Updates on the Princeton Axion Search (PXS)

Saptarshi Chaudhuri

August 6, 2024

DMRadio Collaboration Meeting

Team Members

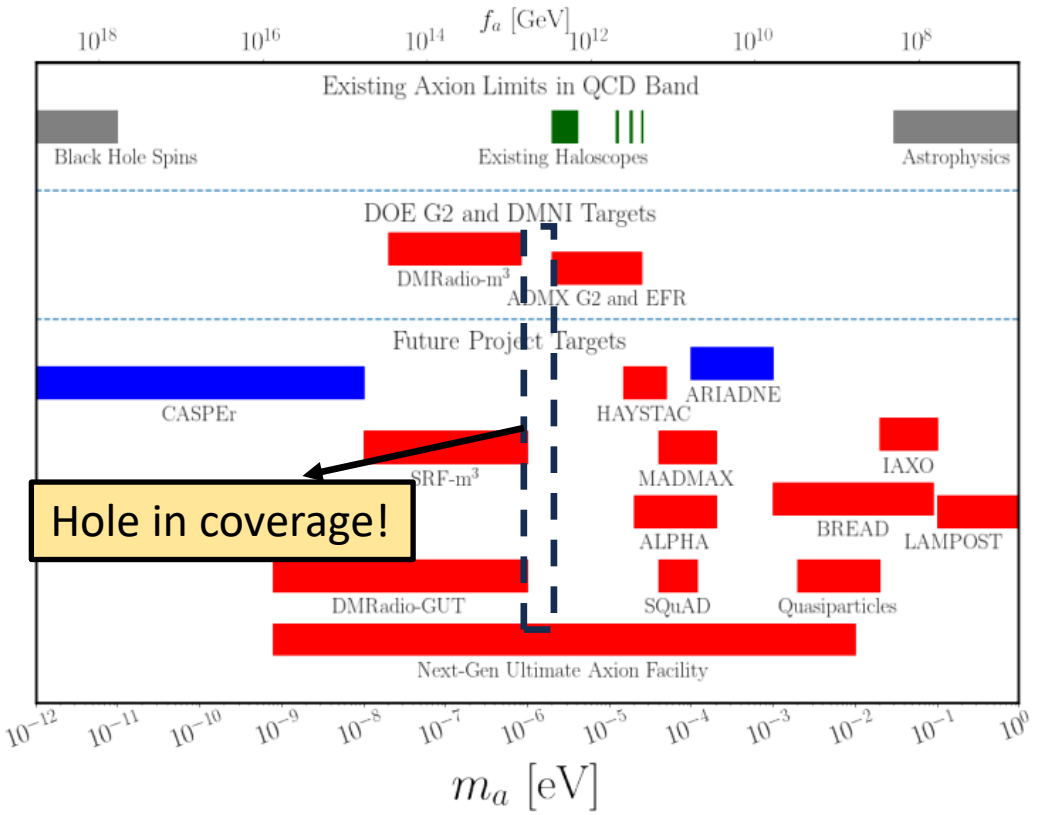
Princeton: Joelle-Marie Begin, Saptarshi Chaudhuri, Roman Kolevatov, Nate Otto, Lyman Page, Joe Wiedemann

DOE PPPL: Siwei Chen, Yi Li, Yuhu Zhai

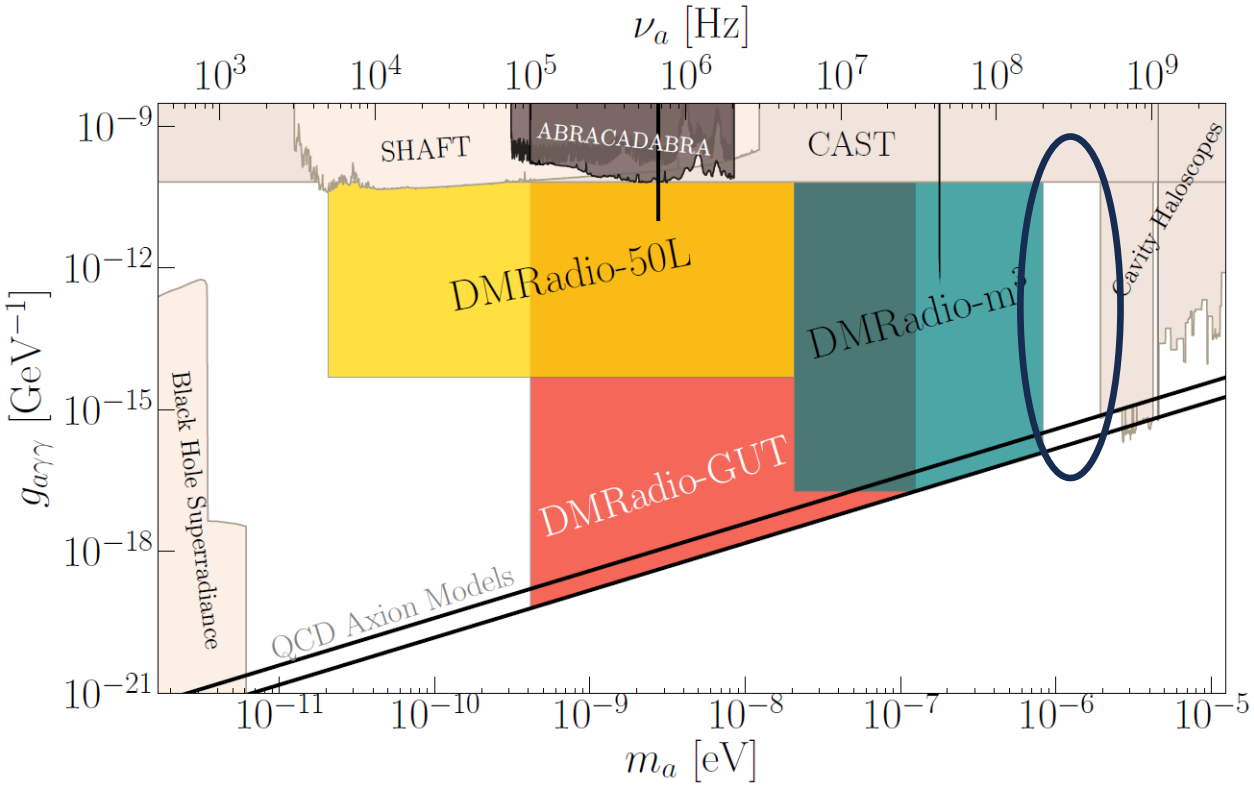
Caltech/JPL: Peter Day, Farzad Faramarzi, Jonas Zmuidzinas

PXS: a 0.8-2.1 μeV QCD axion search

- Addressing critical transitional frequency range between DMRadio program and traditional cavity haloscopes (ADMX, CAPP, HAYSTAC…)



Snowmass 2021 White Paper on Axion Dark Matter, arxiv:2203.14923v3 (2023)



Brouwer, et al. (DMRadio collaboration) arxiv:2203.11246, PRD **106**, 112003 (2022)

Funded by Simons Foundation

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December 11, 2023

News

PRINCETON UNIVERSITY

Ultra-powerful magnet facility launches at PPPL

By Raphael Rosen, Princeton Plasma Physics Laboratory on Feb. 7, 2024, 1:14 p.m.

A thank you to all of the students and postdoc!

Postdoc
- Roman Kolevatov

PhD Thesis Students
- Joelle-Marie Begin
- Nate Otto
- Joe Wiedemann

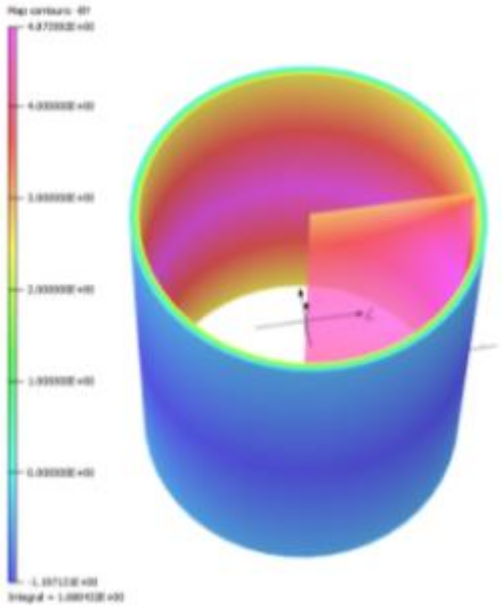
Senior Thesis Students
- Haaris Mian
- Bryan Oller

Experimental Projects
- Rahul Balaji
- Andrei Kasevitch
- Dongyeob Kim
- Bowei Liu
- Nicolas Patino
- Damiano Tietto
- Dmitrii Trunin
- Zack Gelles
- Victor Ivo
- Ilia Kochergin
- Anna Biggs
- Maxim Borovkov
- Carolina Figueiredo
- Zihan Zhou
- Josef Zimmerman

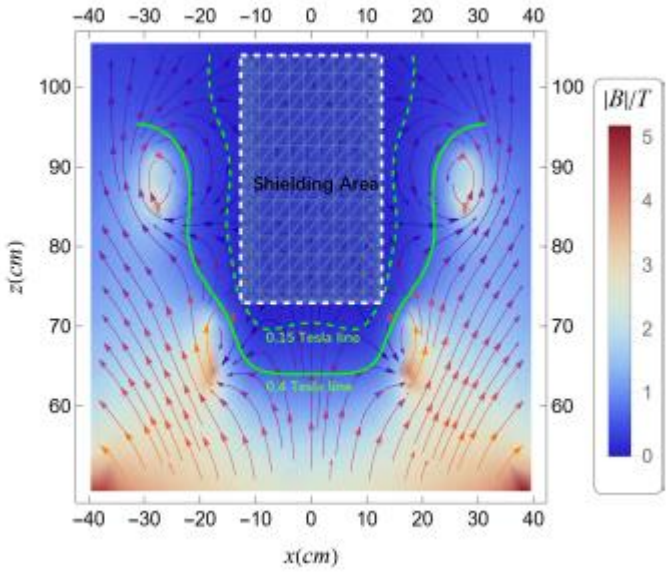
Summer Undergraduates
- Nicholas Callan
- Jessica Fox
- Nathaniel Bruss
- Oyu Enkhbold
- Vivian Huang
- Nastassia Patnaik
- Pranav Vadapalli
- Deniz Erdag
- Nicky He
- Rebecka Maehring
- Ryan Marin
- Paolo Montoya

New axion search magnet w/ PPPL

- Many magnets use NbTi conductor, immersed in liquid helium
- Conduction-cooled Nb3Sn magnet → no liquid helium, higher fields



Magnet design: Y. Zhai, PPPL

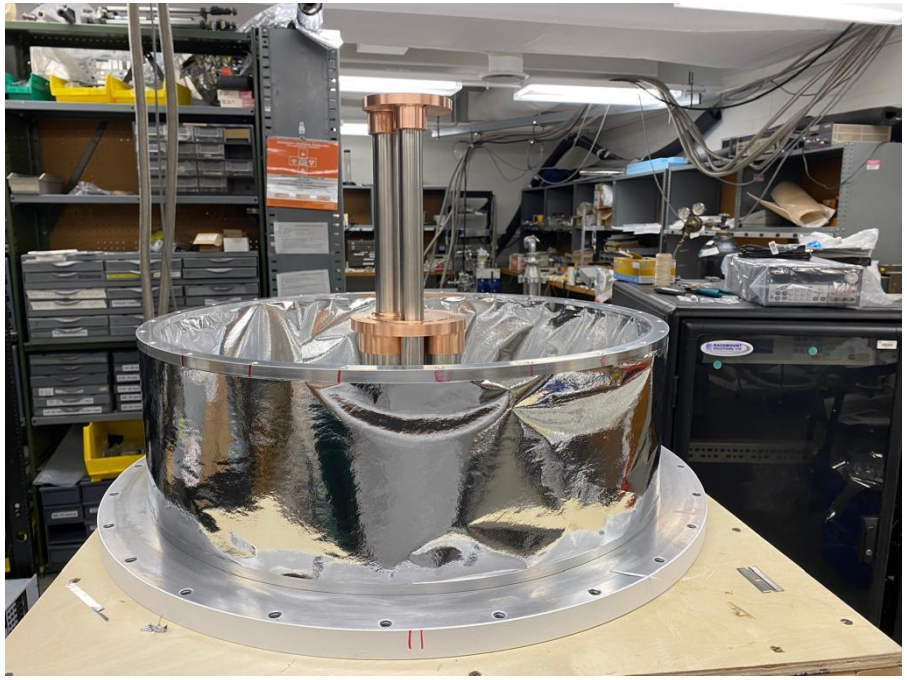


Bucking coil analysis: Z. Zhou
(experimental project)

PXS magnet design: 5 Tesla, 78.7 cm diameter, 101.6 cm height

Validation efforts underway with test magnet

- Build 5 Tesla coil at 30% length scale to elucidate interfaces, validate thermal and mechanical performance, field profile and shielding
- Test cryostat constructed in spring

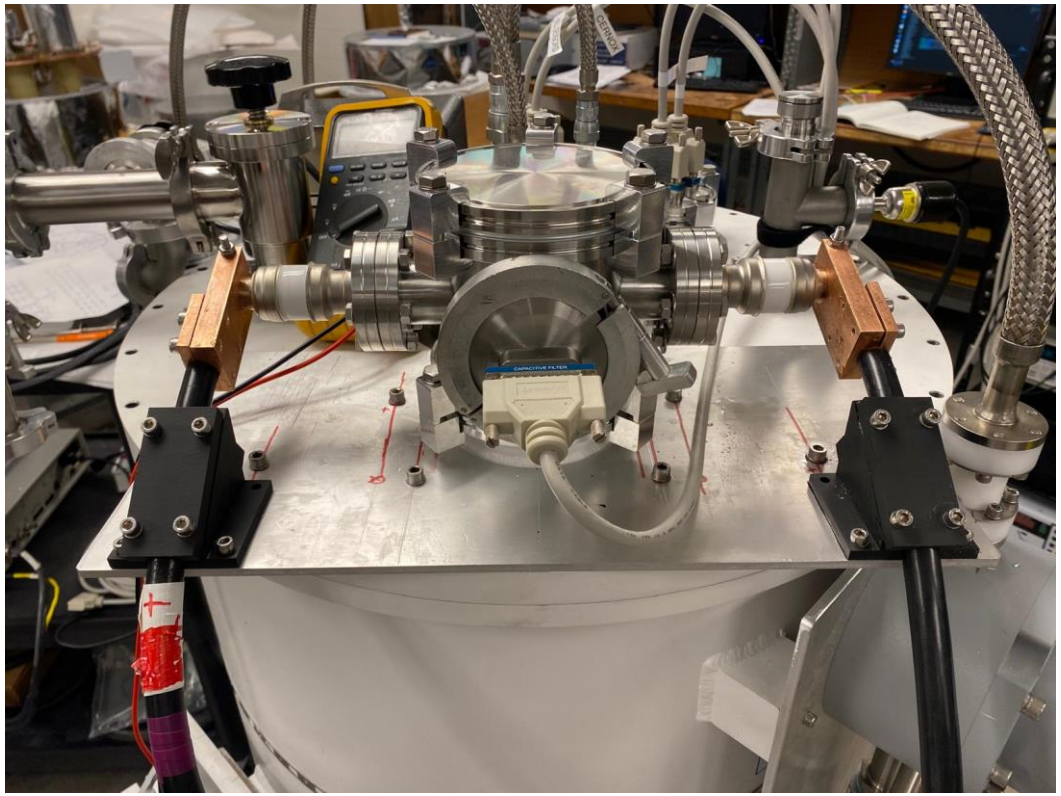


Cryostat undergoing insulation blanketing

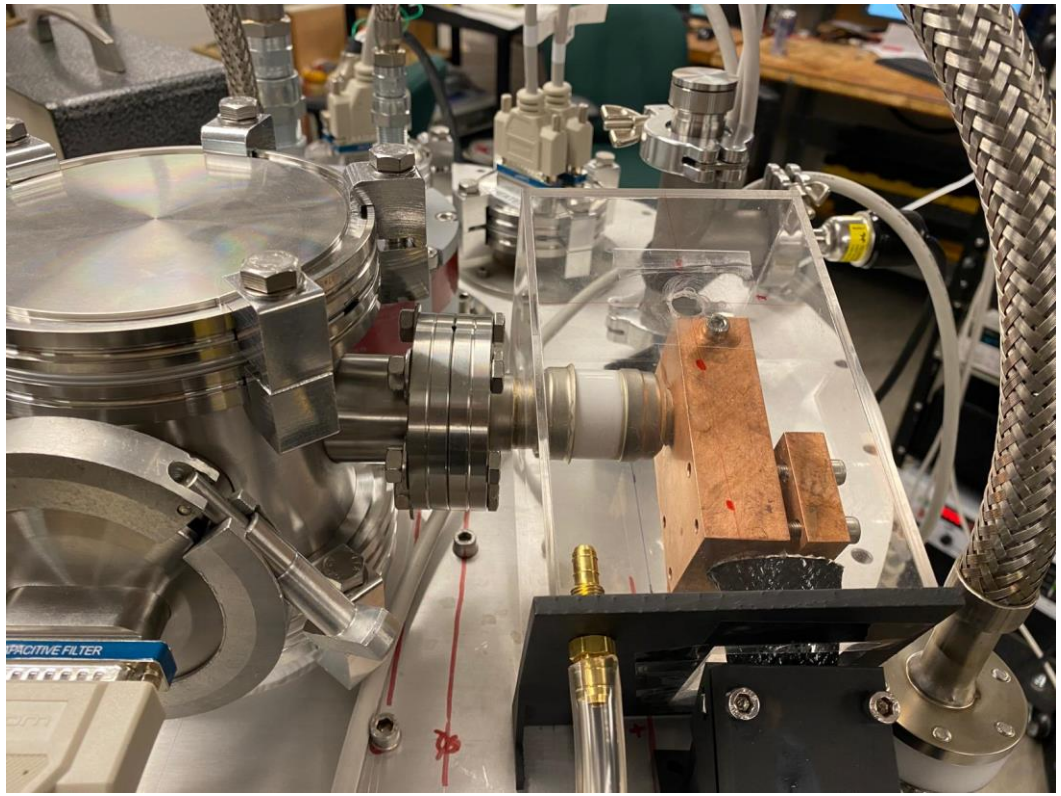
Joelle and Lyman mounting cryostat to frame

Joints and copper current leads validated

- Verified low resistance in conductor joint tests at PPPL
- Ran 650 amps to 40K stage through copper leads



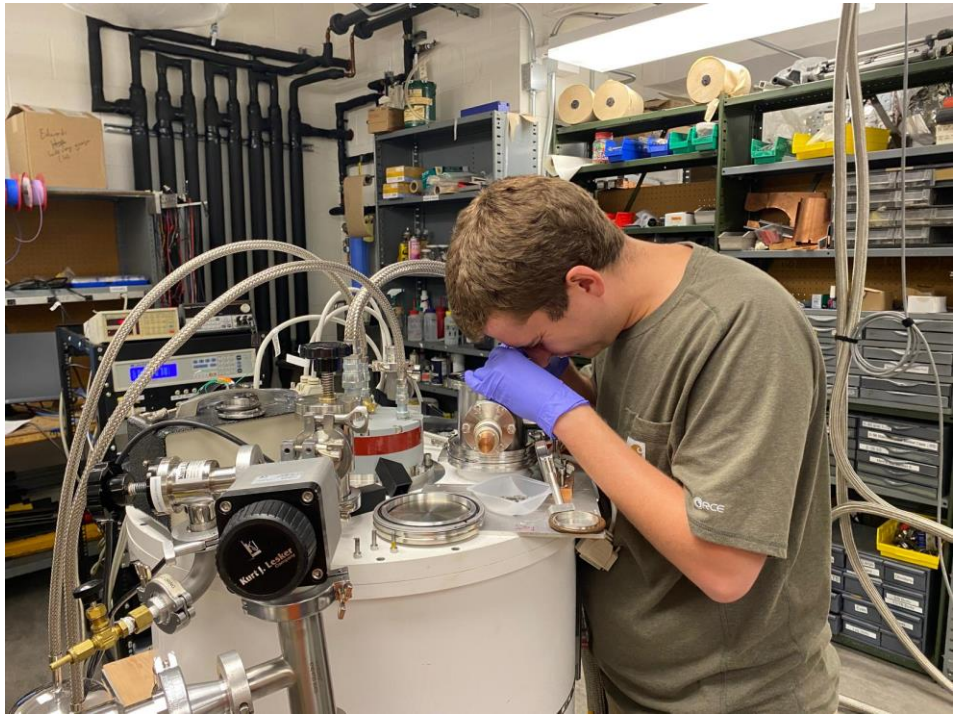
High-current vacuum feedthrough



Nitrogen purge system for preventing moisture

Next steps

- Run HTS leads to 4K, fabricate pulse tube shielding
- Validation of conduction cooling mechanism at PPPL
- Delivery of model coil in the autumn



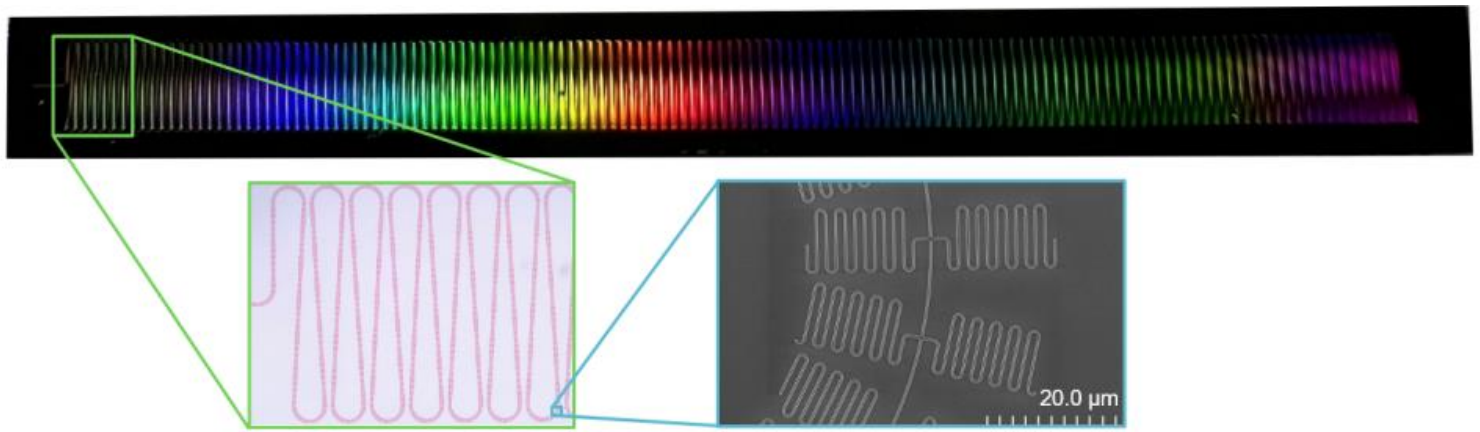
Roman working on current lead assembly

Joe and Lyman installing HTS leads

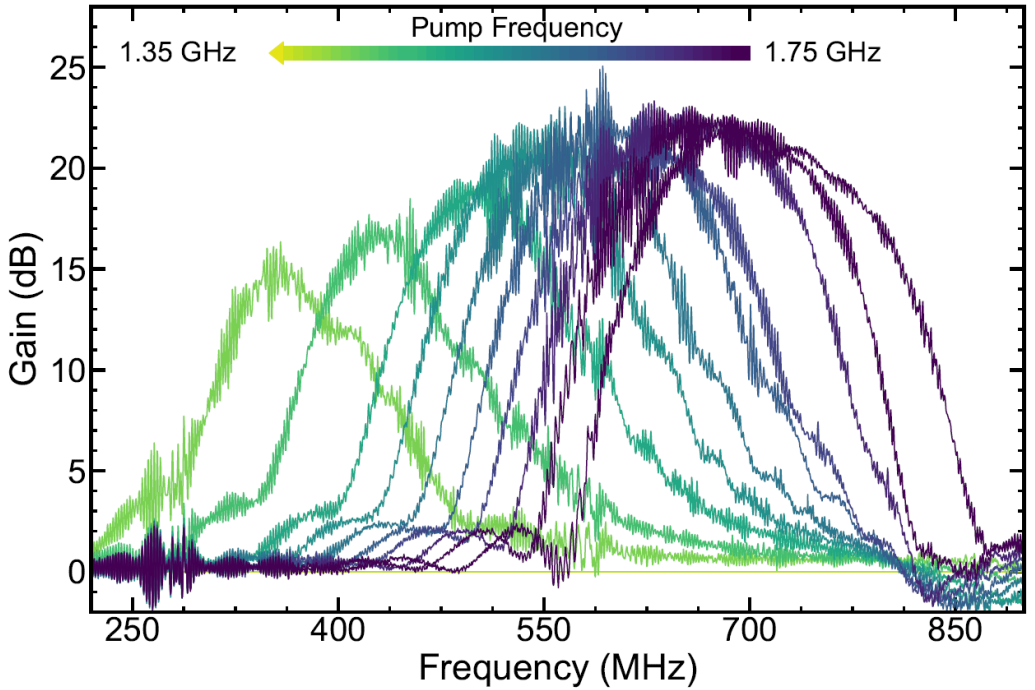
New amplifier technology desirable

- dc SQUIDs and resonator-based Josephson parametric amplifiers challenging to use at 200-500 MHz
- Possible solution in collaboration with P.K. Day and J. Zmuidzinas, Caltech/JPL: traveling-wave parametric amplifier (TWPA) utilizing kinetic inductance nonlinearity
  - Broadband amplification
  - Demonstrated system noise performance of few times SQL at higher frequencies (~4-7 GHz)
  - See: Eom et al, *Nature Physics*, 2012; S. Chaudhuri et al, *APL*, 2017; S. Shu, et al, *Phys. Rev. Research*, 2021; Malnou, *Phys. Rev. X Quantum*, 2021; F. Faramarzi, et al, arxiv: 2402.11751

Low-frequency KI-TWPA demonstrated down to 400 MHz

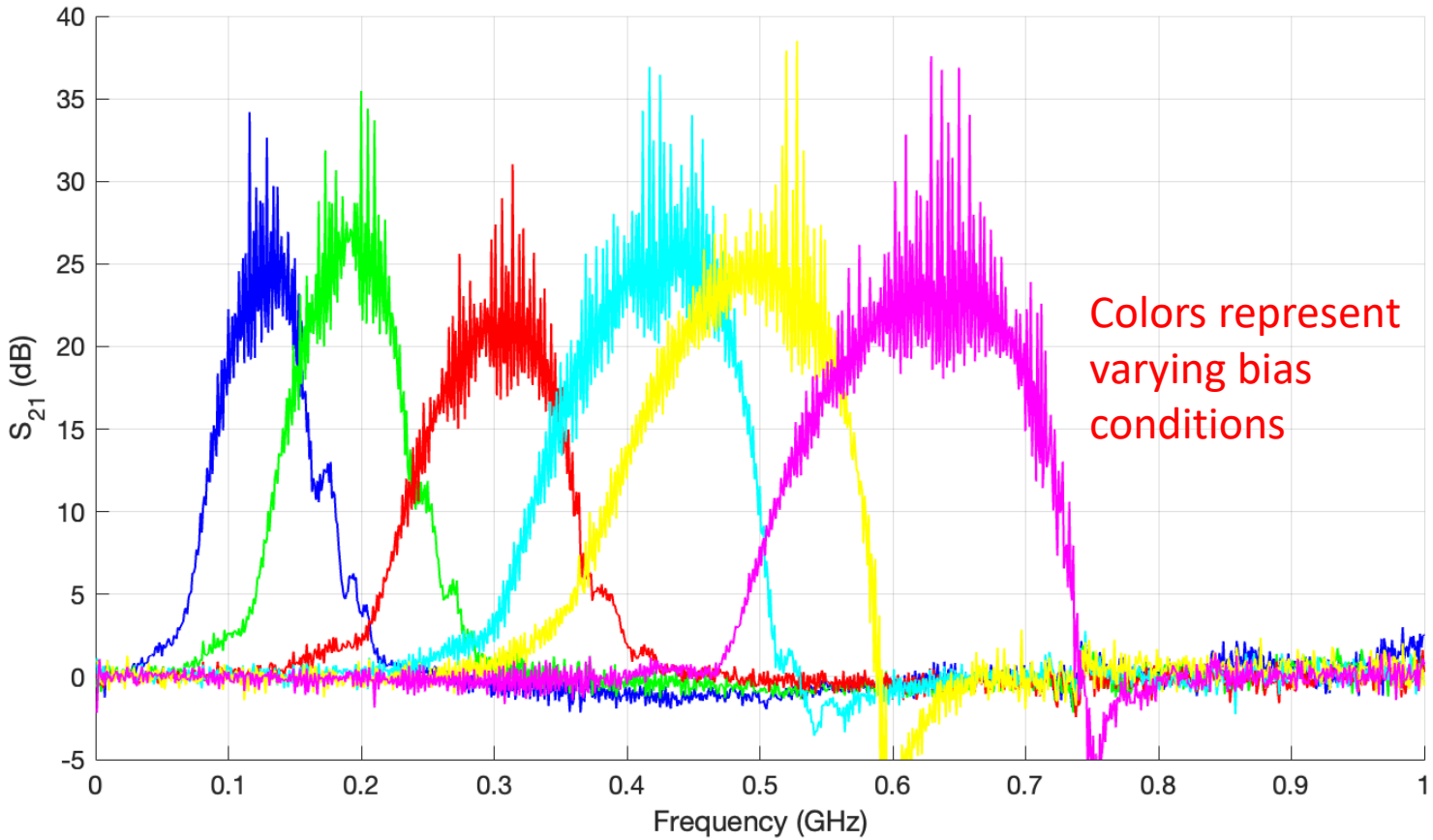


arxiv: 2406.00530



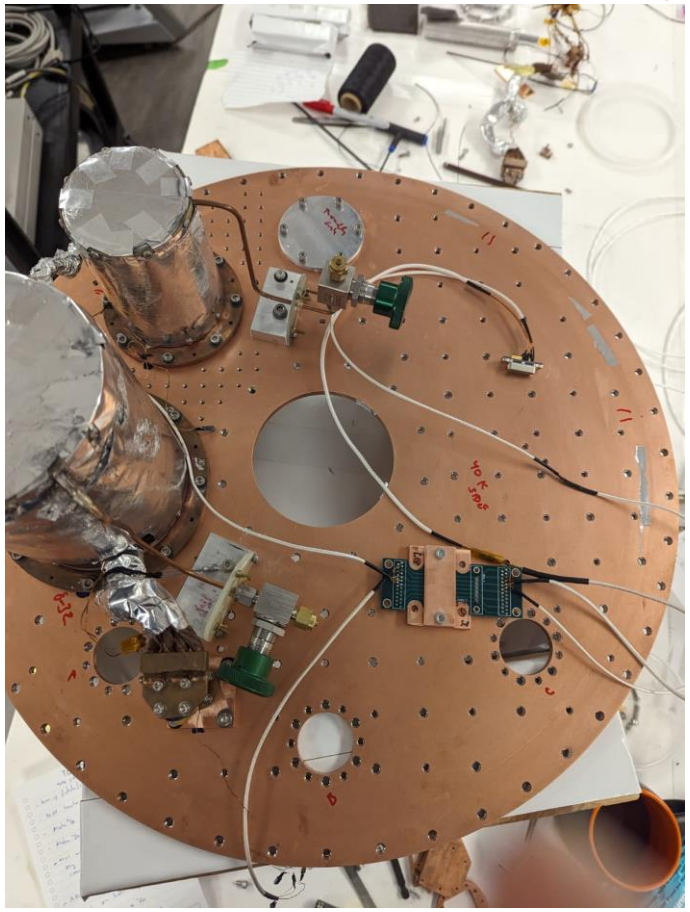
- Capacitively shunted TiN inverted microstrip transmission line <.01c velocity
- Pump power of 300 nW, factor of x1000 improvement over previous CPW architecture
- Signal processing at image tone ~3 GHz to reduce complexity
- Initial system noise measurements < 3 quanta, presently improving noise calibration and auxiliary microwave components

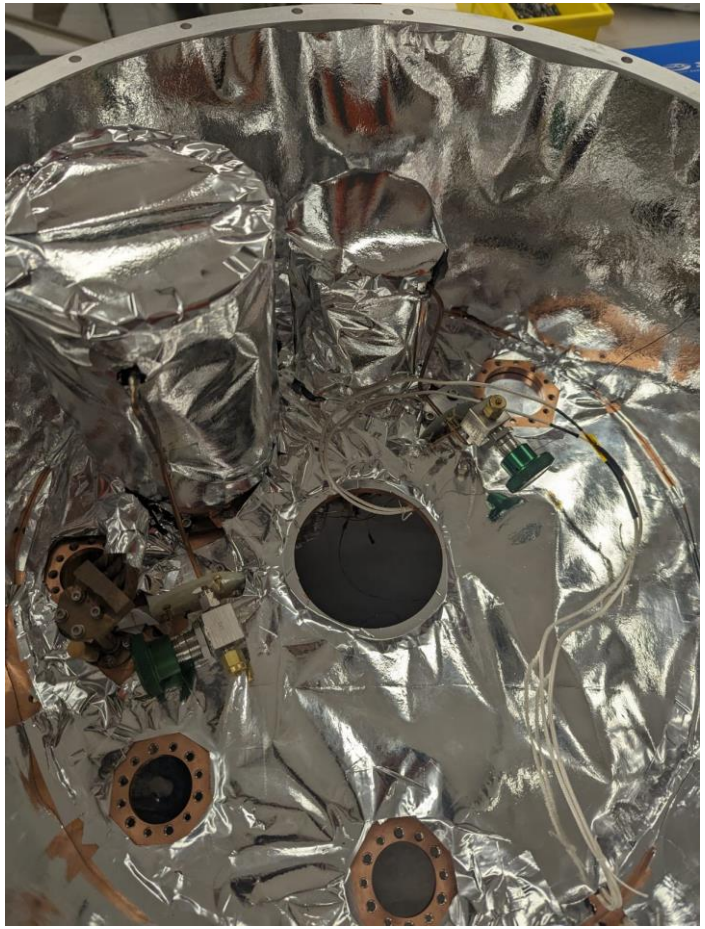
Next steps



- Will characterize lower-frequency TWPA. Initial measurement: ~25 dB over 100-700 MHz
- Studying feasibility of squeezing with kinetic inductance TWPAs
- DR to study noise and device physics, He3 cryostat to study full readout chain

Infrastructure under development for readout

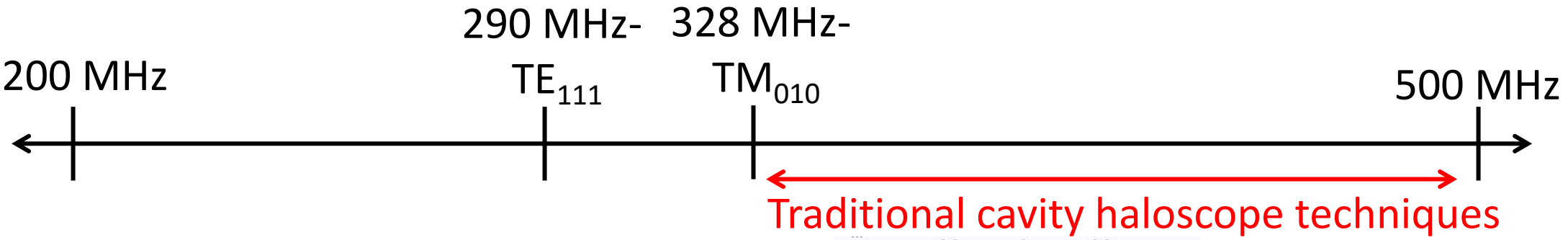


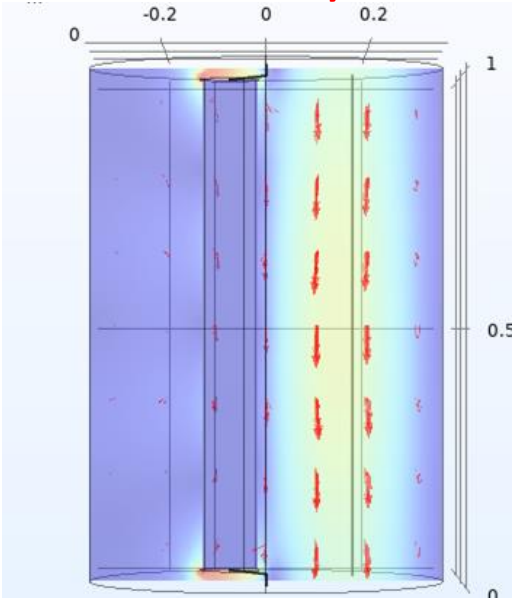


- DR commissioned in late May (<7 mK), DC wiring installed, detailed studies of still-MXC load curves
- DR RF wiring and component installation over August and September
- Commissioning of He3/He4 fridge over the next month

Resonator design to probe transitional range

- Based on cylindrical barrel of 70cm diameter, 102 cm height

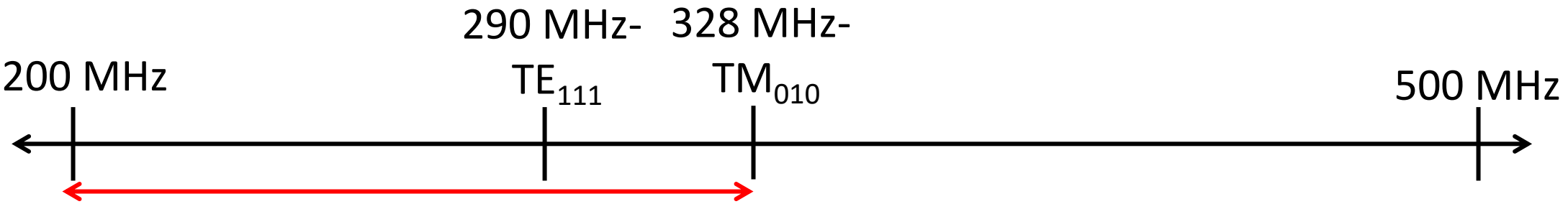




Cavity simulation
(Nate Otto)

Resonator design to probe transitional range

- Producing resonances below TE_{111} studied for DMRadio-m^3
- See AlShirawi, et al, arxiv: 2302.14084 (2023)!



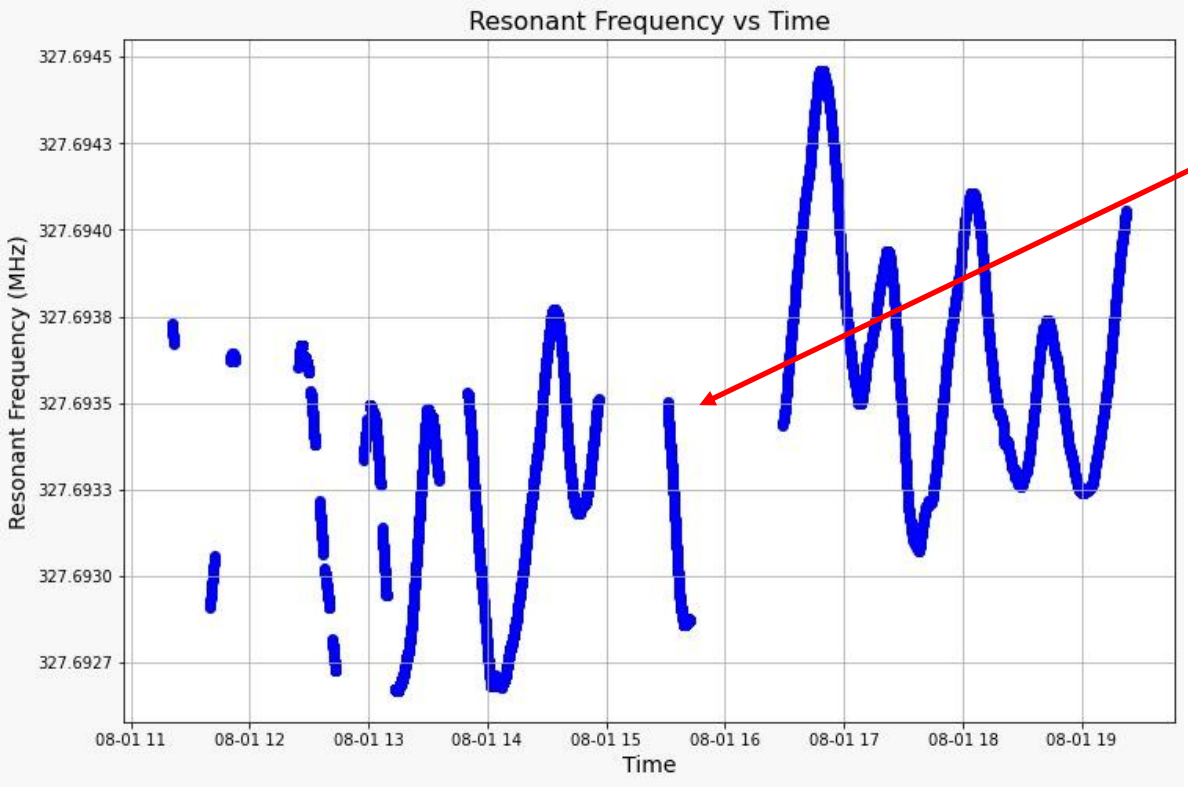
- PXS approach below 330 MHz: Combine traditional tuning rod infrastructure with concepts from AlShirawi, et al, to produce modes that efficiently couple to axion. Simulation and tuning specification in progress.

Room temperature test cavity

- Al 1100 rolled and welded cylinder with 6061 endcaps

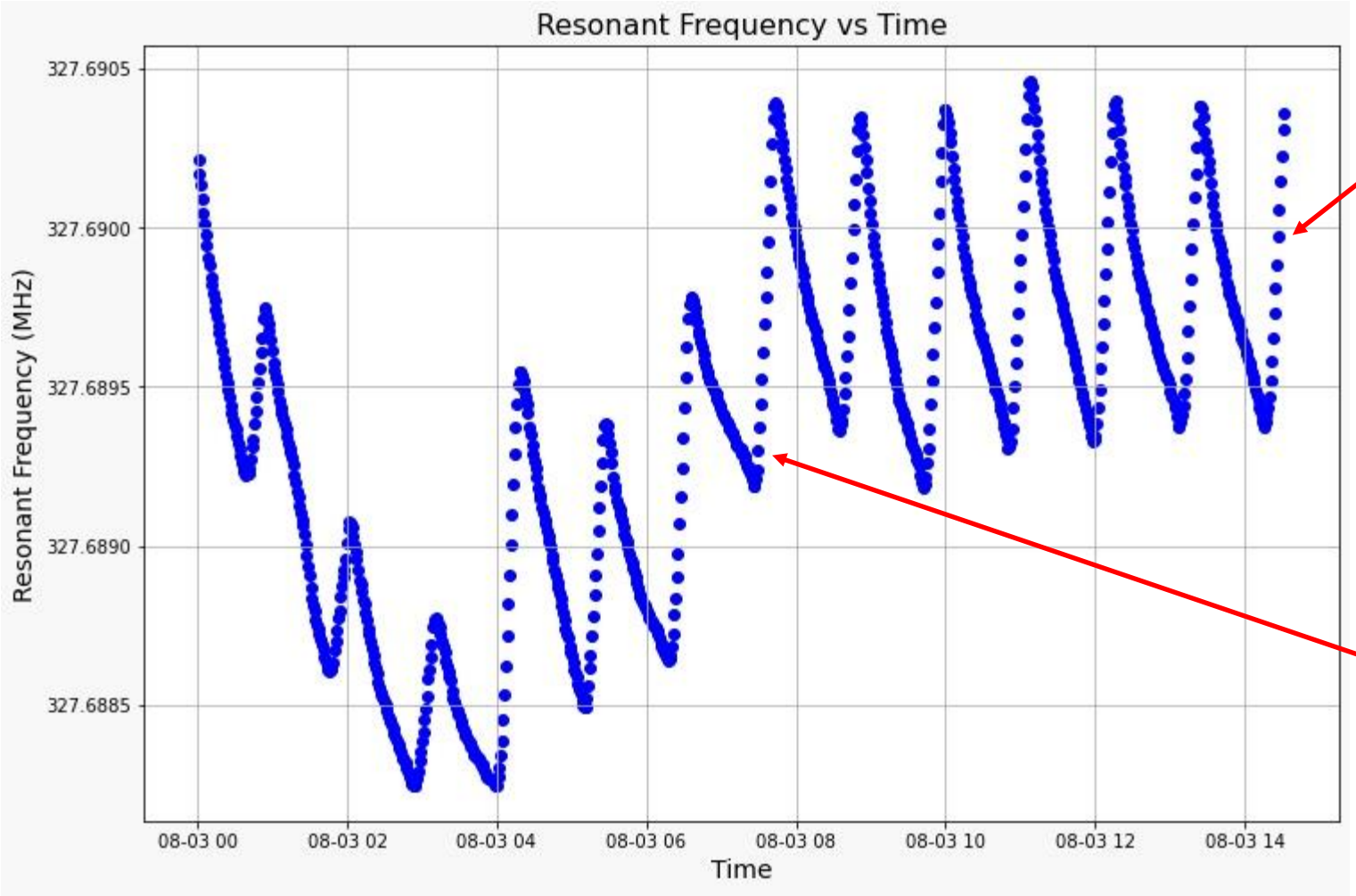
Cavity characterization

- TM010 frequency of 327.7 MHz measured, with Q of 48k
- Frequency spot on, within 10% of expected Q
- Bead pull measurements started over the past week, analyzing background variation



Nate removes bag of plastic endcaps from top of cavity

Cavity characterization- temperature variation?



1 kHz shift in frequency can be explained by ~130 mK shift in temperature

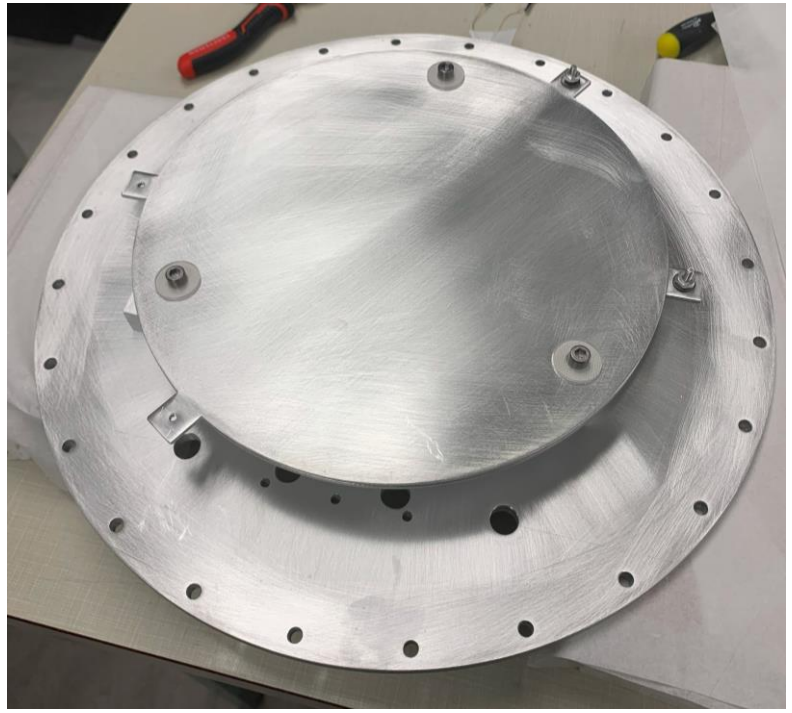
7am: campus energy controls turn on

Next steps

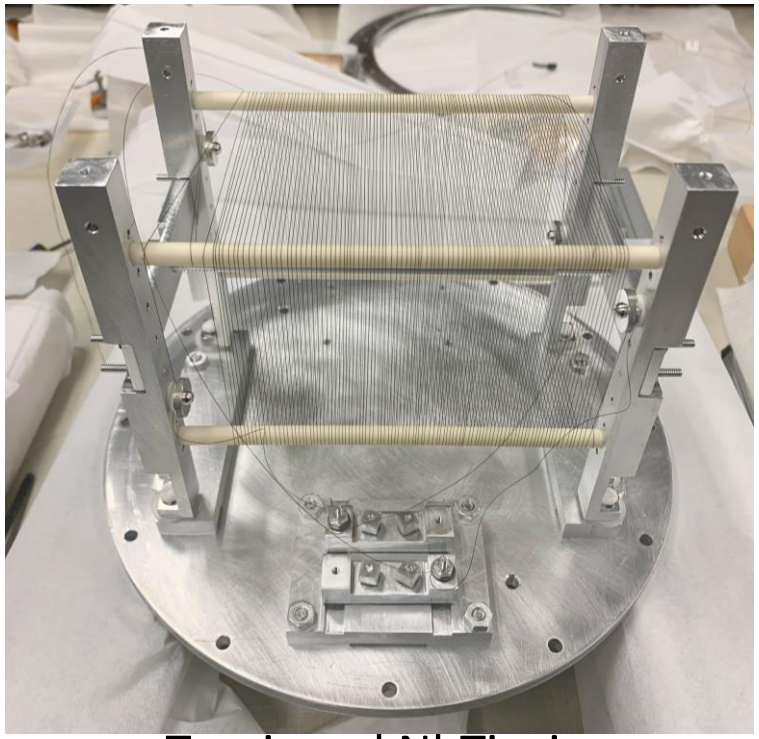
- Continue with bead pull measurements
- Short-term goal: map mode magnetic field by differencing dielectric and metallic beads
- Select and fabricate first tuning rod (380-500 MHz)
- Continue with investigation of lower frequencies

Joint R&D with the DMRadio collaboration

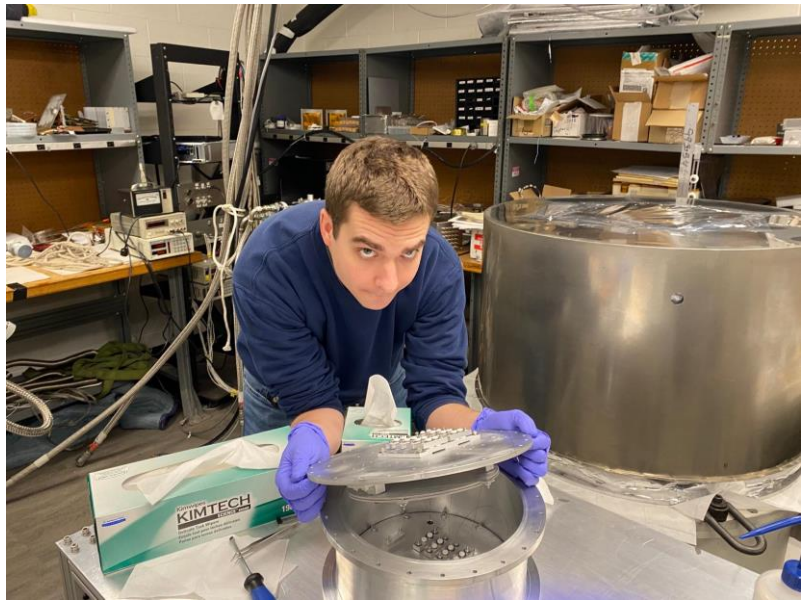
- Working together to realize searches at lower, sub-μeV axion masses
- Particular focus on resonators and readouts



Al 1100 parallel-plate capacitor

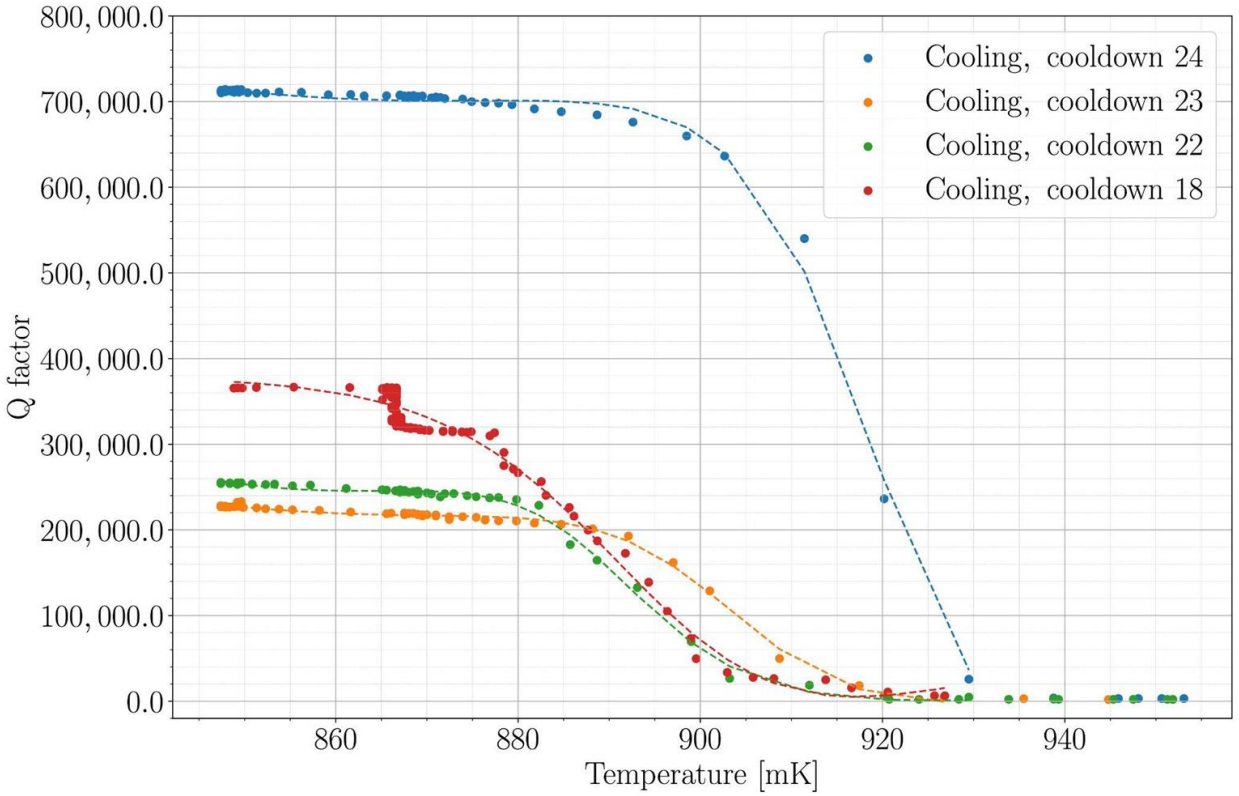


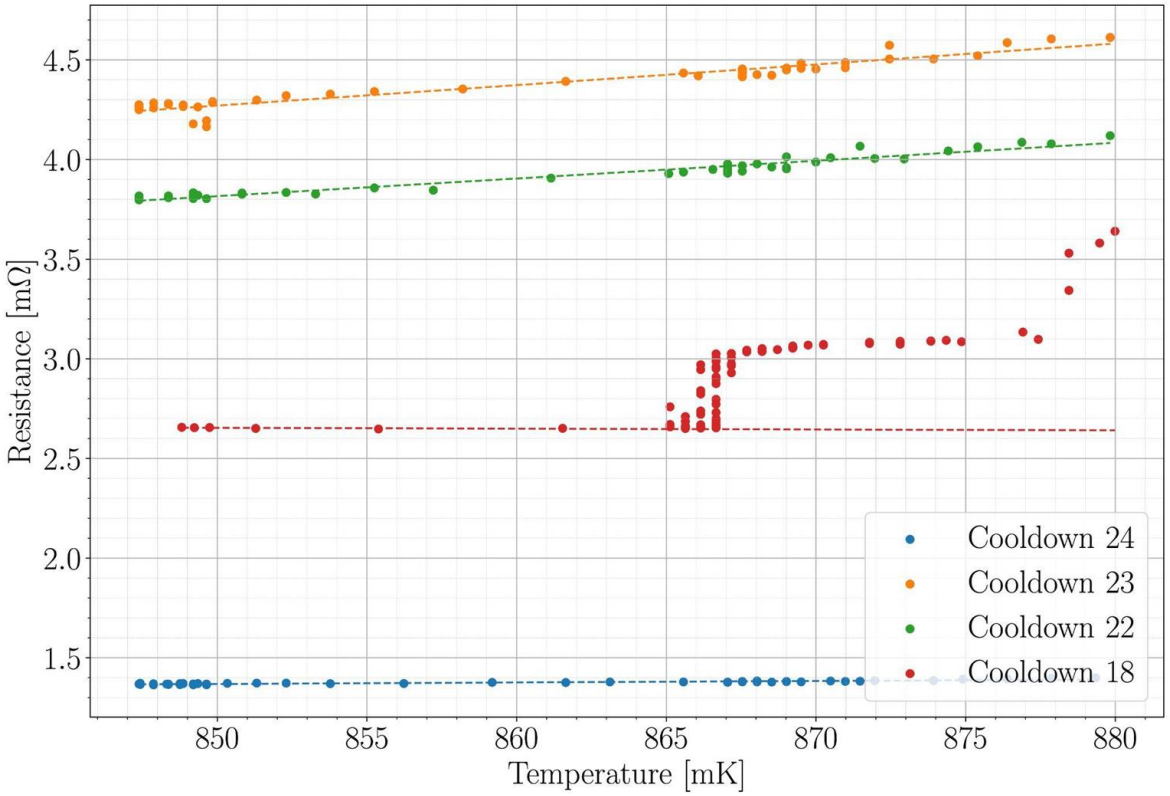
Tensioned NbTi wire on 1100/alumina frame



Roman Kolevatov closing up LC resonator apparatus

Q vs T dependence



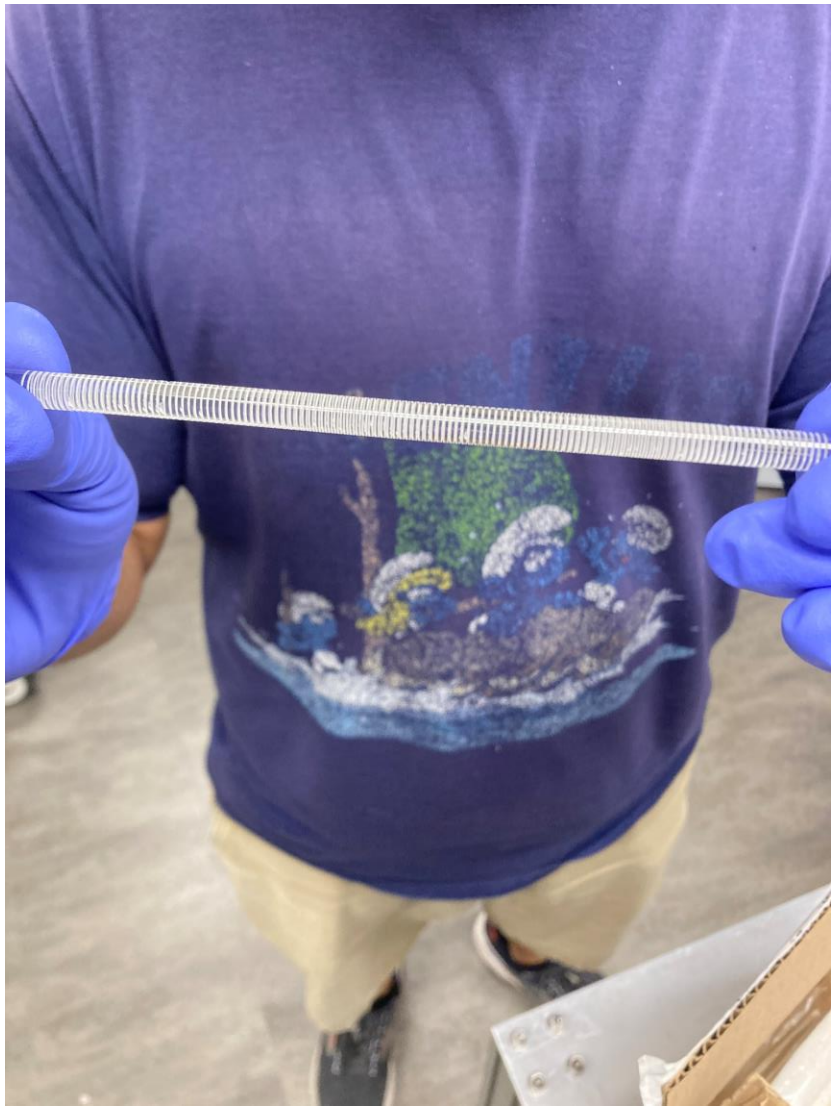


State-of-the-art new record value Q~710,000 at 301 kHz!

Nagahama et. al 2016: Q of 500,000 @ 896 kHz and 250,000 @ 948 kHz (order of magnitude smaller volume)

Sapphire grooving for next coil

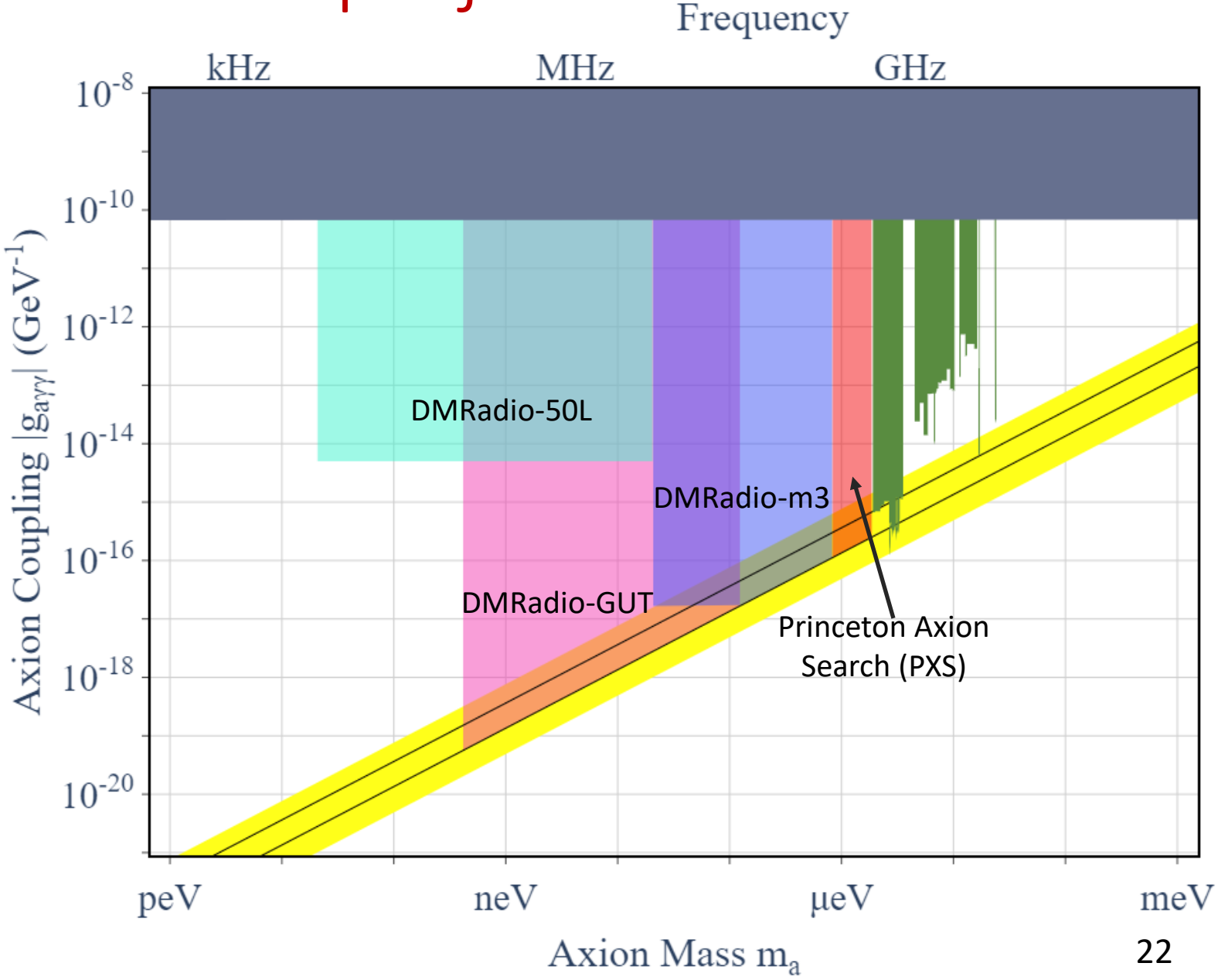
- Suspect Q limitation due to loss in alumina+ formvar-coated wire
- Next coil will be sapphire rod wound with PTFE or bare NbTi wire



PXS initial science projections and outlook

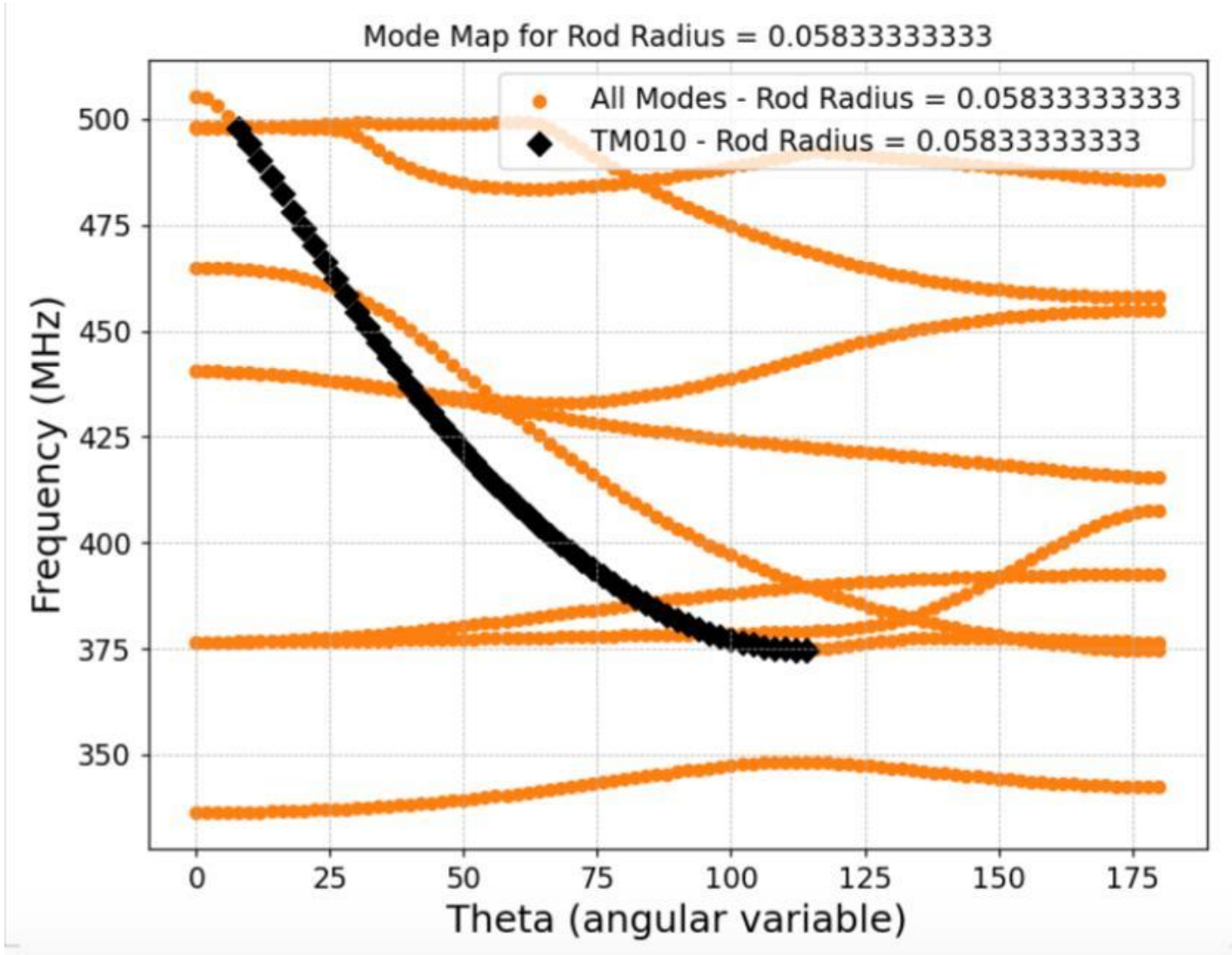
- 0.8-2.1 μeV (200-500 MHz) QCD axion search
- 5T, 500L (78.7cm bore) magnet in collaboration with PPPL
- Q=100,000-200,000 copper resonator cooled to 40mK
- Readout noise: 15x quantum limit (7.5 noise quanta)

Fully operational in 2027. DFSZ sensitivity with 200 days of integration time.



Questions?

Mode map


Mode Map for Rod Radius = 0.05833333333
All Modes - Rod Radius = 0.05833333333
TM010 - Rod Radius = 0.05833333333
Frequency (MHz)
500
475
450
425
400
375
350
0
25
50
75
100
125
150
175
Theta (angular variable)

More photos