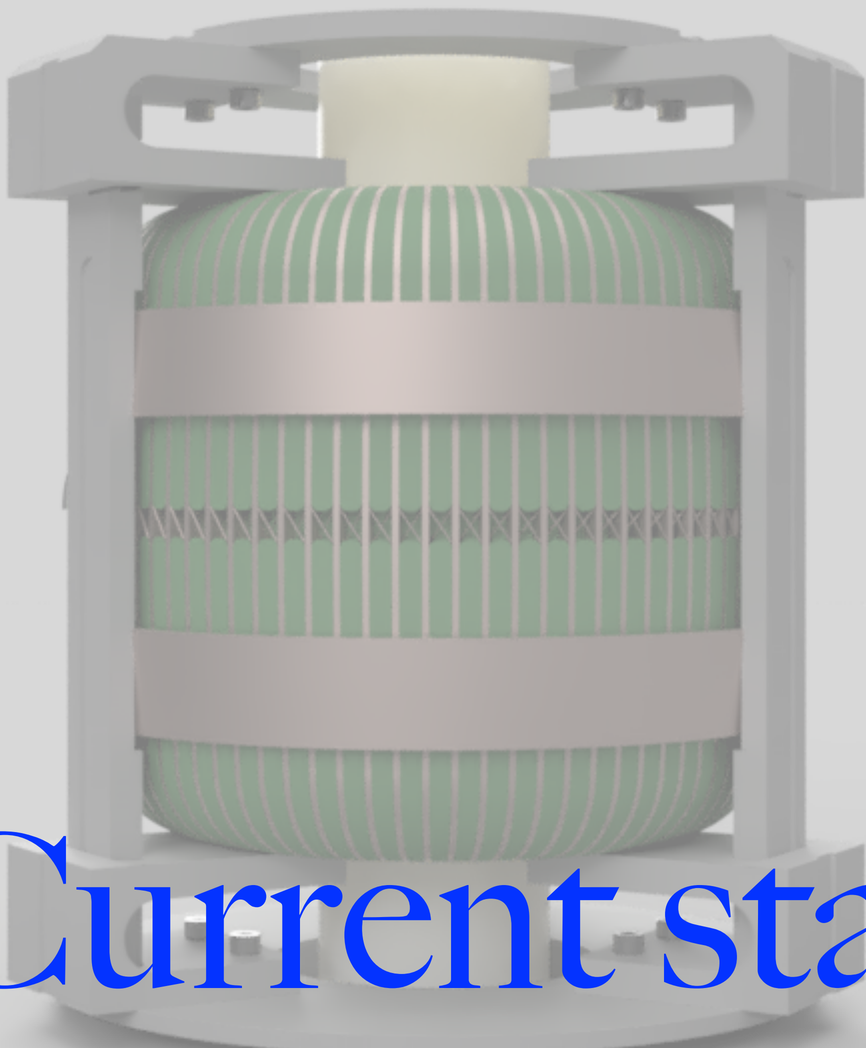
ABRACADABRA:

Current status and future plans

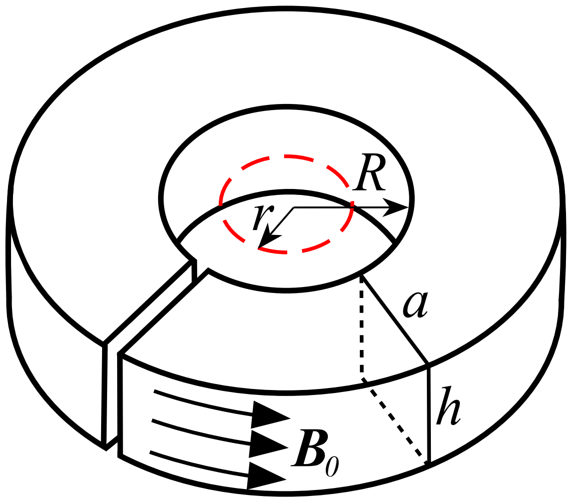


Yoni Kahn
UIUC

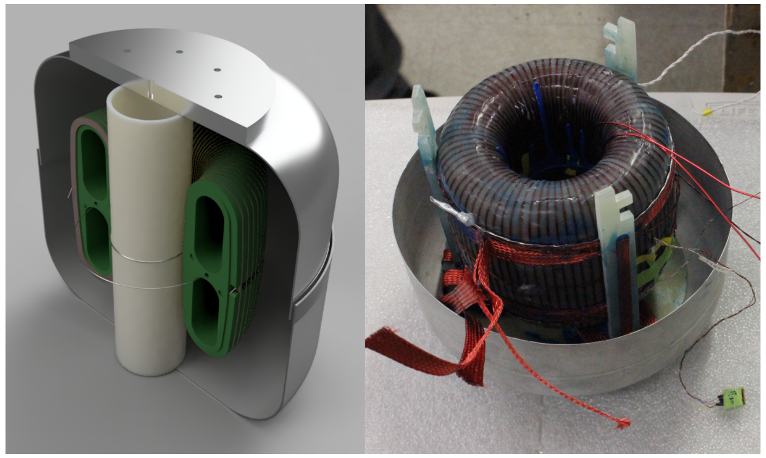
LDMA 2019, Venice, 11/22/19

Outline

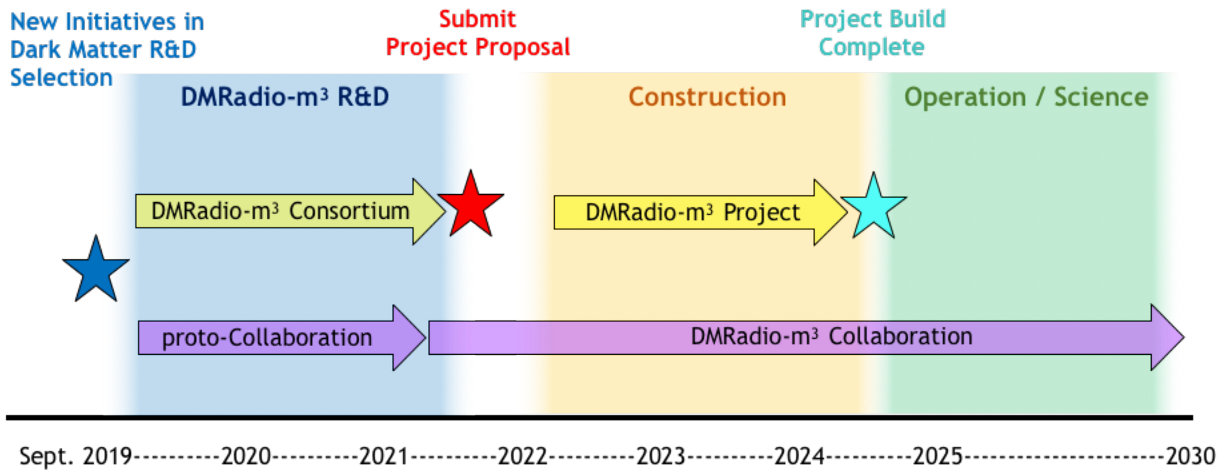
1. ABRA theory



2. ABRA-10cm



3. ABRA+DMRadio Future



Axion searches with magnetic fields

$$\underbrace{\nabla \times \mathbf{B}_a = \frac{\partial \mathbf{E}_a}{\partial t}} - g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

Cavity regime: $\lambda_{\mathrm{Comp}} \sim R_{\mathrm{exp}}$

e.g. ADMX

$$\nabla \times \mathbf{B}_a = \cancel{\frac{\partial \mathbf{E}_a}{\partial t}} \underbrace{- g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}}_{\mathbf{J}_{\mathrm{eff}}}$$

Quasistatic regime: $\lambda_{\mathrm{Comp}} \gg R_{\mathrm{exp}}$

e.g. ABRACADBRA

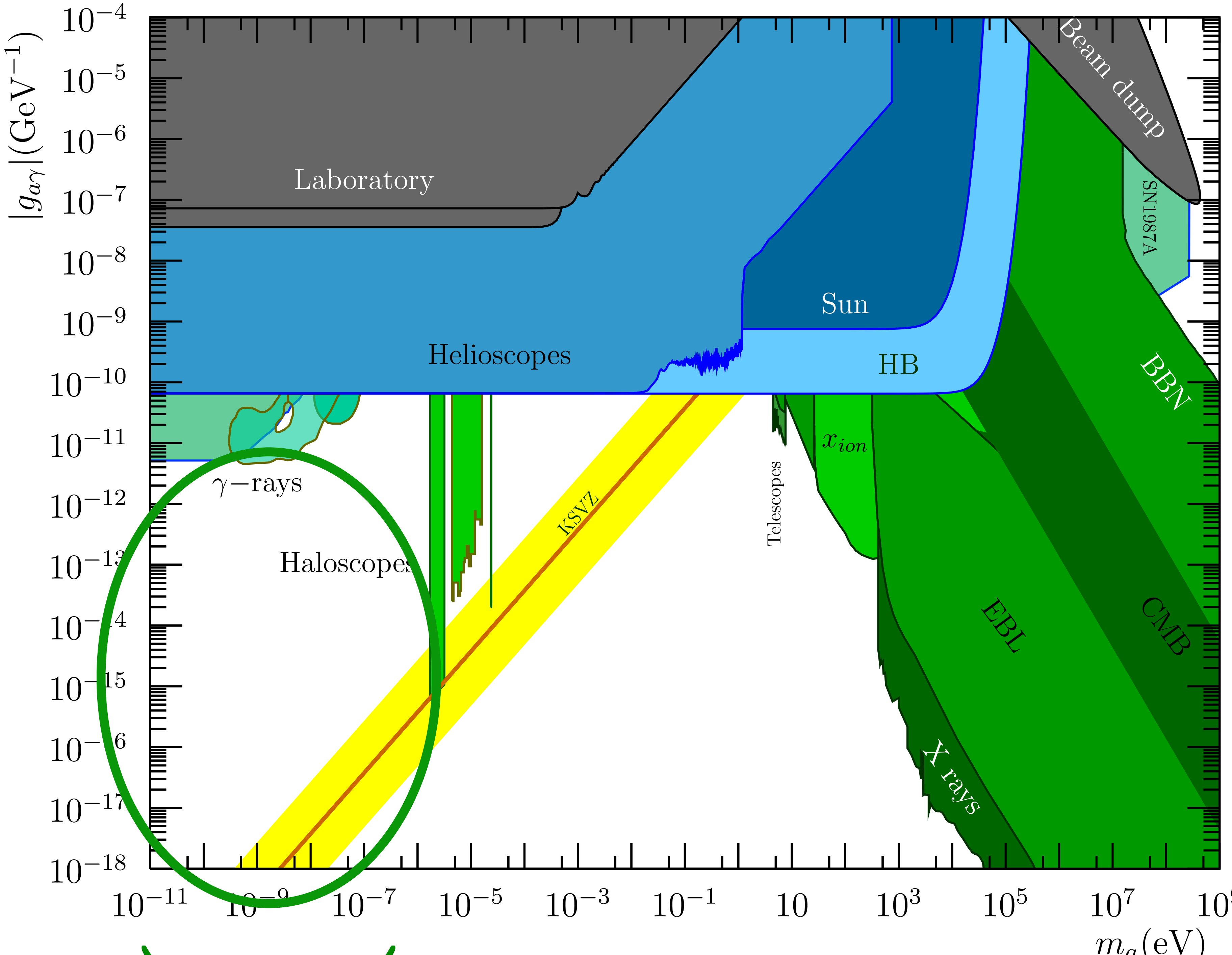
$$\cancel{\nabla \times \mathbf{B}_a} = \frac{\partial \mathbf{E}_a}{\partial t} - g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

Radiation regime: $\lambda_{\mathrm{Comp}} \ll R_{\mathrm{exp}}$

e.g. MADMAX

Axion-photon parameter space

[Irastorza and Redondo, Prog. Part. Nucl. Phys. 2018]



Plenty of room at the bottom!

Quasistatic

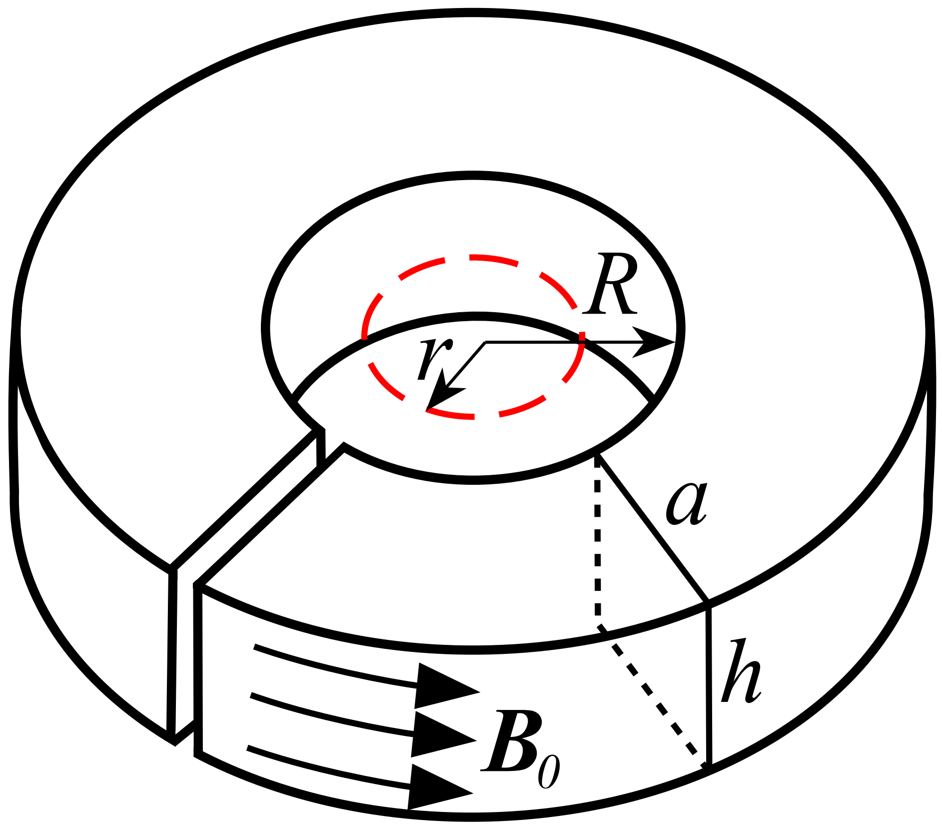
Cavity

Radiation

Quasistatic regime: ABRACADABRA

A **B**roadband/**R**esonant **A**pproach to **C**osmic **A**xion **D**etection with an **A**mplifying **B**-field **R**ing **A**pparatus

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

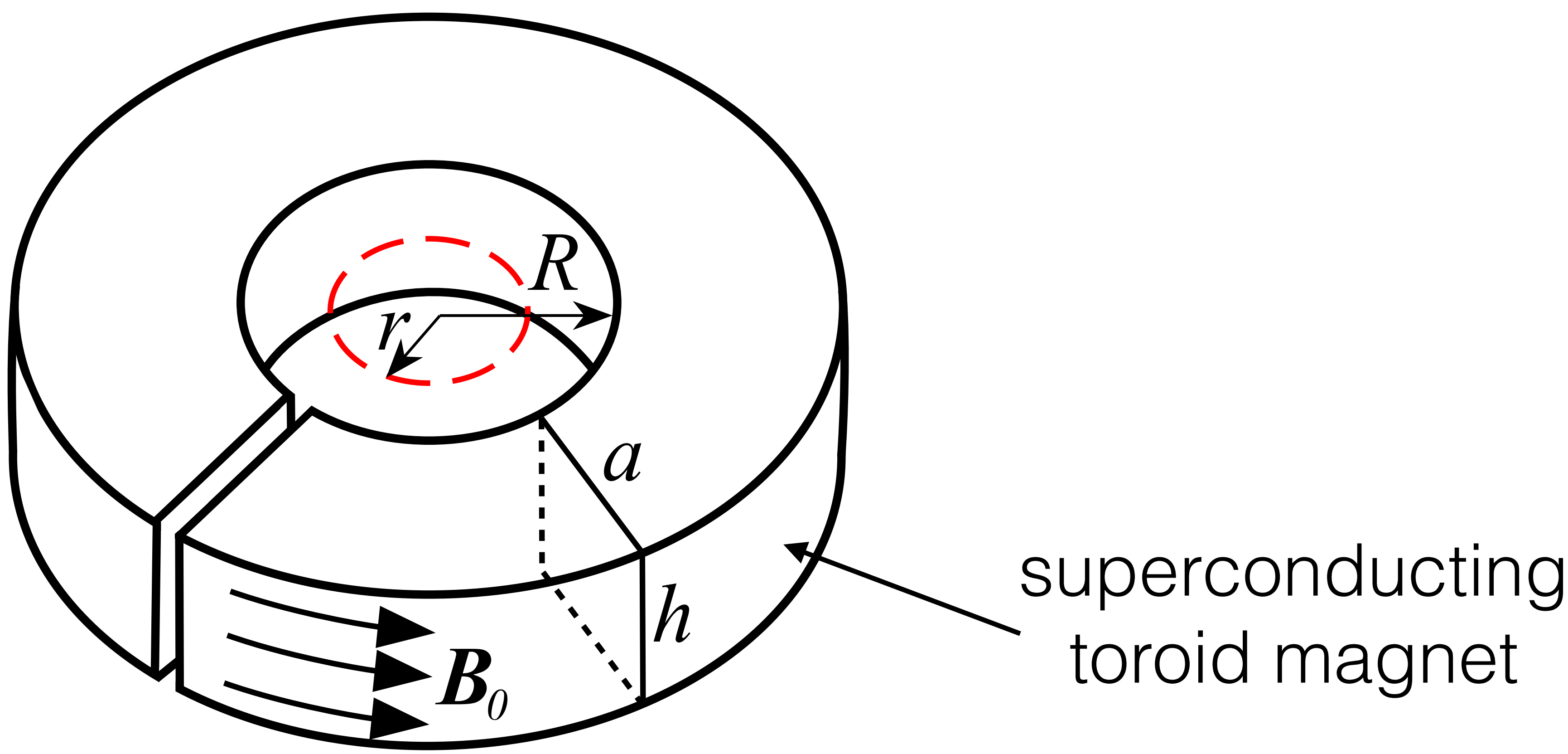


[**YK**, Safdi, Thaler, PRL 2016]

Quasistatic regime: ABRACADABRA

A Broadband/**R**esonant **A**pproach to **C**osmic **A**xion **D**etection with an **A**mplifying **B**-field **R**ing **A**pparatus

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



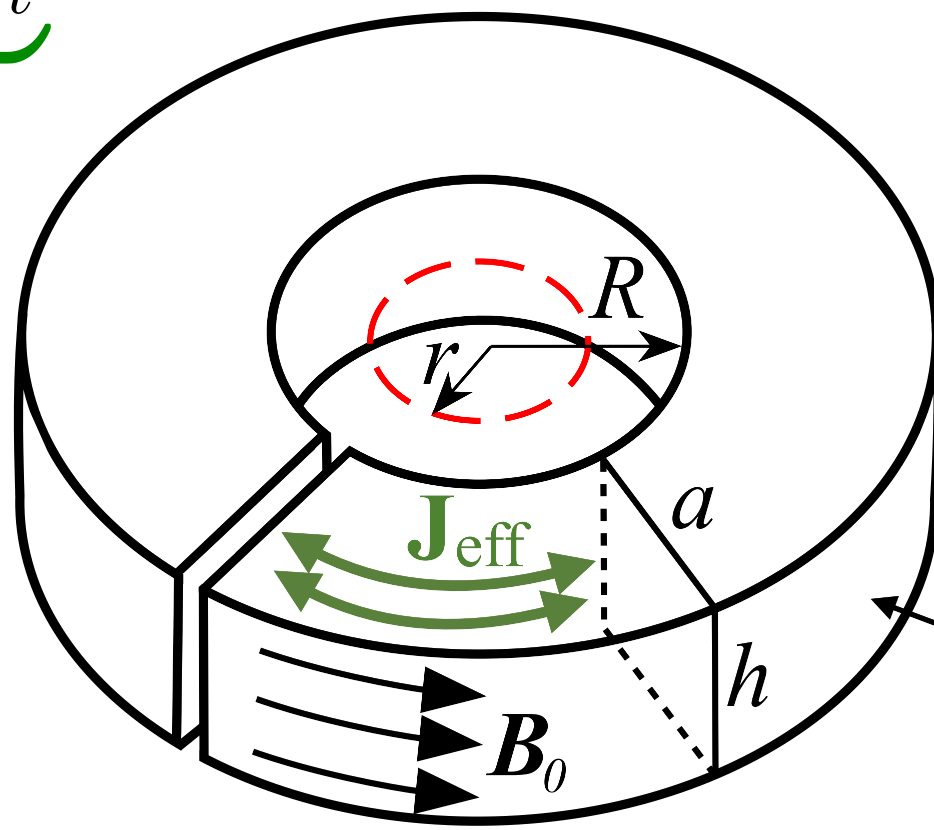
[**YK**, Safdi, Thaler, PRL 2016]

Quasistatic regime: ABRACADABRA

A **B**roadband/**R**esonant **A**pproach to **C**osmic **A**xion **D**etection with an **A**mplifying **B**-field **R**ing **A**pparatus

$$\nabla \times \mathbf{B}_a = \cancel{\frac{\partial \mathbf{E}_a}{\partial t}} - \underbrace{g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}}_{\mathbf{J}_{\text{eff}}}$$

$$a(t) = \frac{\sqrt{2\rho_{\text{DM}}}}{m_a}\cos(m_a t)$$



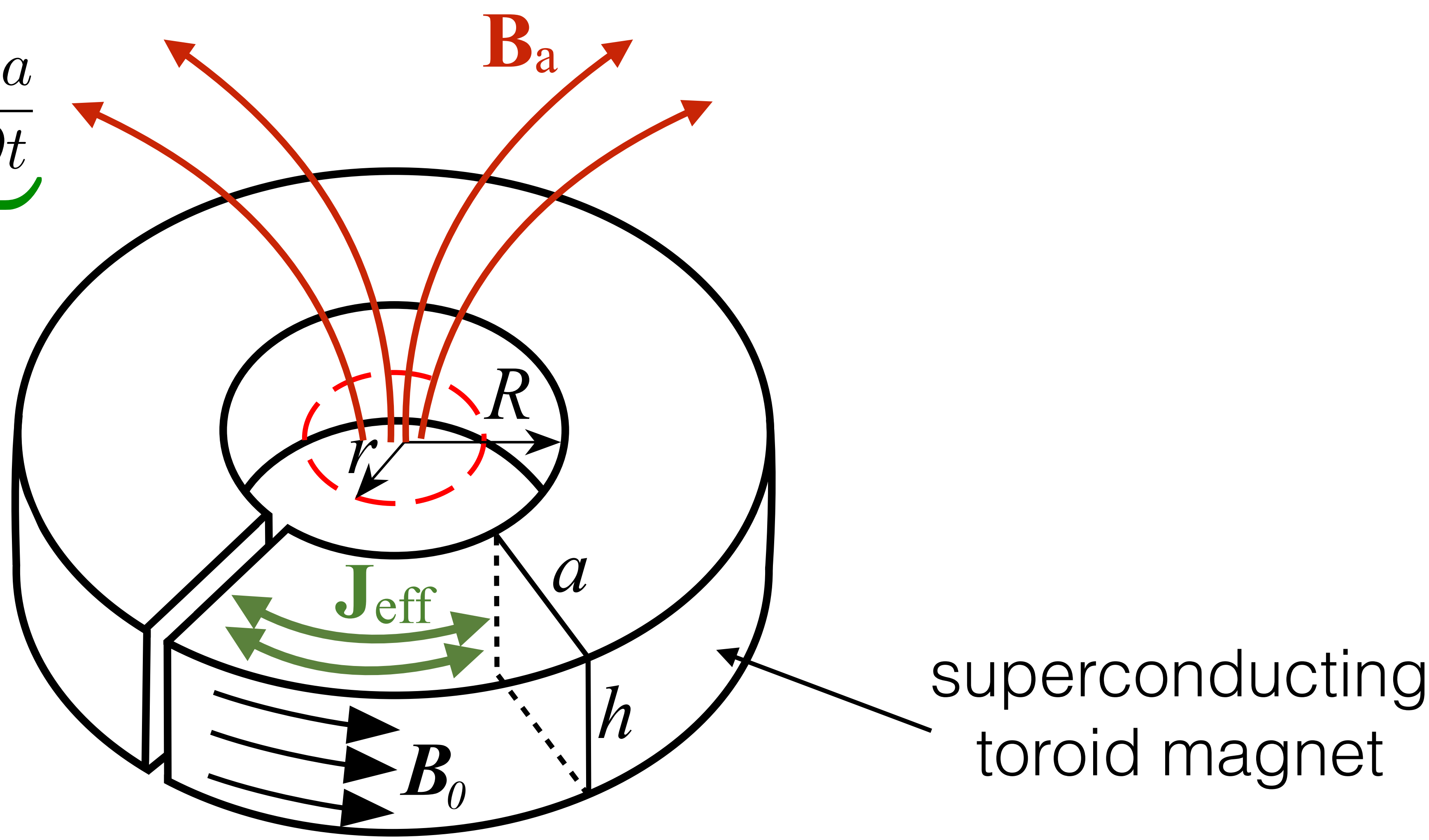
[**YK**, Safdi, Thaler, PRL 2016]

Quasistatic regime: ABRACADABRA

A **B**roadband/**R**esonant **A**pproach to **C**osmic **A**xion **D**etection with an **A**mplifying **B**-field **R**ing **A**pparatus

$$\nabla \times \mathbf{B}_a = \frac{\partial \mathbf{E}_a}{\partial t} - \underbrace{g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}}_{\mathbf{J}_{\text{eff}}}$$

$$a(t) = \frac{\sqrt{2\rho_{\text{DM}}}}{m_a}\cos(m_a t)$$



[**YK**, Safdi, Thaler, PRL 2016]

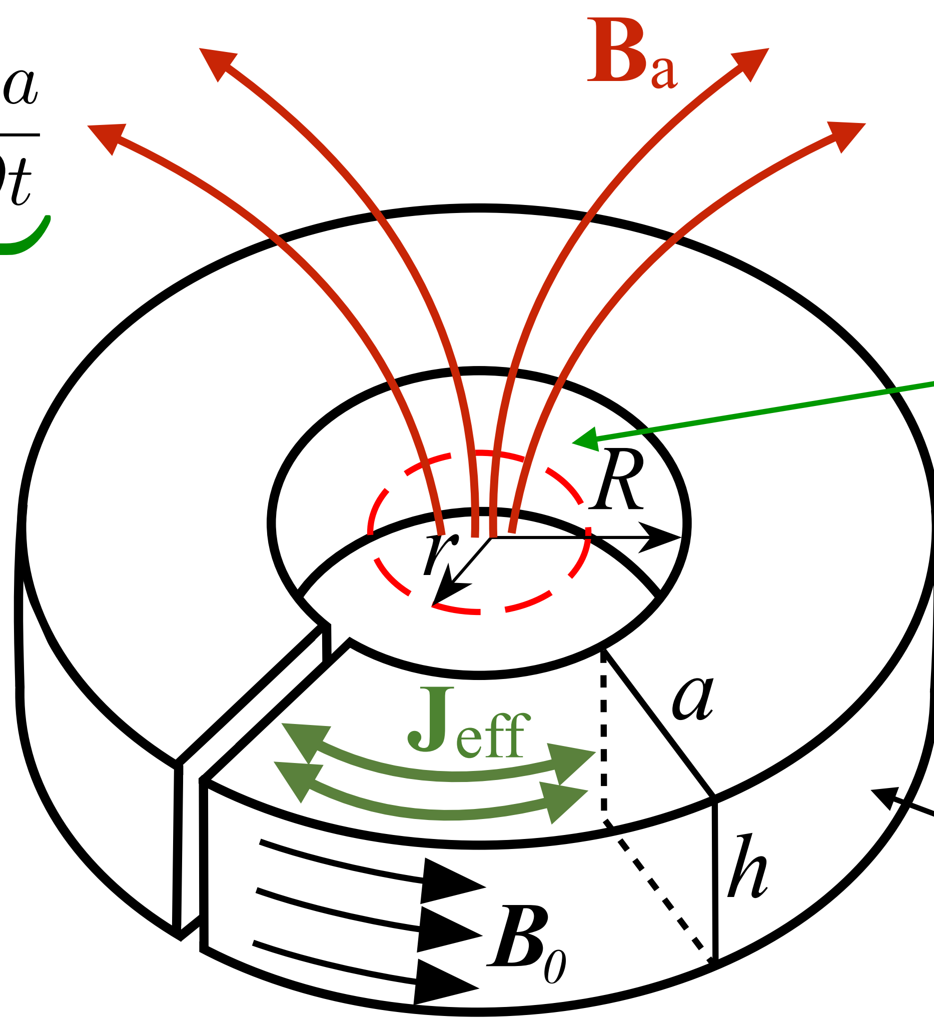
Quasistatic regime: ABRACADABRA

A Broadband/**R**esonant **A**pproach to **C**osmic **A**xion **D**etection with an **A**mplifying **B**-field **R**ing **A**pparatus

$$\nabla \times \mathbf{B}_a = \frac{\partial \mathbf{E}_a}{\partial t} - g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

$\mathbf{J}_{\text{eff}}$

$$a(t) = \frac{\sqrt{2\rho_{\text{DM}}}}{m_a}\cos(m_a t)$$



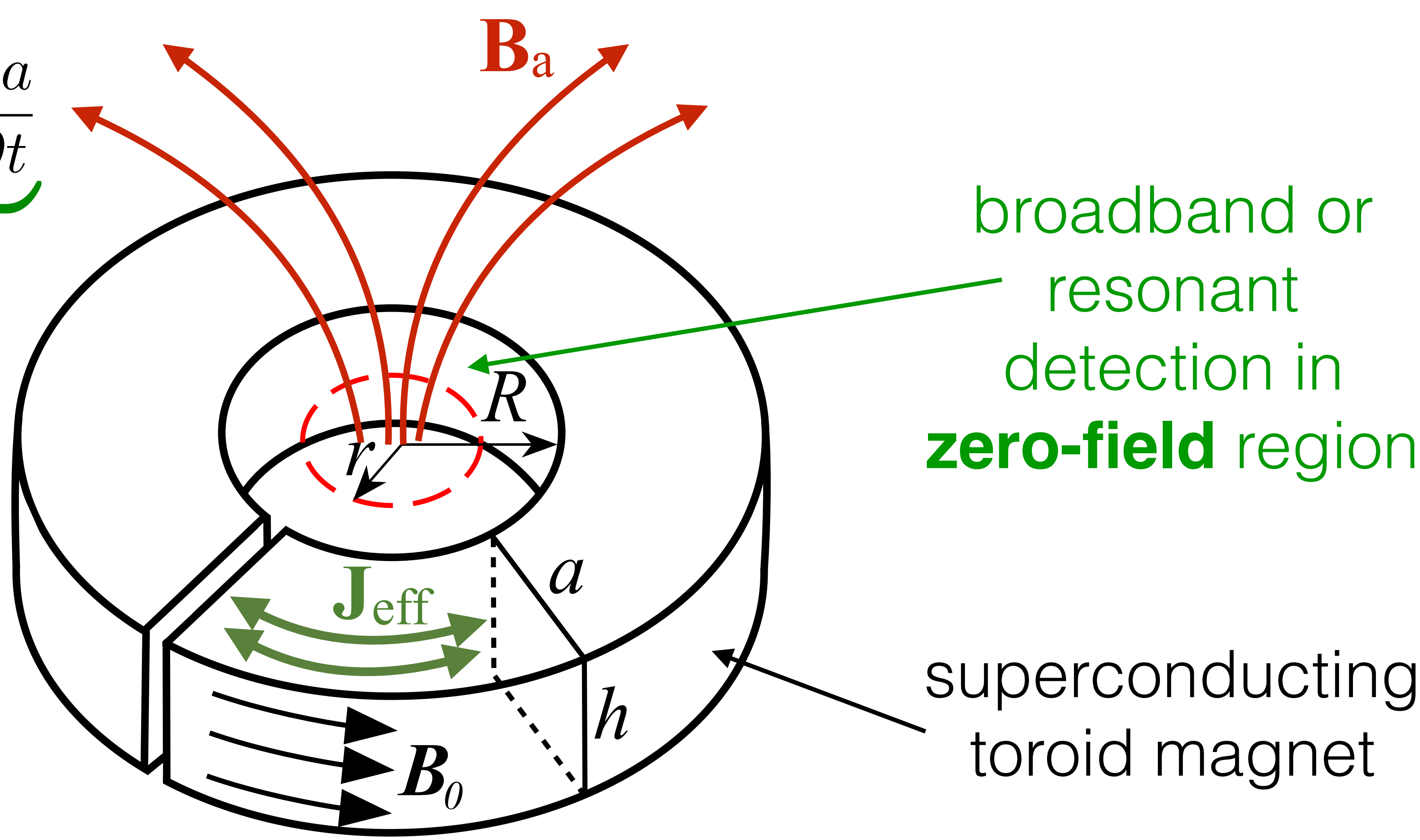
[**YK**, Safdi, Thaler, PRL 2016]

Quasistatic regime: ABRACADABRA

A **B**roadband/**R**esonant **A**pproach to **C**osmic **A**xion **D**etection with an **A**mplifying **B**-field **R**ing **A**pparatus

$$\nabla \times \mathbf{B}_a = \frac{\partial \mathbf{E}_a}{\partial t} - \underbrace{g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}}_{\mathbf{J}_{\text{eff}}}$$

$$a(t) = \frac{\sqrt{2\rho_{\text{DM}}}}{m_a}\cos(m_a t)$$



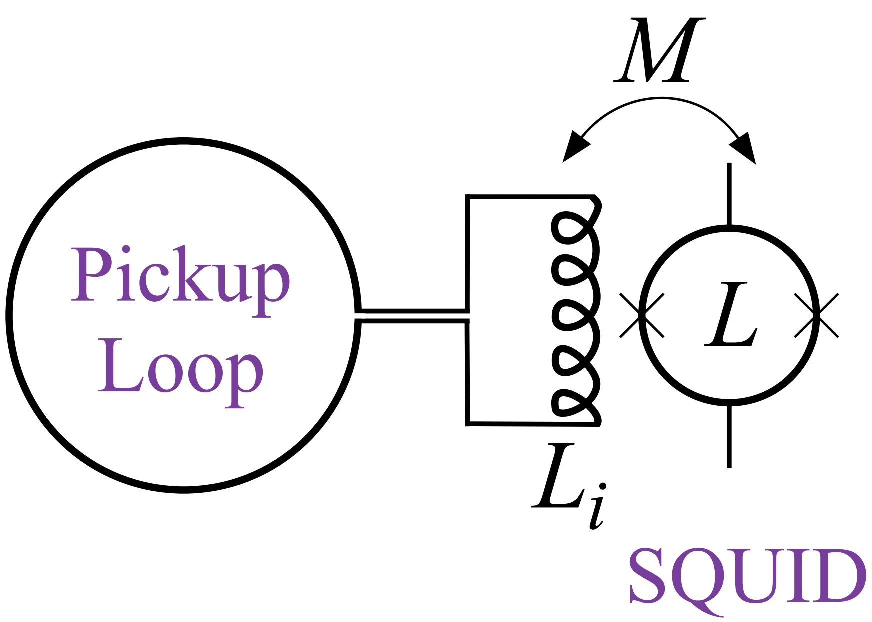
$$\langle \Phi(t)^2 \rangle \sim g_{a\gamma\gamma}^2 \rho_{\text{DM}} B_0^2 V^{5/3}$$

Volume enhancement at low masses compared to cavity

[**YK**, Safdi, Thaler, PRL 2016]

Two readout strategies

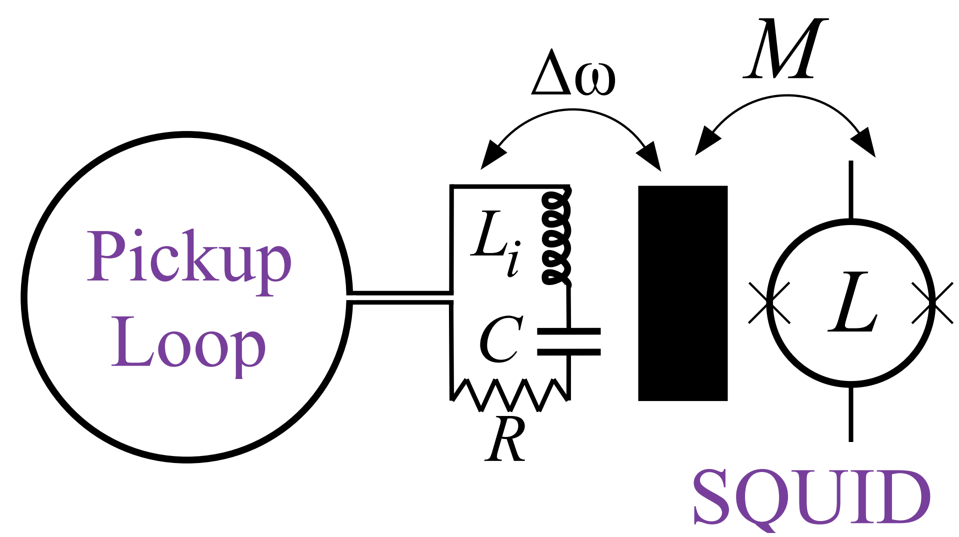
Broadband



$$g_{a\gamma\gamma}^{\mathrm{lim}} \propto \left(\frac{m_a}{t}\right)^{1/4} S_{\Phi,0}^{1/2}$$

Not optimal, but very useful
for initial search over wide range

Resonant



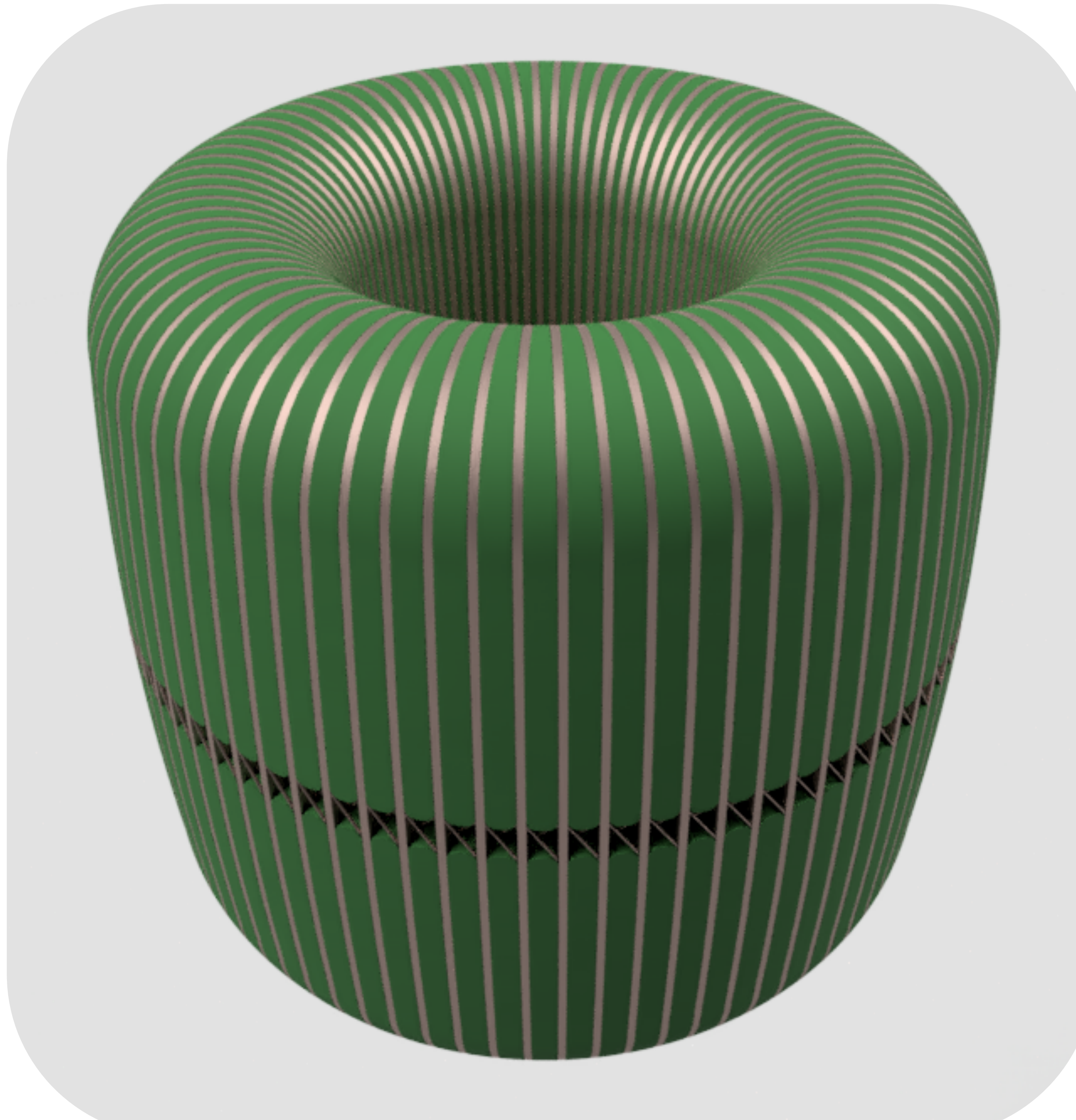
$$g_{a\gamma\gamma}^{\mathrm{lim}} \propto \left(\frac{1}{t}\right)^{1/4} \sqrt{\frac{k_B T}{Q_0}}$$

Theoretically optimal, but have
to pick a scan strategy
(exploit quantum speedup eventually)

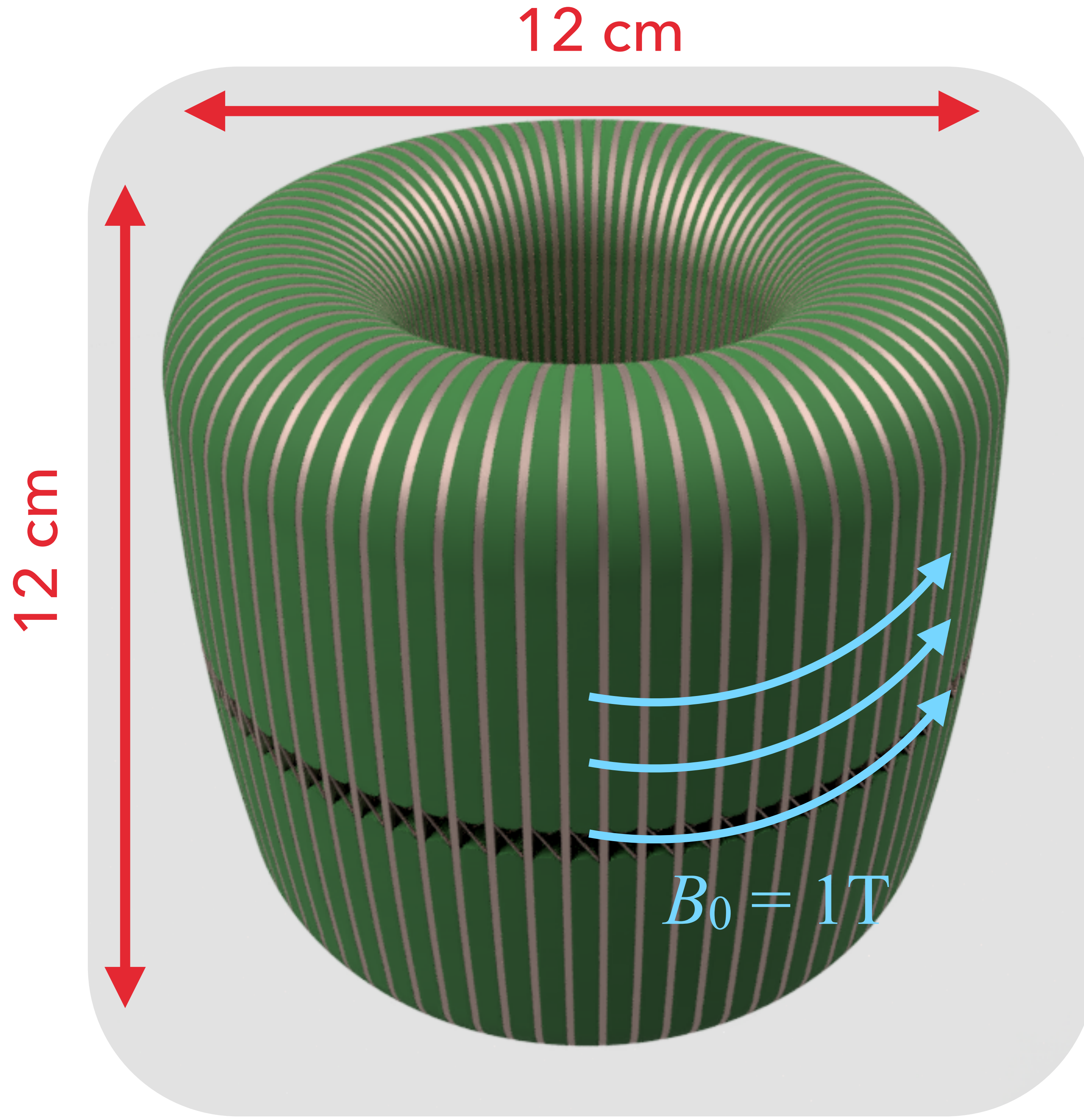
[Chaudhuri et al., arXiv:1803.01627]

Current apparatus (ABRA-10cm) uses broadband,
future version (DM Radio Cubic Meter) will incorporate resonator

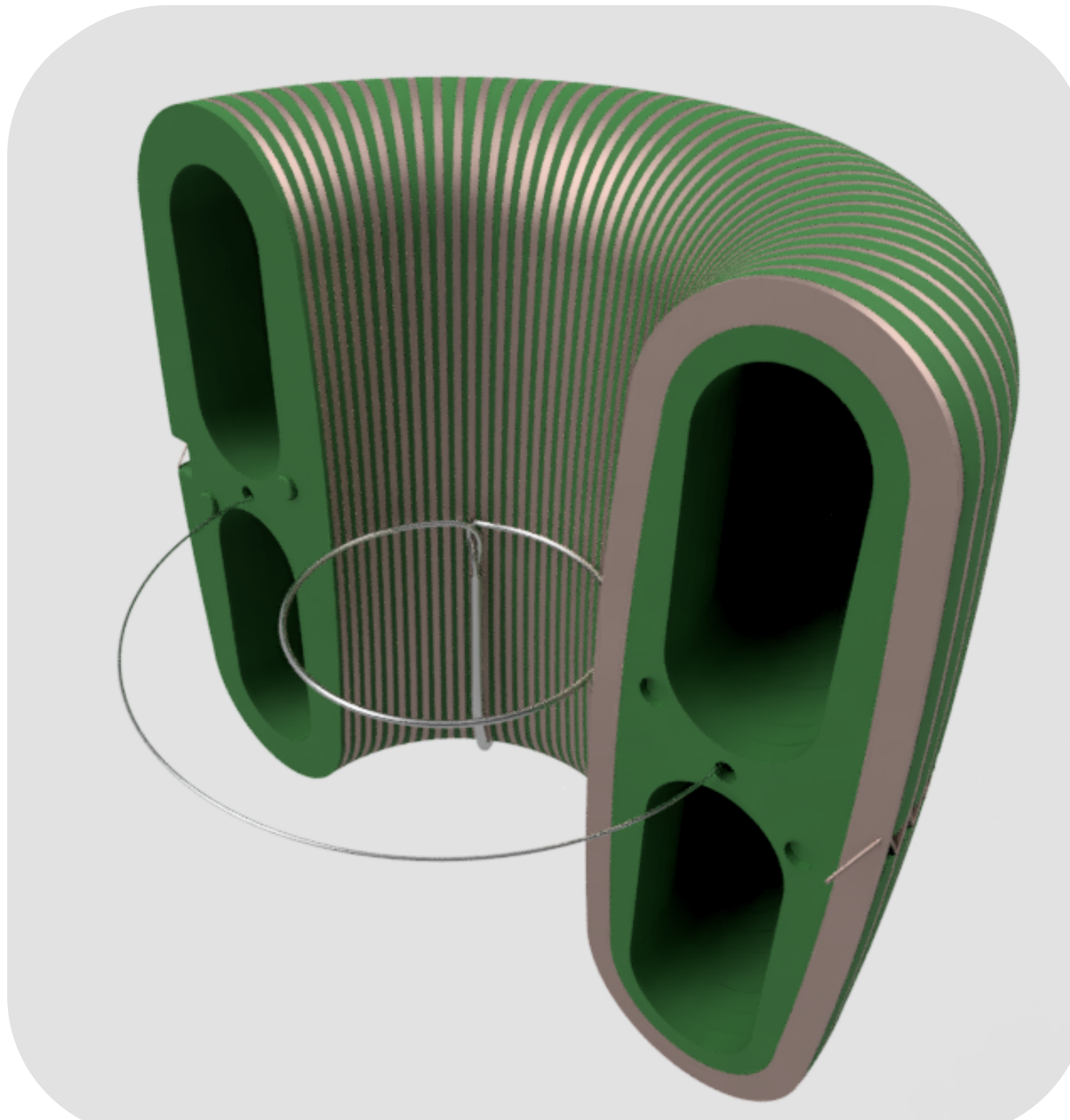
Dissecting ABRA-10cm



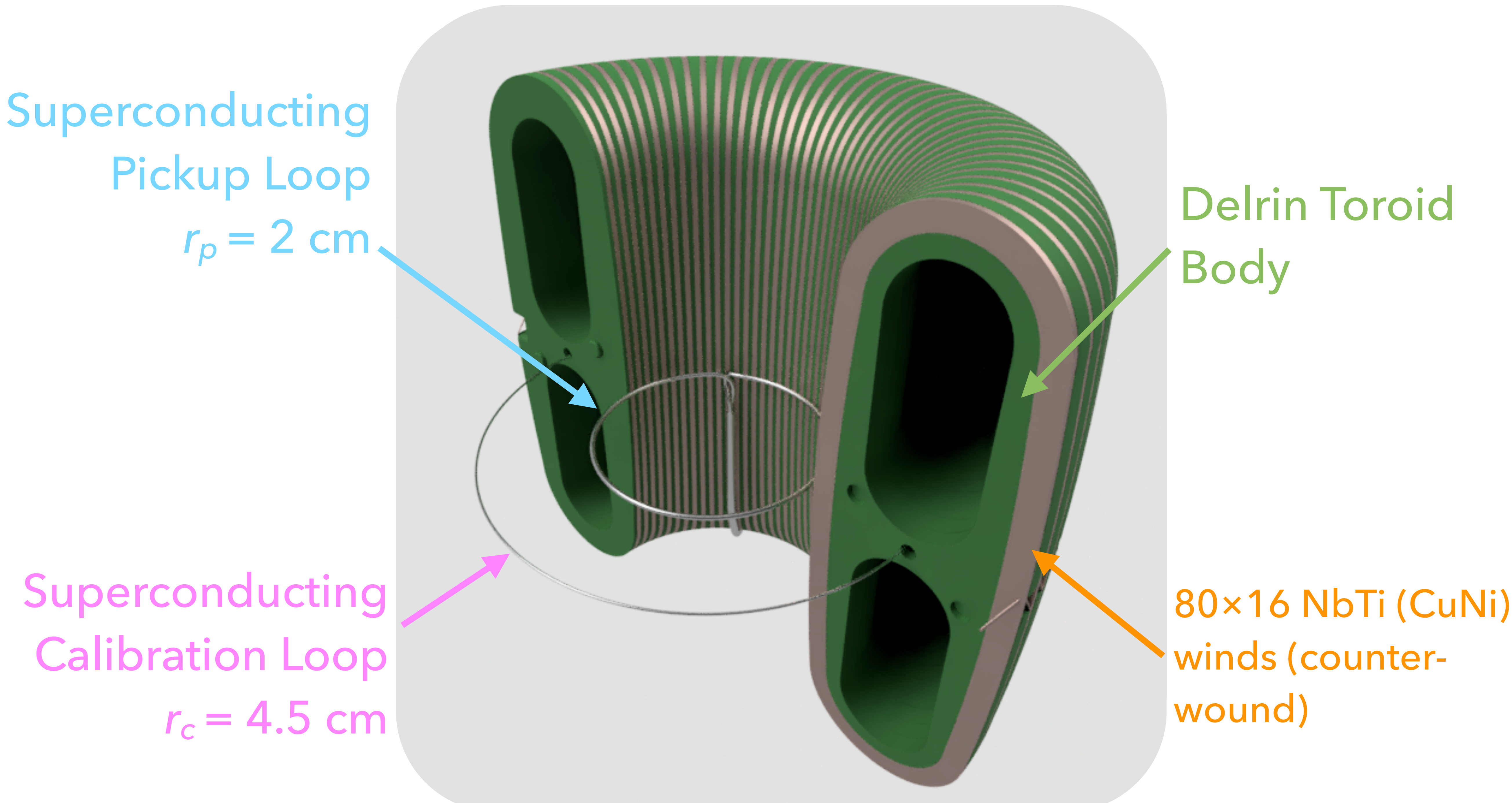
Dissecting ABRA-10cm



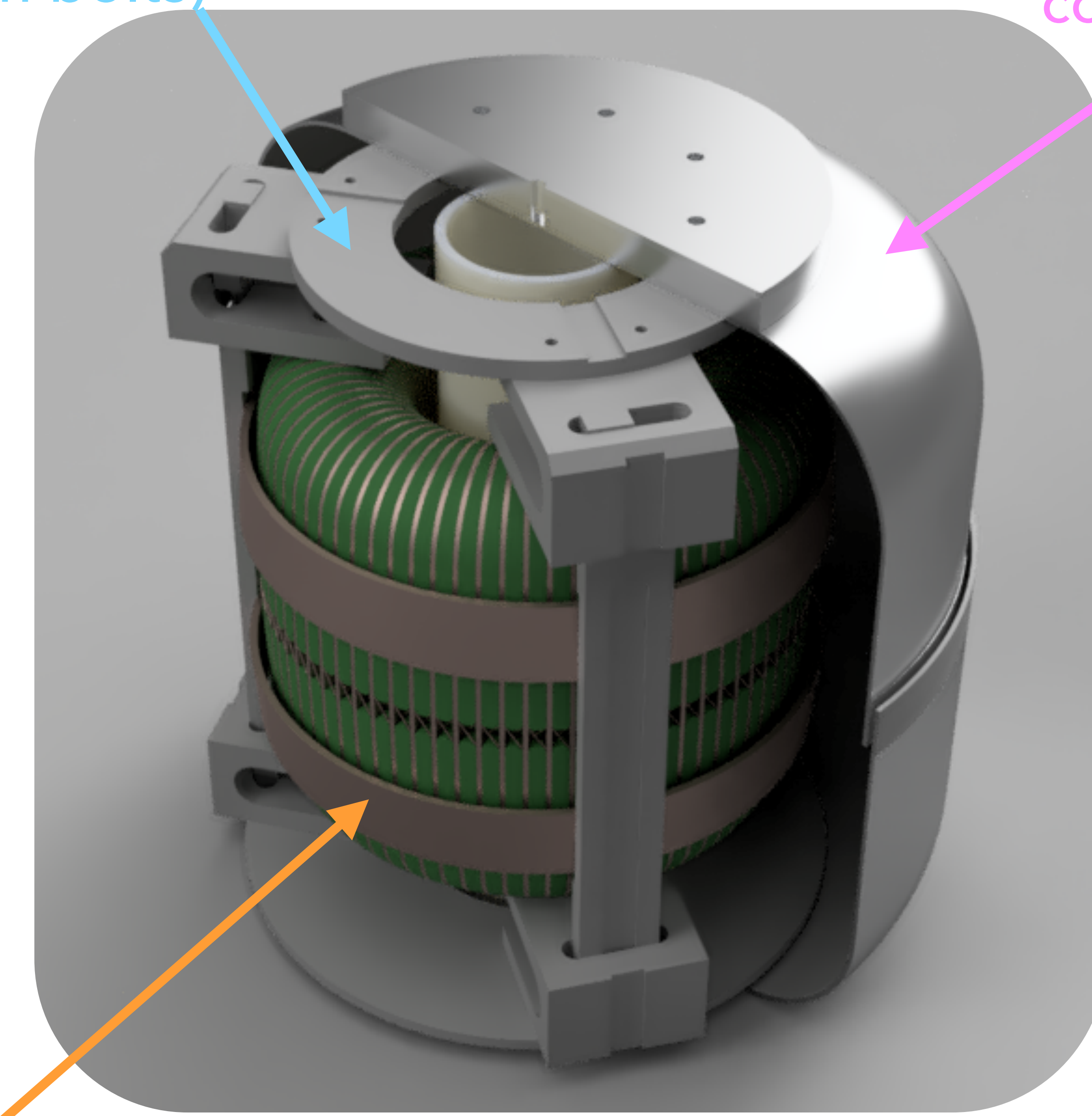
Dissecting ABRA-10cm



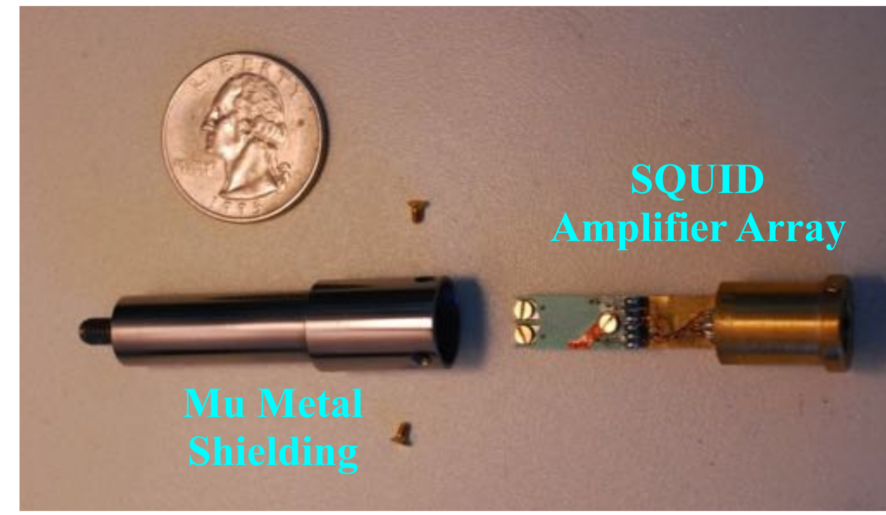
Dissecting ABRA-10cm



Dissecting ABRA-10cm



ABRA-10cm broadband readout



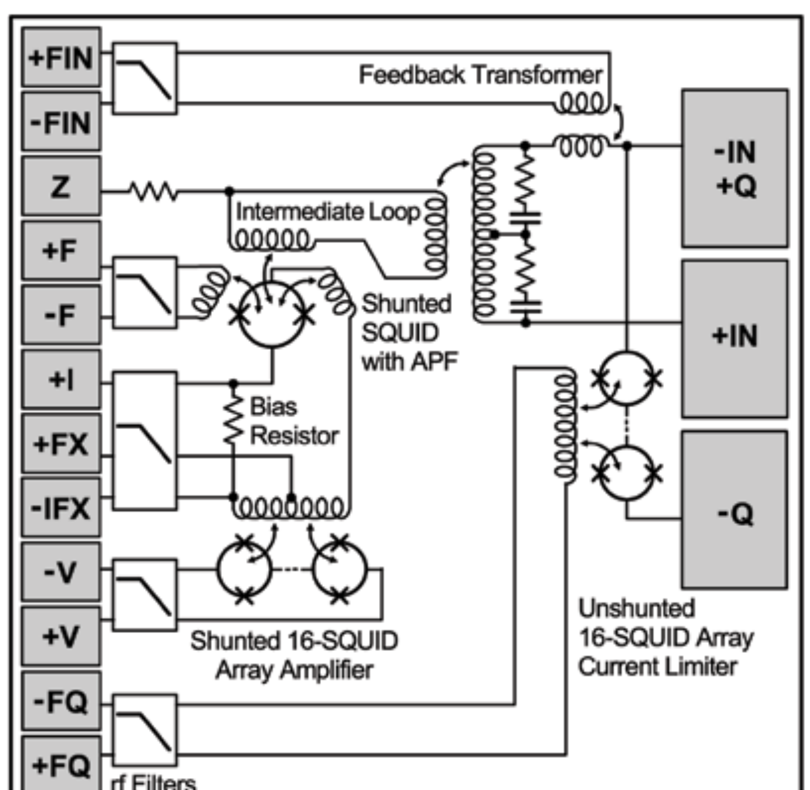
Off-the-shelf Magnicon DC SQUIDs

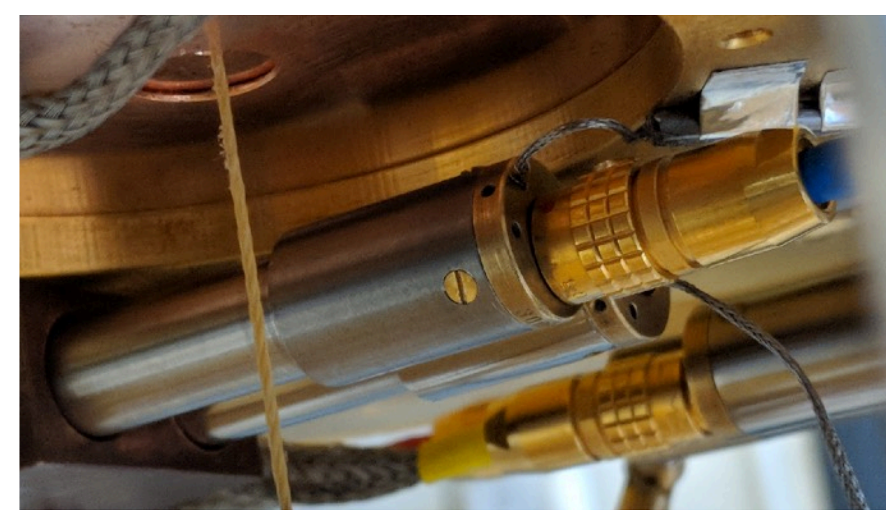
$$S_{\Phi,0}^{1/2} \sim 10^{-6}\Phi_0/\sqrt{\mathrm{Hz}}$$

Optimized for temperatures < 1 K

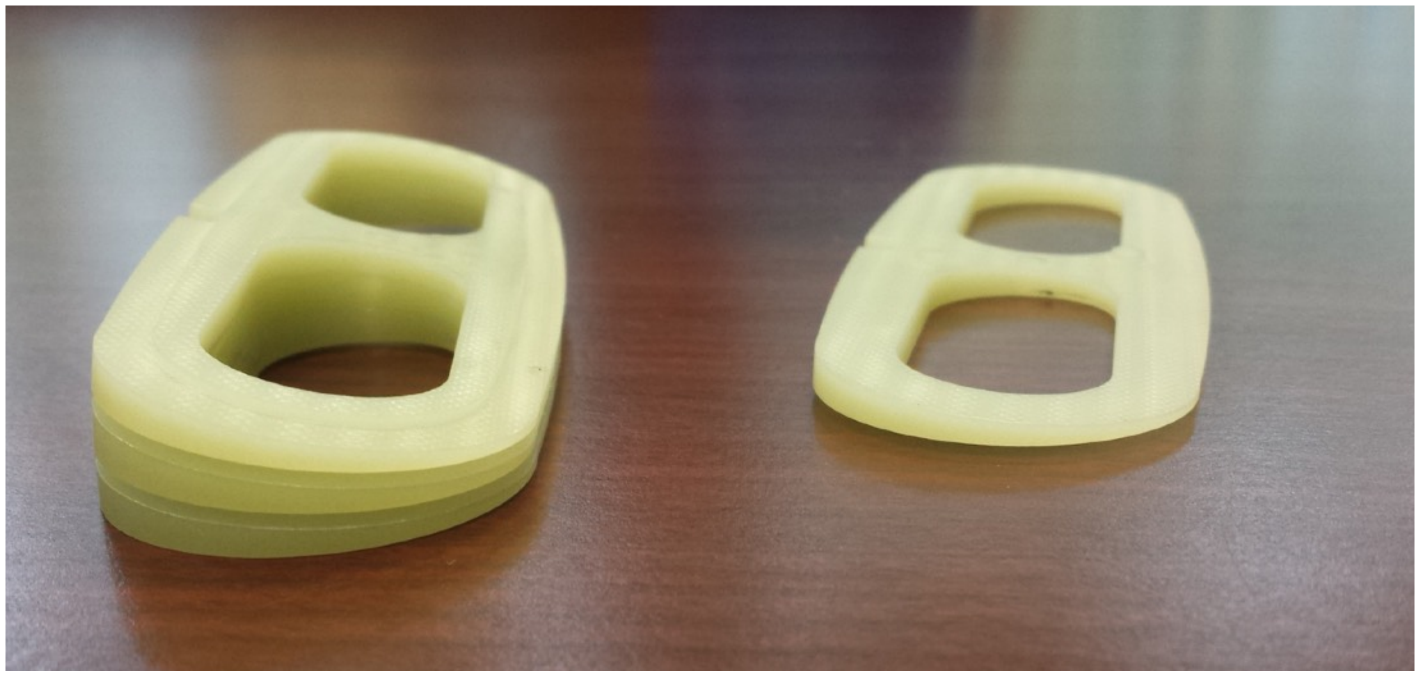
Typical gain

$1.3\ \mathrm{V}/\Phi_0$





Assembling ABRA-10cm

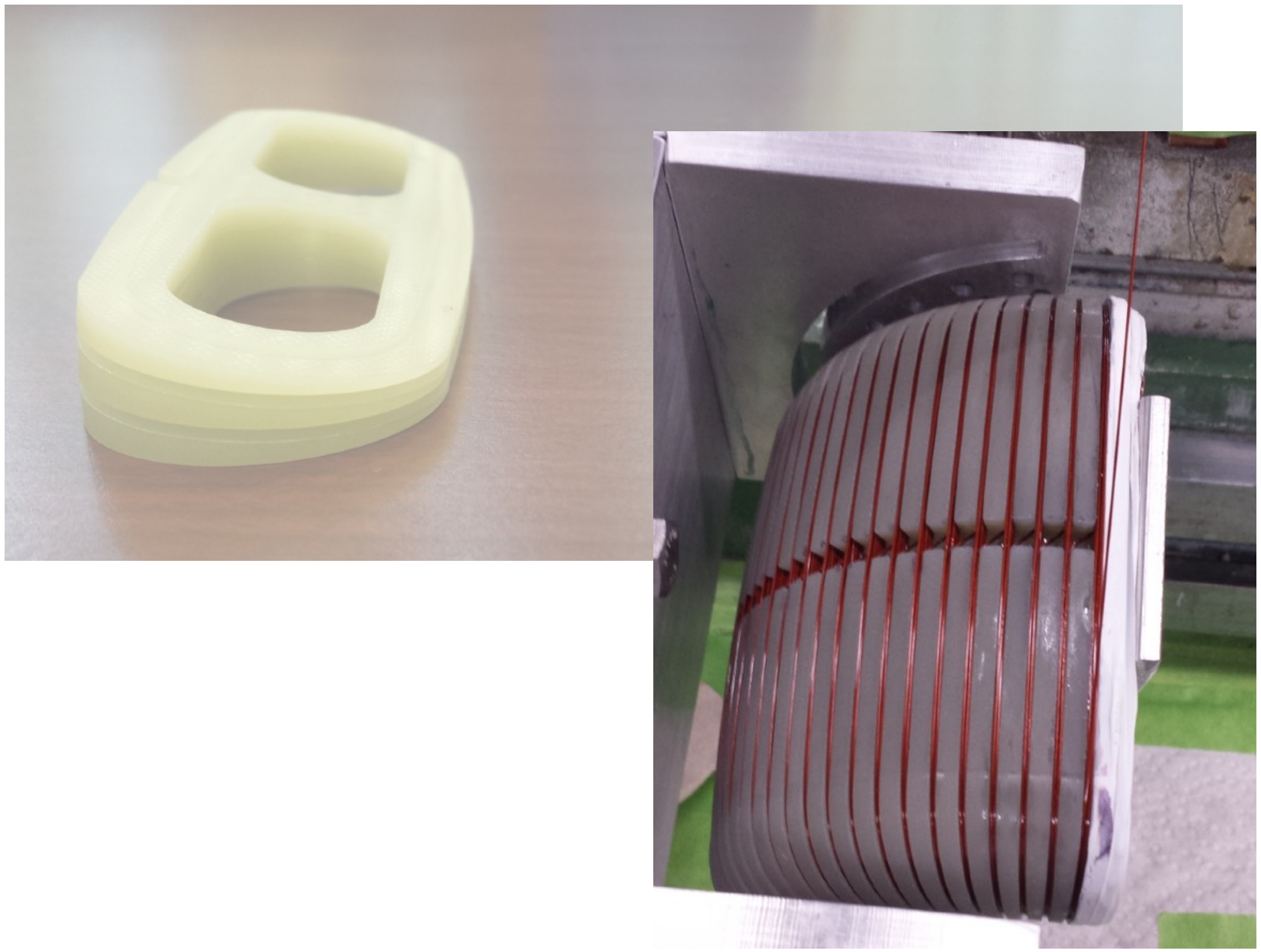


SUPERCONDUCTING SYSTEMS INC.

(Normally make MRI magnets!)

Magnet

Assembling ABRA-10cm



SUPERCONDUCTING SYSTEMS INC.

(Normally make MRI magnets!)

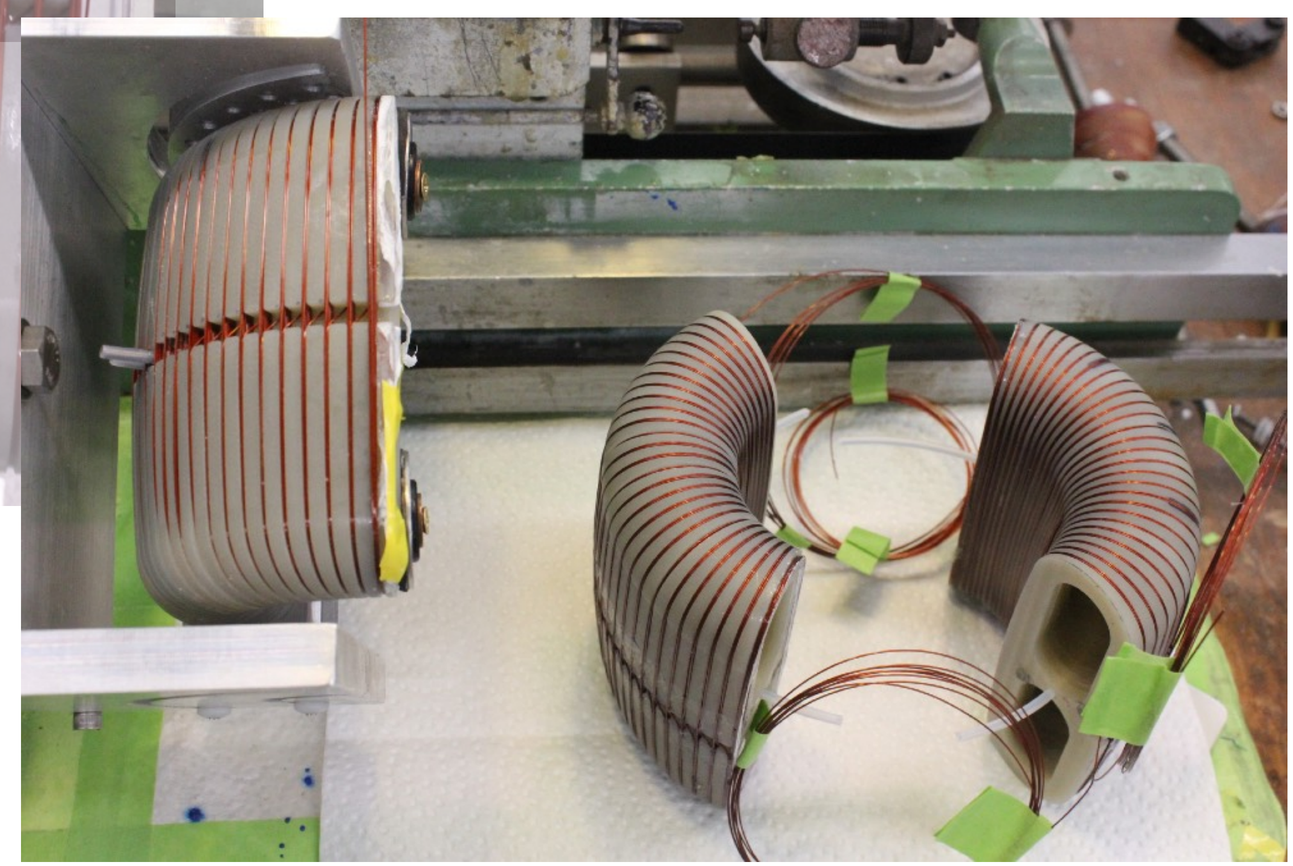
Magnet

Assembling ABRA-10cm

SUPERCONDUCTING SYSTEMS INC.

(Normally make MRI magnets!)

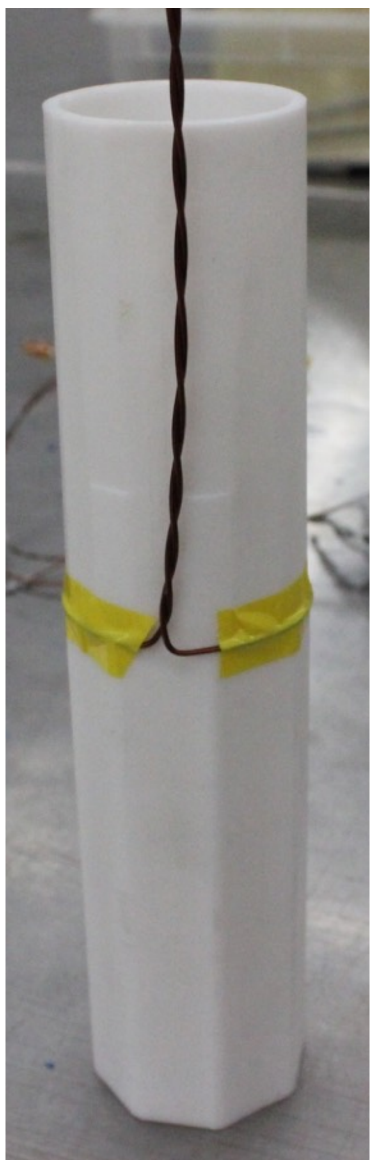


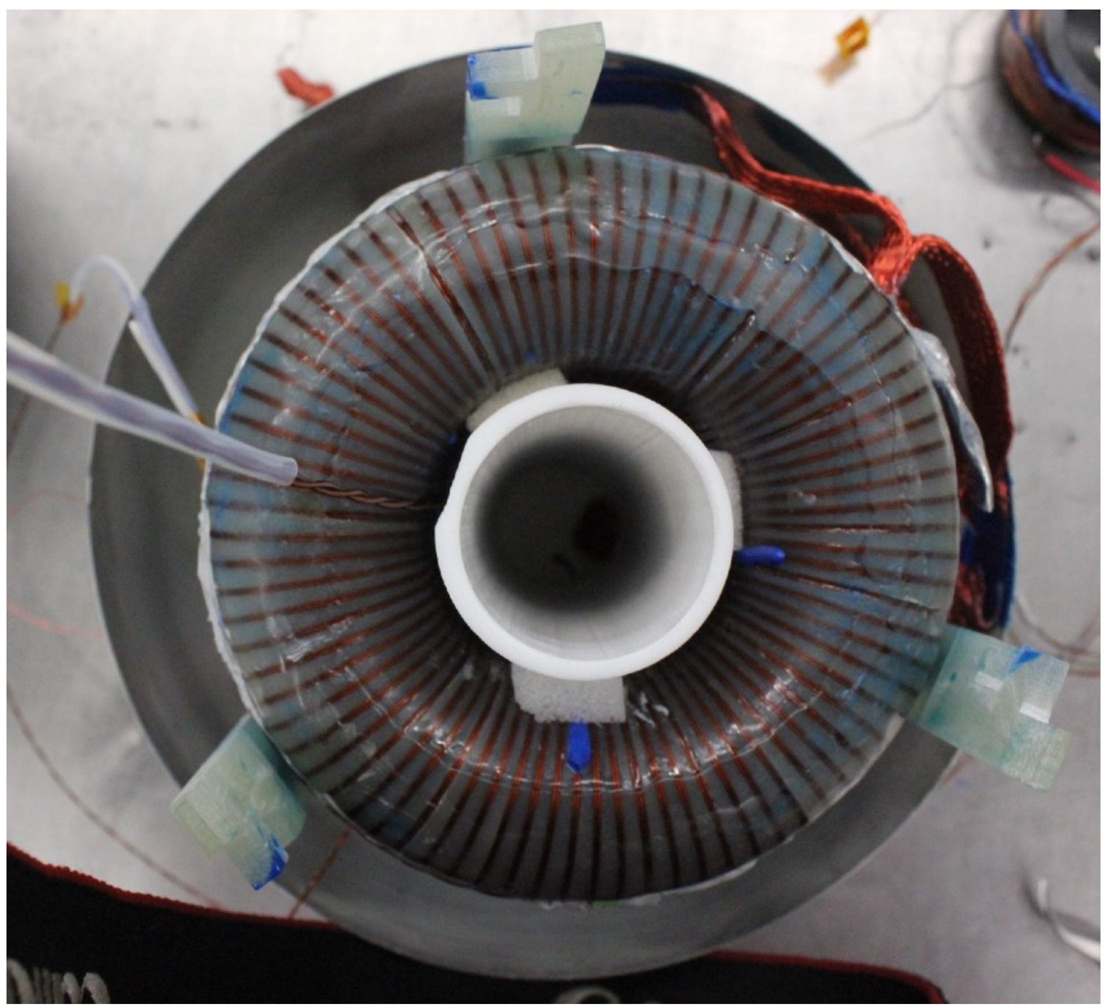


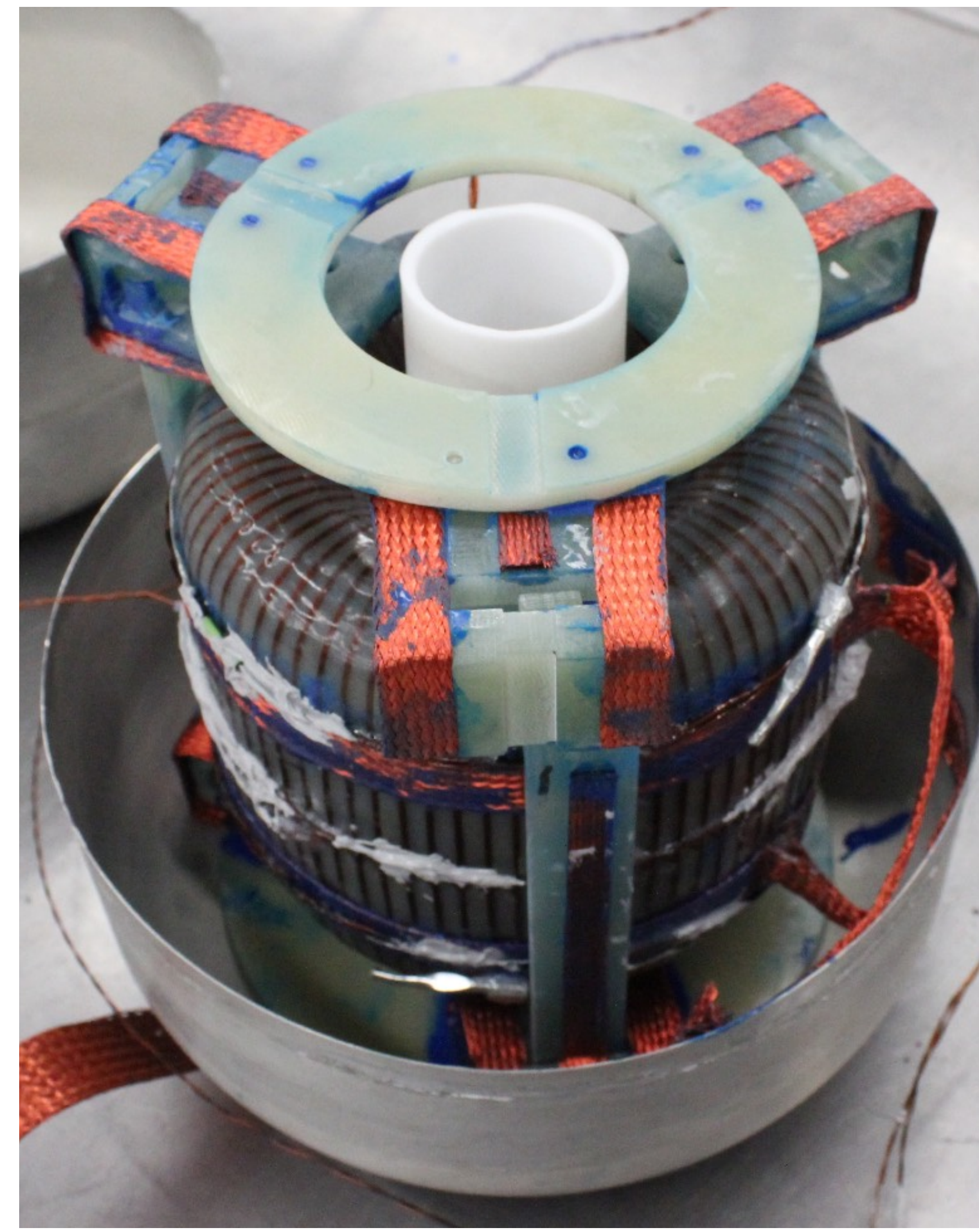
Magnet

Assembling ABRA-10cm

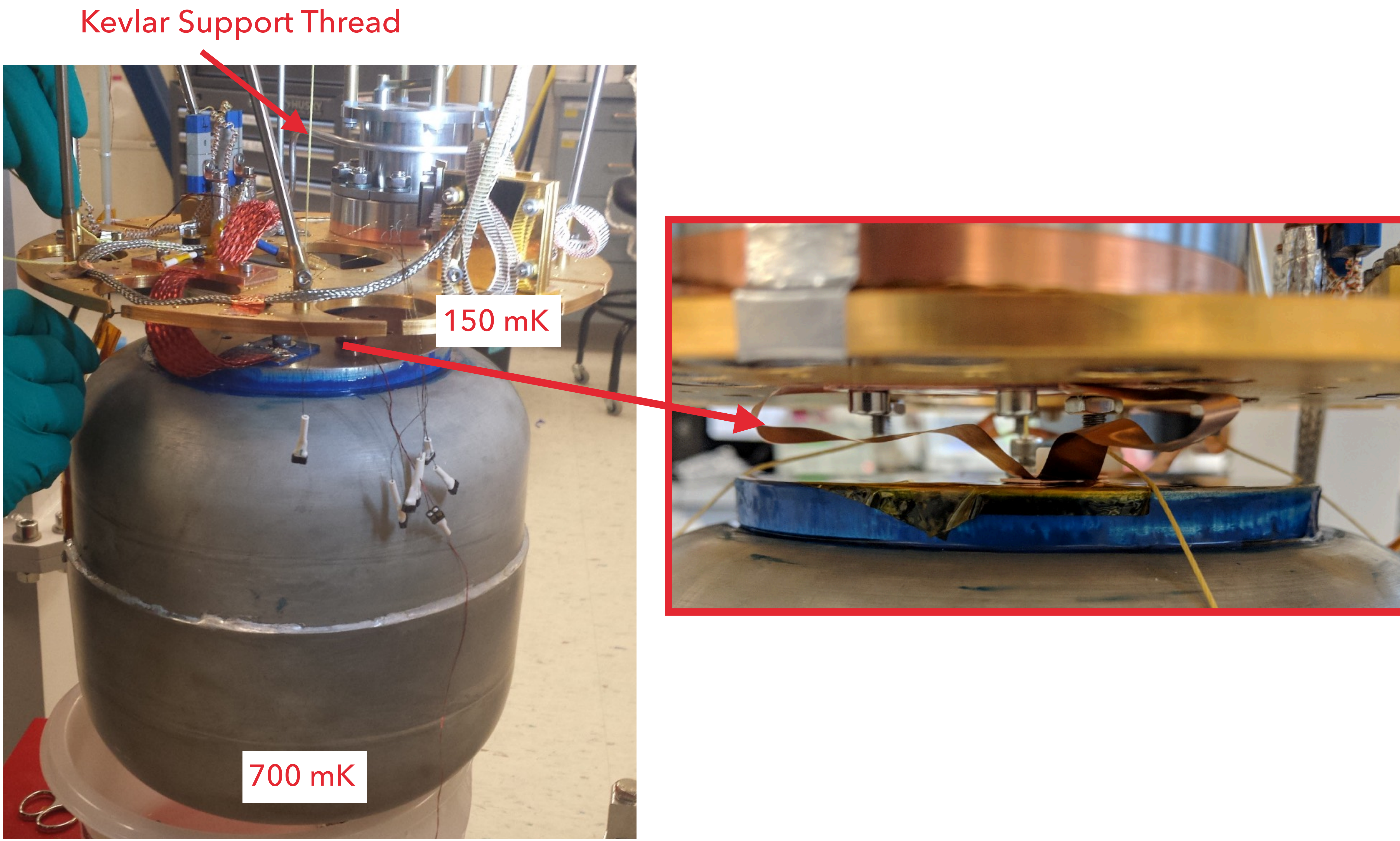
Pickup Loop on insulating PTFE support cylinder





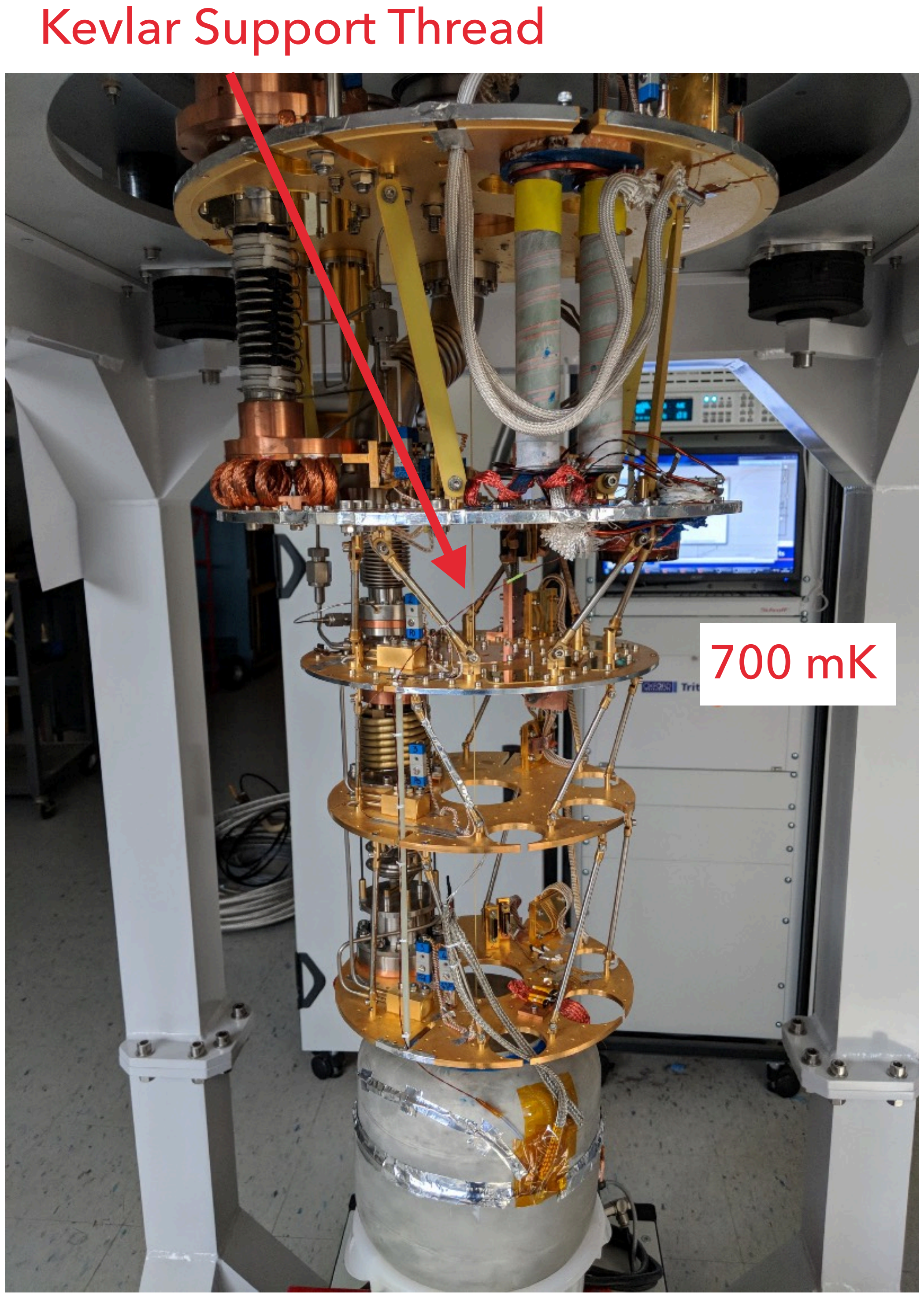


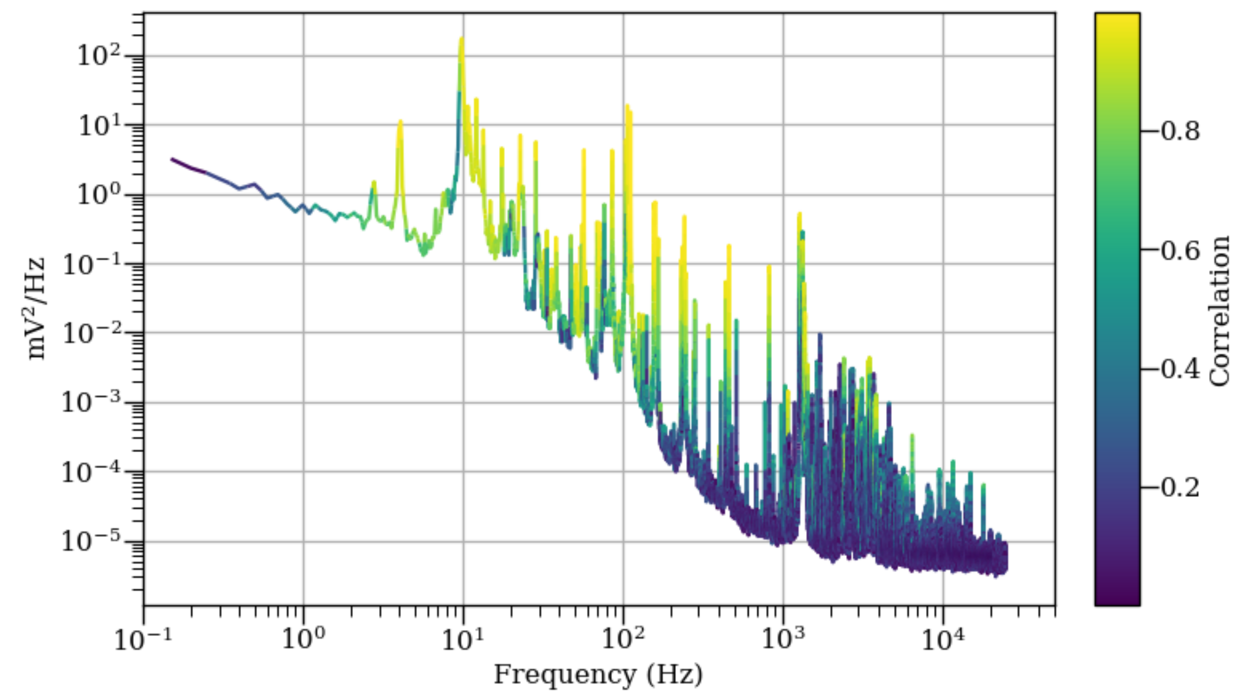
Mounting ABRA-10cm



Vibration isolation

[ABRA-10cm, Phys. Rev. D 99, 052012 (2019)]



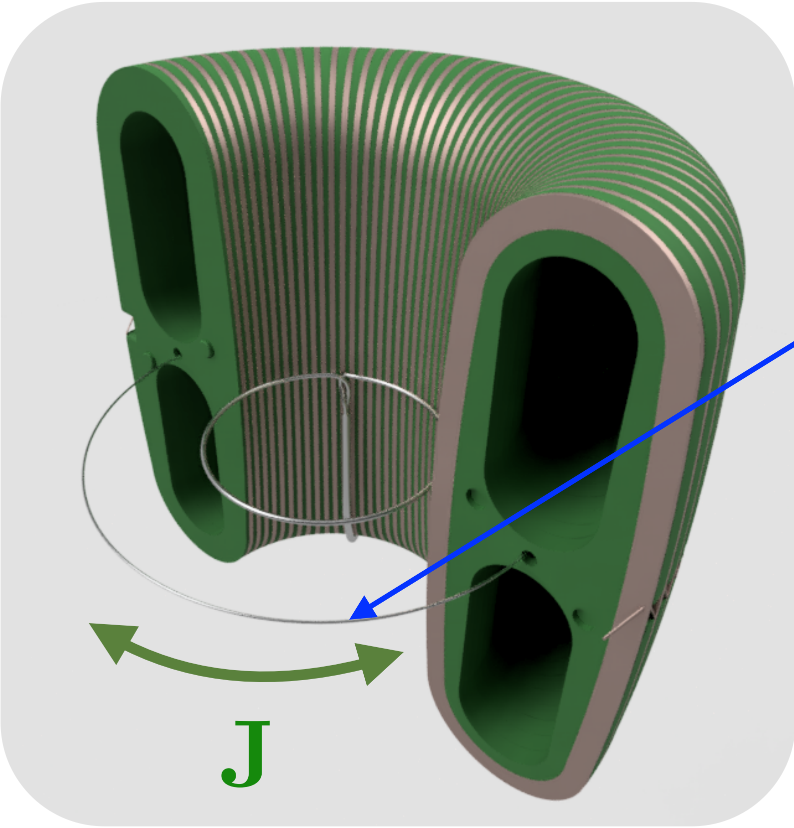


Accelerometer-flux noise correlation

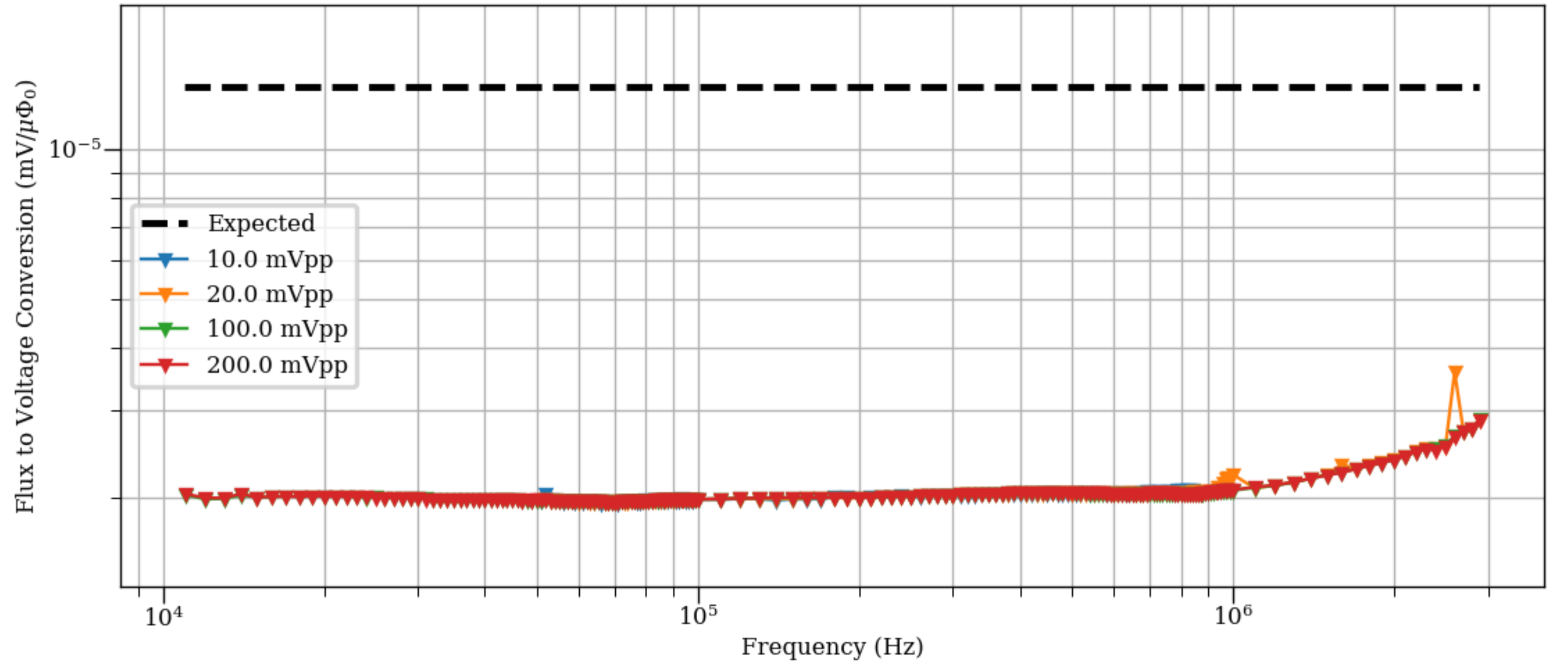
Suspect fringe-field sourced vibration is driving our low-frequency noise: design consideration for future m³ experiment

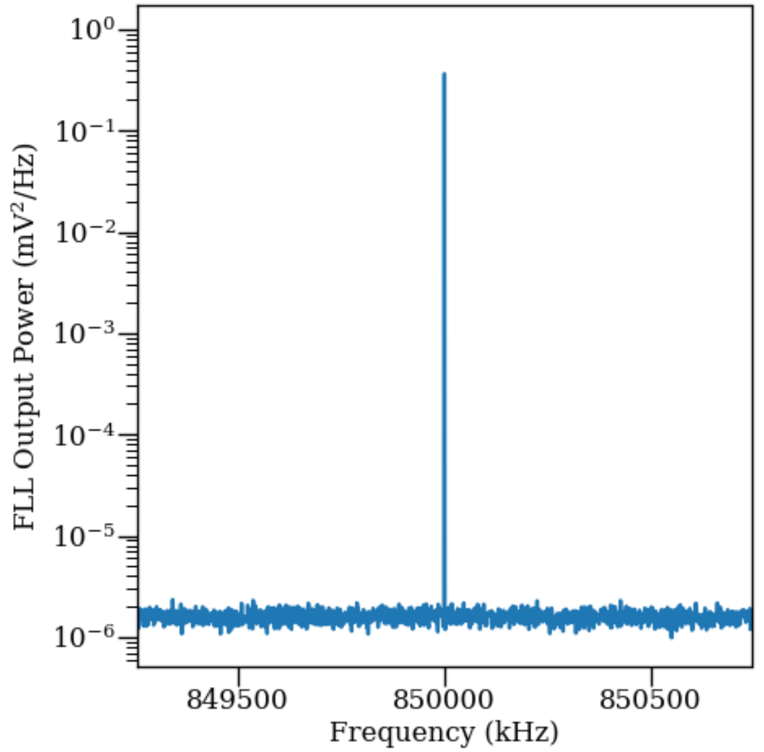
Calibration

[ABRA-10cm, Phys. Rev. D 99, 052012 (2019)]



AC current in calibration loop mimics axion signal





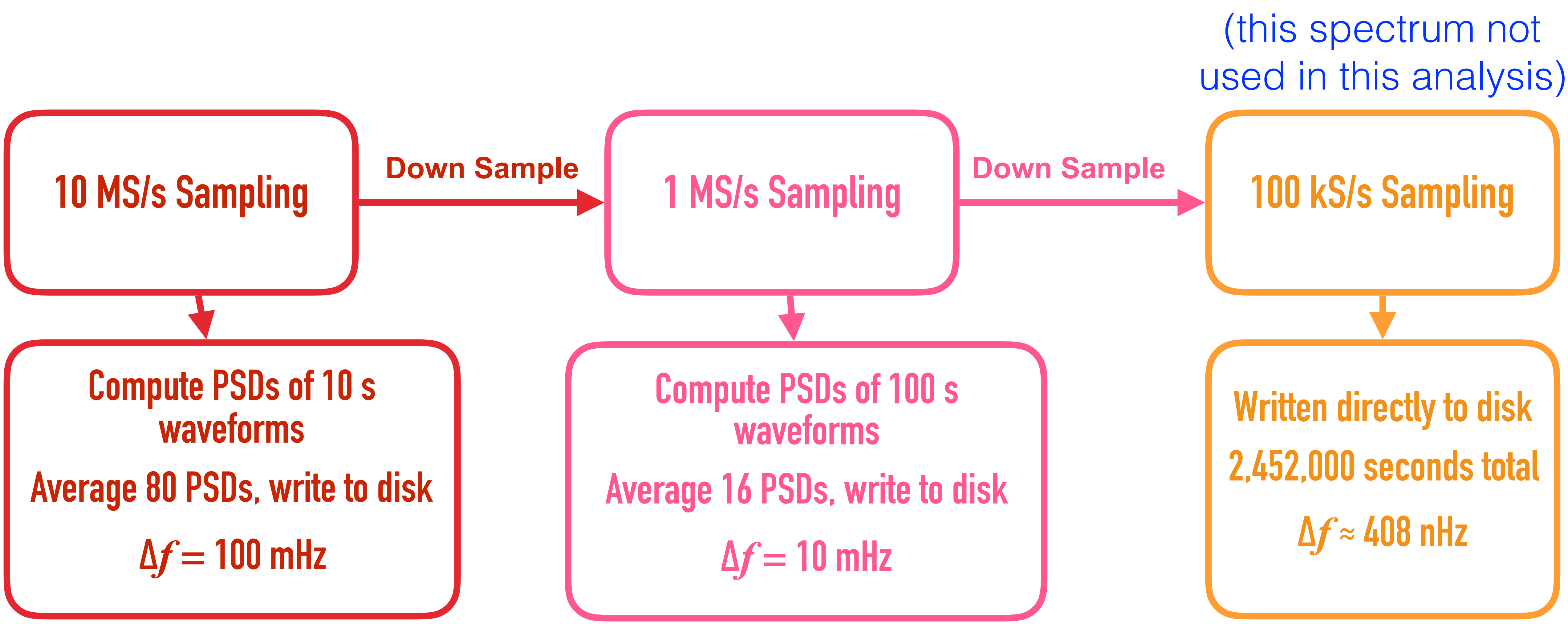
Fine scan from 10 kHz - 3 MHz at multiple amplitudes.

Gain lower than expected by ~6.5, fixed in next run

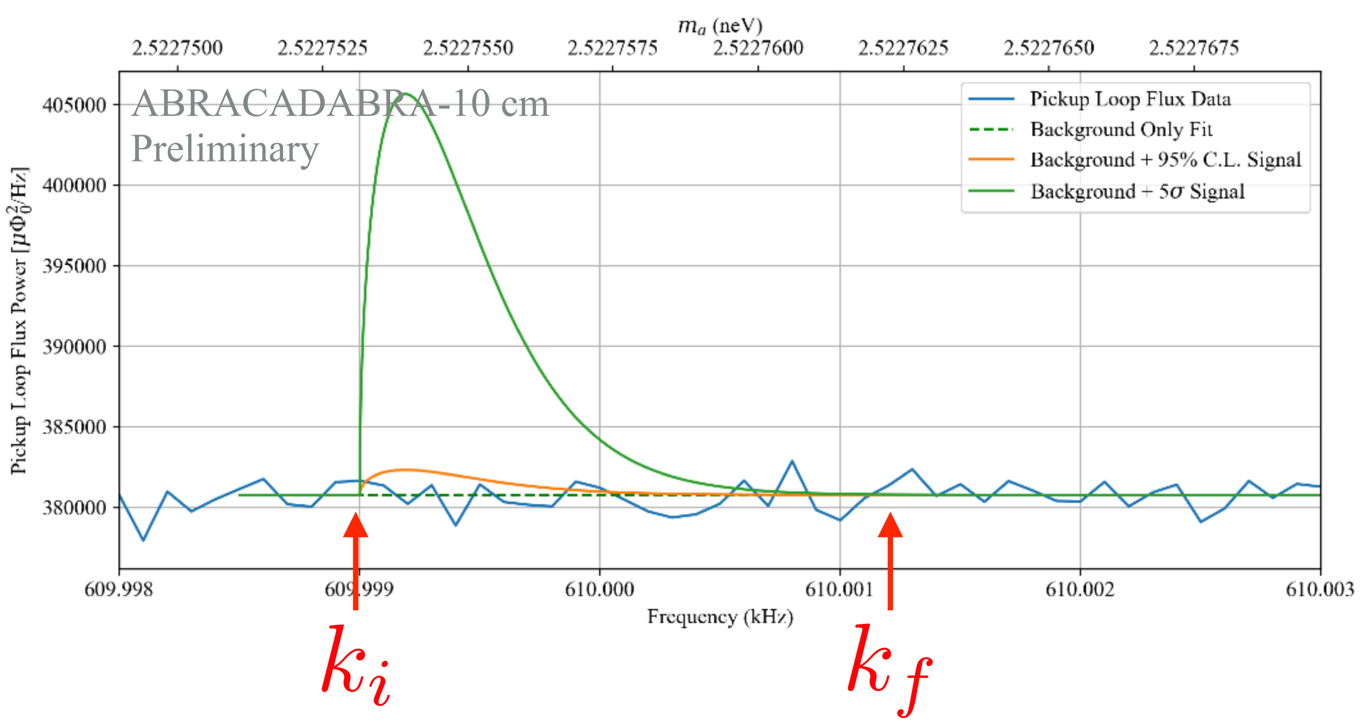
Data collection procedure

Data collected with magnet on for 4 weeks
(2.4 x 10^6 s at 10 MS/s) in July-August 2018

AlazarTech ATS9870 8-bit Digitizer
locked to a Rb oscillator frequency standard



Axion search



Running average of PSD is Erlang-distributed:

$$P(\bar{\mathcal{F}}_k; N_{\rm avg}, \lambda_k) = \frac{N_{\rm avg}^{N_{\rm avg}}}{(N_{\rm avg}-1)!}\frac{(\bar{\mathcal{F}}_k)^{N_{\rm avg}-1}}{\lambda_k^{N_{\rm avg}}} e^{-\frac{N_{\rm avg}\bar{\mathcal{F}}_k}{\lambda_k}}$$

Construct likelihood function and test statistic from likelihood ratio:

$$\mathcal{L}(\mathbf{d}_{m_a}|A,\mathbf{b}) = \prod_{j=1}^{\mathcal{N}} \prod_{k=k_i(m_a)}^{k_f(m_a)} P(\bar{\mathcal{F}}_{j,k}; N_{{\rm avg},j}, \lambda_{j,k})$$

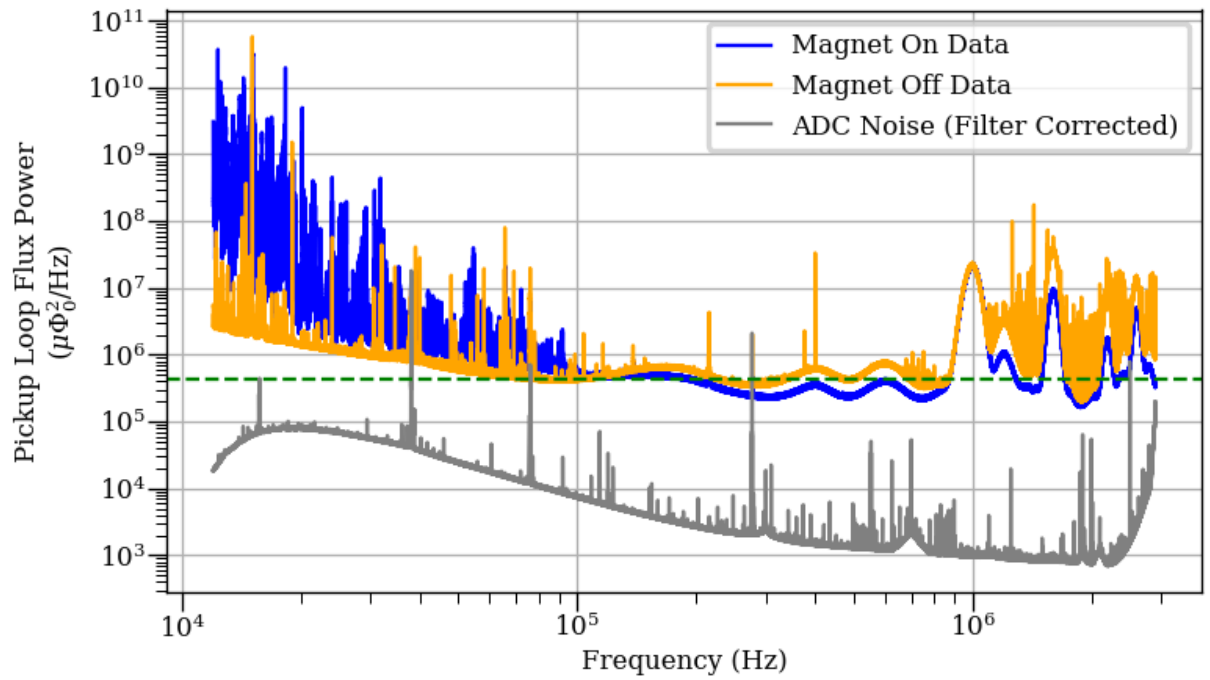
spectra — freq. bins

$$\mathrm{TS}(m_a) = 2\ln\left[\frac{\mathcal{L}(\mathbf{d}_{m_a}|\hat{A},\hat{\mathbf{b}})}{\mathcal{L}(\mathbf{d}_{m_a}|A=0,\hat{\mathbf{b}}_{A=0})}\right]$$

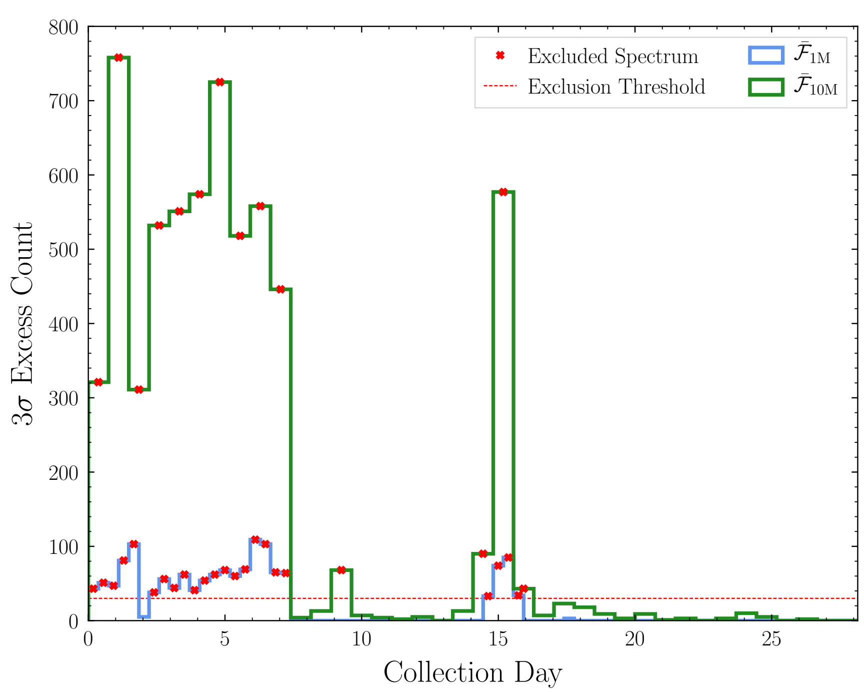
8.1 millions mass points between 75 kHz and 2 MHz,
5σ threshold for discovery (accounting for look-elsewhere)
corresponds to TS = 56.1

Veto and data cleaning

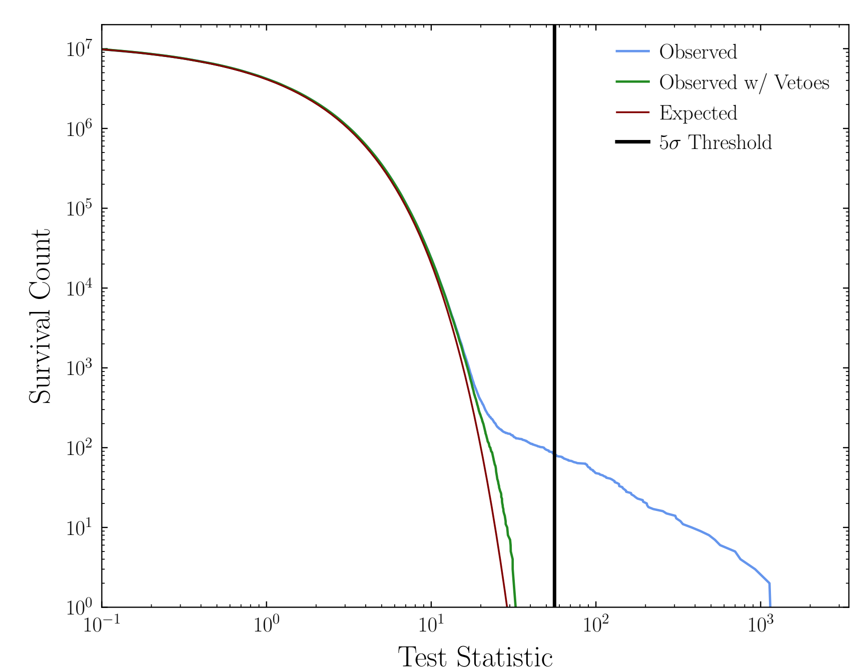
[ABRA-10cm, Phys. Rev. D 99, 052012 (2019)]



Took 2 weeks of magnet-off data; any excesses vetoed in corresponding magnet-on data



After vetos, discard datasets with transient noise (30% of exposure)



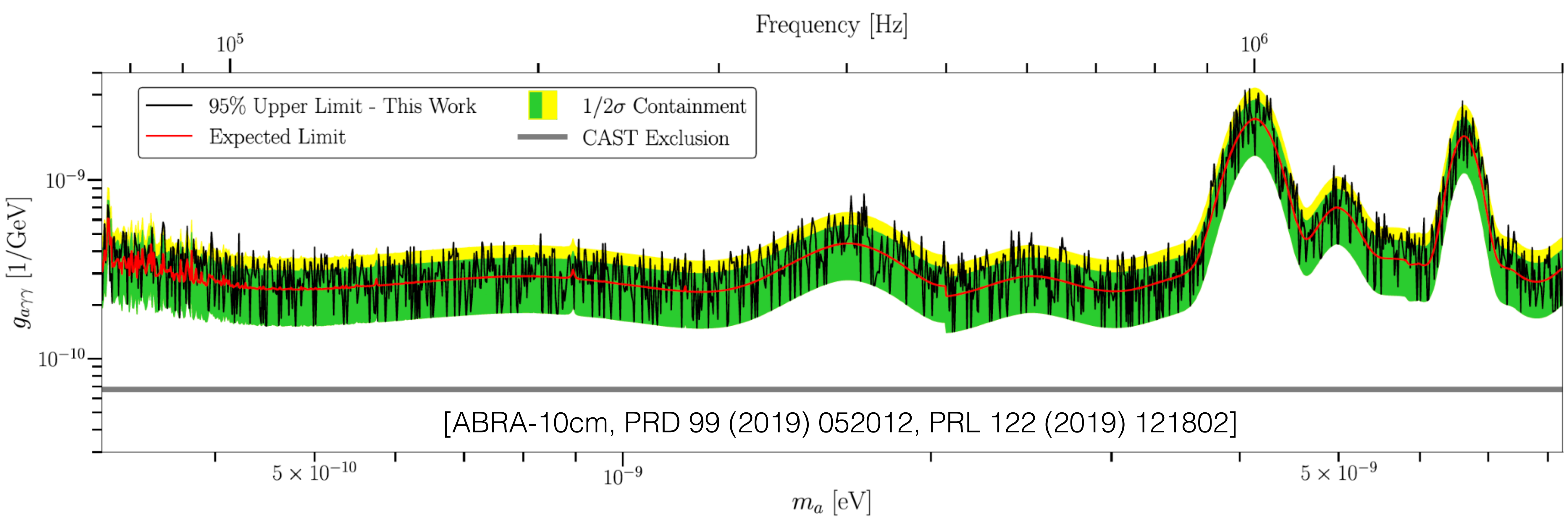
Remaining data consistent w/null hypothesis

Axion Limits

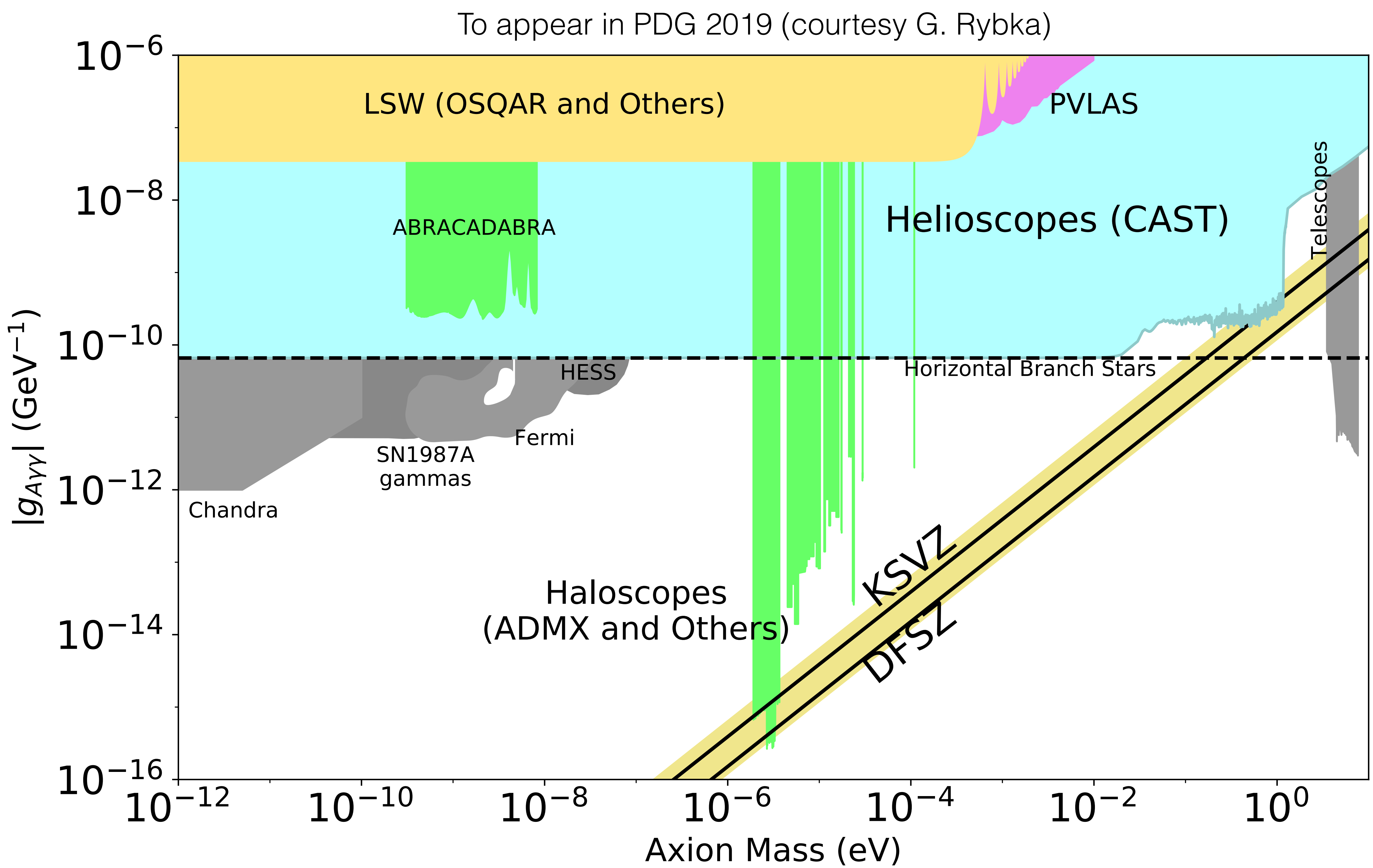
25384 mass points excluded from analysis due to magnet off veto (0.2%)
Of these, only 83 appeared in magnet-on (and were vetoed)

Mass range for analysis set by data cleanliness,
working to turn this into a blinding/unblinding procedure for next run

First laboratory axion exclusions at 95% c.l. in this mass range:

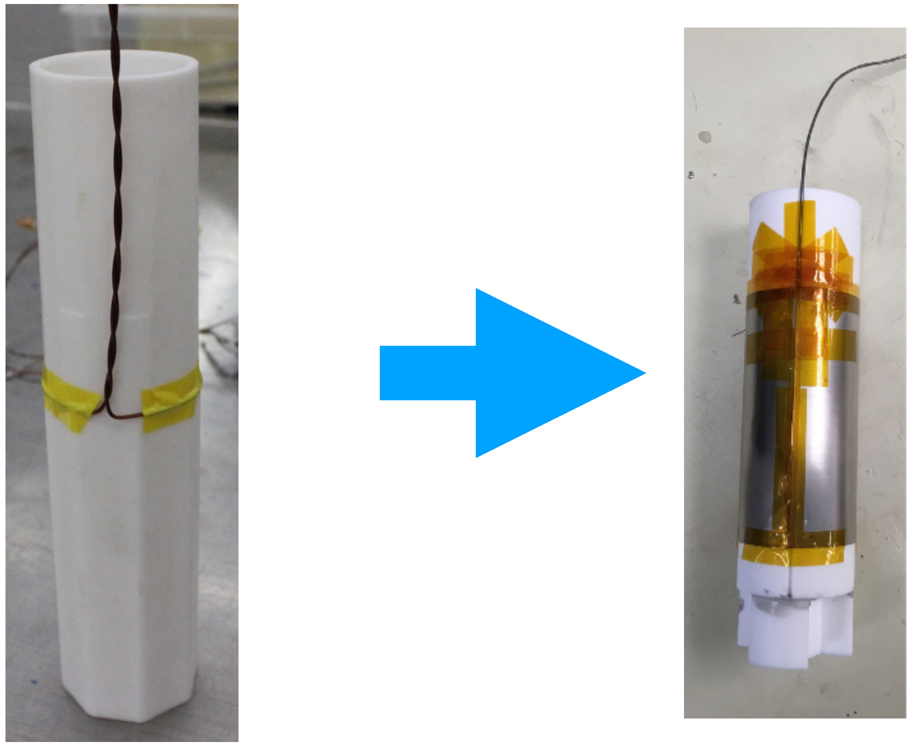


ABRA-10cm Run 1 Limits

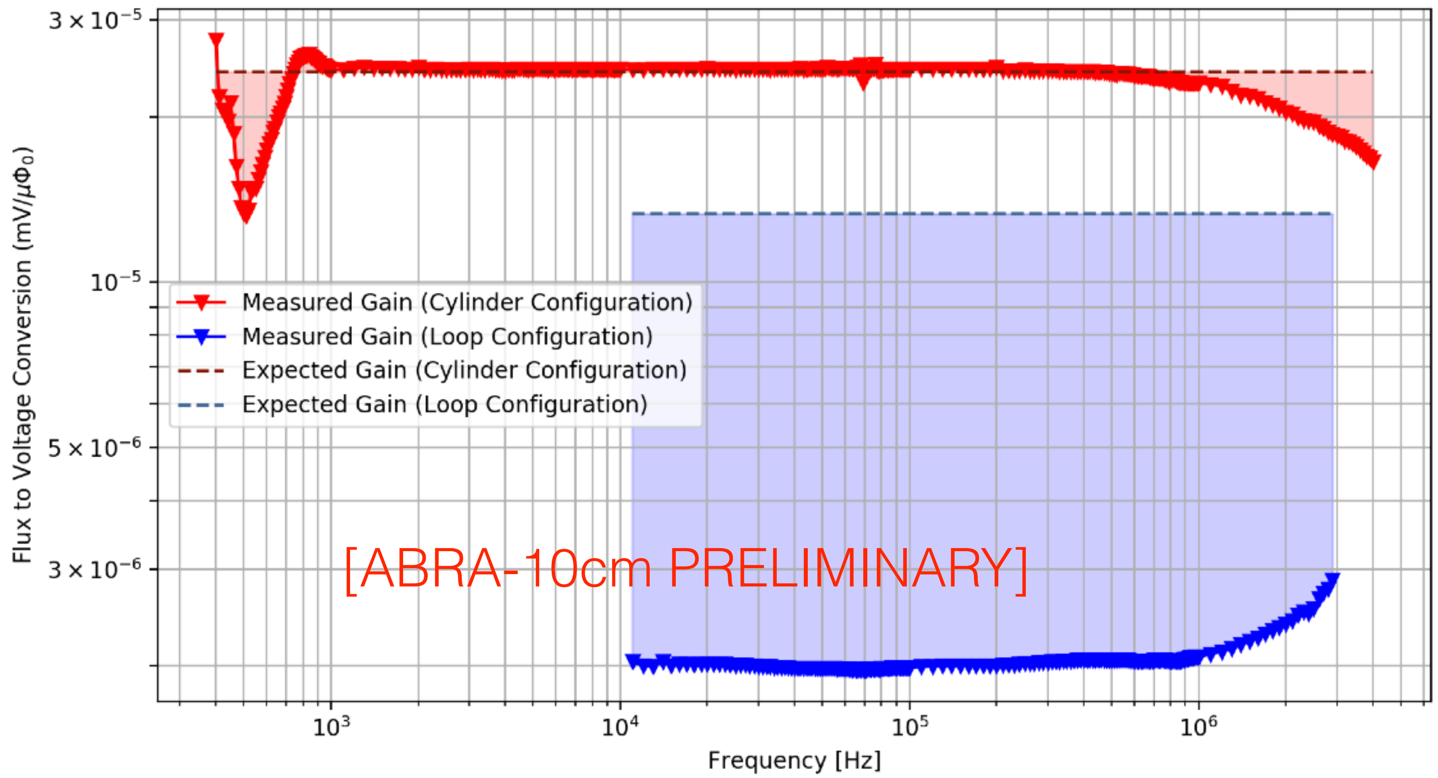


ABRA-10cm Run 2 plan

Reduced inductance by replacing pickup loop with pickup cylinder and reducing wiring



Gain now matches theoretical value: factor of ~10 in sensitivity



Incorporating active feedback to reduce noise below 1 kHz

~1-month broadband run planned before end of 2019: expect to beat CAST limits

ABRACADABRA
Collaboration

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

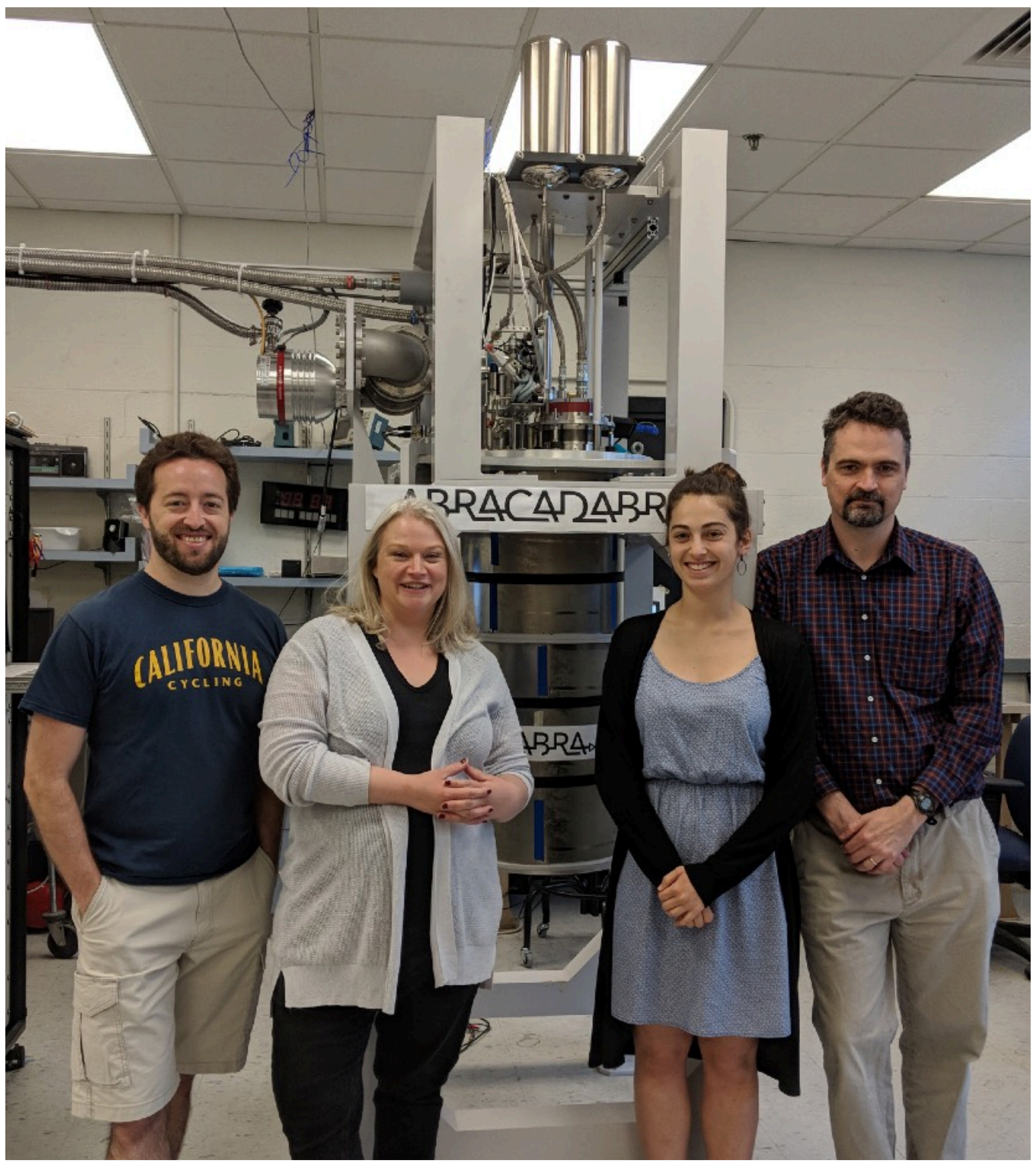
TUNL
Triangle Universities Nuclear Laboratory

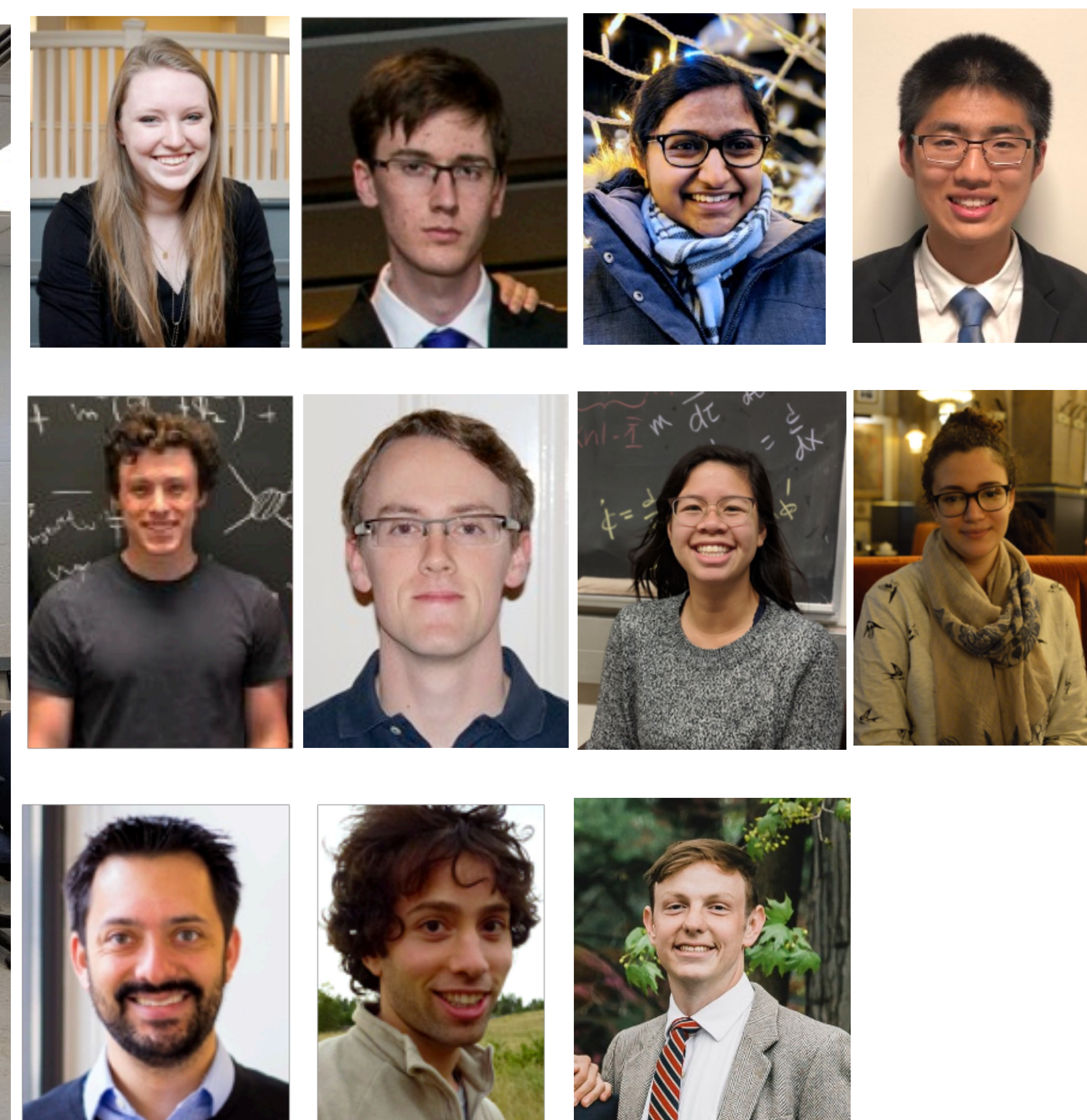
UNIVERSITY OF MICHIGAN

Berkeley
UNIVERSITY OF CALIFORNIA

BERKELEY LAB

NSF





Leading up to a cubic meter experiment

- ABRA-10cm: Running at MIT.
- DMRadio-Pathfinder (dark photon DM): Running at Stanford.
- DMRadio-50L: Under Construction at Stanford.

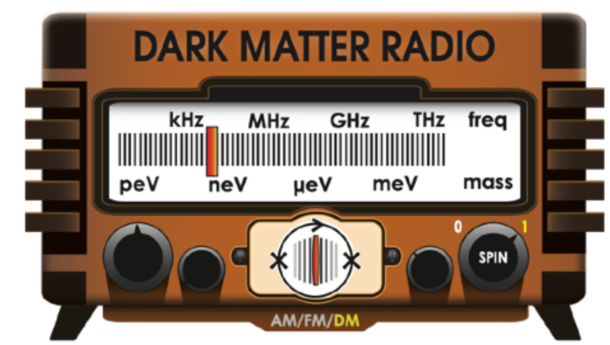
- DMRadio-m^3 R&D Consortium recently funded by DOE HEP Dark Matter Small Initiatives Program for ~$1M.
  - Includes ABRACADABRA PIs (Henning and Winslow).
  - 2 years.
  - Goal: Develop 30% Design, focused on magnet.
  - Develop Full Proposal for m^3 experiment.
- First PI meeting at MIT earlier this month, developing plan for merger by Summer 2020.

DM Radio Cubic Meter: Consortium

Funded as part of DOE New Initiatives in Dark Matter program

R&D Phase Consortium Leadership:

Name	Institution	Role / Team Lead
Kent Irwin	SLAC and Stanford	Consortium PI
Karl van Bibber	UC Berkeley	Magnet
Lindley Winslow	MIT	Magnetic shielding, vibration
Saptarshi Chaudhuri	Princeton	Control system, scan
Peter Graham	Stanford	Theory
Reyco Henning	UNC Chapel Hill	Calibration and DAQ
Dale Li	SLAC	Cryomechanical
Hsiao-Mei Cho	SLAC	SQUID
Wes Craddock	SLAC	Lead Engineer
Nadine Kurita	SLAC	Project Management Plan



U.S. DEPARTMENT OF ENERGY | Office of Science

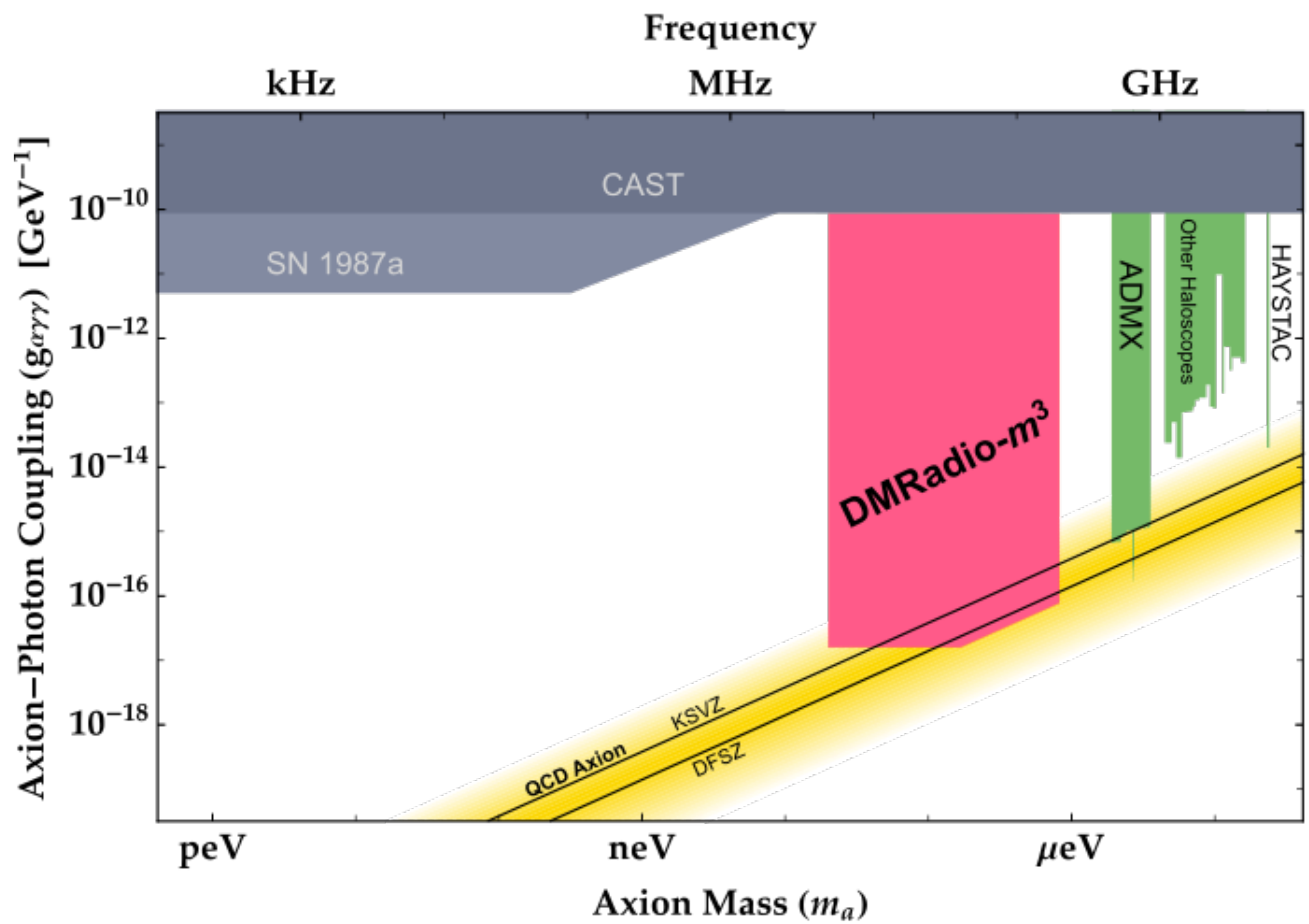
SLAC

PRINCETON UNIVERSITY

DM Radio Cubic Meter: Science Goals

Cubic Meter Experiment

- 1 m^3 detection volume
- 20 mK temperature
- Q = 10^6 (resonant readout)
- 4T B-Field
- Frequency range 5 MHz– 200 MHz
- DC SQUID with noise @ 20× quantum limit
- 3 years of live scan time
- Quantum readout techniques would enable QCD sensitivity at lower masses

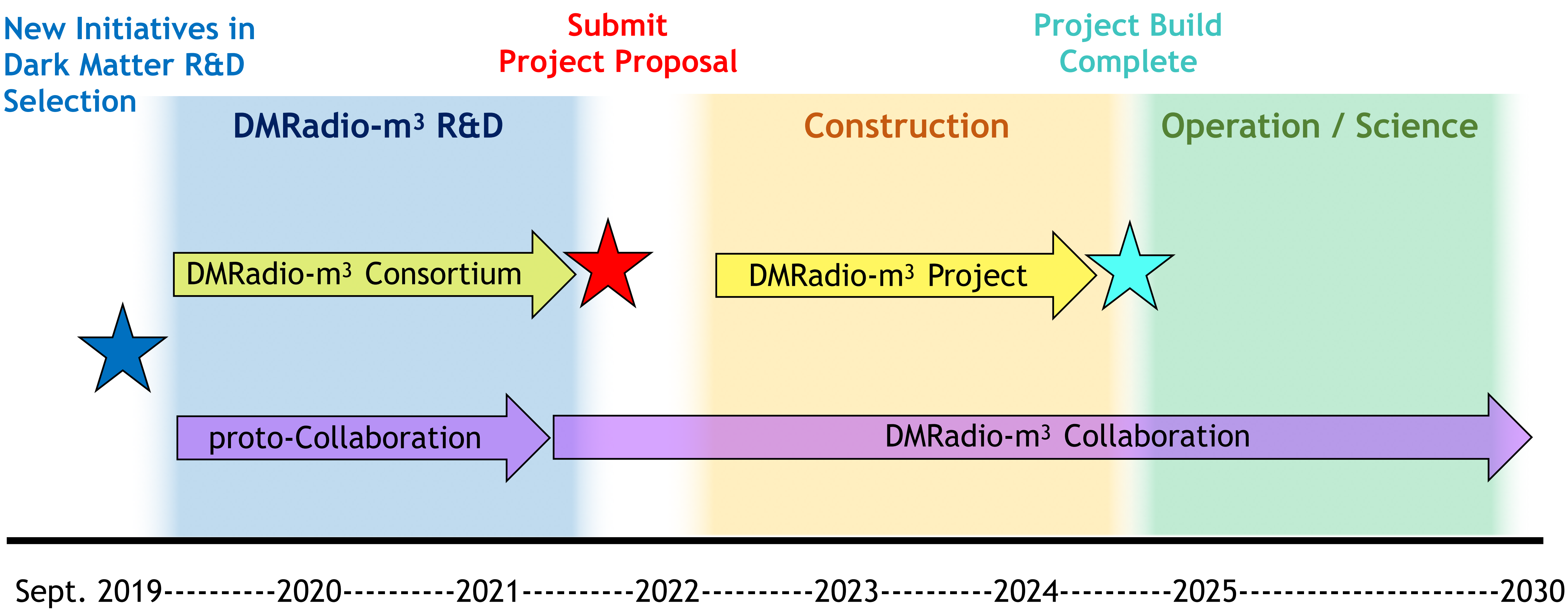


DM Radio Cubic Meter: Timeline

2020-2021: DM Radio-m^3 R&D

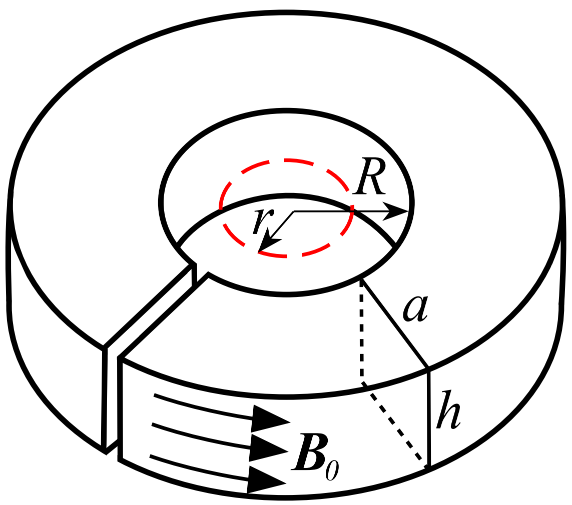
2022-2025: DM Radio-m^3 Proposed Project Build

2025-2030: DM Radio-m^3 Science Scanning

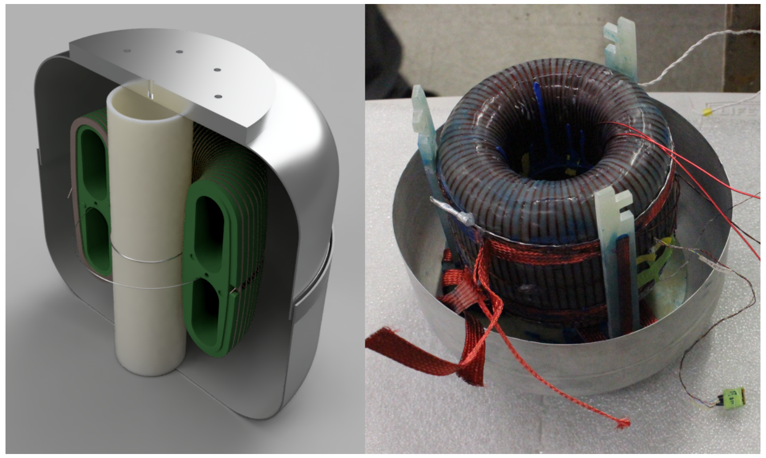


Conclusion

ABRACADABRA: First broadband axion search below 1 μeV



10 cm detector w/1 month exposure: leading laboratory limits



Developing proposal for m³ experiment w/resonant readout to reach QCD line