Broadband Parametric Amplifiers for Dark Matter Searches and QIS

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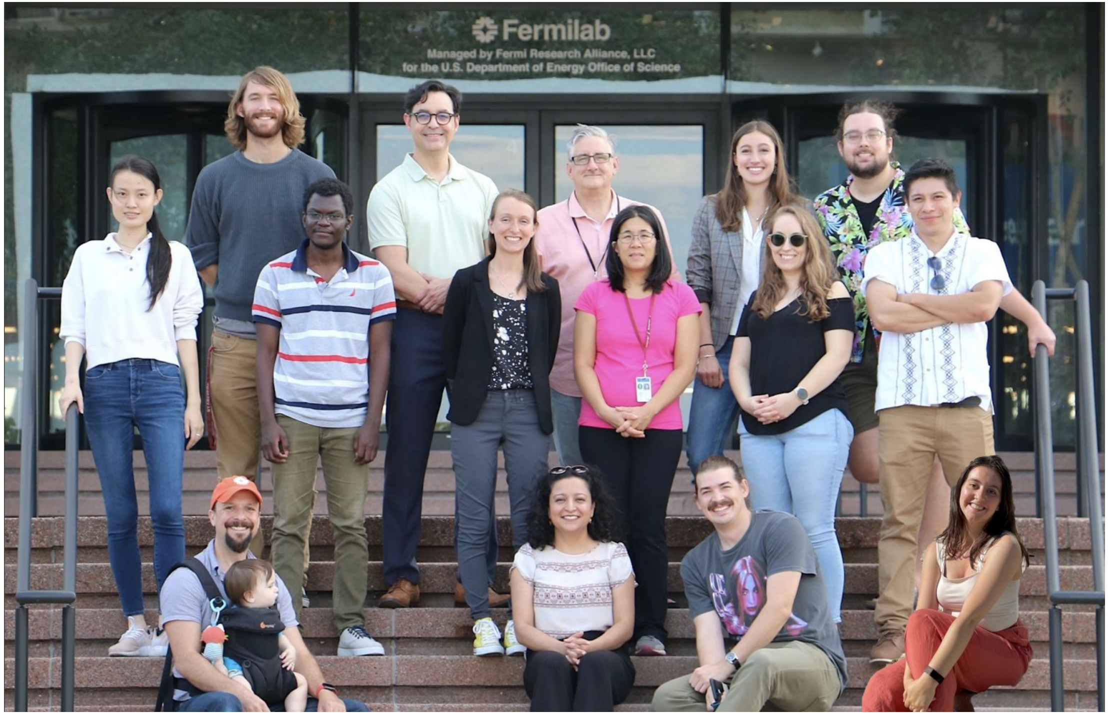
4 October 2023 -- BREAD Collaboration Meeting



Particle physicists developing qubits and quantum sensors for low-threshold particle detection

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Daniel Baxter
Rakshya Khatiwada
Daniel Bowring
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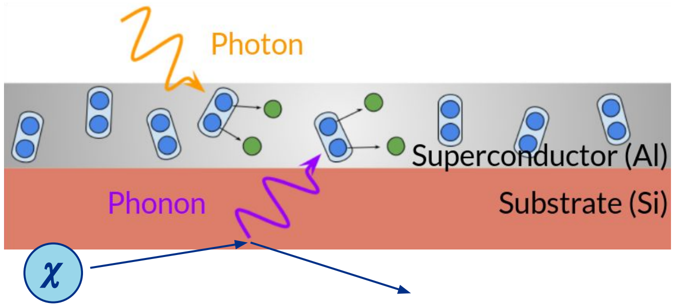
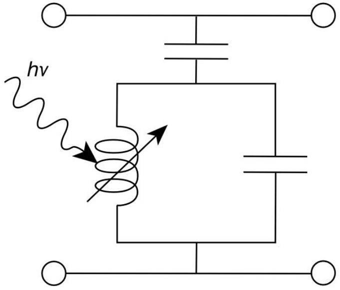
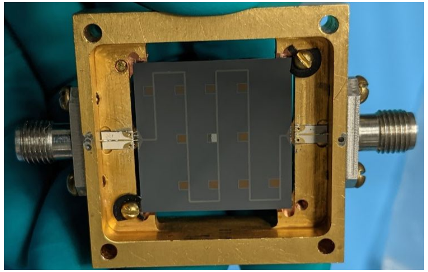
Superconducting RF Sensors for Particle DM Detection



Kinetic Inductance Phonon-Mediated Detectors





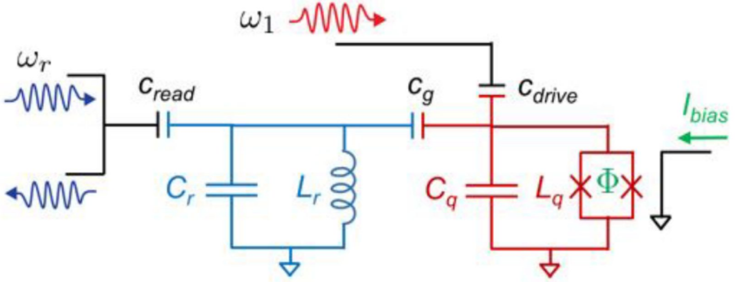
RF readout, frequency-multiplexed devices

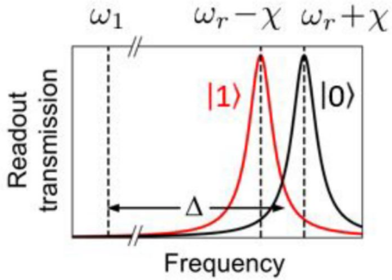
- Common readout electronics/scheme
- **Common challenge: noise**

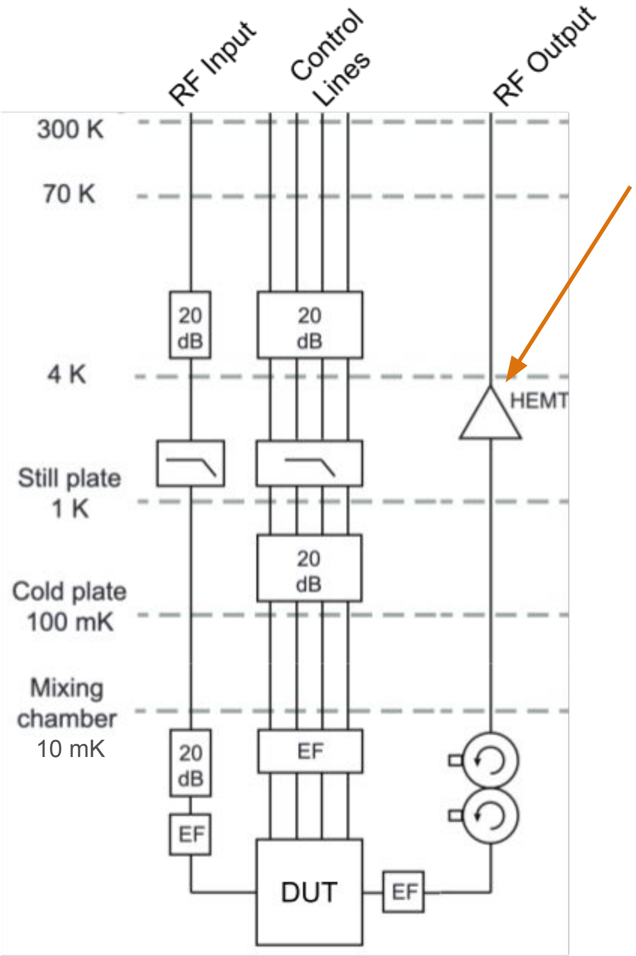
KIPMDs → energy resolution

Qubits → single shot fidelity

Superconducting Qubits







Typical Cryogenic Setup

First stage amplification: HEMT

- Widely commercially available
- Low noise (T_n ~ 4-10 K)

Reducing amplifier noise temperature → improved SNR

Quantum-limited amplifier as first stage amplification

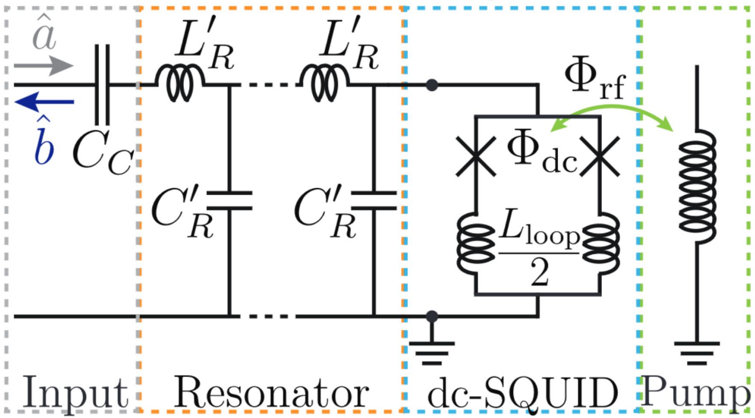
- SQL @ 6 GHz: 150 mK
- Noise scales linearly with T_n

→ Direct improvement in KIPMD energy resolution & qubit single shot fidelity (SSF)

Option 1: Josephson Parametric Amplifier

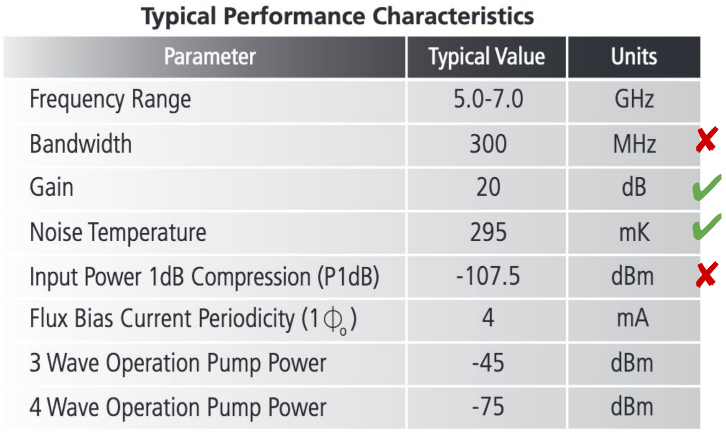
Single resonance feature provides amplification by extracting energy of pump tone

- Pro: commercially available
- Con: narrow gain band: few -- 700 MHz
  - Flux tuning allows user to select frequency of maximal gain
- Con: low saturation power



P. Kruger, K. Fedorov

Raytheon BBN JPA

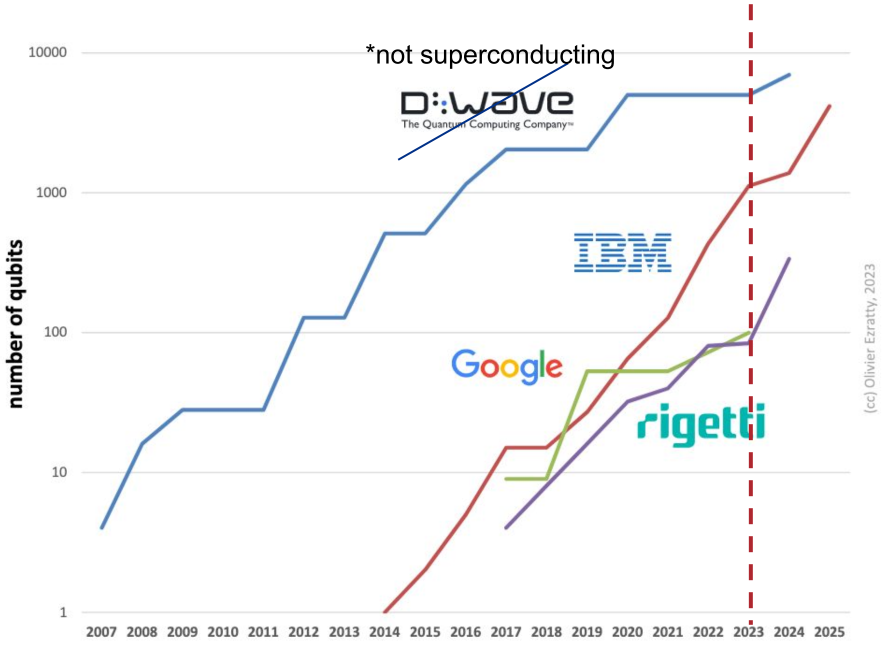


Typical Performance Characteristics

Parameter	Typical Value	Units	
Frequency Range	5.0-7.0	GHz	
Bandwidth	300	MHz	✗
Gain	20	dB	✓
Noise Temperature	295	mK	✓
Input Power 1dB Compression (P1dB)	-107.5	dBm	✗
Flux Bias Current Periodicity (1Φ_0)	4	mA	
3 Wave Operation Pump Power	-45	dBm	
4 Wave Operation Pump Power	-75	dBm	

Untenable solution for large arrays required for computation, particle detection.

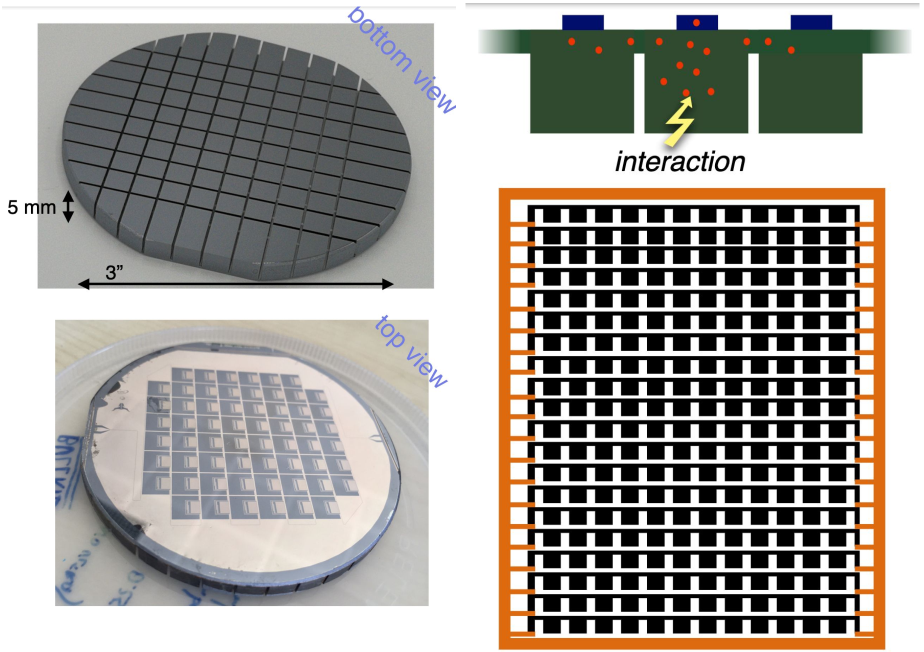
Scaling Up: Qubits & KIPMDs



20 x 10^6 qubits to break RSA-2048 encryption

arXiv:1905.09749

BULLKID Concept (*M. Vignati*)



60 resonators/wafer x 20 wafers/stack

→ **1200 resonators!**

Option 2: Traveling Wave Parametric Amplifiers

Signal amplification obtained by injecting a pump tone into a nonlinear transmission medium which modulates the line's inductance per unit length.

- Josephson effect (J-TWPA): Long array of Josephson junctions/SQUIDs (~100s)
- Kinetic inductance effect (KI-TWPA): high KI material transmission line (NbTiN)

Offer wide (GHz) bandwidth, high saturation power, and near quantum-limited noise performance.

J-TWPA developed by MIT-LL, primary source → supply more restricted now

- Group at Washington University St. Louis developing devices based on MIT-LL design

Need: An avenue for expanding the supply of TWPA to the experimental community

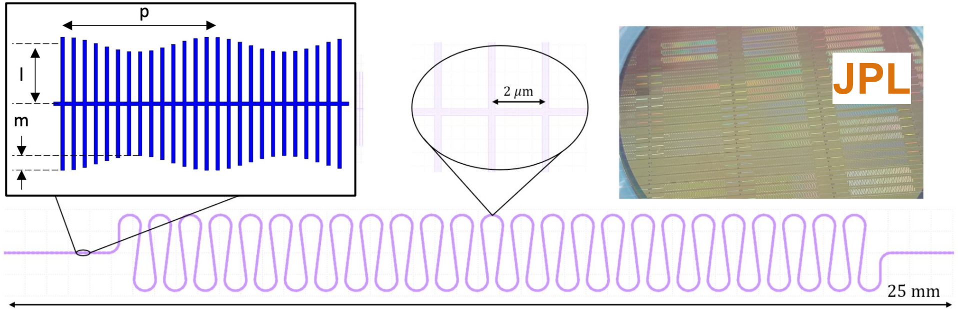
J-TWPA: *C. Macklin et al, Science, 2015.*

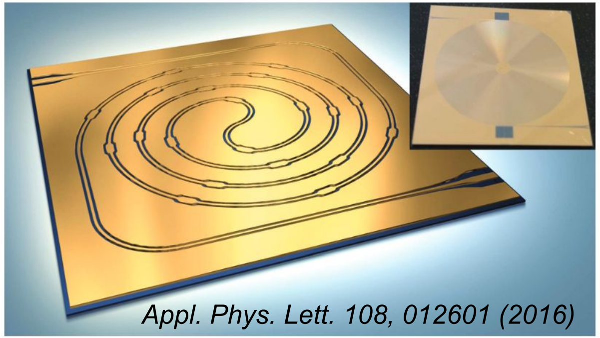
Kinetic Inductance TWPA

Developed by groups at JPL and NIST

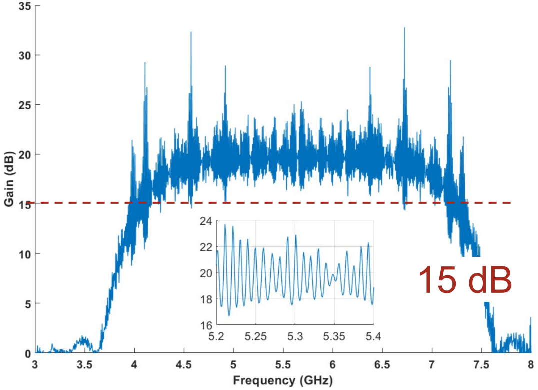
Figures of merit:

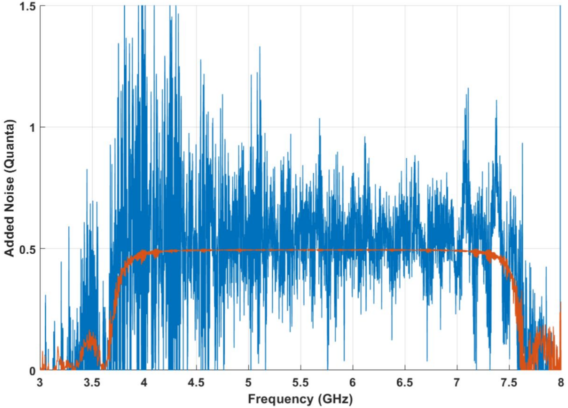
- Gain: > 15 dB
- Bandwidth: > 4 GHz
- Saturation power: > -60 dBm
- Operates at SQL





Appl. Phys. Lett. 108, 012601 (2016)





N. Kilmovich et al. arXiv:2306.11028 (2023)

<u>Other KI-TWPA references:</u>

G. Che et al. arXiv:1710.11335 (2017)
S. Shu et al. Phys. Rev. Research 3, 023184 (2021)
M. Malnou et al. PRX Quantum 2, 010302 (2021)
M. Malnou et al. arXiv:2110.08142 (2021)

Fermilab LDRD Proposal

Partnering with Peter Day (JPL) to produce and characterize KI-TWPAs

Our proposal would establish:

1. The KI-TWPA as a viable *community* option for broadband, quantum-limited RF amplification
2. The pathway from JPL to Fermilab for the supply of these amplifiers
3. The infrastructure and expertise at Fermilab to make use of these amplifiers and disseminate them to multiple Fermilab efforts

Anticipated throughput: 6 devices/year during LDRD

- More going forward, depending on demand, funds

Fermilab Low-Background Cryogenic Facilities

Located in the MINOS experimental hall at Fermilab, 100 meters underground

Fermilab LDRD Proposal: Technical & Scientific Goals

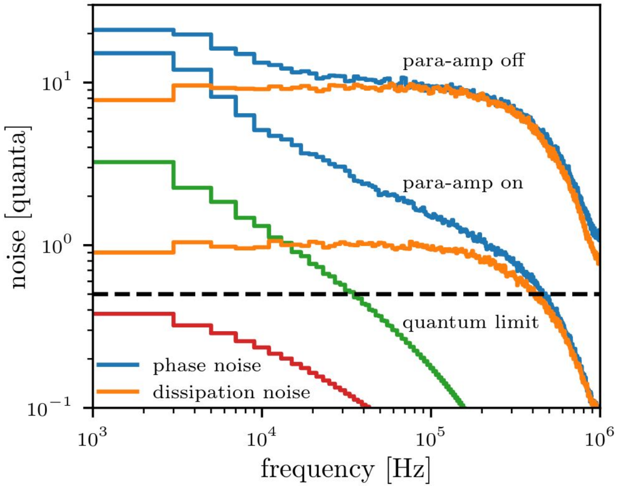
Instrument the NEXUS & QUIET facilities for KI-TWPA characterization and application

Apply KI-TWPA readout to achieve the following:

1. Demonstration of a KIPMD with an eV-scale energy resolution
2. A DM search using a low-threshold KIPMD
3. Demonstration of near quantum-limited amplification of an array of frequency-multiplexed superconducting qubits

KI-TWPA Application: MKIDs & KIPMDs

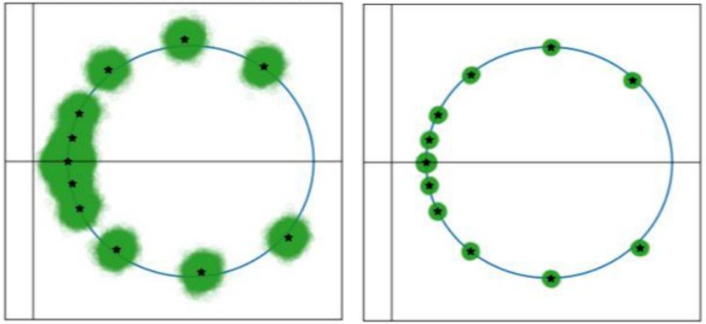
Optical MKID device w/ KI-TWPA



Zobrist *et al.* Appl. Phys. Lett. **115**, 042601 (2019)

Caltech device w/ KI-TWPA

Idealized transmission



KIPA Off → KIPA On

x4.2 improvement in RMS

“Ramanathan, Wen, in prep. (Golwala group, Caltech)”

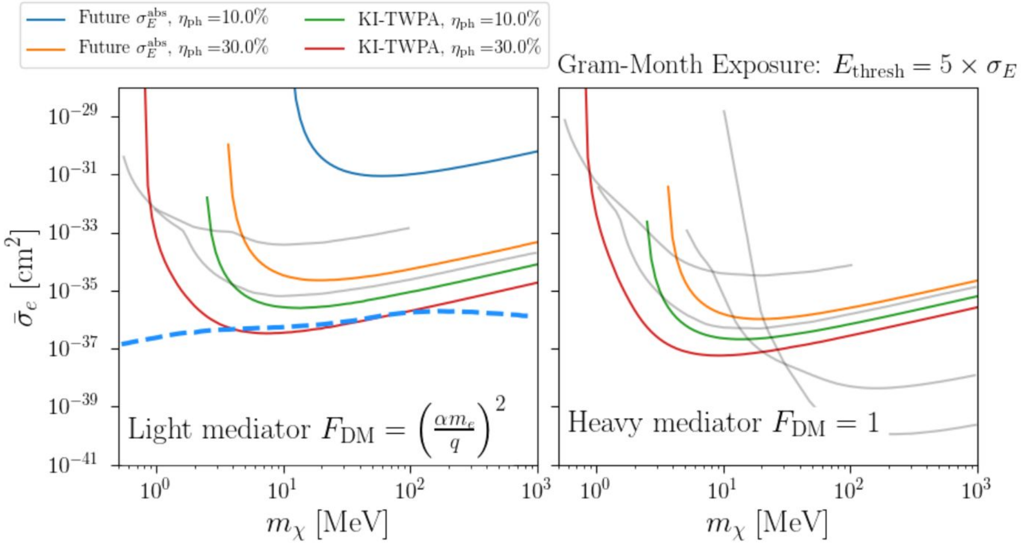
KI-TWPA Application: KIPMDs at FNAL

Current device: σ_E^{abs} = 2.6 eV with η_{ph} ~ 1%

- Previous device: η_{ph} = 8%
- Improved RF transmission: 4x improvement in σ_E^{abs}

Adding a KI-TWPA: 4-7x improvement in σ_E^{abs}

KI-TWPA Readout for KIPMDs enables:
(i) the first demonstration of eV-scale resolution
(ii) the first DM search with these devices
(iii) reaching unexplored parameter space for DM.

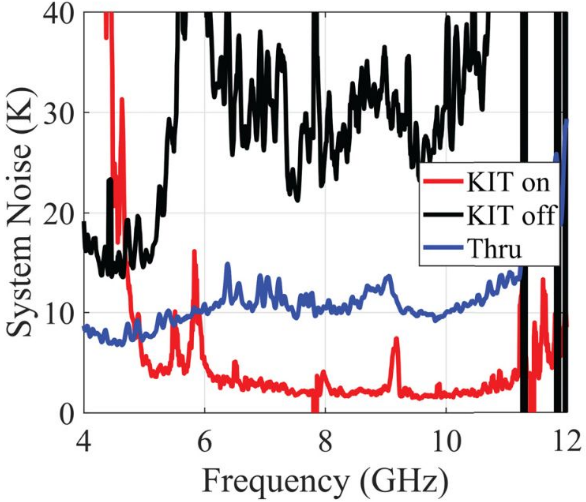


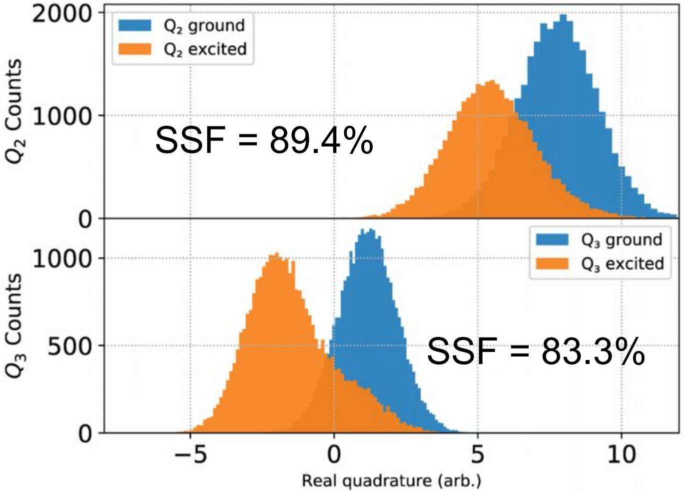
	Current	**η_{ph} = 10%**	***η_{ph} = 30%***	**KI-TWPA + η_{ph} = 10%**	***KI-TWPA+ η_{ph} = 30%***
σ_E^{abs} [eV]	2.6	0.65	*0.65*	0.14	*0.14*
σ_E [eV]	320	6.5	*2.2*	1.4	*0.47*
E_{thresh} [eV]	1600	32.5	*11*	7	*2.35*
ER M_χ^{min} [MeV]	--	15	*4*	3	*0.9*

η_{ph} ≡ energy absorbed in MKID/energy deposited in substrate

KI-TWPA Application: Qubits

NIST & Raytheon BBN demonstrated KI-TWPA use with superconducting qubits

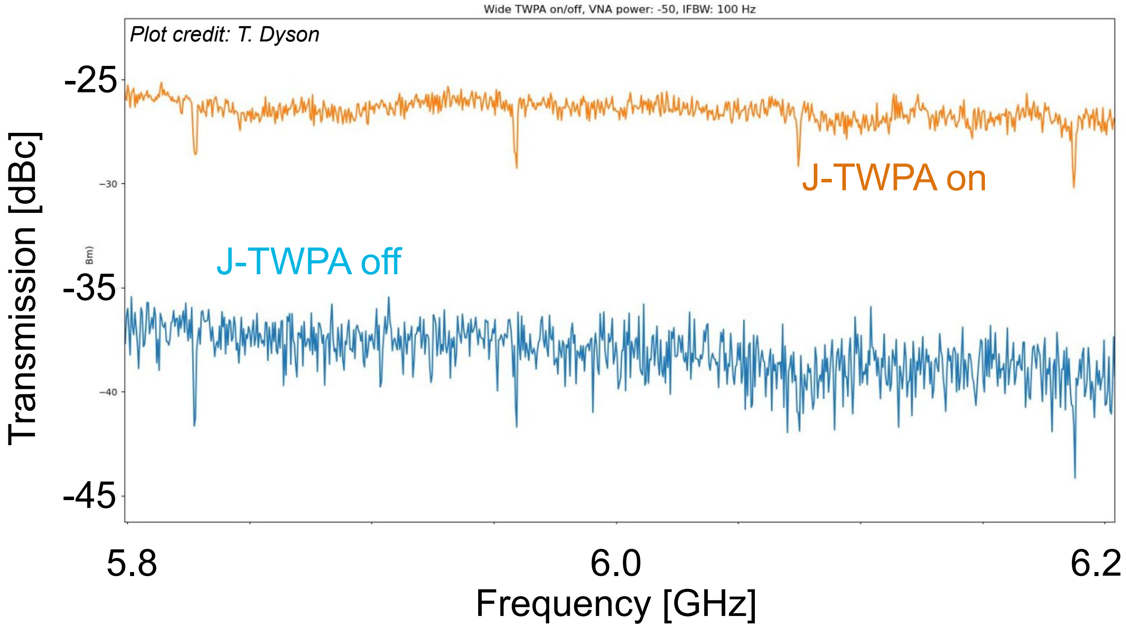




- ~10x noise reduction across >4 GHz bandwidth
  - 10(6) GHz: 1.4(4.1) photons of added noise at 10 GHz
- Simultaneous readout of 2 qubits with fidelity approaching 90%

L. Ranzani et al. Appl. Phys. Lett. 113, 242602 (2018)

KI-TWPA Application: Qubits at FNAL


Plot credit: T. Dyson

Daniel Bowring's ECA

- **MIT-LL J-TWPA**
- 4 transmon chip

Demonstrated ~10 dB of gain

Clear reduction of noise

Objective: demonstrate simultaneous readout of 4 qubits with SSF ≥ 90%

Setup allows direct comparison of J-TWPA and KI-TWPA with identical chip, transmission line, and readout electronics

Conclusion

- Kinetic Inductance Traveling Wave Parametric Amplifiers offer a promising alternative to JPAs and Josepshon TWPAs.
  - Shown to operate near the SQL of noise across 4 GHz of bandwidth.
- Future arrays of qubits and KIPMDs will require these amplifiers, while other RF experiments will benefit from their availability.
- Seeking LDRD support to outfit Fermilab cryogenic facilities for KI-TWPA characterization and application.
  - Will enable first of its kind low-threshold dark matter search with KIPMDs
- Will establish a pool of KI-TWPAs at FNAL for experimenters, resolving the current challenges due to limited J-TWPA availability.

Thank You!

D. Temples
FNAL

D. Bowring
FNAL

S. Golwala
Caltech

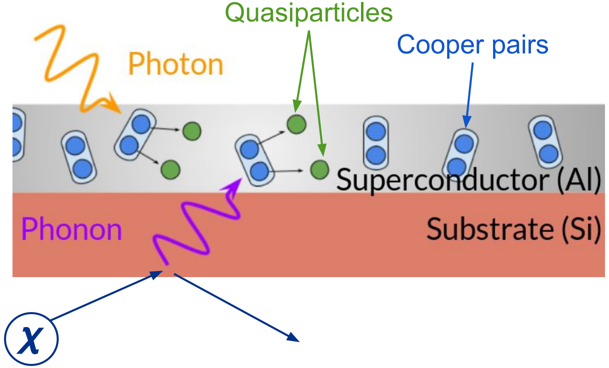
Advertisement: Have a need for cryogenic broadband low-noise RF amplifiers?

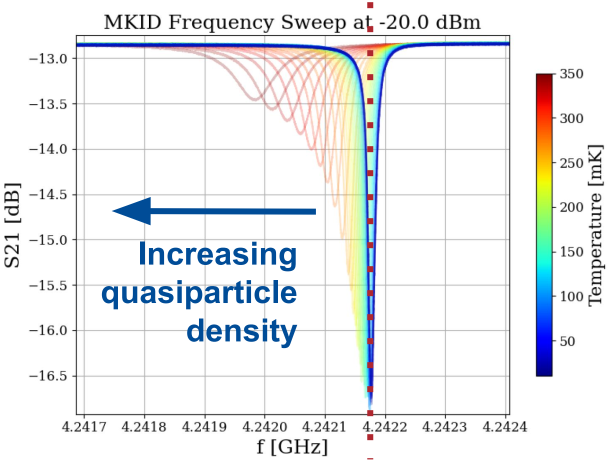
Acknowledgement: KI-TWPAs sourced from Peter Day, JPL.

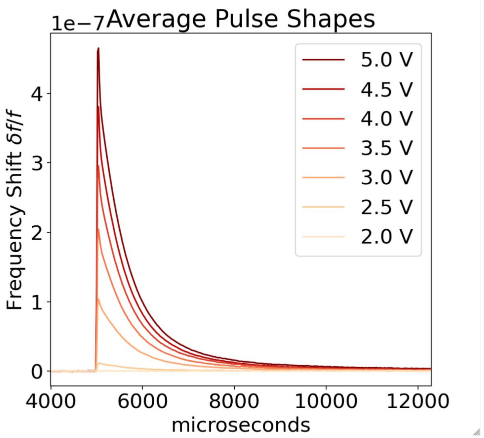
Kinetic Inductance Phonon-Mediated Detectors

Phonon-mediated MKIDs: superconducting microwave LC resonators deposited on a crystalline insulating substrate (e.g., silicon).

We aim to demonstrate these devices as eV-scale microcalorimeters given their sensitivity to athermal phonons produced by particle interactions in the substrate propagating to, and breaking Cooper pairs in, the superconductor.







Kinetic Inductance Phonon-Mediated Detectors for Dark Matter

Dark matter detection down to fermionic thermal relic mass limit of a few keV requires sensitivity to eV-scale depositions (sub-eV quanta).

MKID-based microcalorimeters:

- **Fast.** 10 μs rise time and O(ms) fall times demonstrated at NEXUS.
  - Directly sense athermal phonons rather than waiting for a thermal distribution to be reached.
- **Scalable.** Natively frequency multiplexable: no cryogenic multiplexers, identical warm electronics for a 1 resonator device up to O(10^3) resonators.

Currently performance limited by energy resolution

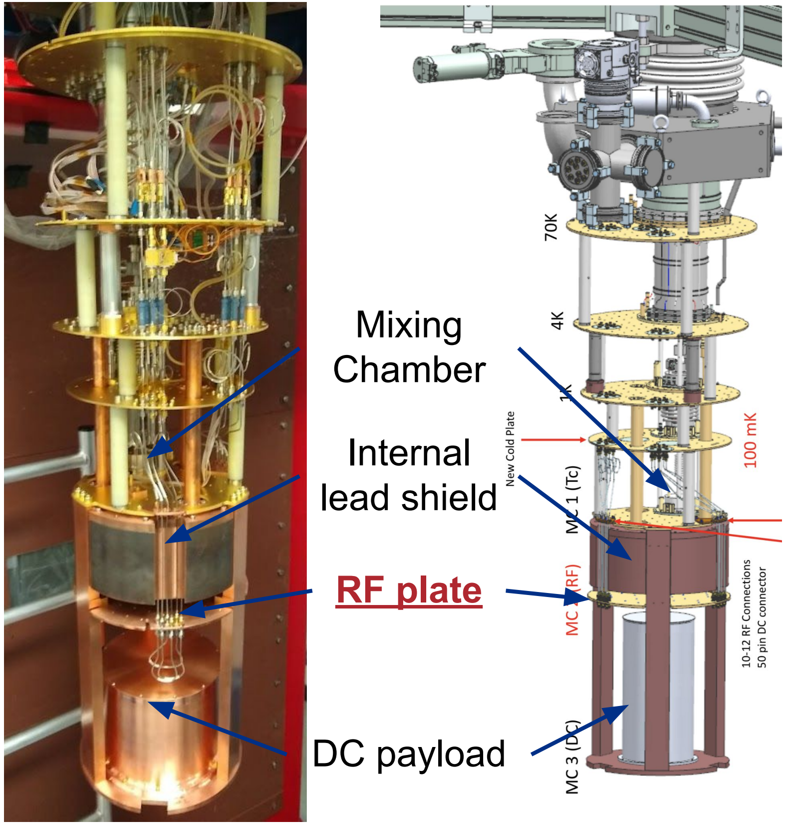
- TES sensors: $\sigma_E = 2.7$ eV (SuperCDMS)
- Phonon-mediated MKID sensors: $\sigma_E = 26$ eV (BULLKID)

To date, no DM searches yet performed with phonon-mediated MKID devices.

NEXUS: Northwestern EXperimental Underground Site

Key facility features:

- CryoConcept HEXADRY dilution refrigerator
- 107 m rock overburden (300 mwe)
  - Muon flux reduced by ~500x
- Moveable lead shield & **B** shielding
- $\mathcal{O}$(100) dru background rate (NaI)
- Optical photon & DD neutron calib. systems



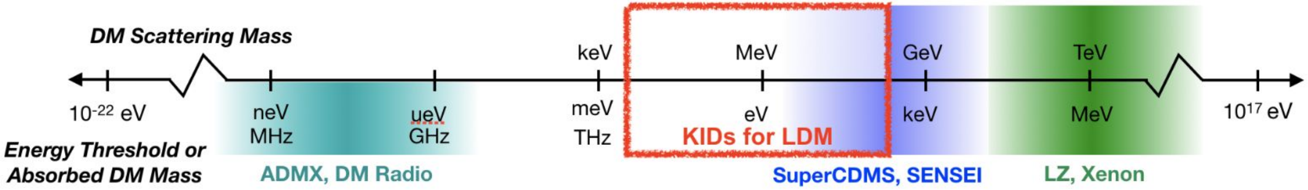
Mixing Chamber

Internal lead shield

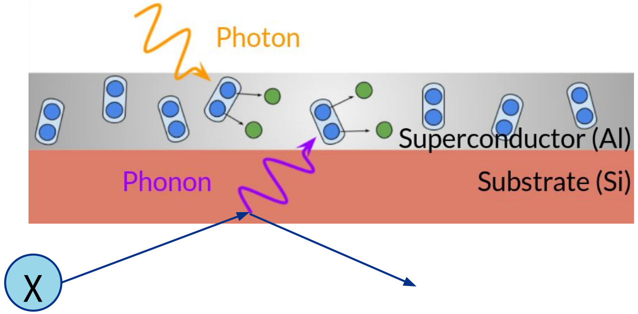
RF plate

DC payload

Phonon-mediated Kinetic Inductance Detectors for Dark Matter



- **Alternative to TES.** KIDs are faster, highly multiplexable with no extra electronics, and non-dissipative (lower heat load & amenable to QIS techniques)
- State of the art energy resolution (threshold):
  - KID (phonon-mediated): σ_E=26 eV (~125 eV) [CALDER, Supercond. Sci. Technol. 31, 075002 (2018)]
  - TES: σ_E=2.65 eV (12.5 eV) [SuperCDMS, Phys. Rev. D 104, 032010 (2021)]
- No direct DM search with KID devices performed to date.
- Ultimate KID sensitivity lies between qubits and TES. Provides the ability to study effects of interest for qubits with a better understood detector (stress microfractures, Cherenkov radiation).



Interactions in substrate produce meV-scale athermal phonons that propagate freely until they are absorbed by the superconductor, breaking Cooper pairs ($E_{ph} > 2\Delta \sim \mathcal{O}(100)$ μeV)

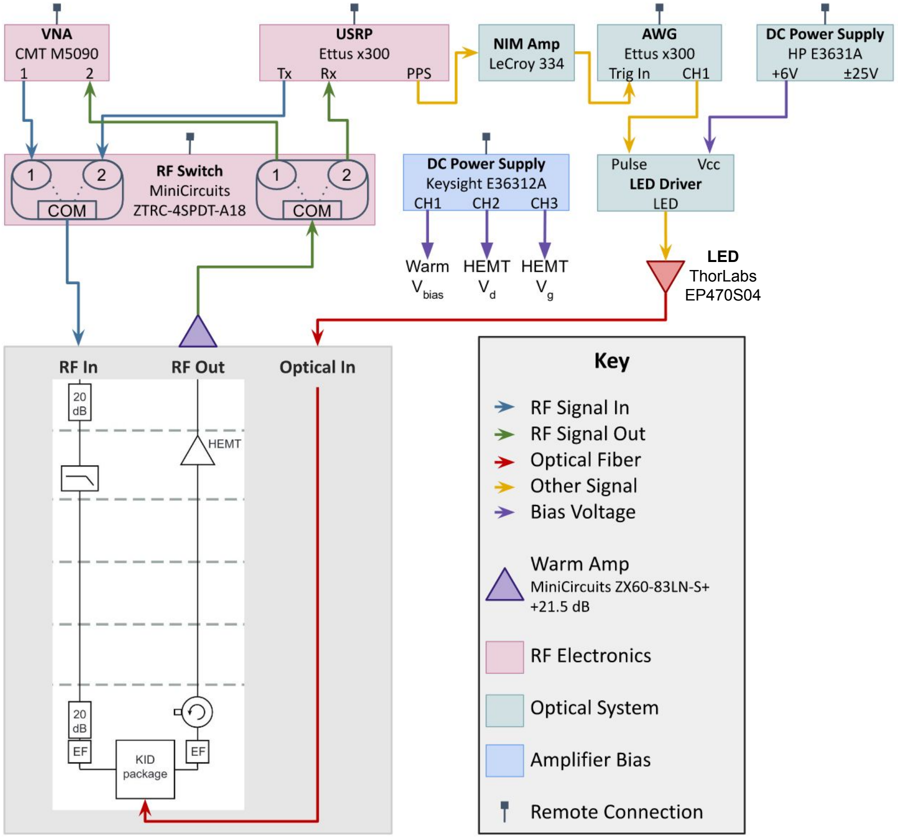
MKID Warm Electronics and LED Calibration System

Fully remote-controllable system

- Ettus x300 USRP & GPU SDR
  - DAQ stability issues largely resolved
  - Server, client running on same PC
- DAQ PC GPU GeForce RTX 2080 Ti
  - Planned upgrade to RTX 6000 Ada
  - >4x more memory, cores

Optical Calibration System

- 470 nm LED (ThorLabs EP470S04)
- Up to ~5 mW optical power
- Fiber pointing at rear of device
- Pulse burst synced to USRP clock
- Pulse profiles:
  - 1 µs @ 10 Hz / 2 µs @ 5 Hz
  - Limited to 0.001% duty cycle



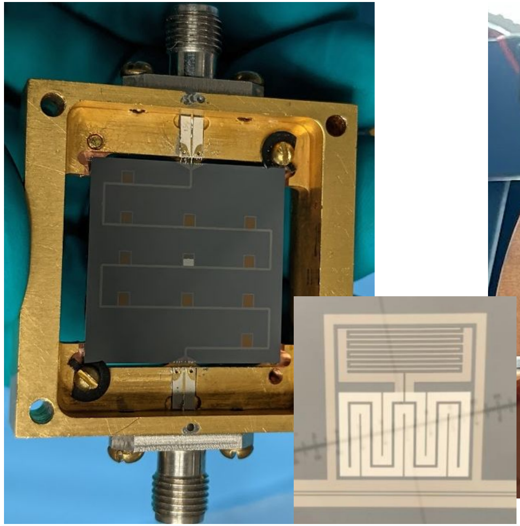
Readout & Optical Calibration System

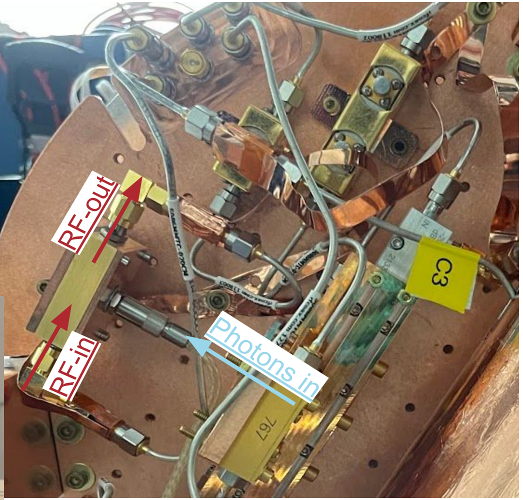
FNAL-I Device (O. Wen) 3.9--4.4 GHz

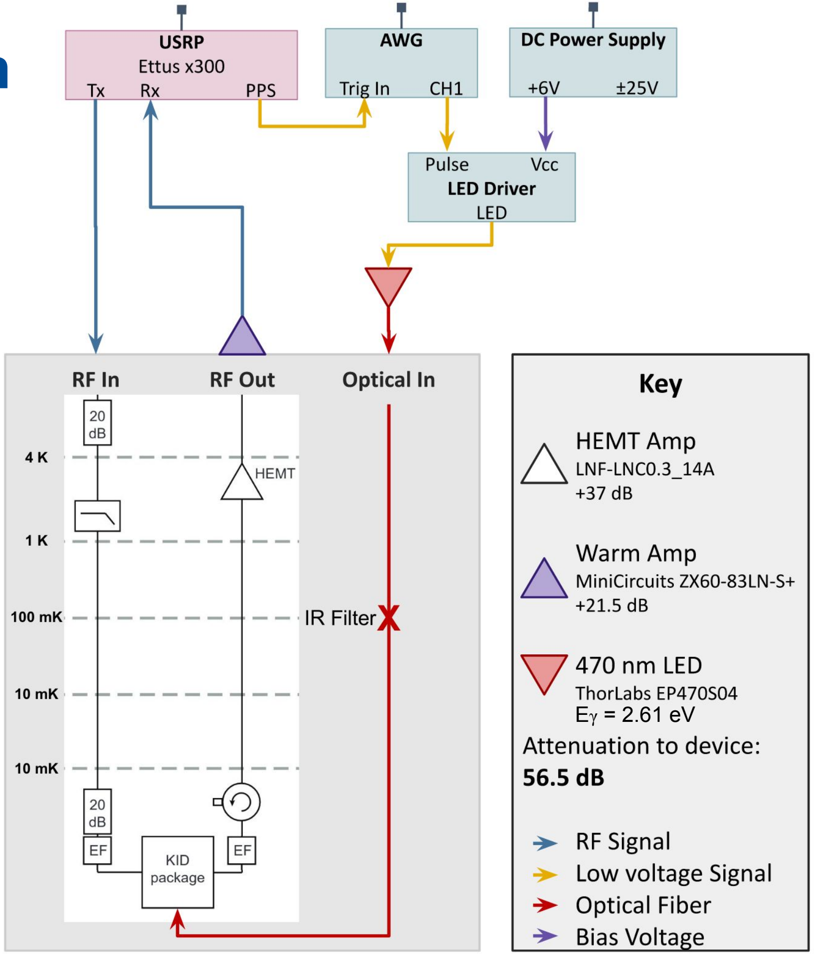
- Phonon sensitive resonator 30 nm Al inductor (4.24 GHz)
- 10x Nb resonators
- ~1g high-resistivity Si substrate

DAQ: Ettus Research x300 USRP

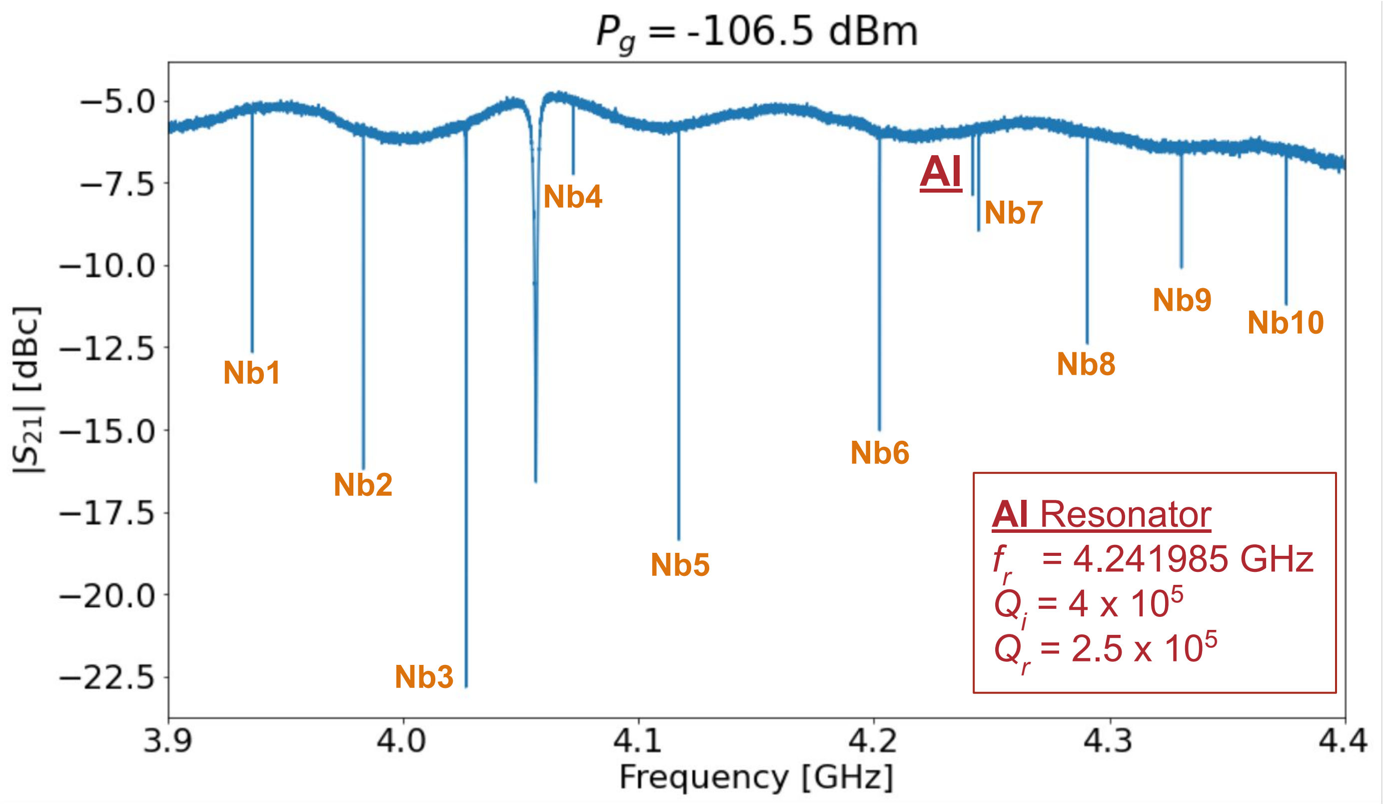
Correlated noise removal with off-resonant tones







“Fermilab I” Resonance Spectrum



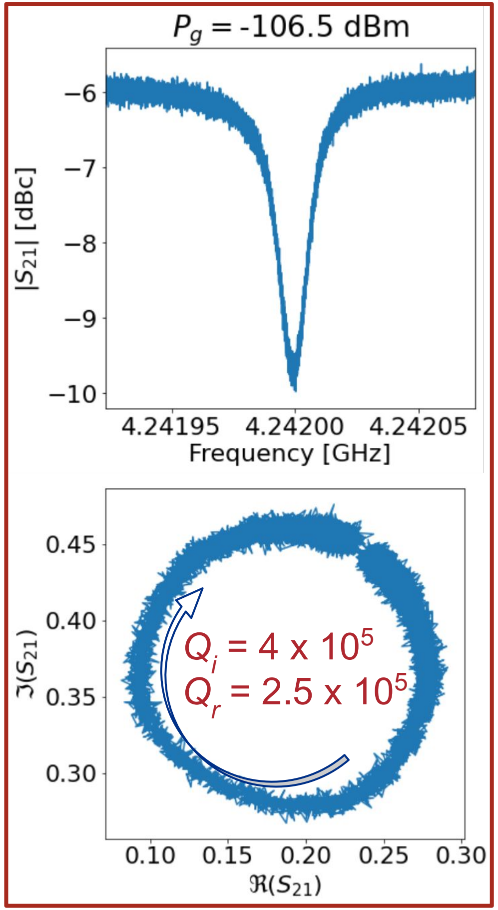
Al Resonator

f_r = 4.241985 GHz

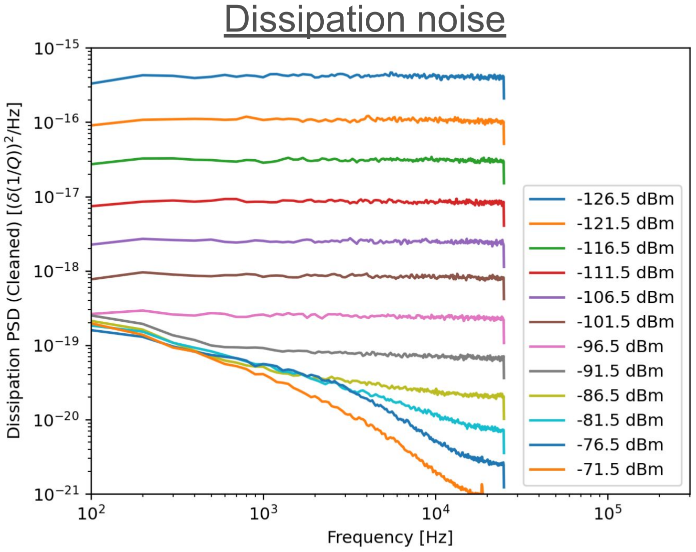
Q_i = 4 x 10^5

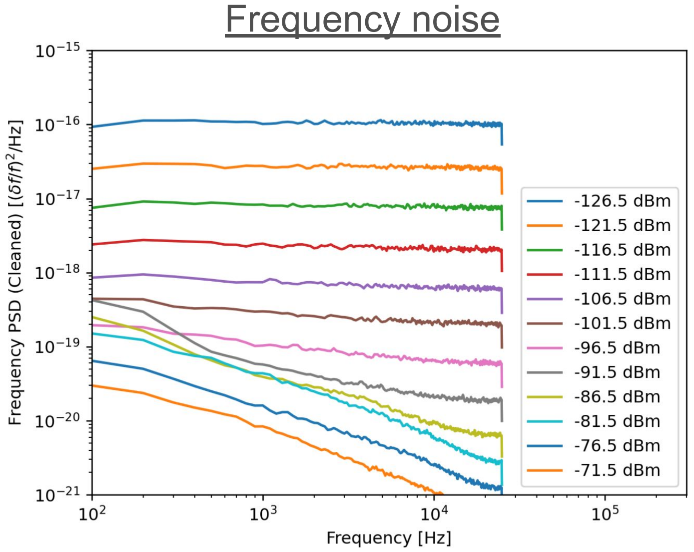
Q_r = 2.5 x 10^5

FNAL-I Device Performance

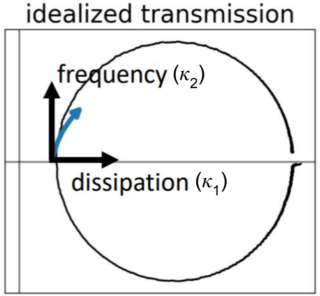


$Q_i = 4 \times 10^5$
$Q_r = 2.5 \times 10^5$





- White amplifier noise dominated at low readout powers
- Frequency quadrature 1/f TLS noise (O. Wen's talk M-2-2)
- Correlated κ_1-κ_2 noise of unknown origin at highest readout powers



$\sigma_{df/f}$ = 3.6 x 10^{-9} $\sigma_{qp}^{\kappa 2}$ = 0.49 μm^{-3}

$\sigma_{1/Q}$ = 7.4 x 10^{-9} $\sigma_{qp}^{\kappa 1}$ = 0.85 μm^{-3}

Determined via optimal filter on noise data (LED pulse signal template)