Discovering the Dark Universe

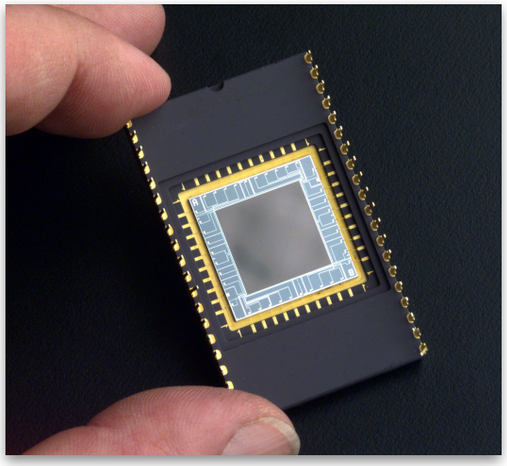
Asher Berlin - NYU

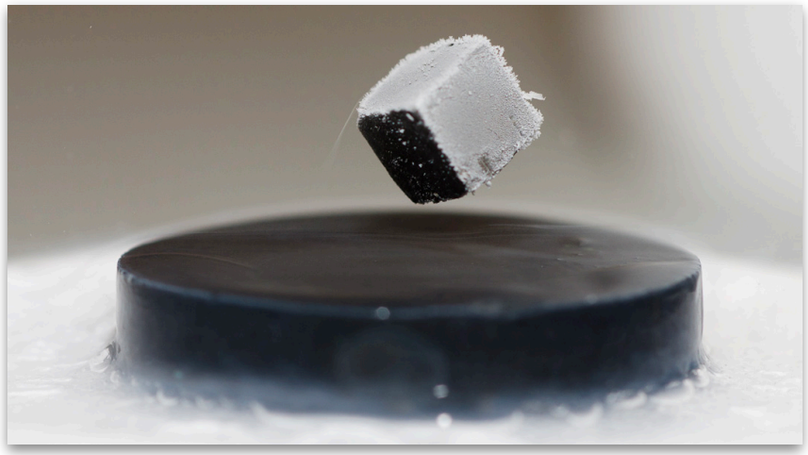
Fermilab

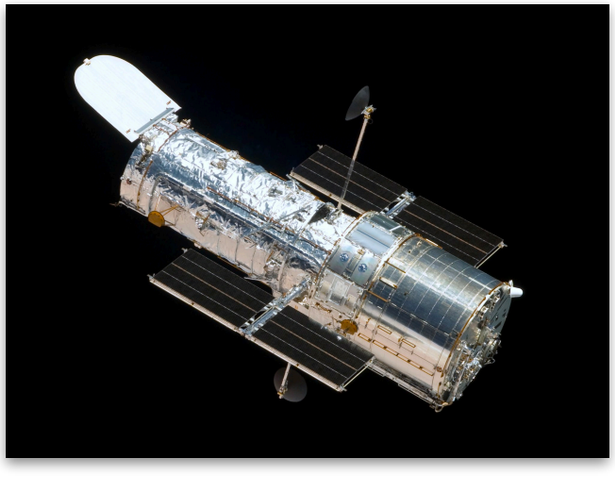
February 18, 2021

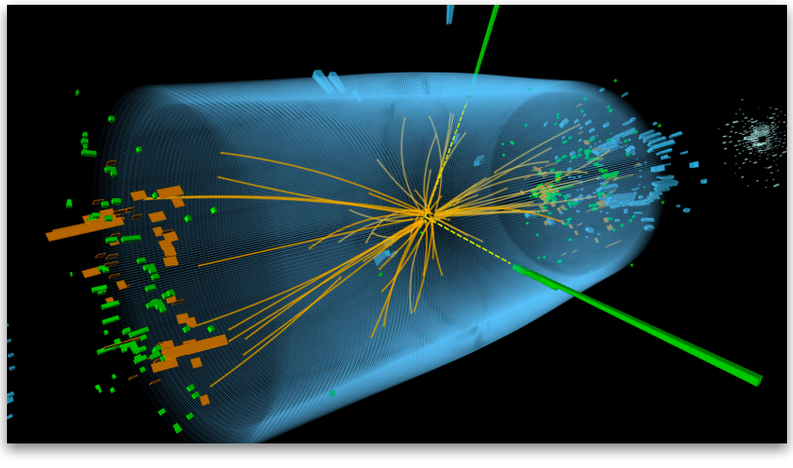
Technology & Fundamental Physics

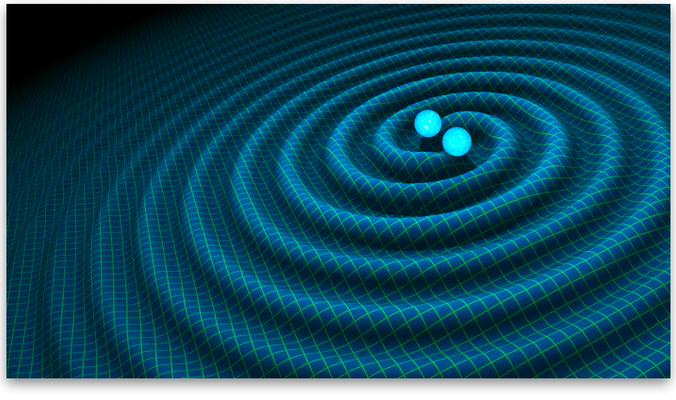
New technology opens windows into new physics



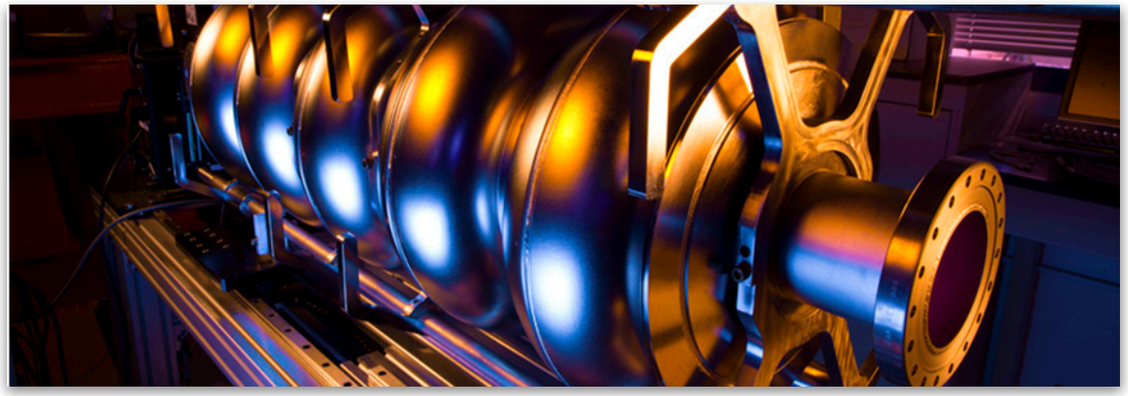


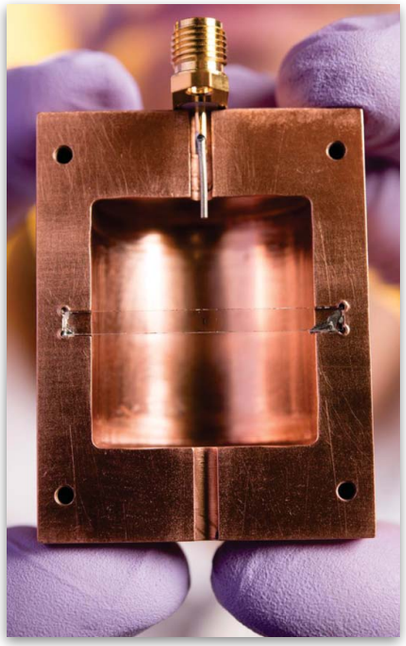






Technology & Fundamental Physics

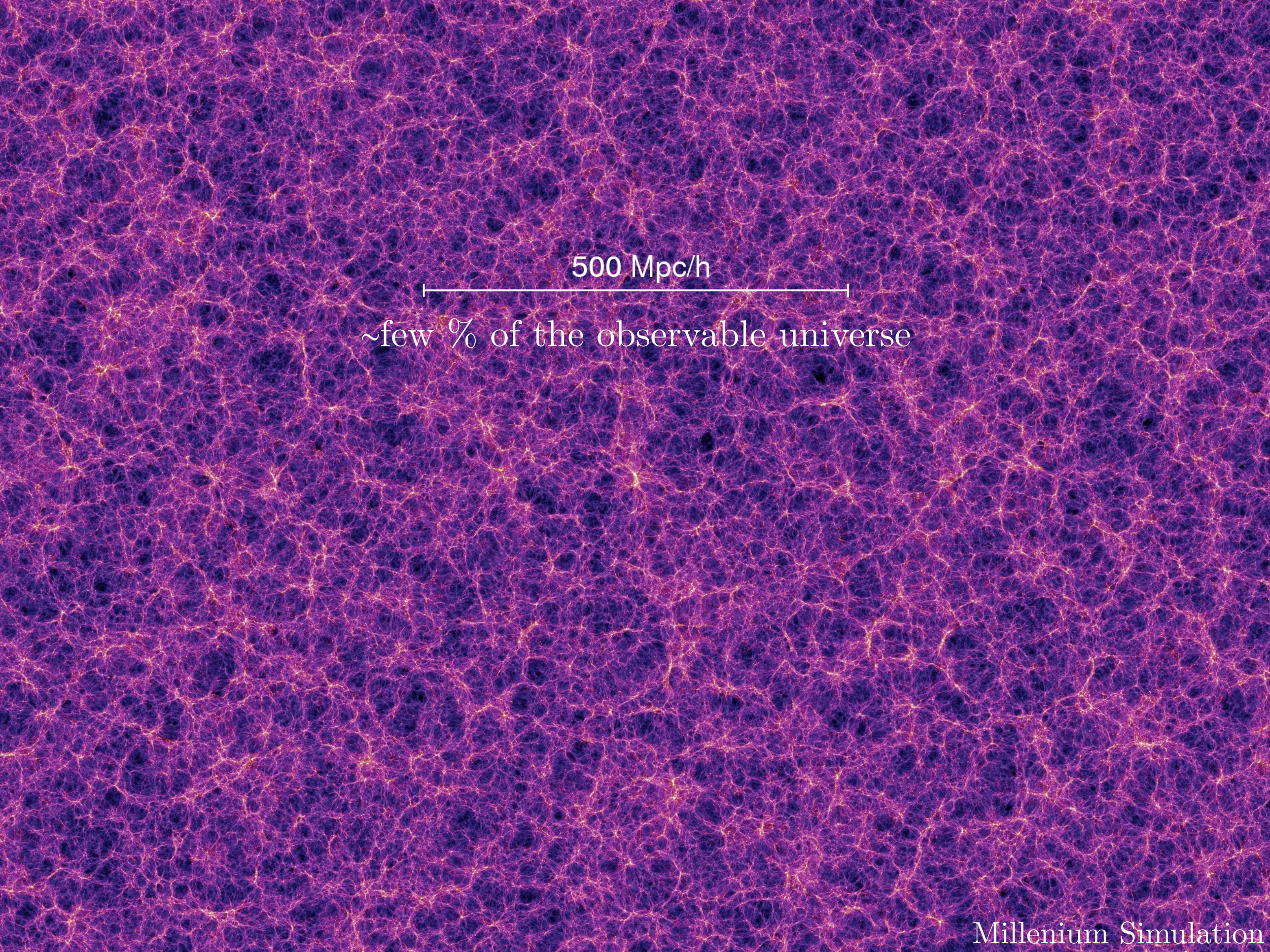




There is an opportunity to explore new physics
at previously unaccessible scales with developing technology.

How can developments in quantum sensing be
steered to make the biggest impact
on fundamental physics?

What is the nature of dark matter?


500 Mpc/h
~few % of the observable universe
Millenium Simulation

What Have We Learned?

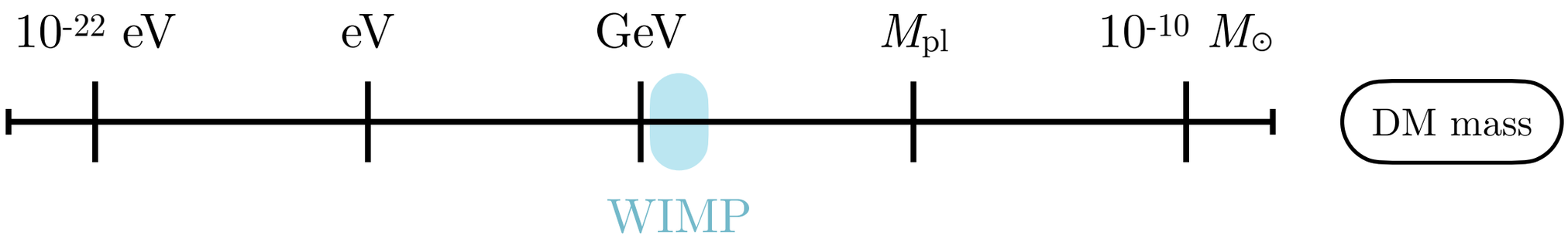
Resides in galaxies (including our own)

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

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

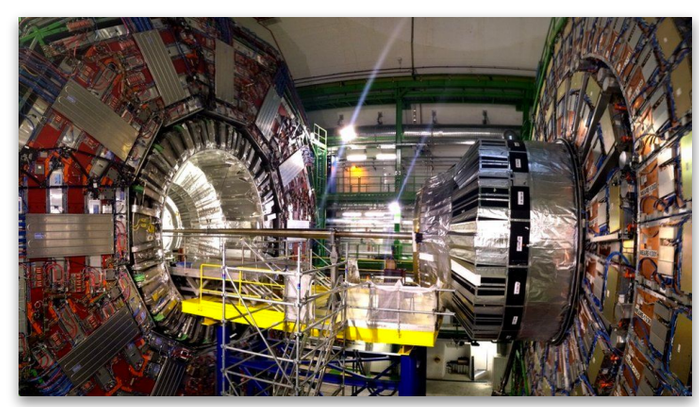
Few heavy particles or many light particles?
What is the dark matter mass?

What Have We Learned?



The search for WIMPs has been an incredible success.

What now?



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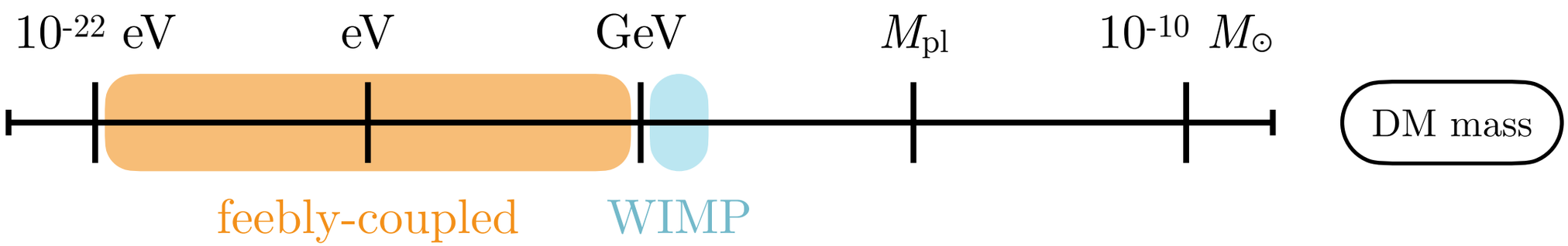
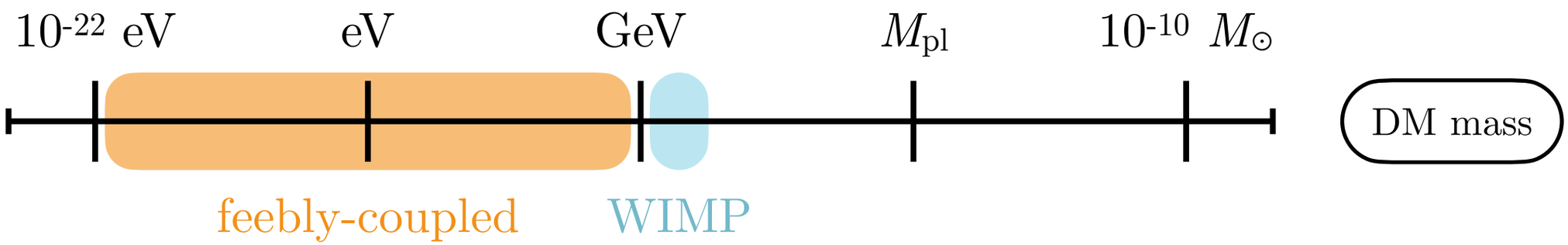


quantum precision detectors

Quiet and coherent enough to build up a detectable signal.

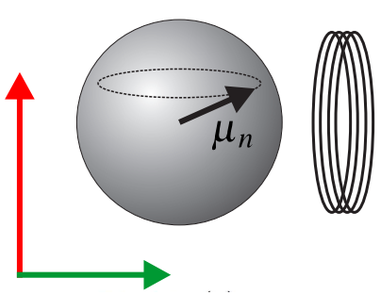
We can now explore a wide range of previously unaccessible scales.

New Physics with Quantum Sensors

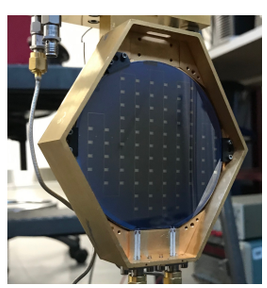


QIS for dark matter physics
(QuantISED)

NMR

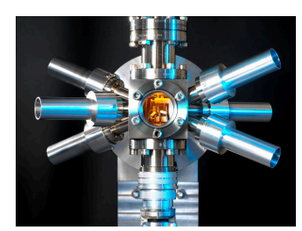


KIDs



SRF cavities

atomic clocks



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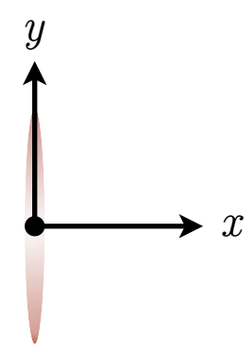
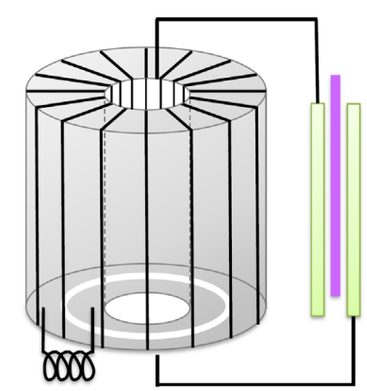
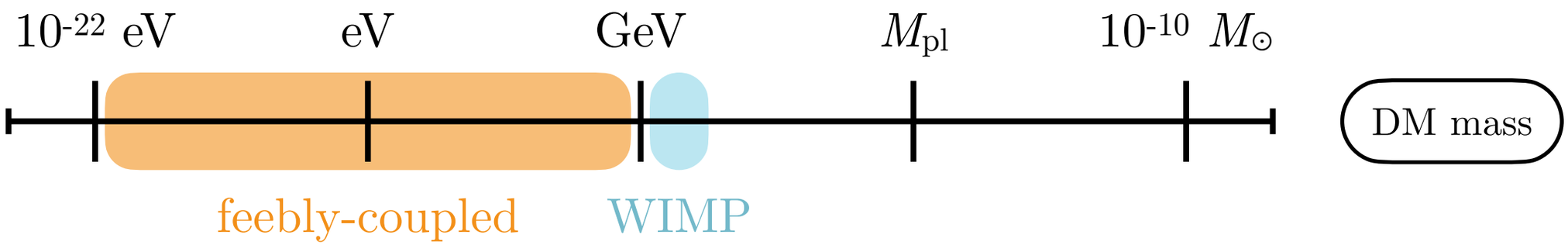


LC circuits



$+\cdots$

New Physics with Quantum Sensors



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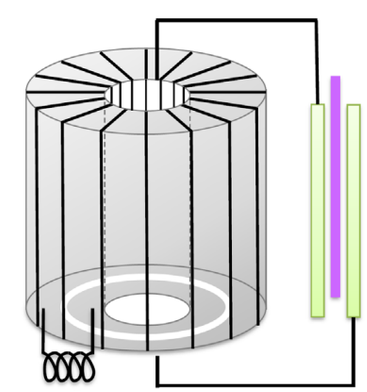
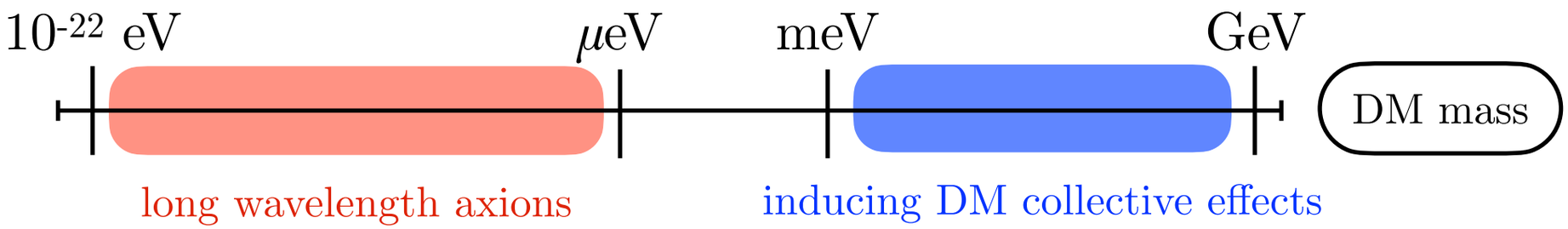


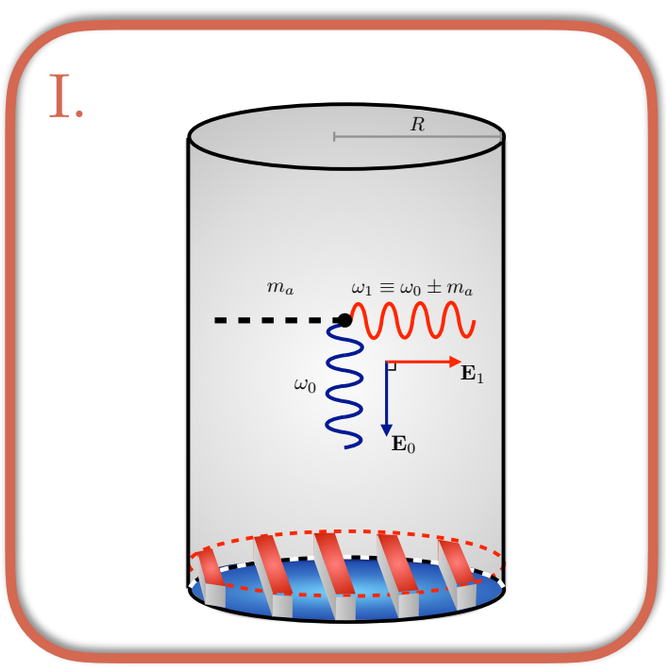
quantum computation

testbed for quantum sensors

Discovering the Dark Universe



superconducting cavities



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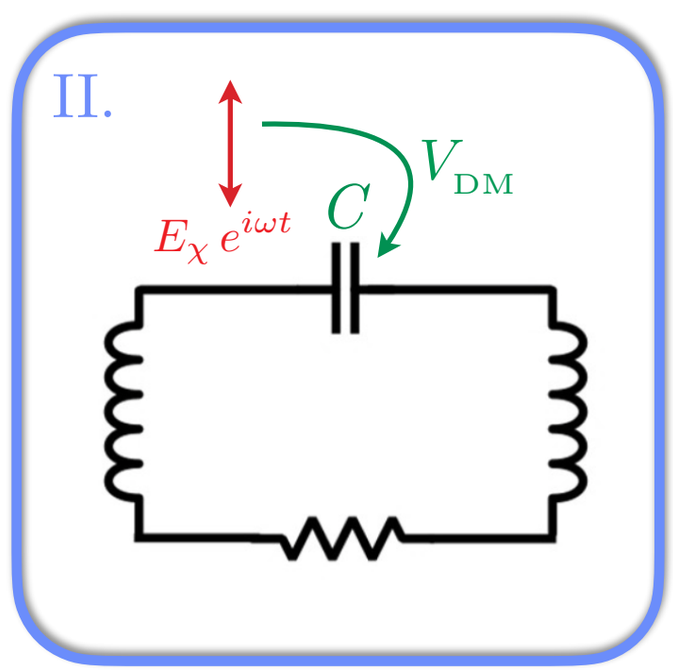
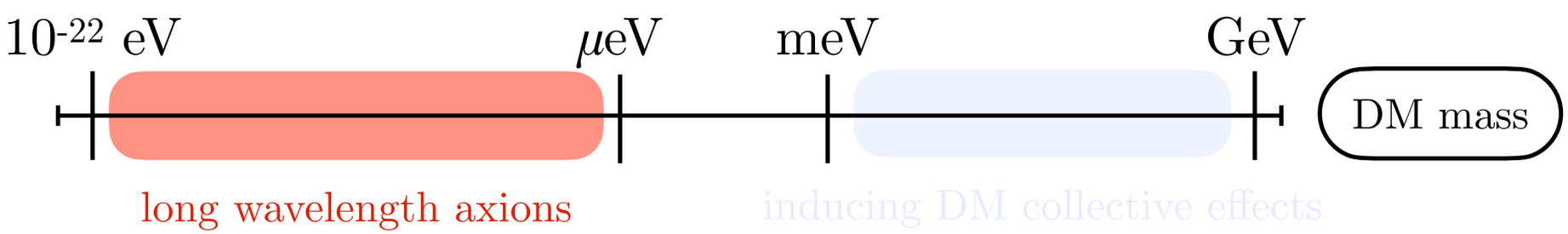


Future

Discovering the Dark Universe



A. Berlin, R. D'Agnolo, S. Ellis, C. Nantista, J. Neilson, P. Schuster, S. Tantawi, N. Toro, K. Zhou, JHEP 2020

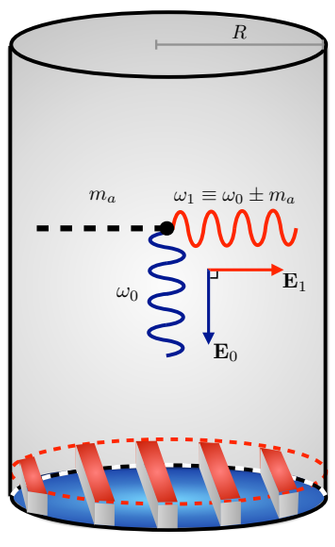
A. Berlin, R. D'Agnolo, S. Ellis, K. Zhou, arXiv:2007.15656

superconducting cavities

LC circuits

Future

I.



II.

III.

Ways Forward

Sub-eV Dark Matter

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

pseudo-Goldstone bosons are naturally light and weakly-coupled

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

large scale

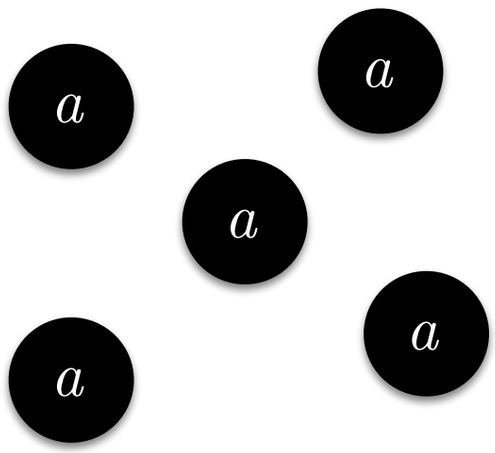
explains the smallness of the neutron's electric dipole moment

generic and detectable

How to think about axions dynamically?

Sub-eV Axion Dark Matter

axion dark matter ~ classical field



smaller mass
(larger density)

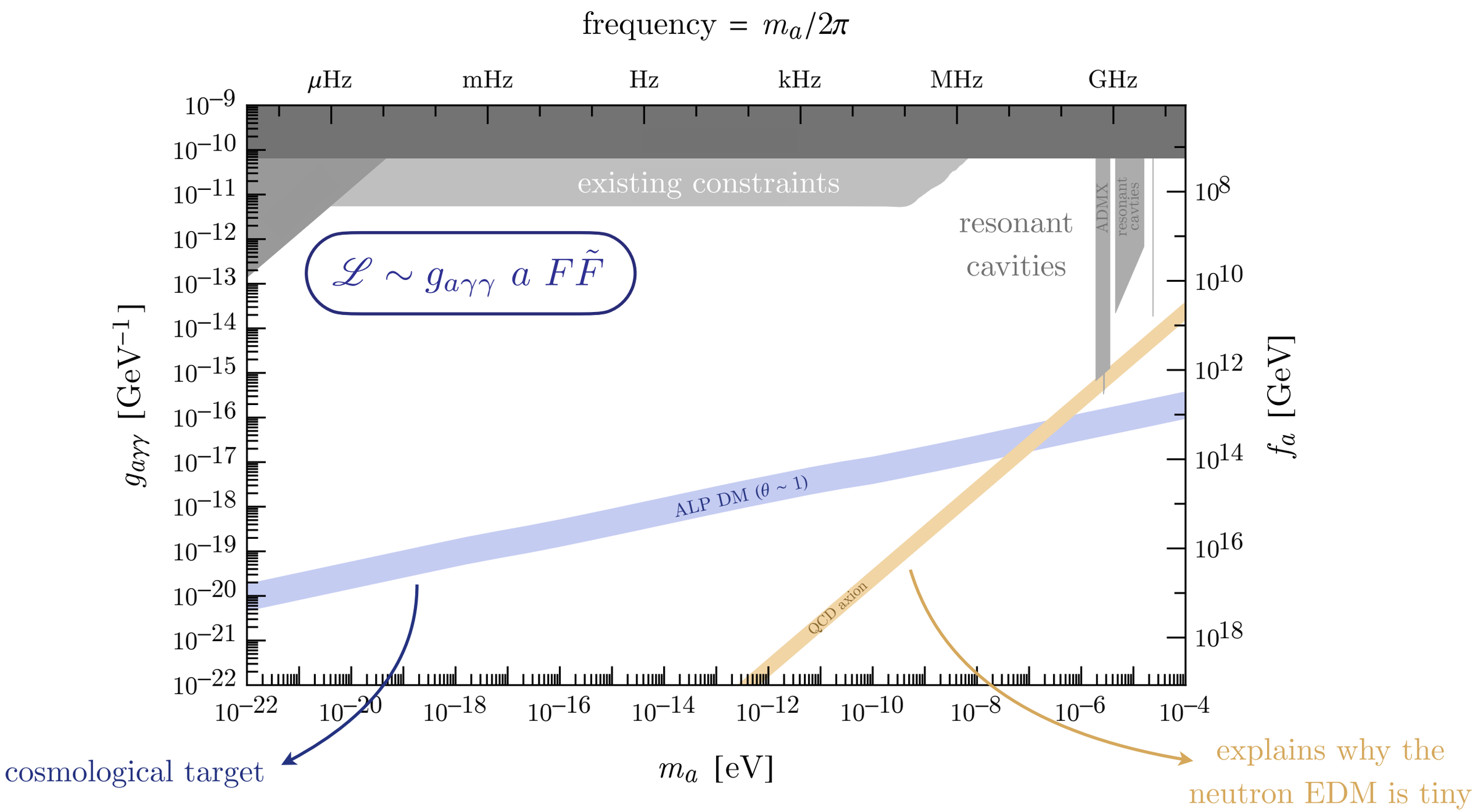
wave properties

$$a \propto \cos m_a t$$

frequency: $m_a \sim \text{month}^{-1} - \text{GHz}$

coherence time: $\tau_a \sim \dfrac{1}{m_a\, v_{\rm DM}^2} \sim 1 \text{ ms} - 10^5 \text{ yrs}$

Sub-eV Axion Dark Matter



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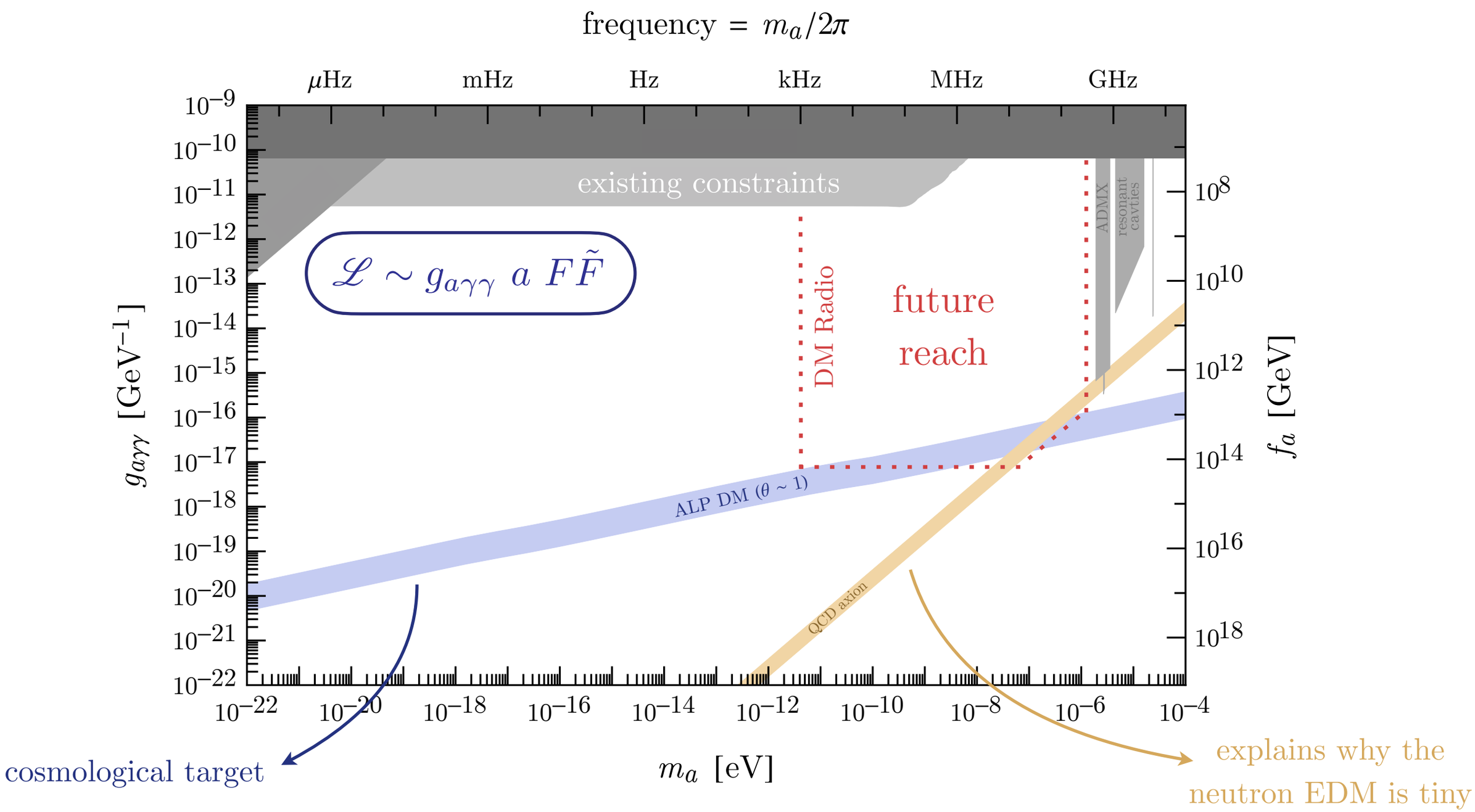
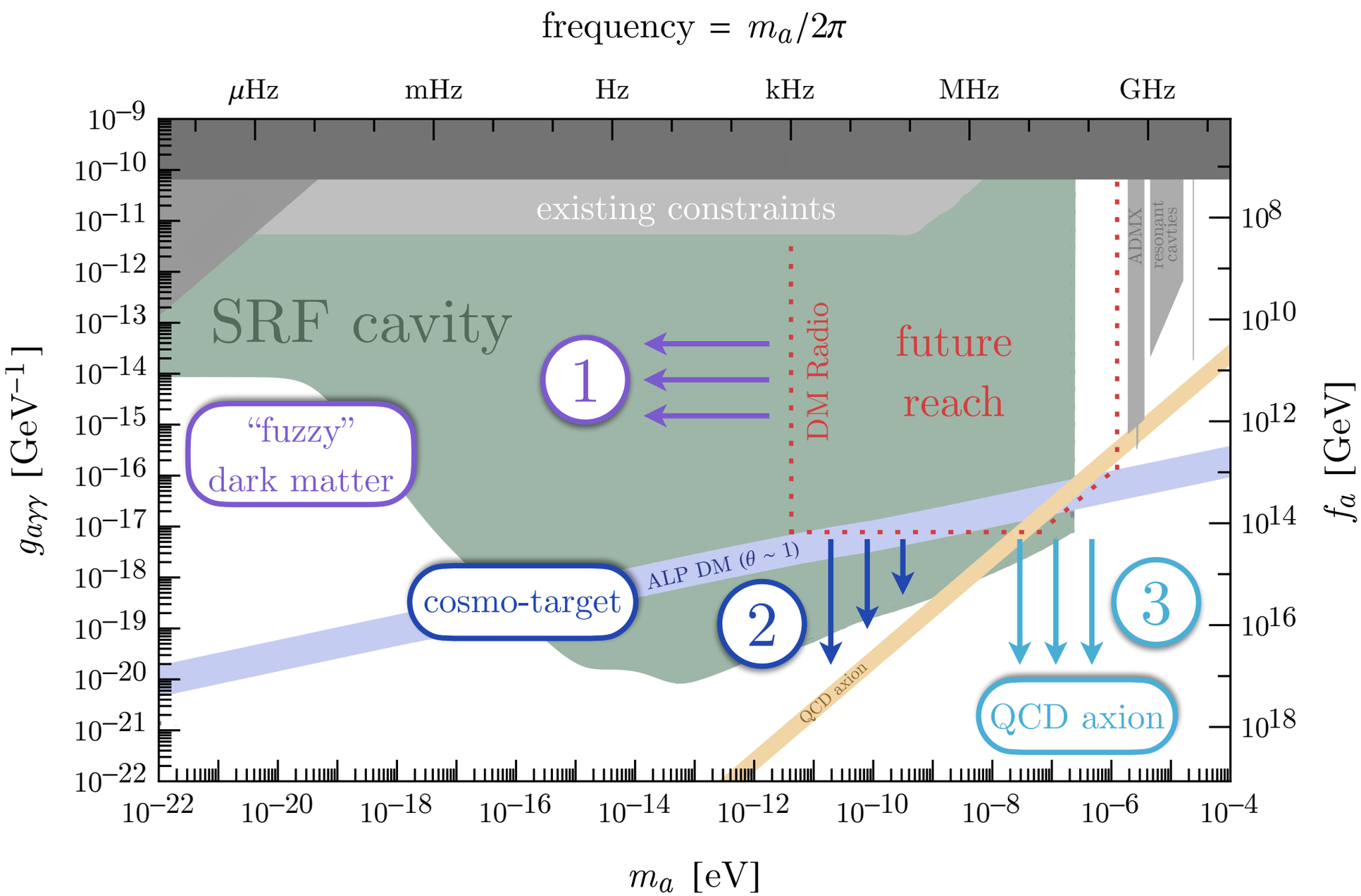


Goals



Goal 1: smaller masses

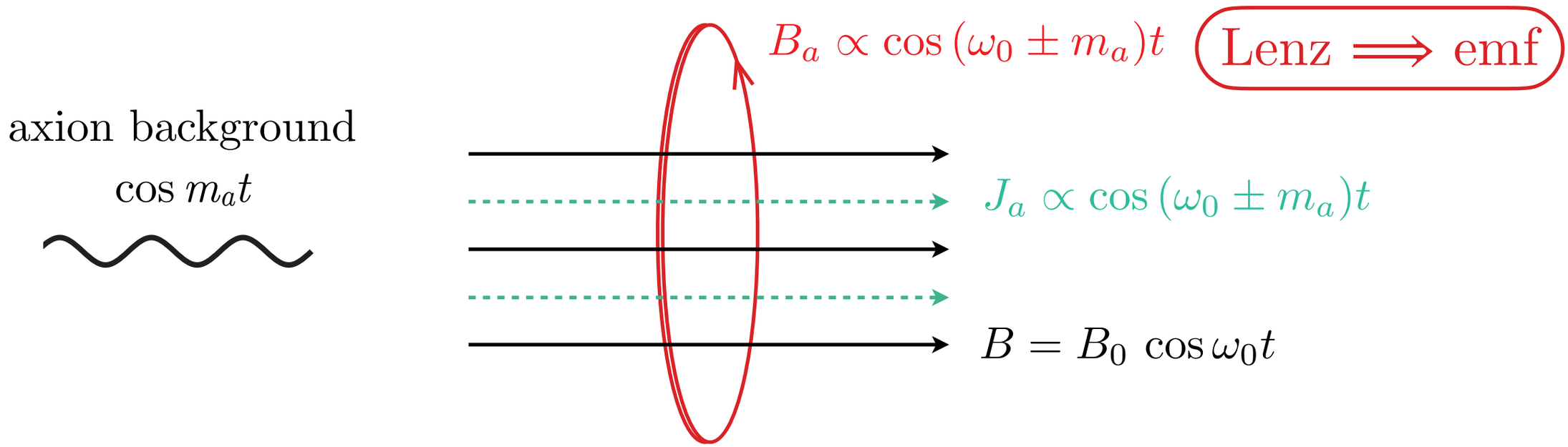
Goal 2: better scaling

Goal 3: smaller couplings

Axion Electrodynamics

$$\mathscr{L} \sim g_{a\gamma\gamma}\, a\, F\tilde{F} \sim \vec{J}_a \cdot \vec{A}$$

$\vec{J}_a \sim g_{a\gamma\gamma}\, \vec{B}\, \partial_t a$ (effective current)



axion drives power into detector that is resonantly matched to oscillating emf

<u>axion-induced emf</u>: $\mathcal{E}_a \propto \partial_t B_a \propto (\omega_0 \pm m_a) \cos(\omega_0 \pm m_a)t$

Static-Field vs. Oscillating-Field

axion-induced emf: $\mathcal{E}_a \propto (\omega_0 \pm m_a) \cos(\omega_0 \pm m_a)t$

Static-Field Resonators

$(\omega_0 = 0\ ,\ \text{resonator frequency} = m_a)$

resonator frequency ~ axion mass

Very difficult to build resonators below ~ kHz

small axion masses $\Longrightarrow$ suppressed emf

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

Oscillating-Field/Heterodyne Resonators

$(\omega_0 \neq 0\ ,\ \text{resonator frequency} = \omega_0 + m_a)$

$(m_a \ll \omega_0)$

resonator frequency $\sim \omega_0 + m_a \sim \omega_0$

Can operate at preferred resonant frequency ~ GHz

signal power independent of axion mass for $m_a \ll \omega_0$

✓ Goal 1: smaller masses

✓ Goal 2: better scaling

Static-Field vs. Oscillating-Field

axion-induced emf: $\mathcal{E}_a \propto (\omega_0 \pm m_a) \cos(\omega_0 \pm m_a)t$

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Can operate at preferred resonant frequency ~ GHz

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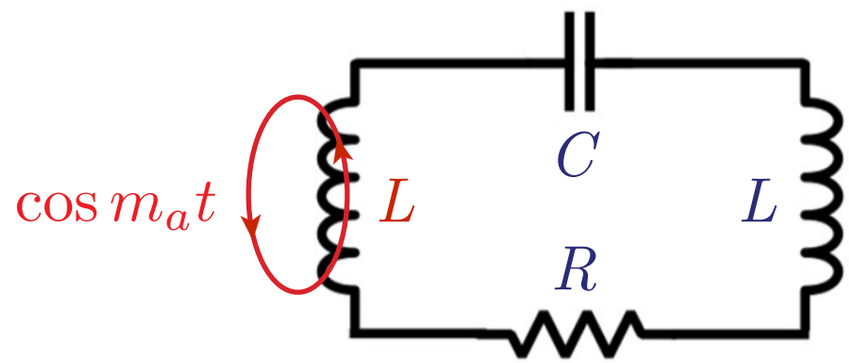
What are concrete examples of static-field and heterodyne resonators?

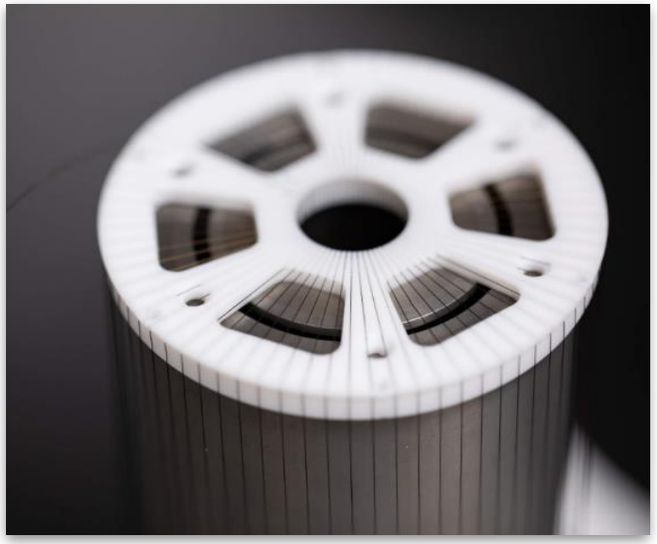
Static-Field Resonators

LC circuit (DM Radio)

(static applied B-field)

axion emf drives power into circuit





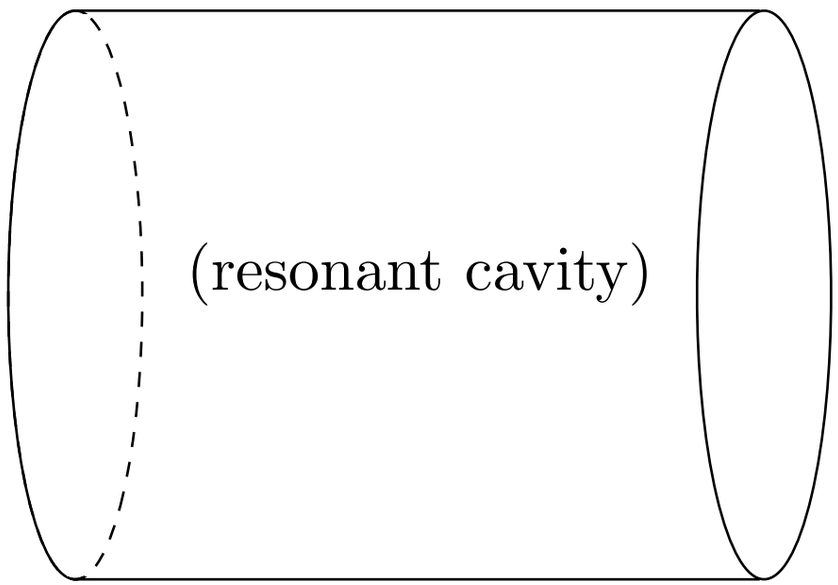
LC resonant frequency $\sim m_a$

very difficult to build LC resonators and read out signal below $\sim$ kHz

$$\text{signal} \sim \frac{\text{detector size}}{\text{axion Compton wavelength}}$$

$\sim 10^{-6}$ for kHz axion frequencies

Heterodyne/Oscillating-Field Resonators



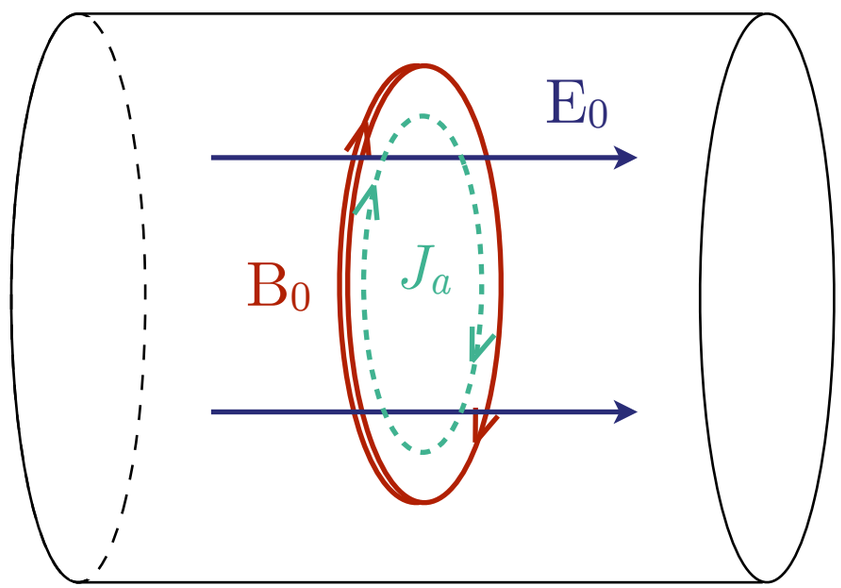
"Frequency Conversion" between two ~ GHz cavity modes

Heterodyne/Oscillating-Field Resonators

axion background

$\cos m_a t$

$\omega_0 \sim$ GHz



TM_{030}

loud driven mode

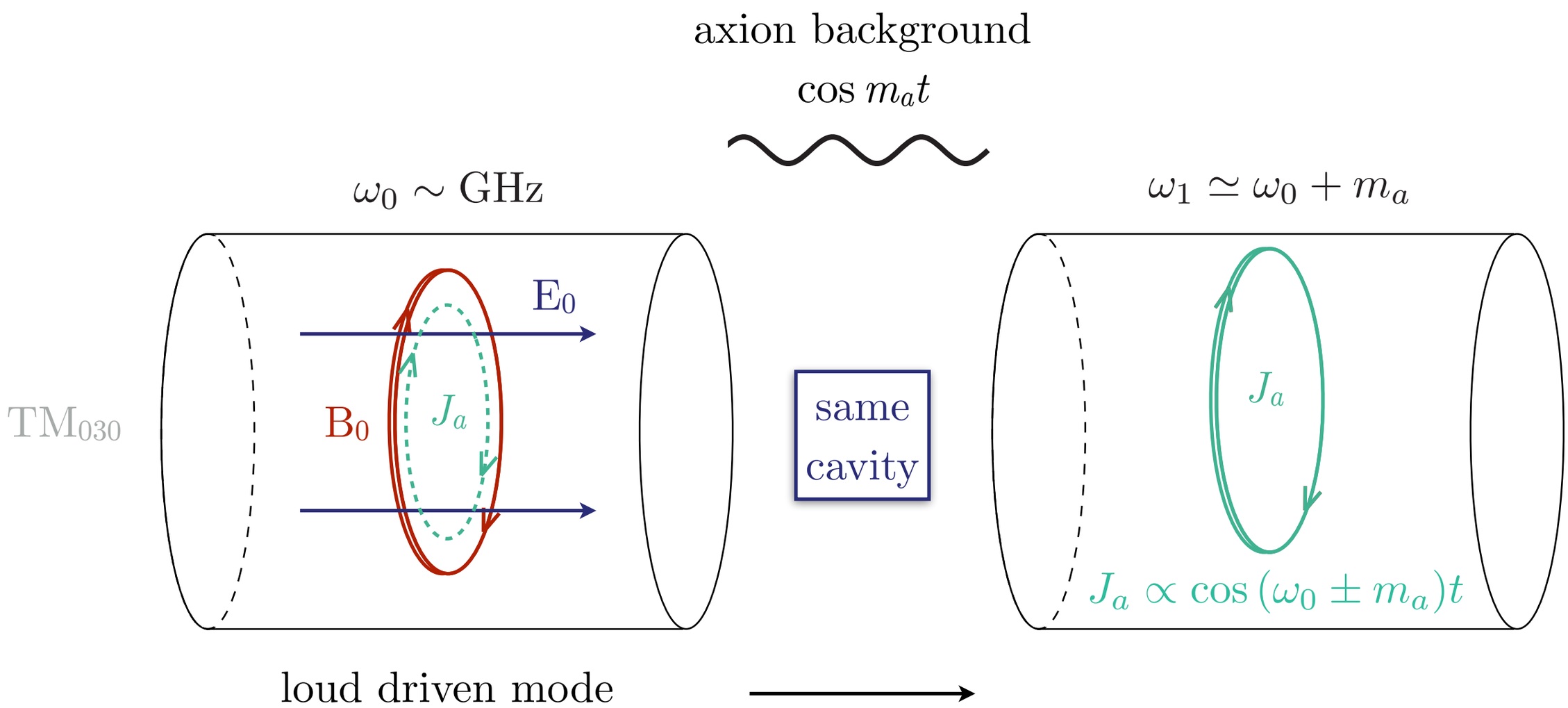
effective axion current

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

"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/Oscillating-Field Resonators



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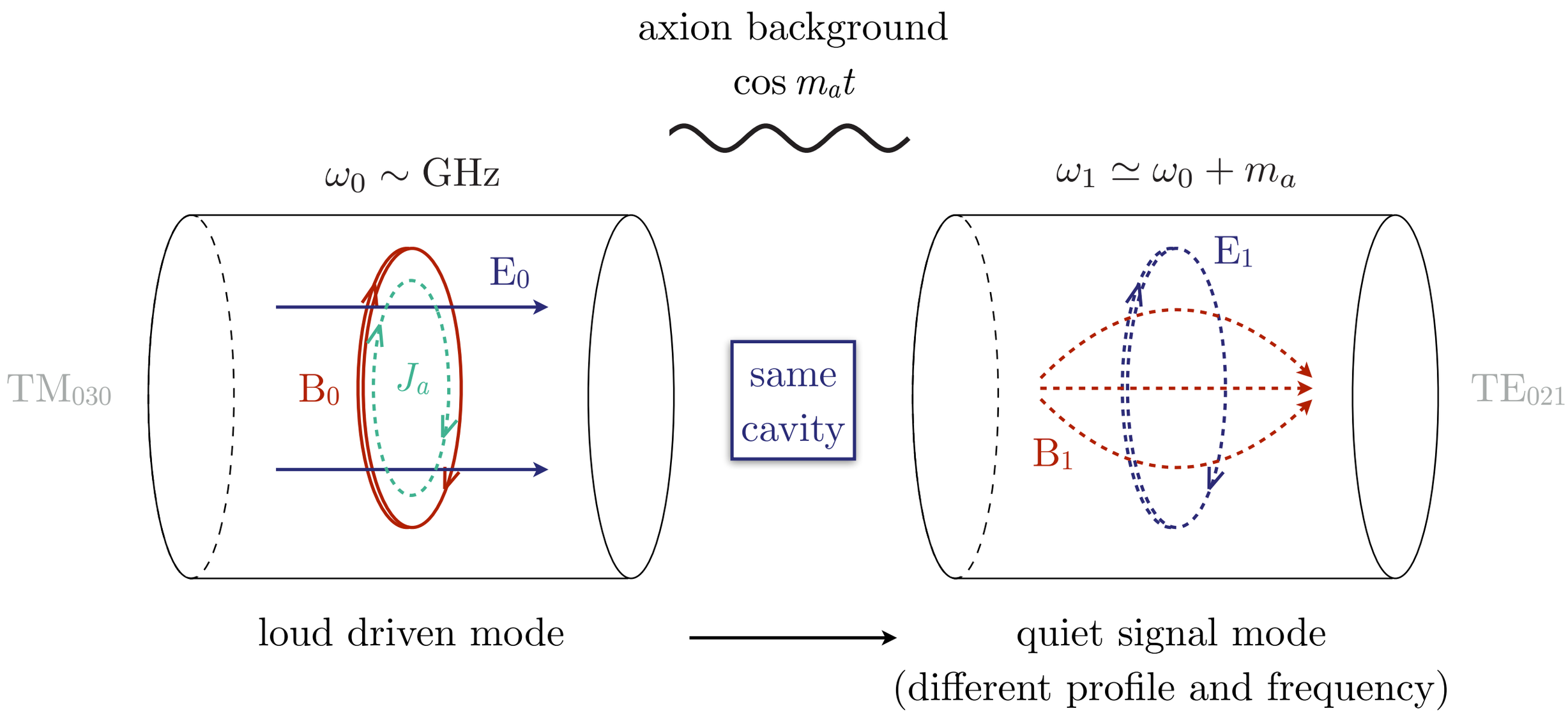

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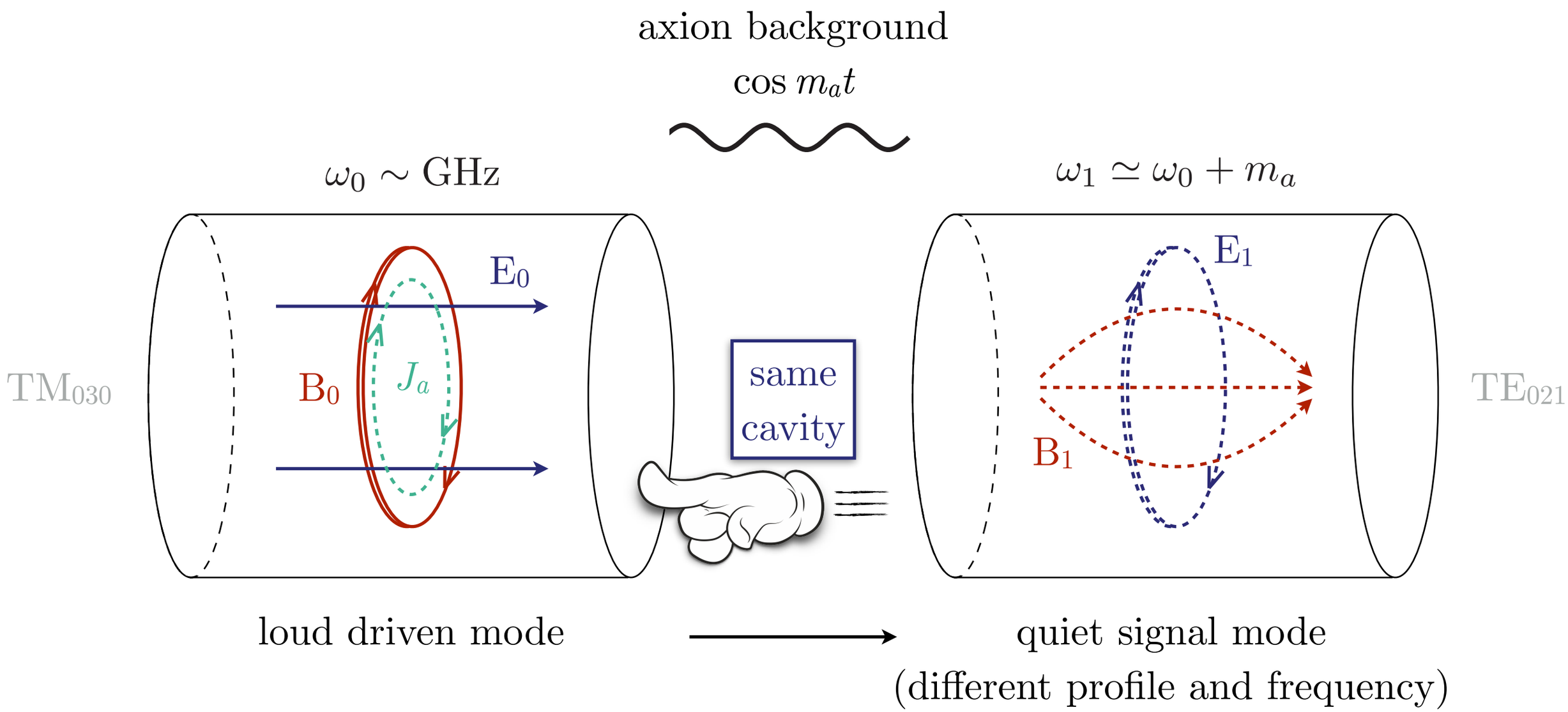

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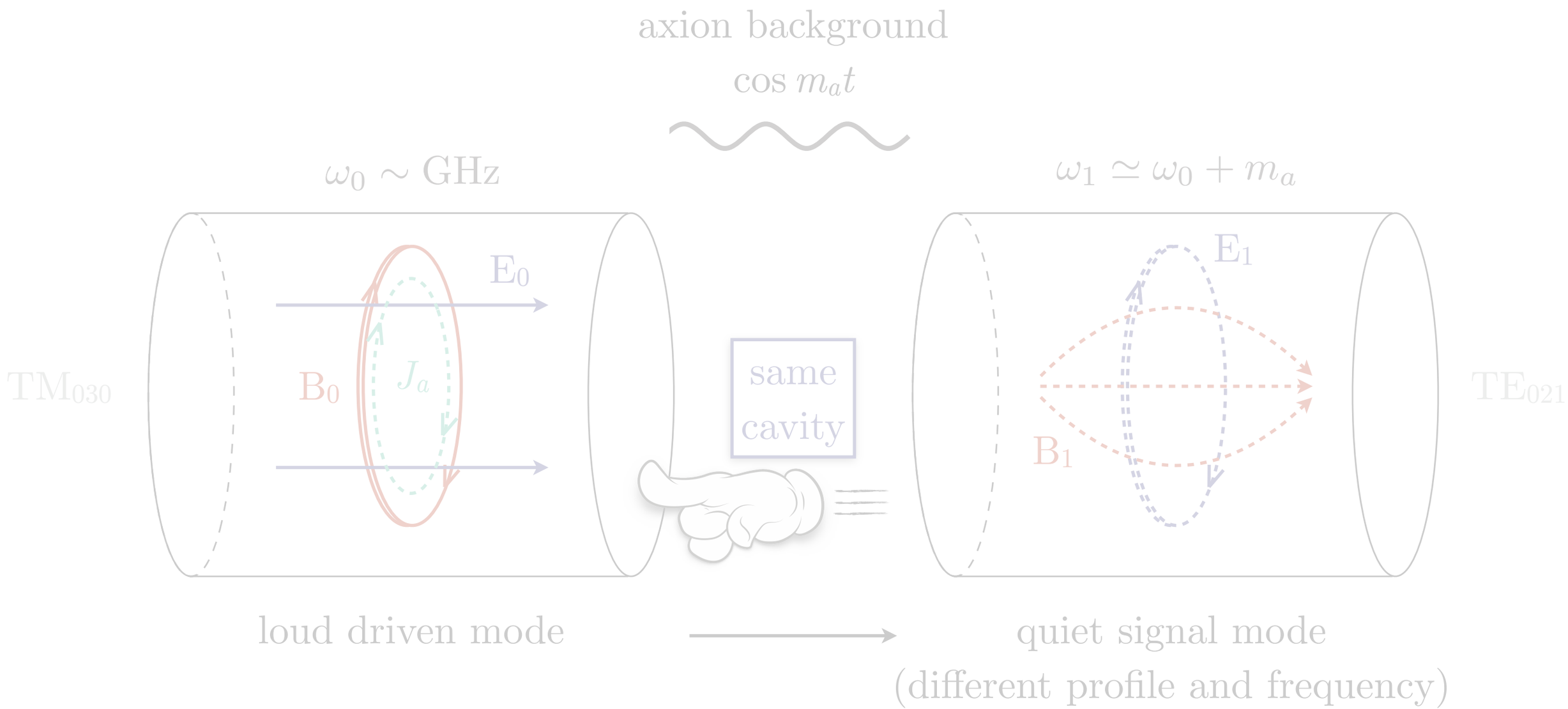
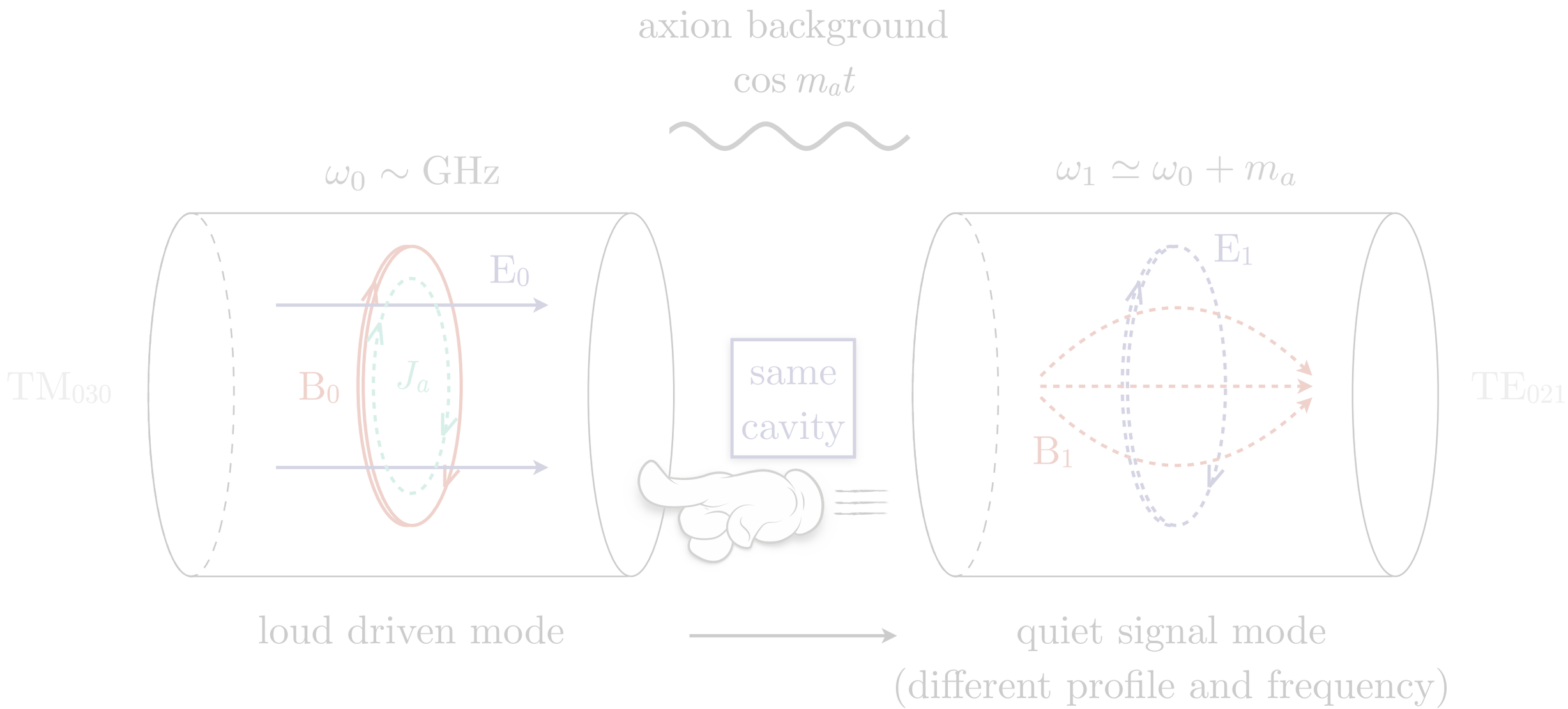


signal mode frequency $\sim \omega_0 + m_a \sim 1/$detector size

signal is always read out at $\sim$ GHz

signal $\sim$ detector size $\times$ GHz ~ 1

Heterodyne/Oscillating-Field Resonators



"Frequency Conversion"

between two ~ GHz cavity modes

heterodyne?

✓ Goal 1: smaller masses

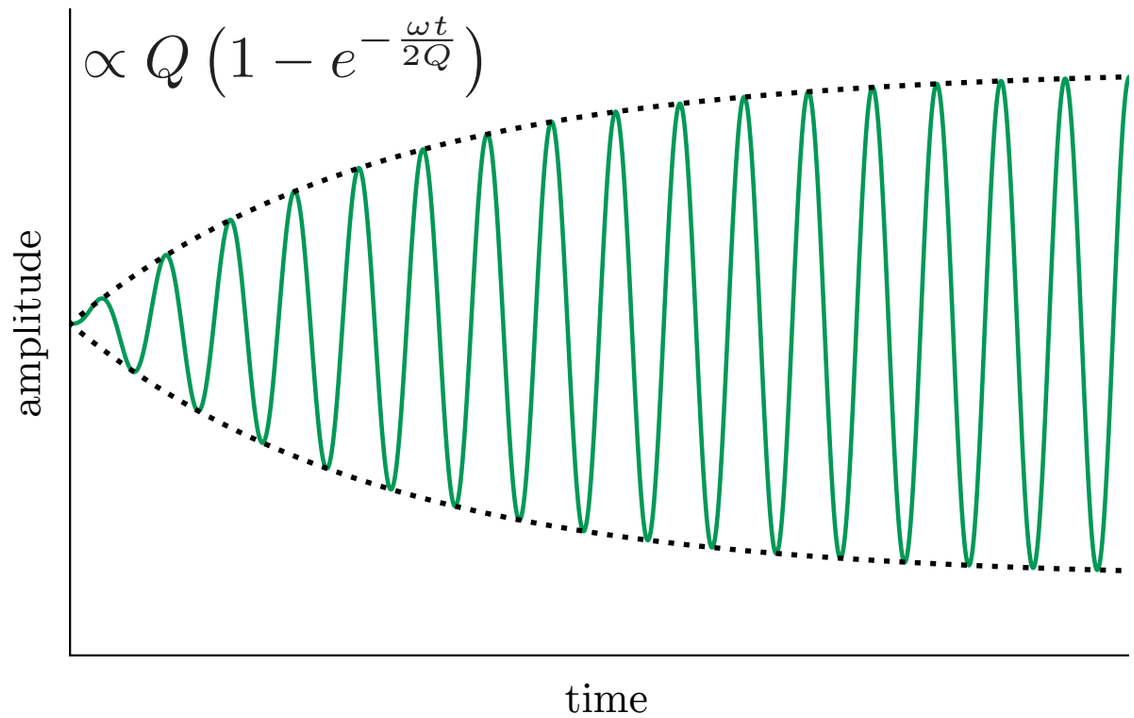
✓ Goal 2: better scaling

Goal 3: smaller couplings

Driven Damped Harmonic Oscillator

resonant mode of a cavity → harmonic oscillator
axion effective current → driving term

<u>axion emf</u>
<u>on resonance</u>



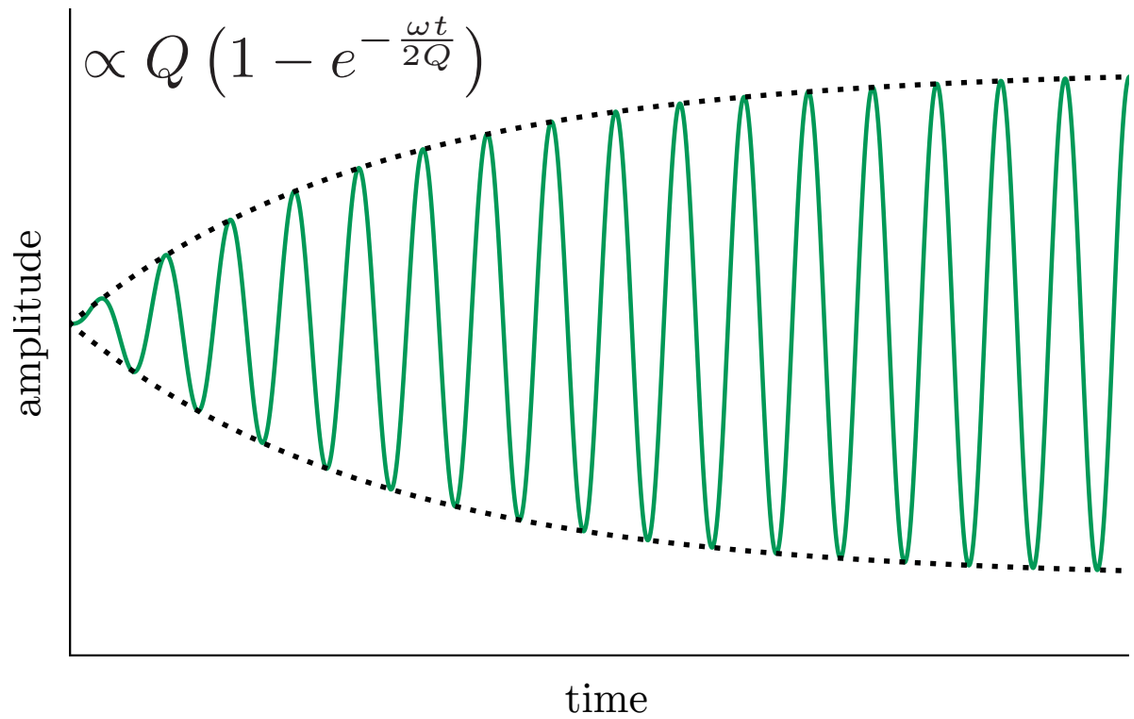
($\sim Q$ oscillations)

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

Driven Damped Harmonic Oscillator

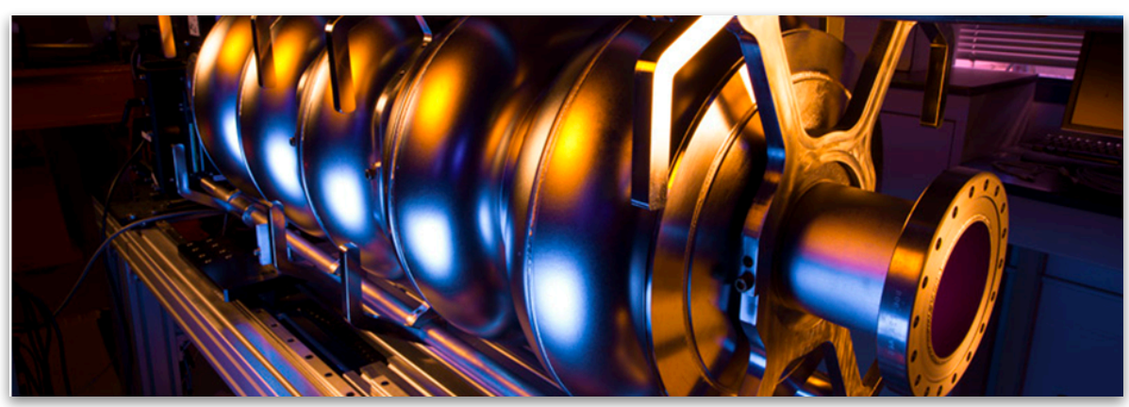
resonant mode of a cavity → harmonic oscillator
axion effective current → driving term

<u>axion emf</u>
<u>on resonance</u>



($\sim Q$ oscillations)

SRF cavities are the most efficient engineered oscillators, commonly employing $Q \gtrsim 10^{10}$



SRF Cavities

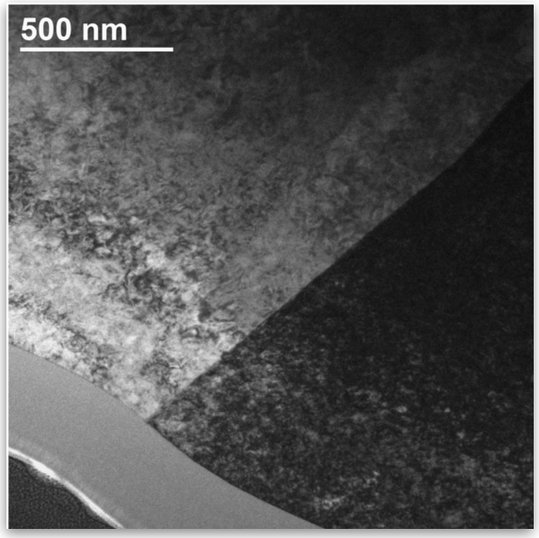
Why superconducting RF cavities?

1. most efficient engineered oscillators
(long coherence $\Longrightarrow$ quantum computation)

2. large oscillating fields
(0.2 T, ~GHz)

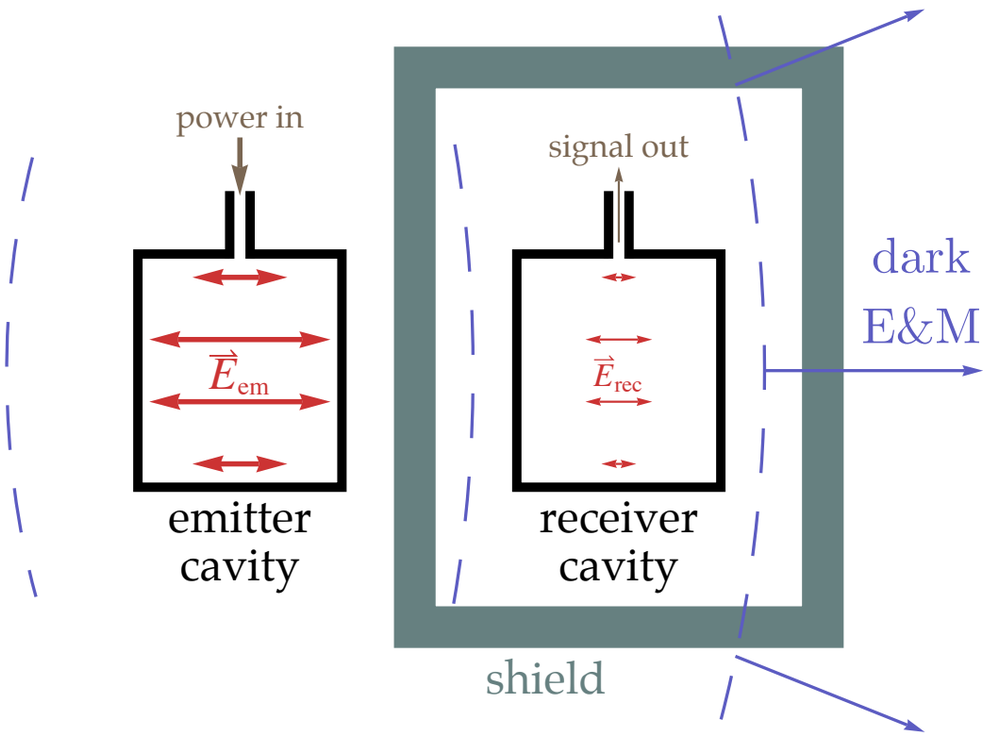
3. precisely manufactured and operated
(nm-precision)

4. already used for new physics searches
(experimentalists)



SRF Cavities

DarkSRF (FNAL)



("light-shining-through-wall")

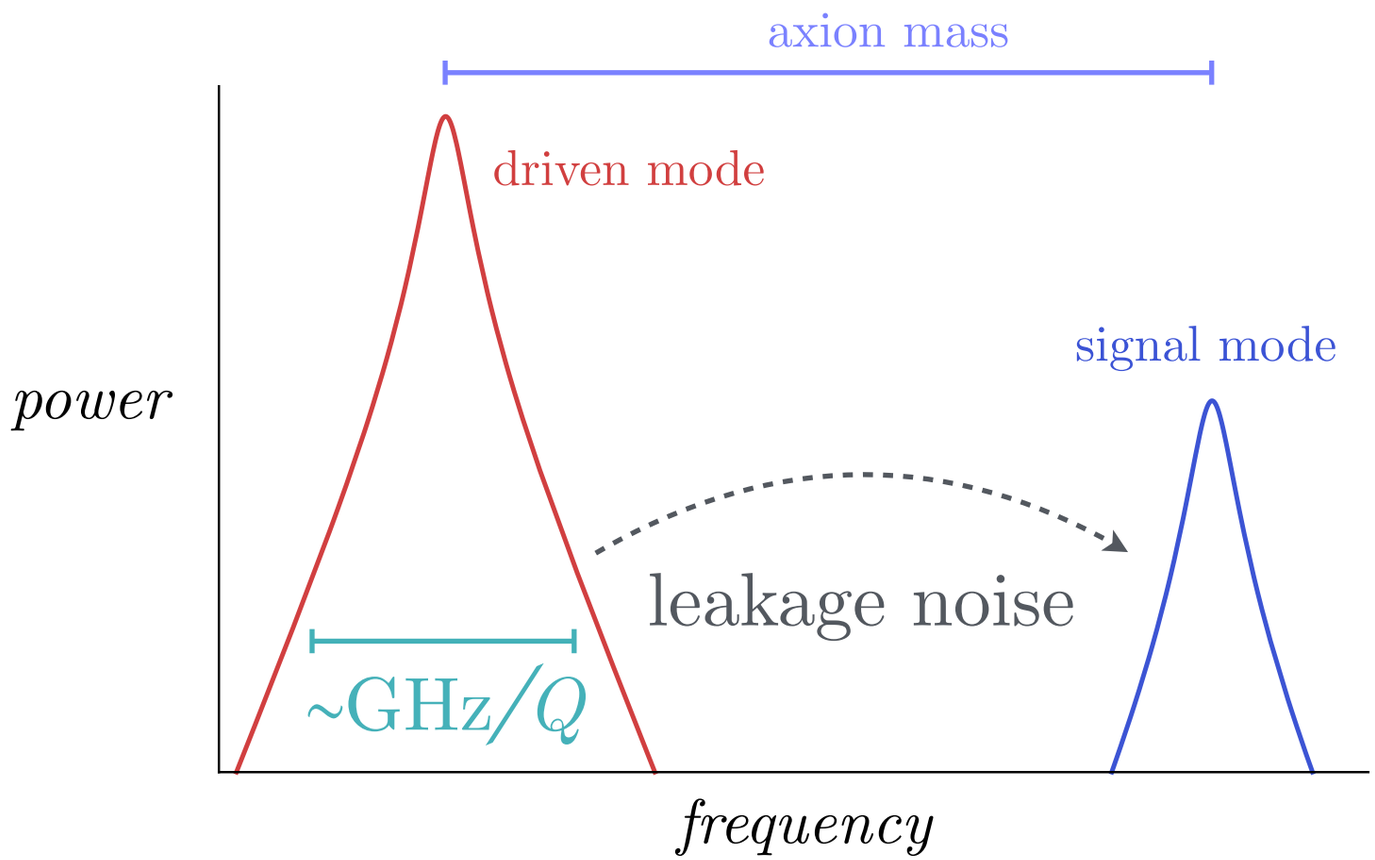
- sub-Hz frequency wobble
- degenerate modes
- resolved thermal noise
- plan for a week run

arXiv:1407.4806

Noise

(Large Q does more than enhance signal)

Large Q also mitigates noise (leakage noise = oscillator, mechanical, ...)



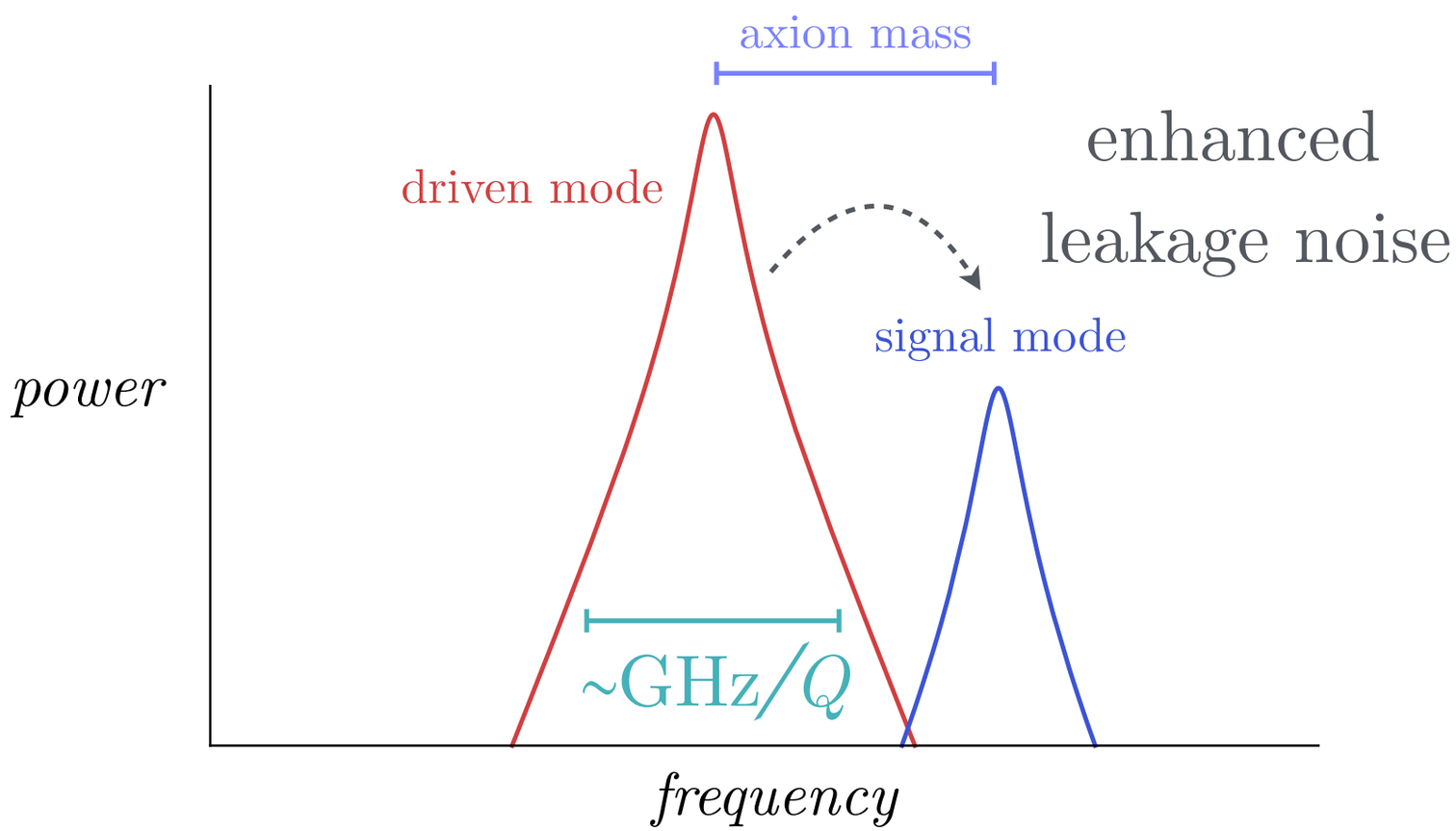
Handles

- modes are separated by *many* bandwidths (large Q)
- modes are spatially distinct

Noise

(Large Q does more than enhance signal)

Large Q also mitigates noise (leakage noise = oscillator, mechanical, ...)



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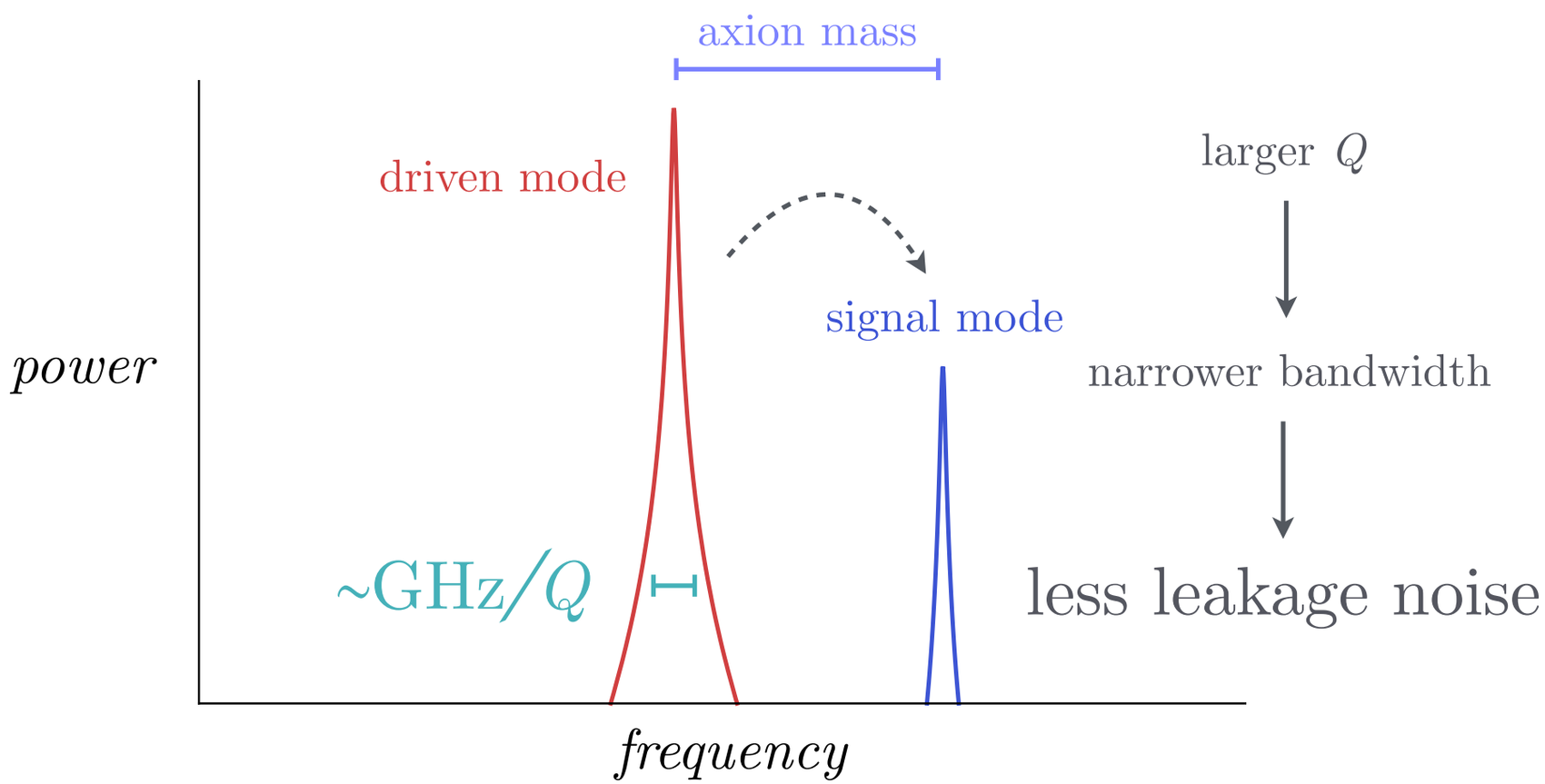
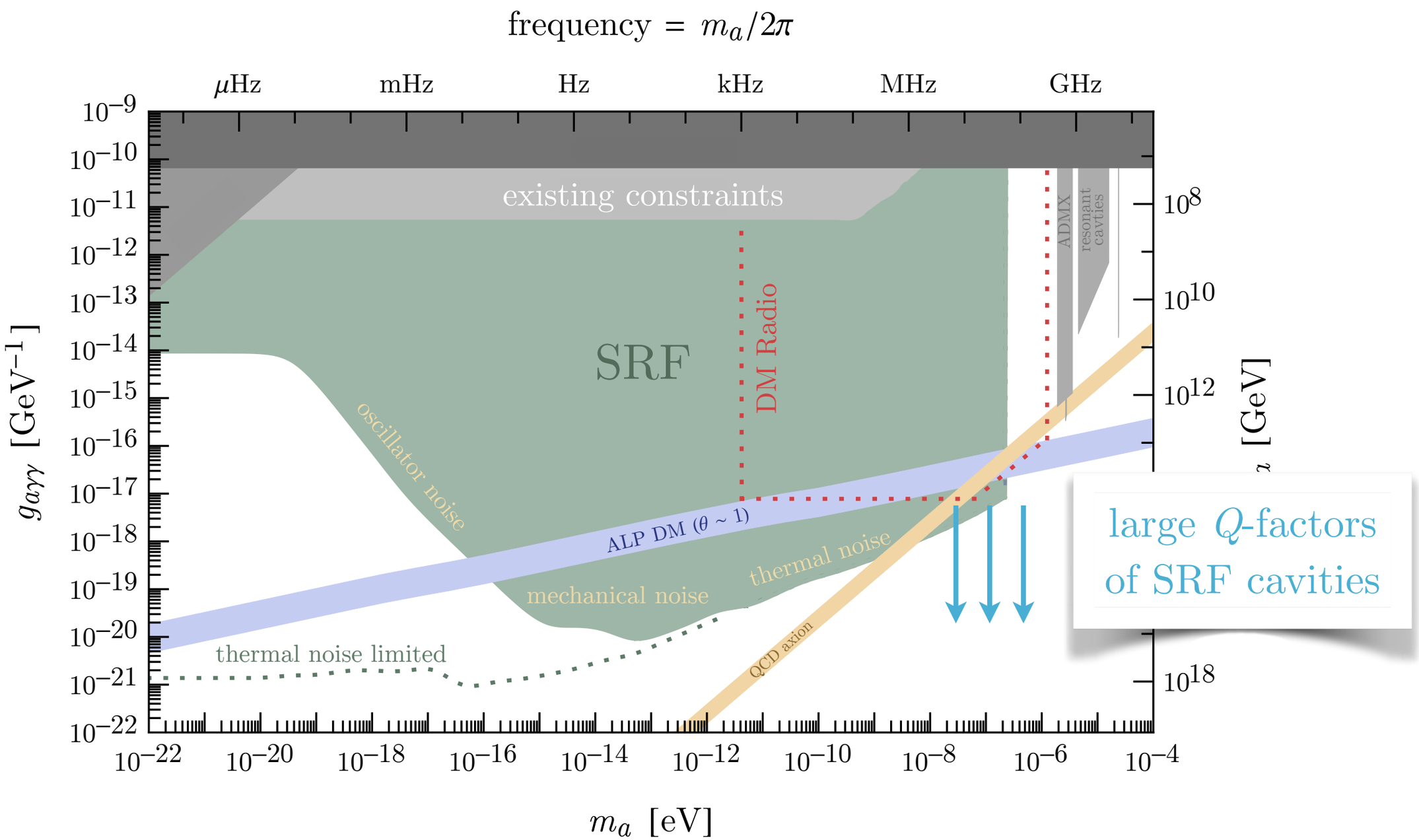


Handles

- modes are separated by *many* bandwidths (large Q)
- modes are spatially distinct

Goals

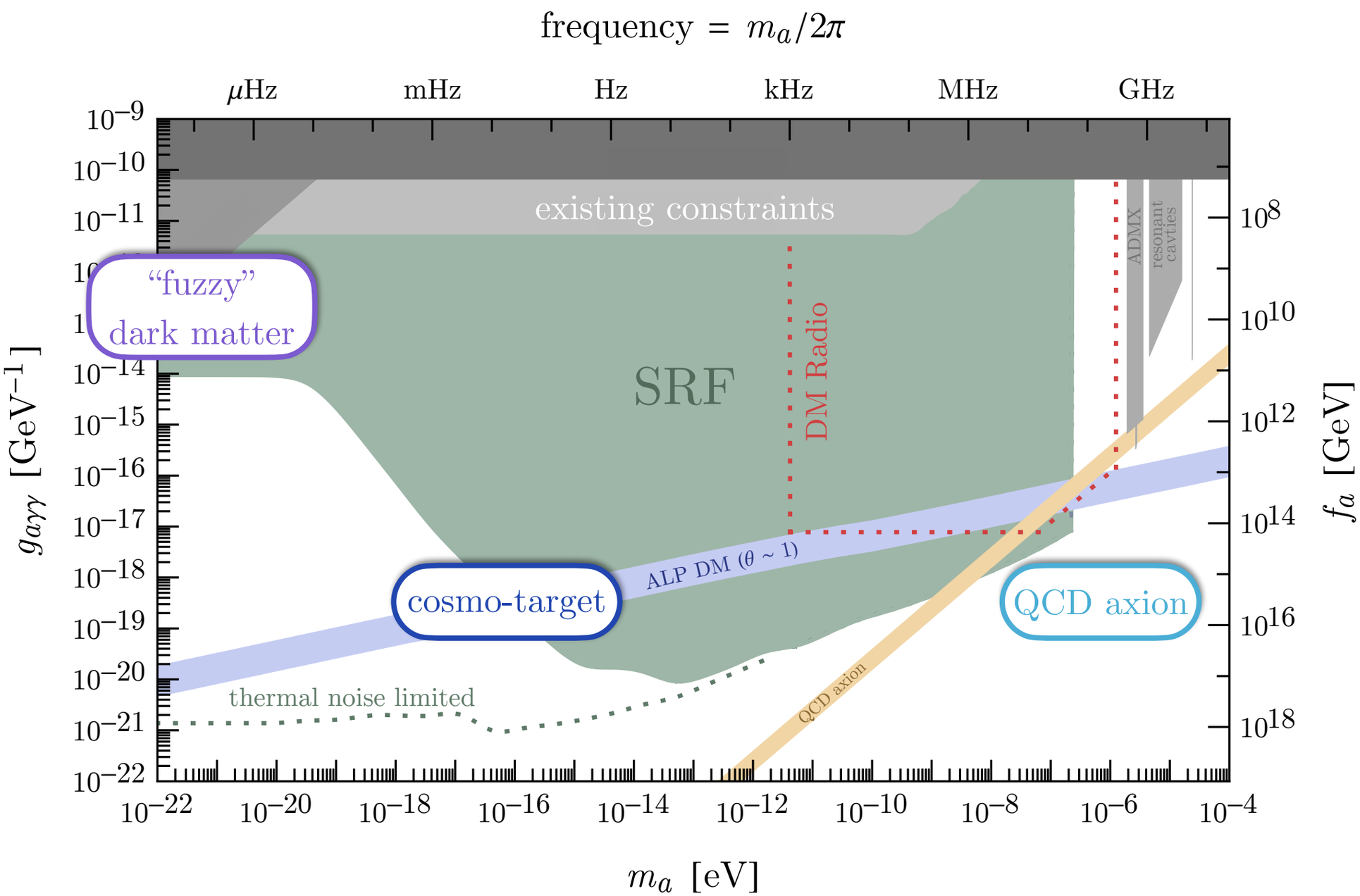


✓ Goal 1: smaller masses

✓ Goal 2: better scaling

✓ Goal 3: smaller couplings

Goals

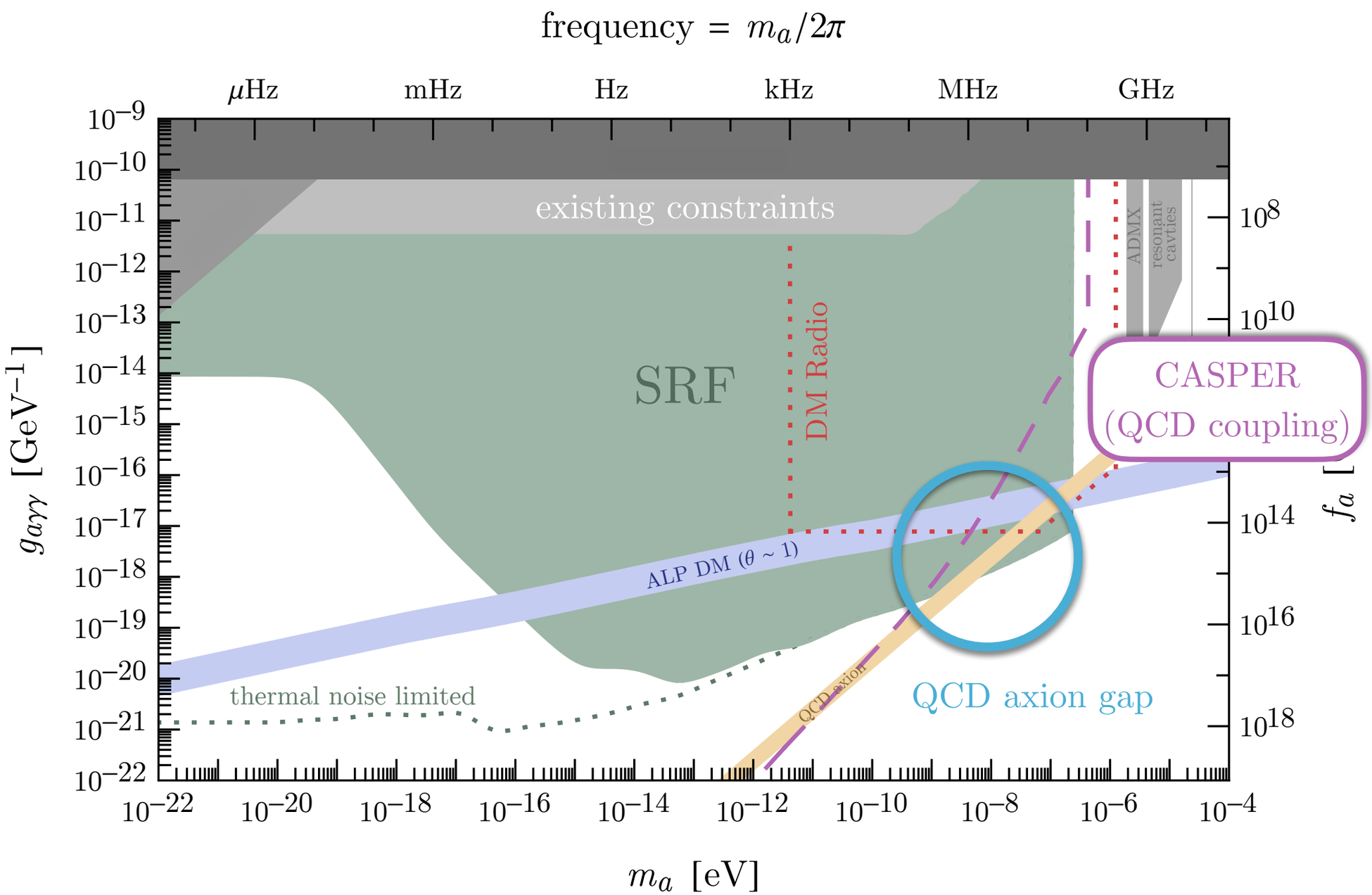


Goal 1: smaller masses

Goal 2: better scaling

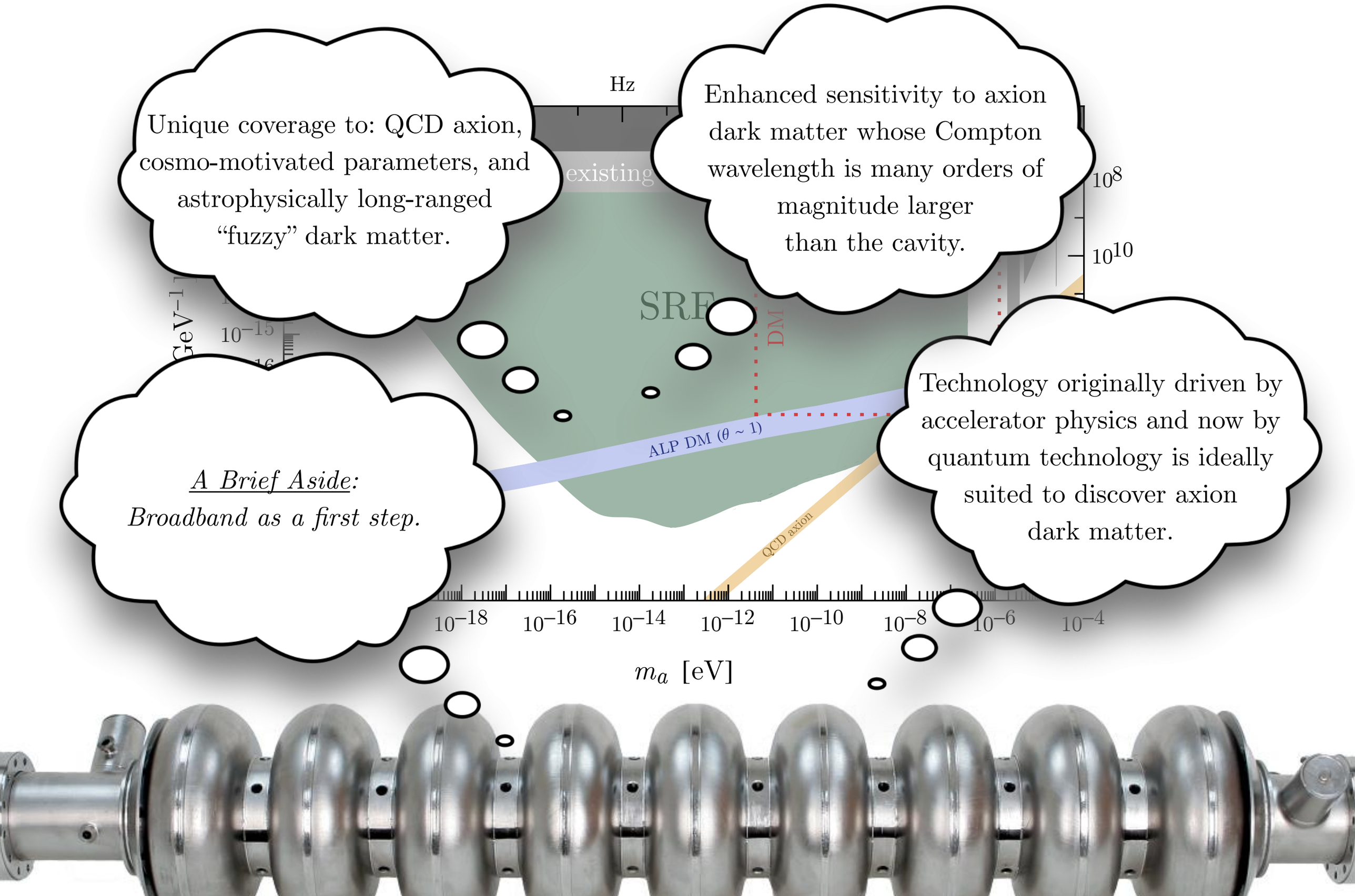
Goal 3: smaller couplings

QCD Axion

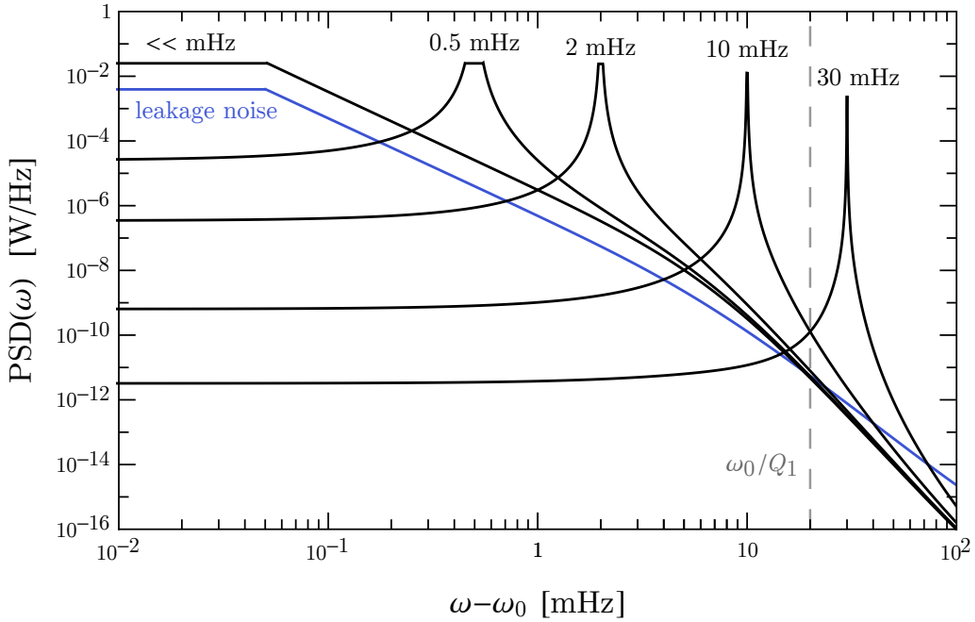


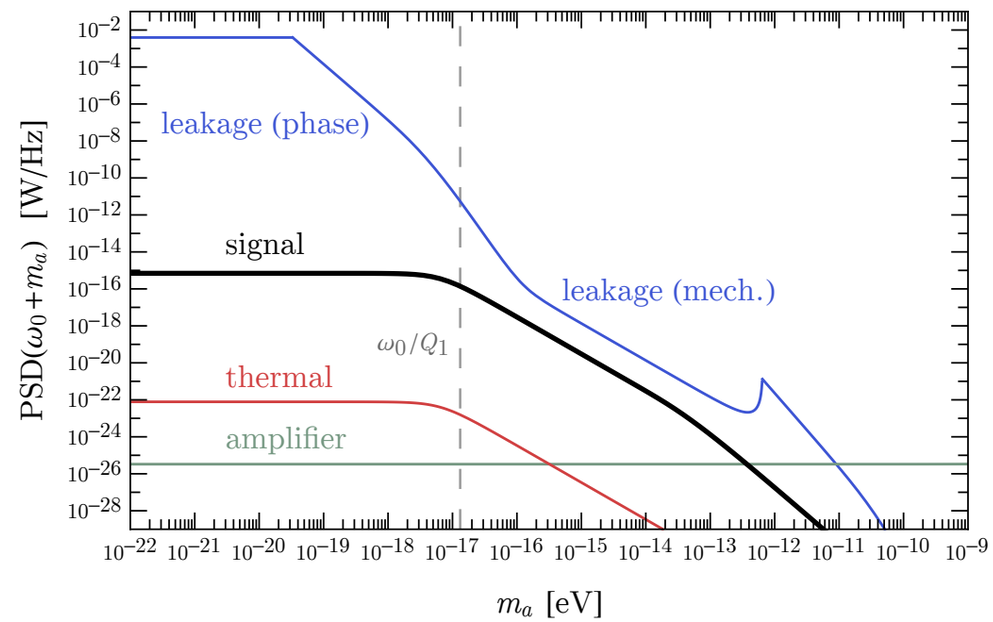
closing the gap in QCD axion coverage

Takeaway


Unique coverage to: QCD axion, cosmo-motivated parameters, and astrophysically long-ranged "fuzzy" dark matter.
Enhanced sensitivity to axion dark matter whose Compton wavelength is many orders of magnitude larger than the cavity.
Technology originally driven by accelerator physics and now by quantum technology is ideally suited to discover axion dark matter.
A Brief Aside:
Broadband as a first step.
Hz
existing
SRF
DM
ALP DM (θ ~ 1)
QCD axion
GeV−1
10−15
10^8
10^10
10−18
10−16
10−14
10−12
10−10
10−8
10−6
10−4
m_a [eV]

Broadband

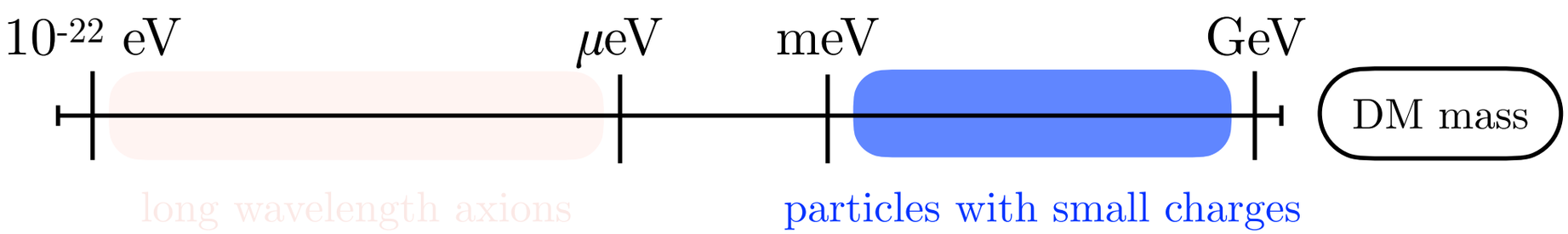




- A simple setup (fixed geometry, degenerate modes): **Broadband** sensitivity to new physics within minutes.
- Signal *and* noise both roll off away resonance $\Longrightarrow$ sensitive to a large mass range.

Discovering the Dark Universe

This idea of using new technology to open up a window into new scales is not unique to one specific technology.



A. Berlin, R. D'Agnolo, S. Ellis, P. Schuster, N. Toro, Phys. Rev. Lett. 2020

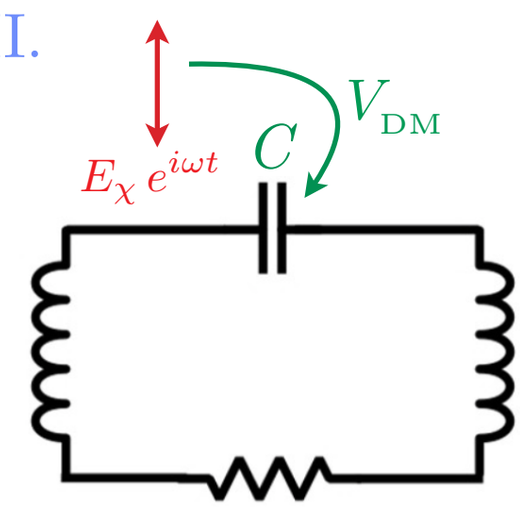
superconducting cavities

LC circuits

Future

I.

II.



III.

Ways Forward

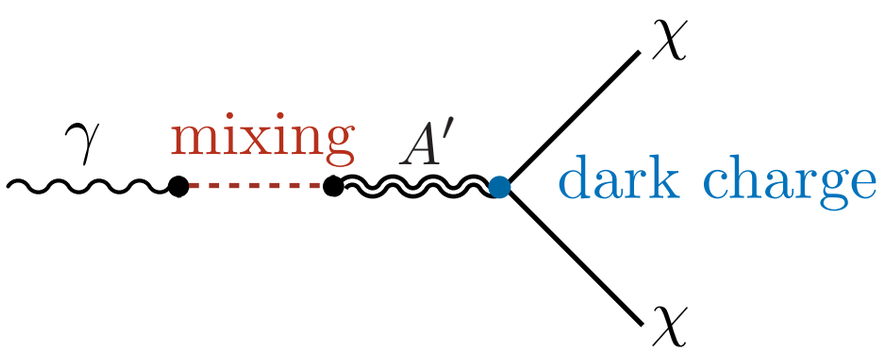
New Long-Ranged Forces

The visible universe is governed by a rich spectrum of forces and particles.

What particle physics governs most of the matter in the universe?

Generic to expect that dark matter couples to new long-ranged forces.

Do they couple to normal matter?

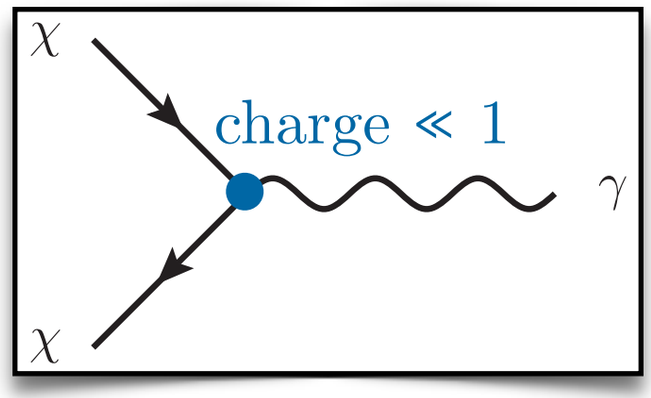


effective DM charge $\sim$ mixing $\times$ dark charge

(small millicharges from, e.g., radiatively induced mixing)

New Long-Ranged Forces

at low-energy and laboratory-distances:



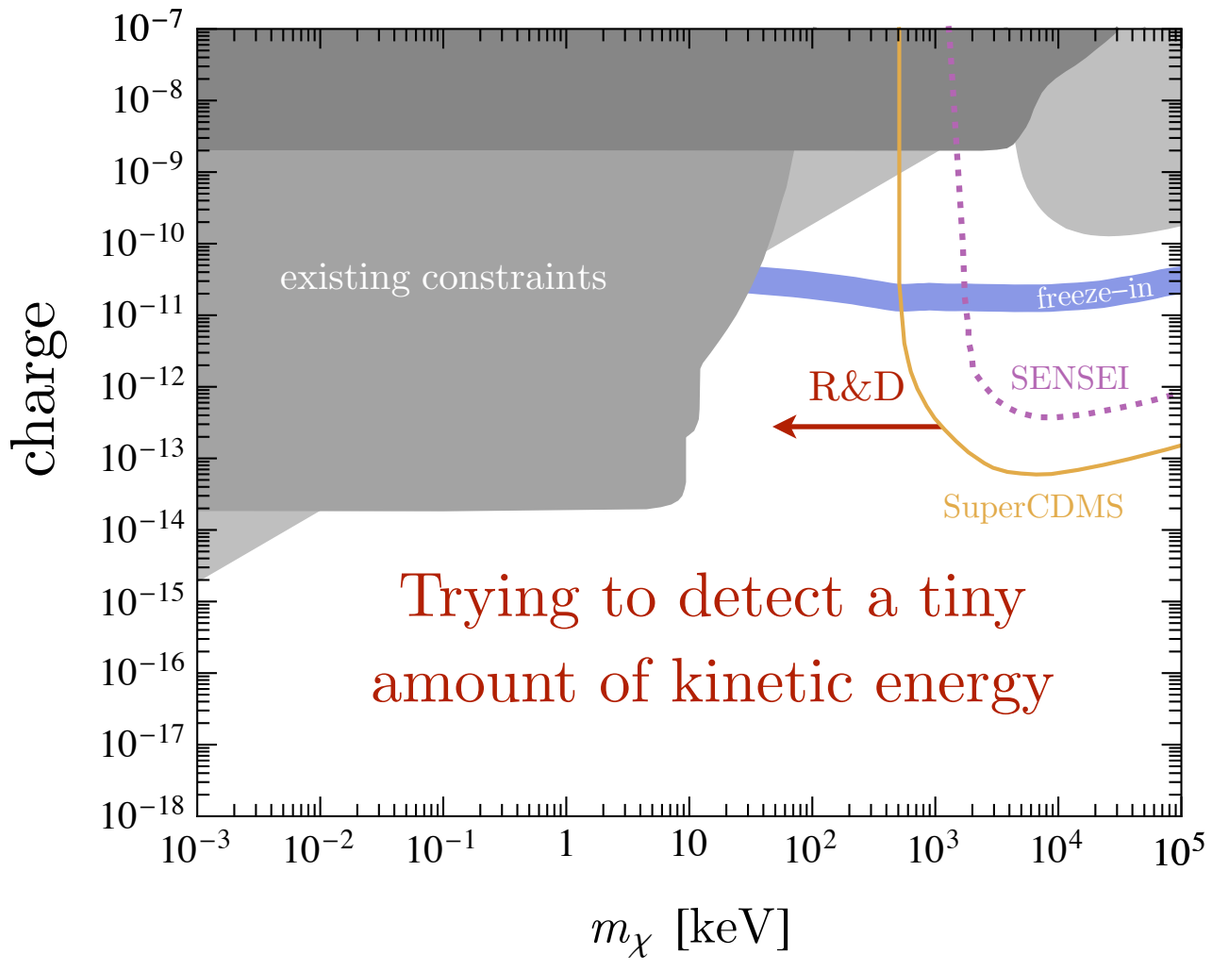
"millicharged"

How is this cosmologically viable/motivated?

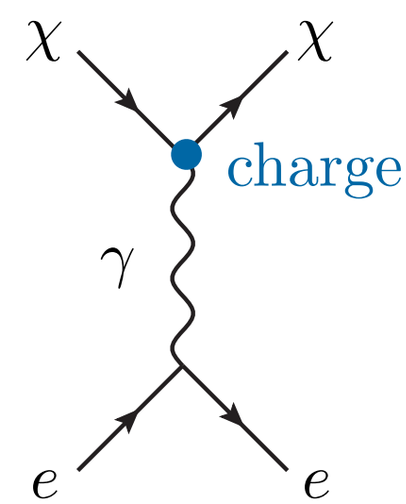
"freeze-in"

DM produced from feeble interactions with normal matter

Millicharged Dark Matter



the target for future direct detection



sub-MeV R&D

- new scattering targets
- new read-out technologies
- ***same philosophy***

How do we access small masses without relying on the tiny amount of associated kinetic energy?

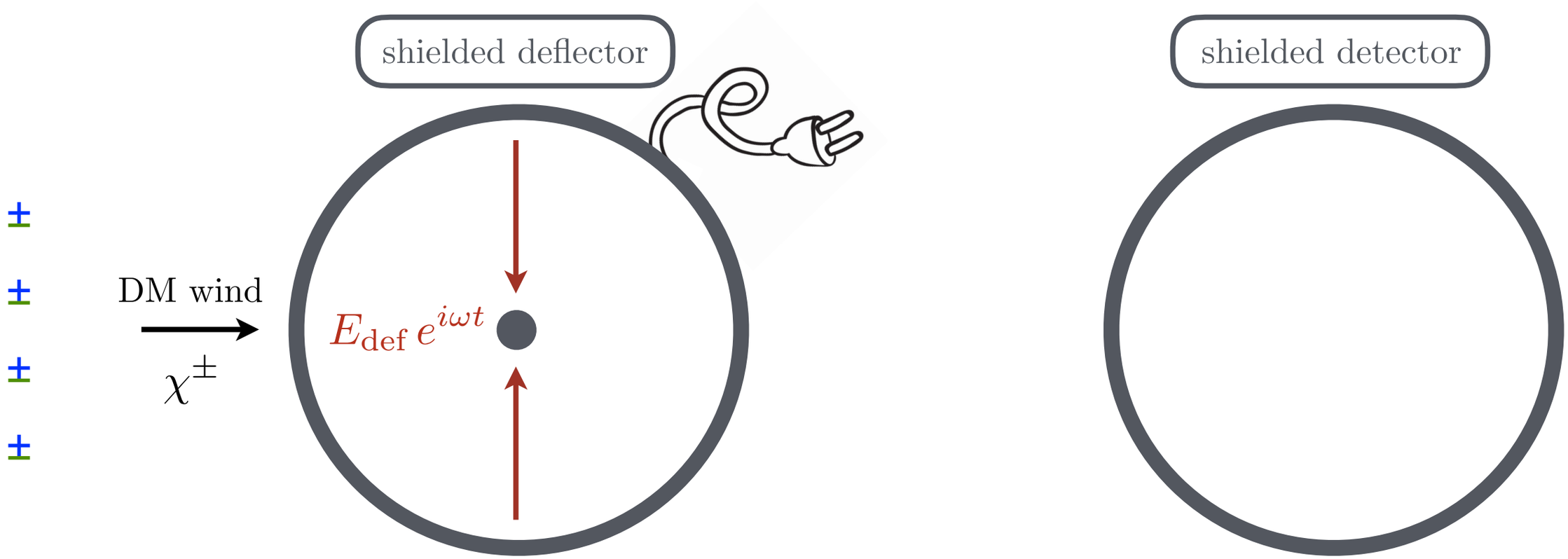
Direct *Deflection*

Inducing and detecting collective "ripples" in the dark matter "fluid"

Direct *Deflection*

A large number density implies more than just large flux, it enables inducing **enhanced** collective effects into the classical DM fluid. This is easier to do for smaller masses.

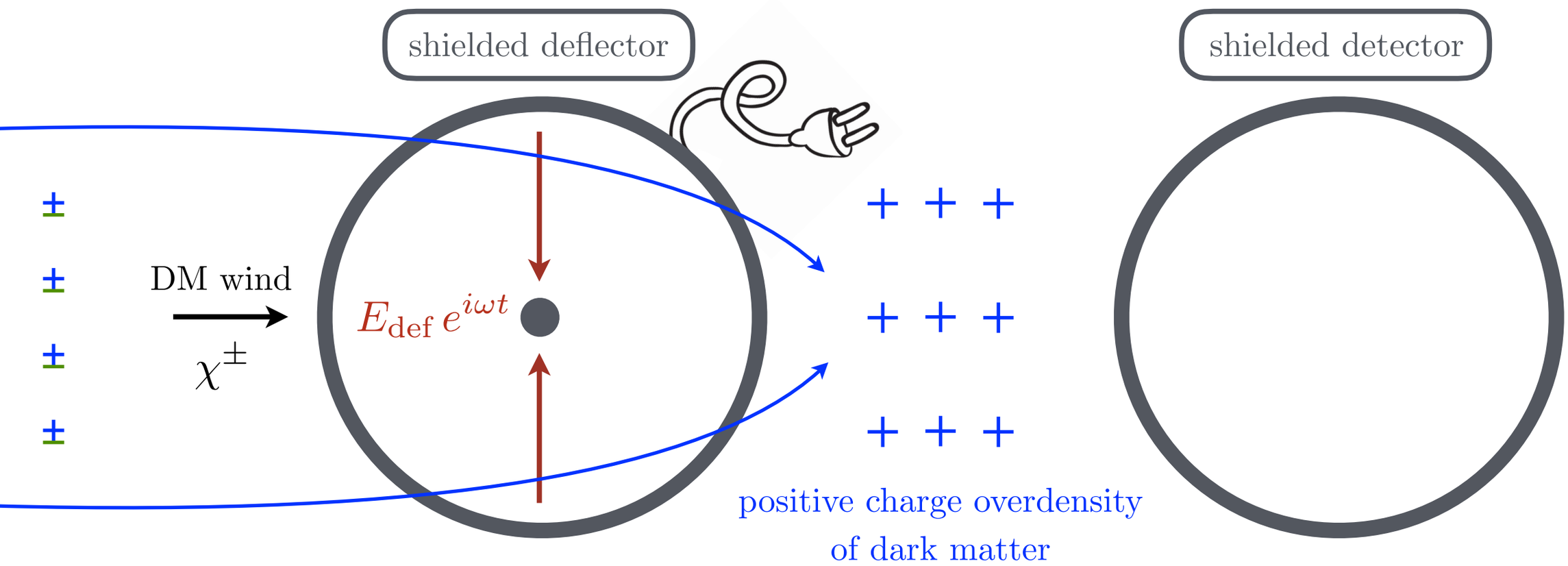
Direct *Deflection*



wind-blowing

(similar to ~~"light-shining-~~through-wall" experiments)

Direct *Deflection*



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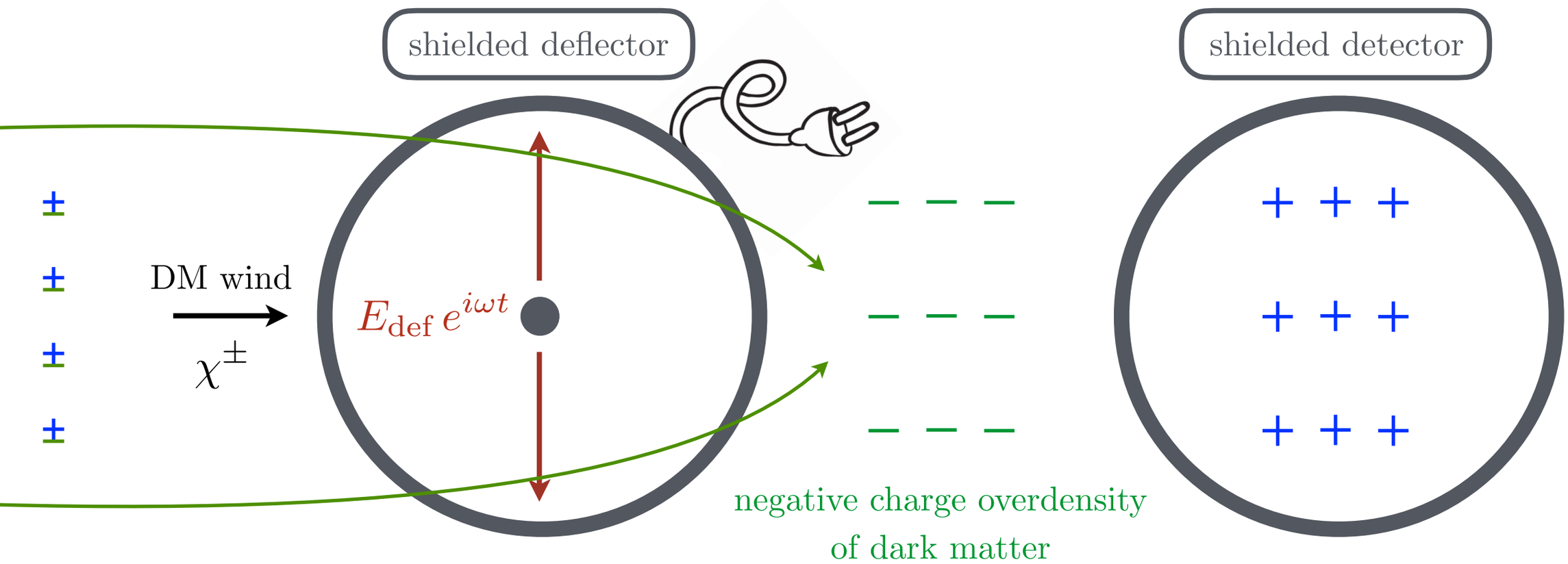

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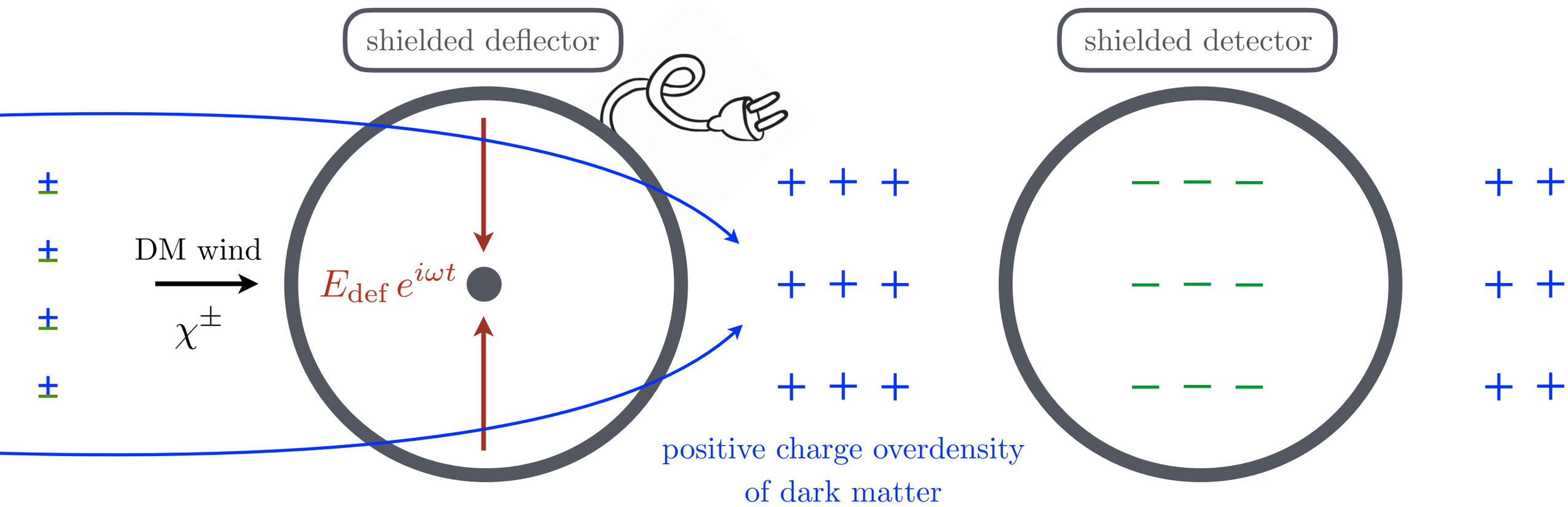

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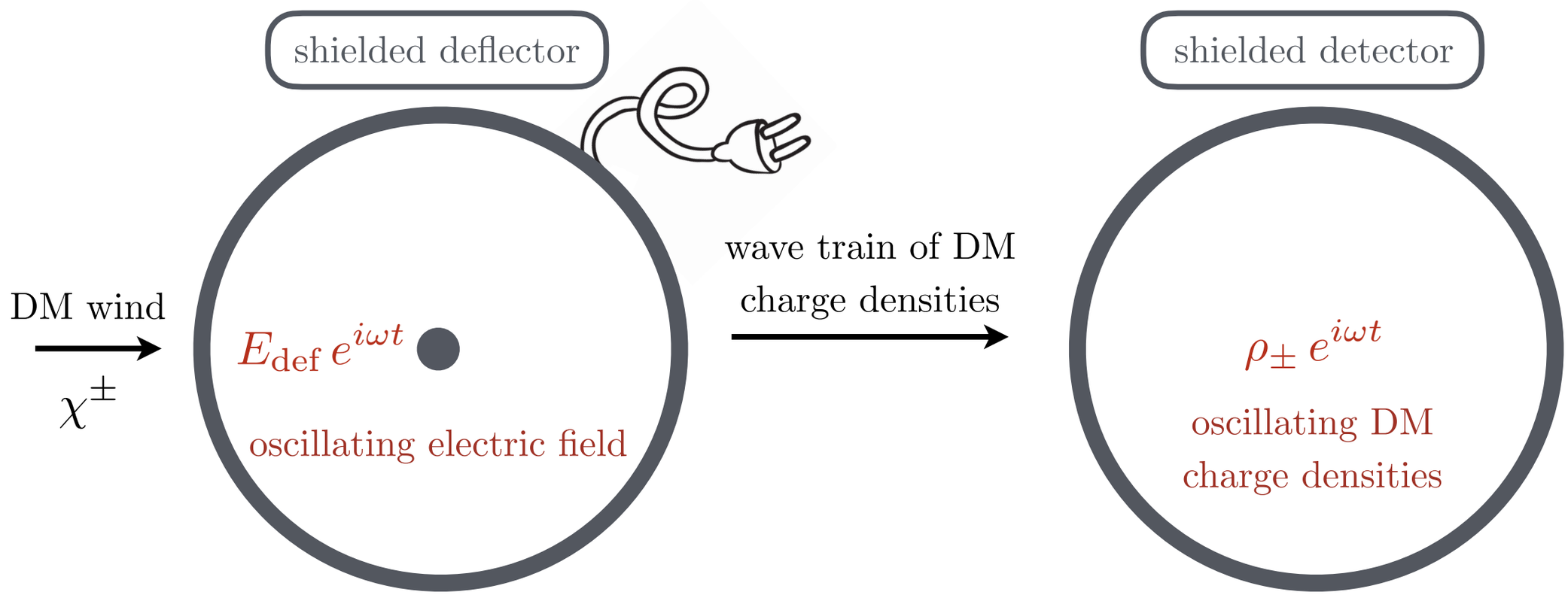
Direct *Deflection*



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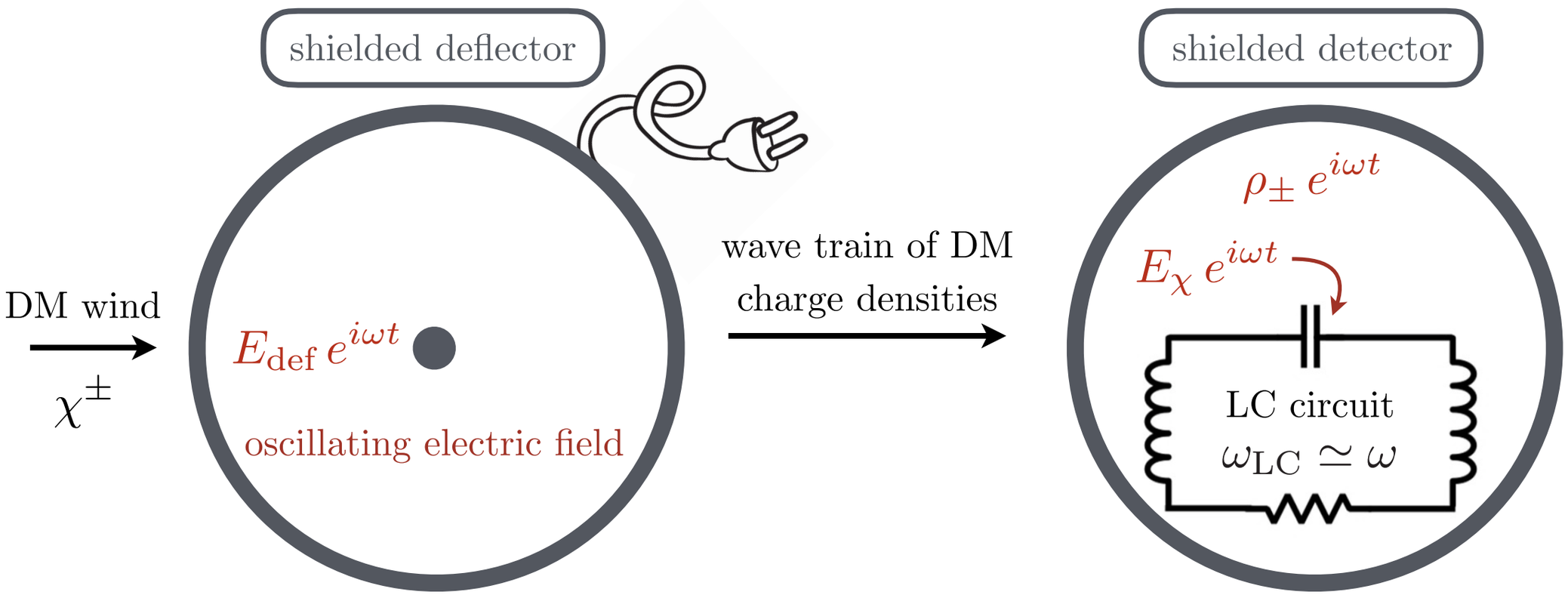


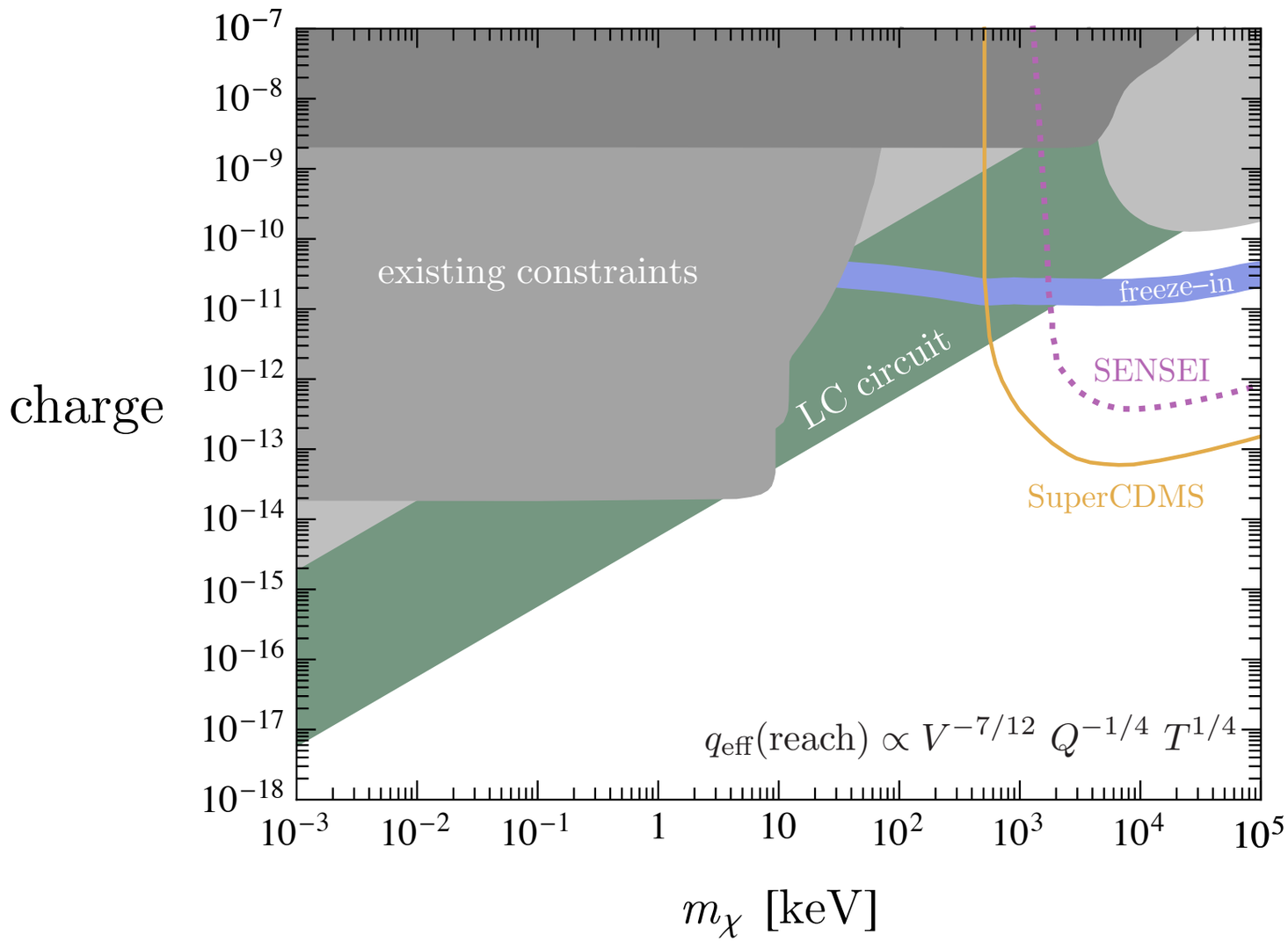
~ DM Radio with fixed frequency and electric pickup

~Debye screening

$$\rho_{\pm} \propto \left(\frac{\text{charge}}{m_{\chi}\, v_{\chi}}\right)^2$$

no kinematic barrier,
small momentum enhancement

Direct *Deflection*



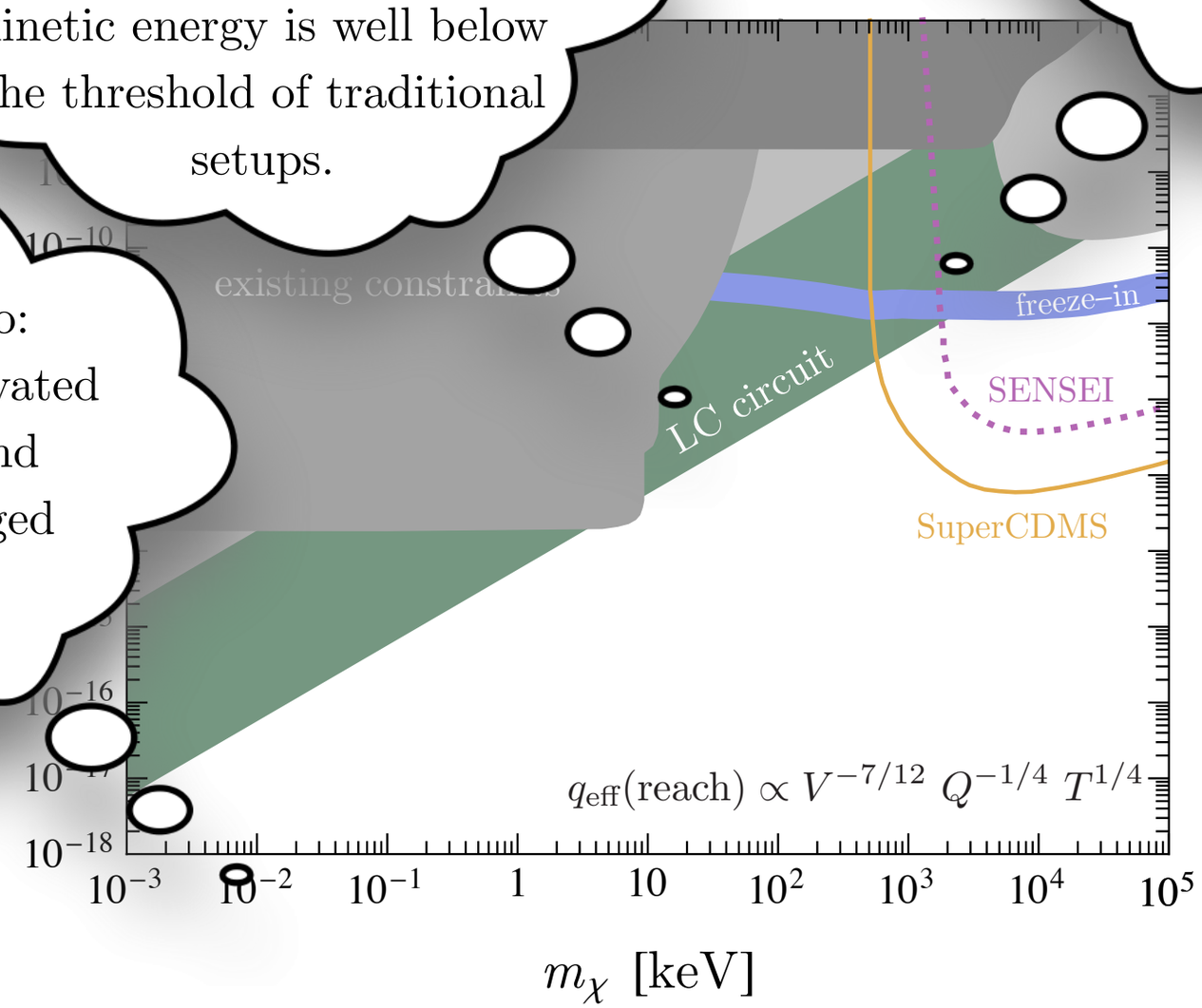
New parameter space within reach (ultimate sensitivity) for 0.1 (10) m³ volumes, 10^3 (10^7) Q-factors, and 4 K (100 mK) temperatures.

Takeaway

Direct *Deflection* opens up entirely new ways to look for dark matter whose kinetic energy is well below the threshold of traditional setups.

Technology driven by quantum sensing is ideally suited to detect small collective effects in the dark matter background.

Unique coverage to: sub-MeV cosmo-motivated parameter space and ultralight millicharged dark matter.



Discovering the Dark Universe

New Physics with SRF Cavities

New Physics with Direct *Deflection*

New Questions

superconducting cavities

I.

LC circuits

II.

Future

III.

Ways Forward

Discovering the Dark Universe

New Physics with SRF Cavities

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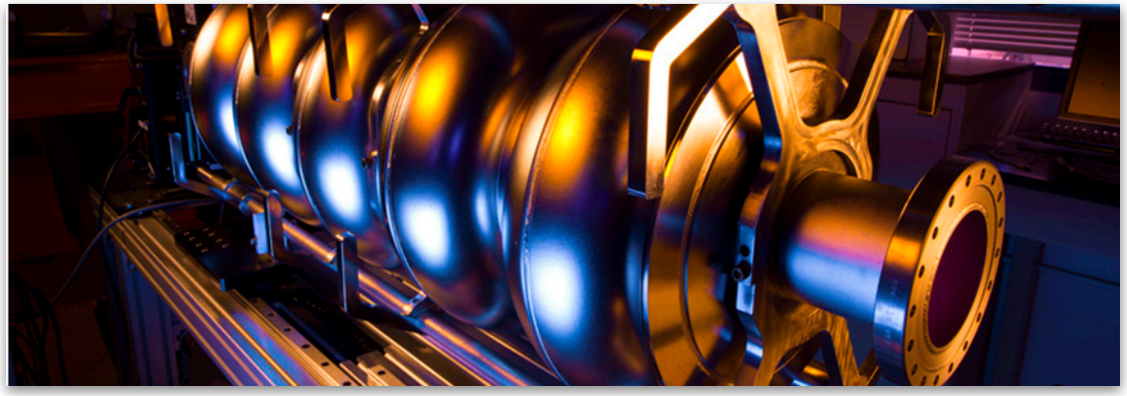
SRF Cavities

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

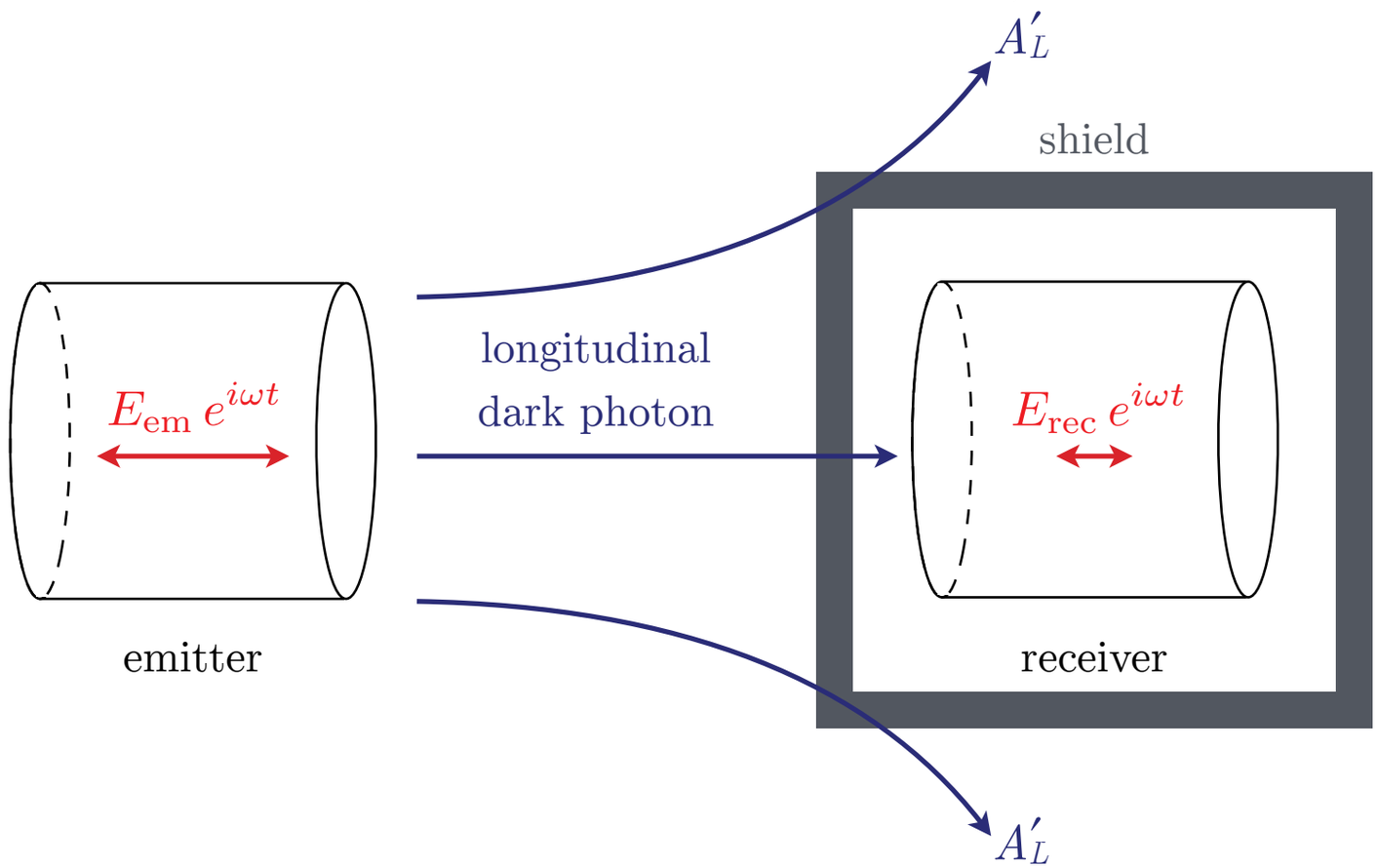
Such as:

- "Frequency Conversion" from high-frequency gravitational waves.
- New physics for free at DarkSRF: Standard Model photon mass, ultralight millicharges, strongly-coupled relics.



New Physics for Free at DarkSRF

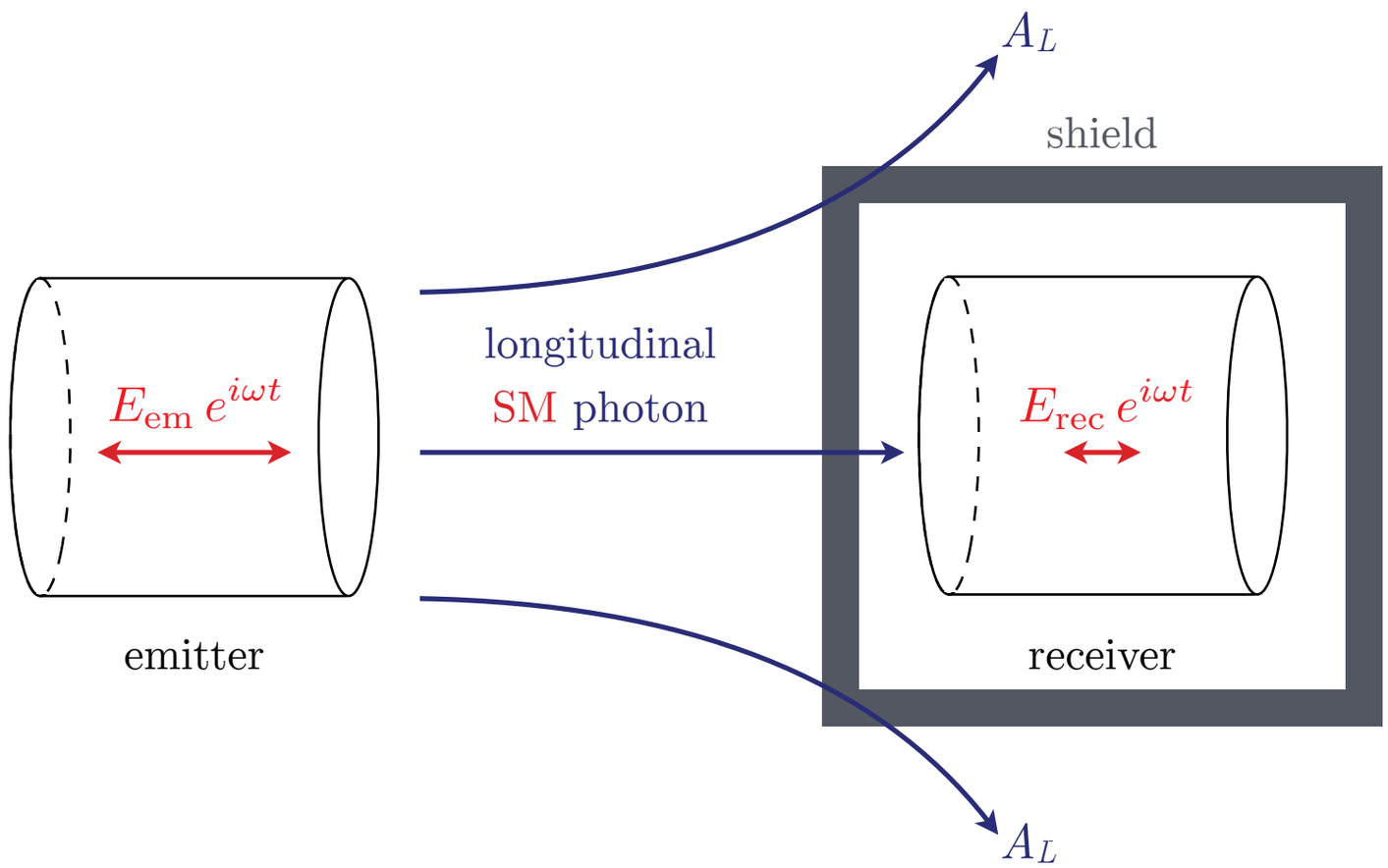
(current physics, current setup)



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

New Physics for Free at DarkSRF: SM Photon Mass

(new* physics, current setup)



<u>a longitudinal mode is a longitudinal mode</u>

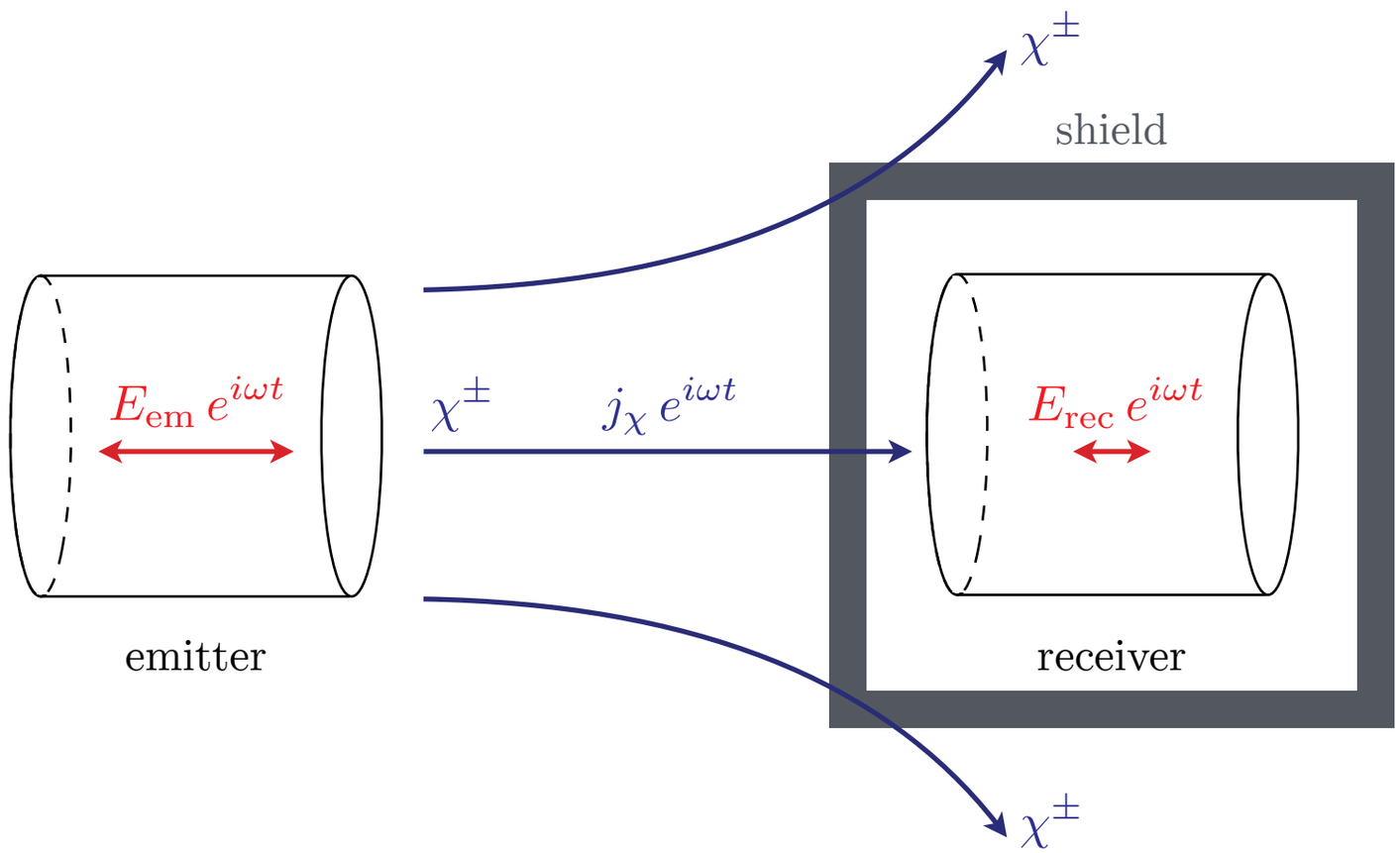
$$m_\gamma \lesssim 6 \times 10^{-16}\ \text{eV} \simeq 10^{-48}\ \text{g}$$

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

A. Berlin, A. Hook

New Physics for Free at DarkSRF: Ultralight Millicharges

(new physics, current setup)



Schwinger pair-production of millicharged particles

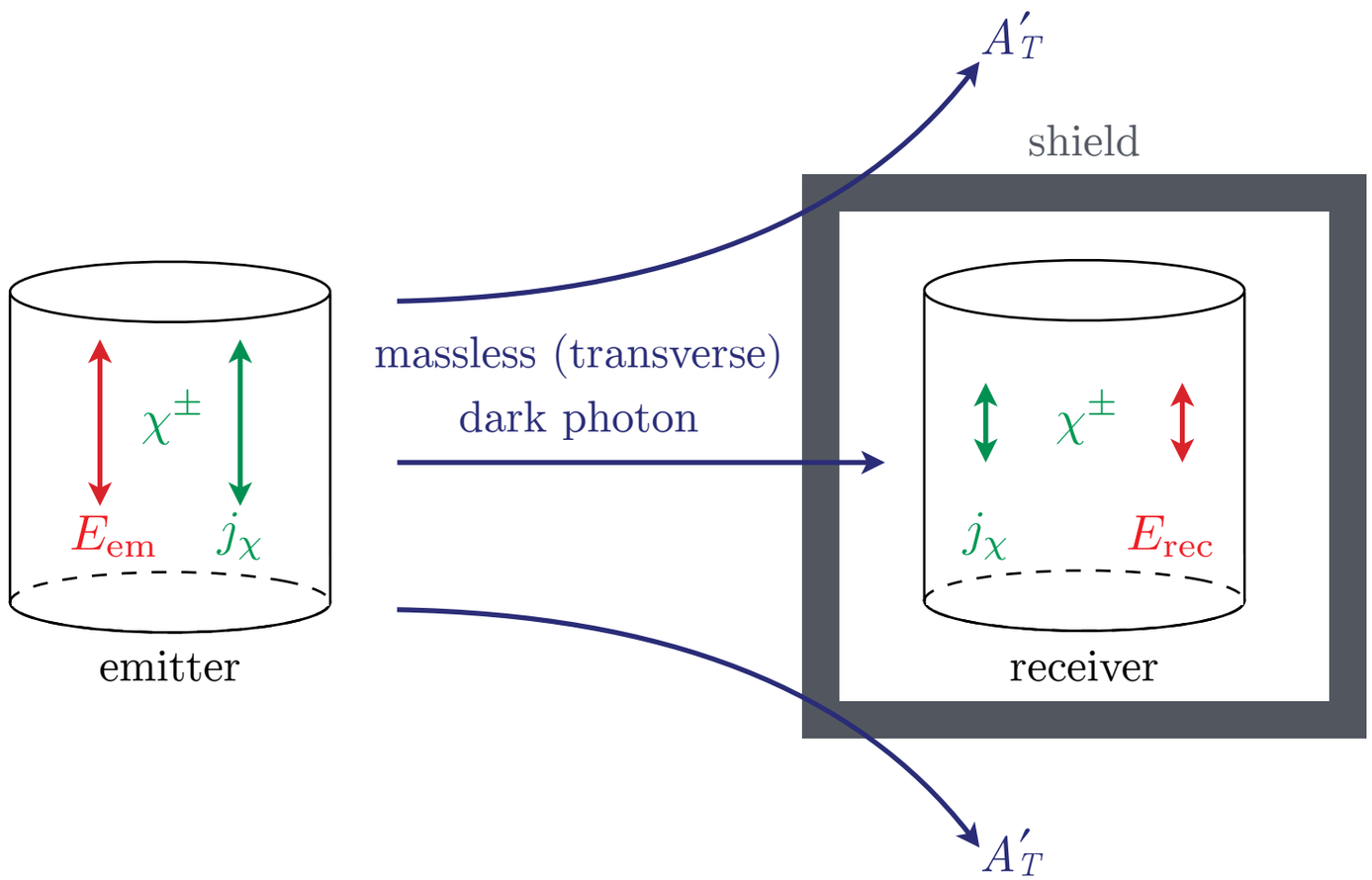
$$E_{\rm cr} \sim 50\ {\rm MV\ m^{-1}} \times \left(\frac{m_\chi}{\rm meV}\right)^2 \left(\frac{q_\chi}{10^{-7}}\right)^{-1}$$

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

A. Berlin, A. Hook, PRD 2020

New Physics for Free at DarkSRF: Strongly-Coupled Relics

(new physics, slightly modified setup)



<u>Strongly-coupled dark matter subcomponents</u>

Above the direct detection "ceiling," where traditional direct detection is useless

Discovering the Dark Universe

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New Physics with Direct *Deflection*

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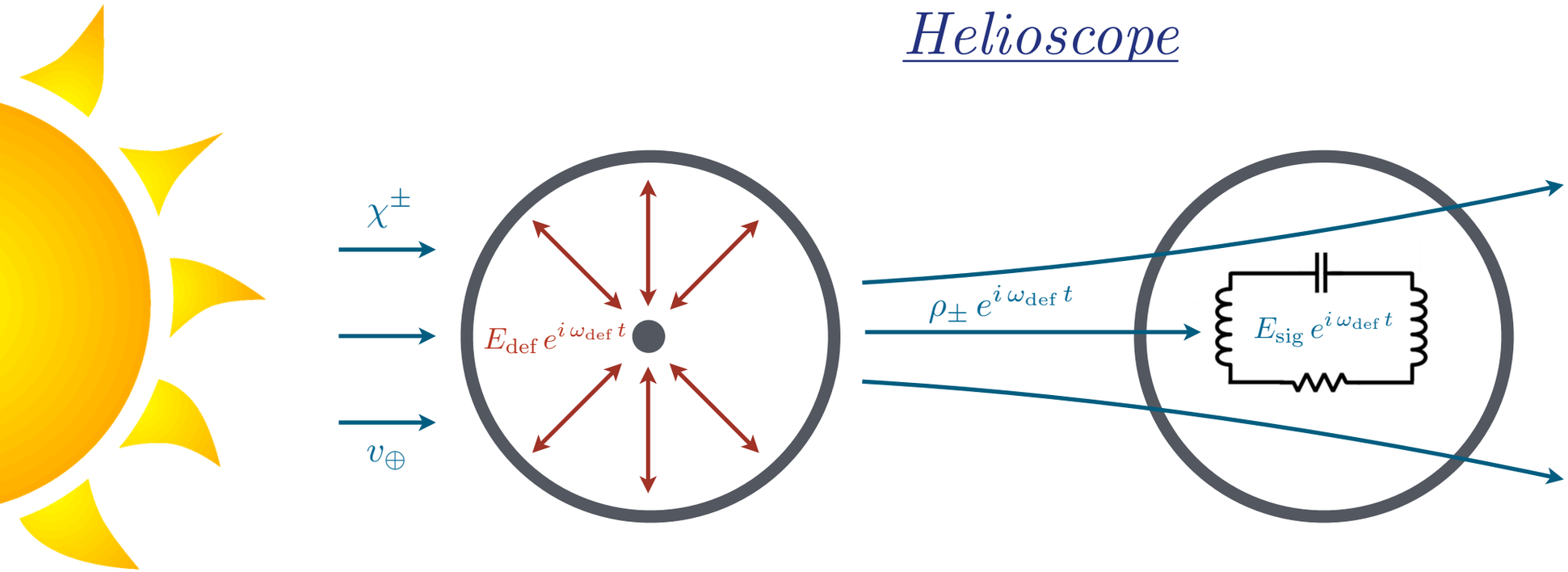
III.

Ways Forward

Direct *Deflection*

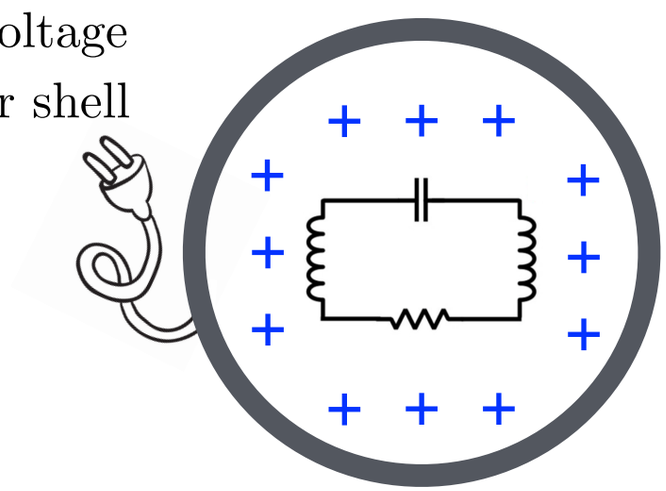
Helioscope



Only lab setup able to look for millicharged particles emitted from the solar interior.

Strongly-Coupled Relics

drive voltage
of outer shell



Other Types of Interactions

spin-coupled
spinning sample of polarized spins
(~ARIADNE)

Discovering the Dark Universe

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New Physics with Direct *Deflection*

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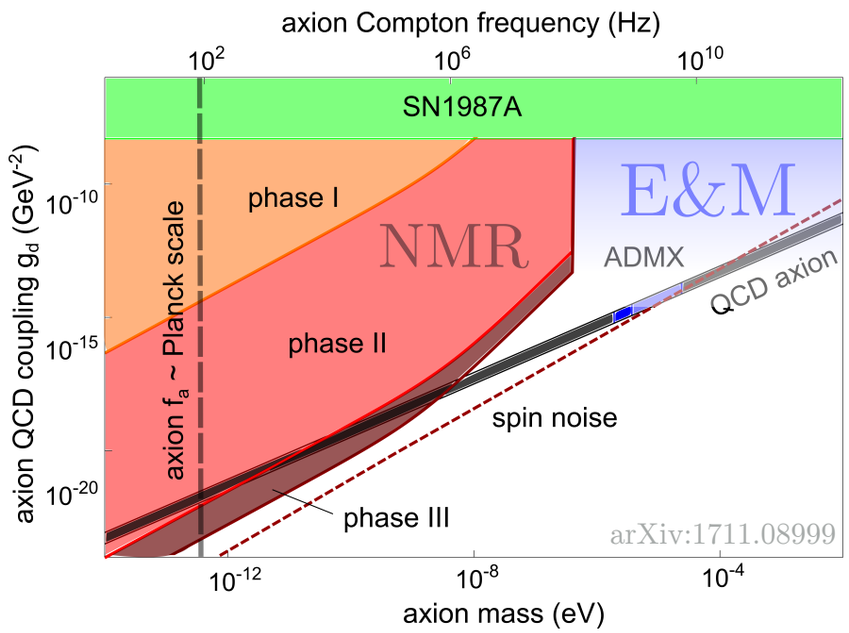
What is Next?

Variety of Axion Couplings

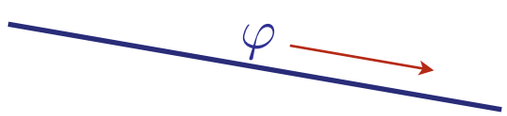


overcoming B-field challenges at > 100 MHz with new techniques

polarized spins coupled to E&M detectors:

1) axion induces oscillating electric dipole
2) oscillating polarization density
3) oscillating displacement current coupled to E&M

Direct Detection of Dark Energy



$m_\varphi \lesssim 10^{-33}$ eV

$$w \simeq \frac{\dot\varphi^2/2 - V}{\dot\varphi^2/2 + V} \in [-1, -0.95]$$

Can we detect the small amount of kinetic energy?

$$\mathscr{L} \sim \frac{\partial_\mu \varphi}{f_\varphi}\, \bar f \gamma^\mu \gamma^5 f + \frac{\varphi}{f_\varphi}\, F\tilde F \quad , \quad \dot\varphi \lesssim \mathrm{meV}^2$$

Cosmic Neutrino Background

(L. Stodolsky 1975)

$$\mathscr{L} \sim G_F\ \bar\nu\gamma^\mu\nu\ \bar e\gamma^\mu\gamma^5 e$$

$$H \sim G_F\,(n_\nu - n_{\bar\nu})\ (\vec v_e \cdot \vec\sigma_e)$$

Can we detect the neutrino-induced torque?

Outlook

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?

Superconducting cavities

Superconducing cavities can explore axion dark matter with Compton wavelengths many orders of magnitude larger than terrestrial scales and energy scales near that of Grand Unified Theories.

LC circuits

LC circuits can detect the small effects from collective excitations of very light particles, corresponding to masses well below the kinematic thresholds of traditional detectors.

Exciting Opportunities Ahead

physics BSM for DarkSRF,
variety of axion couplings,
high-frequency gravitational-waves,
cosmic neutrino background...