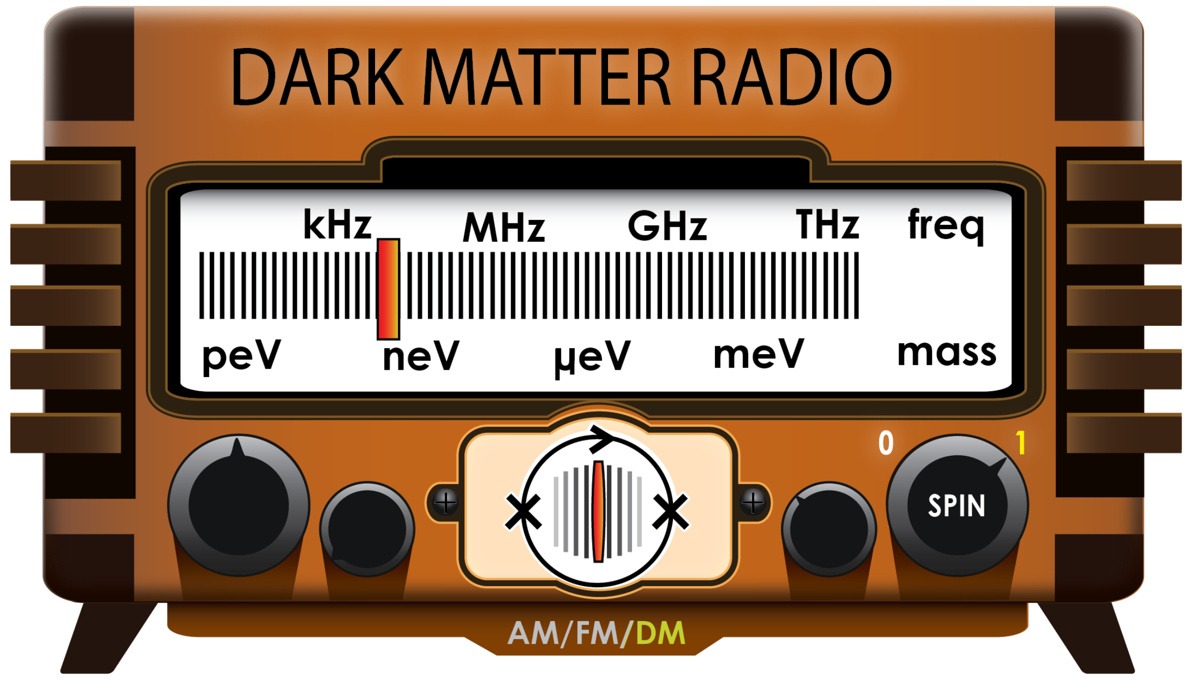


Current Status and Future Prospects of the DMRadio Resonant Lumped Element Axion Searches

Alexander Leder on behalf of the DM Radio Collaboration

CIPANP Meeting 2022

September 2, 2022

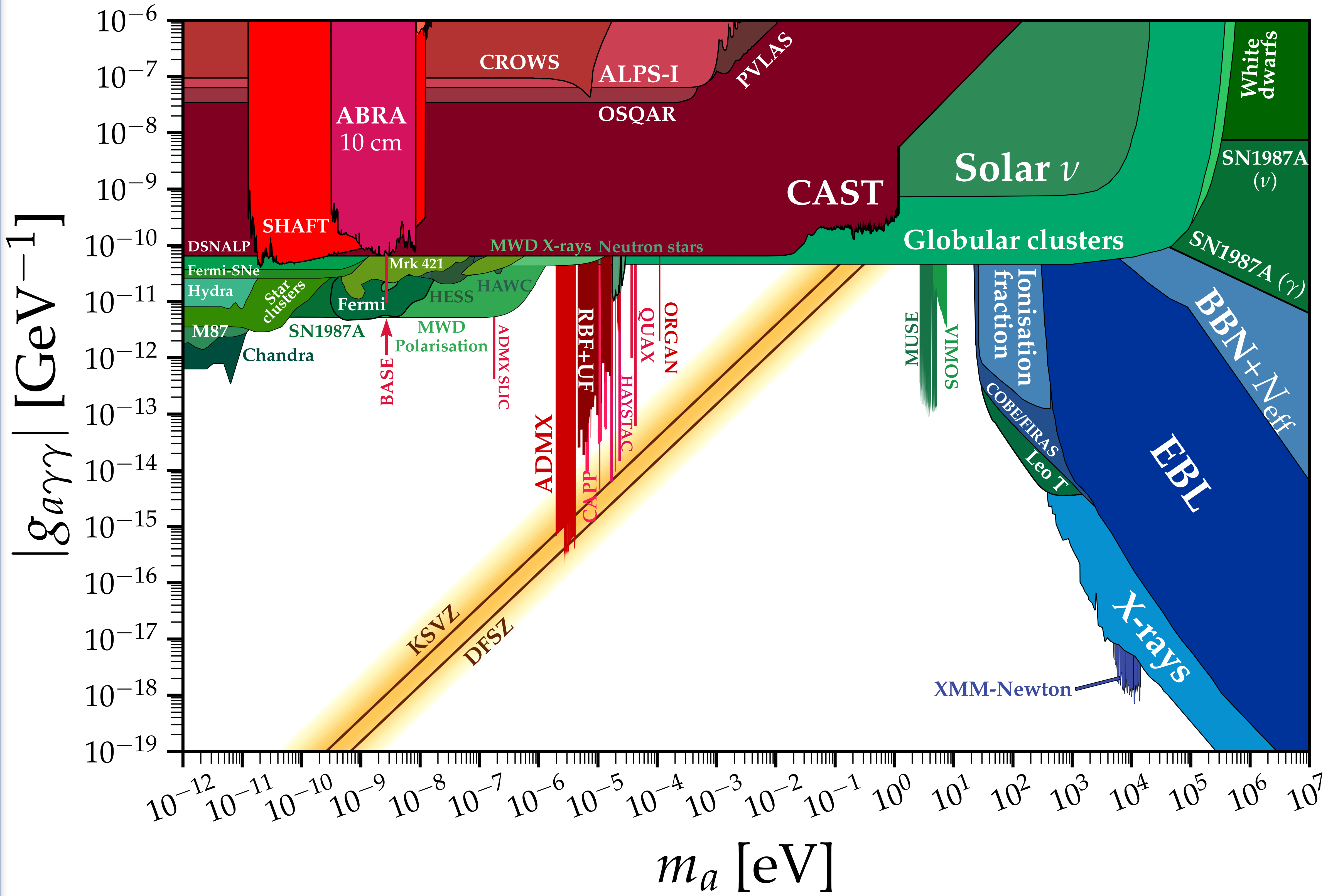
Berkeley Axion Works™

Outline

- Current state of the field
- Overview and status of current DMRadio-efforts - DMRadio-50L
- Overview and status of future DMRadio efforts - DMRadio-m^3
- Conclusion and Outlook

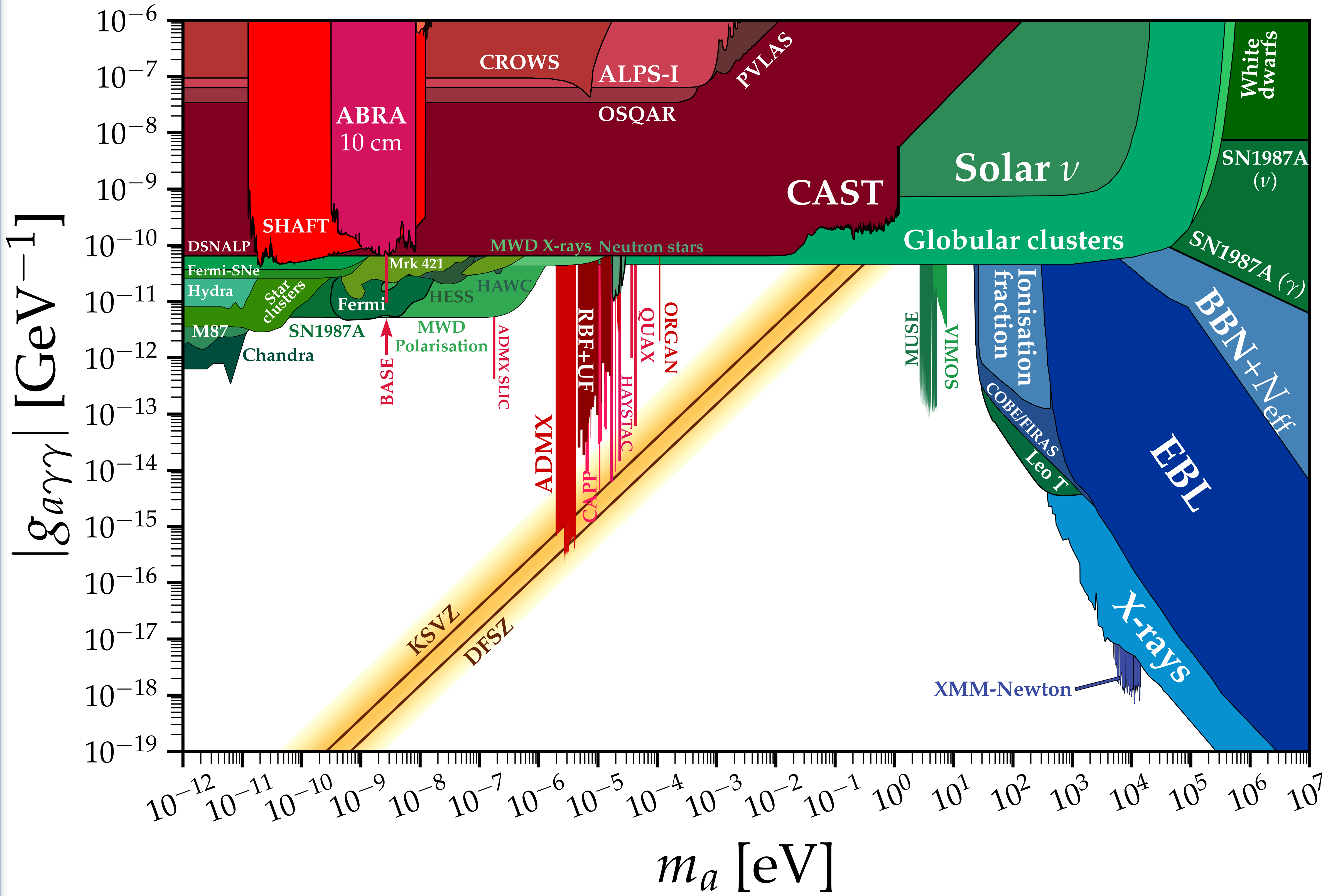
Current State of the Field

- There are over 13 orders of magnitude of mostly unexplored axion parameter space
- Previously, cavity based experiments (ADMX/HAYSTAC/CAPP/ORGAN/QUAX) have only probed a very narrow sliver of the total parameter space in the ~1 GHz range
  - Frequency range limited by cavity geometries
- Other experimental techniques required in order to probe other frequencies/masses



Current State of the Field

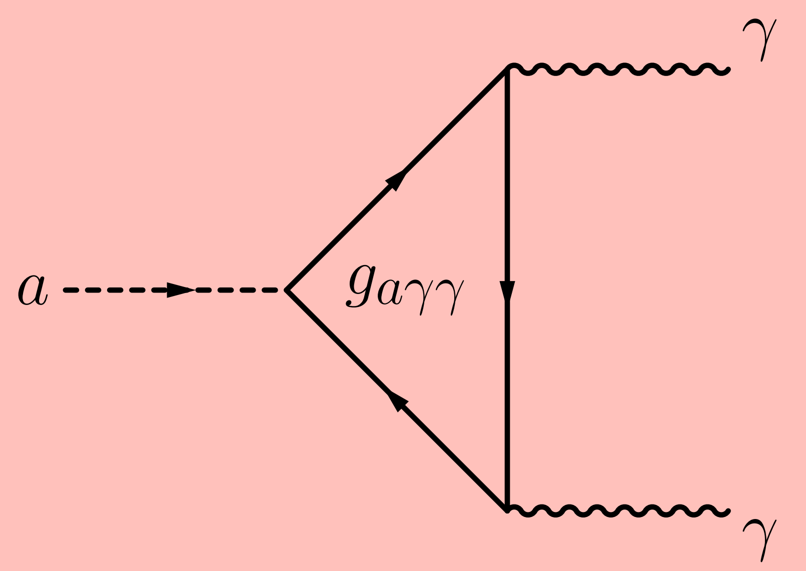
- There is no single preferred mass target for the axion
- We need to cover as many possible masses as possible
- We have divided up the axion field into two regions, a low mass (pre-inflation) and a high mass (post-inflation) region
  - Each region can be best probed with different techniques



Axion as Dark Matter Candidate and Axion E&M

- We treat the axion as a wave instead of an individual particle
  - If the axion mass were 1 neV then for a local DM Density given as ~0.4 GeV/cm^3 this gives a total axion number density close to 1e17 axions/cm^3 !
  - We are looking for a coherent signal across our entire detector
- The physical signal we are looking for is generated through the quantum Primakoff effect
- However; we can rewrite this quantum effect as a modification to Maxwell's wave EM equations with J_{eff} as an effective axion current induced in the presence of a magnetic field
- Our experiments seek to couple to J_{eff} as effectively as possible in order to detect the axion

Quantum Picture



Classical Picture

$$\nabla \cdot \mathbf{E} = -g_{a\gamma\gamma}\mathbf{B} \cdot \nabla a$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} - g_{a\gamma\gamma}\left(\mathbf{E} \times \nabla a - \frac{\partial a}{\partial t}\mathbf{B}\right)$$

$$J_{eff} = g_{a\gamma\gamma}\partial_t a\mathbf{B} \approx g_{a\gamma\gamma}\sqrt{2\rho_{DM}}cos(m_a t)\mathbf{B}$$

DMRadio Family of Experiments

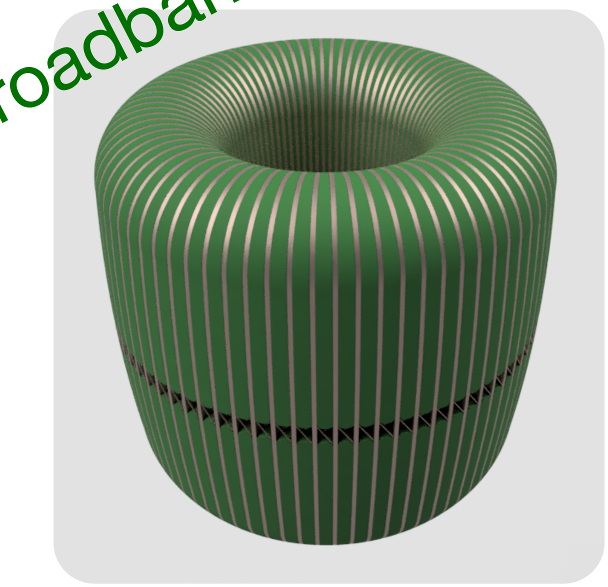
- DMRadio family of experiments compasses four separate experiments
- DMRadio-50L experiment is being optimized from the ground up to search for the axion at the some of the lowest frequencies assessable to lumped-element experiments
- DMRadio-m³ will build upon the experience of DMRadio-50L and seeks to search for the axion in the frequency space between DMRadio-50L and cavity experiments
- Design study funded as part of the DOE Dark Matter New Initiatives program

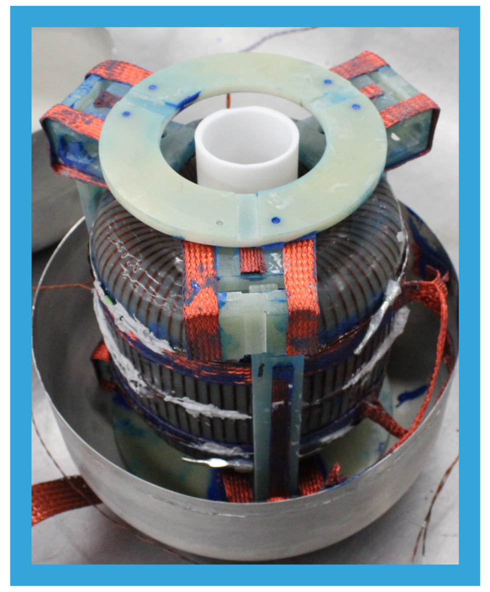
ABRACADABRA

Running

DMRadio-Pathfinder

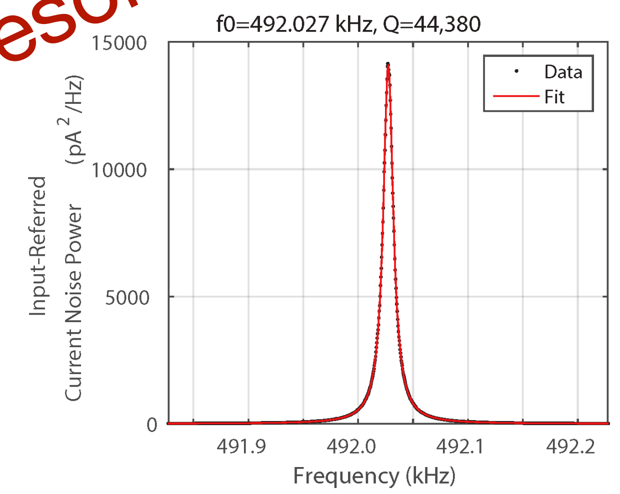
Broadband





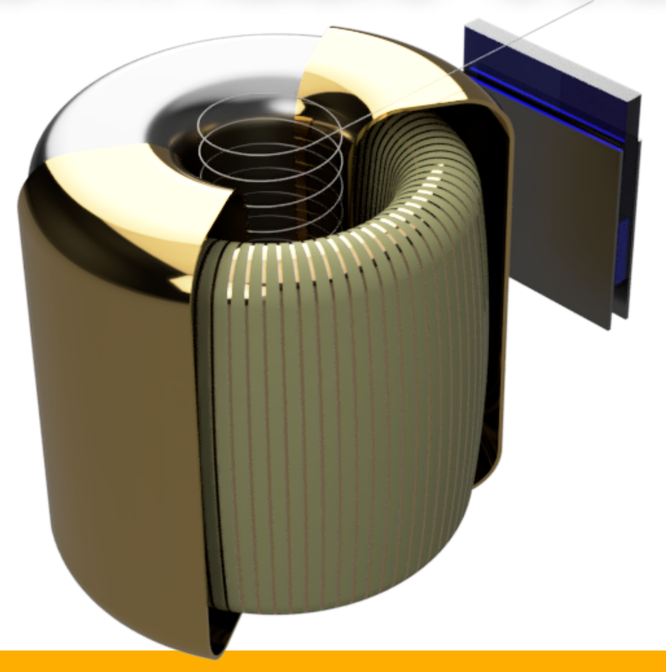
- PRL 122, 121802 (2019)
- PRD 99, 052012 (2019)
- PRL 127, 081801 (2021)

Resonant



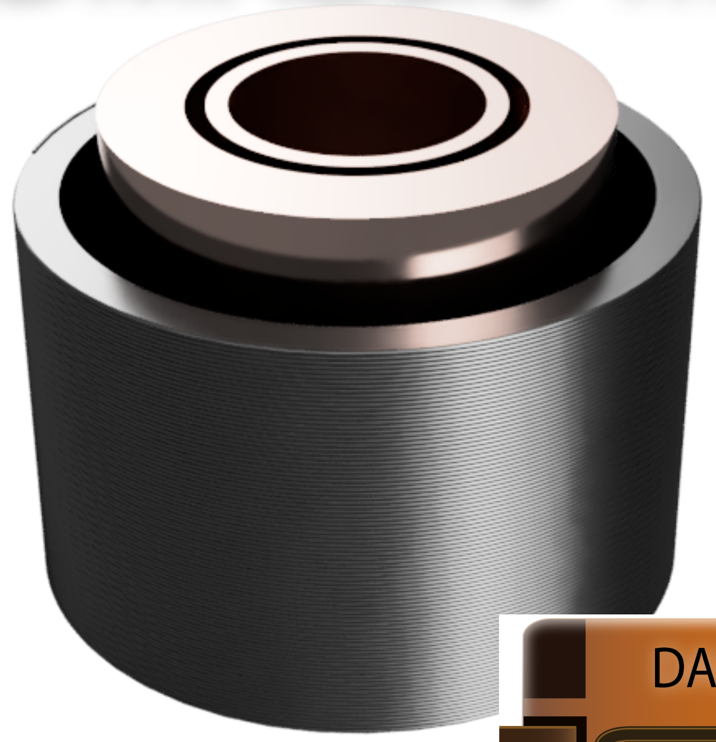
- IEEE Trans. on Appl. Superc., 27, 1(2016)

DMRadio-50L

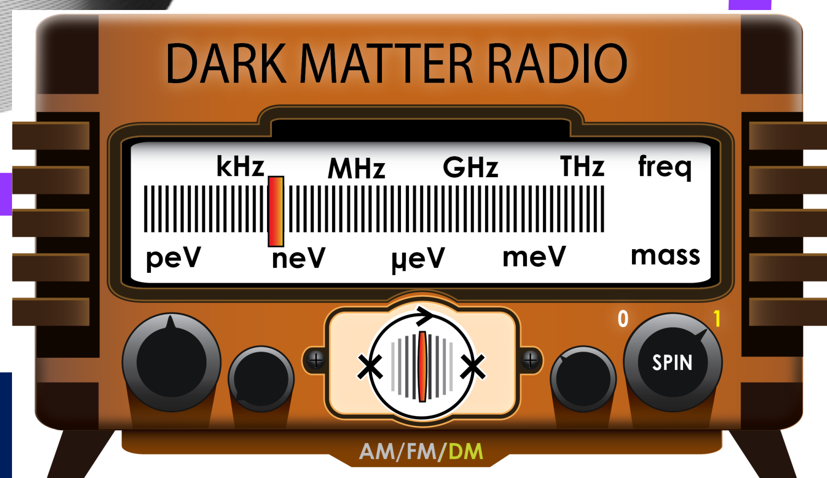


Beginning Construction

DMRadio-m³



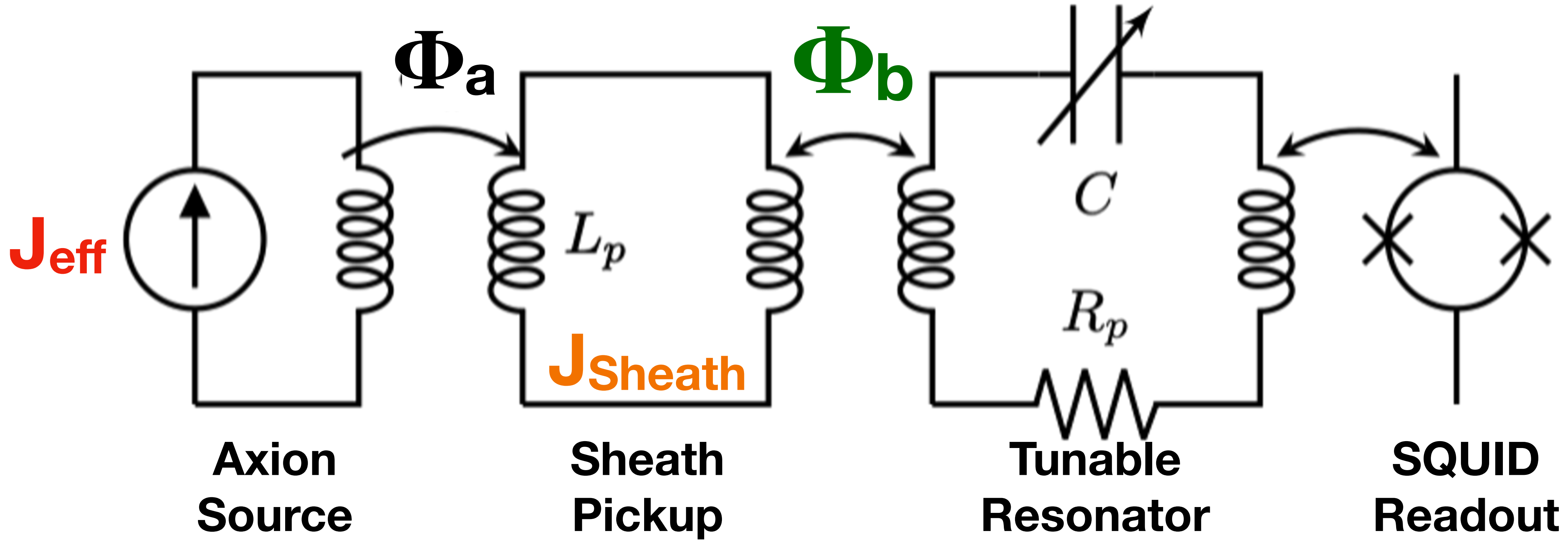
Future

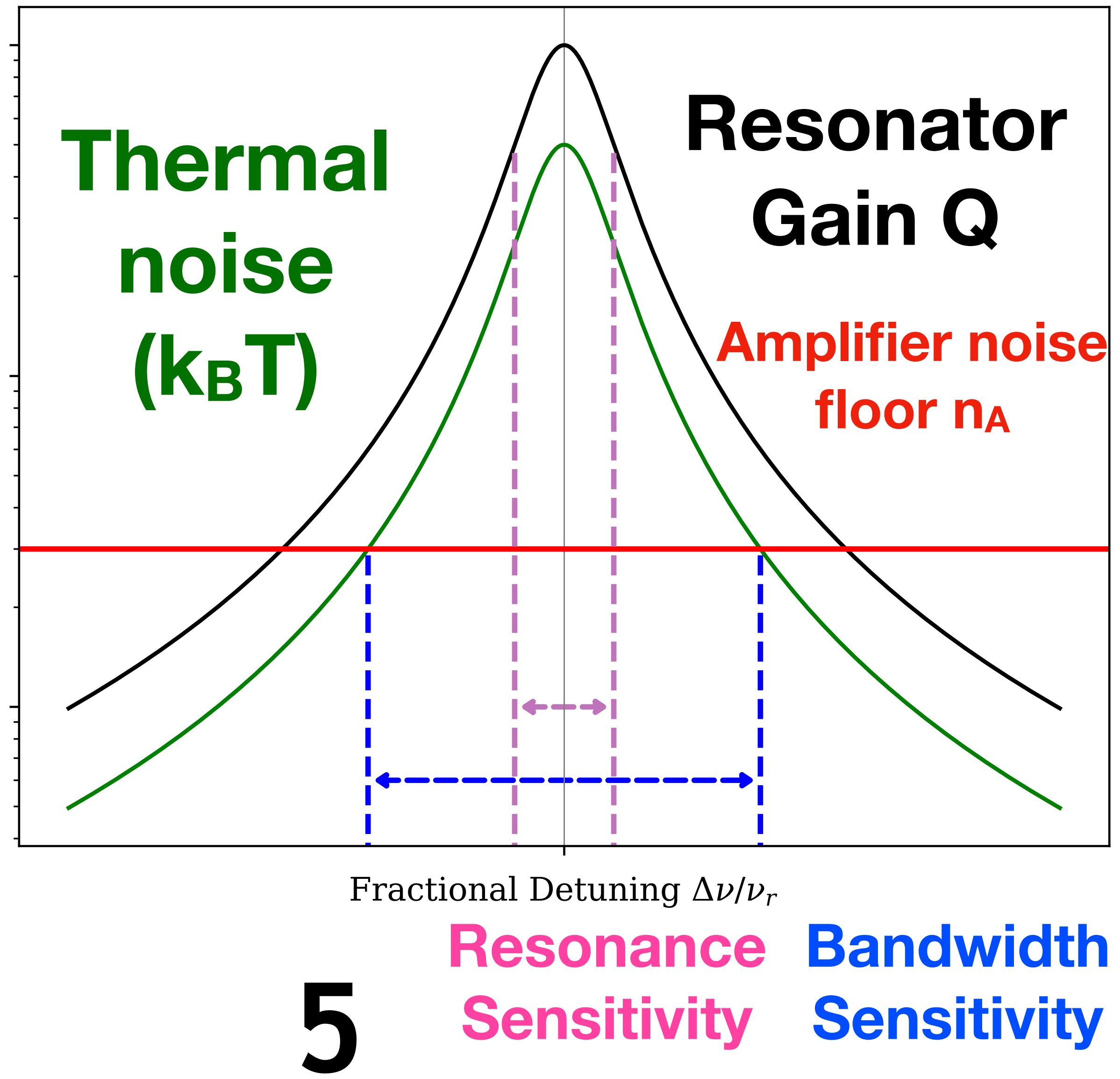


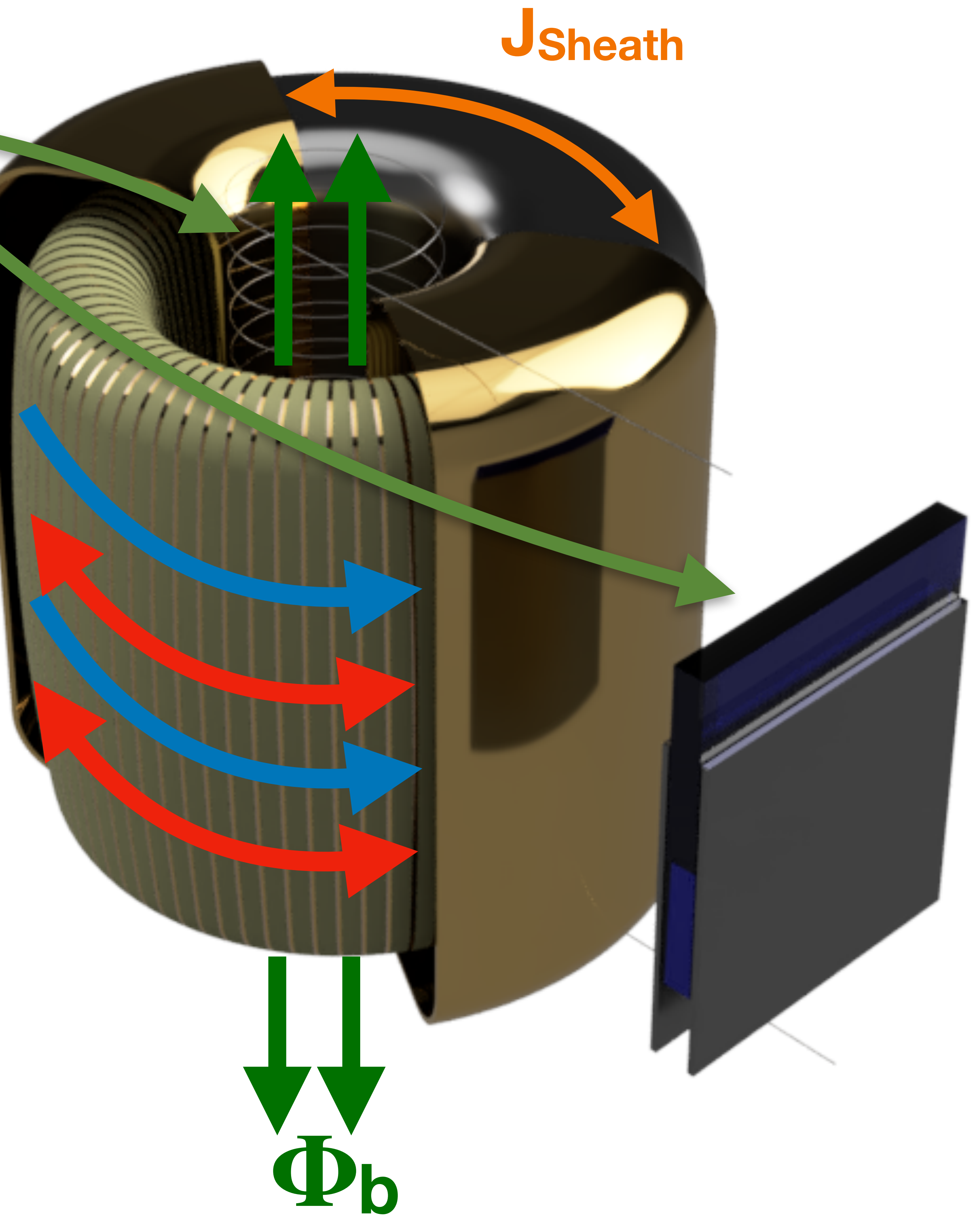
DMRadio-50L

DMRadio-50L Signal Pickup

- The axion signal is inductively coupled to our SQUID readout passing through the sheath and tunable resonator
- We optimize for the width of the bandwidth sensitivity not the resonance sensitivity
- We can write this detector out as an equivalent lumped element circuit design

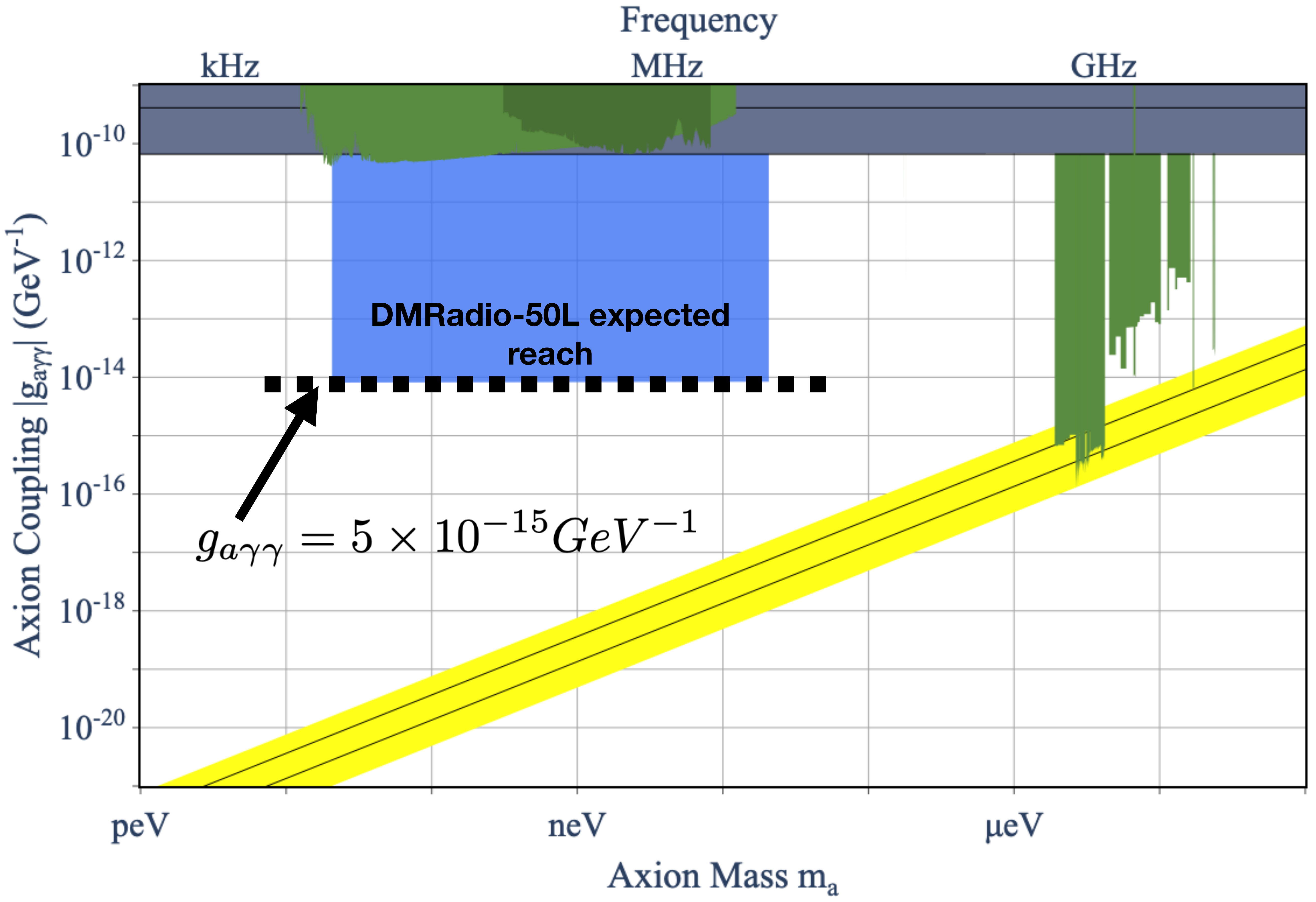






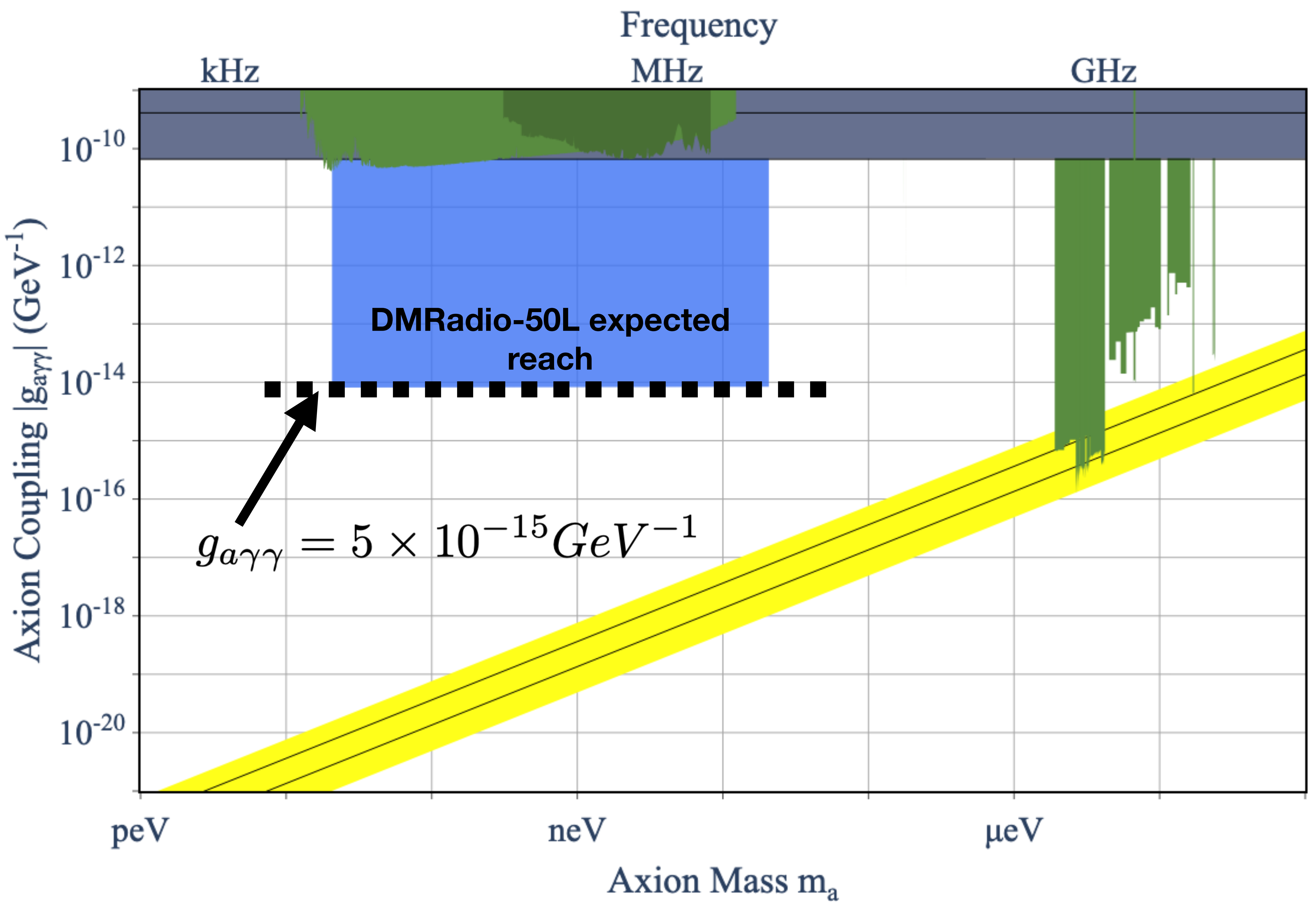
DMRadio-50L Region of Interest

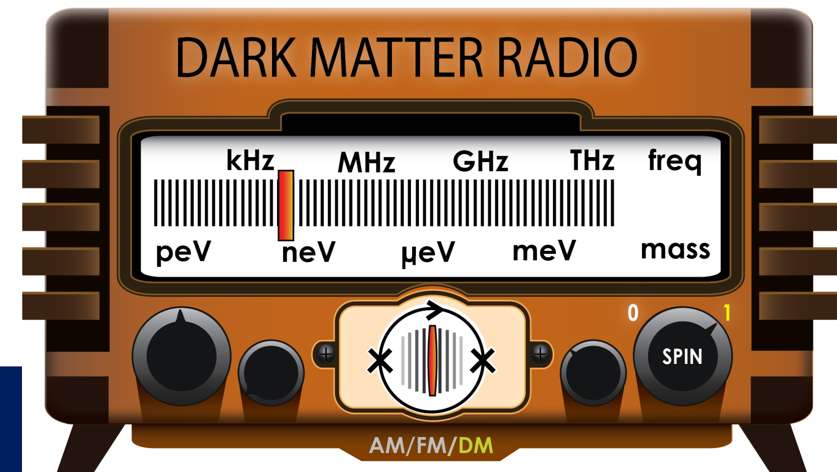
- DMRadio-50L region of interest lies between 20 peV and 20 neV (5 kHz - 5 MHz)
- This drives the overall design campaign of the DMRadio-50L experiment
- Design still has to be feasible and satisfy real world requirements



DMRadio-50L Experiment Goals

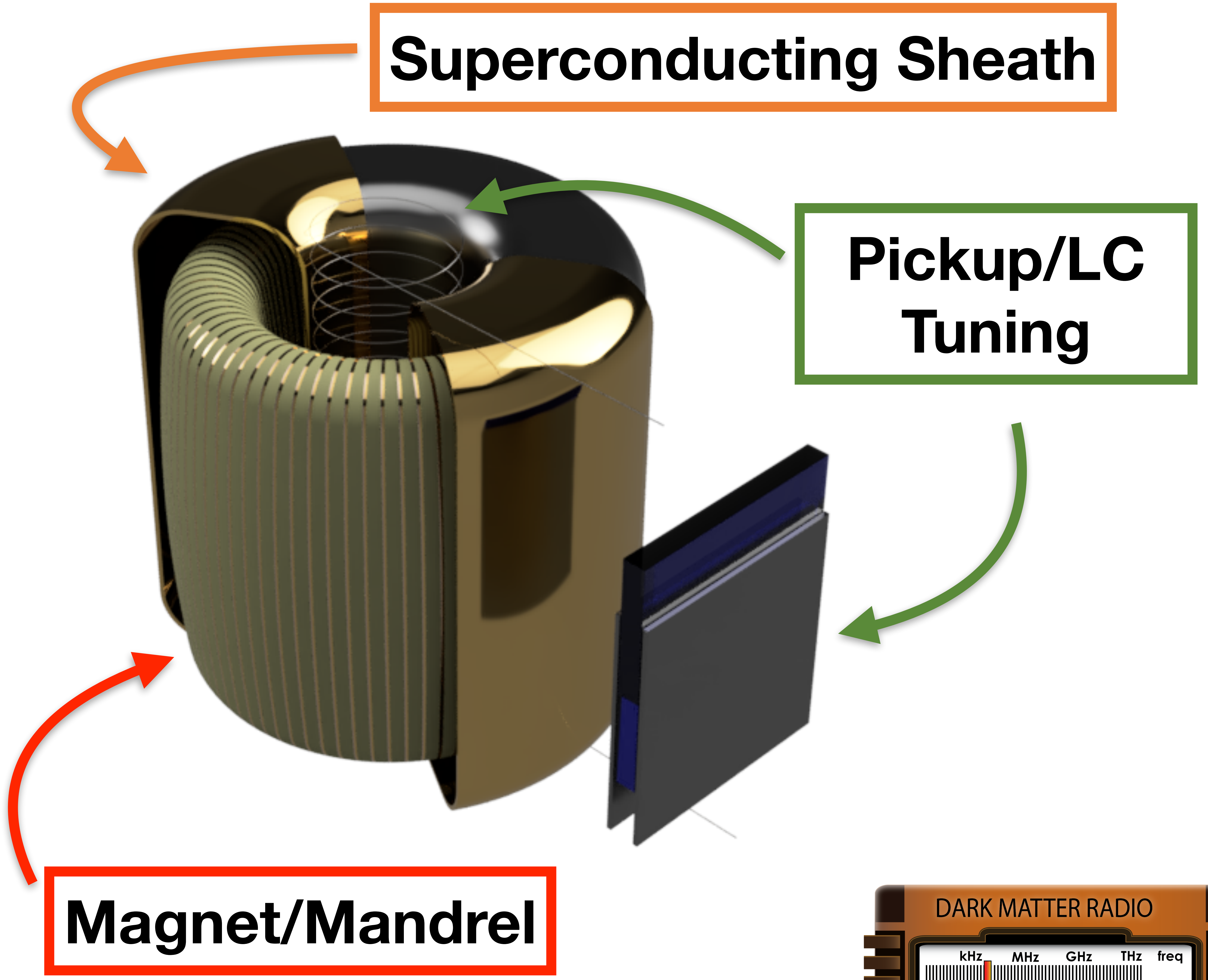
- DMRadio-50L is designed with three main goals in mind:
  - First resonant search for ALPs below 1 μeV
  - Fully optimized experiment from the ground up
  - Physics search over an interesting parameter space for multiple theory models

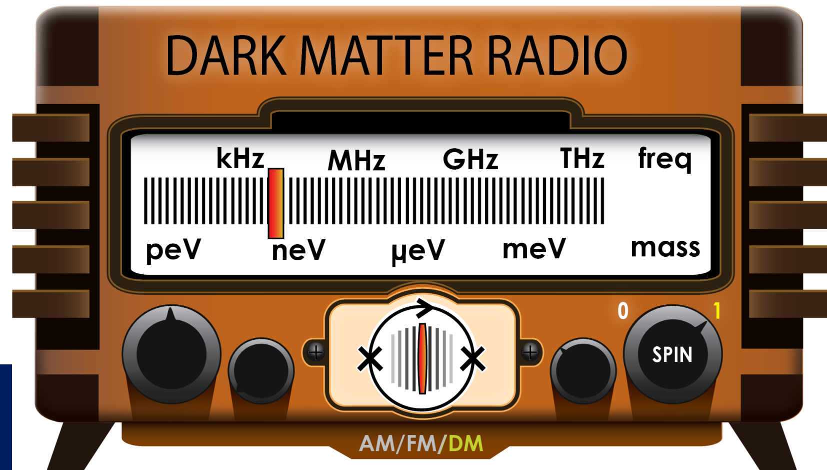




DMRadio-50L Experimental Design

- At these lower masses/frequencies we opted to go with a toroidal experiment
  - Good control of fringe fields
  - Pickup loop is naturally in a low-field region
  - Previous small scale experiments have already shown the potential for high Q's
  - Draw upon ABRA experience
  - Nb sheath shields any lossy elements and allows for signal currents to flow along outside of detector
- Design campaign focused on optimizing all components from the ground up

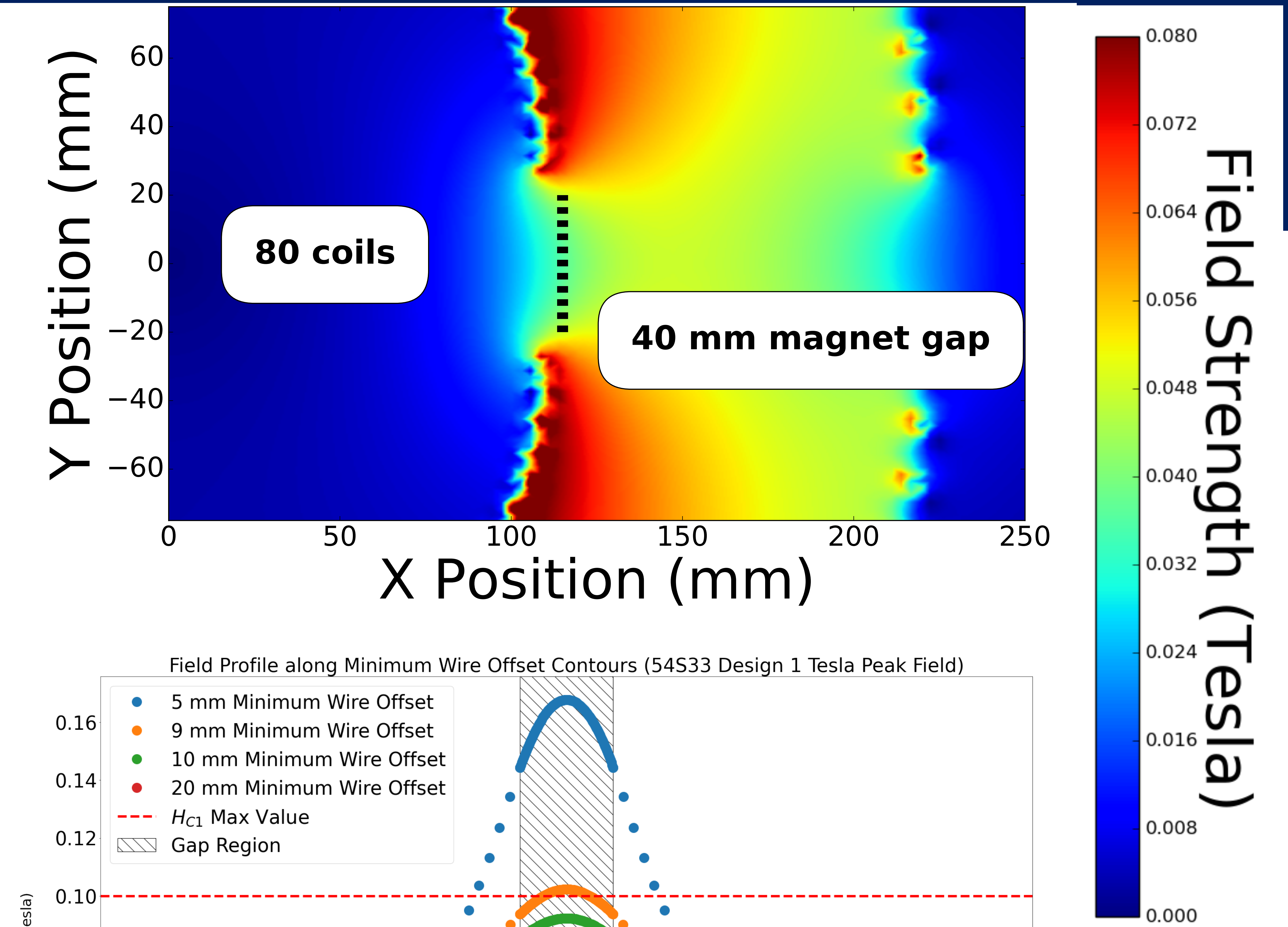


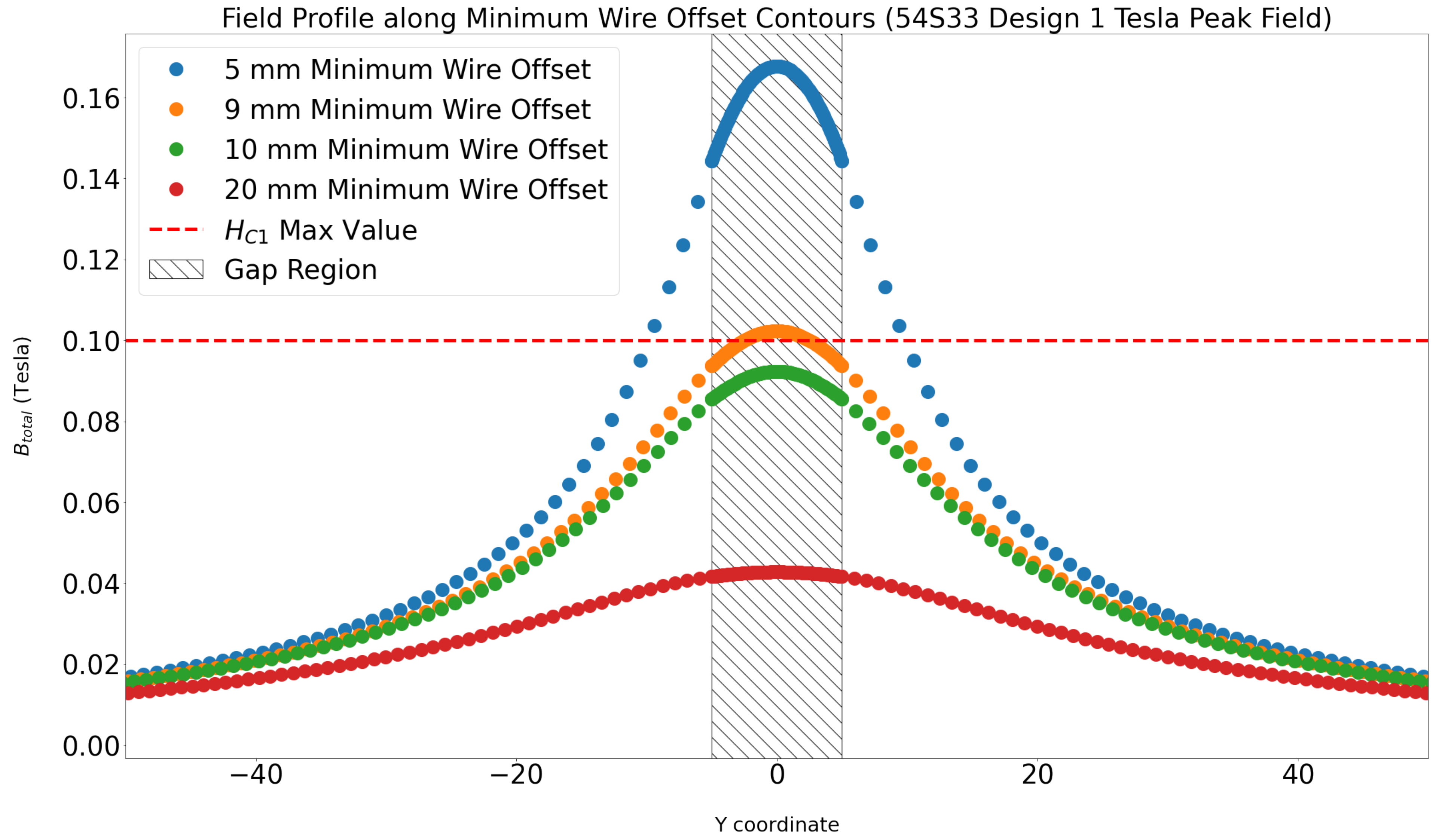


Magnet Design

Parameter	Design Goal
Peak Field	~0.1 Tesla
Max Fringe Field	100 mTesla
Science Volume	50 Liters

- Stray fields must be kept low to avoid driving superconducting components normal
- Potential for operation at higher fields
- Magnet design finalized and being sent out for construction





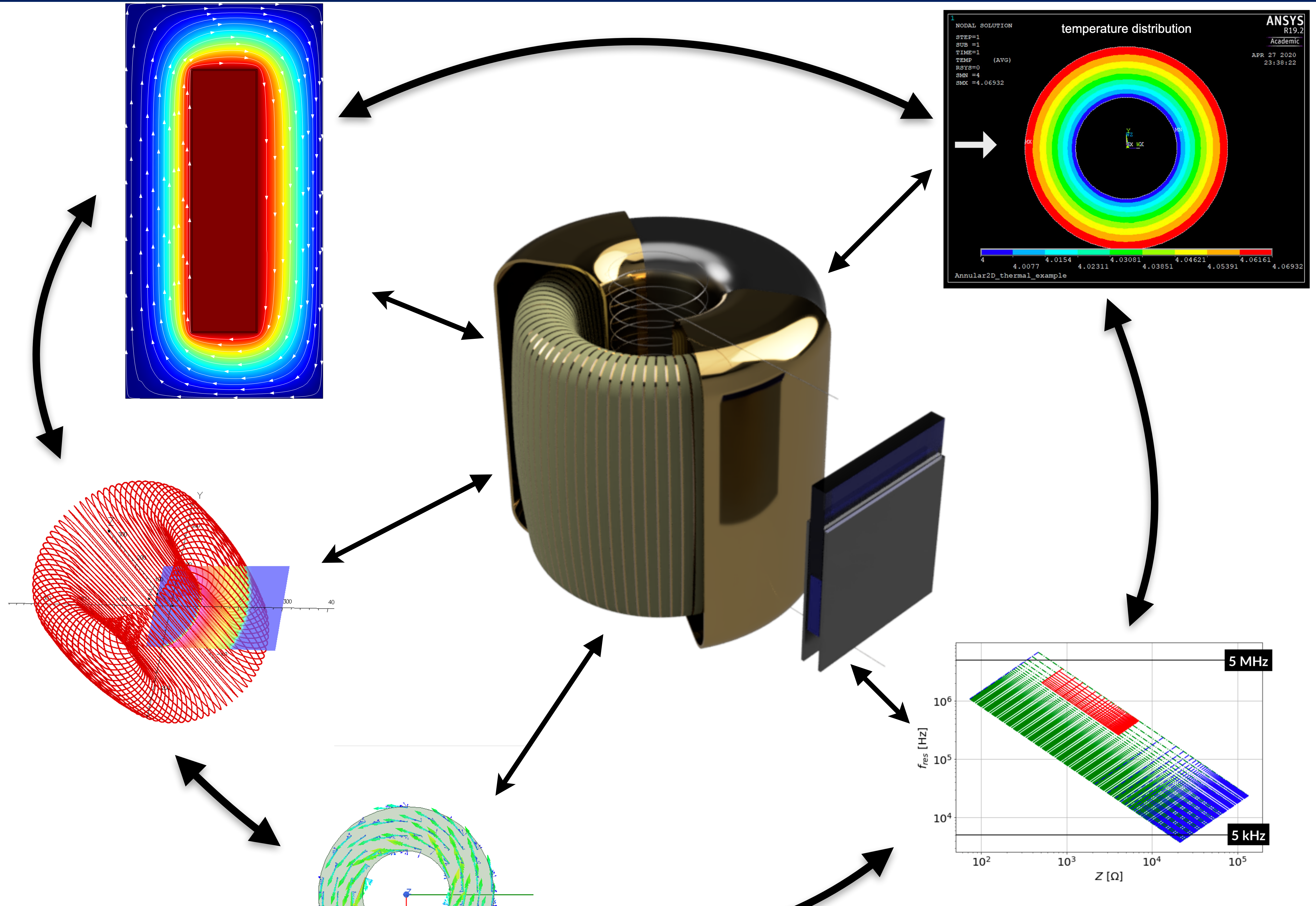
Fringe field profiles along gap

Optimization Campaign

- The DMRadio-50L optimization campaign has multiple components that all have to be simultaneously co-optimized

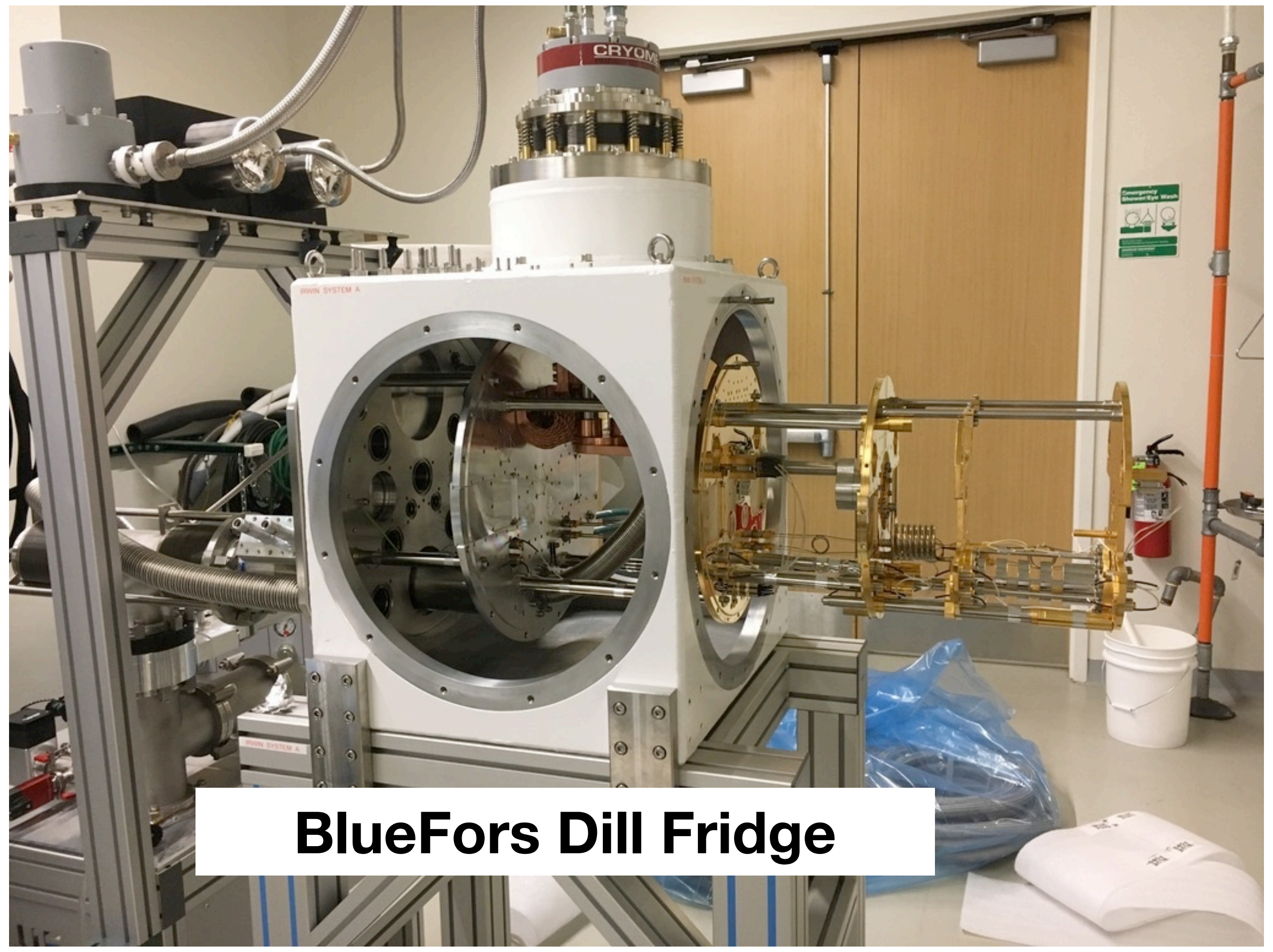
- This is an iterative process, where individual calculations build upon each other

- Experience will inform m³ design as well



Current Status of DMRadio-50L

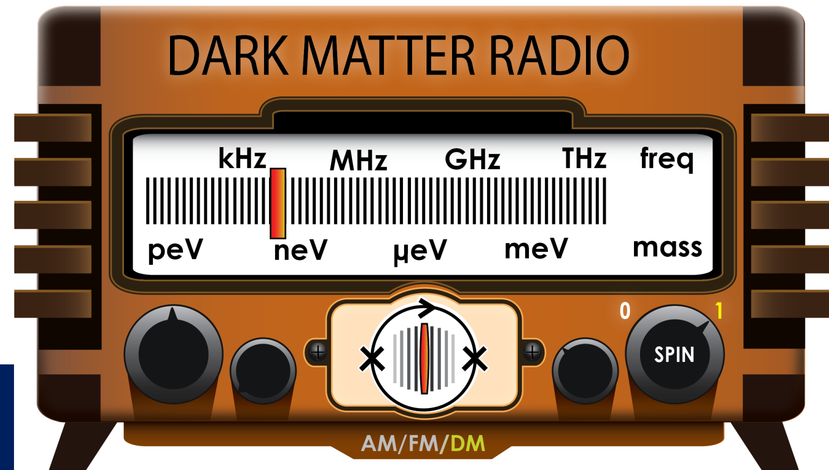
- Construction has begun on the individual components of DMRadio-50L
  - Dill Fridge installed at Stanford
  - Magnet being manufactured by SSI
  - Cyrostat/Sheath design for experiment being finalized
- Experimental verification of simulations/ final design studies will take place over this year
- Data taking scheduled to take place in ~ 2023



BlueFors Dill Fridge

Cryostat goes here!

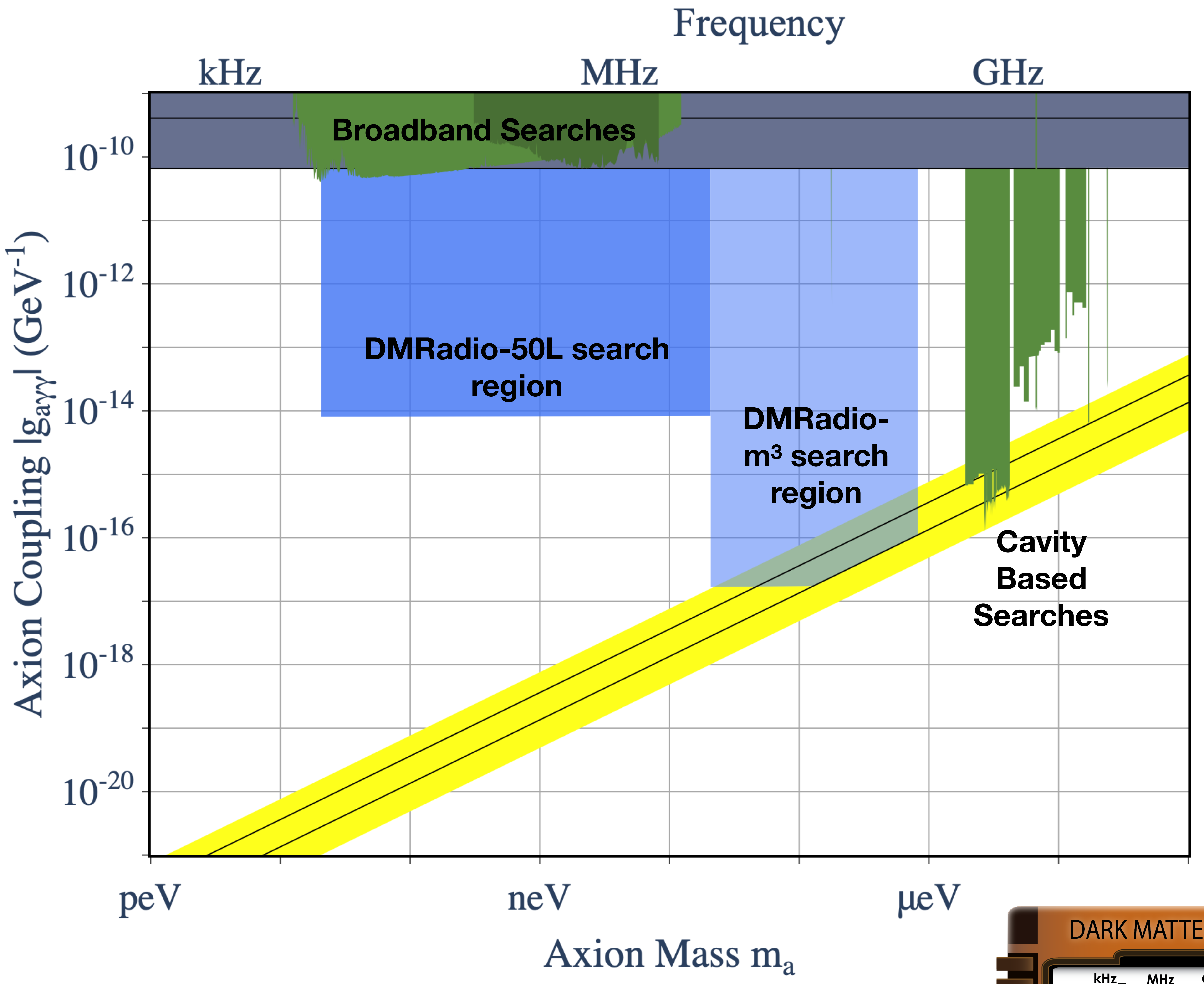
Sheath Design being finalized

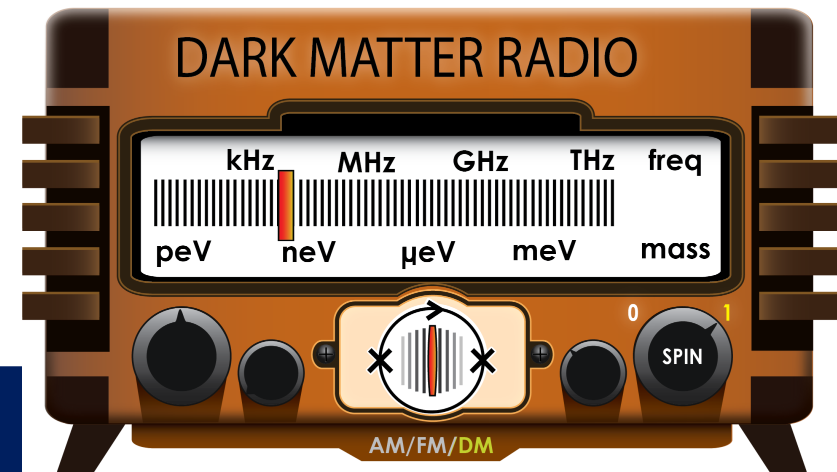


DMRadio-m^3

DMRadio-m³ Experiment Goals

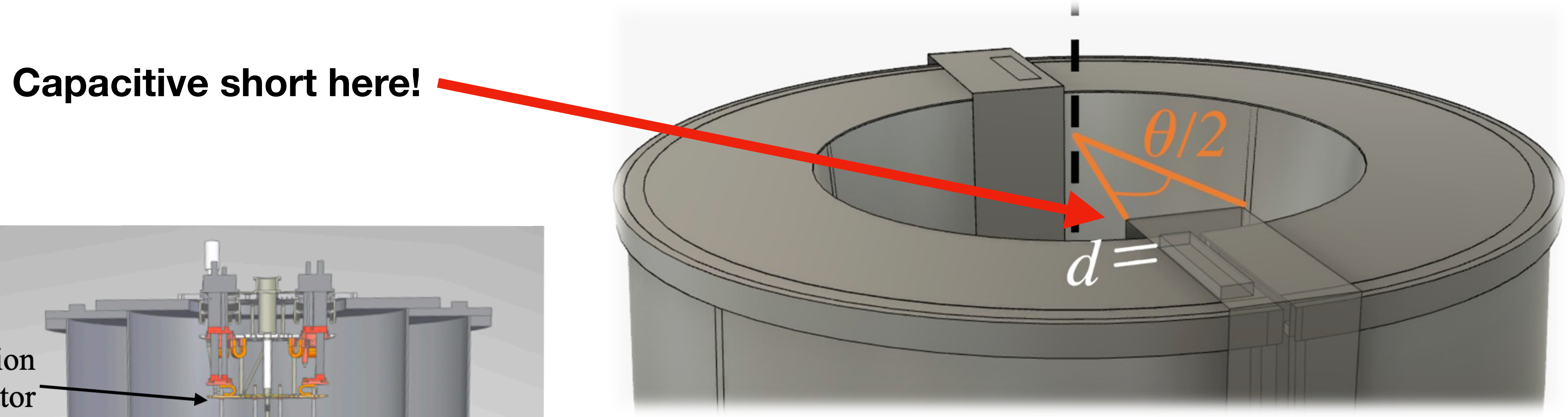
- DMRadio-m³ is optimized to probe for axions at in the frequency range (20 neV < ma < 800 neV (5 MHz < ν_a < 200 MHz)
- DFSZ axion sensitivity above 100 neV / (30 MHz)
- Target Experimental Parameters:
  - B field: 4.3 T
  - Active Volume: 1.25 m³
  - Resonator Q: 1.5e5
  - Target Noise Temperature: 20 mK
  - SQUID noise parameter: 20xSQL
- Total scan/run time: 5 years with data taking to start in 2026

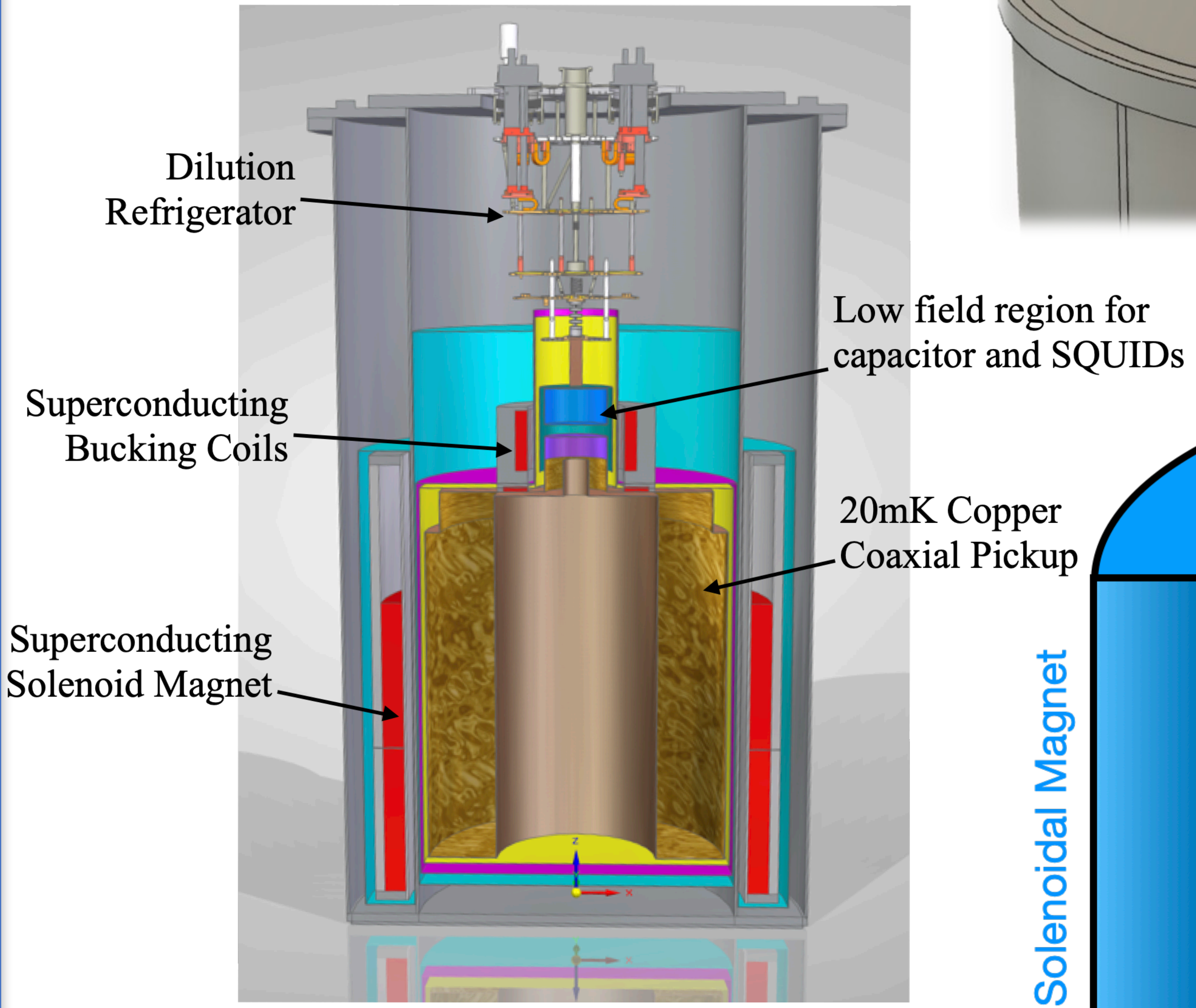


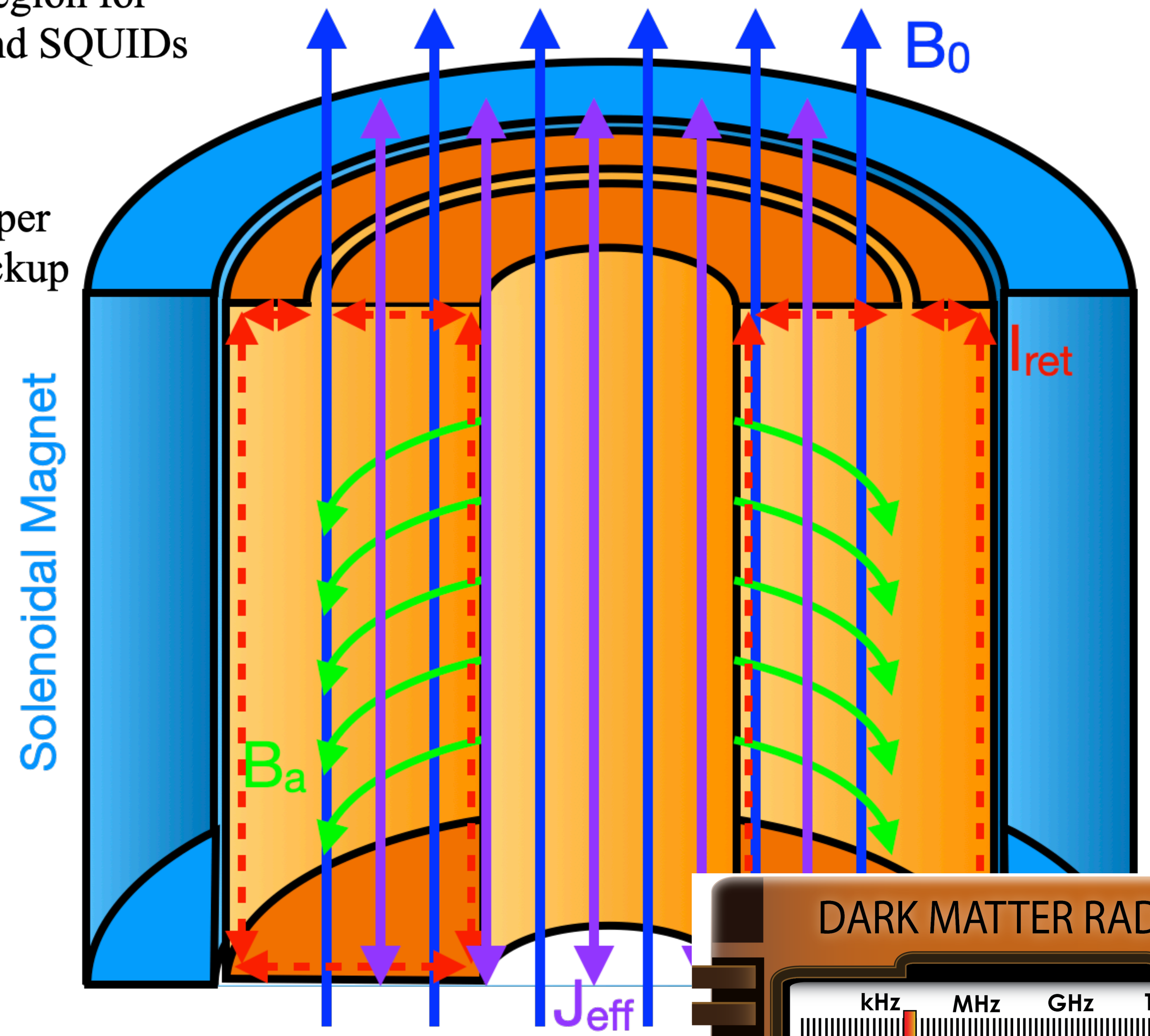


DMRadio-m³ Experimental Design

- There is a fundamental upper limit on the frequencies that can probed by a toroidal design: ~50 MHz
  - Parasitic capacitance will short out signal
  - Axion signal will also undergo destructive interference with intrinsic cavity modes
- Therefore DMRadio-m³ is going with a solenoidal geometry
  - Coaxial pickup will be placed inside the high field region - Aiming for Q of at least 10^5
- Pickup geometry prevents coupling outside loss into resonator

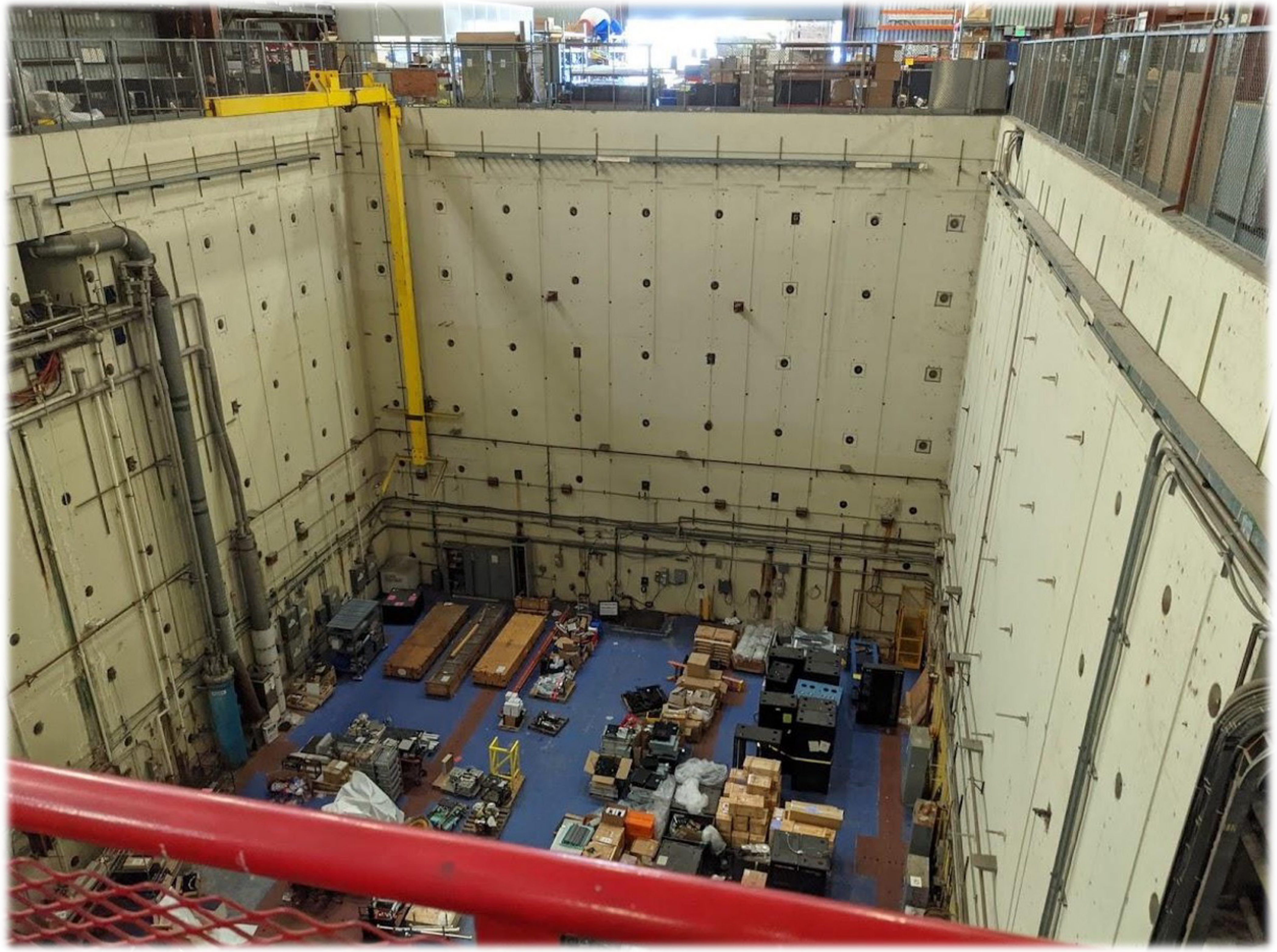


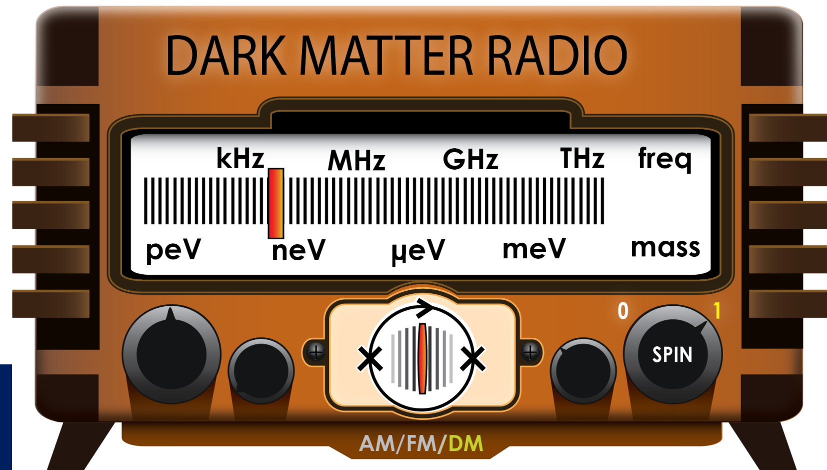




DMRadio-m^3 Status

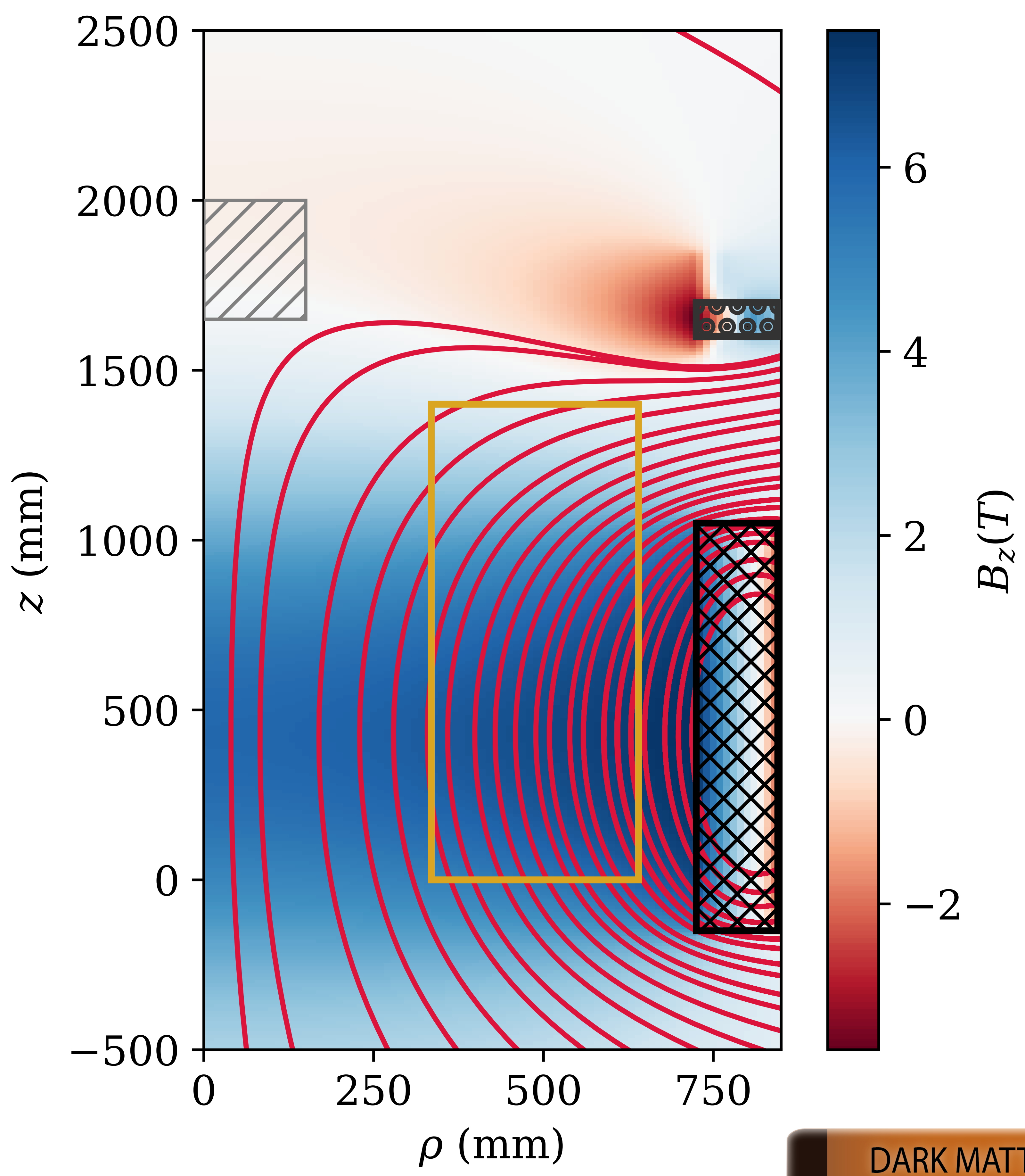
- DMRadio-m^3 will be constructed at SLAC national lab
- Much of the experience gained from the design and construction of the 50L experiment will inform the design of the corresponding DMRadio-m^3 components
- Currently undertaking a simulation campaign to ensure that experiment will reach sensitivity target





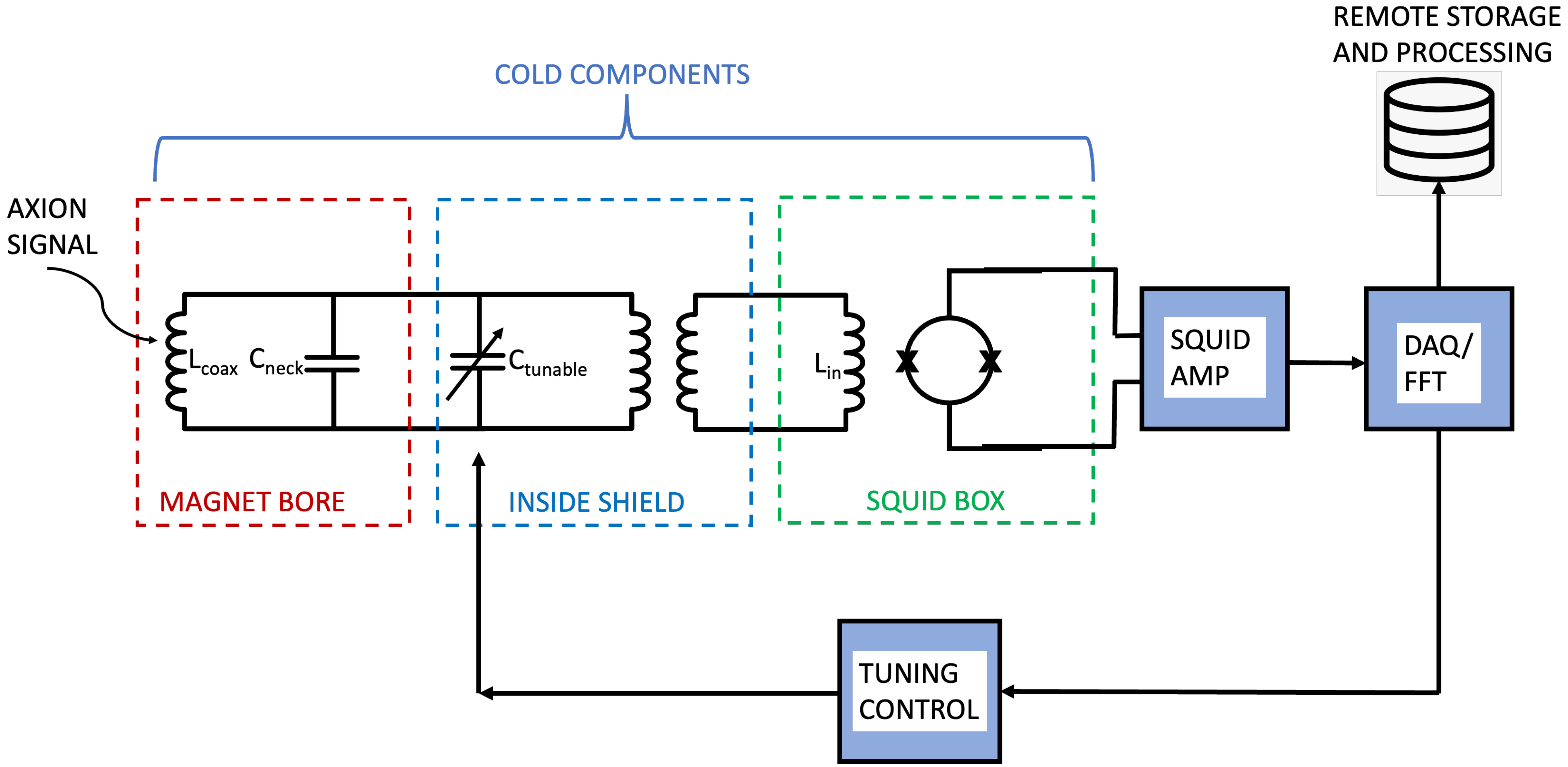
DMRadio-m^3 Magnetic Field Modeling

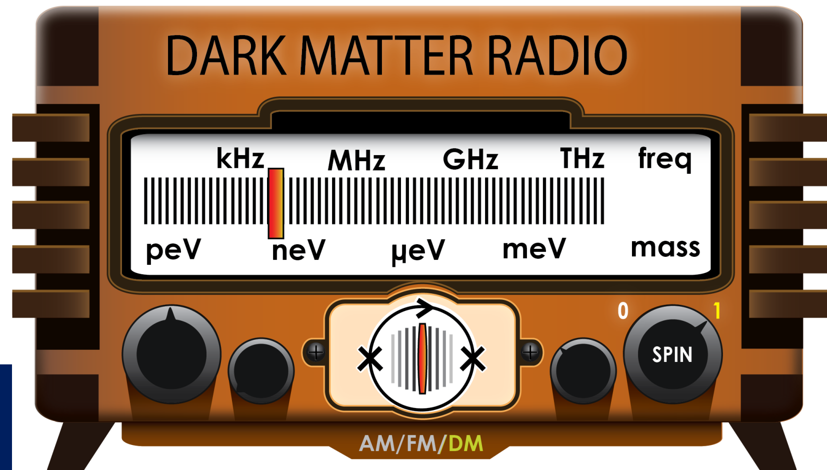
- Specific experimental requirements necessitate careful simulation
- 4.5 T peak field strength with bucking coils to reduce field profile near sensitive electronics
  - < 400 mT field 20 cm above the pickup coax
- Field profiles were used an input to the coupling calculations used in sensitivity study



DMRadio-m³ Effective Circuit Model

- As with 50 L, m³ can be modeled by an effective circuit model - the lumped element approach
- Individual components optimized to maximize axion signal power transferal to SQUID readout
- Currently performing calculations to measure the effect of any MQS breakdowns for a given detector design
- These simulations are then fed into the sensitivity calculations

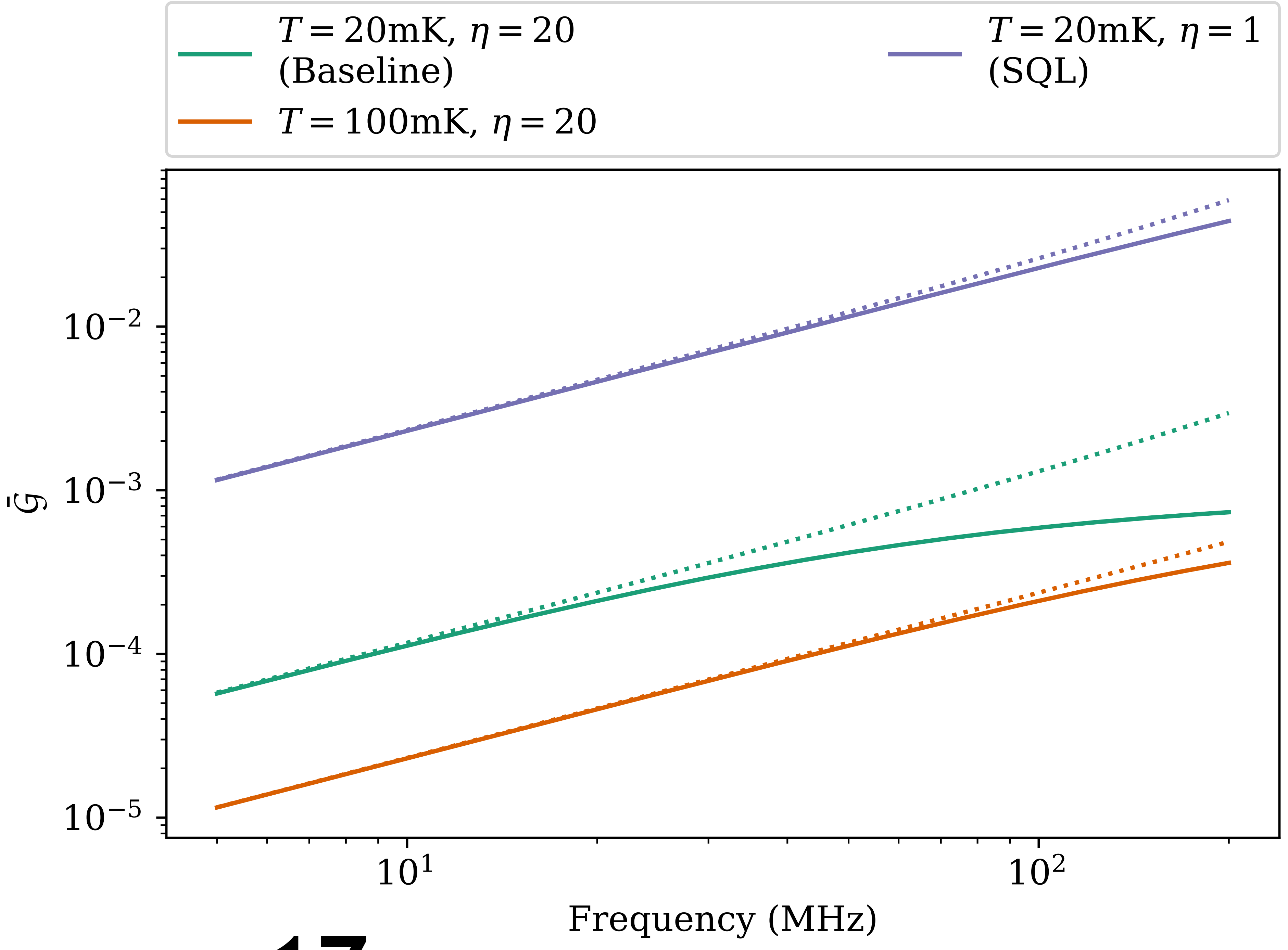




DMRadio-m³ Sensitivity Calculations

- DMRadio-m³ scan rate has been optimized to allow for maximum coupling to axion signal
- $\bar{\mathcal{G}}$ contains all the optimal tradeoff between imprecision and backaction noise
- All sensitivity calculations use conservative target experimental parameters

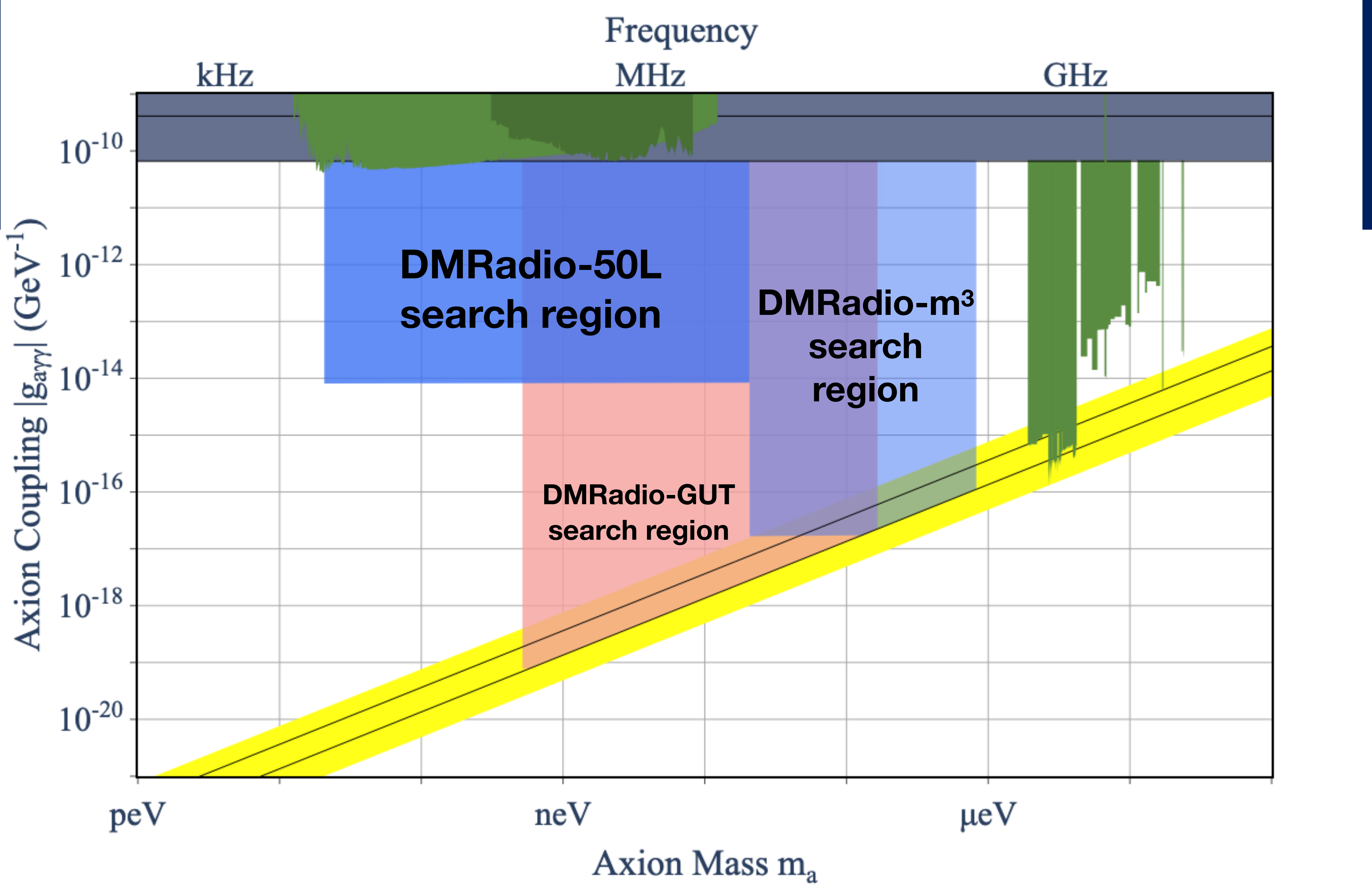
$$\frac{d\log\nu_r}{dt} \propto \frac{g_{a\gamma\gamma}^4 \rho_{DM}^2}{\mathrm{SNR}^2 \nu_r} c_{\mathrm{PU}}^4 Q B_0^4 V^{10/3} \times \bar{\mathcal{G}}(\nu_r, k_B T, \eta_A)$$



For full details on scan rate calculations see: Saptarshi Chaudhuri JCAP12(2021)033 and arxiv: 1803.01627

Summary/Conclusion

- DMRadio family of experiments are looking to probe as a wide of parameter space as possible starting with DMRadio-50L
- DMRadio-50L will be a optimized toroidal experiment designed to probe lower mass models
- DMRadio-m³ will utilize a solenoidal geometry in order to probe higher mass axion models and build on experience gained by 50L design and operation
- DMRadio-m³ search region designed to compliment the search region of DMRadio-50L and cavity based searches while maintaining optimal axion coupling
- DMRadio-GUT experiment also being developed in parallel designed to probe down to QCD axion level over a 10 year scan time and serve as testbed for quantum sensor technology
- Data taking to begin in 2023 (50L) and 2026 (m³)



Parameter	Design Range
Search Region (m³)	5 MHz - 200 MHz
Search Region (50L)	5 kHz - 5 MHz
Sensitivity Goal (m³)	DFSZ above 30 MHz
Sensitivity Goal (50L)	5e-15 1/GeV

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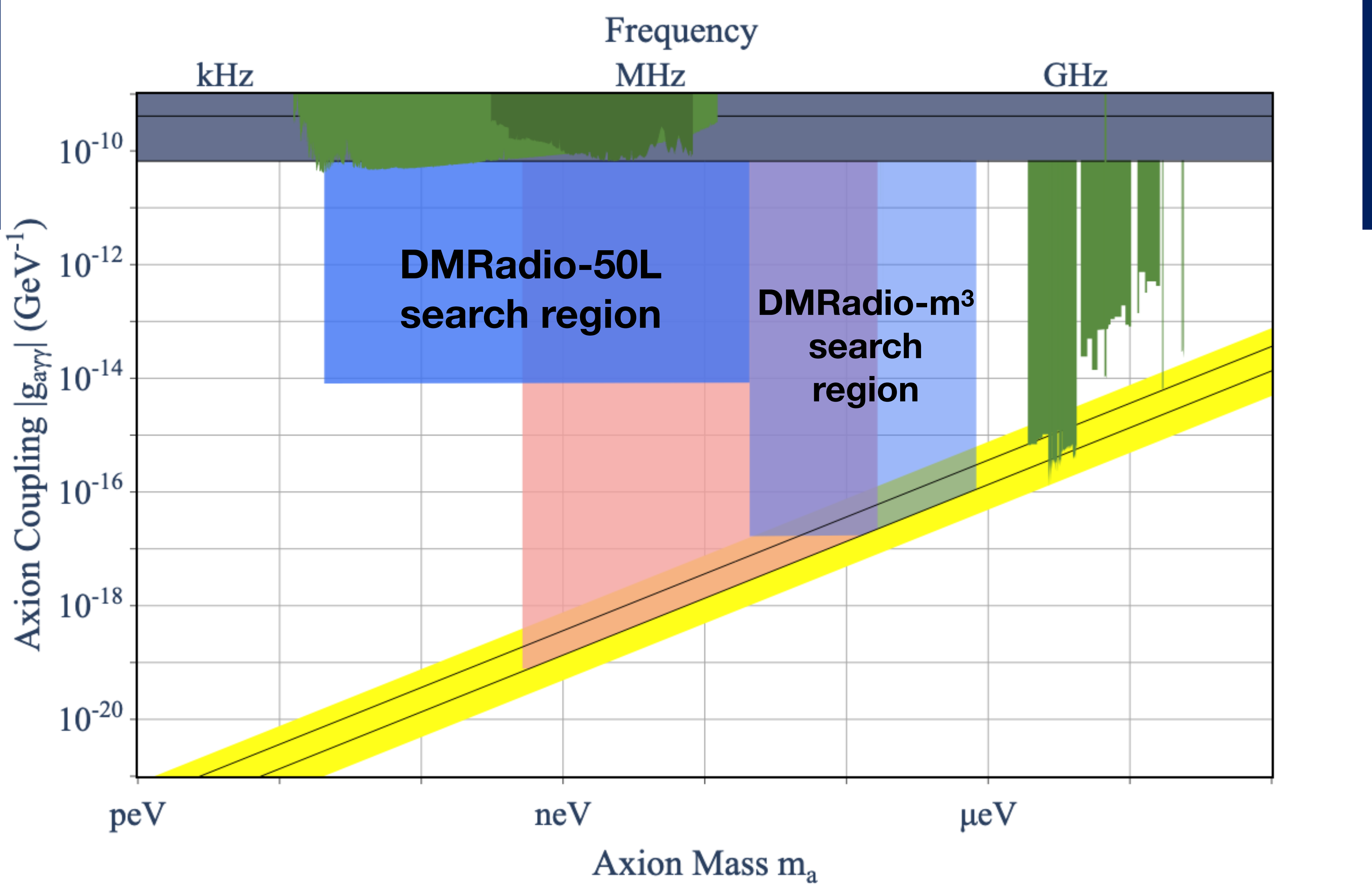

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Santa Clara University

DMRadio Collaboration

DARK MATTER RADIO

For further reading:
50L - stay tuned!
M^3 - arxiv: 2204.13781
GUT - arxiv: 2203.11246

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Thank you! Any Questions?

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Stanford University
Berkeley UNIVERSITY OF CALIFORNIA
THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL
CAL STATE EAST BAY
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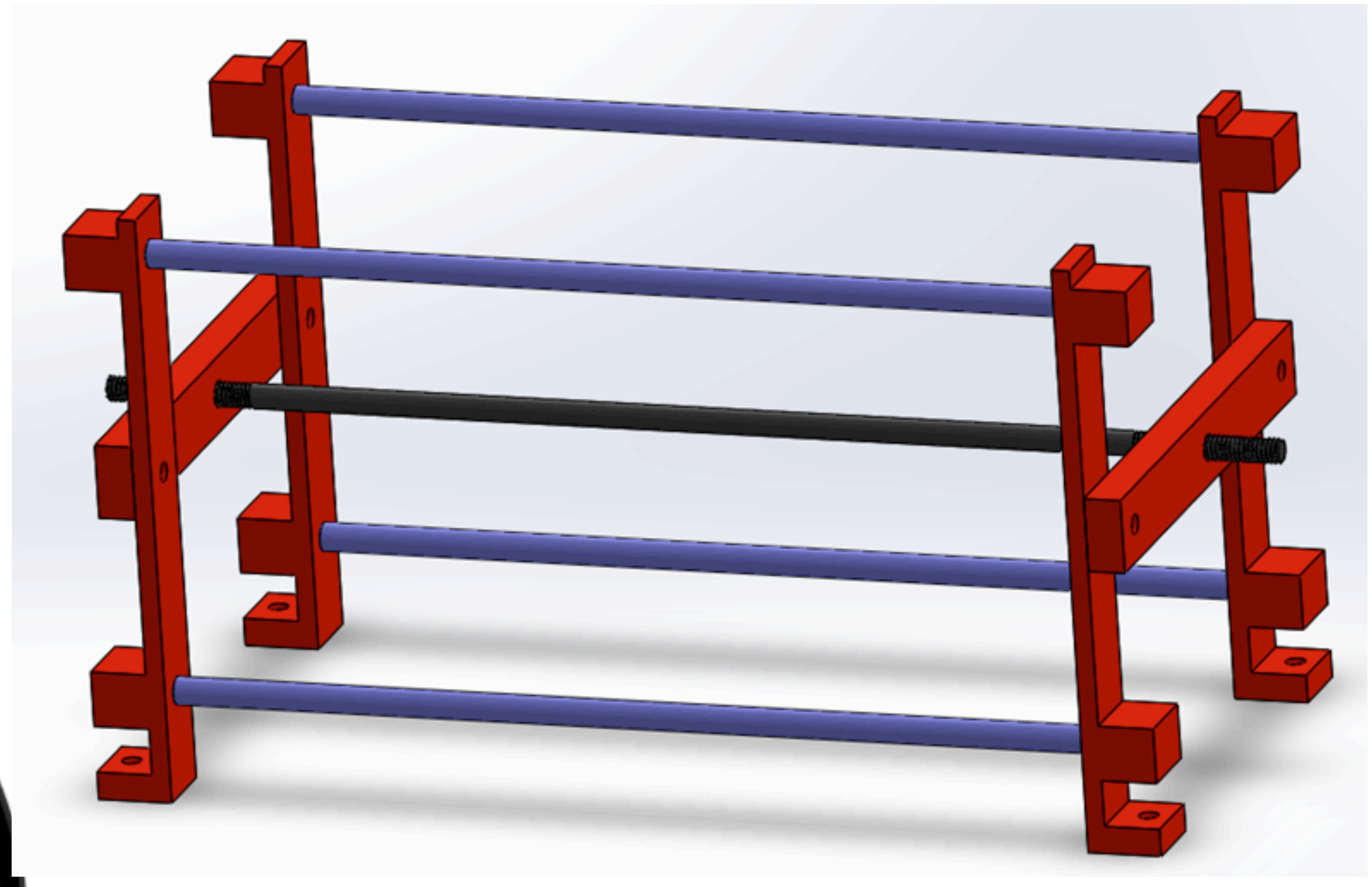
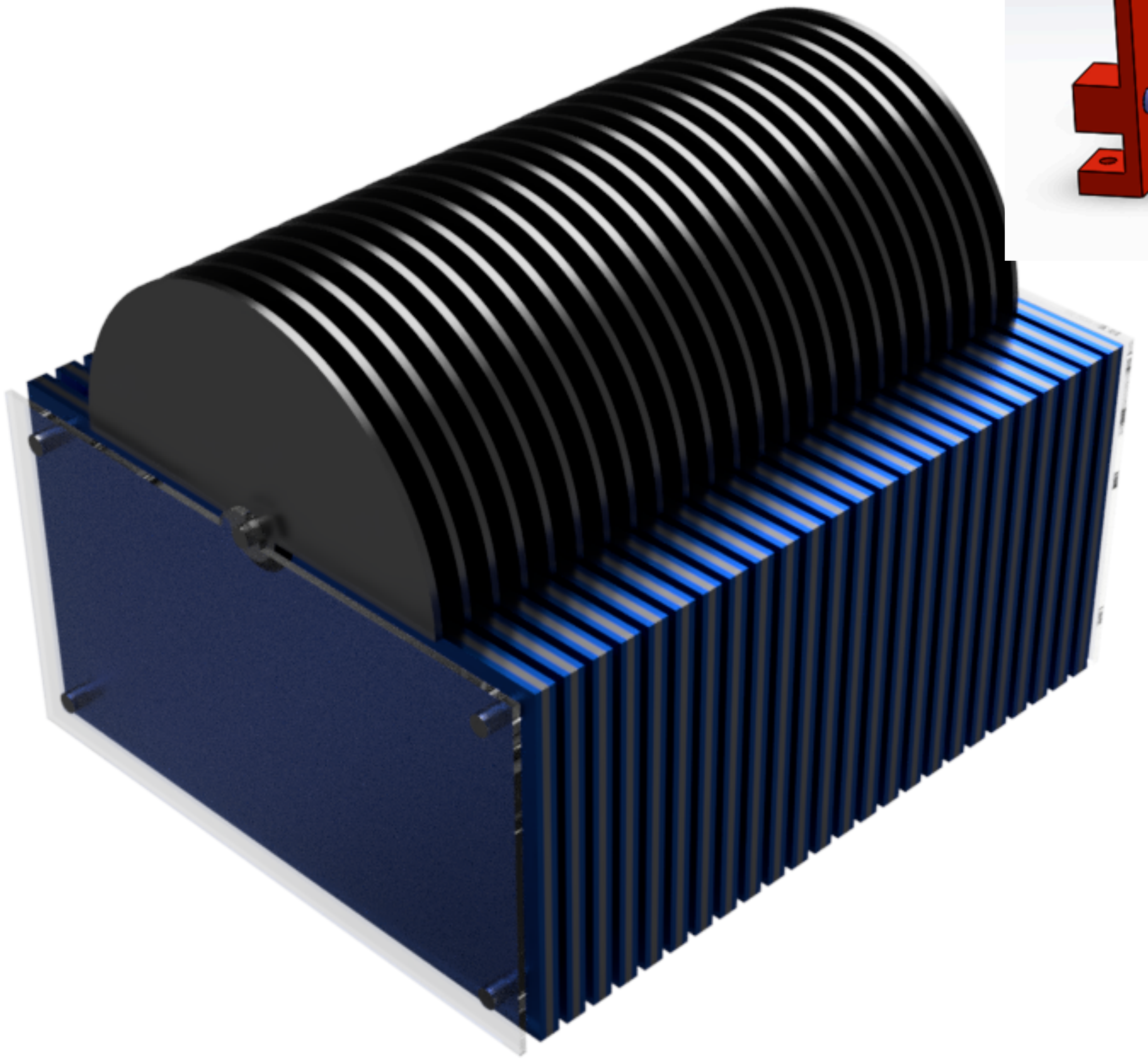
TUNL TRIANGLE UNIVERSITIES NUCLEAR LABORATORY
GORDON AND BETTY MOORE FOUNDATION
NSF
U.S. DEPARTMENT OF ENERGY Office of Science
HEISING-SIMONS FOUNDATION

Backup Slides

DMRadio-m³ Tunable Resonator

- In order to cover the frequency range needed by DMRadio-m³ tunable capacitor will need to cover range of 10 pF - 5 nF
- LC resonator package will be swapped out at different frequencies
- 1 part in 1e6 frequency resolution required
- Dual capacitor design being implemented
- Drawing from design and experience gained from DMR-50 L resonator design



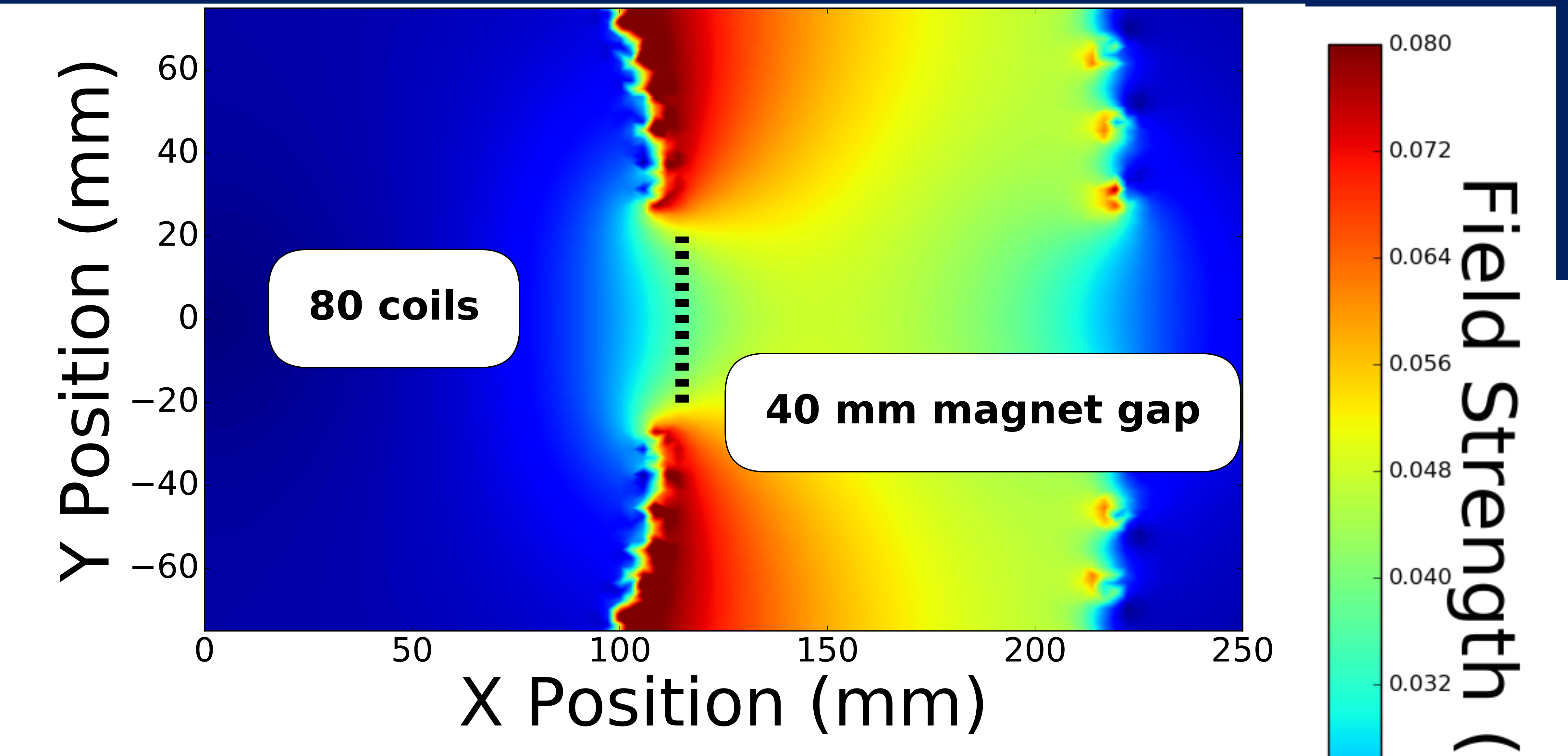


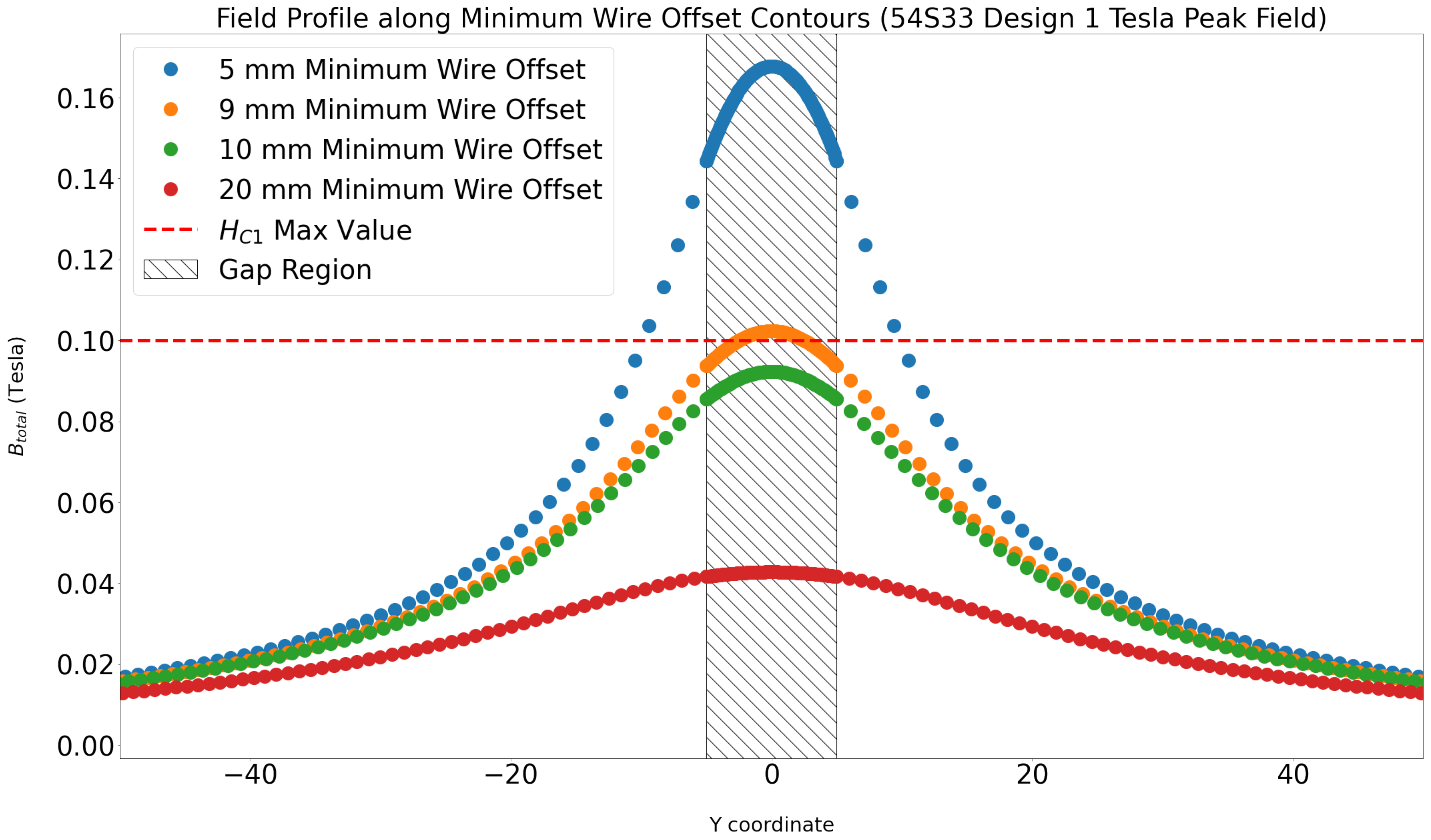
CAD designs of capacitor plates and inductor frames

Magnet Design

Parameter	Design Goal
Peak Field	0.1-1 Tesla
Max Fringe Field	100 mTesla
Science Volume	50 Liters

- Stray fields must be kept low to avoid driving superconducting components normal
- Design for operation at higher fields built in
- Magnet design finalized and submitted to SSI for delivery by 2023

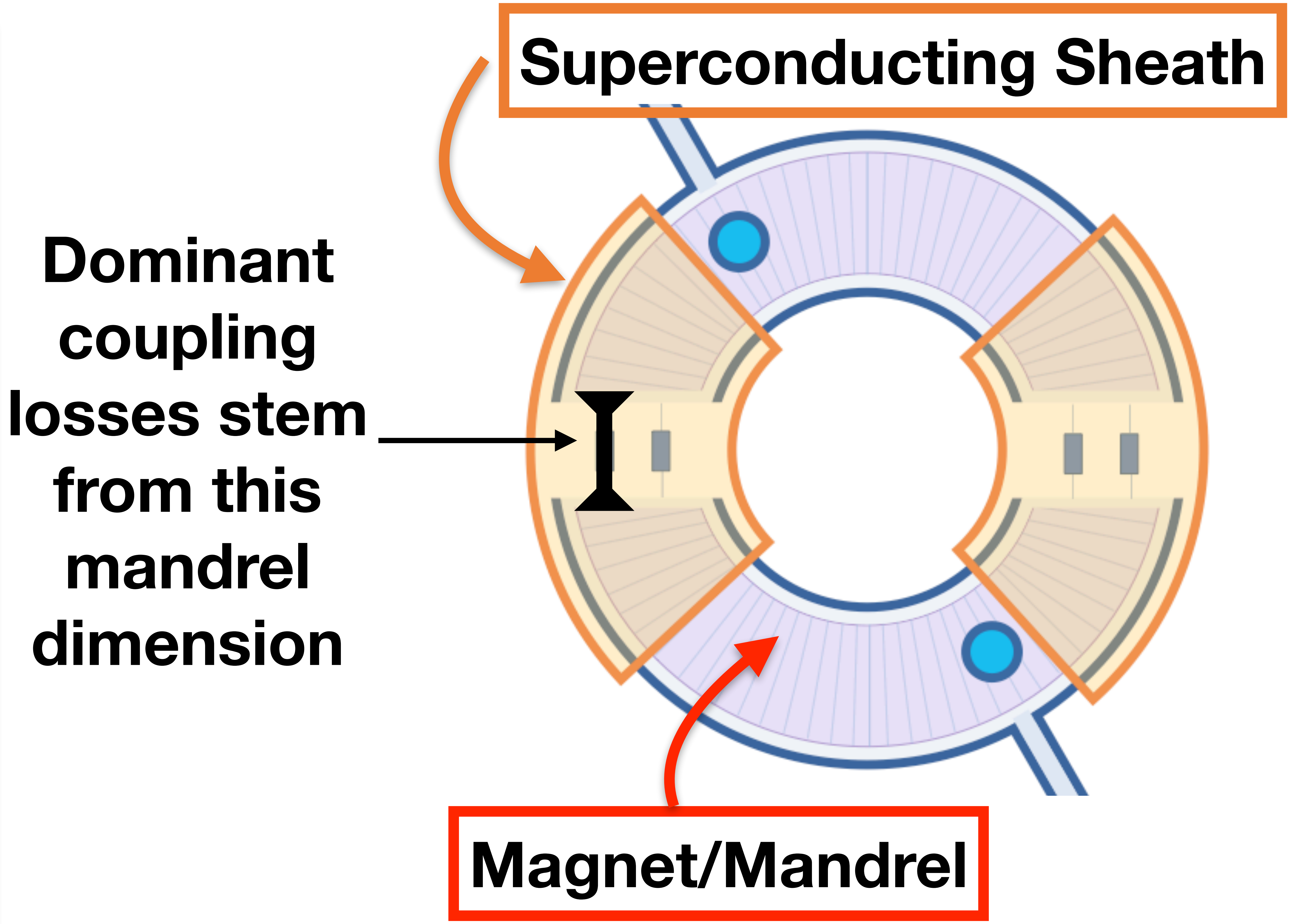




Fringe field profiles along gap

Simulating Sheath Modes

- Work performed by Alex Droster utilizing HFSS simulations
- Two goals:
  - Find the lowest order racetrack modes inside the sheath
  - Minimize coupling between pickup loop and lossy materials
- A variety of sheath materials/coatings were also tested and shown only to contribute minority to coupling losses

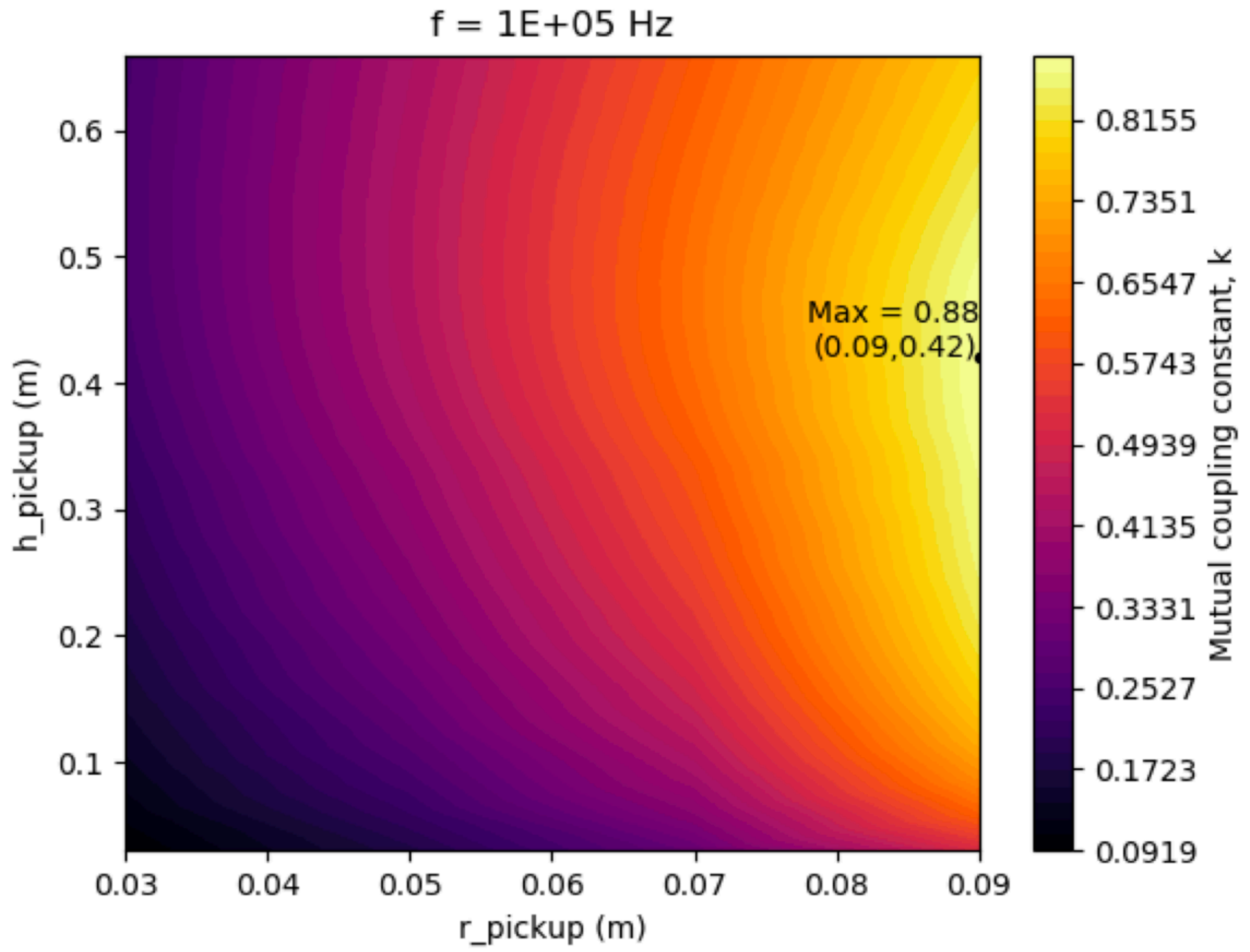


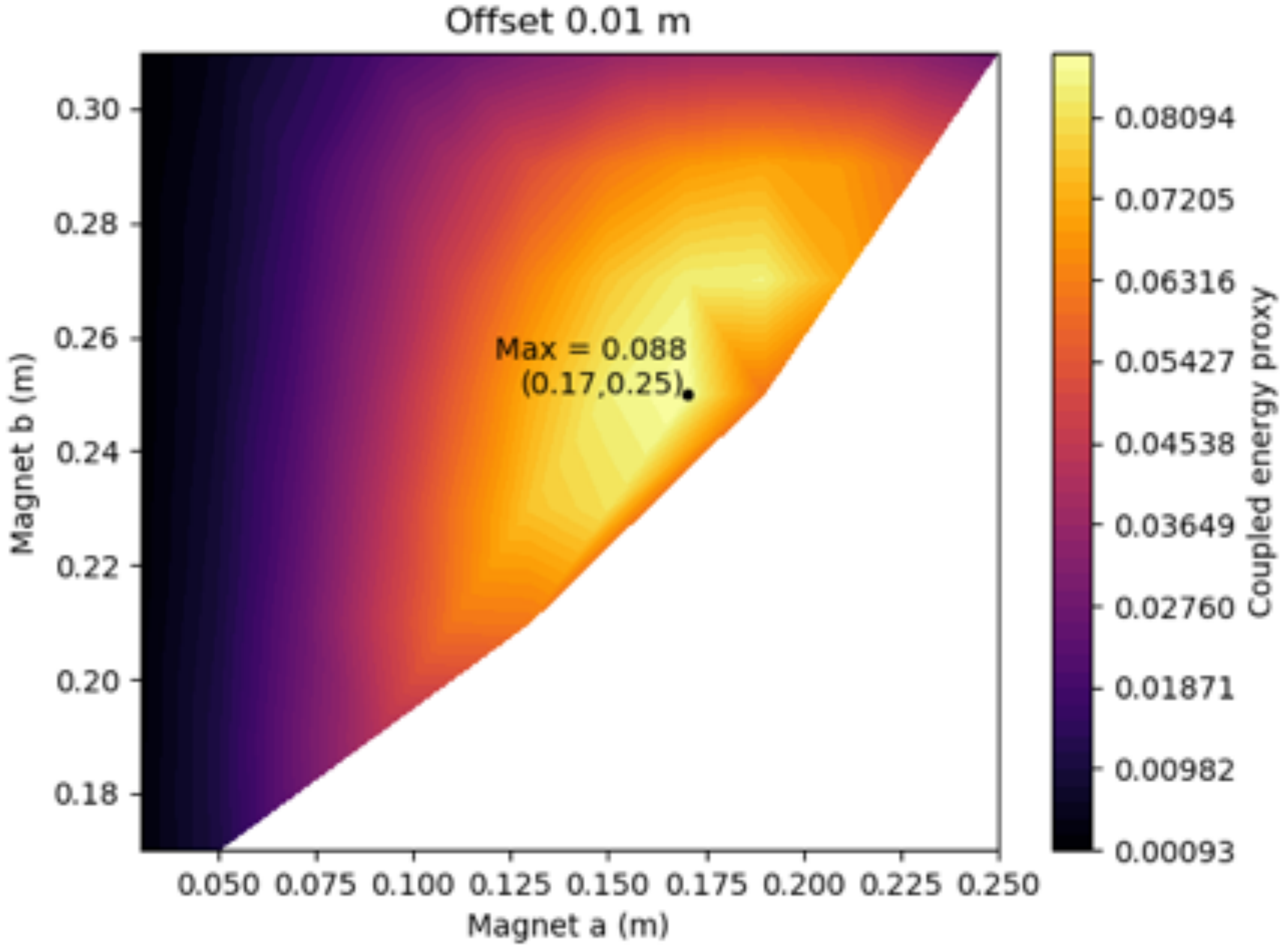
Top-down view of 50 L Design

Sheath/Pickup Signal Coupling

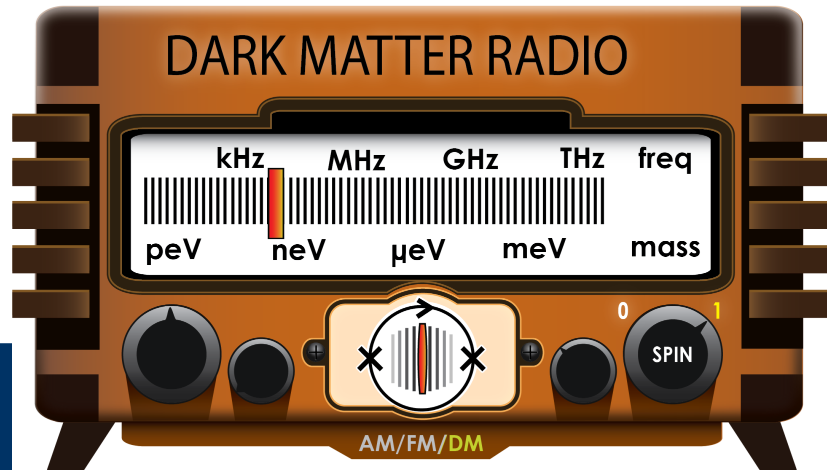
- Work performed by Chiara Salemi
- Simulations have scanned across a wide variety of dimensions for both the sheath and pickup
- Submitted design have been optimized for maximum coupling between axion and sheath and sheath and pick up system

Scans of pickup dimensions on axion coupling efficiency



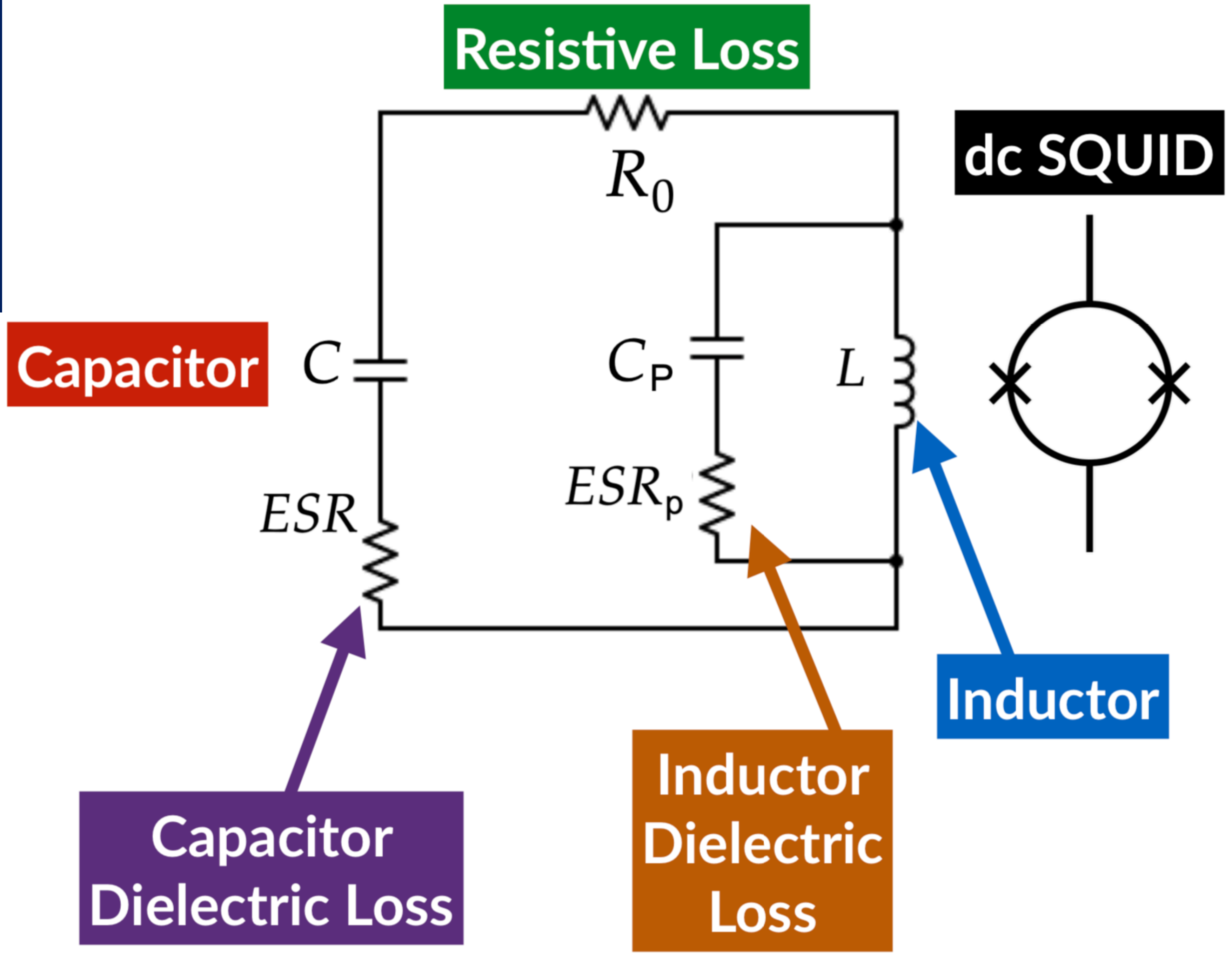


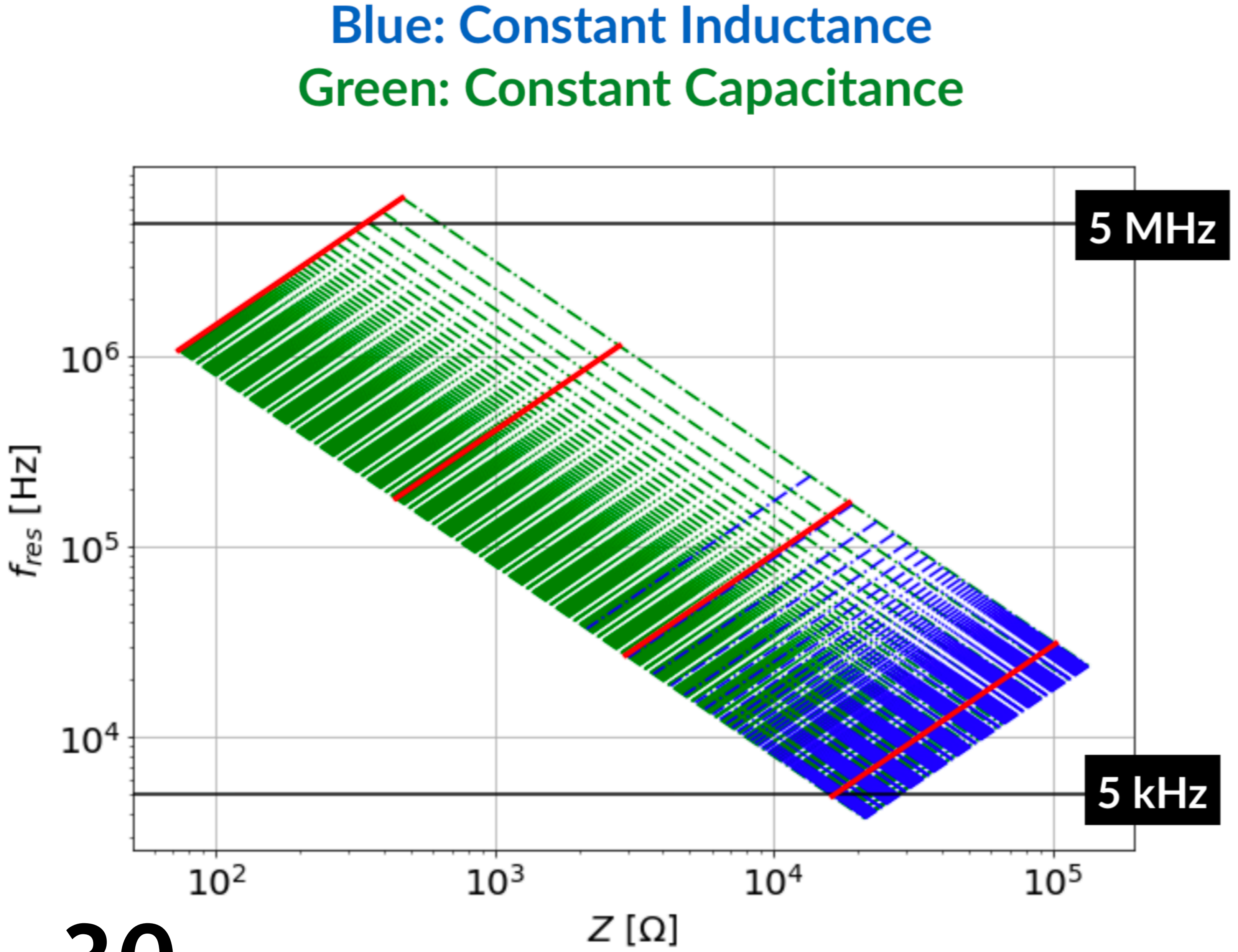
Maximum signal efficiency occurs when pickup maximally fills out center region



Resonator Q Optimization

- We have also looked into a variety of LC resonator designs
- Resonator circuit model allow us to minimize losses while still maximizing Q across multiple frequencies
- Proposed designs will then be tested with a dip probe at 4K

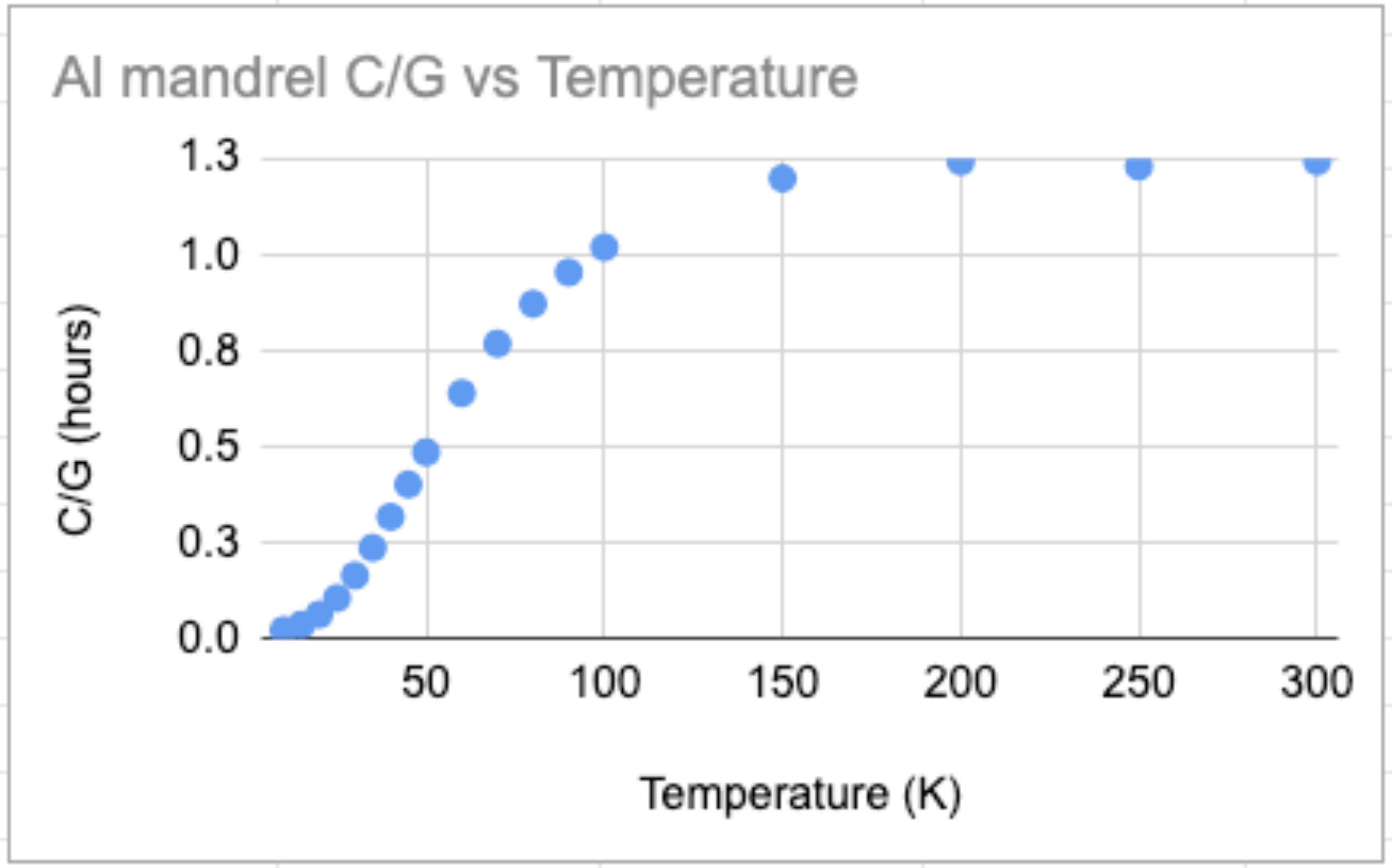




Scan of possible LC combinations and their resulting impedance/ resonance

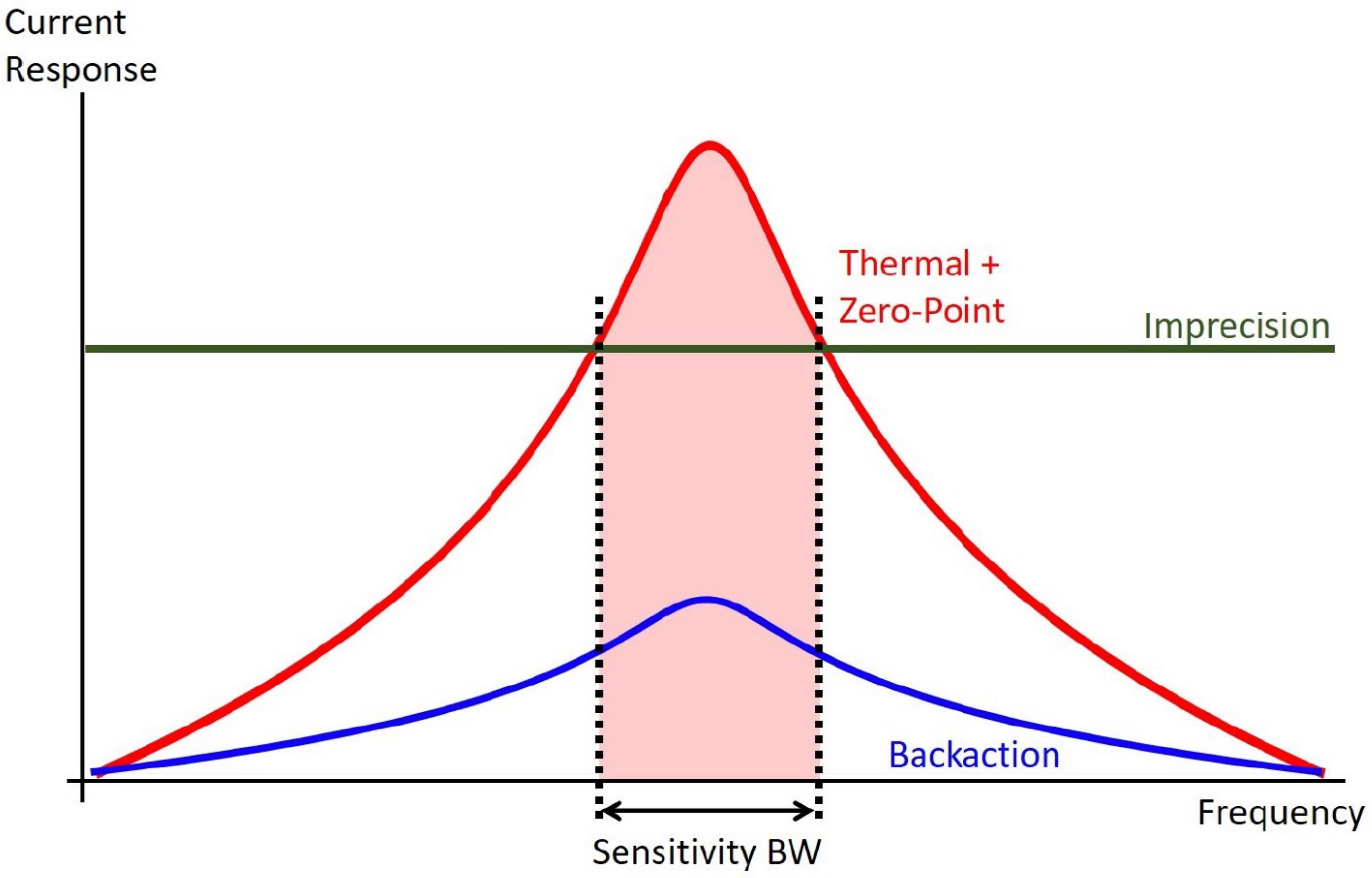
Cryogenic Cooling

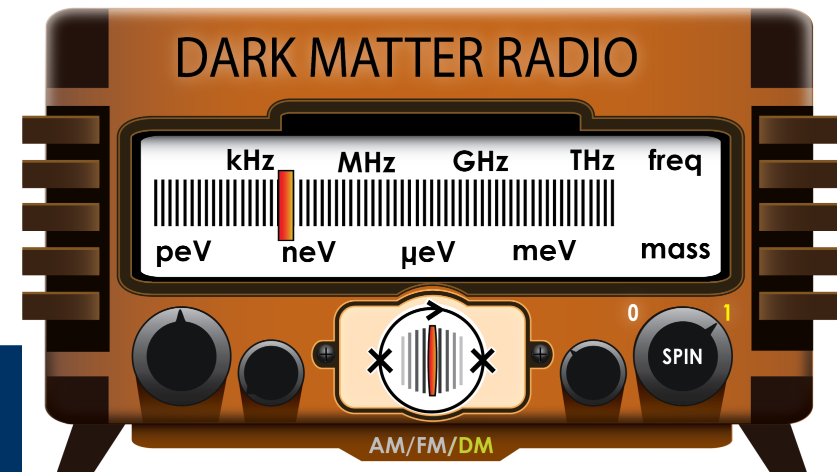
- Work Performed by Maria Simanovskaia
- Cool down profiles have been simulated in ANSYS
- Not all components have to be cooled all the way down to base temperature
- Looking into designs that can be cooled in less than a week
- Biggest constraint is the available cooling power from the pulse tubes



Sensitivity Bandwidth

- Imprecision noise = Uncertainty in measurement of variable in question
- Backaction noise = due to the measurement of a specific quantum state
- There exists a tradeoff between the imprecision and back action noise levels
- Inside sensitivity BW, the signal to noise ratio remains the same





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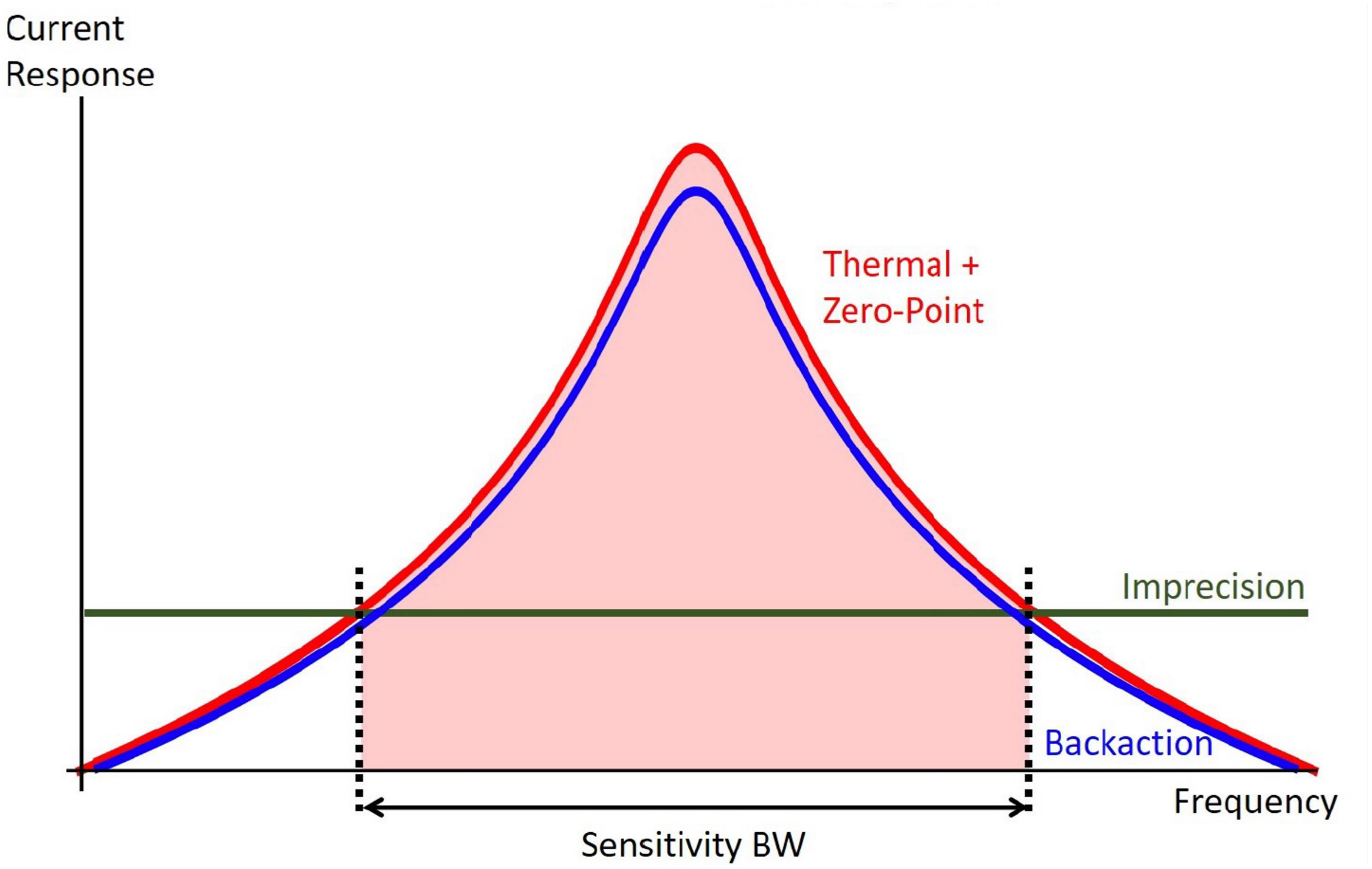
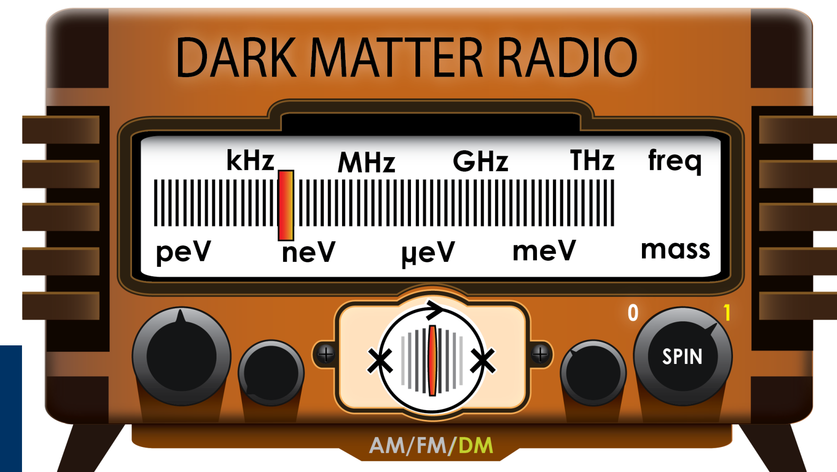
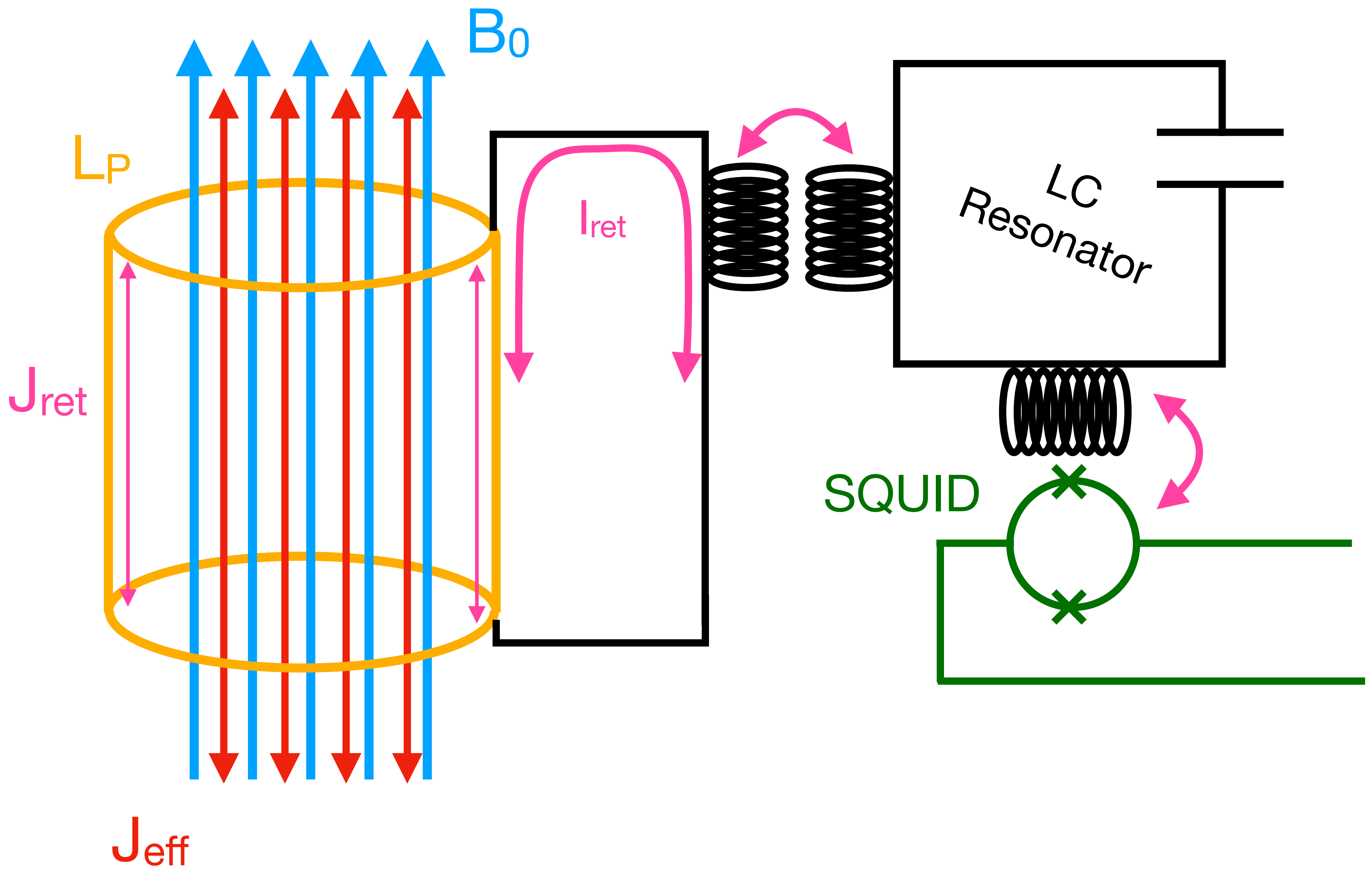


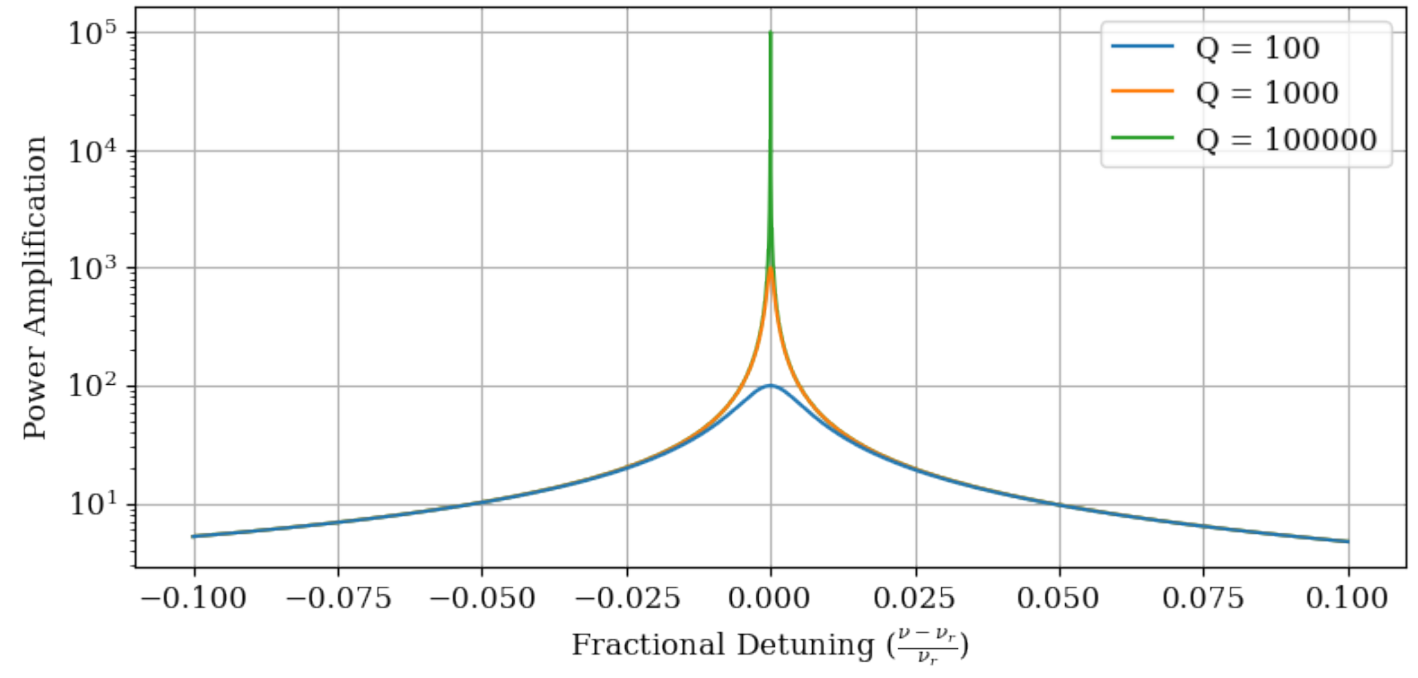


Building A Dark Matter Radio

Turning Magnetic Fields into Currents

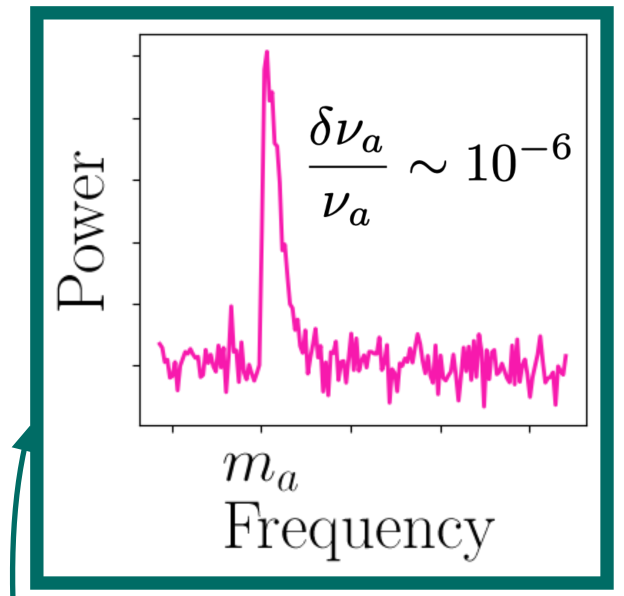
- Establish a large static magnetic field
- Axion DM turns this into an AC effective current
- Surrounding the effective current with an inductor that creates a return current
- Inserting a capacitor into the circuit creates an LC resonator and amplifies the current by $Q \sim 10^6$
- Couple the return current into a sensitive SQUID current sensor
  - The current is extremely tiny!
  - Aiming to detect excess power of 10^{-24} W!
- But we have to tune!





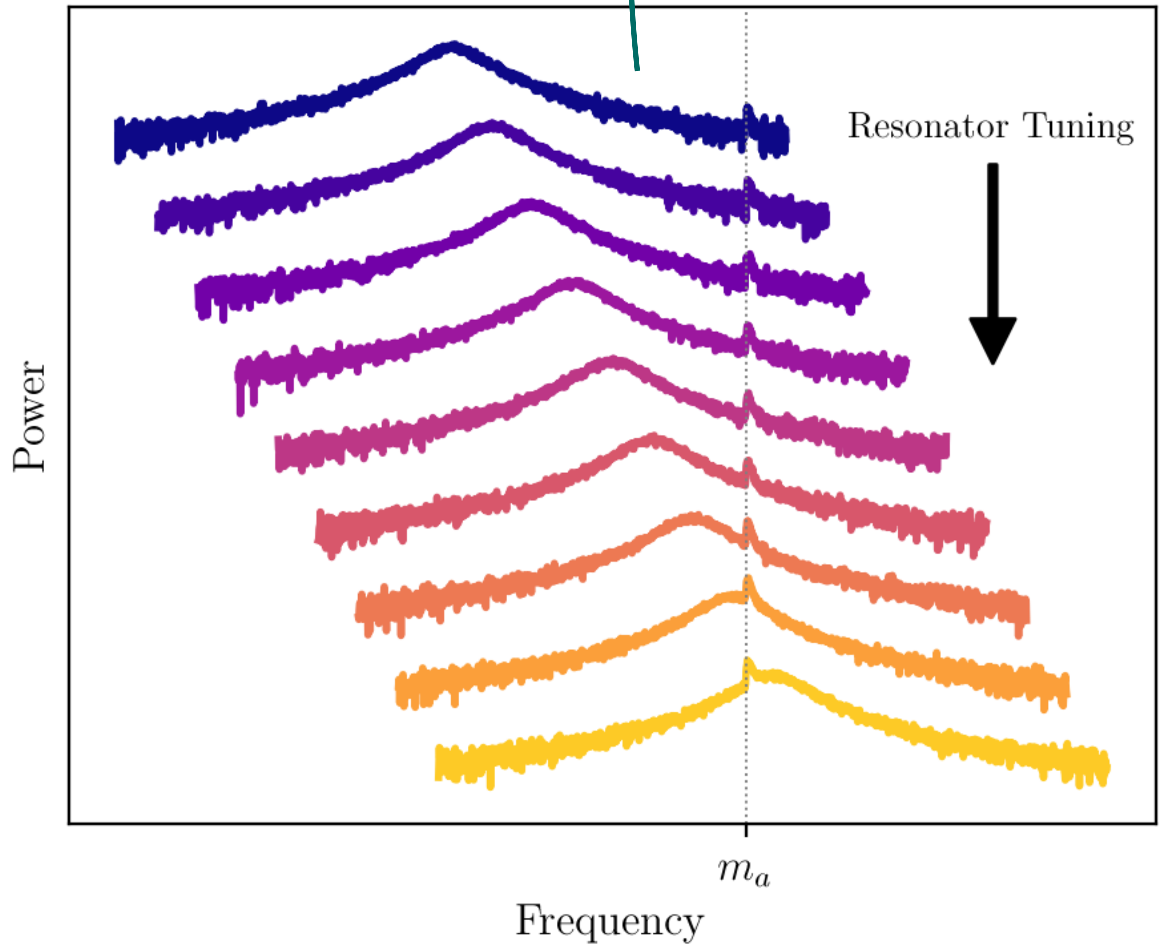
Axion Signal

$$\mathrm{SNR} = g_{a\gamma\gamma}\rho_{\mathrm{DM}} m_a \frac{c_{\mathrm{PU}}^2 B_0^2 V^{5/3} Q}{k_B T}\sqrt{t\delta\nu_a}$$



- Axion will appear as a tiny excess of power at the frequency equal to the axion mass

- Axion signal is coherent over $(v_{obs}v_0)^{-1} \sim 10^6$ periods
  - Signal width of $\Delta\nu/\nu \sim 10^6$
  - Places an upper limit on how much the resonator can ring up



- Can write down the scanning rate at a fixed coupling strength (see Chaudhuri et.al arXiv:1803.01627)

$$\frac{\partial\nu_r}{\partial t} = \frac{1}{\mathrm{SNR}^2}\left(\frac{g_{a\gamma\gamma}^4\rho_{\mathrm{DM}}^2}{v_0 v_{\mathrm{obs}}}\right)\left(\frac{\nu_r c_{\mathrm{PU}}^4 V^{10/3} B_0^4 Q}{n_A(\nu_r)k_B T}\right)$$

- We want a detector with
  - Large volume (V)
  - Large B field ($B_0 \sim$ Tesla)
  - Low loss resonator (Large-Q factor)
  - Low Temperature ($T \sim$ mK)
  - Low Amplifier Noise ($n_A \sim$ SQL or better)

Detector figure of merit:

$$\mathcal{F} = \frac{c_{\mathrm{PU}} V^{\frac{5}{6}} B_0 Q^{\frac{1}{4}}}{n_A^{\frac{1}{4}} T^{\frac{1}{4}}}$$