Receiver Noise in the Sikive-Type Axion Haloscope

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On the behalf of ADMX collaboration

Strong CP problem

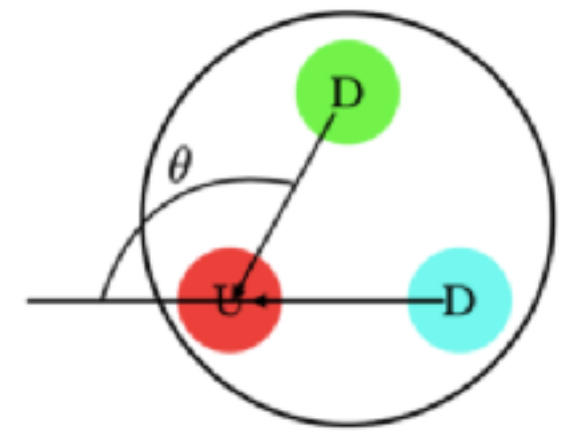
- SU(3) theories naturally have a phase term θ contributing to CP violation (e.g. weak interaction).
  - QCD would have a neutron electric dipole moment d_n of $10^{-16}\mathrm{e}\cdot\mathrm{cm}$
  - nEDM collaboration at PSI $d_n < 1.8\times10^{-26}\mathrm{e}\cdot\mathrm{cm}$, $\theta < 5\times10^{-11}$

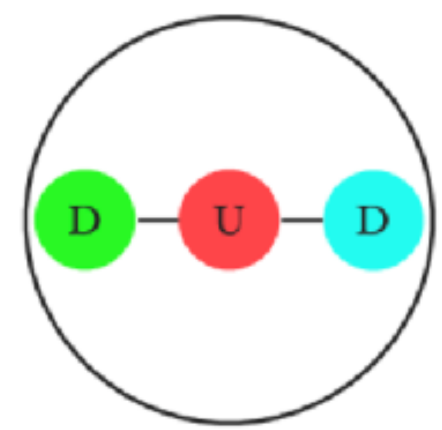
    C. Abel et al., Phys. Rev. Lett. 124, 081803 (2020)
- The strong CP problem solution: $U_{\mathrm{PQ}}(1)$ axial symmetry

  R. D. Peccei and Helen R. Quinn, Phys. Rev. Lett. 38, 1440 (1977)
- New particle beyond standard model, QCD axion

  F. Wilczek, Phys. Rev. Lett. 40, 279 (1978)

  Steven Weinberg, Phys. Rev. Lett. 40, 223 (1978)

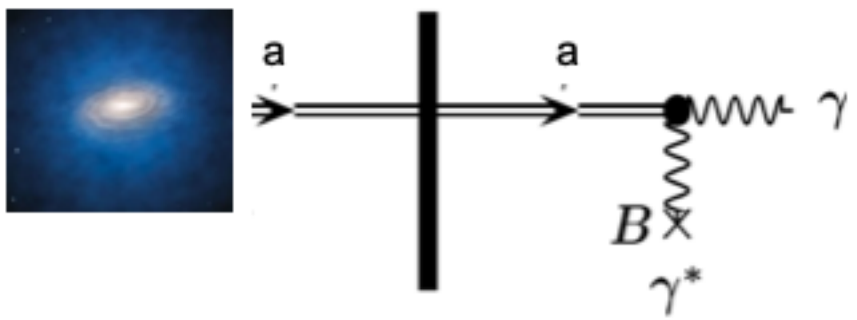




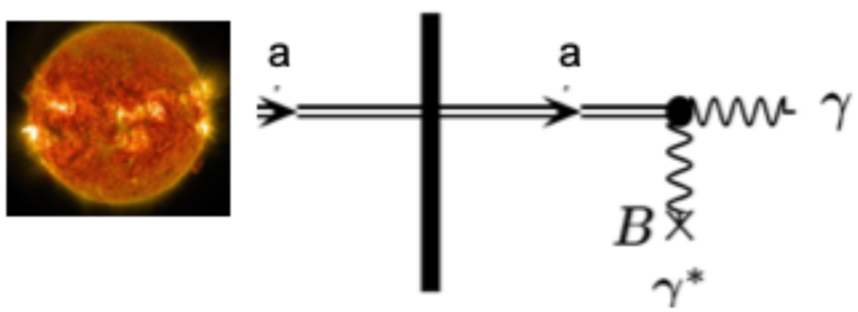
Credit to Anson Hook, arXiv:1812.02669

QCD axion search

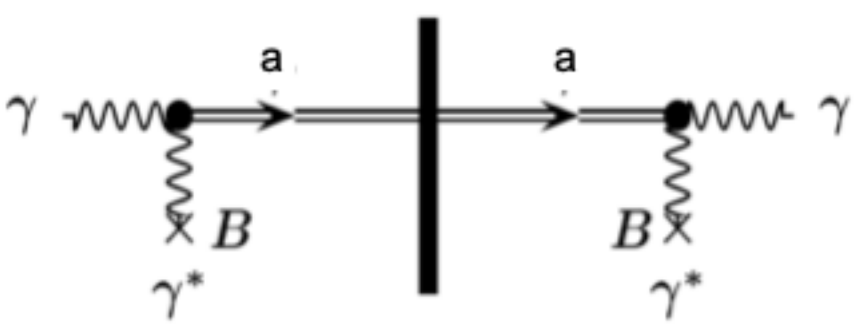
- Haloscope:
  - Axion dark matter



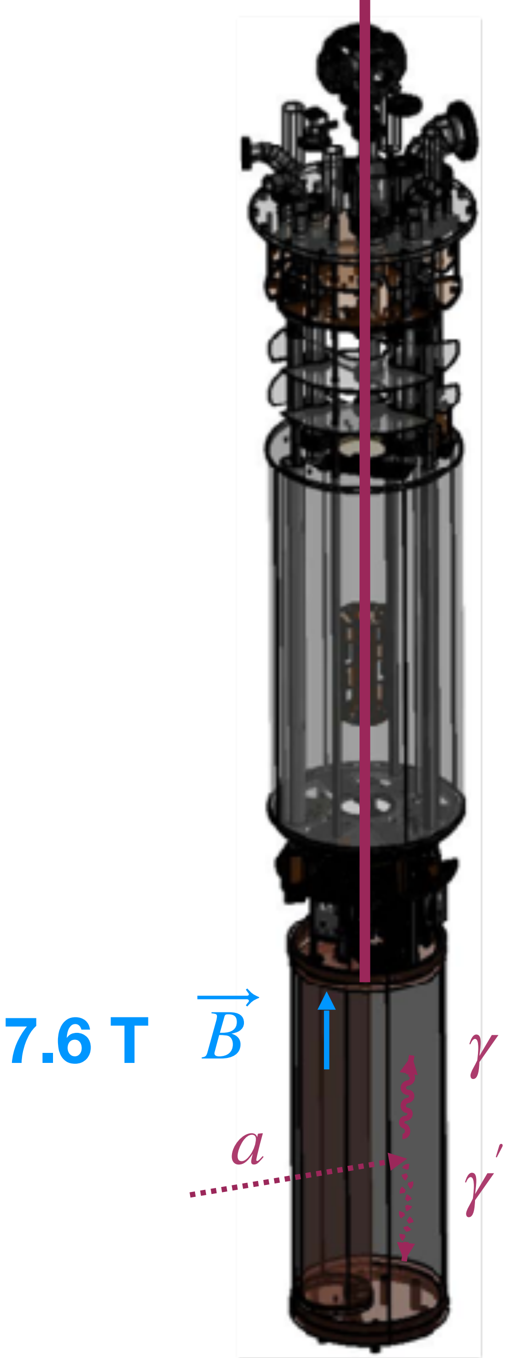
- Helioscope:
  - Astrophysical objects



- Lab production:
  - “light-shining-through-walls”

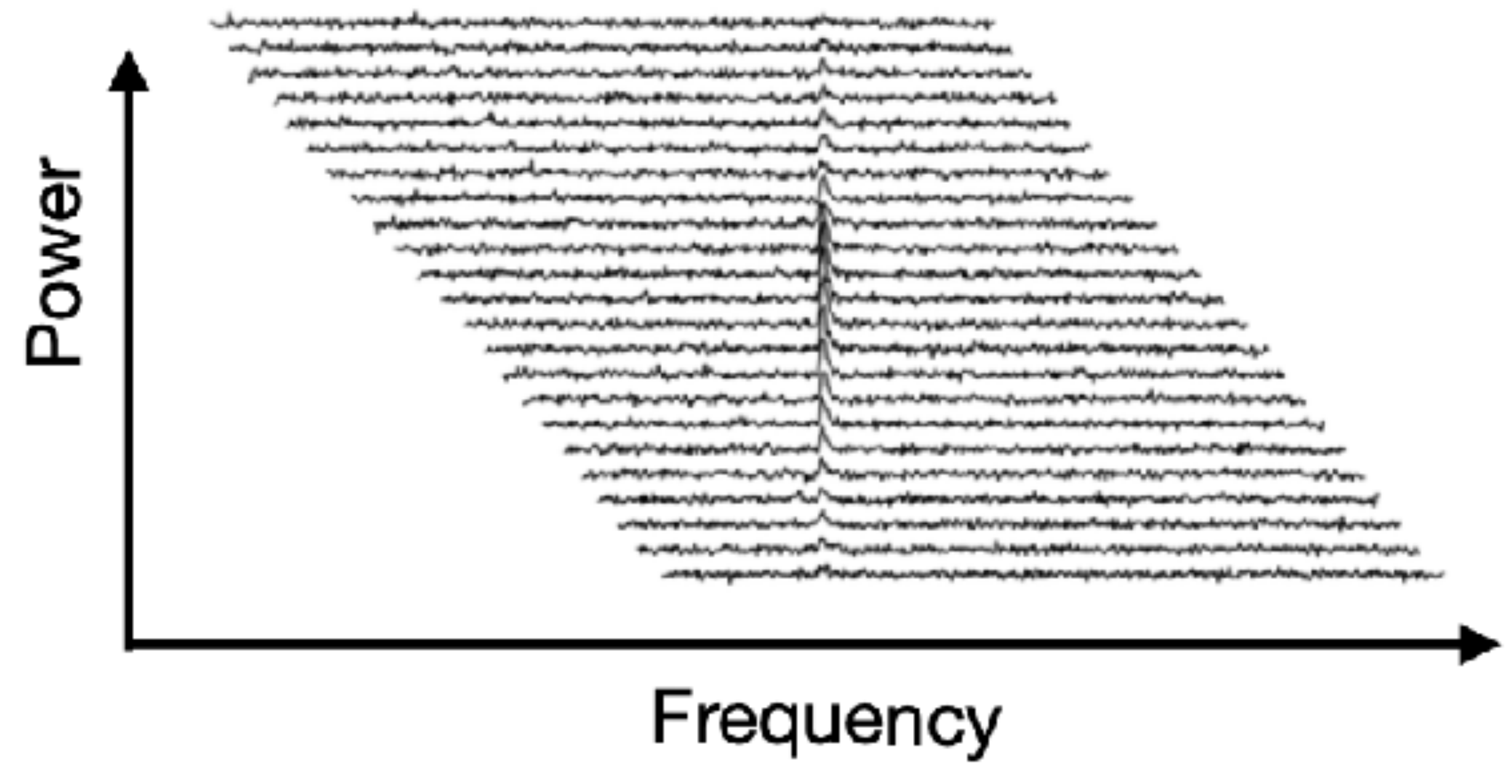


Axion Dark Matter eXperiment



Axion Haloscope

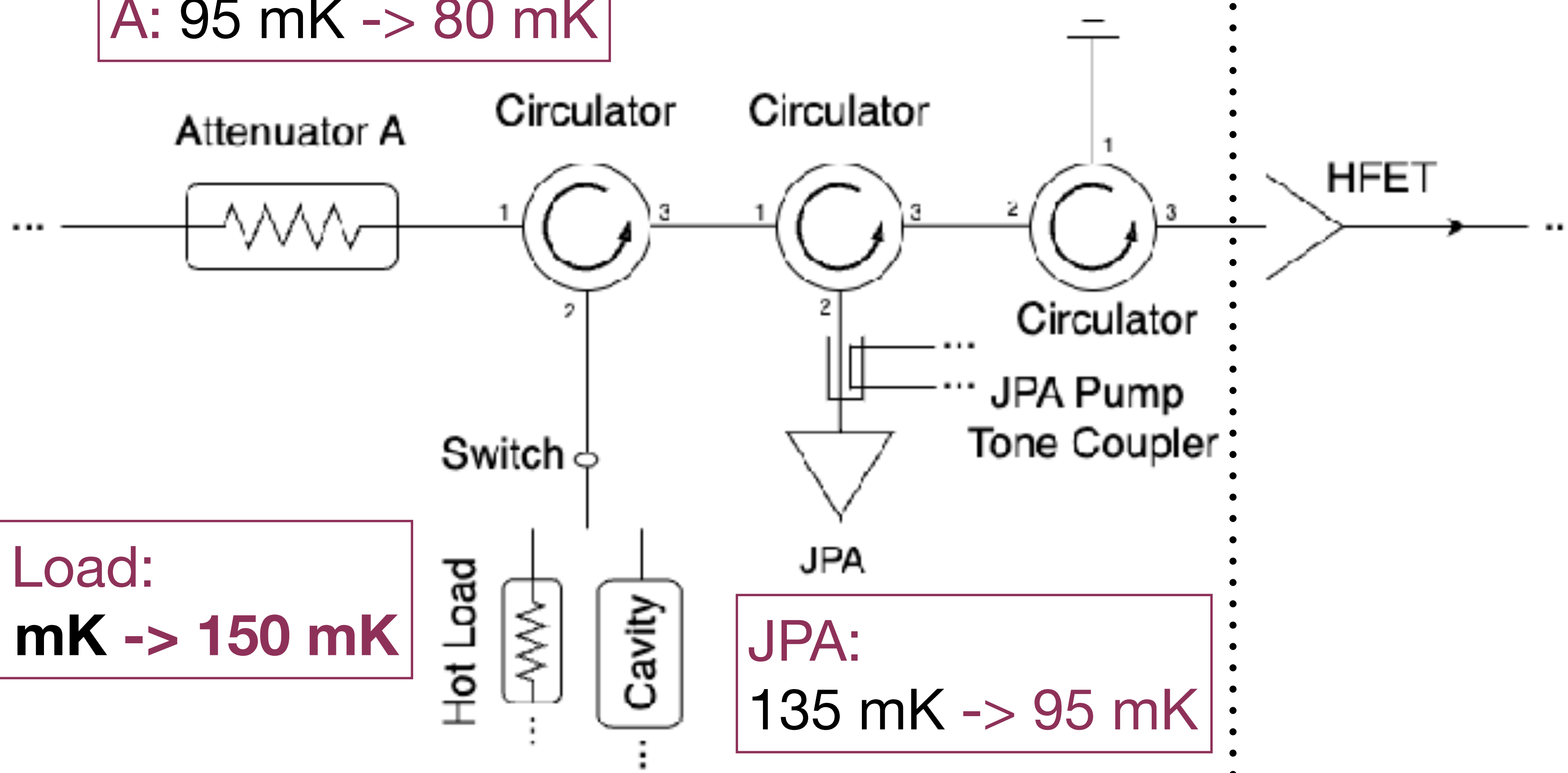
Pierree Sikivie PRL 51:1415 (1983)



- Cold dark matter: $m_a \approx hf, Q_a \sim 10^6$
- $P_{\rm sig} \propto {B_0}^2 QVC \sim 10^{-23} W$ at $\mathcal{O}(1)$ GHz / $\mathcal{O}(5)$ μeV
- $\delta P_{\rm bkg} \propto T_{\rm blackbody} + T_{\rm 1stamp}$

Best performance

A: 95 mK -> 80 mK



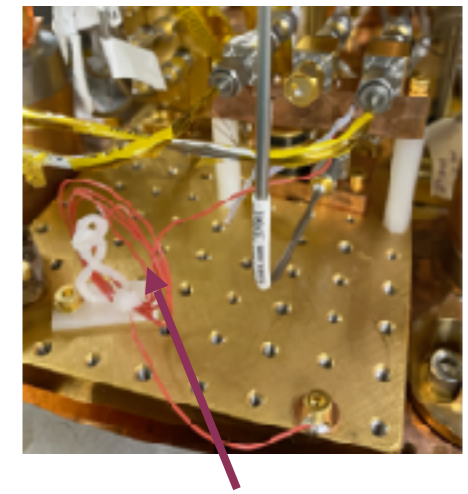
Hot Load:
475 mK -> 150 mK

JPA:
135 mK -> 95 mK

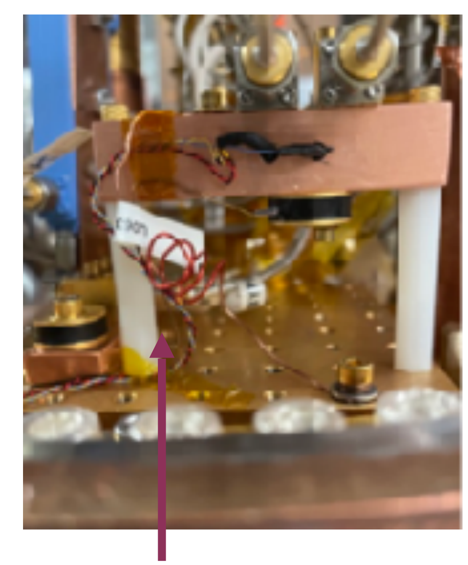
Cavity: 130 mK -> 135 mK

milliKelvin space

4K space



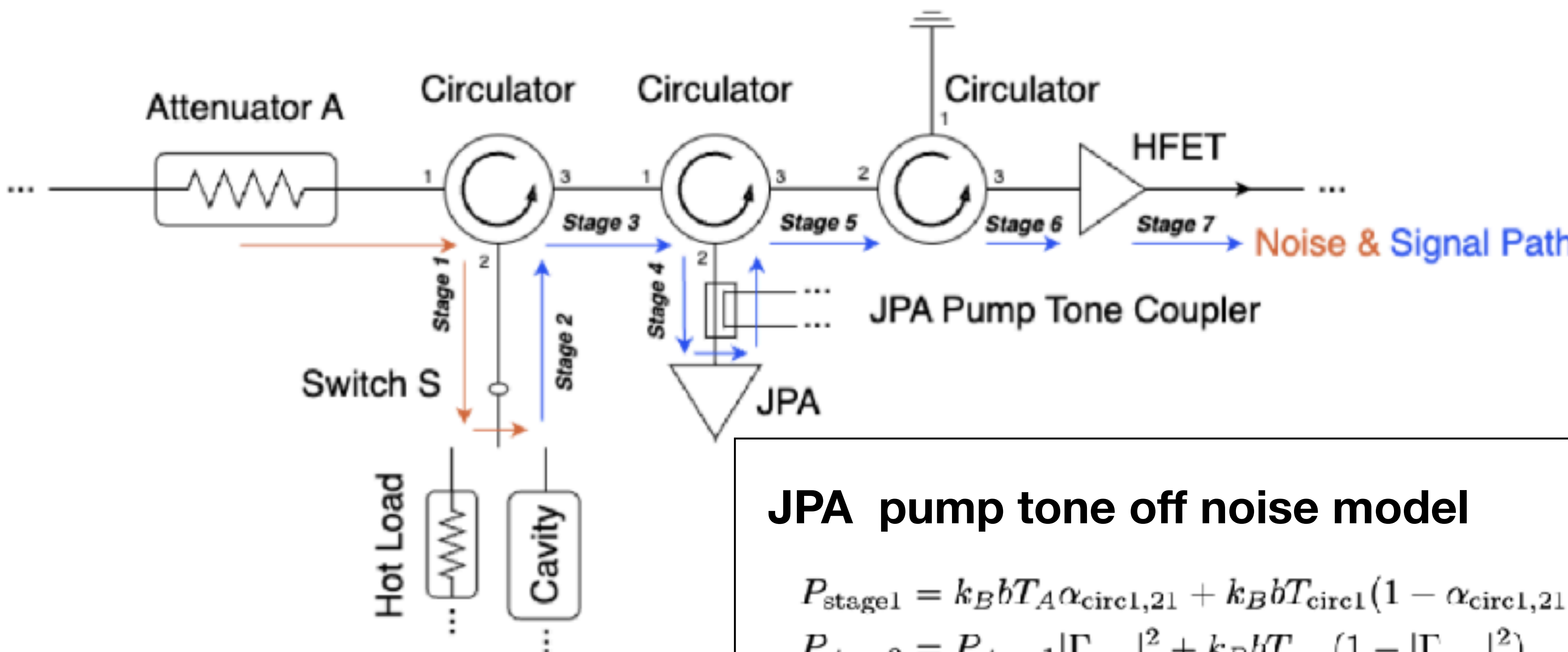
Old heat load thermal link



Upgraded at WUSTL

Detailed Noise model

- Account for thermal gradients in the milliKelvin space



P: noise power at different stages
T: noise temperature
α: transmissivity of power
Γ: reflection coefficient

JPA pump tone off noise model

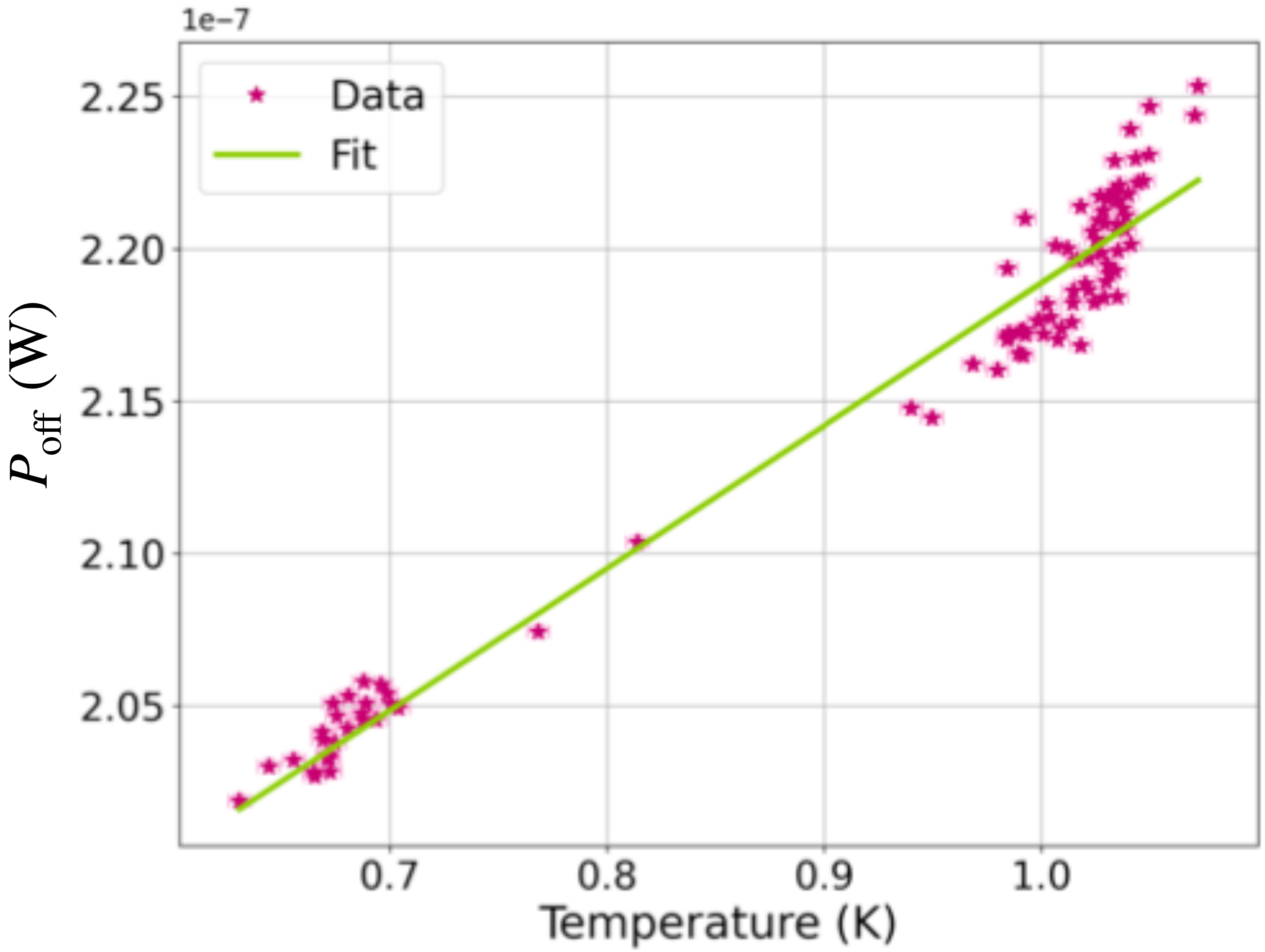
$$
\begin{aligned}
P_{\text{stage1}} &= k_B b T_A \alpha_{\text{circ1,21}} + k_B b T_{\text{circ1}}(1 - \alpha_{\text{circ1,21}}) \\
P_{\text{stage2}} &= P_{\text{stage1}} |\Gamma_{\text{cav}}|^2 + k_B b T_{\text{cav}}(1 - |\Gamma_{\text{cav}}|^2) \\
P_{\text{stage3}} &= P_{\text{stage2}} \alpha_{\text{circ1,32}} + k_B b T_{\text{circ1}}(1 - \alpha_{\text{circ1,32}}) \\
P_{\text{stage4}} &= P_{\text{stage3}} \alpha_{\text{circ2,21}} + k_B b T_{\text{circ2}}(1 - \alpha_{\text{circ2,21}}) \\
P_{\text{stage5}} &= P_{\text{stage4}} \alpha_{\text{circ2,32}} + k_B b T_{\text{circ2}}(1 - \alpha_{\text{circ2,32}}) \\
P_{\text{stage6}} &= P_{\text{stage5}} \alpha_{\text{circ3,32}} + k_B b T_{\text{circ3}}(1 - \alpha_{\text{circ3,32}}) \\
P_{\text{stage7}} &= G_{\text{HFET}}(P_{\text{stage6}} + k_B b T_{\text{HFET}}) \\
P_{\text{noise,out}} &= G_{\text{post}} P_{\text{stage7}}.
\end{aligned}
$$

Variation in the noise calibration

	Switch to Cavity	Switch to HL
JPA pump off	$$\begin{aligned} P_{\text{stage1}} &= k_B b T_A \alpha_{\text{circ1,21}} + k_B b T_{\text{circ1}}(1-\alpha_{\text{circ1,21}}) \\ P_{\text{stage2}} &= P_{\text{stage1}}\lvert\Gamma_{\text{cav}}\rvert^2 + k_B b T_{\text{cav}}(1-\lvert\Gamma_{\text{cav}}\rvert^2) \\ P_{\text{stage3}} &= P_{\text{stage2}}\alpha_{\text{circ1,32}} + k_B b T_{\text{circ1}}(1-\alpha_{\text{circ1,32}}) \\ P_{\text{stage4}} &= P_{\text{stage3}}\alpha_{\text{circ2,21}} + k_B b T_{\text{circ2}}(1-\alpha_{\text{circ2,21}}) \\ P_{\text{stage5}} &= P_{\text{stage4}}\alpha_{\text{circ2,32}} + k_B b T_{\text{circ2}}(1-\alpha_{\text{circ2,32}}) \\ P_{\text{stage6}} &= P_{\text{stage5}}\alpha_{\text{circ3,32}} + k_B b T_{\text{circ3}}(1-\alpha_{\text{circ3,32}}) \\ P_{\text{stage7}} &= G_{\text{HFET}}(P_{\text{stage6}} + k_B b T_{\text{HFET}}) \\ P_{\text{noise,out}} &= G_{\text{post}} P_{\text{stage7}}. \end{aligned}$$	**Stage 2 : cavity** $\lvert\Gamma_{\text{cav}}\rvert = 0$ $T_{\text{cav}} \to T_{\text{HL}}$
JPA pump on	**Stage 5: JPA** A parametric amplifier with added noise ~~A perfect mirror~~ $$\begin{aligned} P_{\text{stage5}} = &\,(G_{\text{JPA}}(P_{\text{stage4}} + P_{\text{JPA},S}) \\ &+ (G_{\text{JPA}}-1)(P_{\text{I}} + P_{\text{JPA},I}))\alpha_{\text{circ2,32}} \\ &+ k_B b T_{\text{circ2}}(1-\alpha_{\text{circ2,32}}), \end{aligned}$$	**Stage 2 & Stage 5**

Switch to Cavity & JPA pump off

1280 MHz example



- Whole miliKelvin-space mixing chamber plate (MXC) warm-up or cool-down together
- 4K-space is insensitive to the O(10) mK temperature gradient on MXC

$$T_{\text{sys,off,mxc}} = \frac{T_{\text{mxc}} + T_{\text{HFET}}}{\alpha_1 \alpha_2}$$

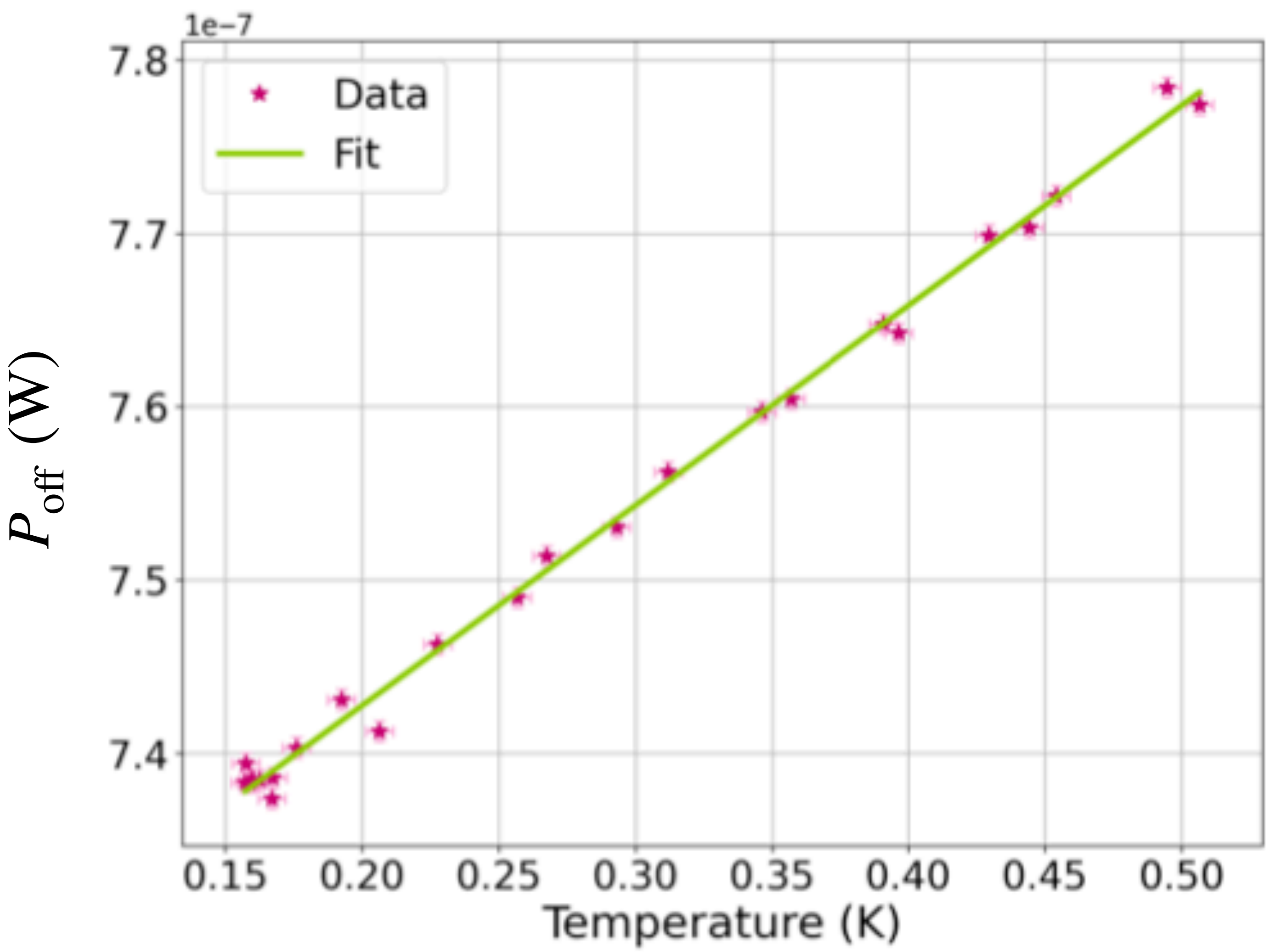
$$P_{\text{off}} = C(T + T_{\text{fit}})$$

$$T_{\text{HFET}} = 3.94 \pm 0.09 \text{ K}$$

α_1: transmissivity of power from the **cavity to JPA**

α_2: … JPA to HFET

Switch to HL & JPA pump off



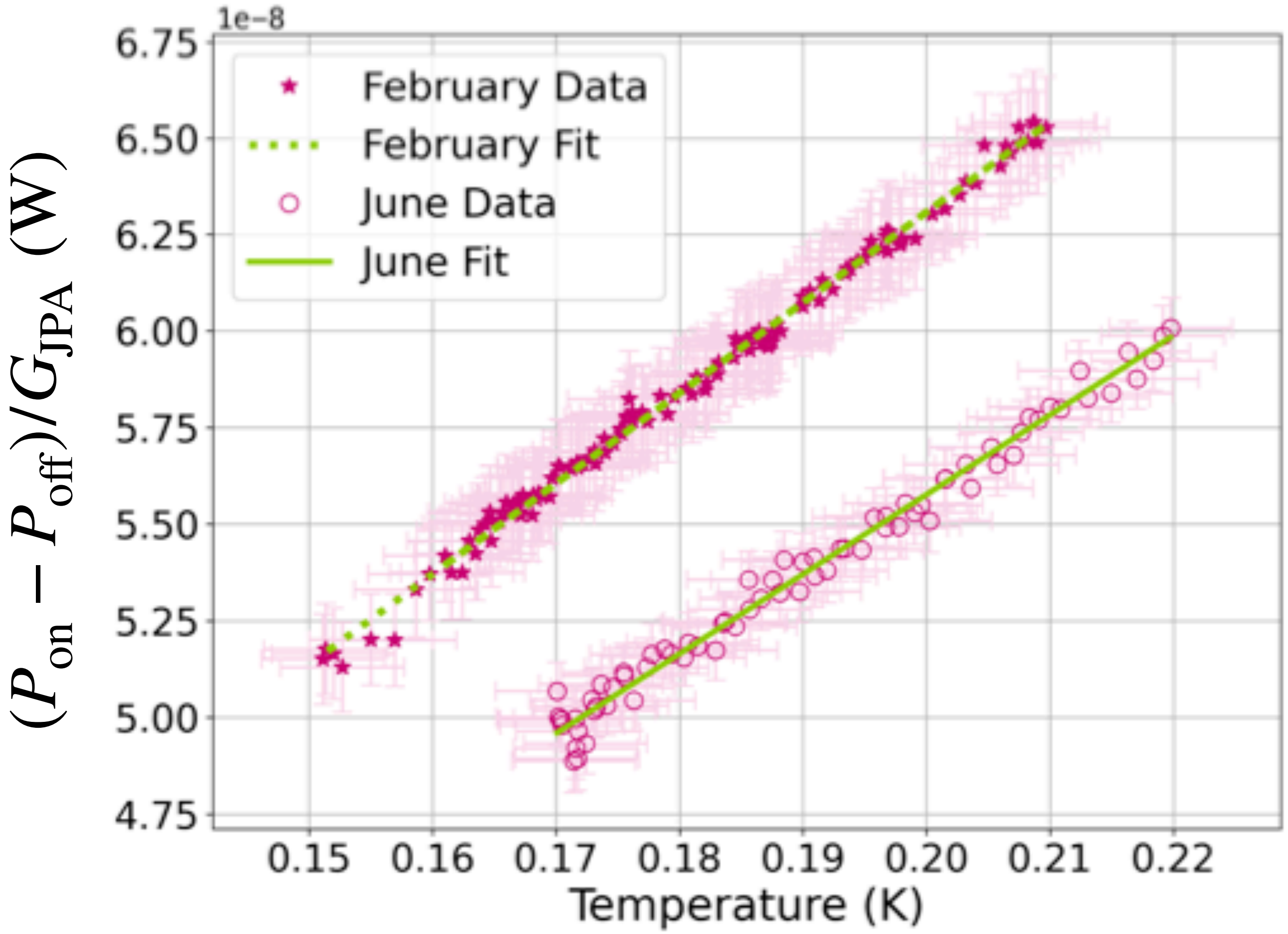
- Only $T_{\rm HL}$ changes, and other temperature changes are negligible

$$\mathrm{T}_{\rm sys,off,HL} = T_{\rm HL} + \frac{T_{\rm circ}(1-\alpha_1\alpha_2)}{\alpha_1\alpha_2} + \frac{T_{\rm HFET}}{\alpha_1\alpha_2}$$

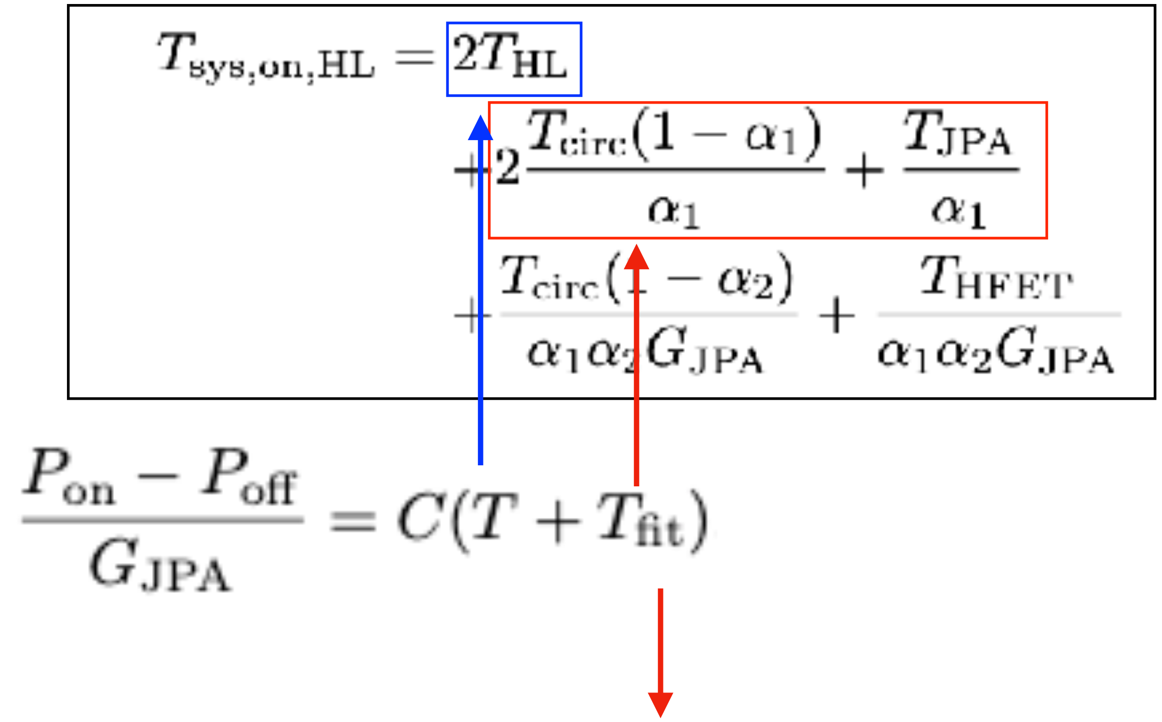
$$P_{\rm off} = C(T + T_{\rm fit})$$

$$T_{\rm HFET}/\alpha_{\rm eff} = 6.16 \pm 0.23 \ \mathrm{K}$$

Switch to HL and JPA pump on



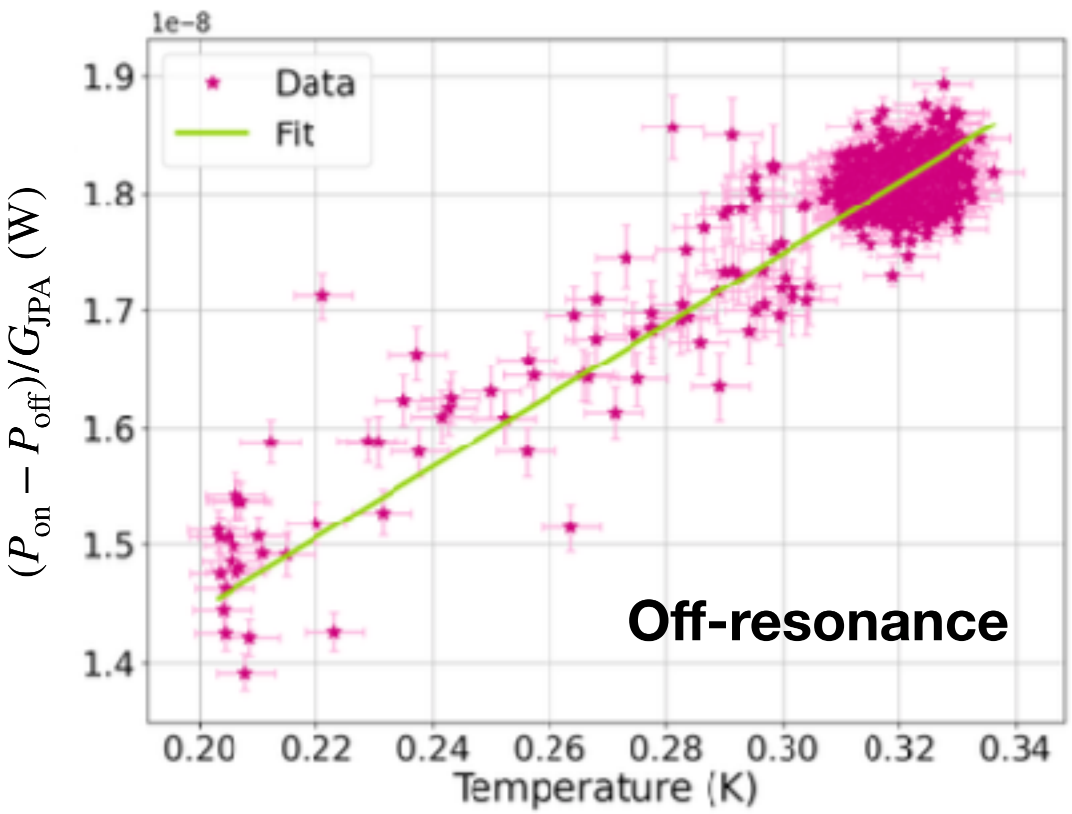
- Only $T_{\rm HL}$ changes
- But the initial temperature gradients on MXC plate is non-negligible
- Two calibrations with different $G_{\rm JPA}$

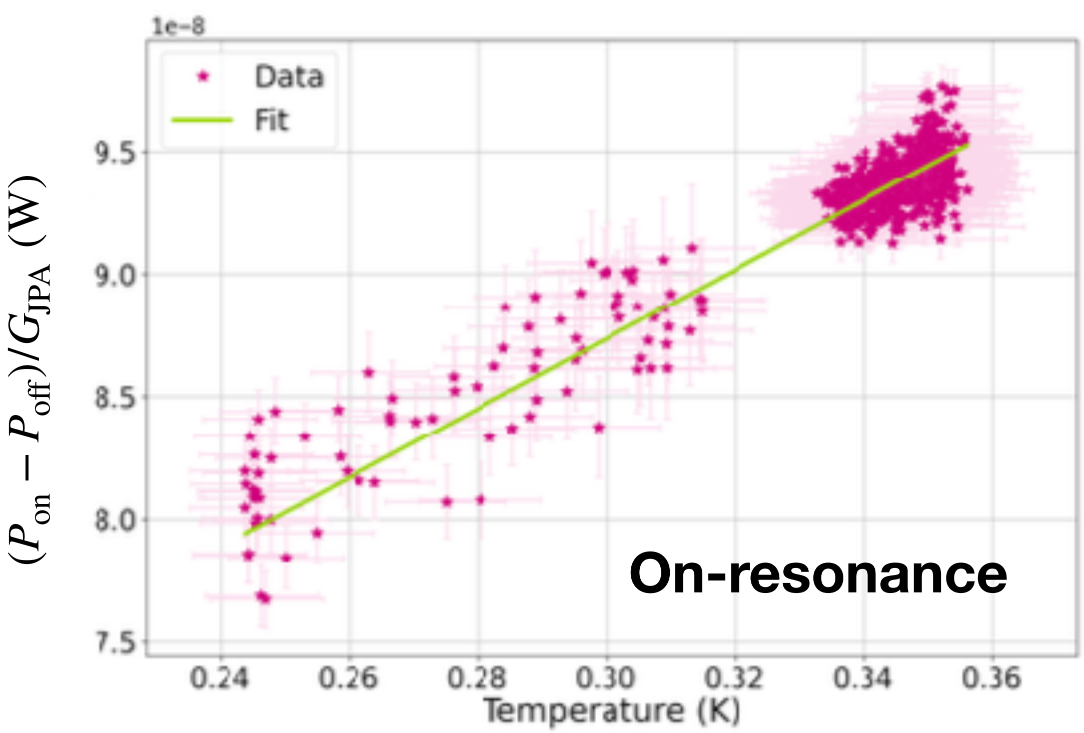


$$T_{\rm JPA,eff,Feb} = 0.137 \pm 0.022 \ {\rm K}$$

$$T_{\rm JPA,eff,Jun} = 0.134 \pm 0.021 \ {\rm K}$$

Switch to Cavity and JPA pump on





$$T_{\rm sys,on} = T_{\rm stage1}|\Gamma_{\rm cav}|^2 + T_{\rm cav}(1 - |\Gamma_{\rm cav}|^2) + T_{\rm stage1} + 2\frac{T_{\rm circ}(1-\alpha_1)}{\alpha_1} + \frac{T_{\rm JPA}}{\alpha_1} + \frac{T_{\rm circ}(1-\alpha_2)}{\alpha_1\alpha_2 G_{\rm JPA}} + \frac{T_{\rm HFET}}{\alpha_1\alpha_2 G_{\rm JPA}}.$$

$$\frac{P_{\rm on} - P_{\rm off}}{G_{\rm JPA}} = C(T + T_{\rm fit})$$

$$T_{\rm JPA,eff,off-res} = 0.300 \pm 0.028 \text{ K}$$

$$T_{\rm JPA,eff,on-res} = 0.330 \pm 0.026 \text{ K}$$

Comparison

$$T_{\mathrm{HFET}}/\alpha_{\mathrm{eff}} = \frac{1}{G_{\mathrm{JPA}} - \mathrm{SNRI}} \cdot \left(\mathrm{SNRI} \cdot G_{\mathrm{JPA}} \cdot (T_{\mathrm{JPA,eff}} + 2T_{\mathrm{HL}}) - G_{\mathrm{JPA}} \cdot T_{\mathrm{HL}} - \mathrm{SNRI} \cdot T_{\mathrm{circ}}(1-\alpha_2)/\alpha_2 \right)$$

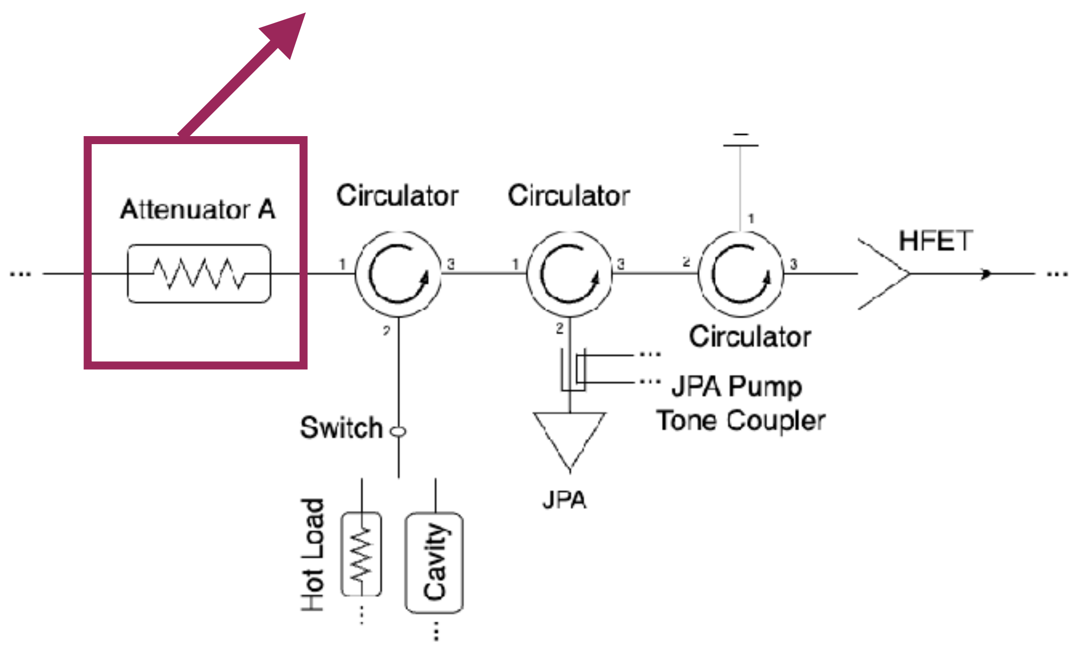
Quantity	**Value (K)**	**Condition**
T_{HFET}	4.12 ± 0.28	JPA-off-cavity
$T_{\mathrm{HFET}}/\alpha_{\mathrm{eff}}$	6.16 ± 0.23	JPA-off-hot-load
	6.11 ± 0.31	JPA-on-hot-load (inferred)
	6.33 ± 0.39	JPA-on-cavity on res. (inferred)
	5.64 ± 0.39	JPA-on-cavity off res. (inferred)
$T_{\mathrm{JPA,eff}}$	0.134 ± 0.021	JPA-on-hot-load
	0.330 ± 0.026	JPA-on-cavity on resonance
	0.300 ± 0.028	JPA-on-cavity off resonance

- Consistent transmissivity $\alpha = 0.67 \pm 0.05$
  VS pre-experiment test $\alpha = 0.643 \pm 0.003$
- Consistent noise calibration results confirmed
- ~ 200 mK more noise when cavity is connected (data taking)

Future plan

- Investigate better circulators for better isolation between the cavity and JPA
- Design a switchless hot load

Serve as a switchless hot load



https://arxiv.org/pdf/2411.07172v1

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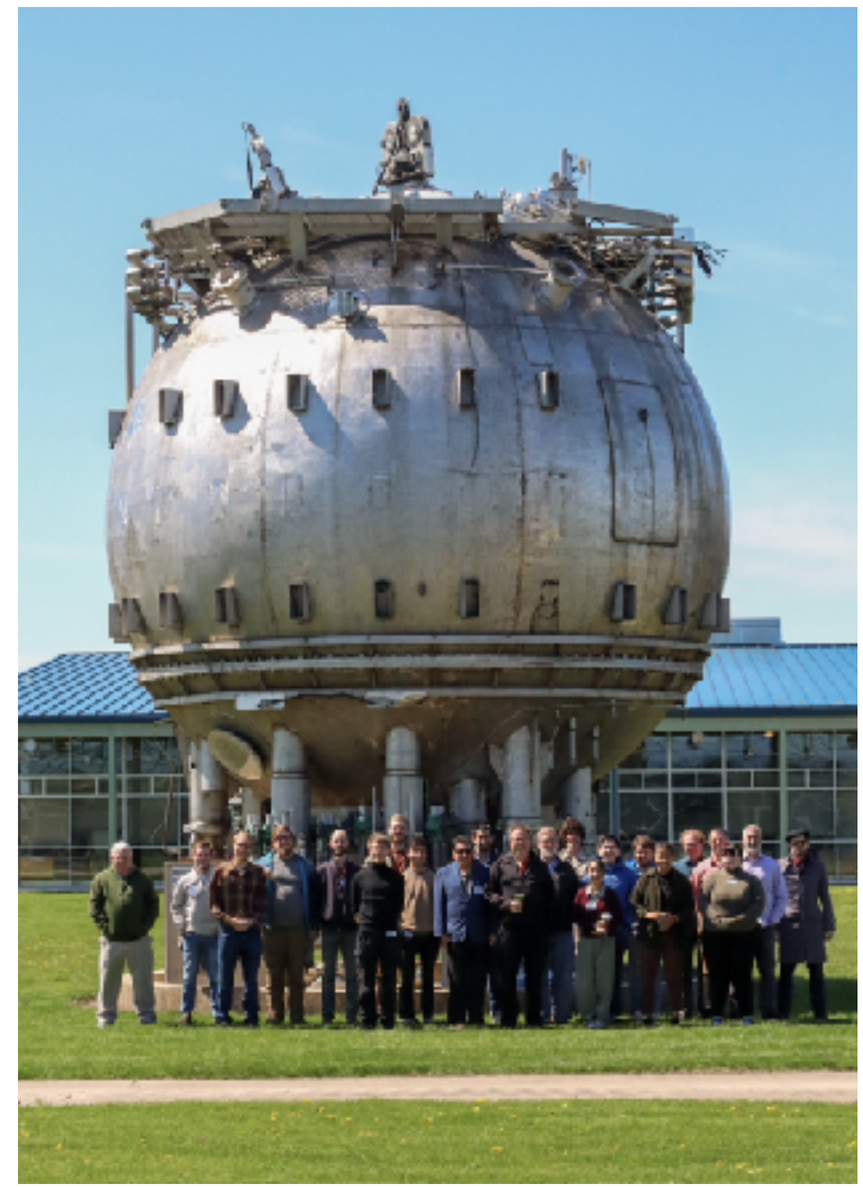
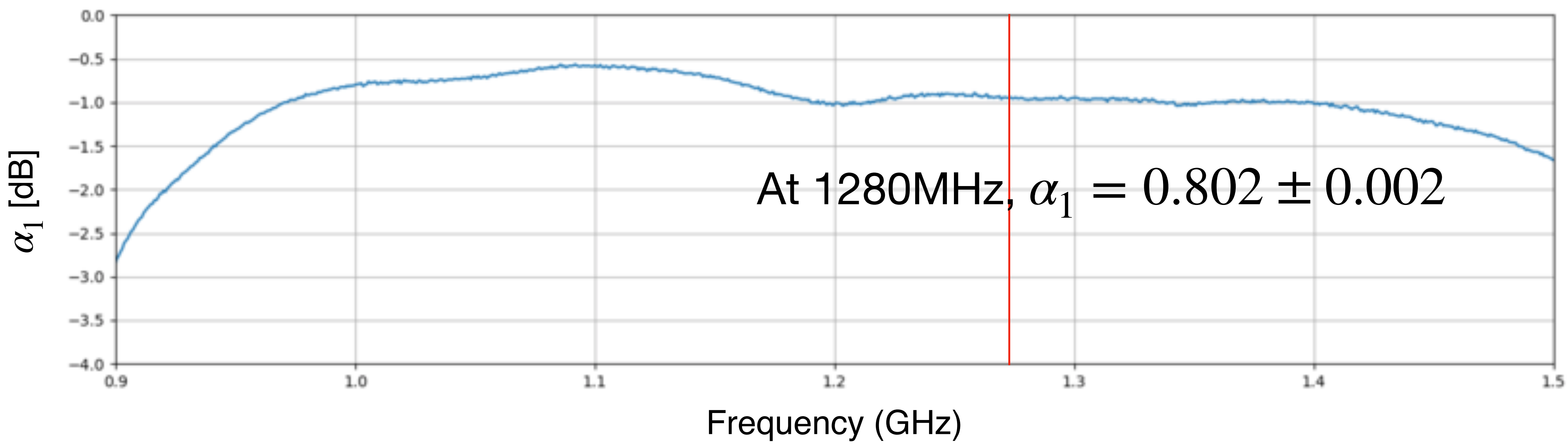


April 2024

Backup

Comparison with JPA pump off

Pre-experiment test at WashU



HL	$T_{\mathrm{HFET}}/\alpha_{\mathrm{eff}} = 6.16 \pm 0.23$ K
Cavity	$T_{\mathrm{HFET}} = 3.94 \pm 0.09$ K

→ $\alpha_{\mathrm{eff}} = 0.67 \pm 0.05$

↕

- Consistent with the assumption: $\alpha_2 \alpha_1 = \alpha_1^2 = 0.643 \pm 0.003$