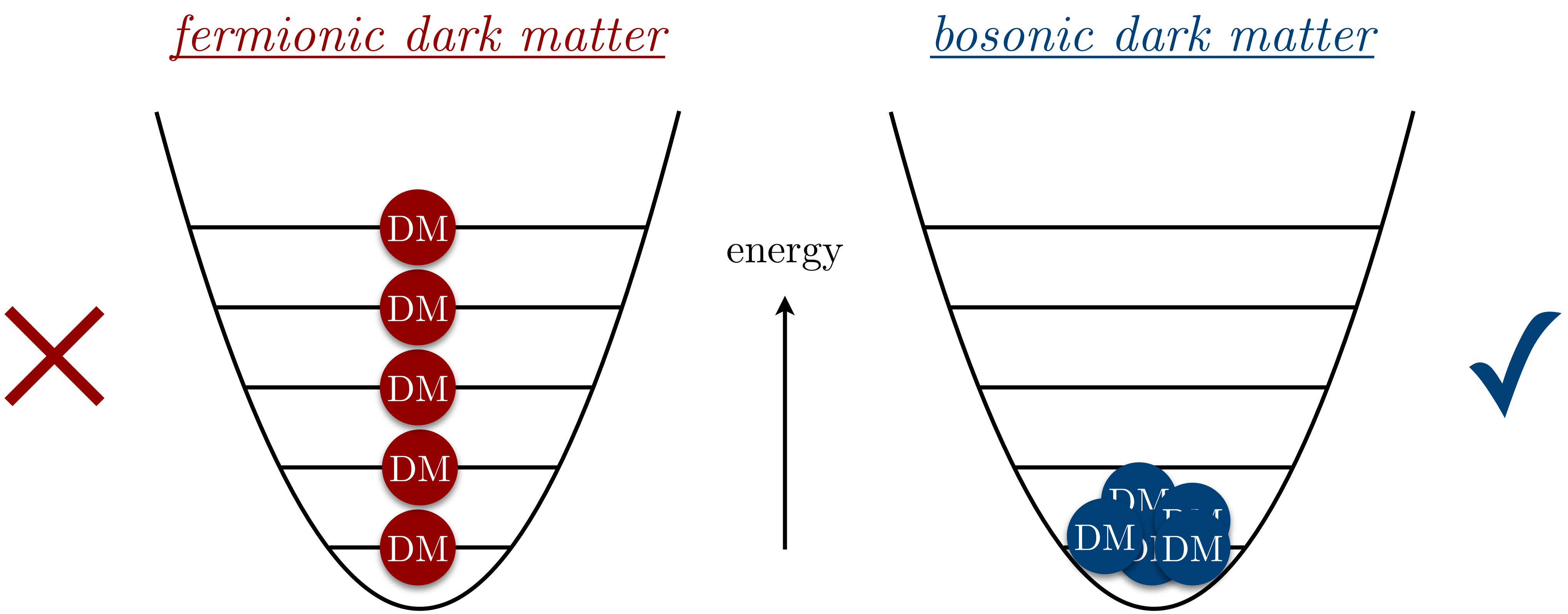
# New Opportunities to Detect Axion Dark Matter

Asher Berlin - Fermilab

Rencontres de Blois
May 16, 2023

# Sub-eV Axion Dark Matter

existence of galaxies $\Longrightarrow$ sub-eV dark matter must be a boson, "$a$"



*fermionic dark matter*

*bosonic dark matter*

sub-eV fermions

Fermi velocity exceeds the gravitational escape velocity of galaxies

# Sub-eV Axion Dark Matter

existence of galaxies $\Longrightarrow$ sub-eV dark matter must be a boson, "$a$"

pseudo-Goldstone bosons are naturally light and weakly-coupled

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

# Sub-eV Axion Dark Matter

existence of galaxies $\Longrightarrow$ sub-eV dark matter must be a boson, "$a$"

pseudo-Goldstone bosons are naturally light and weakly-coupled

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

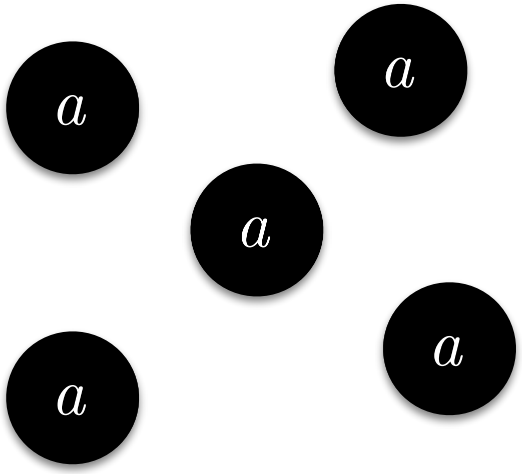
large scale

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*



smaller mass
(larger density)

---

*wave properties*

$$\boxed{a \propto \cos m_a t}$$

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

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

# 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*

# 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*

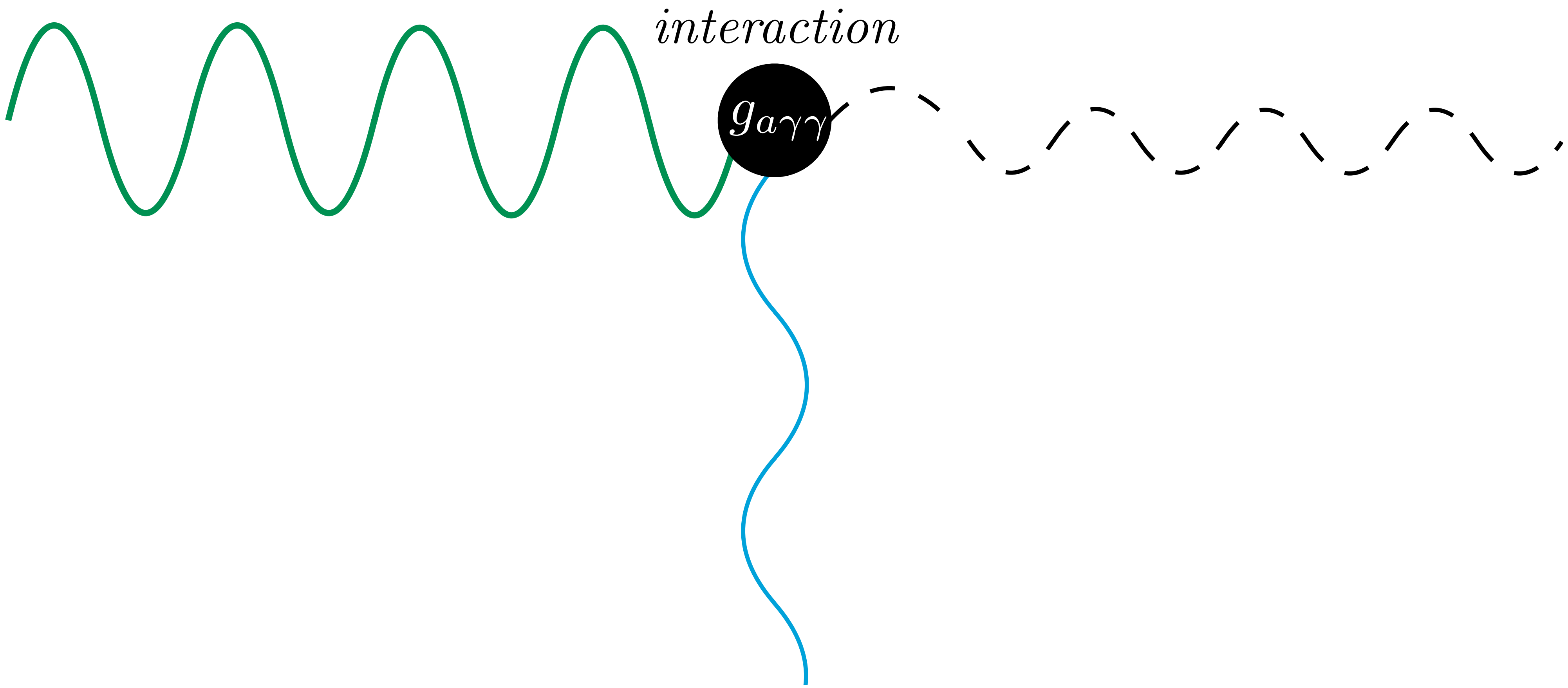
Based on work with R. D'Agnolo, S. Ellis, C. Nantista, J. Neilson, P. Schuster, S. Tantawi, N. Toro, K. Zhou
arXiv:1912.11048, arXiv:1912.11056, arXiv:2007.15656
and with T. Trickle, arXiv:2305.05681

# 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*

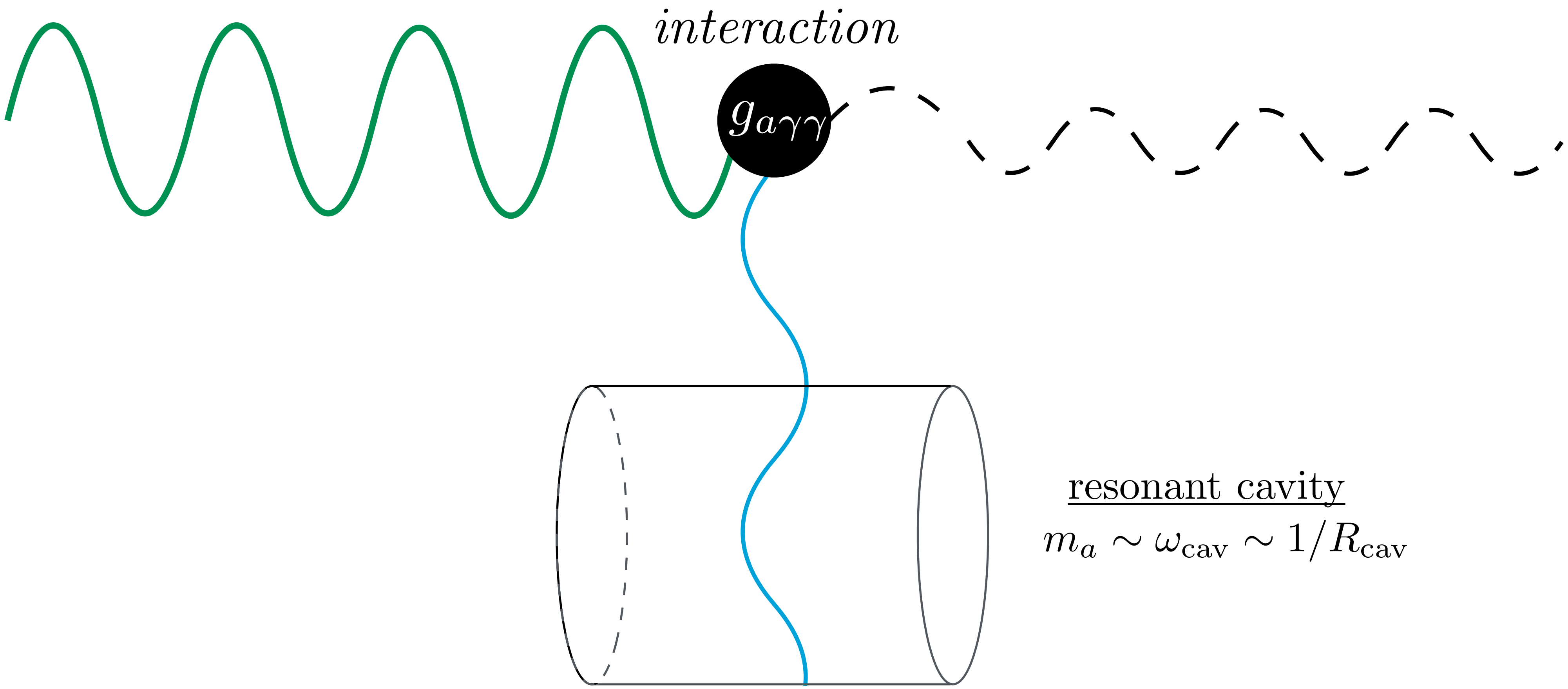
$\sim \cos \cancel{\omega_0} t$

(frequency ~ your choice)

*galactic axion field*

$\sim \cos m_a t$

(frequency ~ axion mass)



*interaction*

$g_{a\gamma\gamma}$

resonant cavity

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

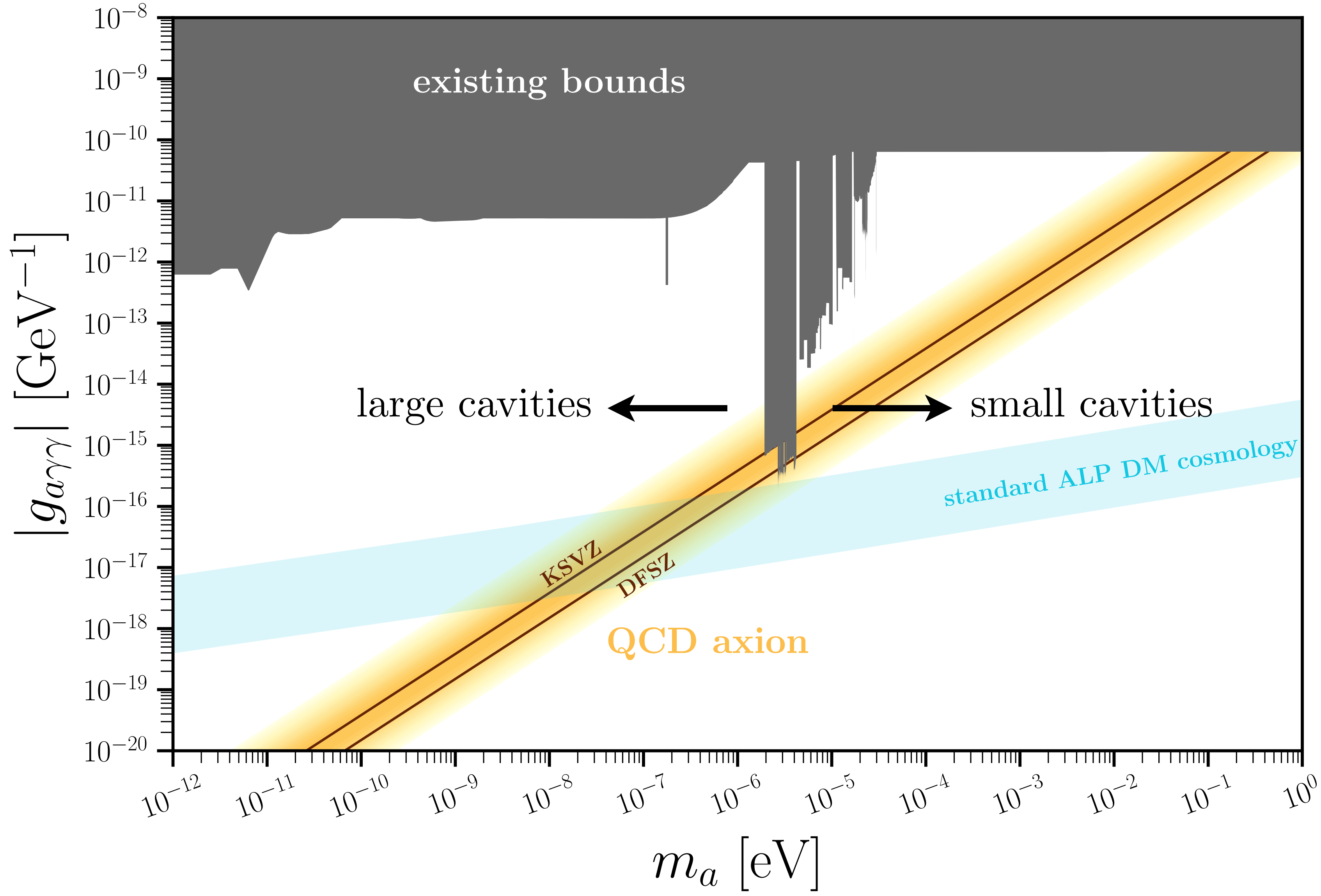
*signal EM field* $\sim \cos(\cancel{\omega_0} + m_a)t$

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

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

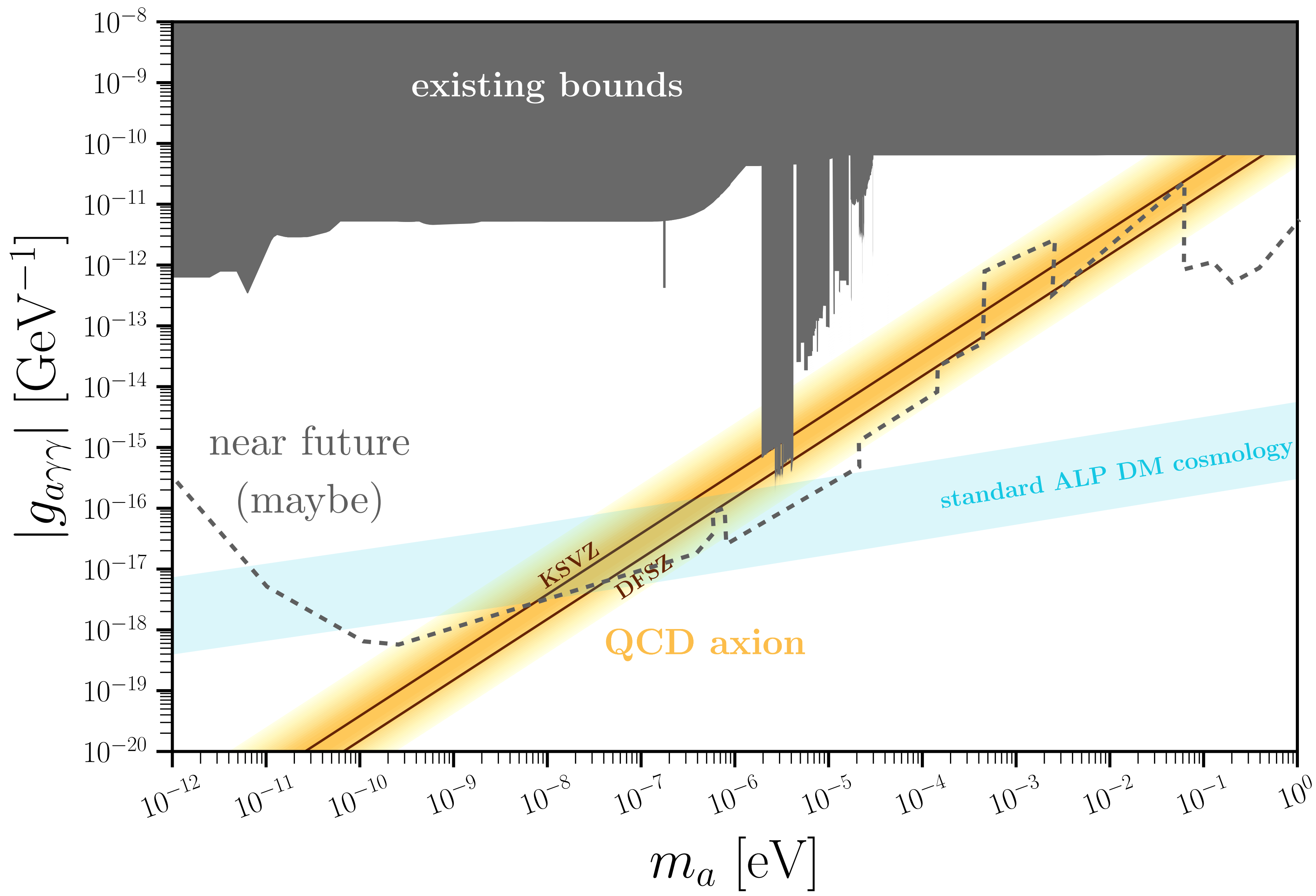


ADMX, HAYSTAC,
ORGAN, ...

*Cavities limited to a narrow range*

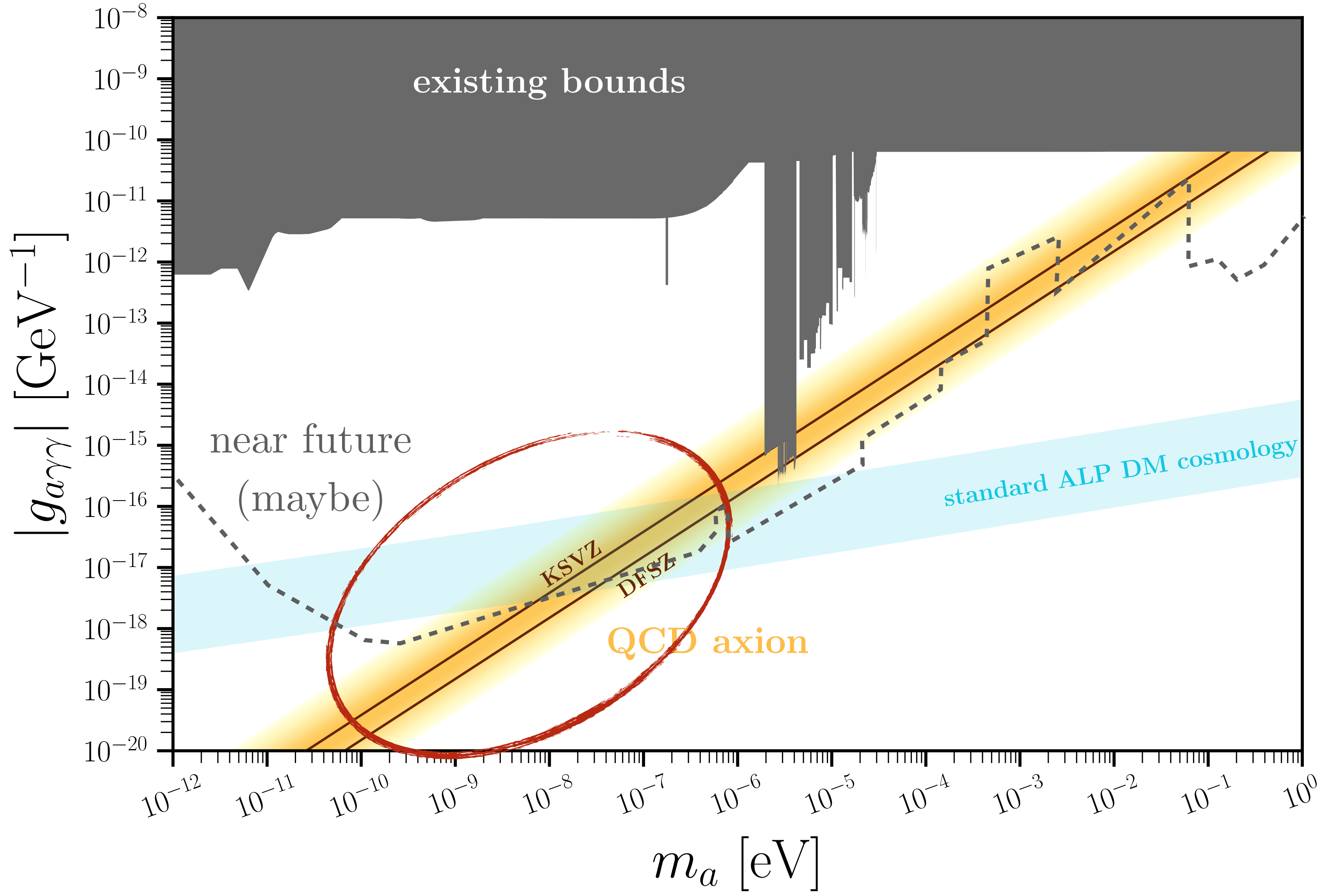
# Photon-Coupling

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



# Photon-Coupling

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

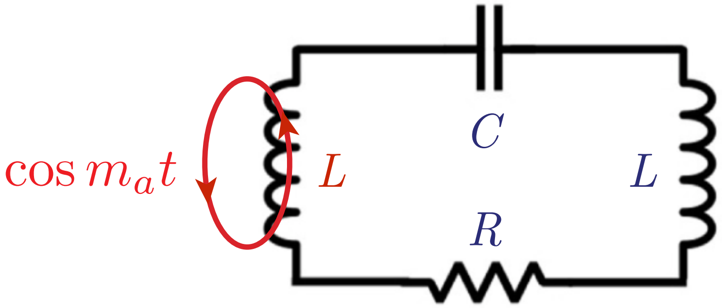


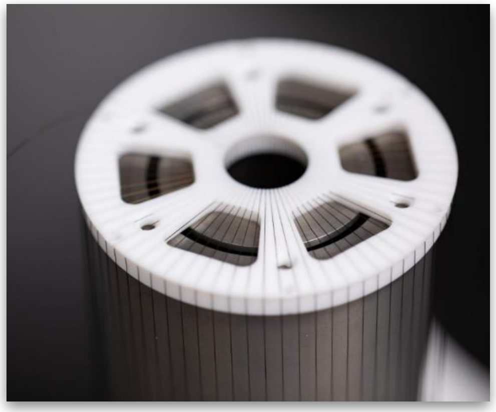
*How to explore smaller masses?*

# Below ~Micro-eV

## LC circuits (DMRadio)

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





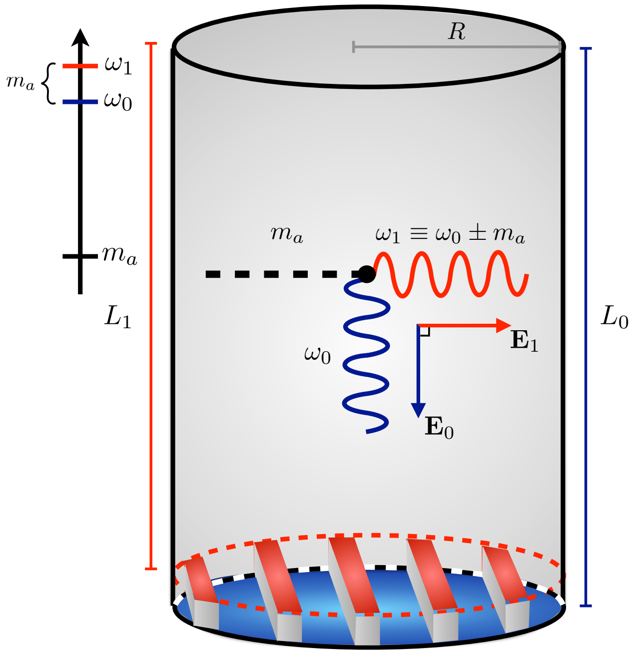
Drive power into LC circuit

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

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

## 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

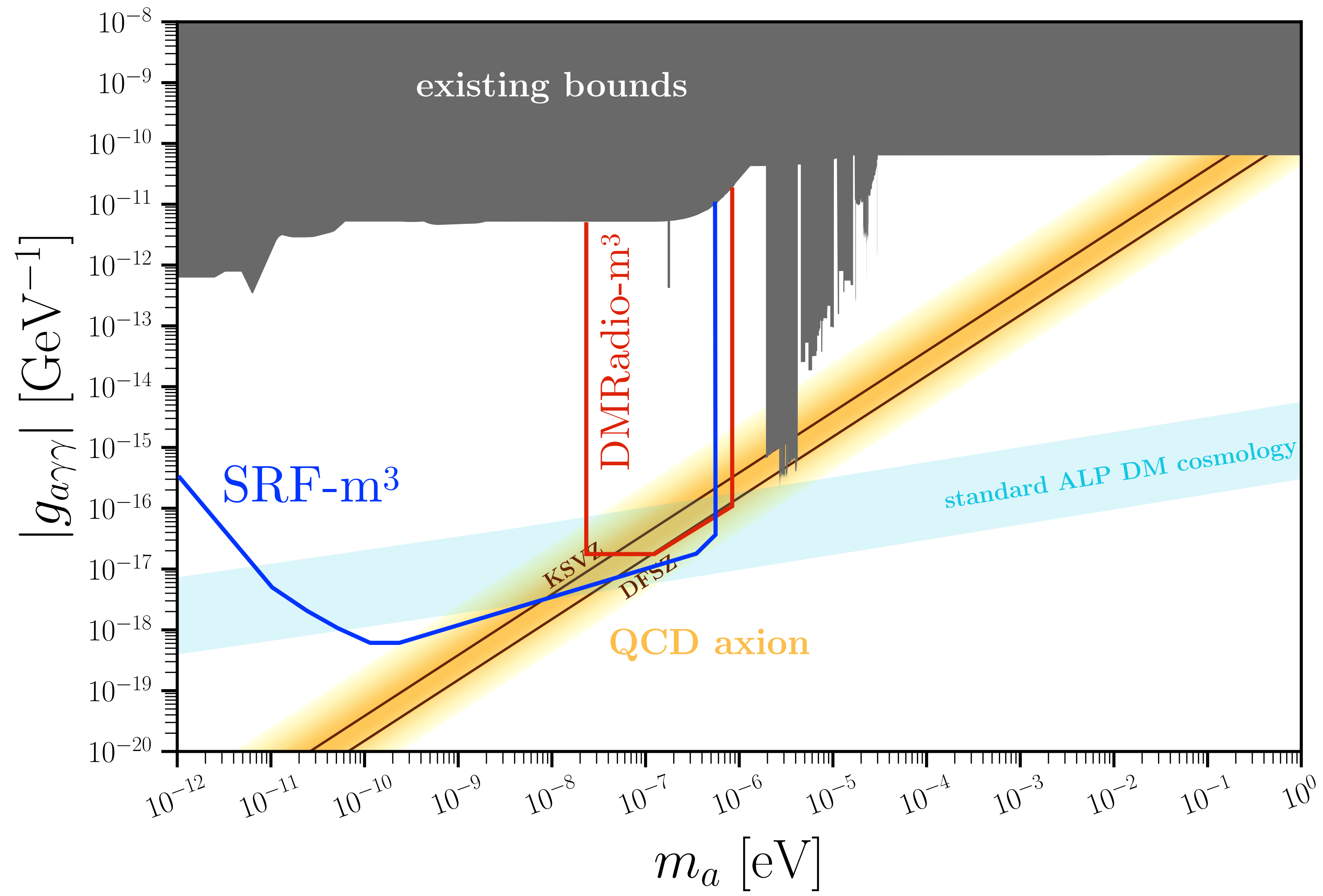


Transfer power between
two nearly-degenerate cavity modes

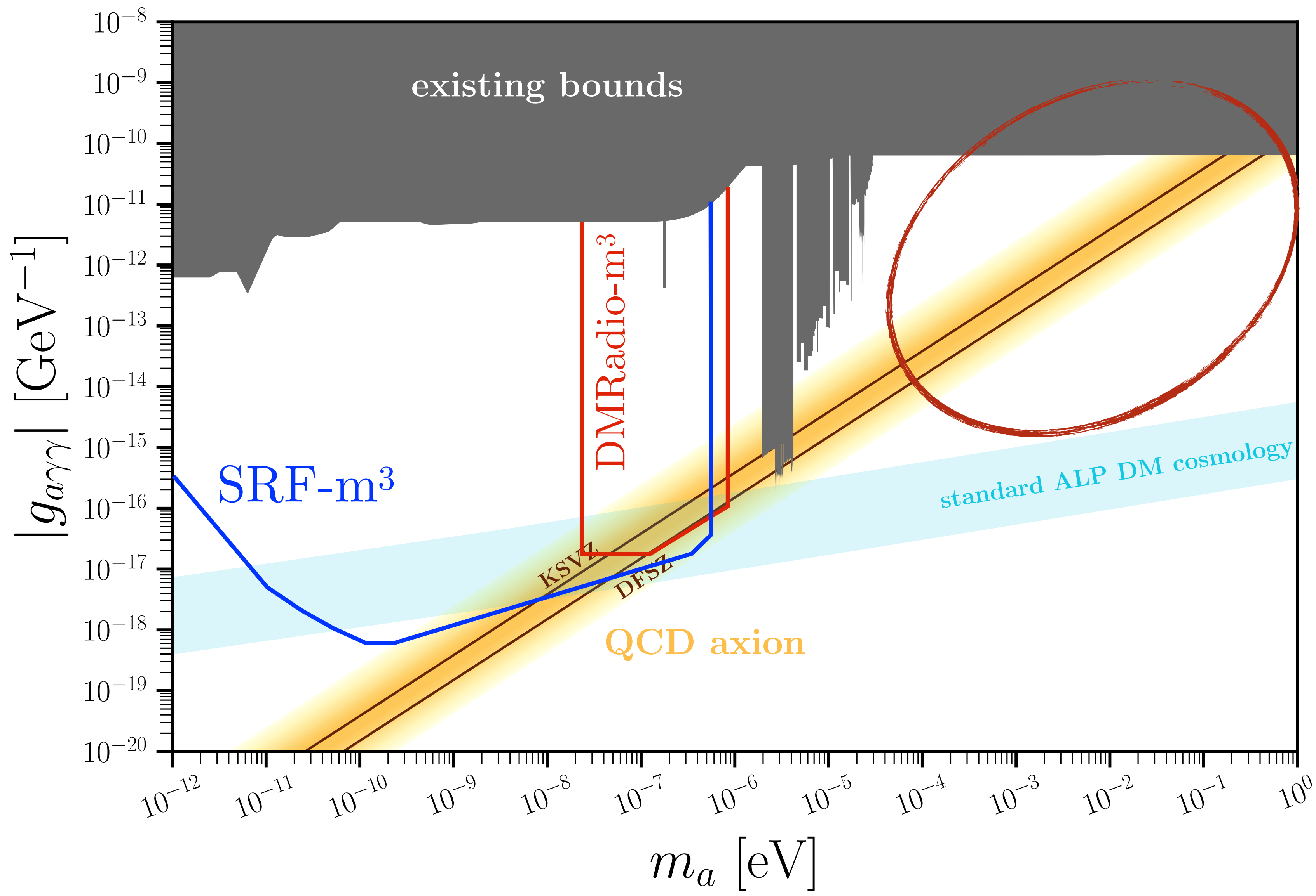
$$\Delta\omega \sim m_a \ll \omega \sim \text{GHz}$$

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

# Below ~Micro-eV



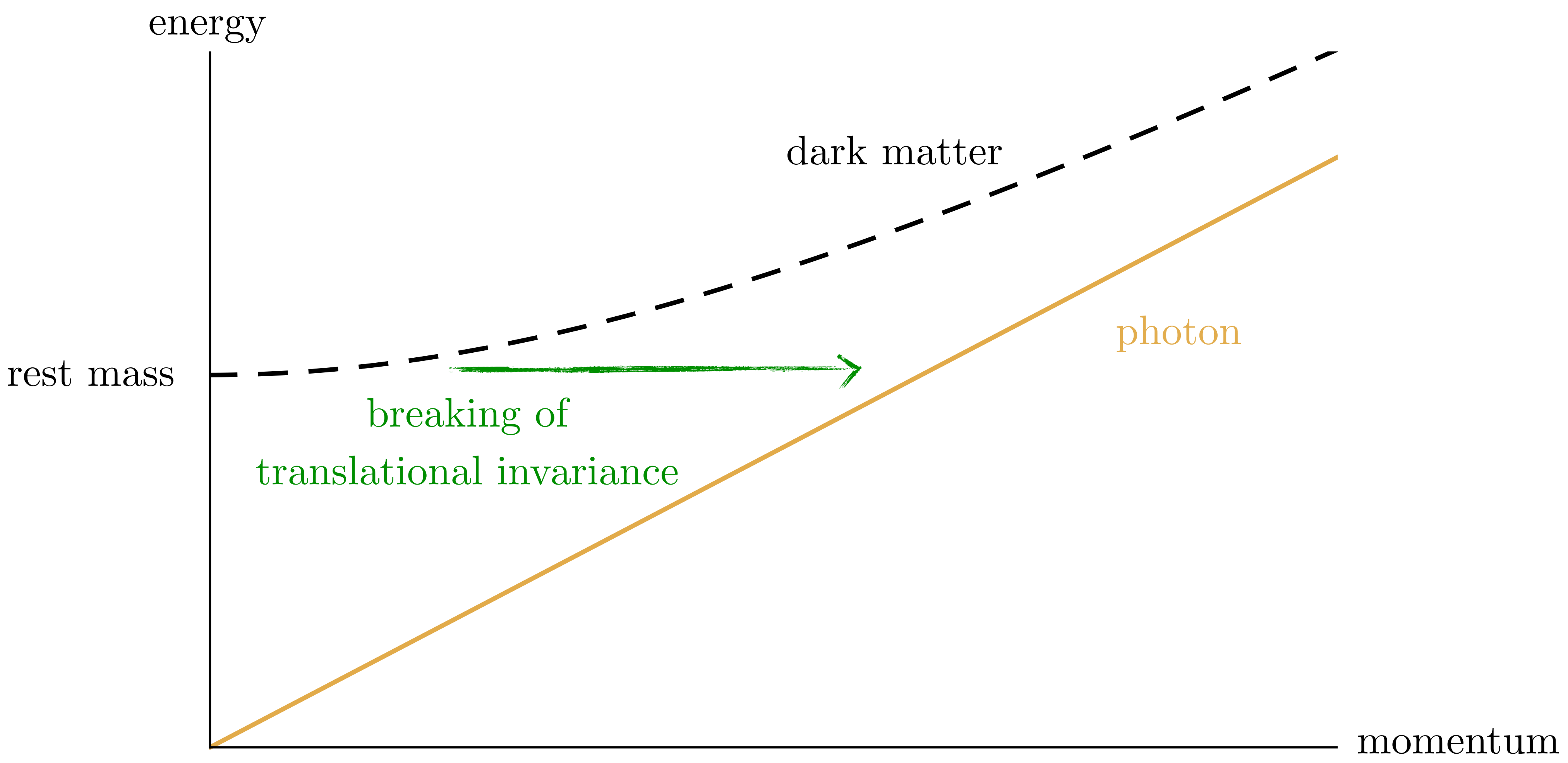
# Above ~Micro-eV



*How to explore higher masses?*

# Above ~Micro-eV

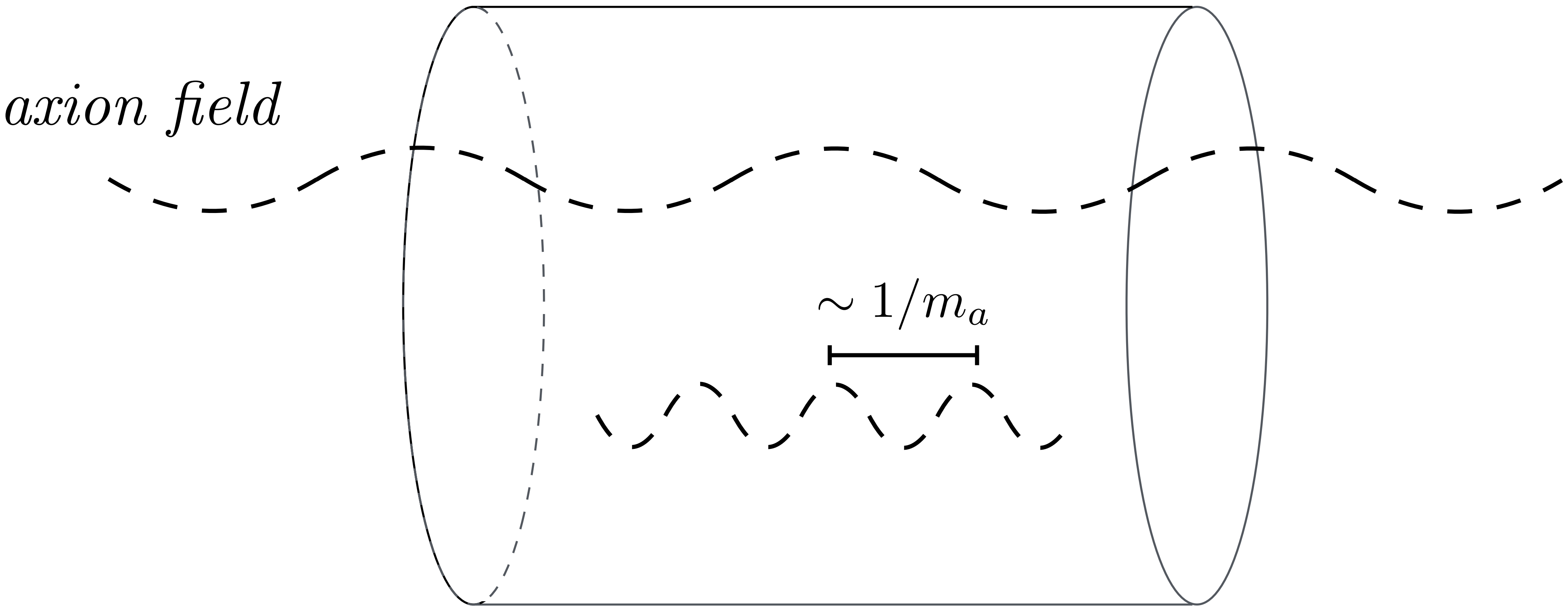
In vacuum, axions do not convert into photons in uniform B-fields of “infinite" extent (compared to the axion Compton wavelength).



*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).



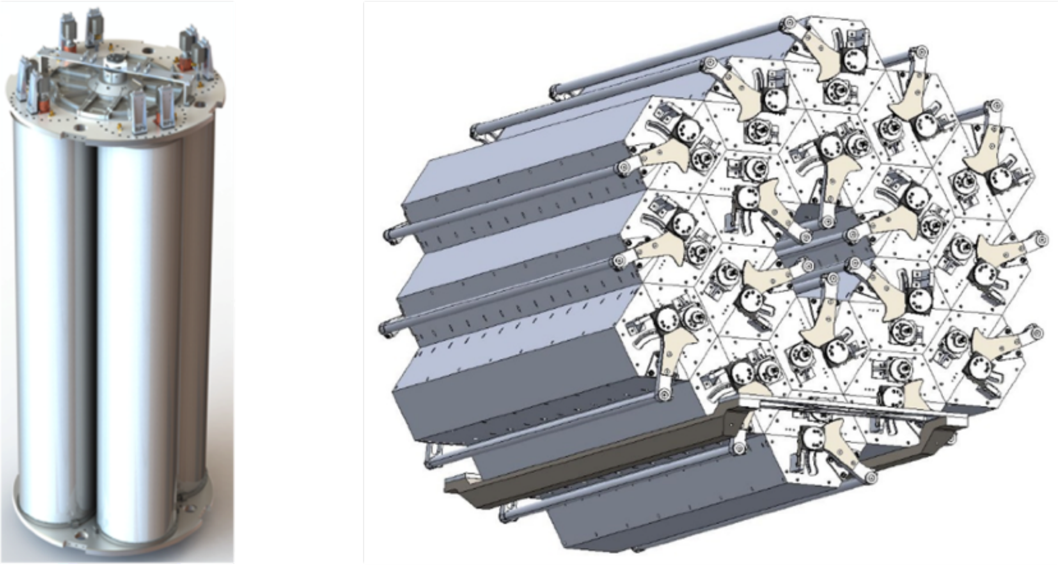
Momentum mismatch is more difficult at higher axion masses (smaller wavelengths).

# Above ~Micro-eV

*breaking translational invariance on small scales*

## Resonant Cavity (ADMX-EFR)

arXiv:2203.14923

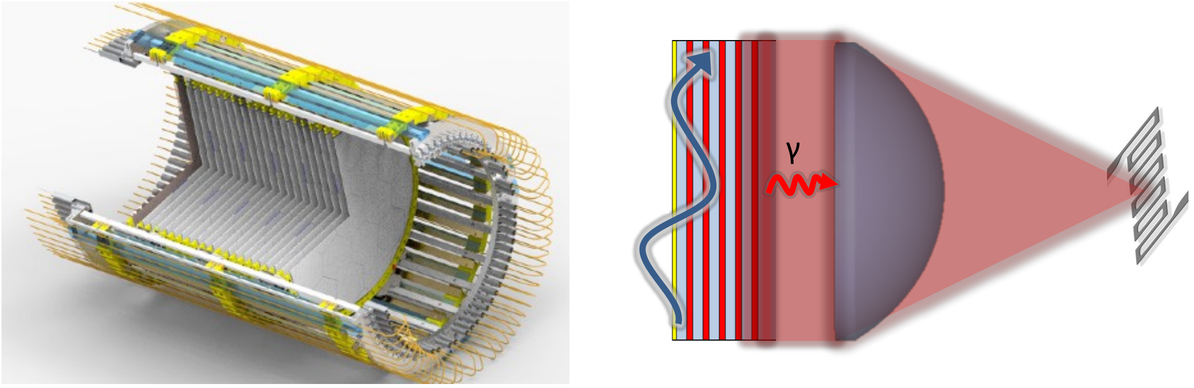


combine signal from 18 smaller cavities

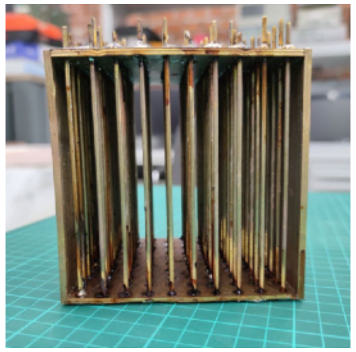
2-4 GHz ~ 8-16 $\mu$eV

## Dielectric/Plasma (MADMAX, LAMPOST, ALPHA)

arXiv:1901.07401, arXiv:2110.01582, arXiv:1904.11872



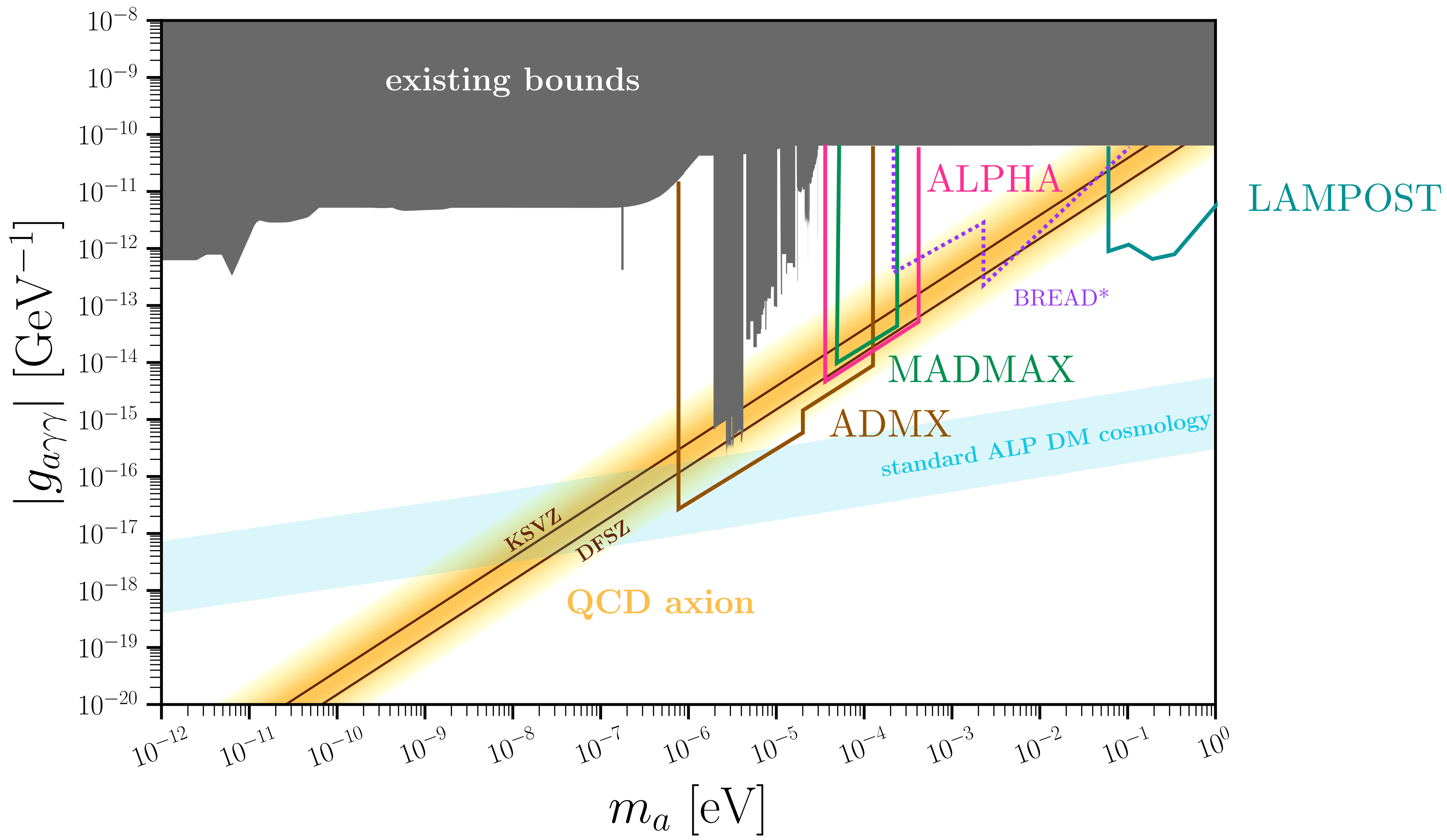
MADMAX/LAMPPOST: dielectric stacks



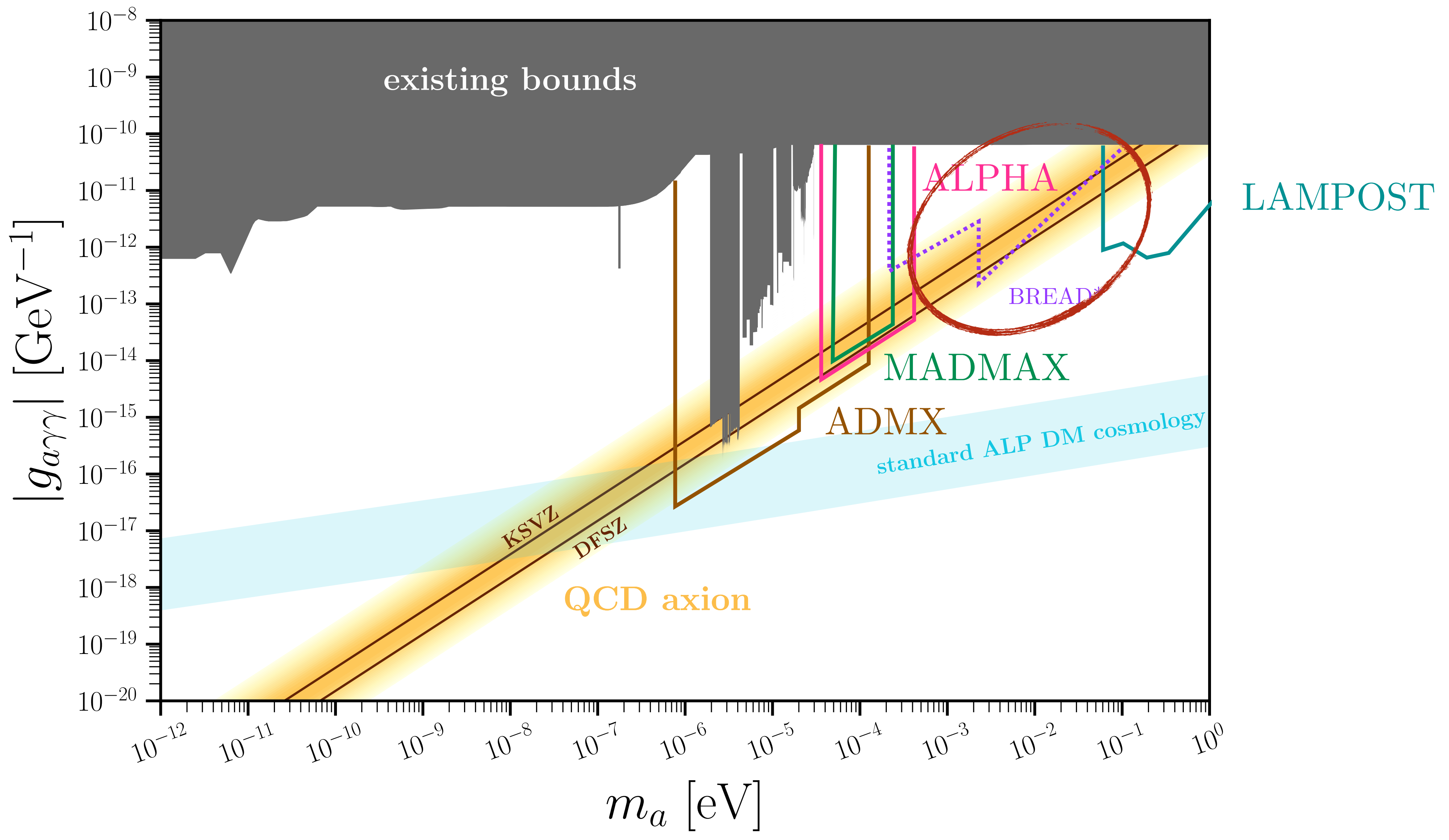
ALPHA: wire metamaterial

modify photon's dispersion relation

# Above ~Micro-eV



# Above ~Micro-eV

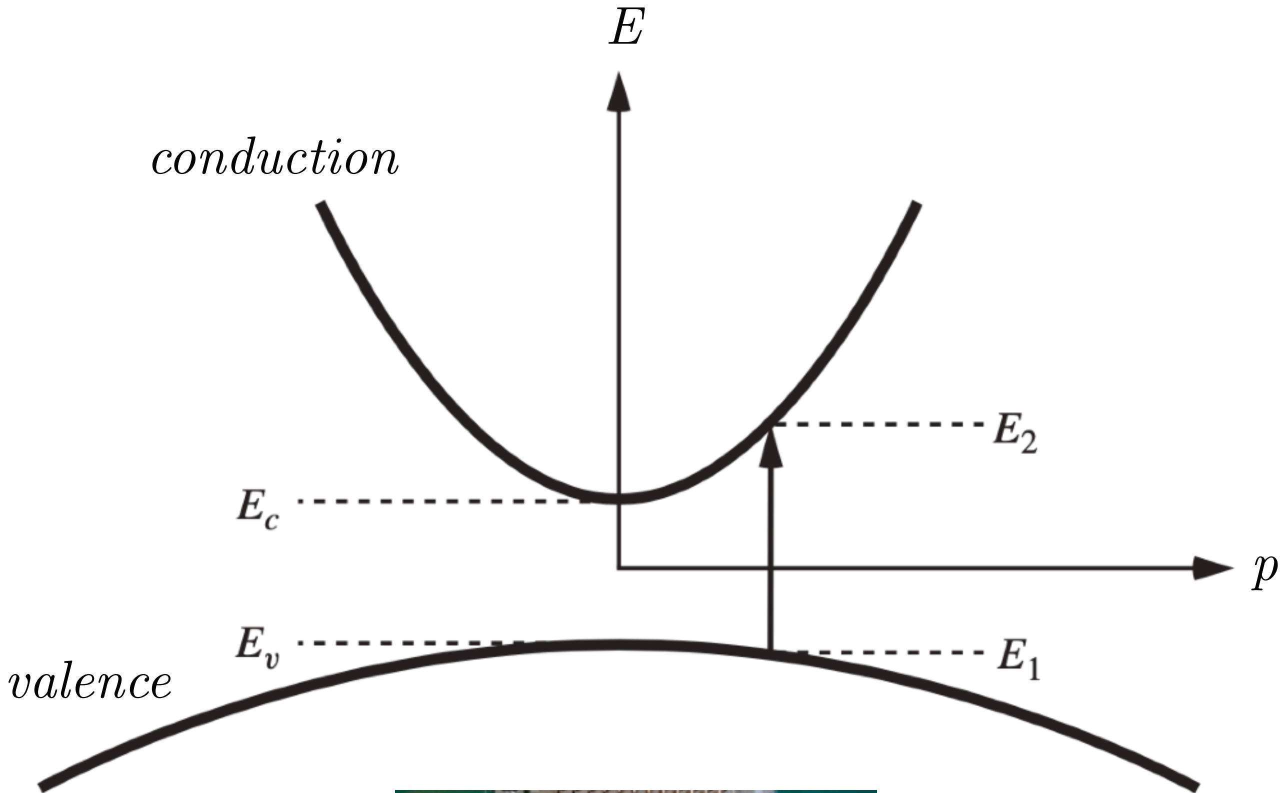


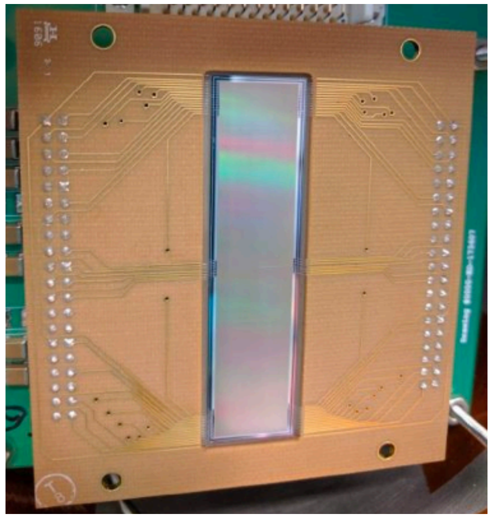
*How to explore remaining gaps in coverage?*

# Above ~Micro-eV

*In-Medium Excitations*

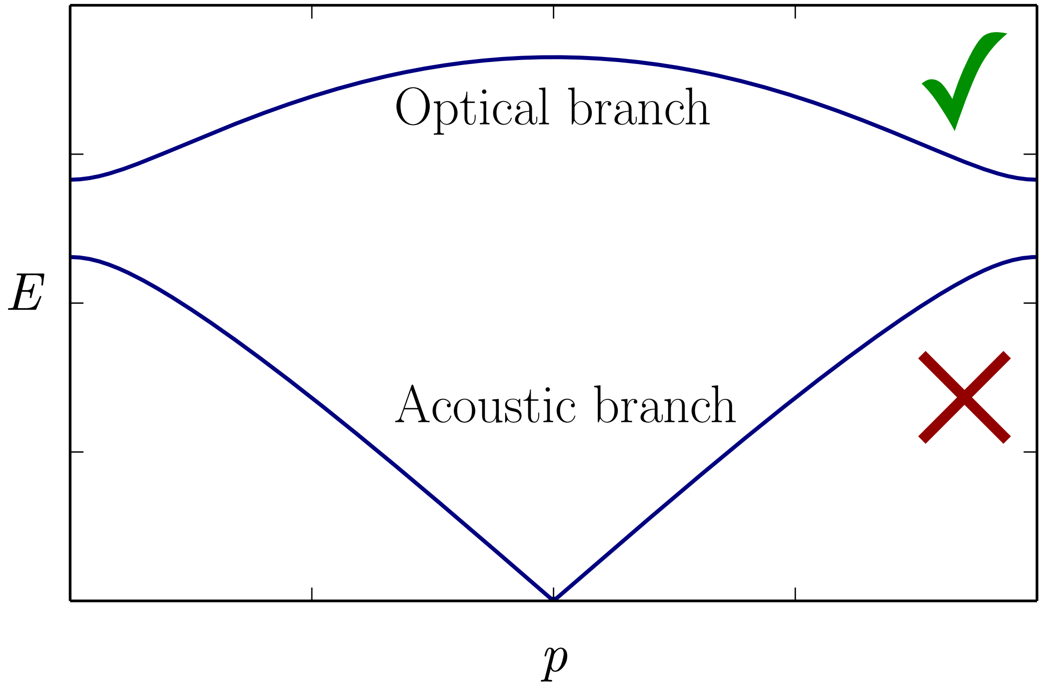
Electronic (eV)

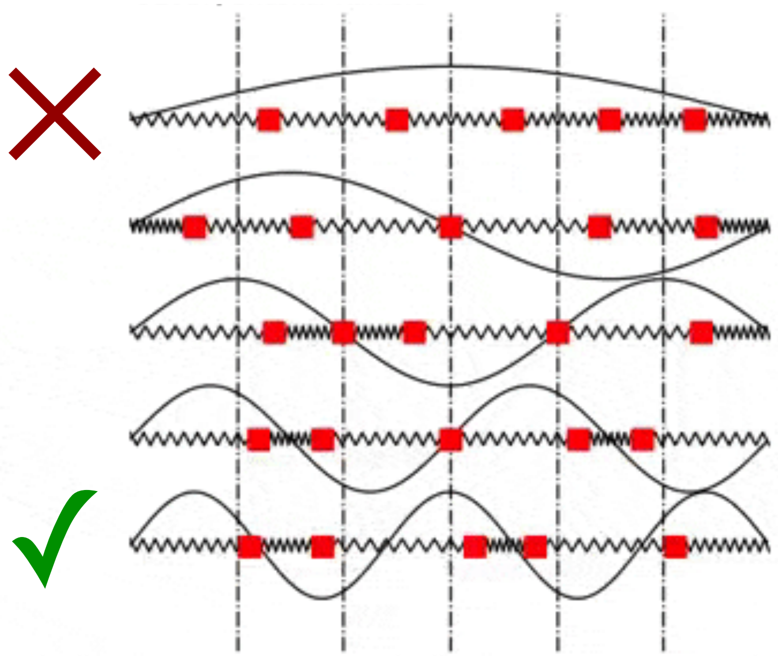




*(semiconductors)*

Phonon (meV)

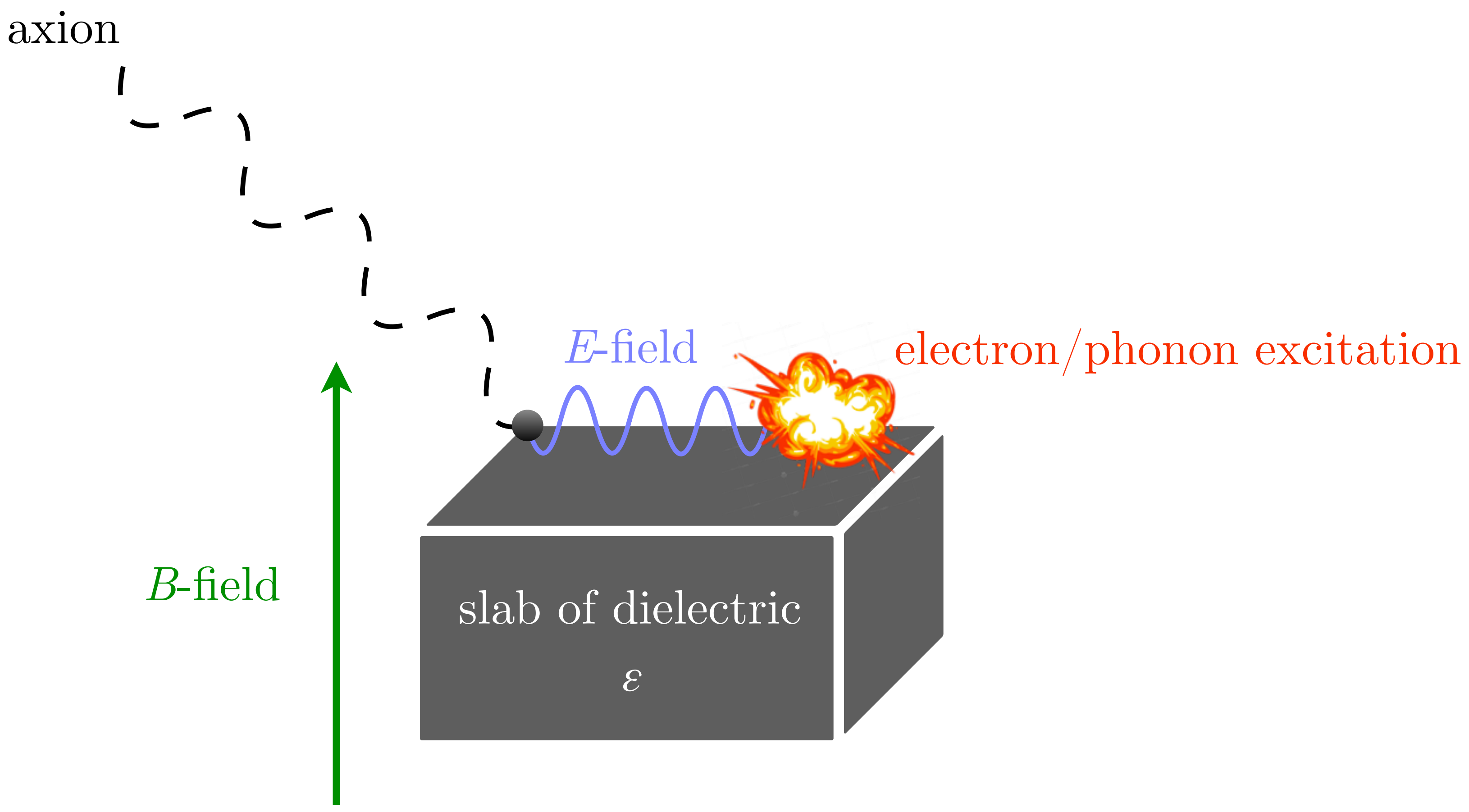




# Above ~Micro-eV

*In-Medium Excitations*

(arXiv:2305.05681)



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

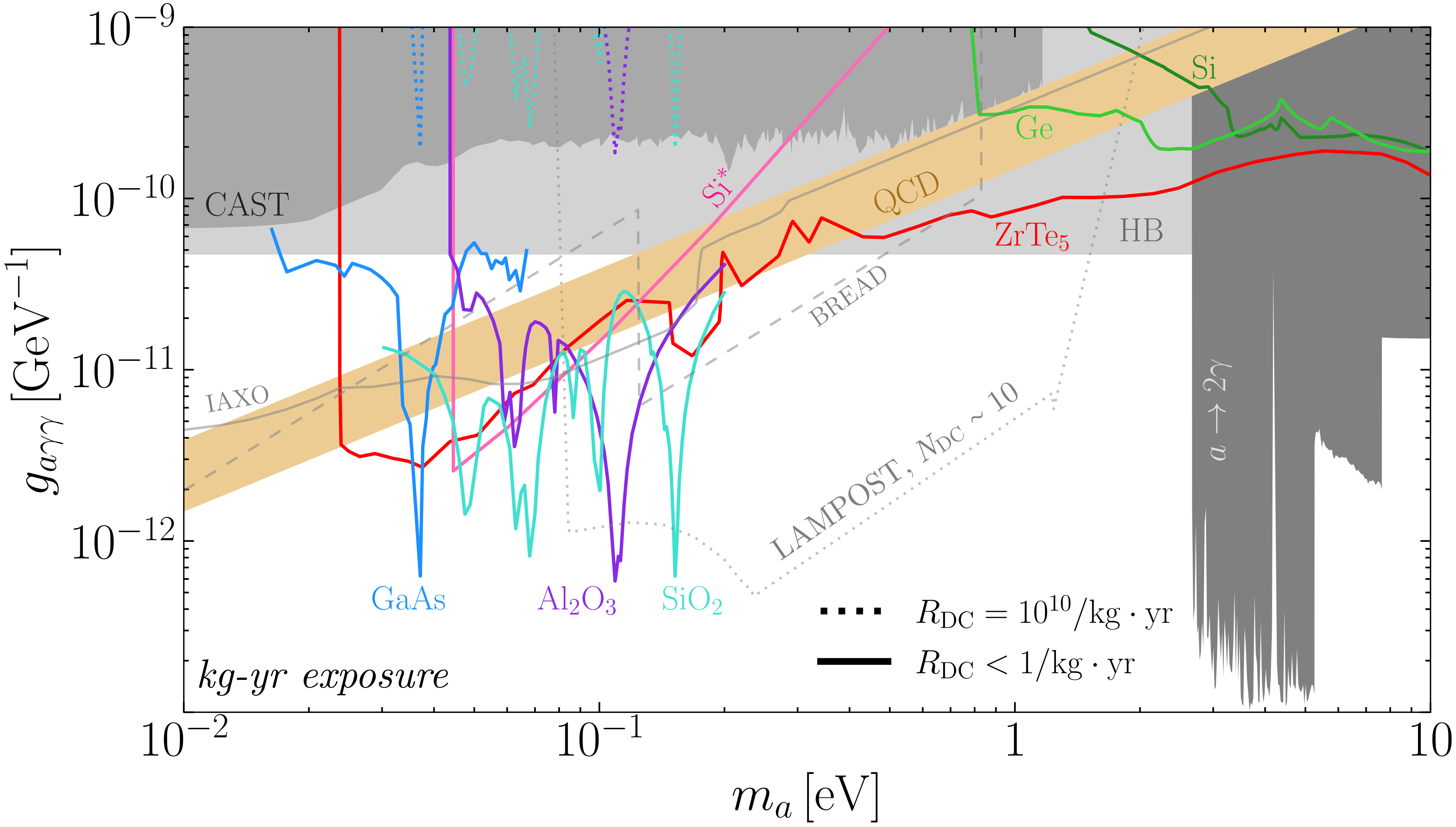
inclusive rate accounting
for *all* in-medium excitations
(photon, phonon, electronic, ...)

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

# Above ~Micro-eV

*In-Medium Excitations*

(arXiv:2305.05681)



# 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*

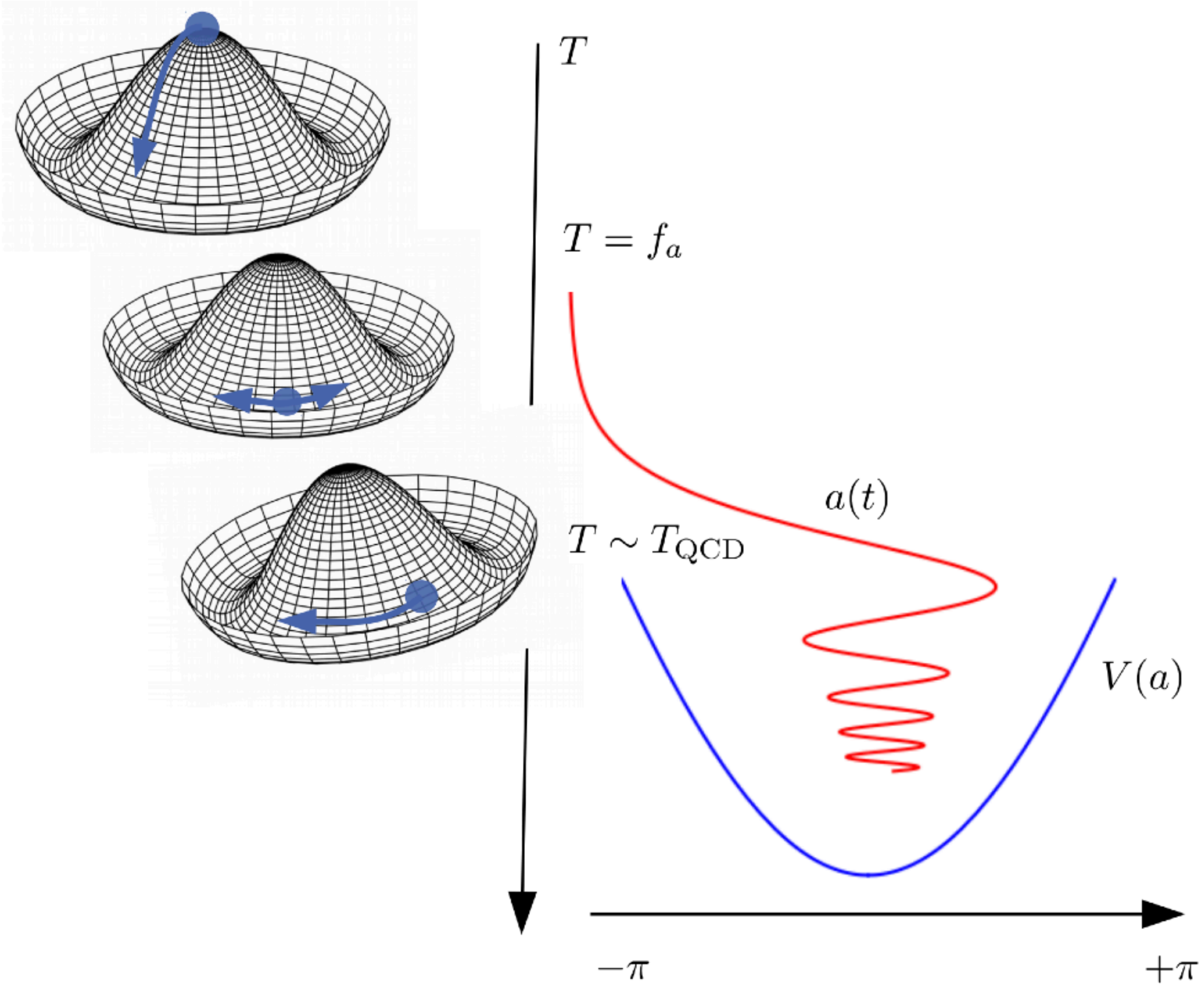
*Spin-Forces*

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

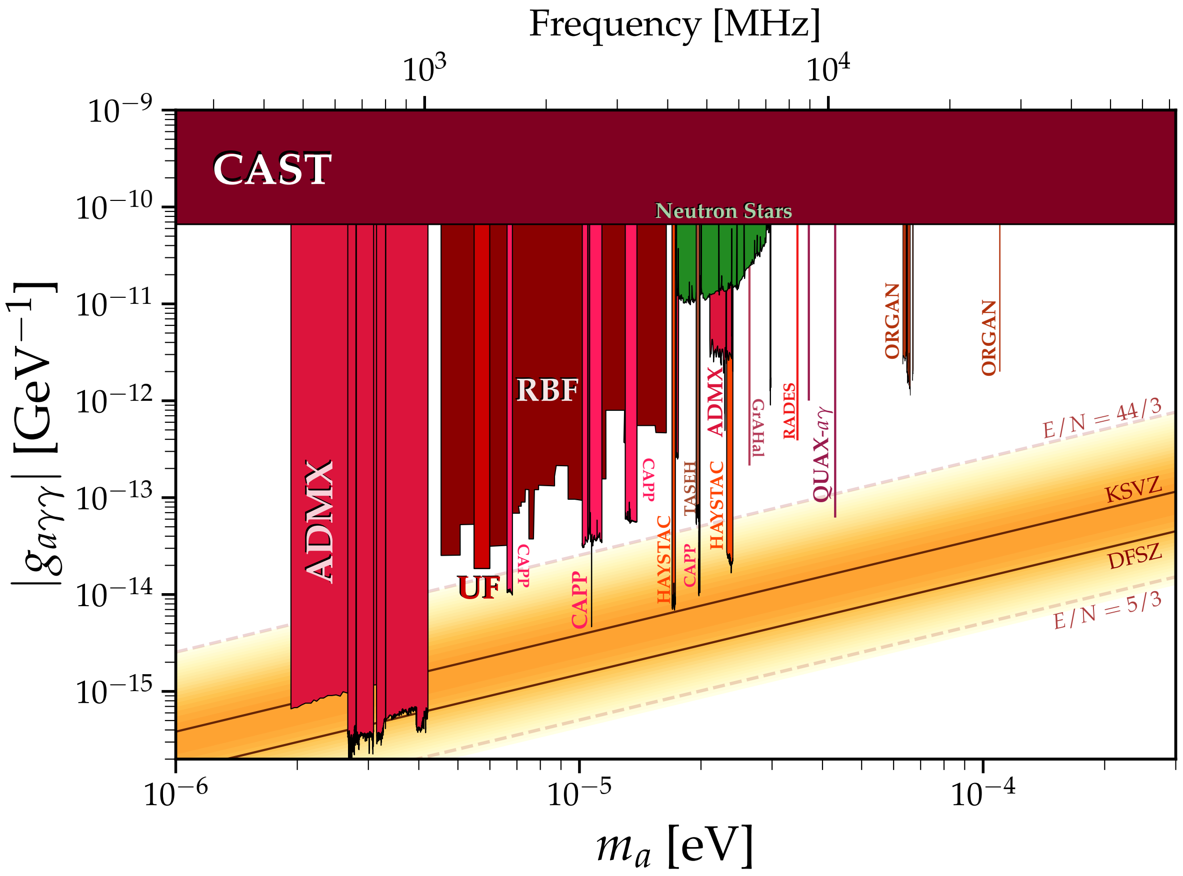
Most-motivated mass range for QCD axion dark matter is $m_a \sim (0.1 - 100)\ \mu\text{eV}$



# QCD-axion at ~Micro-eV

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

## Photon-coupling



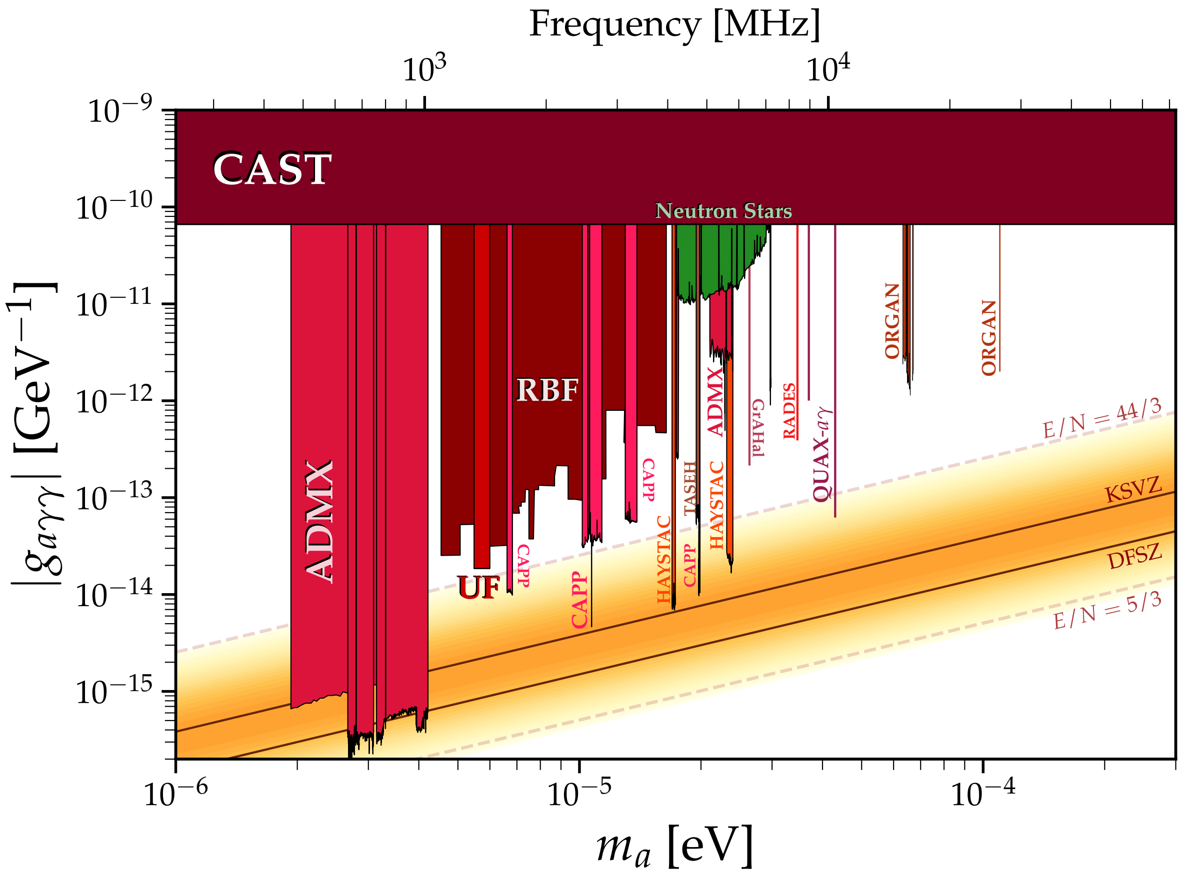
## Cavities across the globe

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

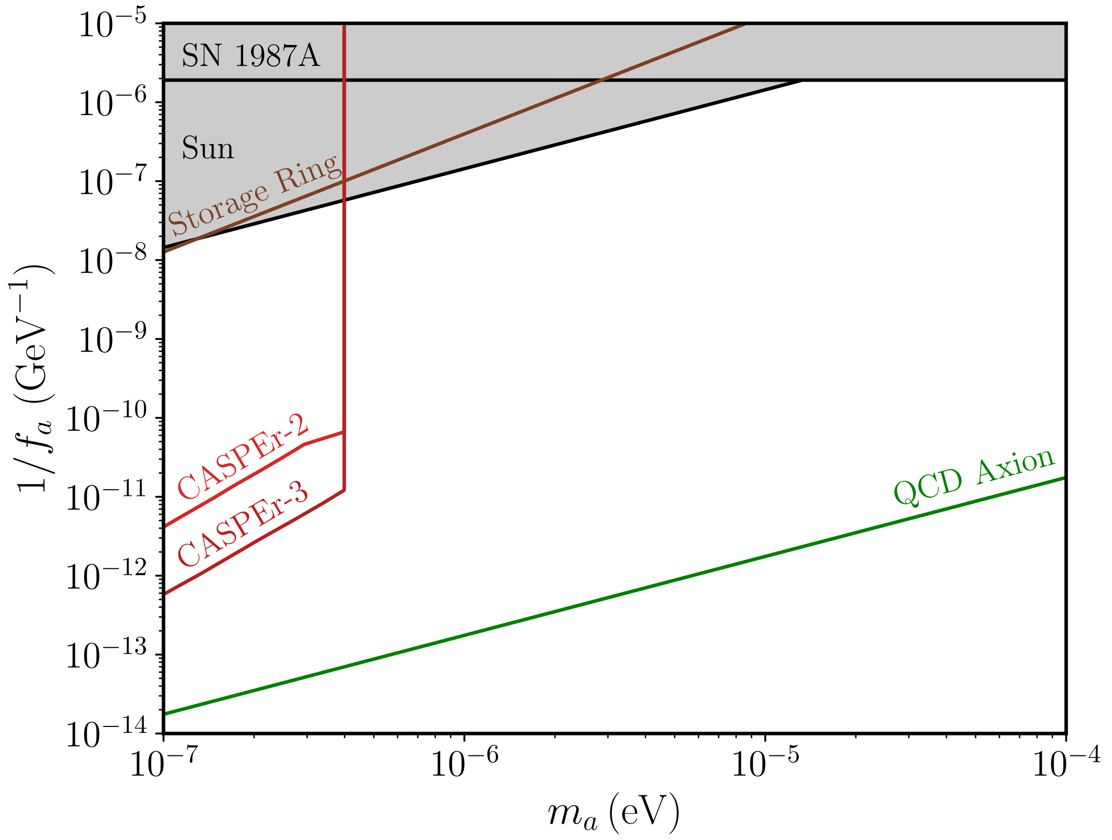
# QCD-axion at ~Micro-eV

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

## Photon-coupling



## QCD-coupling

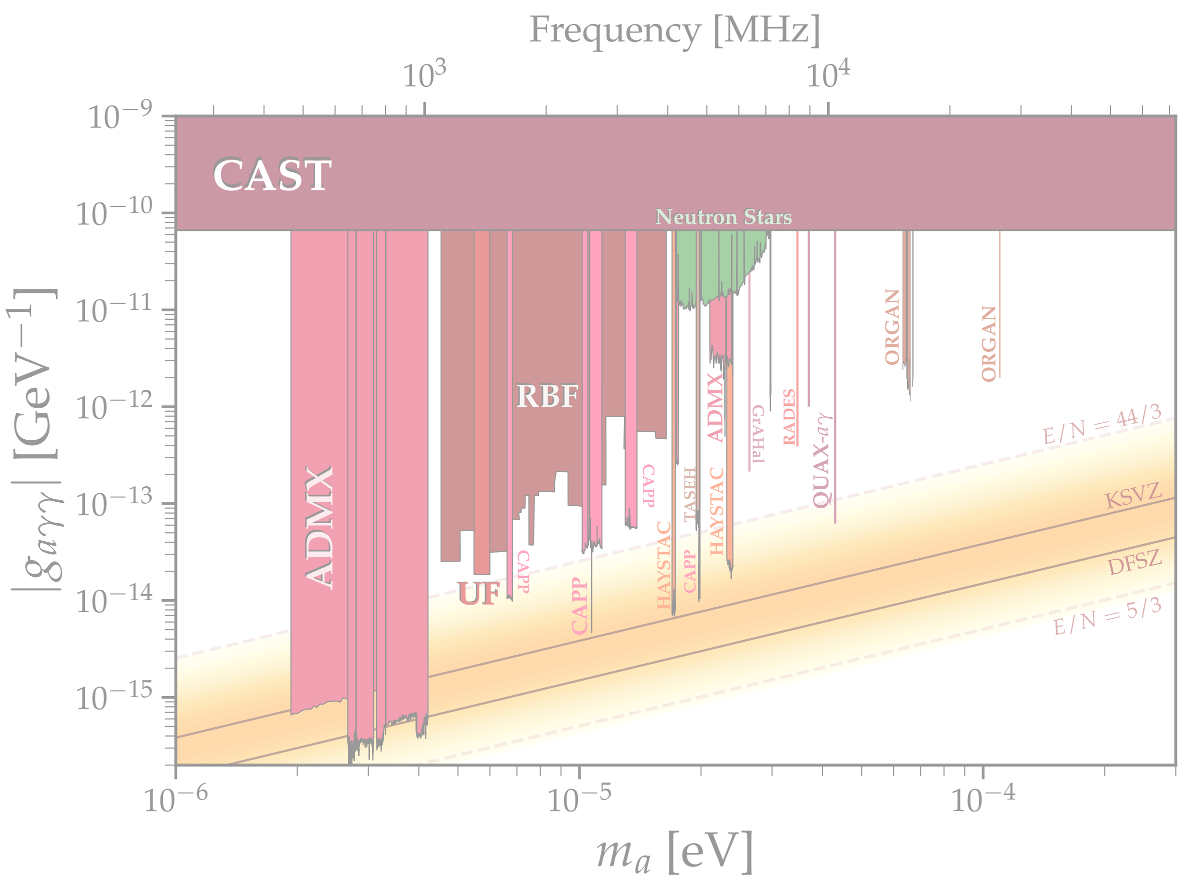


But the defining coupling is to QCD, which gives rise to nuclear effects,
such as oscillating nucleon/atomic EDMs.

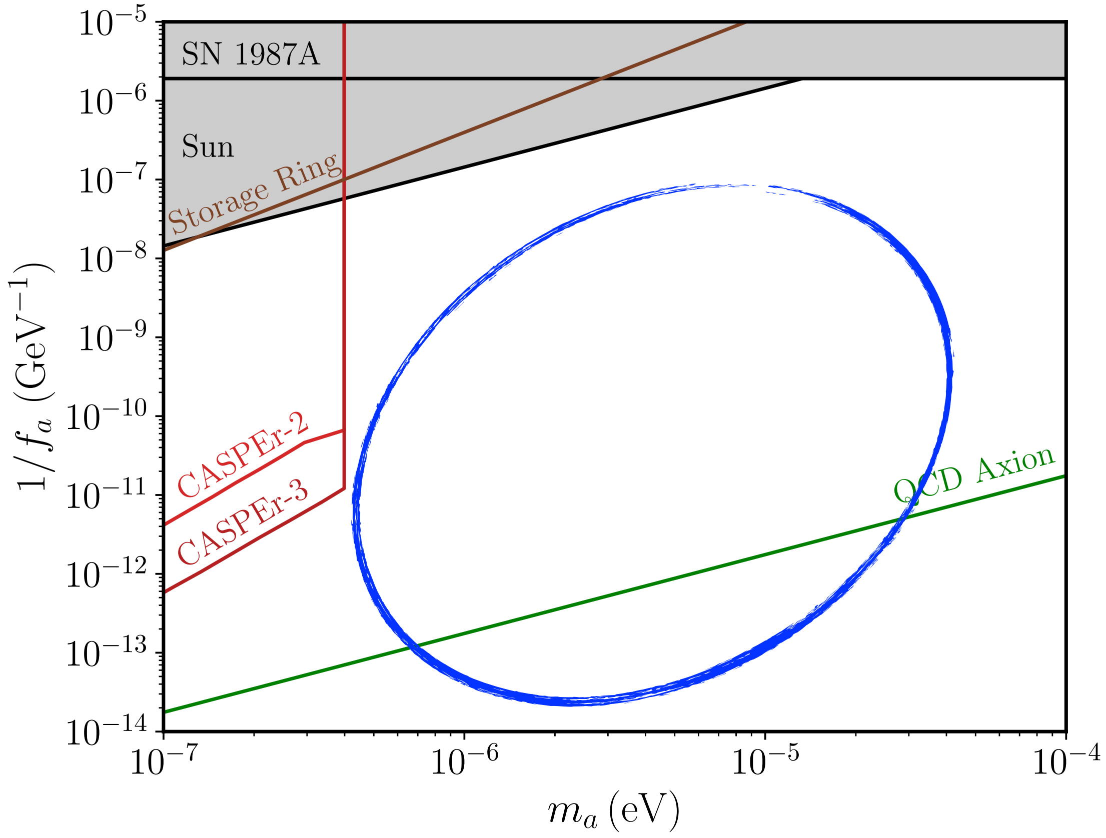
# QCD-axion at ~Micro-eV

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

Photon-coupling



QCD-coupling

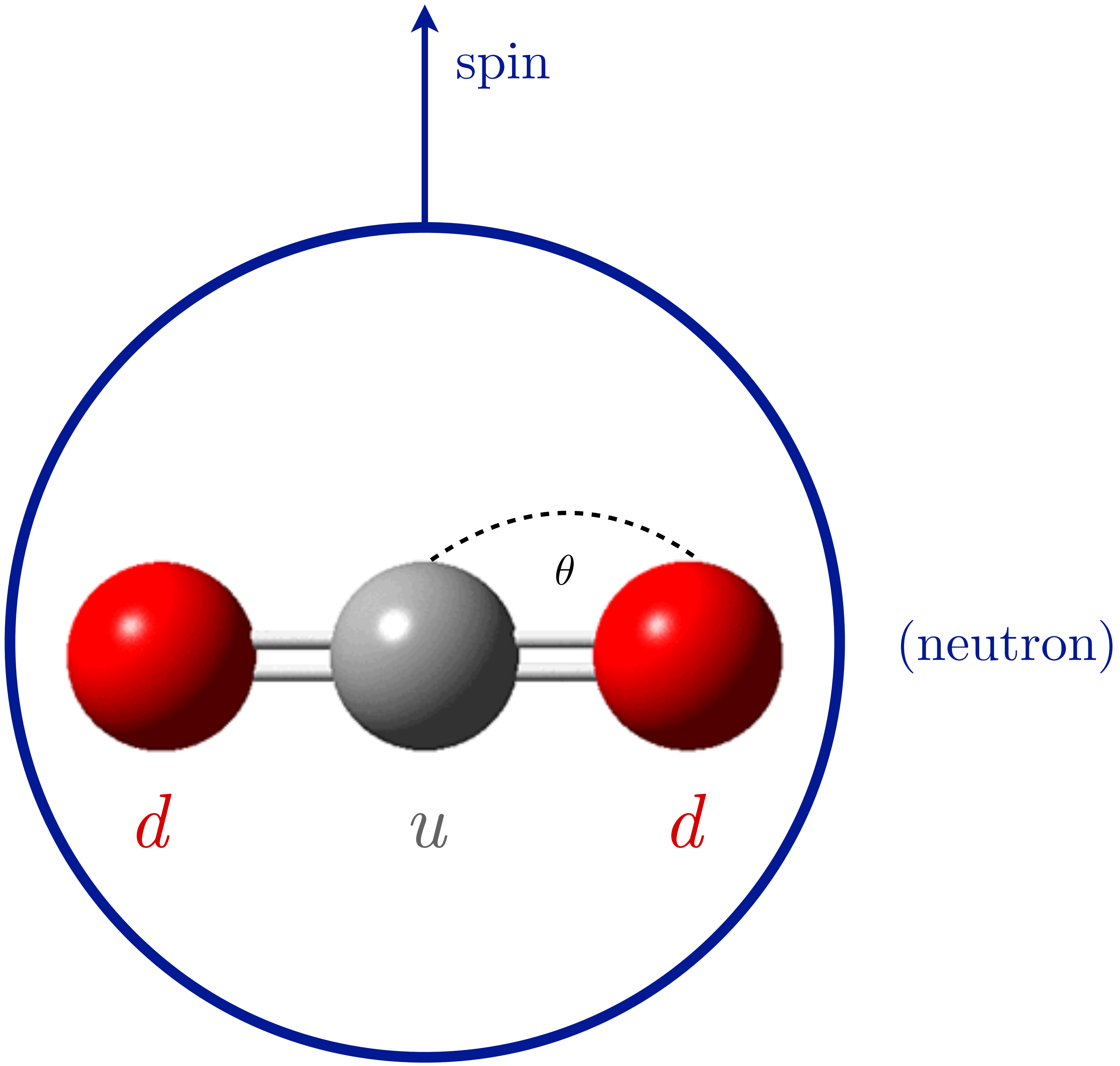


But the defining coupling is to QCD, which gives rise to nuclear effects, such as oscillating nucleon/atomic EDMs.

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

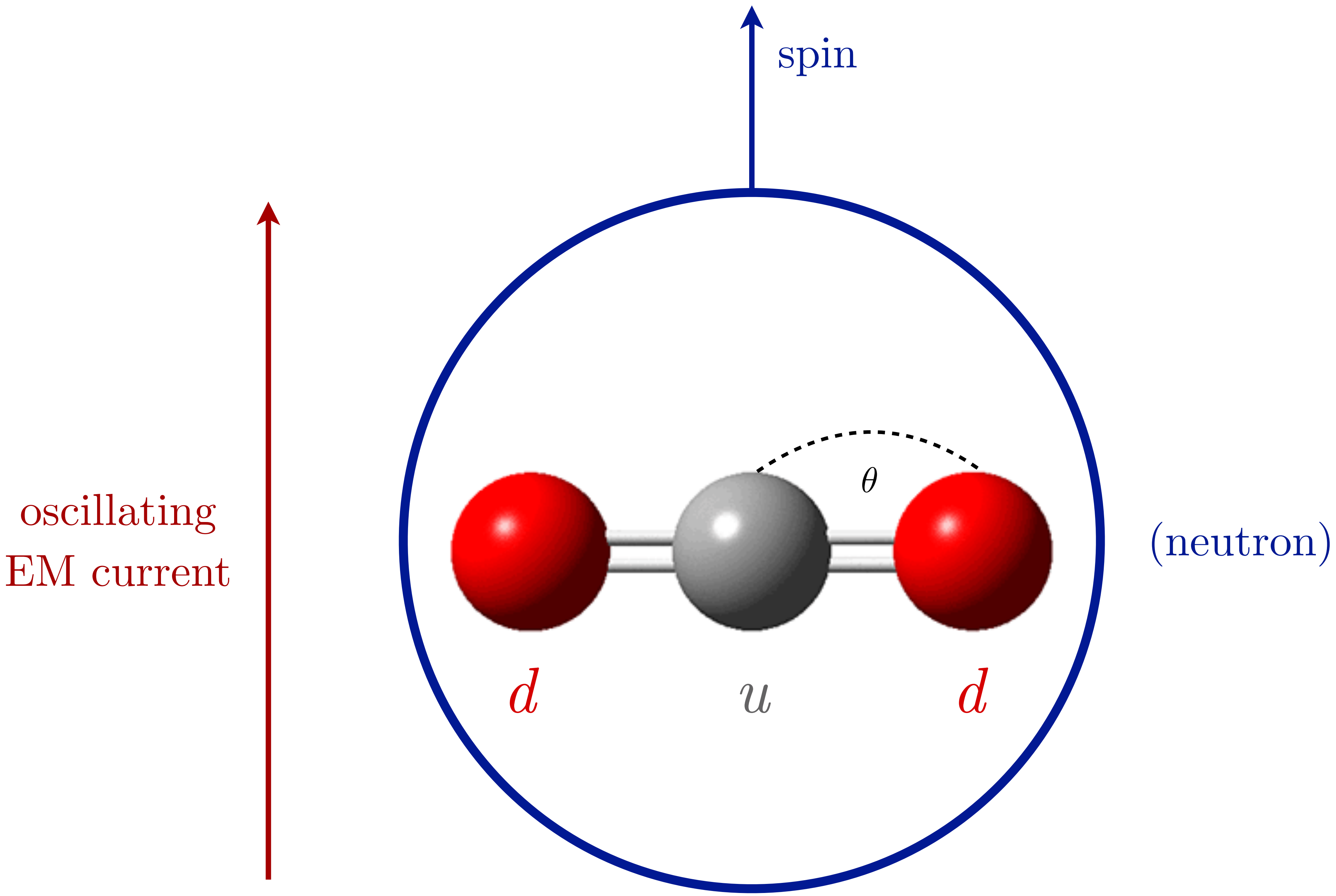
*How do we confirm that a signal in cavity haloscopes is* ***the*** *QCD axion?*

# Oscillating Electric Dipole



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

# Oscillating Electric Dipole



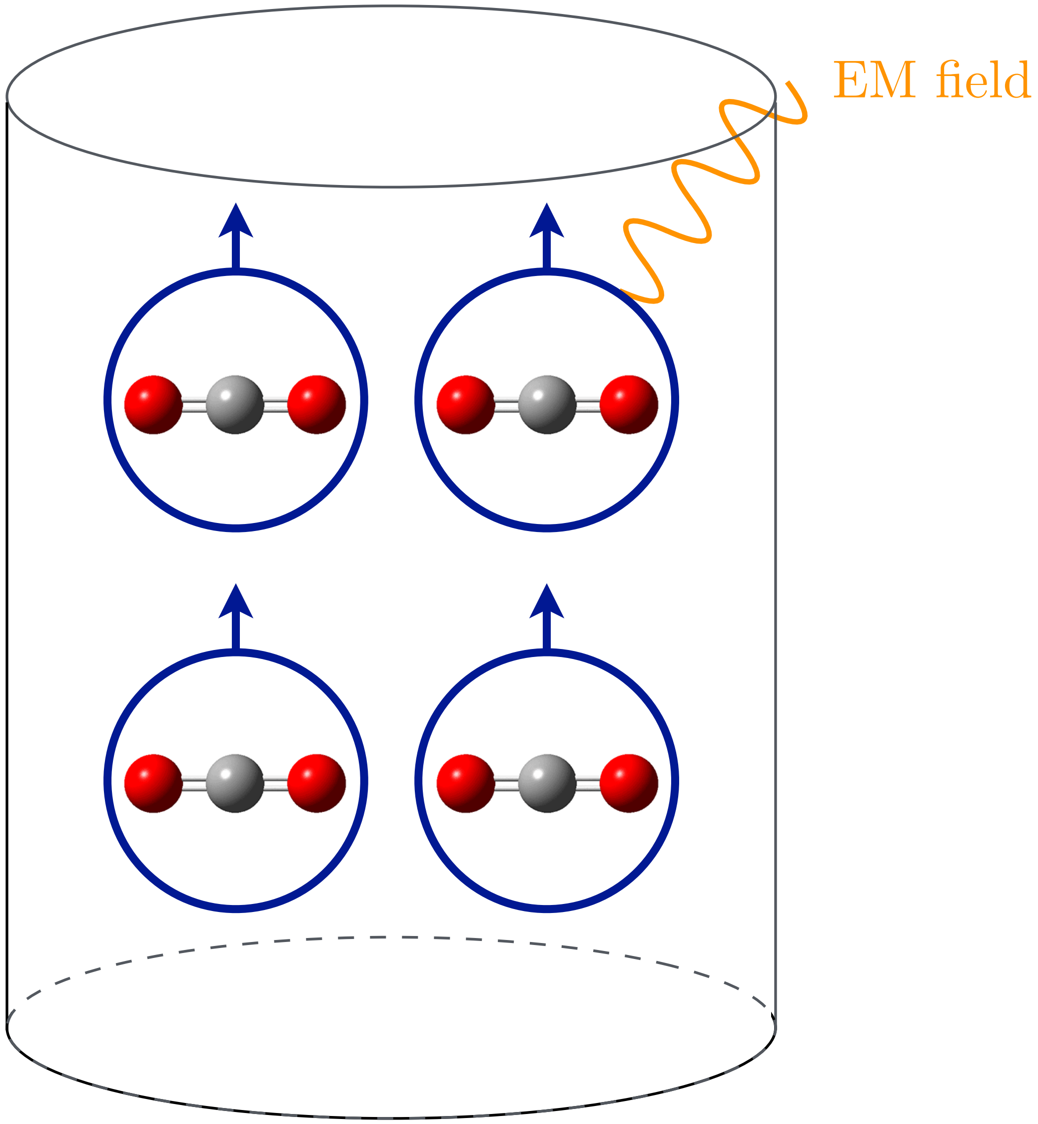
spin

oscillating
EM current

(neutron)

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

# Polarization Haloscope

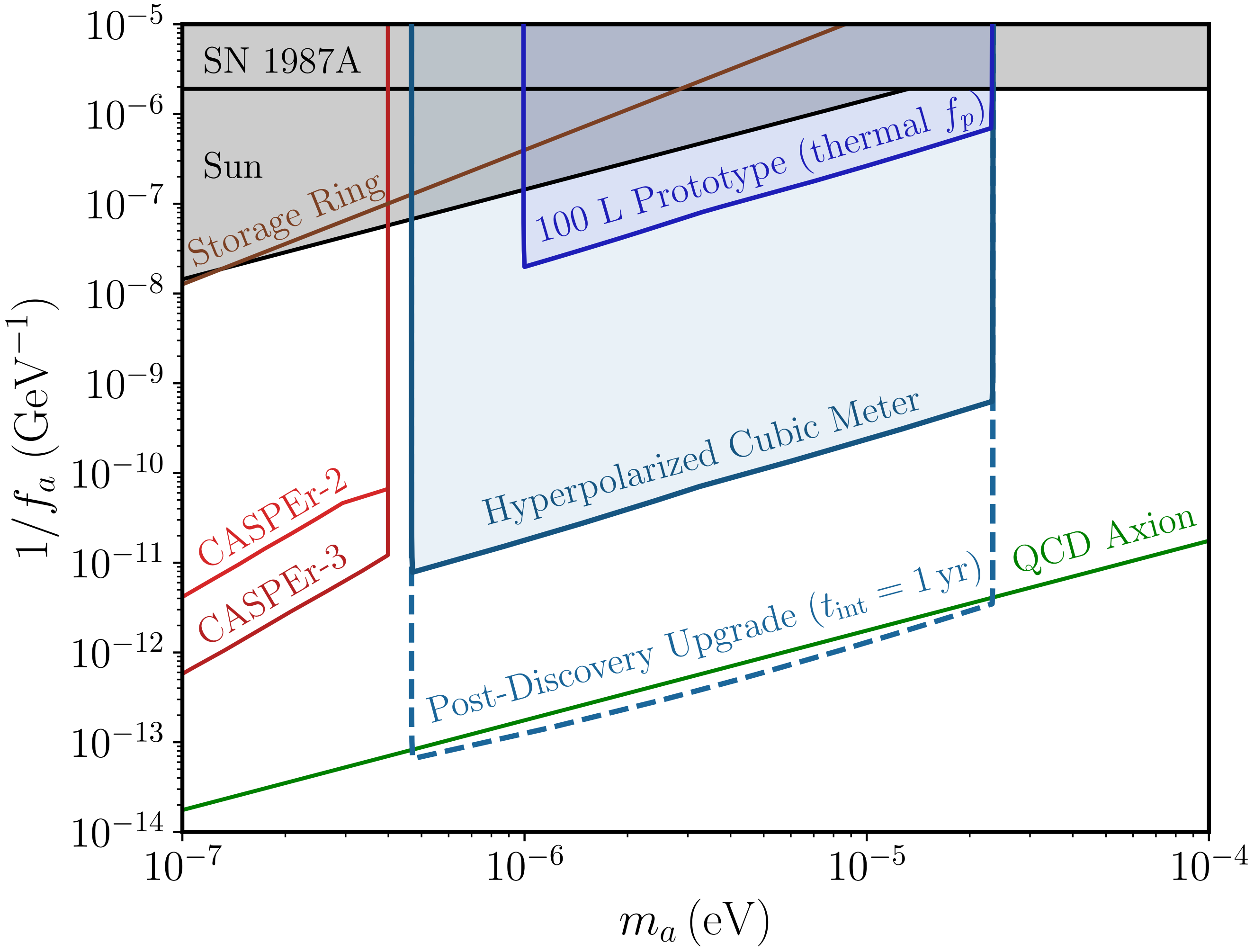


Polarization Haloscope: polarized nuclear material inside cavity

(no $B$-field needed, in principle)

# Projected Sensitivity

arXiv:2209.12901



Optimal Materials

*(abundant and stable rare Earth nuclei)*

| | $^{161}$Dy | $^{153}$Eu | $^{155}$Gd |
|---|---|---|---|
| estimated $\langle S_z \rangle$ ($e$ fm$^3$ $\theta_a$) | 4.3 | 1.0 | 1.2 |
| estimated $\lvert d_A \rvert$ ($10^{-3}$ $e$ fm $\theta_a$) | 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*

# 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*

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

# III. Spin-coupled Axions

# Axion Wind

## *The Usual Story*

(coupling of axion to fermion's spin)

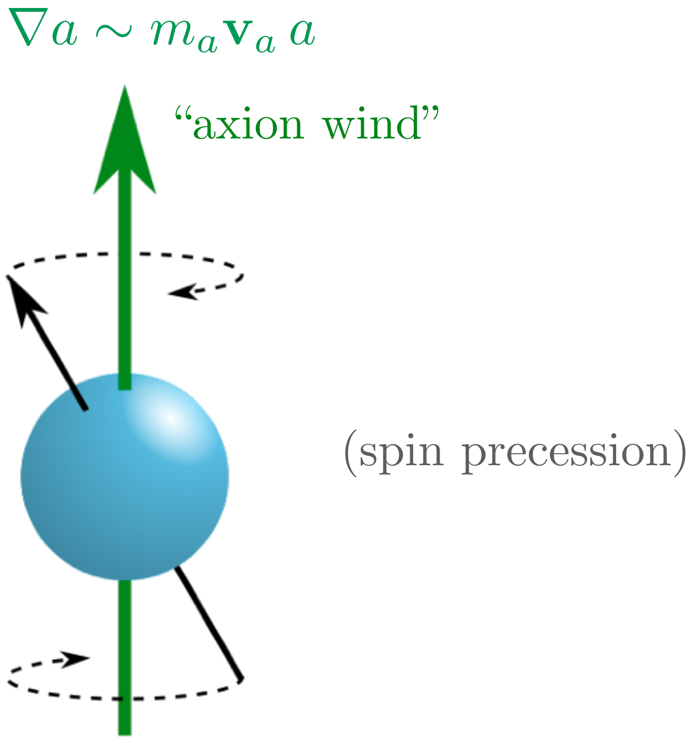
$$\mathscr{L} \sim g_{aff}\, \partial_\mu a\; \bar{f}\gamma^\mu\gamma^5 f$$

$$\Big\downarrow$$

(*effective* spin-coupled magnetic field)

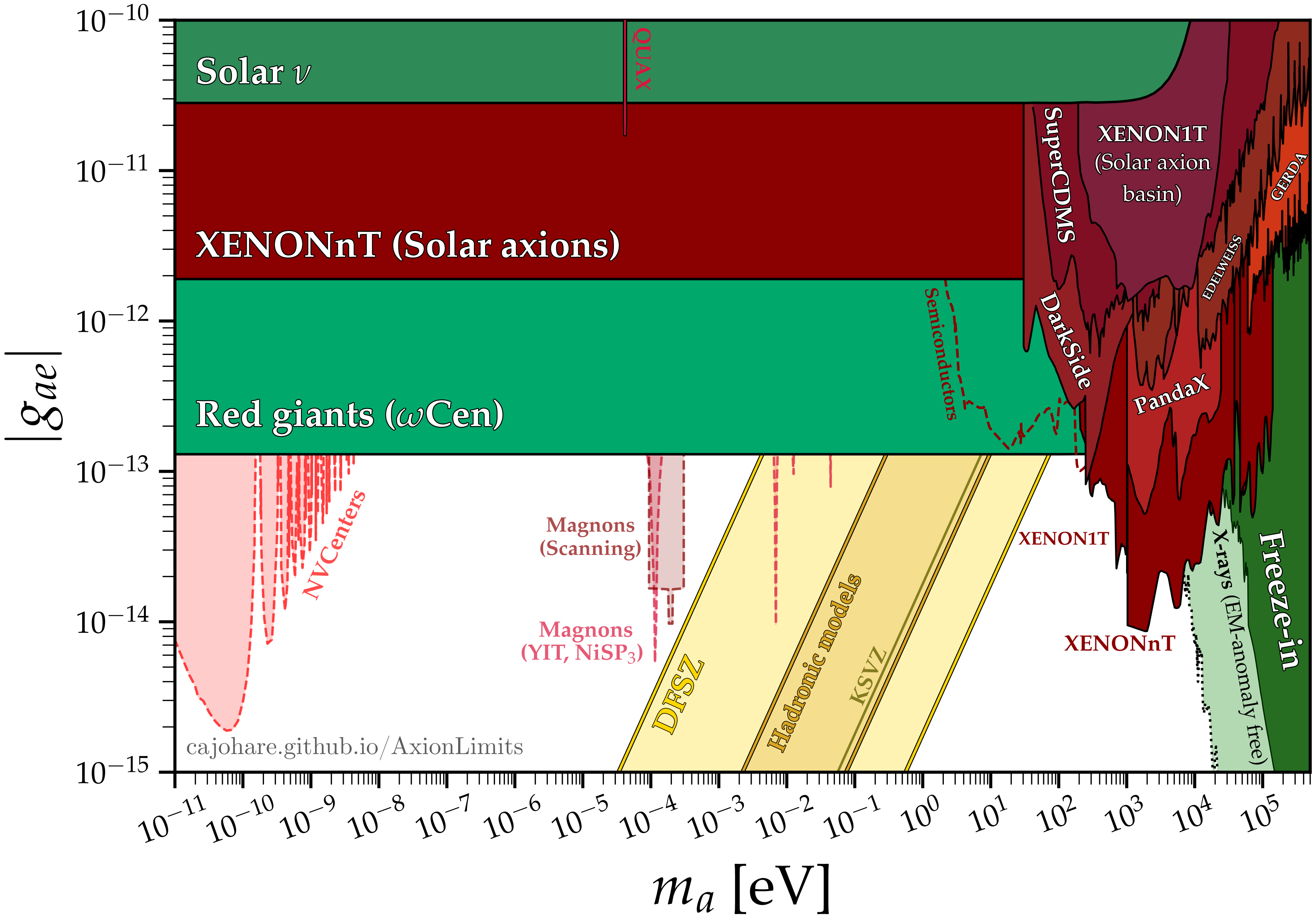
$$(\mu\, B)_{\text{eff}} \sim g_{aff}\, \nabla a$$

$$\Longrightarrow$$



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

# Axion Wind


Solar $\nu$
QUAX
XENONnT (Solar axions)
SuperCDMS
XENON1T
(Solar axion
basin)
GERDA
EDELWEISS
Red giants ($\omega$Cen)
Semiconductors
DarkSide
PandaX
NVCenters
Magnons
(Scanning)
Magnons
(YIT, NiSP$_3$)
DFSZ
Hadronic models
KSVZ
XENON1T
XENONnT
X-rays (EM-anomaly free)
Freeze-in
cajohare.github.io/AxionLimits
$|g_{ae}|$
$10^{-10}$
$10^{-11}$
$10^{-12}$
$10^{-13}$
$10^{-14}$
$10^{-15}$
$10^{-11}$
$10^{-10}$
$10^{-9}$
$10^{-8}$
$10^{-7}$
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^{0}$
$10^{1}$
$10^{2}$
$10^{3}$
$10^{4}$
$10^{5}$
$m_a$ [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

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

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

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

the usual *effective*
spin-coupled *B*-field

# Spin-Coupled Axions

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

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

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

the usual *effective*
spin-coupled $B$-field

*effective* spin-coupled vector potential

→ *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

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

---

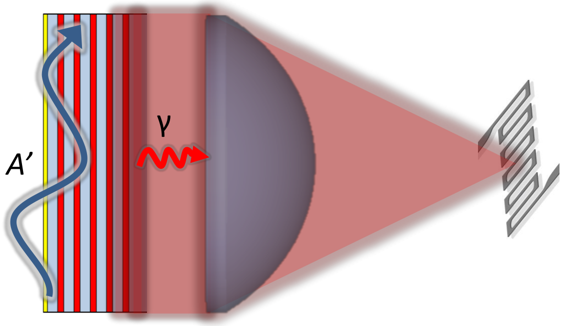
All signals scale as $\ddot{a}$ or $\dot{a}\,\dot{\sigma} \sim \dot{a}\,\mu\,\sigma \times B$

*(corrects or invalidates some previously-claimed signals)*

*(more interesting at higher masses)*

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

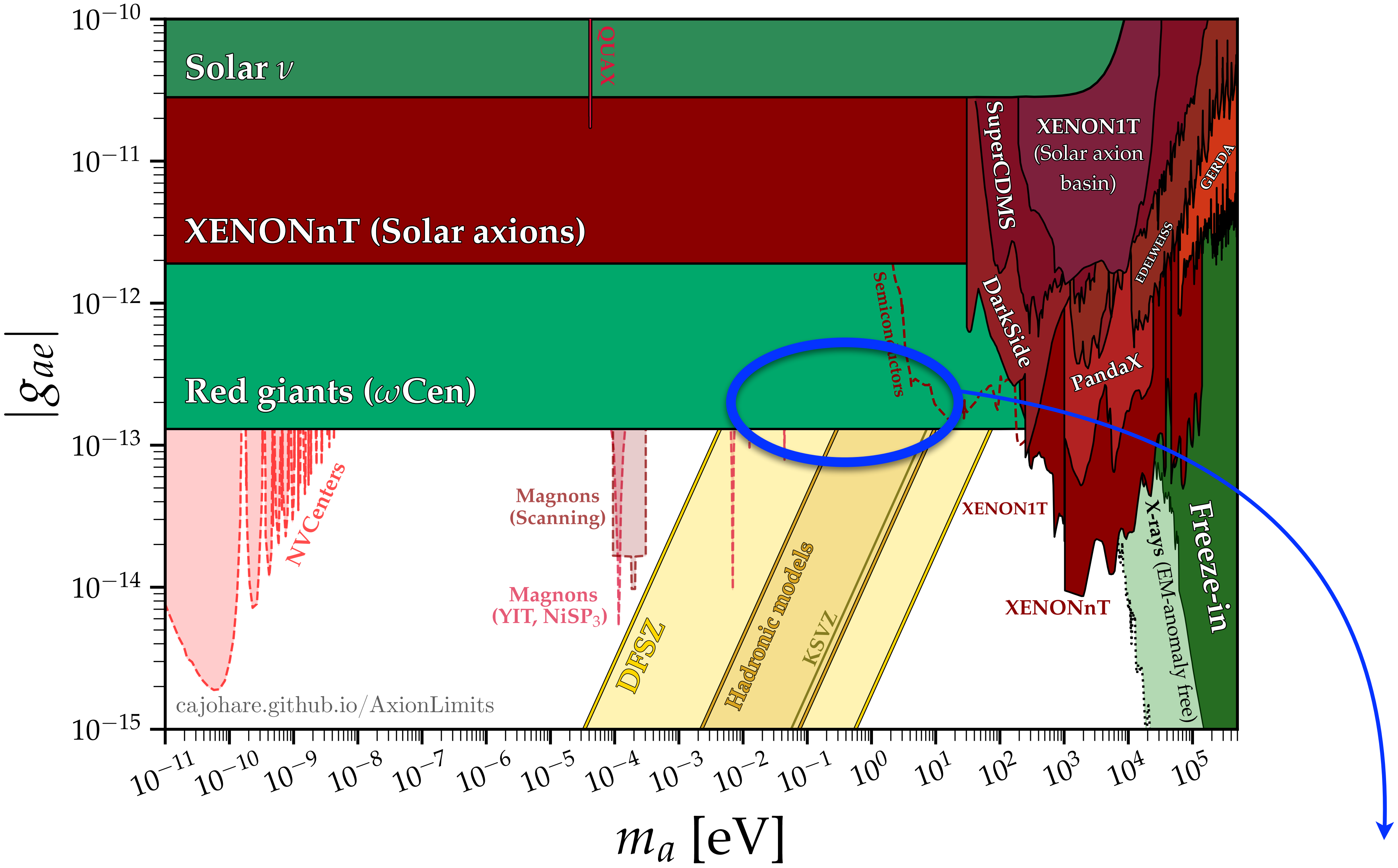
*(place polarized material in EM detectors)*



*~ 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*

# Outlook

A shift in our priors has motivated a larger set of signals.
Many bang-for-buck experiments > single catch-all experiment.

Important to explore wide-range of masses and couplings.

There are still many regions of axion parameter space
that require new ideas to explore.

Theory and experiment are evolving together in this effort.
The role of theorists is crucial in emerging fields.

# Back Up Slides

# Below ~Micro-eV

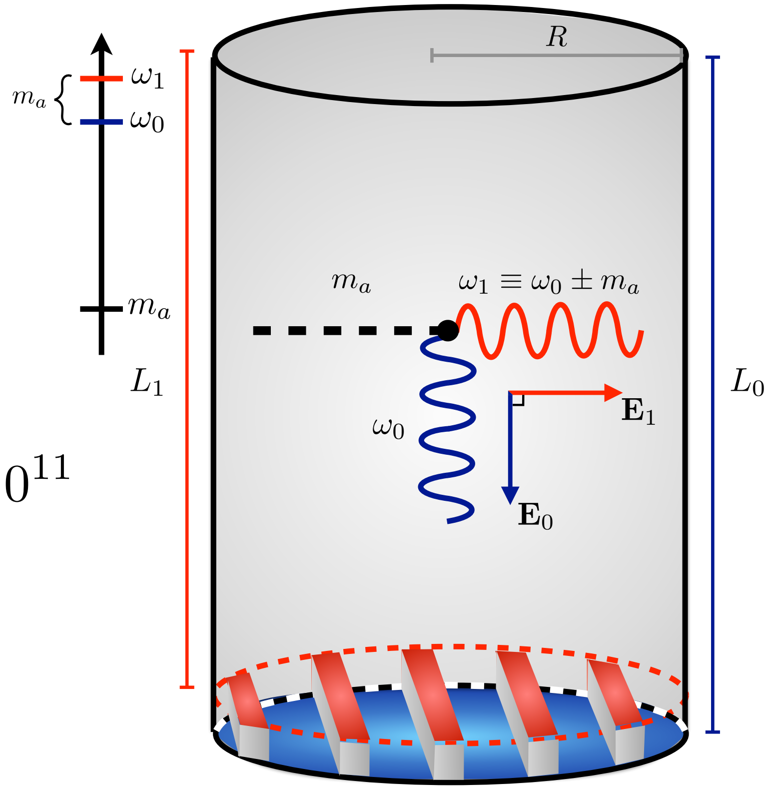
## Heterodyne/Upconversion (SRF cavities @ Fermilab/SLAC)

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

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

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

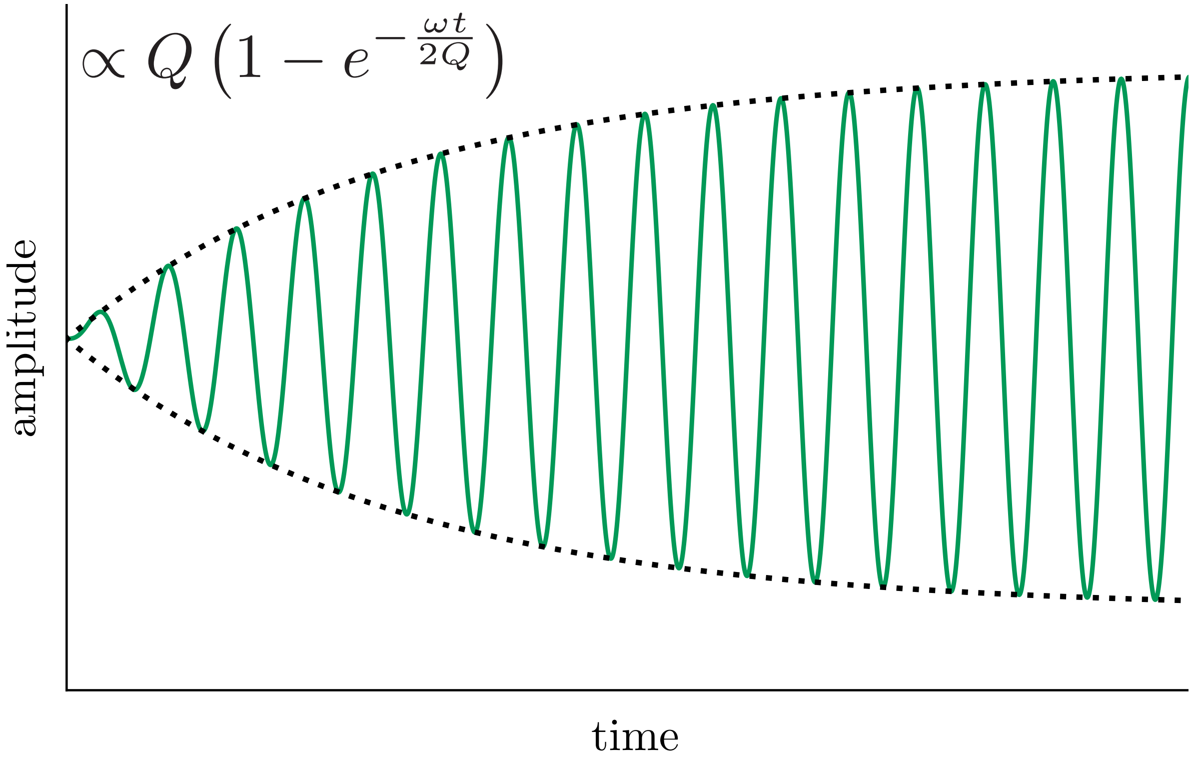


$m_a \sim \omega_{\text{sig}} - \omega_{\text{pump}} \ll \omega_{\text{pump}} \implies$ small mechanical deformations to tune for small masses

signal power ∝ detector size × mode frequency ∼ 1

# Driven Damped Harmonic Oscillator

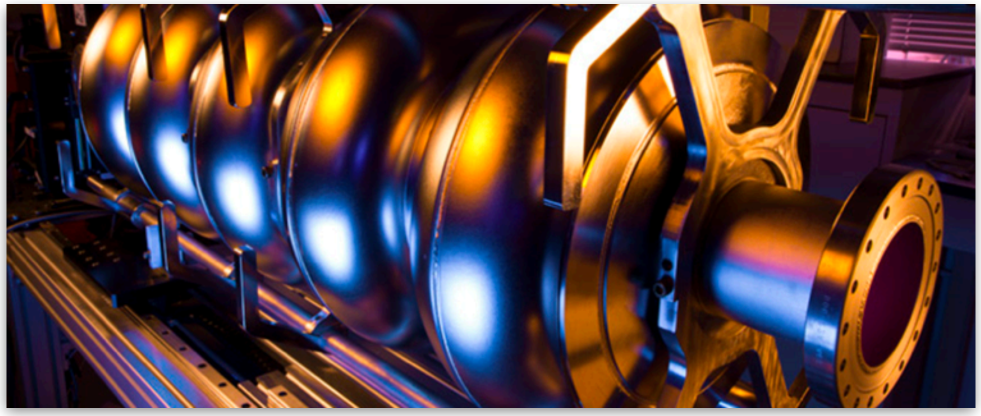
axion signal
on resonance



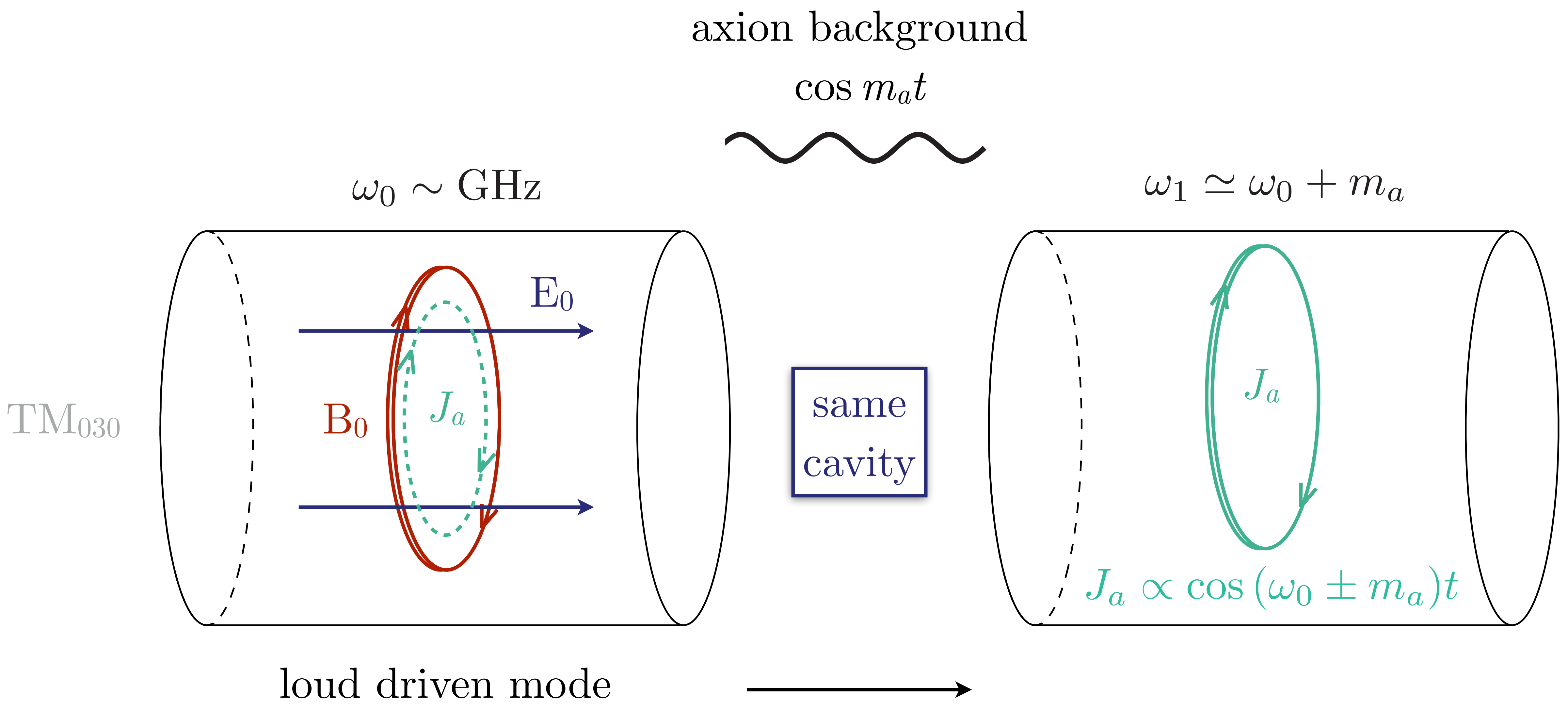
($\sim Q$ oscillations)

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

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



# Heterodyne Detection of Axion Dark Matter



axion background

$\cos m_a t$

$\omega_0 \sim \text{GHz}$

$\omega_1 \simeq \omega_0 + m_a$

$\text{TM}_{030}$

$\text{E}_0$

$\text{B}_0$

$J_a$

same cavity

$J_a$

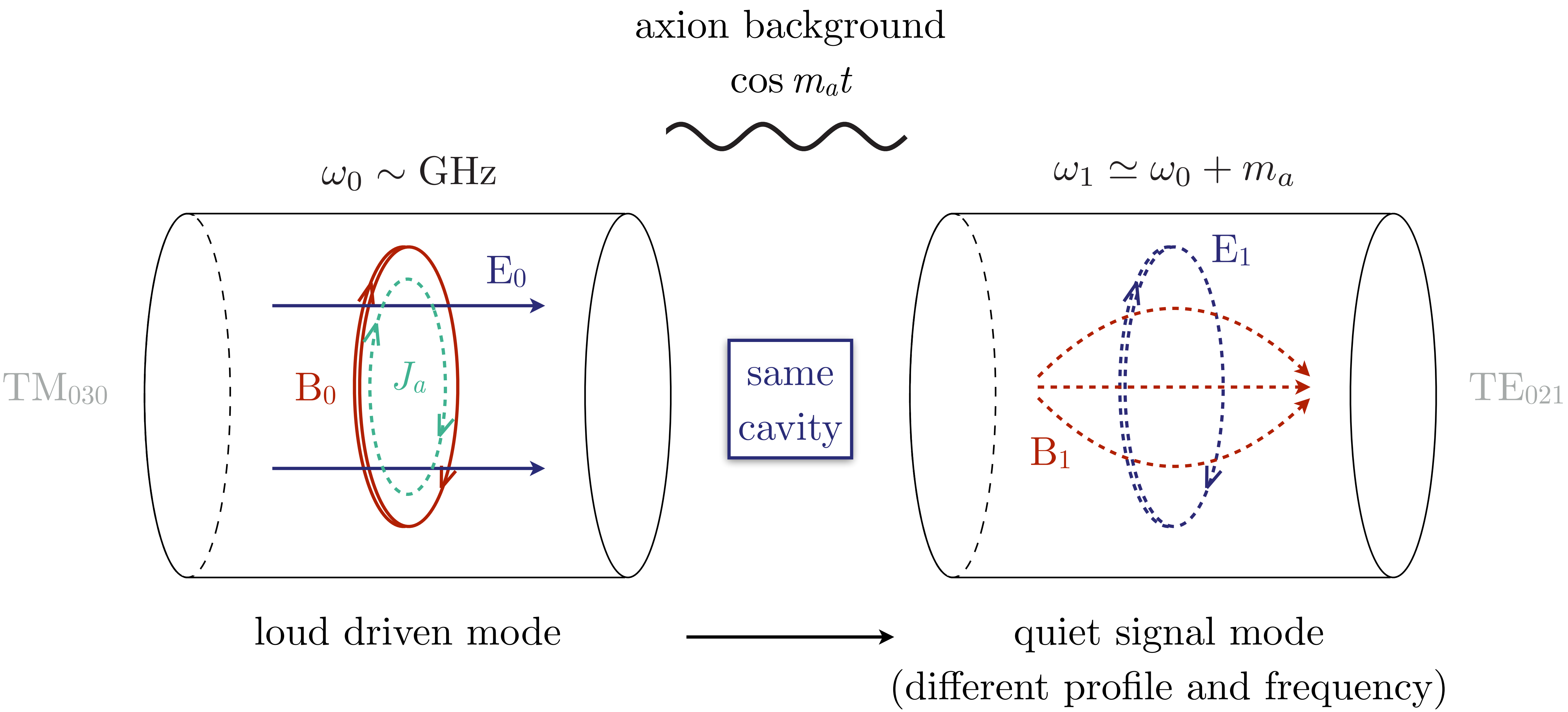
$J_a \propto \cos{(\omega_0 \pm m_a)t}$

loud driven mode

"Frequency Conversion" between two ~ GHz cavity modes

1. Prepare the cavity with a large amount of power at mode $\omega_0$ .
2. Axion dark matter resonantly transfers a small amount of power to mode $\omega_1$ .
3. Scan over frequency-splittings (axion masses) by slightly deforming the cavity.

# Heterodyne Detection of Axion Dark Matter



axion background

$\cos m_a t$

$\omega_0 \sim \text{GHz}$

$\omega_1 \simeq \omega_0 + m_a$

same cavity

loud driven mode

quiet signal mode

(different profile and frequency)

"Frequency Conversion" between two ~ GHz cavity modes

1. Prepare the cavity with a large amount of power at mode $\omega_0$ .
2. Axion dark matter resonantly transfers a small amount of power to mode $\omega_1$ .
3. Scan over frequency-splittings (axion masses) by slightly deforming the cavity.

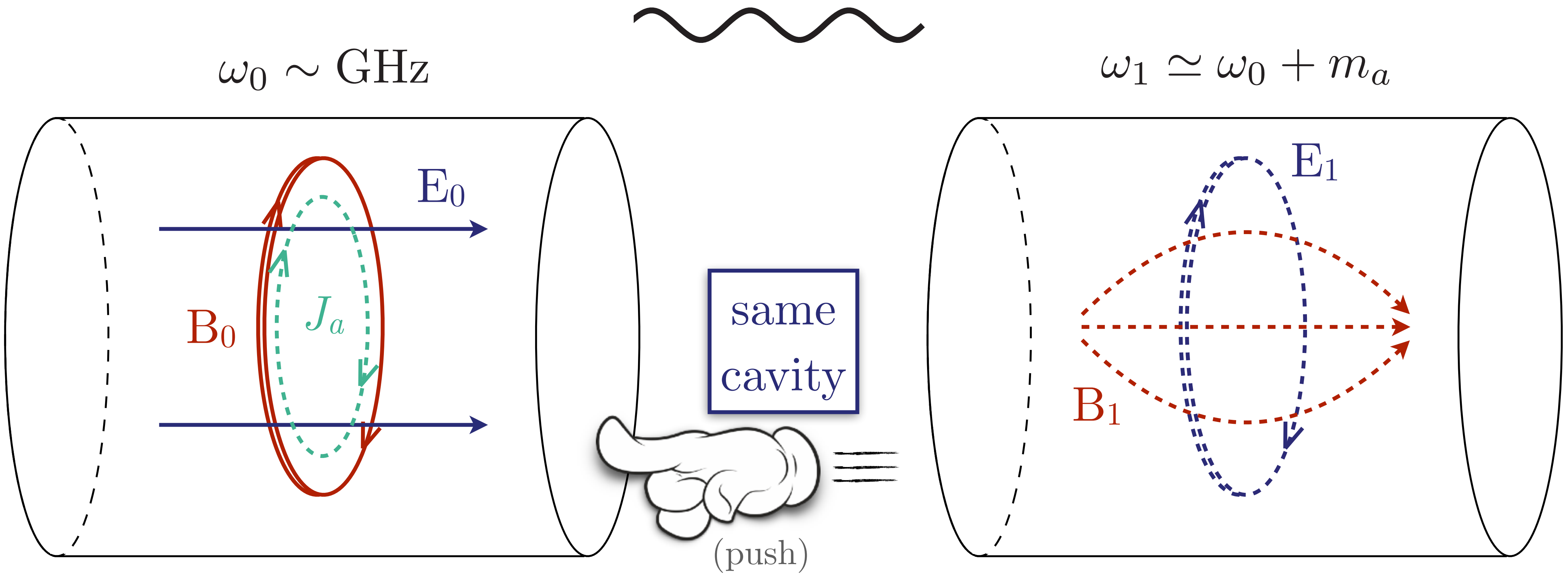
# Heterodyne Detection of Axion Dark Matter

axion background

$\cos m_a t$

$\omega_0 \sim$ GHz

$\omega_1 \simeq \omega_0 + m_a$



TM030

TE021

loud driven mode $\longrightarrow$ quiet signal mode (different profile and frequency)

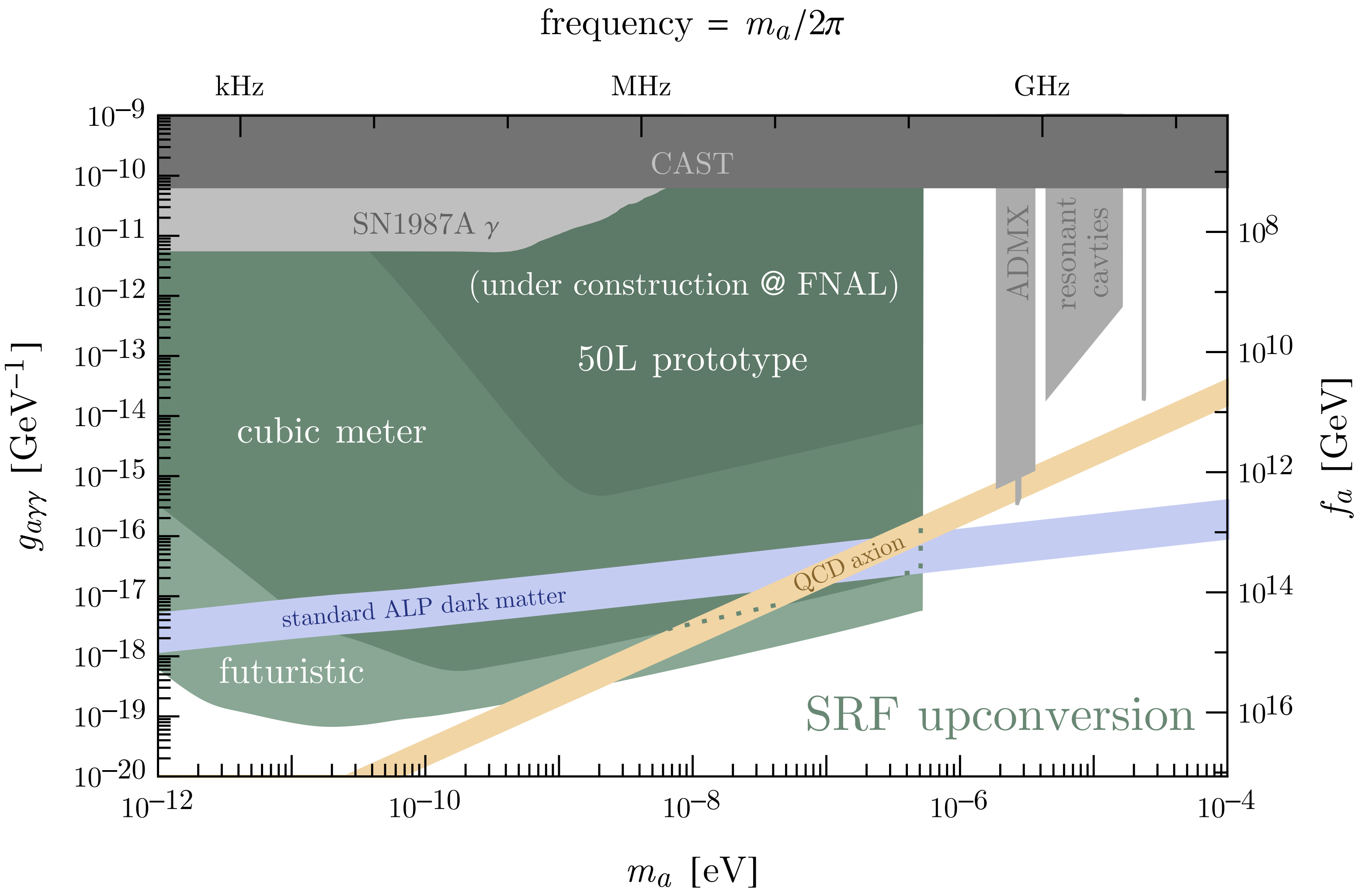
## “Frequency Conversion” between two ~ GHz cavity modes

1. Prepare the cavity with a large amount of power at mode $\omega_0$ .
2. Axion dark matter resonantly transfers a small amount of power to mode $\omega_1$ .
3. Scan over frequency-splittings (axion masses) by slightly deforming the cavity.

# Heterodyne Detection of Axion Dark Matter

Axion Dark Matter

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



signal is always read out at ~ GHz

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

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