HIGHLIGHTS FROM AXION PHYSICS

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

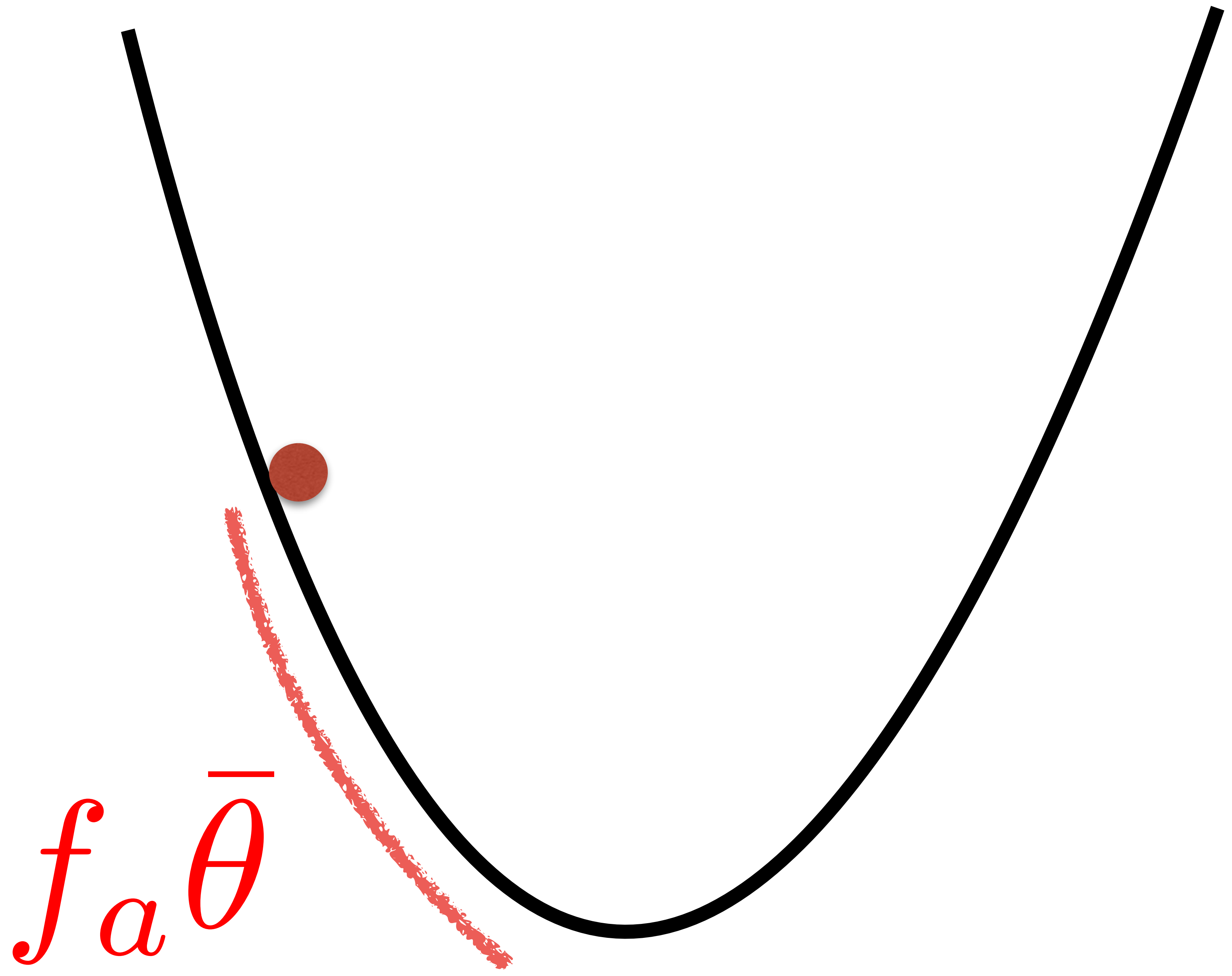
Universe: $$N_{\rm DM} \simeq 10^{-3} \left(\frac{\rm eV}{m_{\rm DM}} \right)$$

$$V(a) =$$

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


Energy
$f_a\bar{\theta}$
Dimensionless

Classical Equation of Motion



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

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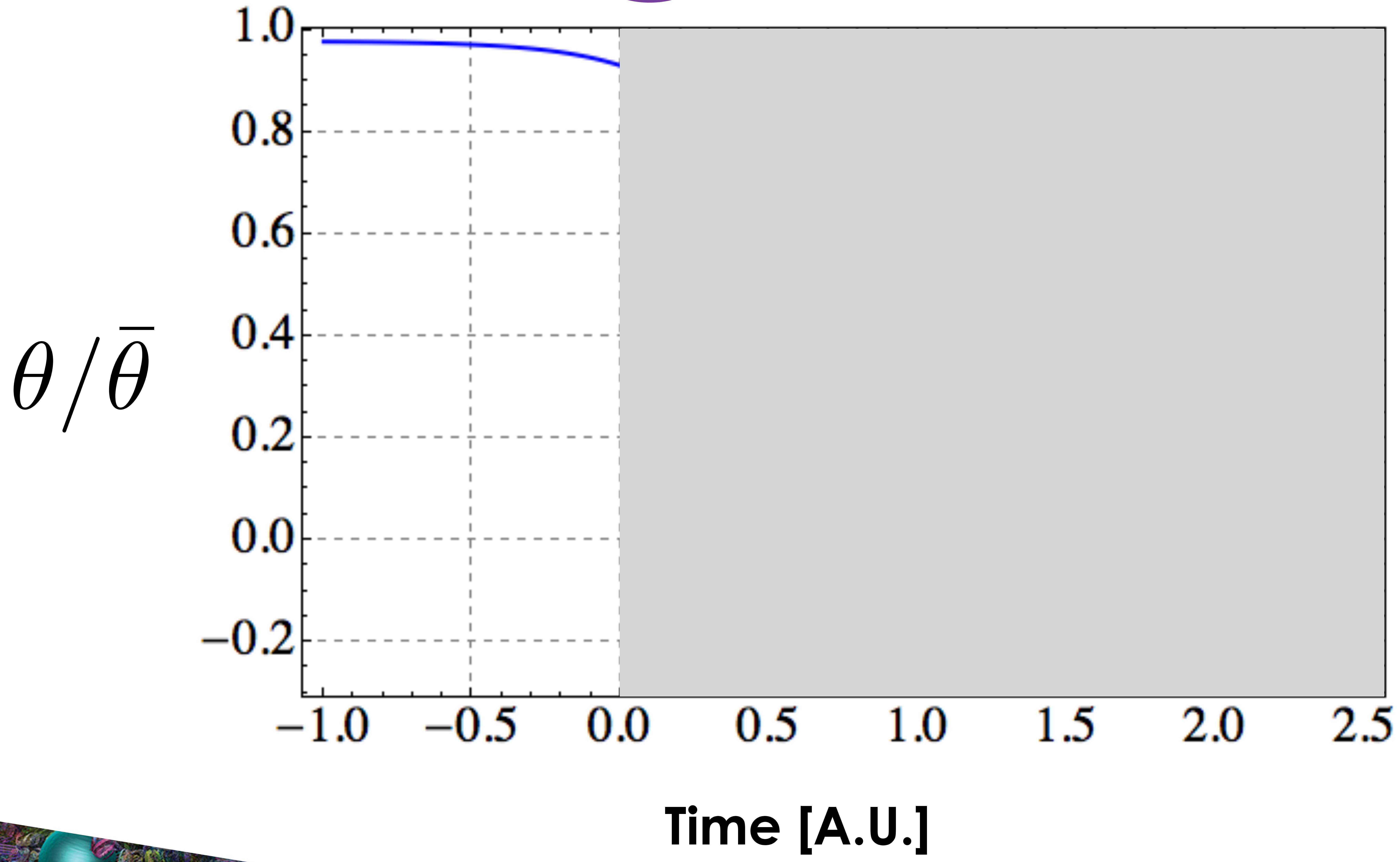
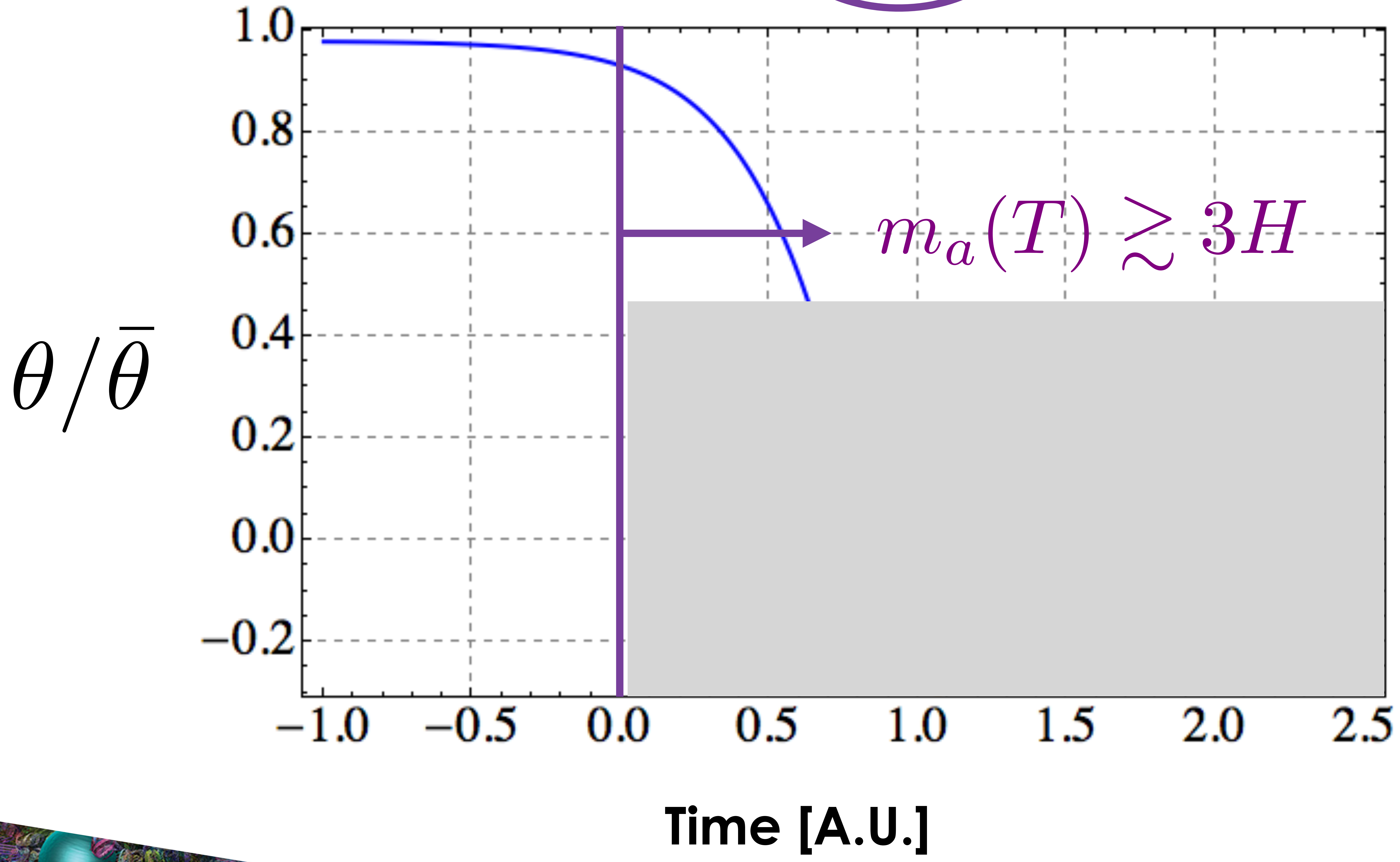
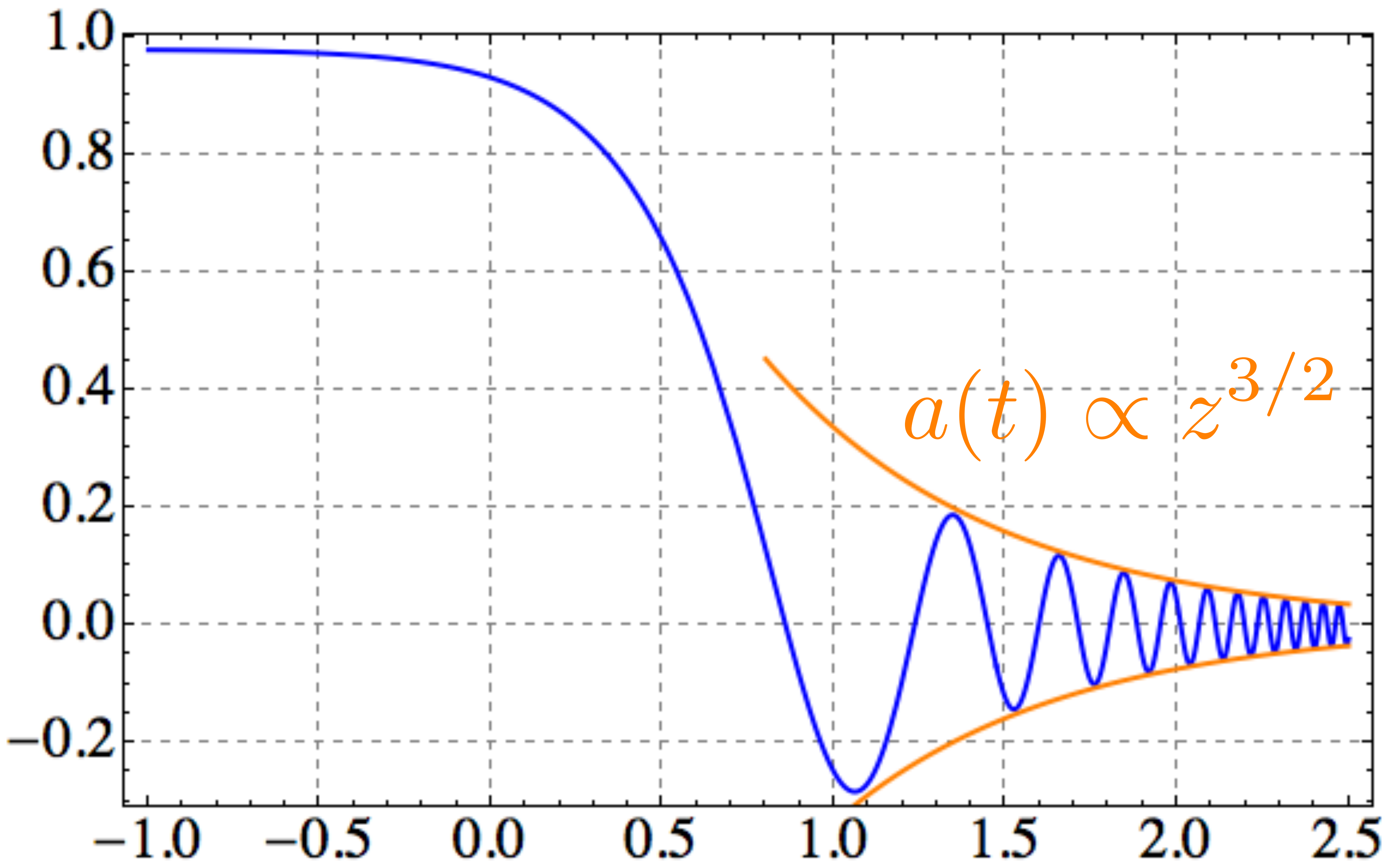


$$\ddot{\theta} + 3H\dot{\theta} + m_a^2(T)\theta = 0$$



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

$\theta/\bar{\theta}$



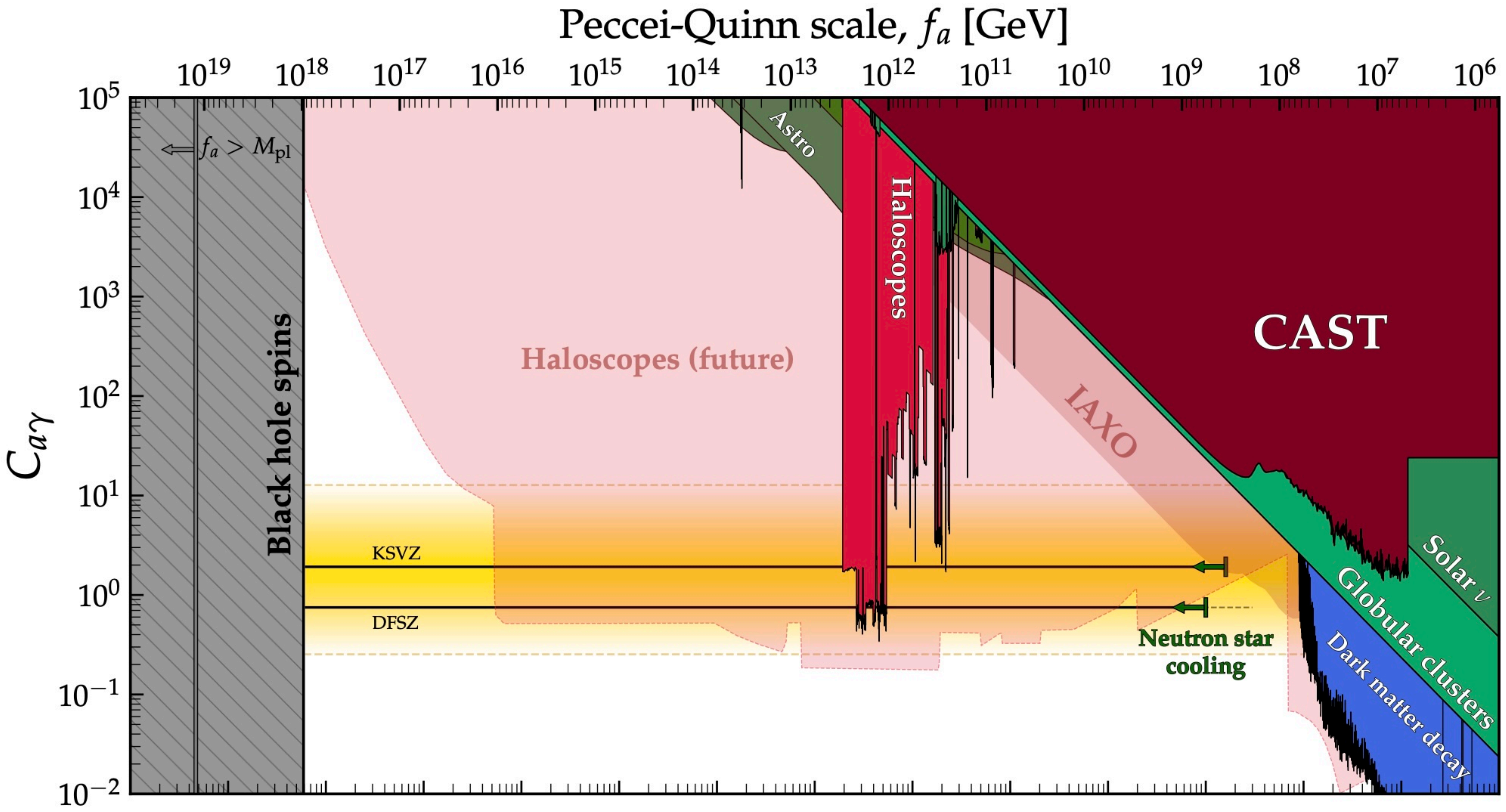
Time [A.U.]

Redshifts as cold dark matter

WHY DO I LIKE AXIONS?

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

EXPERIMENTAL REACH



WHY DO I LIKE AXIONS?

3. A clean probe of high energies

CLEAN PROBES OF HIGH ENERGIES

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

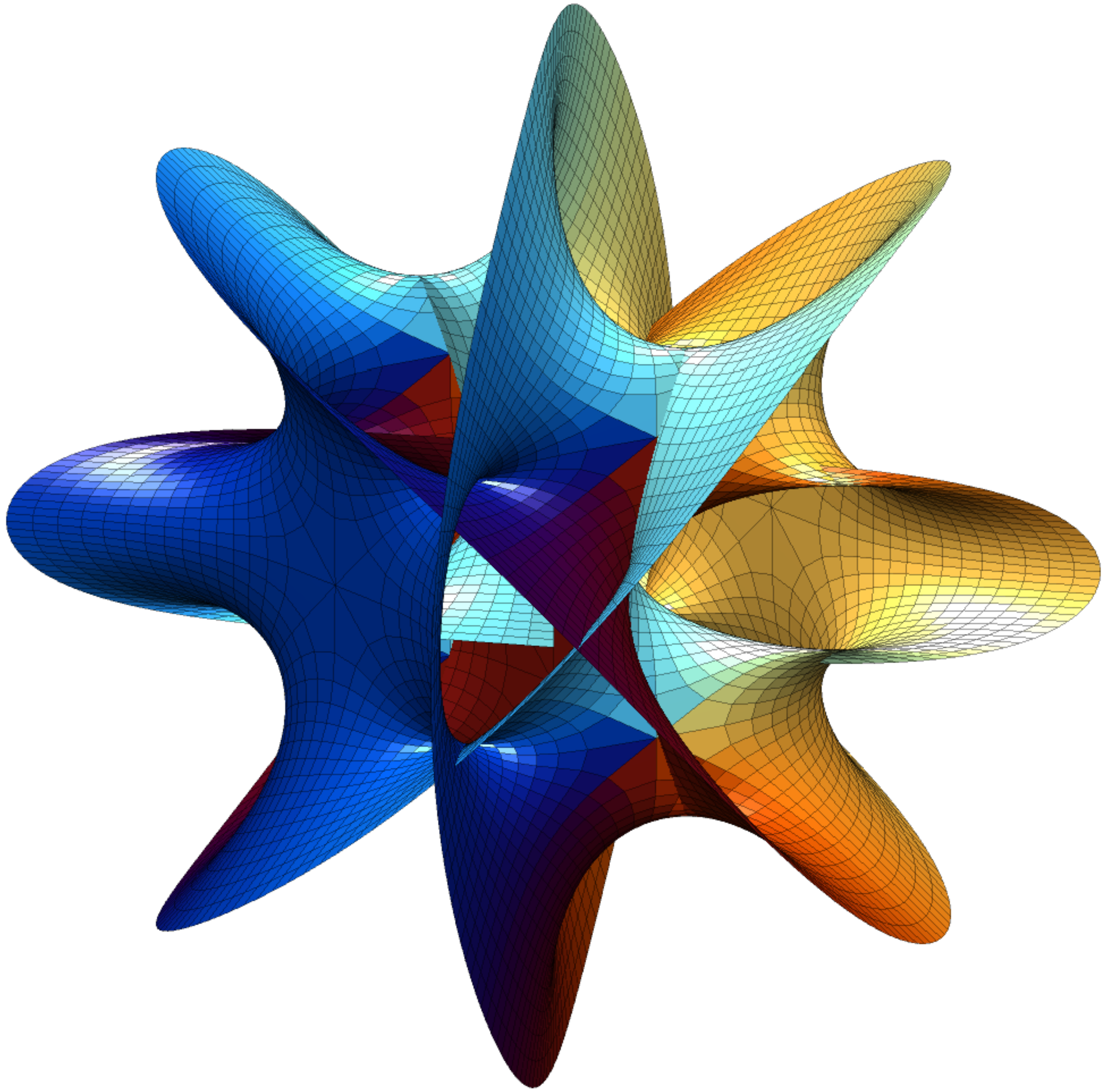
CLEAN PROBES OF HIGH ENERGIES

$$\mathcal{A}_{\mathrm{UV}} = \mathcal{A}_{\mathrm{IR}}$$

WHY DO I LIKE AXIONS?

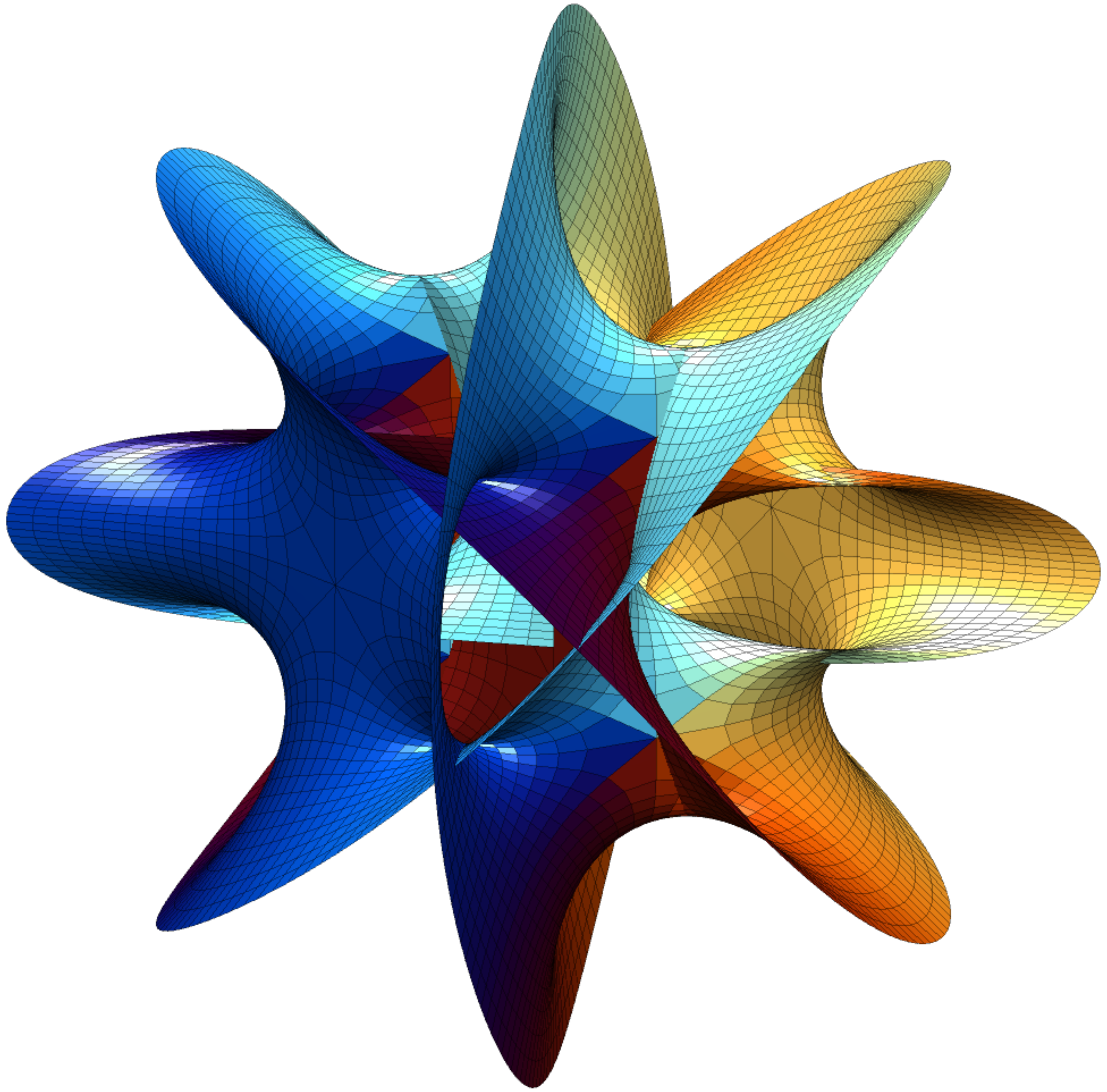
4. Generically predicted in string theory

GENERIC UV PREDICTION



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

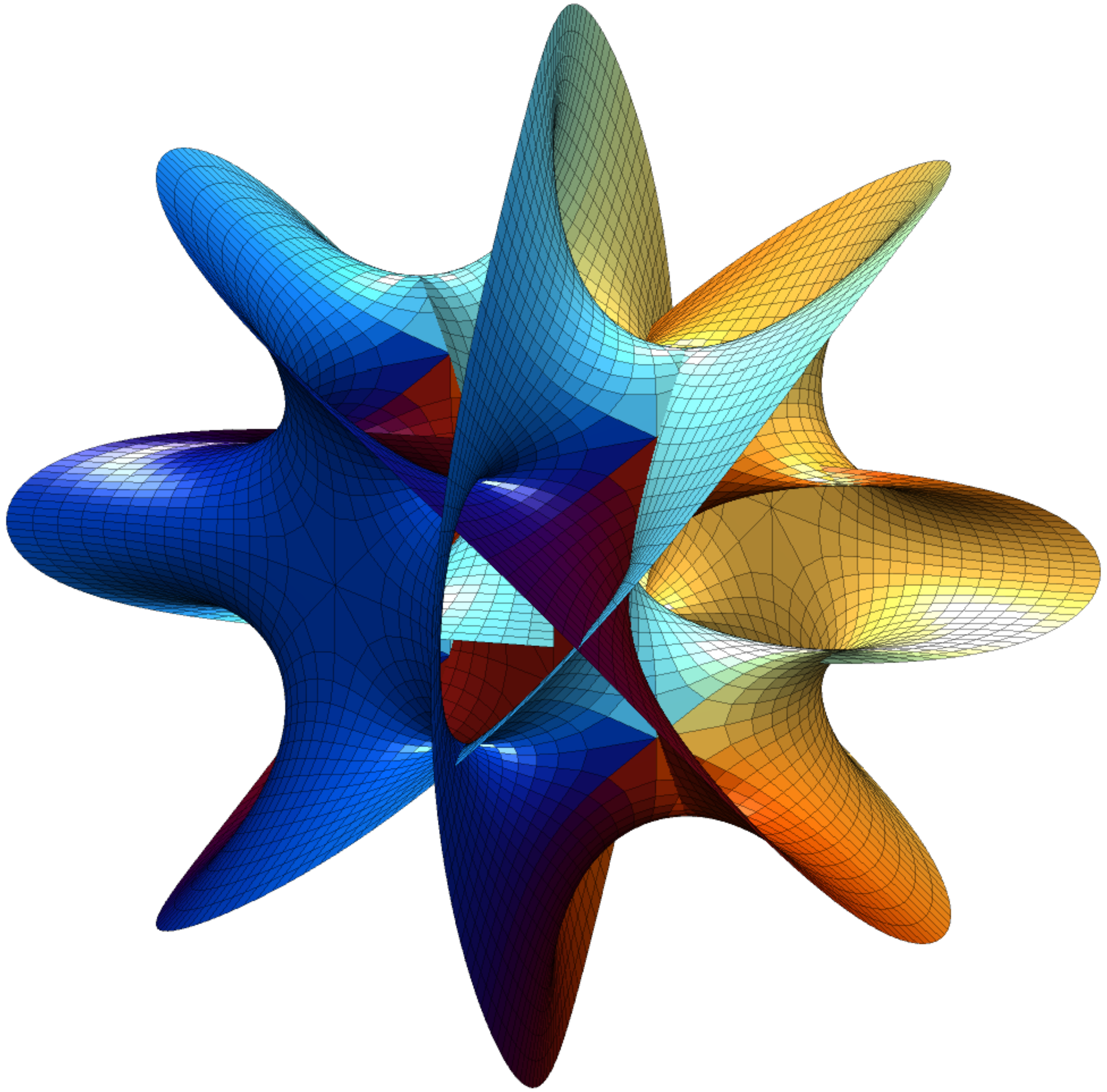
GENERIC UV PREDICTION



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

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

GENERIC UV PREDICTION



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

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

$$A \to A + d\Lambda$$

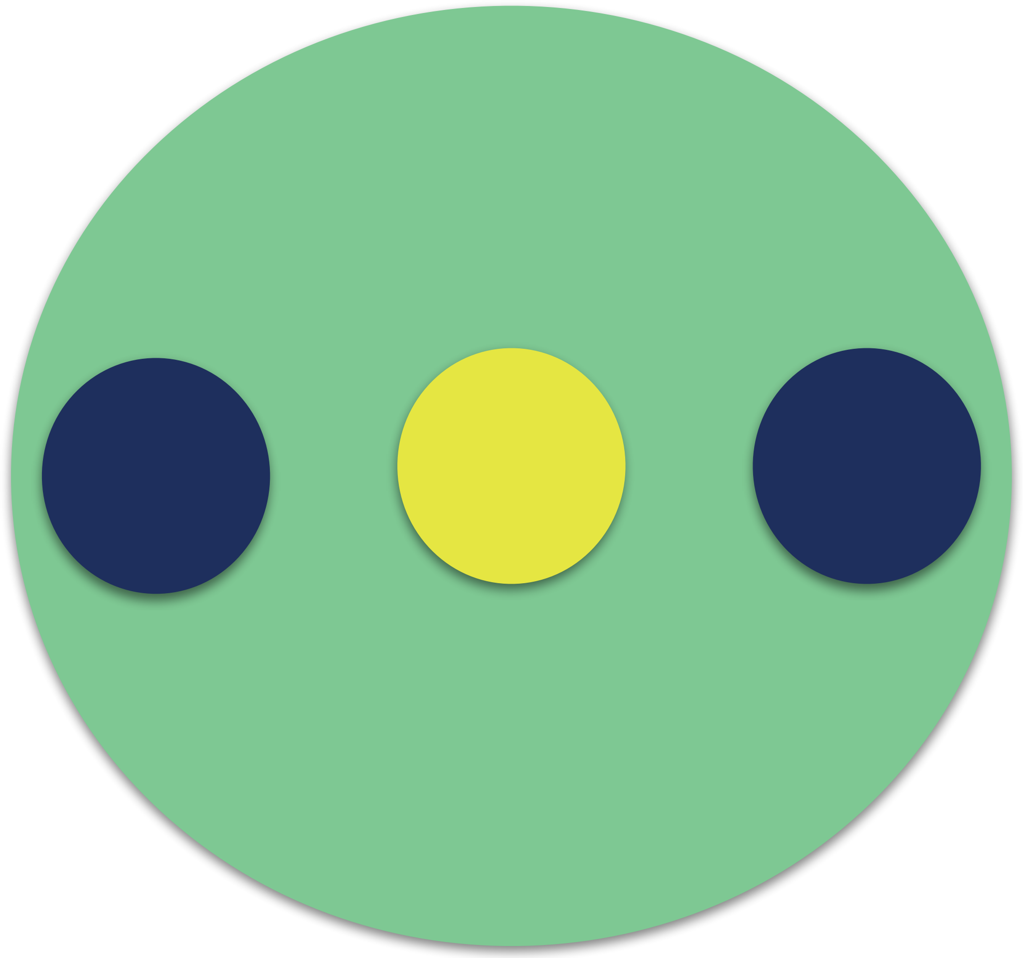
$$a = \int_C A$$

WHY DO I LIKE AXIONS?

5. They solve a puzzle of the Standard Model

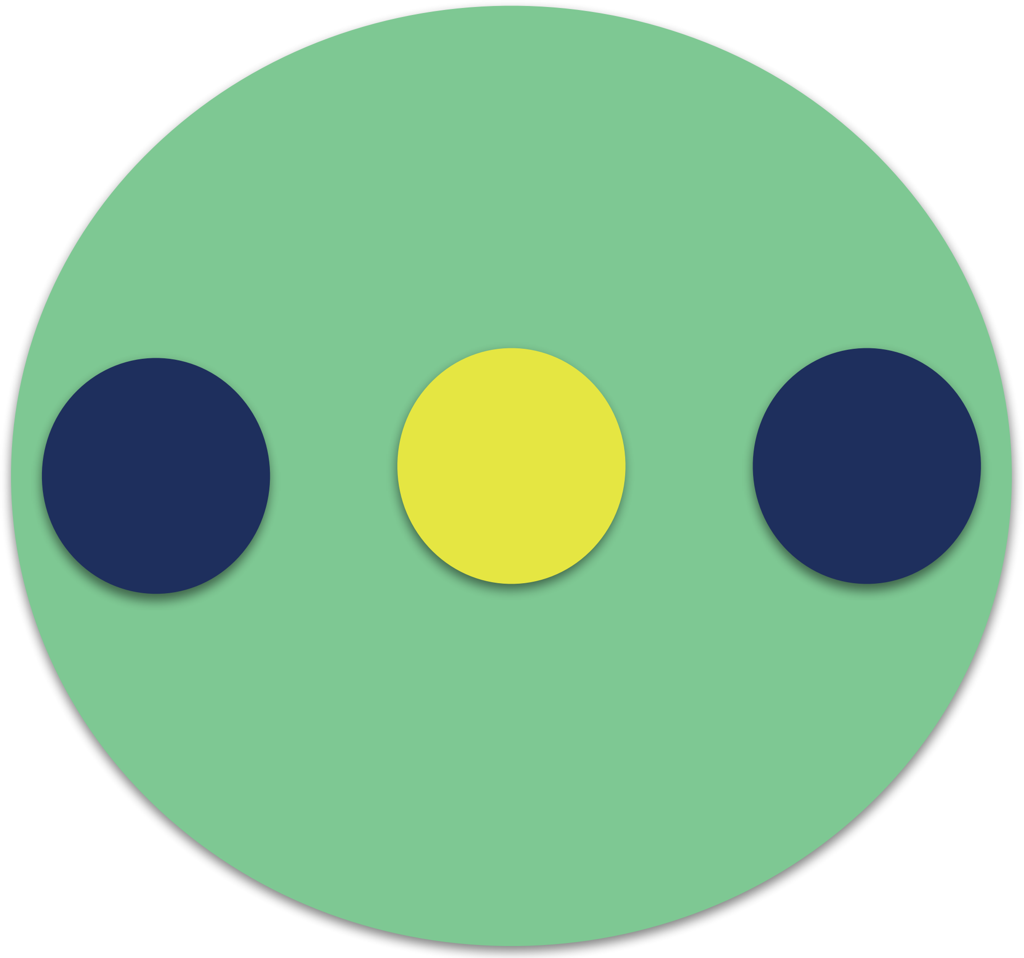
$$\theta G\tilde{G}$$

Neutron $\theta = 0$

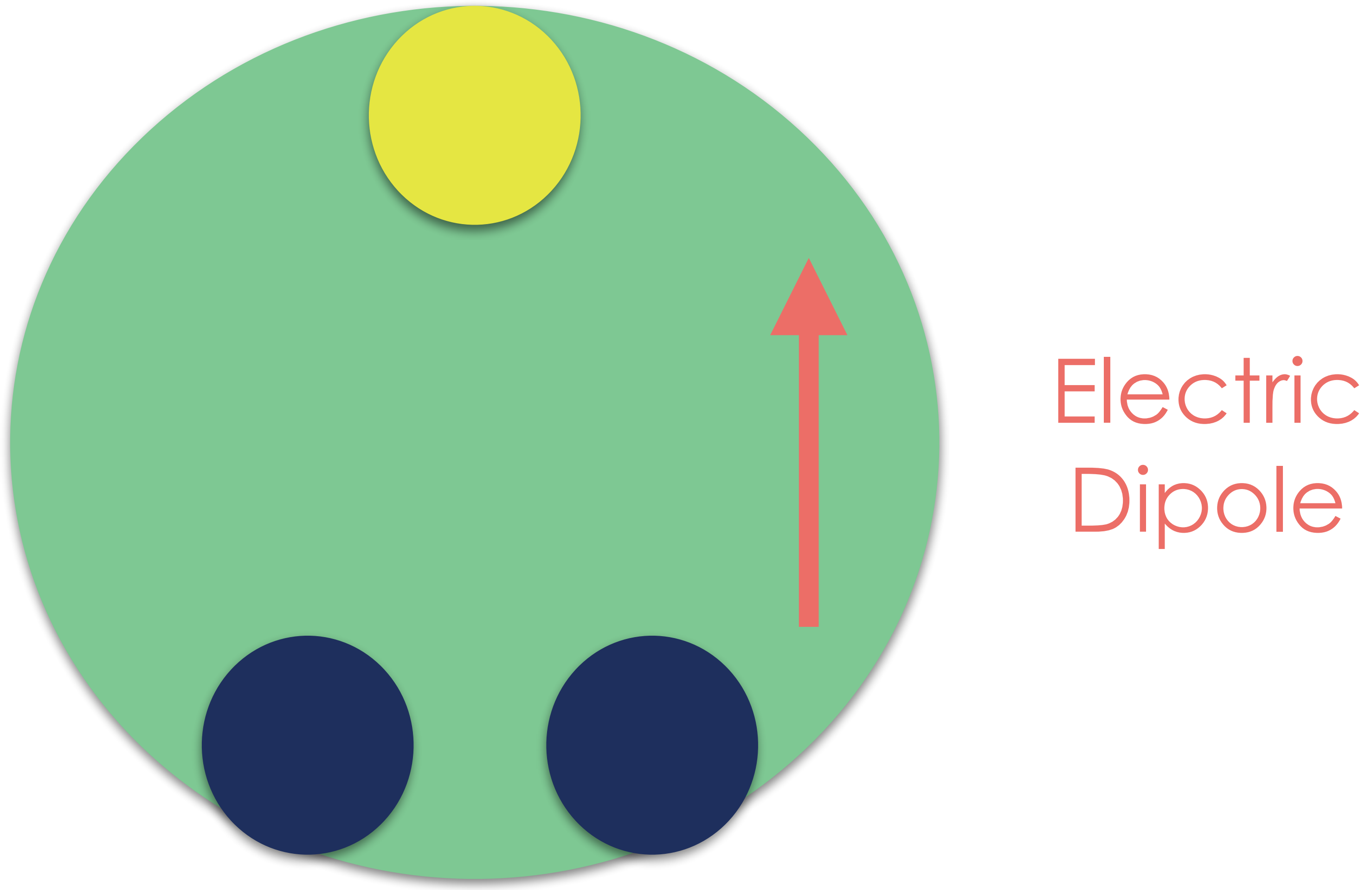


$$\theta G\tilde{G}$$

Neutron $\theta = 0$

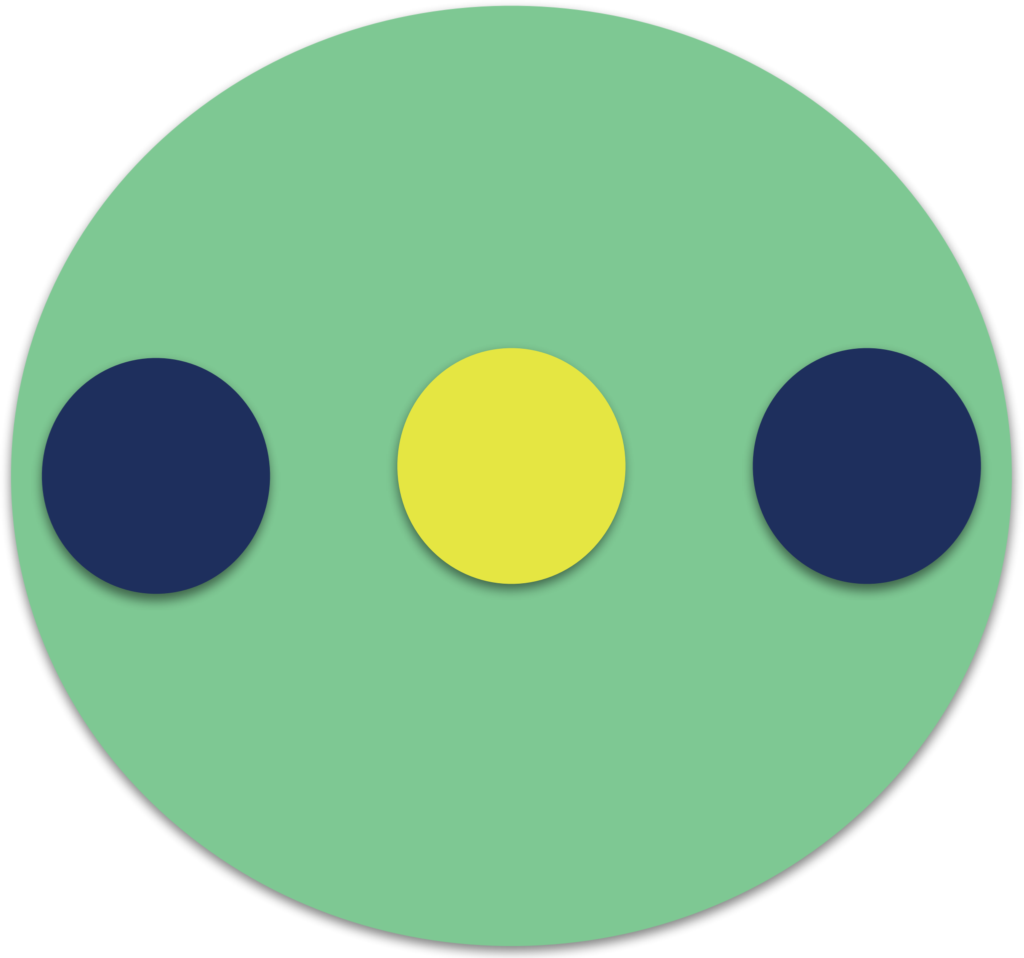


Neutron $\theta \neq 0$

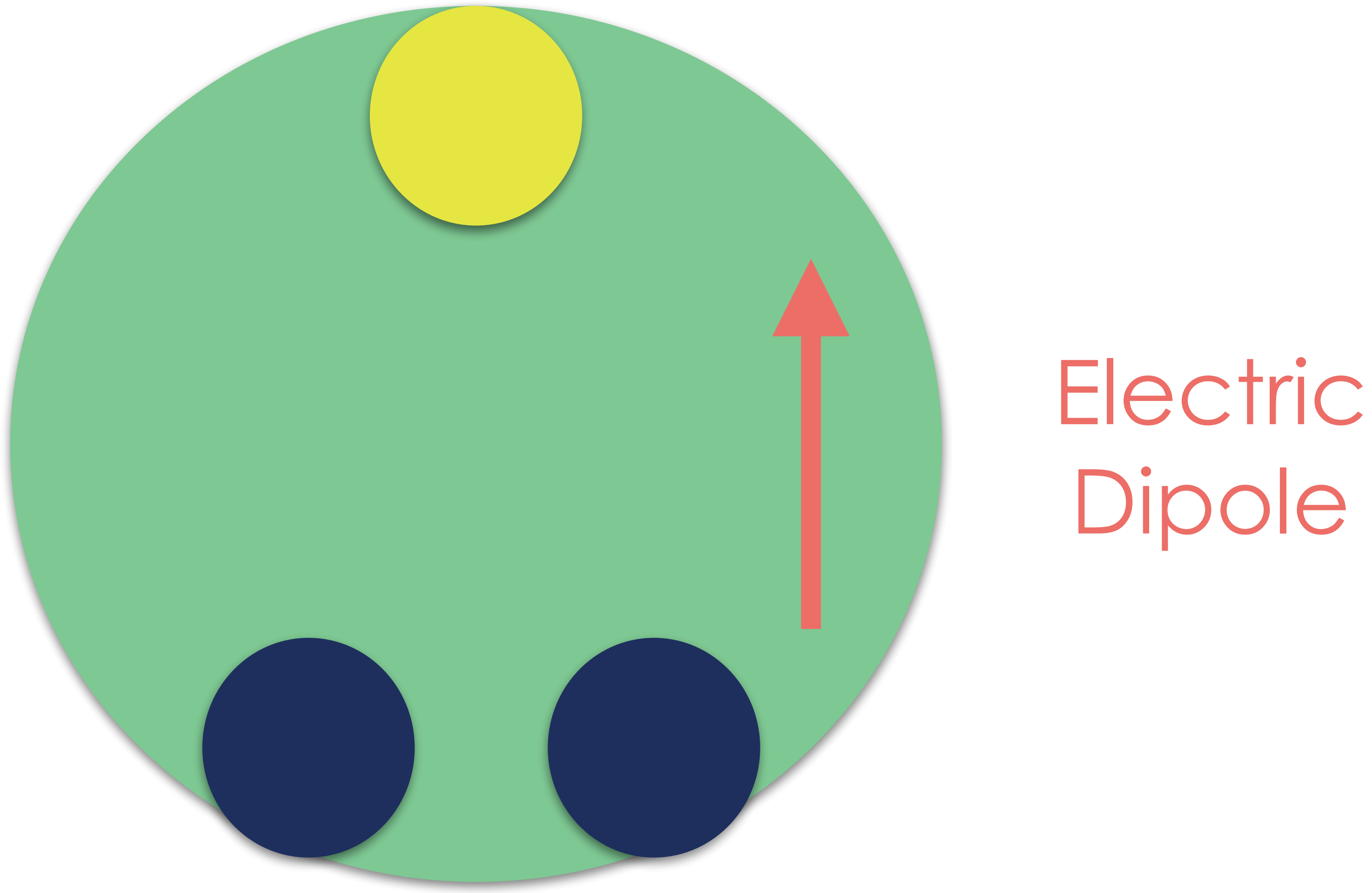


$$\theta G\tilde{G}$$

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

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

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

HIGHLIGHTS

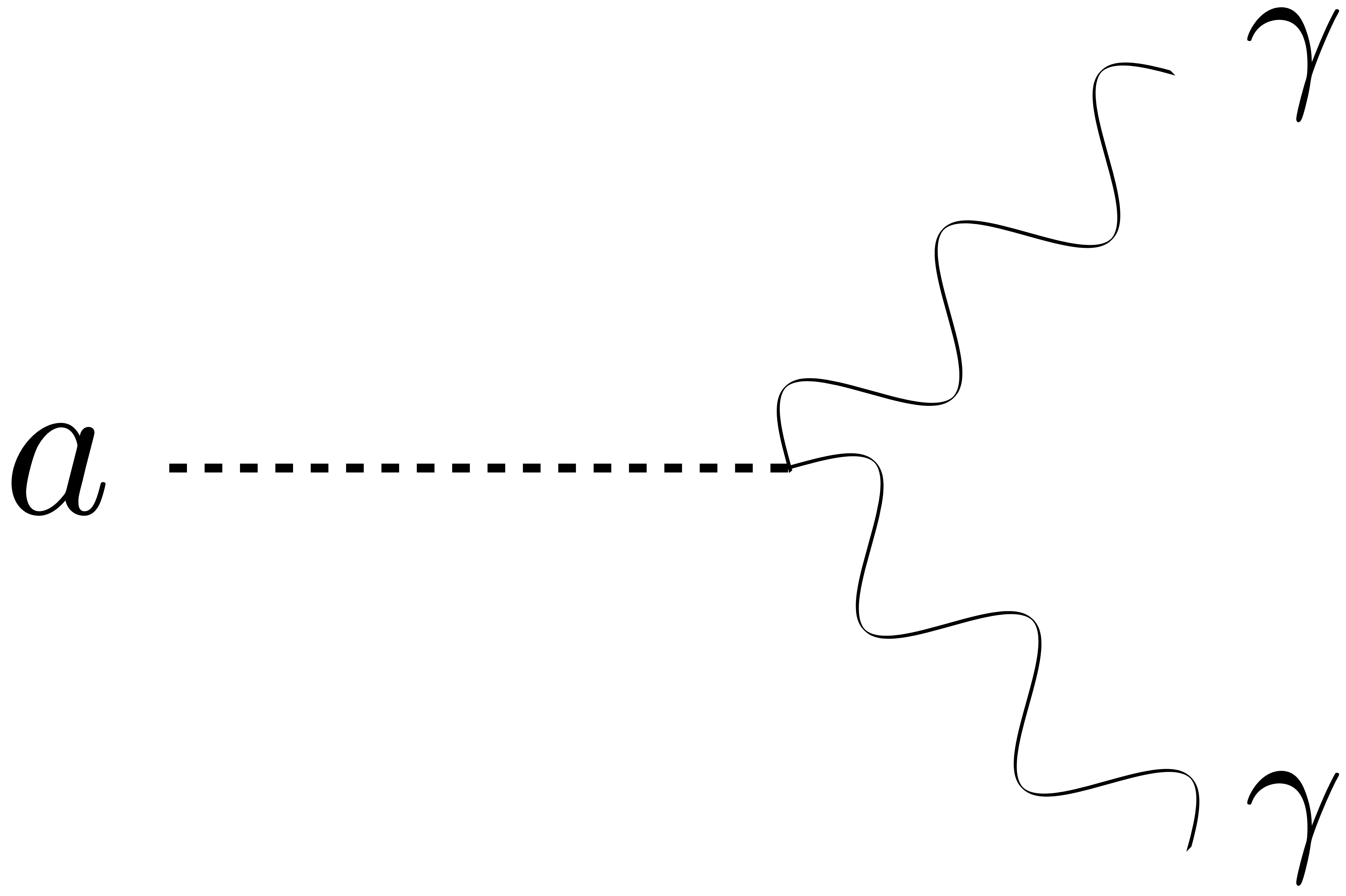
Laboratory

Astrophysics

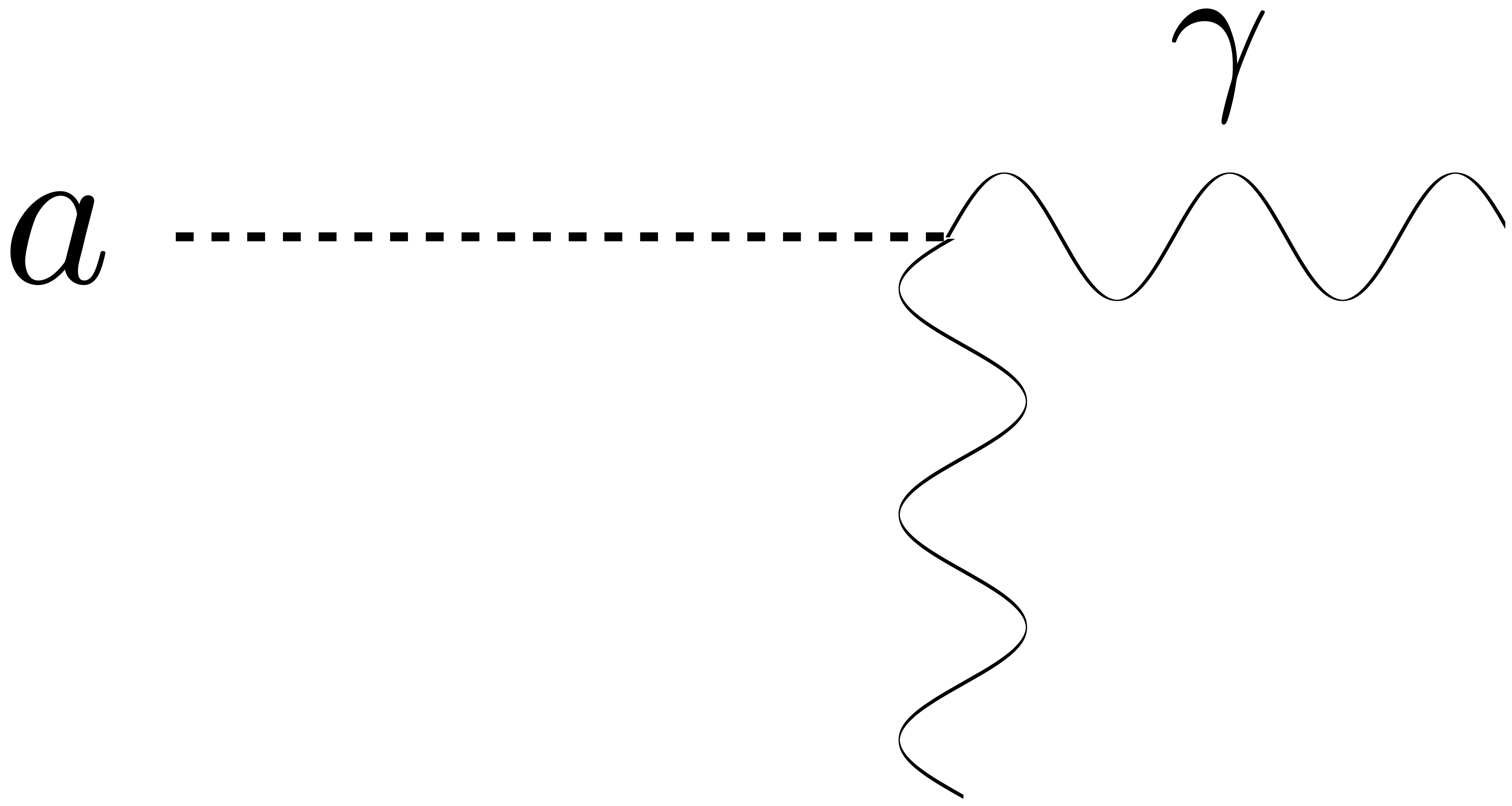
Theory


AXION DARK MATTER
IN THE LABORATORY

PHOTONS



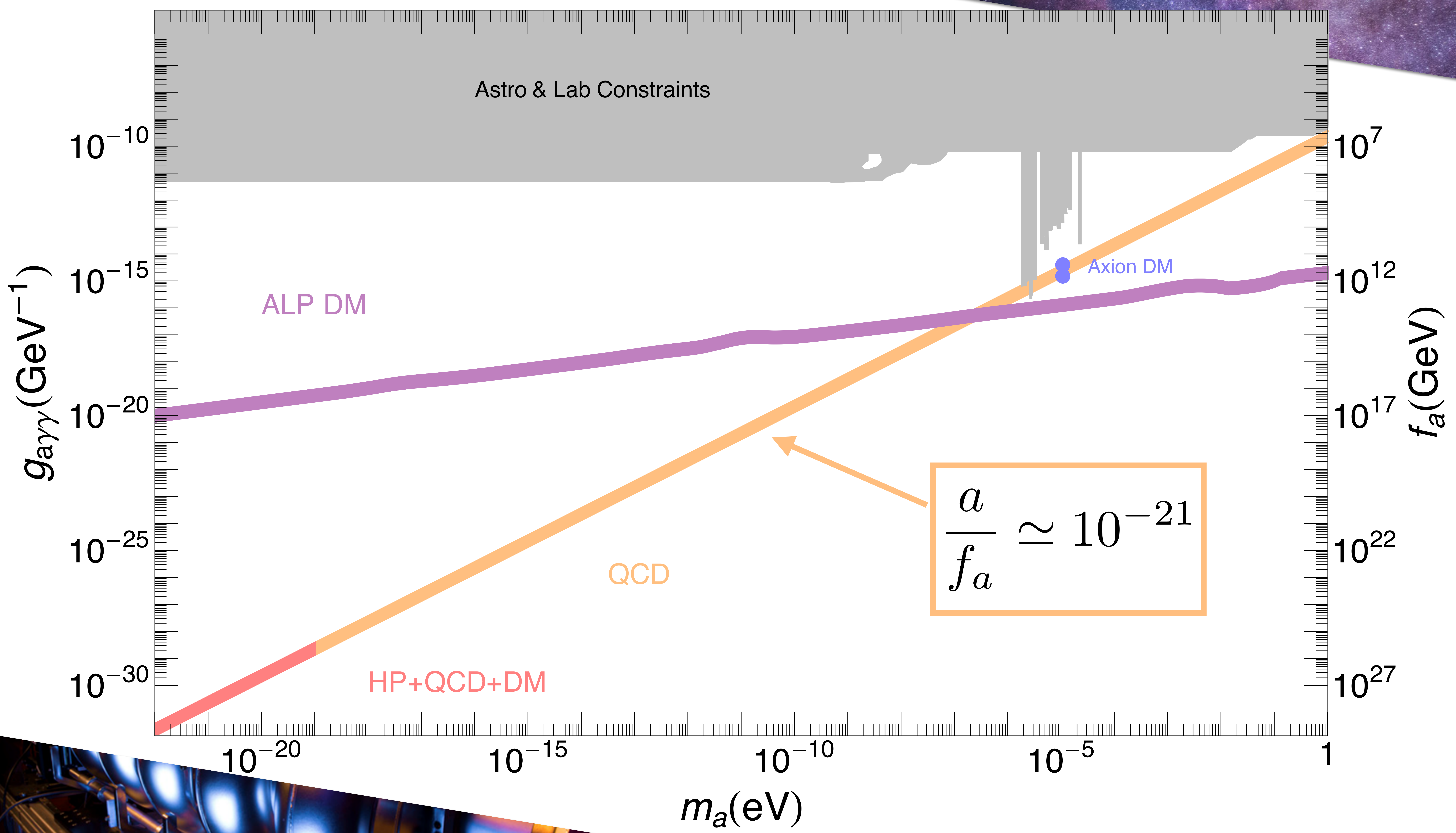
ALP DARK MATTER DETECTION



Background

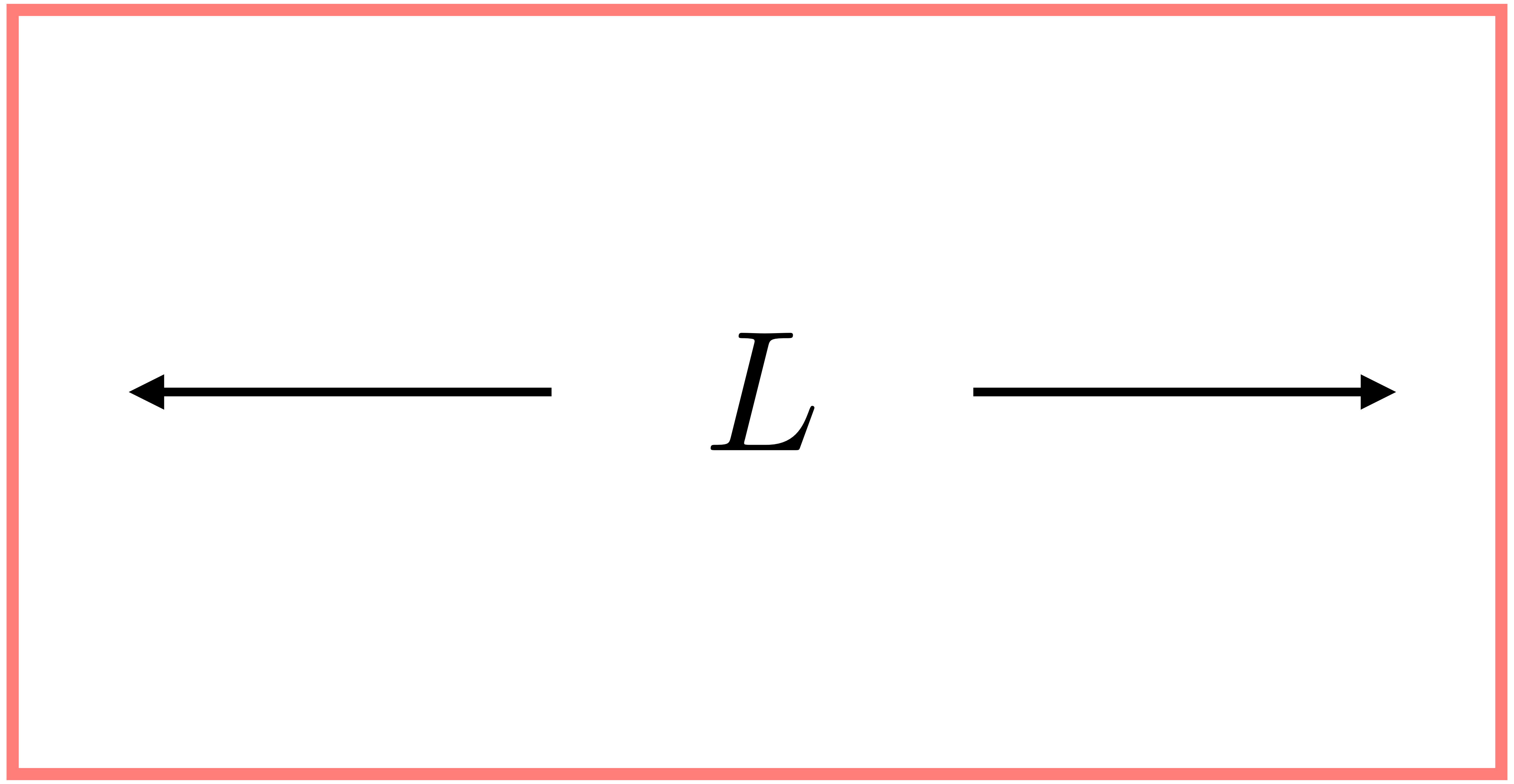
$$\sim \frac{a}{f_a} E_{\rm bkg} \simeq \boxed{10^{-21} E_{\rm bkg}}$$

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



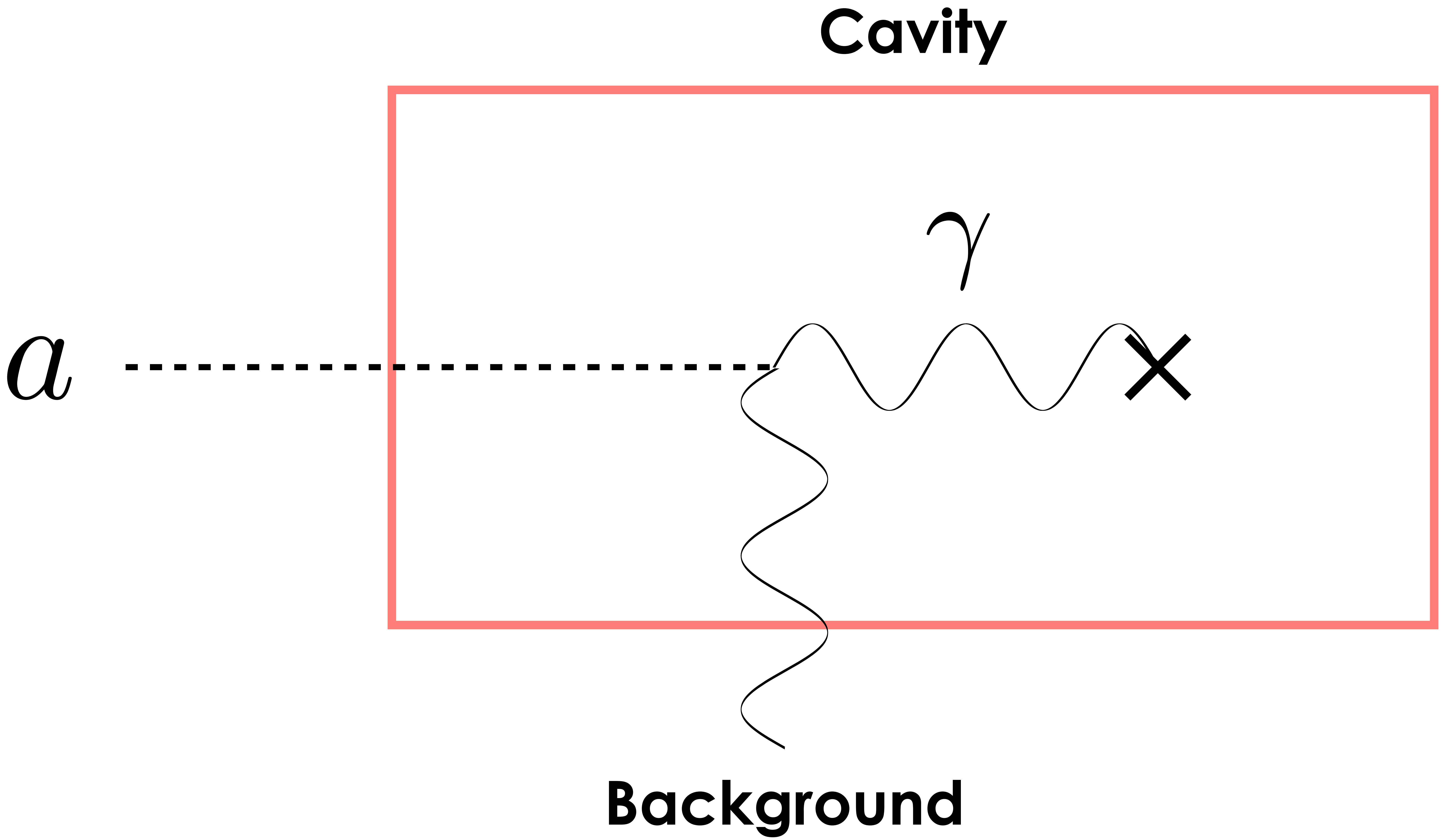
Astro & Lab Constraints
ALP DM
Axion DM
QCD
HP+QCD+DM
$\frac{a}{f_a} \simeq 10^{-21}$
$g_{a\gamma\gamma}(\mathrm{GeV}^{-1})$
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
$f_a(\mathrm{GeV})$
10^{7}
10^{12}
10^{17}
10^{22}
10^{27}
$m_a(\mathrm{eV})$
10^{-20}
10^{-15}
10^{-10}
10^{-5}
1

Cavity



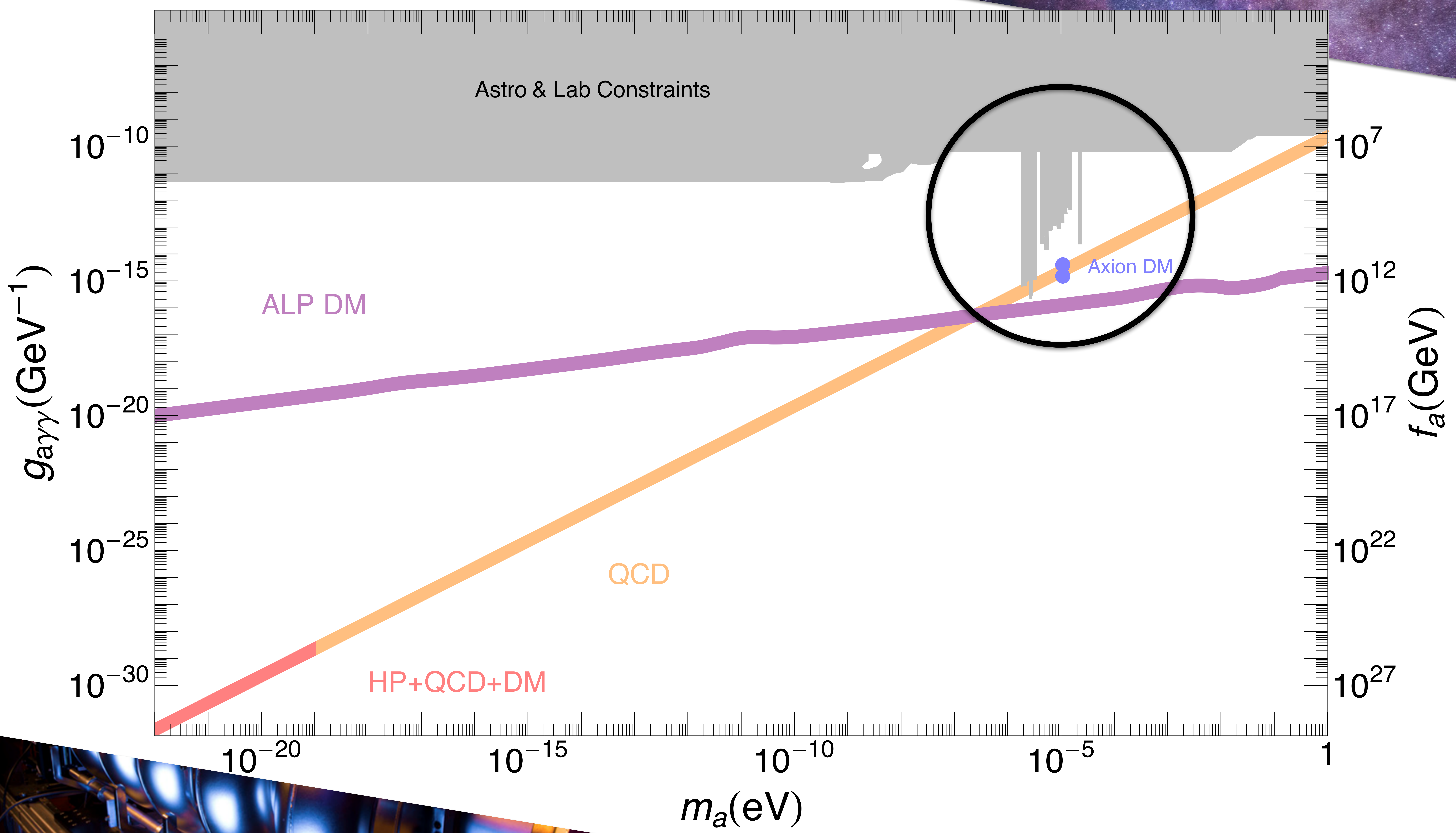
$$m_\gamma \simeq \frac{1}{L}$$

AXION DARK MATTER DETECTION



Resonance

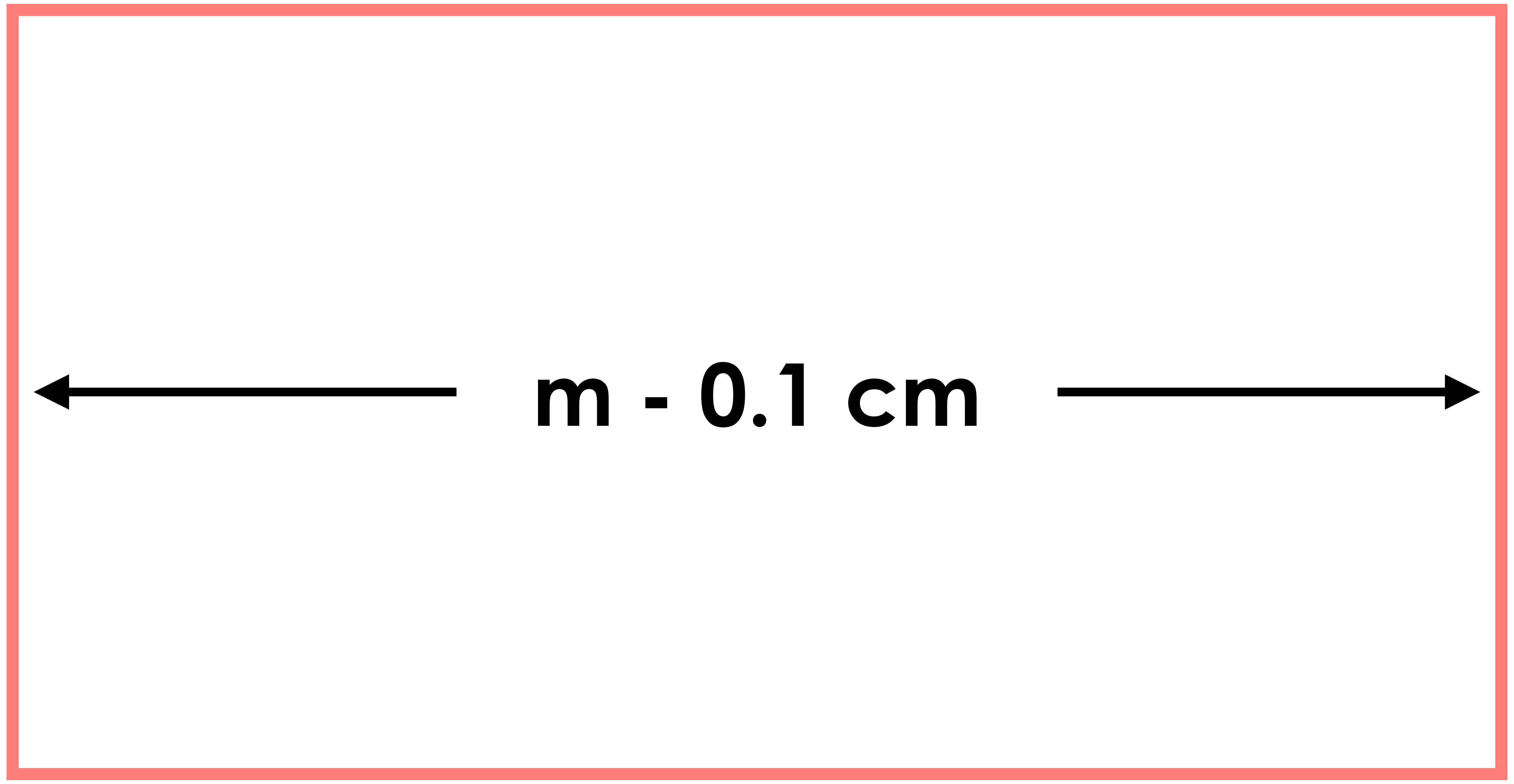
$$m_a \simeq \frac{1}{L}$$



Astro & Lab Constraints
Axion DM
ALP DM
QCD
HP+QCD+DM
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
$g_{a\gamma\gamma}(\text{GeV}^{-1})$
$f_a(\text{GeV})$
$m_a(\text{eV})$

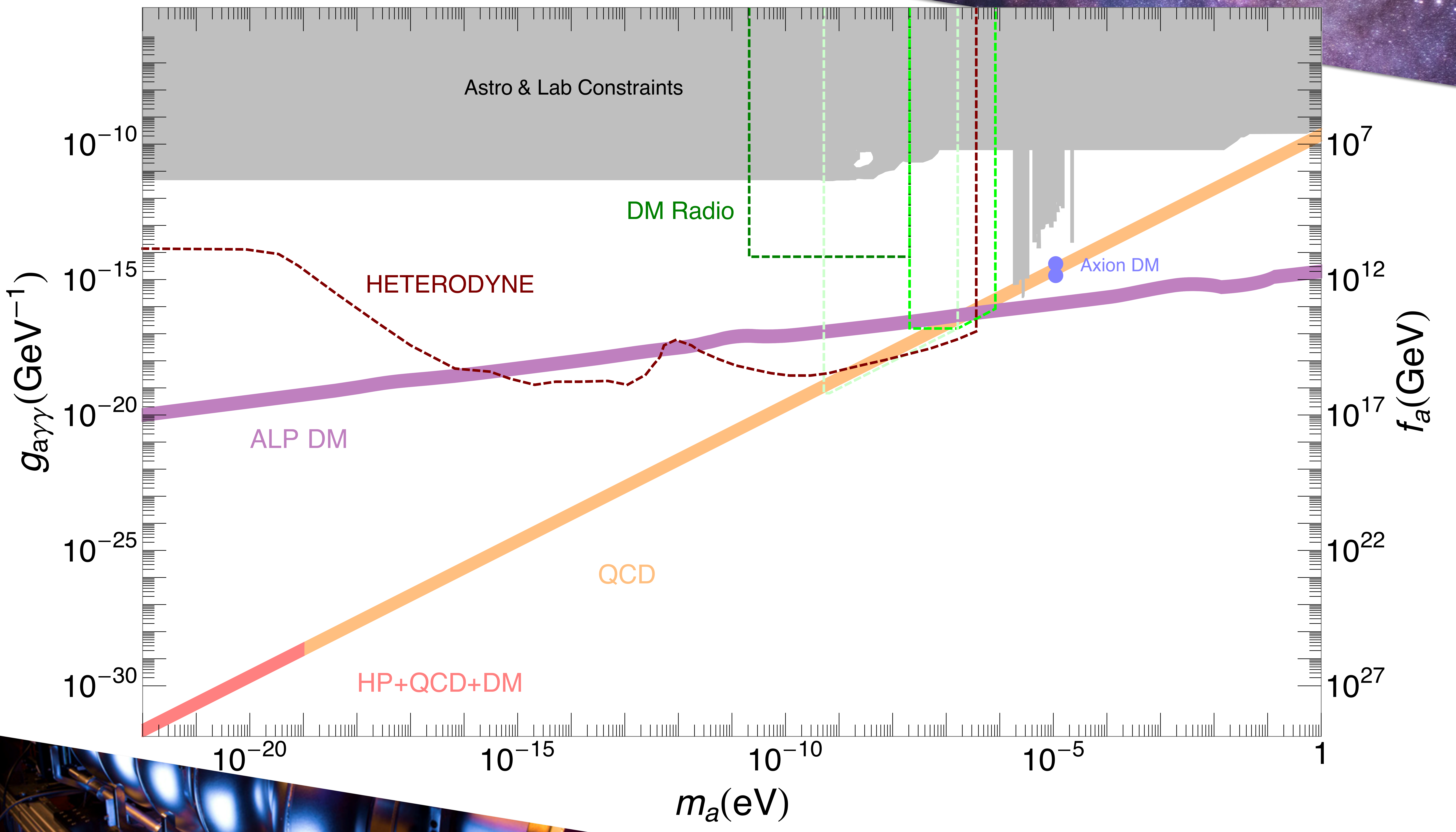
AXION DETECTION

Cavity



Low noise electronics
High quality factors

Astro & Lab Constraints
Impractical
(fine control of
huge cavities)
Axion 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

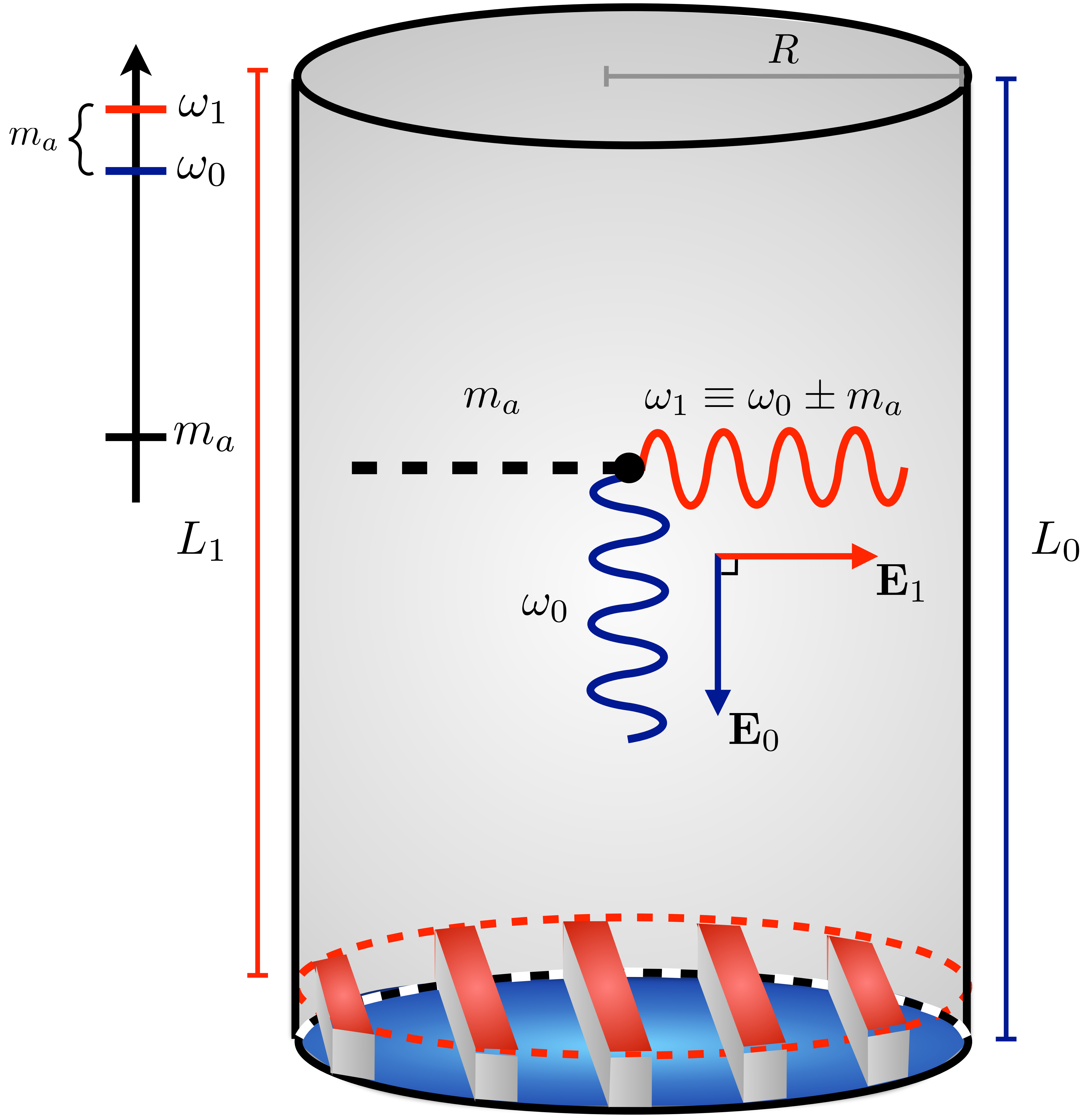


Astro & Lab Constraints
DM Radio
HETERODYNE
Axion DM
ALP DM
QCD
HP+QCD+DM
$g_{a\gamma\gamma}(\mathrm{GeV}^{-1})$
$f_a(\mathrm{GeV})$
$m_a(\mathrm{eV})$
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
10^{7}
10^{12}
10^{17}
10^{22}
10^{27}
10^{-20}
10^{-15}
10^{-10}
10^{-5}
1

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]

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

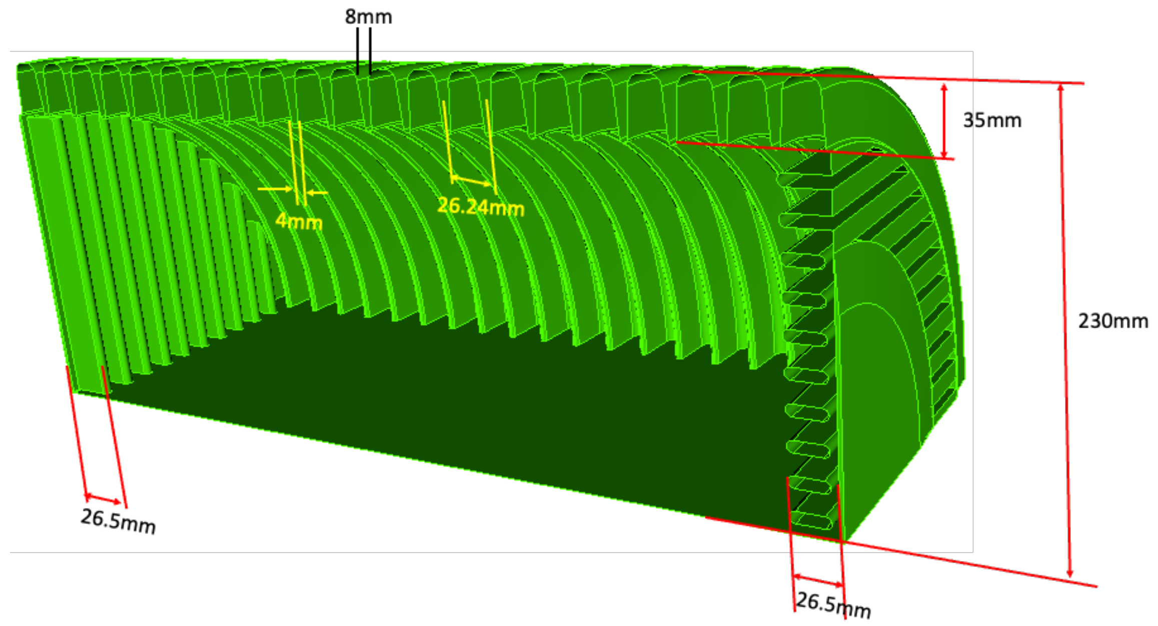
$$\boxed{\partial_t(\mathbf{B}) \simeq i\omega_0\mathbf{B} \qquad \omega_1 \simeq \omega_0 + m_a}$$

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

THREE PROTOTYPES

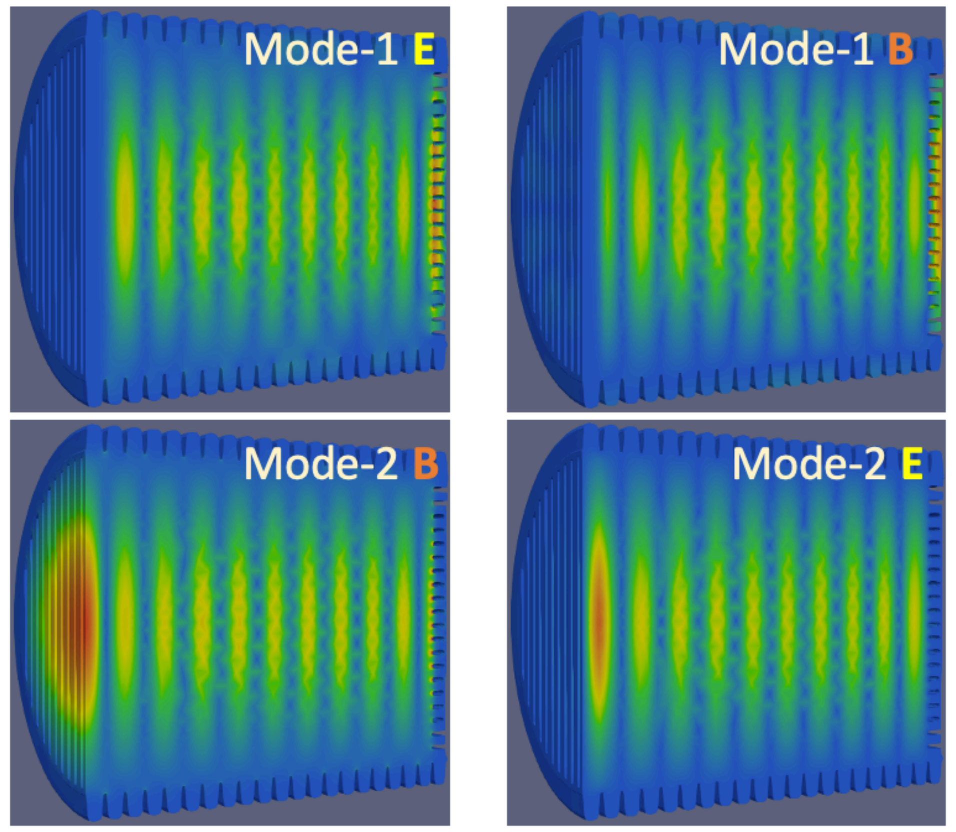
SLAC NATIONAL ACCELERATOR LABORATORY

2507.07173



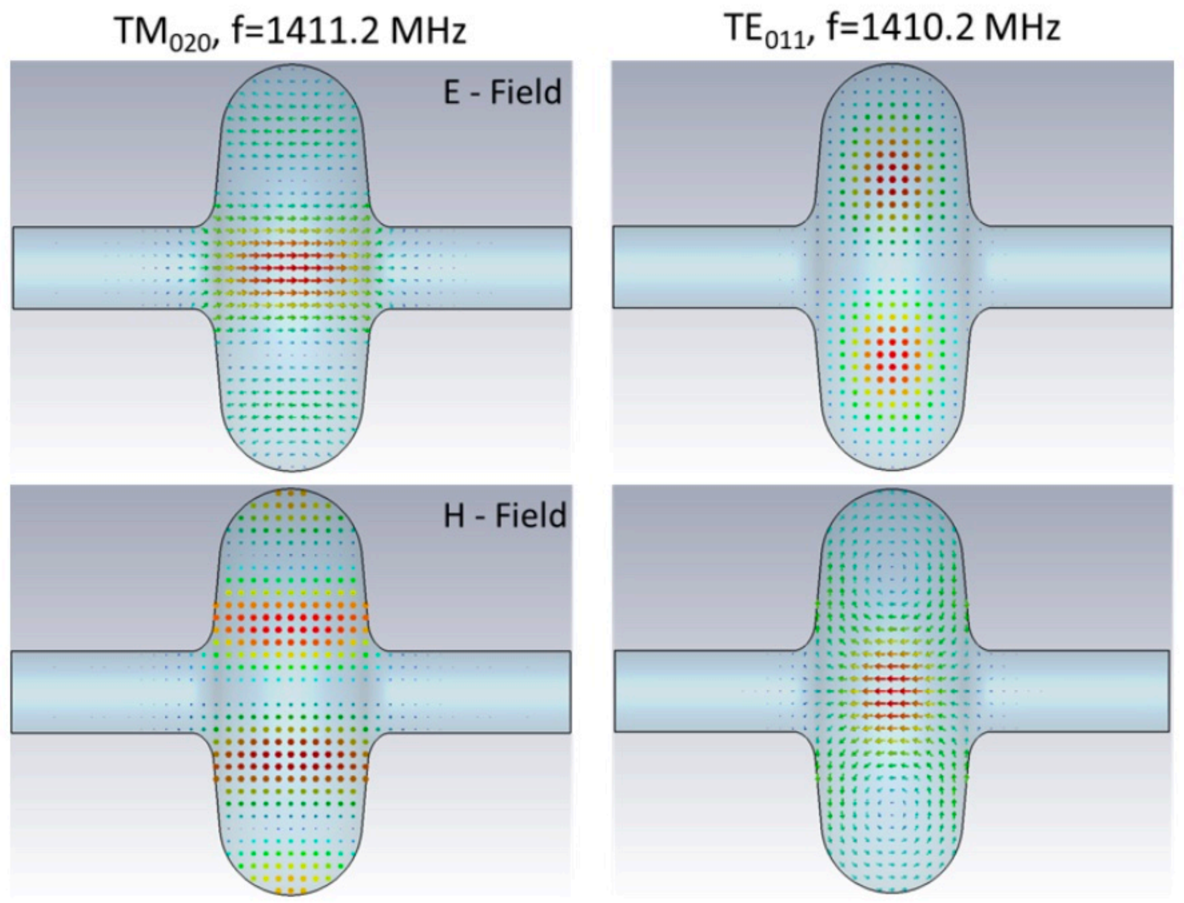
HE11
polatization-1 (E,B)

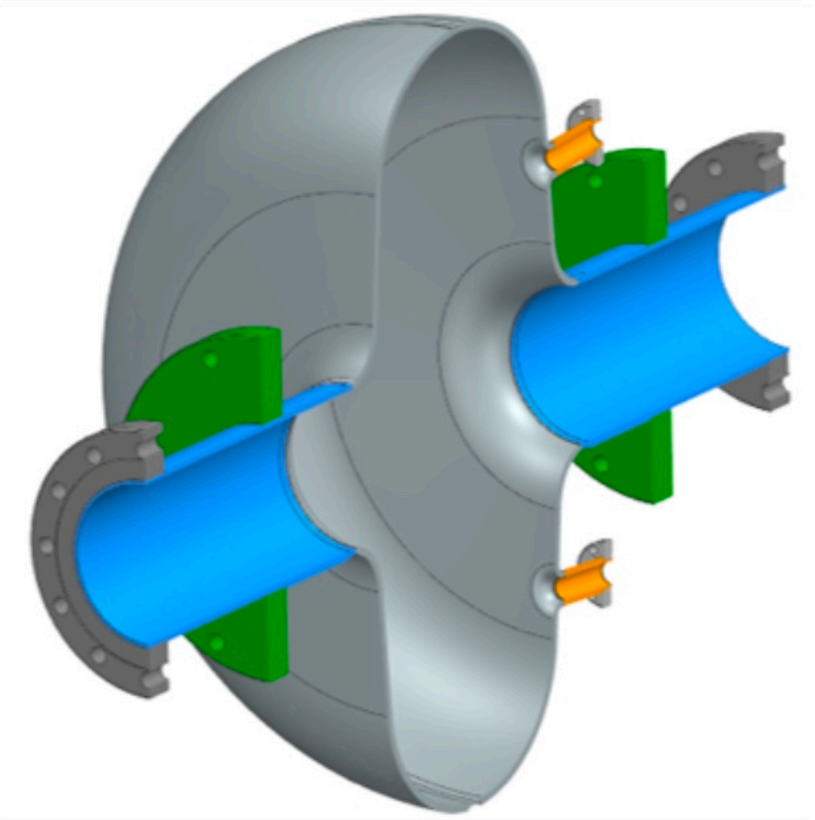
HE11
polatization-2 (B,E)



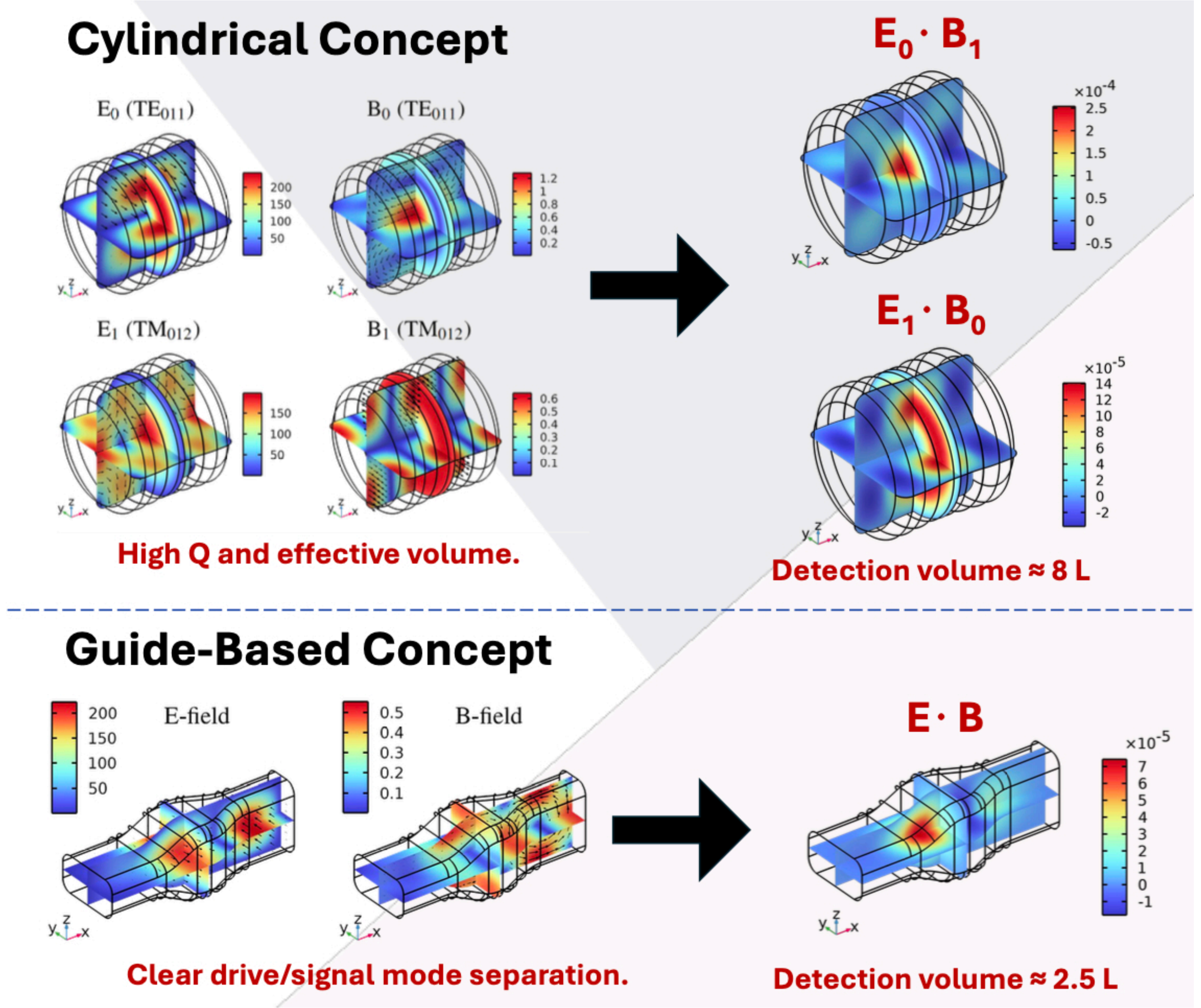
Fermilab

arXiv:2207.11346

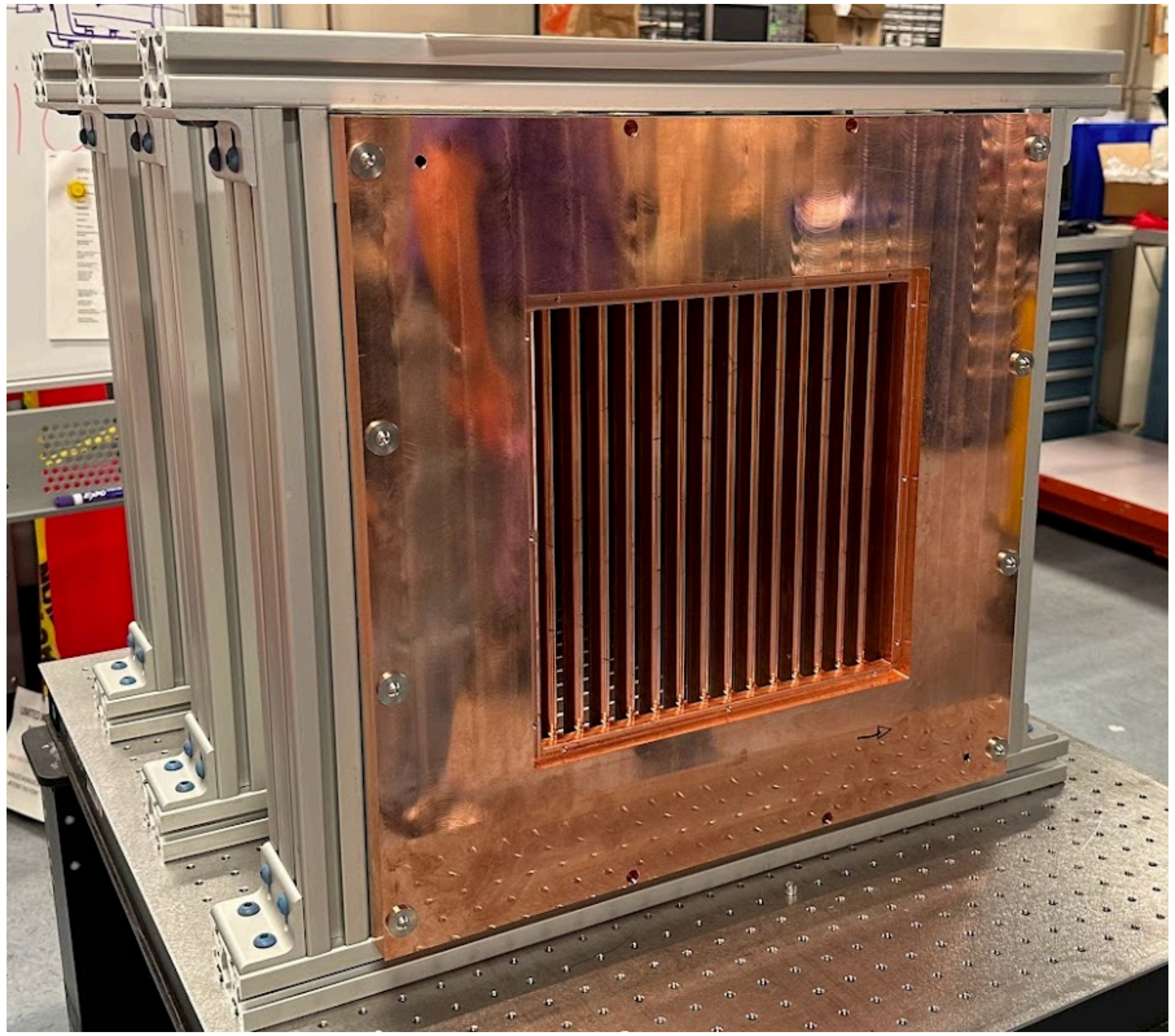


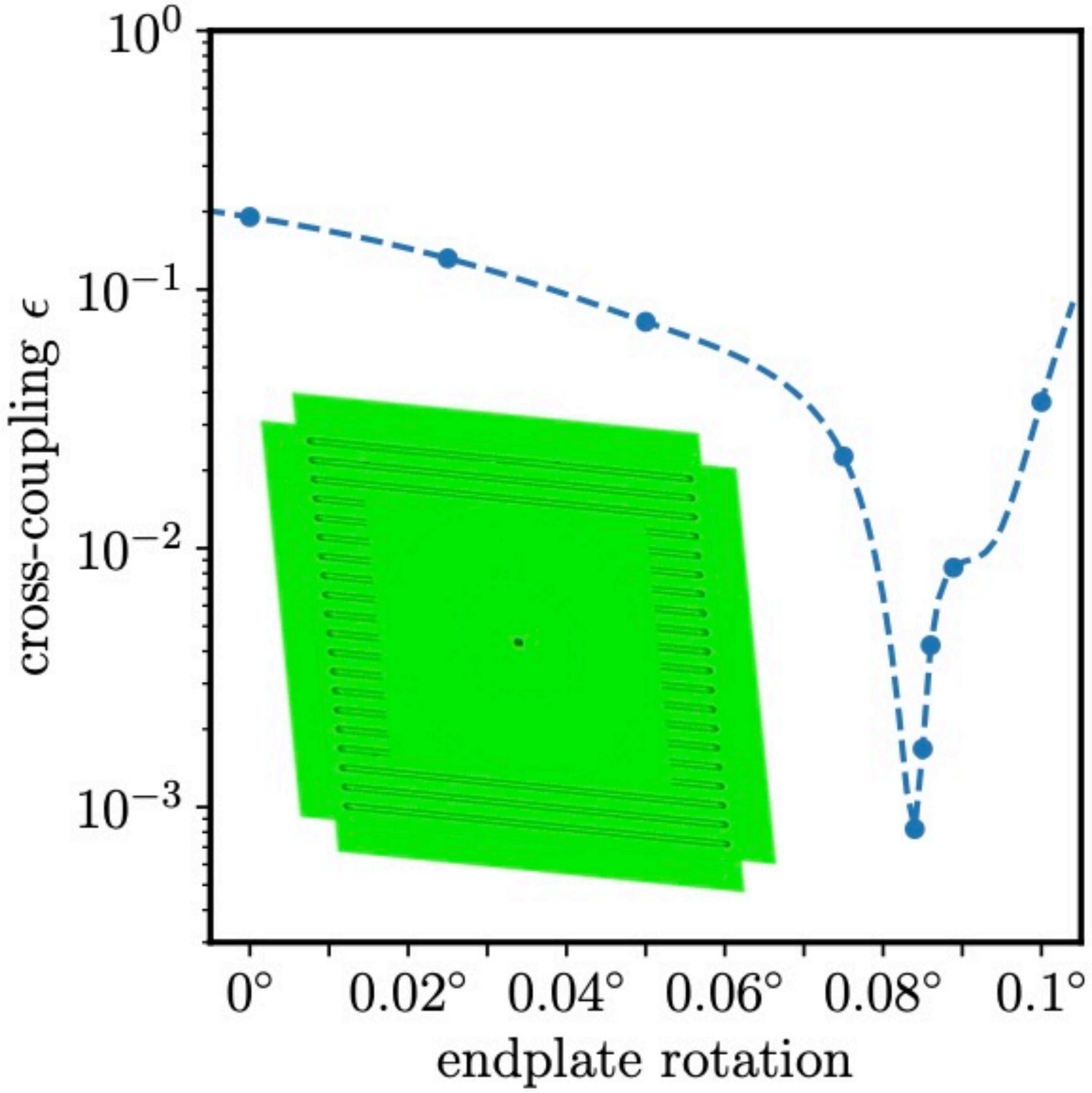


CERN

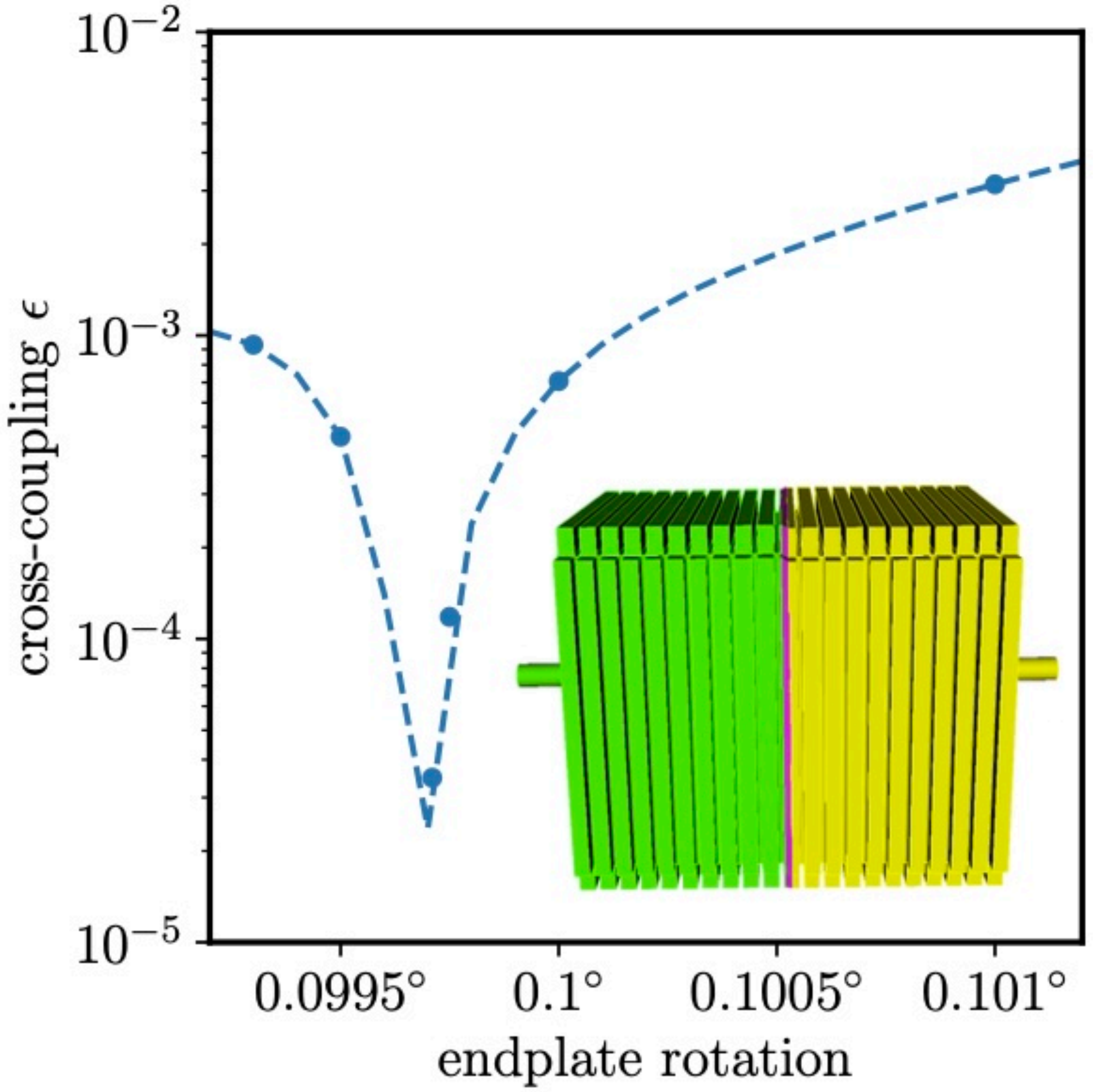


2507.07173

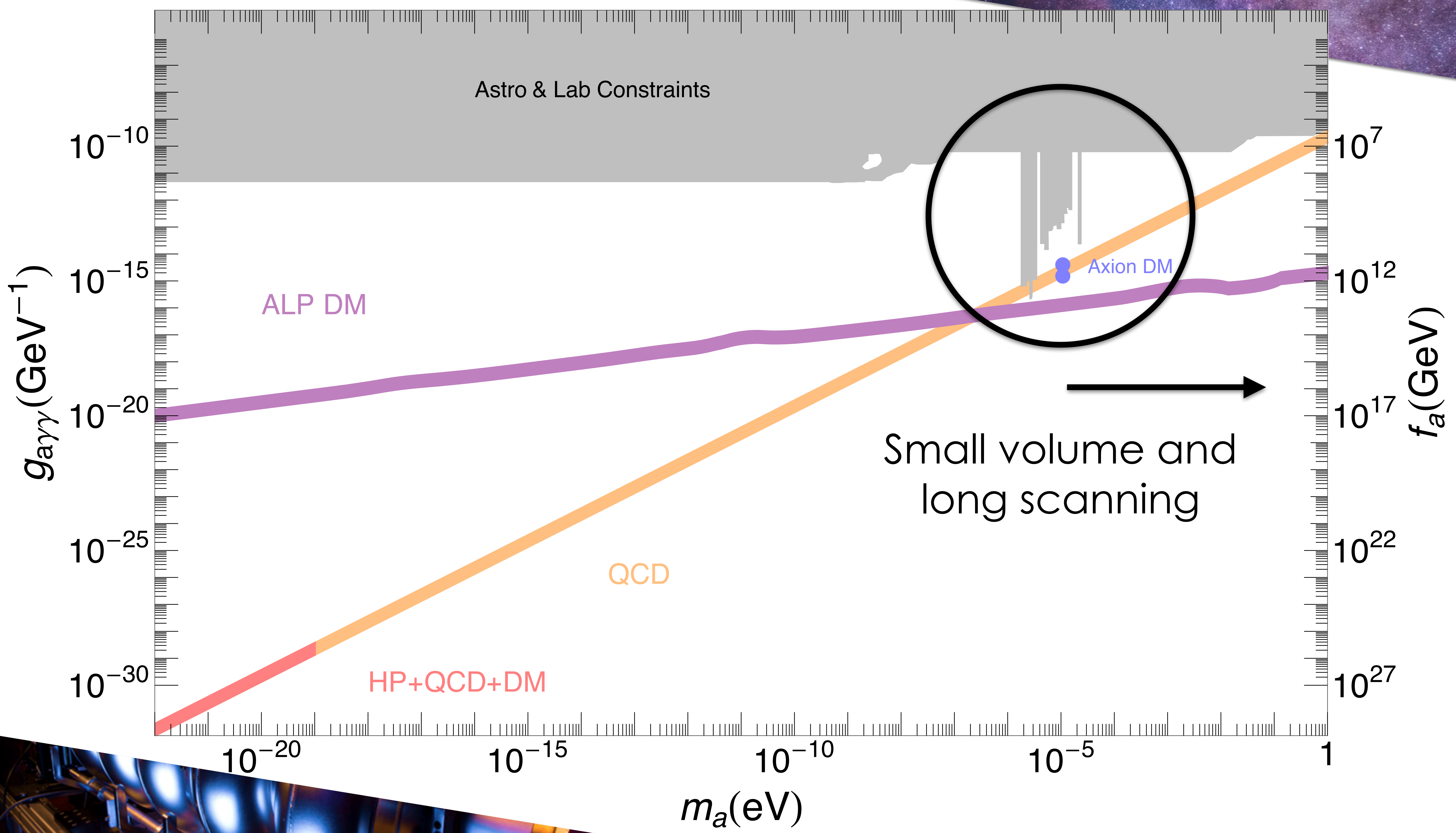




10^0
10^{-1}
10^{-2}
10^{-3}
cross-coupling ϵ
0° 0.02° 0.04° 0.06° 0.08° 0.1°
endplate rotation



10^{-2}
10^{-3}
10^{-4}
10^{-5}
cross-coupling ϵ
0.0995° 0.1° 0.1005° 0.101°
endplate rotation



Small volume and
long scanning

MANY MORE COMING SOON

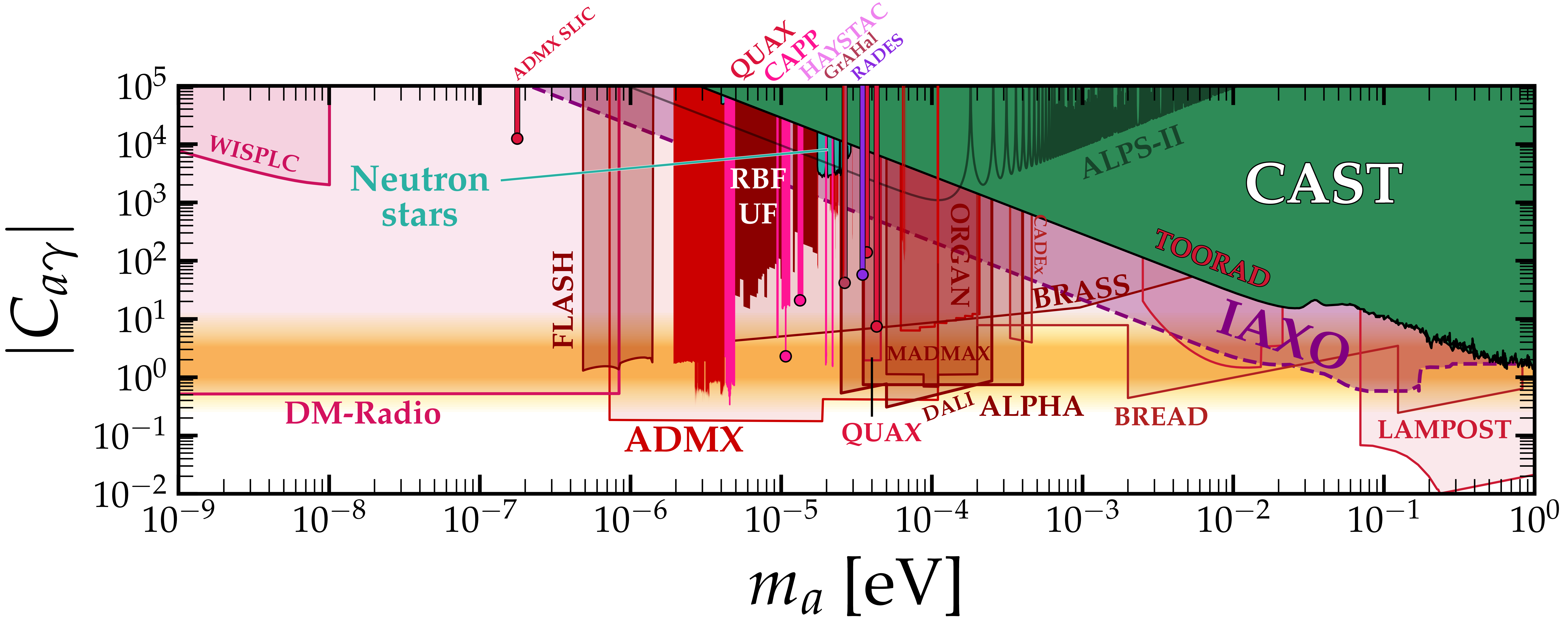
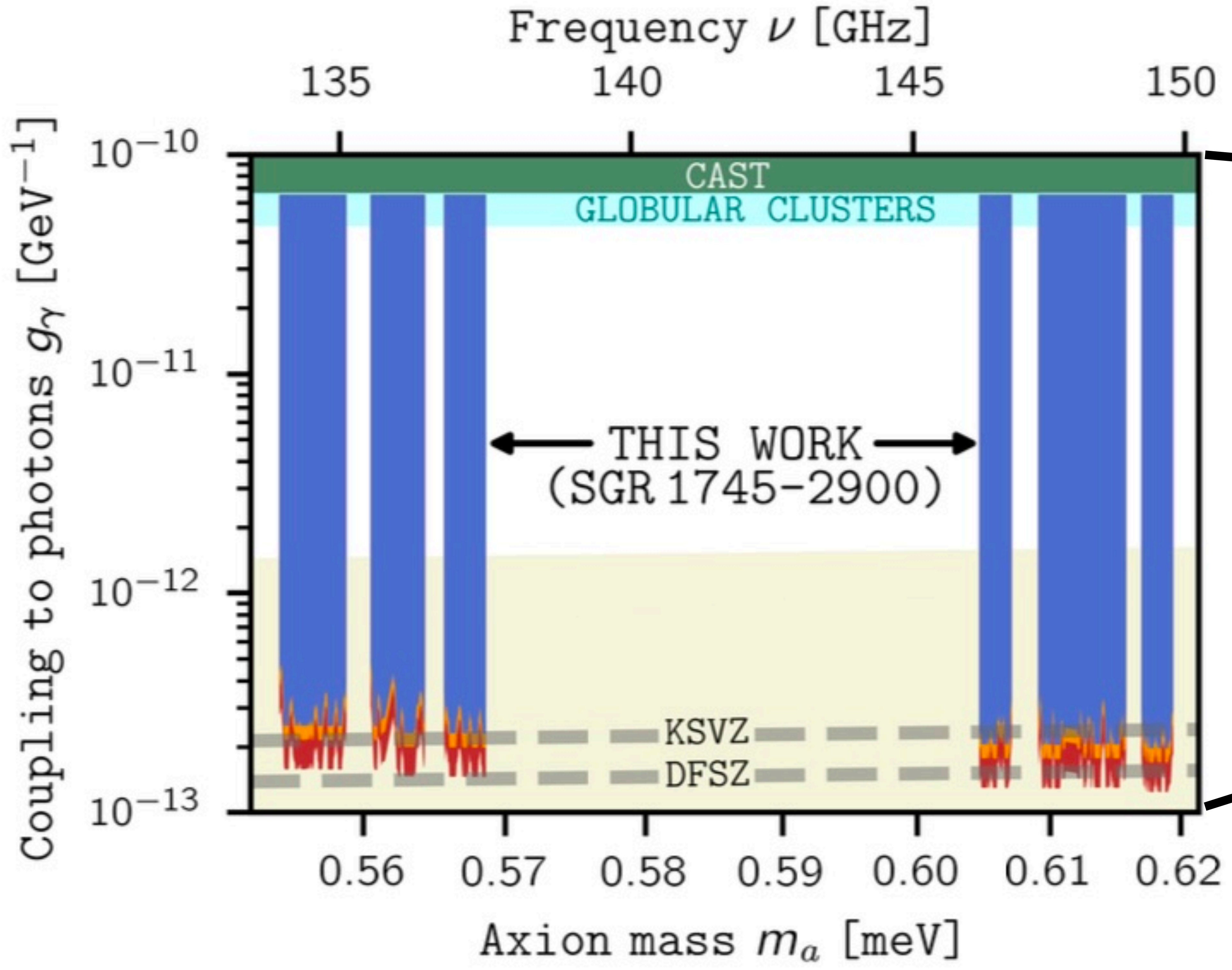


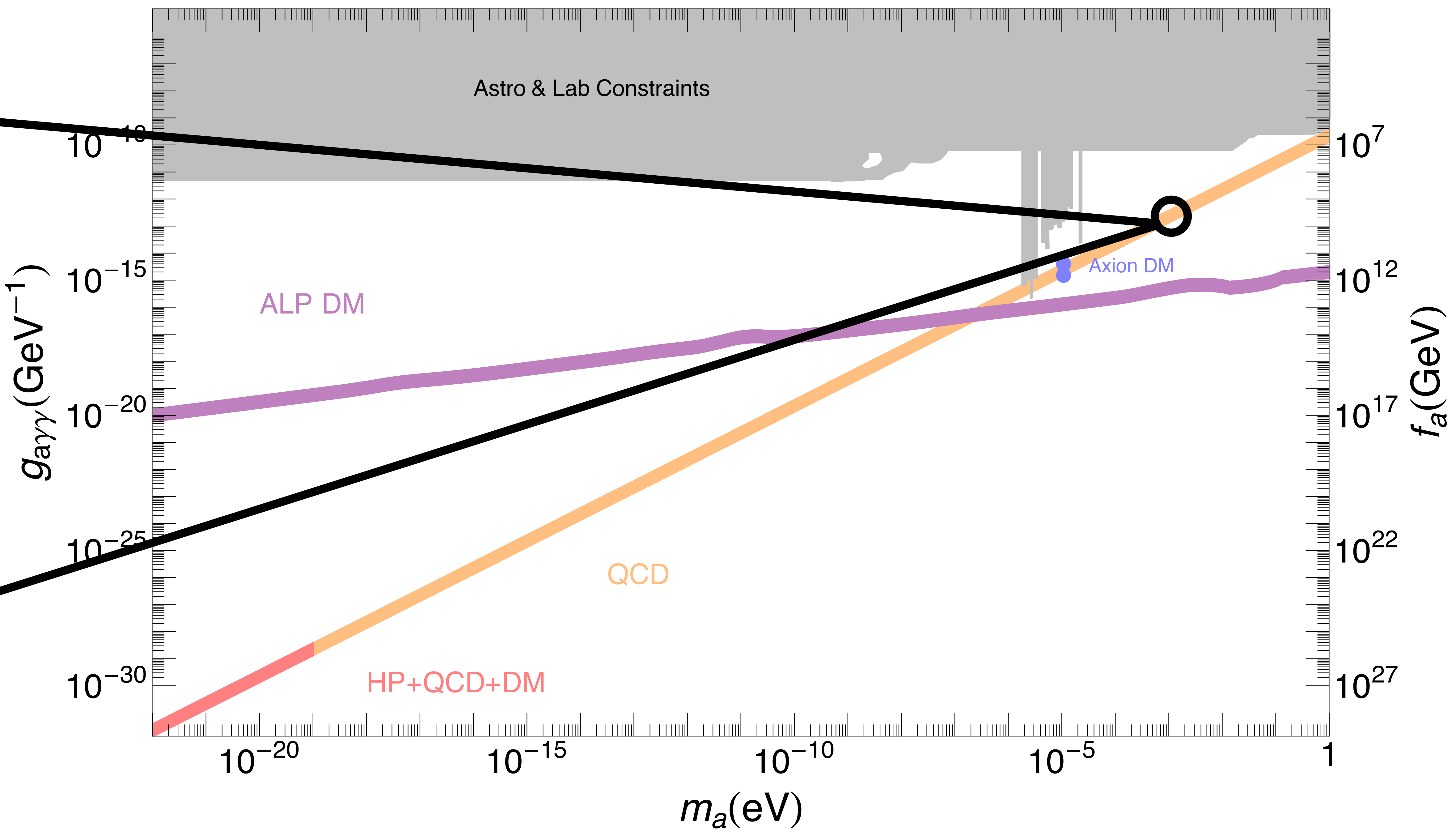
Figure from PDG and C. O'Hare

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


NEWS FROM
ASTROPHYSICS

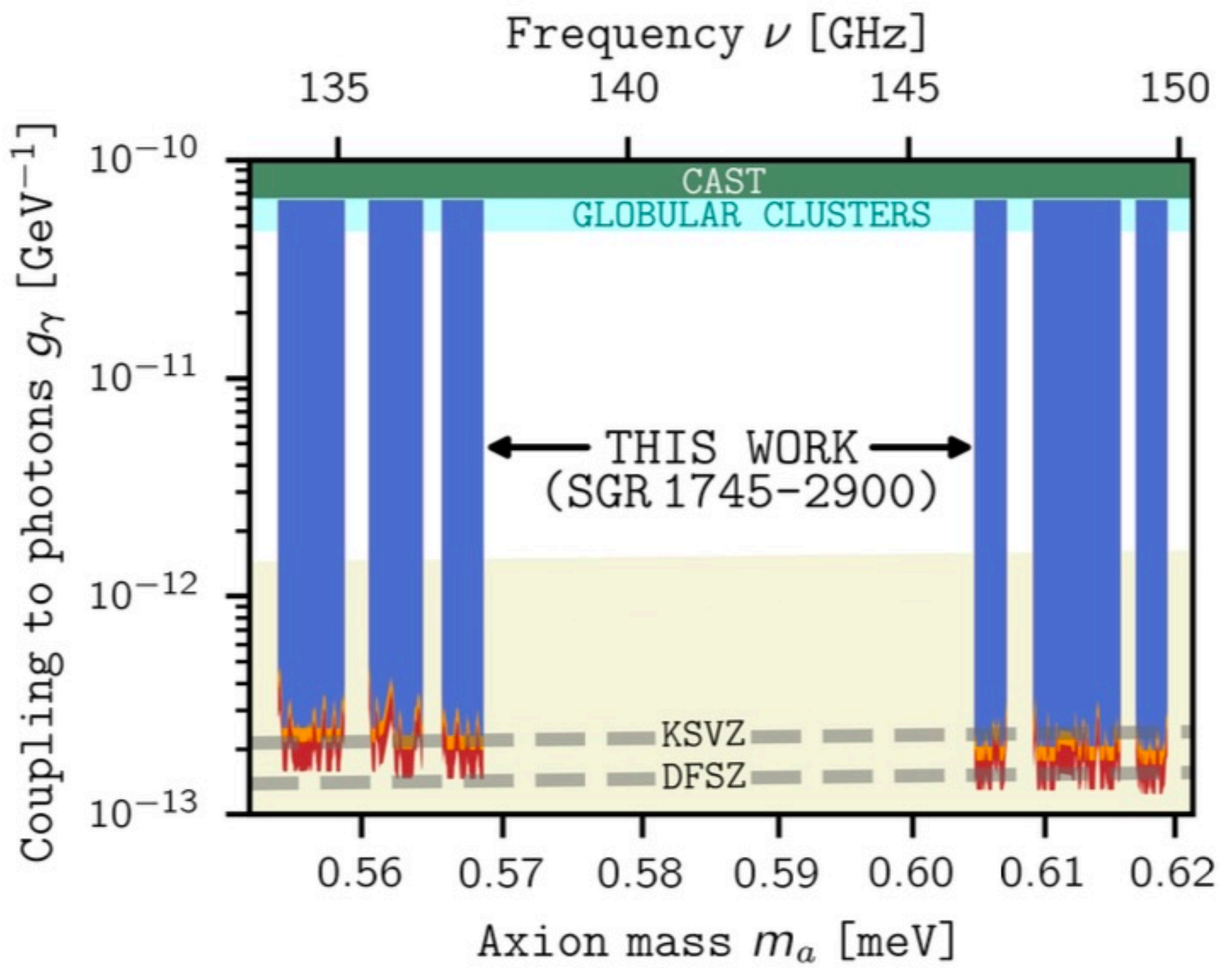
MAGNETARS
arXiv:2512.06441



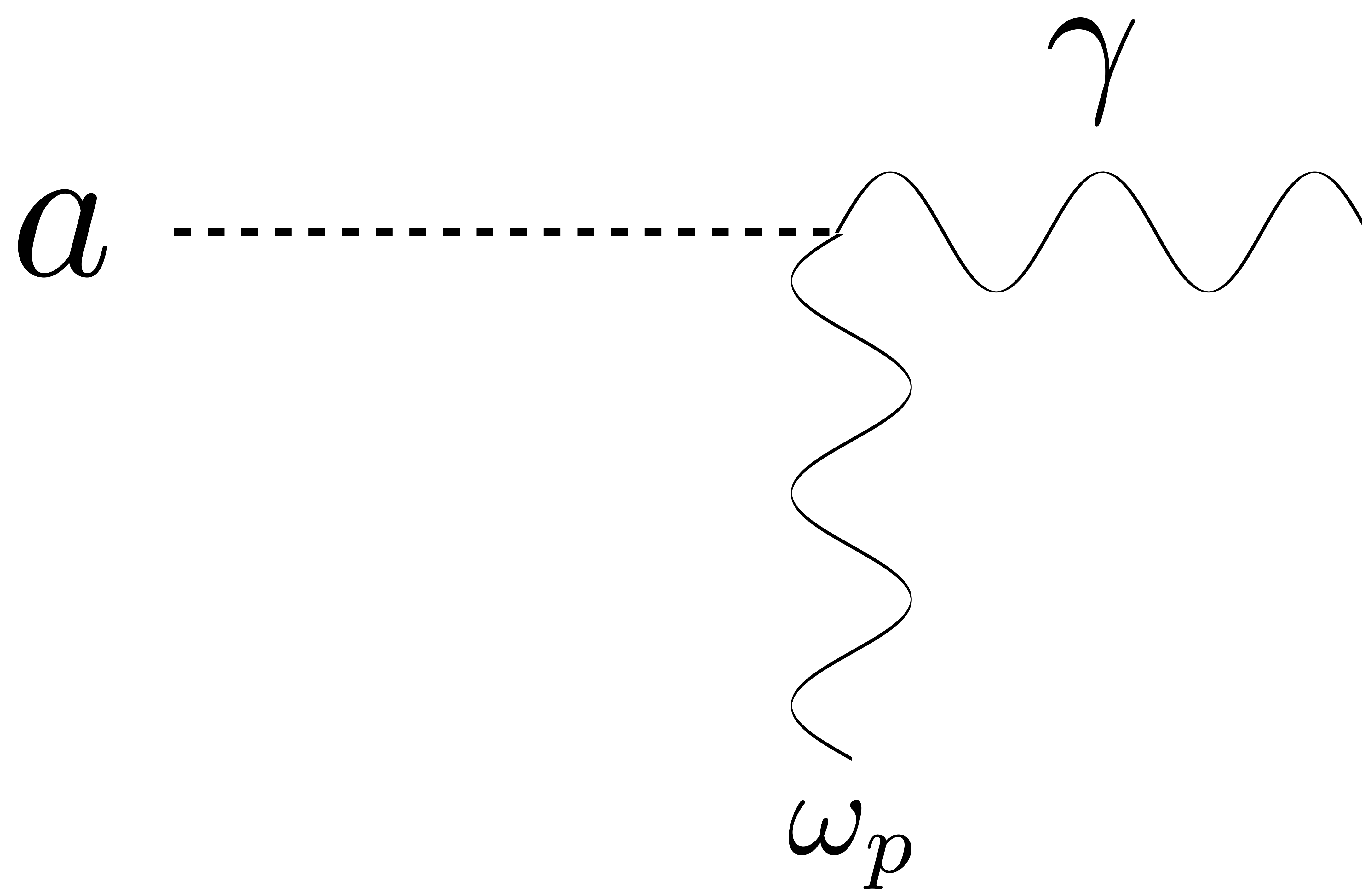


MAGNETARS

arXiv:2512.06441



Radio band



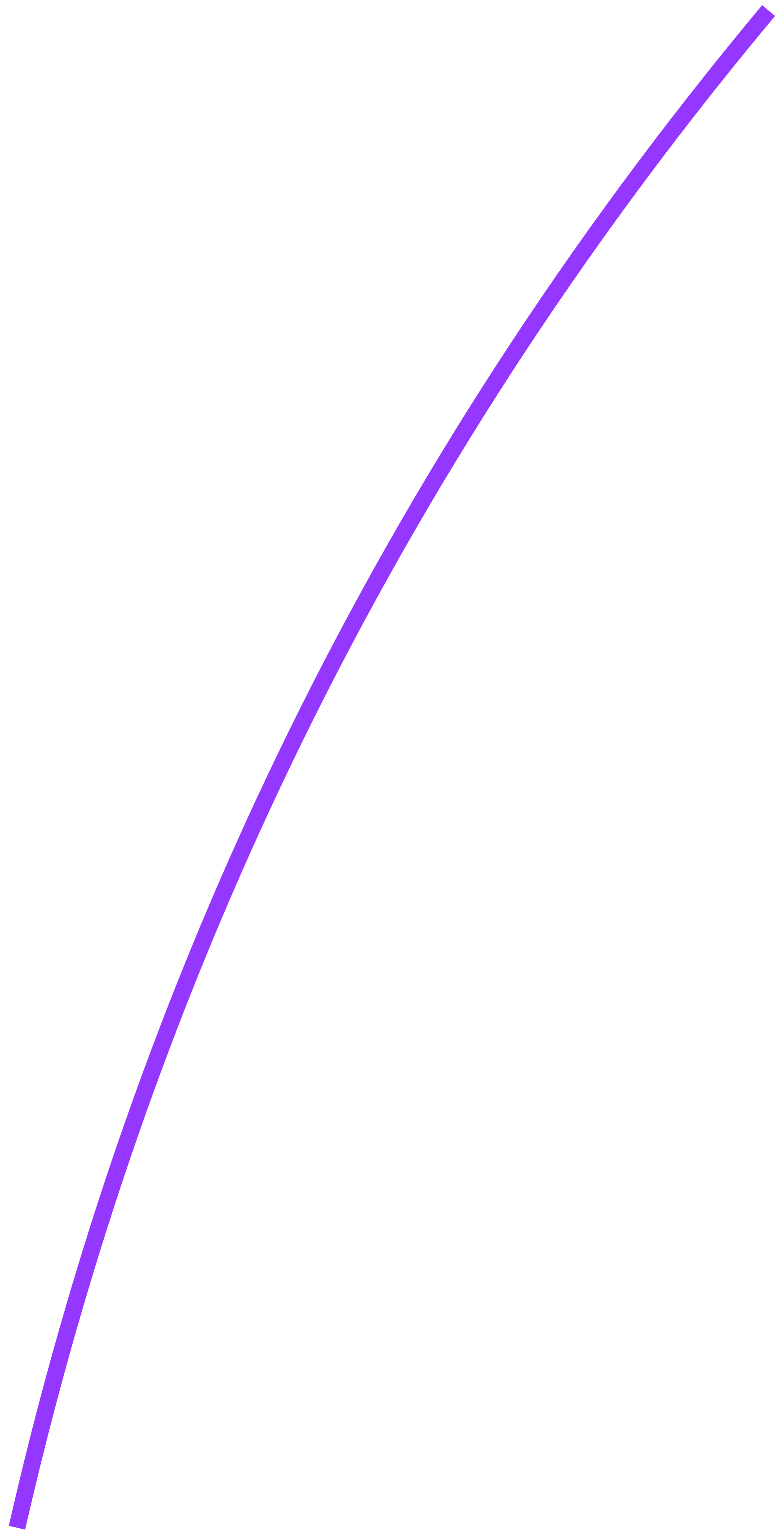
MAGNETAR

$B \simeq 10^{11}$ T

$d \simeq 10$ km

CMB POLARIZATION

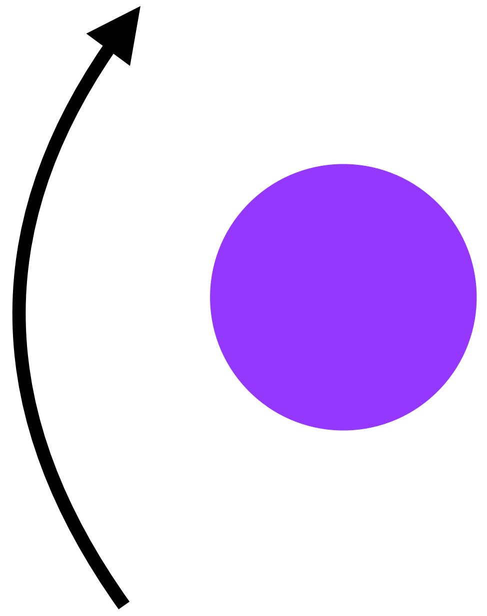
arXiv:1912.02823
arXiv:2205.13962



Axion string

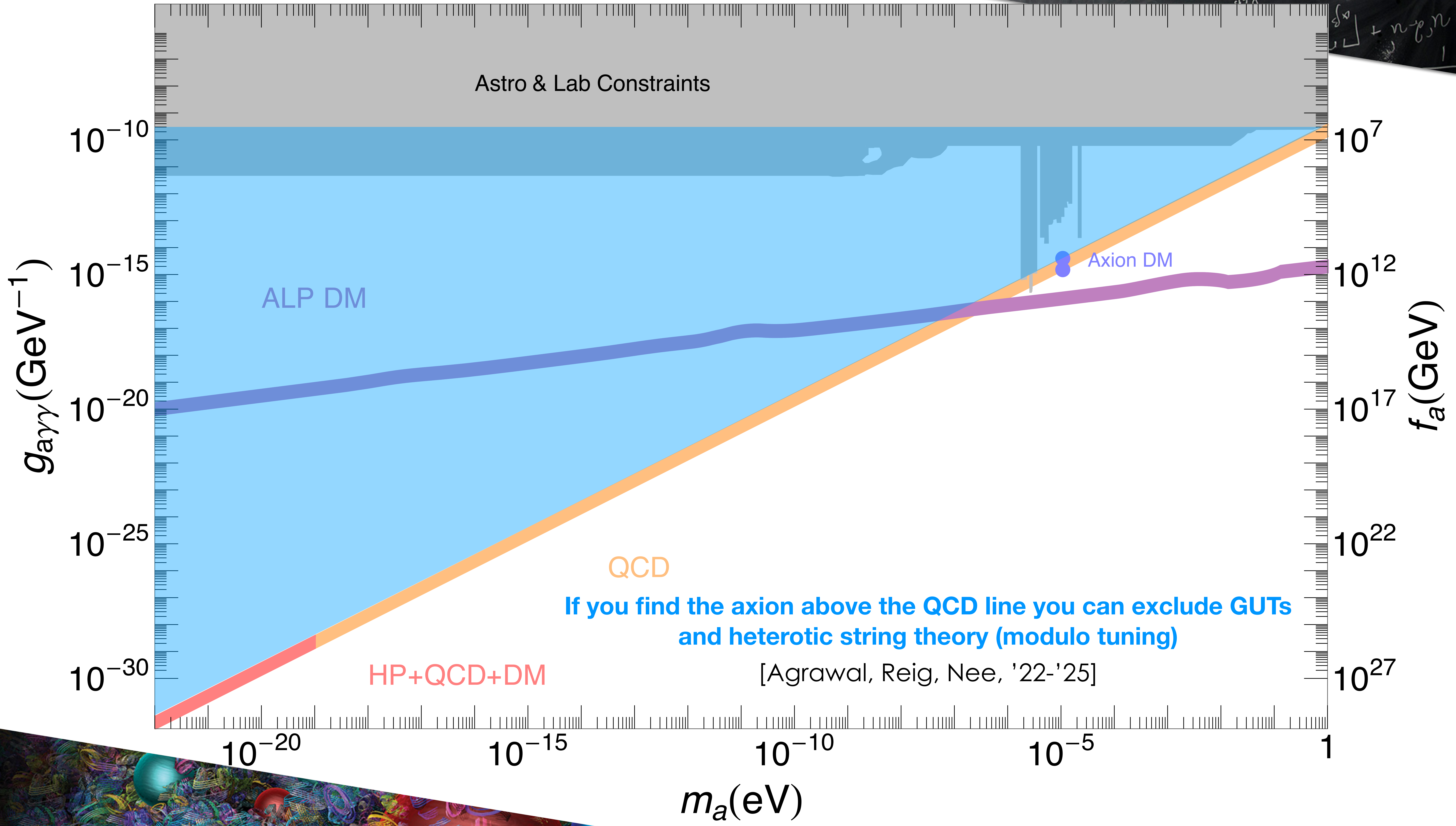
$$\mathcal{A}_{\mathrm{EM}} \frac{\alpha}{4\pi} \frac{a}{f_a} \mathbf{E} \cdot \mathbf{B}$$

$$\Delta \Phi = \pm \mathcal{A}_{\mathrm{EM}} \alpha$$



$$\Delta a = 2\pi f_a$$

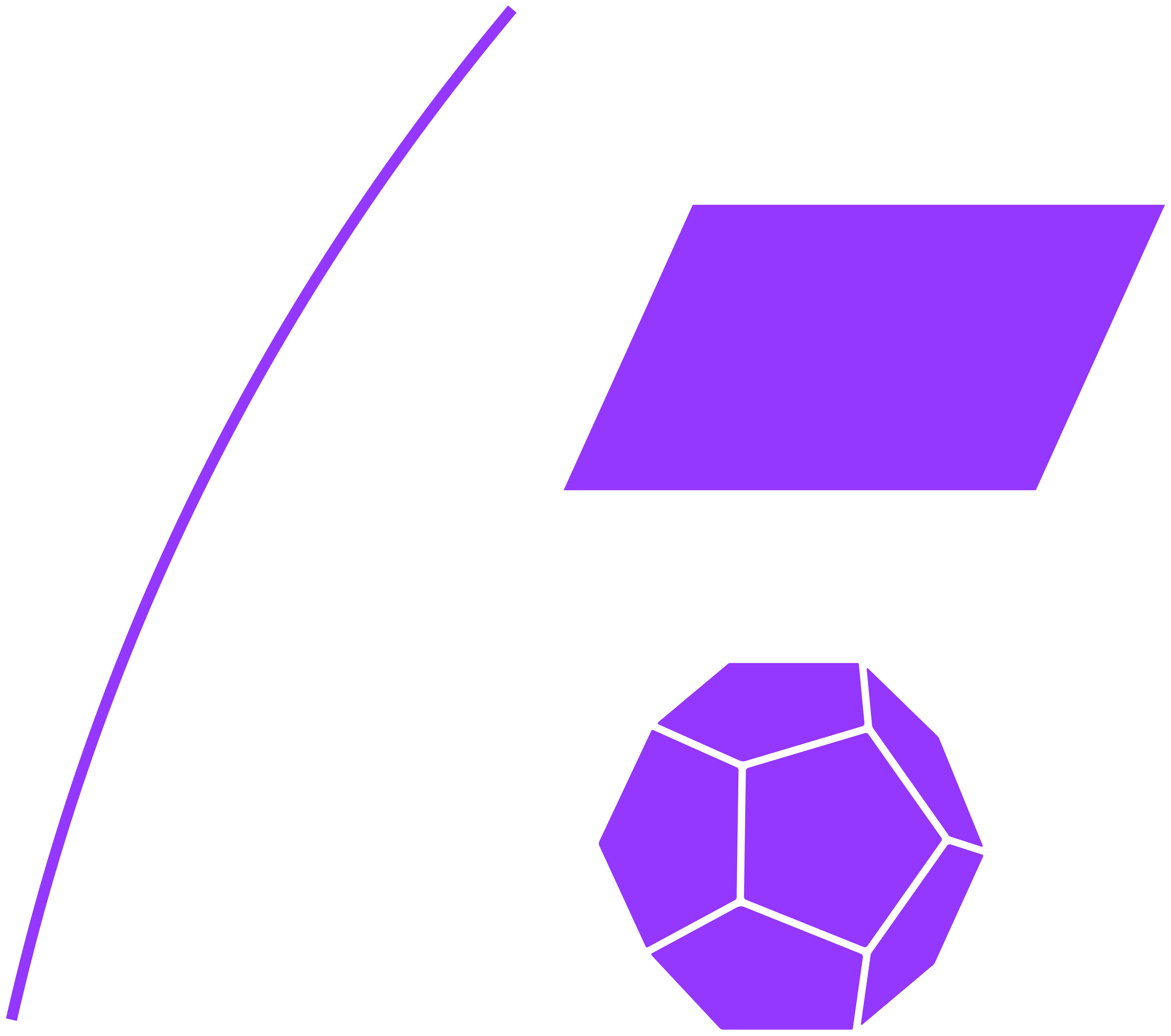
AXION THEORY



Astro & Lab Constraints
ALP DM
Axion DM
QCD
If you find the axion above the QCD line you can exclude GUTs and heterotic string theory (modulo tuning)
[Agrawal, Reig, Nee, '22-'25]
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

ASK ME FOR MORE

Higher-form symmetries



Axions and the eta’

$$\frac{\alpha_s}{2\pi}\frac{a}{f_a}G\widetilde{G}$$

$$\downarrow$$

$$V_{\eta'} = c f_\pi^2 \Lambda_{\mathrm{QCD}}^2 H(\det U) + \mathrm{h.c.}$$

$H(\cdot)$ is unknown

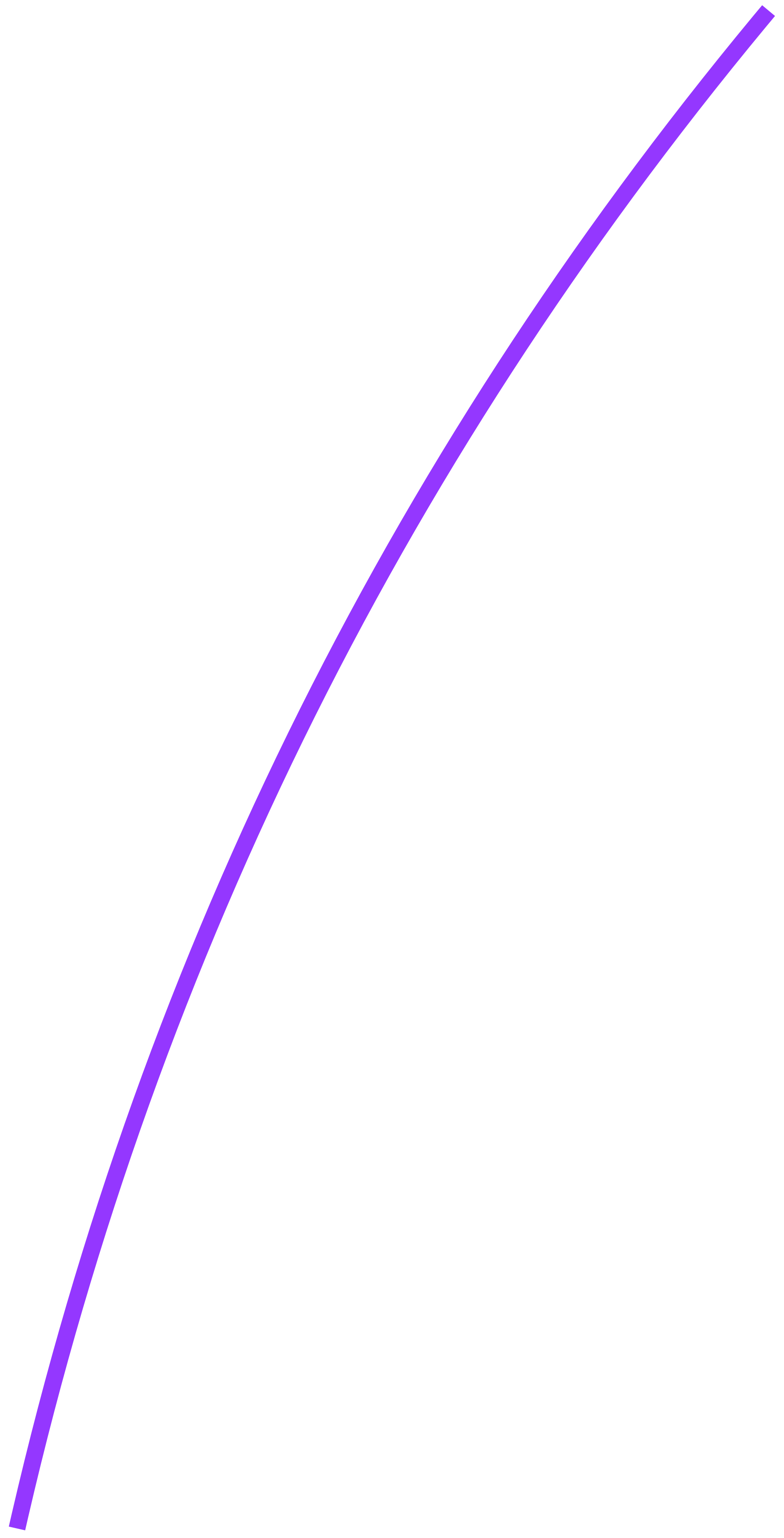
CONCLUSION

- 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 couple of decades
- Axions are unique probes of the deep UV (and allow theorists to endlessly disagree)

BACKUP

CMB POLARIZATION

arXiv:1912.02823
arXiv:2205.13962



Axion string

$$\rho \simeq f_a^2 H^2$$

Like radiation during RD
Like matter during MD

Behavior from simulation, normally

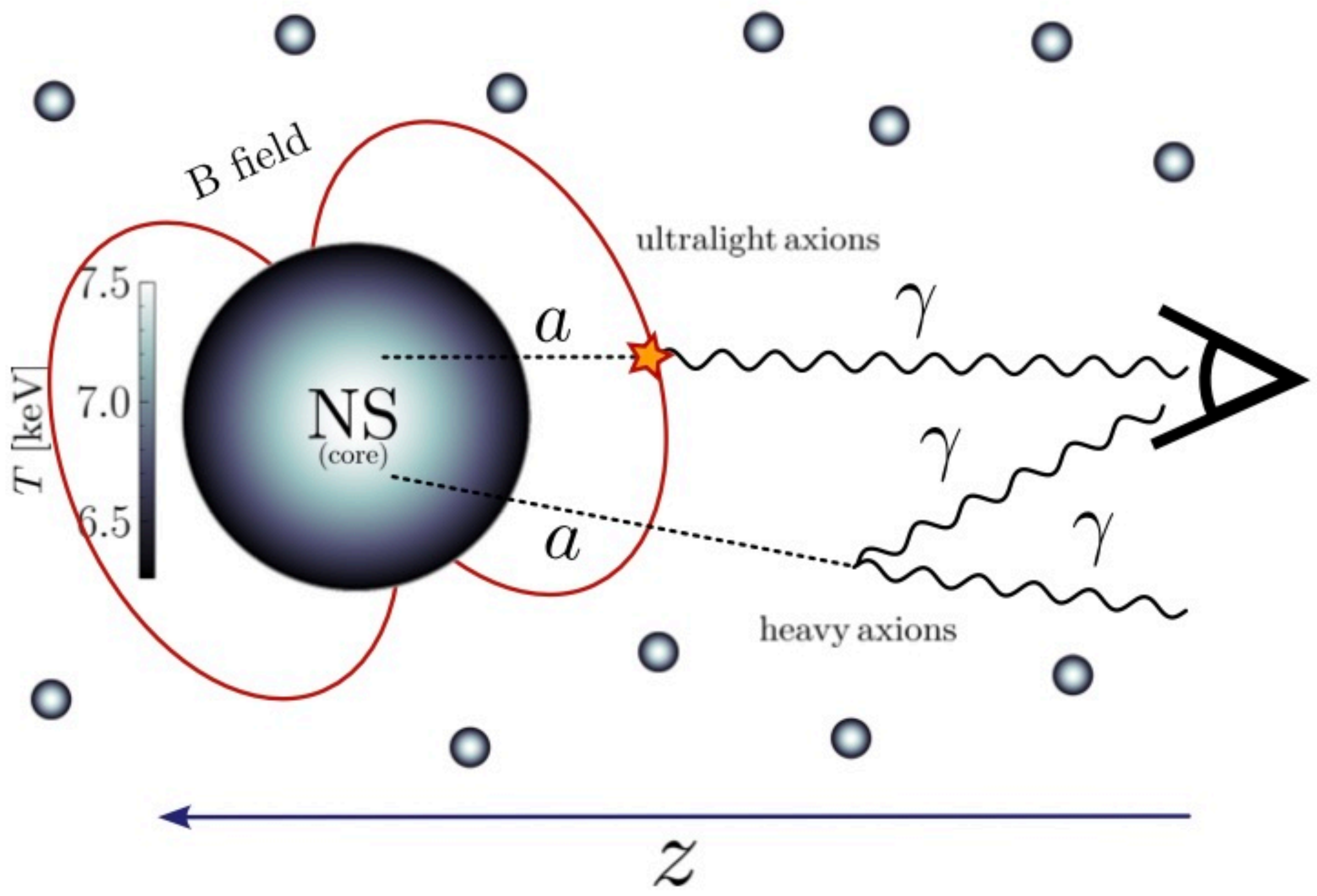
$$\rho \sim a^{-2}$$

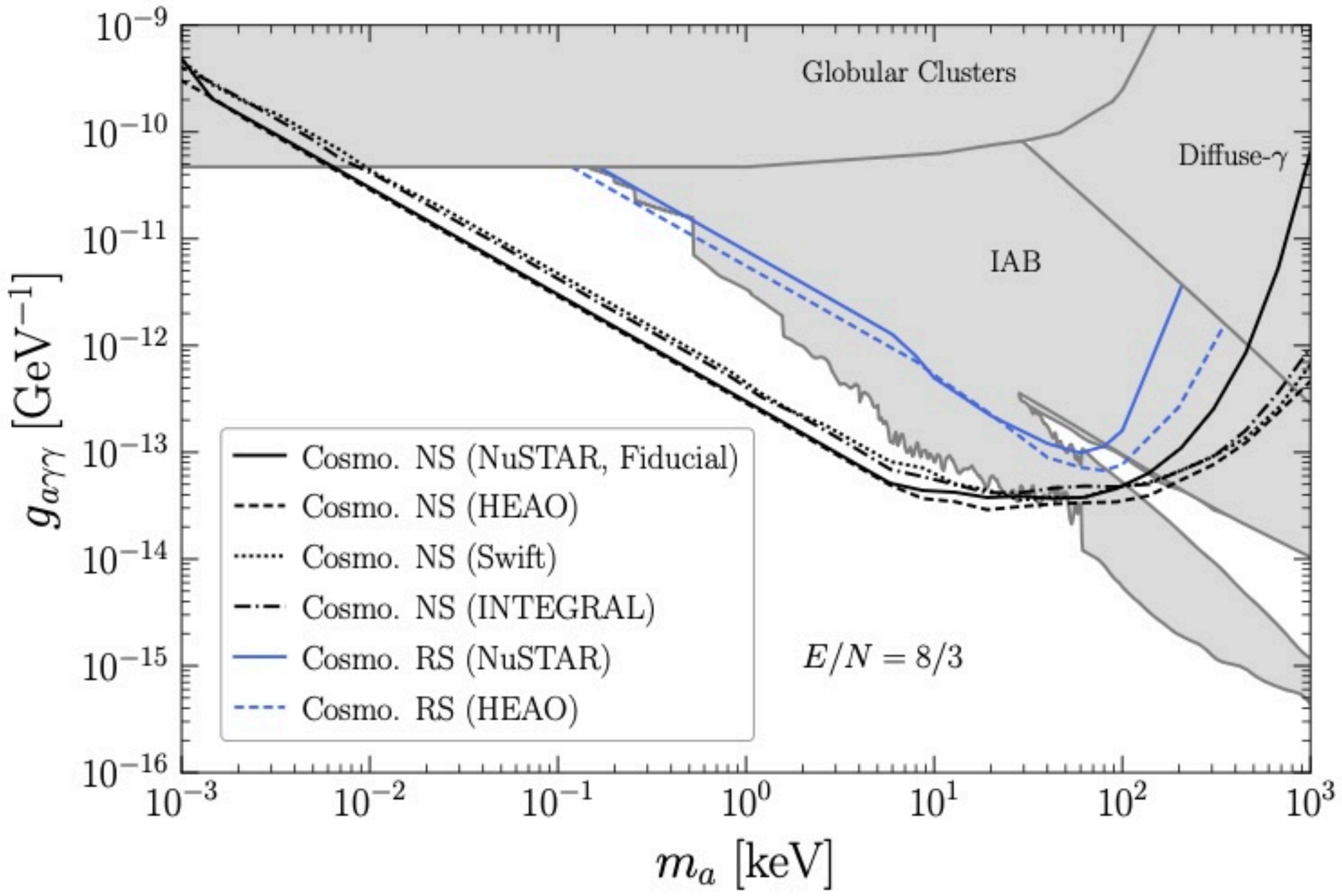
$$m_a \lesssim H$$

Otherwise domain walls destroy the network (if NDW=1)
Or create a DW problem (NDW>1)

NEUTRON STARS

arXiv:2512.15849





$U(1)_A$ IN THE CHIRAL LAGRANGIAN

$$U = e^{i \frac{\eta'}{f_\eta} \frac{\pi^a \lambda^a}{2 f_\pi}}$$

$U(1)_A$ IN THE CHIRAL LAGRANGIAN

$$\mathcal{L} = \frac{f_\pi^2}{4}\mathrm{Tr}[(\partial_\mu U)^\dagger \partial^\mu U)] + V_\pi + V_{\eta'} + \ldots$$

$U(1)_A$ IN THE CHIRAL LAGRANGIAN

$$V_\pi = b f_\pi^2 \Lambda_{\text{QCD}} \text{Tr}[MU + \text{h.c.}]$$

$$M = \text{diag}(m_u e^{i\alpha_u}, m_d e^{i\alpha_d}, m_s e^{i\alpha_s})$$

$U(1)_A$ IN THE CHIRAL LAGRANGIAN

$$V_{\eta'} = c f_\pi^2 \Lambda_{\rm QCD}^2 H(\det U) + \text{h.c.}$$

$H(\cdot)$ is unknown

ALL OF THE ABOVE DOESN'T MATTER FOR THE AXION

$$\mathcal{L} = \frac{f_\pi^2}{4}\mathrm{Tr}[(\partial_\mu U)^\dagger \partial^\mu U] - b f_\pi^2 \Lambda_{\mathrm{QCD}} \mathrm{Tr}[MU + \mathrm{h.c.}] - c f_\pi^2 \Lambda_{\mathrm{QCD}}^2 H(e^{i\theta(a)F} \det U)$$

ALL OF THE ABOVE DOESN'T MATTER FOR THE AXION

$$\mathcal{L} = \frac{f_\pi^2}{4}\mathrm{Tr}[(\partial_\mu U)^\dagger \partial^\mu U] - b f_\pi^2 \Lambda_{\mathrm{QCD}} \mathrm{Tr}[MU + \mathrm{h.c.}] - c f_\pi^2 \Lambda_{\mathrm{QCD}}^2 H(e^{i\theta(a)F}\det U)$$

U(1) rotation

$$\mathcal{L} = \frac{f_\pi^2}{4}\mathrm{Tr}[(\partial_\mu U)^\dagger \partial^\mu U] - b f_\pi^2 \Lambda_{\mathrm{QCD}} \mathrm{Tr}[M e^{i\theta(a)} U + \mathrm{h.c.}] - c f_\pi^2 \Lambda_{\mathrm{QCD}}^2 H(\det U)$$

ALL OF THE ABOVE DOESN'T MATTER FOR THE AXION

$$\mathcal{L} = \frac{f_\pi^2}{4}\mathrm{Tr}[(\partial_\mu U)^\dagger \partial^\mu U] - b f_\pi^2 \Lambda_{\mathrm{QCD}} \mathrm{Tr}[M e^{i\theta(a)} U + \mathrm{h.c.}] - \underline{c f_\pi^2 \Lambda_{\mathrm{QCD}}^2 H(\det U)}$$

$$\Lambda_{\mathrm{QCD}} \gg M$$

$$\langle \eta' \rangle = 0$$

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$\Lambda_{\mathrm{QCD}} \gg M$

Integrate out eta'

$\langle \eta' \rangle = 0$

$$\mathcal{L} = \frac{f_\pi^2}{4}\mathrm{Tr}[(\partial_\mu U)^\dagger \partial^\mu U] - b f_\pi^2 \Lambda_{\mathrm{QCD}} \mathrm{Tr}[M e^{i\theta(a)} e^{i\frac{\pi^a \lambda^a}{2 f_\pi}} + \mathrm{h.c.}]$$

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$$\mathcal{L} = \frac{f_\pi^2}{4}\mathrm{Tr}[(\partial_\mu U)^\dagger \partial^\mu U] - b f_\pi^2 \Lambda_{\mathrm{QCD}} \mathrm{Tr}[M e^{i\theta(a)} e^{i\frac{\pi^a \lambda^a}{2 f_\pi}} + \mathrm{h.c.}]$$

We don't need to know the eta' potential to know the axion potential
(at leading order)

BASIC IDEA

[Agrawal, Reig, Nee, '22-'24]

$$\frac{\alpha}{8\pi}\frac{a}{f_a}\left(\mathcal{A}_1 G\widetilde{G} + \mathcal{A}_2 F\widetilde{F}\right)$$

$\mathcal{A}_{1,2}$ are topological couplings that do not run under RGE flow

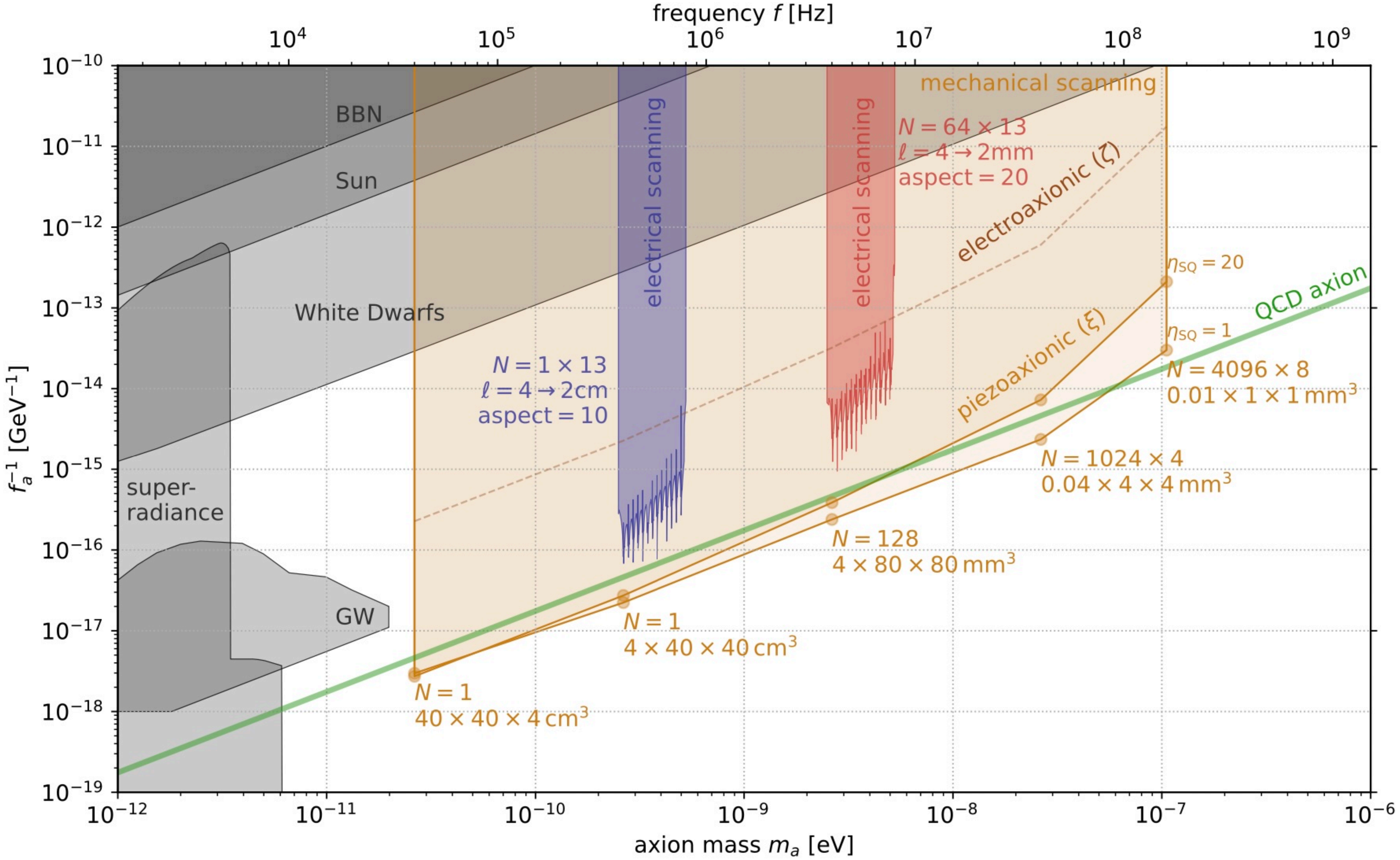
The symmetry properties of the UV theory can be detected in the IR

CONCLUSION

- 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 couple of decades
- Axions are unique probes of the deep UV
- We do not know the chiral Lagrangian. Is this a problem? **Yes, but not for axion physics**

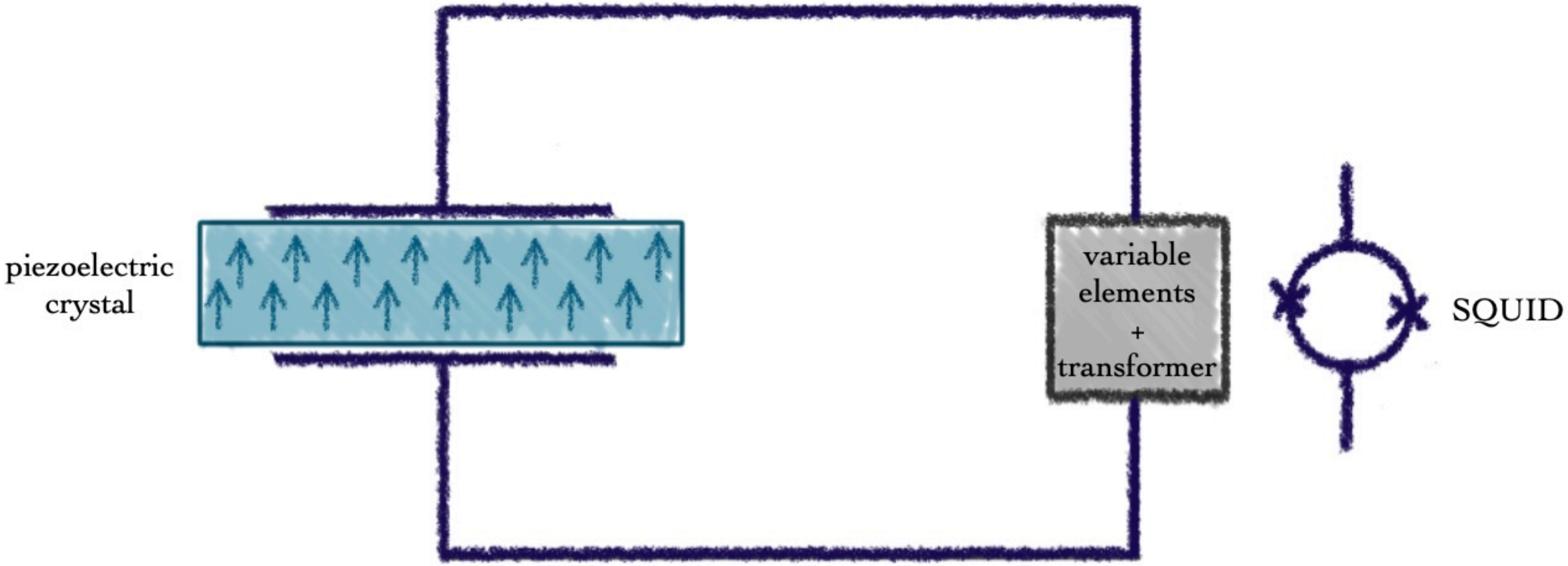
PIEZOAXIONIC EFFECT

[Arvanitaki, Madden, Van Tilburg '23]



PIEZOAXIONIC EFFECT

[Arvanitaki, Madden, Van Tilburg '23]



$$\mathbf{T} = \frac{\partial U}{\partial \mathbf{S}} = +\mathbf{c}^D\mathbf{S} - \mathbf{h}^\intercal\mathbf{D} - \boldsymbol{\xi}\hat{\mathbf{I}}\overline{\theta}_a,$$

$$\mathbf{E} = \frac{\partial U}{\partial \mathbf{D}} = -\mathbf{h}\mathbf{S} + \boldsymbol{\beta}^S\mathbf{D} - \boldsymbol{\zeta}\hat{\mathbf{I}}\overline{\theta}_a.$$

$$Q \simeq 10^9$$

PIEZOAXIONIC EFFECT

[Arvanitaki, Madden, Van Tilburg '23]

$$\frac{a}{f_a} G\widetilde{G} \quad \longrightarrow \quad \frac{a}{f_a} N^\dagger \vec{\sigma} N \cdot \vec{E}$$

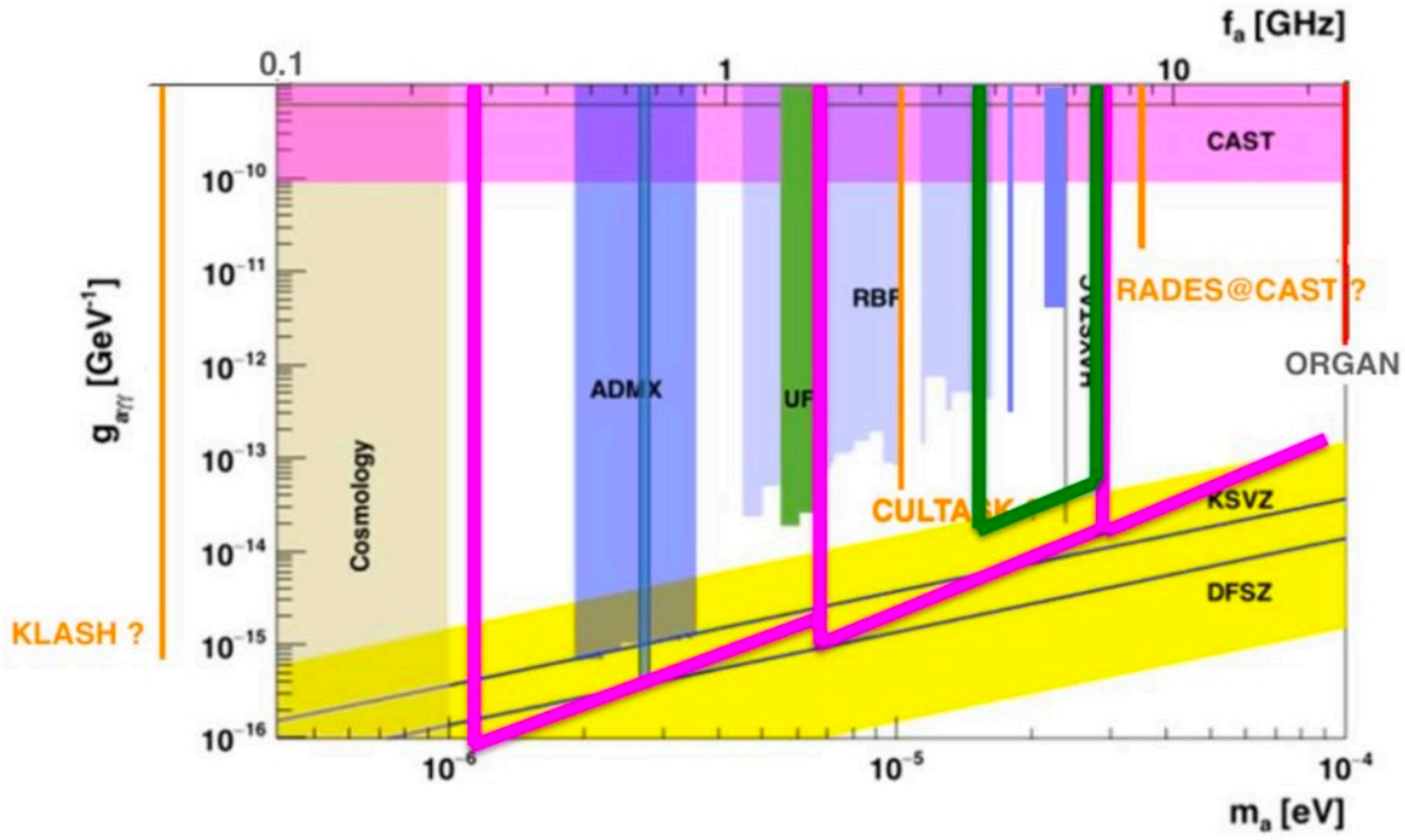
PIEZOAXIONIC EFFECT

[Arvanitaki, Madden, Van Tilburg '23]

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

Polarization I

GRAHAL



Phase 1

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

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

Phase 2

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

Up to 43 T in a smaller volume

$U(1)_A$ IN THE CHIRAL LAGRANGIAN

$$V_{\eta'} = c f_\pi^2 \Lambda_{\mathrm{QCD}}^2 H(\det U) + \mathrm{h.c.}$$

Selection Rules of $U(1)_A$

$$H = H(\theta - F\eta')$$

$U(1)_A$ IN THE CHIRAL LAGRANGIAN

$$V_{\eta'} = c f_\pi^2 \Lambda_{\text{QCD}}^2 H(\det U) + \text{h.c.}$$

Instantons always generate single-valued potentials that are manifestly periodic

$$= \cos(n\theta - F n \eta')$$

LARGE-N

$$H(\det U) = \frac{1}{N}(i \log \det U)^2 + \text{h.c.} + \mathcal{O}(1/N^2)$$

$$\frac{F}{N} \to 0$$

Witten '79, '80
Di Vecchia, Veneziano '79

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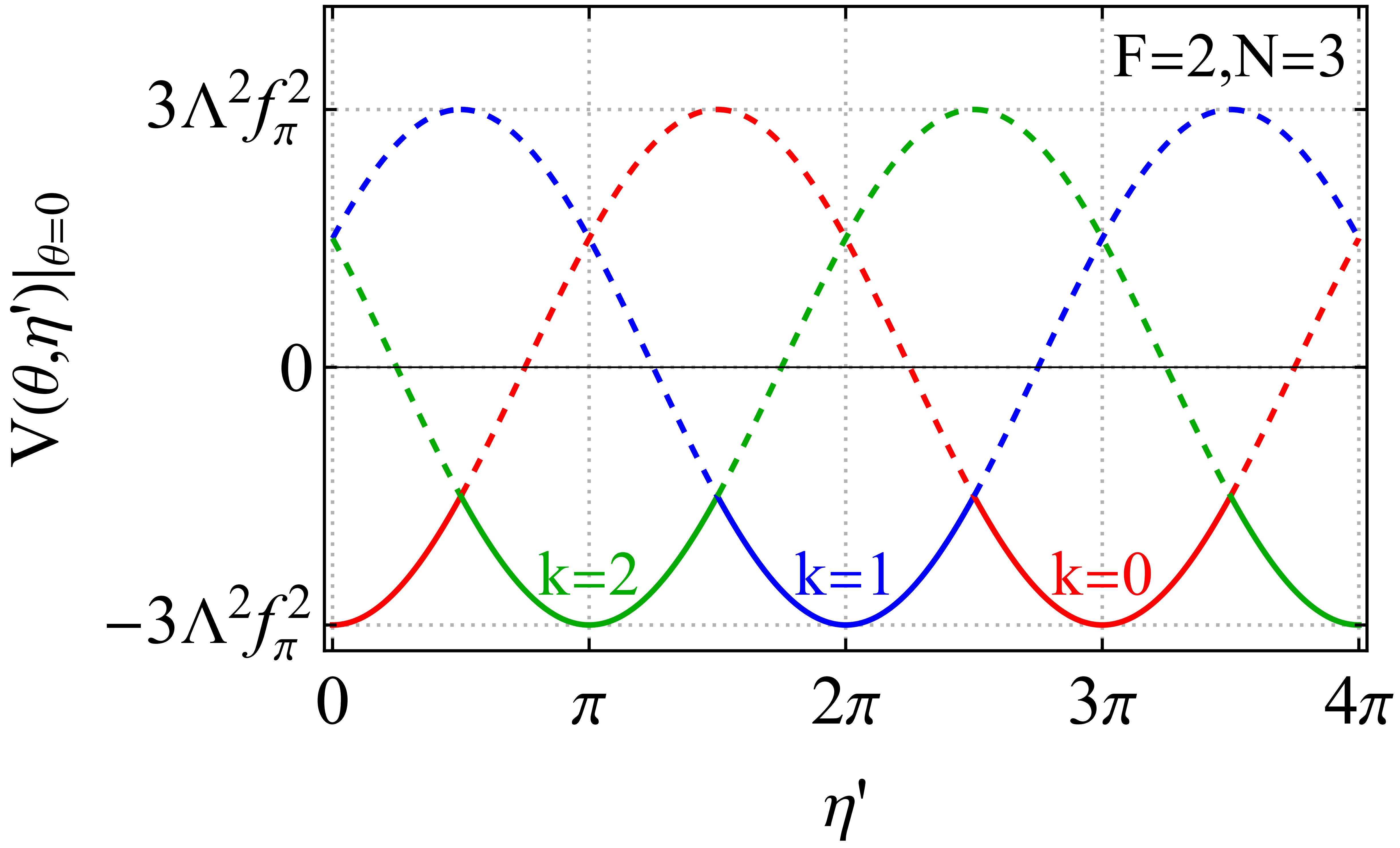

Witten '79, '80
Di Vecchia, Veneziano '79

SUSY QCD

[Csaki, RTD, Kuflik, Ruhdorfer '23]

$$H_{\mathrm{SUSY}}(\det U) = (\det U)^{-\frac{1}{|N-F|}}$$

|N-F| branches

- F < N: Gaugino condensation
- F = N, N+1: Instantons
- F > N+1: Gaugino condensation in the dual gauge group