Northwestern

Design of low T$_c$ TES chips as sensors for low background calorimeter arrays

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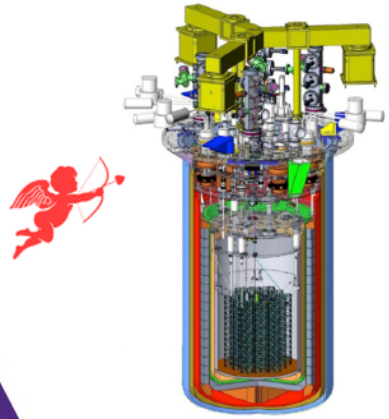

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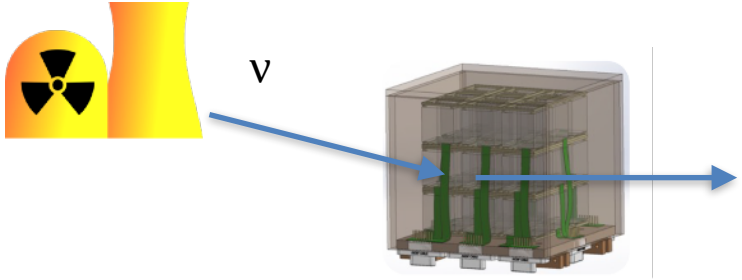


Calorimetric technique

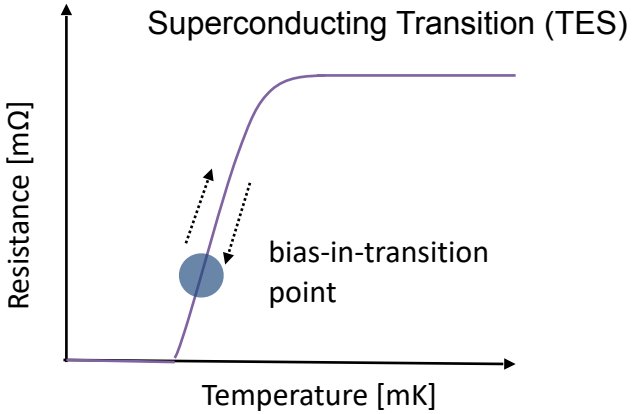
Absorber
low heat capacity:
C (T) α T^3 at low temperature

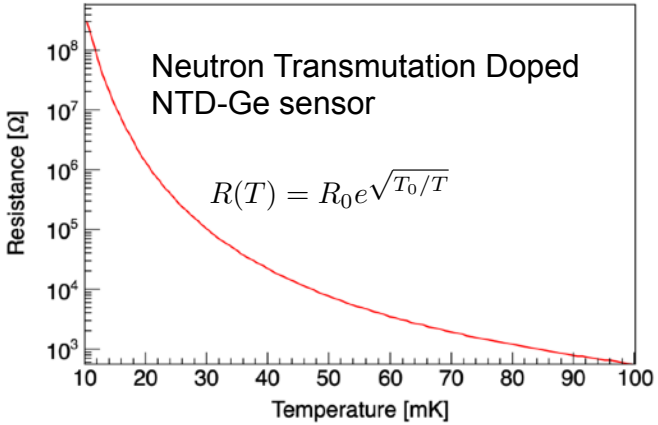
Event releasing energy in the crystal

phonon sensor

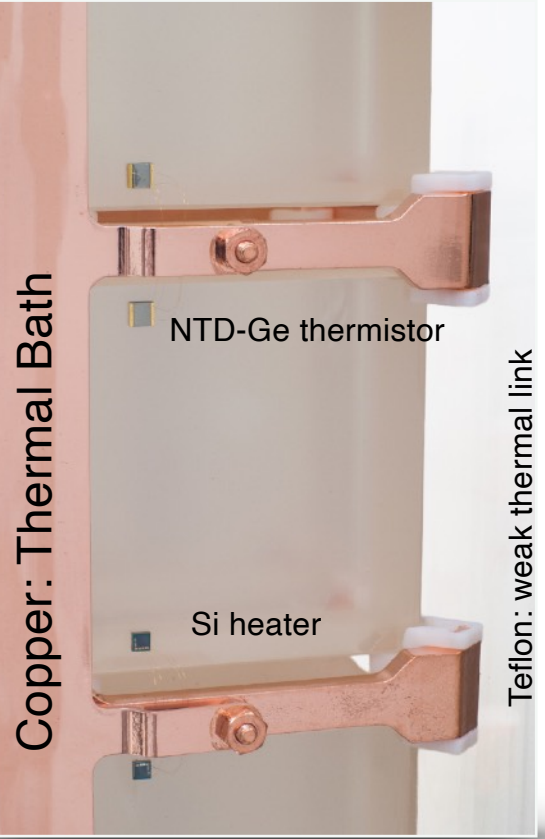
Thermal conductance (G)

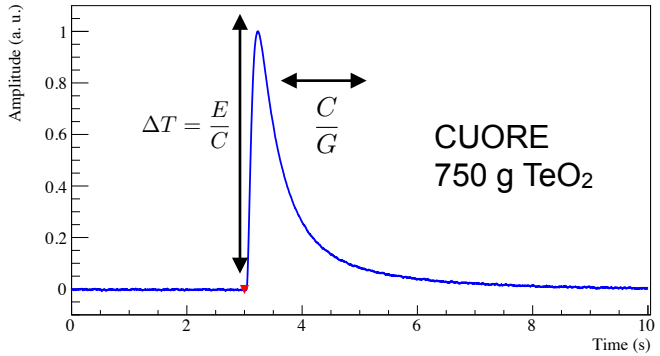
Temperature
~ 10 - 50 mK

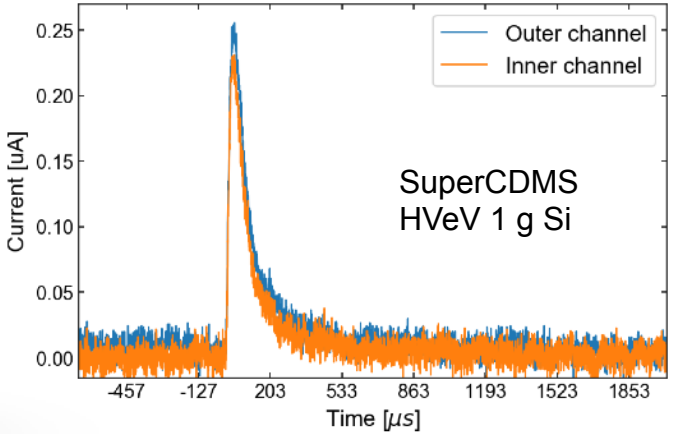




Calorimetric technique







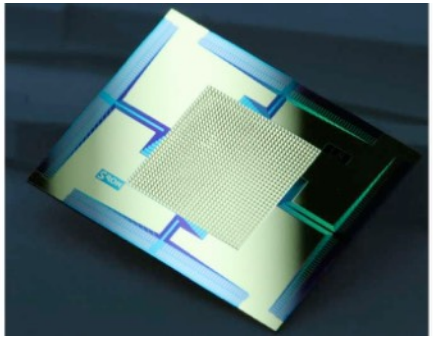
NTD readout:

- Minimal handling: Sensor preparation independent of target
- Versatile: Sensor glued to various absorbers
- High impedance (slow) - thermal signal only

TES readout:

- Sensor directly on target Material handling and process compatibility
- Fast low impedance sensor - athermal and/or thermal signal
- Position dependence/Pulse shape
- SQUID multiplexing

TES arrays in micro-calorimeter experiments

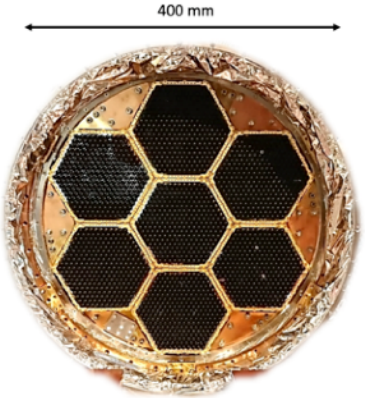


X-IFU Prototype array (1000 pixels)

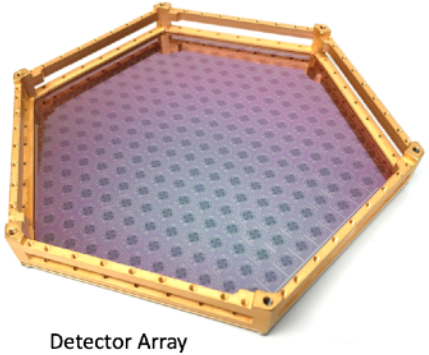
Progress in low Tc TES sensors allows for
- Excellent energy resolution
- Fast sensors with SQUID multiplexed readout

—> Technology of choice:
- **X-ray:** X-IFU (Athena backup detector) (launch in 2030s)
  1.3 eV at 6 keV, ~3000 pixels, frequency domain multiplexing 40:1)

- **CMB:**
  Polarbear 2A (Deployed 2018)
  7588 pixels, 40:1 frequency domain multiplexing
  CMB-S4 (2027 - 2035)
  ~500,000 TES sensors

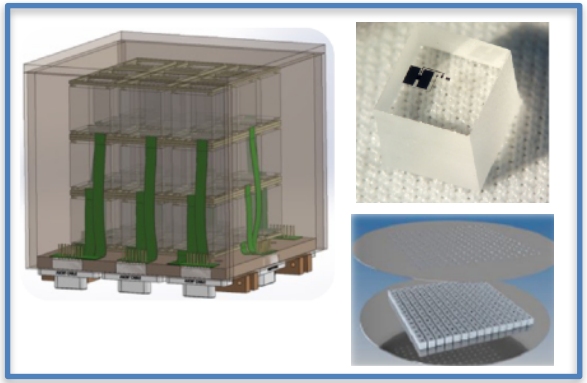


Polarbear 2 -
7588 detectors



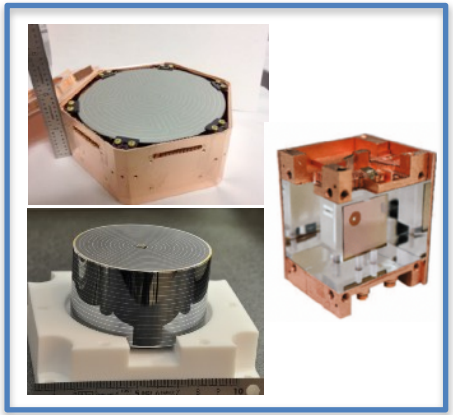
Prototype
CMB-S4 ~500,000 TES detectors

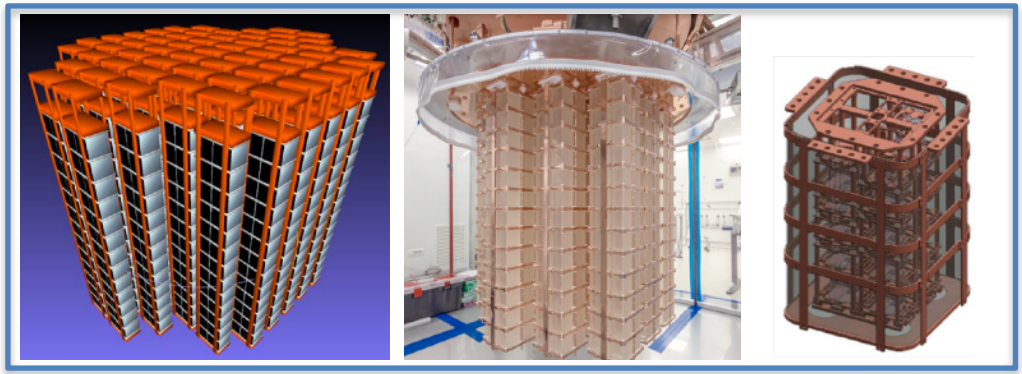
Present Macro-calorimeter experiments



CEvNS
- NUCLEUS 1-g scale absorbers ($CaWO_4$, Al_2O_3 - TES) 10 g total,
- Ricochet 40-g scale absorbers (Ge - NTD/TES, Zn with TES readout chip) ~1 kg at ILL reactor 2023

Dark matter
- SuperCDMS Si & Ge (1 g - kg) TES,
- CRESST $CaWO_4$, Al_2O_3 (24 g - 300 g) TES
- EDELWEISS Ge (30 g - 800 g) - NTD

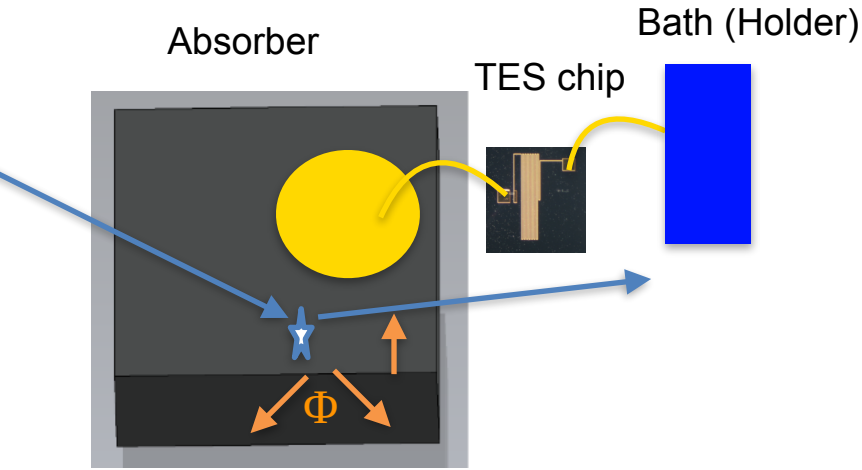




Neutrinoless double beta decay ($0\nu\beta\beta$)
- CUORE ~750 kg TeO_2, 988 crystals NTD, CUPID ~500 kg Li_2MoO_4 ~1600 crystals NTD/TES -> CUPID-1ton 1 ton of ^{100}Mo, 2 ton of Li_2MoO_4 TES,
- AMoRE 6 kg (AMoRE I) - 200 kg in ~400 crystals MMC

TES readout chip development

- Fast low-impedance device
- Versatility - only requires to deposit Au on target
- Mass fabrication on single wafers
- Design at Northwestern:
  - Model devices
  - Optimize geometry for resistance and thermal conductance



- Argonne National Laboratory
  (Expertise developing novel low T_c TES recipes)
- Investigating Ir/Pt & AlMn/Pd bilayer systems
  ~900 mΩ/square & 125 mΩ/square

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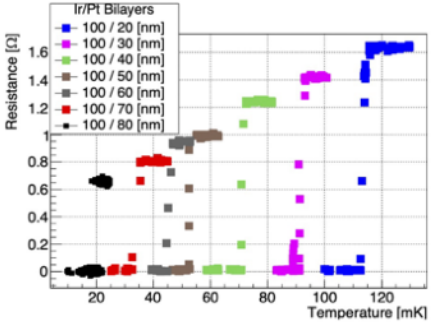

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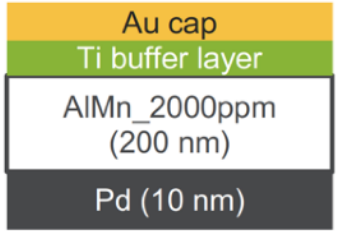
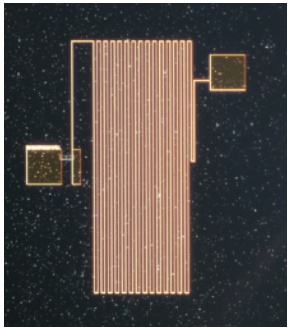
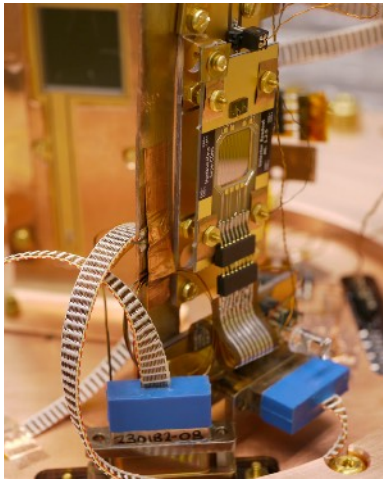
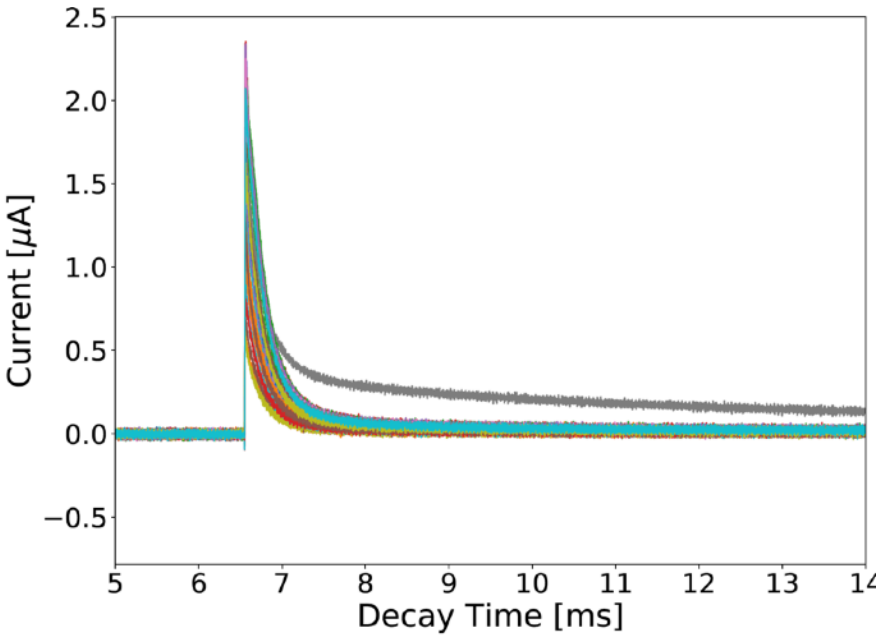


Results from 1st engineering run at NEXUS

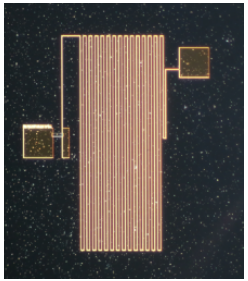




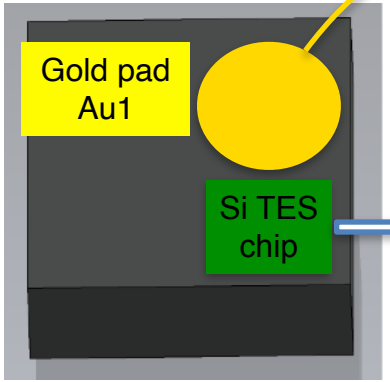


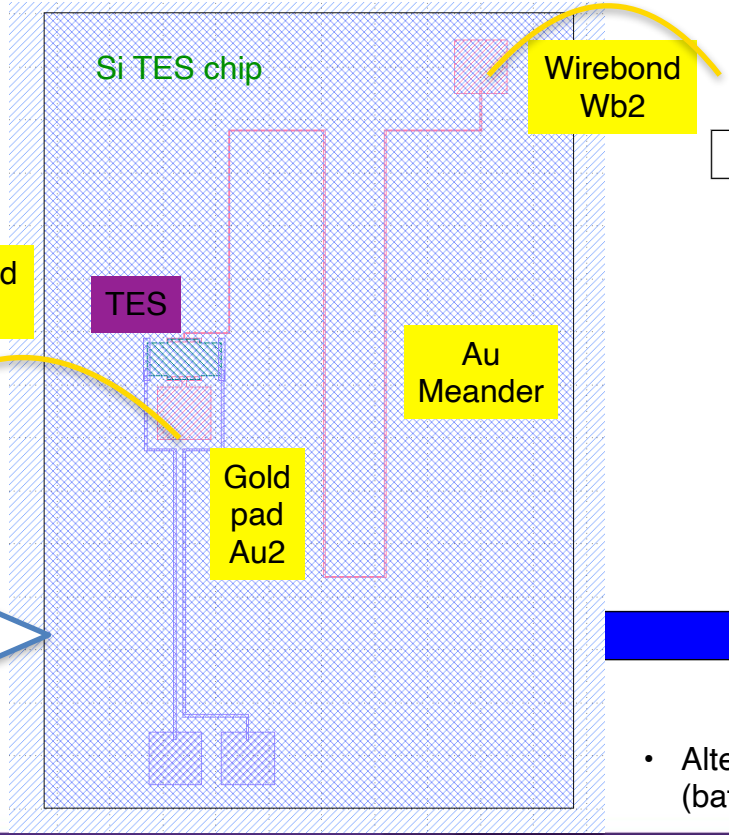
- First TES chips fabricated by Argonne National Laboratory (Ir/Pt 100 nm /20 nm)
- Operated at NEXUS - Cryoconcept DU fridge at Fermilab (100 m.w.e. at MINOS underground)
- Na_{22} source data (saturation removed)
- No absorber yet

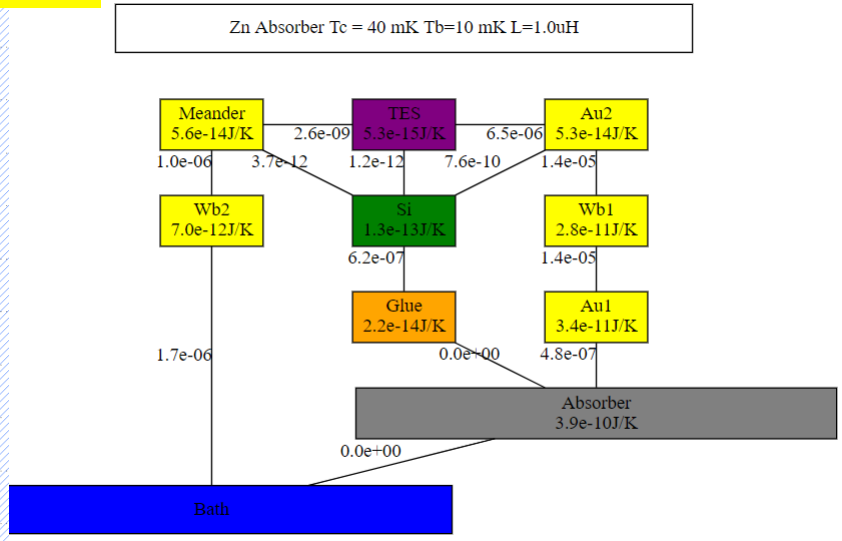
Thermal model of the TES readout



Absorber



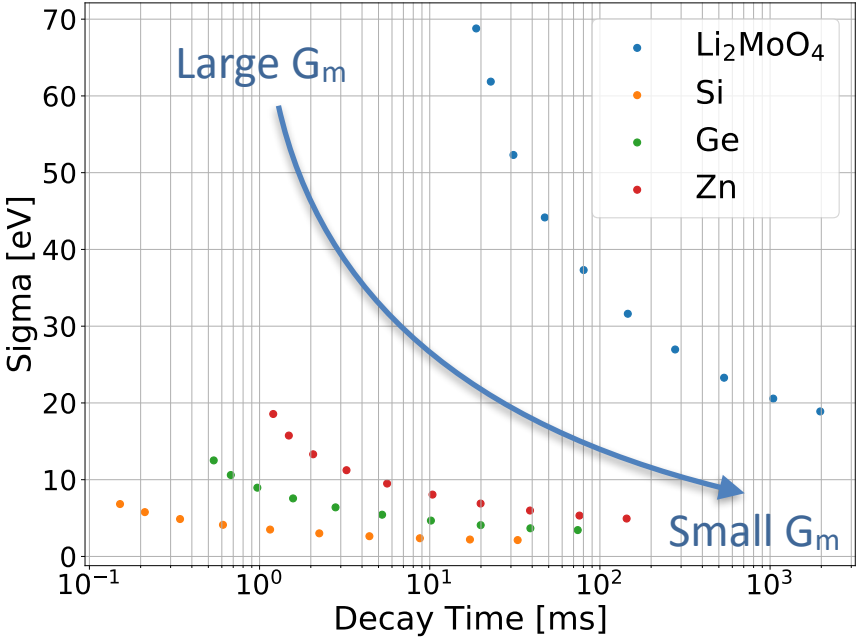




- Alternative option: Mount TES chip on holder (bath)

Thermal model results

- Assumed T_c = 40 mK, T_b = 10 mK
- Heat capacitance C_m and conductance G_m of Au meander from experimental measurement
  - Results for various Au meander length (G_m)
- Targets considered here
  - Si (~2 g) & Ge (~5 g) Dark matter, CEνNS
  - Zn (~7 g) CEνNS
  - Li_2MoO_4 (~300 g) $0\nu\beta\beta$



Application in fundamental Science: CEνNS

Standard model allowed process
Coherent interaction:

$$\sigma = \frac{G_F^2 N^2}{4\pi} E_\nu^2$$

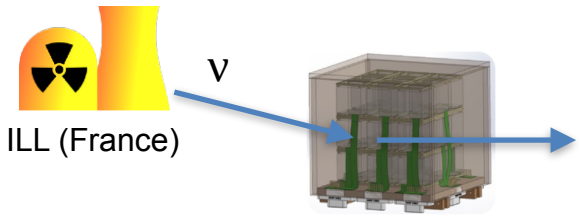
First observed August 2017 by COHERENT

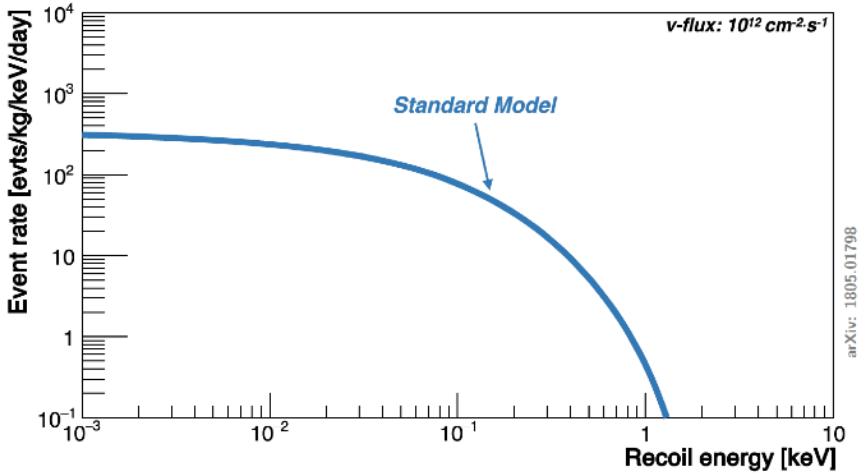
—> Probe the neutrino sector / weak interactions

—> Search for new physics

—> Potential for application in reactor monitoring

Enabling technology:
Advances in dark matter & neutrino detectors with low threshold





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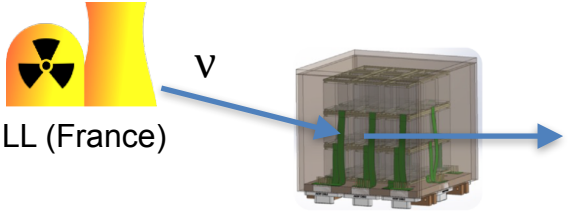
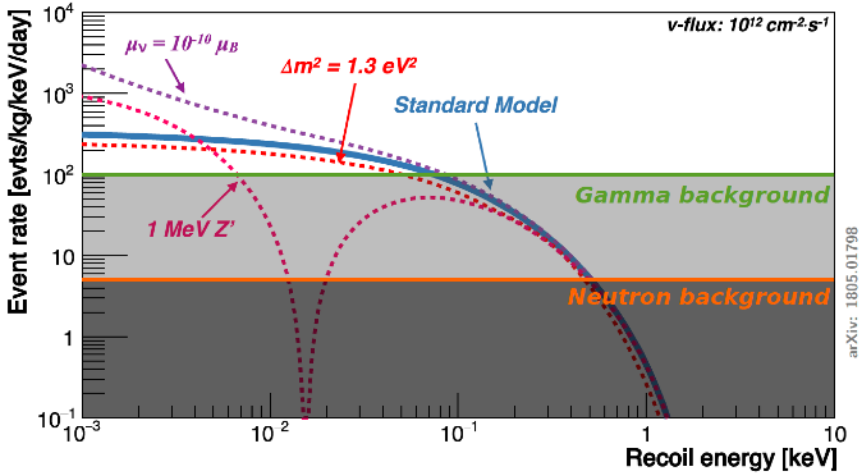




Application in the search for new physics via CEvNS

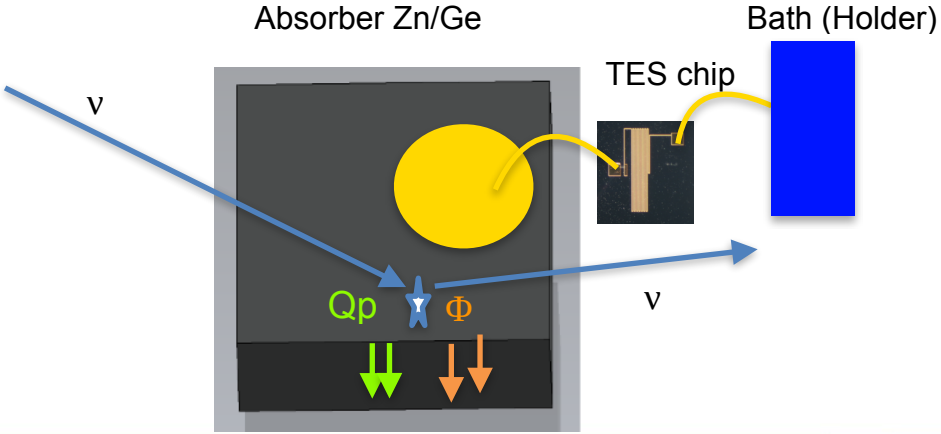
2 Technologies:

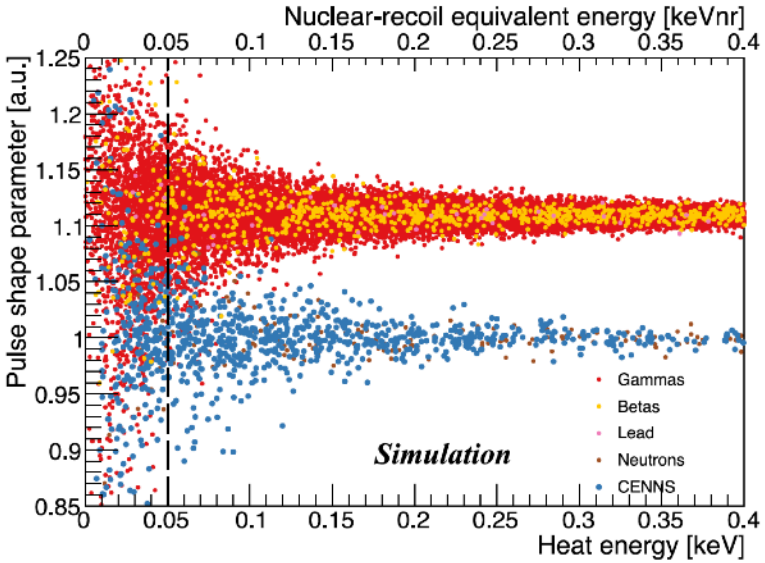
A) Ionization + phonon calorimeters from EDELWEISS

- Mature technology, but challenging ionization thresholds
- Compatible with TES + Ionization readout option

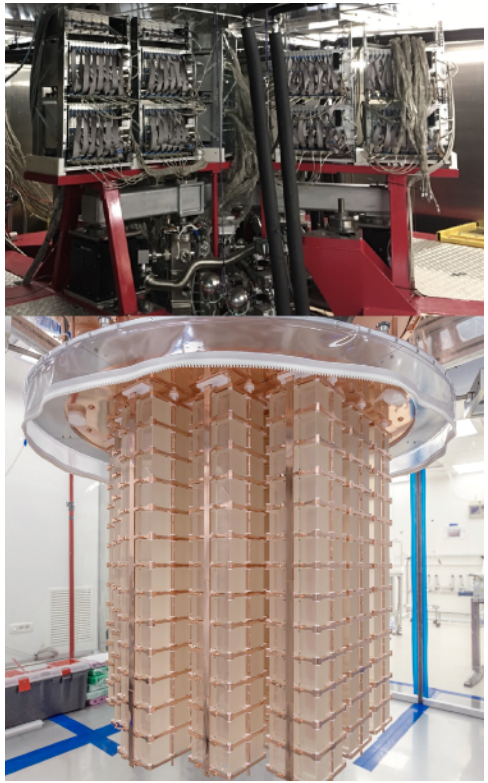
B) Superconducting absorber with TES readout

- Pulse shape sensitivity (E phonon > Superconducting gap)
- Simplifies detector design with single channel
- Multiplexed readout for 2nd gen. experiments





Application in neutrinoless double beta decay

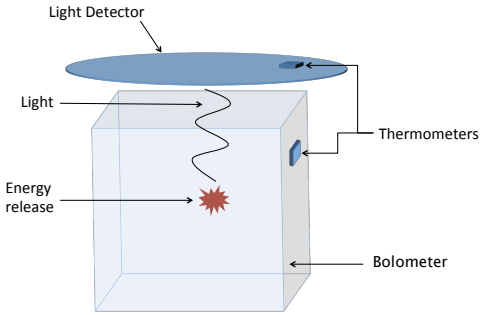


Practicality:

CUORE: TeO_2 988 detectors with front-end electronics on top of the cryostat

CUPID: Li_2MoO_4 ~3200 readout channels
CUPID 1-ton: O(10,000) readout channels

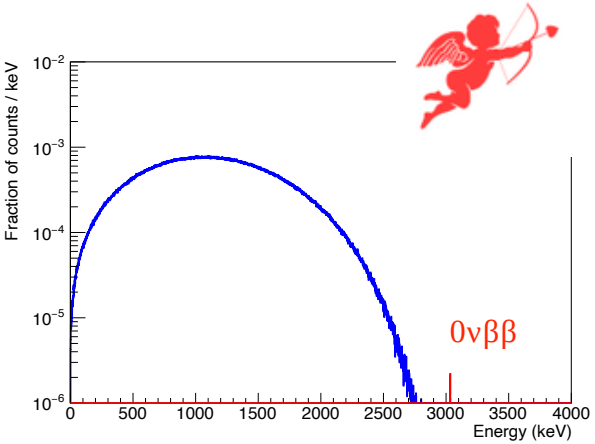
Would prefer higher density readout - Multiplexing capability



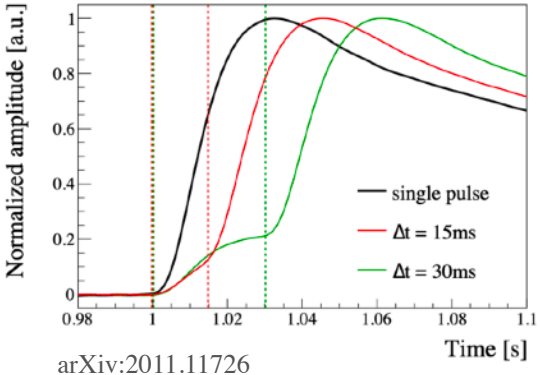
Science:

<u>CUPID</u> background goal:
10^{-4} counts/keV/kg/yr at 3034 keV
<u>CUPID 1-ton</u>: 5 x 10^{-6} counts/keV/kg/yr

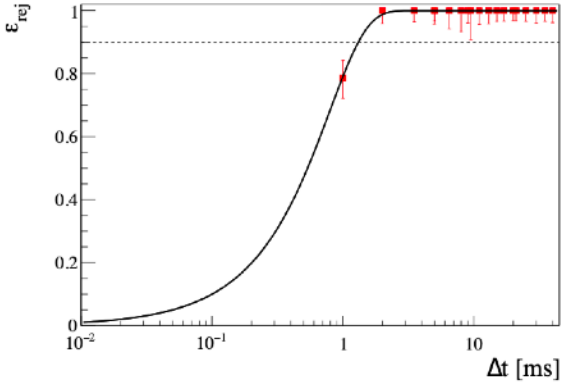
Pile-up issue: Mis-reconstructed pile-up of the extremely rare ($2\nu\beta\beta$) process



Application in neutrinoless double beta decay



arXiv:2011.11726

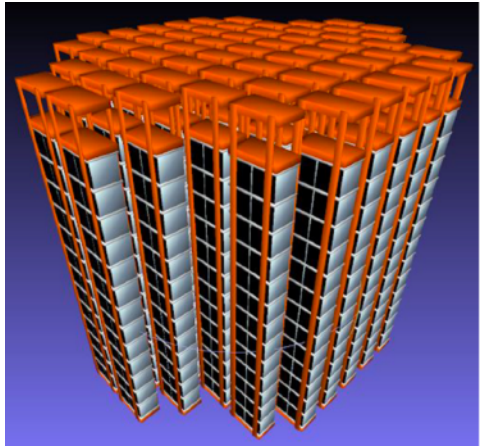


^{100}Mo $2\nu\beta\beta$ rate:
Largest rate of $0\nu\beta\beta$ candidate isotopes

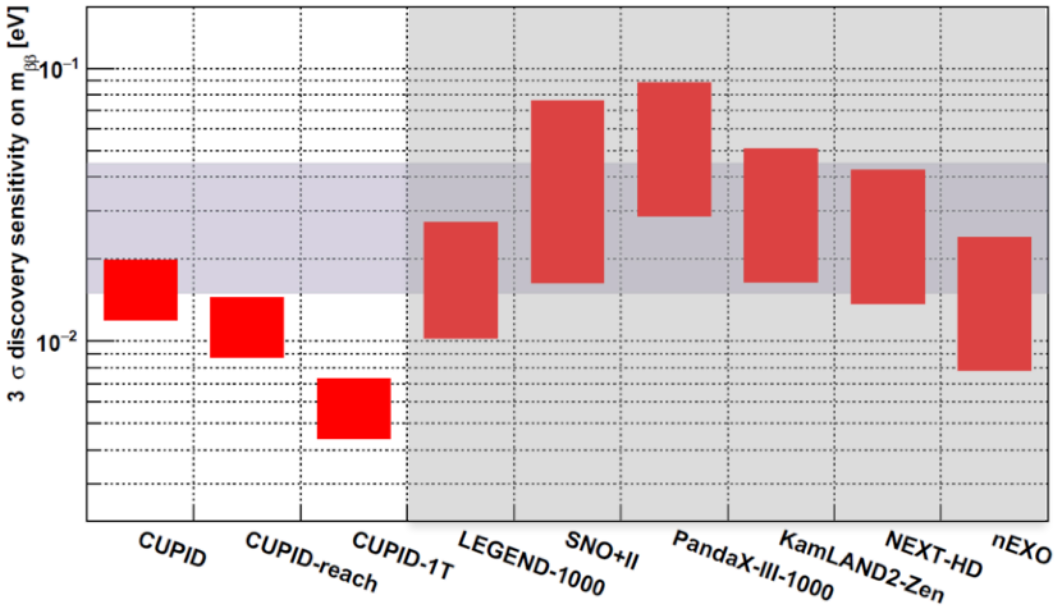
$$T_{1/2} = \left(7.12^{+0.18}_{-0.18}(stat.) \pm 0.10(syst.)\right) \cdot 10^{18}$$

—> pile-up mitigation (algorithms/sensors)

CUPID goal: sub-ms time-resolution
Easily achievable with TES/Challenge for NTD



Application in neutrinoless double beta decay



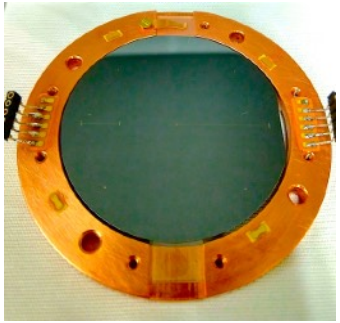
See arXiv:1907.09376

CUPID background goal is challenging with NTDs

CUPID-reach and CUPID 1T require pile-up suppression by more than an order of magnitude

Low impedance TES, MMC, or KID sensors required

TES readout chip - complementary to ANL/Berkeley Ir/Pt TES based LD development



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Conclusion

Clear science motivations:

- Flexibility of absorber
- Multiplexed readout for large scale arrays
- Pulse shape discrimination with superconducting absorber/films on surfaces
- Pile-up mitigation in $0\nu\beta\beta$

Timeline ahead:

- Now: New AlMn chips being fabricated at ANL
    - T_c checks at UMass Amherst, NEXUS @Fermilab & MIT
- This year: First tests with Si/Ge absorbers
- Then: Proceed to tuning of devices for superconducting and Li_2MoO_4 absorbers