HAYSTAC

HAYSTAC: a Haloscope At Yale Sensitive To Axion Cold dark matter

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HEISING-SIMONS FOUNDATION

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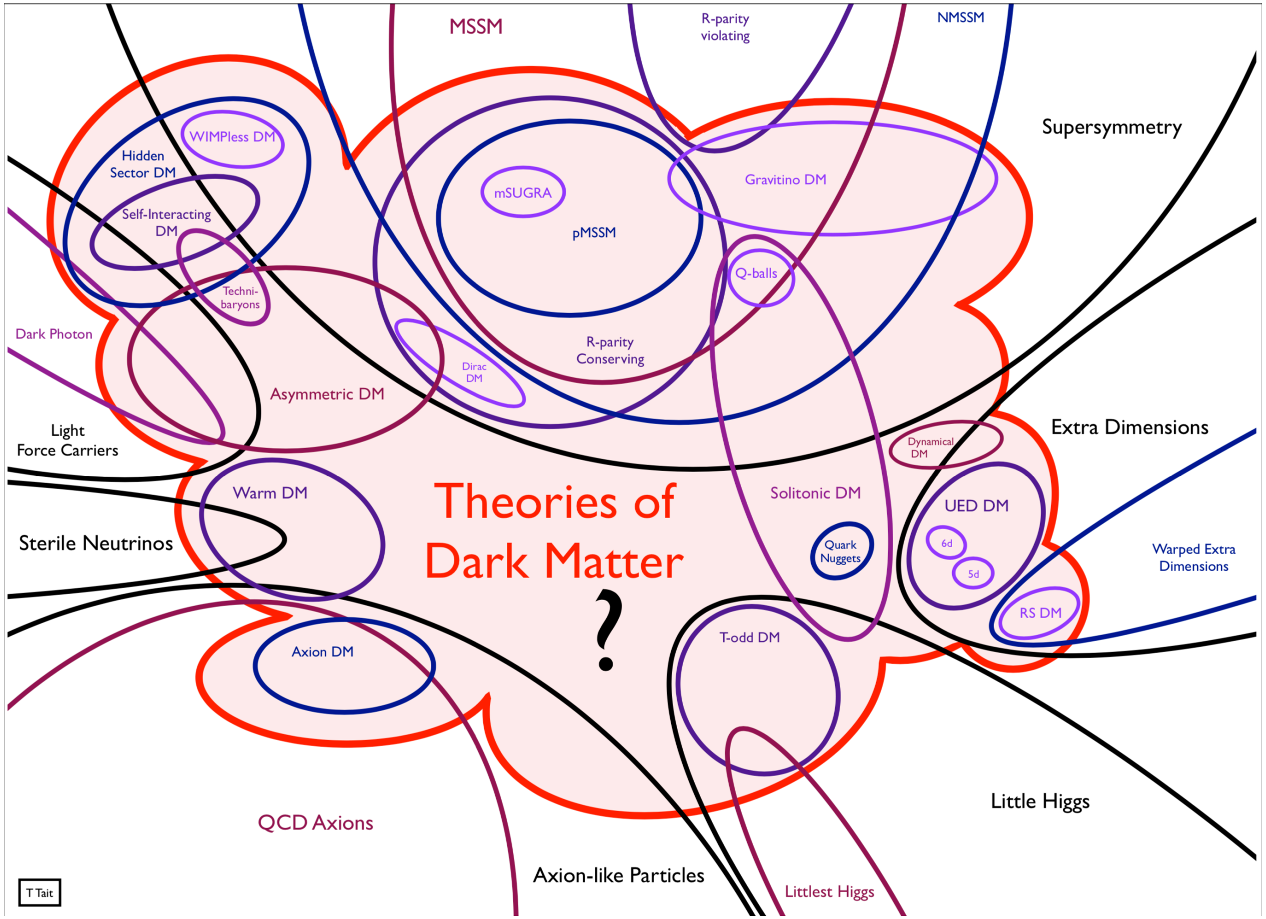
Outline

This talk is designed to give a broad overview of the various HAYSTAC results and the current R&D projects currently underway

- Introduction to Axion Dark Matter
- Overview of the HAYSTAC experiment
- Summary of Phase 1/2 Results
- Current R&D projects
- Summary/Conclusion

Introduction

Dark Matter Theories



- This is a very active area of research
- With so few concrete requirements for any DM candidate you can easily create any number of particles that can fit the bill

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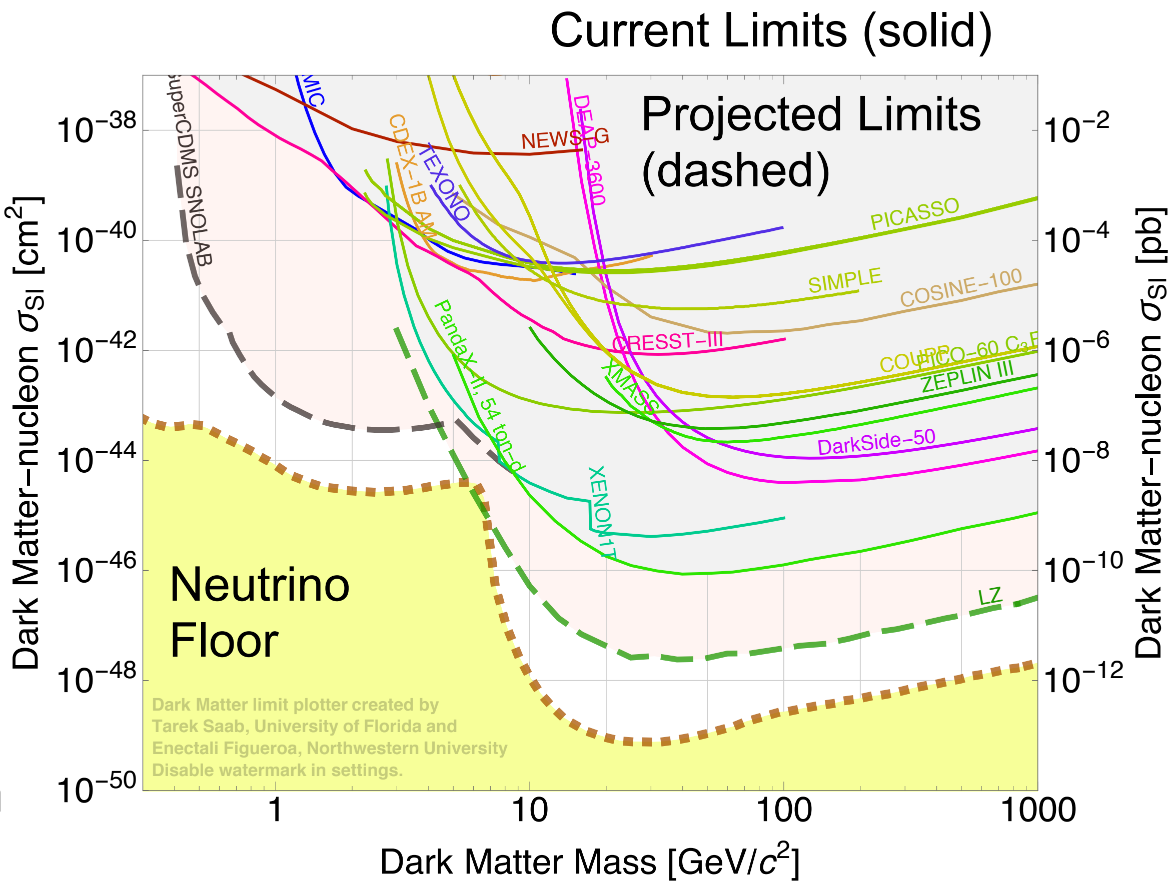
Dark Matter Searches so Far

- For many years one of the dominant DM candidates was the WIMP
- This was very low hanging fruit that could be easily probed with state-of-the-art detectors as those shown in this session
- A lot of the interesting parameter space has been explored
- Other DM candidates have recently gained interest from the community



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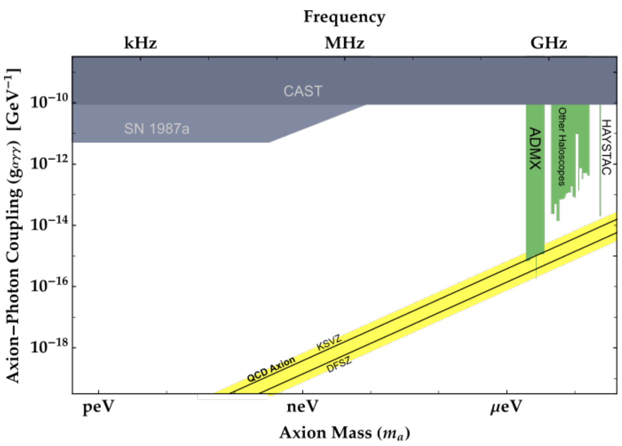
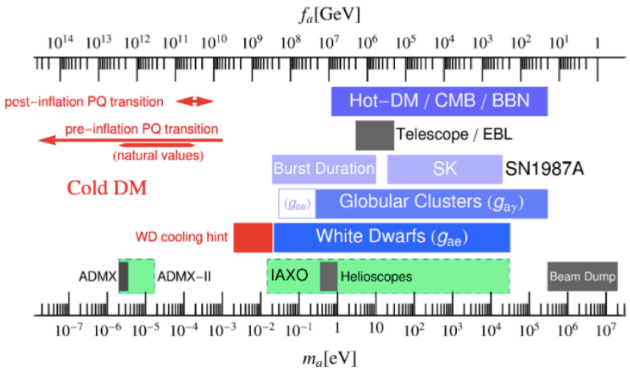
Axions as DM Candidate





- Axions represent a new class of ultra light (high number density) DM candidates
- They check off many of the requirements for a DM candidate:
  - Cold (non-relativistic)
  - Stable
  - Feeble interaction strength
  - Production mechanisms possible in early universe
  - Naturally come about via Peccei Quinn solution to strong CP problem

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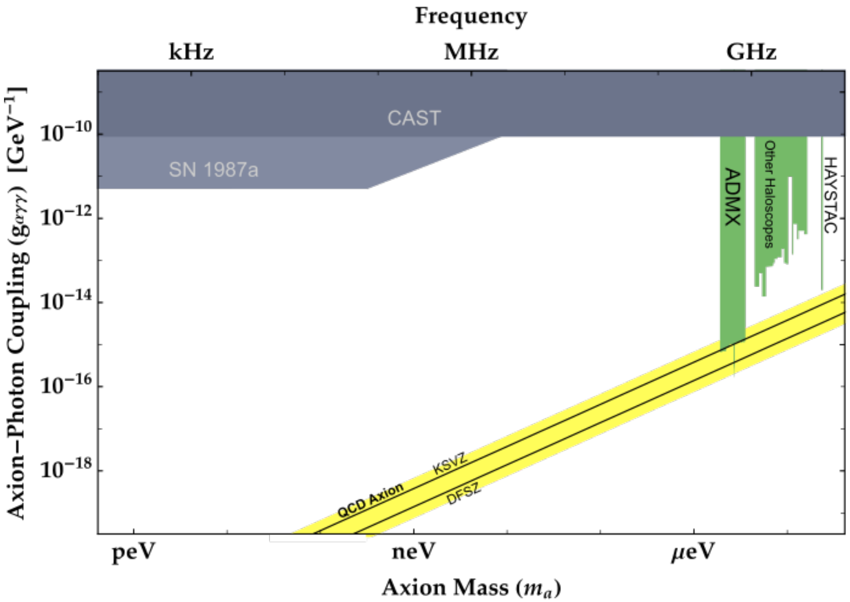
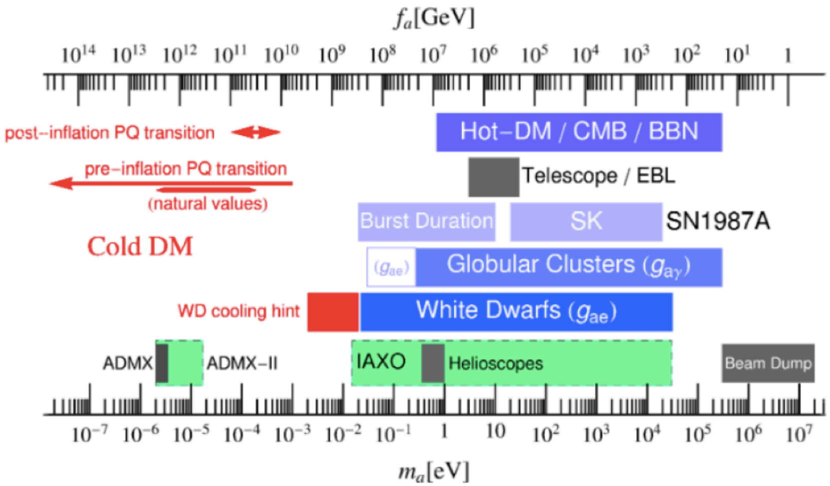
Axions as DM Candidate



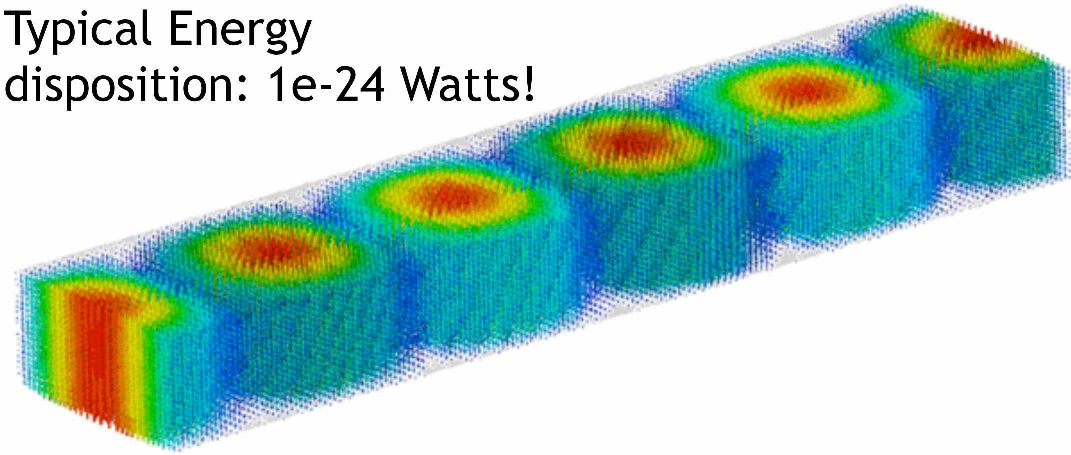


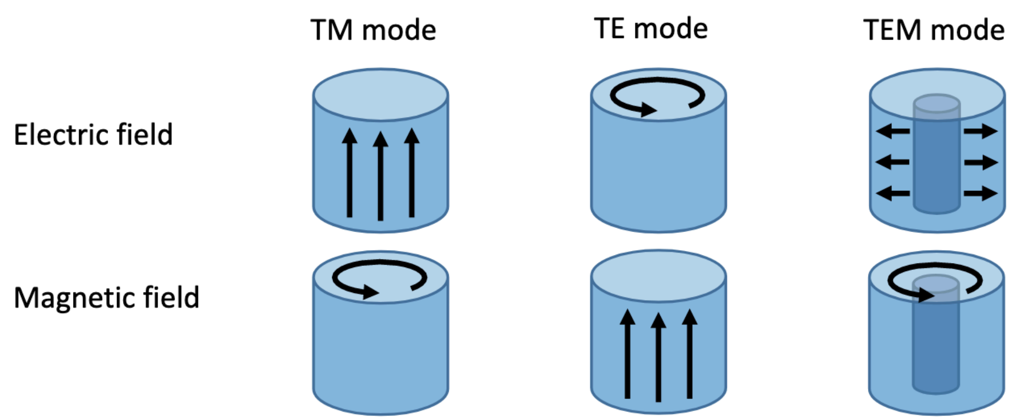
- Very open parameter space
- We need to probe across all 12+ orders of magnitude of possible axion masses
- You can no longer use traditional particle physics detection techniques to search for axions
- Low mass however equals high number density

Axion Dark Matter Detection

- In the case of Axions:
  - Axions only sometimes convert into photons in the presence of an external magnetic field
  - The rate is proportional to the magnetic field and the axion's coupling strength
  - Axions are also extremely light and slow, so there is very little energy to start with
- So let us start with a sealed metal cavity in a uniform external magnetic field
- In this cavity you have intrinsic EM modes that fill the volume

Typical Energy disposition: 1e-24 Watts!





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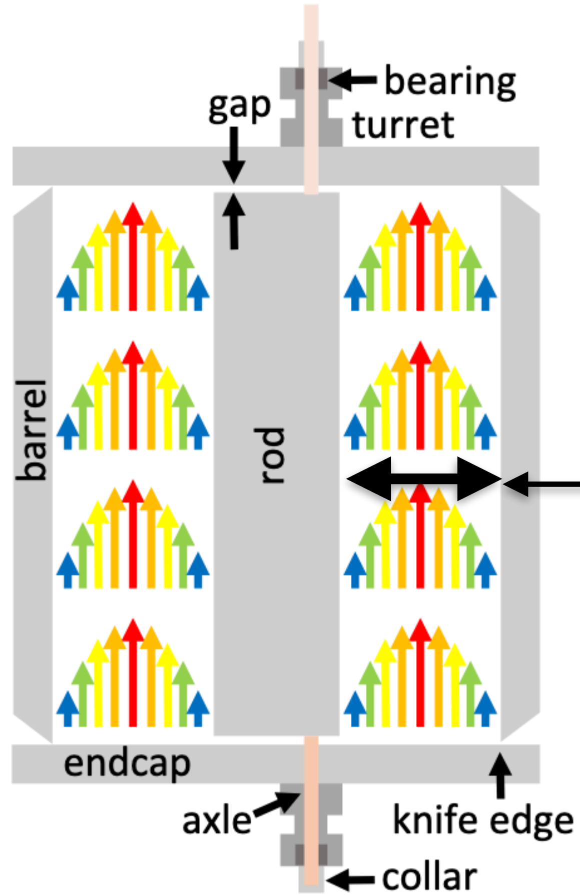
Cavity Based Axion Searches

- For maximum energy transferal you want your detector to as closely match the mass/energy of the incoming particle
- The Axion has a uniform energy profile so we need to look at the EM modes that most nearly resemble a uniform field
- However; boundary conditions make this impossible to achieve everywhere



Axions are depositing their energy uniformity throughout the cavity volume!

This smallest dimension is what drives the overall size/ frequency range of the experiment

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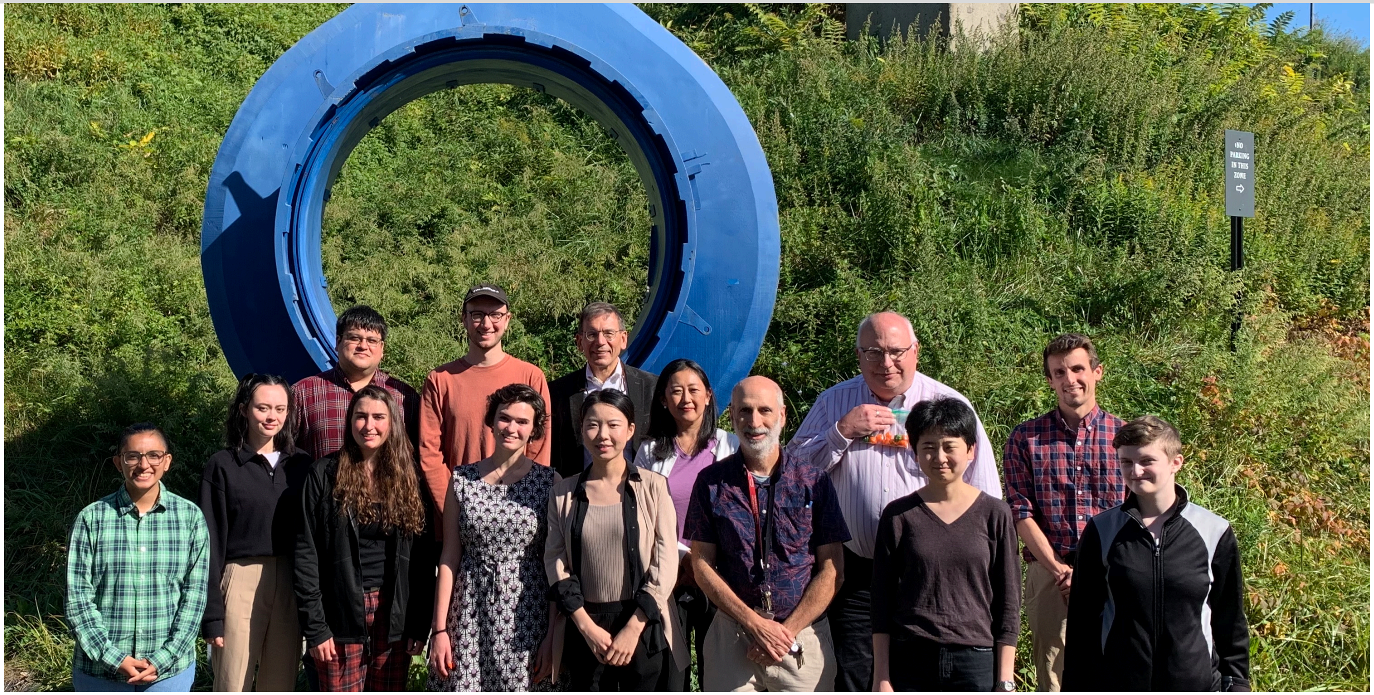
Scale of Axion Experiments

ADMX experiment
Mass range: ~ 0.6 GHz
Lower frequency means larger cavity, complex cryogenic infrastructure

ADMX and HAYSTAC bracket the frequency range that can be accessed through cavity based experiments

HAYSTAC experiment
Mass range: ~ 5.2 GHz
Smaller cavity, easier to cool and install, potentially some loss of sensitivity

HAYSTAC Collaboration



The HAYSTAC Collaboration is made up of four institutions

UC Berkeley

Alexander Droster
Alexander Leder
Heather Jackson
MacKenzie Wooten
Karl van Bibber

Yale University

Sidney Cahn
Mike Jewell

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Steve Lamoreaux
Reina Maruyama

Johns Hopkins

Danelle Speller

CU Boulder

Mehmet Anil
Maxime Malnou
Kelly Wurtz
Konrad Lehnert

NSF

With support from:

HEISING-SIMONS
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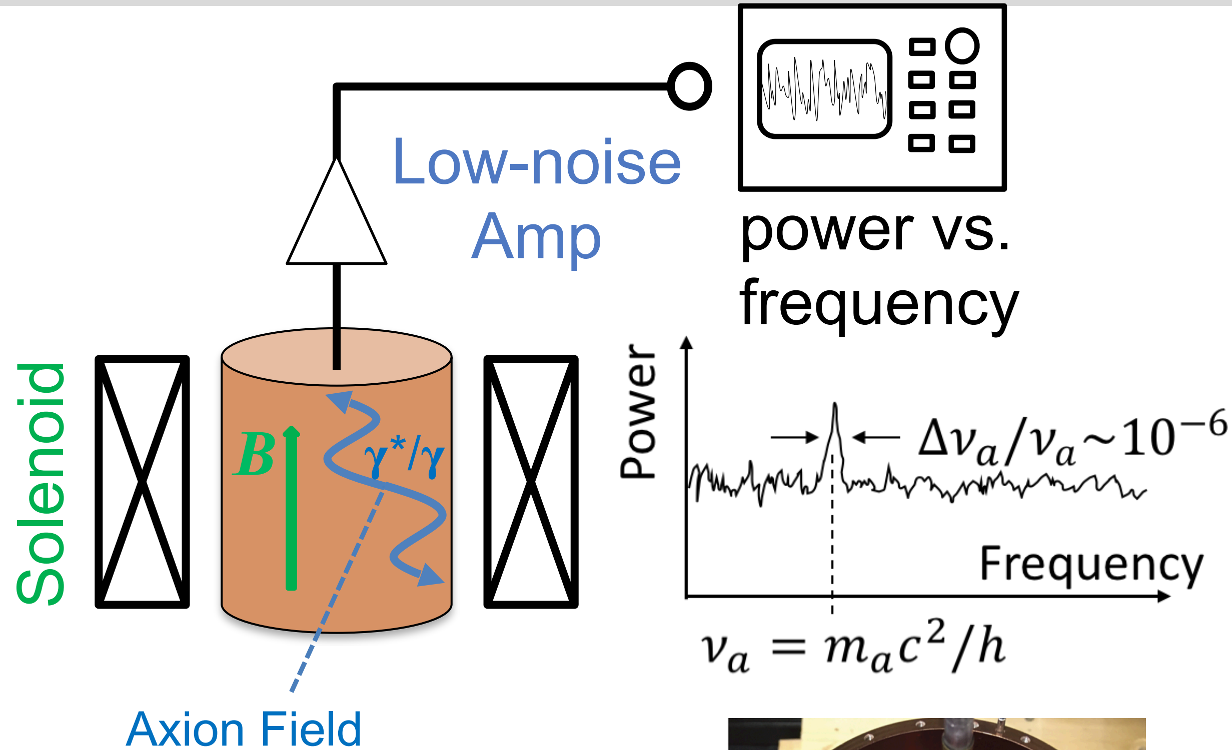
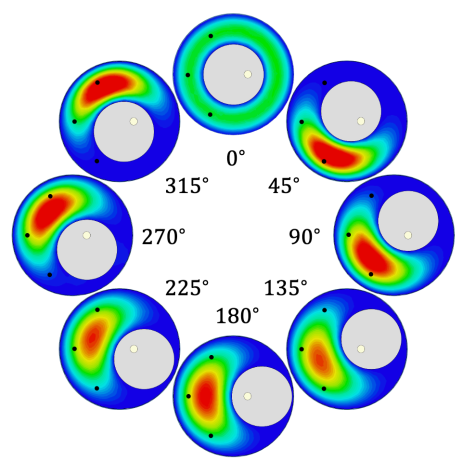
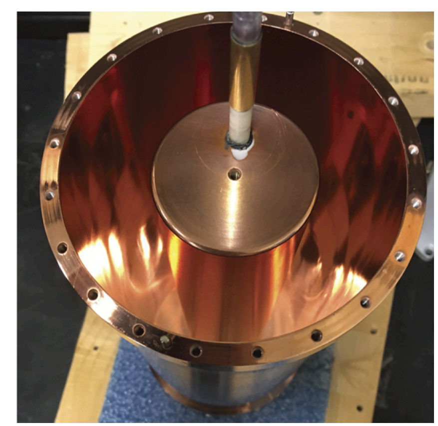
Probing Axions with HAYSTAC

- Cavity based experiments measure the coupling between a DC external magnetic field and the axion
- Inside a a tunable cavity, we can search for a excess in signal power at resonance of detector
- Searches seek to find small energy deposition in power spectrum
- Requires low temperature/noise environments







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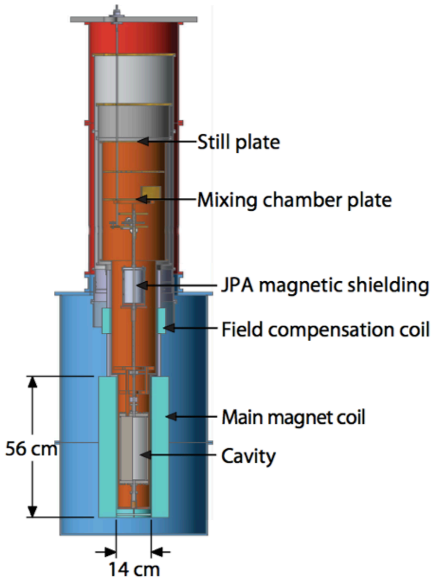
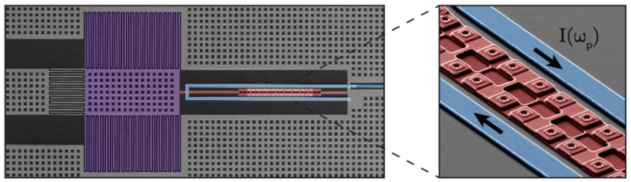
HAYSTAC Experimental Setup

$$P_s \propto B_0^2 V Q_L C_{nml} g_{\gamma\gamma a}^2$$

$$SNR = \frac{P_S}{kT_S}\sqrt{\frac{t}{\Delta\nu_A}}$$





- In order to probe the most DM parameter space in the shortest time we need:
- Large magnetic field (9 Tesla)
- Low temperature (127 mK)
- Low noise environment (2.3 quanta)
- Good Form Factor (C_{010} ~ 0.5)
- High Q (1e4)
- Large Volume (1.5 L)

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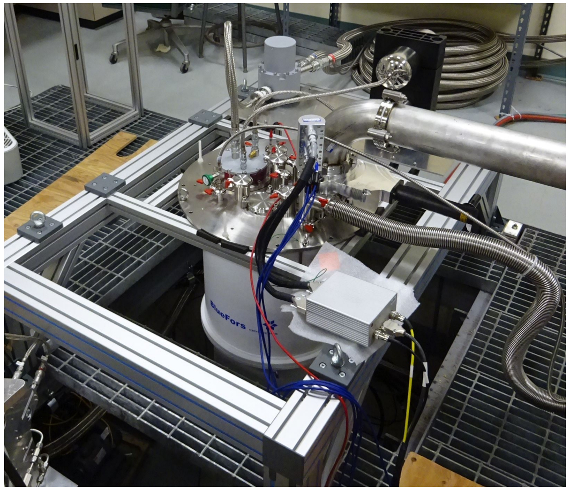
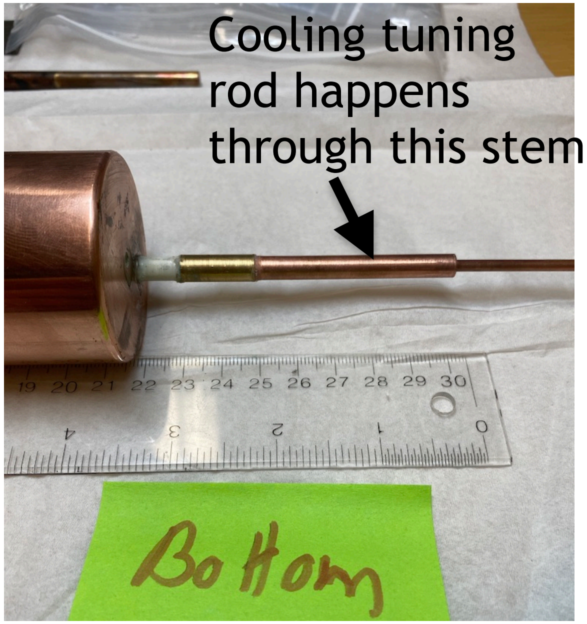
Cooling down the Experiment

- It is absolutely vital that the whole experiment gets cooled down to as low of a temperature as possible
  - Cool superconducting magnet
  - Minimize noise on our readout electronics
- Remember that we are looking at power deposited in our cavity region
- Anything hotter than our readout will radiate photons that can also deposit power





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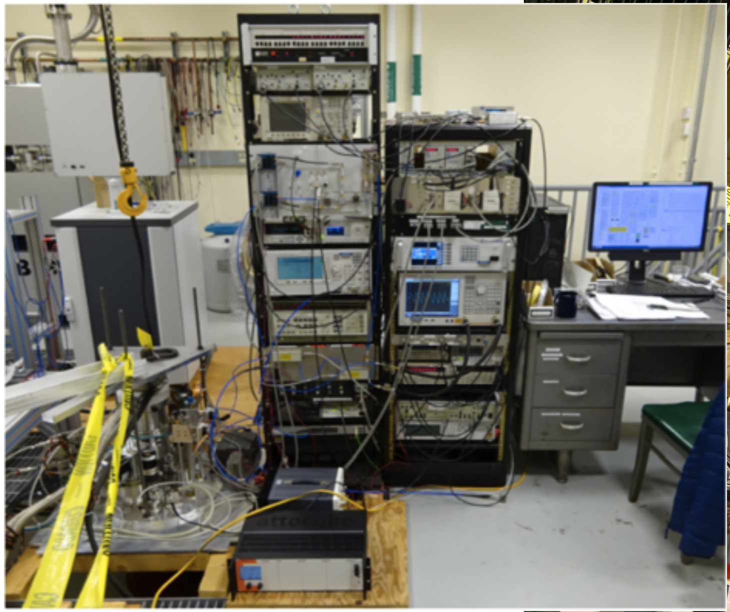
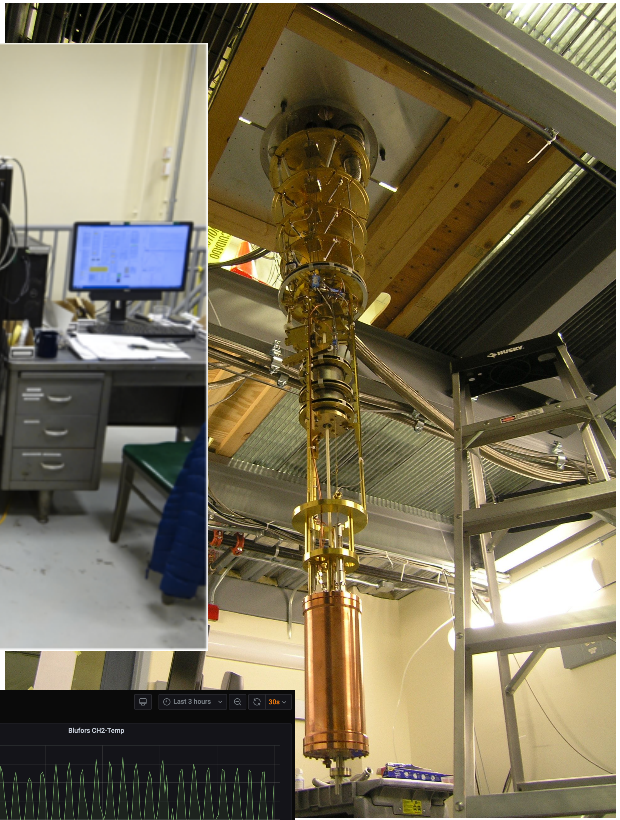
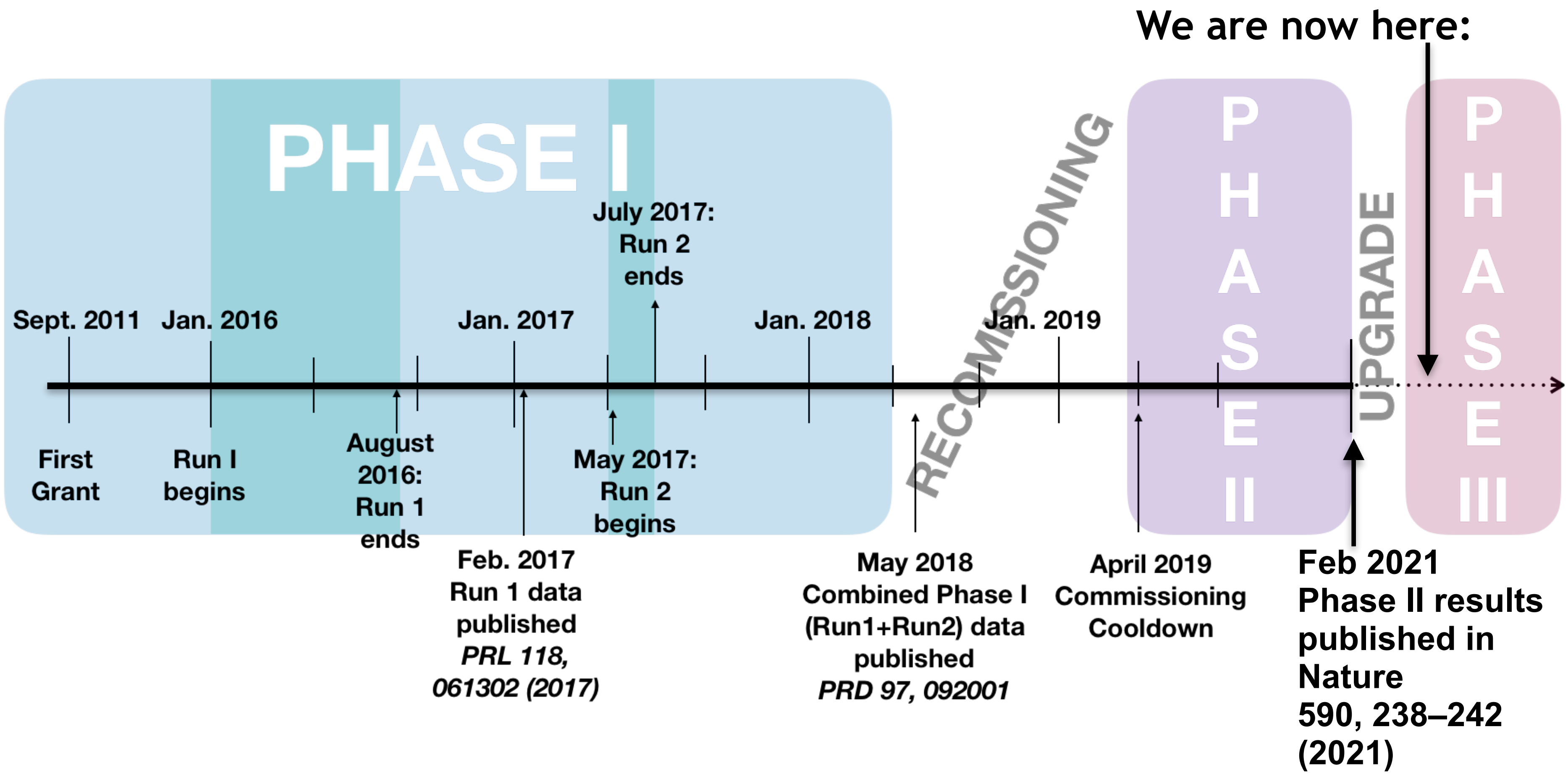
HAYSTAC Infrastructure

- New BlueFors dilution refrigerator installed at Yale
- New variable temperature stage
- Improved cavity support structure
- Software upgrades





HAYSTAC Experiment Timeline



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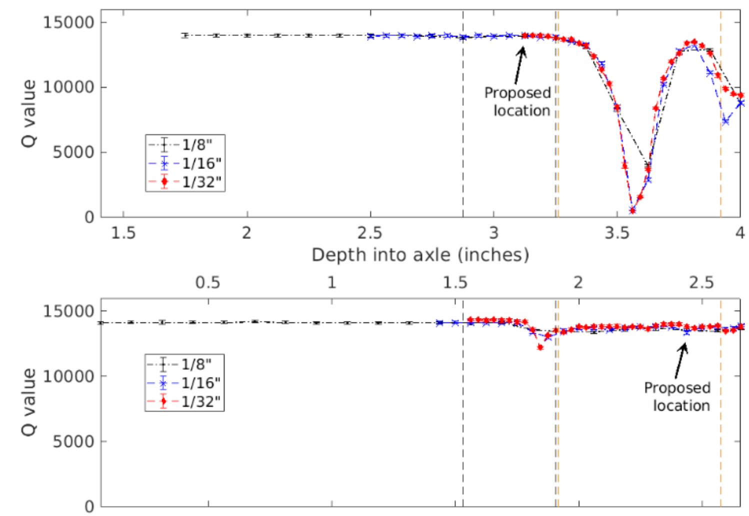
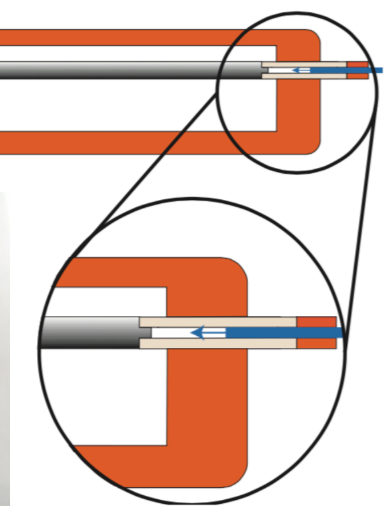
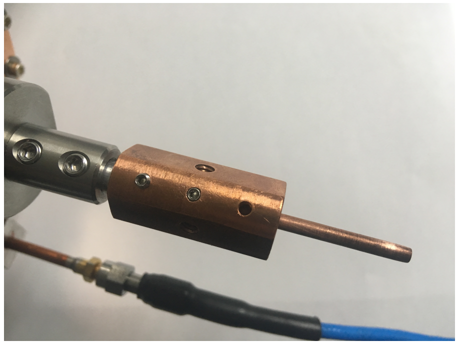
Phase I/II Results

HAYSTAC Phase I – Hot Rod

- HAYSTAC designed to provide a platform for new cavity and amplifier technologies in the 3-12 GHz range
- Phase I implemented first solution to the hot rod problem
- Solution tested to ensure minimum effect on Q of cavity







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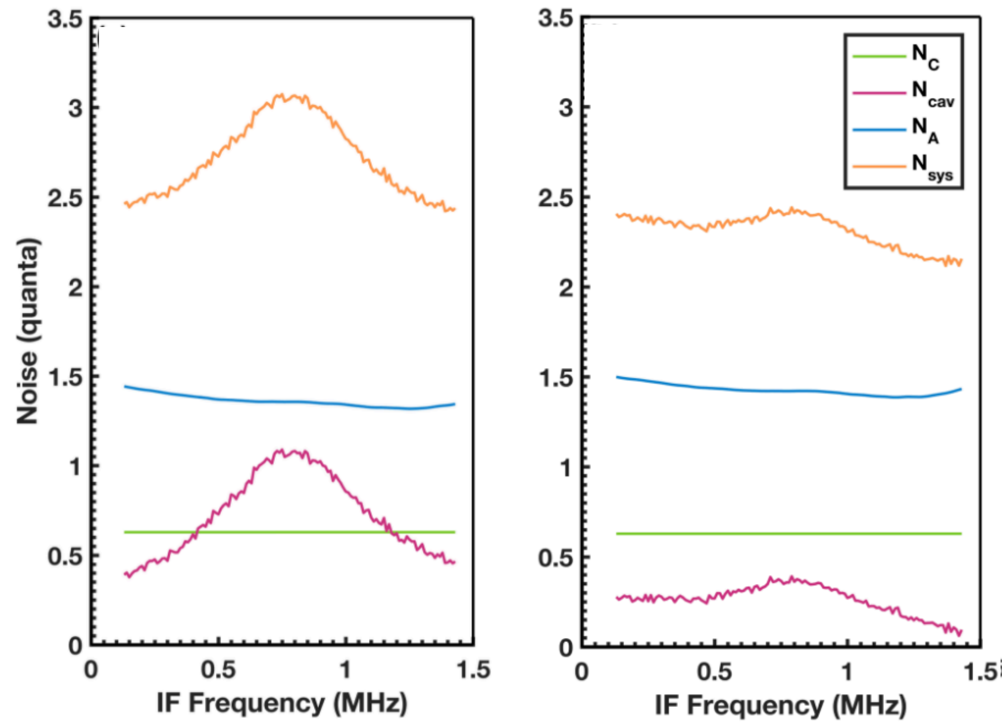
HAYSTAC Phase I – Noise Level

- Run 2 of Phase I achieved noise level 2 times the standard quantum limit
- This was possible thanks in part to solving the hot rod rod problem
- The problem still remains though



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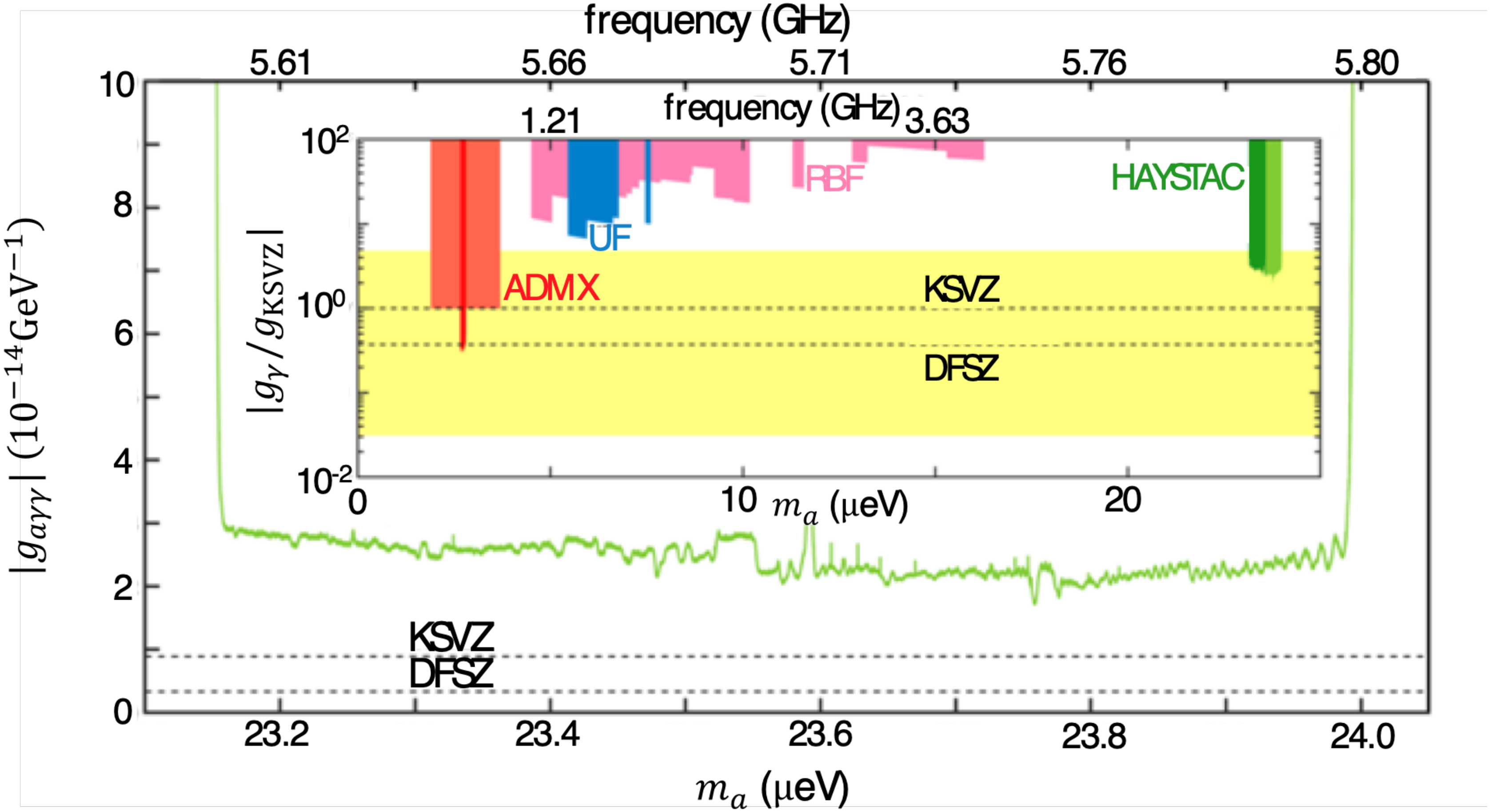
HAYSTAC Phase I – Results

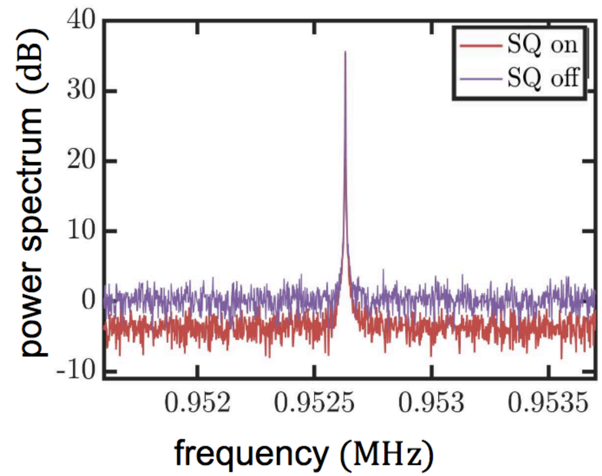
Put it all together….

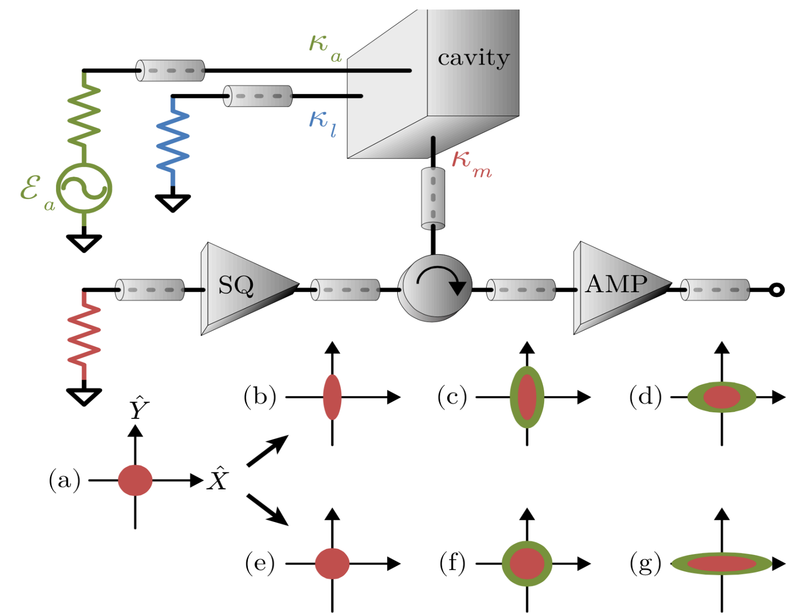


Highest frequencies/masses probed by a cavity experiment so far!

HAYSTAC Phase II – Squeezed State

- We have been able to demonstrate the first squeezed state receiver in a microwave cavity
- Improvement in SNR has been shown uniformly across a large bandwidth





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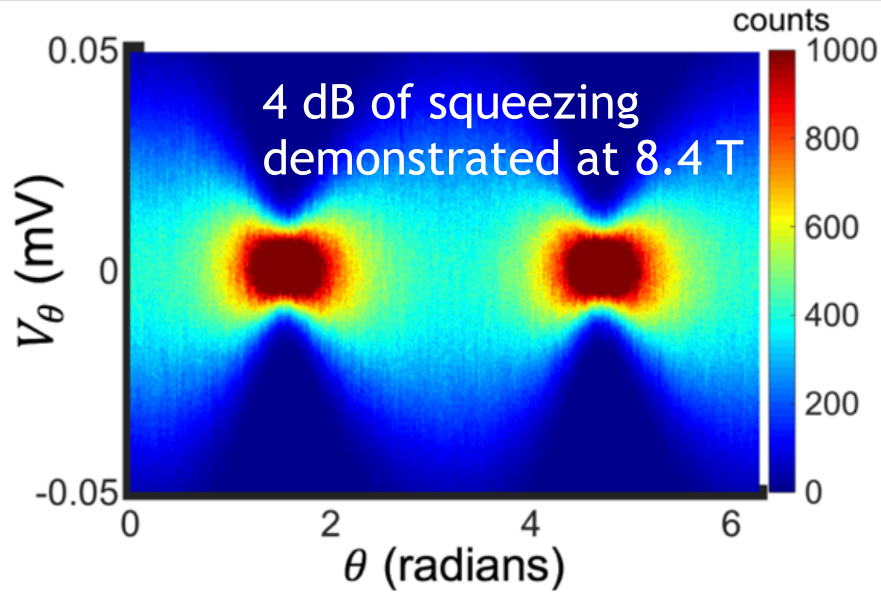
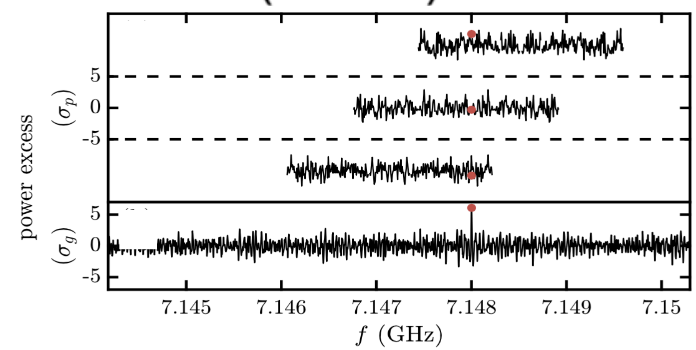
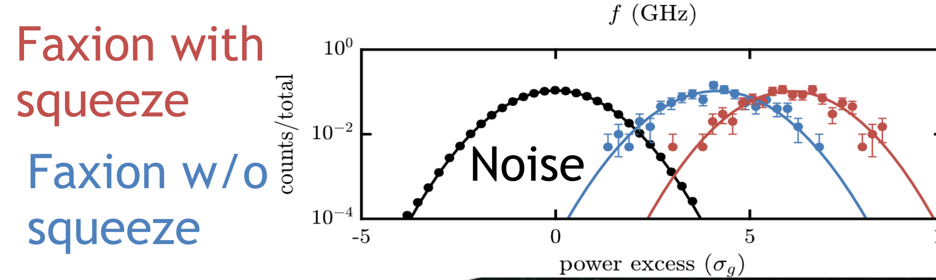
HAYSTAC Phase II – Squeezed State

- Phase II implemented new squeezed state receivers to further improve performance
- We have seen a factor of 2.1 improvement in the scan rate with benchtop tests using injected test axion signals

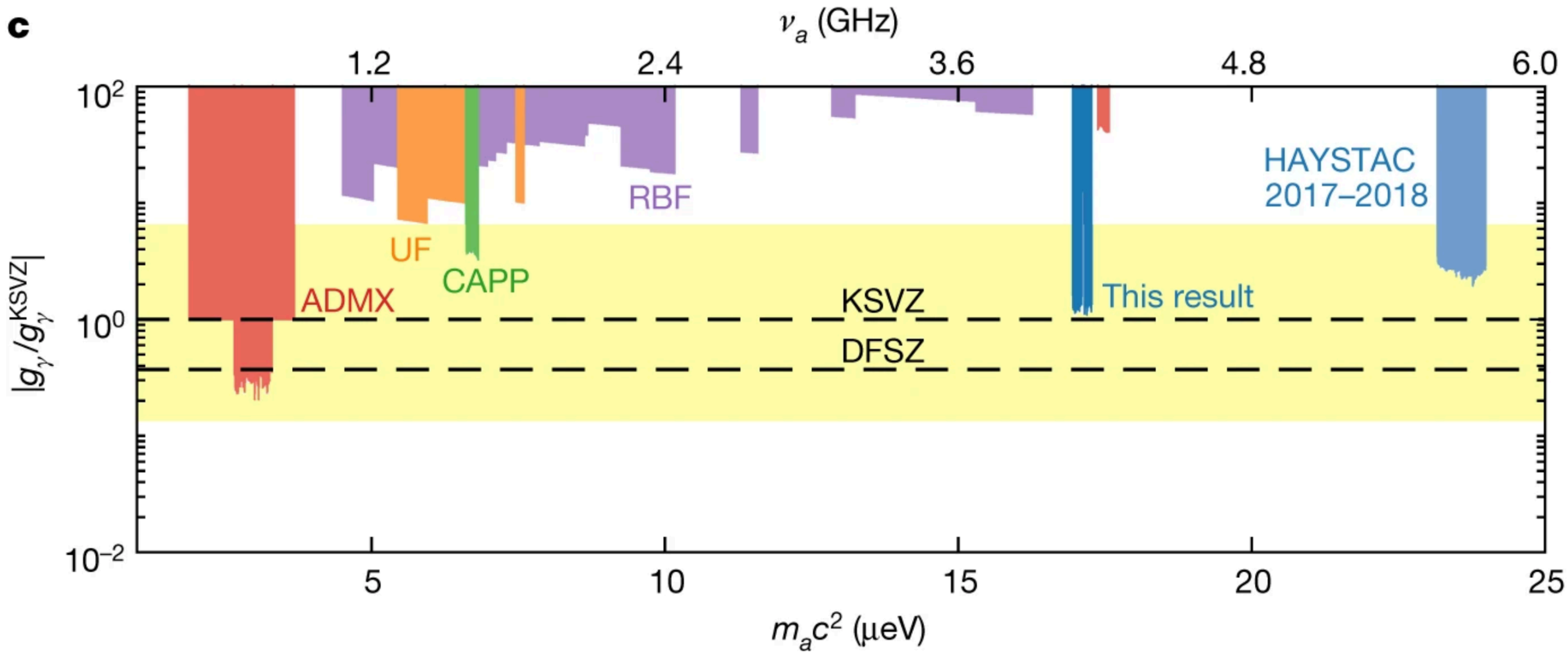






HAYSTAC Phase II – Results

Put it all together….



- Phase I shows the full range of the HAYSTAC experiment
- Phase II shows the potential of squeezers

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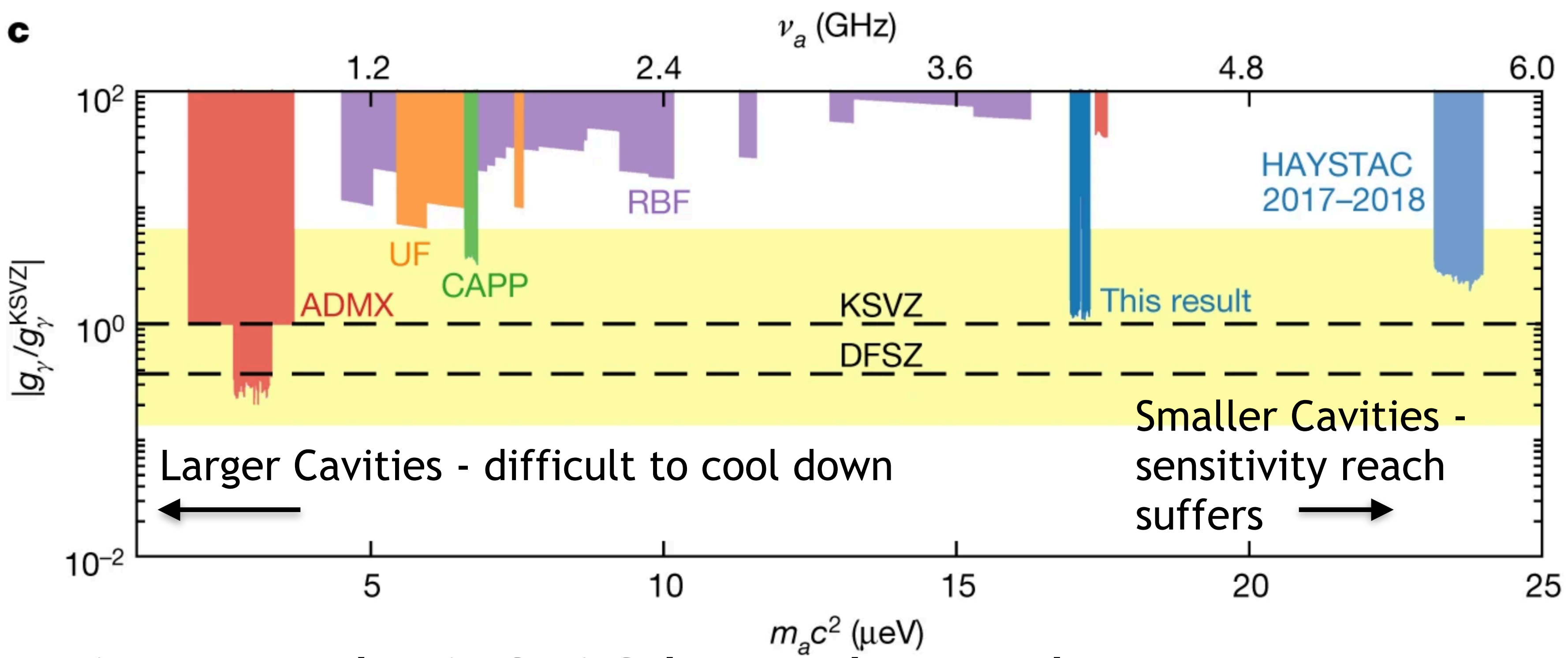
Moving Forward



- ADMX and HAYSTAC have shown the sensitivity range of cavity based axion searches
- Outside of this range the engineering constraints present a problem

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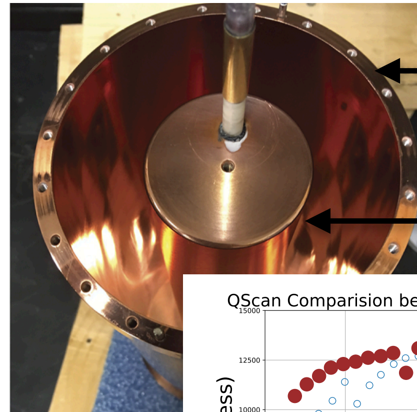
Present and Future Projects

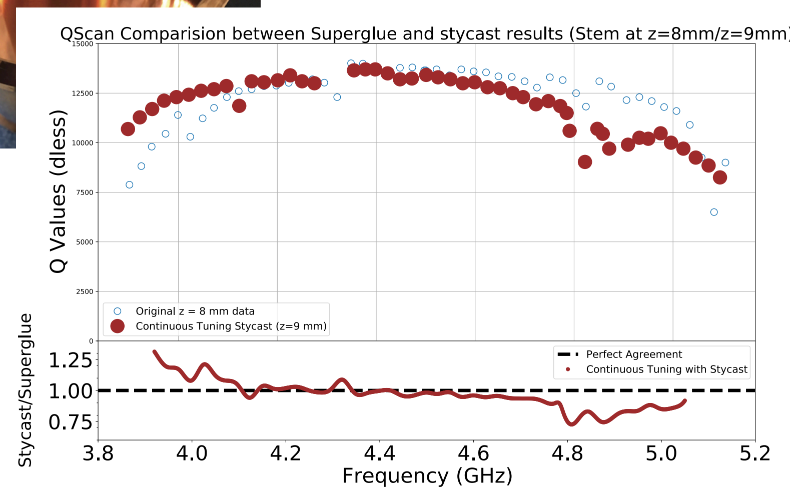
Moving Forward

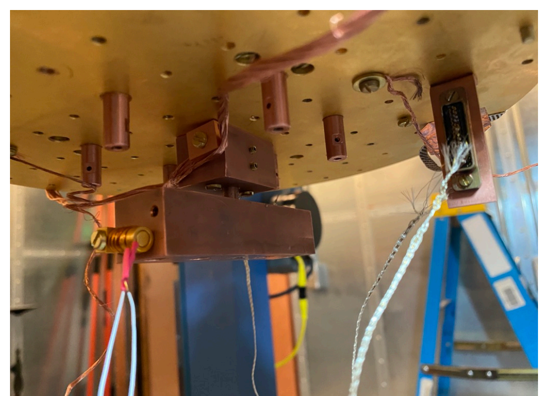
- We are actively analyzing Phase IIb data now
- We paid particular attention to finding a way to thermally connect the tuning rod without losing cavity performance



Cavity wall = 60 mK

Tuning Rod = 225 mK





Also performed a series of mock cool downs to test thermalization on a test piece

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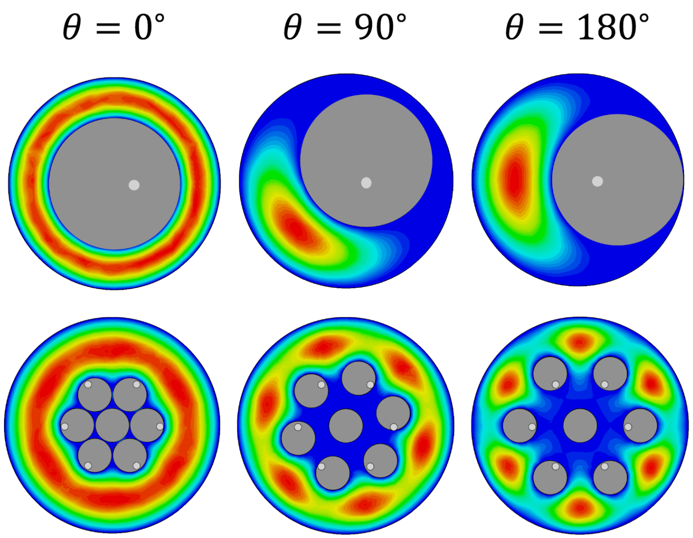
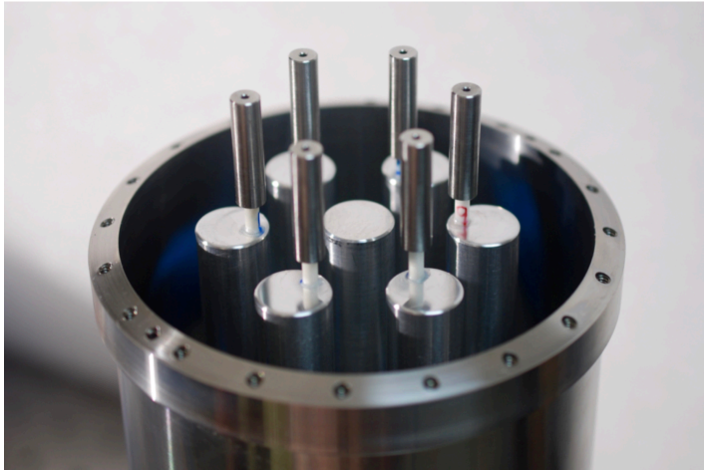
Current R&D Efforts– Multi-rod Cavity

- HAYSTAC is a testbed for new techniques to probe higher frequency (read mass) axion models
- Symmetric tuner has a superior form factor compared to asymmetric tuning mechanisms
- 7-rod cavity has been constructed and plated and is undergoing additional testing at Berkeley





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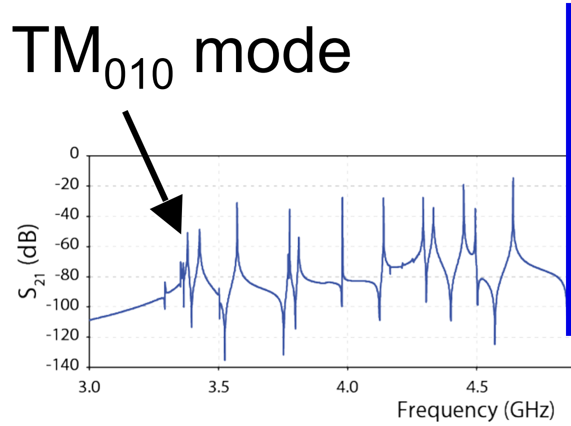
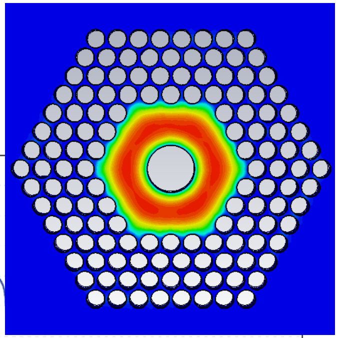
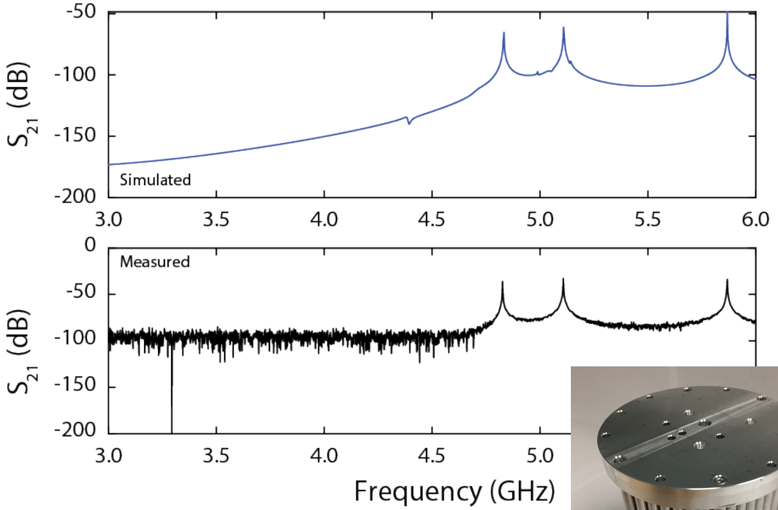
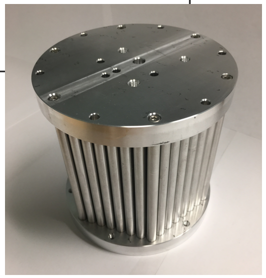
Current R&D Efforts– Photonic Band Gap (PBG)

- Other frequency modes create a forest of mode that can hybridize, reducing the overall form factor
- PBGs are a regular lattice of rods that contain a specific mode in their center region
- Other modes freely propagate out – clear out intruder modes



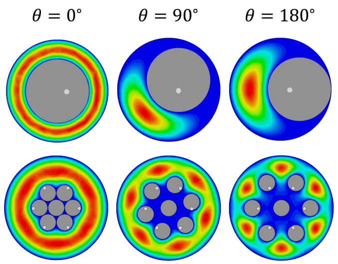


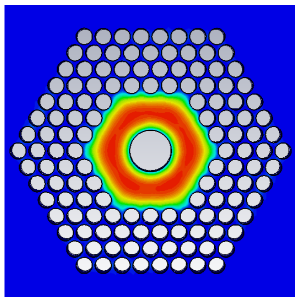


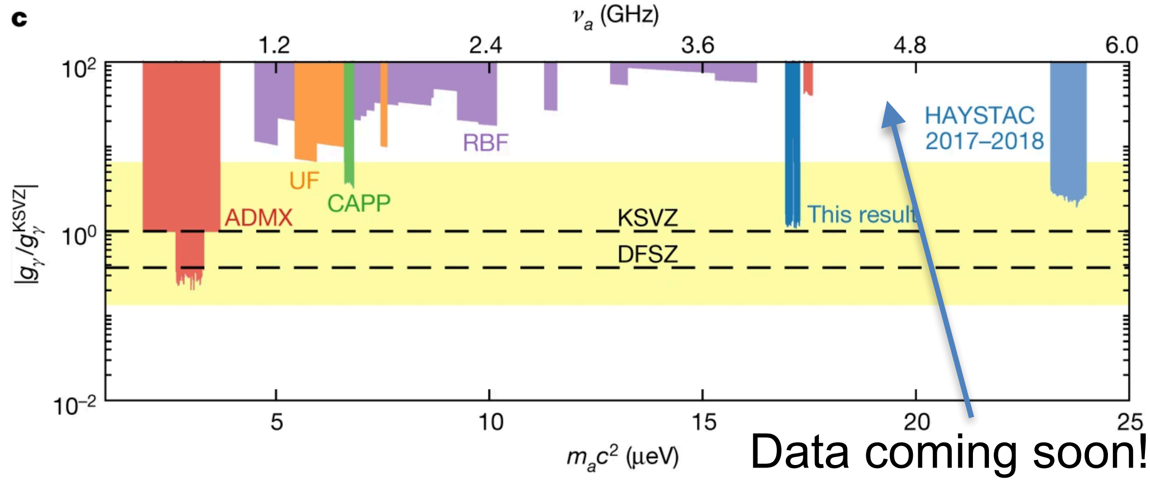


Summary/Conclusion

Conclusion







- The HAYSTAC experiment has demonstrated the highest frequency sensitivity for cavity axion searches and has successfully implemented squeezing in an axion experiment
- There is lots of exciting R&D underway to further expand the frequency reach of cavity based experiments

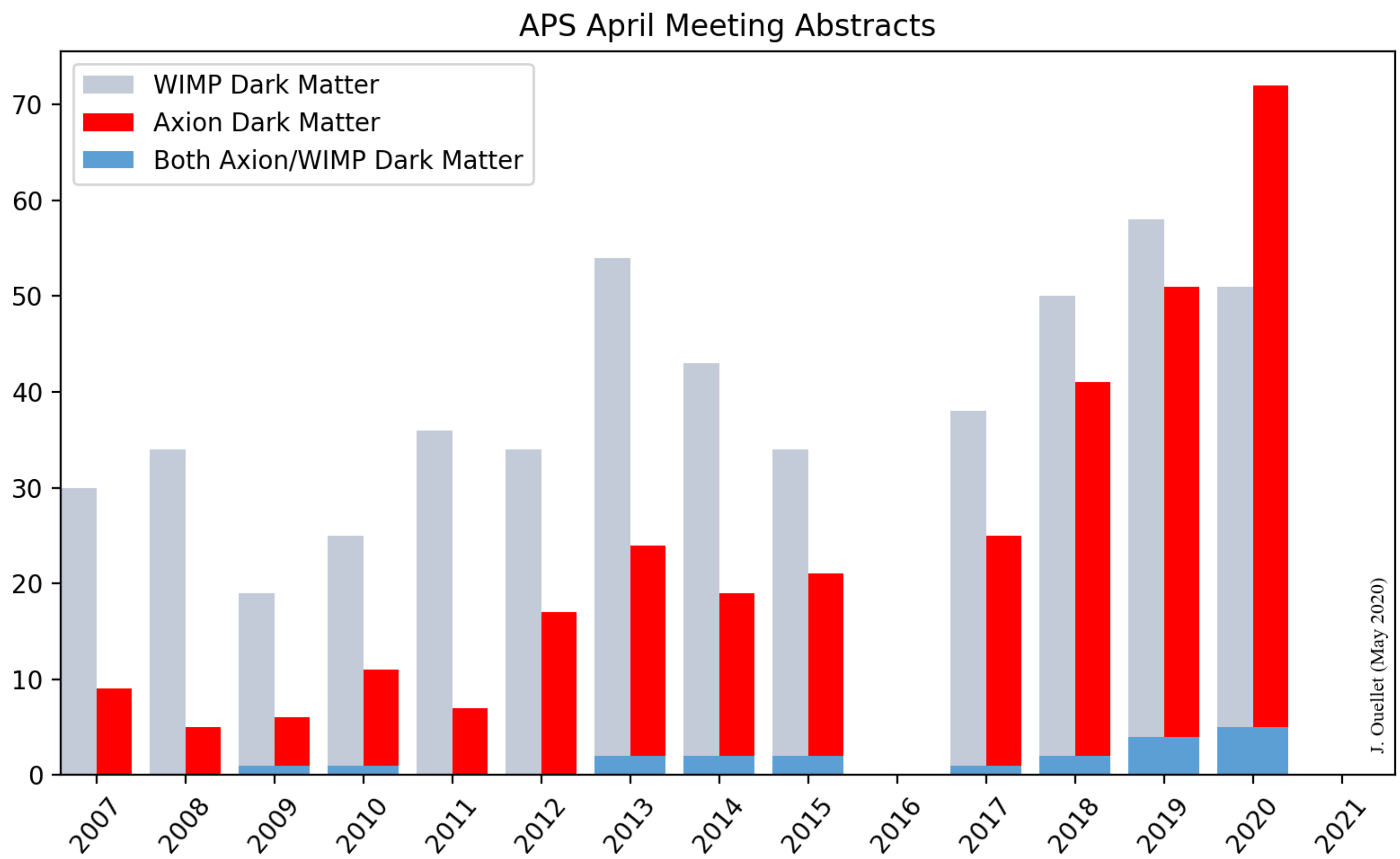
Any additional questions: aleder@berkeley.edu

Thank you for your attention

Questions/Comments?

Extra Slides

Axions as DM Candidate



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Finding yourself in a Squeeze

- What is squeezing?
- The Heisenberg UC principal is always valid
- Start with a general quantum mechanical state that always satisfies the HUC principal
- You can create a series of mathematical operations on this wave function that inversely affect the UC in pos/momentum

$$\Delta x \Delta p = \frac{\hbar}{2}$$

$$\Psi(x) = C_0 exp(-\frac{(x-x_0)^2}{2\omega_0^2} + ip_0 x)$$

$$\zeta = re^{-i\theta}$$

$$(\Delta x_\Psi)^2 = \frac{e^{-2\zeta}}{2m\omega}$$

$$(\Delta p_\Psi)^2 = \frac{m\omega e^{+2\zeta}}{2}$$

Finding yourself in a Squeeze

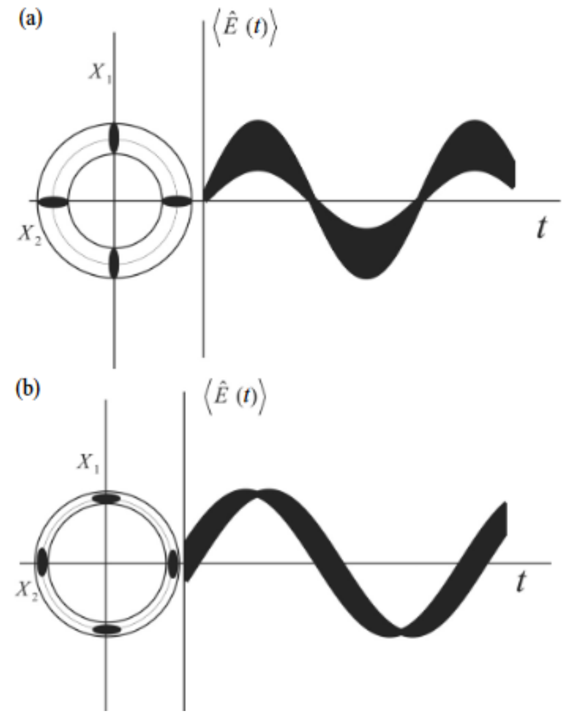
- Now we can create a state where we are in control of the uncertainty in either the position or momentum
- You can do this for any pair of commuting variables, including Energy/Time

$$(\Delta x_\Psi)^2 = \frac{e^{-2\zeta}}{2m\omega}$$

$$(\Delta p_\Psi)^2 = \frac{m\omega e^{+2\zeta}}{2}$$

Finding yourself in a Squeeze

- If you then draw out the resulting wave functions you can then pick one:
    - High degree of certainty about the amplitude (energy) of the wave
    - OR
    - High degree of certainty about phase (timing) of the wave
- On HAYSTAC we don't care as much about when the axion interacted



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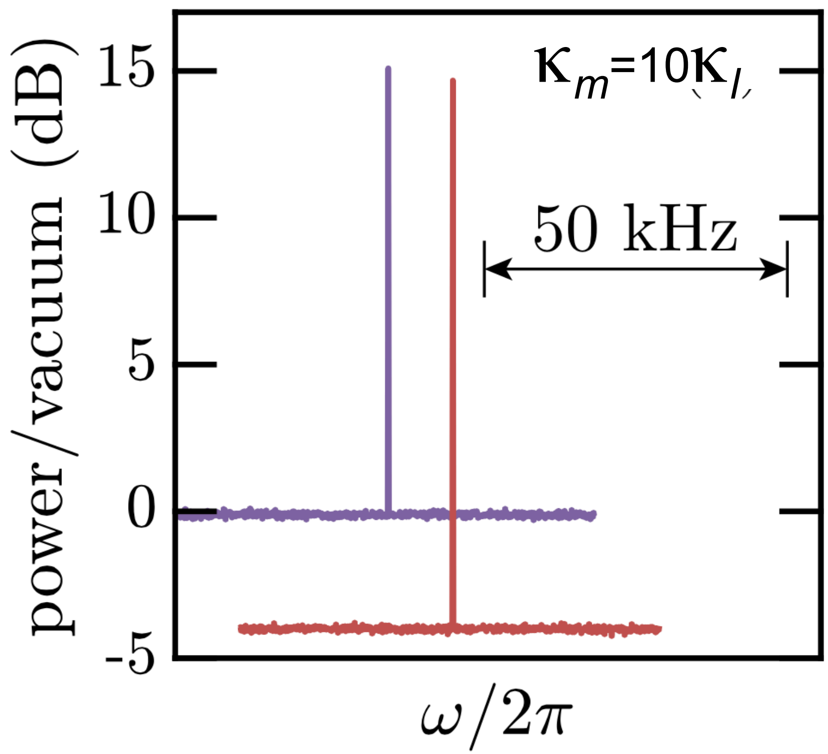
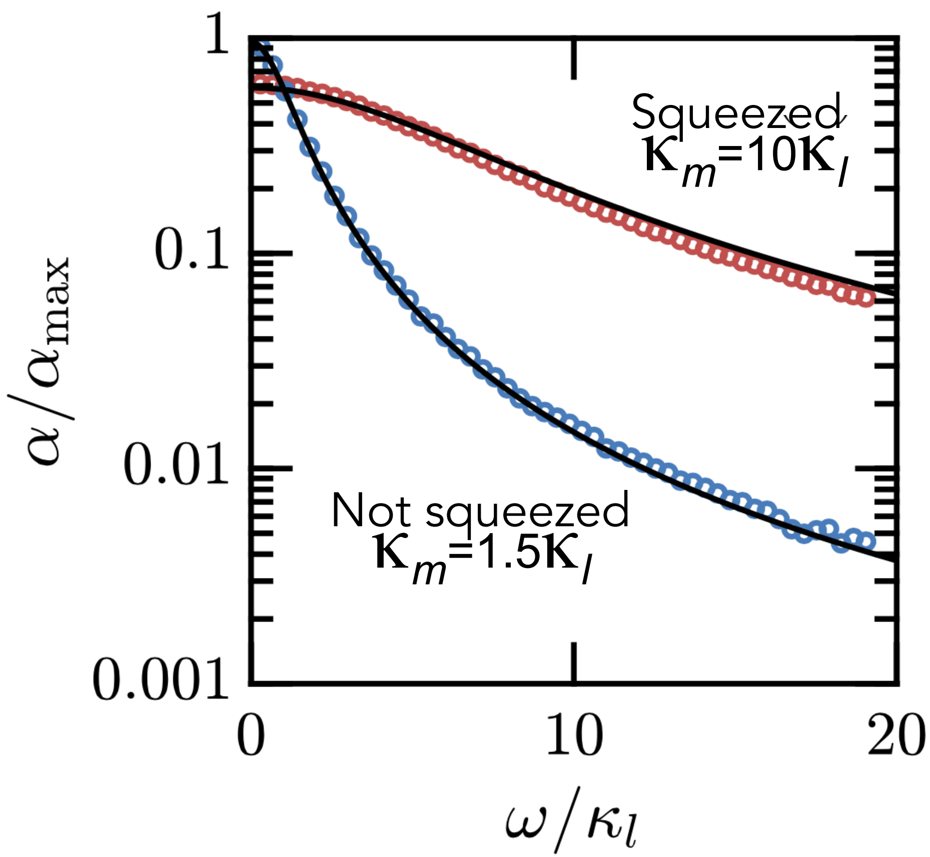
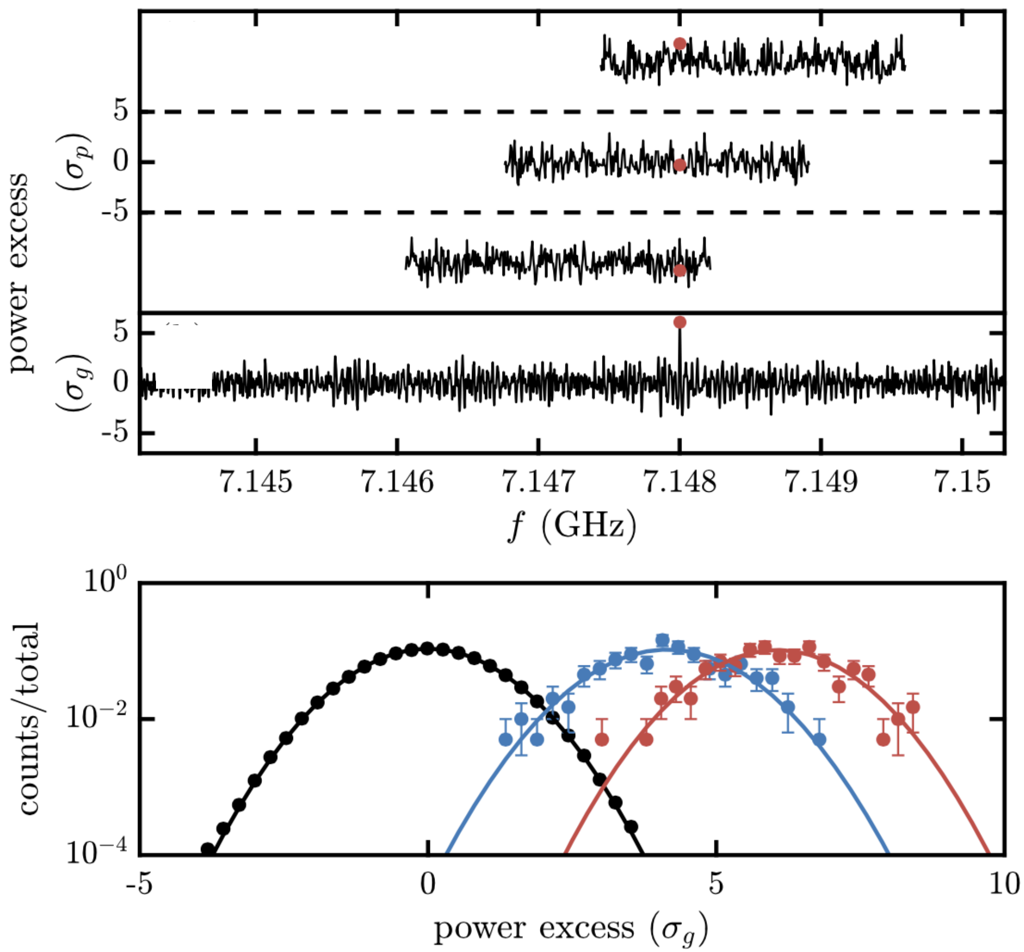
Squeezing implies uniformly higher S/N over a wider bandwidth





The scan rate with squeezing optimizes at large overcoupling of the cavity, thus higher BW

Corresponding factor of 2.12 speedup in scan rate demonstrated



- ❑ Mock axion search conducted on the JILA testbed
- ❑ Synthetic signal injected into the system of unknown frequency
- ❑ Search protocol repeated 200 times for each configuration, data plotted in terms of their standard deviation
- ❑ Results are μ_s = 6.05 ± 0.07 (with squeezing), μ_s = 4.15 ± 0.07 (w/o), leading to 2.12 ± 0.08 speedup
- ❑ HAYSTAC commissioning has now demonstrated squeezing
- ❑ JILA working on x10 speedup

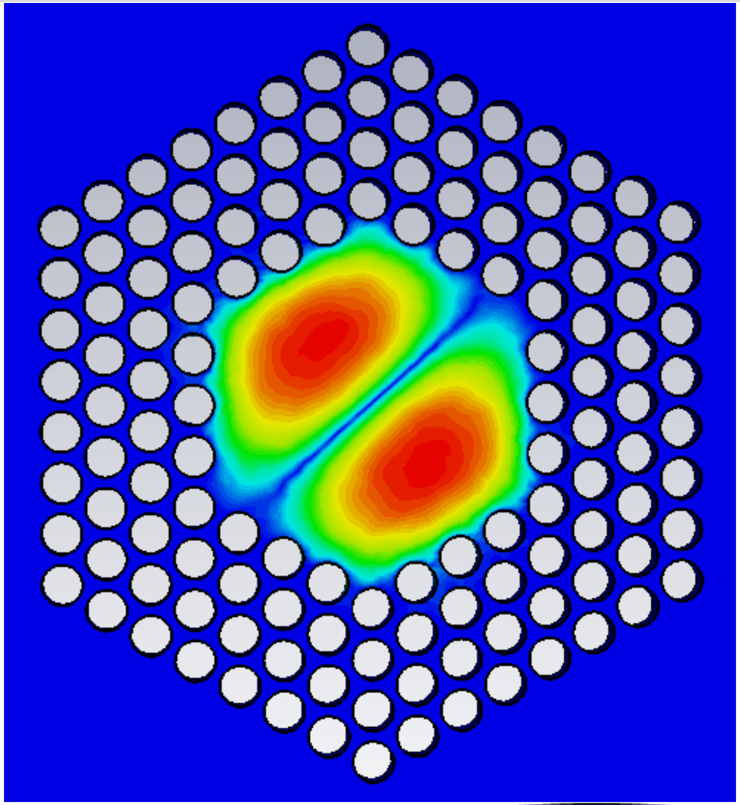
Photonic Band Gap (PBG) background

Basic definition

- Periodic lattice of metal and/or dielectric rods with an open boundary
- Band gap behavior: certain frequencies cannot propagate through lattice ("disallowed")

Creation of a PBG resonator

- Defect in lattice confines "disallowed" modes
- All other modes propagate out
- Our case: confine TM modes, not TE modes



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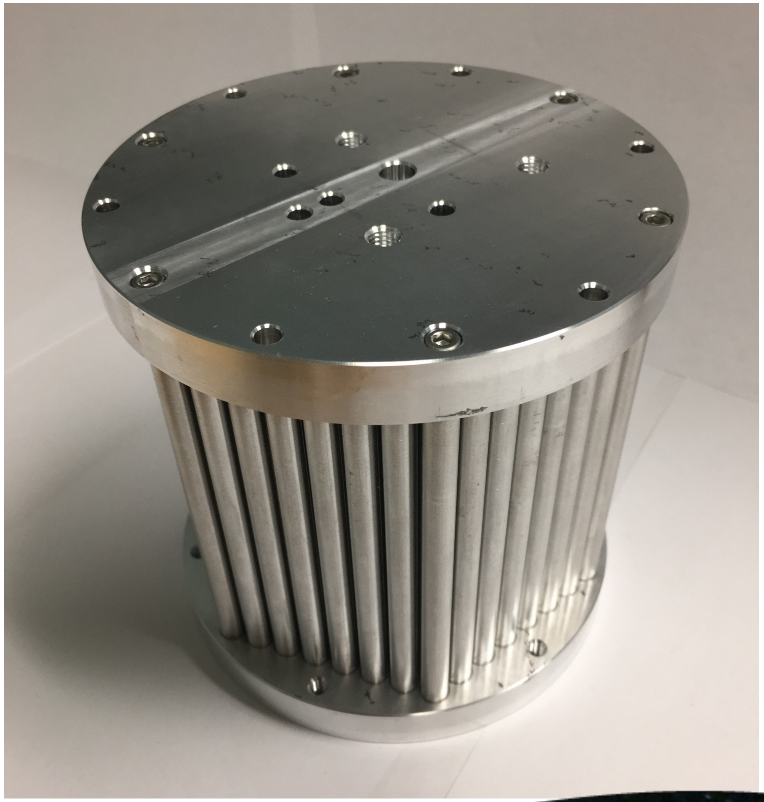
Aluminum prototype “stock” lattice

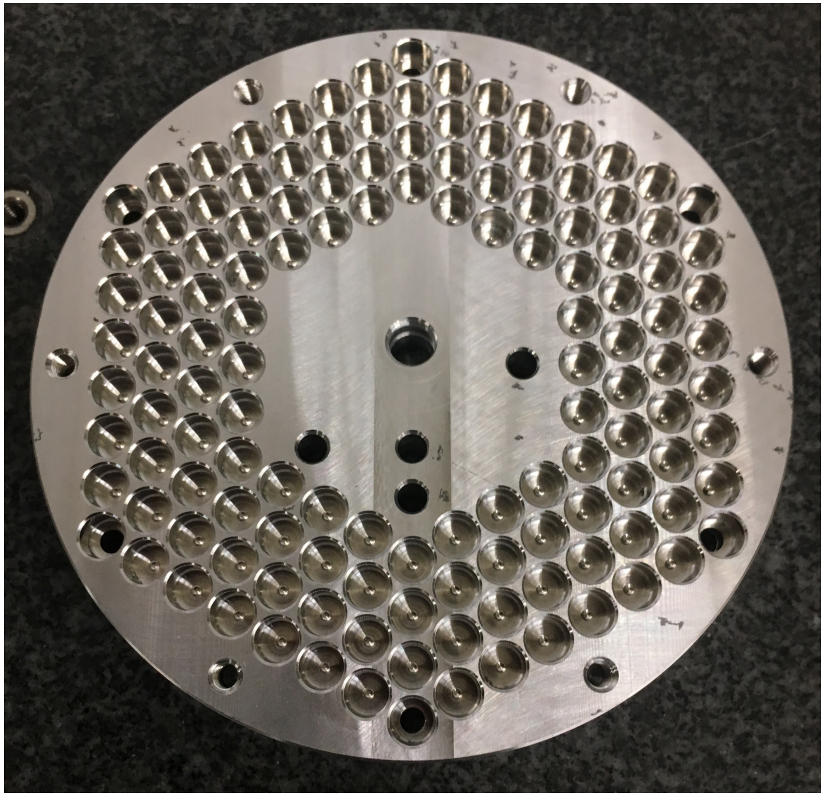
Prototype goals

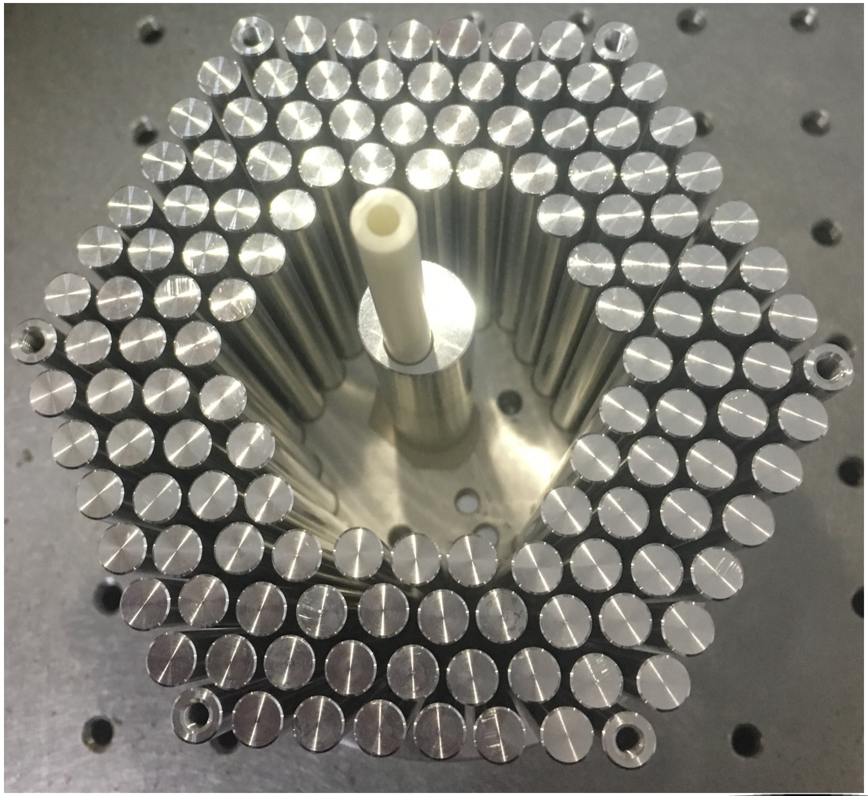
- Investigate tuning:
  - Single tuning rod in defect (same as HAYSTAC cavity)
  - Tuning range: 7.4 to 9.4 GHz
- Study fabrication possibilities:
  - Alignment/tolerances
  - Assembly options
  - Try plating

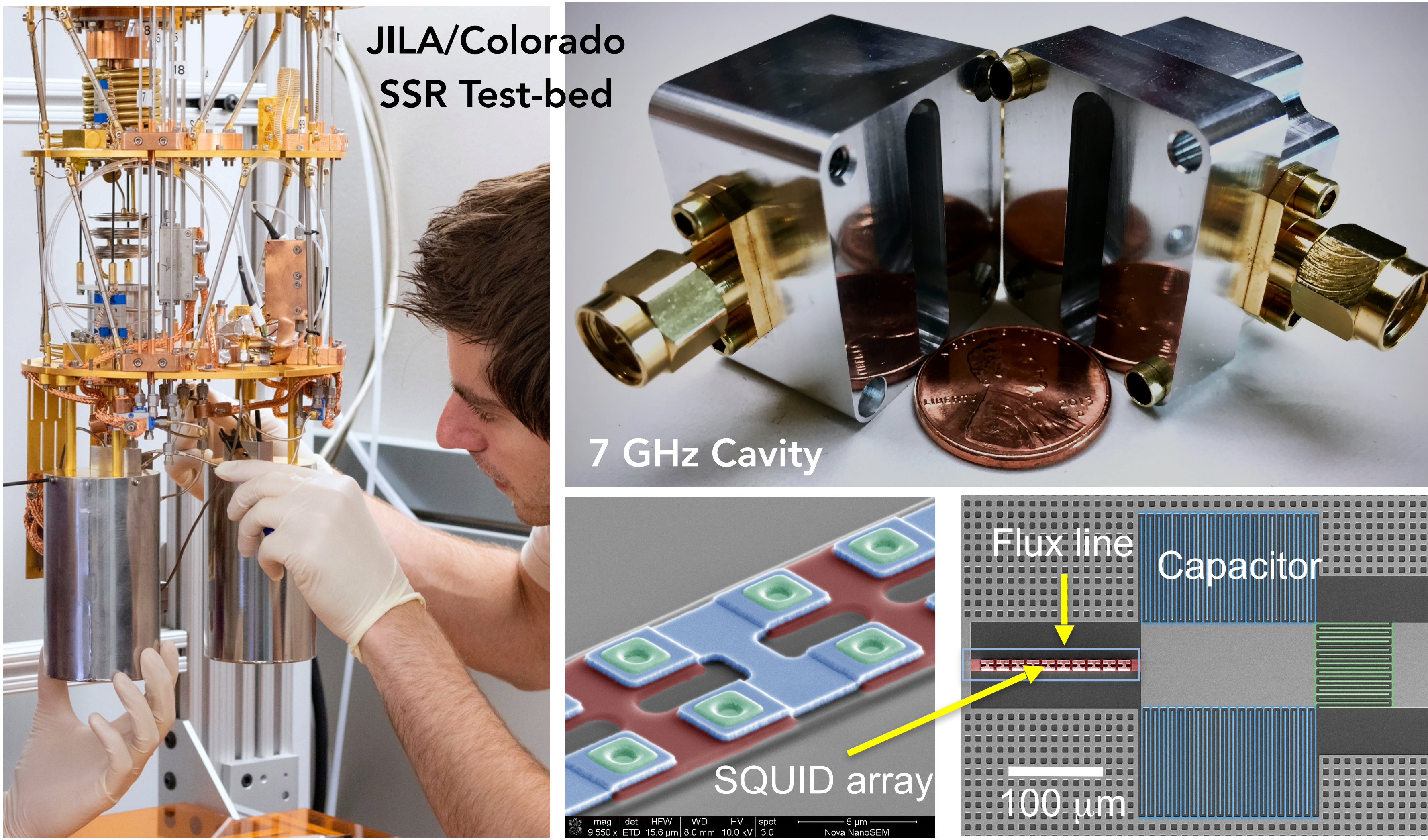


HAYSTAC

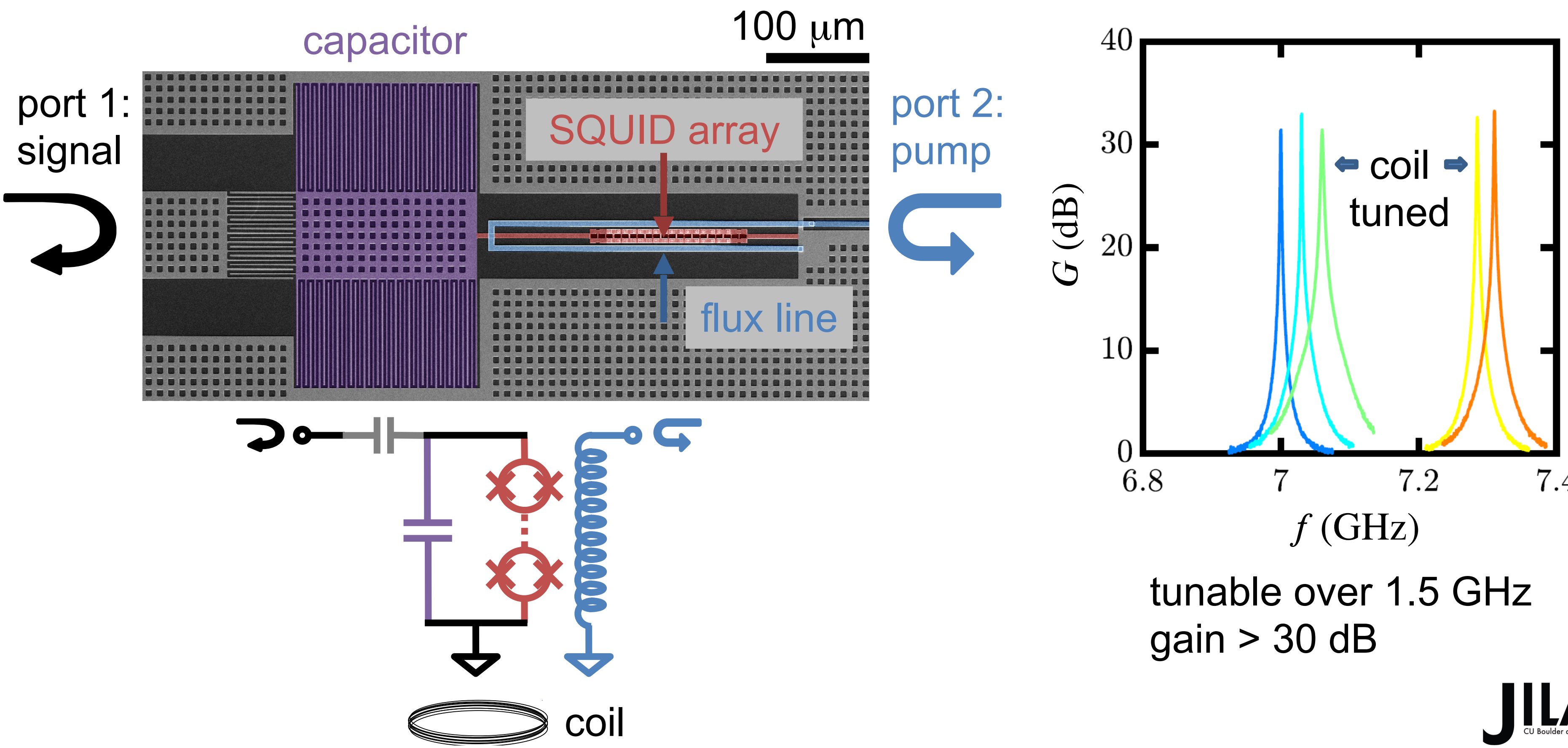
Aluminum prototype “stock” lattice






JILA/Colorado
SSR Test-bed
7 GHz Cavity
Flux line
Capacitor
SQUID array
100 µm
mag 9 550 x
det ETD
HFW 15.6 µm
WD 8.0 mm
HV 10.0 kV
spot 3.0
5 µm
Nova NanoSEM

Low noise amplification with Josephson parametric amplifiers

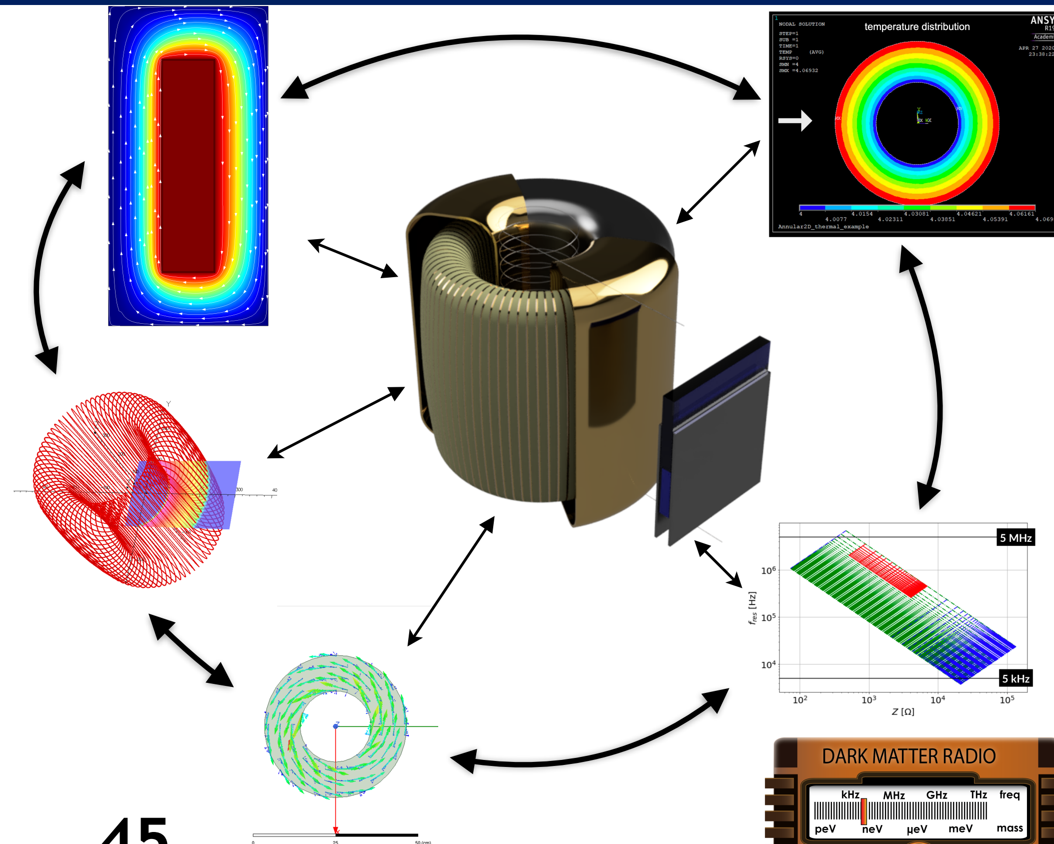


tunable over 1.5 GHz
gain > 30 dB

JILA CU Boulder and NIST

Optimization Campaign

- The DM Radio 50 L campaign has multiple components that all have to be simultaneously co-optimized
- This is an iterative process, where individual calculations build upon each other
- Here we are going to talk about the main 5 campaigns that have gone into the design of the 50 L experiment
- Experience will inform m³ design as well - see other talks in section

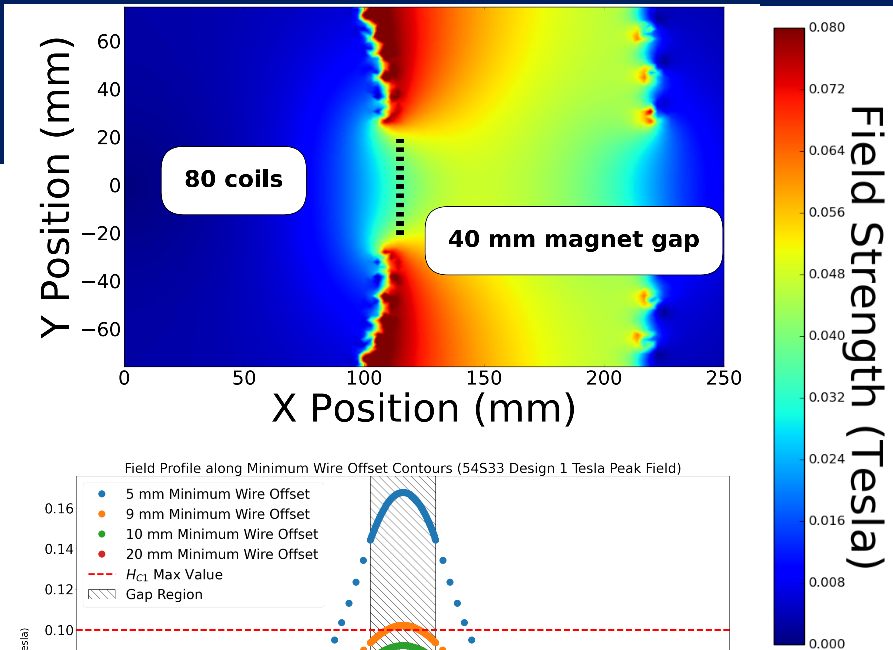


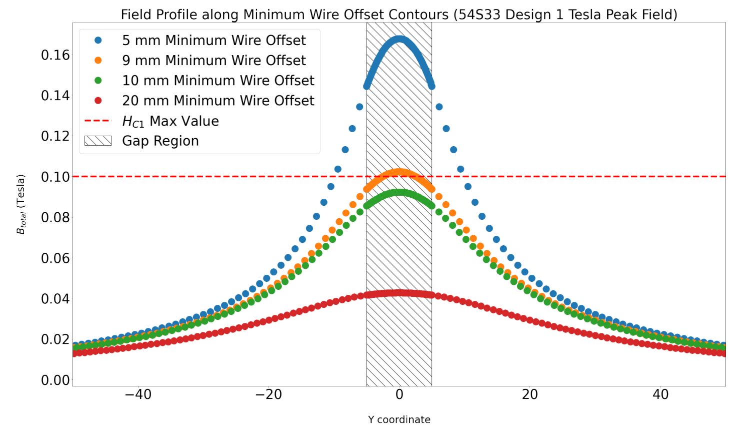
DARK MATTER RADIO

Magnet Design

Parameter	Design Goal
Peak Field	0.1-1 Tesla
Max Fringe	100 mTesla
Science	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 end of 2021



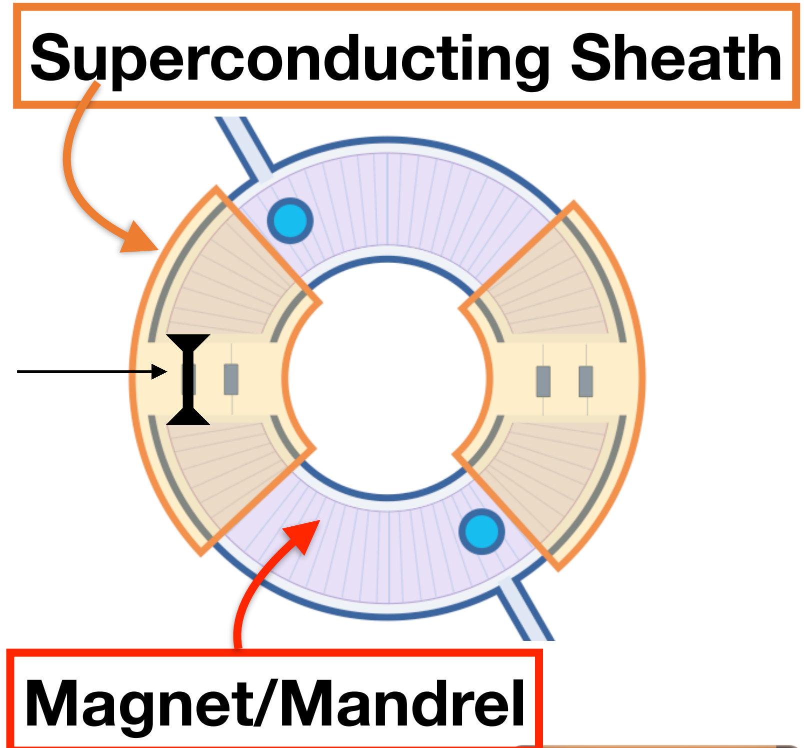


Fringe field profiles along gap

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

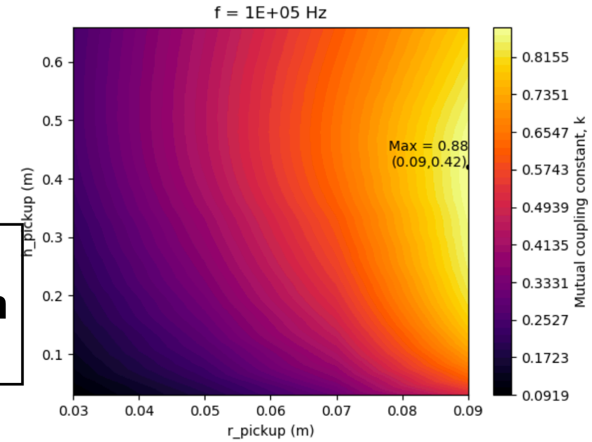
Dominant coupling losses stem from this mandrel dimension

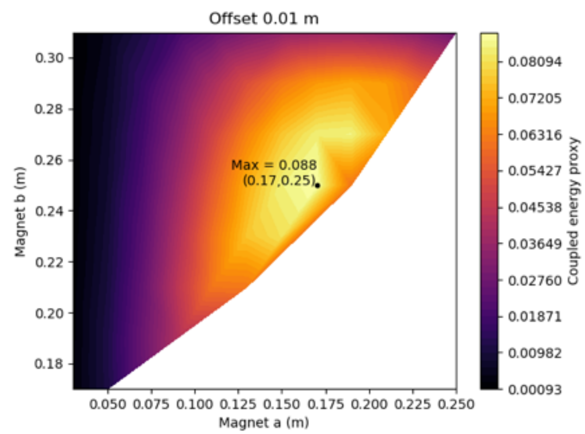


Sheath/Pickup Signal Coupling

- 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



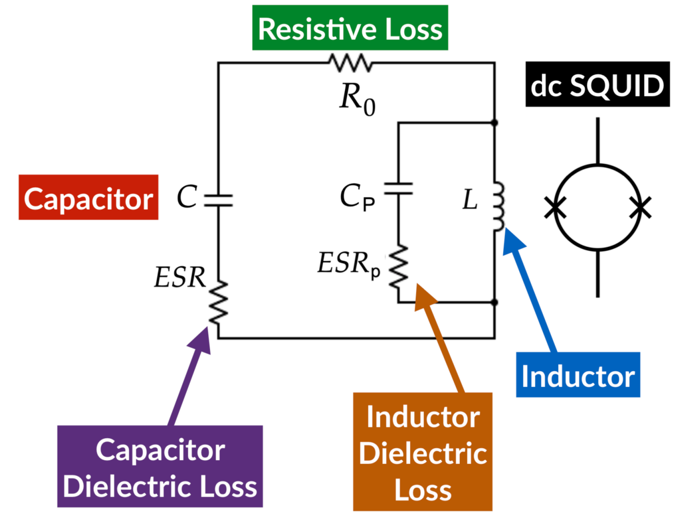


Maximum signal efficiency occurs when pickup maximally fills out center region

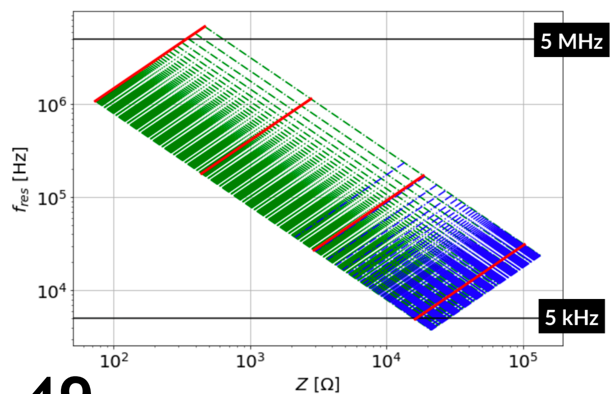
Resonator Q Optimization

- We have also looked into a variety of LC resonator designs
- For full details - see Singh talk later in this session (K19.00004)
- 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

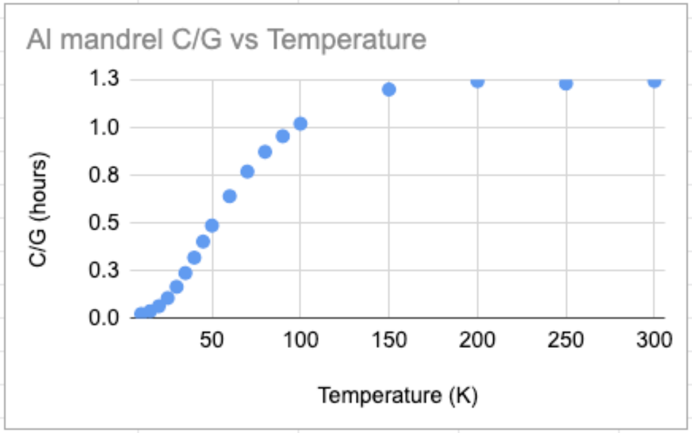


Blue: Constant Inductance
Green: Constant Capacitance



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

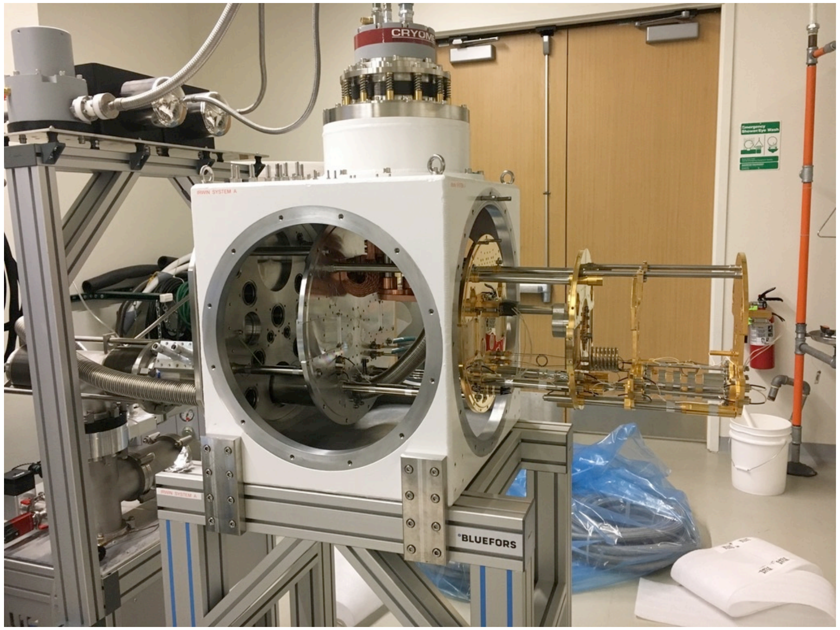


Current Status of DMR 50 L

- Construction has begun on the individual components of DMR 50L - for example the magnet

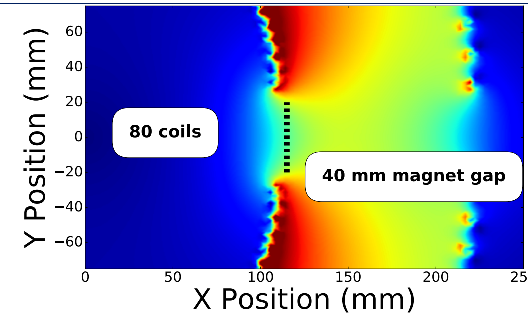
- Experimental verification of sims/final design studies will take place over 2021

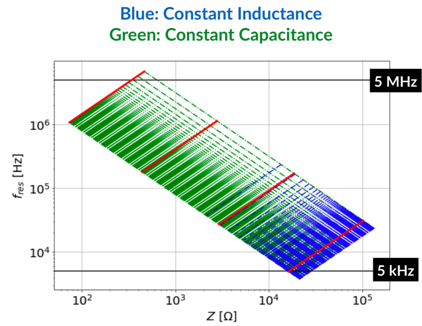
- Data taking scheduled to take place in ~ 2022

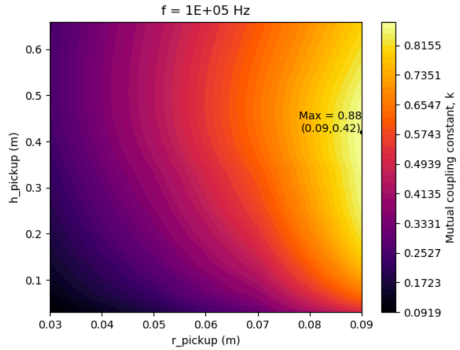


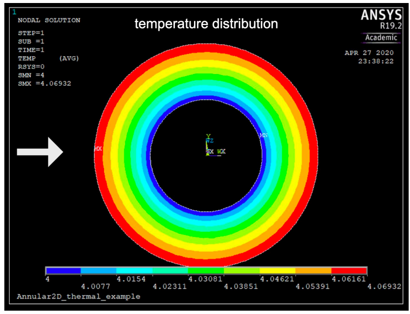
Summary/Conclus

- We are on track to deliver a fully optimized from the ground up 50L detector design for lower mass axion searches
- We have embarked on a series of simulation/modeling campaigns to minimize all possible losses while still maximizing SNR
- Simulation verification with data underway
- Construction has started with data taking to begin in ~ 2022









Parameter	Design
Search	5 kHz - 5 MHz
Scan Time	3 years
Sensitivity	5e-15 1/GeV

Sensitivity and Timescales

Summary

- **DMRadio-50L**
  - Demonstration of magnet + resonator
  - Search for Axion-like particles
  - 20 peV < m_a < 20 neV (5 kHz < ν_a < 5 MHz)
  - $g_{a\gamma\gamma} < 5 \cdot 10^{-15}$ GeV^{-1}
  - Beginning Construction
  - 3-year scan starting in ~2022
  - Afterwards: Next generation sensors

- **DMRadio-m³**
  - Probing QCD axion models
  - 20 neV < m_a < 800 neV (5 MHz < ν_a < 200 MHz)
  - DFSZ axion sensitivity above 100 neV (30 MHz)
  - Design funded by DOI New Initiatives Program
    - PreCDR in preparation
  - 5-year scan time starting in ~2025