A Broadband/Resonant Approach to Axion Dark Matter Detection

[arXiv:1602.01086]

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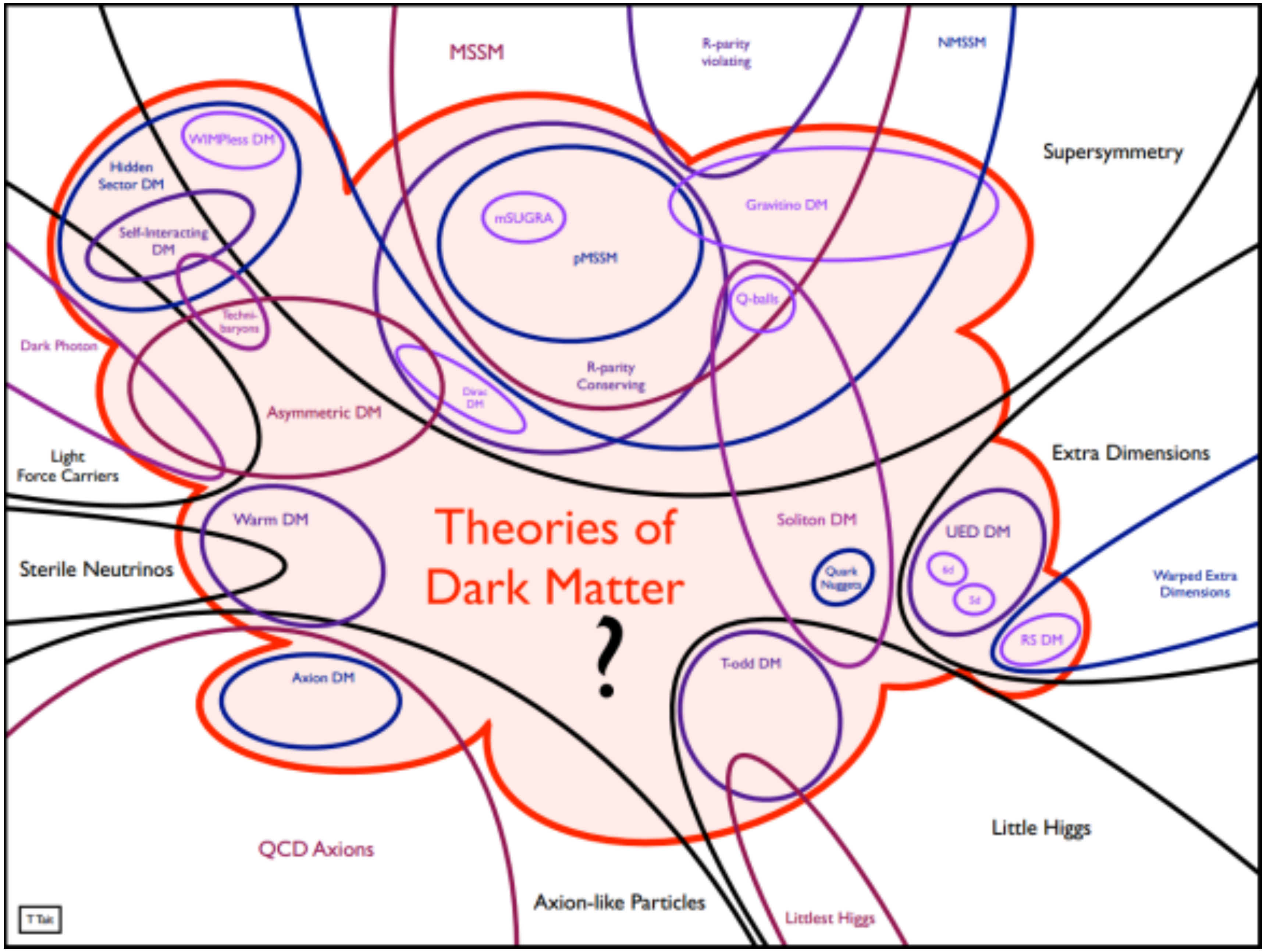
Princeton University

with Ben Safdi and Jesse Thaler @ MIT

Fermilab HEP Theory Seminar, 4/21/16

Dark Matter - beyond WIMPS



[T. Tait]

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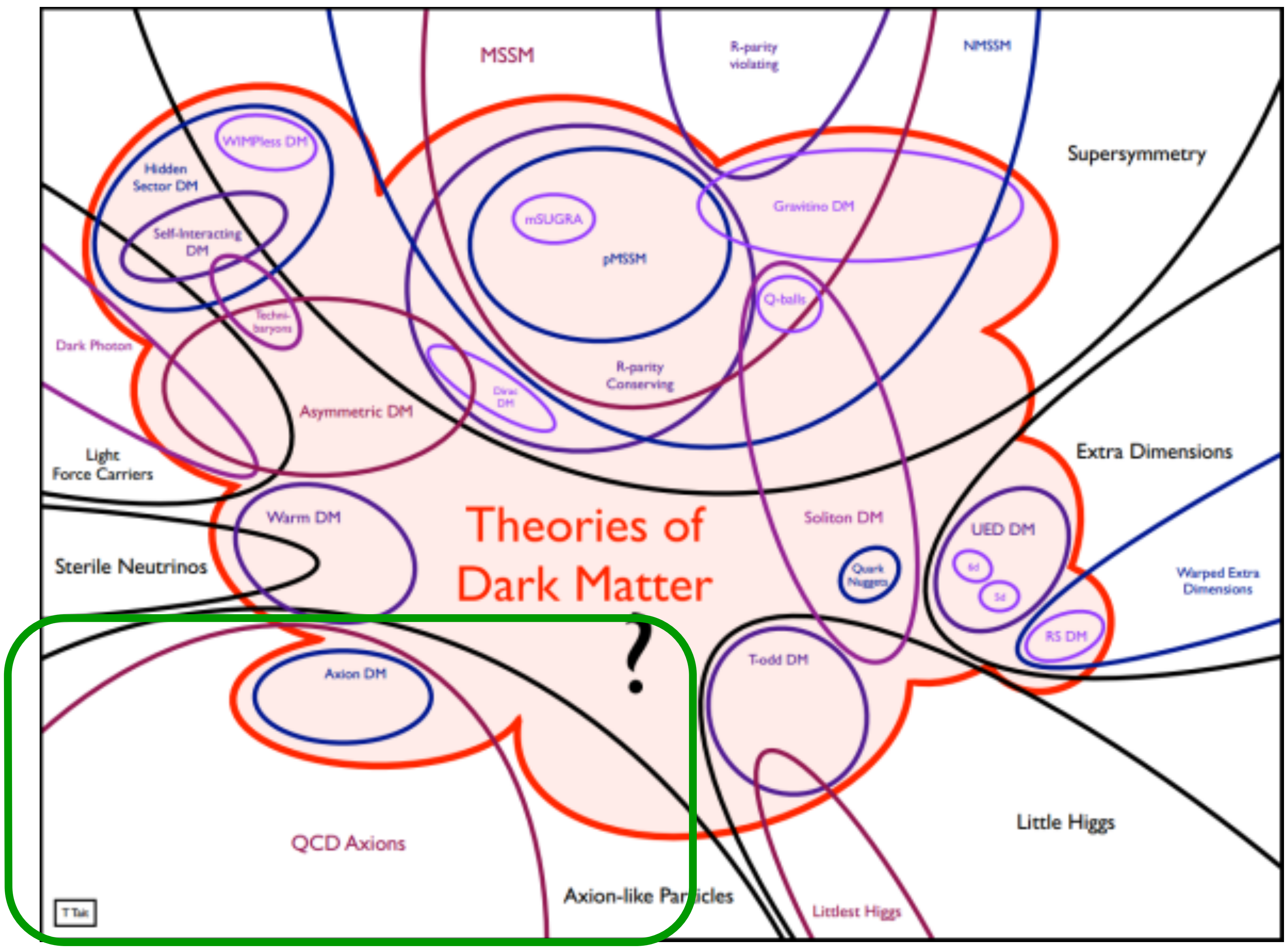


[T. Tait]

Axions and ALPS

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \widetilde{F}^{\mu\nu}$$

Axions: $m_a \propto g_{a\gamma\gamma}$

ALPs: $m_a,\ g_{a\gamma\gamma}$ independent

Axions: also couple to $G_{\mu\nu}\widetilde{G}^{\mu\nu}$

ALPs: not necessarily

Can be very light! Mass protected by a shift symmetry $a \to a + \mathrm{const.}$ because $F_{\mu\nu}\widetilde{F}^{\mu\nu}$ is a total derivative

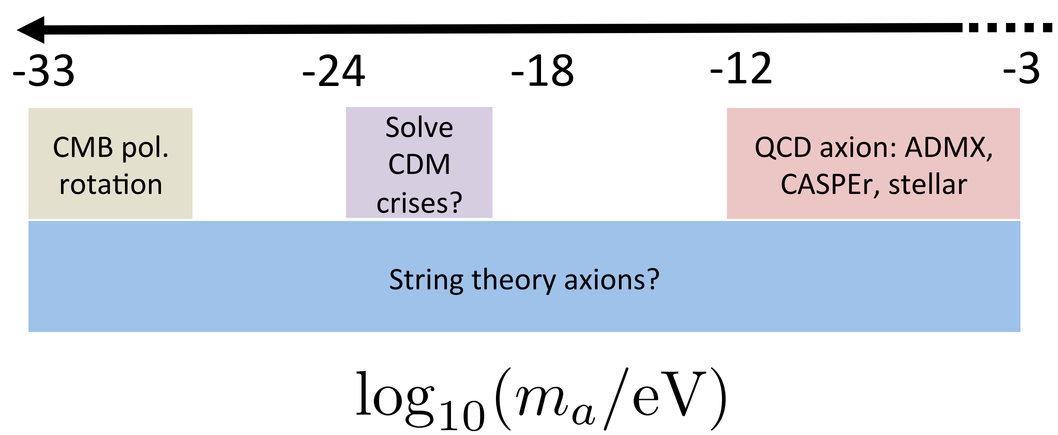
Motivations for light axions:

- Strong CP problem
- String theory

Can be DM either by thermal production (> eV) or misalignment production (< eV)

Axion-like-particle (ALP) parameter space

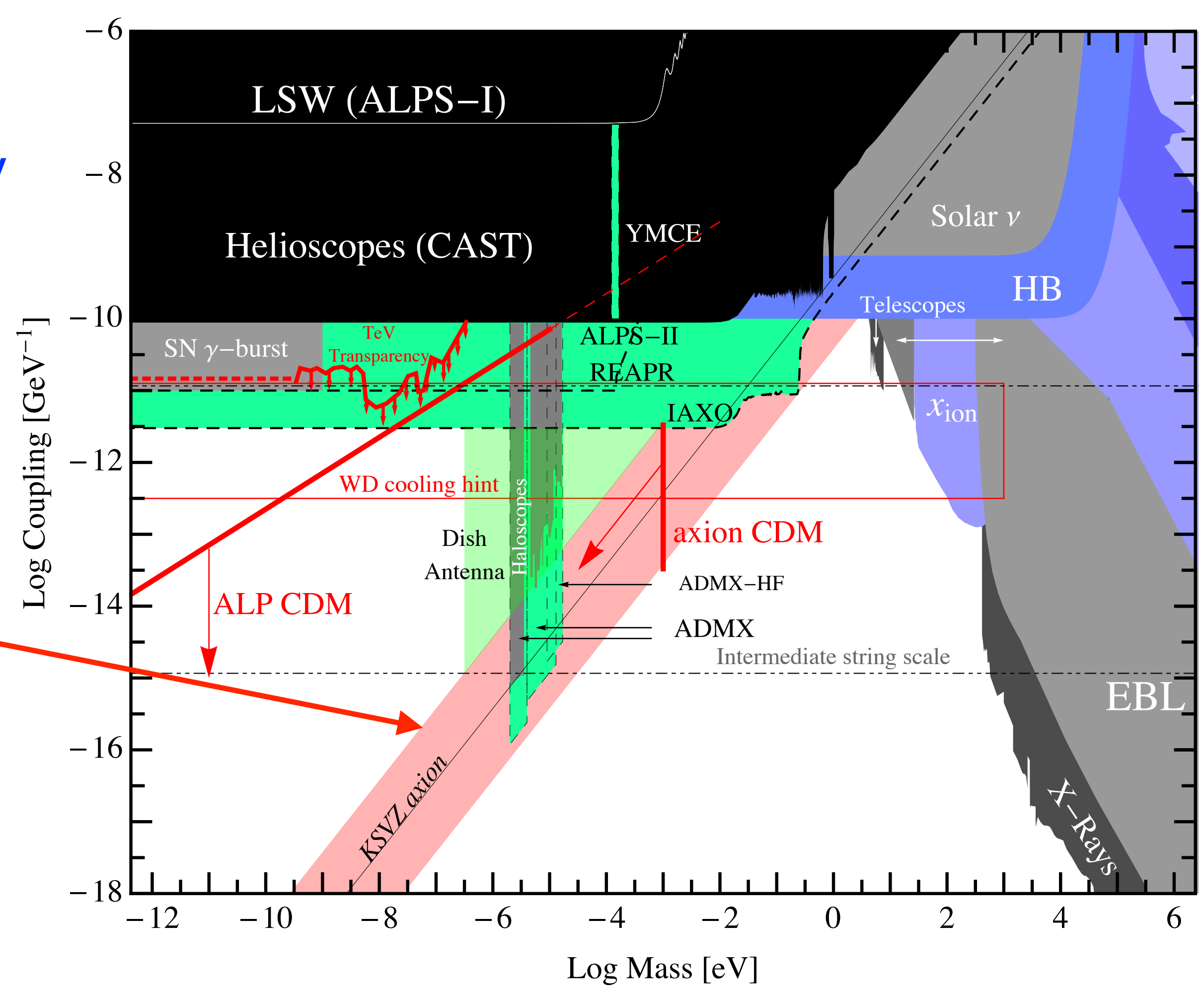
Enormous mass range:



[D. Marsh, 1510.07633]

Couples very weakly to photons:

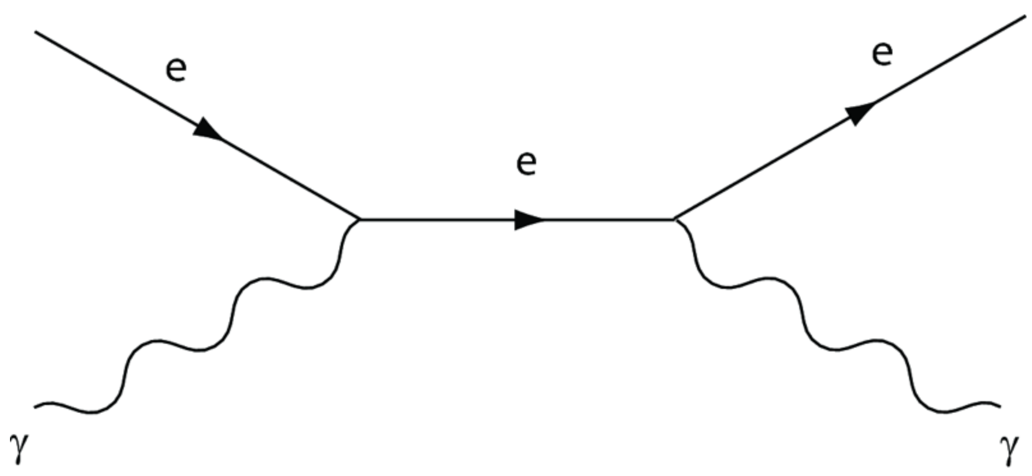
QCD axion: mass ∝ coupling



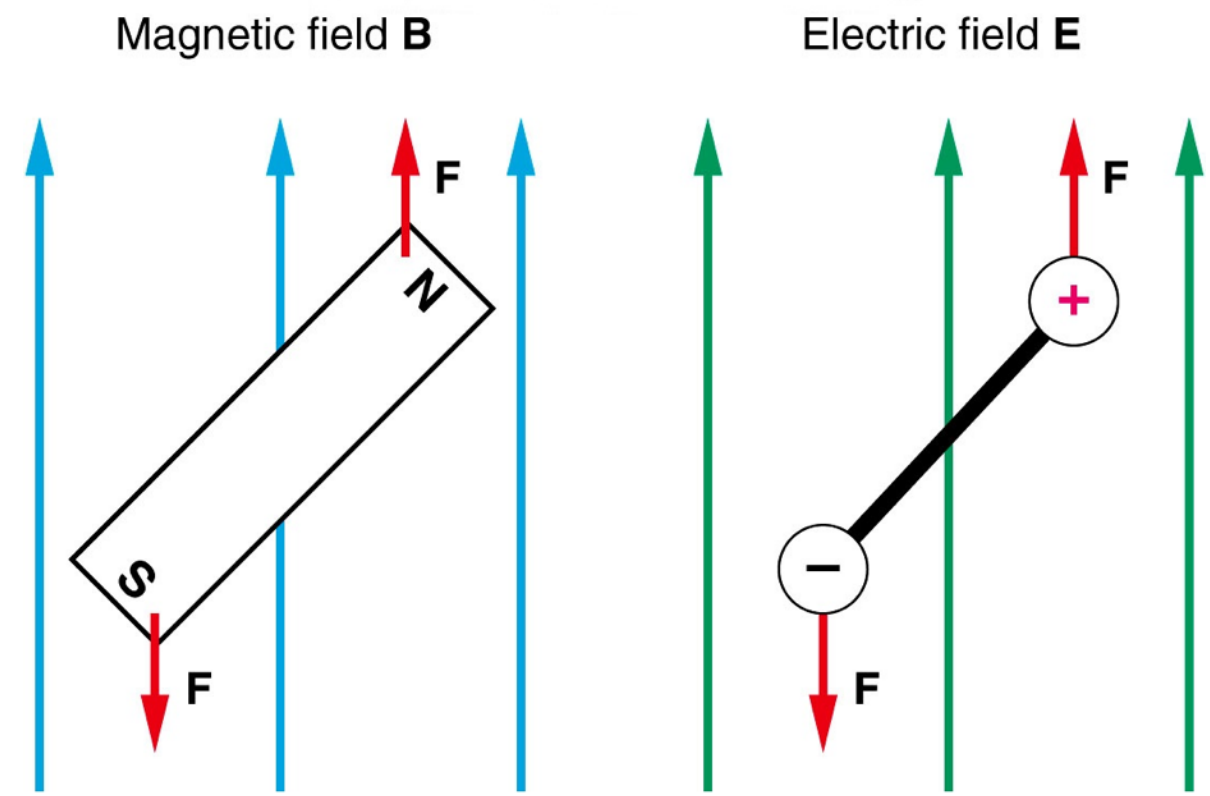
[Snowmass, 1311.0029]

ALP DM: field, not particle

Useful analogy:



vs.

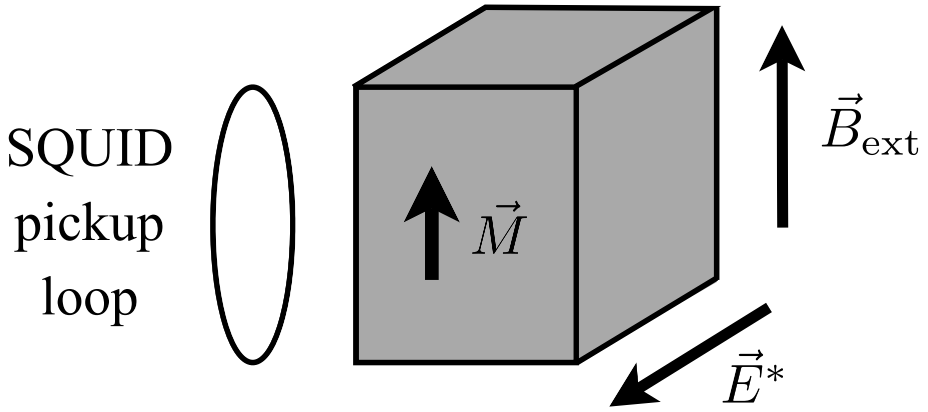


Light bosonic DM behaves collectively:
think in terms of charges and currents,
not Feynman diagrams

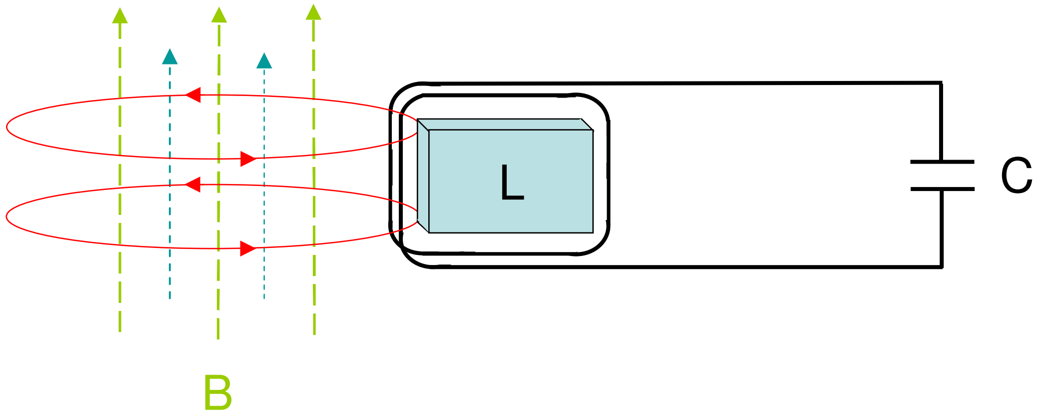
Strategies for ALP DM detection

Resonant cavity (ADMX)

Nuclear EDMs (CASPEr)



LC circuit (Thomas/Cabrera/Sikivie)



Signal is a weak, oscillating magnetic field

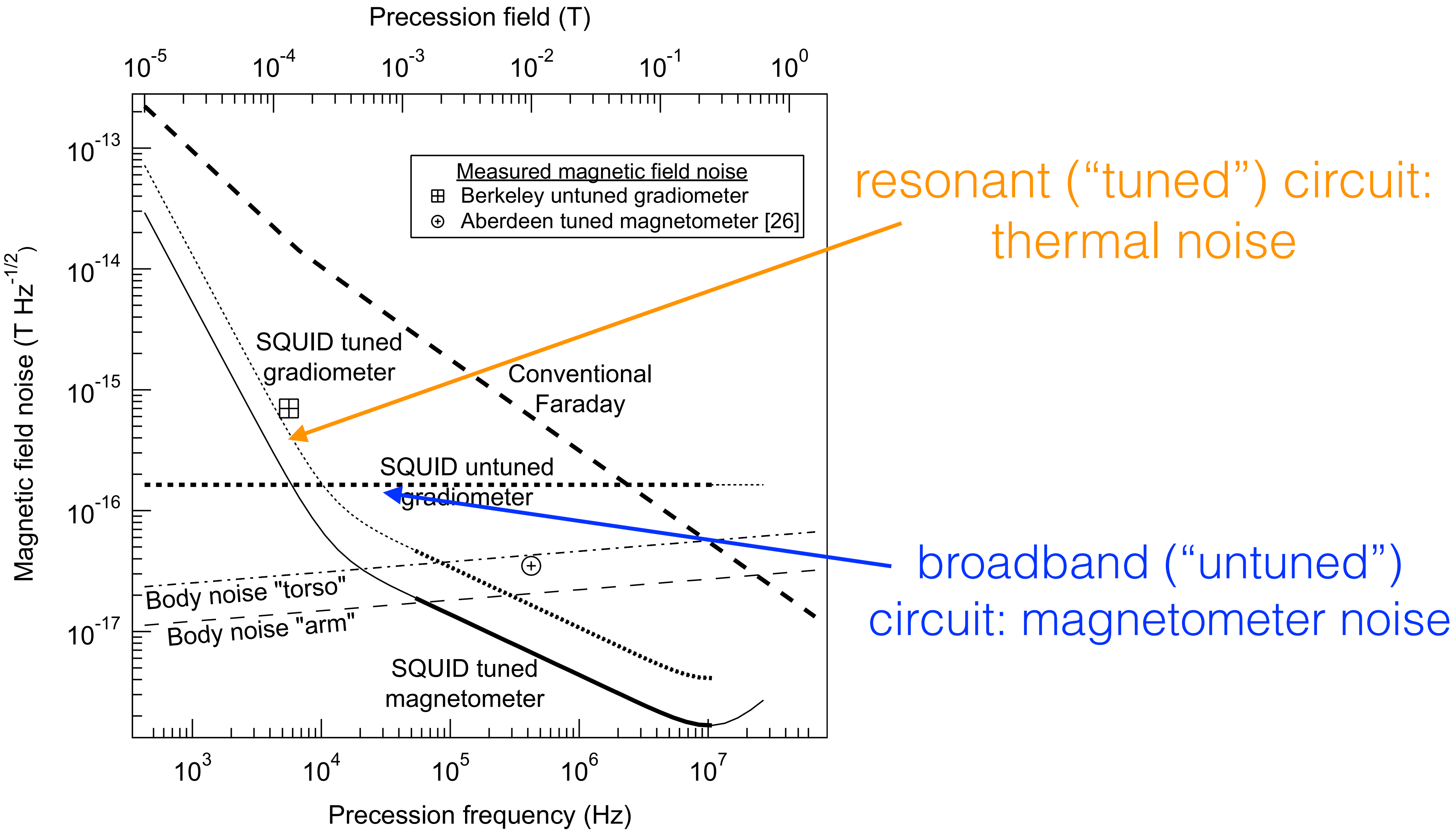
All require resonance, scanning over frequencies

Broadband: a new approach?

Does axion DM detection require resonant enhancement?

Hints from precision magnetometry:

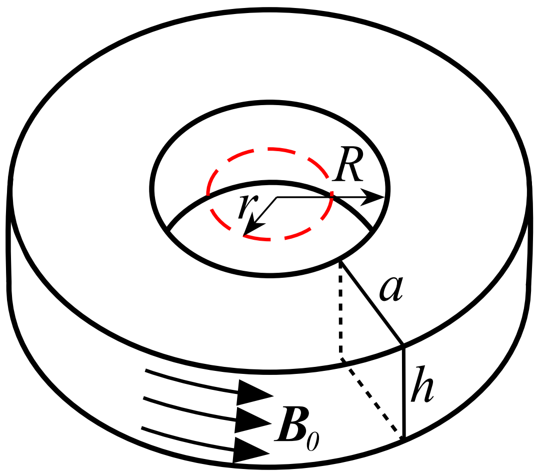
[Myers et al 2007]



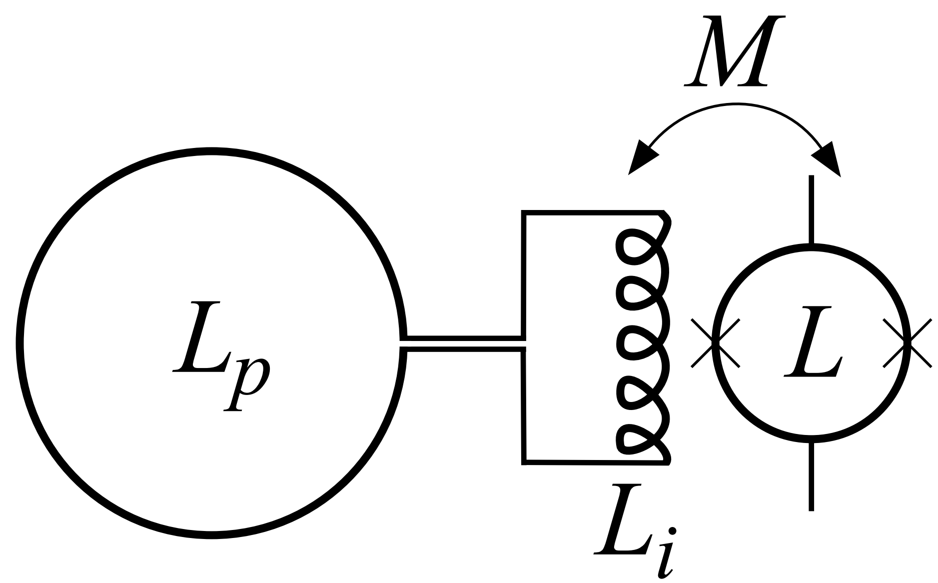
Requires superconducting pickup: zero-field detection

Outline

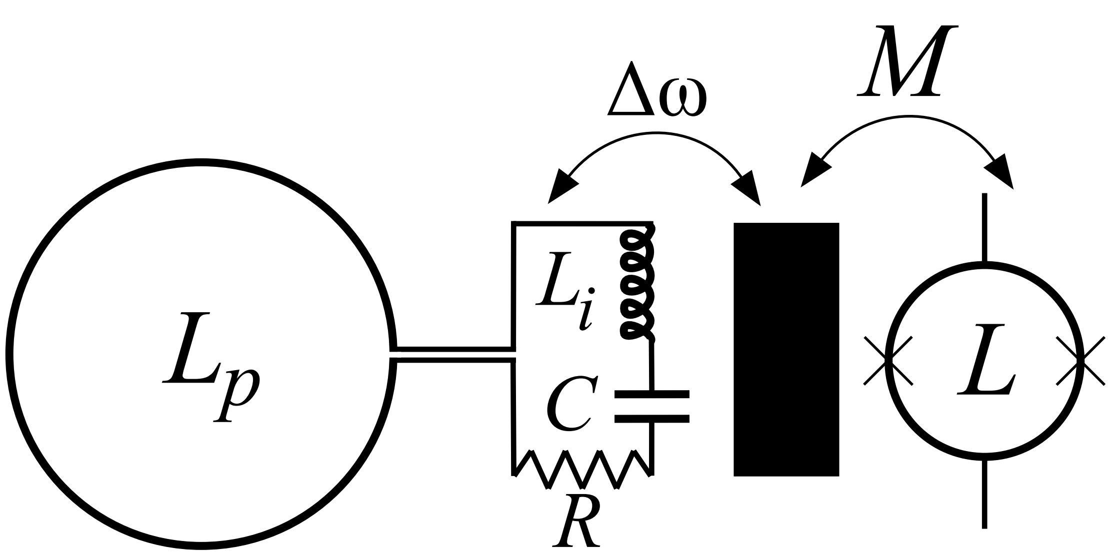
I. Experimental design



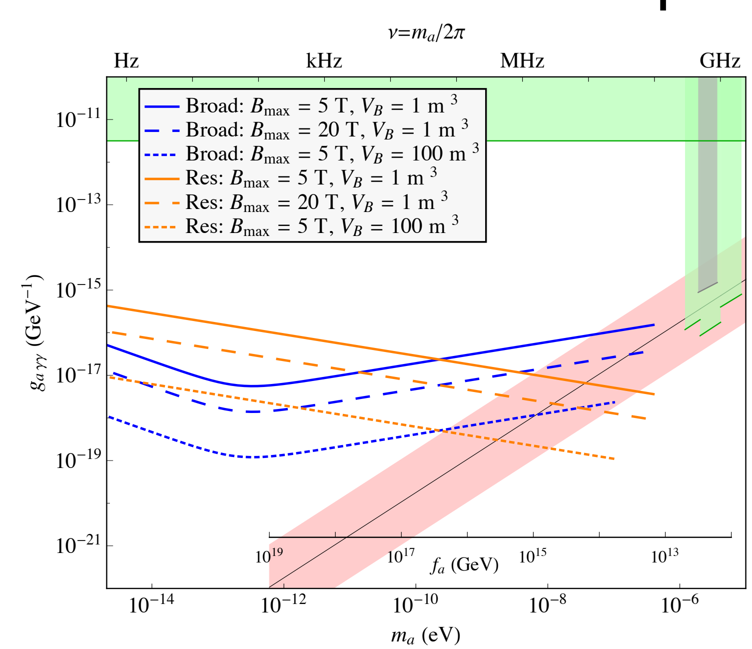
II. Broadband readout



III. Resonant readout



IV. Reach and comparison



ALP DM: Properties today

$\boxed{\text{Focus on mass range } m_a \ll 1\mathrm{eV}}$

Bosonic DM + macroscopic occupation # = classical field:

$$a(t) = a_0 \sin(m_a t) = \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_a} \sin(m_a t)$$

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Spatially and temporally coherent on macroscopic scales:

$$\lambda \sim \frac{2\pi}{m_a v_{DM}} \approx 100 \text{ km} \, \frac{10^{-8} \text{ eV}}{m_a}$$

$$\tau \sim \frac{2\pi}{m_a v_{DM}^2} \approx 0.4 \text{ s} \, \frac{10^{-8} \text{ eV}}{m_a}$$

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induces oscillating response fields:

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$$\nabla \times \mathbf{B}_r = \frac{\partial \mathbf{E}_r}{\partial t} - g_{a\gamma\gamma} \left(\mathbf{E}_0 \times \nabla a - \mathbf{B}_0 \frac{\partial a}{\partial t} \right)$$

$$\nabla \cdot \mathbf{E}_r = -g_{a\gamma\gamma} \mathbf{B}_0 \cdot \nabla a$$

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gradients suppressed by $v_{DM} \sim 10^{-3}$

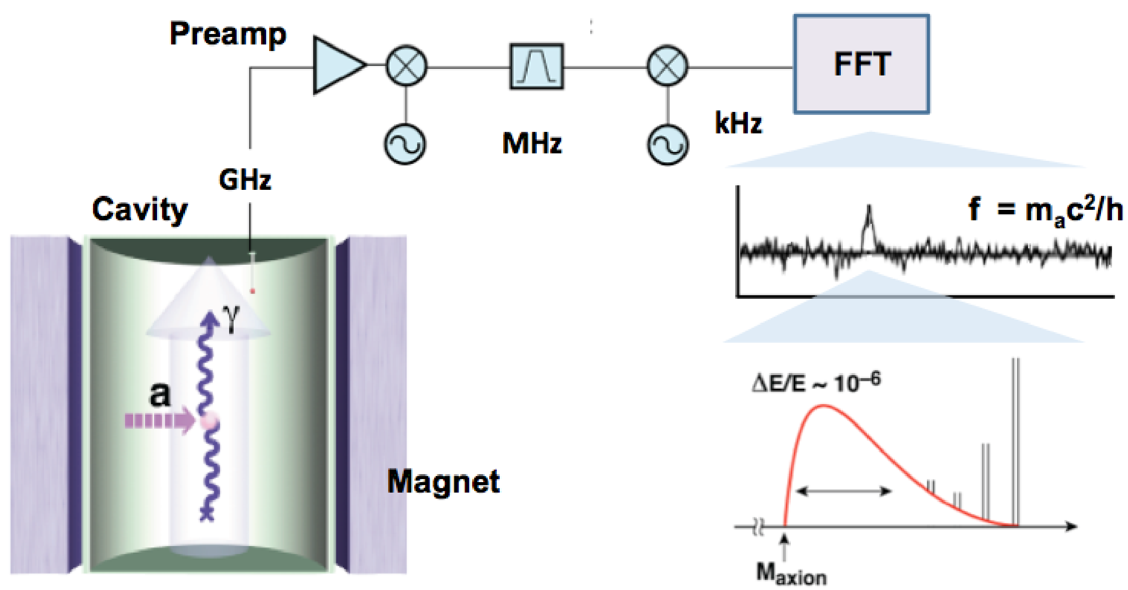
ADMX: resonant cavity detection

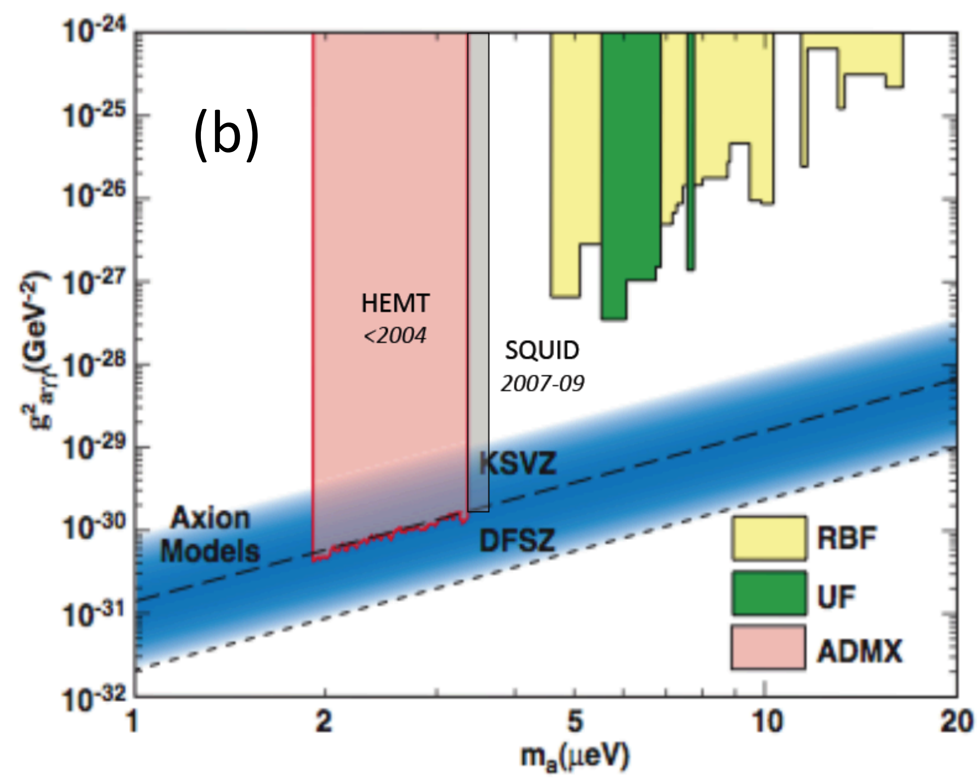
[http://depts.washington.edu/admx/]

$$\mathcal{L} \supset a\mathbf{E} \cdot \langle \mathbf{B} \rangle$$

static B-field

$$P \sim g_{a\gamma\gamma}^2 \frac{\rho_{\rm DM}}{m_a} B_0^2 V Q$$





- Measures coupling to $F_{\mu\nu}\widetilde{F}^{\mu\nu}$
- Measurement taken in external B field
- Cavity b.c. fix mass range to cavity size

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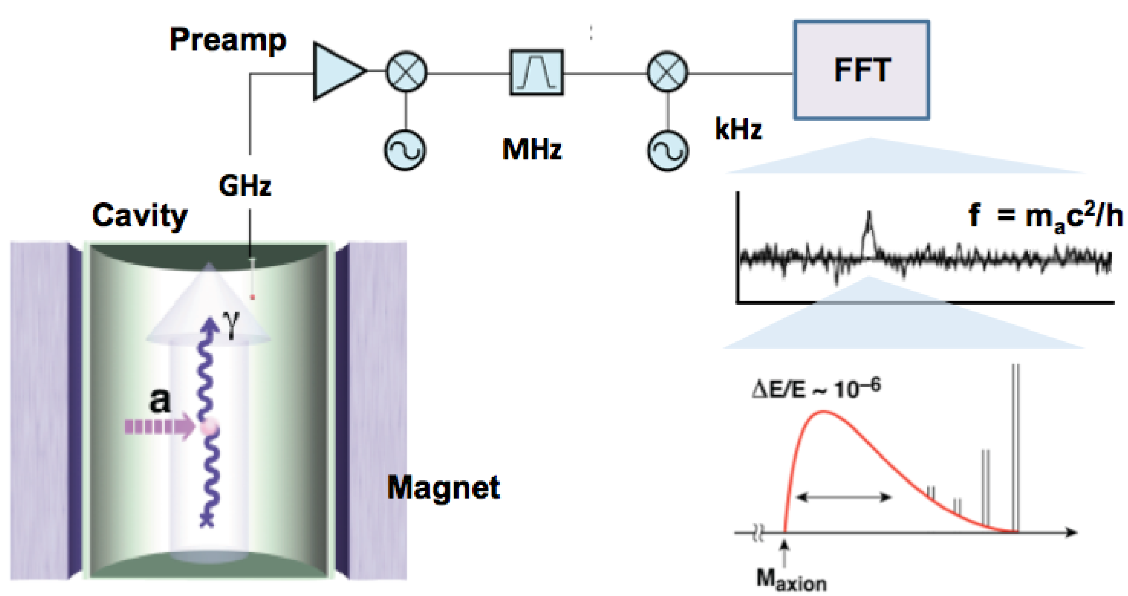

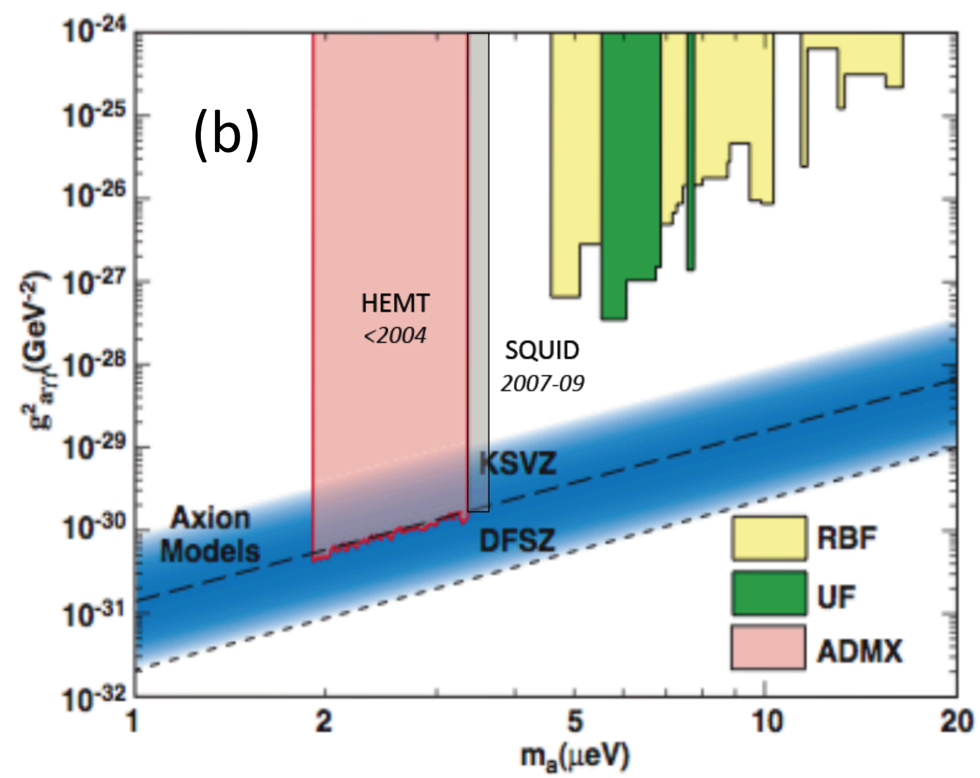

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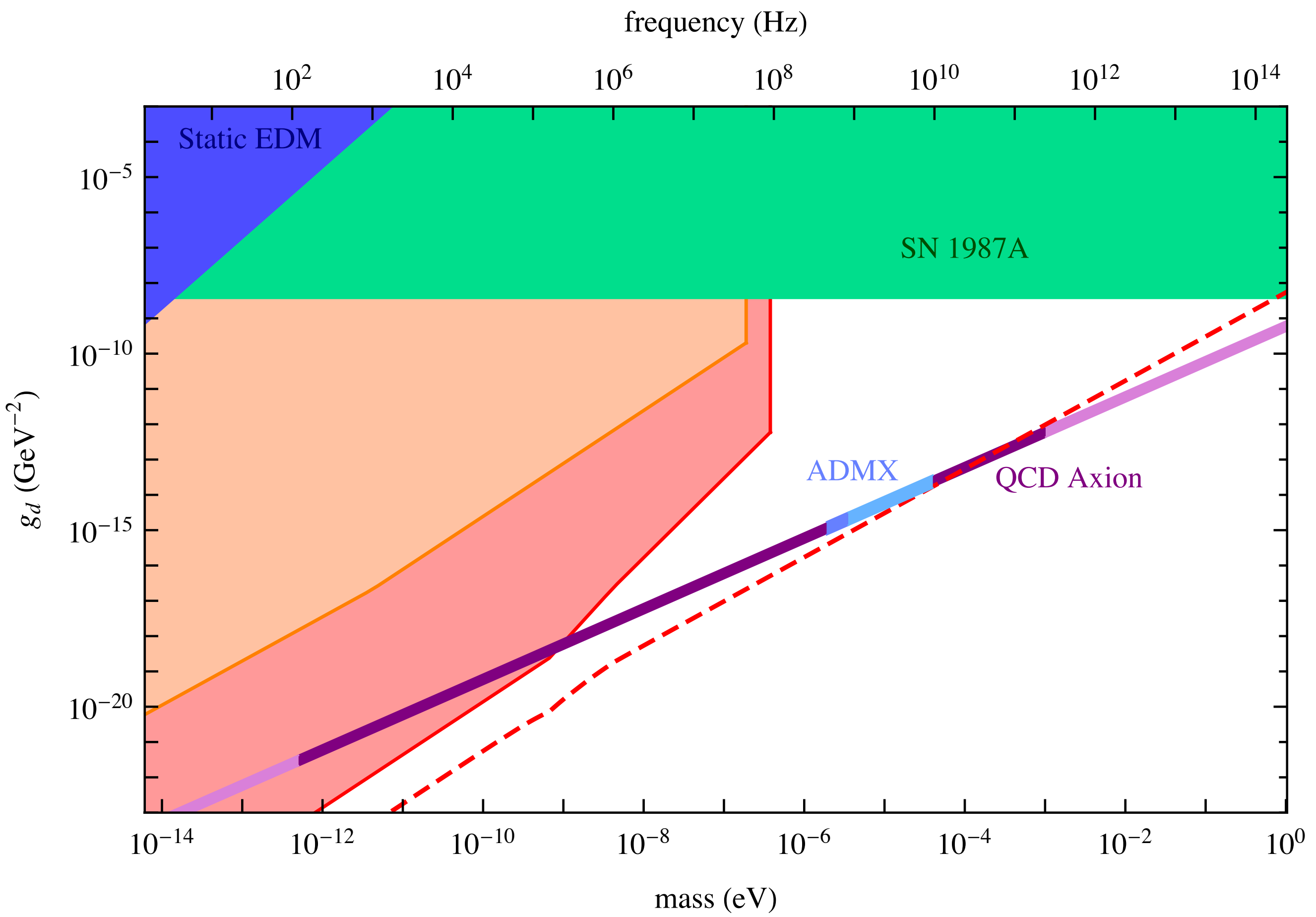
- Cavity b.c. fix mass range to cavity size

CASPEr: NMR detection

[Budker et al., 1306.6089]

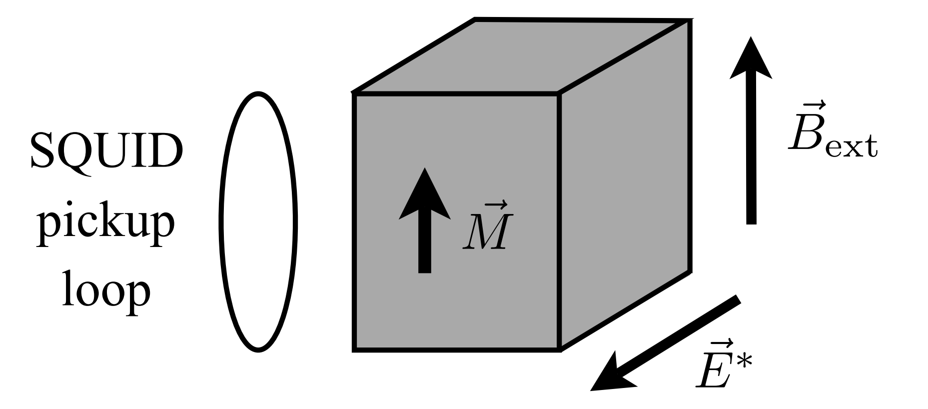
$$\mathcal{L} \supset -\frac{i}{2}\underbrace{g_d a}_{d_n \approx 2.4\times 10^{-16}\frac{a}{f_a} e\cdot\mathrm{cm}\ \text{for QCD}}\overline{N}\sigma_{\mu\nu}\gamma_5 N F^{\mu\nu}$$

$$d_n = g_d \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_a}\cos(m_a t)$$



resonance

$$M(t) \approx np\mu E^{*}\epsilon_S d_n \frac{\sin\left[(2\mu B_{\mathrm{ext}} - m_a)t\right]}{2\mu B_{\mathrm{ext}} - m_a}\sin(2\mu B_{\mathrm{ext}} t)$$



- Measures coupling to $G_{\mu\nu}\widetilde{G}^{\mu\nu}$ through nucleon spin
- Measurement taken in external B (and E) field
- Sensitivity to much lower masses! Win by volume

Axion-sourced current

$$\nabla \times \mathbf{B}_r = \frac{\partial \mathbf{E}_r}{\partial t} - g_{a\gamma\gamma}\left(\mathbf{E}_0 \times \nabla a - \mathbf{B}_0 \frac{\partial a}{\partial t}\right)$$

Axion-sourced current

$$v_{DM} \ll 1$$

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(quasistatic approximation)

$$\implies \mathbf{J}_{\rm eff} = g_{a\gamma\gamma}\sqrt{2\rho_{\rm DM}}\cos(m_a t)\mathbf{B}_0$$

Current follows lines of **B,** oscillates at axion mass

How to detect an oscillating current?

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- Radiated power (at infinity) $\propto g_{a\gamma\gamma}^2$
- Time-varying flux (locally) $\propto g_{a\gamma\gamma}$

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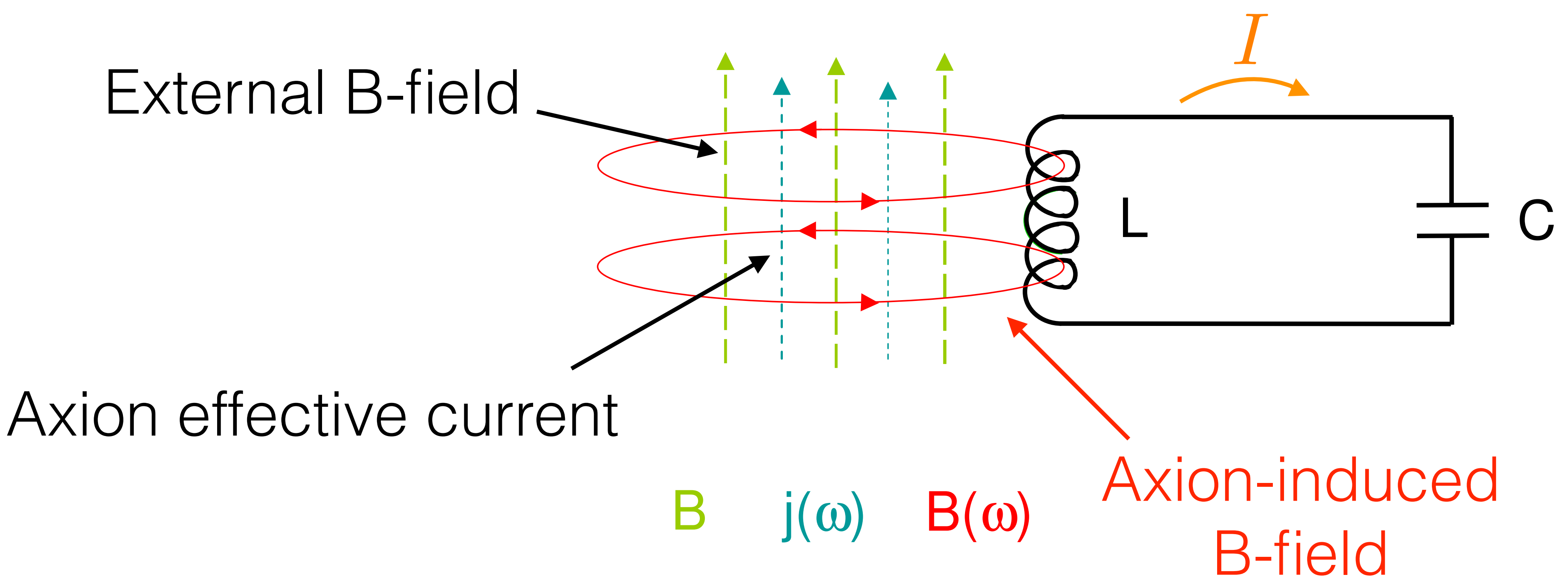
LC pickup

[S. Thomas and B. Cabrera; P. Sikivie et al, 1310.8545]



$$I = \frac{Q}{L} V_B g_{a\gamma\gamma} \sqrt{2\rho_{\mathrm{DM}}} B_0$$

- Measures coupling to $F_{\mu\nu}\widetilde{F}^{\mu\nu}$ (like ADMX)
- Measurement taken in external B-field
- Same volume enhancement, sensitivity to small m_a

Summary: existing proposals

- Resonant conversion: mass pinned to size of cavity
- Require some kind of tuning to attain resonance
- Signal detection in external fields

Goal: cover low masses, keep volume enhancement, but detection in zero external field region

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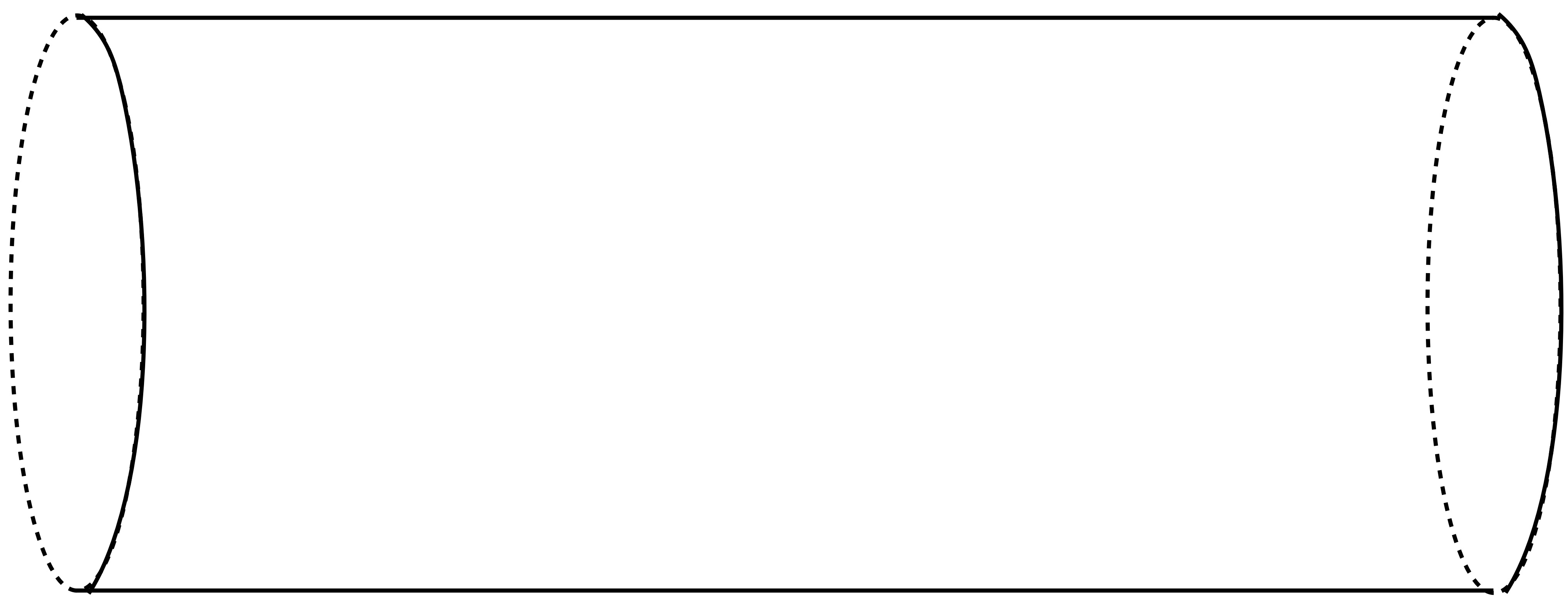
ABRACADABRA!

(J. Thaler)

Toy example: solenoid



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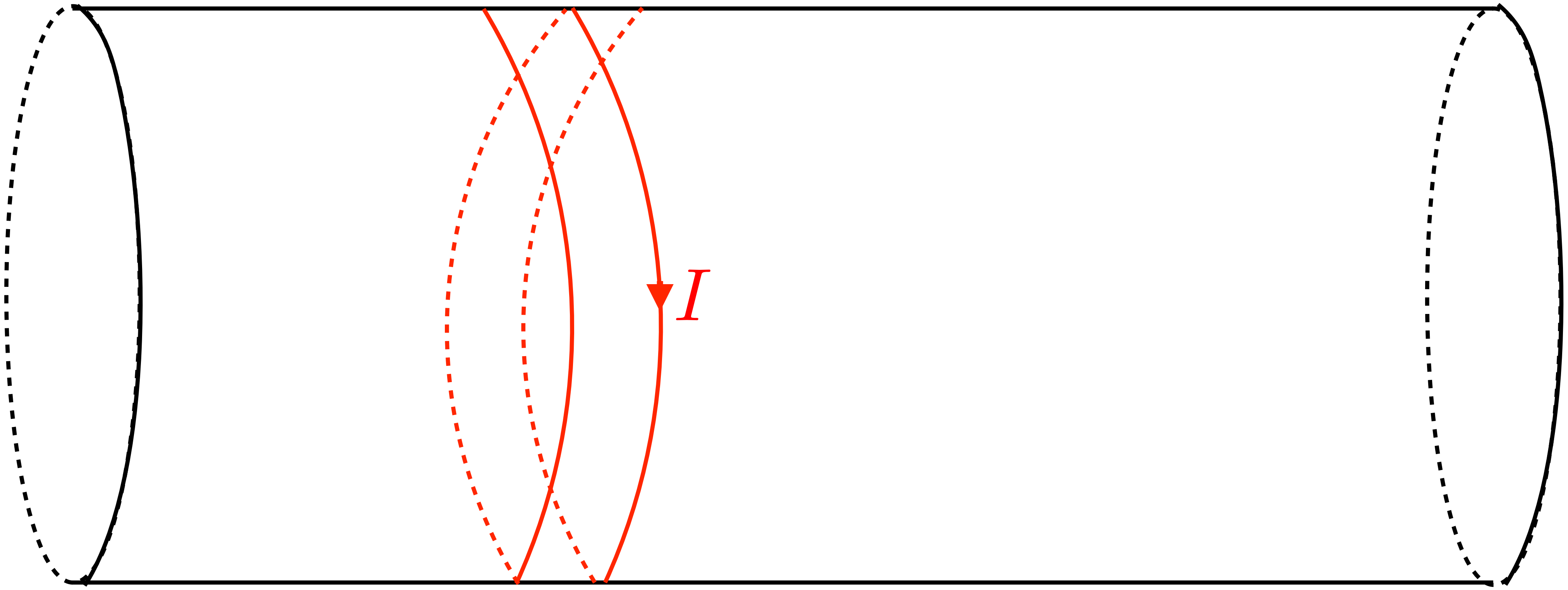

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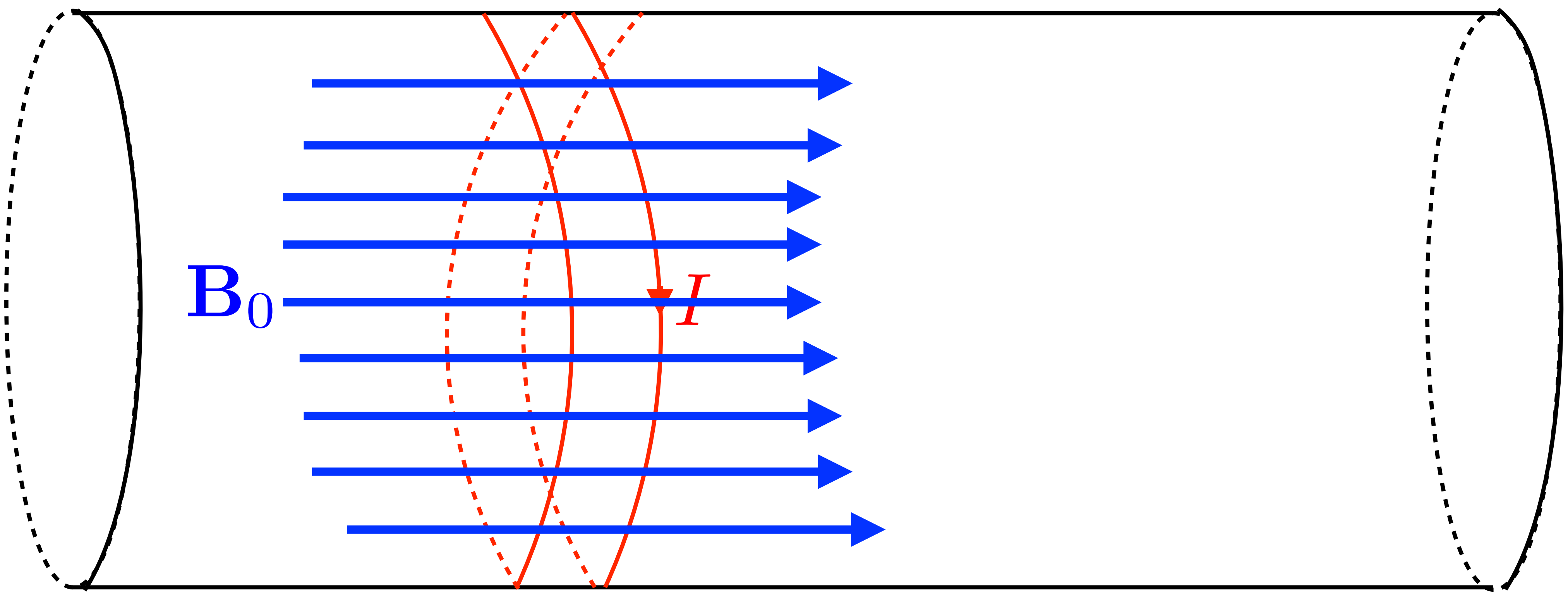
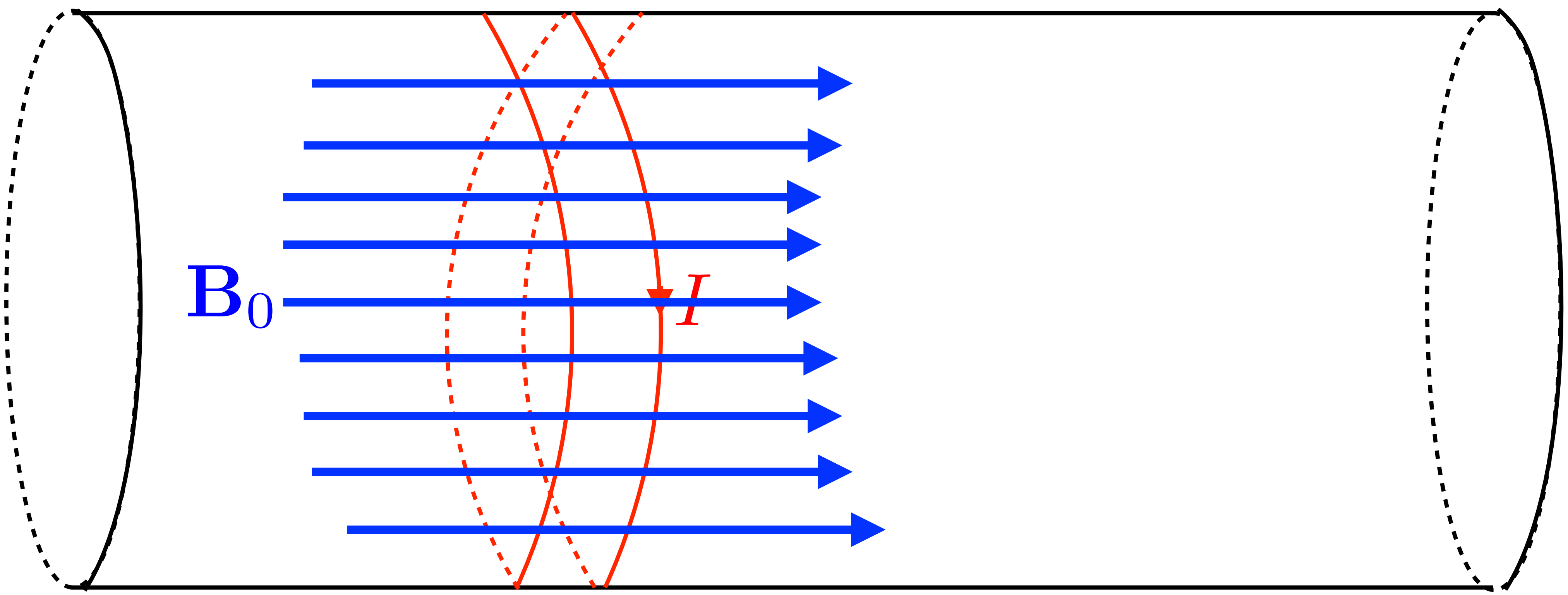


Toy example: solenoid

In the presence of axion DM:



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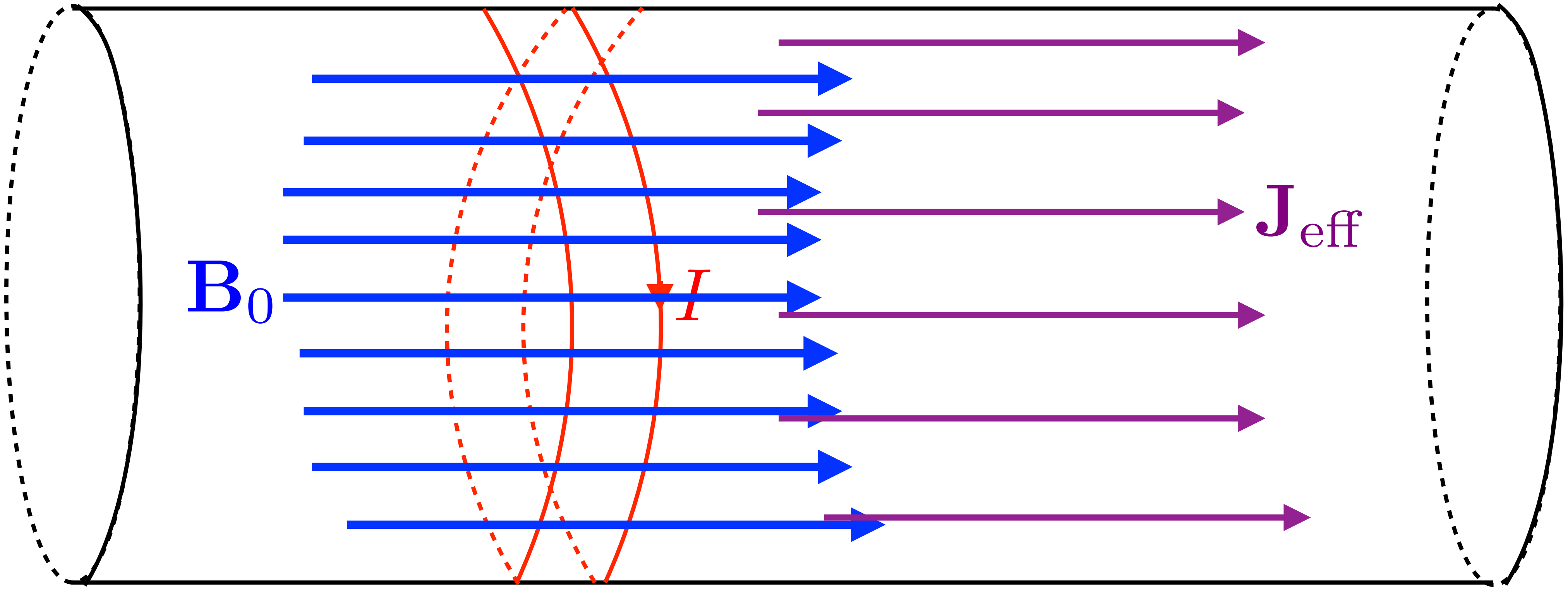

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Current-carrying wire

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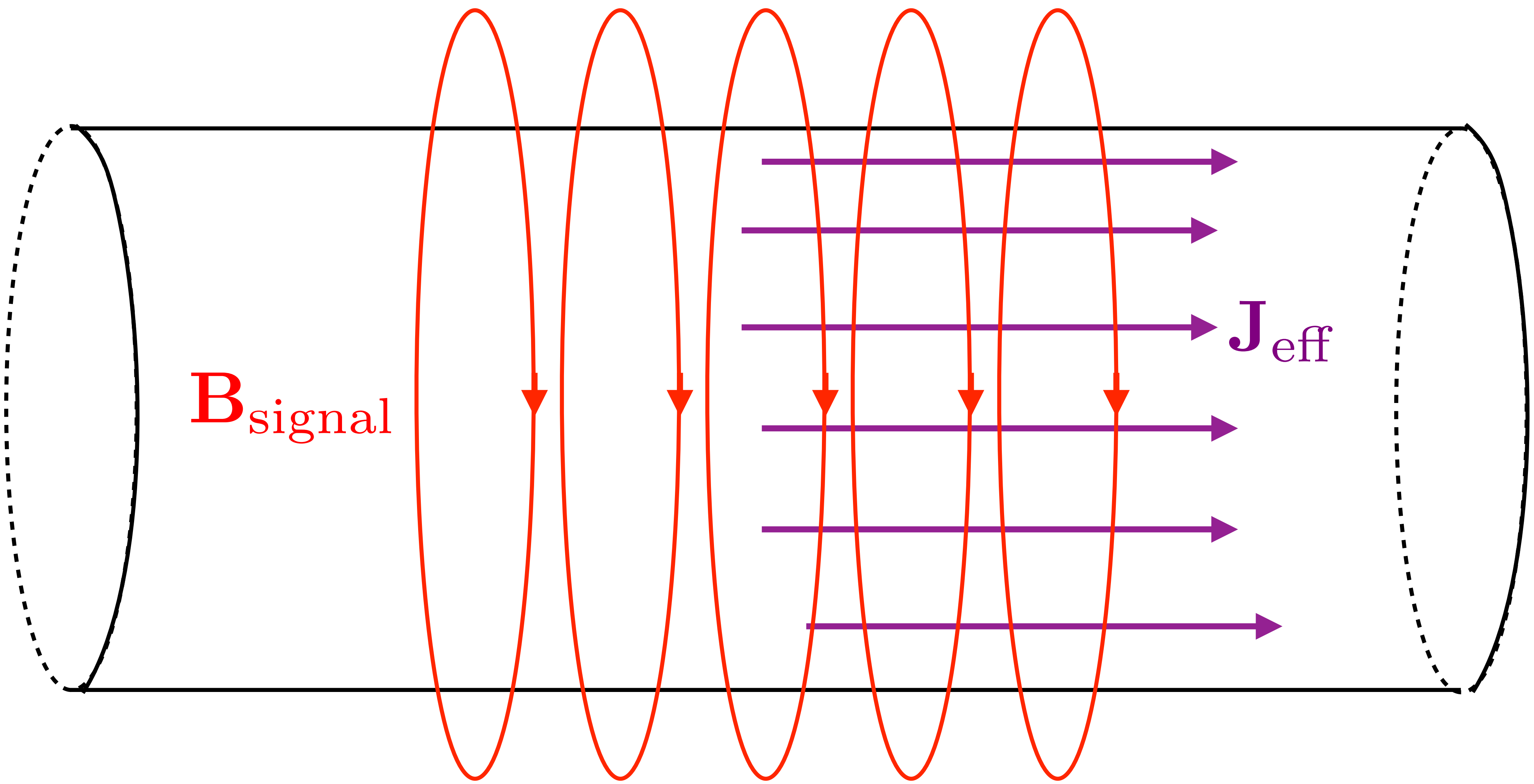

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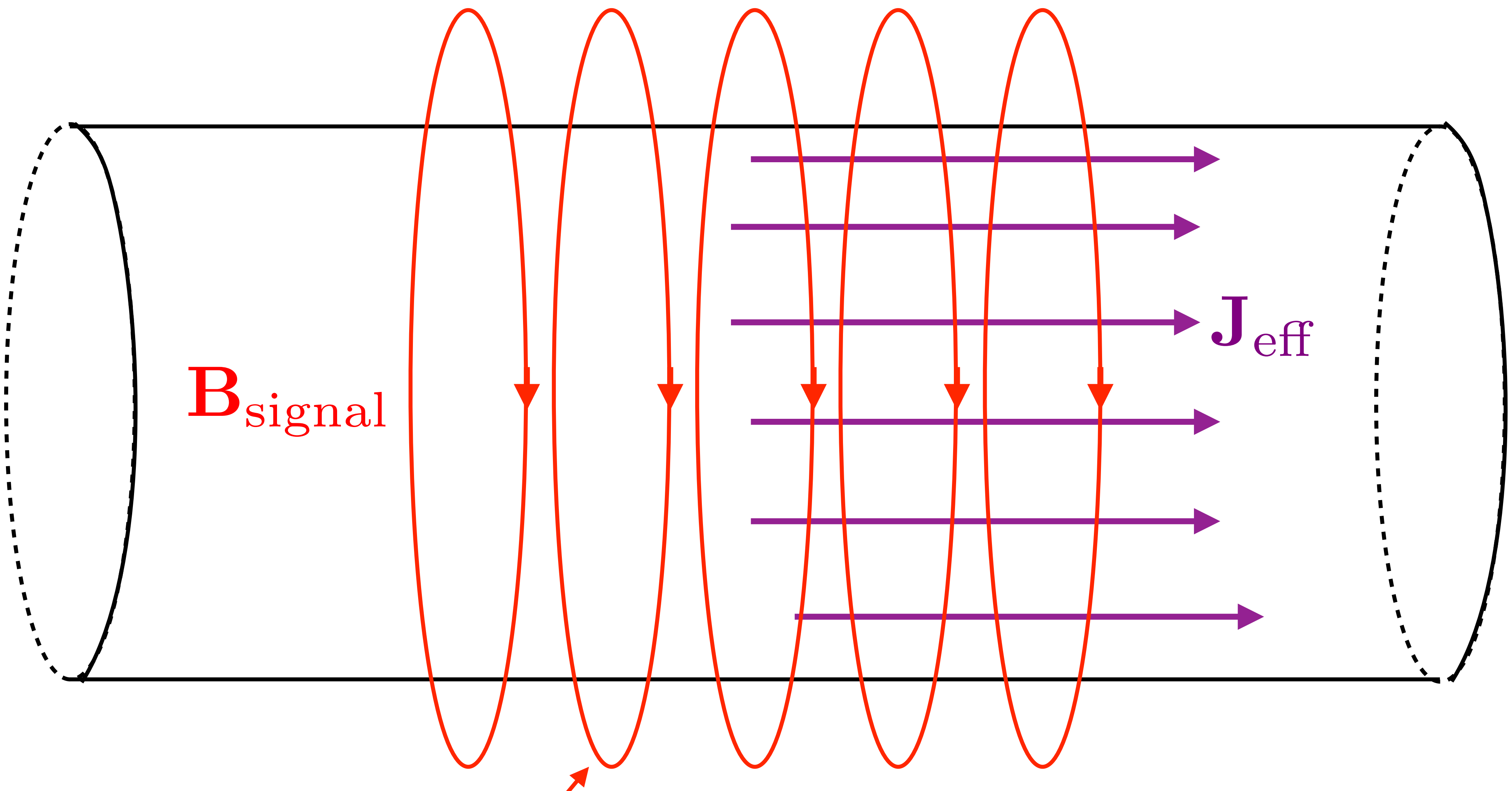
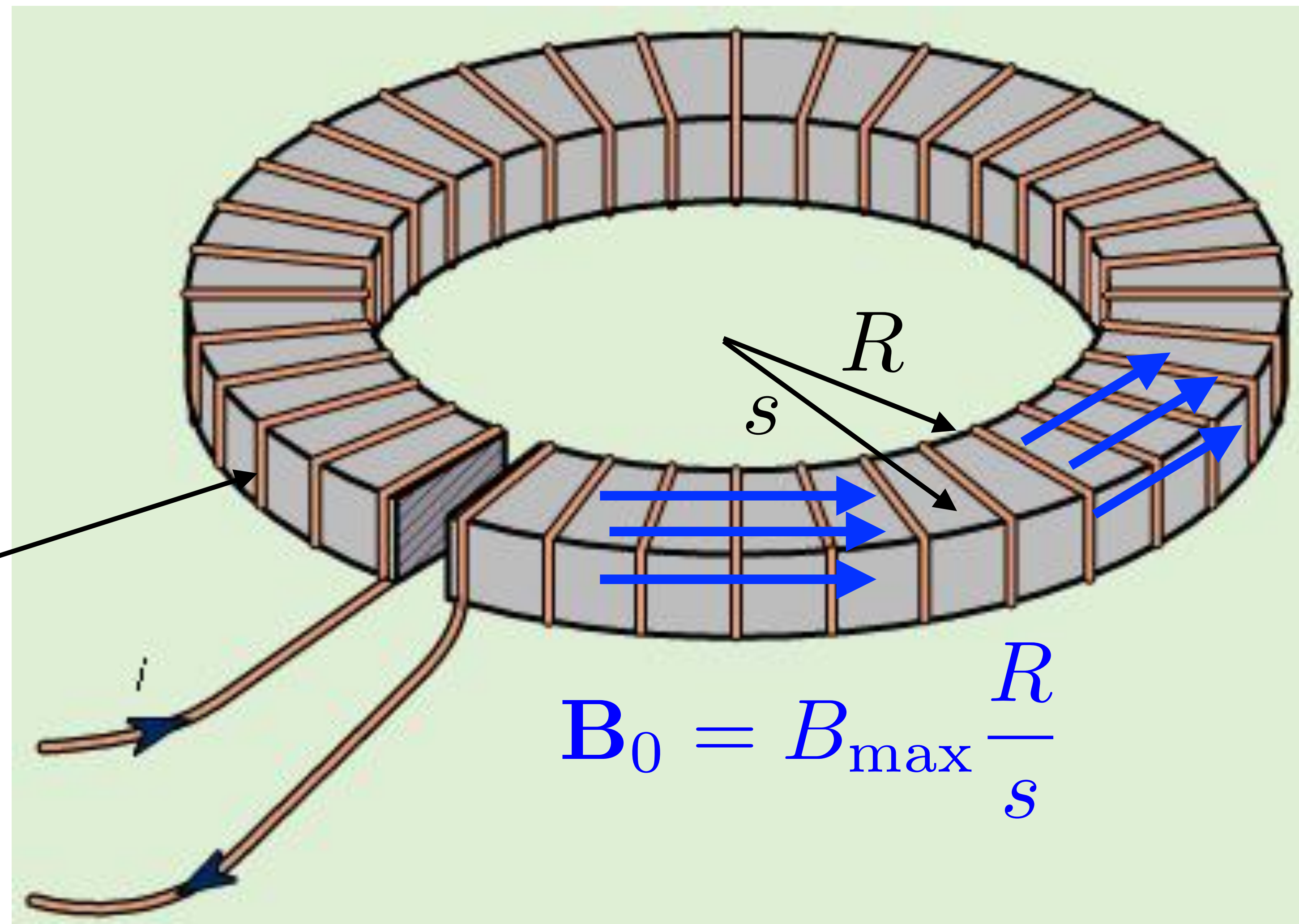


Can detect axion-induced flux outside field region!

Toroid: no axion

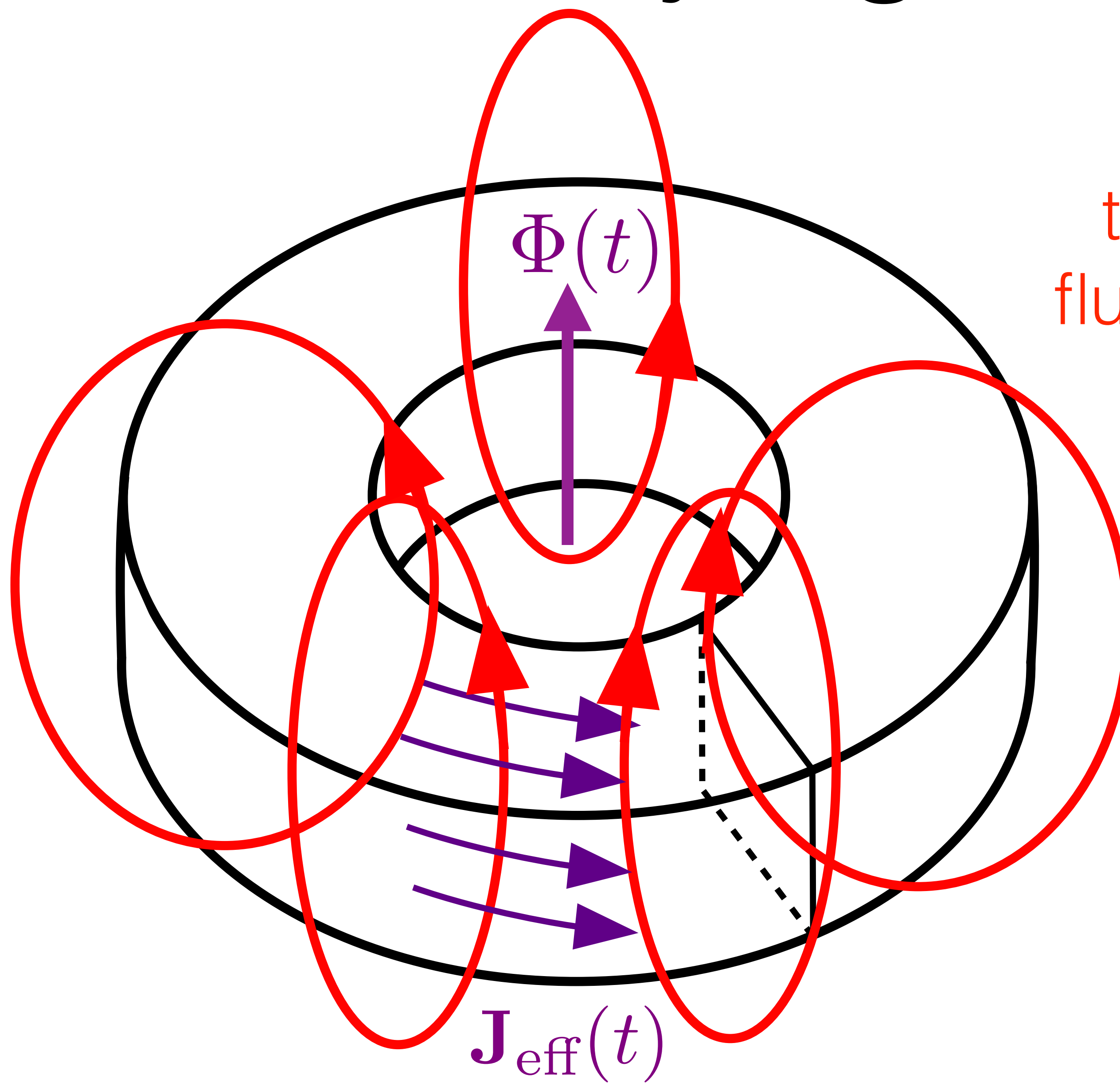
Bend solenoid around into a toroid to reduce fringe fields



superconducting wires

Magnetic field confined to toroid:
no flux through center

Toroid with axion: current-carrying loop



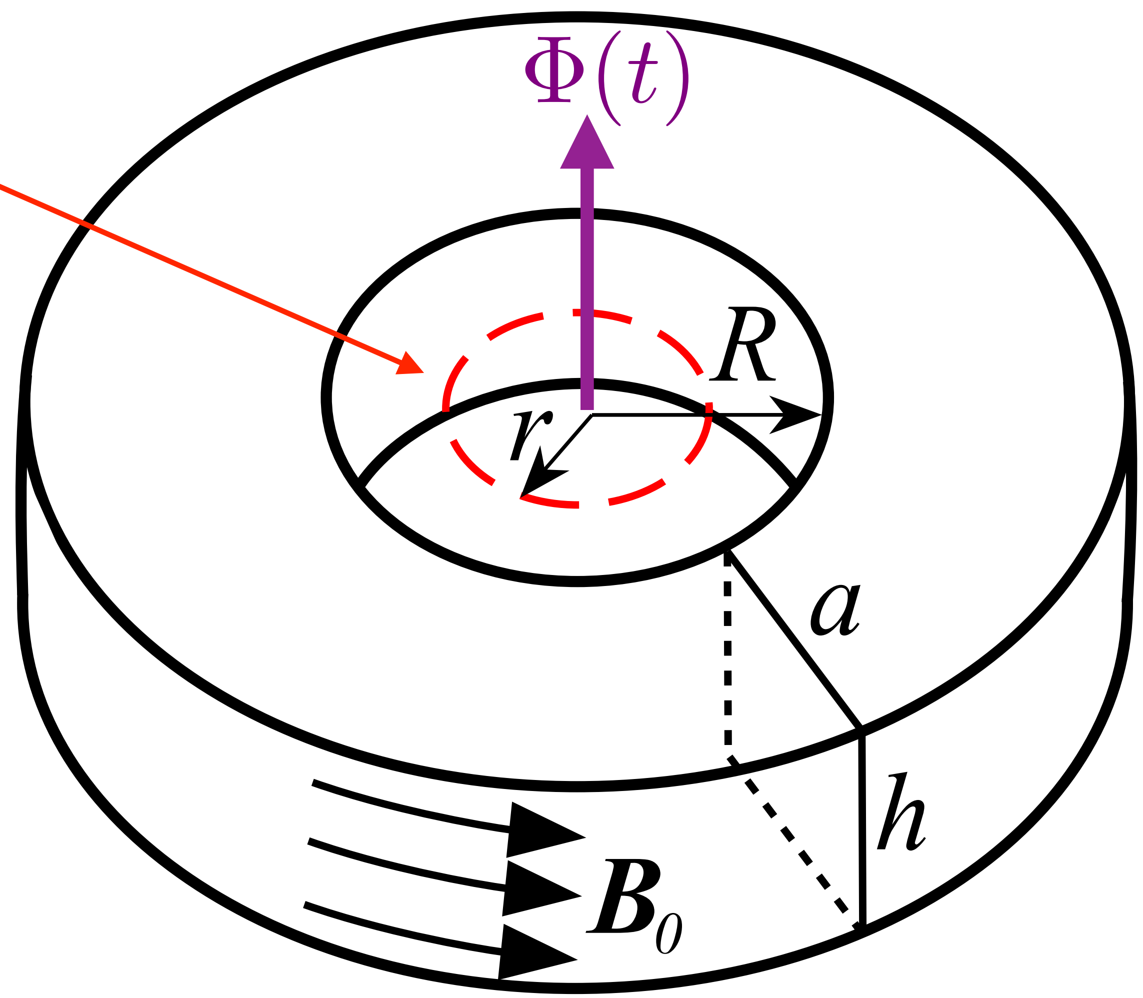
toroidal geometry:
flux adds **coherently**
in center

Signal: time-varying flux through center

Key point: measure signal in zero-static-field region!

Signal flux

pickup loop



$R, h, a \ll m_a^{-1}$

(quasistatic)

$$\mathbf{B}_0 = B_{\max} \frac{R}{s}$$

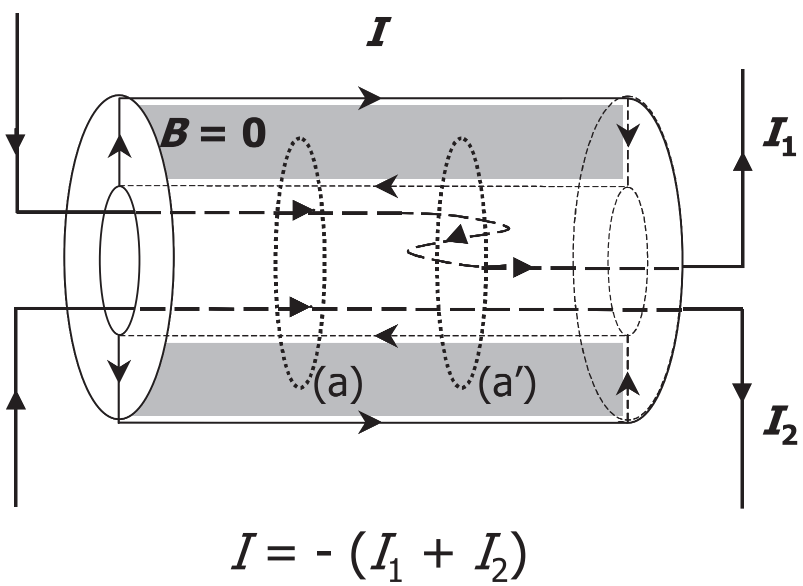
Effective toroid volume

$$\Phi_{\text{pickup}}(t) = g_{a\gamma\gamma}\, B_{\max}\, \sqrt{2\rho_{\text{DM}}}\, \cos(m_a t)\, V_B$$

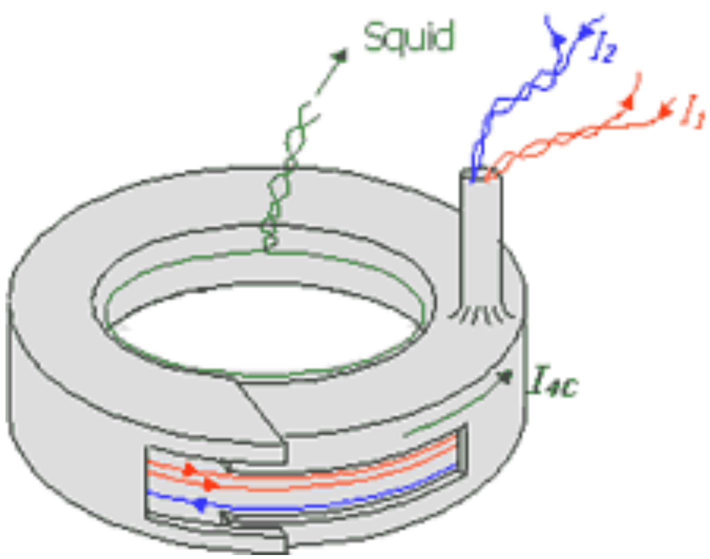
Couple this flux into SQUID magnetometer through either broadband or resonant readout circuit

Self-screening?

Borrow analysis of cryogenic current comparators



solenoid



toroid

Meissner return current
actually generates signal!

Some rough numbers

GUT-scale KSVZ axion: $|g_{a\gamma\gamma}| = 2.2 \times 10^{-19}\,\mathrm{GeV}^{-1}$

R = r = a = h/3= 4 m: $V_B = 100\ \mathrm{m}^3$

Average axion-induced B-field for B_{max} = 5 T:

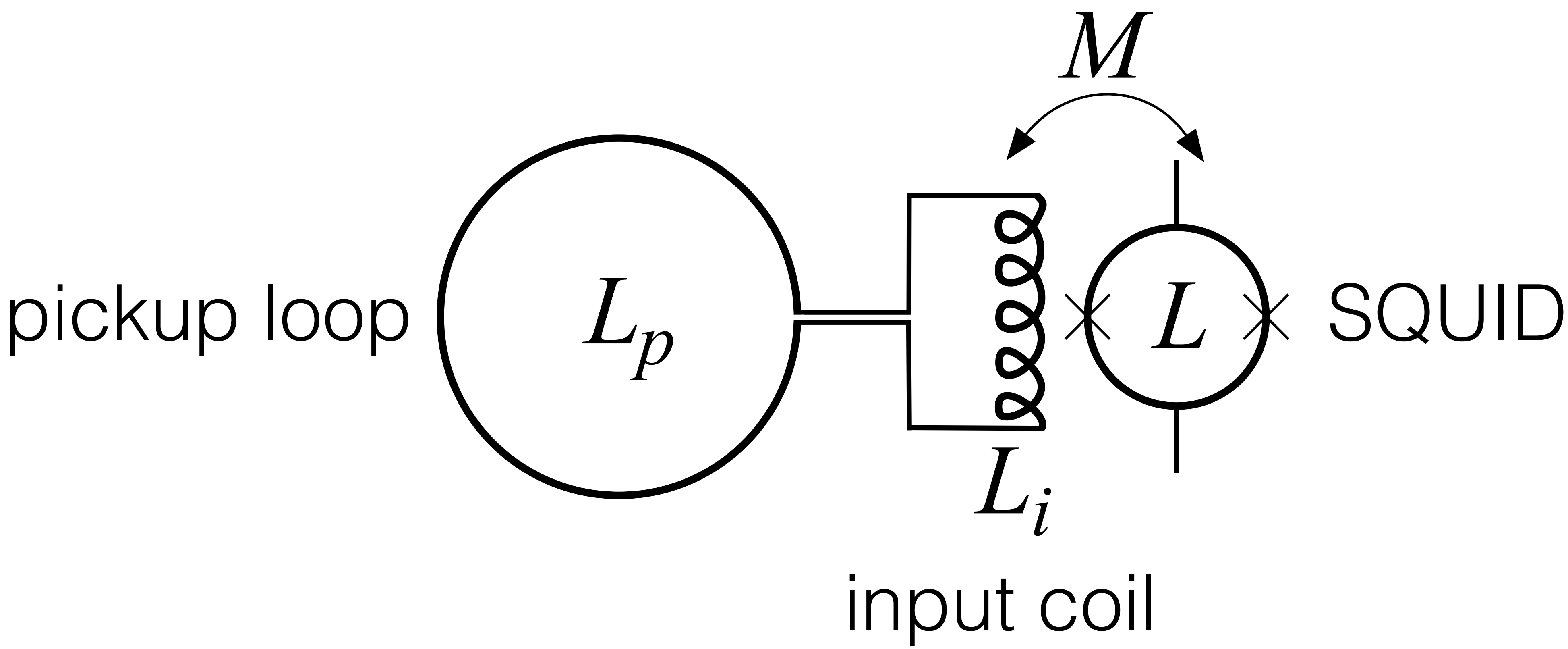
$$\boxed{B_{\mathrm{avg}} = 2.5 \times 10^{-23}\ \mathrm{T}}$$

For 1 year of measurement, can achieve signal-to-noise of 1 with $S_\Phi^{1/2} = 1.2 \times 10^{-19}\ \mathrm{Wb}/\sqrt{\mathrm{Hz}}$

achievable by coupling to commercial SQUIDS!

Assuming axion is all of DM, only free parameter is $g_{a\gamma\gamma}$ as a function of m_a

Broadband: readout circuit



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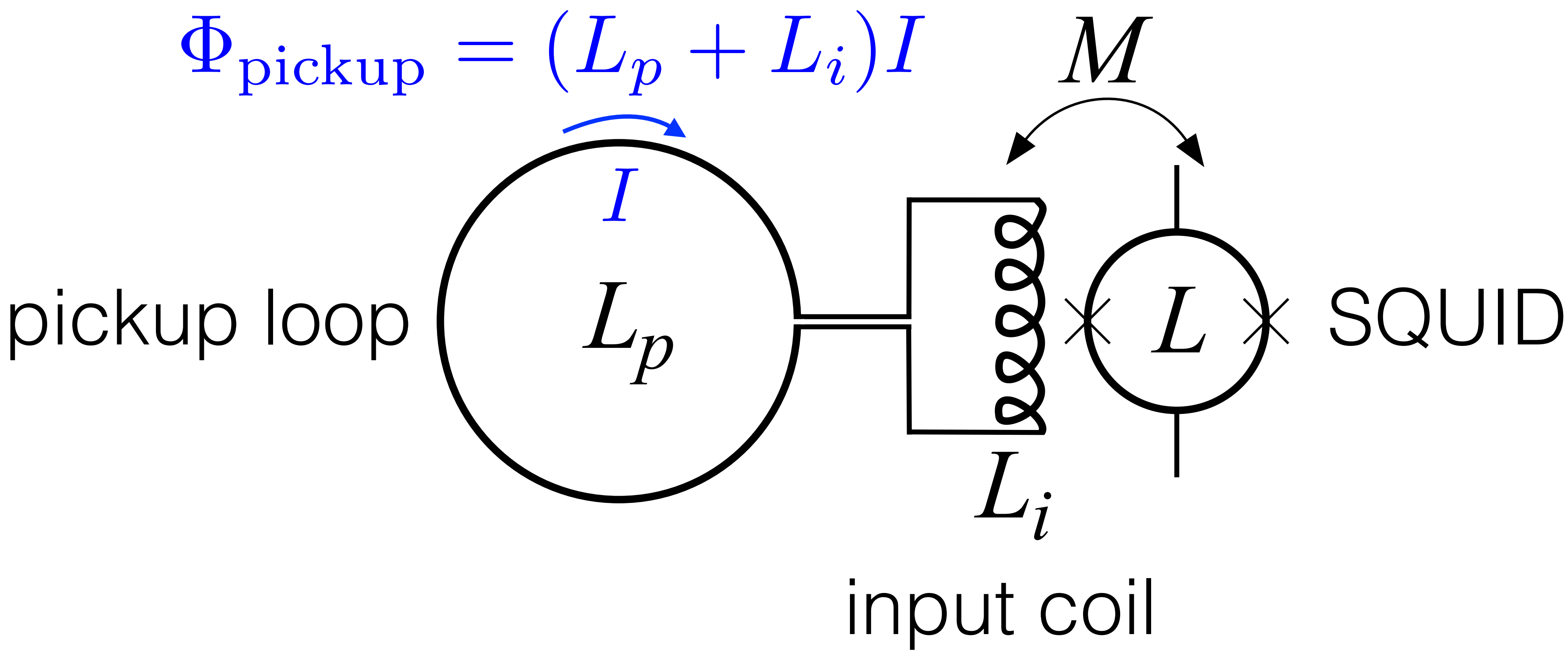

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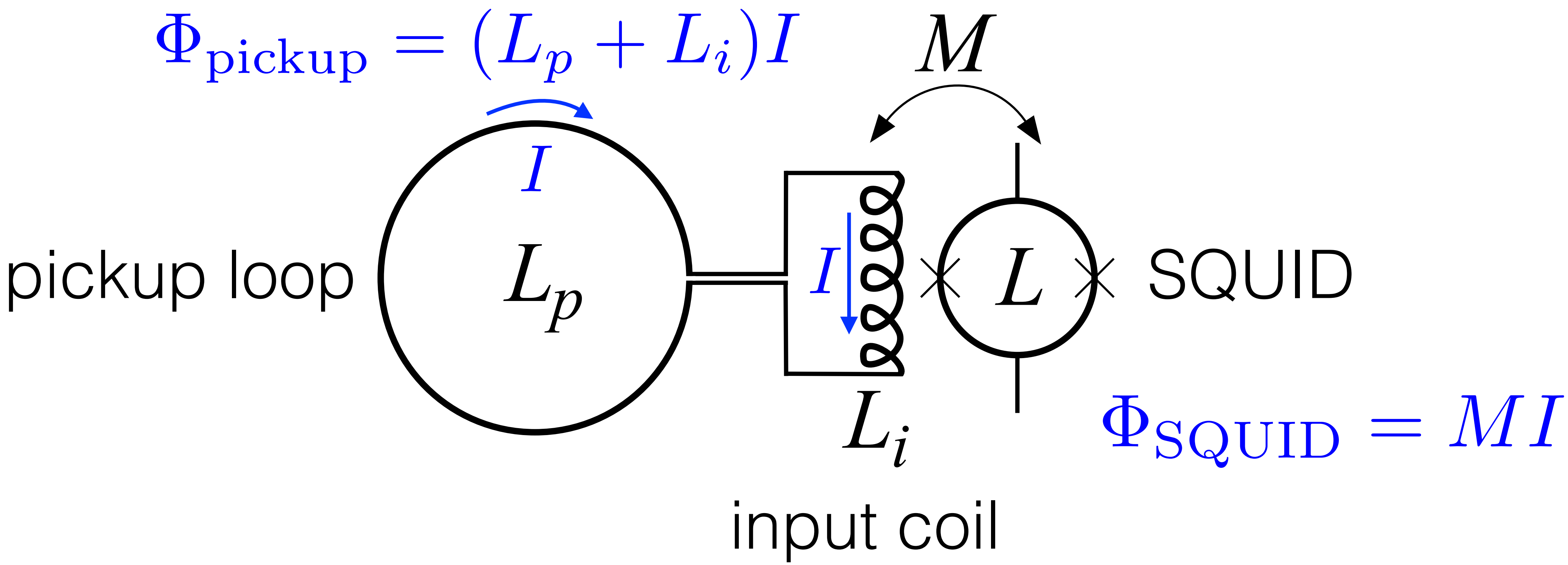

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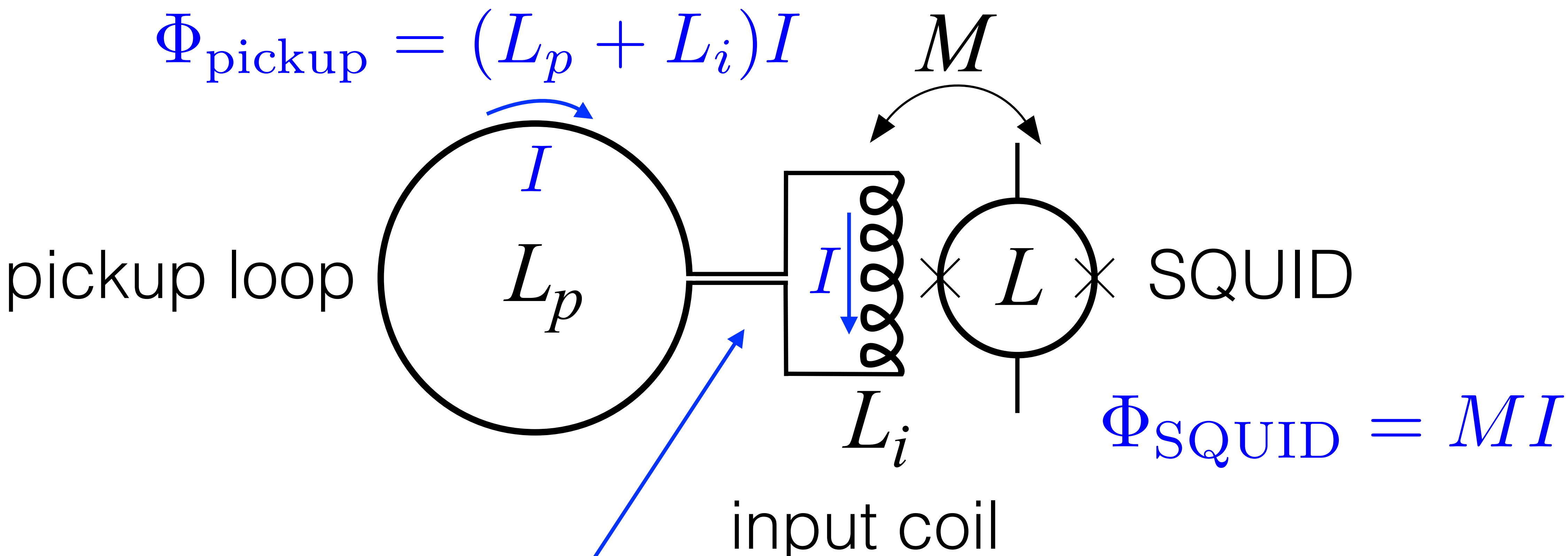

pure superconducting = **zero** thermal noise (at low freq.)

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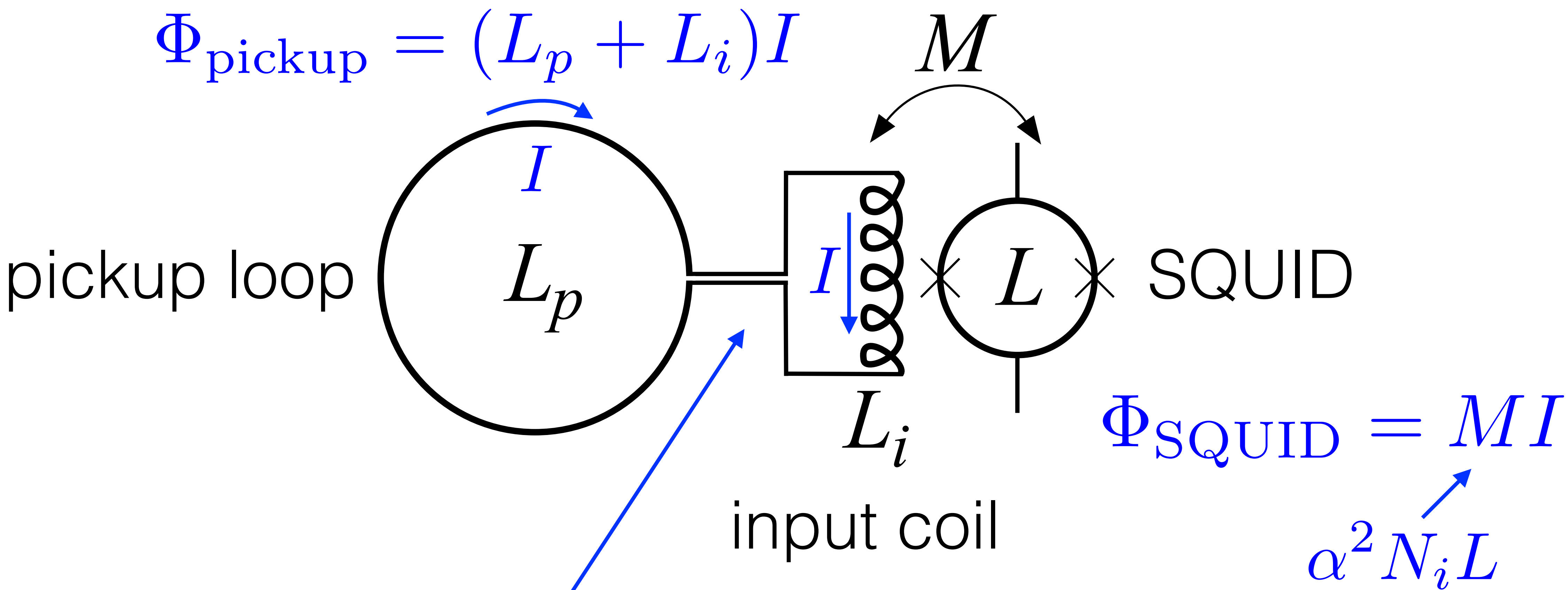

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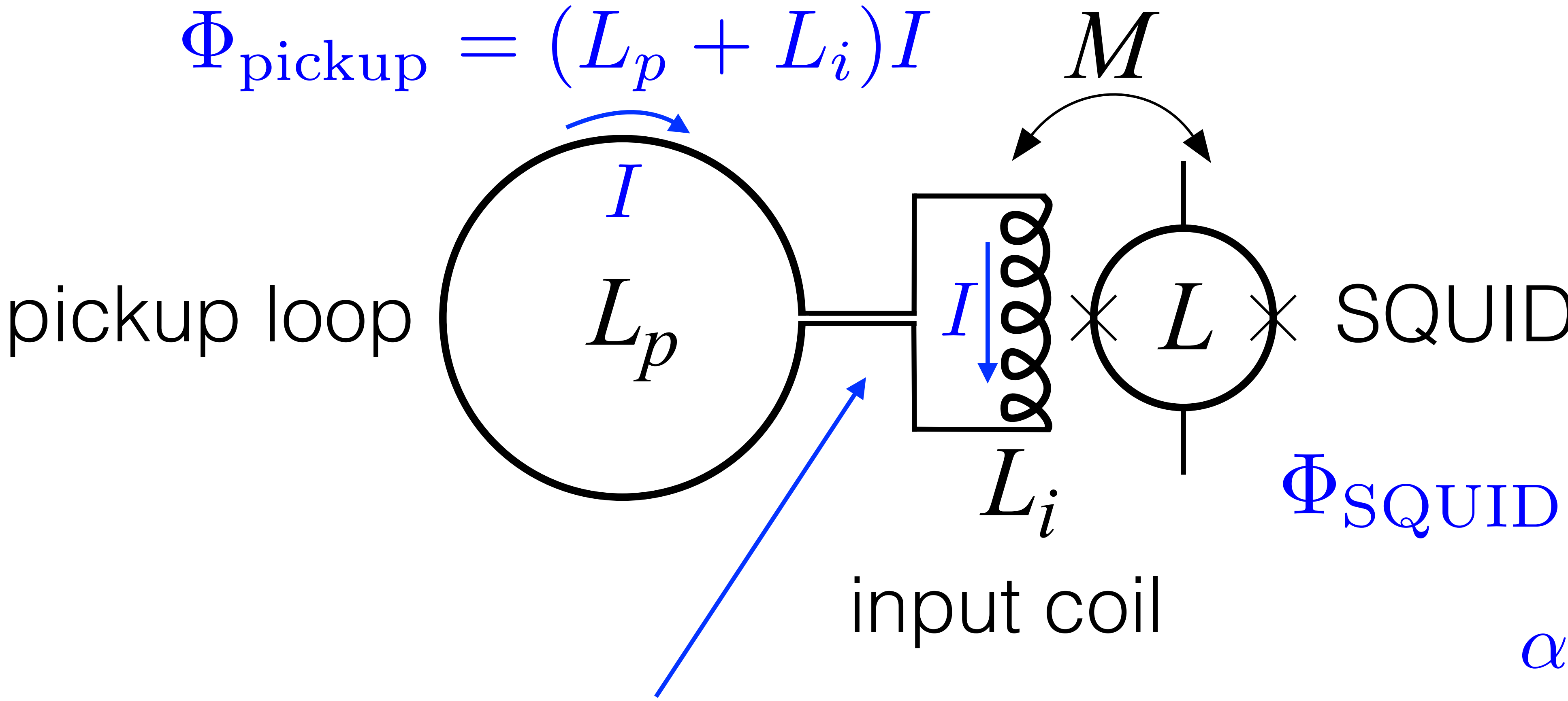
Inductance matching: $L_i \approx L_p \implies \Phi_{\text{SQUID}} \approx \frac{\alpha}{2}\sqrt{\frac{L}{L_p}}\Phi_{\text{pickup}}$

Broadband: readout circuit

$$\Phi_{\text{pickup}} = (L_p + L_i)I$$



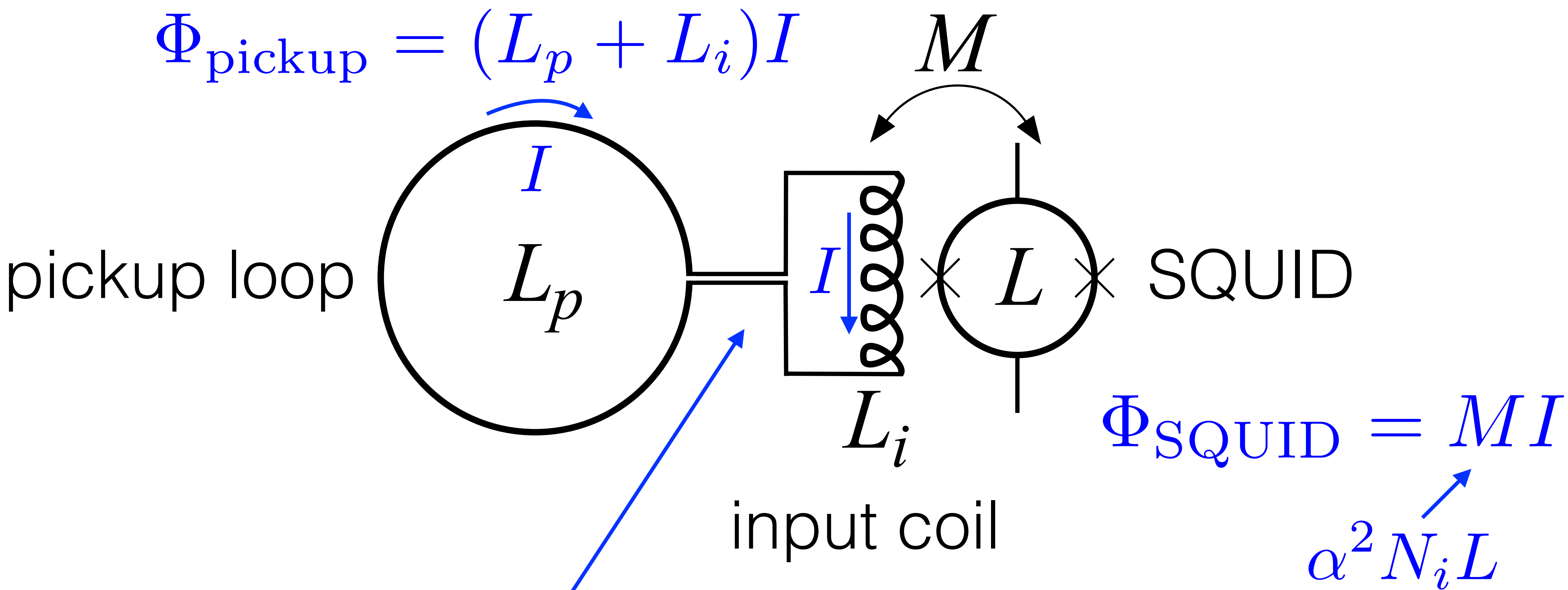
$$\Phi_{\text{SQUID}} = \underset{\alpha^2 N_i L}{M} I$$

pure superconducting = **zero** thermal noise (at low freq.)

Inductance matching: $L_i \approx L_p \implies \Phi_{\text{SQUID}} \approx \underbrace{\frac{\alpha}{2}\sqrt{\frac{L}{L_p}}}_{\approx 0.01}\Phi_{\text{pickup}}$

Optimal coupling: $\frac{1}{2}\int \mathbf{B}^2\, dV = \frac{\Phi^2}{2L_p} \longrightarrow \approx 0.01$

Broadband: readout circuit



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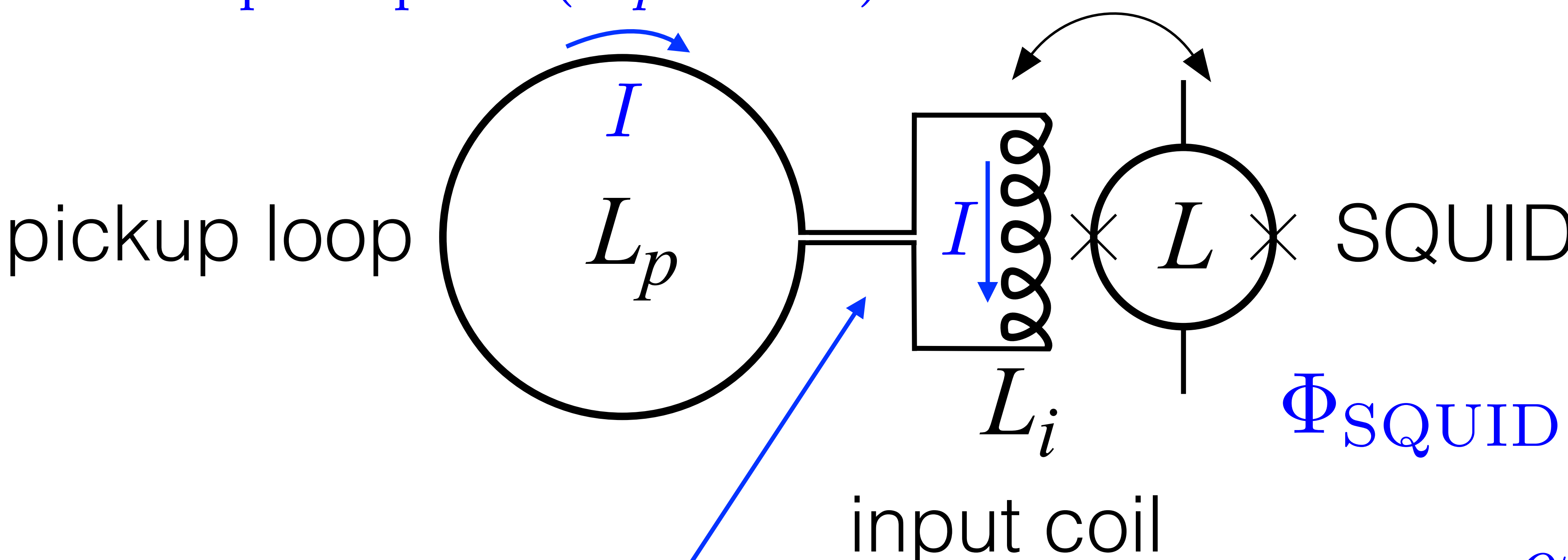
huge area = amplification

Broadband: readout circuit

$\Phi_{\text{pickup}} = (L_p + L_i)I$



$\Phi_{\text{SQUID}} = \underbrace{M}_{\alpha^2 N_i L} I$

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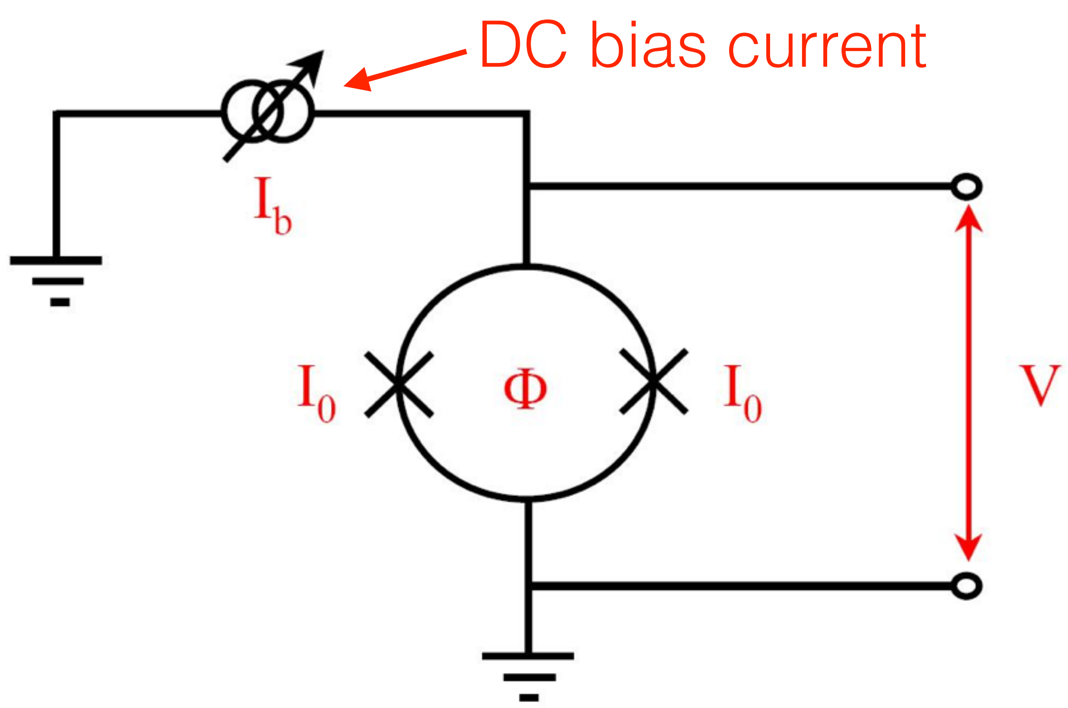
Optimal coupling: $\frac{1}{2}\int \mathbf{B}^2\, dV = \frac{\Phi^2}{2L_p} \longrightarrow \approx 0.01$

huge area = amplification

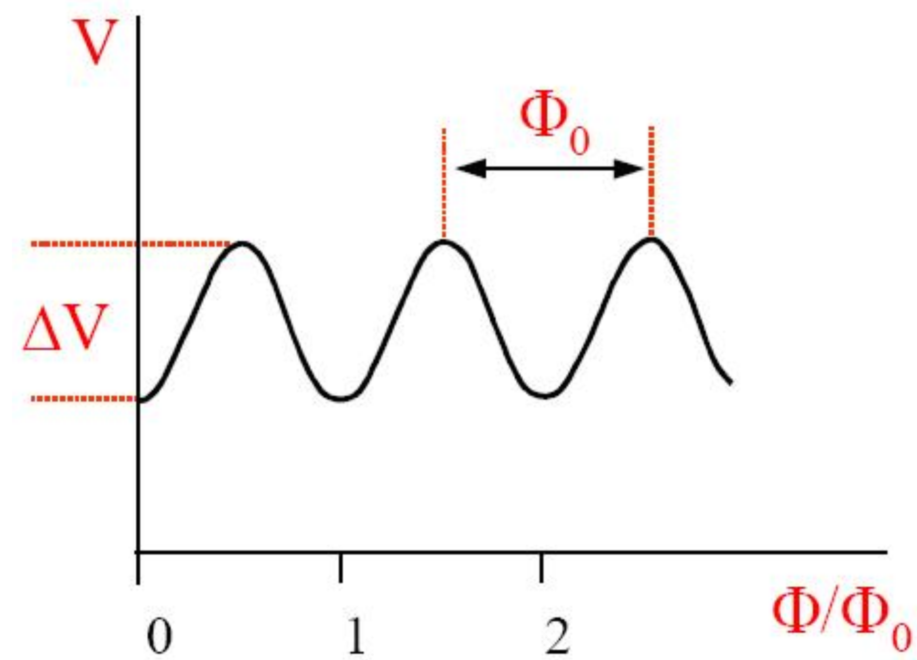
Broadband: response is frequency-independent!

(DC) SQUID basics

Cartoon picture: extremely sensitive flux-to-voltage amplifier



change in flux induces
current across junction
(DC Josephson effect)



measure extremely small fractions
of Φ_0 by fitting sine curve

$$\Phi_0 = \frac{h}{2e} = 2.1 \times 10^{-15}\ \mathrm{Wb} = 2.1 \times 10^{-15}\,\mathrm{T} \cdot \mathrm{m}^2$$

Broadband: SQUID noise

Typical SQUID noise (thermal voltage and current fluctuations):

$$S_{\Phi,0}^{1/2} \sim 10^{-6} \Phi_0 / \sqrt{\mathrm{Hz}}$$

$A_{\mathrm{SQUID}} \sim (30\,\mu\mathrm{m})^2$
$\Longrightarrow$ field sensitivity of $2\,\mathrm{pT}/\sqrt{\mathrm{Hz}}$ at SQUID

Ultimate limit is shot noise:

$$S_{\Phi}^{1/2} = L\, S_{J,0}^{1/2} = \sqrt{\frac{11}{8} h L} / \sqrt{\mathrm{Hz}}$$

dominates below ~ 60 mK

For L ~ 1 nH, only ~ 0.5 x typical noise,
not much improvement possible

Broadband: S/N and sensitivity

Take data for time t:

If $t < \tau$, S/N improves like $\sqrt{t}$ (random walk)

Our regime is $t \gg \tau$: $S/N \sim |\Phi_{\rm SQUID}|\,(t\tau)^{1/4}/S_{\Phi,0}^{1/2}$

$$S/N = 1$$

$\Longrightarrow$ sensitivity to

$$g_{a\gamma\gamma} > 6.3\times 10^{-18}\ \mathrm{GeV}^{-1}\left(\frac{m_a}{10^{-12}\ \mathrm{eV}}\frac{1\ \mathrm{year}}{t}\right)^{1/4}\frac{5\ \mathrm{T}}{B_{\max}}\times\left(\frac{0.85\ \mathrm{m}}{R}\right)^{5/2}\sqrt{\frac{0.3\ \mathrm{GeV/cm^3}}{\rho_{\rm DM}}\frac{S_{\Phi,0}^{1/2}}{10^{-6}\Phi_0/\sqrt{\mathrm{Hz}}}}$$

improves at low masses
from coherence time

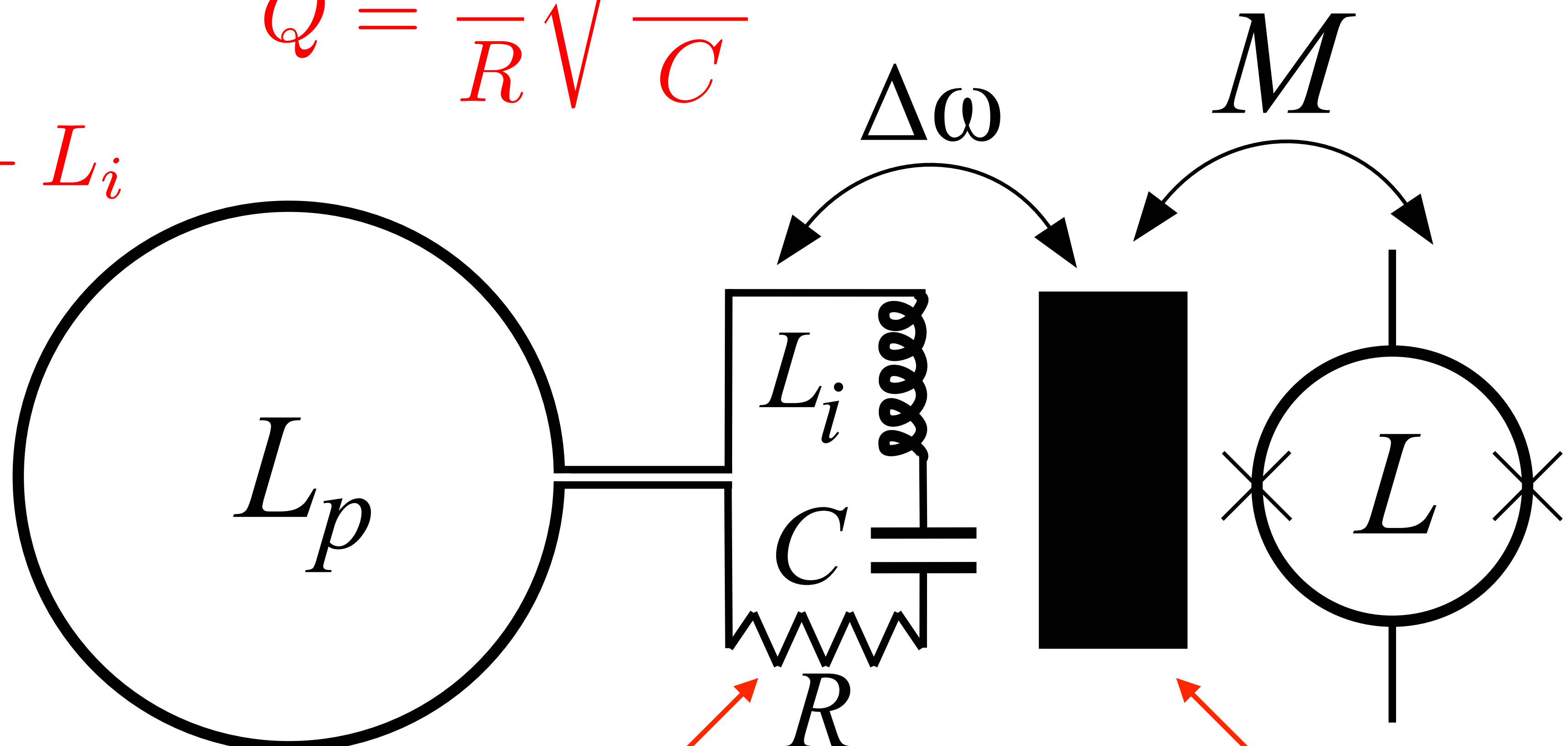
R = r = a = h/3:
tall toroid increases B-field energy

Scale up dimensions to 4m, can probe GUT-scale axions!

Resonant: readout circuit

$$Q = \frac{1}{R}\sqrt{\frac{L_T}{C}}$$

$$L_T = L_p + L_i$$



irreducible resistance (resistance in series rather than parallel)

black box: match circuit bandwidth to signal

New source of noise: thermal noise in pickup RLC circuit

Resonant: bandwidth matching

$v_{DM} = 10^{-3} \implies$ intrinsic signal bandwidth:

$$\frac{\Delta\omega}{\omega} = 10^{-6}$$

Intrinsic LC circuit bandwidth: $\frac{\Delta\omega_{\mathrm{LC}}}{\omega} = \frac{1}{Q}$ $\quad Q = \frac{1}{R}\sqrt{\frac{L_T}{C}}$

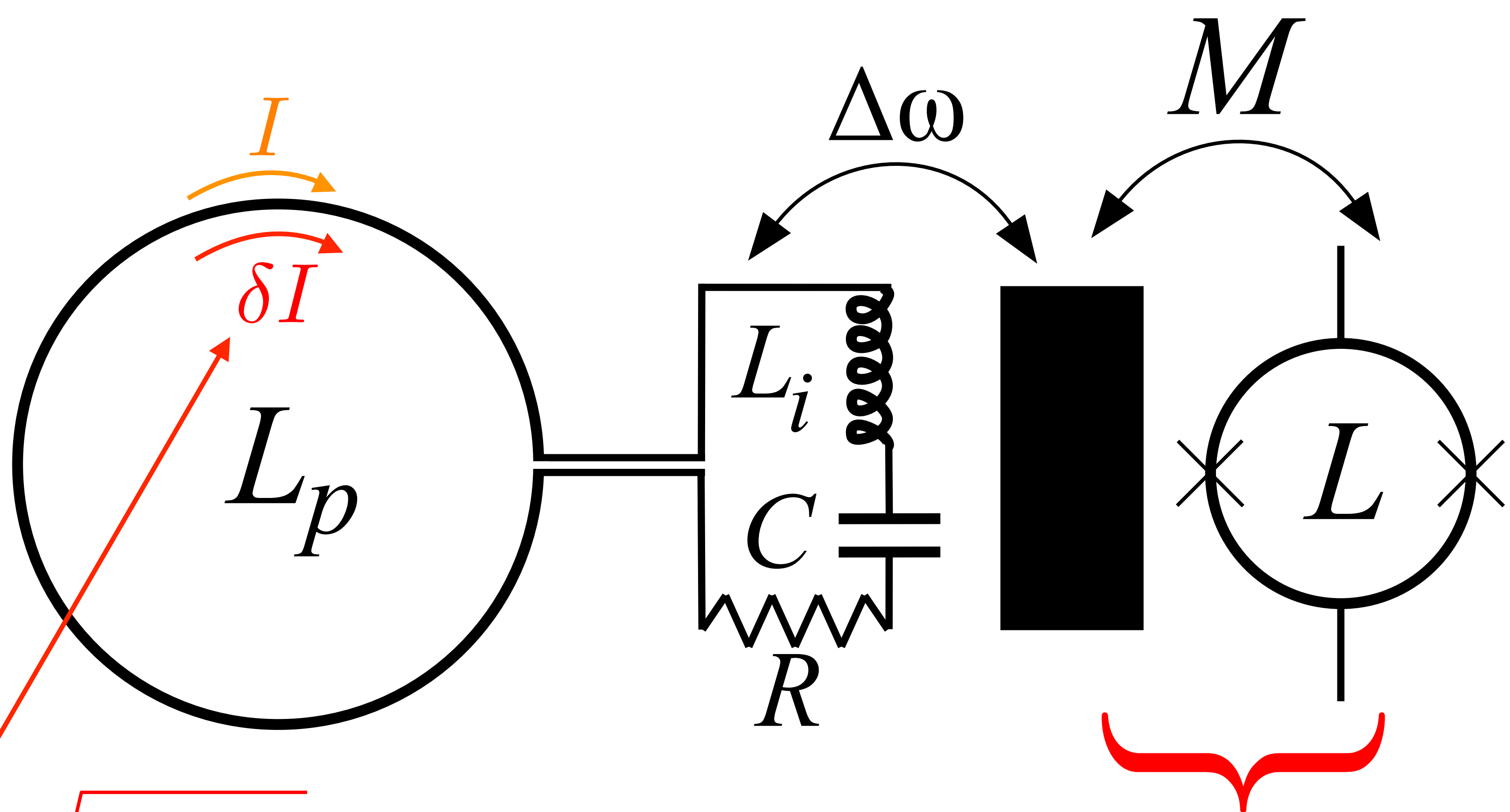
have to wait at least one cycle: $\Delta\omega_{\mathrm{LC}} > \frac{2\pi}{\Delta t}$

Can potentially use "black box" (e.g. feedback damping) to broaden bandwidth without decreasing Q: take Q = 10^6* but larger may be possible

*comparable to existing Nb superconducting LC circuits

Resonant: noise

Can show thermal noise dominates at 0.1 K up to Q = 10^8



$$S_I^{1/2} = \sqrt{\frac{4k_B T}{R}}$$

Resonant: S/N and sensitivity

$$P_S = Q_0 \frac{m_a \Phi^2_{\mathrm{pickup}}}{2L_T}, \qquad P_N = k_B T \sqrt{\frac{m_a}{2\pi t_{\mathrm{e-fold}}}}$$

energy stored in tank circuit

each e-fold of frequency scanned for equal time

$$P_S / P_N = 1$$

$\Longrightarrow$ sensitivity to

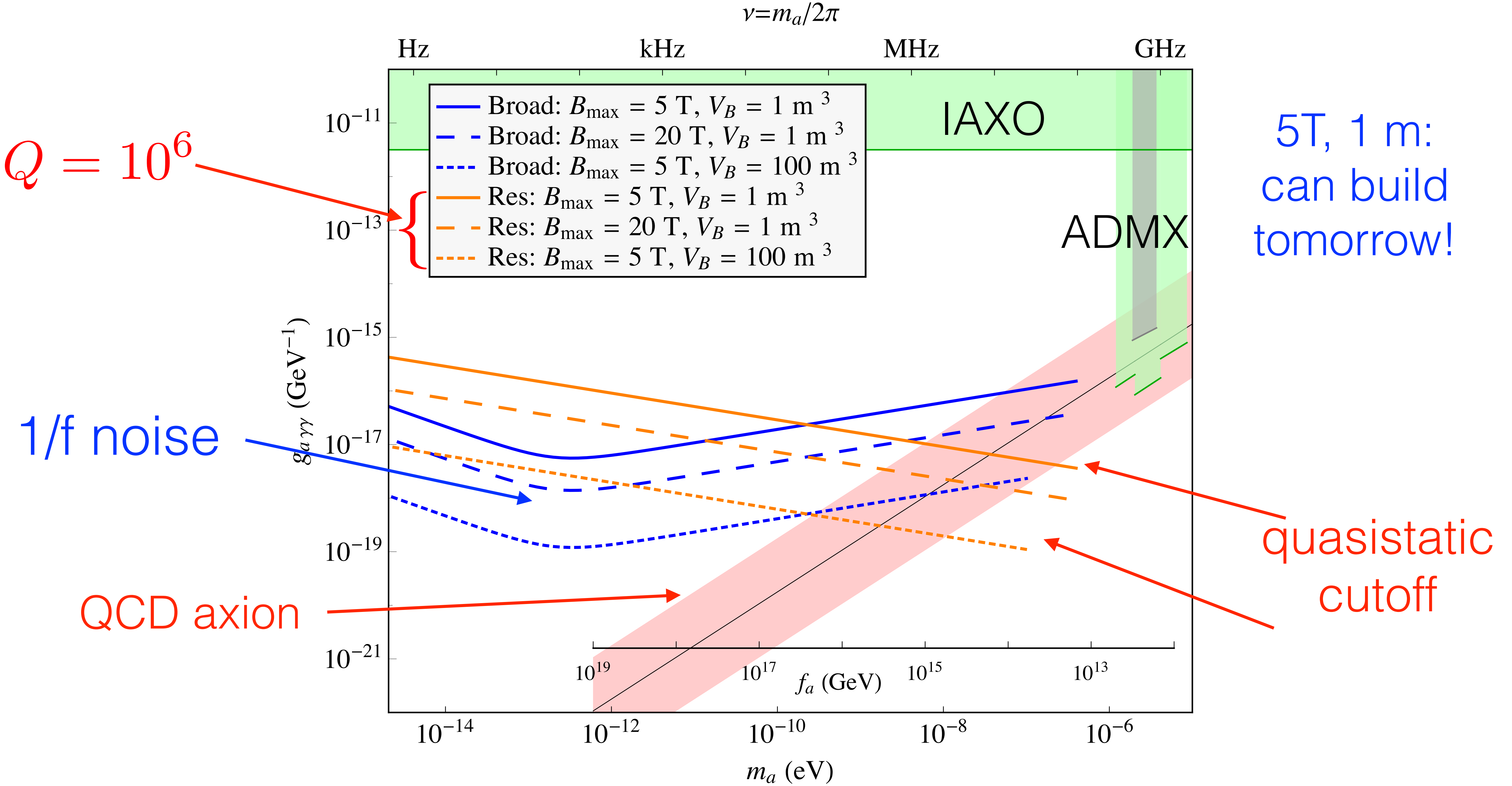
$$g_{a\gamma\gamma} > 9.0 \times 10^{-17}\ \mathrm{GeV}^{-1} \left(\frac{10^{-12}\ \mathrm{eV}}{m_a} \frac{20\ \mathrm{days}}{t_{\mathrm{e-fold}}}\right)^{1/4} \times \frac{5\ \mathrm{T}}{B_{\max}} \left(\frac{0.85\ \mathrm{m}}{R}\right)^{5/2} \sqrt{\frac{0.3\ \mathrm{GeV/cm^3}}{\rho_{\mathrm{DM}}} \frac{10^6}{Q_0} \frac{T}{0.1\ \mathrm{K}}}$$

improves at high masses

improves at low temp

Broadband and resonant reach

1 year **total** measurement time



With same experimental parameters,

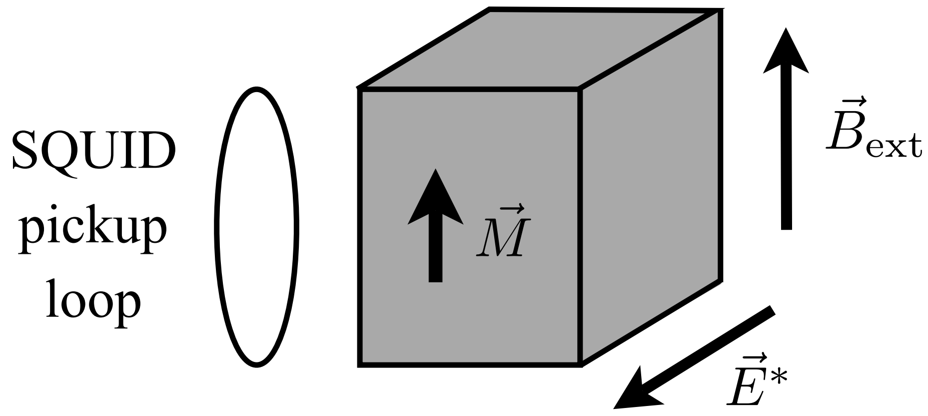
broadband for low frequencies, resonant for high frequencies

Comparison to existing proposals

ADMX

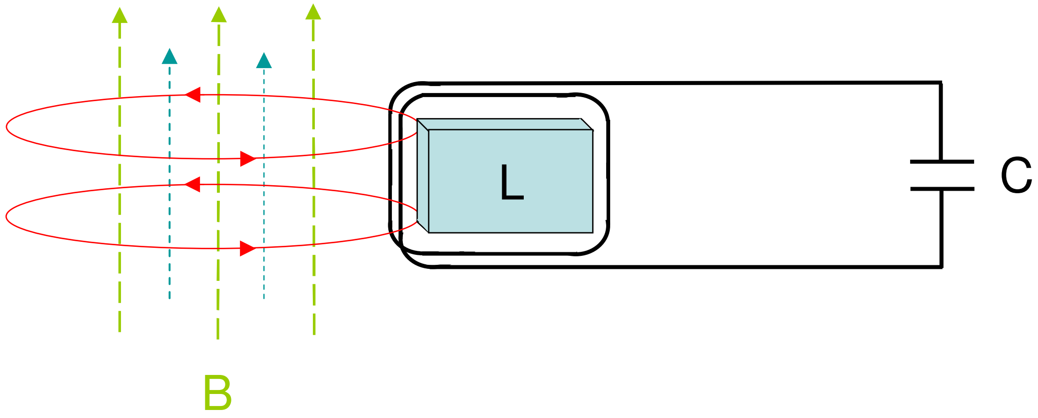
Complementary: we probe lower masses with volume enhancement

CASPEr



Complementary: we measure coupling to photons instead of nuclear EDMs, probe QCD axion for $f_a < M_{\text{GUT}}$

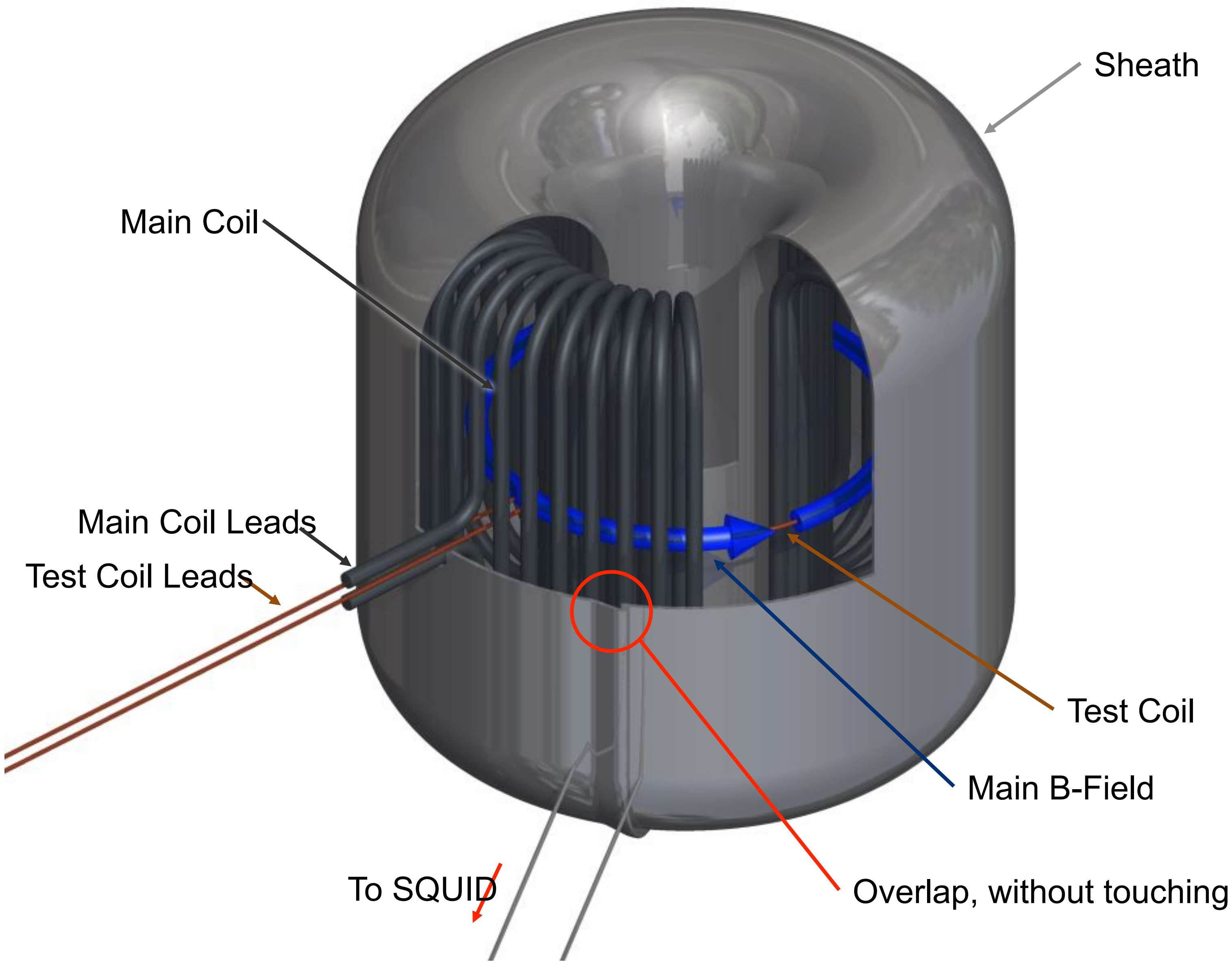
Thomas/Cabrera/Sikivie LC circuit

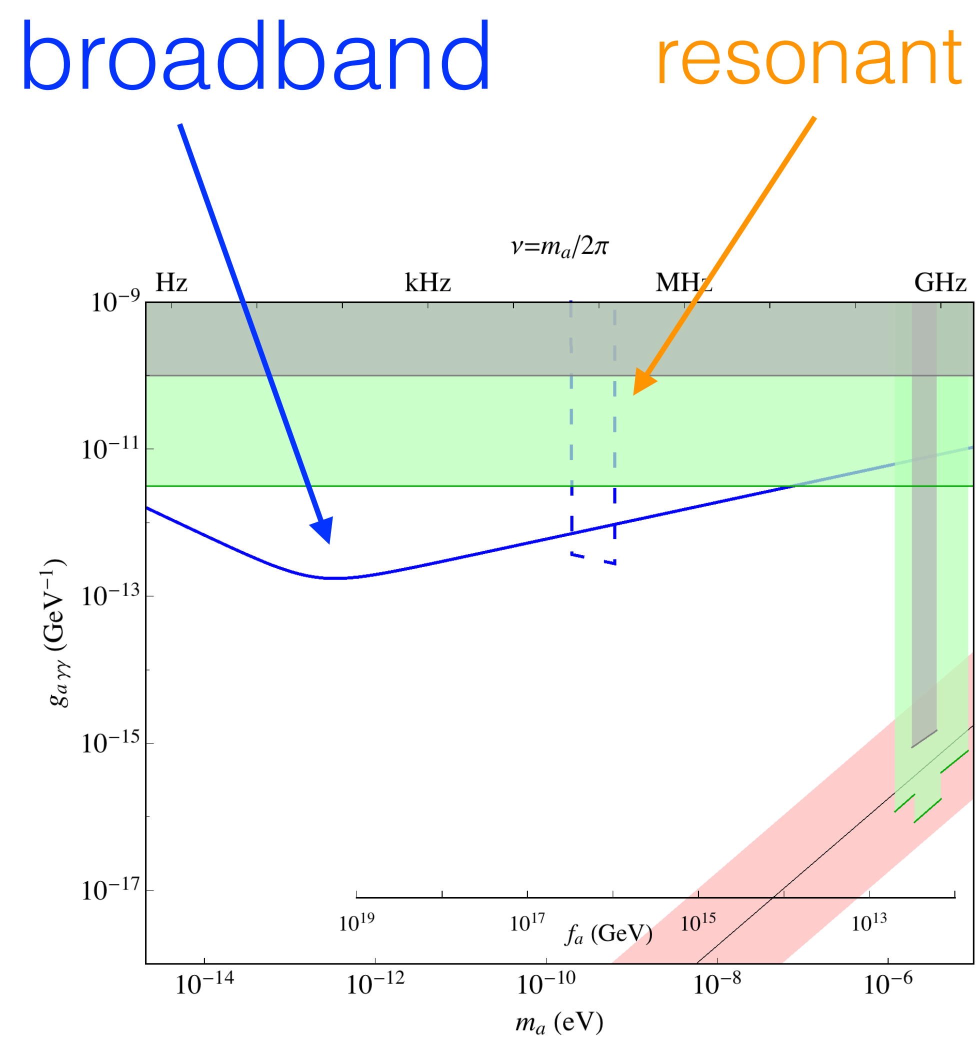


Our pickup is in zero-field region, advantages at low frequencies with broadband readout

MIT prototype

R ~ 10 cm



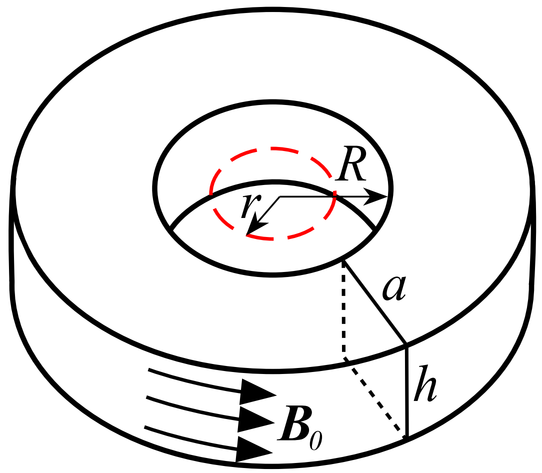


(1 month data-taking)

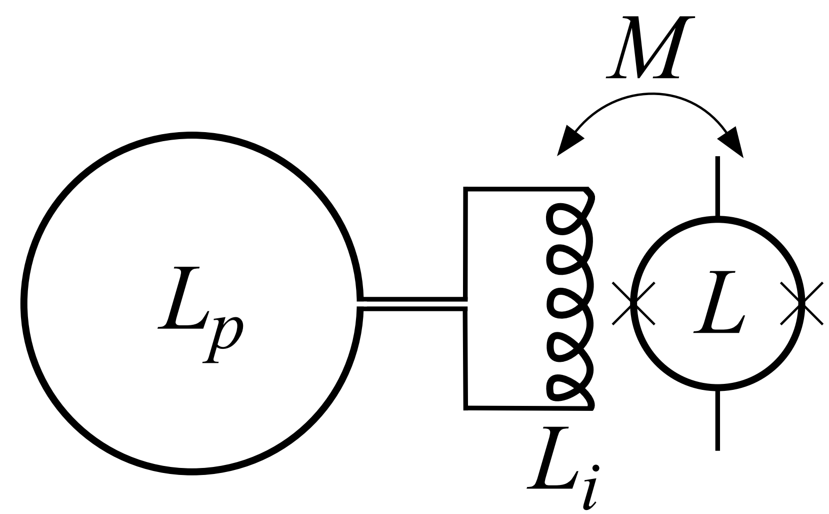
Interesting physics with first-stage experiment!

Summary

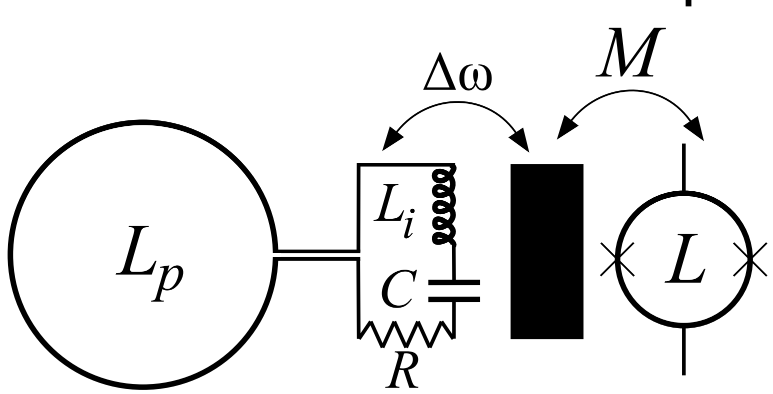
I. Zero-field pickup geometry



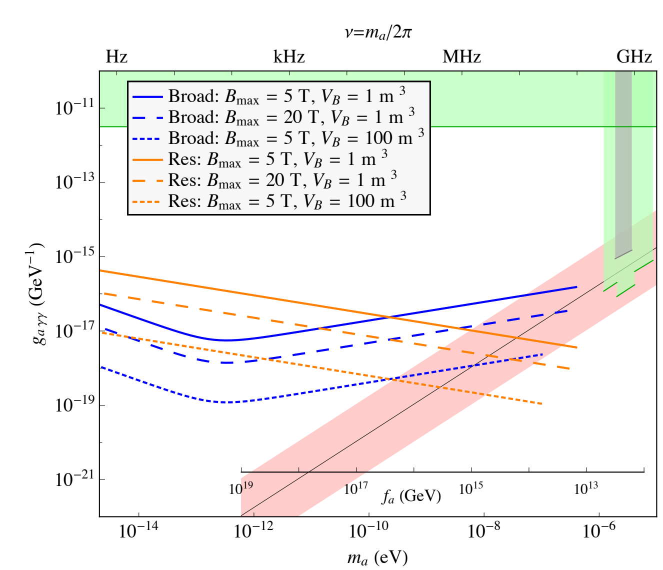
II. Broadband readout for low frequencies



III. Resonant readout for high frequencies, with feedback damping



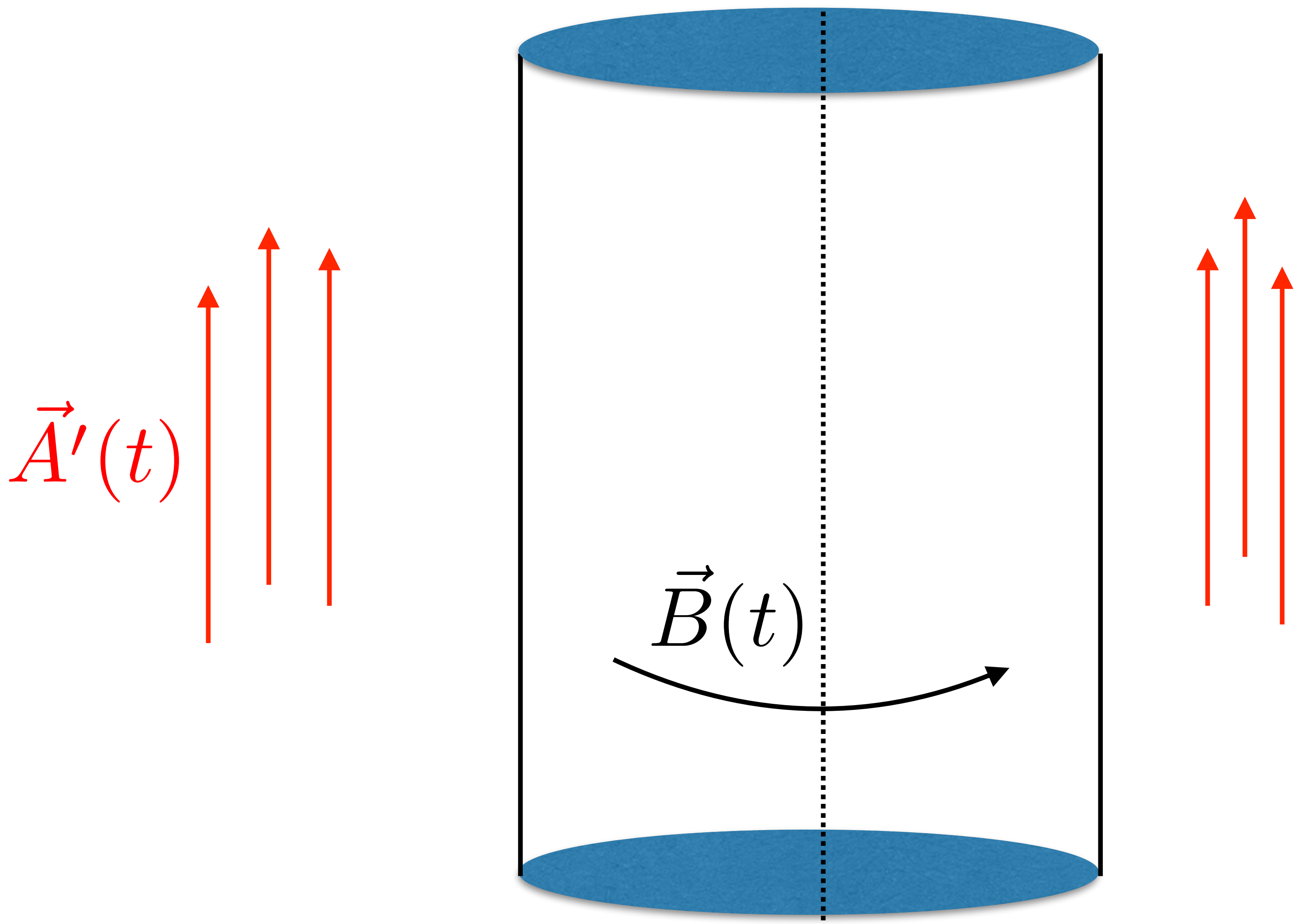
IV. Can probe the GUT-scale QCD axion!



Backup slides

Dark photon applications

$$\mathcal{L} = \mathcal{L}_{EM} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{\gamma'}A'_\mu A'^\mu - \epsilon e J^\mu_{EM} A'_\mu$$



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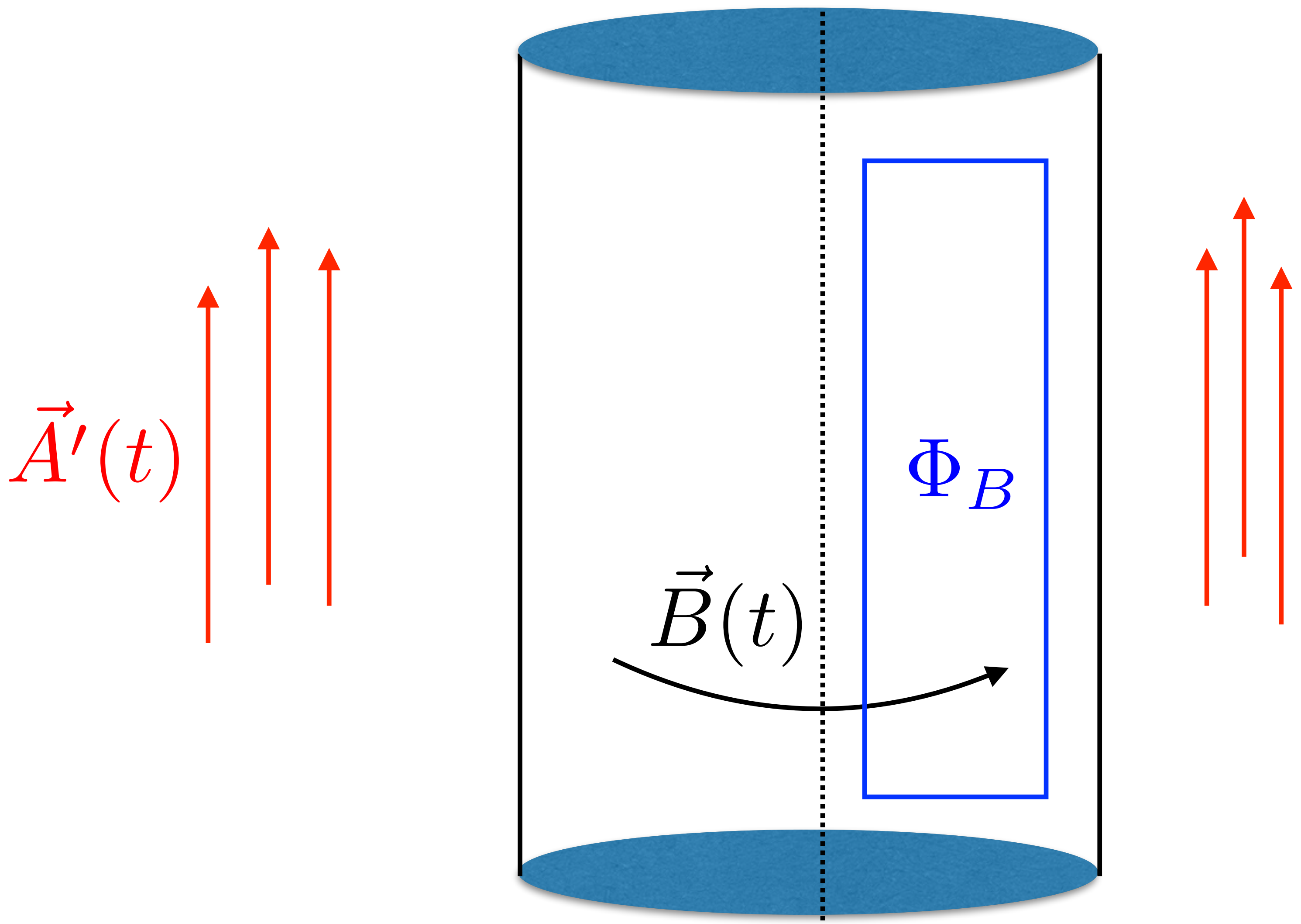
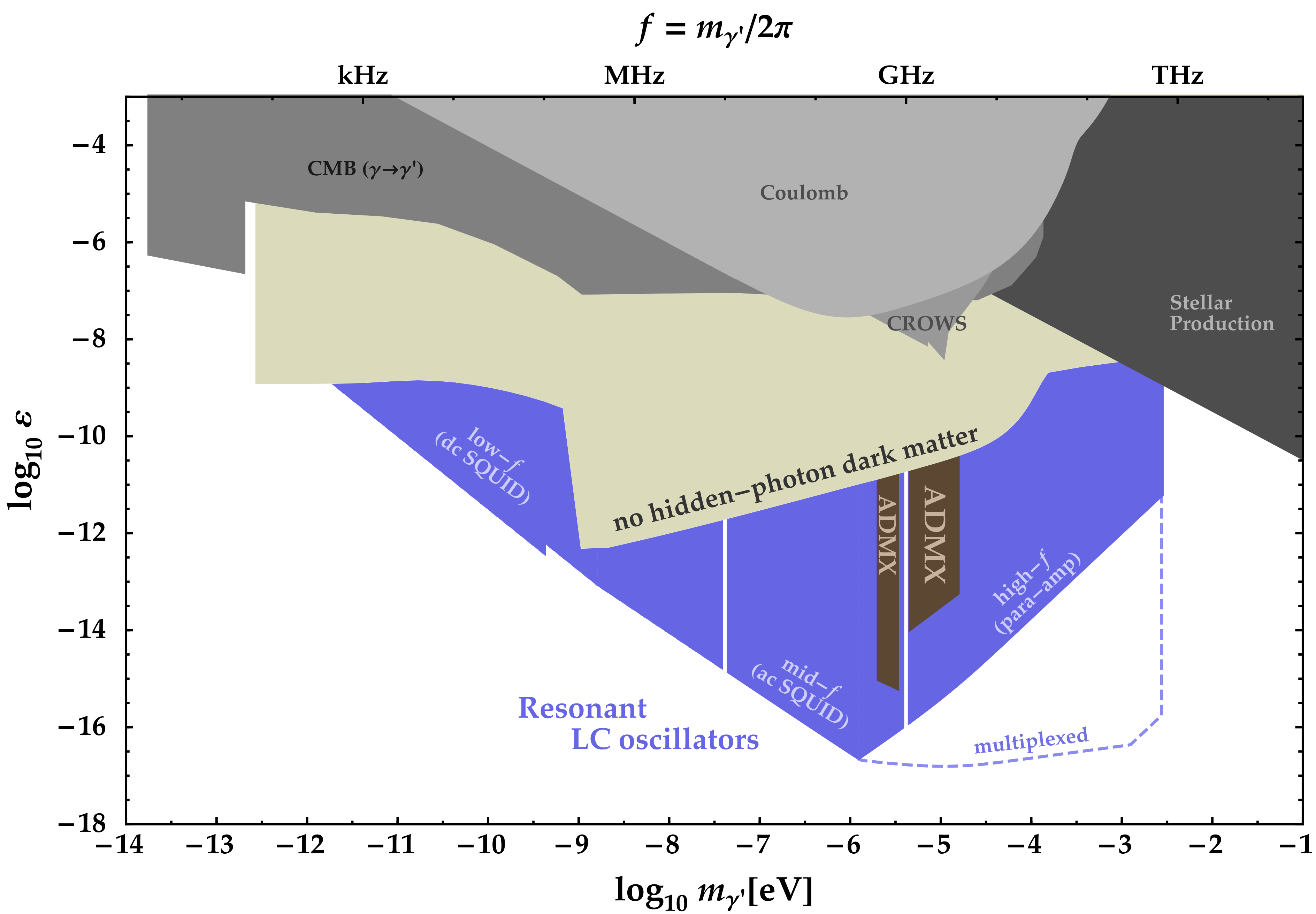


Try detecting B-field with broadband strategy?
No tuning necessary!

Broadband dark photon reach

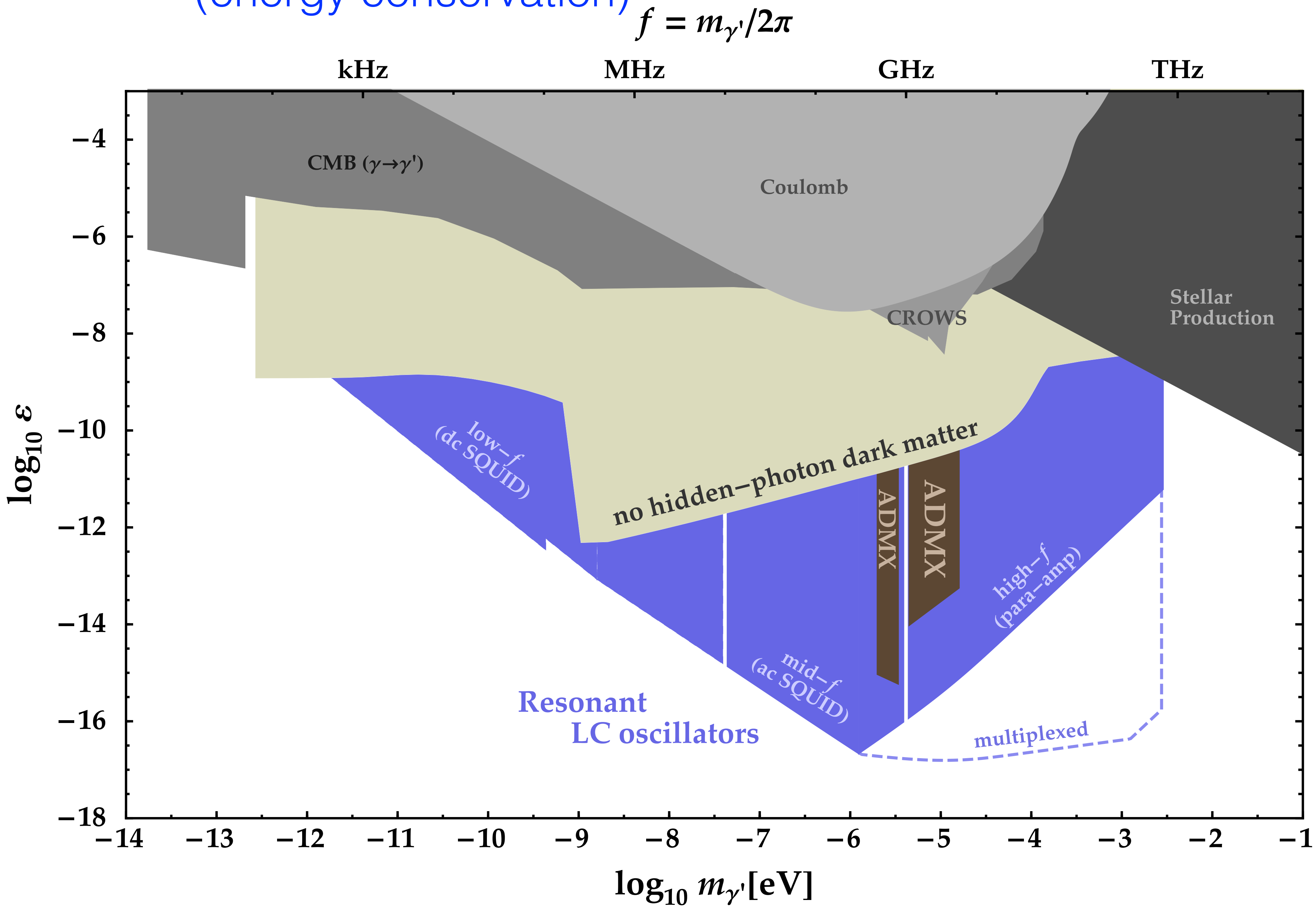


[Chaudhuri et al., 1411.7382]

Broadband dark photon reach

Assume $\Phi_{\mathrm{SQUID}} = 0.025\Phi_B$, 1 year running as with axions

(energy conservation)



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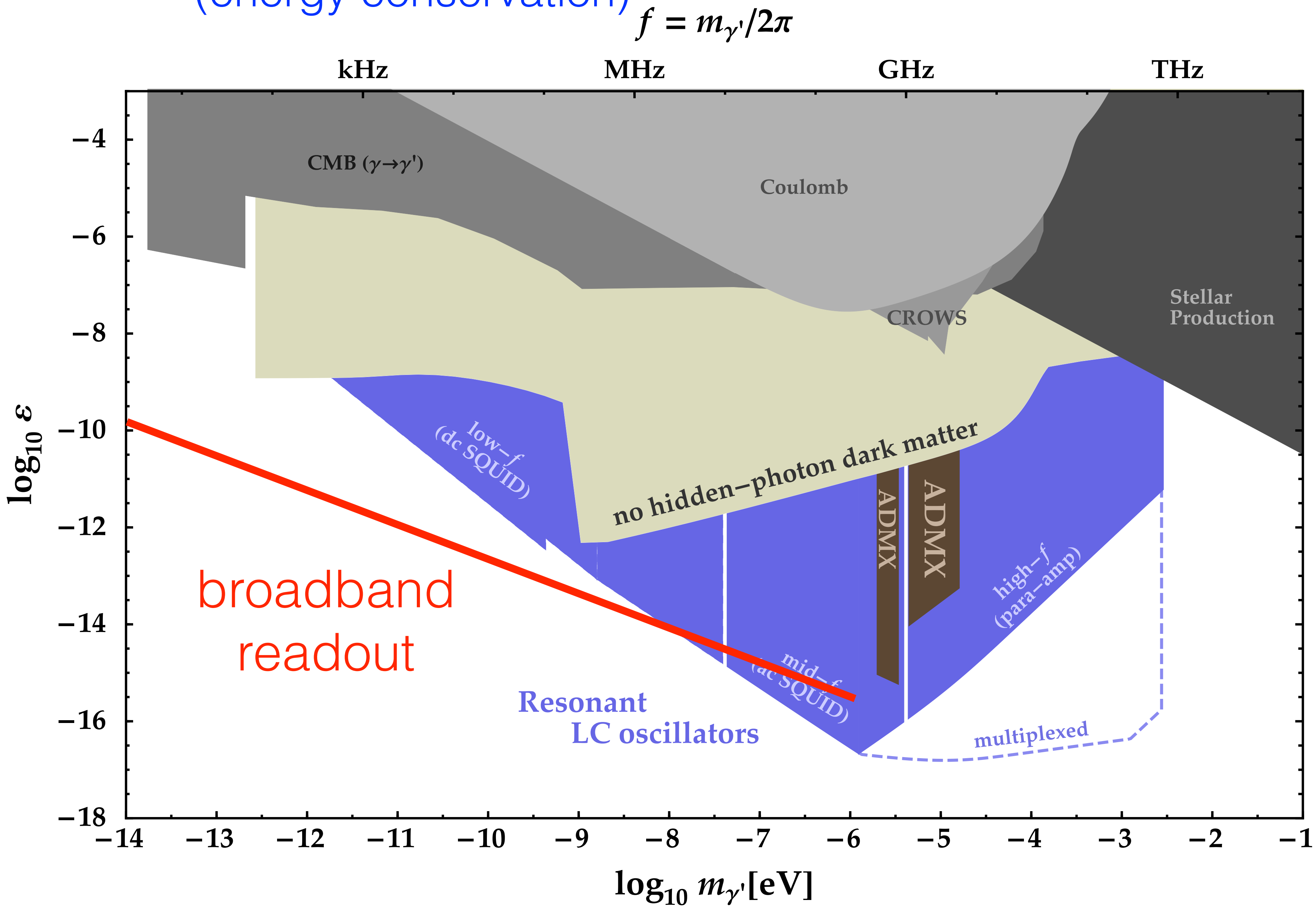

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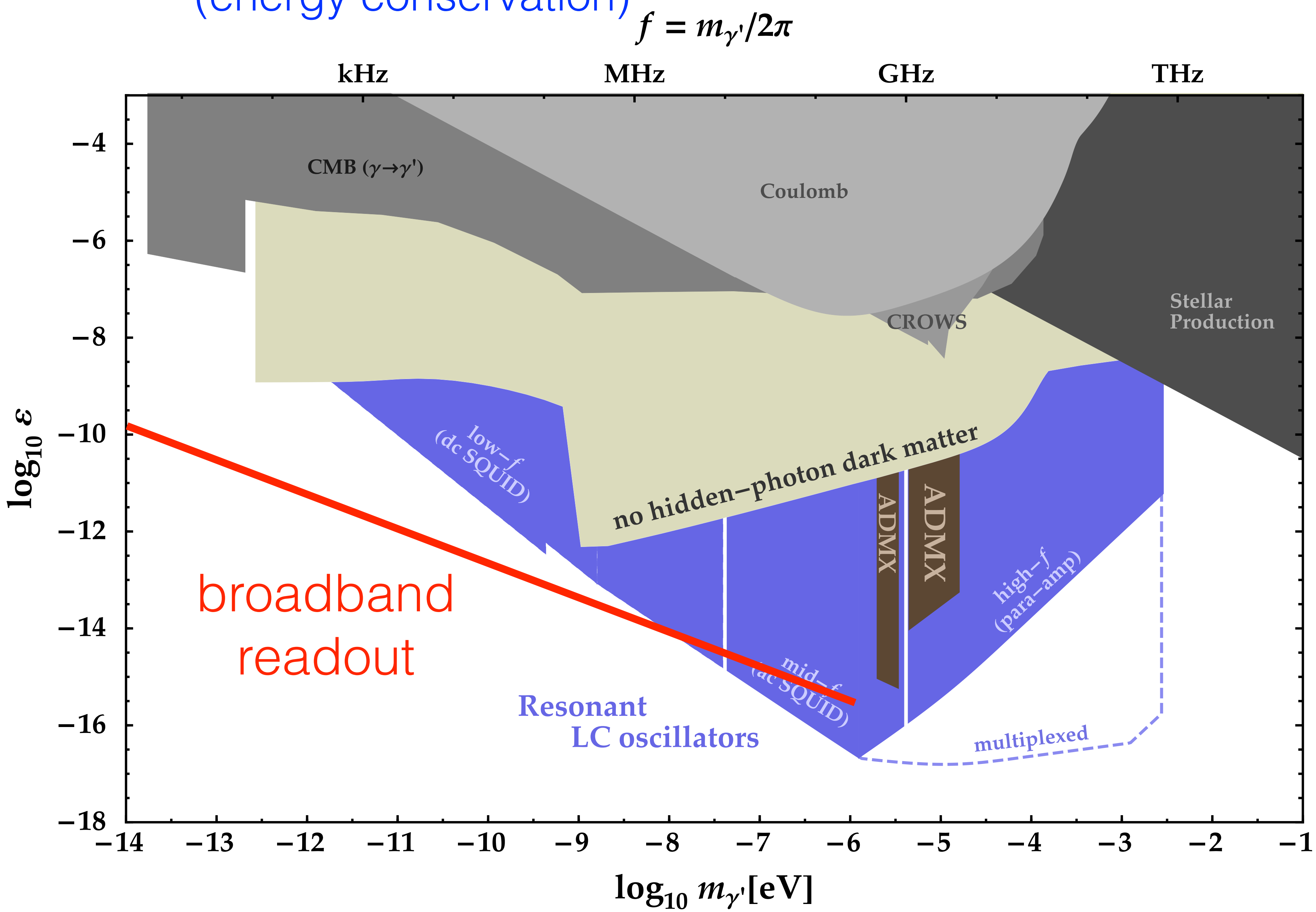


[Chaudhuri et al., 1411.7382]

Complementary to high-frequency LC readout

Dark photon reach calculation

$$\mathbf{B} \approx \epsilon\sqrt{2\rho_{\mathrm{DM}}}\,m_{\gamma'}R\,\hat{\phi}$$

$$\Phi_B \approx \frac{1}{2}\epsilon\sqrt{2\rho_{\mathrm{DM}}}\,m_{\gamma'}R^2h = \frac{1}{2\pi}\epsilon\sqrt{2\rho_{\mathrm{DM}}}\,m_{\gamma'}V_{\mathrm{shield}}$$

$$\Phi_{\mathrm{SQUID}} = 0.025\Phi_B$$ (energy conservation: $\frac{\Phi_B^2}{2L} = \int \mathbf{B}^2\,dV$)

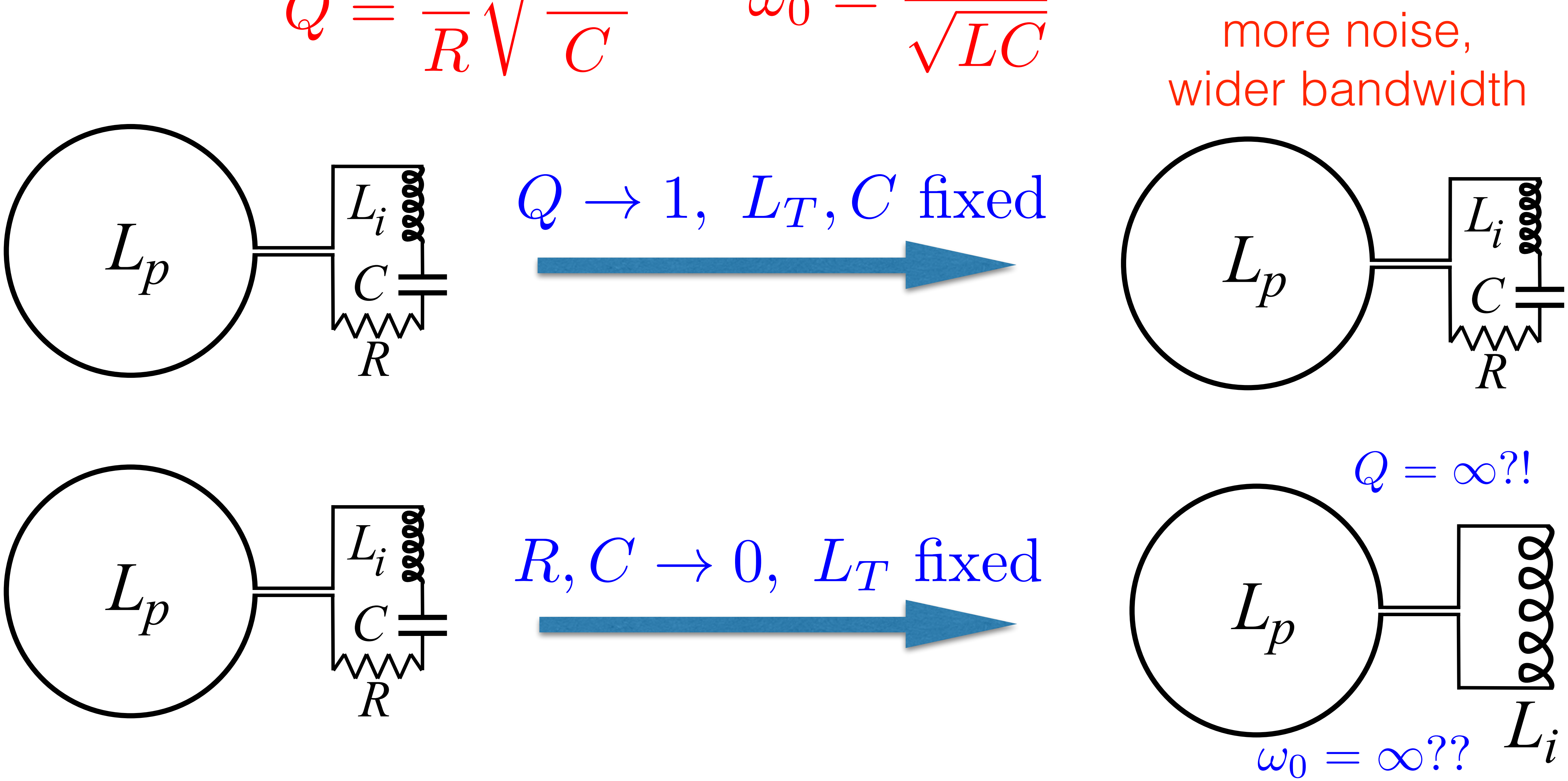
$$S/N \sim |\Phi_{\mathrm{SQUID}}|\,(t\tau)^{1/4}/S_{\Phi,0}^{1/2}$$

$$S/N = 1 \implies$$

$$\boxed{\epsilon > 1.5\times10^{-13}\times\left(\frac{10^{-10}\ \mathrm{eV}}{m_{\gamma'}}\right)^{3/4}\left(\frac{1\ \mathrm{year}}{t}\right)^{1/4}\times\frac{1\ \mathrm{m}^3}{V_{\mathrm{shield}}}\sqrt{\frac{0.3\ \mathrm{GeV/cm}^3}{\rho_{\mathrm{DM}}}}\frac{S_{\Phi,0}^{1/2}}{10^{-6}\ \Phi_0/\sqrt{\mathrm{Hz}}}}$$

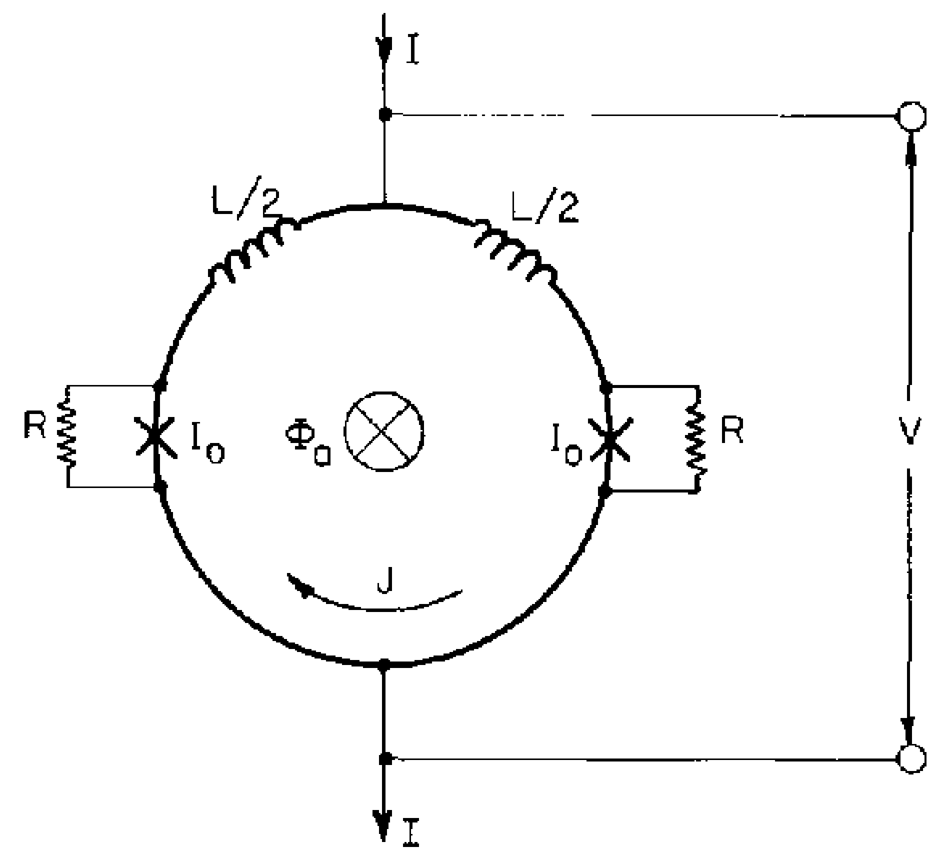
Broadband $\neq$ non-resonant!

$$Q = \frac{1}{R}\sqrt{\frac{L_T}{C}} \qquad \omega_0 = \frac{1}{\sqrt{LC}}$$



Q is not an appropriate variable
to describe a purely inductive circuit

Origin of SQUID noise



Junction shunt resistance introduces thermal noise:

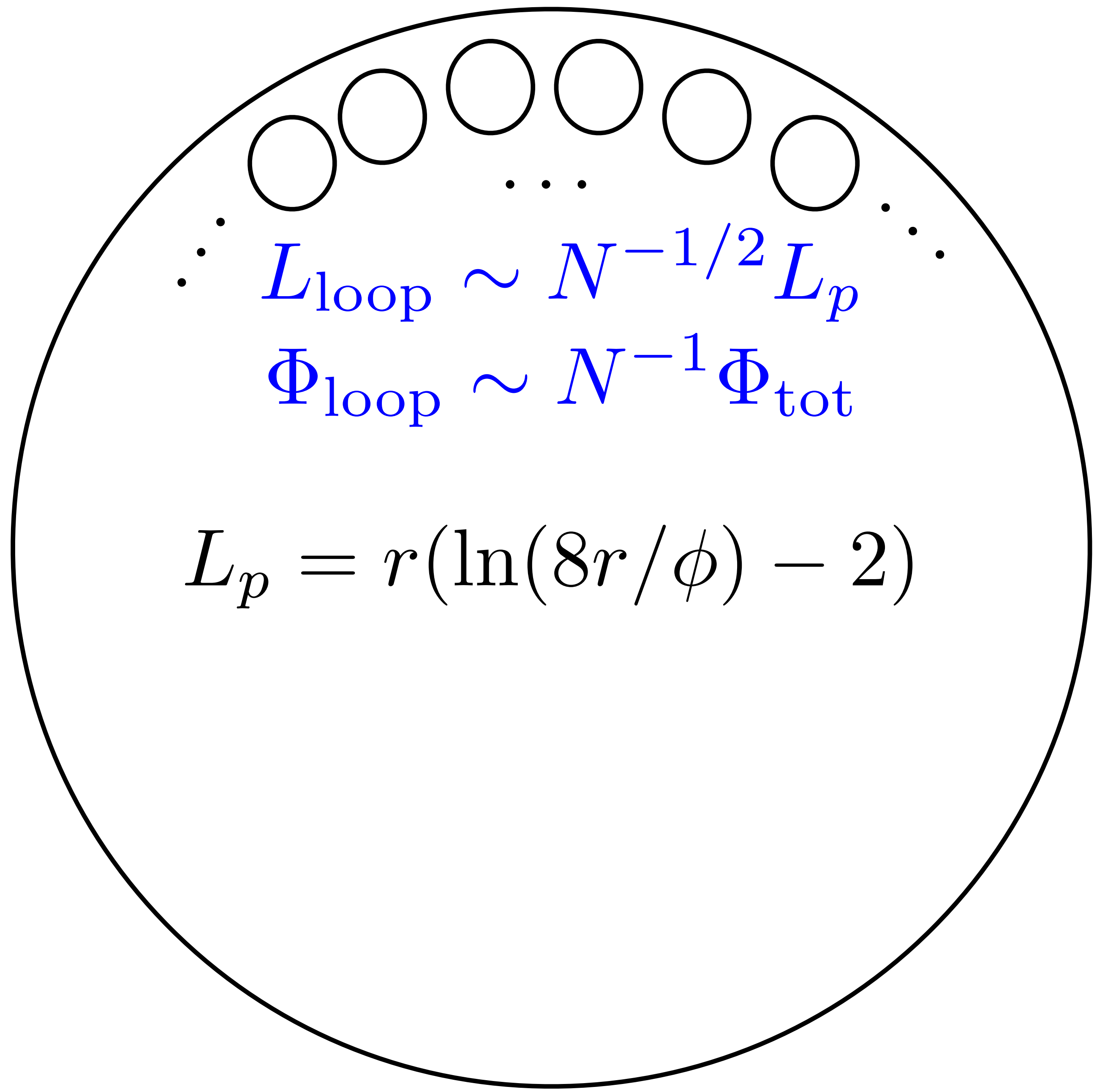
$$\cancel{S_V \approx 16 k_B T R}$$

always subdominant
in resonant circuit
(suppressed by narrow bandwidth)

$$S_J \approx 11 k_B T / R$$

Inductance matching

N loops
in parallel:



$$L_{\text{loop}} \sim N^{-1/2} L_p$$

$$\Phi_{\text{loop}} \sim N^{-1} \Phi_{\text{tot}}$$

$$L_p = r(\ln(8r/\phi) - 2)$$

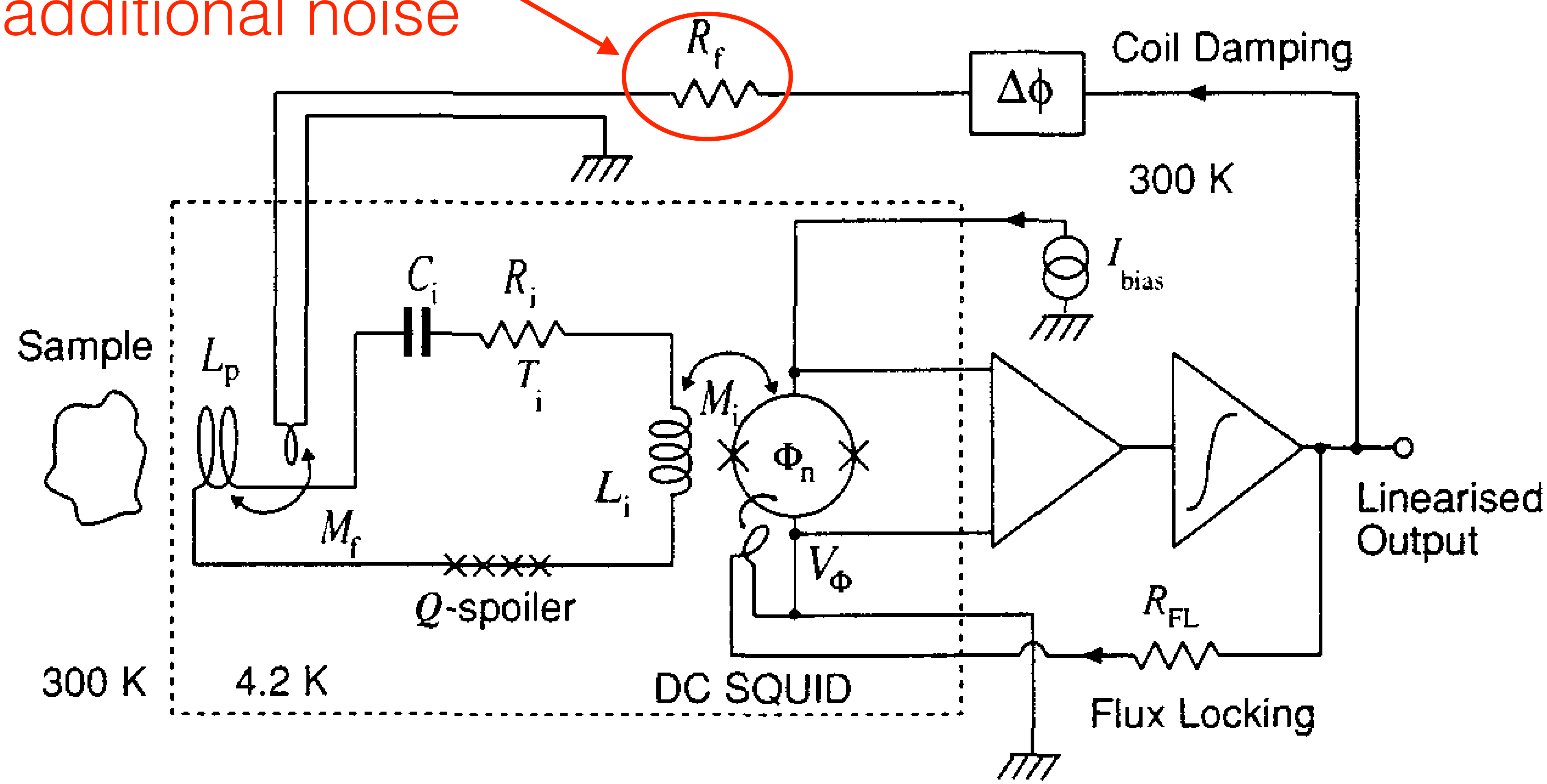
$$\implies L_{\text{eff}} \sim N^{-1/2} L_p$$

Could also use "pie-slice" loops (fractional-turn magnetometer),
or slitted sheath as in 1411.7382

Resonant: feedback damping

Trick from SQUID magnetometry:
can widen bandwidth without increasing thermal noise

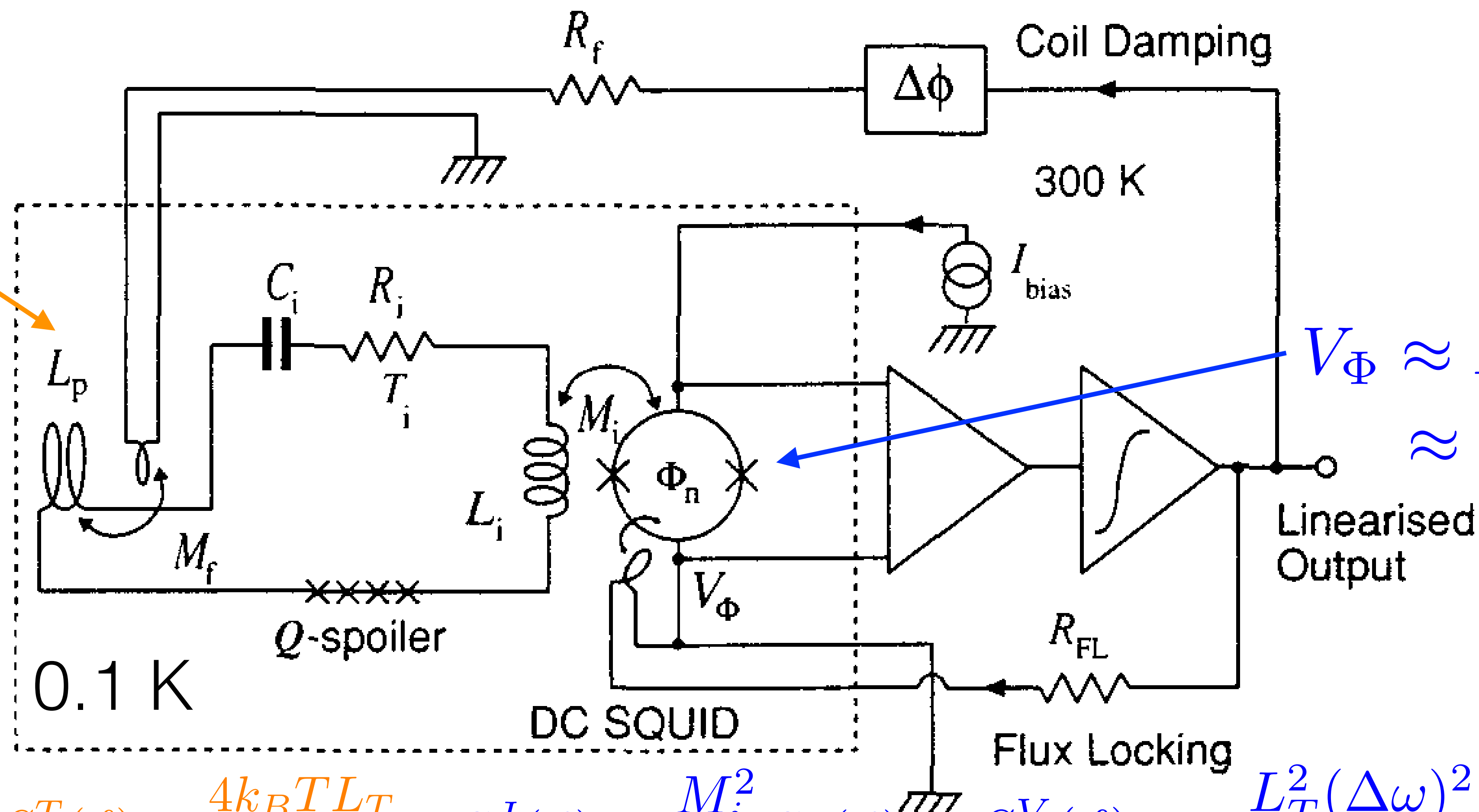
decreases loaded Q,
but not part of resonant circuit
so no additional noise



[Seton et al. *Mag. Res. Mat.* 1999]

Dominance of thermal noise in resonant circuit

N_s turns



$V_\Phi \approx R/L$

$\approx 10^9$ Hz

$$S_\Phi^T(f) = \frac{4k_B T L_T}{N_s^2 \omega Q_0} \qquad S_\Phi^J(f) \approx \frac{M_i^2}{N_s^2} S_J(f) \qquad S_\Phi^V(f) \approx \frac{L_T^2(\Delta\omega)^2}{N_s^2\omega^2 M_i^2 V_\Phi^2} S_V(f)$$

Optimize w.r.t. N_s:

thermal

$< 10^{-2}$

shot noise

$$S_\Phi(f) \approx \frac{4k_B T L_p}{\omega Q_0}\left[1 + \frac{4\times 10^{-6}}{\alpha^2}\frac{Q_0 \Delta\omega}{\omega}\cancel{\frac{\Delta\omega}{V_\Phi}} + 10^{-6} Q_0 \alpha^2 \frac{\omega}{V_\Phi}\left(\frac{11}{4} + \frac{S_{J,0}}{4k_B T}\right)\right]$$

Other noise sources

- Shielding noise: can reduce with superconducting shield
- Current noise: probably minimal if current-carrying wires are superconducting, but may contribute small azimuthal current. Can reduce with a bias current in toroid, or envelop toroid in overlapping superconducting shield
- 1/f SQUID noise: dominant below 50 Hz, worse at low temperatures, maybe mitigate with modulation?