

# SUPERCONDUCTING DETECTORS FOR RICOCHET

CE $\nu$ NS Heaven: Into the Blue Sky

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Wouter Van De Pontseele on behalf of RICOCHET

Massachusetts Institute of Technology

March 25, 2023

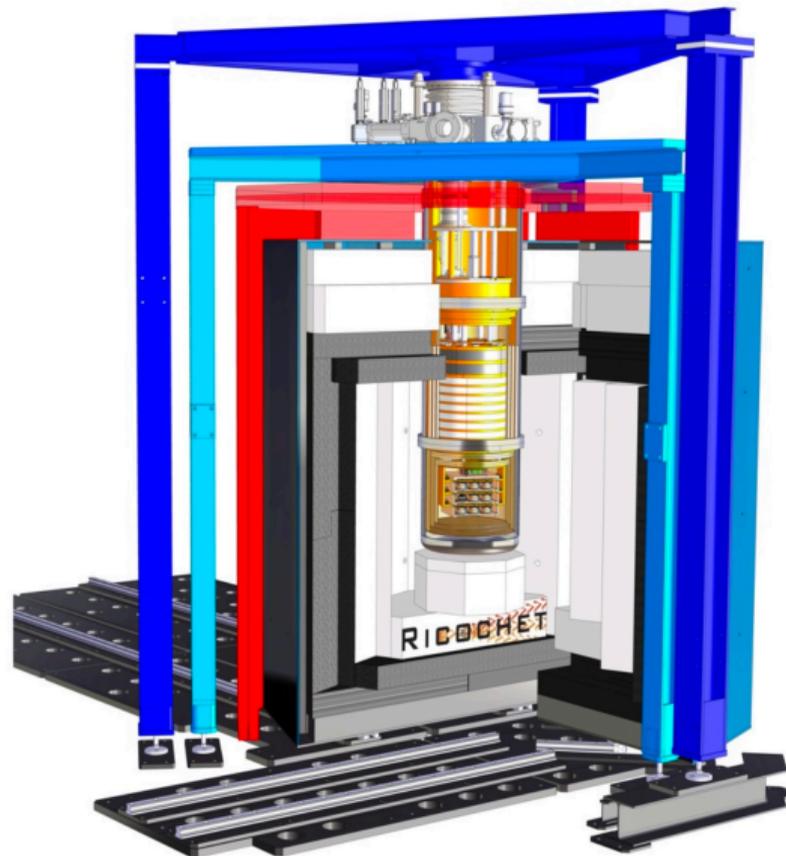
wvdp@mit.edu

# THE RICOCHET EXPERIMENT: CRYOCUBE + Q-ARRAY

- Ricochet consists of a double cryogenic detector payload at the bottom of a dilution refrigerator ( $\approx 10$  mK):  
**Cryocube** (Ge target) and **Q-Array** (Zn/Al/Sn target).

## Q-Array:

- Platform to test superconducting technologies for CE $\nu$ NS.
- Modular kg-scale detector with **superconducting crystals**.



# THE RICOCHET EXPERIMENT: CRYOCUBE + Q-ARRAY

## Expanding collaboration

Argonne National Laboratory

Lincoln Laboratory

Massachusetts Institute of Technology

Northwestern University

University of Massachusetts Amherst

Université de Lyon

Université Paris-Saclay

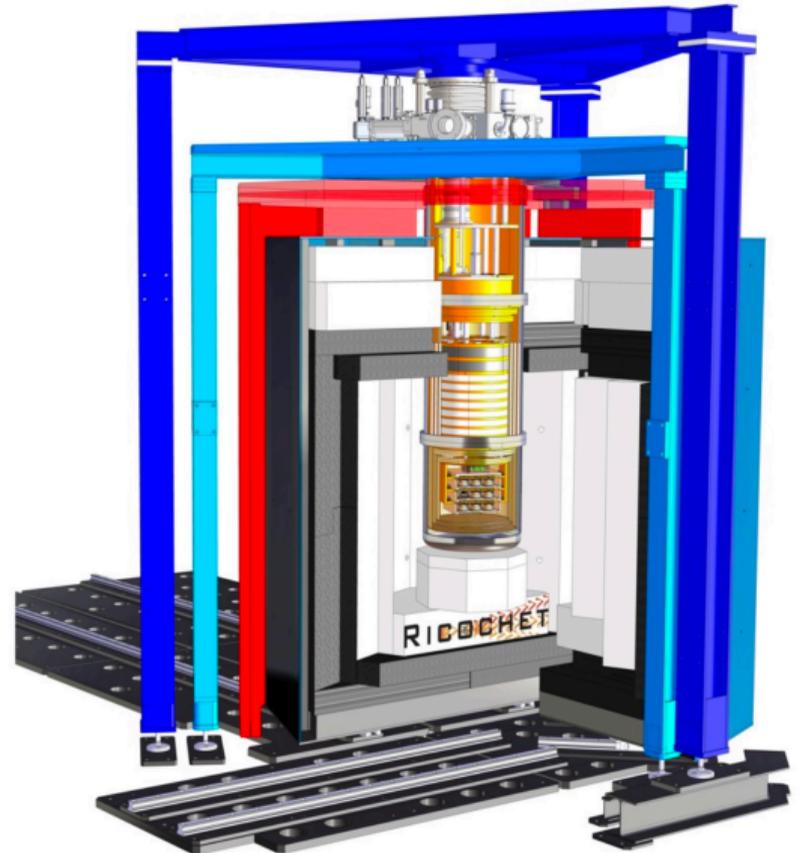
Université Grenoble Alpes

Institut Laue-Langevin

University of Toronto

University of Oxford

Joint Institute for Nuclear Research

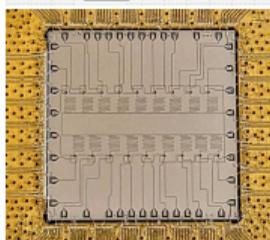
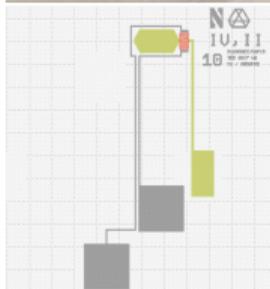
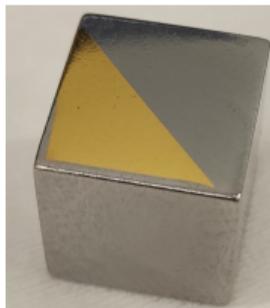


## Hardware R&D

Superconducting crystals (Zn, Al, and Sn) as absorbers.

Transition edge sensor “chips” as sensors.

Cryogenic RF-SQUID resonators.



## Advantage / Goal

Access to **lower thresholds**; timing as recoil discriminator

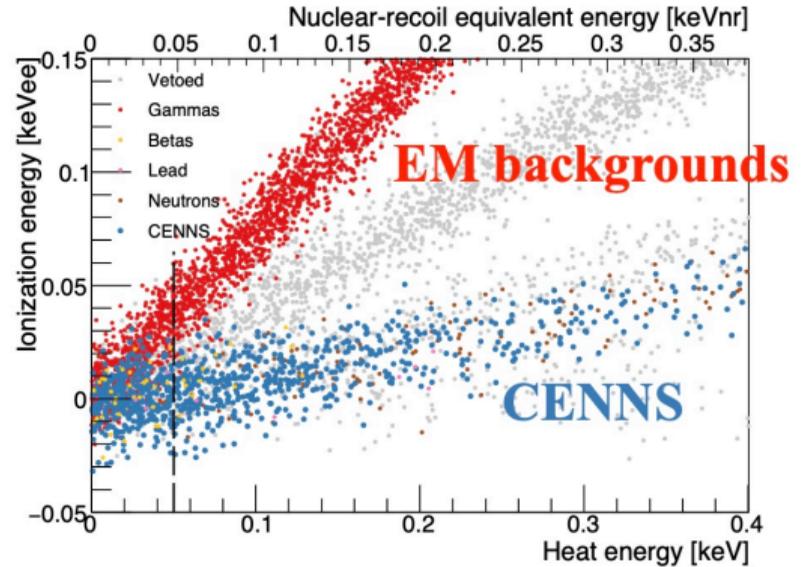
Modular fast readout; **standardised fabrication** process

**Multiplexed** readout, scalable and reduced heatload.

## Semiconductor Crystal

- heat readout using NTD's
- Ionisation readout using an applied voltage

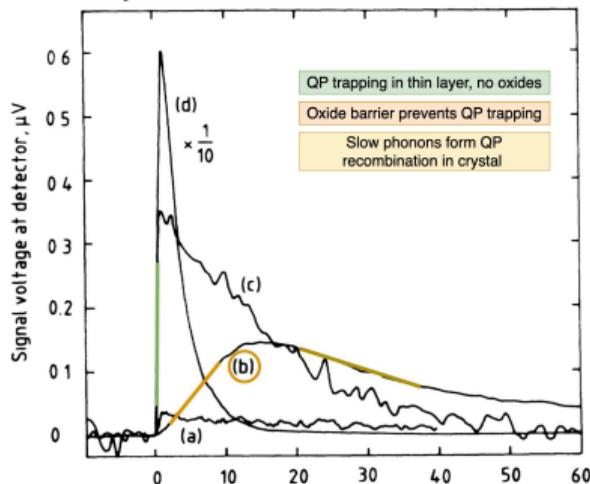
→ ER/NR discrimination and discrimination against heat-only events.  
→ Ultimate threshold limited by ionisation.



## Superconducting Crystal

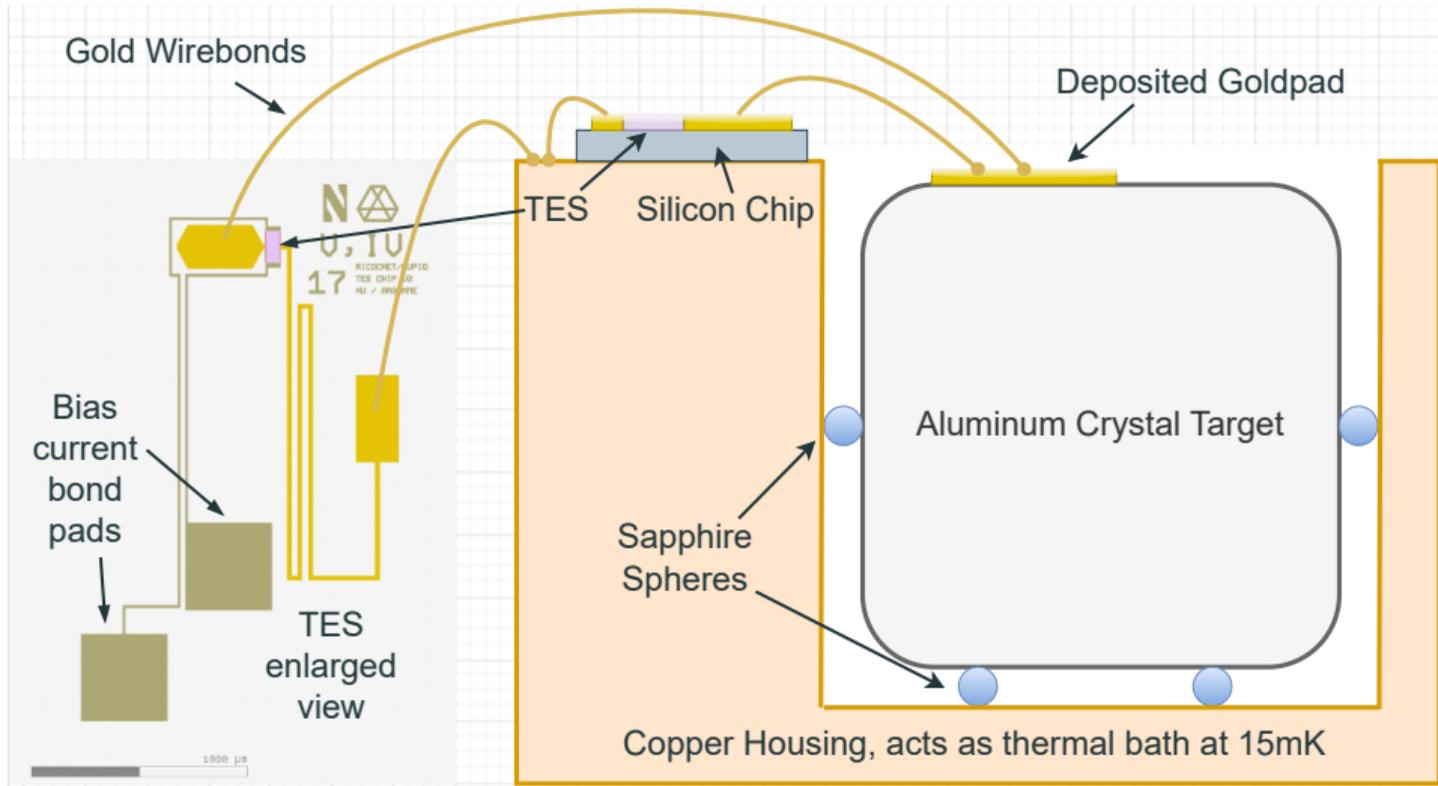
- Particle interactions create excited cooper pairs (quasi-particles, QP) and phonons in the crystal.
- prompt phonons make it into the gold deposit.
- Gold deposit traps quasi-particles if no oxide layer is present.
- QPs can recombine in crystal leading to a slow phonon component.

PhysRevLett.64.954 (1990)

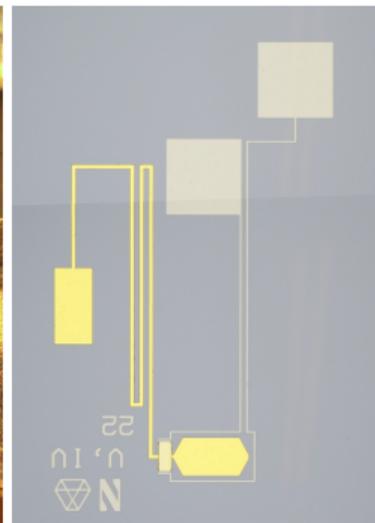
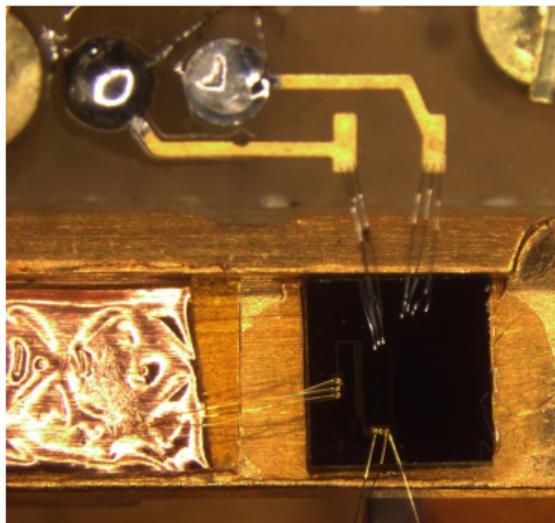
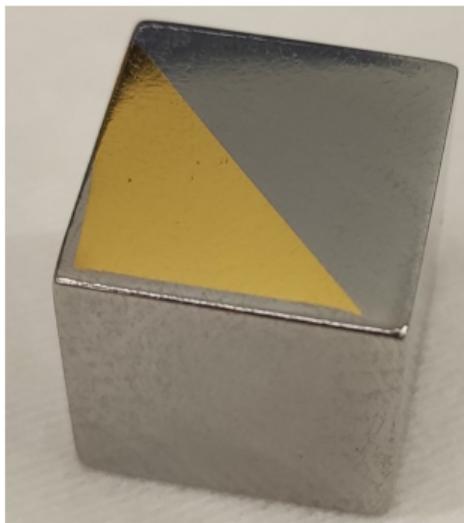


- rich physics with different time scales might enable ER/NR discrimination.
- Ultimate threshold limited by meV cooper pair binding energy.

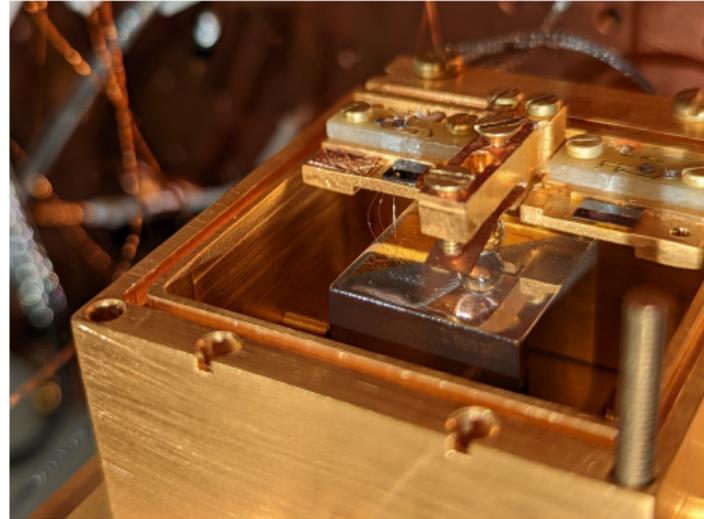
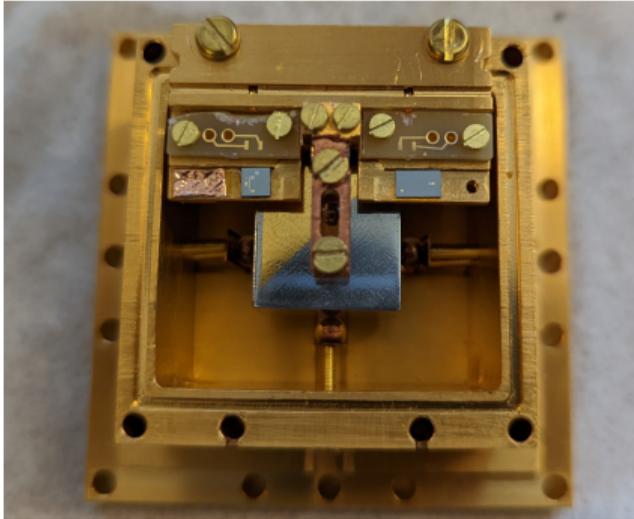
# TRANSITION EDGE SENSOR READOUT OF A SUPERCONDUCTING CRYSTAL



- **Al crystal** with a 200 nm goldpad ( $\approx 1 \text{ cm}^2$ ) connected through an Ti adhesion layer.
- **Al-Mn TES** fabricated at Argonne and mounted using GE Varnish.
- Gold plated copper box with **sapphire balls** as isolation.



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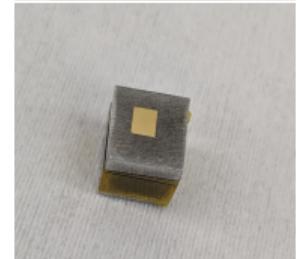
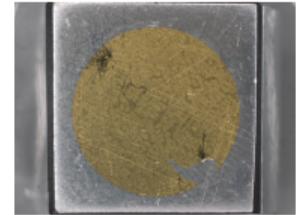


Crystals **fabricated** by RMD in Massachusetts

- **Vertical Bridgman growth:** slow cooling of molten material by moving its container from a hot zone into a cold one
- Diamond wire saw cut to  $\mathcal{O}(\text{cm})$ -scale.
- Polishing using finer polishing compounds successively.
- Al (N=27), Zn (N=64) or Sn (N=120).

**Gold deposit** to collect phonons and/or trap quasi-particles

- Non-magnetic Ti adhesion layer, gap below the crystal's gap.
- Gold might be superconducting due to the proximity effect,  $\mathcal{O}(1\ \mu\text{m})$ , preventing phonon transport to the TES.
- Natural oxide impedes quasi-particle trapping but might affect proximity effect.

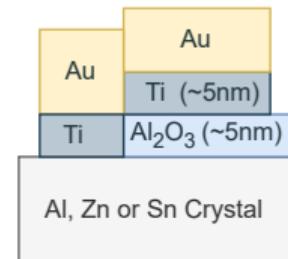
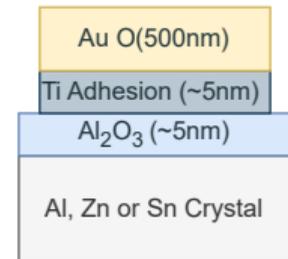
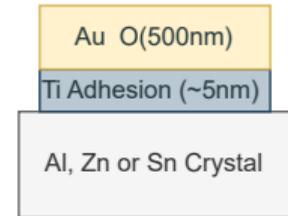


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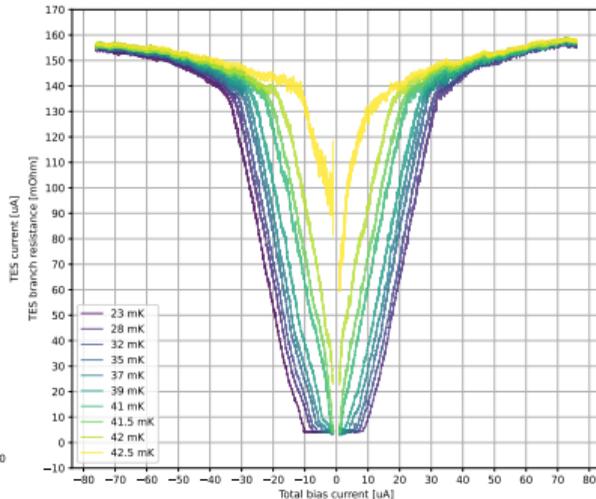
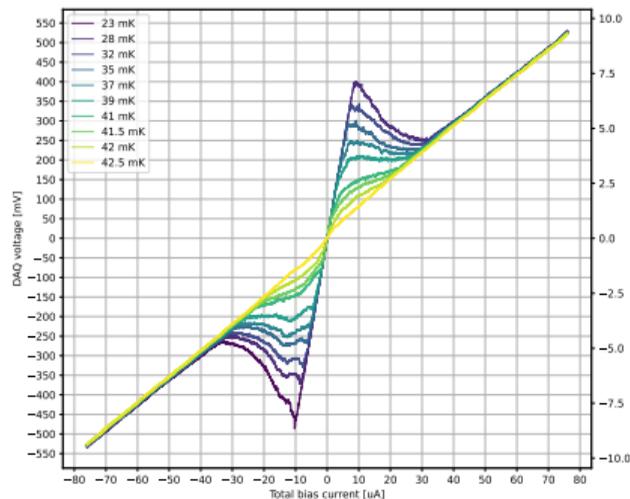
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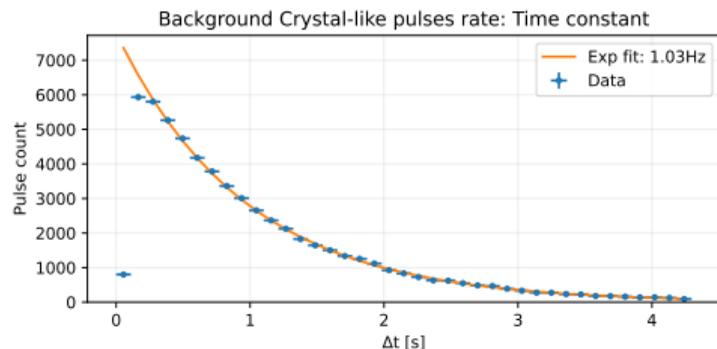
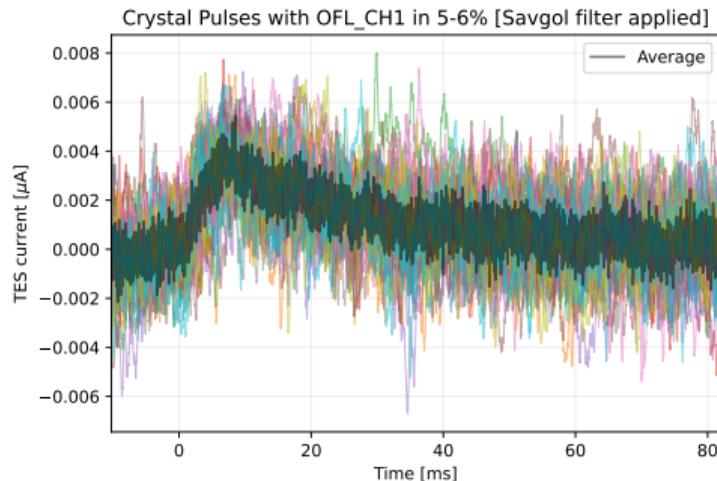


# TES AND AL CRYSTAL MEASUREMENTS: PRELIMINARY RESULTS

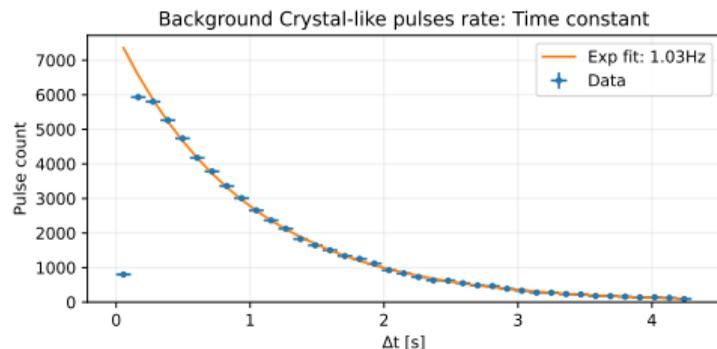
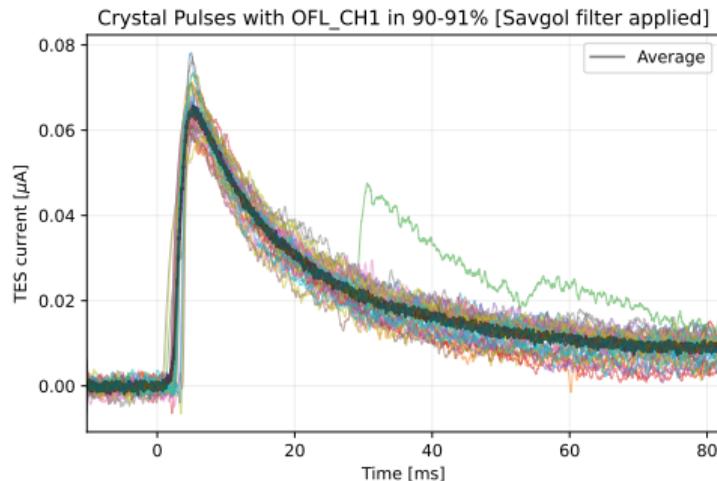
- Al TES doped with magnetic manganese impurities fabricated by ANL.
- Kept in transition using bias current and electro-thermal feedback.
- TES **transition** at 43 mK and **biased** at  $\mathcal{O}(30\%)$  of normal resistance.



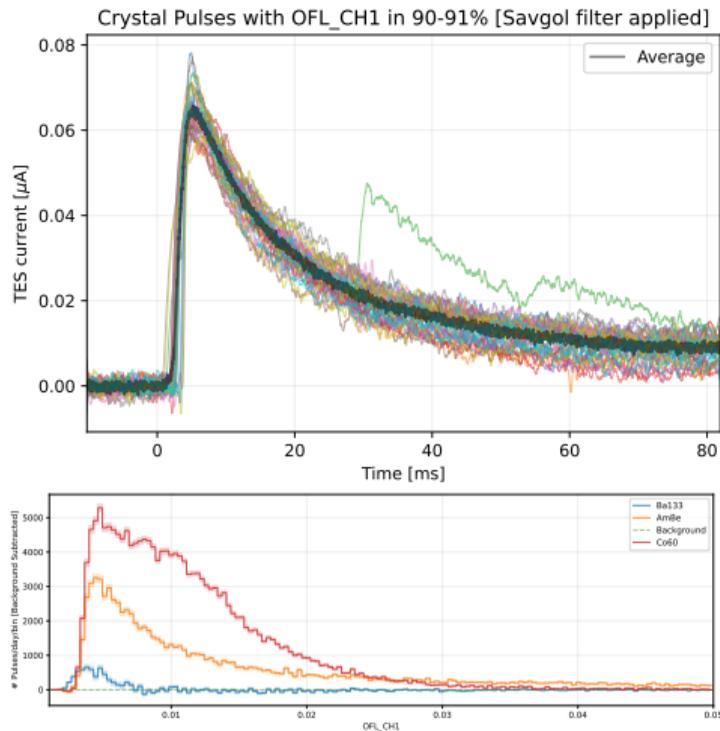
- **Data** taken in Summer 2022 with
  - No source (background)
  - external sources: Gamma's (Co60, Ba133) and neutrons (Ambe)
- About 15 hours data per source @ 100 kHz in streaming mode.
- Processed with PyCRP
  - Triggering with Gaussian derivative filter
  - Reduced quantities calculated using **optimal filter template**.
  - Rates between 1 Hz to 5 Hz.



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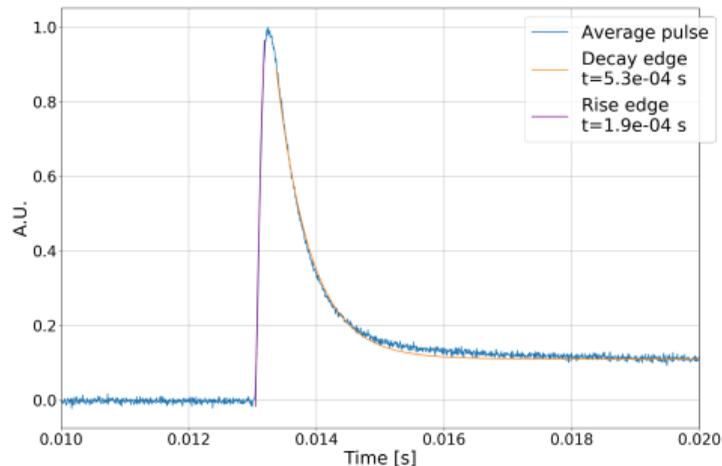


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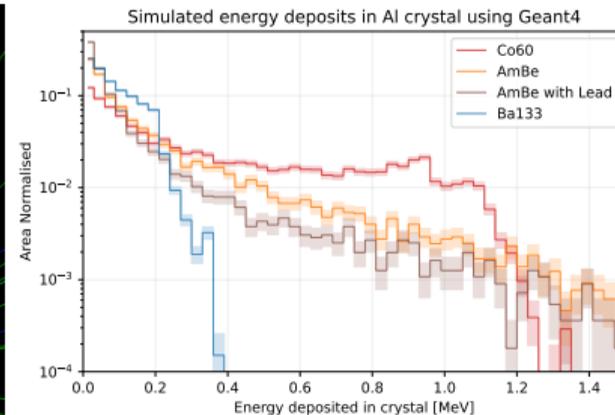
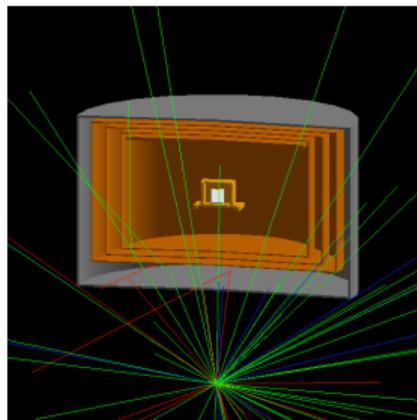
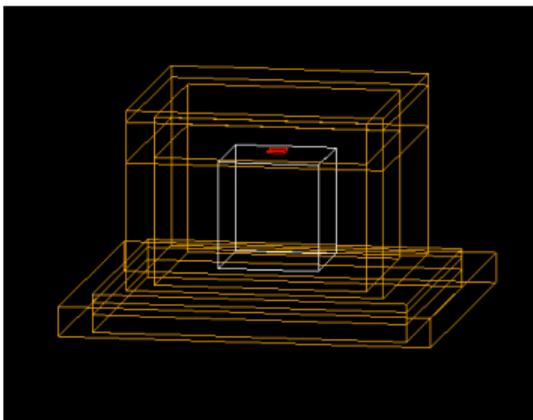


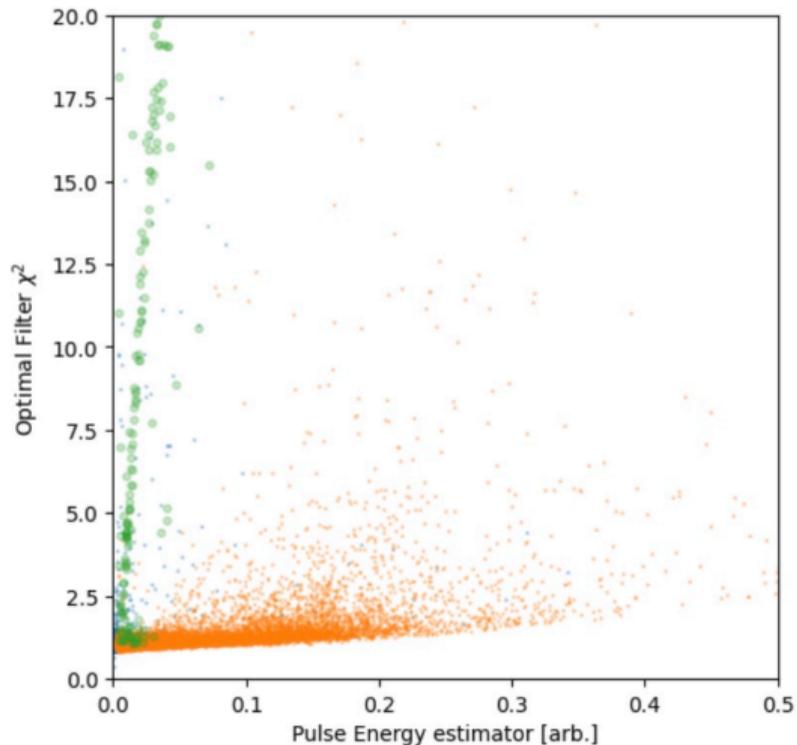
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Similar Al crystal observing pulses right now  
100 m underground at Fermilab



- TES-Crystal electro-thermal modelling used to interpret pulse shapes.
- GEANT4 is used to **simulate the energy deposits** of radioactive sources into to crystal.
- Data-analysis still in progress. The current prototype is not expected to have competitive energy resolution.





## Crystal-like pulses

- Rise time of  $\approx 2$  ms
- Fall time of  $\approx 10$  ms
- Slow component of  $\approx 60$  ms
- Typical amplitude of  $\mathcal{O}(40$  nA)

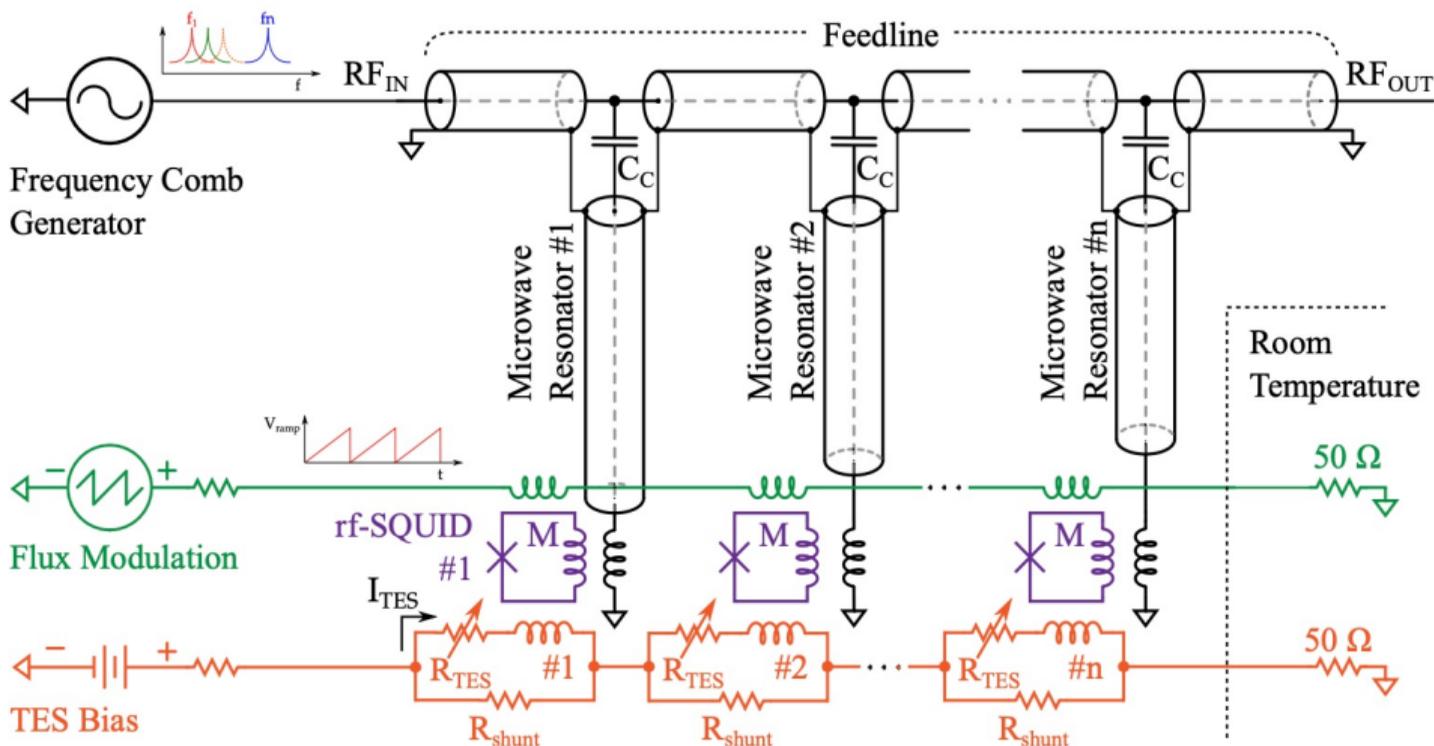
## TES-like pulses

- Factor  $\approx 100$  rarer
- Rise time of  $\approx 3$   $\mu$ s
- Fall time of  $\approx 0.1$  ms
- Slow component of  $\approx 1$  ms

ER/NR shape differences being studied.

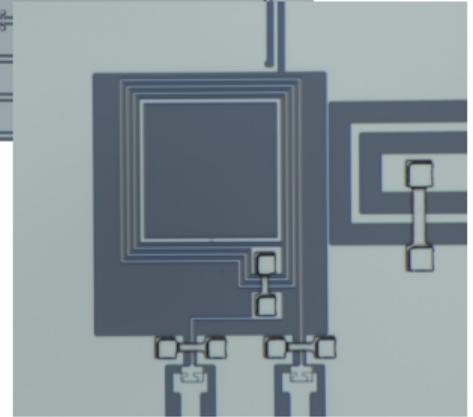
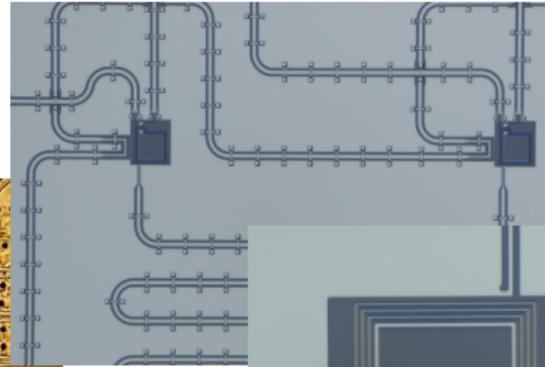
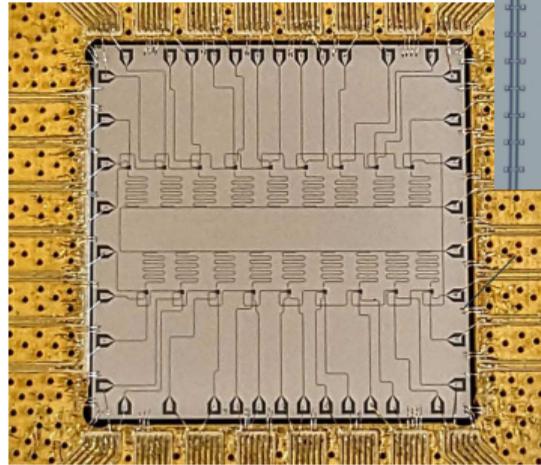
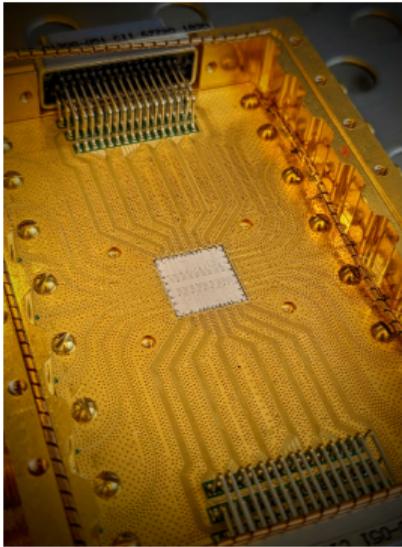
# RF SQUID MULTIPLEXING

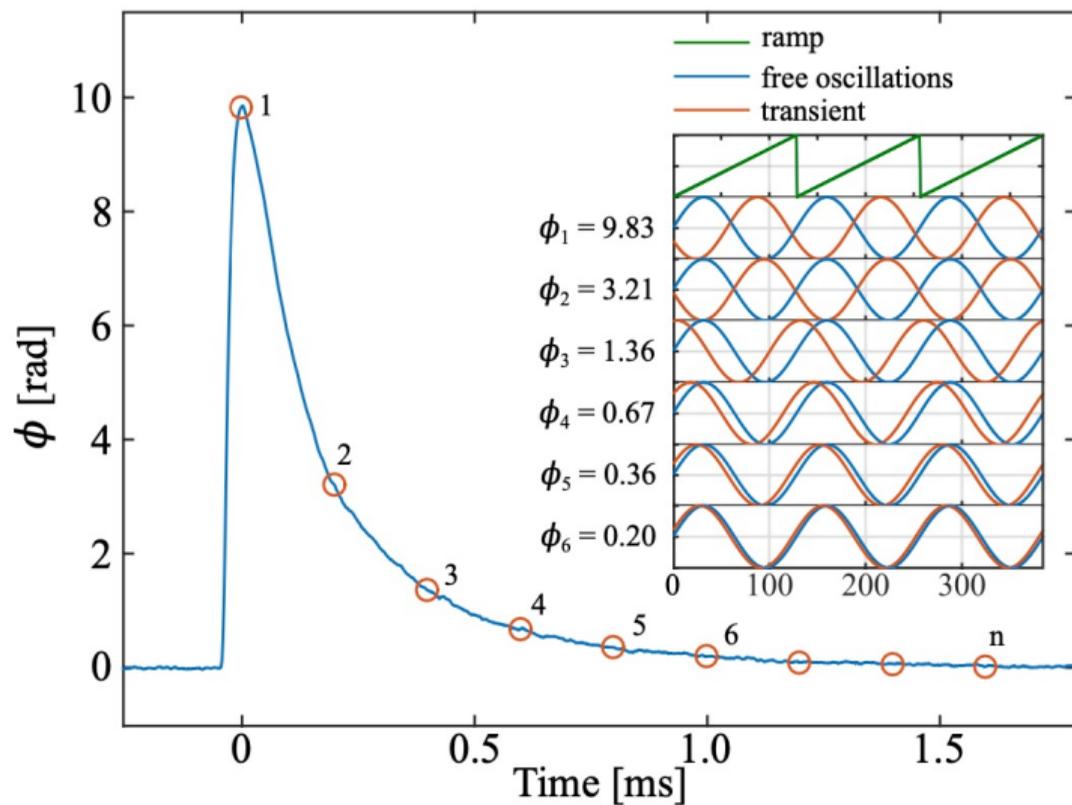
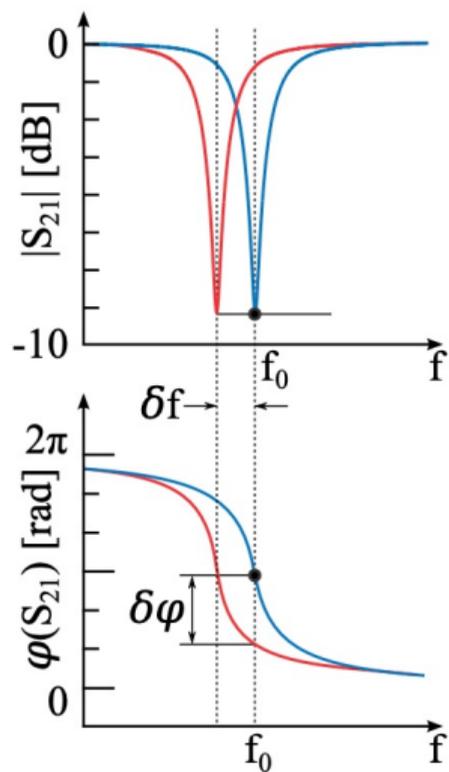
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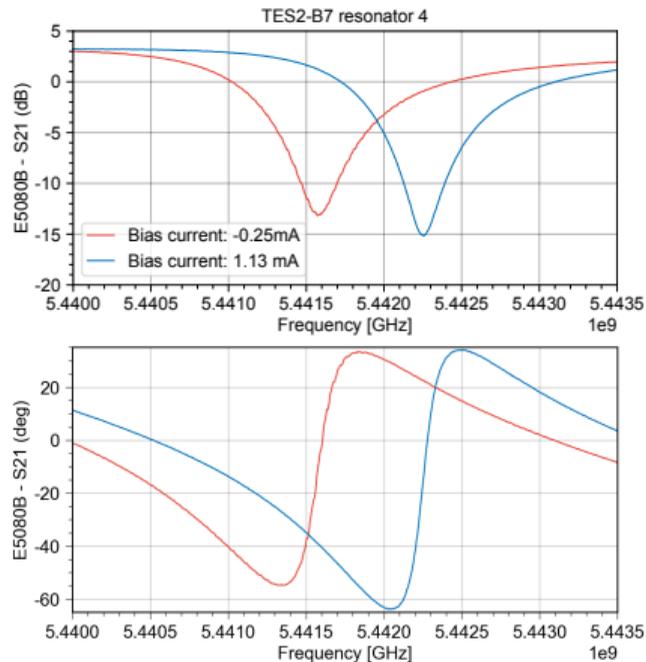
# RF SQUID MULTIPLEXING DESIGNED AT MIT FOR RICOCHET

6 and 18 channel resonator devices fabricated at Lincoln Laboratories and tested at MIT.

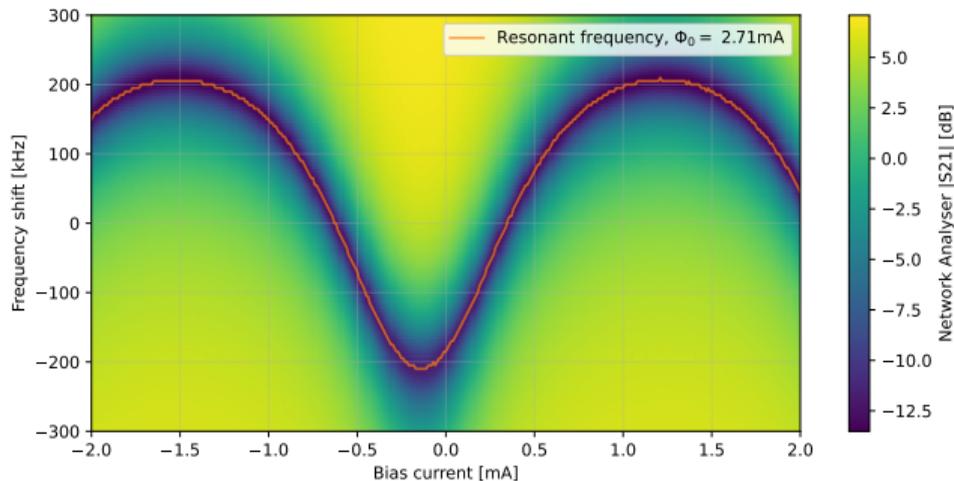




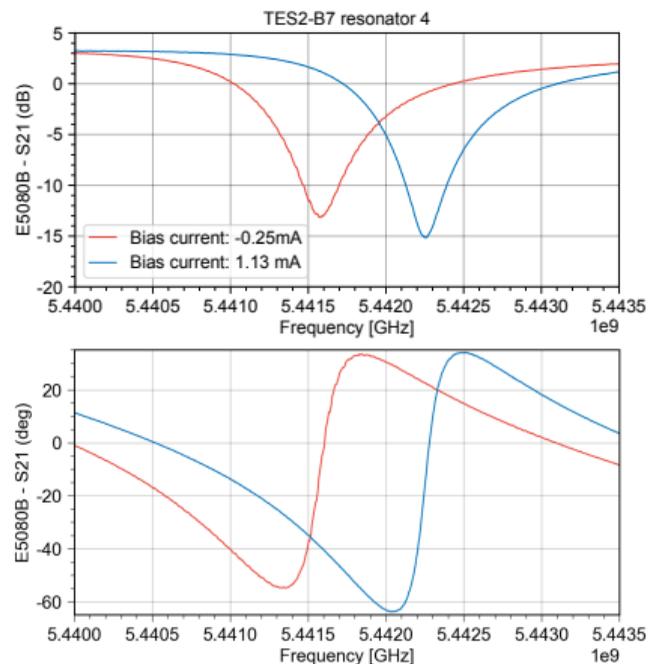
Resonant frequency depends on the current through the inductance.



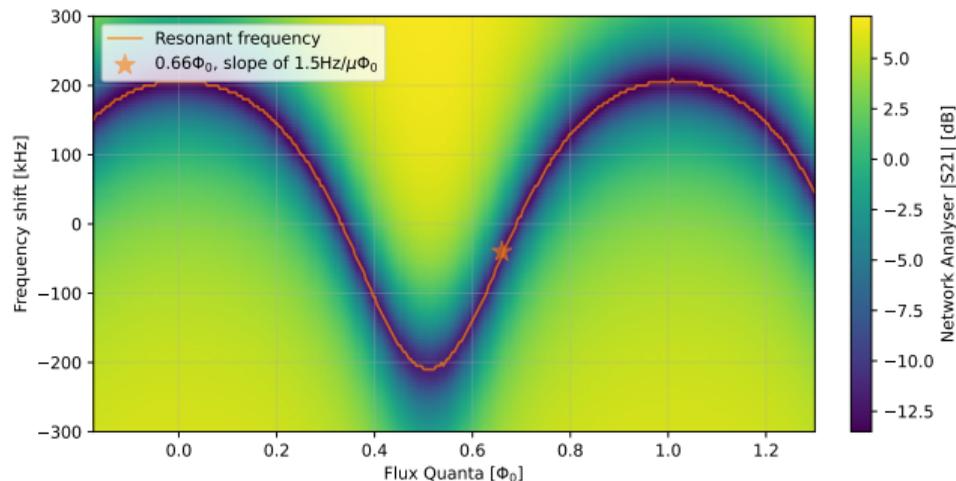
- Periodicity enables determination of flux quantum  $\Phi_0$ .



Resonant frequency depends on the current through the inductance.



- **Periodicity** enables determination of flux quantum  $\Phi_0$ .
- **Optimal sensitivity** of  $\approx 2\mu\Phi_0/\sqrt{\text{Hz}}$  measured, noise dominated by HEMT readout.

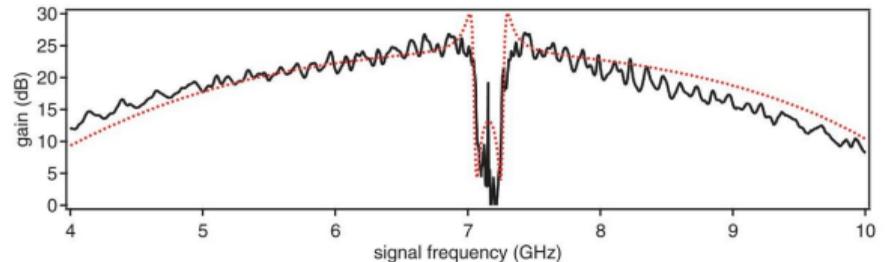
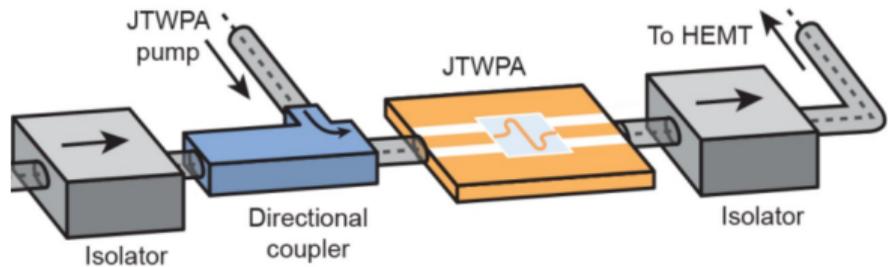
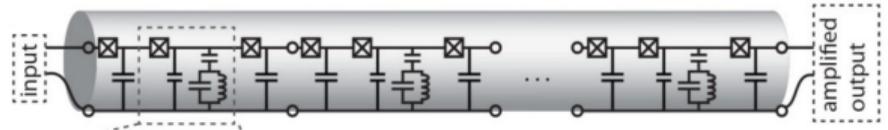


# JOSEPHSON TRAVELLING WAVE PARAMETRIC AMPLIFIER (JTWPA)

Lowering the multiplexing noise floor further by going beyond HEMTs...  
Quantum Amplifiers!

Signal amplification by exchanging pump power into signal and idler tone with Josephson junctions as a non-linear element.

- Transmission device.  $\mathcal{O}(1000)$  cells.
- Up to  $\mathcal{O}(3\text{ GHz})$  bandwidth with **20 dB gain**.
- Designed by Kevin O'Brien's group at MIT, fabrication at Lincoln Laboratory.



## CONCLUSION & OUTLOOK

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## The Ricochet Experiment

- CE $\nu$ NS **cross-section** using cryogenic detectors.
- Expected to take reactor **data in 2024** in France.

## Superconducting Crystal and TES Measurements

- **Pulses** in prototype superconducting Al crystal.
- Energy **calibration using sources** in progress.

## Q-Array RF multiplexed Readout

- Optimised **18-resonator devices** fabricated.
- R&D into **high dynamic range quantum amps**.

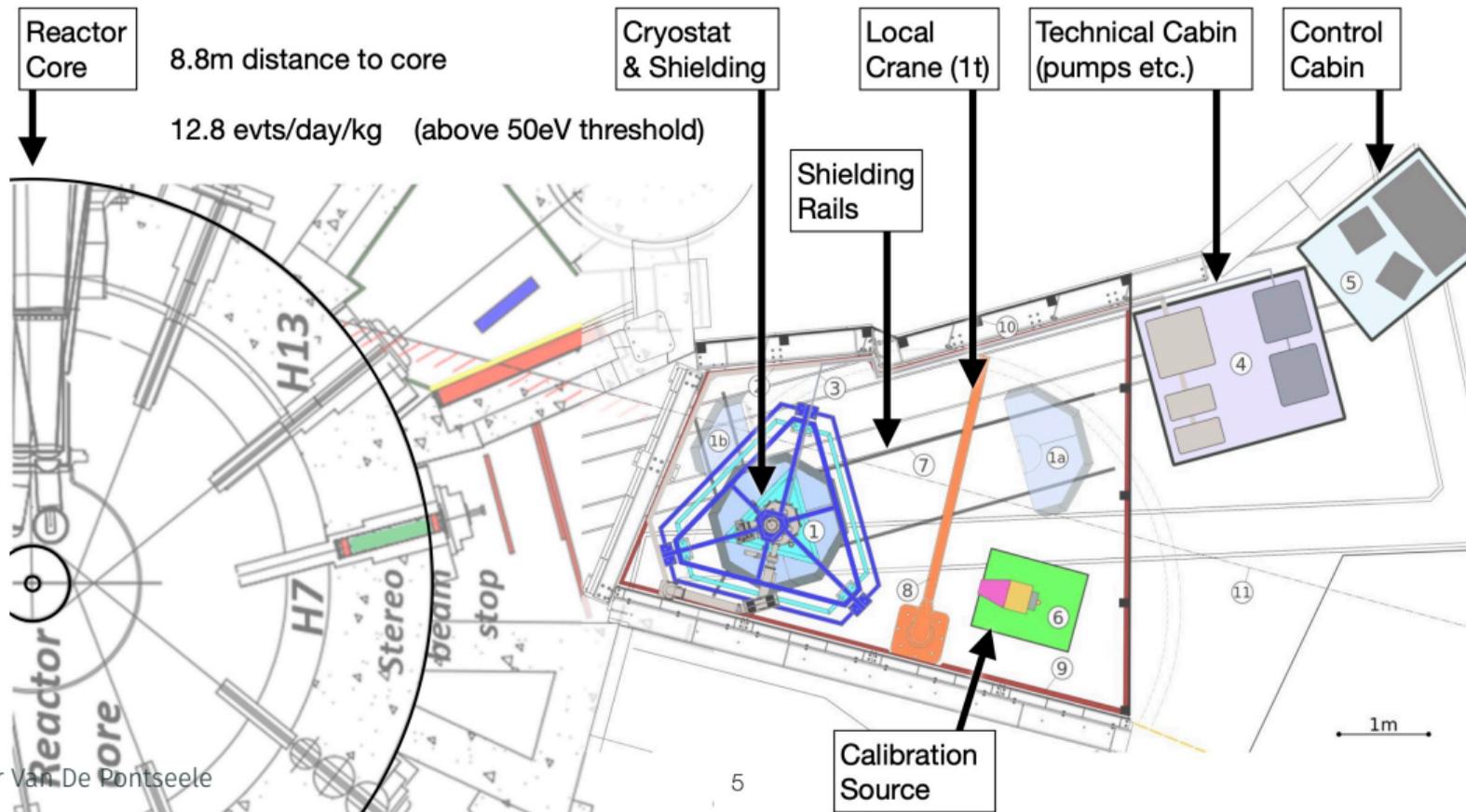


Thank you!

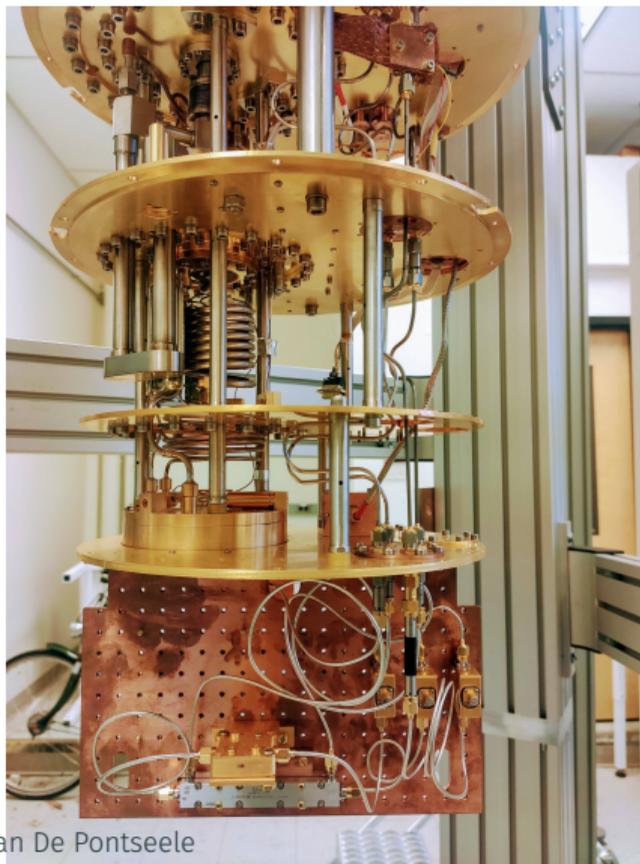
WVDP@MIT.EDU

Special thanks to  
RICOCHET, Lincoln Laboratories & SLAC

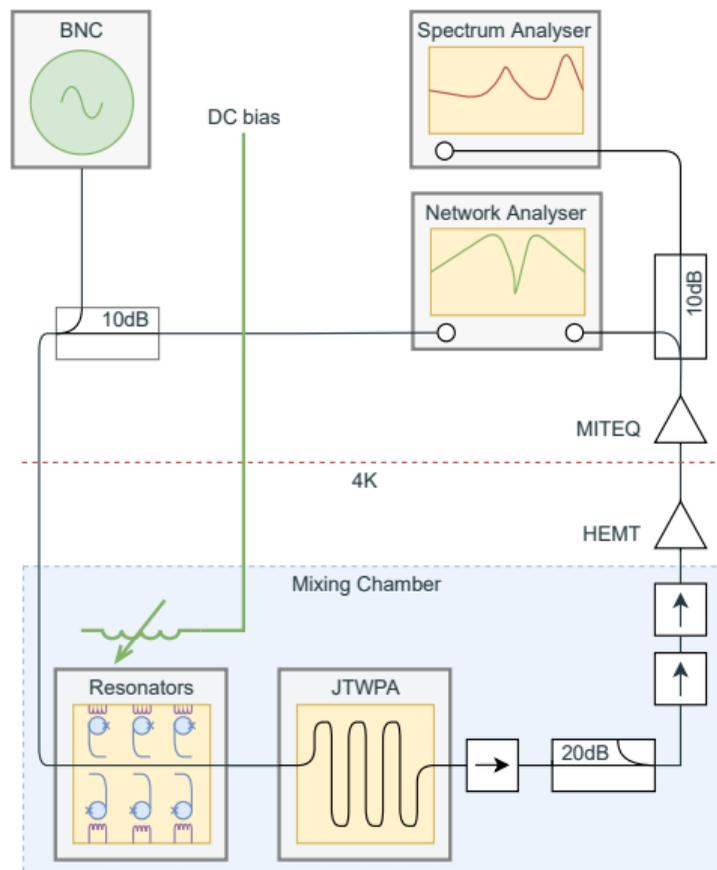
# THE RICOCHET EXPERIMENT @ ILL REACTOR IN FRANCE



# SIMPLIFIED MEASUREMENT SETUP AT MIT



Wouter Van De Pontseele



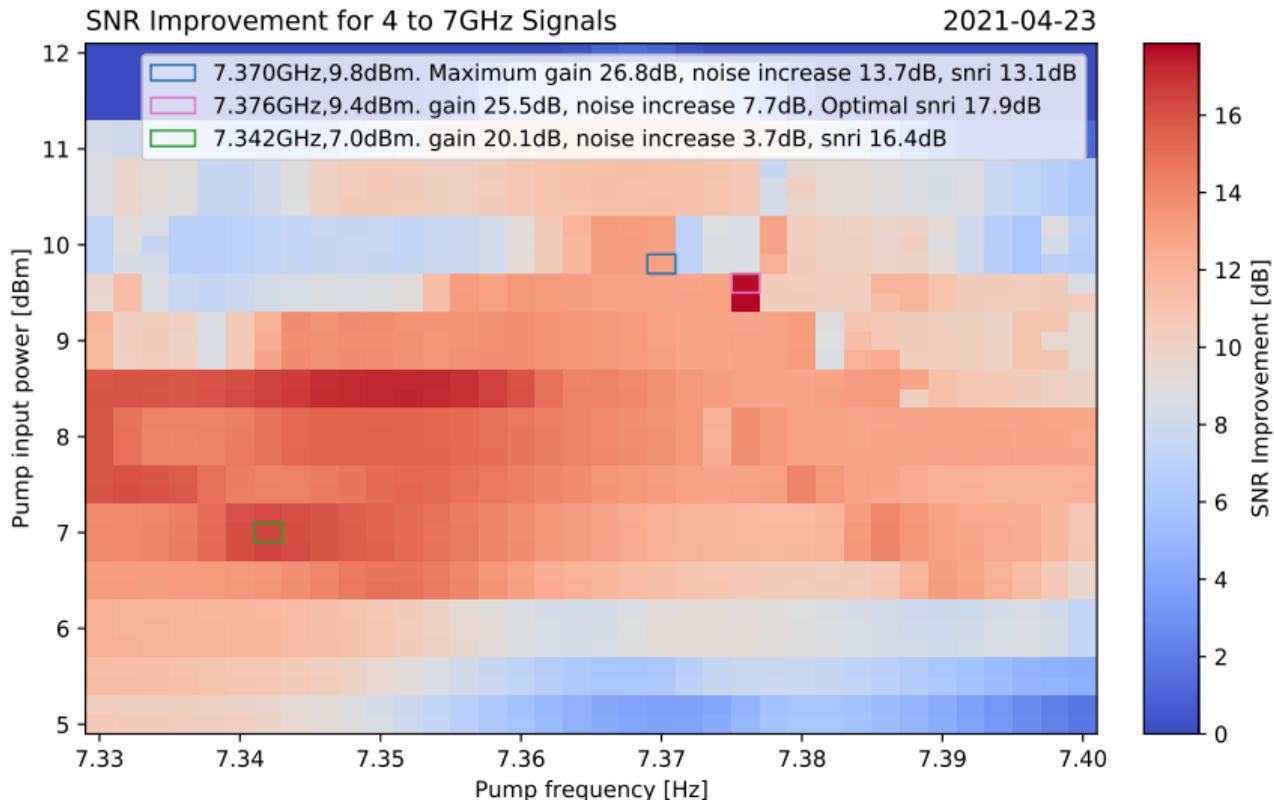
# TRAVELLING WAVE PARAMETRIC AMPLIFIERS: SIGNAL TO NOISE RATIO IMPROVEMENT

## Quantum amplifier

between RF multiplexer and HEMT increases the **SNR**.

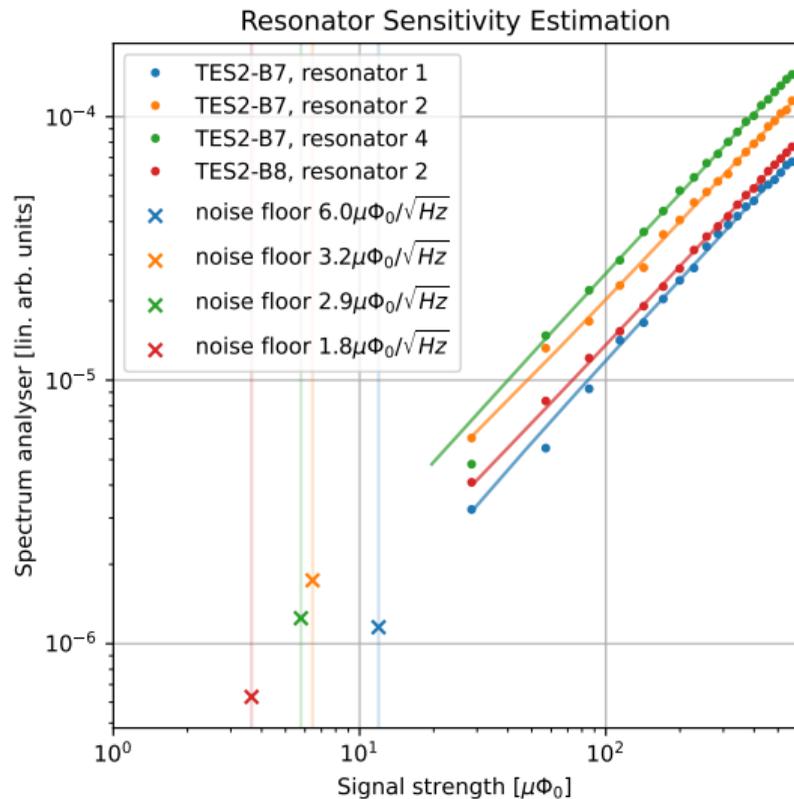
$SNRI[dB] =$

$$Gain(TWPA)[dB] - \text{noise increase}[dB]$$



# SMALL SIGNAL SENSITIVITY

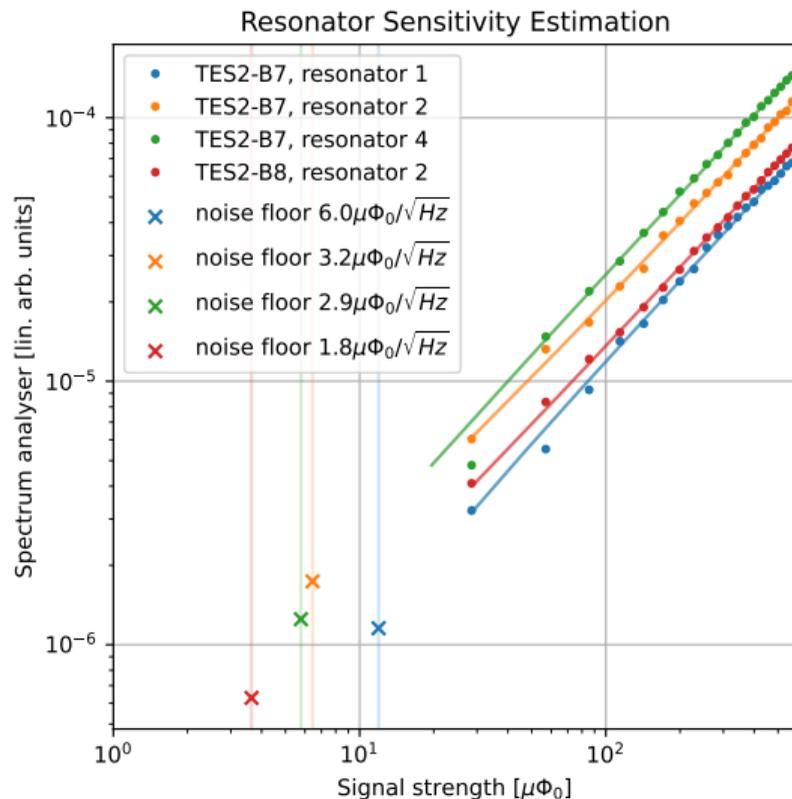
- Calibrate the signal in RFSQUID flux  $\Phi_0$ .
- Vary the signal strength.



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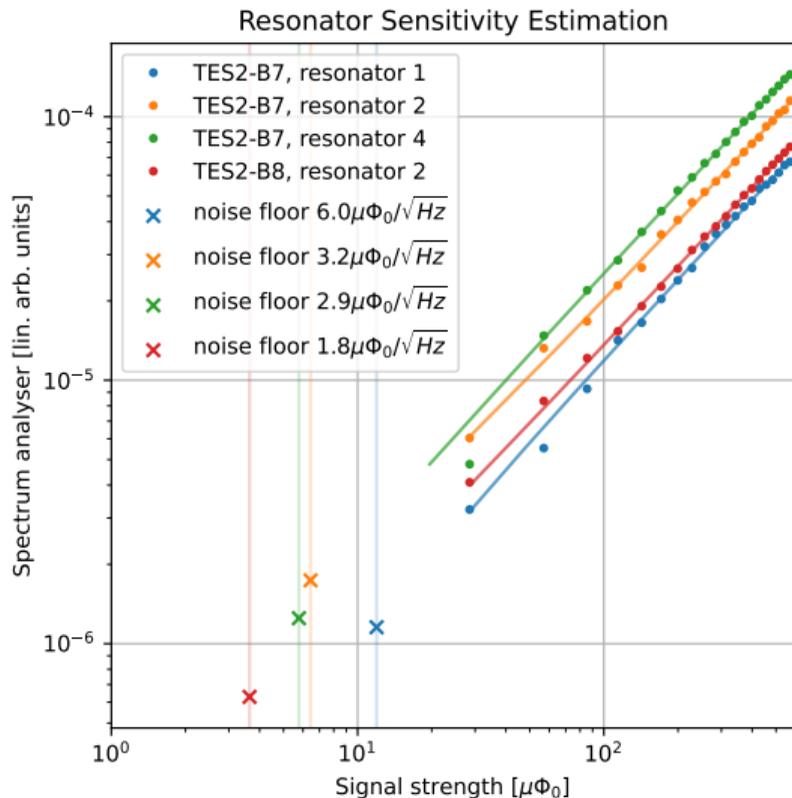
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- Vary the signal strength.
- Get the signal amplitude from PSD.
- Get the noise without signal from PSD.

todo



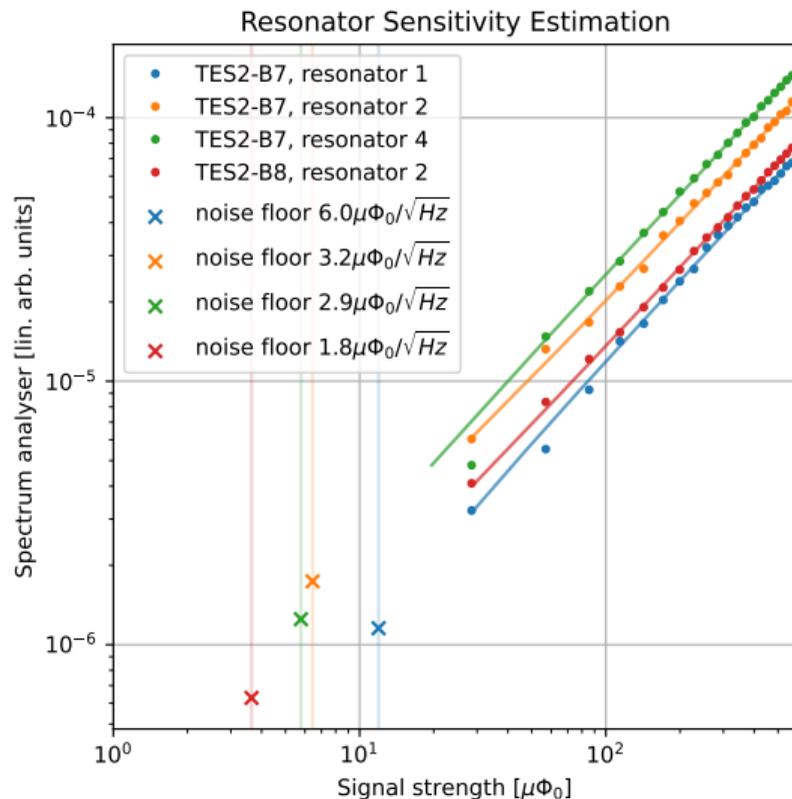
## SMALL SIGNAL SENSITIVITY

- Calibrate the signal in RFSQUID flux  $\Phi_0$ .
- Vary the signal strength.
- Get the signal amplitude from PSD.
- Get the noise without signal from PSD.
- Fit the signal strength to obtain a sensitivity given the small signal frequency. (24 kHz shown here).



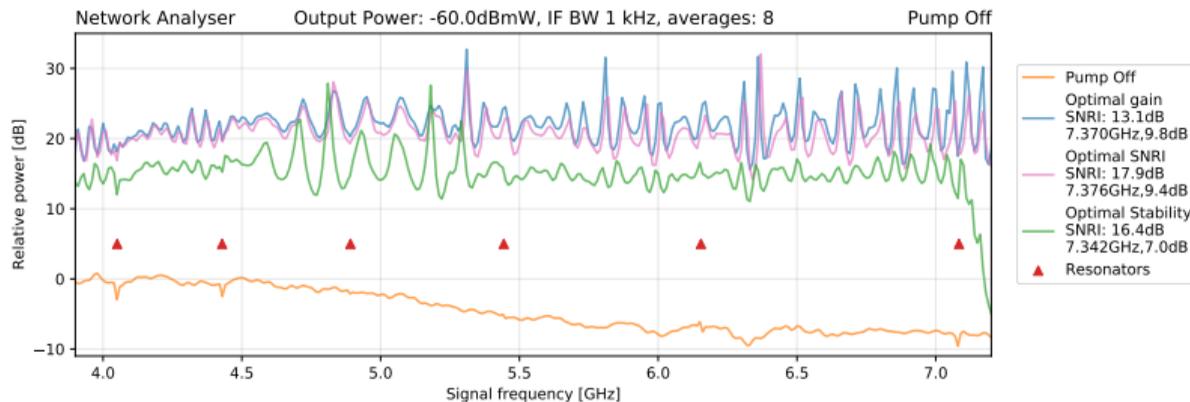
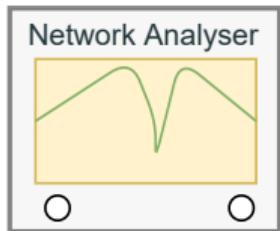
Similar in performance compared to the DCSQUID readout scheme or better at low frequencies.

Currently investigating the excess noise above design simulation of  $\approx 0.5 \mu\phi_0/\sqrt{\text{Hz}}$ .



# TRAVELLING WAVE PARAMETRIC AMPLIFIERS: PRELIMINARY GAIN PROFILE

Gain:



Amplifier **ready for deployment** if carefully calibrated.

**Gain** above 20 dB with a Signal-to-Noise Ratio Improvement (SNRI) above 15 dB in a 3 GHz bandwidth.

## Shower Evolution

The simple timing picture above is not the full story, since quasi-particles and phonons "mix" during the cascade process.

Athermal phonons can break Cooper pairs (up to the pair breaking energy) and quasi-particles likewise can create athermal phonons.

For ballistic quasiparticles and phonons, time scales governed by propagation velocity.

