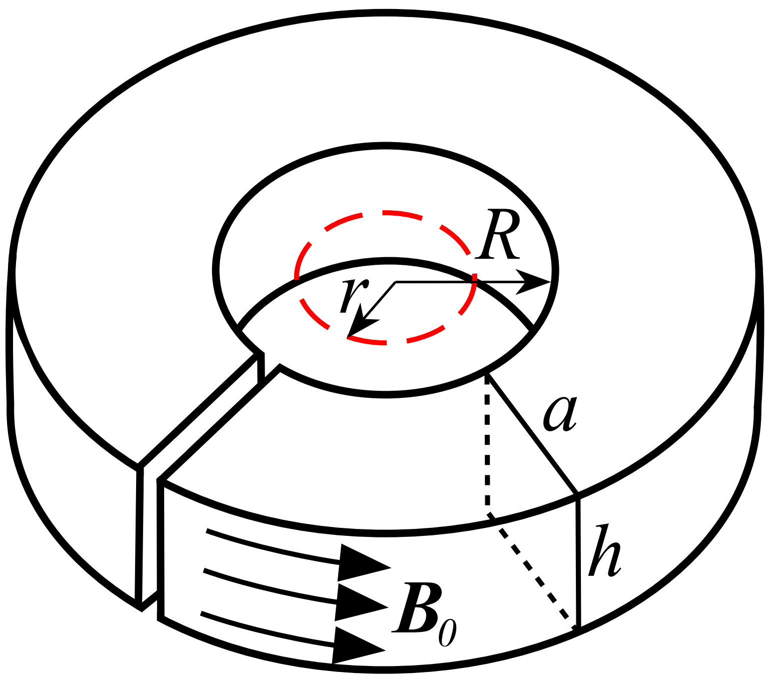
Prospects for Cosmic Axion Detection with ABRACADABRA

Jesse Thaler

GPMFC Workshop on Ultralight Dark Matter, Washington, DC — January 27, 2017

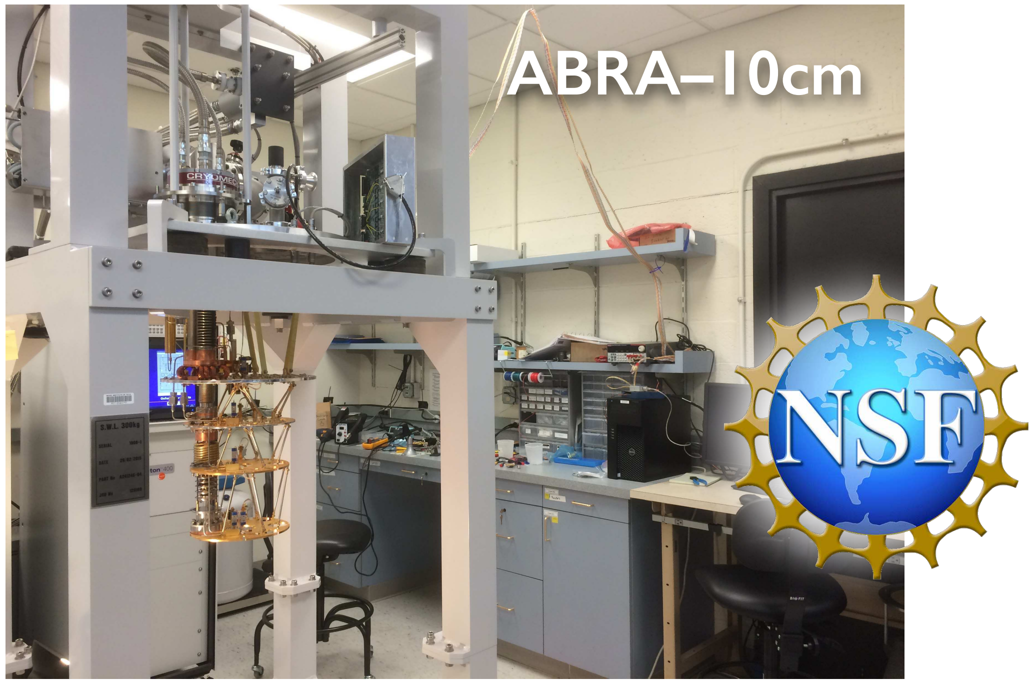
A Broadband/Resonant Approach to Cosmic Axion Detection with an Amplifying B-field Ring Apparatus

From Theory…



[Kahn, Safdi, JDT, 1602.01086]

…to Experiment

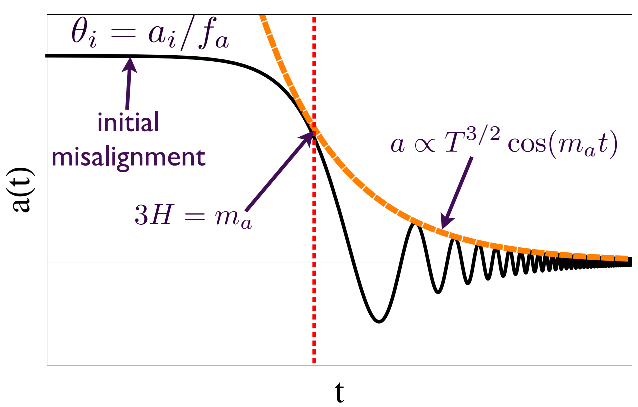


[development at MIT under NSF EAGER with PI Winslow, Conrad, Formaggio, Heine, Kahn, Minervini, Ouellet, Perez, Radovinsky, Safdi, JDT, Winklehner]

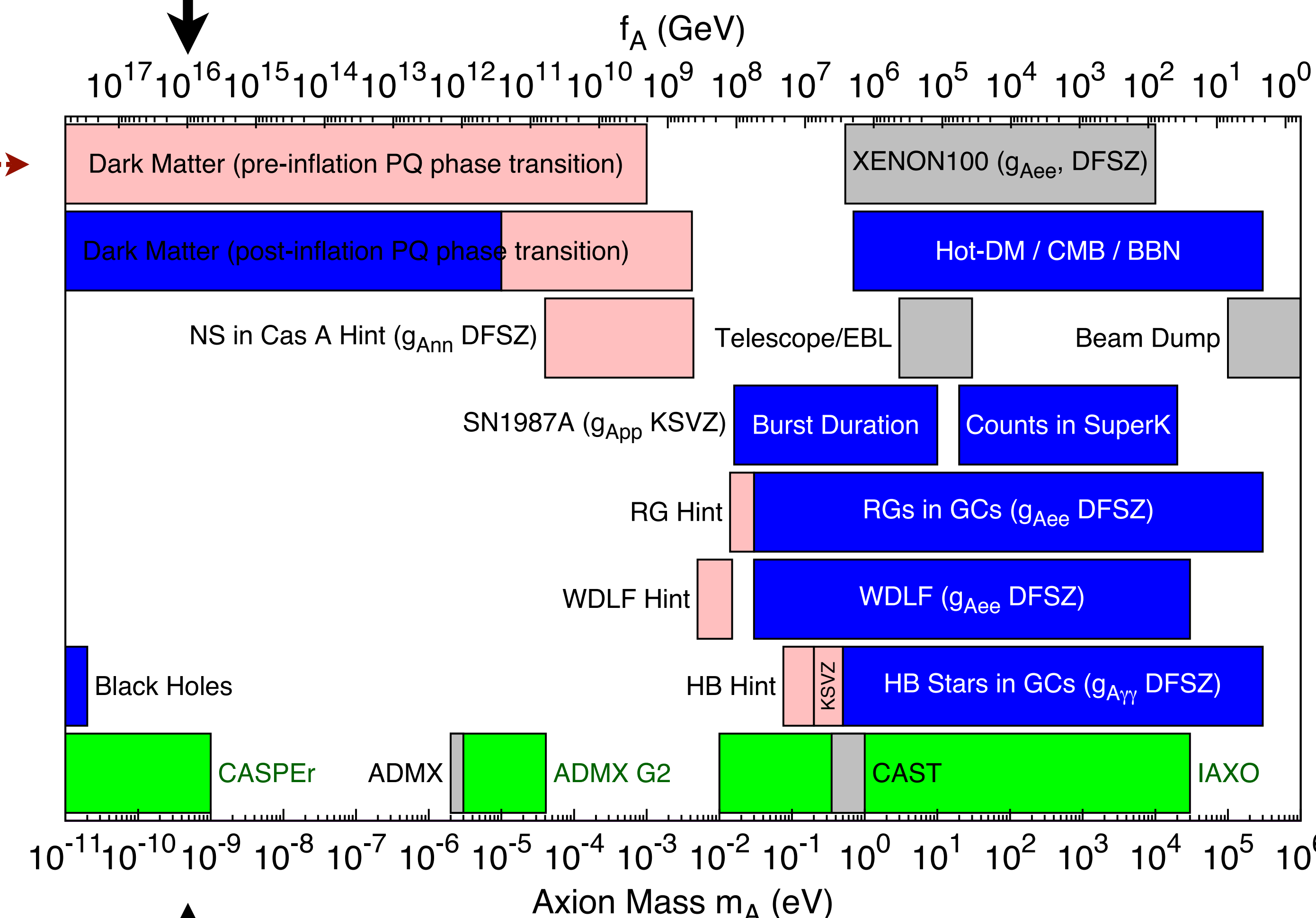
Ultimate Goal: ABRACADABRA–1m (or 10m)

GUT-scale QCD Axion Dark Matter

Strong CP solution at well-motivated mass scale…



…and right DM abundance with 1% tuning in initial misalignment angle.



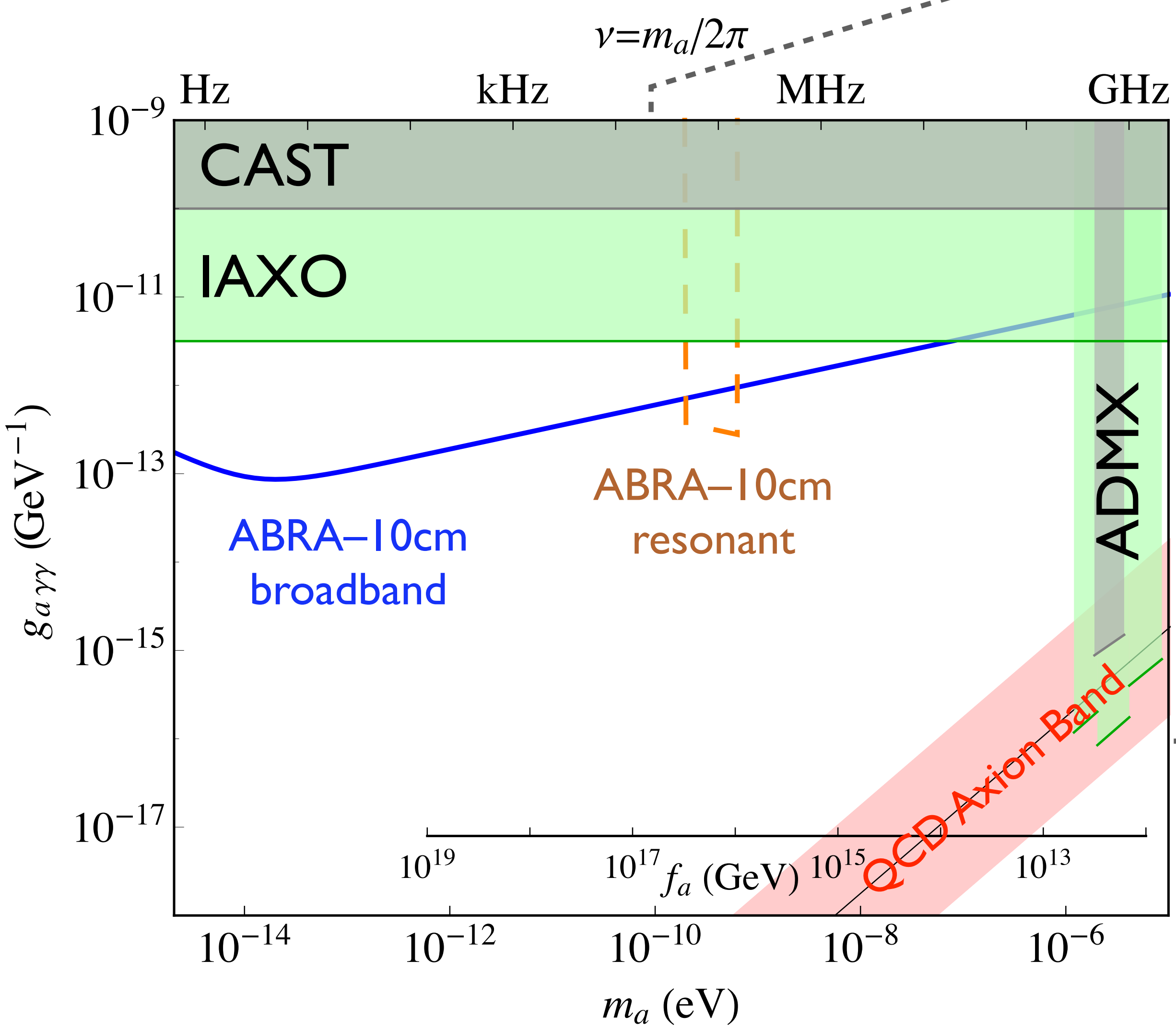
[2016 PDG Axion Review]

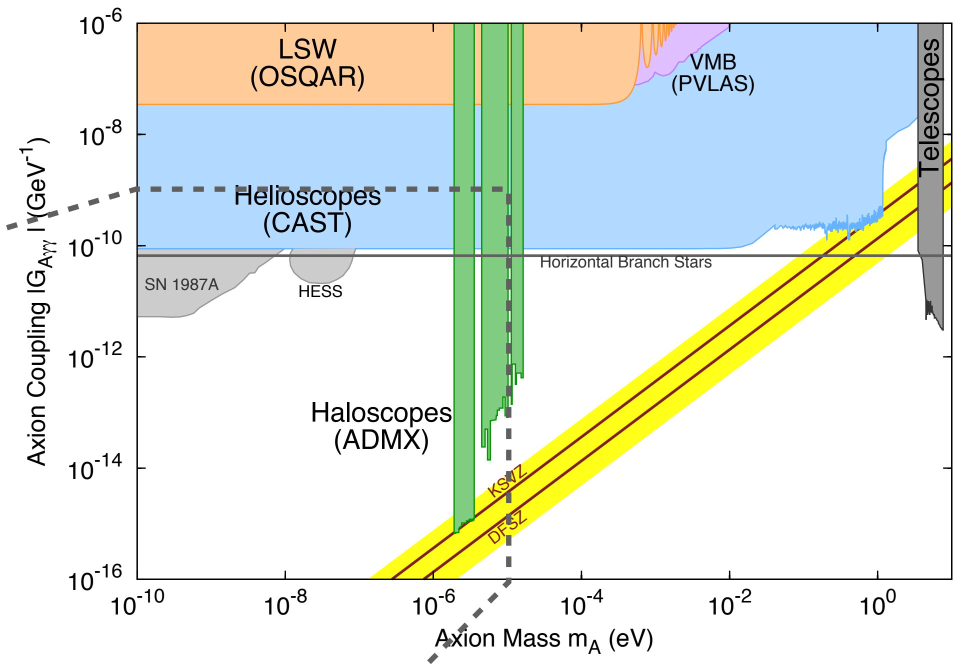
10^{-22} T signal @ 250 kHz

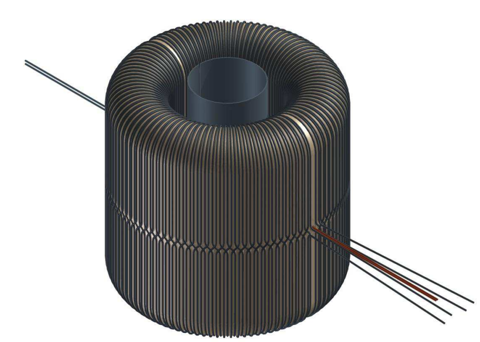
Initial Target: ABRACADABRA–10cm

Axion-like DM coupled to Electromagnetism

$$\mathcal{L} \supset g_{a\gamma\gamma}\, a\, \mathbf{E} \cdot \mathbf{B}$$



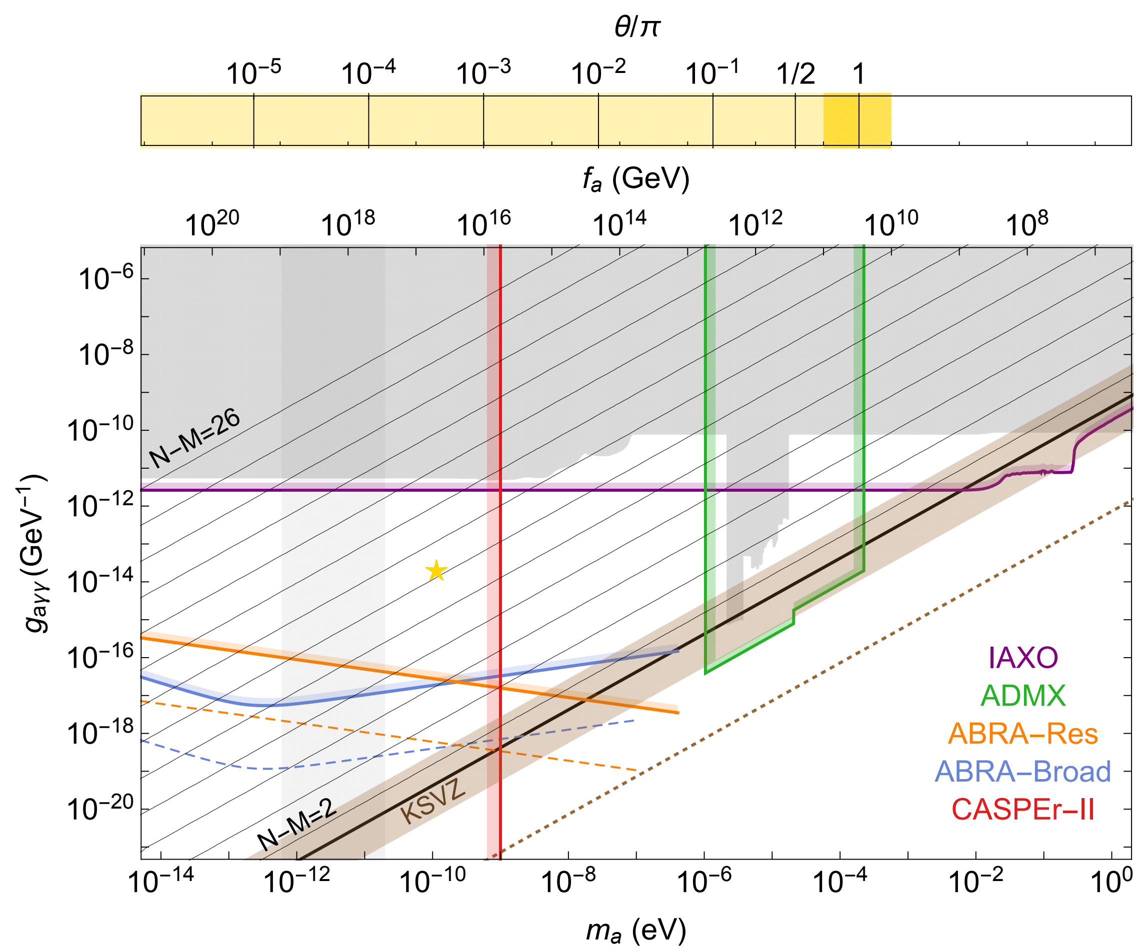




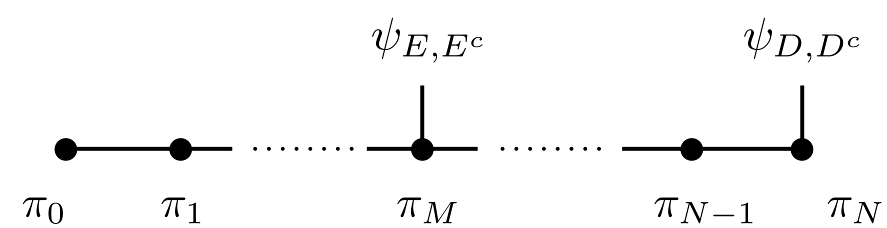
Substantial discovery potential for small scale prototype

Initial Target: ABRACADABRA–10cm

Solve Strong CP with Exponentially Large E&M Coupling?

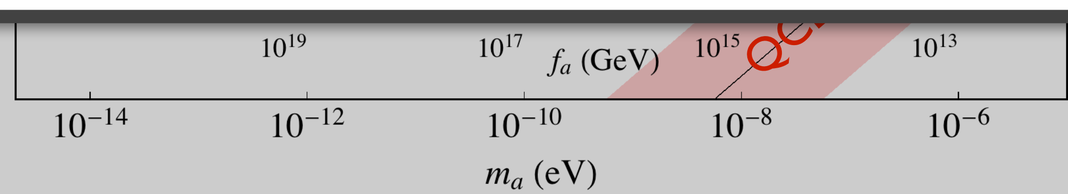


A "Clockwork" Axion:



Further motivation to cover full axion parameter space

[Farina, Pappadopulo, Rompineve, Tesi, 1611.09855]
[based on Choi, Im, 1511.00132; Kaplan, Rattazzi, 1511.01827; Giudice, McCullough, 1610.07962]
[appears to evade misalignment bounds from Ariasa, Cadamuro, Goodsell, Jaeckel, Redondo, Ringwald, 1201.5902]



Substantial discovery potential for small scale prototype

ABRACADABRA: Cosmic Axion Detection

Cold Axion DM ≈ Classical Field Oscillations

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

e.g. $m_a \sim 10^{-9}$ eV

$\lambda_{\rm Comp} \sim 1$ km

$\tau_{\rm Comp} \sim$ few μs

Local DM Velocity

$$v_{\rm DM} \simeq 10^{-3}$$

$\Rightarrow$

Spatial Coherence

$$\lambda_{\rm deB} \simeq \frac{\lambda_{\rm Comp}}{v_{\rm DM}}$$

Temporal Coherence

$$\tau_{\rm deB} \simeq \frac{\tau_{\rm Comp}}{v_{\rm DM}^2}$$

(motivates Q~10^6 resonators)

Key Experimental Feature:

complementary to cavities like ADMX

$$\lambda_{\rm Comp} \gg R_{\rm exp}$$

Review of Axion Electrodynamics

$$\mathcal{L} \supset g_{a\gamma\gamma}\, a\, \mathbf{E} \cdot \mathbf{B}$$

Modified Maxwell Equations:

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

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{B} = g_{a\gamma\gamma} \frac{\partial a}{\partial t} \mathbf{B} + g_{a\gamma\gamma} \nabla a \times \mathbf{E} + \frac{\partial \mathbf{E}}{\partial t}$$

[see, e.g., Sikivie, 1983; Wilczek, 1987]

Review of Axion Electrodynamics

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

$\partial E/\partial t$ suppressed for $\lambda_{Comp} \gg R_{exp}$
(MQS = magnetoquasistatic limit)

[see, e.g., Sikivie, 1983; Wilczek, 1987]

Review of Axion Electrodynamics

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$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{B}_{\text{response}} = \boxed{g_{a\gamma\gamma}\frac{\partial a}{\partial t}\mathbf{B}} + g_{a\gamma\gamma}\cancel{\nabla a} \times \mathbf{E} + \cancel{\frac{\partial \mathbf{E}}{\partial t}}$$

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

$\partial E/\partial t$ suppressed for $\lambda_{Comp} \gg R_{exp}$ (MQS = magnetoquasistatic limit)

Static External Field

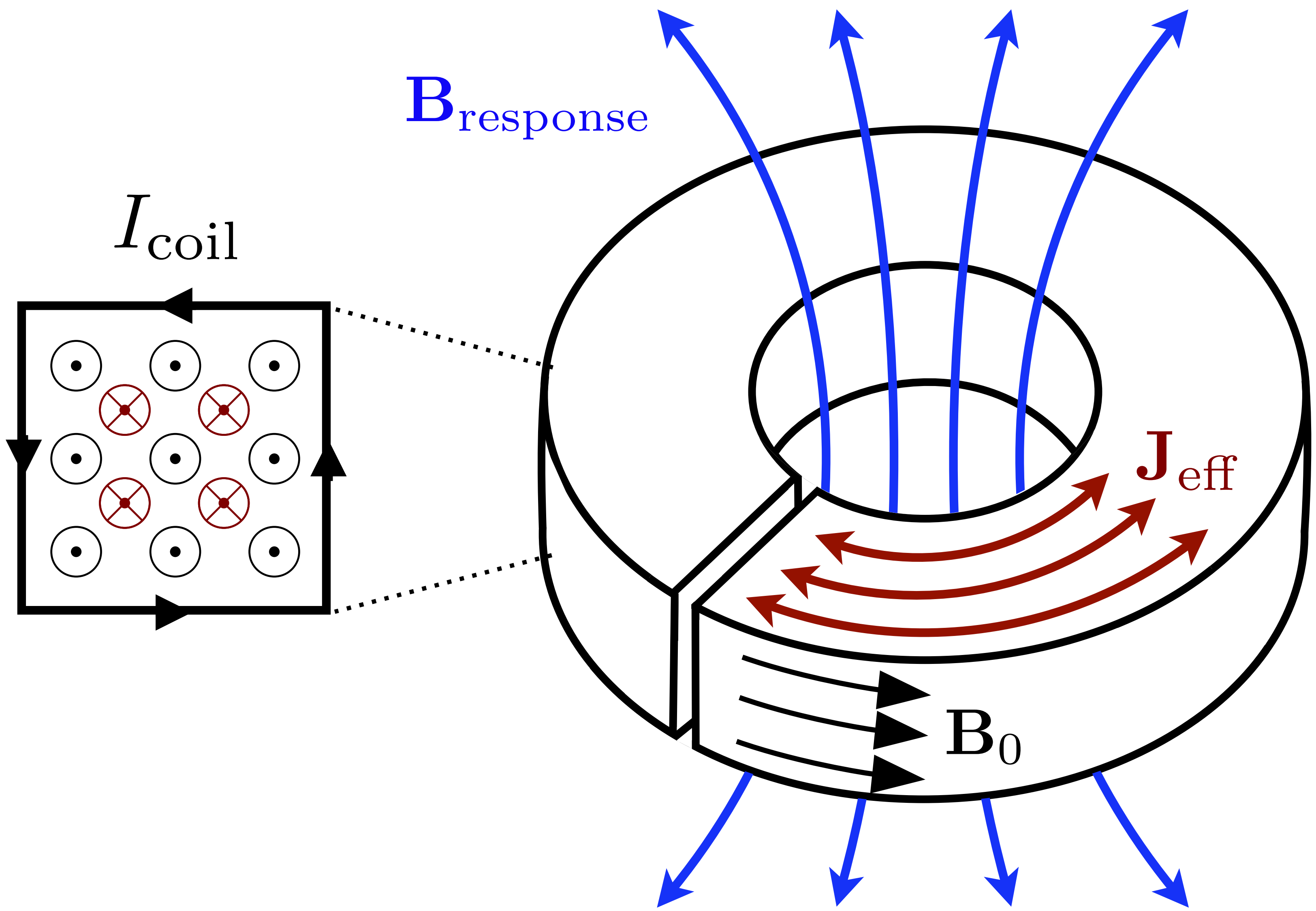
Axion-Induced Effective Current:

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

Parallel to external field

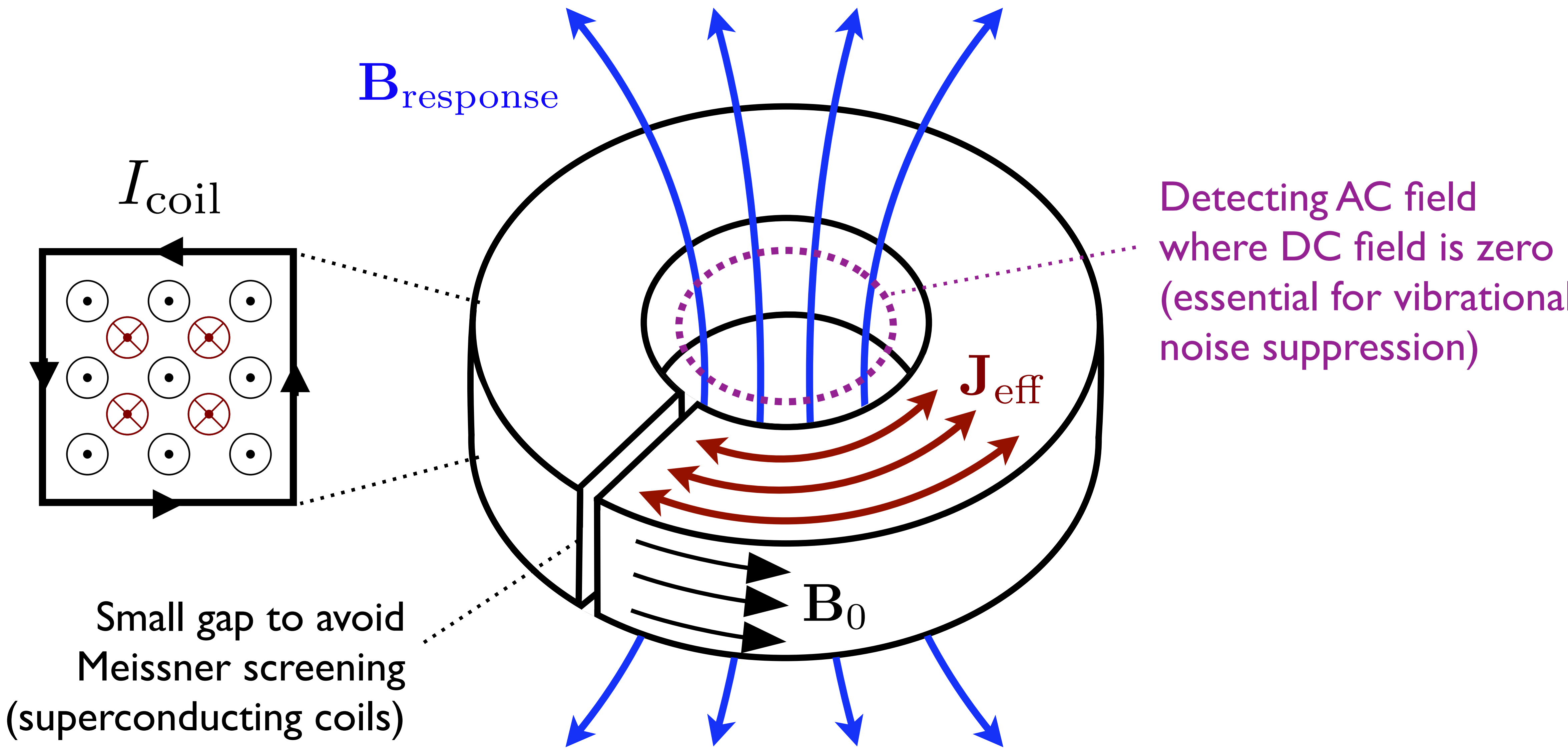
[see, e.g., Sikivie, 1983; Wilczek, 1987]

ABRACADABRA: Amplifying B-field Ring Apparatus



[Kahn, Safdi, JDT, 1602.01086]
[for a related solenoidal design, see Thomas, Cabrera, 2010; Sikivie, Sullivan, Tanner, 1310.8545]

ABRACADABRA: Amplifying B-field Ring Apparatus

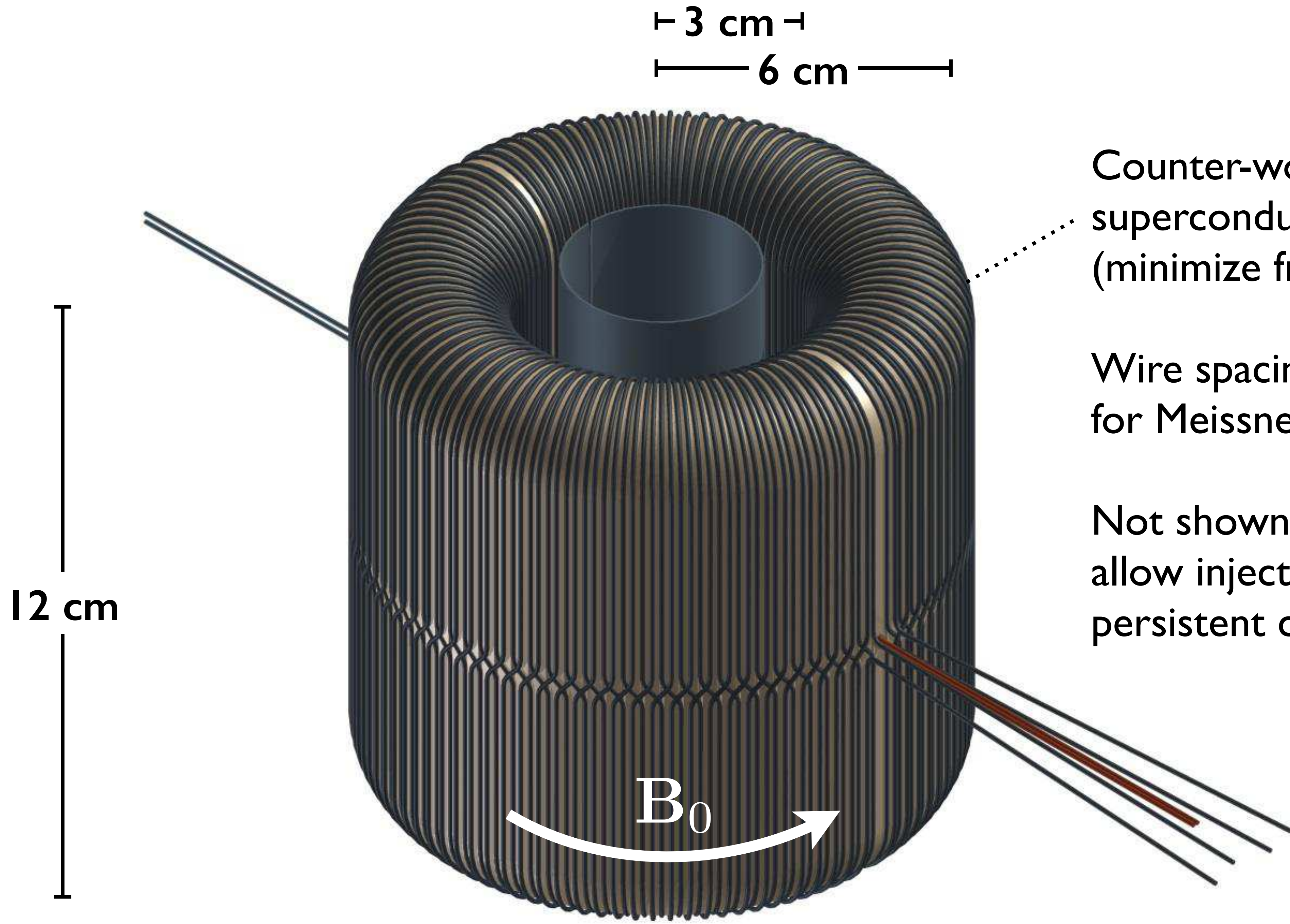


geometric factor, typically O(10%)

$$\Phi_a(t) = g_{a\gamma\gamma}\sqrt{2\rho_{\text{DM}}}\cos(m_a t) \times (B_{\max} V_{\text{toroid}}\, G_{\text{toroid}})$$

[Kahn, Safdi, JDT, 1602.01086]
[for a related solenoidal design, see Thomas, Cabrera, 2010; Sikivie, Sullivan, Tanner, 1310.8545]

ABRA–10cm: Prototype Toroid Design



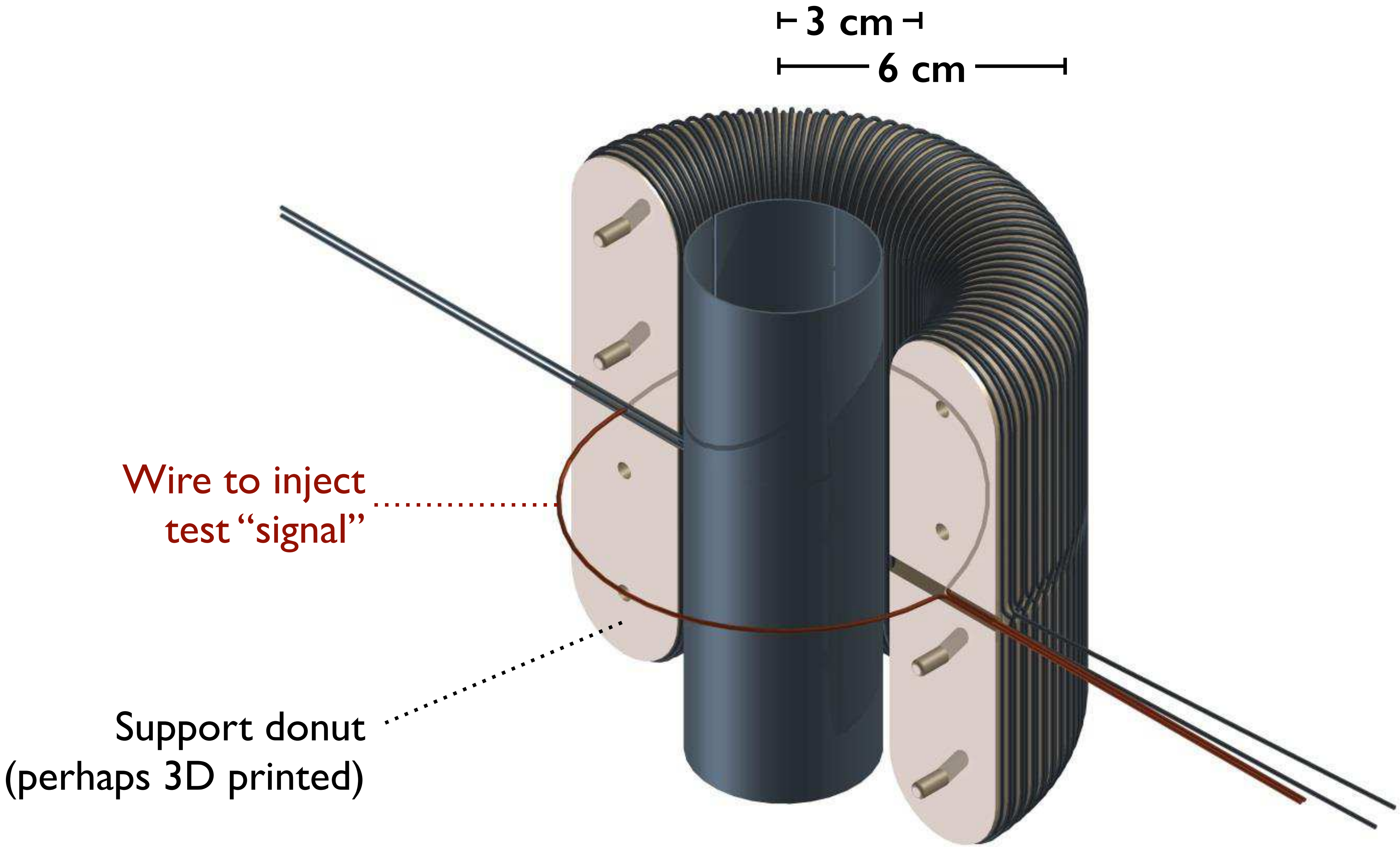
Counter-wound NbTi superconducting coils (minimize fringe fields)

Wire spacing sufficient for Meissner gap

Not shown: shunt to allow injection of persistent current

$B_{max} = 1\ T$ $\quad$ $I_{coil} = 120\ A$ $\quad$ $V_{toroid} = 1020\ cm^3$ $\quad$ $G_{toroid} = 0.057$

ABRA–10cm: Prototype Toroid Design

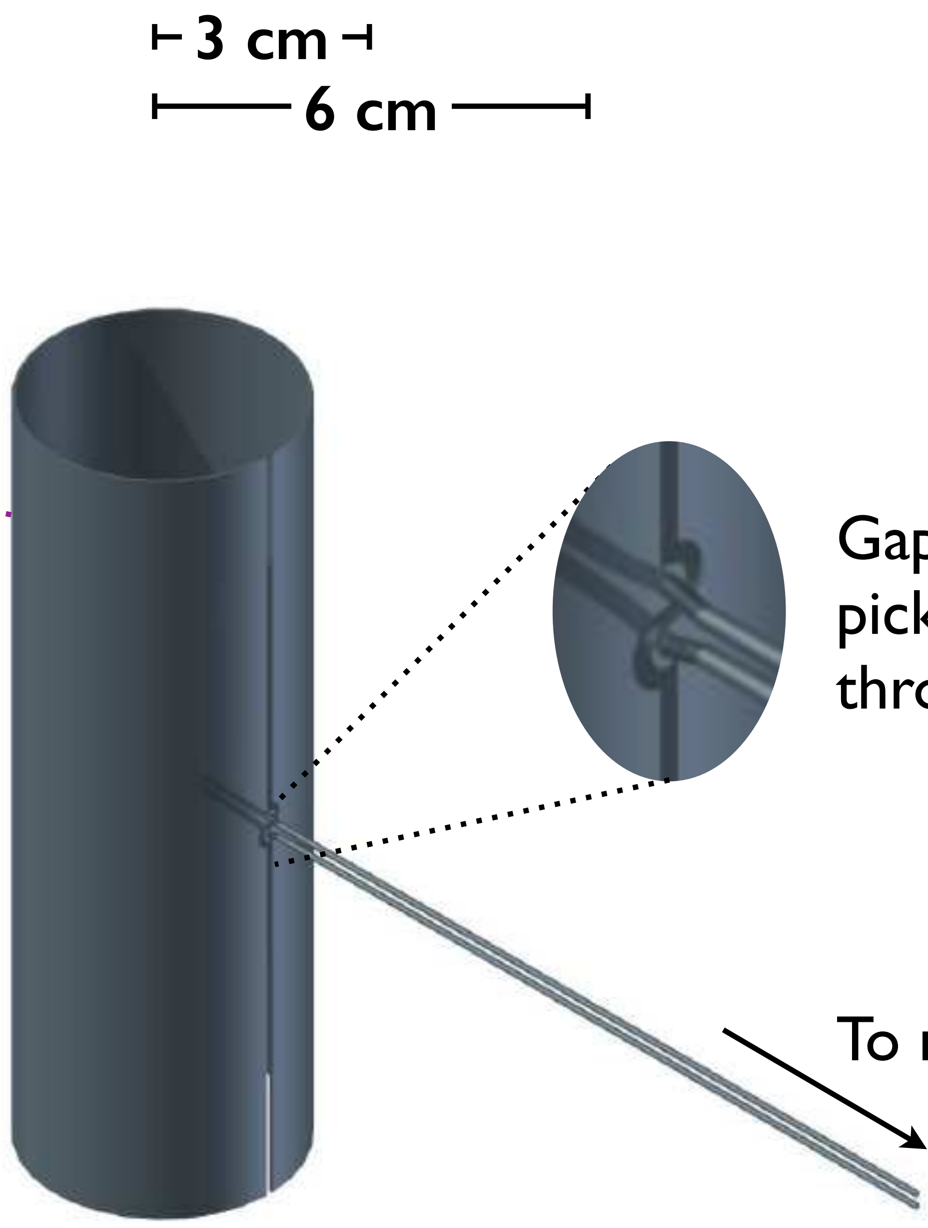


$B_{max} = 1\ T$ $\quad I_{coil} = 120\ A$ $\quad V_{toroid} = 1020\ cm^3$ $\quad G_{toroid} = 0.057$

ABRA–10cm: Prototype Toroid Design

Superconducting
pickup cylinder

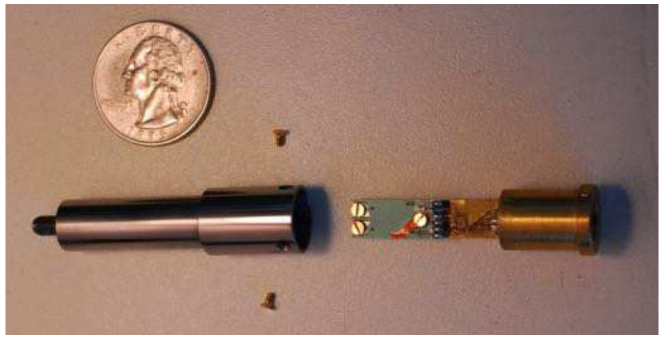
Minimize inductance
with tall cylinder
(advice from K. Irwin)



Gap to force
pickup current
through SQUID

To readout circuit

SQUID pickup + amplifier
(shown: Magnicon amplifier array)

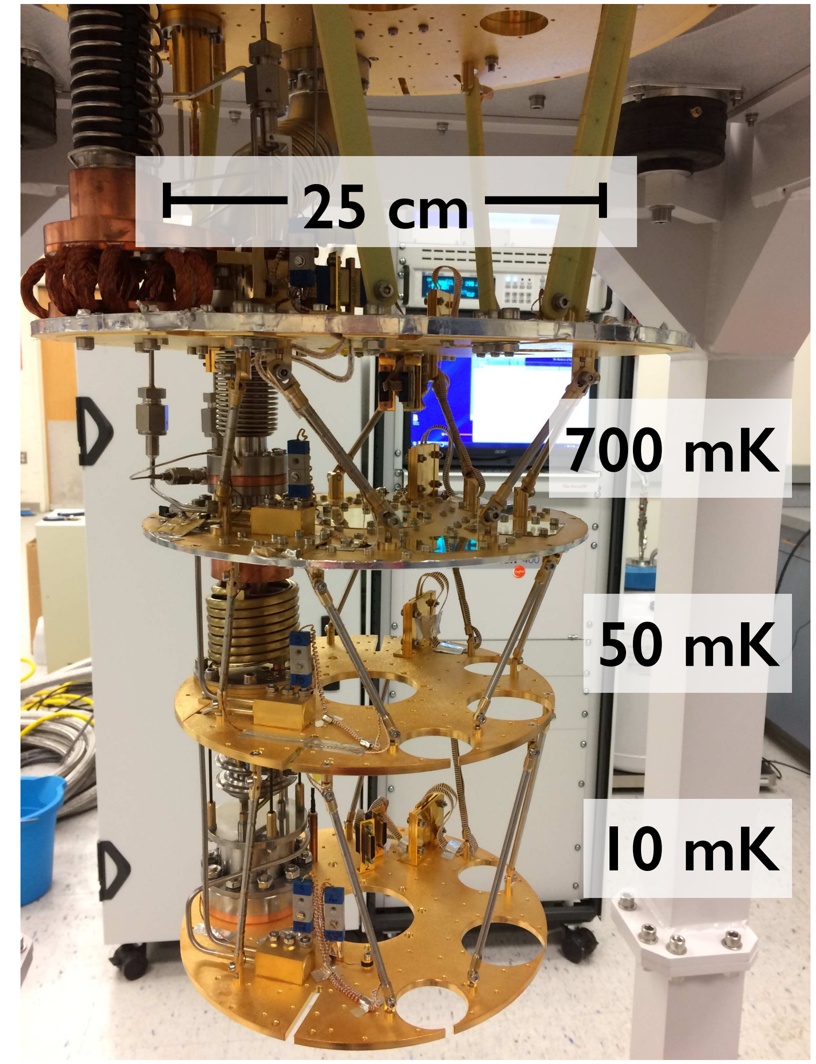


Cryogenics & Shielding

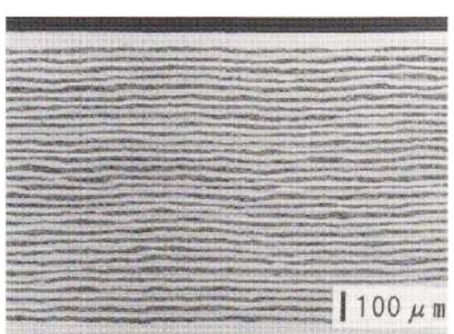
Dilution Refrigerator: Oxford Instruments Triton 400

12 L working volume
Cryogen-free
Can run for weeks unattended

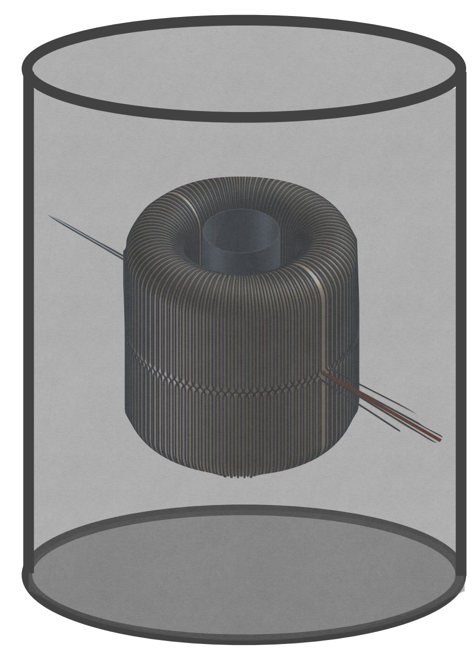
Day job: CUORE $0\nu\beta\beta$ R&D



Magnetic Shielding:

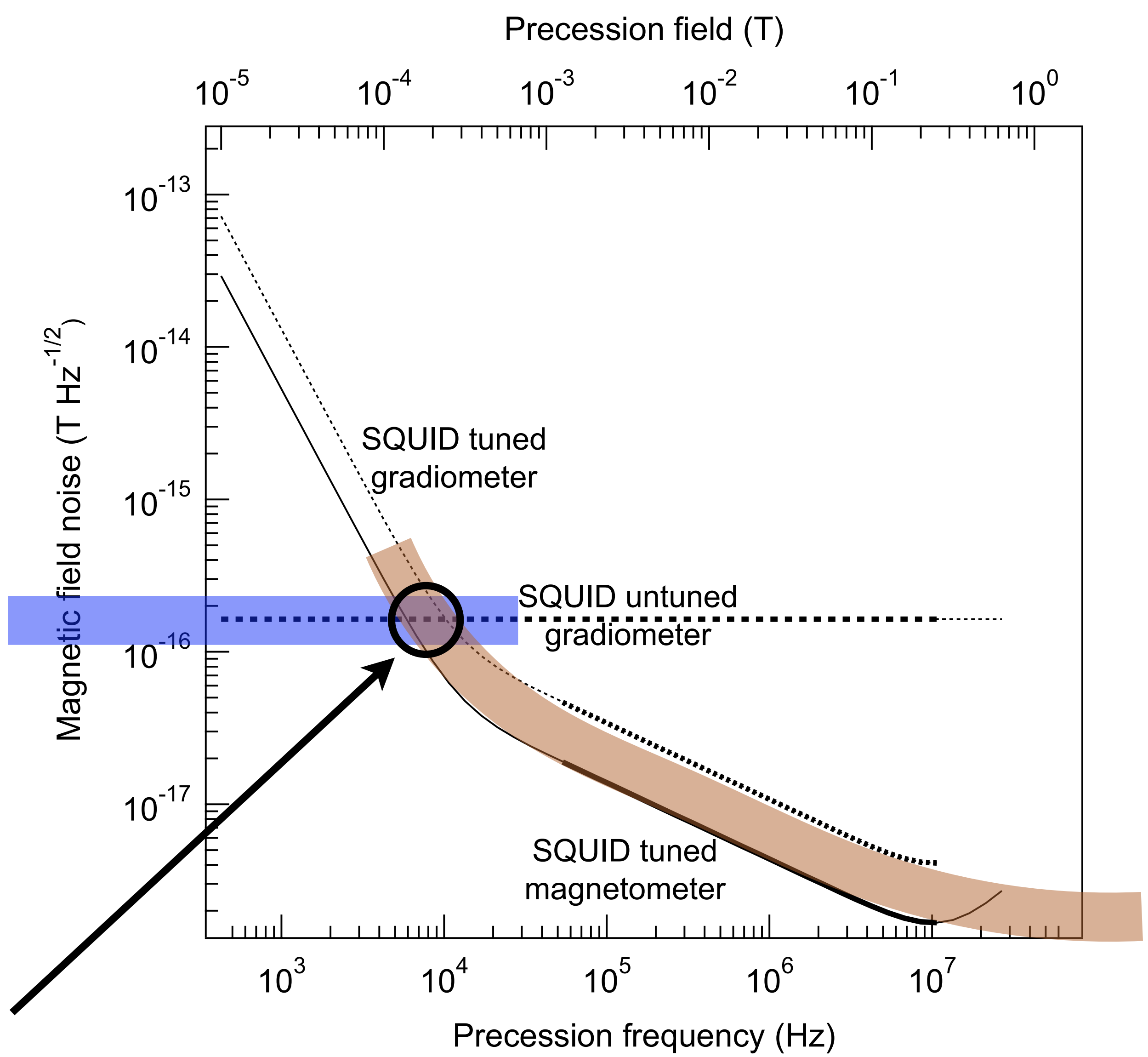


Ideally superconducting
← Multilayer NbTi/Nb/Cu sheet?
Alternatively, In/Cu?



ABRACADABRA: A Broadband/Resonant Approach

Minimize circuit noise for given axion mass



Example from low-field MRI

Broadband

Dominated by SQUID noise

Resonant

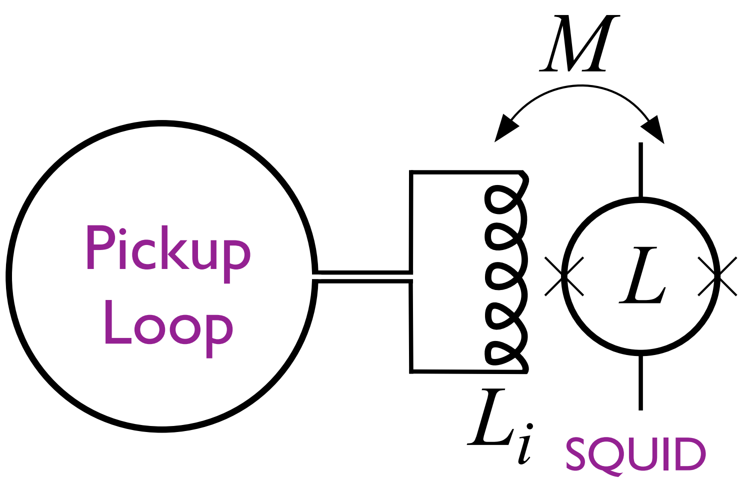
Dominated by thermal noise

Temperature-dependent crossover

[figure adapted from Myers, et al., Journal of Magnetic Resonance, 2007;
see related discussion in Jaeckel, Redondo, 1308.1103]

Complementary Readout Strategies

Lower Frequencies: Broadband



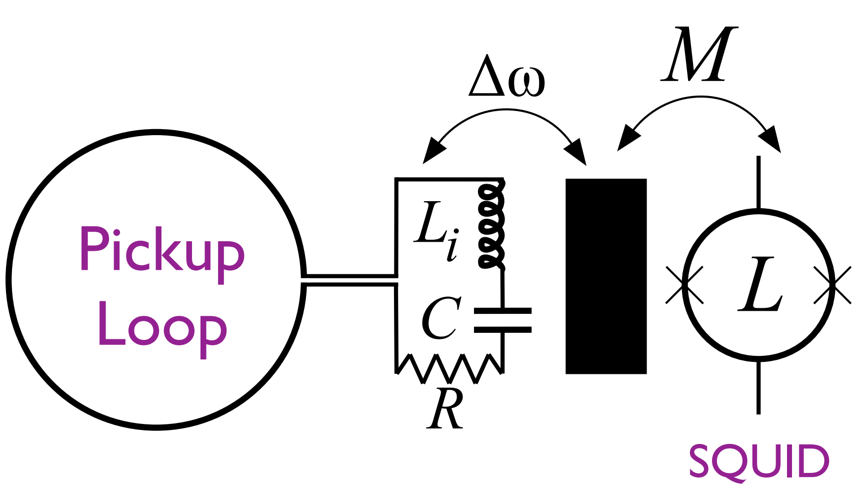
Superconducting circuit ⇒ SQUID noise dominates

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

Close to shot noise limit
1/f noise present at lower frequencies

[also good for transients, see Zioutas @ Axion DM 2016]

Higher Frequencies: Resonant



Pickup RLC circuit ⇒ inevitable dissipation

$$Q = \omega_0\, L_{\text{circuit}}/R_{\text{circuit}}$$

Q-enhancement of signal…
…but thermal noise dominates at 100 mK up to $Q = 10^8$

Complementary Readout Strategies

Lower Frequencies: Broadband

lower mass ⇒ longer coherence time

minimize inductance with "tall" geometry; optimal sensitivity scales like $(R_{\text{exp}})^{-5/2}$

$$g_{a\gamma\gamma}^{\min} \propto \left(\frac{m_a}{t_{\text{total}}}\right)^{1/4} \frac{\sqrt{L_{\text{circuit}}}}{B_{\max} V_{\text{toroid}} G_{\text{toroid}}} \frac{1}{\sqrt{\rho_{\text{DM}}}} S_{\Phi,0}^{1/2}$$

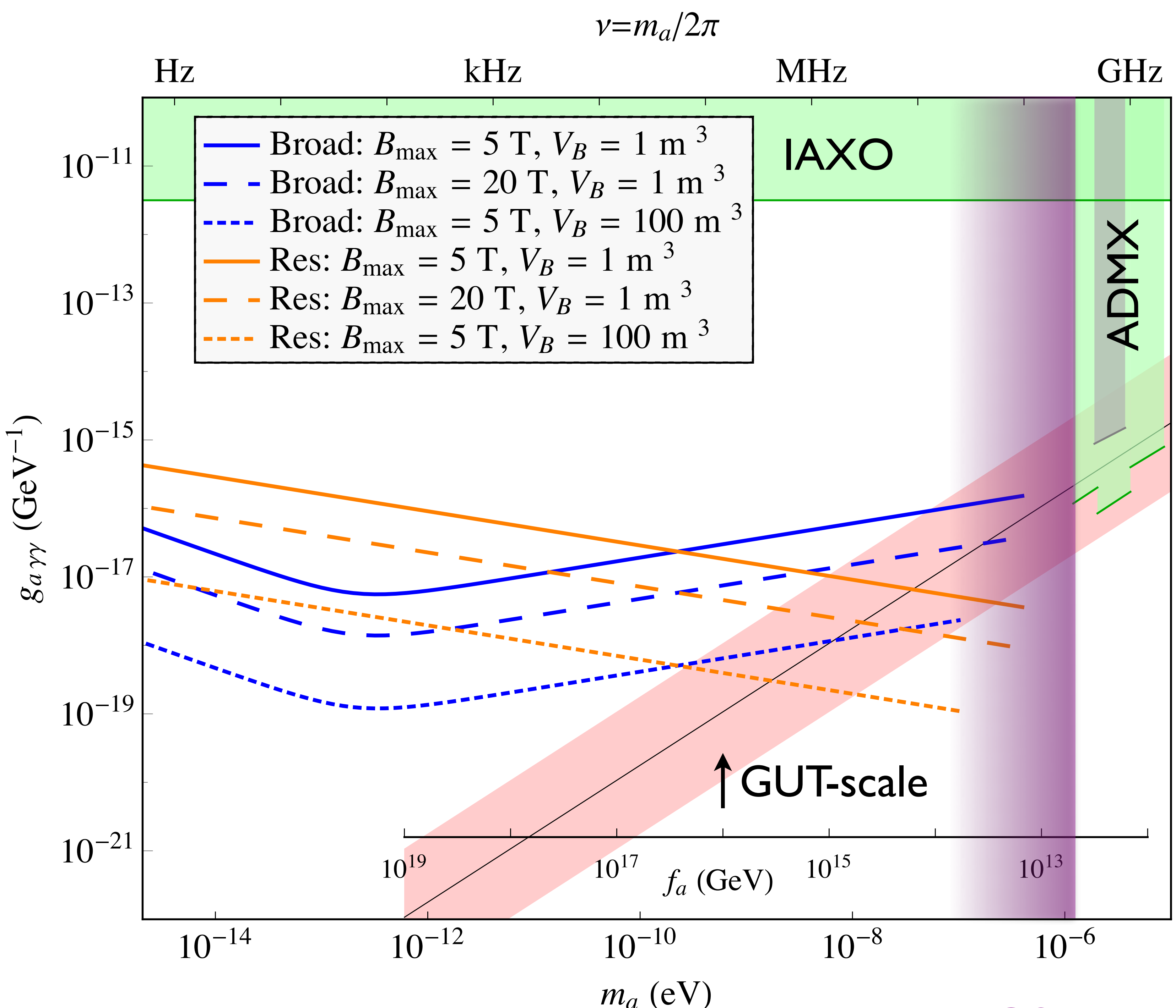
Higher Frequencies: Resonant

depends on resonant scanning strategy

want low T and high Q

$$g_{a\gamma\gamma}^{\min} \propto \left(\frac{1}{m_a t_{\text{e-fold}}}\right)^{1/4} \frac{\sqrt{L_{\text{circuit}}}}{B_{\max} V_{\text{toroid}} G_{\text{toroid}}} \frac{1}{\sqrt{\rho_{\text{DM}}}} \sqrt{\frac{T}{Q}}$$

ABRACADABRA: Potential Future Reach



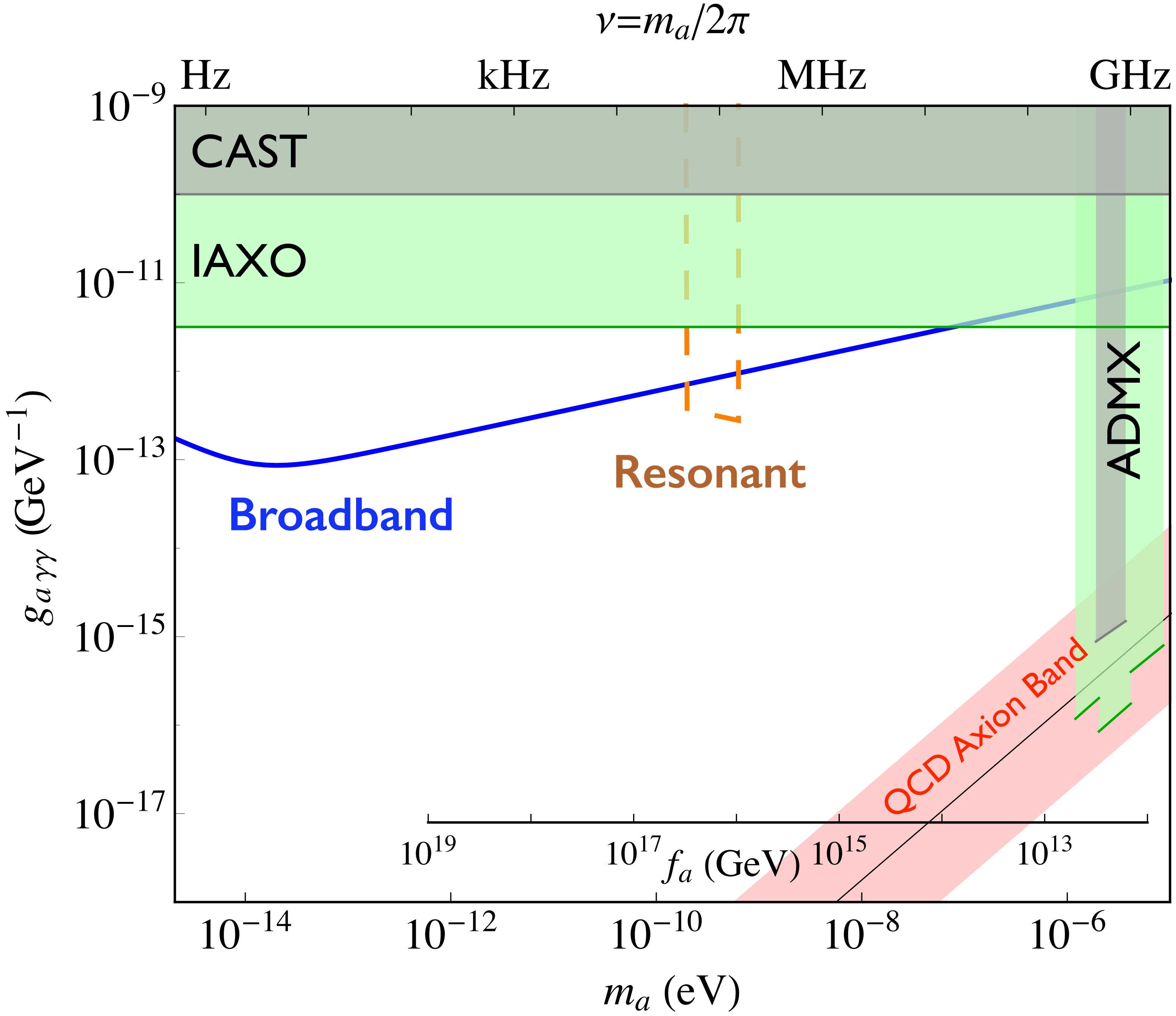
1 year sensitivity
SNR ≈ 1
$V_B = V_{toroid}\, G_{toroid}$

Broadband
T < 60 mK
1/f knee @ 50 Hz

Resonant
T = 100 mK
Q = 10^6

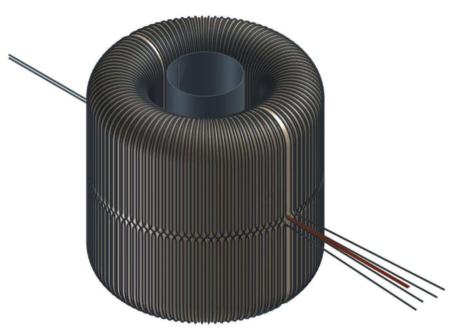
MQS approximation breaks down
(precisely where ADMX begins)

ABRA–10 cm: Potential Reach in 2017



1 month sensitivity
SNR ≈ 1

Assumes SQUID or thermal noise dominates



Not bad for a one liter frozen donut

The ABRACADABRA Collaboration @ MIT

Janet Conrad, Joe Formaggio, Sarah Heine, Yoni Kahn (Princeton), Joe Minervini, Jonathan Ouellet, Kerstin Perez, Alexey Radovinsky, Ben Safdi, JDT, Daniel Winklehner, ***Lindley Winslow (NSF EAGER PI)***

Anticipated timeline for ABRA–10cm:
Magnet installation by May for Summer 2017 data taking

Seeking broader collaboration for ABRA–1m!

MIT Laboratory for Nuclear Science **MIT Plasma Science & Fusion Center** **Superconducting Systems, Inc.**

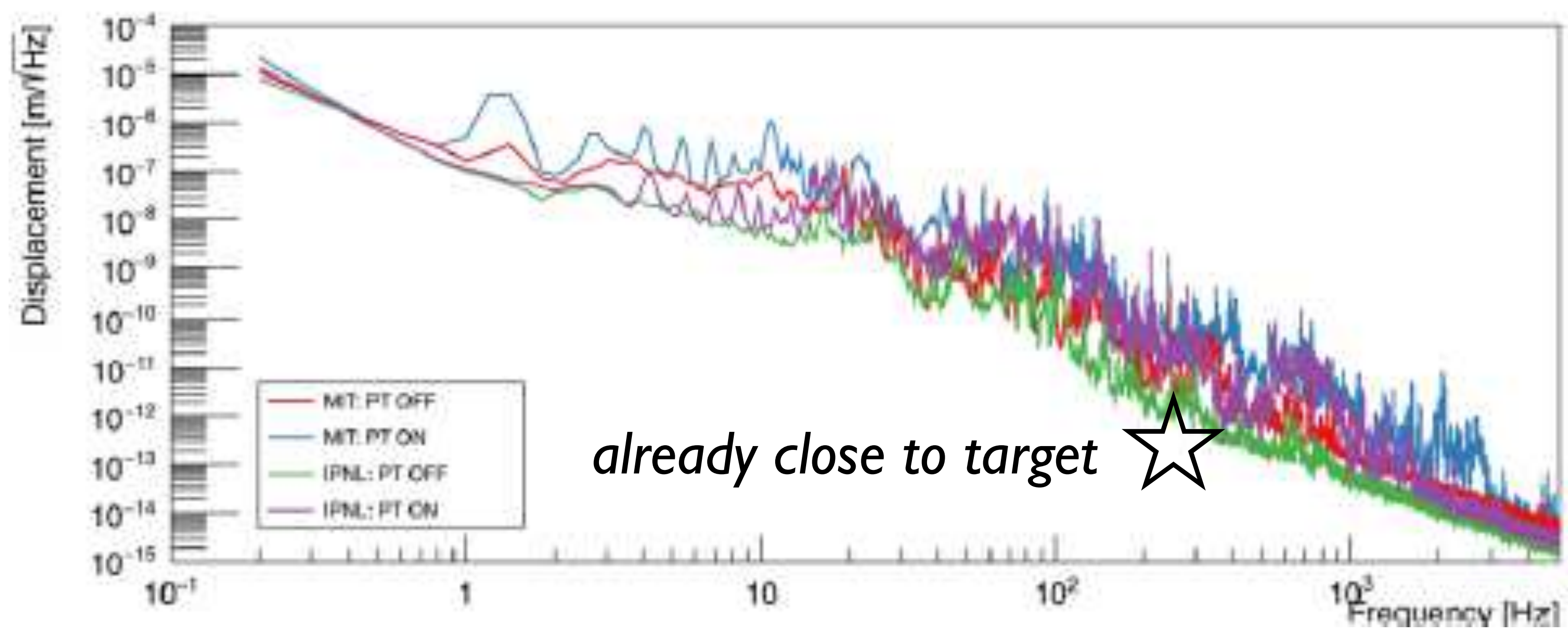
Key Challenges for ABRA–10cm: Noise, Noise, Noise

SQUID Target: $S_B^{1/2} \simeq 10^{-2}\ \mathrm{fT}/\sqrt{\mathrm{Hz}}$ @ 250 kHz

fringe field

Vibrational Noise? $S_B^{1/2} \simeq (10^{-6} B_{\max})\, S^{1/2}_{\text{displacement}} / R_{\text{exp}}$

(see backup slide for environmental magnetic noise)



Essential that pickup cylinder is in zero-field region

Future Challenges for ABRA–1m

Cool a meter-sized experiment?

Yes: CUORE = 1.5 ton @ 10 mK*

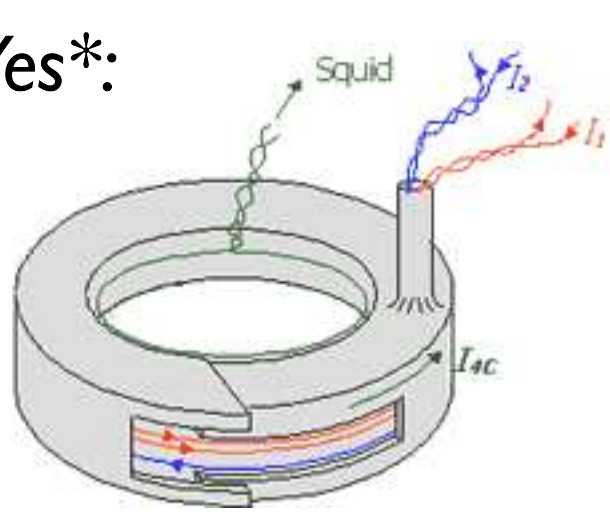
But maybe pickup @10 mK, but toroid @ 1 K?

Achieve vibrational isolation?

Yes: Use LIGO-grade technology for* $\approx 10^6$ *gain*

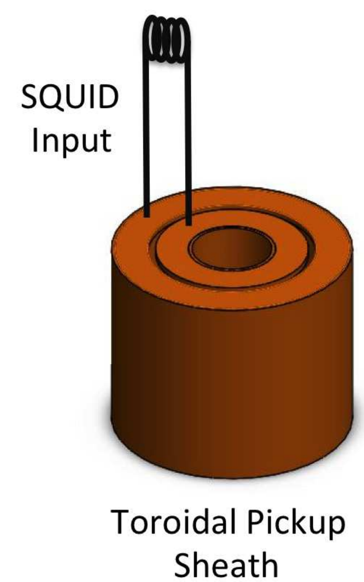
Optimize pickup geometry?

Yes:*



Cryogenic Current Comparators

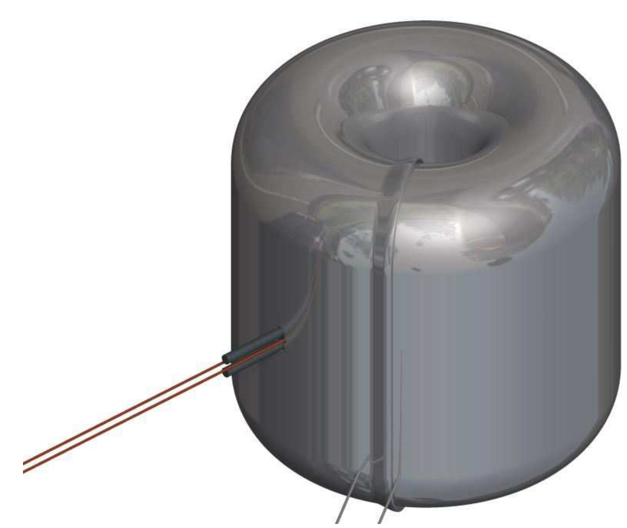
+



Dark Matter Radio

[1411.7382, 1610.09344]

=

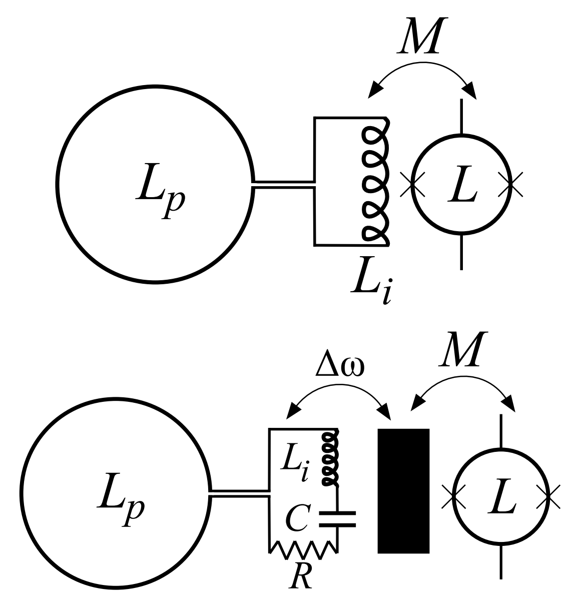


"Pickup Snake Swallowing Its Tail"

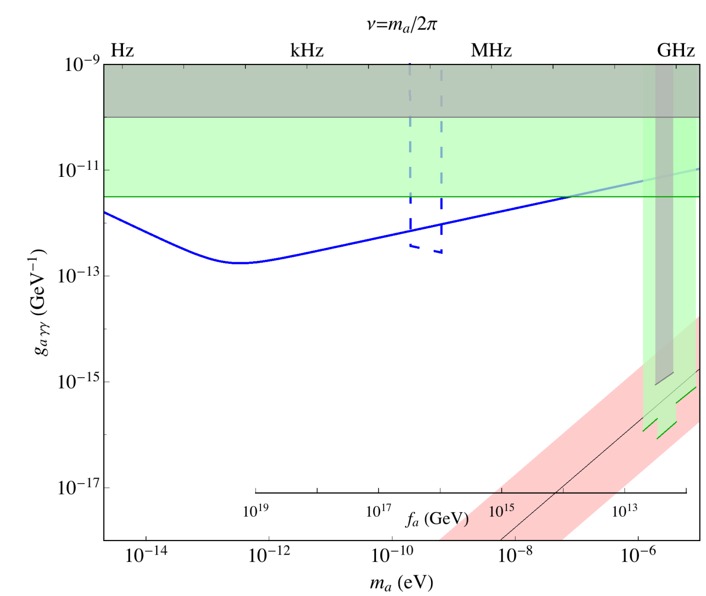
A Broadband/Resonant Approach to Cosmic Axion Detection with an Amplifying B-field Ring Apparatus

Toroidal geometry with zero-field pickup

Complementary readout strategies



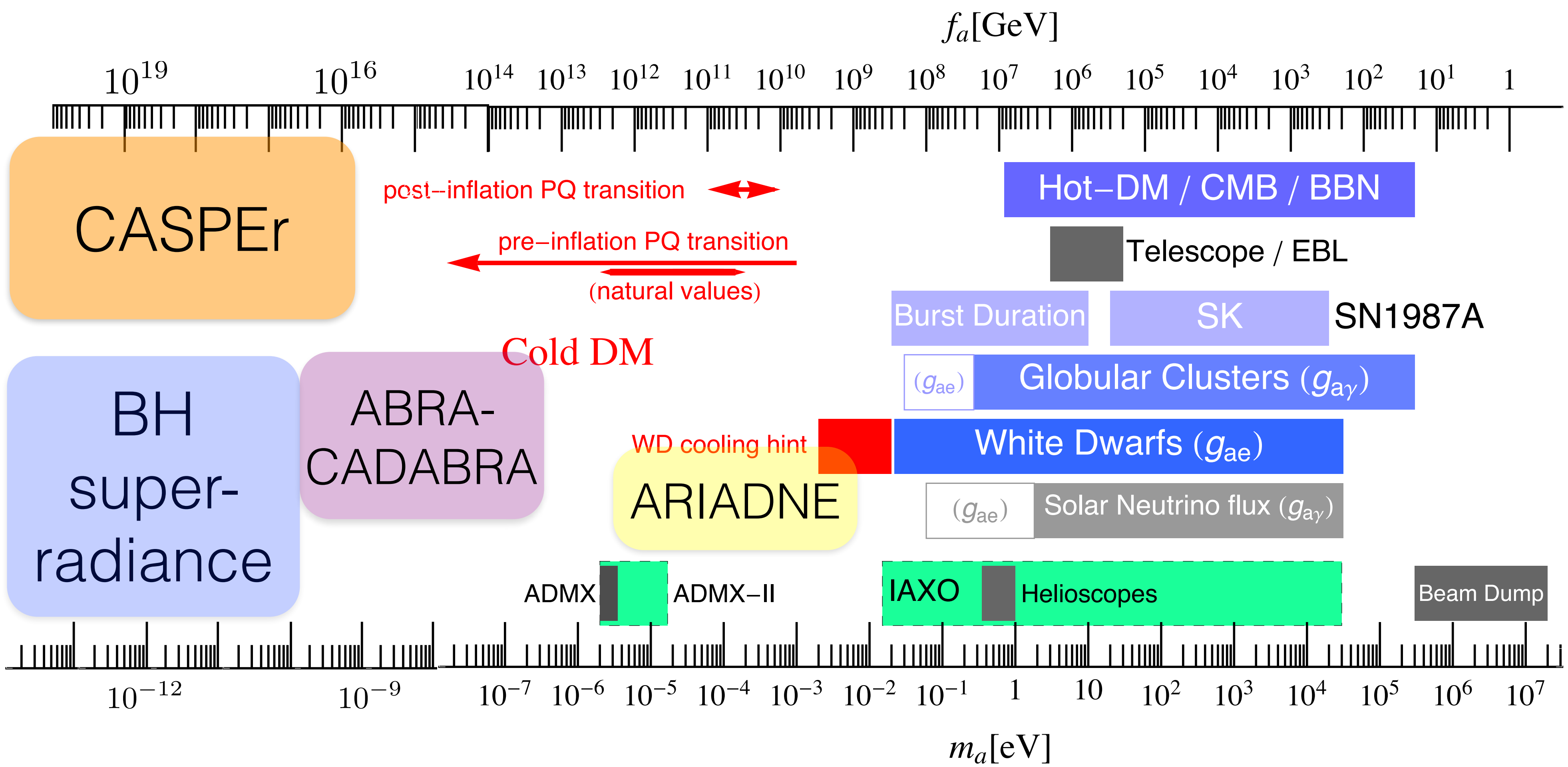
Anticipated results from ABRA–10cm in 2017



Ultimate Goal: Probe GUT-scale QCD Axion Dark Matter

A Broadband/Resonant Approach to Cosmic Axion Detection with an Amplifying B-field Ring Apparatus

Multiple Promising Strategies to Fully Explore QCD Axion



[adapted from Essig et al., 1311.0029]

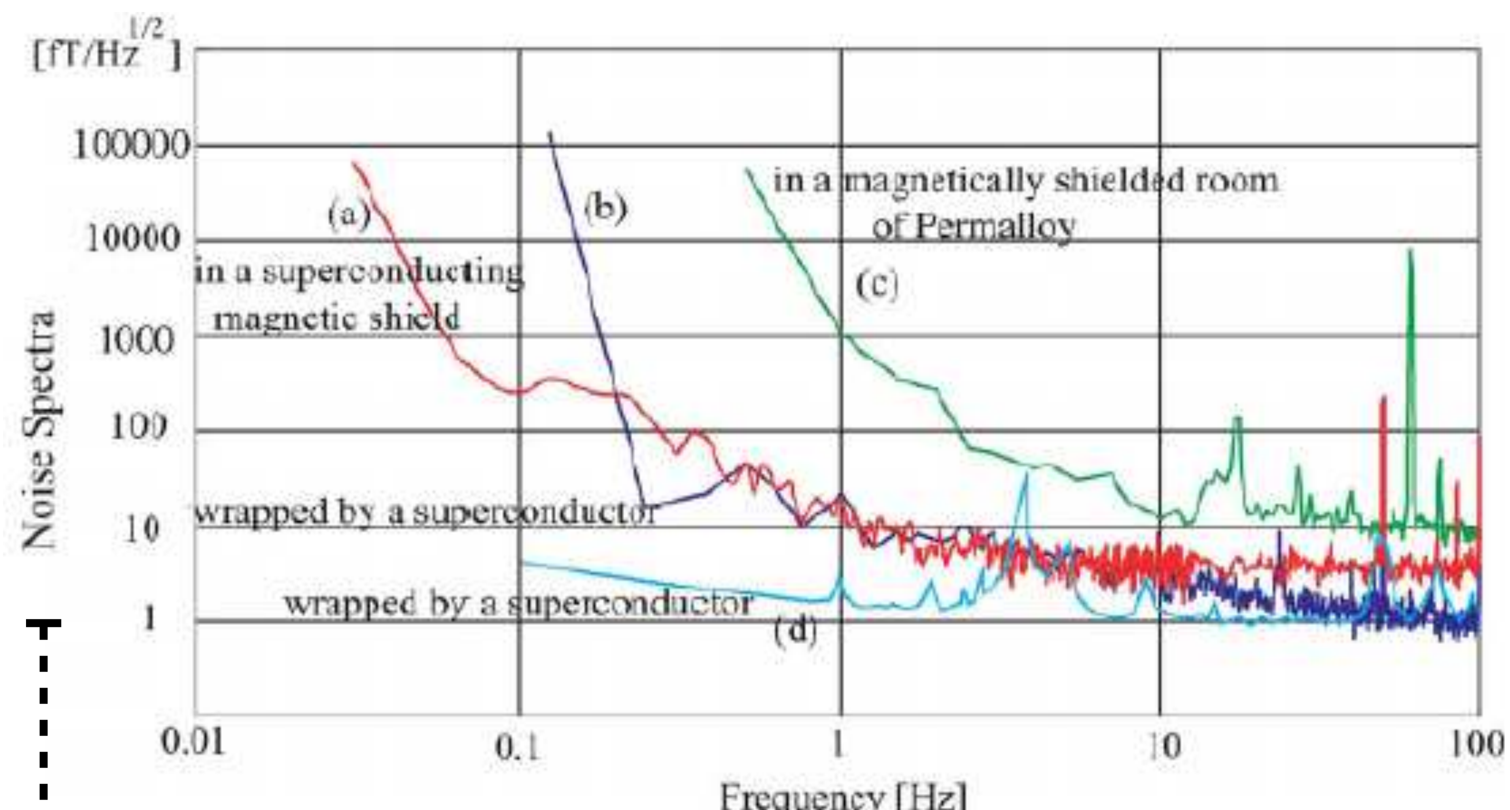
Backup Slides

Key Challenges for ABRA–10cm: Noise, Noise, Noise

SQUID Target: $S_B^{1/2} \simeq 10^{-2}\ \mathrm{fT}/\sqrt{\mathrm{Hz}}$ @ 250 kHz

Environmental Magnetic Noise?

If you don't shield fully:



With dedicated effort, target seems achievable

x10^3