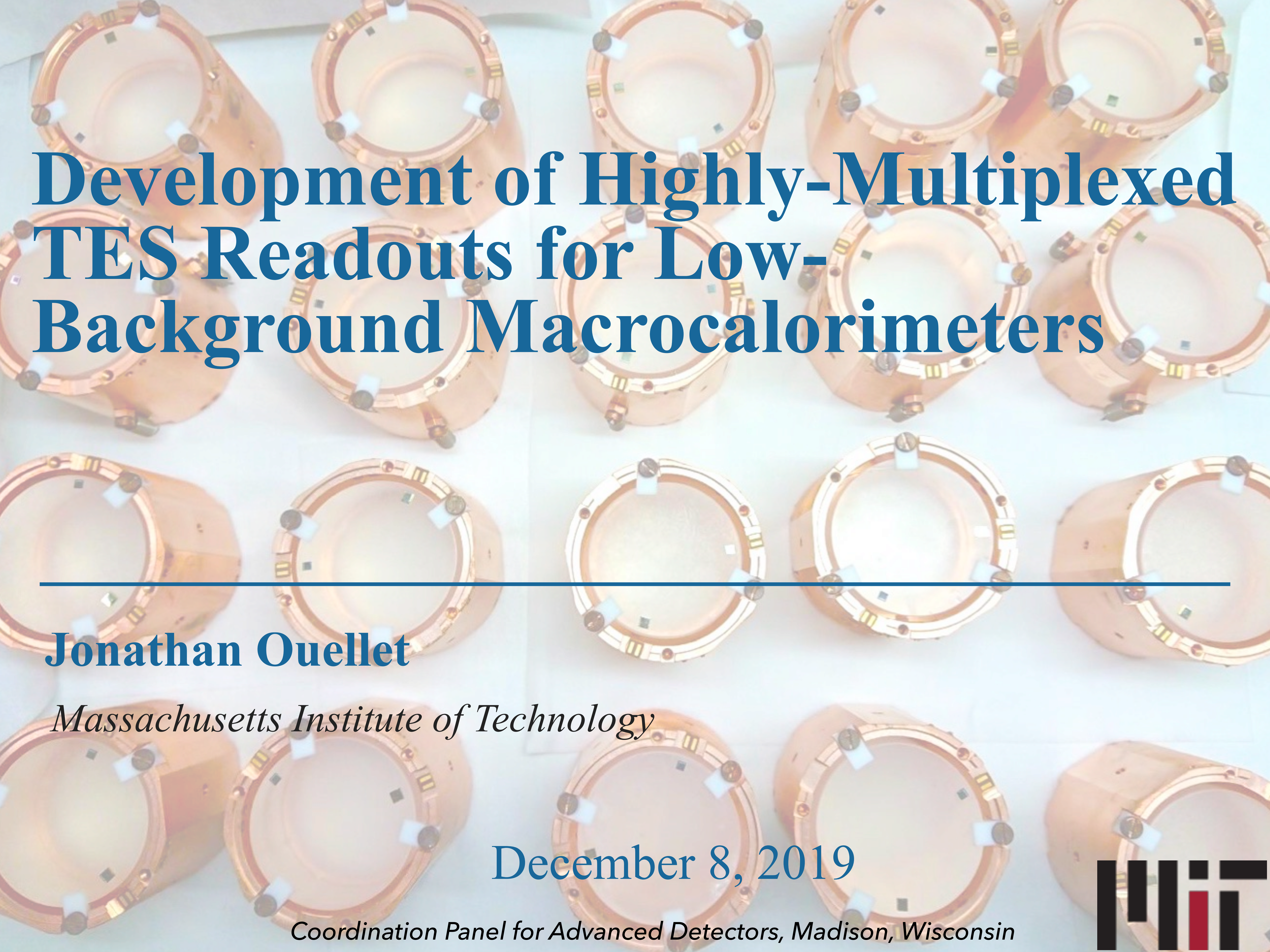


Development of Highly-Multiplexed TES Readouts for Low-Background Macrocalorimeters

Jonathan Ouellet

Massachusetts Institute of Technology

December 8, 2019

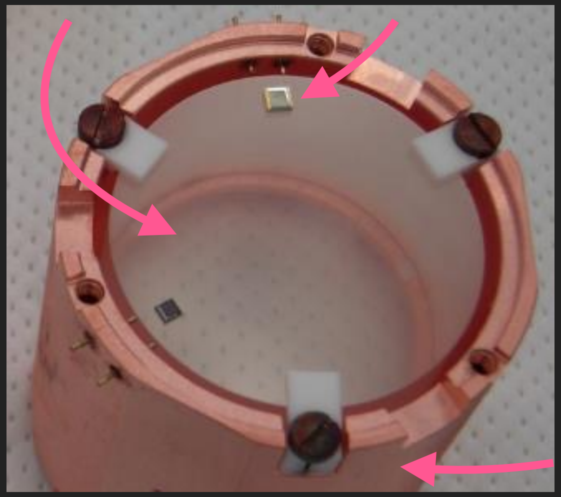
Coordination Panel for Advanced Detectors, Madison, Wisconsin

Thermal Detectors

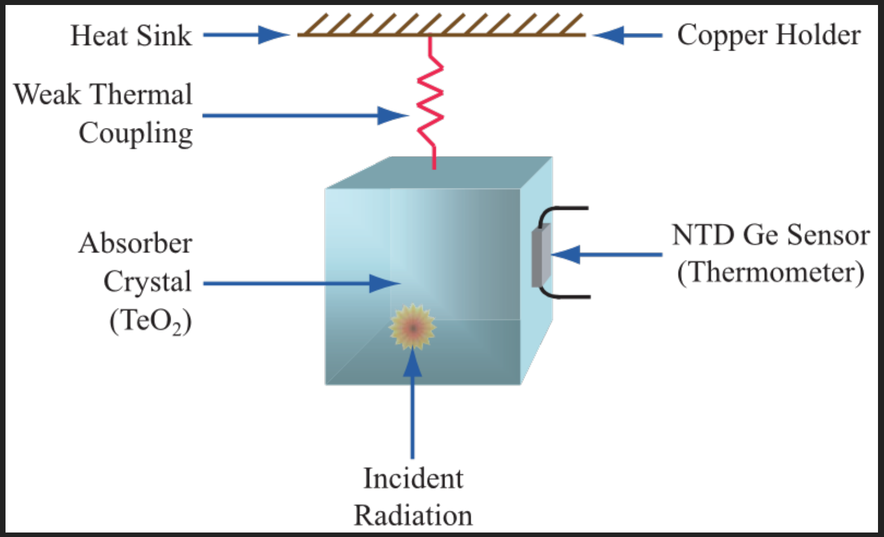
- Converts deposited energy into a change in temperature of the detector
  - Energy → Phonons → Phonon detection
- Consists of an absorber and thermometer
- Microcalorimeter → small mass absorbers (≲1 gram)
  - Bolometer arrays (cosmic microwave background)
  - Single photon counting (nano-bolometers)
  - Can be fabricated onto boards
- Macrocalorimeters → large mass absorbers (from grams - kilograms)
  - Large target mass (neutrino & dark matter), large isotope mass (β-decay, ββ-decay), etc
  - Typically measuring individual events
  - Instrumented individually

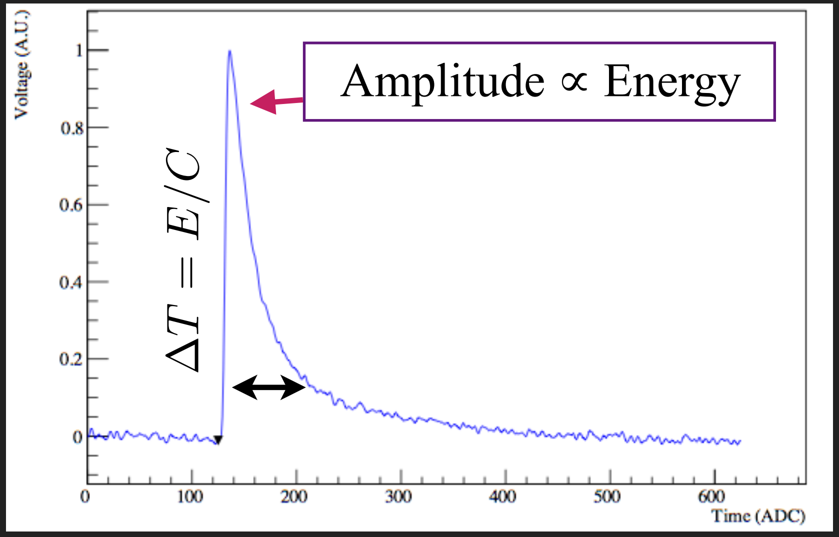
Crystal bolometer

Thermometer

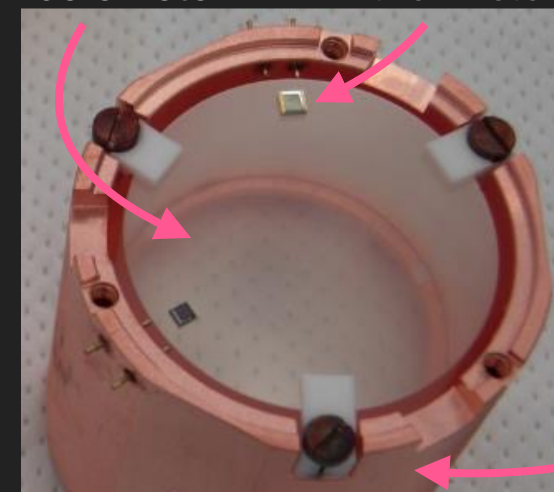


Thermal Bath 10 mK

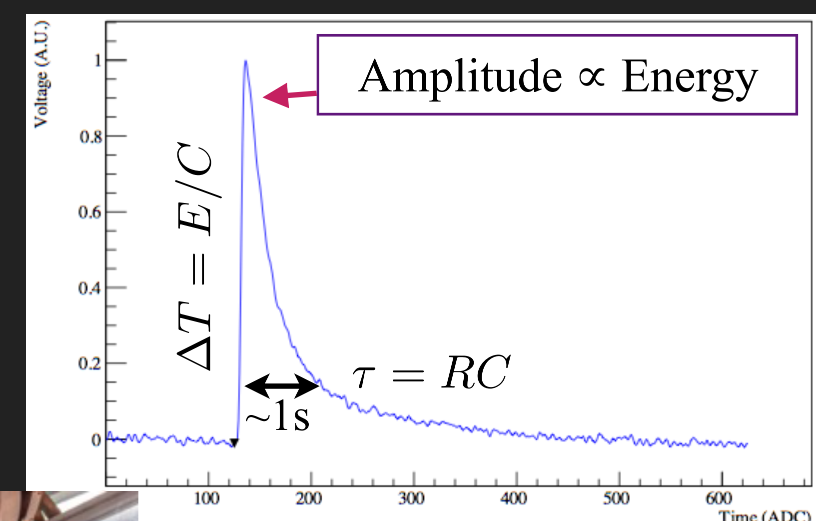


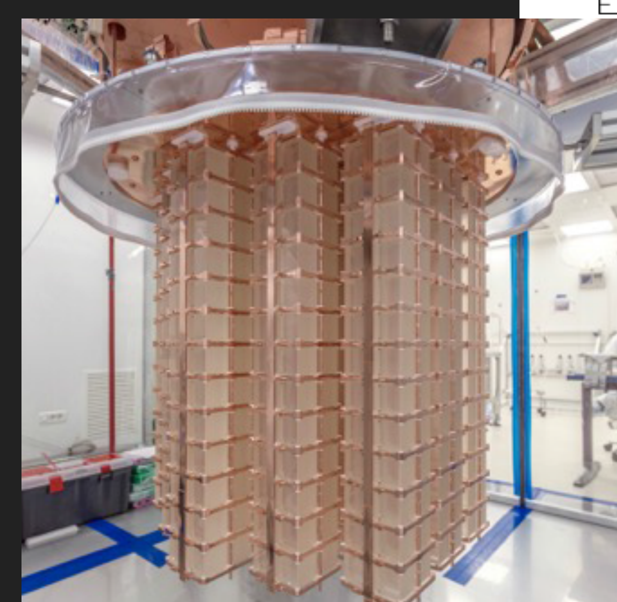


Macrocalorimeter Detectors



- Detectors are segmented
  - Position reconstruction, background identification, etc
- Excellent energy resolution → ~0.2% FWHM
- Excellent detection thresholds → < 1 keV_{ee} for DM
- Absorbers can be made from a variety of materials for a range of purposes
  - Mo, Te, Se → 0νββ
  - Ge, $CaWO_4$ → Dark Matter
  - Superconductors → CEvNS
- Easily scalable into large arrays. Current detectors operating ~ton scale detectors with 1000s of channels.

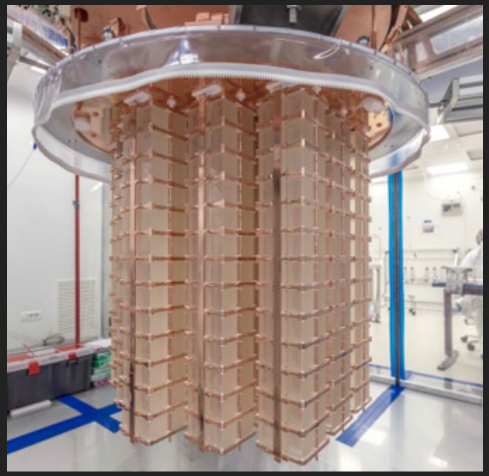


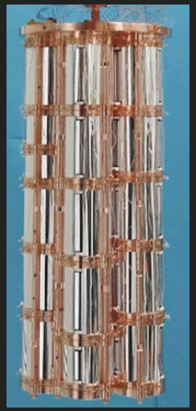


Neutrinoless Double Beta Decay (NP)

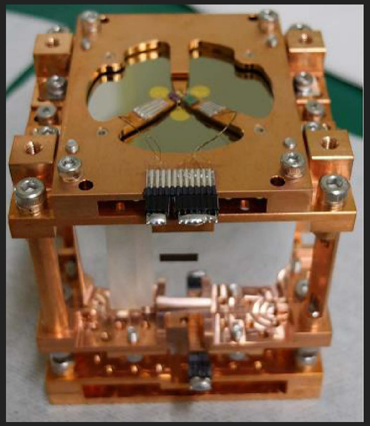
- Question of the Dirac/Majorana nature of the neutrino
  - Beyond the SM generation of neutrino mass (seesaw mechanism)
  - Demonstrates violation of lepton number and has implications for baryon asymmetry of the universe
- Listed as a priority in the 2015 DOE NSAC long range plan
  - CD-0 Mission Need for next-generation ton-scale $0\nu\beta\beta$ experiment
- Currently CUORE is the largest running macrocalorimeter experiment
  - O(1000) channels
  - Using ~GΩ NTDs with O(1000) readout channels
  - CUPID looking to instrument O(2000) readout channels

CUORE
Absorber: TeO_2
Thermometer: NTDs
Mass: 741 kg





CUPID-0 / CUPID-Mo
Absorber: $LiMoO_4$, ZnSe
Light Detector: Ge
Thermometer: NTDs
Mass: 5-10 kg

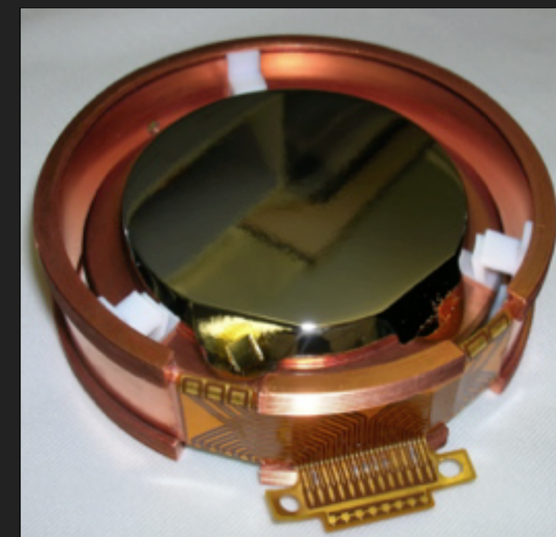


AMoRE
Absorber: $CaMoO_4$
Light Detector: Ge
Thermometer: MMC
Mass: 5-10 kg

Coherent Elastic ν-Nucleus Scattering (NP/HEP)

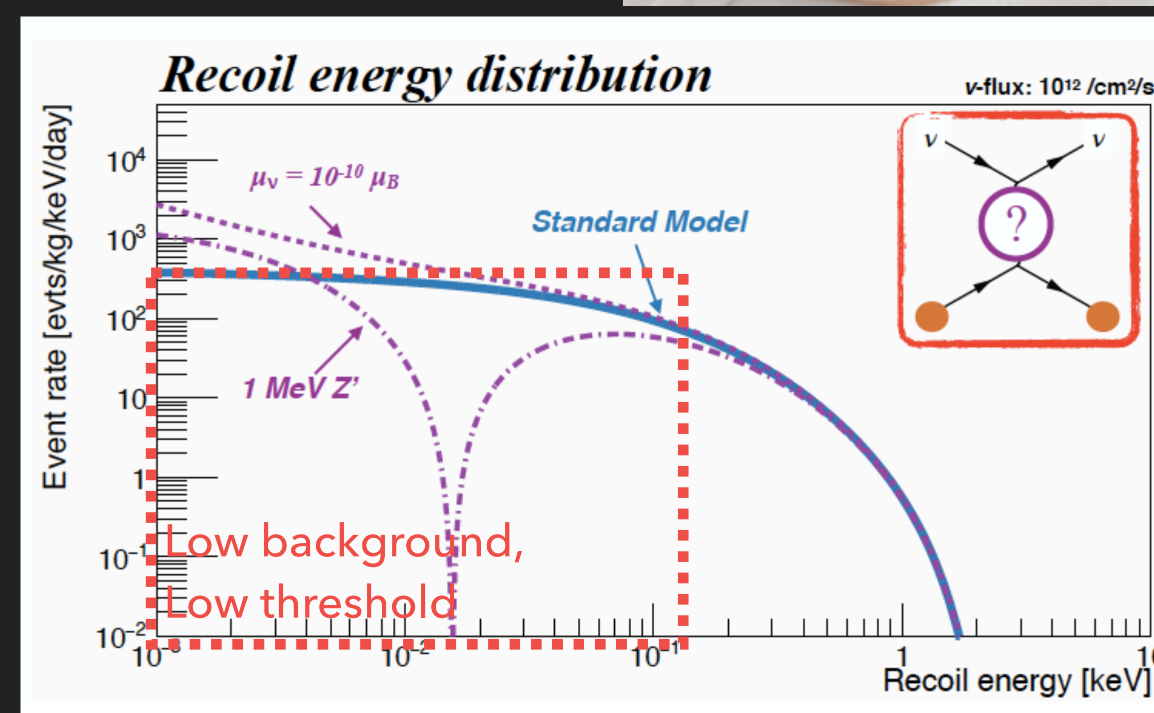
RICOCHET
A Coherent Neutrino Scattering Program

- Low energy tests of weak interactions
  - New force carriers, neutrino magnetic moment, sterile neutrino, etc…
  - Non-proliferation applications
  - High interaction cross section, but very low recoil energy
- Requires large target masses, low thresholds, and low backgrounds



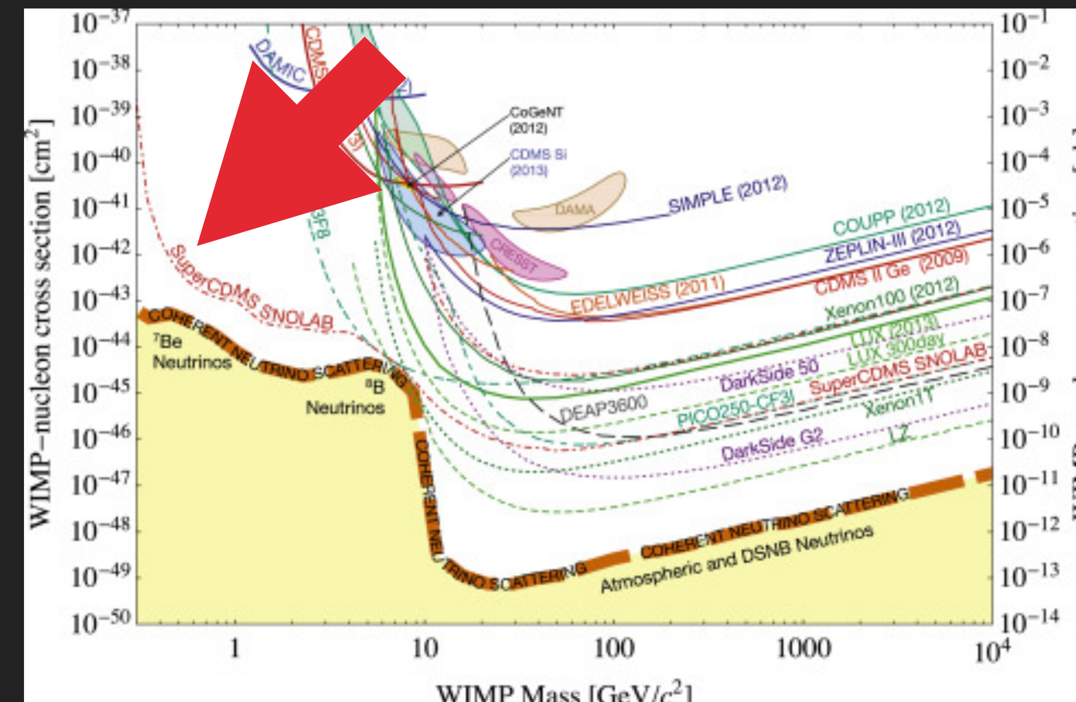
Ge detectors

Superconducting bolometers



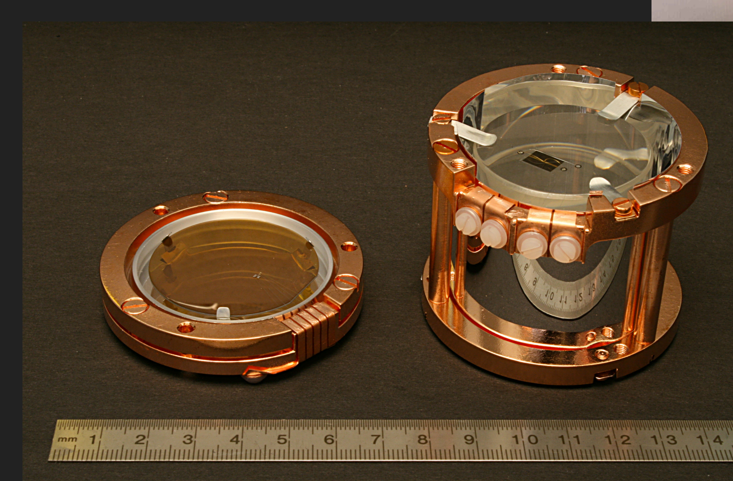
Low Mass WIMP Dark Matter (HEP)

- Low mass dark matter
    - Asymmetric dark matter models
- Running experiments like CDMS, Edelweiss, CRESST
    - Already employing TES based readouts, on a small number of channels
    - Small multiplexing factor
- Lower thresholds may require smaller mass absorbers
    - May increase channel count for same mass
- Additional techniques like Luke-Neganov amplification
    - Extremely promising for low thresholds, but adds a different set of challenges
    - May not be possible for exotic (superconducting) materials



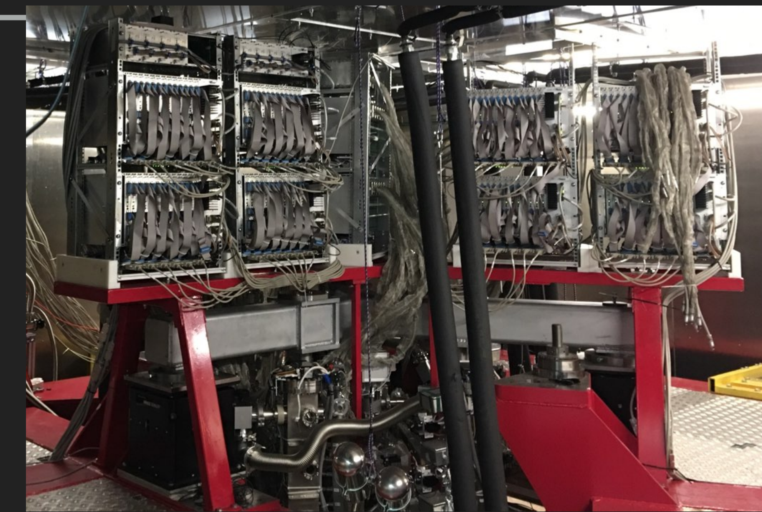
Ge absorber

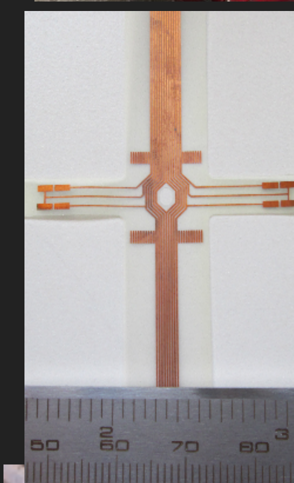
CaWO4 absorber

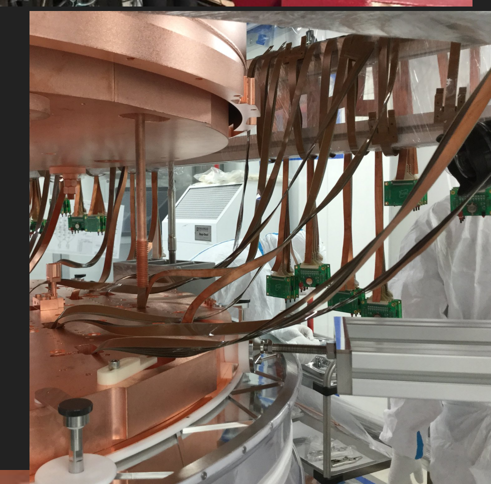


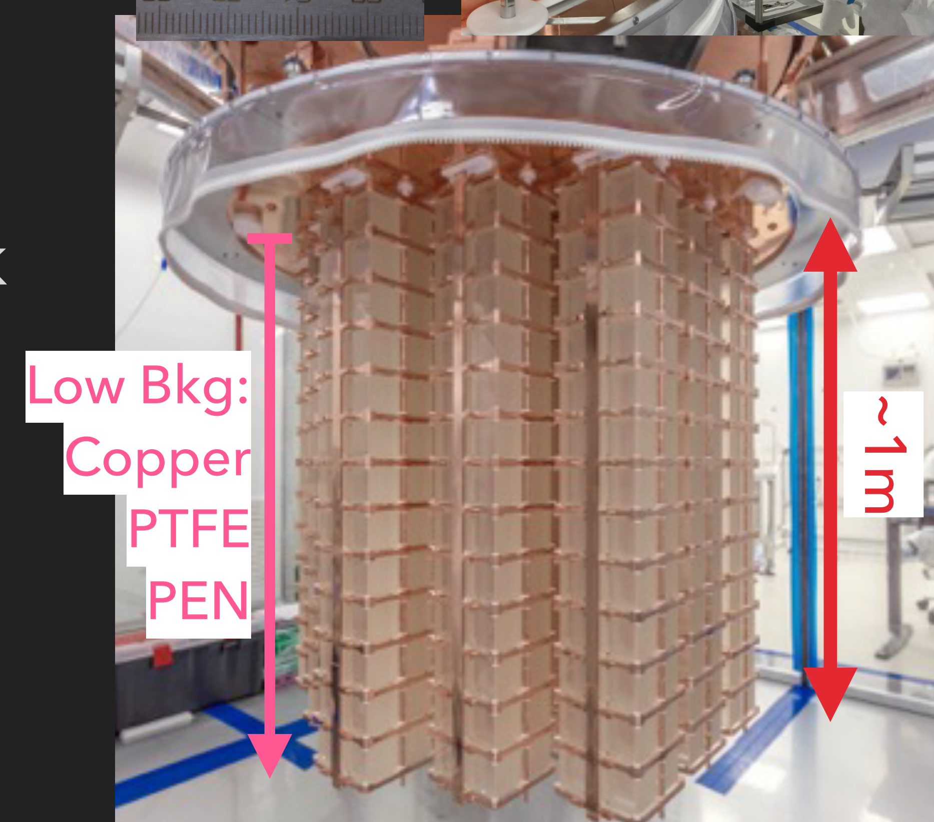
Outline of the Basic Needs

- Larger distance: Signals need to travel distances of ~1m with very low loss (loss ↔ noise)
- Low Radioactivity: All materials near to detectors must be ultra-low radioactivity
  - Materials above shields need to be low radioactivity, but requirements are less stringent
- Multiplexing: Need to be capable of instrumenting 100~1000s of channels
  - Extremely challenging to wire each channel individually
  - Detector working points need to be individually set
- Lower Temperatures: Operation at (bath) temperatures of 10~50 mK
- Bandwidth: Signal bandwidths in the 100 kHz range
  - Next generation 0νββ detectors will need ~100 μs timing resolution
  - CEvNS and Low Mass WIMP detectors require the bandwidth to perform PSD between signal-like events vs background-like events



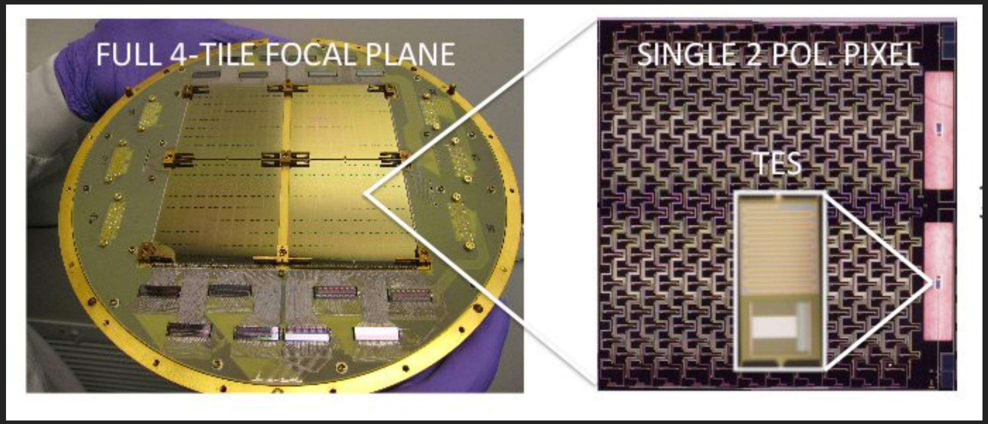




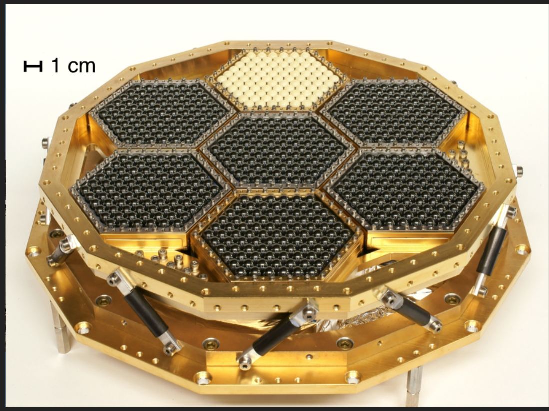


Not Reinventing the Wheel on Multiplexing

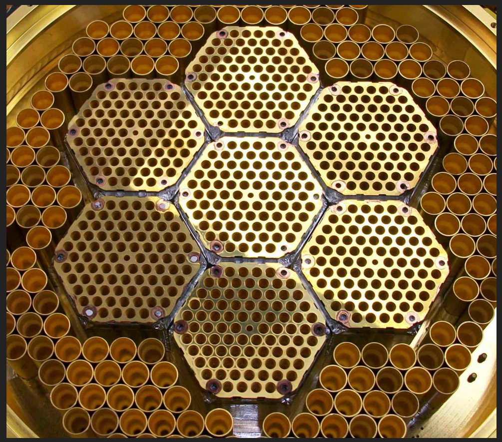
- CDMS has been using TES readout sensors for small number of channels
- CMB experiments have been using large arrays of multiplexed microbolometers
  - Current generation of detectors are instrumenting O(5,000) channels
  - Next generation (CMB-S4) instrumenting ~500,000 channels
- ^{163}Ho-based direct neutrino mass experiments
  - Expandable detector made of an array of 1024-channel boards
  - NIST designed rf-SQUID multiplexing
- Large arrays of onboard microcalorimeters
  - Micro-fabrication production
  - Detectors sizes ~10 cm
  - Typical temperatures of 100-300 mK
  - Detectors can typically be biased together



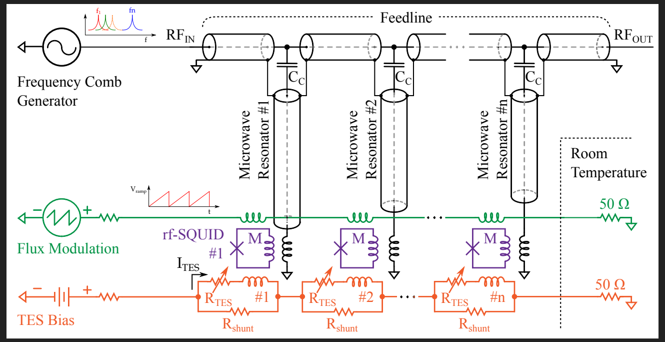
Keck Array ~2500 channels

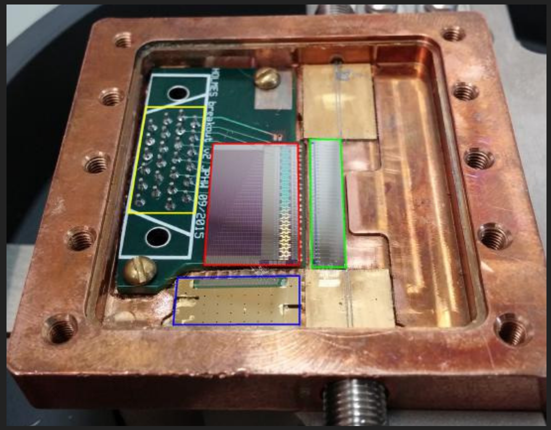


POLARBEAR ~1300 channels



SPTpol 1600 Channels





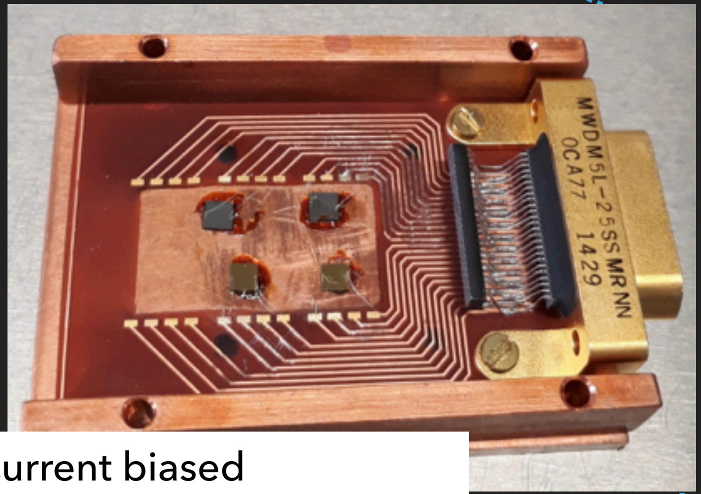
HOLMES ~32000 channels (Goal)

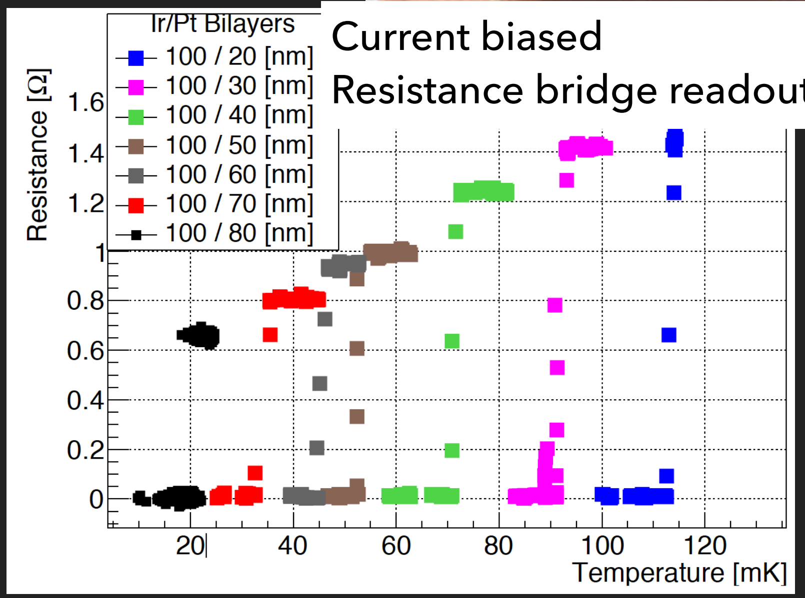
TES READOUT R&D FOR

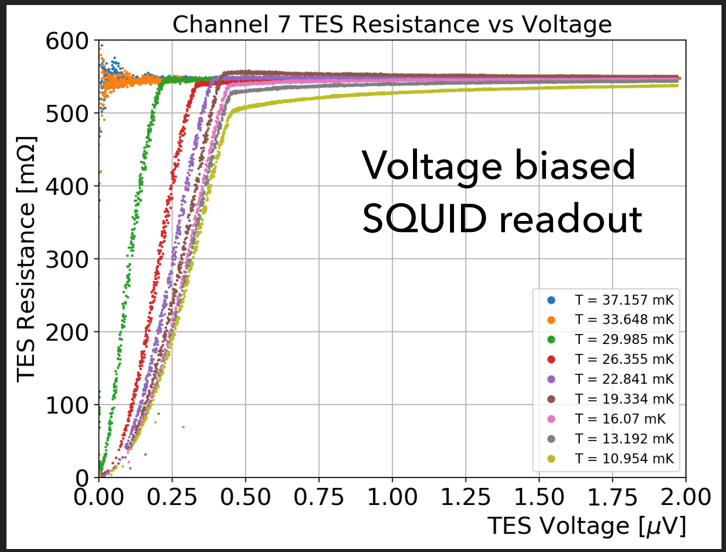
CUPID

Development of Low Temperature TES Sensors

- UC Berkeley with Argonne collaborating to develop bilayer TES sensors with low T_cs
  - Tested in a cryogenic facility at UCB
- Ir/Pt bilayers and Au/Ir/Au trilayers showing promise
  - ✓ Demonstrating transitions as low as ~20 mK
  - Ability to tune the precise transition temperature by adjusting layer thickness
  - Transitions stable over time and consistent across a single wafer
- Other TES parameters like R_0, α, β can be tuned by adjusting other production parameters (like heating, cooling times, patterning etc)
  - ✘ α values estimated to be of O(100), β ~ 1. But this is not precisely measured yet
  - ✘ Need to determine optimal TES patterning
- ✘ Production (nearly) robust and repeatable



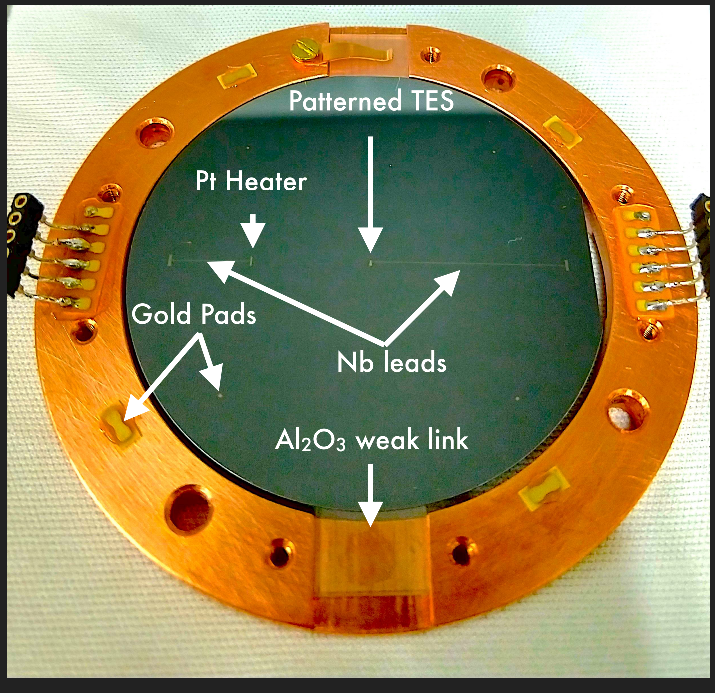


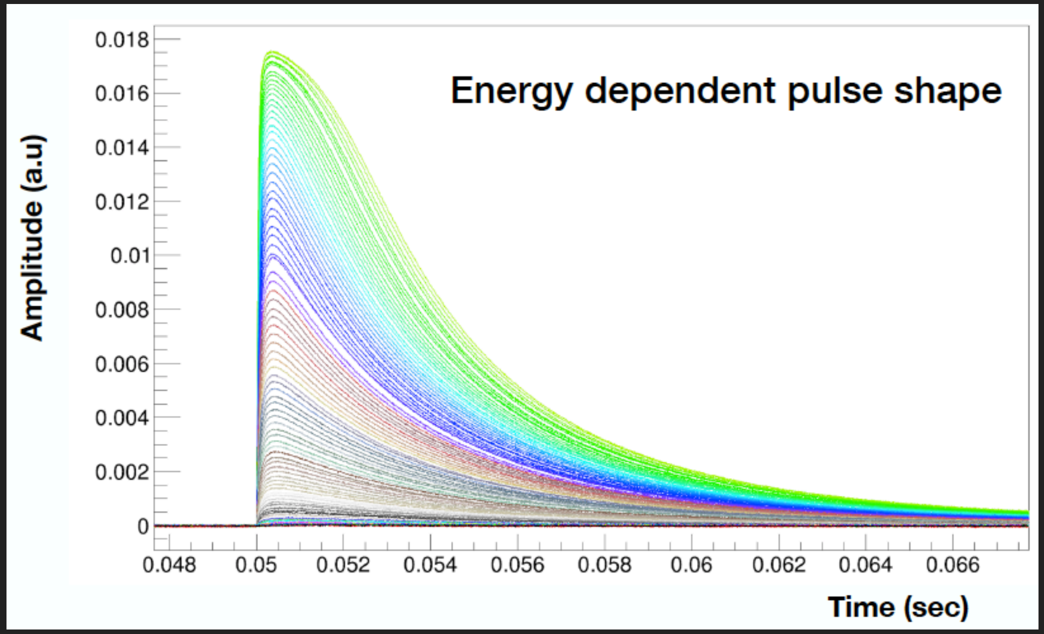


Courtesy of B. Welliver (Berkeley/LBNL)

Already Deploying these Low Temperature TES Sensors

- Already operating a Ge wafer instrumented with a TES sensor as a light detector
- Currently operating at 32 mK
- Able to observe injected pulses
  - Decay times: ~4 ms
  - Rise times: ~200 us
- Still need to optimize the electrothermal circuit and working point
- Demonstrated ability to identify pulser pulses separated by 70 us
  - Pileup rejection for 0νββ experiments
  - Maybe useful for PSD for particle ID

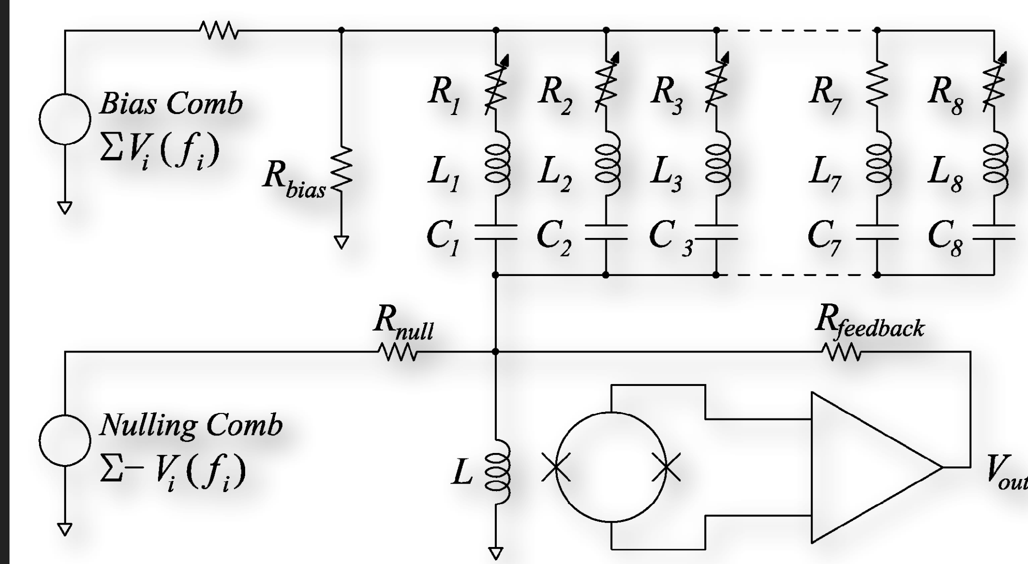




Courtesy of B. Welliver (Berkeley/LBNL)

dc Multiplexing Readout

- Investigating dc SQUID based multiplexing with frequency comb
- Can achieve multiplexing factor O(10)
  - Set by the bandwidth of the dc-SQUID (feedback circuit)
- Injecting frequency bias comb with a set of LC resonators to address each TES individually
  - Each bias frequency can have its power individually set
  - ✘ Setting the width of the resonators
- ✘ Signals need to travel the ~meter distance between the TES and SQUID on carrier frequency of ~MHz
  - Low background wiring needs to have ~10 MHz bandwidth
- ✘ Magnetic flux & capacitive noise
- Being developed at Berkeley as part of CUPID
- No results yet, electronics are built, testing to begin soon

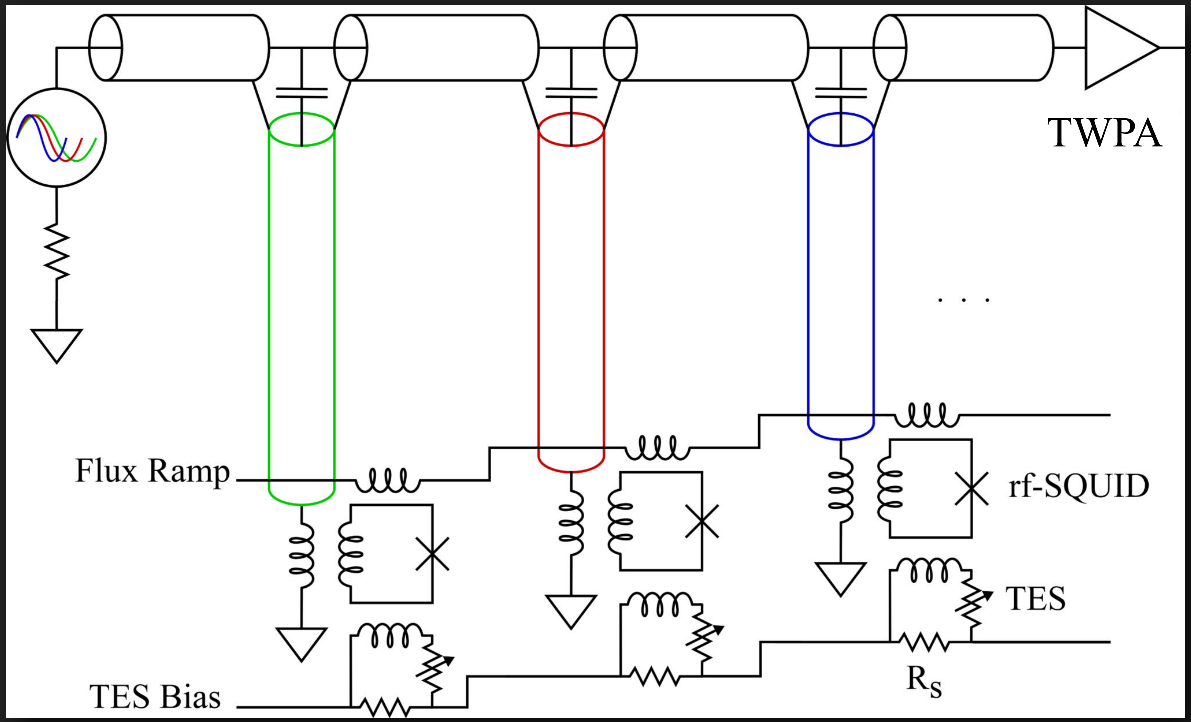


IEEE Trans. Appl. Supercond. 15 (2) 2005

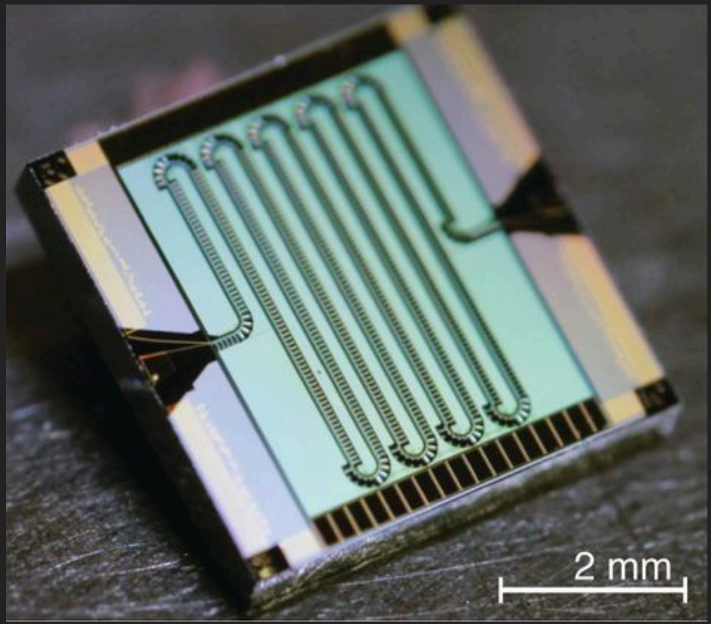
rf Multiplexing Readout

- Multiplexing based on rf SQUIDs
  - Similar to HOLMES design
  - Multiplexing factors up to 100~1000s
  - Carrier frequencies in the ~GHz range
- ✘ Cannot use common TES bias line
  - Need one bias line per TES
- ✘ Signals need to travel the ~meter distance between the TES and SQUID un-mixed
  - Low background wiring only needs to have ~100 kHz bandwidth
- ✘ Magnetic flux & microphonics noise?
- TWPA final amplification stage
  - Can achiever higher gain with SQL limited noise floor
- Being developed at MIT as a collaboration between CUPID+Ricochet groups
  - Working with Lincoln Labs to design cold electronics
  - Testing NIST & SLAC designed warm readout electronics
- No results yet, electronics are still being built

RICOCHET A Coherent Neutrino Scattering Program

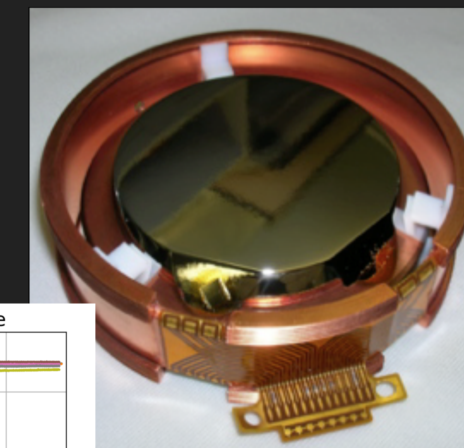


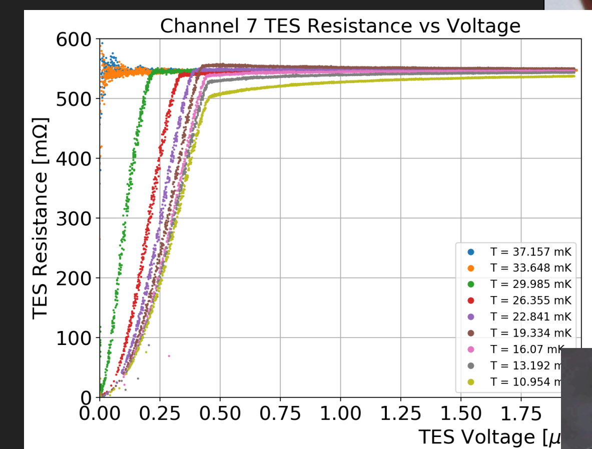
Appl. Phys. Lett 111 (24) 2017

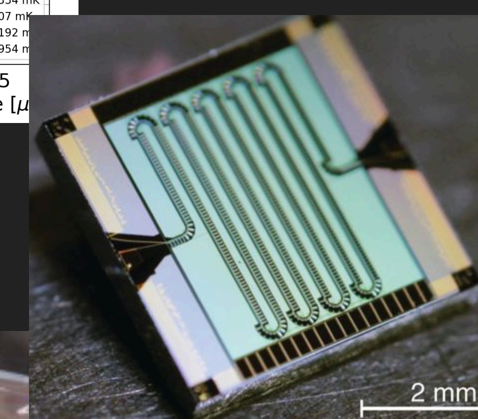


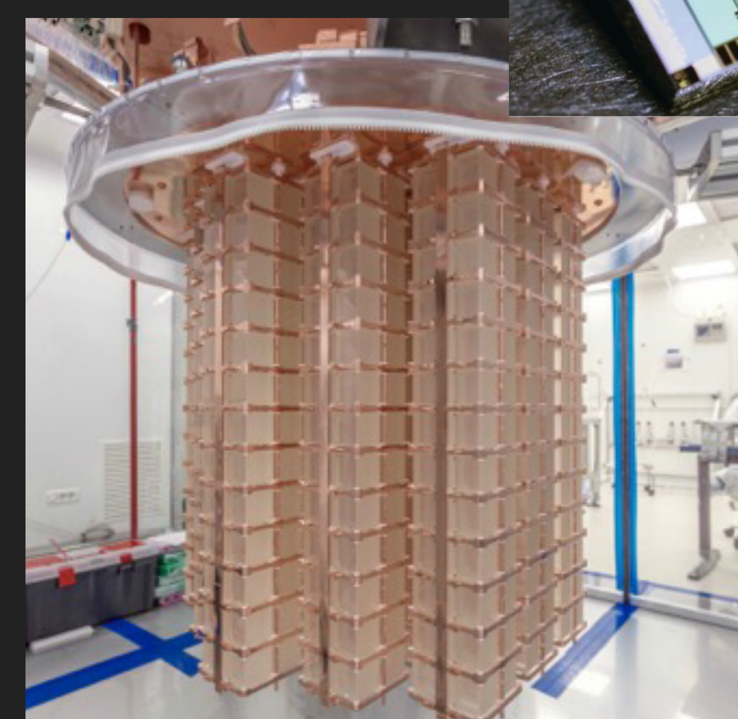
Conclusions

1. Macrocalorimeters are a very versatile detector technology with a wide array of HEP and nuclear physics applications
2. Next generation detectors need to balance
   - Very low noise readouts
   - Low background materials
   - Scalability to large numbers of channels and physically large detectors
3. Potential application of QIS low-noise superconducting sensors to multiplex macrobolometer detectors
   - But technological challenges still exist









Thank you for your attention!

Applications for Quantum Computing?

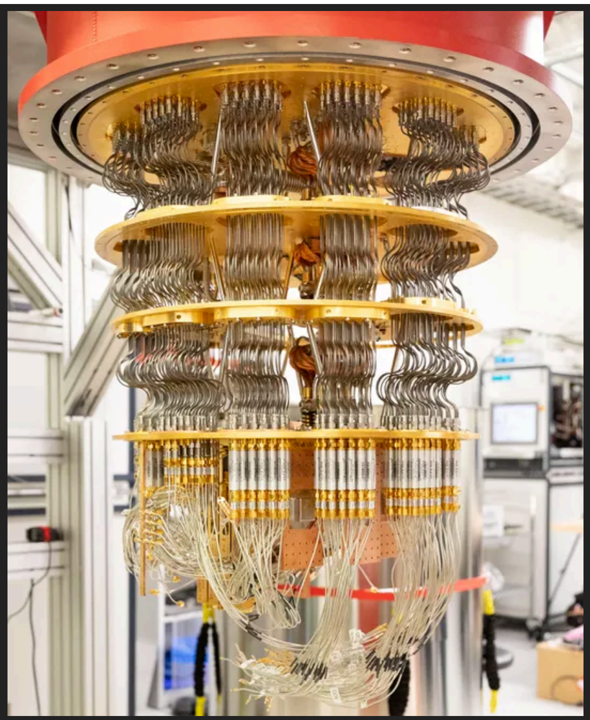
- DOES NP/QIS Grant to answer the question: Does natural radioactivity decrease the coherence time of qubits?
- Solution: low radioactivity quantum computers & sensors
  - Well developed shielding techniques from DM and 0νββ experiments
  - Low radioactivity materials and manufacturing known and well developed
- Need low radioactivity manufacturing techniques for superconducting circuits
  - Probably this is wiring and readouts materials rather than the qubit fabrication itself

Early FY 2018 NP QIS/QC Awards

Lead Insitution	PI	Title	Description
University of Washington	Martin Savage	Nuclear Physics Pre-Pilot Program in Quantum Computing	to support pre-pilot researc Quantum Computing (QC) a expertise into the nuclear t address scientific applicatic research. This pre-pilot pro community at the national Challenge problems in nucl QIS
MIT	Joseph Formaggio	Investigating Natural Radioactivity in Superconducting Qubits	to measure the impact of b coherence times. MIT will b radiation transport models to be deployed in various q coordinate this effort with l Labs). PNNL will be respons their calibrated measureme
ANL	Ian Cloet	Quantum Simulators for Nuclear Physics: Theory	to support a postdoctoral f Quantum Simulations for N begin to develop the exper QCD simulations on Quantu Simulators.
ANL	Valentine Novosad	Superconducting Quantum Detectors for Nuclear Physics and QIS	to work on the proposal fo for Nuclear Physics and QIS
LLNL	Stephan Frederich	Thorium 229mTh	to study of the feasibility of transition of 229mTh by im such as MgF2

FY 2018 Awards Made Through Annual Sol

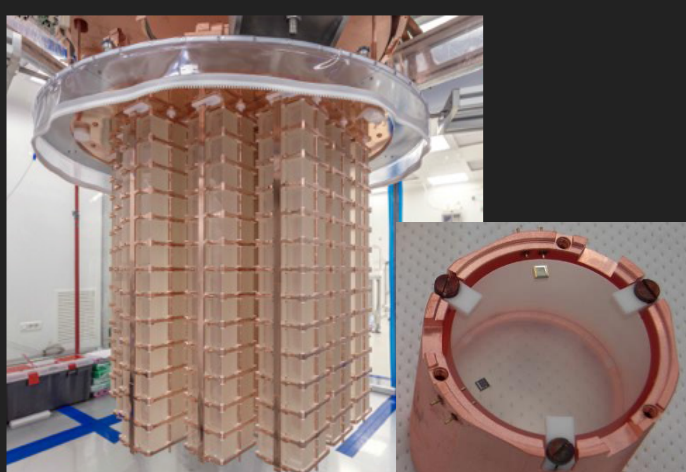
U.S. DEPARTMENT OF ENERGY | Office of Science — RHIC User Meeting — June 6, 2019

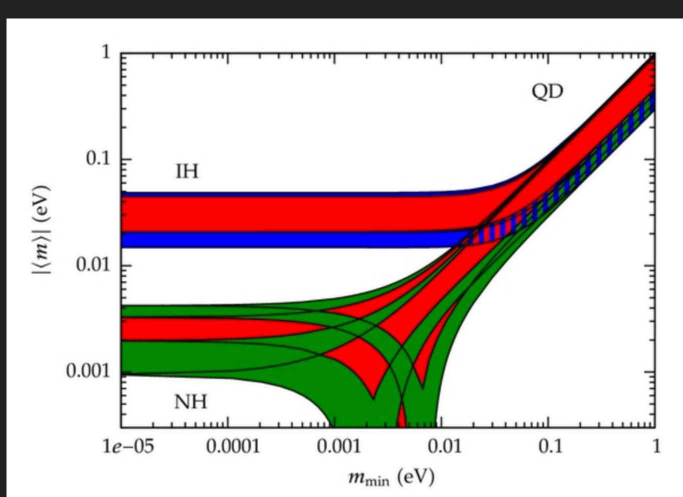


Broad Range of Physics Applications

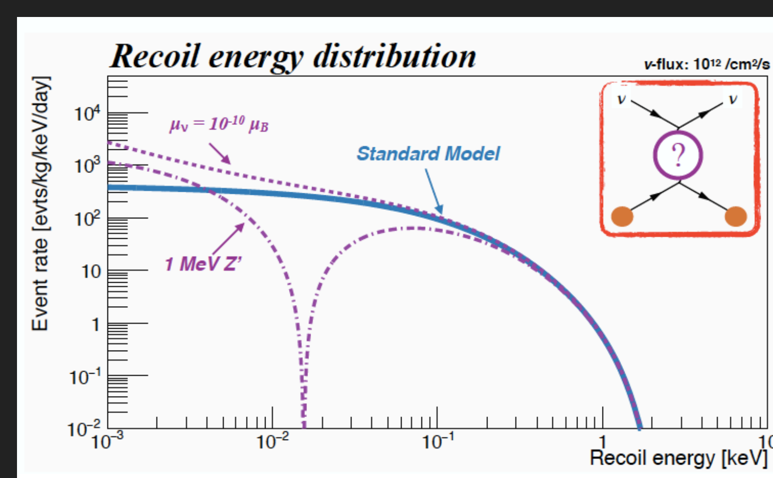
Nuclear Physics ⟷ HEP

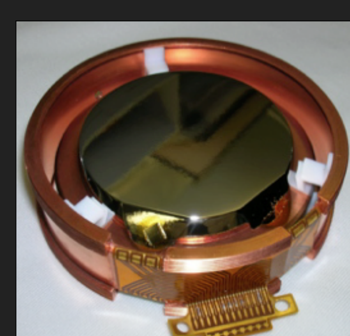
0νββ





CEνNS





WIMPs