Neutrinoless Double Beta Decay Searches with Bolometric Detectors

T. O’Donnell

Virginia Tech

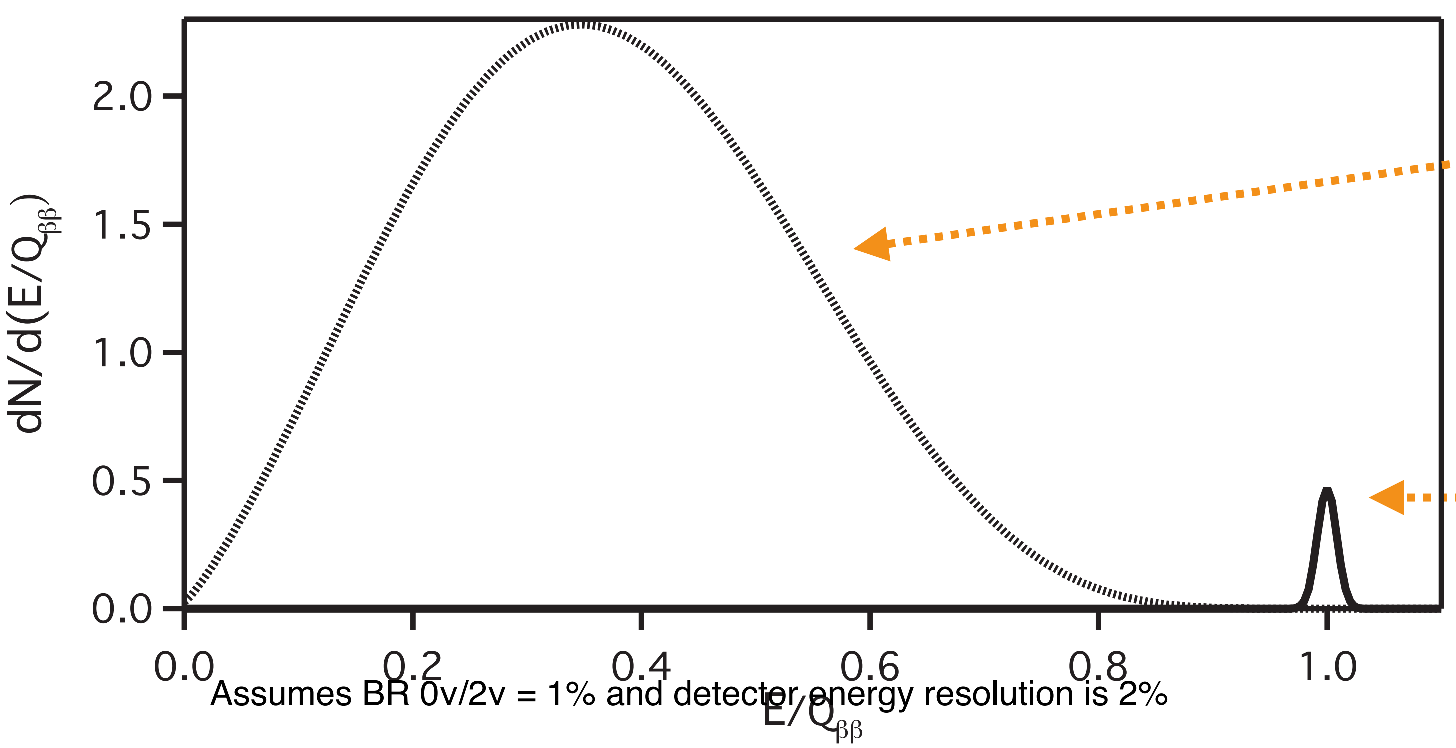
BLV 2019 - Oct 21 2019

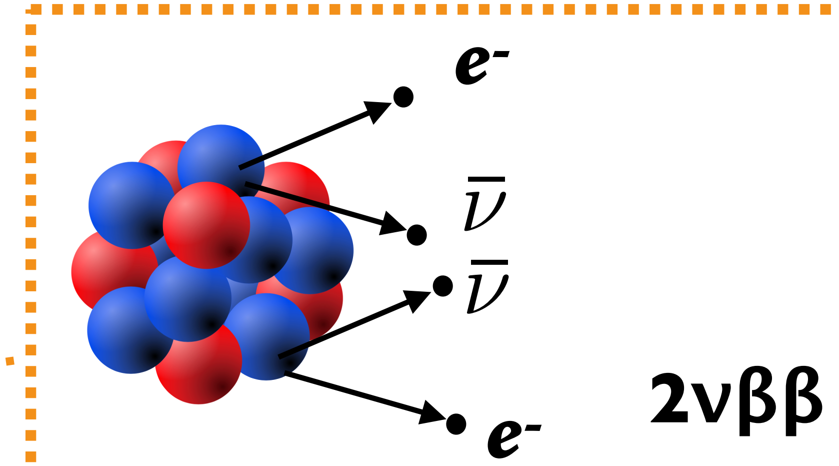
Outline

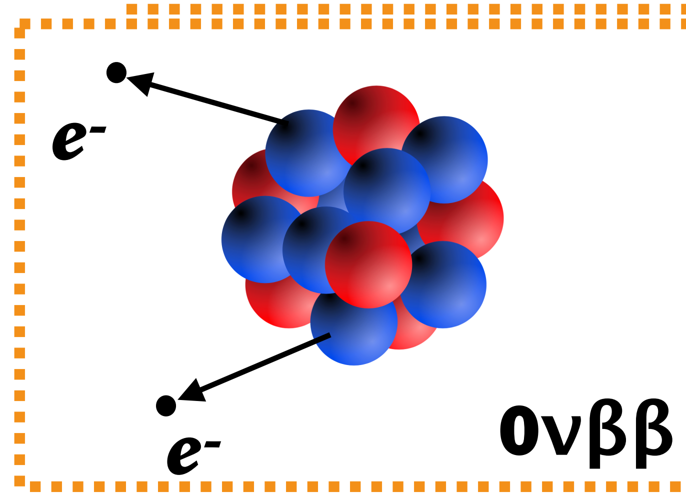
- Introduction to cryogenic bolometers
- CUORE: Status for TeO_2 bolometers
- Towards CUPID with scintillating bolometers
    - CUPID-0
    - CUPID-Mo
- AMORE: Another approach with scintillating bolometers
- Conclusions

Double-Beta Decay Signature

Summed-energy spectrum of final state electrons







In case of background

$$T^{0\nu}_{1/2} \text{ sensitivity } \propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$$

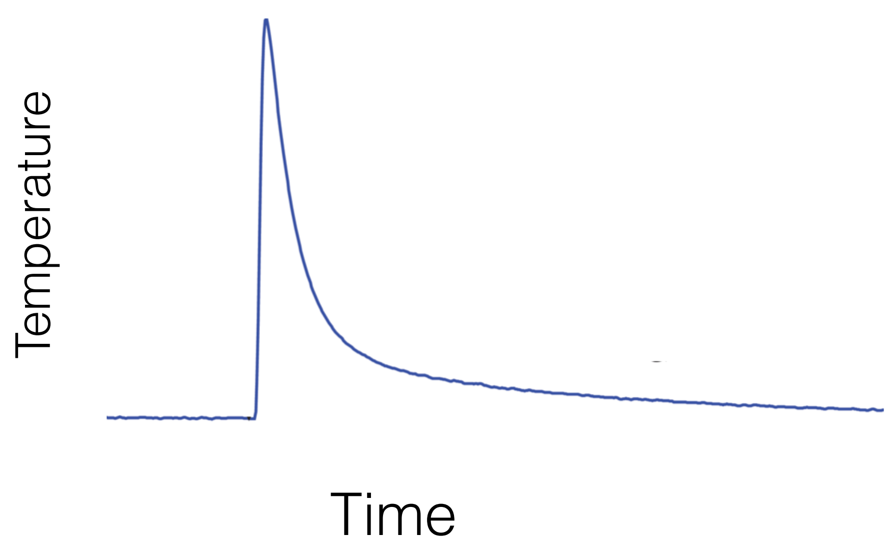
If background free

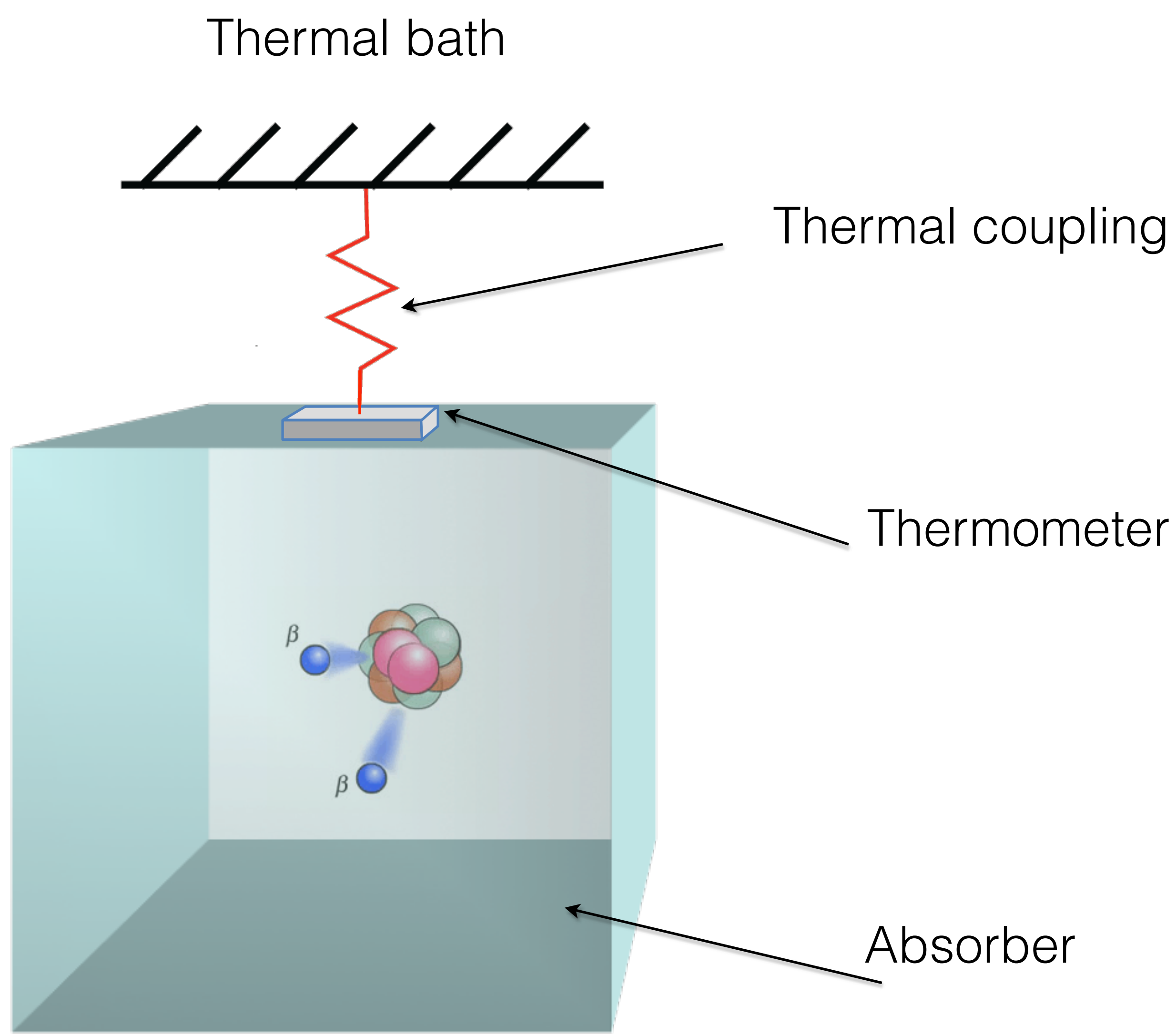
$$T^{0\nu}_{1/2} \text{ sensitivity } \propto a \cdot \epsilon \cdot M \cdot t$$

a	isotopic abundance of source
ε	detection efficiency
M	Total detector mass
b	bkg rate per unit mass per unit energy
t	exposure time
δE	energy resolution

Macro Bolometer Technique

- The absorbed energy causes an increase in absorber temperature
- For dielectric crystal absorbers, heat capacity $\sim T^3$

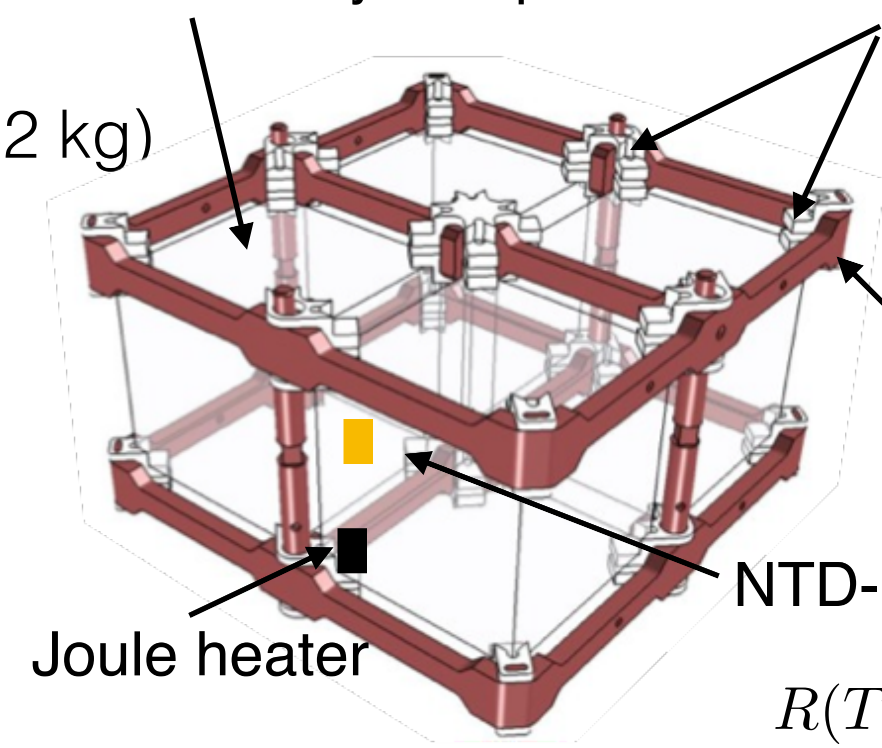




- Typically operated at ~10mK
- With appropriate calibration temperature change can be used to measure energy absorbed
- Relative energy resolution of 0.2~0.3% routinely achieved

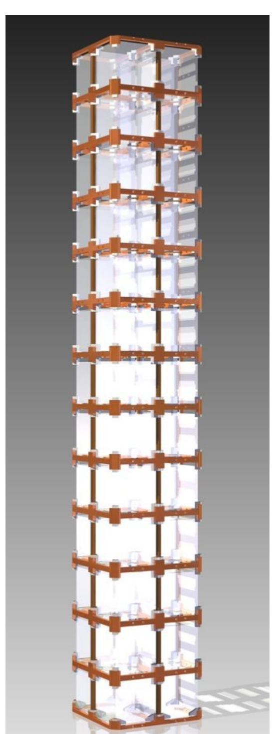
CURE

- Array of 988 $^{nat}TeO_2$ bolometers (742 kg)
- Operated at (T~11 mK)
- Target isotope ^{130}Te (206 kg)
- Q-value: 2527.5 keV

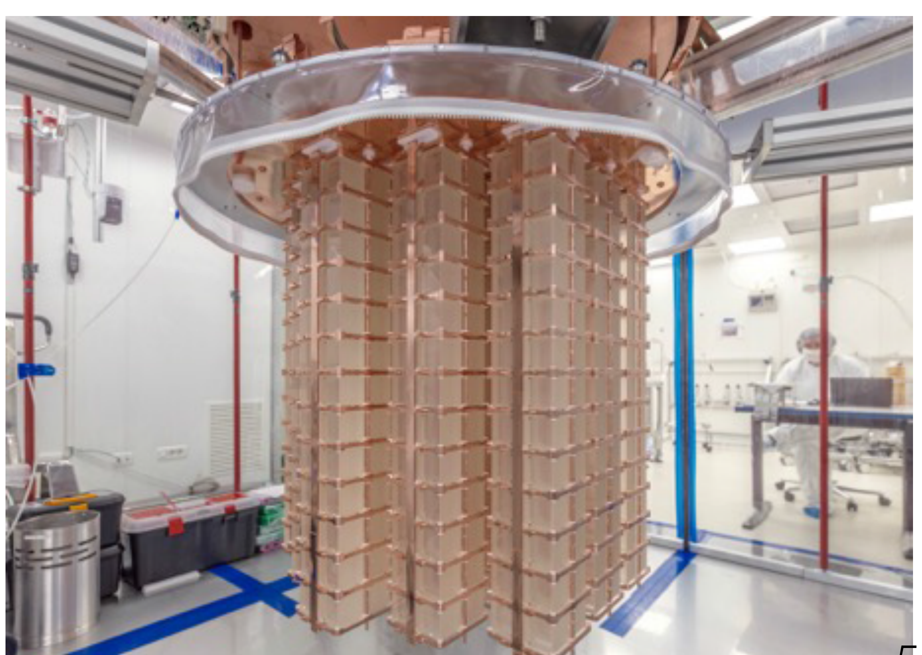


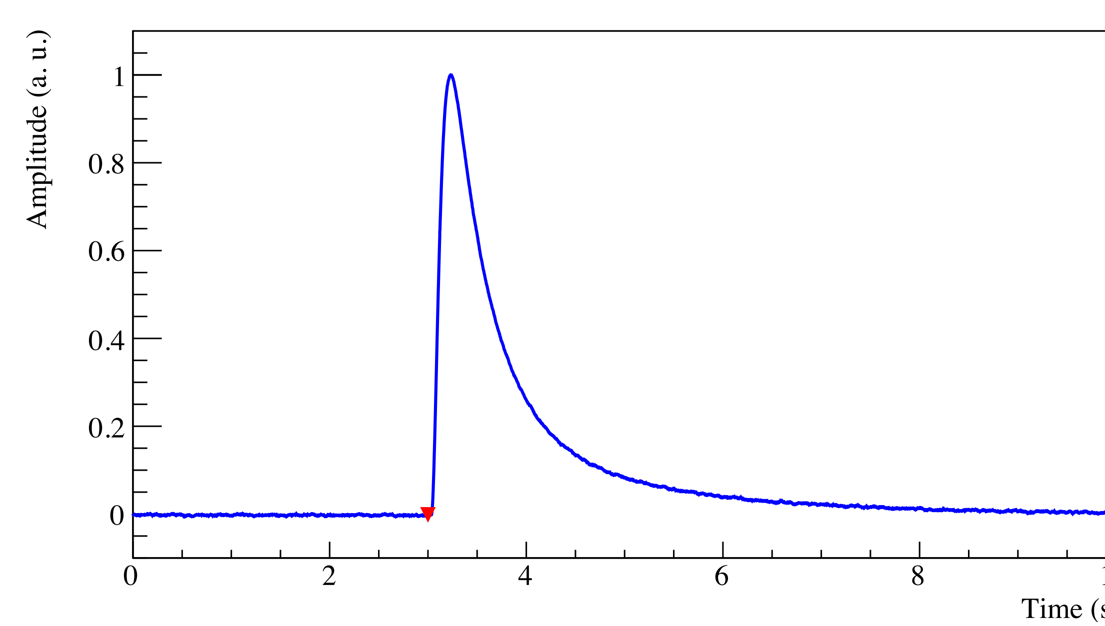
$$R(T) = R_0 \exp\sqrt{T_0/T}$$

13 floors per tower

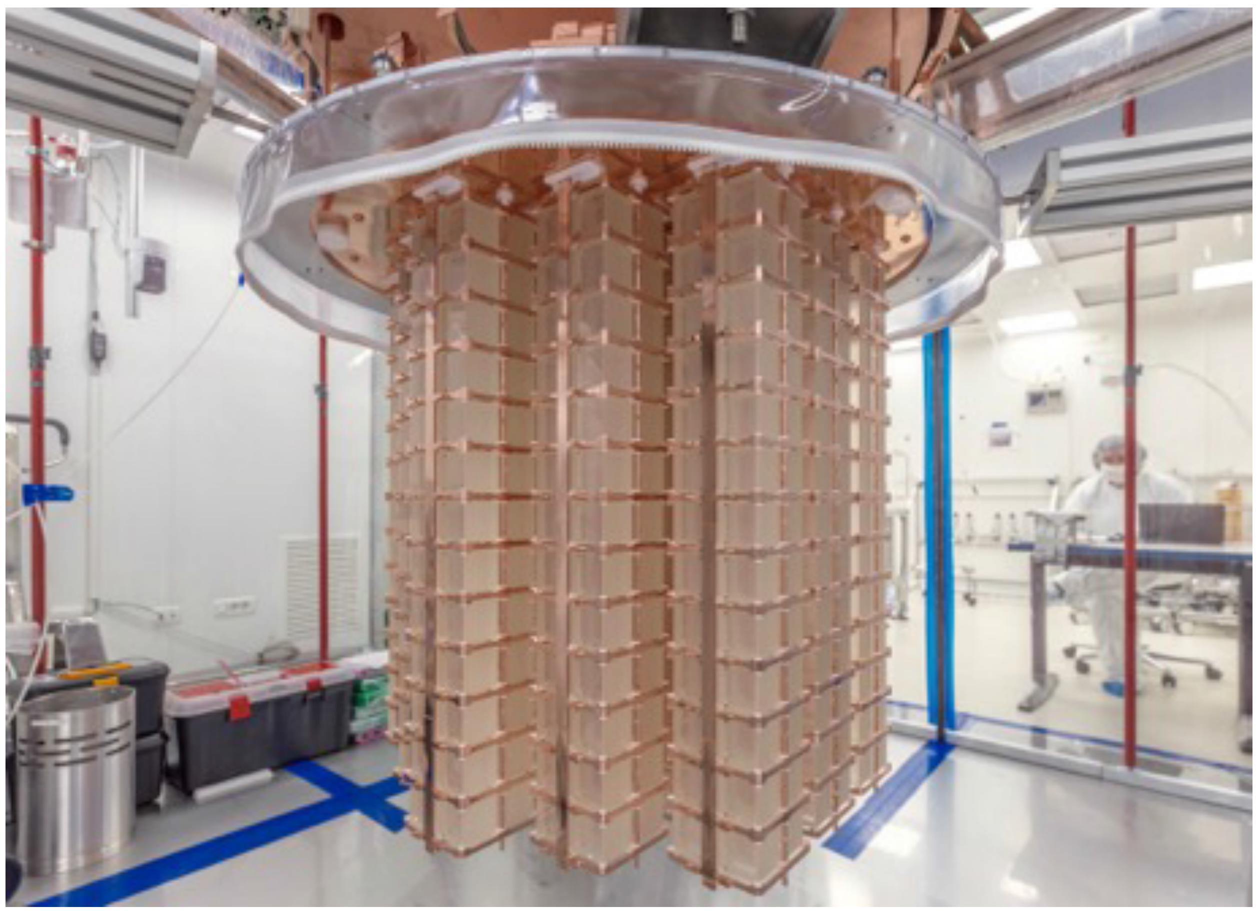


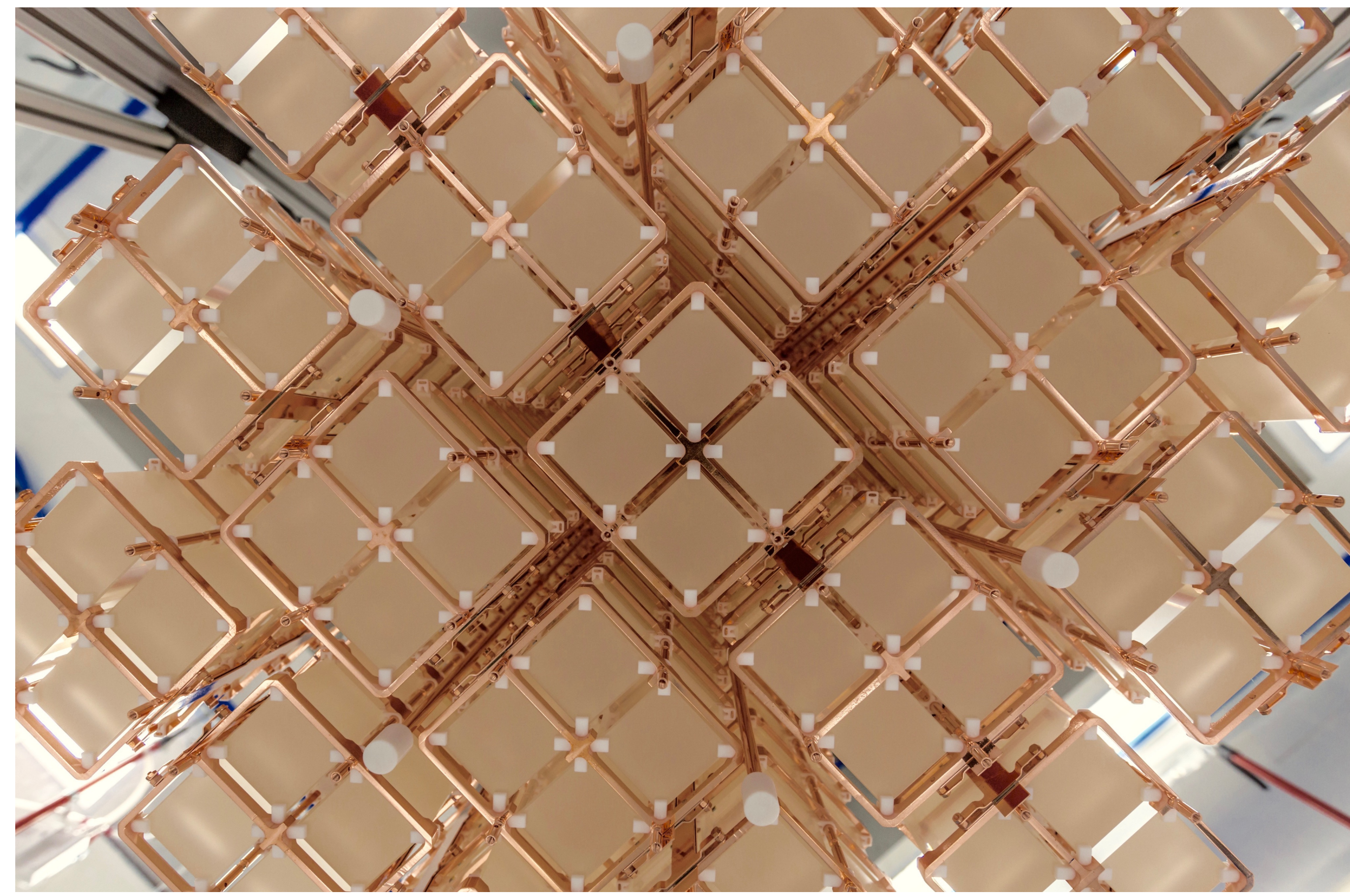
19 towers in total



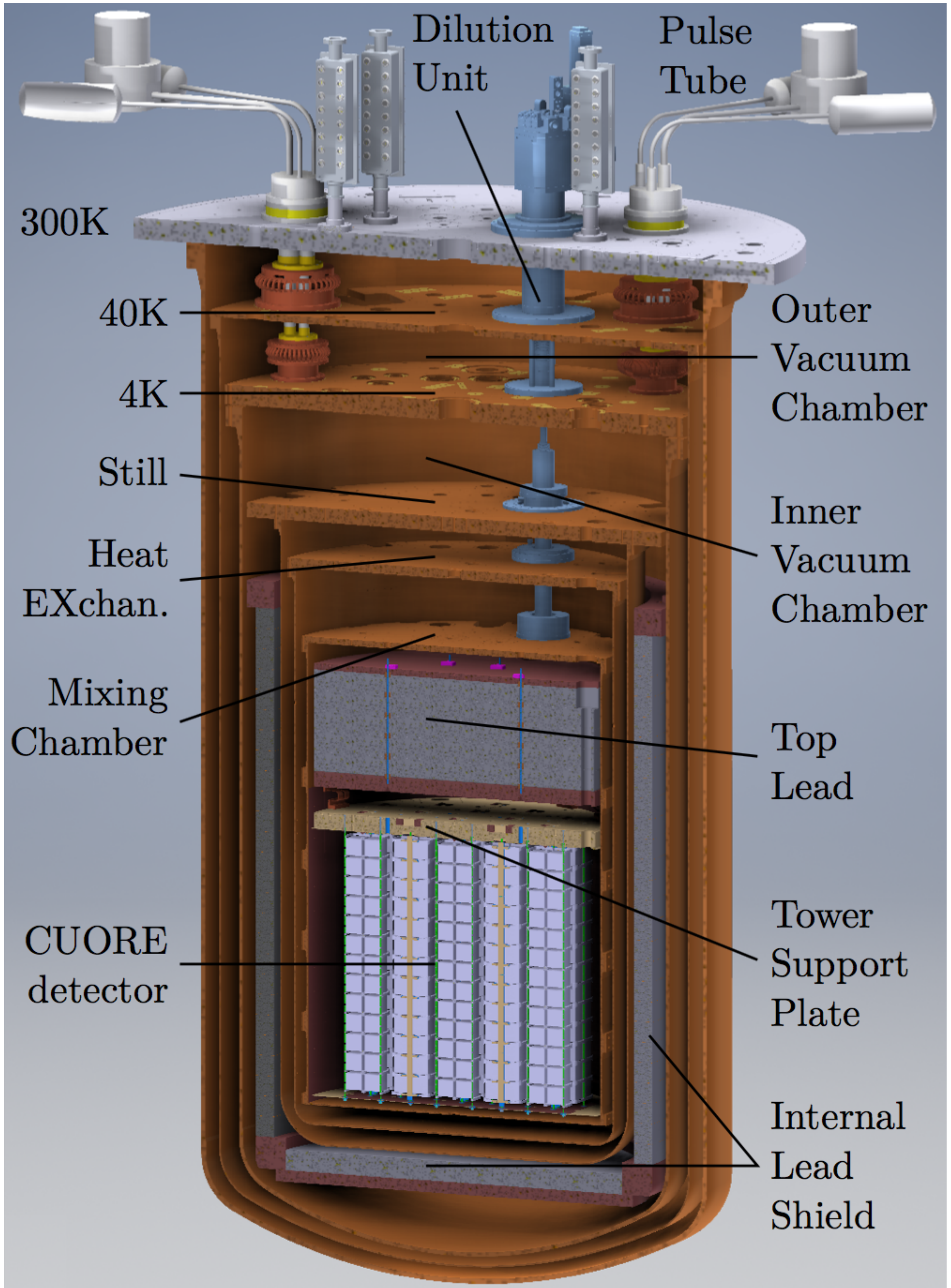


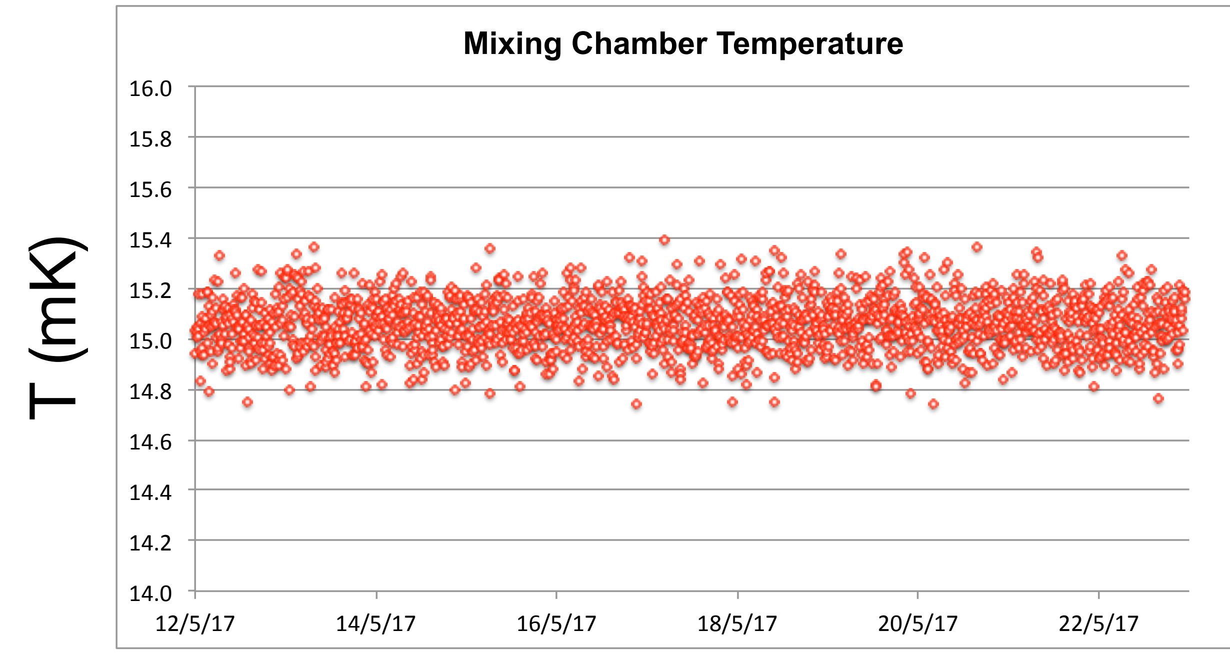
CUORE ‘just’ before vessel closure





CUORE Cryogenics

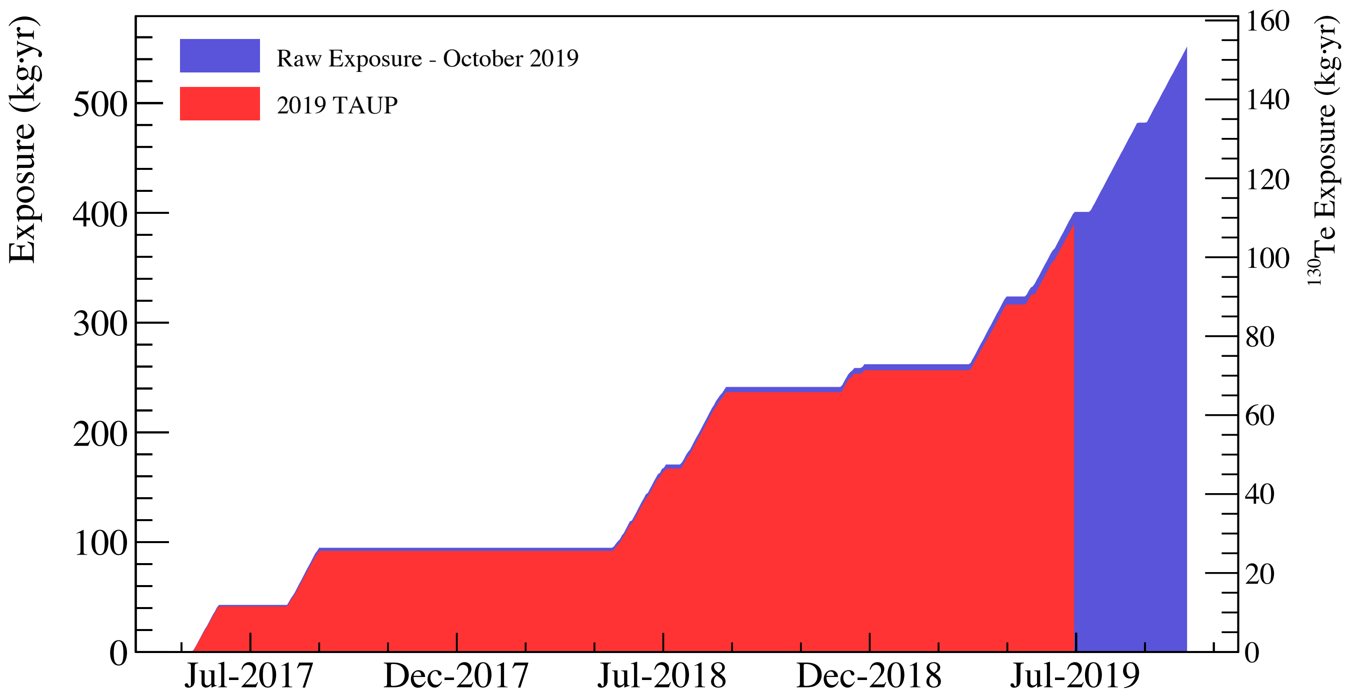




- Powerful ^{3}He-^{4}He dilution refrigerator precooled by pulse tubes
- Capable of cooling detector payload down to ~7mK
- Demonstrates it is practical to operate tonne-scale detector at mK temperatures

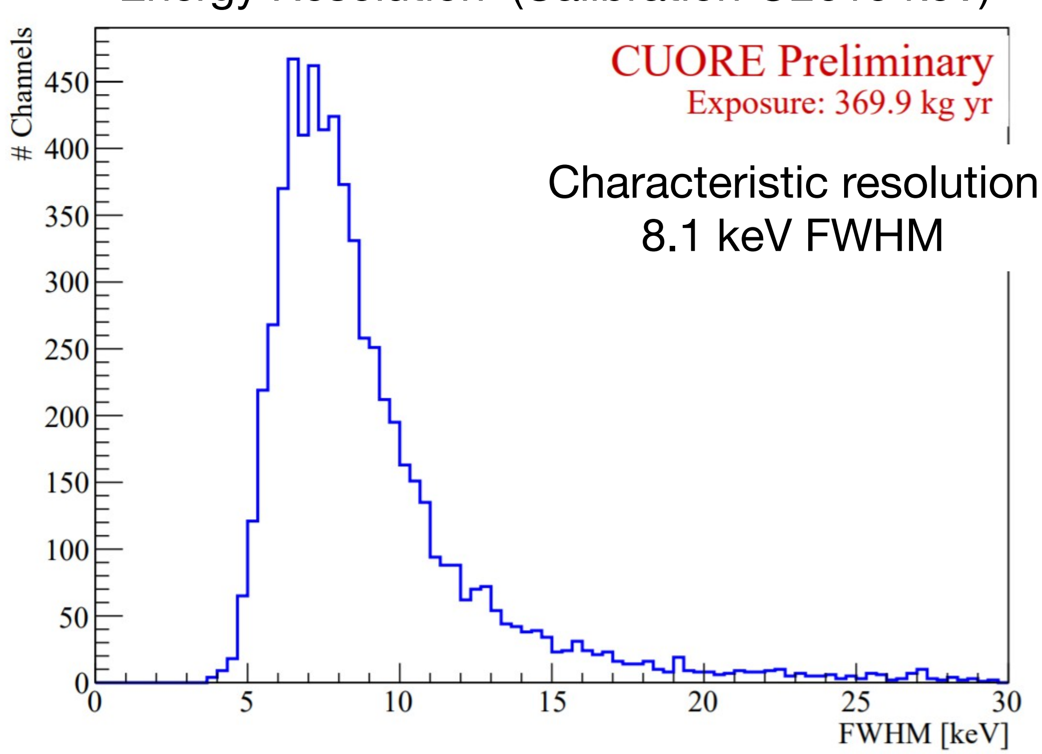
CUORE Status

Exposure vs. Time

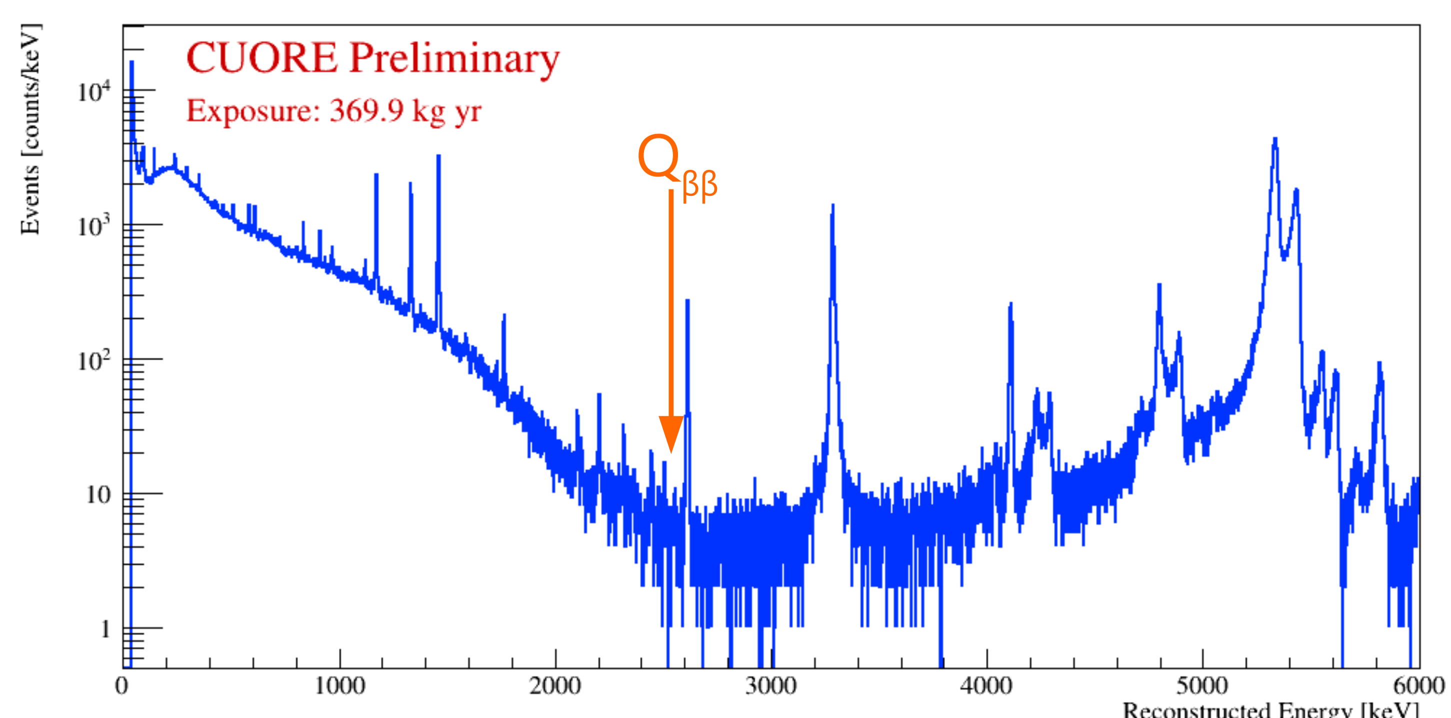


- Significant effort devoted to understanding the system and optimizing data-taking conditions
- Now taking data stably, exposure steadily increasing

Energy Resolution (Calibration @2615 keV)

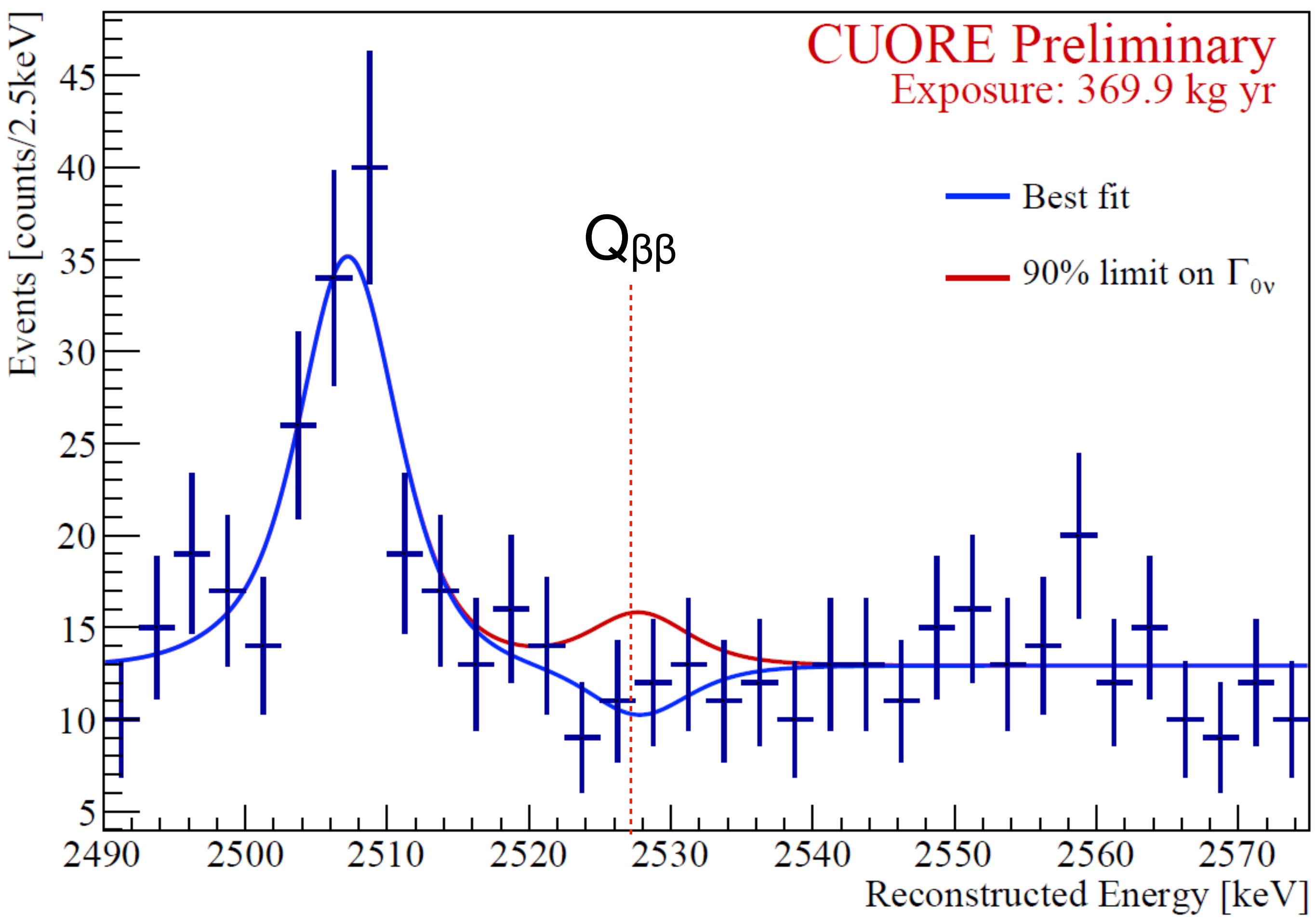


Observed Energy Spectrum (all detectors)



CUORE:0νββ Search

Unblinded Candidate Spectrum



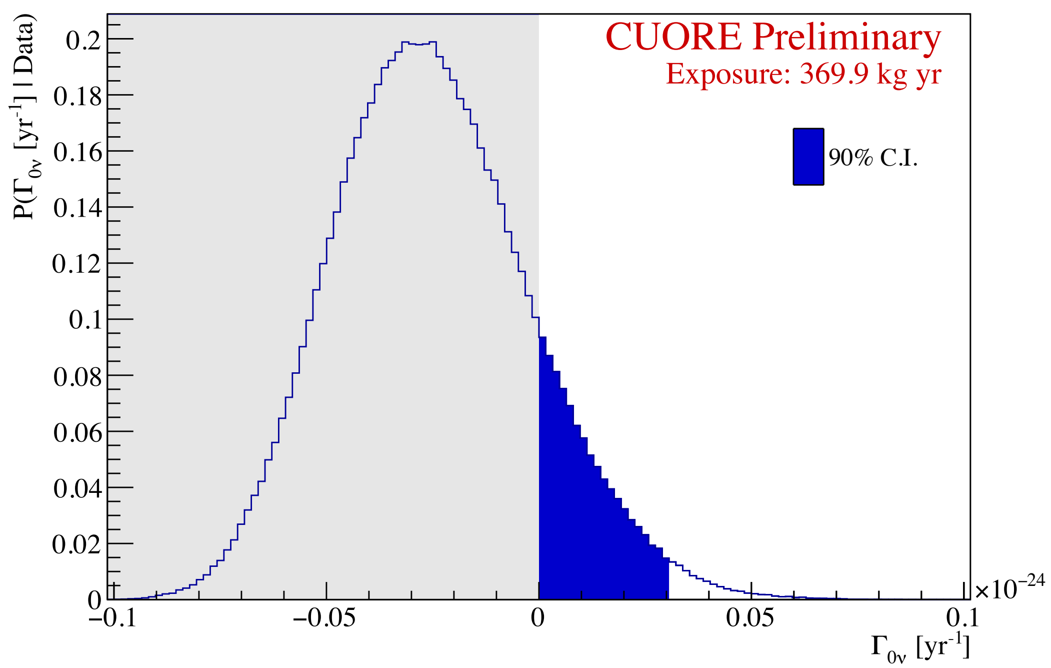
- Total exposure: 370 kg*yr TeO_2
- Detection efficiency: 77.23 +/- 0.18 %
  - Analysis cuts: 87.41 +/- 0.18 %
  - Containment: 88.350 +/- 0.090 %
- UEML Fit model:
  - flat continuum (BI),
  - posited peak for NLDBD
  - peak for ^{60}Co

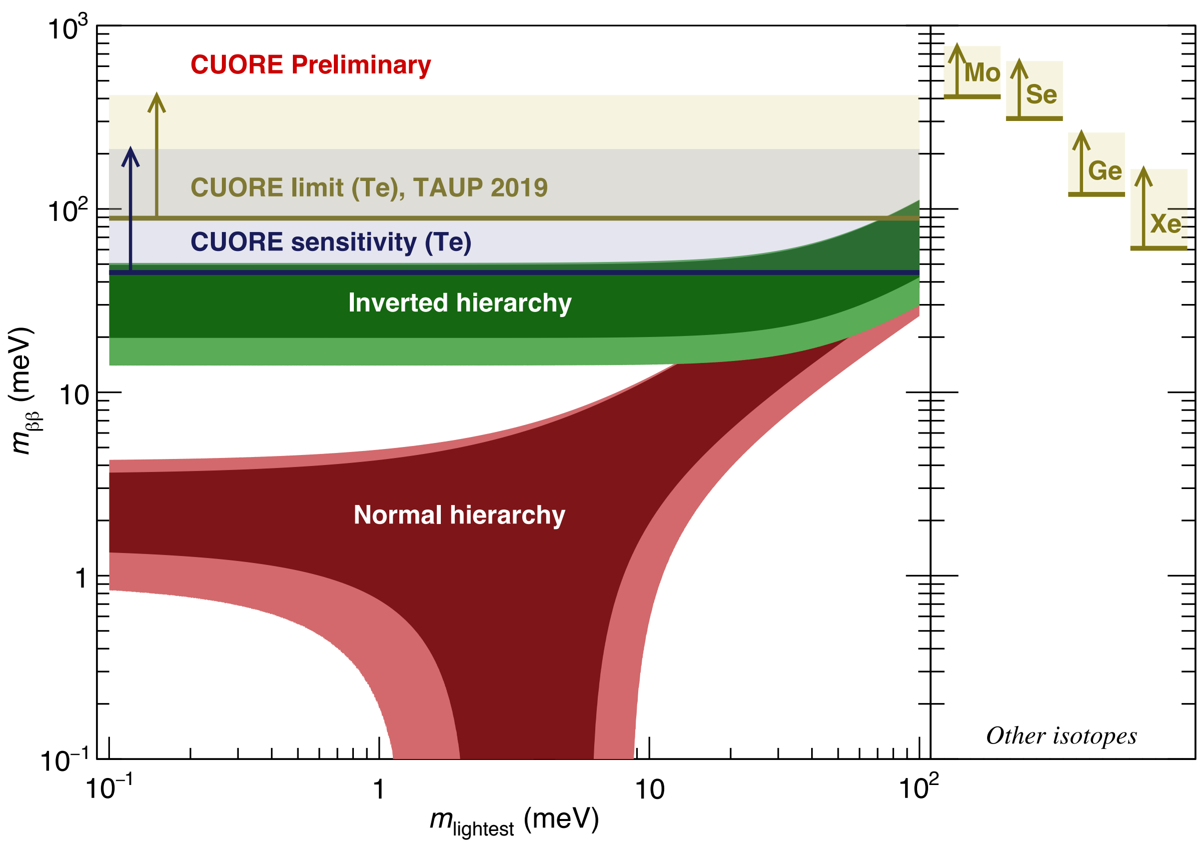
$$\mathrm{BI} = (1.37 \pm 0.07) \times 10^{-2} \ \ \mathrm{cnts}/(\mathrm{keV} \cdot \mathrm{kg} \cdot \mathrm{yr})$$

CUORE Preliminary

- No evidence for NLDBD !

CUORE:0νββ Search





- Place a Bayesian lower limit on the half life

$$T^{0\nu}_{1/2} > 2.3 \times 10^{25} \text{yr} \quad (90\% C.I)$$

CUORE Preliminary

- The median sensitivity of our data is

$$T^{0\nu}_{1/2} = 1.5 \times 10^{25} \text{yr}$$

13% chance to get stronger lower limit than the one observed

$$m_{\beta\beta} < 0.09 - 0.42\, \text{eV}$$

CUORE Preliminary

- Range from NMEs adopted

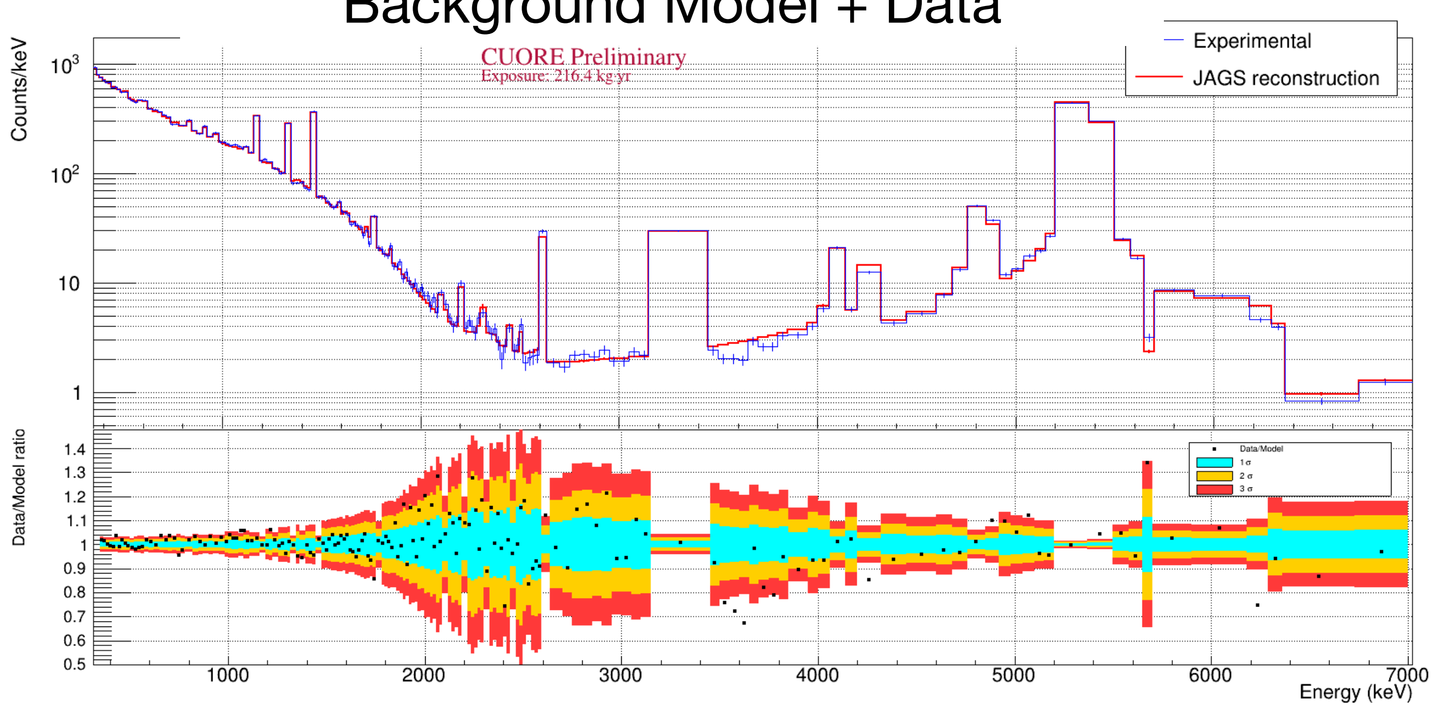
CUORE: Background model

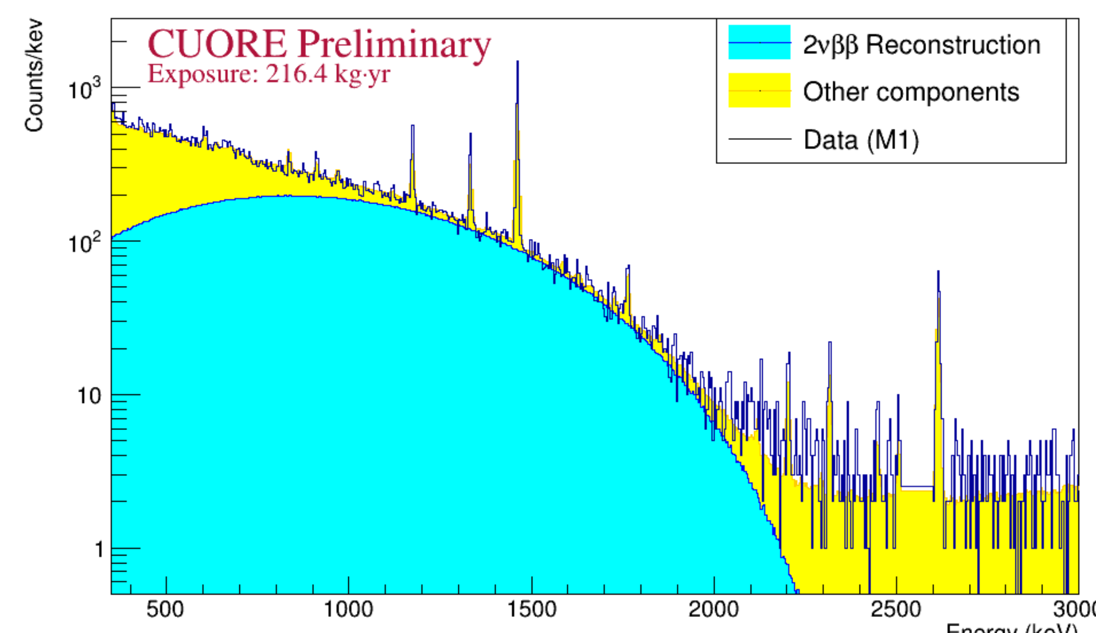
- Reconstruct background components through a Bayesian fit to the full data spectrum
- Detailed GEANT4-based simulations, modeling the detector geometry and particle interactions
- Exploit geometric and temporal correlations to constrain near and far background sources
- Important input for physics such as $2\nu\beta\beta$ studies
- Directly measure background originating from the cryostat

Model Components

Volume	Type	Components
TeO_2	Bulk	$2\nu\beta\beta$, ^{210}Pb, ^{232}Th, ^{228}Ra-^{208}Pb, ^{238}U-^{230}Th, ^{230}Th ^{226}Ra-^{210}Pb, ^{40}K, ^{60}Co, ^{125}Sb, ^{190}Pt
TeO_2	Surface (0.01 μm)	^{232}Th, ^{228}Ra-^{208}Pb, ^{238}U-^{230}Th, ^{226}Ra-^{210}Pb, ^{210}Pb
TeO_2	Surface (1 μm)	^{210}Pb
TeO_2	Surface (10 μm)	^{210}Pb, ^{232}Th, ^{238}U
CuNOSV	Bulk	^{232}Th, ^{238}U, ^{40}K, ^{60}Co, ^{54}Mn
CuNOSV	Surface (0.01 μm)	^{210}Pb, ^{232}Th, ^{238}U
CuNOSV	Surface (1 μm)	^{210}Pb, ^{232}Th, ^{238}U
CuNOSV	Surface (10 μm)	^{210}Pb, ^{232}Th, ^{238}U
Roman lead	Bulk	^{232}Th, ^{238}U, ^{108m}Ag
Top lead	Bulk	^{232}Th, ^{238}U, ^{210}Bi
Ext. lead	Bulk	^{210}Bi
CuOFE	Bulk	^{232}Th, ^{238}U, ^{60}Co
External	-	Cosmic muons

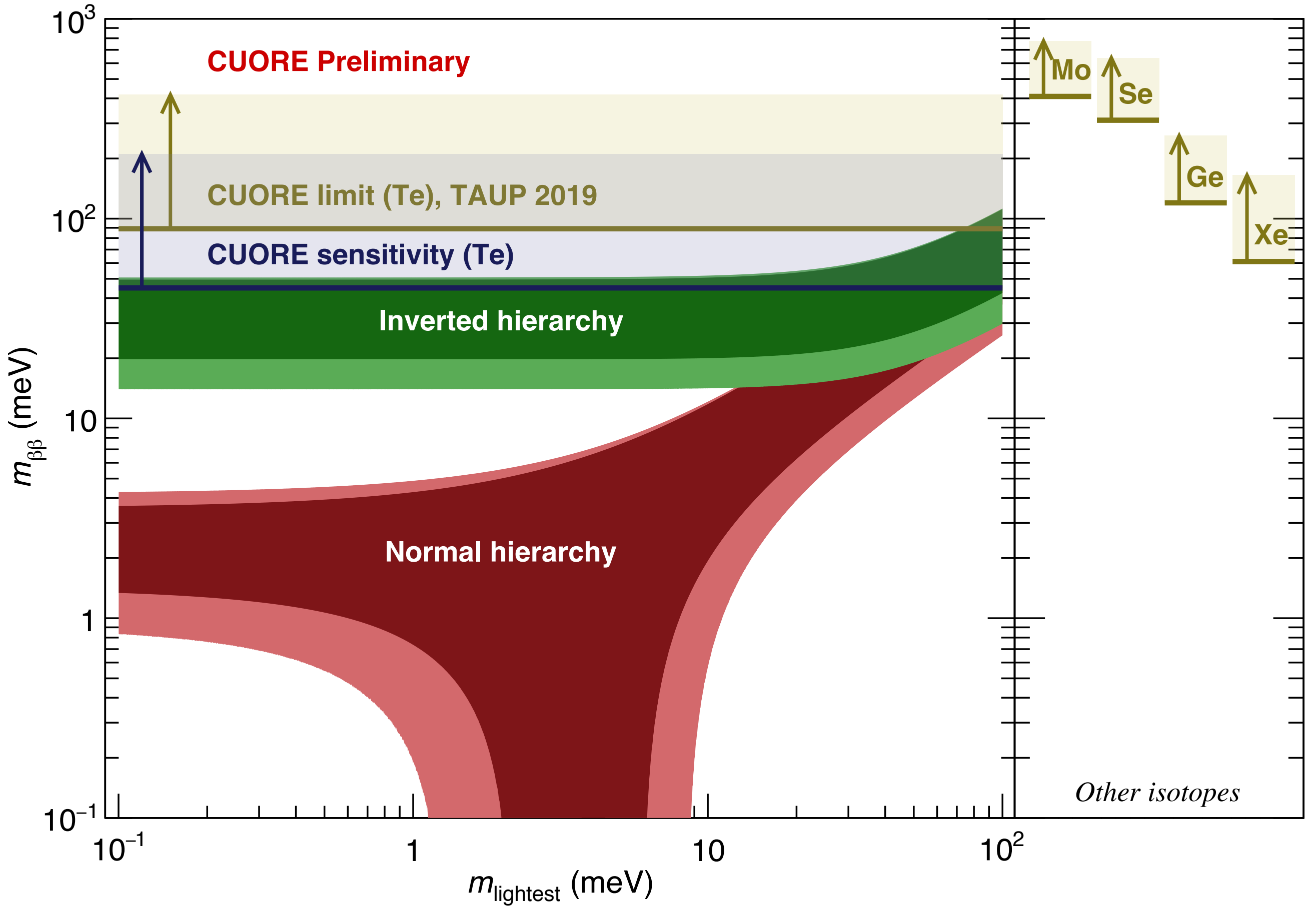
Background Model + Data





$$T^{2\nu}_{1/2} = (8.2 \pm 0.1(\text{stat})) \times 10^{20}\text{yr}$$

CUORE Preliminary



Projected CUORE Sensitivity

- CUORE sensitivity (5 yrs livetime)

$$T_{1/2}^{0\nu\beta\beta} = 9.0 \times 10^{25}\text{y}$$

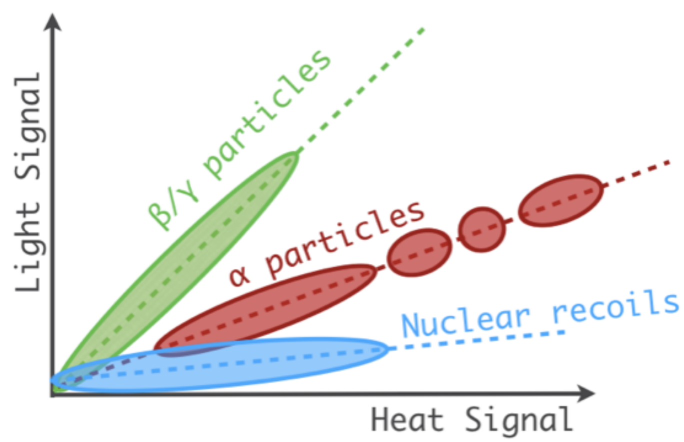
$$\text{m}_{\beta\beta} < 50 - 200 \text{ meV}$$

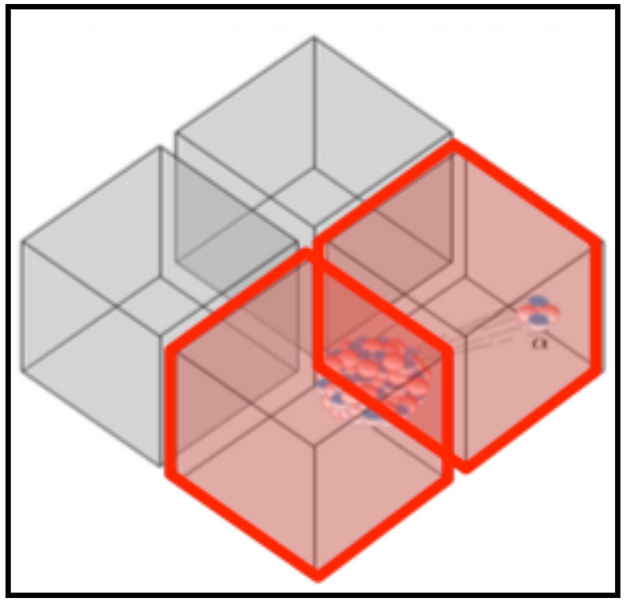
What about fully probing the IH region ?

- Requires half-life sensitivity on the order of 10^{27} years !
- To do this with ~500 kg of isotope in a reasonable time (10 y) requires background free experiment (b < 10^{-4} c/kev/kg/y)

CUPID: CUORE Upgrade with Particle ID

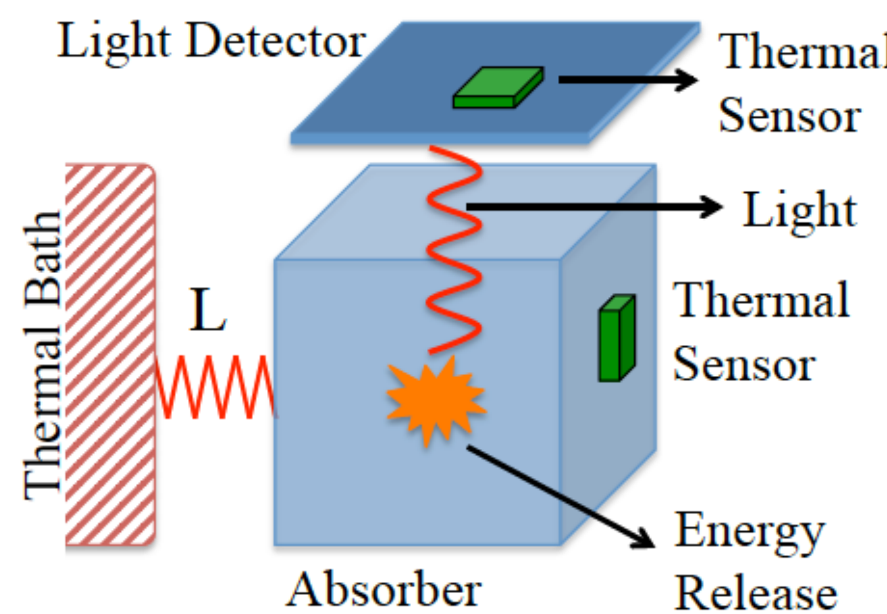
- Dominant background is degraded alphas from surface contamination
- Leverage other energy loss mechanisms to tag particle type





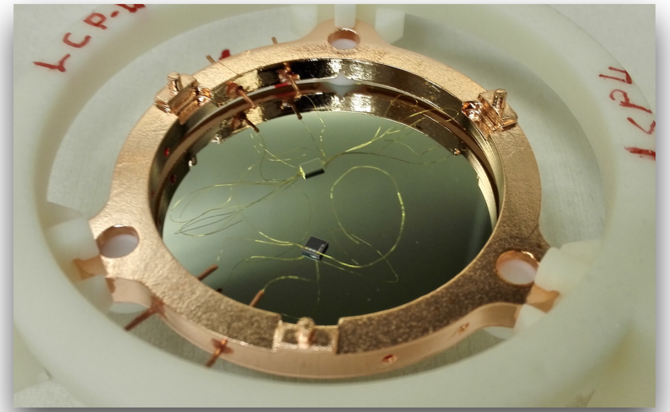
- Demonstrator efforts

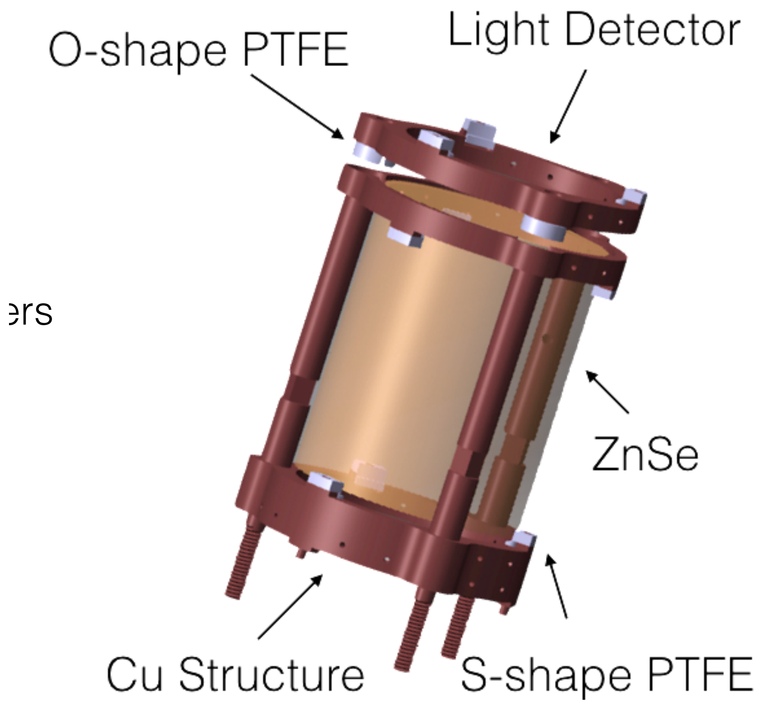
  - Enriched $Zn^{82}Se$ scintillating bolometers
  - Enriched $Li_2{}^{100}MoO_4$ scintillating bolometers



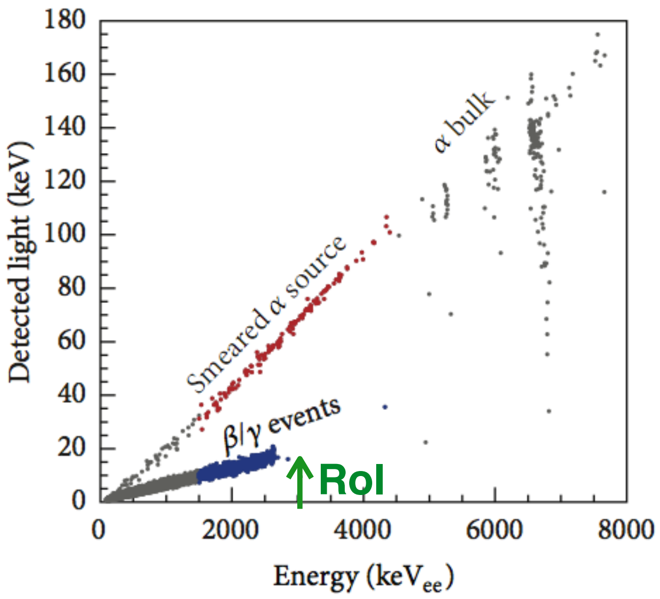
CUPID-0: $Zn^{82}Se$

- Array of 26 cylindrical ZnSe scintillating bolometers, 24 enriched to 95% in ^{82}Se
- 10.5 kg of ZnSe / 5.17kg of ^{82}Se
- Q-value: 2998 keV
- Operated in old CUORE-0 cryostat at LNGS
- NTD-Ge thermistors used as thermal sensors
- Reflective foils to improve light collection

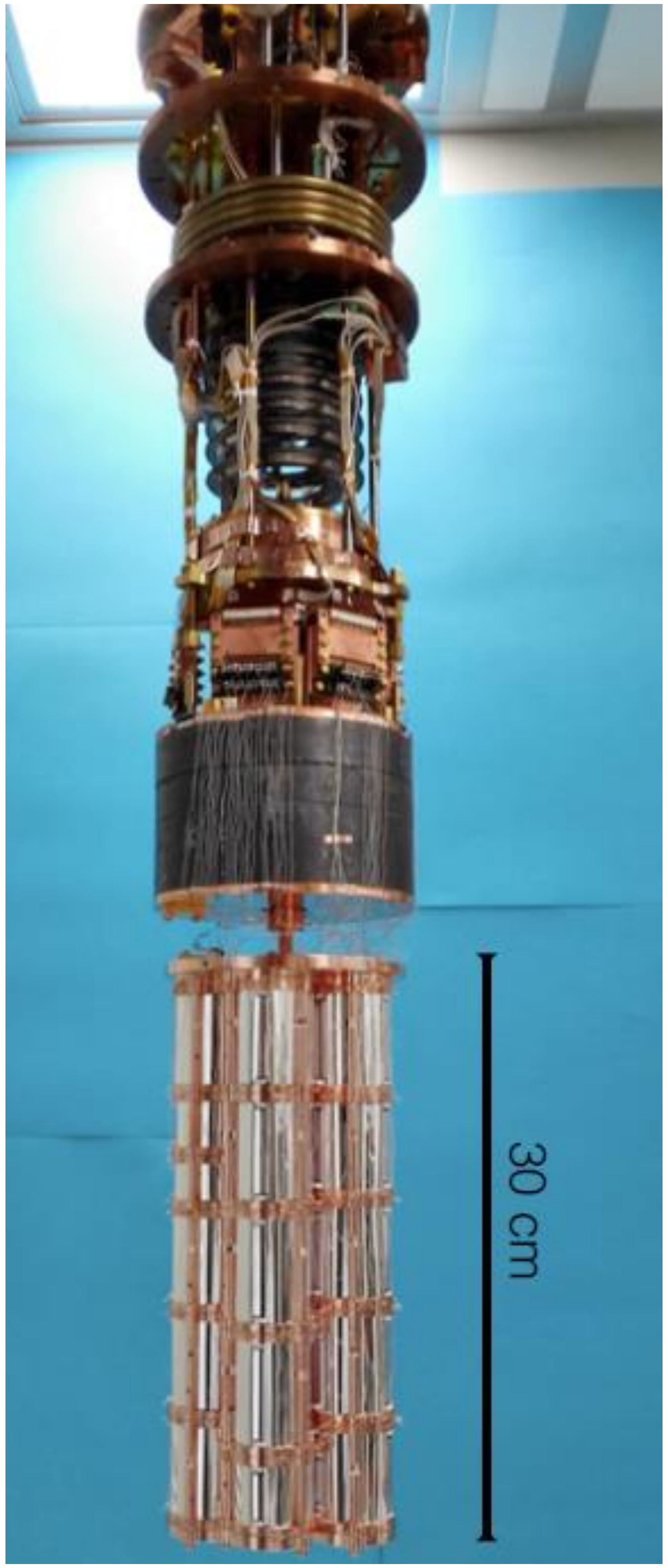




Calibration scatter plot of a ZnSe crystal

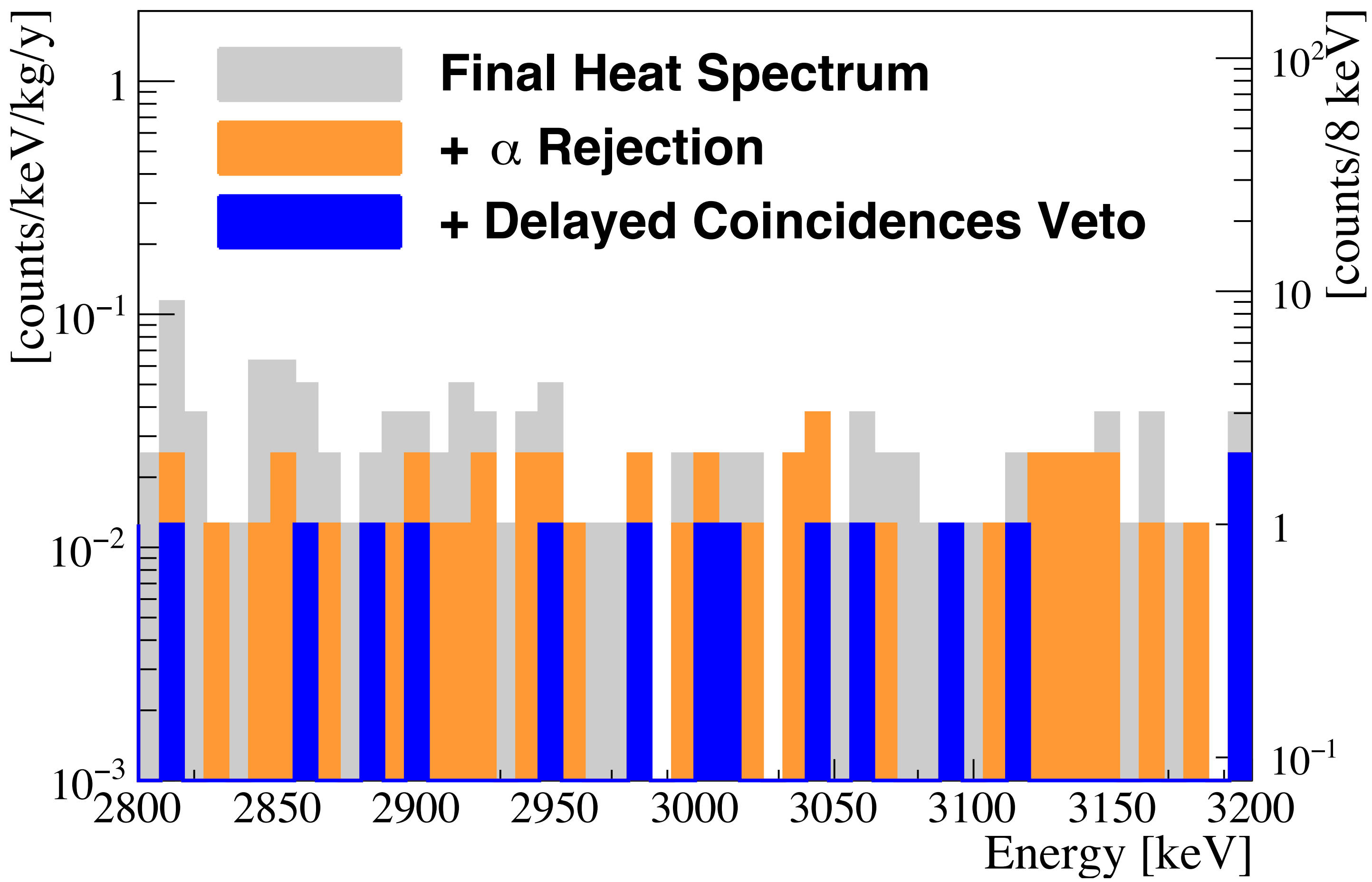


J.W. Beeman et al., J. Instrum. 8 (2013) P05021.



Figs. courtesy of CUPID-0 collaboration

CUPID-0: Zn^{82}Se Phase 1 Final Results



O. Azzolini *et al.* Phys. Rev. Lett. 123, 032501

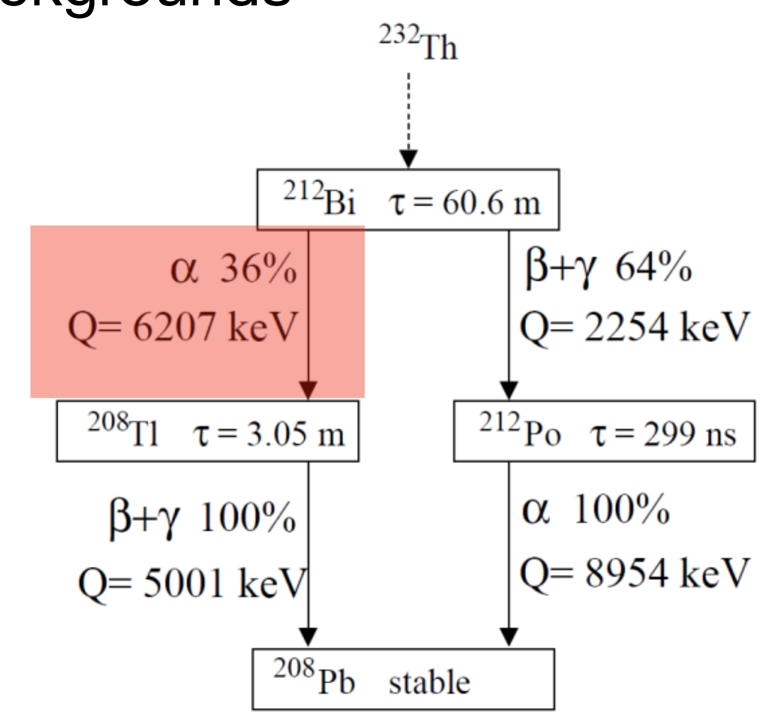
$$\mathrm{Bkg} = 3.5 \times 10^{-3} \mathrm{cnts}/(\mathrm{keV} \cdot \mathrm{kg} \cdot \mathrm{yr})$$

$$\mathrm{T}^{0\nu}_{1/2} > 3.5 \times 10^{24} \mathrm{yr} \;\; (90\% C.I)$$

- 10x improvement of ^{82}Se half-life limit

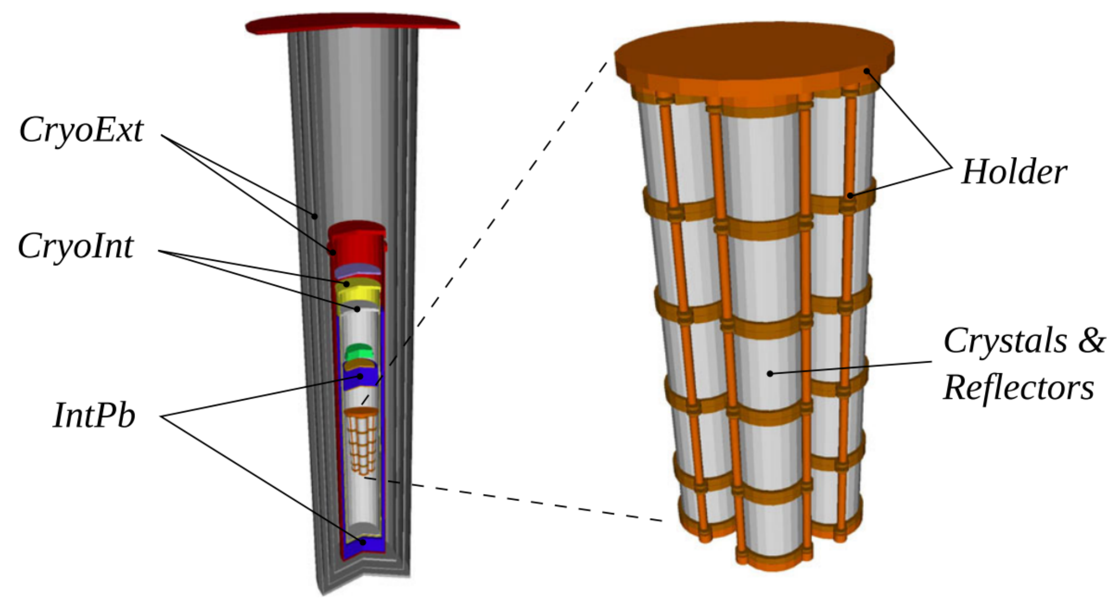
- Demonstrate using heat/light dual signals to tag alphas

- Developed delayed coincidence tagging analysis to tag surface beta backgrounds



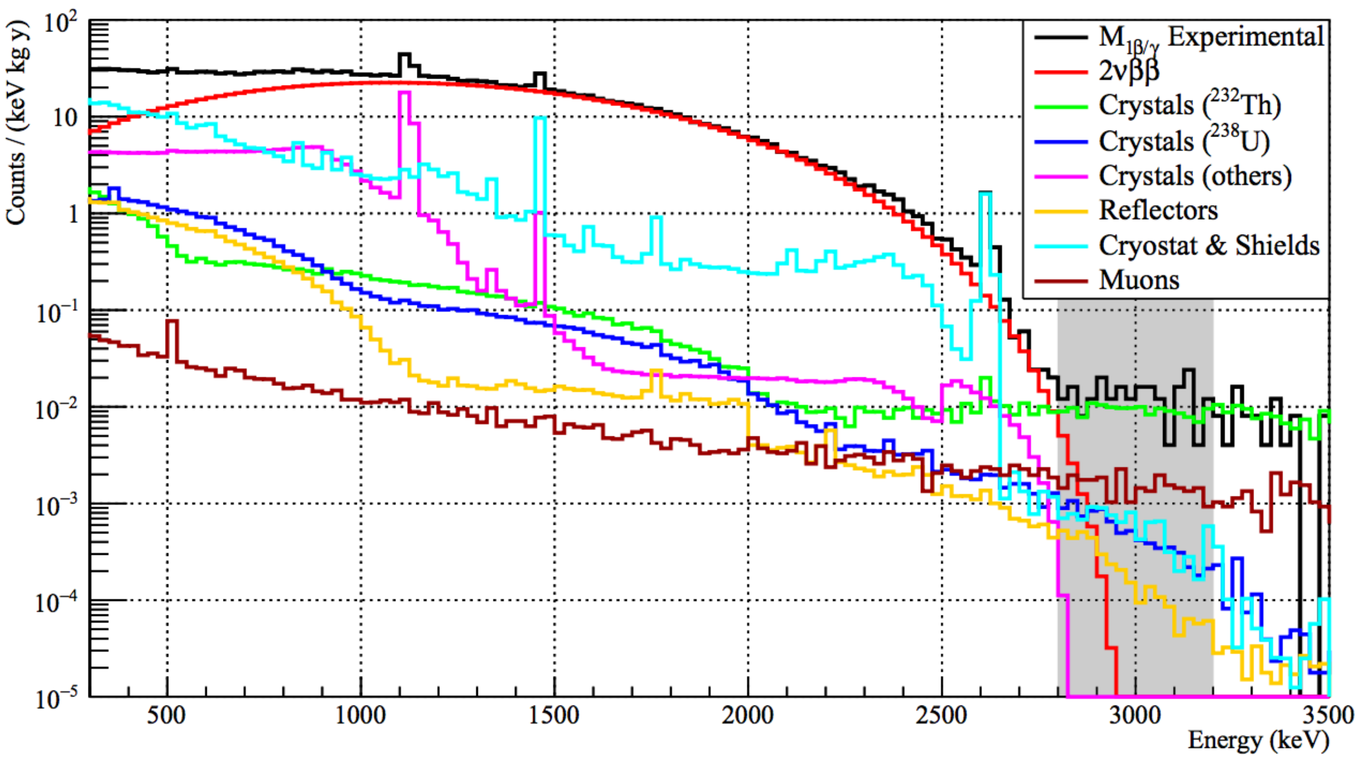
- Energy resolution ~ 20 keV FWHM

CUPID-0: Background Model



Eur. Phys. J. C (2019) 79 :583

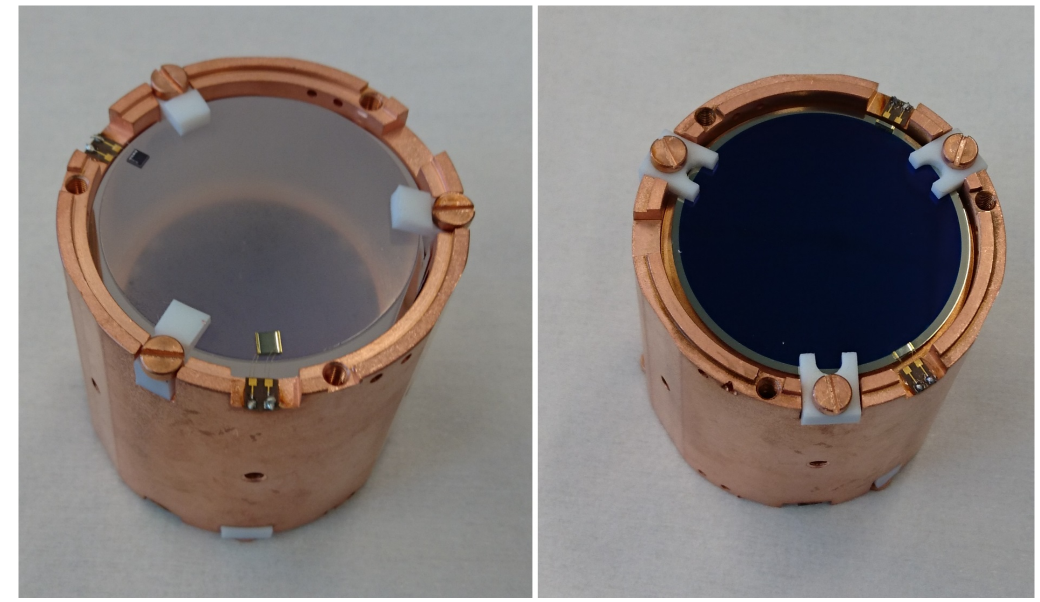
- **~44% muons**
- **~33% contaminations ZnSe crystals**
- **~17% cryostat**
- **~6% reflecting foil and holders**

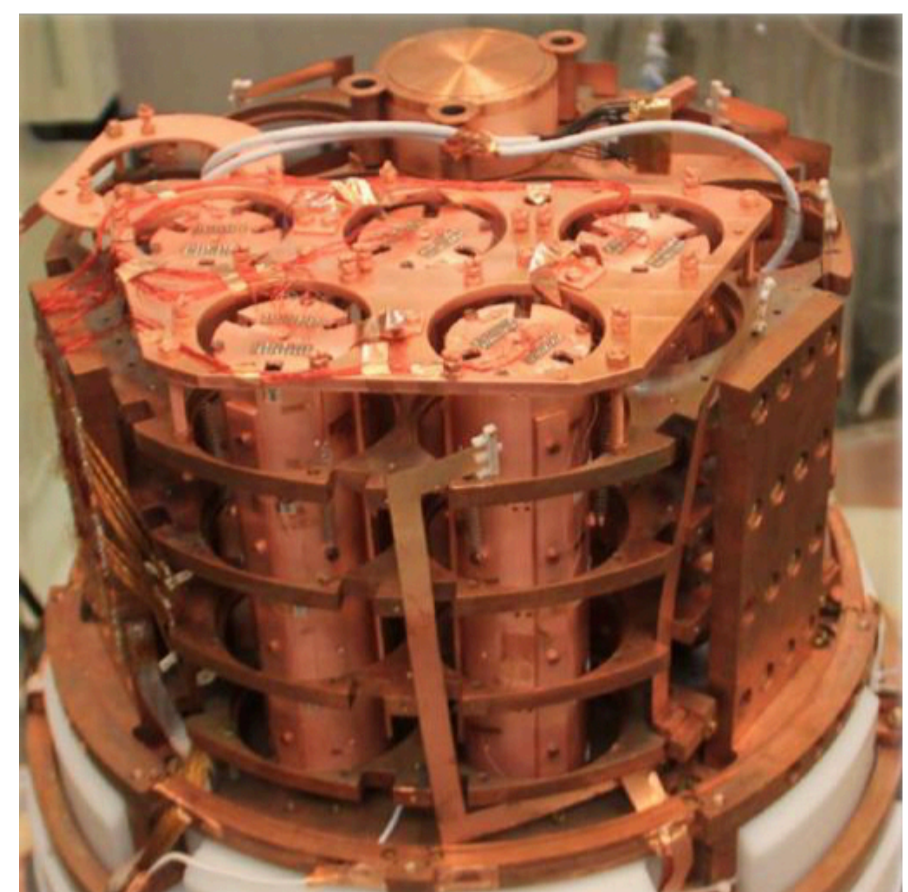


- CUPID-0 Phase 2 now underway with:
  - muon veto
  - New copper shield
  - No reflecting foils

CUPID-Mo: $Li_2{}^{100}MoO_4$

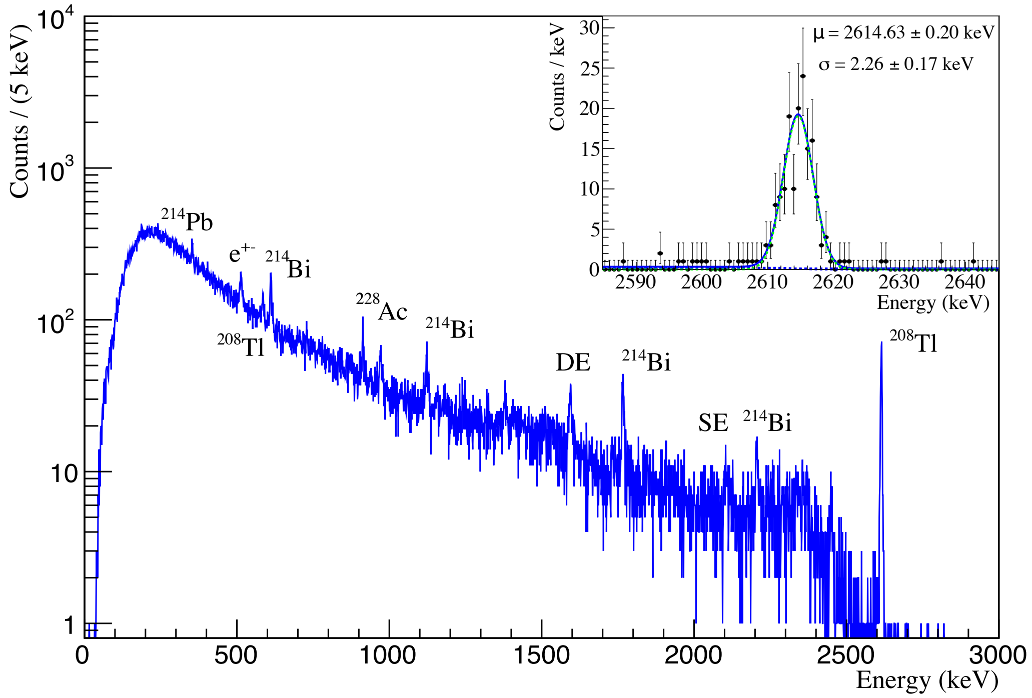
- Array of 20 cylindrical $Li_2{}^{100}MoO_4$ crystals
- Crystal: 44mm-diameter, 45mm high, ~0.2kg, enriched to 97% in ^{100}Mo
- Each crystal instrumented with Ge wafer secondary bolometer as light detector
- NTD-Ge thermistors as thermal sensors
- Crystals are surrounded by reflecting foil to improve light collection
- Currently operating at Modane Underground Lab
- Q-value: 3034 keV





CUPID-Mo: Energy Resolution

Calibration Energy Spectrum



https://arxiv.org/abs/1909.02994

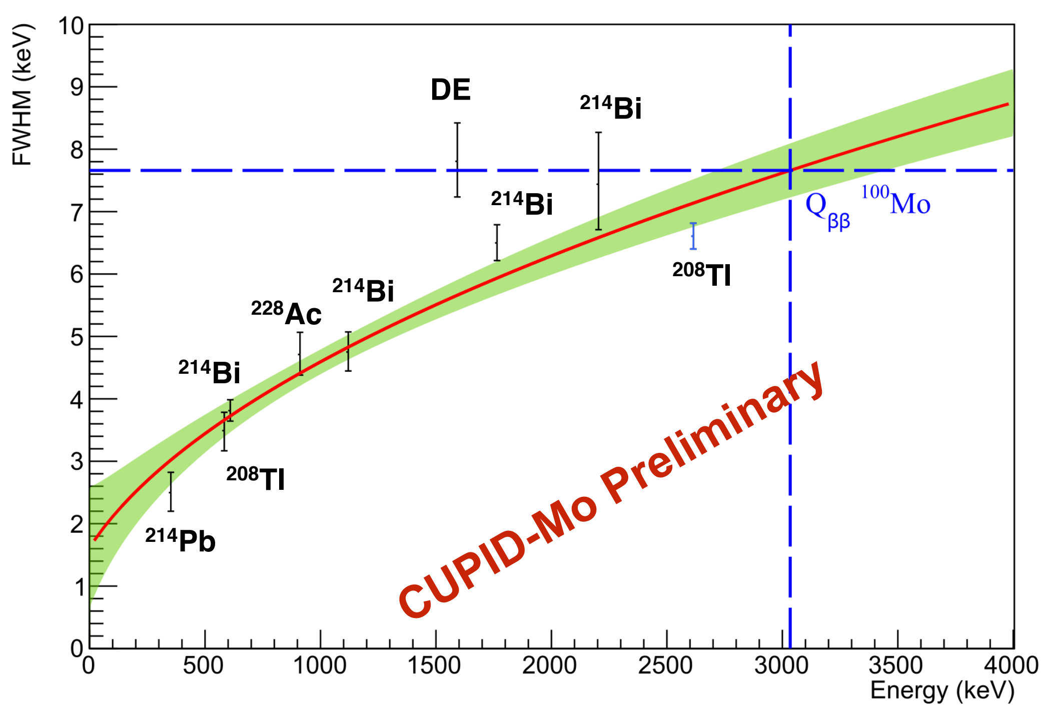
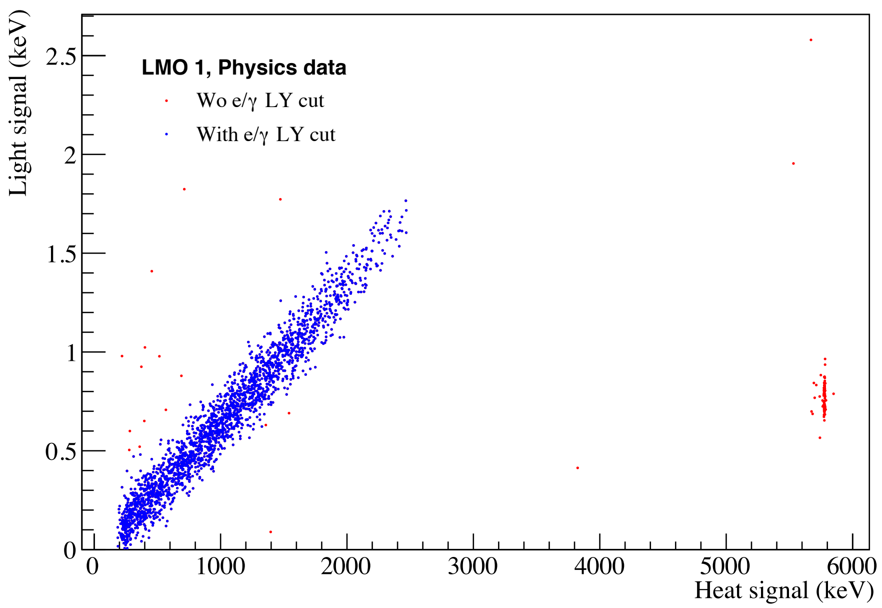


Fig. courtesy of B. Schmidt (CUPID-Mo)

- CUPID-Mo data show good bolometer performance for the 20 detectors with good energy linearity and resolution
- Energy resolution @ 2615 keV is
  6.7 keV FWHM (with a spread of 1.9 keV)
- Extrapolating to Q-value: (7.7 +/- 0.4) keV
- Bolometers operated at ~20 mK

CUPID-Mo: PID + Radiopurity



- CUPID-Mo data show PID based on heat-light signals is working well
  > 99.9 % alpha rejection
  >99.9 % beta/gamma acceptance
- ^{238}U and ^{232}Th backgrounds in crystals
  - U: ~0.5 uBq/Kg
  - Th: ~0.3 uBq/kg

- https://arxiv.org/abs/1909.02994

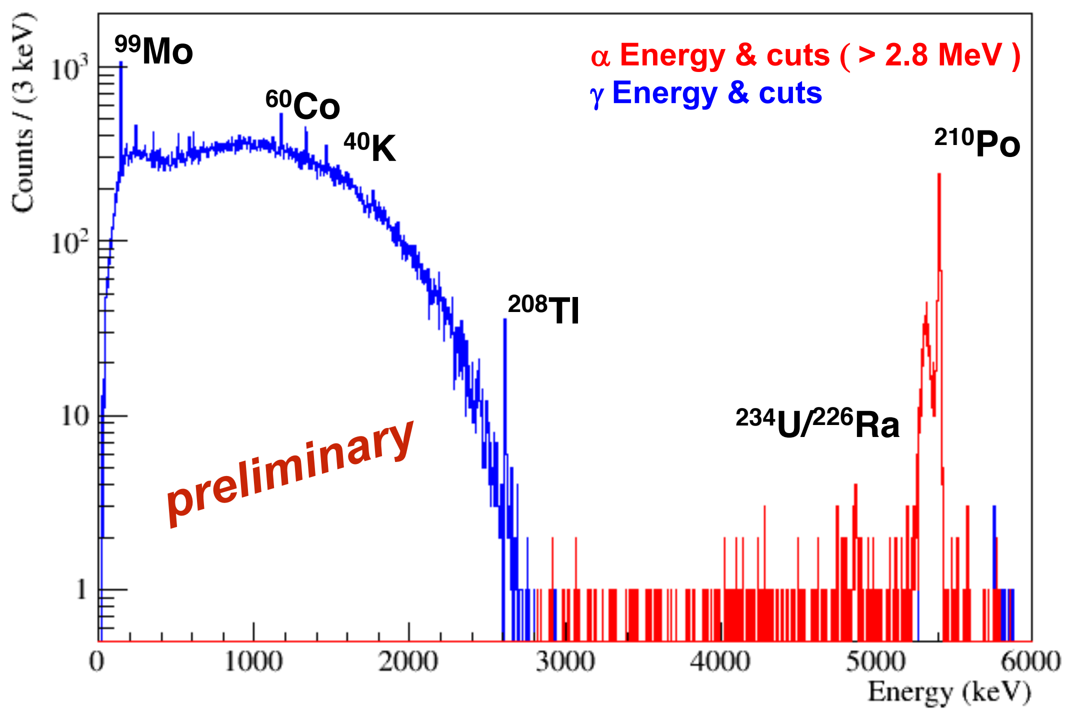


Fig. courtesy of CUPID-Mo

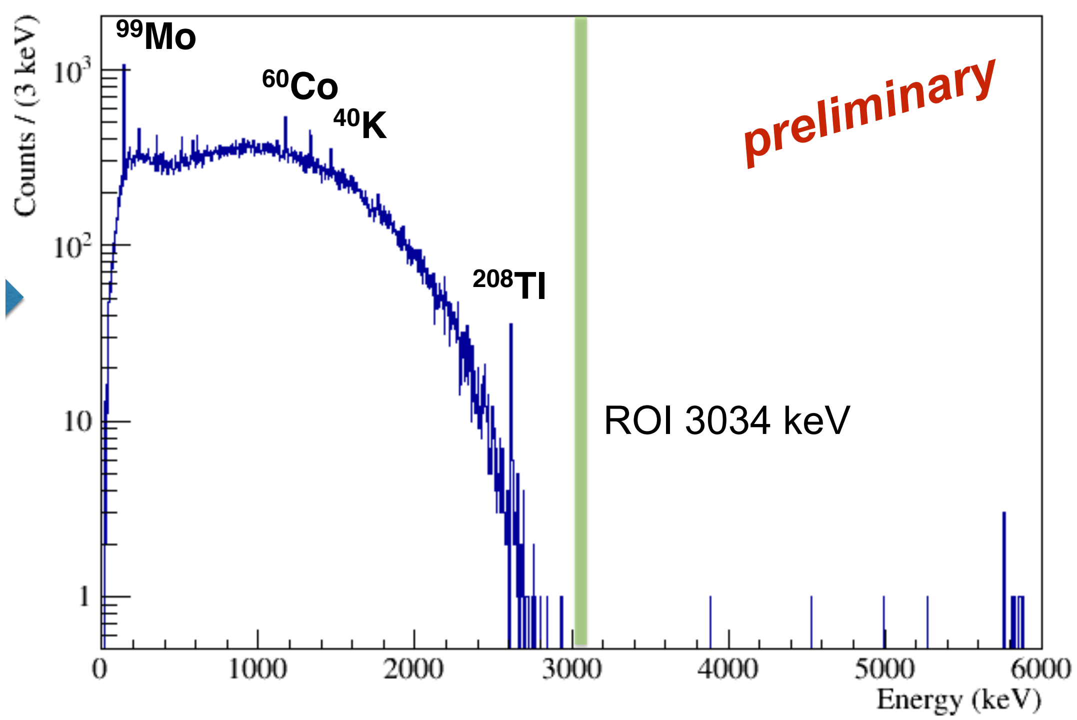
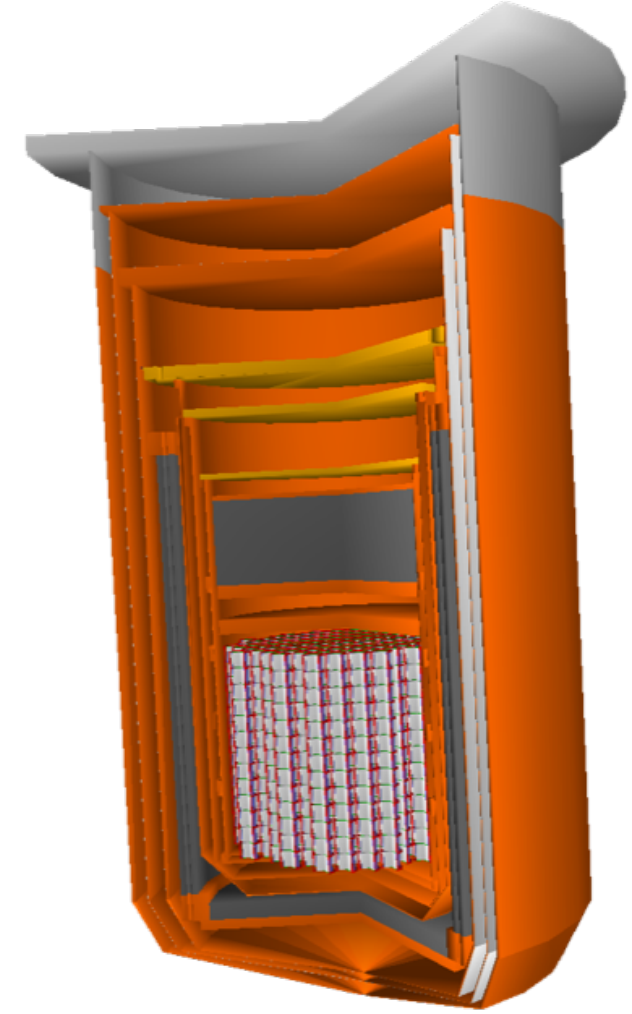
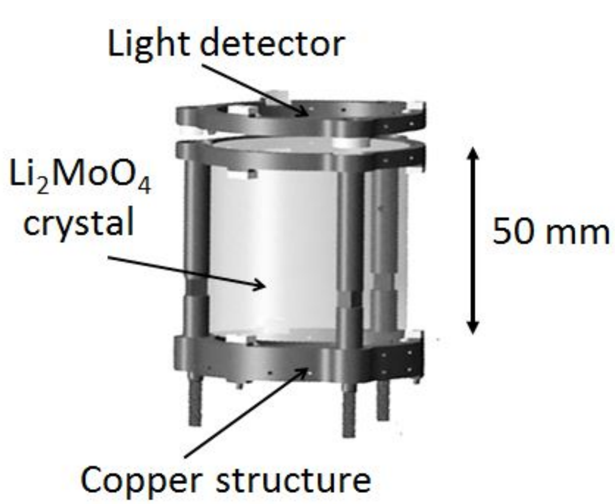


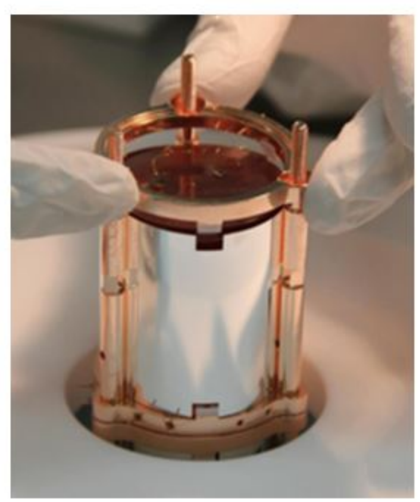
Fig. courtesy of CUPID-Mo

CUPID



- Array of ~1500 $Li_2{}^{100}MoO_4$ scintillating bolometers enriched to >95% in ^{100}Mo, ~250kg of ^{100}Mo
  - Reuse CUORE Cryogenic Infrastructure
  - PID using scintillation signal
  - External muon veto





Parameter	CUPID Baseline
Crystal	$Li_2{}^{100}MoO_4$
Detector mass (kg)	472
^{100}Mo mass (kg)	253
Energy resolution FWHM (keV)	5
Background index (counts/(keV·kg·yr))	10^{-4}
Containment efficiency	79%
Selection efficiency	90%
Livetime (years)	10
Half-life exclusion sensitivity (90% C.L.)	1.5×10^{27} y
Half-life discovery sensitivity (3σ)	1.1×10^{27} y
$m_{\beta\beta}$ exclusion sensitivity (90% C.L.)	10–17 meV
$m_{\beta\beta}$ discovery sensitivity (3σ)	12–20 meV

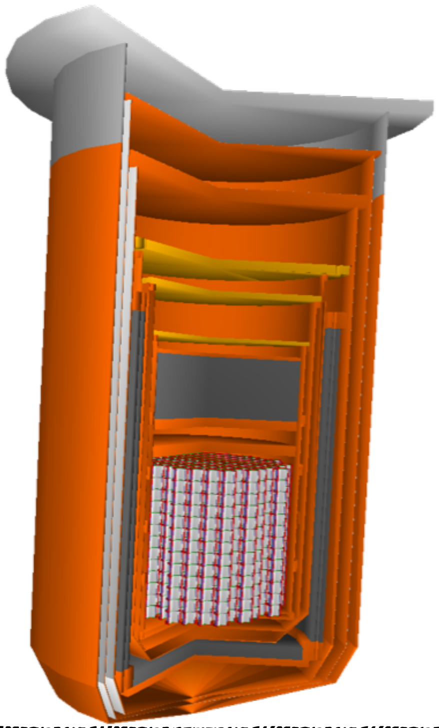
CUPID preCDR

https://arxiv.org/abs/1907.09376

CUPID Background Model

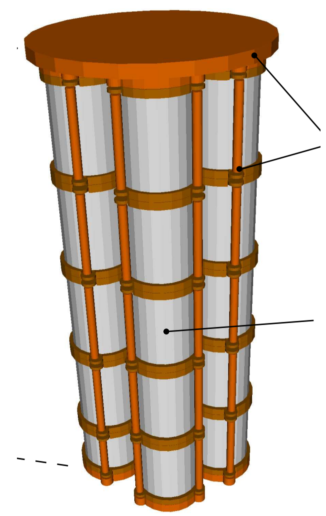
- Data-driven background model

CUORE background model



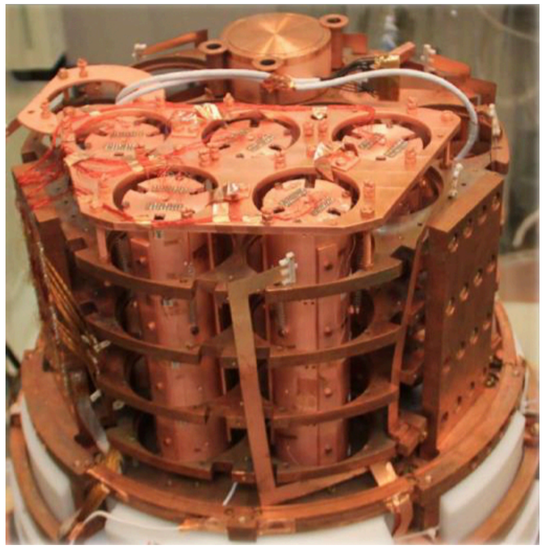
+

CUPID-0 background model



+

Assumptions on Li_2MoO_4 performance (now verified with CUPID-Mo)



Characterize gamma-induced background from Cryogenic system aka ‘far sources’

Model is fit to CUORE data

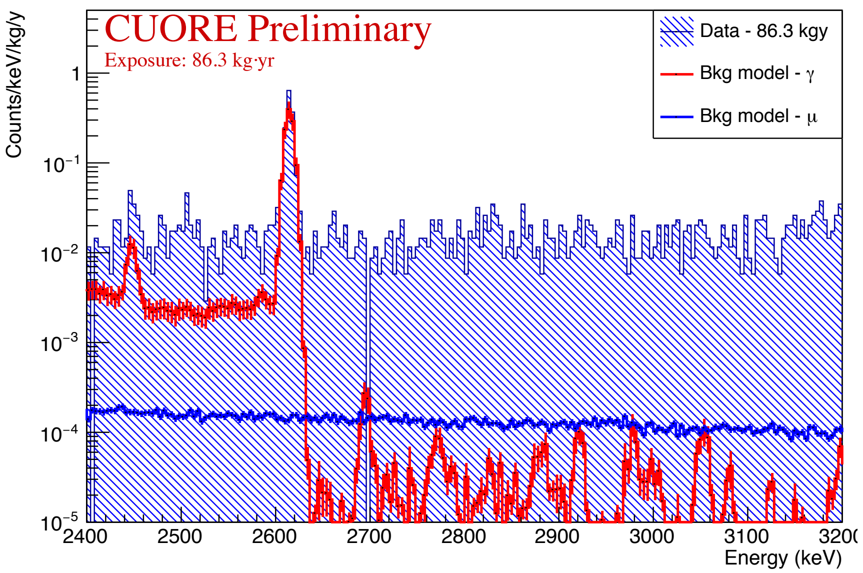
Characterize background after alpha-rejection, beta-gamma background from ‘near sources’

Model is fit to CUPID-0 data

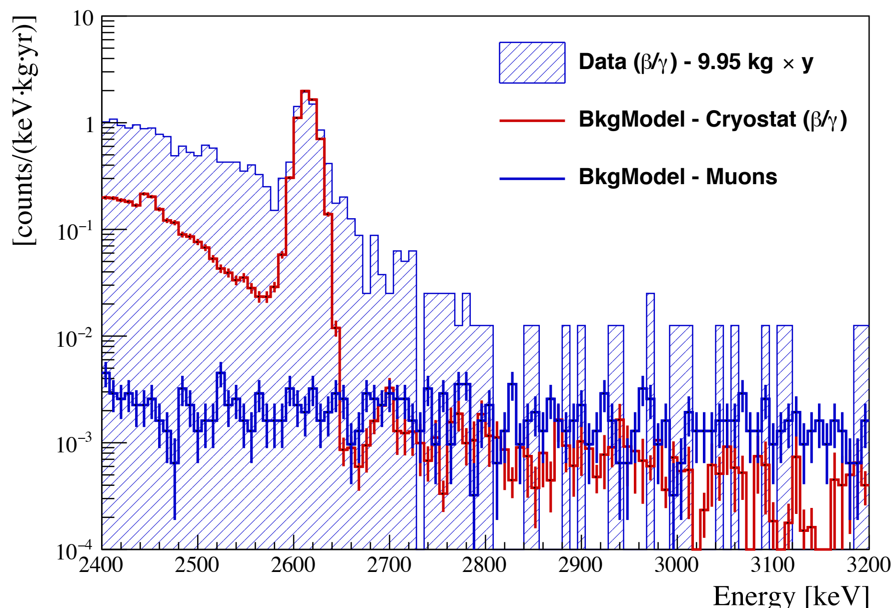
U/Th bkg levels
Energy resolution
PID performance
Pulse timing for pile-up rejection

CUPID Background Model

CUORE



CUPID-0

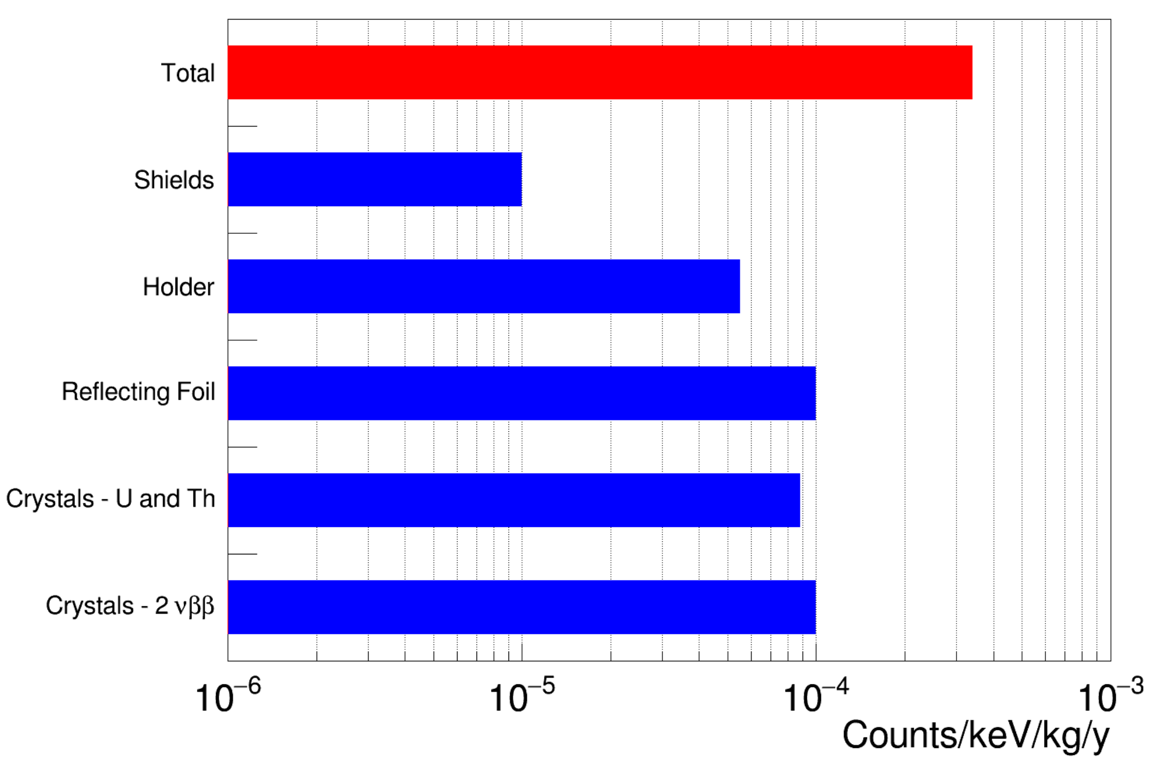


Eur. Phys. J. C (2019) 79 :583

Li_2MoO_4 assumptions

Material	^{238}U	^{232}Th
Li_2MoO_4 bulk [μBq/kg]	10	3
Li_2MoO_4 surface 10 nm [nBq/cm^2]	3	2
Li_2MoO_4 surface 10 μm [nBq/cm^2]	0.8	<0.03
Reflecting foil surface 10 μm [nBq/cm^2]	8.7	<0.7
Cu bulk [μBq/kg]	<10	<2
Cu surface 10 μm [nBq/cm^2]	14	5

CUPID pre-CDR Background Budget



- Very conservative assumptions in baseline pre-conceptual design
- Data from CUPID-Mo show 10x better radiopurity than assumed
- Improvements in pile-up possible with faster sensors
- Replace or remove reflective foil

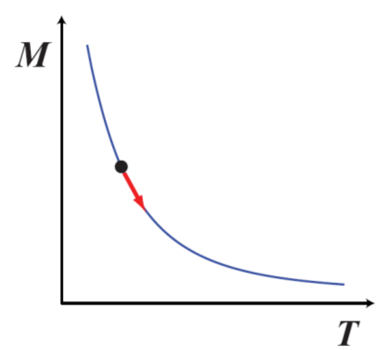
CUPID preCDR

https://arxiv.org/abs/1907.09376

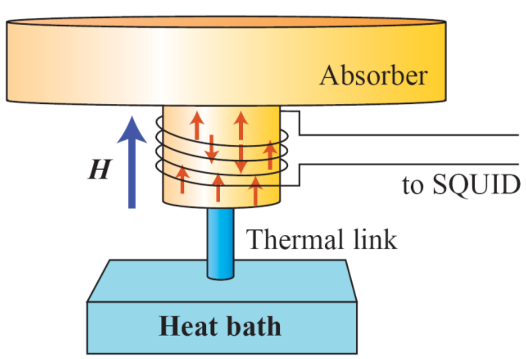
AMORE

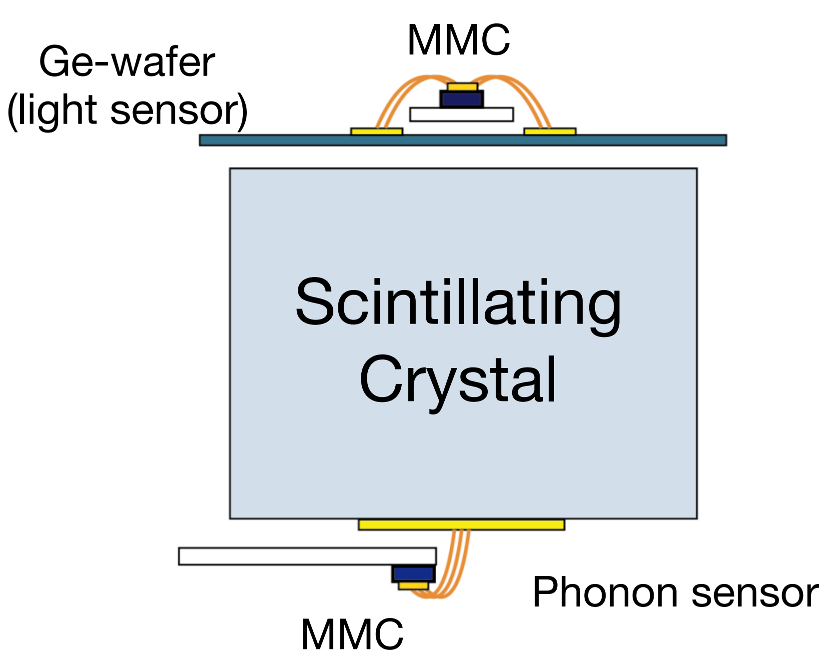
- Advanced Mo-based Rare process Experiment
- Project to search for neutrino less double beta decay of ^{100}Mo using cryogenic scintillating bolometers, i.e $^{depl.}Ca^{100}MoO_4$ or $Li_2{}^{100}MoO_4$ based in YangYang Lab in Korea
- Temperature sensor: Metallic Magnetic Calorimeter

Magnetization of paramagnetic alloy depends on temperature



Read out with a SQUID

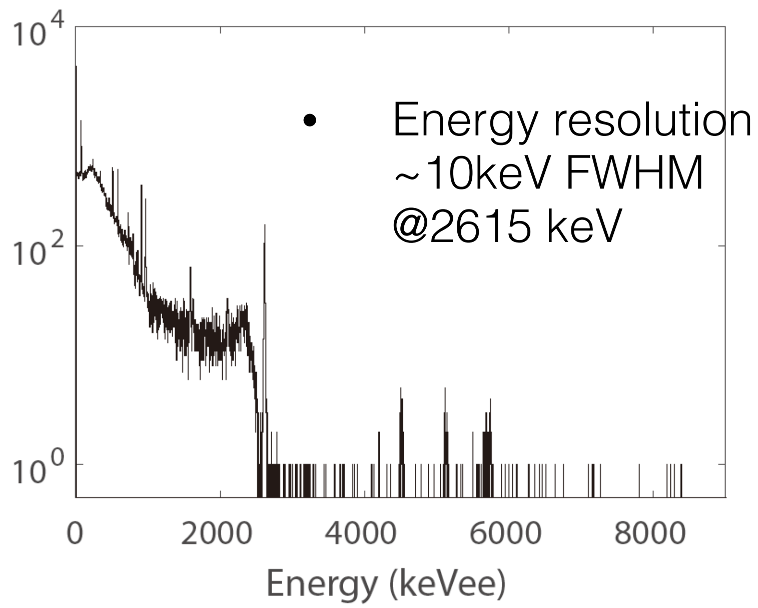


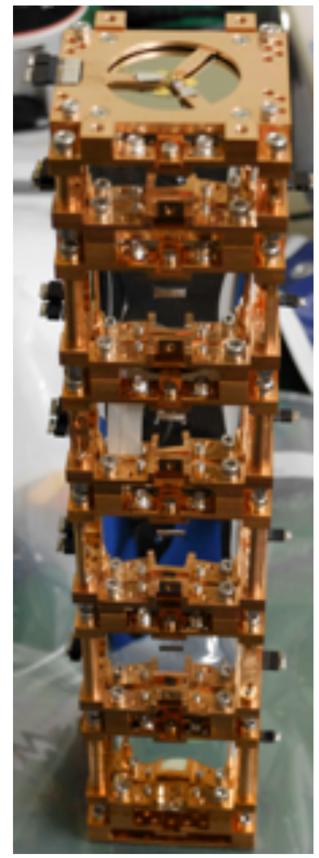


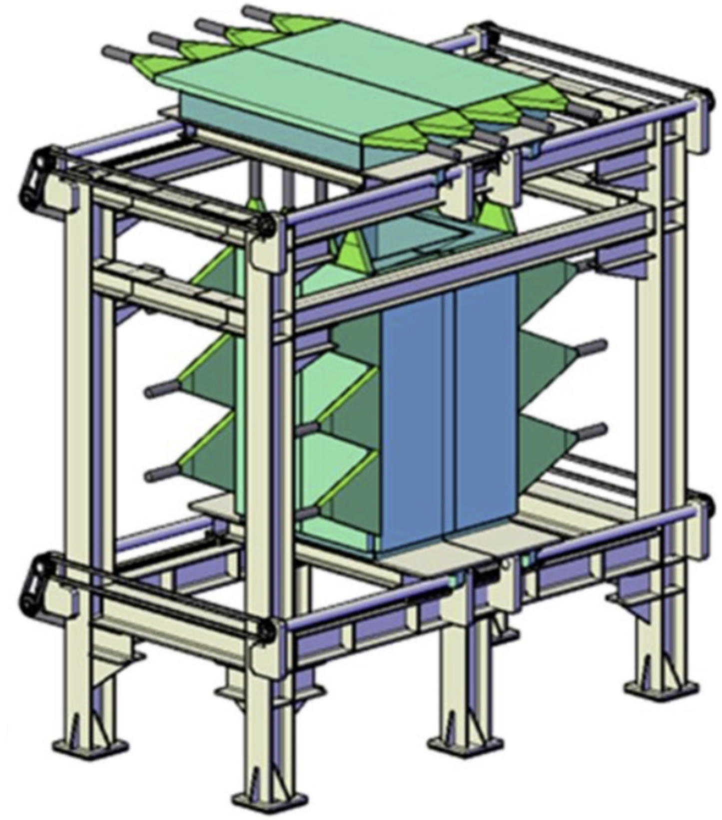
Figs. courtesy Yong-Hamb Kim (AMORE)

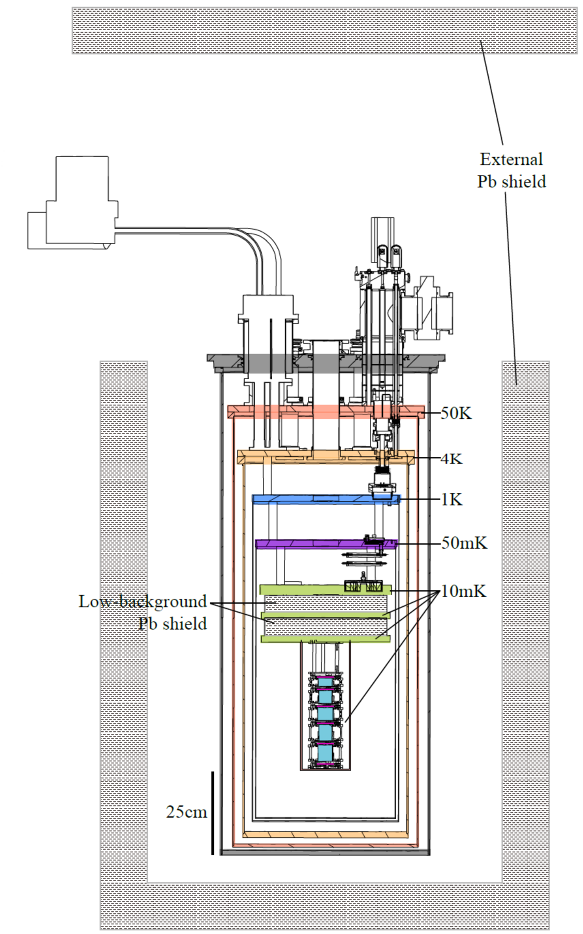
AMORE-Pilot

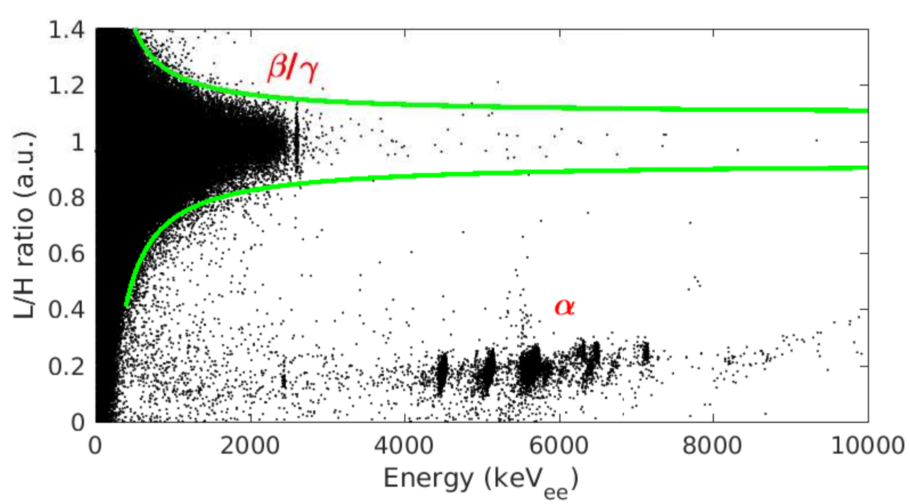
- 6 $^{depl.}Ca^{100}MoO_4$ crystals
- 95% enrichment in ^{100}Mo



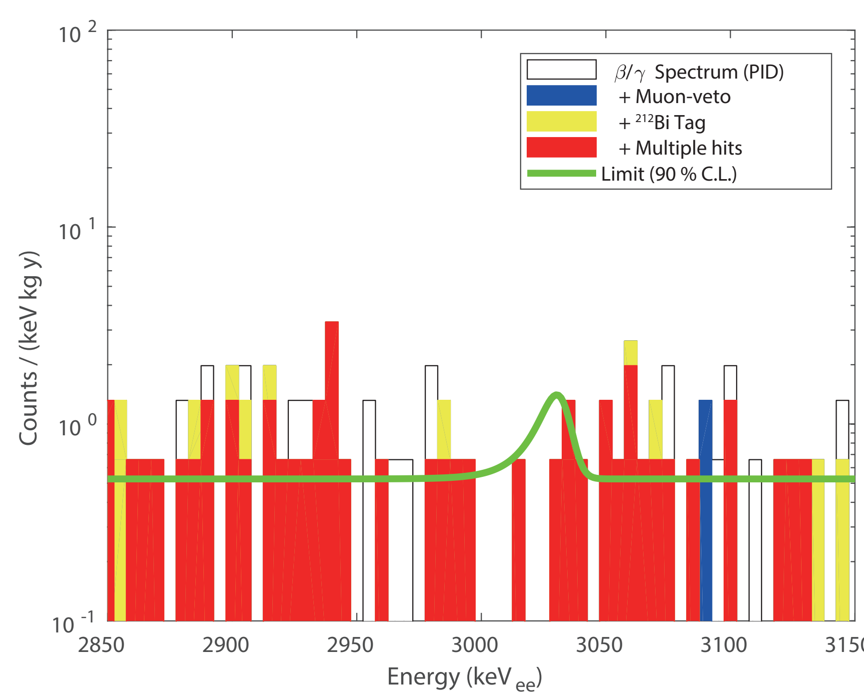








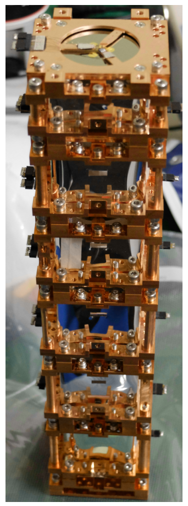
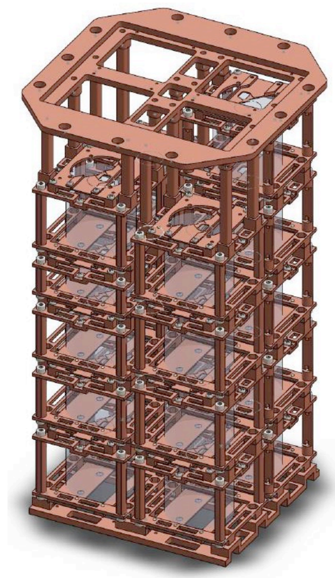
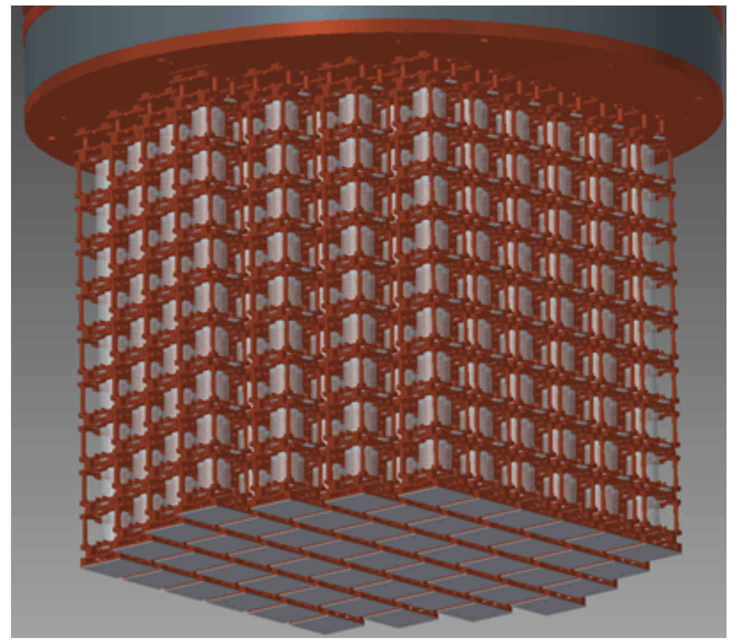
- Demonstrate excellent PID based on heat/light signal



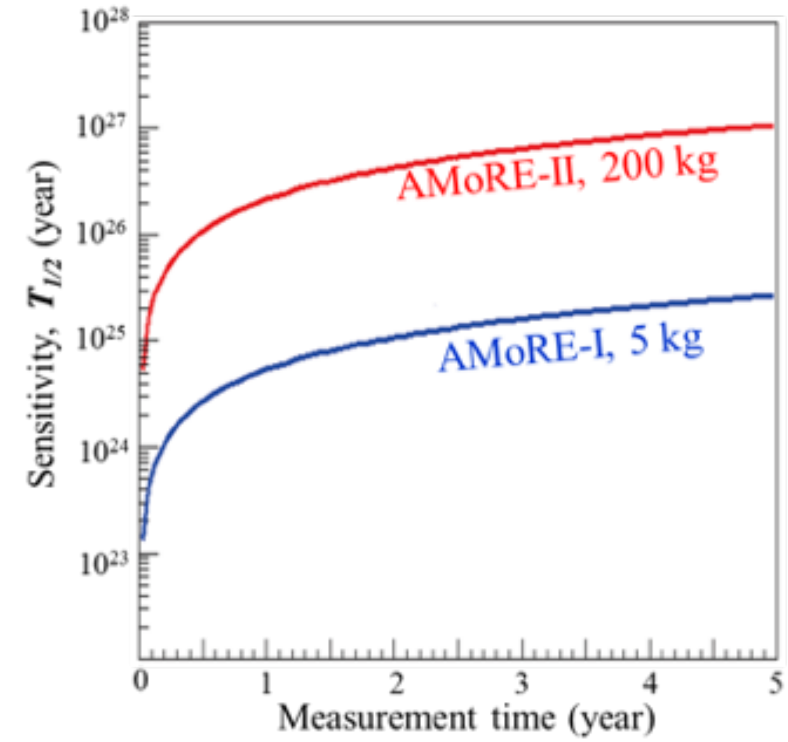
111 kg·day exposure
0.55 ckky bkg.
$T^{0\nu} > 1\times10^{23}$ y

Figs. courtesy Yong-Hamb Kim (AMORE)

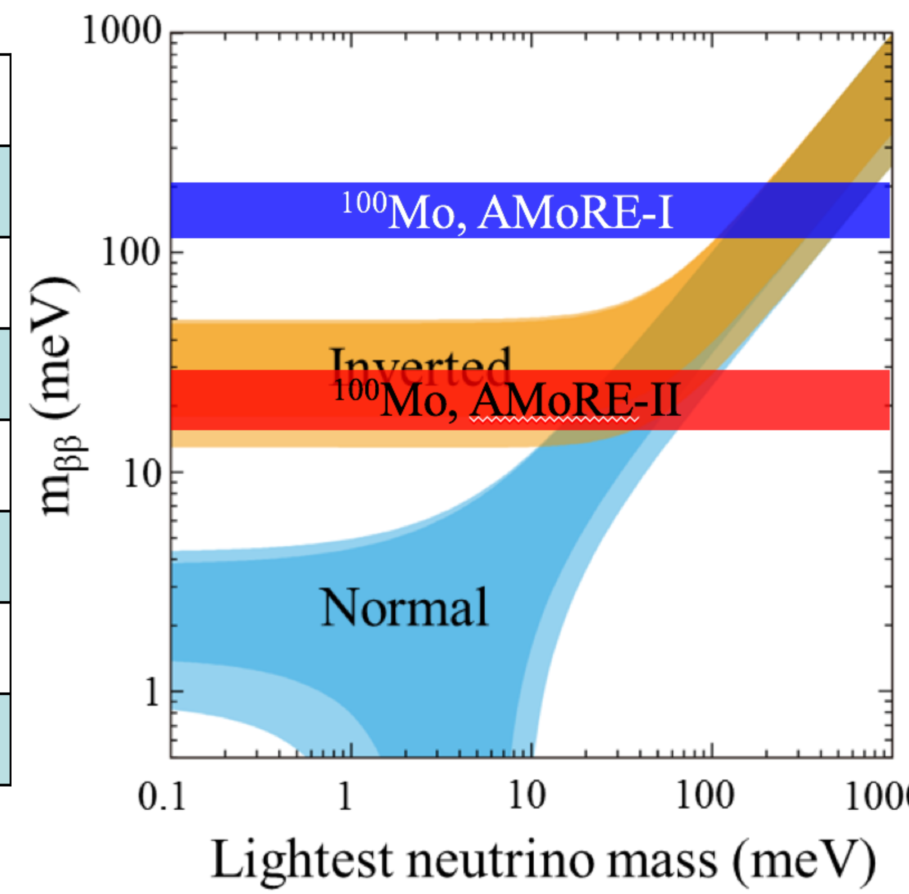
AMORE Program

Pilot	AMORE-I	AMORE-II
		

Both $CaMoO_4$ and Li_2MoO_4



	Pilot	AMoRE-I	AMoRE-II
Mass	1.9 kg	~6 kg	~200 kg
Channels	12	36	1000
Bkg. Goal (ckky)	0.01	0.0015	0.0001
Sensitivity($T_{1/2}$) (year)	$\sim 10^{24}$	$\sim 10^{25}$	$\sim 5\times10^{26}$
Sensitivity(m_{ee})	380-640	120-200	17-29
Location	Y2L	Y2L	New Lab
Schedule	2017-2018	2019~	2021~



Figs. courtesy Yong-Hamb Kim (AMORE)

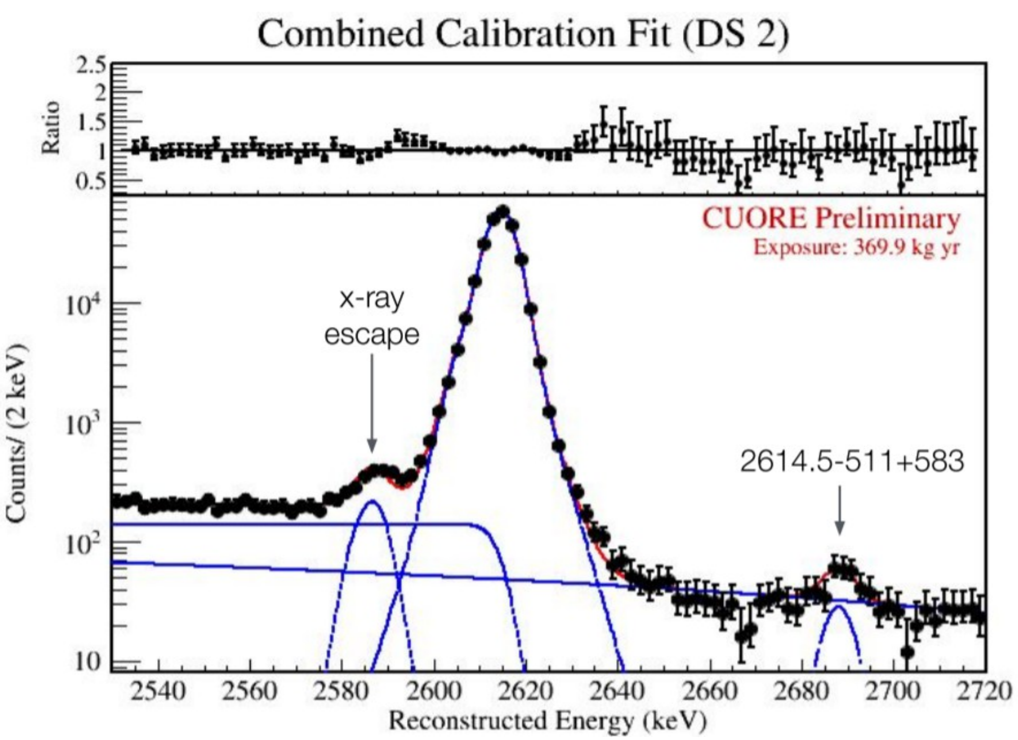
Conclusions & Acknowledgements

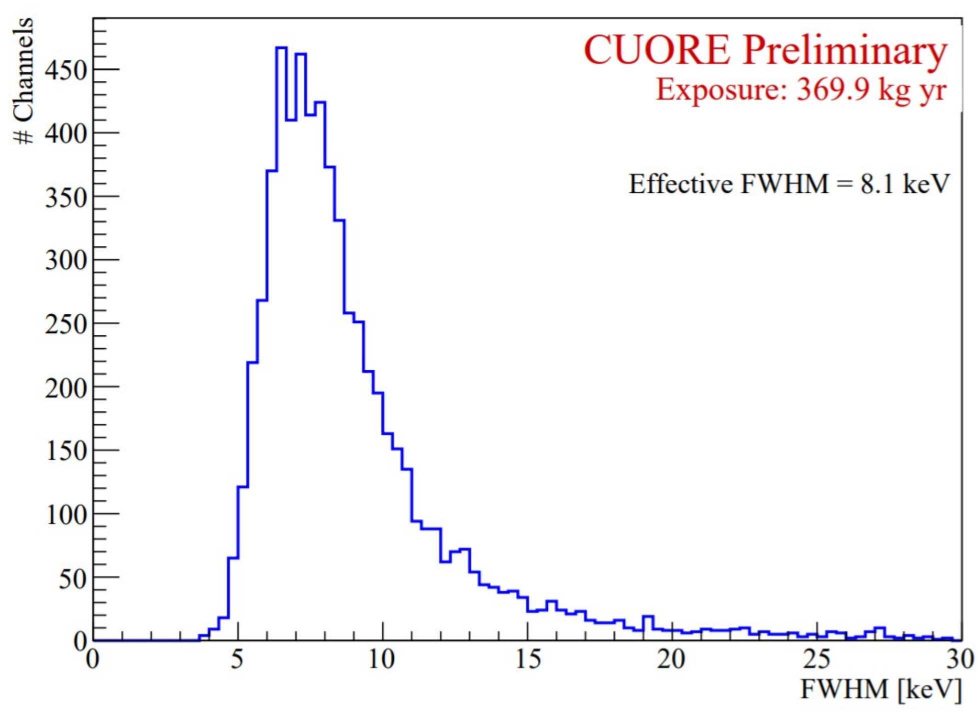
- CUORE (742 kg TeO_2 array) shows it is possible to operate a large array of macro bolometers at ultra-low cryogenic temperatures
- Small (~20 detector) pilot experiments using scintillating bolometer arrays have made tremendous progress (CUPID-0, Lumineu, CUPID-Mo, AMORE-pilot)
- $Li_2{}^{100}MoO_4$ scintillating bolometers enriched in ^{100}Mo is the baseline choice for CUPID which aims for discovery sensitivity of m_{bb}: 12~20 meV
- The AMORE program aims for similar sensitivity with ^{100}Mo-based bolometers, exploring both $^{depl.}Ca^{100}MoO_4$ and $Li_2{}^{100}MoO_4$
- An attractive feature of scintillating bolometers is flexibility of target isotope: ZnSe, $CaWO_4$, $CdWO_4$ show promise.
- Innovative R&D on detector technologies should continue. If (when) discovery is made, there will be a need to confirm and explore in other nuclei

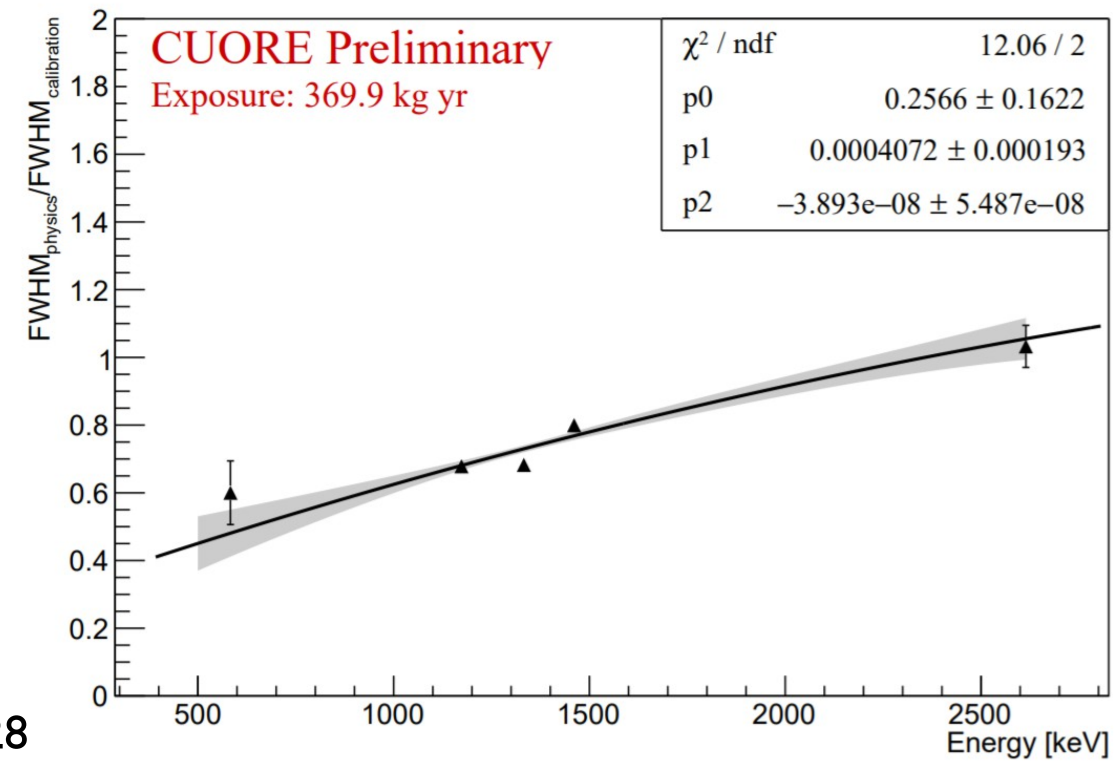
Many thanks the CUORE, CUPID, CUPID-0, CUPID-Mo and AMORE collaborations for providing material for this talk

Extra slides

CUORE: Lineshape and energy resolution

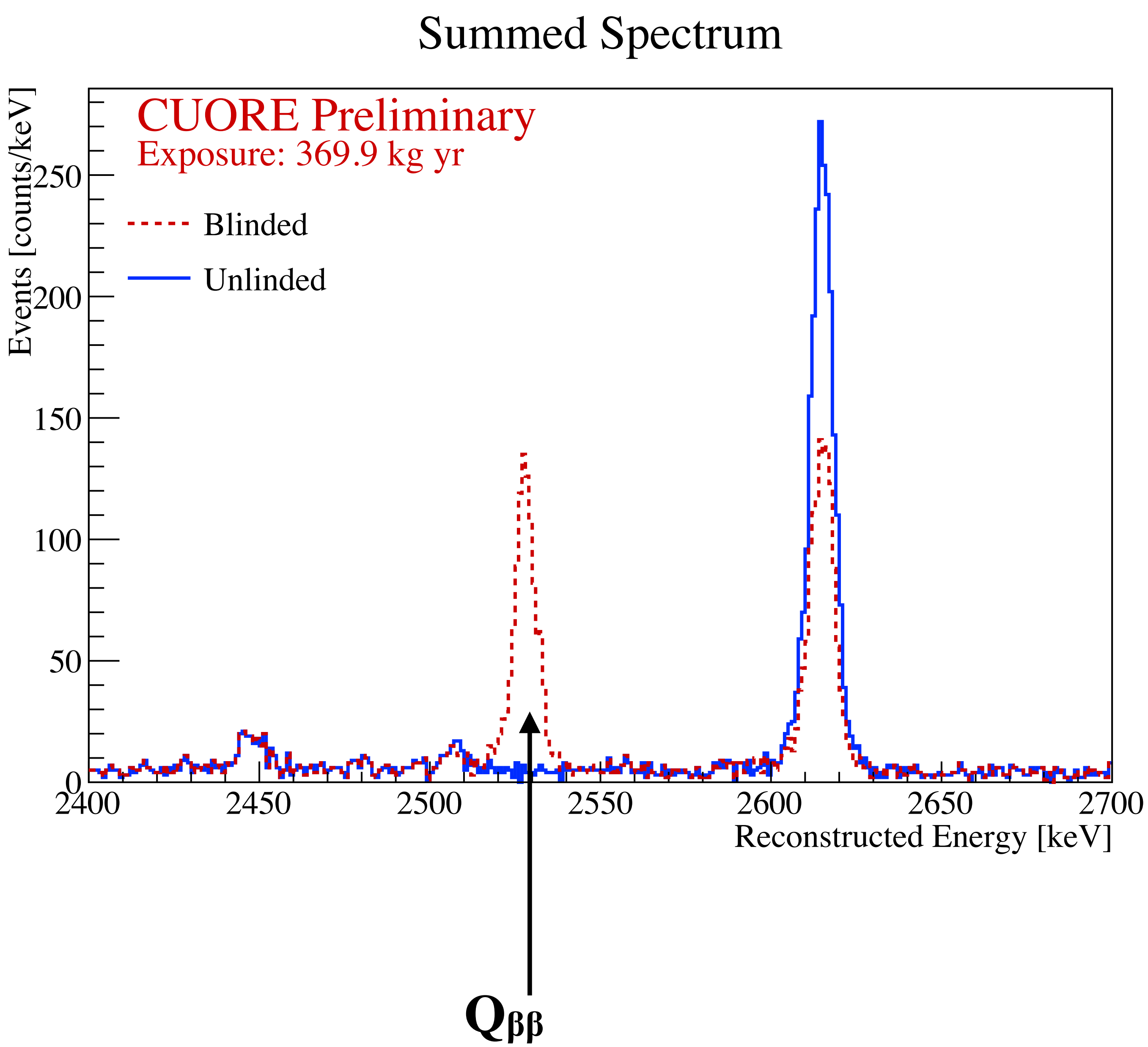






Blinding procedure

- To blind we randomly move a fraction of events from +/- 20 keV of 2615 keV to the Q-value and vice versa
- Blinding produces an artificial peak around the 0vDBD Q-value hiding the real 0vDBD rate of ^{130}Te
- This method avoids introducing discontinuities in the spectrum
- When all data analysis procedures are fixed the data are eventually unblinded



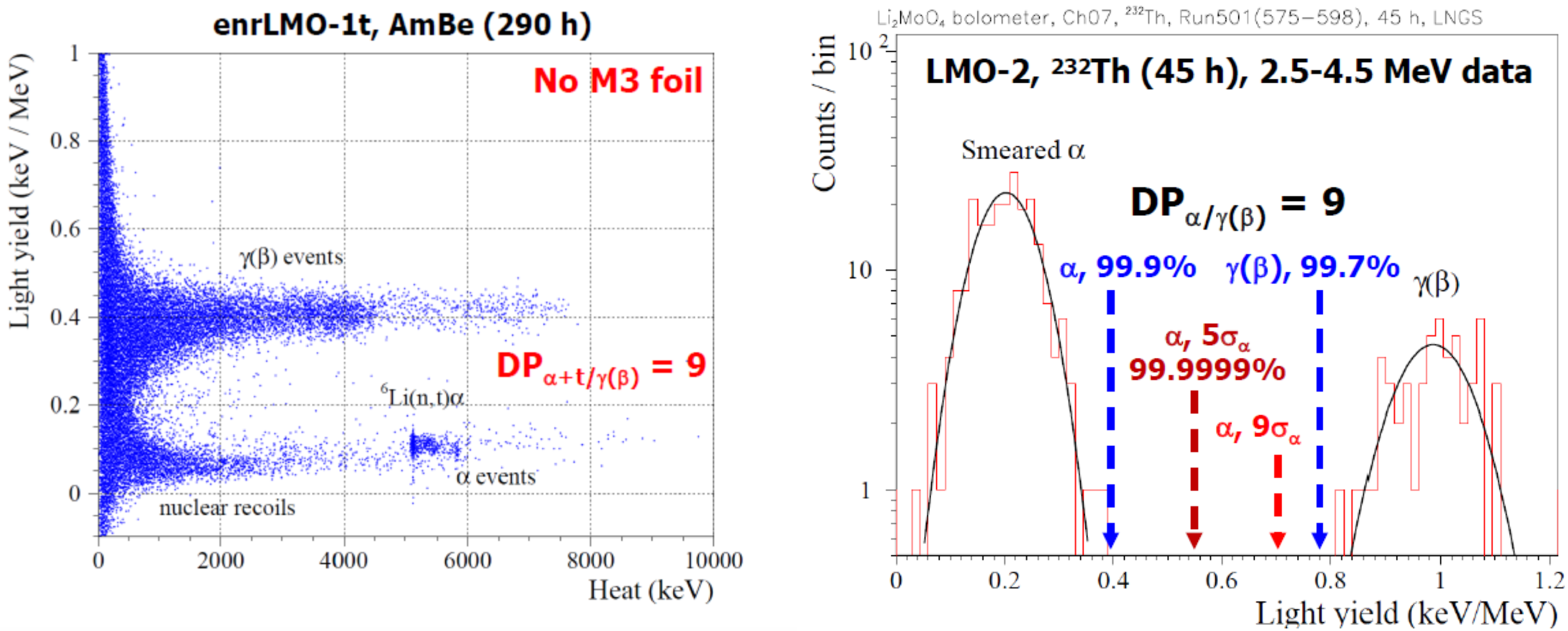
Event selection: efficiencies

Event selection occurs after periods of low-quality data (~1% of the total live time) are removed.

Detection Efficiency	(95.958 +/- 0.003)%
Anti-coincidence	(98.954 + 0.151 -0.161) %
Pulse shape analysis	(92.037 +/- 0.108)%
All cuts except containment	**(87.412 ± 0.175) %**
$0\nu\beta\beta$ containment	**(88.350 ± 0.090) %**

CUPID: $Li_2{}^{100}MoO_4$

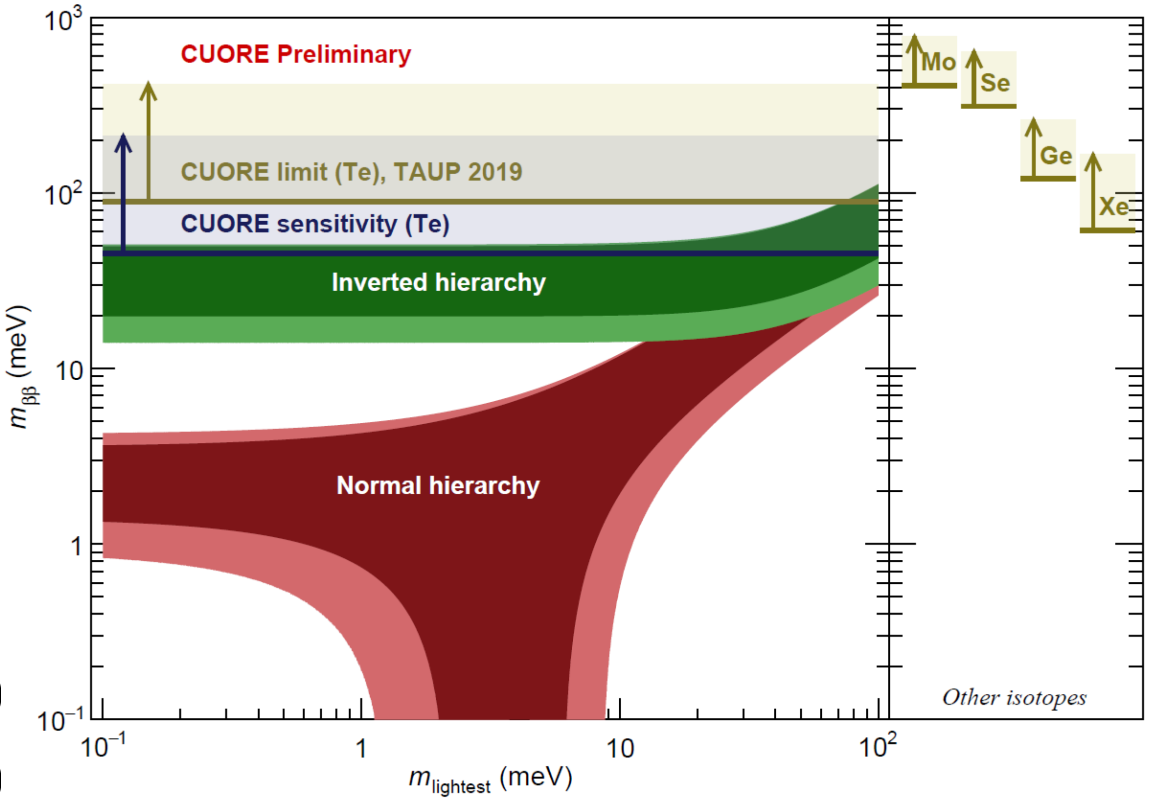
- LMO alpha/beta discrimination using heat and light signals



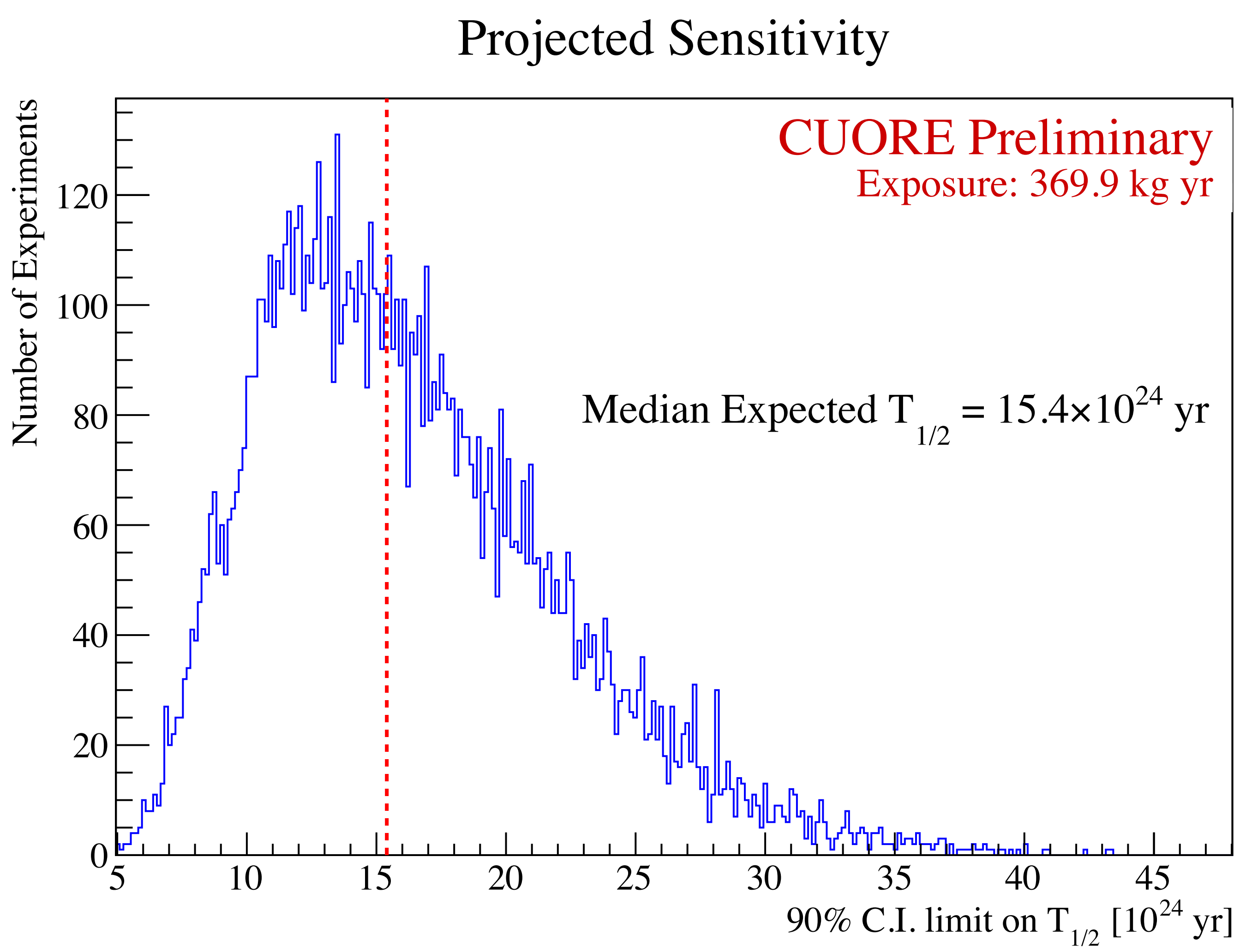
Figs. Courtesy of Andrea Giuliani, CSNSM, Saclay

NMEs

JHEP02 (2013) 025
Nucl. Phys. A 818, 139 (2009)
Phys. Rev. C 87, 045501 (2013)
Phys. Rev. C 87, 064302 (2014)
Phys. Rev. C 91, 034304 (2015)
Phys. Rev. C 91, 024613 (2015)
Phys. Rev. C 91, 024309 (2015)
Phys. Rev. C 91, 024316 (2015)
Phys. Rev. Lett. 105, 252503 (2010)
Phys. Rev. Lett. 111, 142501 (2013)

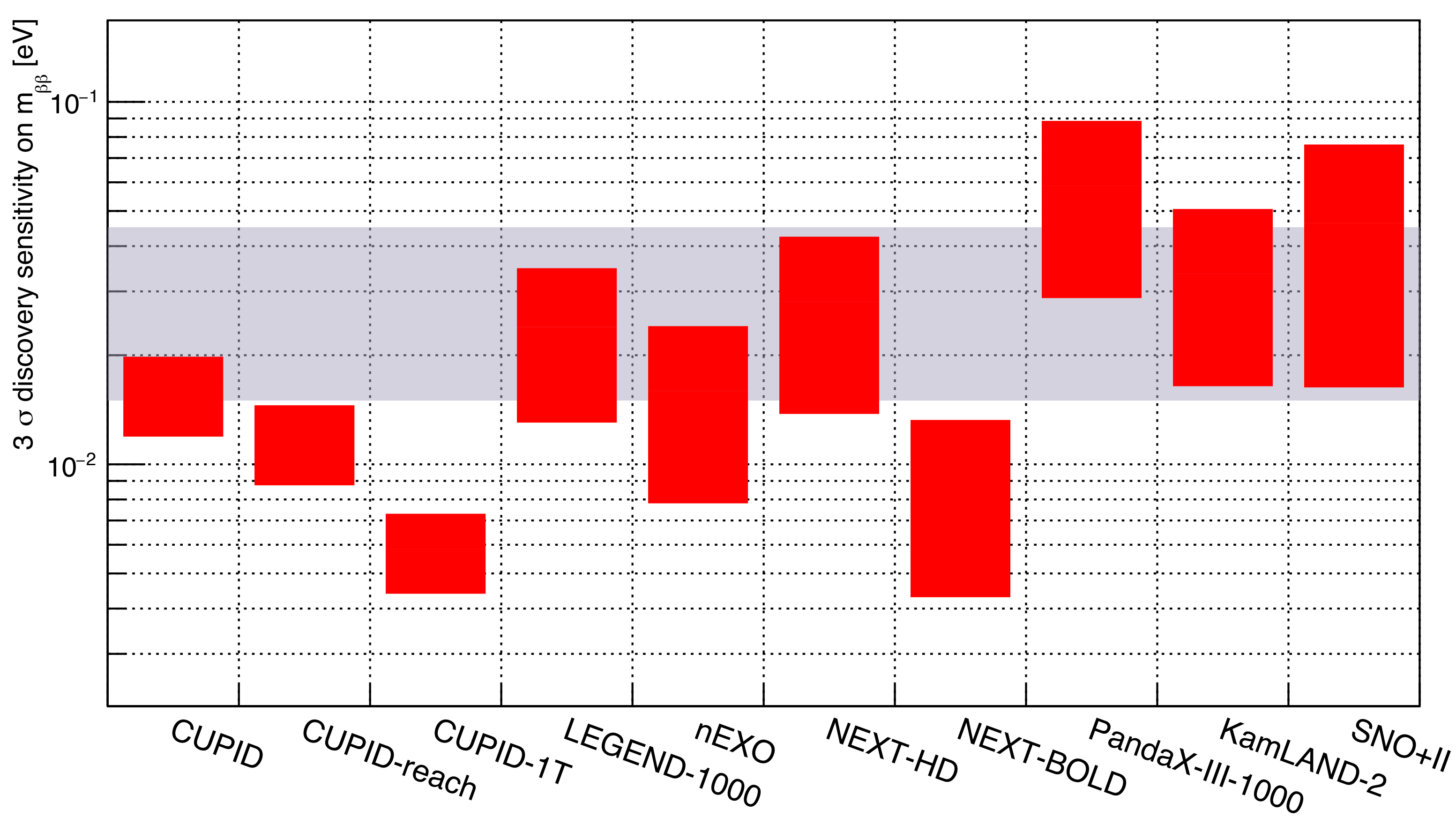


CUORE Median Expected Sensitivity



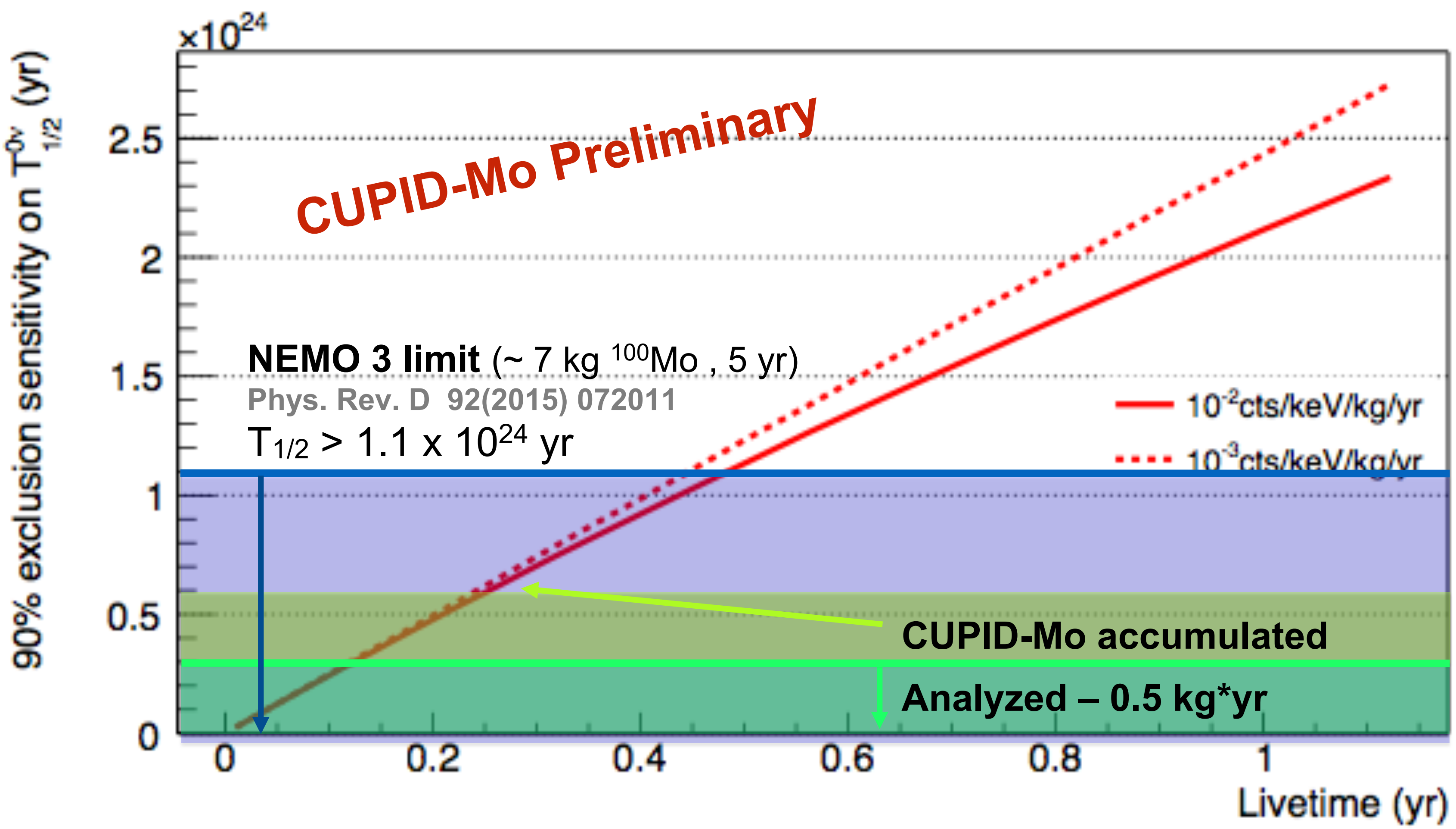
CUPID Scenarios

Parameter	CUPID Baseline	CUPID-reach	CUPID-1T
Crystal	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$
Detector mass (kg)	472	472	1871
^{100}Mo mass (kg)	253	253	1000
Energy resolution FWHM (keV)	5	5	5
Background index (counts/(keV·kg·yr))	10^{-4}	2×10^{-5}	5×10^{-6}
Containment efficiency	79%	79%	79%
Selection efficiency	90%	90%	90%
Livetime (years)	10	10	10
Half-life exclusion sensitivity (90% C.L.)	1.5×10^{27} y	2.3×10^{27} y	9.2×10^{27} y
Half-life discovery sensitivity (3σ)	1.1×10^{27} y	2×10^{27} y	8×10^{27} y
$m_{\beta\beta}$ exclusion sensitivity (90% C.L.)	10–17 meV	8.2–14 meV	4.1–6.8 MeV
$m_{\beta\beta}$ discovery sensitivity (3σ)	12–20 meV	8.8–15 meV	4.4–7.3 meV



CUPID-Mo: NLDBD Sensitivity

- Now: accumulated > 1 kg*yr of physics data
- $T_{1/2} > 3*10^{23}$ yr at 90% C.L with
  ~0.5 kg*yr exposure (~0.27 kg*yr of ^{100}Mo), 81% signal acceptance



- **Confirmed:** Bolometric performance & reproducibility, exceeded expectations for radiopurity (bulk) ✓
- Next: Use Geant4 MC and data to build a detailed background model
- Introduce data blinding
- Optimize $0\nu\beta\beta$ analysis cuts
- **Goal**: Reach > 2 kg * yr of physics exposure, ~6 month with 19/20 detectors, 90% analysis efficiency 75% $0\nu\beta\beta$ containment

Slide courtesy of B. Schmidt and CUPID-Mo collaboration