Axion Production and Detection using Superconducting RF Cavities

Vijay Narayan

with

Ryan Janish, Surjeet Rajendran, and Paul Riggins

[in preparation]

New light boson?

Many hints for BSM (DM, inflation, quantum gravity, ...)

Where to look? Cast a wide net

Even if new physics is at very high energies, there can be low energy observables

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Even if new physics is at very high energies, there can be low energy observables

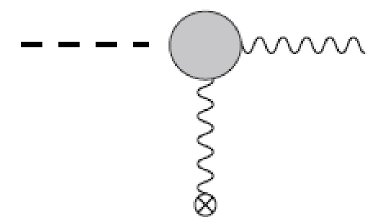
Axions (neutral pseudoscalar) are a generic expectation

$$\mathcal{L} \supset \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} (\partial_\mu a)^2 - \frac{1}{2} {m_a}^2 a^2 + \frac{1}{4} g a F_{\mu\nu} \widetilde{F}^{\mu\nu}$$

Light and weakly-coupled to EM. How can we detect?

Axion EM Searches

Coherent axion-photon conversion in static B_0



$$P_{a\gamma} \sim 10^{-17} \left(\frac{g}{10^{-10}\ \mathrm{GeV}^{-1}}\right)^2 \left(\frac{B_0}{5\ \mathrm{T}}\right)^2 \left(\frac{L}{10\ \mathrm{m}}\right)^2$$

Oscillation length suppressed for $qL \sim m_a^2 L/\omega \gtrsim 1$

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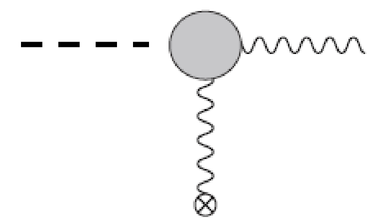

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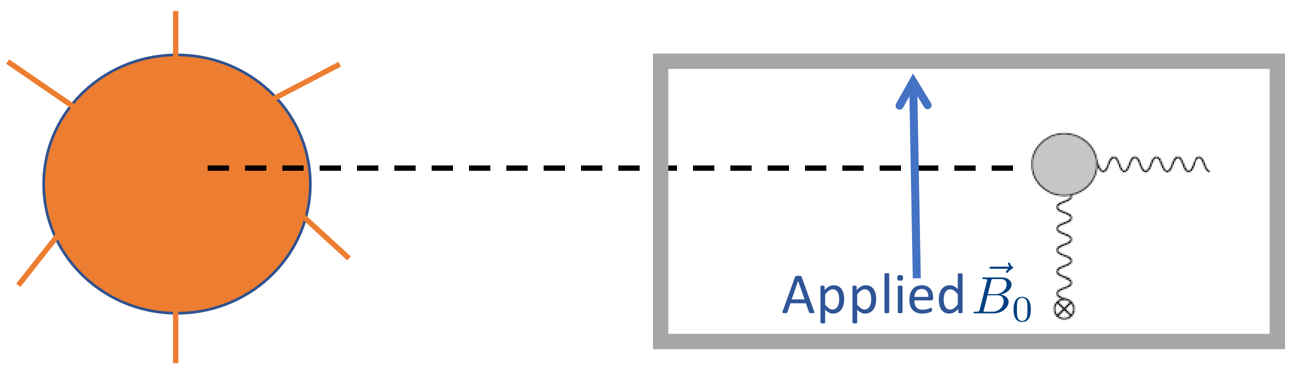
“Sun shining through Wall”



[Irastorza et al, ‘17]

CAST: $g < 7.10^{-11}$ GeV^{-1} for $m_a <$ eV

Strongest limits – comparable to stellar cooling bounds

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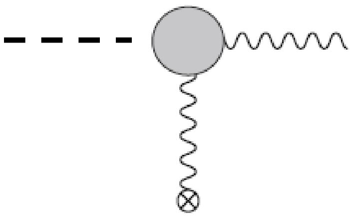

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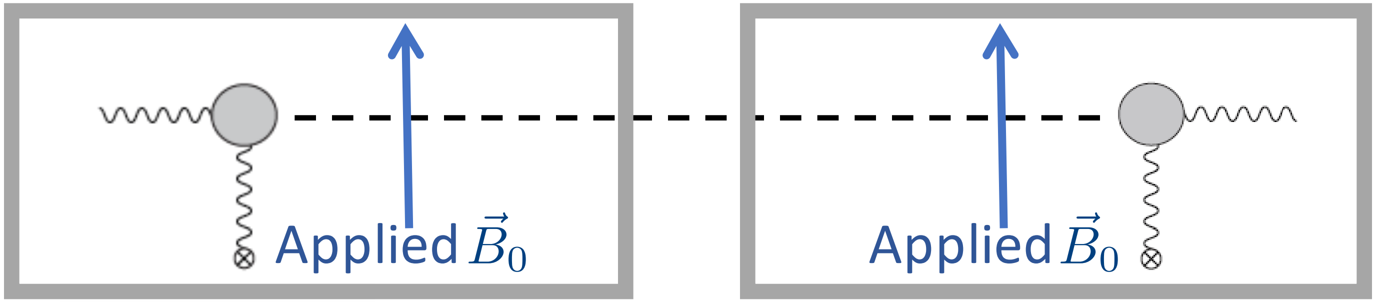

[van Bibber et al '87]

Possible at optical or radio frequencies

Key point: need large EM fields to overcome small coupling

Optical vs. RF

[..., Graham et al ‘16]

Status of LSW

Optical vs. RF

[..., Graham et al '16]

Status of LSW

Optical Cavities

ω, L^{-1} are independent

ALPS: $g < 5.10^{-8}$ GeV^{-1}
for $m_a < 5.10^{-4}$ eV

Next generation with L ~ 100 m
ALPS II (projected): $g < 2.10^{-11}$ GeV^{-1}

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RF Cavities

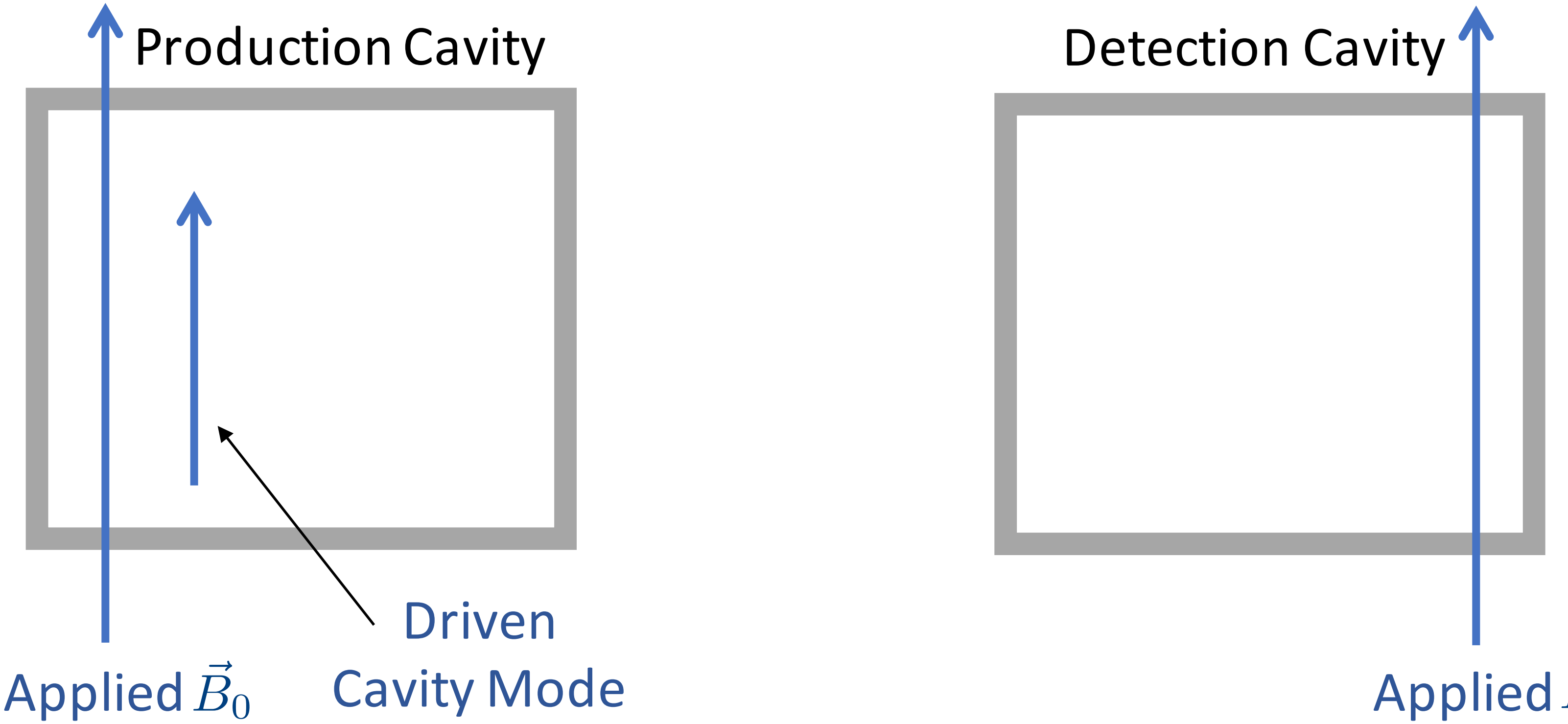
$\omega, L^{-1} \sim \mathcal{O}(\mathrm{GHz})$

CROWS: $g < 7.10^{-8}$ GeV^{-1}
for $m_a < 5.10^{-6}$ eV

This work: possibilities with superconducting RF technology?

LSW with RF Cavities

[Hoogeveen, '92]



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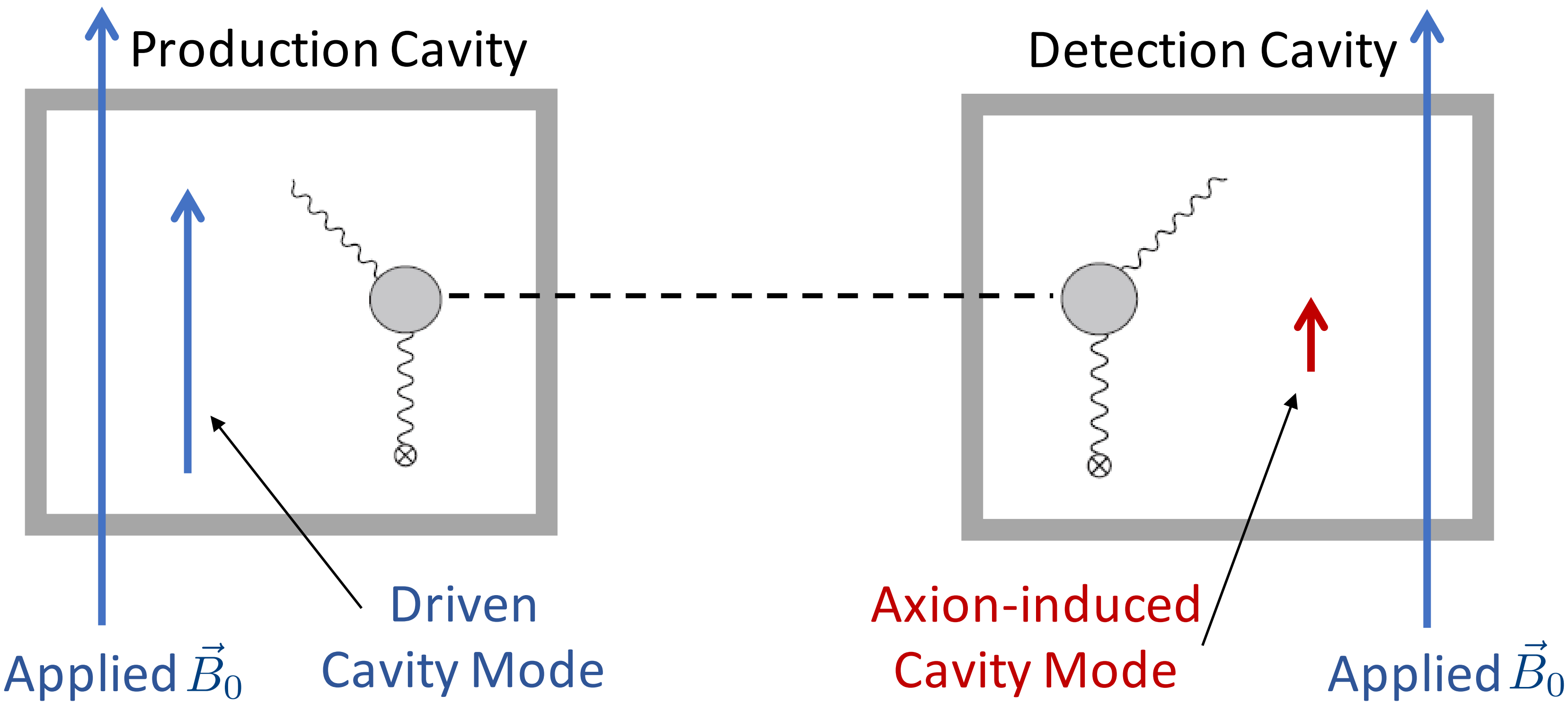

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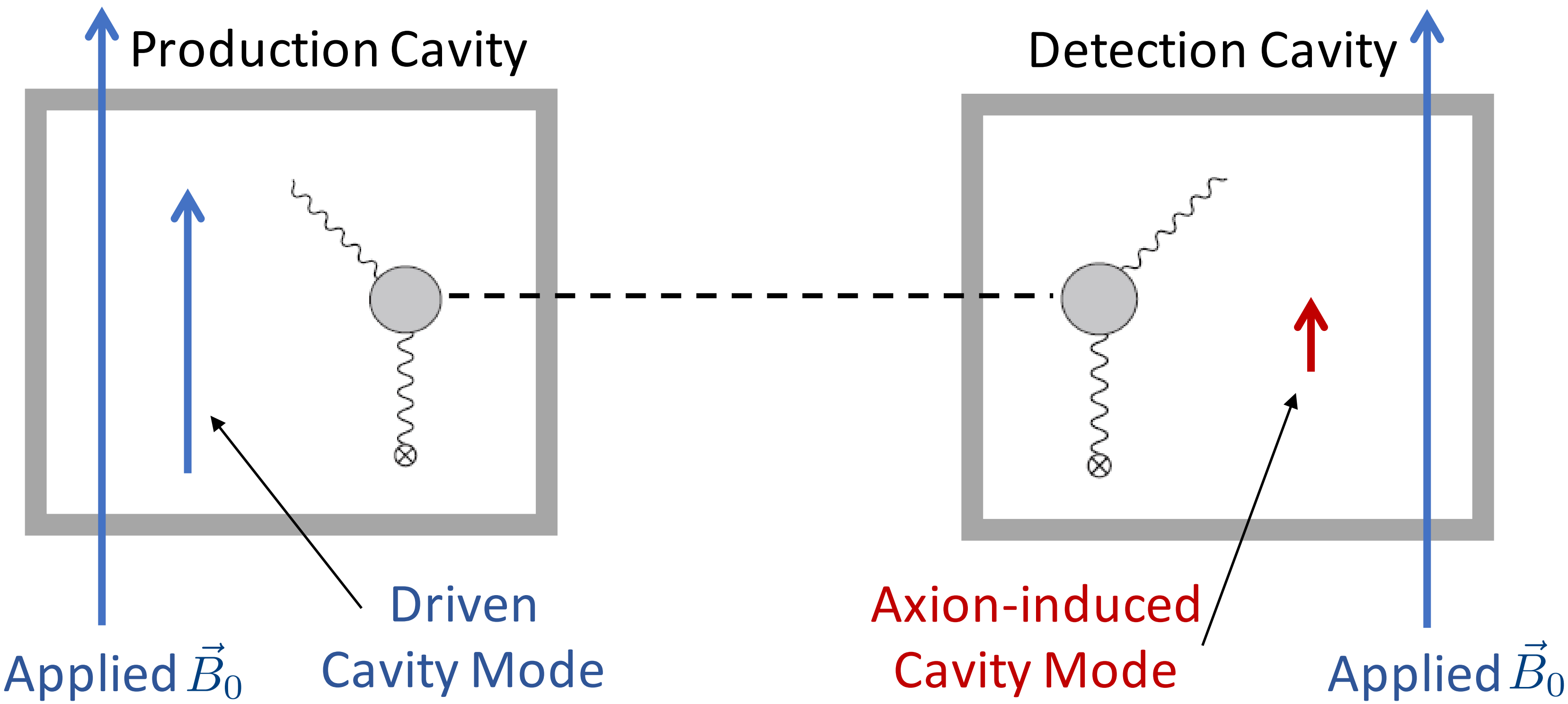
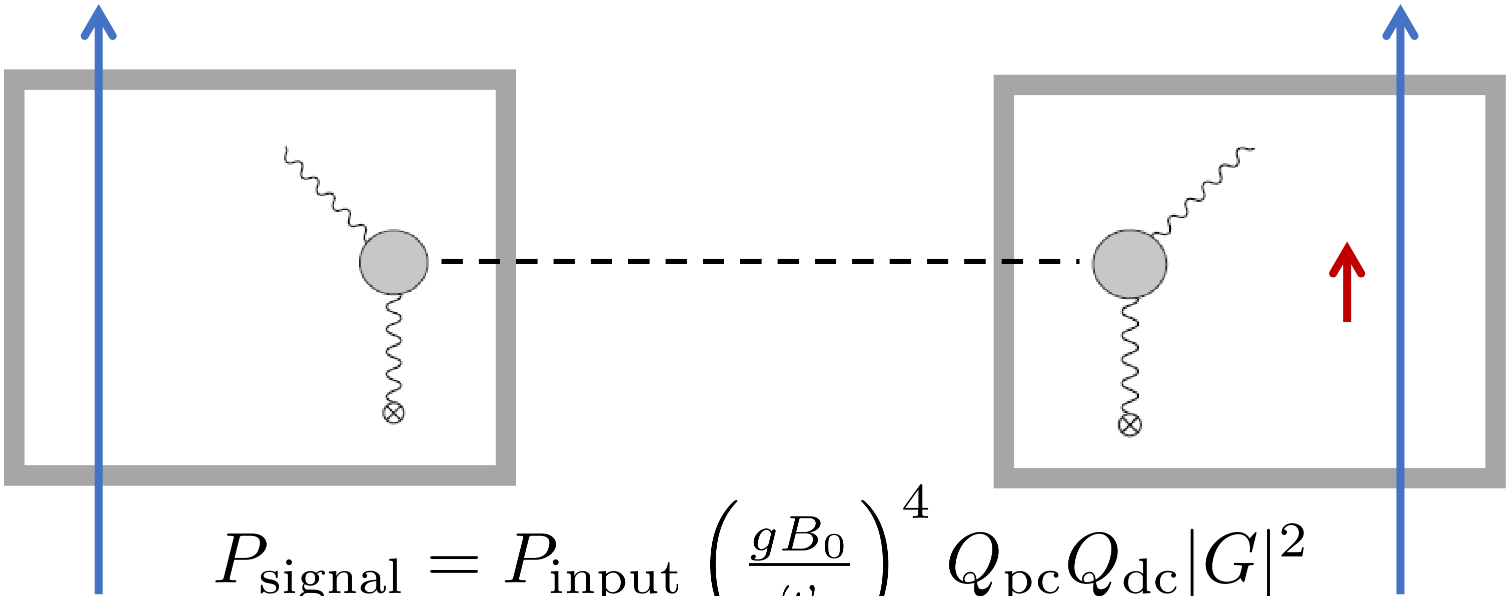


$$P_{\rm signal} = P_{\rm input} \left(\frac{g B_0}{\omega} \right)^4 Q_{\rm pc} Q_{\rm dc} |G|^2$$

O(1) form factor

Exponential cut off for $m_a > \omega$

LSW with SRF Cavities



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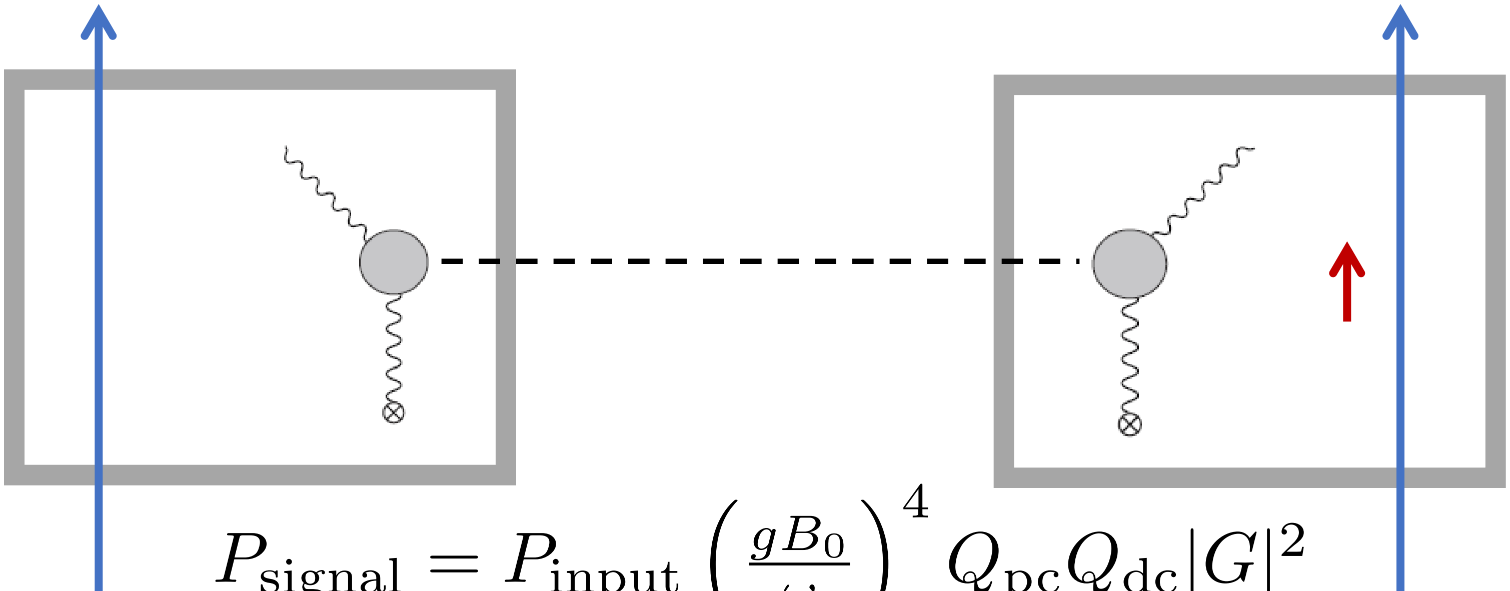
Normal conducting RF $Q \sim 10^5 - 10^6$

Superconducting RF $Q \sim 10^{10} - 10^{11}$

LSW with SRF Cavities



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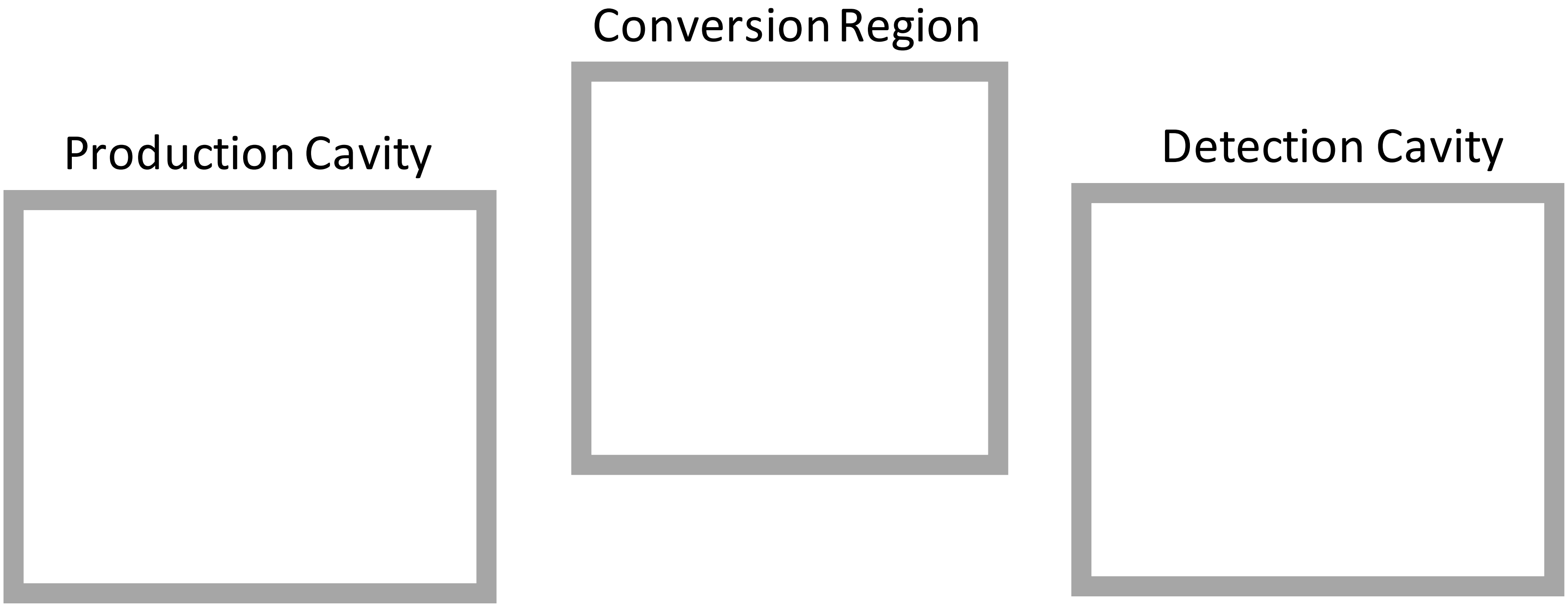
Superconducting RF $\quad Q \sim 10^{10} - 10^{11}$

B > O(0.2 T) critical field degrades SRF quality factor

Challenge: re-design such that large B and high-Q can coexist

New Design for LSW with SRF



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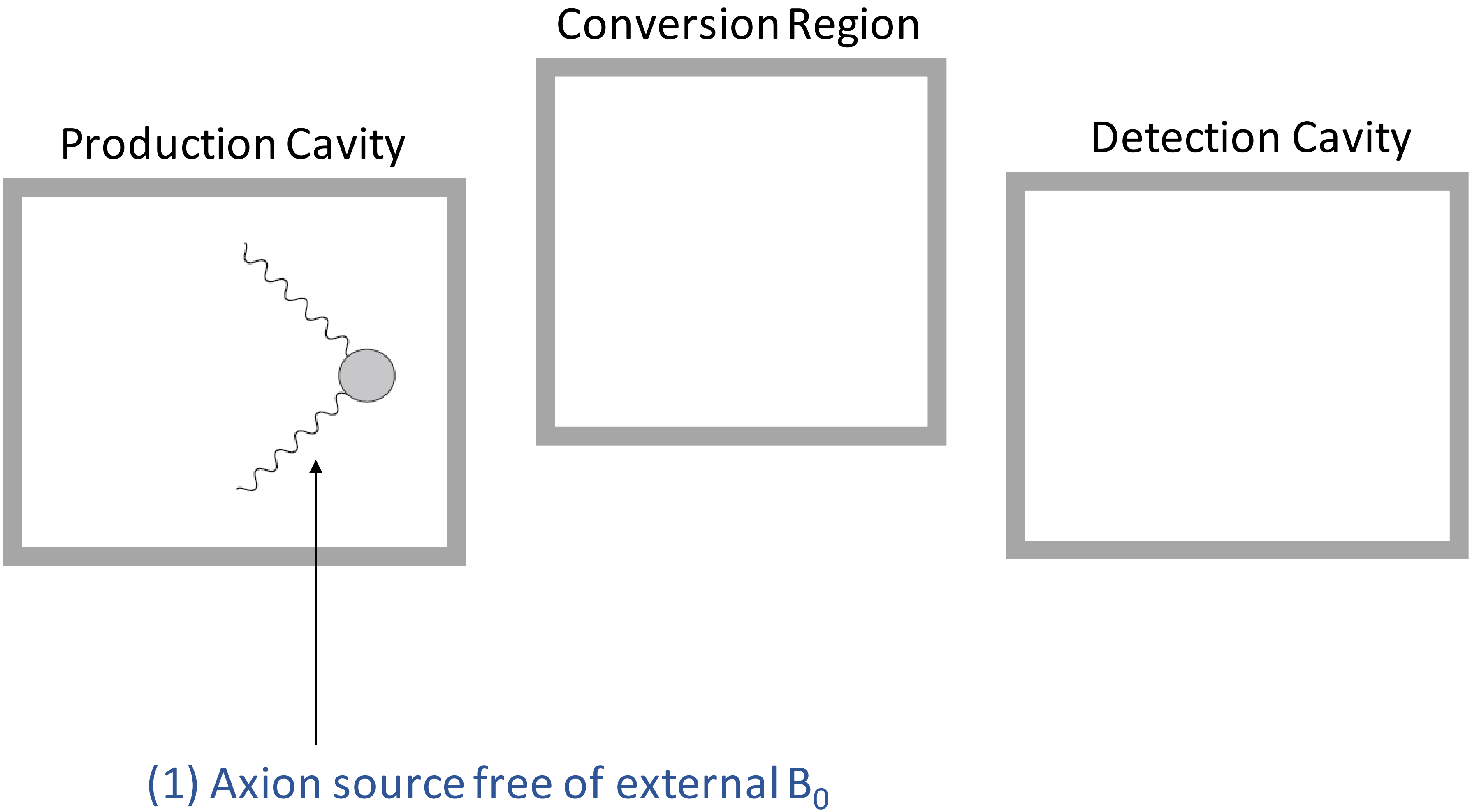

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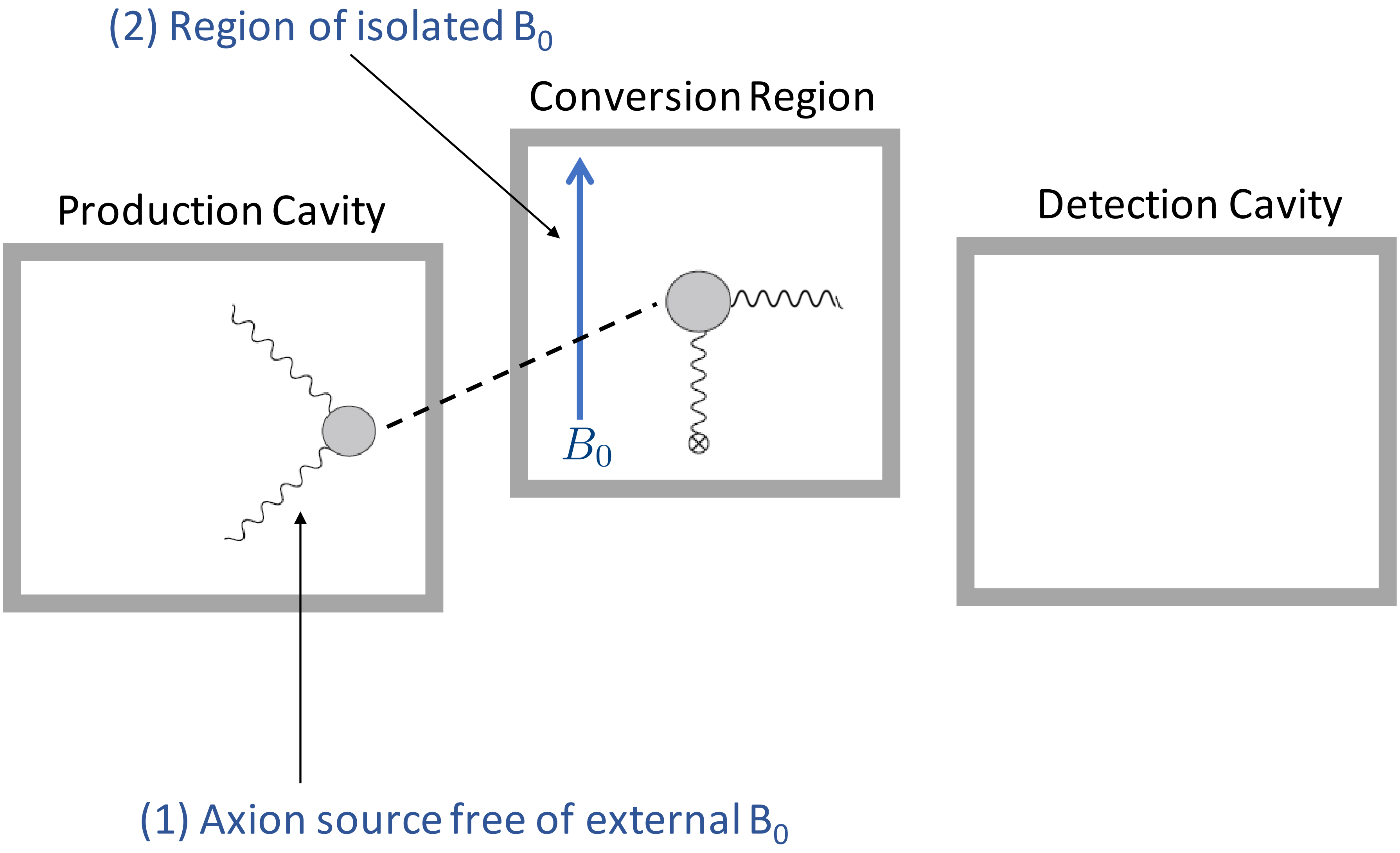

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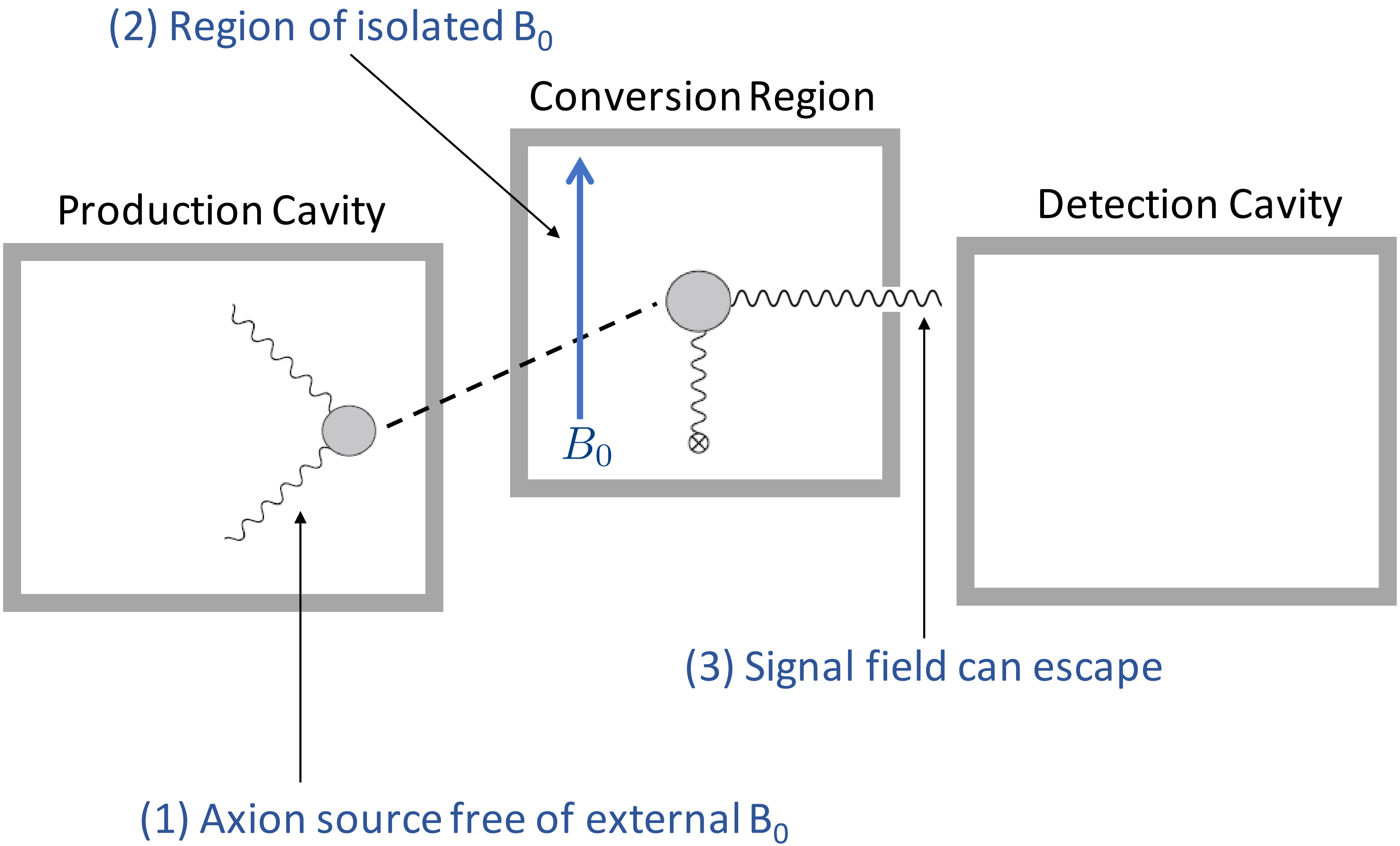

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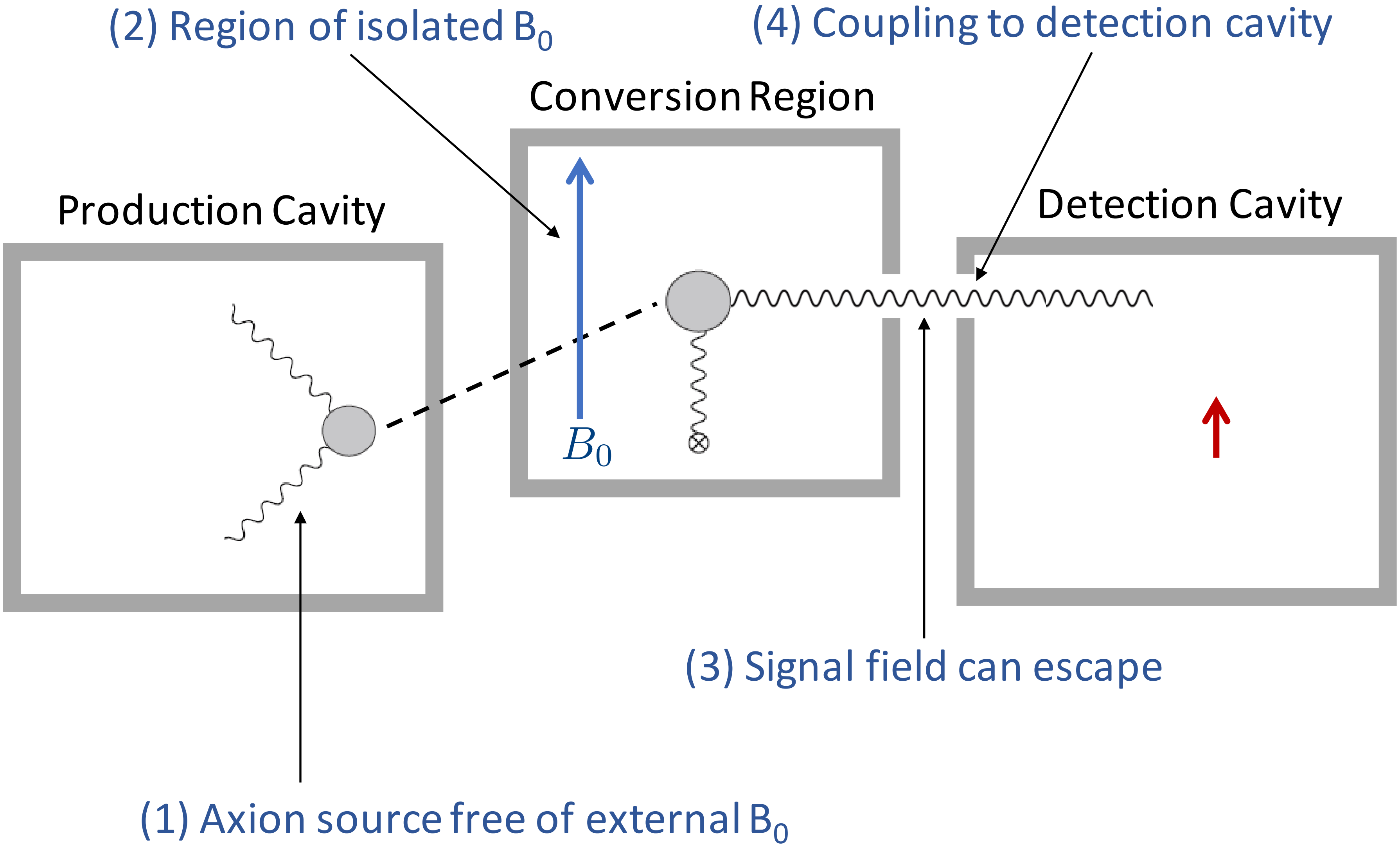

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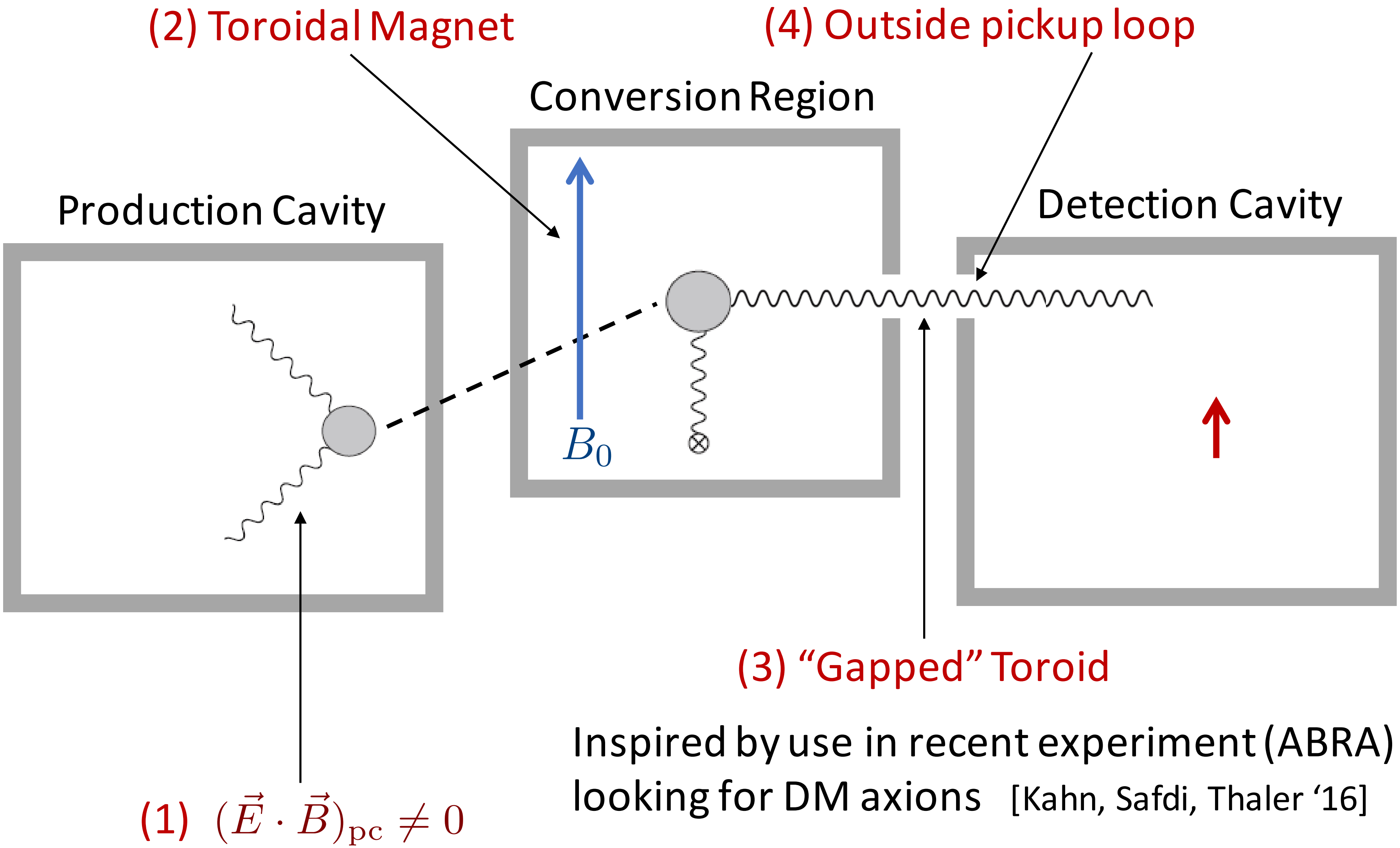

Inspired by use in recent experiment (ABRA) looking for DM axions [Kahn, Safdi, Thaler '16]

Axion Electrodynamics

Axion EOM: $$(\Box + m_a^2)a(x) = -g\vec{E}\cdot\vec{B}$$

Modifies Maxwell: $$\vec{\nabla}\cdot\vec{E} = -g\vec{B}\cdot\vec{\nabla}a$$

$$\vec{\nabla}\times\vec{B} = \frac{\partial\vec{E}}{\partial t} - g\left(\vec{E}\times\vec{\nabla}a - \vec{B}\frac{\partial a}{\partial t}\right)$$

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Axion Production $\Rightarrow$ $a(x) = -ge^{i\omega t}\int_{\mathrm{pc}} d^3y \;\; \frac{e^{ik|\vec{x}-\vec{y}|}}{4\pi|\vec{x}-\vec{y}|}(\vec{E}\cdot\vec{B})$

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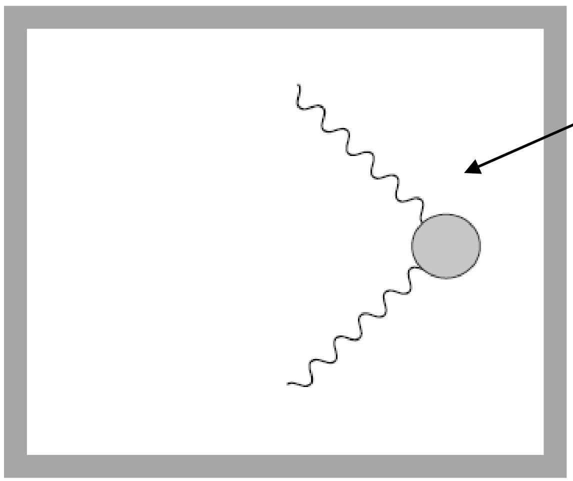
Conversion in B_0 $\Longrightarrow$ "Effective" current $\vec{J}_{\mathrm{eff}} = g\vec{B}_0\frac{\partial a}{\partial t}$

Production with SRF

(1) Axion source without external B_0



Multiple cavity modes such that E.B not identically vanishing

Fundamentally limited by SRF EM field strength:

$$(\vec{E}\cdot\vec{B})_{\rm pc} \lesssim (0.2\ {\rm T})^2$$

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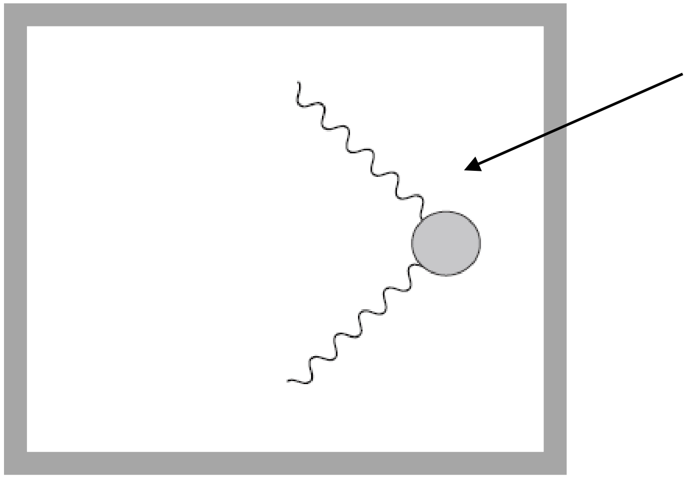

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$$(\vec{E}\cdot\vec{B})_{\rm pc} \lesssim (0.2\ {\rm T})^2$$

Compare with normal conducting RF with external static B_0

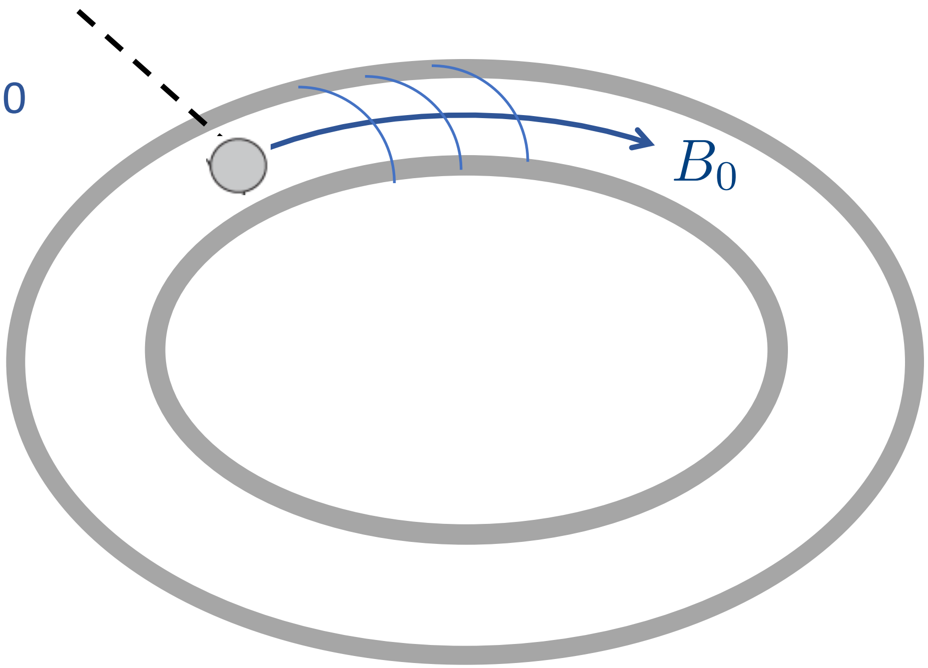
$$(\vec{E}\cdot\vec{B}) \sim (0.1\ {\rm T})^2 \left(\frac{P_{\rm input}}{100\ {\rm W}}\right)^{\frac{1}{2}} \left(\frac{Q_{\rm pc}}{10^5}\right)^{\frac{1}{2}} \left(\frac{B_0}{5\ {\rm T}}\right)$$

Real advantage of high-Q is on detection side!

Conversion Region

(2) Confine large static B_0

Generated by wrapped DC current-carrying superconducting wires



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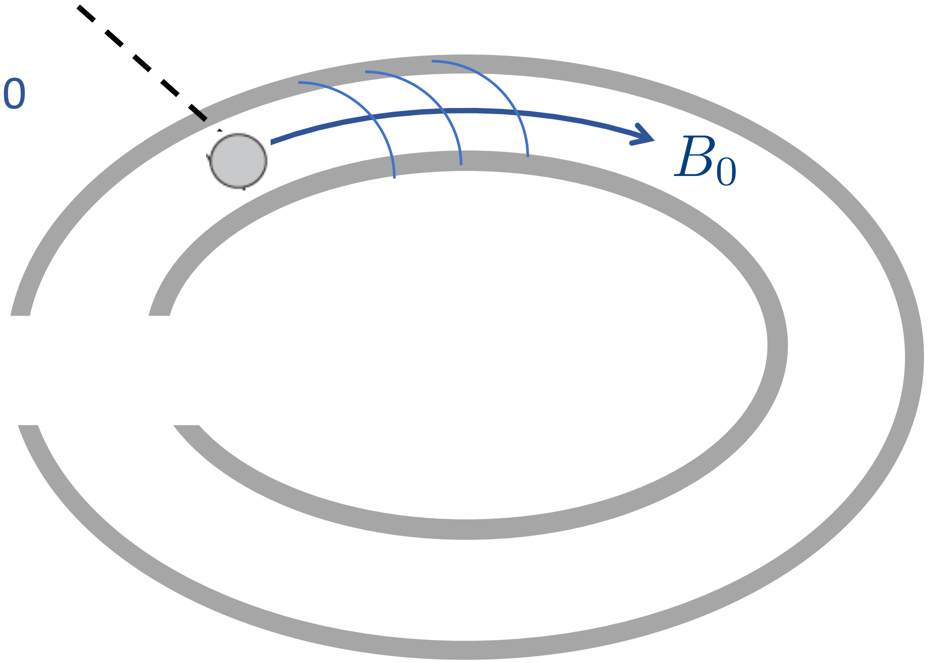

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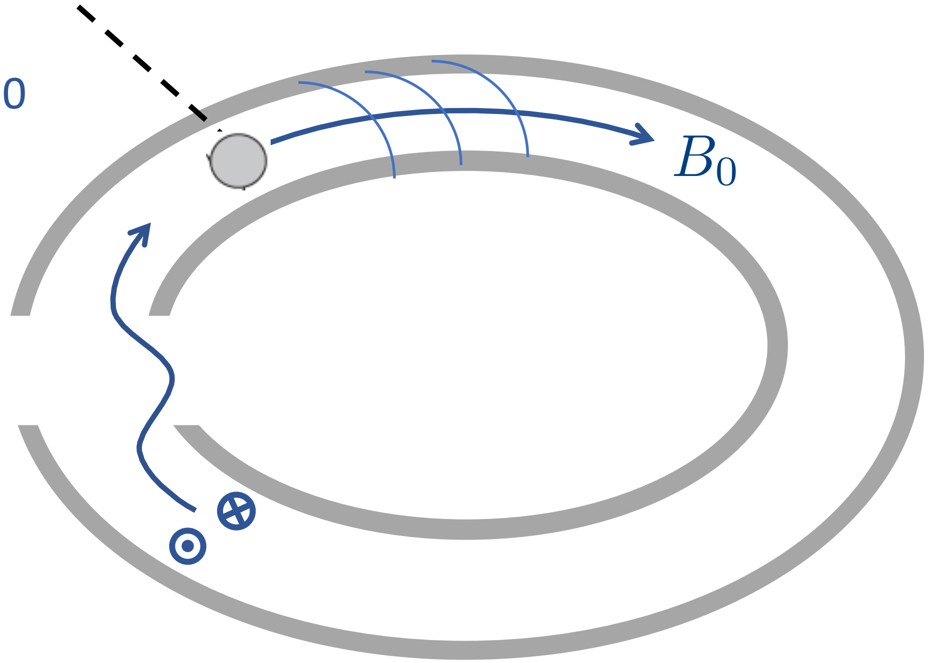

Any leakage of B_0 outside due to fringe effects, can be made small

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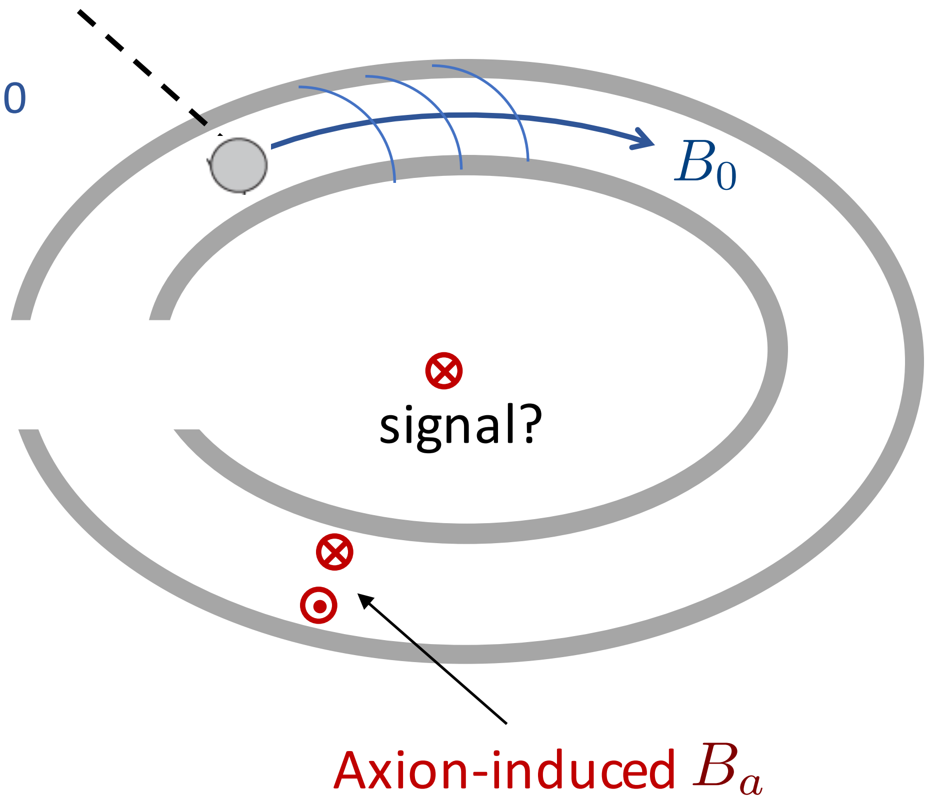

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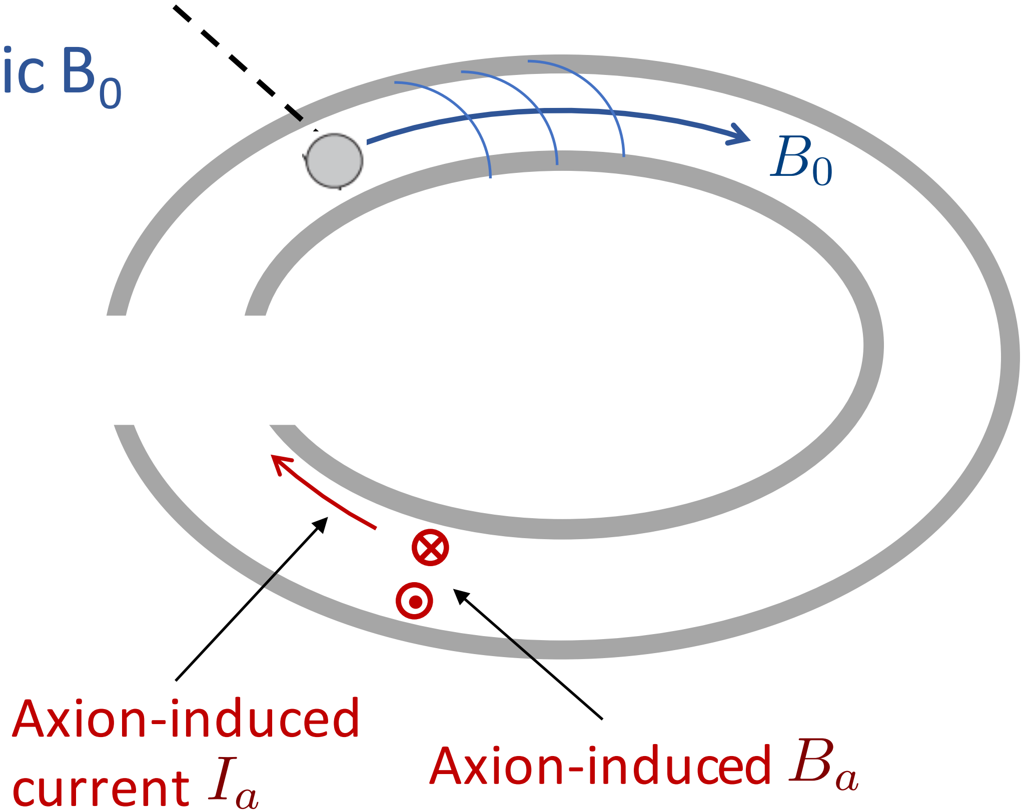

Meissner effect: B_a is screened outside
Sets up super-current I_a on inner surface

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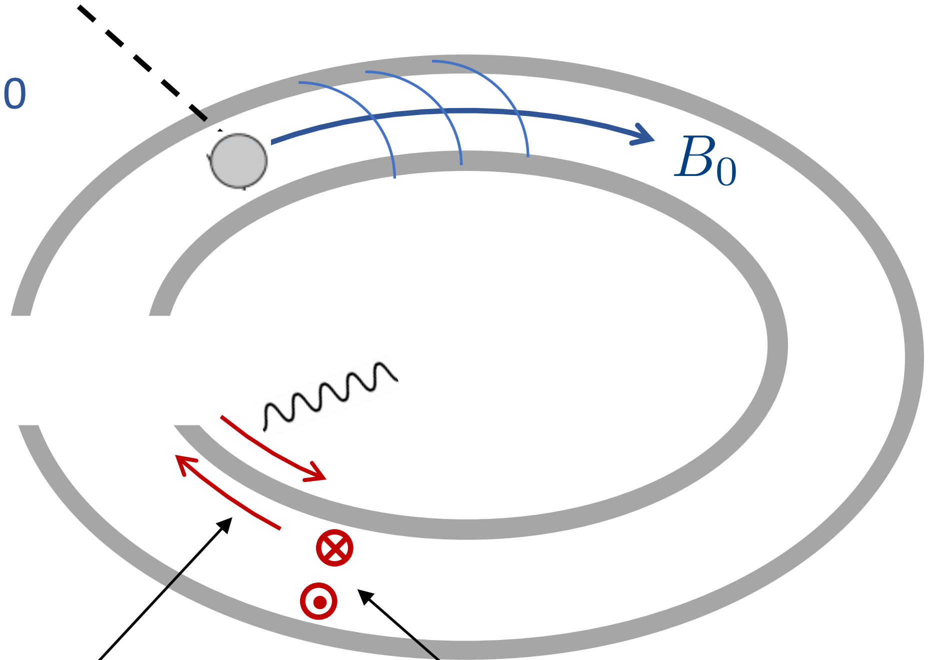

(3) Allow RF signal to propagate out

Meissner effect: B_a is screened outside
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For small (quasi-static) frequencies:
I_a returns along outer surface

Signal is unaffected!

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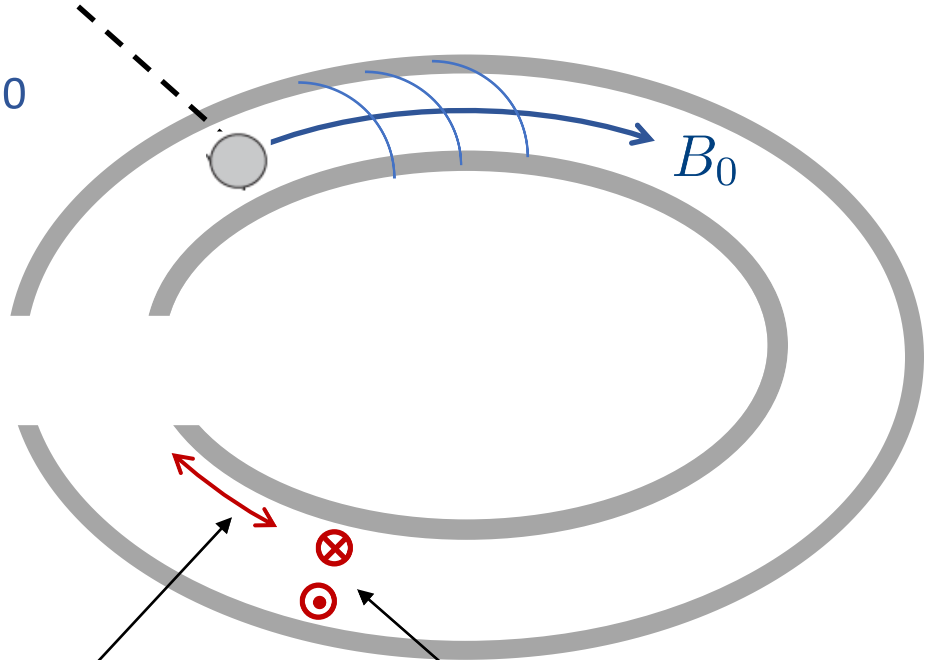

Meissner effect: B_a is screened outside
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For sufficiently large frequencies:
I_a becomes spatially modulated

Signal is suppressed!

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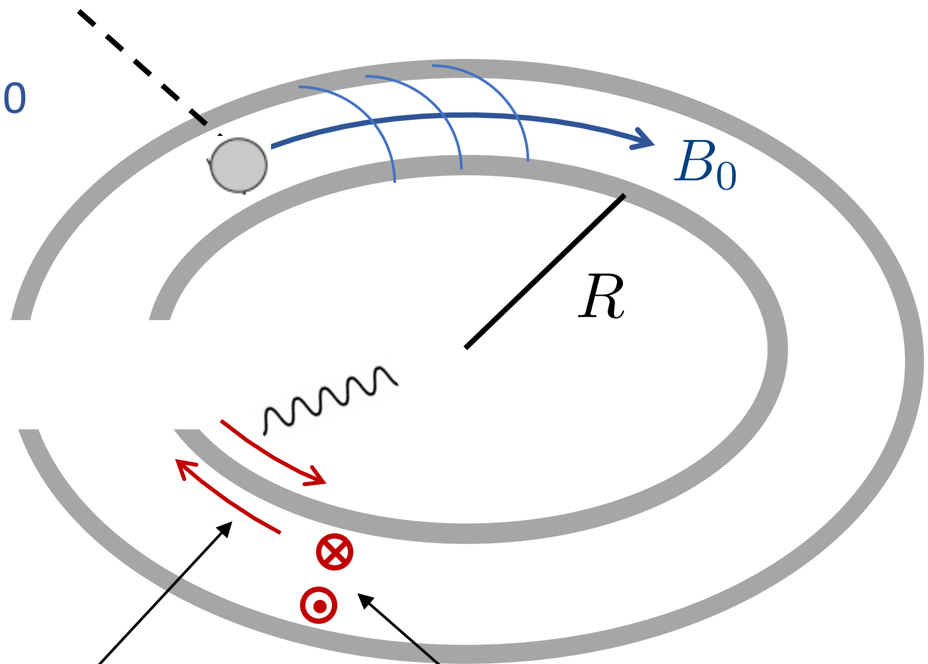


Meissner effect: B_a is screened outside
Sets up super-current I_a on inner surface

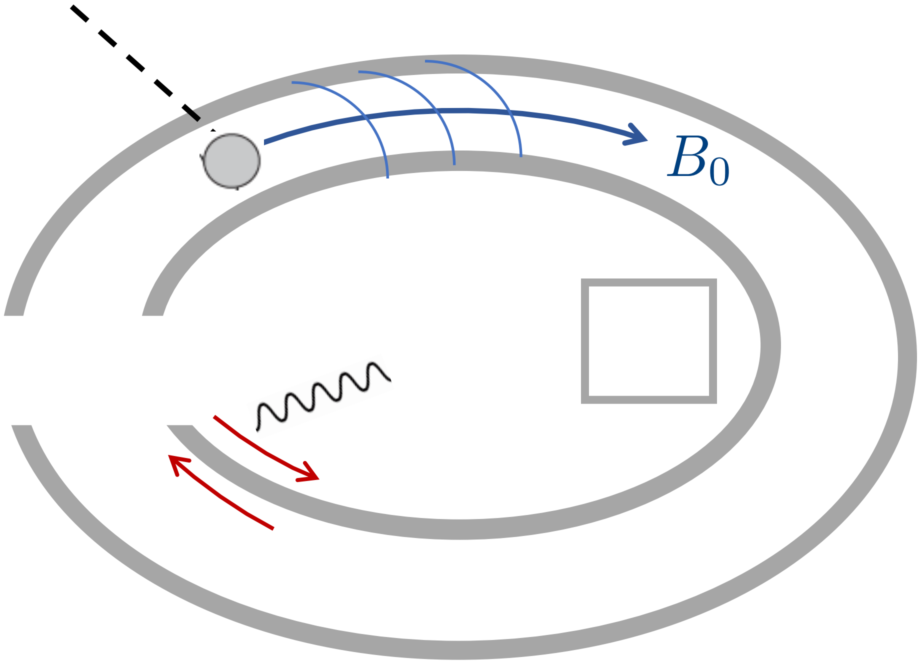
Critical scale set by toroid radius:

$$R \sim \omega^{-1}$$

Signal propagates O(1)

Signal Pickup

(4) Couple signal to SRF detection cavity



$$I_a \sim 10^{-23}\ \mathrm{A} \left(\frac{g}{10^{-11}\ \mathrm{GeV}^{-1}}\right)^2 \left(\frac{B_{\mathrm{pc}}}{0.2\ \mathrm{T}}\right)^2 \left(\frac{B_0}{5\ \mathrm{T}}\right)$$

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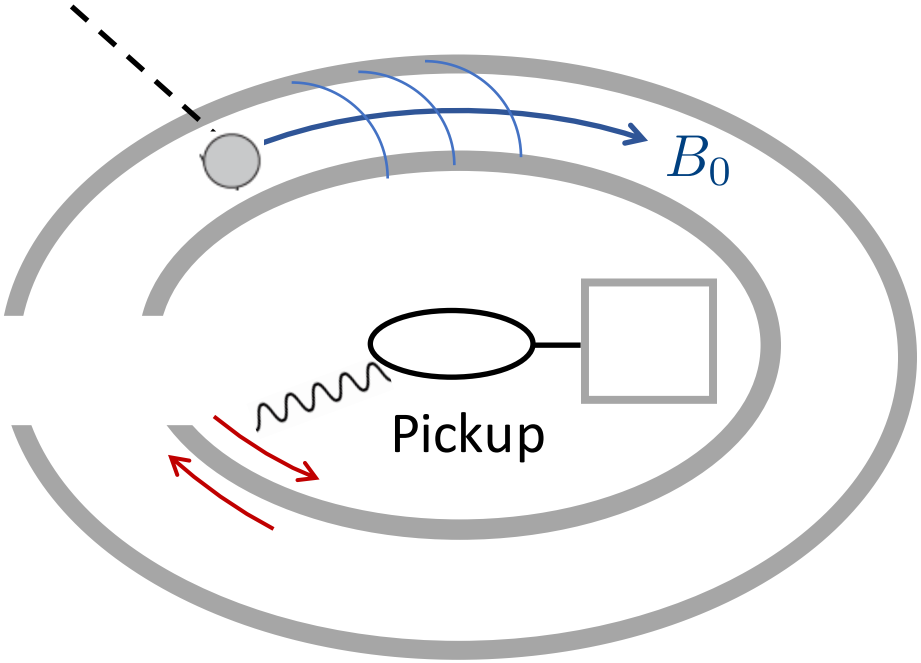

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Amplify RF signal by Q?

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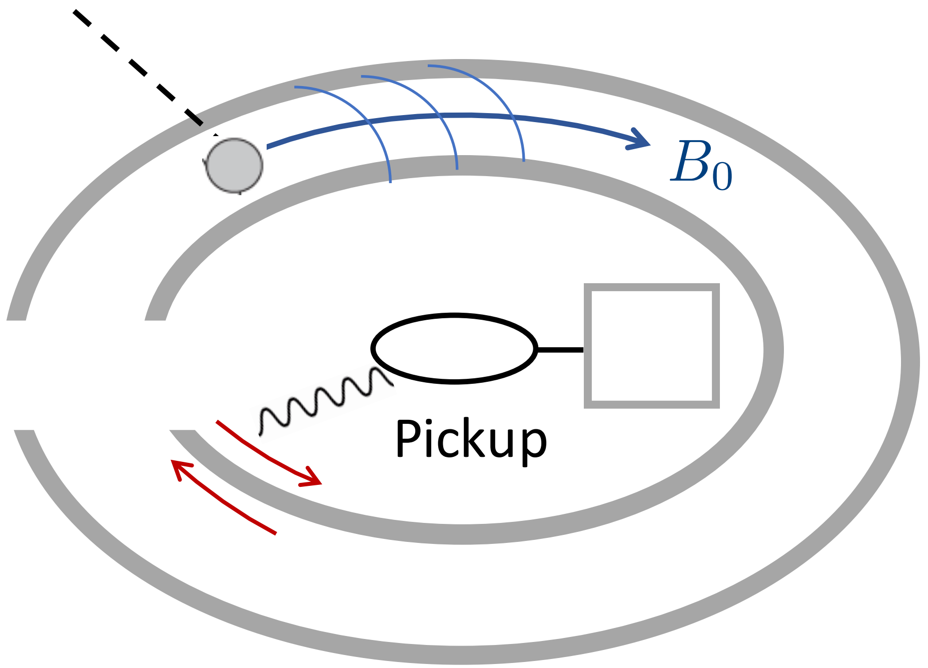

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Toroid is not a perfect “source” - non-negligible back-reaction

Must account for toroid impedance as well

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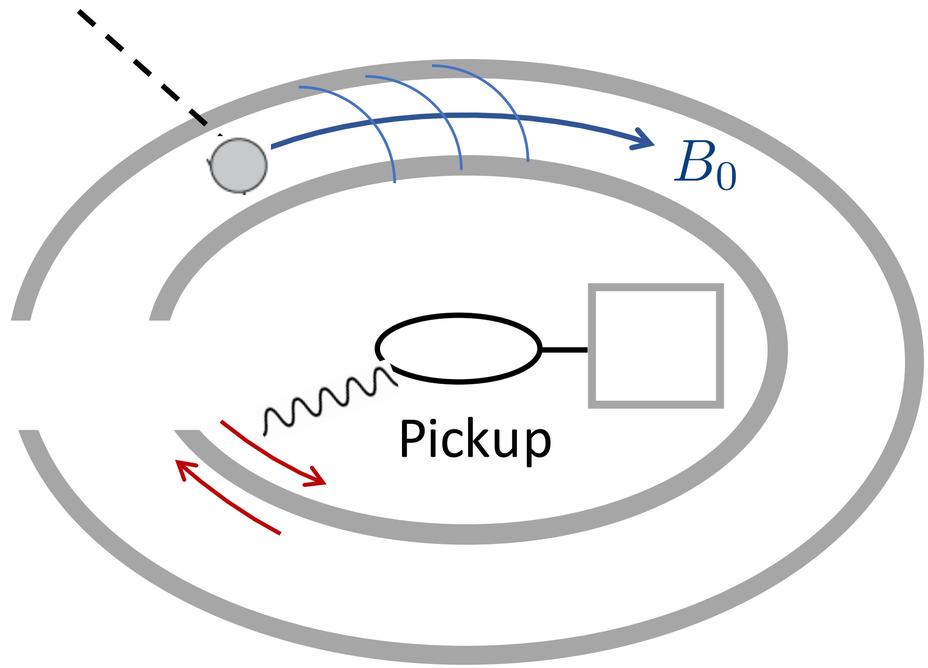

Parasitic Capacitance

$$C_d \lesssim 10^{-2}\ \mathrm{pF}$$

Toroid size

$$L_d \sim 100\ \mathrm{nH}$$

Superconductor

$$R_d \gtrsim 10^{-9}\ \Omega$$

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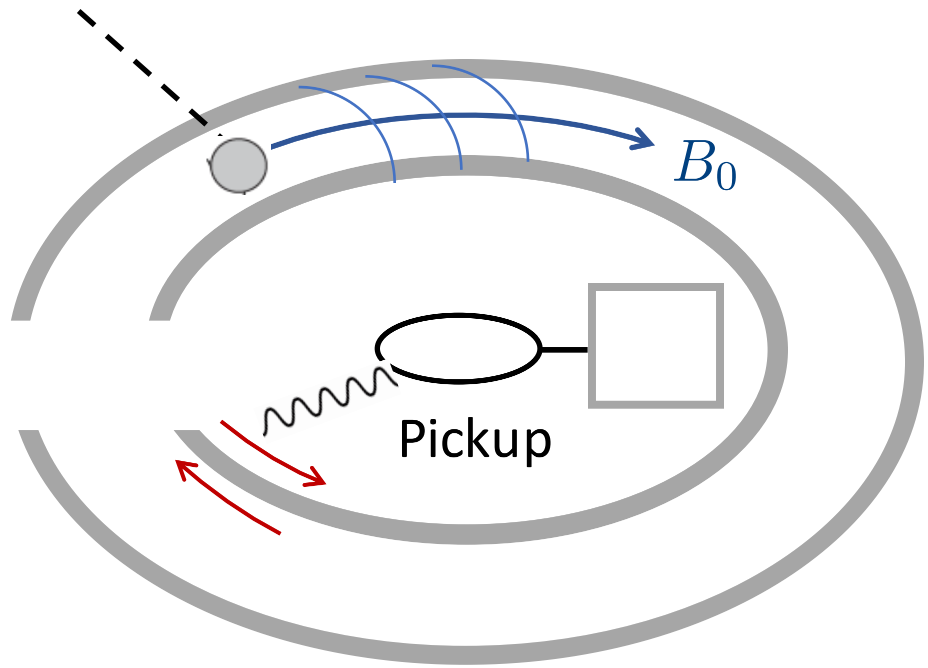

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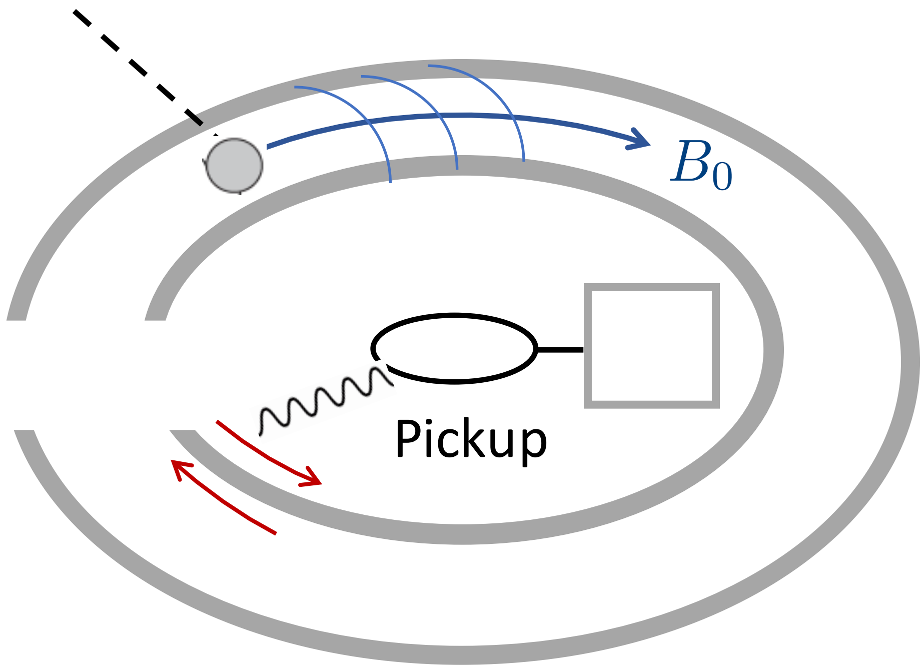

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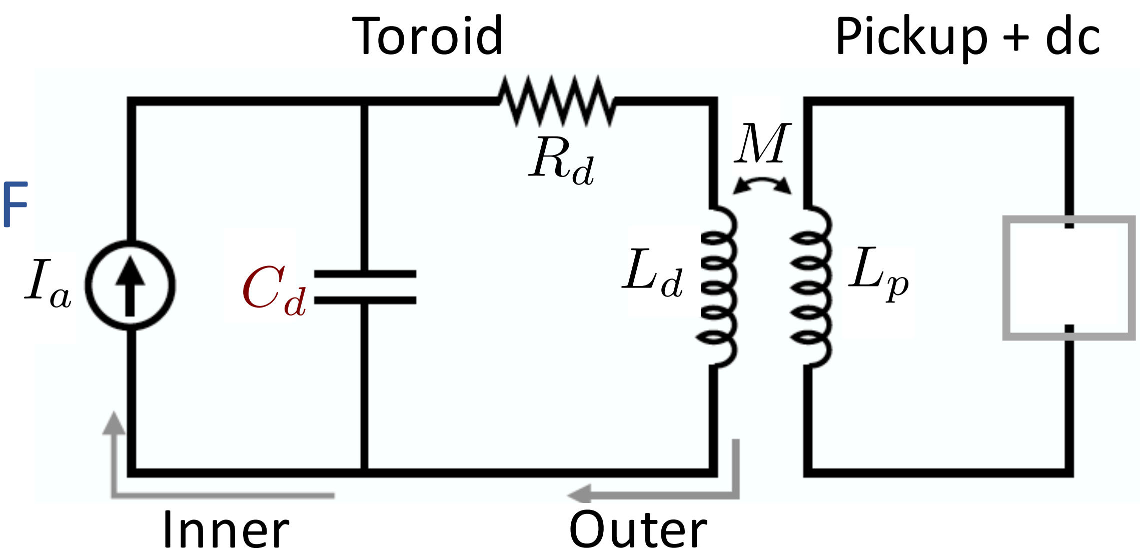

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Optimal Signal Strength

$$\epsilon_1 \equiv R_d C_d \omega \qquad \epsilon_2 \equiv L_d C_d \omega^2$$

$$P_{\mathrm{signal}} = \tfrac{1}{8} Q |I_a|^2 \omega L_d \cdot \min\left\{1, \tfrac{1}{Q \epsilon_1 \epsilon_2}\right\}$$

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Impedance matched
max power draw

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Impedance matched max power draw

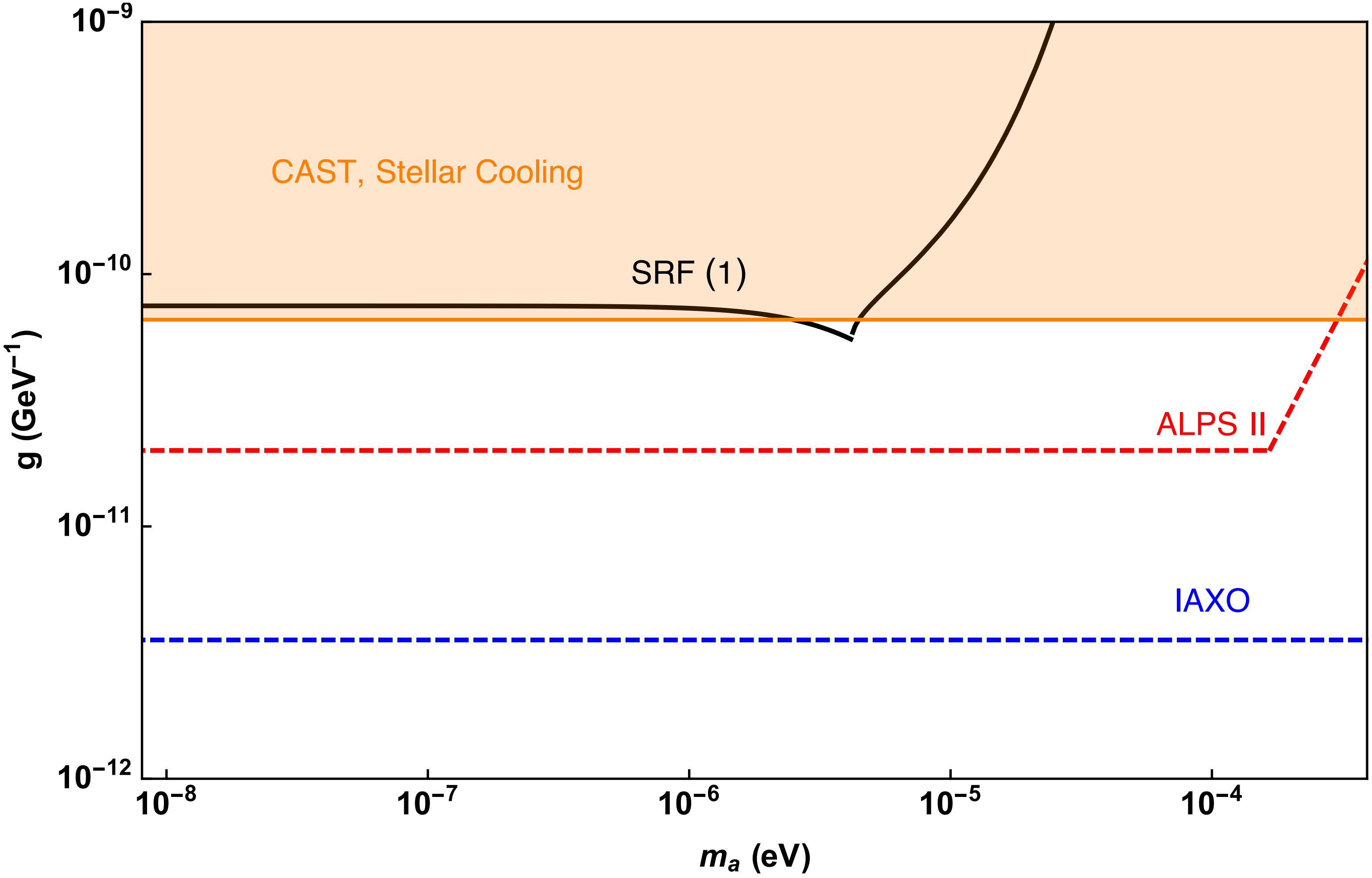
Narrowband signal detection $P_{\text{noise}} = T_{\text{sys}}/t_{\text{int}}$

Standard Quantum Limit $T \gtrsim \omega \approx 50 \text{ mK}$

Sensitivity $Q = 10^{11}$ $B_{\rm pc} = 0.2$ T $B_0 = 5$ T

$t_{\rm int} = 1$ year $C_d = 10^{-2}$ pF (1) $R_d = 10^{-4}\ \Omega$

$T_{\rm sys} = 0.1$ K $L_d = 100$ nH



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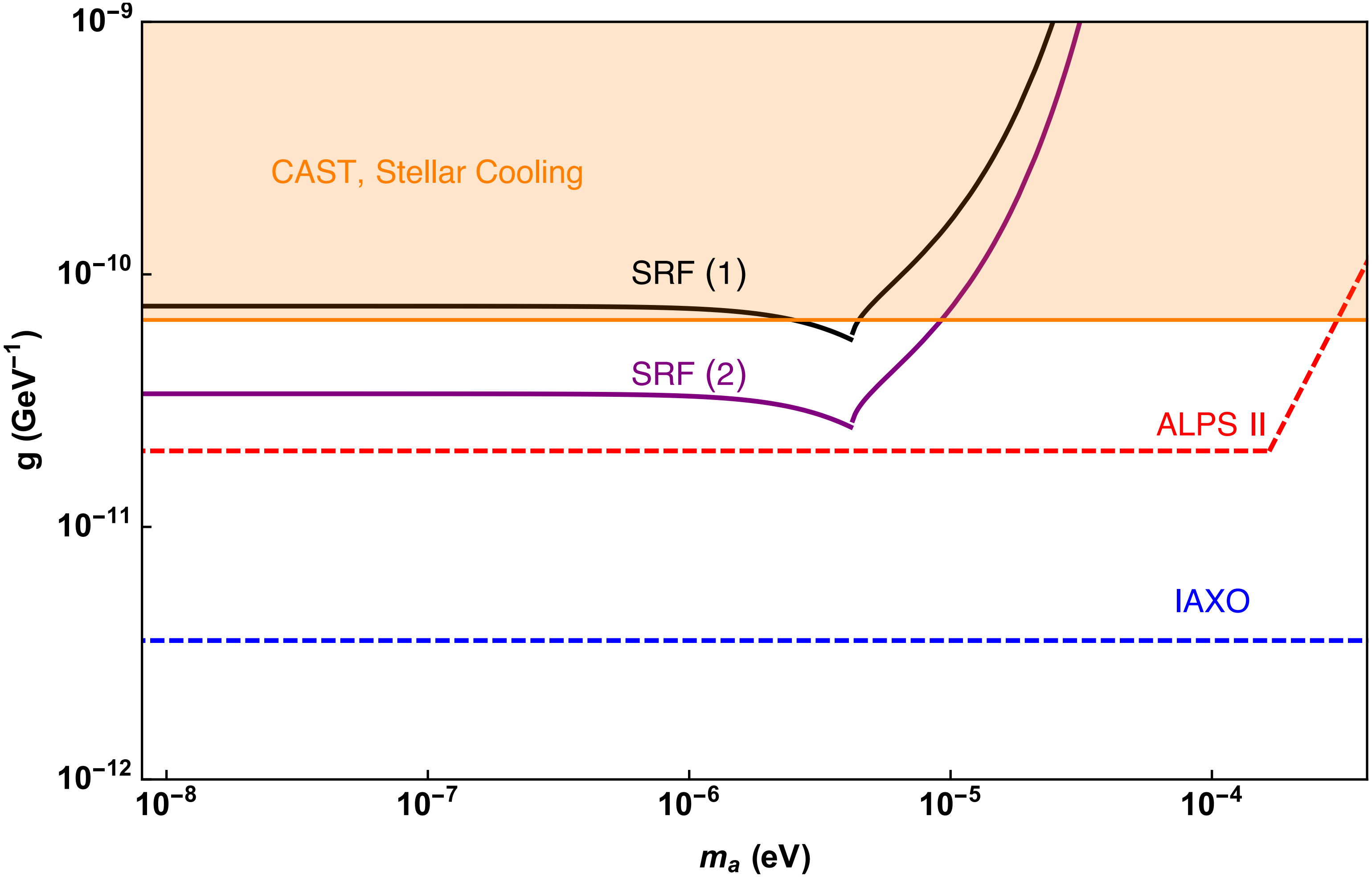

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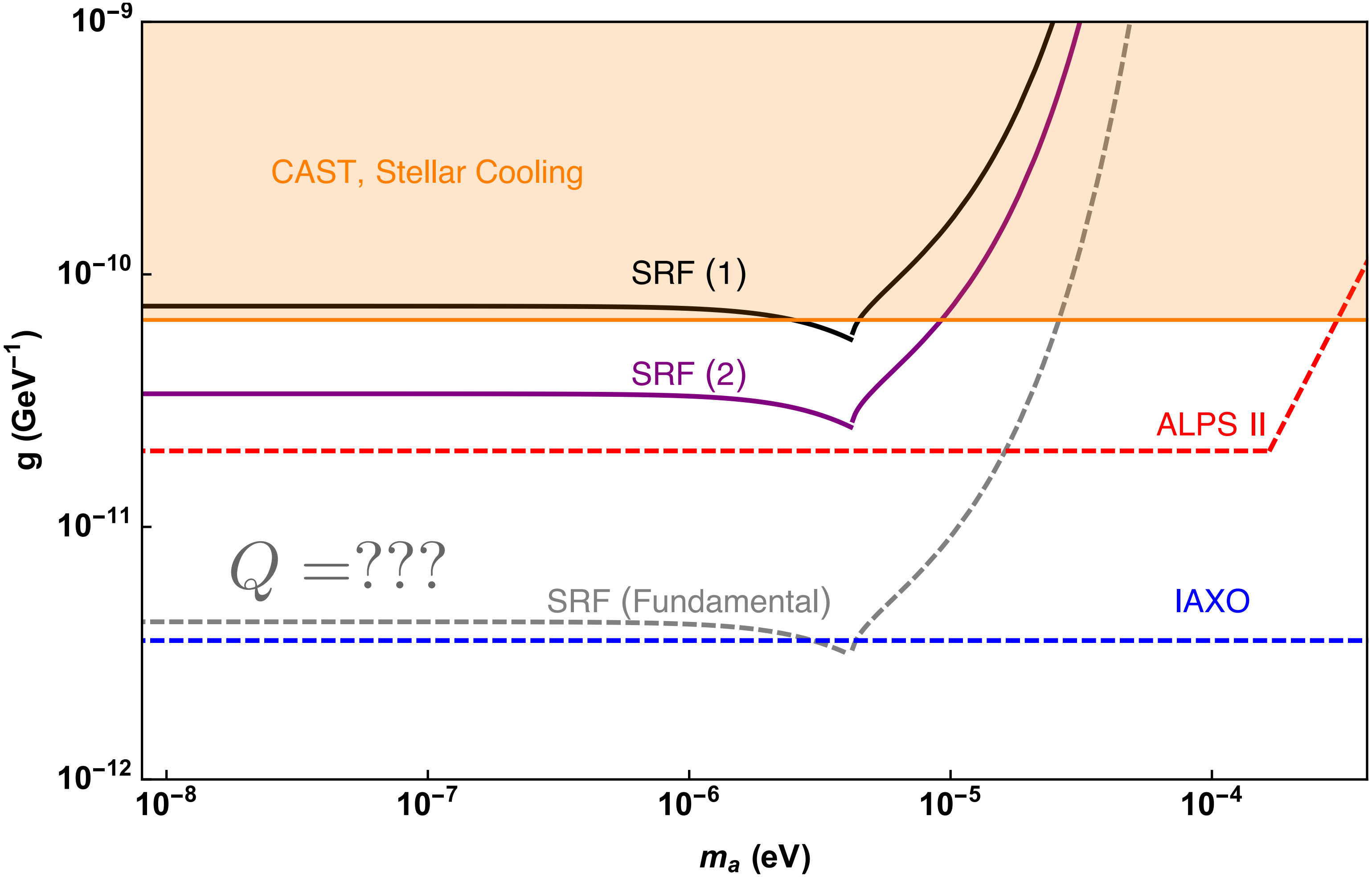

Summary

Propose new design for a lab search of axions based on LSW with SRF cavities

Particular realization uses toroid as a conversion region

Consider influence of fundamental factors such as signal back-reaction and screening, optimal sensitivity

Comparable and complementary to future optical searches!