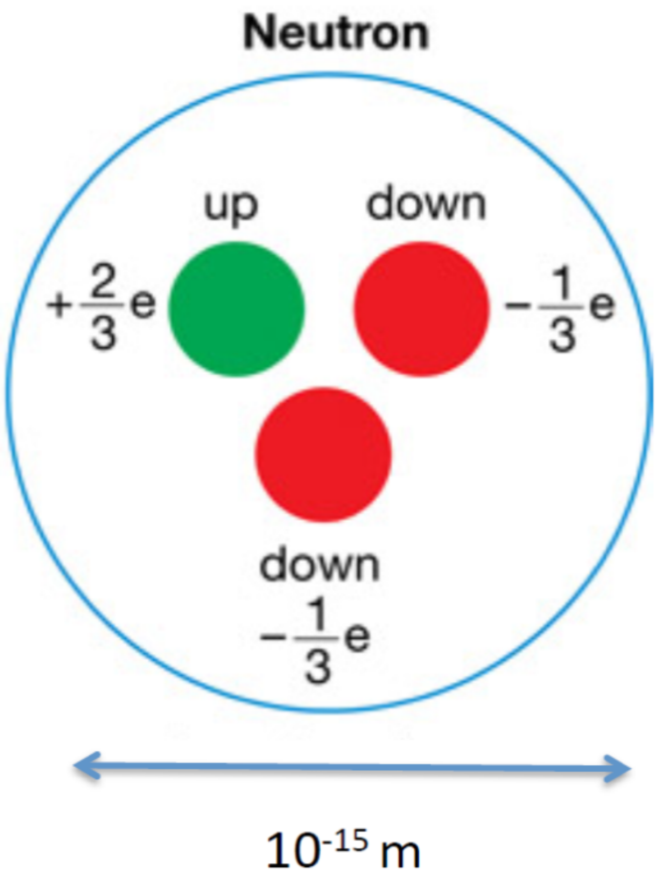
Status of ADMX:
Run1C-extended result and Run1D progress

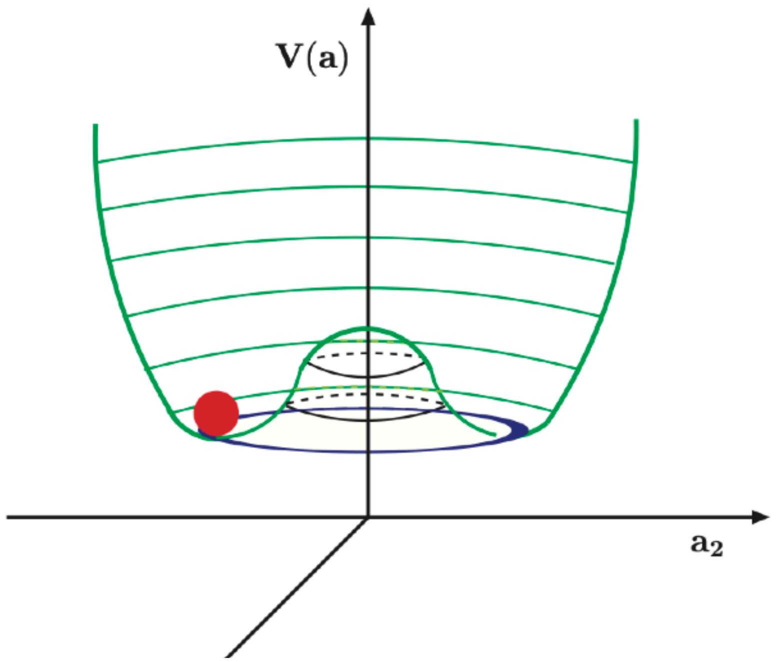
Dan Zhang,
Postdoctoral researcher,
University of Washington

Motivation of QCD axions

- SU(3) theories naturally have a phase term contributing to CP violation (e.g. weak interaction).
    - QCD would have a neutron electric dipole moment d_n of 10^{-16} e · cm
    - nEDM collaboration at PSI (C. Abel et al, 2020) $d_n < 1.8 \times 10^{-26}$ e · cm
- The strong CP problem solution: $U_{\mathrm{PQ}}(1)$ axial symmetry (Peccei, Quinn, 1977)
    - New particle beyond standard model, QCD axion *(Weinberg, Wilczek, 1978)*

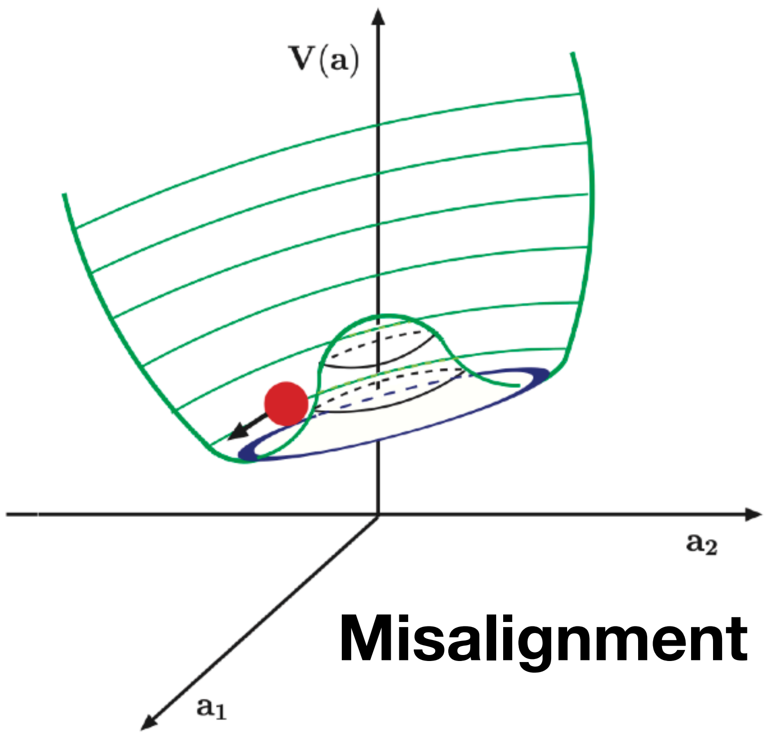


QCD Axion as dark matter



Peccei-Quinn symmetry $U_{PQ}(1)$ is spontaneously broken at a temperature of the universe $\mathbf{T_{PQ}}$ corresponding to the PQ breaking scale f_a. **Axions are massless**

Post-inflation: $T_{PQ} < T_{reheat}$



Misalignment

Near the QCD phase transition ($T_{univ} = \Lambda_{QCD} \approx 200$ MeV), $U_{PQ}(1)$ becomes a ‘tilting Mexican Hat’ potential. **Axions become massive.**

$O(1)\ \mu\mathrm{eV}$ to $O(1)\ \mathrm{meV}$

Pre-inflation doesn’t give preference on axion mass from cosmological point of view

Detecting Axions

$$\mathcal{L} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{i}{2} g_d a \bar{N}\sigma_{\mu\nu}\gamma_5 N F_{\mu\nu} + g_{aNN}(\partial_\mu)\bar{N}\gamma^\mu\gamma_5 N + g_{aee}(\partial_\mu)\bar{e}\gamma^\mu\gamma_5 e$$

Coupling to Photons

Coupling to Nucleon EDM

Coupling to Axial Nuclear Moment

Coupling to Axial Electron Moment

Adapted from Y. Kahn, See also Graham and Rajendran, Phys.Rev. D88 (2013) 035023

Detecting Axions

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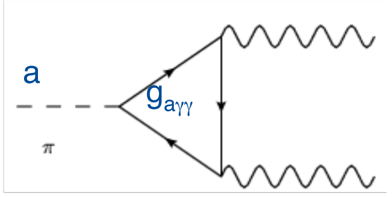


Coupling to Photons

Coupling to Nucleon EDM

Coupling to Axial Nuclear Moment

Coupling to Axial Electron Moment

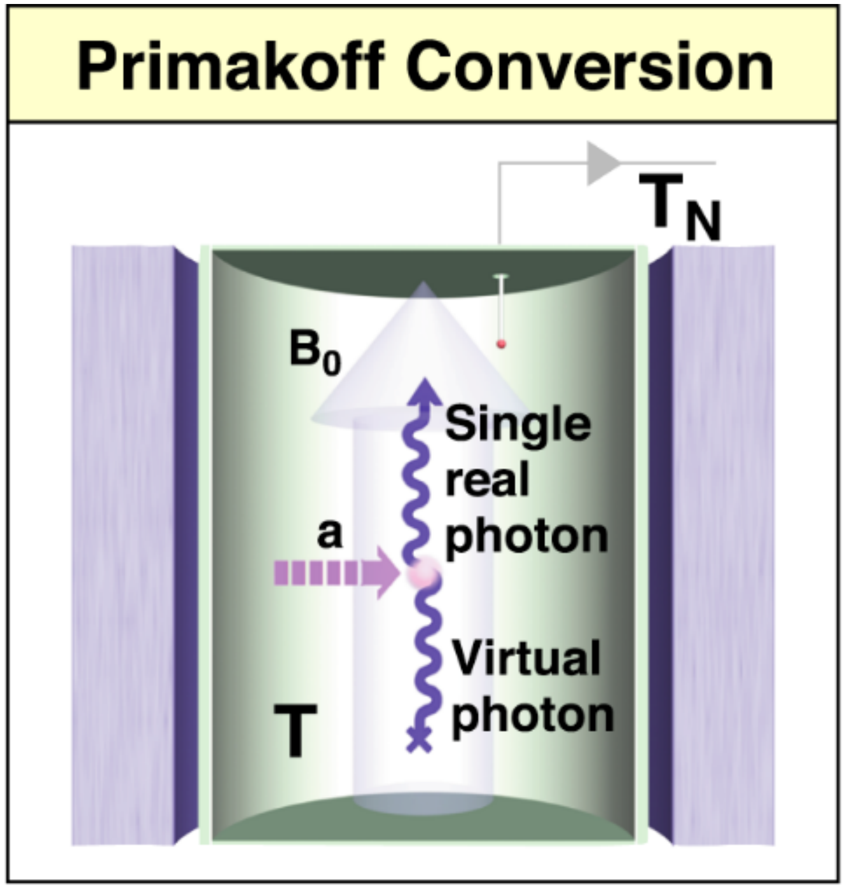
Clean experimental signal
Well developed techniques
Ripe for incorporating quantum sensing techniques

Promising experimental techniques under development

Adapted from Y. Kahn, See also Graham and Rajendran, Phys.Rev. D88 (2013) 035023

Axion Haloscope

Sikivie PRL 51:1415 (1983)

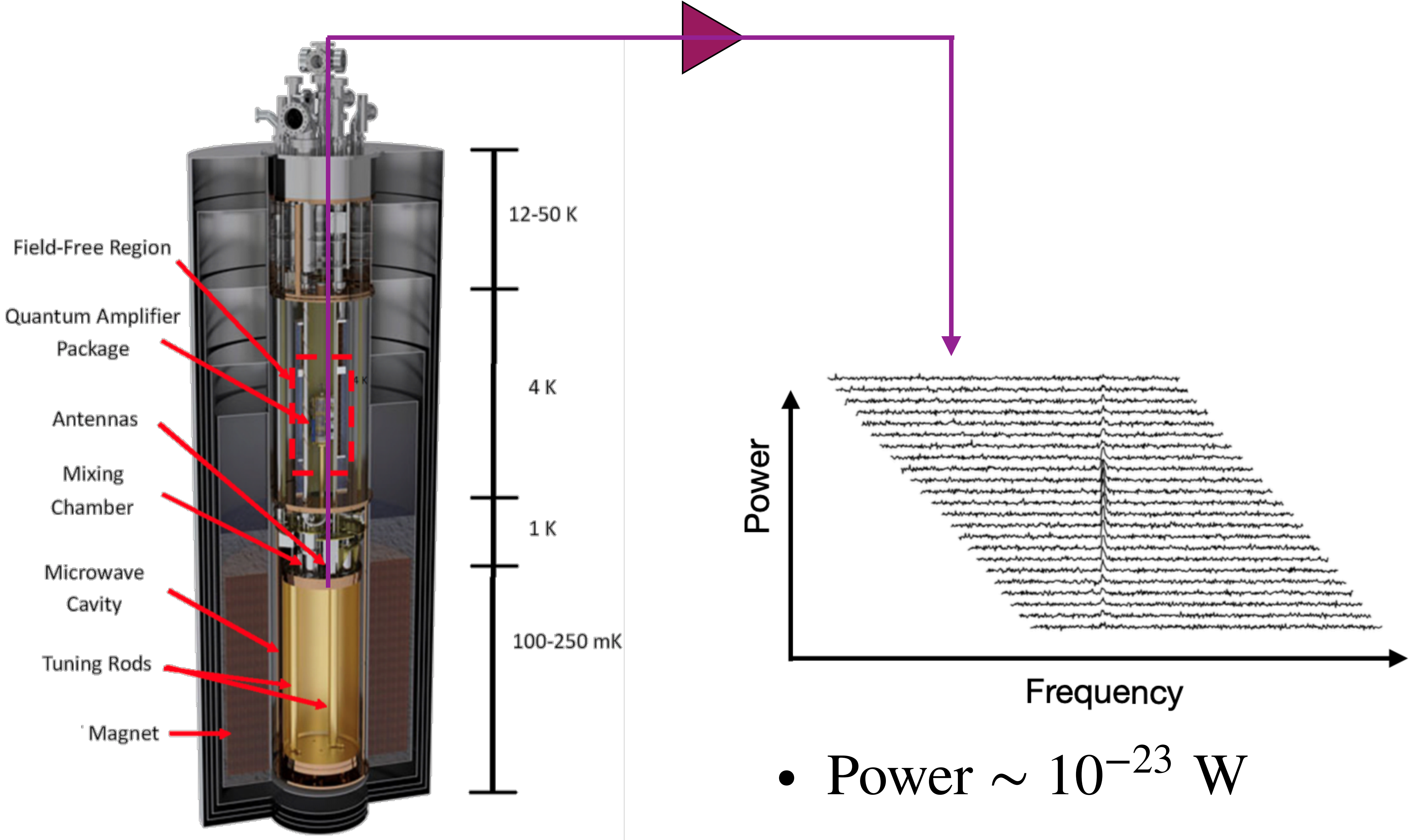


$$P_{\text{sig}} \propto {B_0}^2 Q V^2 C$$

$$P_{\text{bkg}} \propto T_{\text{black body}} + T_{\text{1st amp}}$$

- A strong magnetic field can stimulate Dark Matter Axions conversion to photons.
- Controllable experimental parameters for axion signal
  - B_0: magnetic field
  - Q: quality factor of the resonator (assume smaller than axion intrinsic Q)
  - V: volume of the resonator
  - C: form factor, overall effective overlap between the resonant mode and B_0
- Mainly contribution to backgrounds
  - Black body radiation
  - The 1st stage amplifier noise

Axion Dark Matter Experiment



- Power ~ 10^{-23} W

7.6 T magnetic field

ADMX collaboration

ADMX Collaboration meeting Jan 2023

Collaborating Institutions:

University of Washington
Washington University St. Louis
University of Western Australia
University of Florida
University of Sheffield
University of Western Australia
Stanford University / SLAC
UC Berkeley
Fermilab
Pacific Northwest National Laboratory
Lawrence Livermore National Laboratory
Los Alamos National Laboratory

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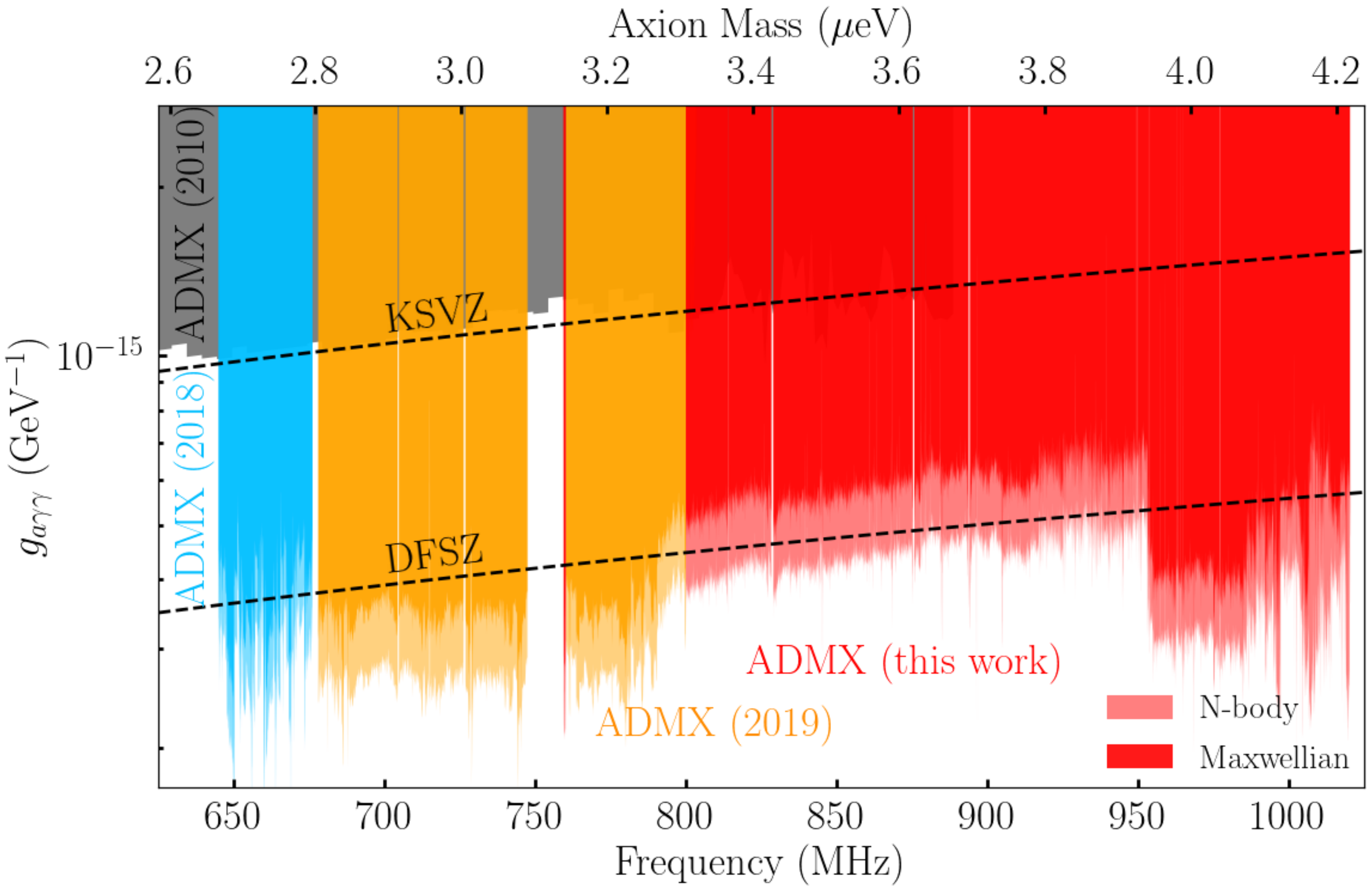
ADMX Recent Published Results

Excluded parameter space over the last 5 years



Bartram et al. PRL 127, 261803 (2021)

- Quantum amplifiers applied
  - MSA (micro-strip squid amplifier)
  - JPA (Josephson parametric amplifier)
- Able to run at any low temperature, ideally can reach zero added noise

ADMX 2022: Run1C-extend

- 5 month data-taking (Aug to Dec, 2022) in the parameter space not reaching DFSZ sensitivity before

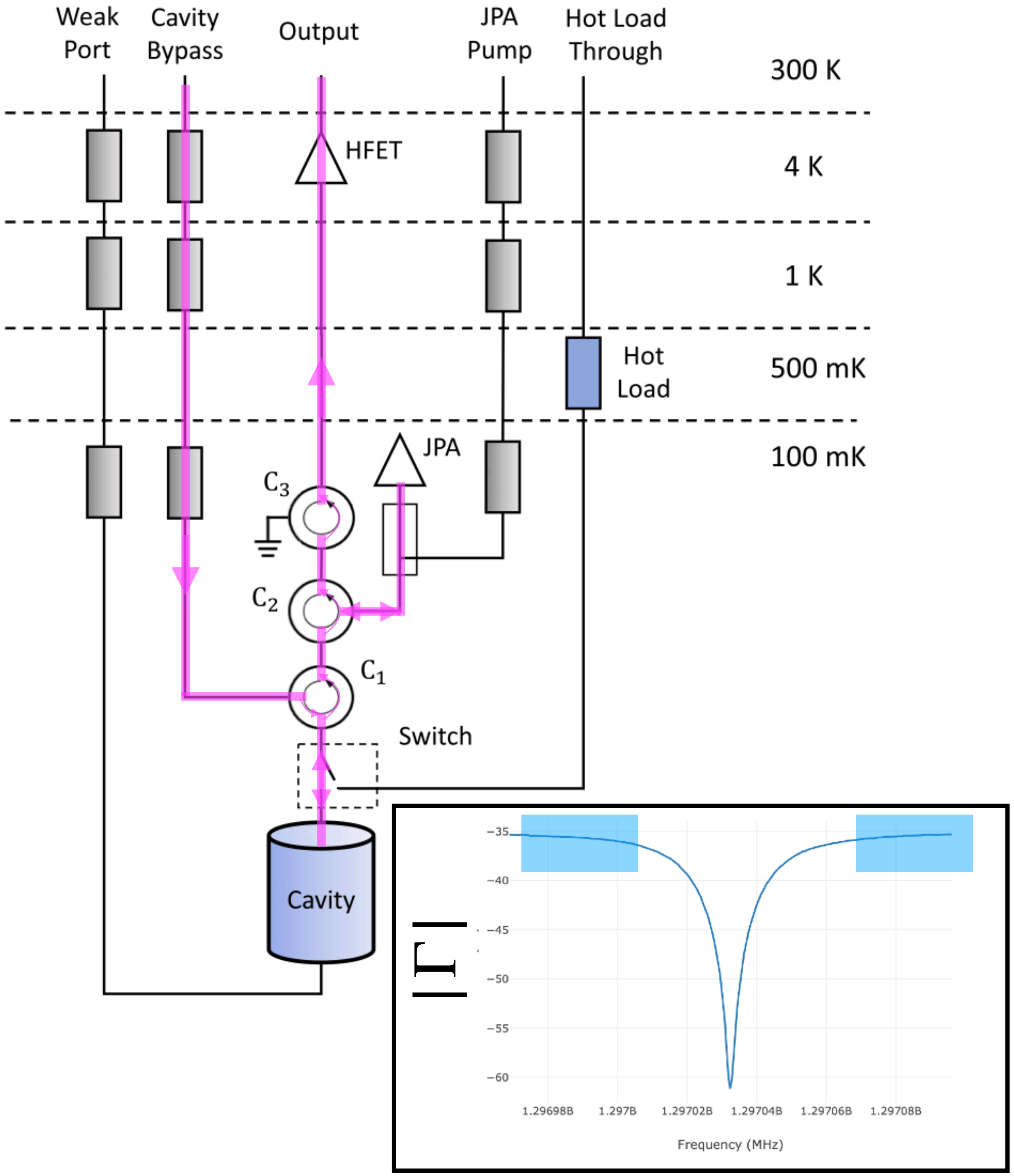
- Starting at 950MHz and go down in frequency (span 6MHz) — **too unstable**

  - Inaccurate JPA gain measurements with reflection measurements

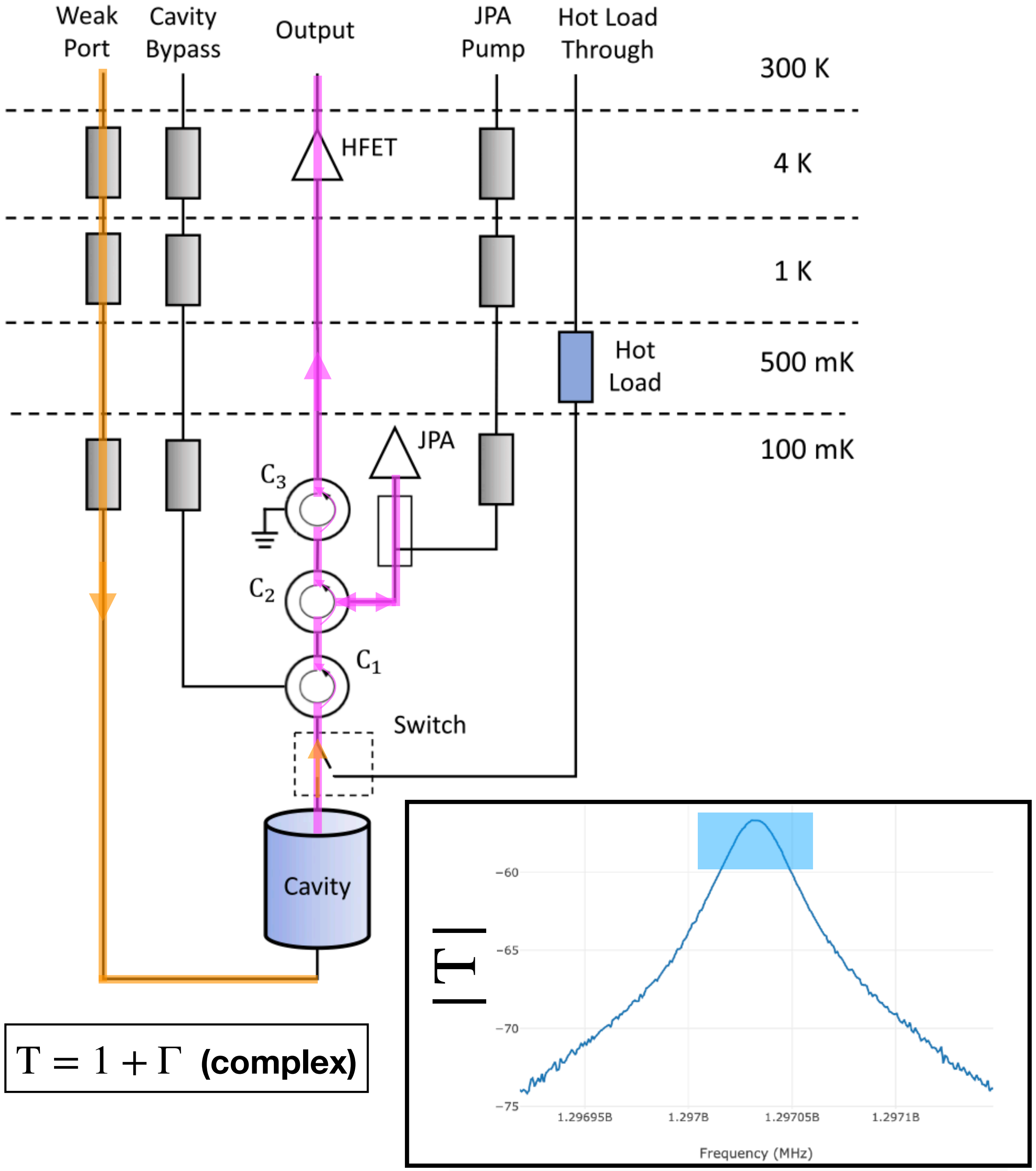
- Starting at 792MHz and go up (span 15MHz) — **stable**

Gain measurement

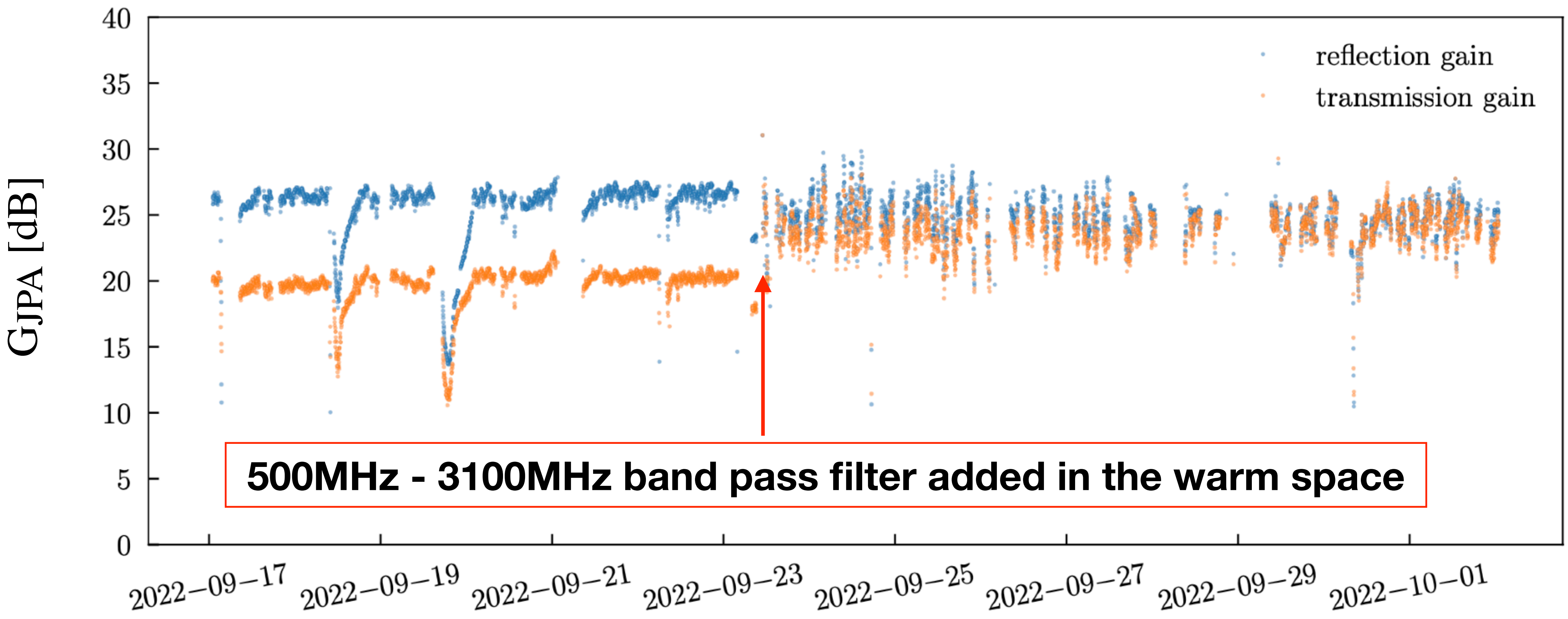
Reflection:
compare off-resonance for JPA on/off



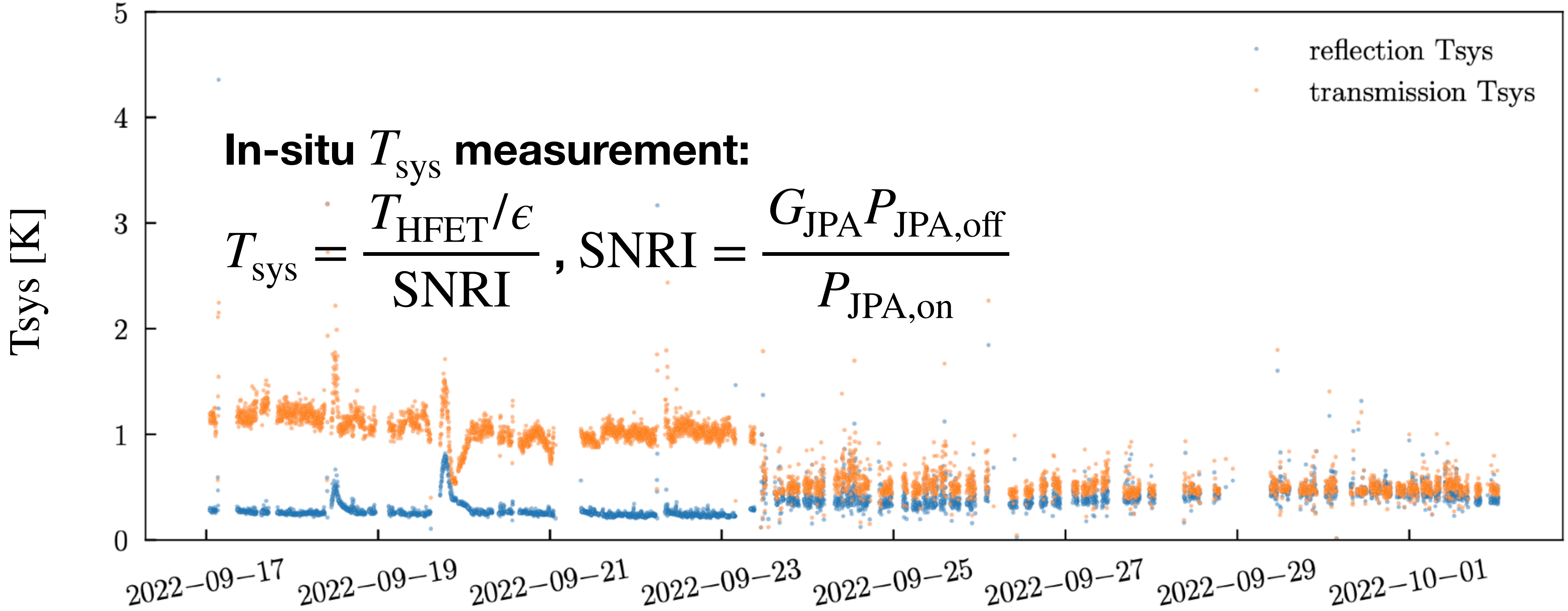
Transmission:
compare on-resonance for JPA on/off



$T = 1 + \Gamma$ **(complex)**



500MHz - 3100MHz band pass filter added in the warm space

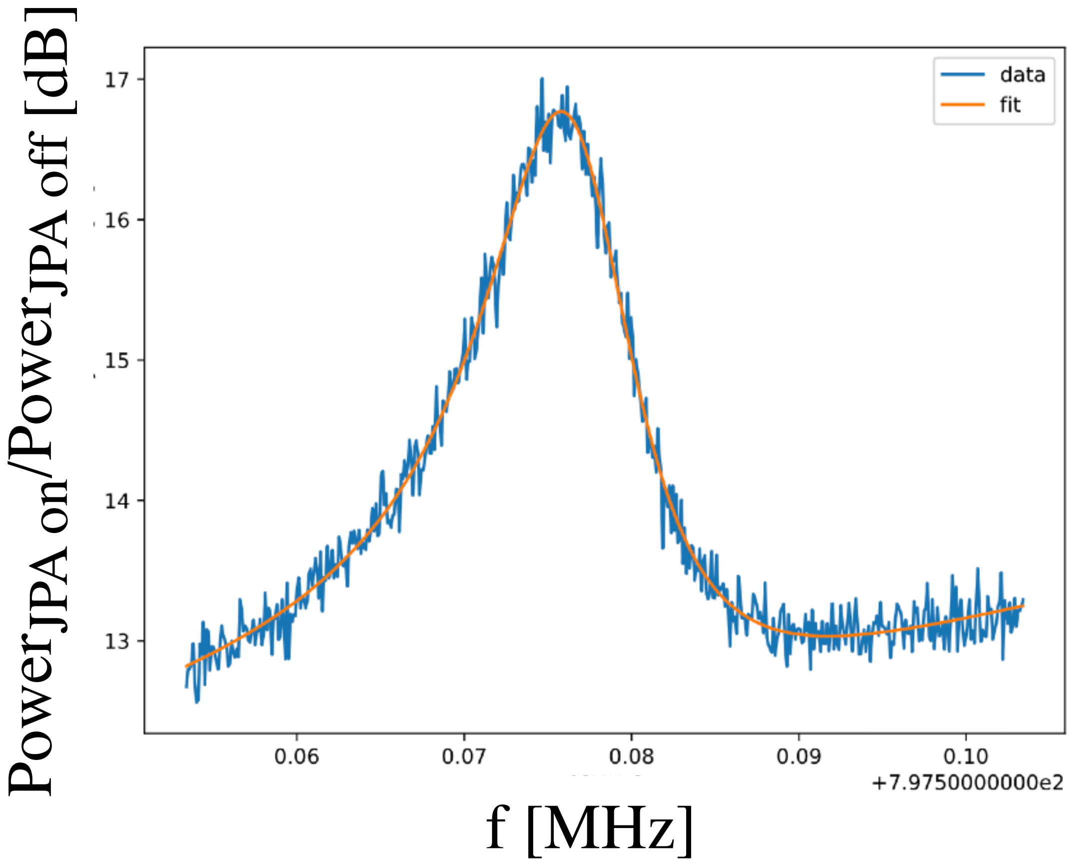


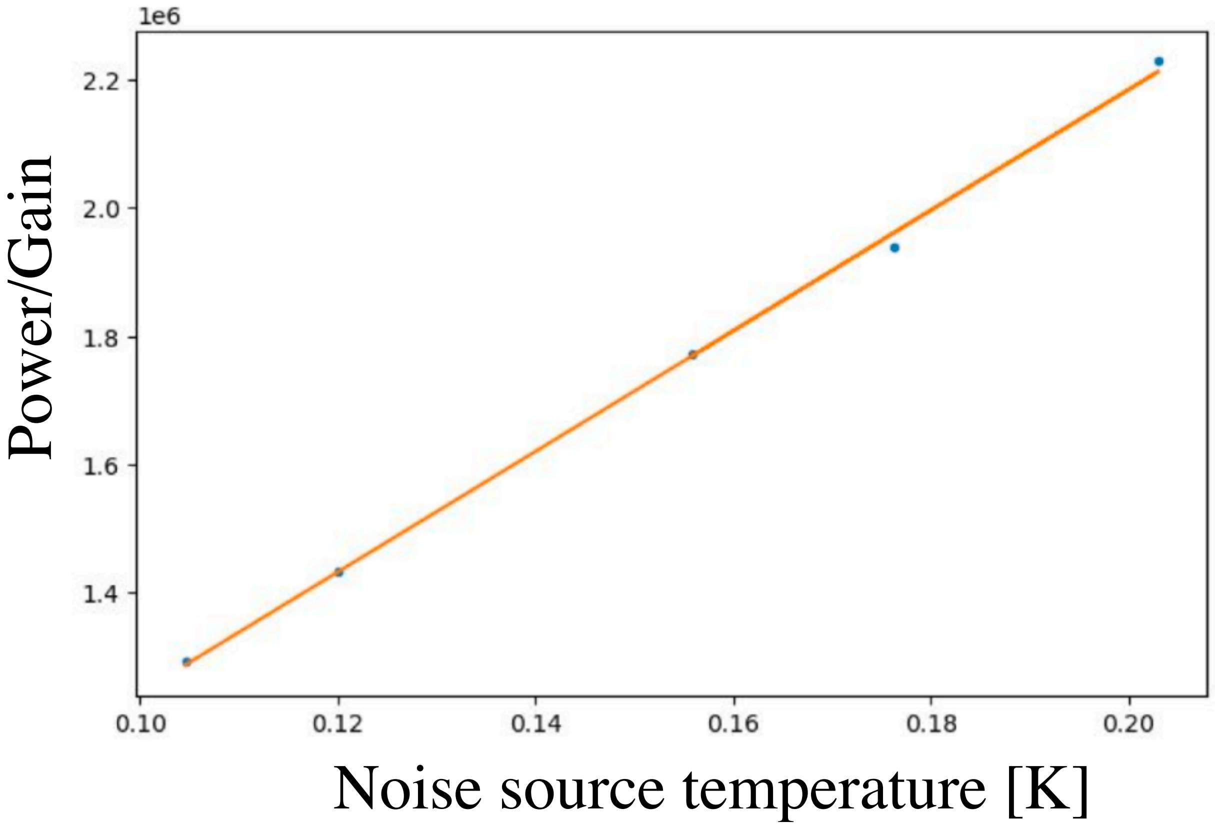
In-situ $T_{\rm sys}$ measurement:

$$T_{\rm sys} = \frac{T_{\rm HFET}/\epsilon}{\rm SNRI}, \quad {\rm SNRI} = \frac{G_{\rm JPA} P_{\rm JPA,off}}{P_{\rm JPA,on}}$$

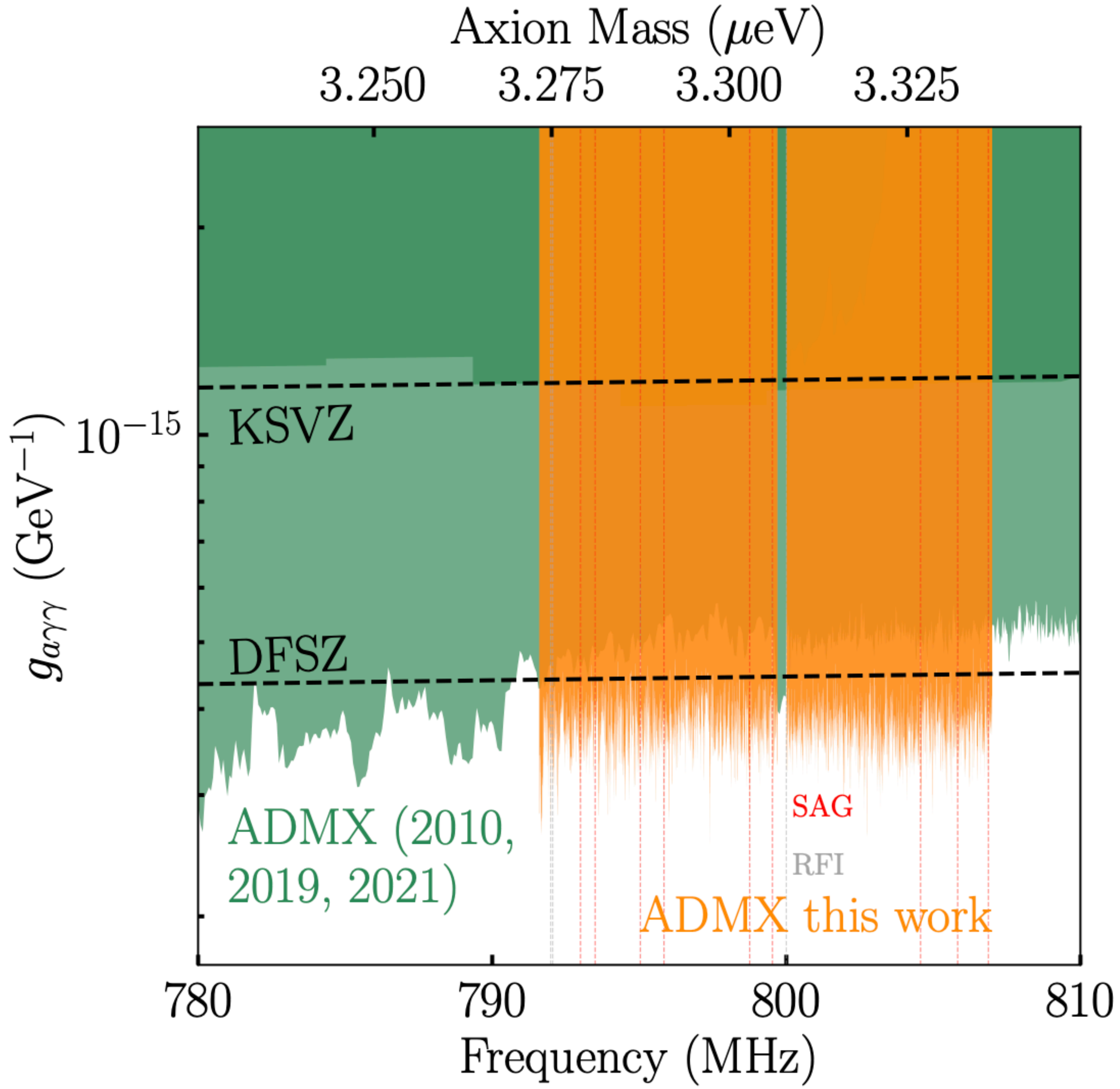
Run1C-extended result 792 to 807 MHz

- Noise temperature T_{sys}: $0.48 \pm 0.05\ \mathrm{K}$,
    - JPA gain: $21 \pm 1\ \mathrm{dB}$, cavity at 100 mK
    - JPA added noise: 100~200 mK (only estimation due to hot rod)
- Post-experiment measurement
    - Smaller residue magnetic field
    - JPA added noise 65 mK at 800MHz with 22 dB gain





Preliminary result

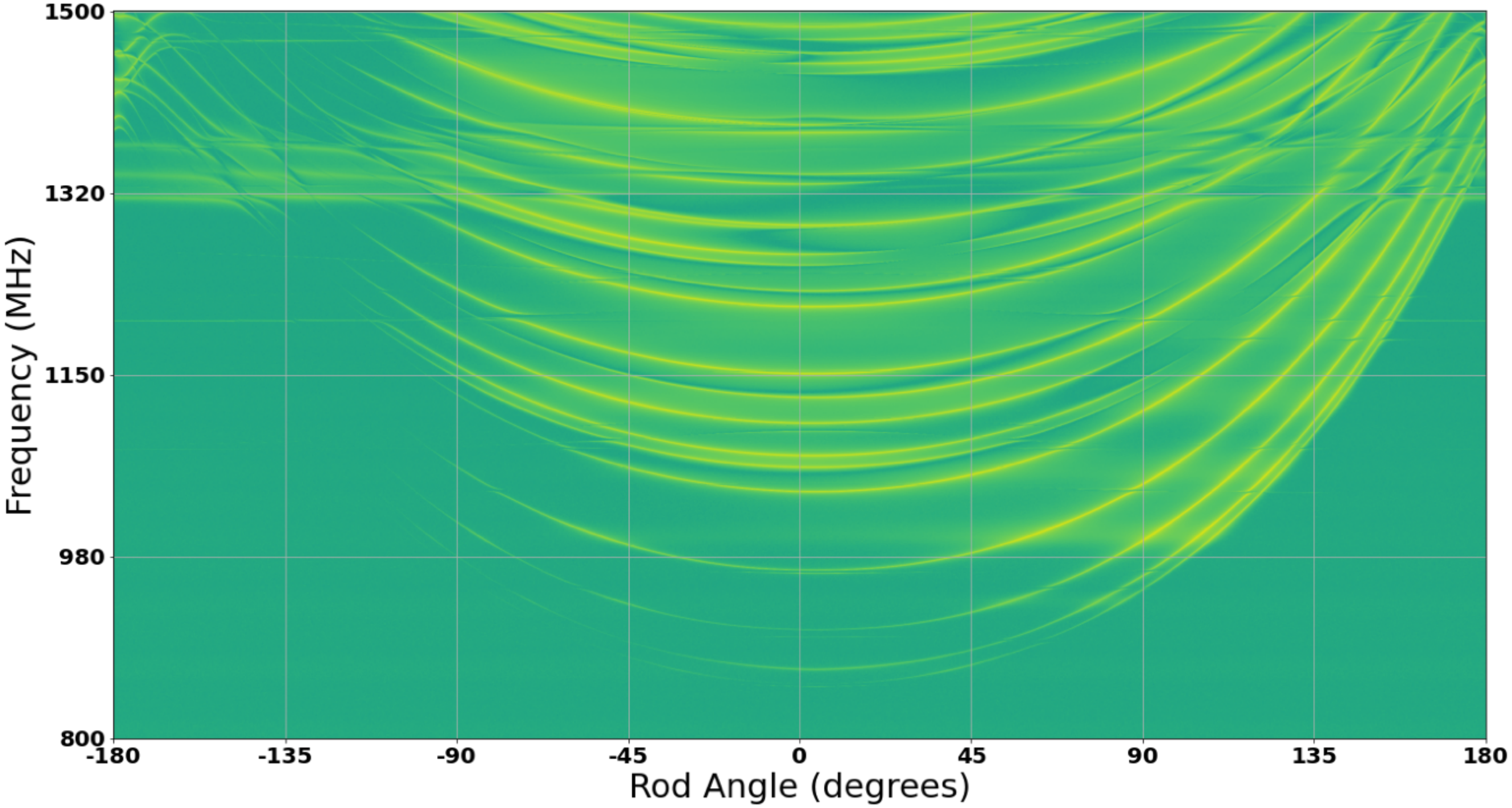


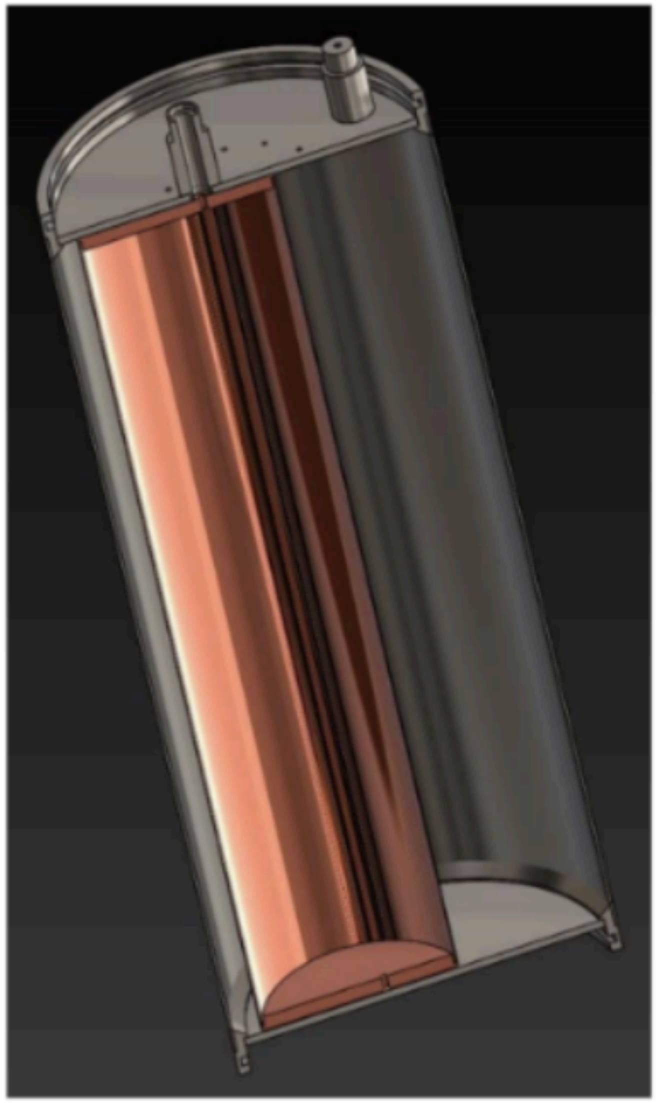
SAG: synthetic axions

RFI: identified non-signal interferences

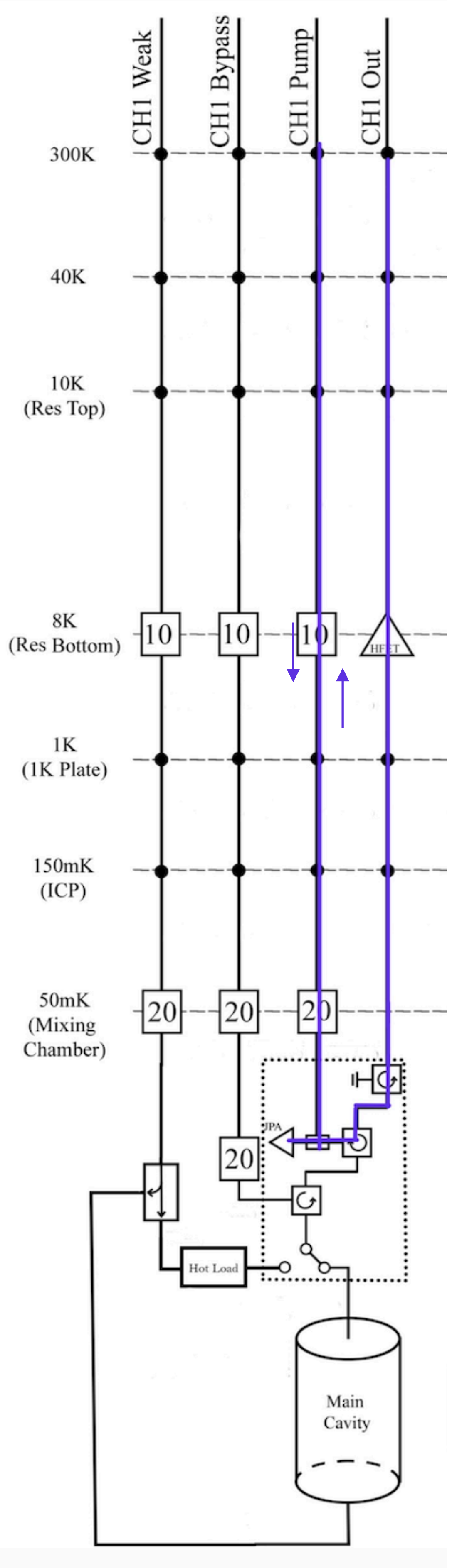
Run1D coverage

- New Cavity, new tuning rod
- Prioritizing 1.2-1.3 GHz
- Unloaded Q: 70k reached at 1K





Extra JPA gain monitoring



- Preserve JPA Gain measurement with reflection
- Resume JPA Gain measurement with transmission
- Add a new probe:
  - 20 dB smaller than JPA pump probe by network analyzer
  - Circulator insertion loss can be subtracted

Run1D JPA noise measurement

- $T_{\mathrm{sys}} = 2T_{\mathrm{MXC}} + T_{\mathrm{JPA}}/\alpha_1$
  - T_{JPA}: JPA added noise at the JPA reference plane
  - α_1(-0.9 to -1dB): linear attenuation between antenna and JPA

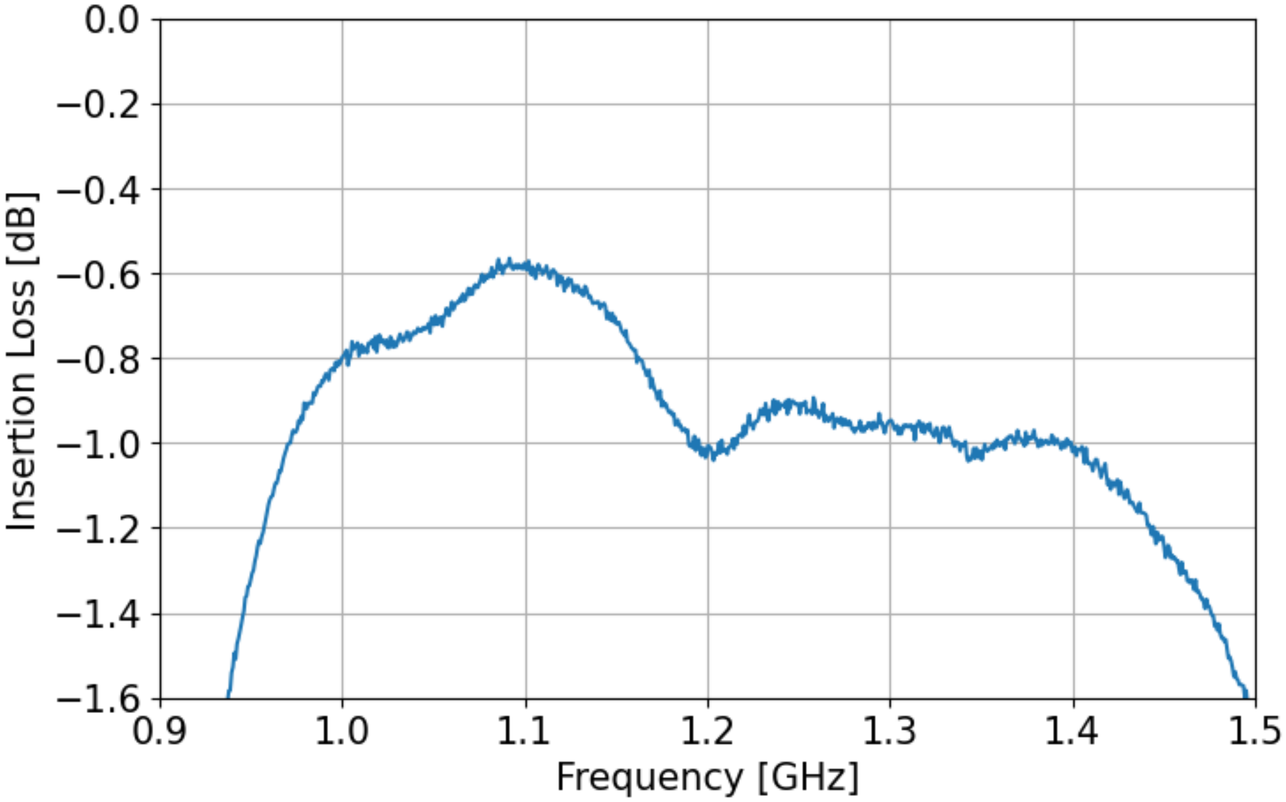
- **Similar to Run1C-extended scenario**
  - $T_{MXC} = 100\ \mathrm{mK}, T_{\mathrm{JPA}} = 83\ \mathrm{mK}$

$$T_{\mathrm{sys}} = 356\ \mathrm{mK}$$

- **Very optimistic scenario:**
  - $T_{MXC} = 50\ \mathrm{mK}, T_{\mathrm{JPA}} = 29\ \mathrm{mK}$

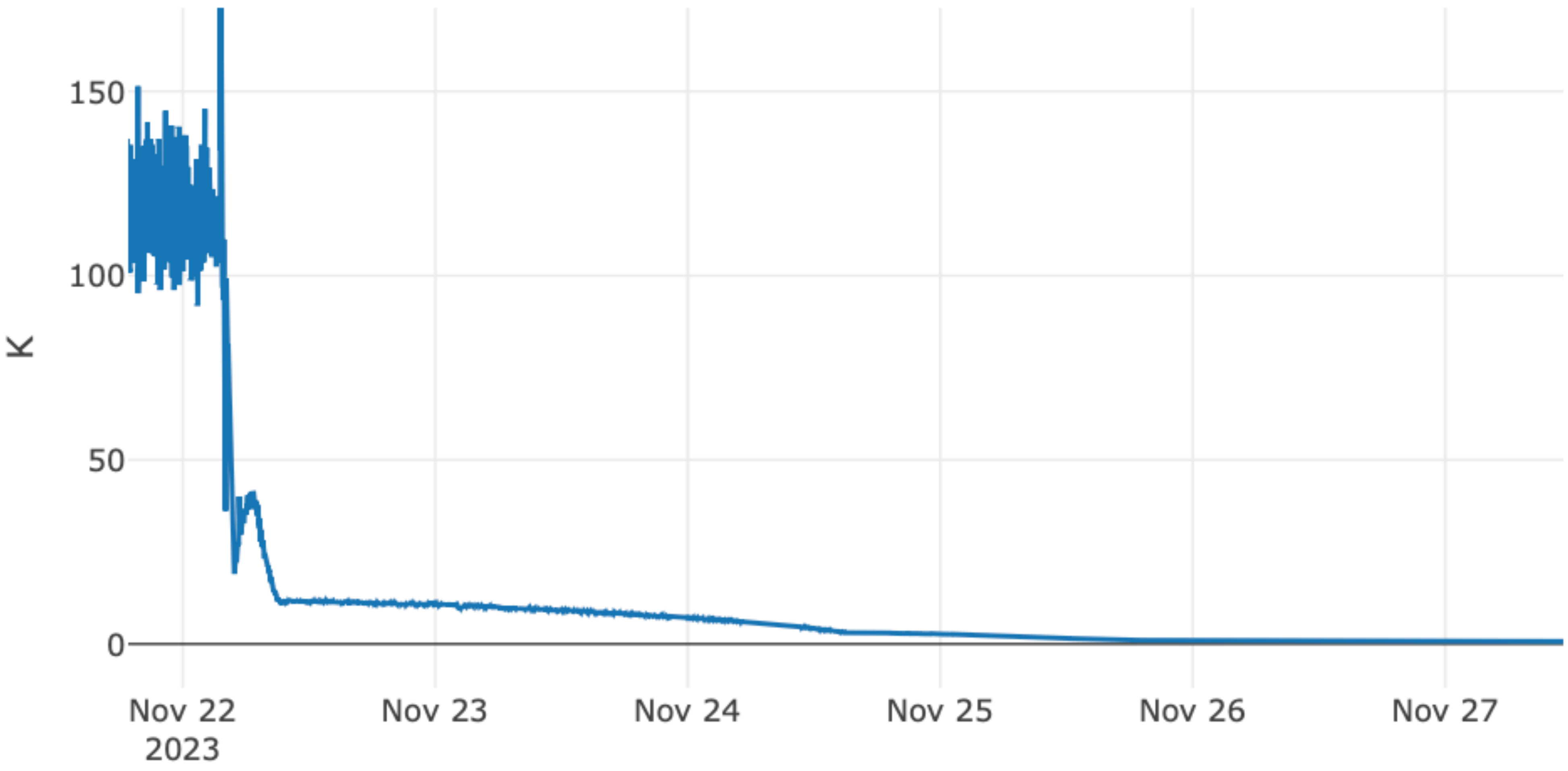
$$T_{\mathrm{sys}} = 163\ \mathrm{mK}$$

Cavity antenna to JPA



Cooling down on-going

- Studies in queue before data taking:
  - He-3/He-4 mixture ratio test
  - Synthetic axion generator test
  - JPA noise study



Run1D SideCar

- Superconducting rod deployed (Nb with Nb_3Sn coating)
- Unloaded Q reached 7k (very comparable to the old version), simulation expecting 20% improvement
- Targeting for data taking at ~5.5 GHz

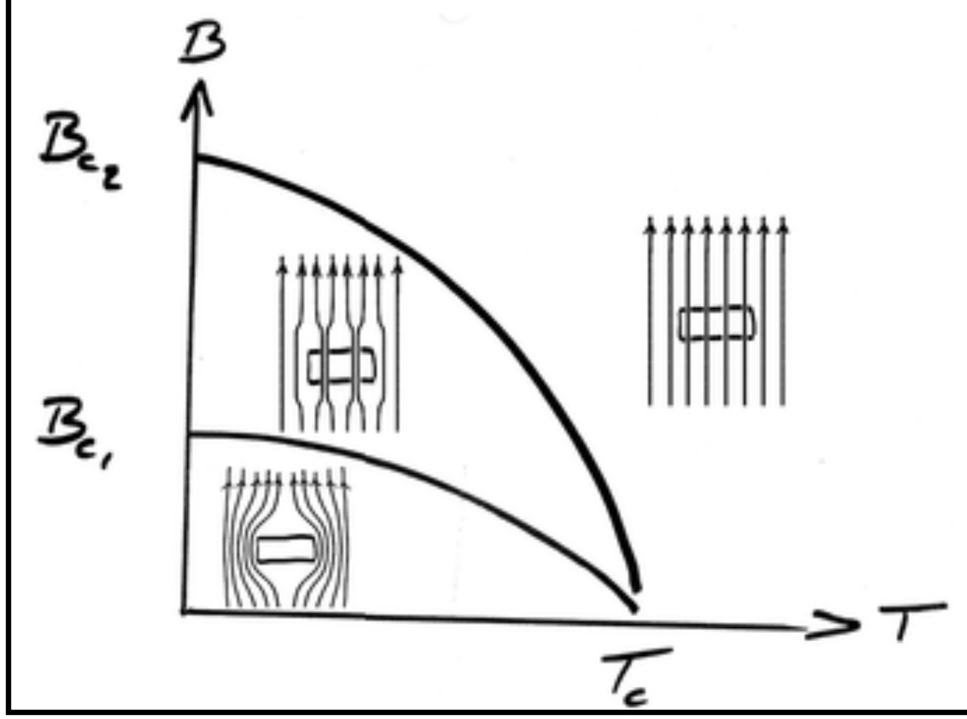
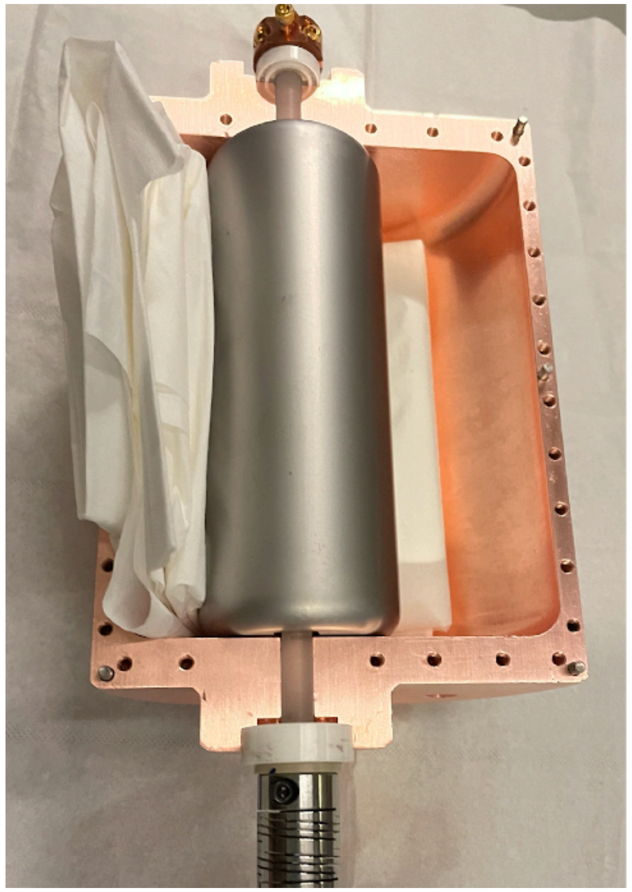
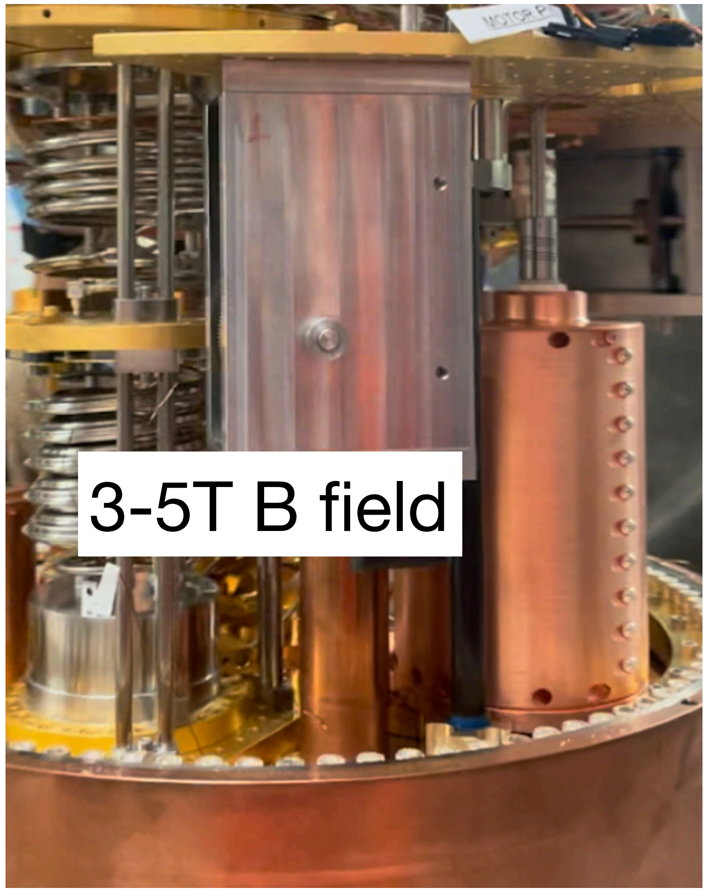


Image: Type 2 Superconductors Phase Diagram, Wikipedia

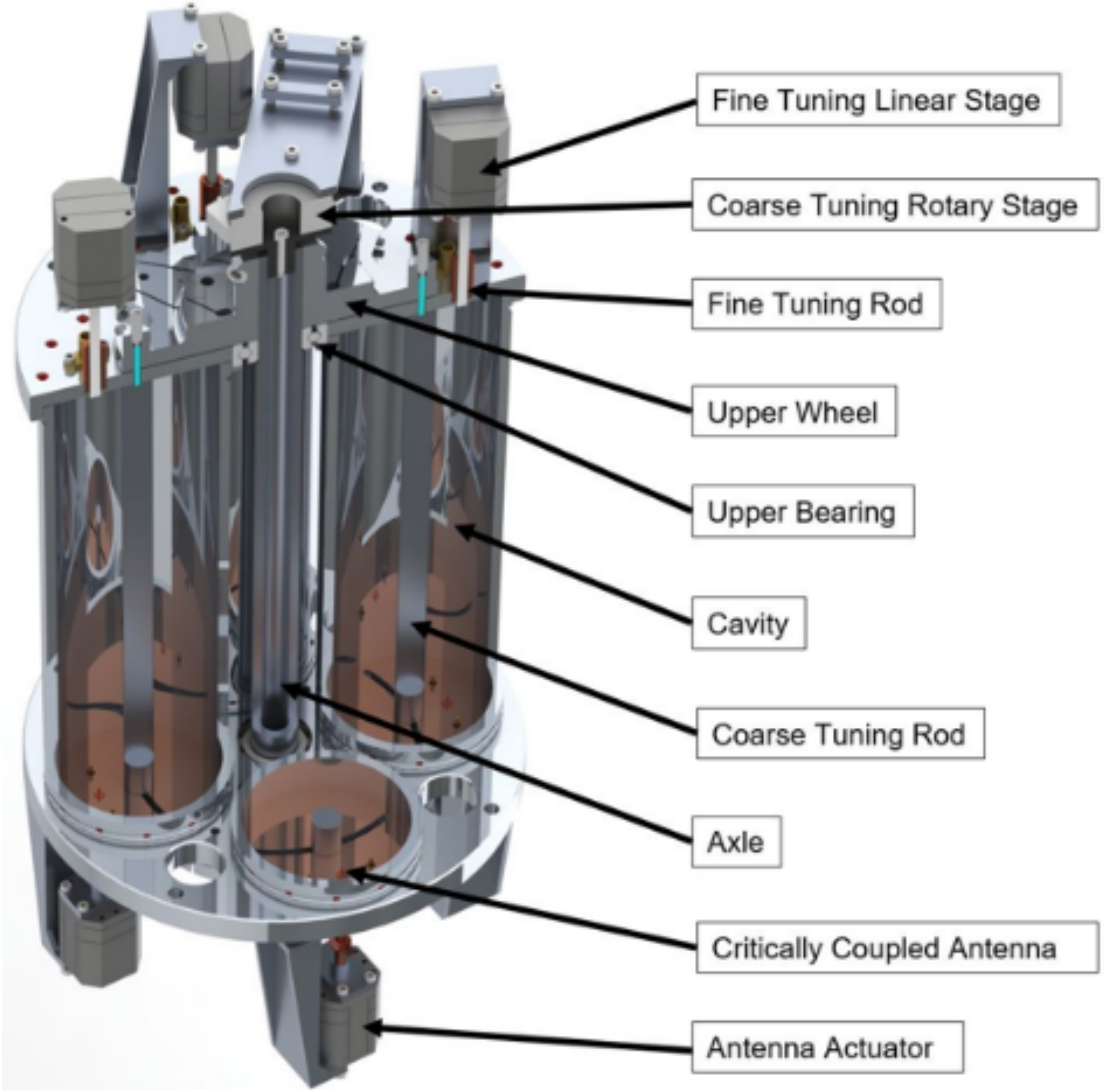




3-5T B field

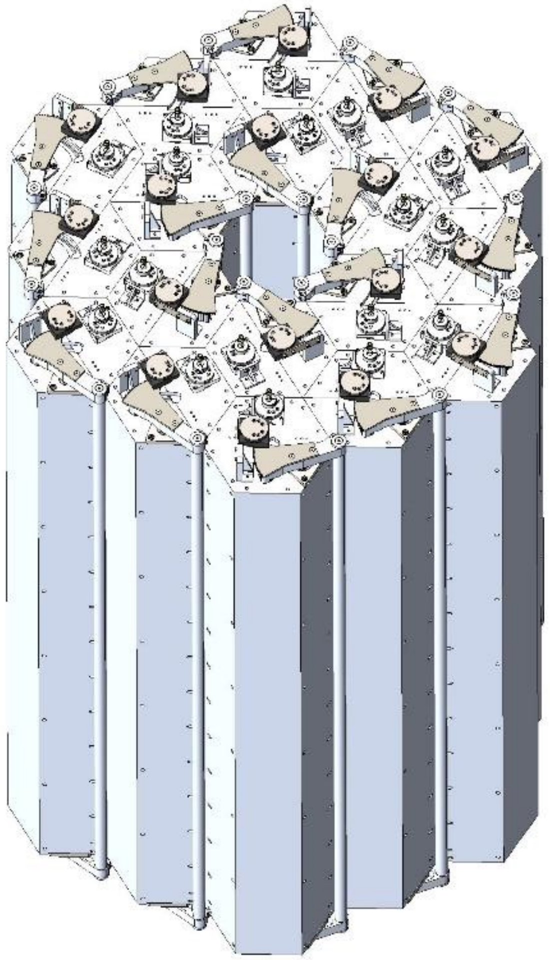
Future plan: Multicavity Systems

ADMX up to 2GHz: 4-Cavity array

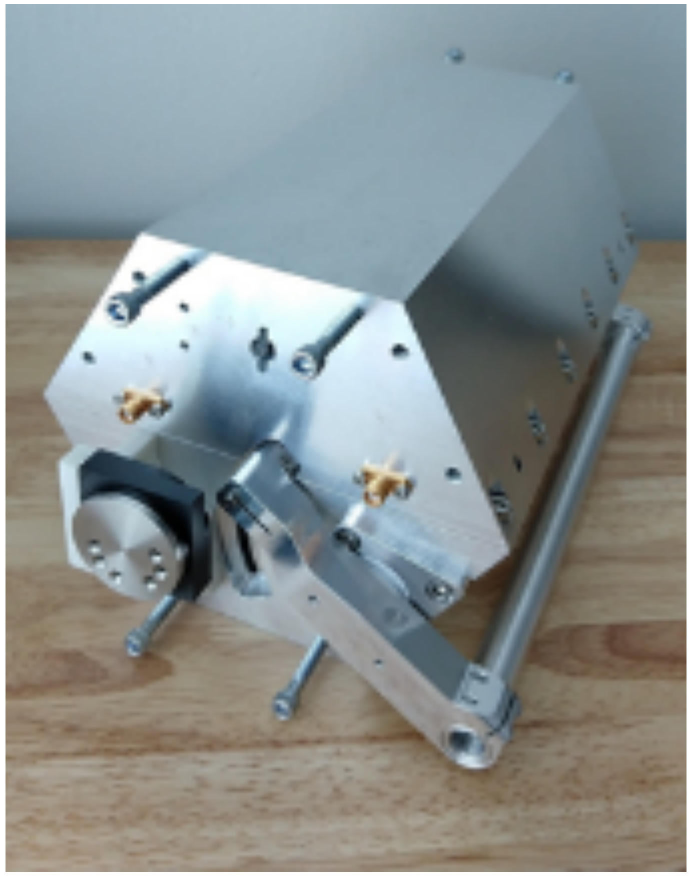


ADMX Extended Frequency Range: 2-4GHz

18 cavity array



First Prototypes:



Conclusion

- With the help of quantum sensors, Axion Haloscopes are going into ‘discovery phase’
  - Run1C-extended: 792-807 MHz has reached DFSZ sensitivity now
  - Run1D will prioritize data taking in 1.2-1.3GHz in 2024