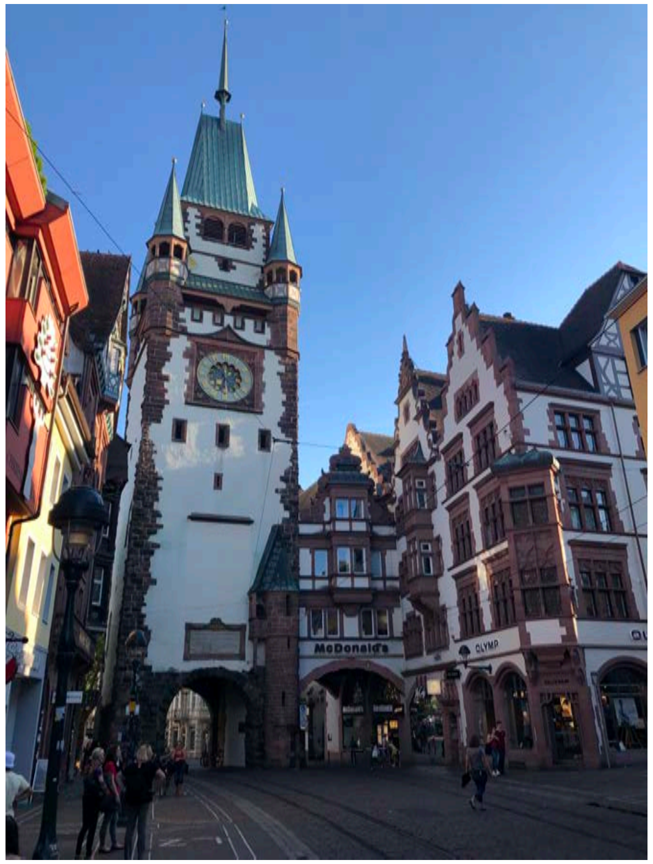
THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

TUNL



Results and update from the ABRACADABRA search for sub-μeV axion dark matter

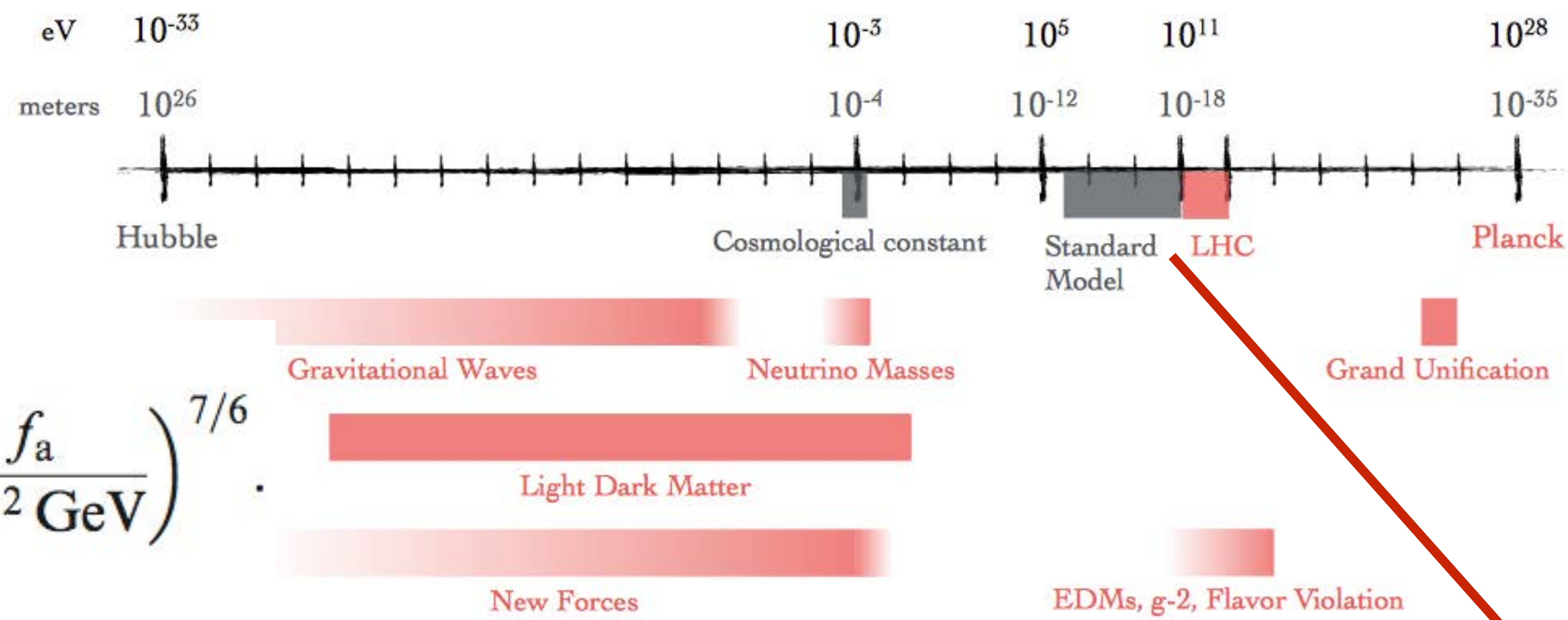
Reyco Henning
University of North Carolina at Chapel Hill
Triangle Universities Nuclear Laboratory

Outline

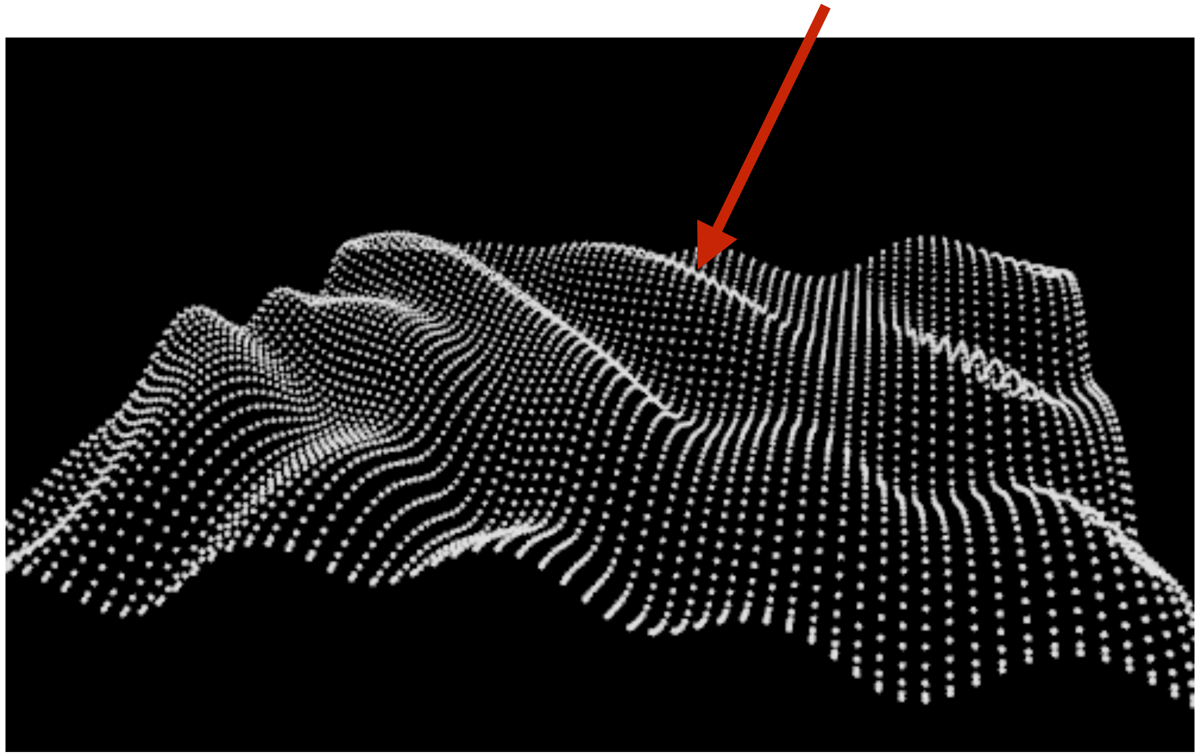
- Motivation
- ABRA Concept
- Results from 10cm prototype
- Future Plans

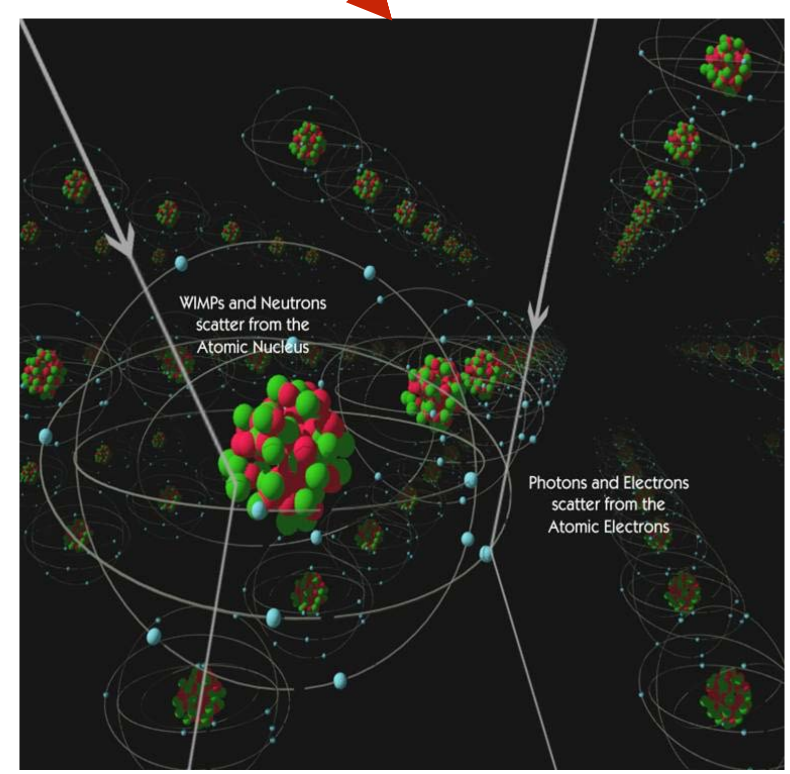
Axion as “Light” DM

Arvanitaki

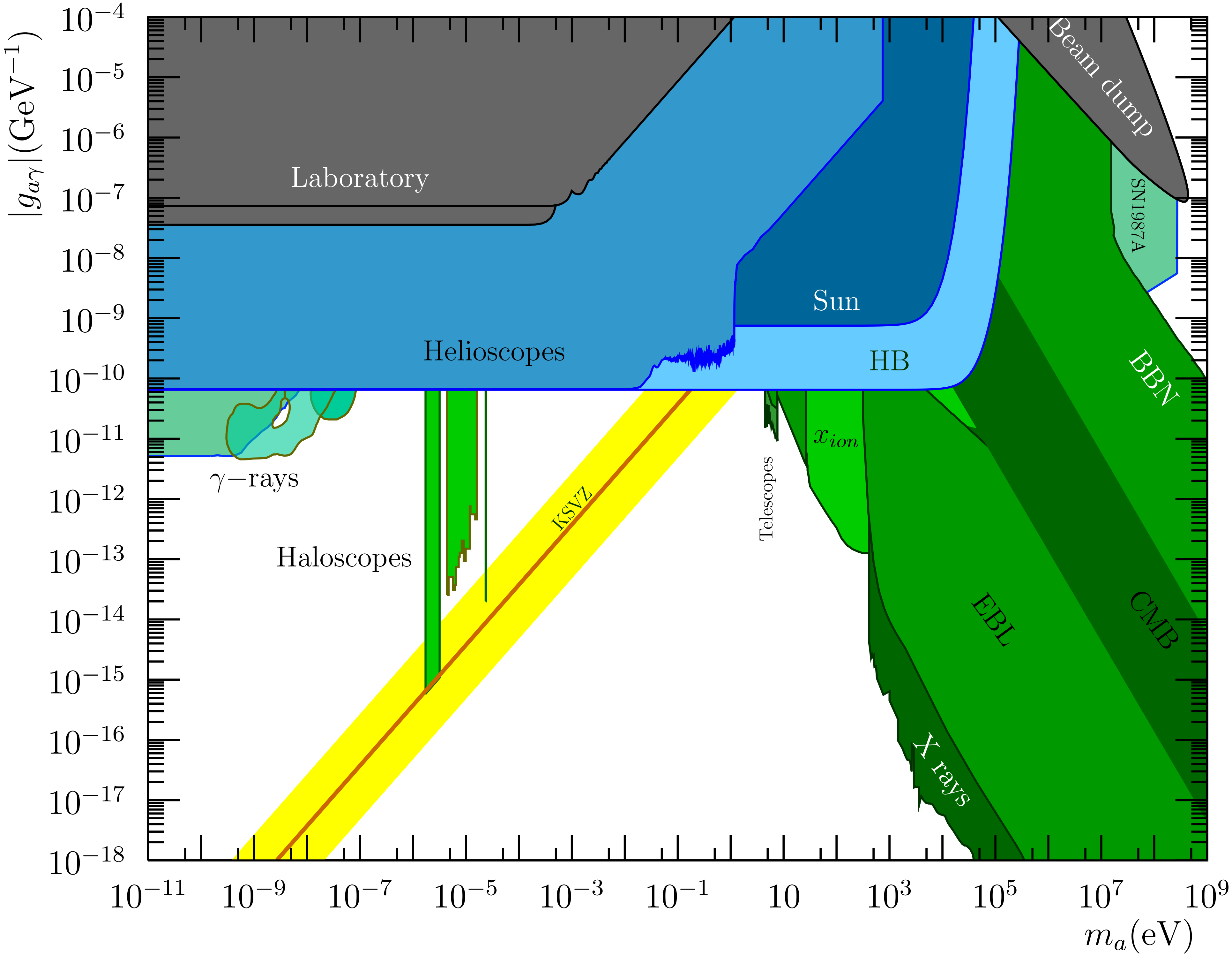


$$\Omega_a \sim \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{7/6}.$$





Motivation



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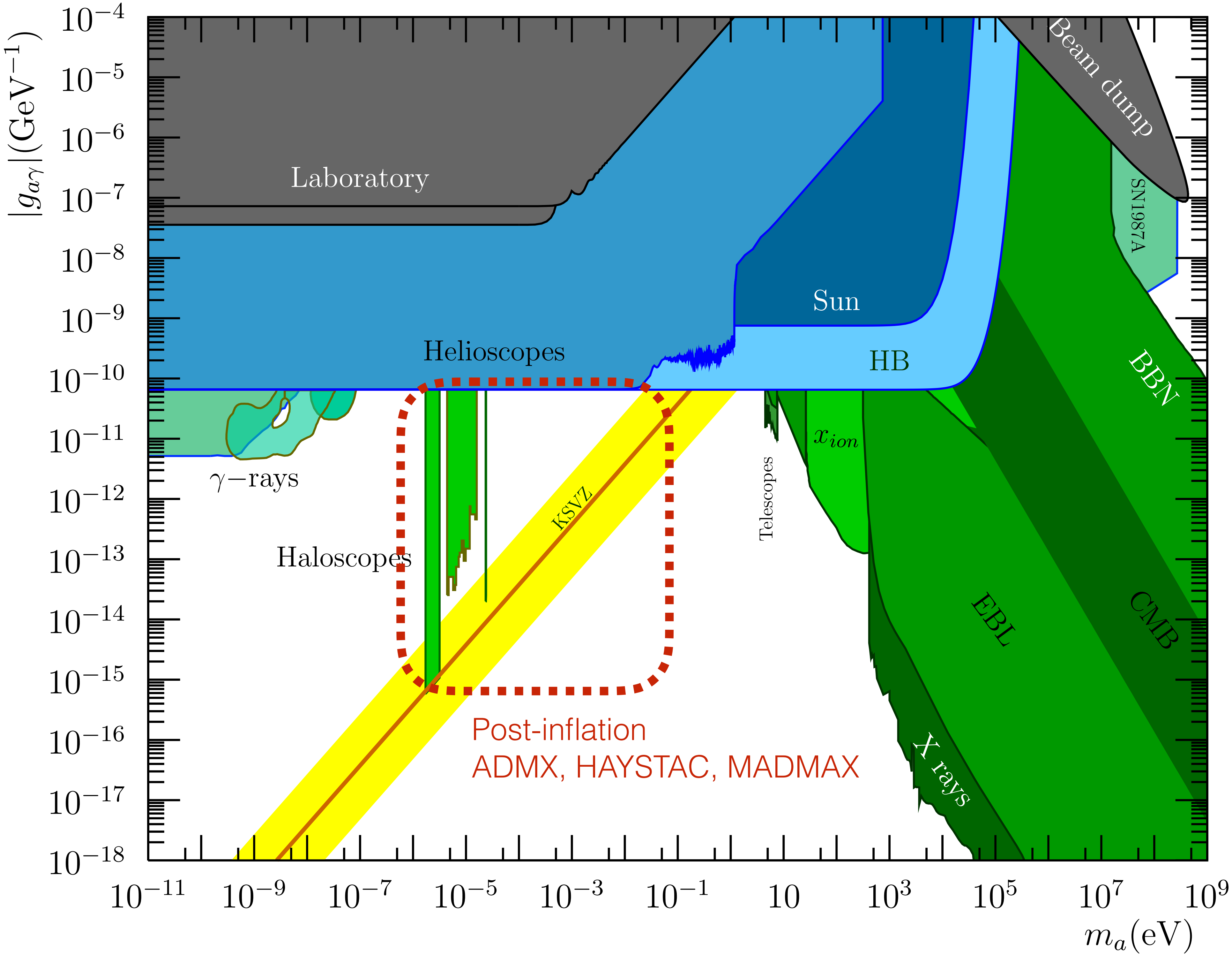
Motivation



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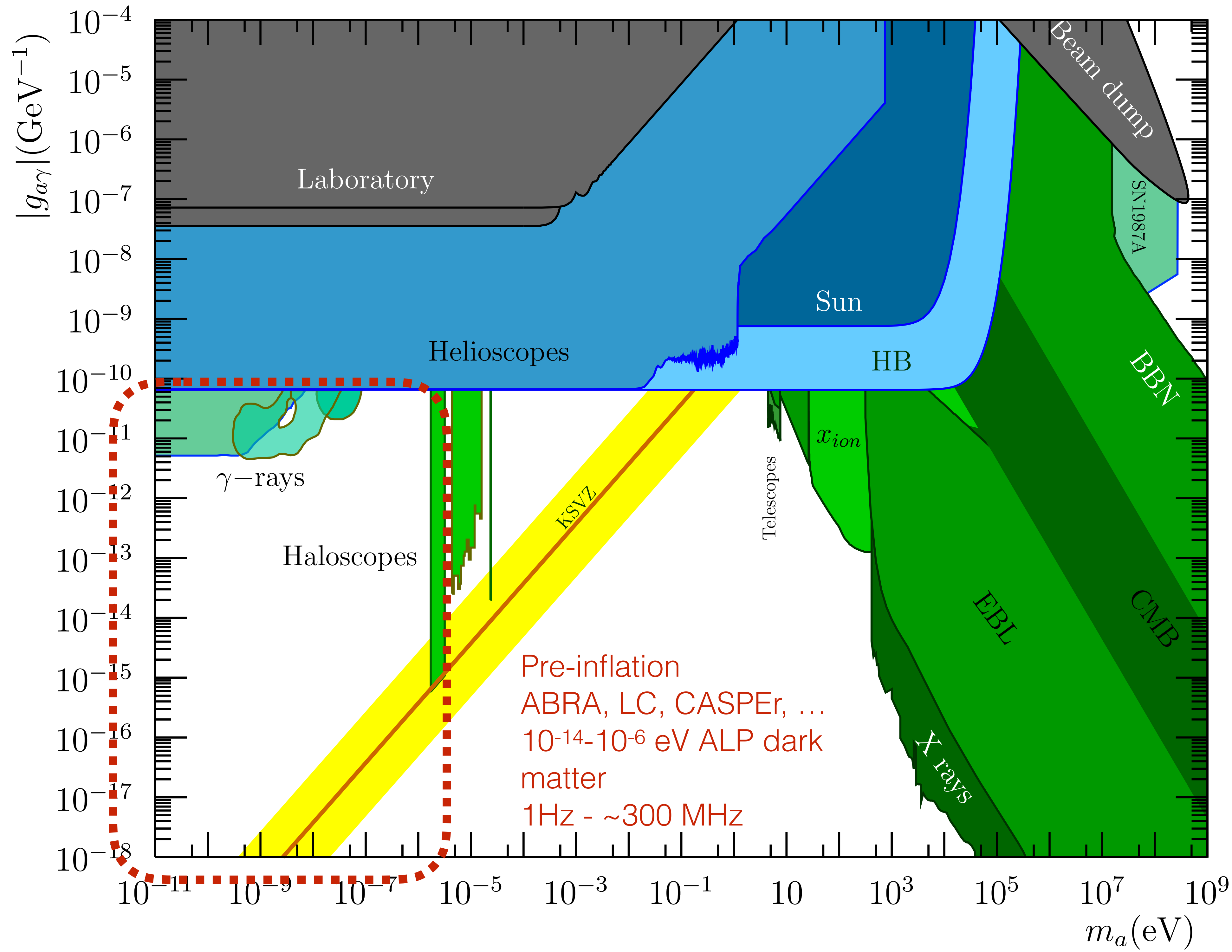

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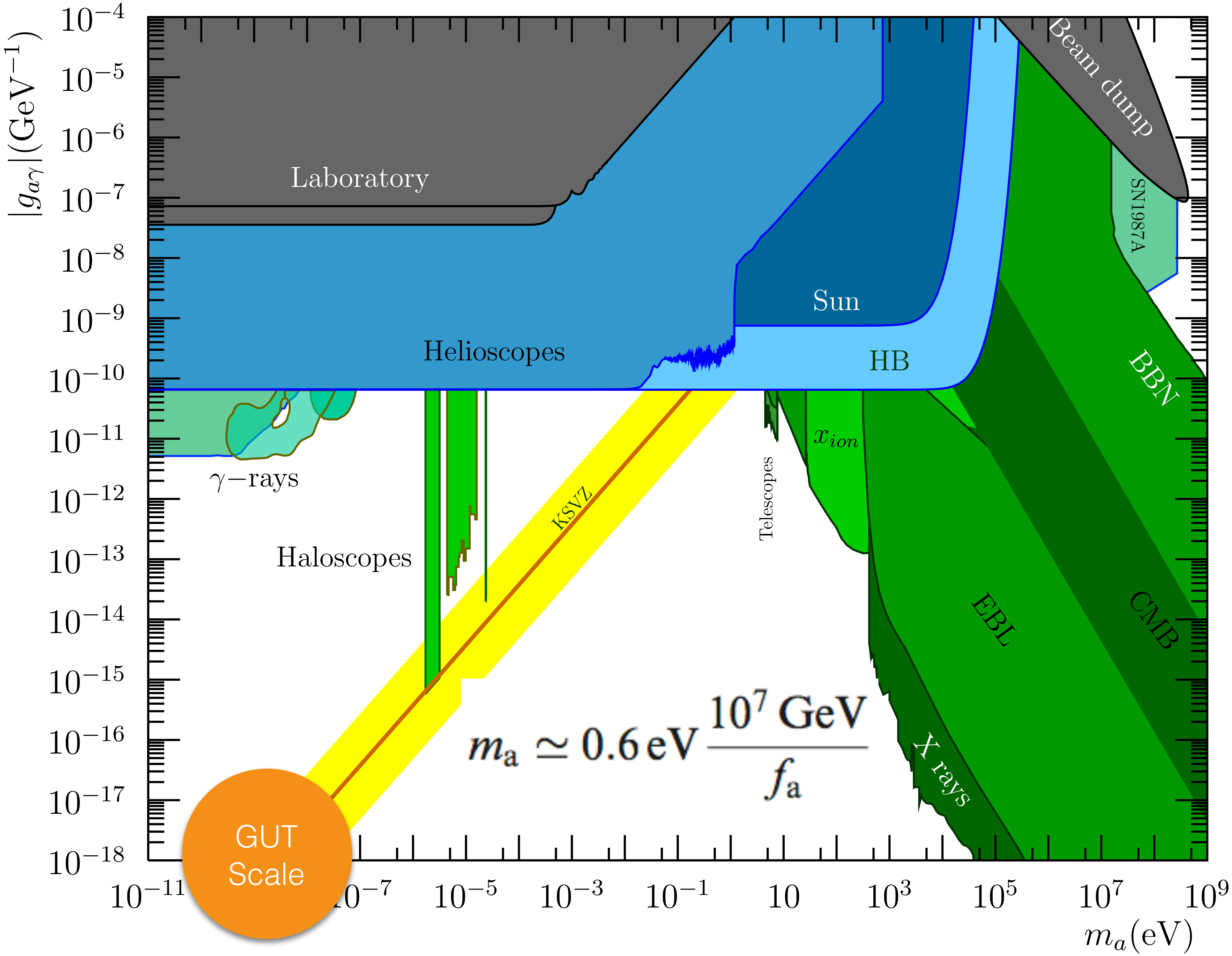

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ABRACADABRA

A Search for Low-Mass Axion Dark Matter*

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

*PRL 117 (2016) 141801

ABRA Concept

Treat ultralight axion DM as coherent field

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

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Generic axion modifies Ampere's Law:

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

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Magnetoquasistatic limit

E=**0**, DM *v* ~10^{-3}

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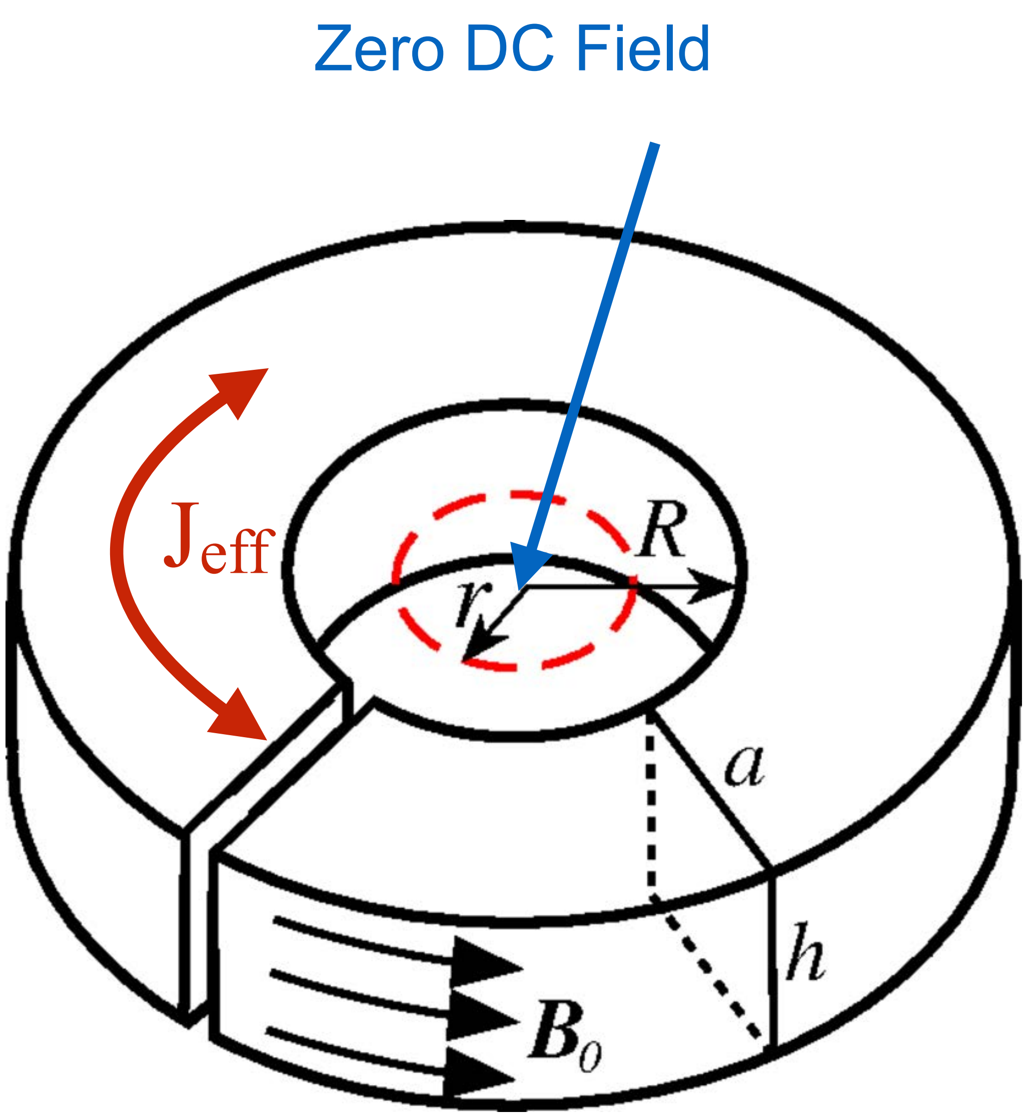
Yields axion-induced effective current:

$$\mathbf{J}_{\mathrm{eff}} = g_{a\gamma\gamma}\sqrt{2\rho_{\mathrm{DM}}}\cos(m_a t)\mathbf{B_0}$$



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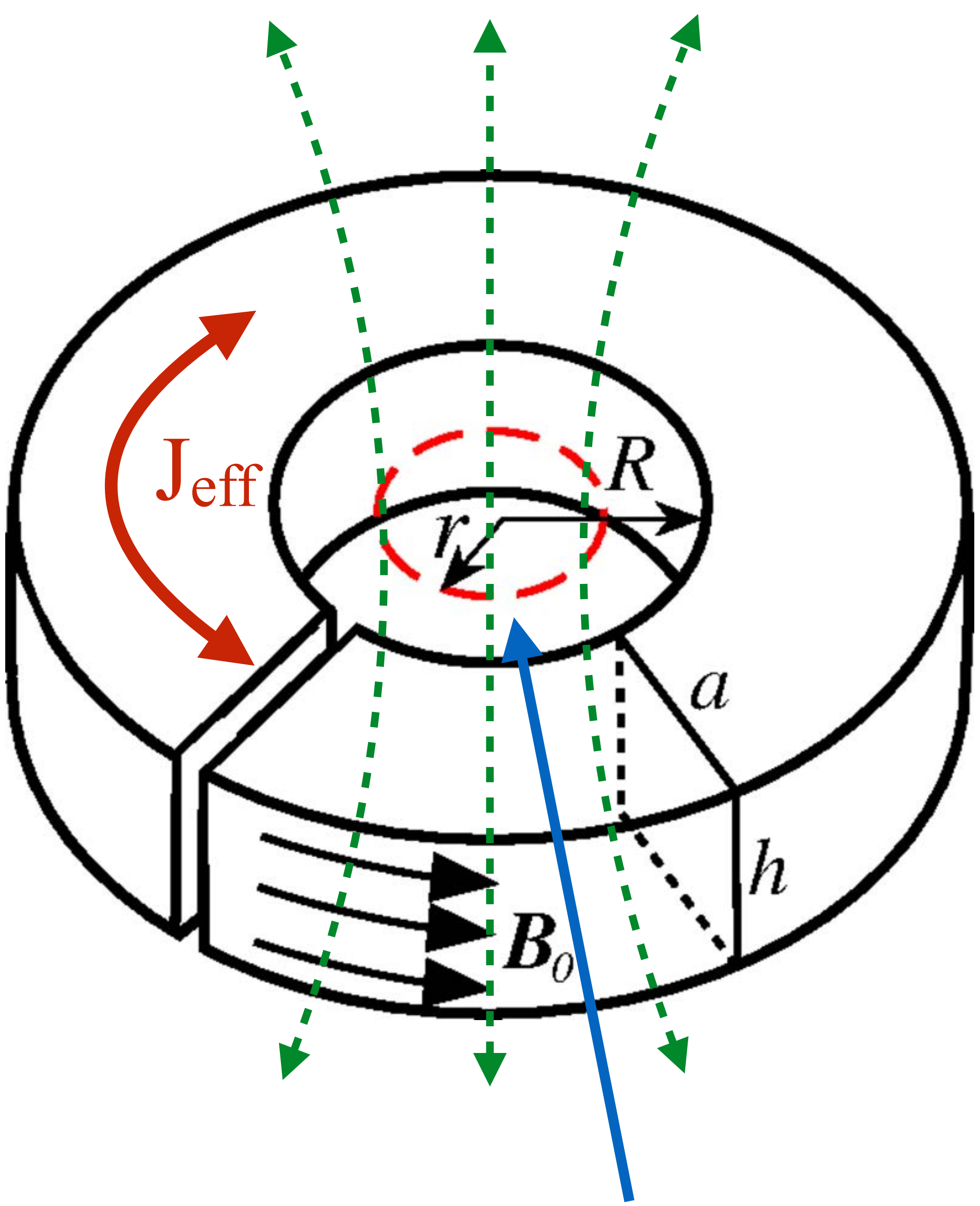
Induces oscillating magnetic field in torus

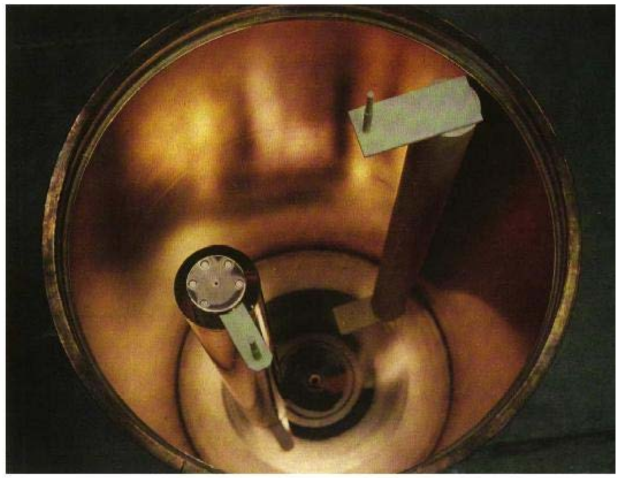
Induced B-field

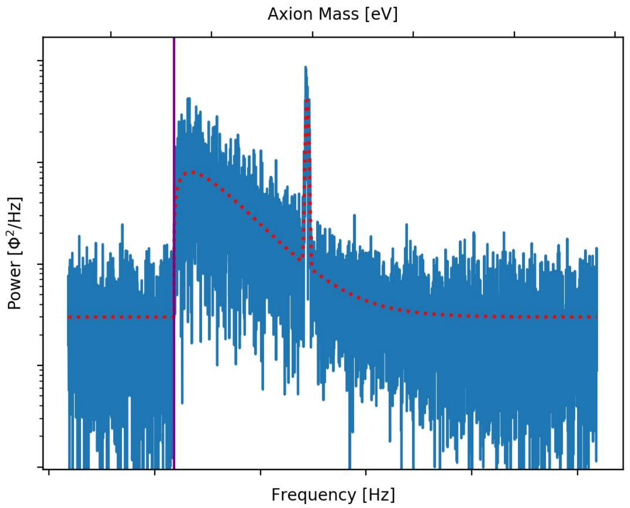


Measure induced field using pickup loop
DC B-field free

Historical Interlude

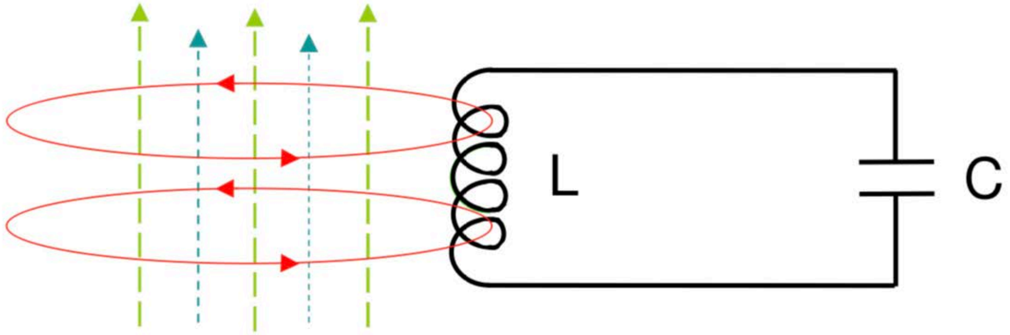
Sikivie Proposal using RF cavities: PRL 51 (1983) 1415





PRD 97 (2018) 123006

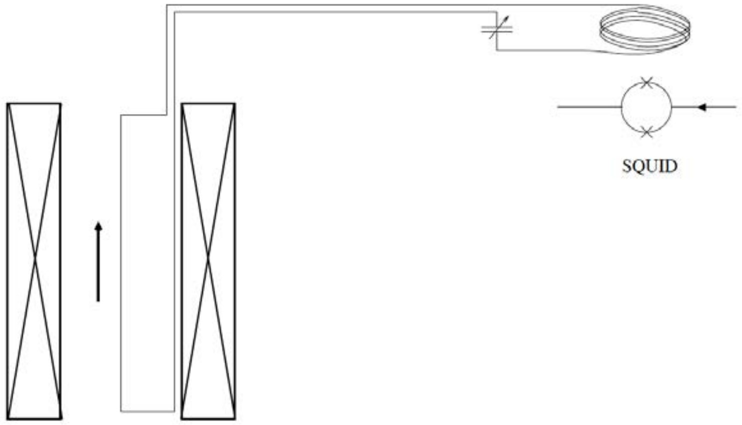
Tuned LC Circuit (no cavity):
Cabrera, Thomas, 2010



Solenoidal Magnet: PRL 112 (2014) 131301

DM Radio Dark Photon Detection: PRD 92 (2015) 075012

Toroidal Magnet: **ABRACADABRA**: PRL 117 (2016) 141801



Two Readout Strategies

Broadband

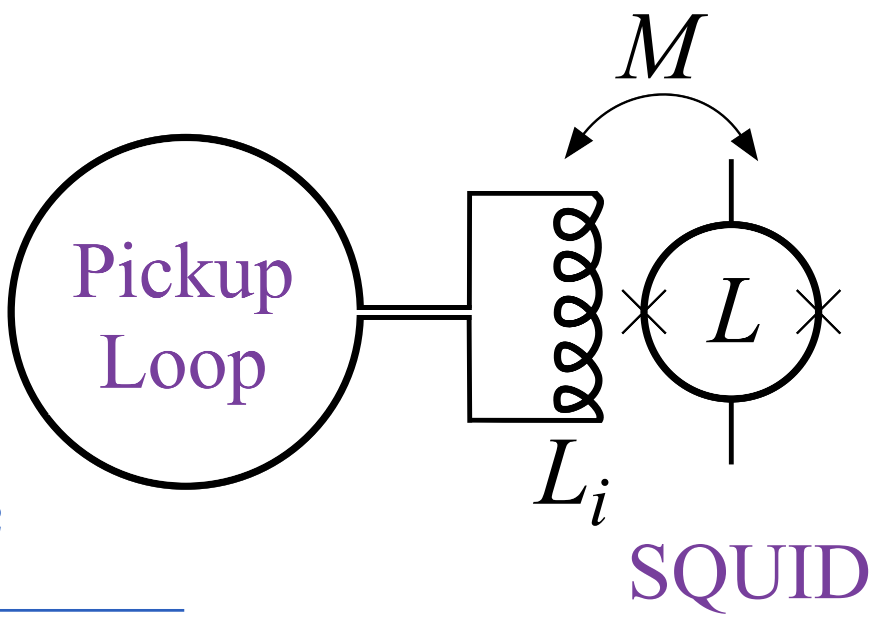
Scan all frequencies simultaneously

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



Resonant

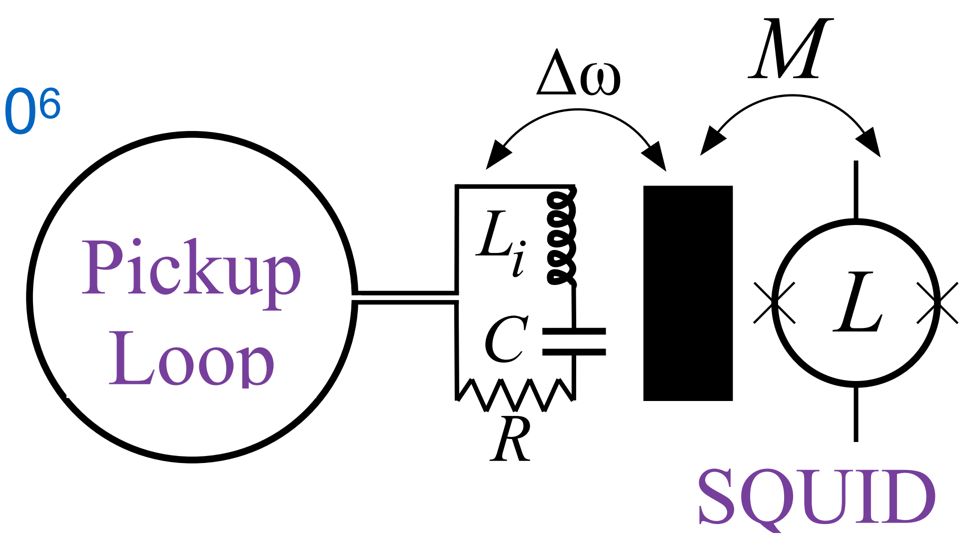
Resonance enhancement by adding capacitor with Q ~ 10^6

Scan across frequencies

Thermal noise in pickup loop dominates

Resonance Mode Sensitivity:

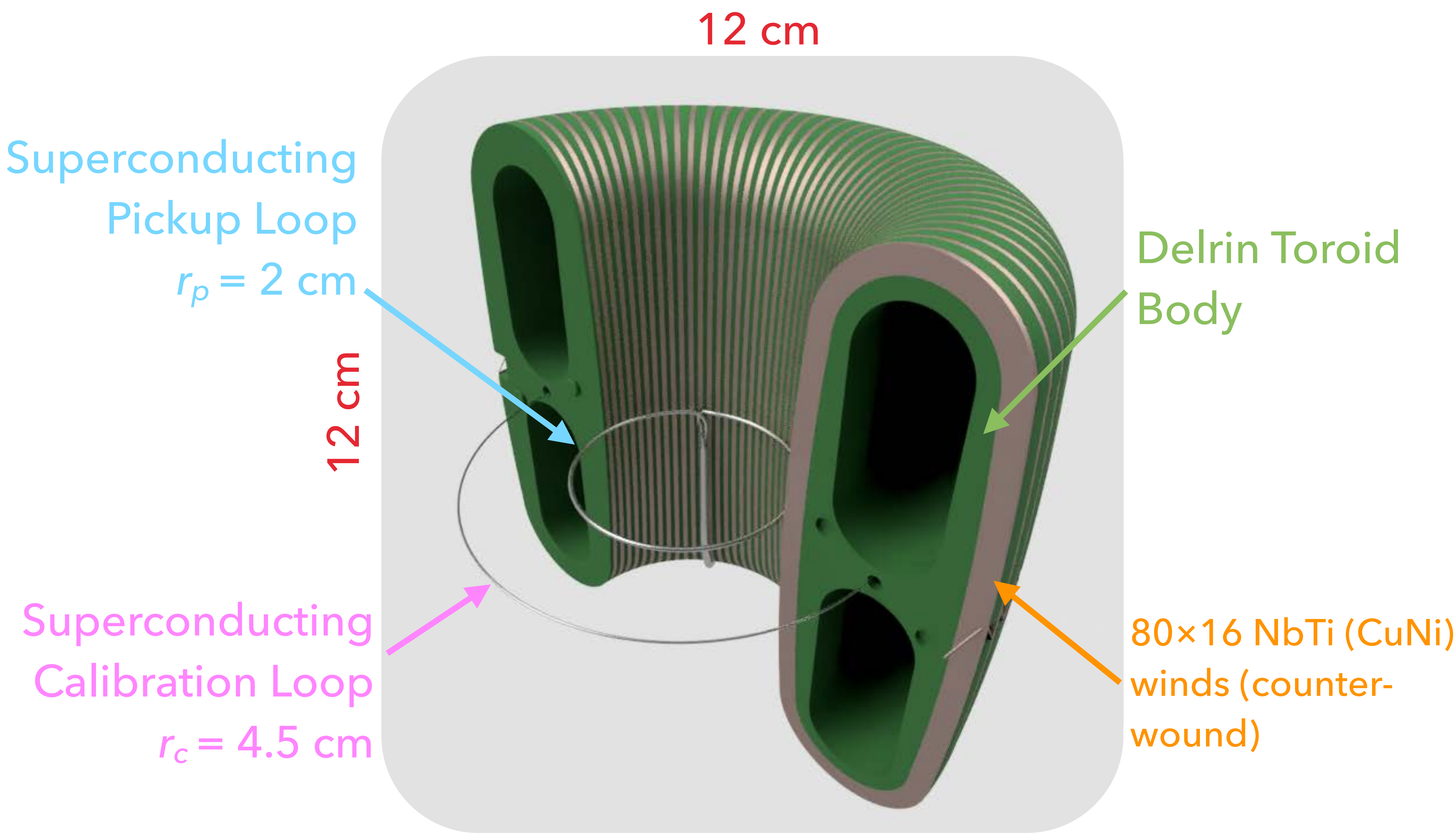
$$g_{a\gamma\gamma} \propto \sqrt{L_T}\left(\frac{1}{m_a t}\right)^{\frac{1}{4}} \frac{1}{B_{\max} G V_B} \sqrt{\frac{k_B T}{\rho_{\mathrm{DM}} Q_0}}$$



Prototype: ABRACADABRA-10 cm

PRD 99 (2019) 052012, PRL 122 (2019) 121802

Dissecting ABRACADABRA-10 cm



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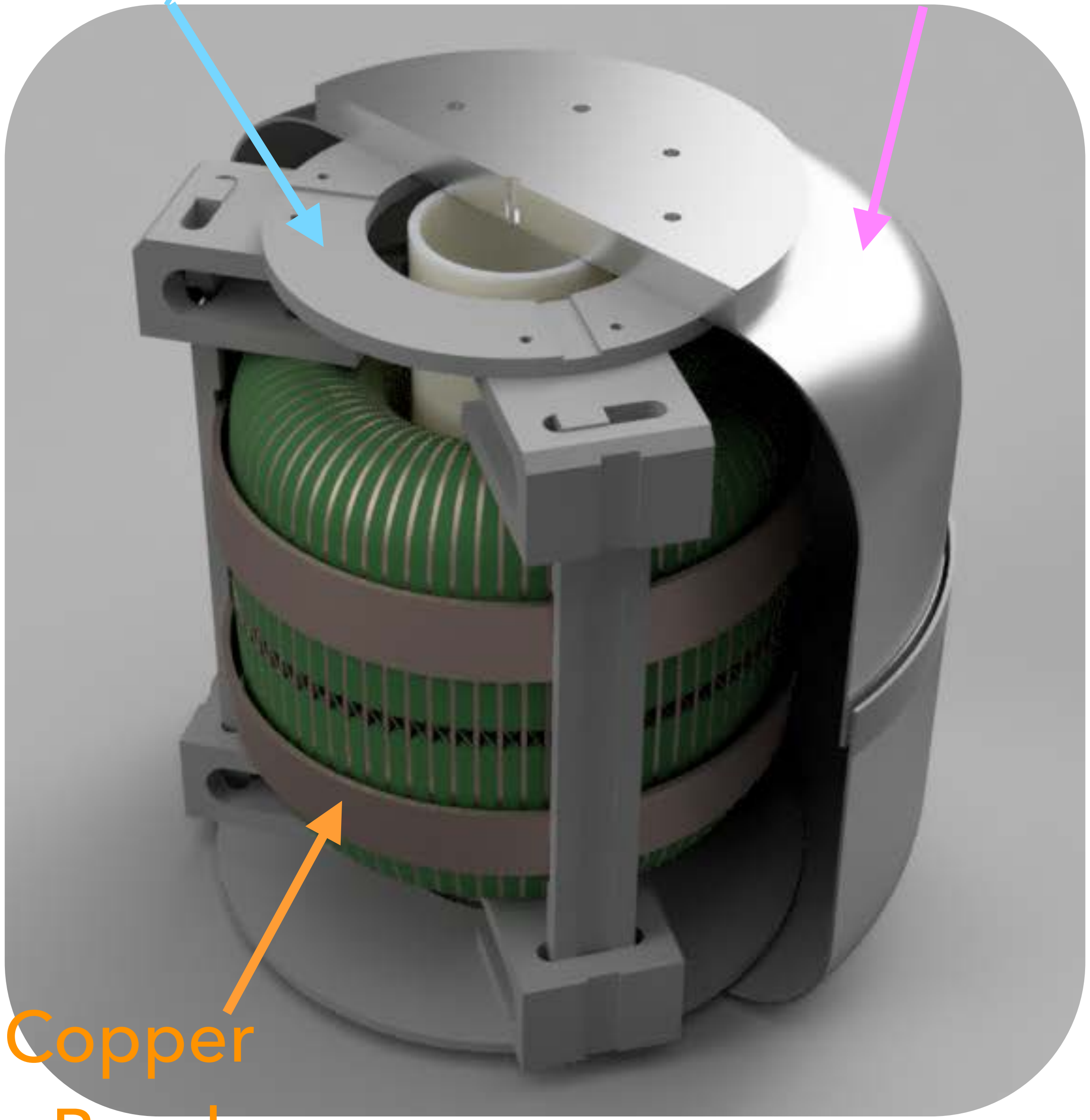
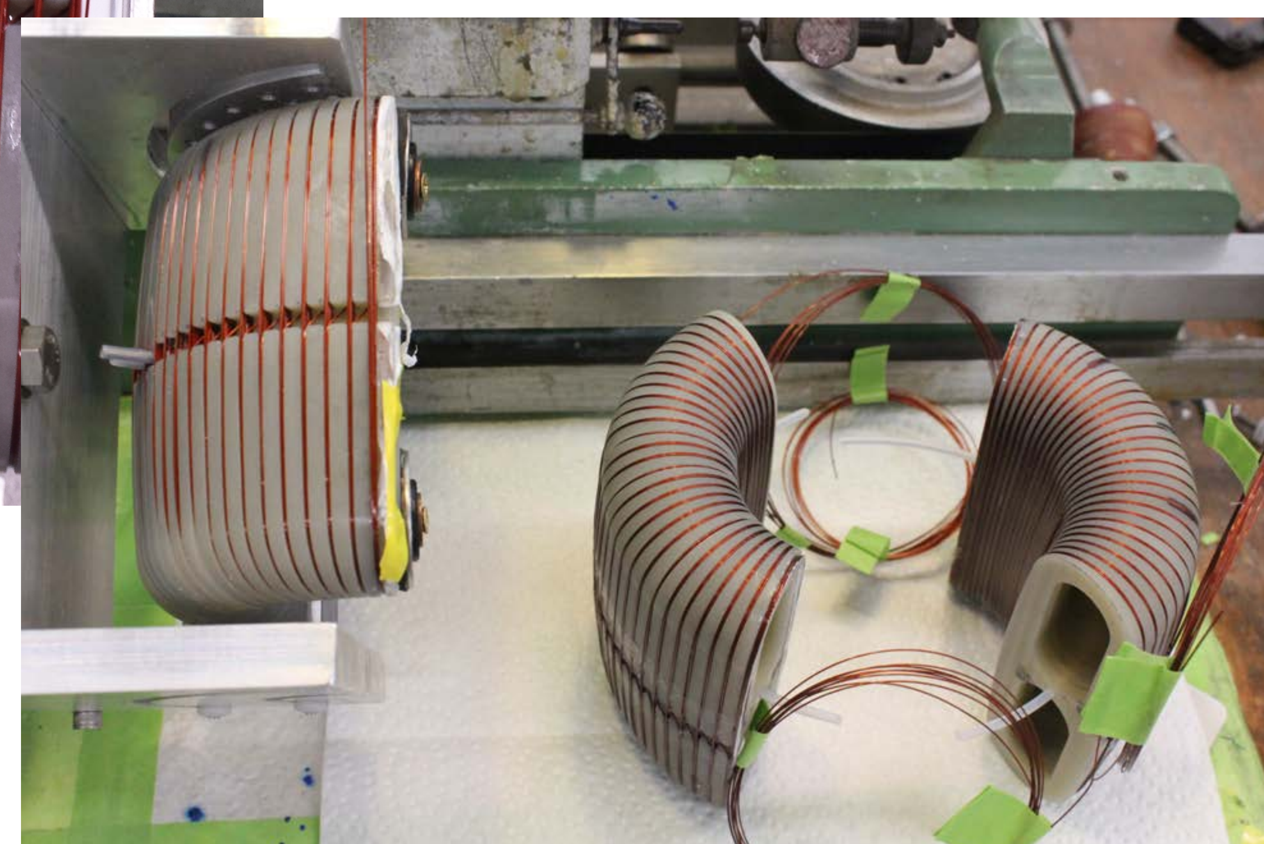


Assembling ABRACADABRA-10 cm

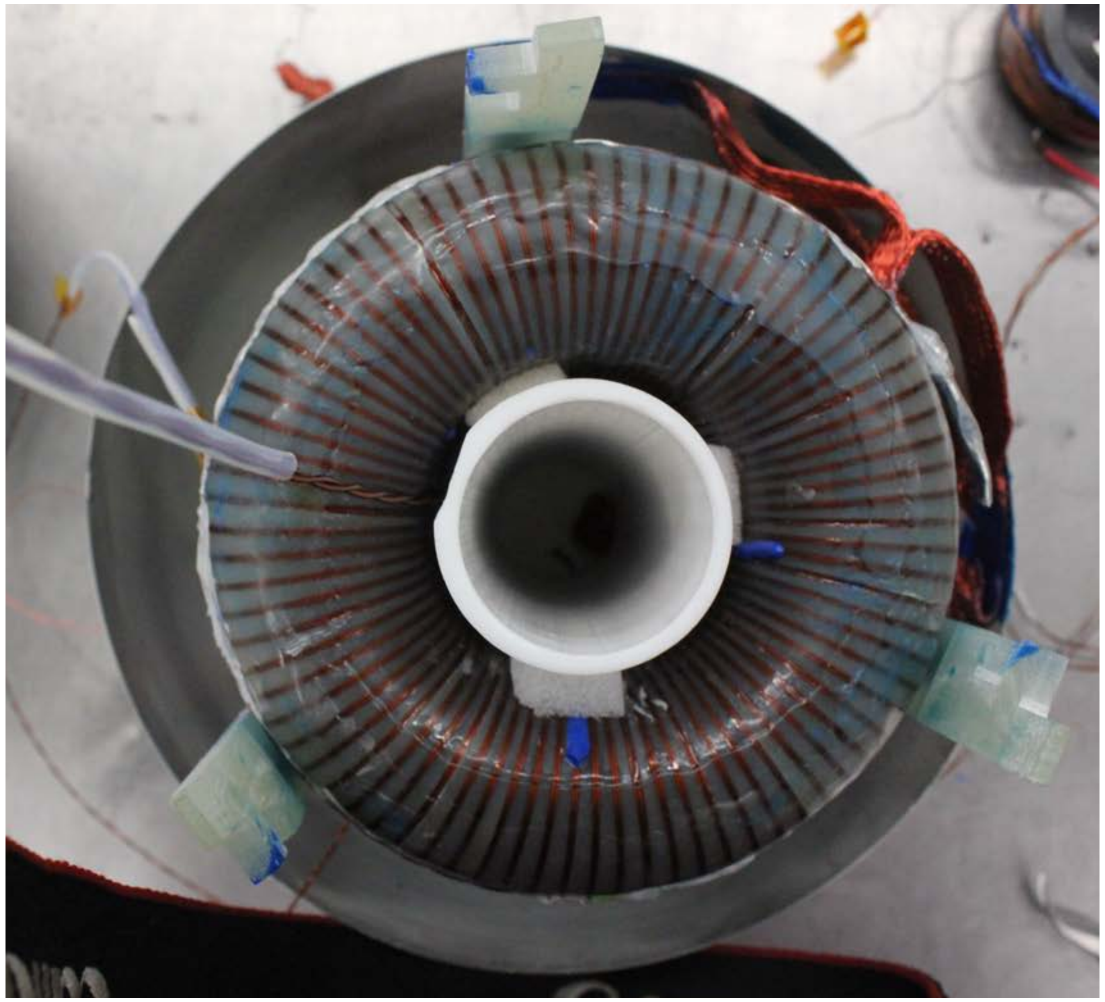
SUPERCONDUCTING SYSTEMS INC.

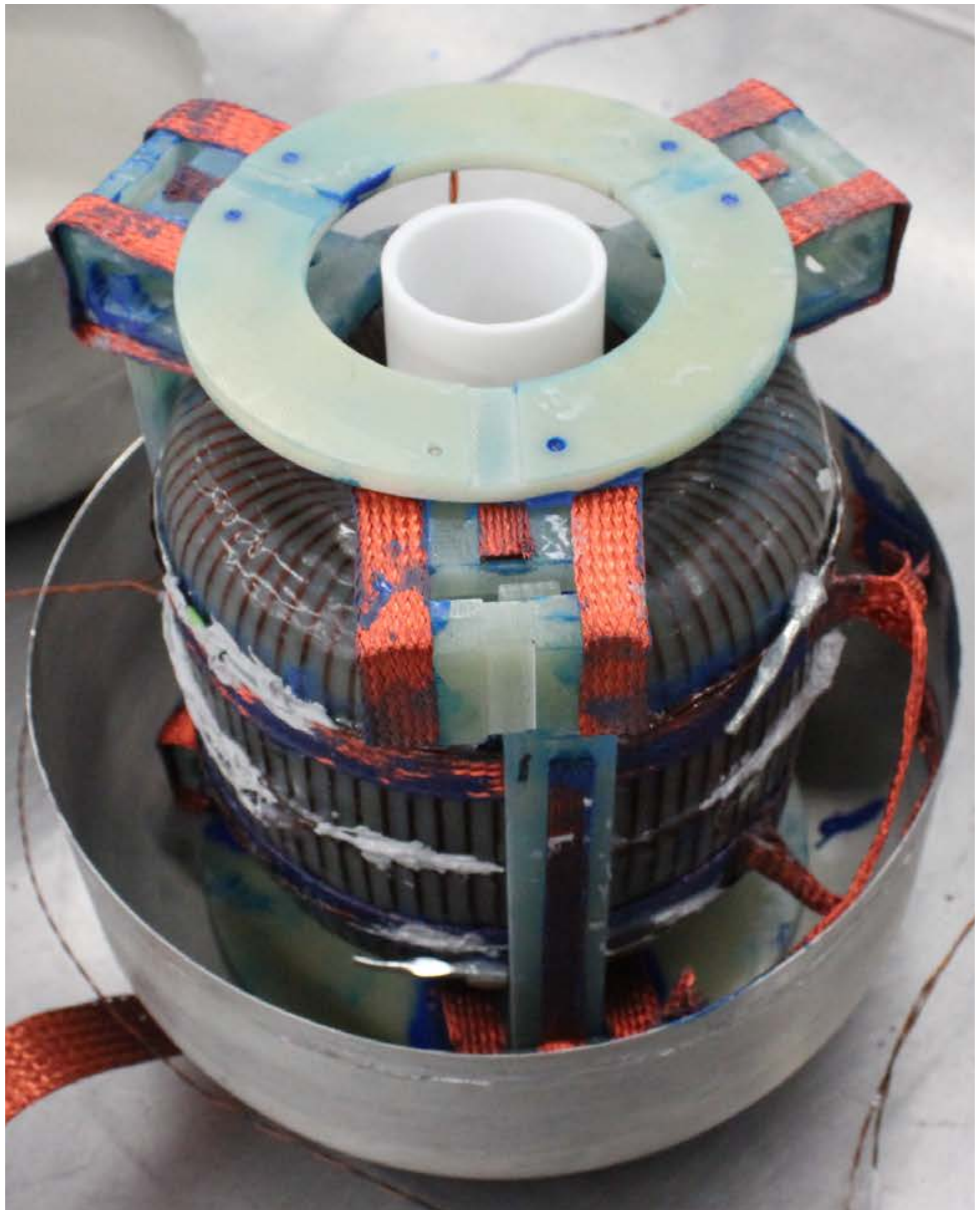
(Normally make MRI magnets!)



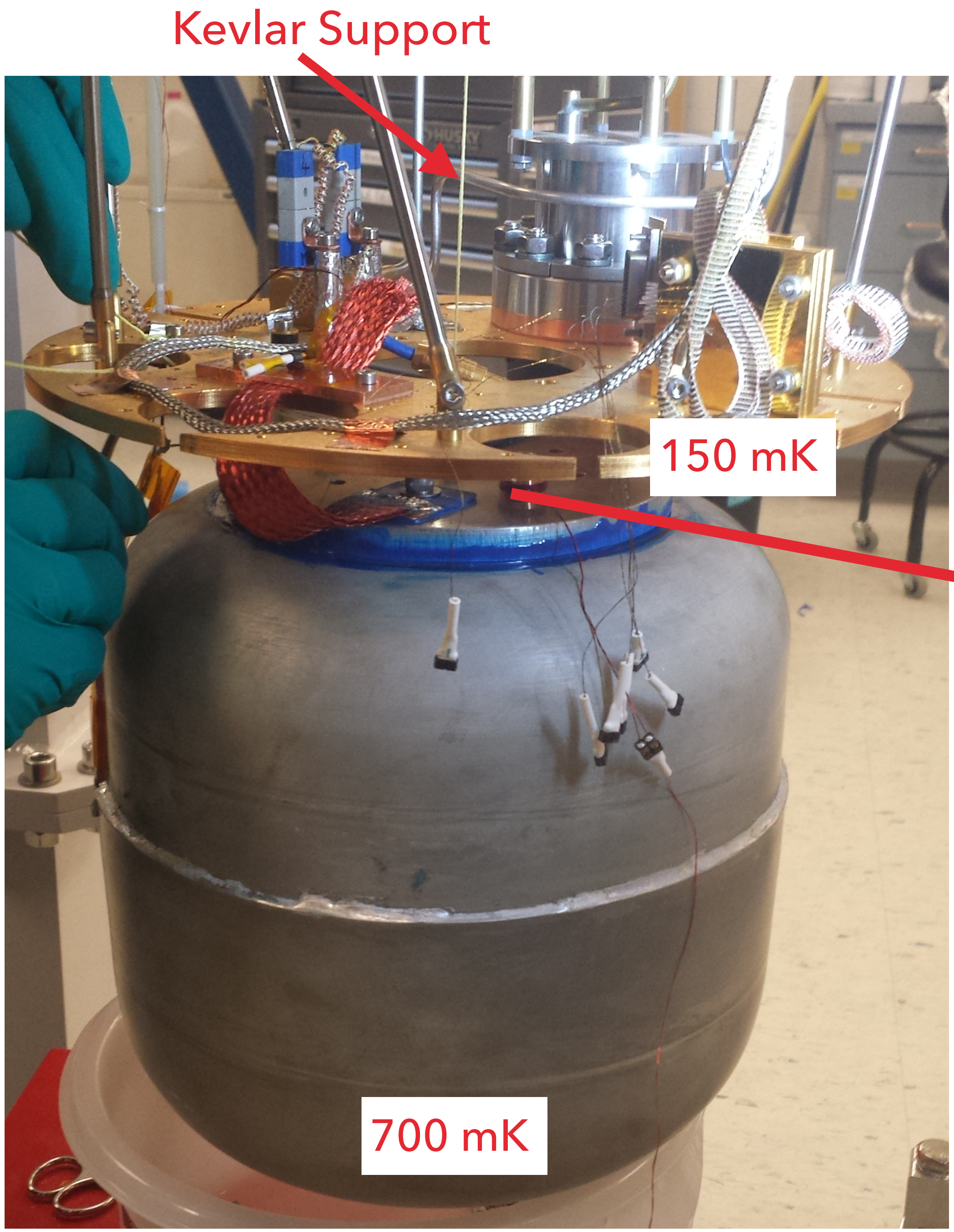
Assembling ABRACADABRA-10 cm

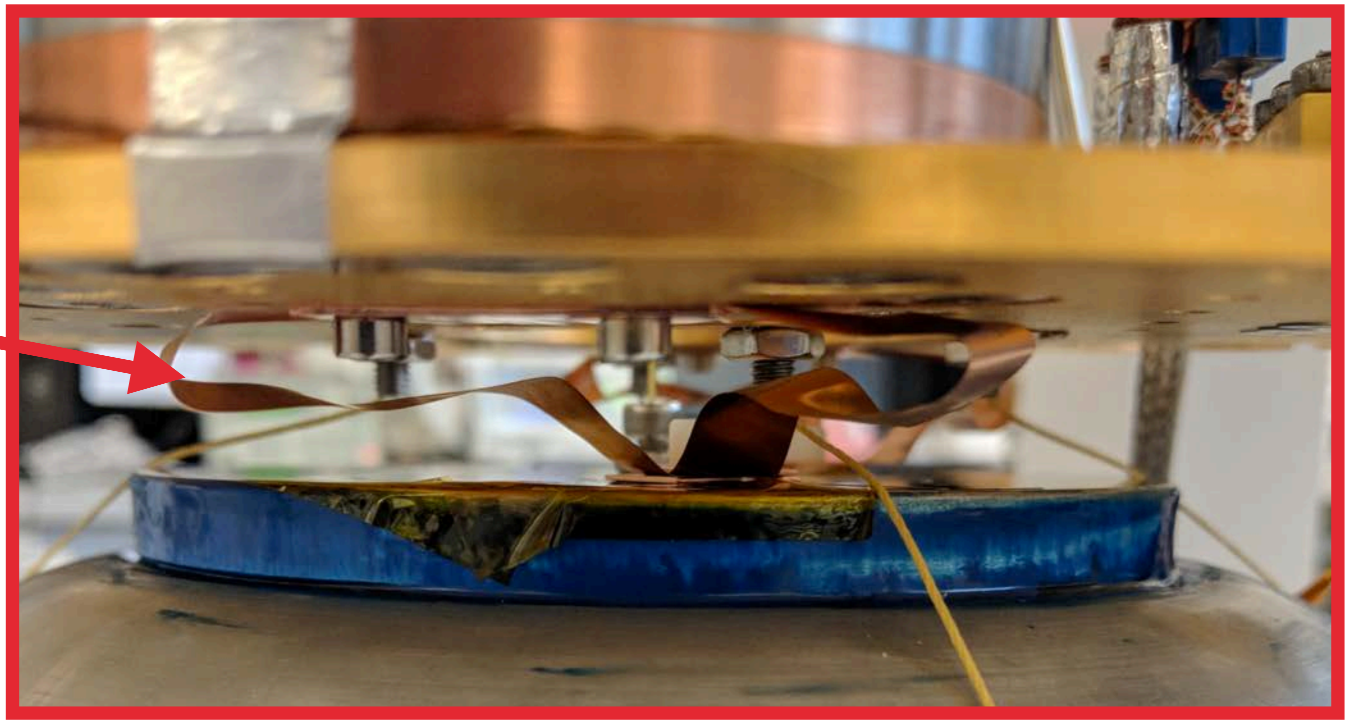
Pickup Loop





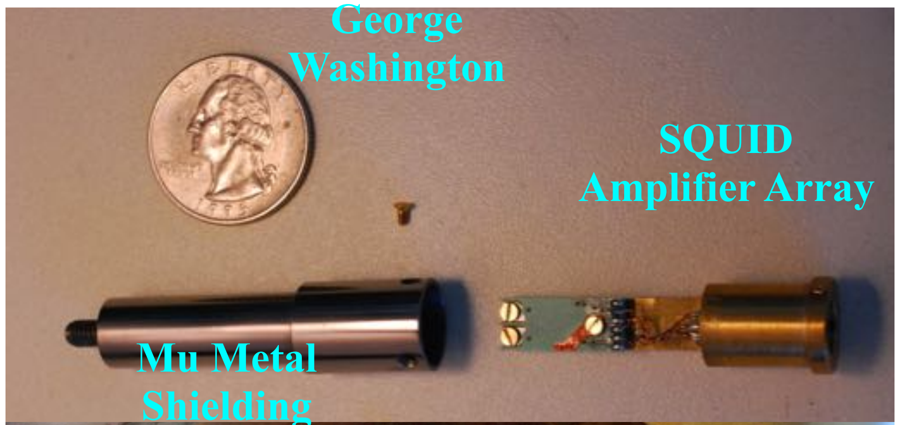
Mounting ABRA

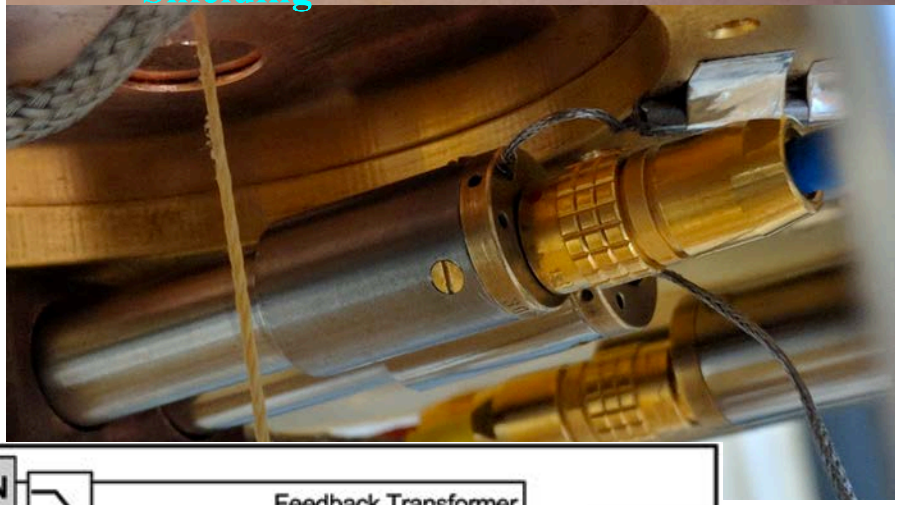


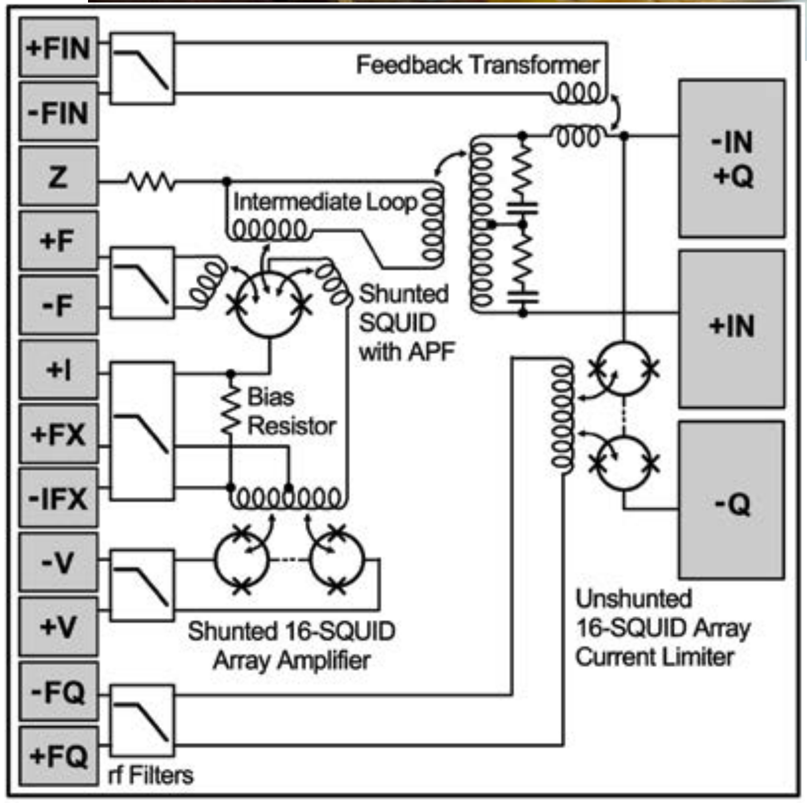


SQUID Readout

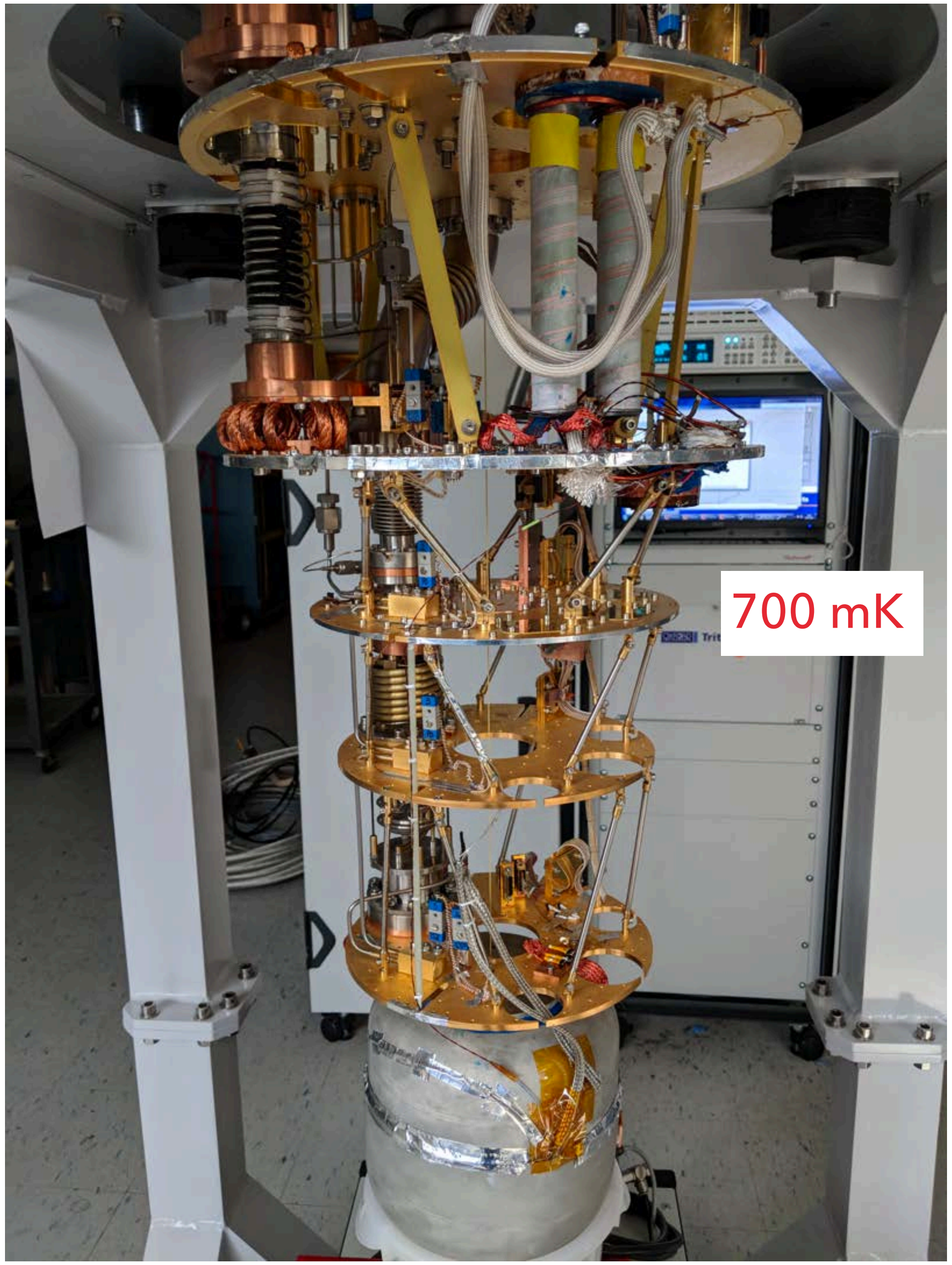
- Off-the-shelf Magnicon DC SQUIDs
  - 2 Stage
  - Typical noise floor ~1 $\mu\Phi_0/(\mathrm{Hz})^{1/2}$
  - Optimized for operation < 1 K
  - Typical gain of ~1.3 V/Φ_0
- No resonator (i.e. broadband readout)



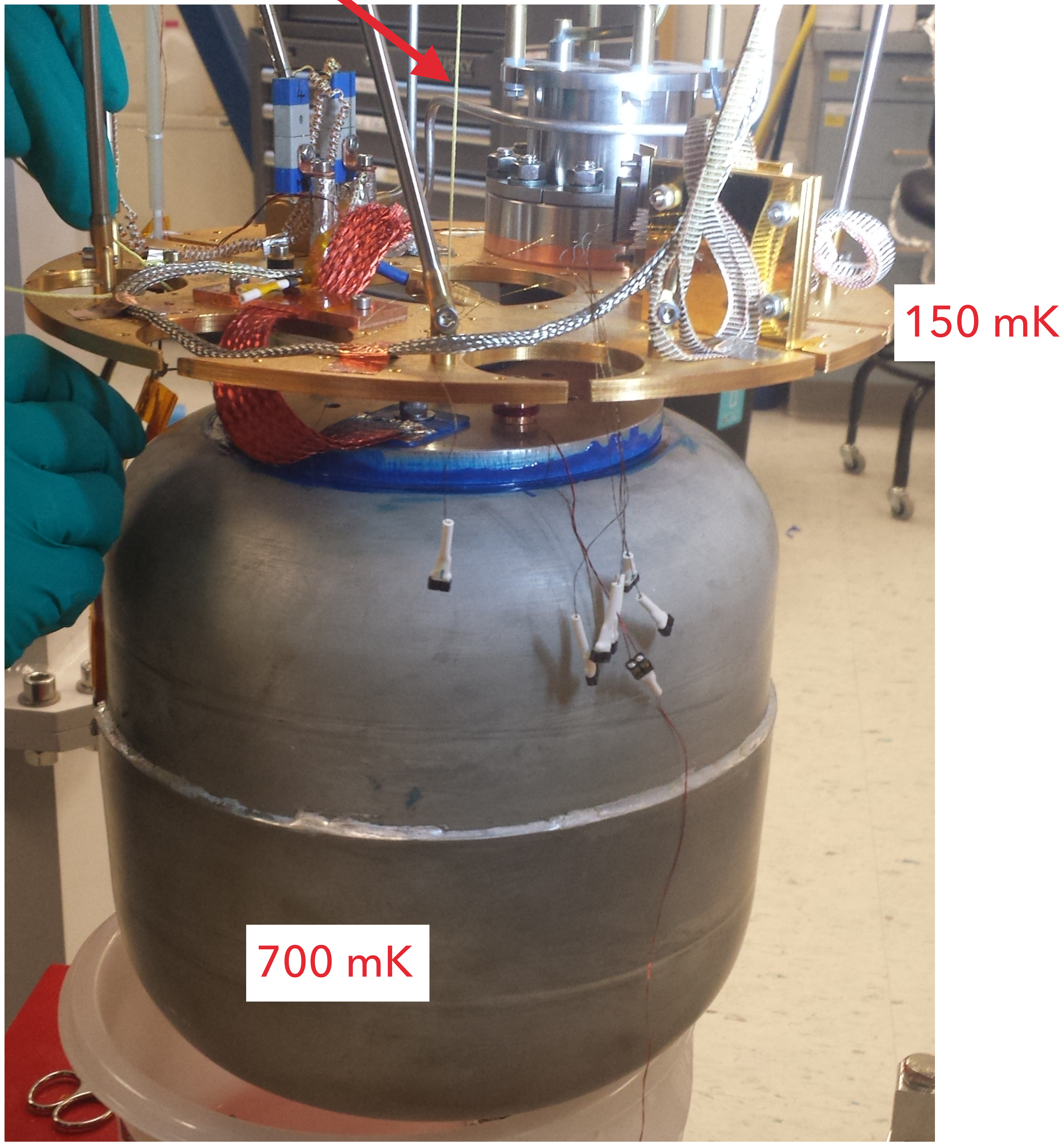




Mechanical Suspension System

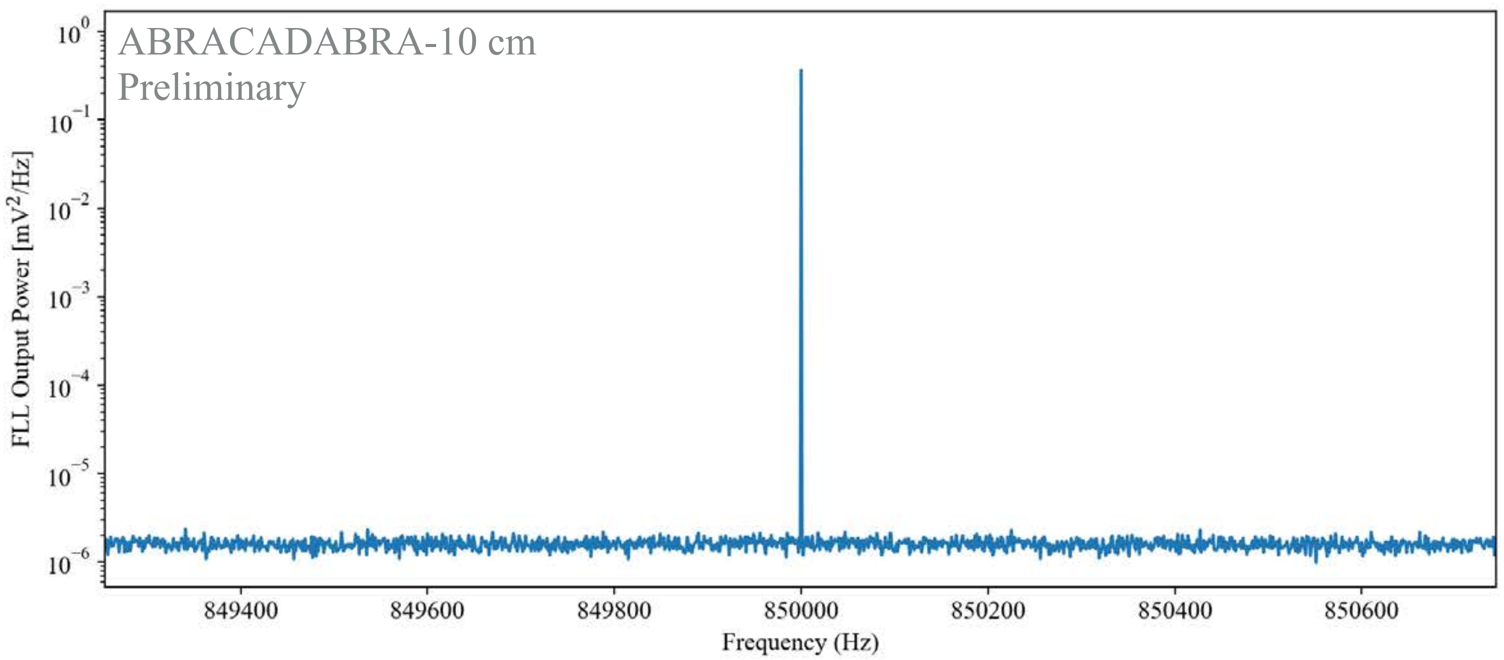


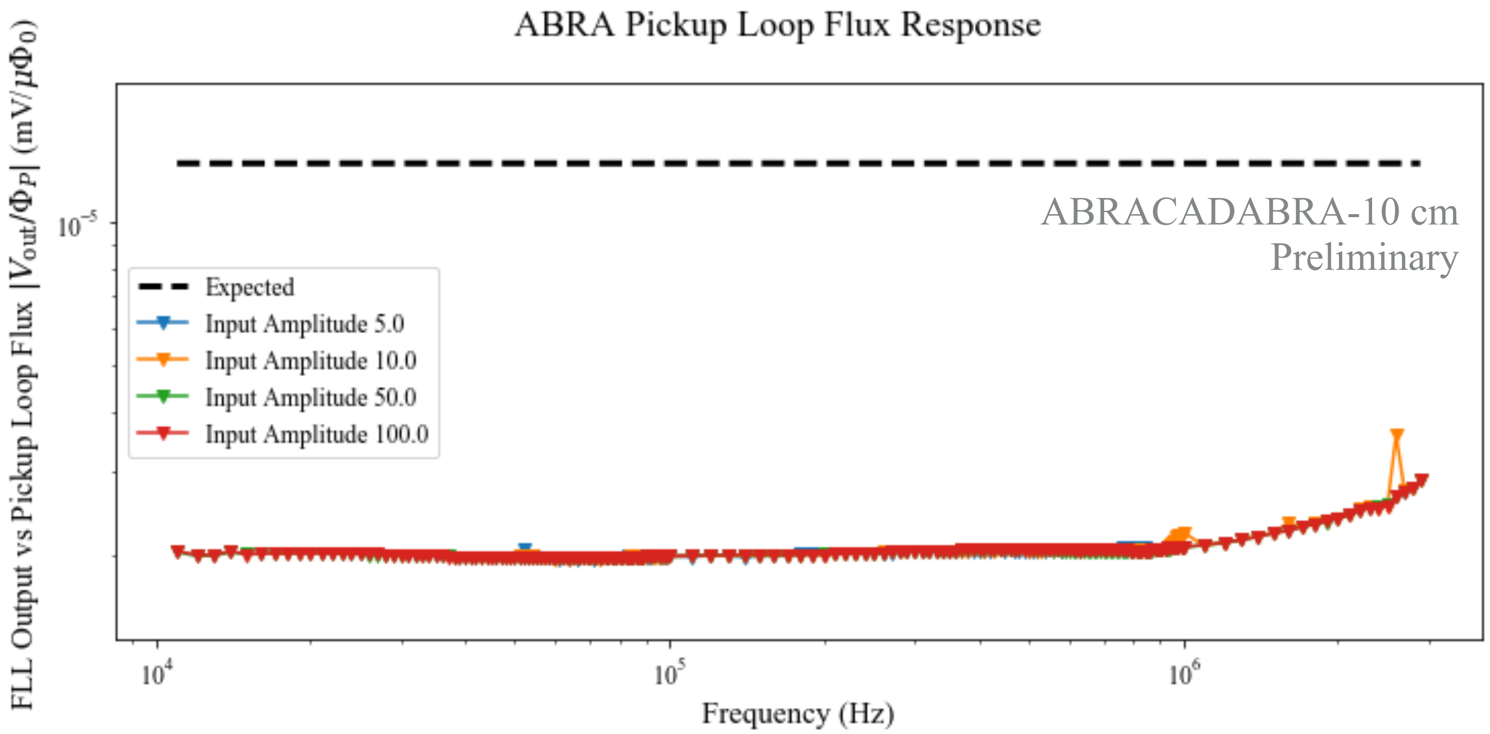
Kevlar Support



Calibration

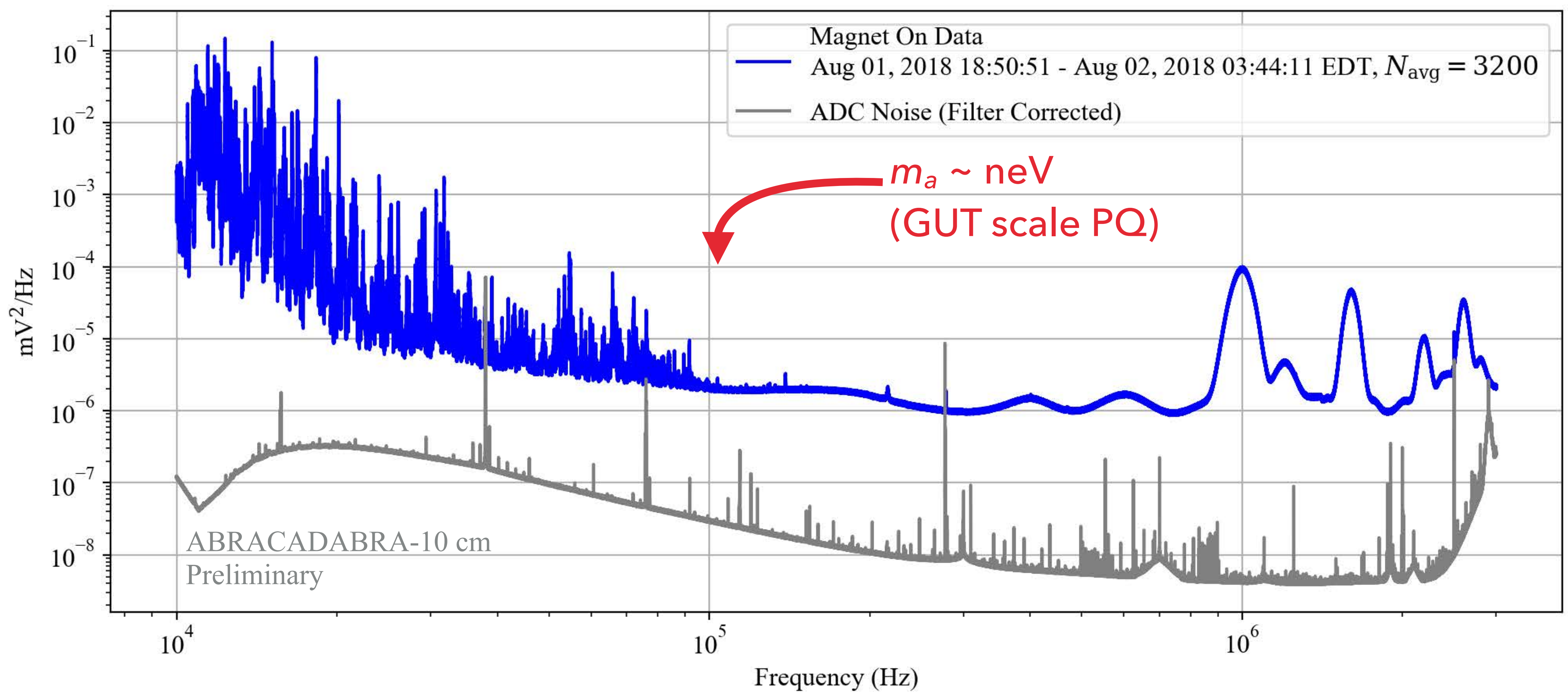
- Calibrate by injecting AC current into the calibration loop
- Fine scan from 10 kHz - 3 MHz at multiple amplitudes
- Gain lower than expected by a factor of ~6.5. To be improved in next phase





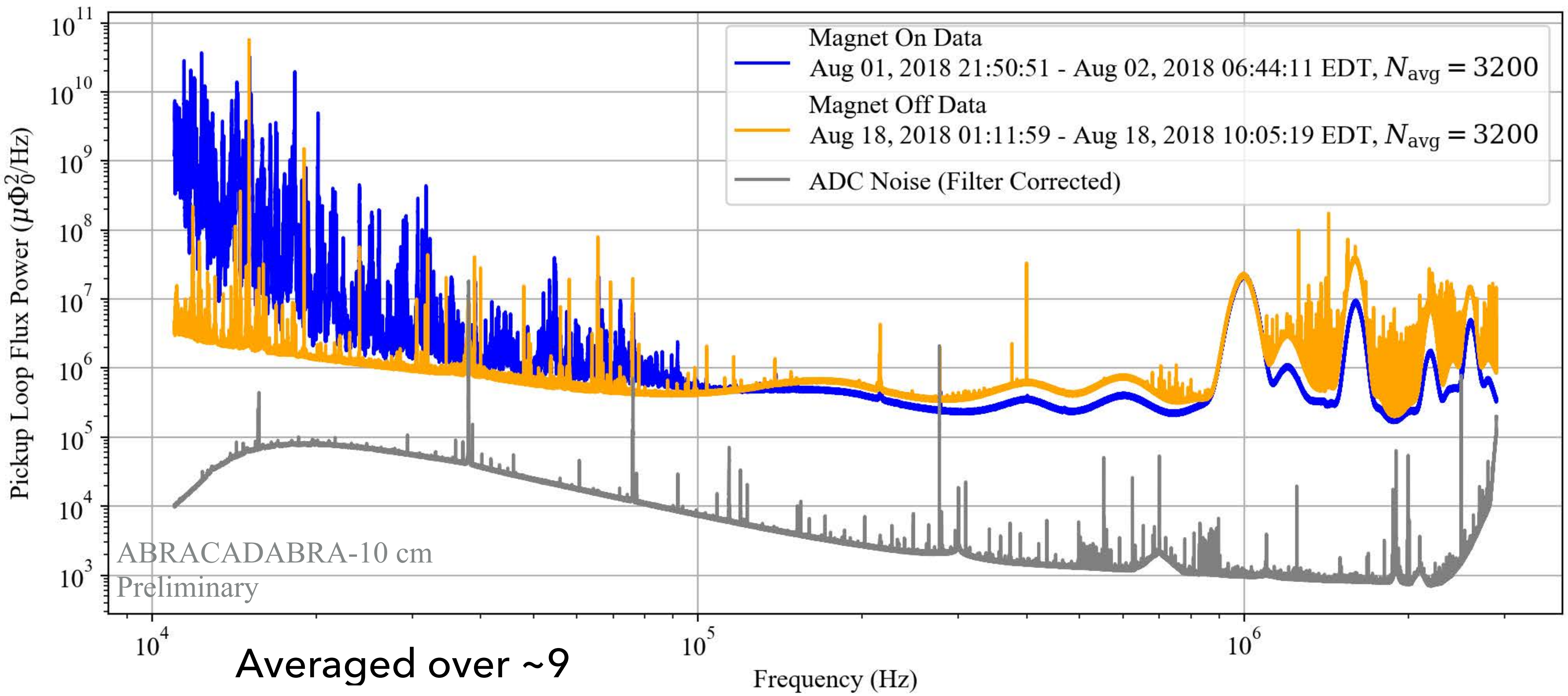
Example Spectrum

~9 hours of data



- 10 kHz high-pass and 1.9MHz anti-aliasing filters before digitizer
- Digitizer-only data show spurious noise spikes that were vetoed.

Magnet Off Data

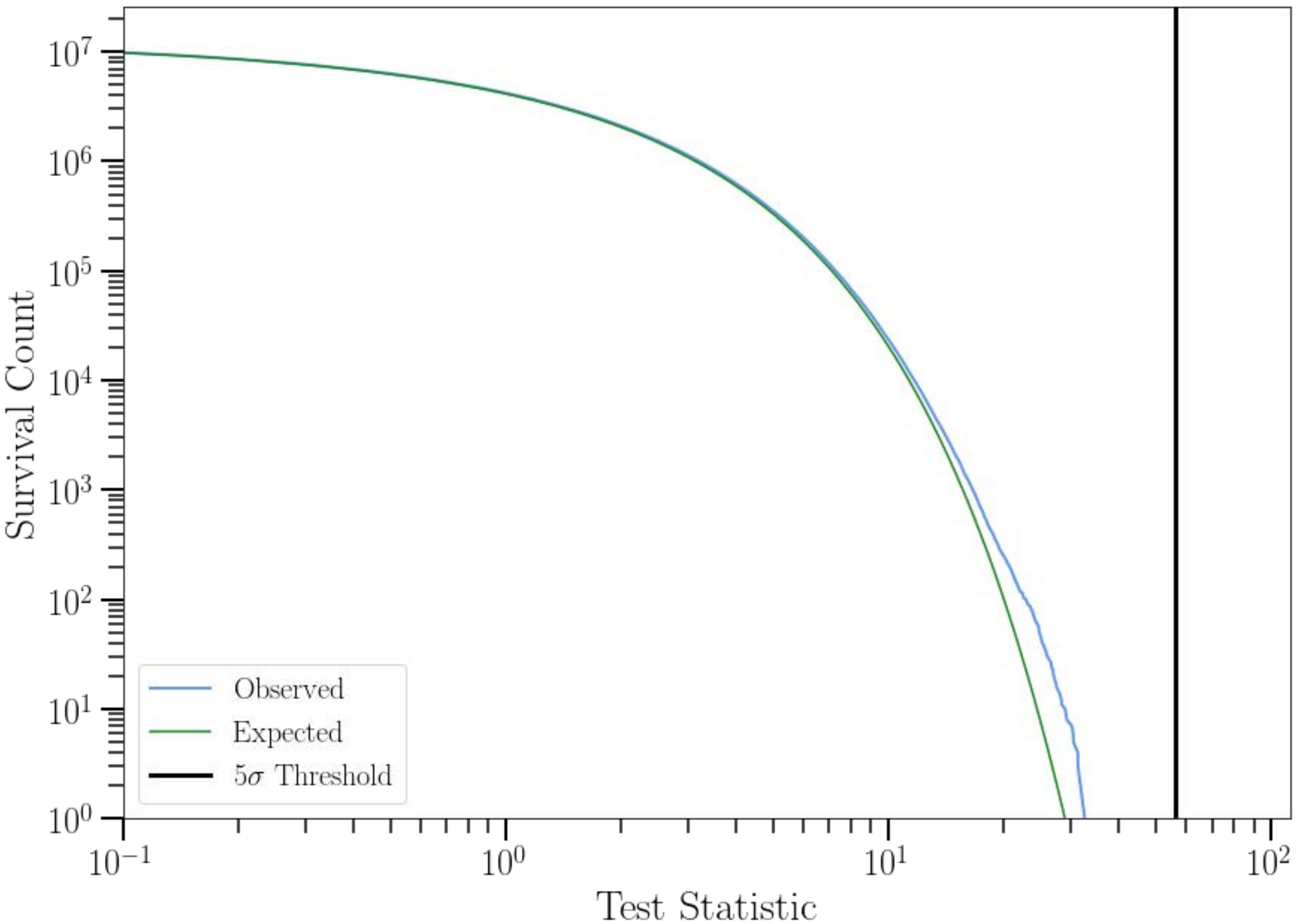


- Collected 2 weeks of magnet off data with the same configuration
- High frequency transient noise also present
- Noise increases < 10kHz
- Used for spurious signal veto

ABRACADABRA-10cm Axion Search

Axion Search Approach

- Search range to 75 kHz - 2 MHz (m_a in 0.31 — 8.1 neV).
- 8.6 million mass points
- For each mass point, calculate a likelihood function
- Axion discovery search based on a log-likelihood ratio test, between the best fit and the null hypothesis
- 5σ discovery threshold: TS>56.1
- Accounts for Look Elsewhere Effect.



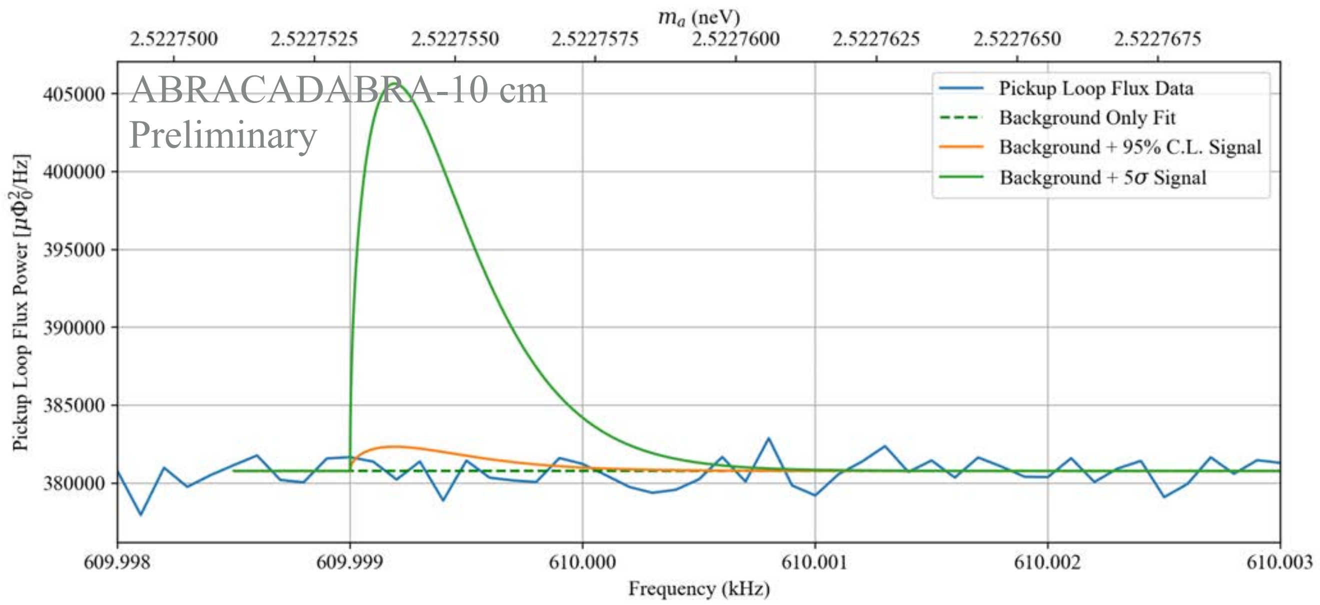
For details, see: PRD 97 (2018) 123006

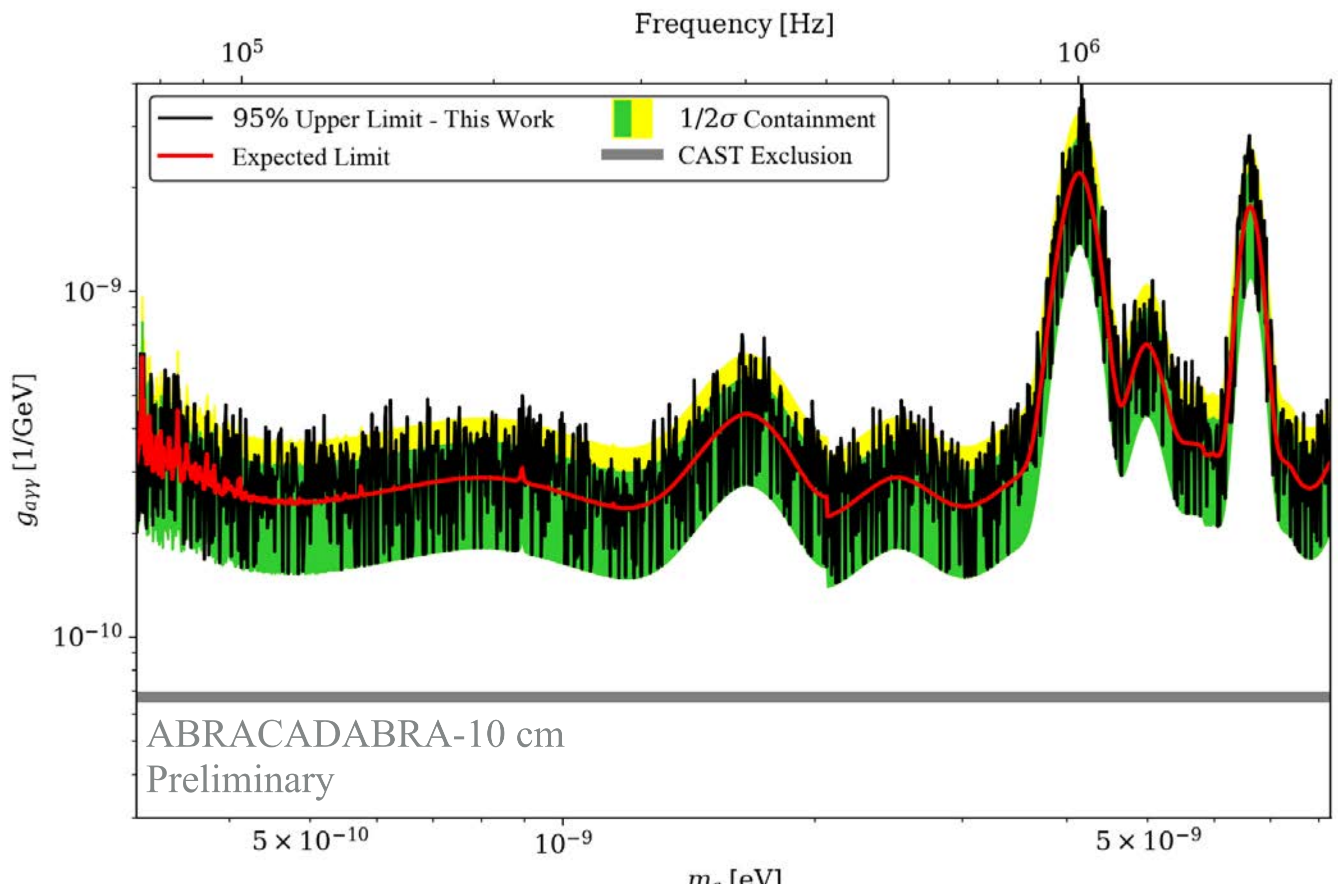
Axion Limits

- We saw no 5σ excesses that were not vetoed by Magnet off or digitizer data

  87 (0) mass points were vetoed in the 10MS/s (1MS/s) data

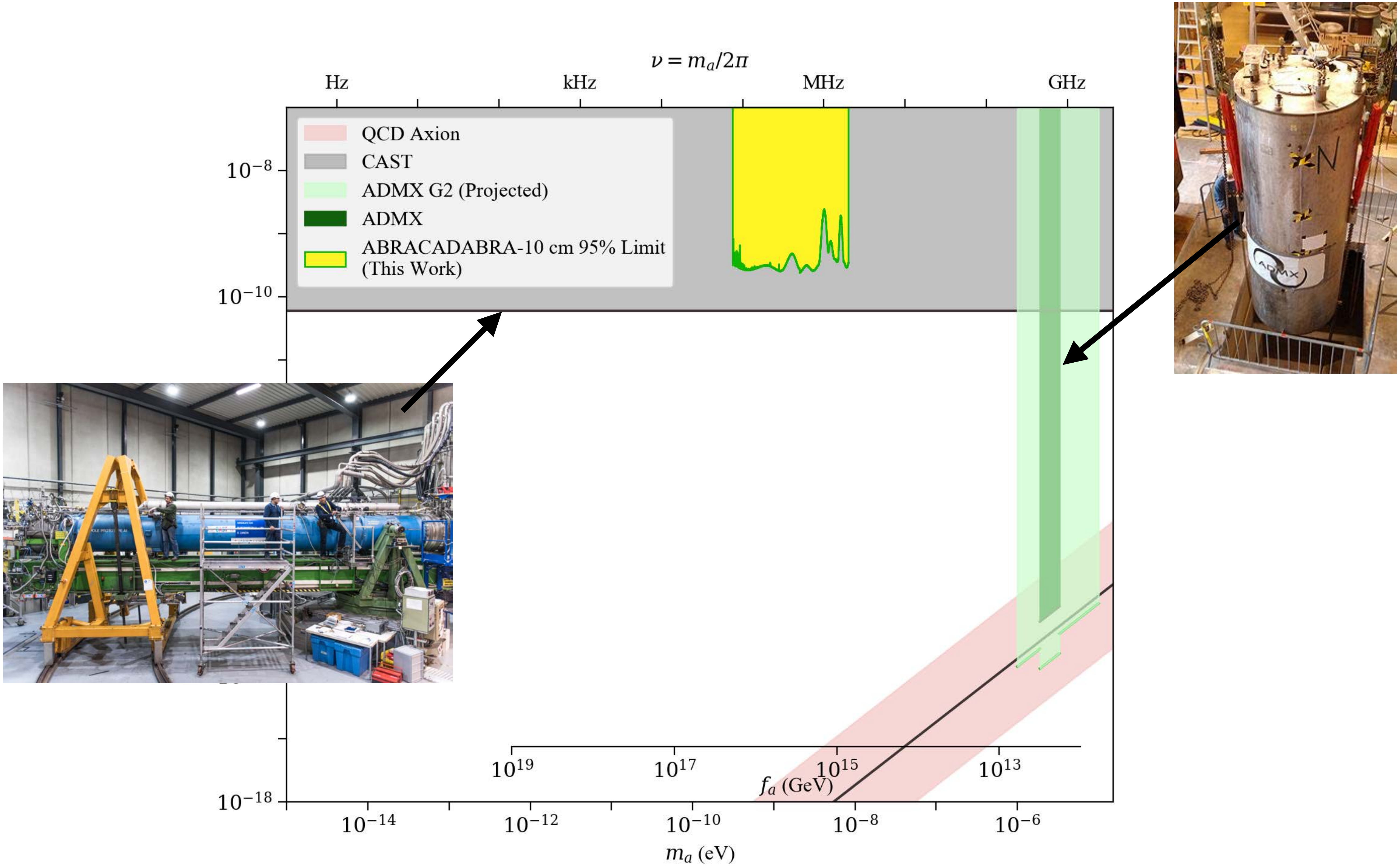
- We place 95% C.L. upper limits using a similar log-likelihood ratio approach



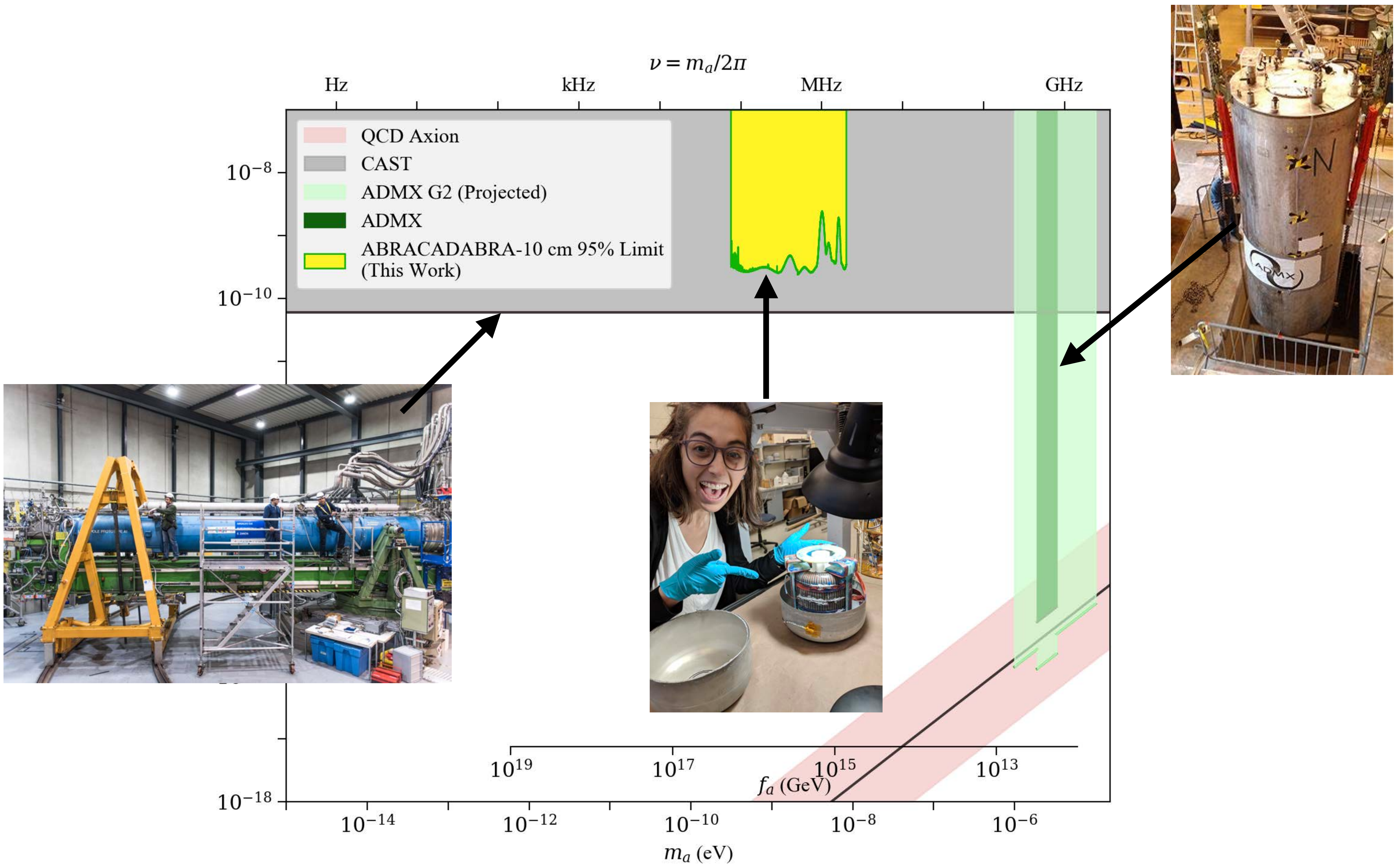


For details, see: PRD 97 (2018) 123006

ABRACADABRA-10 cm Run 1 Limits



ABRACADABRA-10 cm Run 1 Limits



ABRACADABRA

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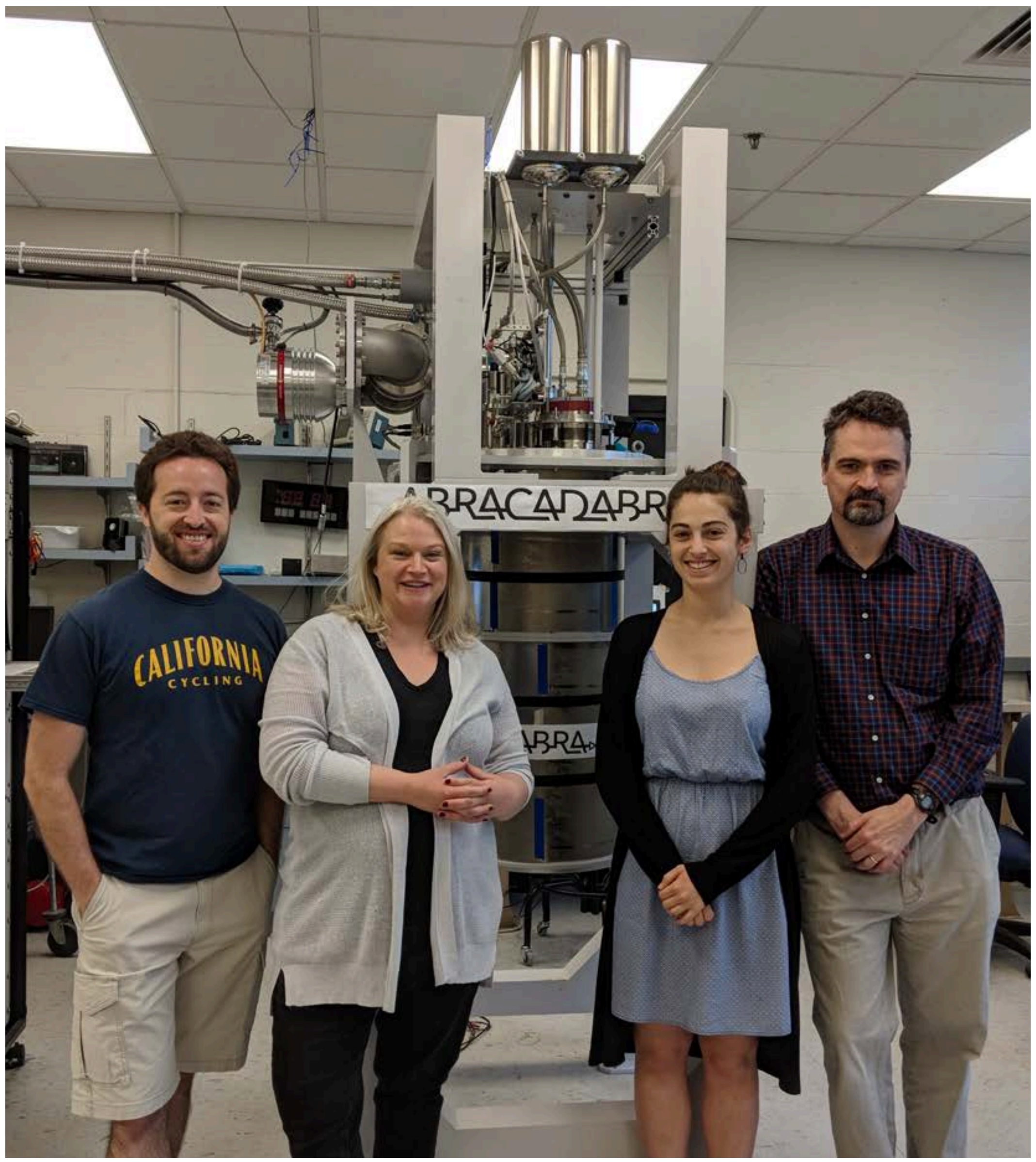
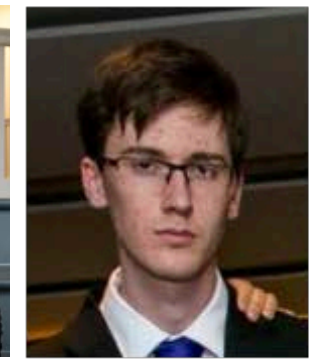
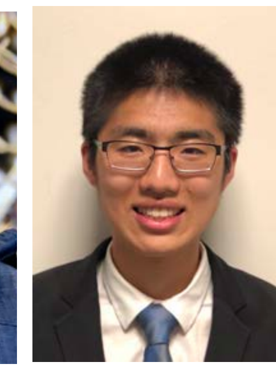
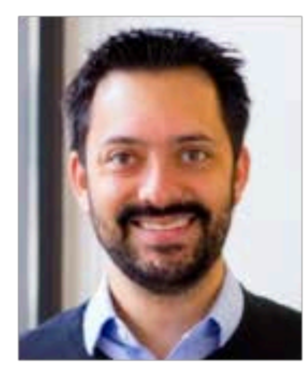


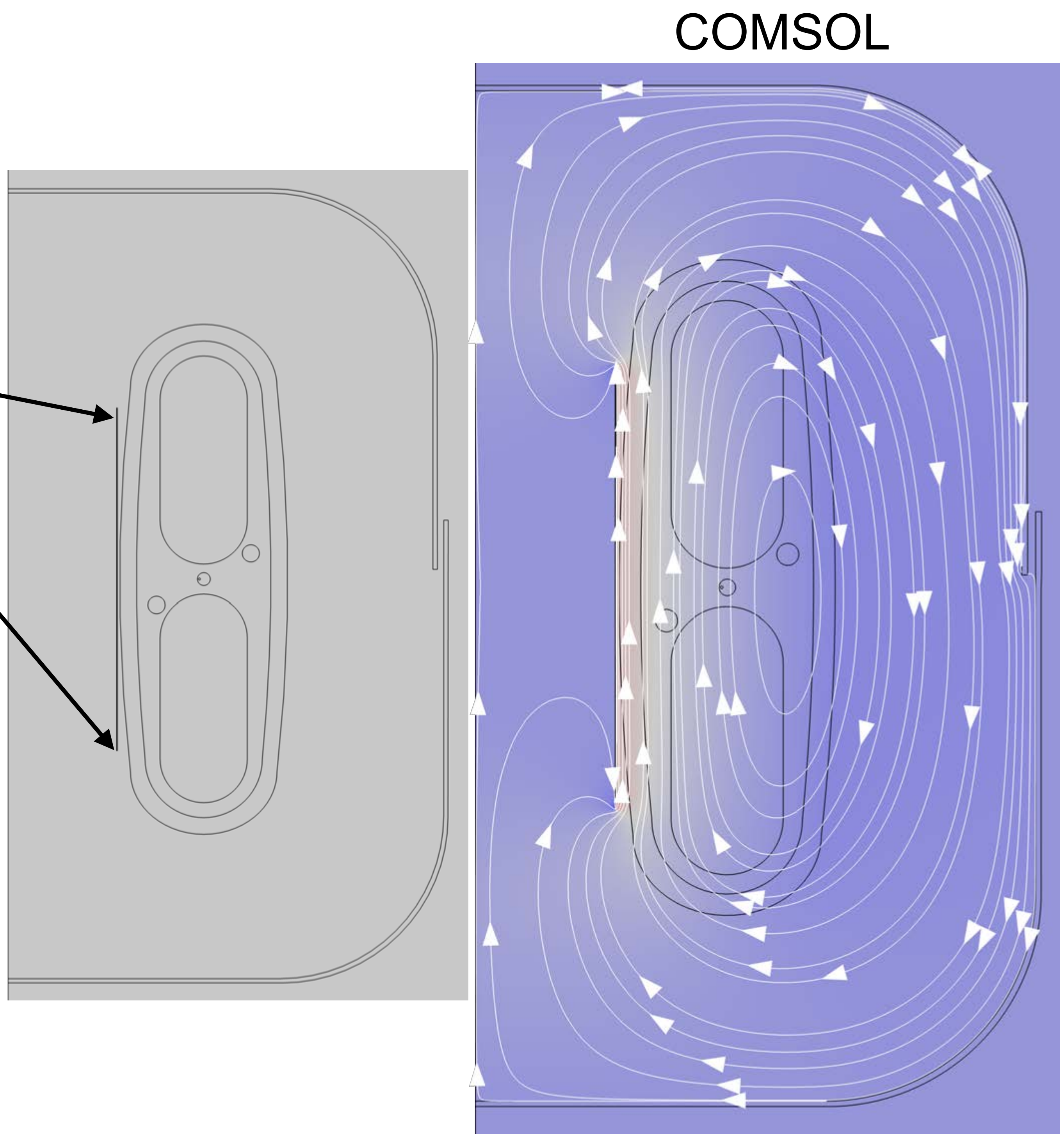




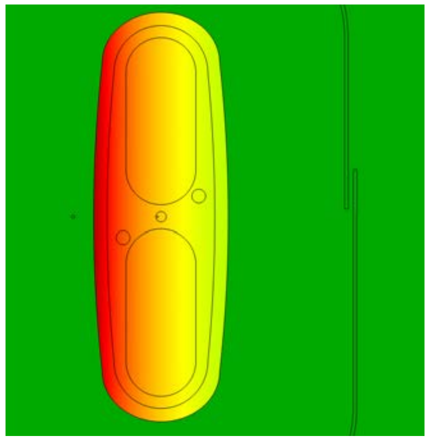


Next ABRA-10 cm run

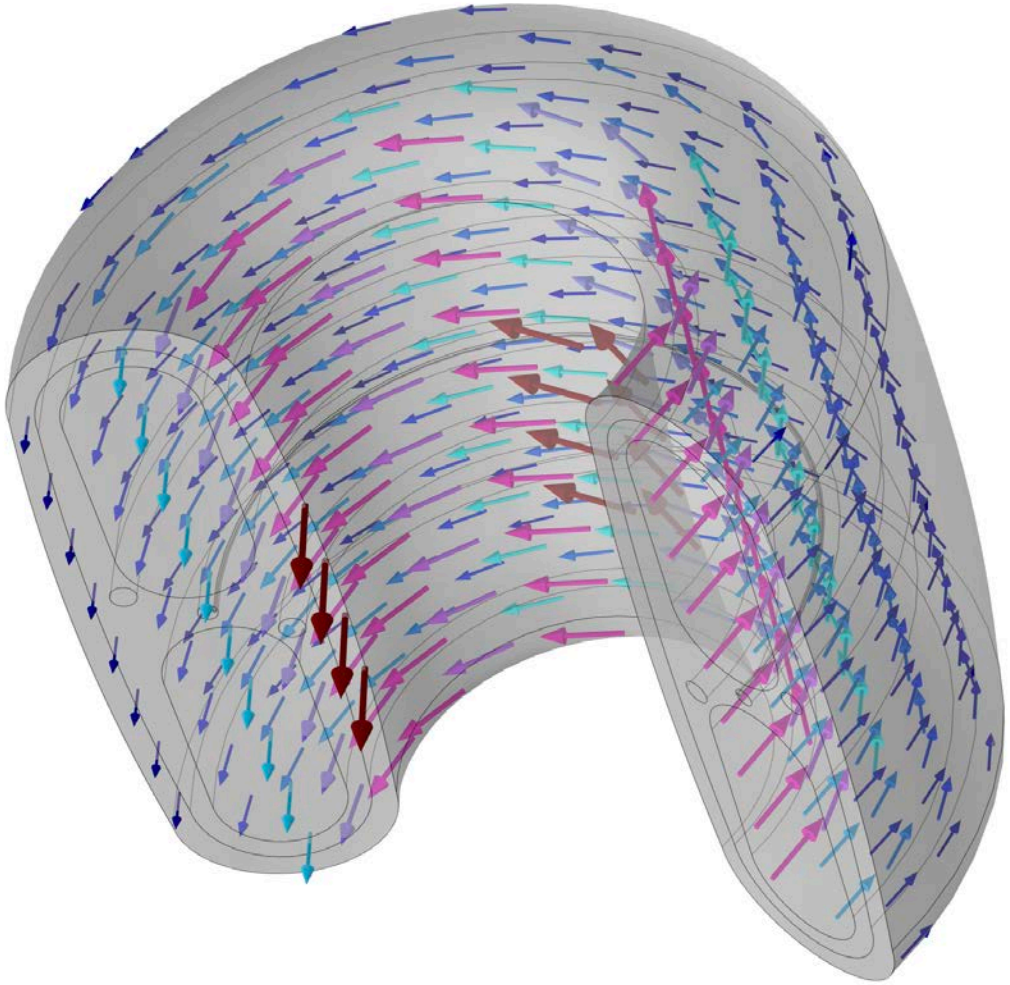
- Reduce wiring lengths — reduce parasitic inductances
- Cylindrical Pickup loop to reduce loop inductance
- Study losses in magnet materials by running loop w/o magnet.
- Resonator
- New Run this summer

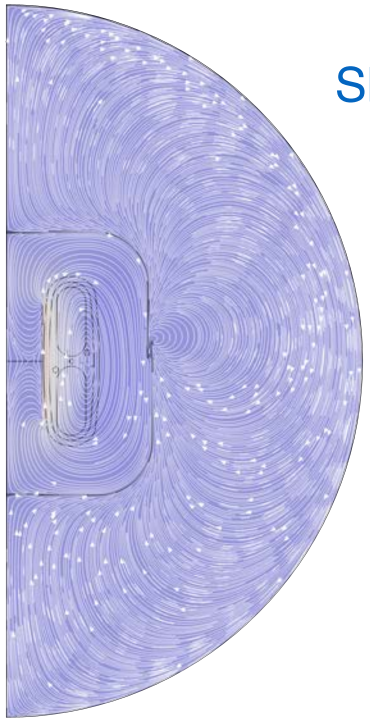


COMSOL Simulation



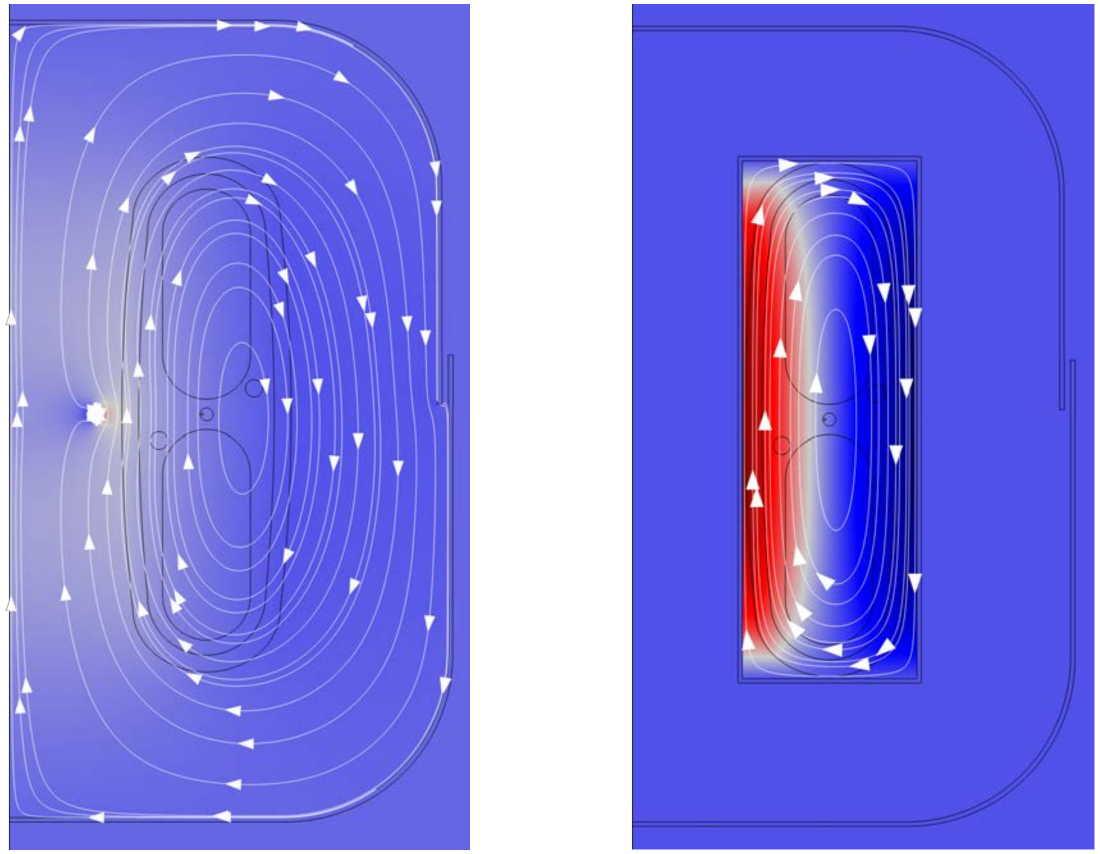
Axion effective current in ABRA-10cm toroid





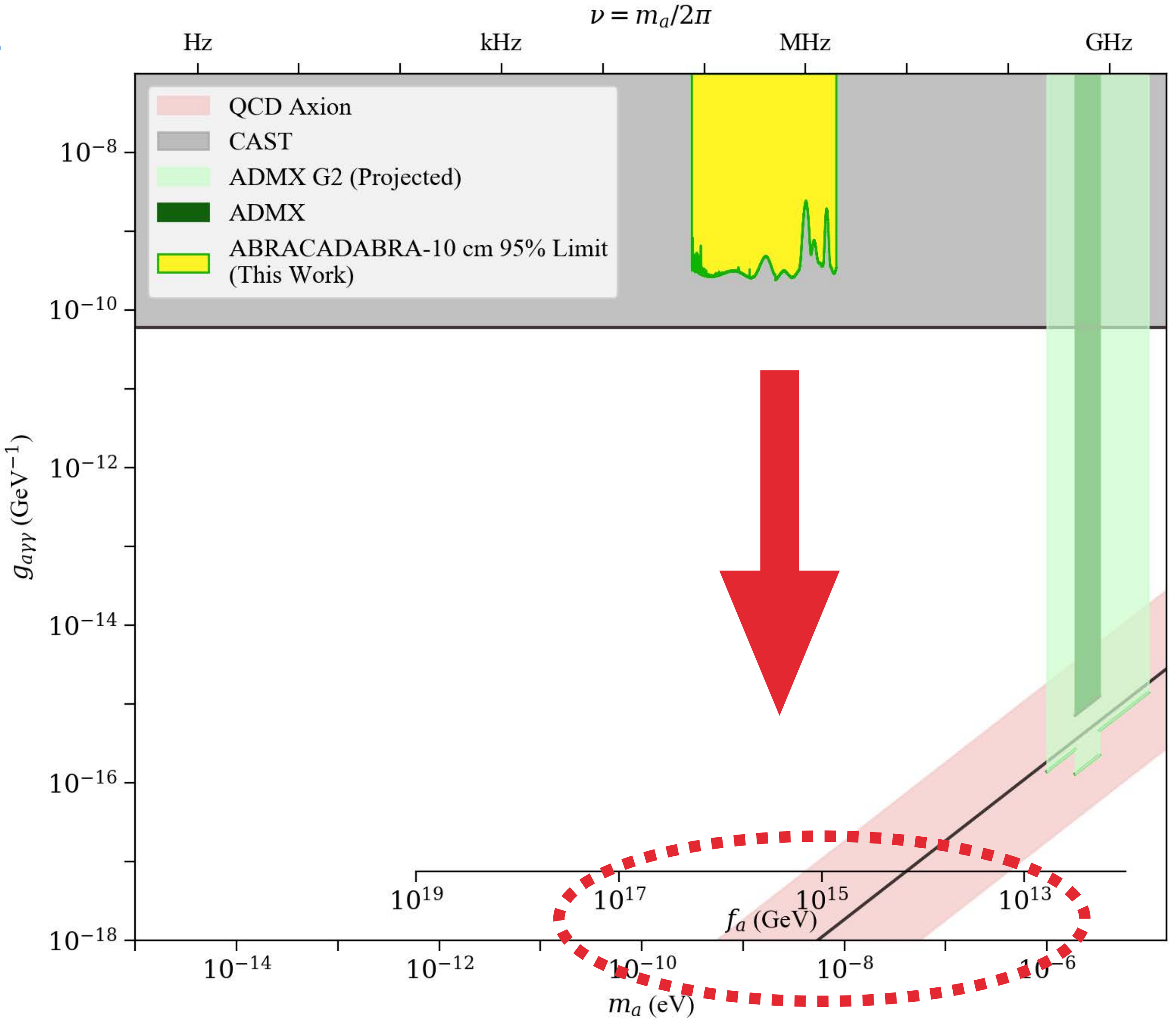
Shield simulation

Pickup Loop vs. Sheath

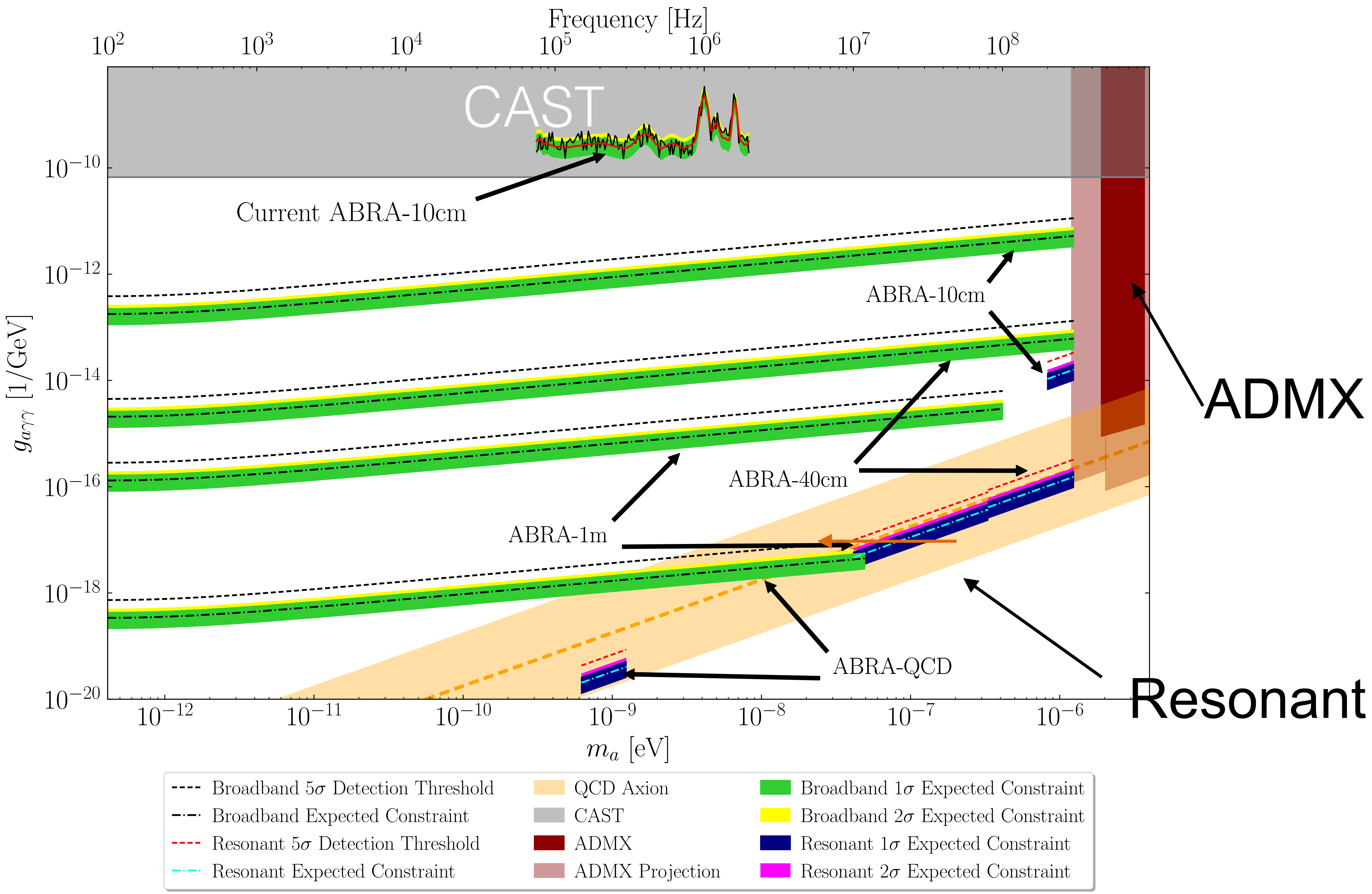


ABRACADABRA-1 m

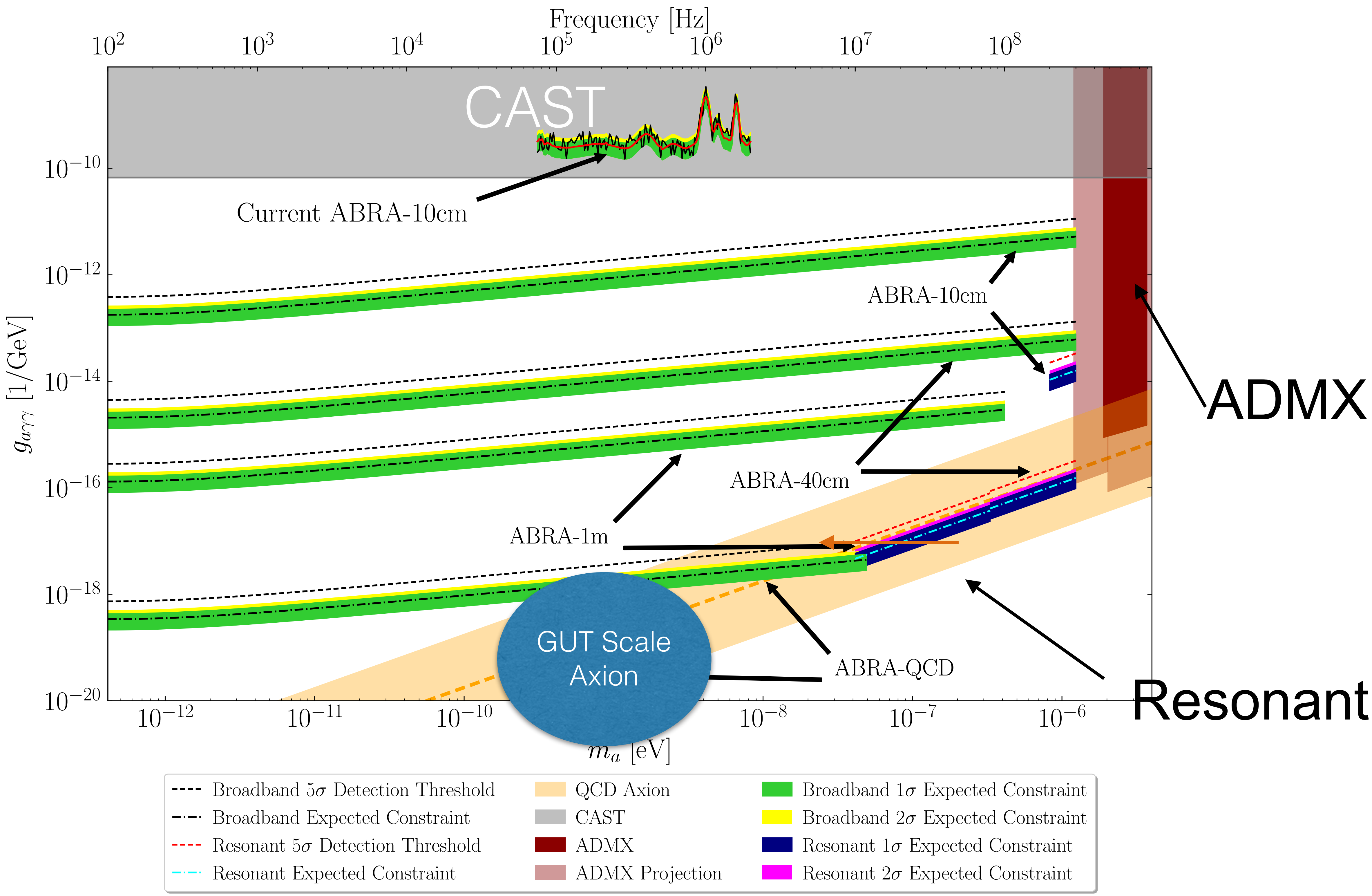
- Meter scale detector with a max field of B_0=5T
  - Resonator readout with optimized scan strategy: 1803.01627, 1904.05806
  - Reach for QCD Axion m_a ~ 0.1-1 μeV
  - Operating at 20 mK
  - Beyond SQL readout
- Proposals in development w/ DMRadio.
- Ultimate Goal: Probing the GUT scale QCD axion (m_a ~ neV)



ABRACADABRA Program

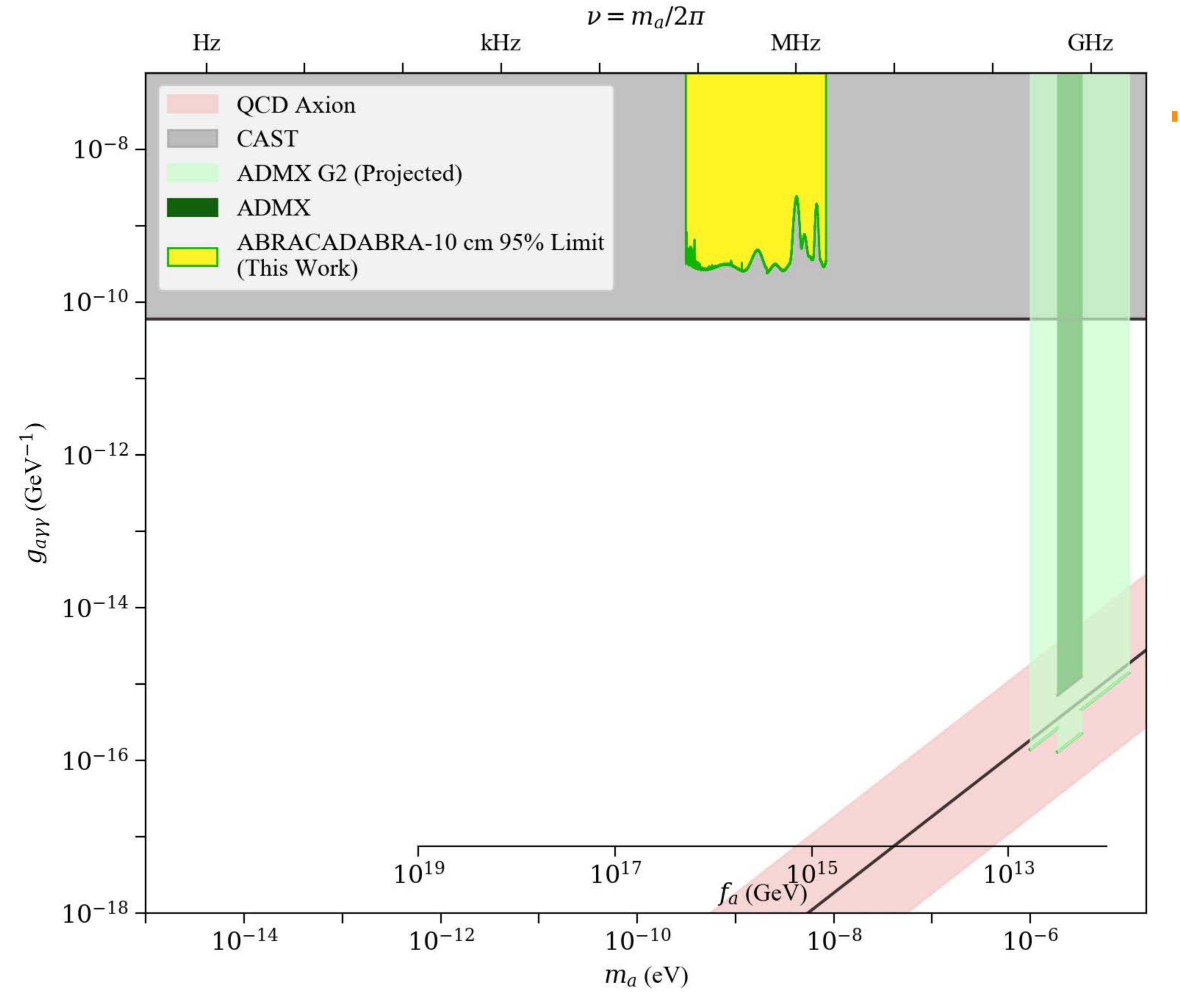


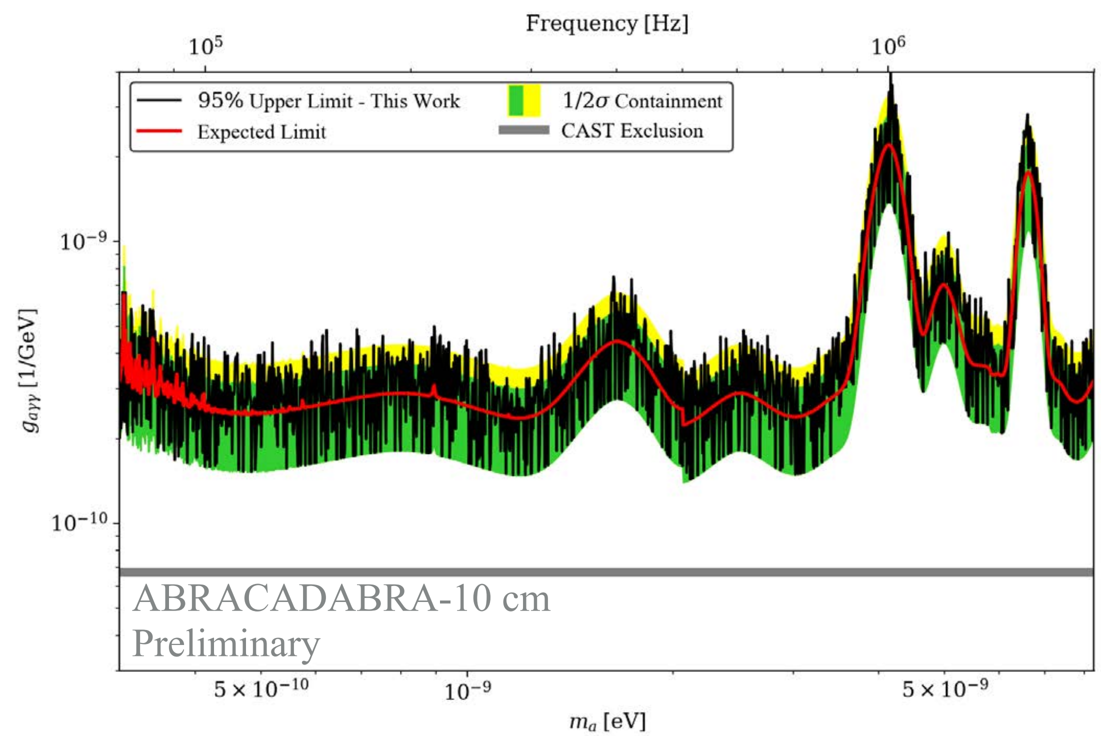
ABRACADABRA Program



Summary

- We have built and operated the first broadband search for Axion Dark Matter in the sub μeV range.
- With a 10 cm scale detector and 1 month of exposure, we are competitive with the leading limits in the field.
- Developing proposal for a ~1 m scale experiment with resonant readout to reach QCD axion line





BONUS SLIDES

Peccei-Quinn Mechanism

wikipedia

- Trivial explanation: One quark is massless

aps.org

- Spontaneous Symmetry breaking at high mass scale (f_a) leads to CP conservation.
  PRL 38, 1440 (1977); PRD 16, 1791 (1977)

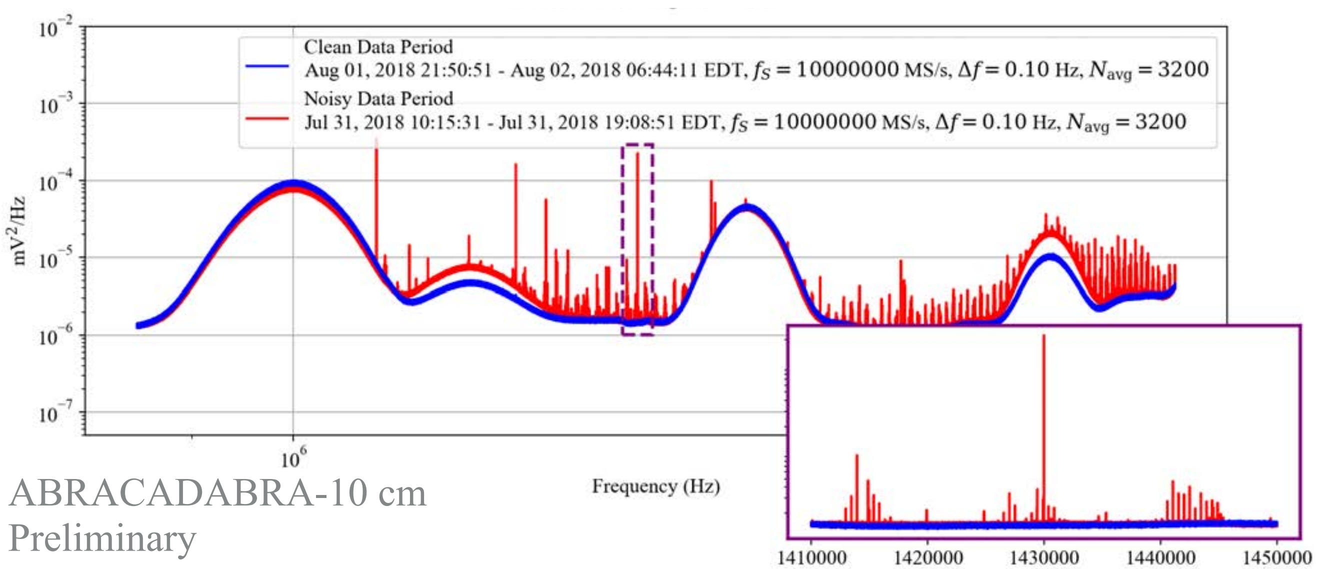
- Wilczek & Weinberg: Leads to new particle: **Axion** PRL 40, 223 (1978); PRL 40, 279 (1978).

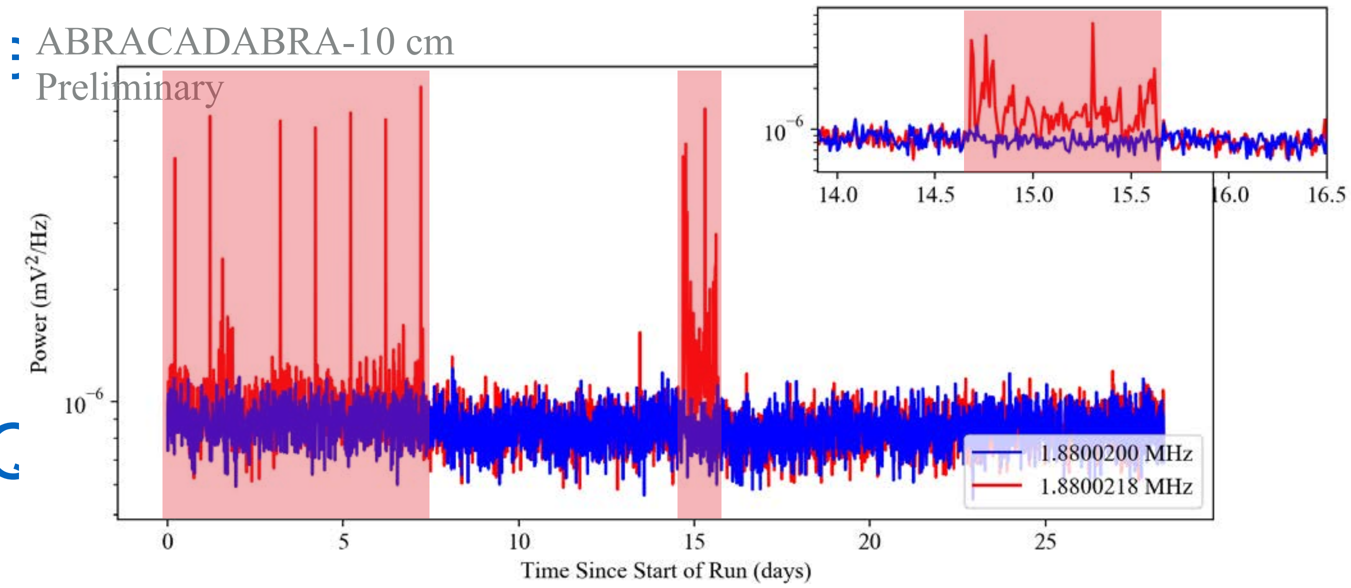
MIT

- Discover Axion, solve Strong CP problem

nobelprize.org

Transient Noise at High Frequency

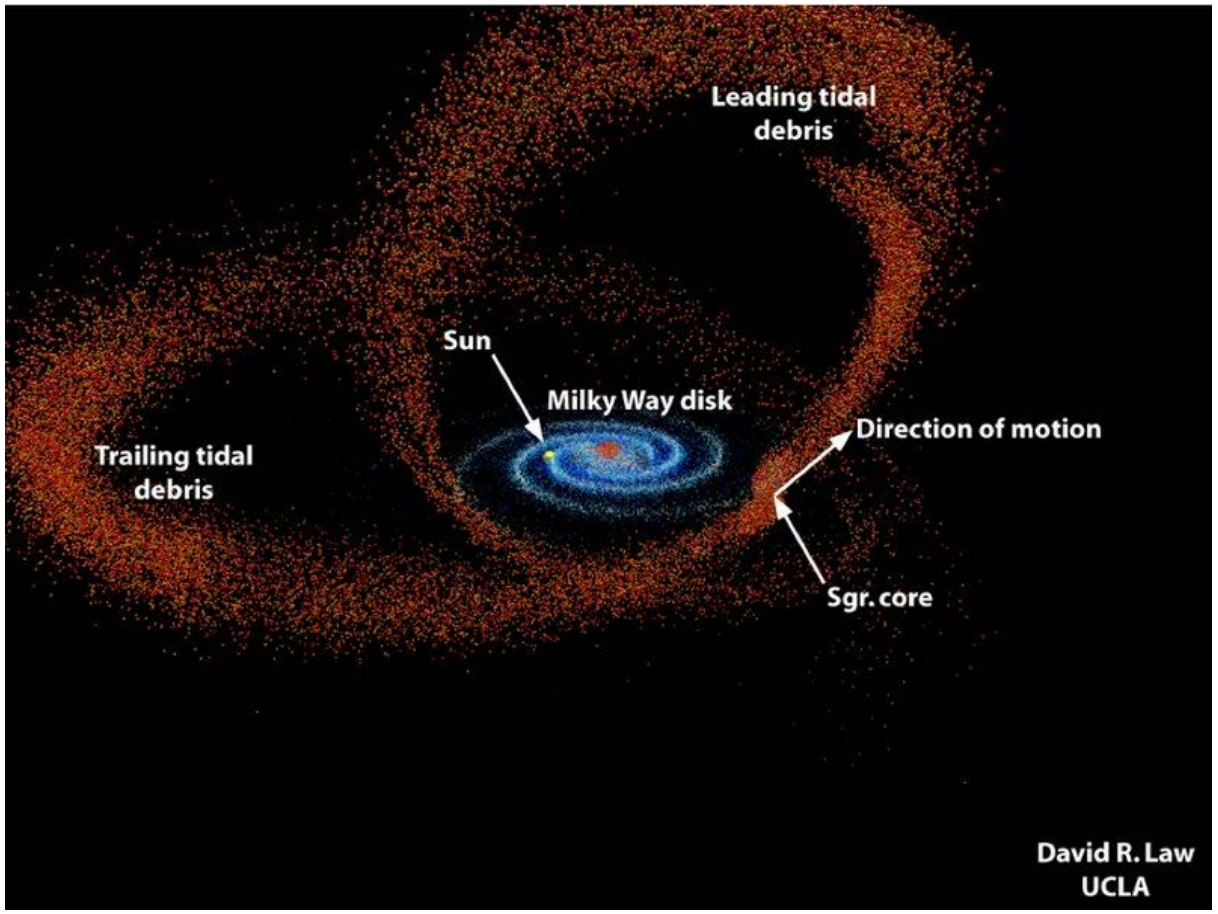


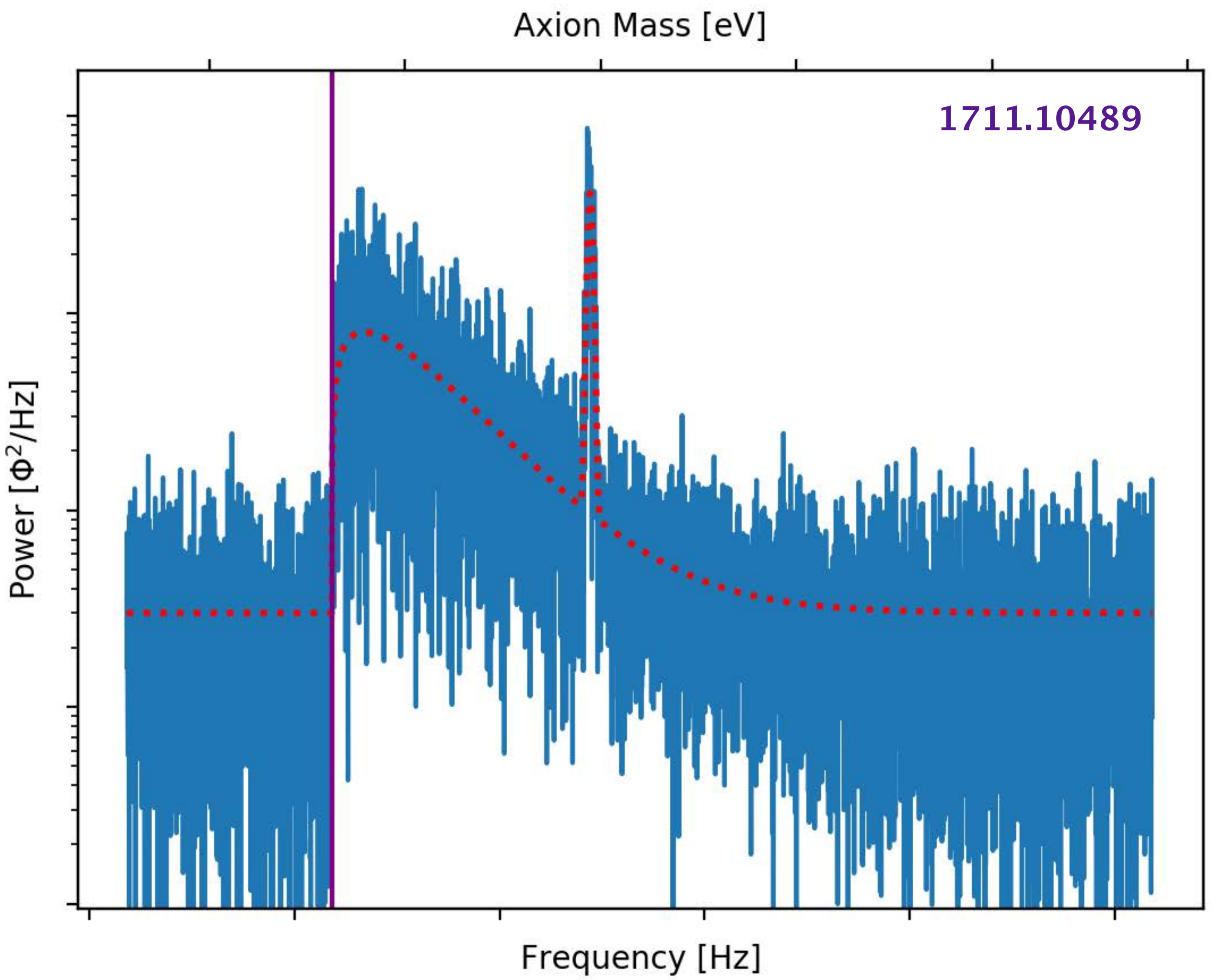


- Investigating the digitizer/DAC shielding, etc…

- In the present analysis, we had to discard ~30% of the data

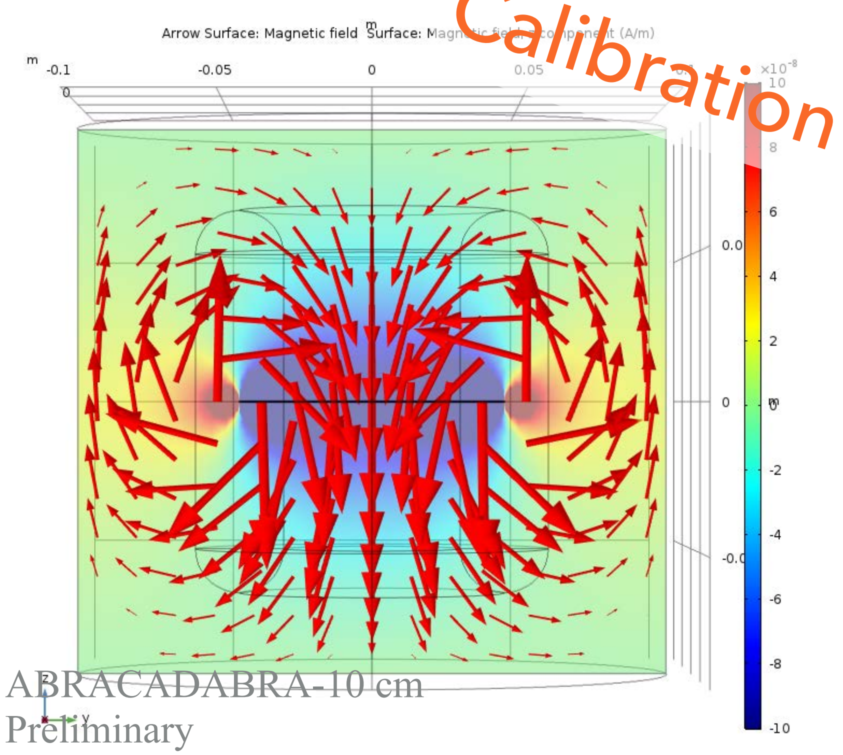
Axion Astrophysics

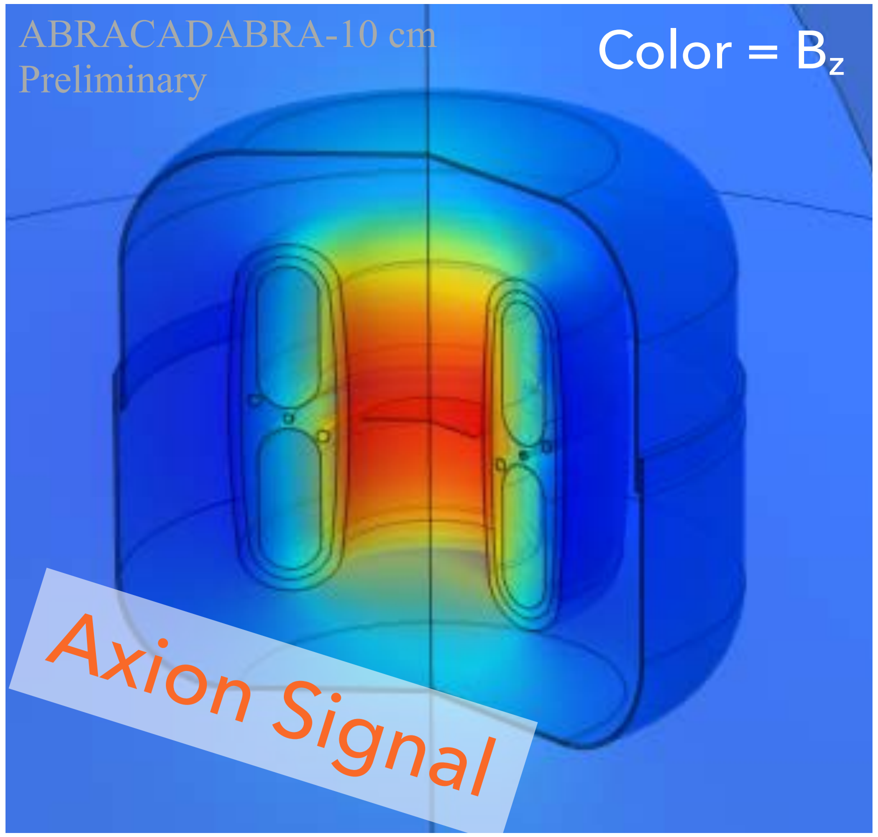




Simulations in COMSOL

- Geometric factor encodes the flux through the pickup loop due to the integrated effective current
- Use COMSOL simulations to calculate the coupling to the axion field (and confirm calibration coupling)
  - Simulation of ABRACADABRA-10 cm geometry and superconducting shield
  - Material properties need to be measured in the future
  - Losses in Magnet Materials

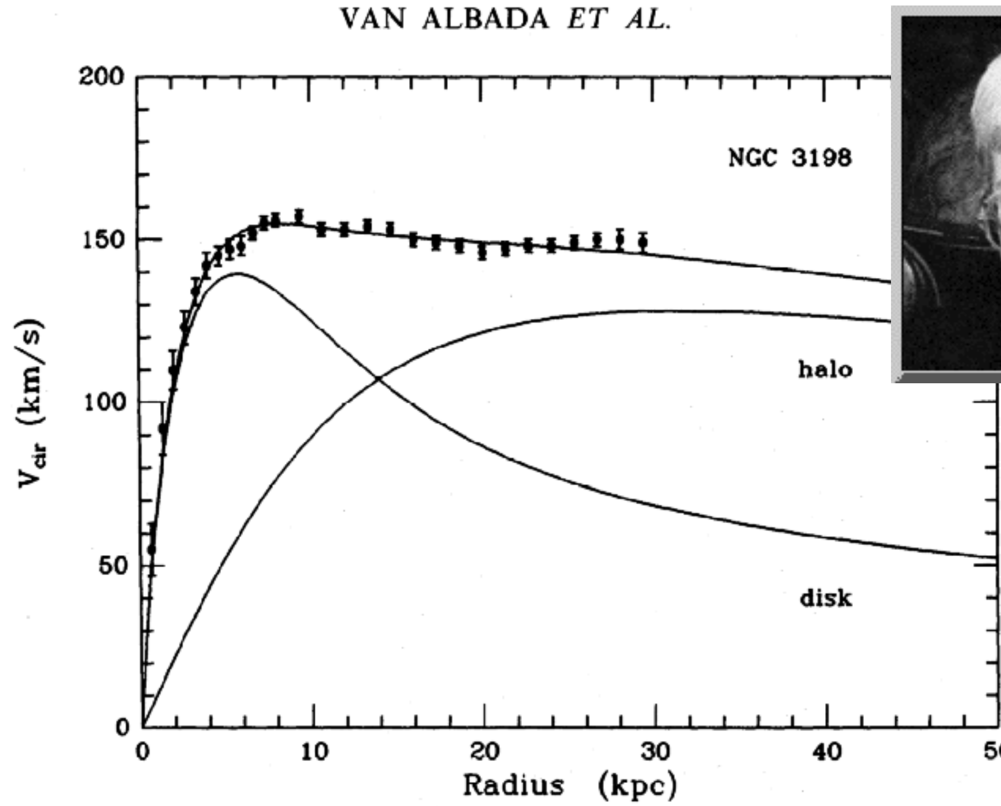




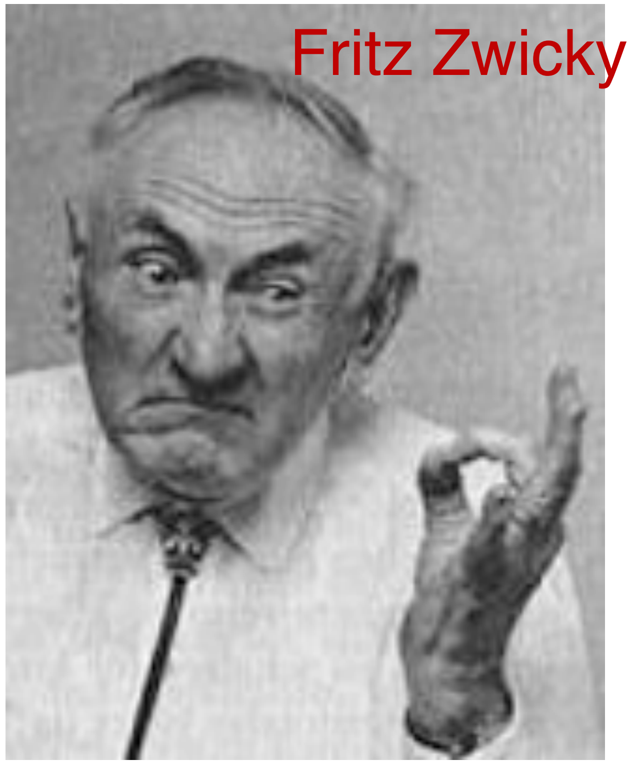
Evidence for Dark Matter is Gravitational

- Galactic Rotation Curves
- Peculiar velocities of galaxies in clusters
- X-Ray emission of hot gas in clusters.
- Weak gravitational lensing
- Cosmic Microwave background (indirect)

- Big Bang Nucleosynthesis predicts it cannot be baryonic



Vera Rubin

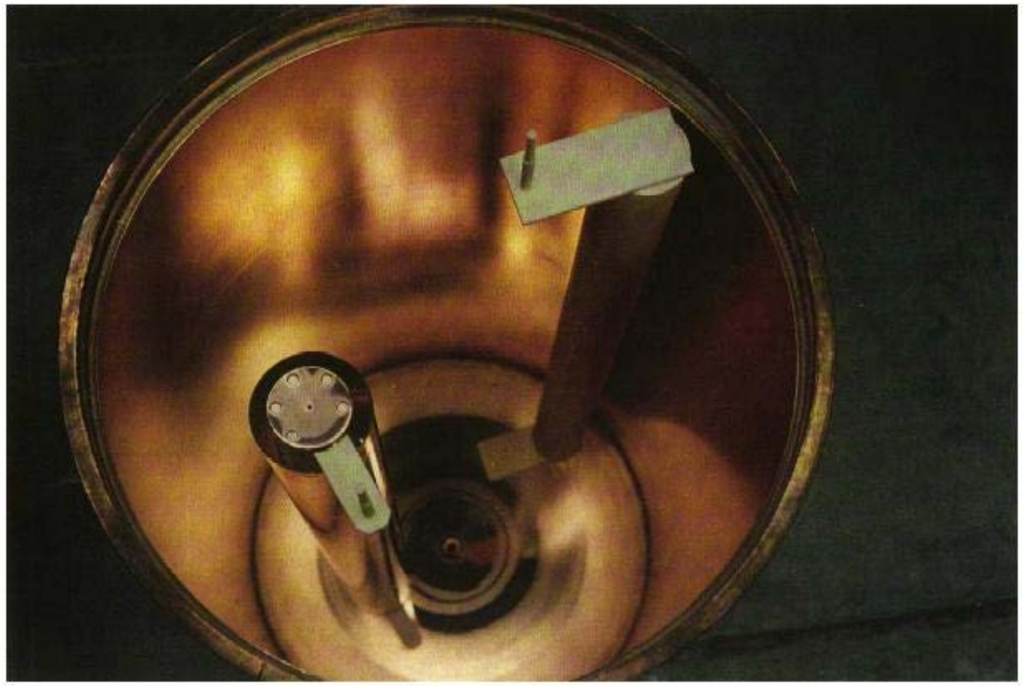


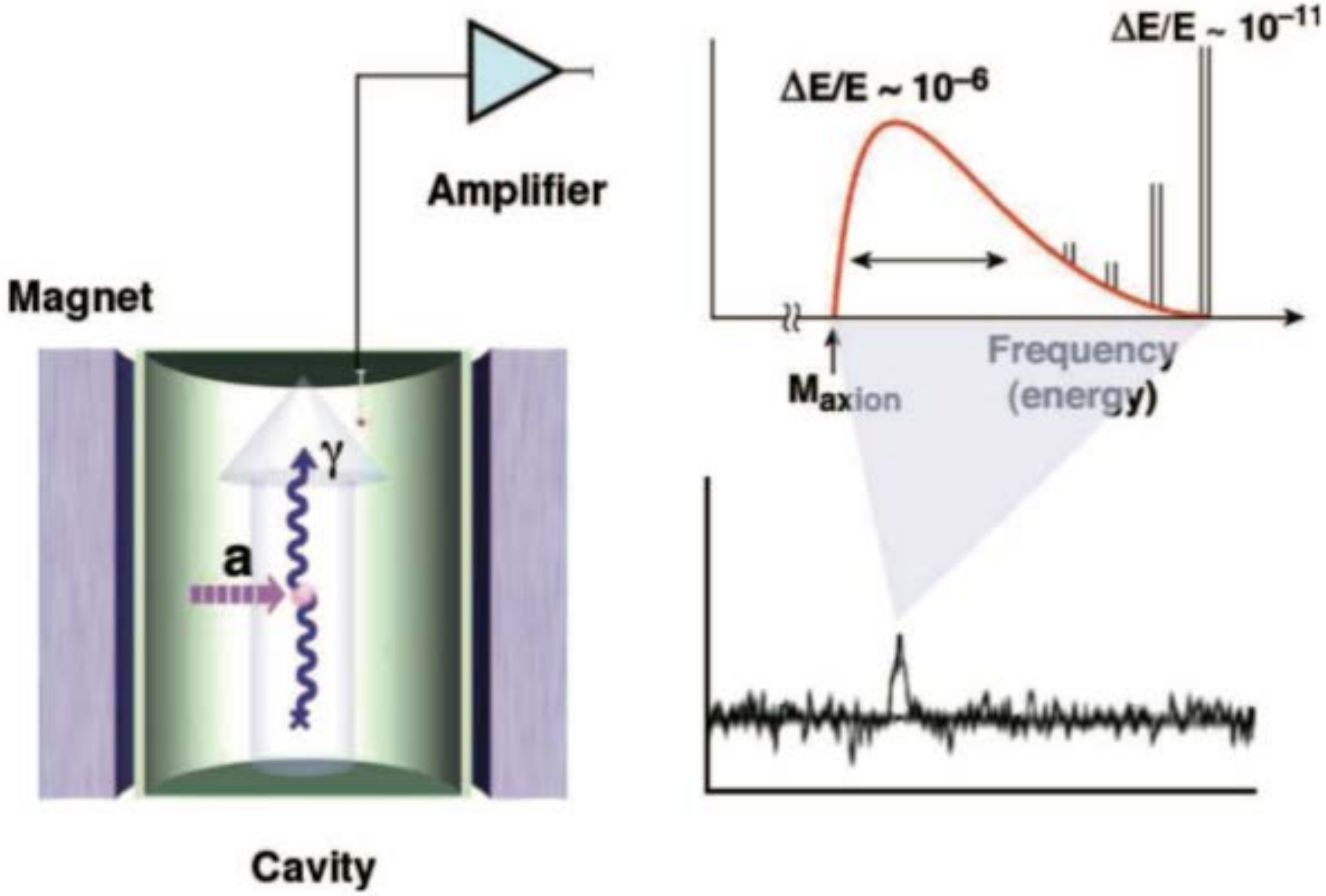
Fritz Zwicky

Microwave Cavities

Sikivie PRL 51(1983) 1415

- Cosmic relic axions (Dark Matter) with masses ~ microwave energies
- Resonant conversion of axion in high-Q cavity in magnetic field
- ADMX Current state of the art. HAYSTAC, MADMAX, others coming online





Carosi, G. , et al, Contemporary Physics, 49: 4, 281

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

10 MS/s Sampling → Down Sample → **1 MS/s Sampling** → Down Sample → **100 kS/s Sampling**

10 MS/s Sampling ↓

Compute PSDs of 10 s waveforms

Average 80 PSDs, write to disk

$\Delta f = 100$ mHz

1 MS/s Sampling ↓

Compute PSDs of 100 s waveforms

Average 16 PSDs, write to disk

$\Delta f = 10$ mHz

100 kS/s Sampling ↓

Written directly to disk

2,452,000 seconds total

$\Delta f \approx 408$ nHz