Optical Photon Detectors for CUPID using Transition-Edge Sensors

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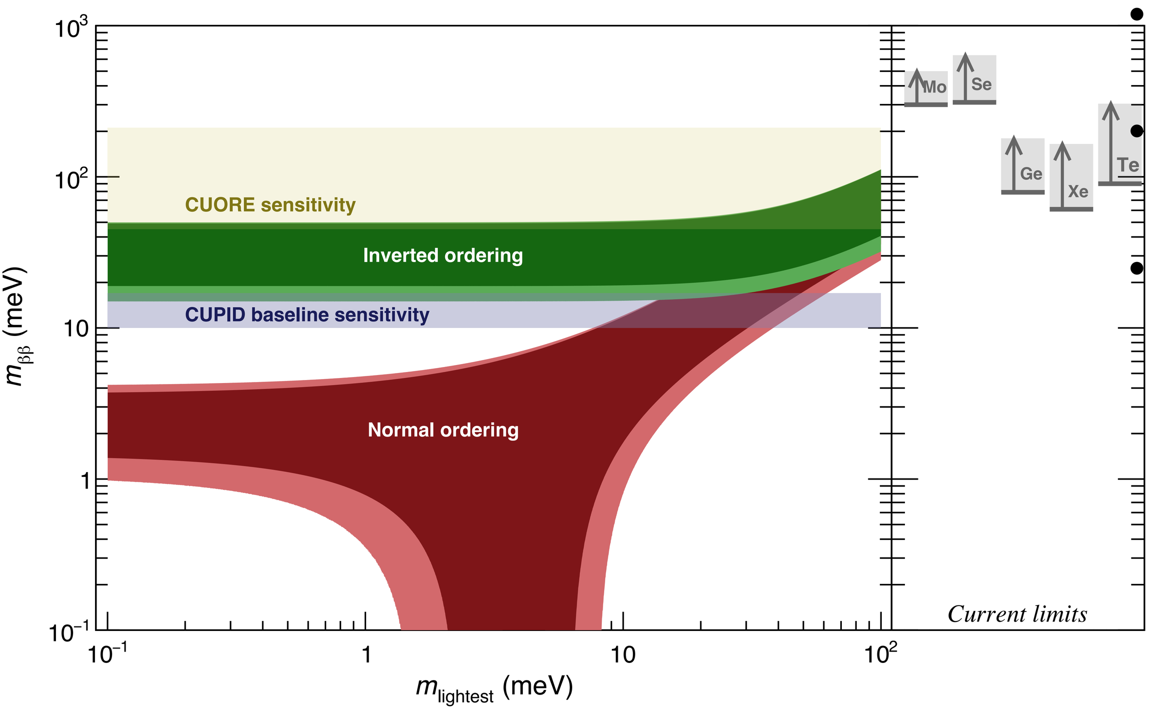
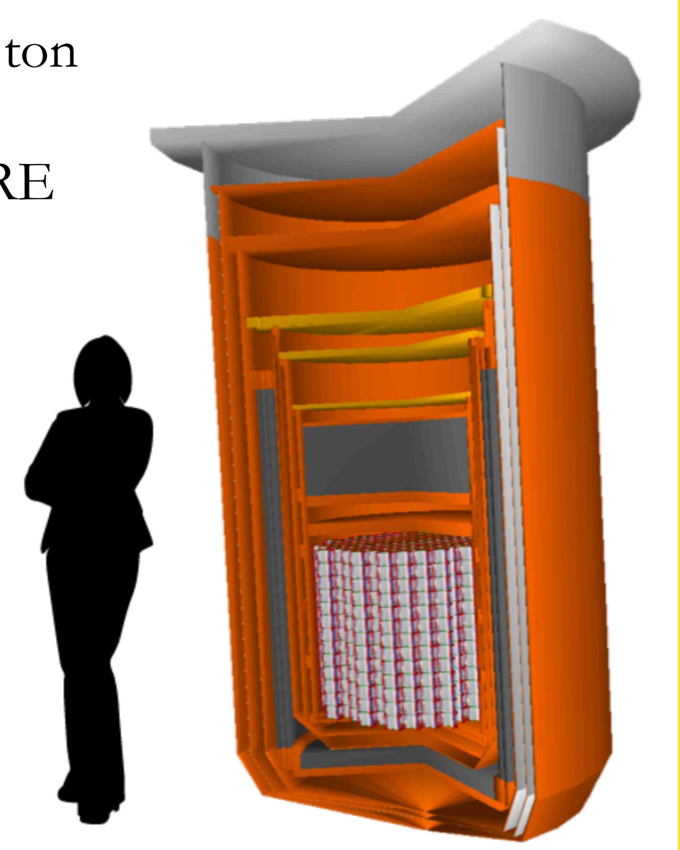
CUPID: CUORE Upgrade with Particle ID

Next generation bolometric search for $0\nu\beta\beta$ experiment [1]



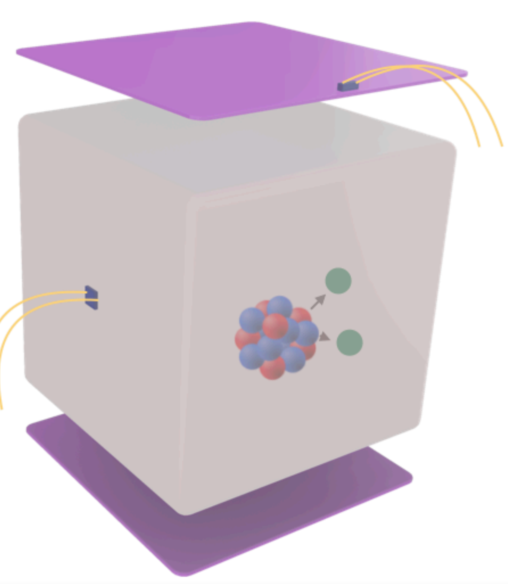
- Increase sensitive mass by enrichment
- Active background rejection through α / $(\beta$-$\gamma)$ separation
- Goal:
  - ➡ $\triangle E_{FWHM} \leq 5$ keV @ 2615 keV
  - ➡ B = 0.1 c/keV/ton/y in ROI
  - ➡ $<m_{\beta\beta}> \sim 10$ meV discovery sensitivity (10 yrs of live time)

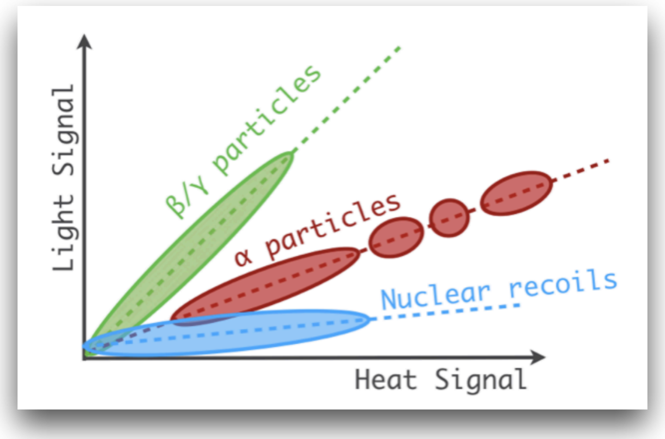
- CUORE has successfully demonstrated that a ton scale bolometric experiment is feasible
- CUPID will build on the experience of CUORE and use its cryogenic infrastructure
- Li_2MoO_4 detectors recognized as baseline
- Enrichment > 95%
- 1596 crystals with ~ 240 kg of ^{100}Mo
- 1710 light-detectors
- Demonstrated active background rejection



Rendering of CUORE cryostat with 1500 crystals inside it

Particle ID

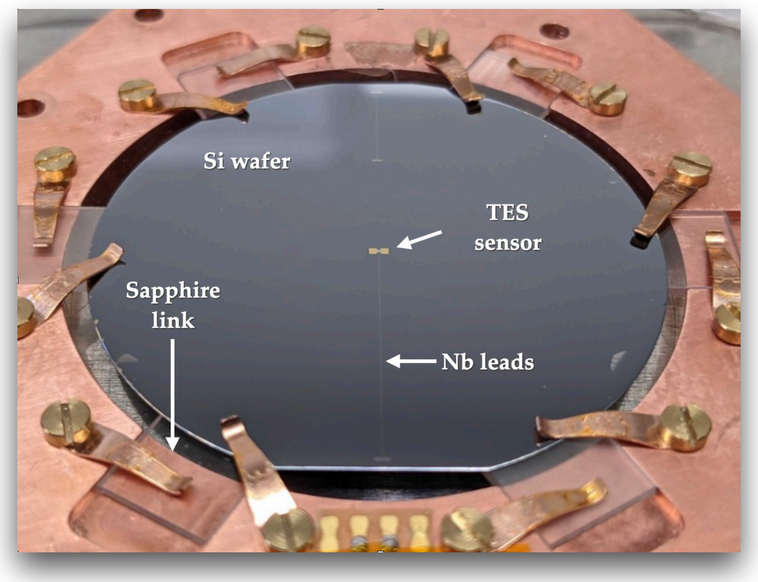




- Dominant background is degraded alphas from surface contamination
- Leverage energy loss mechanism in the crystal to tag particle type
- Use auxiliary low temperature calorimeter to detect light. Should have
  - ❑ High radiopurity
  - ❑ Low heat capacity
  - ❑ High photon collection efficiency
  - ❑ Very low threshold (~ 100 eV)
  - ❑ Excellent timing resolution to reject $2\nu\beta\beta$ pile up events

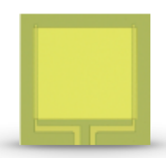
Transition-edge sensors for photon detectors

- Low transition temperature with relatively fast fabrication time possible with "bilayers"
- Negative electrothermal feedback keeps TES stable and decreases sensor time constant ; faster pulses
- Iridium goes superconducting at ~ 140 mK. Use proximity effect of a normal metal (like, Au and Pt) to reduce the T_c



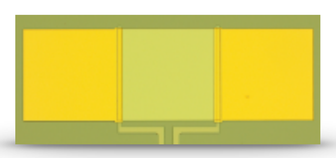
Device specification:

- 2" Silicon wafer as optical photon absorber
- Ir/Pt bilayer with Nb traces as electrical leads (tested out different thicknesses)
  - 100 nm/ 60 nm
  - 45 nm / 20 nm

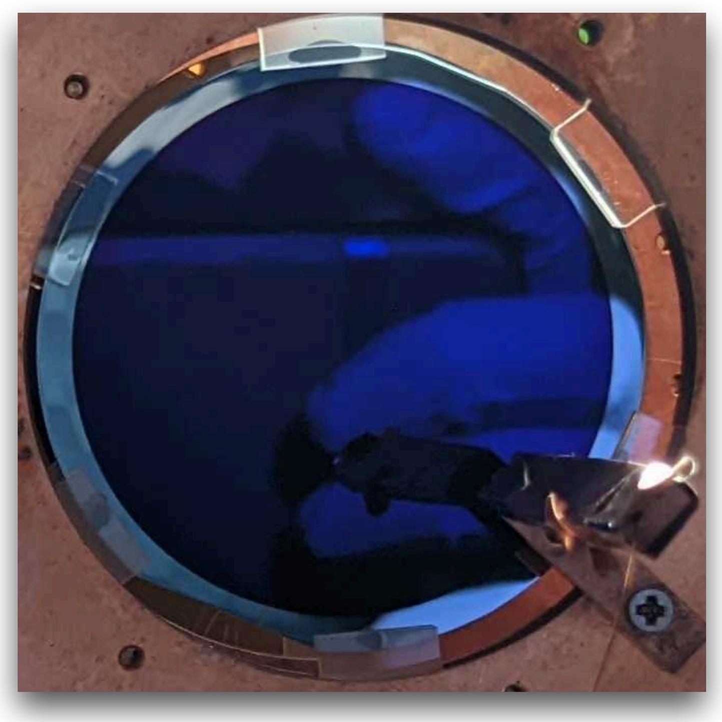


square Ir/Pt bilayer TES

- Transition temperature of ~ 30 - 40 mK
- Typical sensor dimension 300 μm x 300 μm
- Deposited Au pads, coupling the TES to the wafer for better phonon collection efficiency
- T_c relatively unchanged with addition of Au pads but signal-to-noise improves drastically



square Ir/Pt bilayer TES in the middle with Au pads on both sides



Anti-reflective (AR) coating

- 68 nm Si_3N_4 coating
- Estimated reflectance
  - ▸ < 3% for λ = 400-700 nm
  - ▸ < 0.5% for λ = 550-600 nm

Acknowledgements

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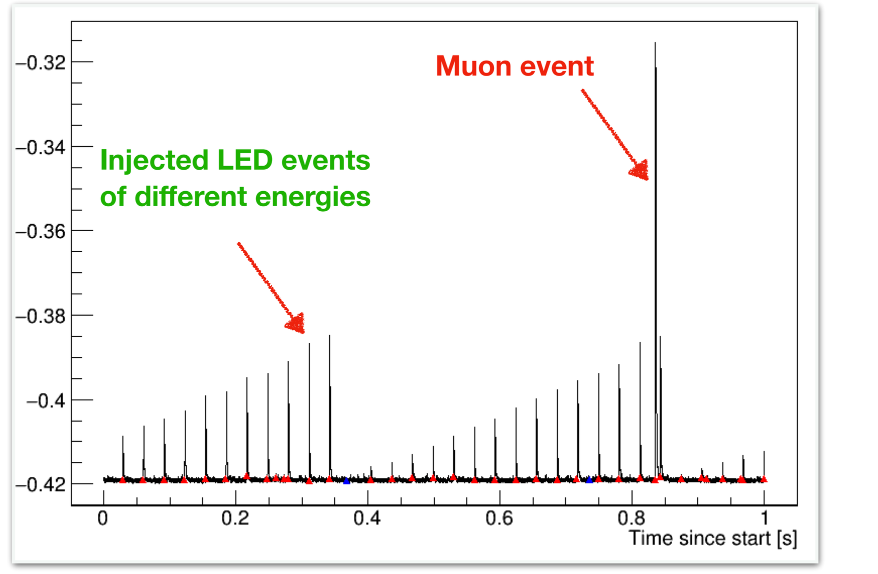
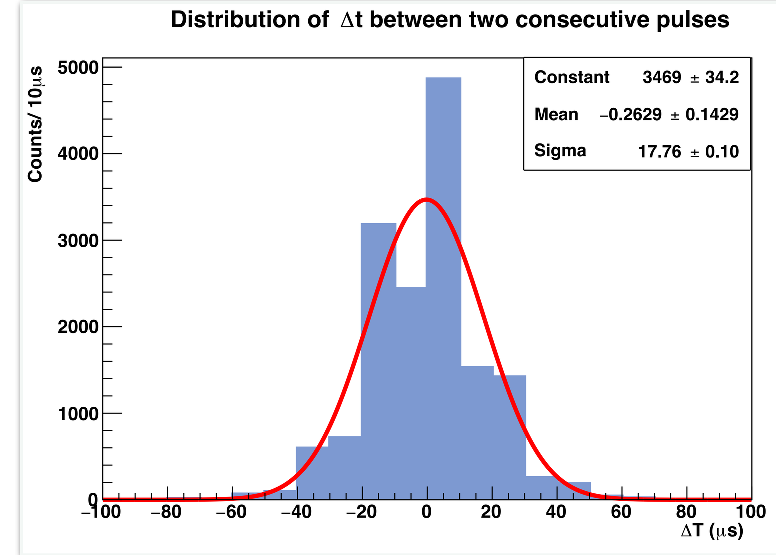
Detector performance

Timing resolution

- Generate a train of LED pulses (λ = 600nm) with known separation time (>> decay time of the pulse)
- Examine distribution of trigger time between the subsequent pulses in detector response
- Timing resolution of Δt < 20 μs
- Detector satisfies the criteria for rejecting $2\nu\beta\beta$ pile up events

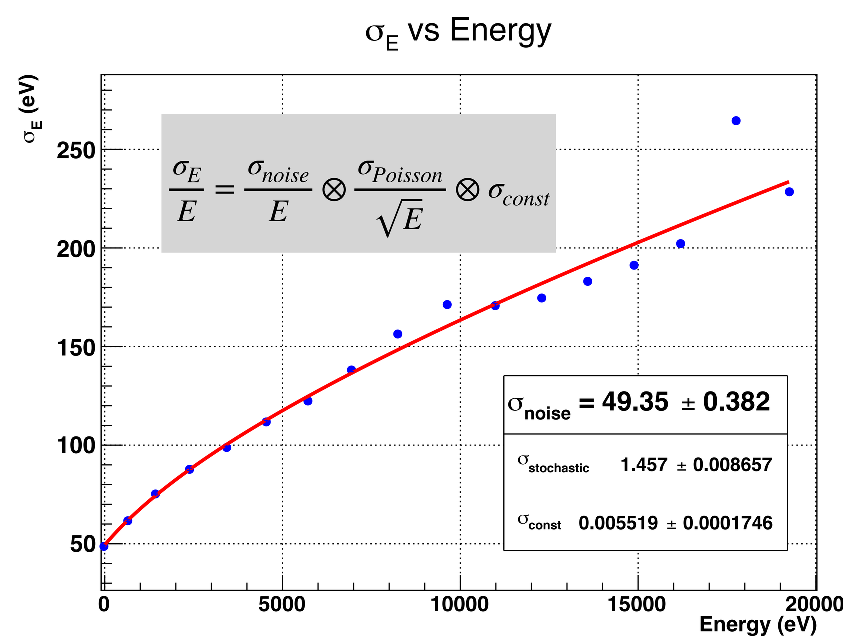


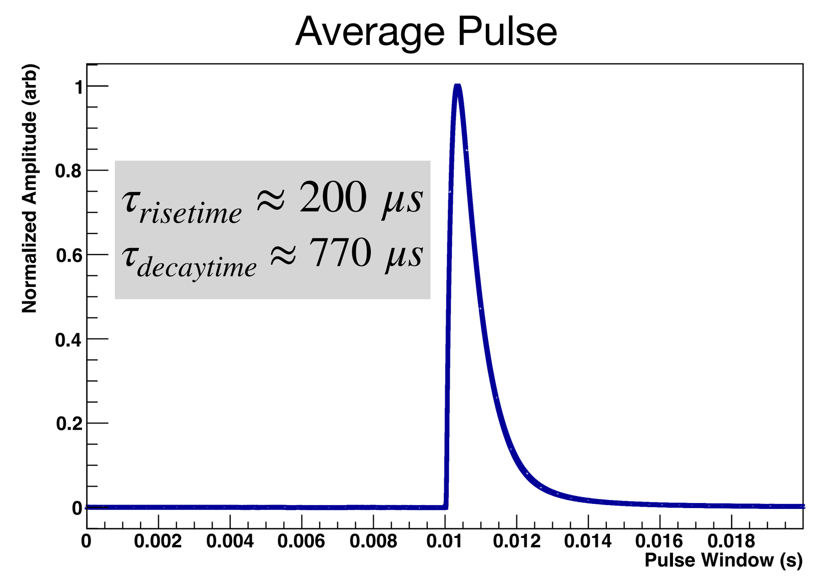


(left) Detector response to train of LED pulses of varying amplitude injected at 32 Hz (right) distribution of Δt between two consecutive pulses

Energy resolution

We perform energy calibration using photon statistics[2]. The 600 nm LED kept at room temperature was coupled to an optical fiber facing the opposite side of the wafer where the TES is deposited.





TES wafer	Risetime	Decaytime	Baseline Resolution
With AR coating	200 μs	770 μs	~ 50 eV
Without AR coating	198 μs	884 μs	~82 eV

We compared the performance of detectors with and without AR coating and validated that the AR coating does not degrade performance.

Detector satisfies the CUPID criteria for baseline noise (rms)

References

[1] Armstrong, W. R. "CUPID pre-CDR." *arXiv. org Repository* 2019 (2019). (arXiv:1907.09376)
[2] Cardani, L., et al. "Al/Ti/Al phonon-mediated KIDs for UV–vis light detection over large areas." *Superconductor Science and Technology* 31.7 (2018): 075002.