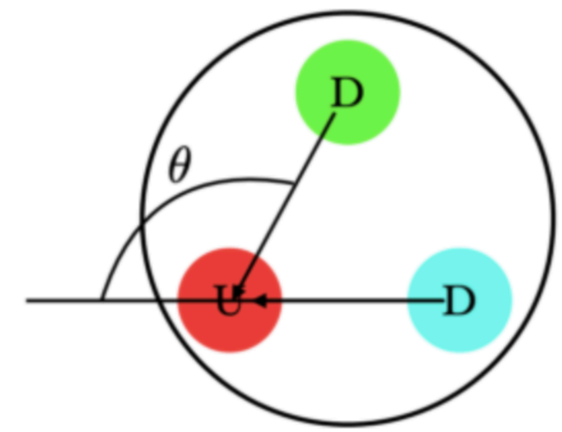
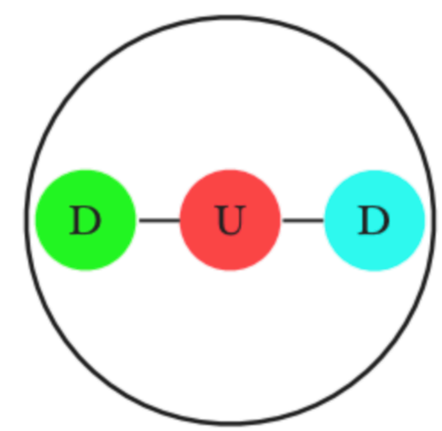
Overview of Axion Dark Matter eXperiment

Dan Zhang
University of Washington,
Postdoctoral Researcher

QCD axion

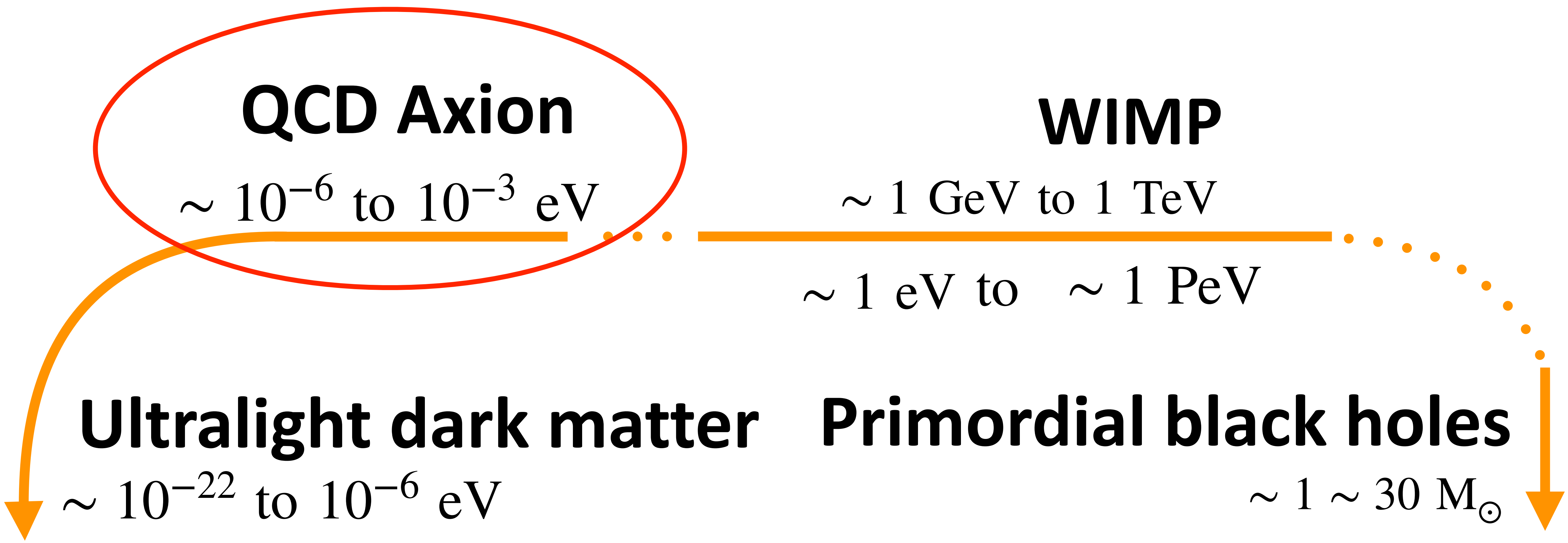
- Quantum Chromodynamics -> the strong interaction naturally has CP violation terms
    - QCD would have a neutron electric dipole moment d_n of $10^{-16}\mathrm{e}\cdot\mathrm{cm}$
    - nEDM collaboration at PSI $d_n < 1.8\times10^{-26}\mathrm{e}\cdot\mathrm{cm}, \theta < 5\times10^{-11}$
- The strong CP problem solution: $U_{\mathrm{PQ}}(1)$ axial symmetry
- New particle beyond standard model, QCD axion





Credit to Anson Hook, arXiv:1812.02669

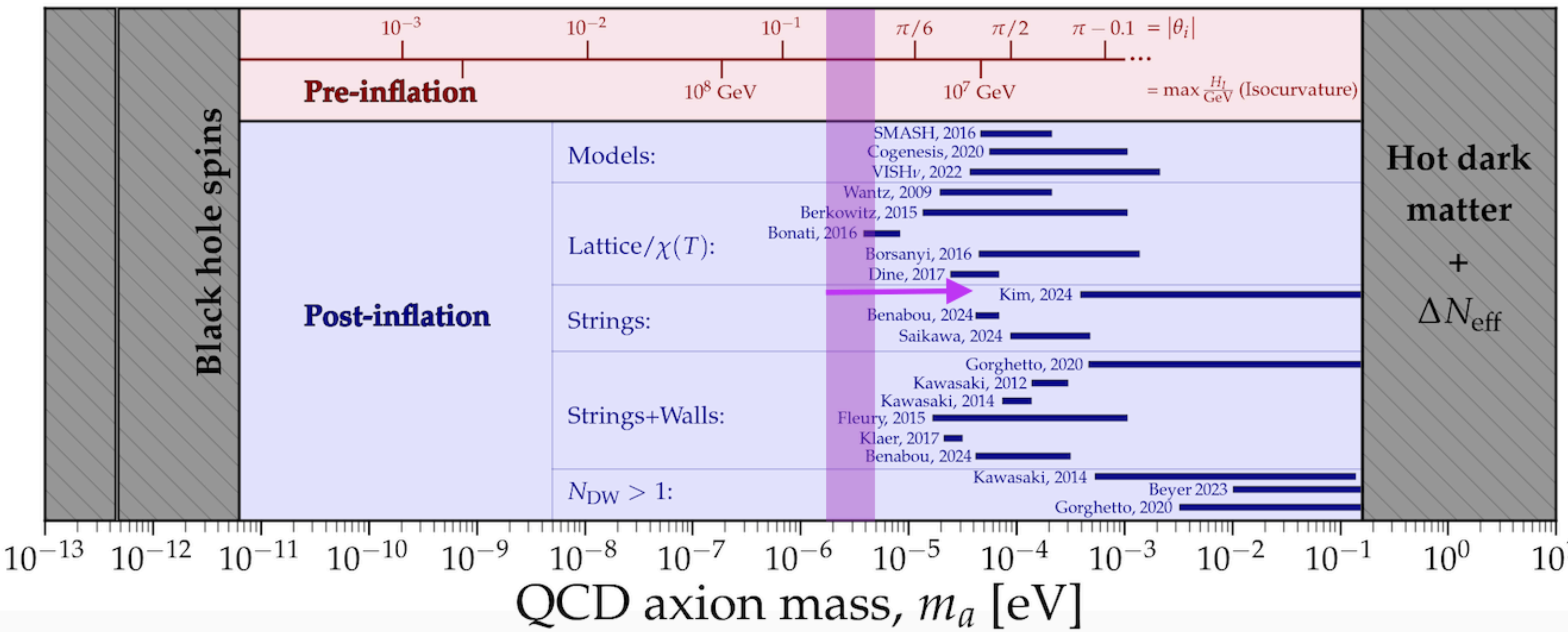
Non-baryonic Dark Matter Candidates



- Wave-like: mass $\ll$ 10 eV, occupancy number $N \approx \frac{\rho_{\rm DM}}{m}\lambda_{\rm dB}^3 \gg 1$

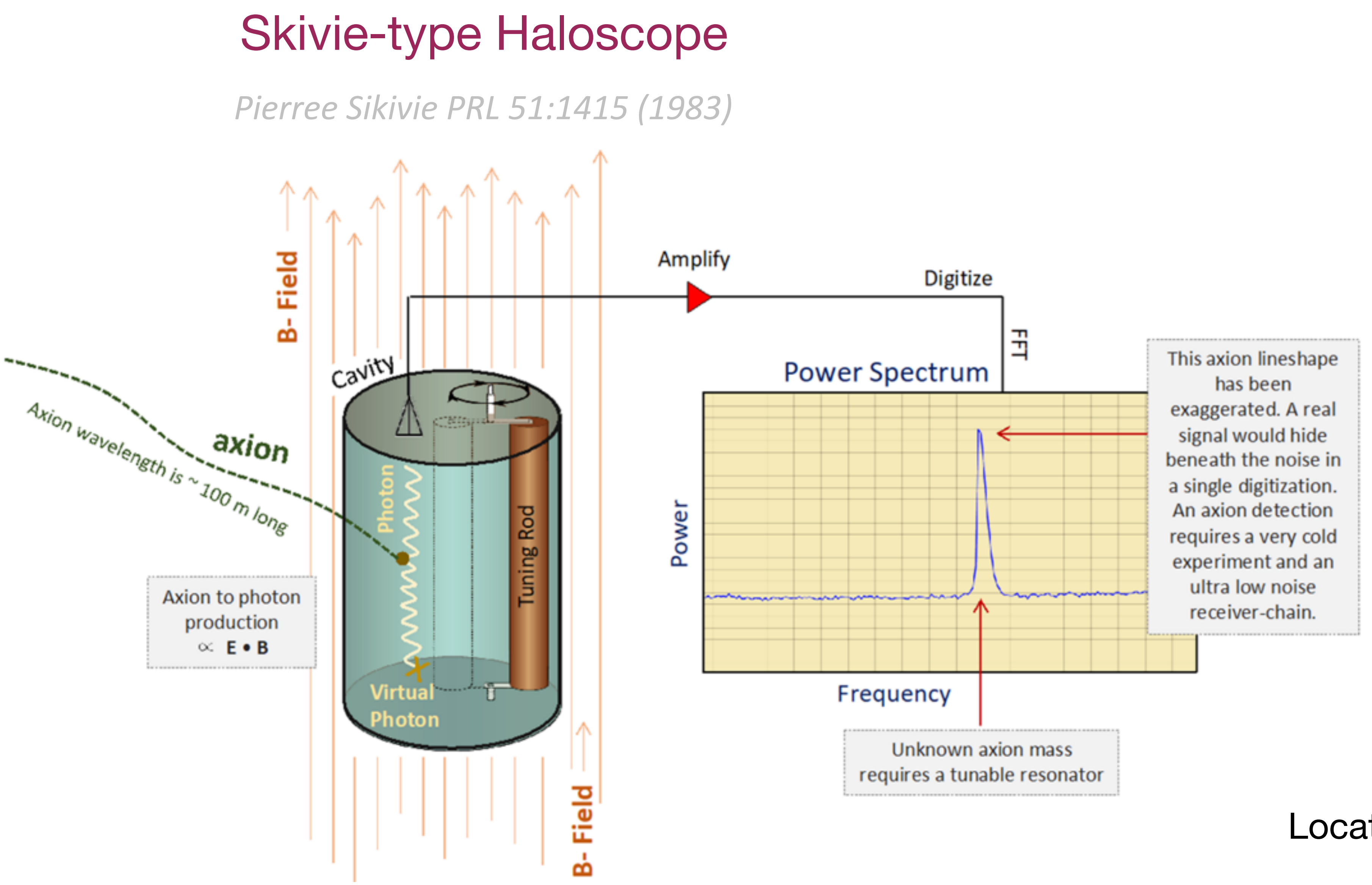
Axion dark matter

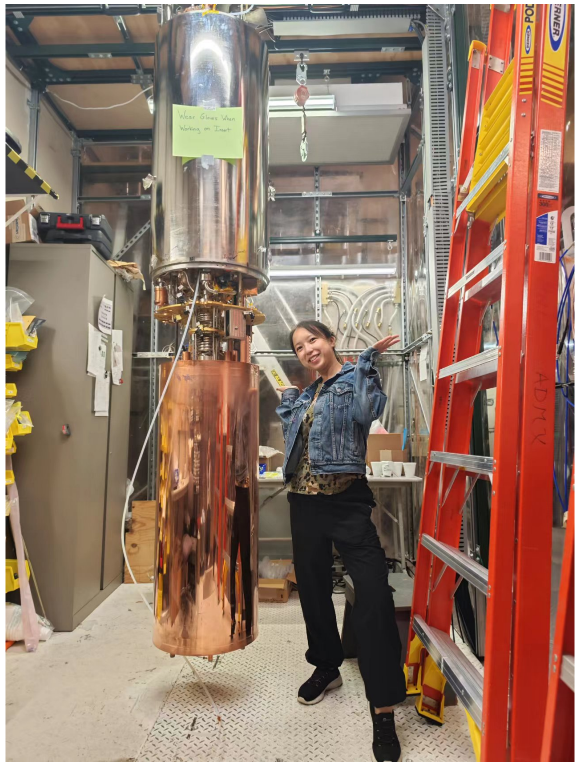
ADMX benchmark model coverage so far



Plot from Ciaran A. J. O'Hare, PoS COSMICWISPers (2024) 040

Axion Dark Matter eXperiment



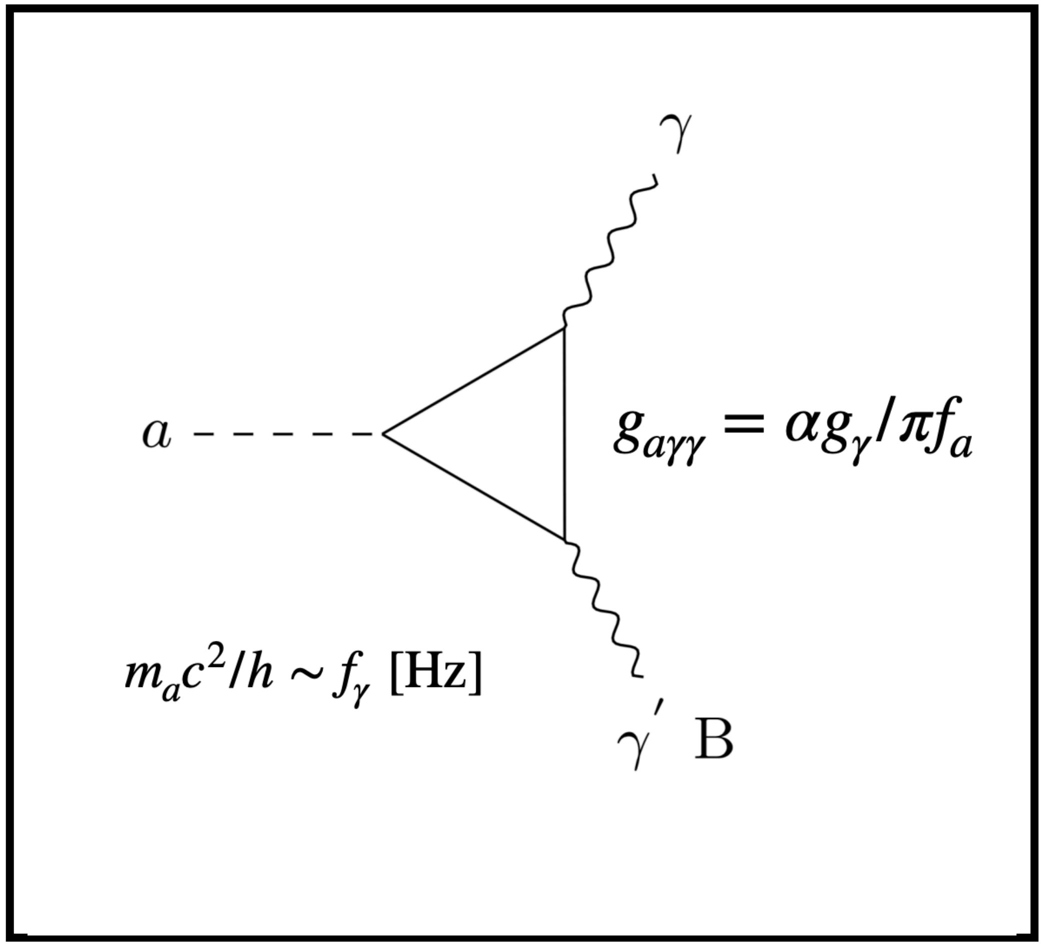


Location: University of Washington

- Non-relativistic dark matter: $m_a \approx hf, Q_a \sim 10^6, \mathcal{O}(1)\text{GHz}$
- $\delta P_{\text{bkg}} \propto T_{\text{blackbody}} + T_{\text{amplifier}}$

Signal power

$$P_a = 2 \times 10^{-23}\ \mathrm{W} \times \left(\frac{g_\gamma}{0.36}\right)^2 \left(\frac{\rho}{0.45\ \mathrm{GeV/cm^3}}\right)\left(\frac{f_a}{1.3\ \mathrm{GHz}}\right)$$



Properties relate to the nature of Axions

- g_γ: model related (KSVZ:-0.97, DFSZ: 0.36)
- ρ: local dark matter density
- $f_a \approx m_a / h$: mass of Axions

$$\times \left(\frac{B_0}{7.68\ \mathrm{T}}\right)^2 \left(\frac{V}{107\ l}\right)\left(\frac{Q_L}{25{,}000}\right)\left(\frac{C_{010}}{0.34}\right)$$

Properties relate to controllable factors

- B_0: magnetic field
- V: volume of the cavity
- C_{010}: form factor
- Q_L: loaded quality factor

Signal to noise ratio

Signal: $P_a = 3.5 \times 10^{-23}$ W $\overset{E = hf_a}{\longleftrightarrow}$ 40 photons/s

---

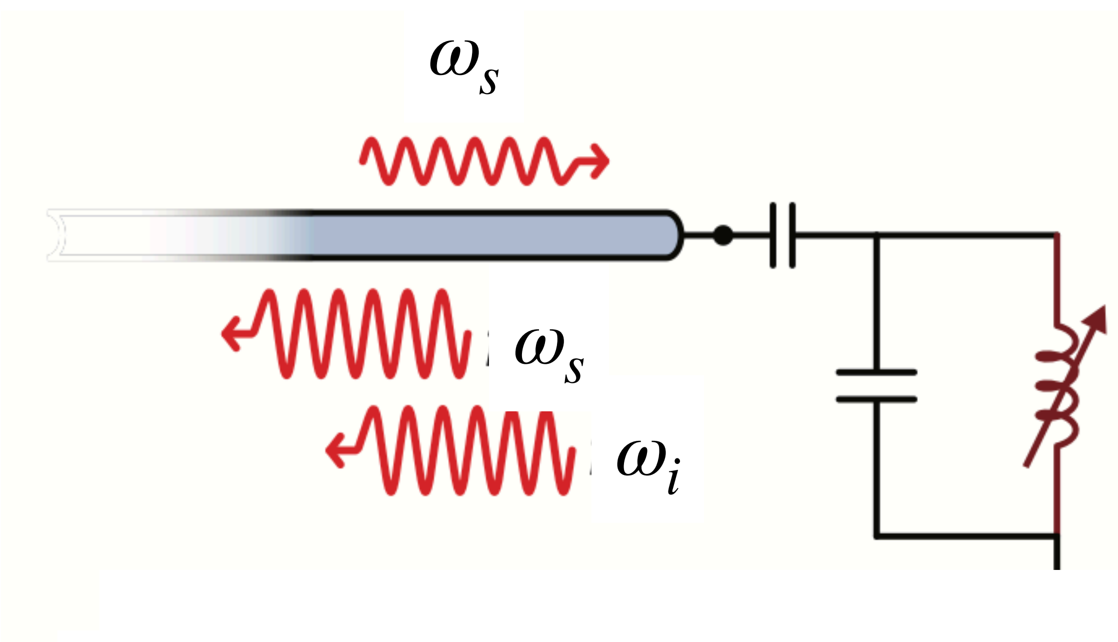
Noise: $\delta P_{\text{bkg}} = k_B T_{\text{sys}} b / \sqrt{bt} = k_B T_{\text{sys}} \sqrt{b/t}$

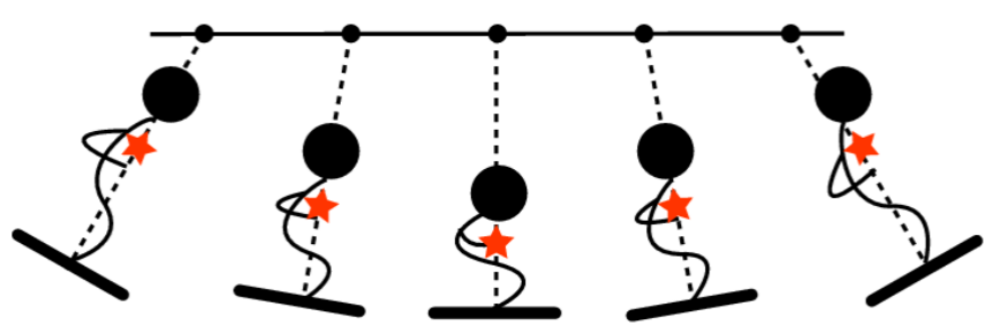
- k_B: Boltzmann constant [J/K]
- T_{sys}: system noise temperature [K]
- b: noise integration bandwidth [Hz]
- t: integration time [s]

Signal to noise ratio (SNR): $\text{SNR} = \dfrac{P_a}{\delta P_{bkg}}$

Current-Bias Josephson Parametric Amplifier

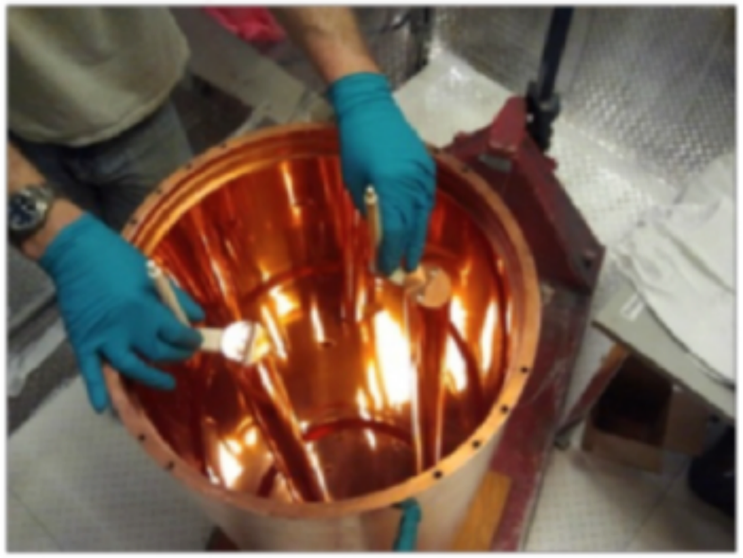
- Energy conservation brings in idler frequency
  $\omega_\mathrm{p} = \omega_\mathrm{s} + \omega_\mathrm{i}$
- Standard Quantum Limit: ground state of a harmonic oscillator is 1/2 quanta + 1/2 quanta receiver noise (50mK @ 1GHz)



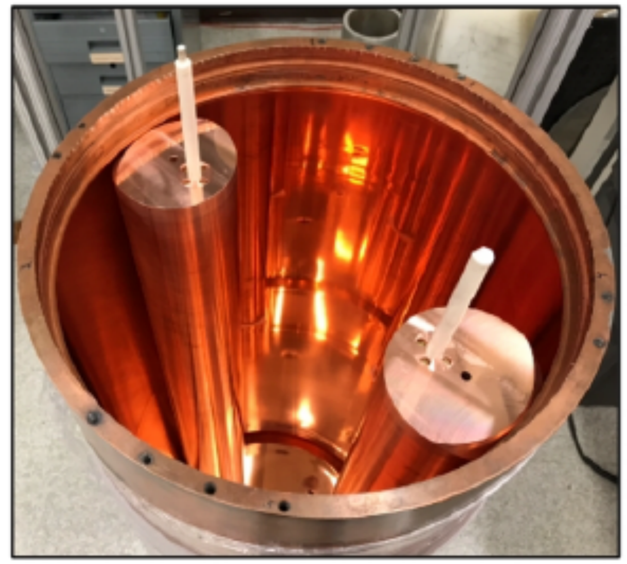


$$L_0 + \delta L \cos(2\pi\omega_p t + \phi_p)$$

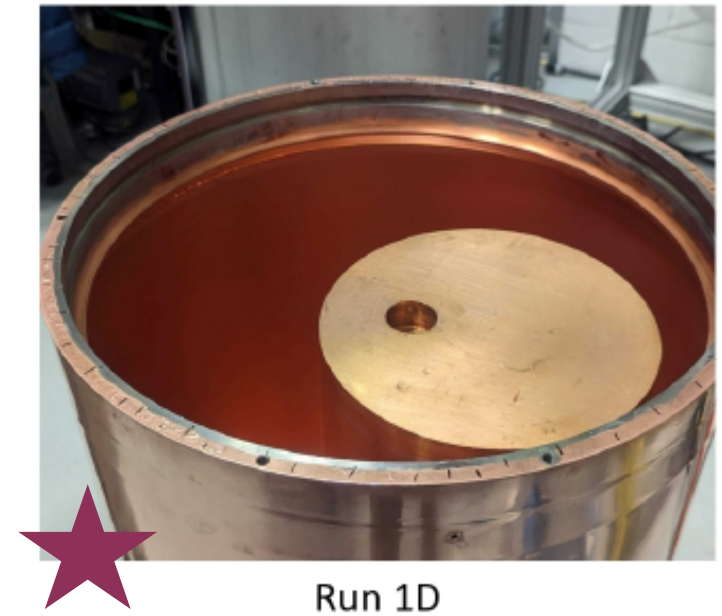
ADMX 2024 —Run1D-Part1



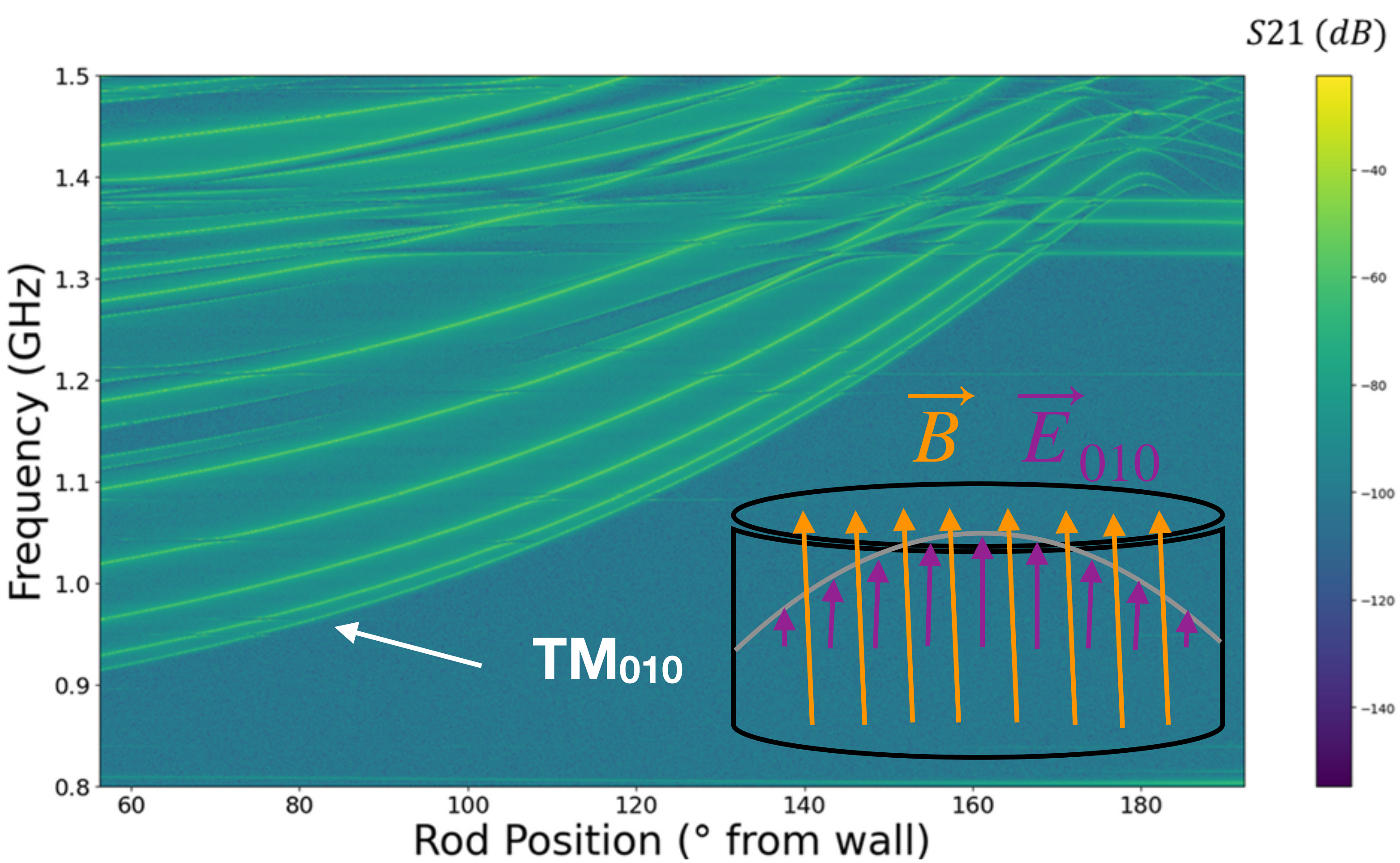
Run 1A+1B



Run 1C



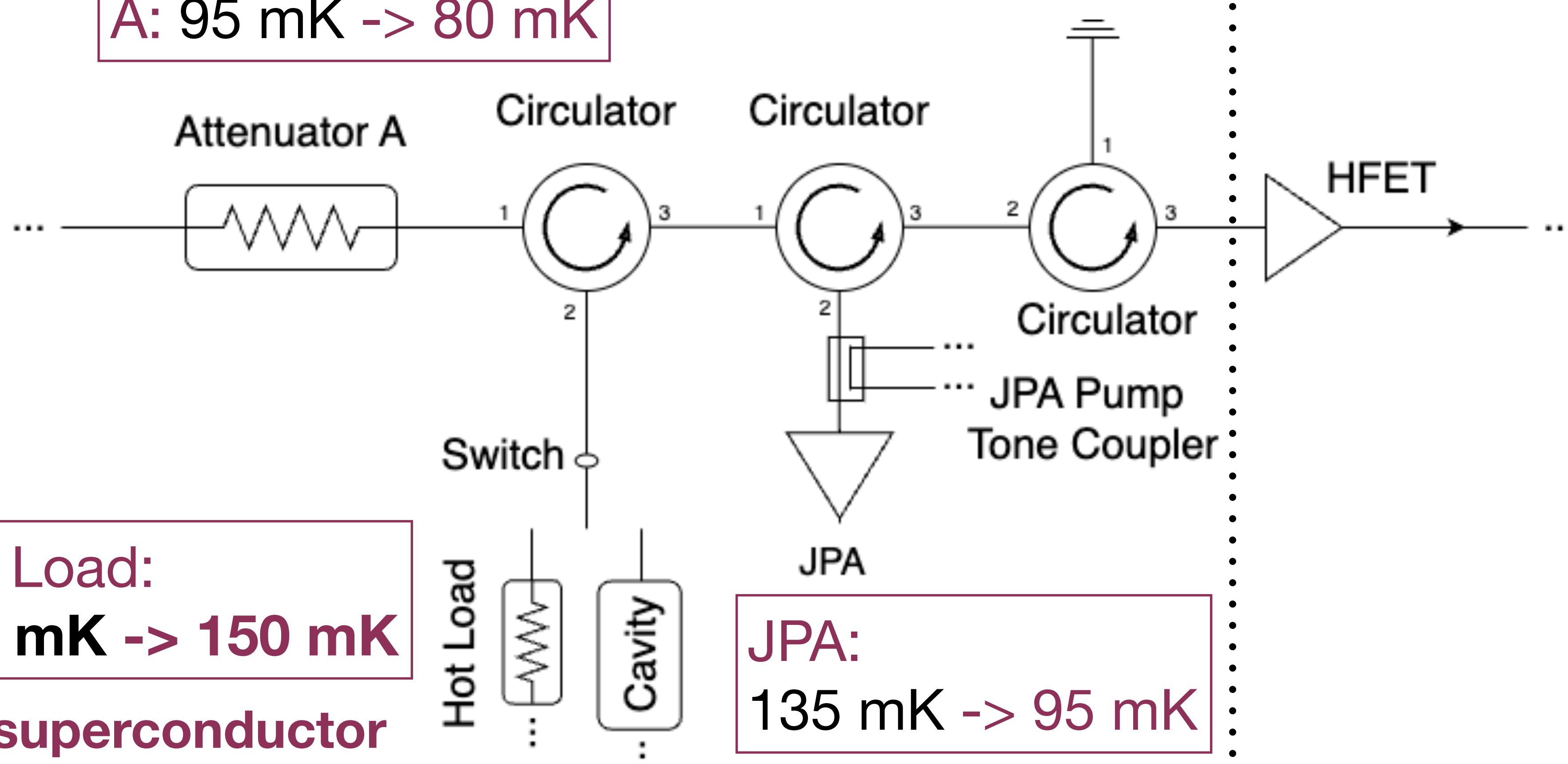
Run 1D



- 1 – 1.4GHz
- Volume:
  cavity 136L - rod 29L
- **Longest** run after ADMX implemented dilution refrigerator
- Run1D-Part1:
  KSVZ discovery ability

Improved temperature performance

A: 95 mK -> 80 mK



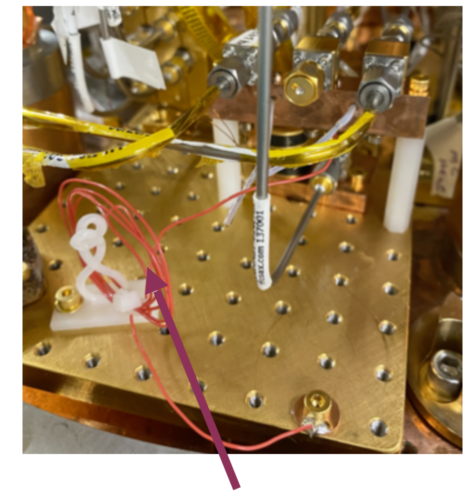
Hot Load:
475 mK -> 150 mK

JJ superconductor
Al $T_c = 1.2\ \mathrm{K}$

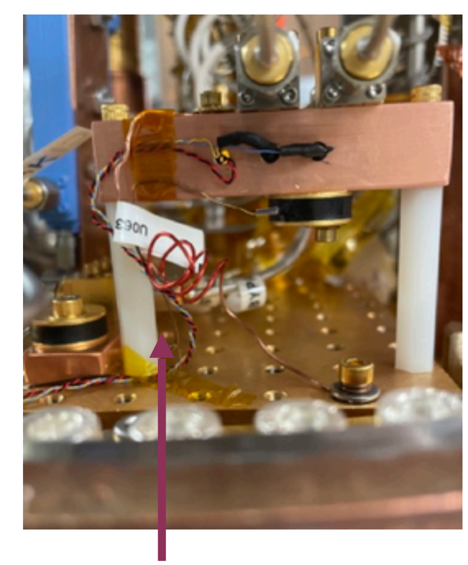
JPA:
135 mK -> 95 mK

Cavity: 130 mK -> 135 mK

milliKelvin space | **4K space**

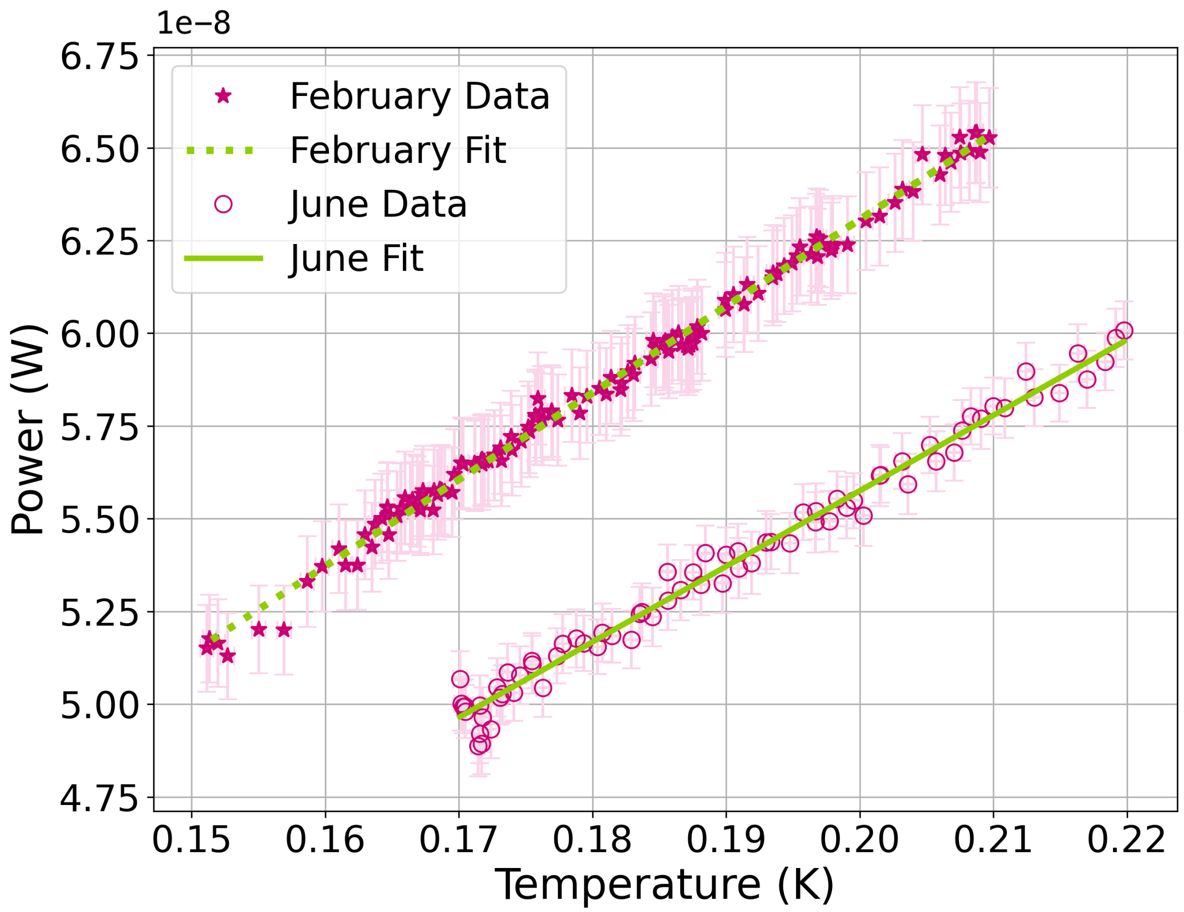


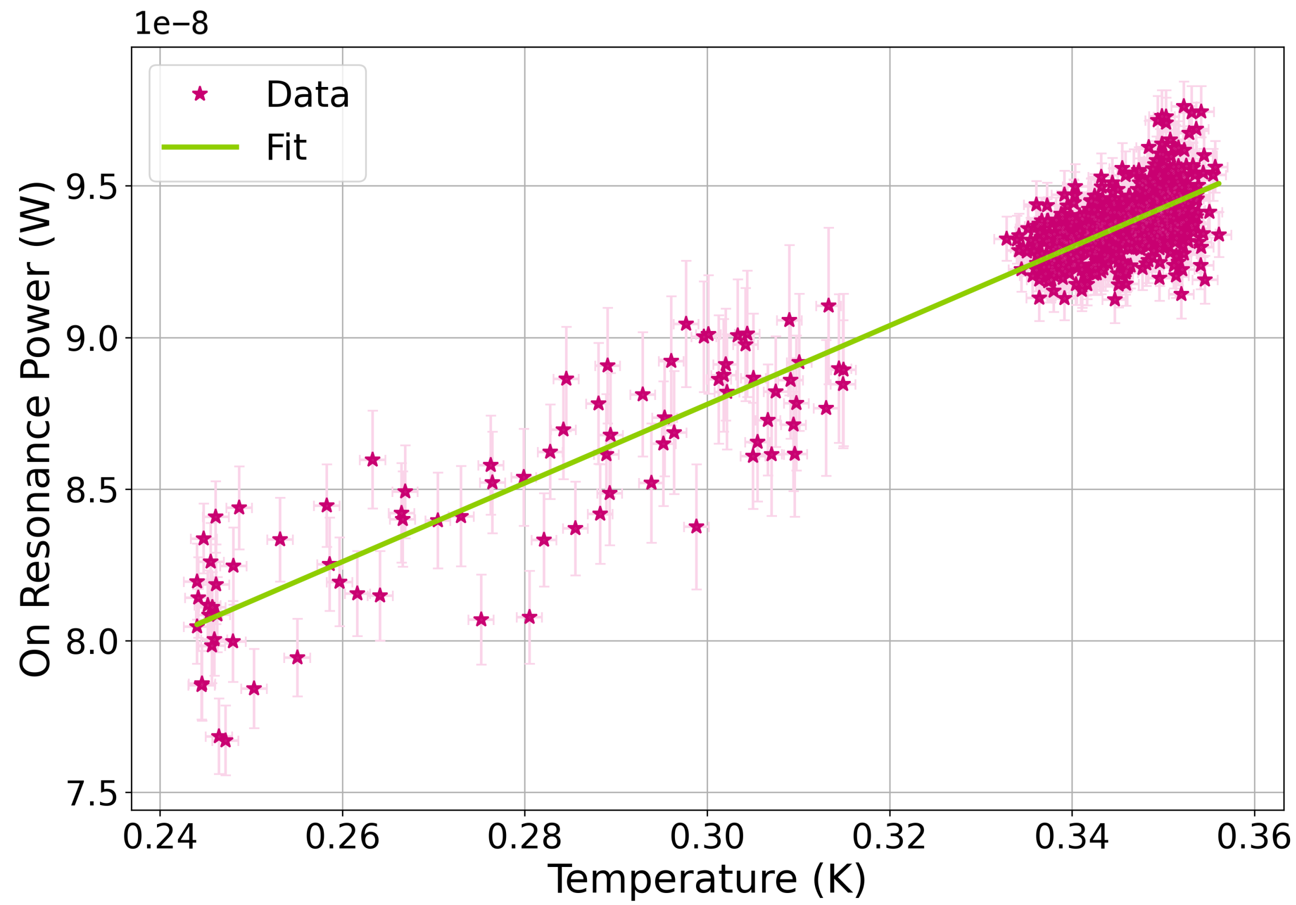
Old heat load thermal link



Upgraded at WUSTL

Improved Understanding of Receiver Noise





Hot load JPA-on noise calibration:

T_JPA,eff = 0.14 ± 0.02 K

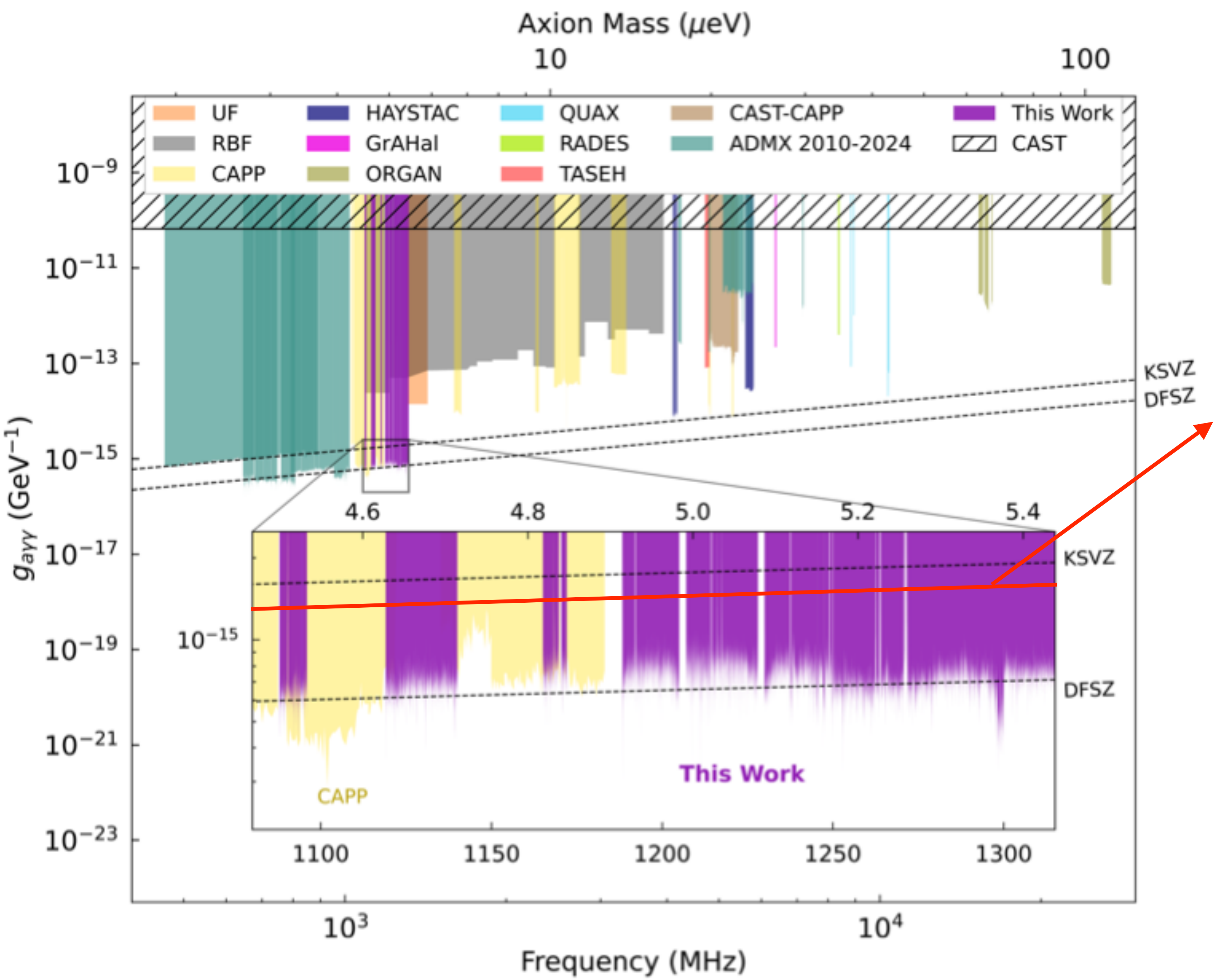
Cavity JPA-on noise alibration:

T_JPA,eff = 0.37 ± 0.02 K

1280 MHz example, *M. Guzzetti et.at, PhysRevD.111.092012*

- ~ 200mK more noise when cavity is connected (data taking)

Run1D-Part1 Result

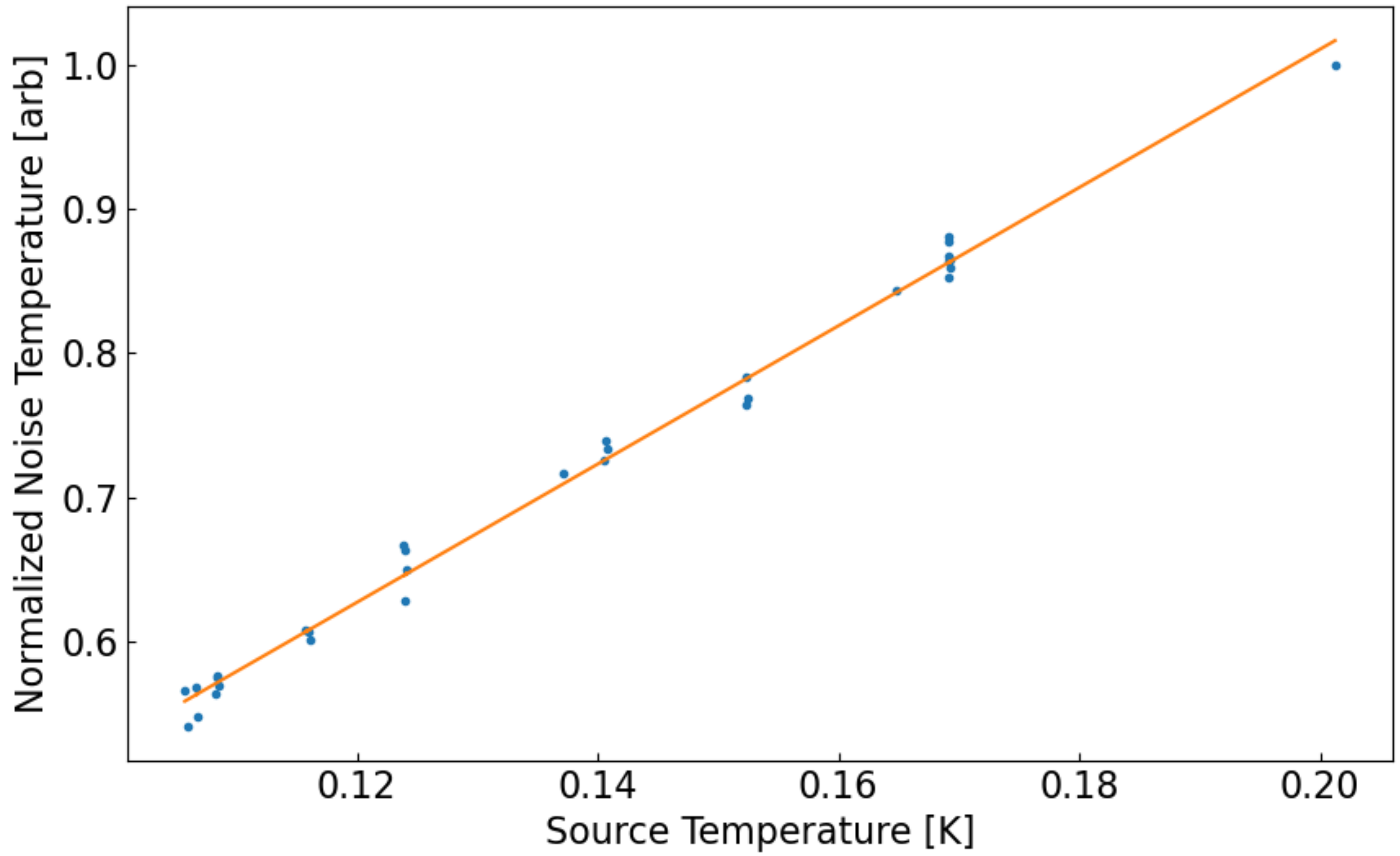


arxiv:2504.07279

- 90% CL limit is different from 90% discovery limit
- A guideline of our 'discovery ability'
  - Each ~1kHz is an independent experiment, 160MHz -> 200,000

New flux-pump JPA

Plot credit: Jonah Hoffman, graduate student at WUSTL



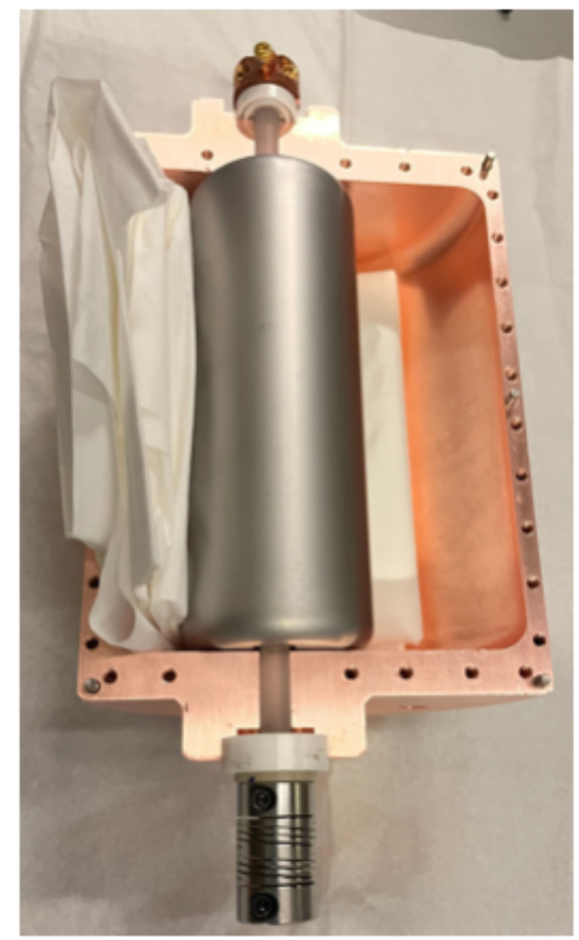
- Manufactured at WUSTL
- Significant improvement on JPA added noise:
  - $T_{\text{added}} = 20.5\ \text{mK}$ (compared to $140\ \text{mK}$ in the previous run)
  - Low pass filter of JPA DC bias + co-axial line for DC bias instead of twisted pairs

ADMX-SideCar

- Type-II superconductor cavity implementation: higher quality factor
- Quantum amplifier under high-magnetic field
    - Kinetic-Inductance Traveling Wave Parametric Amplifier (KI-TWPA)


Sidecar Installed in ADMX insert Dec 2023

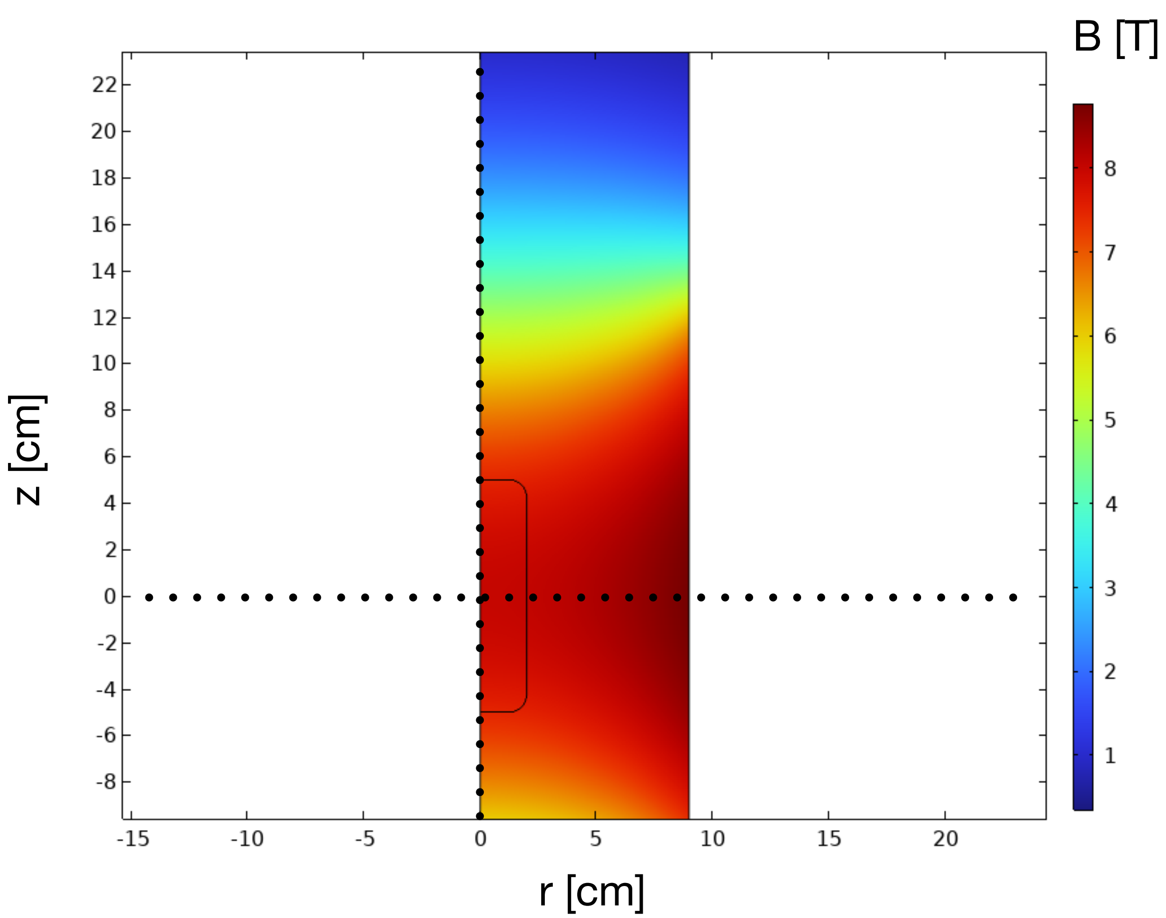

Rod with Cu-Sapphire Axle Inserts


Rod being installed in Cavity Half

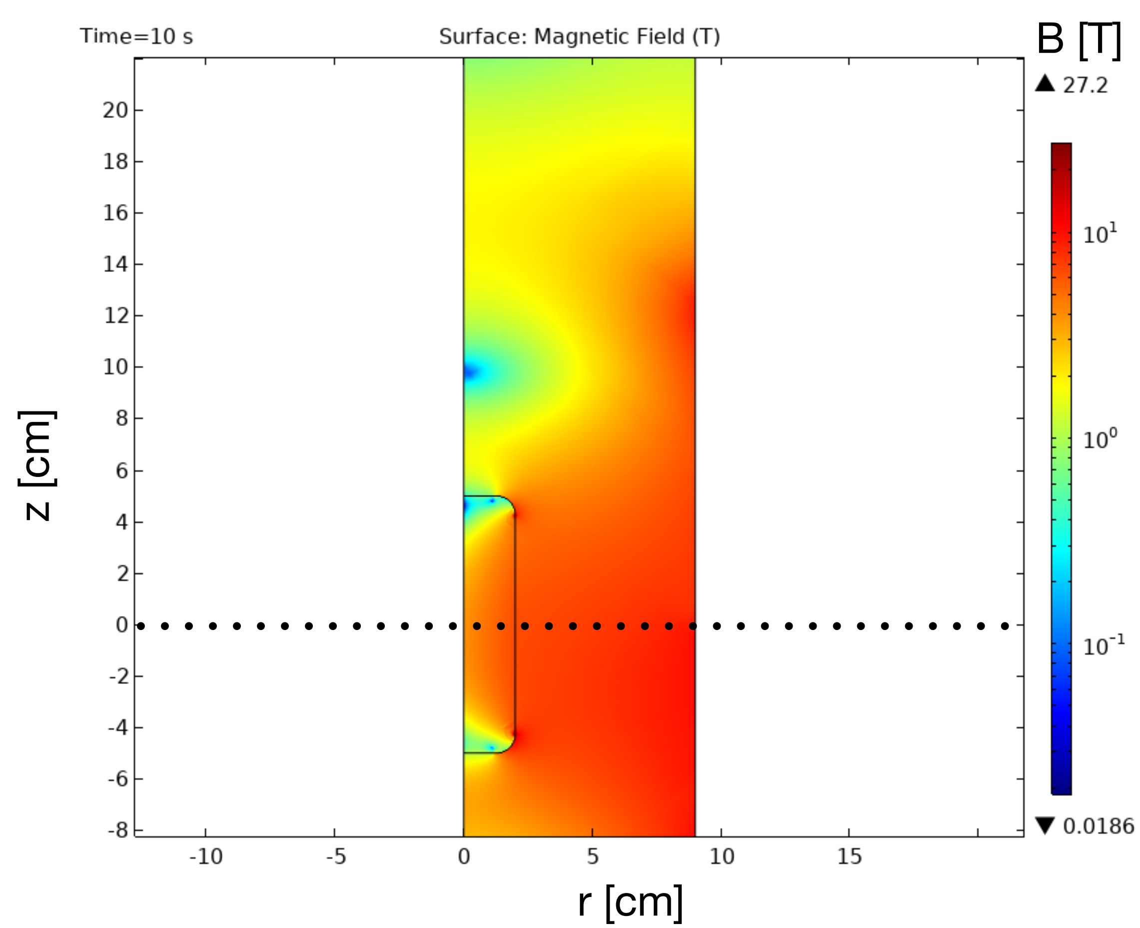
Magnetic field distortion

- COMSOL simulation
  - H-ϕ formulation or Time-dependent-Ginzburg-Landau theory
- Test of distortion in queue

Original B field



Stabilized B field distortion

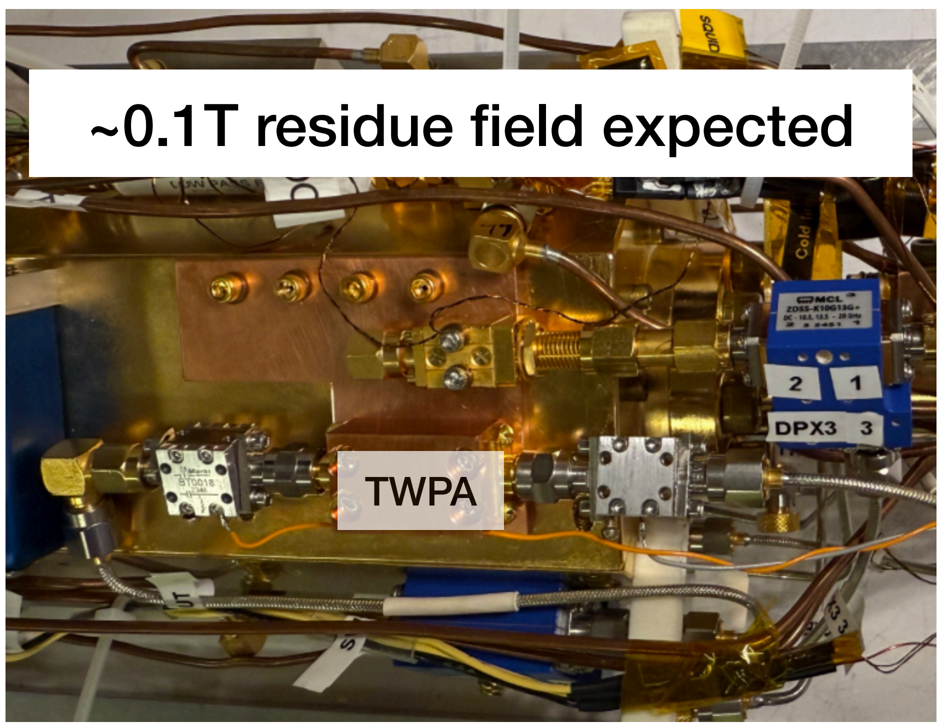


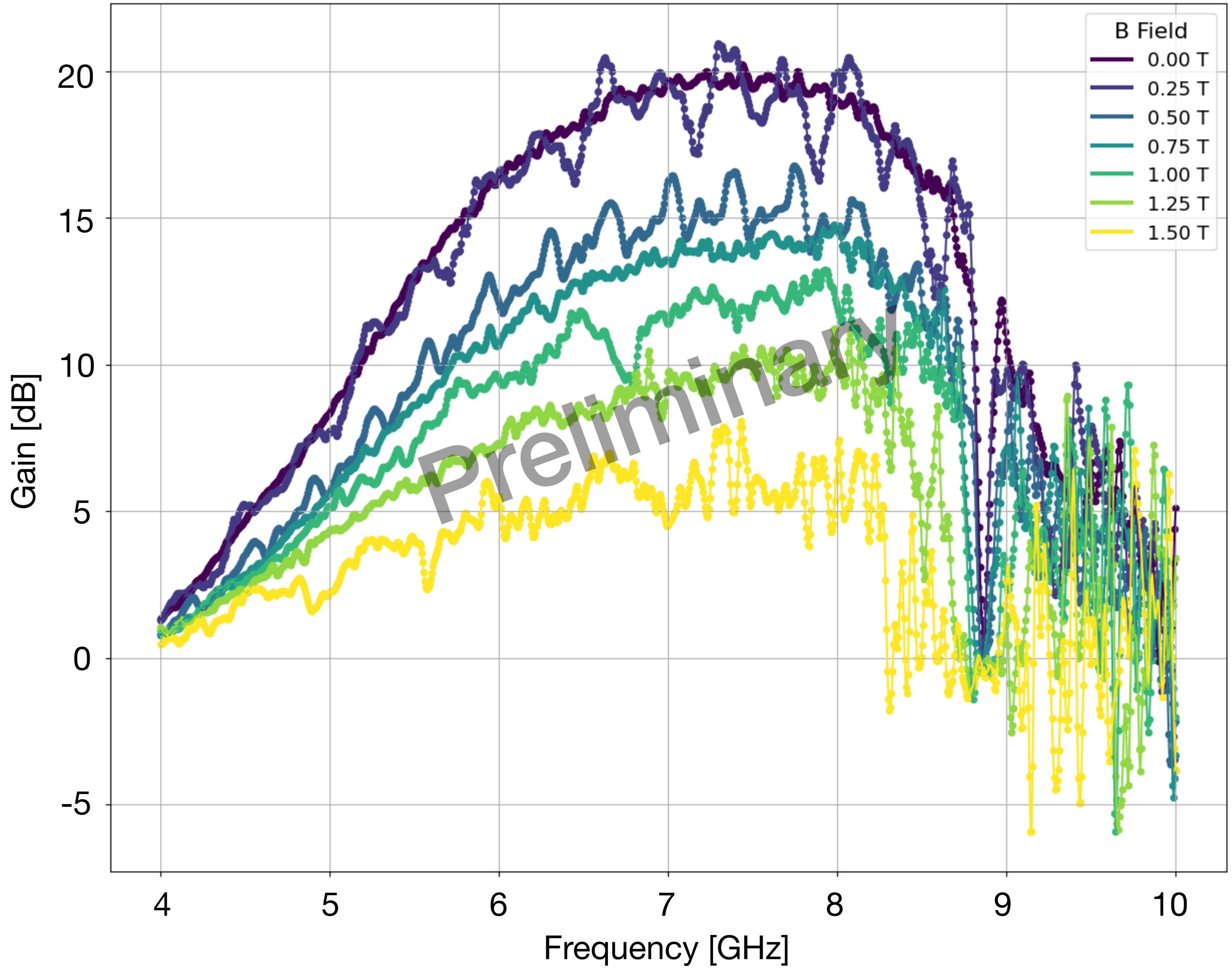
Plot credit: Madeleine Carhart, graduate student at UW

KI-TWPA with B Field Tolerance

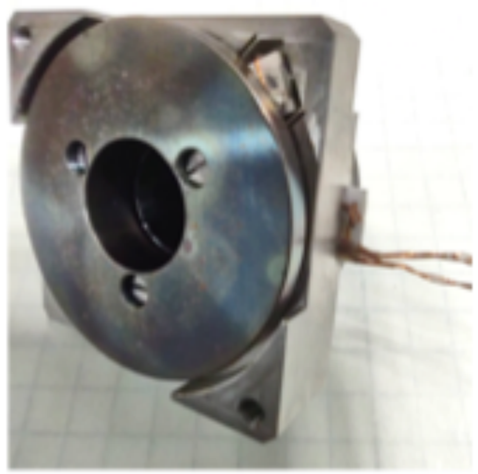
- Borrowed from Christian Boutan (PI at PNNL)
- Gain under parallel B field: three-way mixing, pump tone at 14.2 GHz

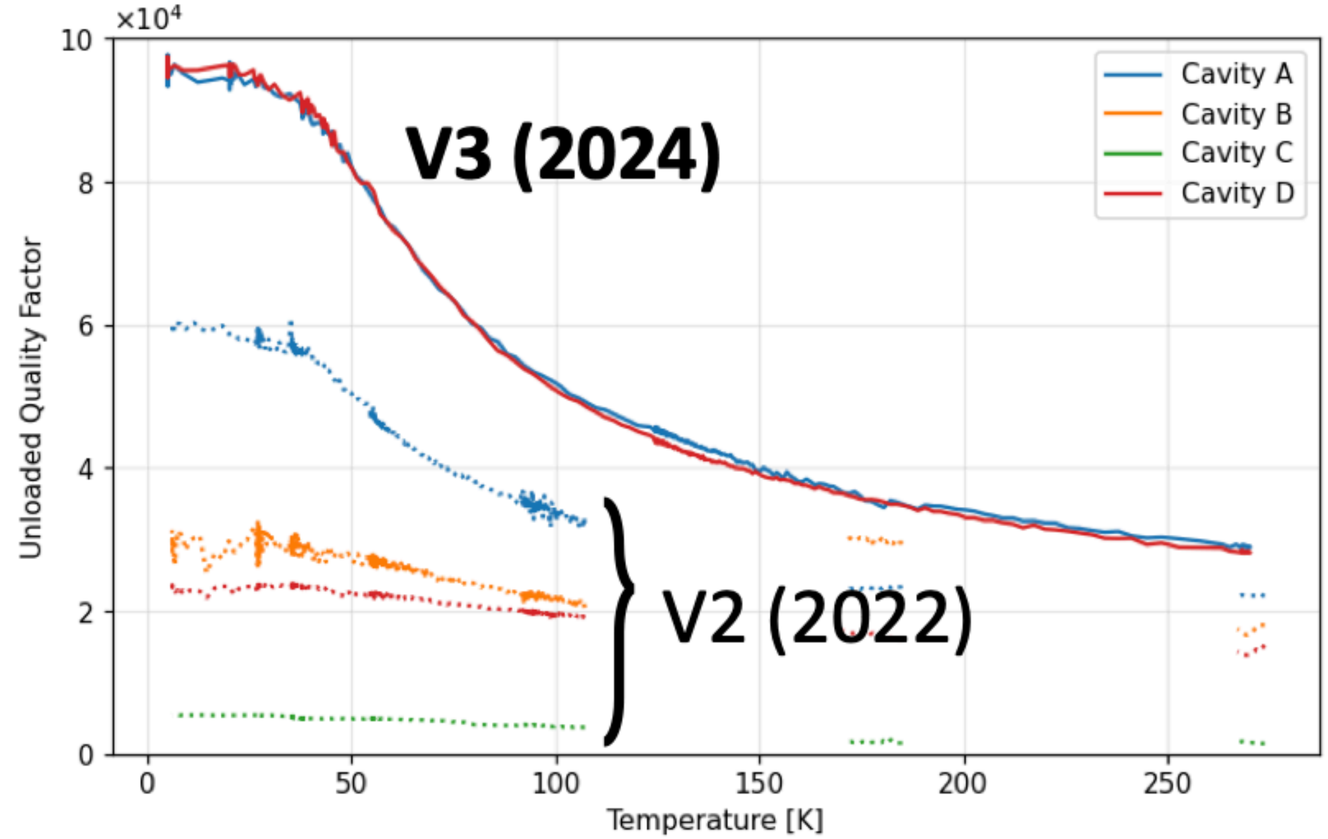
Plot credit: Christian Boutan, this work is sponsored by DOE HEP Early Career Award

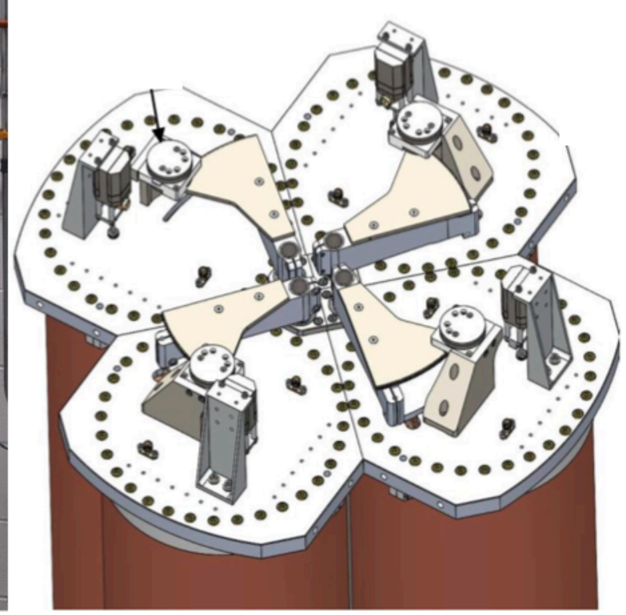


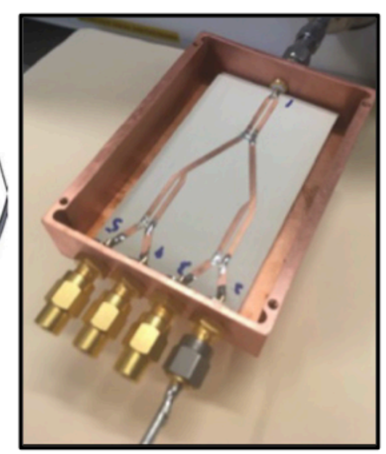


Preparation for four-cavity system







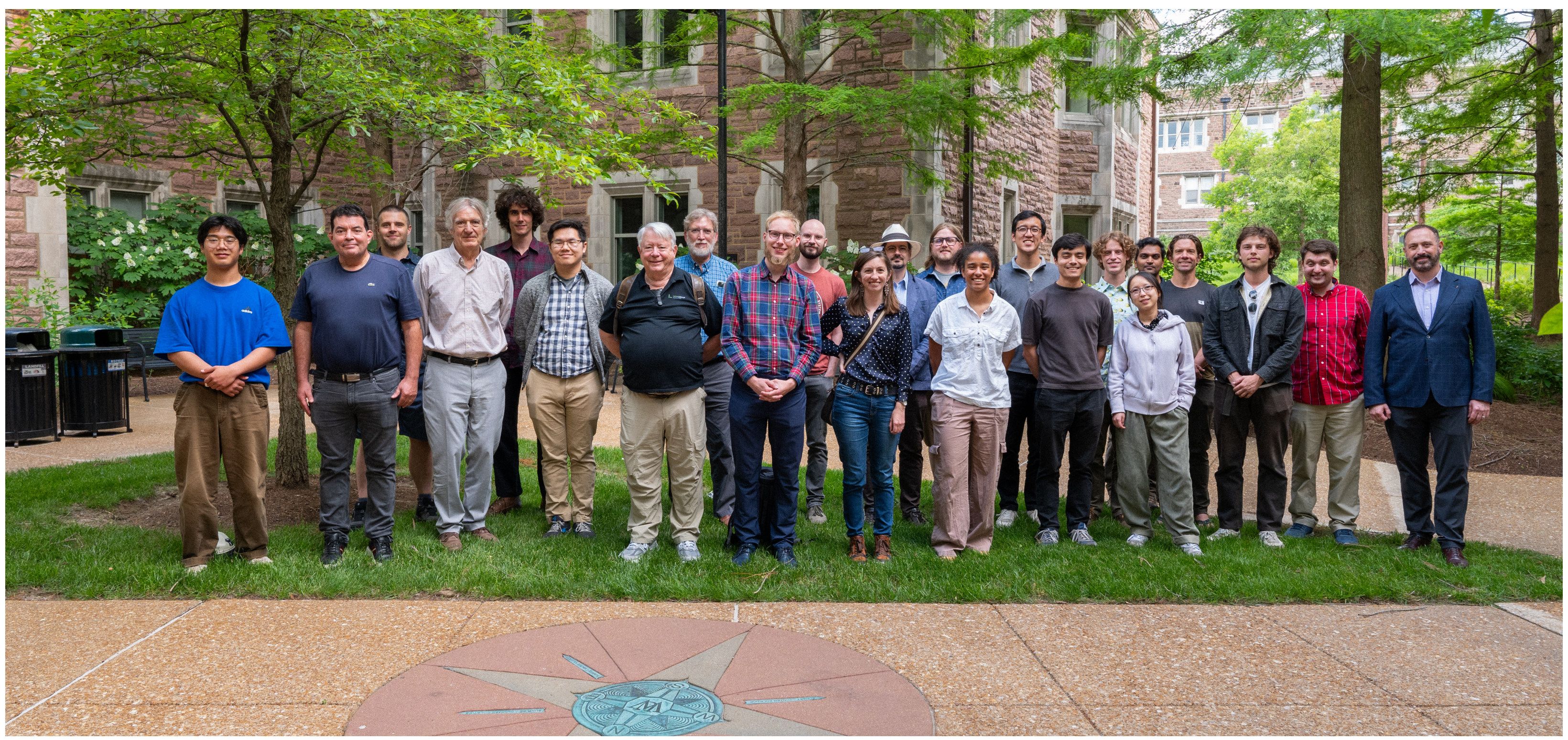


- 1.7 to 2.2 GHz
- 4 Cavities, V = 85 L
- Coherent Power combination
- JPA readout

Plot credit: Stefan Knirck, PI at Harvard

Acknowledgement

May 2025 ADMX Collaboration Meeting



This work is supported by U.S. Department of Energy through Awards No DE-SC0009800, No. DE-SC0009723, No. DE-SC0010296, No. DE-SC0010280, No. DE-SC0011665, No. DEFG02-97ER41029, No. DE-FG02-96ER40956, No. DE-AC52-07NA27344, No. DE-C03-76SF00098, No. DE-SC-0022148 and No. DE-SC0017987. Fermilab is a U.S. Department of Energy, Office of Science, HEP User Facility managed by Fermi Research Alliance, LLC (FRA), under Contract No. DE-AC02-07CH11359. Additional support was provided by the Heising-Simons Foundation and by the Lawrence Livermore National Laboratory LDRD office. PNNL is a multi-program national laboratory operated for the U.S. DOE by Battelle Memorial Institute under Contract No. DE-AC05-76RL01830. UWA and Swinburne participation is funded by the ARC Centre of Excellence for Engineered Quantum Systems and CE170100009, Dark Matter Particle Physics, CE200100008. The Sheffield group acknowledges support from the UK Science and Technology Facilities Council (STFC) under grants ST/ T006811/1 and ST/X005879/1. CRB is supported by DOE Office of Science, High Energy Physics, Early Career Award (FWP 77794 at PNNL). Chelsea Bartram acknowledges support from the Panofsky Fellowship at SLAC. John Clarke acknowledges support from the U.S. Department of Energy, Office of Science, National Quantum Information Science Research Centers.

Summary

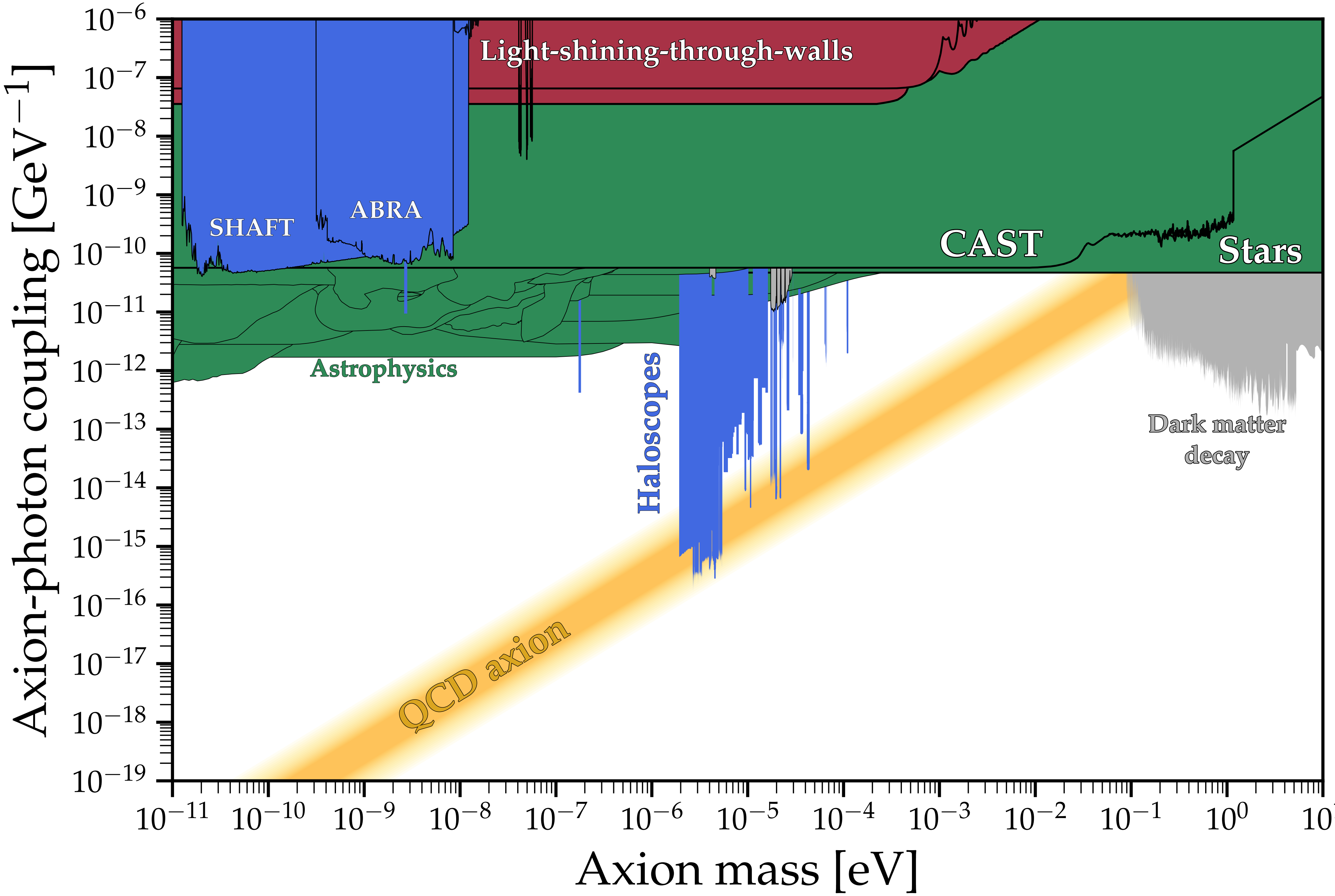
- ADMX continues to search for QCD axion dark matter with benchmark model discovery
- R&D on-going for superconducting cavities and novel quantum amplifiers
- Future ADMX plans to implement multi-cavity system for higher mass axions (up to 2.2 GHz)

Backup

Exclusion limit landscape

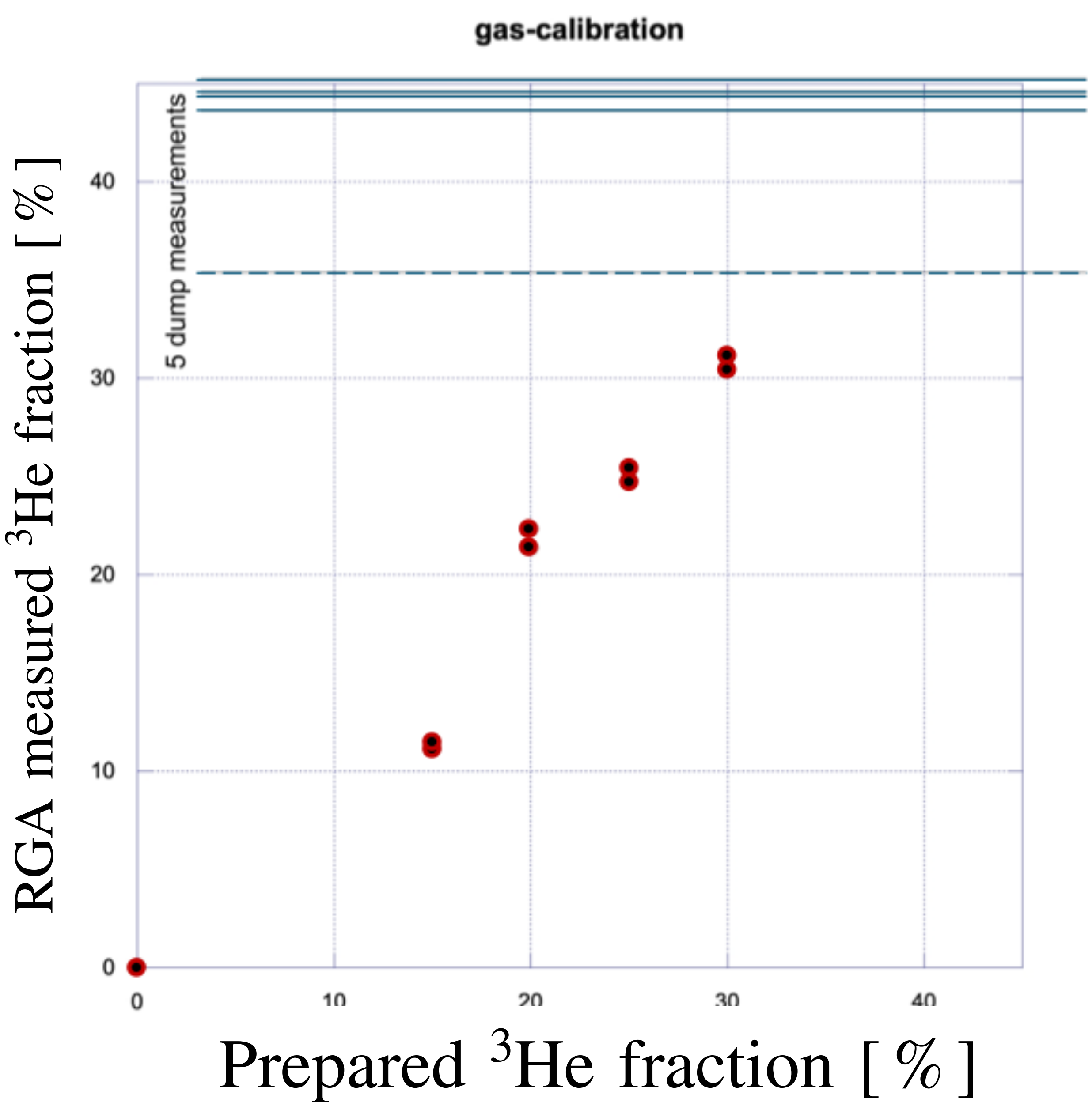
- KSVZ and DFSZ are benchmark models for QCD axion dark matter

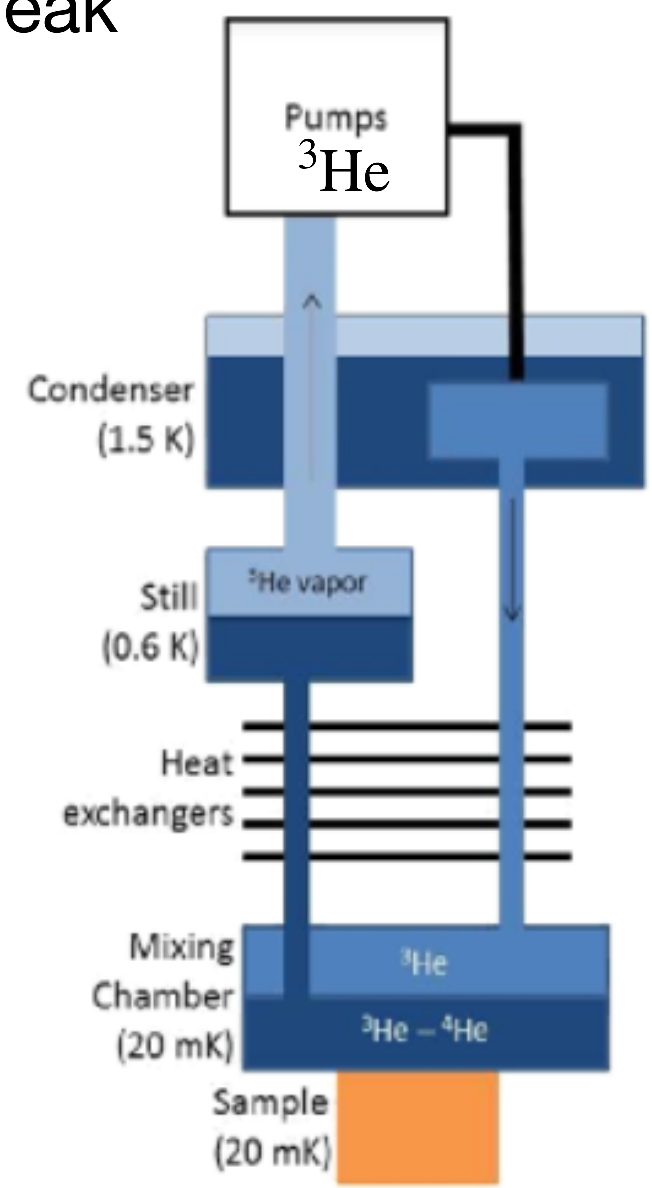
Plot from Ciaran A. J. O'Hare



Upgrade status — ^{3}He/^{4}He ratio

- Measurement (2025): $^3\mathrm{He}/(^3\mathrm{He} + {}^4\mathrm{He}) = 45\,\%$ (volume)
- Initial (2014-2015): $^3\mathrm{He}/(^3\mathrm{He} + {}^4\mathrm{He}) = 24\,\%$
- ^{4}He is lost more -> likelv to be a ^{4}He superfuild leak





Increase in cooling power expected!

Plot credit: Cyrus Goodman, Charles Hanretty (Research Engineers at UW)