Title: Axion production and detection with superconducting RF cavities

Speakers: Vijay Narayan

Series: Particle Physics

Date: July 26, 2019 - 1:00 PM

URL: http://pirsa.org/19070001

Abstract: We propose a novel design of a laboratory search for axions based on photon regeneration with superconducting RF cavities. Our particular setup uses a toroid as a region of confined static magnetic field, while production and detection cavities are positioned in regions of vanishing external field. This permits cavity operation at quality factors of Q ~ 10Â^{1}â•° - 10Â^{1}Â^{2}. The limitations due to fundamental issues such as signal screening and back-reaction are discussed, and the optimal sensitivity is calculated. This experimental design can potentially probe axion-photon couplings beyond astrophysical limits, comparable and complementary to next generation optical experiments.

New light boson?

Strong evidence for physics BSM. Where to look?

Physics in far UV can lead to low-energy observables, including new light degrees of freedom

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Axions 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, weakly-coupled particle. How to detect?

Axion EM Searches

Coherent axion-photon conversion in static B_0

$$P_{a\to\gamma} \sim (gB_0L)^2 \sim 10^{-19}\left(\frac{g\ \mathrm{GeV}}{10^{-11}}\right)^2\left(\frac{B_0}{5\ \mathrm{T}}\right)^2\left(\frac{L}{10\ \mathrm{m}}\right)^2$$

Coherence if $qL \sim \frac{m_a^2 L}{\omega} \lesssim 1$

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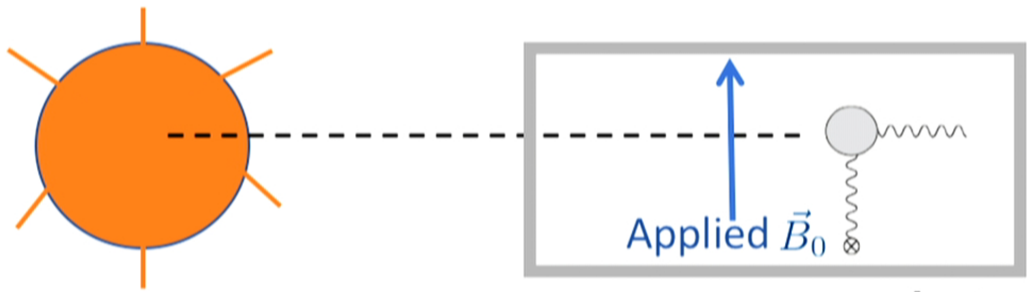
"Sun shining through a Wall"



[Irastorza et al, '17]

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

(comparable to stellar cooling bounds)

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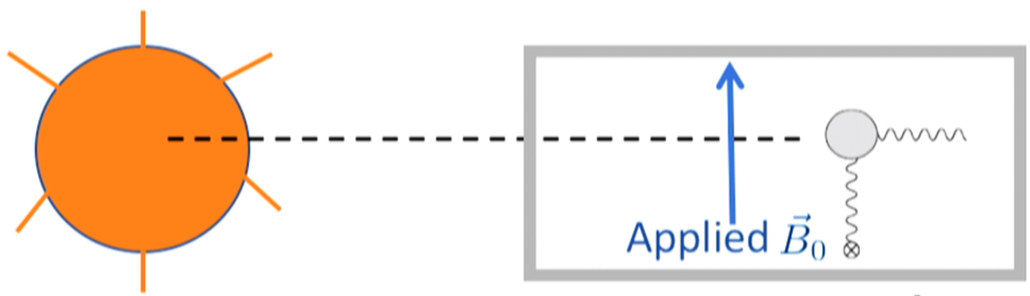

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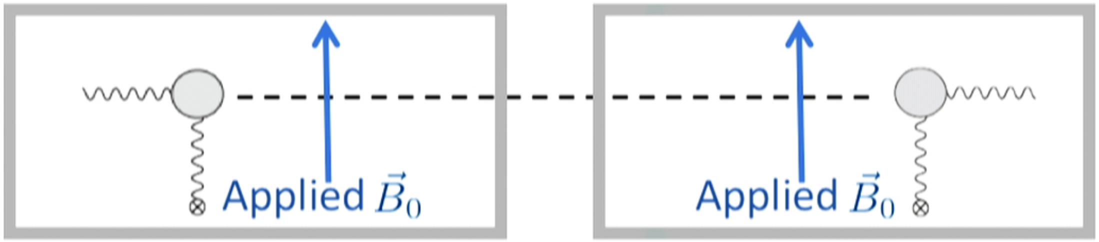

[van Bibber et al '87, ...]

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 Cavities

ω, L^{-1} are independent

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

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

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RF Cavities

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

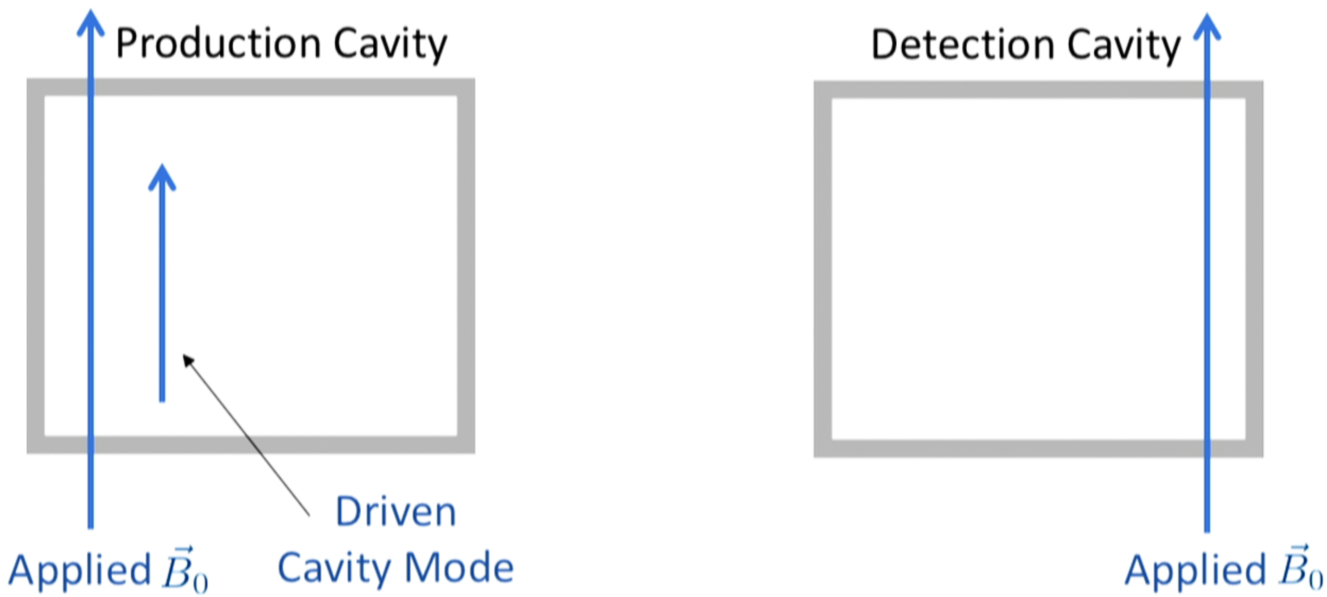
CROWS: $g < 10^{-7}\ \mathrm{GeV}^{-1}$
for $m_a <$ μeV

This work: possibilities with superconducting RF technology?

See: [Bogorad, Hook, Kahn, Soreq, '19]
for very distinct proposal

LSW with RF Cavities

[Hoogeveen, '92]



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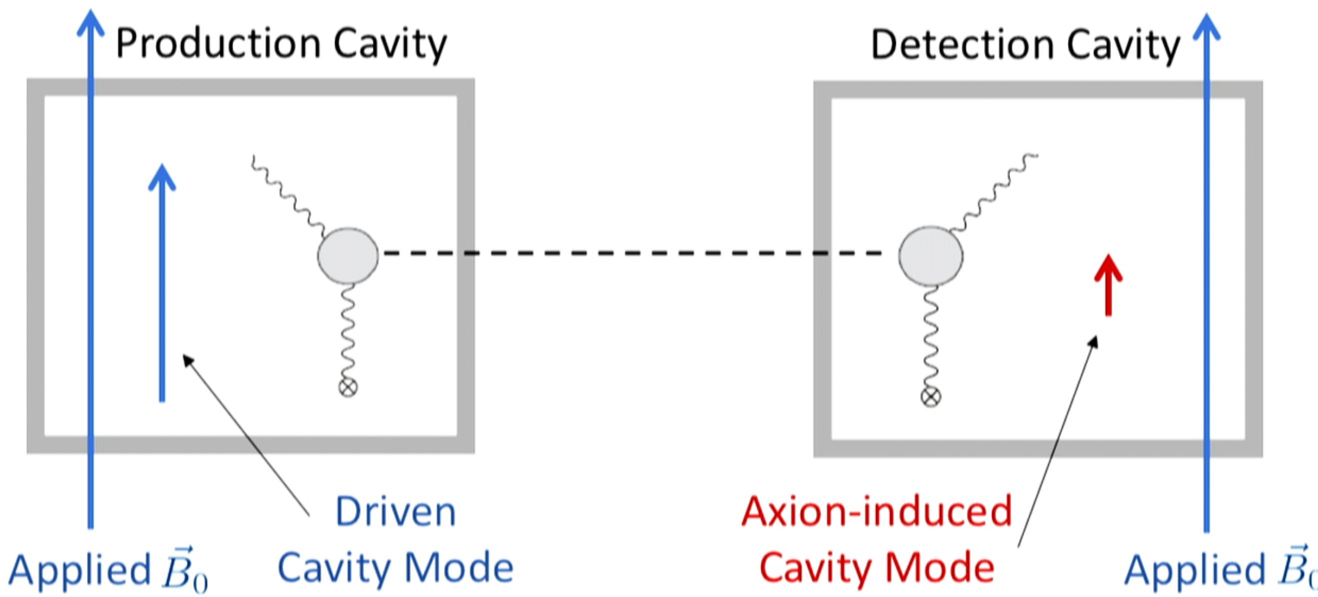
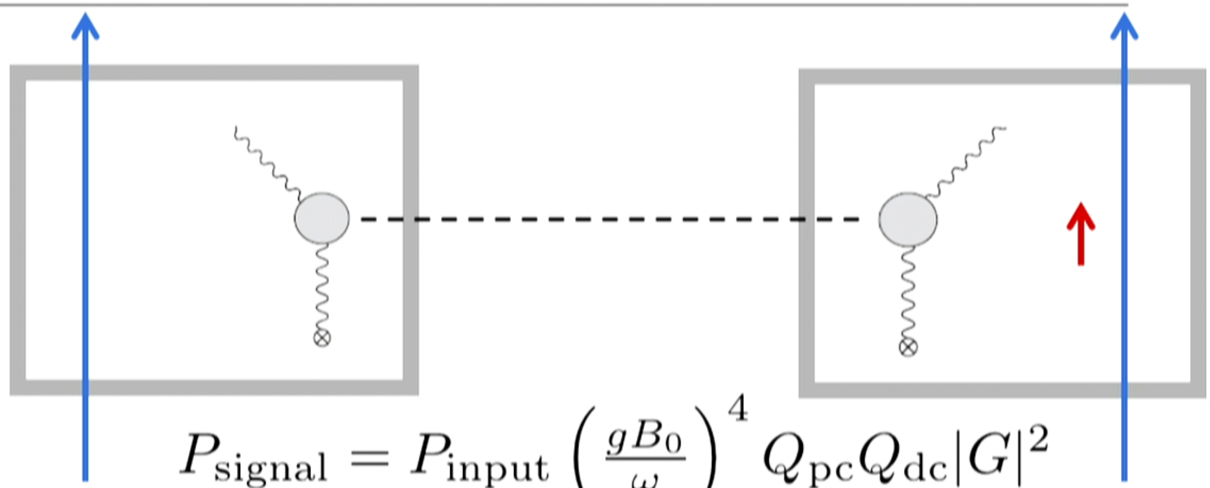


$$P_{\text{signal}} = P_{\text{input}} \left(\frac{gB_0}{\omega}\right)^4 Q_{\text{pc}} Q_{\text{dc}} |G|^2$$

O(0.1) Form factor
Exponential cut off for $m_a > \omega$

LSW with SRF Cavities

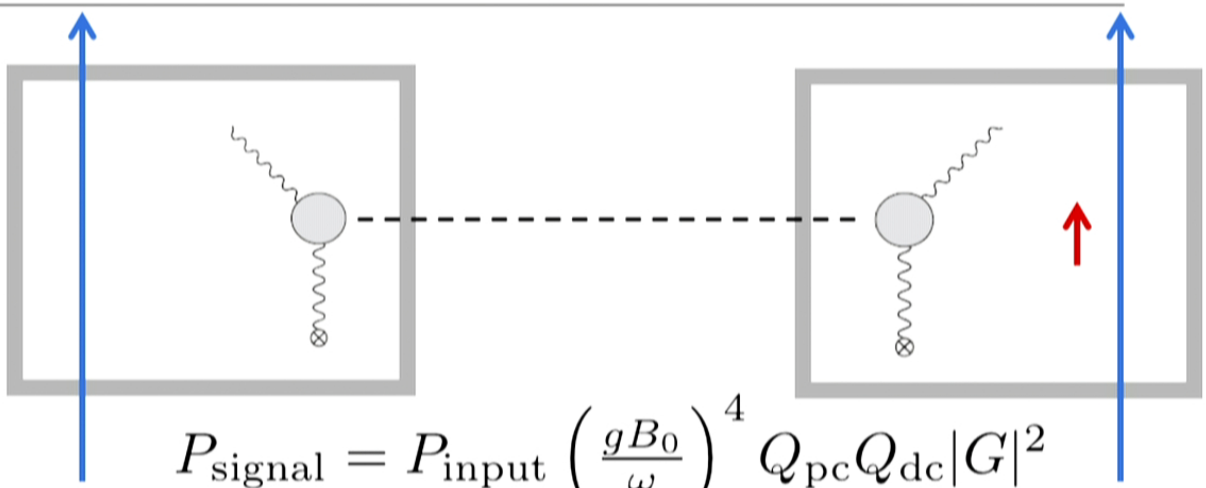


$$P_{\text{signal}} = P_{\text{input}} \left(\frac{gB_0}{\omega}\right)^4 Q_{\text{pc}} Q_{\text{dc}} |G|^2$$

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

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

LSW with SRF Cavities



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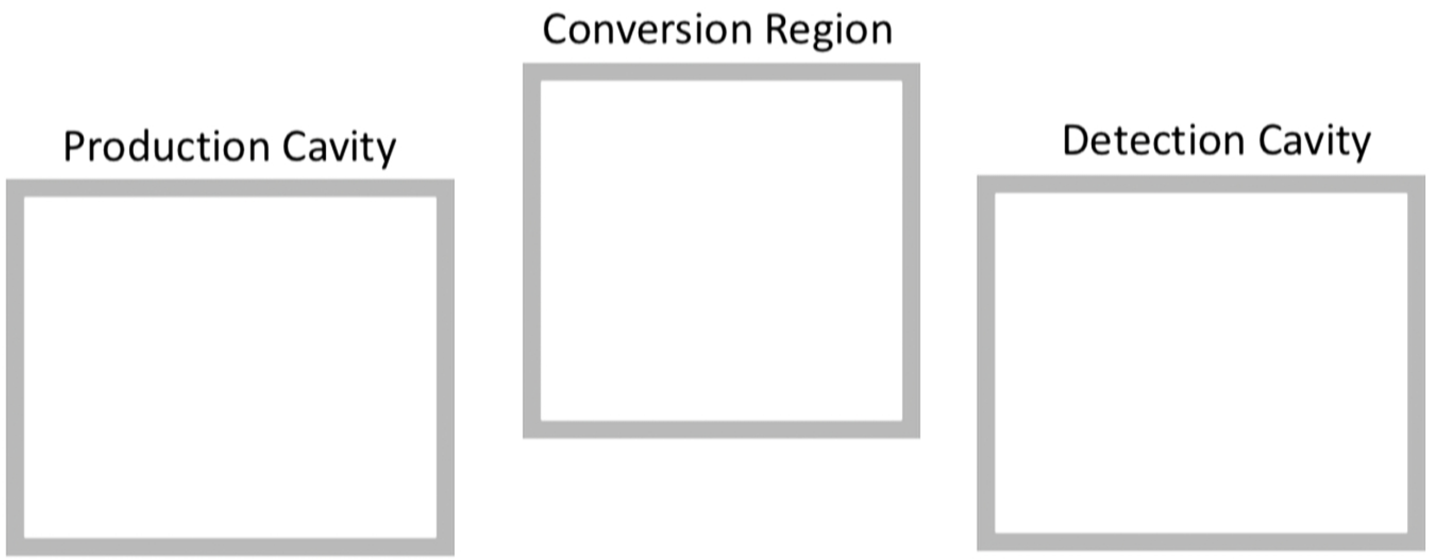
Superconducting RF $Q \sim 10^{10} - 10^{12}$

B > O(0.2 T) critical field, flux penetration degrades Q

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

New Design for LSW with SRF



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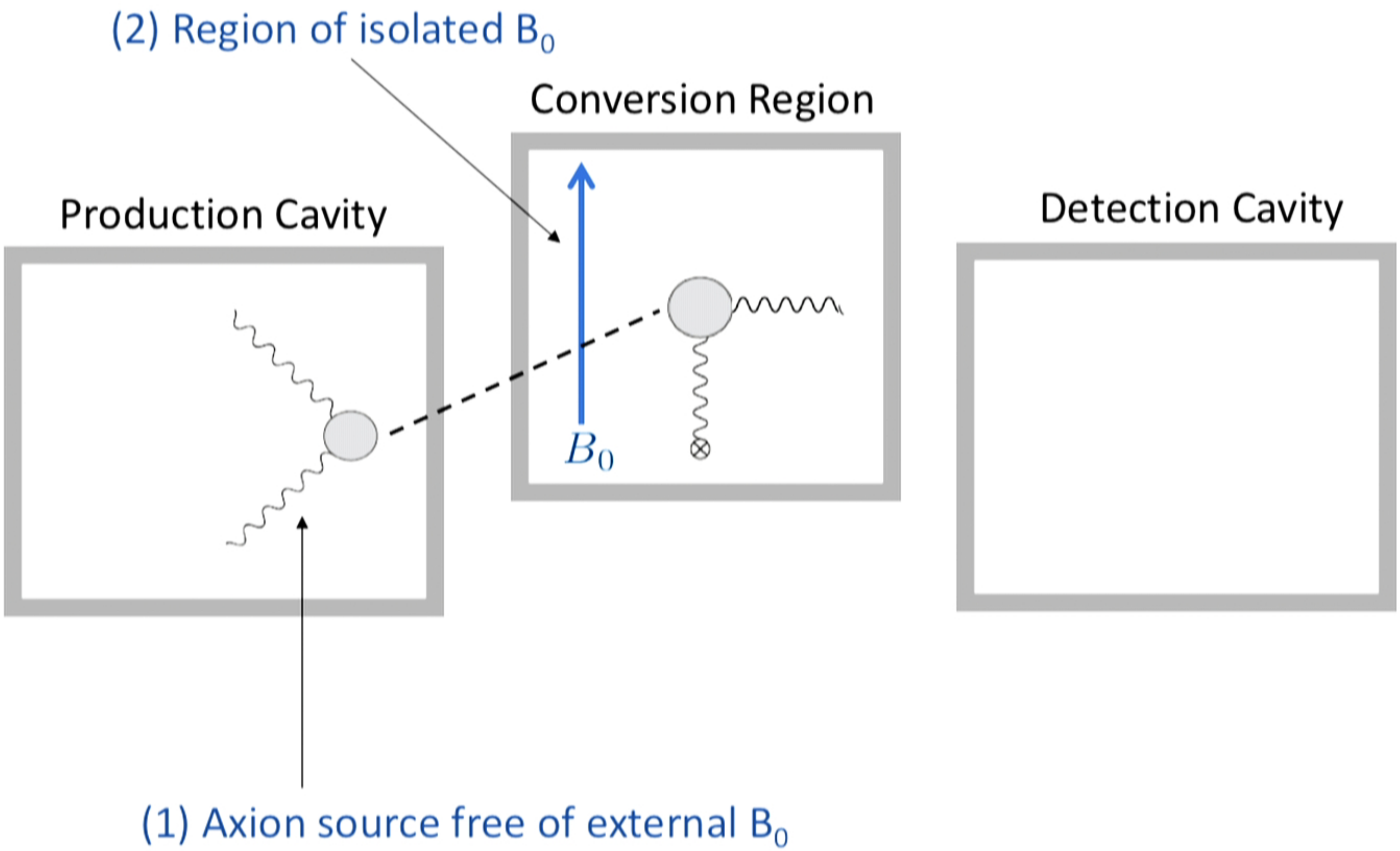

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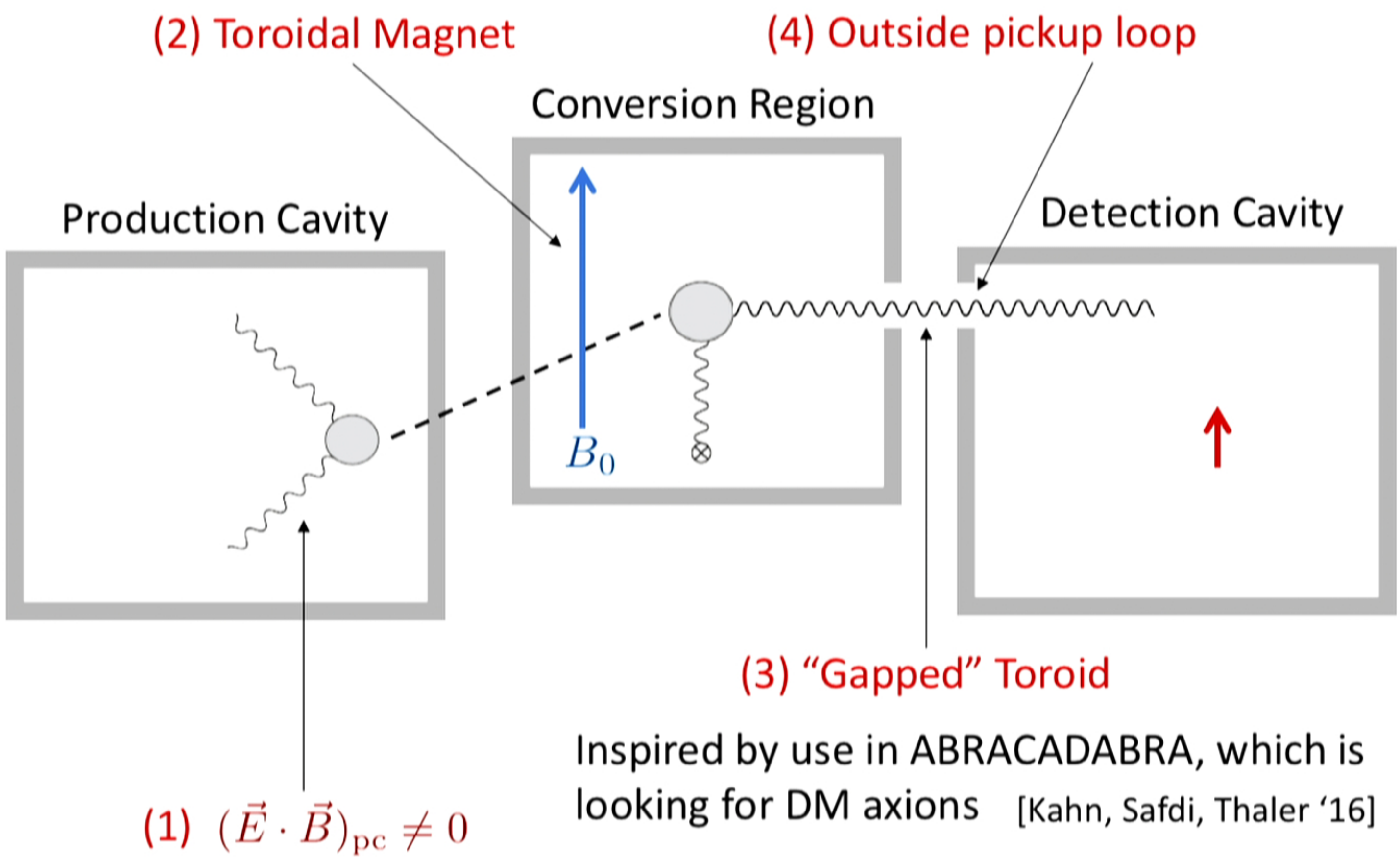

Inspired by use in ABRACADABRA, which is looking for DM axions [Kahn, Safdi, Thaler '16]

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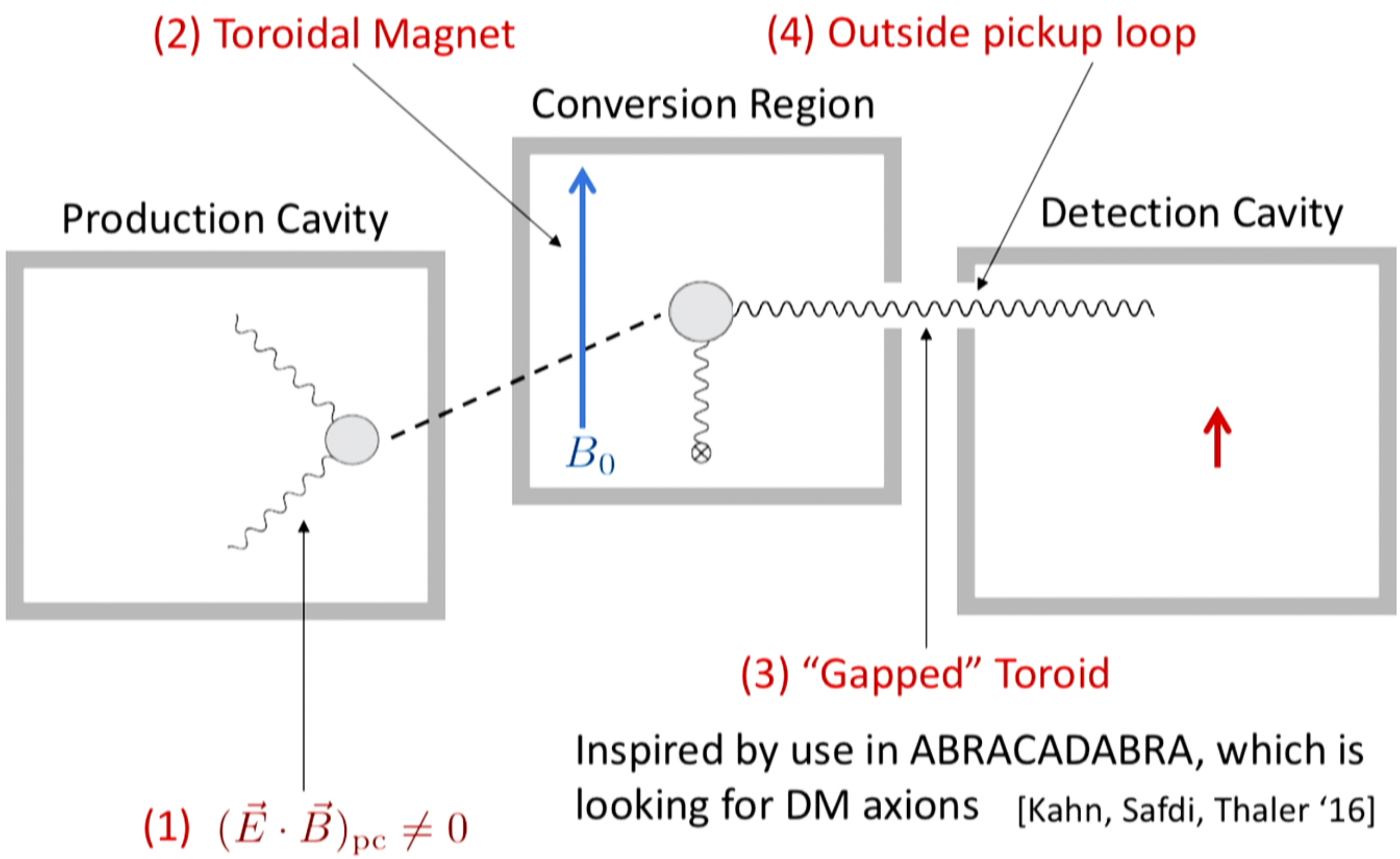

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Axion Electrodynamics

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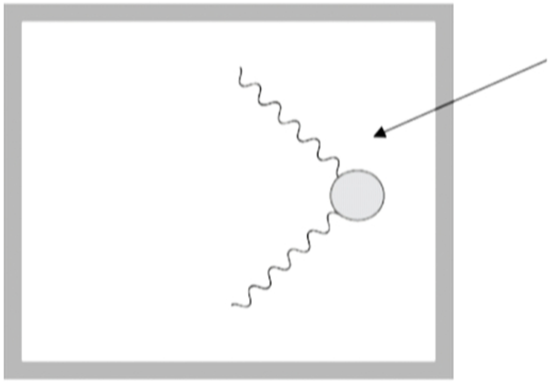
Axion Production $\Longrightarrow$ $a(x) = -ge^{i\omega t}\int_{\rm pc} d^3y \ \frac{e^{ik|\vec{x}-\vec{y}|}}{4\pi|\vec{x}-\vec{y}|}(\vec{E}\cdot\vec{B})$

SRF Axion Source

(1) Axion source without external B_0



Cavity mode(s) such that E.B not identically vanishing

Fundamentally limited by SRF critical field (independent of Q, input power, etc.)

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

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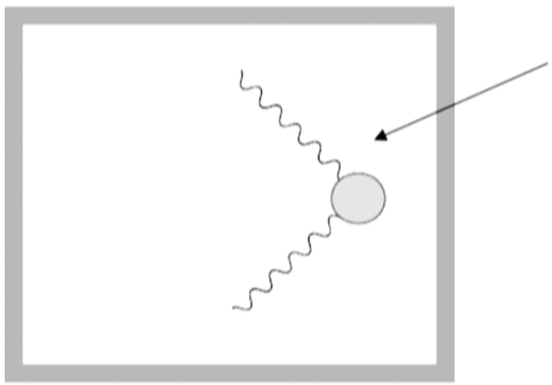

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Compare with normal conducting RF with external B_0

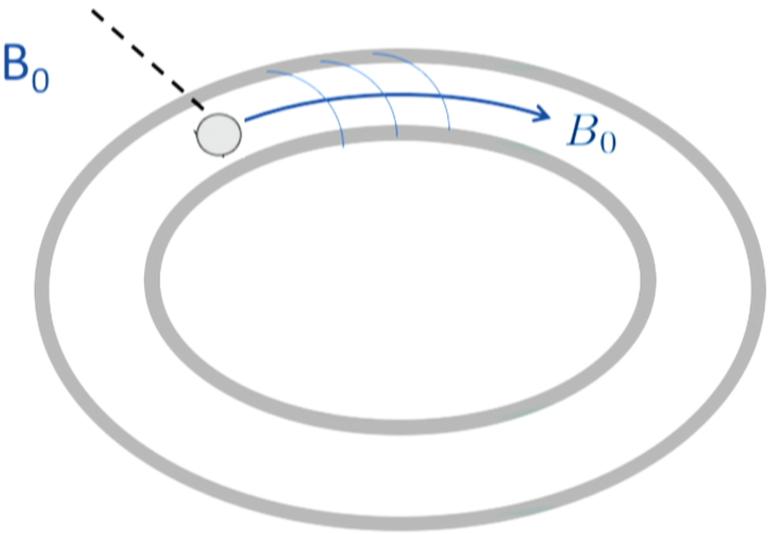
$$(\vec{E}\cdot\vec{B}) \sim (0.1\ {\rm T})^2 \left(\frac{P_{\rm input}}{100\ {\rm W}}\right)^{\frac{1}{2}} \left(\frac{Q_{\rm pc}}{10^5}\right)^{\frac{1}{2}} \left(\frac{B_0}{5\ {\rm T}}\right)$$

Real advantage of high-Q is on detection side!

Gapped Toroid Conversion Region

(2) Confine large static B_0

Generated by wrapped DC current-carrying superconducting wires



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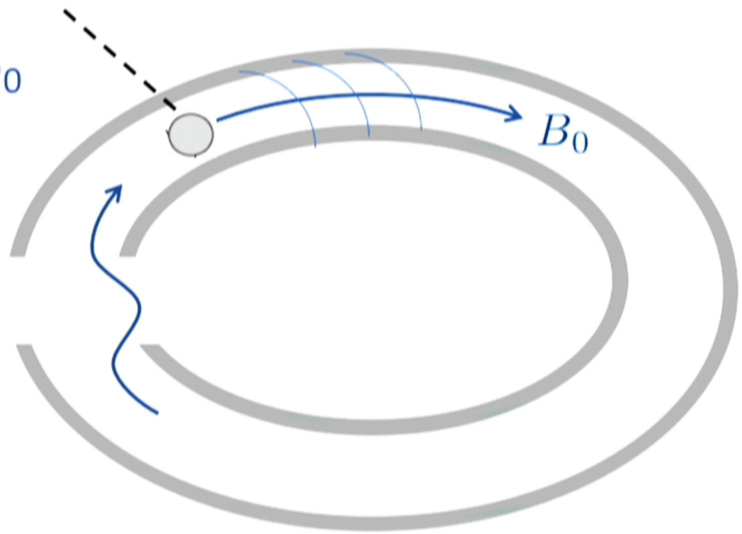
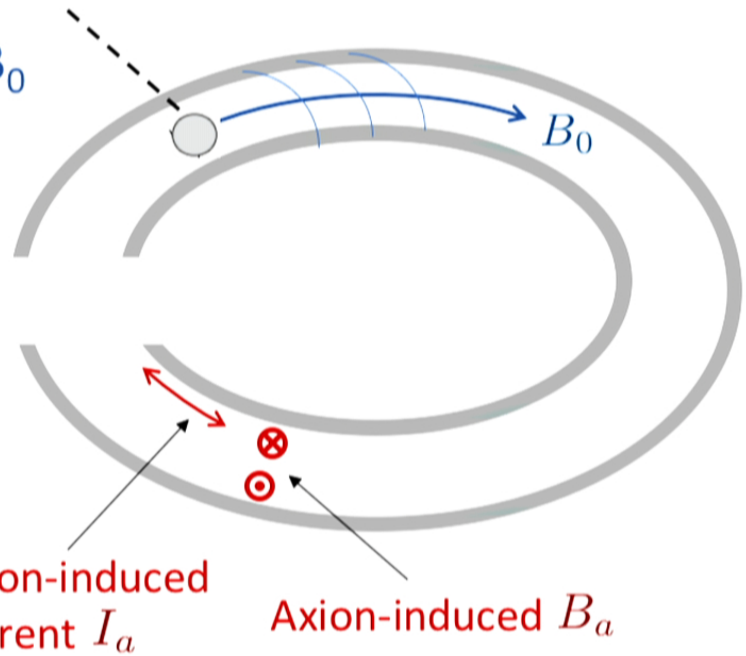
(3) Allow RF signal to propagate out



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

Conversion Region

(2) Confine large static B_0



(3) Allow RF signal
to propagate out

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

For sufficiently large frequencies:
I_a has significant spatial gradients **Signal parametrically suppressed**

Conversion Region

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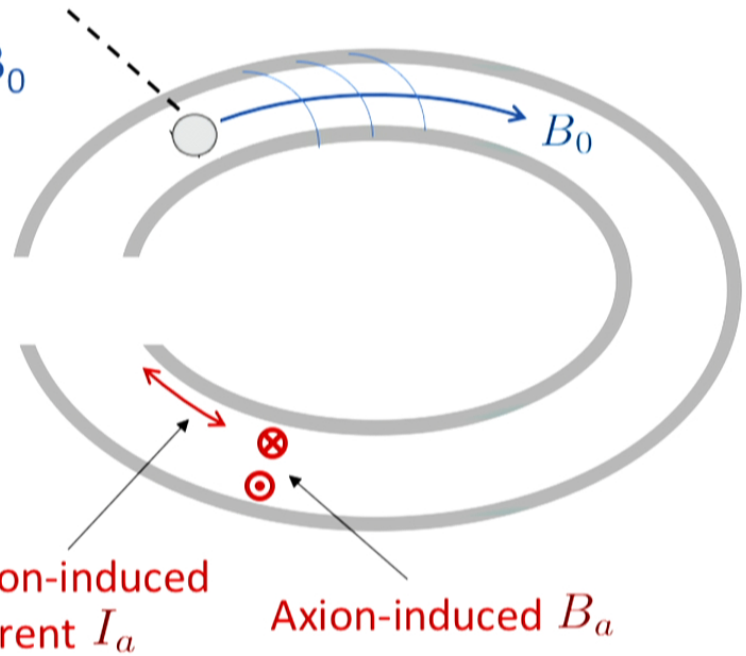

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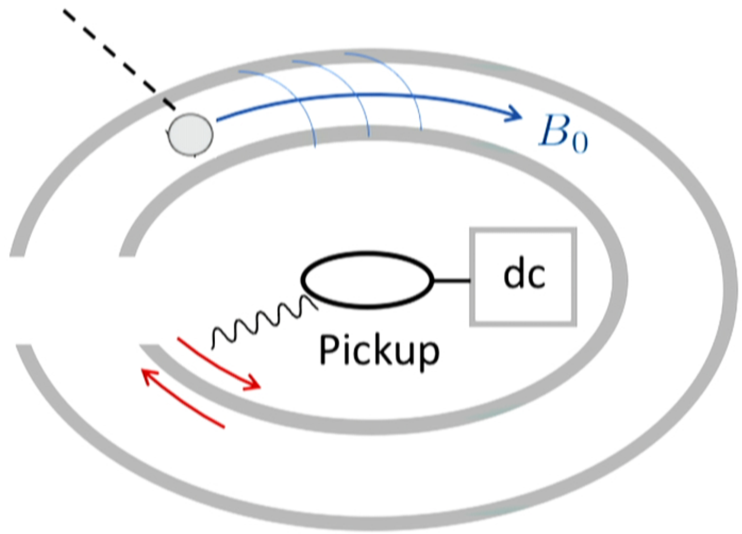
Signal Pickup

(4) Couple signal to SRF detection cavity



$$B_a \sim \frac{g^2 B_{\rm pc}^2 B_0}{\omega^2} \sim 10^{-26}\ \mathrm{T}\ \left(\frac{g\ \mathrm{GeV}}{10^{-11}}\right)^2 \left(\frac{B_{\rm pc}}{0.2\ \mathrm{T}}\right)^2 \left(\frac{B_0}{5\ \mathrm{T}}\right)$$

Amplify RF signal by Q?

Toroid is not a perfect "source" - non-negligible back-reaction

Must account for toroid impedance as well

Signal Pickup

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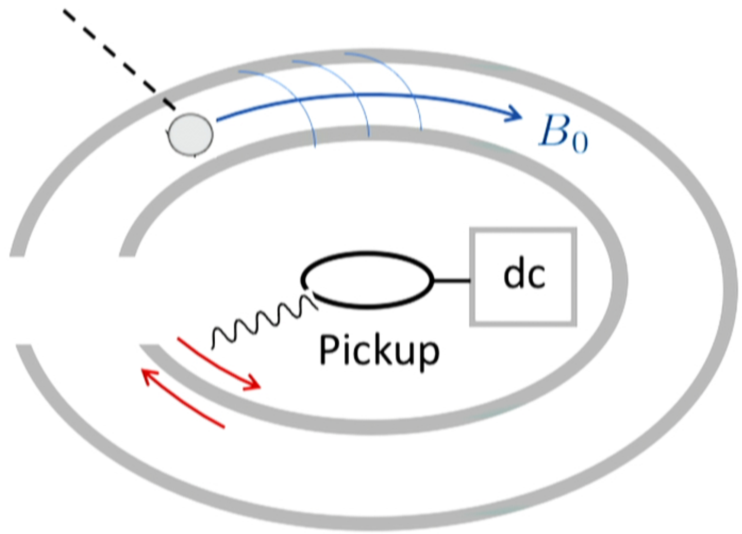

Gap capacitance	Toroid inductance	Superconductor
$C_t \sim 10^{-2}\ \mathrm{pF}\left(\frac{d}{\mathrm{mm}}\right)$	$L_t \sim 125\ \mathrm{nH}\left(\frac{R}{10\ \mathrm{cm}}\right)$	$R_t \gtrsim 10^{-9}\ \Omega$

Optimal Signal Strength

Adjust pickup to impedance match $L_p \sim \frac{QR_t}{\omega}$

$$\Rightarrow P_{\max} \sim |I_a|^2 \frac{(L_t \omega)^2}{R_t}$$

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$$\Rightarrow P_{\max} \sim |I_a|^2 Q L_t \omega_0$$

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Optimal Signal Strength

Optimal signal

$$P_{\text{signal}} \sim |I_a|^2 (L_t \omega) \cdot \min\left\{ \frac{L_t \omega}{R_t},\ Q \right\}$$

Donut limited

Cavity limited

Narrowband noise

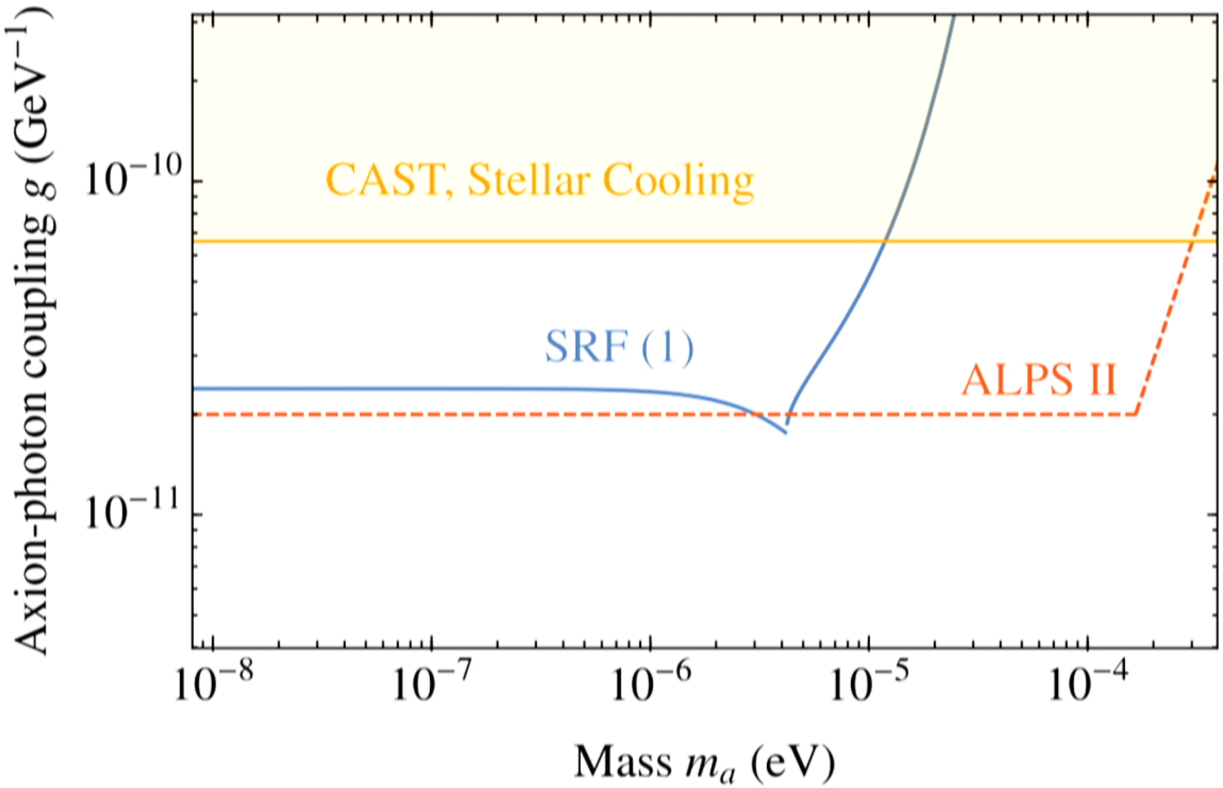
$$P_{\text{noise}} = \frac{T_{\text{sys}}}{t_{\text{int}}} \qquad T_{\text{sys}} \gtrsim \omega \sim 50 \text{ mK}$$

Quantum limited

Projected Sensitivity $B_{pc} = 0.2\text{ T}$ $B_0 = 5\text{ T}$

$L_t = 125\text{ nH}$ $T_{sys} = 0.1\text{ K}$ $t_{int} = 1\text{ year}$

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



Projected Sensitivity $B_{pc} = 0.2$ T $B_0 = 5$ T

$L_t = 125$ nH $T_{sys} = 0.1$ K $t_{int} = 1$ year

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