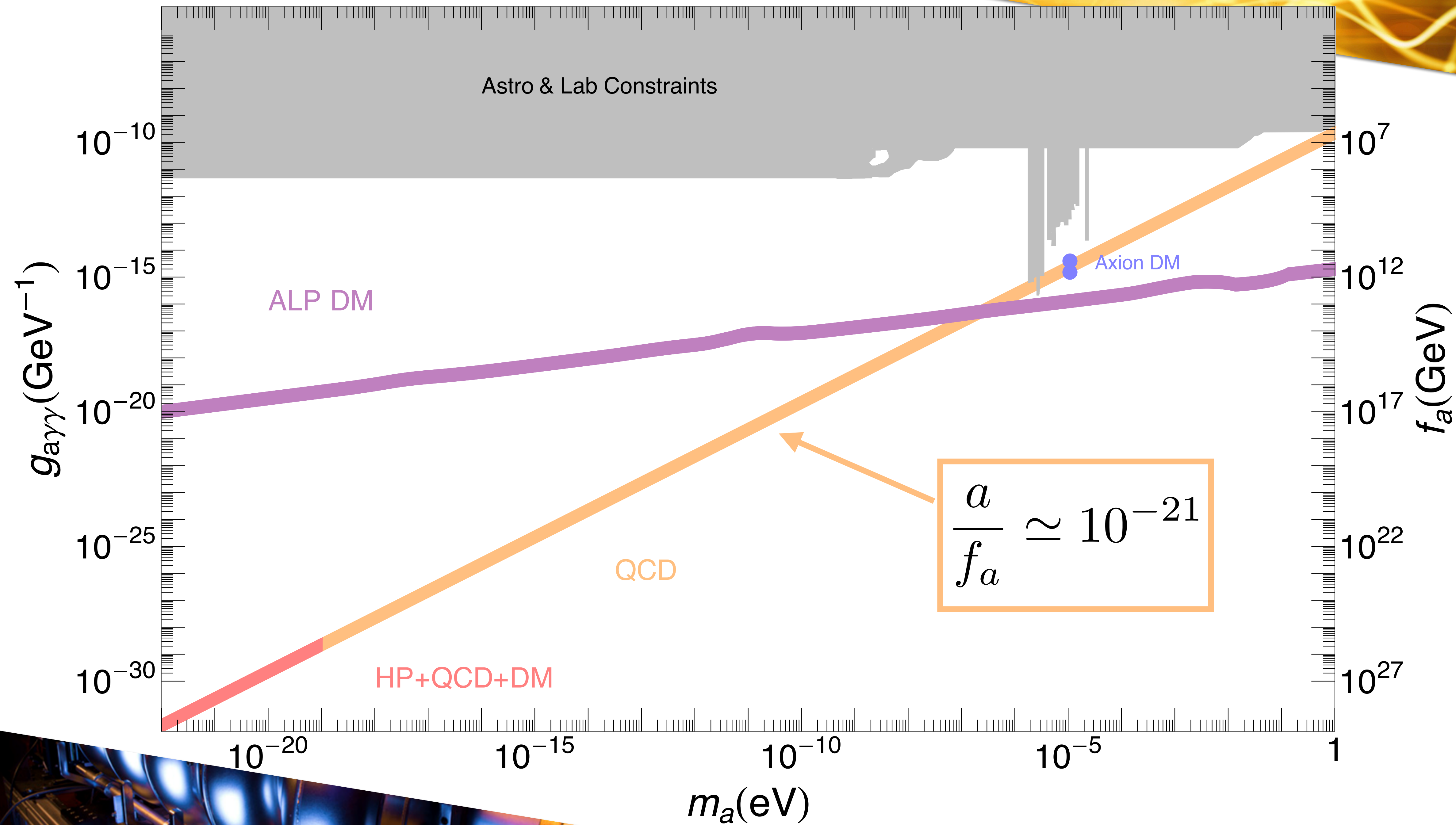
PHOTONS



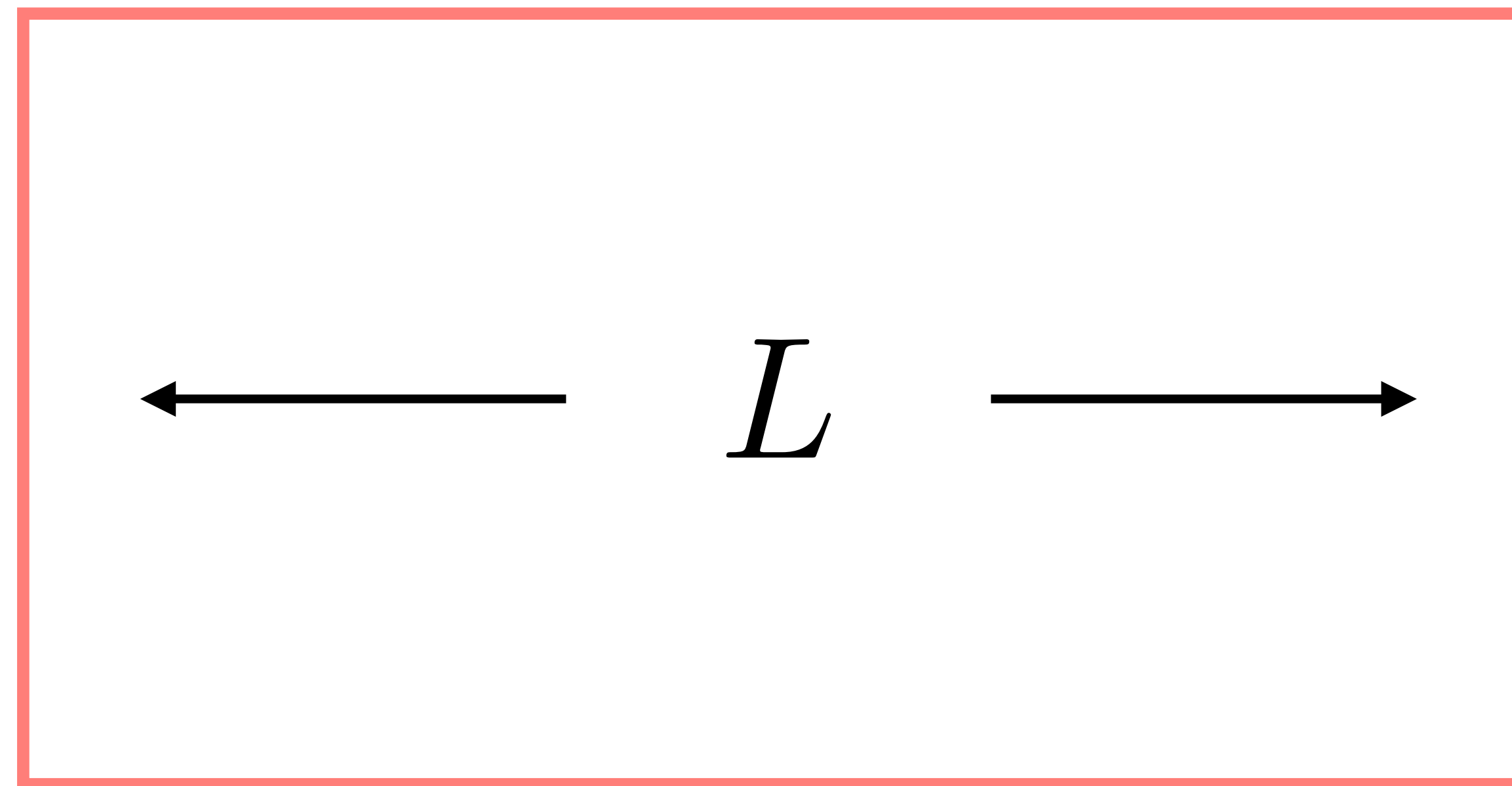


$$\sim \frac{a}{f_a} E_{\text{bkg}} \simeq 10^{-21} E_{\text{bkg}}$$

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

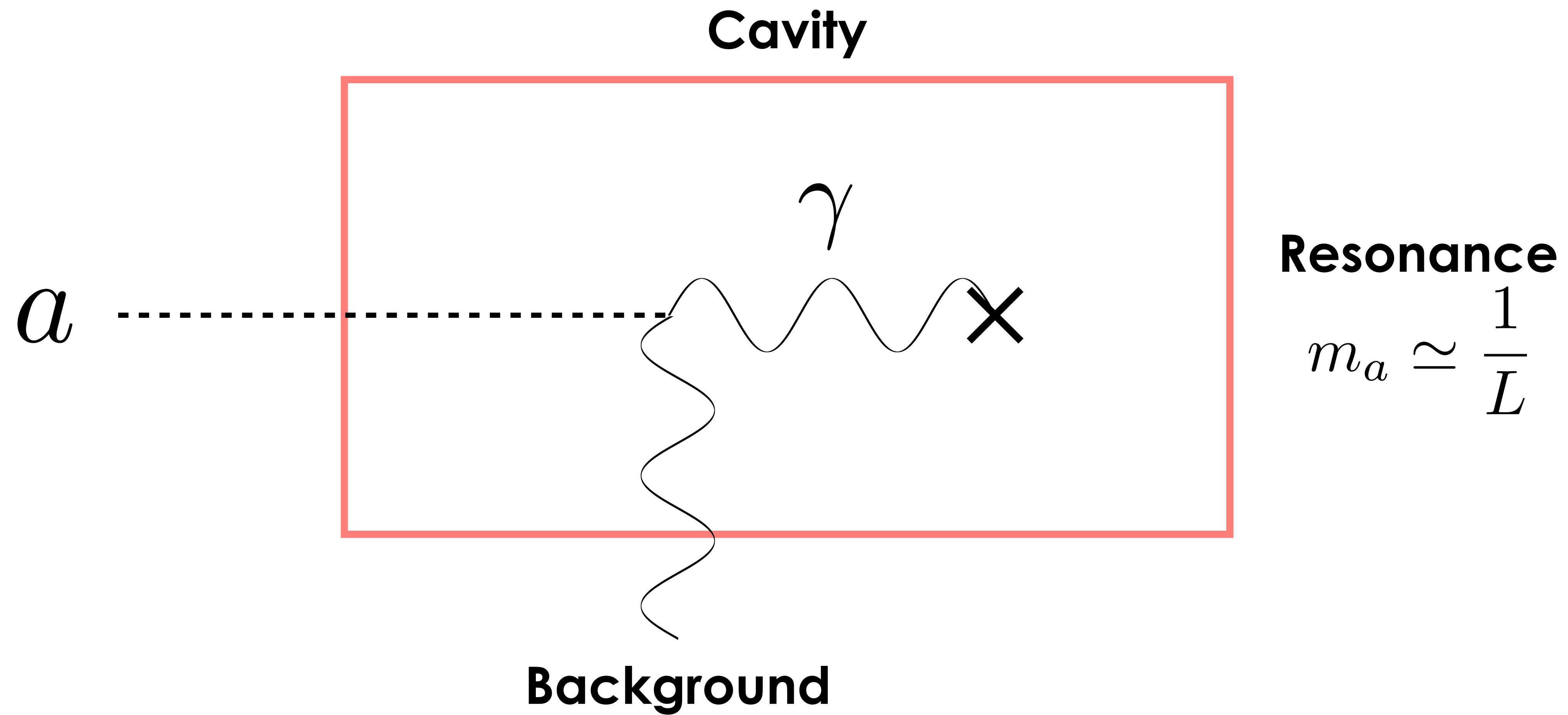


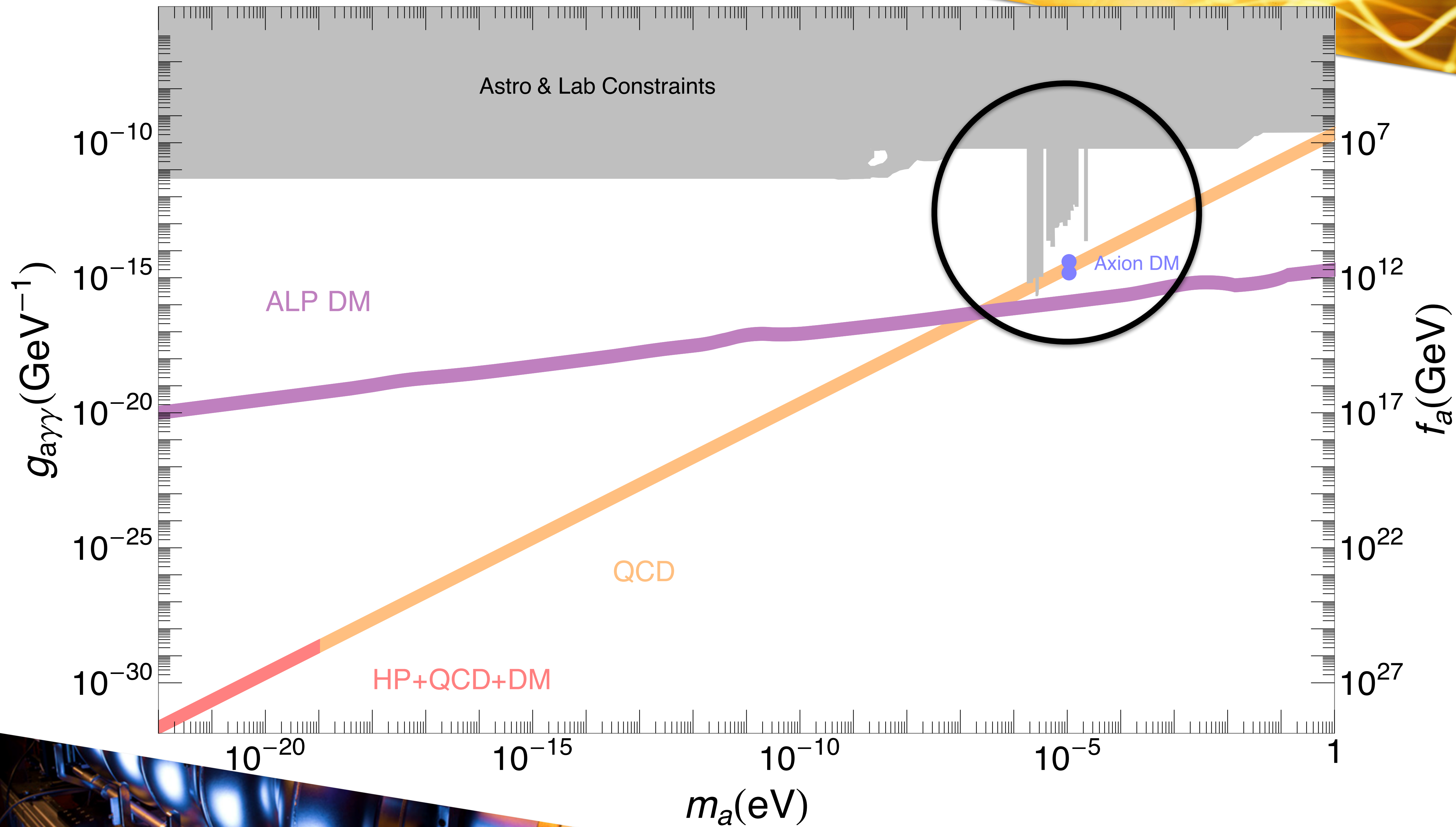
Cavity



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

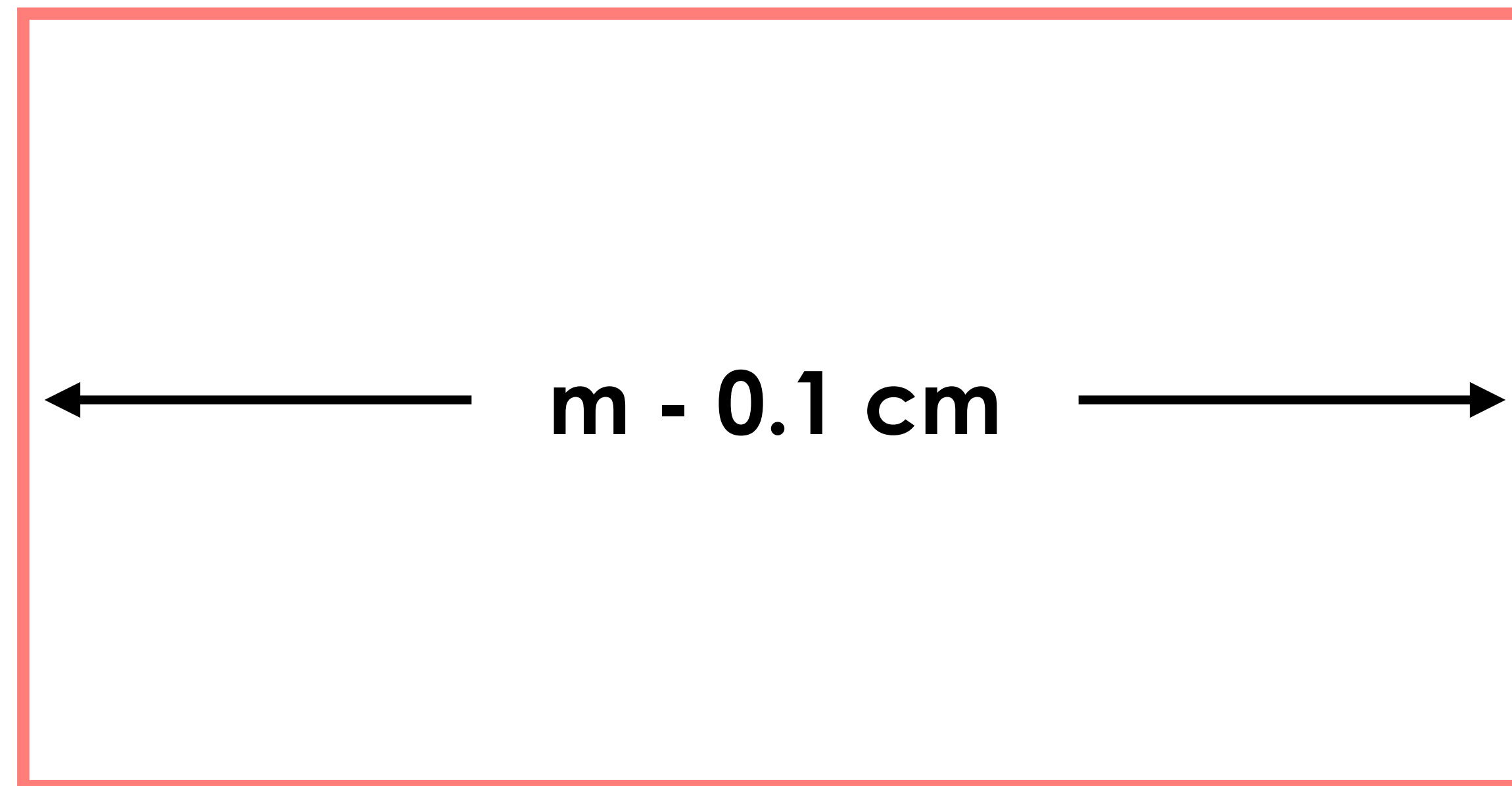
AXION DARK MATTER DETECTION



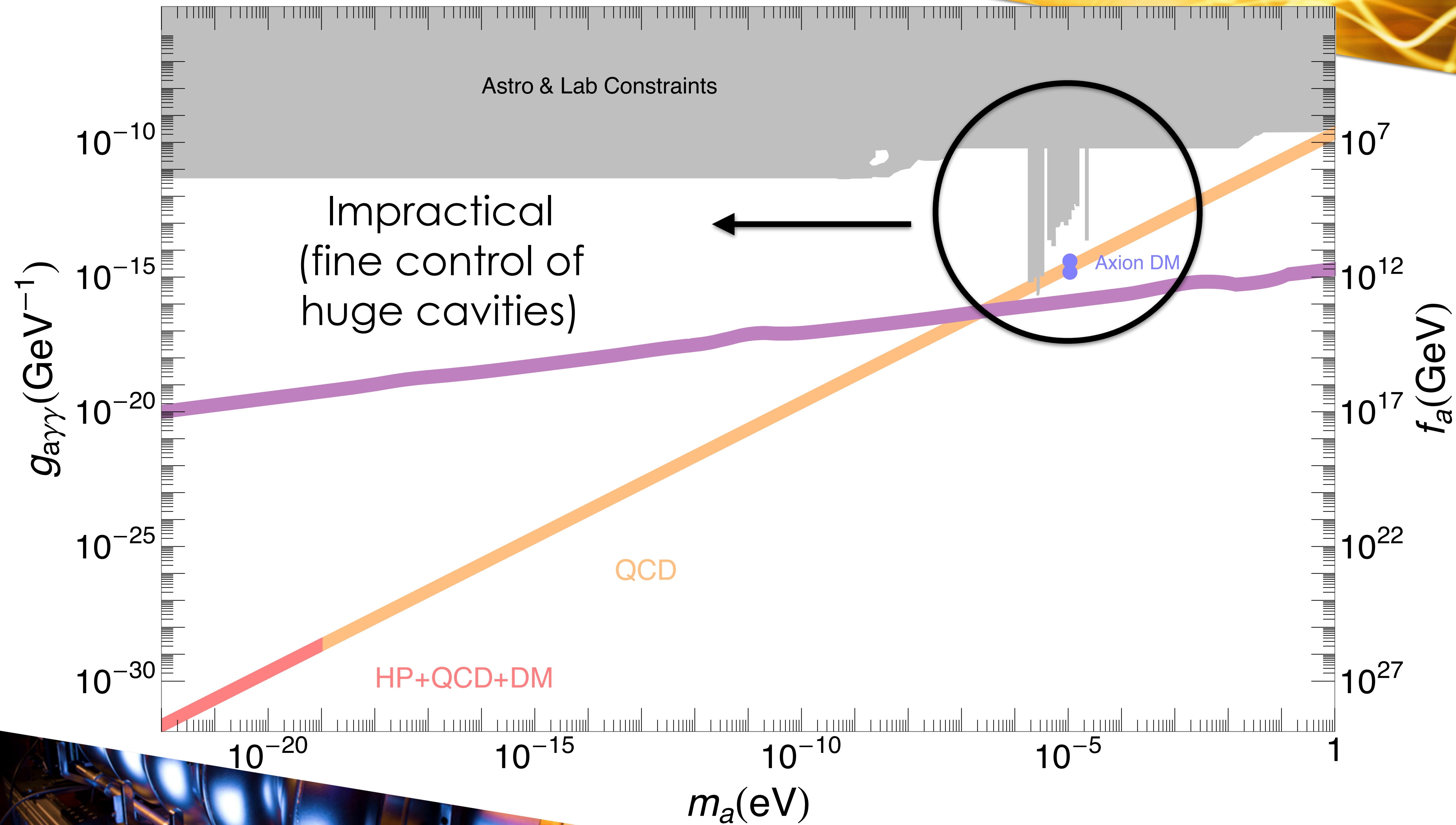


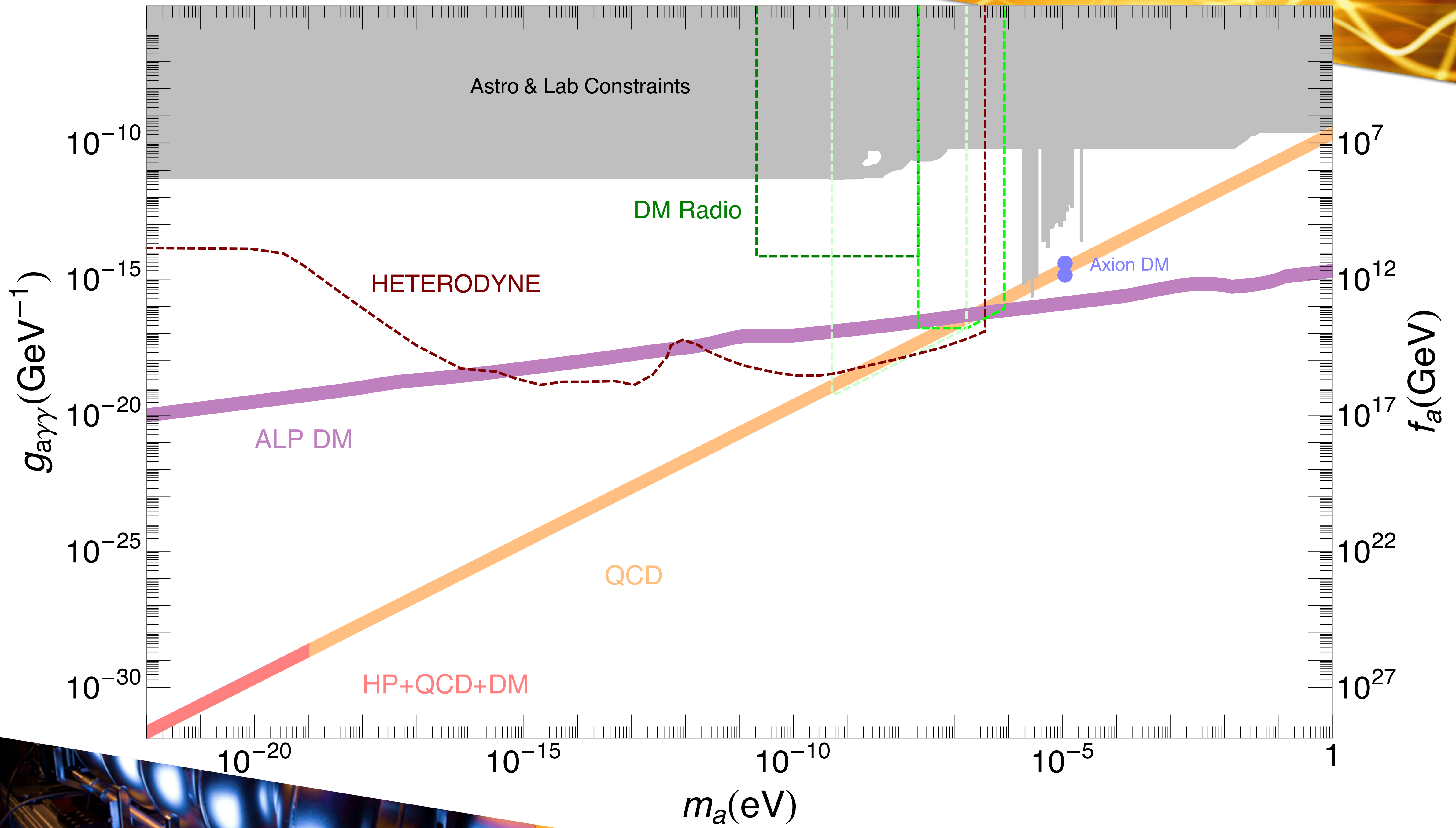
AXION DETECTION

Cavity



Low noise electronics
High quality factors

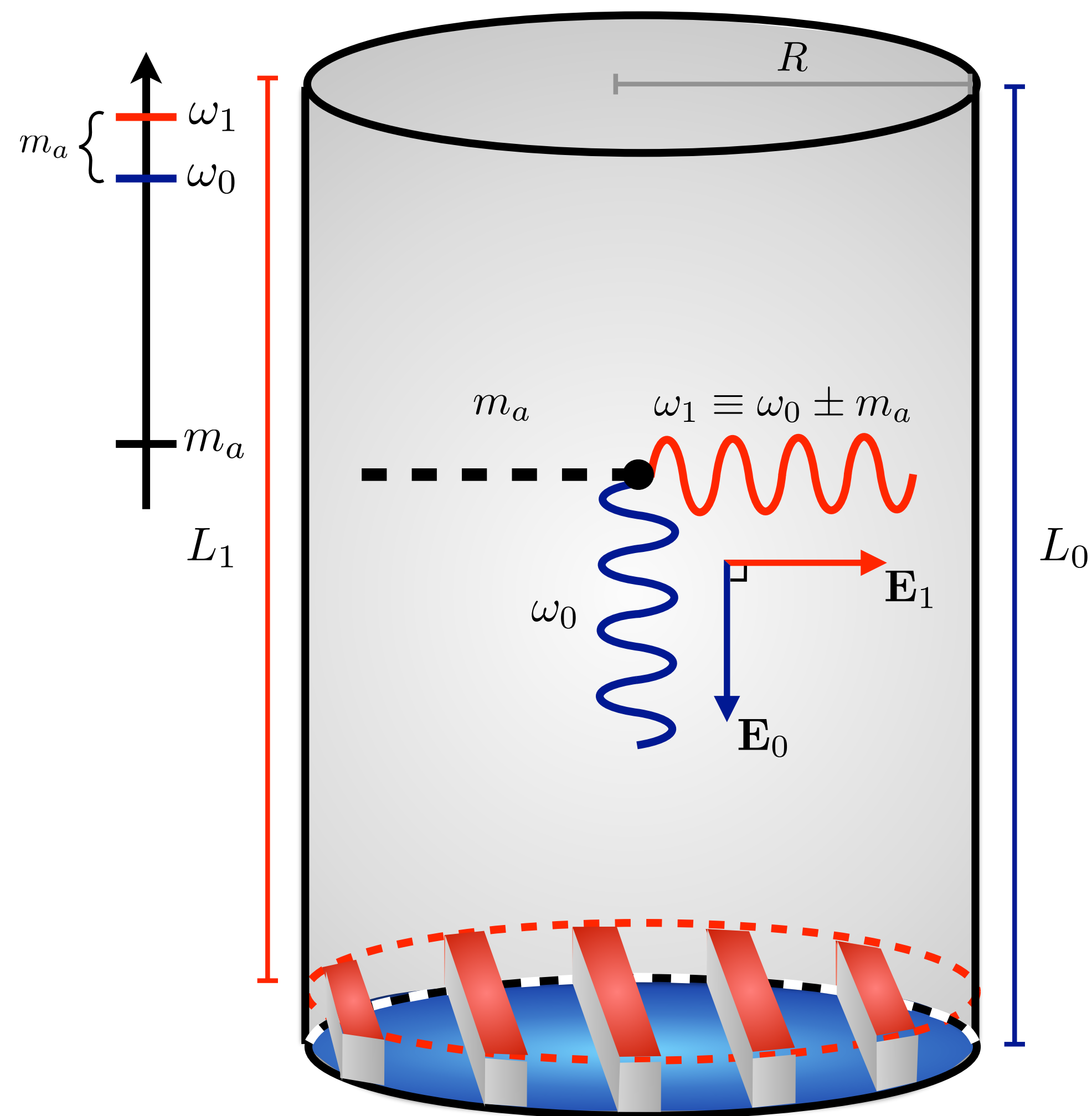




HETERODYNE DETECTION

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

[Berlin, RTD, S. Ellis, K. Zhou'20]



HETERODYNE DETECTION

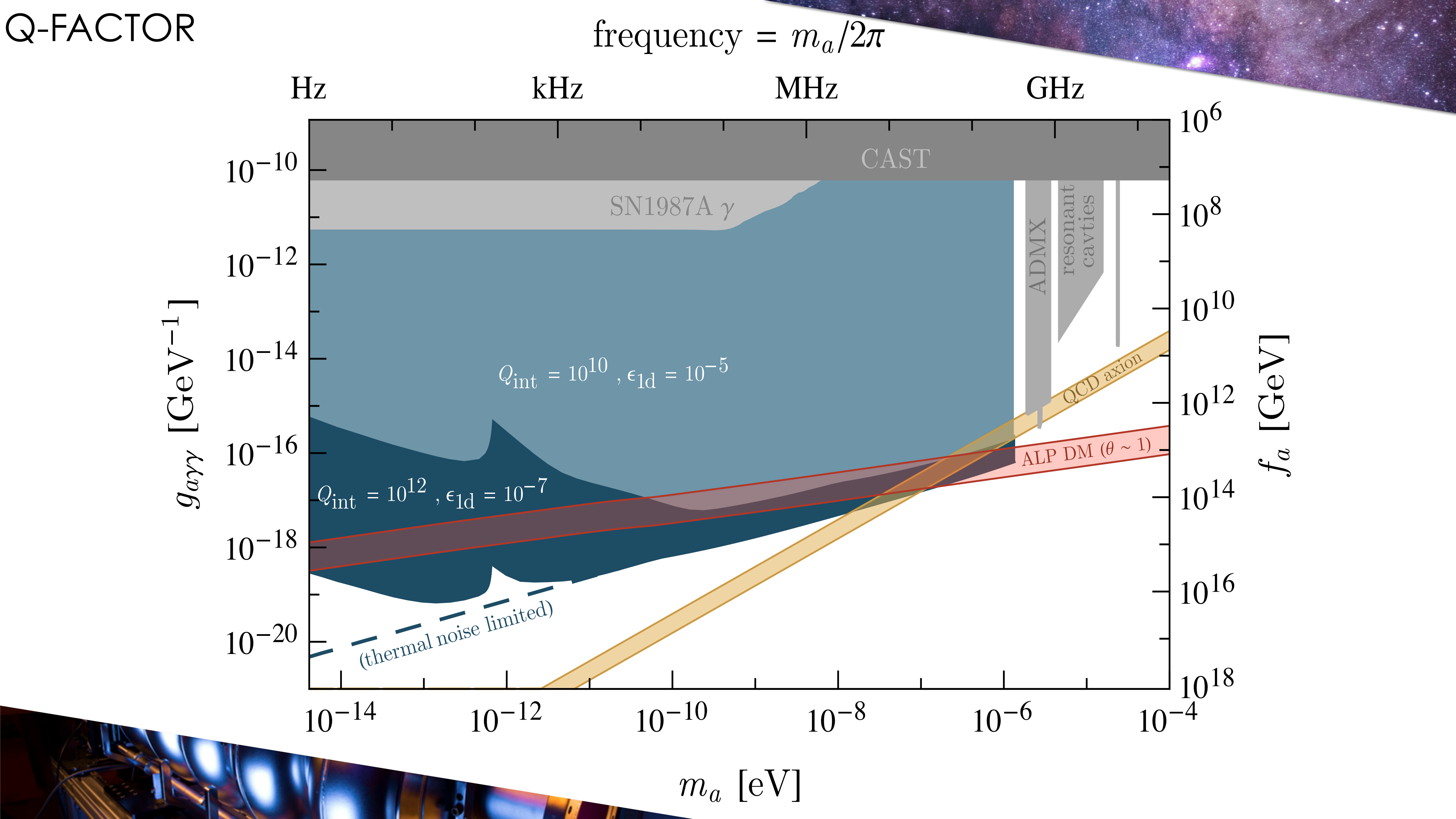
[Berlin, RTD, S. Ellis, C. Nantista, J. Nielson, P. Schuster, S. Tantawi, N. Toro, K. Zhou'19]

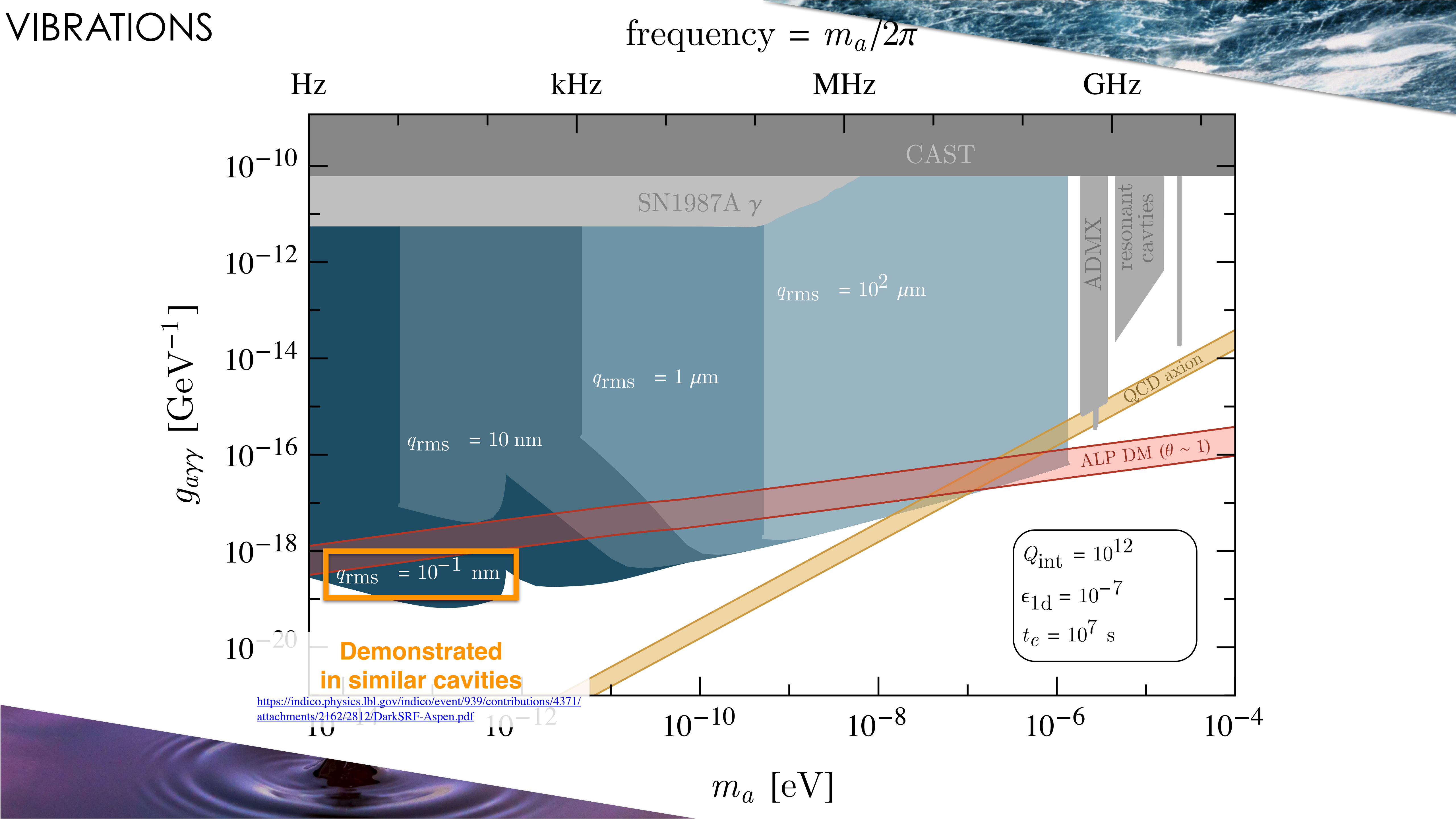
[Berlin, RTD, S. Ellis, K. Zhou'20]

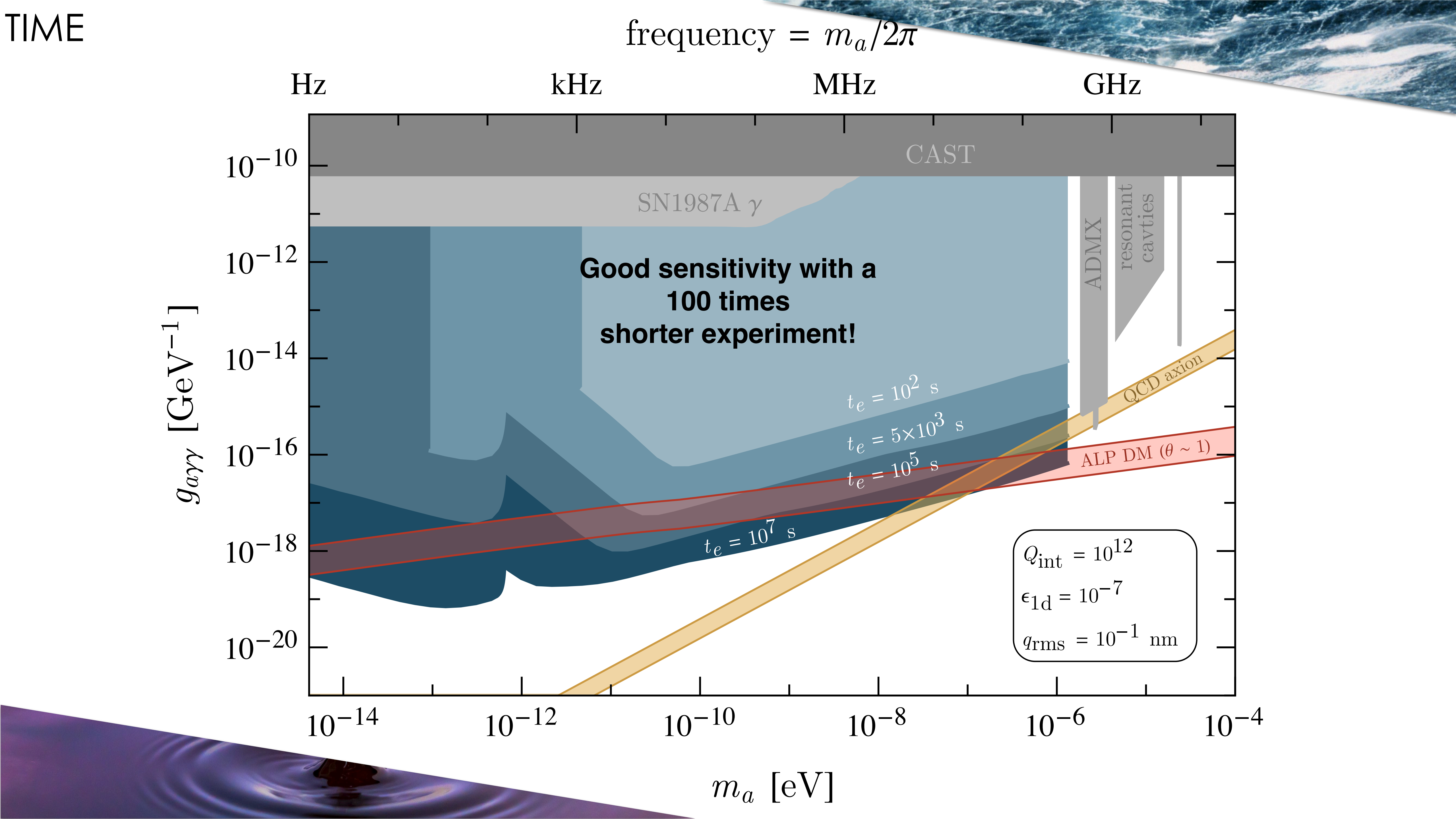
$$\sum_n \left(\partial_t^2 + \frac{\omega_n}{Q_n} \partial_t + \omega_n^2 \right) \mathbf{E}_n = g_{a\gamma\gamma} \partial_t (\mathbf{B} \partial_t a)$$

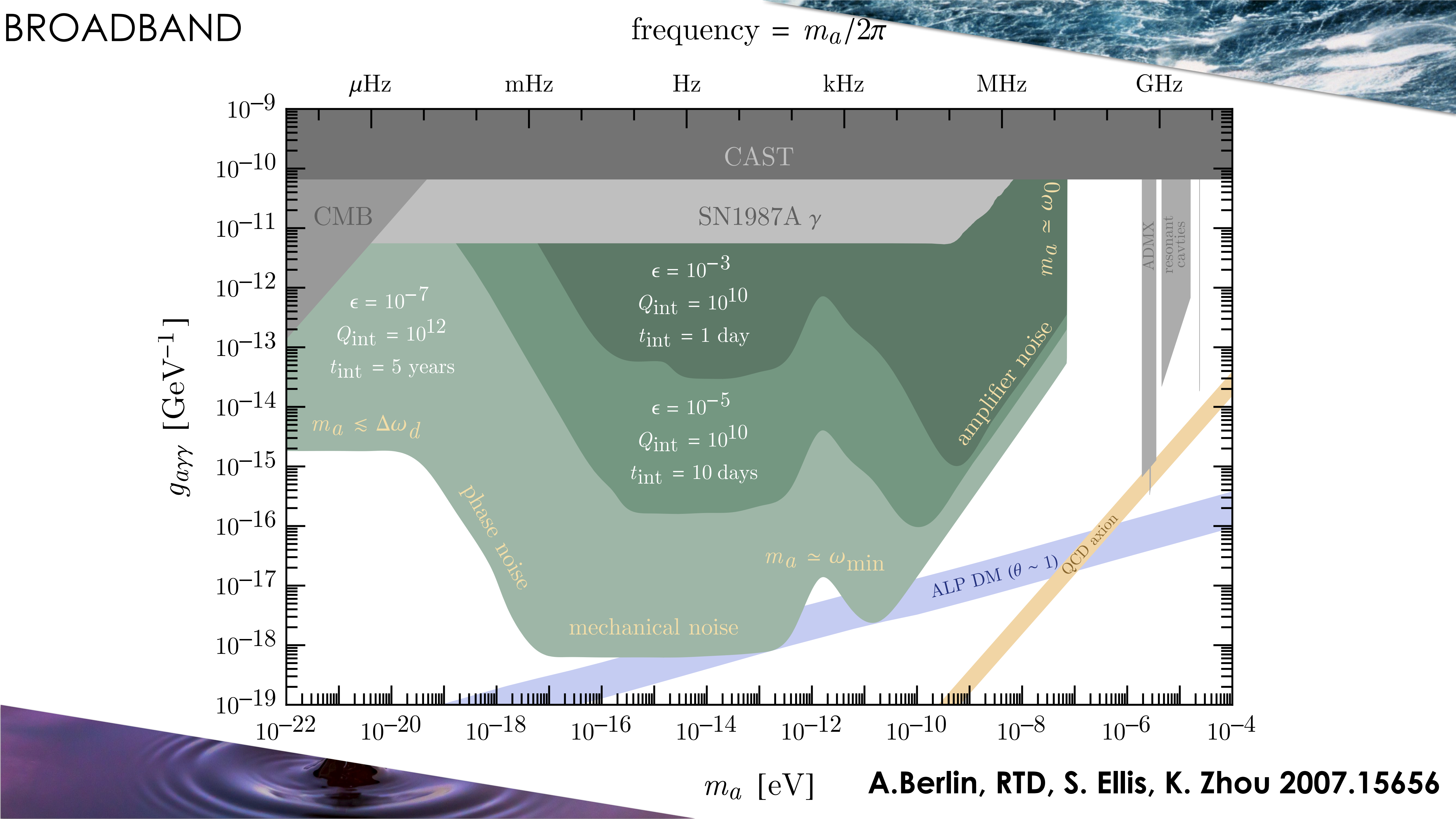
$$\partial_t (\mathbf{B}) \simeq i\omega_0 \mathbf{B} \quad \omega_1 \simeq \omega_0 + m_a$$

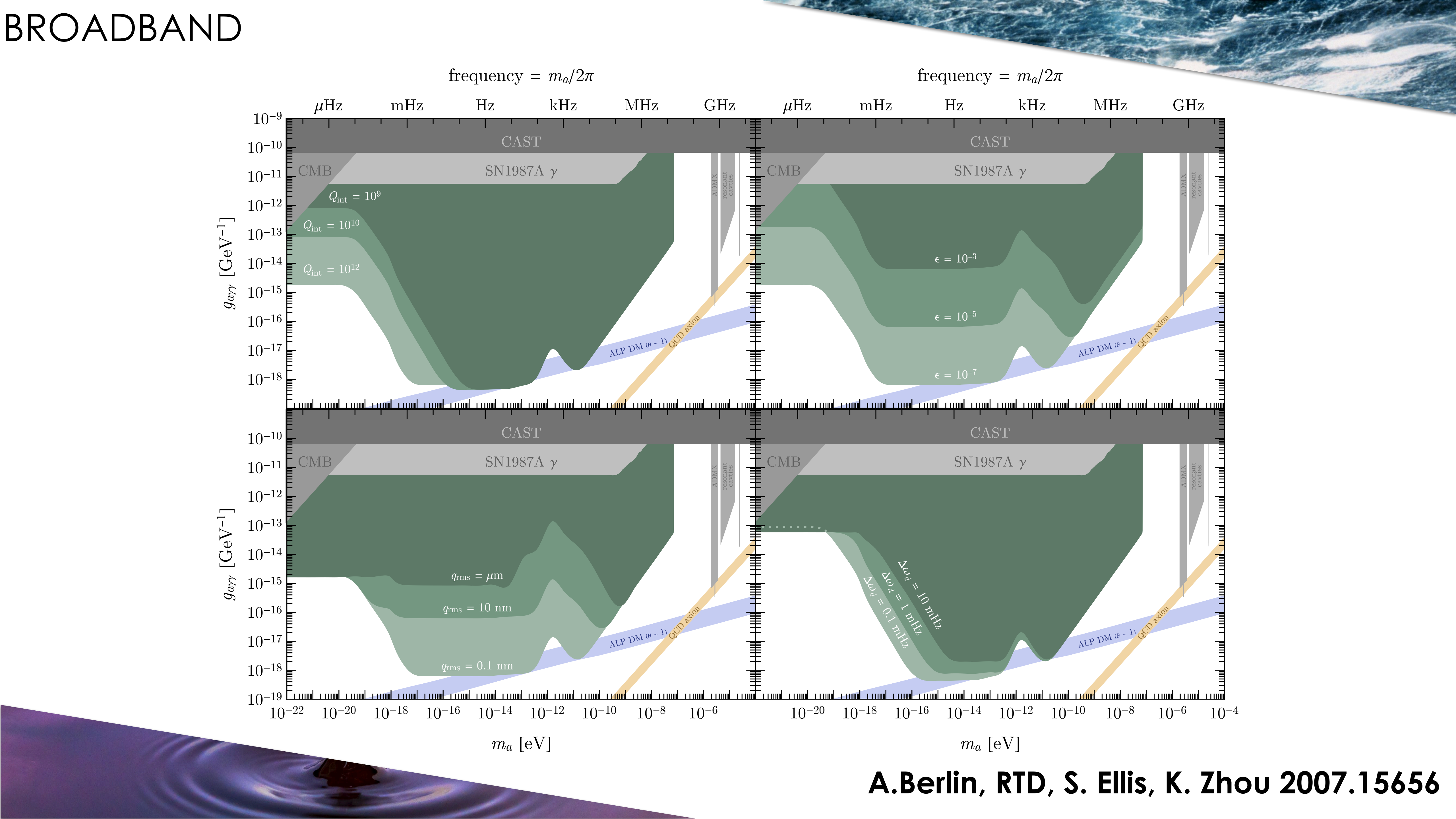
$$\partial_t J_{\text{eff}} = g_{a\gamma\gamma} \partial_t (\mathbf{B} \partial_t a) \propto \omega_0 m_a \gg m_a^2$$









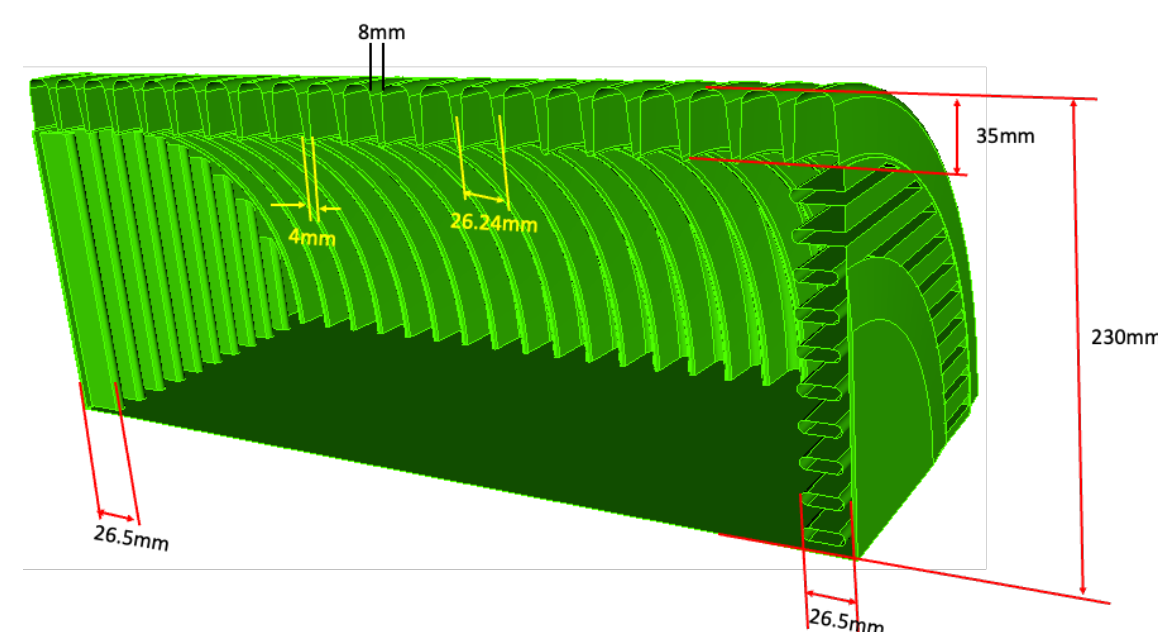


THREE PROTOTYPES

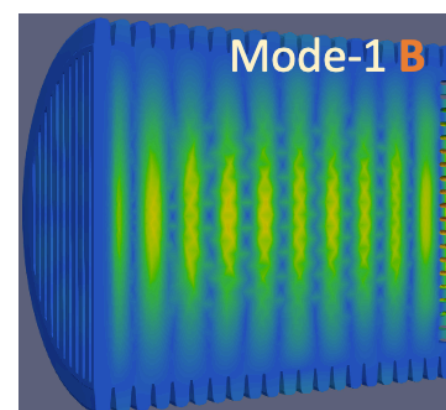
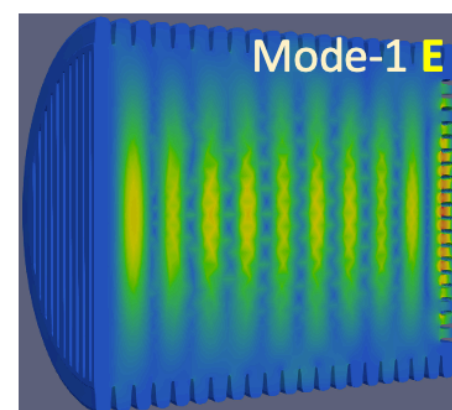


2507.07173

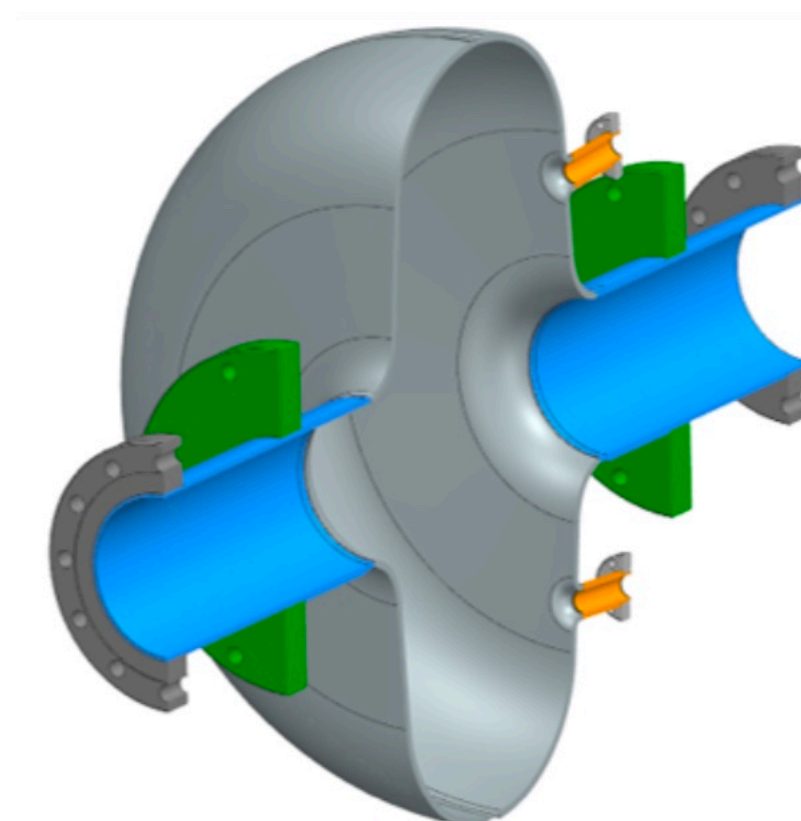
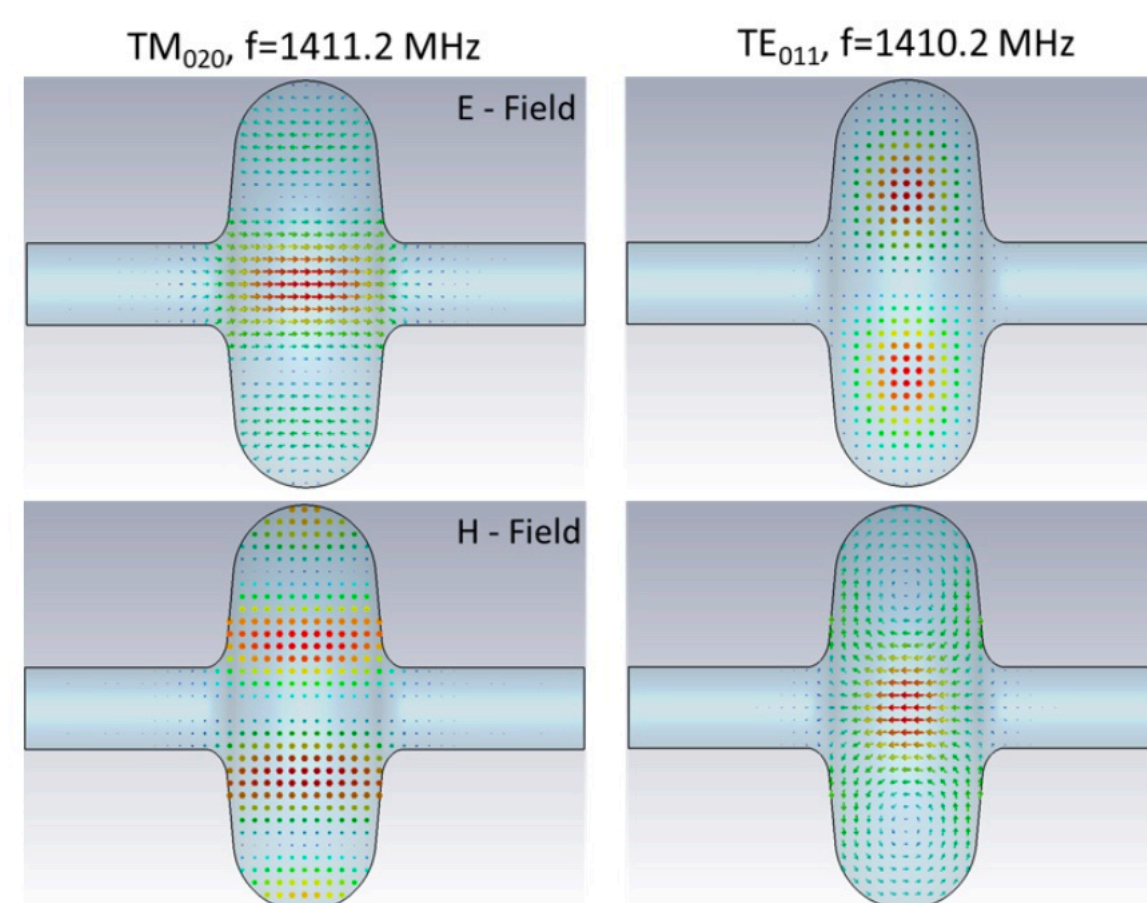
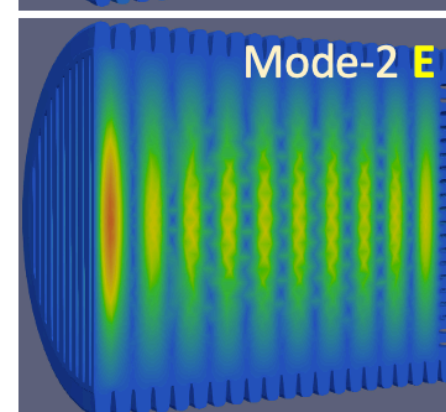
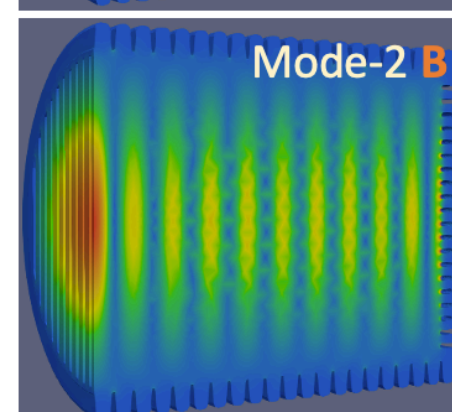
arXiv:2207.11346



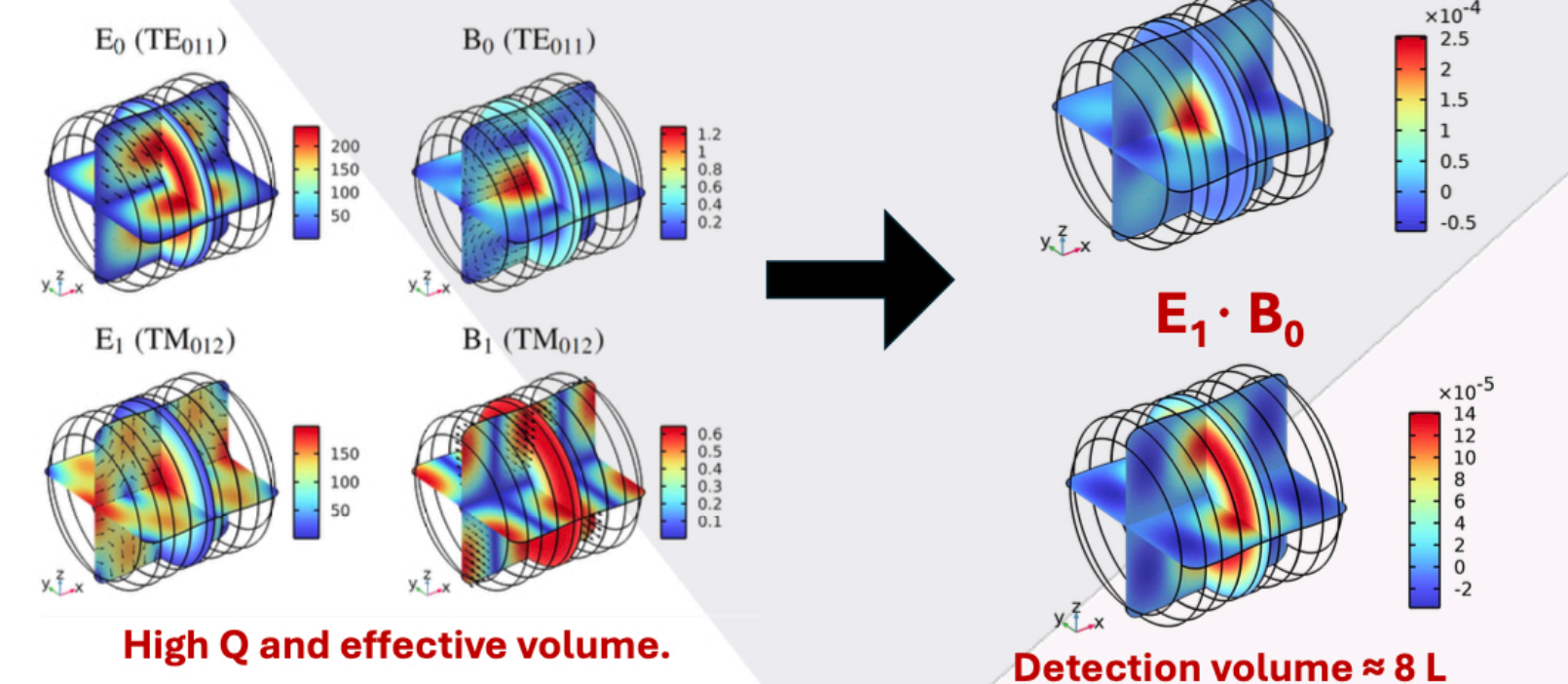
HE11
polatization-1 (E,B)



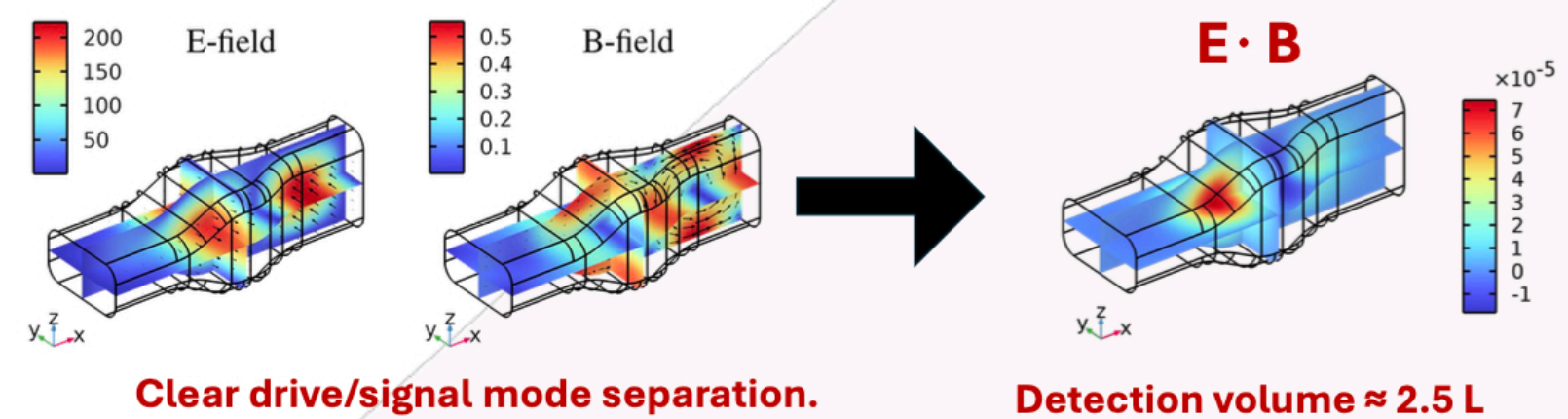
HE11
polatization-2 (B,E)



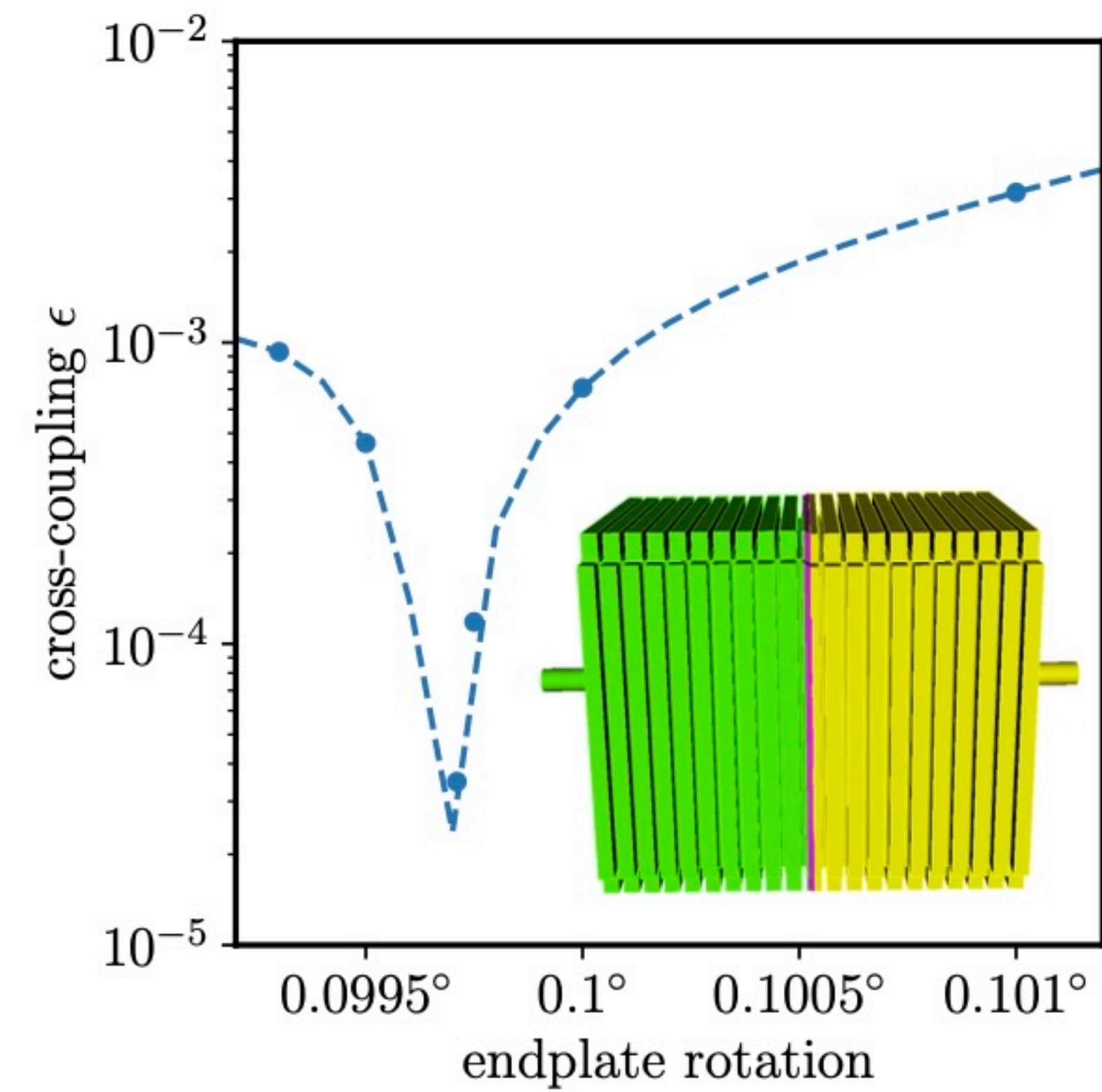
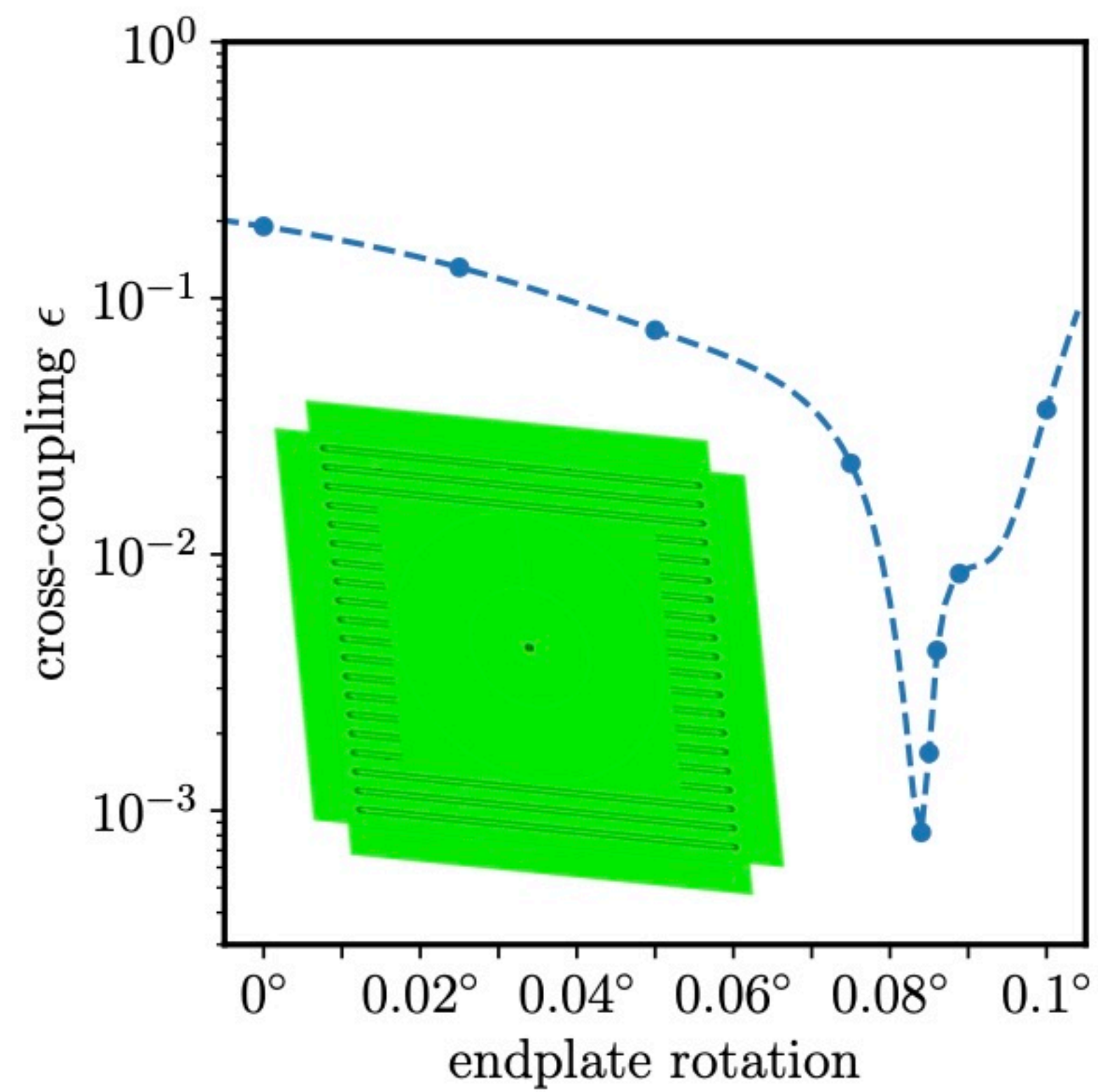
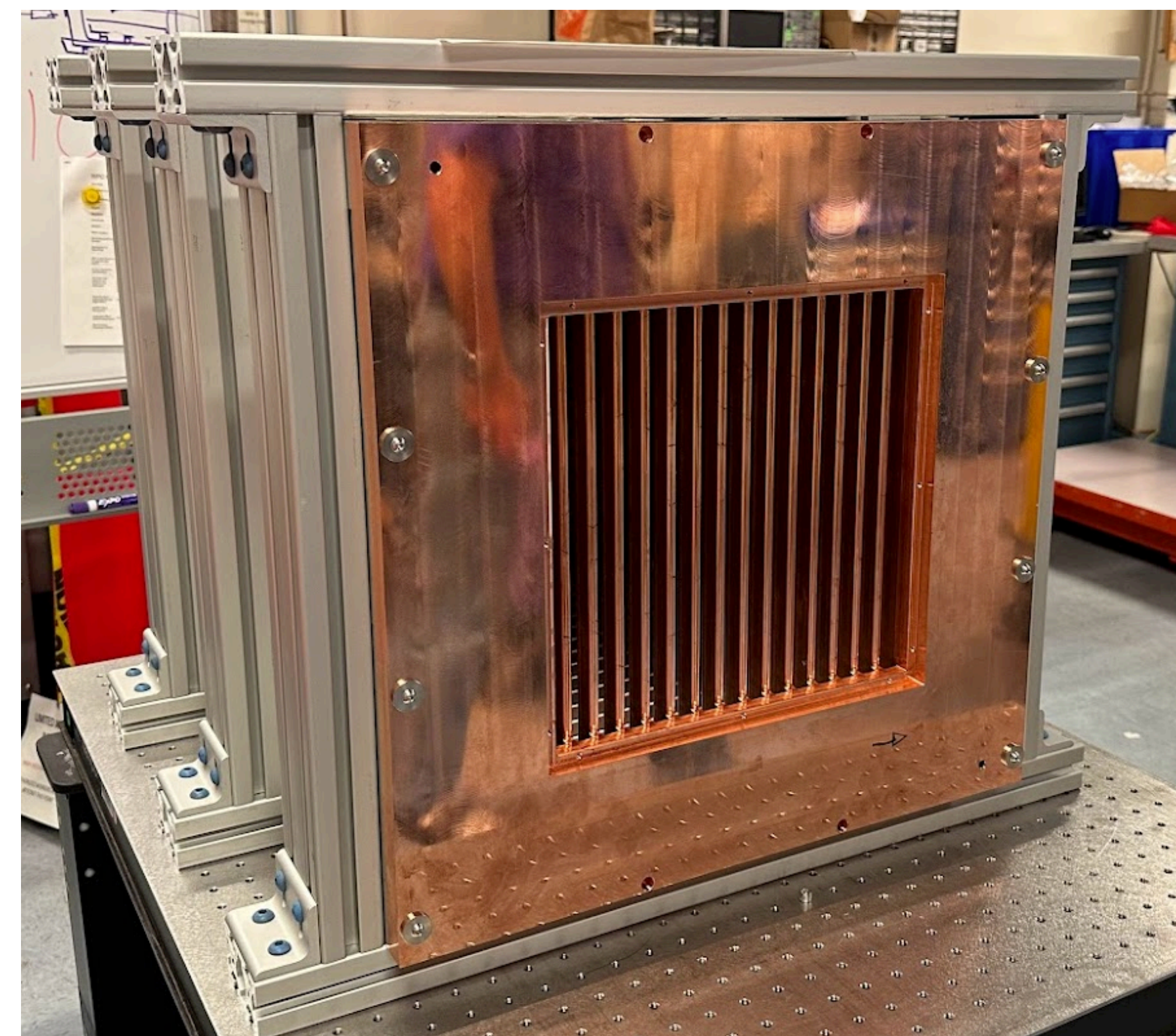
Cylindrical Concept



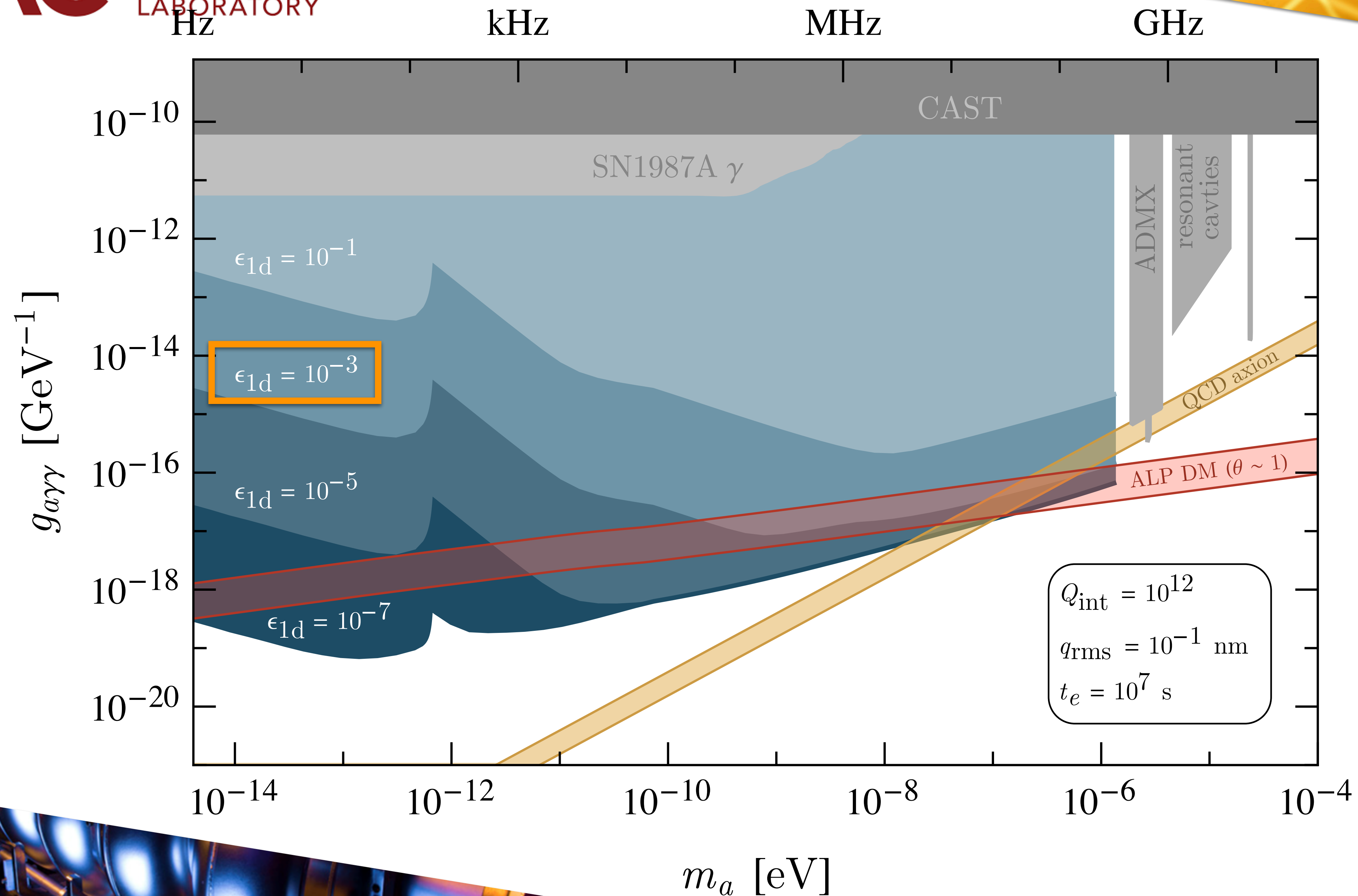
Guide-Based Concept



2507.07173

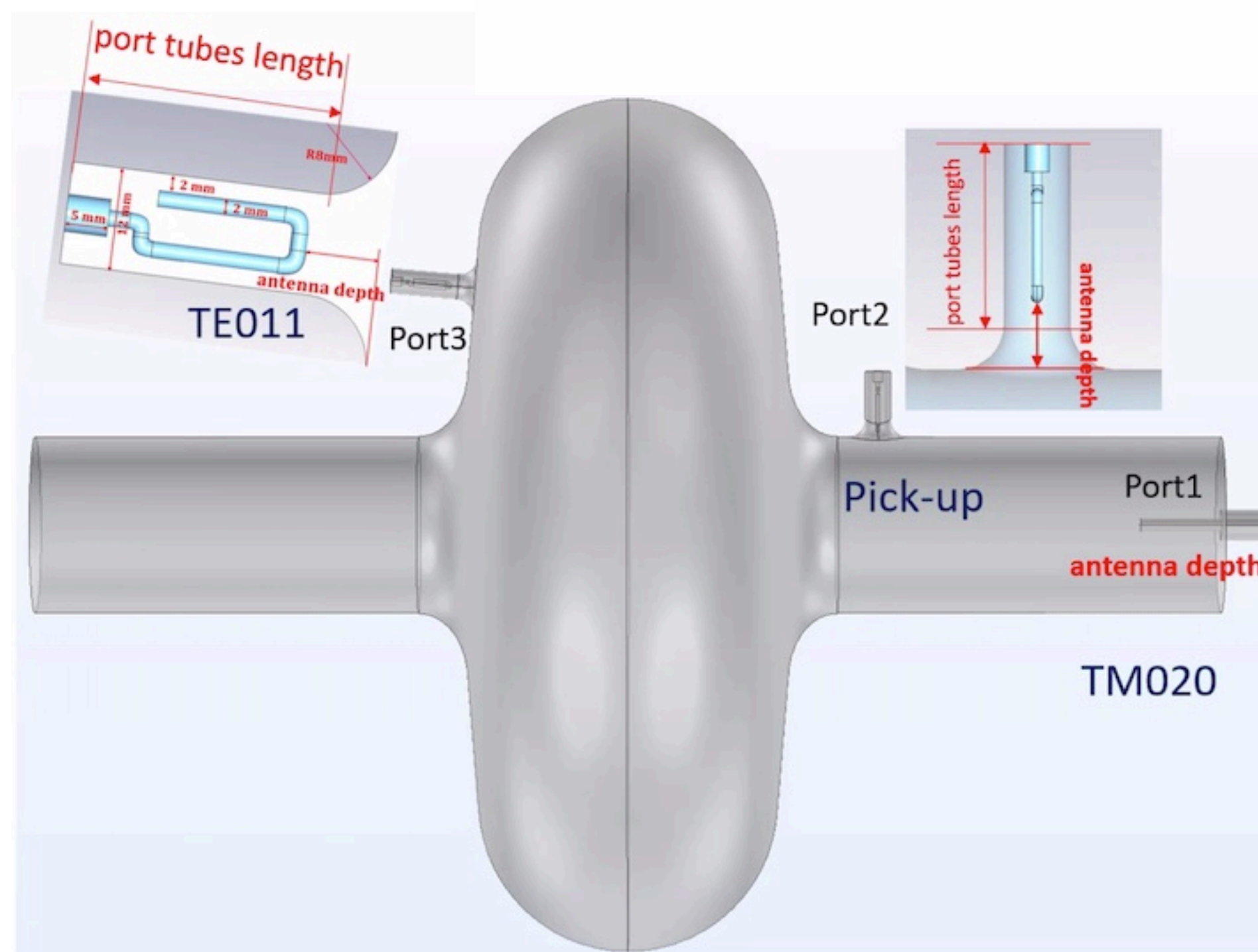


$$\text{frequency} = m_a / 2\pi$$



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



CHASE

Cryogenic **H**eterodyne **A**xion **S**earch **E**xperiment



L. Balocchi, D. Barrientos, I. Bloch, S. Calatroni, RTD, S. Ellis, T. Koetting, N. Koss, A. Macpherson, L. Millar



Phase A 2026

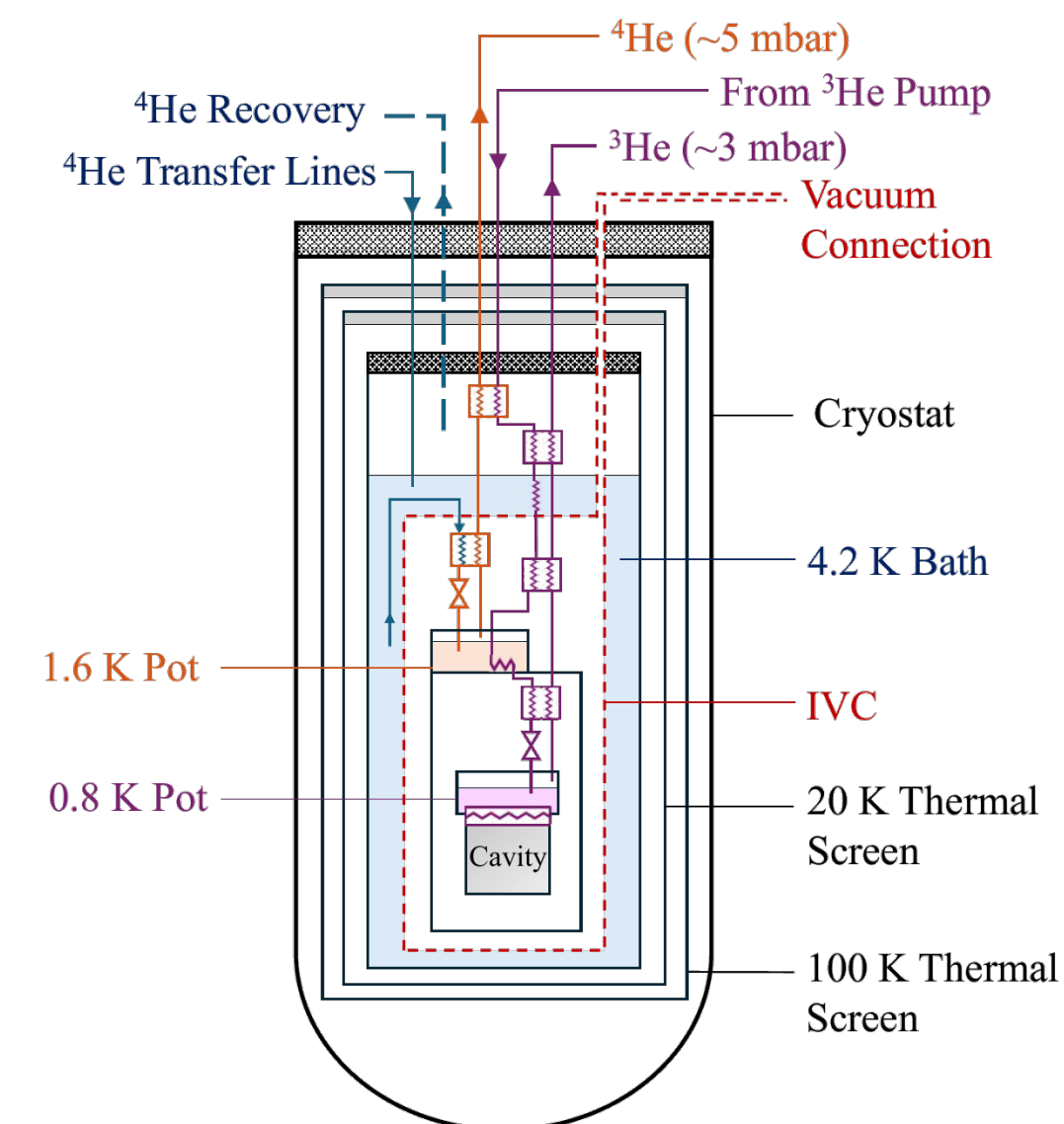
Wet cryostat
 ≈ 1.5 K.

Phase B 2027

Cavity inside inner
vacuum chamber
 ≈ 1.5 K

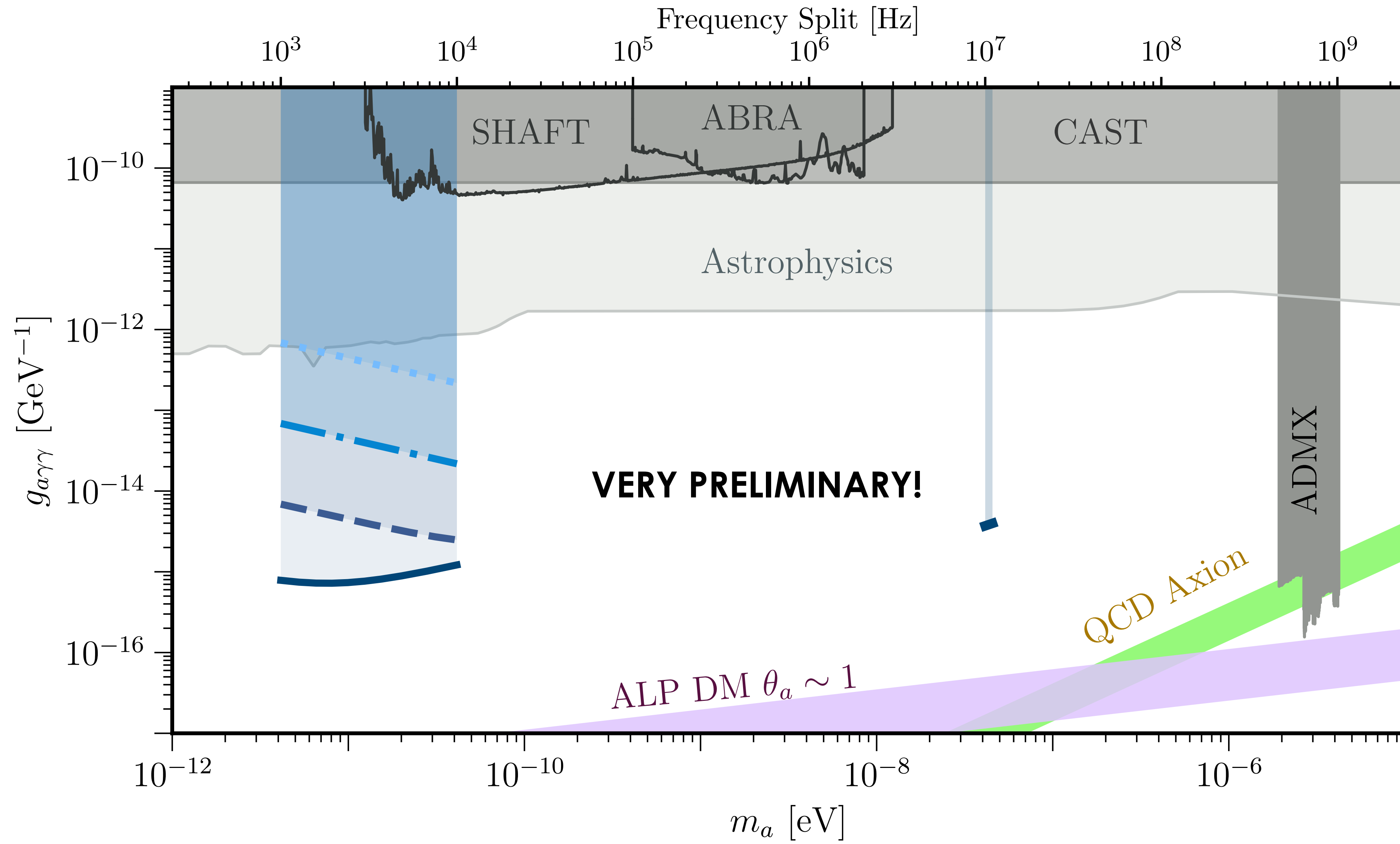
Phase C 2028

^3He cooling
 ≈ 0.8 K. & Data
taking.



Some Nearby Future Plans

Finalize cavity design.
Measure the vibration spectrum in our environment.
Finalize the scan strategies.



GLUON COUPLING
DETECTION

$$\frac{a}{f_a} G \tilde{G}$$



$$\frac{a}{f_a} N^\dagger \vec{\sigma} N \cdot \vec{E}$$


$$\frac{a}{f_a} G \tilde{G}$$



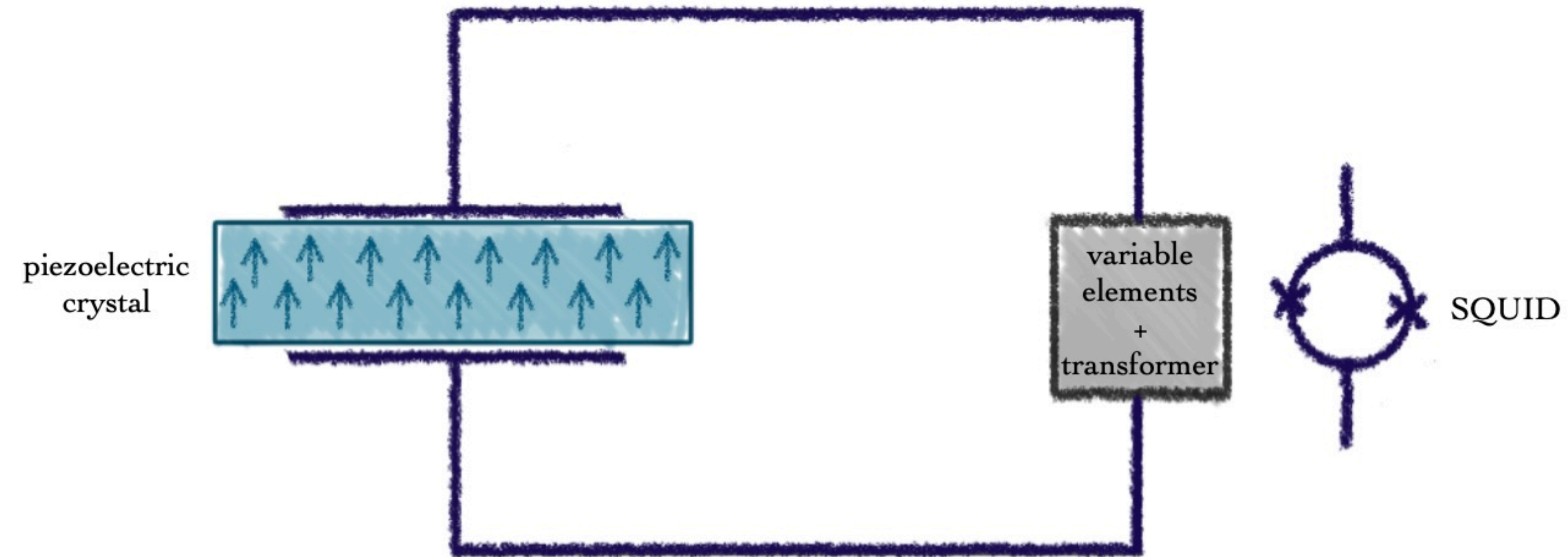
$$\frac{a}{f_a} \underline{N^\dagger \vec{\sigma} N} \cdot \vec{E}$$

Polarization



PIEZOAXIONIC EFFECT

[Arvanitaki, Madden, Van Tilburg '23]

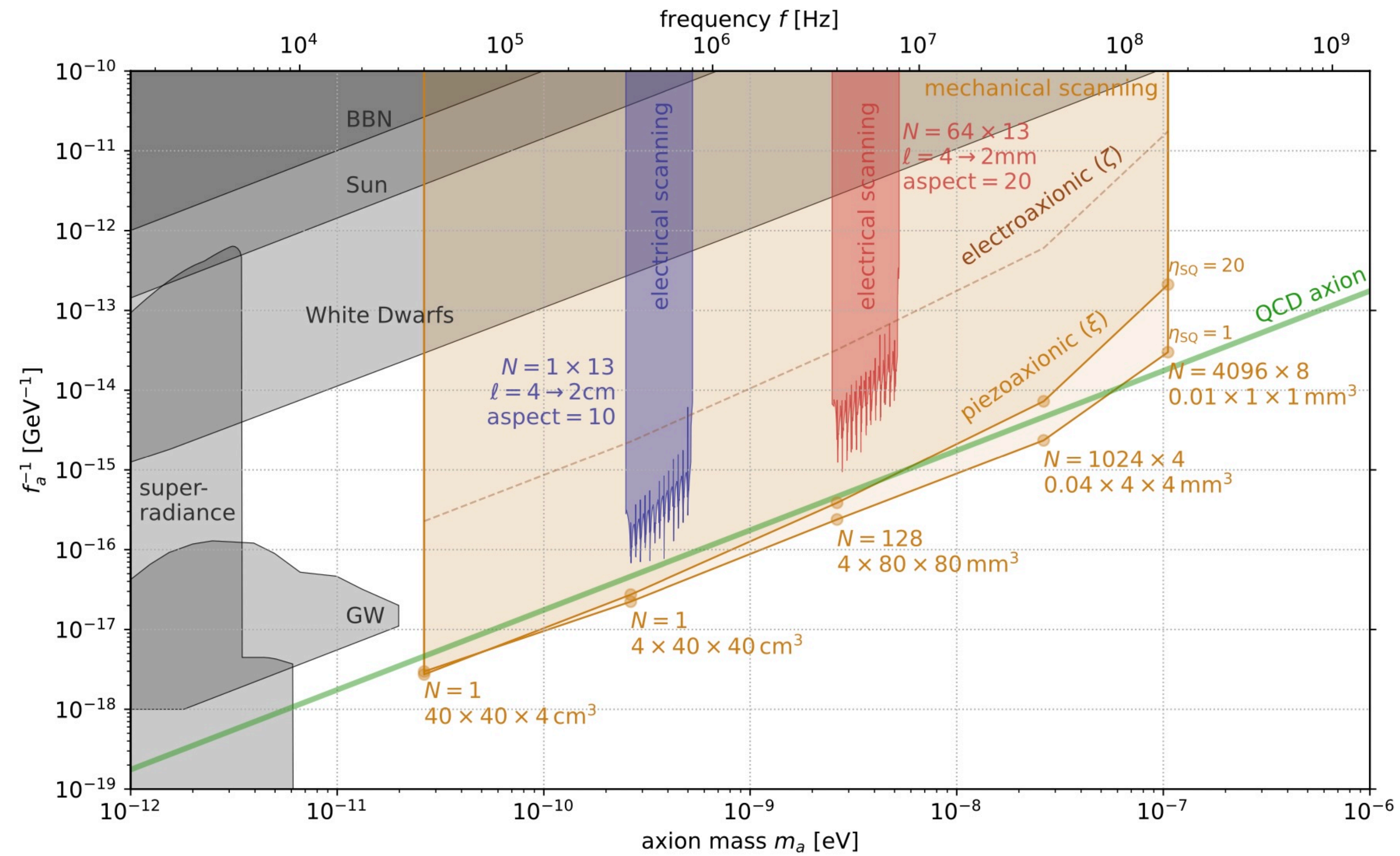


$$Q \simeq 10^9$$

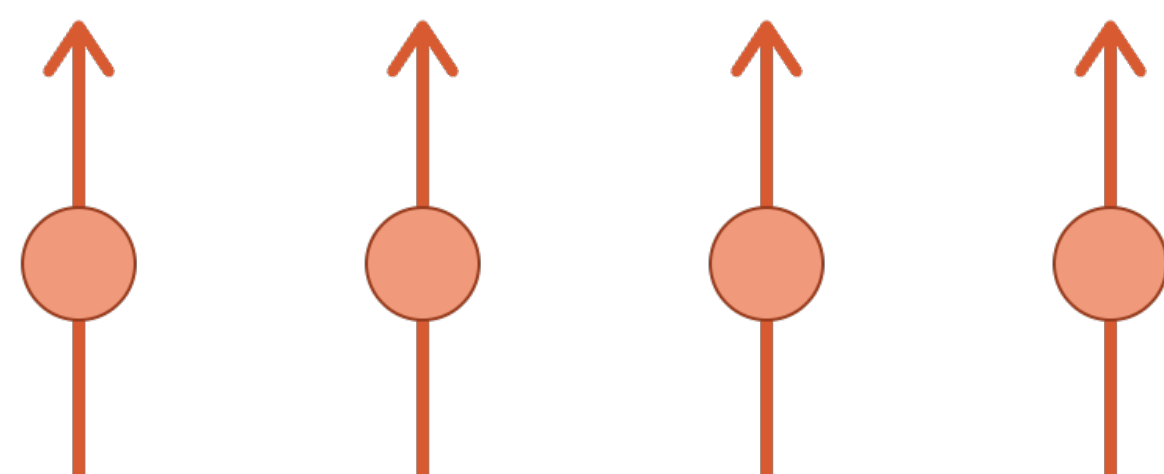
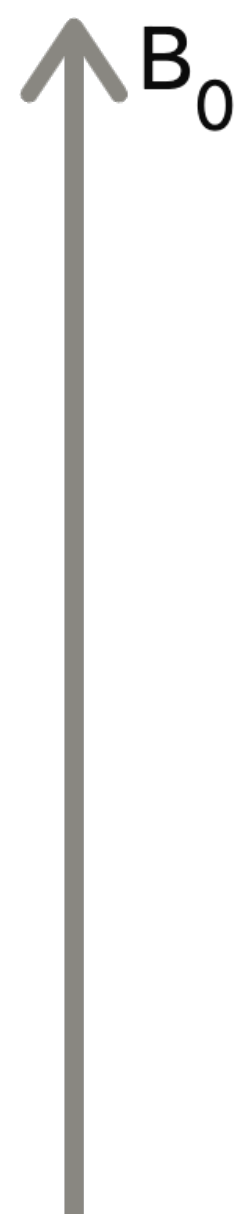
$$\begin{aligned}\mathbf{T} &= \frac{\partial U}{\partial \mathbf{S}} = +\mathbf{c}^D \mathbf{S} - \mathbf{h}^\top \mathbf{D} - \xi \hat{\mathbf{I}} \bar{\theta}_a, \\ \mathbf{E} &= \frac{\partial U}{\partial \mathbf{D}} = -\mathbf{h} \mathbf{S} + \beta^S \mathbf{D} - \zeta \hat{\mathbf{I}} \bar{\theta}_a.\end{aligned}$$

PIEZOAXIONIC EFFECT

[Arvanitaki, Madden, Van Tilburg '23]

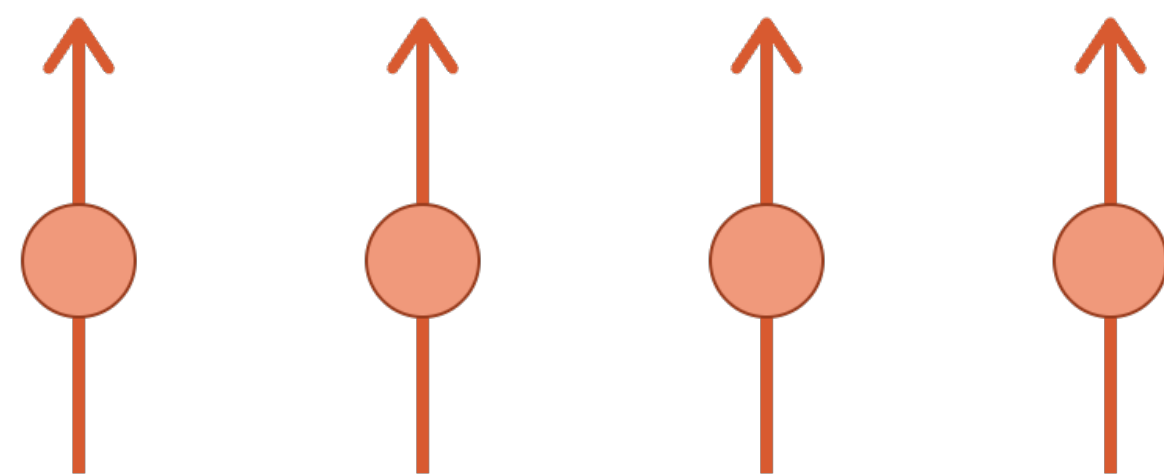
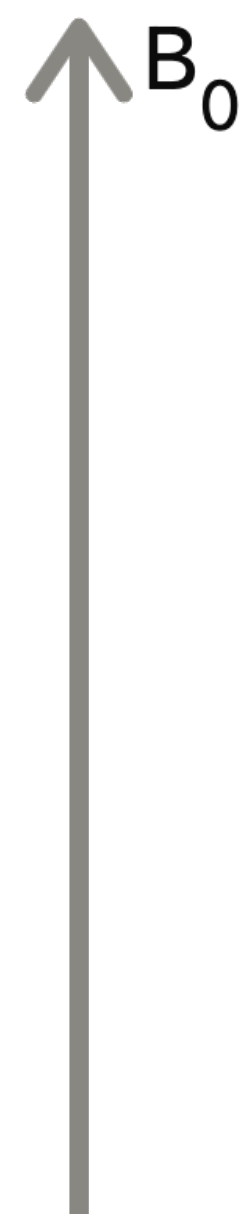


(a) Static field only



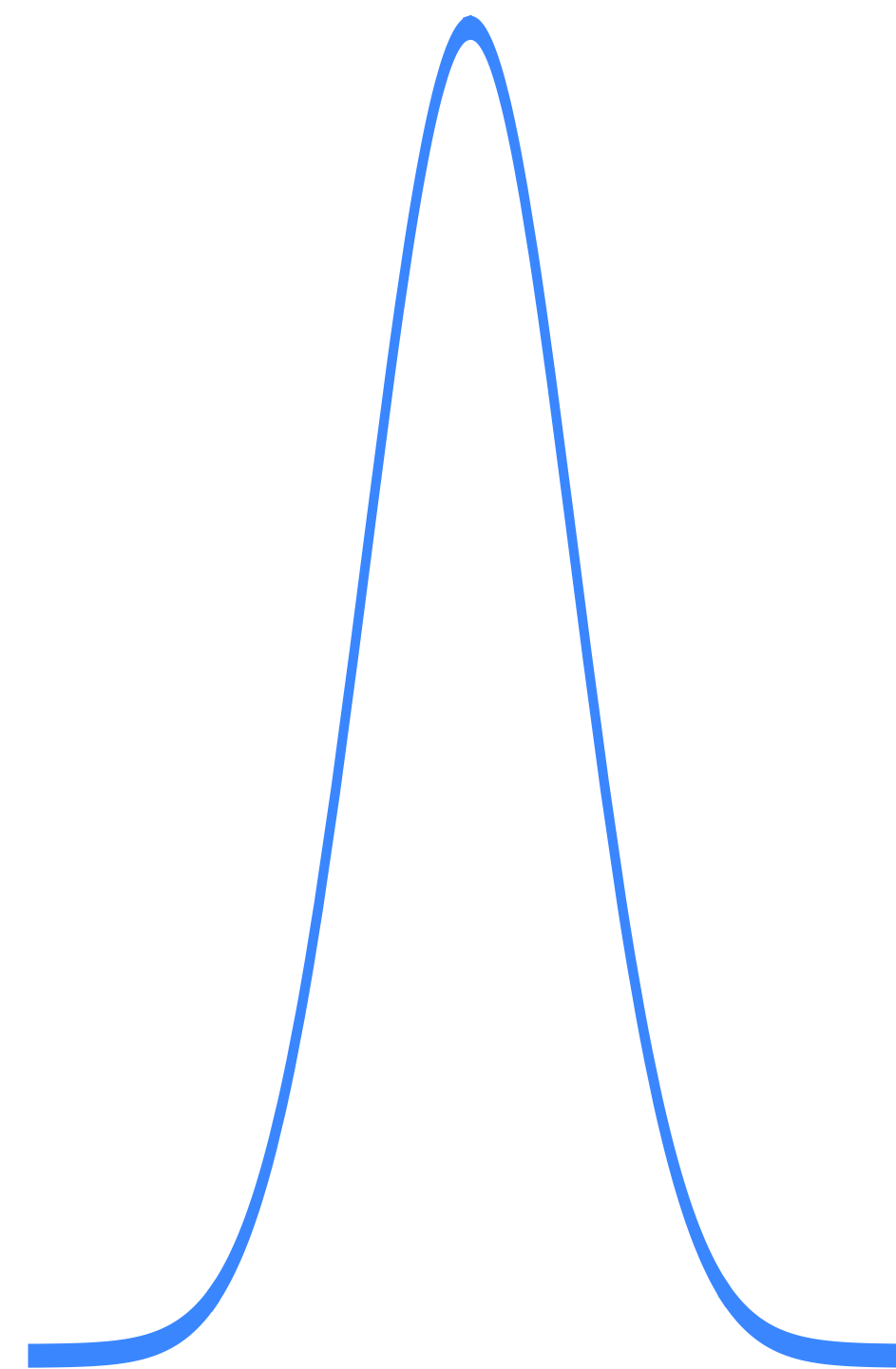
Net polarization $M \parallel B_0$

(a) Static field only



Net polarization $M \parallel B_0$

$$\omega \simeq m_a$$

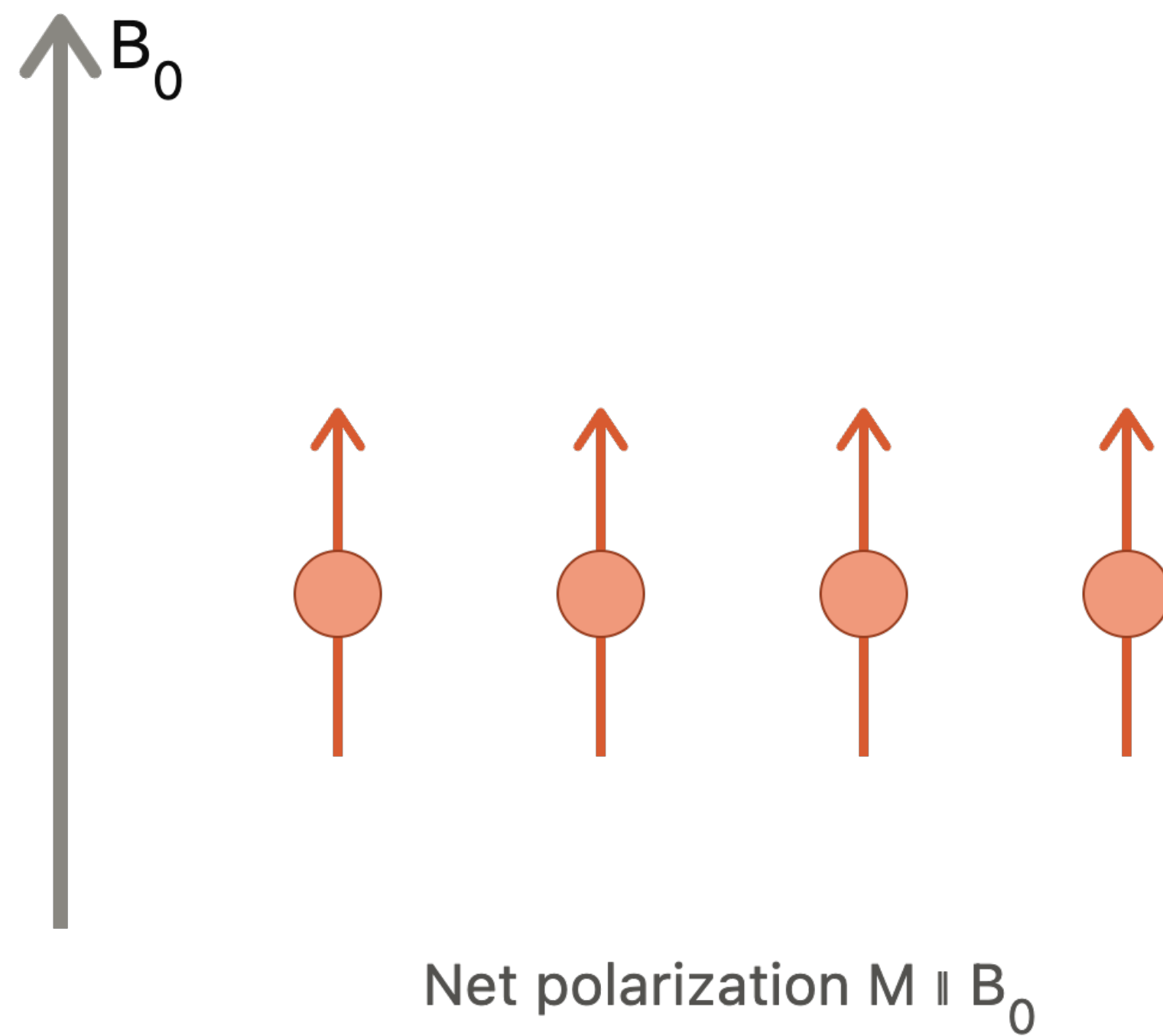


$$V(\omega)$$

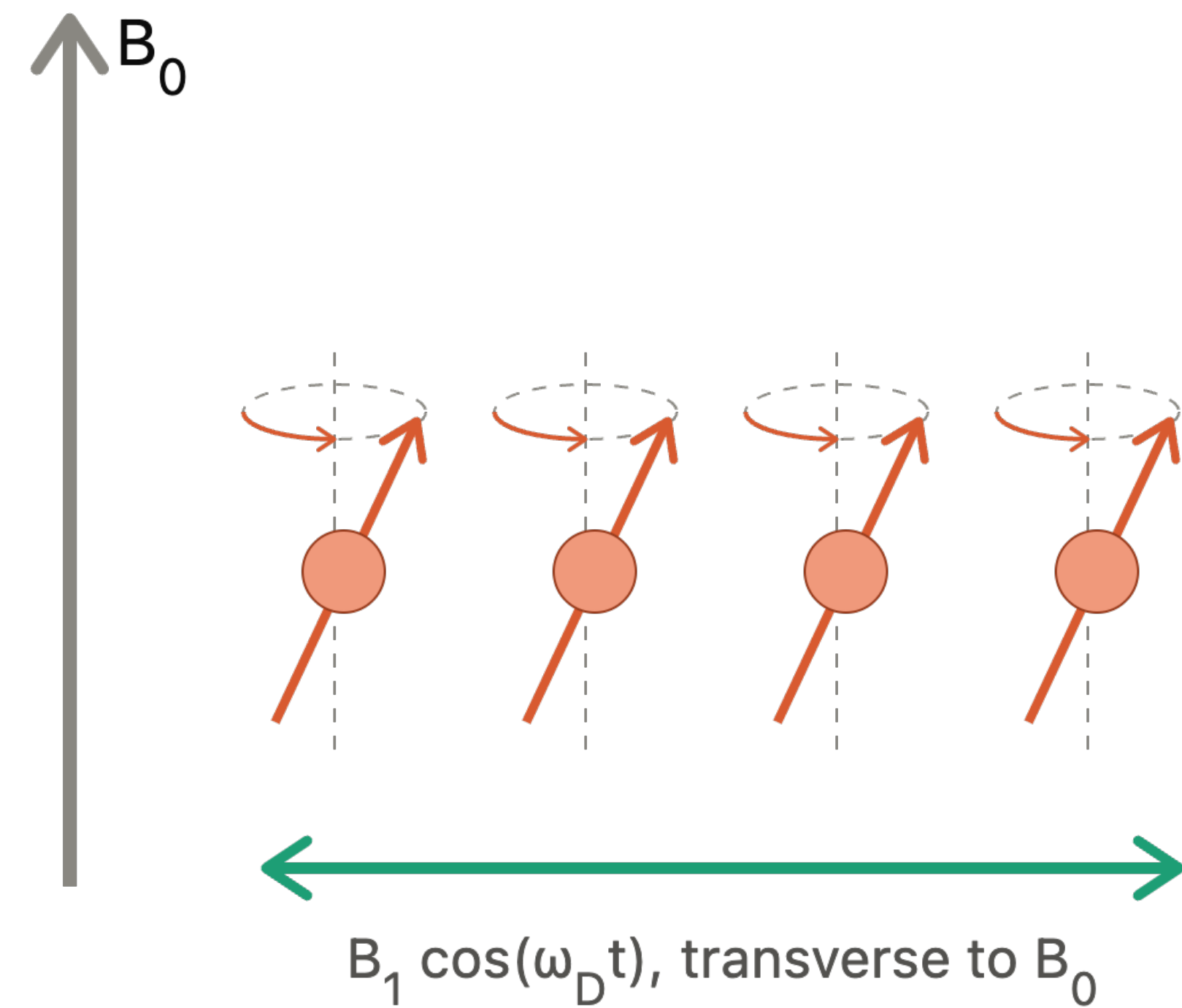
HETERODYNE PIEZOAXIONS

[RTD, Madden, Yahya In preparation]

(a) Static field only



(b) Transverse drive at ω_D

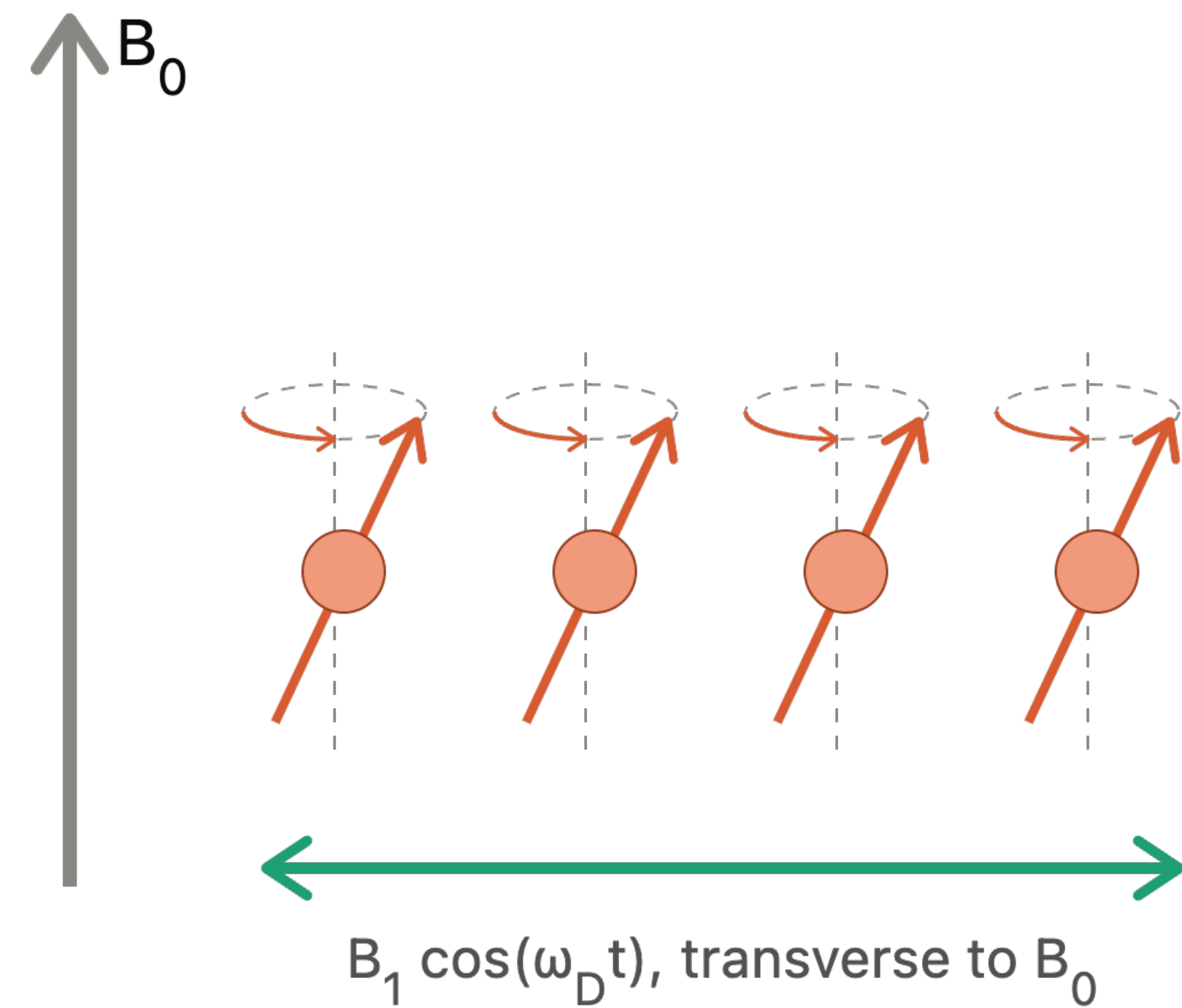


HETERODYNE PIEZOAXIONS

[RTD, Madden, Yahya In preparation]

$$|\mathbf{B}_0| \gg |\mathbf{B}_1|$$

(b) Transverse drive at ω_D

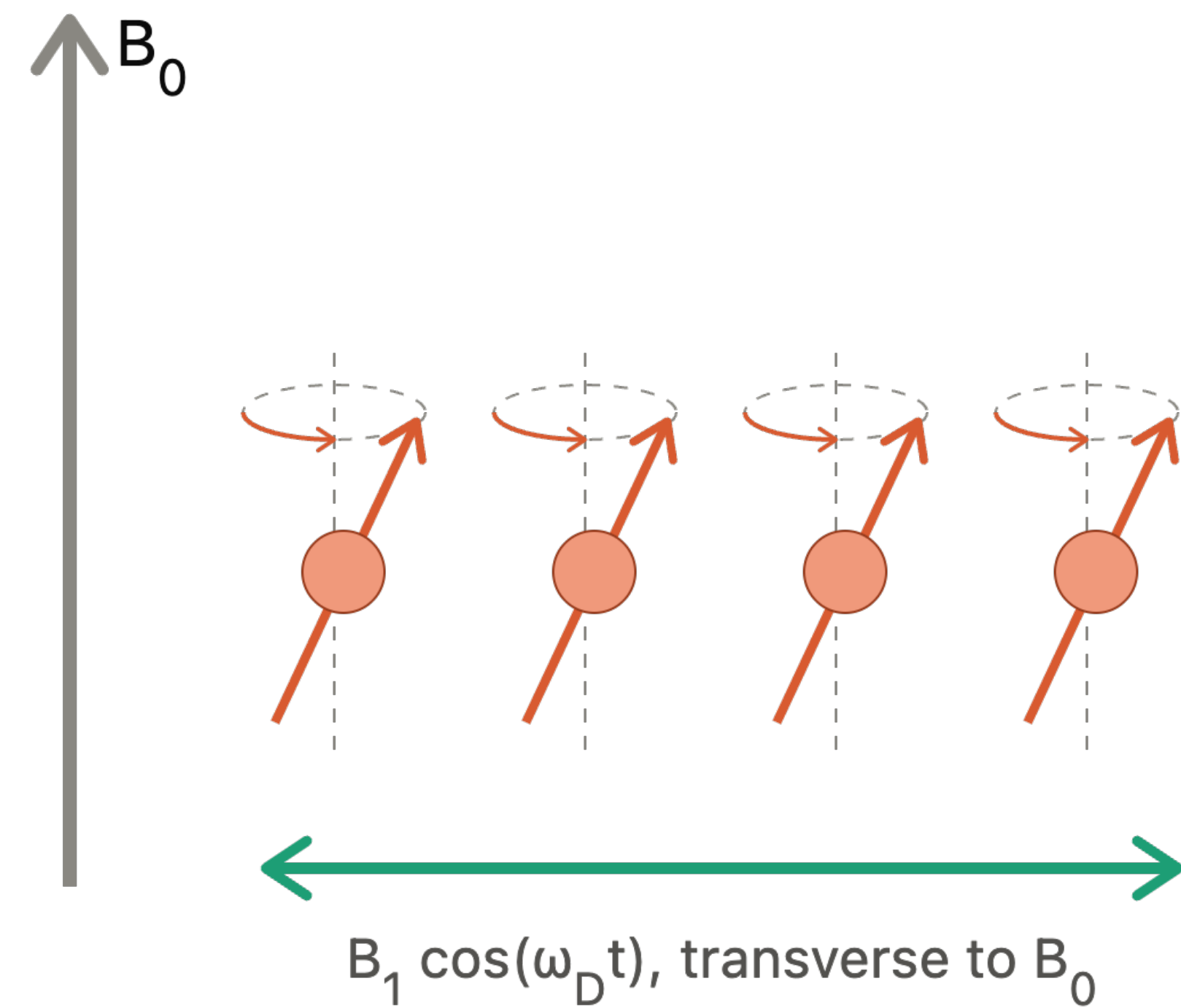


HETERODYNE PIEZOAXIONS

[RTD, Madden, Yahya In preparation]

$$\omega_D = \omega_{\text{Larmor}} = \gamma B_0$$

(b) Transverse drive at ω_D

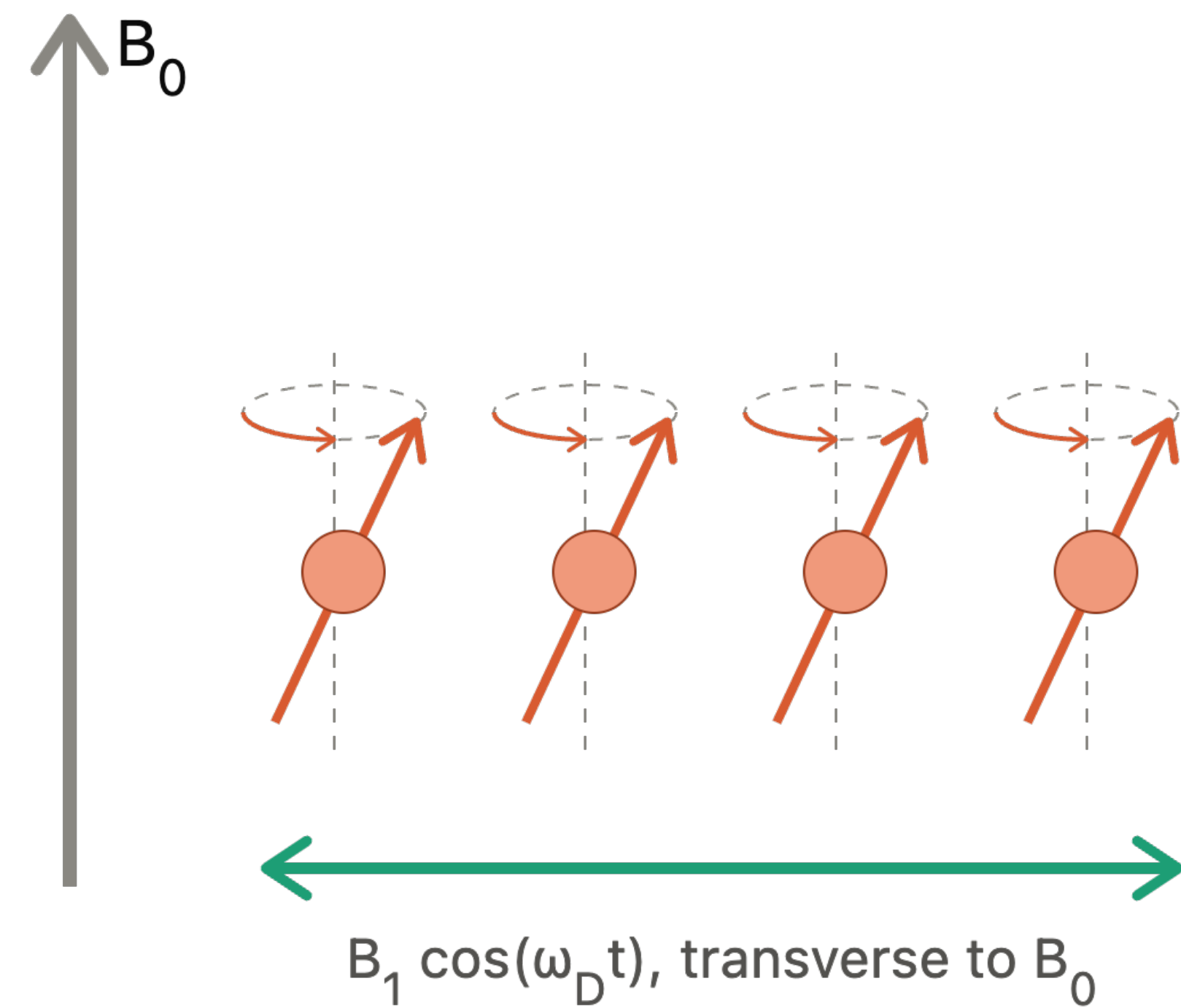


HETERODYNE PIEZOAXIONS

[RTD, Madden, Yahya In preparation]

$$\mathbf{I}(t) \simeq \mathbf{I}^{(0)} \cos \frac{\gamma |\mathbf{B}_1| t}{2}$$

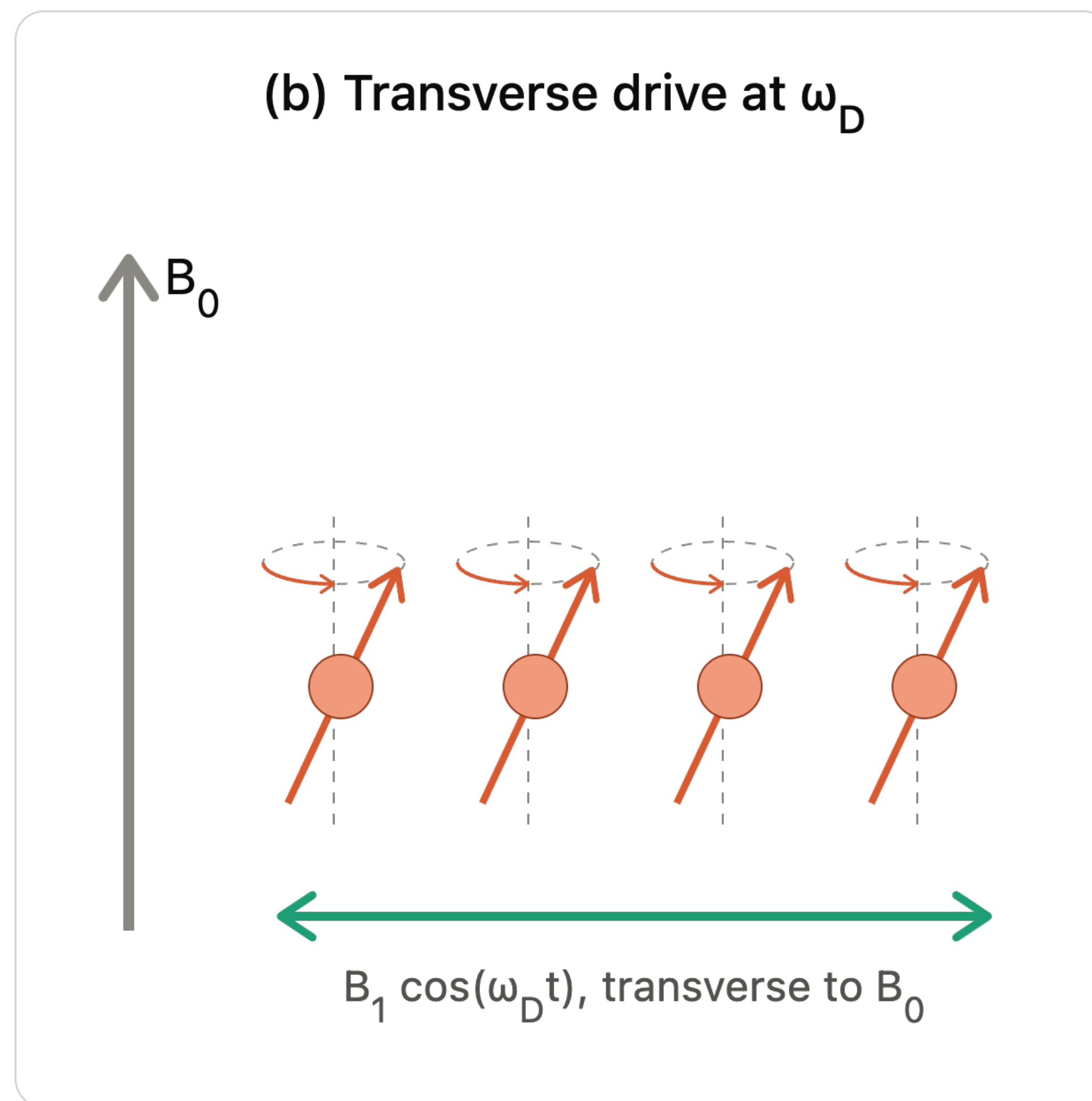
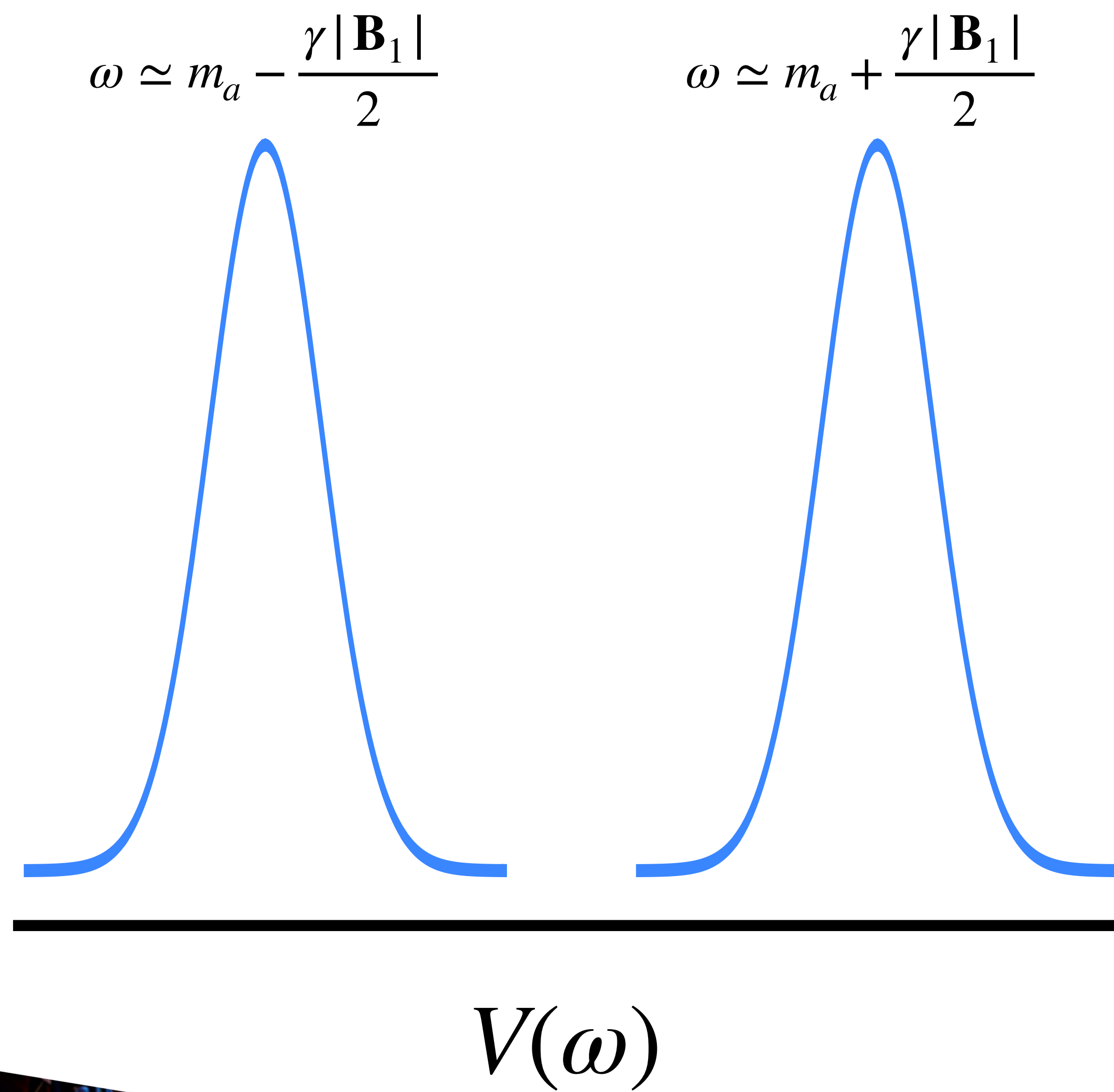
(b) Transverse drive at ω_D





$$\mathbf{I}(t) \simeq \mathbf{I}^{(0)} \cos \frac{\gamma |\mathbf{B}_1| t}{2}$$

$$\begin{aligned} \mathbf{T} &= \frac{\partial U}{\partial \mathbf{S}} = +\mathbf{c}^D \mathbf{S} - \mathbf{h}^\top \mathbf{D} - \xi \hat{\mathbf{I}} \bar{\theta}_a, \\ \mathbf{E} &= \frac{\partial U}{\partial \mathbf{D}} = -\mathbf{h} \mathbf{S} + \beta^S \mathbf{D} - \zeta \hat{\mathbf{I}} \bar{\theta}_a. \end{aligned}$$

DISADVANTAGES

1.

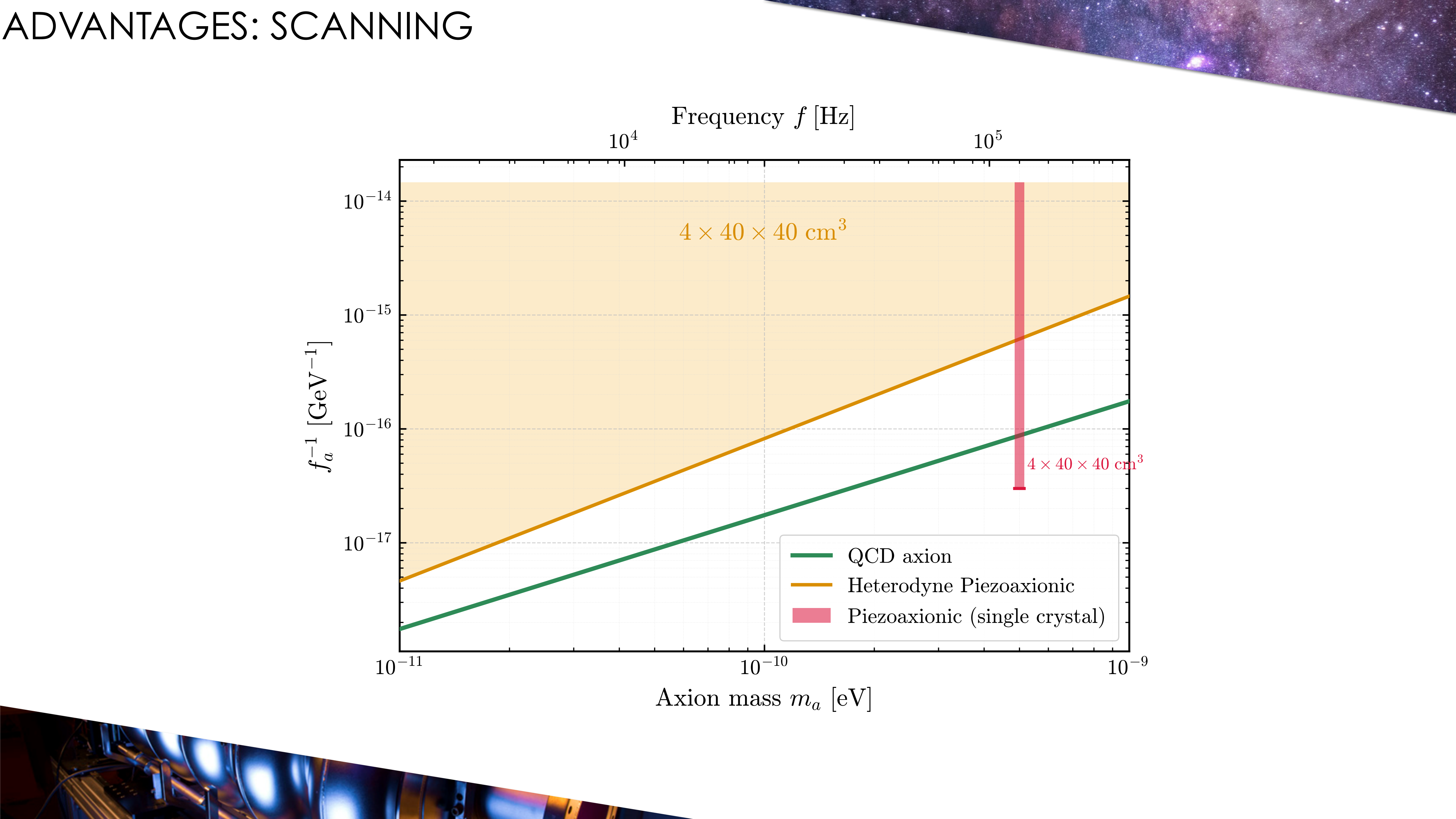
$$g_{a\gamma\gamma} \sim t_{\text{int}}^{-1/4}$$

$$\frac{t_{\text{int}}}{t_{\text{int}}^{\text{het}}} \sim \frac{T_1}{T_2} \sim 10^5$$

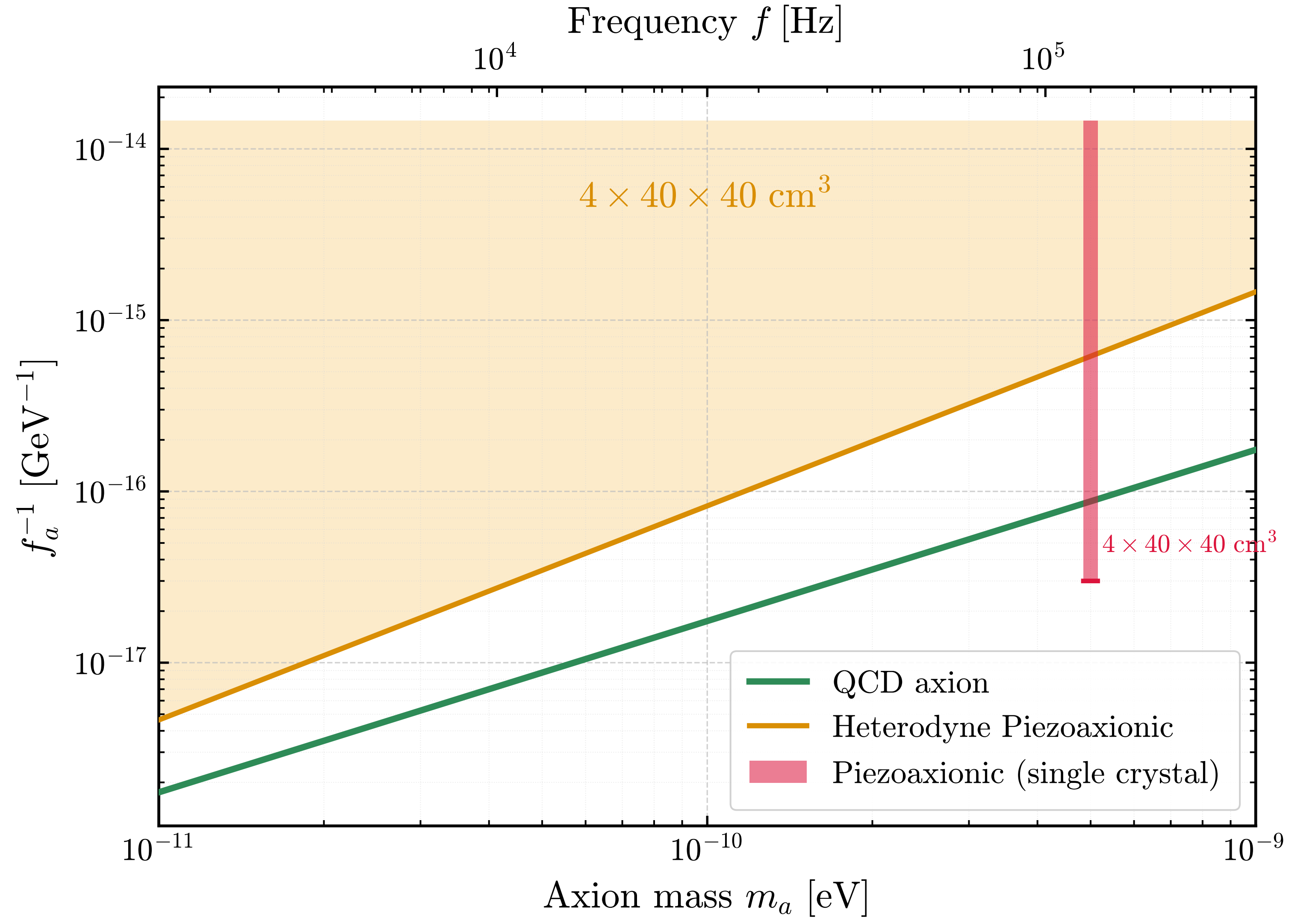
DISADVANTAGES

1. $g_{a\gamma\gamma} \sim t_{\text{int}}^{1/4}$ $\frac{t_{\text{int}}}{t_{\text{int}}^{\text{het}}} \sim \frac{T_1}{T_2} \sim 10^5$

2. $\Delta\omega_{\text{sig}} \sim \frac{m_a}{Q_a}$ $\Delta\omega_{\text{sig}}^{\text{het}} \sim \frac{1}{T_2} \sim \text{kHz}$



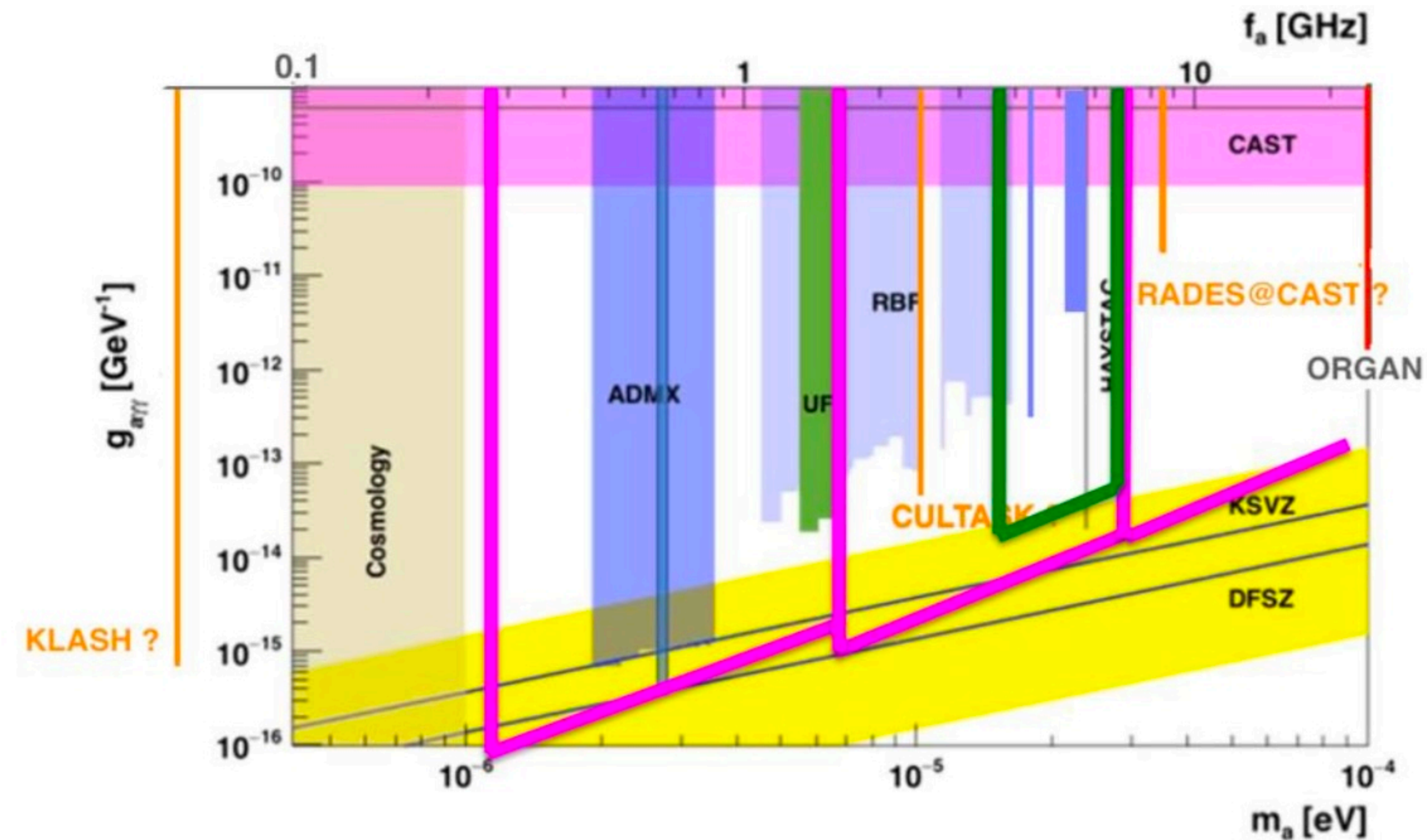
ADVANTAGES: SCANNING



- Why do we like axions? **For pretty good reasons**
- If the axion is dark matter we will cover (most of) the QCD line in the next decades (optimistically)
- Axions are unique probes of the deep UV (and allow theorists to endlessly disagree)



BACKUP



Phase 1

$$B = 14 \text{ T}, f = 4 \text{ GHz}, T = 50 \text{ mK}$$

$$m_a \geq 10^{-5} \text{ eV}$$

Phase 2

$$B = 9 \text{ T}, V = \text{m}^3$$

Up to 43 T in a smaller volume