SQUID Magnetometer Detection of Axion Dark Matter

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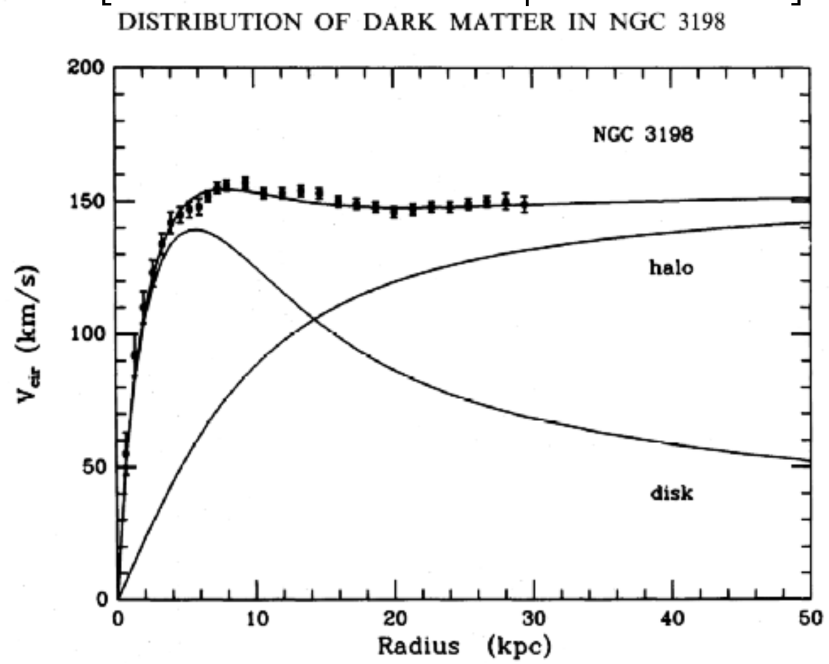
Princeton University

Symmetry Tests in Nuclei and Atoms, KITP, 9/22/16

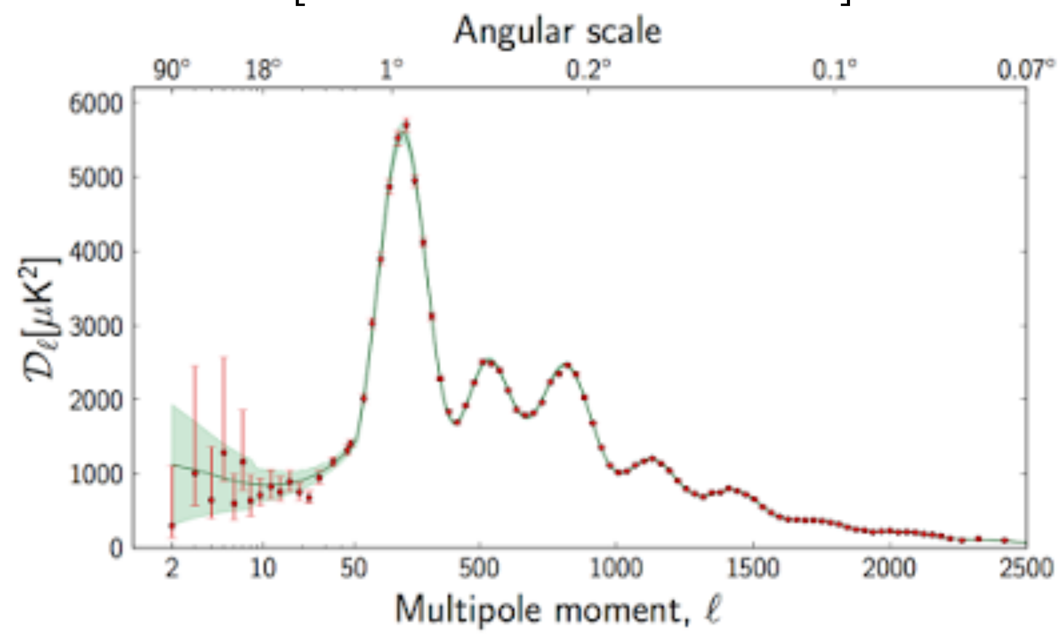
Dark matter: things we know

[van Albada et al. ApJ 295 1985]



Galaxies have halos

[Planck collab. A&A 2014]



Universe is 26.8% DM

[Via Lactea, Zemp MPLA 24 2009]

DM forms structures

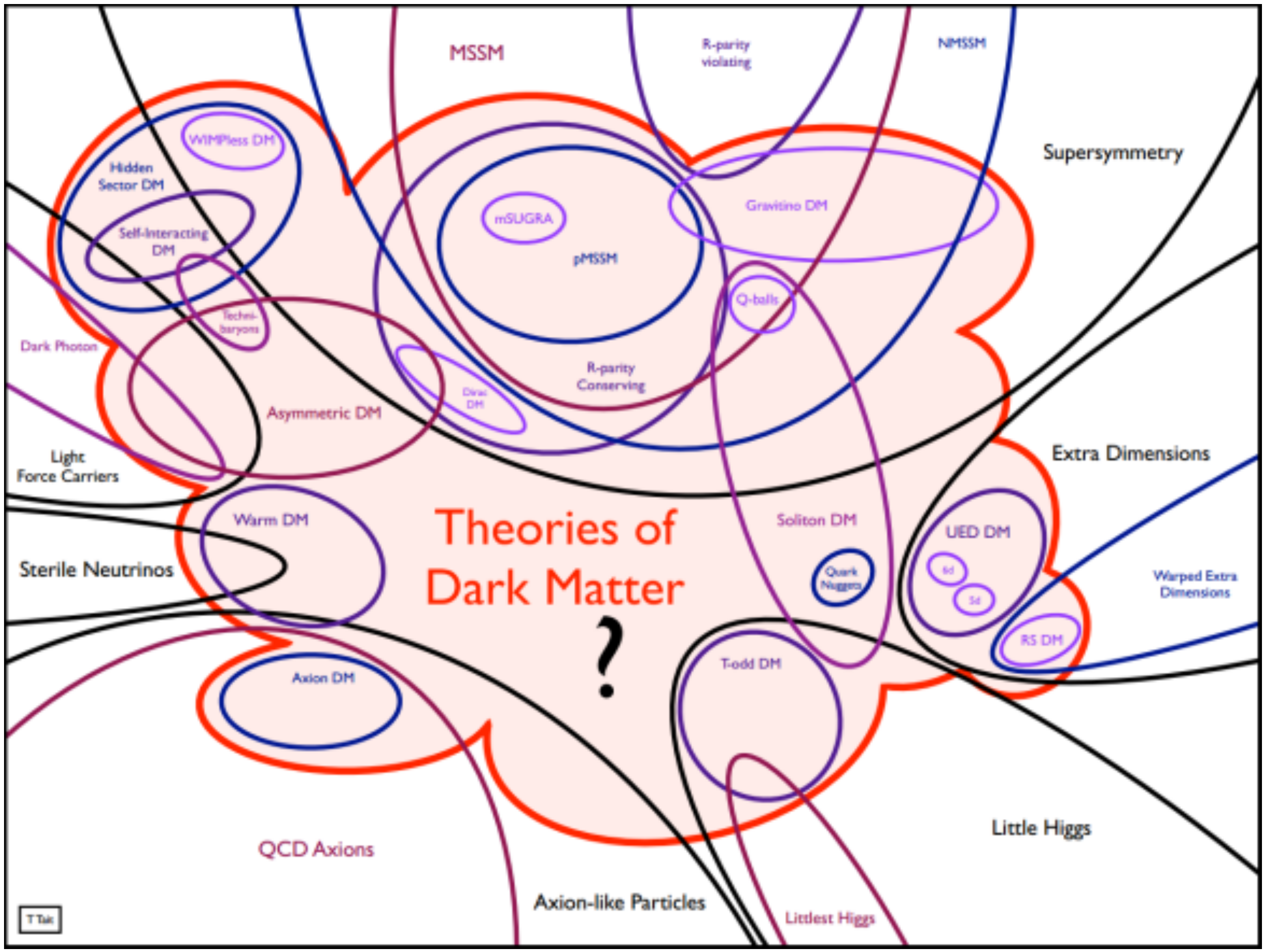
[Markevitch et al. ApJ 606 2003]

$\sigma/m < 1.3\,\mathrm{barn/GeV}$

Dark matter: things we don't know

Dark sector?

Mass?



[T. Tait]

Non-gravitational interactions?

Local phase space structure?

Will focus on axion dark matter for this talk

Axion-SM interactions

[Graham and Rajendran, Phys. Rev. D88 (2013)]

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \widetilde{F}^{\mu\nu} - \frac{i}{2} g_d a \overline{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu} + g_{aNN} (\partial_\mu a) \overline{N} \gamma^\mu \gamma_5 N + g_{aee} (\partial_\mu a) \overline{e} \gamma^\mu \gamma_5 e$$

Axion-photon conversion	Nucleon EDM	Nuclear axial moment	Electron axial moment

Nuclear axial moment and Electron axial moment: $\propto \nabla a$

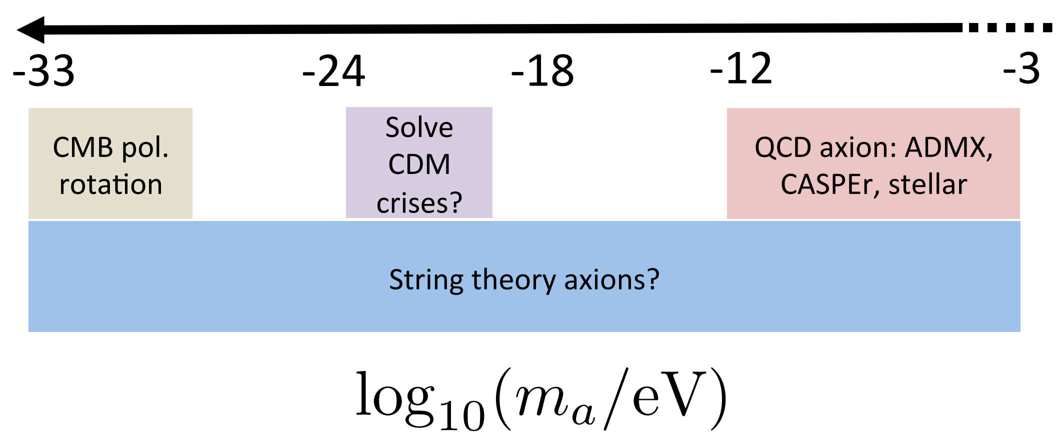
Note: for QCD axion, $m_a \sim 6 \times 10^{-10}\ \mathrm{eV} \left(\frac{10^{16}\ \mathrm{GeV}}{f_a} \right)$

All couplings of order $1/f_a$

For "axion-like particles" (ALPs), couplings independent of m_a

ALP parameter space

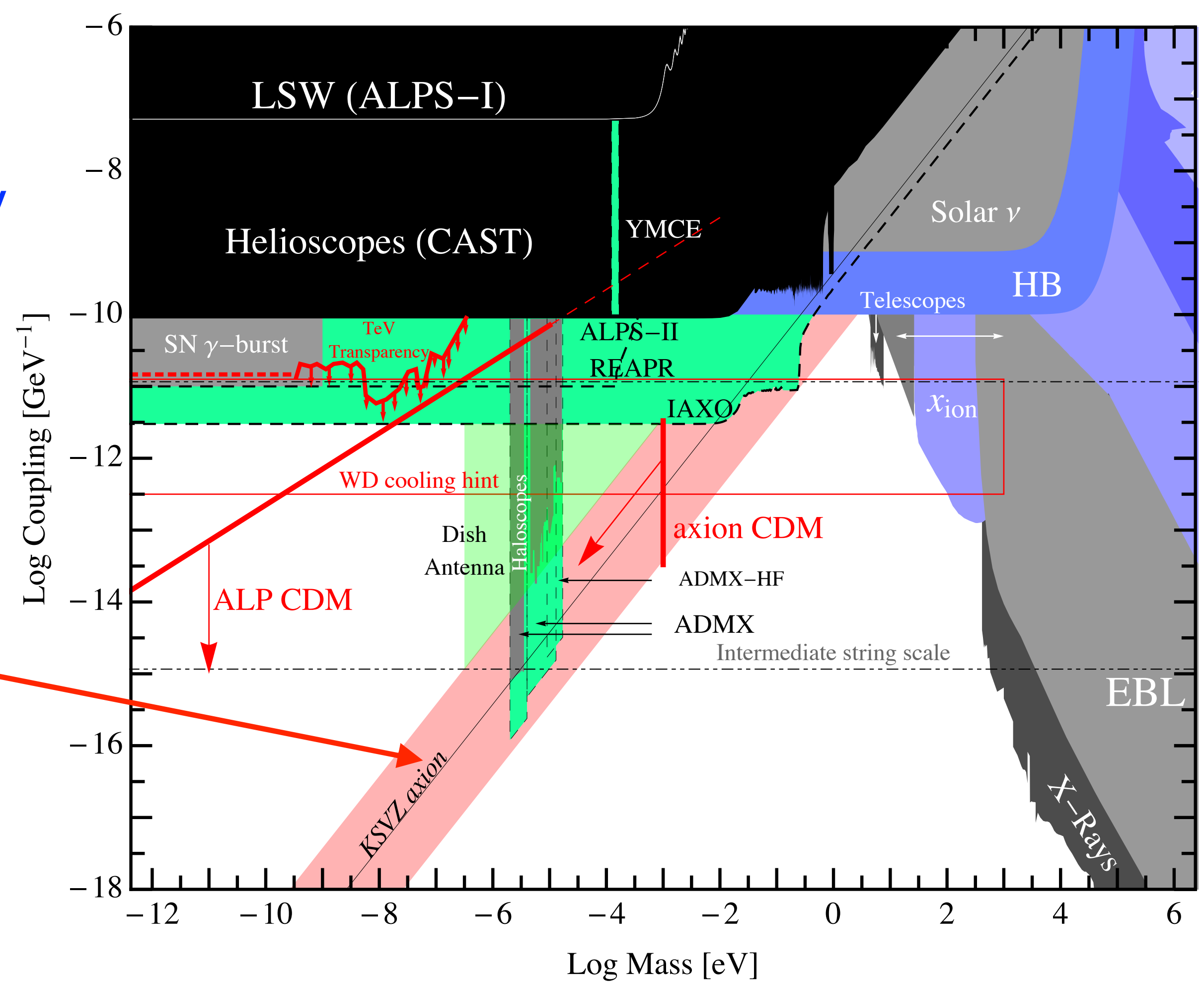
Enormous mass range:



[D. Marsh, 1510.07633]

Couples very weakly to SM:

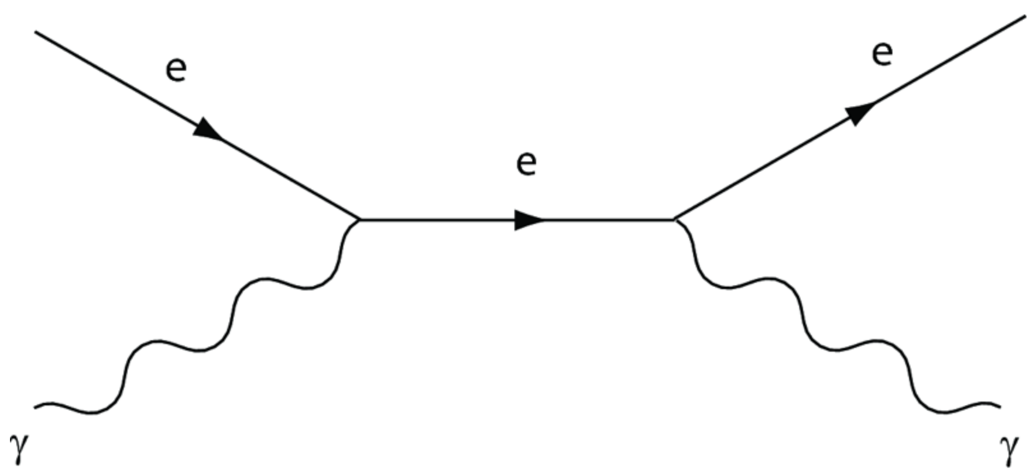
QCD axion: mass ∝ coupling



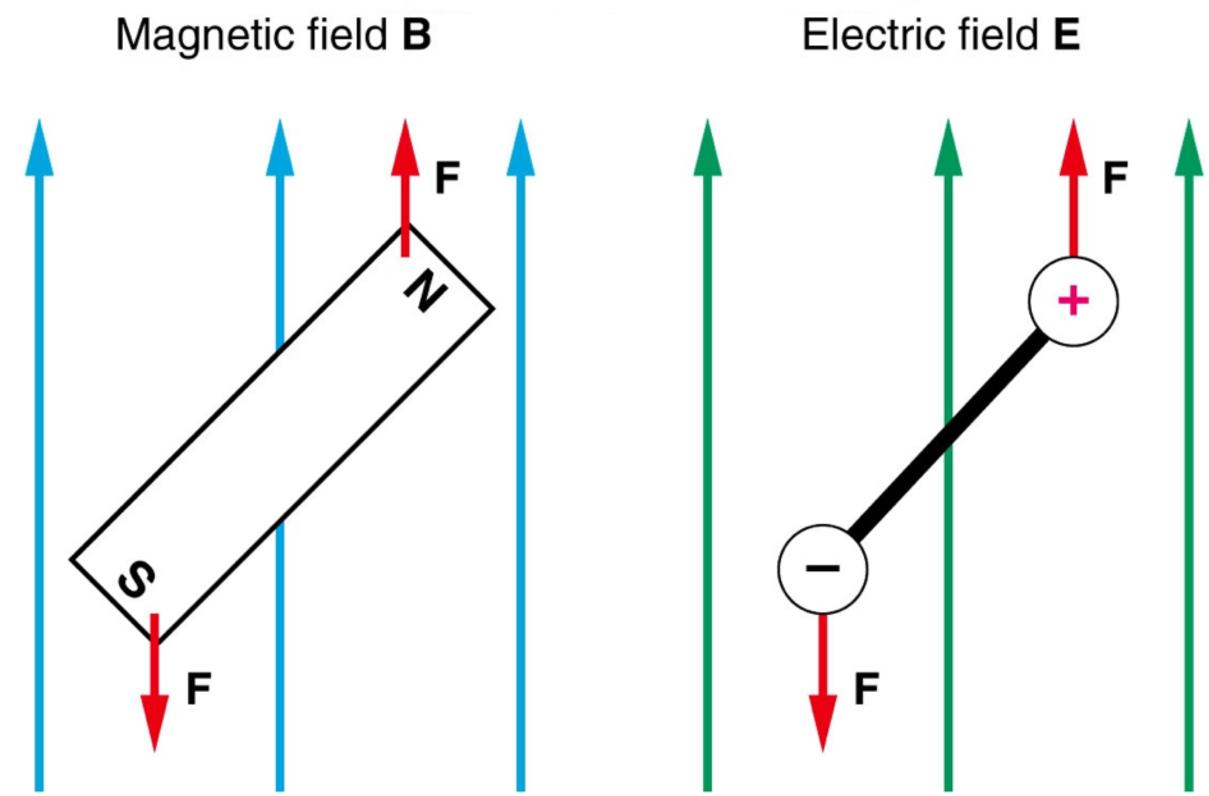
[Essig et al., 1311.0029]

Axion DM: field, not particle

Useful analogy:



vs.



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

Properties of axion DM

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:

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

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

Properties of axion DM

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

In axion DM background, get oscillating observables:

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

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

} Harmonic response from static fields

$$d_n = g_d a$$

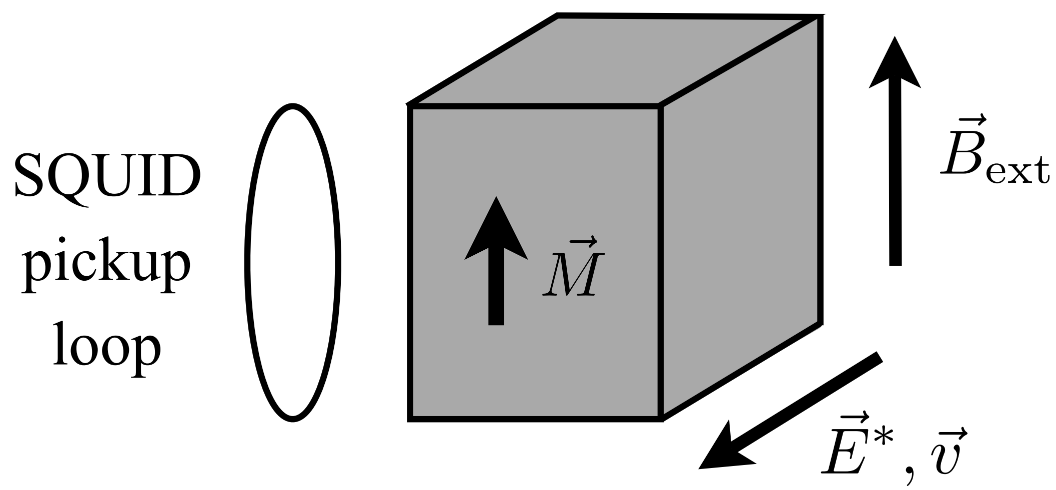
Time-varying EDM

$$H_N \supset g_{aNN} \nabla a \cdot \vec{\sigma}_N$$

Spin-dependent force

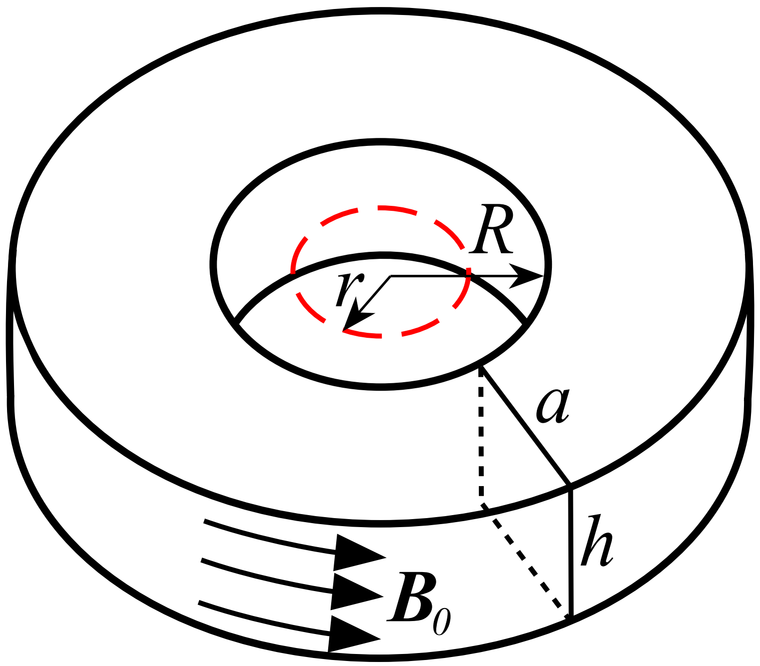
Two strategies for light ALP DM detection

Axion-sourced spin precession (CASPEr)



$\mathbf{M}_T \propto d_n,\, g_{aNN}$

Axion-sourced magnetic flux (ABRACADABRA)

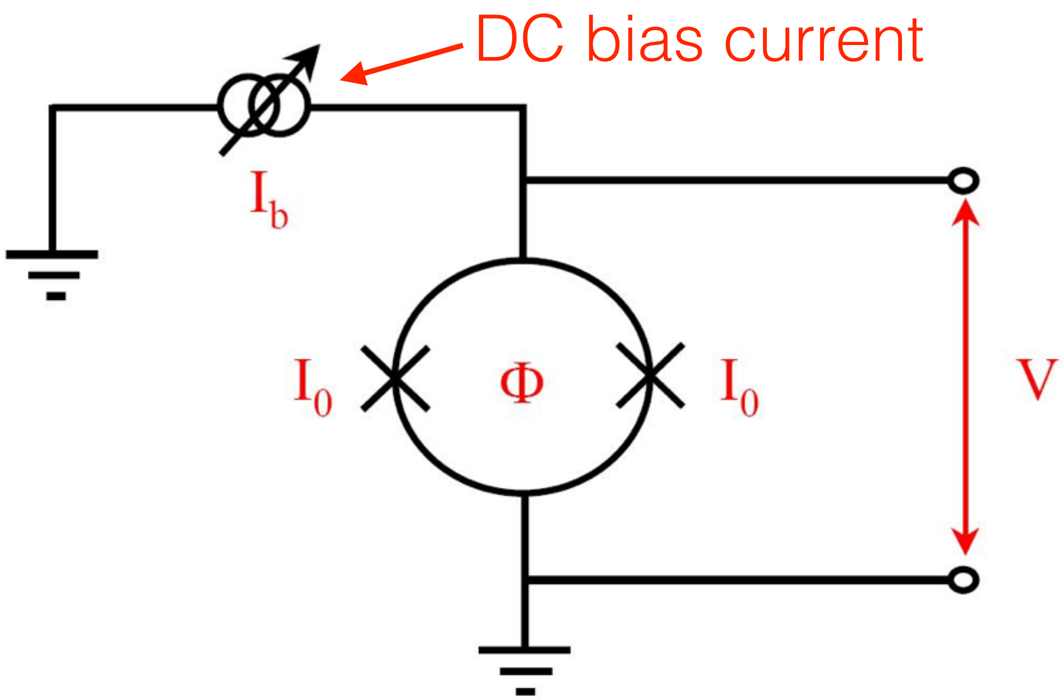


$\mathbf{B}_r \propto g_{a\gamma\gamma}$

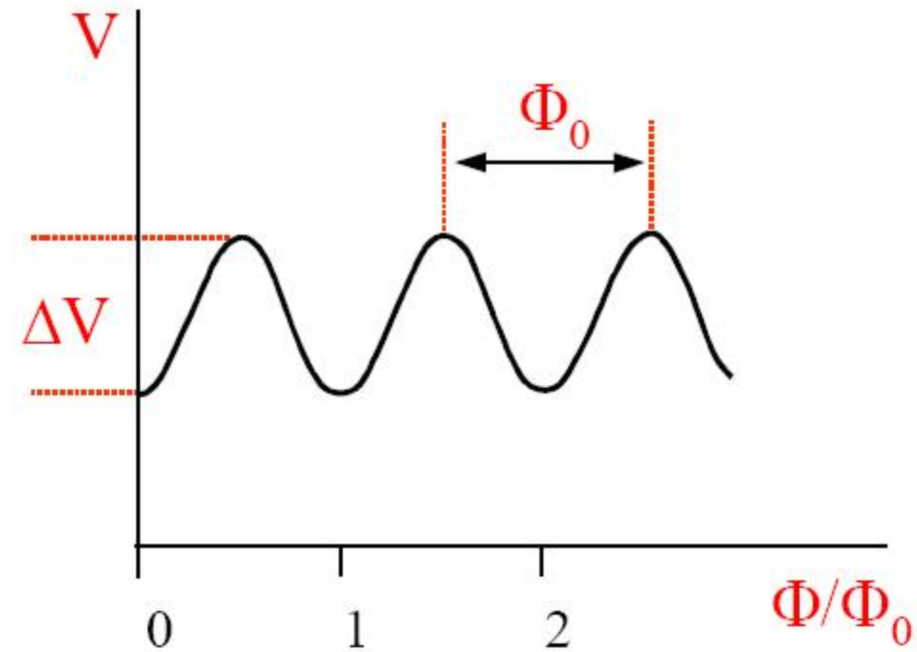
Signal is a weak, oscillating magnetic field: SQUID detection!

SQUID magnetometry 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

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

SQUID noise

Typical SQUID noise (thermal voltage and current fluctuations):

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

$A_{\text{SQUID}} \sim (30\,\mu\text{m})^2$

$\Longrightarrow$ field sensitivity of $2\,\text{pT}/\sqrt{\text{Hz}}$ at SQUID

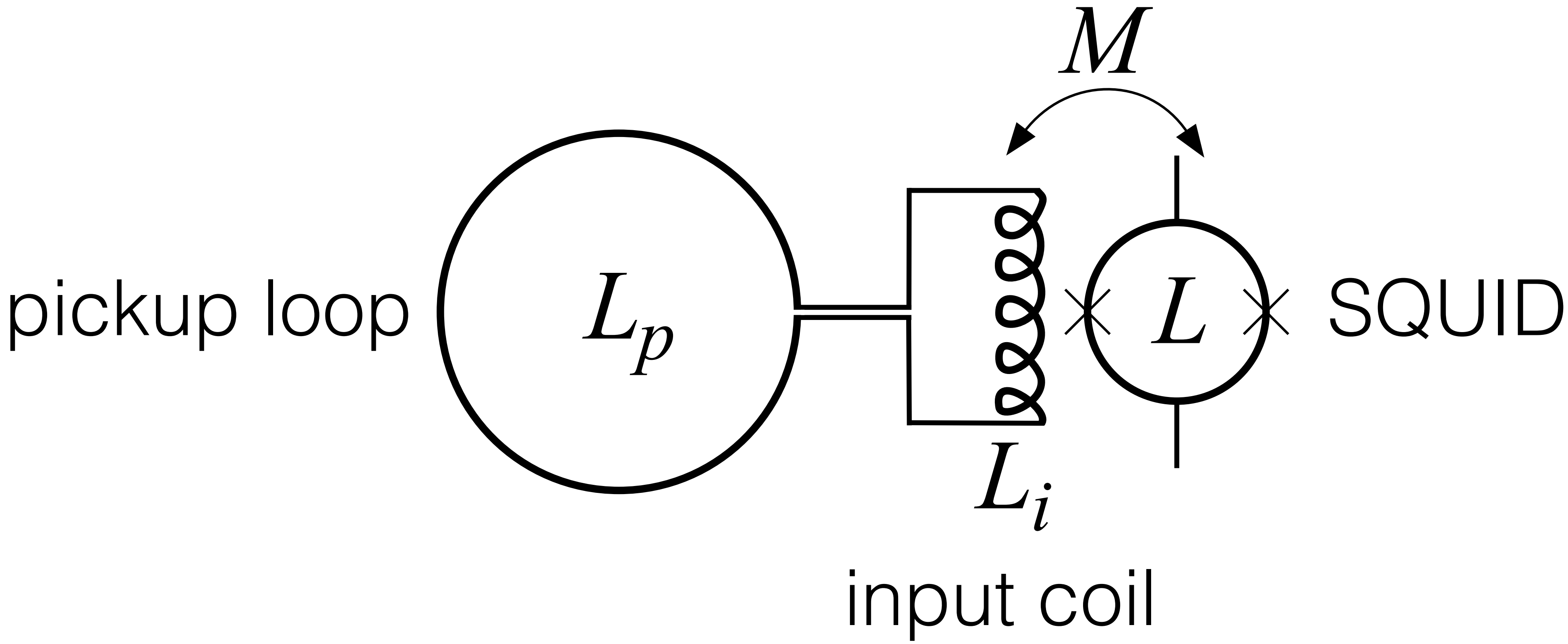
Ultimate limit is shot noise:

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

dominates below ~ 60 mK

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

Readout circuit: broadband



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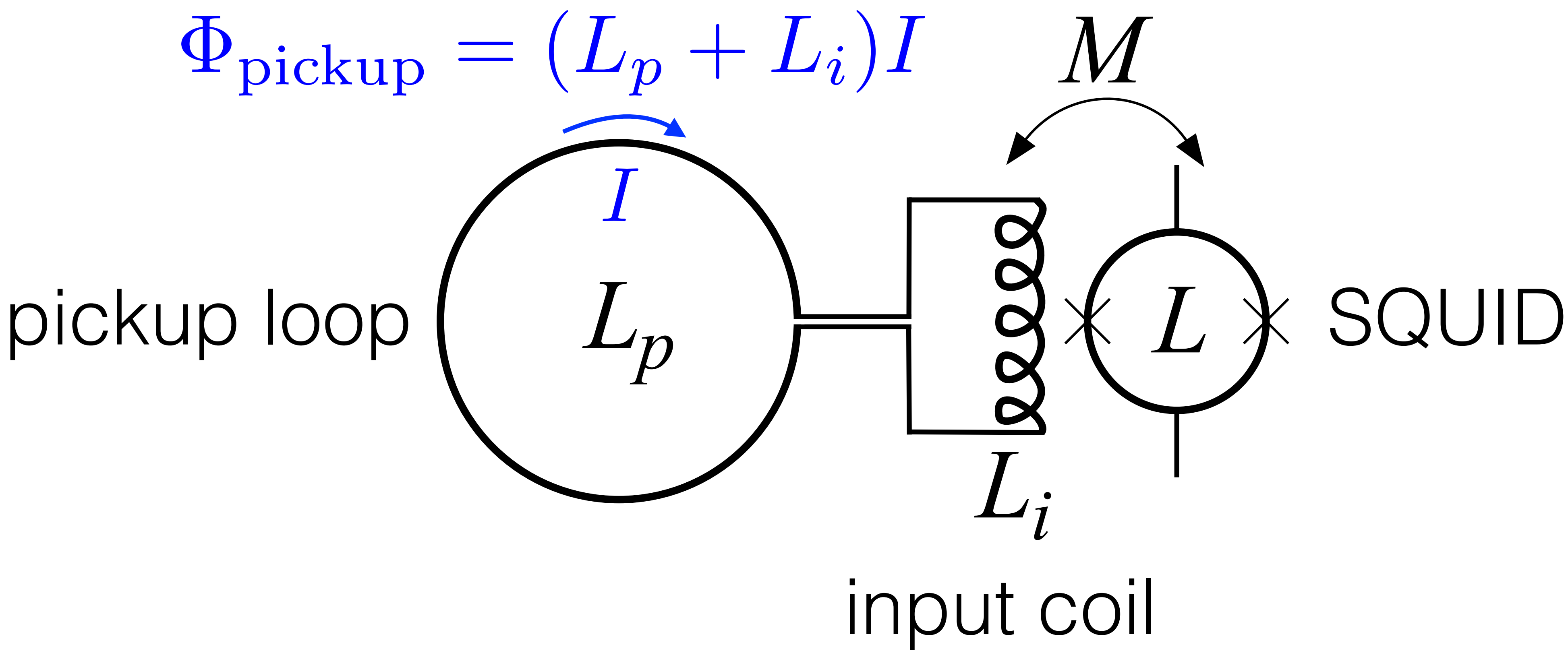

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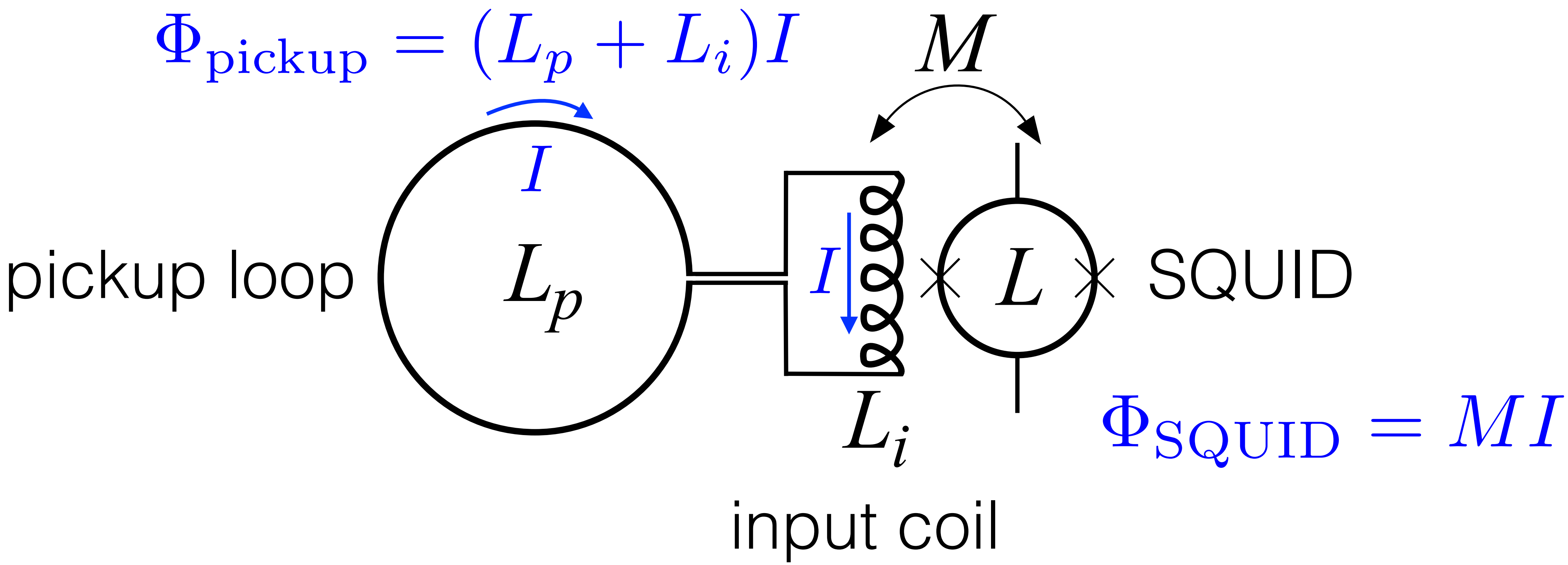

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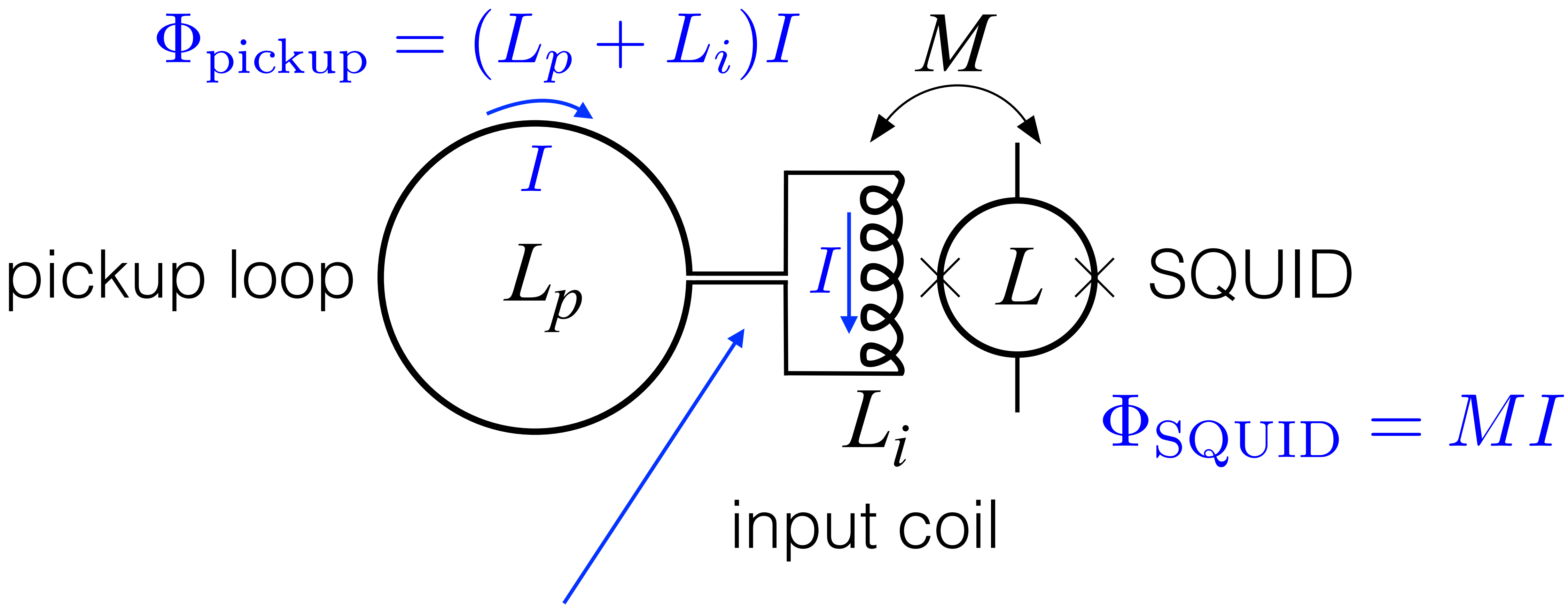
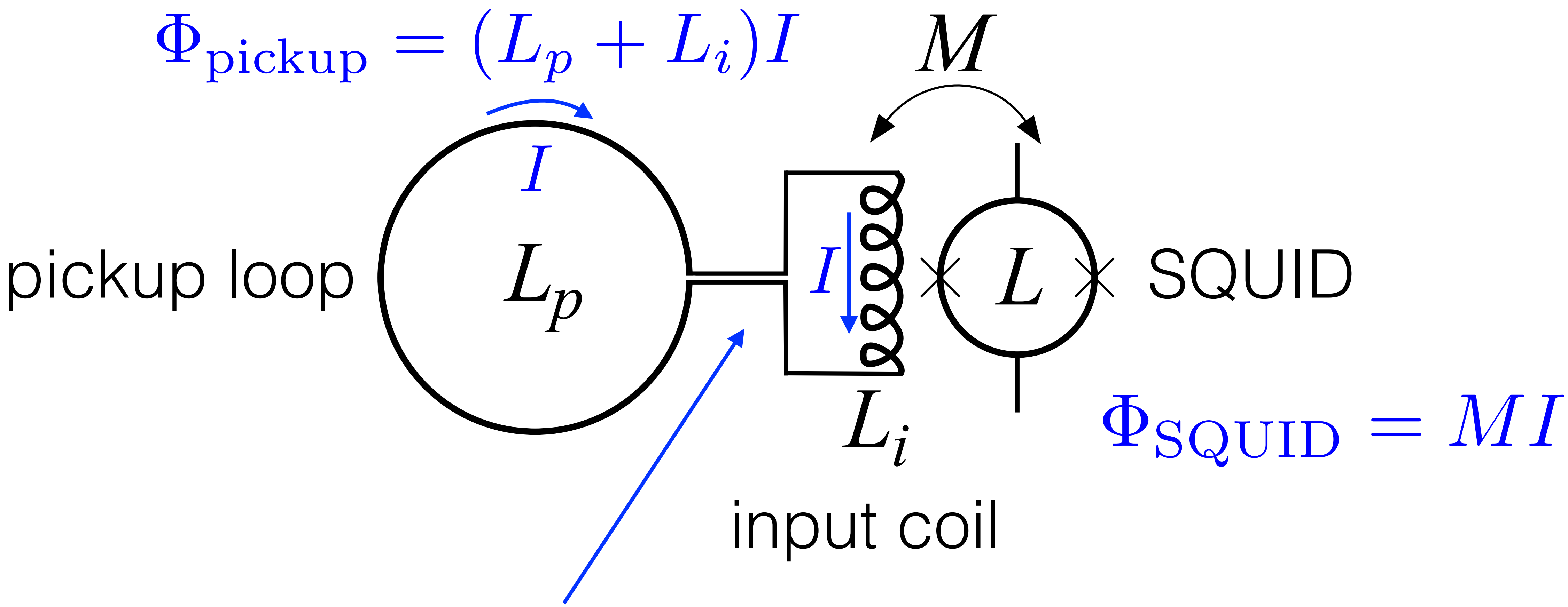


pure superconducting = **zero** thermal noise (at low freq.)

Noise dominated by SQUID noise

Readout circuit: broadband



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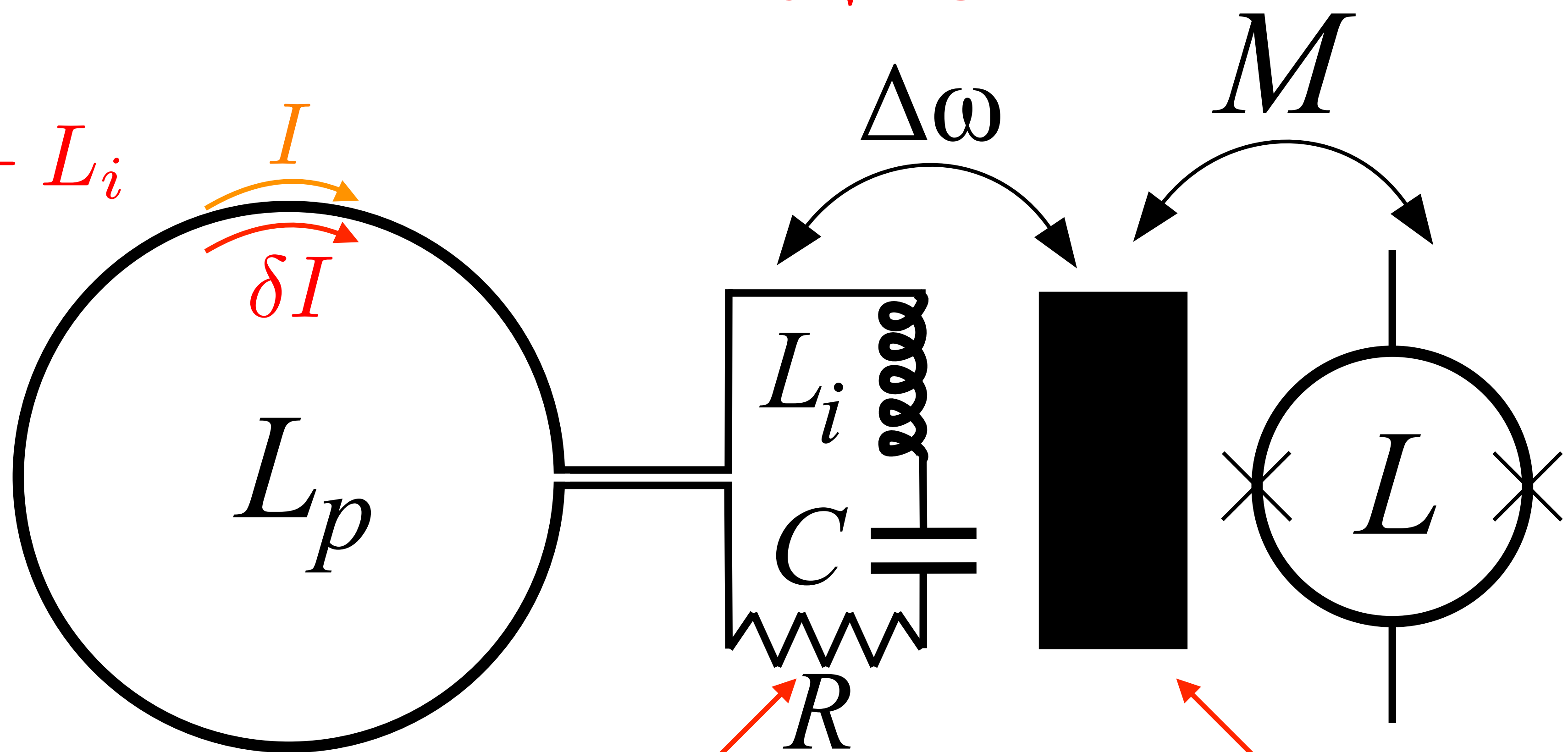
Broadband: response is frequency-independent

Readout circuit: resonant

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

$$L_T = L_p + L_i$$



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

irreducible resistance

feedback: match circuit bandwidth to signal

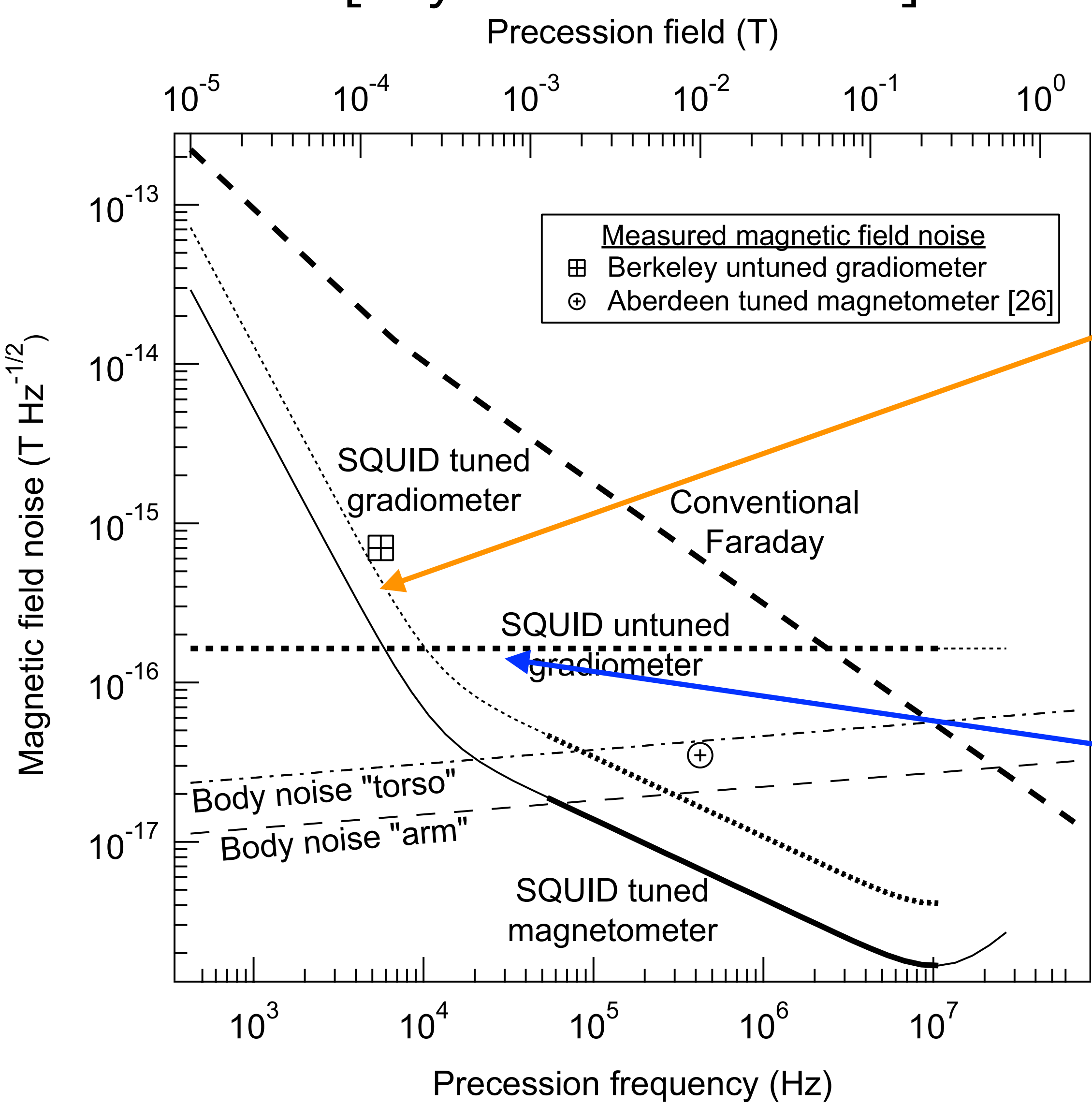
Can show thermal noise dominates at 0.1 K up to $Q = 10^8$

Broadband vs. resonant

Depends on frequency!

Borrow results from medical magnetometry:

[Myers et al 2007]



resonant (“tuned”) circuit: thermal noise

broadband (“untuned”) circuit: magnetometer noise

Requires superconducting pickup: zero-field detection

CASPEr: NMR with axion DM

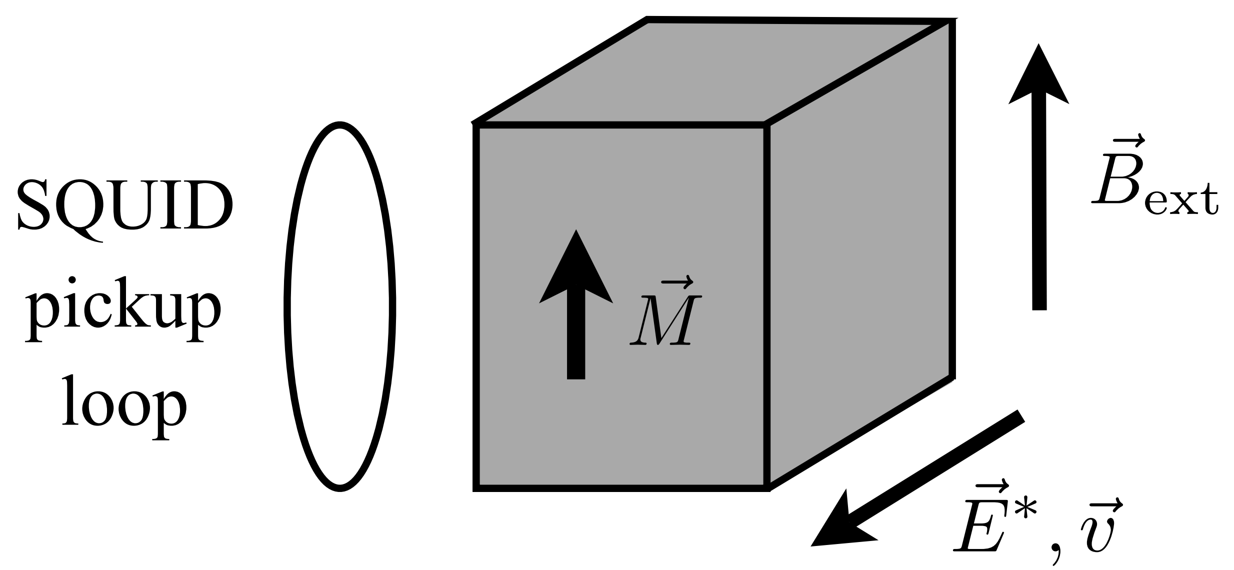
[Budker et al., Phys. Rev. X 2014; Graham and Rajendran, Phys. Rev. D 2013]

Nuclei immersed in axion DM can have:

Oscillating EDM and/or Spin-dependent force

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

$$H_N \supset g_{aNN}\sqrt{2\rho_{DM}}\cos(m_a t)\vec{v}\cdot\vec{\sigma}_N$$



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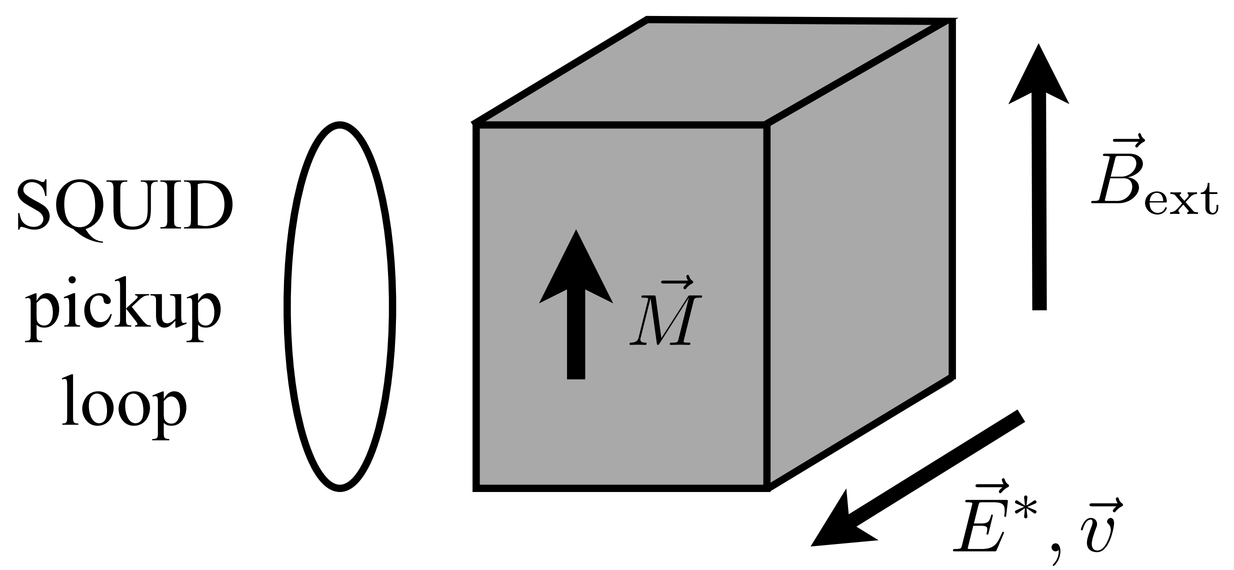
Polarize some spins, watch them precess around:

External E field and/or Axion field velocity



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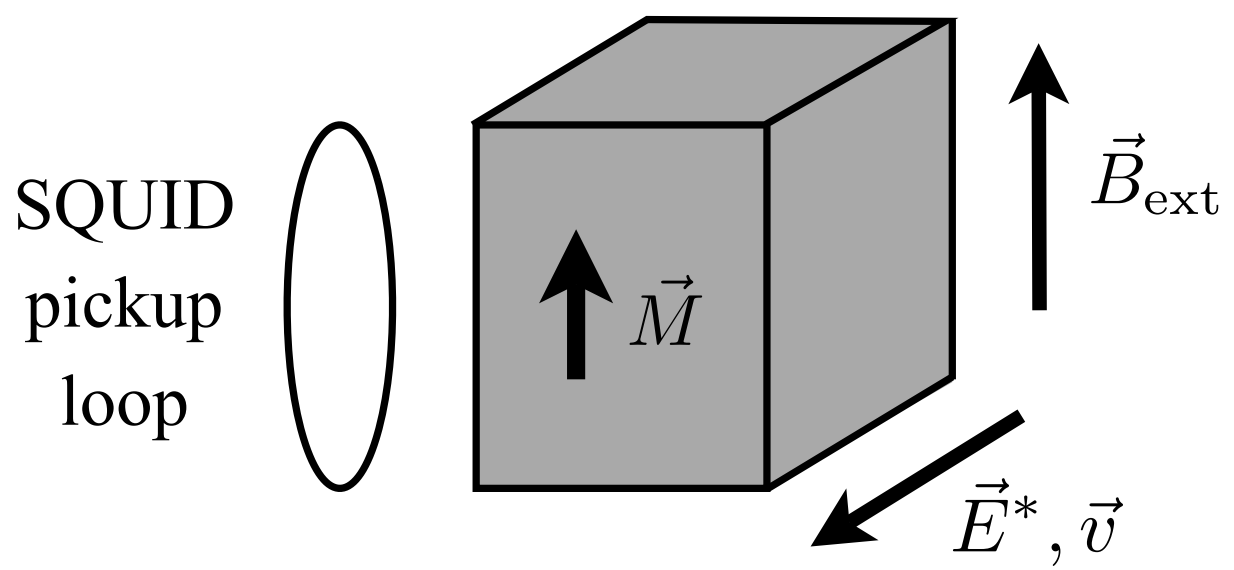


Axion DM is like NMR pulse

Resonance in transverse magnetization when $2\mu B_{\mathrm{ext}} = m_a$

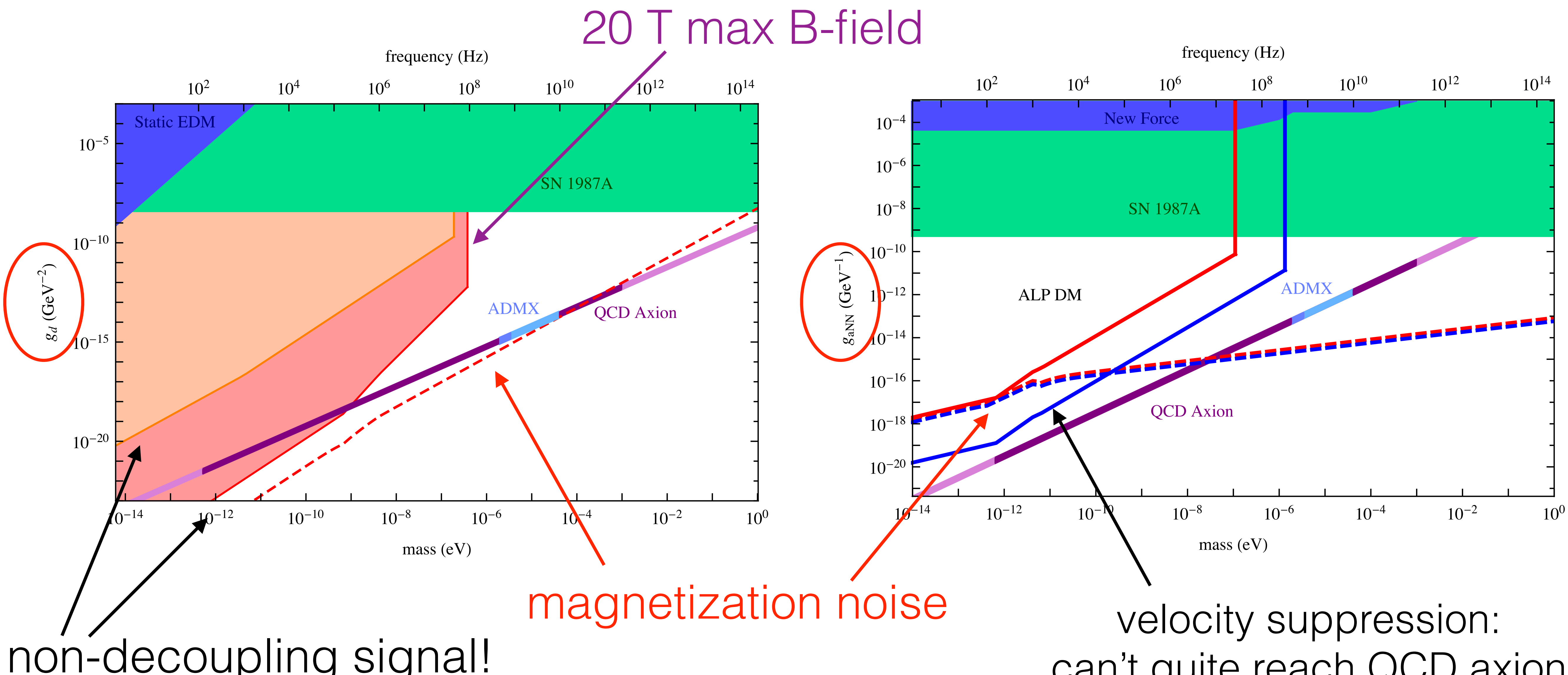
CASPEr Reach

CASPEr-Electric

[Budker et al., Phys. Rev. X 2014]

CASPEr-Wind

[Graham and Rajendran, Phys. Rev. D 2013]



Resonant tuning, but broadband readout:
dominated by SQUID noise in principle

CASPEr Reach

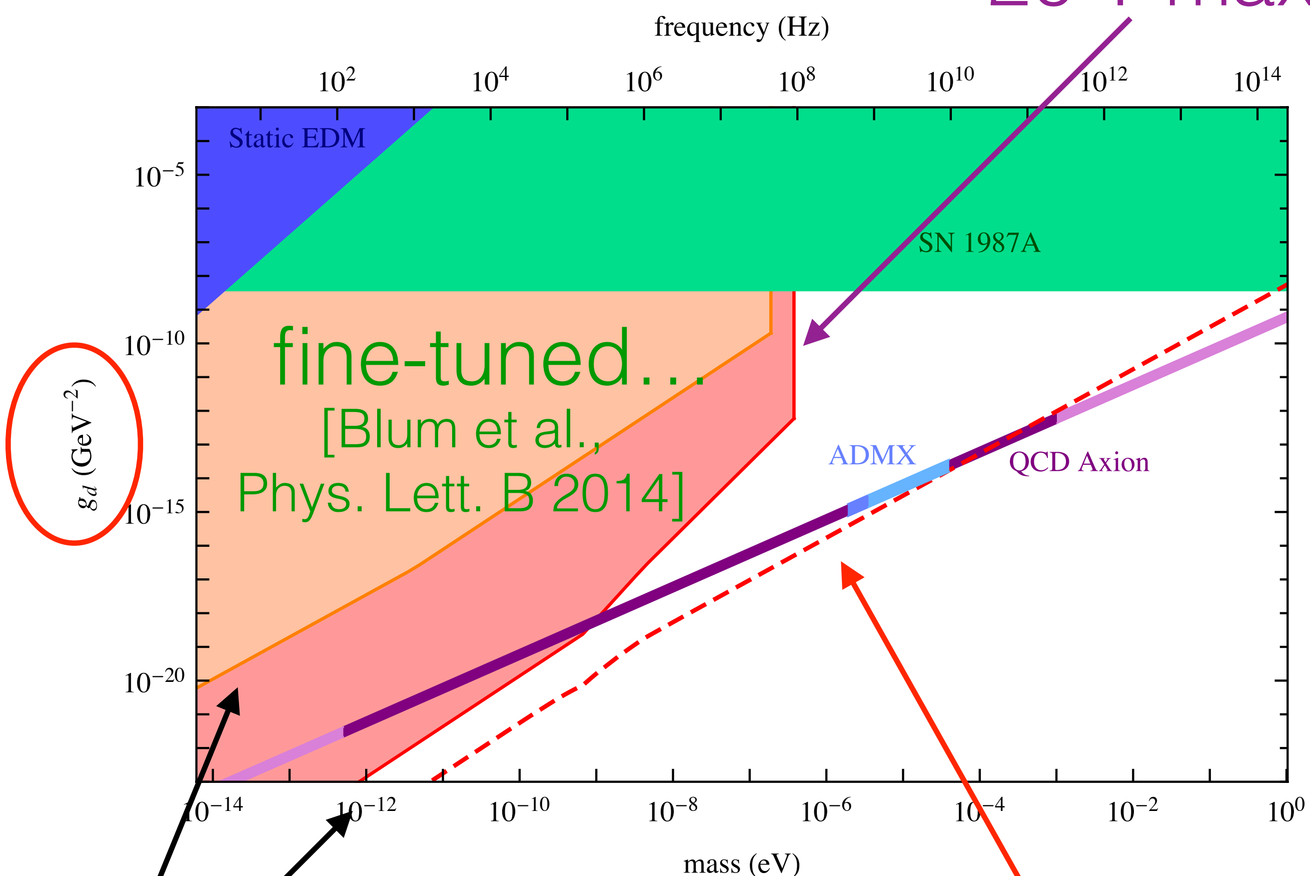
CASPEr-Electric

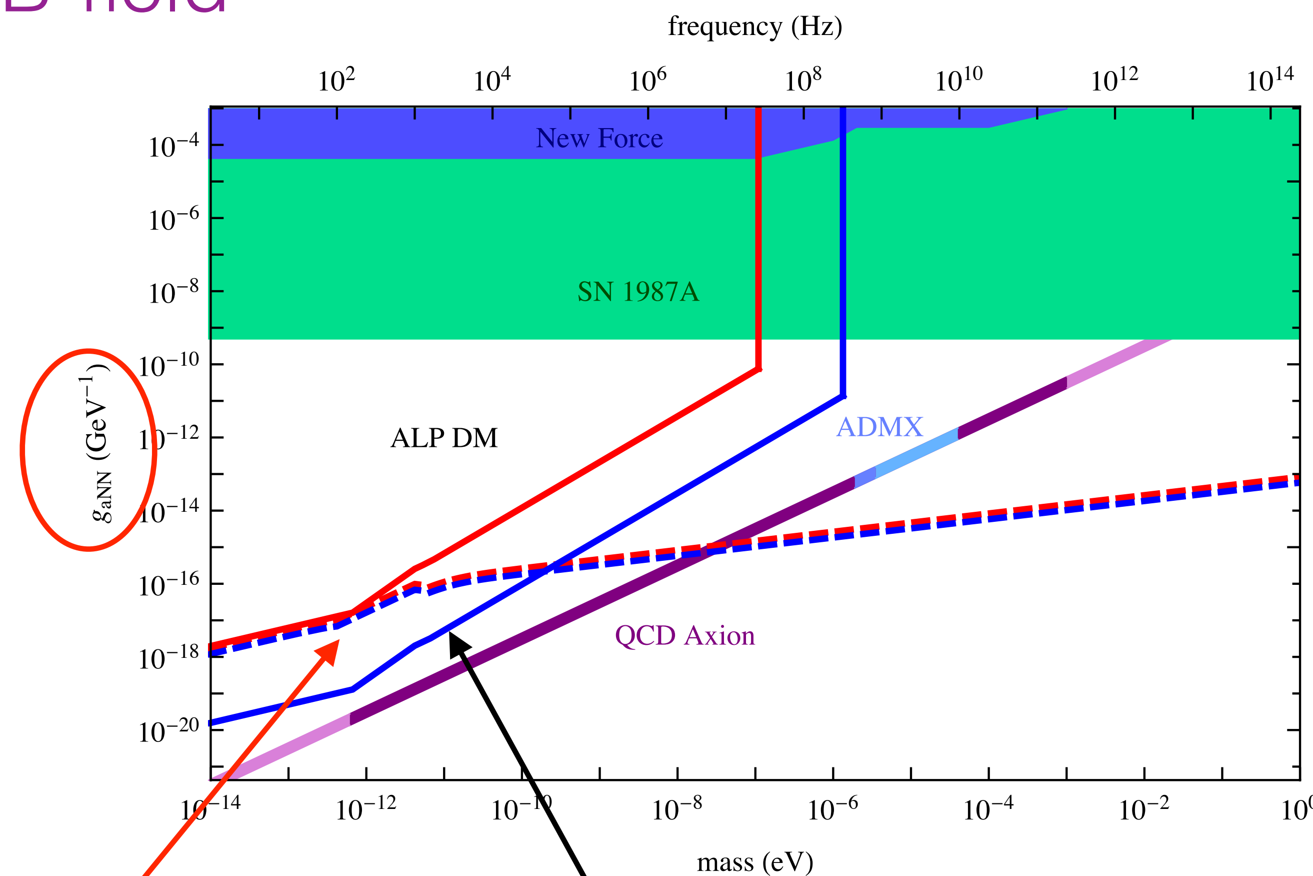
[Budker et al., Phys. Rev. X 2014]

CASPEr-Wind

[Graham and Rajendran, Phys. Rev. D 2013]

20 T max B-field





magnetization noise

non-decoupling signal!

velocity suppression:
can't quite reach QCD axion

Resonant tuning, but broadband readout:
dominated by SQUID noise in principle

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)

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(quasistatic approximation)

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

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

How to detect an oscillating current?

Axion-sourced current

$$v_{DM} \ll 1$$

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How to detect an oscillating current?

- Radiated power (at infinity)
- Time-varying flux (locally)

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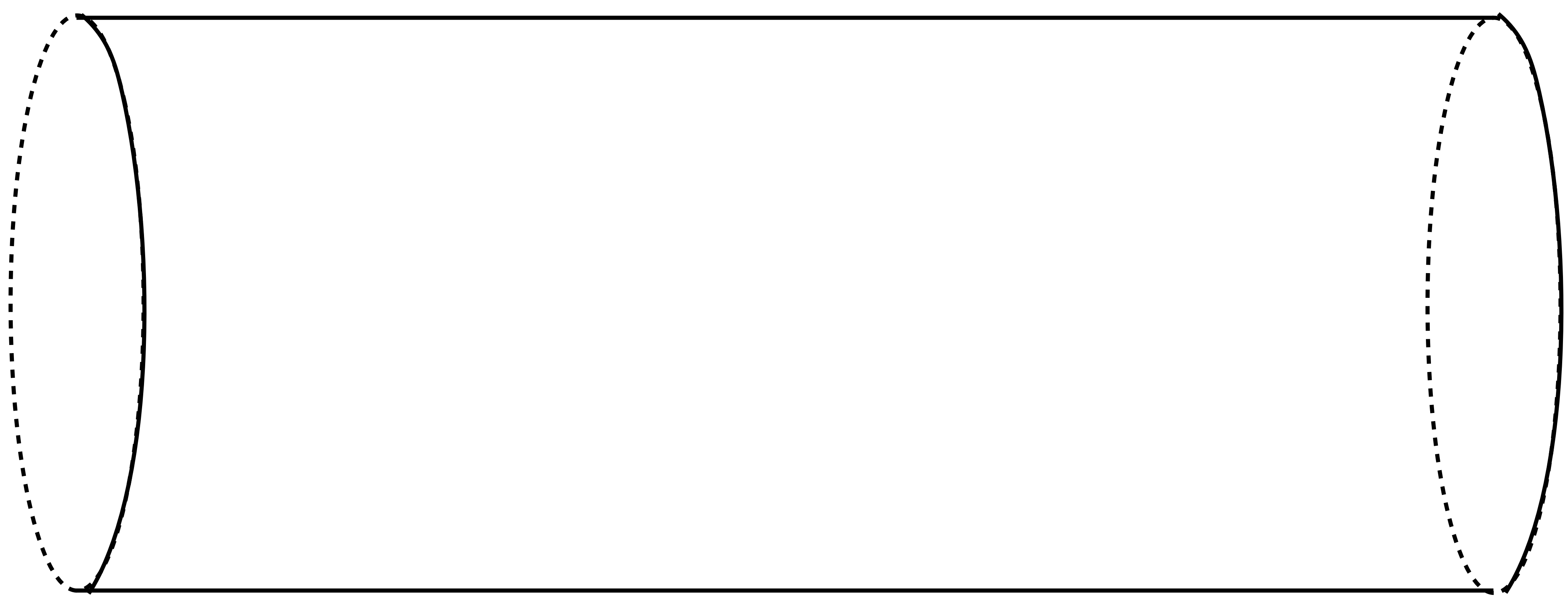
Toy example: solenoid



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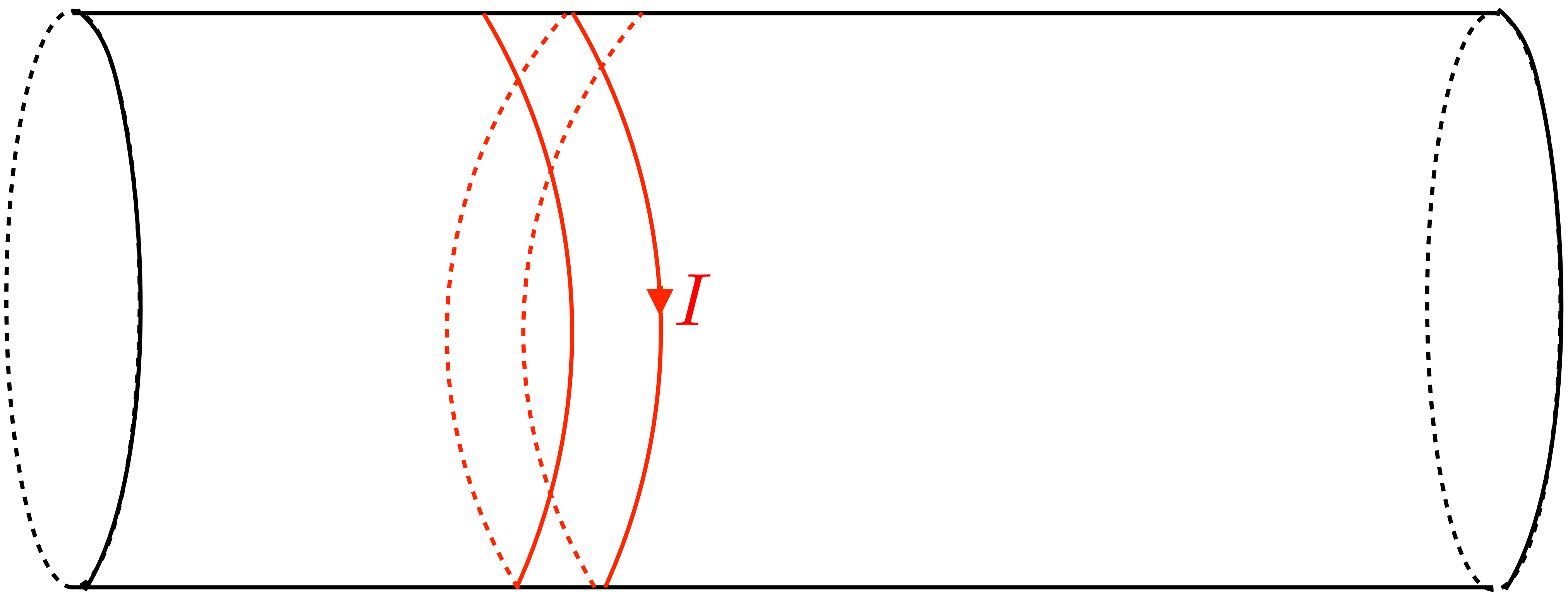

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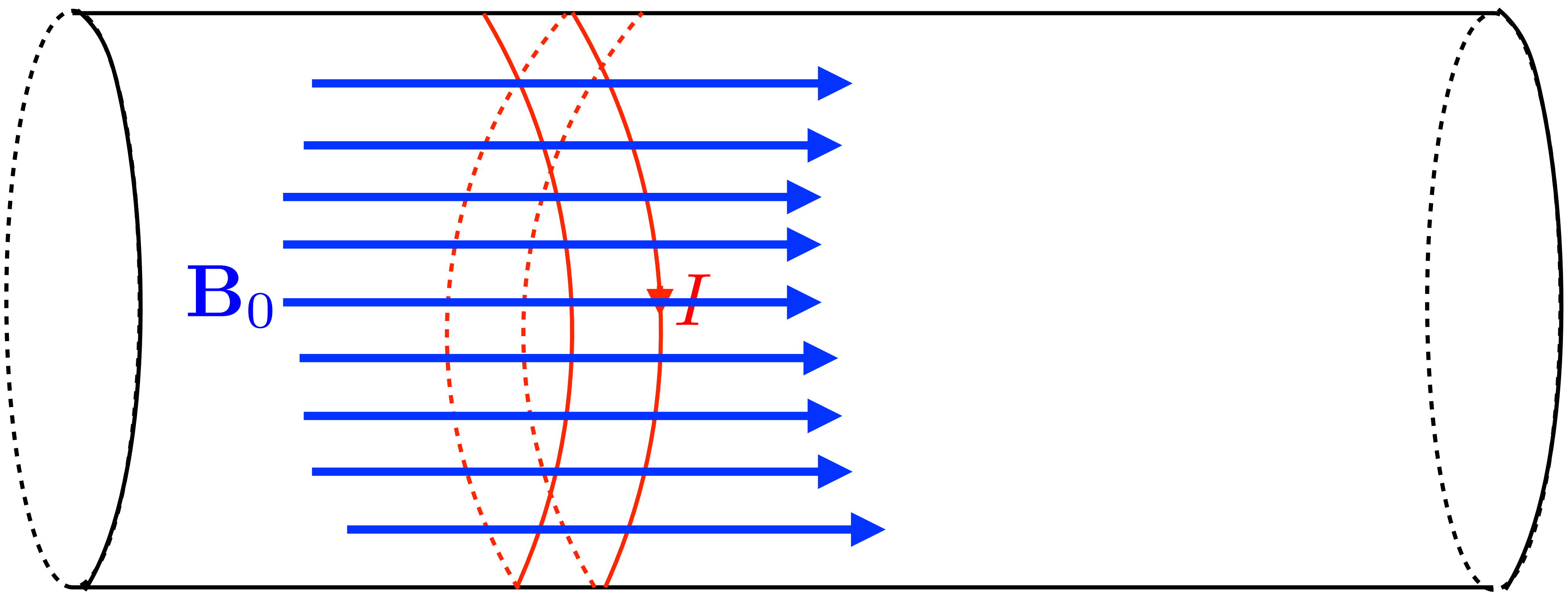
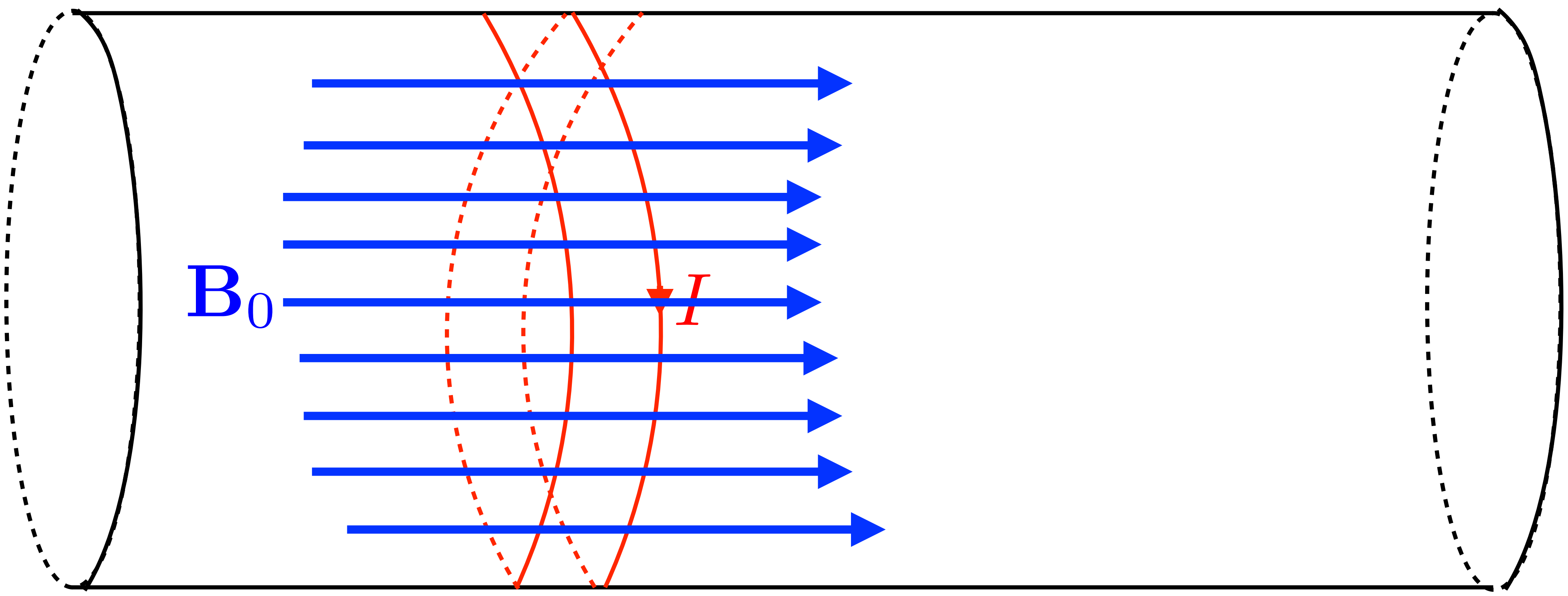


Toy example: solenoid

In the presence of axion DM:



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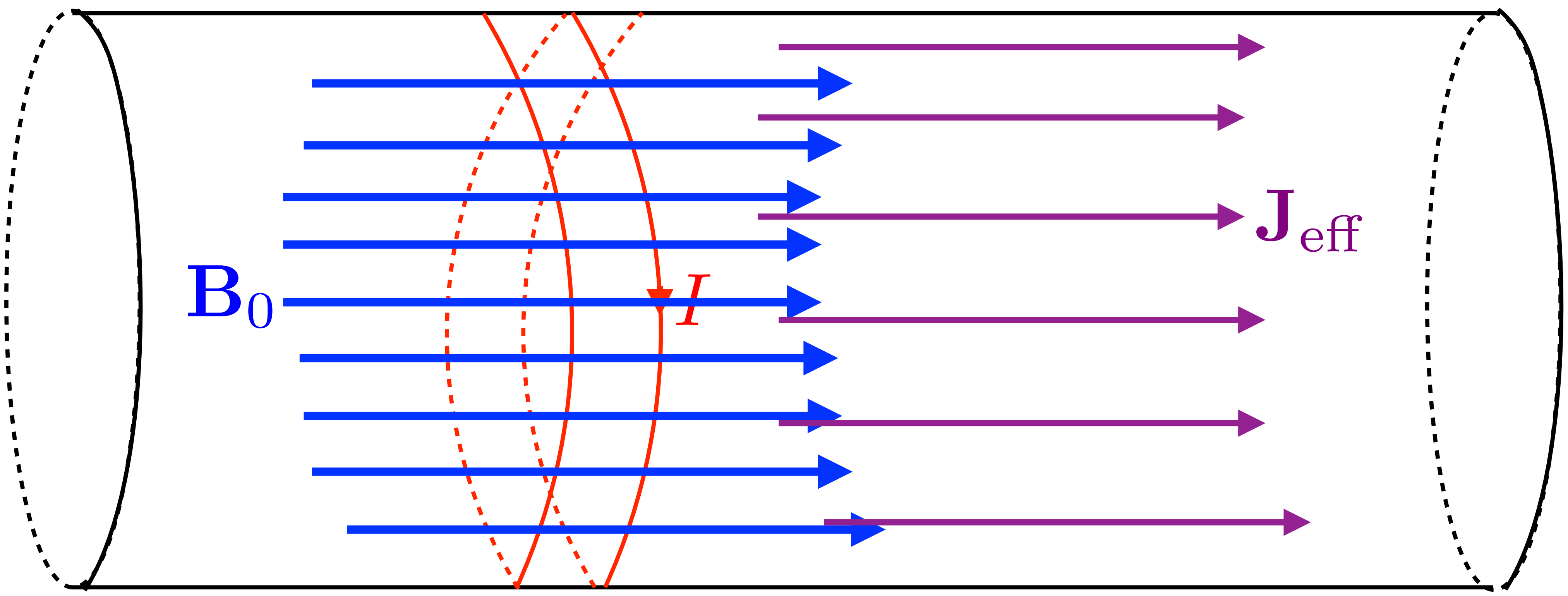

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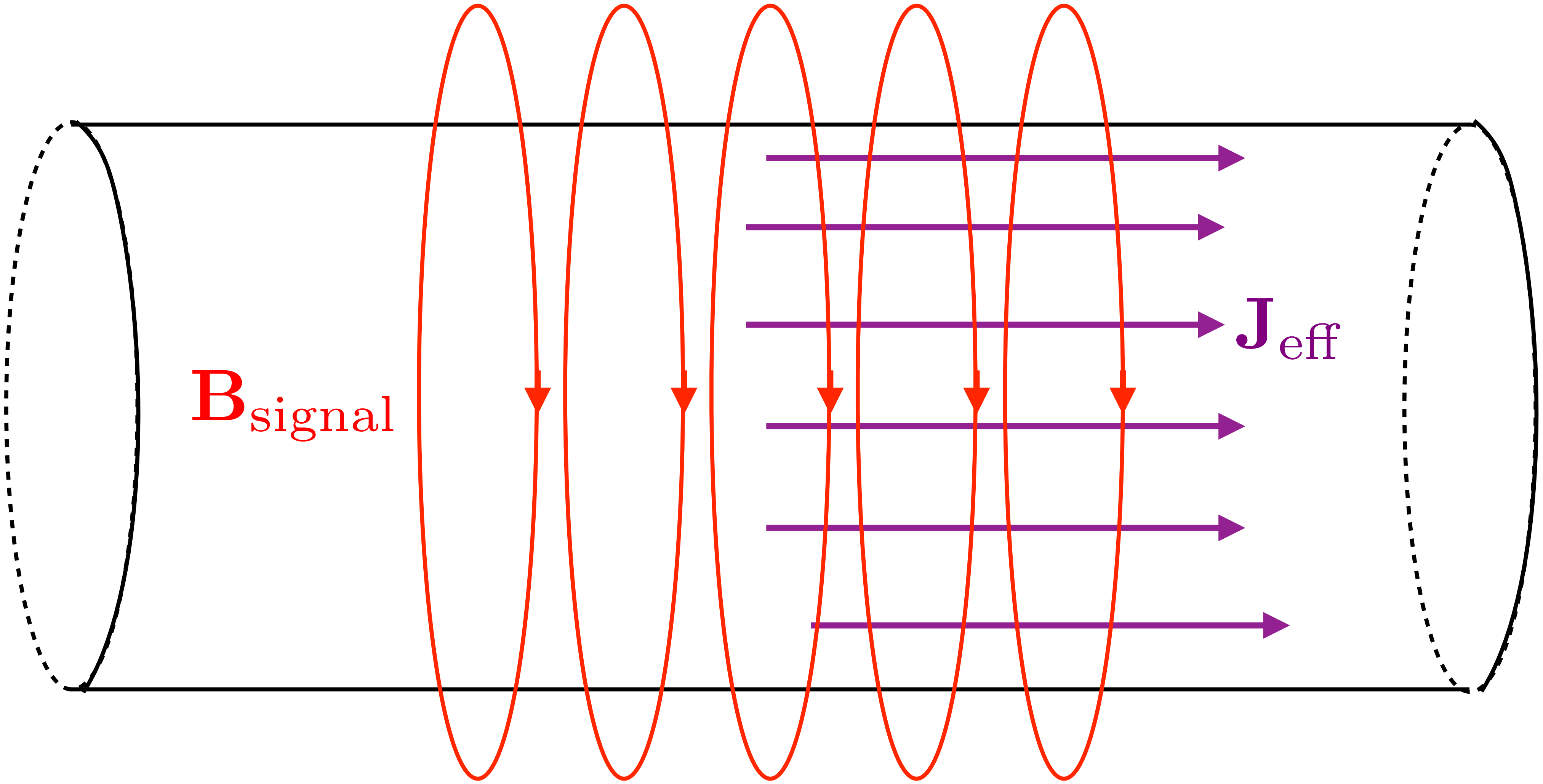
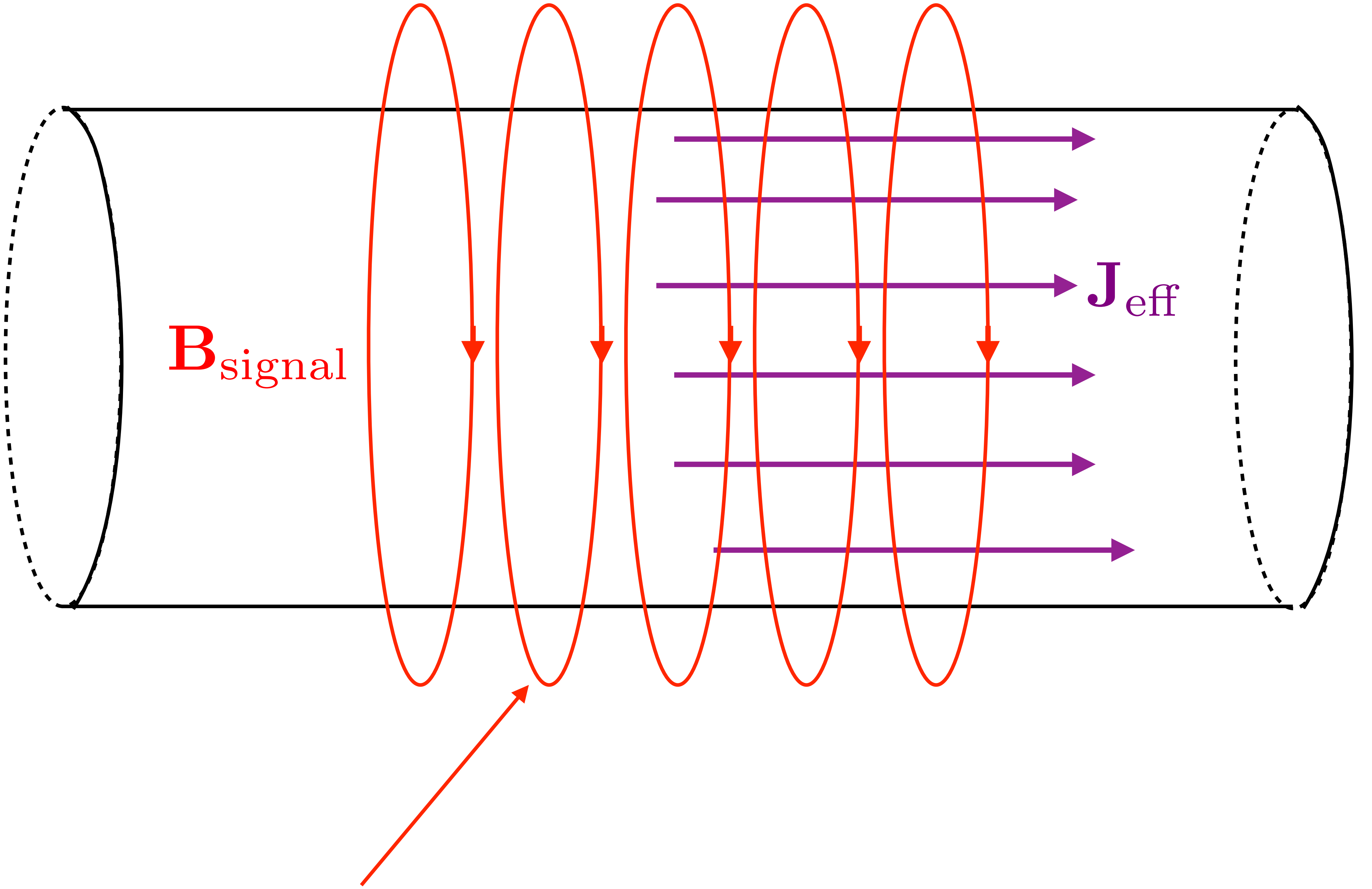
Current-carrying wire

Current-carrying wire

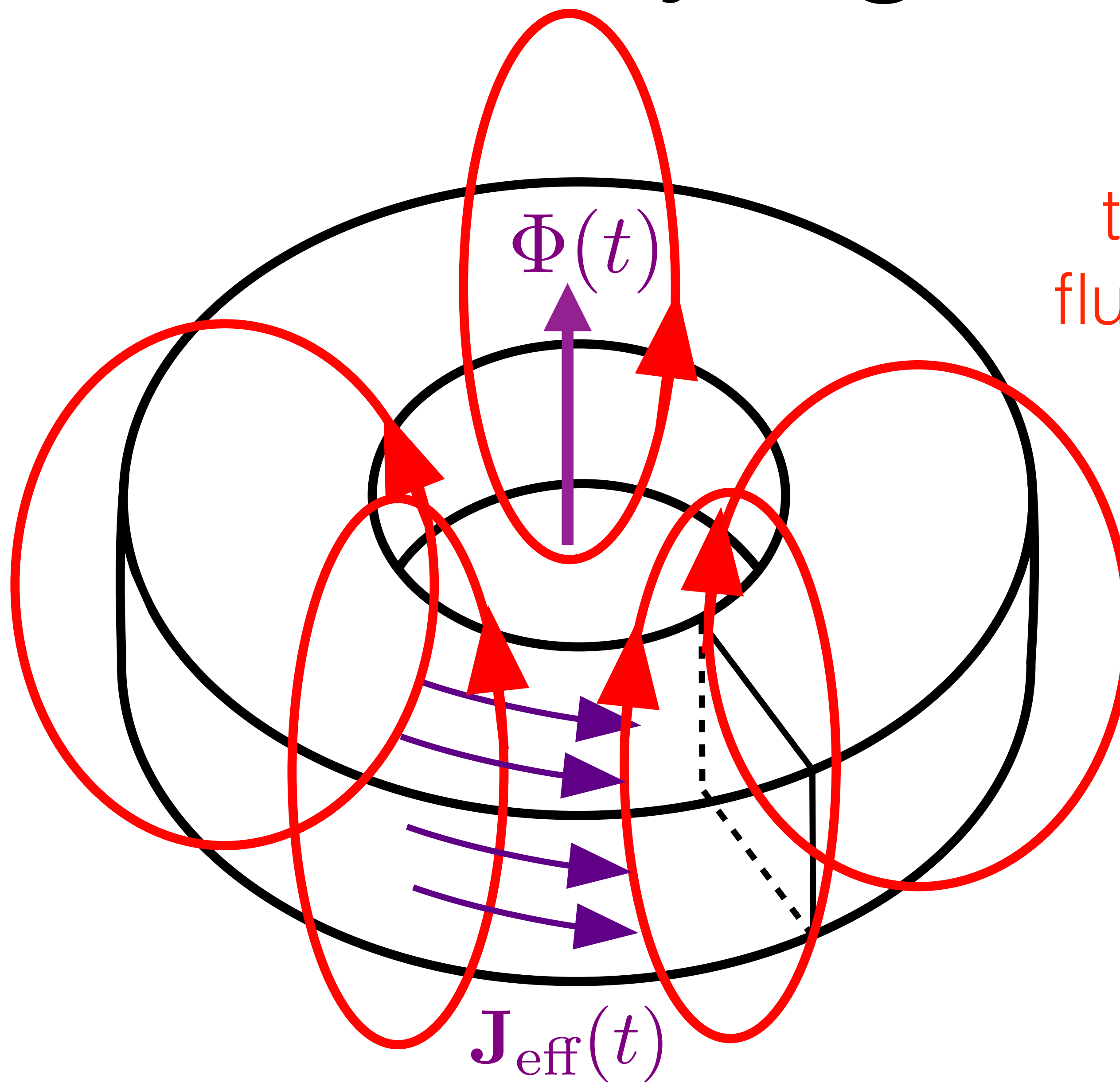


Current-carrying wire



Can detect axion-induced flux outside field region!

Toroid with axion: current-carrying loop



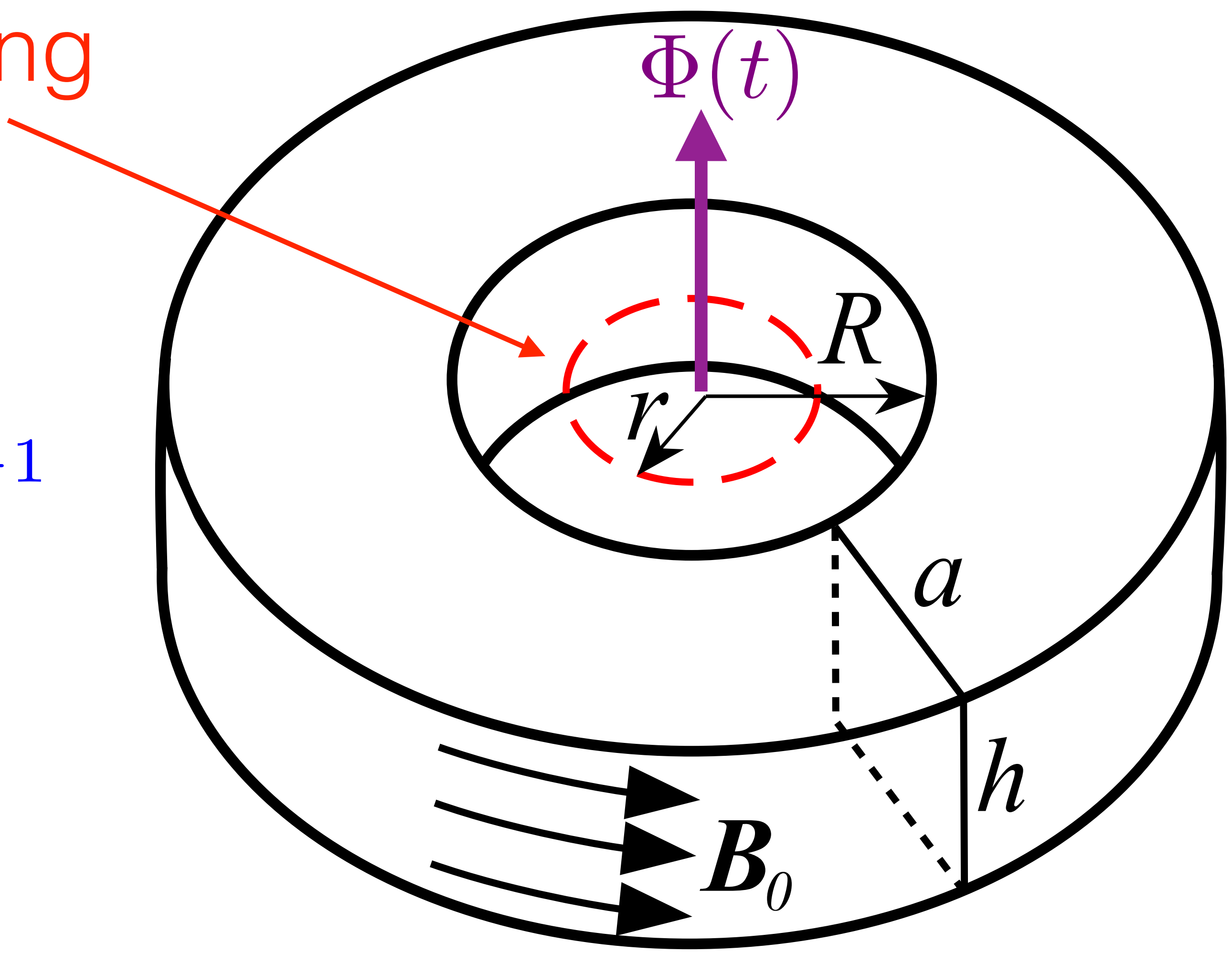
toroidal geometry: flux adds **coherently** in center

Signal: time-varying flux through center

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

ABRACADABRA!

[YK, Safdi, Thaler, PRL 2016]



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

(quasistatic)

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

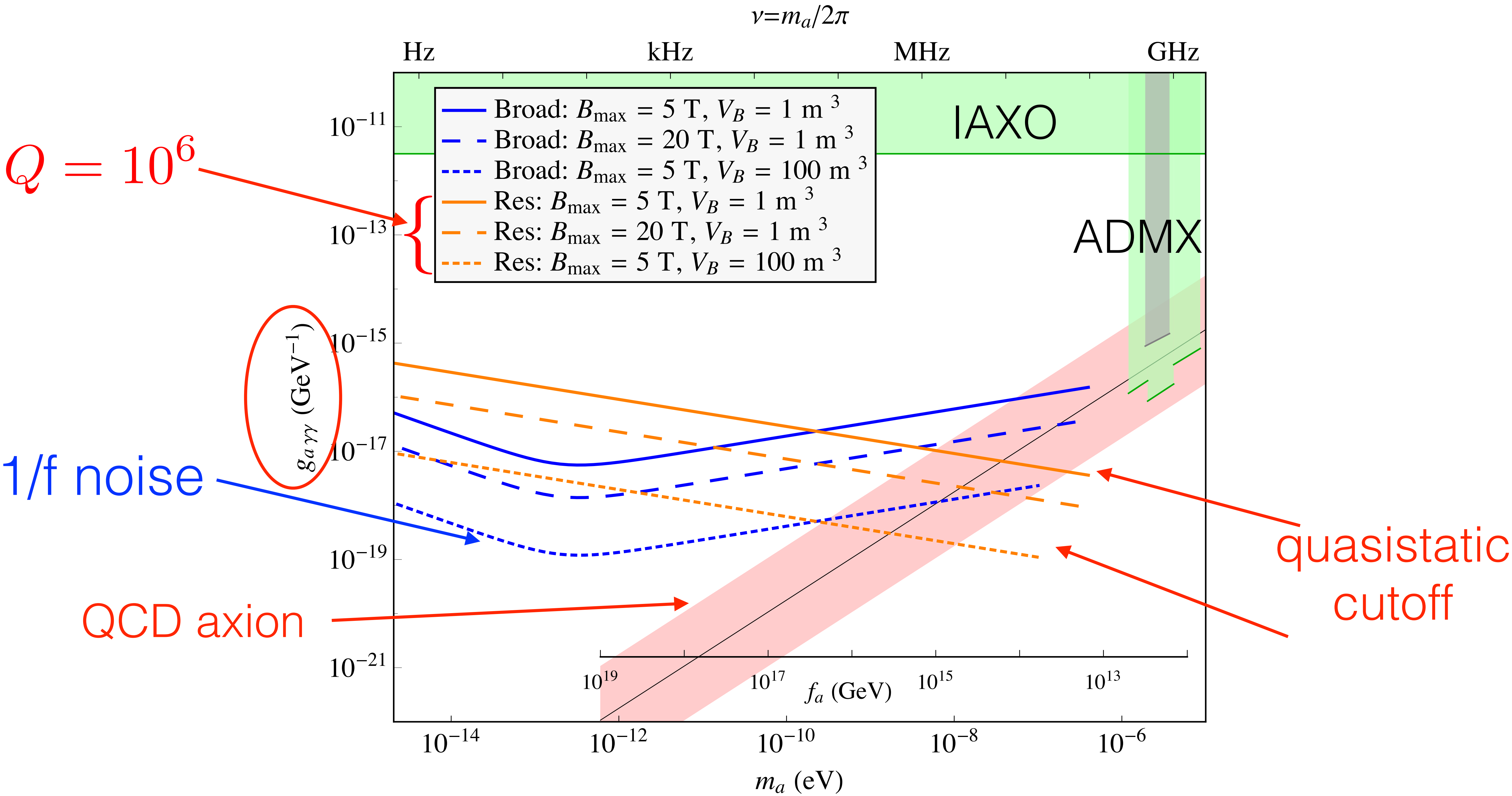
Effective toroid volume

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

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

ABRACADABRA reach

1 year **total** measurement time

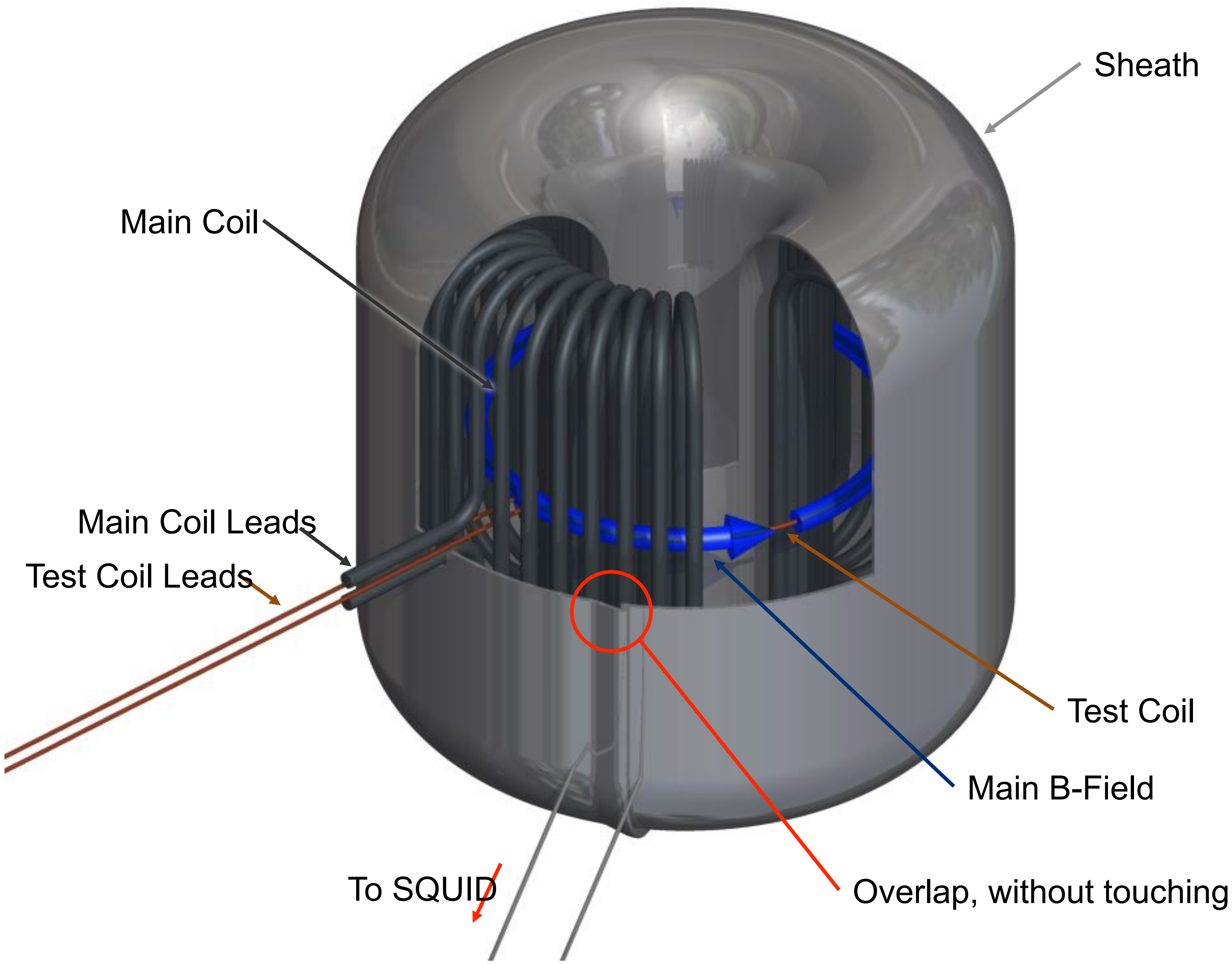


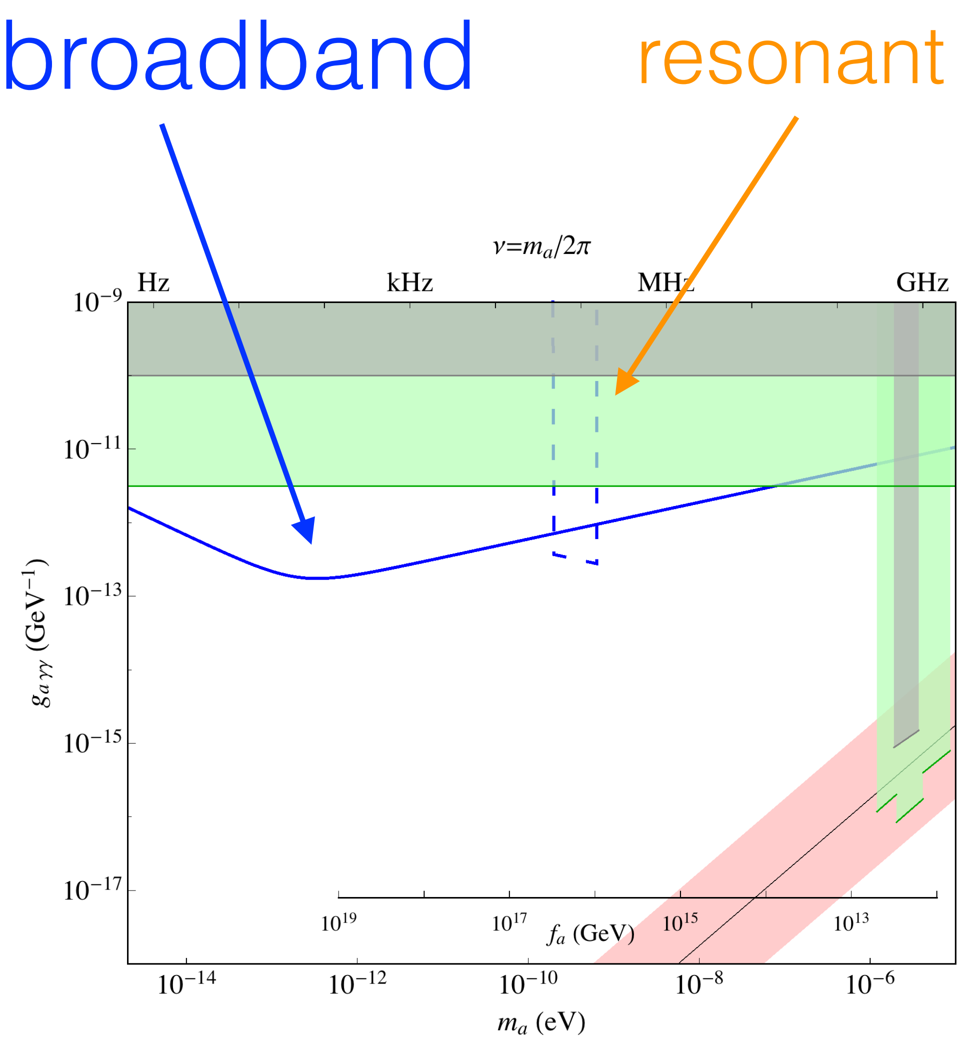
With same experimental parameters,

broadband for low frequencies, resonant for high frequencies

MIT prototype

R ~ 10 cm

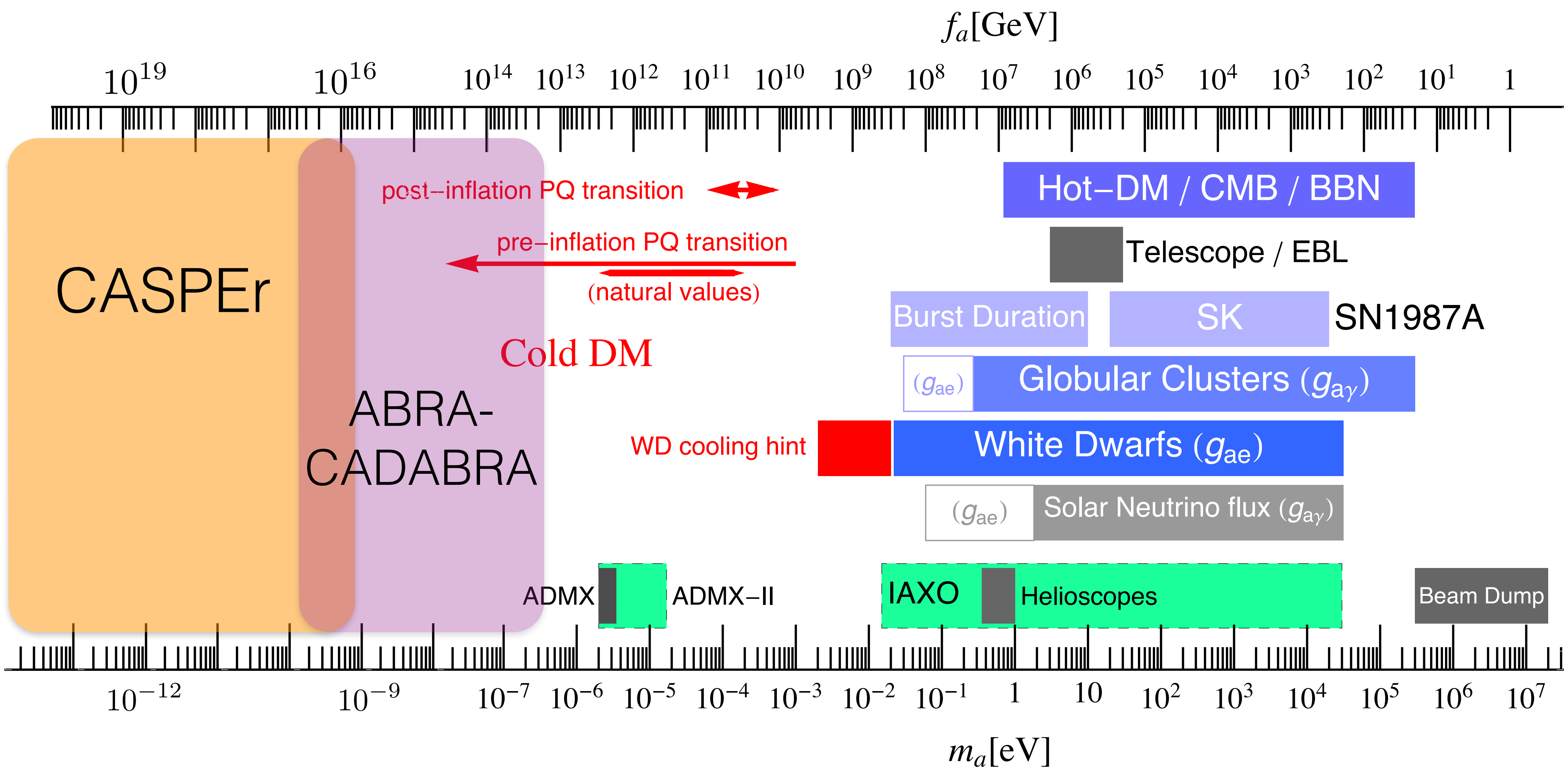




(1 month data-taking)

Interesting physics with first-stage experiment!

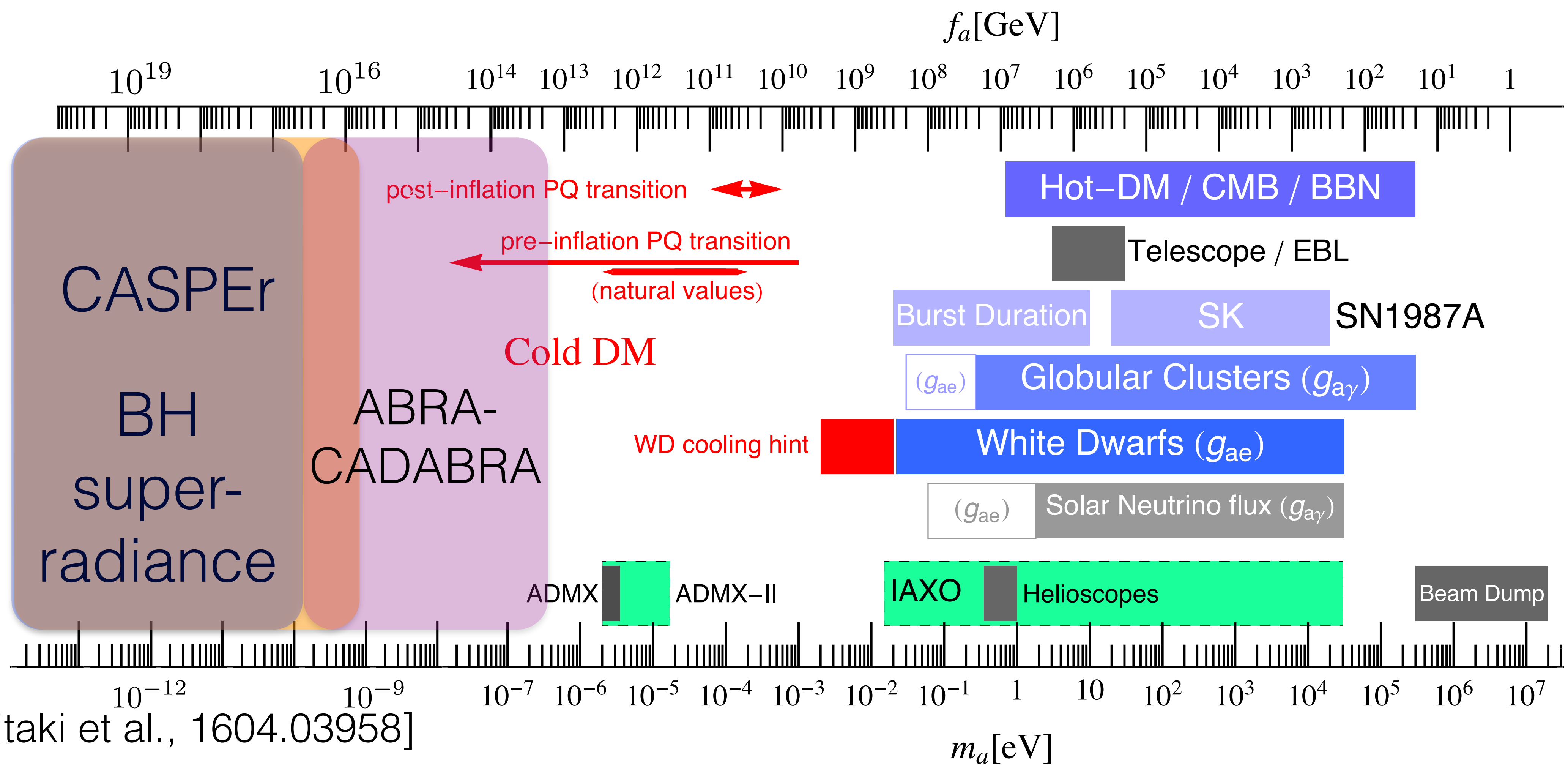
Outlook for QCD axion DM



[adapted from Essig et al., 1311.0029]

Overlapping probes of GUT-scale physics!

Outlook for QCD axion DM



[Arvanitaki et al., 1604.03958]

[adapted from Essig et al., 1311.0029]

Overlapping probes of GUT-scale physics!

Backup slides

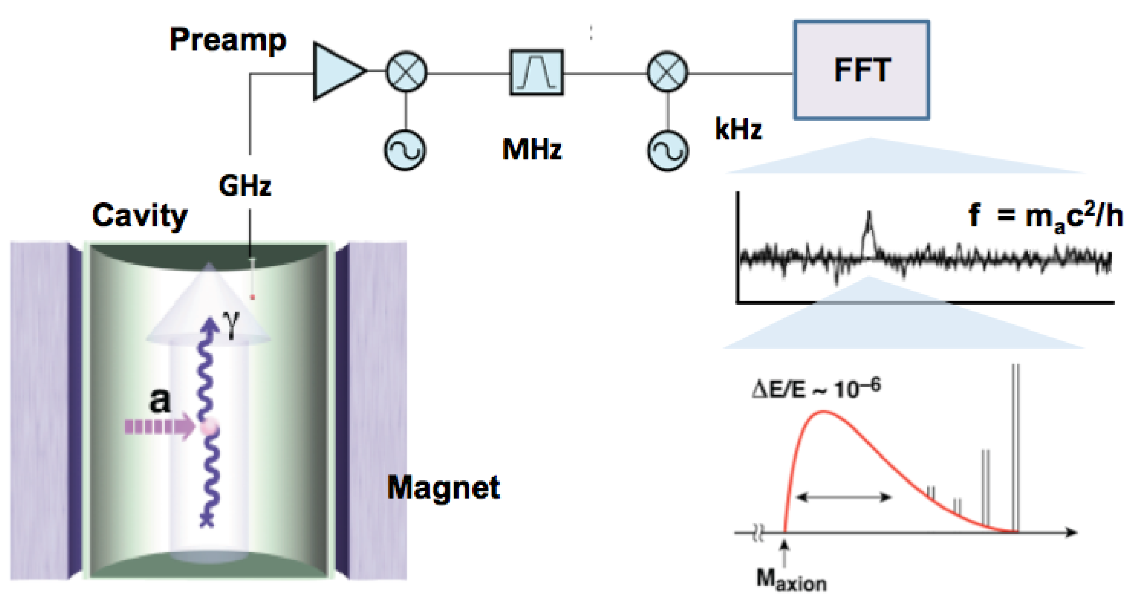
ADMX: resonant cavity detection

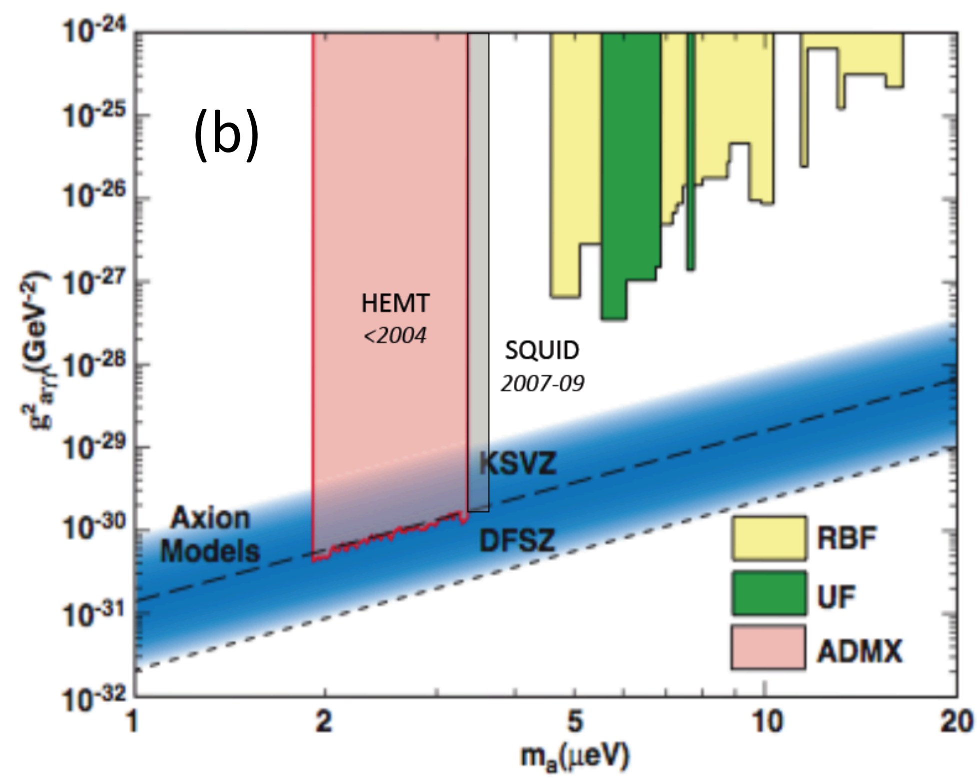
[http://depts.washington.edu/admx/]

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

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

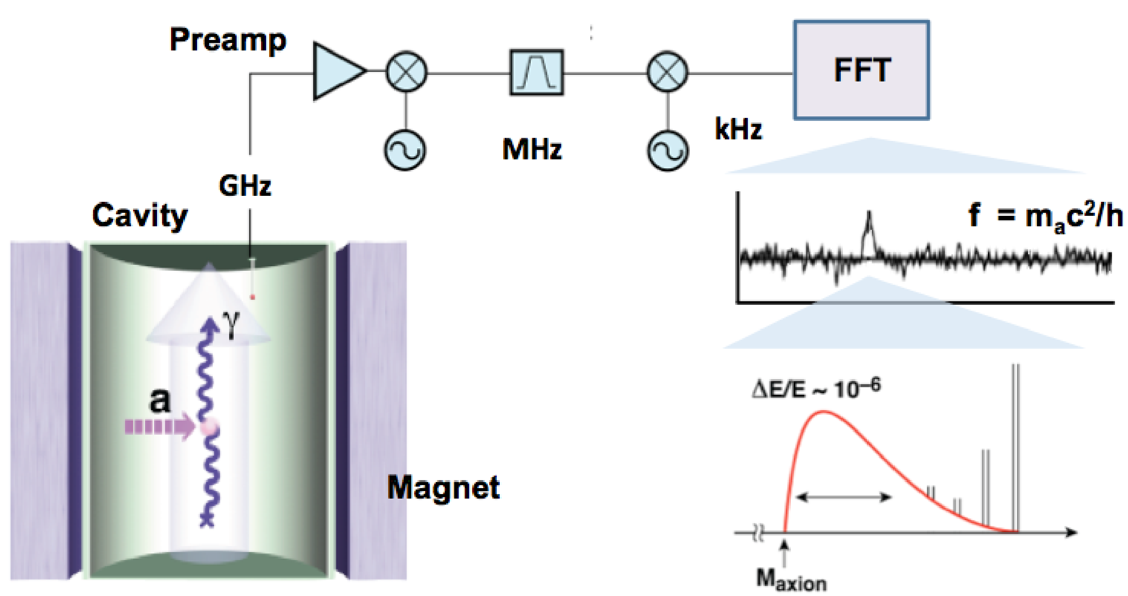
ADMX: resonant cavity detection

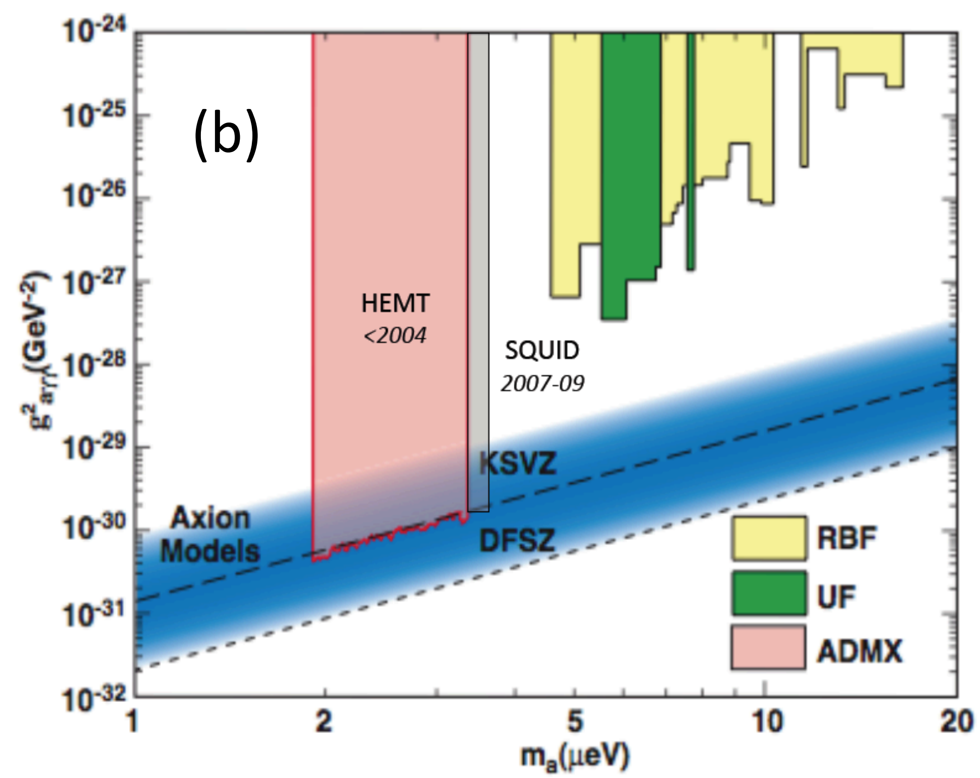
[http://depts.washington.edu/admx/]

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

static B-field

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

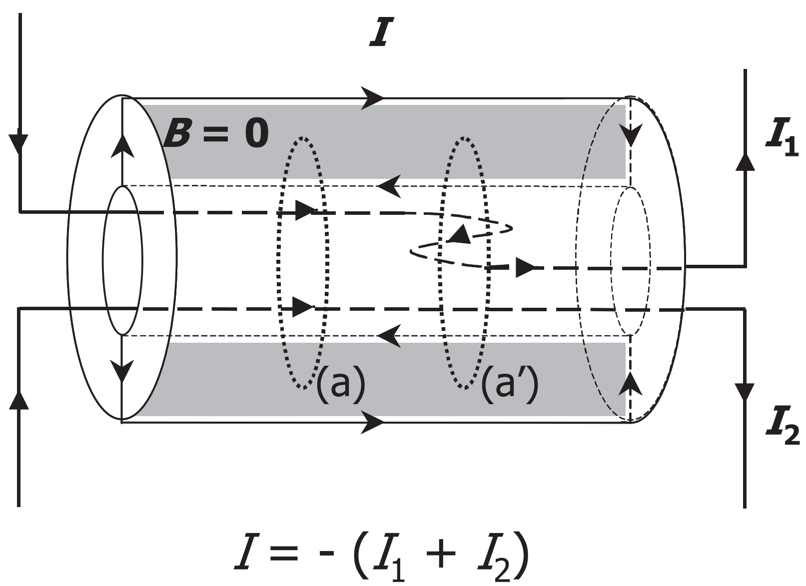




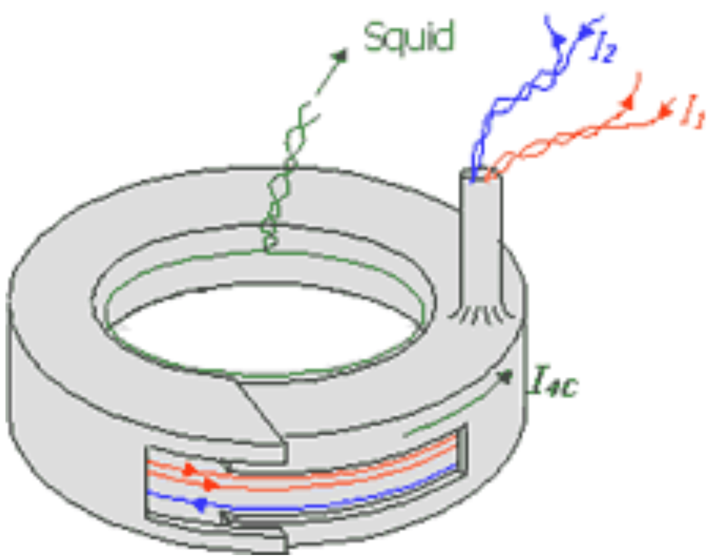
- Measures coupling to $F_{\mu\nu}\widetilde{F}^{\mu\nu}$
- Measurement taken in external B field
- Cavity b.c. fix mass range to cavity size

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:

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

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: 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: bandwidth matching

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

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

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

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

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: S/N and sensitivity

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

energy stored in tank circuit

each e-fold of frequency scanned for equal time

$$P_S / P_N = 1$$

$\Longrightarrow$ sensitivity to

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

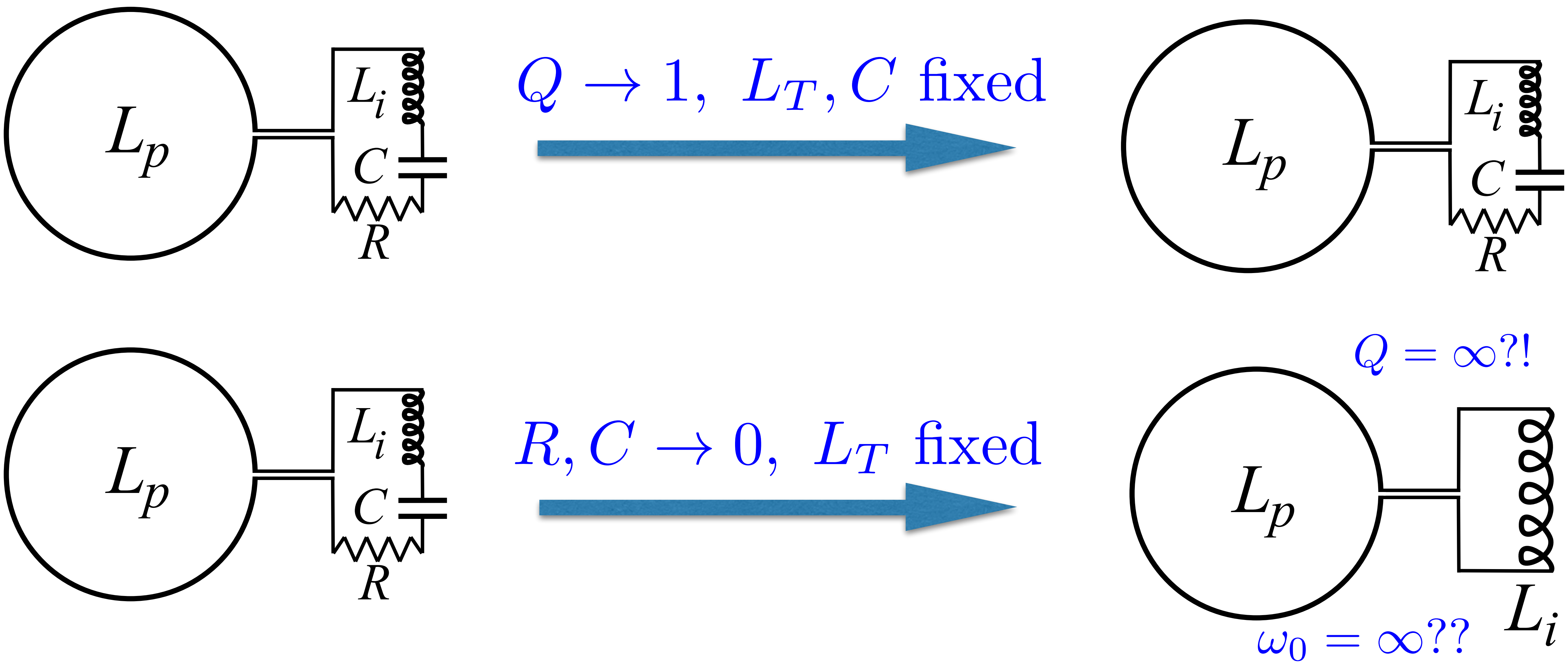
improves at high masses

improves at low temp

Broadband $\neq$ non-resonant!

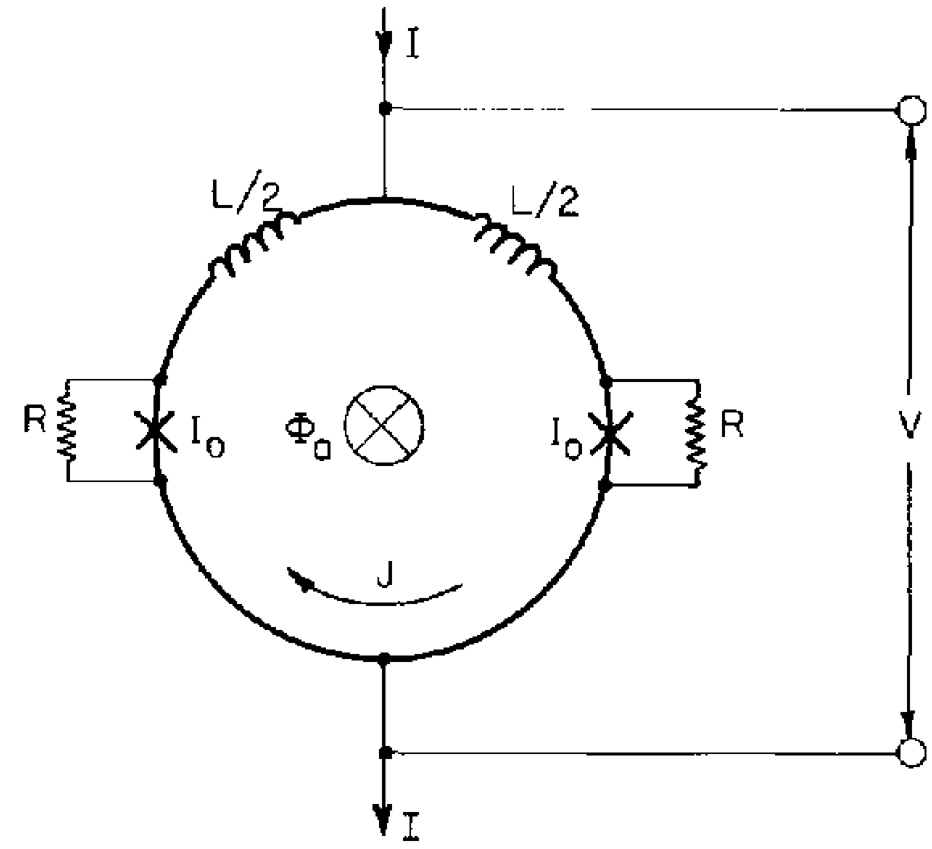
$$Q = \frac{1}{R}\sqrt{\frac{L_T}{C}} \qquad \omega_0 = \frac{1}{\sqrt{LC}}$$

more noise,
wider bandwidth



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

Origin of SQUID noise



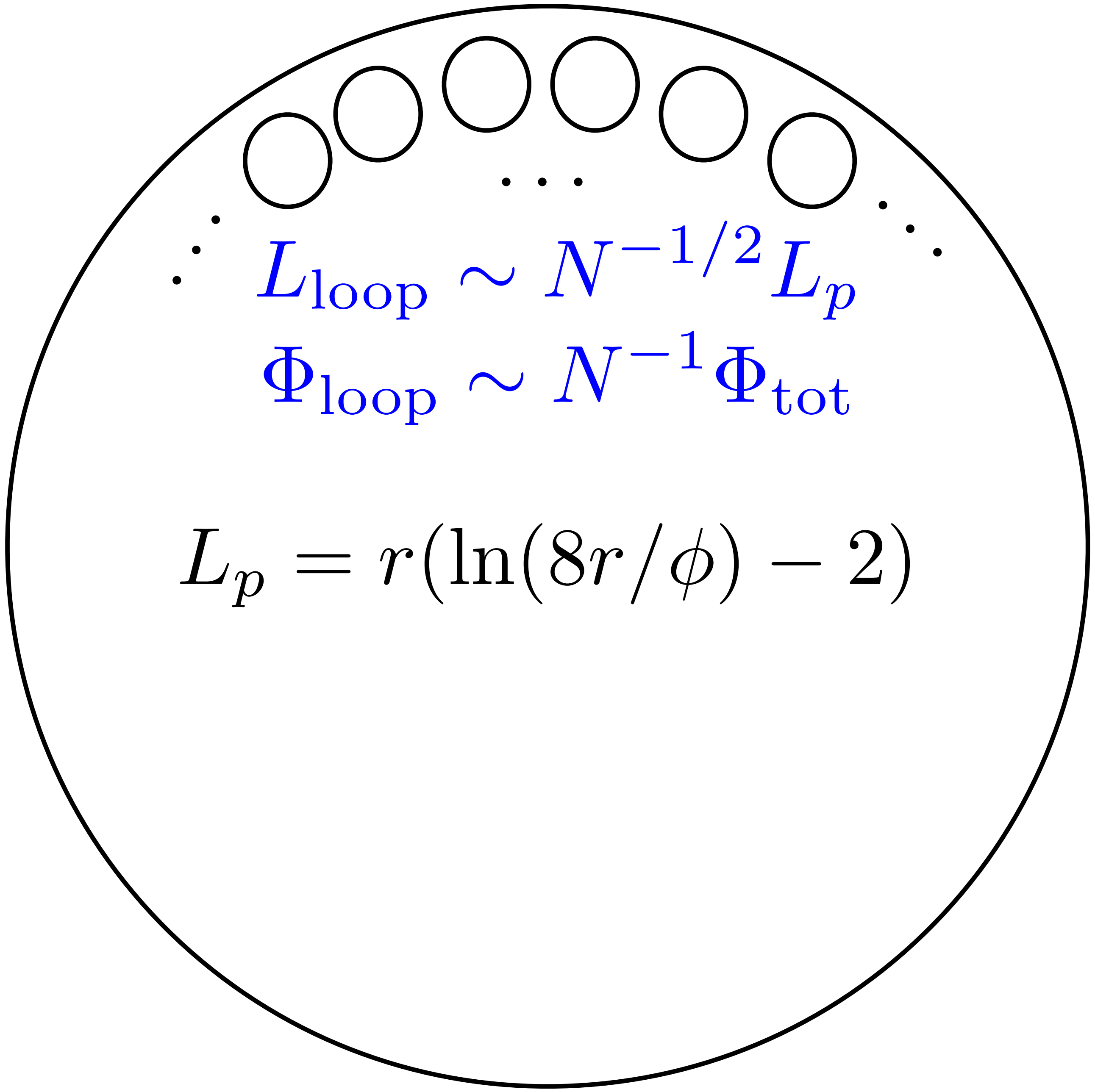
Junction shunt resistance introduces thermal noise:

$$S_V \approx 16 k_B T R \qquad\qquad S_J \approx 11 k_B T / R$$

always subdominant
in resonant circuit
(suppressed by narrow bandwidth)

Inductance matching

N loops
in parallel:



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

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

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

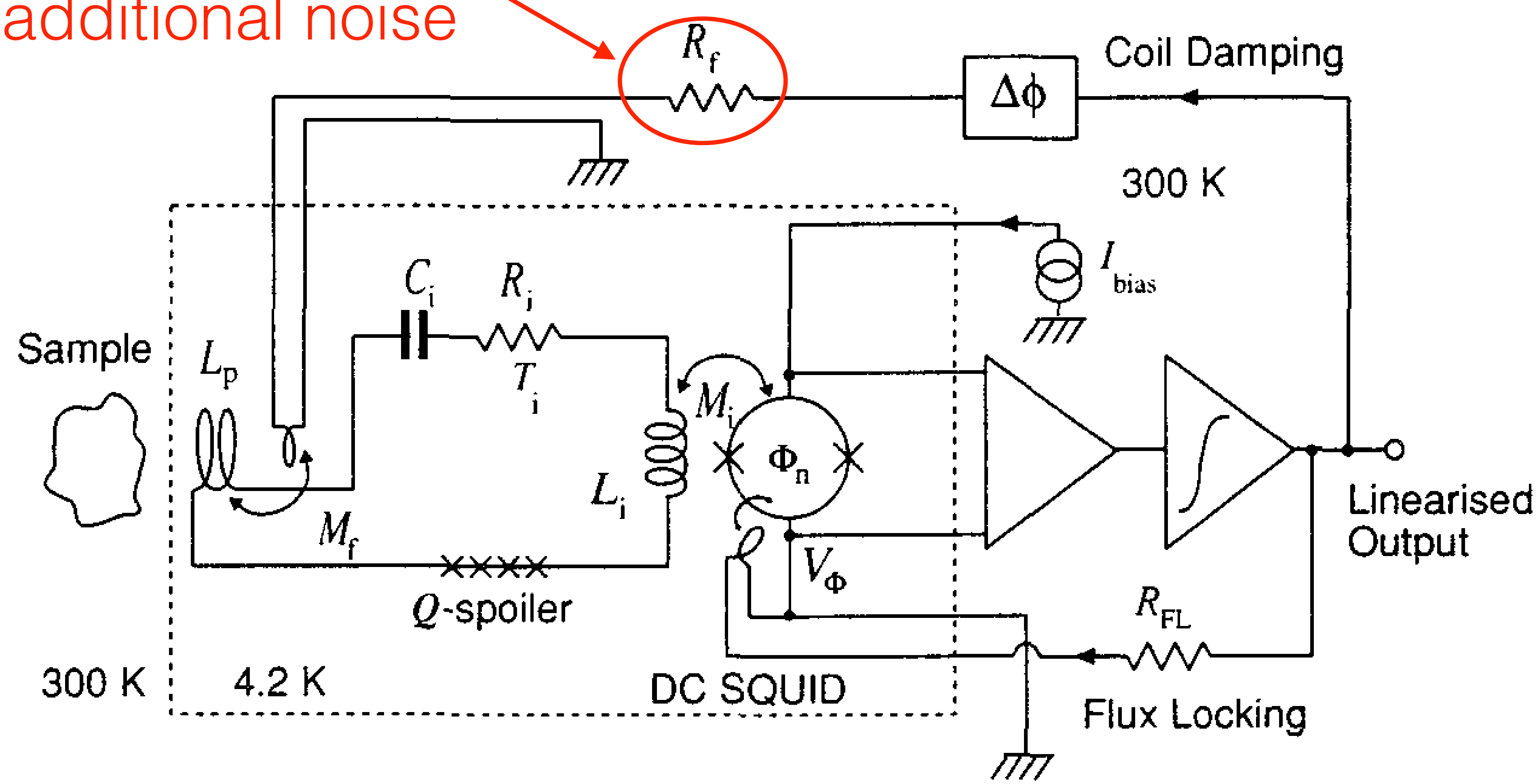
$$\implies L_{\rm eff} \sim N^{-1/2} L_p$$

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

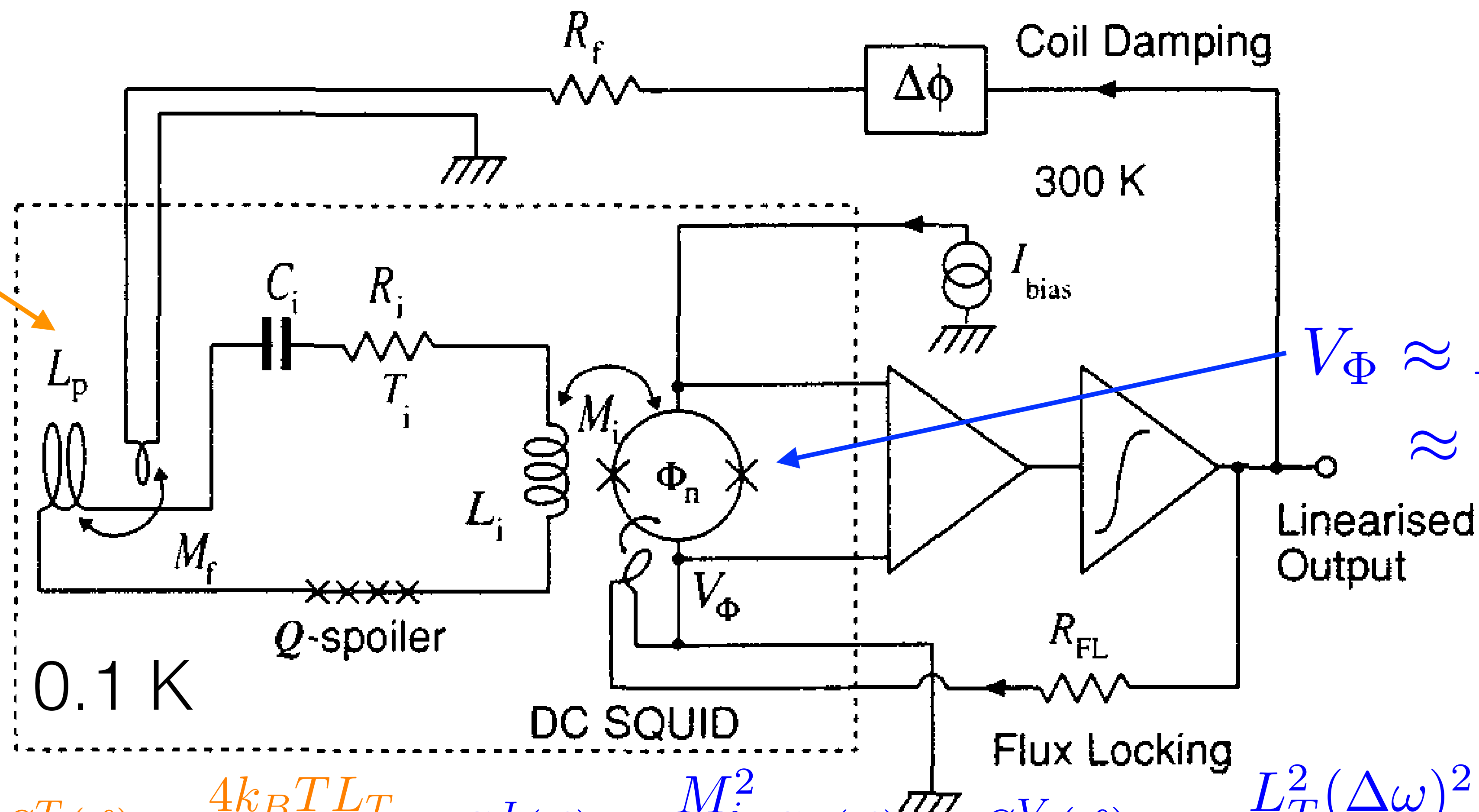
decreases loaded Q,
but not part of resonant circuit
so no additional noise



[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

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

Optimize w.r.t. N_s:

thermal

$< 10^{-2}$

shot noise

$$S_\Phi(f) \approx \frac{4k_BTL_p}{\omega Q_0}\left[1 + \frac{4\times10^{-6}}{\alpha^2}\frac{Q_0\Delta\omega}{\omega}\frac{\Delta\omega}{V_\Phi} + 10^{-6}Q_0\alpha^2\frac{\omega}{V_\Phi}\left(\frac{11}{4} + \frac{S_{J,0}}{4k_BT}\right)\right]$$

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?