THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

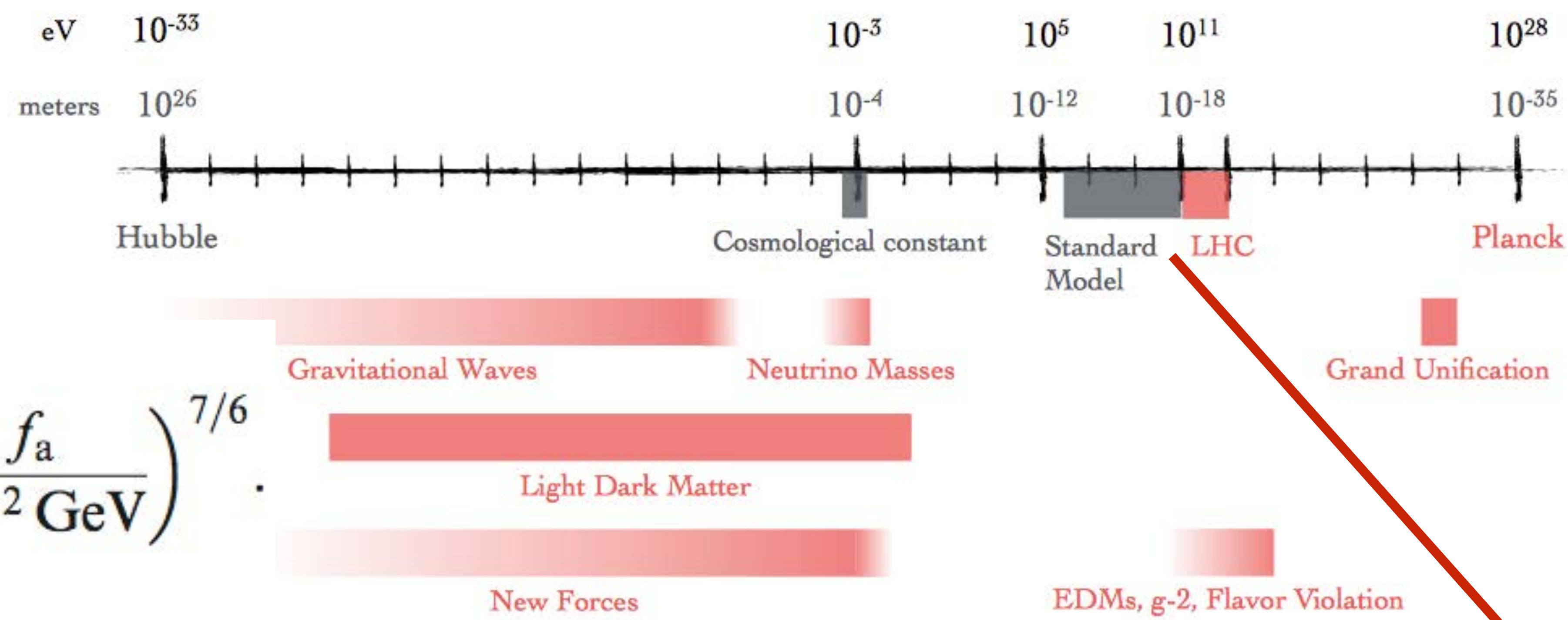
TUNL

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

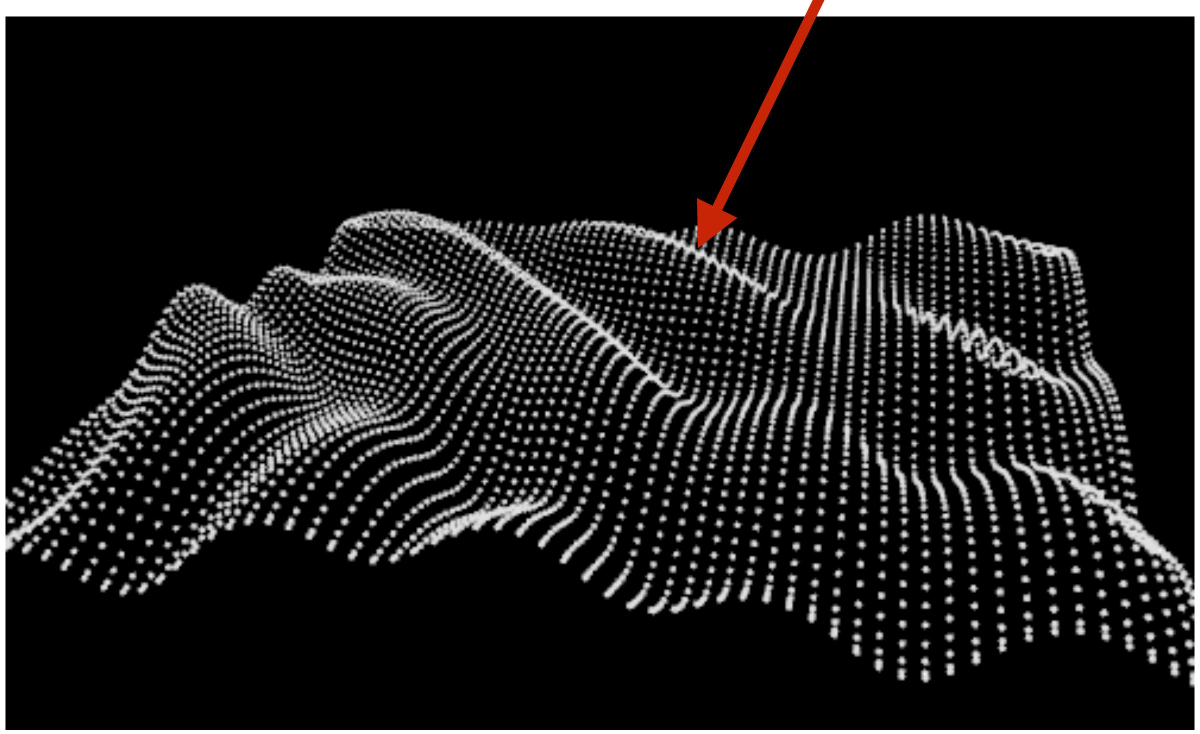
Reyco Henning
University of North Carolina at Chapel Hill
Triangle Universities Nuclear Laboratory

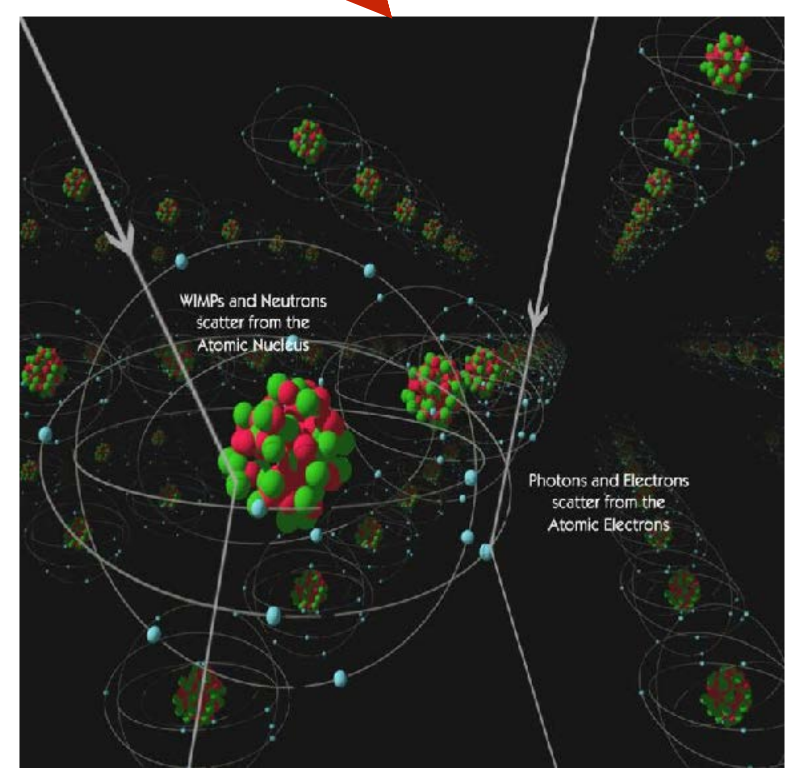
Axion as “Light” DM

Arvanitaki



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



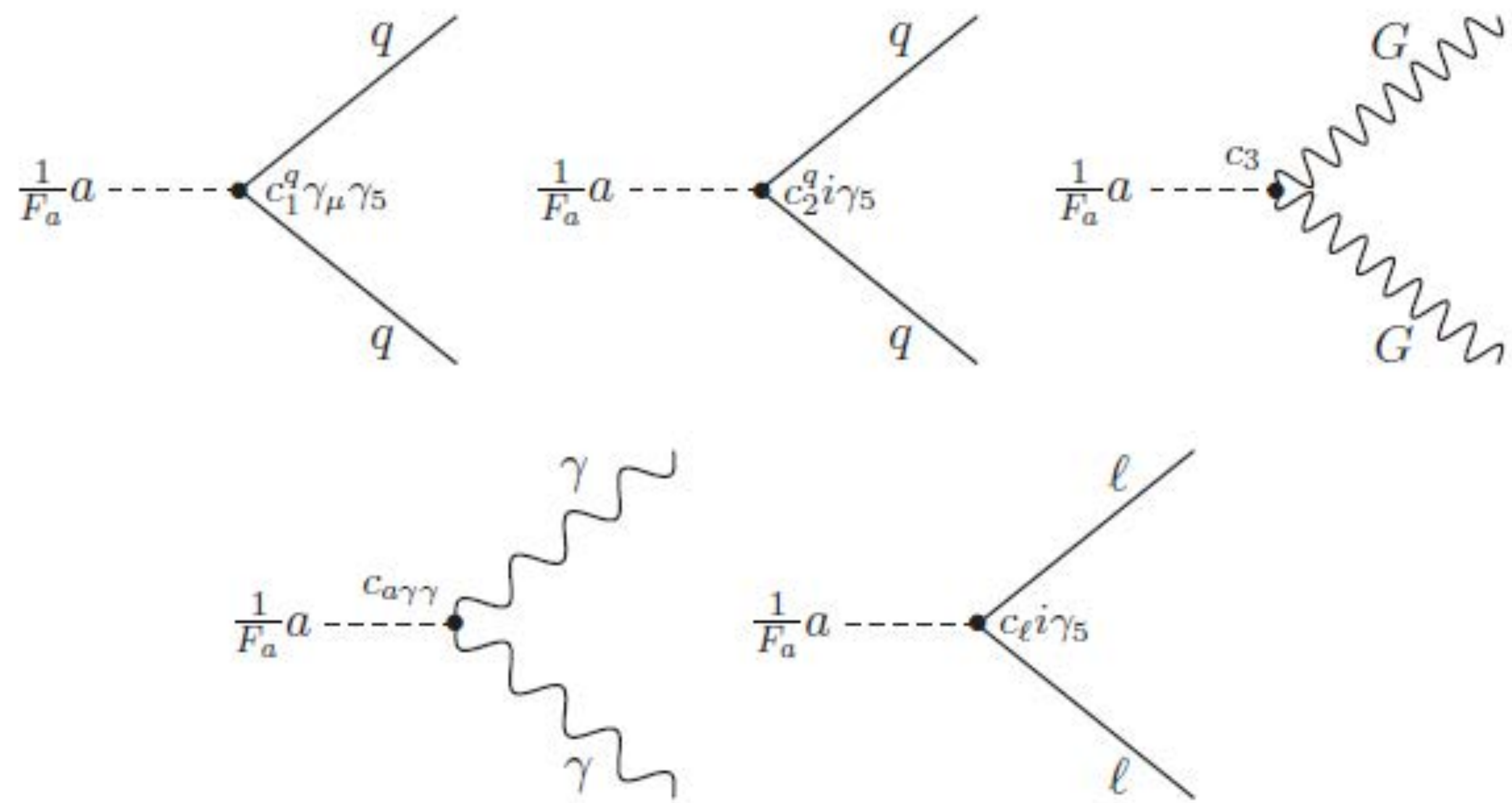


QCD Axion Properties

$$m_{\mathrm{a}} \simeq 0.6\,\mathrm{eV}\,\frac{10^7\,\mathrm{GeV}}{f_{\mathrm{a}}}$$

f_a : PQ Symmetry Breaking Scale
Relationship Model-dependent

Rev.Mod.Phys. 82 (2010) 557



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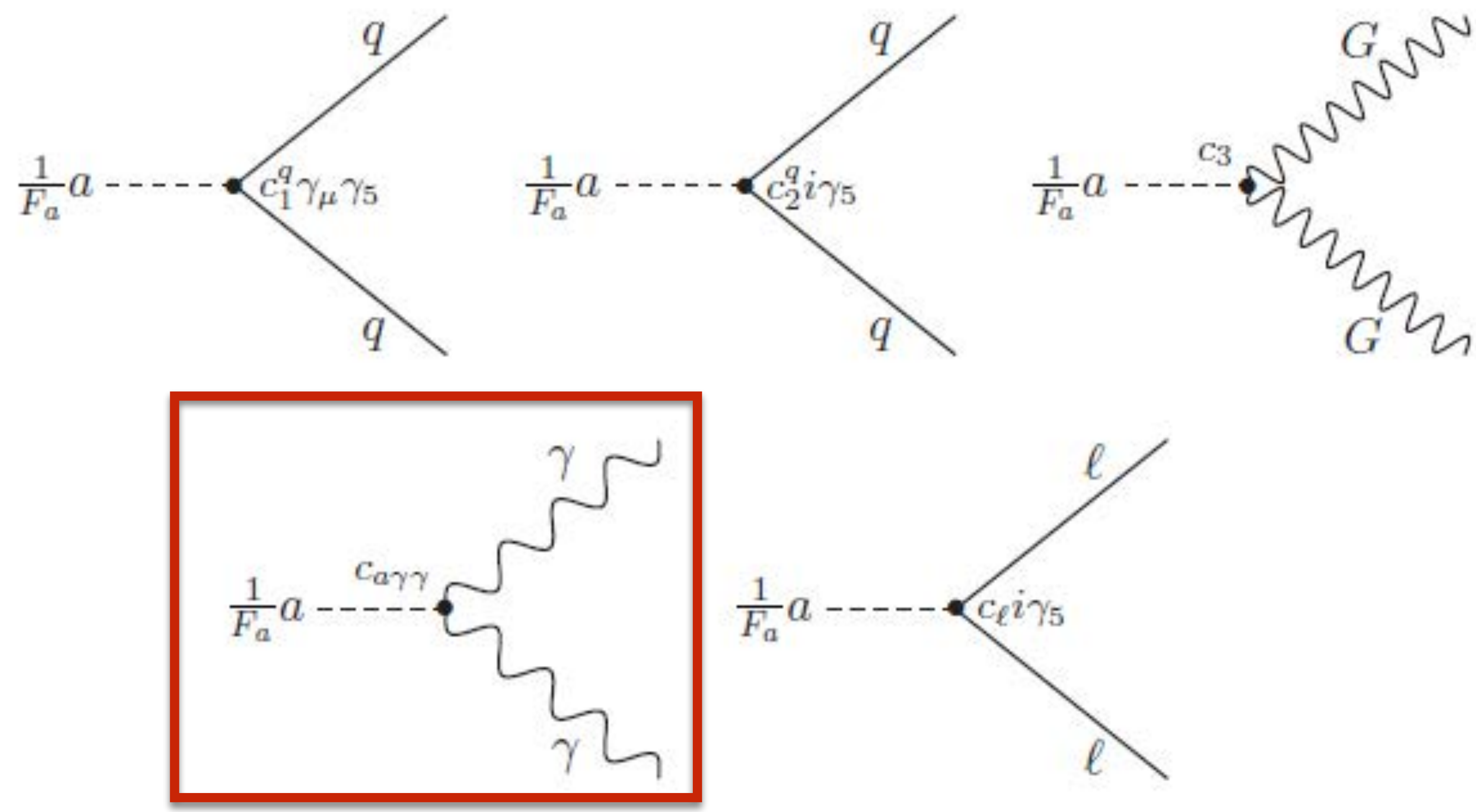
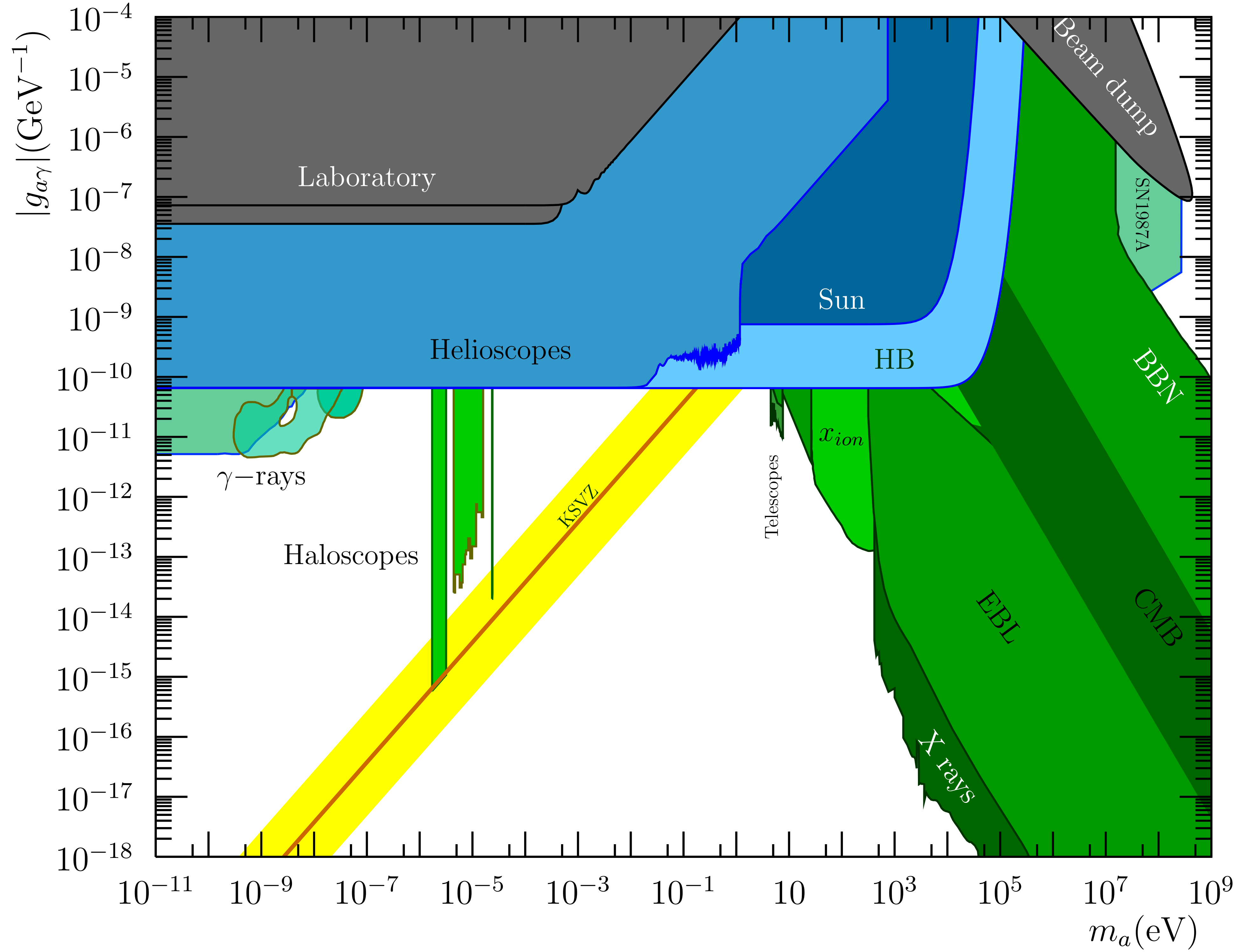
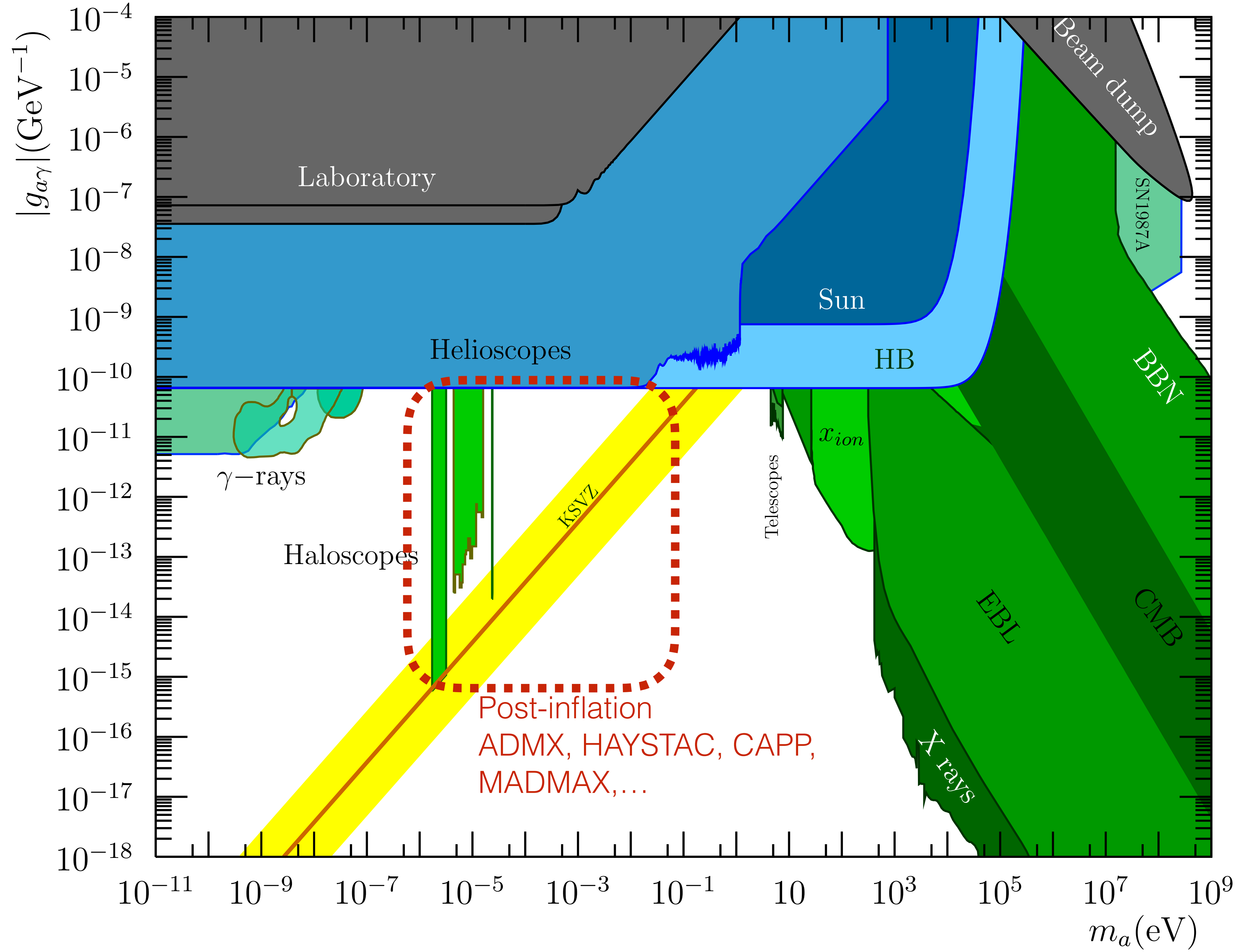


Context



1801.08127

Context



1801.08127

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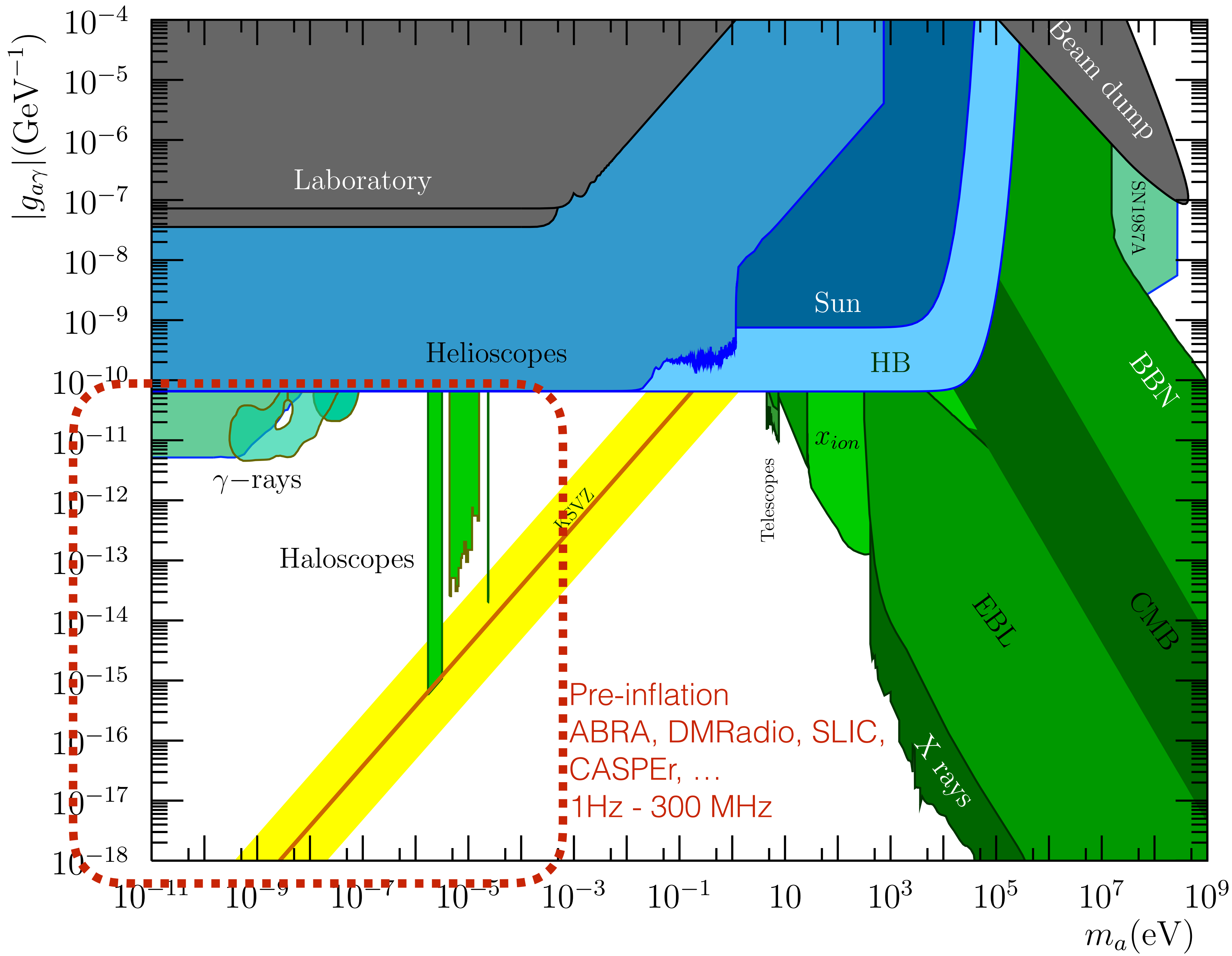

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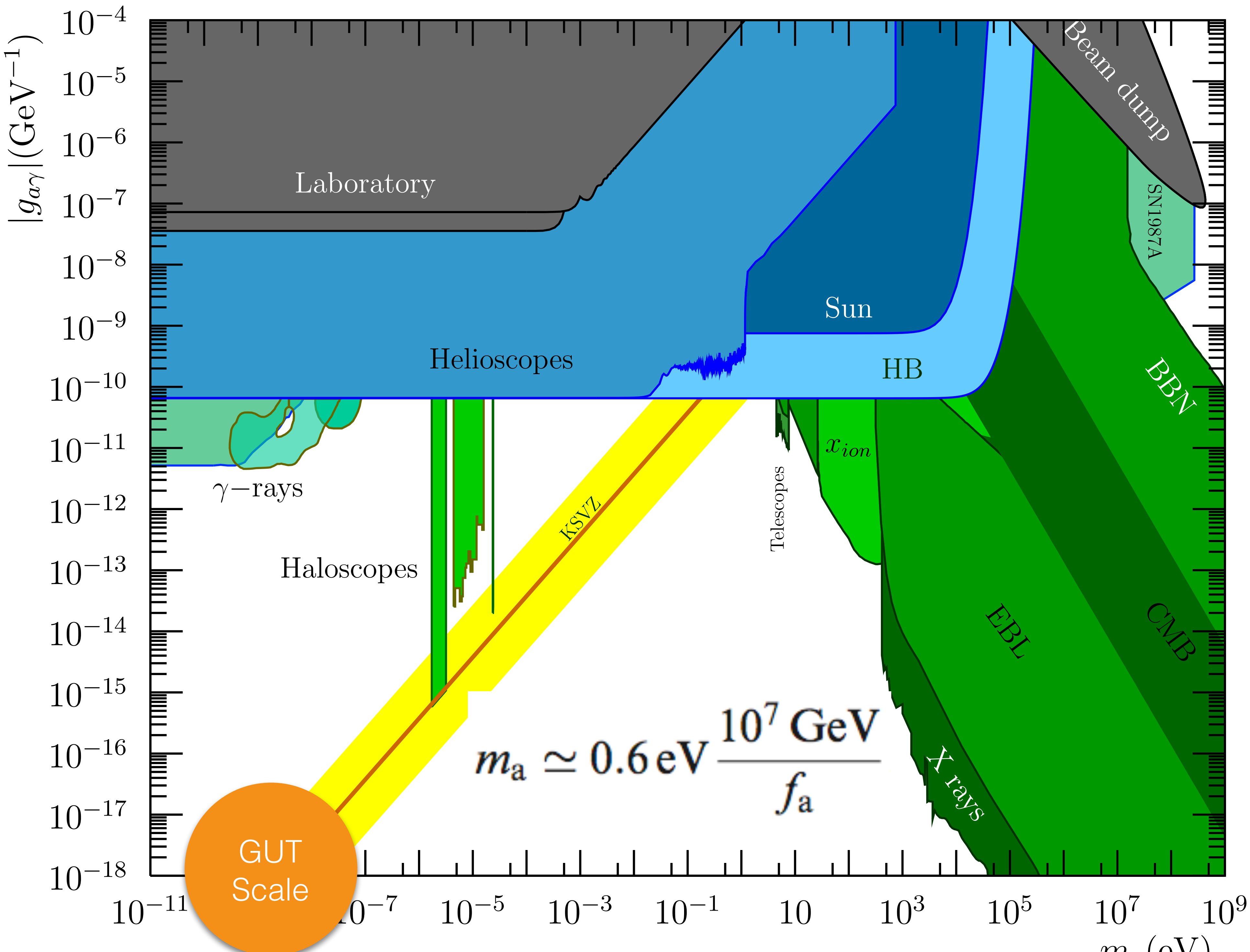
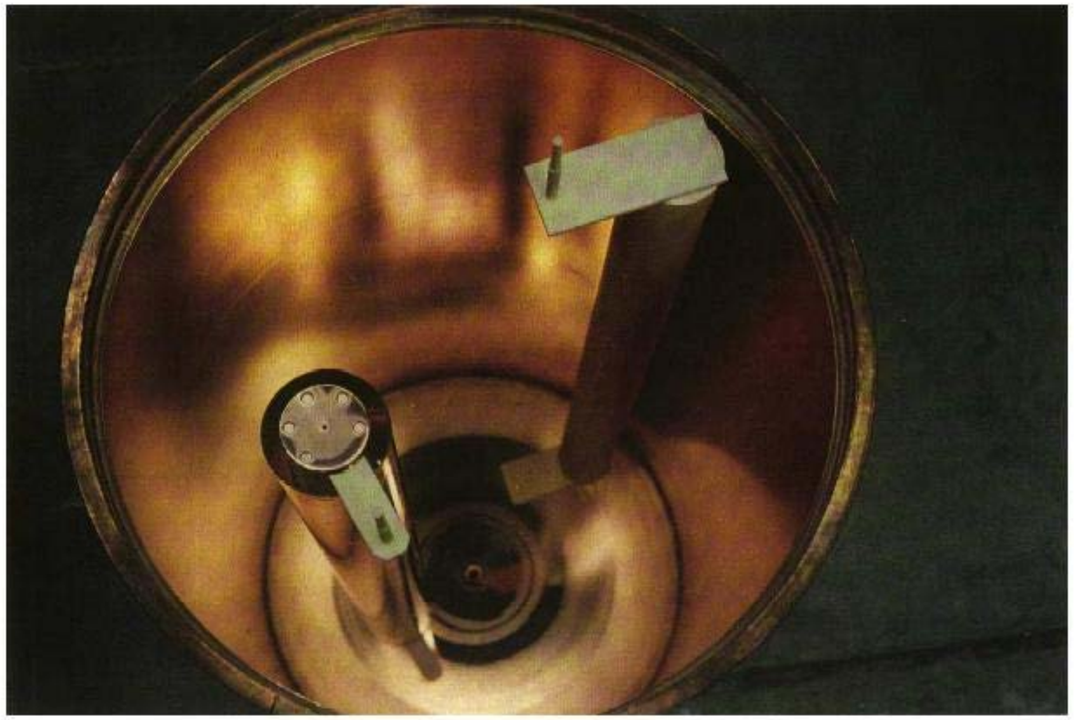


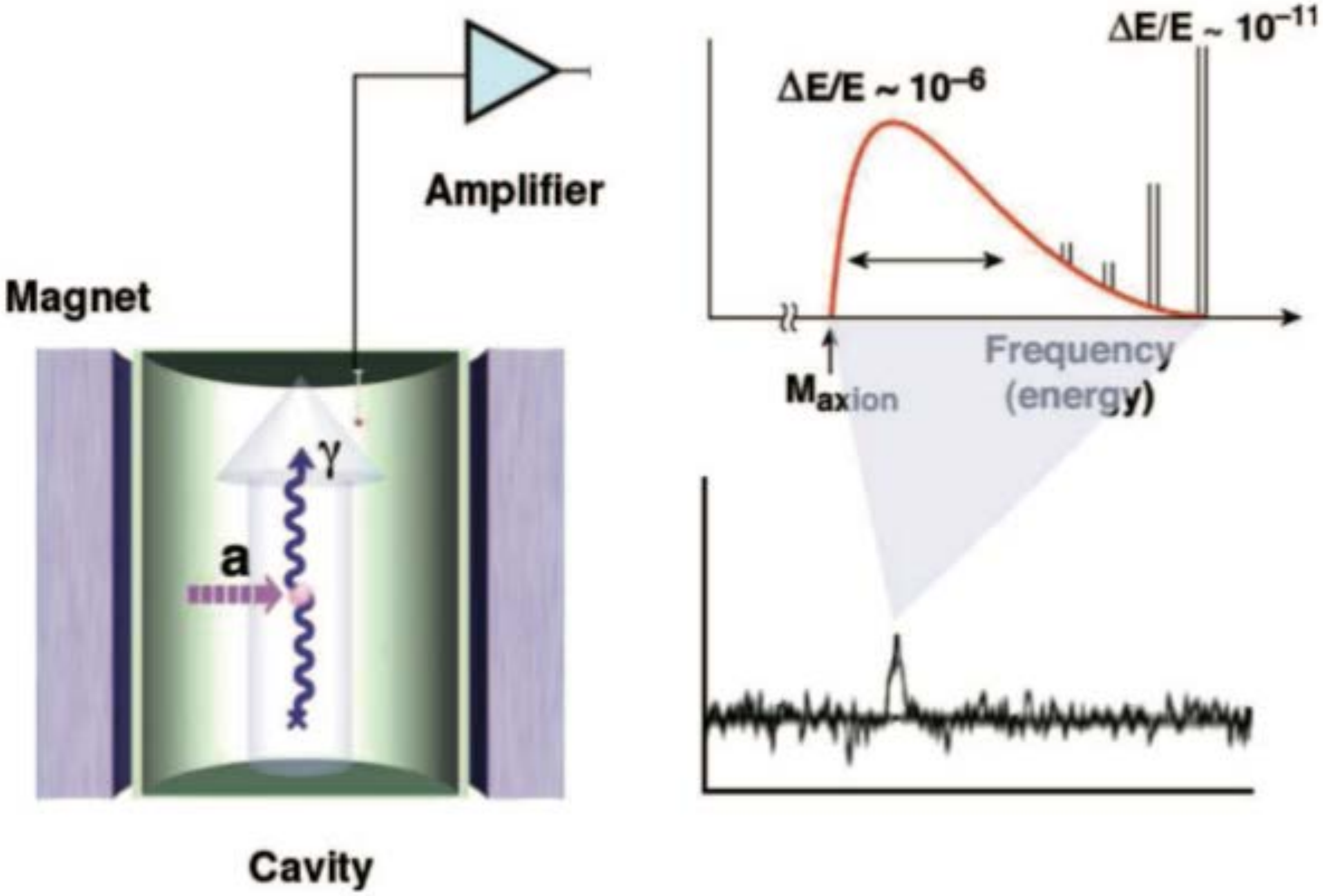
1801.08127

Microwave Cavities

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, CAPP, others coming online

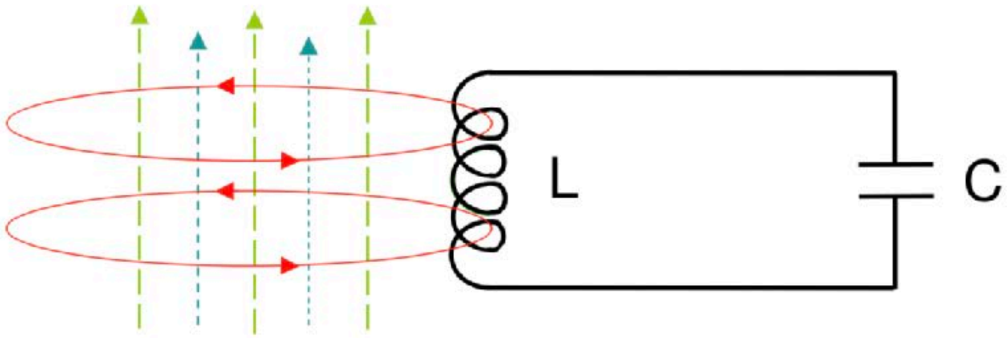




Carosi, G. , et al, Contemporary Physics, 49: 4, 281

Alternative: Lumped Element

Tuned LC Circuit:
Cabrera, Thomas, 2010



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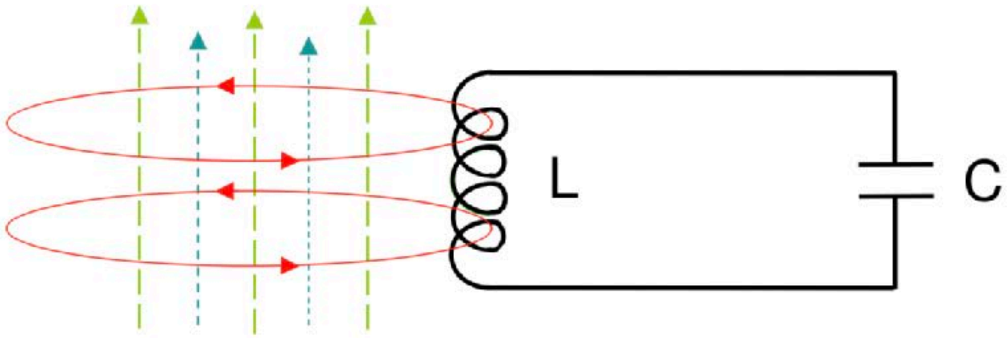
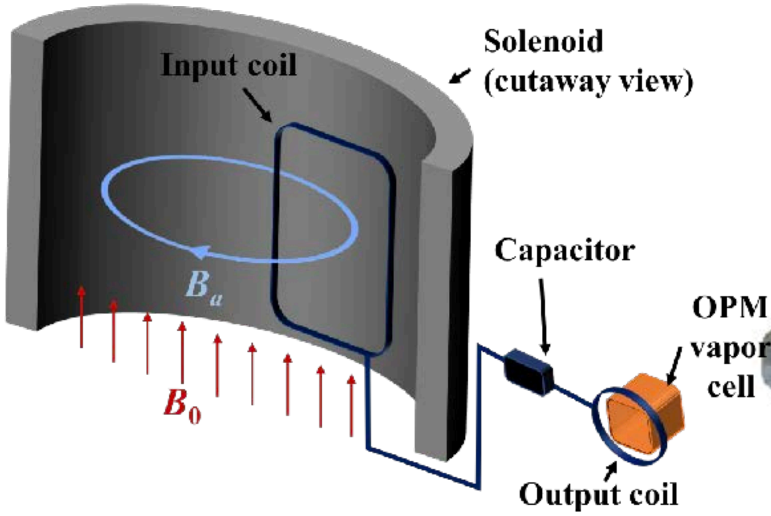
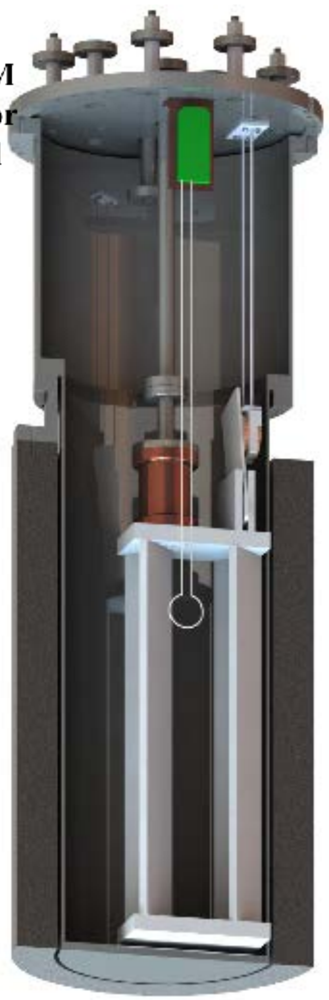


Solenoidal Magnet:
PRL 112 (2014) 131301;
PRD 97 (2019) 072011;
1911.05722





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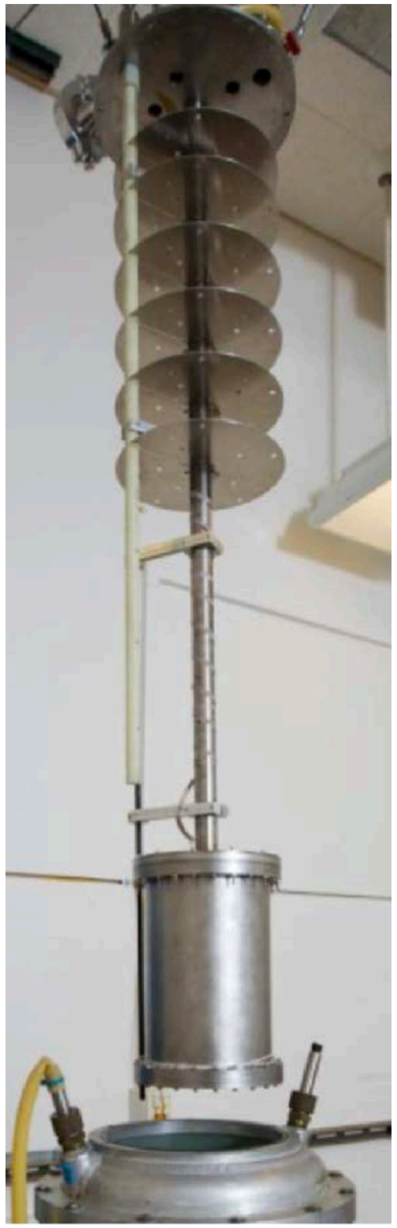

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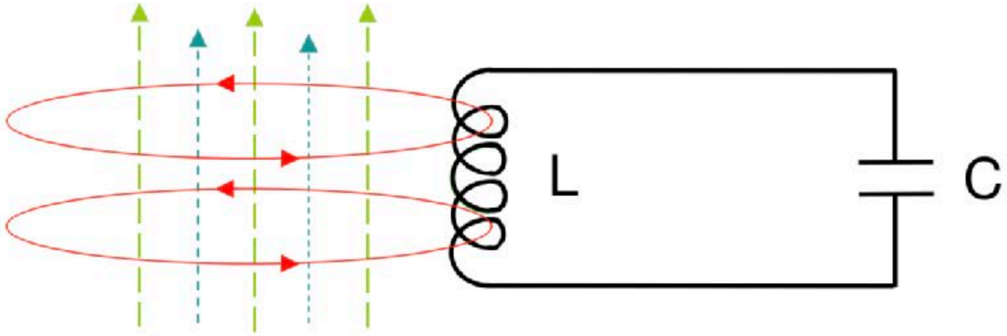

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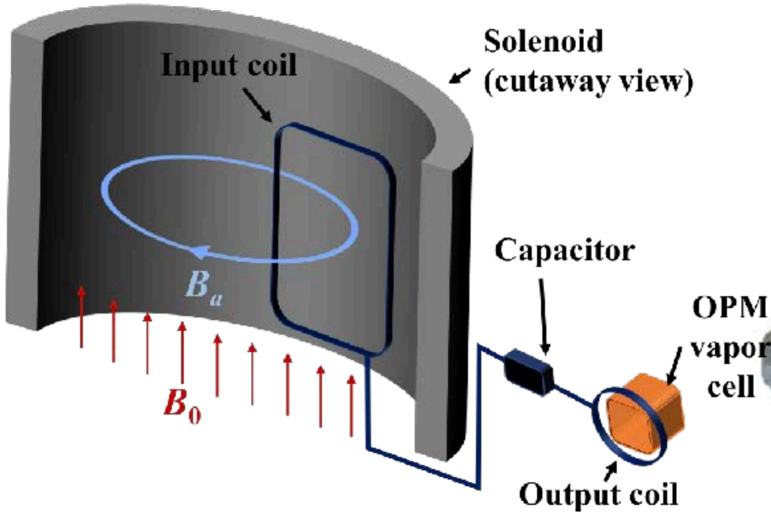
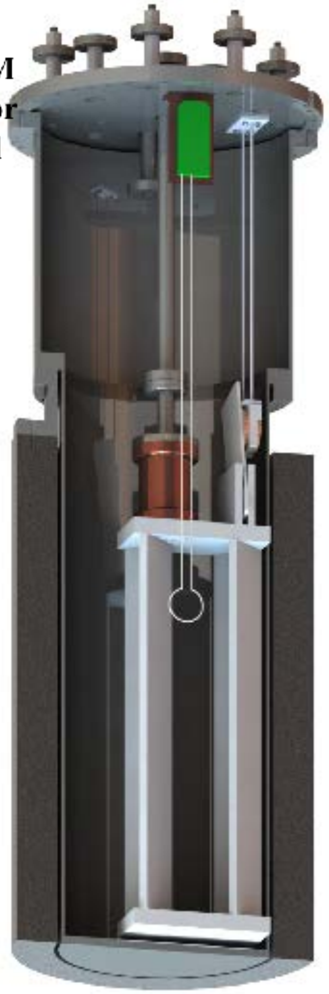


DM Radio Dark Photon
Detection: *PRD 92 (2015) 075012*



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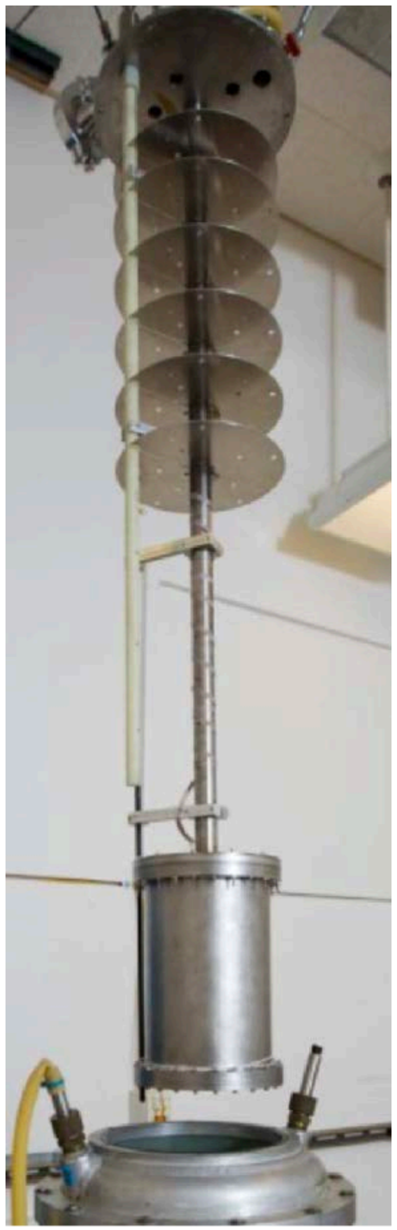

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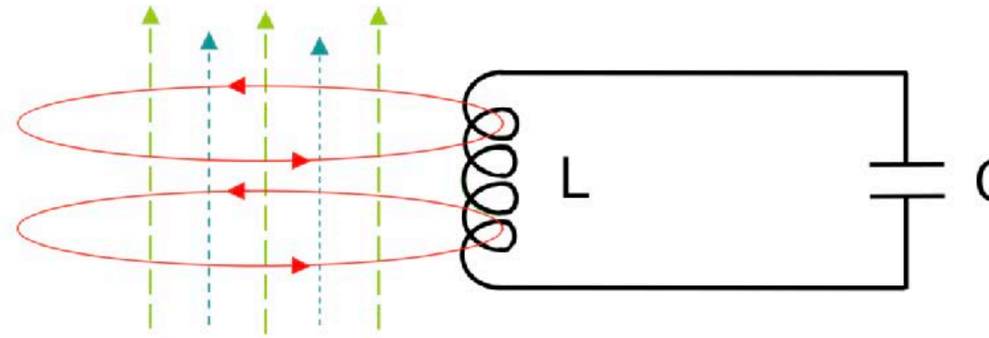

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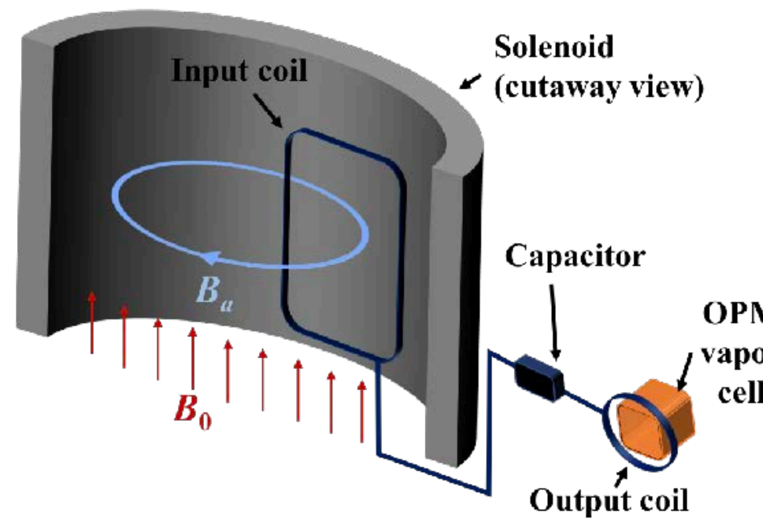
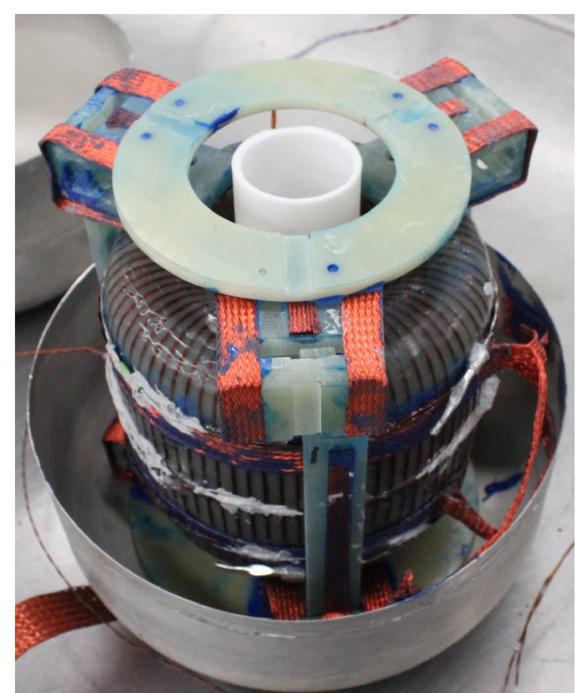


DM Radio Dark Photon Detection: *PRD 92 (2015) 075012*

Toroidal Magnet:
ABRACADABRA:
PRL 117 (2016) 141801



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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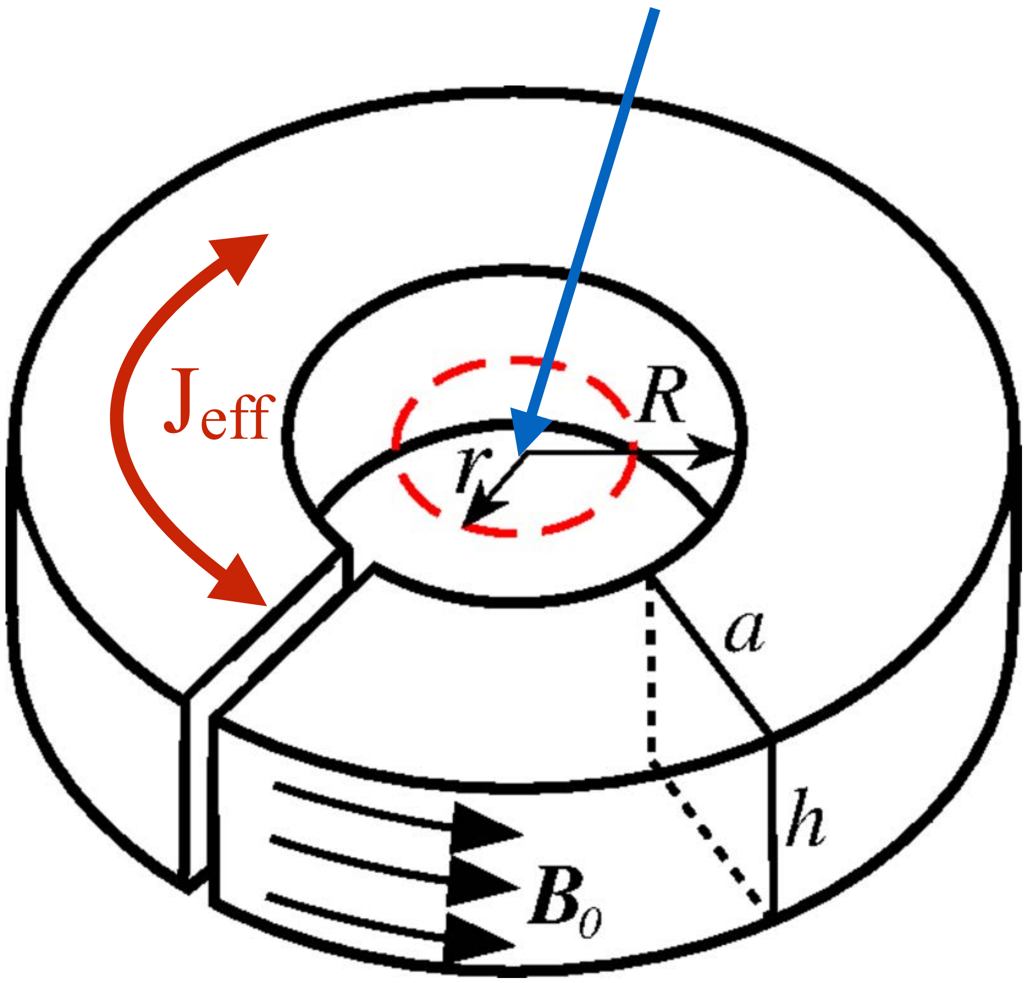
Yields axion-induced effective current:

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

Zero DC Field



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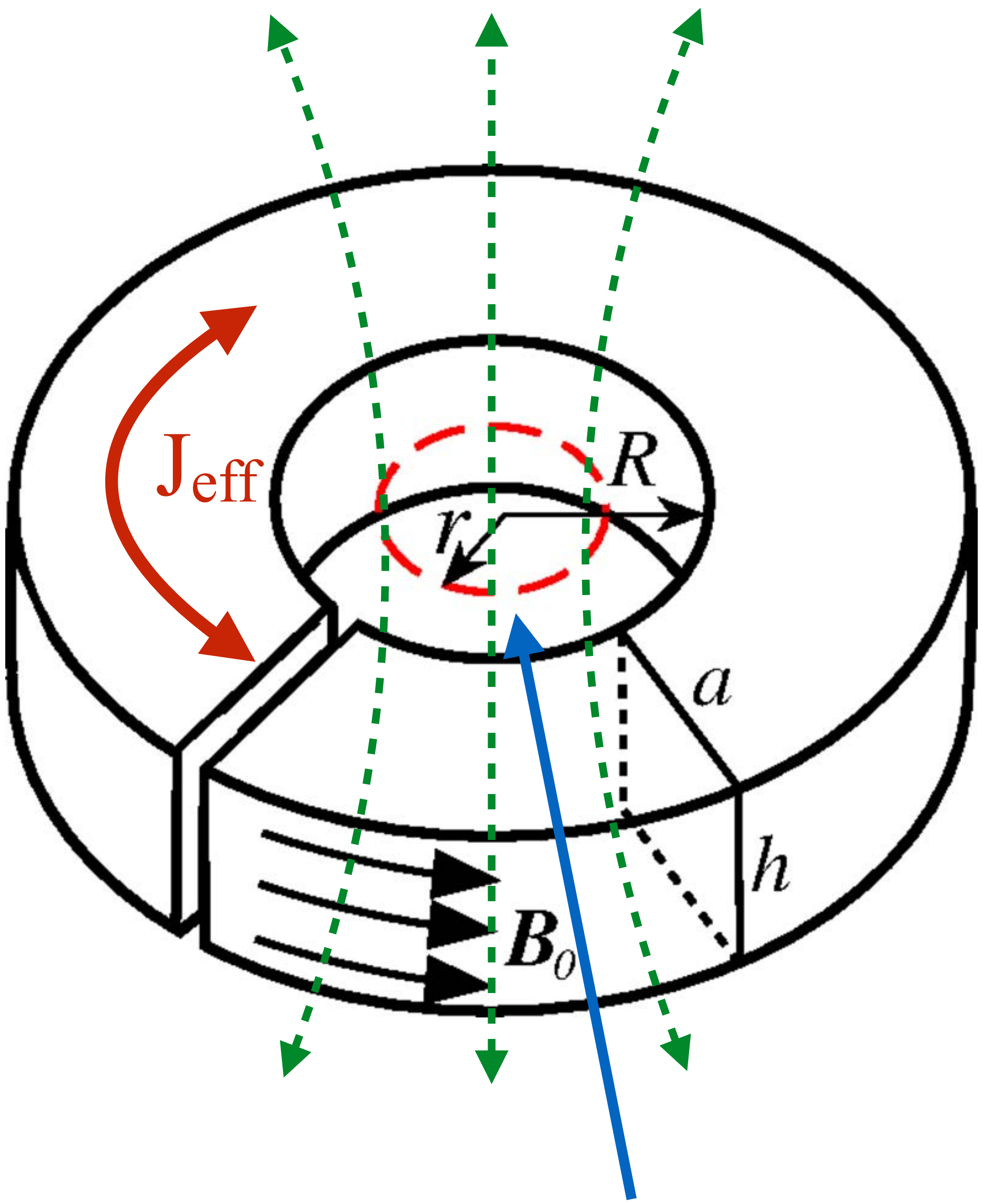
Induces oscillating magnetic field in torus

Induced B-field

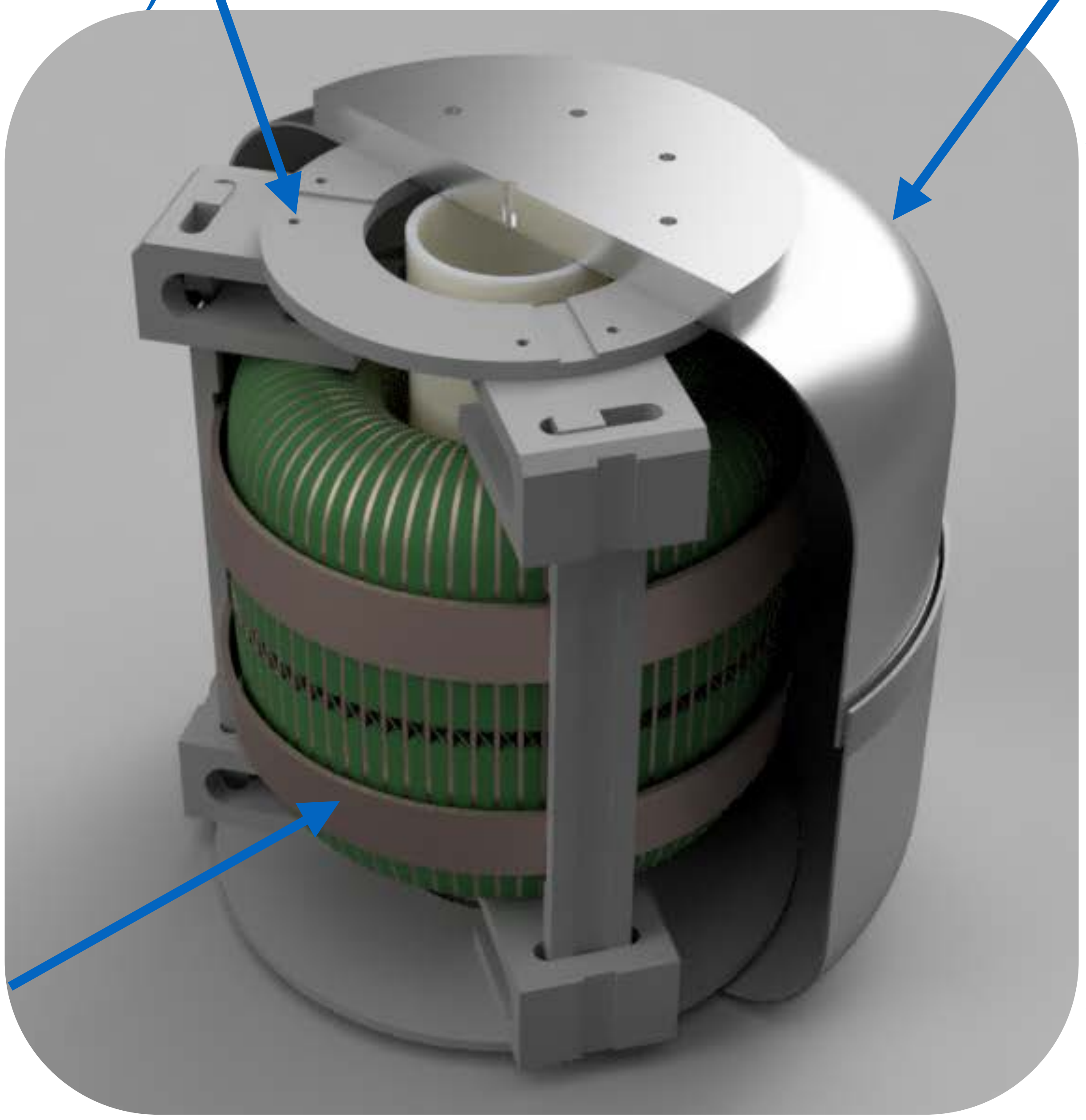


Measure induced field using pickup loop
DC B-field free

Dissecting ABRACADABRA-10 cm

G10 Support structure
(nylon bolts)

Superconducting tin coated
copper shield

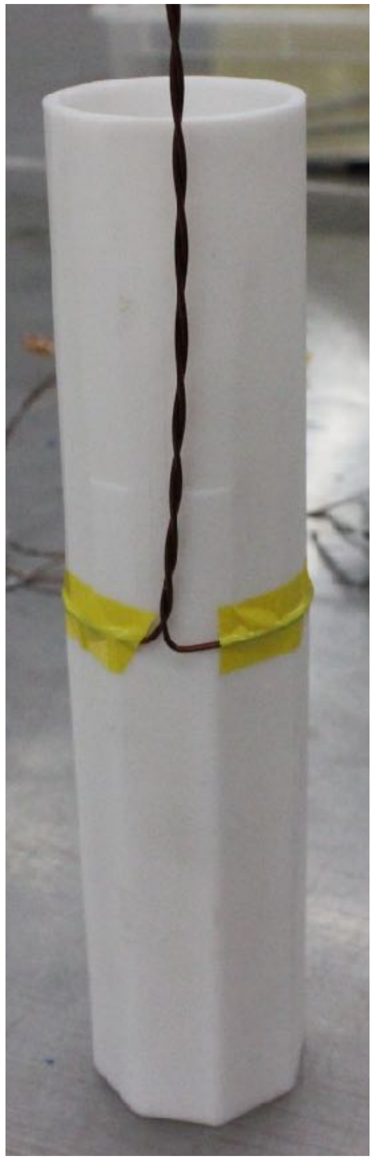


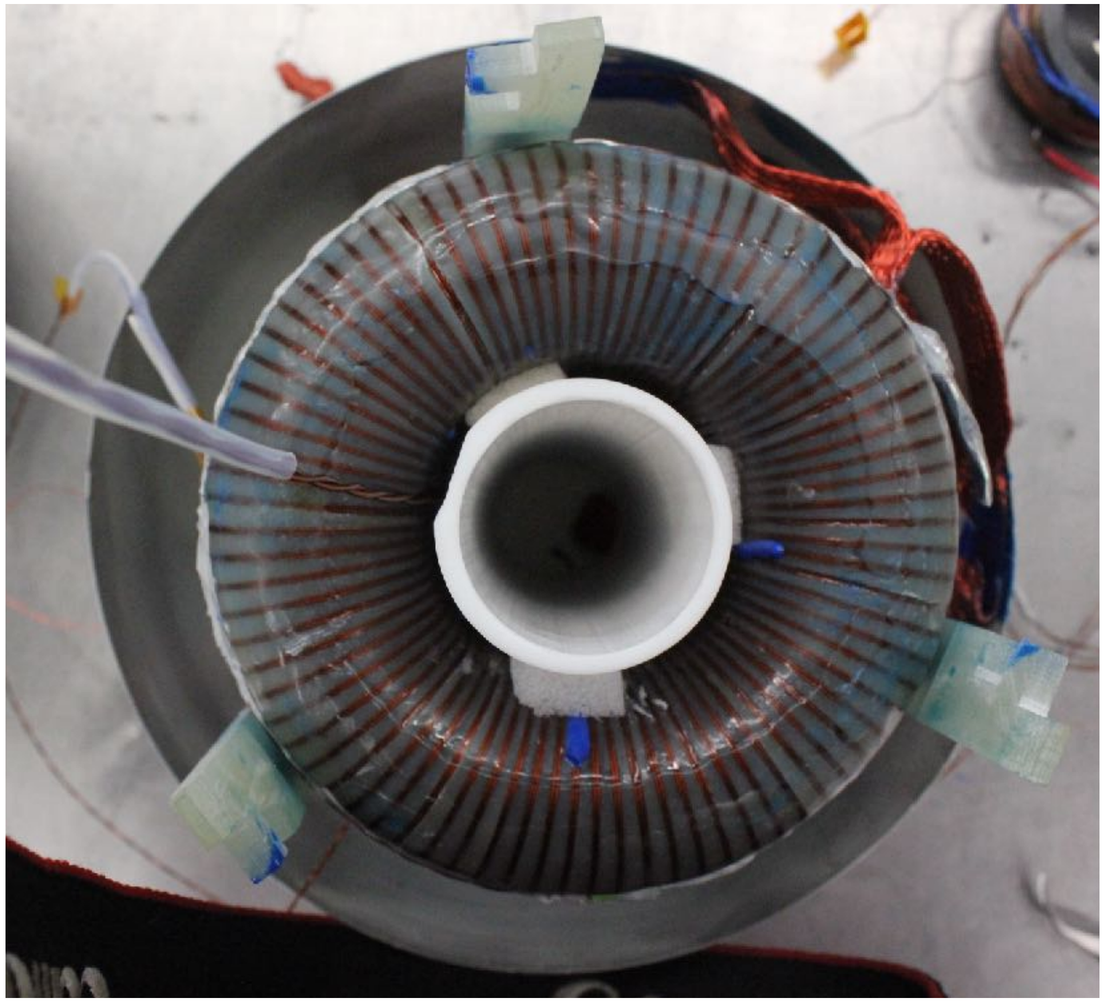
12cm

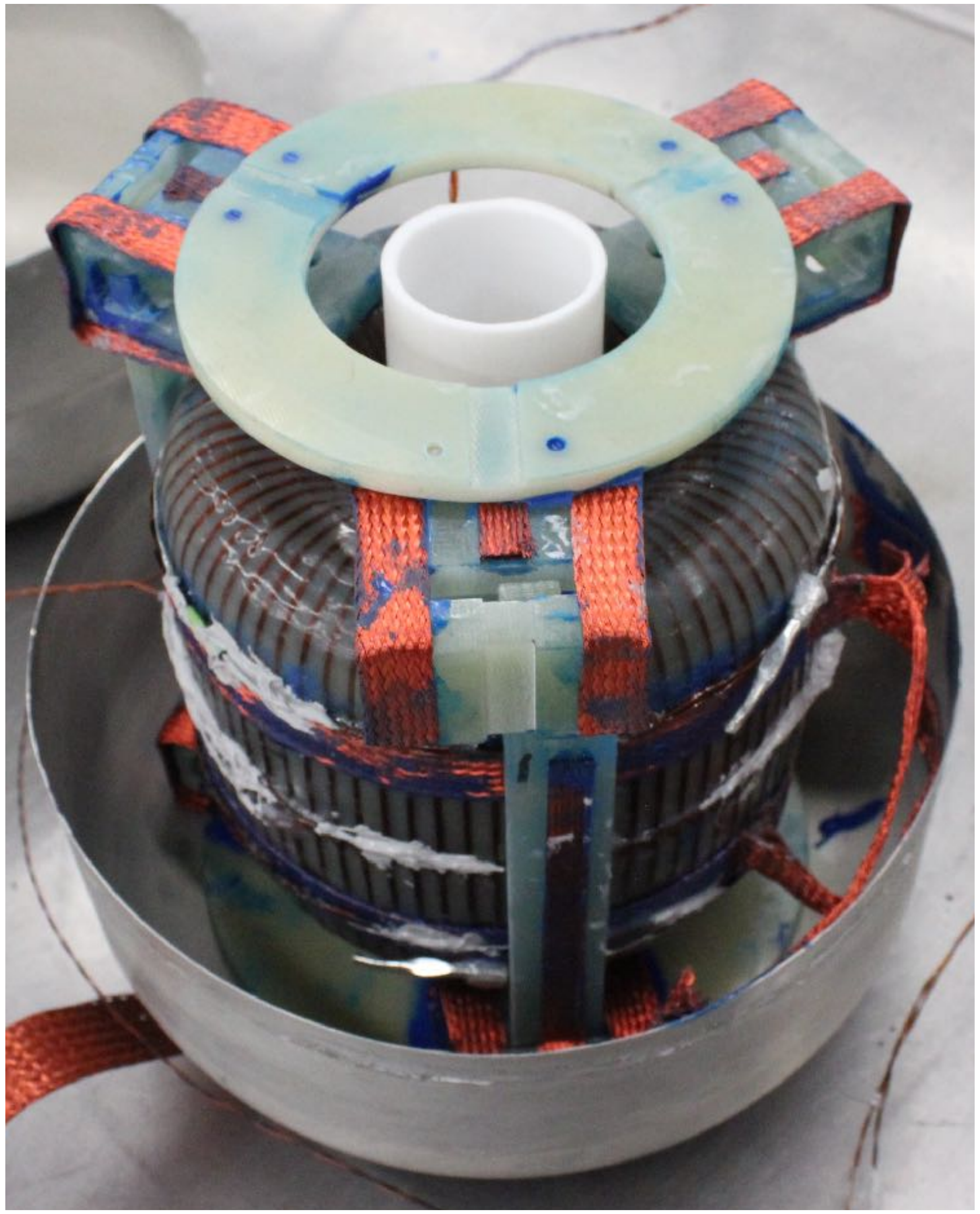
Copper Thermalization
Bands

Assembling ABRACADABRA-10 cm

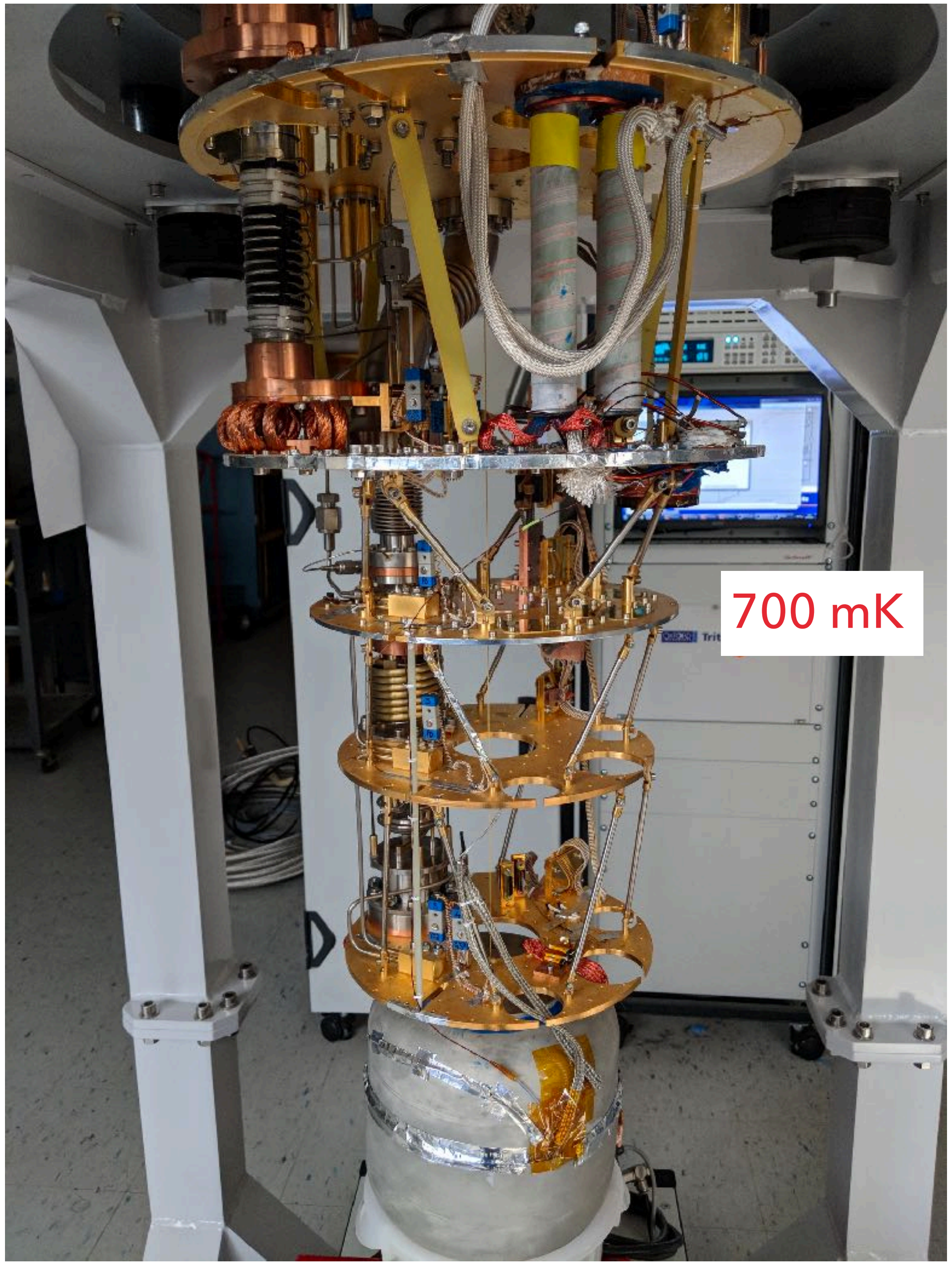
Pickup Loop



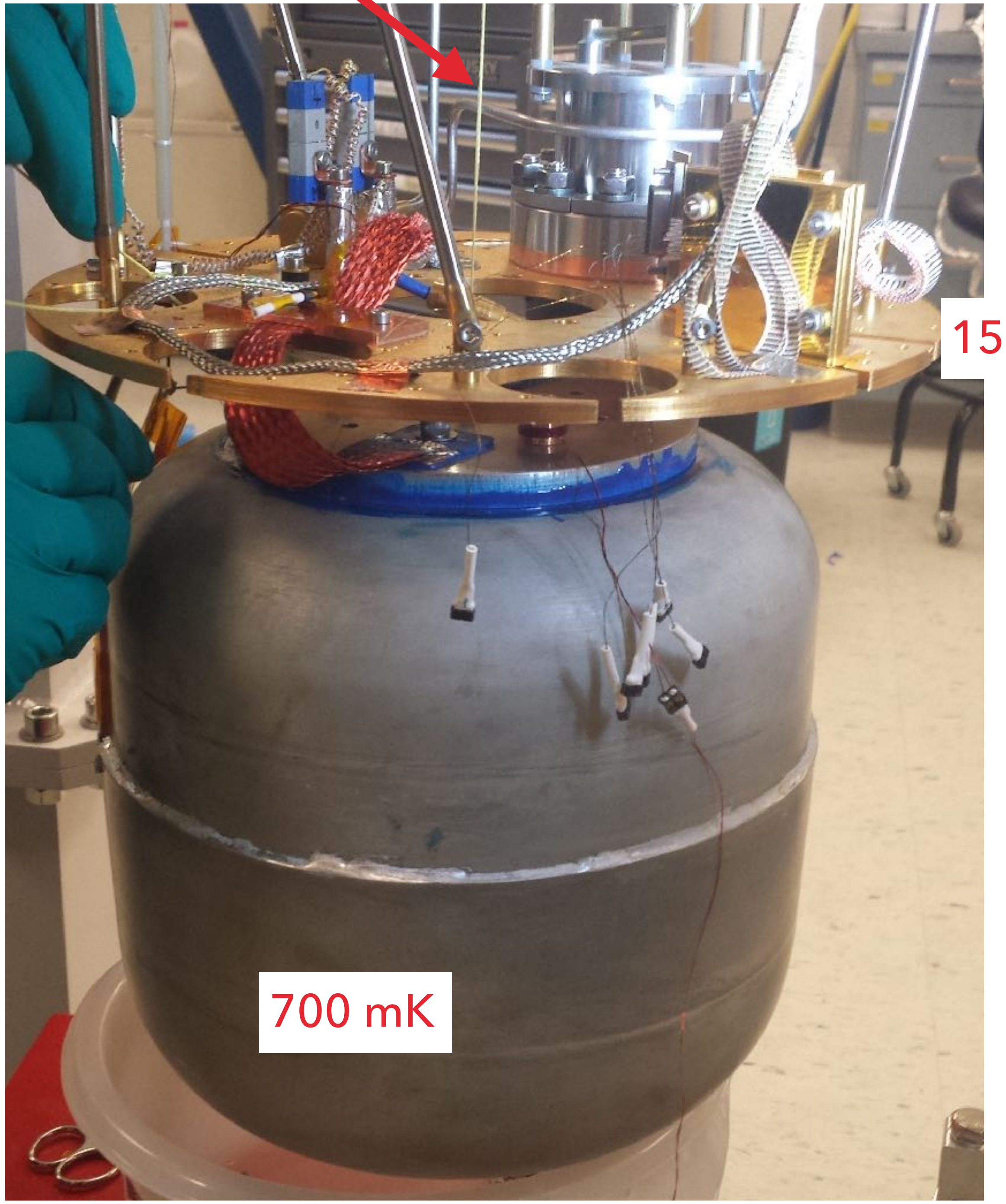




ABRA-10cm Mounted

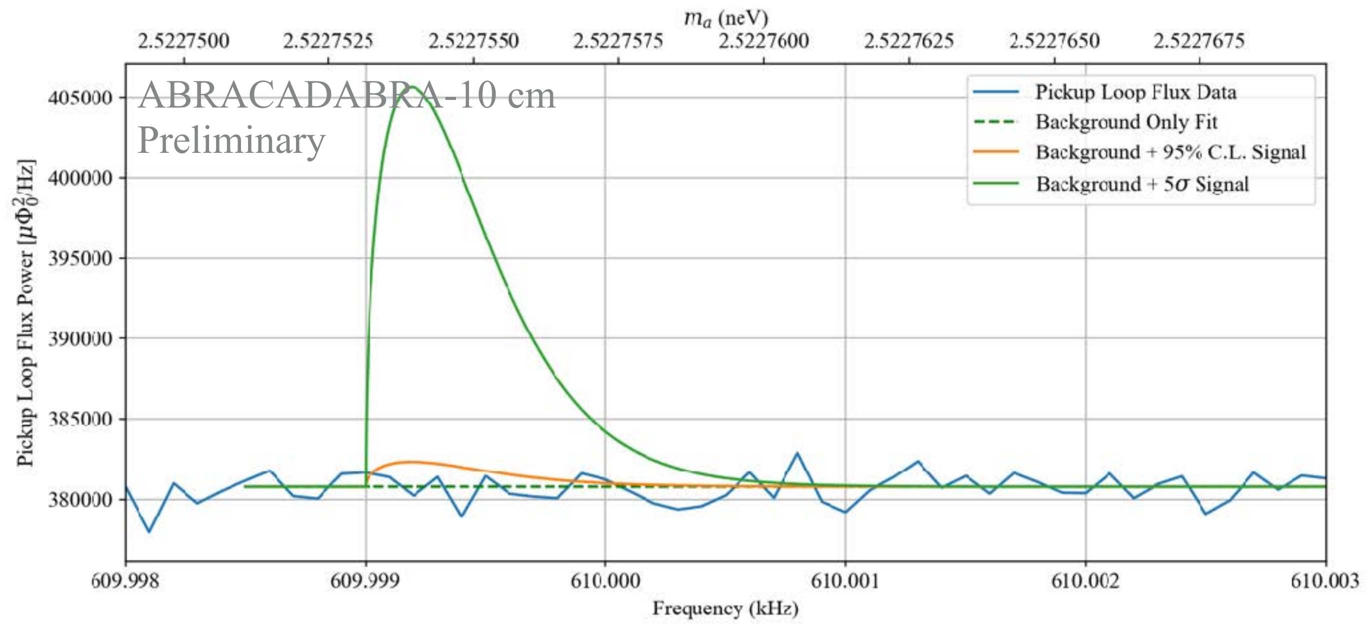


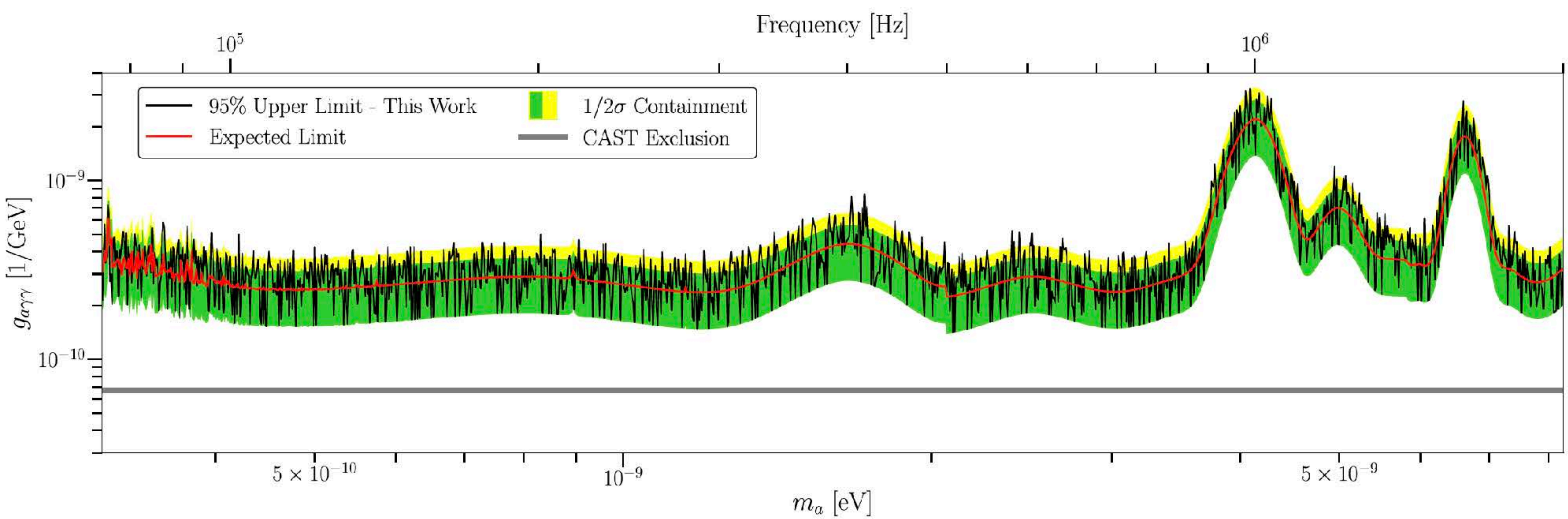
Kevlar Support



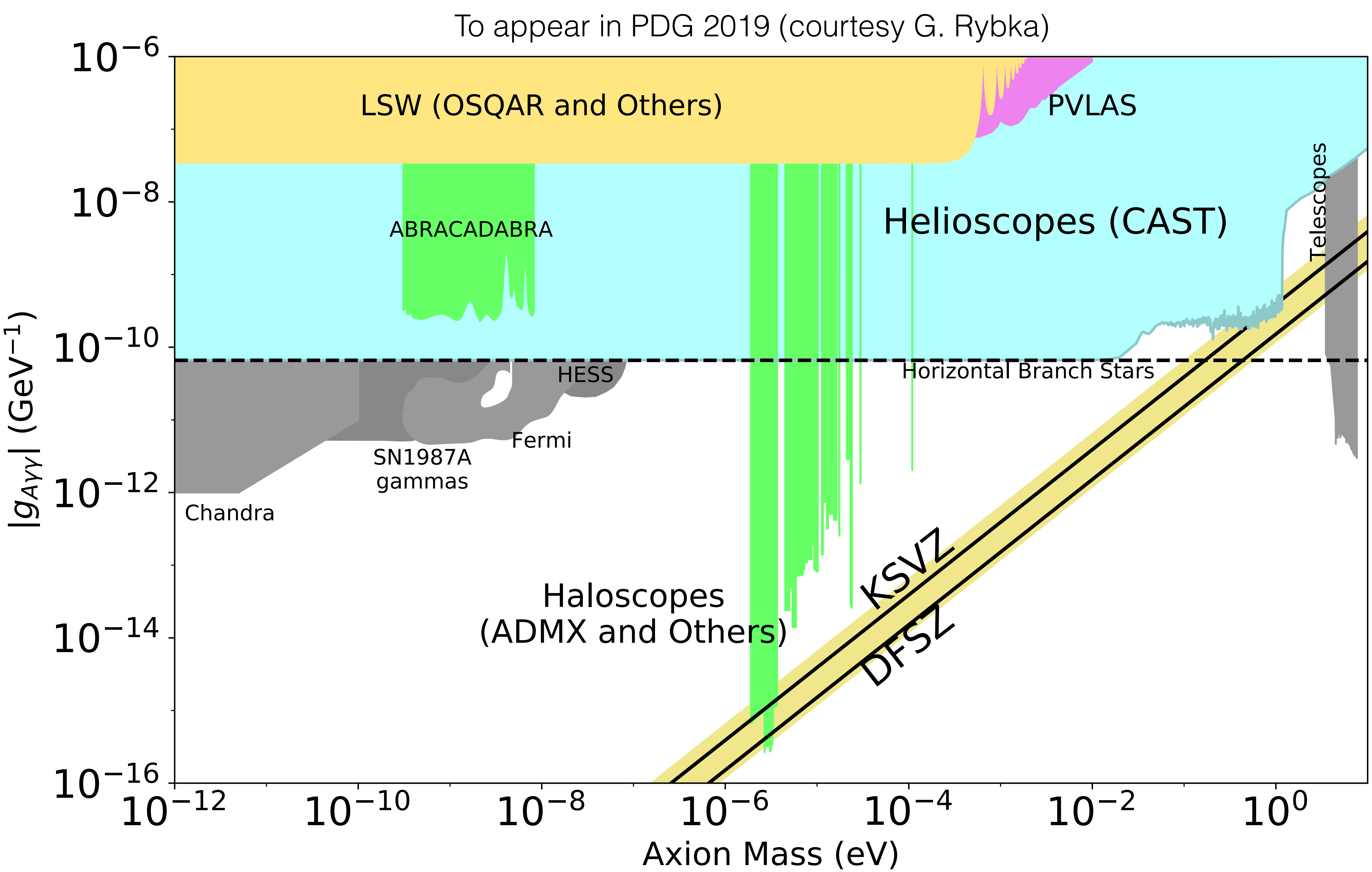
Axion Limits

- Broadband Data-taking in summer 2018. No resonator.
- No 5σ excesses that were not vetoed by Magnet off or digitizer data
- Published results: PRD 99 (2019) 052012; PRL 122 (2019) 121802





ABRACADABRA-10 cm Run 1 Limits



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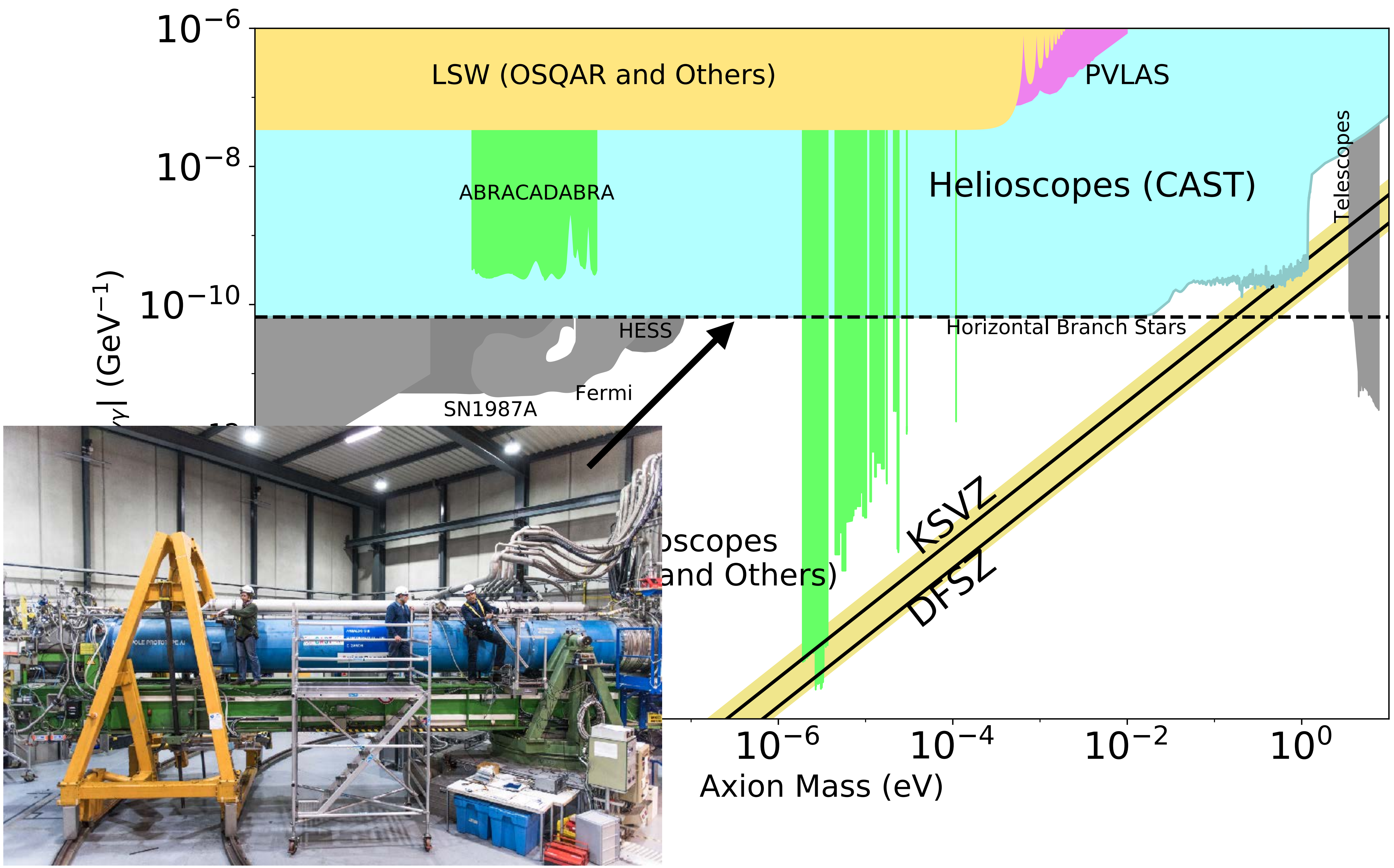

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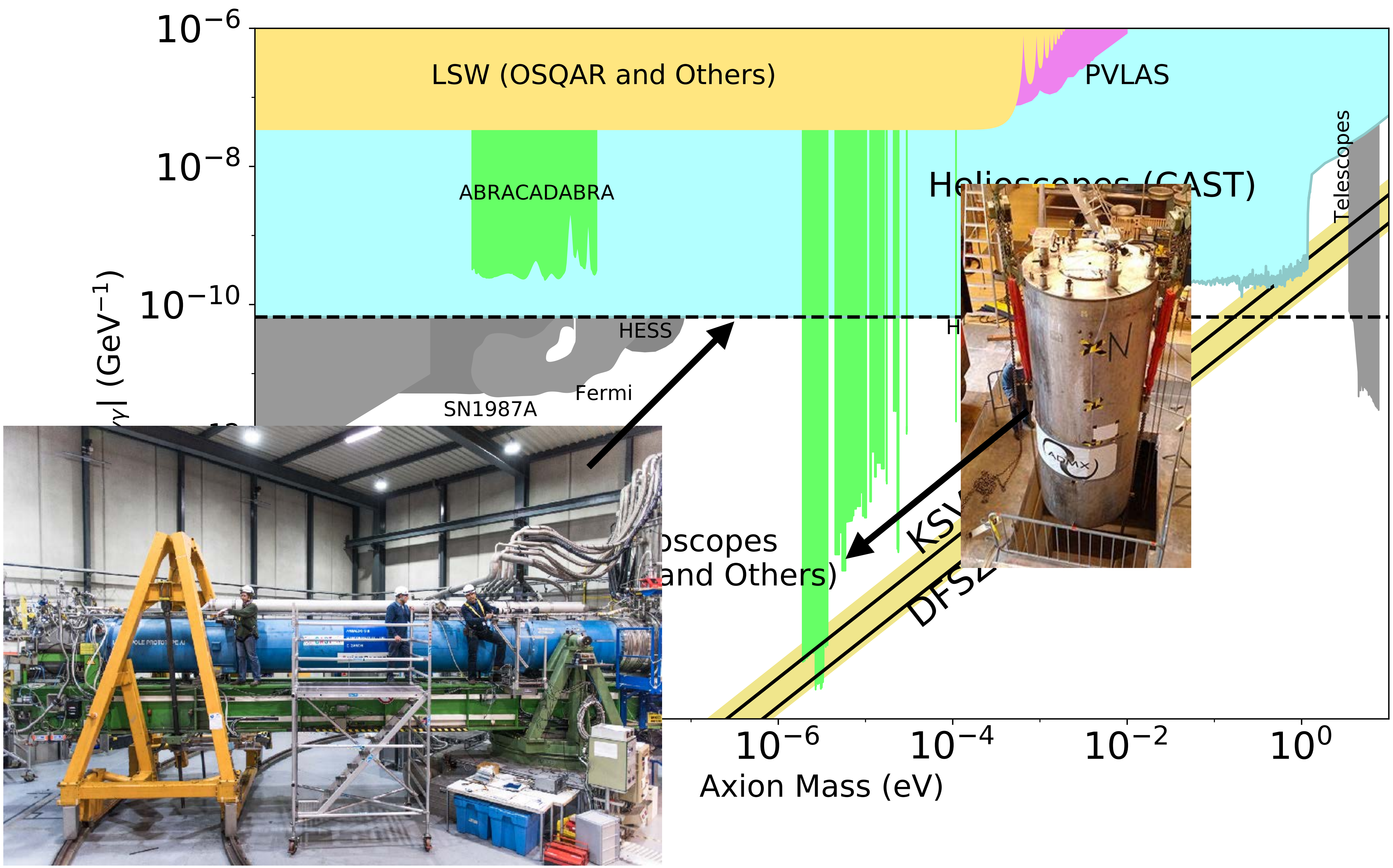

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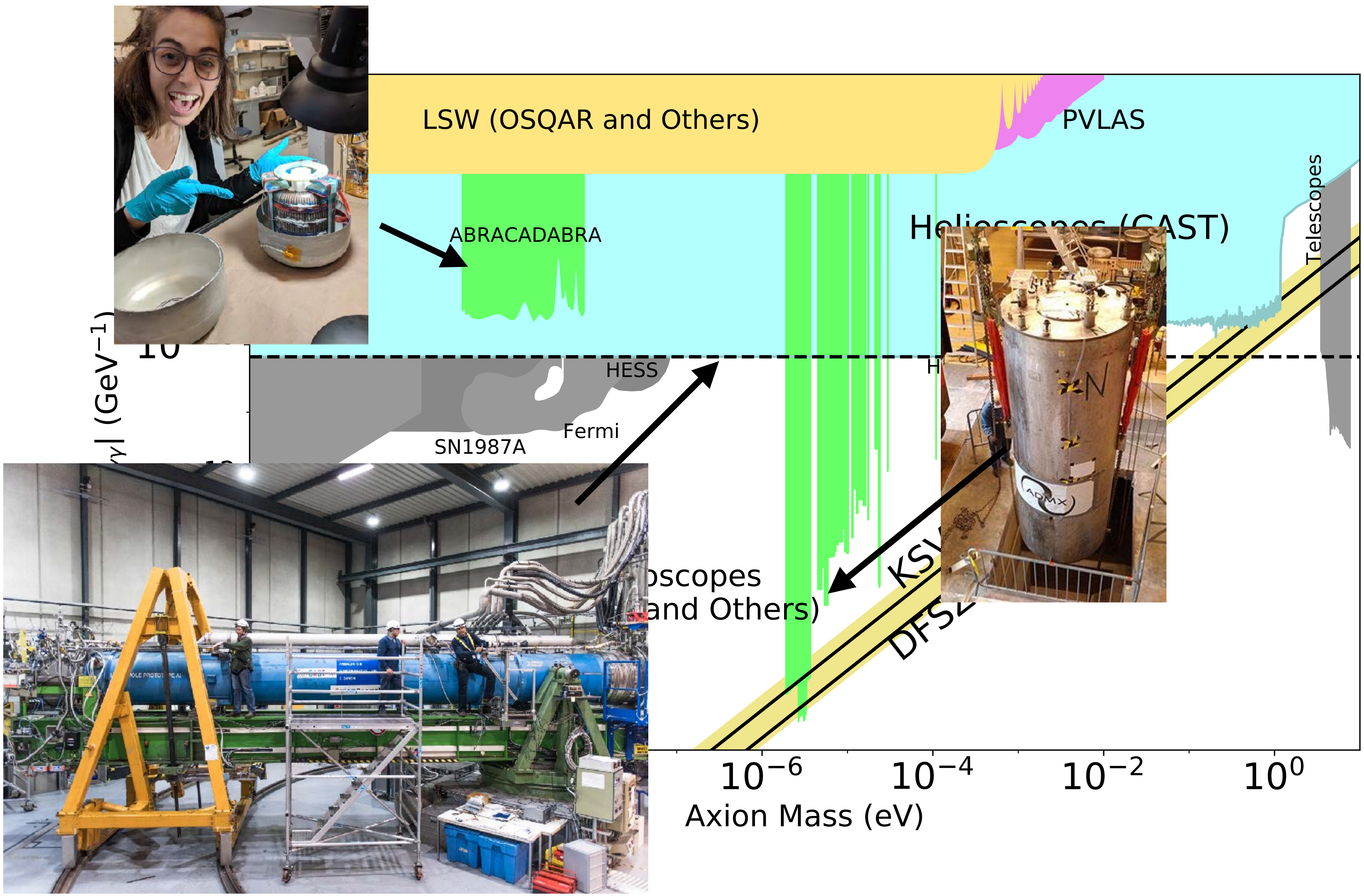


ABRACADABRA

MIT

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

TUNL
TRIANGLE UNIVERSITIES NUCLEAR LABORATORY

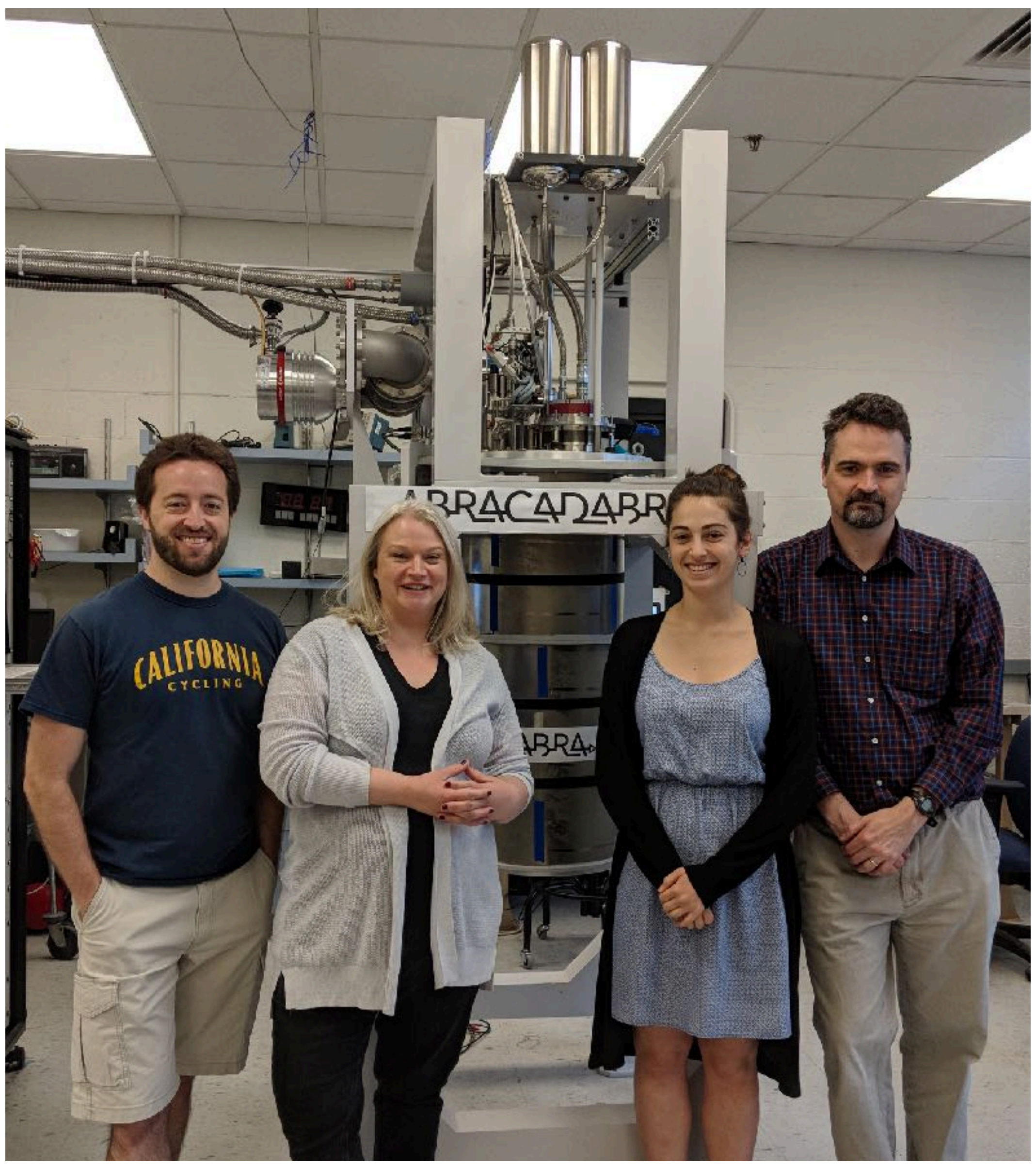
KICP

UNIVERSITY OF MICHIGAN

Berkeley
UNIVERSITY OF CALIFORNIA

BERKELEY LAB

NSF



Future Plans

Leading up to a Cubic Meter Experiment

- ABRA-10cm: Running at MIT.
- DMRadio-Pathfinder (Vector 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 ABRA PIs (Henning and Winslow).
    - 2 years.
    - Goal: Develop 30% Design, focused on magnet.
    - Develop Full Proposal for 1m^3 experiment.
- Organizational kickoff meeting at MIT last 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:

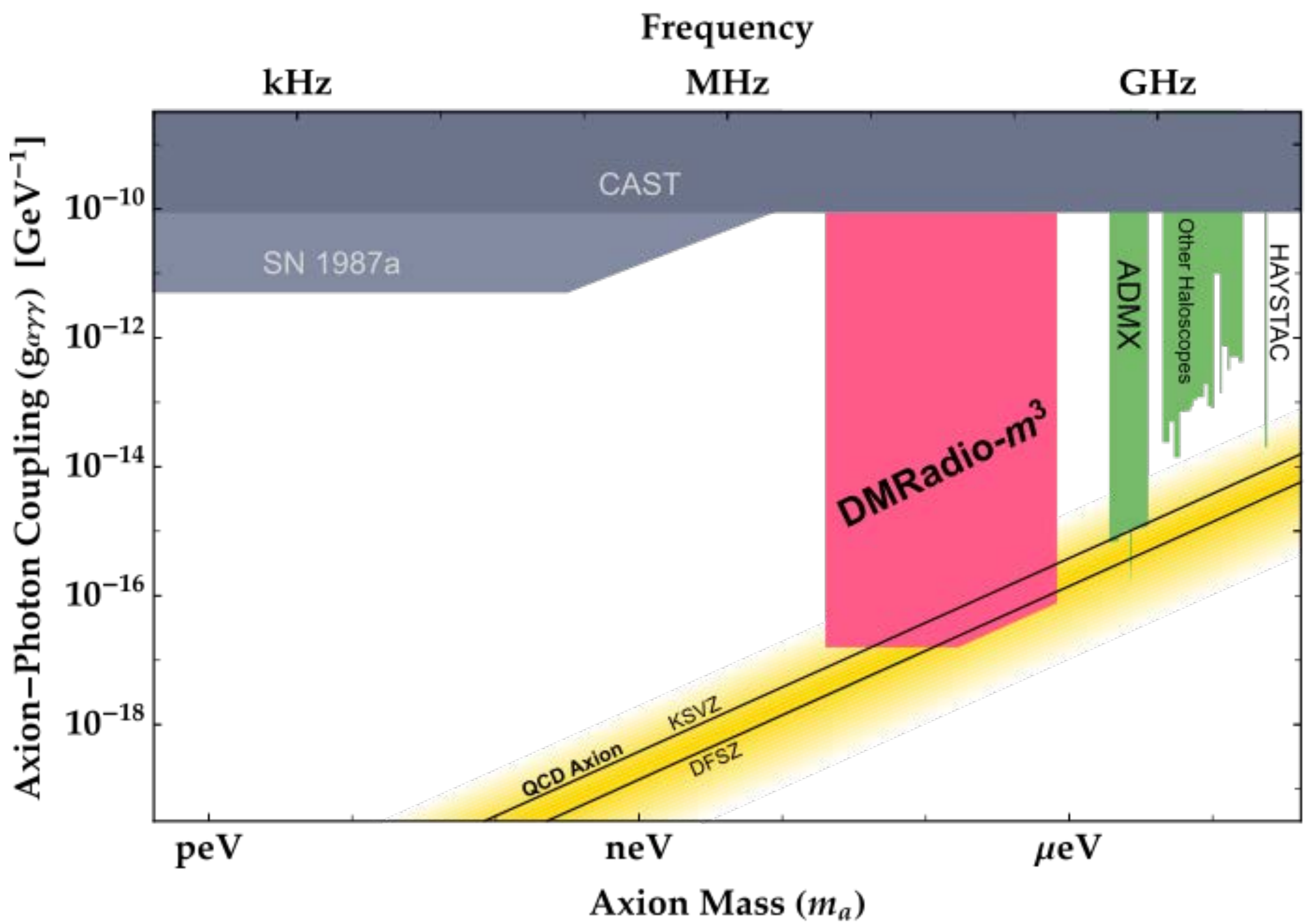
Project manager for R&D phase: Dale Li

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

DM Radio Cubic Meter Science Goals

Cubic Meter Experiment

- 1 m^3 Detection Volume
- 20 mK Temperature
- 4 Tesla Magnetic Field
- 5 MHz – 200 MHz
- dc SQUID with 20× quantum limit
- 3 years of live scan time
- Quantum Acceleration would enable QCD sensitivity at lower mass

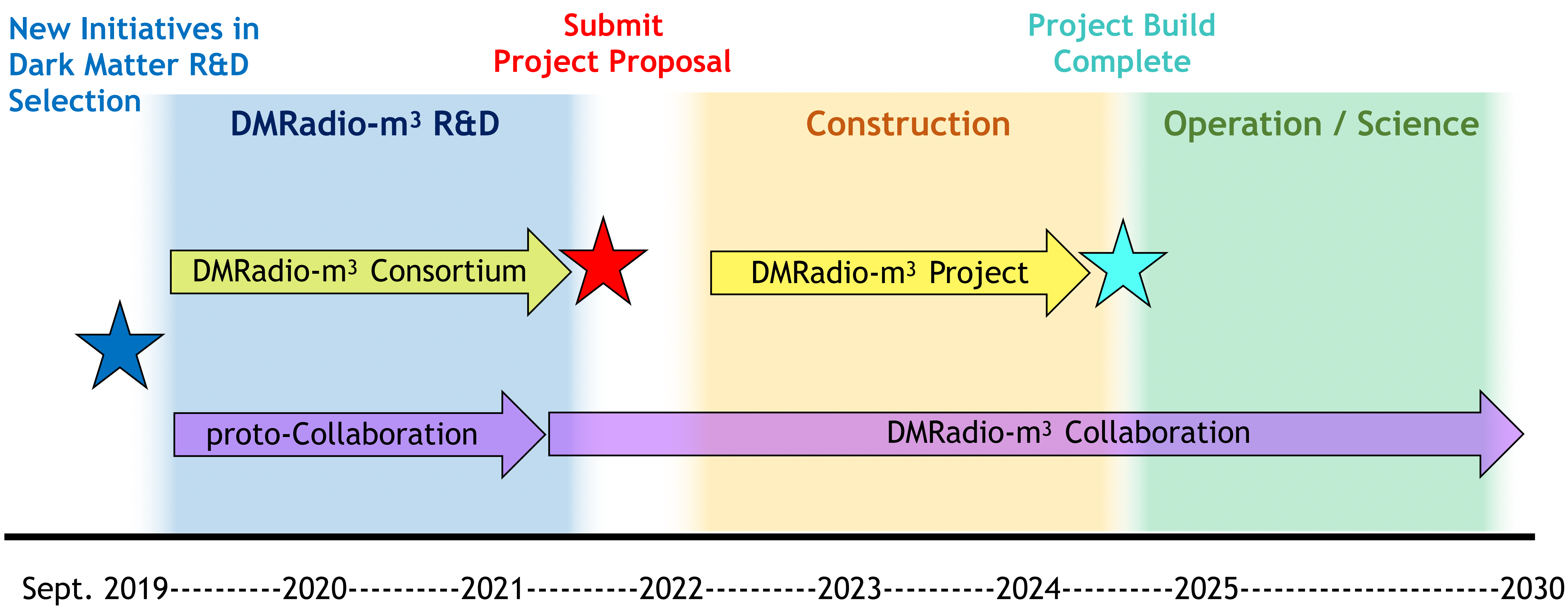


DM Radio Cubic Meter Timeline

2020-2021: DM Radio-m³ R&D

2022-2025: DM Radio-m³ Proposed Project Build

2025-2230: DM Radio-m³ Science Scanning



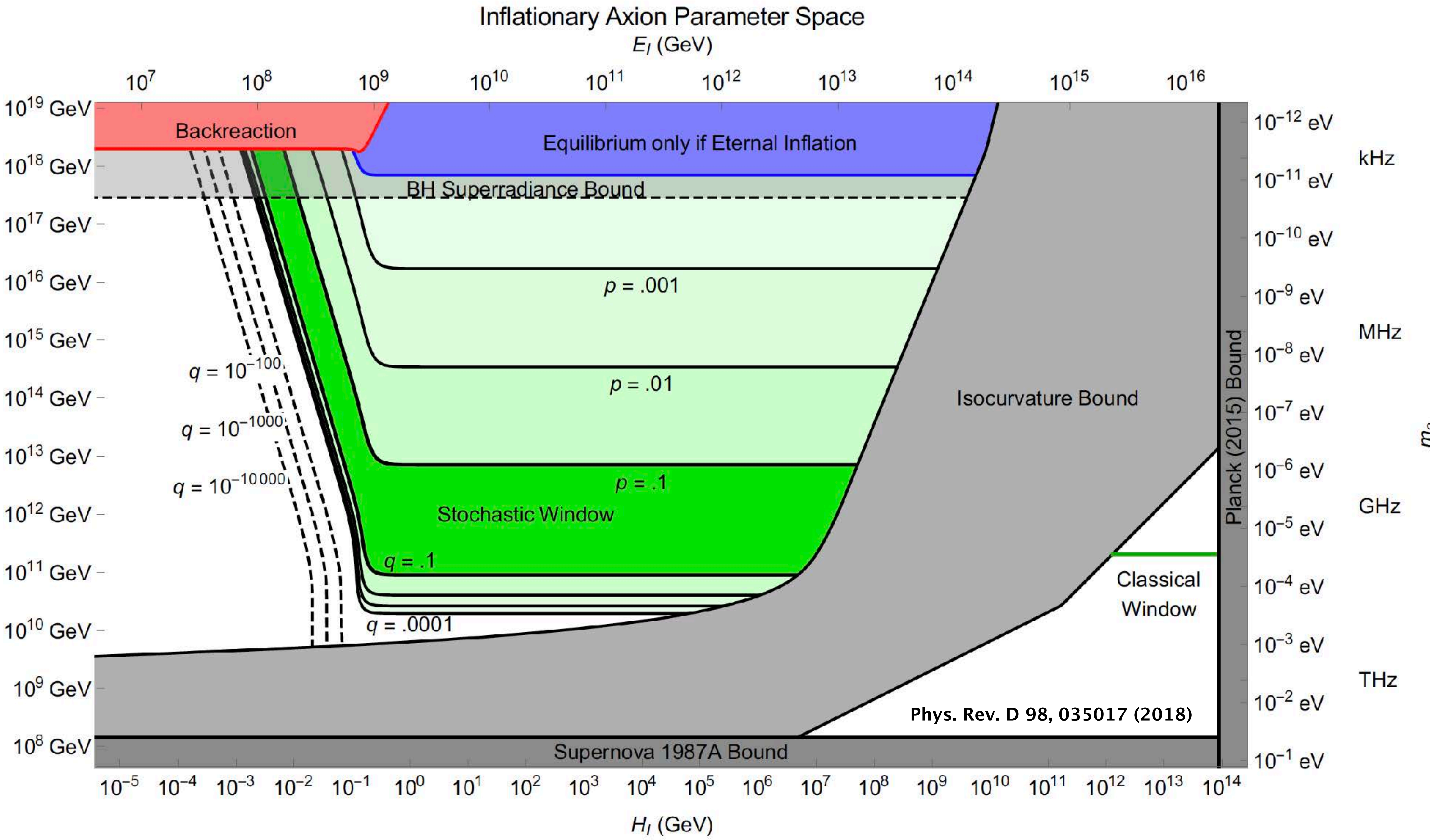
Conclusion

- 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^3 scale experiment with resonant readout to reach QCD axion line
- Opens up other well-motivated axion mass ranges

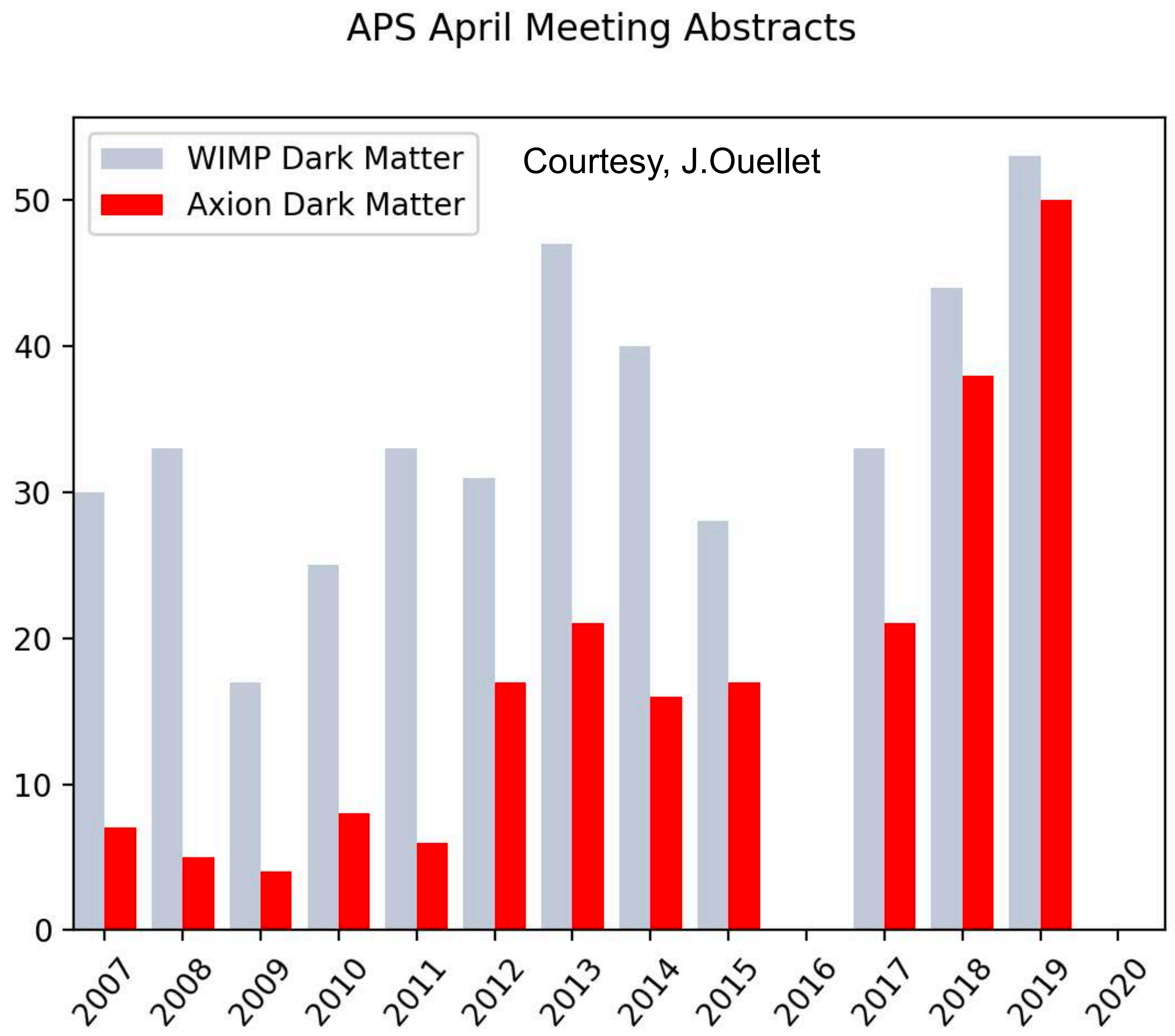
BONUS SLIDES

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)
Backreaction
Equilibrium only if Eternal Inflation
BH Superradiance Bound
$p = .001$
$p = .01$
$p = .1$
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
H_I (GeV)
kHz
MHz
GHz
THz
Phys. Rev. D 98, 035017 (2018)

Axions Catching up to WIMPs



Two Readout Strategies

Broadband

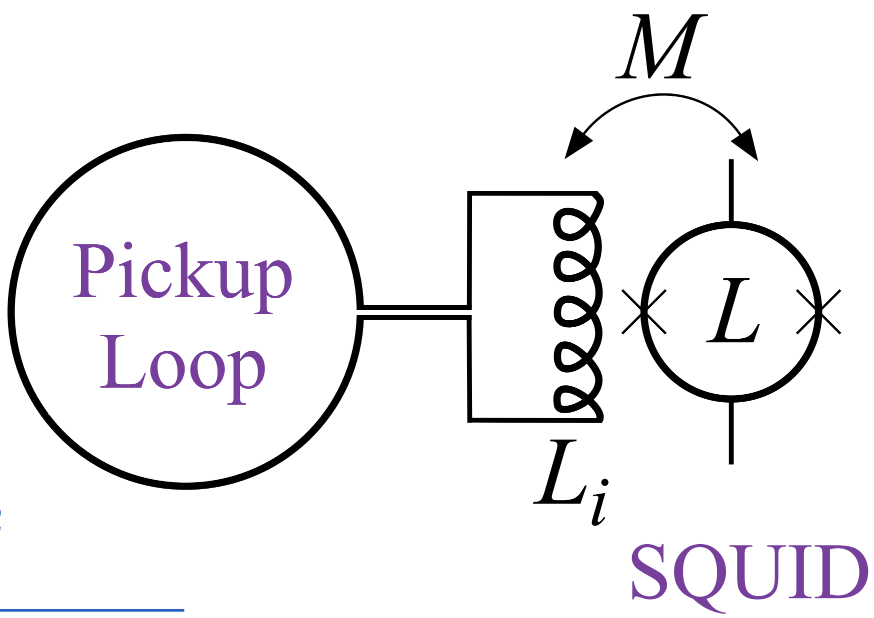
Scan all frequencies simultaneously

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



Resonant

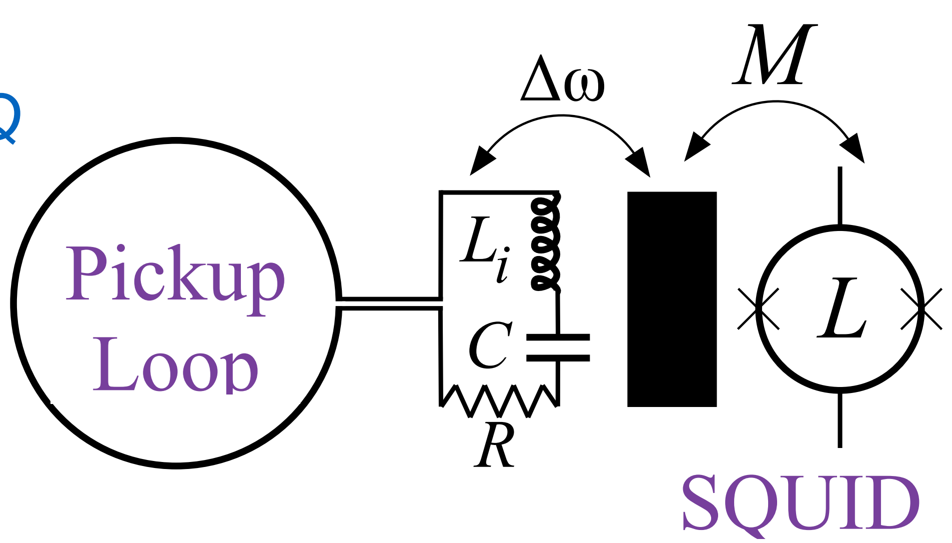
Resonance enhancement by adding capacitor with high-Q

Scan across frequencies

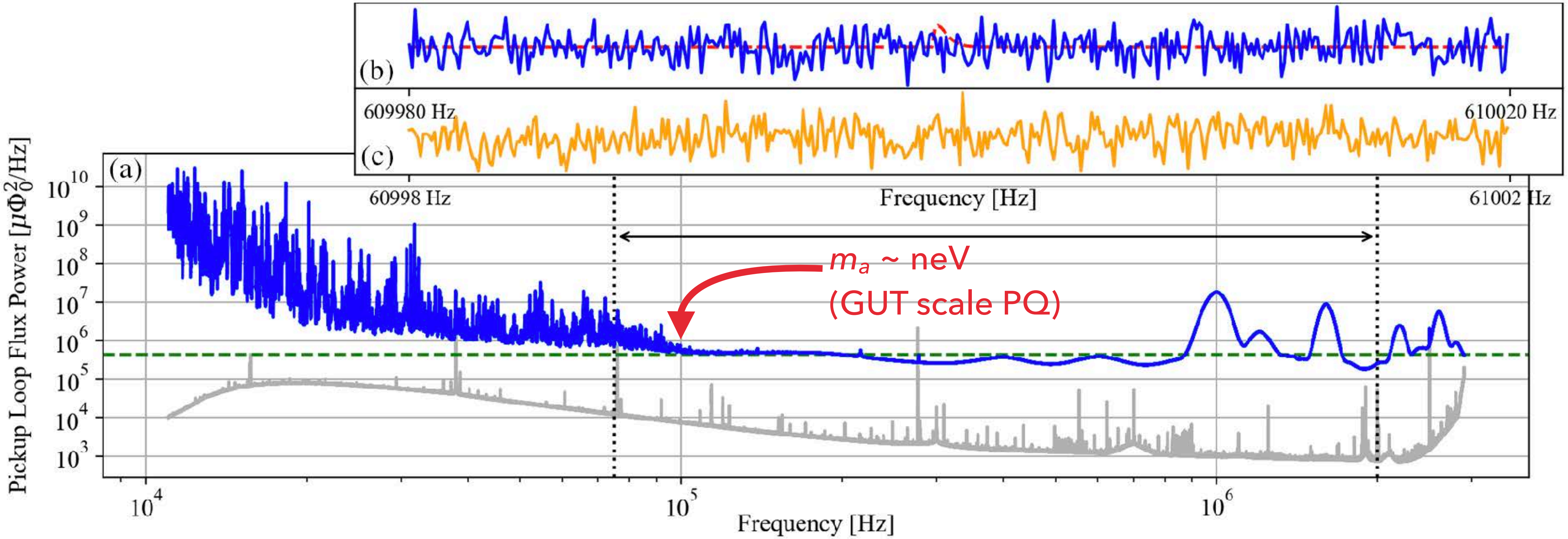
Thermal noise in pickup loop dominates

Resonance Mode Sensitivity:

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



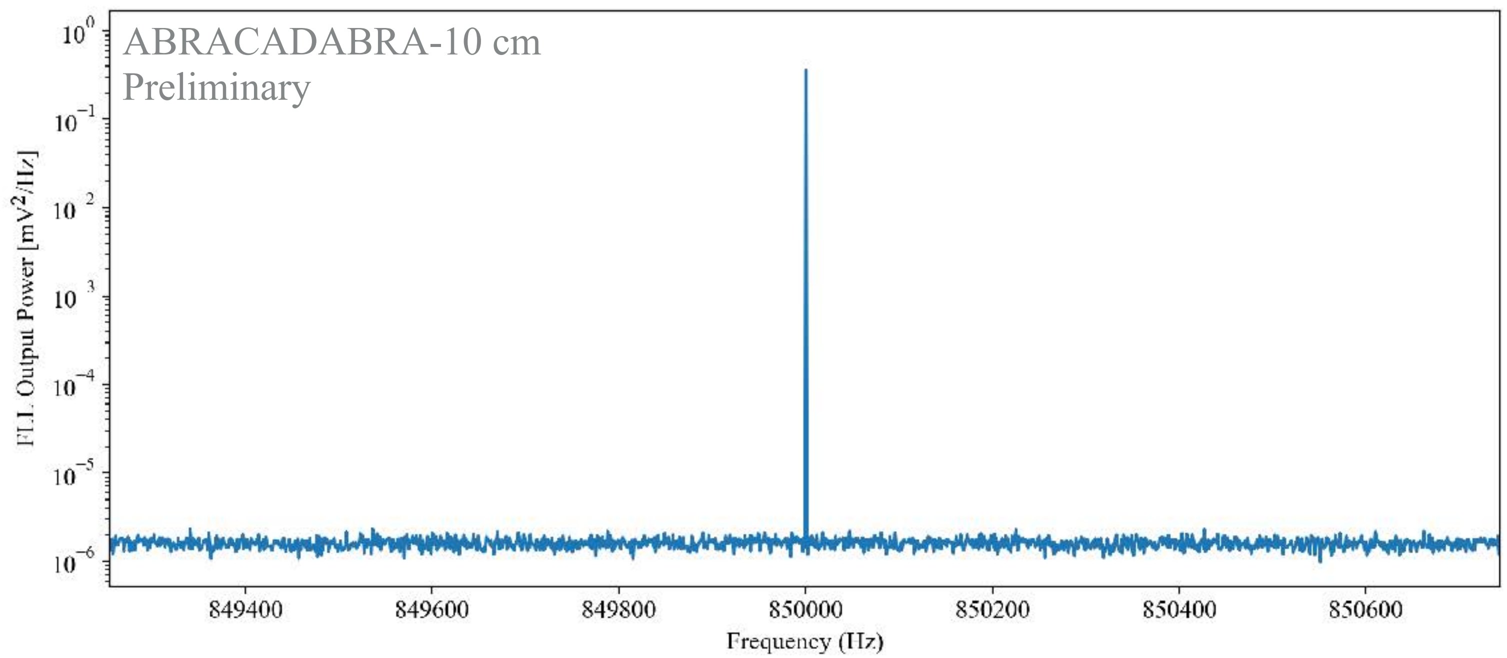
Example Spectrum

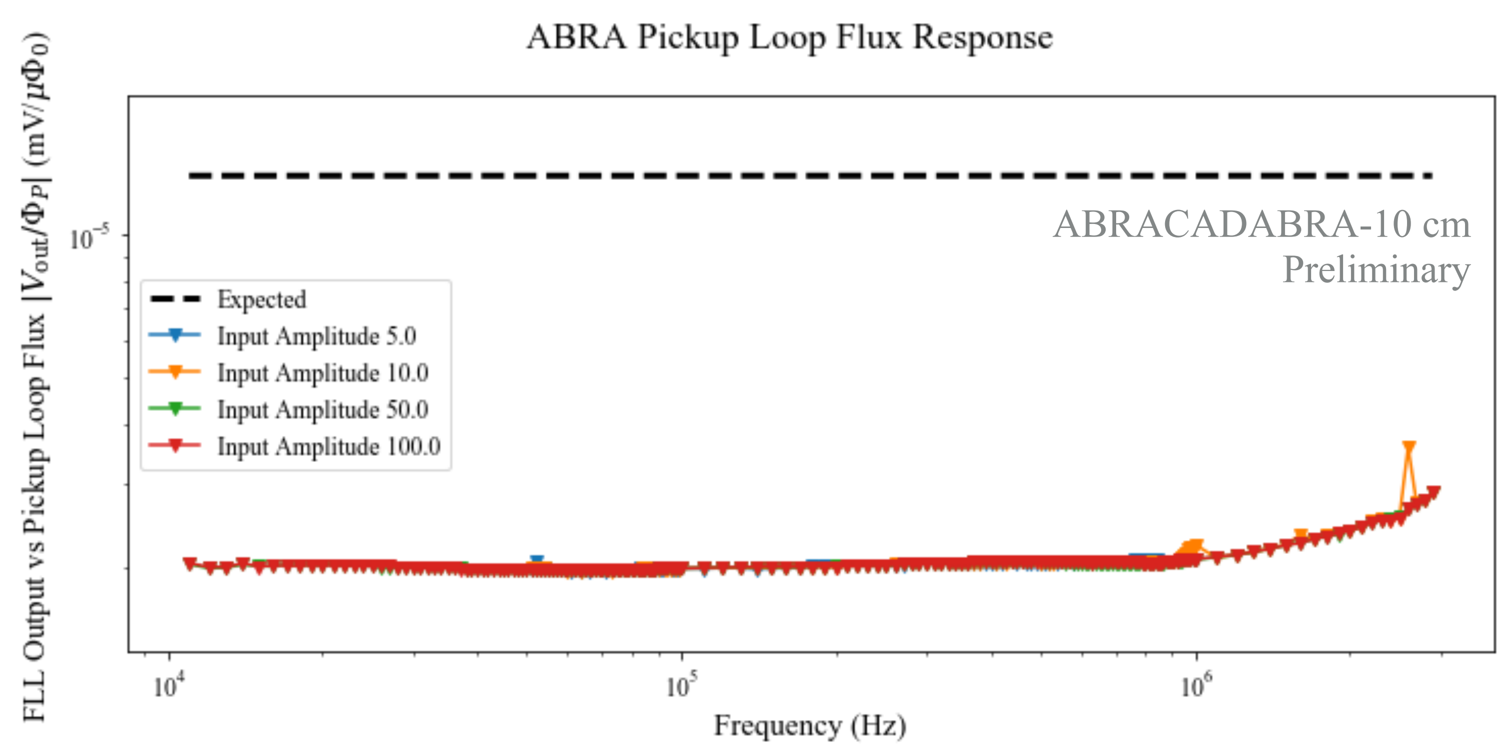


- 10 kHz high-pass and 1.9MHz anti-aliasing filters before digitizer
- Digitizer-only data show spurious noise spikes that were vetoed.

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. Corrected for next phase





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 ↓

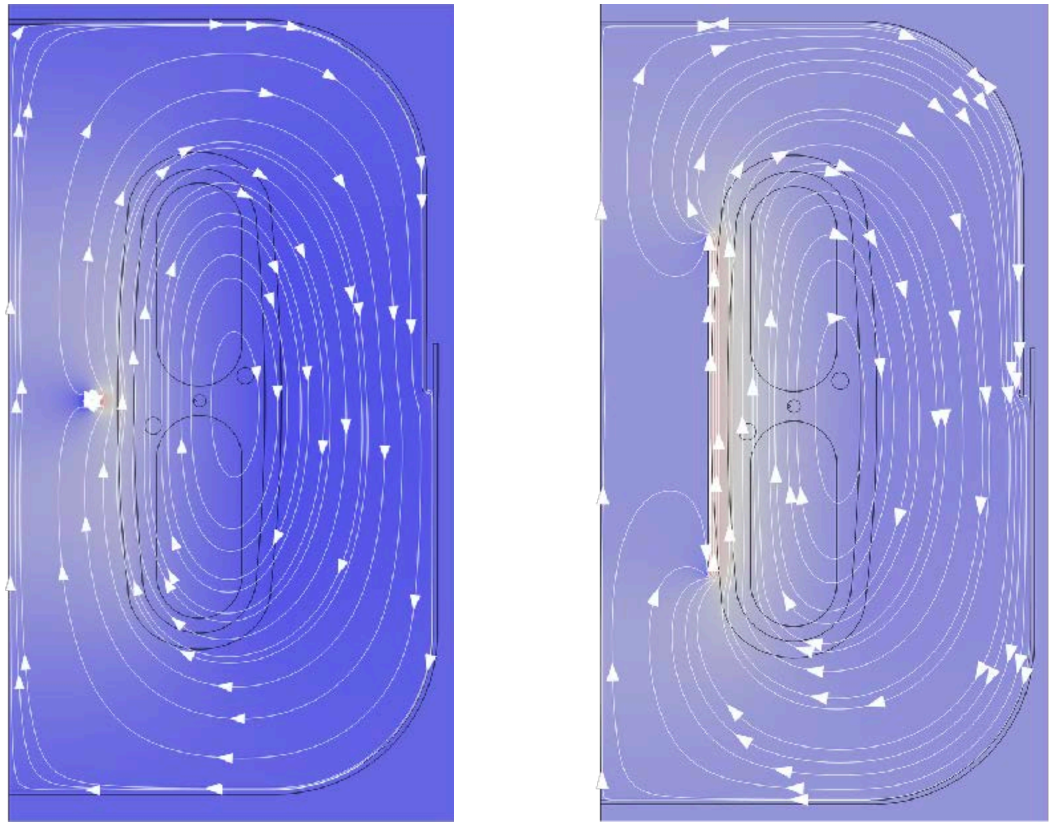
Written directly to disk

2,452,000 seconds total

$\Delta f \approx 408$ nHz

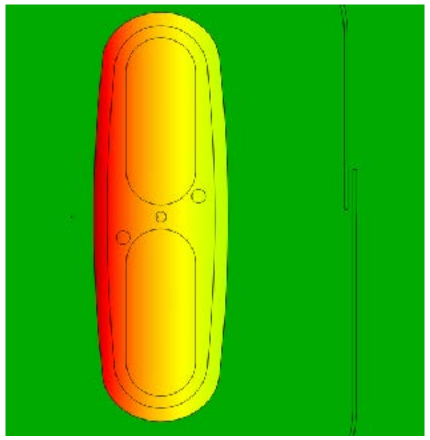
Next ABRA-10 cm run

- Reduced wiring lengths — reduced parasitic inductances
- Cylindrical Pickup loop to reduce loop inductance
- Boosted gain by factor ~10
- Had to implement active feedback to reduce noise <1kHz
- Broadband run planned by end of 2019

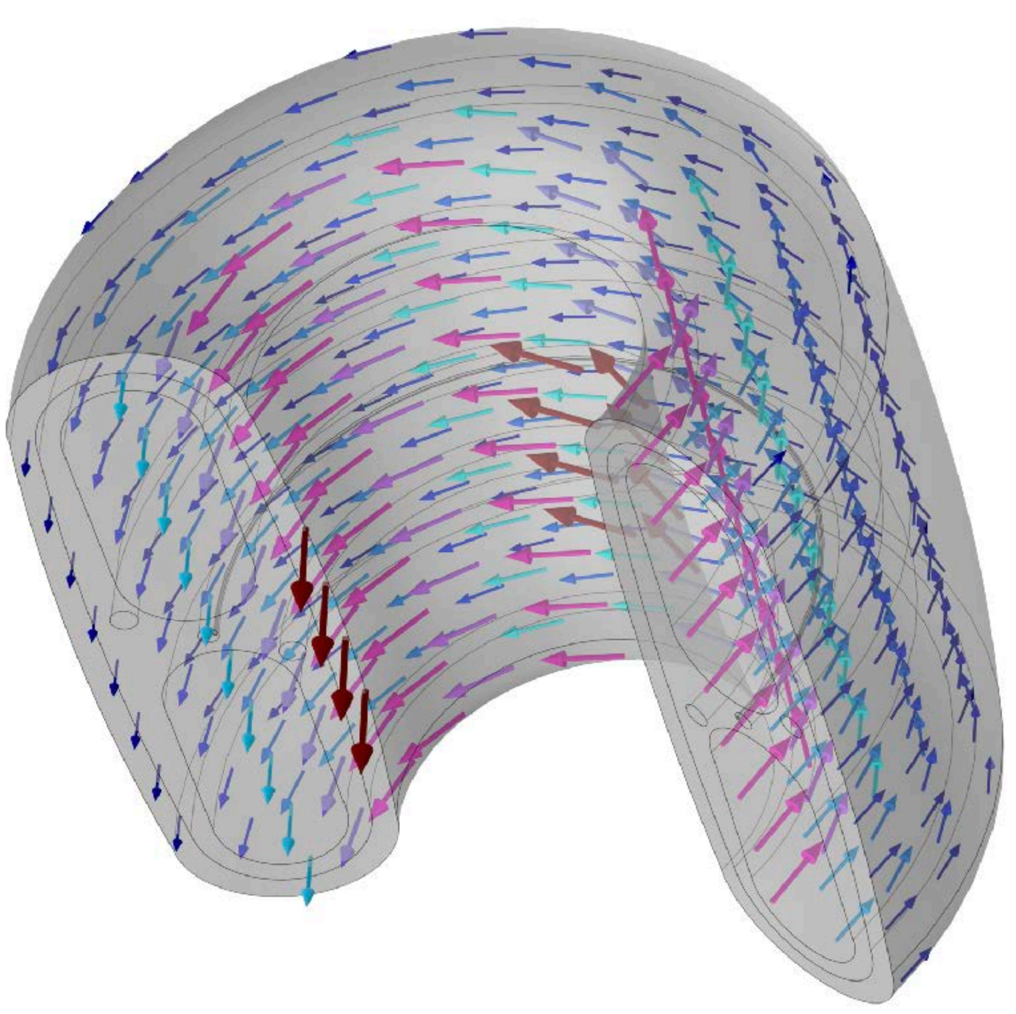


COMSOL

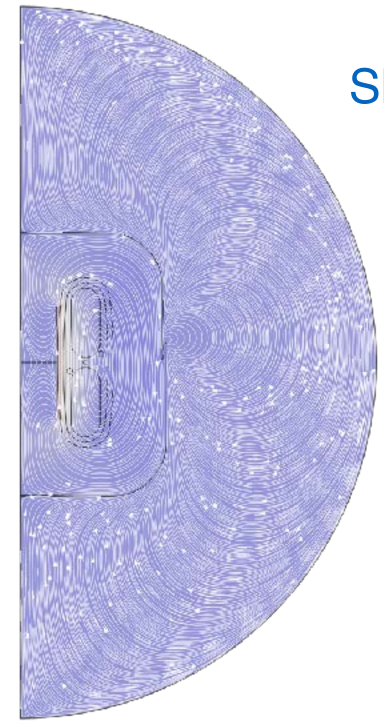
COMSOL Simulation



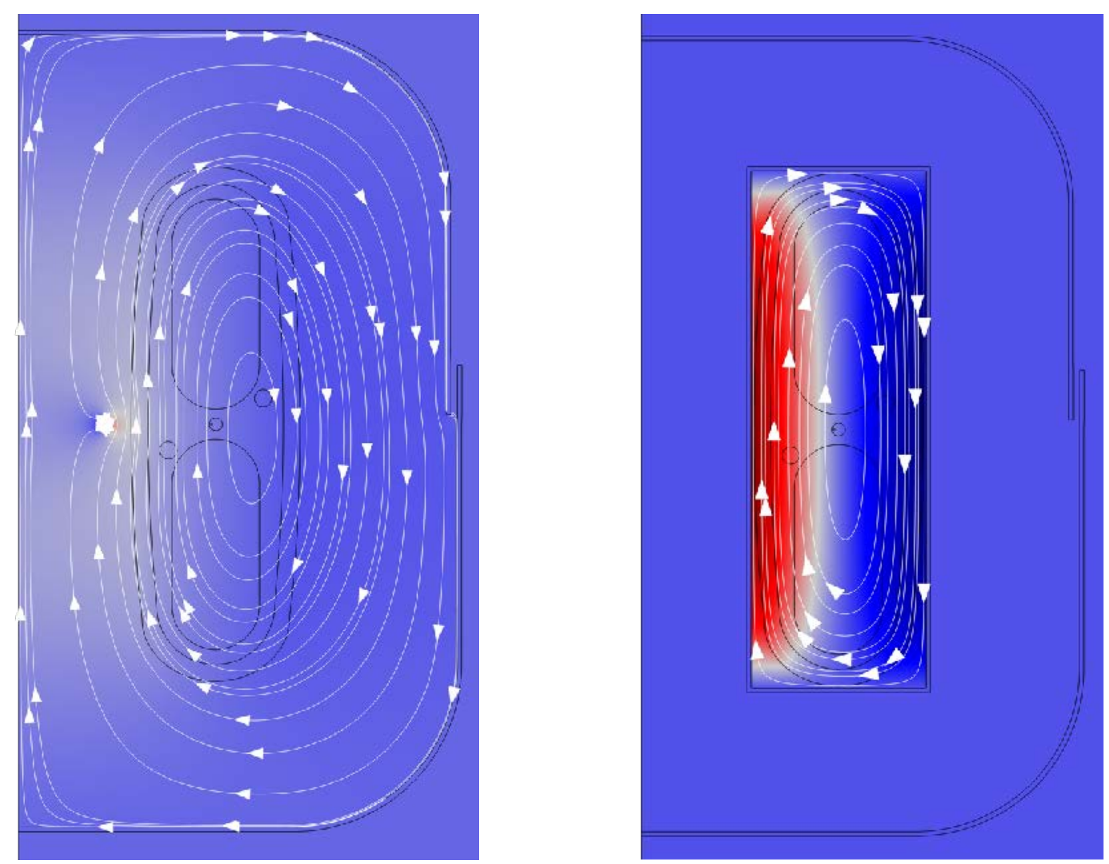
Axion effective current in
ABRA-10cm toroid



Shield simulation

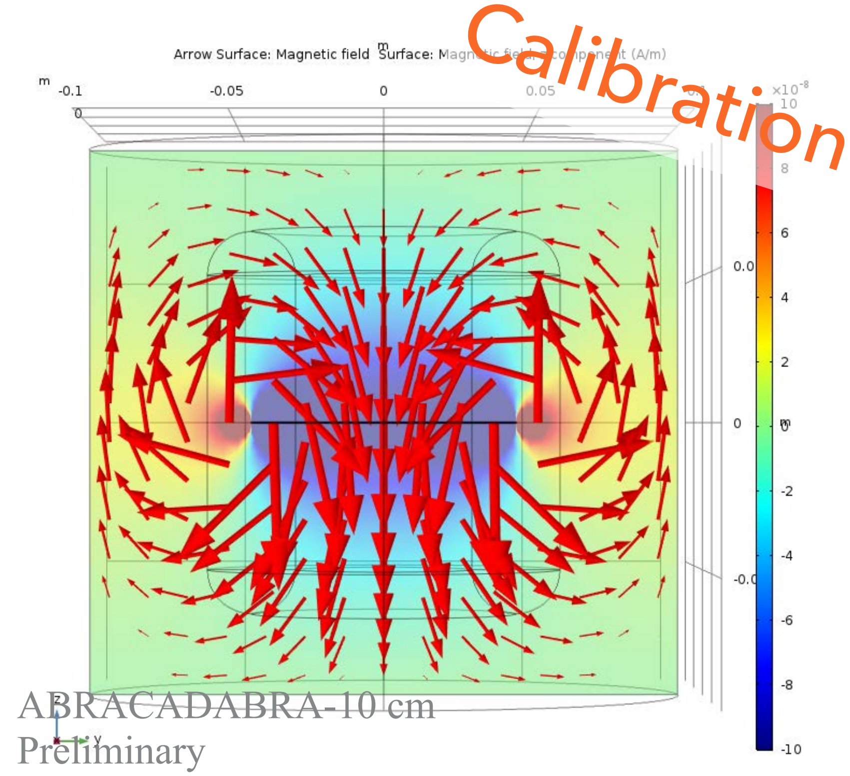


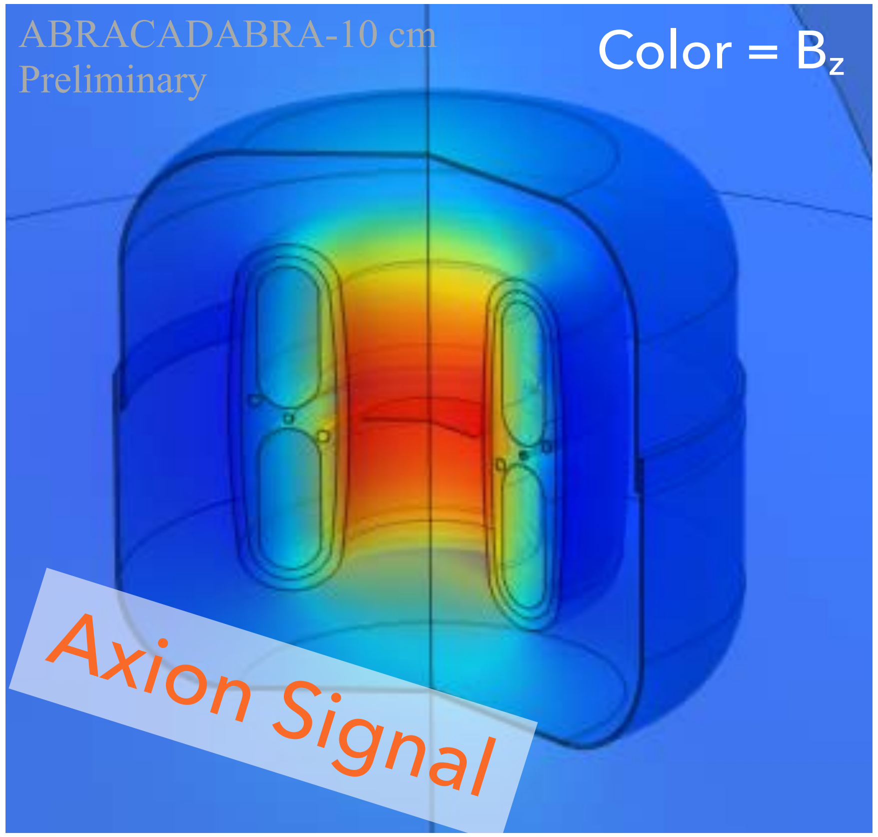
Pickup Loop vs. Sheath



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



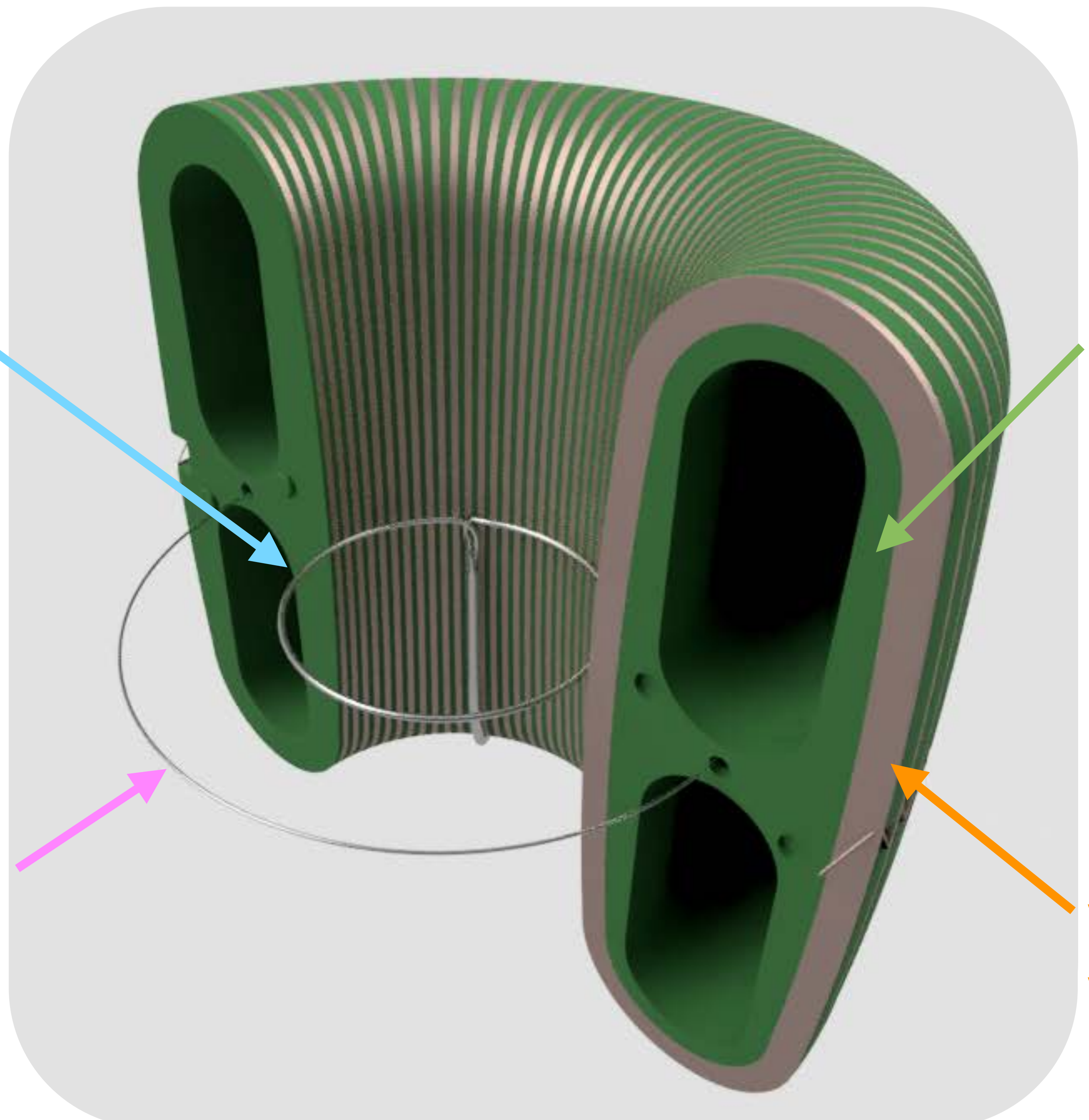


Dissecting ABRACADABRA-10 cm

12 cm

Superconducting Pickup Loop
$r_p = 2$ cm

12 cm

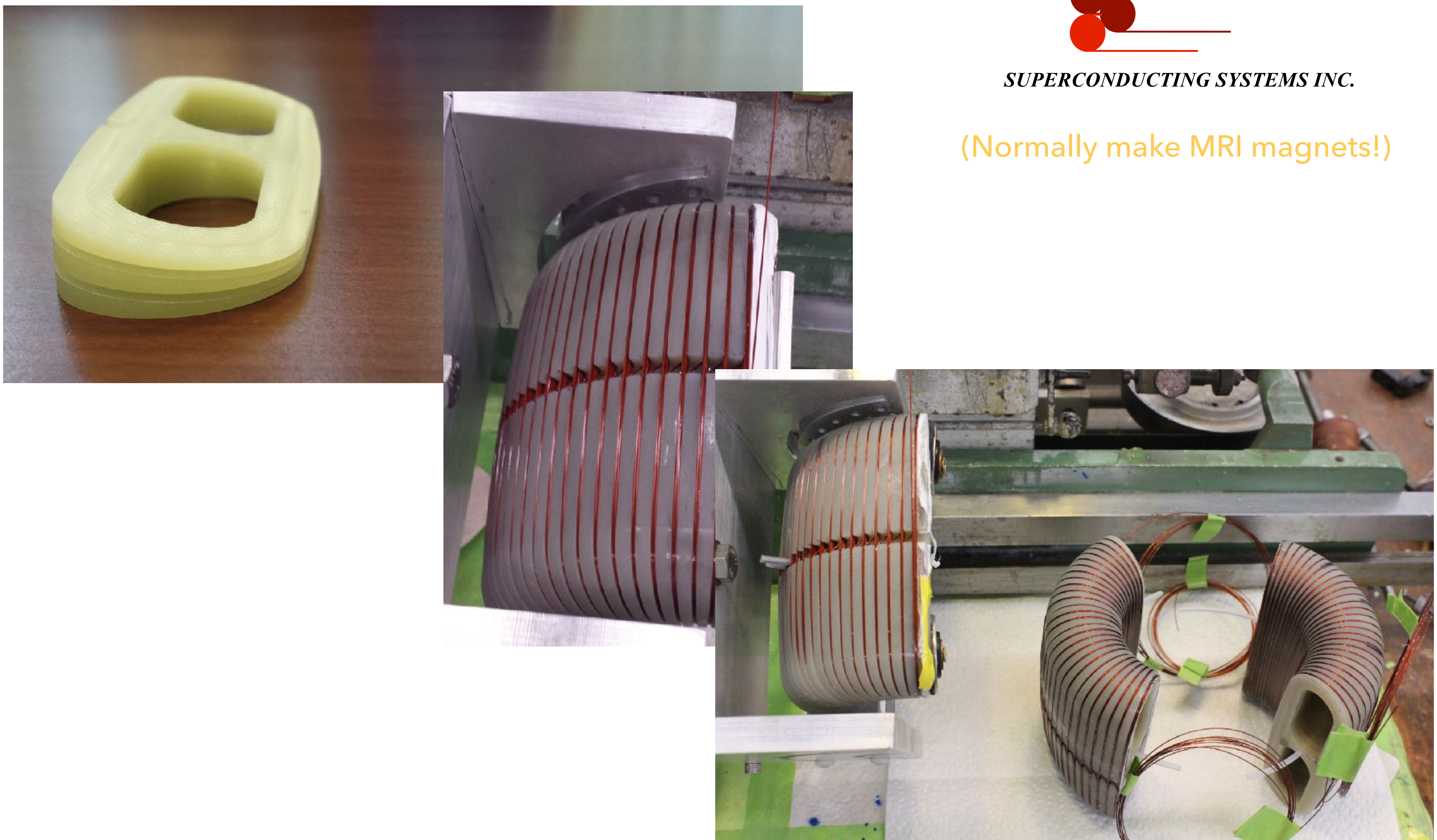


Delrin Toroid Body

Superconducting Calibration Loop
$r_c = 4.5$ cm

80×16 NbTi (CuNi) winds (counter-wound)

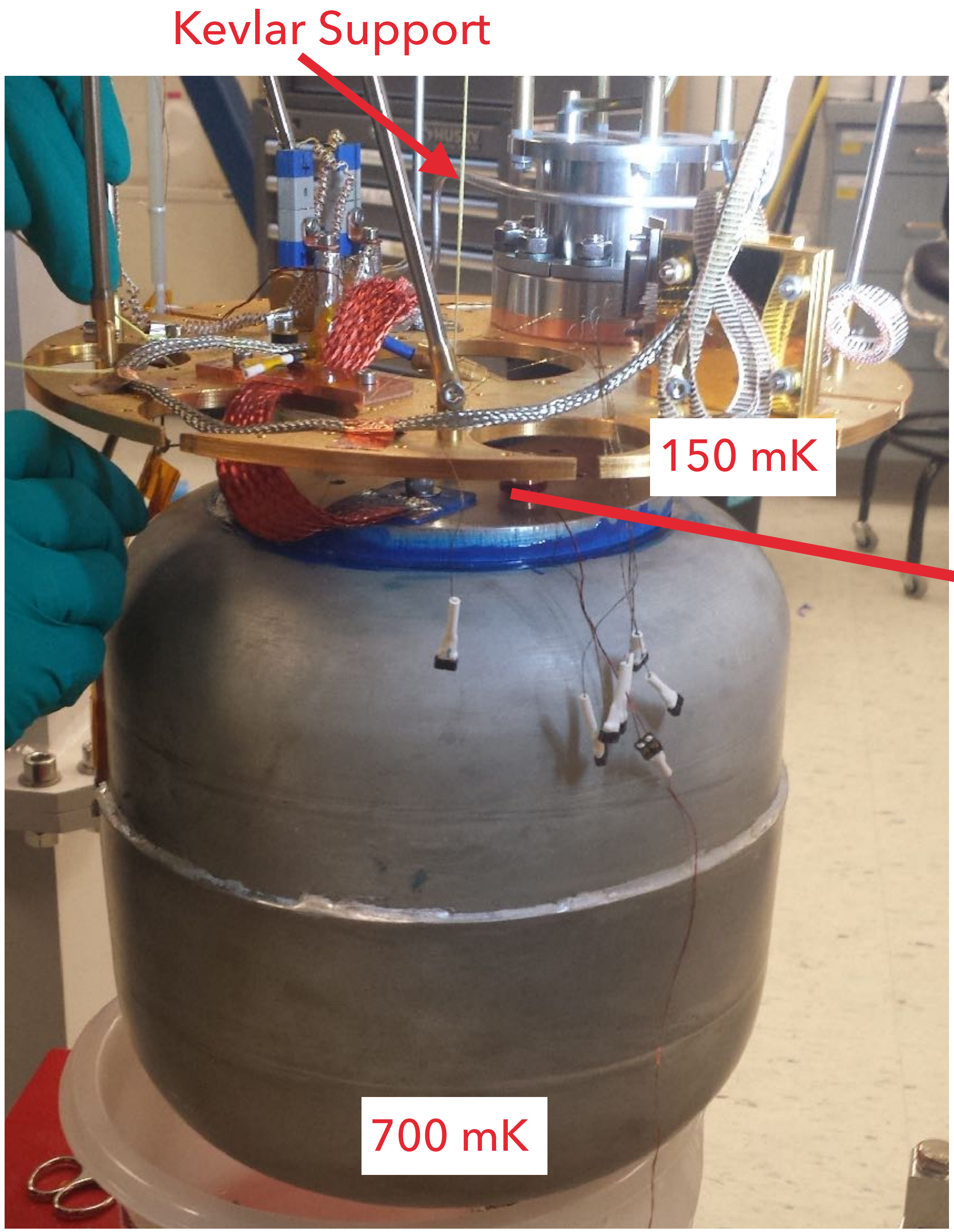
Assembling ABRACADABRA-10 cm

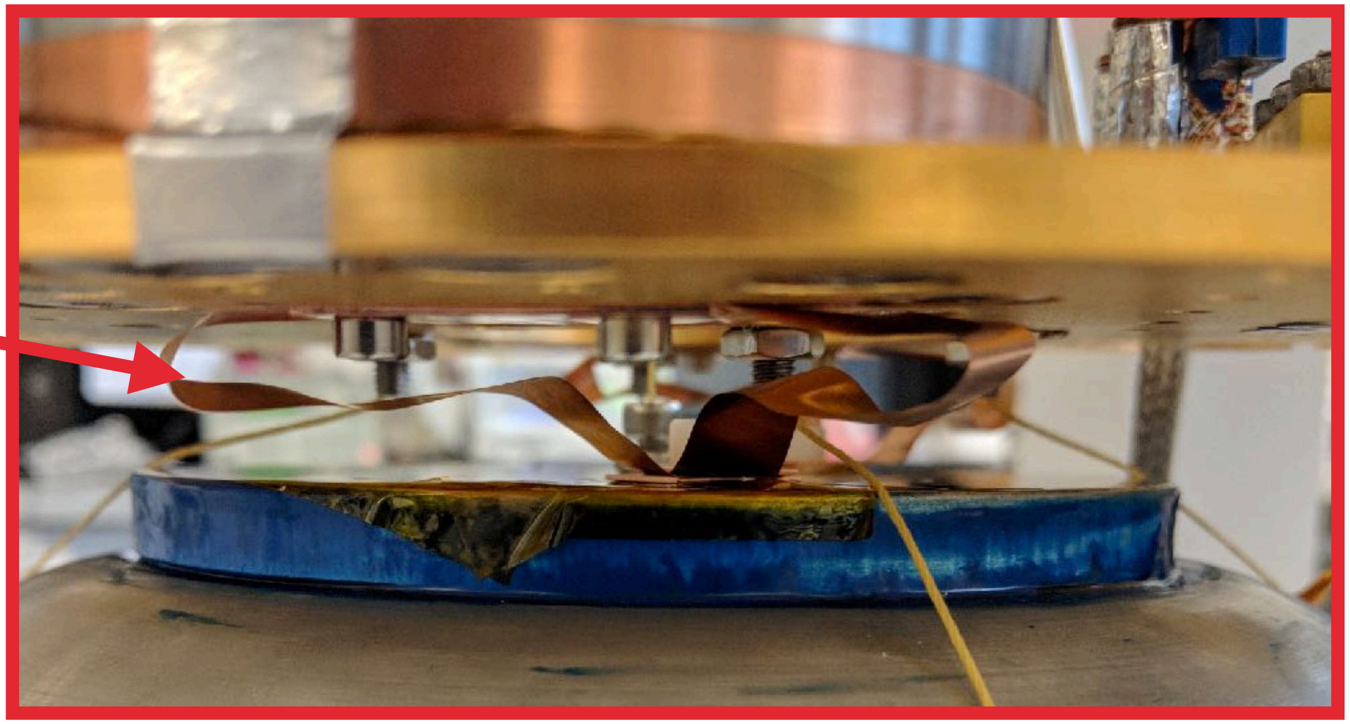


SUPERCONDUCTING SYSTEMS INC.

(Normally make MRI magnets!)

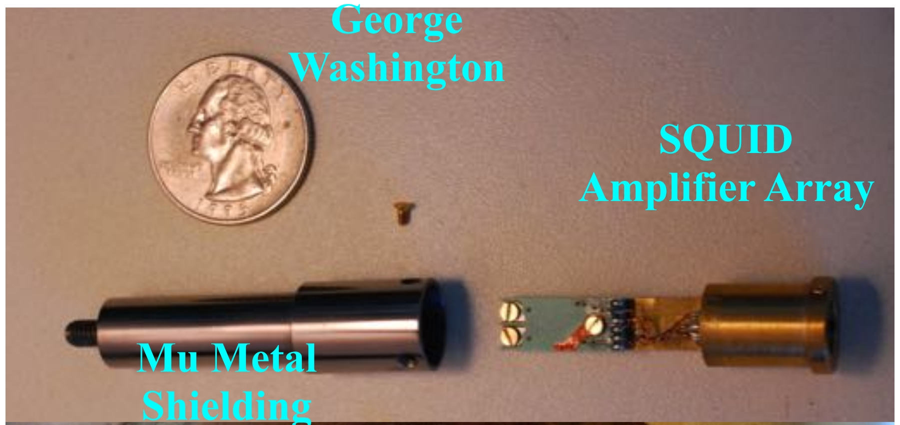
Mounting ABRA

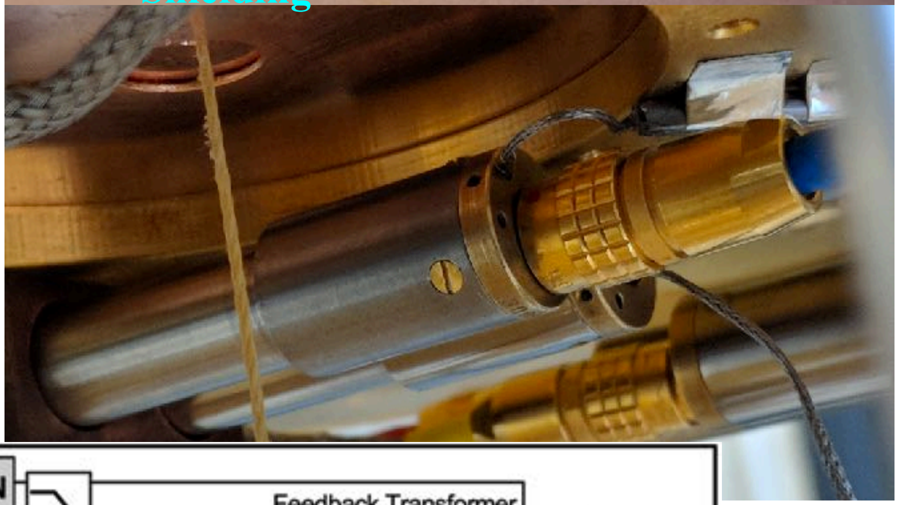


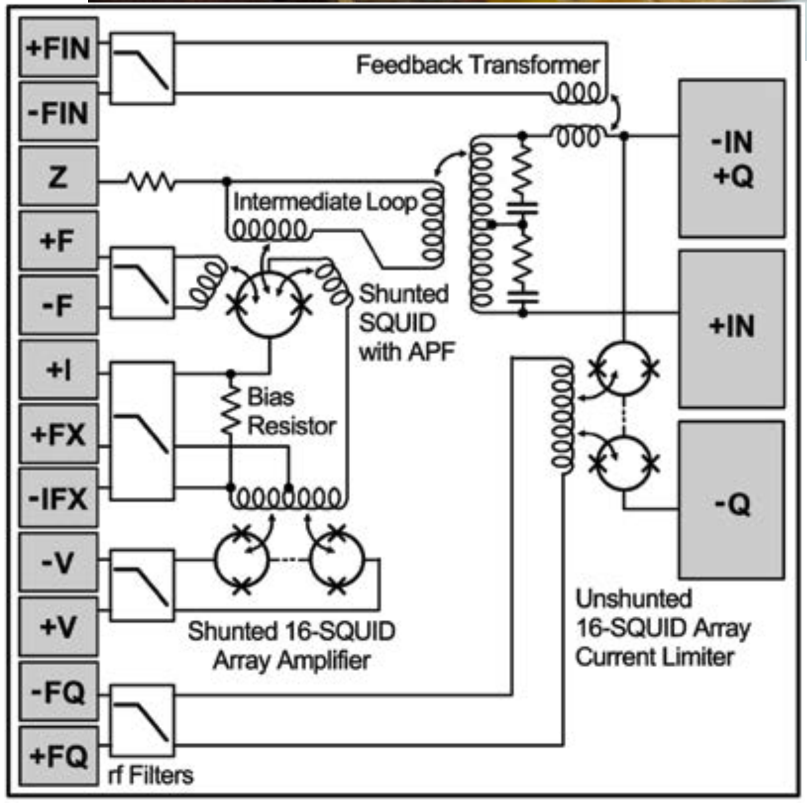


SQUID Readout

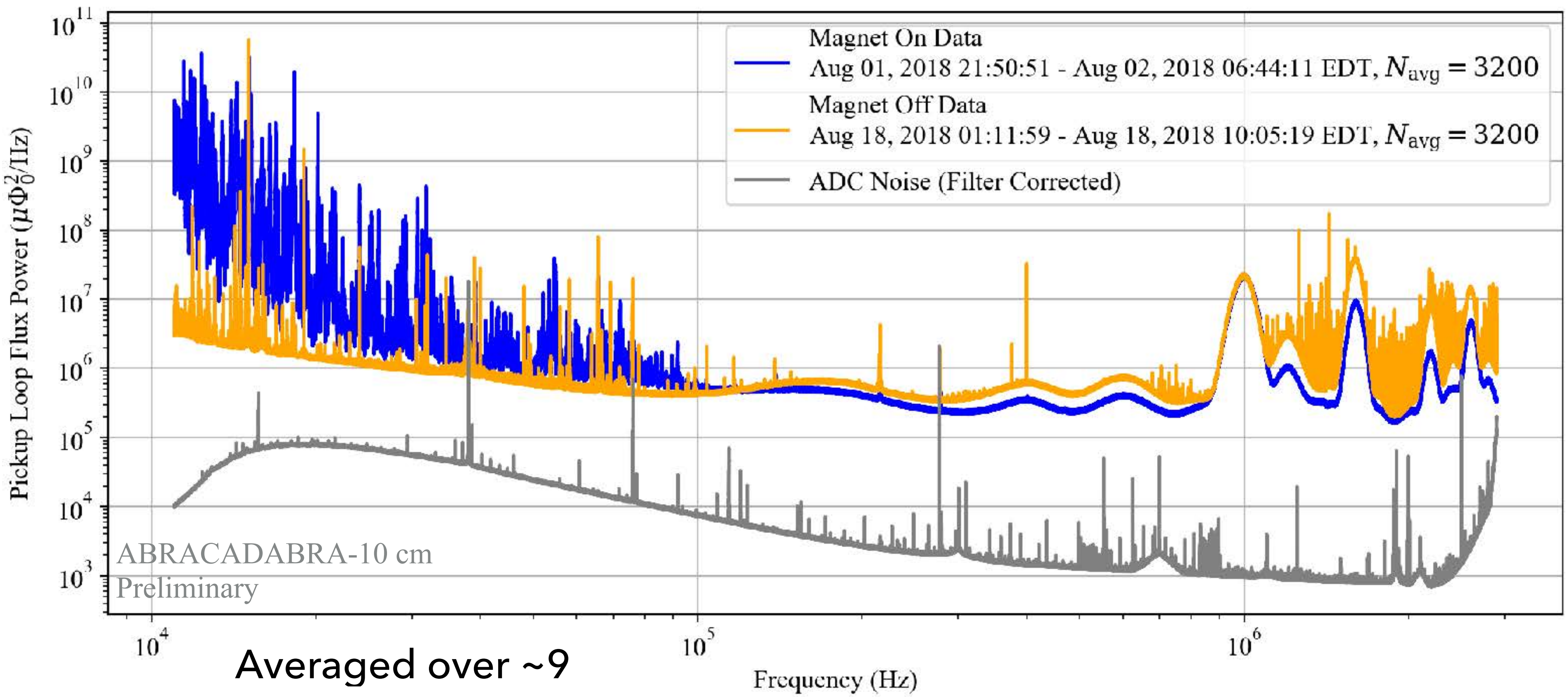
- Off-the-shelf Magnicon DC SQUIDs
  - 2 Stage
  - Typical noise floor ~1 $\mu\Phi_0/(\mathrm{Hz})^{1/2}$
  - Optimized for operation < 1 K
  - Typical gain of ~1.3 V/Φ_0
- No resonator (i.e. broadband readout)





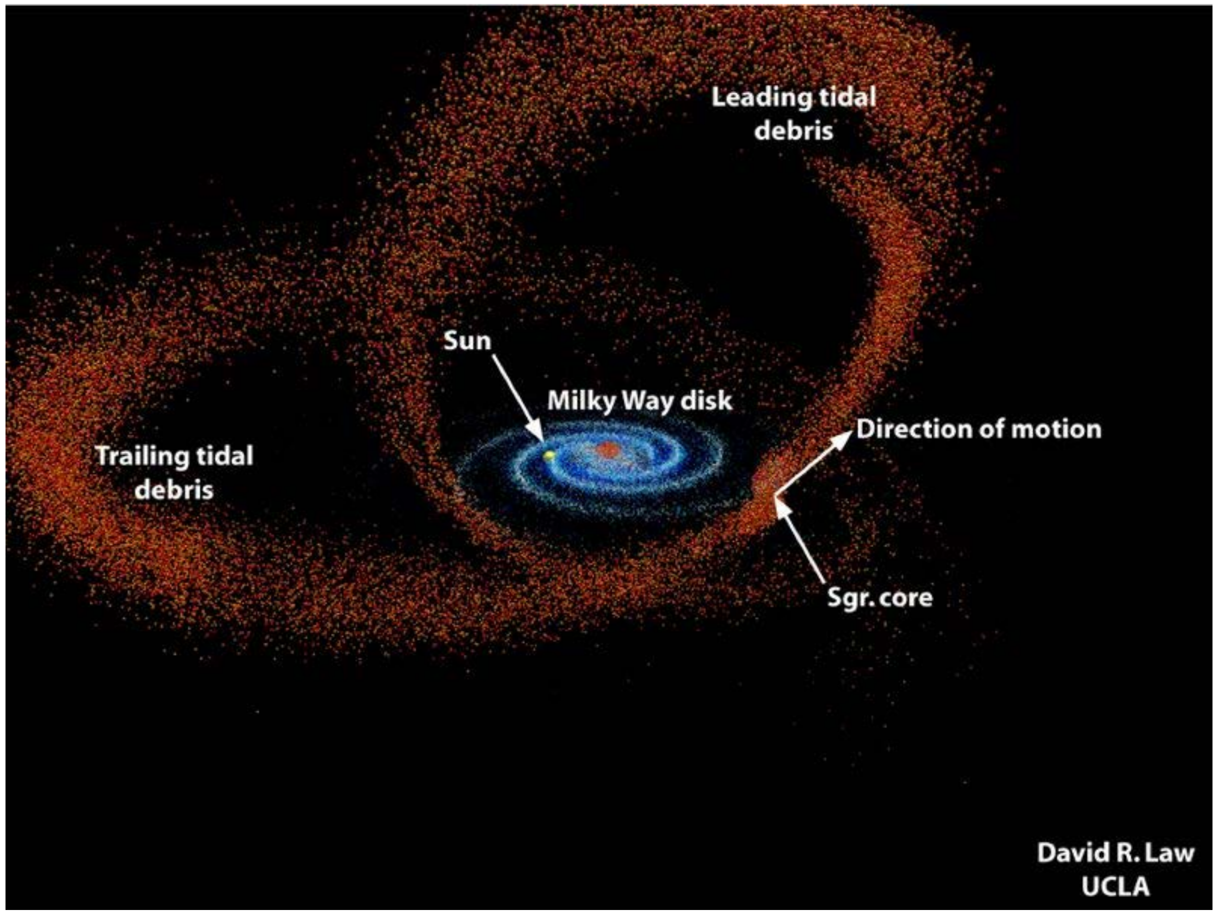


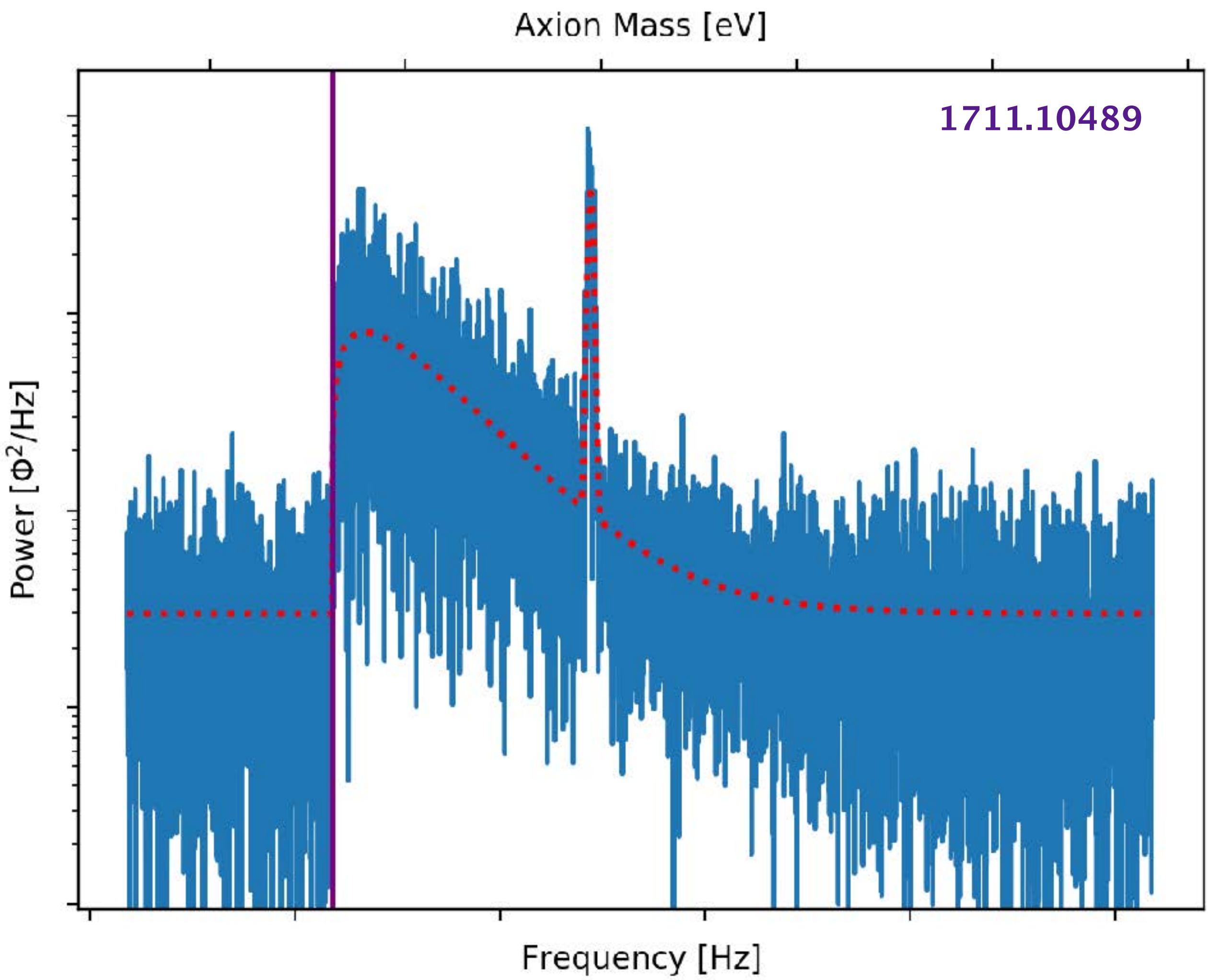
Magnet Off Data



- Collected 2 weeks of magnet off data with the same configuration
- High frequency transient noise also present. Reduced lifetime 30%
- Used for spurious signal veto

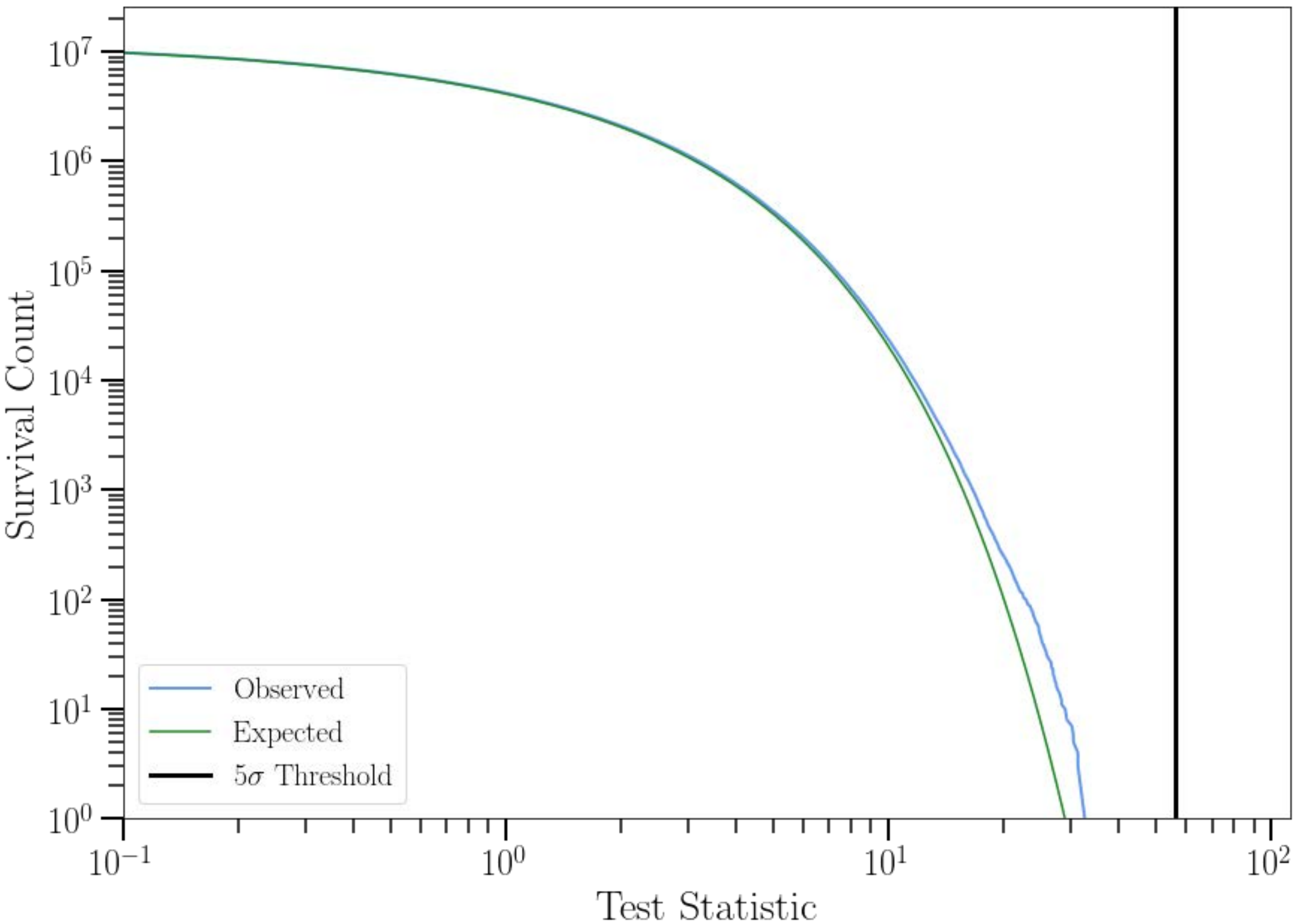
Axion Astrophysics





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.

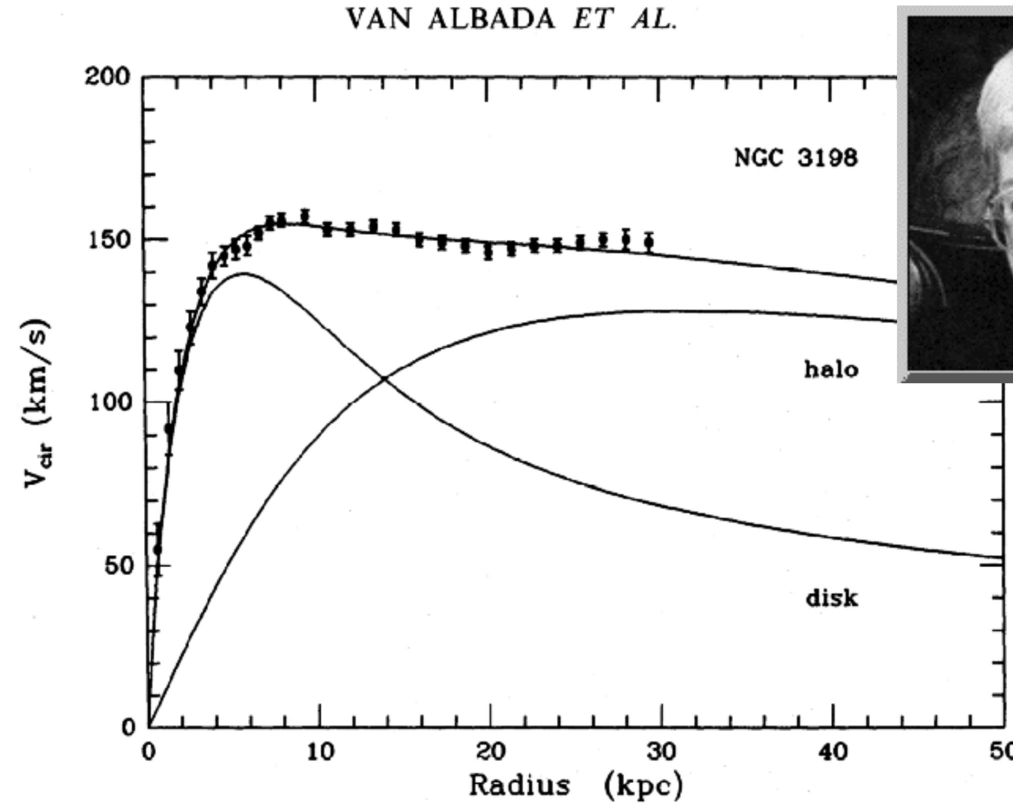


For details, see: PRD 97 (2018) 123006

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