Axion Production and Detection with Superconducting RF Cavities

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(UC Berkeley)

[RJ, Narayan, Rajendran, Riggins, 1904.07245]

Axion-like Particles (ALPs)

A new light boson? Physics in the far UV can lead to light, weakly-coupled particles.

ALPs that couple to photons are a generic possibility

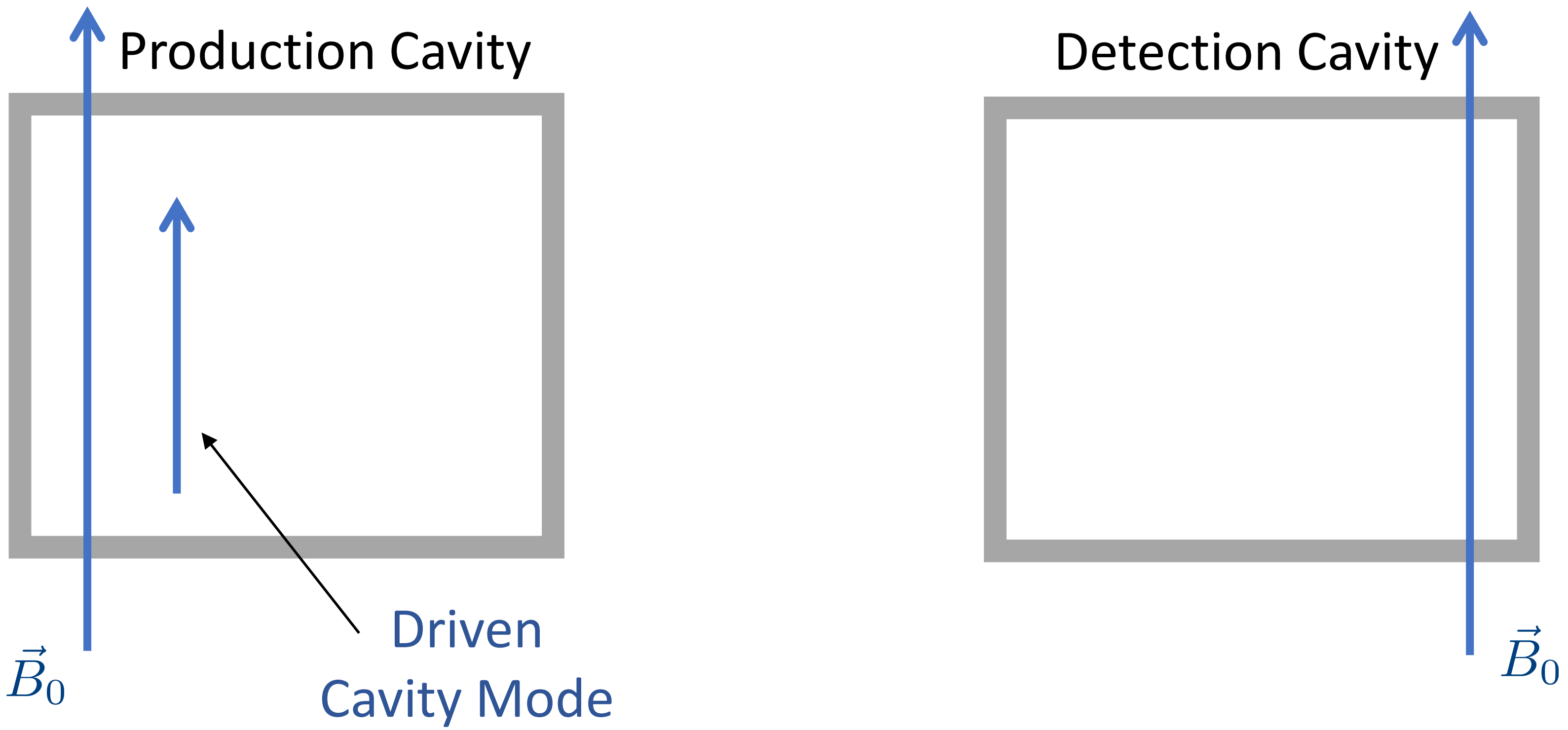
$$\mathcal{L} \supset \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a{}^2a^2 + \frac{1}{4}gaF_{\mu\nu}\widetilde{F}^{\mu\nu}$$

Detection Opportunity

ALP-photon mixing in a magnetic field

Light Shining Through Walls (LSW)

[Hoogeveen, '92]



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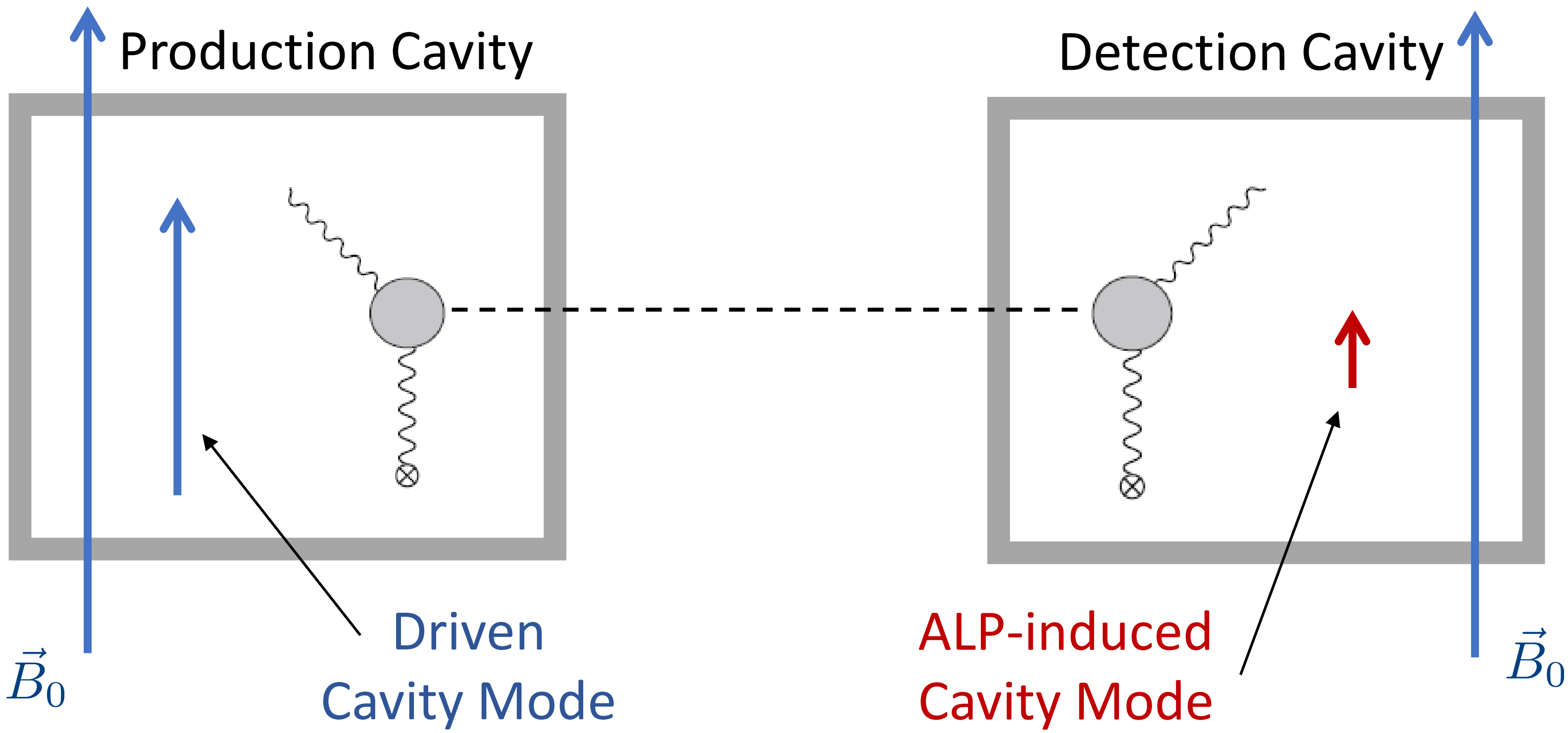

Light Shining Through Walls (LSW)

[Graham et al '16]

Optical Cavities

ω, L^{-1} are independent

ALPS $g < 5\text{x}10^{-8}\ \text{GeV}^{-1}$
for $m_a < \text{meV}$

Next generation with L ~ 100 m
ALPS II (projected): $g < 2\text{x}10^{-11}\ \text{GeV}^{-1}$

RF Cavities

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

CROWS $g < 10^{-7}\ \text{GeV}^{-1}$
for $m_a < \mu\text{eV}$

Next generation ???

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Next generation ???

This work: Utilize superconducting RF technology to reach g < 7x10^{-12} GeV^{-1} in a next generation LSW ALP search

See [Bogorad, Hook, Kahn, Soreq, '19] for a different approach

Light Shining Through Walls (LSW)

$$P_{\mathrm{signal}} = P_{\mathrm{input}} \left(\frac{gB_0}{\omega} \right)^4 Q_{\mathrm{pc}} Q_{\mathrm{dc}} |G|^2$$

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O(0.1) geometric form factor, exponentially suppressed for $m_a > \omega$

Light Shining Through Walls (LSW)

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Conventional Conducting RF: $Q \sim 10^5 - 10^6$

Superconducting RF: $Q \sim 10^{10} - 10^{12}$

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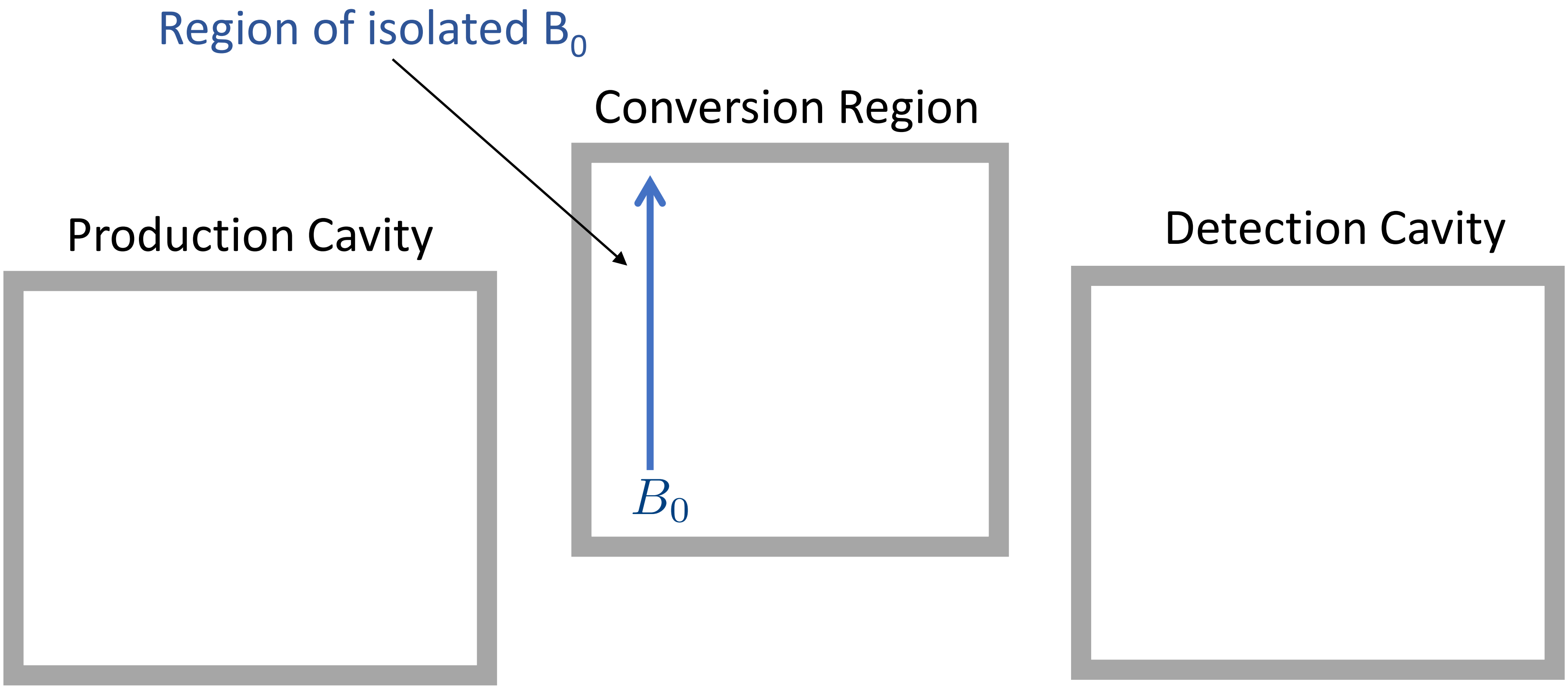
Type-II Superconductor Critical Field O(0.2 T)

Fields exceeding critical will degrade Q.

Flux tubes penetrate the SC, have a dissipative interaction with an electric current.

Challenge: re-design such that large B and SRF cavity can co-exist

LSW with SRF Cavities



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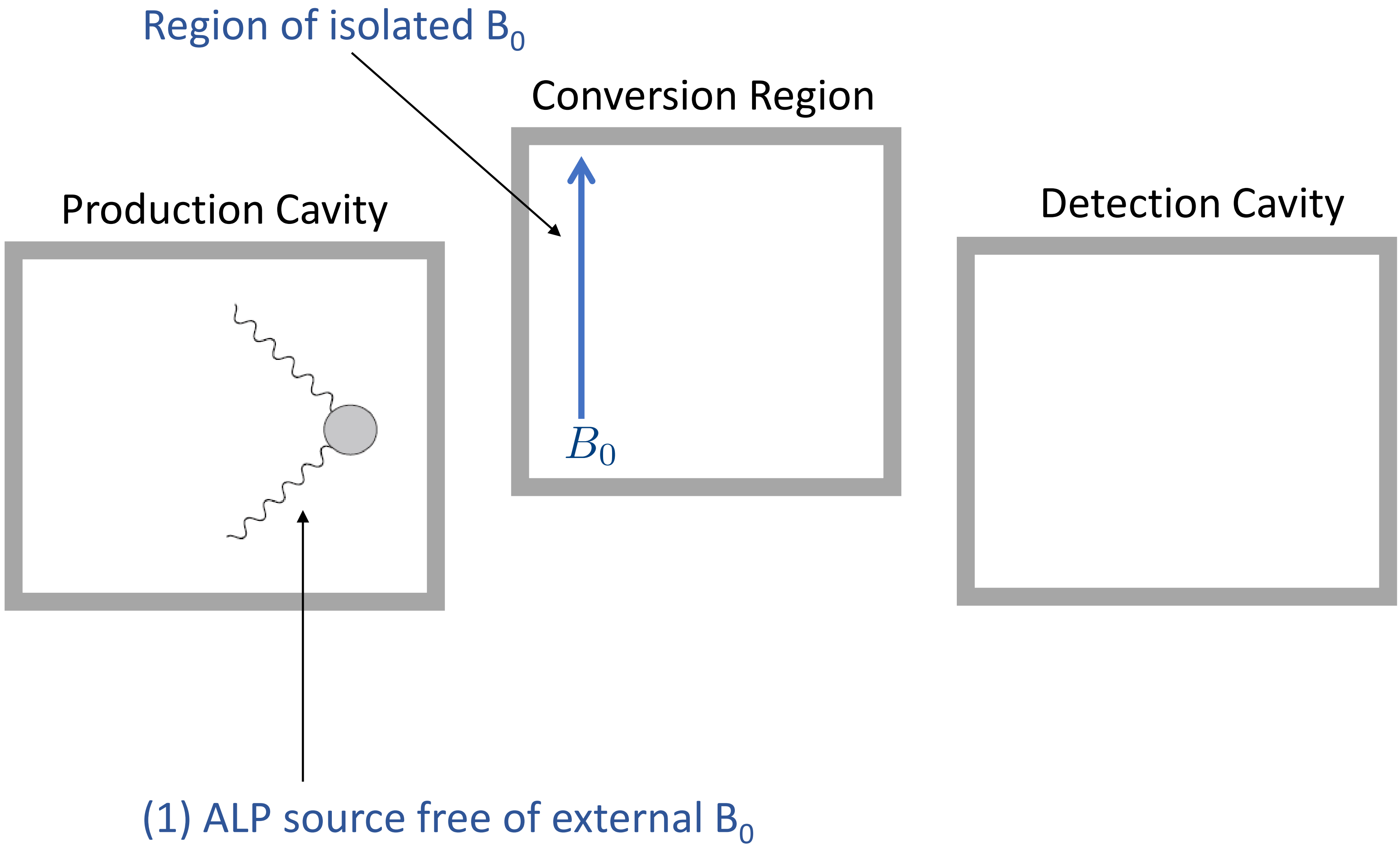

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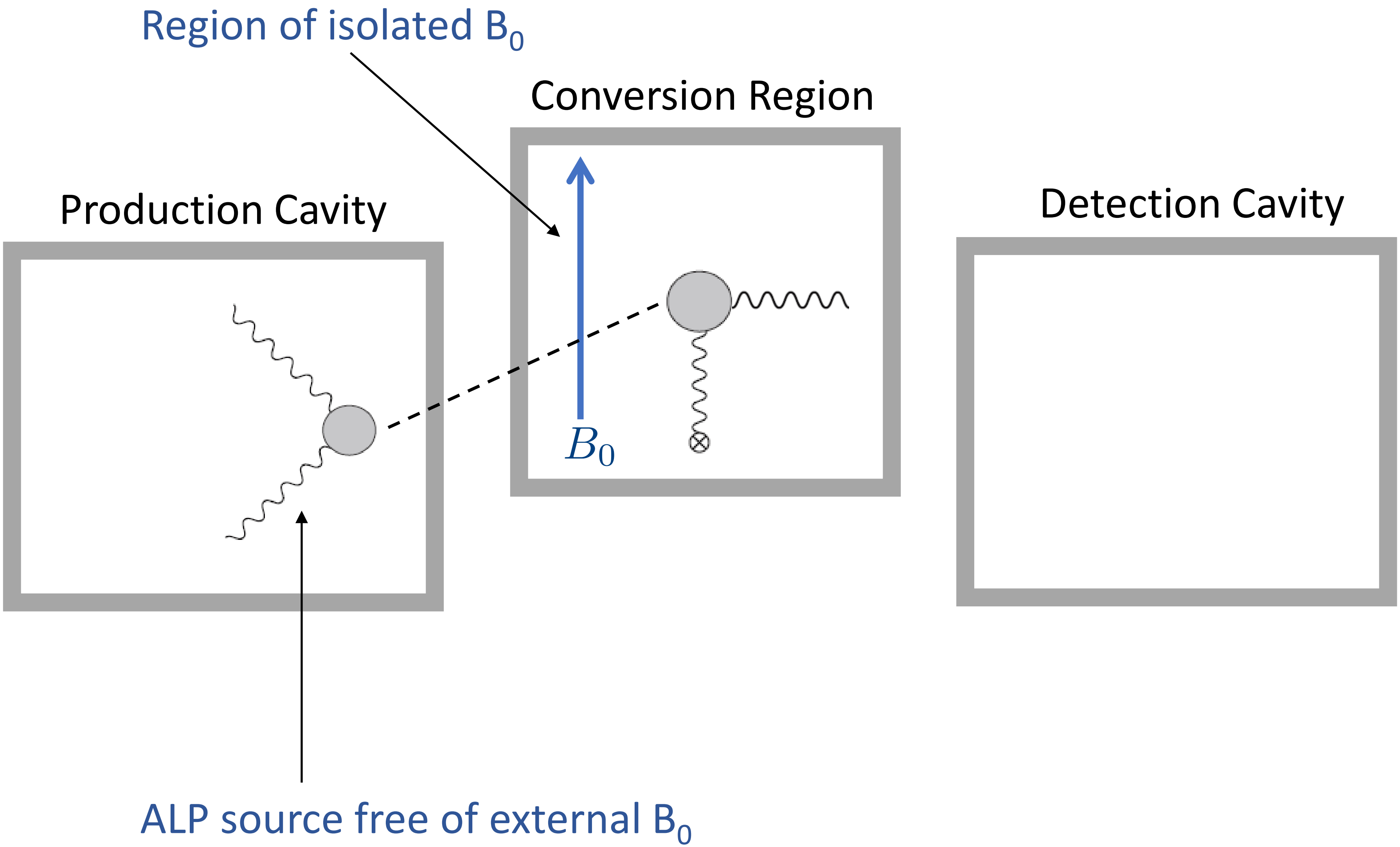

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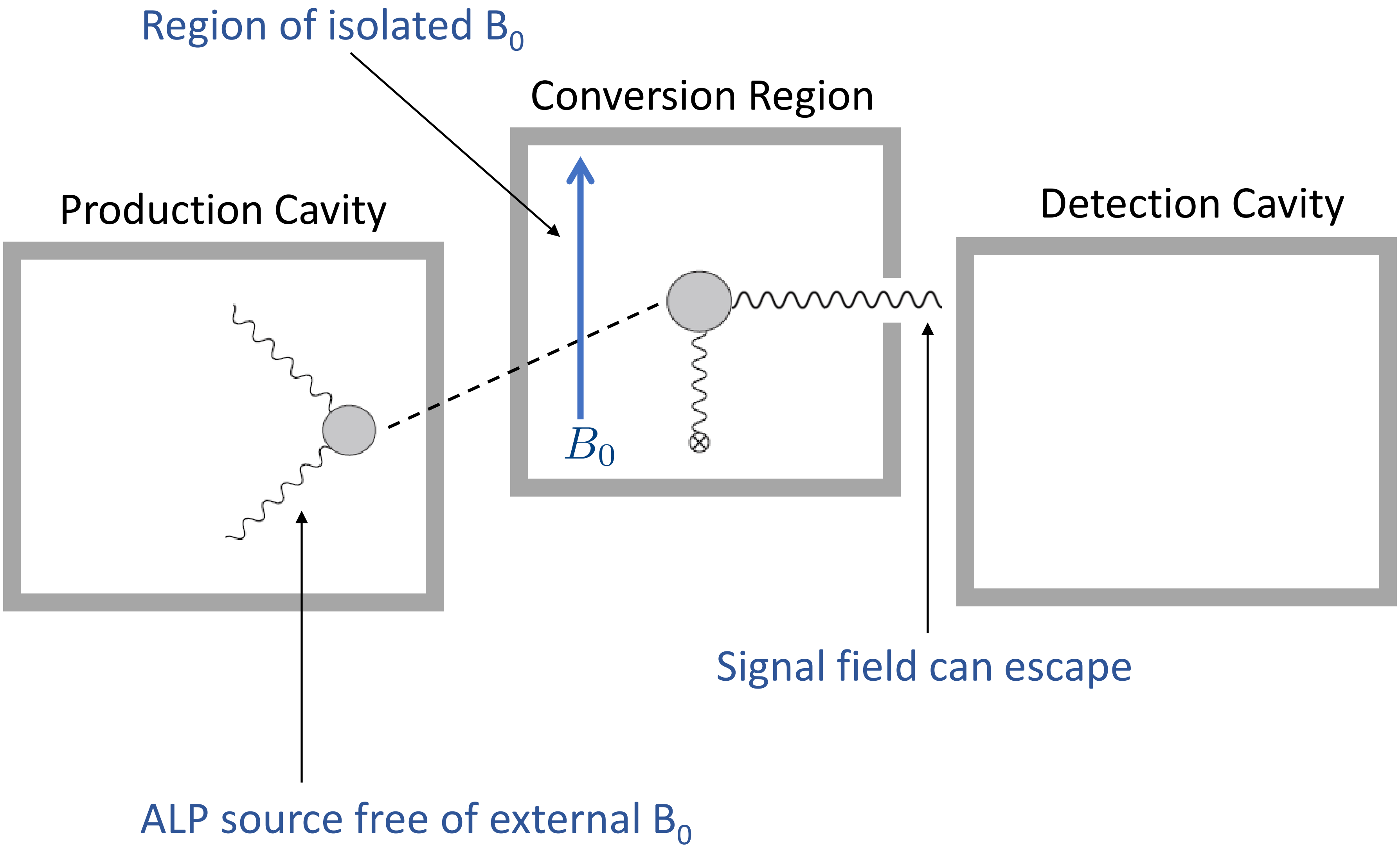

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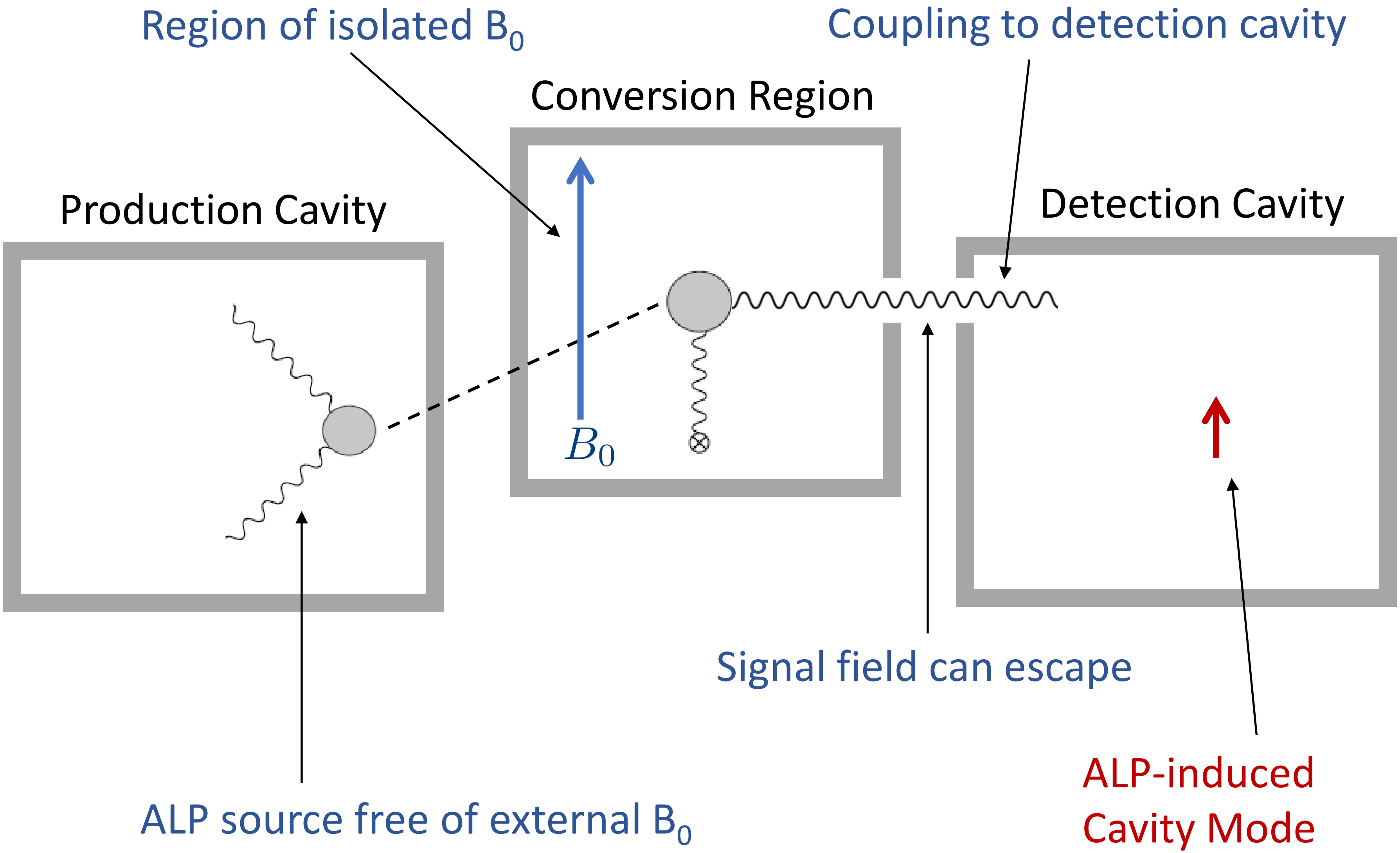

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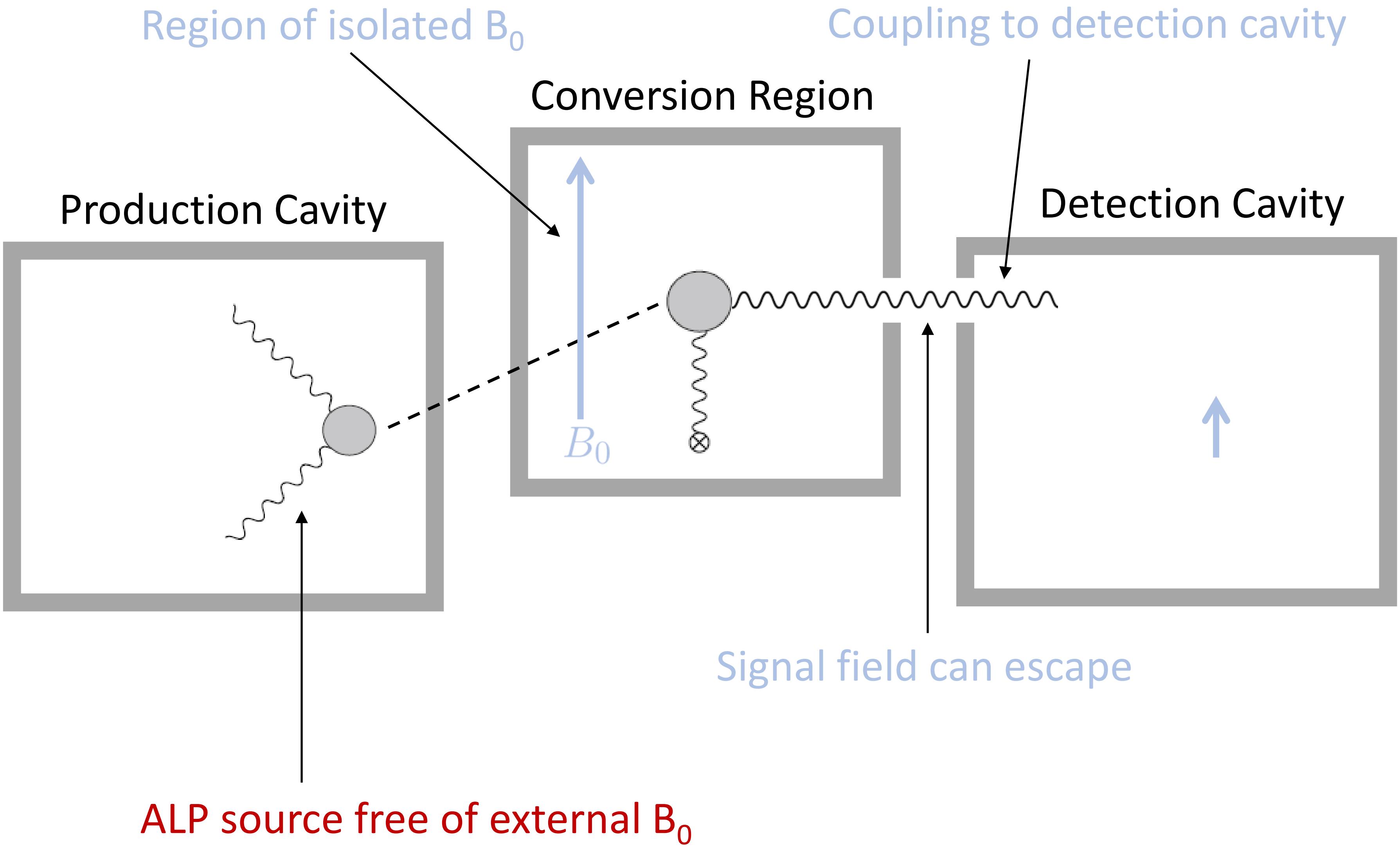

SRF Axion Source

Axion production

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

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

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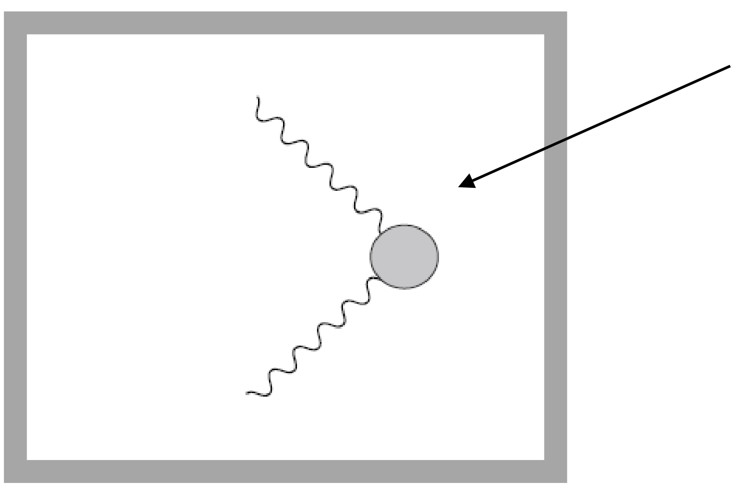
ALP source free of external B_0

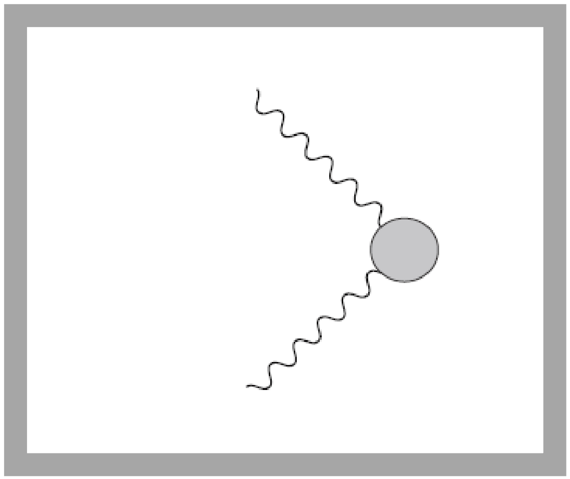


Drive cavity mode(s) such that $\vec{E}\cdot\vec{B}$ is not identically zero.

May require exciting two modes, ω_1 and ω_2, which produces axions of frequency $\omega_1 \pm \omega_2$

SRF Axion Source

ALP source free of external B_0



Input power is limited to prevent quenching

Maximal source magnitude is the critical field

$$\vec{E} \cdot \vec{B} \lesssim (0.2\ \mathrm{T})^2$$

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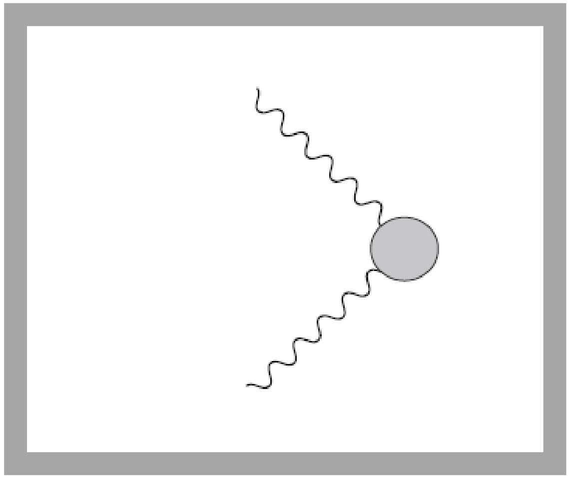

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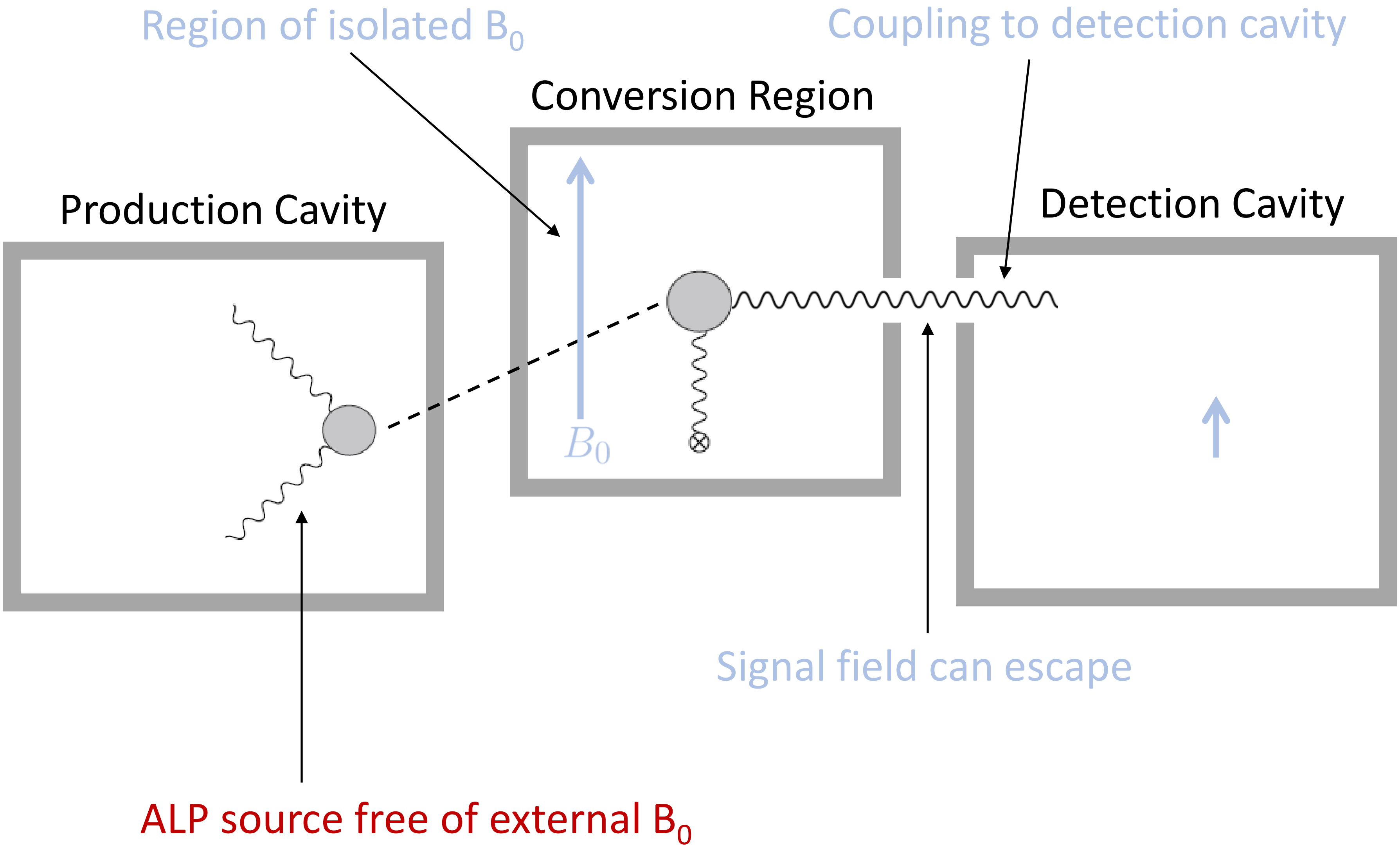
Comparable to conventional cavity with sufficient input power:

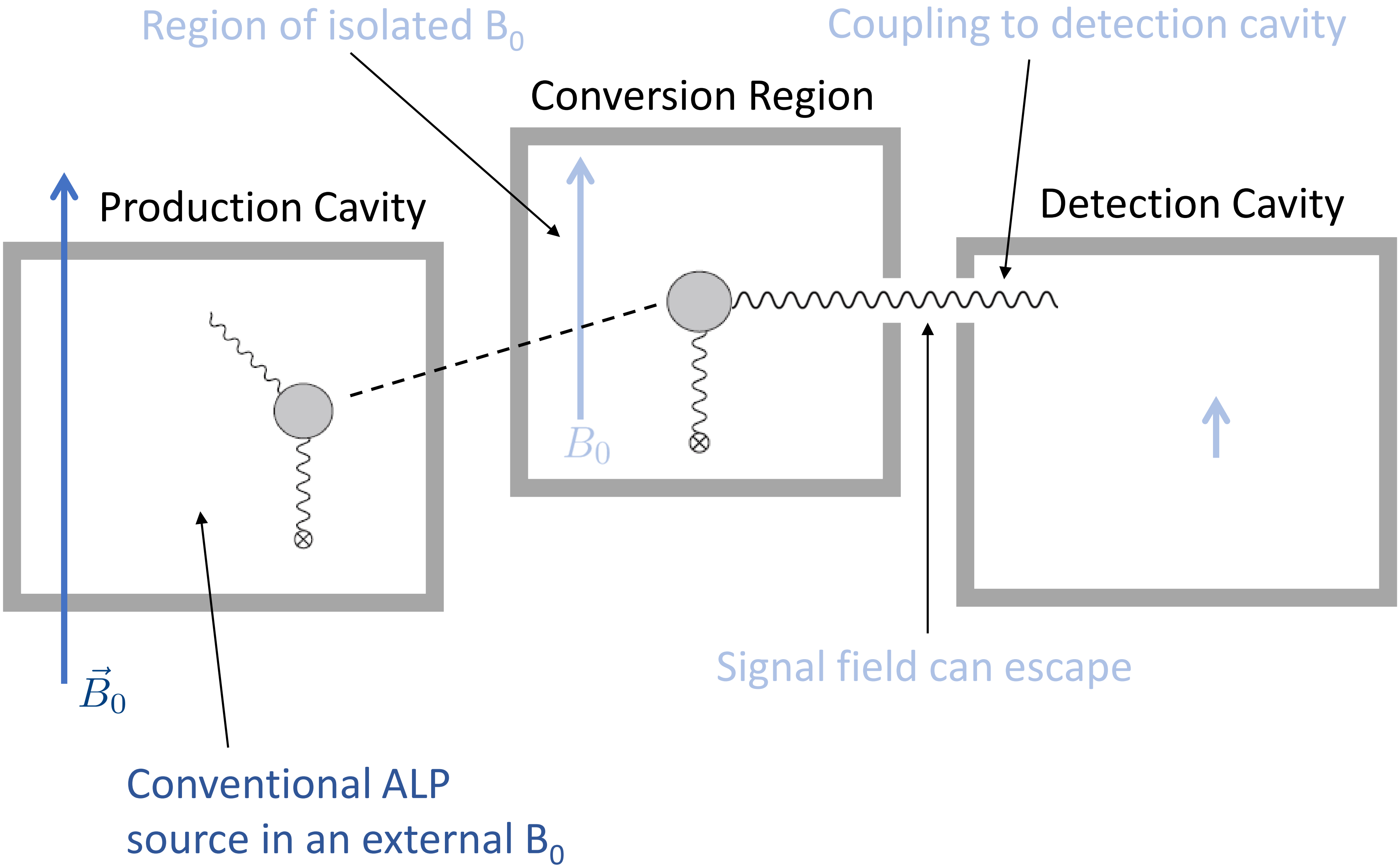
$$(\vec{E} \cdot \vec{B}) \sim (0.1\ \mathrm{T})^2 \left(\frac{P_{\mathrm{input}}}{100\ \mathrm{W}} \right)^{\frac{1}{2}} \left(\frac{Q_{\mathrm{pc}}}{10^5} \right)^{\frac{1}{2}} \left(\frac{B_0}{5\ \mathrm{T}} \right)$$

Fundamental advantage of SRF is in the detection cavity

LSW with SRF Cavities



LSW with RF and SRF Cavities



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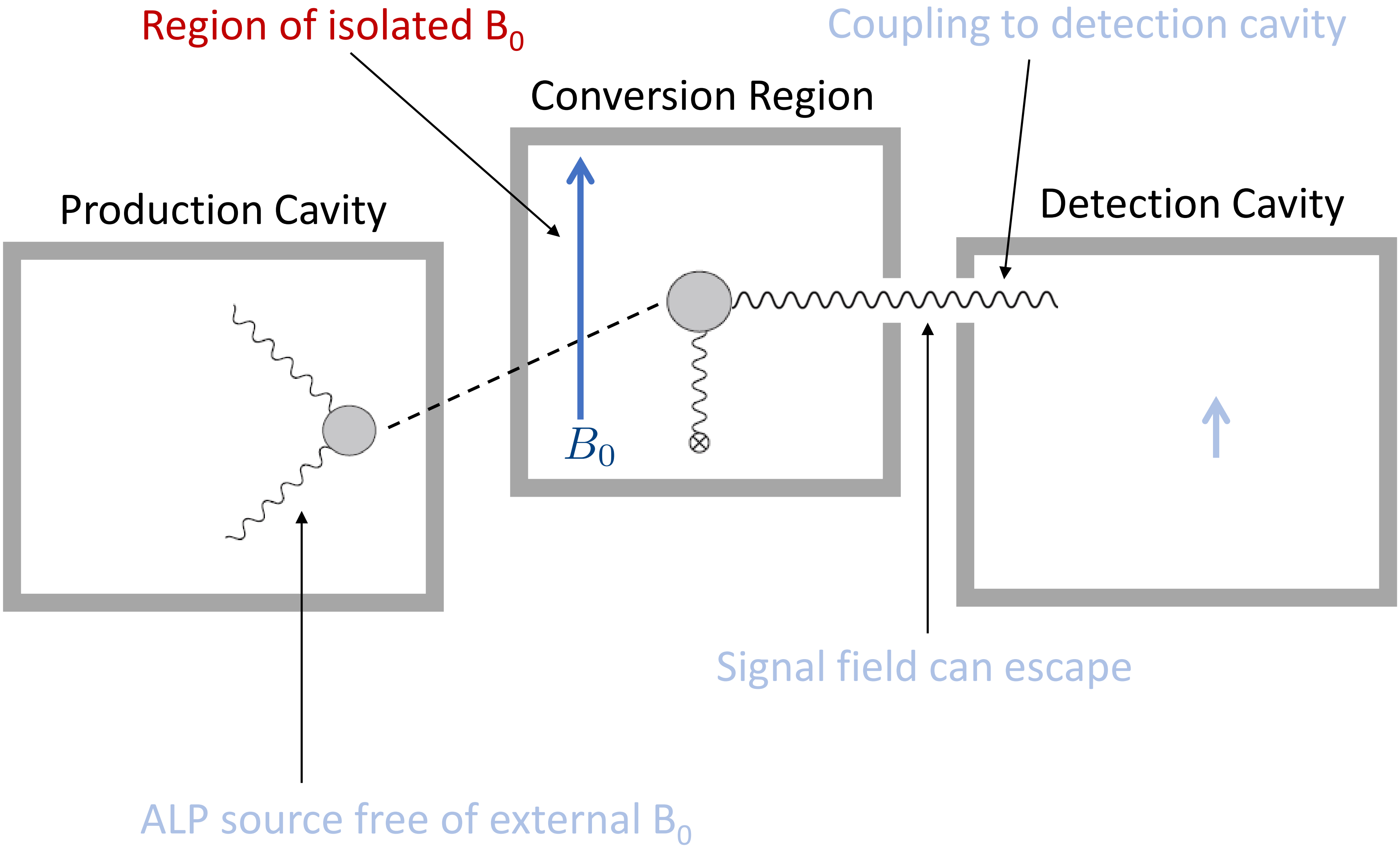
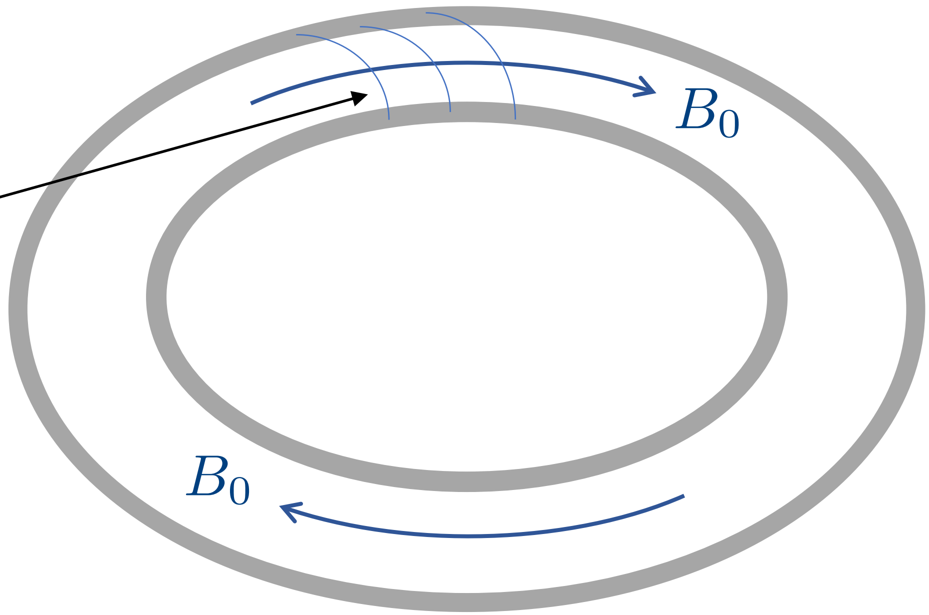


Gapped Toroid Conversion Region

Confine large static B_0

Toroidal Magnet

Toroidal frame wrapped with DC current-carrying superconducting wires



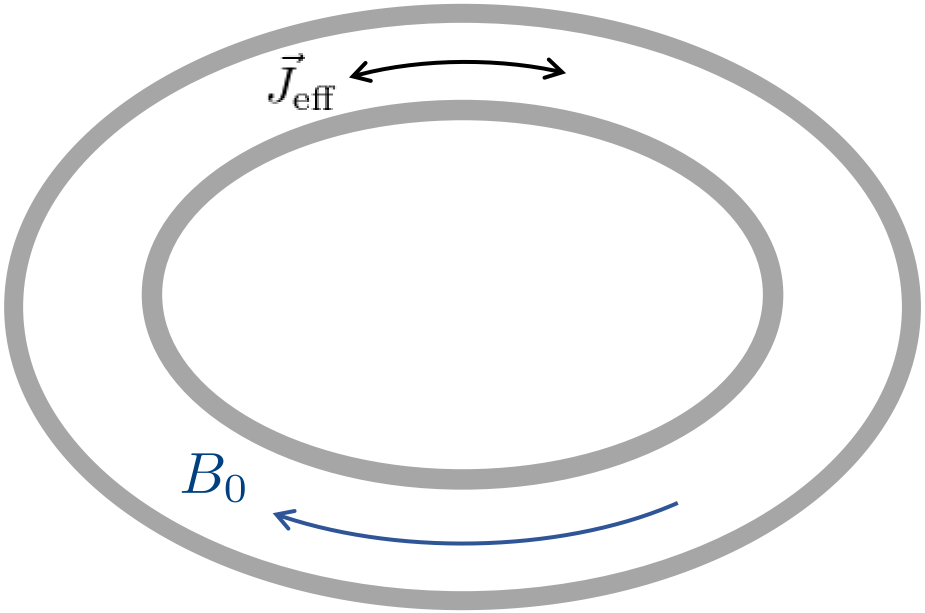
Magnetic field (ideally) vanishes outside of toroid. In practice, there are small external fringe fields $\sim 10^{-6} B_0$.

Gapped Toroid Conversion Region

ALP-photon conversion

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

Conversion in B_0 $\sim$ Effective Current $\vec{J}_{\rm eff} = g\vec{B}_0\frac{\partial a}{\partial t}$



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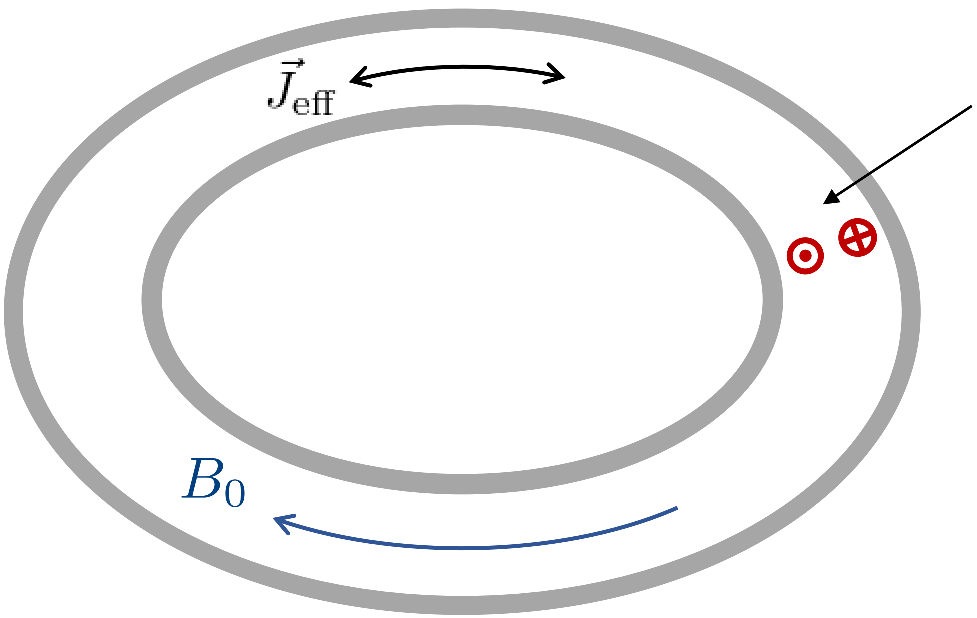

Effective current sources a real, poloidal AC field B_a

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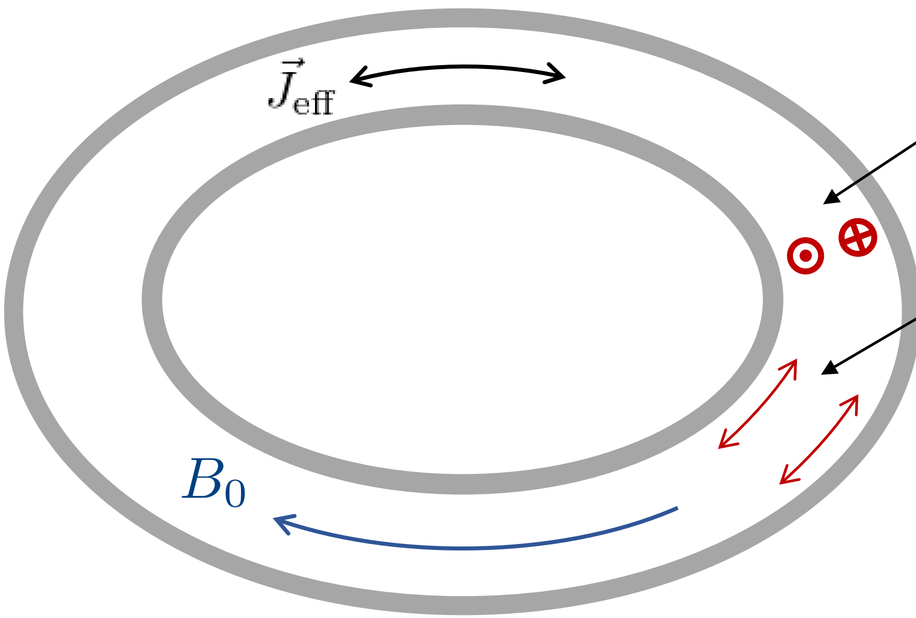


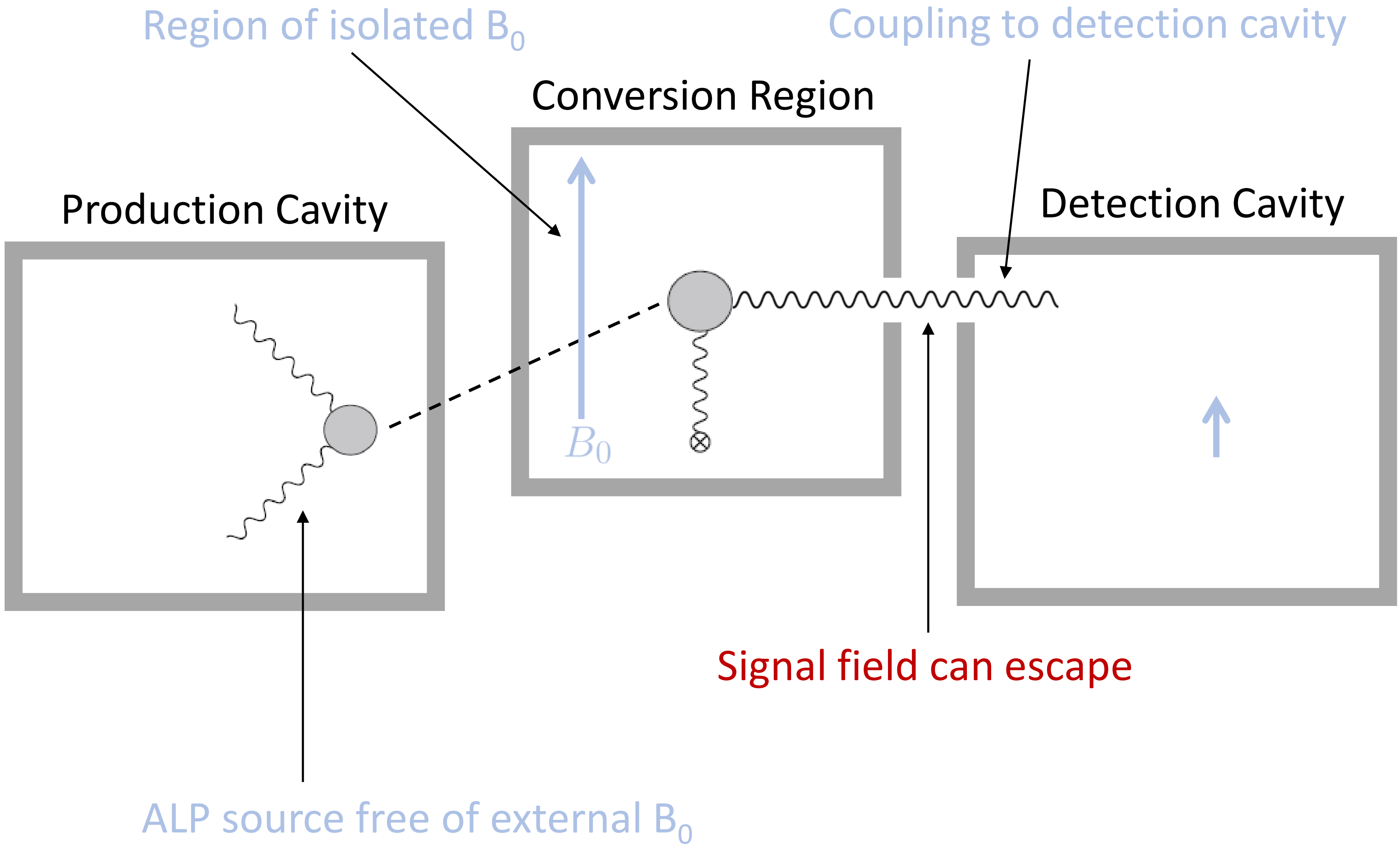
Effective current sources a real, poloidal AC field B_a

B_a drives toroidal AC screening current I_a along inner surface.

$$I_a \sim \int J_{\mathrm{eff}}\, da$$

$$I_a \approx 10^{-13} \text{ nA} \left(\frac{g \text{ GeV}}{10^{-11}}\right)^2 \left(\frac{B_{\mathrm{PC}}}{0.1 \text{ T}}\right)^2 \left(\frac{B_0}{5 \text{ T}}\right) \left(\frac{R}{10 \text{ cm}}\right)^3$$

LSW with SRF Cavities



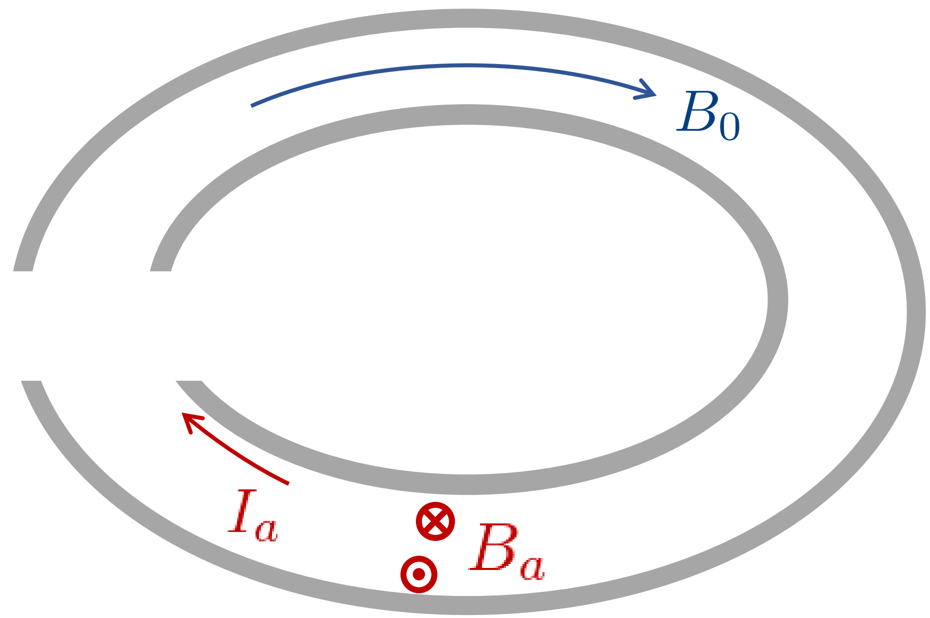
Gapped Toroid Conversion Region

Allow RF signal to escape

Gapped Toroid

Inspired by the dark matter ALP search ABRACADABRA

[Kahn, Safdi, Thaler '16]



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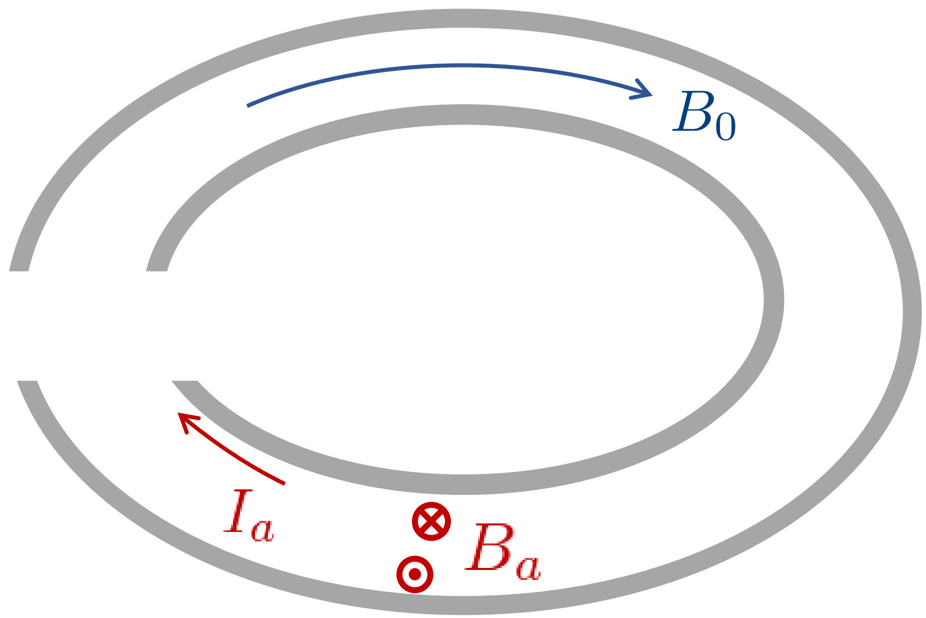
Gap must be large enough to prevent parasitic capacitance, but small enough to minimize external fringe fields.



Propagation of I_a near the gap depends on the toroid radius R.

Gapped Toroid Conversion Region

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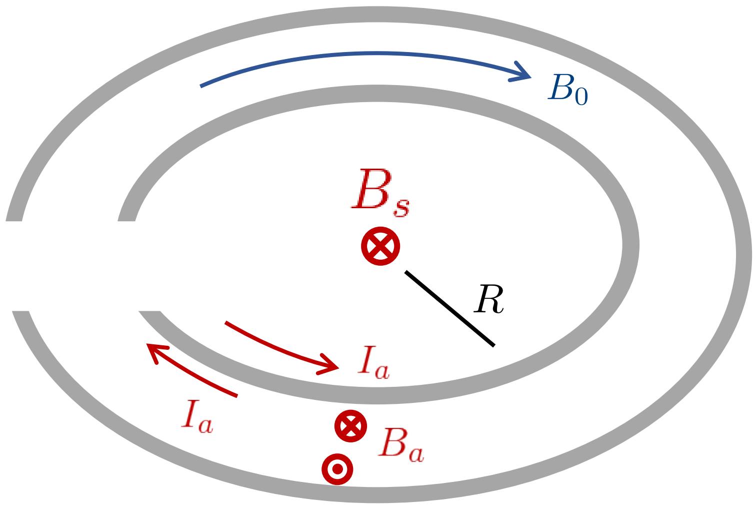
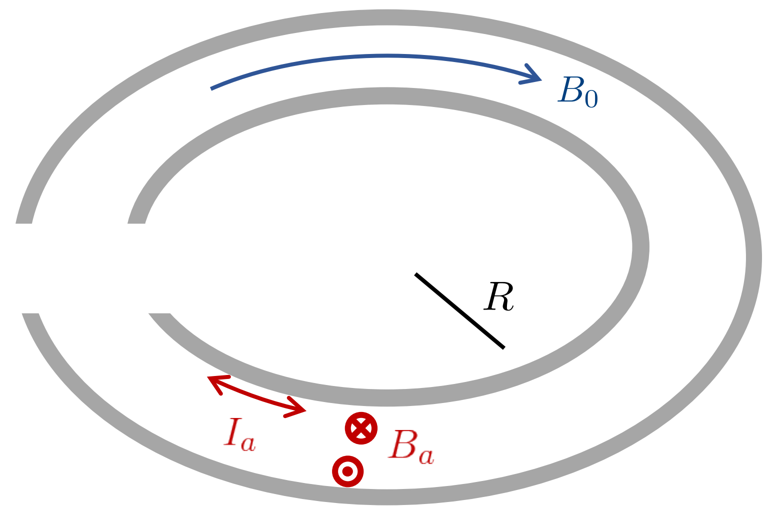




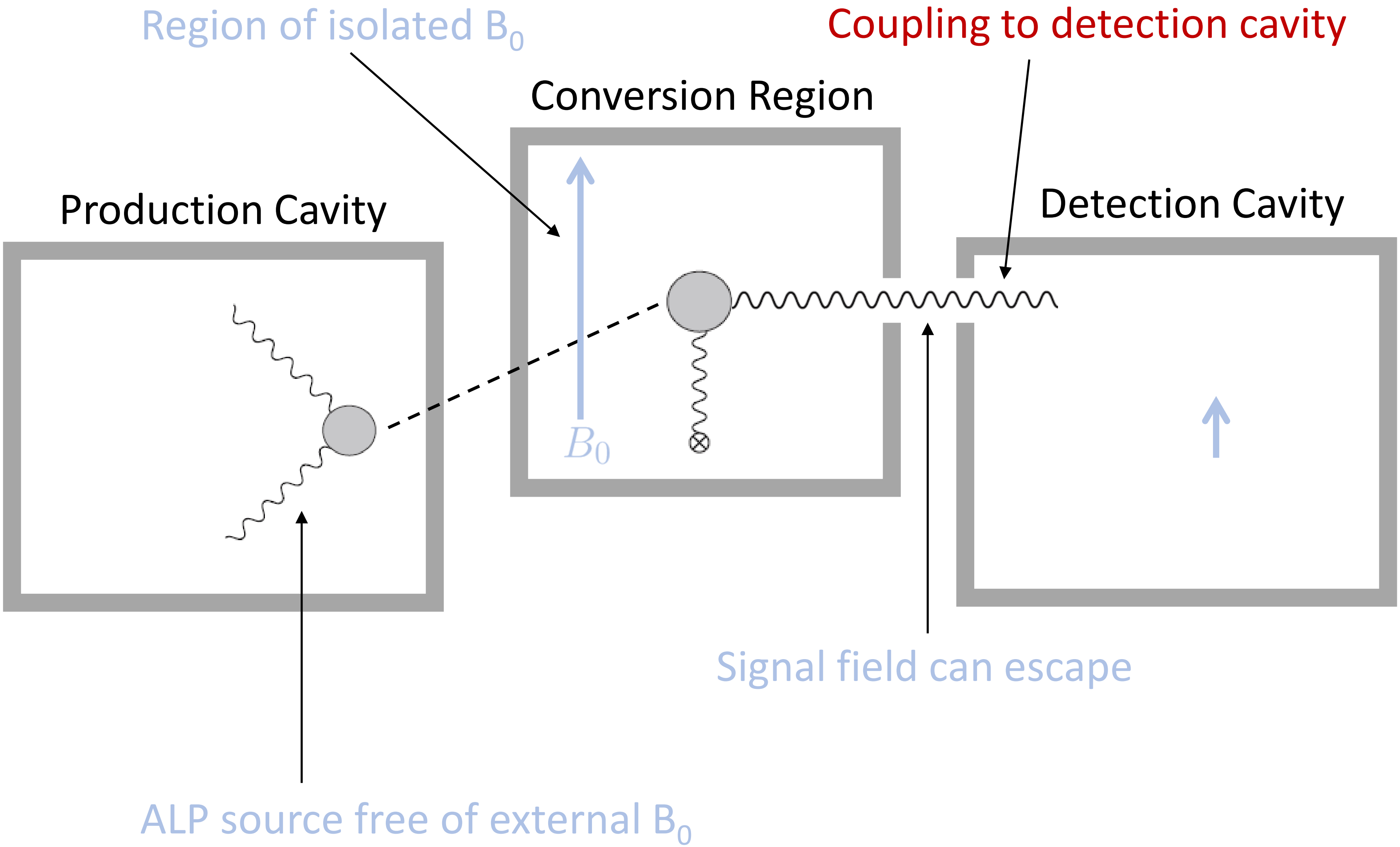
Quasistatic $(R\omega \ll 1)$

I_a is spatially uniform, returns on outer surface and sources external magnetic field B_s – "Current Comparator Limit"

Screened $(R\omega \gg 1)$

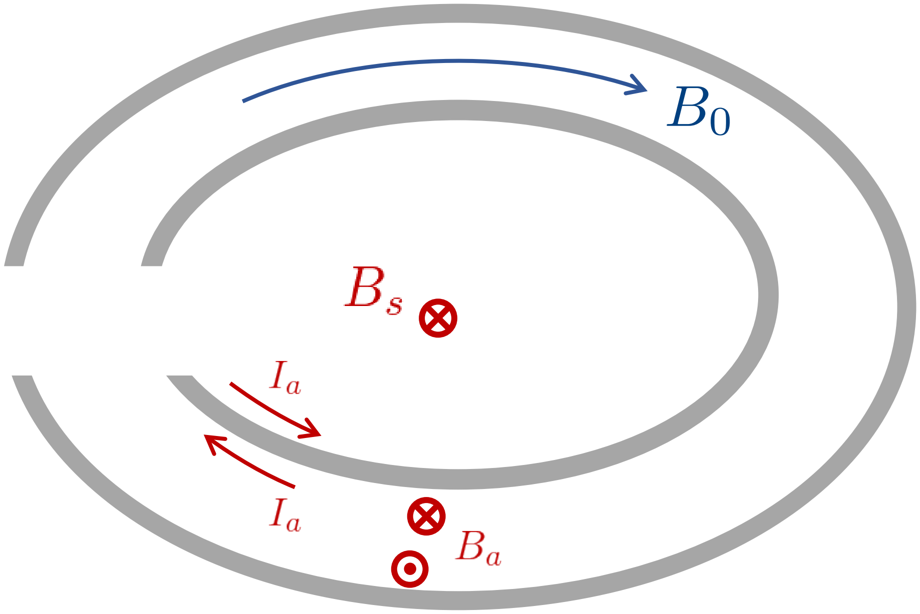
I_a varies rapidly, preventing current from propagating to outer surface and suppressing external field by powers of ωR.

LSW with SRF Cavities



Detection Cavity

Couple signal to SRF detection cavity



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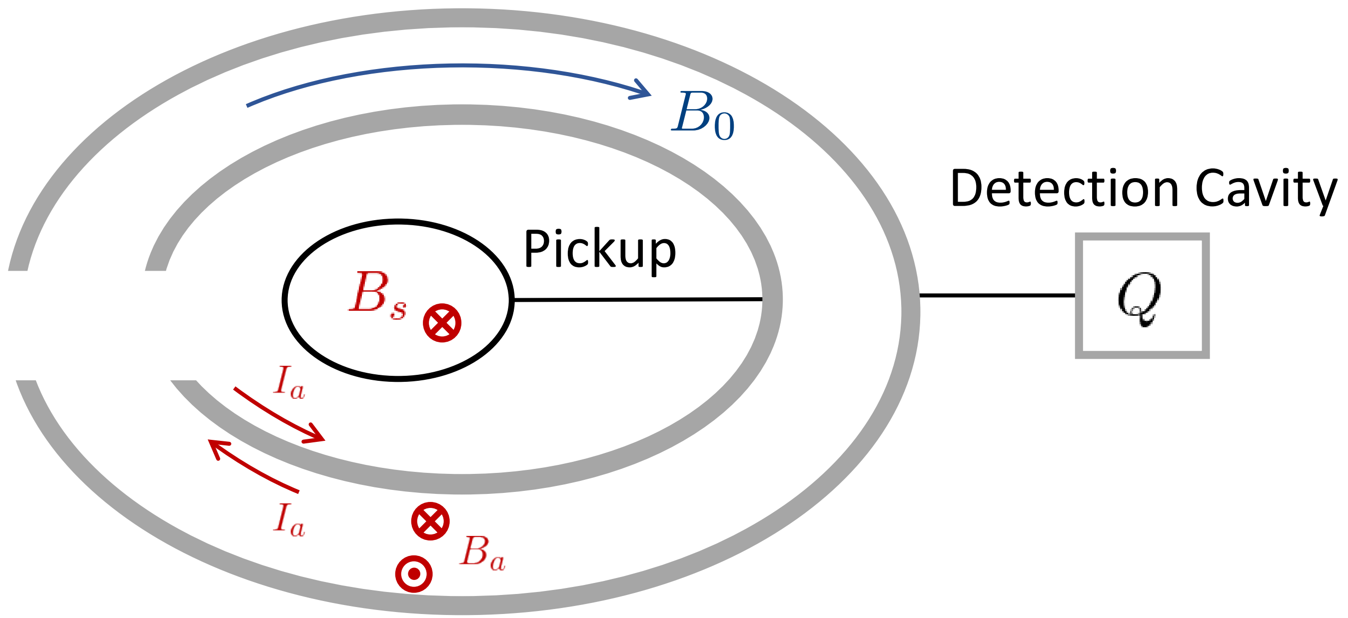

External current I_a can be coupled to a high-Q SRF detection cavity, e.g. though a pickup loop. A different technique may be preferred in practice, but the optimal signal power is unchanged.

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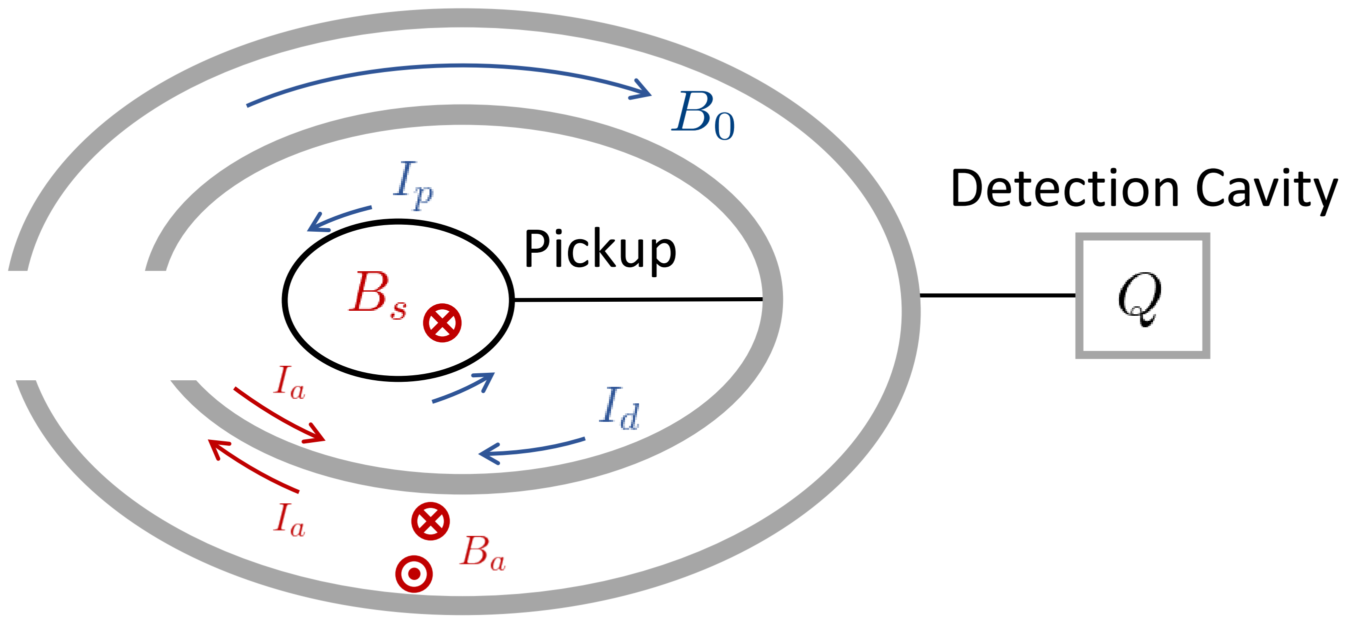

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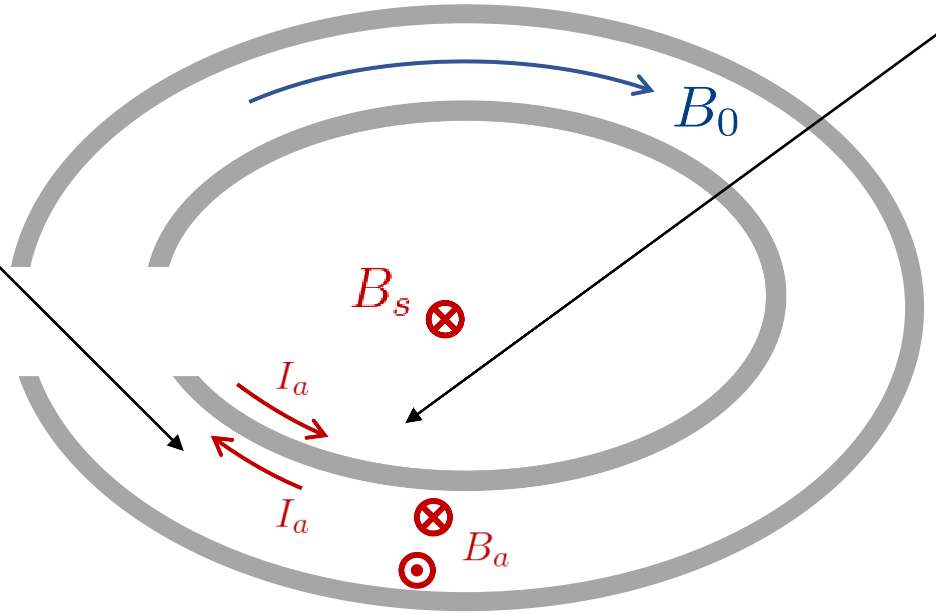
Signal is amplified by Q, but saturates for sufficiently large Q due to dissipative backreaction current on the toroid surface.

Optimal Cavity-Toroid Coupling

How do we maximize the RF signal in the detection cavity?

The inner surface of the toroid is a current source I_a, supplied by the axion field.

The outer surface of the toroid is an inductor fed by the source I_a.



Together, the axion field and toroid form a non-ideal current source with a maximum obtainable power draw.

Optimal Cavity-Toroid Coupling

Maximum power is extracted when the impedance of the detection cavity matches that of the toroid.

$$P_{\max} = \frac{1}{8}|I_a|^2 \frac{(\omega L_t)^2}{R_t}$$

Inductance of the toroid

Resistance of the toroid

$$\approx 10^{-29}\ \mathrm{W}\ \left(\frac{g\,\mathrm{GeV}}{10^{-11}}\right)\ \left(\frac{100\,\mathrm{n\Omega}}{R_t}\right)$$

$$\approx 140\ \frac{\text{axions}}{\text{year}}\ \left(\frac{10^{-5}\,\mathrm{eV}}{m_a}\right)$$

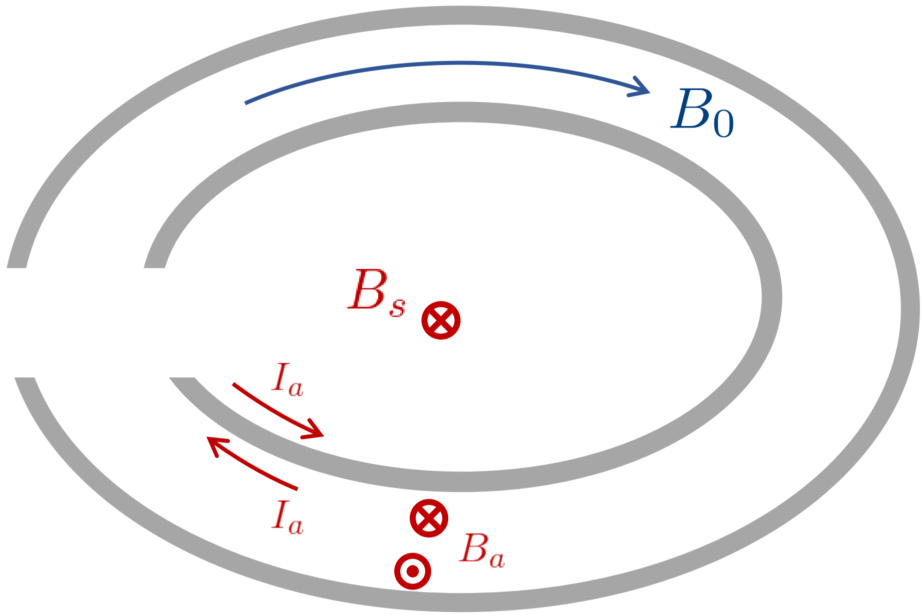
For small Q, impedance matching is not feasible as it demands a pickup inductance which prohibitively perturbs the resonance frequency. We must “undercouple”:

$$P_{\mathrm{uc}} = \frac{1}{2}|I_a|^2 \omega L_t Q$$

Amplification by detector cavity Q-factor

Toroid Resistance

Type-II Superconducting wires will contain possibly-dissipative flux tubes due to the large, static conversion magnetic field.



Dissipation is due to the Lorentz force between flux tubes and current:

$$R_t \propto \vec{B}_0 \times \vec{I}$$

Vanishes for an ideal toroid!

Fringe fields will cause B_0 to not be perfectly toroidal, tilted by an angle B_{ff}/B_0:

$$R_t \approx R_\perp \frac{B_{ff}}{B_0} \approx 100\,\mathrm{n\Omega} \left(\frac{B_{ff}}{10^{-6}\,\mathrm{T}}\right) \left(\frac{5\,\mathrm{T}}{B_0}\right)$$

Signal Strength

Optimal signal power for a given Q is the minimum of the matched and undercoupled powers

$$P_{\text{signal}} \approx g^4 \frac{B_{\text{PC}}^4 B_0^2}{\omega^6} \text{ Min}\left(\frac{\omega L_t}{R_t}, Q\right)$$

Toroid Limited

Cavity Limited

Threshold Q $\quad \dfrac{L_t \omega}{R_t} \approx 10^{10} \left(\dfrac{R}{10 \text{ cm}}\right)\left(\dfrac{100 \text{ n}\Omega}{R_t}\right)$

Superconducting Toroid: $R_t \gtrsim \text{n}\Omega$

Narrowband noise

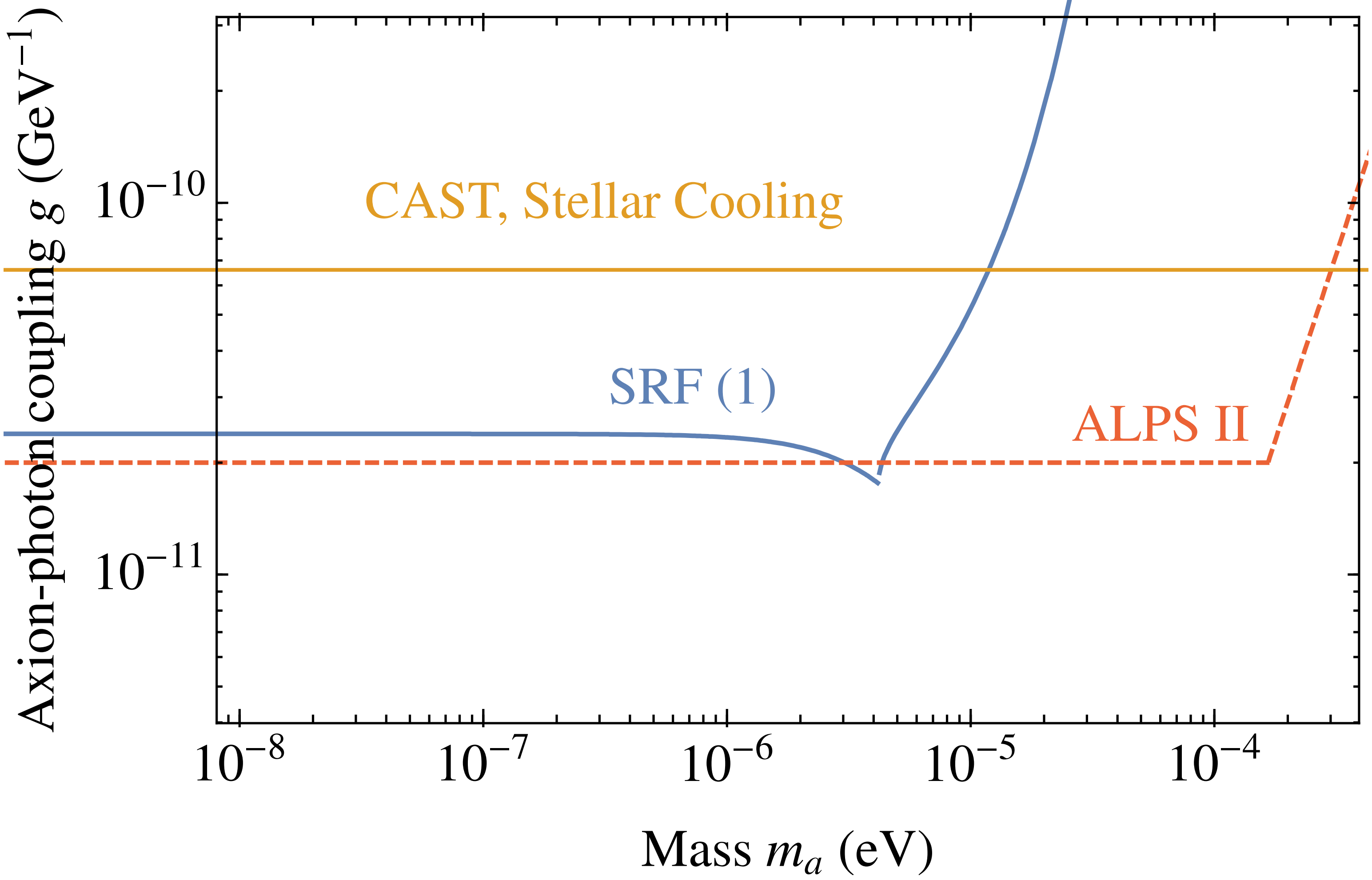
$$P_{\text{noise}} = \frac{T_{\text{sys}}}{t_{\text{int}}} \qquad T_{\text{sys}} \gtrsim \omega \sim 50 \text{ mK}$$

Quantum Limited

Projected Sensitivity

$T_{\text{sys}} = 0.1\ \text{K},\ t_{\text{int}} = 1\ \text{year},\ R = 10\ \text{cm},\ \nu = 1\ \text{GHz},\ B_{\text{PC}} = 0.2\ \text{T},\ B_0 = 5\ \text{T}$

$(1)\ R_t = 100\ \text{n}\Omega\ \ \text{and}\ \ Q \geq 10^{10}$



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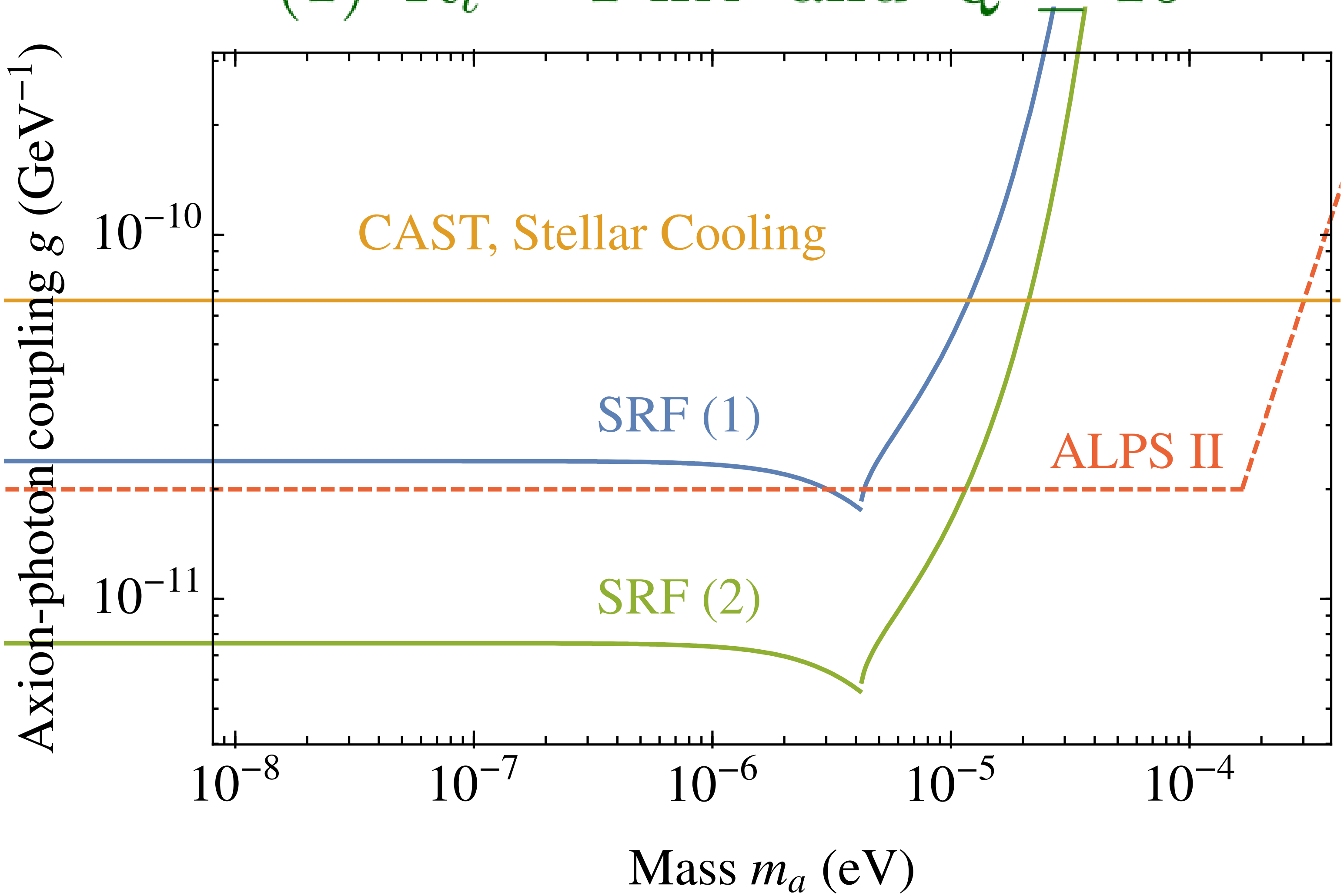
$(1)\ R_t = 1\ \text{n}\Omega\ \text{and}\ Q \geq 10^{12}$



Axion Production and Detection with Superconducting RF Cavities

A new design for an LSW ALP search based on SRF cavities

Our realization uses a gapped toroid to confine the magnetic field responsible for ALP-photon conversion, protecting the SRF cavities from quenching.

Major engineering challenges: matching the cavity frequencies and coupling the detection cavity without degrading Q.

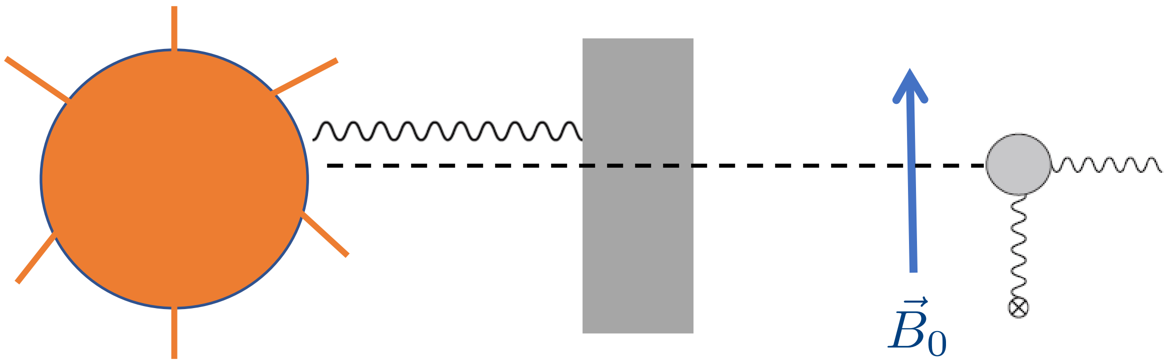
Comparable and complementary to future optical LSW searches and stellar constraints

Axion Production and Detection with Superconducting RF Cavities

Extra Slides

Stellar ALP Searches

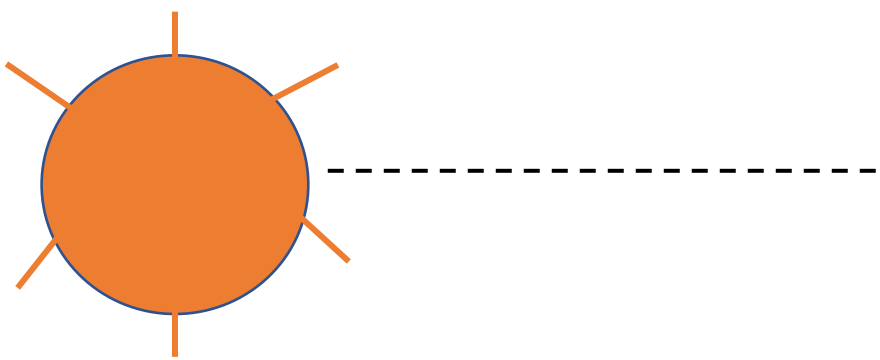
“Sun shining through a Wall” [Sikivie ‘83, Irastorza et al, ’17]



CAST

g < 7x10^{-11} GeV^{-1}
for m_a < eV

Stellar Cooling

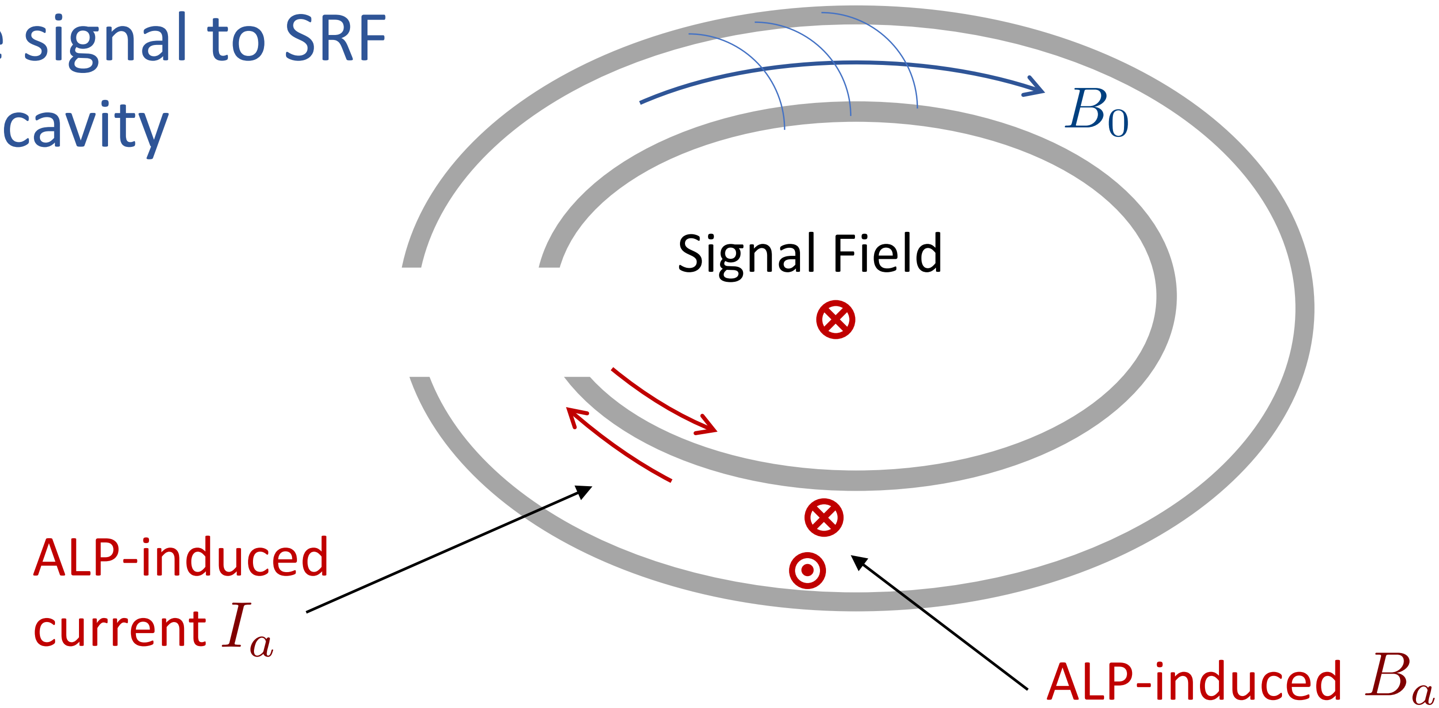


HB Stars

g < 7x10^{-11} GeV^{-1}
for m_a < keV

Gapped Toroid Conversion Region

(4) Couple signal to SRF detection cavity

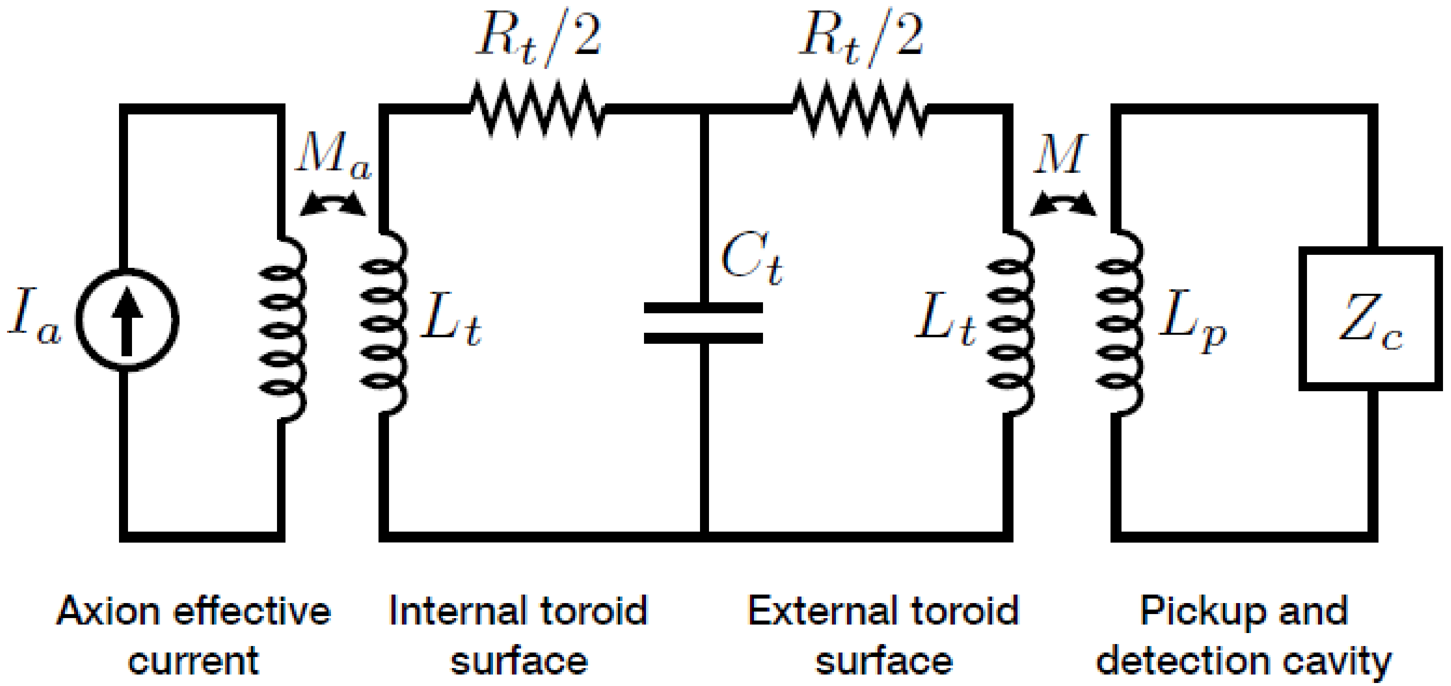


$$I_a \approx 10^{-13}\ \mathrm{nA} \left(\frac{g\ \mathrm{GeV}}{10^{-11}}\right)^2 \left(\frac{B_{\mathrm{PC}}}{0.1\ \mathrm{T}}\right)^2 \left(\frac{B_0}{5\ \mathrm{T}}\right) \left(\frac{R}{10\ \mathrm{cm}}\right)^3$$

$$B_a \approx 10^{-26}\ \mathrm{T} \left(\frac{g\ \mathrm{GeV}}{10^{-11}}\right)^2 \left(\frac{B_{\mathrm{PC}}}{0.1\ \mathrm{T}}\right)^2 \left(\frac{B_0}{5\ \mathrm{T}}\right) \left(\frac{R}{10\ \mathrm{cm}}\right)^2$$

Optimal Signal Power

Maximal signal power follows from an equivalent circuit for the axion – toroid – cavity system.



Three current paths on the toroid: completely internal, completely external, or wrapping internal and external

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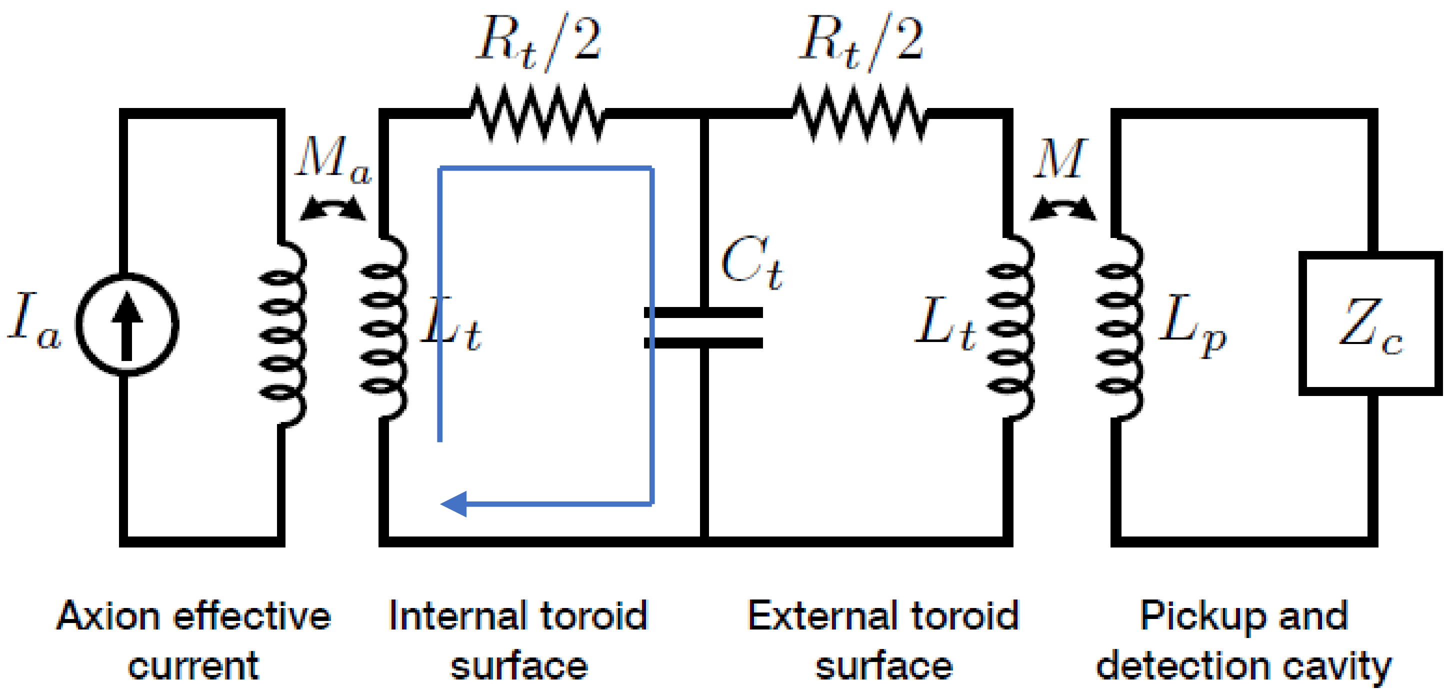

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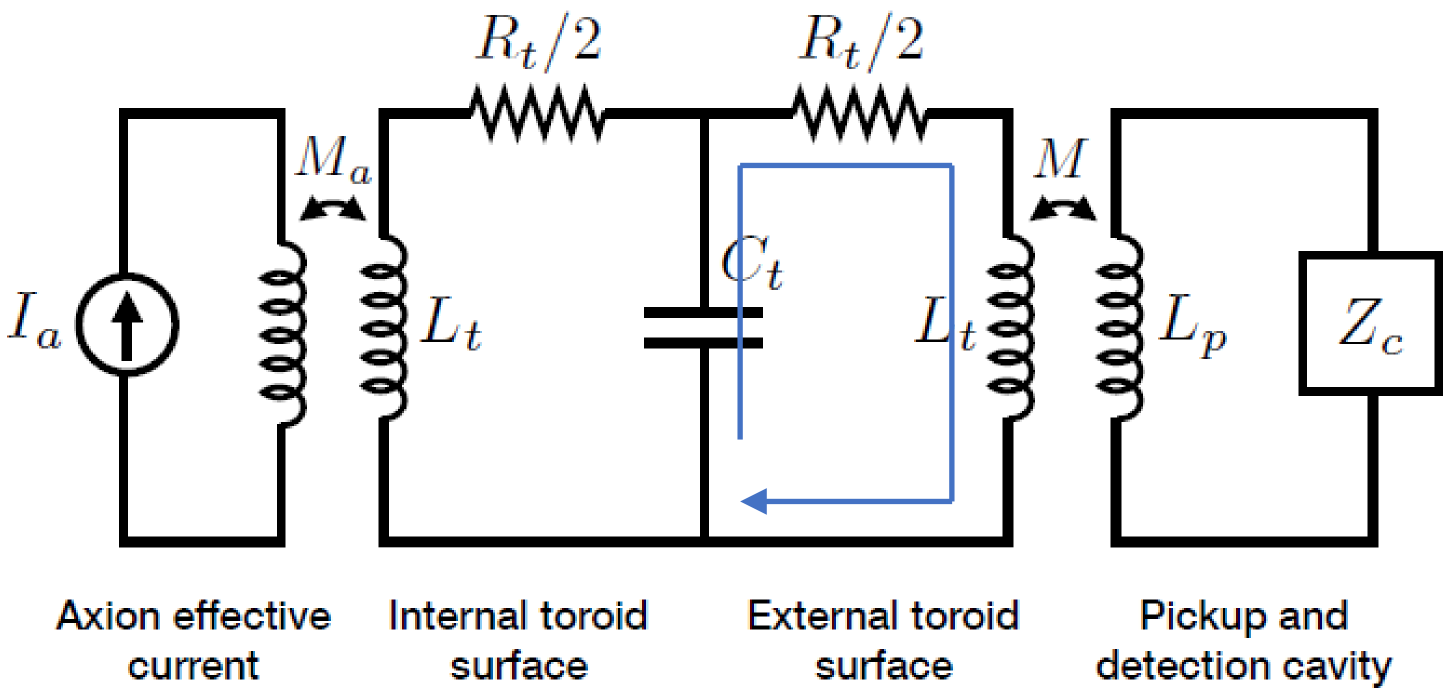

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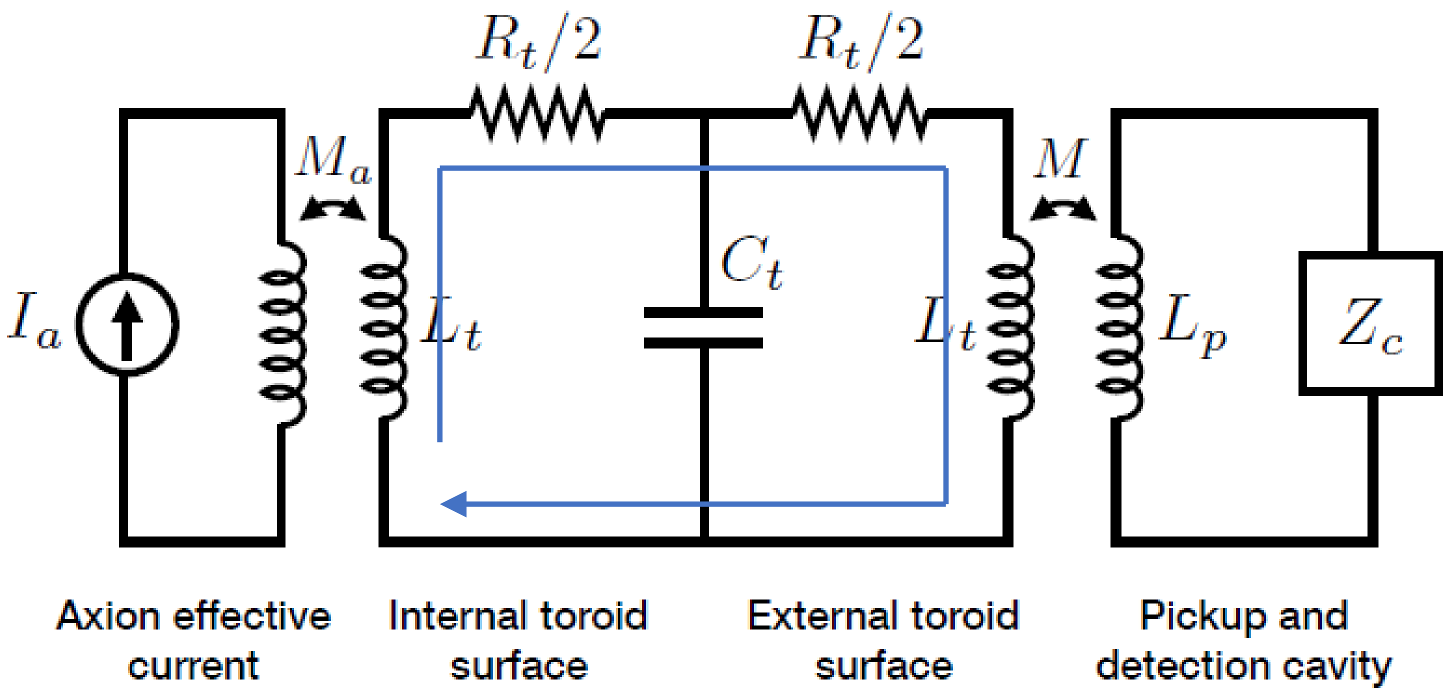
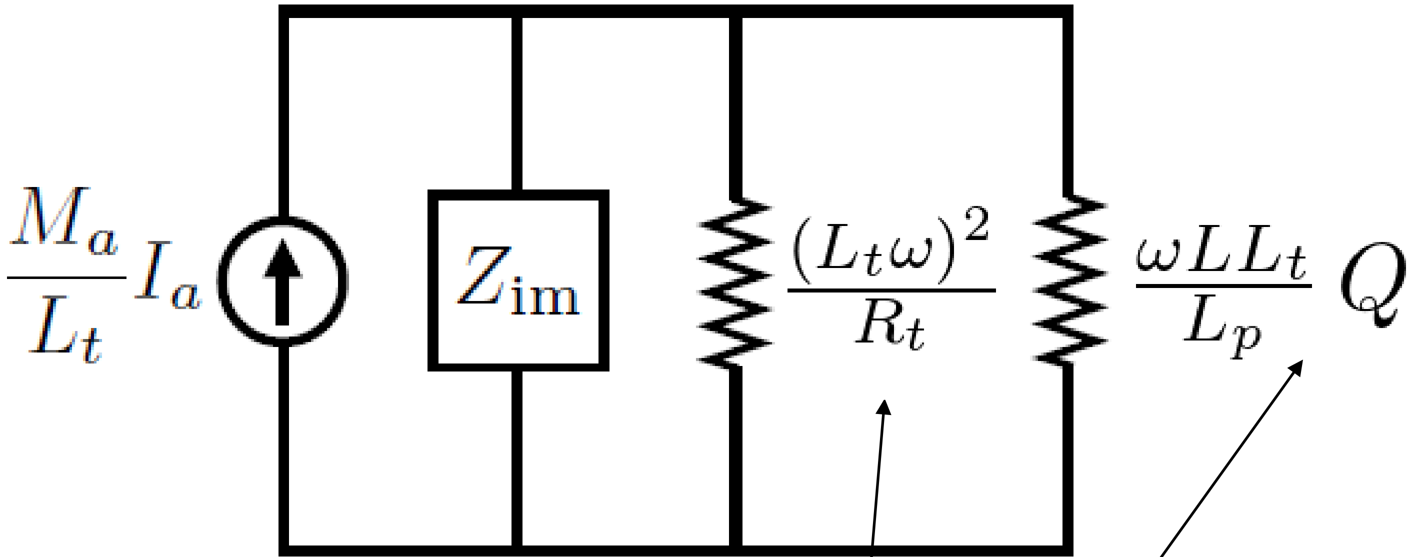
Optimal Signal Power

Maximal signal power follows from an equivalent circuit for the axion – toroid – cavity system.



Three current paths on the toroid: completely internal, completely external, or wrapping internal and external

Optimal Signal Power



Circuit simplifies:

Resistor for dissipation in the toroid

Resistor for dissipation detection cavity

Imaginary impedance (determines resonance frequency)

Maximum power is transferred to the cavity when L_P is tuned such that the two resistance are equal.

Optimal Signal Power

Tuning L_p alters the resonance frequency, which is given by the zero of Z_{im}

$$Z_{\text{im}} \sim \left(\frac{2}{i\omega L_t} + i\omega C_t + \frac{1}{i\omega \frac{L_t}{L_p} L} + i\omega \frac{L_p}{L_t} C \right)^{-1}$$

$$\omega_{\text{res}} \sim \omega_0 \sqrt{1 + 2\frac{L}{L_p}}$$

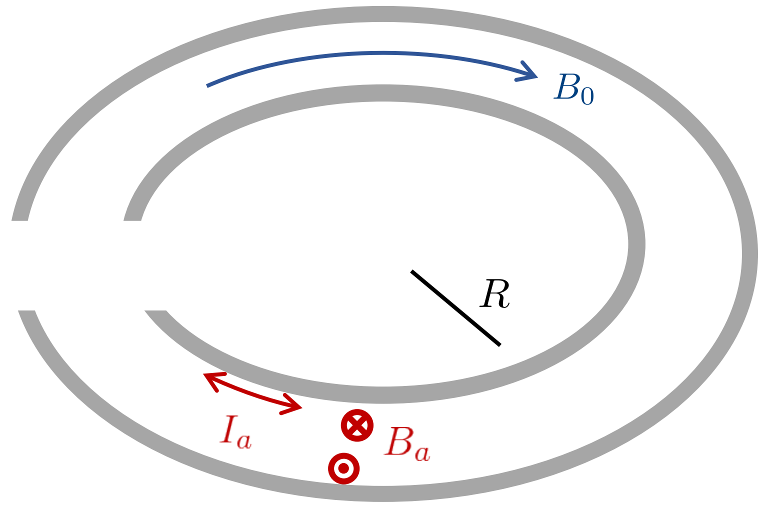
Require L_p >> L to preserve resonance near GHz – otherwise it is not the detection cavity that will rung up, but the pickup loop.

This obstructs impedance matching for small Q, as the optimal L_p is

$$L_p^{\text{match}} = \frac{L}{L_t \omega} R_t Q \gg L$$

$$Q \gg \frac{L_t \omega}{R_t}$$

AC Screening



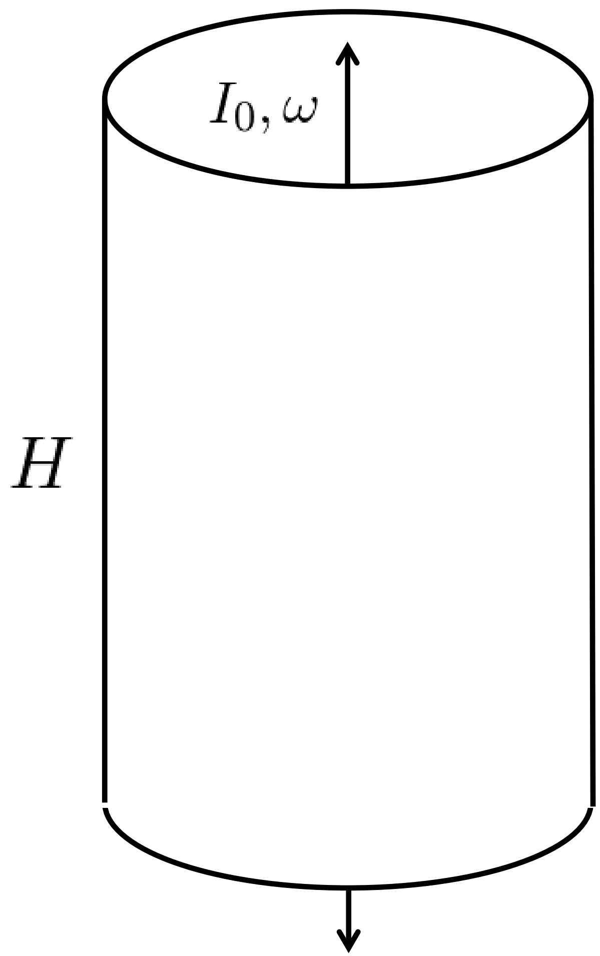
Increasing the frequency above the quasistatic limit will suppress the external current and external field.

Suppression will scale as a power-law in frequency.

This is hard to calculate in the full toroid geometry, but we can see the nature of the effect in a simpler case.

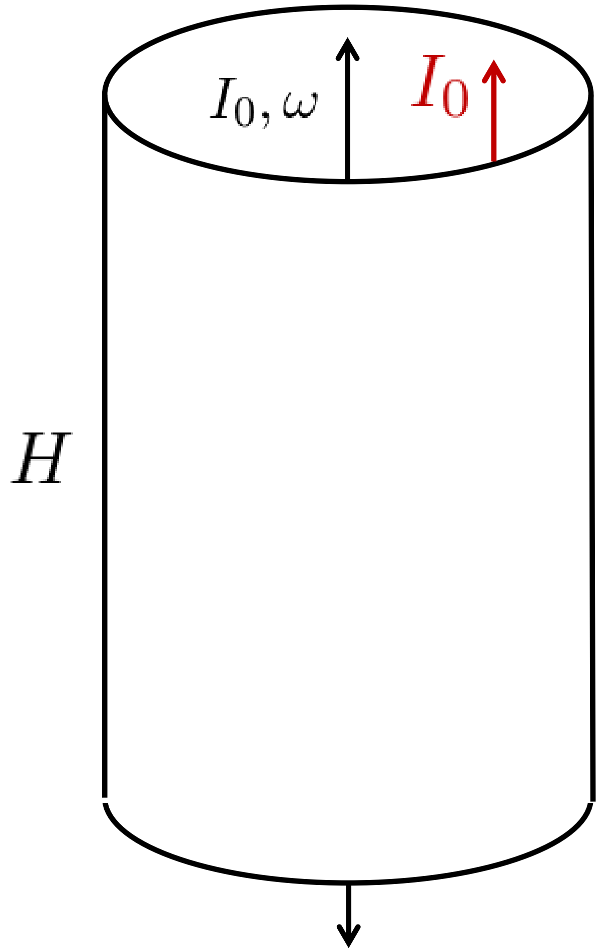
Toy Model of Screening

An AC current is switched on inside of a finite cylindrical, conducting shell – what are the external fields in the vicinity of the conductor?



Toy Model of Screening

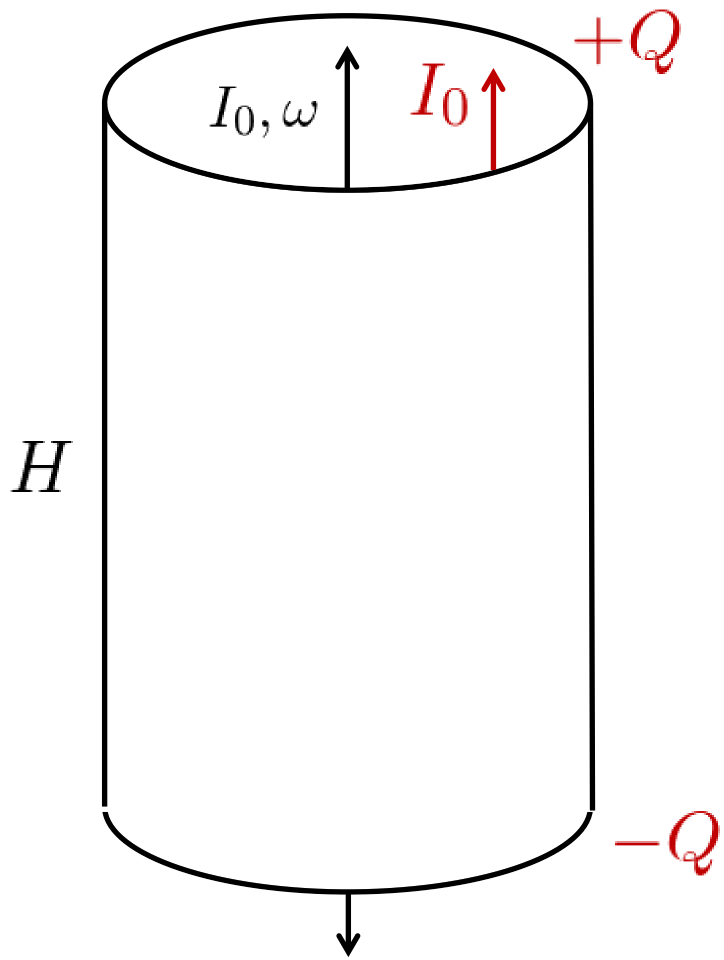
An AC current is switched on inside of a finite cylindrical, conducting shell – what are the external fields in the vicinity of the conductor?



A screening current must first be established on the inner surface.

Toy Model of Screening

An AC current is switched on inside of a finite cylindrical, conducting shell – what are the external fields in the vicinity of the conductor?

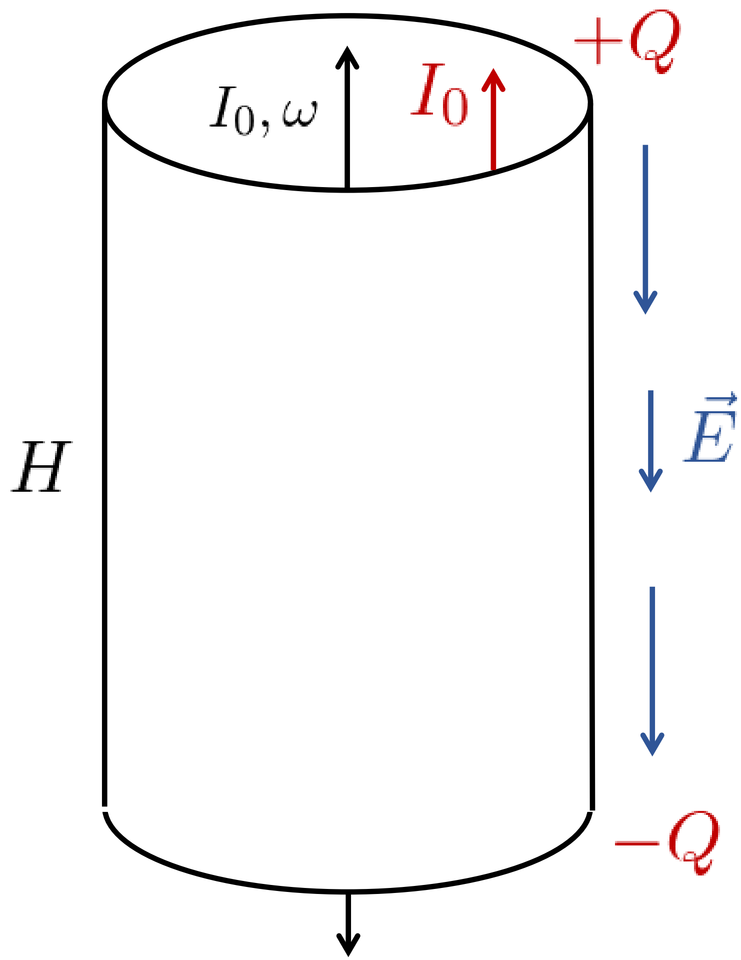


A screening current must first be established on the inner surface.

This causes a build-up of charge on the edges, which backreacts on the screening current

Toy Model of Screening

An AC current is switched on inside of a finite cylindrical, conducting shell – what are the external fields in the vicinity of the conductor?

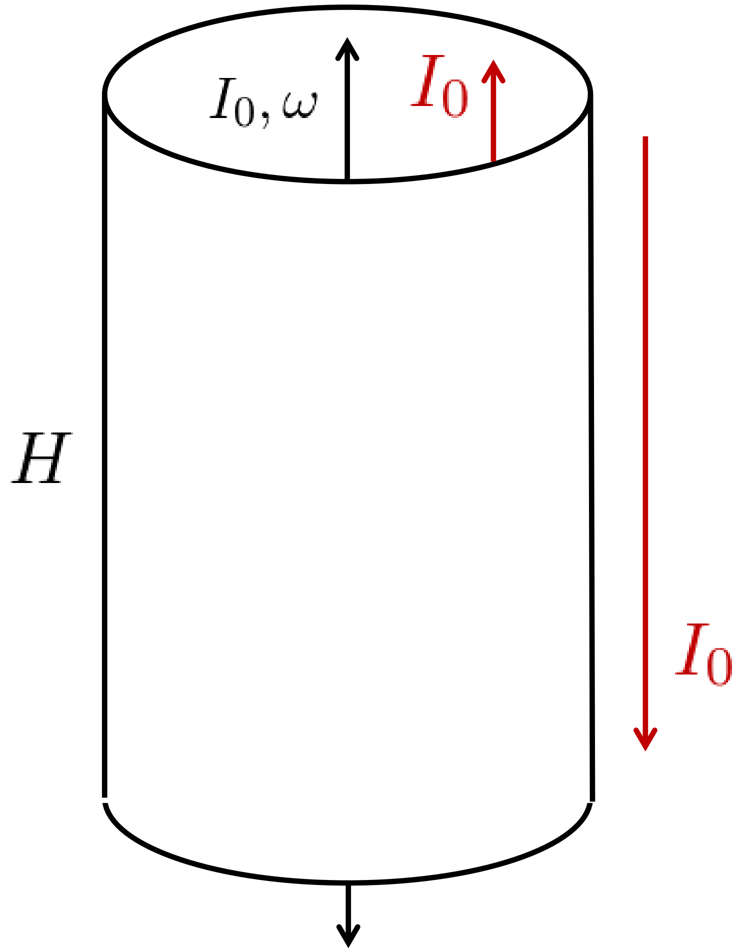


Quasistatic $(\omega H \ll 1)$

Edge charges source quasistatic Coulomb field, with uniform direction along the cylinder.

Toy Model of Screening

An AC current is switched on inside of a finite cylindrical, conducting shell – what are the external fields in the vicinity of the conductor?



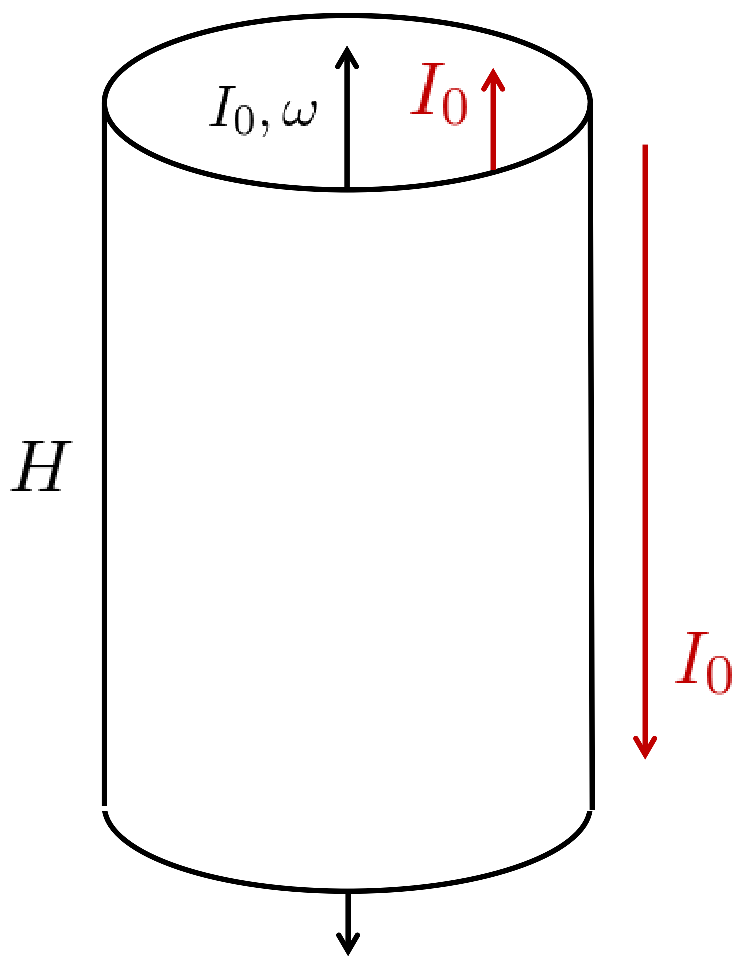
Quasistatic $(\omega H \ll 1)$

Edge charges source quasistatic Coulomb field, with uniform direction along the cylinder.

Coulomb field drives uniform external current, eliminating charge build-up.

Toy Model of Screening

An AC current is switched on inside of a finite cylindrical, conducting shell – what are the external fields in the vicinity of the conductor?



Quasistatic $(\omega H \ll 1)$

Edge charges source quasistatic Coulomb field, with uniform direction along the cylinder.

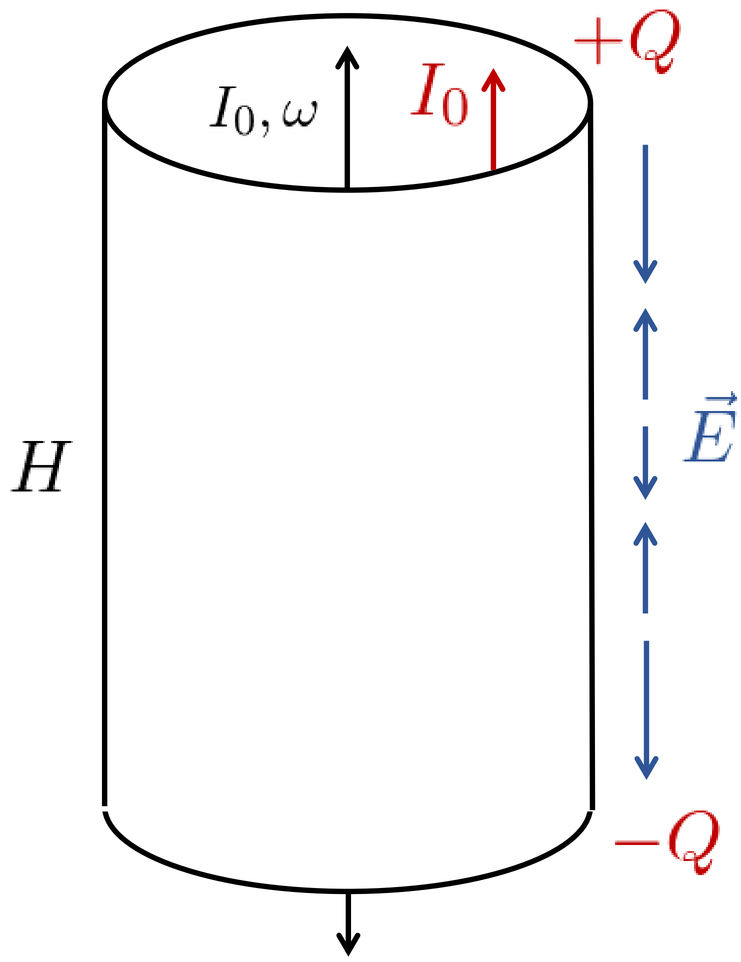
Coulomb field drives uniform external current, eliminating charge build-up.

External current sources a field equal to that of the central current.

No Screening

Toy Model of Screening

An AC current is switched on inside of a finite cylindrical, conducting shell – what are the external fields in the vicinity of the conductor?

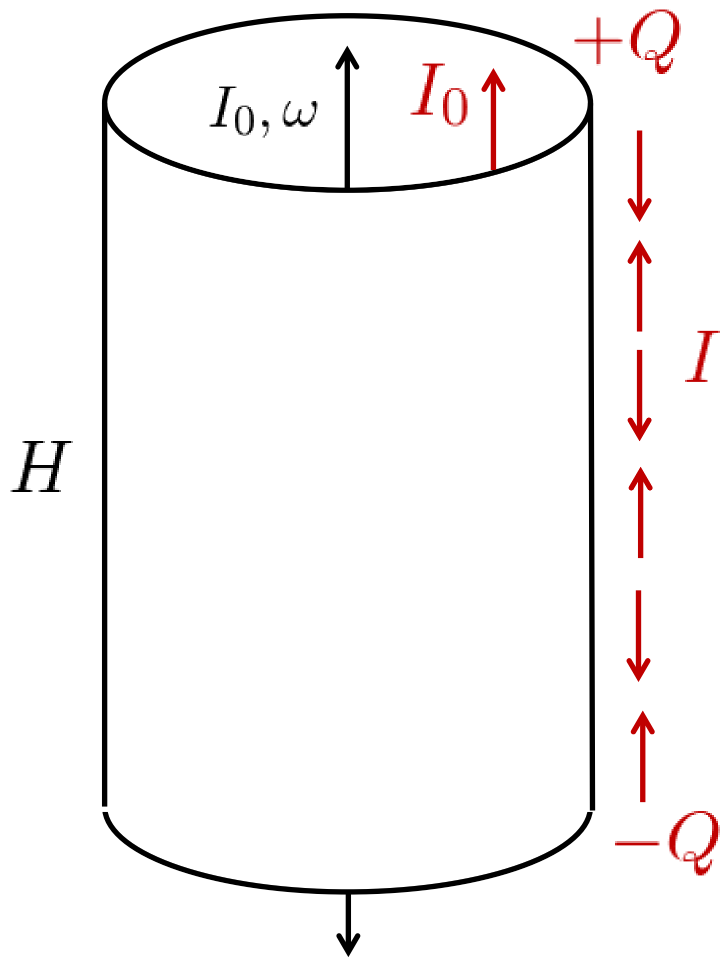


Screened $(\omega H \gg 1)$

Edge charges source radiative electric field, with alternating direction.

Toy Model of Screening

An AC current is switched on inside of a finite cylindrical, conducting shell – what are the external fields in the vicinity of the conductor?



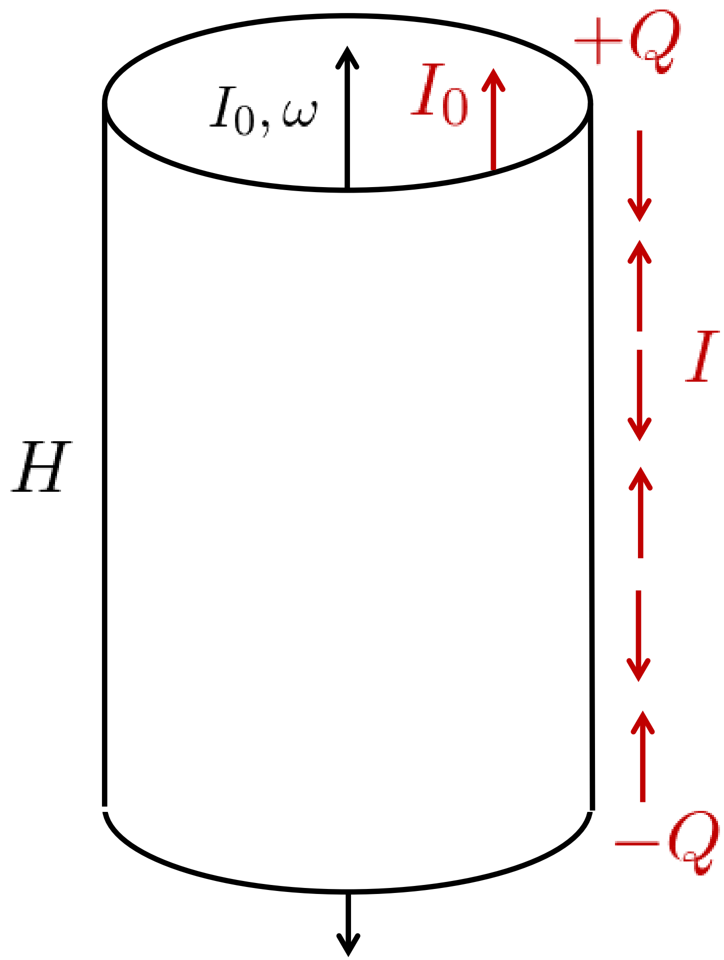
Screened $(\omega H \gg 1)$

Edge charges source radiative electric field, with alternating direction.

Radiative field drives spatially alternating current, charge build-up is maintained.

Toy Model of Screening

An AC current is switched on inside of a finite cylindrical, conducting shell – what are the external fields in the vicinity of the conductor?



Screened $(\omega H \gg 1)$

Edge charges source radiative electric field, with alternating direction.

Radiative field drives spatially alternating current, charge build-up is maintained.

Non-uniform external current sources a multi-pole field, suppressed relative to the field of the internal current.

Power-law Screening