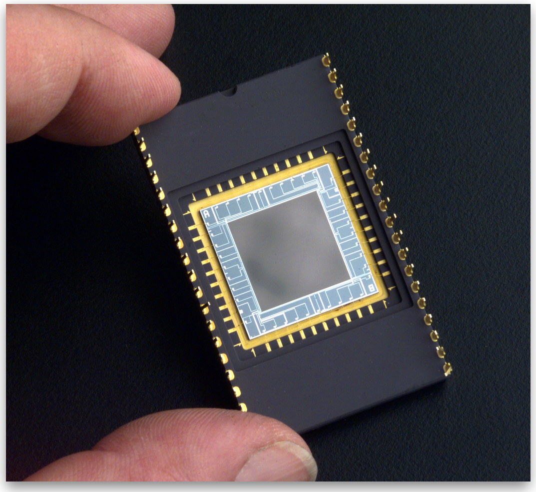
Precision Sensors for Axion Dark Matter and Beyond

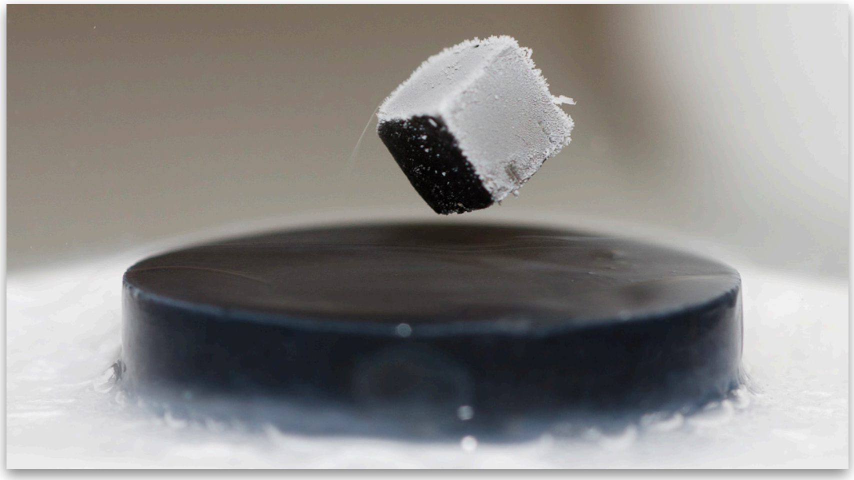
Asher Berlin - Fermilab

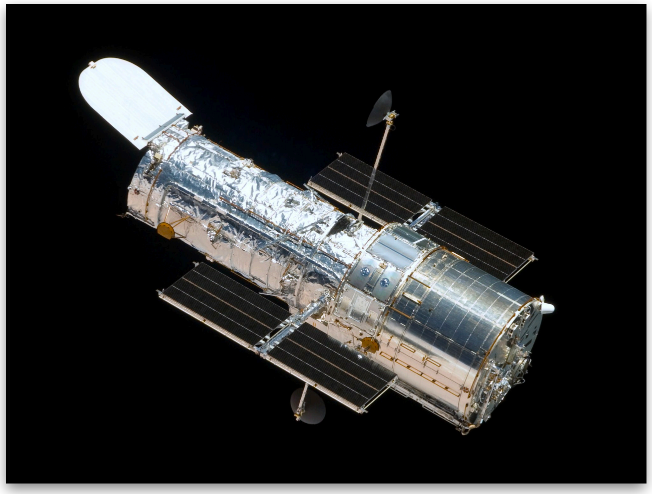
PASCOS
July 28, 2022

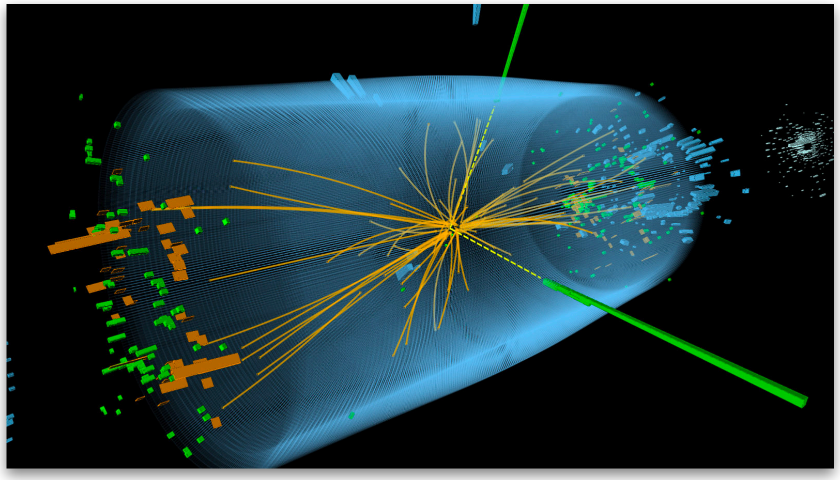
Technology and Fundamental Physics

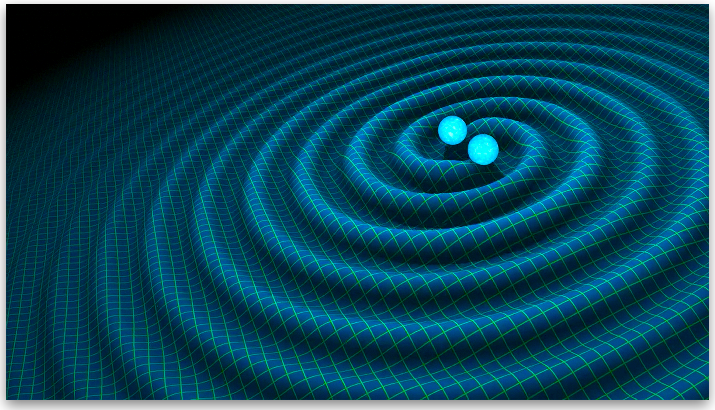
New technology opens windows into new physics.











What Have We Learned?

Dark matter resides in galaxies (including our own).

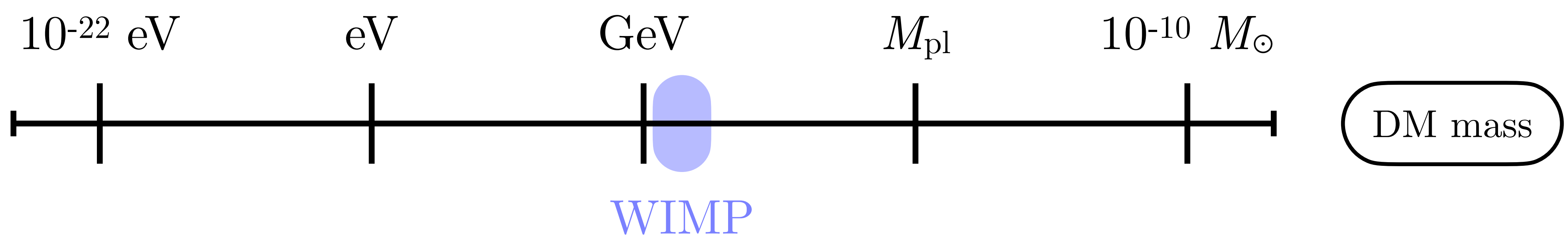
velocity: $v_{\rm DM} \sim 100$ km/s $\sim 10^{-3}\, c$

mass density: $m_{\rm DM}\, n_{\rm DM} \sim$ GeV/cm^3

Few heavy particles or many light particles?
What is the dark matter mass?

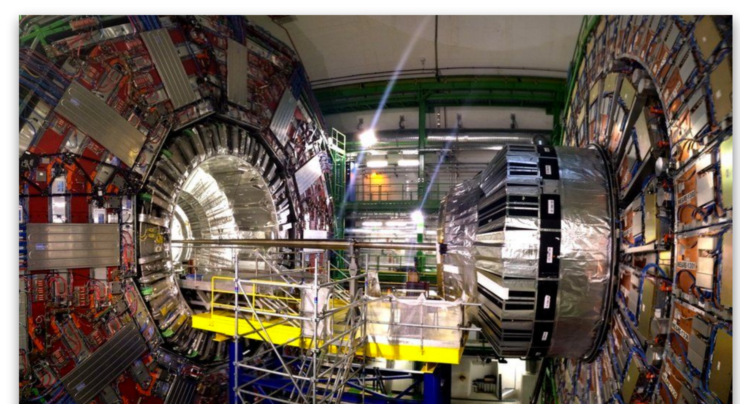
What Have We Learned?

What Have We Learned?

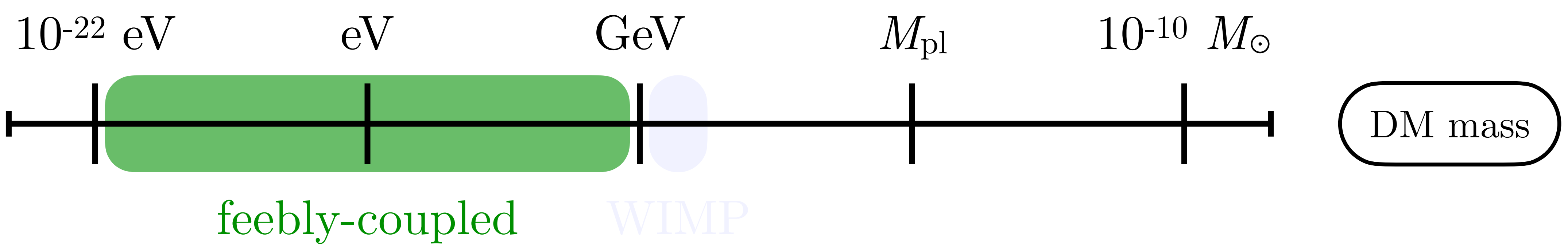


The search for WIMPs has been an incredible success.

What now?



Where are We Going?



The search for WIMPs has been an incredible success.

What now?

Maybe the dark matter and hierarchy problem are not solved together.

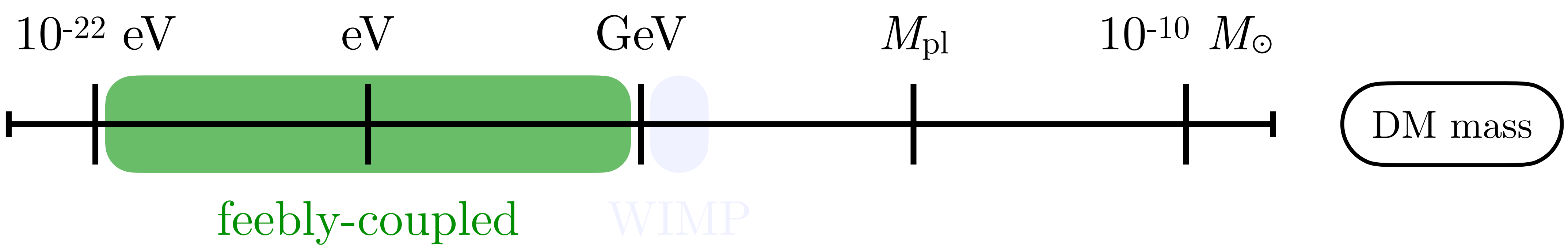
↓

If so, the space of motivated signals is dramatically enlarged.

↓

This motivates a strong diversification of the experimental program.

Where are We Going?



precision detectors

Quiet and coherent enough to build up a detectable signal.

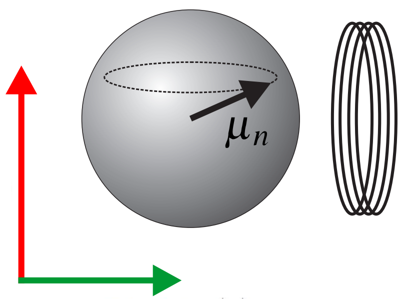
We can now explore a wide range of previously unaccessible scales.

Where are We Going?

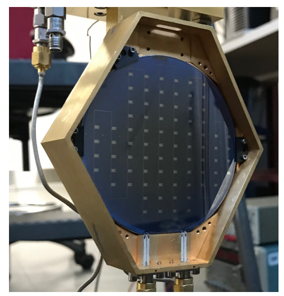
New Sensors for BSM physics

a ~~single catch-all experiment~~ $\rightarrow$ multitude of bang-for-buck experiments

NMR

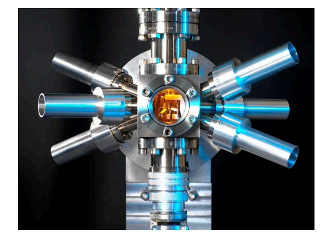


KIDs



SRF cavities

atomic clocks/interferometers



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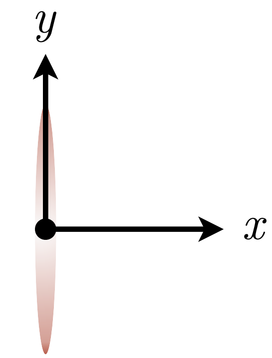
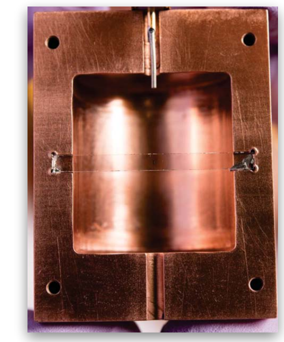
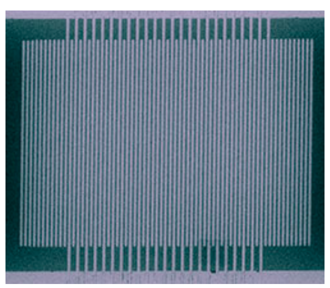


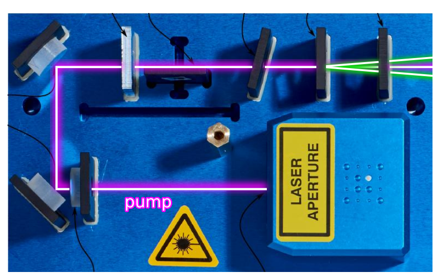
SC qubit



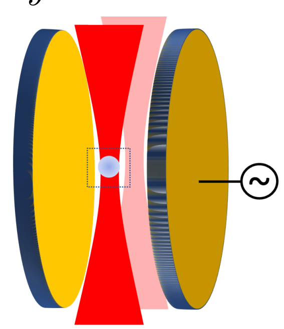
SNSPDs



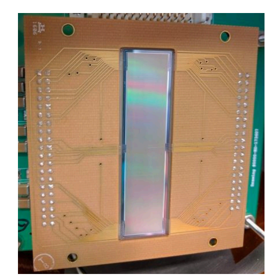
nonlinear optics



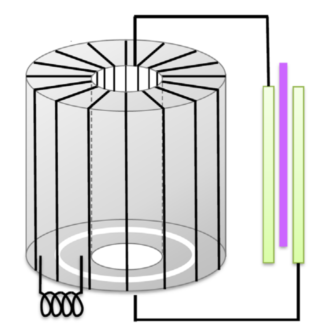
optically levitated dielectrics



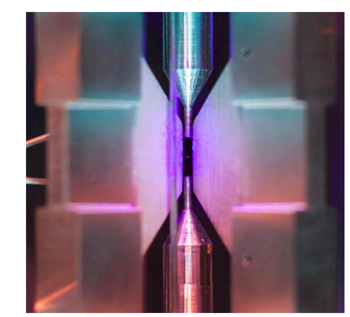
skipper CCDs



LC circuits



ion traps



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Where are We Going?

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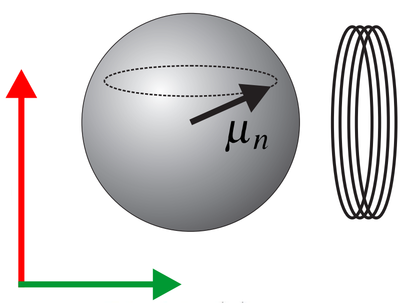

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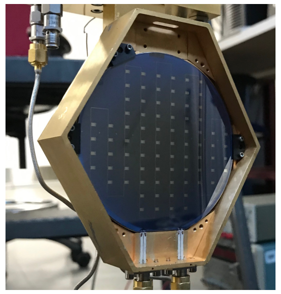

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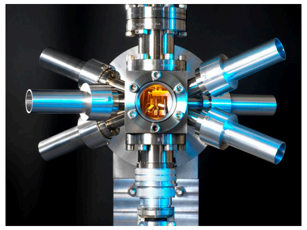

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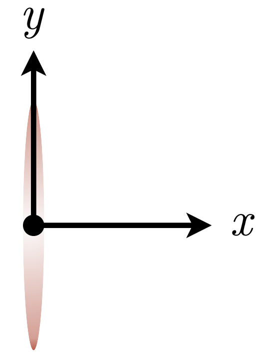

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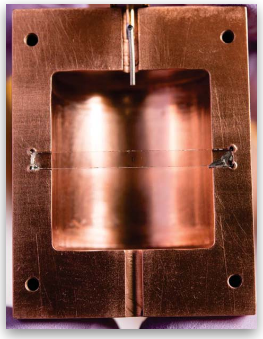

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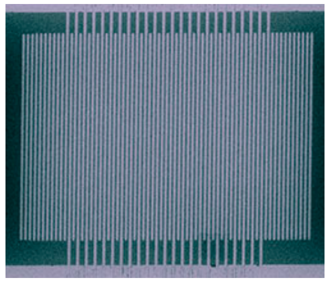
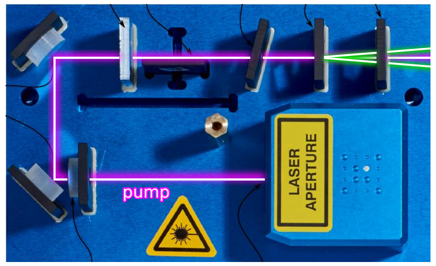


nonlinear optics



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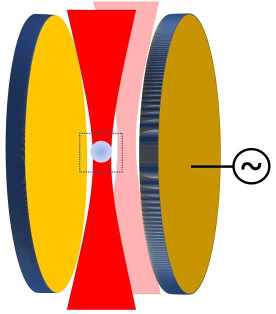

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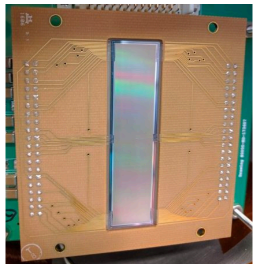

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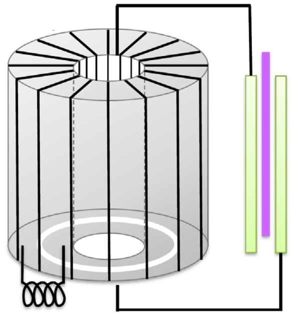

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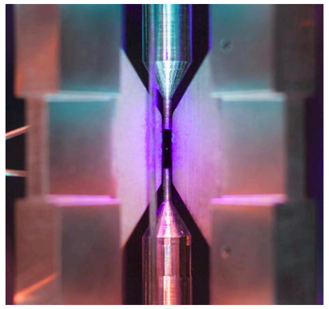

What is the role of a theorist?

Creative repurposing of existing detectors.

Motivating/conceiving/designing new small-scale experiments.

This is especially crucial in emerging fields.

Outline

Axion Dark Matter

I.

resonant cavities
LC circuits
dielectrics/plasmas
NMR, ...

Superconducting Cavities

II.

axions
dark photons
millicharged particles
gravitational waves, ...

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I. Axion Dark Matter

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

$$\mathscr{L} \sim \frac{\partial_\mu a}{f_a} J^\mu_{\text{SM}} \sim \frac{a}{f_a} G\tilde{G} + \frac{a}{f_a} F\tilde{F} + \cdots$$

large scale

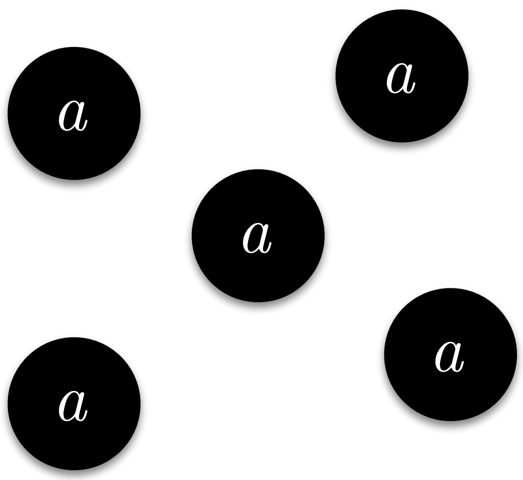
explains the smallness of the neutron's electric dipole moment

generic and detectable

How to think about axions dynamically?

Sub-eV Axion Dark Matter

axion dark matter ~ classical field



smaller mass
(larger density)

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wave properties

$$a \propto \cos m_a t$$

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

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

Axion Electrodynamics

prepared EM field

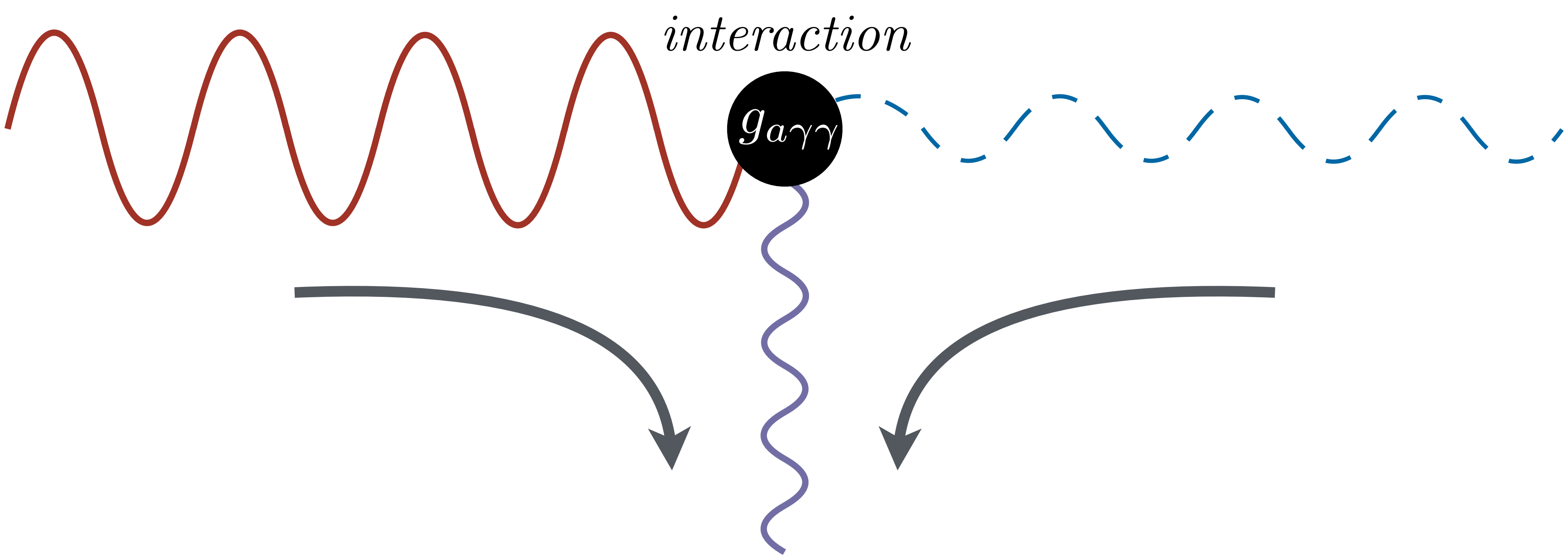
$\sim \cos \omega_0 t$

(frequency ~ your choice)

galactic axion field

$\sim \cos m_a t$

(frequency ~ axion mass)



signal EM field

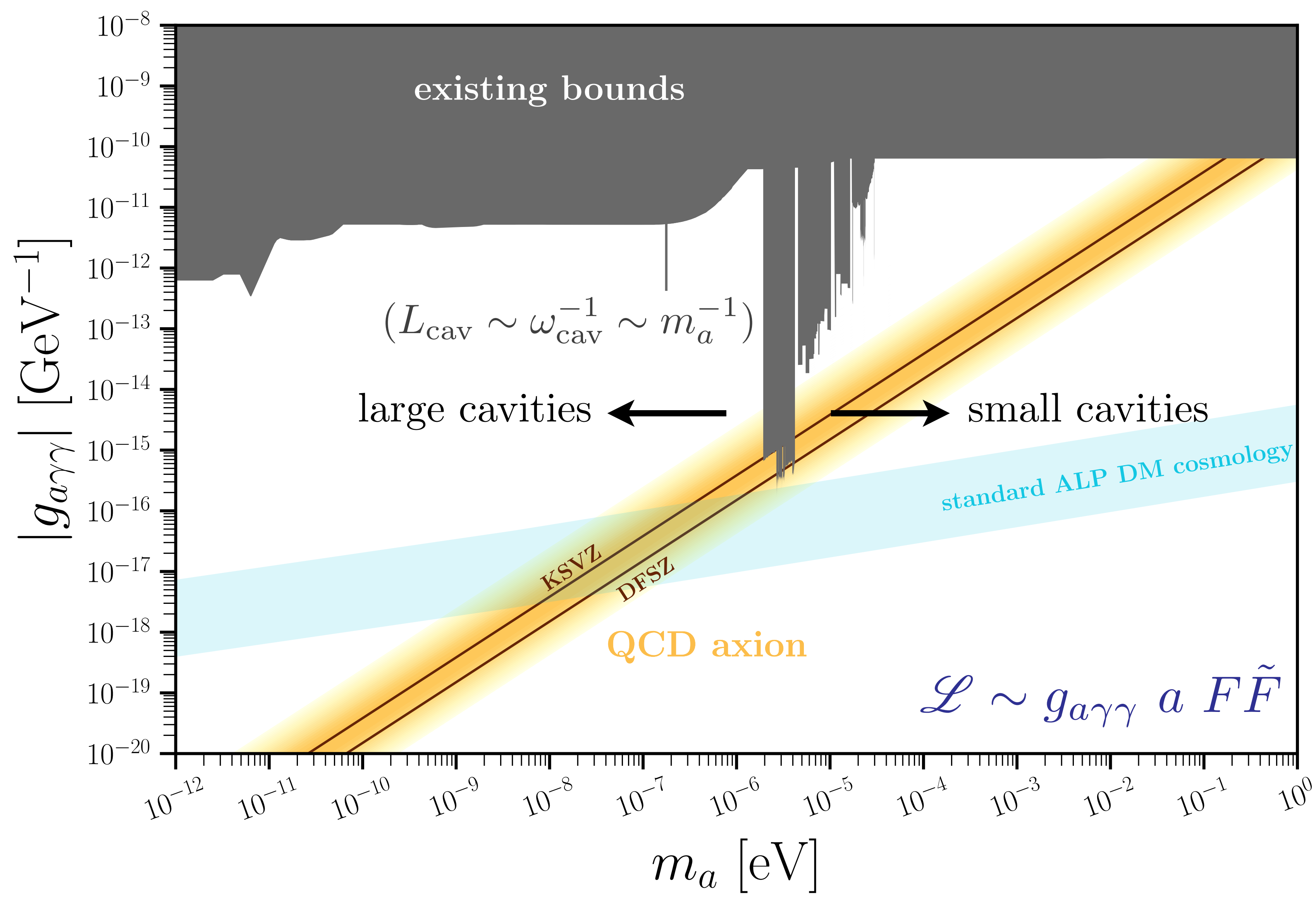
$\sim \cos (\omega_0 + m_a) t$

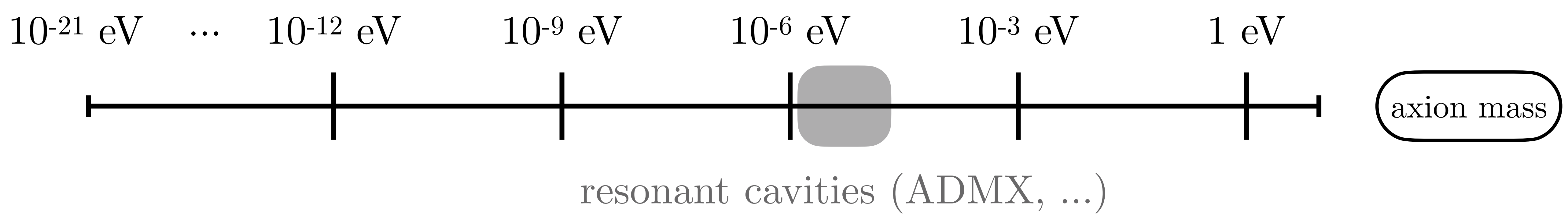
ideal detector is resonantly matched to signal frequency

signal power $\propto (\omega_0 + m_a) \cos (\omega_0 + m_a) t$

Axion Parameter Space

(axion + $B \to$ photon)





Axion Parameter Space

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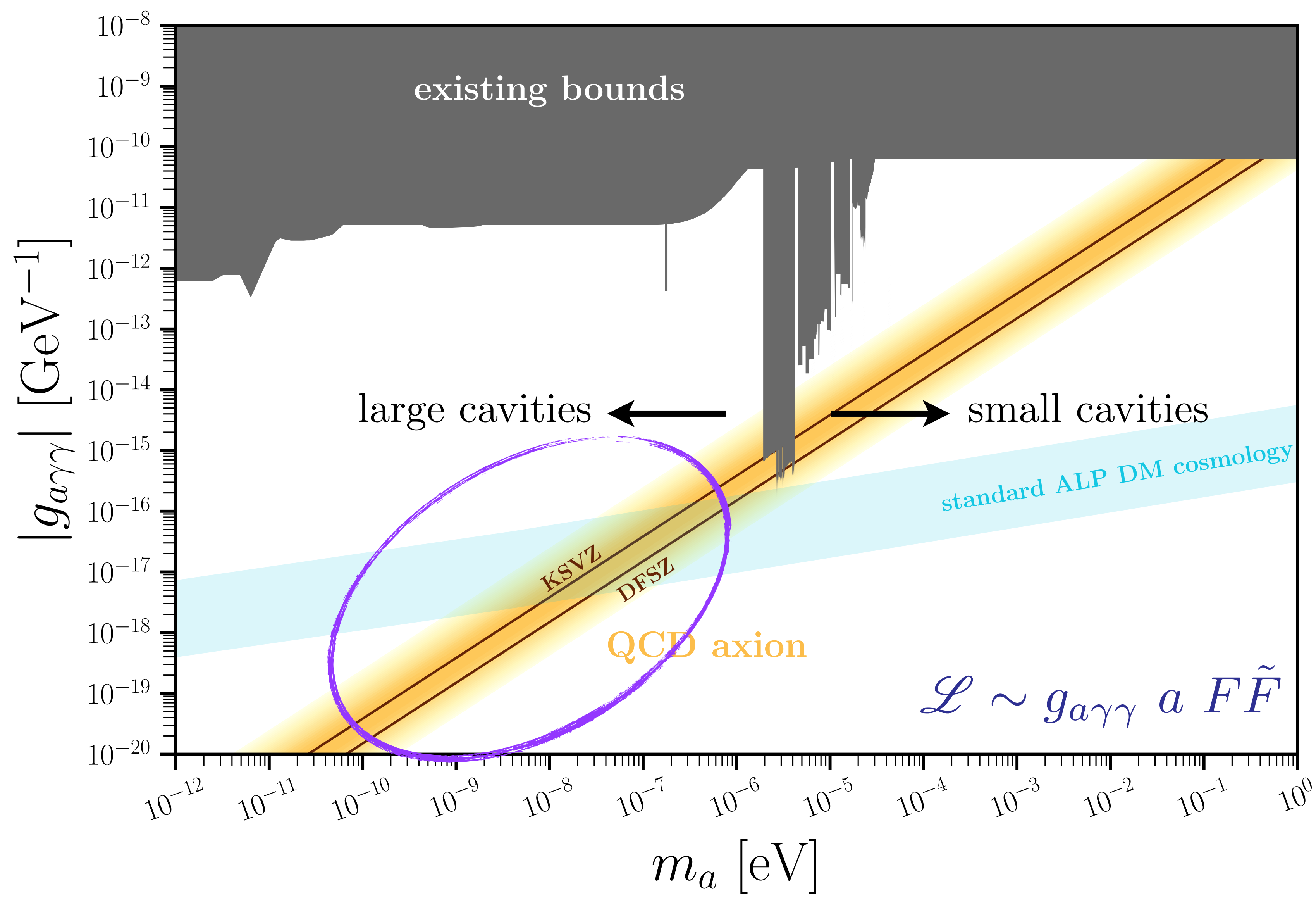
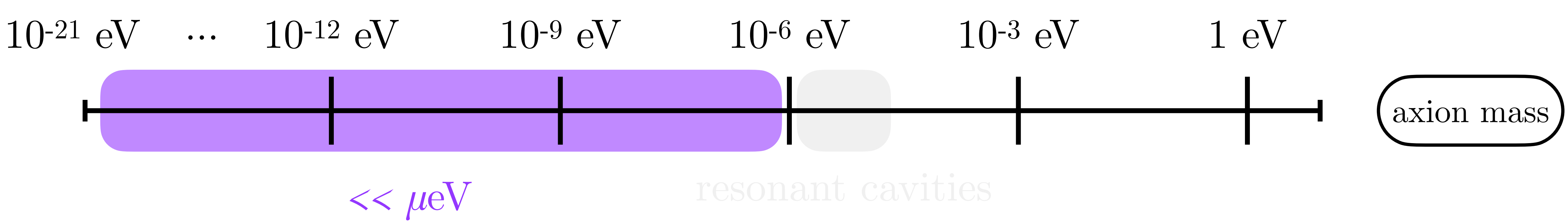
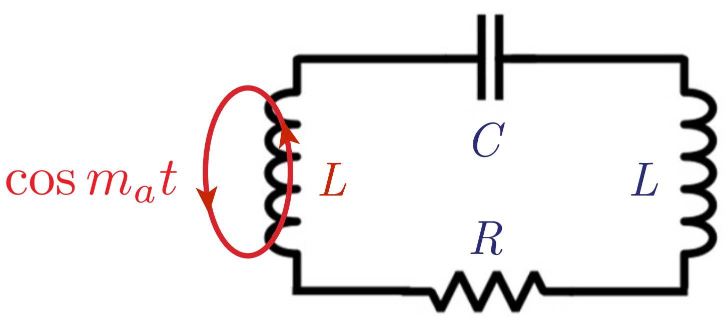


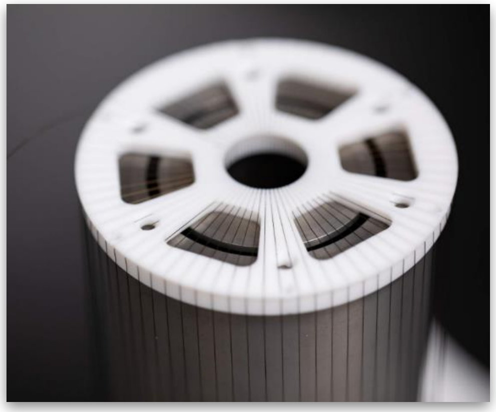


Below ~Micro-eV

LC circuits (DMRadio)

arXiv:2204.13781, arXiv:2203.11246



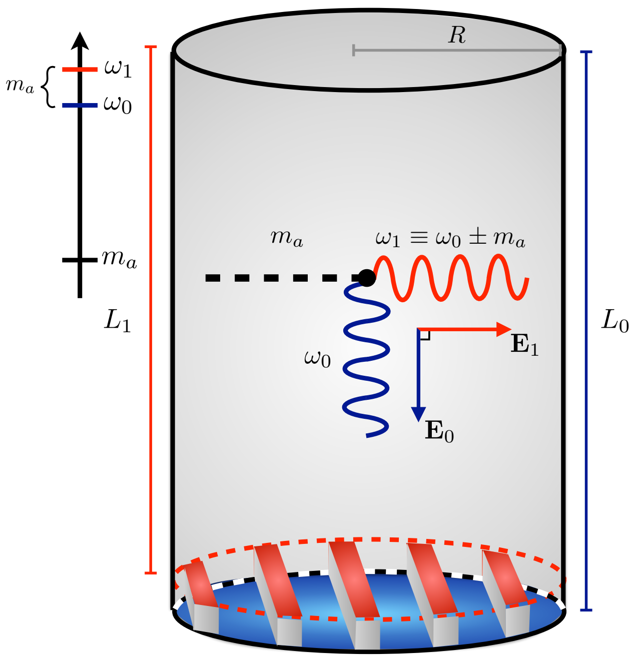


$$\omega_{\rm LC} \sim \frac{1}{\sqrt{LC}} \sim m_a \ll \frac{1}{\text{length}}$$

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

Heterodyne/Upconversion (SRF cavities)

arXiv:1912.11048, arXiv:1912.11056, arXiv:2007.15656

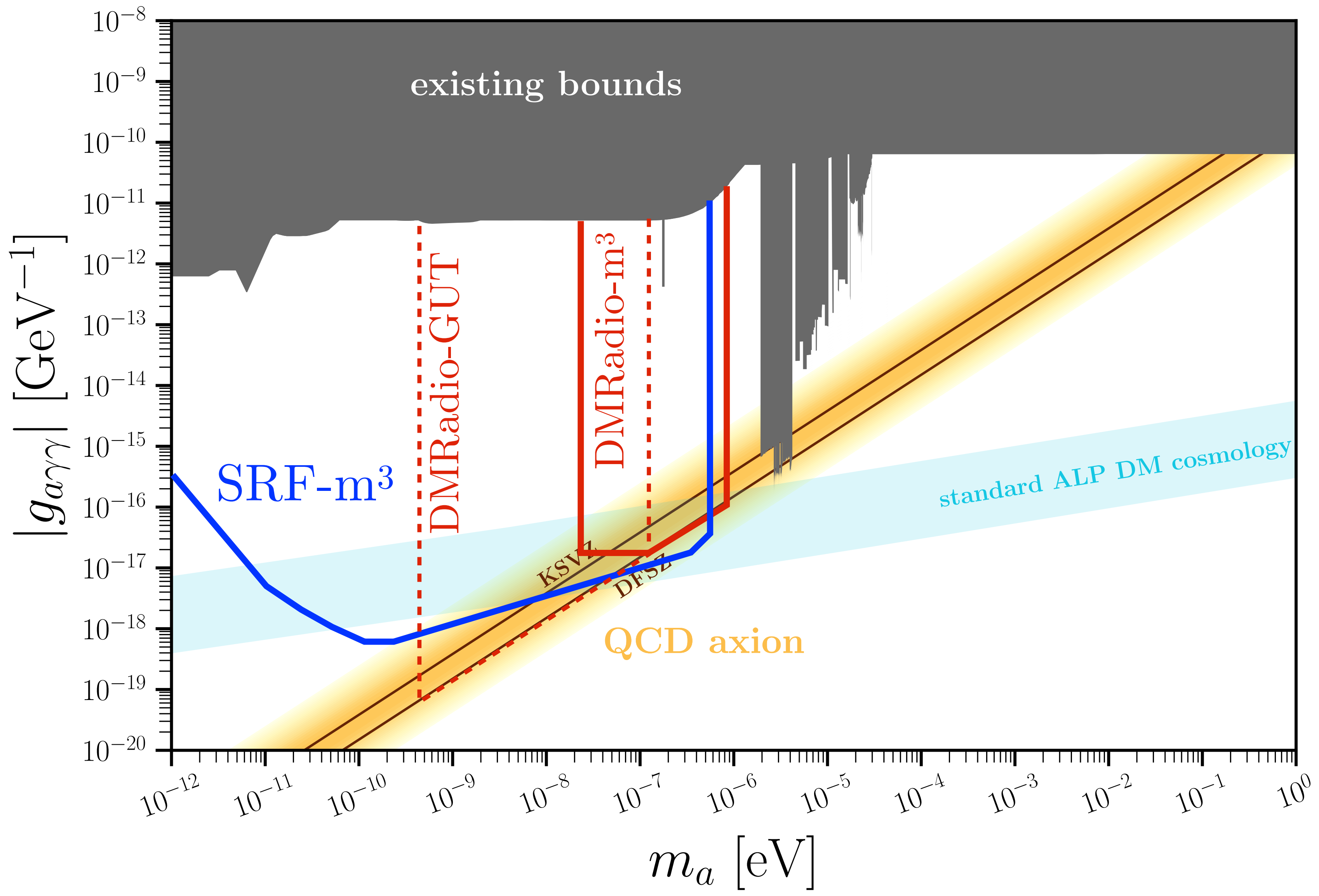


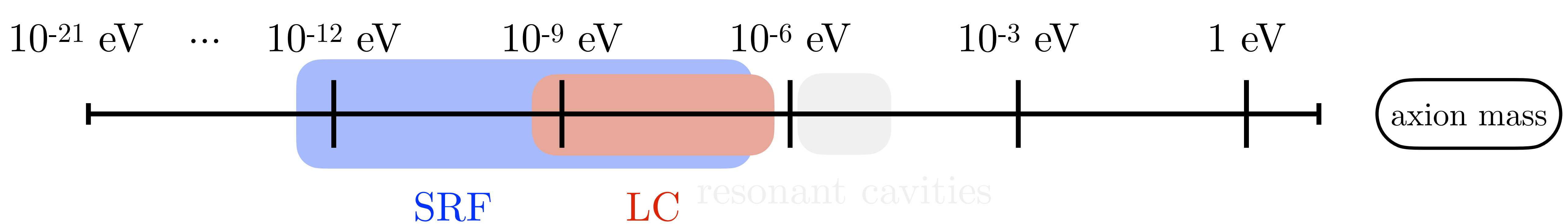
$$\Delta\omega \sim m_a \ll \omega \sim \text{GHz}$$

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

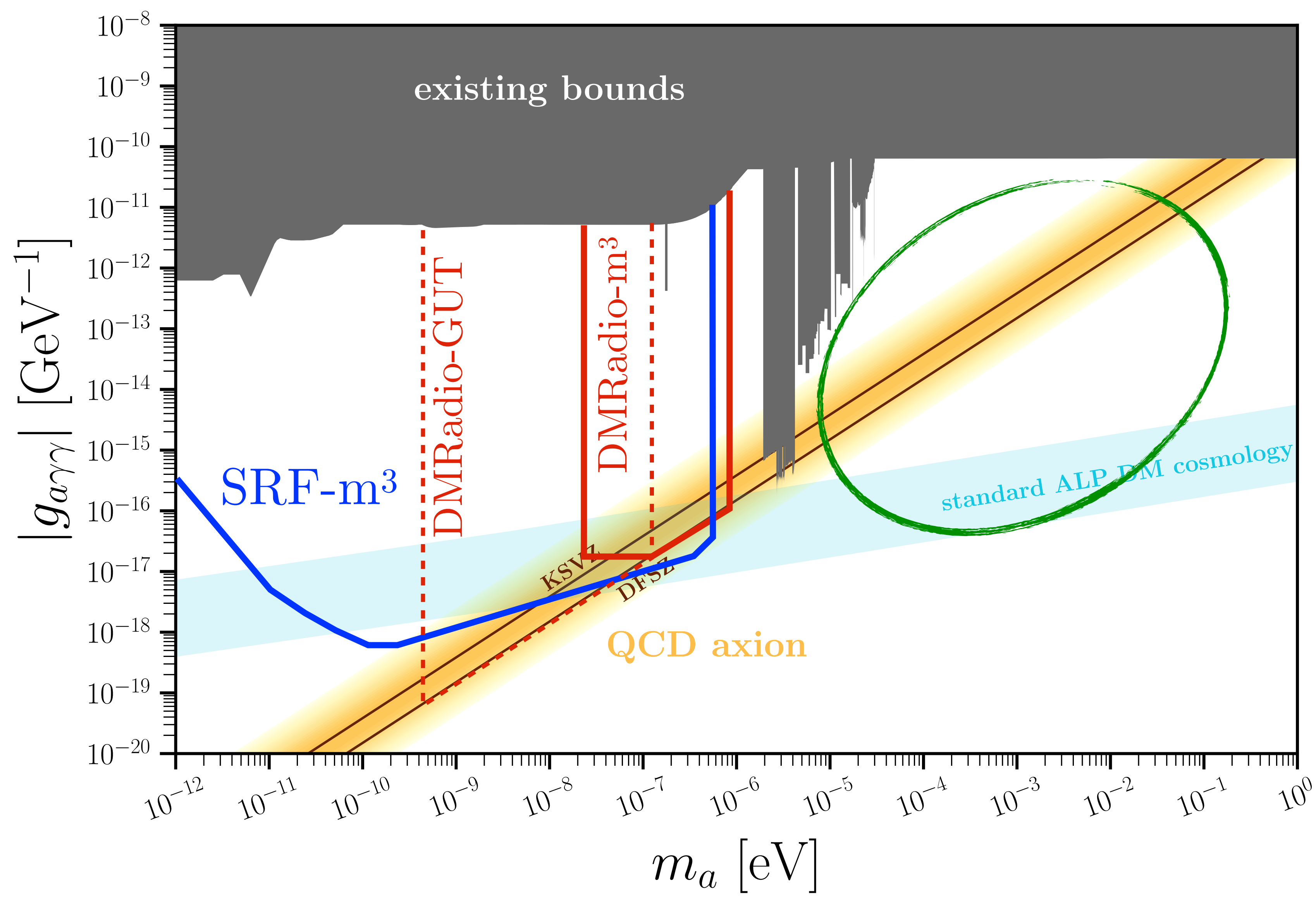
will come back to this later

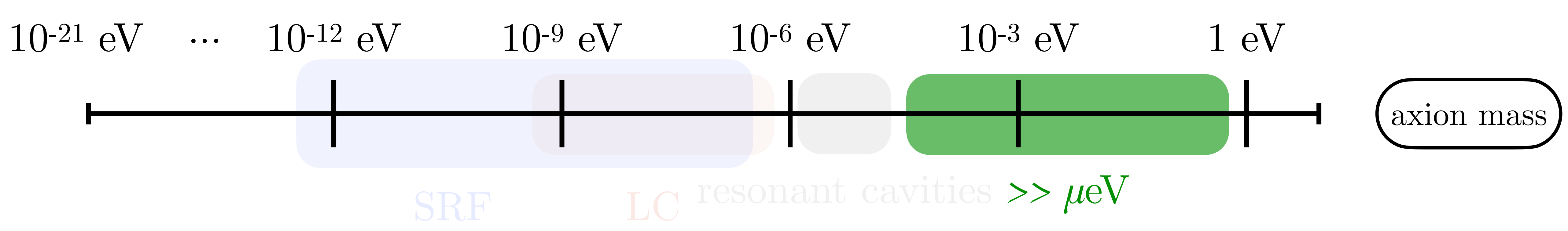
Below ~Micro-eV





Above ~Micro-eV

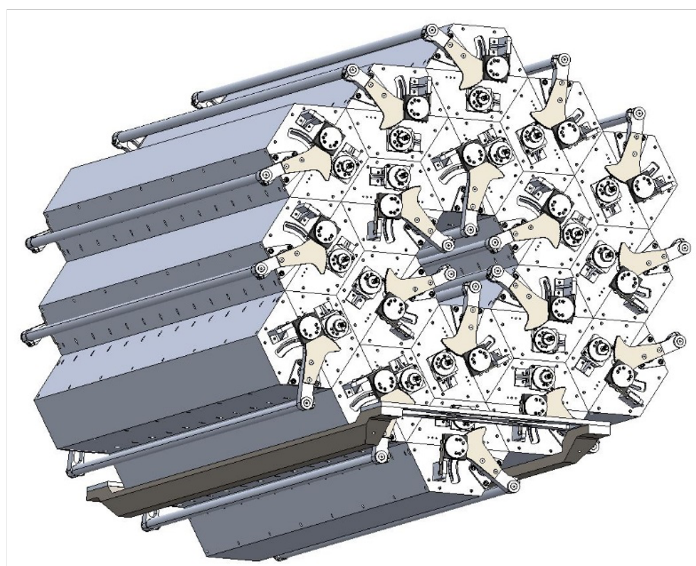




Above ~Micro-eV

Resonant Cavity (ADMX-EFR)

arXiv:2203.14923

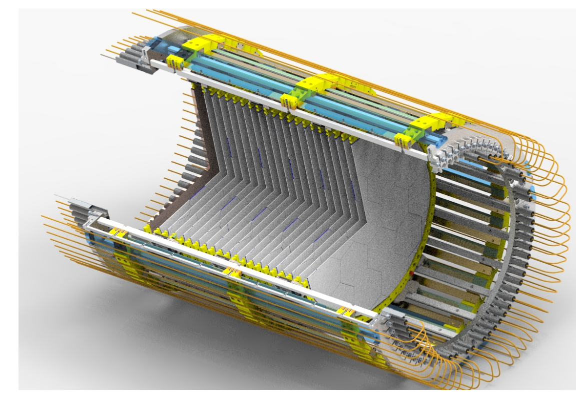


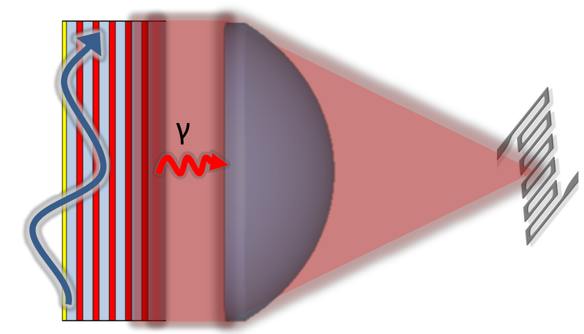
combine signal from 18 smaller cavities

2-4 GHz ~ 8-16 μeV

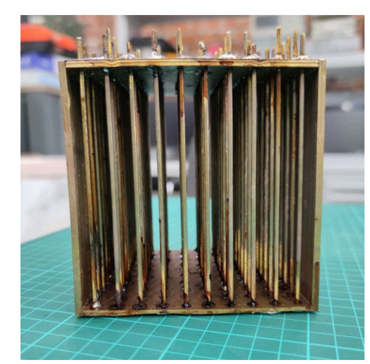
Dielectric/Plasma (MADMAX, LAMPOST, ALPHA)

arXiv:1901.07401, arXiv:2110.01582, arXiv:1904.11872





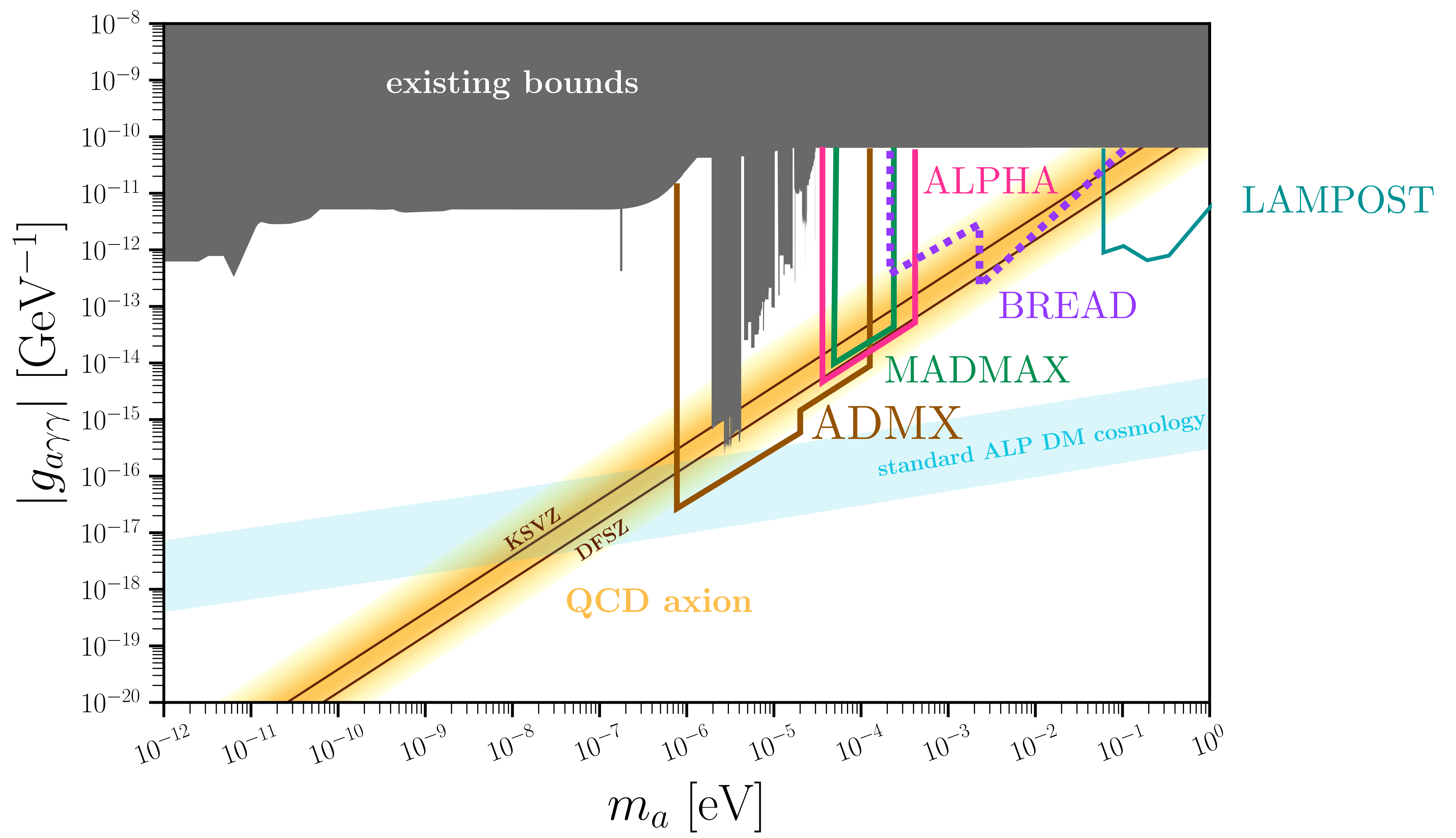
MADMAX/LAMPPOST: dielectric stacks

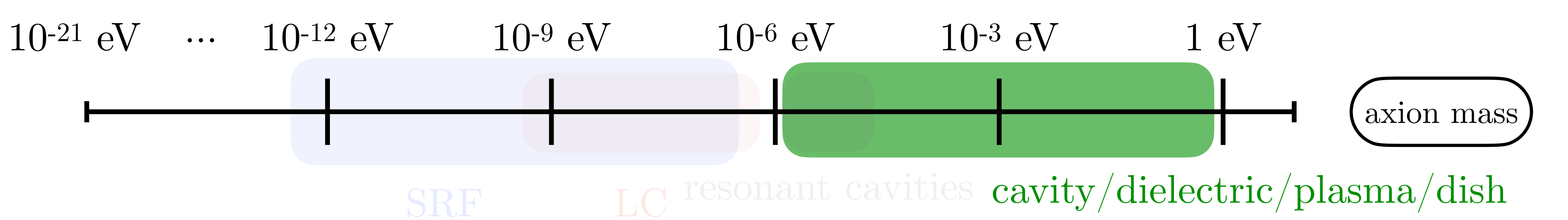


ALPHA: wire metamaterial

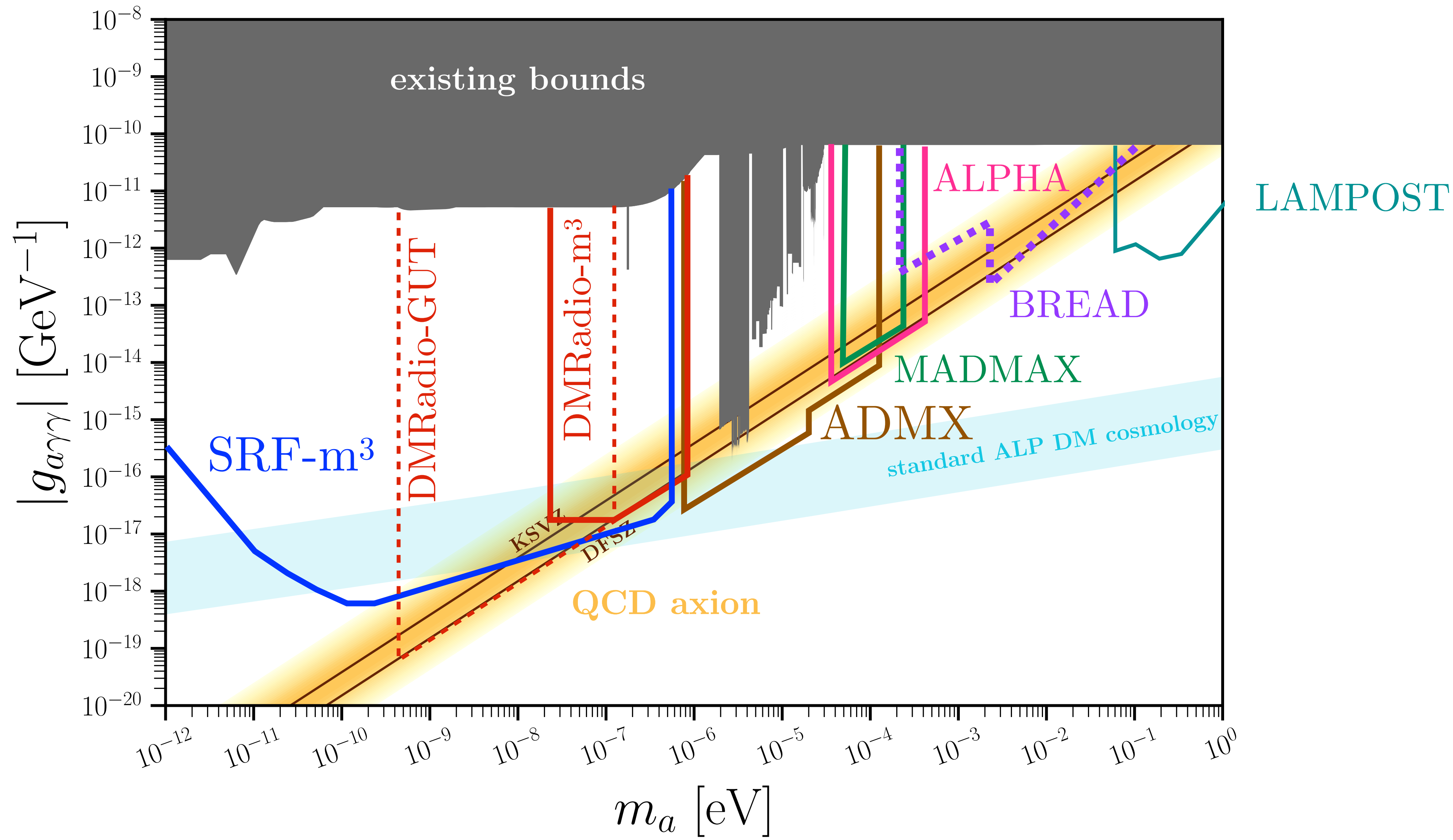
modify photon's dispersion relation

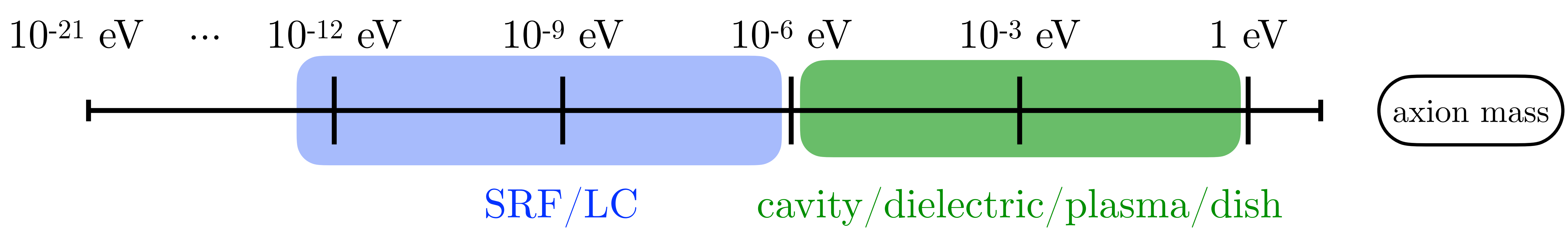
Above ~Micro-eV





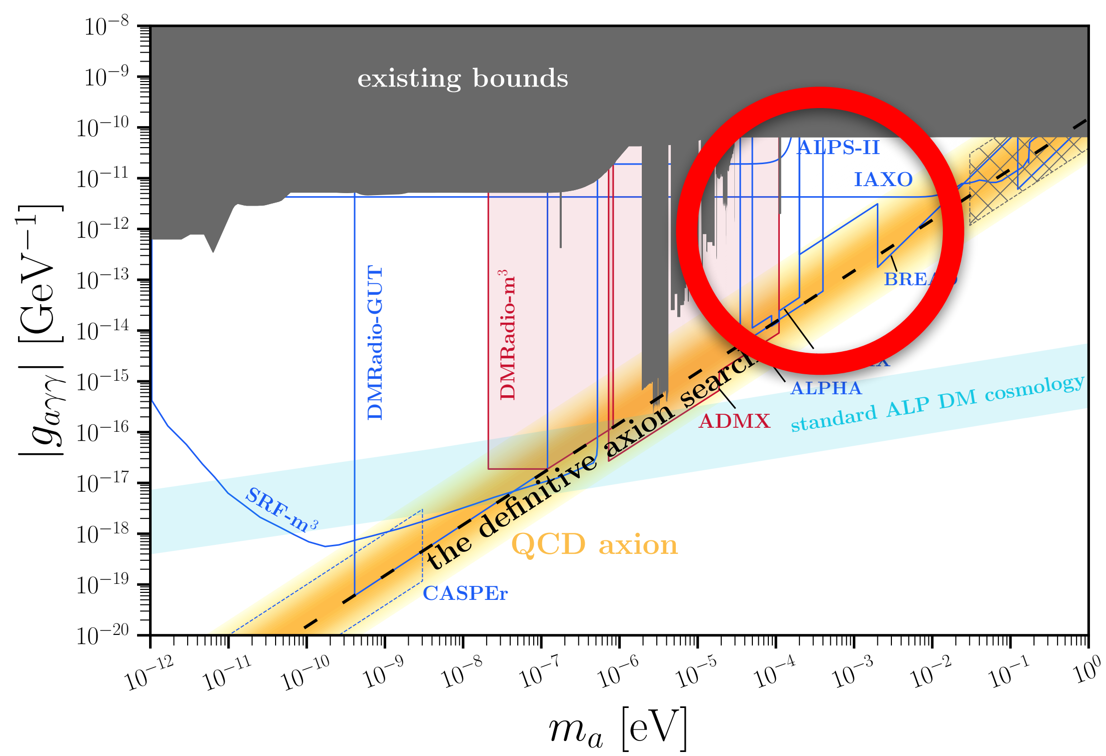
Summary of Projections



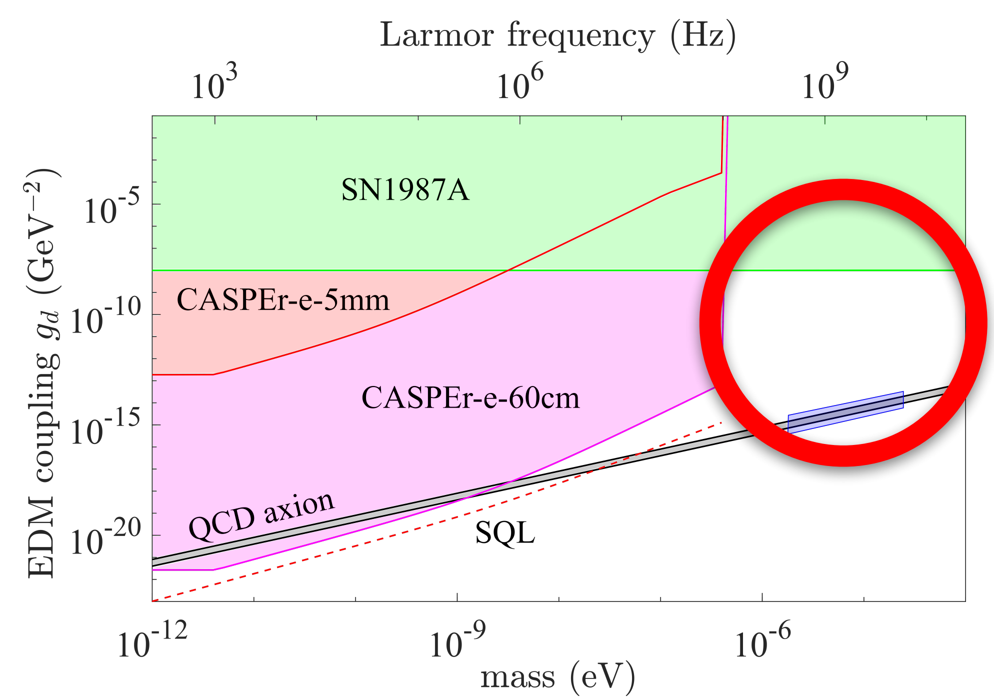


Opportunities in Axion Detection

EM-coupled DM at $m_a \sim$ meV $\sim$ THz



QCD-coupled DM at $m_a > \mu$eV $\sim$ GHz



Outline

Developing even a single technology opens up a versatile array of new physics opportunities.

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resonant cavities
LC circuits
dielectrics/plasmas
NMR, ...

Superconducting Cavities

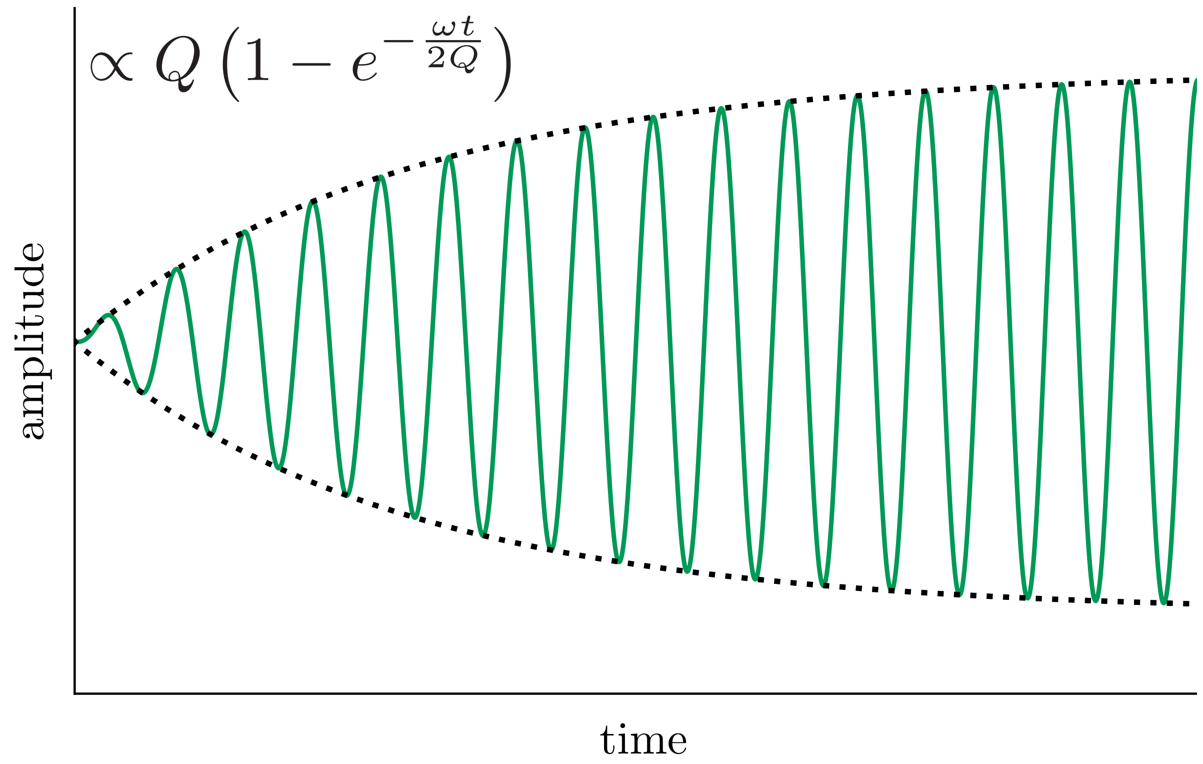
II.

axions
dark photons
millicharged particles
gravitational waves, ...

II. Superconducting Cavities

Driven Damped Harmonic Oscillator

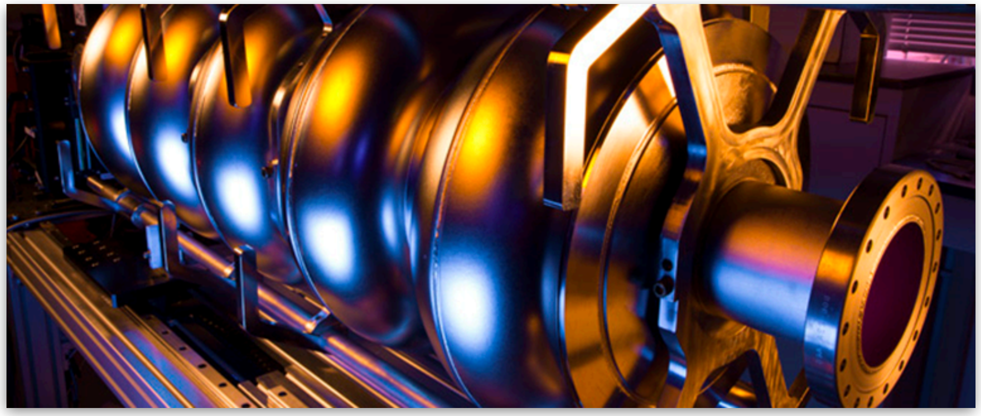
axion signal
on resonance



(~ 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

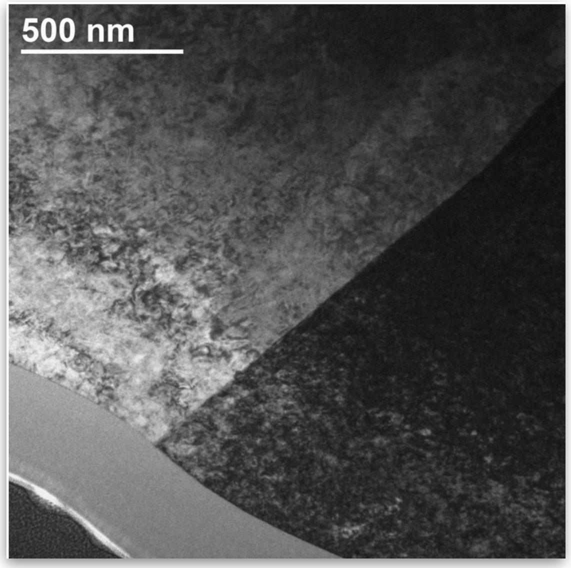
(0.2 T, ~GHz)

3. precisely manufactured and operated

(nm-precision)

4. already used for new physics searches

(experimentalists)



Heterodyne Detection of Axion Dark Matter

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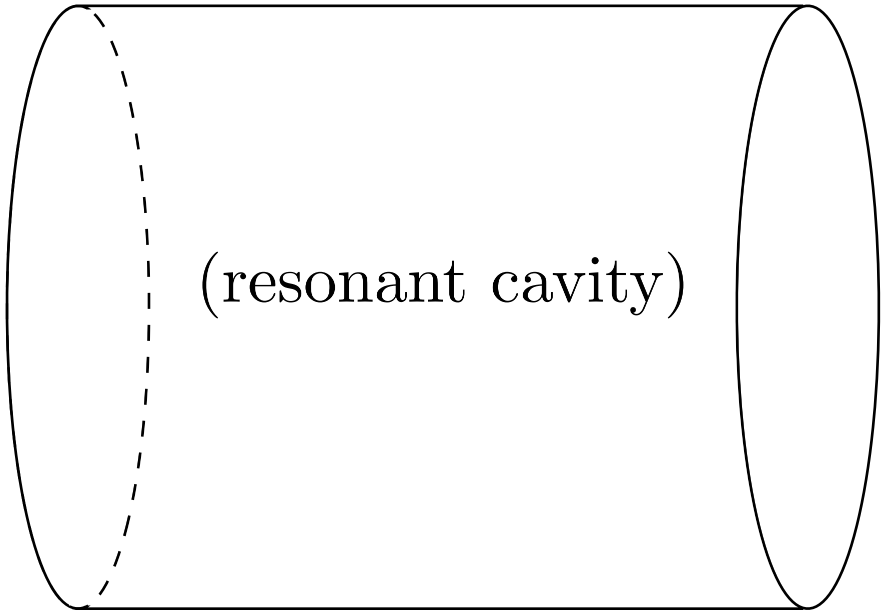
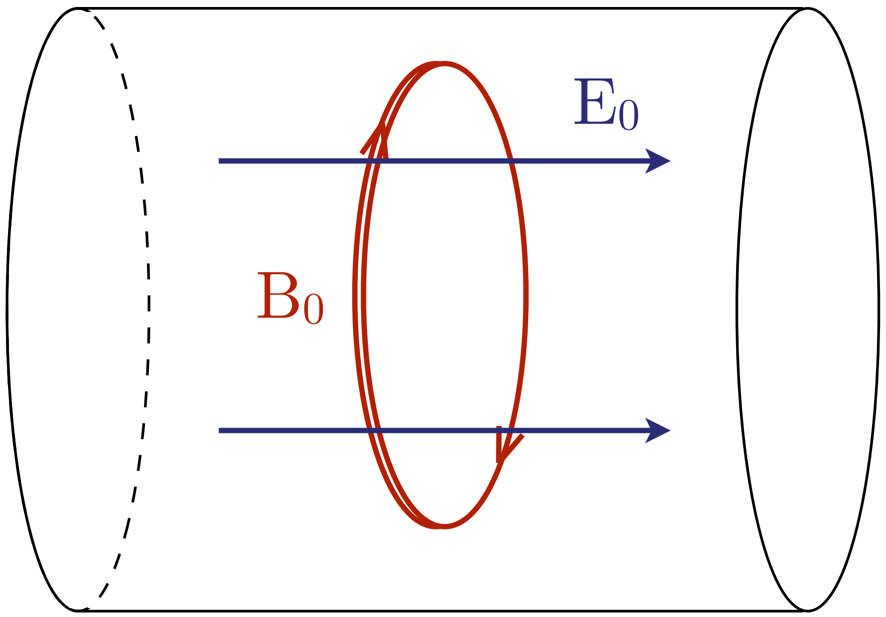


“Frequency Conversion” between two ~ GHz cavity modes

Heterodyne Detection of Axion Dark Matter

$\omega_0 \sim$ GHz

TM030



loud driven mode

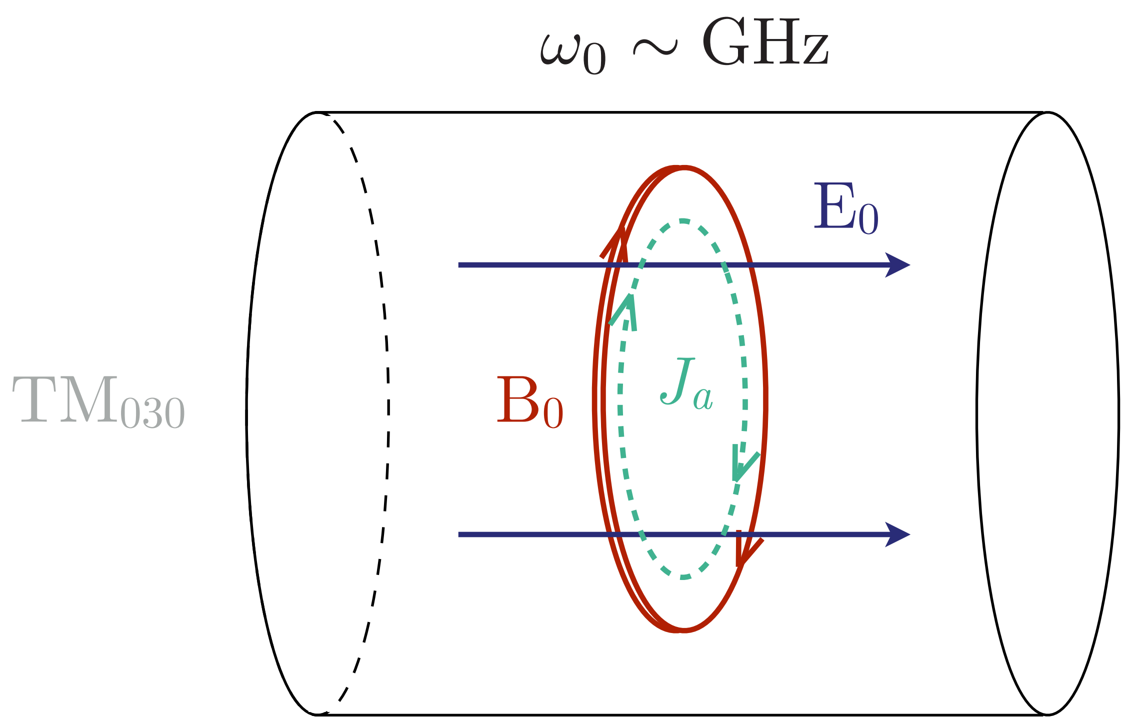
"Frequency Conversion" between two ~ GHz cavity modes

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

$\cos m_a t$



loud driven mode

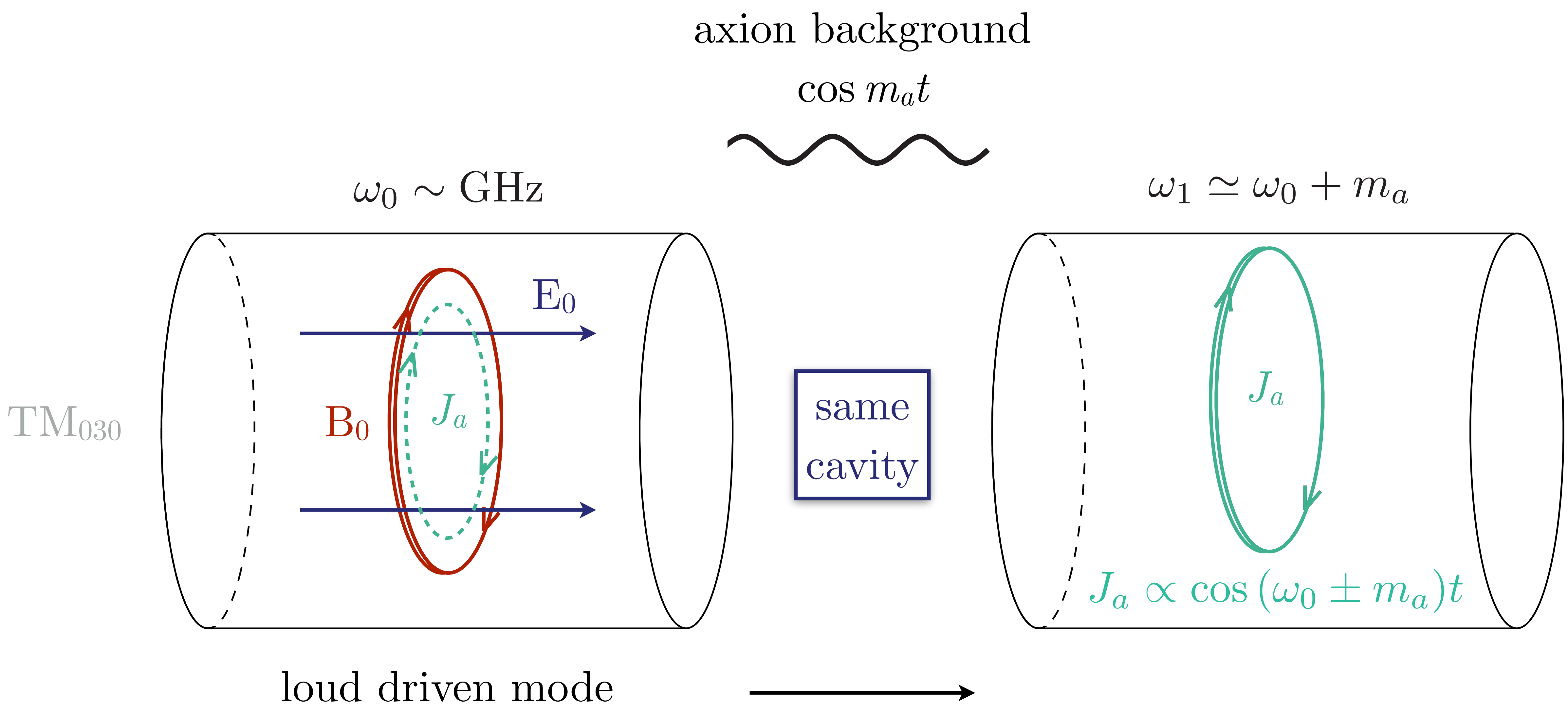
<u>effective axion current</u>

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

<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



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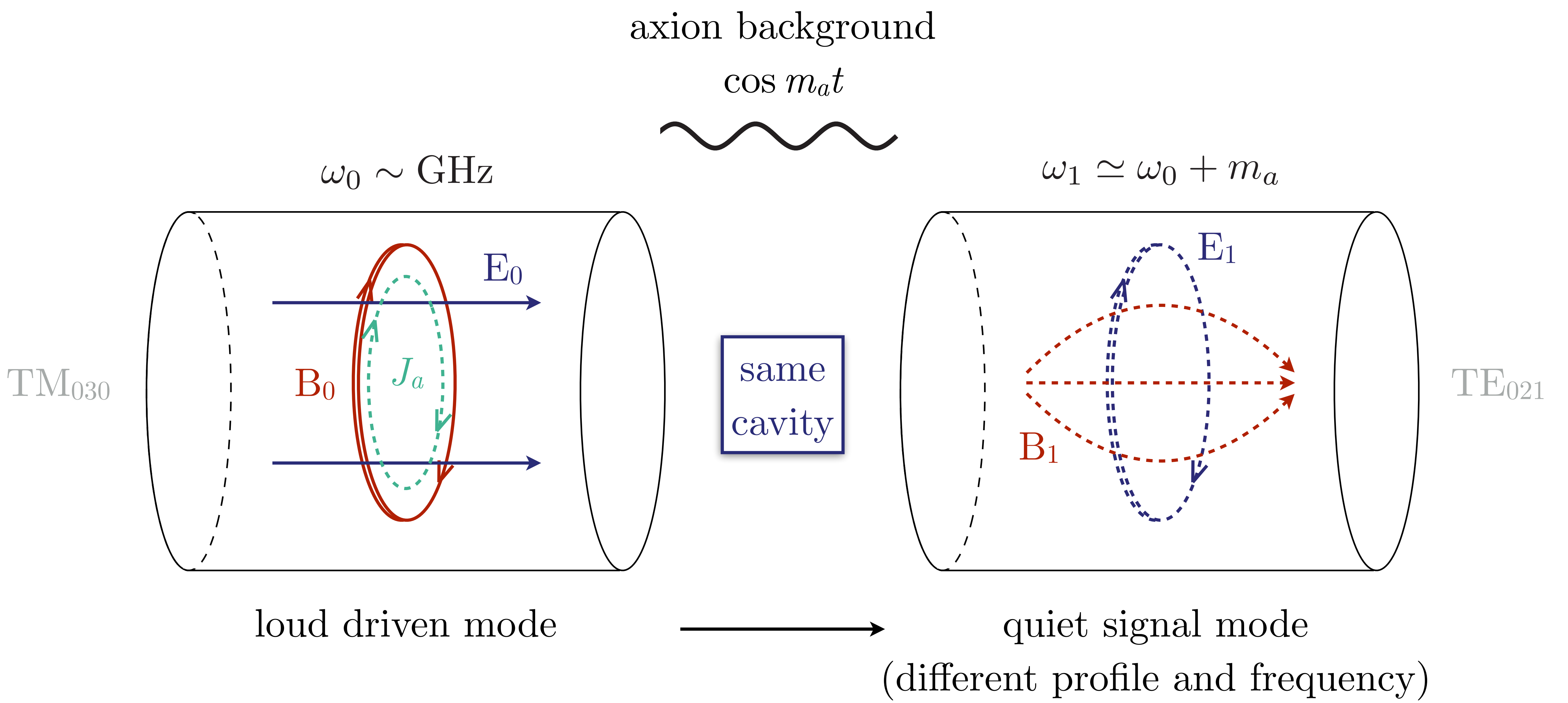

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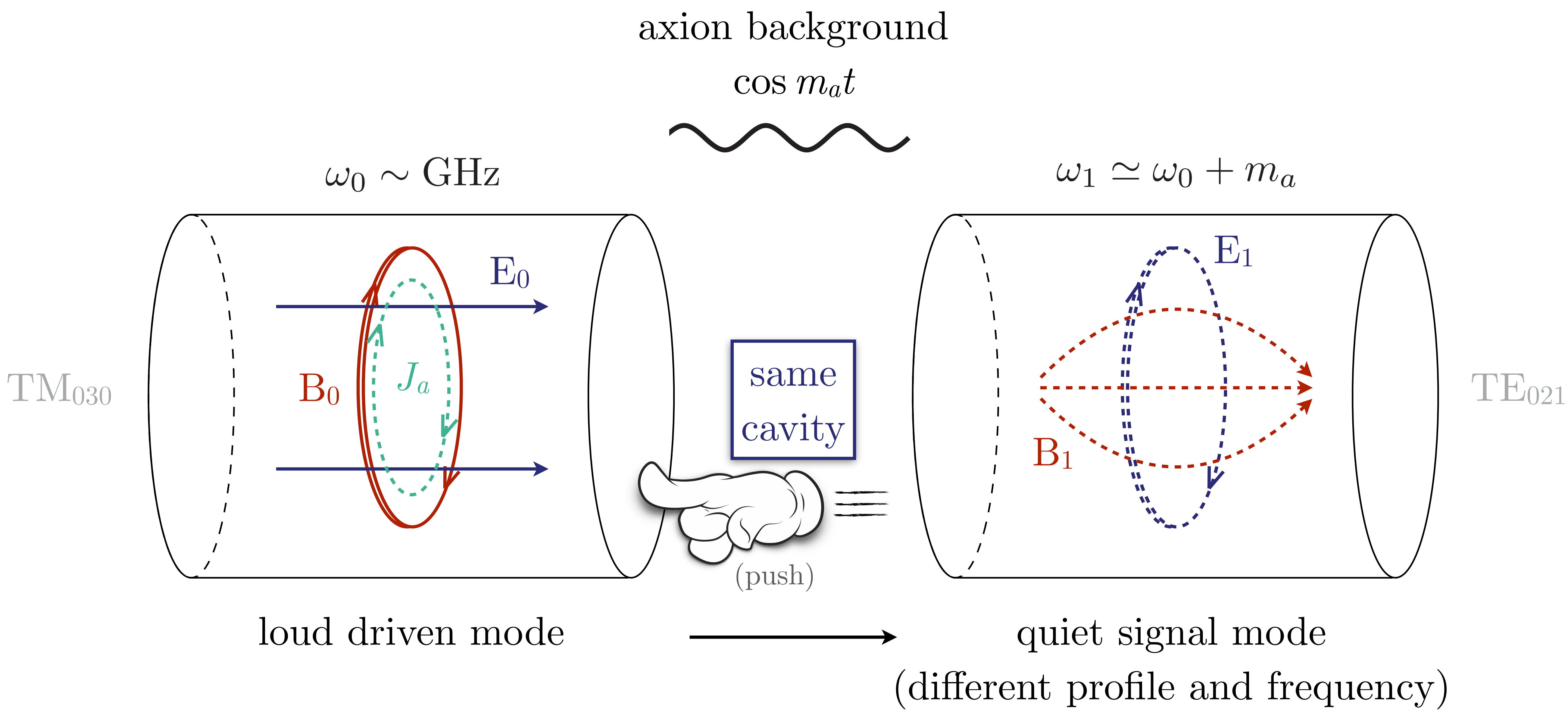

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Heterodyne Detection of Axion Dark Matter

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

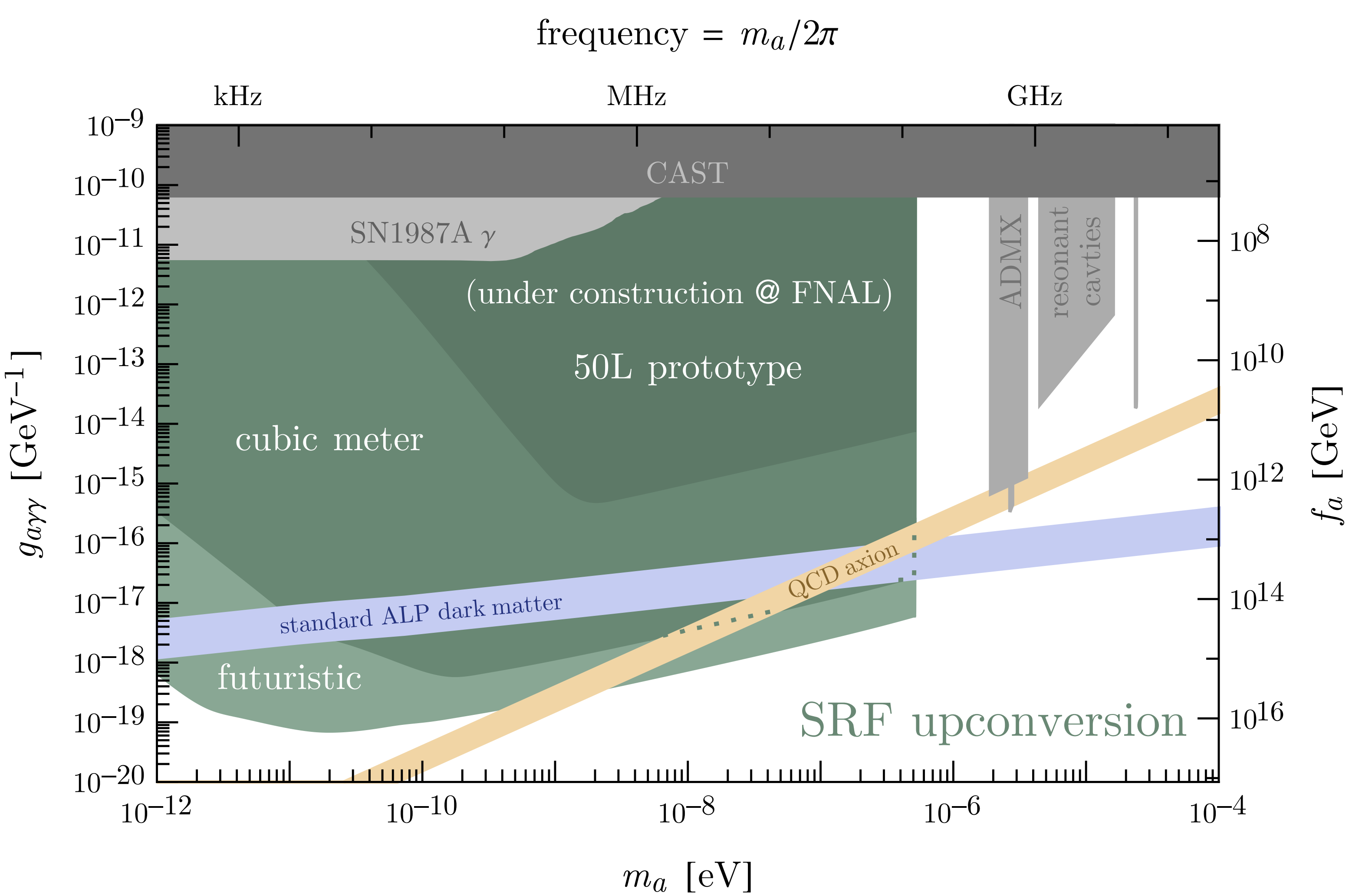
Directly benefit from $Q \sim 10^{11}$

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

Heterodyne Detection of Axion Dark Matter

<u>Axion Dark Matter</u>

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



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

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

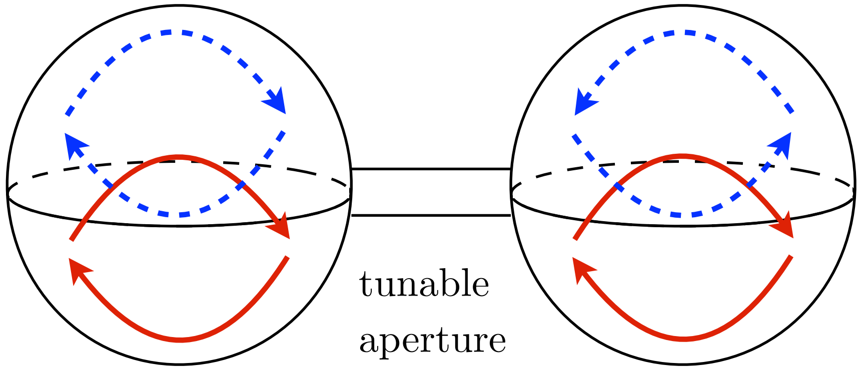
signal power enhanced by GHz$/m_a \gg 1$

Heterodyne Detection of Gravitational Waves

High-Frequency Gravitational Waves (MAGO)

arXiv:gr-qc/0103006 arXiv:gr-qc/0203024, arXiv:gr-qc/0502054

Gravitational wave transfers power from driven mode to quiet mode.



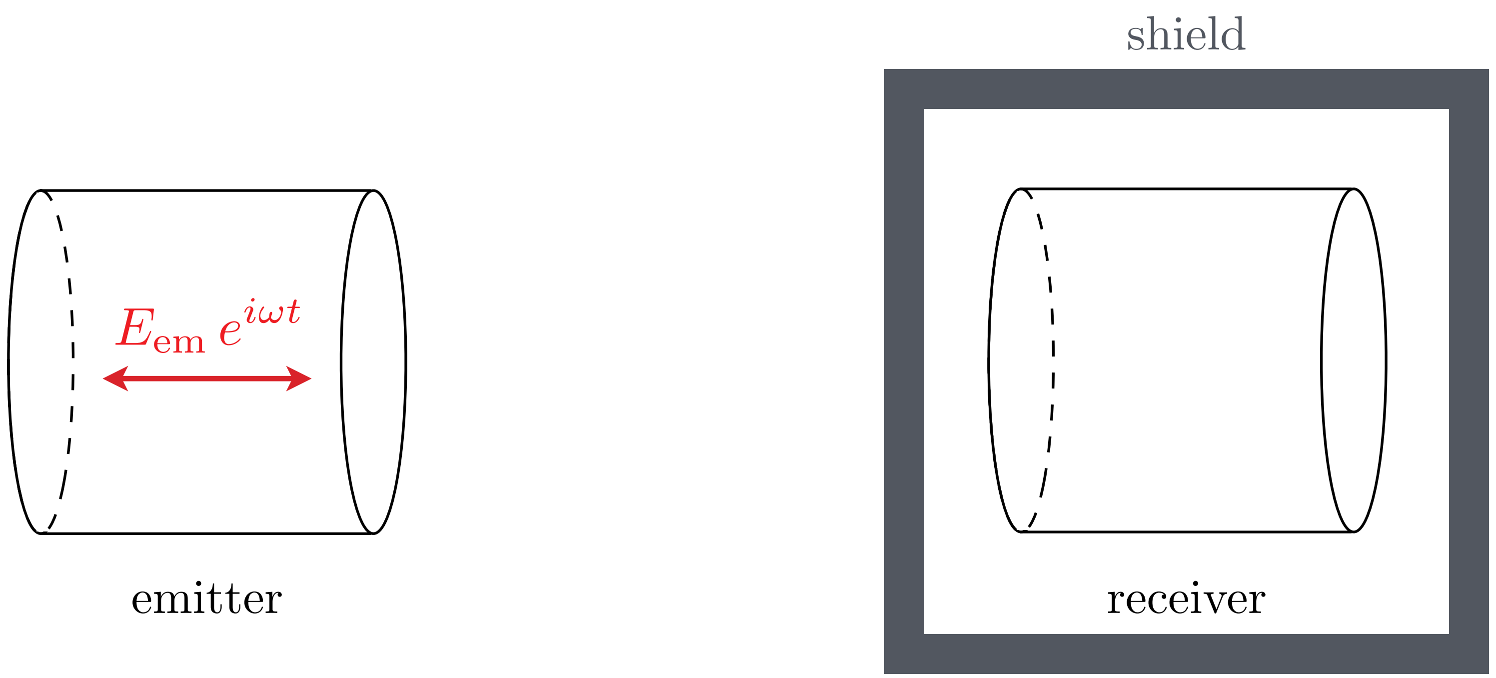
transition between symmetric and antisymmetric modes

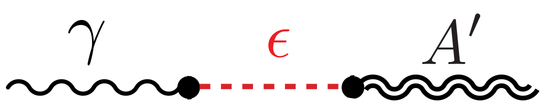
strain sensitivity ~ 10^{-23} for kHz - MHz frequencies

(Revitalization in preparation with D. Blas, R. D'Agnolo, S. Ellis, R. Harnik, Y. Kahn, J. Schutte-Engel, and M. Wentzel)

Ultralight Dark Photons

DarkSRF, light-shining-through wall at Fermilab





arXiv:1407.4806

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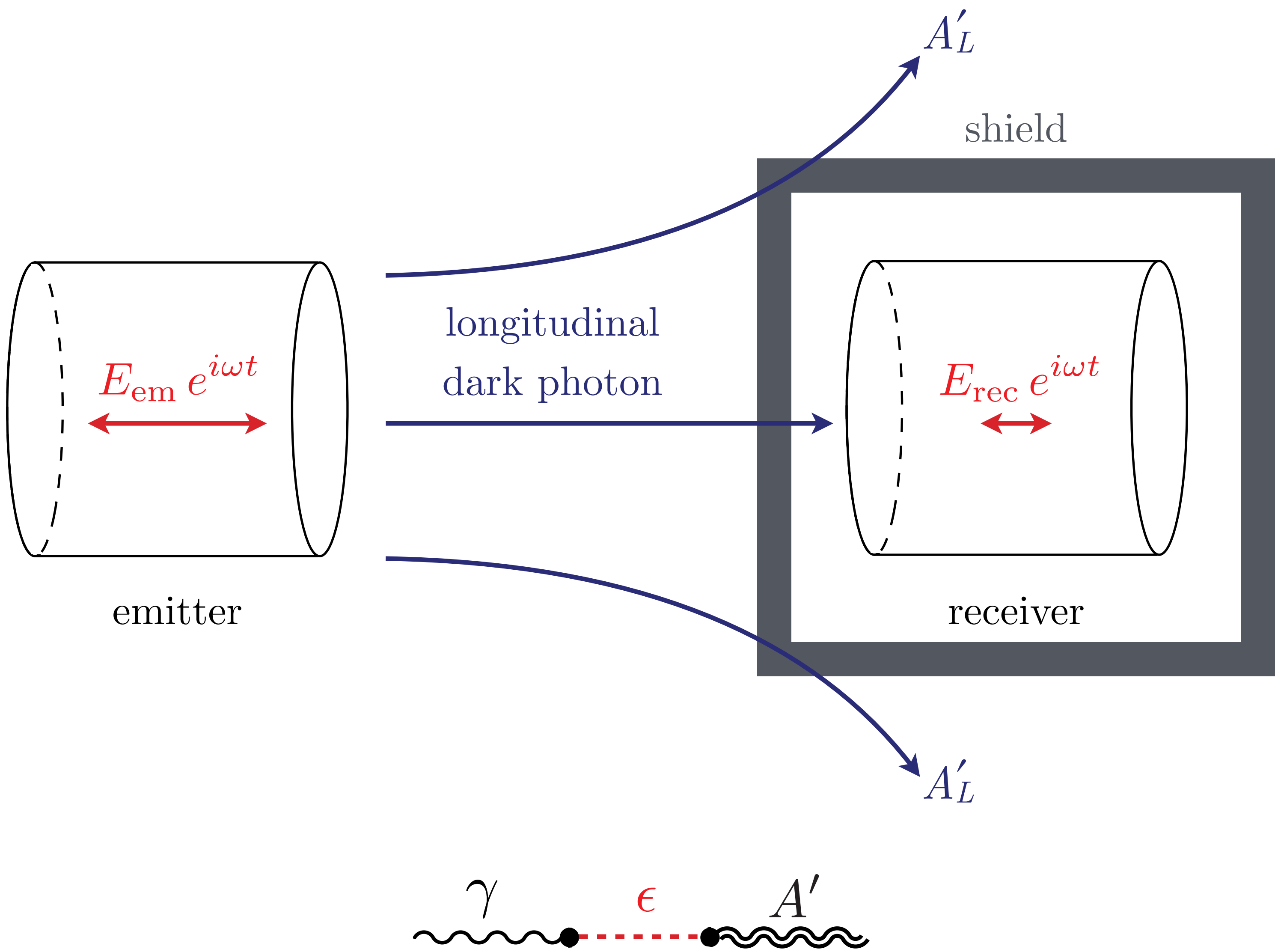
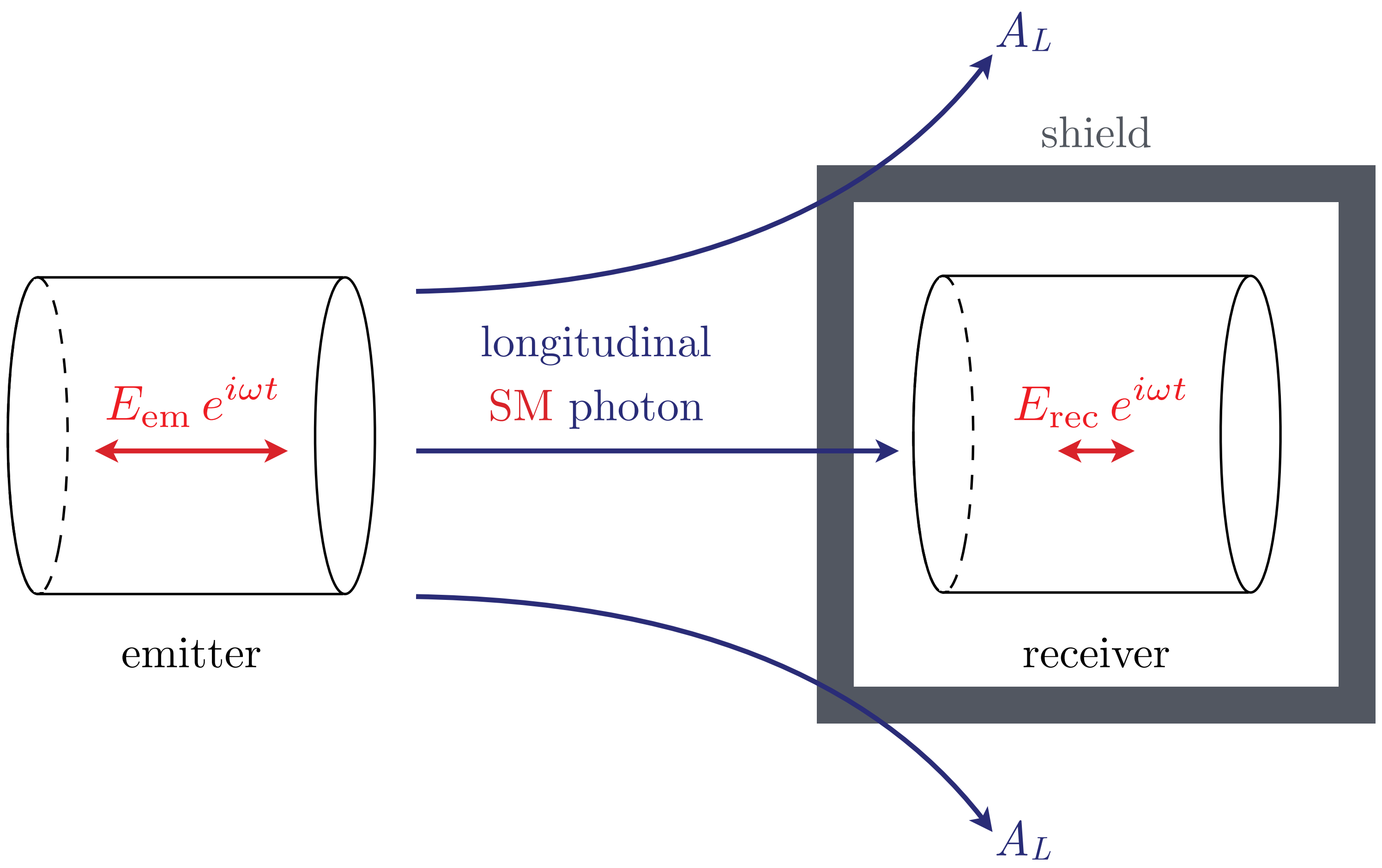


$$\epsilon\, m_{A'} \lesssim 6 \times 10^{-16}\ \text{eV} \simeq 10^{-48}\ \text{g}$$

arXiv:1407.4806

Standard Model Photon Mass

DarkSRF, light-shining-through wall at Fermilab



a longitudinal mode is a longitudinal mode

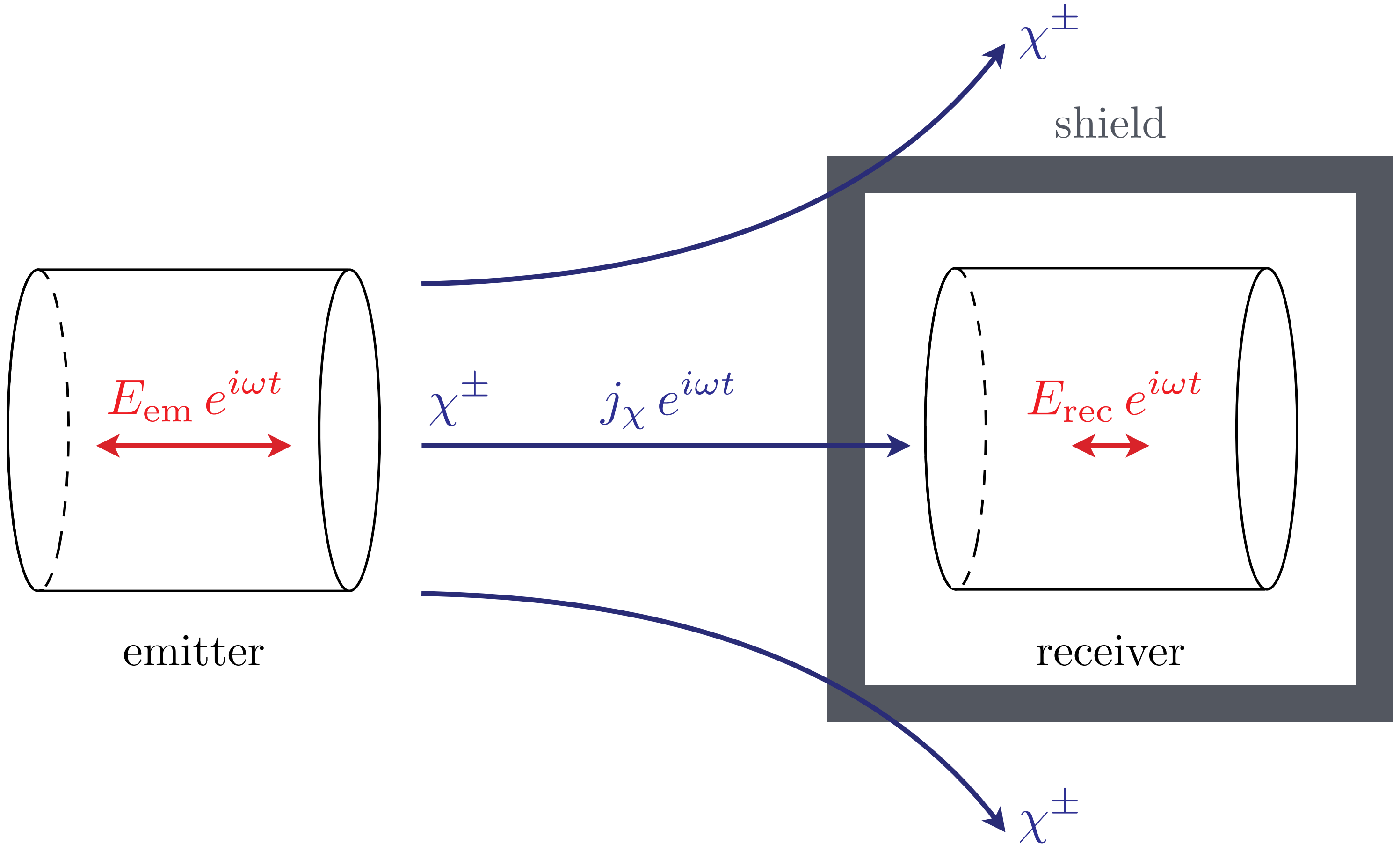
$$m_\gamma \lesssim 6 \times 10^{-16}\ \mathrm{eV} \simeq 10^{-48}\ \mathrm{g}$$

(best direct laboratory bound on the SM photon mass in 50 years)

A. Berlin, A. Hook

Ultralight Millicharged Particles

DarkSRF, light-shining-through wall at Fermilab



Schwinger pair-production of millicharged particles

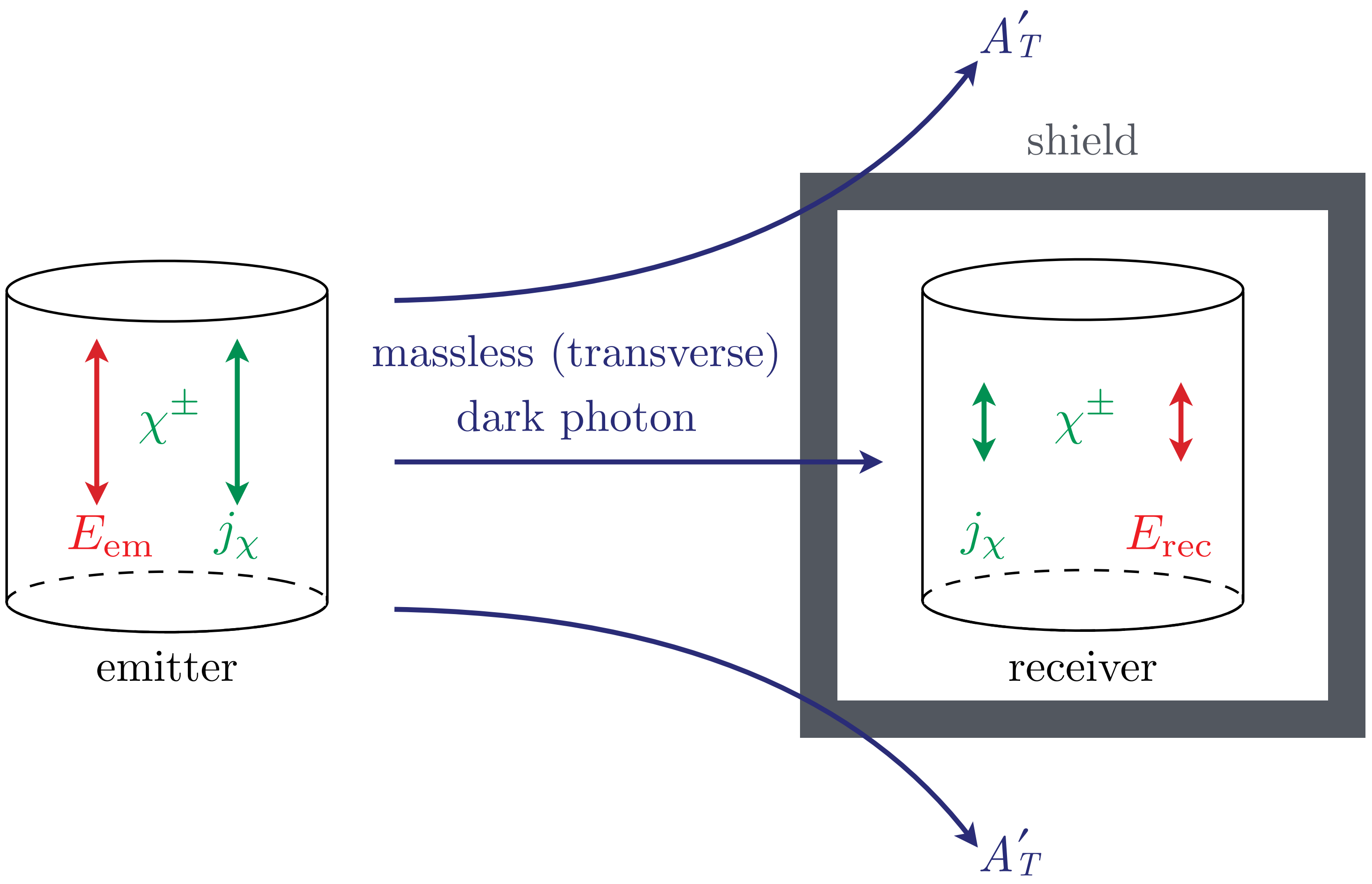
$$E_{\rm cr} \sim 50 \text{ MV m}^{-1} \times \left(\frac{m_\chi}{\rm meV}\right)^2 \left(\frac{q_\chi}{10^{-7}}\right)^{-1}$$

(best laboratory sensitivity to light millicharges by > five orders of magnitude)

arXiv:2001.02679

Millicharged Dark Matter

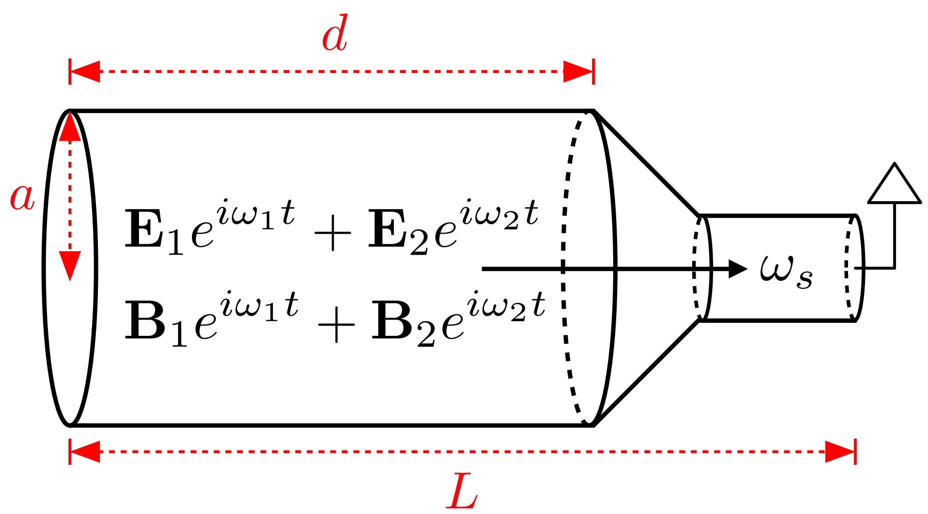
DarkSRF, light-shining-through wall at Fermilab

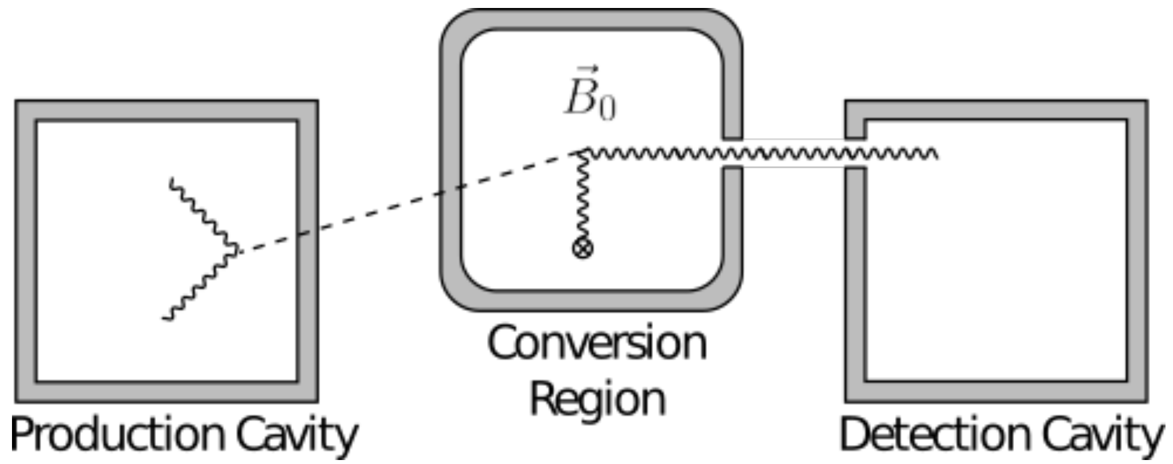


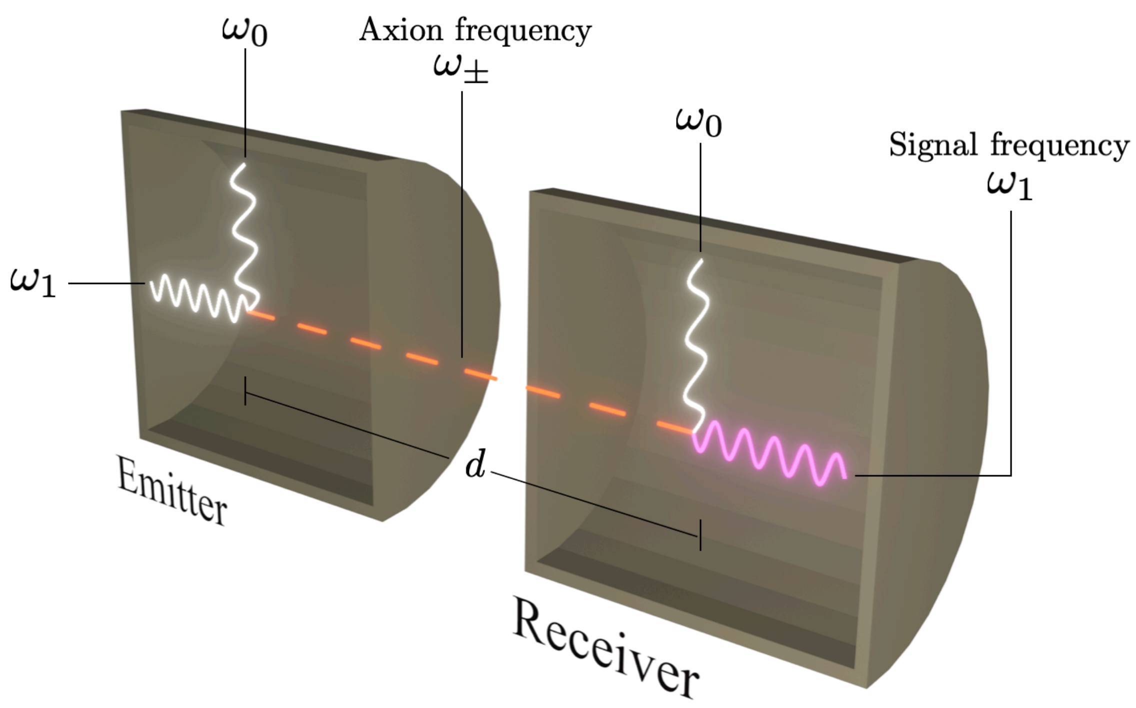
Strongly-coupled dark matter subcomponents

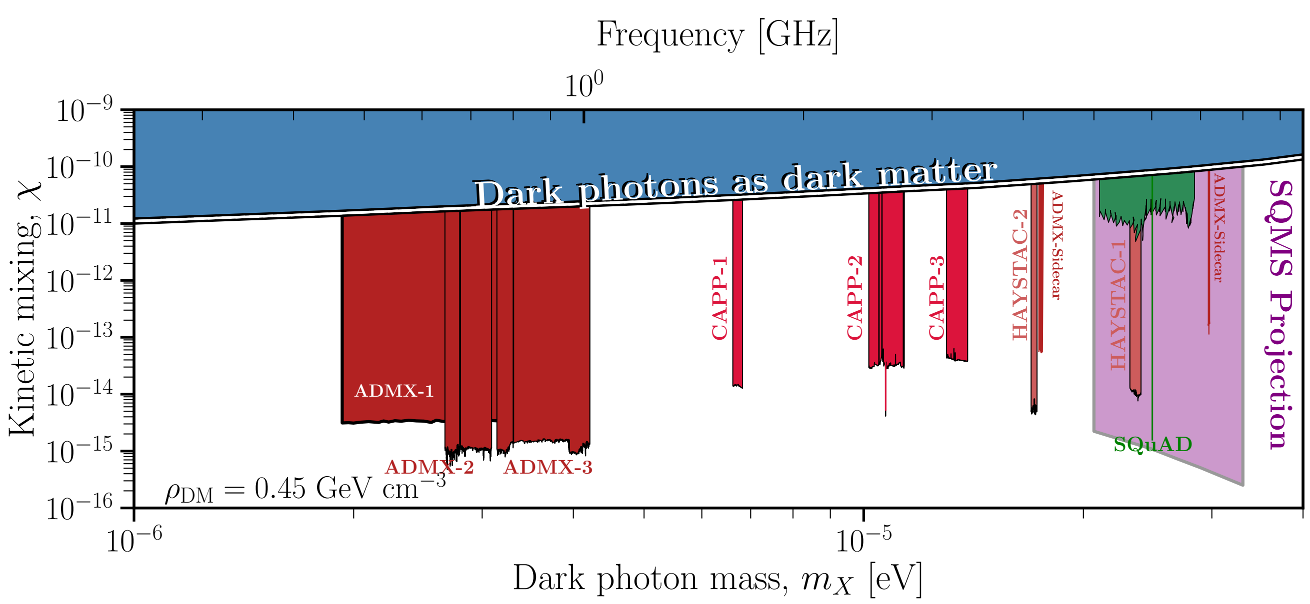
(In preparation with R. D'Agnolo, S. Ellis, and J. Radkovski)

Many Other Applications





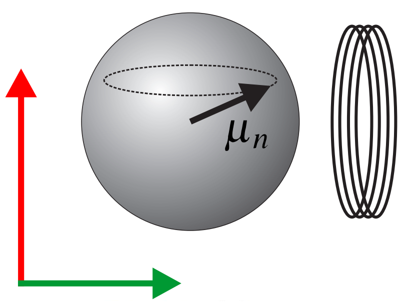




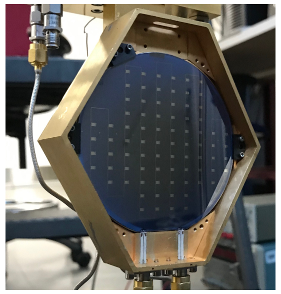
Searches for New Particles, Dark Matter, and Gravitational Waves with SRF Cavities
arXiv:2203.12714

Outlook

NMR

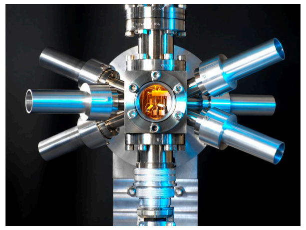


KIDs

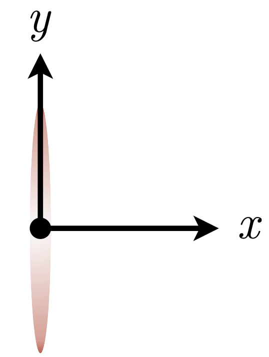


SRF cavities

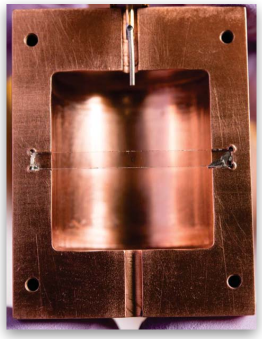
atomic clocks/interferometers



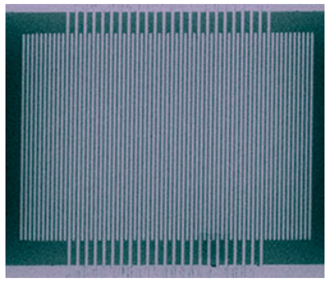
$<$ *SQL*



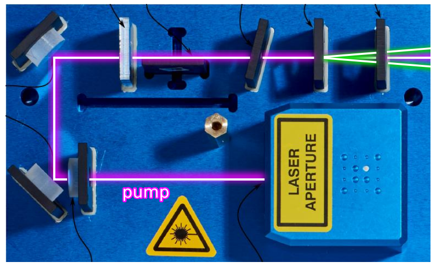
SC qubit



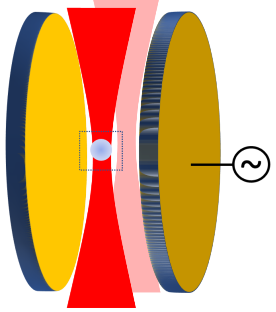
SNSPDs



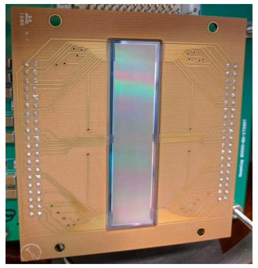
nonlinear optics



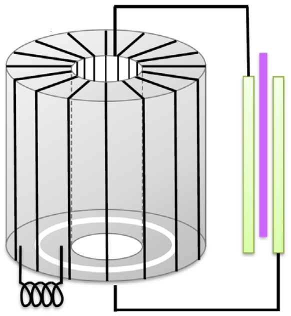
optically levitated dielectrics



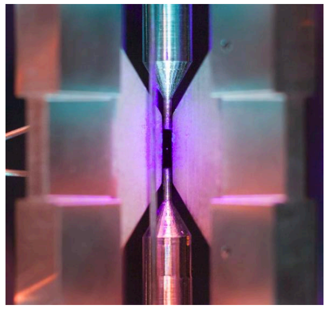
skipper CCDs



LC circuits



ion traps



+... many more

Outlook

NMR

SNSPDs

Now is an important time

We are now beginning to explore physics beyond the Standard Model at scales currently unaccessible with previous technology.

How can technologies coming online be steered to make the biggest impact on fundamental physics?

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

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

see “Snowmass2021 Theory Frontier: Theory Meets the Lab”
arXiv:2203.10089

SC qubit

ion traps