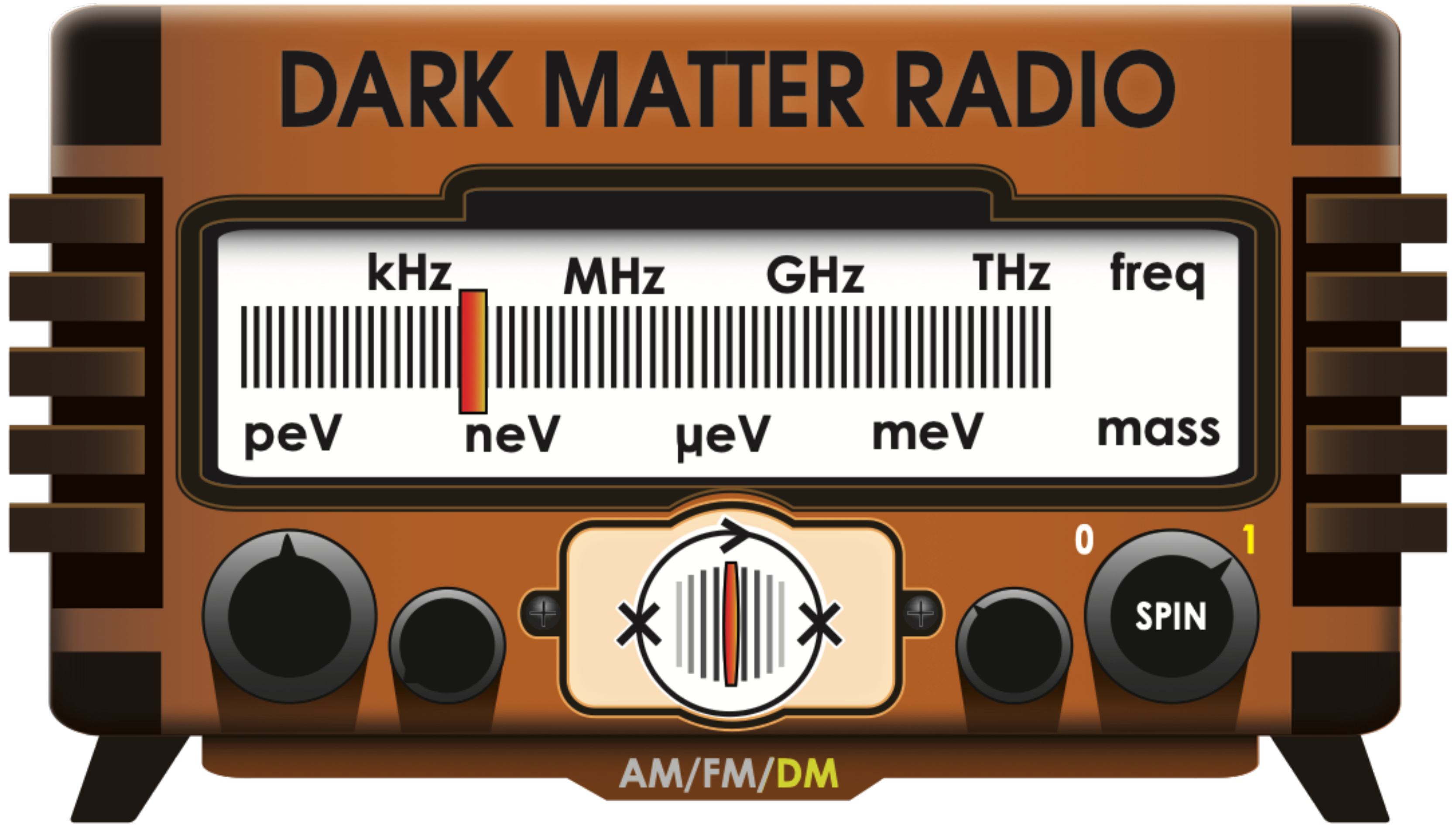
THE UNIVERSITY
of NORTH CAROLINA
at CHAPEL HILL

TUNL

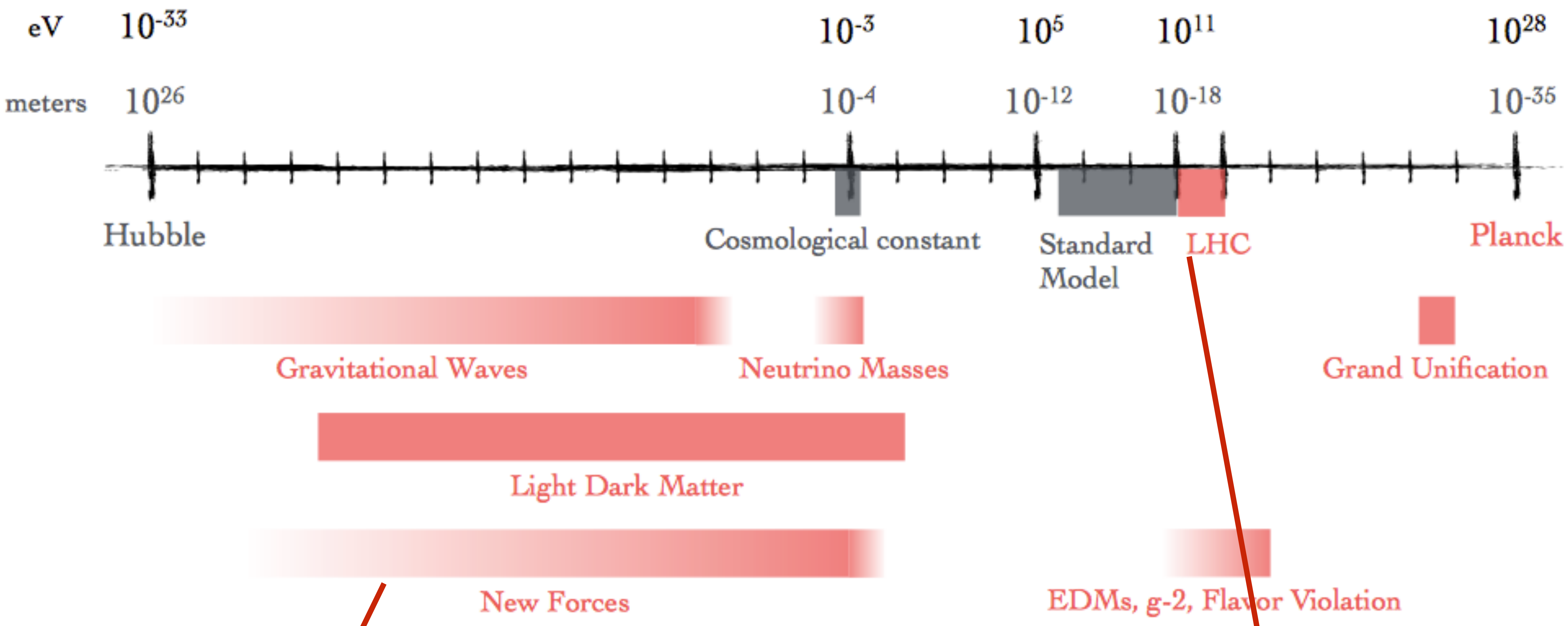


The DMRadio Program

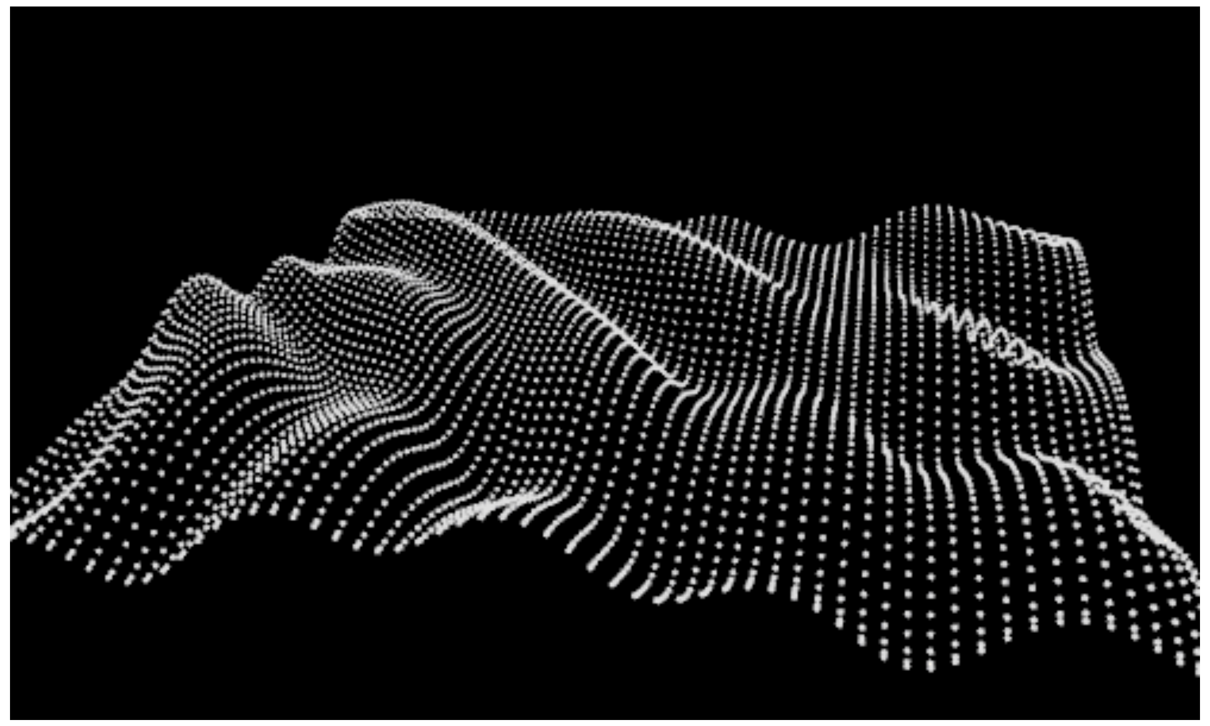
Reyco Henning
University of North Carolina at Chapel Hill
Triangle Universities Nuclear Laboratory

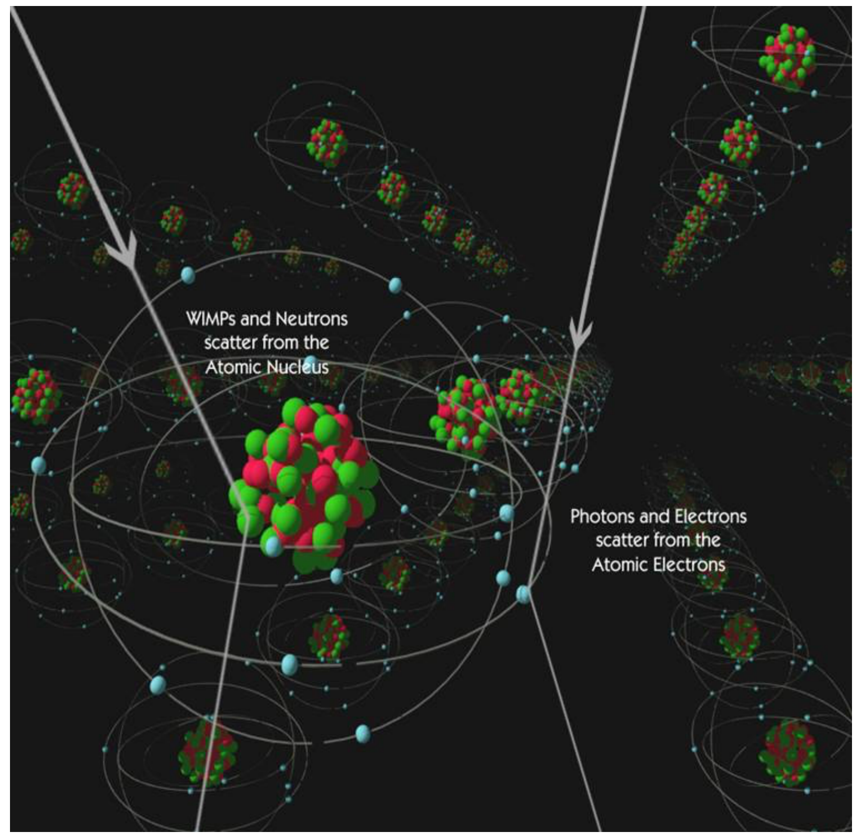
Axion as "Light" DM

Arvanitaki



$$\Omega_a \sim \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{7/6}.$$

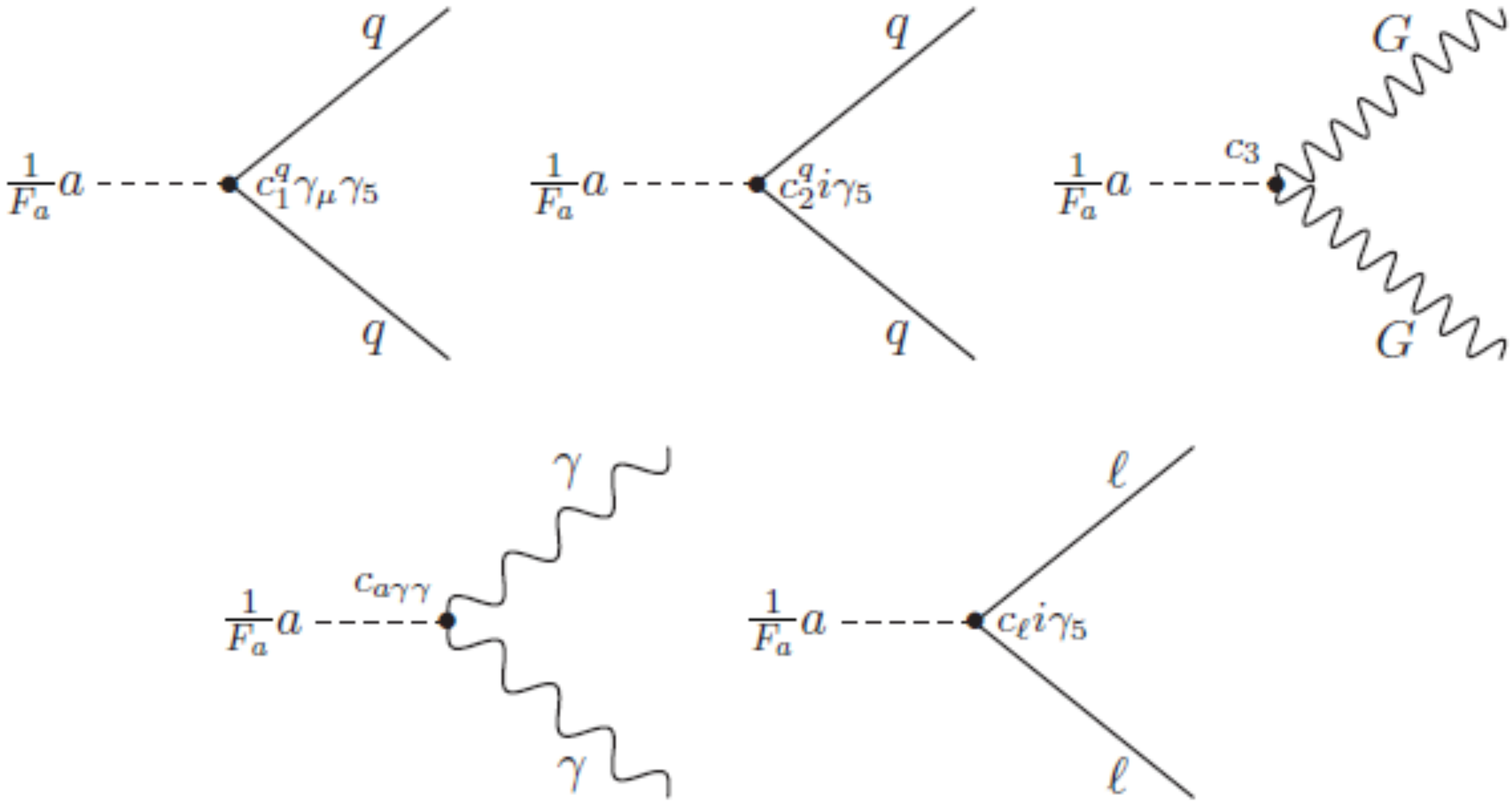




QCD Axion Couplings

$$m_a \simeq 0.6\,\mathrm{eV}\,\frac{10^7\,\mathrm{GeV}}{f_a}$$

f_a : PQ Symmetry Breaking Scale
Relationship Model-dependent



Rev.Mod.Phys. 82 (2010) 557

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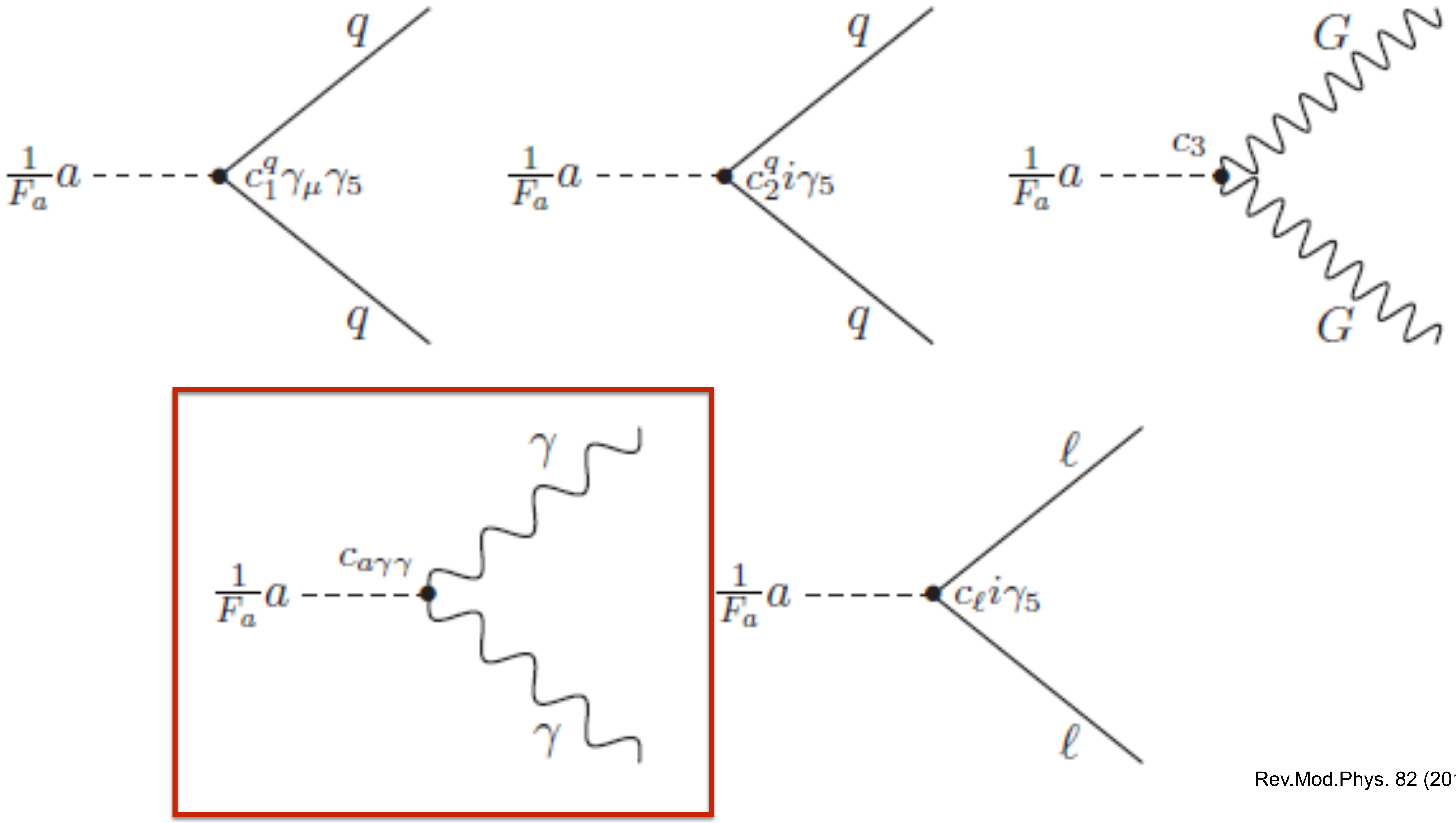
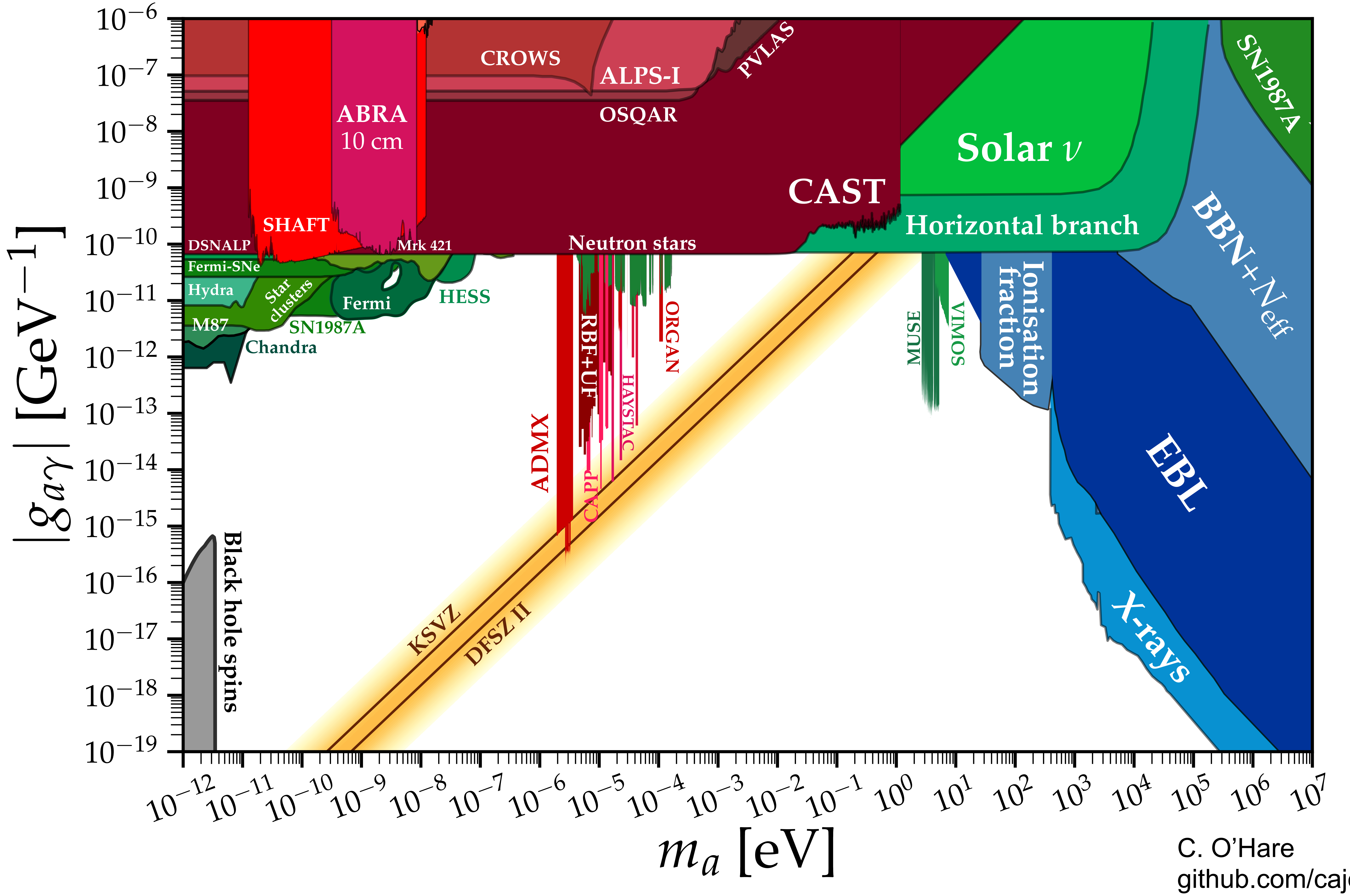


Rev.Mod.Phys. 82 (2010) 557

Current Landscape



C. O'Hare
github.com/cajohare/AxionLimits

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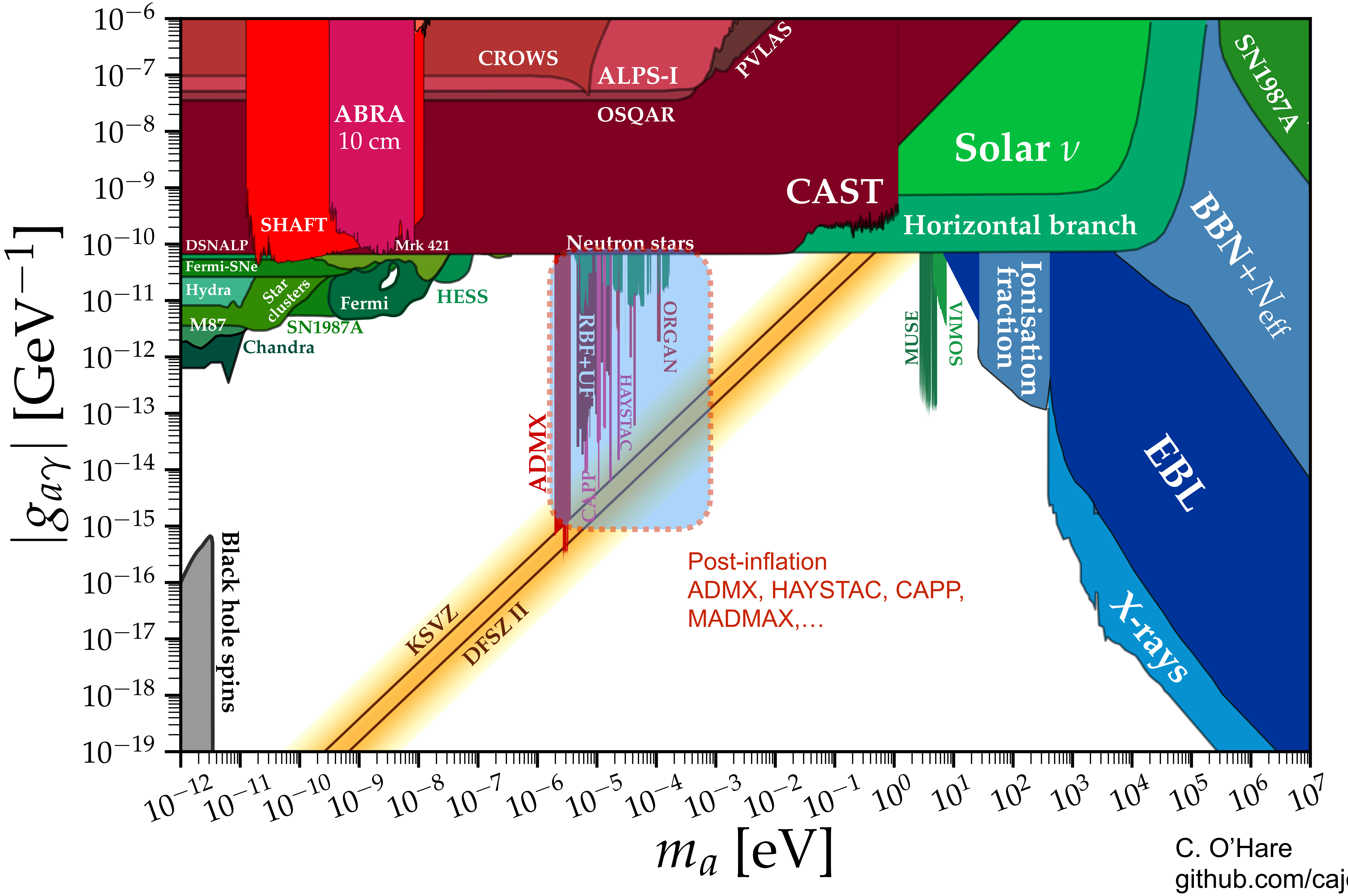

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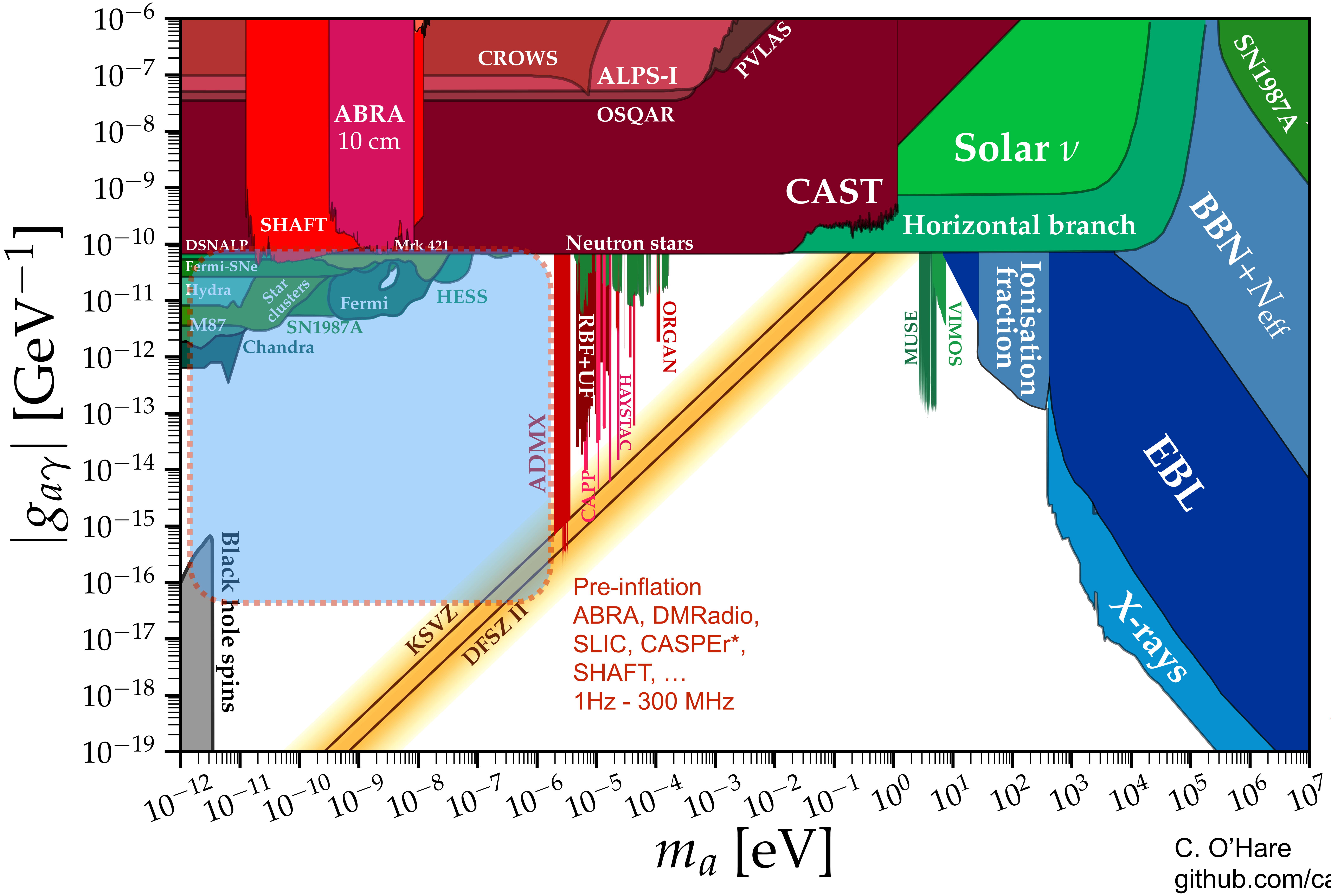

*different coupling

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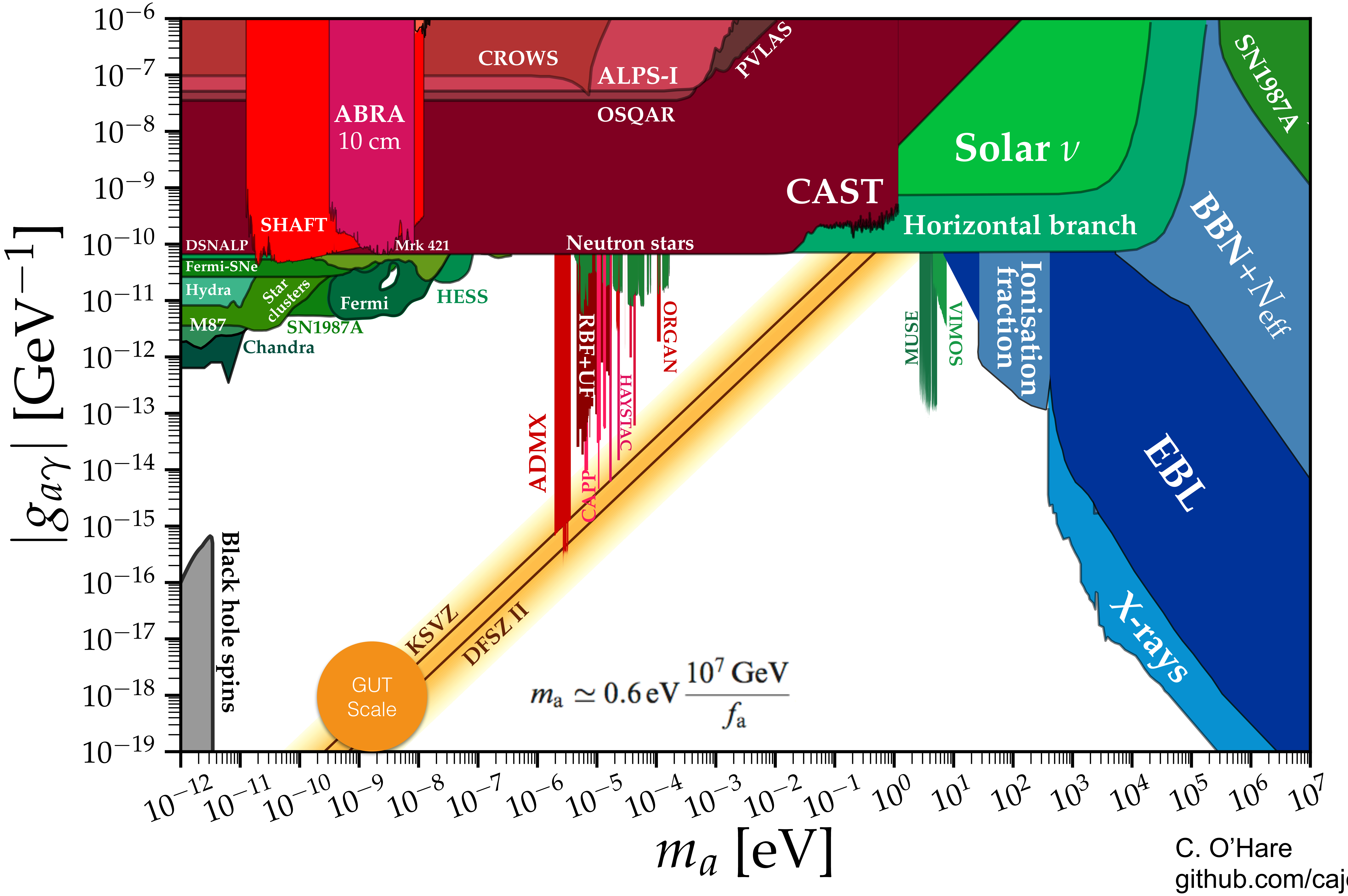

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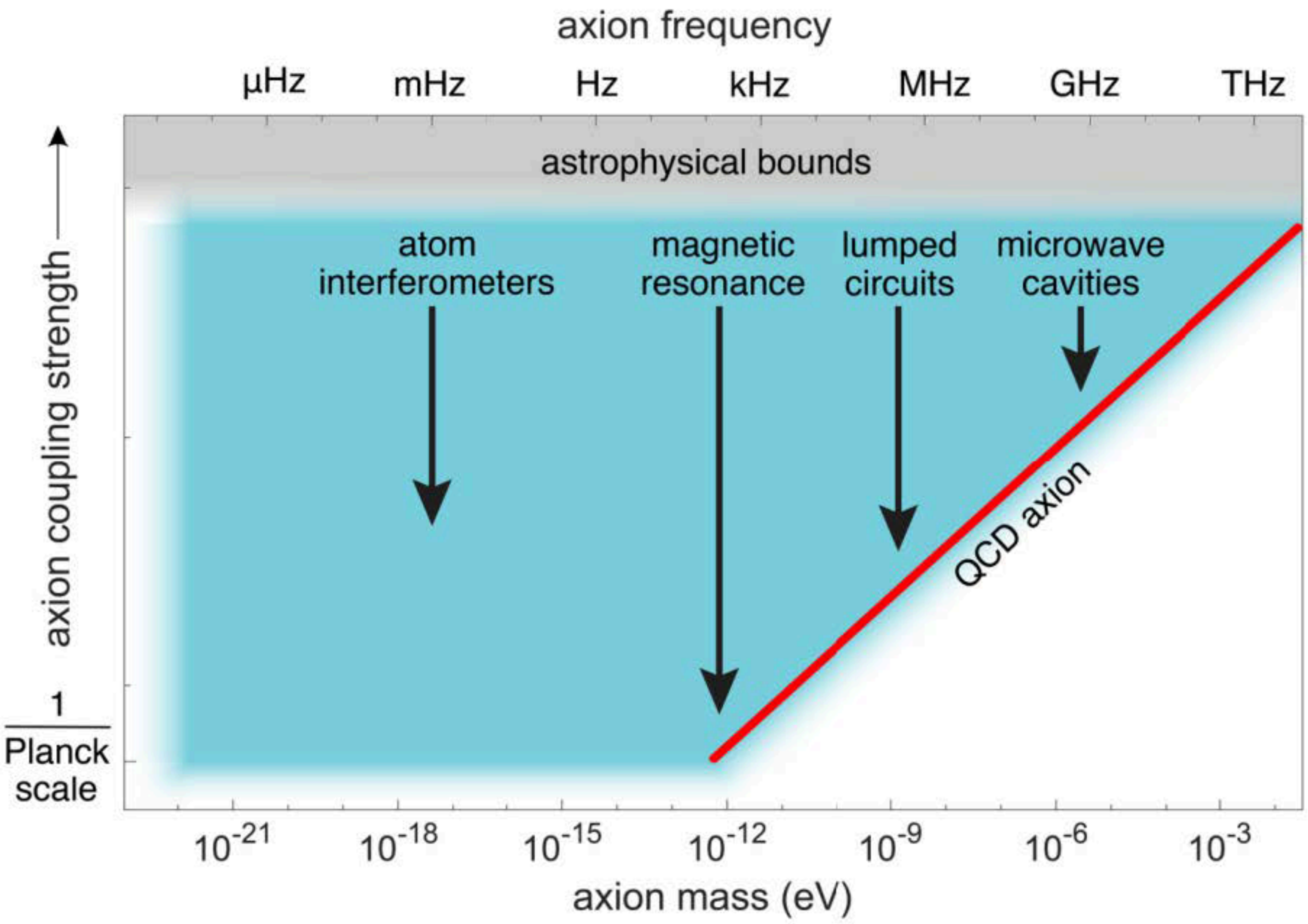
Ultralight Dark Matter Parameter Space



Office of High Energy Physics (HEP) Department of Energy Office of Science. Basic research needs for dark matter small projects new initiatives. Technical report, Dec 2018.

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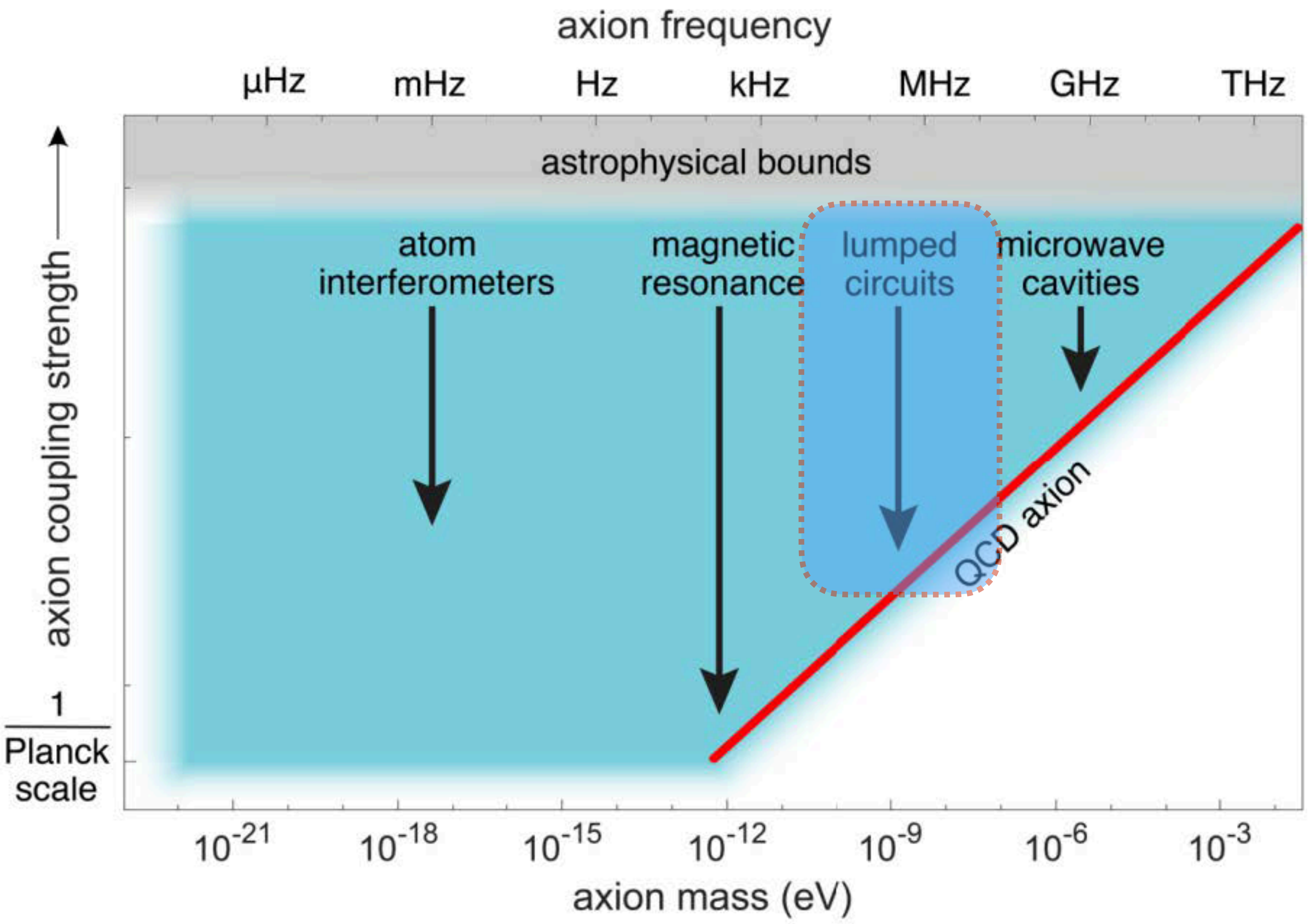

Office of High Energy Physics (HEP) Department of Energy O ce of Science. Basic research needs for dark matter small projects new initiatives. Technical report, Dec 2018.

Lumped Element Fundamentals

Treat ultralight axion DM as coherent field

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

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E=0, DM $v \sim 10^{-3}$

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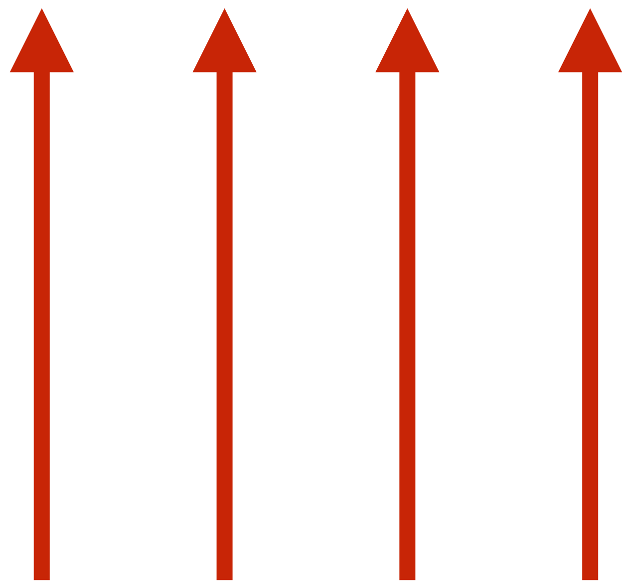

Static B-Field

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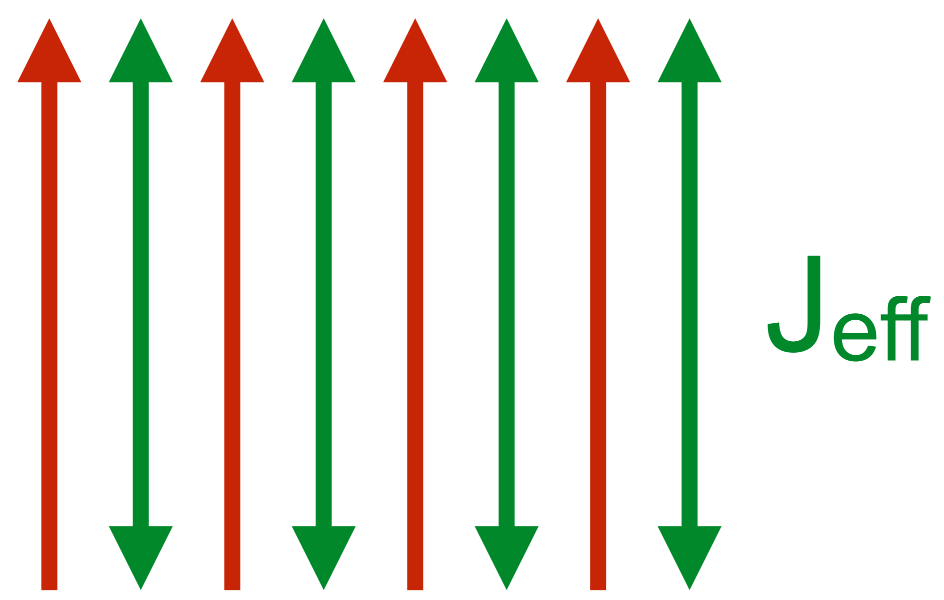

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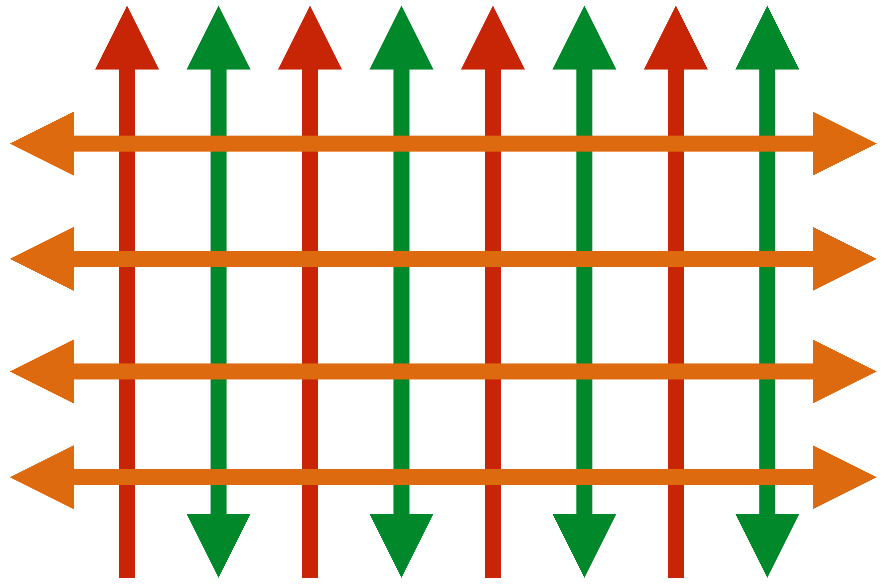

DM-axion
Induced B-field

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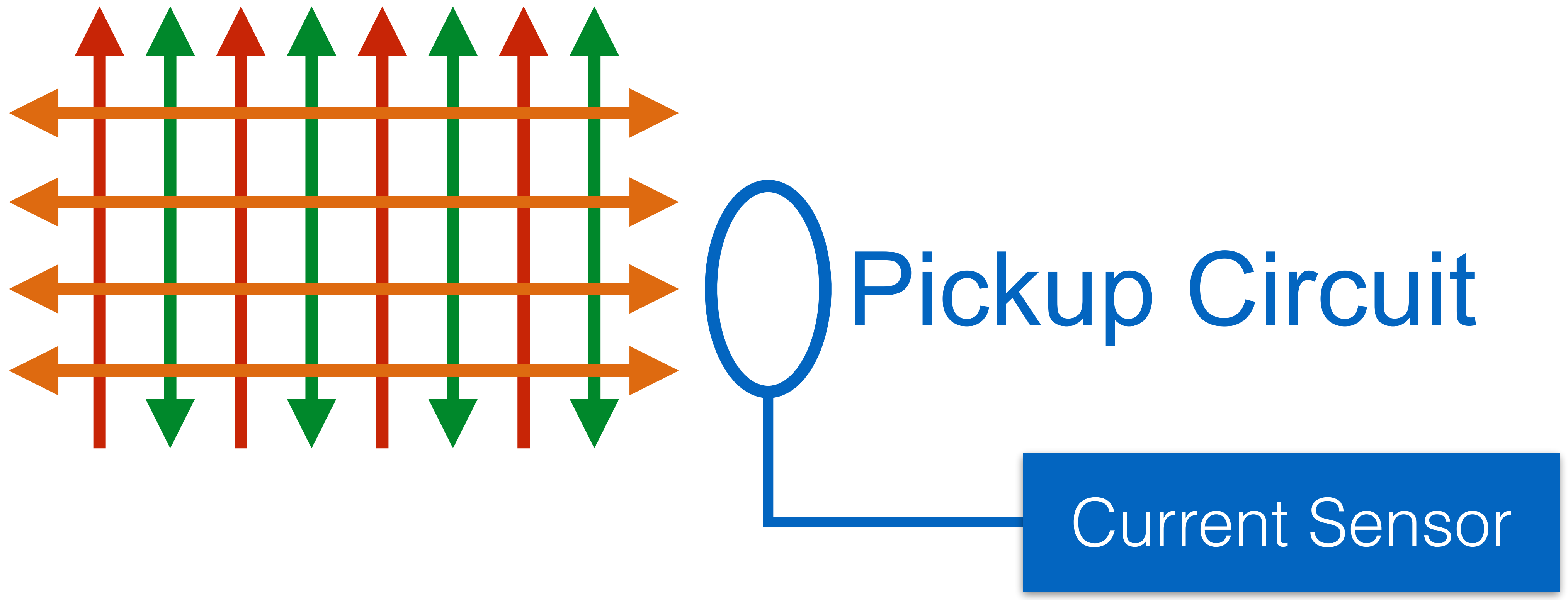

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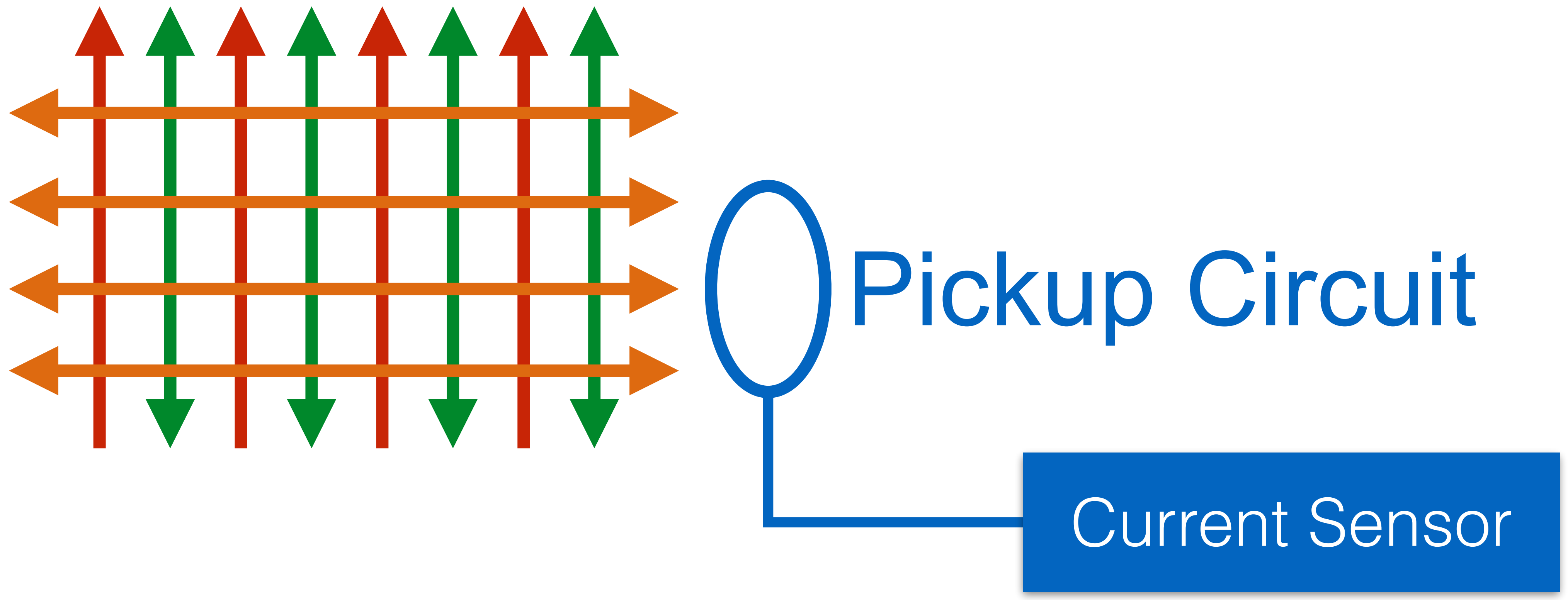
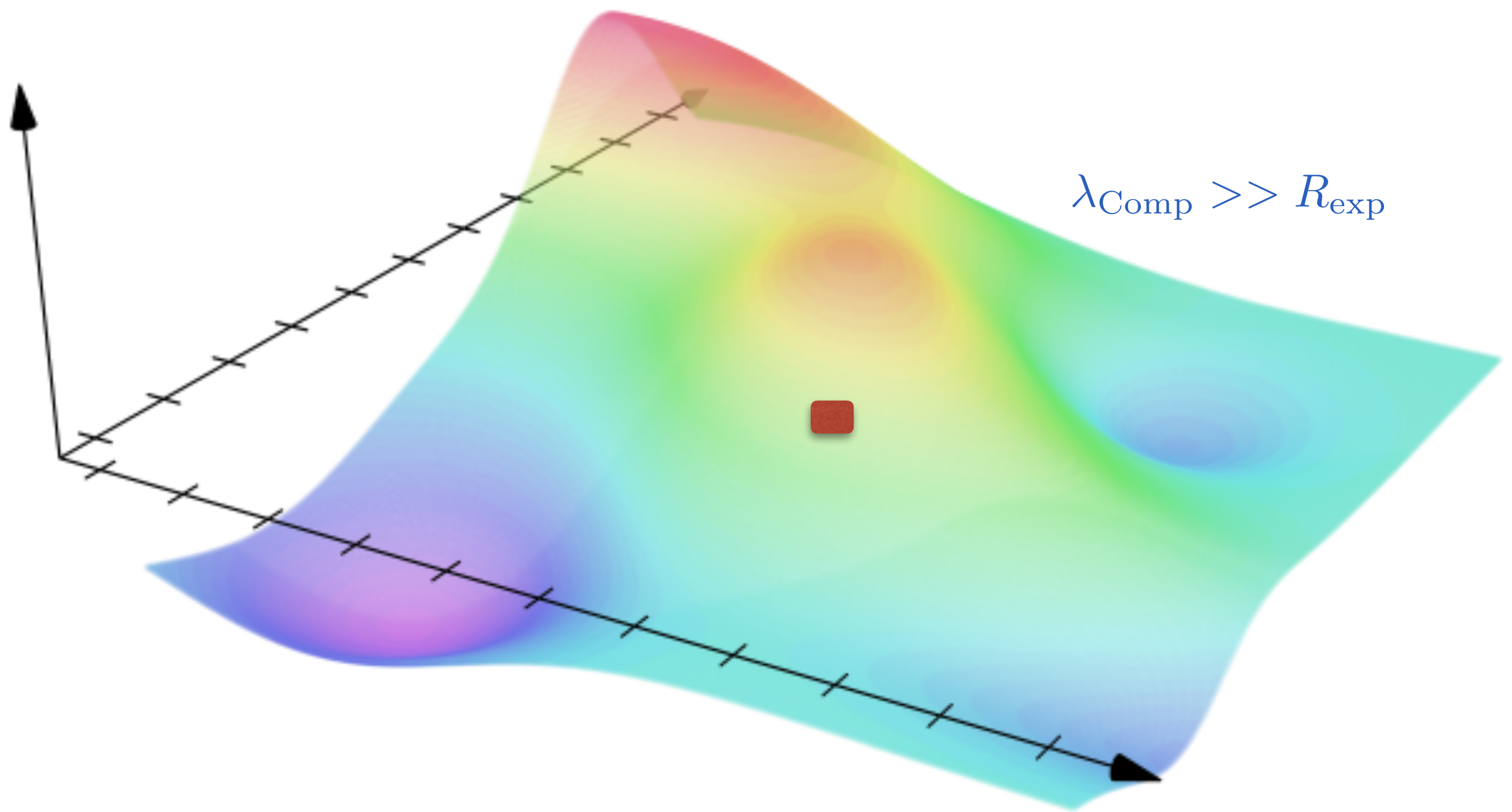


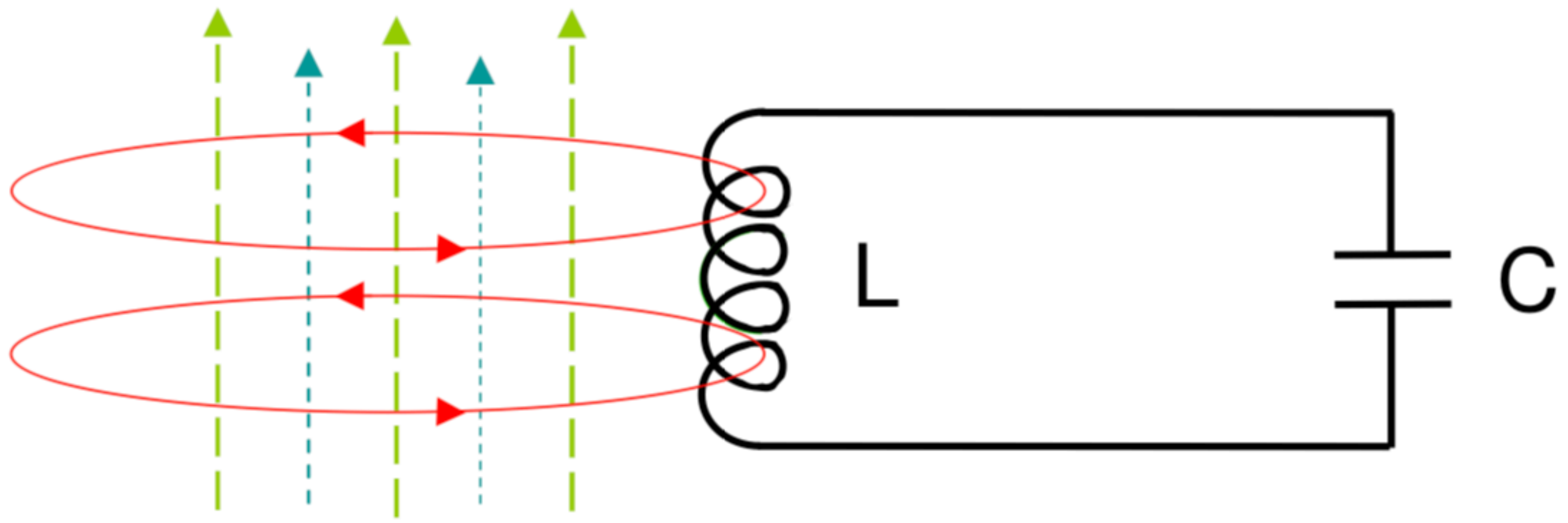
Near-field limit: λ >> Size of Experiment

$$\tau \sim \frac{2\pi}{m_a v_{\rm DM}^2} \approx 0.4\,{\rm s}\frac{10^{-8}\,{\rm eV}}{m_a} \qquad \lambda \sim \frac{2\pi}{m_a v_{\rm DM}} \approx 100\,{\rm km}\frac{10^{-8}\,{\rm eV}}{m_a}$$

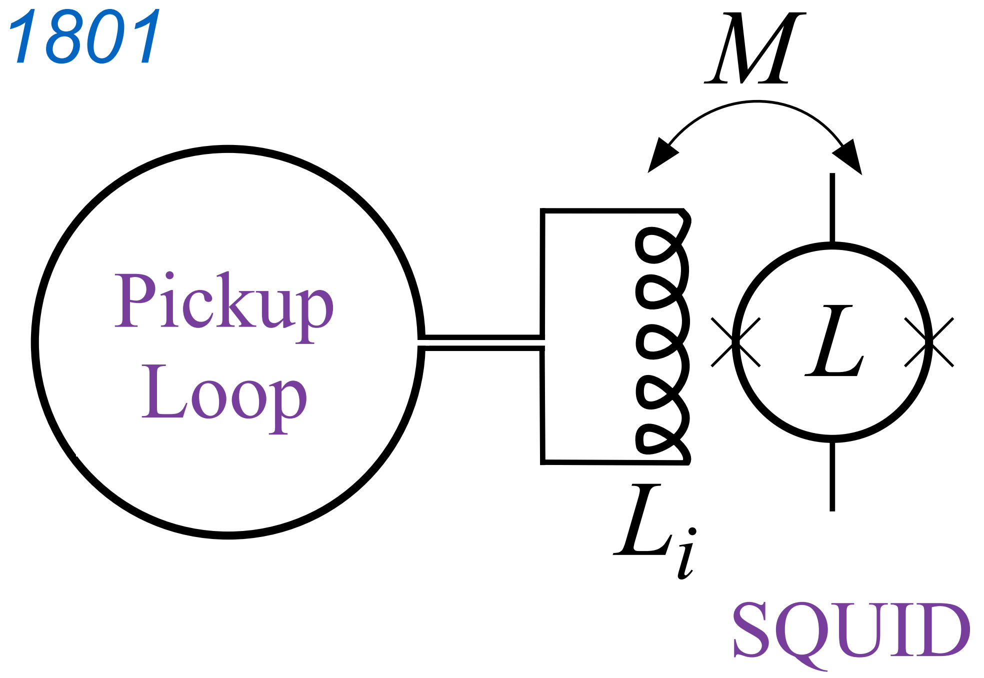


History: Lumped Element

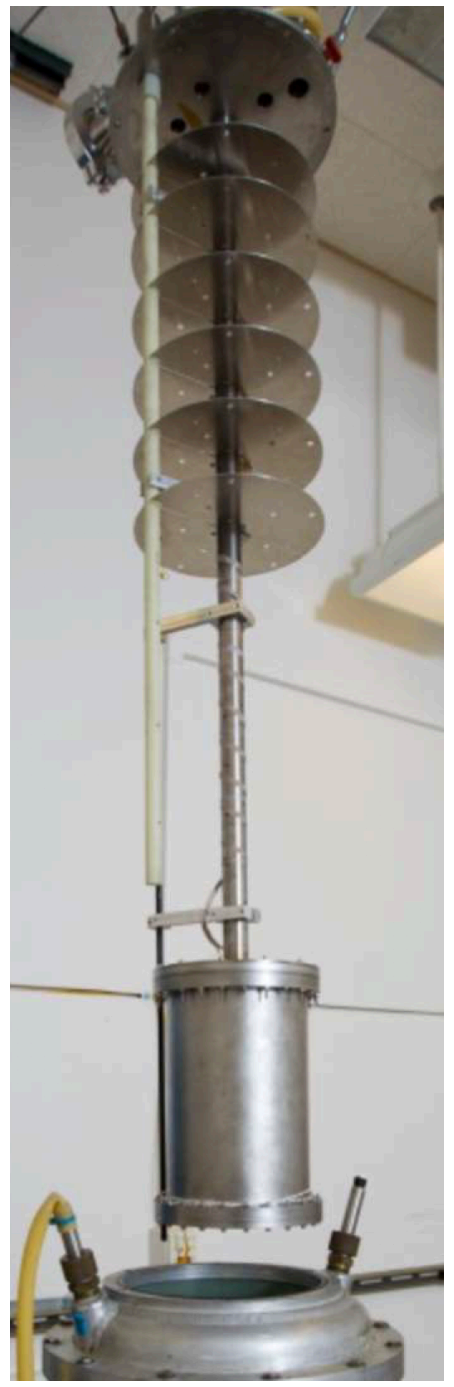
Tuned LC Circuit Readout: *Cabrera, Thomas, 2010*

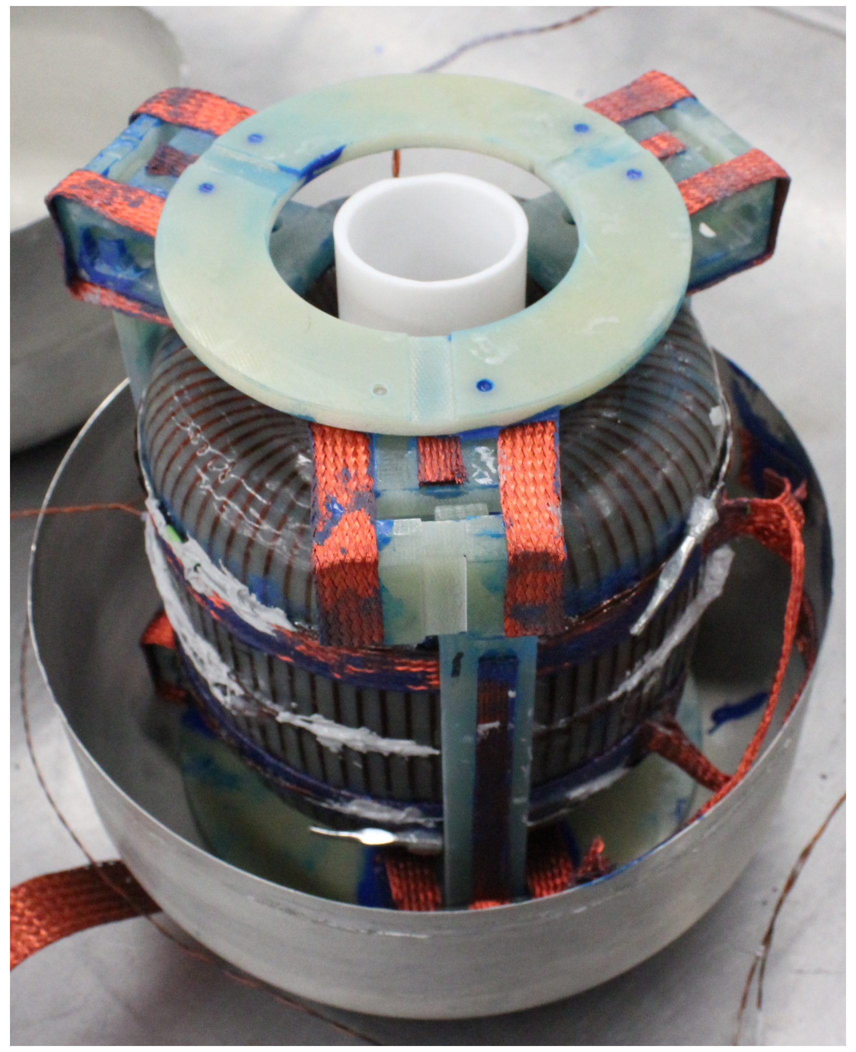


Broadband Readout
PRL 117 (2016) 141801

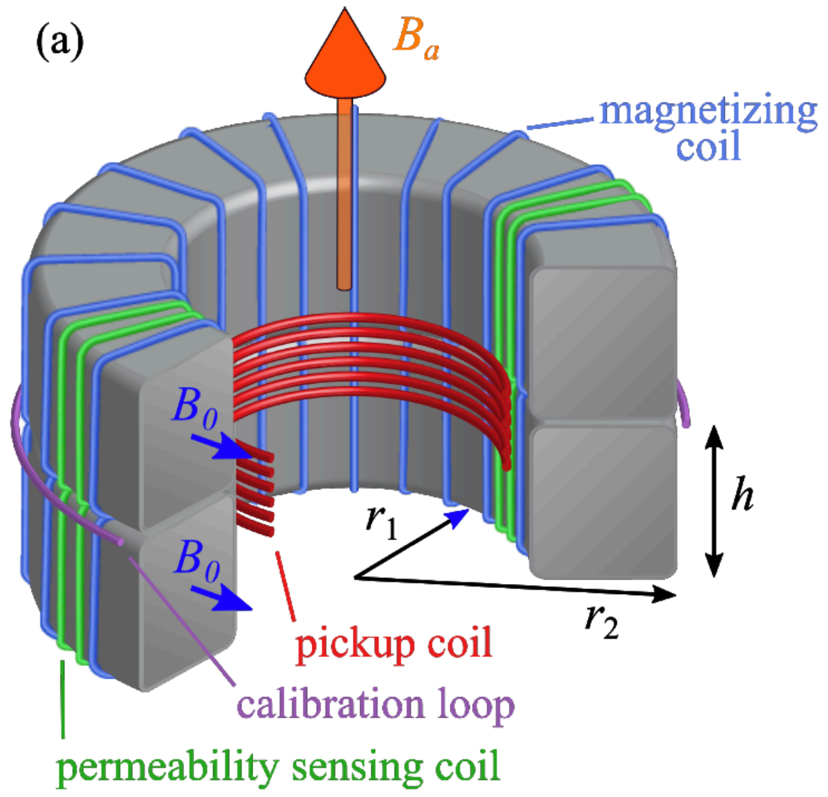


DM Radio Dark Photon Search
PRD 92 (2015) 075012

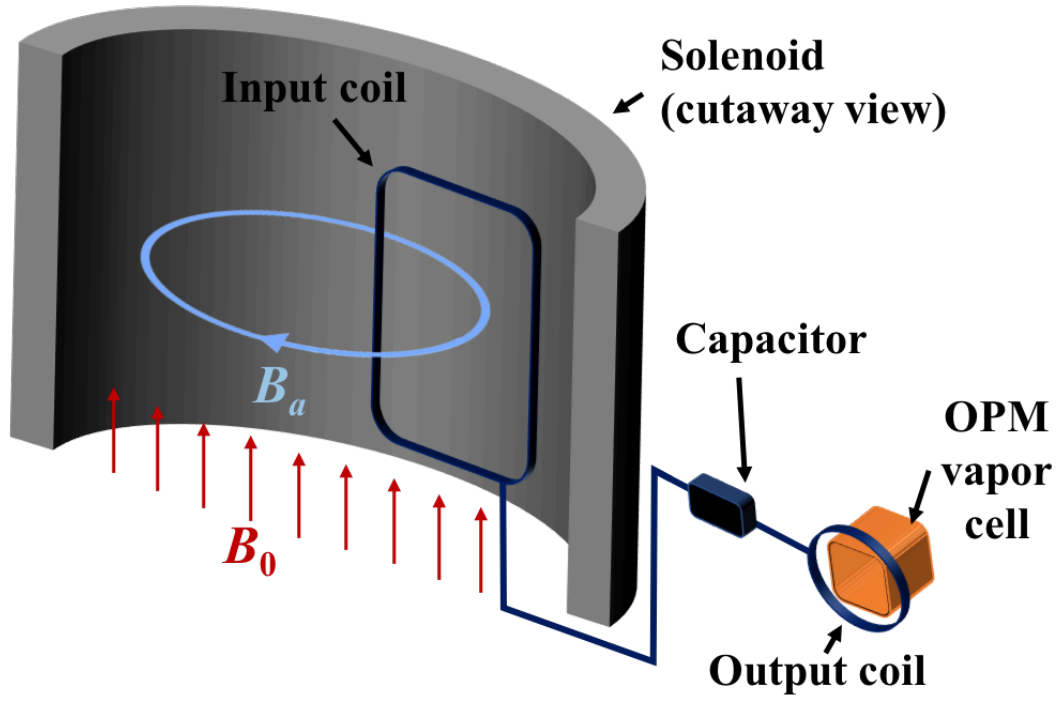


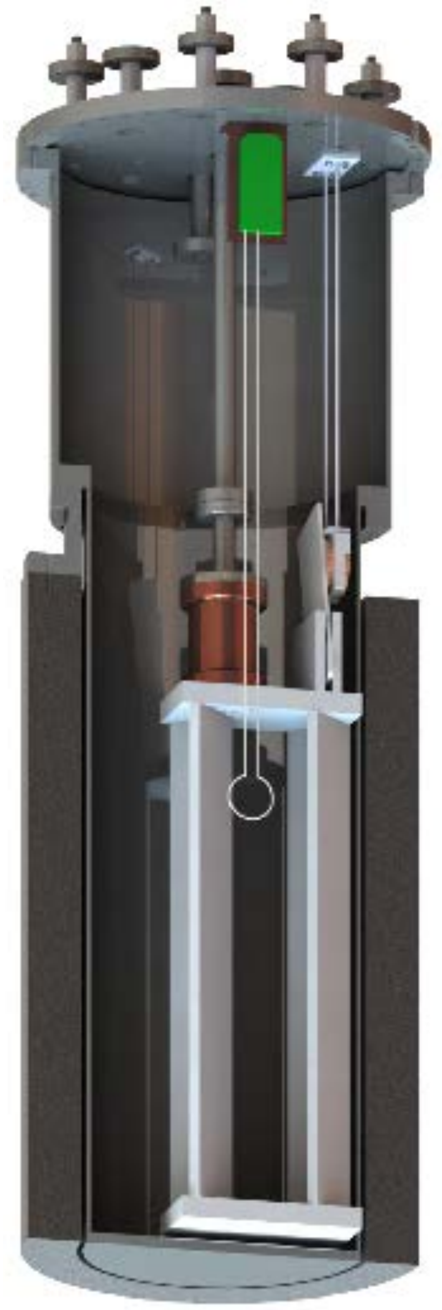


Toroidal Magnet
ABRACADABRA:
PRL 122 (2018) 121802
SHAFT:
Nature Physics 17 (2021) 79



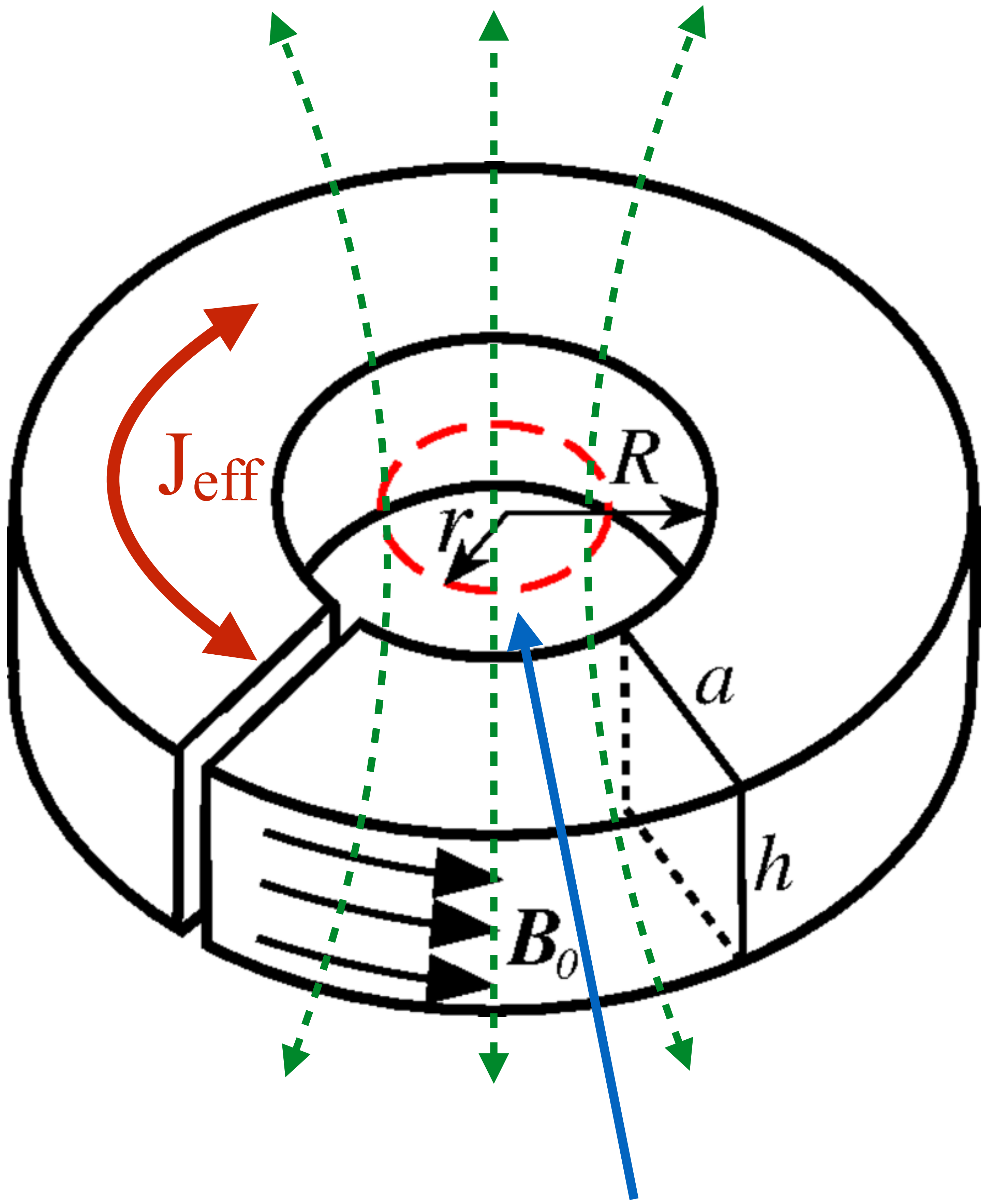
Solenoidal Magnet:
PRL 112 (2014) 131301
PRD 97 (2019) 072011
PRL124 (2020) 241101



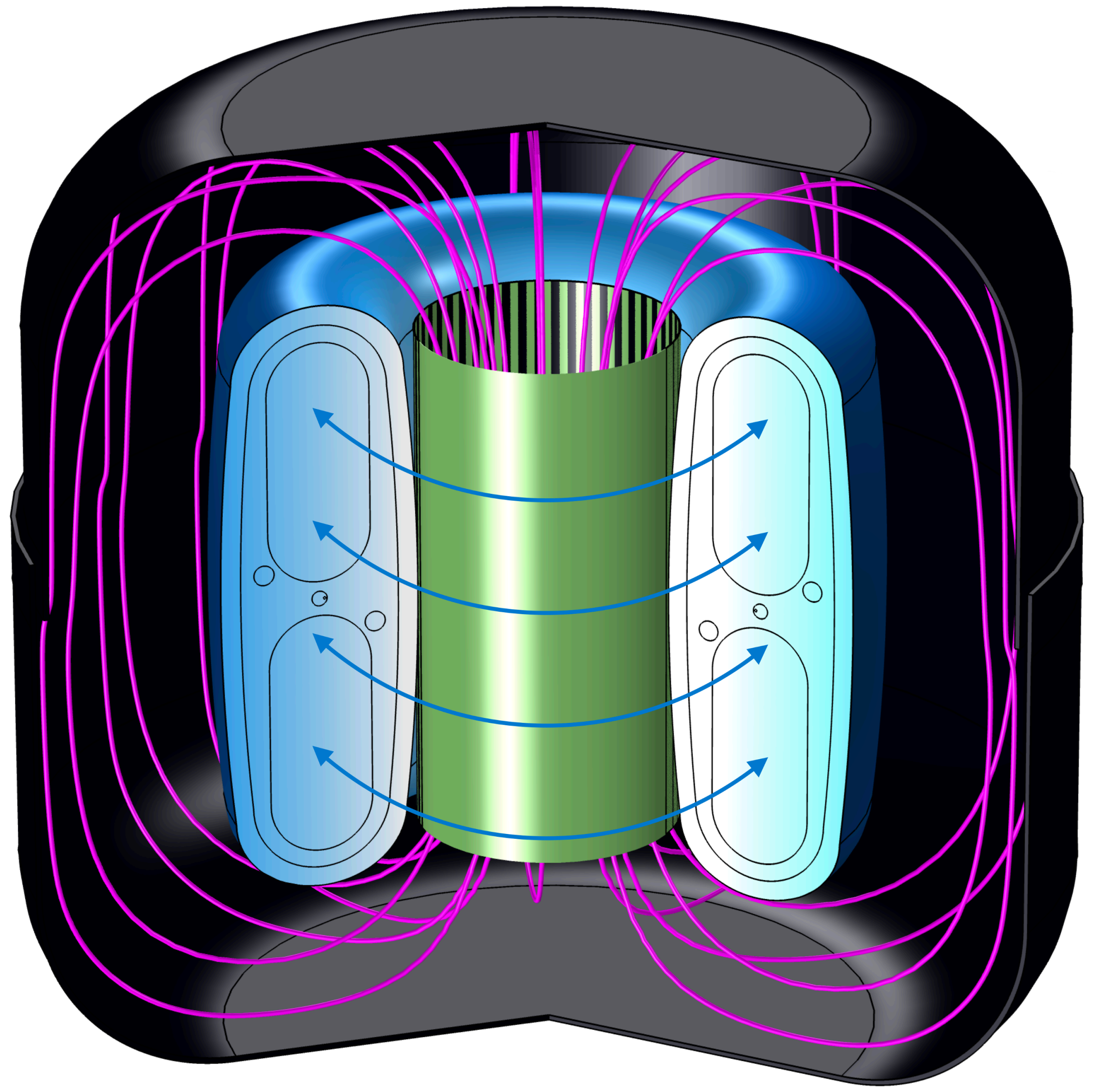


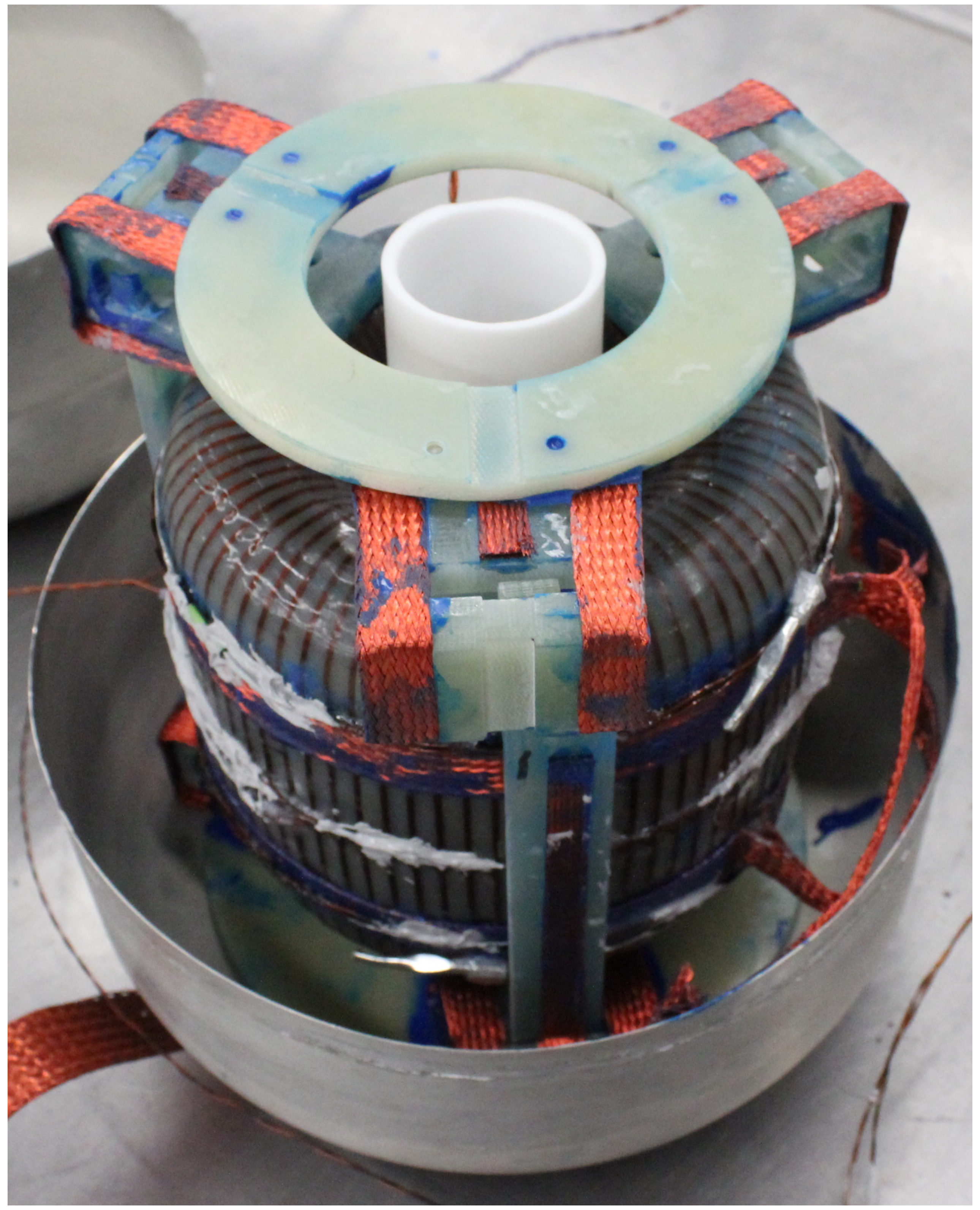
ABRACADABRA-10cm

Induced B-field



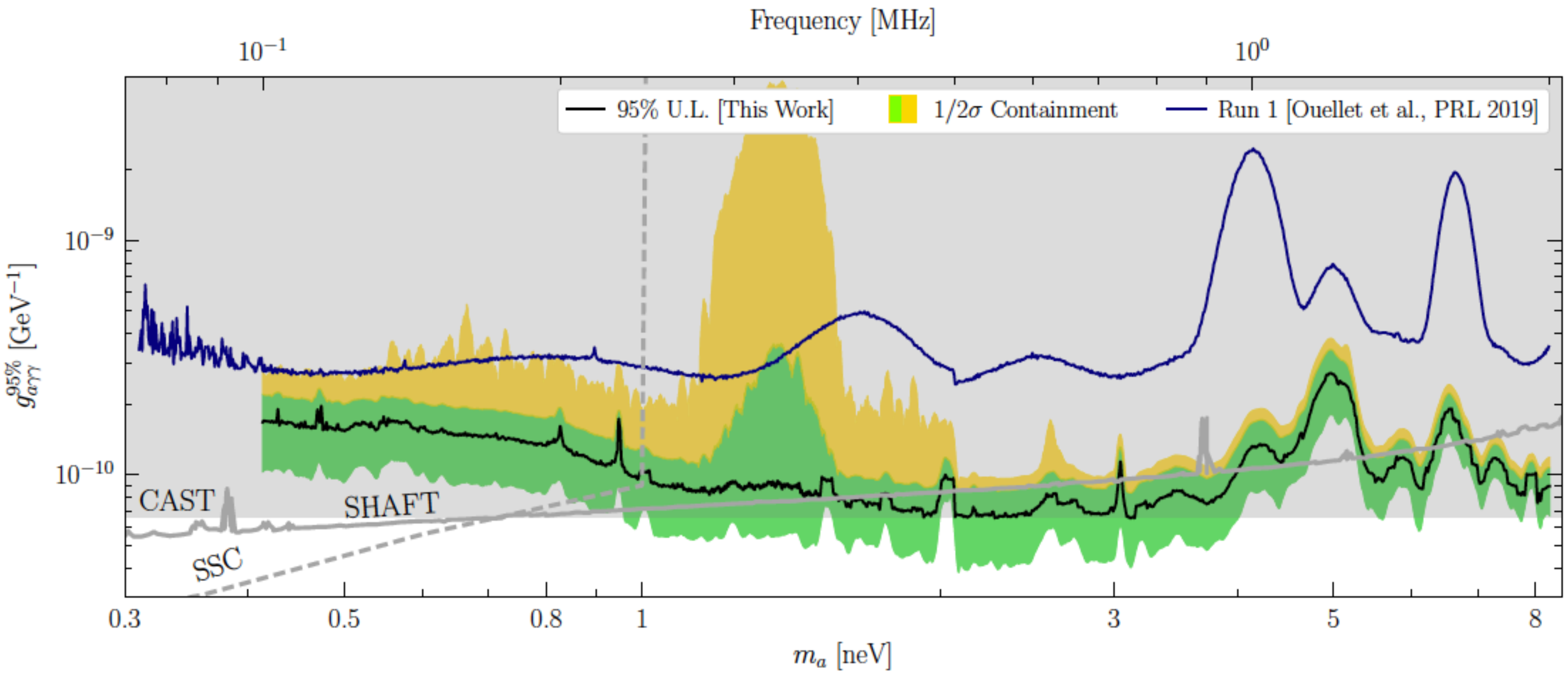
Measure induced field using pickup loop
DC B-field free





ABRACADABRA-10cm Results

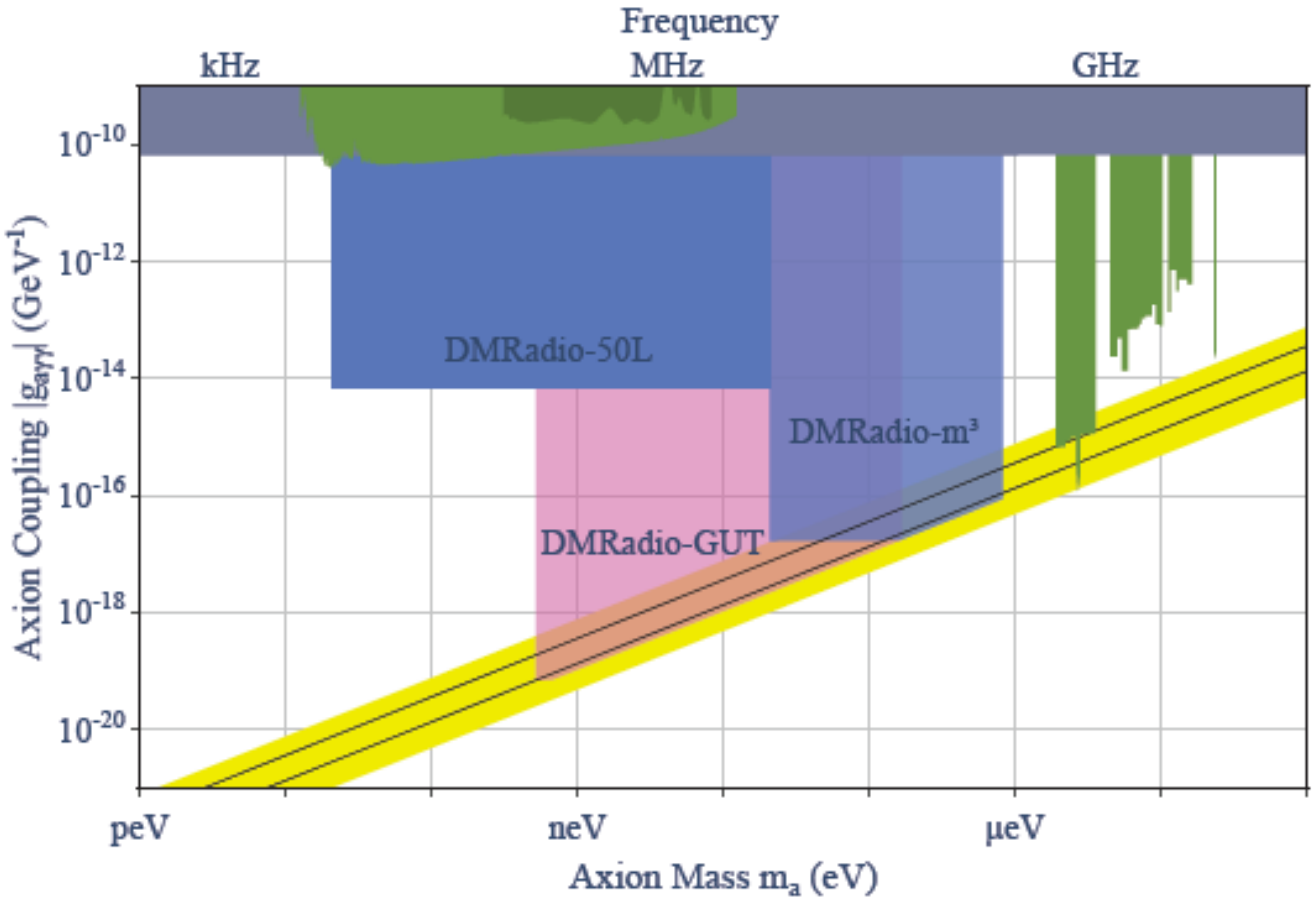
- First Broadband Search: *PRL 122 (2018) 121802*
- Made improvements to pickup, cabling, data-analysis and cleaning
- New Broadband Limits: 2102.06722



DM Radio Program

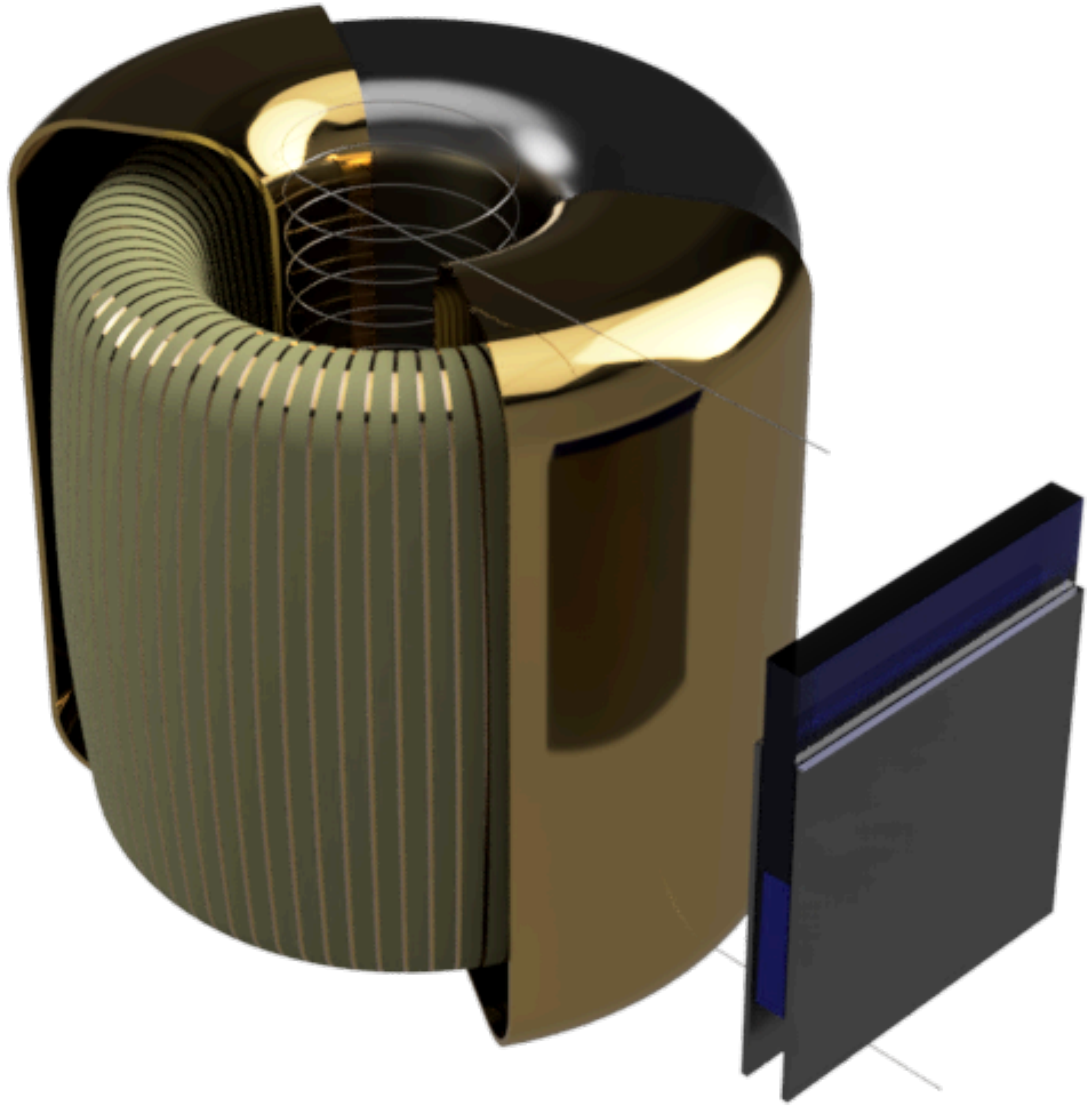
DMRadio Program overview

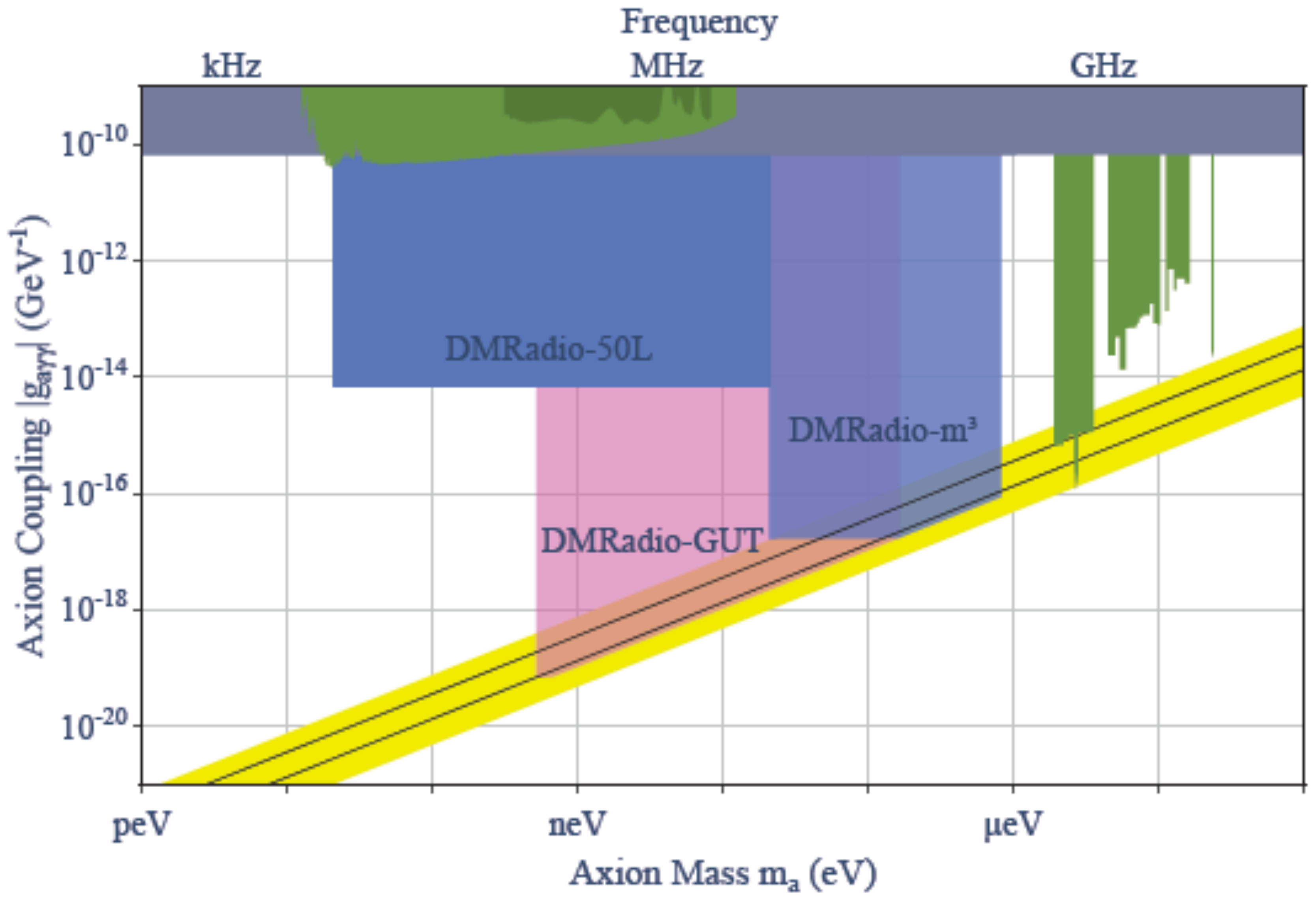
- Merger of ABRACADABRA and DMRadio Collaborations
- Continue R&D with ABRA
- DMRadio-50L is currently being constructed and is an ALP search and testbed for advanced quantum sensors.
- DMRadio-m³ uses mature technology and will provide a flagship axion experiment
- DMRadio-GUT is a future GUT-scale axion search capable of probing ~neV axions with ~10m-scale magnets and quantum readout.

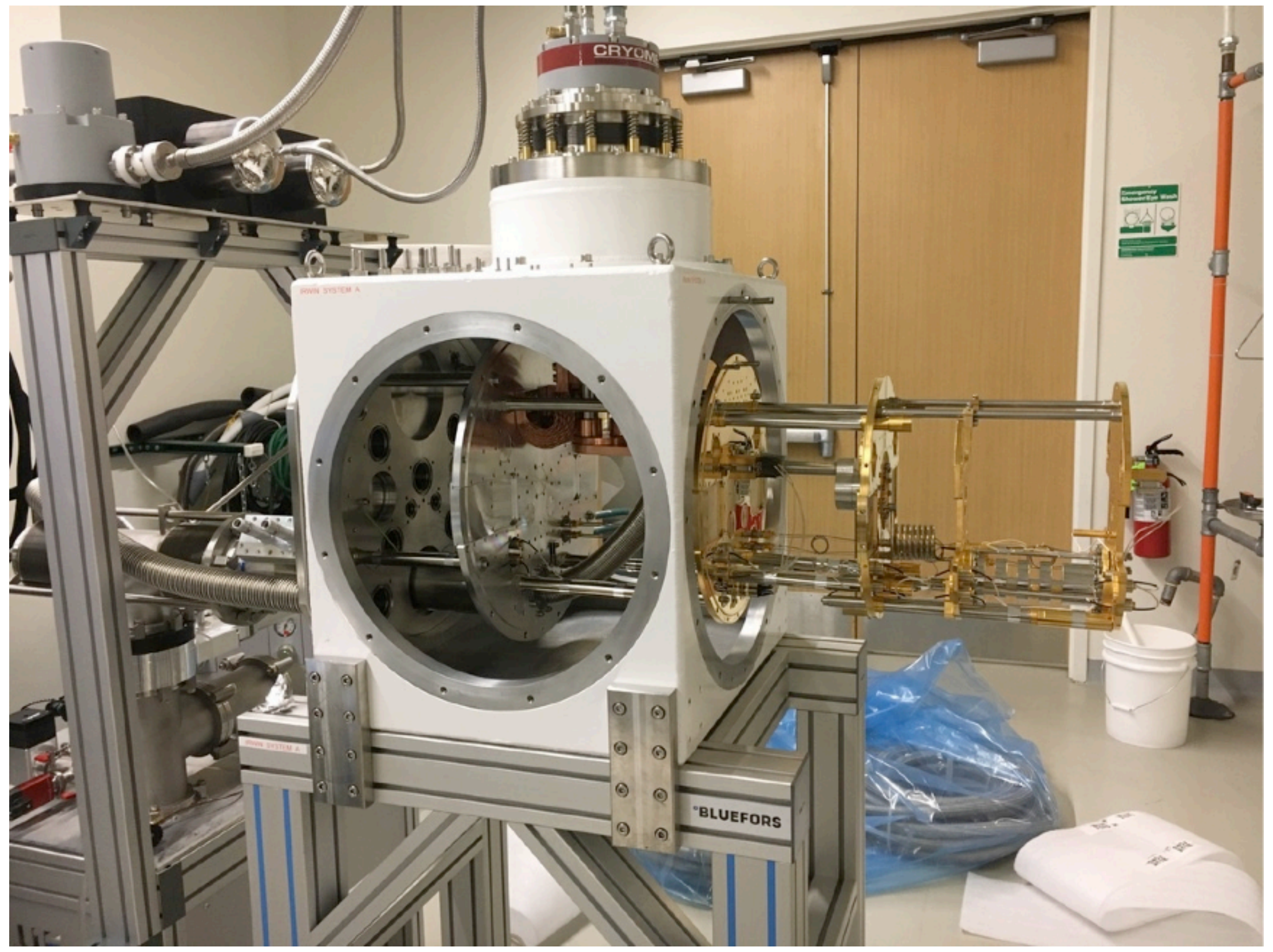


DM Radio 50l

- Toroidal Magnet: 0.1-1.0 T
- 50l Science Volume of Magnet
- Super conducting sheath coupled to pickup
- Tunable LC Resonator
- 50 MHz Upper Limit Toroidal Design of this Size
- In design/early construction phase
- Data-taking starting ~2022

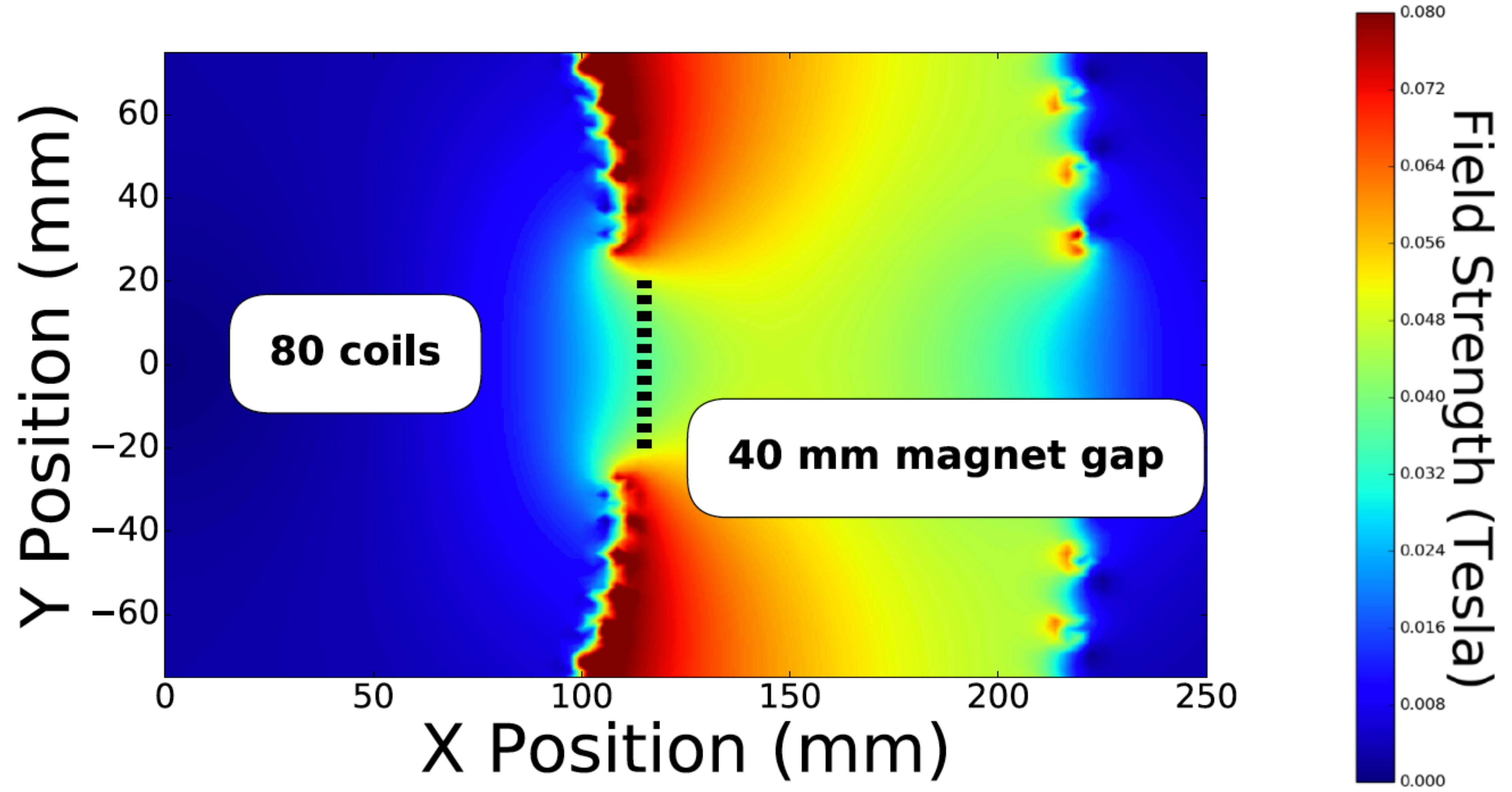




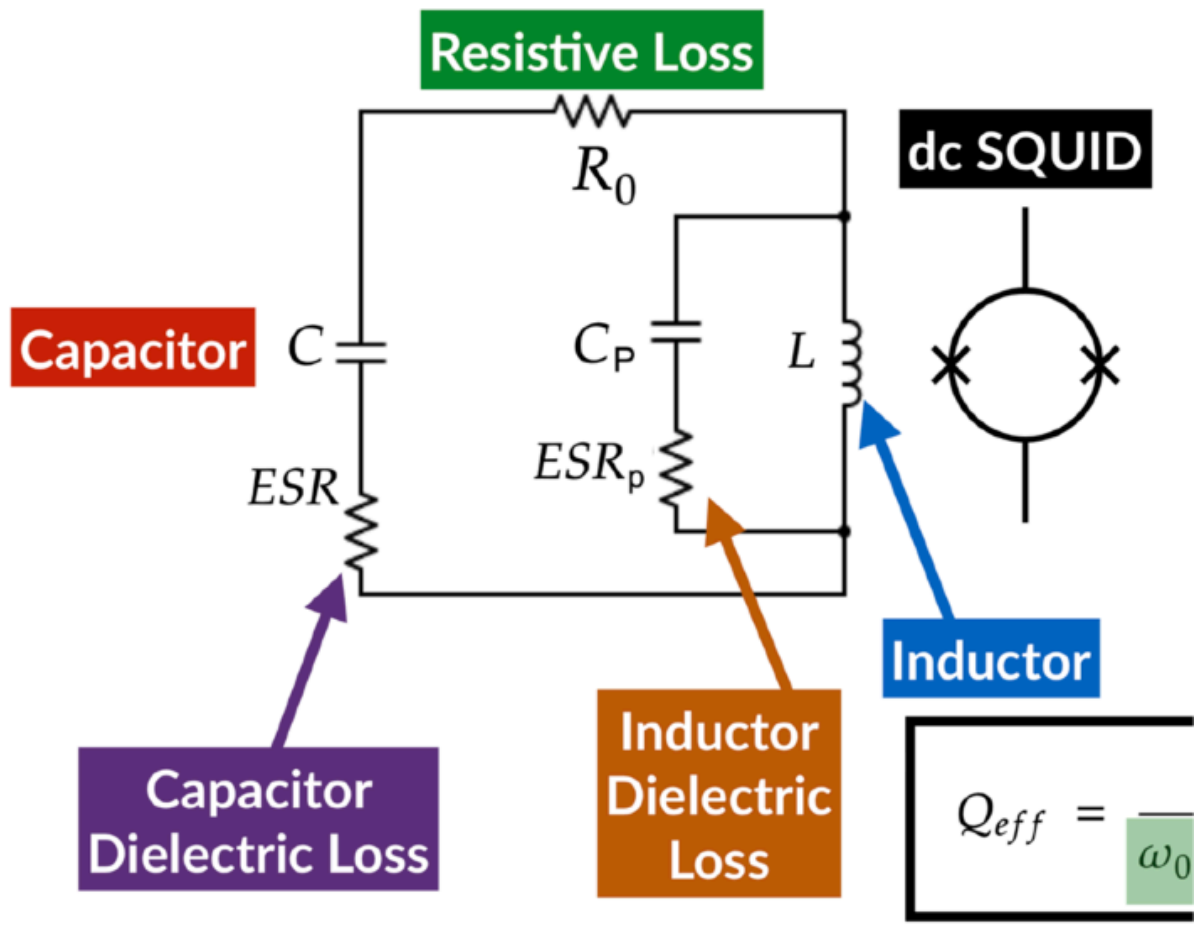


DM Radio 50l Design Studies

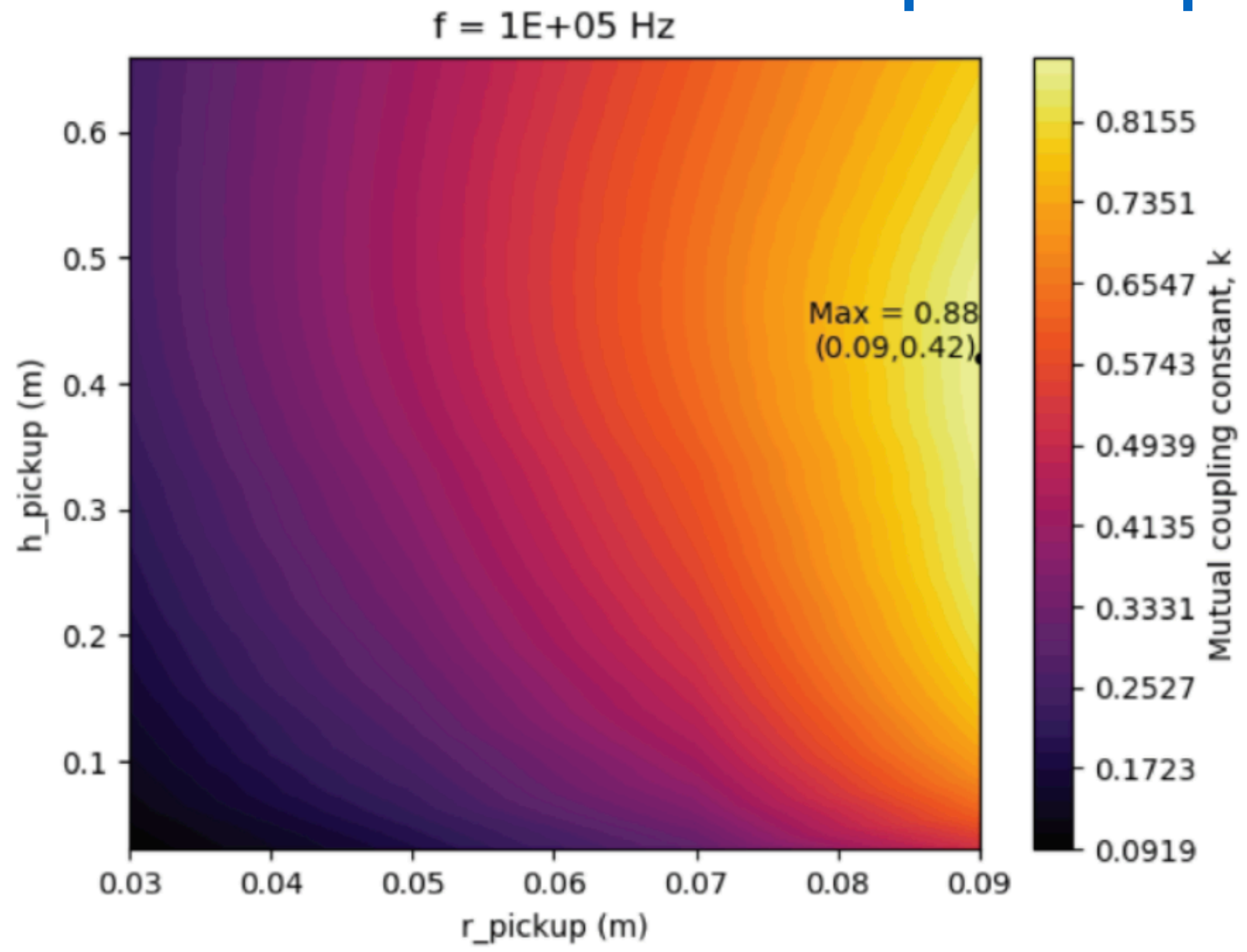
Magnet Fringe Fields

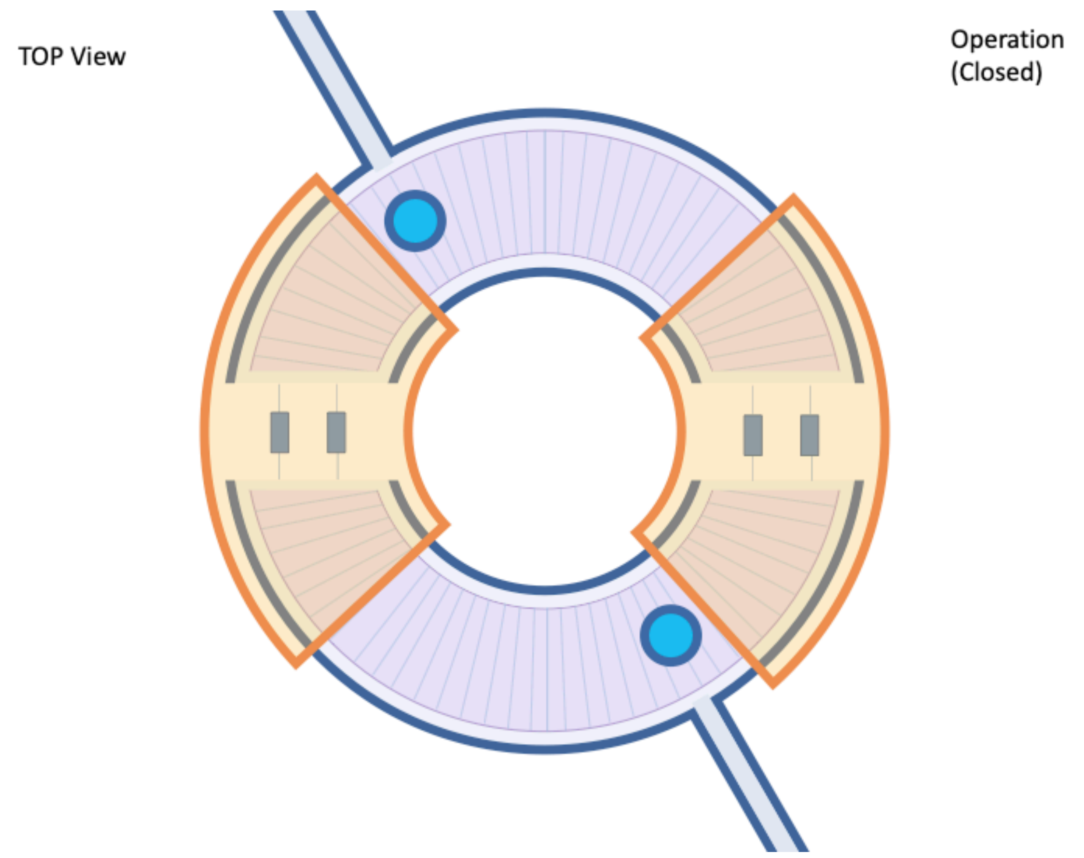


Resonator Optimization

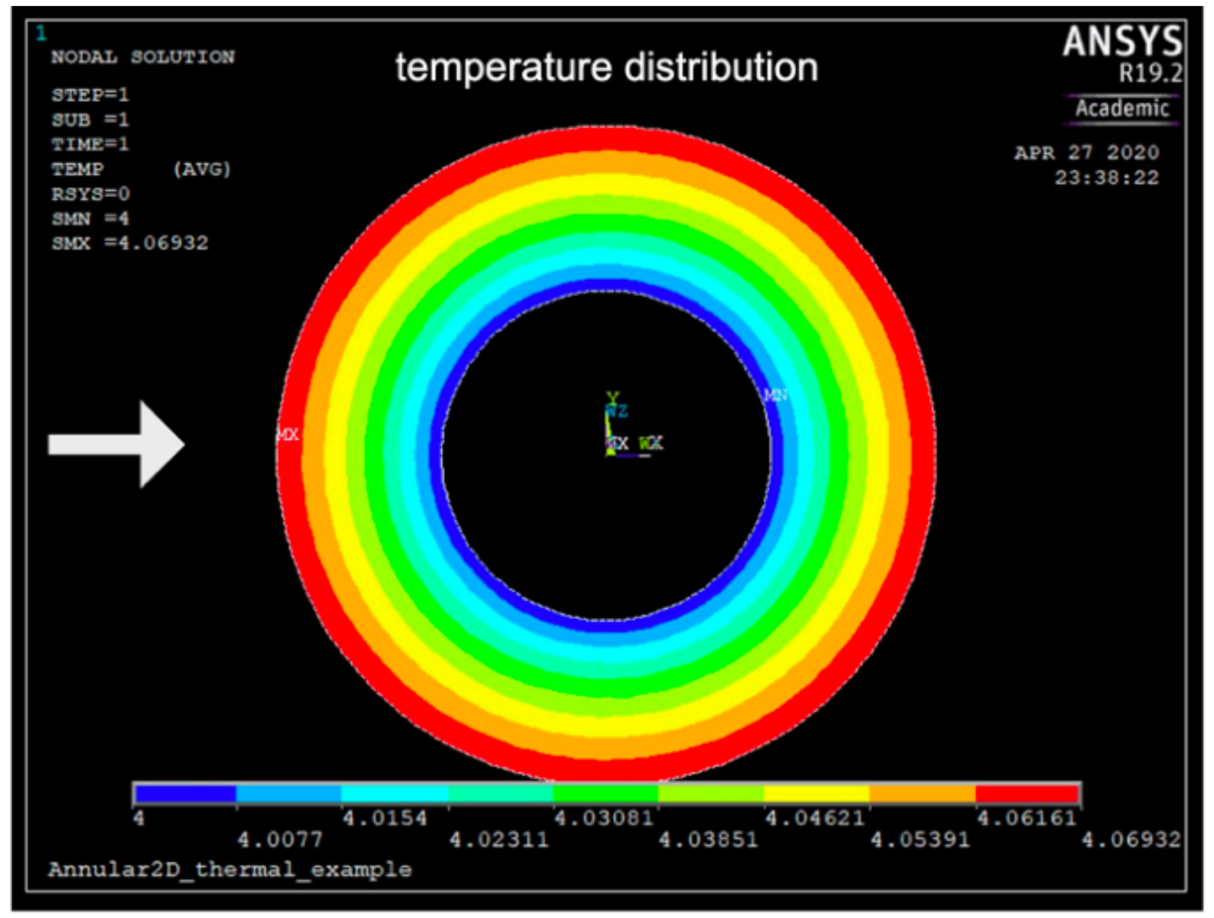


Optimal Sheath/ Pickup Coupling





Thermal Studies

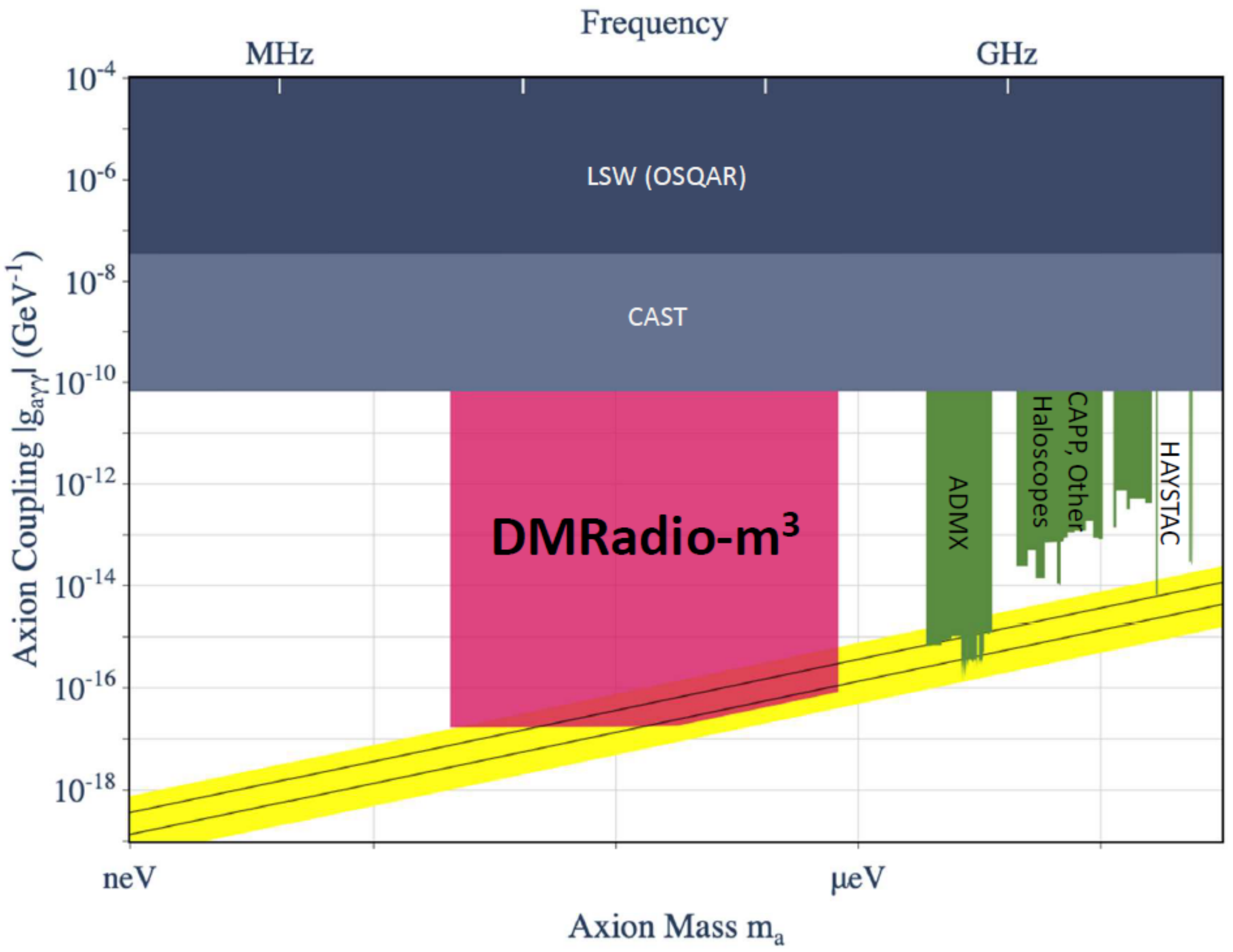


DMRadio-m³

DMRadio-m^3 Science Goals

1. Probe the QCD axion band from 5 – 200 MHz ($\sim$ 20neV – 0.8μeV) at 3σ, with systematics at least 5 times smaller.
2. Detect or exclude KSVZ axions from 10 – 200 MHz ($\sim$ 40neV – 0.8μeV) at 3σ, with systematics at least 5 times smaller.
3. Detect or exclude DFSZ axions from 30 – 200 MHz ($\sim$ 0.12μeV – 0.8μeV) at 3σ, with systematics at least 5 times smaller.
4. Confirm any axion detection to $> 5\sigma$.

>1.5 decades of well motivated axion mass coverage enabled by lumped-element resonators

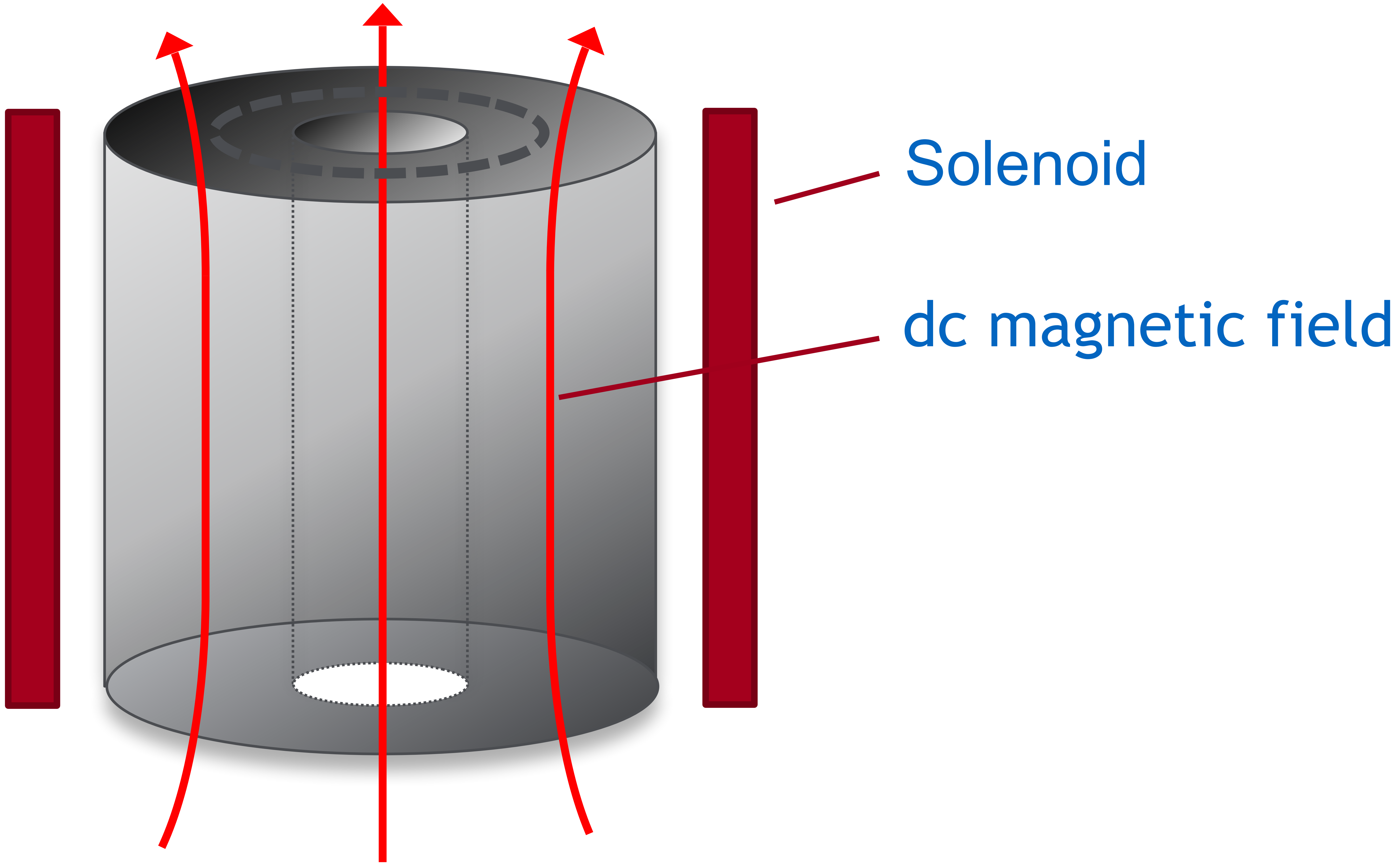


Design Study funded by DOE- HEP Proposal Submission in 2022

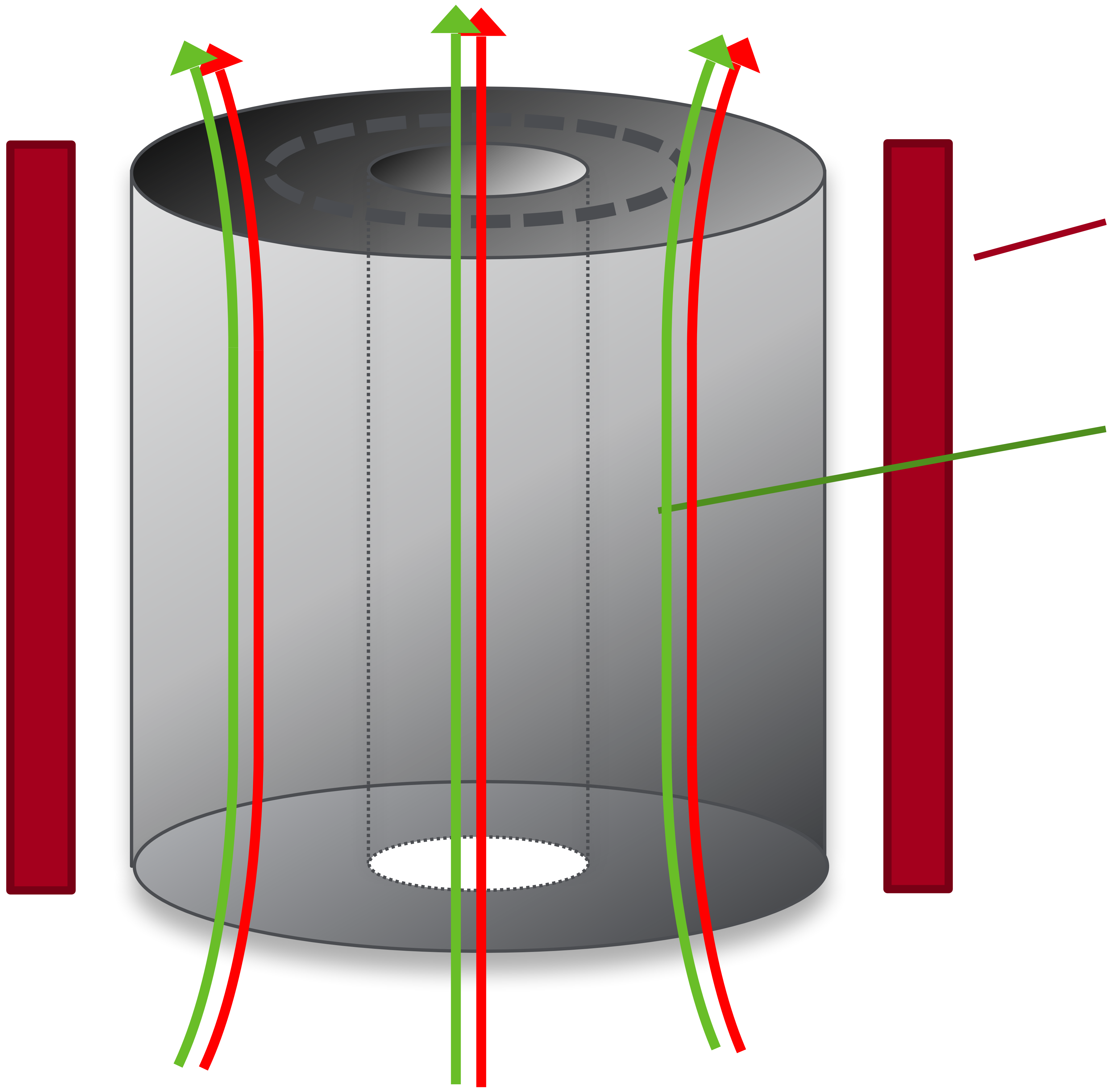
Axion signal coupling

Solenoidal Design:

- Cheaper magnet
- Allows search to 200MHz



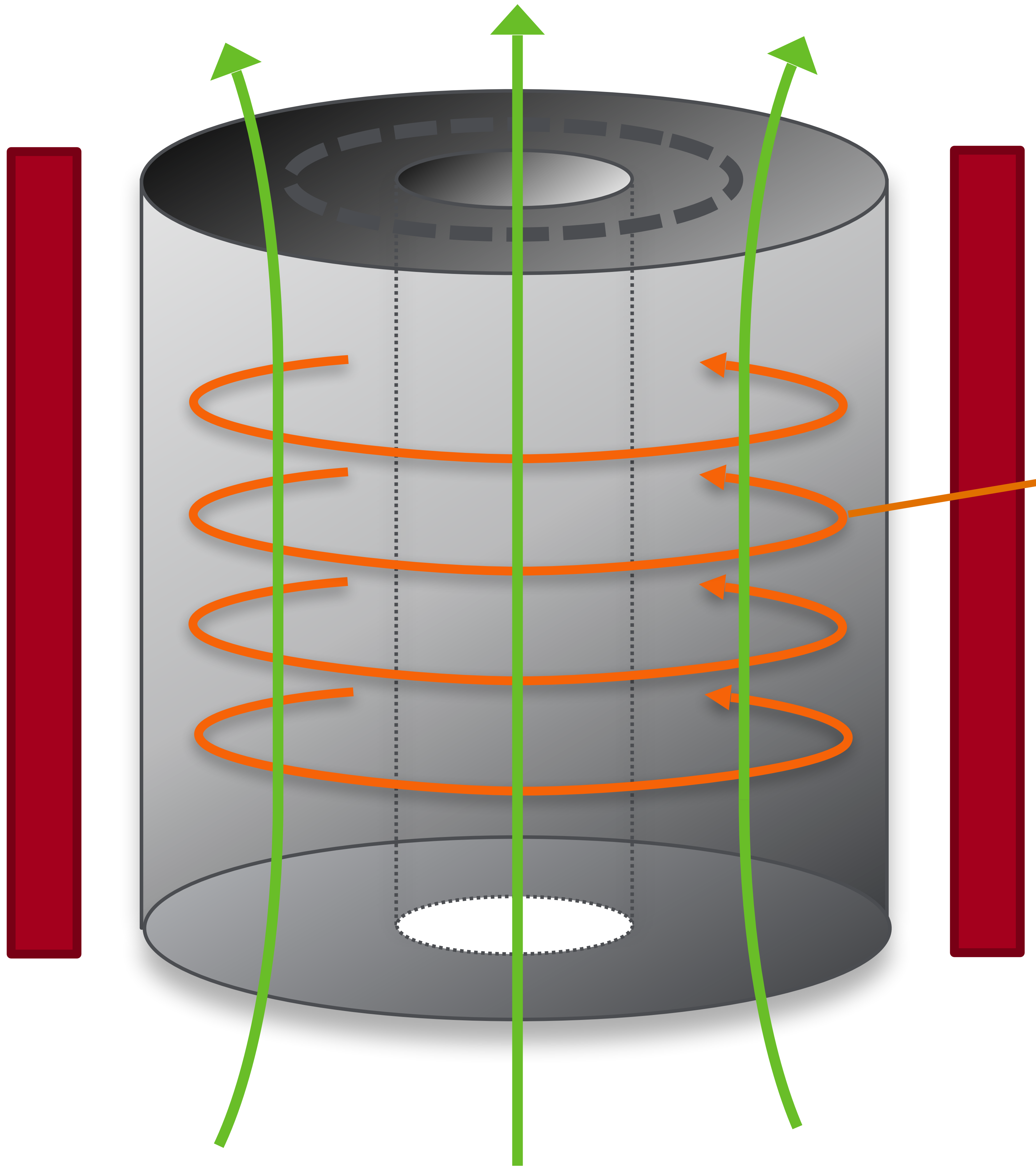
Axion signal coupling



Solenoid

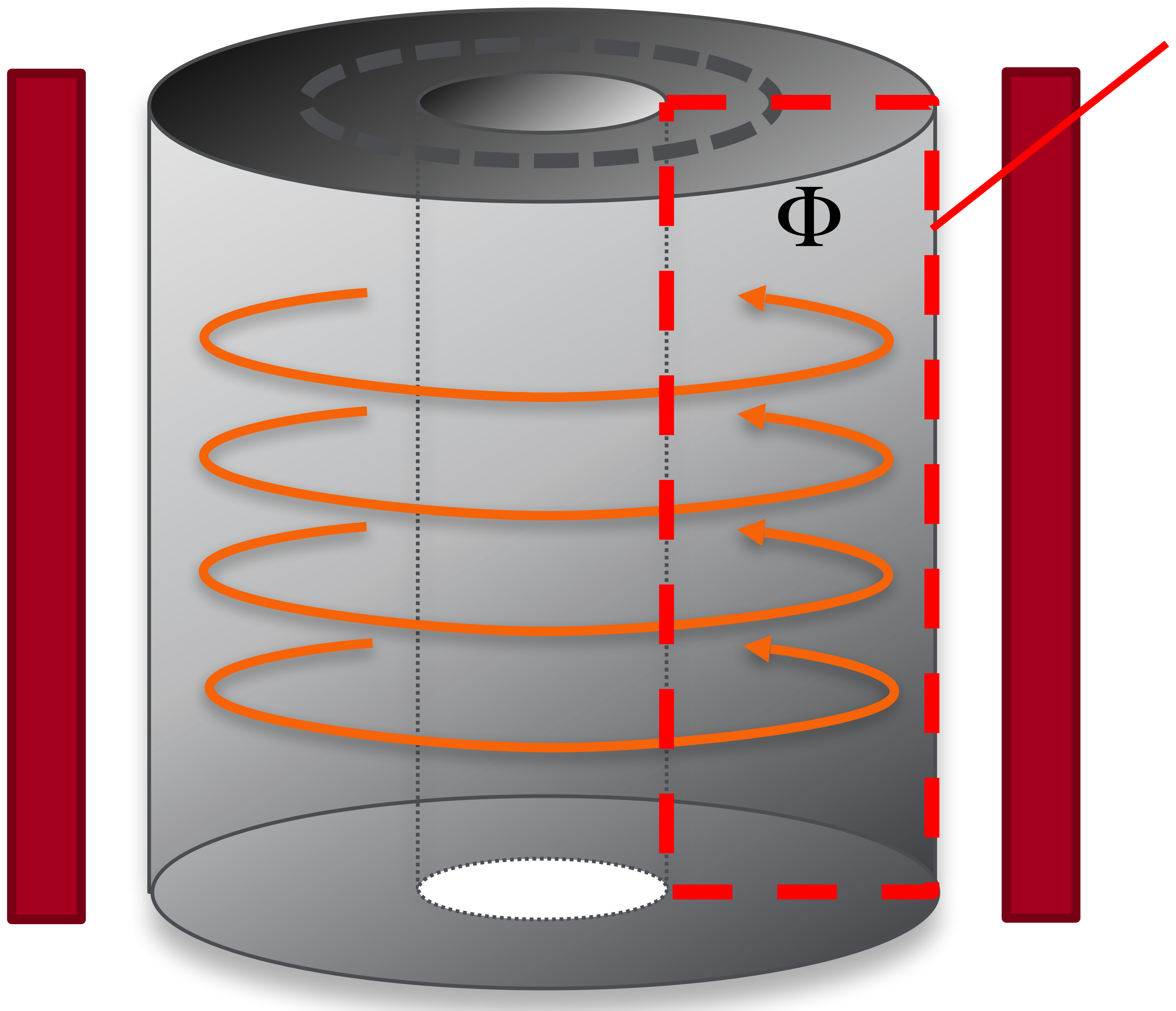
Effective current induced by axions parallel to dc magnetic field

Axion signal coupling



Azimuthal ac B field induced by axion effective currents

Axion signal coupling

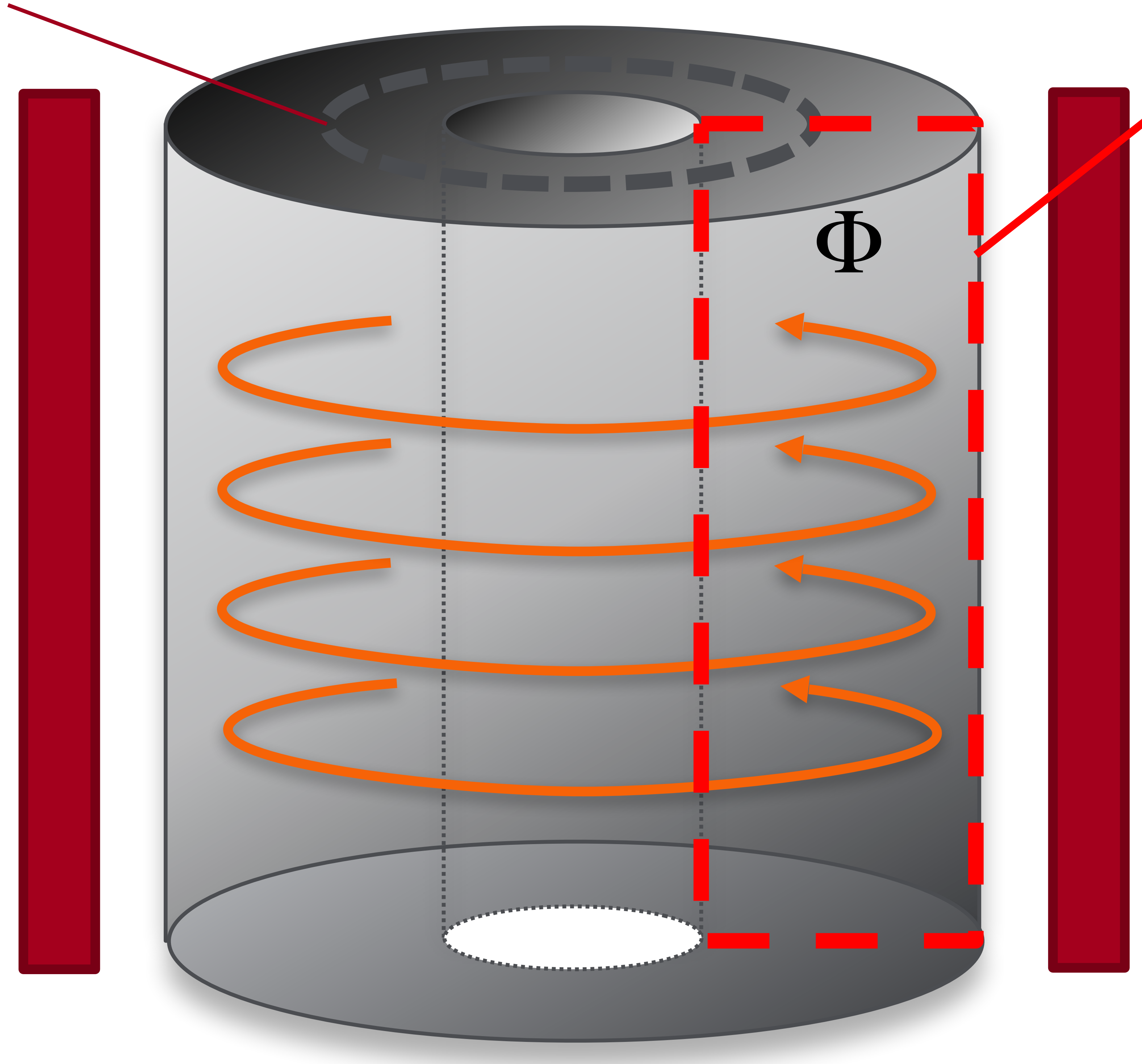


Ac B field from axions induces Flux F through dashed cross-section of the coaxial pickup

Axion signal coupling

Slit in top end of coax
Voltage V=dΦ/dt across slit

Ac B field from axions induces Flux Φ through dashed cross-section of the coaxial pickup

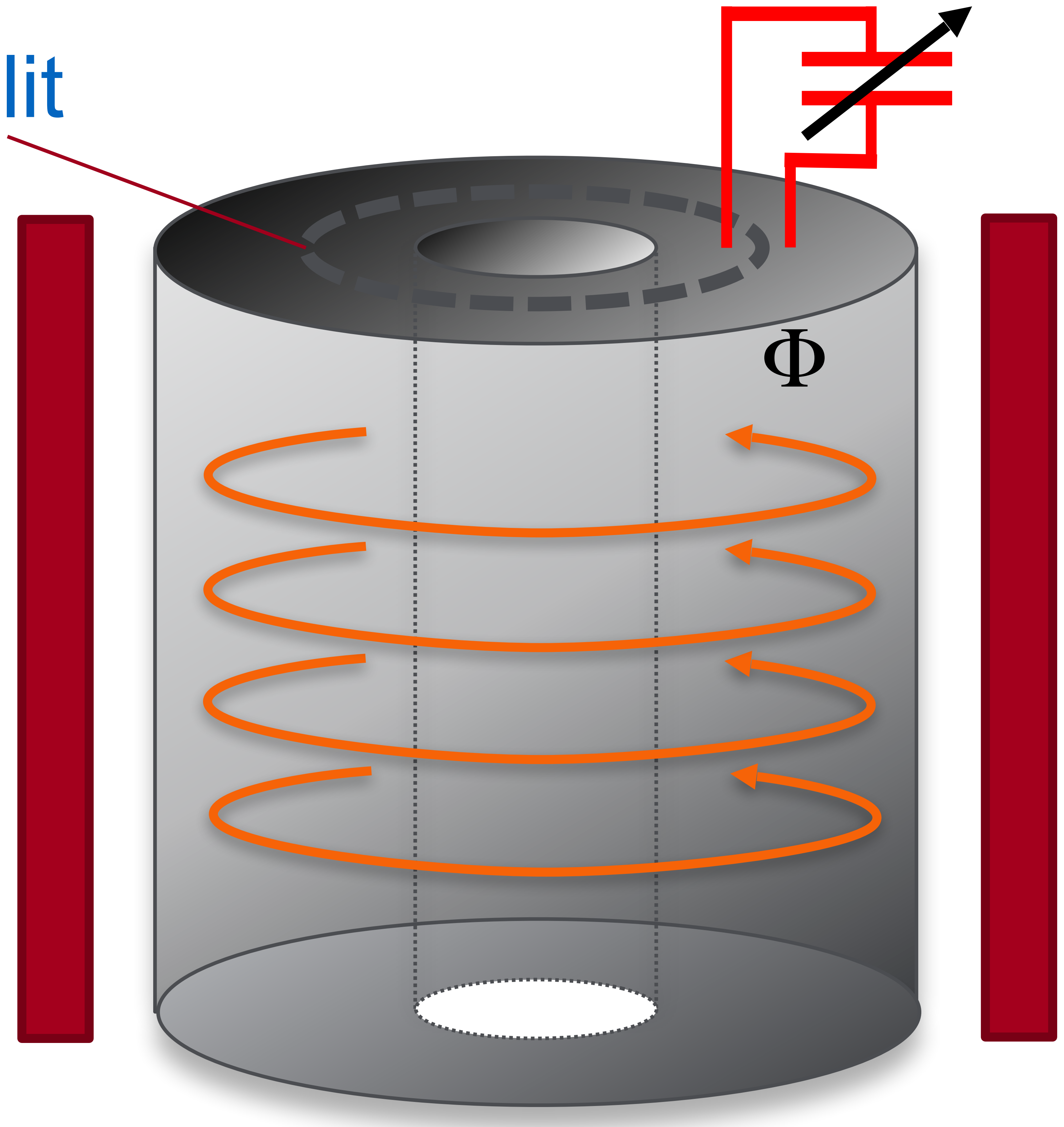


Closed (shorted) end of coax

Axion signal coupling

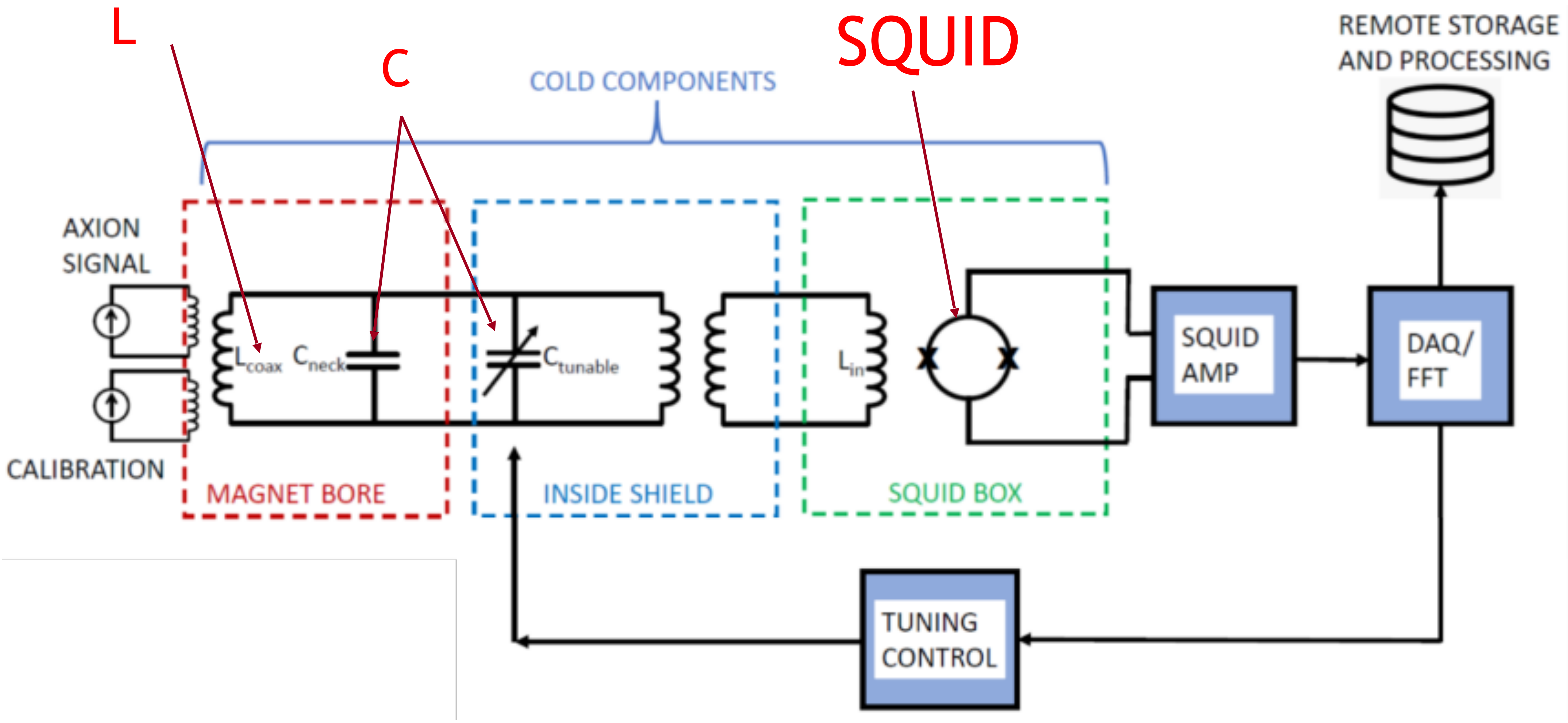
Slit in top end of coax
Voltage V=dΦ/dt across slit

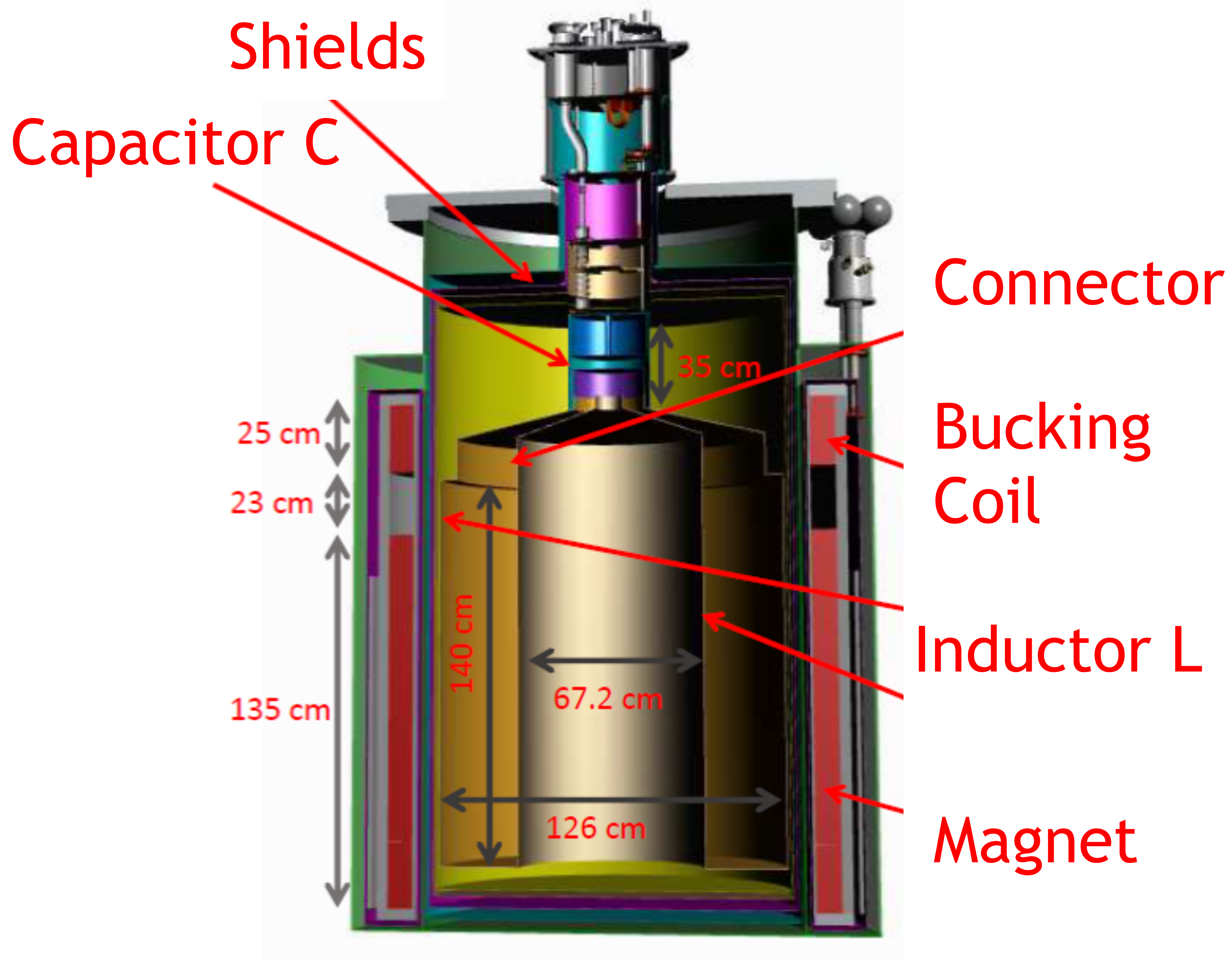
With a tunable capacitor, forms a lumped-element resonator



Closed (shorted) end of coax

System overview – signal flow





Full optimization of axion scan: see arxiv:1803.01627

Statistical error budget

Statistical error budget quantified by "performance figure of merit"

Overlap correction	C_x	1.04
Magnetic field	B_{eff}	Reference 3.6 T **Goal: 4.3 T**
Magnet volume	V	1.25 m^3
Quality factor	Q	150,000
Coax temperature	T	0.02 K
SQUID noise parameter	η	20× quantum limit
Figure of merit	$\mathscr{P}_{\text{FOM}}$	Reference: 112 **Goal: 134**

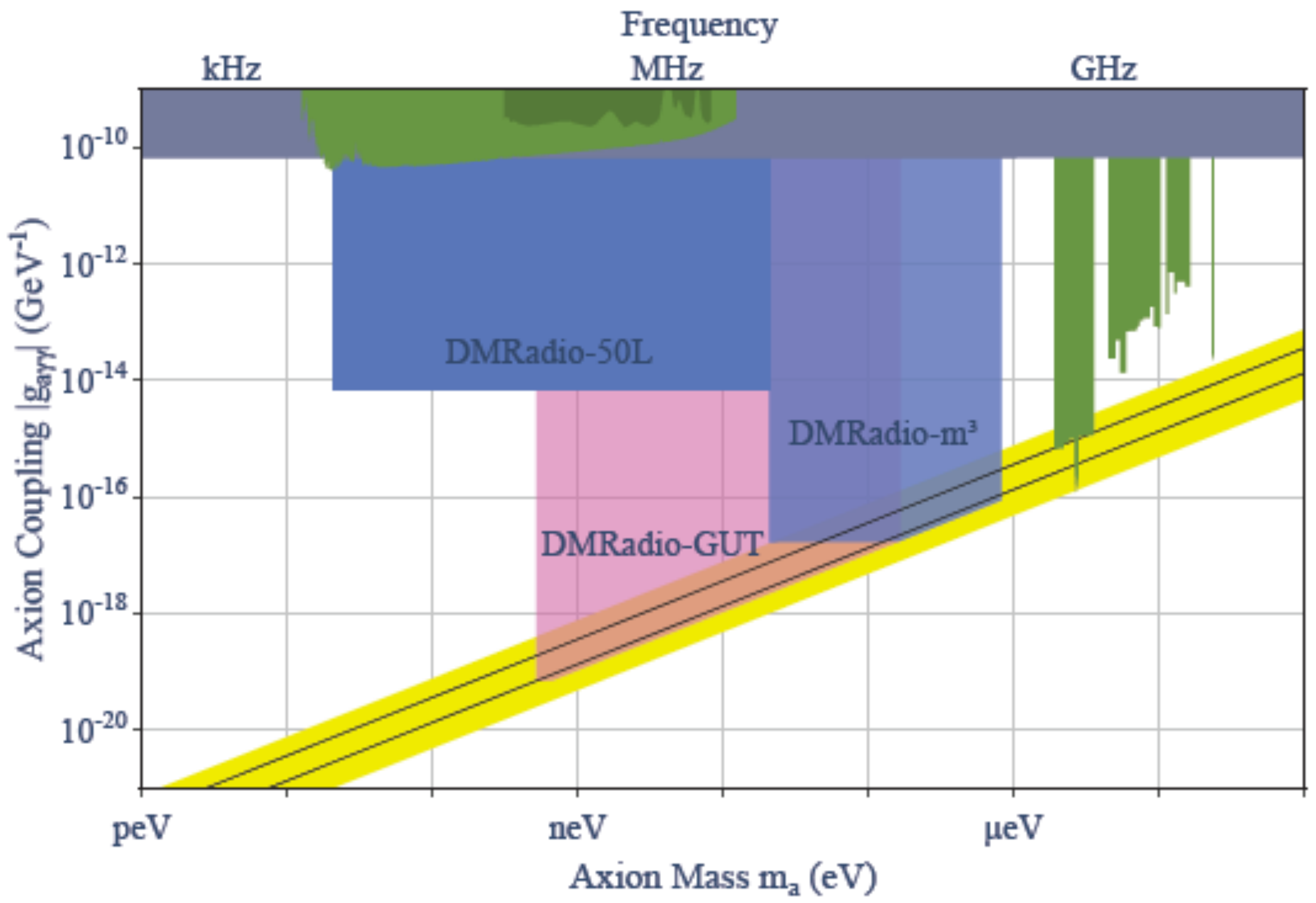
$$\mathscr{P}_{\text{FOM}} = \frac{C_{\text{x}} B_{\text{eff}} V^{5/6} Q^{1/4}}{\eta^{1/4} T^{1/4}}$$

arxiv:1803.01627

DM Radio GUT

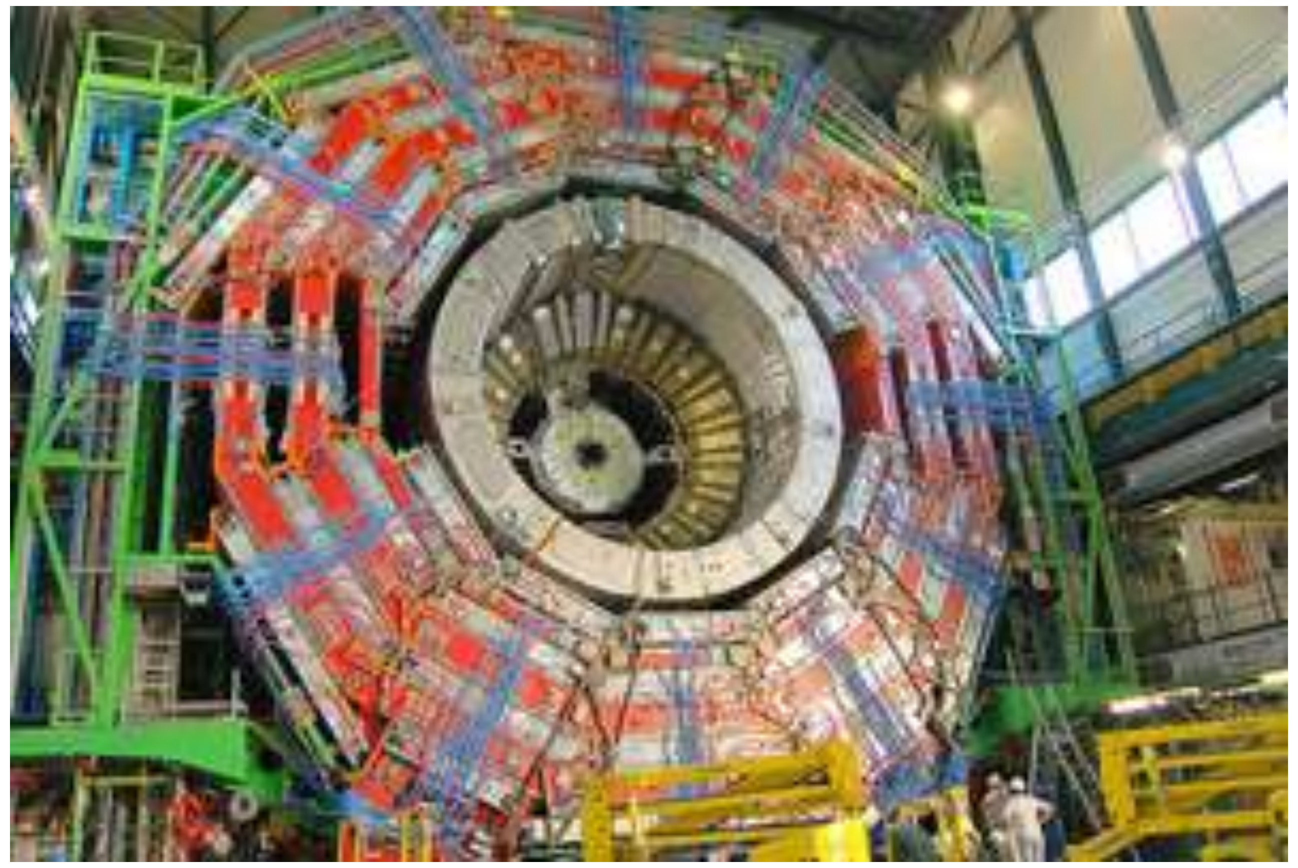
DMRadio-GUT: ambitious, long-term experiment to look for GUT-scale QCD axions

$$\mathscr{P}_{\mathrm{FOM}} = \frac{C_{\mathrm{x}} B_{\mathrm{eff}} V^{5/6} Q^{1/4}}{\eta^{1/4} T^{1/4}}$$

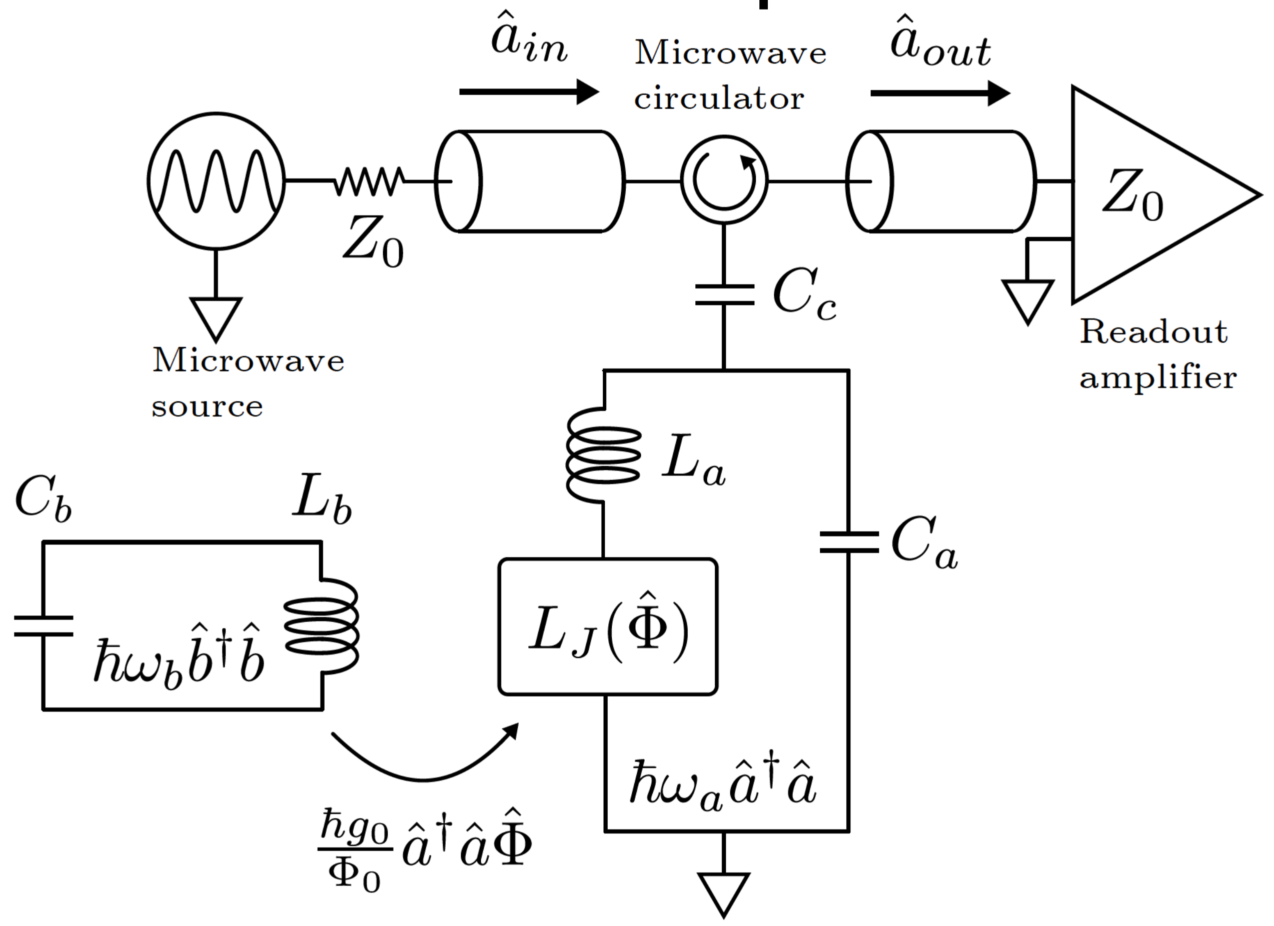


- 12T, 10m³ , 570 MJ magnet
  - CMS: 3.8T peak field, 2.3 GJ
- Q = 2x10⁷ (Material selection, design)
- 20 dB of backaction noise reduction below SQL
- 7 years of run time

CMS



RQU Amplifier



The DMRadio Scientific Collaboration

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HEISING-SIMONS FOUNDATION

GORDON AND BETTY MOORE FOUNDATION

NSF

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Berkeley UNIVERSITY OF CALIFORNIA

Stanford University

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

CAL STATE EAST BAY

PRINCETON UNIVERSITY

Santa Clara University

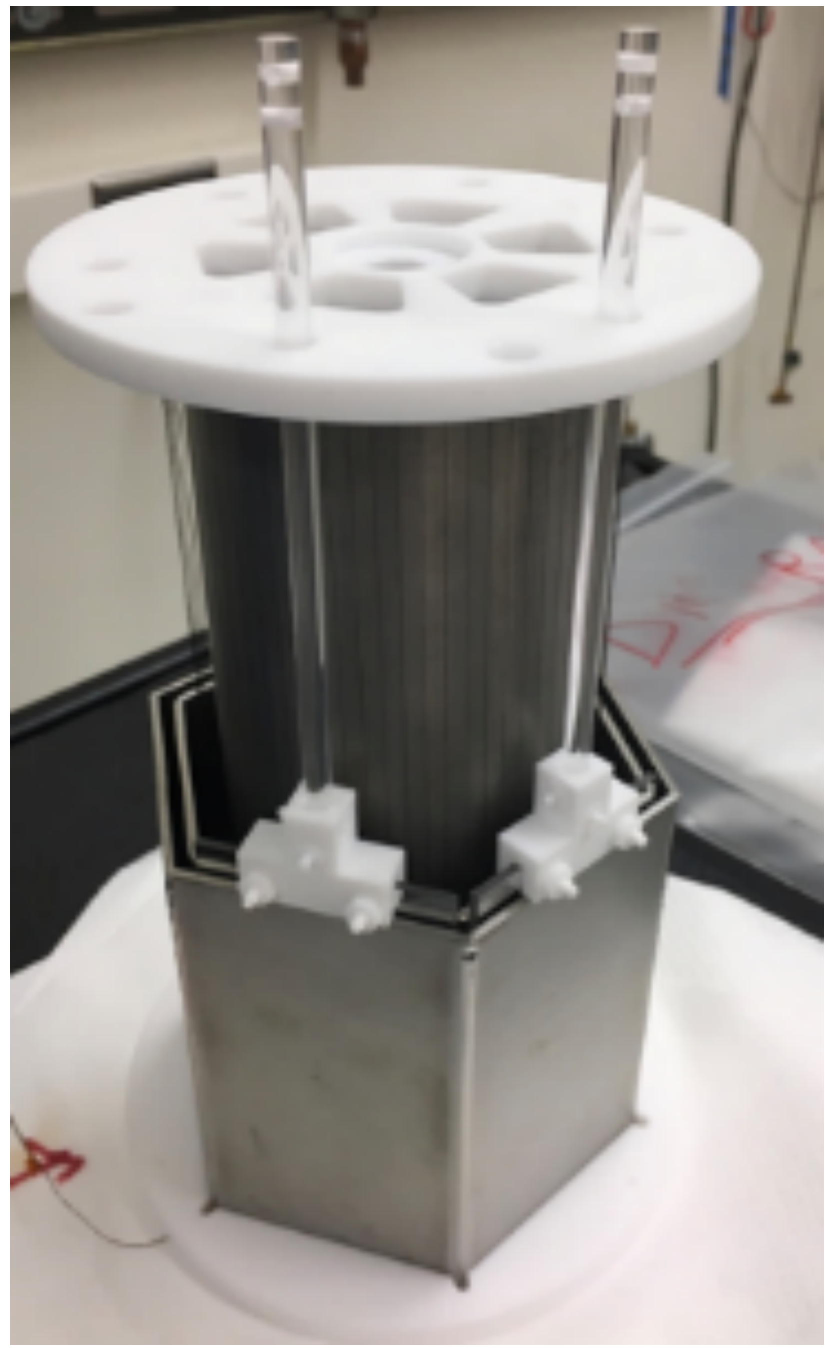
BERKELEY LAB

Conclusions

- DMRadio Program provide path to probe pre-inflation DM QCD axions using lumped-element resonators
- Several Experiments in progress or being proposed.

BONUS SLIDES

DMRadio-m3 tuned capacitor



Tuning with insertible dielectrics
High purity sapphire
(DM Radio Pathfinder)

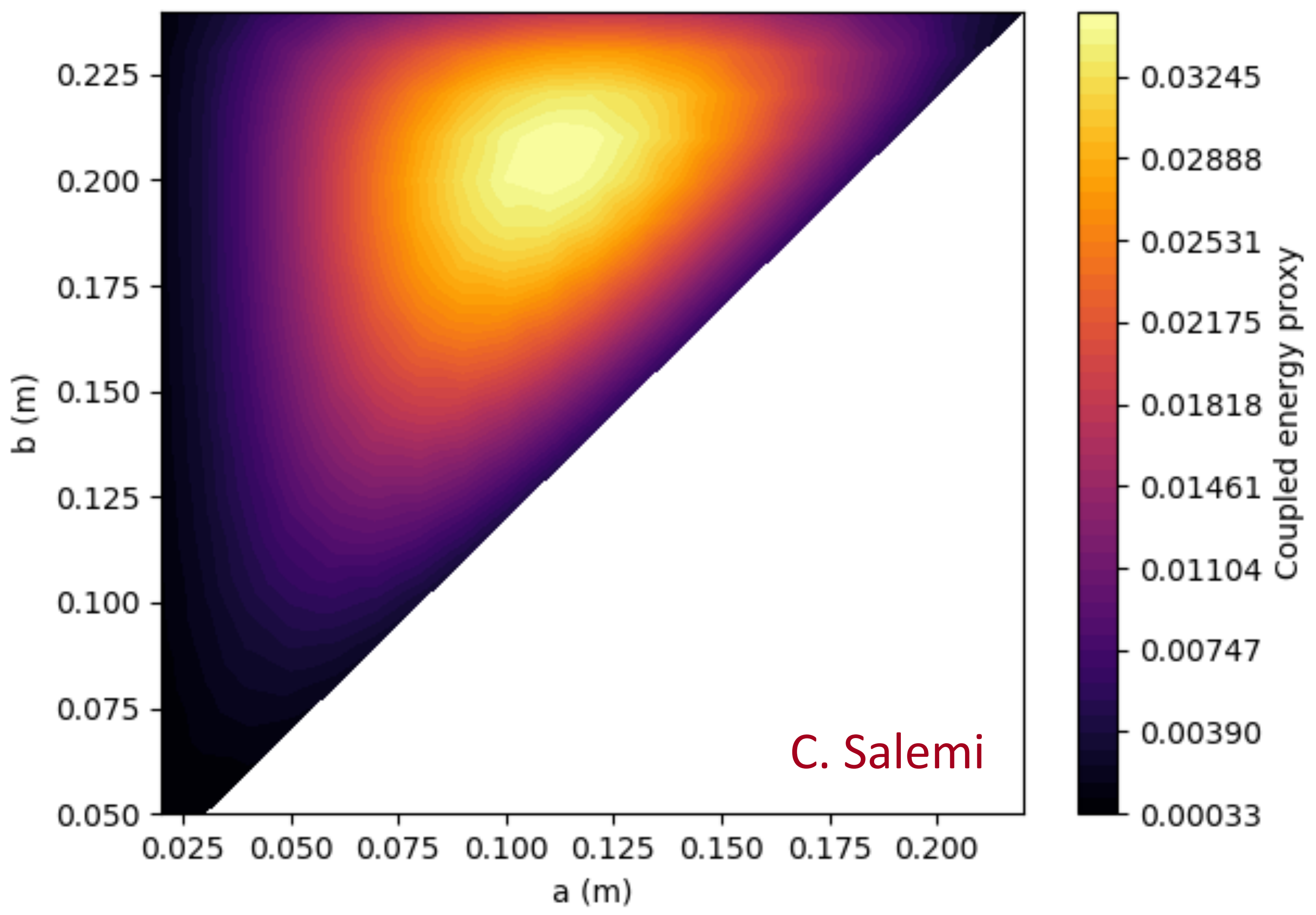
- DMRadio-m3 is in a low magnetic field, shielded environment, and uses superconducting electrodes
- Baseline tunable capacitor design uses an insertable dielectric (low-loss sapphire)
- At least two capacitor sets are required to cover the full frequency range of DMRadio-m3
- Reliable numbers for 20 mK loss in sapphire over DMRadio-m3 frequency range are not available. We are developing infrastructure to screen sapphire at 20 mK.
- Backup capacitor design utilizes vacuum-gap rotary design. It would require more capacitor set swaps.

DMRadio-m3 dc SQUID

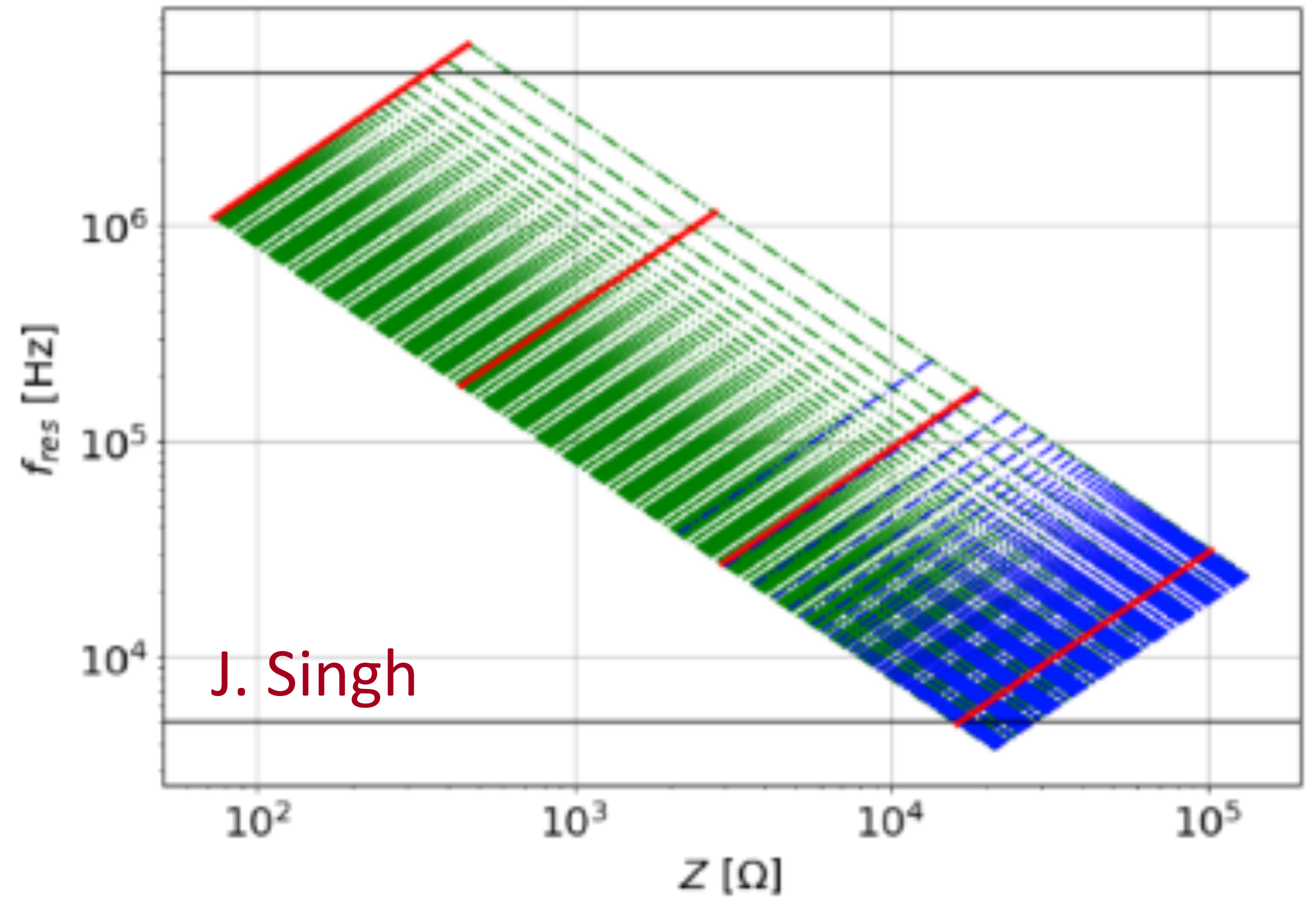
- DM Radio requires either one or two dc SQUID channels (2^{nd} for calibration).
- DM Radio specifies SQUID sensitivity at 20x the quantum limit. This performance was previously achieved with a commercial Quantum Design SQUID in a high-Q, low-temperature electromagnetic resonator (Falferi, APL 93, 172506 (2008)).
- We are evaluating SQUIDs from NIST, Magnicon, Quantum Design, Star Cryo, SeeQC, VTT.
- We are evaluating room-temperature preamplifiers from NIST and Magnicon (e.g. XXF-1), as well as a possible SLAC design.
- Two SQUID modules being defined
  - Low noise (20x the quantum limit), 50 MHz bandwidth module.
  - High bandwidth module (200 MHz).

A Sample of Current Collaboration Work

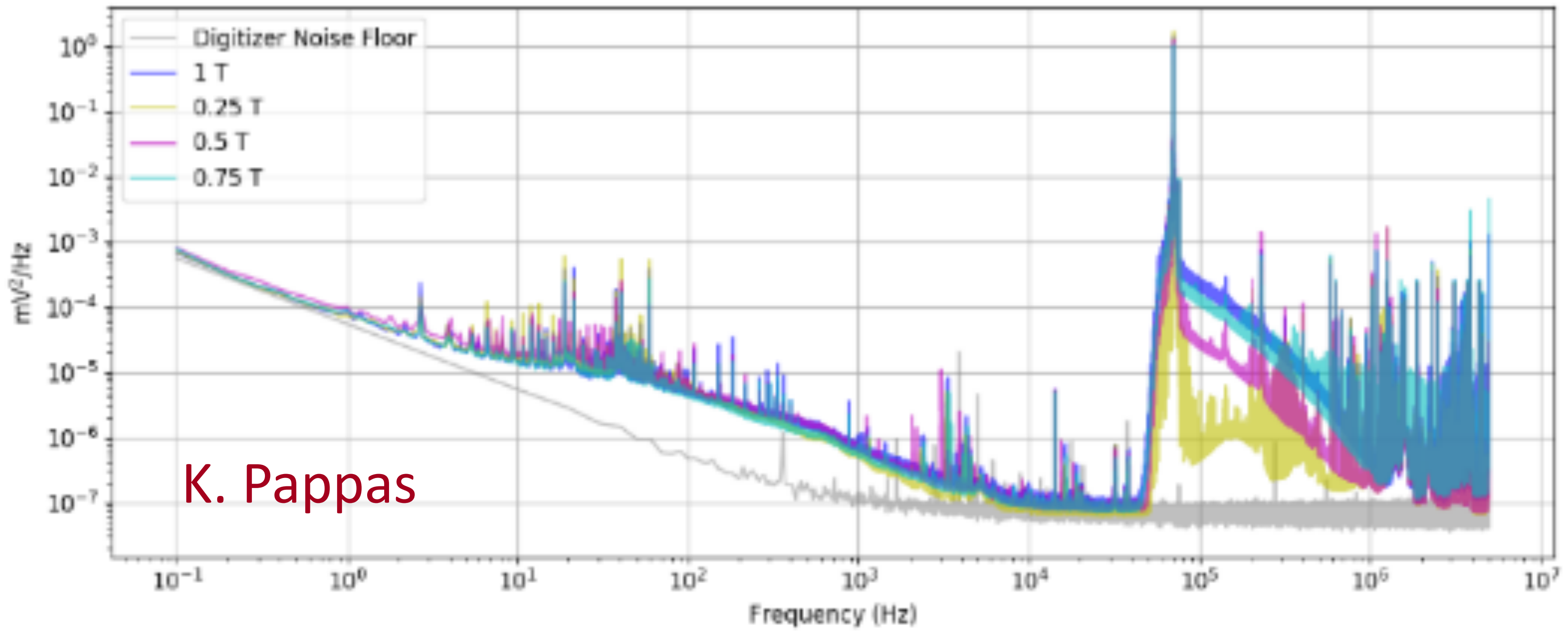
Optimization of Coupled Energy – DMRadio 50L



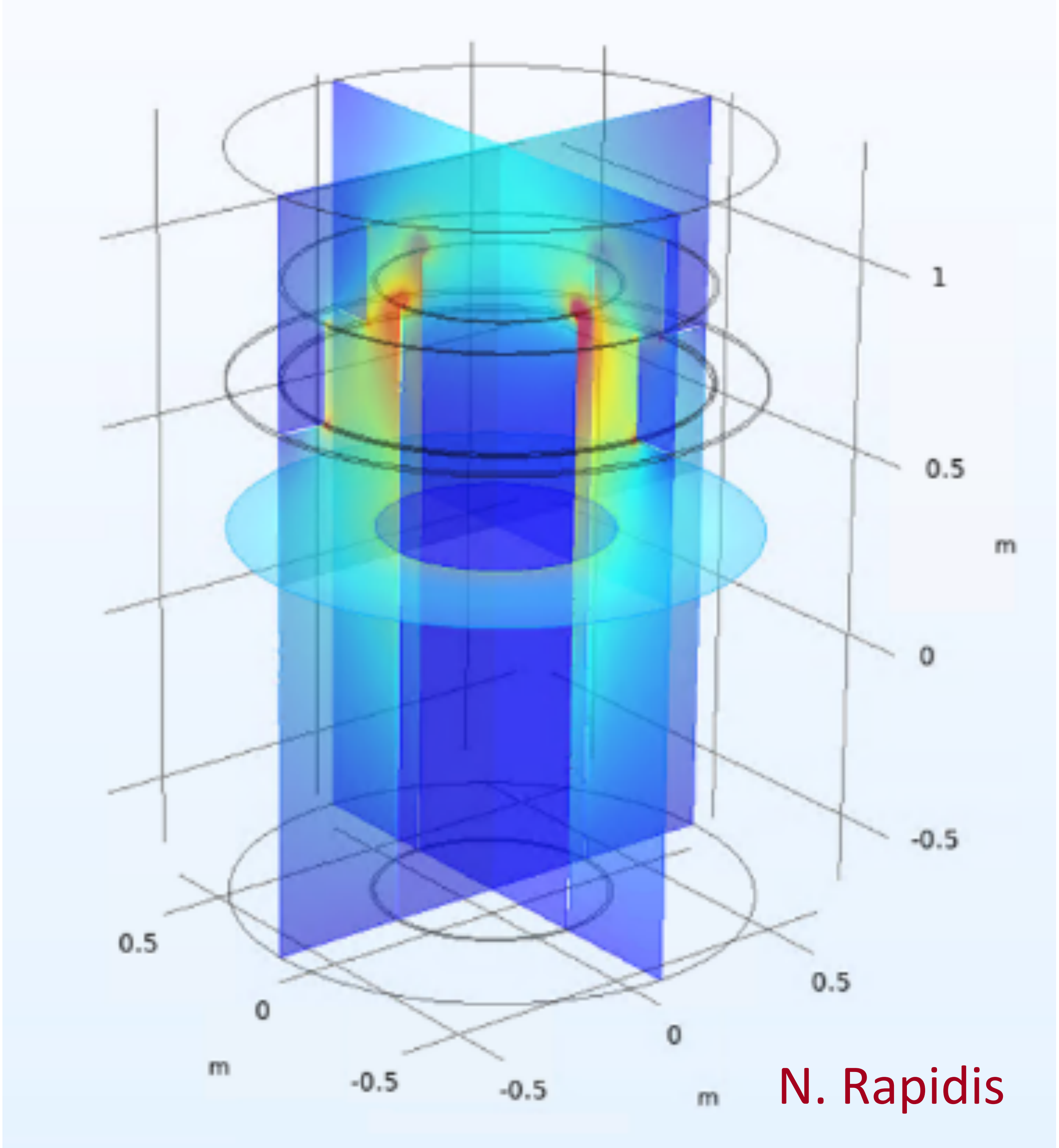
LC Resonator Design - DMRadio 50L



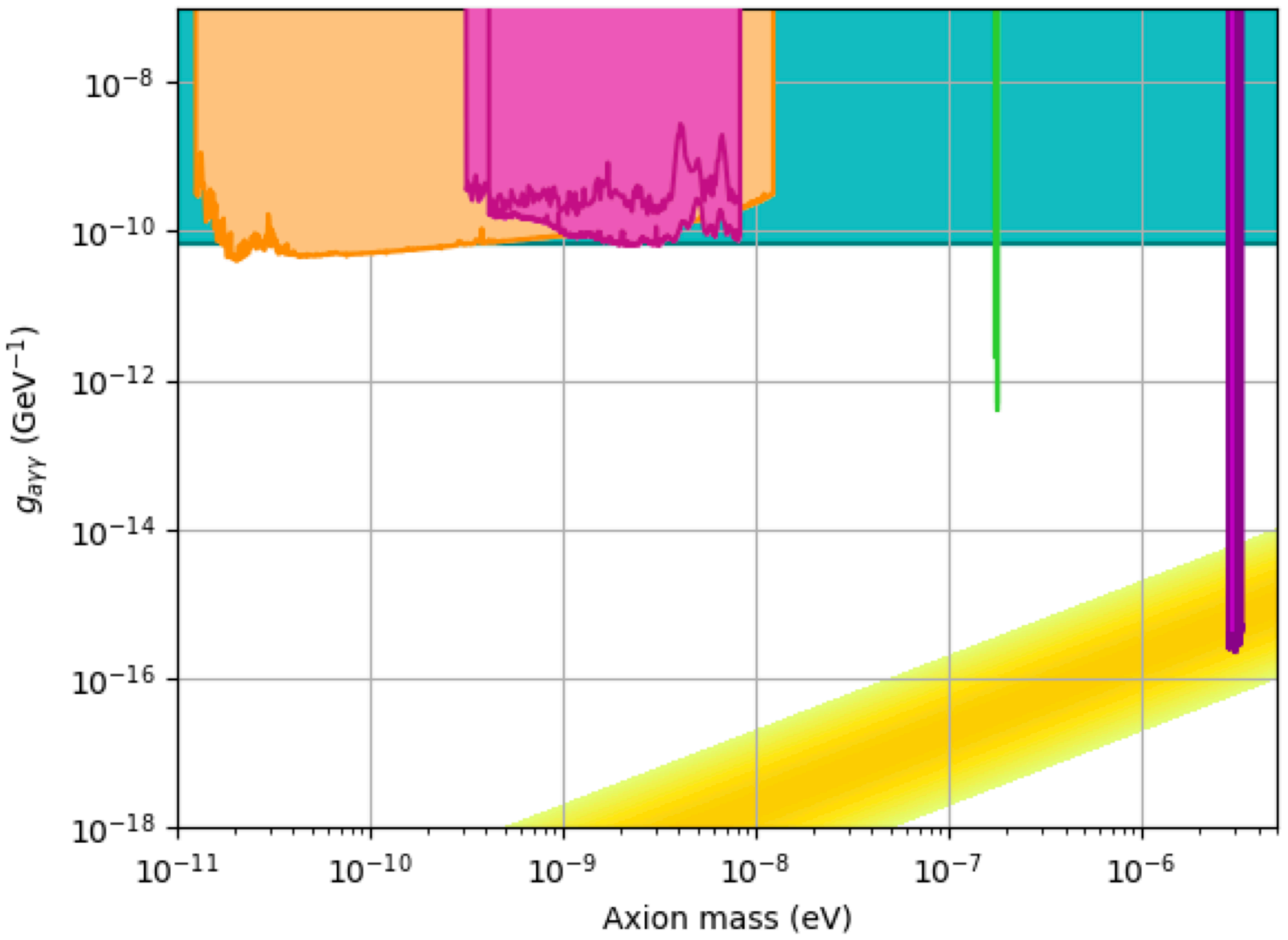
Noise Studies in ABRACADABRA



Electric Field in the DMRadio m³ Coaxial Inductor

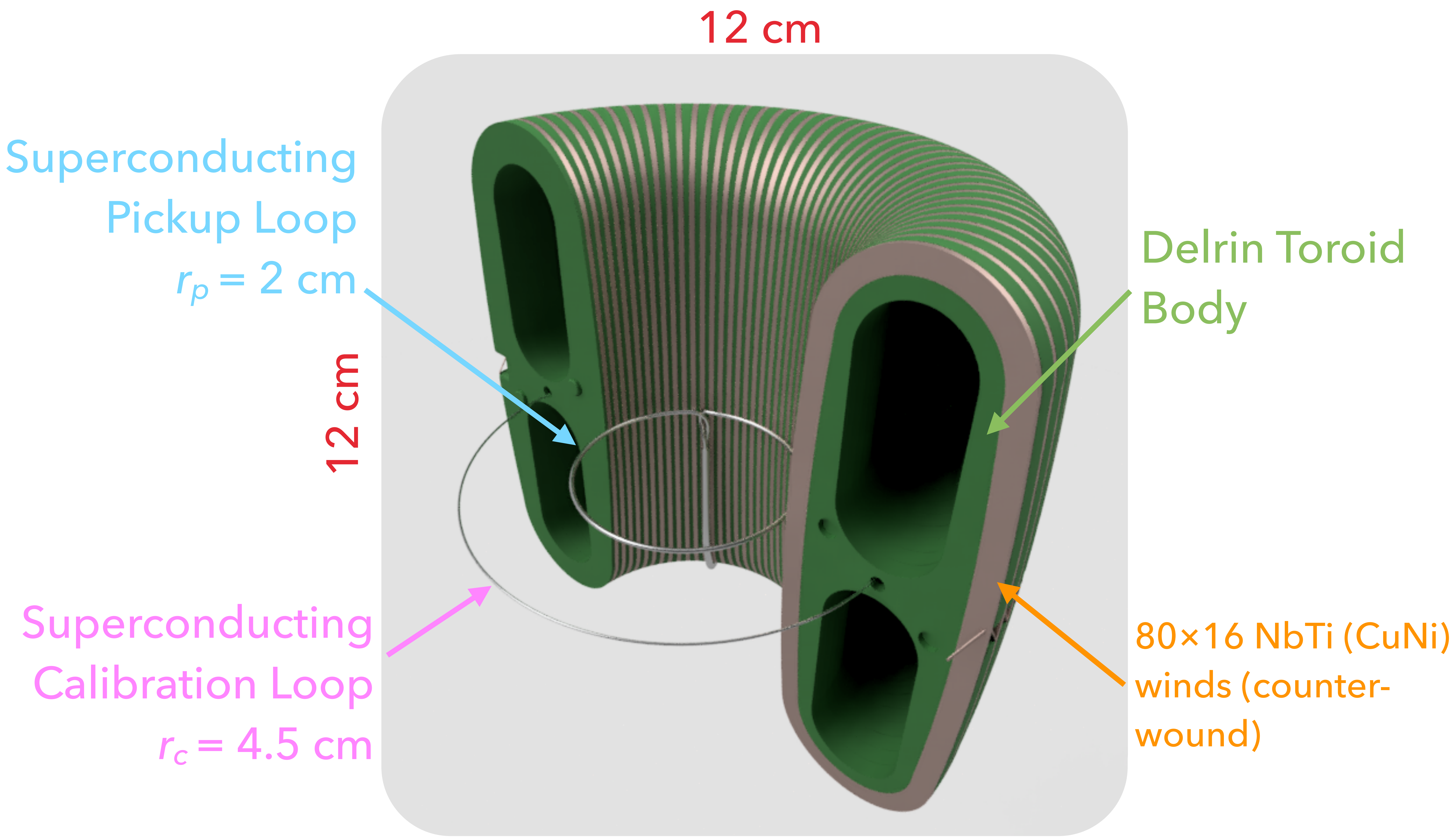


Many studies already performed in support of the current design or DMRadio 50L and similar studies underway for DMRadio m³.

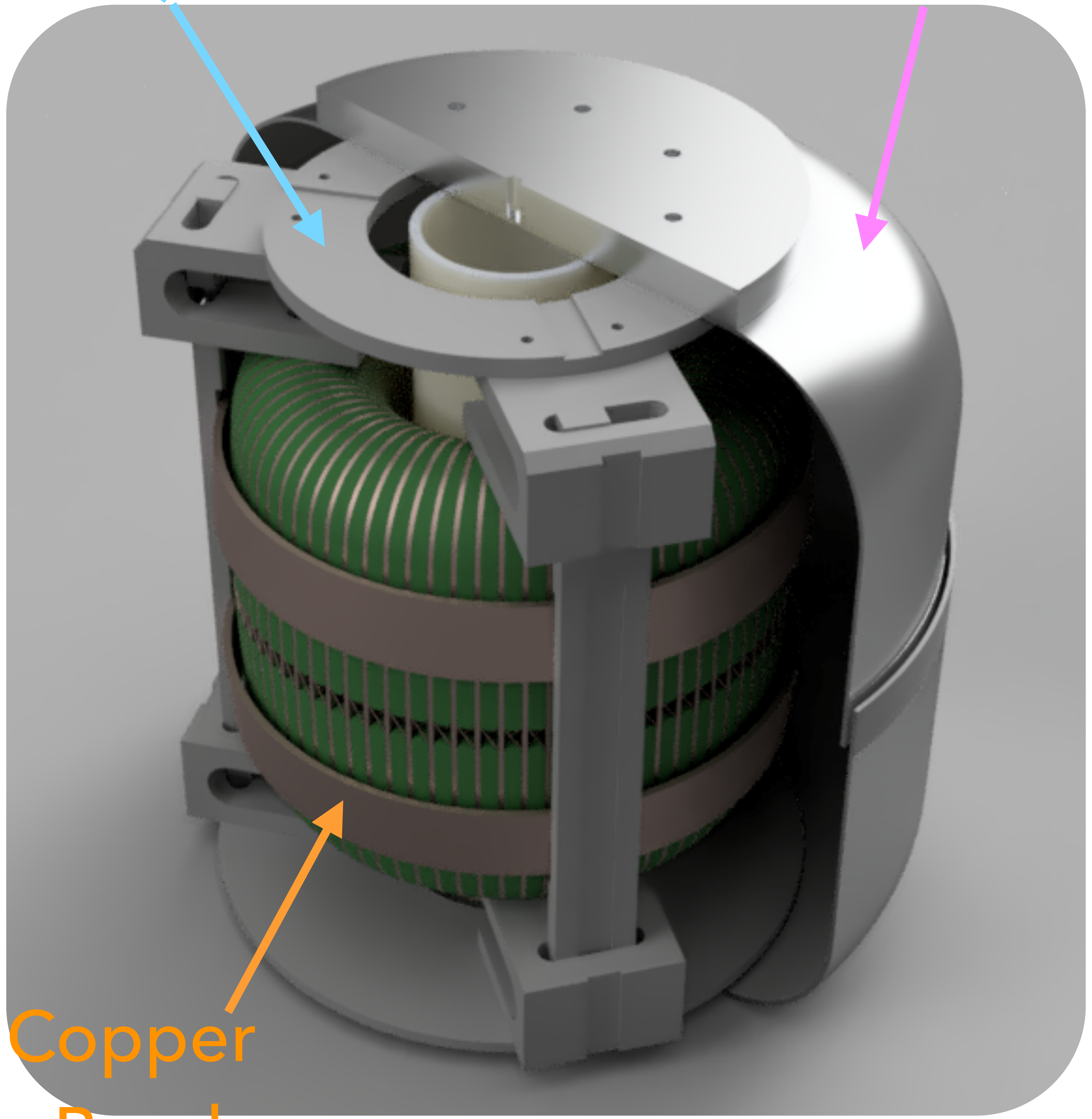


10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
$g_{a\gamma\gamma}$ (GeV^{-1})
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
Axion mass (eV)

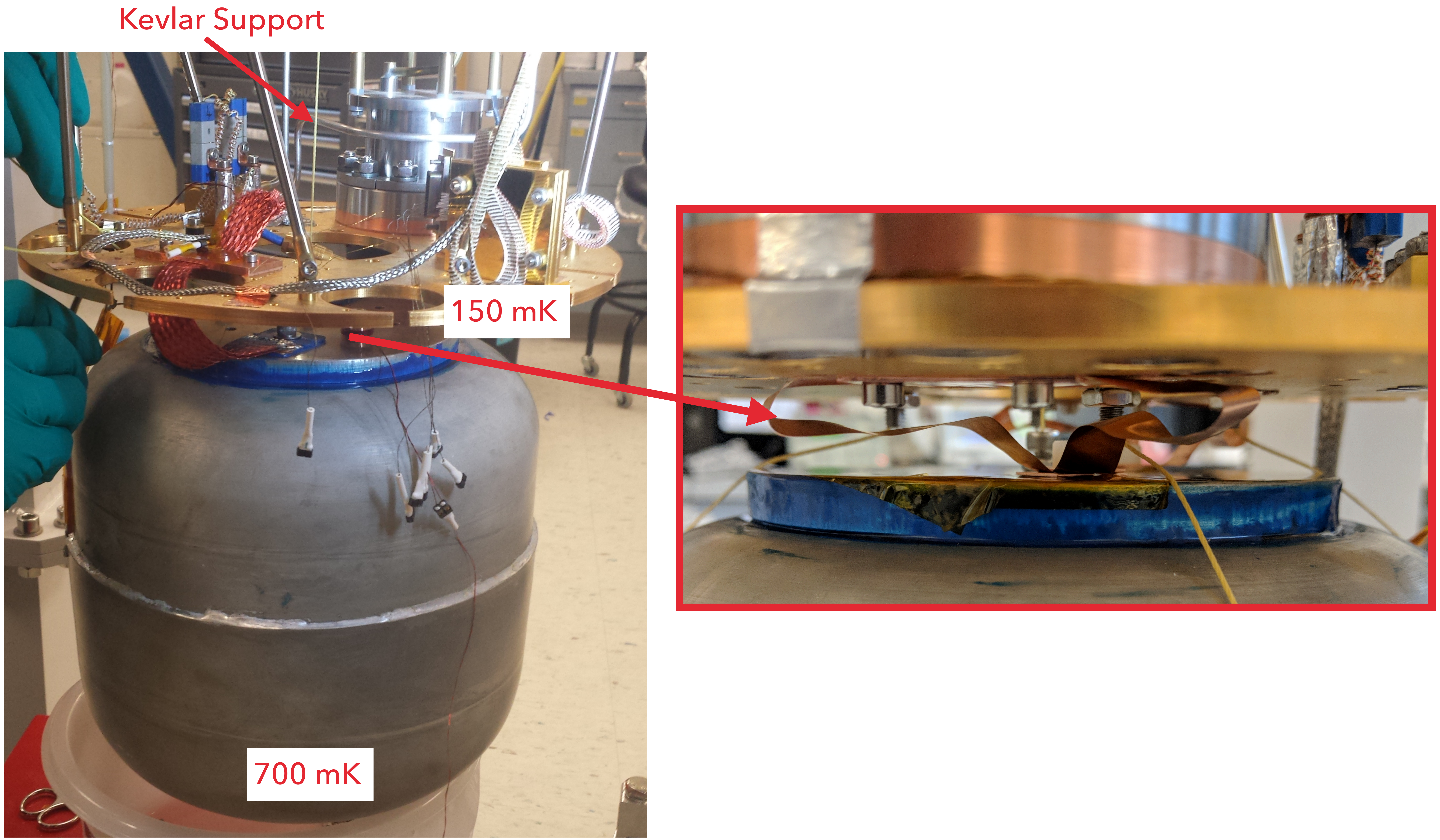
Dissecting ABRACADABRA-10 cm



Dissecting ABRACADABRA-10 cm



Mounting ABRA



Two Readout Strategies

Broadband

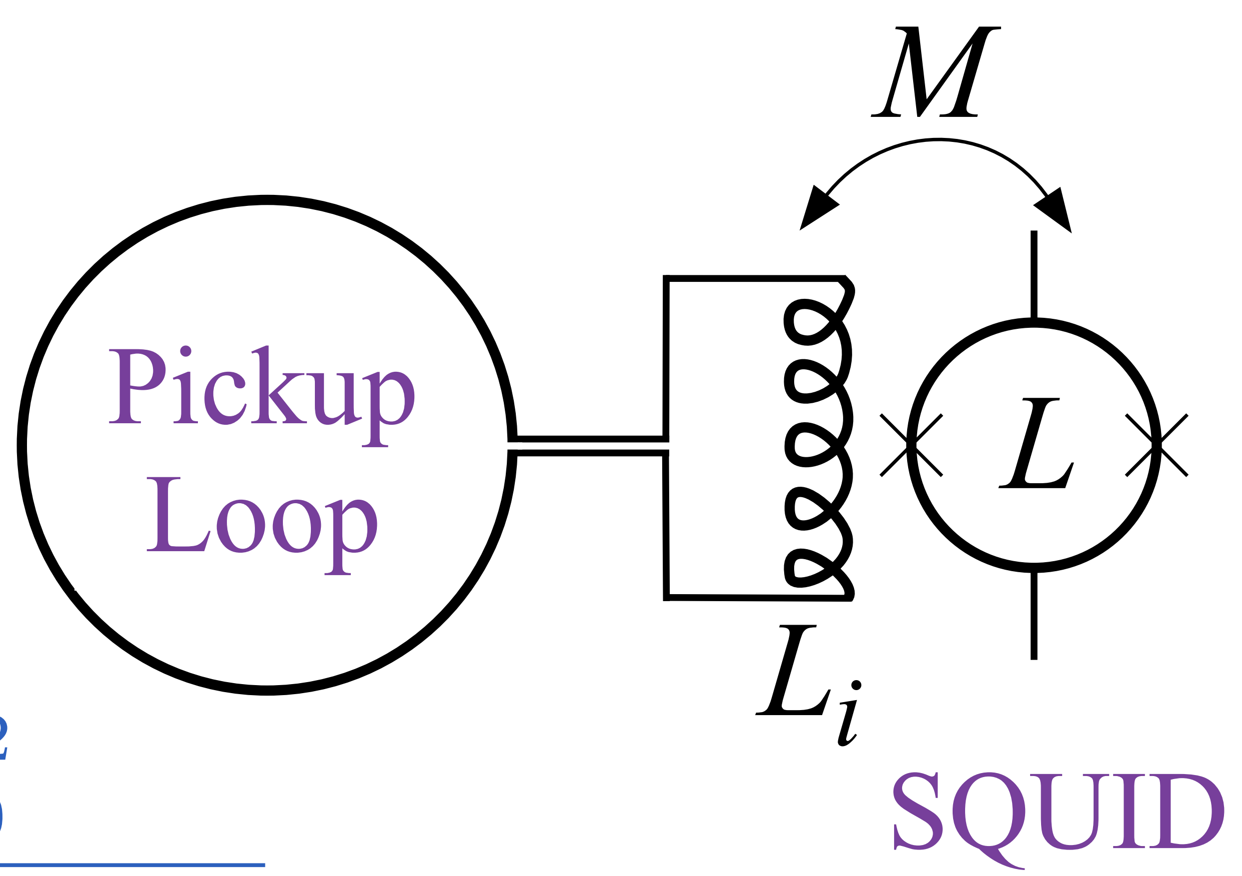
Scan all frequencies simultaneously

> ~50 Hz dominated by flux noise in SQUID magnetometer:

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

< ~50Hz 1/*f* noise dominates

Broadband Sensitivity: > ~50 Hz $\quad g_{a\gamma\gamma} \propto (\frac{m_a}{t})^{\frac{1}{4}} \frac{S_{\Phi,0}^{1/2}}{B_{\max} G V_B \sqrt{\rho_{\mathrm{DM}}}}$



Resonant

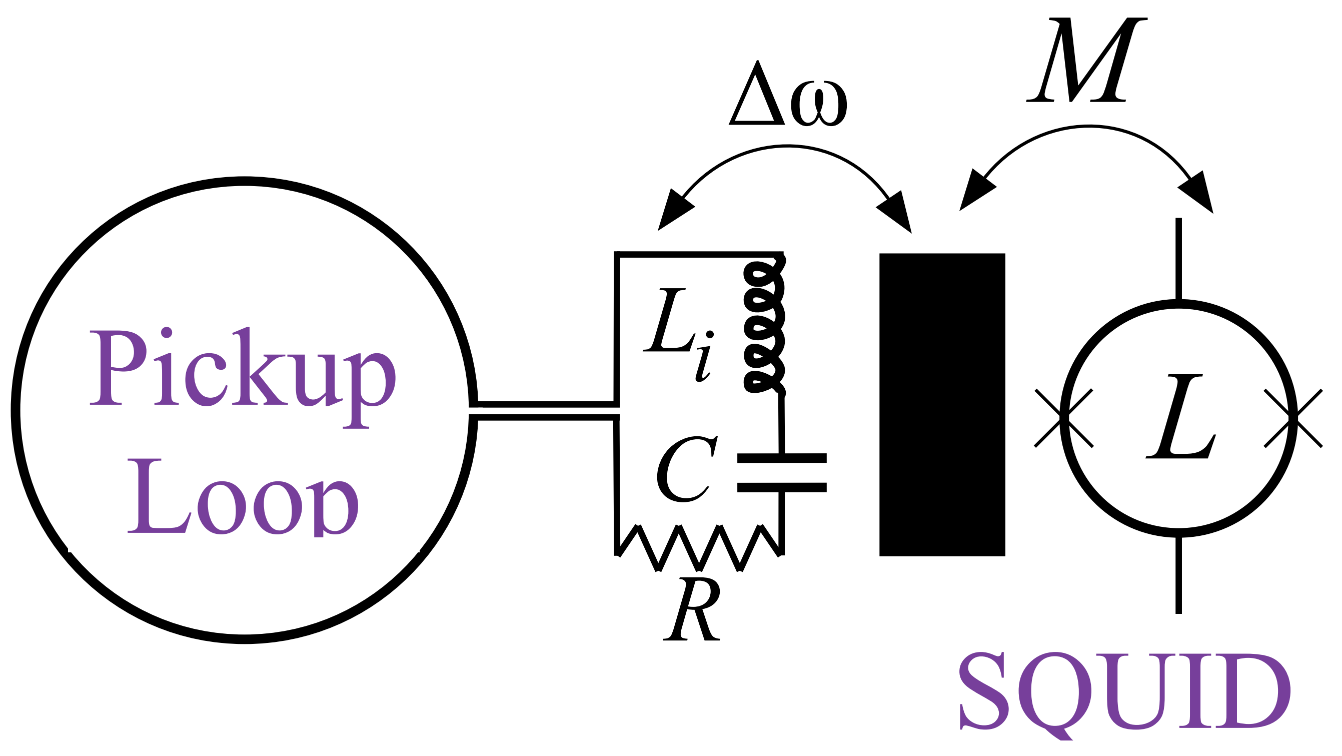
Resonance enhancement by adding capacitor with *Q* ~ 10^6

Scan across frequencies

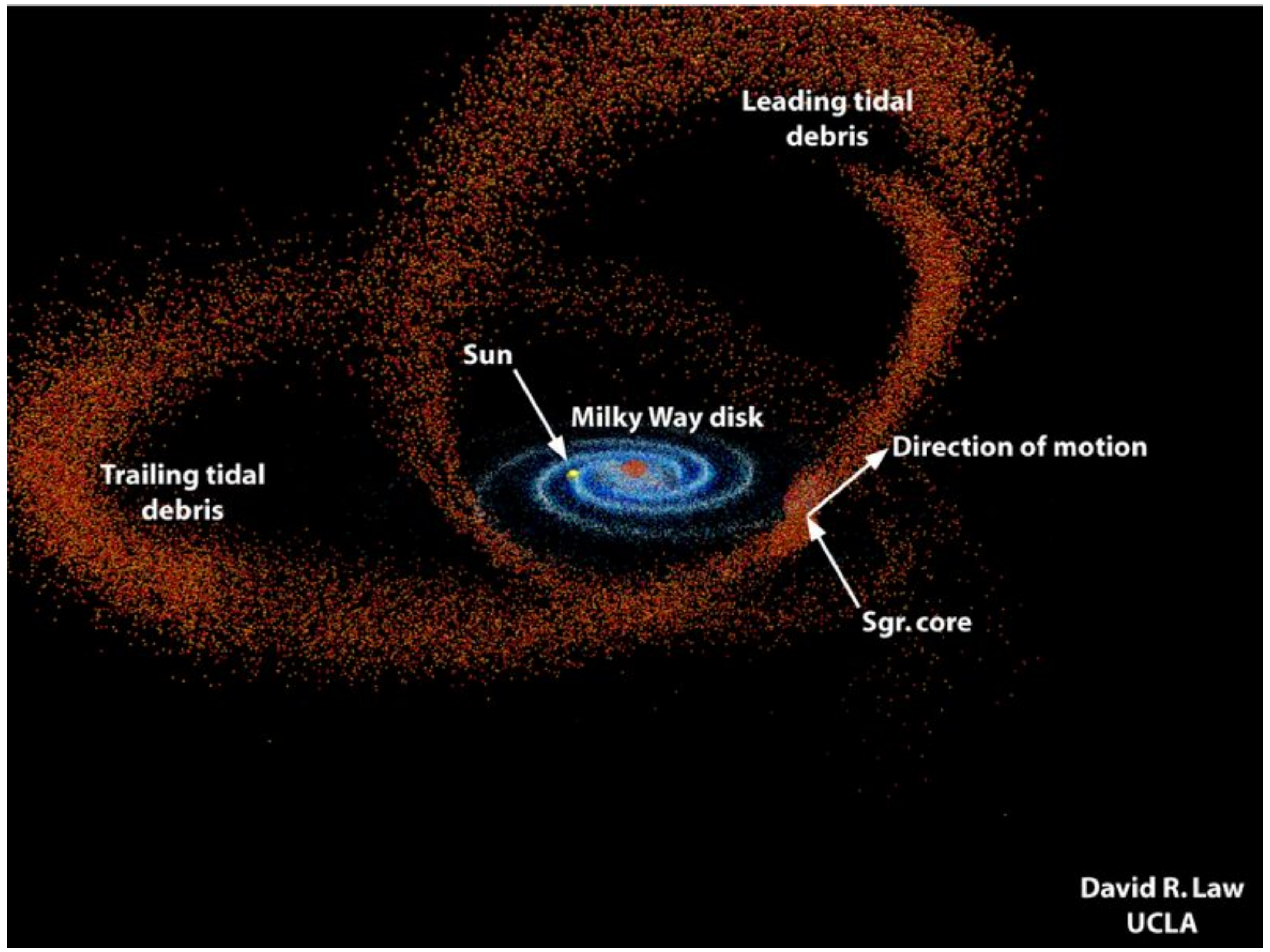
Thermal noise in pickup loop dominates

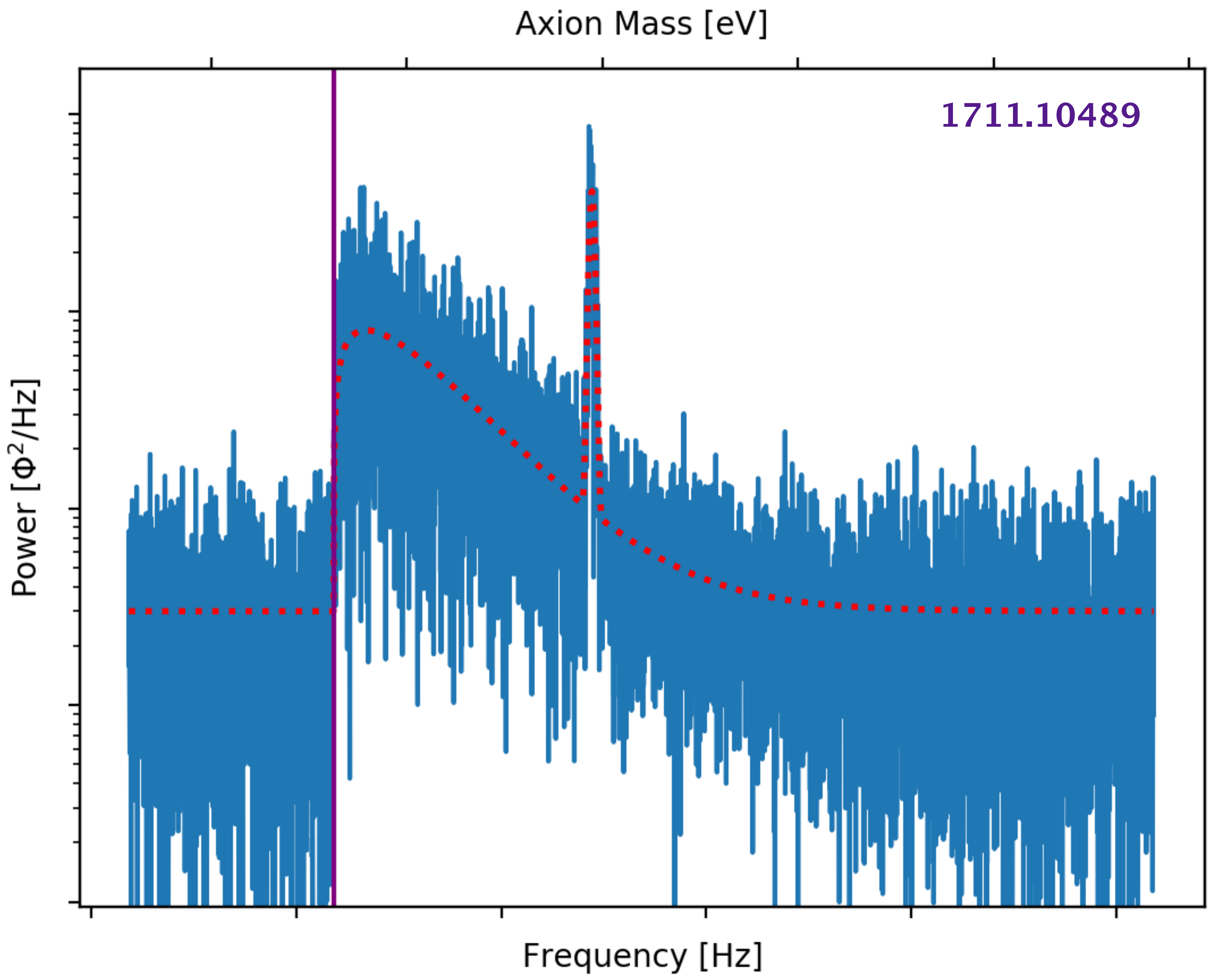
Resonance Mode Sensitivity:

$$g_{a\gamma\gamma} \propto \sqrt{L_T}(\frac{1}{m_a t})^{\frac{1}{4}} \frac{1}{B_{\max} G V_B} \sqrt{\frac{k_B T}{\rho_{\mathrm{DM}} Q_0}}$$



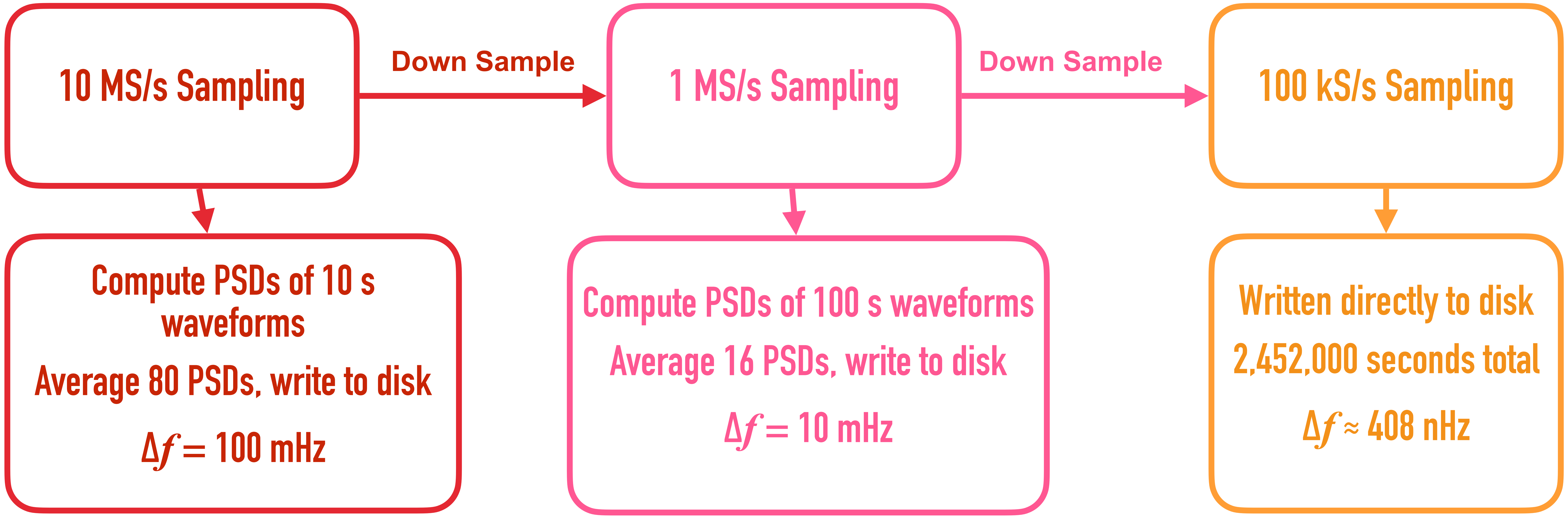
Axion Astrophysics





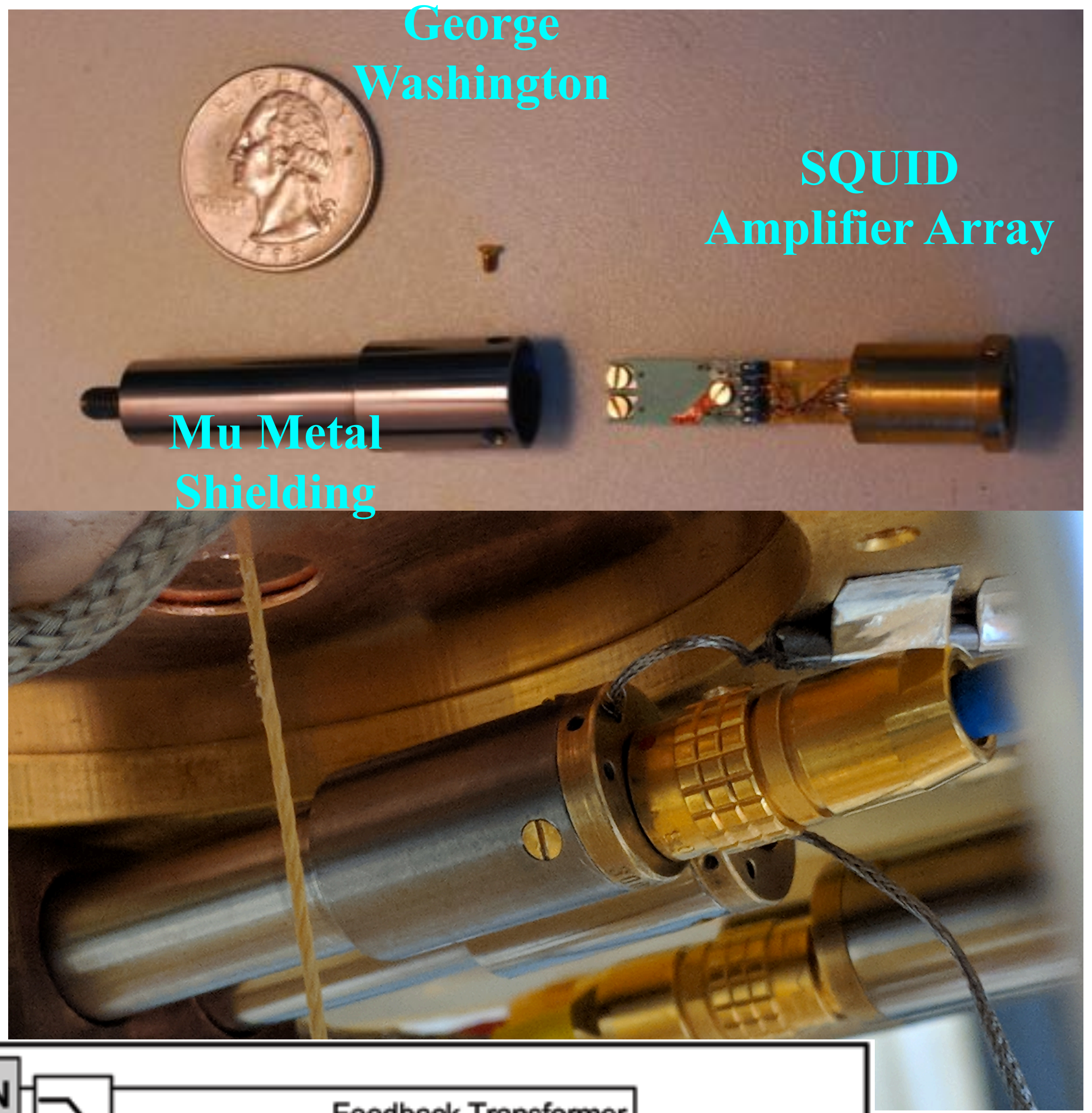
Broadband Data Collection Procedure

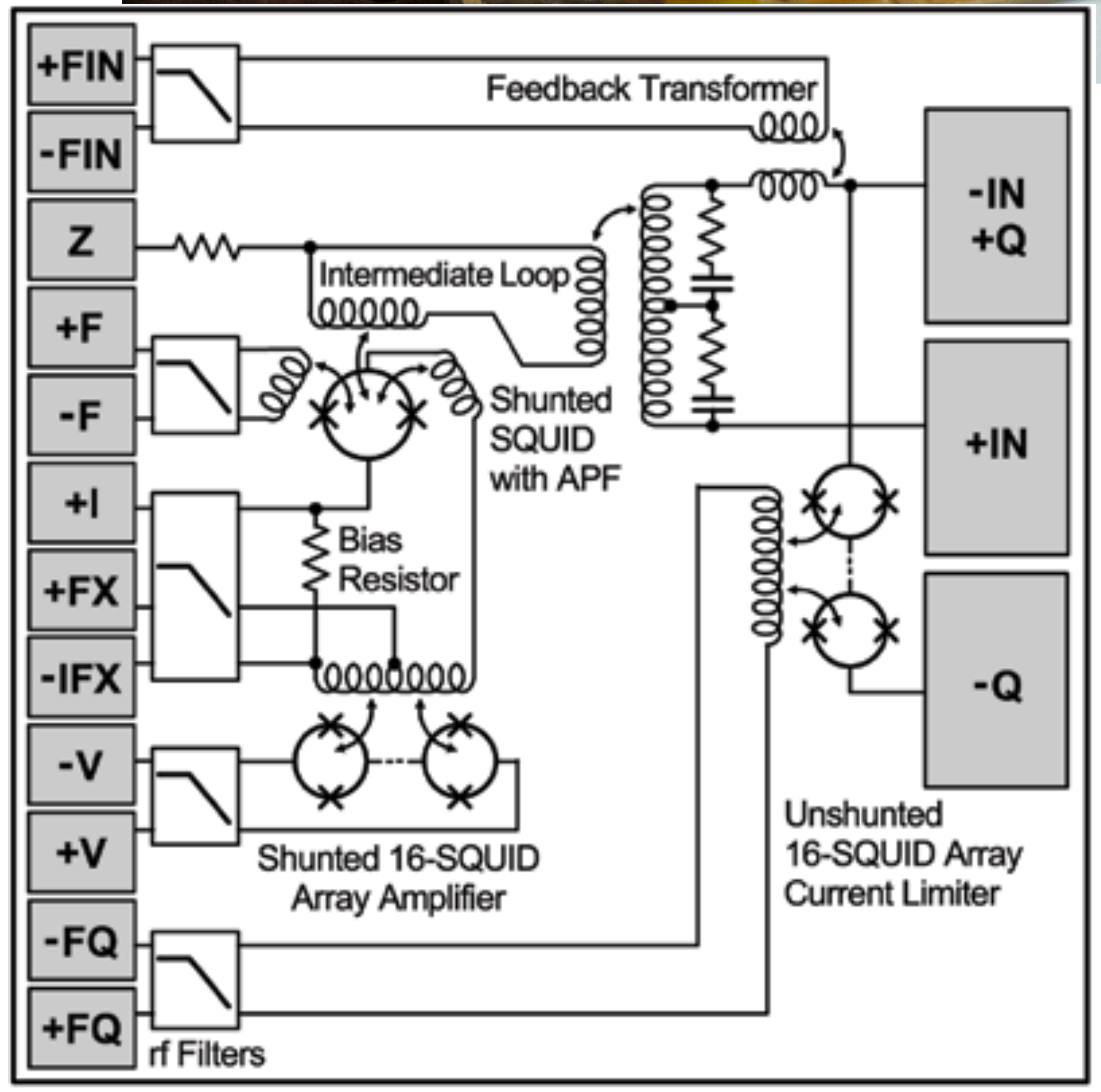
- Collected data with magnet on continuously for 4 weeks from July - August
- AlazarTech ATS9870 8-bit Digitizer locked to a Rb oscillator frequency standard
- 10 MS/s for 2.4 × 10^6 seconds (25T samples total)
- Apply FFTW on-the-fly on DAQ machine to compute Power Spectral Distributions (PSD)
- Acquisition (currently) limited to 1 cpu and 8 TB max data size



SQUID Readout

- Off-the-shelf Magnicon DC SQUIDs
  - 2 Stage
  - Typical noise floor ~1 $\mu\Phi_0/(\mathrm{Hz})^{1/2}$
  - Optimized for operation < 1 K
  - Typical gain of ~1.3 V/Φ_0
- No resonator (i.e. broadband readout)





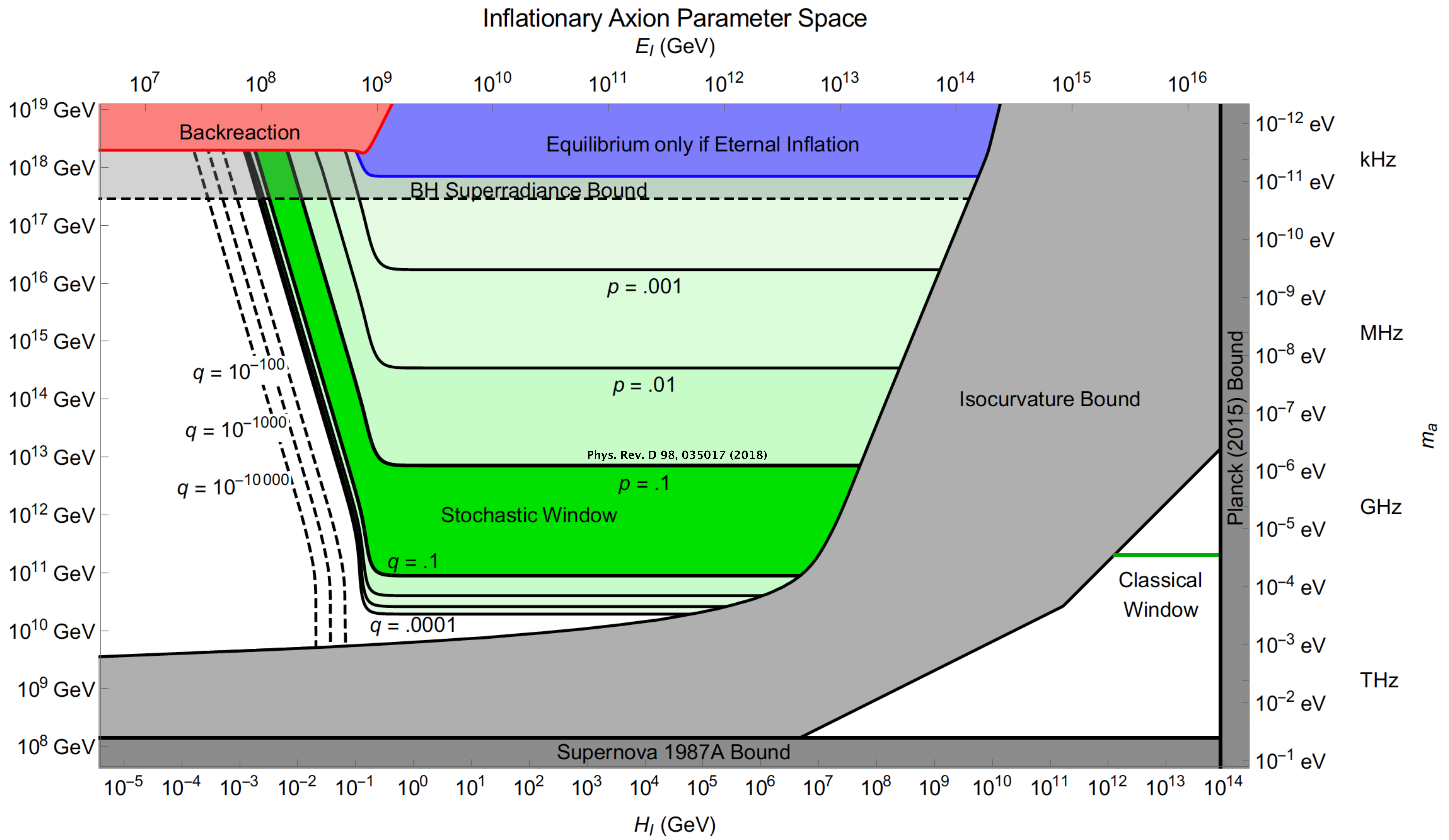
DM Axions Below 1μeV

- Pre-inflation PQ symmetry breaking allows axion masses 10^{-12} to 10^{-4} eV or even beyond

- GUT Scale Axion at ~ 1 neV ($f_a \sim 10^{15}$ GeV) generic feature of String Theories

- Many proposals exist for removing fine tuning of θ required for $m_a \ll 1\mu$eV. Typically require new particles.

- Or can just require long-scale inflation, eg. Phys. Rev. D 98, 035017 (2018)



Inflationary Axion Parameter Space
E_I (GeV)
10^7 10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16}
10^{19} GeV
10^{18} GeV
10^{17} GeV
10^{16} GeV
10^{15} GeV
10^{14} GeV
10^{13} GeV
10^{12} GeV
10^{11} GeV
10^{10} GeV
10^9 GeV
10^8 GeV
Backreaction
Equilibrium only if Eternal Inflation
BH Superradiance Bound
$p = .001$
$p = .01$
Phys. Rev. D 98, 035017 (2018)
$p = .1$
Stochastic Window
$q = .1$
$q = .0001$
$q = 10^{-100}$
$q = 10^{-1000}$
$q = 10^{-10\,000}$
Isocurvature Bound
Planck (2015) Bound
Classical Window
Supernova 1987A Bound
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14}
H_I (GeV)
10^{-12} eV
10^{-11} eV
10^{-10} eV
10^{-9} eV
10^{-8} eV
10^{-7} eV
10^{-6} eV
10^{-5} eV
10^{-4} eV
10^{-3} eV
10^{-2} eV
10^{-1} eV
kHz
MHz
GHz
THz
m_a