Microwave Multiplexed Readout of Transition Edge Sensors for Neutrino Detection

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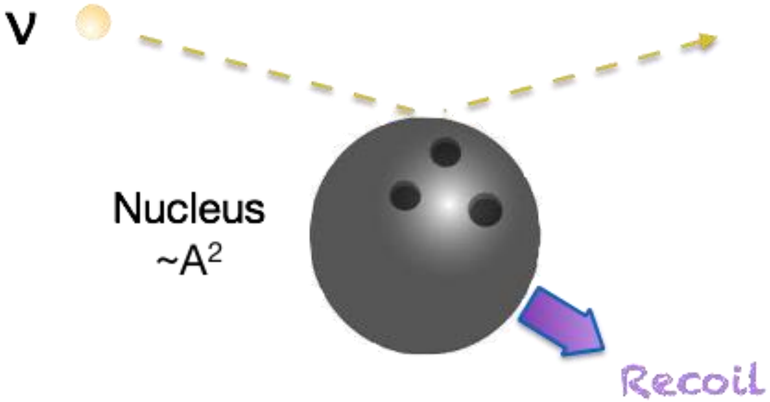
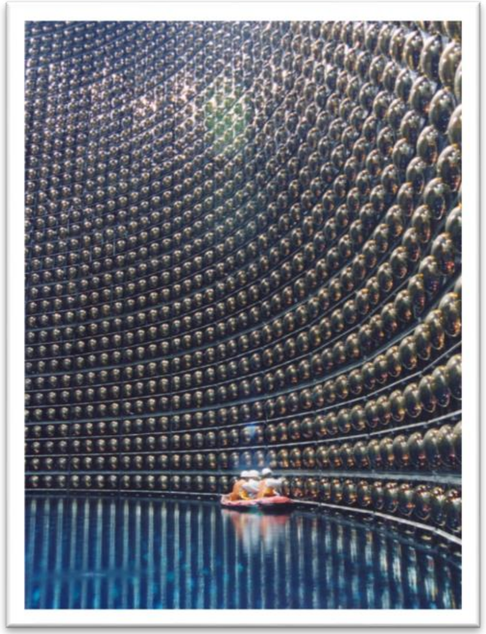
Background

Coherent elastic neutrino-nucleus scattering

- **A new process that achieves a huge increase in the probability for neutrinos to interact with matter**
  - **Significant reduction (10-100x) in required target mass**
  - **Technique recently demonstrated with high energy neutrinos from spallation source**





The Super-Kamiokande detector in Japan, which helped establish neutrino has a mass (a violation of the Standard Model).

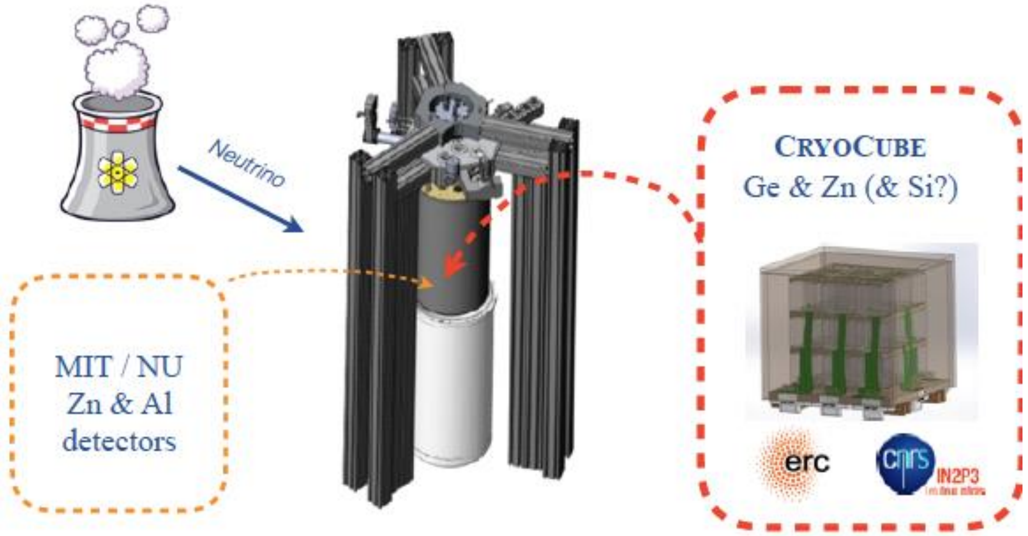
Target: 50 kilotons of water

16 kg NaI detector from COHERENT collaboration

Q-Array

Zinc Superconducting bolometers

Focus of US institutions



Cryocube

Germanium

Focus of French institutions

ERC funding secured

``The first low energy kg-scale CEvNS neutrino observatory combining different targets and different bolometric technologies"

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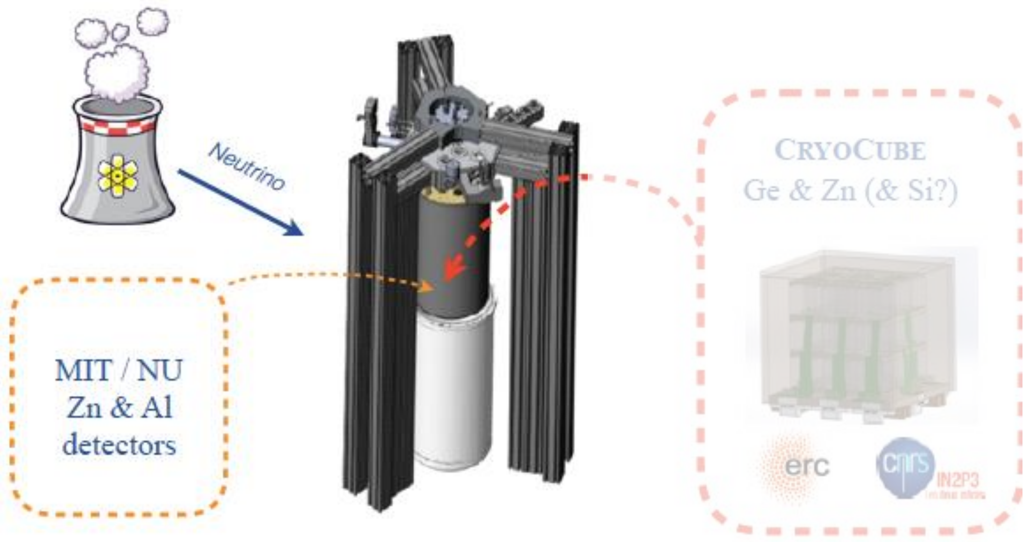

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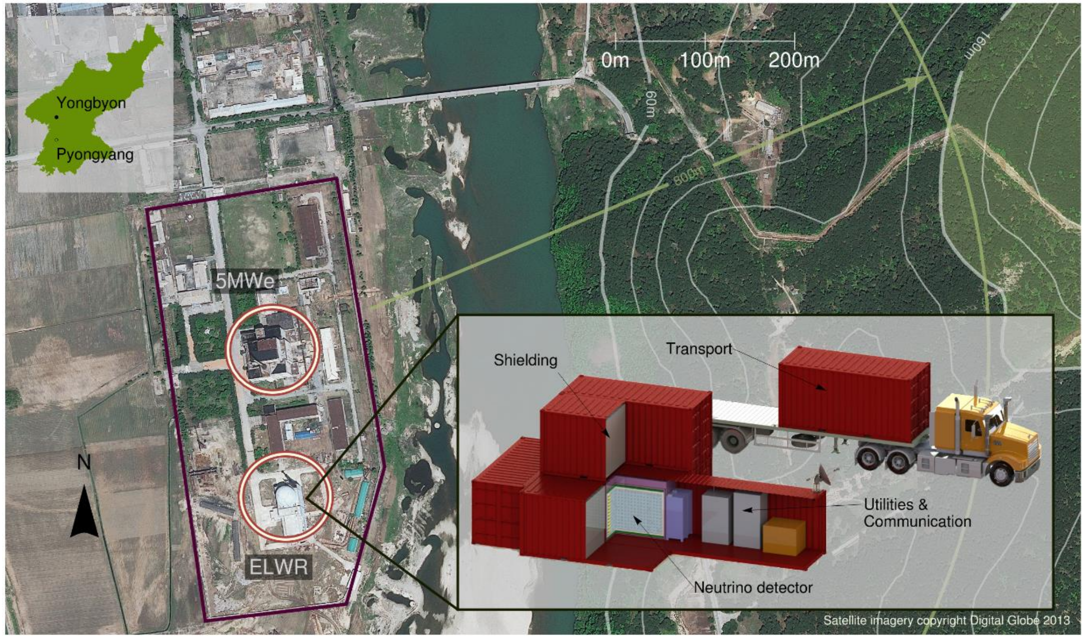
Goal and Motivation

Overall goal: Detect neutrinos from a nuclear reactor using coherent scattering

Motivation

- **Compact remote sensor of reactor neutrinos**
- **Basic science applications: sterile neutrinos, dark matter detection, searching for new forces**
- **Applications to national security: nuclear monitoring, ISR**

Nuclear monitoring concept for conventional neutrino detectors



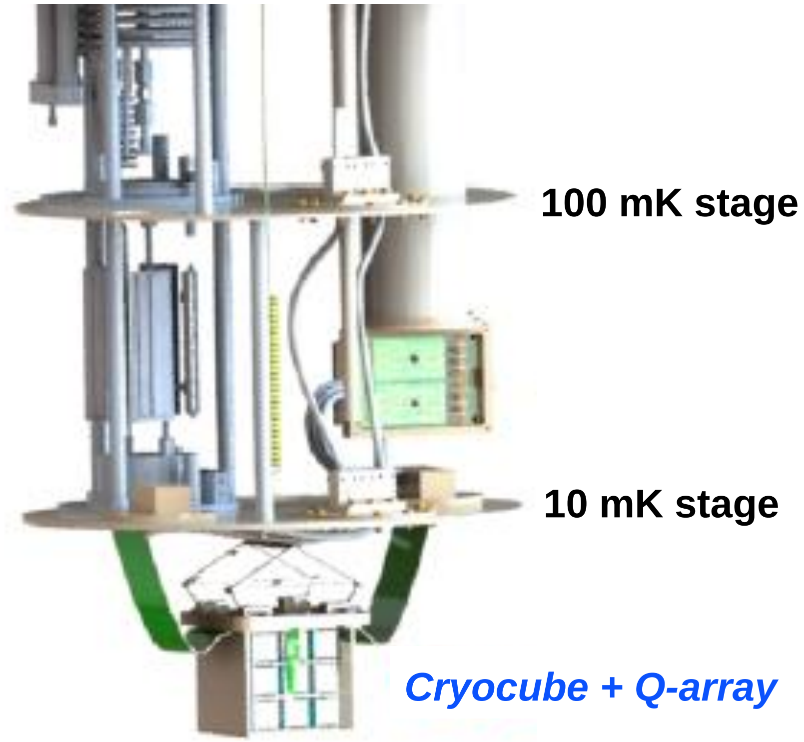
R. Carr et al, arXiv (2018)

Technical approach

Overall goal: Detect neutrinos from a nuclear reactor using coherent scattering

- **Technical challenge: Recoil energy from a nuclear reactor neutrino is 100x smaller than that from a spallation neutron source**
  - **Low energy thresholds are required (< 100 eV)**
  - **Requires better background rejection**

- **Proposed solution: Use an array of superconducting target material with highly sensitive amplifiers**
  - **Small target size lowers the heat capacity; increases sensitivity to small ΔT**
  - **An *array* of these detectors increases the target mass to interact with neutrinos**
  - **Background rates distinguished by time-response in superconductors**

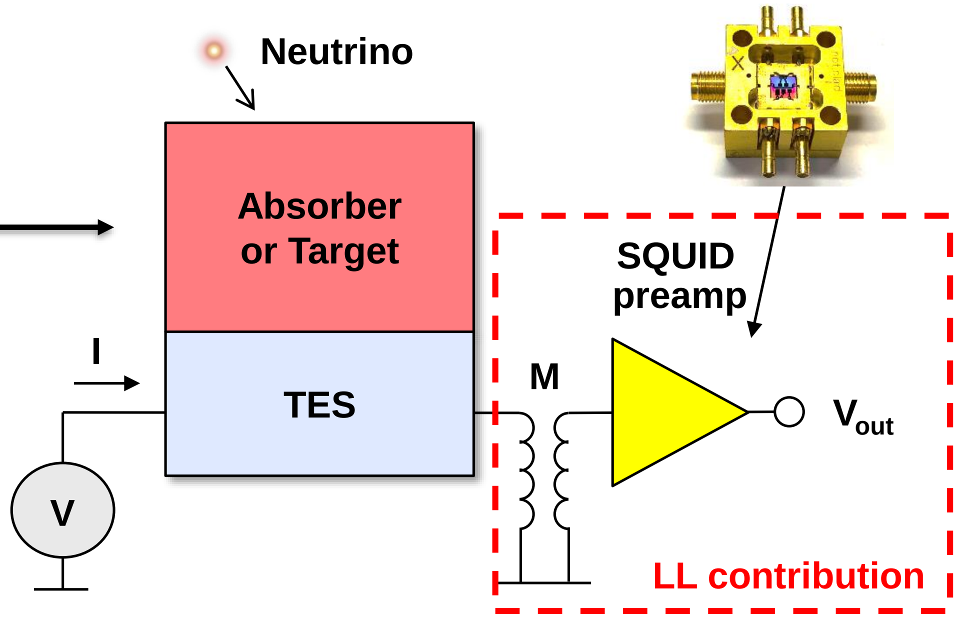


Ricochet Prototype Detector

Cryogenic Bolometer
(Transition Edge Sensor)

A 30-gram Zn detector prototype

Bolometer Schematic



Neutrino

Absorber or Target

TES

I

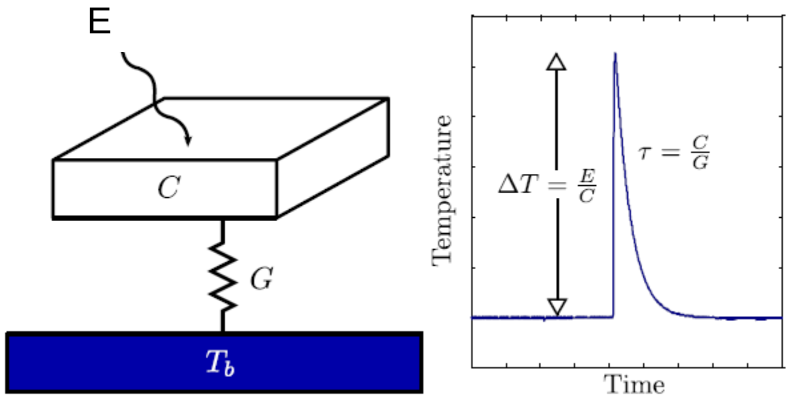
V

M

SQUID preamp

V_{out}

LL contribution



$$\Delta E \approx 2.35\sqrt{k_B T^2 C}$$

Lincoln Lab is building arrays of highly-sensitive superconducting amplifiers to enable the first detection of reactor neutrinos via coherent neutrino scattering

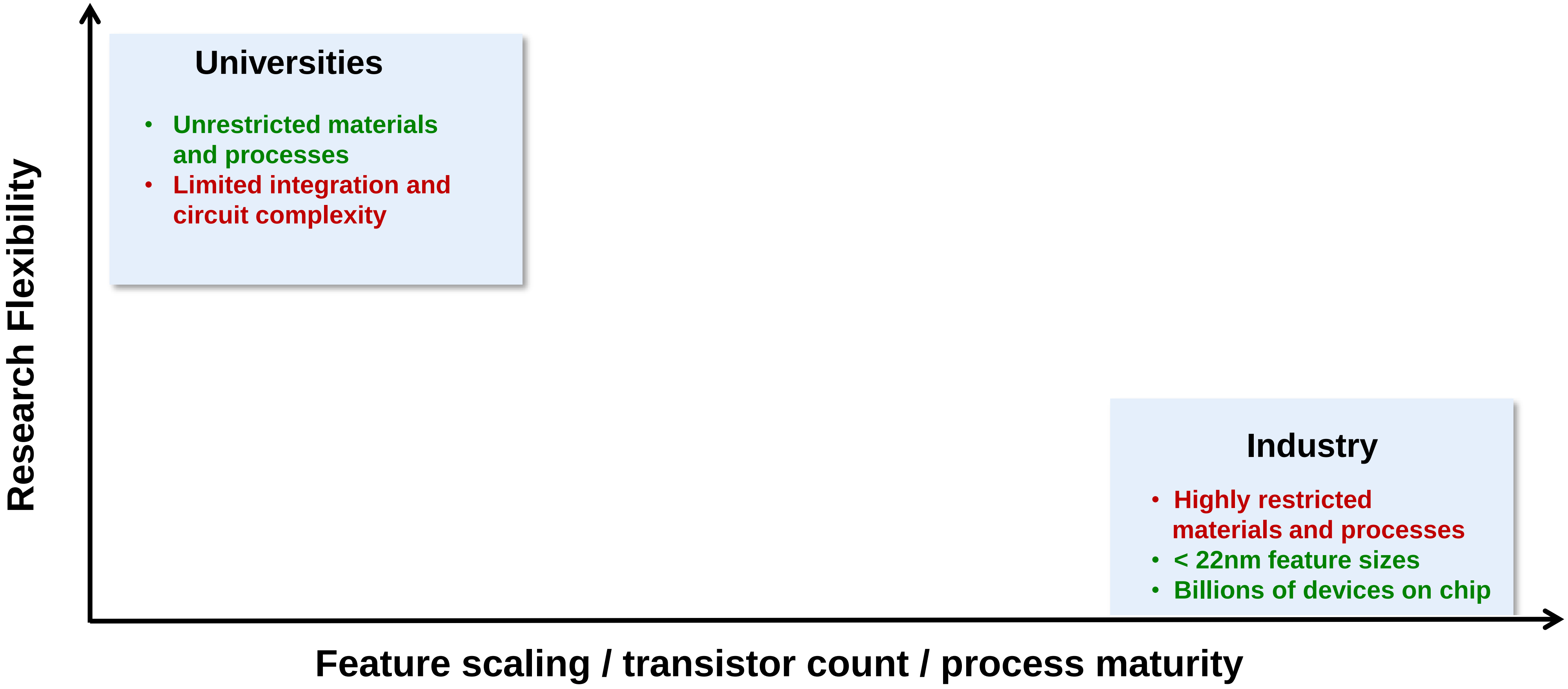
Outline

- Ricochet background
- MIT Lincoln Laboratory capabilities
- Superconducting amplifiers for Ricochet

MIT-LL Microelectronics Laboratory

- 70,000 ft^2 facility: 8100 ft^2 class 10 & 10,000 ft^2 class 100
- DoD trusted foundry
- 90-nm CMOS toolset
- Dedicated tools for planarized multilayer Nb process
- State-of-art 3D integration capabilities

Microelectronics Laboratory's Position in the Silicon Fabrication Community



Research Flexibility

Universities

- Unrestricted materials and processes
- Limited integration and circuit complexity

Industry

- Highly restricted materials and processes
- < 22nm feature sizes
- Billions of devices on chip

Feature scaling / transistor count / process maturity

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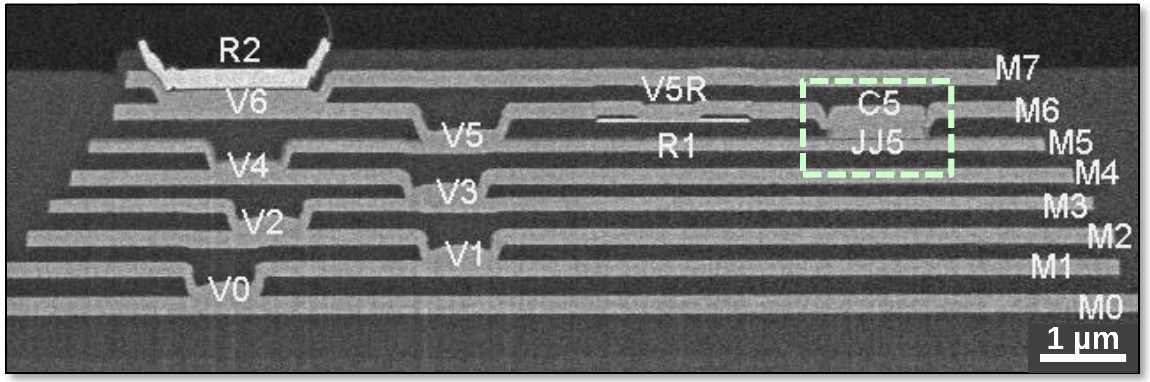
Microelectronics Laboratory is the most advanced Si-based fab facility in the country dedicated to supporting the research and development needs of the Government

Superconducting Fabrication Processes at MIT-LL

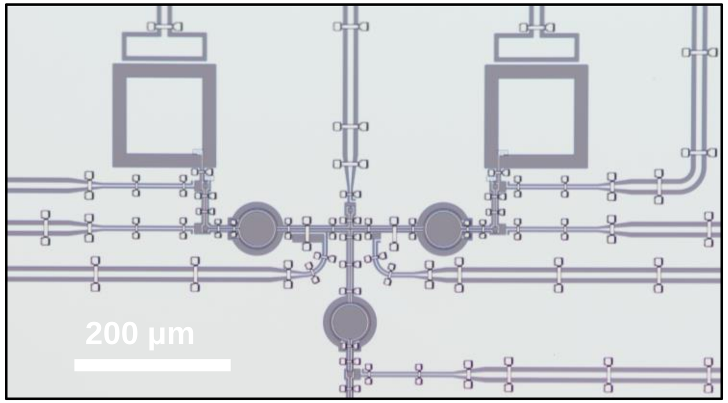
Multi-layer Niobium process

- **World's most advanced single-flux-quantum (SFQ) integrated circuit process**
- **Up to 10 fully-planarized Nb layers**
- **SFQ circuits with ~1 million Josephson junctions demonstrated**
- **Also used for Traveling Wave Parametric Amplifiers**

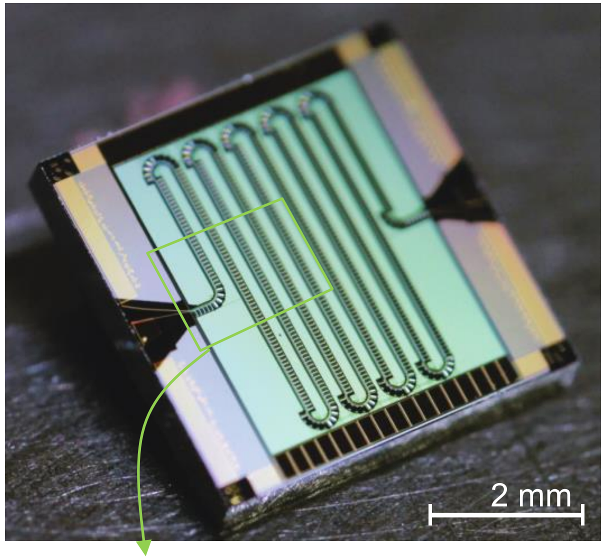


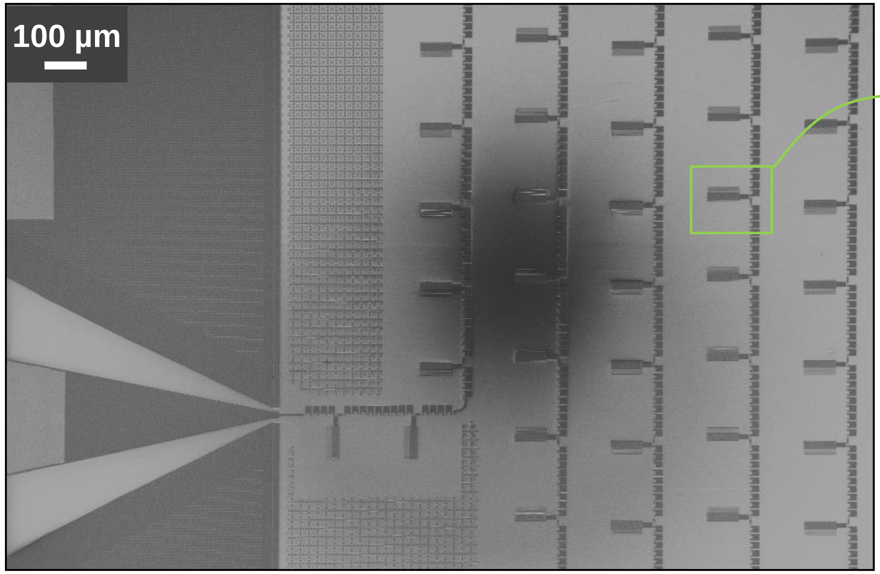
High-Q Aluminum process

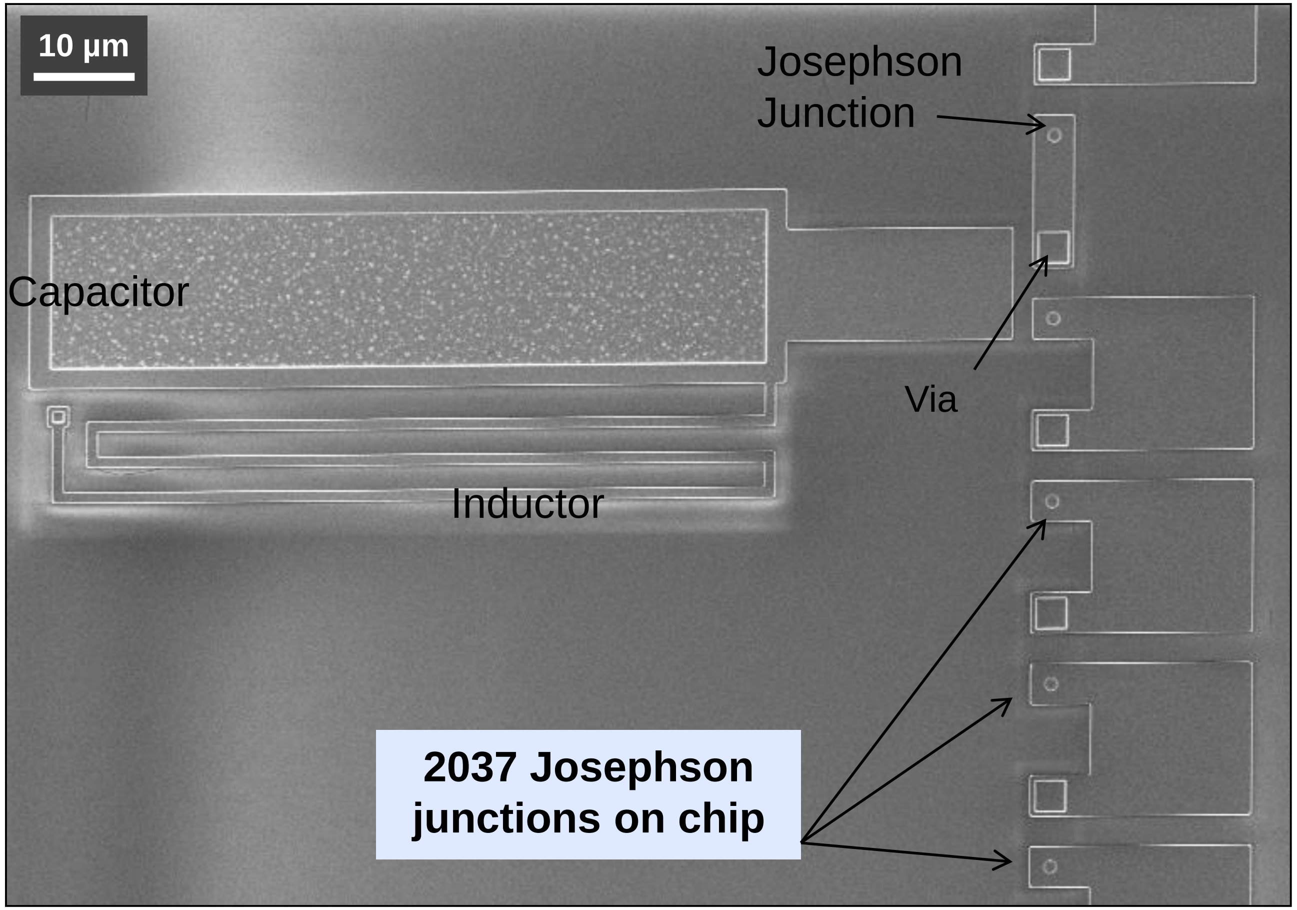
- **Single-layer aluminum process with robust air-bridge crossovers**
- **Resonator quality factors ~1 million at single-photon excitation**
- **Fast turn-around and low cost– ideal for prototyping**
- **Used for high-coherence superconducting qubits**



Traveling Wave Parametric Amplifiers







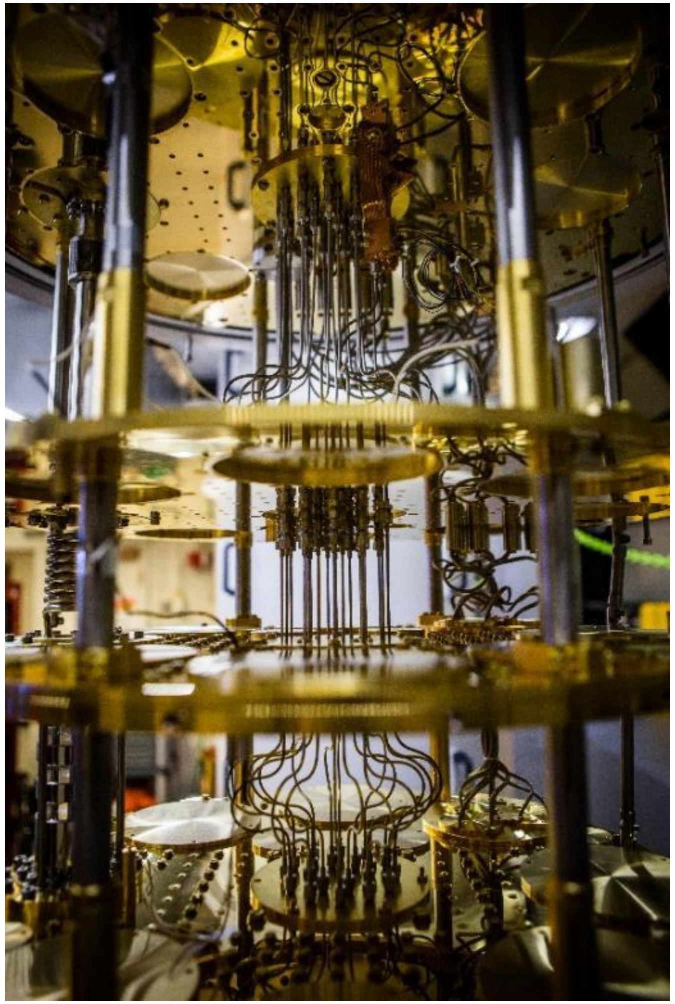
2037 Josephson junctions on chip

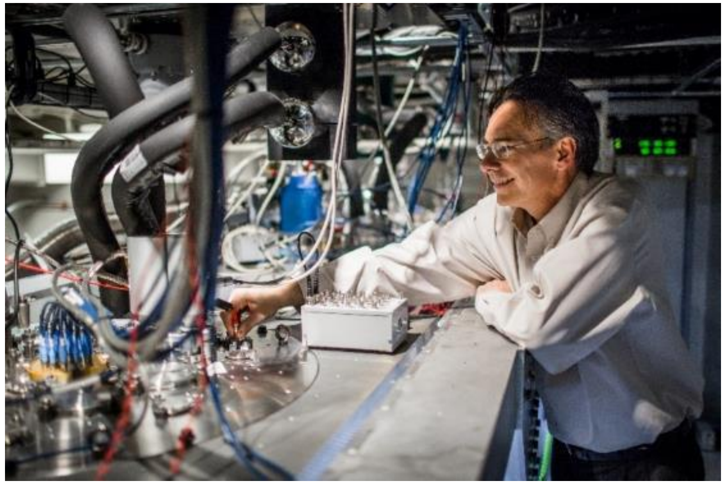
Demonstrated TWPAs with > 20 dB gain over 4.25-8.75 GHz band

K. O’Brien et al., PRL 113, 157001 (2014), C. Macklin et al., Science 350, 307 (2015)

Cryogenic Testing at Lincoln Laboratory

- **Testing of SQUID amplifiers leverages room temperature electronics for qubit readout at MIT/LL**
  - **Multiple delusion refrigerators at 15 mK**
  - **Supporting electronics**
    - **Arbitrary waveform generators**
    - **Network analyzers**
    - **Low noise bias signal generators**
    - **Cryogenic HEMTs**
    - **Traveling-wave parameter amplifiers (TWPAs)**





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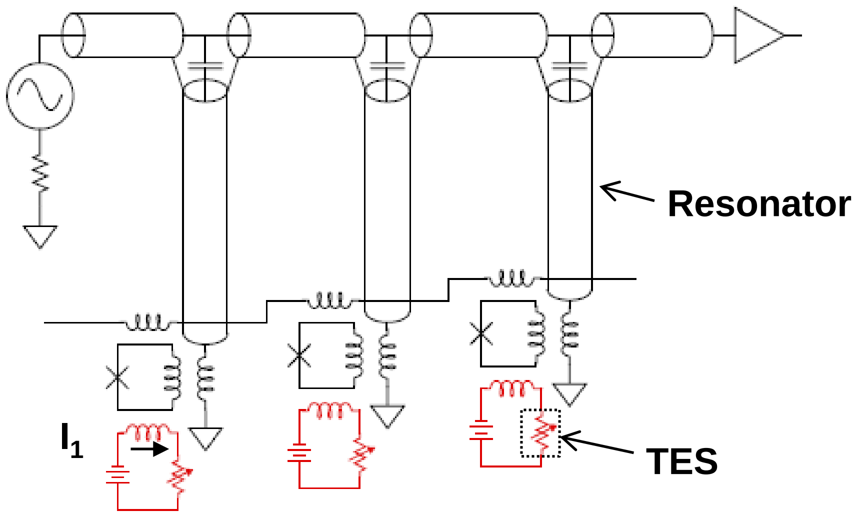
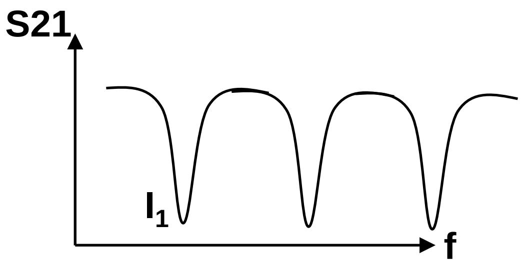
- ⇨ Superconducting amplifiers for Ricochet

SQUID Amplifier Arrays for TES Readout

- Traditionally SQUID amplifiers are used to boost signal above the noise temperature of cryogenic HEMTs (T_N ~ 4 K)
- *Microwave frequency multiplexing* enables high density arrays with limited control lines
- Similar to the method utilized for qubit readout at Lincoln
- 128 TES readout demonstrated on the NIST SLEDGEHAMMER gamma-ray spectrometer
  - Current noise: 19 pA/$\sqrt{\text{Hz}}$

uMux Schematic





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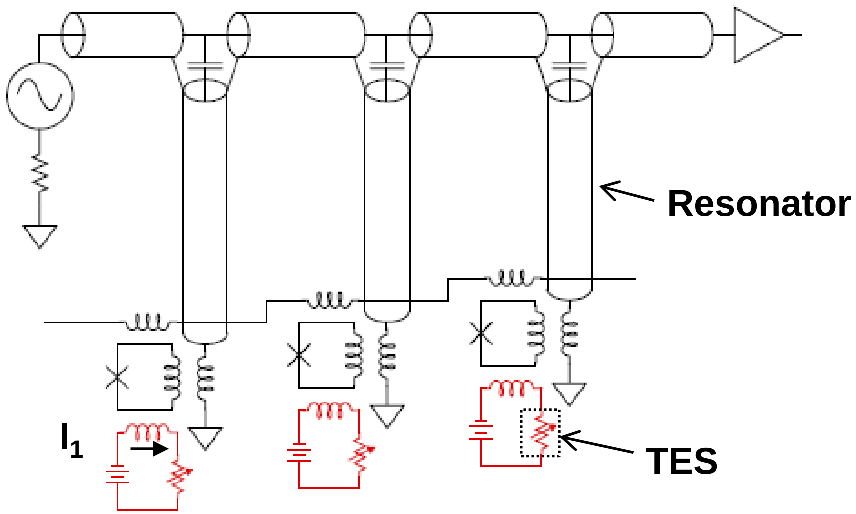
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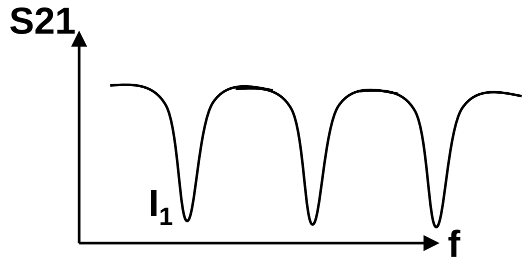

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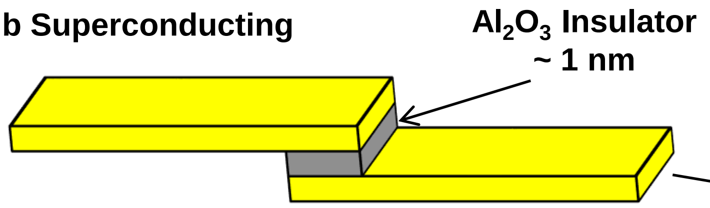
Josephson Junction



$$L = L_J sec(\phi)$$

$$\phi = 2\pi\Phi/\Phi_0$$

Φ_0= 1 flux quanta = 2x10^{-15} Wb

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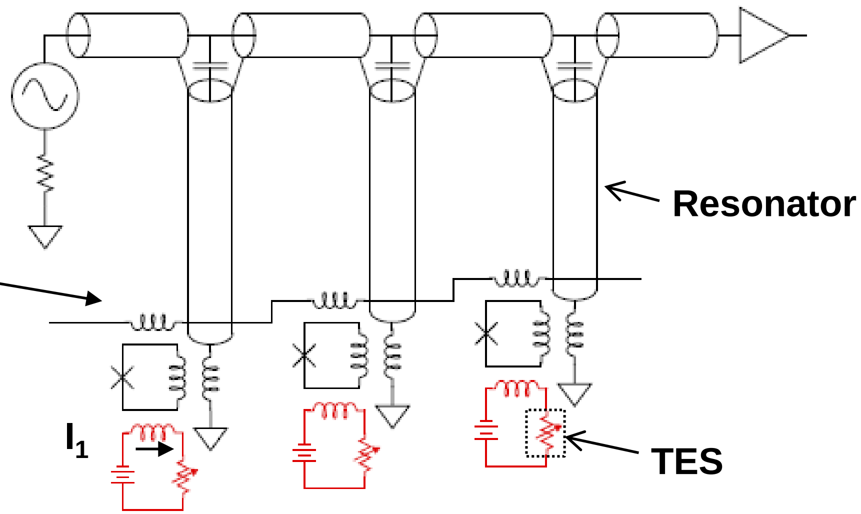

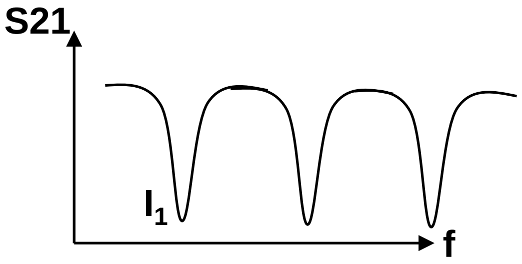

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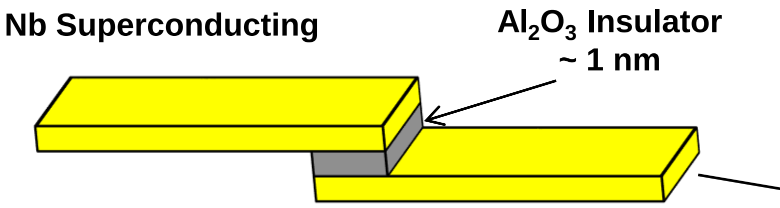

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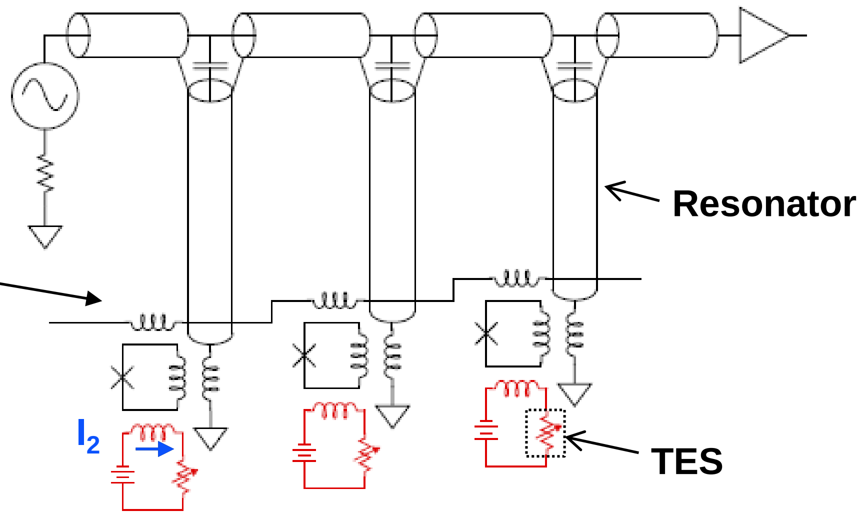
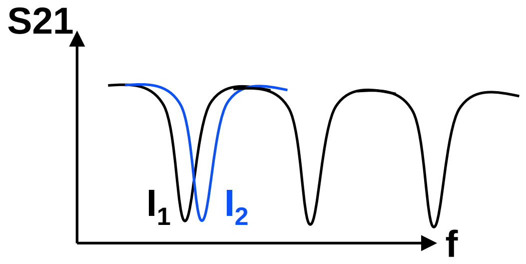
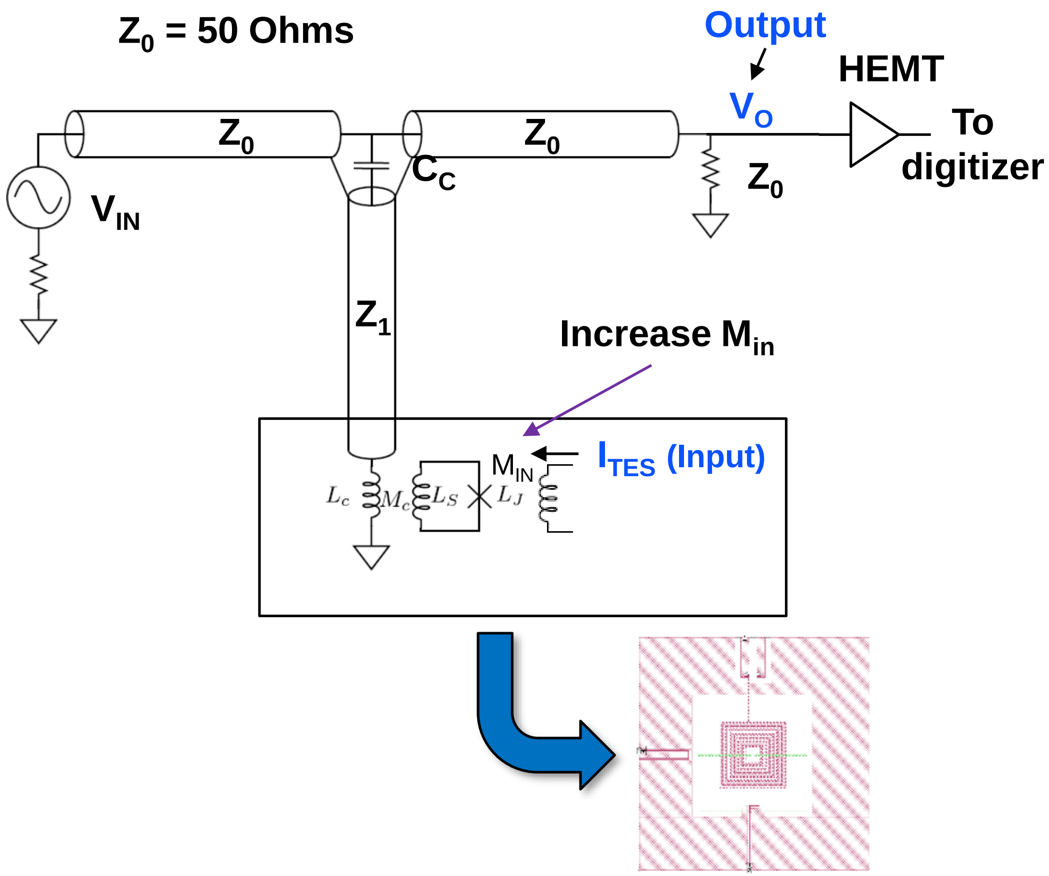




SQUID Amplifier Design: Gain Analysis



- $$\frac{dV_O}{dI_{TES}} = V_{IN}\frac{d\Phi}{dI_{TES}}\frac{dL}{d\Phi}\frac{dw_0}{dL}\frac{dS_{21}}{dw_0}$$ Gain

- $$\boxed{\frac{d\Phi}{dI_{TES}} = M_{IN}}$$

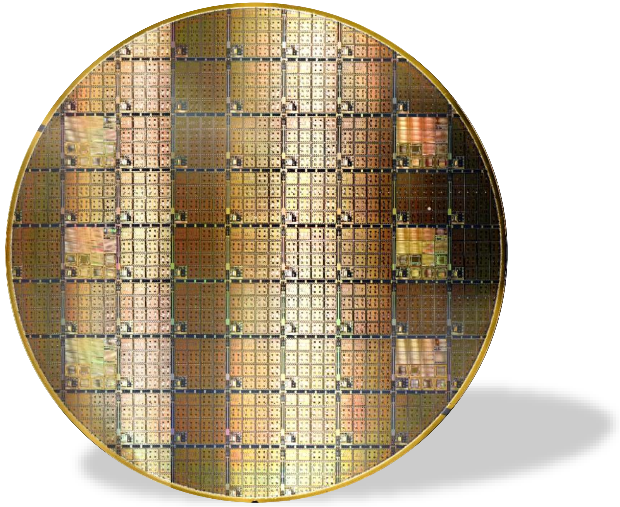
- **Need to increase gain to improve sensitivity**
- **Additional requirements:**
  - **High quality factors in waveguides**
  - **Good resonator frequency control**
  - **Good yield**

Mates, APL 111, 062601 (2017)

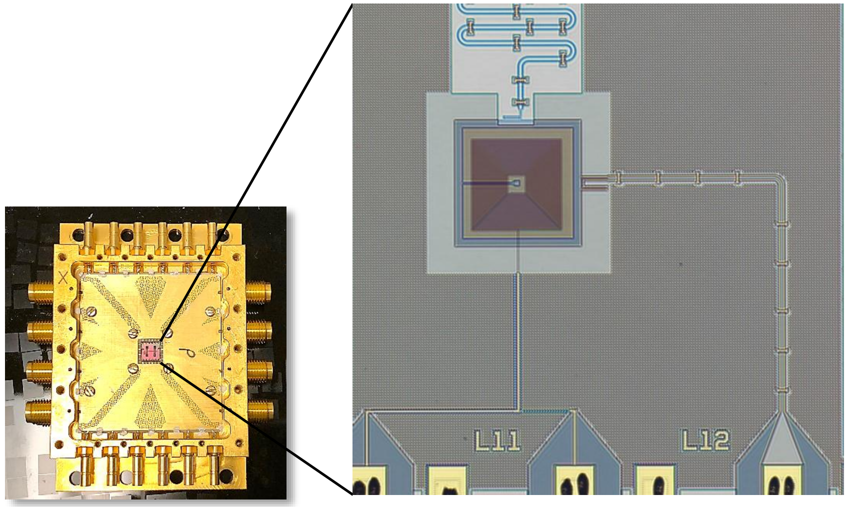
Initial demonstration of scalable amplifiers

- **Demonstrated scalable superconducting SQUID amplifiers (singles) for bolometric neutrino detection**
  - **Microwave multiplexed design**
  - **High Q resonators that can be densely multiplexed**
  - **High pattern fidelity with reproducible resonator frequency**

Wafer fabricated using LL multi-layer Nb process



Superconducting amplifier prototype



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- **Next step: improve amplifier design to enable detection of 100 eV threshold events**
  - **Optimize design parameters for high gain**
  - **Incorporate Lincoln-fabricated Traveling Wave Parametric Amplifiers (TWPAs)**

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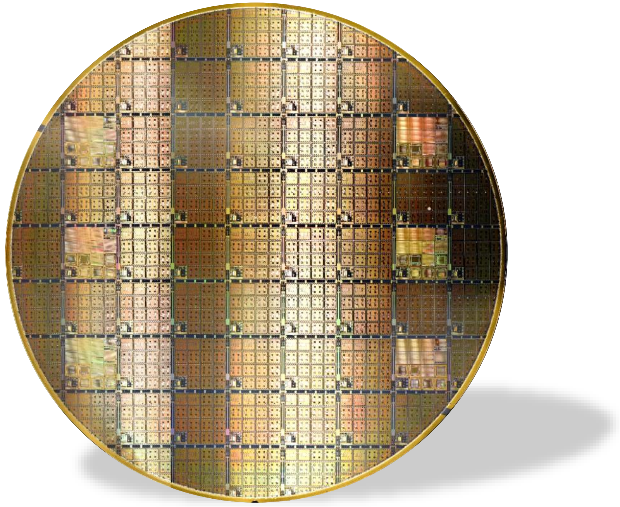

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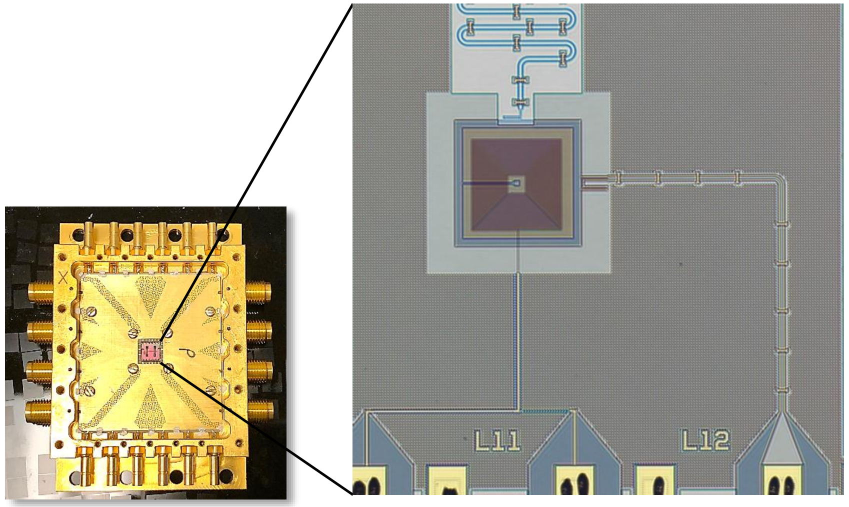
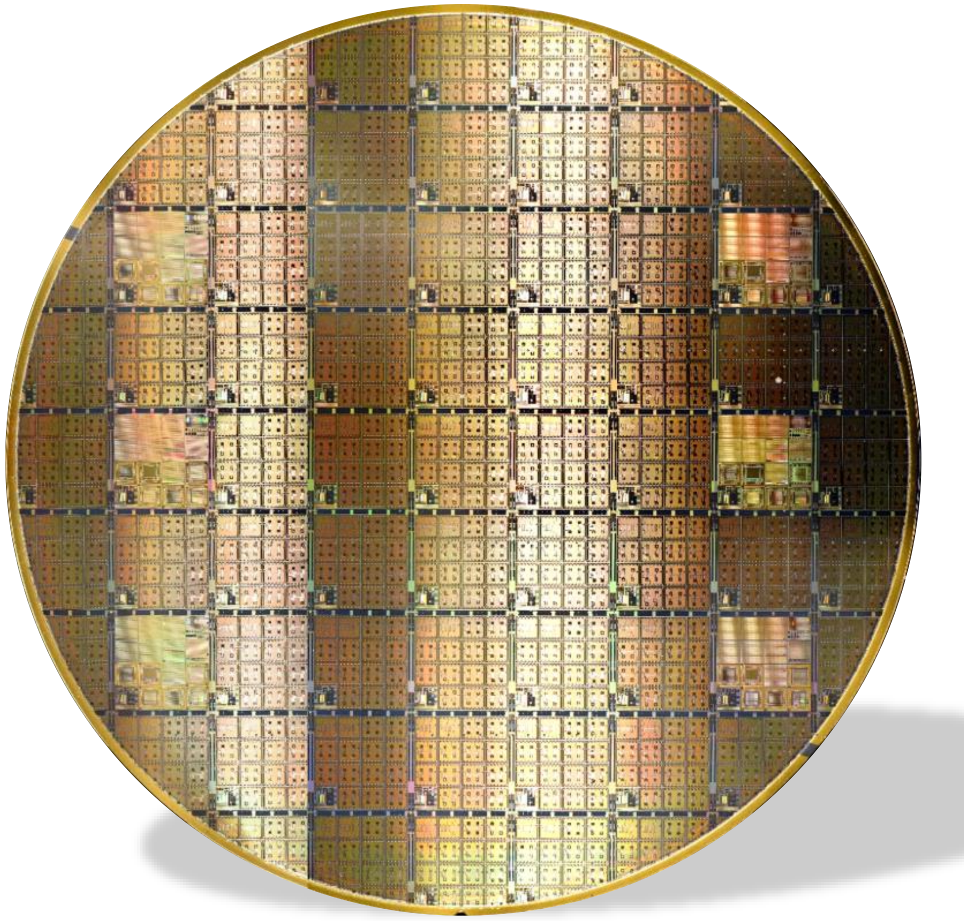


Summary

- MIT-LL is developing scalable superconducting SQUID amplifiers for bolometric neutrino detection
  - Microwave multiplexed design
  - High Q resonators that can be densely multiplexed
  - Optimizing amplifier parameters for high sensitivity
  - Leveraging TWPA technology

- Enabling ongoing Ricochet effort to do a first detection of reactor neutrino using the CEυNS process



RICOCHET