Prospects for a Future Global $0\nu\beta\beta$ Decay Search

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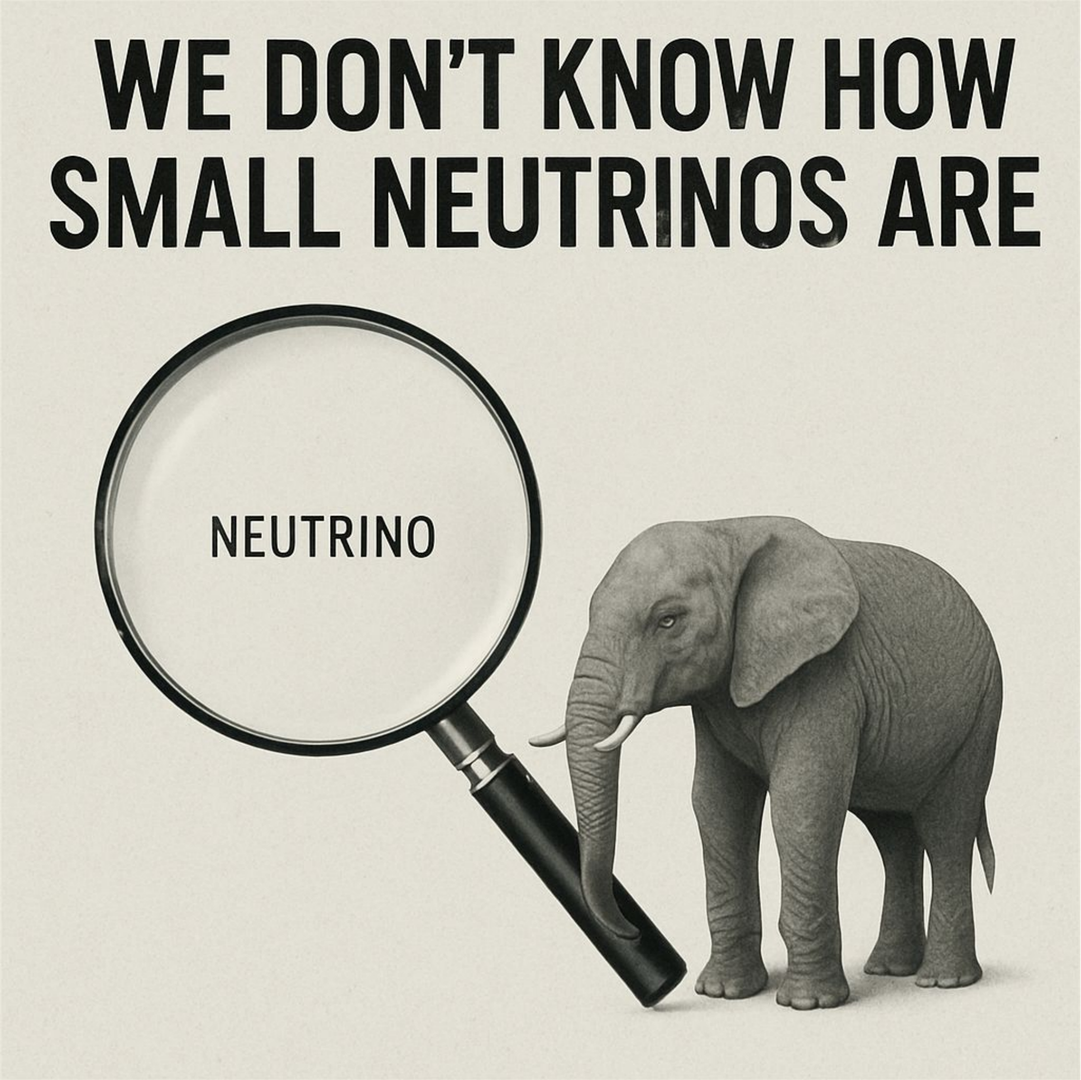
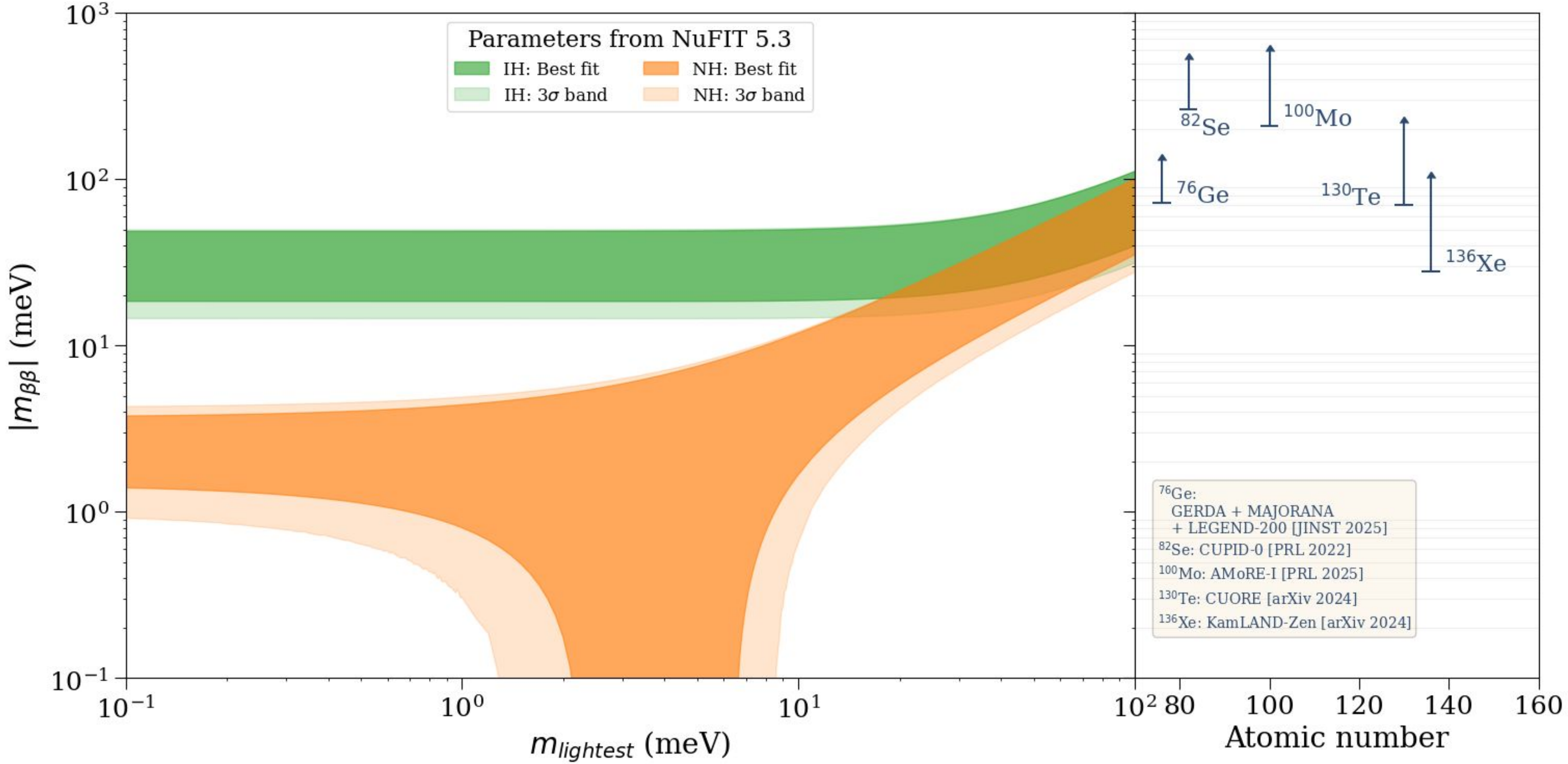

WE DON'T KNOW HOW
SMALL NEUTRINOS ARE
NEUTRINO

Where are we now?

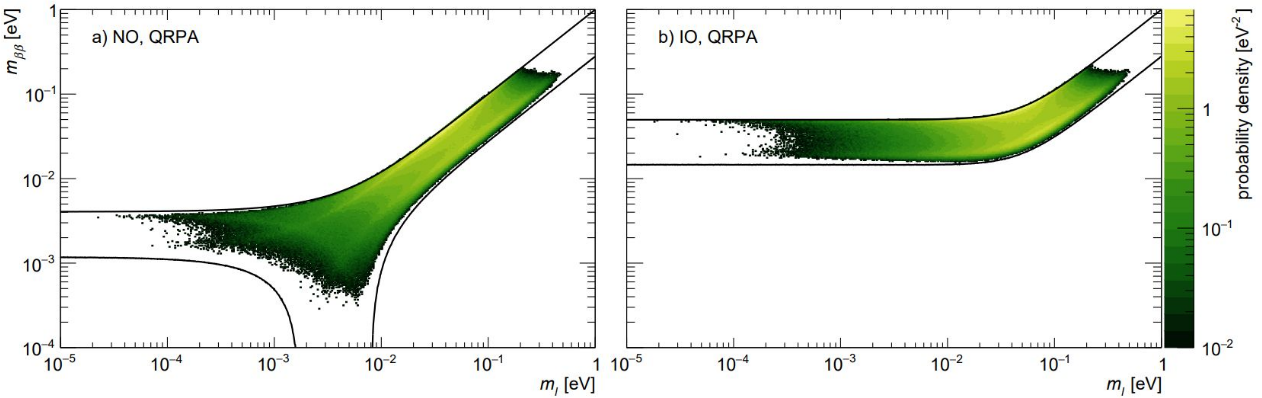


NO does not mean no chance!

Even if the ordering is normal, there is a good chance of discovery in the near future.

In the next 15 years, much of this parameter space will be excluded by experiments *other than* $0\nu\beta\beta$ searches.

What do we do in the case that $m_{lightest}$ is actually quite small?



M. Agostini, G. Benato, and J. A. Detwiler. "Discovery probability of next-generation neutrinoless double-β decay experiments." Physical Review D 96.5 (2017): 053001.

Note: Assumes a uniform prior distribution of Majorana phases and a log-uniform prior distribution on both $m_{\beta\beta}$ and $m_{lightest}$ with experimental constraints imposed.

Note: this does not include more recent limits on Σm_ν

The Landscape for Discovery

What do we do in the case that neutrinos are extremely light? (Even for neutrinos!)

Worst case scenarios:

- NO: $m_{\beta\beta} \approx 1 – 4$ meV
- IO: $m_{\beta\beta} \approx 13 – 50$ meV

In the IO case, the next generation of experiments has a good chance to make a discovery:

- LEGEND-200, CUPID: Sensitivities of ~ $T_{1/2} > 10^{27}$ yr ($m_{\beta\beta} < 15 – 60$ meV)
- LEGEND-1000, nEXO: Sensitivities of ~ $T_{1/2} > 10^{28}$ yr ($m_{\beta\beta} < 6 – 20$ meV)

In the NO case, it is very possible we need to realize the next-next generation of experiments to make a discovery.

How do we get to O(meV) $m_{\beta\beta}$ discovery sensitivities?

Simulating a Beyond Ton Scale Experiment

"Back of the envelope simulations" – signal plus a flat background

Signal parameters:

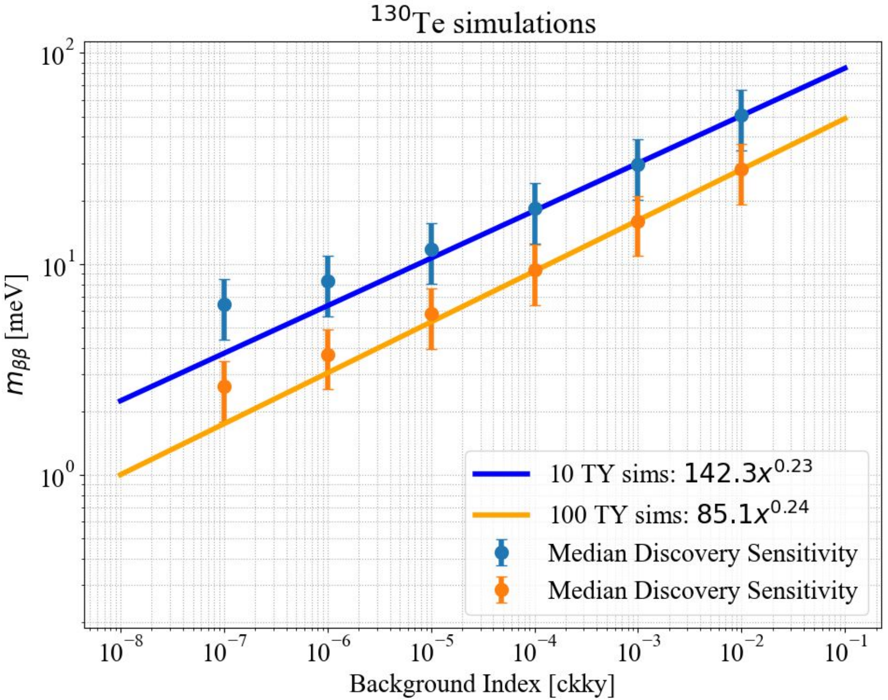
- FWHM = 5 keV
- $\varepsilon = \sqrt{0.6} \approx 0.775$ (signal efficiency)
- $f = \sqrt{0.6} \approx 0.775$ (isotopic fraction)

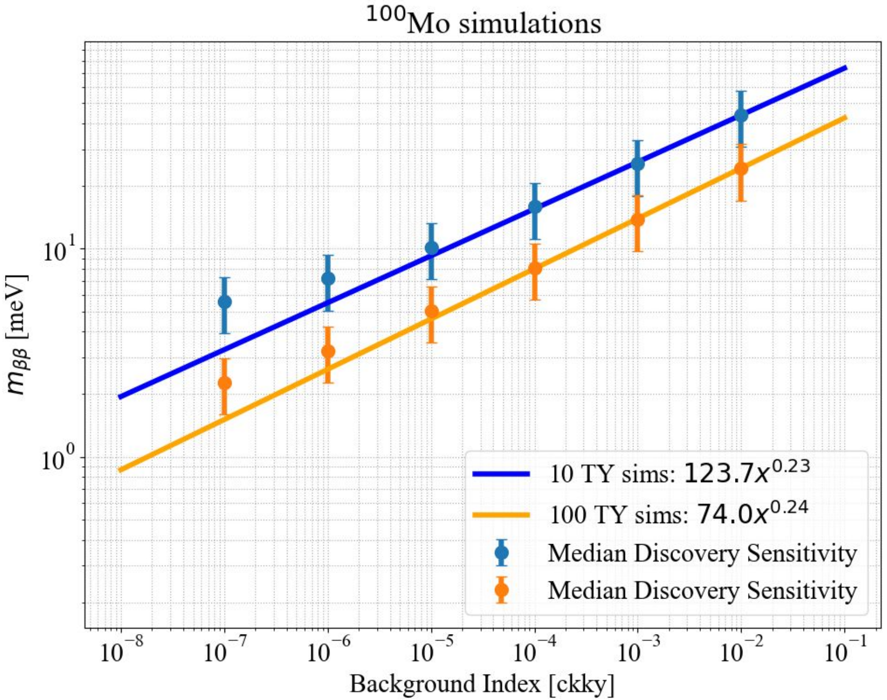
Sweep over background indices from 10^{-7} to 10^{-2} ckky for toy experiments with 10 TY and 100 TY of exposure while varying the injected rate.

Calculate the 3σ discovery sensitivity for all toys, and quote the median.

We're interested in discovery!

Results from Simulations





Note: fits are only to points in [10^{-4}, 10^{-2}] ckky. The power law should only hold in the background-dominated regime

A Potential Answer: Globolo*

“Globolo” is a proposal for a next-next generation distributed array of detectors specifically aimed at probing $0\nu\beta\beta$ decay over the vast majority of the normal ordering regime.

This would involve a series of ton-scale experiments, ideally distributed around the globe.

Today, I will pitch that bolometric experiments present a unique opportunity for such an endeavor.

GLOBOLO

GLOBAL CONSORTIUM OF EXPERIMENTS FOR NEUTRINOLESS DOUBLE BETA DECAY

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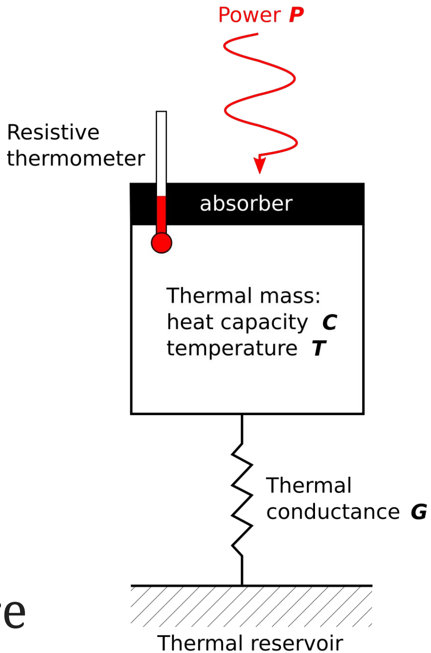
*It’s a working title.

What is a bolometer?

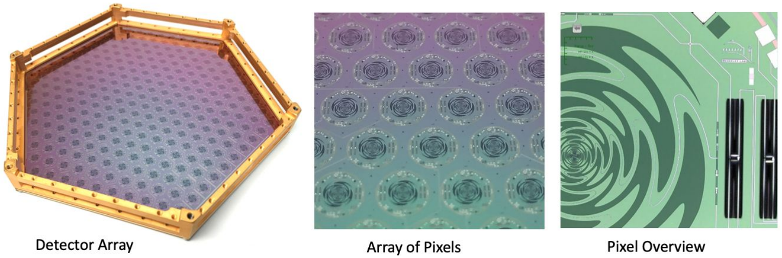
A bolometer is a device which measures power.

Often the terms calorimeters and bolometers get used interchangeably and one will often use “bolometer” though their ultimate goal is to measure energy.

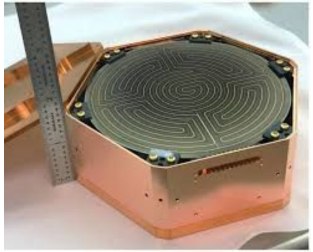
These have been used ubiquitously in CMB experiments, rare event searches, and precision nuclear physics measurements.

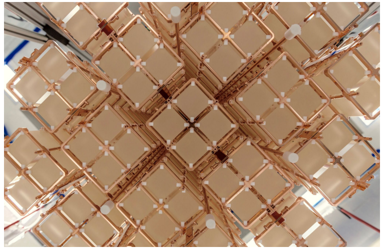


From Wikipedia

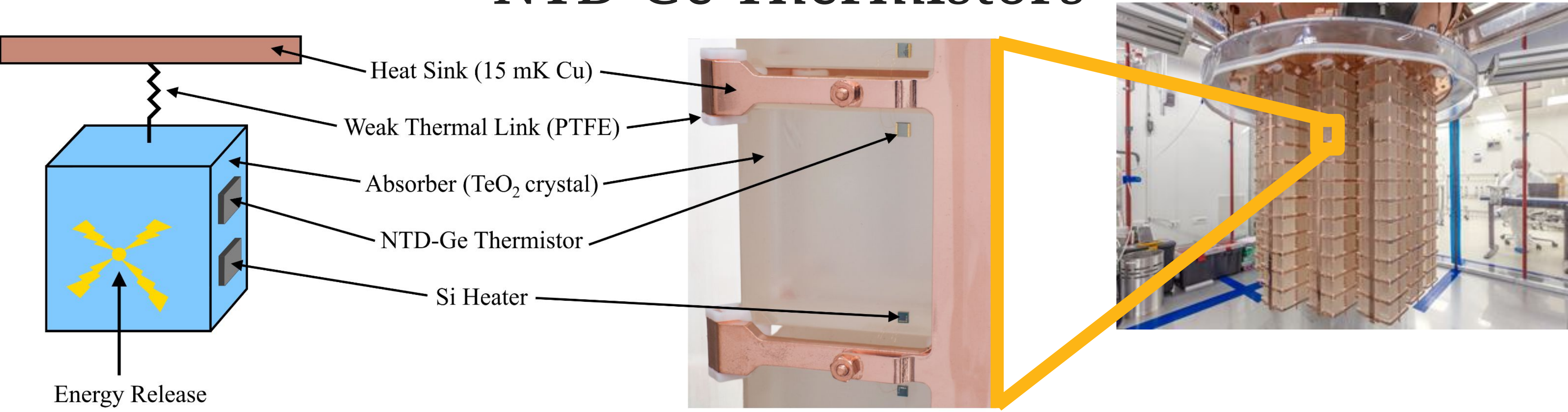


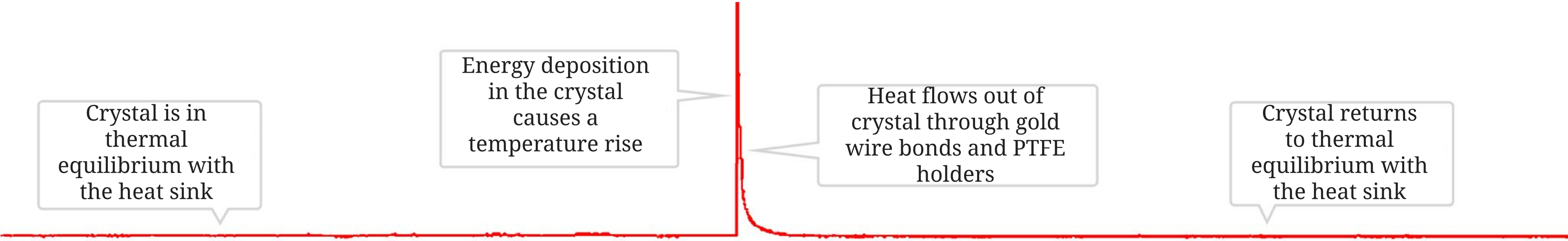
Credit: Aritoki Suzuki/ Berkeley Lab


Credit: E. L. Asamar, SuperCDMS SNOLAB

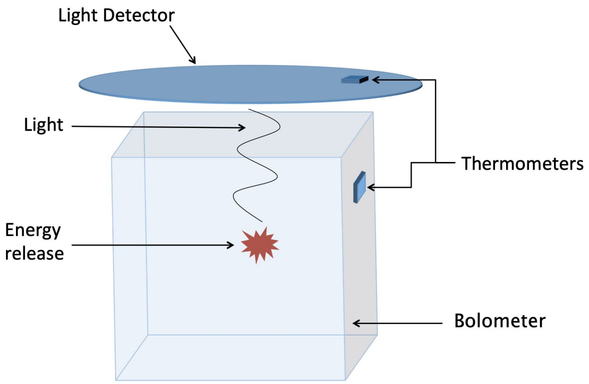

Credit: CUORE Collaboration

CUORE's Detector Technology: NTD-Ge Thermistors



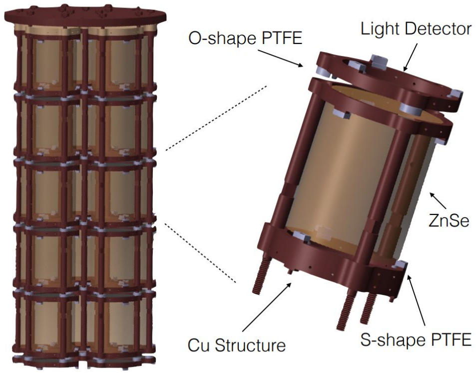


The CUPID Detector Technology: Scintillating Bolometers

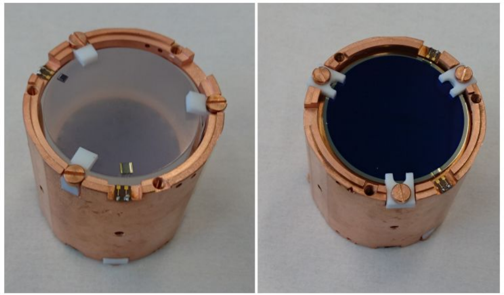


Scintillating crystals can be employed to collect light from events as well as heat.

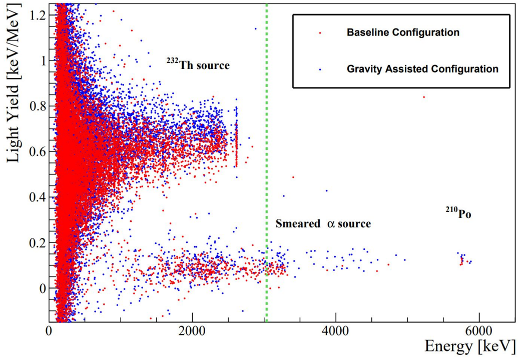
Gamma and beta radiation has a higher light yield per energy than alpha radiation, so alpha backgrounds can be rejected.



Credit: CUPID-0 Collaboration



Credit: CUPID-Mo Collaboration

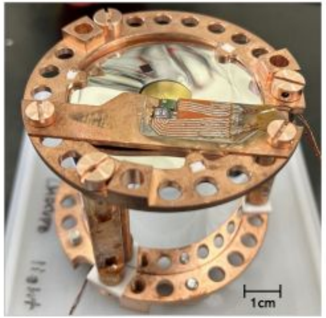


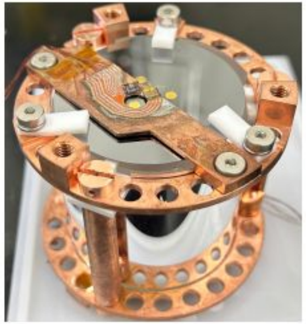
Credit: CUPID Collaboration

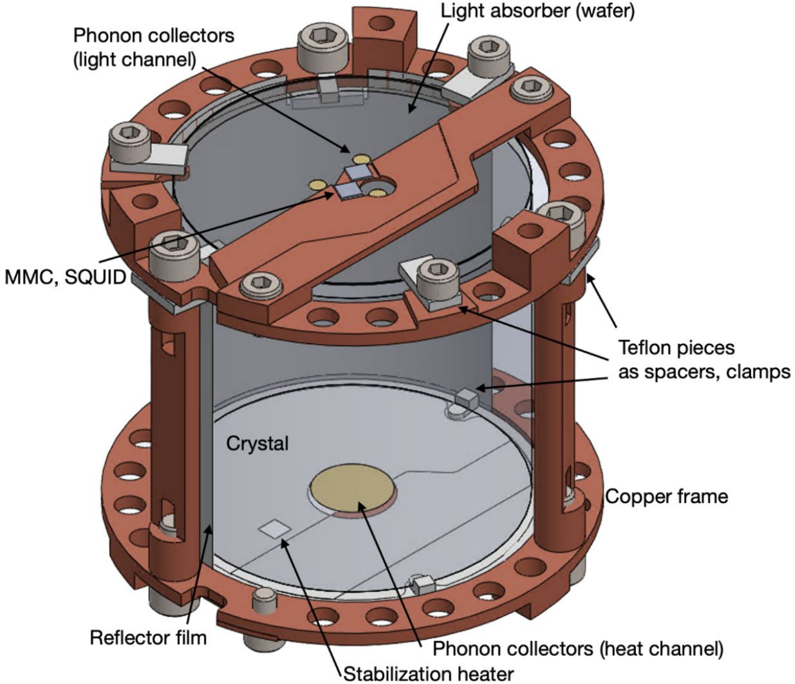
AMoRE's Detector Technology: Metallic Magnetic Calorimeters

Like CUPID-Mo and the planned CUPID, AMoRE uses the dual channel detection scheme:

- heat channel: phonons produced in crystal
- light channel: phonons produced in light-collecting wafter







Images from: Agrawal, A., et al. "Development of MMC-based lithium molybdate cryogenic calorimeters for AMoRE-II." *The European Physical Journal C* 85.2 (2025): 1-13.

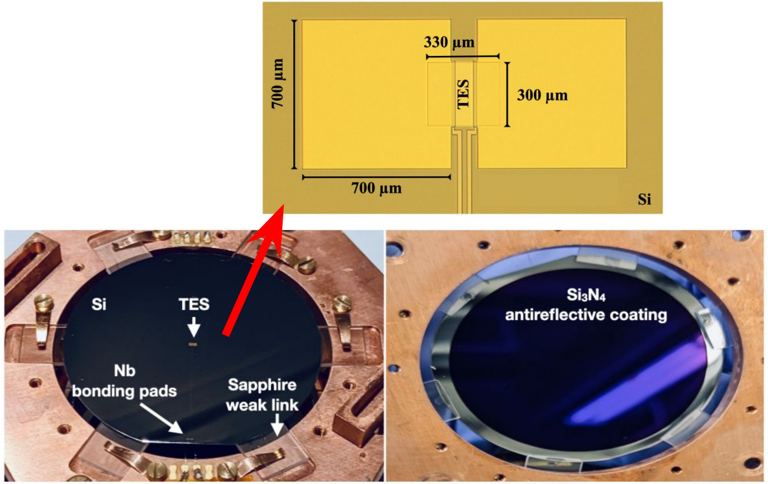
Images from: Singh, V., et al. "Large-area photon calorimeter with Ir-Pt bilayer transition-edge sensor for the CUPID experiment." Physical Review Applied 20.6 (2023): 064017.

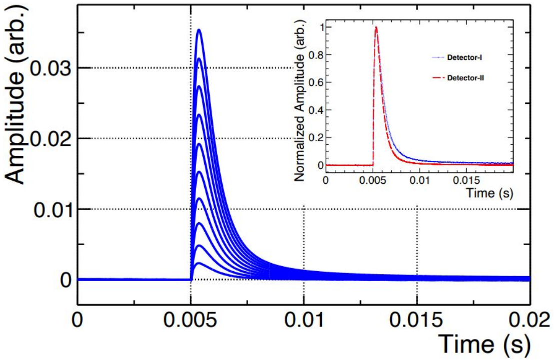
Other options: TES

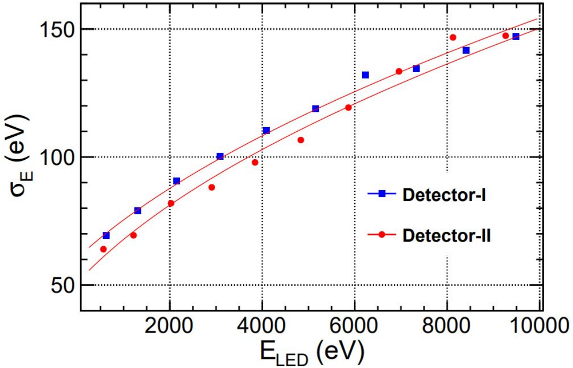
Transition Edge Sensors (TES) have excellent energy resolution and timing resolution.

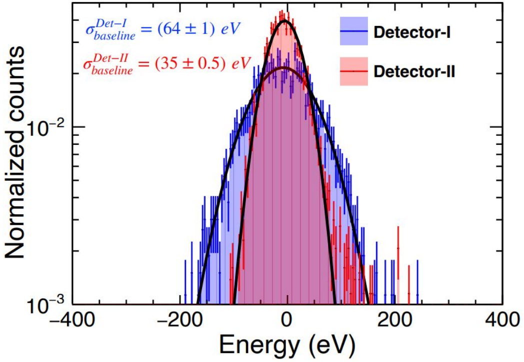
Signals require SQUID amplification.

O(10^3) detectors → Lots of cabling! Requires multiplexing









A Comparison of Current Experiments

Experiment	Isotope	Isotopic Mass [kg]	Isotopic Exposure [kg · yr]	$T_{1/2}$[yr]	$m_{\beta\beta}$ [meV]	Efficiency [%]	Background Index [counts KeV^{-1} kg^{-1} yr^{-1}]
CUORICINO	^{130}Te	11	19.75	$\geq 2.8 \cdot 10^{24}$	$\leq$300–710	79.7 ± 1.4	0.2 ± 0.04
CUORE-0	^{130}Te	10.9	9.8	$\geq 2.7 \cdot 10^{24}$	$\leq$270–760	81.3 ± 0.6	$(5.8 \pm 0.4_{sys} \pm 0.2_{stat}) \cdot 10^{-2}$
CUORE	^{130}Te	206	567	$\geq 3.8 \cdot 10^{25}$	$\leq$70-240	82.5 ± 1.5	$(1.38 \pm 0.07) \cdot 10^{-2}$
CUPID-0	^{82}Se	4.65	8.82	$\geq 4.6 \cdot 10^{24}$	$\leq$263–545	70 ± 1	$(3.5 \pm 1.0) \cdot 10^{-3}$
AMoRE-pilot	^{100}Mo	0.68	0.727	$\geq 3.0 \cdot 10^{23}$	$\leq$1200 - 2100[1]	81.6	0.38
AMoRE-I	^{100}Mo	3	3.89	$\geq 2.9 \cdot 10^{24}$	$\leq$210–610	70.9 ± 1.6	0.025 ± 0.002
CUPID-MO	^{100}Mo	2.26	1.47	$\geq 1.8 \cdot 10^{24}$	$\leq$280 - 490	$67.1 \pm 1.7)$	$(4.7 \pm 1.7) \cdot 10^{-3}$

Current experiments, particularly CUORE, have demonstrated that large-scale detectors can be operated for long periods of time.

CUORE cryostat experimental volume ~ $1m^3$, detector mass = 742 kg $^{nat}TeO_2$

Ton-scale implementations of experiments are realizable now. Getting to tens of TY will require a network of many of these.

Why a Global Distributed Network?

- Infrastructure constraints
  - Cryostats are only so big – reaching tens of TY would require either unrealistically large cryostats or unreasonably long runtimes.
  - Advances in cryostat infrastructure can be expected in the next 15 years. e.g. Planned Colossus cryostat at Fermilab has experimental volume of ~4.7 m^3, about 5x that of CUORE
    - Even as cryostats get larger, cooling power needs to scale accordingly, else cooling time contributes significant hit to potential exposure.
- Costs
  - A distributed network allows countries, labs, institutions to share the financial costs of the experiment (across space *and* time!)

Why a Global Distributed Network?

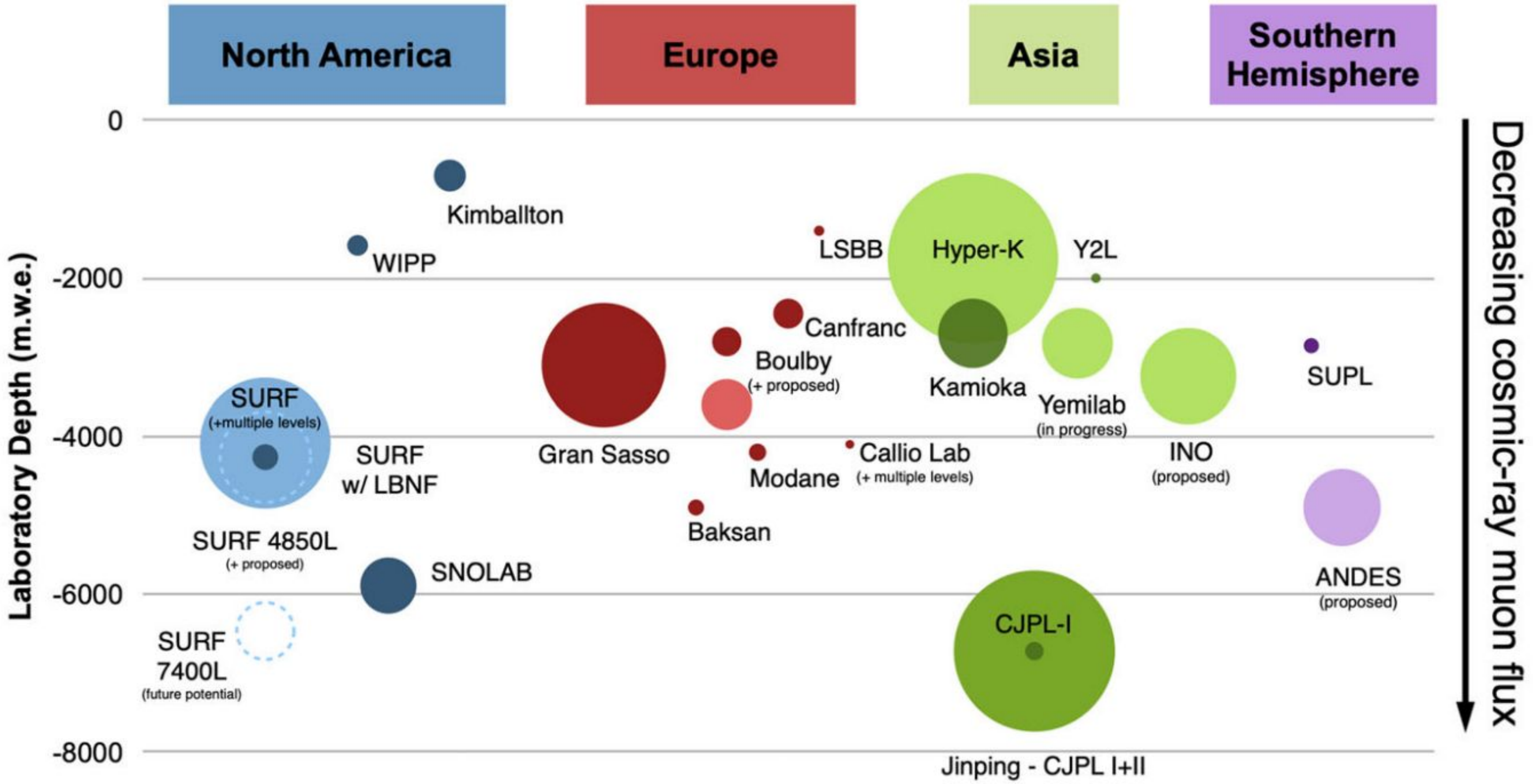
- Background Scaling
  - Self-shielding is not a large effect in e.g. CUPID
    - Pileup, crystals, and detector parts are known to contribute ~10x more in CUPID simulations
    - Self-shielding benefits may have to be considered at BIs < 10^{-5}, but as cryostat volumes grow, the self-shielding will decrease the overall BI
      - Tagging these sorts of background events remains a challenge!
  - Distribution does not cost much in terms of overall sensitivity.

Why a Global Distributed Network?

- Timing & Flexibility in the Scientific Landscape
  - As next-generation detectors begin to turn on, we exclude more of the parameter space, particularly that which is shared by IO and NO.
  - Now is the perfect time. With a horizon of 15 years:
    - Constraints on $m_{lightest}$ will hopefully strengthen by an order of magnitude.
    - The ordering problem will hopefully be resolved.

Image from: L. Baudis, J. Hall, K.T. Lesko, J.L. Orrell, Snowmass 2021 underground facilities and infrastructure overview topical report (2022). arXiv:2212.07037 [hep-ex] (Originally from Jaret Heise, SURF)

The Global Underground Scene



(Some of the) Challenges

- Getting background indices below 1e-5 ckky
  - Self-shielding becomes a possibility.
    - We are studying this now with a new(er) postdoc at MIT now!
  - Pile-up discrimination techniques can be employed.
    - Machine learning opens many possibilities here.
    - Faster detectors will make this less of an obstacle.

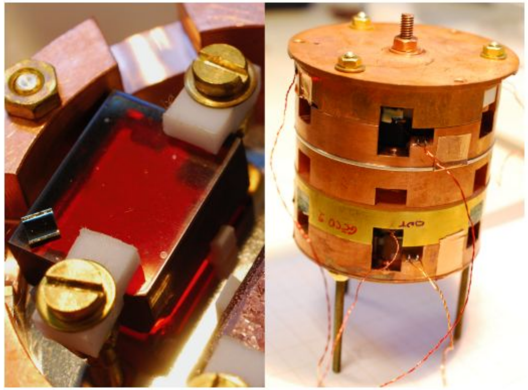
- “Getting to 0.6”
  - In simulations, $\varepsilon f = 0.6$
    - For crystals, the isotopic fraction is <1 even after enriching.
    - Options include enriching, or using e.g. ^{nat}Te and accounting for the factor of 3 difference in isotopic exposure (in mass or live-time.)

Where We Go Next

- Ton-scale experiments will probe and likely rule out the inverted hierarchy in the next generation.
- If the mass ordering is normal, a global network of ton-scale experiments must expand rapidly to remain competitive. If $m_{lightest}$ is small, further expansion will be key to reaching O(meV) sensitivities.
- A distributed network of ton-scale experiments offers a unique approach to scaling while parameter constraints tighten.
- In 15 years, a global effort to build a network of ton-scale experiments across facilities like SNOLAB will likely be necessary.

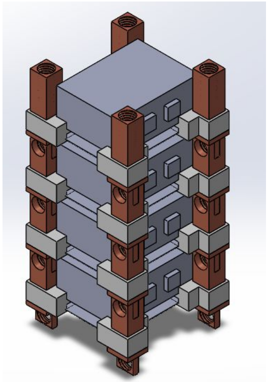
What do we do right now?

- Precision beta decay measurements
  - Small crystal arrays instrumented with TES (similar to previous studies at MIT)
- To prepare for a normal hierarchy experiment, much R&D still needs to be done
  - Hardware and firmware for multiplexing TES with bolometer crystals (μMUX)
- CUTE would be a great test bed for these runs!
  - Even ^{150}In measurements are quick – O(50g · days) give plenty of sensitivity!



Detector to measure the beta decay spectrum of ^{115}In fabricated and operated at IJCLab, Orsay, in collaboration with MIT.

Leder, A. F., et al. "Determining g_A/g_V with high-resolution spectral measurements using a $LiInSe_2$ bolometer." Physical Review Letters 129.23 (2022): 232502.

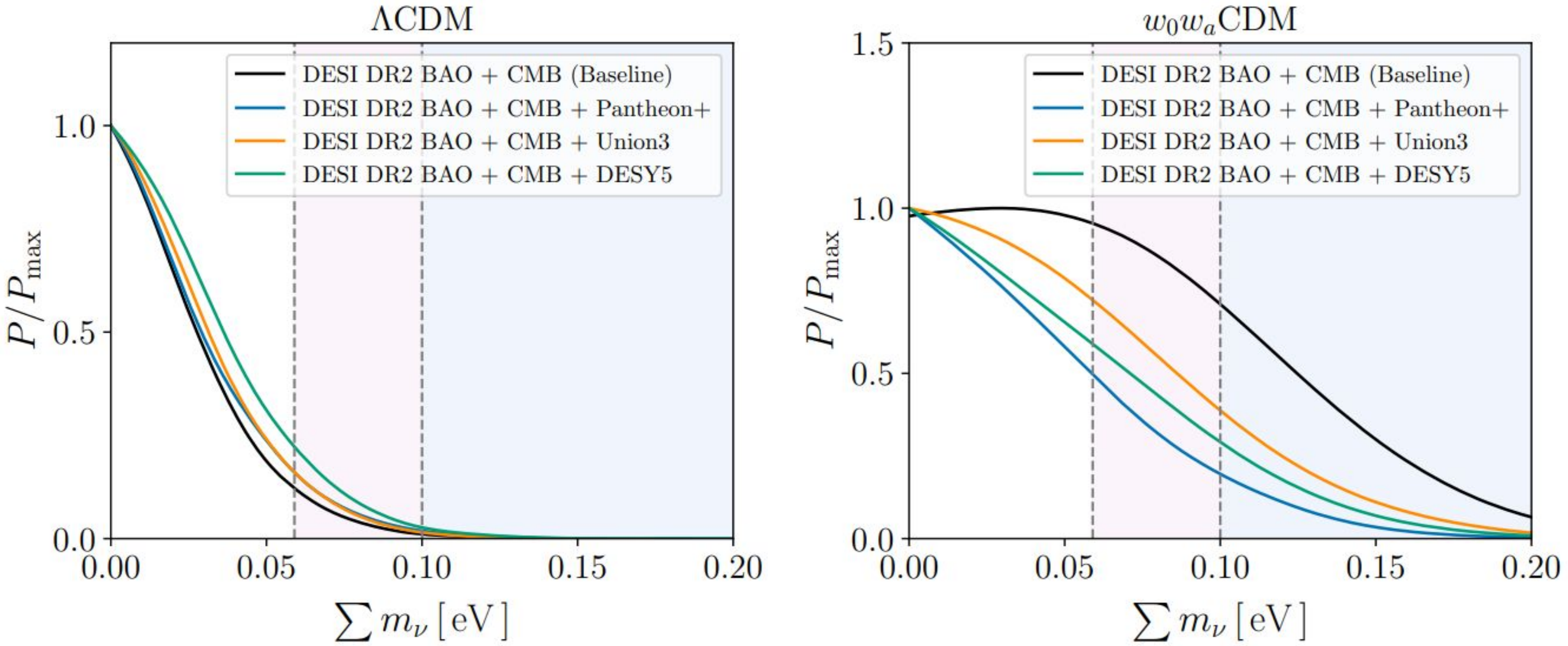


A preliminary CAD design of a multi-crystal detector array. Courtesy: Braeden Baker, MIT

Thank you

Backup

A note on Cosmological Constraints



Elbers, W., et al. "Constraints on neutrino physics from DESI DR2 BAO and DR1 full shape." arXiv preprint arXiv:2503.14744 (2025).

A note on Cosmological Constraints

Blue: $m_{lightest}$ = 0 for IO
Pink: $m_{lightest}$ = 0 for NO

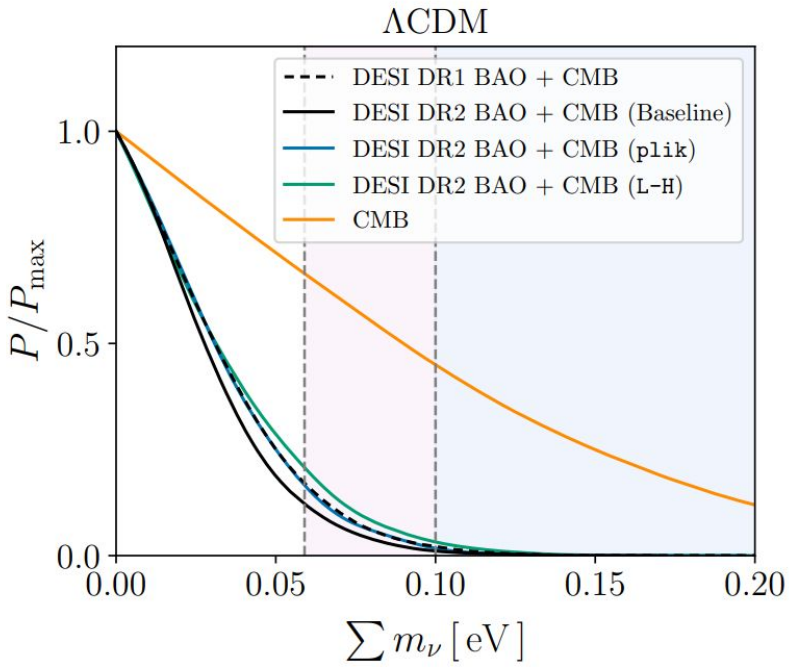
Cosmological limits with "plain ΛCDM" strongly disfavor the allowed values of sum Σm_ν given oscillation parameters.

Limit using $w_a w_0$CDM model:

$$\Sigma m_\nu < 0.16 \text{ eV (95\% CL)}$$

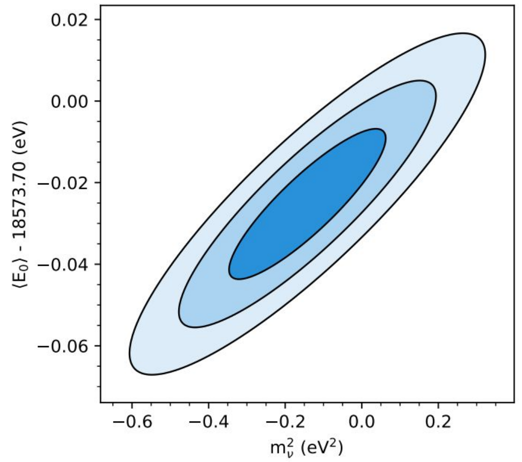
When fitting DESI+CMB+CamSpec with NuFit-6.0 data for $m_{lightest} \geq 0$ with oscillation parameters added, the tension is relieved and allows for either hierarchy:

$$\Sigma m_\nu < 0.112 \text{ eV (95\% CL)}$$



Elbers, W., et al. "Constraints on neutrino physics from DESI DR2 BAO and DR1 full shape." arXiv preprint arXiv:2503.14744 (2025).

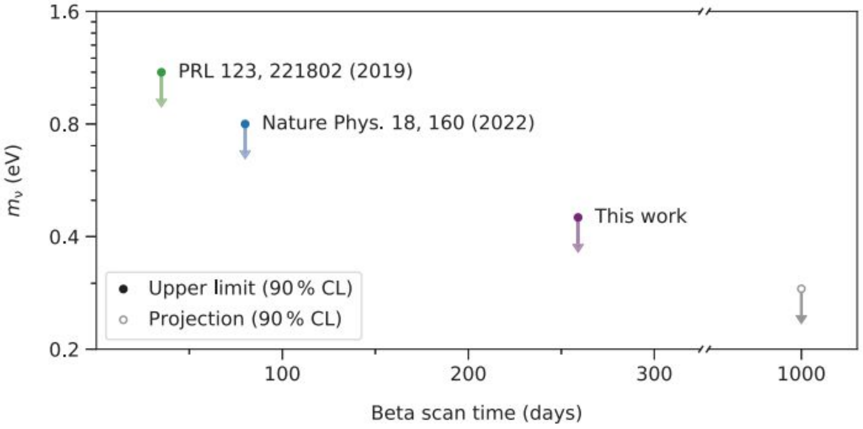
Direct Measurement Constraints



Direct measurements of the effective neutrino mass m_ν is possible by measuring the endpoint of the beta decay spectra.

Best limits currently come from KATRIN:

$$m_\nu < 0.45 \text{ eV (95\% CL)}$$



Do not yet rule out either mass ordering

Note: In this regime, $m_\nu \approx m_{lightest} = \frac{1}{3}\Sigma m_\nu$

Both images from:
KATRIN Collaboration, et al. "Direct neutrino-mass measurement based on 259 days of KATRIN data." *Science* 388.6743 (2025): 180-185.

A Quick Back of the Envelope

Take the number of expected signal counts to be $N_s = \frac{\varepsilon \cdot f \cdot \Gamma \cdot T \cdot M_{obs}}{m_{iso}}$, where:

- Γ = decay rate
- M_{obs} = observed mass
- ε = detection efficiency
- f = isotopic fraction of the detector (M_{iso} / M_{obs})
- m_{iso} = mass of single isotope of interest

For most isotopes of interest, $m_{iso} \sim 100$ Da $\sim 10^{-25}$ kg.

Let $N_s = 3$, and let $\varepsilon f = 0.6$: $T \cdot M_{obs}/\mathrm{kg} \sim 10^{-24}\, T_{1/2}$

To achieve $T_{1/2}$ of order $10^{28–29}$ yr, we need to reach exposures of 10 – 100 TY

A Quick Back of the Envelope

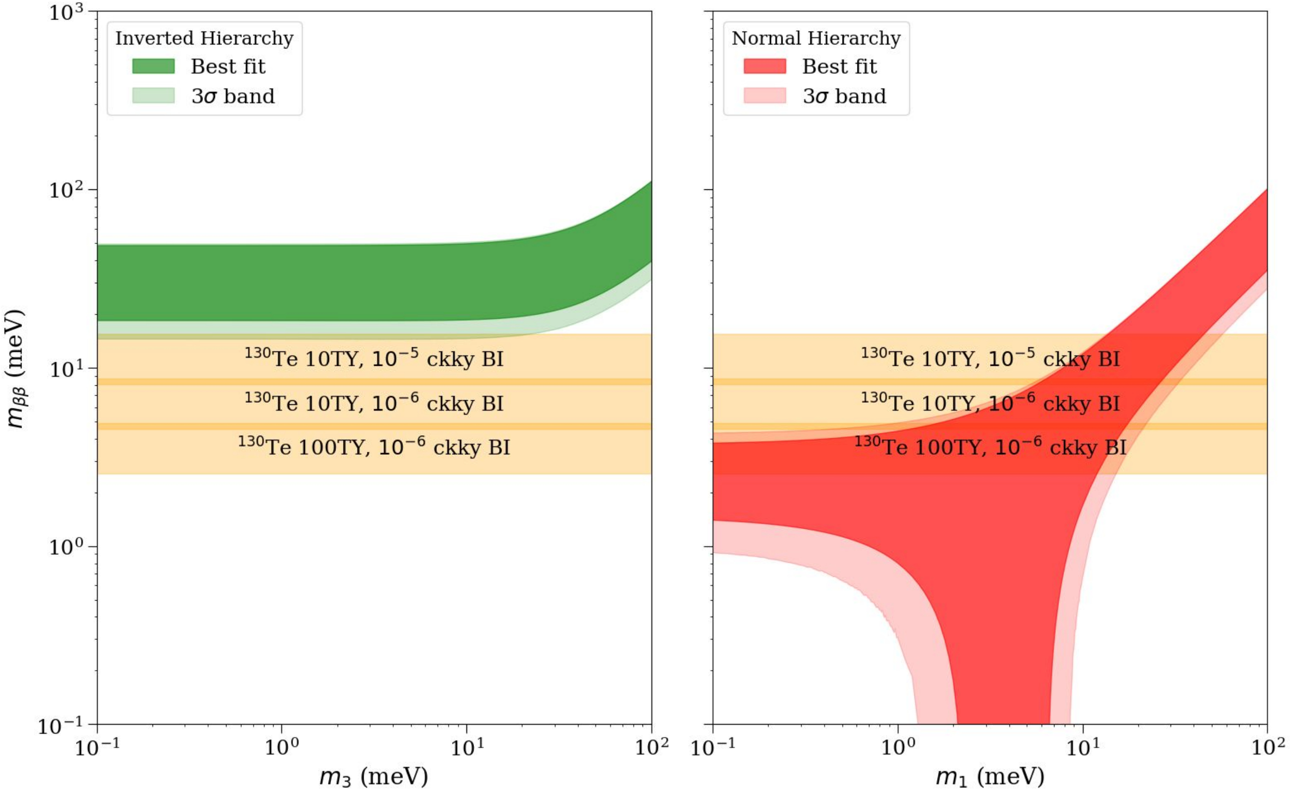
The number of expected background counts is $N_B = B \cdot \Delta E \cdot T \cdot M_{obs}$, where:

- B = background index (counts / (keV kg yr)
- ΔE = ROI width (typically several FWHM)

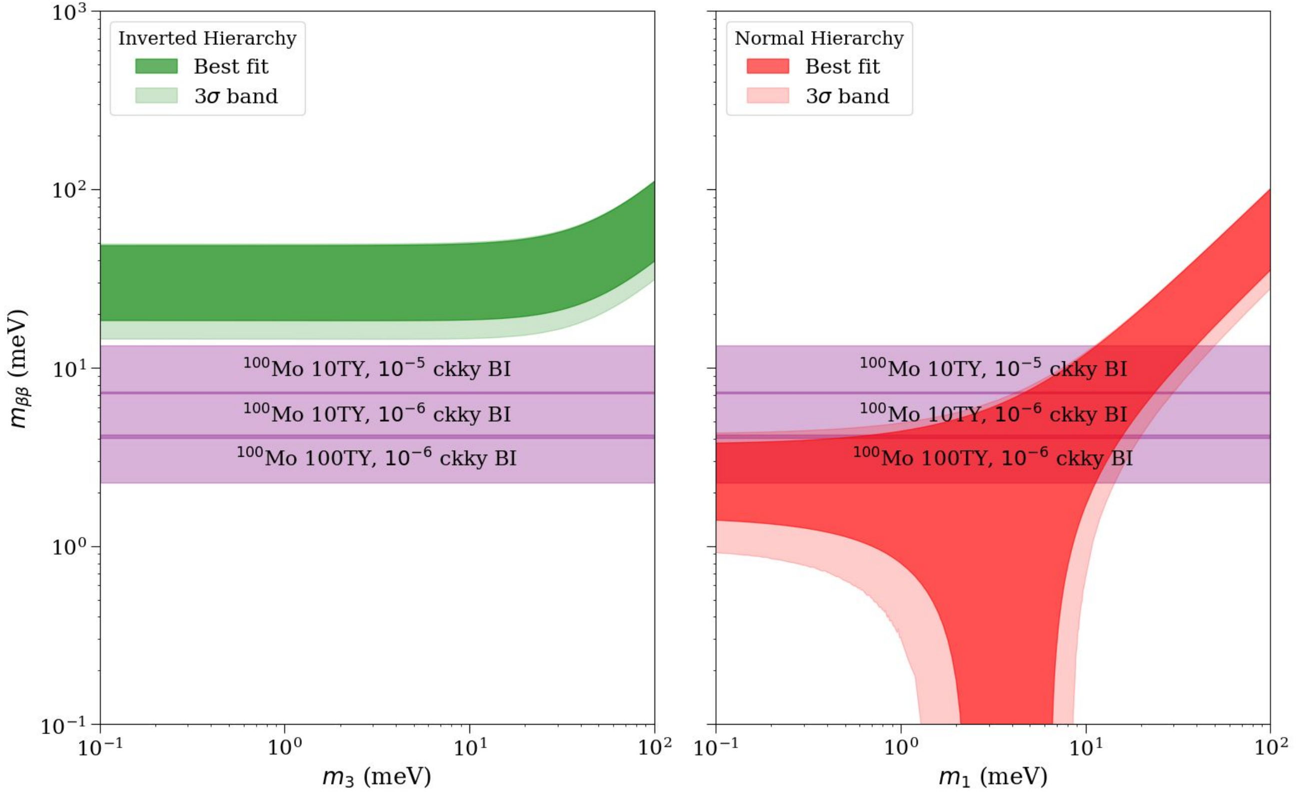
Given resolutions of order 1 – 10 keV, we can take ΔE to be several 10s of keV

For exposures of 10 – 100 TY, the quasi-background-free regime (B ~ 1) requires background indices of order 10^{-5} – 10^{-6} counts/(keV $\cdot$ kg $\cdot$ yr) (ckky)

Limits from Simulations



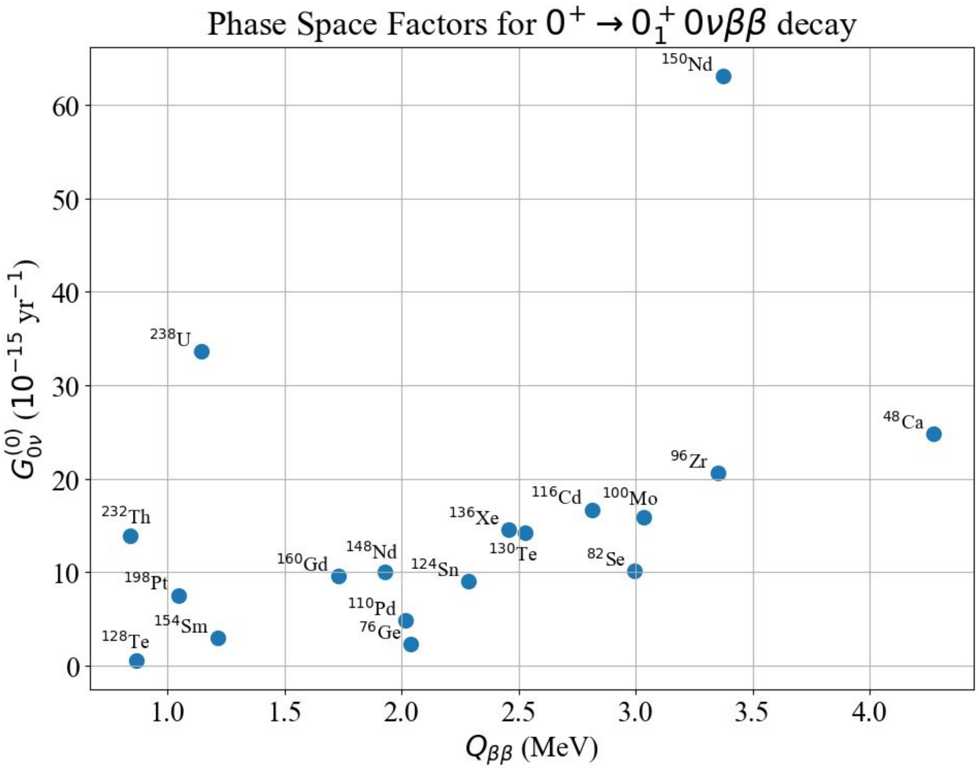
Limits from Simulations



Brief Comparison of Detector Technologies

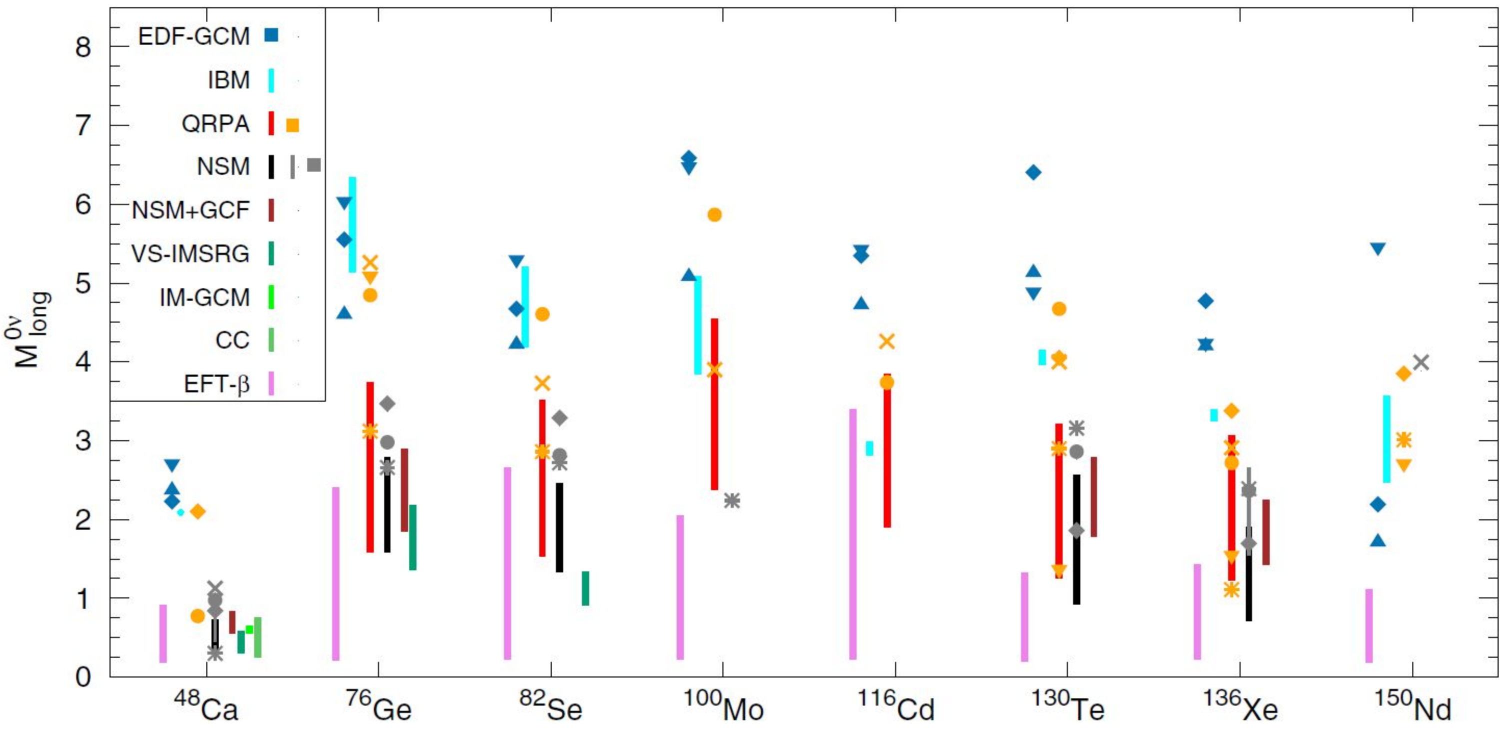
Instrumentation	Pros	Cons
NTD-Ge Thermistors	Proven Technology Good resolution	Slow detector response – O(1s) decay times
MMC	Good response time – O(10 ms) decay times	Resolutions ~ 2x larger than demonstrated in NTD-Ge
TES	Fast detector response – O(ms) decay times Excellent noise resolution	Require more sophisticated readout Significant challenges for macro-calorimeter implementation

Isotope Selection – Phase Space Factors



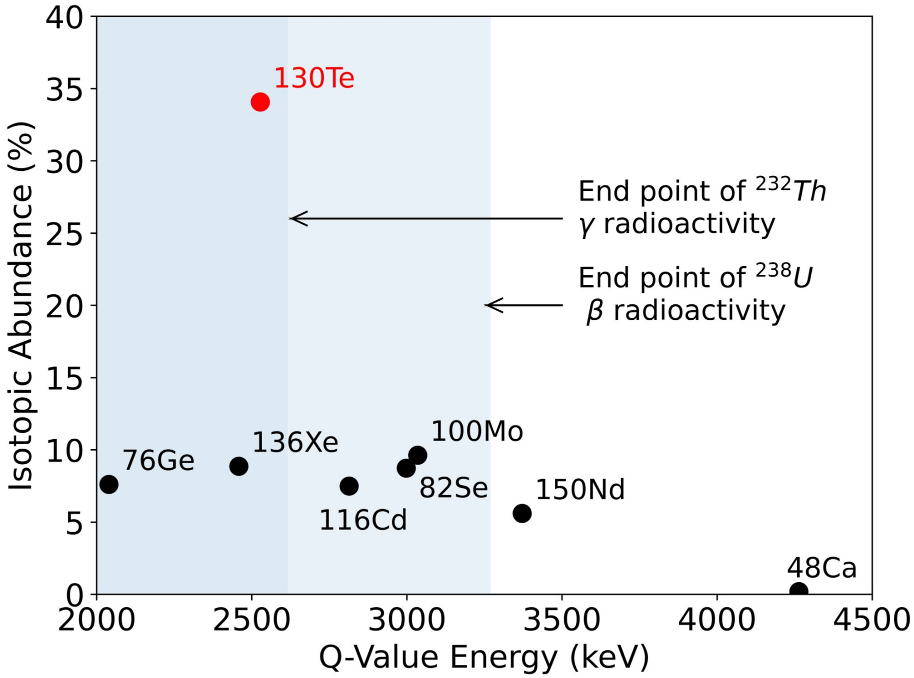
Data from Kotila, J., and F. Iachello. "Phase-space factors for double-β decay." Physical Review C—Nuclear Physics 85.3 (2012): 034316.

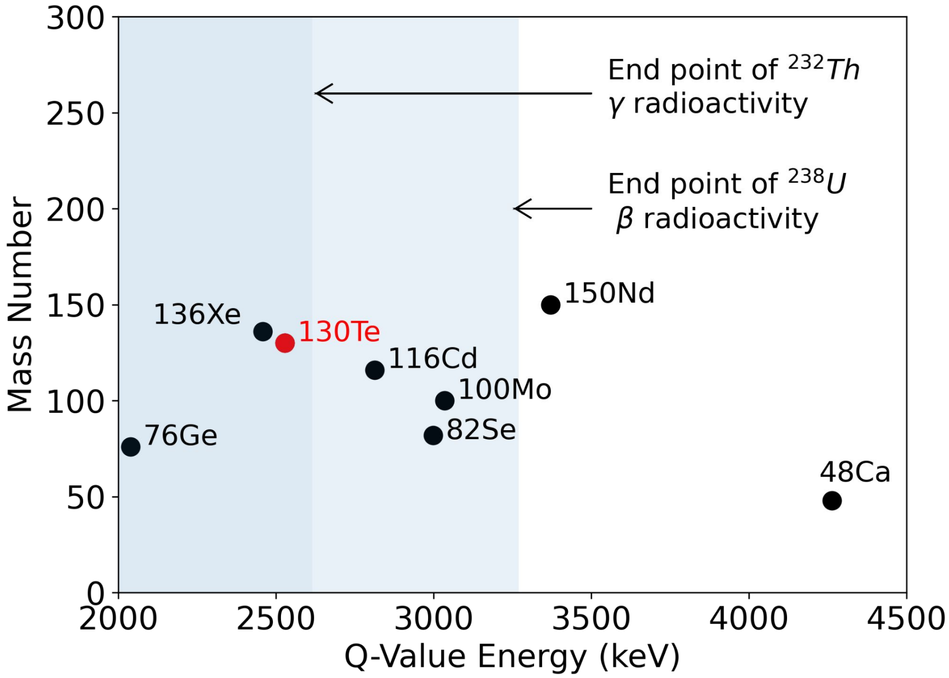
Isotope Selection – Matrix Elements



From Gómez-Cadenas, Juan José, et al. "The search for neutrinoless double-beta decay." La Rivista del Nuovo Cimento 46.10 (2023): 619-692.

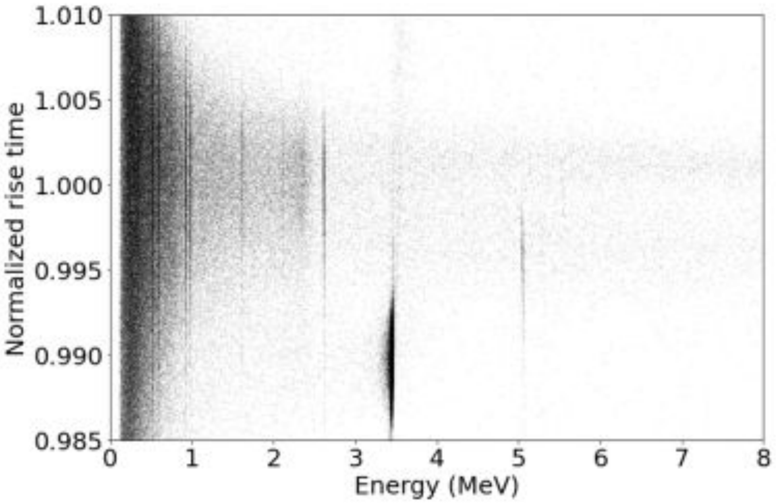
Isotope Selection – Isotopic Abundance

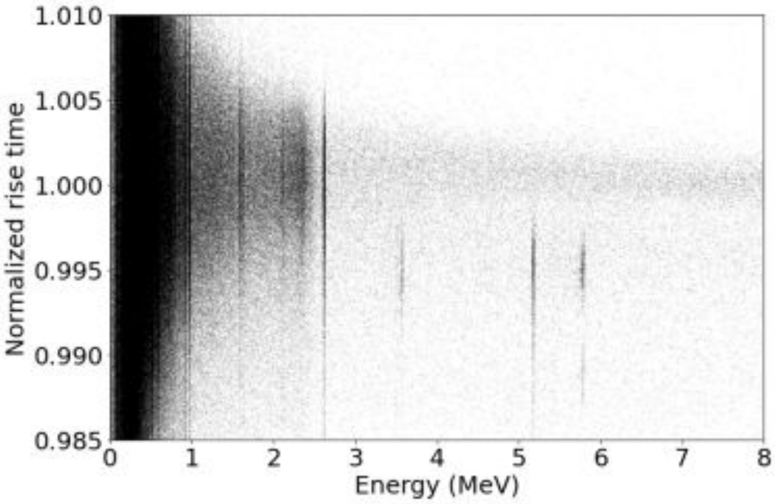




AMoRE’s Detector Technology: Metallic Magnetic Calorimeters

Together, the channels can discriminate alpha events leading to lower backgrounds in the region of interest (ROI).





Images from: Agrawal, A., et al. "Development of MMC-based lithium molybdate cryogenic calorimeters for AMoRE-II." *The European Physical Journal C* 85.2 (2025): 1-13.

Multi-dimensional Light Yield Cut in CUPID-Mo

The geometry of the CUPID-Mo detector array can be exploited to make a 2-dimensional cut on the light yield.

Light yield is fit to normal distributions in energy slices, then mean values fit to a polynomial fit.

The norm light yield cut is shown in red.

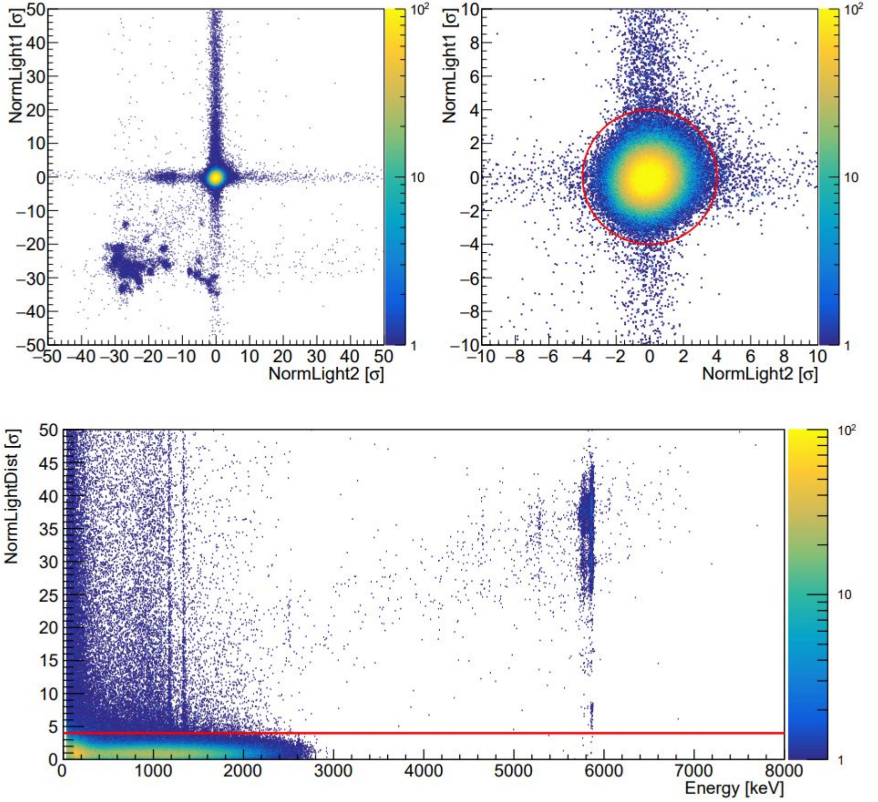


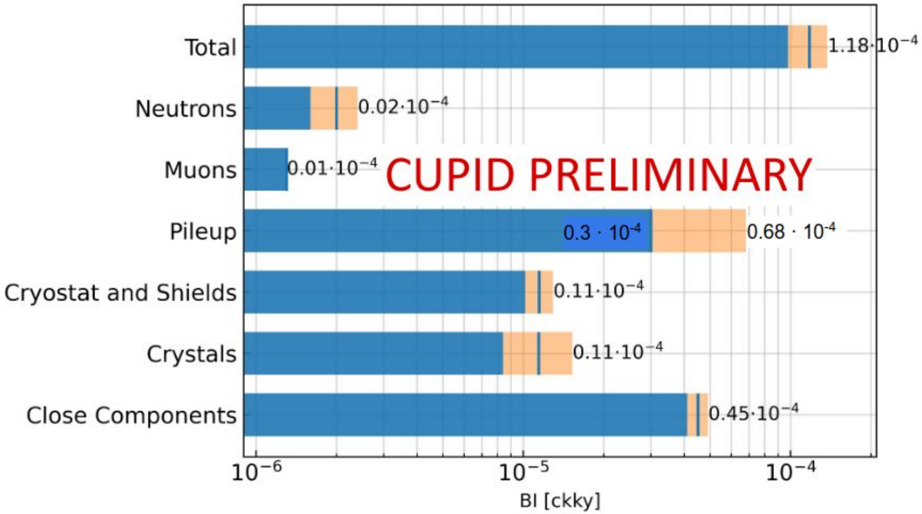
Image from: Augier, C., et al. "Final results on the 0νββ decay half-life limit of 100 Mo from the CUPID-Mo experiment." The European Physical Journal C 82.11 (2022): 1033.

Background Index Projections for CUPID

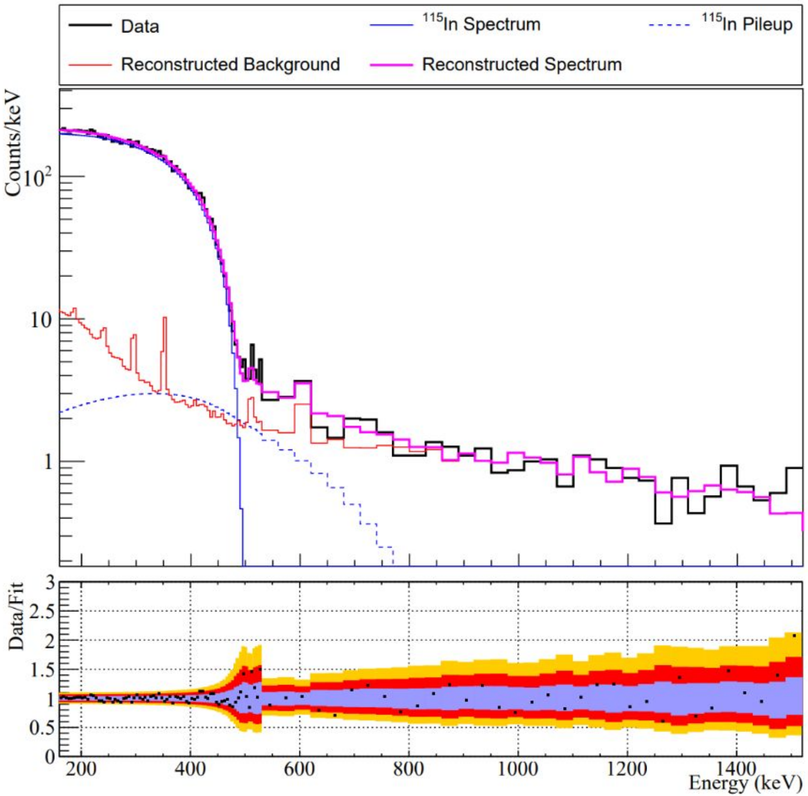
CUPID will use the CUORE cryostat. Total projected BI is dominated by close components and pileup

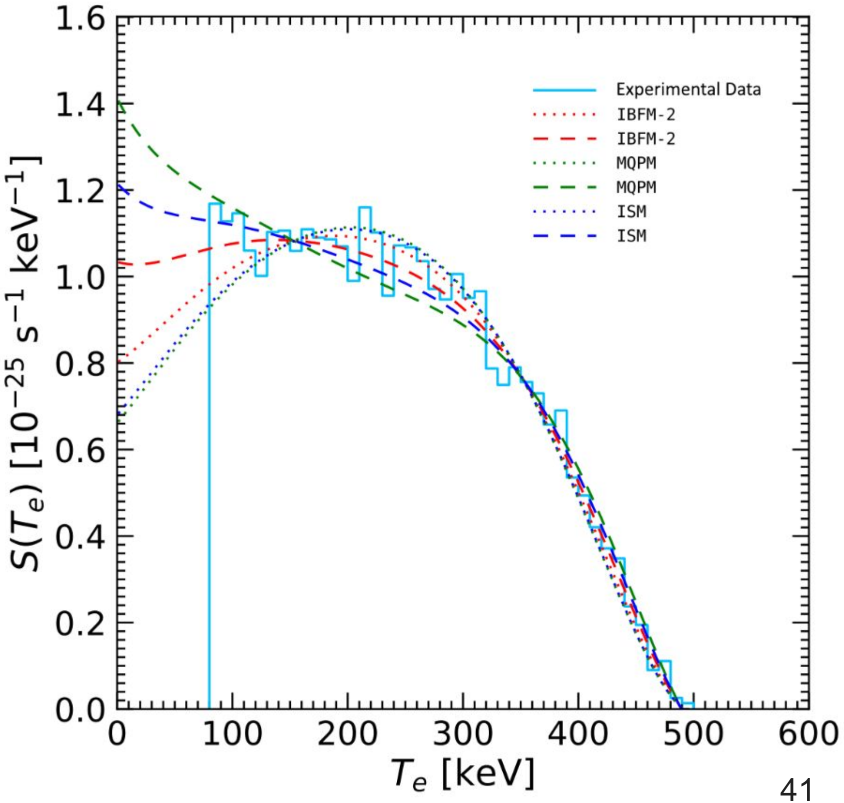
Crystals, cryostats, and shields become a significant problem at BIs of 10^{-5}

To go lower than 10^{-5}, self shielding considerations will need to be made and crystal production techniques and/or enrichment processes will need to be refined



^{115}In spectral measurements





Sensitivity with a Staged Approach