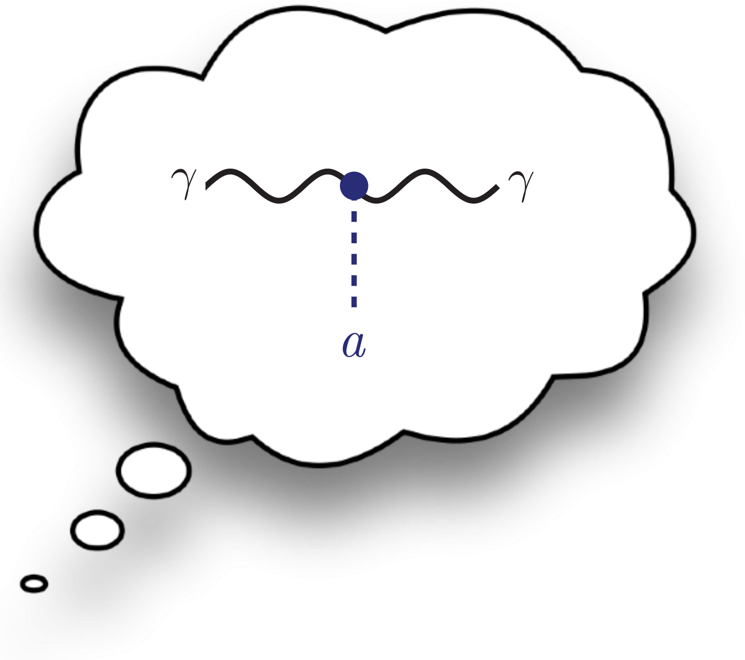
New Opportunities to Detect Axion Dark Matter

Asher Berlin - Fermilab



GUINEAPIG Workshop
July 11, 2023

Axion Dark Matter

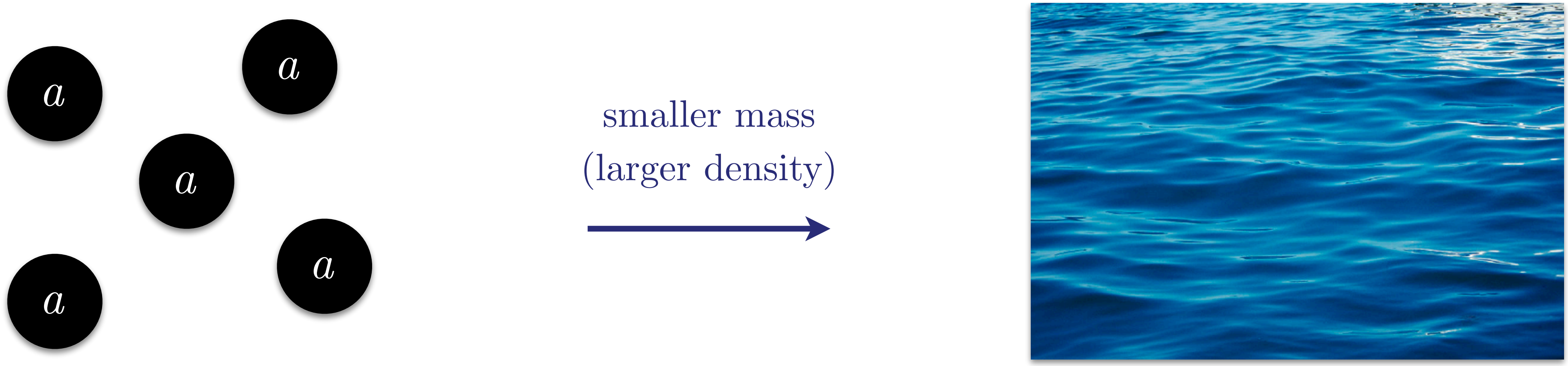
$$\mathscr{L} \sim \frac{\partial_\mu a}{f_a} \left(J^\mu_{\text{QCD}} + J^\mu_{\text{EM}} + J^\mu_{\text{spin}} + \cdots \right)$$

explains the smallness of the neutron's electric dipole moment

How to think about axions dynamically?

Sub-eV Axion Dark Matter

axion dark matter ~ classical field



wave properties

$$a \propto \cos m_a t$$

frequency : $m_a \sim \text{day}^{-1} - 10^{15}\ \text{Hz}$

coherence time : $\tau_a \sim \dfrac{1}{m_a\, v_{\text{DM}}^2} \sim 1\ \text{ns} - 10^3\ \text{yrs}$

Outline

Extending the mass range for EM-coupled axions

I.

Heterodyne (low-mass)

B+dielectric (high-mass)

Confirming ***the*** QCD axion

II.

Polarization Haloscope

Clarifying the spin coupling

III.

EM signals

Spin-Forces

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Spin-Forces

Based on work with R. D'Agnolo, S. Ellis, C. Nantista, J. Neilson, P. Schuster, S. Tantawi, N. Toro, K. Zhou
arXiv:1912.11048, arXiv:1912.11056, arXiv:2007.15656
and with T. Trickle, arXiv:2305.05681

I. EM-coupled Axions

Axion Electrodynamics

prepared EM field

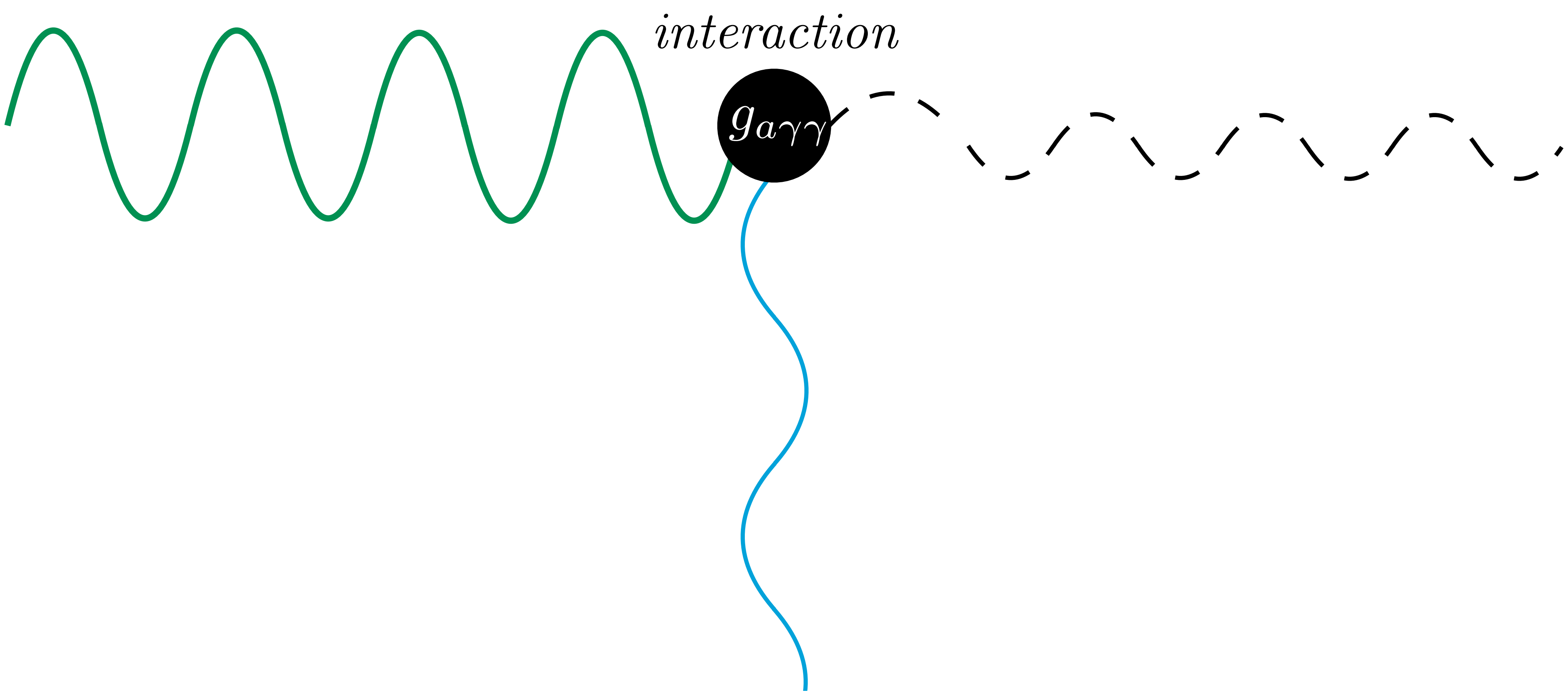
$\sim \cos \omega_0 t$

(frequency ~ your choice)

galactic axion field

$\sim \cos m_a t$

(frequency ~ axion mass)



signal EM field $\sim \cos{(\omega_0 + m_a)t}$

ideal detector is resonantly matched to signal frequency

signal power $\sim (\omega_0 + m_a)\ \cos{(\omega_0 + m_a)t}$

Axion Electrodynamics

static B-field

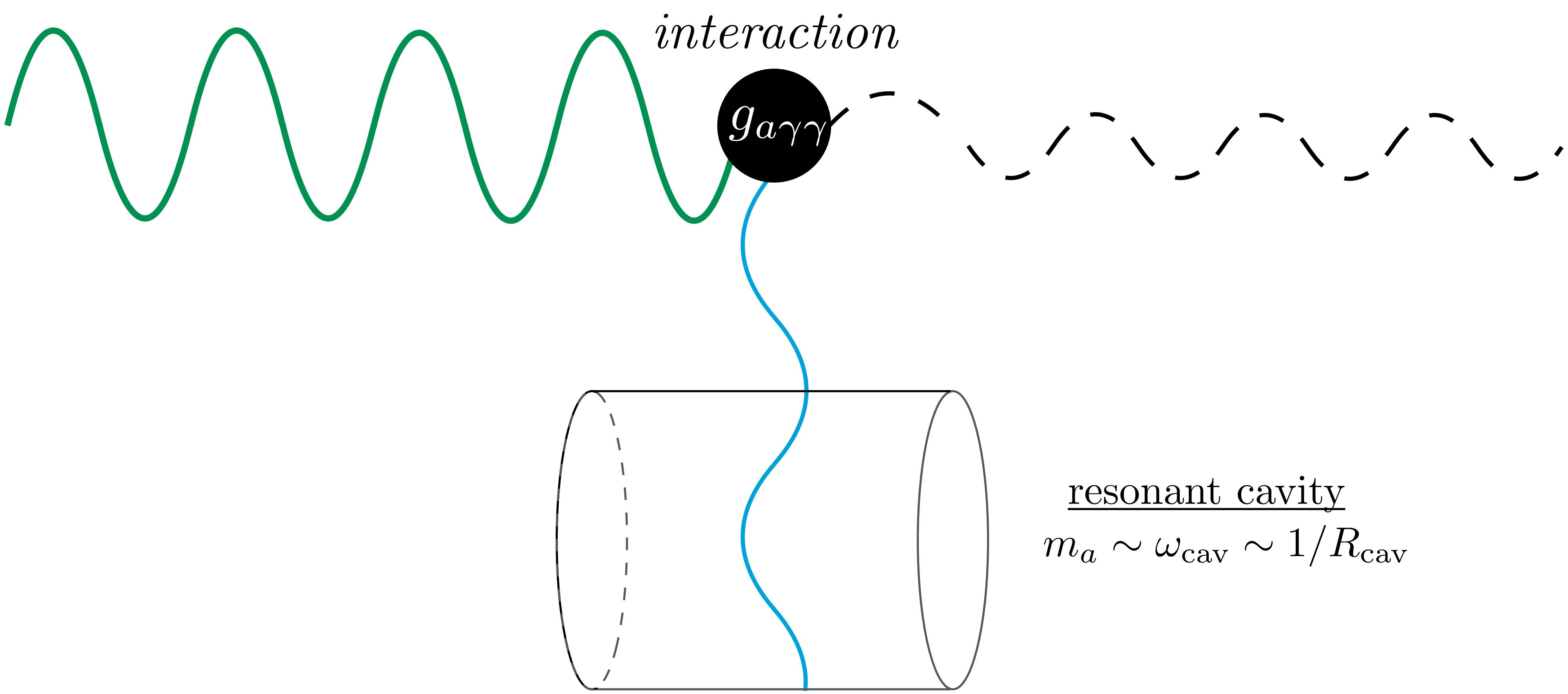
$\sim \cos \cancel{\omega_0} t$

(frequency ~ your choice)

galactic axion field

$\sim \cos m_a t$

(frequency ~ axion mass)



resonant cavity

$m_a \sim \omega_{\rm cav} \sim 1/R_{\rm cav}$

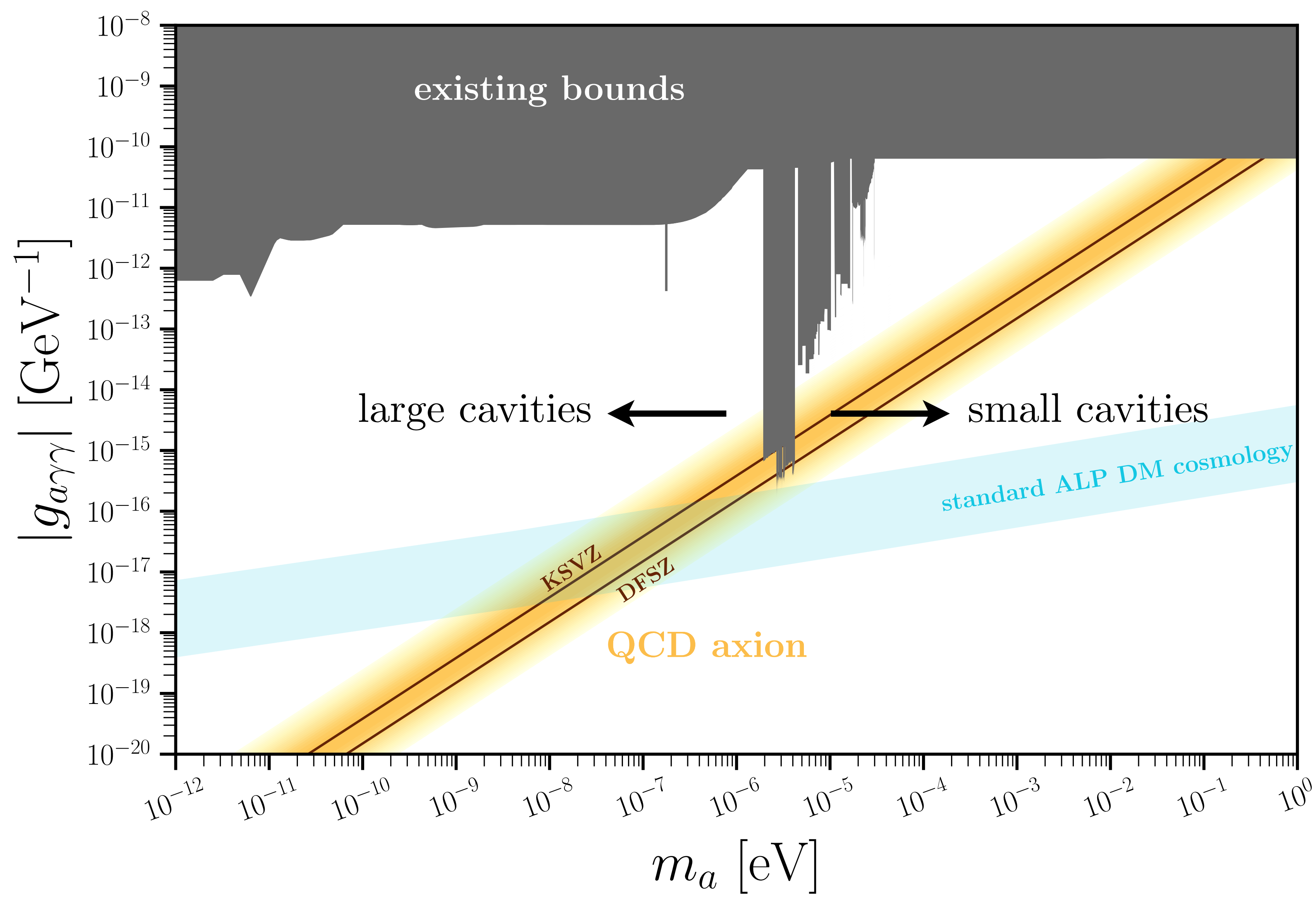
signal EM field $\sim \cos{(\cancel{\omega_0} + m_a)t}$

ideal detector is resonantly matched to signal frequency

signal power $\sim (\cancel{\omega_0} + m_a)\, \cos{(\cancel{\omega_0} + m_a)t}$

Photon-Coupling

$$\mathscr{L} \sim g_{a\gamma\gamma}\, a\, F_{\mu\nu}\, \tilde{F}^{\mu\nu}$$

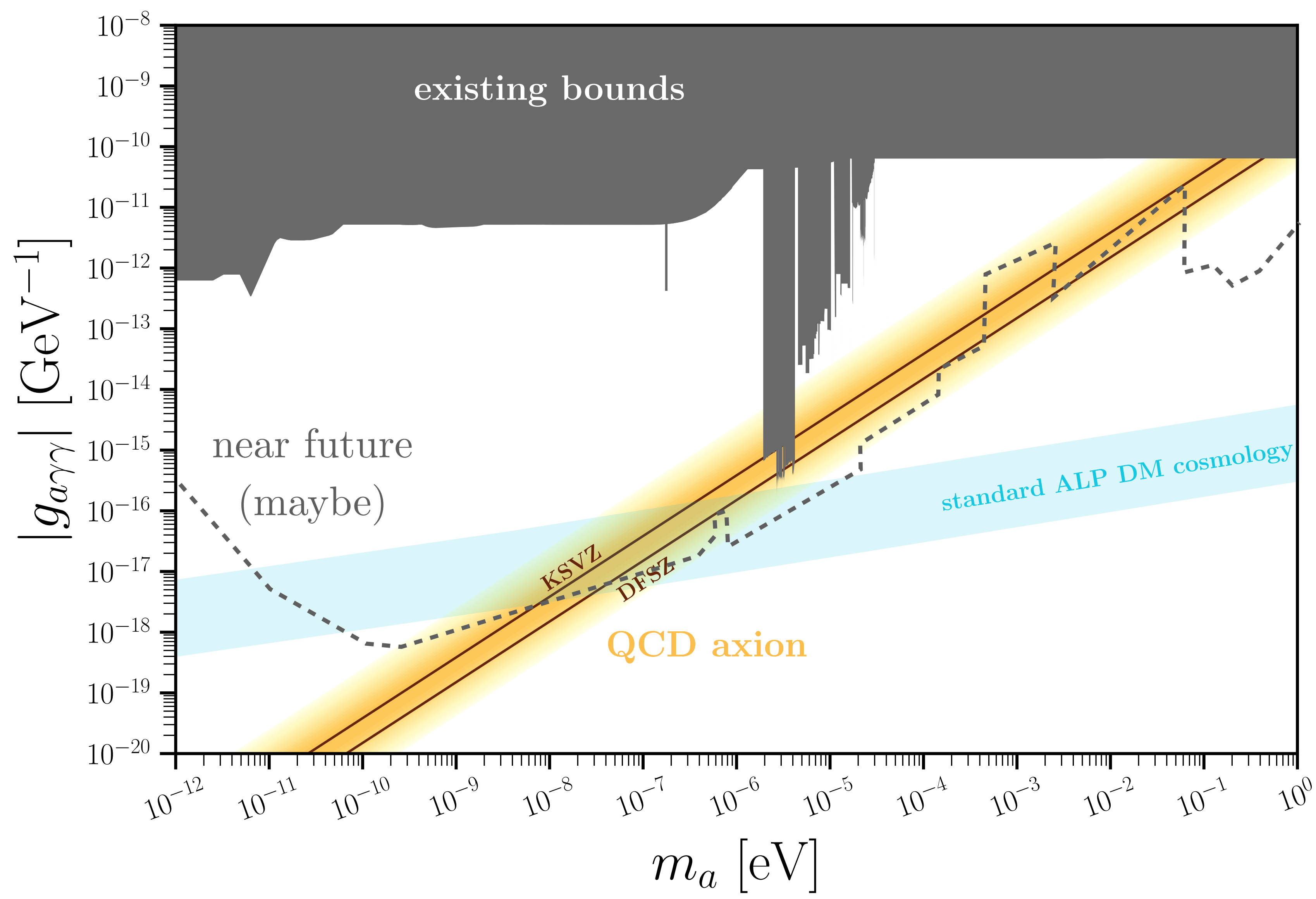


ADMX, HAYSTAC, ORGAN, ...

Cavities limited to a narrow range

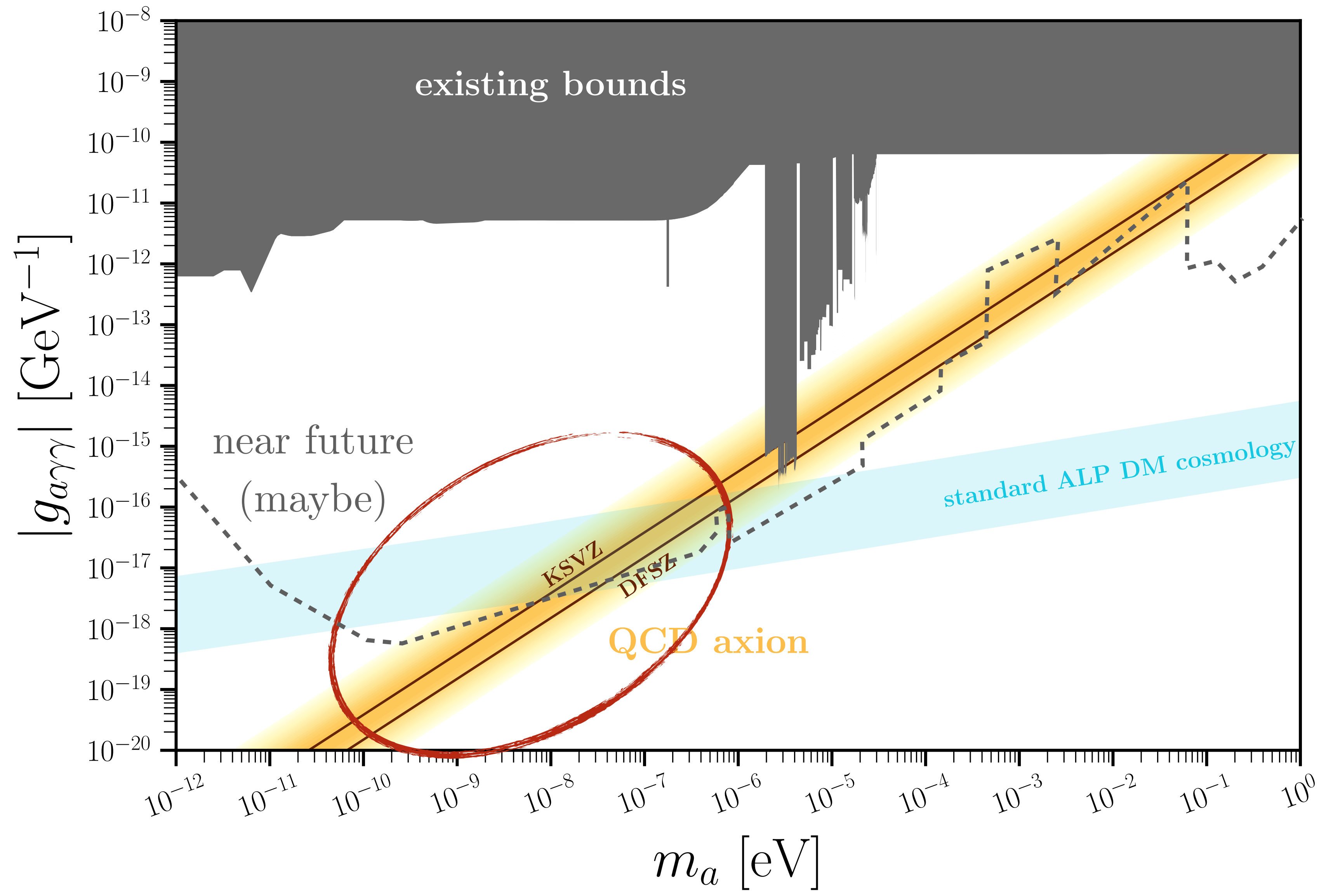
Photon-Coupling

$$\mathscr{L} \sim g_{a\gamma\gamma}\, a\, F_{\mu\nu}\, \tilde{F}^{\mu\nu}$$



Photon-Coupling

$$\mathscr{L} \sim g_{a\gamma\gamma}\, a\, F_{\mu\nu}\, \tilde{F}^{\mu\nu}$$

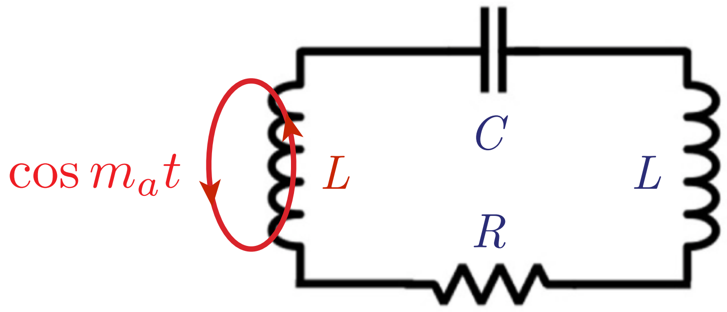


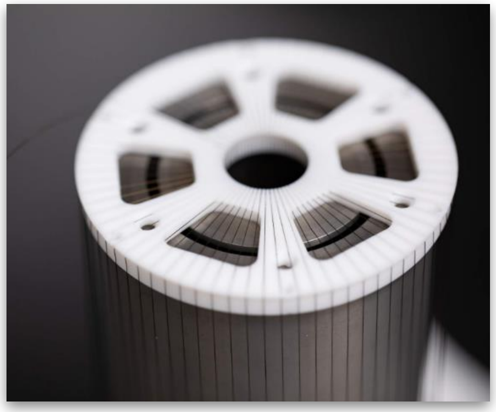
How to explore smaller masses?

Below ~Micro-eV

LC circuits (DMRadio)

S. Chaudhuri, P. Graham, K. Irwin,
J. Mardon, S. Rajendran, Y. Zhao
arXiv:2204.13781, arXiv:2203.11246





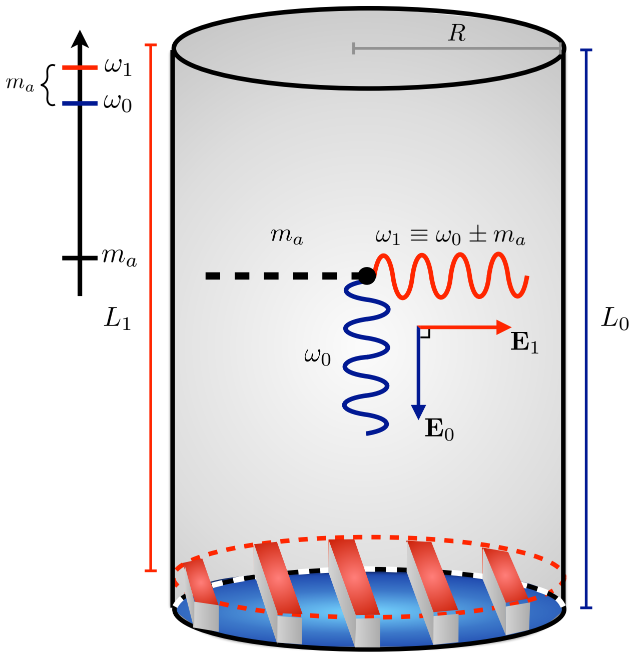
Drive power into LC circuit

$$\omega_{\rm LC} \sim \frac{1}{\sqrt{LC}} \sim m_a \ll \frac{1}{\rm length}$$

$$B \sim \text{few} \times \text{T} \; , \; Q \sim 10^6$$

Heterodyne/Upconversion (SRF cavities)

A. Berlin, R. D'Agnolo, S. Ellis, C. Nantista,
J. Neilson, P. Schuster, S. Tantawi, N. Toro, K. Zhou
arXiv:1912.11048, arXiv:1912.11056, arXiv:2007.15656

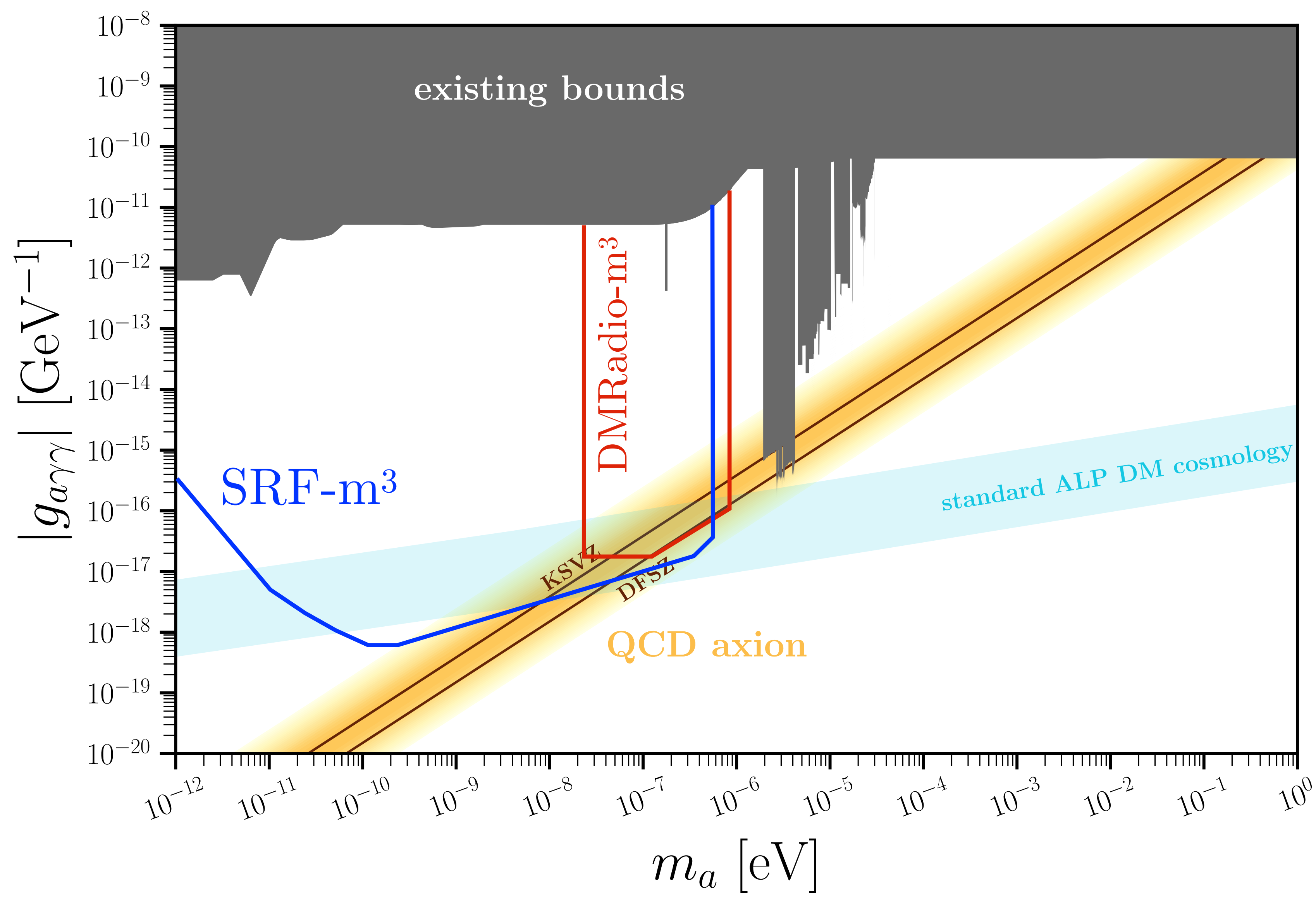


Transfer power between
two nearly-degenerate cavity modes

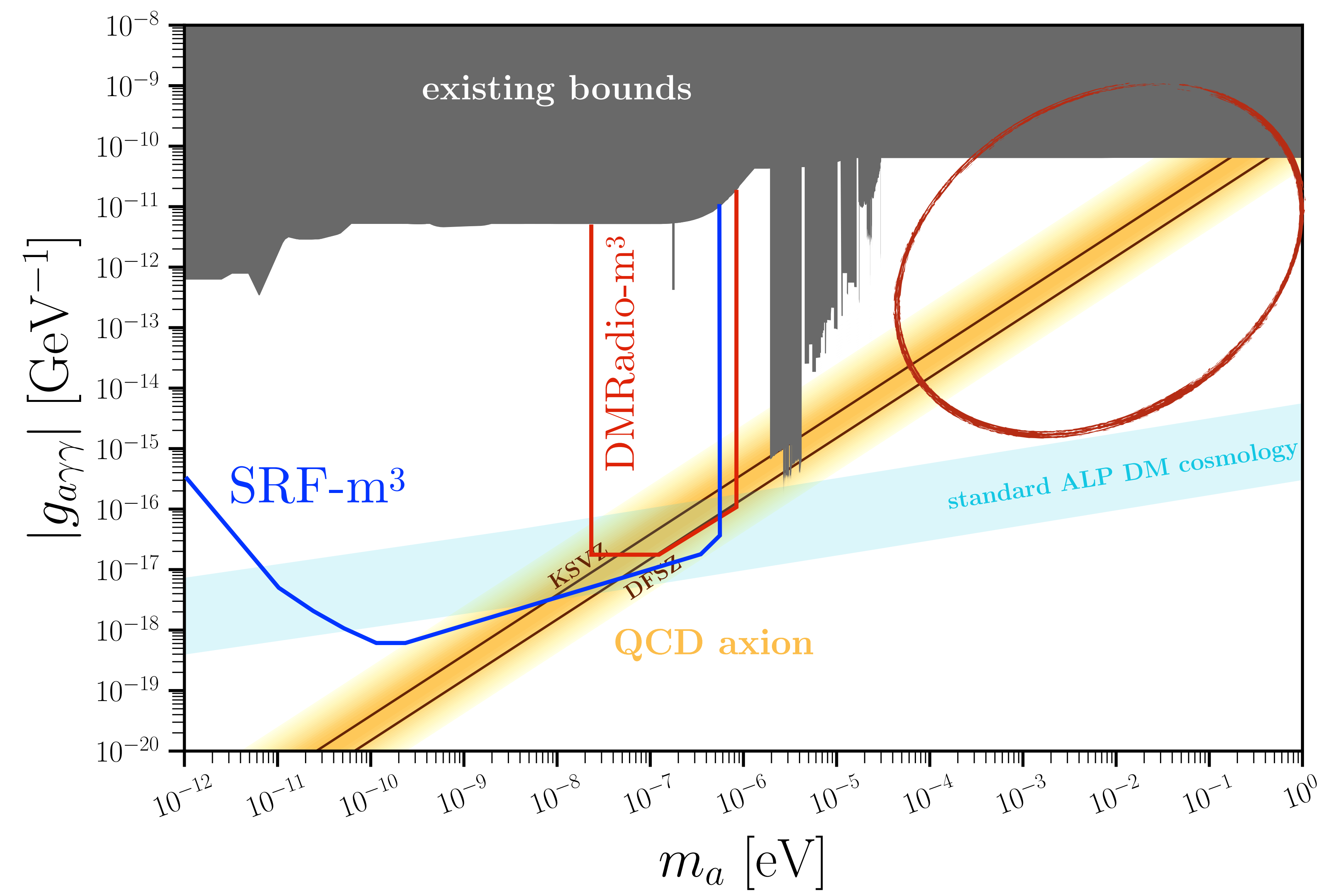
$$\Delta\omega \sim m_a \ll \omega \sim \text{GHz}$$

$$B \sim \text{few} \times 100 \text{ mT} \; , \; Q \sim \text{few} \times 10^{11}$$

Below ~Micro-eV



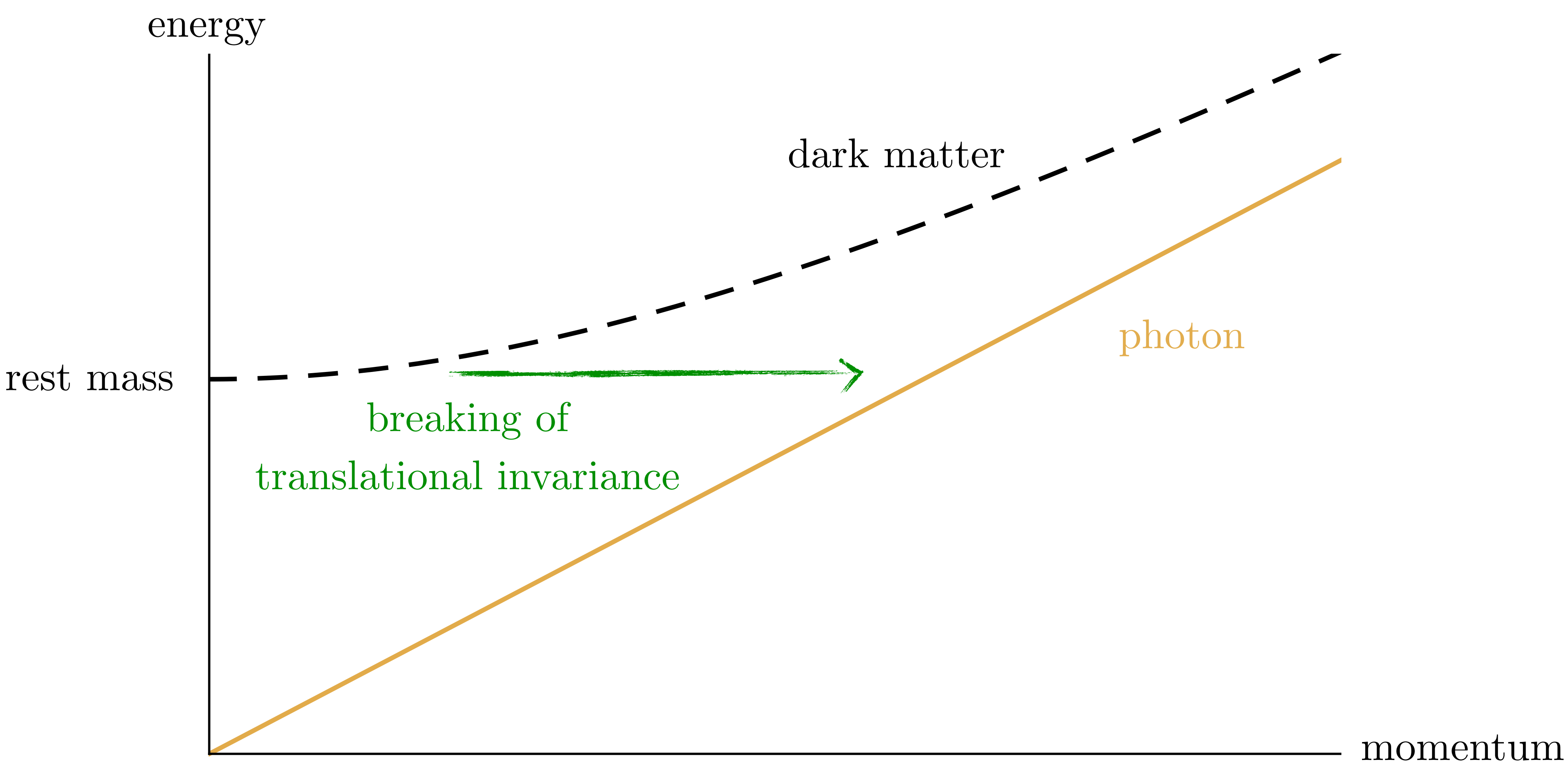
Above ~Micro-eV



How to explore higher masses?

Above ~Micro-eV

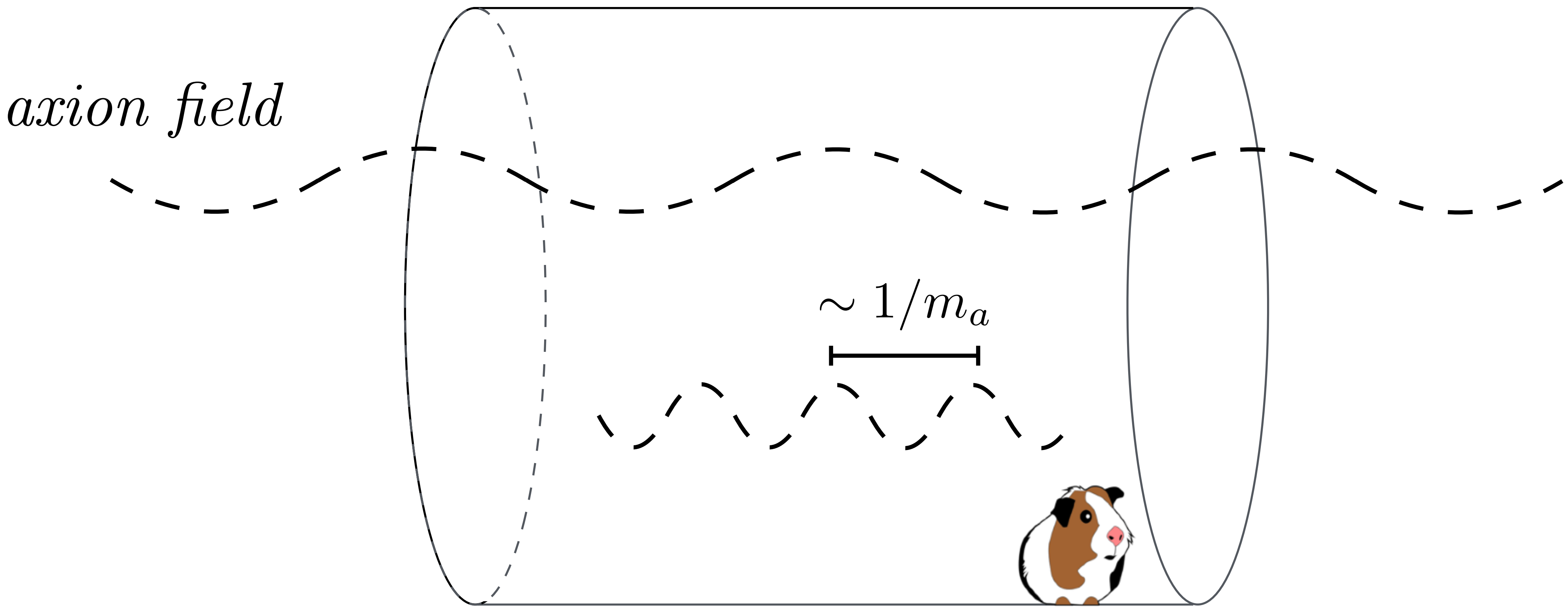
In vacuum, axions do not convert into photons in uniform B-fields of “infinite" extent (compared to the axion Compton wavelength).



momentum mismatch provided by detector

Above ~Micro-eV

In vacuum, axions do not convert into photons in uniform B-fields of “infinite" extent (compared to the axion Compton wavelength).

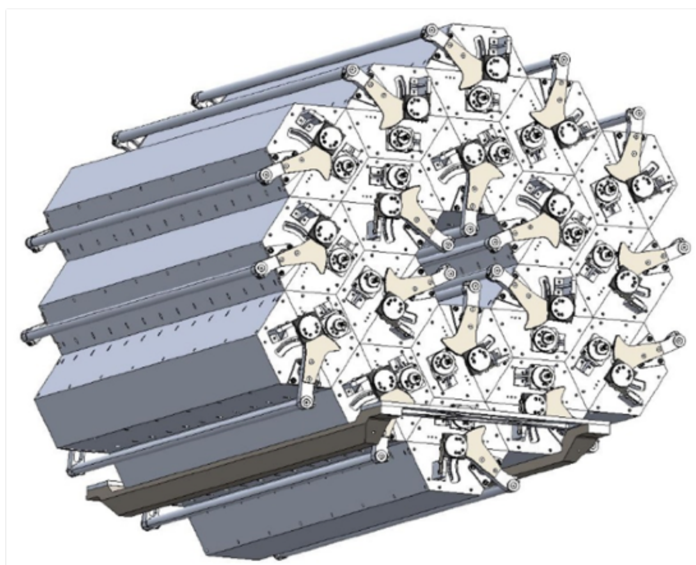


Momentum mismatch is more difficult at higher axion masses (smaller wavelengths).

Above ~Micro-eV

breaking translational invariance on small scales

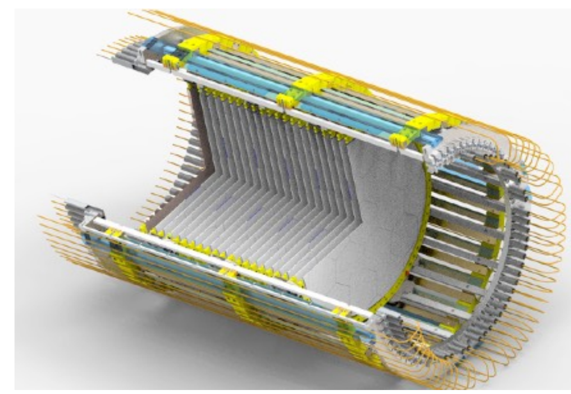
Resonant Cavity
(ADMX-EFR)
arXiv:2203.14923

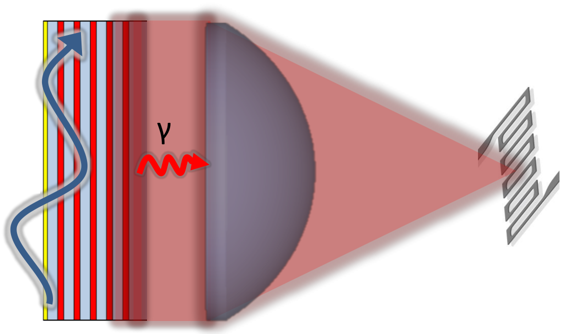


combine signal from 18 smaller cavities

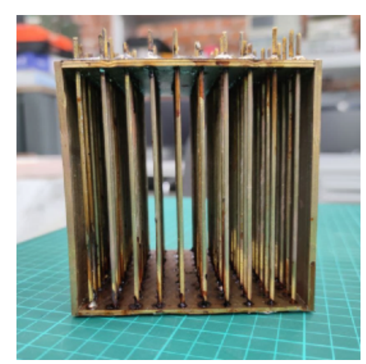
2-4 GHz ~ 8-16 μeV

Dielectric/Plasma
(MADMAX, LAMPOST, ALPHA)
arXiv:1901.07401, arXiv:2110.01582, arXiv:1904.11872





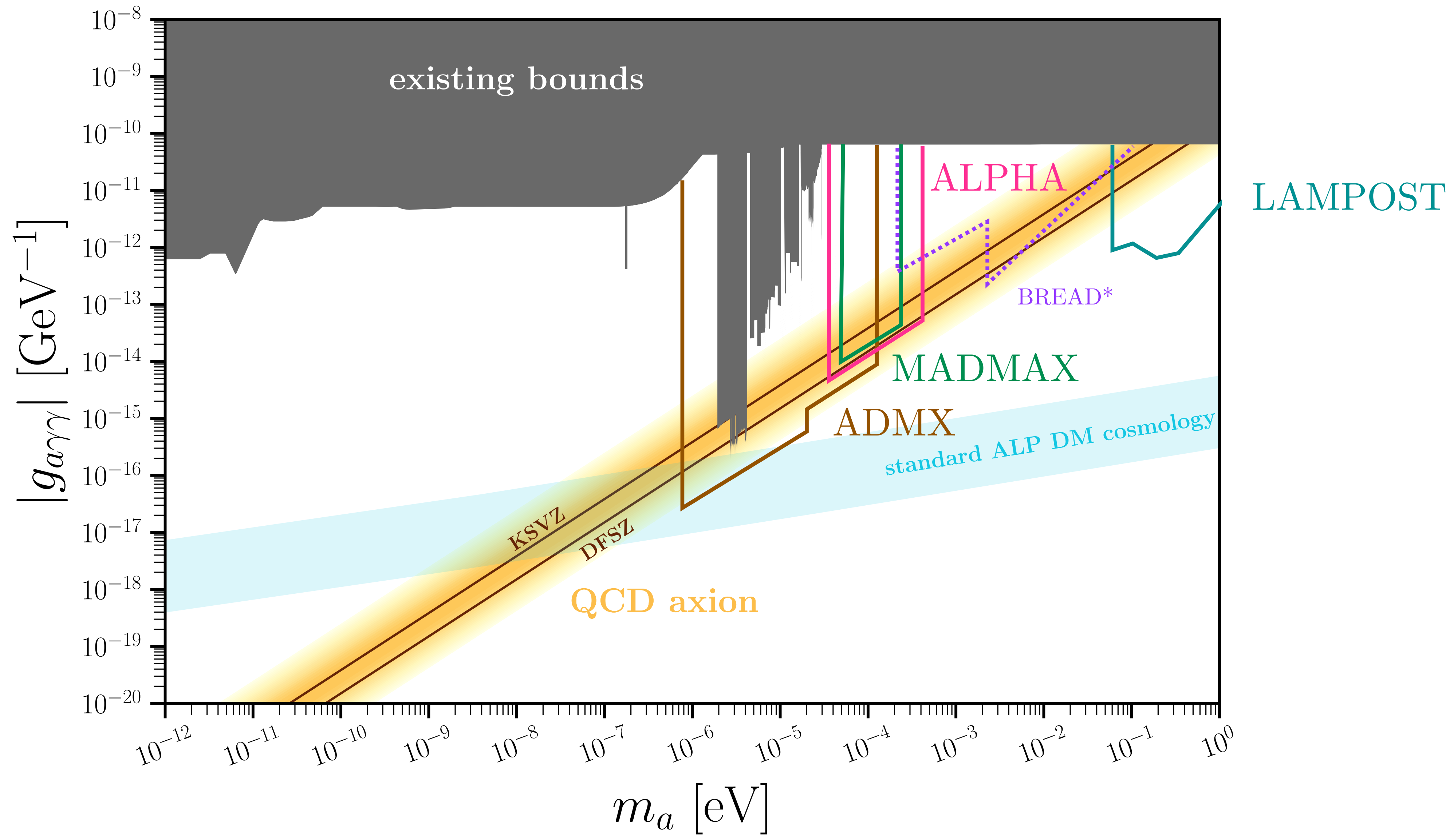
MADMAX/LAMPPOST: dielectric stacks



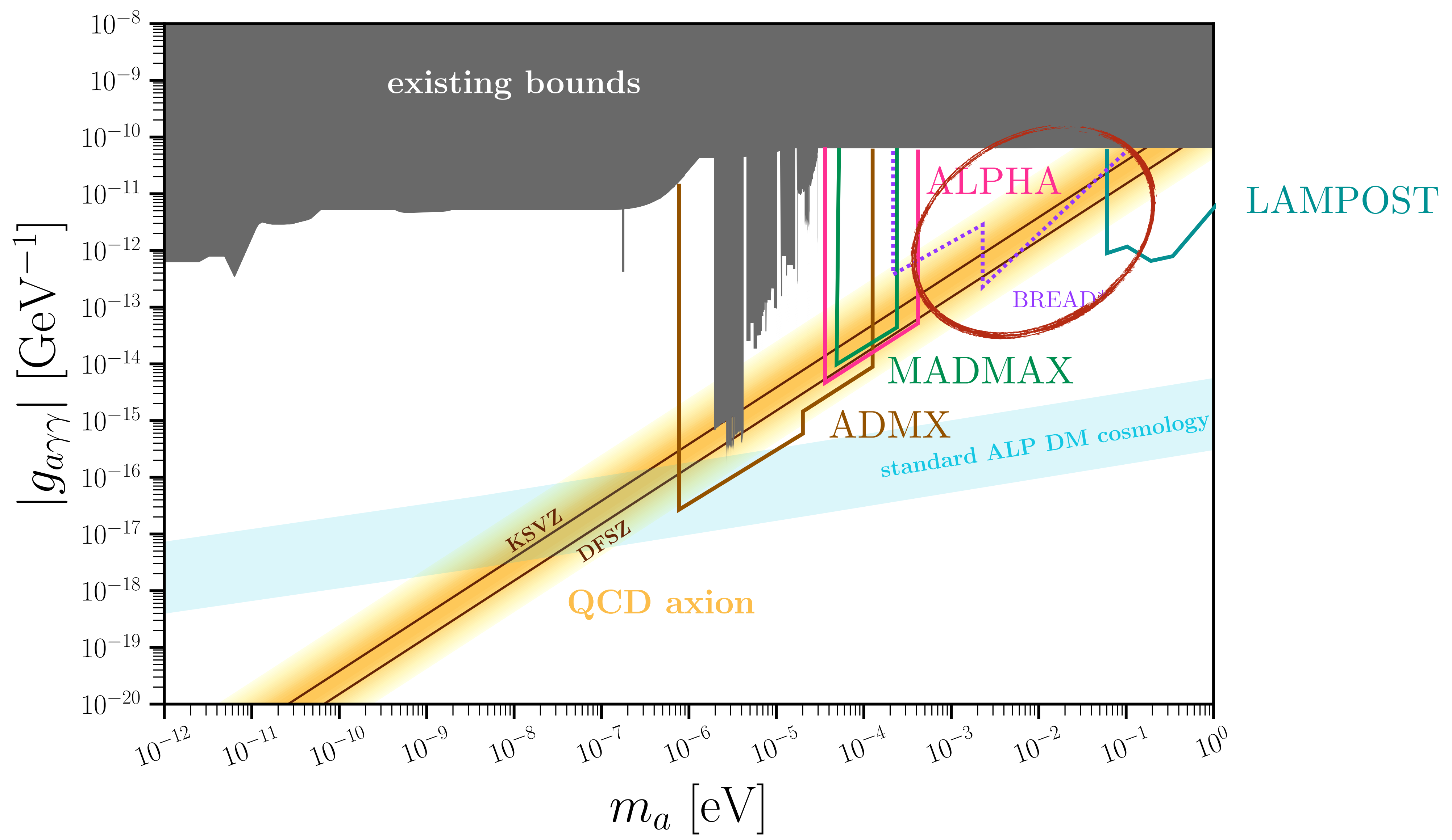
ALPHA: wire metamaterial

modify photon's dispersion relation

Above ~Micro-eV



Above ~Micro-eV

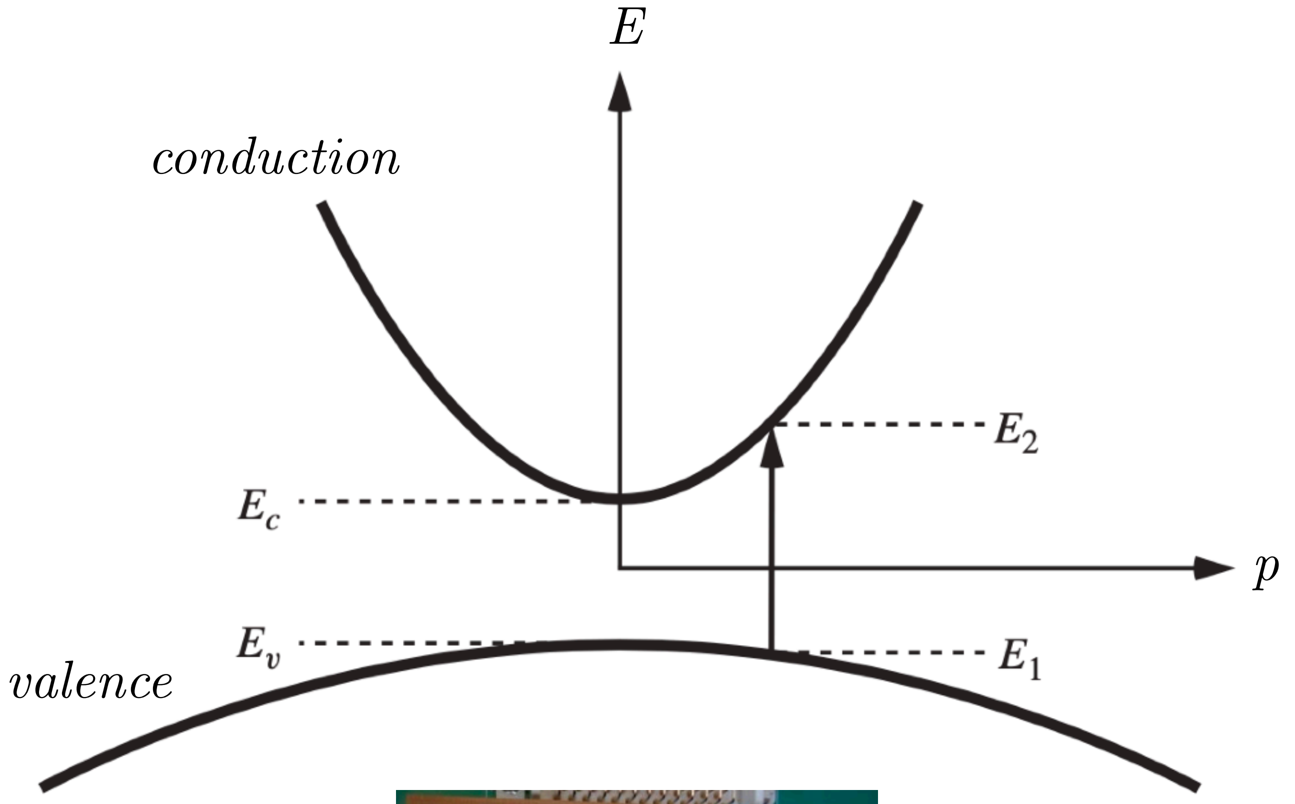


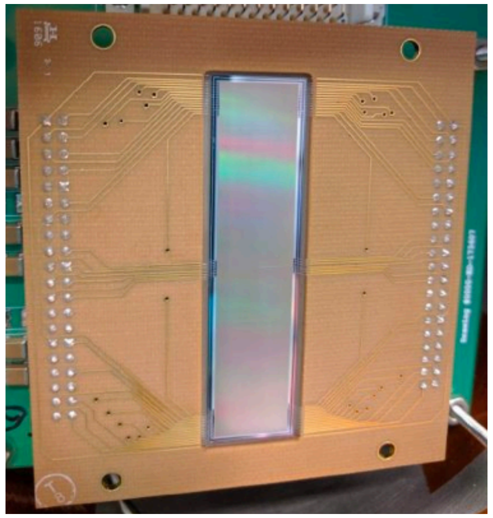
How to explore remaining gaps in coverage?

Above ~Micro-eV

In-Medium Excitations

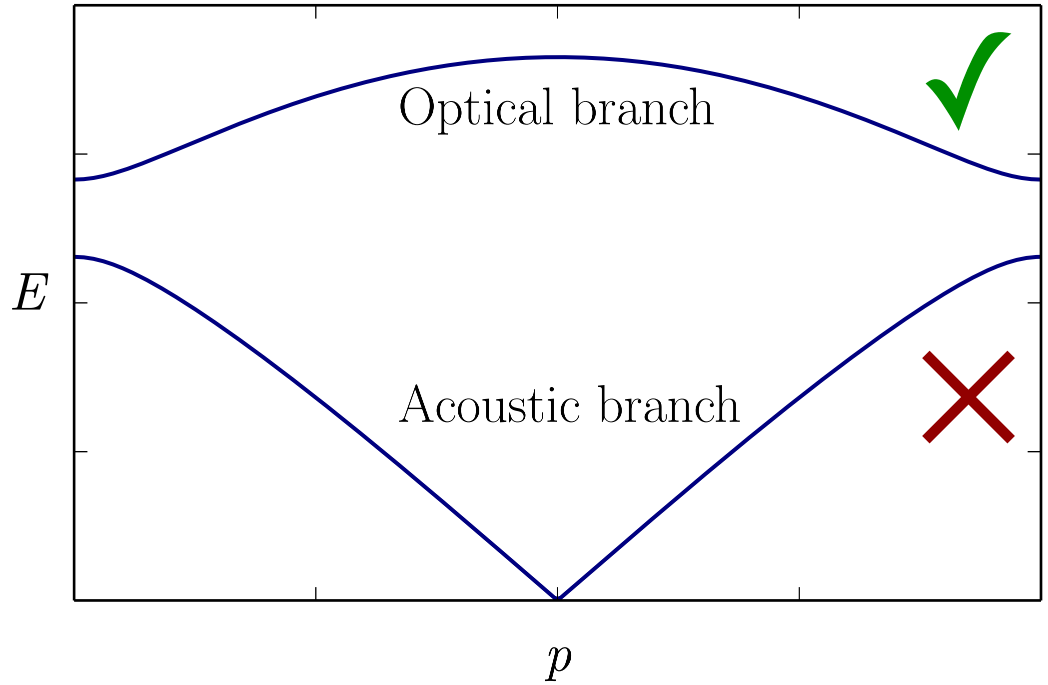
Electronic (eV)

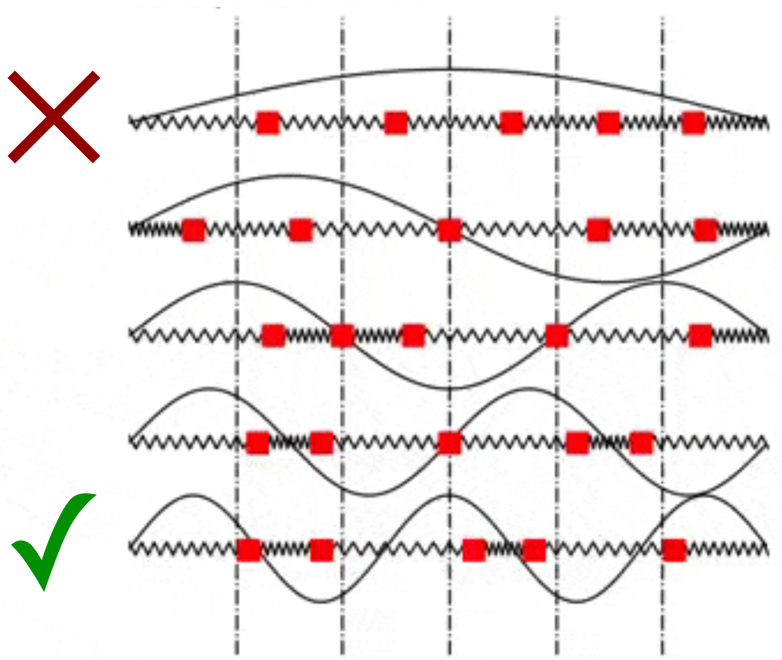




(semiconductors)

Phonon (meV)

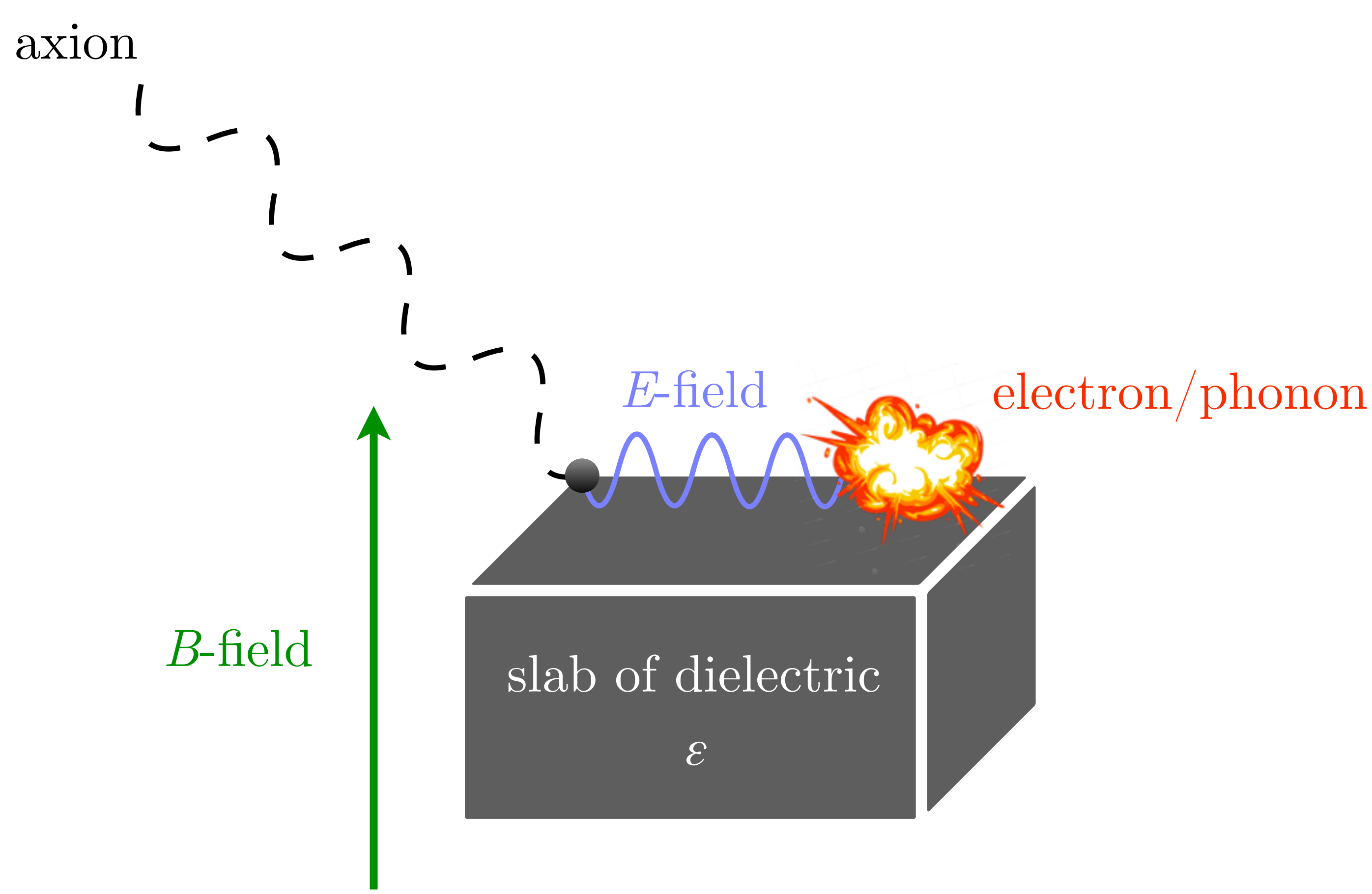




Above ~Micro-eV

In-Medium Excitations

(with Tanner Trickle arXiv:2305.05681)



$$\text{rate} \simeq \left(\frac{g_{a\gamma\gamma}\, B_0}{m_a}\right)^2 \frac{\rho_{\rm DM}}{\rho_{\rm det}}\, \text{Im}\left[\frac{-1}{\varepsilon(m_a)}\right]$$

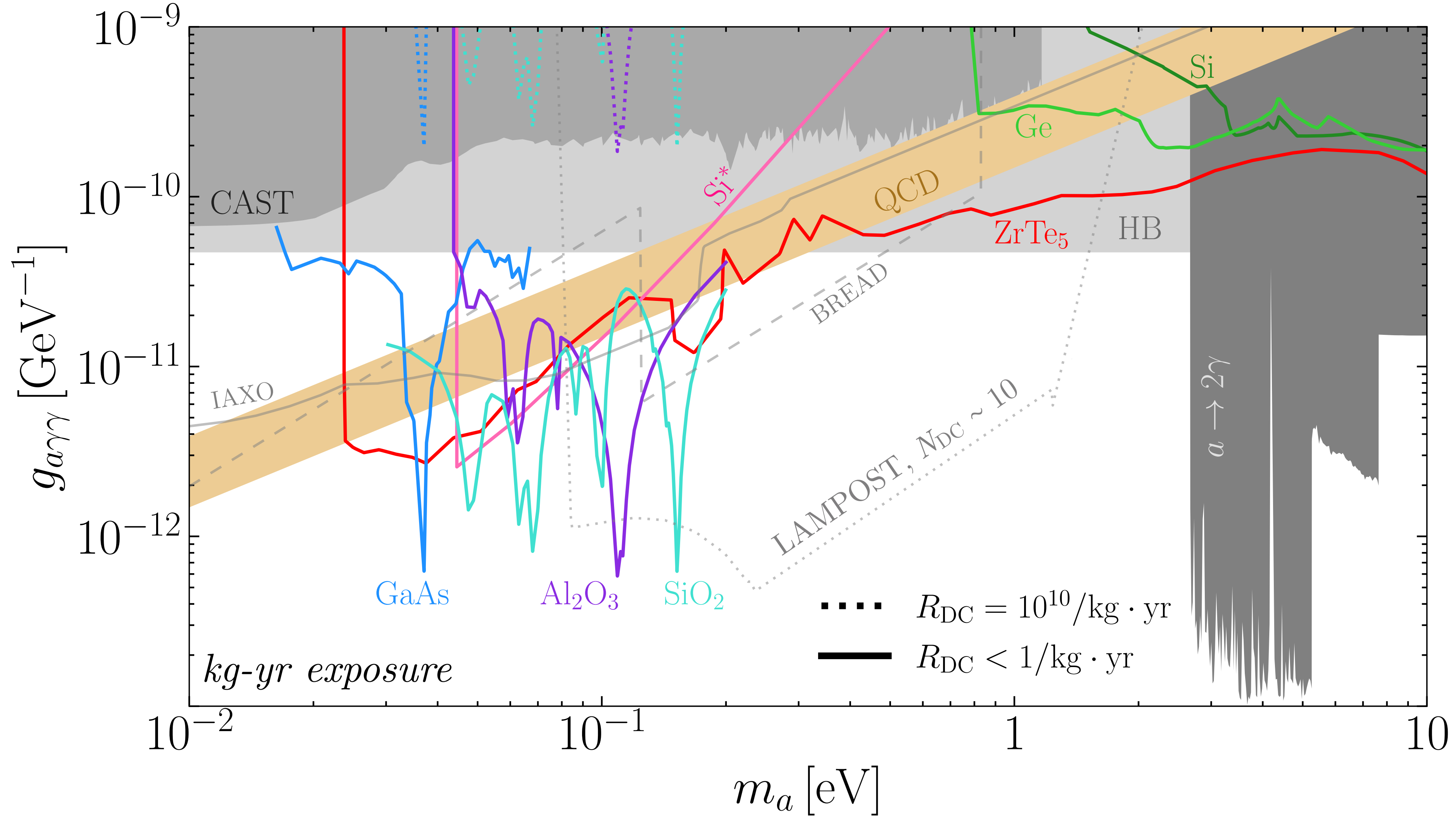
inclusive rate accounting for *all* in-medium excitations (photon, phonon, electronic, ...)

Same materials/sensors are actively being pursued for sub-GeV dark matter scattering.

Above ~Micro-eV

In-Medium Excitations

(with Tanner Trickle arXiv:2305.05681)



$GaAs$, Al_2O_3, SiO_2
optical phonons

Si*, $ZrTe_5$
"novel" electronic excitations

Ge, Si
"standard" electronic excitations

$$g_{a\gamma\gamma} \propto (R_{\rm DC}/M_{\rm T}\, t_{\rm int})^{1/4}$$

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Confirming ***the*** QCD axion

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Polarization Haloscope

Clarifying the spin coupling

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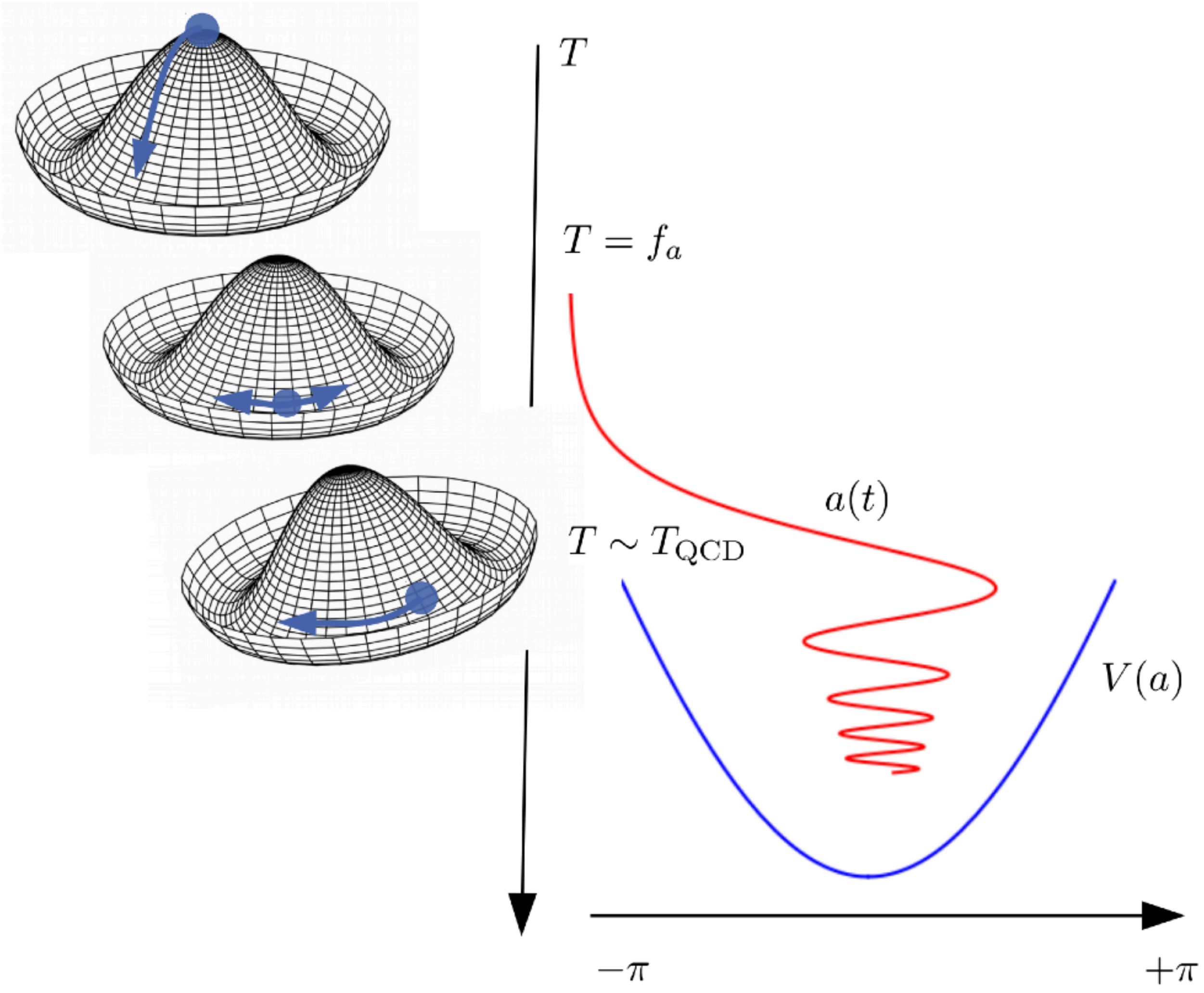
Spin-Forces

Based on work with K. Zhou (many slides also adapted from K. Zhou)
arXiv:2209.12901

II. QCD-coupled Axions

QCD-axion at ~Micro-eV

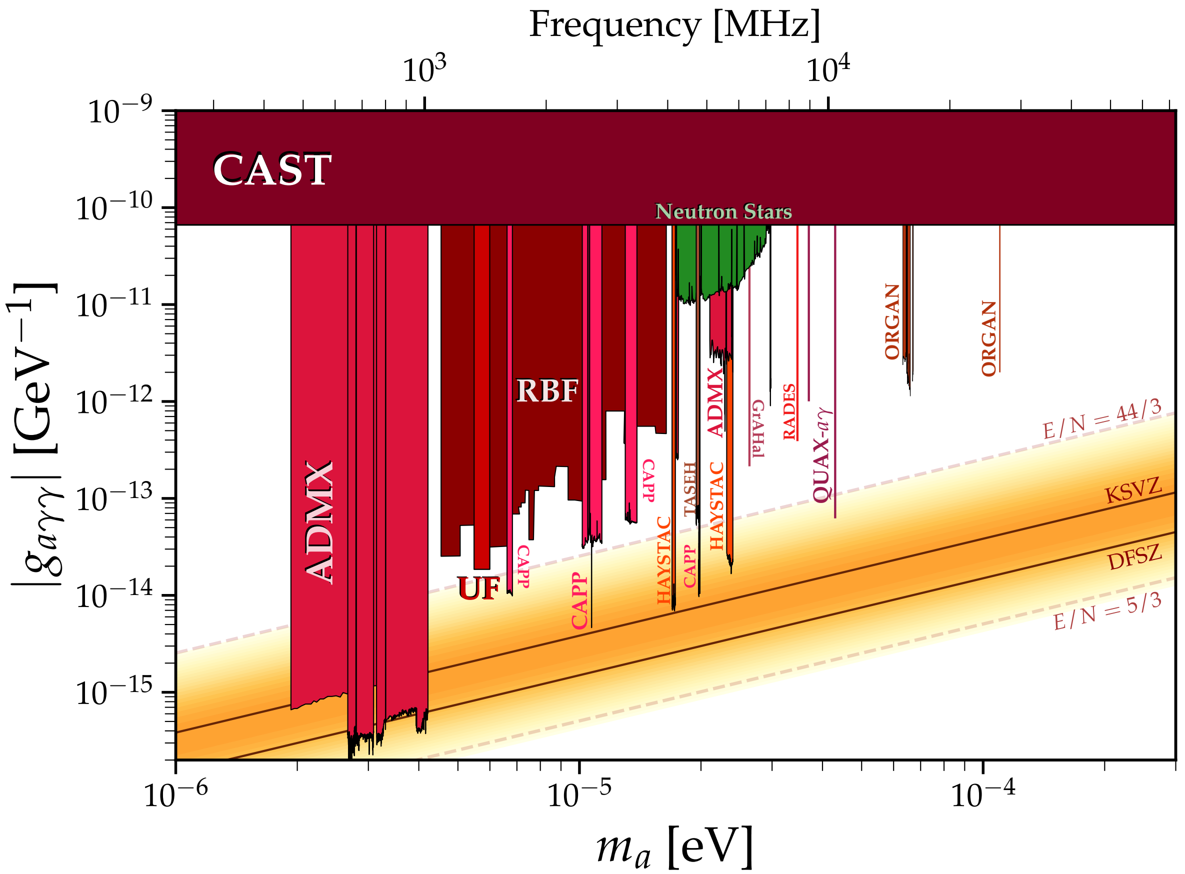
Most-motivated mass range for QCD axion dark matter is $m_a \sim (0.1 - 100)\ \mu\text{eV}$



QCD-axion at ~Micro-eV

Most-motivated mass range for QCD axion dark matter is $m_a \sim (0.1 - 100)\ \mu\text{eV}$

Photon-coupling (model-dependent)



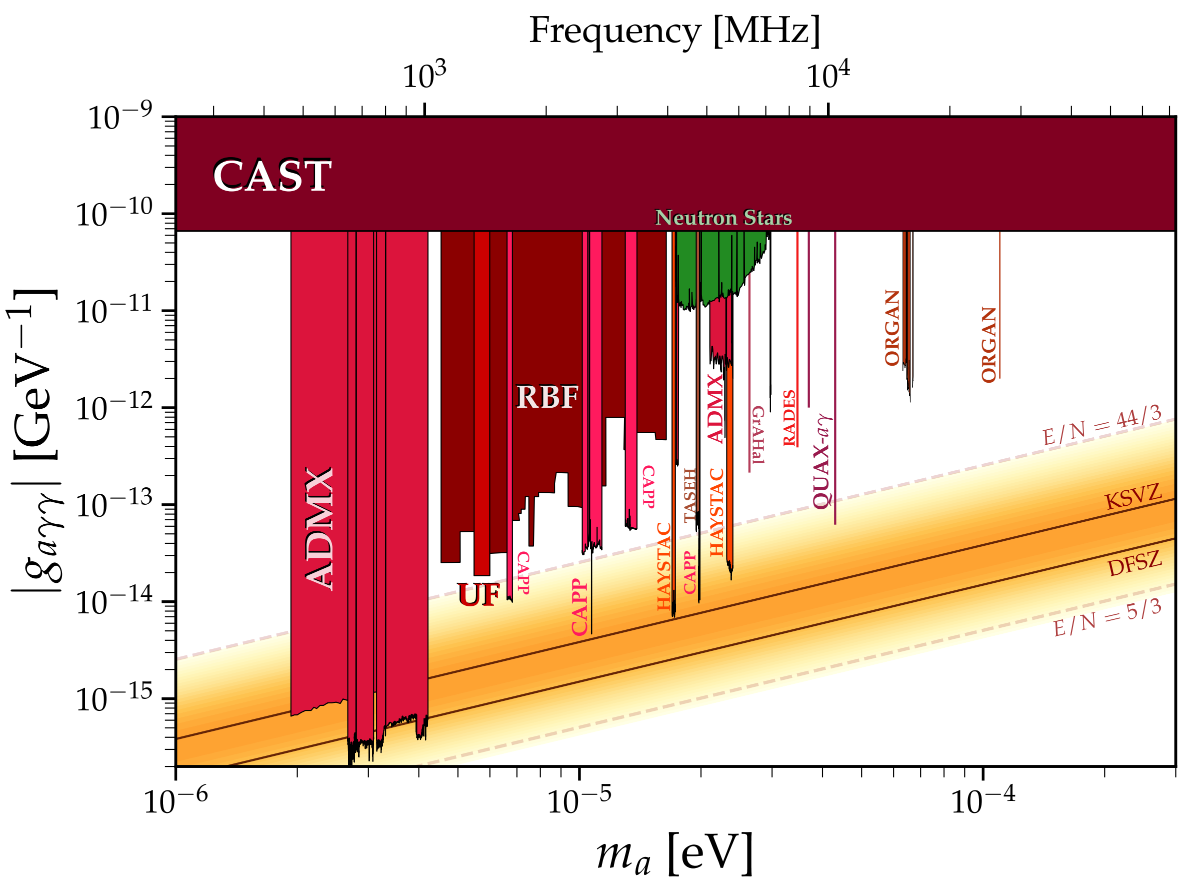
Cavities across the globe

Cavity haloscopes are rapidly growing in maturity, exploring this mass-range with the photon-coupling.

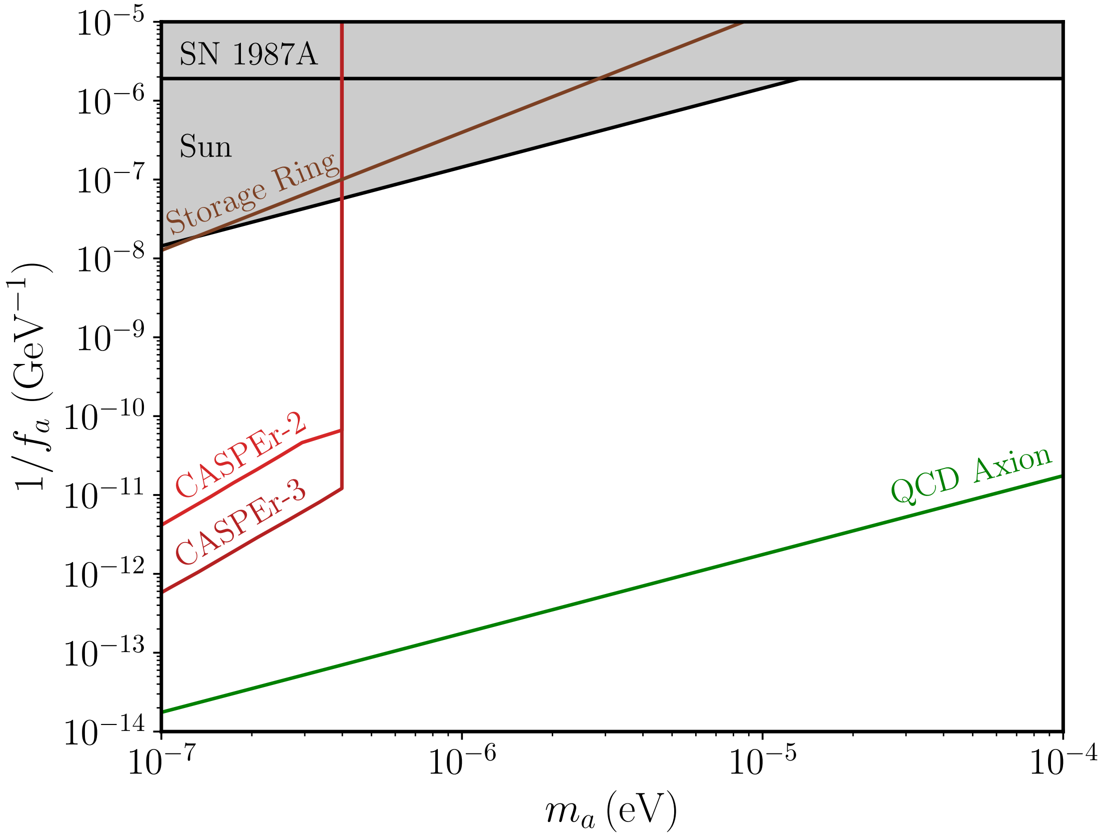
QCD-axion at ~Micro-eV

Most-motivated mass range for QCD axion dark matter is $m_a \sim (0.1 - 100)\ \mu\text{eV}$

<u>Photon-coupling (model-dependent)</u>



<u>QCD-coupling</u>

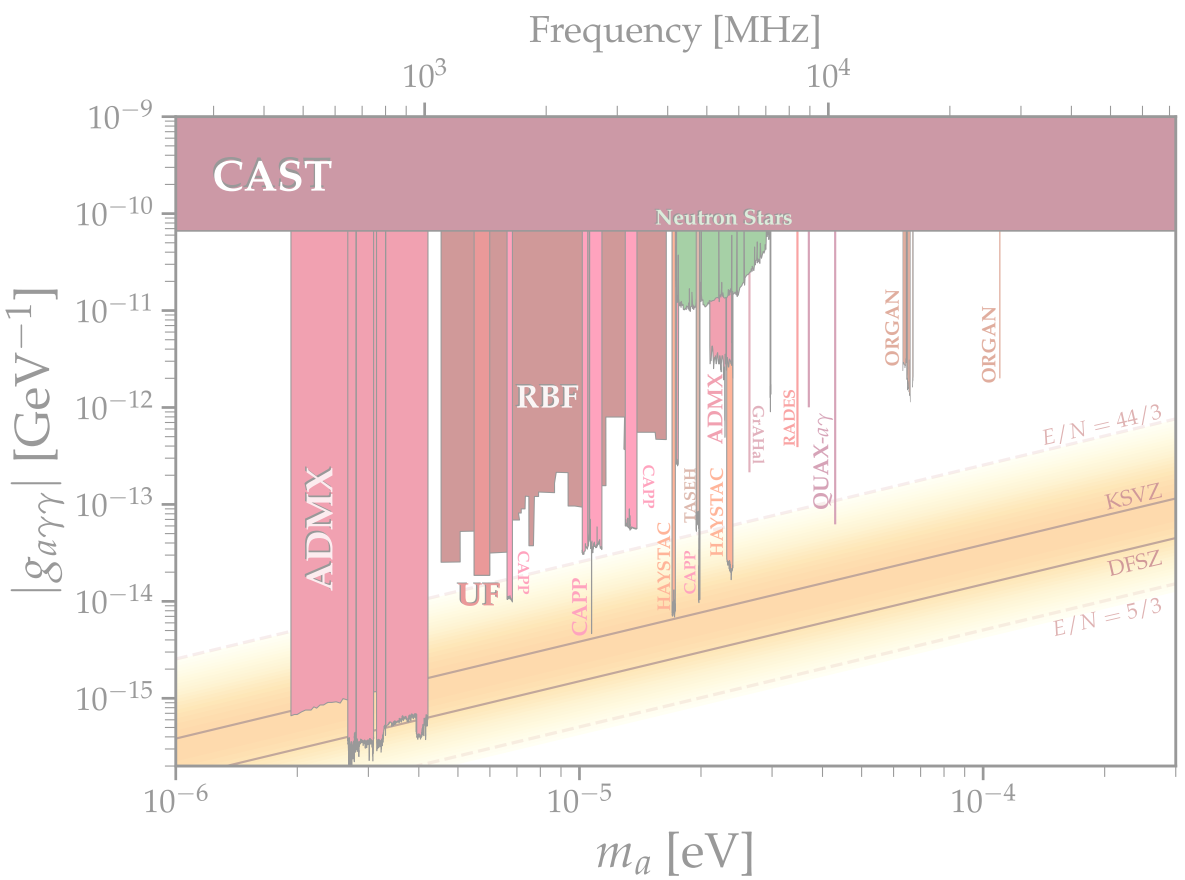


But the defining coupling is to QCD, which gives rise to nuclear effects, such as oscillating nucleon/atomic EDMs.

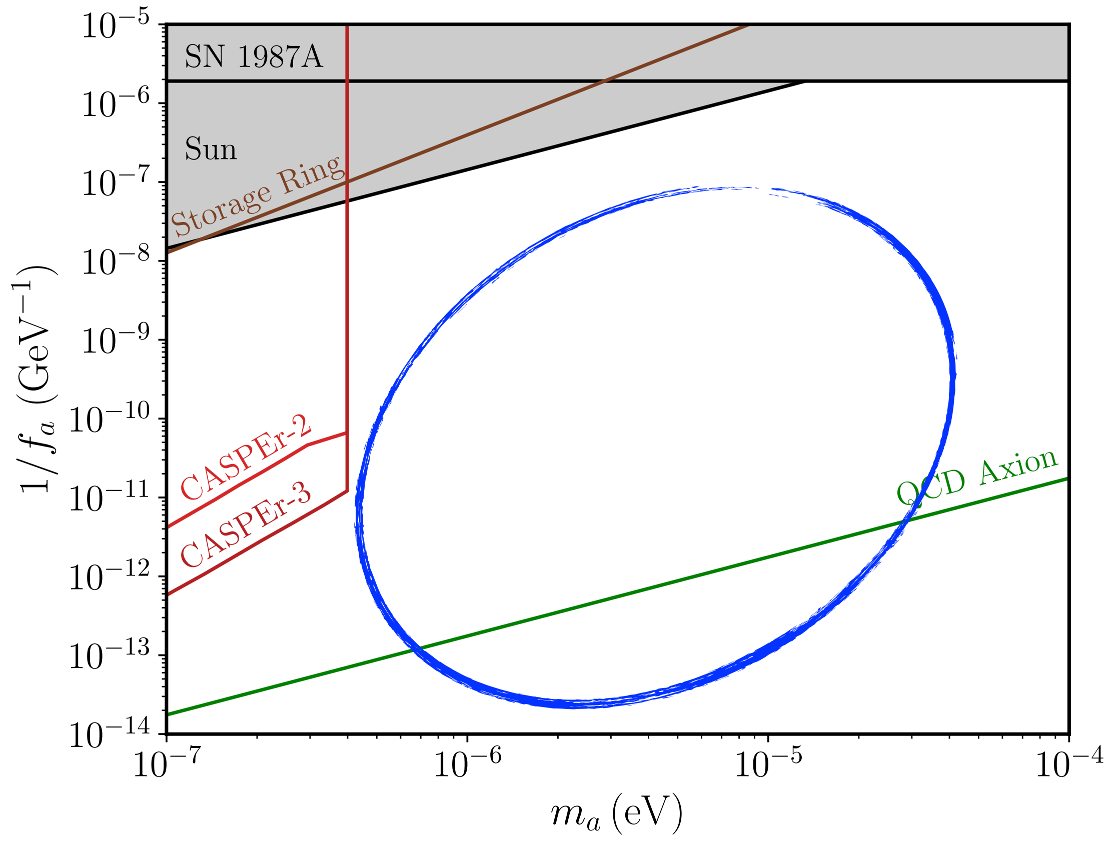
QCD-axion at ~Micro-eV

Most-motivated mass range for QCD axion dark matter is $m_a \sim (0.1 - 100)\ \mu\text{eV}$

Photon-coupling



QCD-coupling

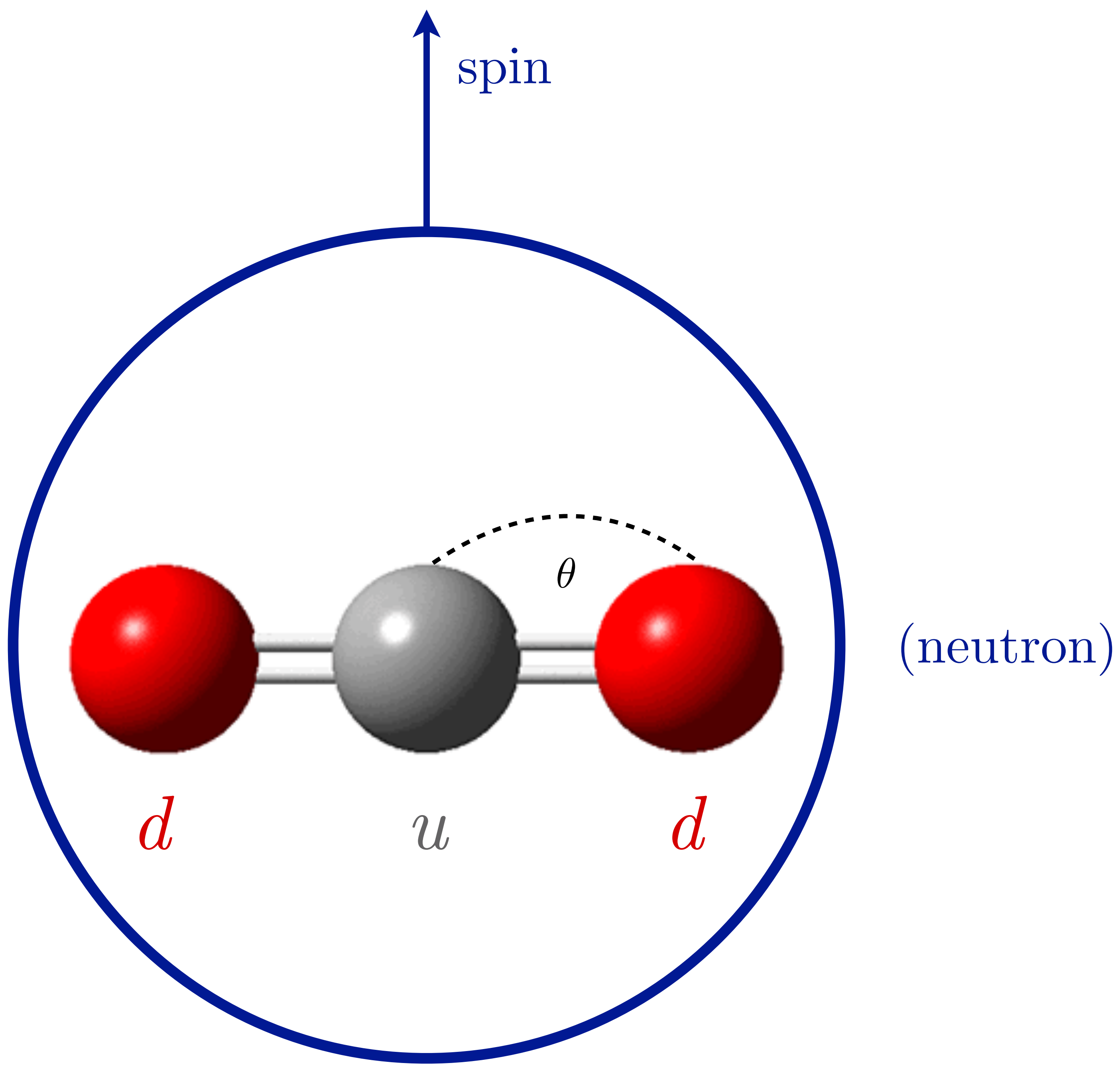


But the defining coupling is to QCD, which gives rise to nuclear effects, such as oscillating nucleon/atomic EDMs.

How to explore the defining coupling in this mass-range?

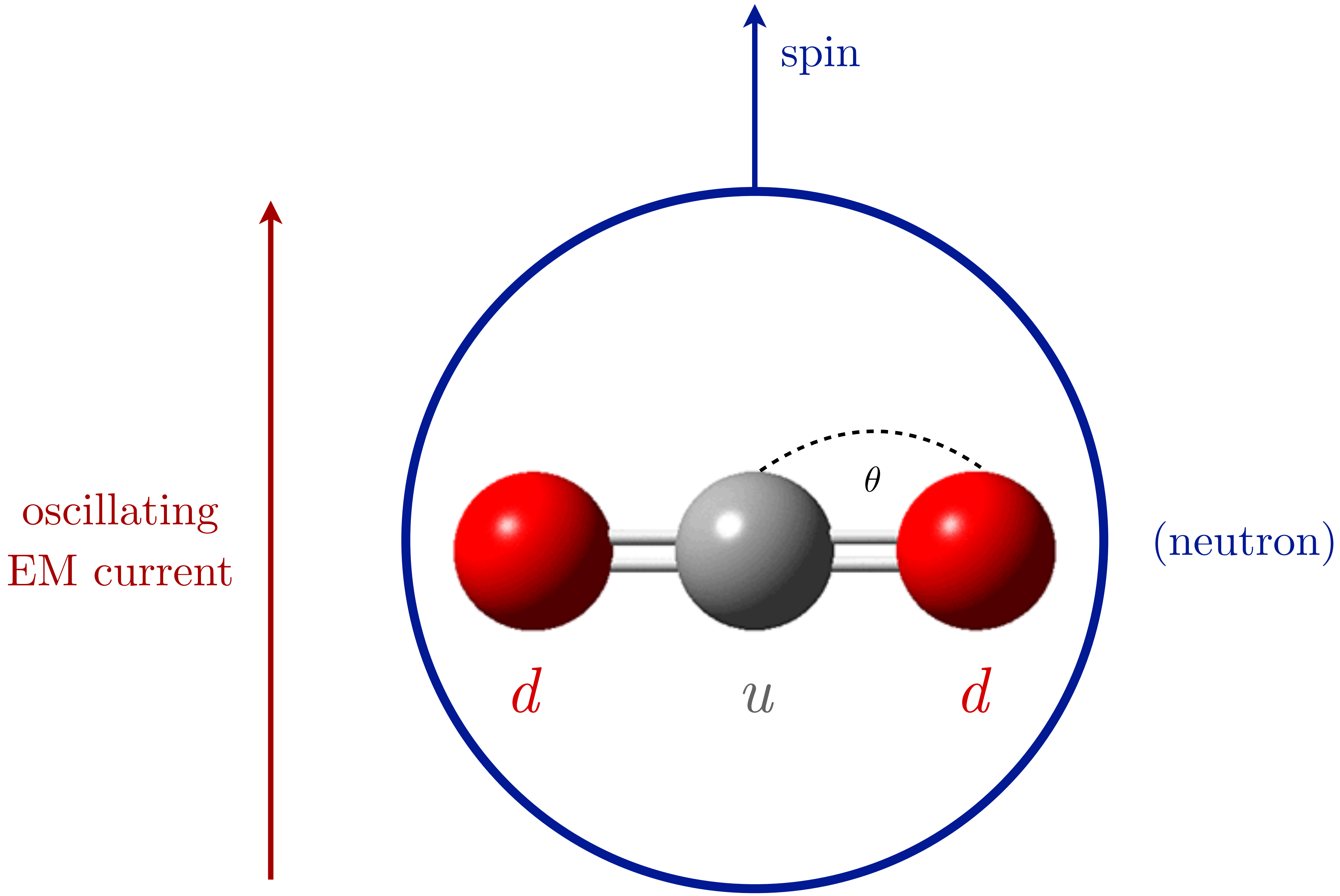
How do we confirm that a signal in cavity haloscopes is ***the*** *QCD axion?*

Oscillating Electric Dipole



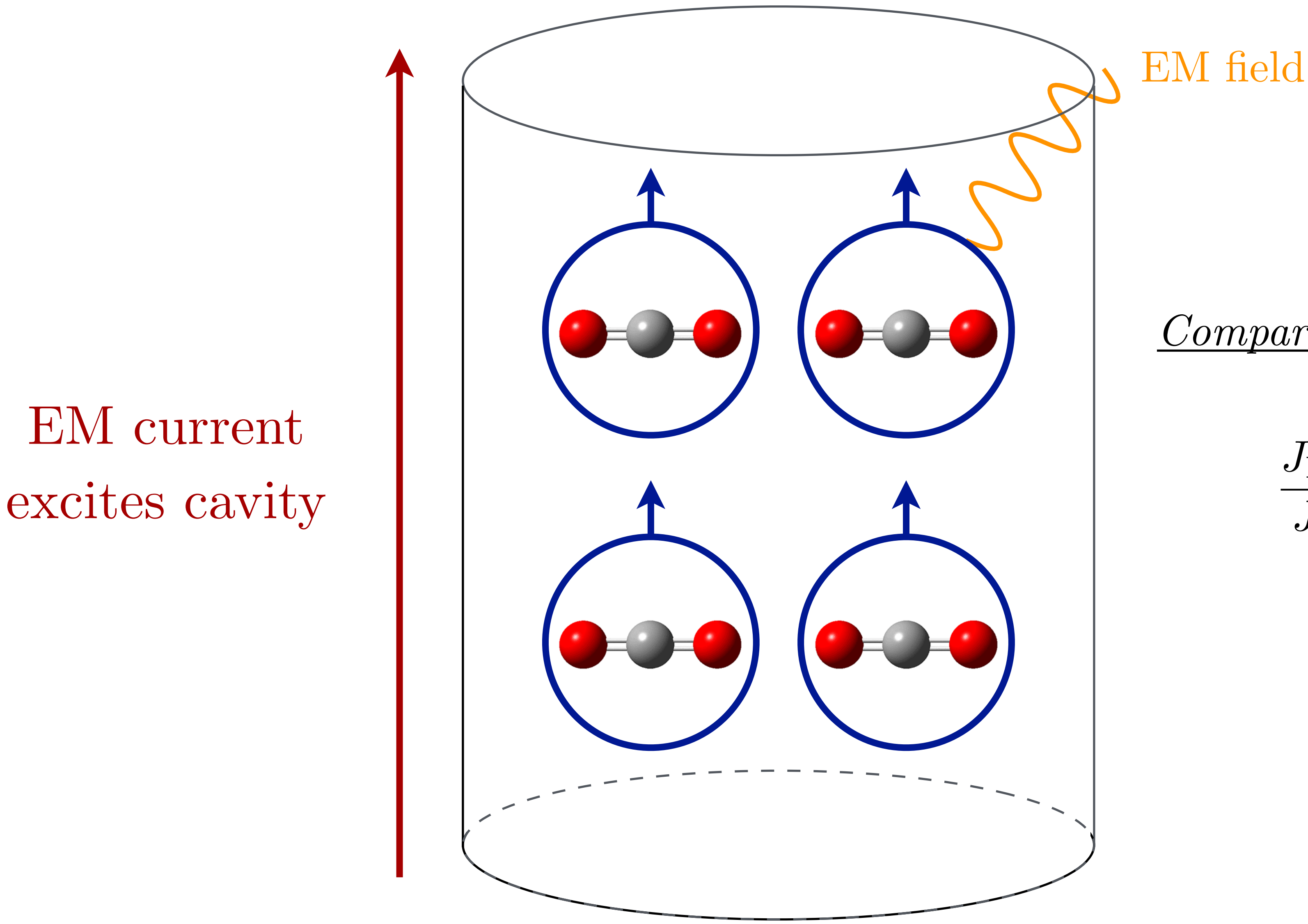
$$\Delta\theta(t) \sim a/f_a \sim 10^{-18} \cos m_a t$$

Oscillating Electric Dipole



$$\Delta\theta(t) \sim a/f_a \sim 10^{-18} \cos m_a t$$

Polarization Haloscope



Compare to cavities for the EM-coupled QCD axion

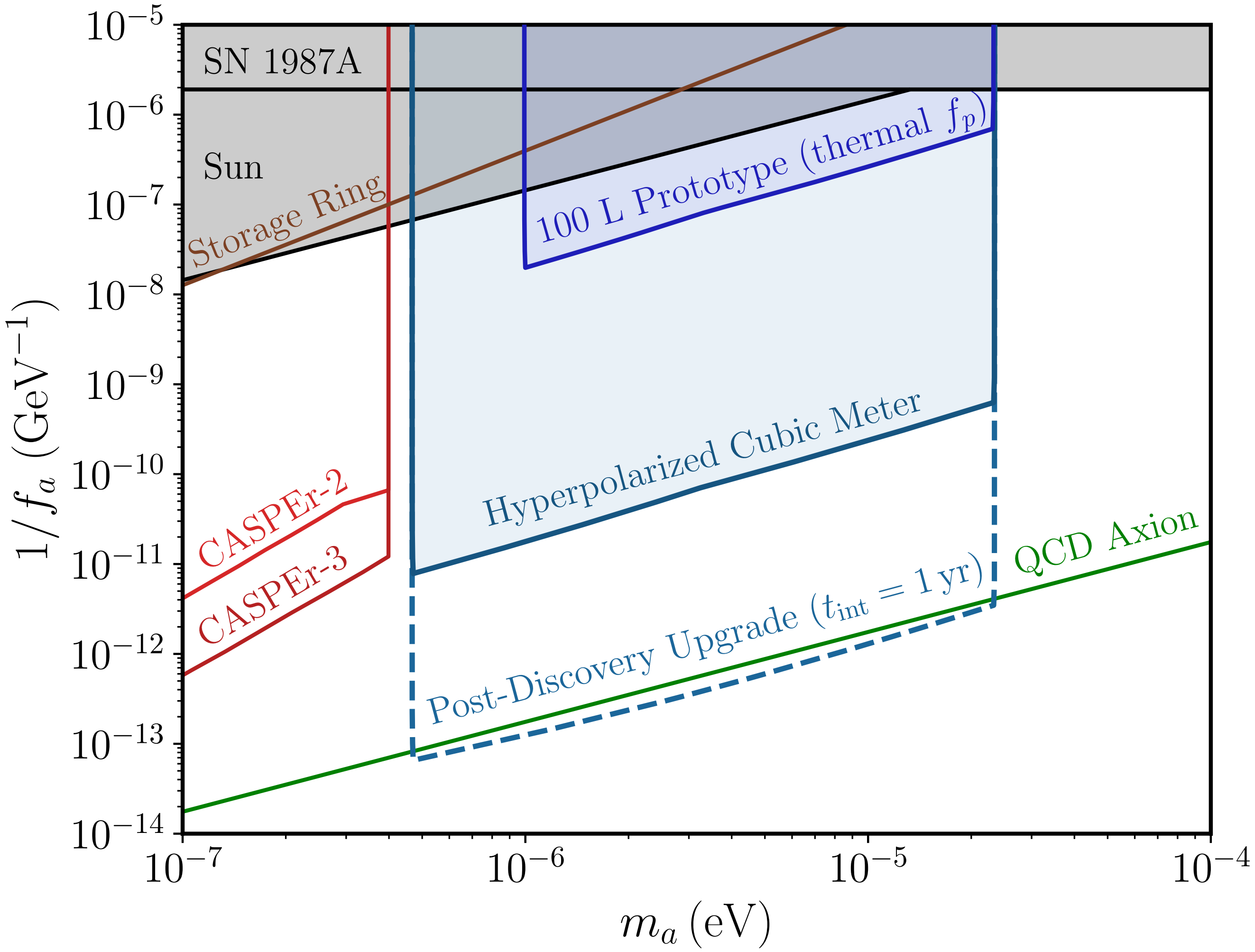
$$\frac{J_{\mathrm{EDM}}}{J_{a\gamma\gamma}} \sim 10^{-3} \times \left(\frac{n_{\mathrm{spin}}}{10^{23}\ \mathrm{cm}^{-3}}\right)\left(\frac{10\ \mathrm{T}}{B}\right)$$

Polarization Haloscope: polarized nuclear material inside cavity

(no B-field needed, in principle)

Projected Sensitivity

with Kevin Zhou arXiv:2209.12901



Optimal Materials

(abundant and stable rare Earth nuclei)

	^{161}Dy	^{153}Eu	^{155}Gd
estimated $\langle S_z \rangle$ (e fm^3 θ_a)	4.3	1.0	1.2
estimated $\lvert d_A \rvert$ (10^{-3} e fm θ_a)	1.2	0.25	0.3
natural abundance	19%	52%	15%
metal price (\$/ton)	300 k	30 k	30 k

Only way to confirm that putative signal is actually the QCD axion in the most motivated mass-range

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Upcoming with A. Millar, T. Trickle, K. Zhou

III. Spin-coupled Axions

Axion Wind

The Usual Story

(coupling of axion to fermion's spin)

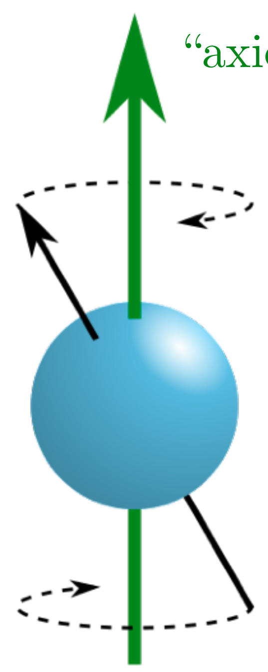
$$\mathscr{L} \sim g_{aff}\, \partial_\mu a\, \bar{f}\gamma^\mu\gamma^5 f$$

↓

(*effective* spin-coupled magnetic field)

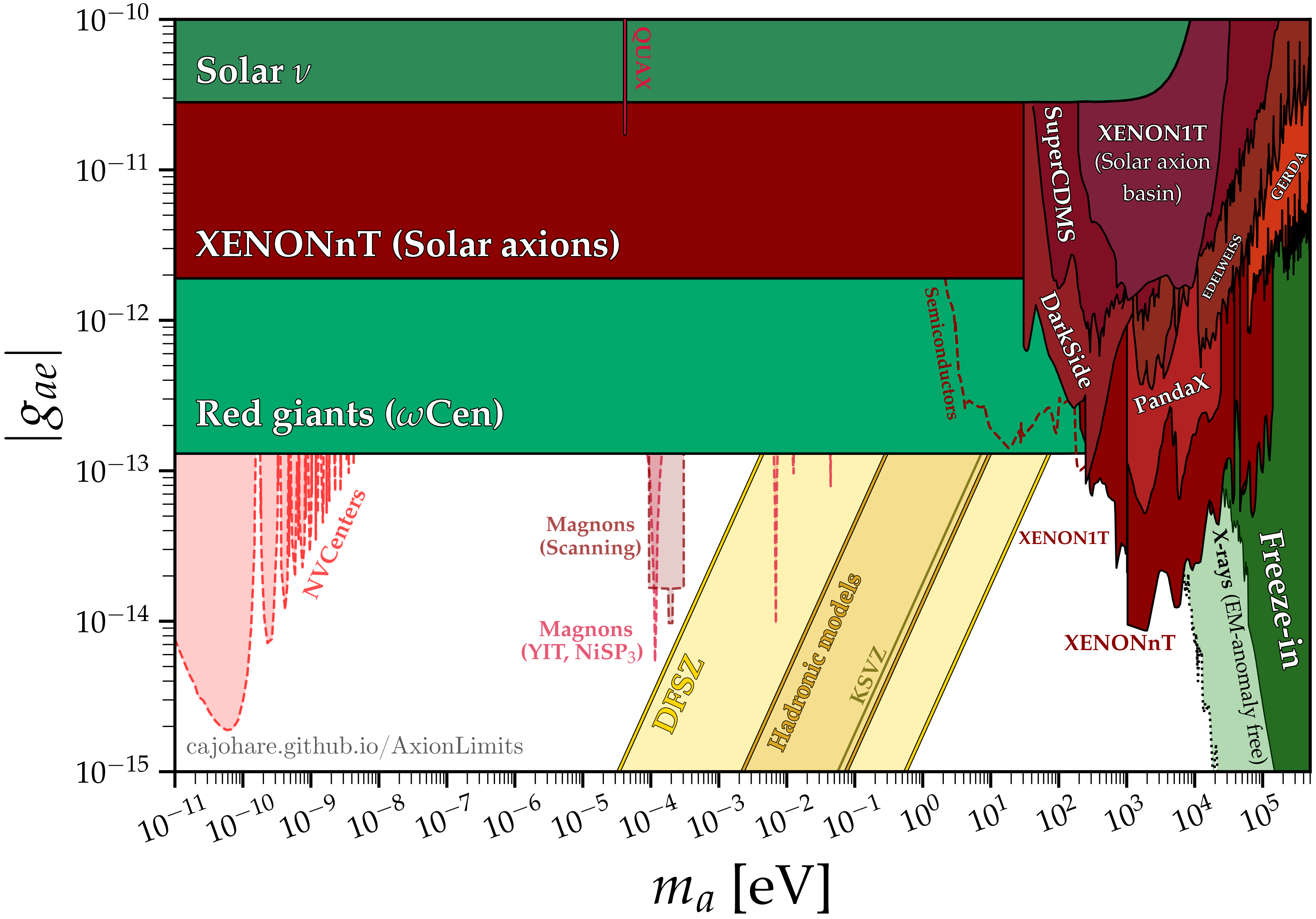
$$(\mu B)_{\text{eff}} \sim g_{aff}\, \nabla a$$

$\Longrightarrow$



The literature is full of discrepancies regarding other possible effects.
What is the final word regarding physical signals?

Axion Wind



Solar ν
QUAX
XENONnT (Solar axions)
Red giants (ωCen)
SuperCDMS
XENON1T (Solar axion basin)
DarkSide
PandaX
EDELWEISS
GERDA
Semiconductors
XENON1T
XENONnT
X-rays (EM-anomaly free)
Freeze-in
NVCenters
Magnons (Scanning)
Magnons (YIT, NiSP3)
DFSZ
Hadronic models
KSVZ
cajohare.github.io/AxionLimits
$|g_{ae}|$
m_a [eV]

Spin-Coupled Axions

$$L \sim \int d^3\mathbf{x}\ g_{aff}\ \partial_\mu a\ \bar{f}\gamma^\mu\gamma^5 f$$

Spin-Coupled Axions

$$L \sim \int d^3\mathbf{x}\ g_{aff}\ \partial_\mu a\ \bar{f}\gamma^\mu\gamma^5 f$$

$$\int d^3\mathbf{x}\ \bar{f}\gamma^\mu\gamma^5 f\ \Big|_{v_f\ =\ 0} \sim (0, \boldsymbol{\sigma}) \quad \xrightarrow{\text{boost}} \quad \int d^3\mathbf{x}\ \bar{f}\gamma^\mu\gamma^5 f\ \Big|_{v_f\ \neq\ 0} \sim (\boldsymbol{v}_f \cdot \boldsymbol{\sigma}\ ,\ \boldsymbol{\sigma})$$

Spin-Coupled Axions

$$L \sim \int d^3\mathbf{x}\; g_{aff}\; \partial_\mu a\; \bar{f}\gamma^\mu\gamma^5 f$$

$$\int d^3\mathbf{x}\; \bar{f}\gamma^\mu\gamma^5 f\;\Big|_{v_f\,=\,0} \sim (0,\boldsymbol{\sigma}) \quad \xrightarrow{\text{boost}} \quad \int d^3\mathbf{x}\; \bar{f}\gamma^\mu\gamma^5 f\;\Big|_{v_f\,\neq\,0} \sim (\boldsymbol{v}_f\cdot\boldsymbol{\sigma}\;,\;\boldsymbol{\sigma})$$

$$L \sim g_{aff}\;\dot{a}\;\boldsymbol{\sigma}\cdot\boldsymbol{v}_f + g_{aff}\;\nabla a\cdot\boldsymbol{\sigma}$$

Spin-Coupled Axions

$$L \sim \int d^3\mathbf{x}\; g_{aff}\; \partial_\mu a\; \bar{f}\gamma^\mu\gamma^5 f$$

$$\int d^3\mathbf{x}\; \bar{f}\gamma^\mu\gamma^5 f\, \Big|_{v_f\,=\,0} \sim (0, \boldsymbol{\sigma}) \quad \xrightarrow{\text{boost}} \quad \int d^3\mathbf{x}\; \bar{f}\gamma^\mu\gamma^5 f\, \Big|_{v_f\,\neq\,0} \sim (\boldsymbol{v}_f \cdot \boldsymbol{\sigma}\;,\; \boldsymbol{\sigma})$$

"axion-wind"

$$L \sim g_{aff}\; \dot{a}\; \boldsymbol{\sigma} \cdot \boldsymbol{v}_f + g_{aff}\; \nabla a \cdot \boldsymbol{\sigma}$$

the usual *effective* spin-coupled B-field

Spin-Coupled Axions

$$L \sim \int d^3\mathbf{x}\; g_{aff}\; \partial_\mu a\; \bar{f}\gamma^\mu\gamma^5 f$$

$$\int d^3\mathbf{x}\; \bar{f}\gamma^\mu\gamma^5 f\,\Big|_{v_f\,=\,0} \sim (0, \boldsymbol{\sigma}) \;\xrightarrow{\text{boost}}\; \int d^3\mathbf{x}\; \bar{f}\gamma^\mu\gamma^5 f\,\Big|_{v_f\,\neq\,0} \sim (\boldsymbol{v}_f\cdot\boldsymbol{\sigma}\;,\;\boldsymbol{\sigma})$$

"axioelectric" "axion-wind"

$$L \sim g_{aff}\;\dot{a}\;\boldsymbol{\sigma}\cdot\boldsymbol{v}_f + g_{aff}\;\nabla a\cdot\boldsymbol{\sigma}$$

the usual *effective* spin-coupled B-field

effective spin-coupled vector potential

$\rightarrow$ *effective* spin-coupled force

$$\boldsymbol{E}_{\text{eff}} \sim g_{aff}\,\frac{d}{dt}(\dot{a}\,\boldsymbol{\sigma})$$

Everything stems from these effects expressed in different frames.

Spin-Coupled Axions

$$\boldsymbol{A}_{\text{eff}} \sim g_{aff}\, \dot{a}\, \boldsymbol{\sigma} \implies \boldsymbol{E}_{\text{eff}} \sim g_{aff}\, \frac{d}{dt}(\dot{a}\, \boldsymbol{\sigma})$$

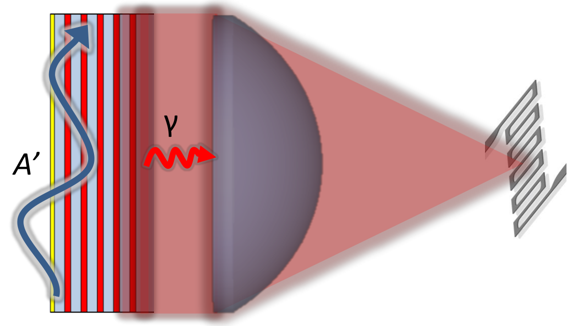
All signals scale as $\ddot{a}$ or $\dot{a}\,\dot{\sigma} \sim \dot{a}\,\mu\,\sigma \times B$

(corrects or invalidates some previously-claimed signals)

(more interesting at higher masses)

E_{eff} can do work, in the form of generating EM currents in polarized material or accelerating blocks of polarized material

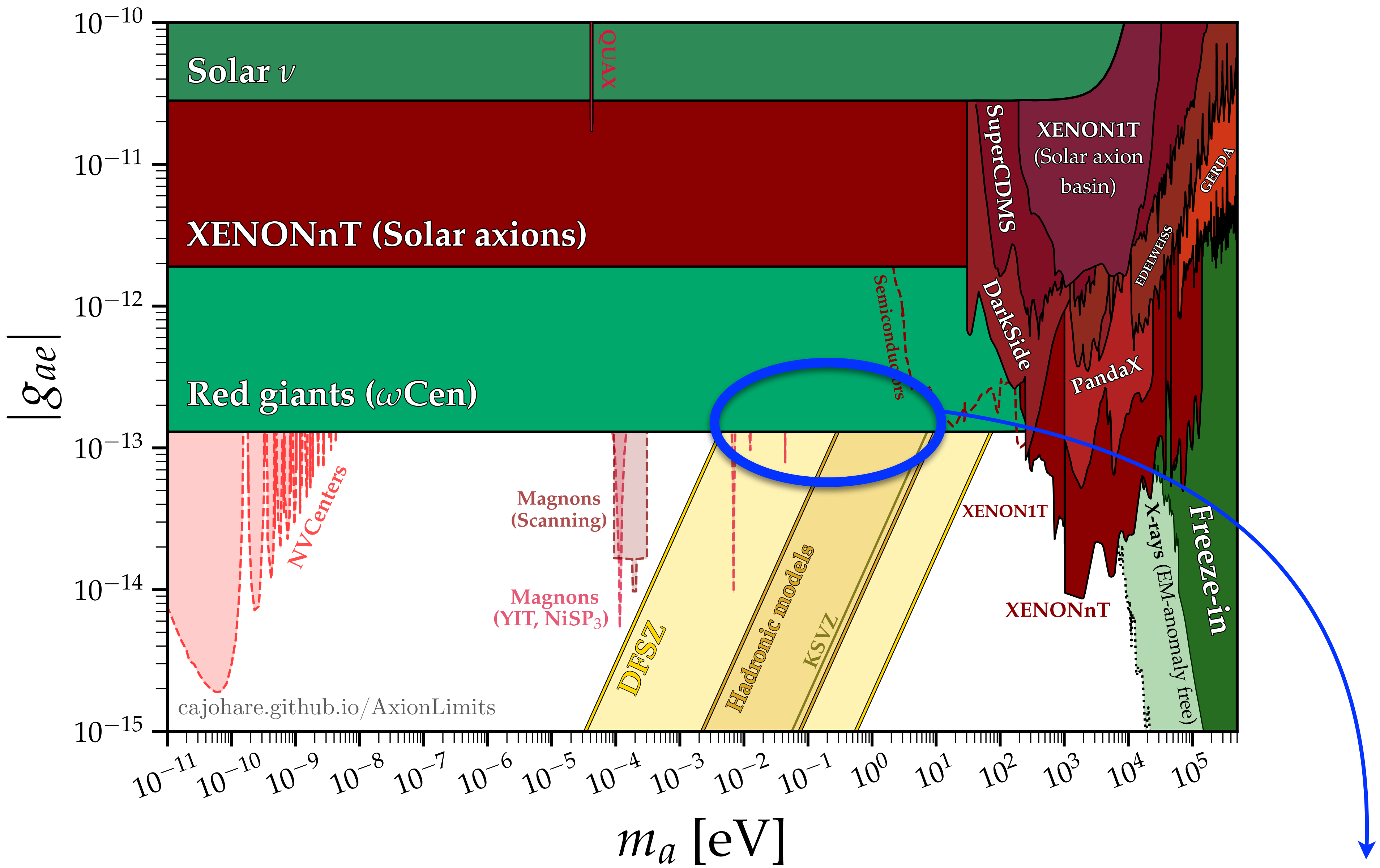
(place polarized material in EM detectors)



~ LAMPOST for spin-coupled axions

Spin-Coupled Axions

Upcoming with A. Millar, T. Trickle, K. Zhou



dielectric stacks of polarized material with single-photon readout

Spin-Coupled Axions

Upcoming with A. Millar, T. Trickle, K. Zhou

$$L \sim g_{aff}\ \dot{a}\ \boldsymbol{\sigma} \cdot \boldsymbol{v}_f + g_{aff}\ \nabla a \cdot \boldsymbol{\sigma}$$

axioelectric *axion wind*

Other Nuggets

Spin-Coupled Axions

Upcoming with A. Millar, T. Trickle, K. Zhou

$$L \sim g_{aff}\,\dot{a}\,\boldsymbol{\sigma}\cdot\boldsymbol{v}_f + g_{aff}\,\nabla a\cdot\boldsymbol{\sigma}$$

axioelectric *axion wind*

Other Nuggets

- Magnetic stacks for the wind coupling (photon readout of spin-waves)

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- Absorption rate for the wind coupling ~ Im[-1/μ] (magnetic energy loss function)

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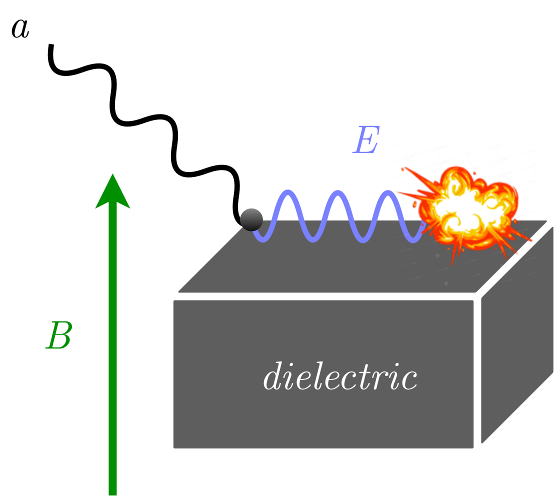
axioelectric *axion wind*

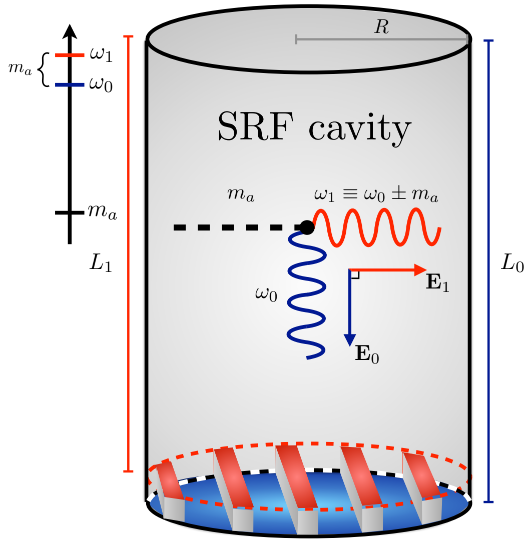
Other Nuggets

- Magnetic stacks for the wind coupling (photon readout of spin-waves)
- Absorption rate for the wind coupling ~ Im[-1/μ] (magnetic energy loss function)
- Mechanical forces on spin-polarized sensors
- **No** EDMs proportional to the field value
- **No** leading order electronic energy shifts in normal materials

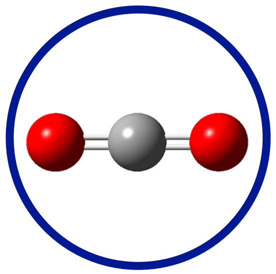
Outlook

Low- and High-Mass EM-coupled Axions

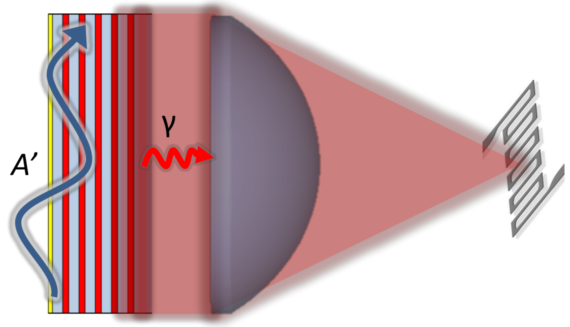




EM signals of QCD- and Spin-coupled Axions



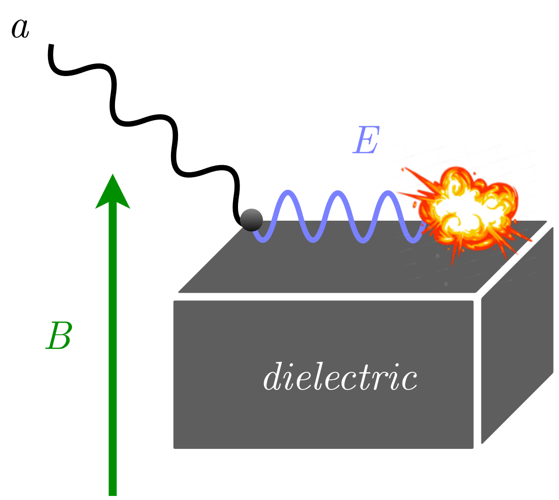
neutron EDM

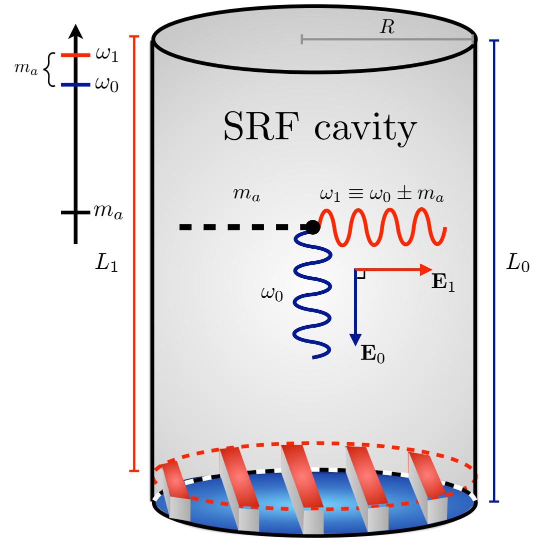


magnetic dielectric stack

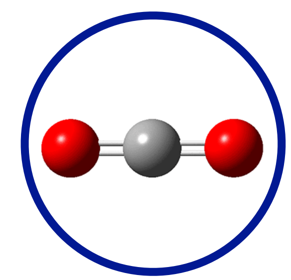
Outlook

Low- and High-Mass EM-coupled Axions

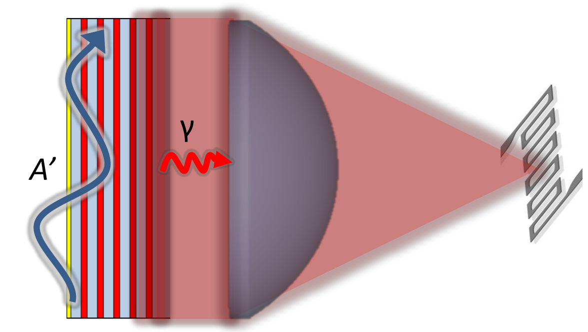




EM signals of QCD- and Spin-coupled Axions



neutron EDM



magnetic dielectric stack

The Motivated Opportunist

Important to explore wide range of masses and couplings.

There are large regions of axion parameter space that require new ideas.

"It is a capital mistake to theorize before one has data. Insensibly one begins to twist facts to suit theories, instead of theories to suit facts."
- *Sherlock Holmes*

+ theory priors →

"It is more important to have beauty in the equations of physics than to have them agree with experiments."
- *Paul Dirac*

Back Up Slides

Axion Electrodynamics

static B-field

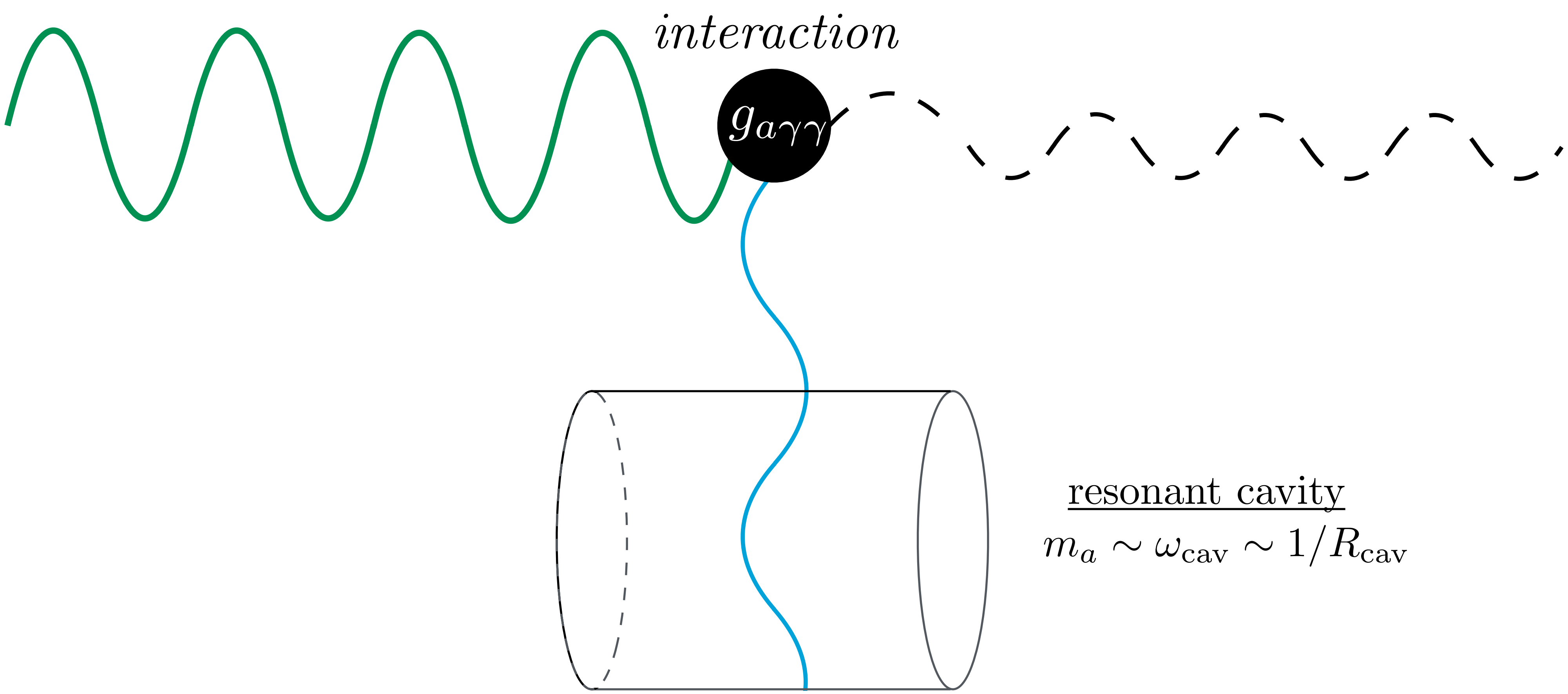
$\sim \cos \cancel{\omega_0} t$

(frequency ~ your choice)

galactic axion field

$\sim \cos m_a t$

(frequency ~ axion mass)



signal EM field $\sim \cos(\cancel{\omega_0} + m_a)t$

ideal detector is resonantly matched to signal frequency

signal power $\sim (\cancel{\omega_0} + m_a)\ \cos(\cancel{\omega_0} + m_a)t$

Axion Electrodynamics

<u>*static B-field*</u>

$\sim \cos \cancel{\omega_0} t$

(frequency ~ your choice)

<u>*galactic axion field*</u>

$\sim \cos m_a t$

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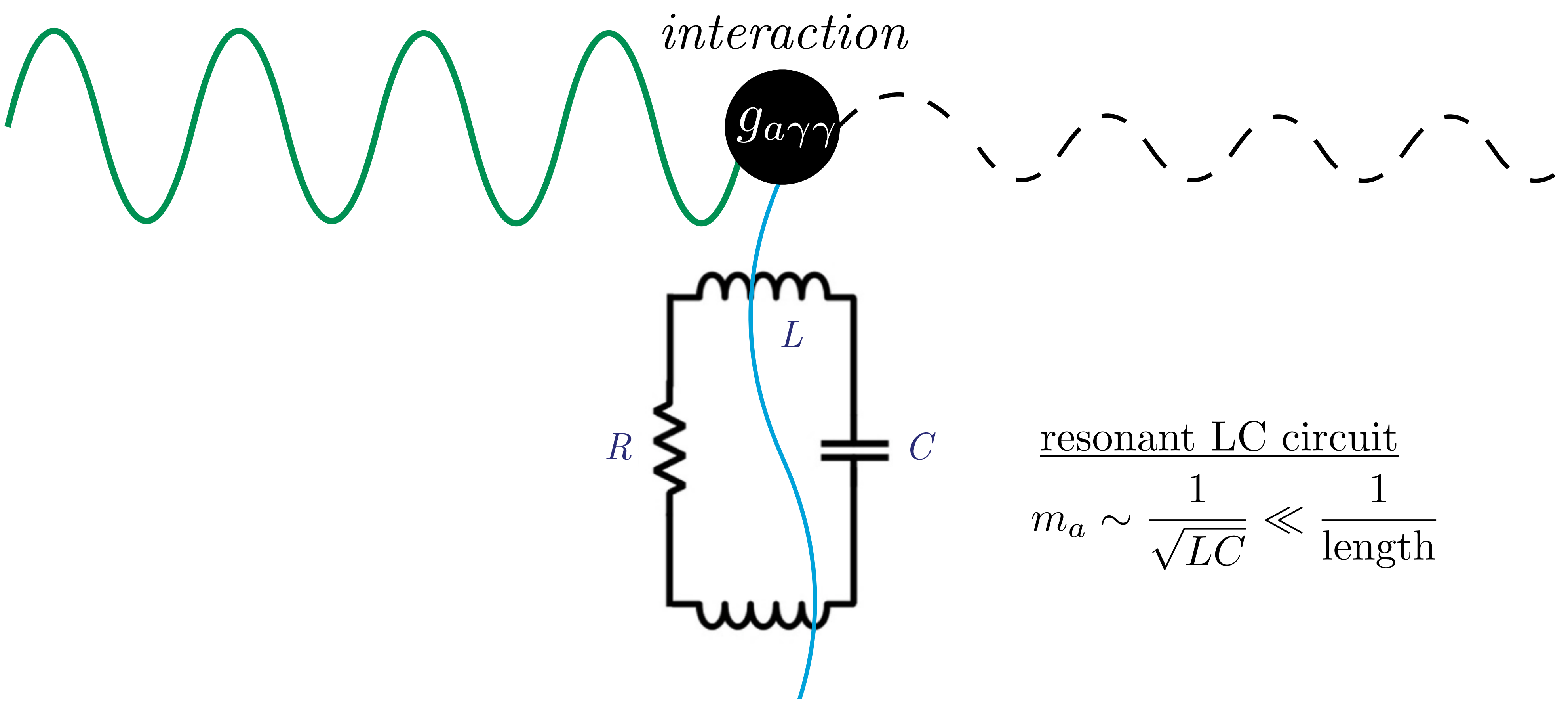


<u>resonant LC circuit</u>

$$m_a \sim \frac{1}{\sqrt{LC}} \ll \frac{1}{\text{length}}$$

<u>*signal EM field*</u> $\sim \cos(\cancel{\omega_0} + m_a)t$

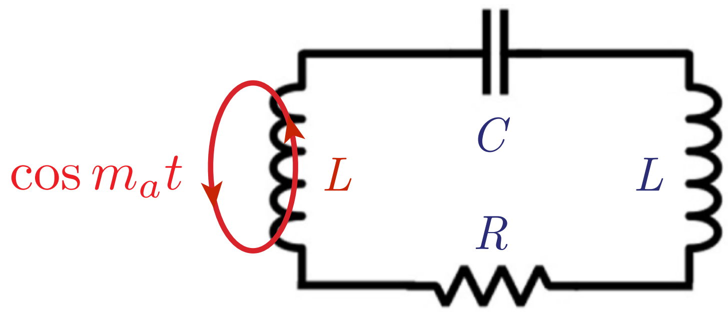
<u>ideal detector is resonantly matched to signal frequency</u>

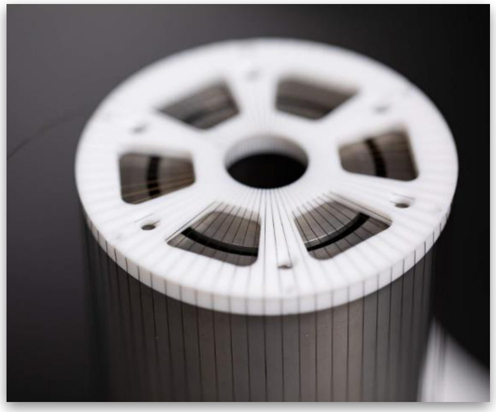
signal power $\sim (\cancel{\omega_0} + m_a)\ \cos(\cancel{\omega_0} + m_a)t$

Below ~Micro-eV

LC circuit (DMRadio @ SLAC)

arXiv:2204.13781, arXiv:2203.11246





$B \sim$ few $\times$ T , $Q \sim 10^6$

$$\omega_{\rm LC} \sim \frac{1}{\sqrt{LC}} \sim m_a \ll \frac{1}{\text{length}}$$

$\omega_{\rm LC} \sim m_a \implies$ difficult to probe $m_a \lesssim 10$ kHz $\sim 10^{-10}$ eV

$$\text{signal power} \propto \frac{\text{detector size}}{\text{axion Compton wavelength}} \ll 1$$

Axion Electrodynamics

pump mode

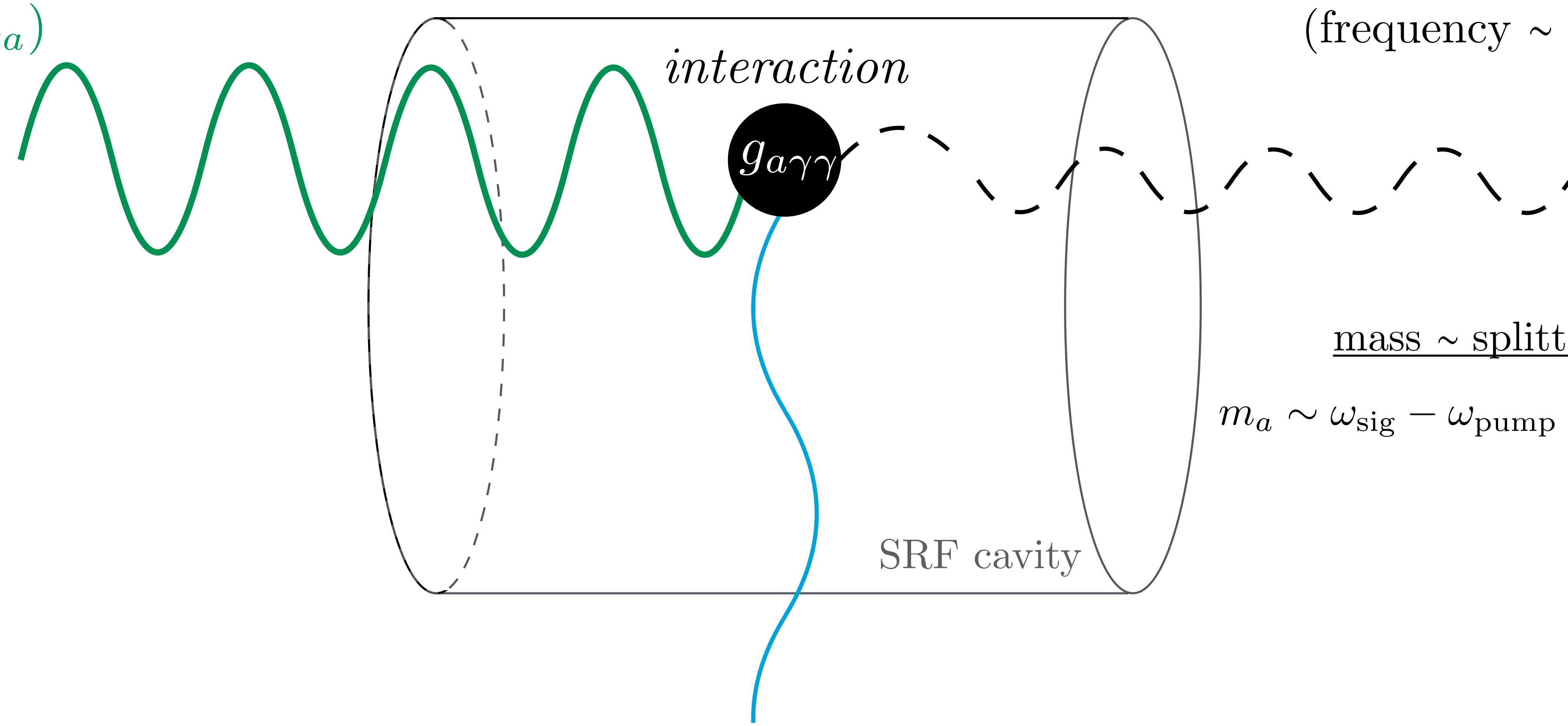
$\sim \cos \omega_0 t$

$(\omega_0 \gg m_a)$

galactic axion field

$\sim \cos m_a t$

(frequency ~ axion mass)



mass ~ splitting

$m_a \sim \omega_{\text{sig}} - \omega_{\text{pump}} \ll \omega_{\text{pump}}$

signal mode $\sim \cos{(\omega_0 + m_a)t} \sim \cos \omega_0 t$

axion mass is resonantly matched to frequency ***splitting***

signal power $\sim (\omega_0 + m_a)\ \cos{(\omega_0 + m_a)t}$

Below ~Micro-eV

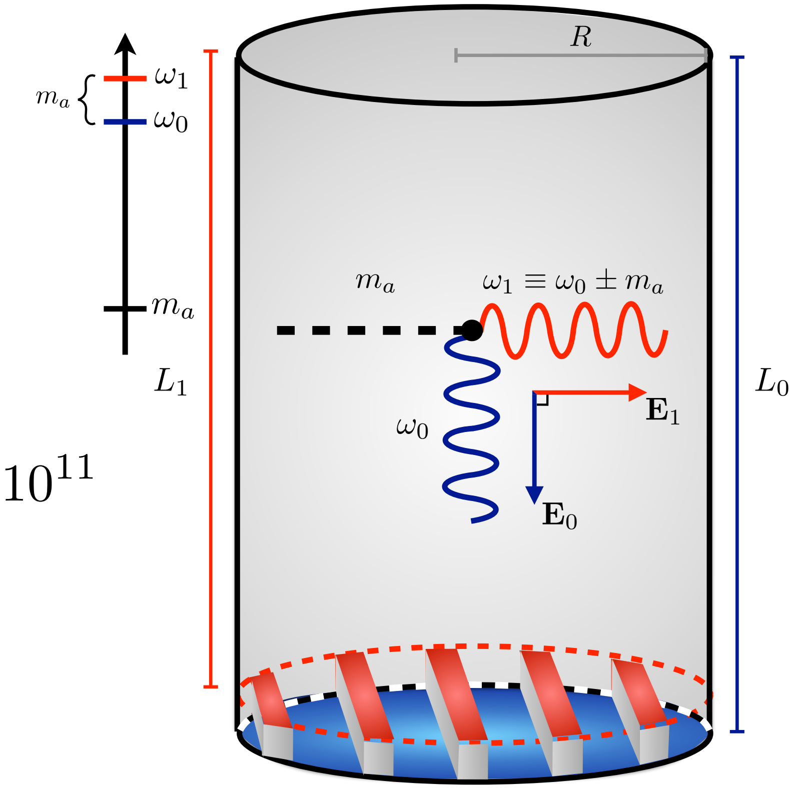
Heterodyne/Upconversion (SRF cavities @ Fermilab/SLAC)

arXiv:1912.11048, arXiv:1912.11056, arXiv:2007.15656

A. Berlin, R. D'Agnolo, S. Ellis, C. Nantista, J. Neilson, P. Schuster, S. Tantawi, N. Toro, K. Zhou

$$\Delta\omega \sim m_a \ll \omega \sim \text{GHz}$$

$$B \sim \text{few} \times 100 \text{ mT} \ , \ Q \sim \text{few} \times 10^{11}$$

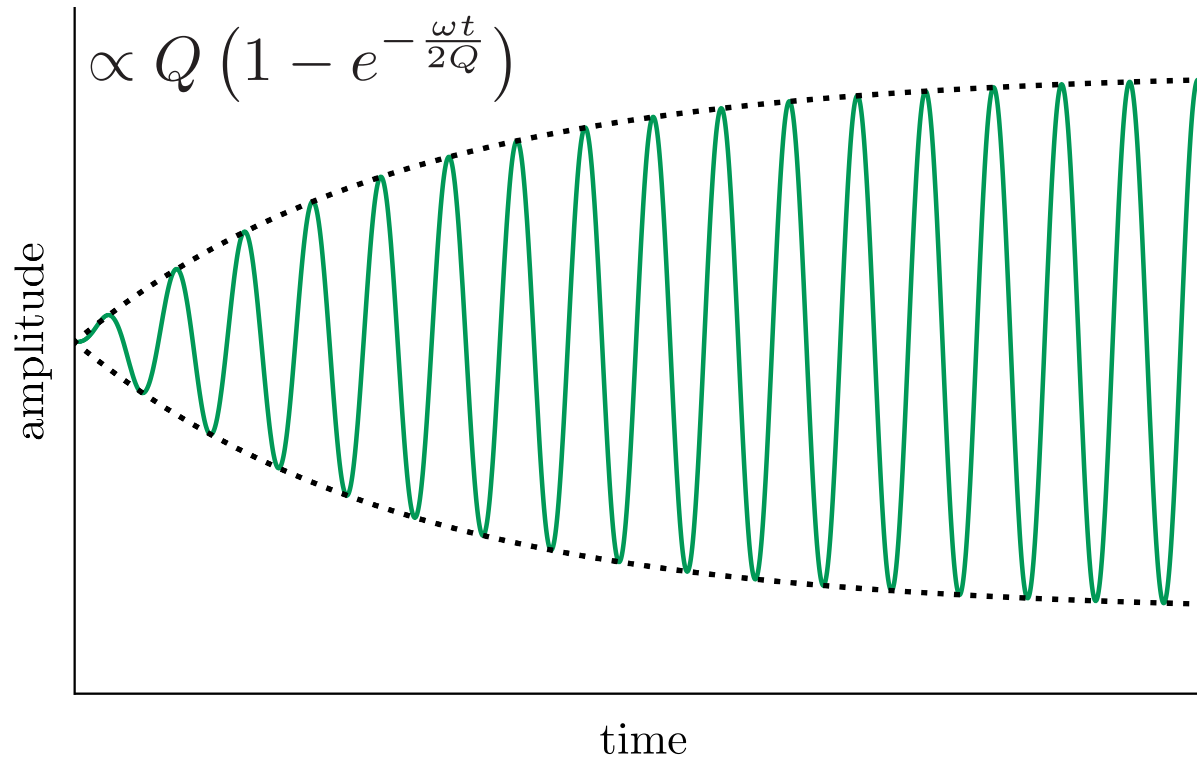


$m_a \sim \omega_{\text{sig}} - \omega_{\text{pump}} \ll \omega_{\text{pump}} \implies$ small mechanical deformations to tune for small masses

signal power $\propto$ detector size $\times$ mode frequency ~ 1

Driven Damped Harmonic Oscillator

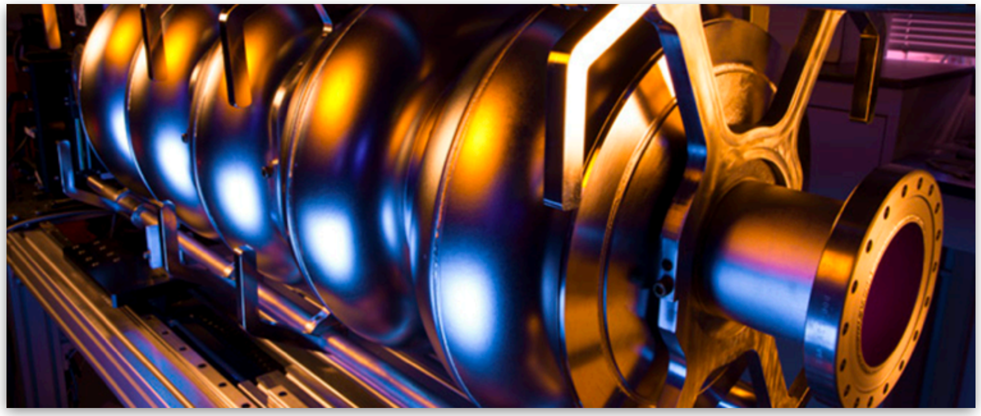
axion signal
on resonance



($\sim Q$ oscillations)

Larger Q means a longer time to resonantly drive power into a resonant detector

SRF cavities are the most efficient engineered oscillators, $Q > 10^{11}$.



SRF Cavities

Why superconducting RF cavities?

1. most efficient engineered oscillators

$Q \sim 10^{11}$

long coherence for quantum computation

2. large oscillating fields

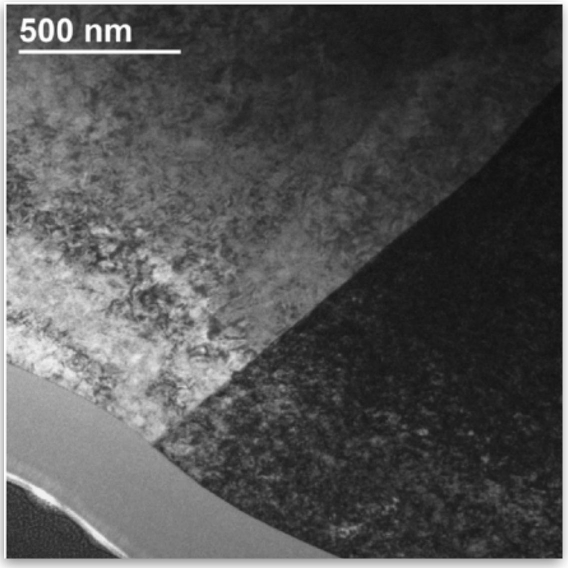
(0.2 T, ~GHz)

3. precisely manufactured and operated

(nm-precision)

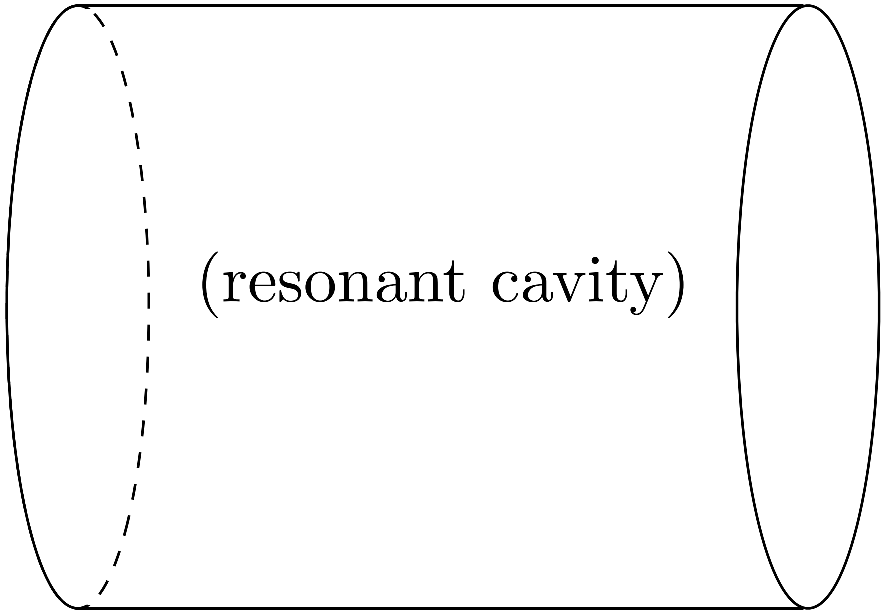
4. already used for new physics searches

(experimentalists)



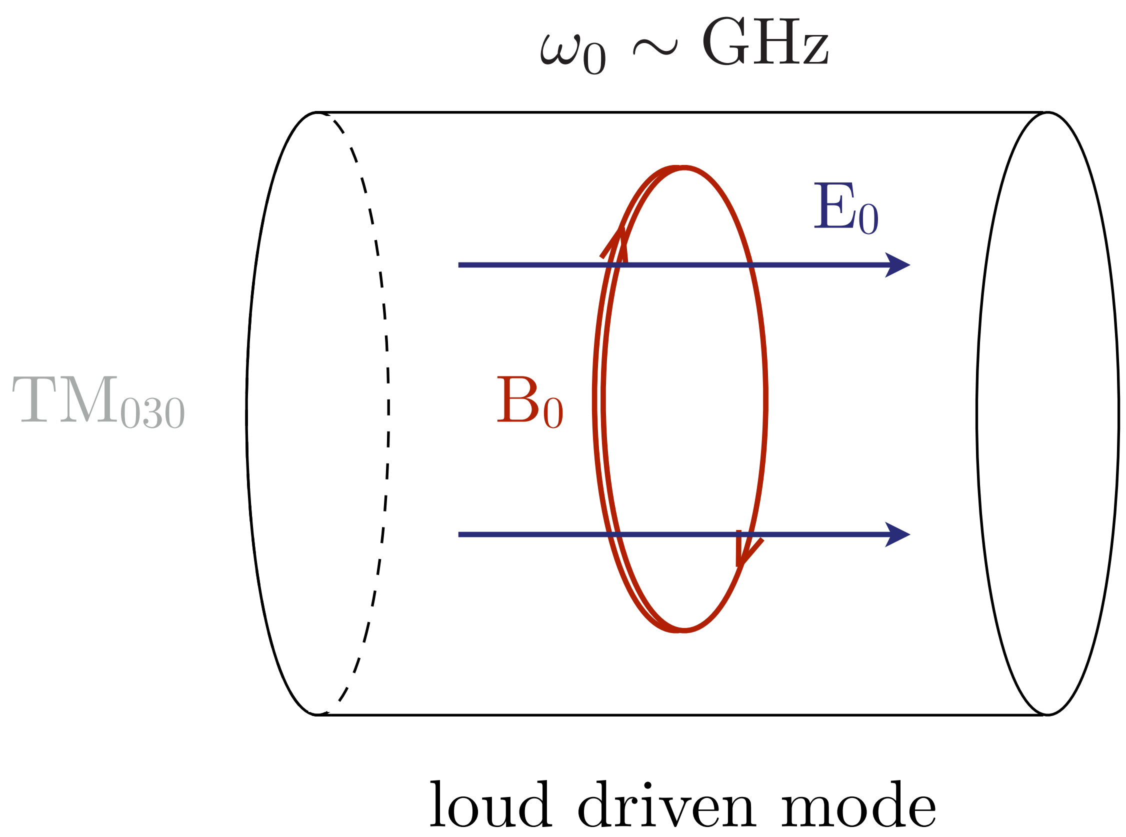
Heterodyne Detection of Axion Dark Matter

Heterodyne Detection of Axion Dark Matter



“Frequency Conversion” between two ~ GHz cavity modes

Heterodyne Detection of Axion Dark Matter



<u>"Frequency Conversion" between two ~ GHz cavity modes</u>

1. Prepare the cavity with a large amount of power at mode ω_0 .
2. Axion dark matter resonantly transfers a small amount of power to mode ω_1 .
3. Scan over frequency-splittings (axion masses) by slightly deforming the cavity.

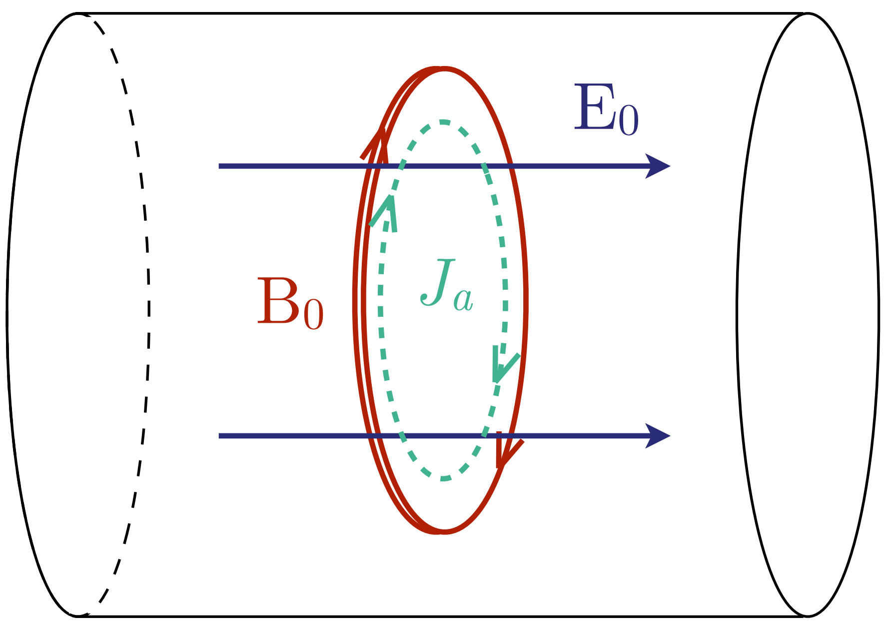
Heterodyne Detection of Axion Dark Matter

axion background

$\cos m_a t$

$\omega_0 \sim$ GHz

TM$_{030}$



loud driven mode

effective axion current

$$J_a \sim g_{a\gamma\gamma}\, B\, \partial_t a$$
$$\propto \cos\left(\omega_0 \pm m_a\right)t$$

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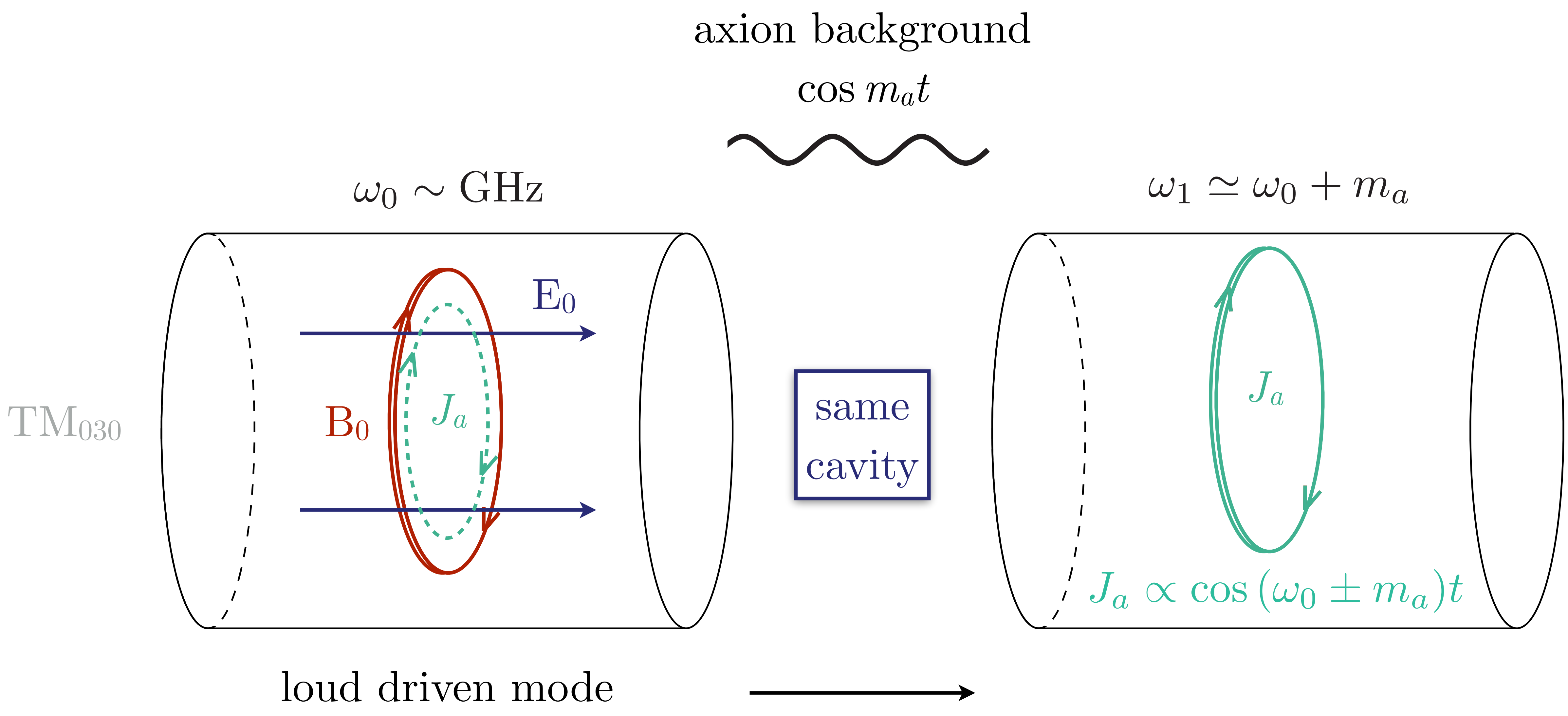

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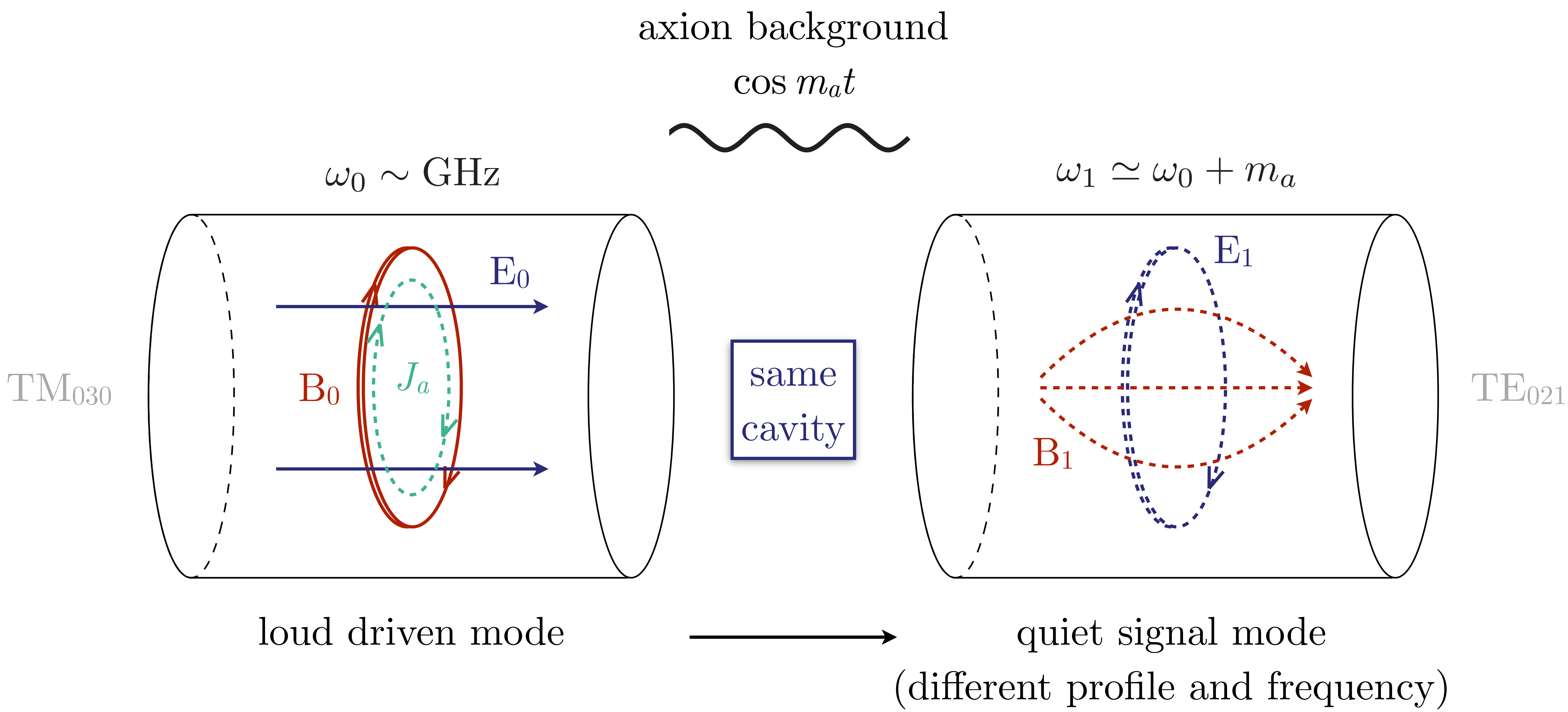

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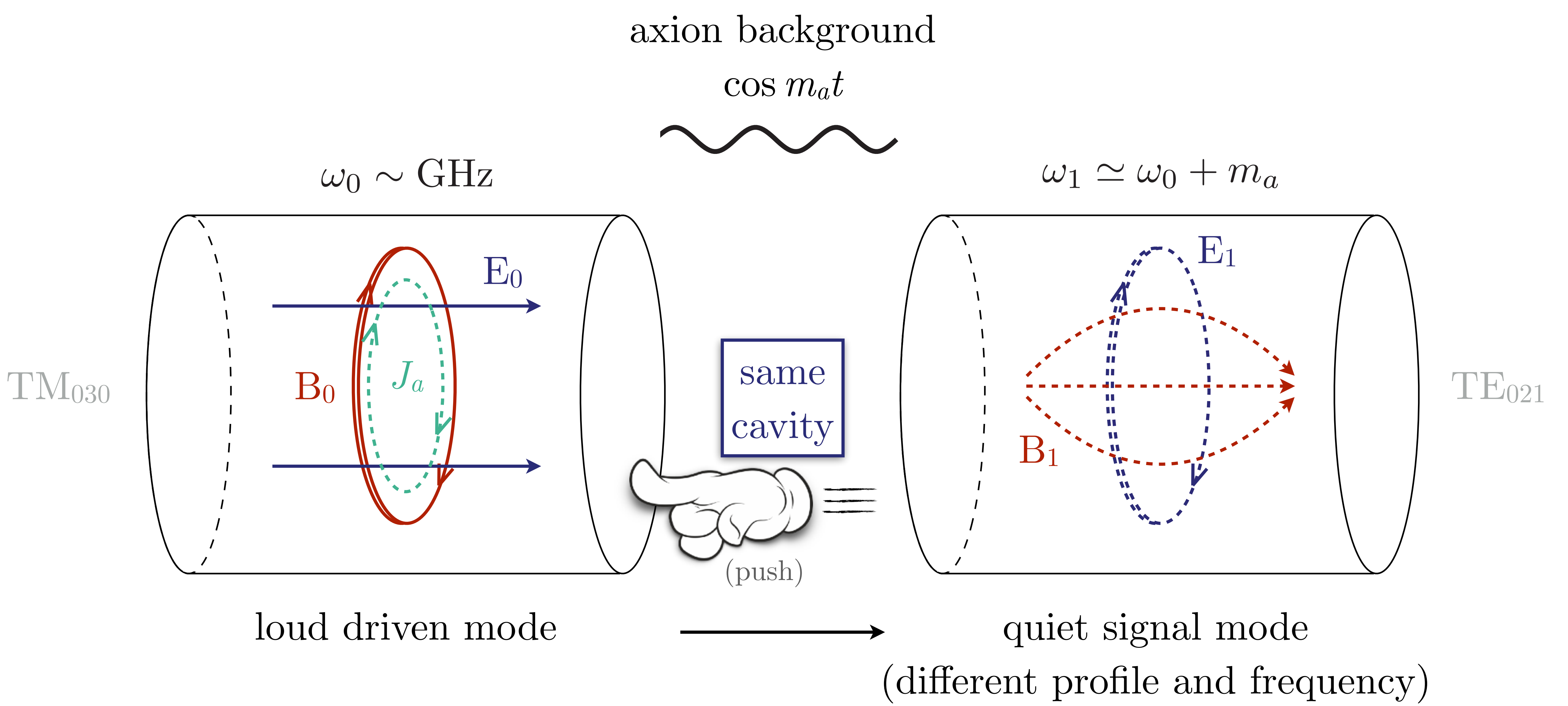

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Heterodyne Detection of Axion Dark Matter

<u>signal is always read out at ~ GHz</u>

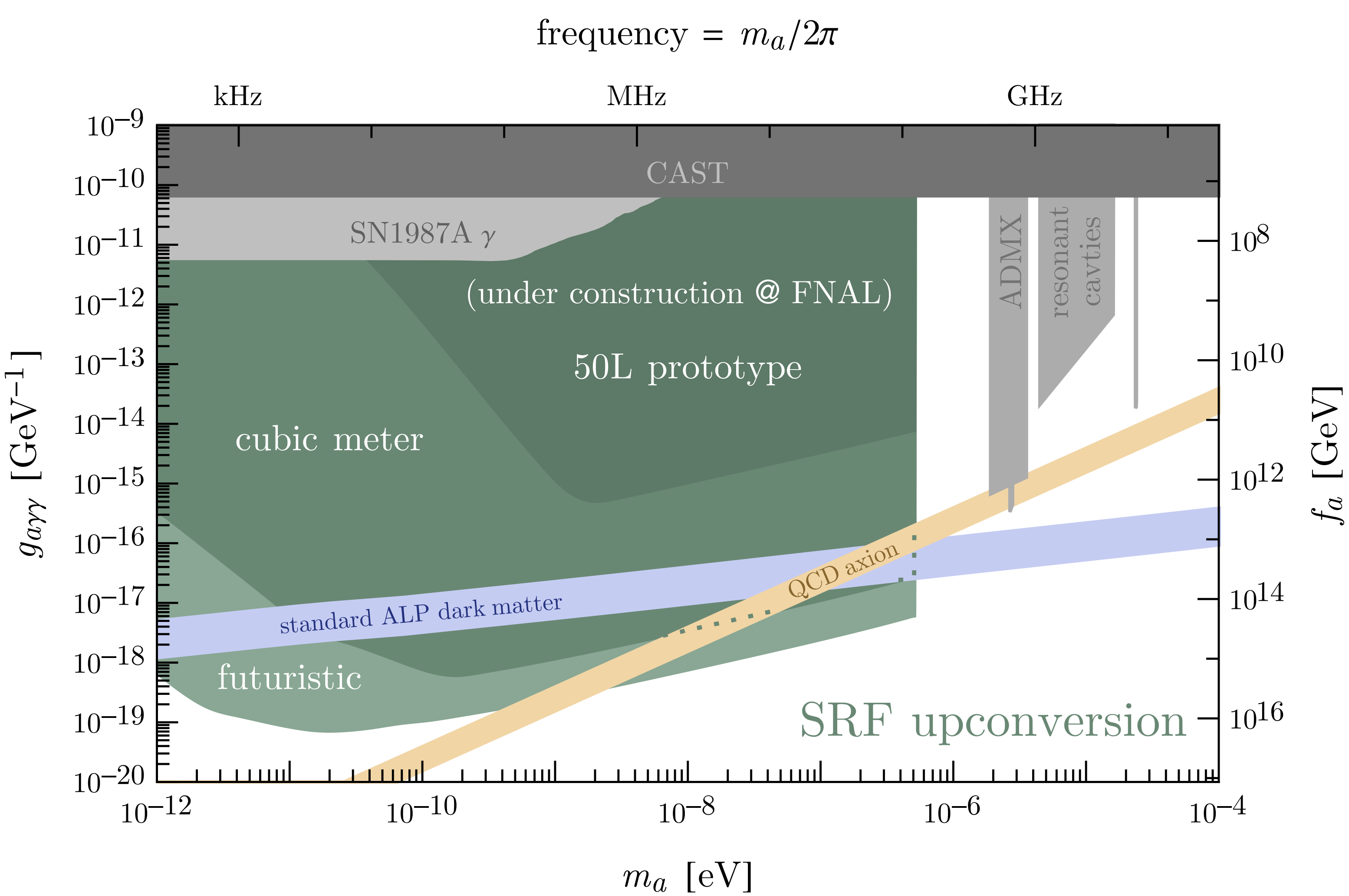
Directly benefit from $Q \sim 10^{11}$

signal power enhanced by $\text{GHz}/m_a \gg 1$

Heterodyne Detection of Axion Dark Matter

Axion Dark Matter

arXiv:1912.11048, arXiv:1912.11056, arXiv:2007.15656, arXiv:2207.11346



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