Development of Transition Edge Sensors for CUPID

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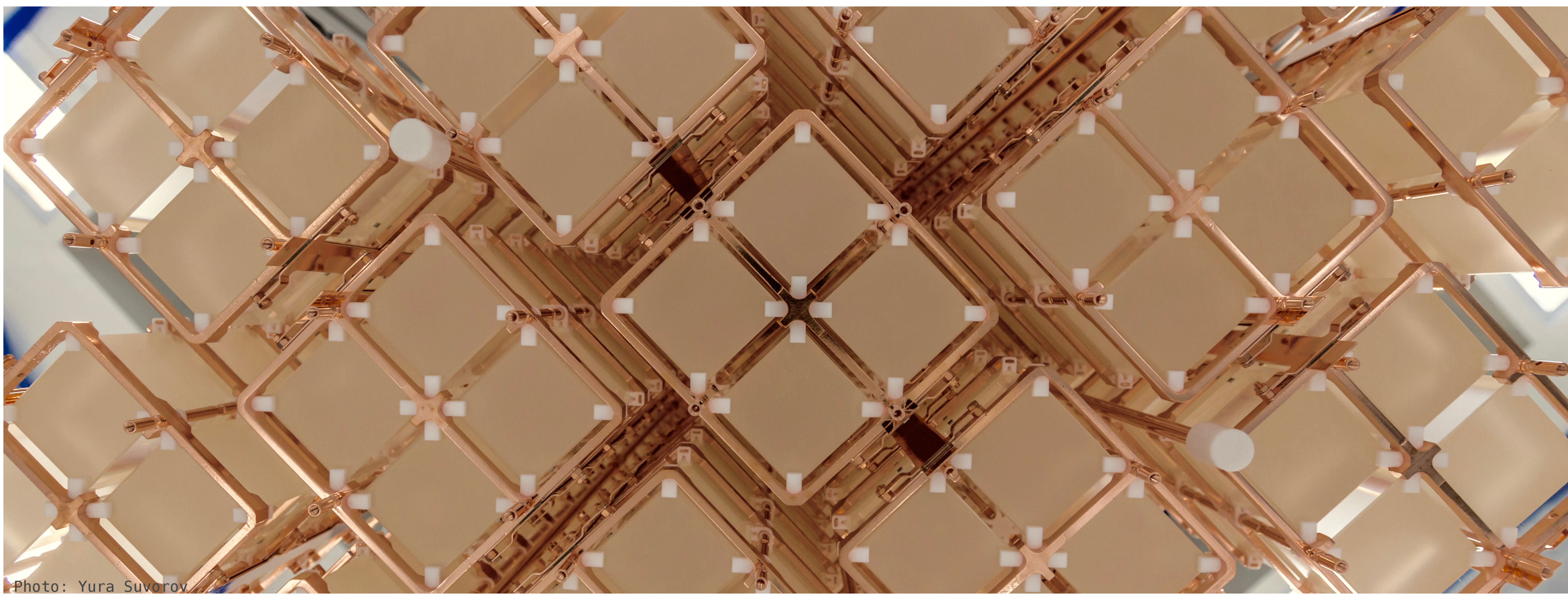
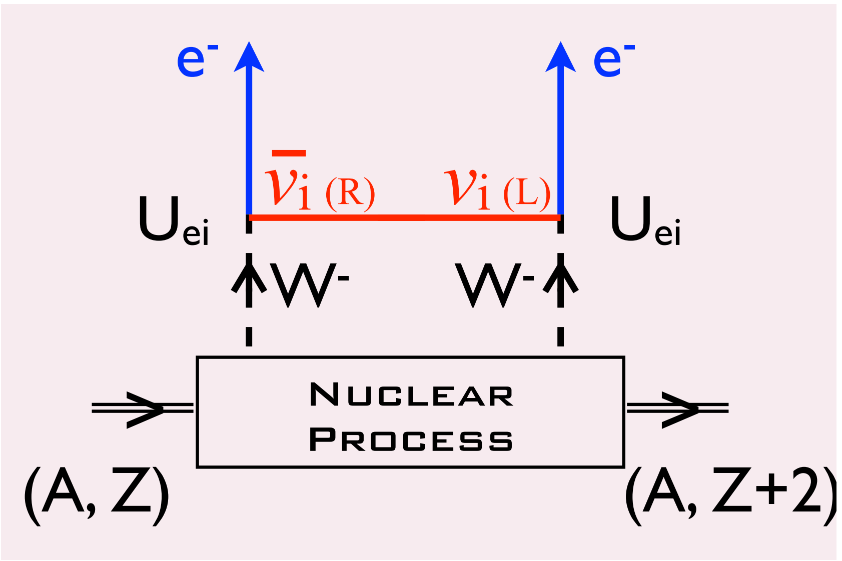
CPAD-2017, Albuquerque, New Mexico.

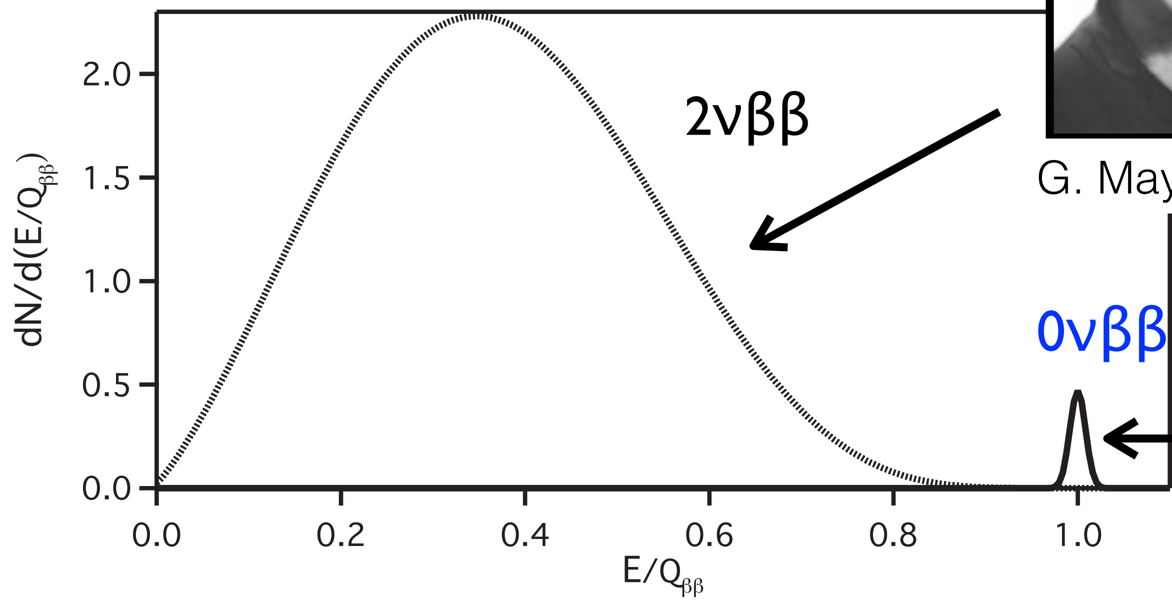


Picture: CUORE detector array

Neutrinoless Double Beta Decay

- Hypothetical ββ decay mode allowed if neutrinos are Majorana particles, i.e $\bar{\nu}_i \equiv \nu_i$





G. Mayer in 1935

1937

E. Majorana in 1937

Phase space factor

Nuclear matrix element

$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}|M^{0\nu}|^2|\langle m_{\beta\beta}\rangle|^2$$

Decay half-life

Effective Majorana ν mass:

$$m_{\beta\beta} \equiv \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$

- For $m_{\beta\beta}$ = 15 meV estimated half lives 10^{27} - 10^{28} years, depending on the nuclear system

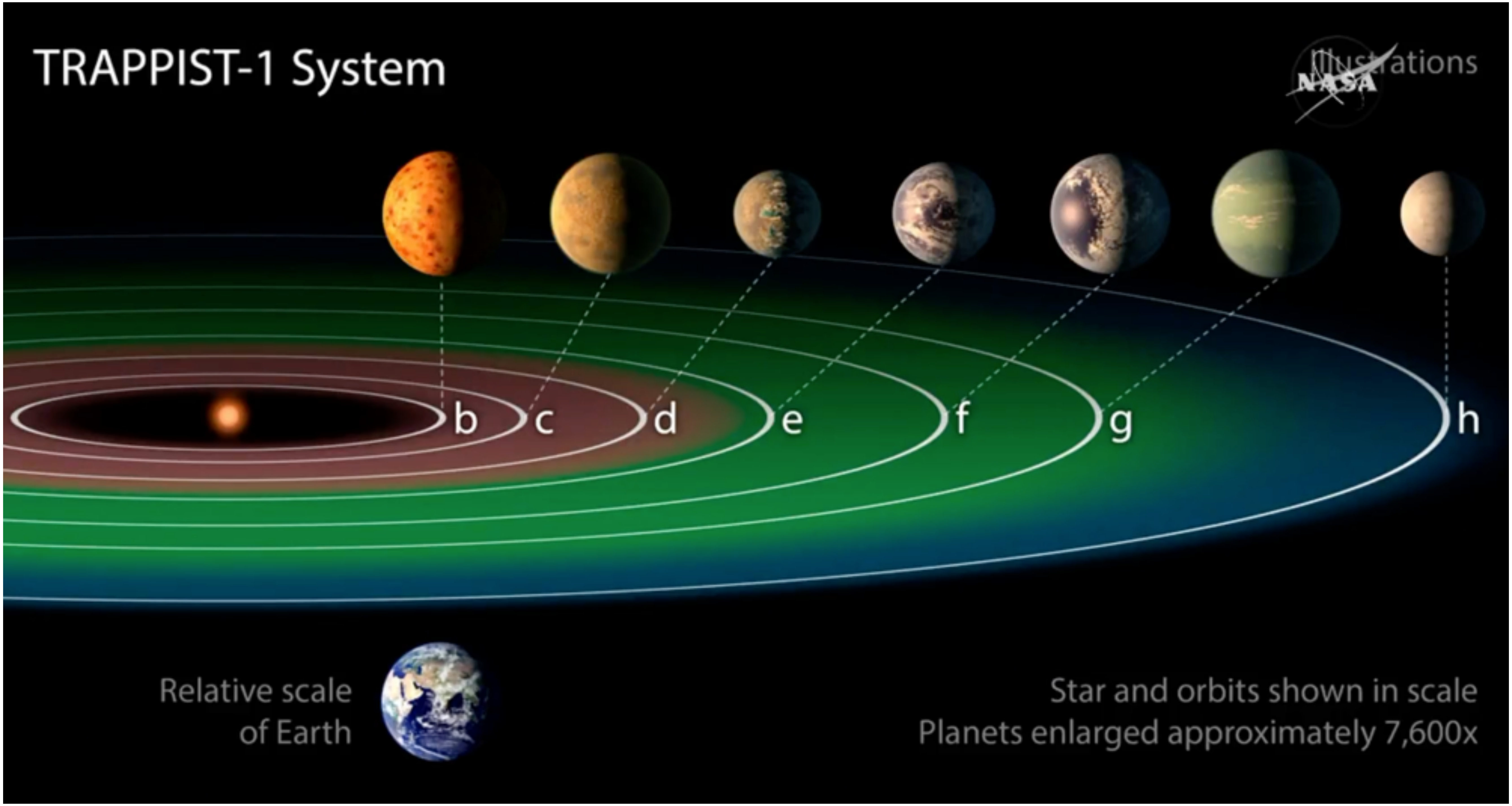
- *Observation of 0νββ would mean*
  - Lepton number violation
  - Neutrinos are Majorana particles
  - Rate measures (effective) electron neutrino mass

Why is it so difficult?

^{14}C	10^4 years
^{40}K	10^9 years
^{232}Th	10^{10} years
The Universe	10^{10} years
Two Neutrino Double Beta	10^{20} years
Neutrinoless Double Beta	$>10^{26}$ years
Proton Decay	$>10^{34}$ years

$$S \ \alpha \ \frac{N_A}{M_{mol}} \eta \sqrt{\frac{Mt}{b \cdot \Delta E}}$$

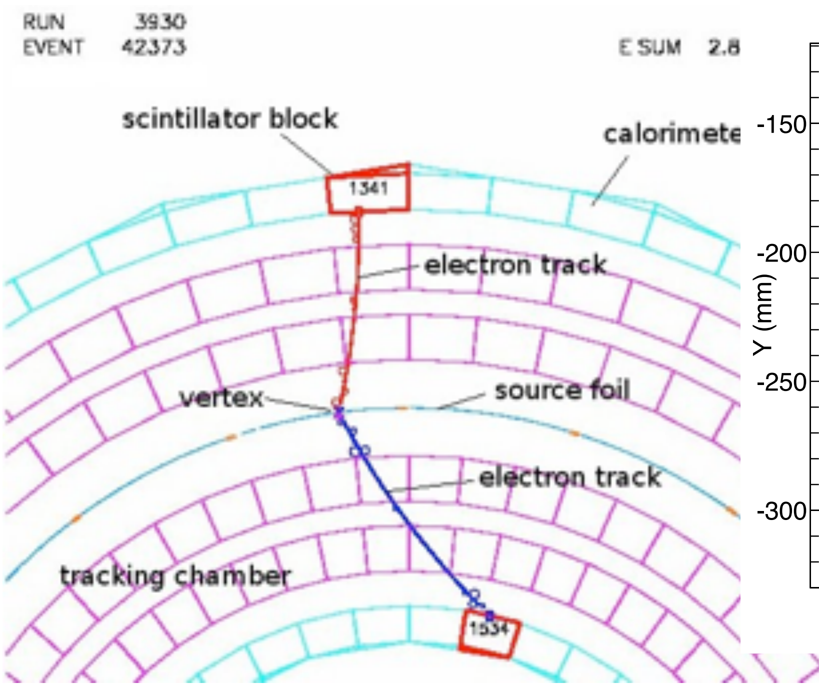
But what’ s the probability of finding this!



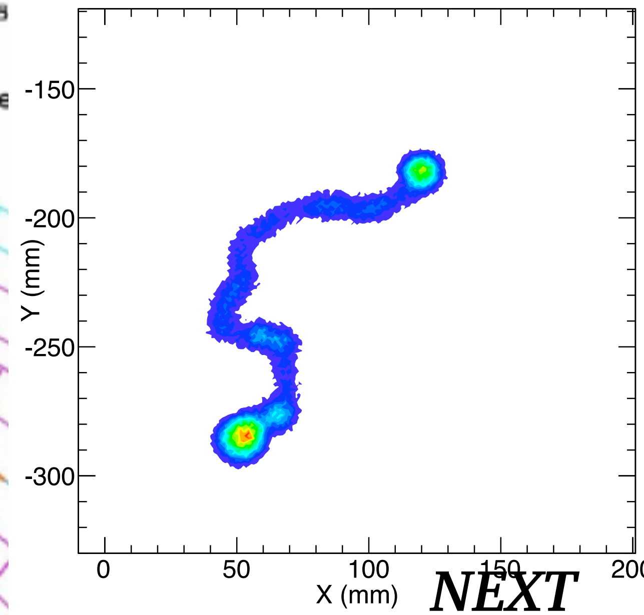
Experimental approaches to the $0\nu\beta\beta$ search

Source external to detector

Example: SuperNEMO



Nemo



NEXT

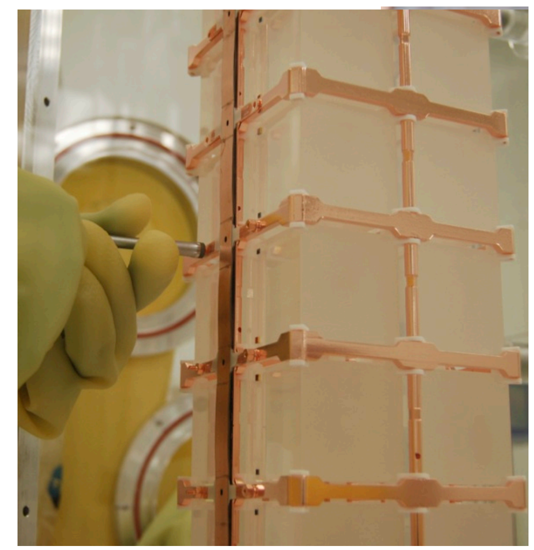
<u>Technology:</u>
Pressurized TPC (10-16 atm)

<u>Pros</u>: event topology, background rejection, multiple isotopes possible.
<u>Cons</u>: detector mass, resolution, acceptance.
<u>Technology</u>: typically tracking detectors.

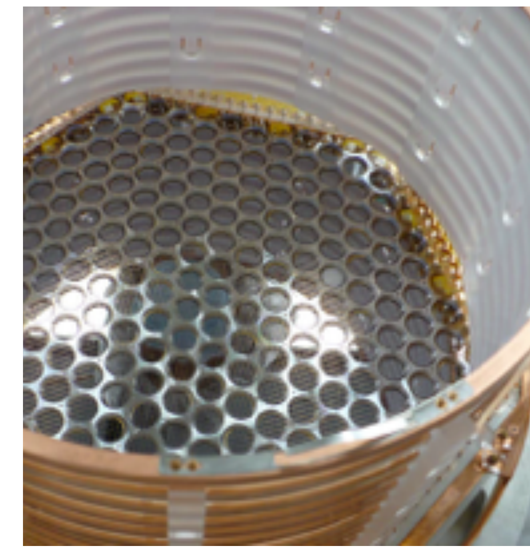
May prove invaluable to test models once $0\nu\beta\beta$ is discovered

Source internal to detector

Example: MAJORANA, EXO, CUORE, SNO+, Kamland-Zen, etc.



CUORE



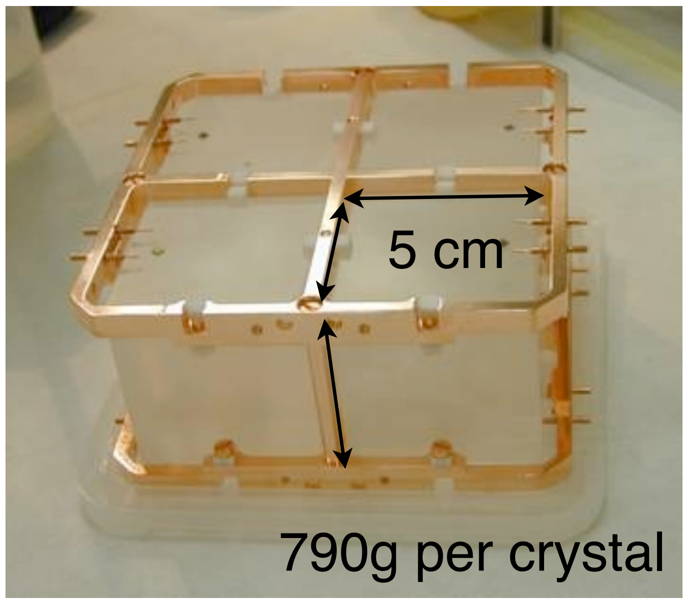
EXO

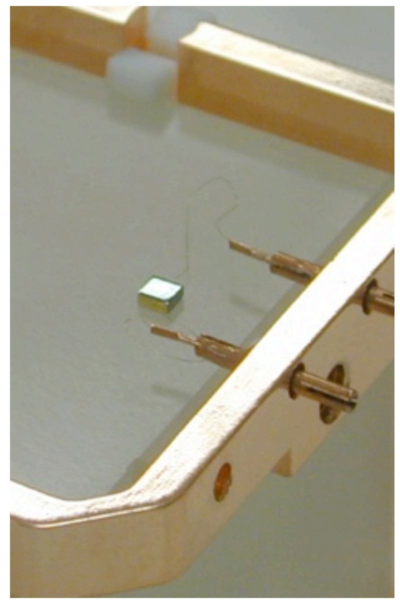
<u>Pros</u>: detector mass, energy resolution, acceptance
<u>Cons</u>: event topology, background rejection
<u>Technology</u>: calorimeters (bolometers, ionization, scintillation), tracking

Typically aimed at $0\nu\beta\beta$ discovery

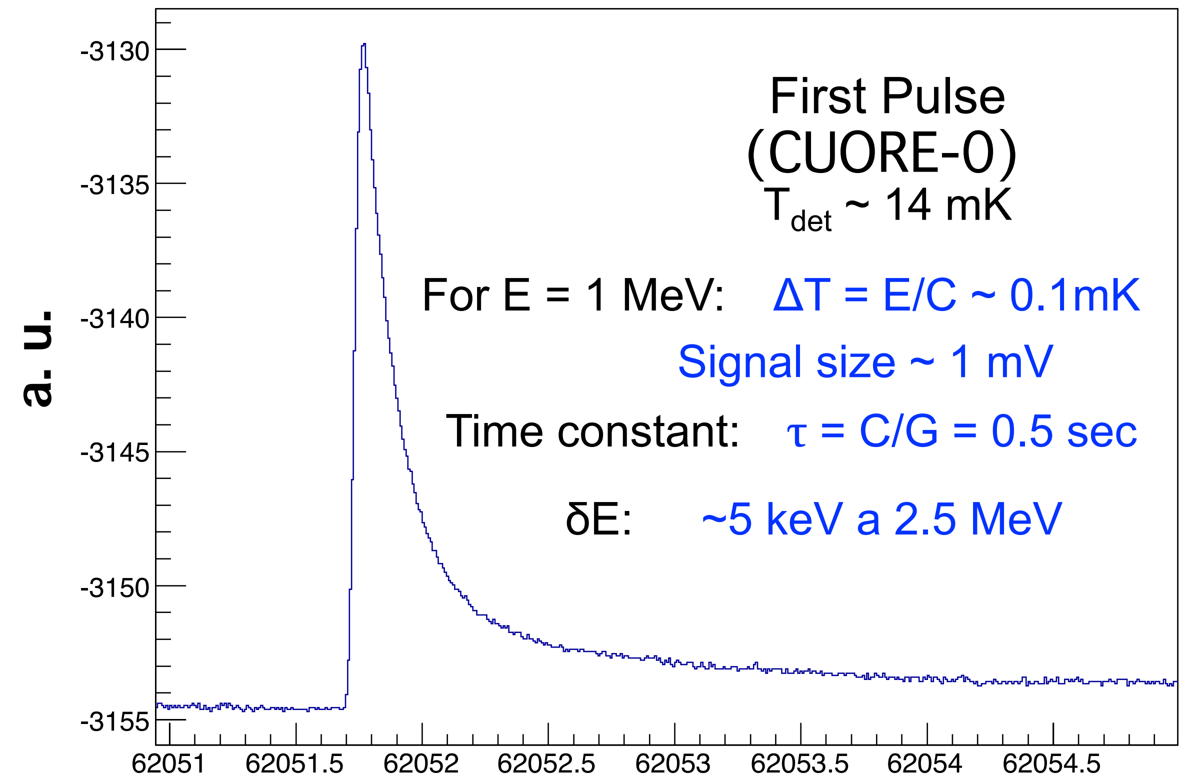
CUORE past and future

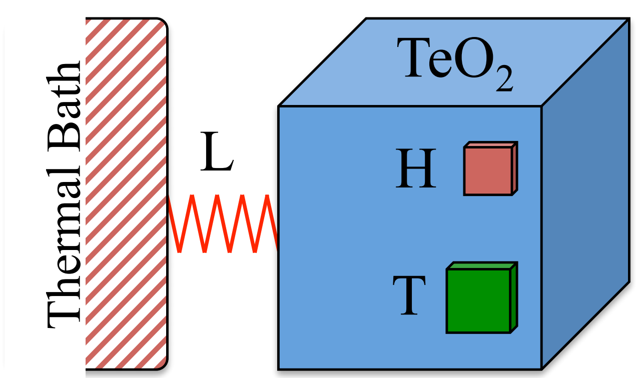
Natural Isotopic Abundance of 34.2%
Q-value = 2528 keV





TeO$_2$ Bolometers (source = detector)





Thermal Bath: Cu-structure

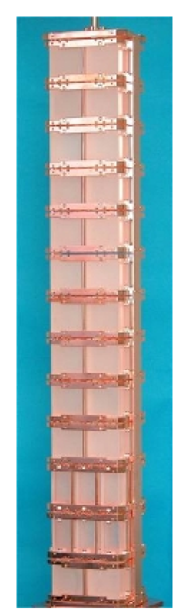
Thermal coupling Teflon +Gold wires

Thermometer:
Ge NTD Termistor
(dR/dT ~ 100kΩ/μK)

MiDBD
1.8 kg ^{130}Te

1997-2001

Cuoricino
11.3 kg ^{130}Te

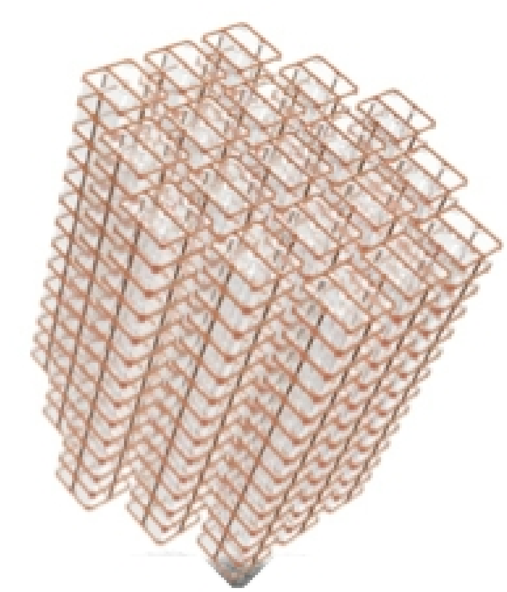


2003-2009

CUORE-0
11 kg ^{130}Te

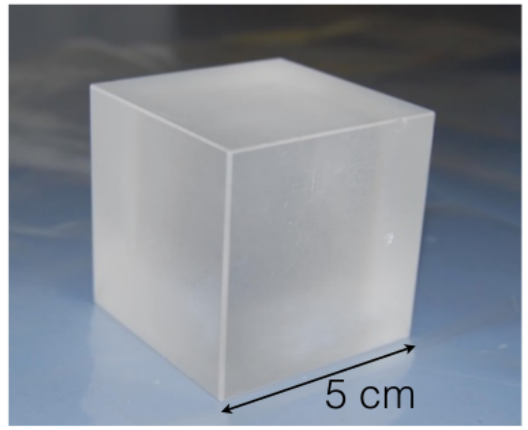
2013-2015

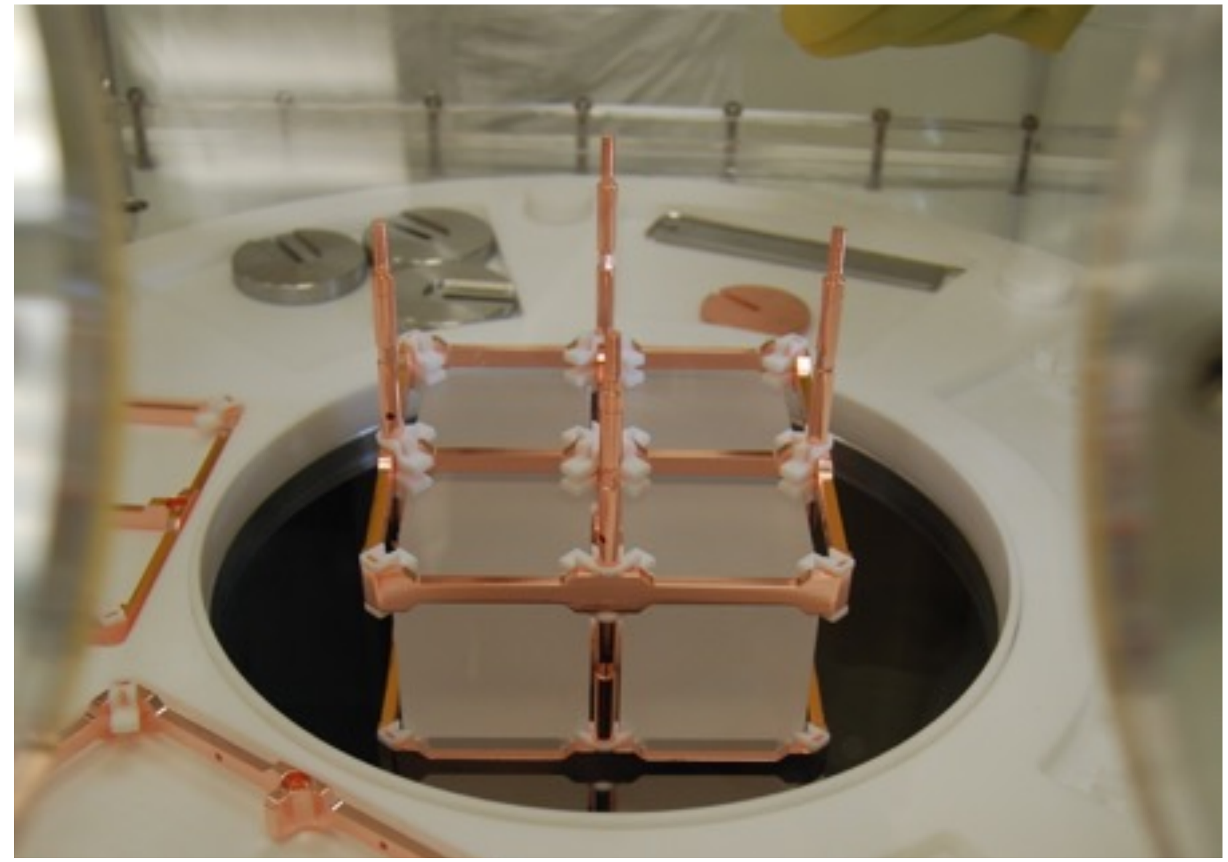
CUORE
206 kg ^{130}Te

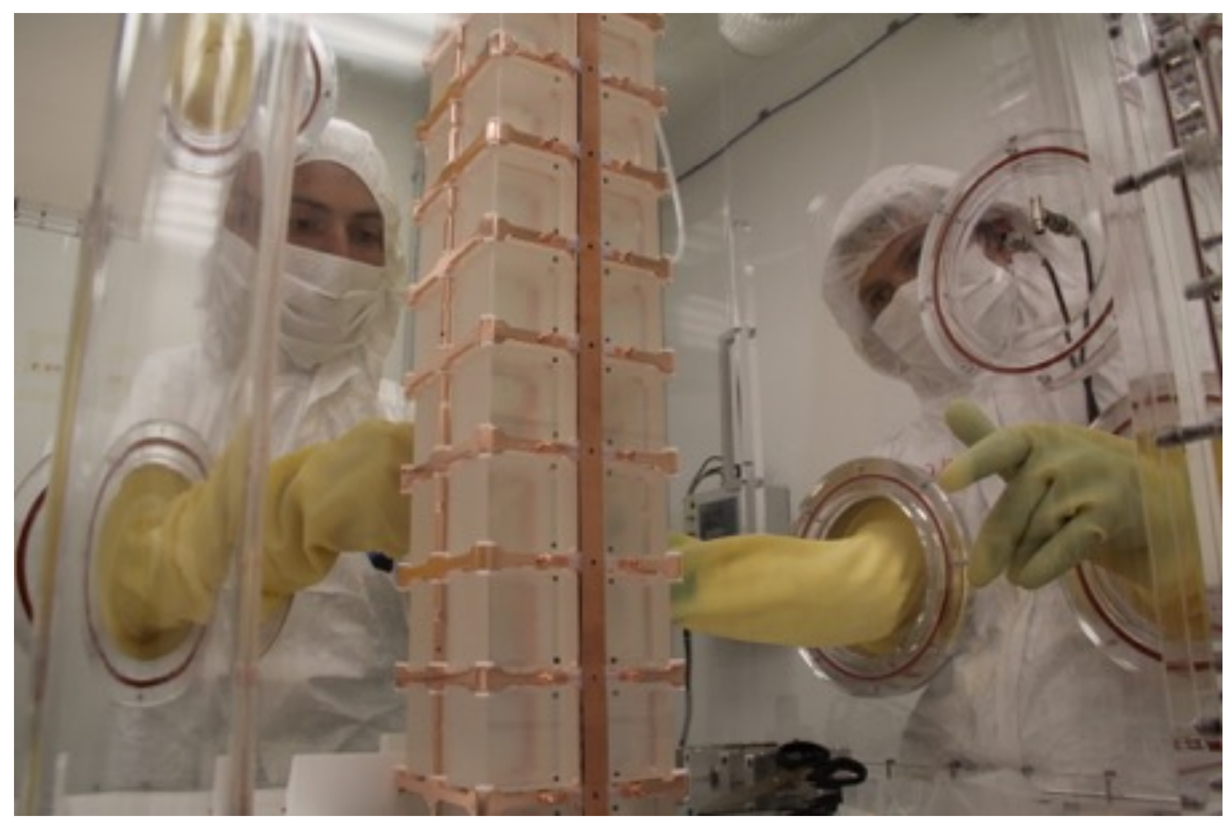


2016-…

CUORE-0/CUORE low background assembly

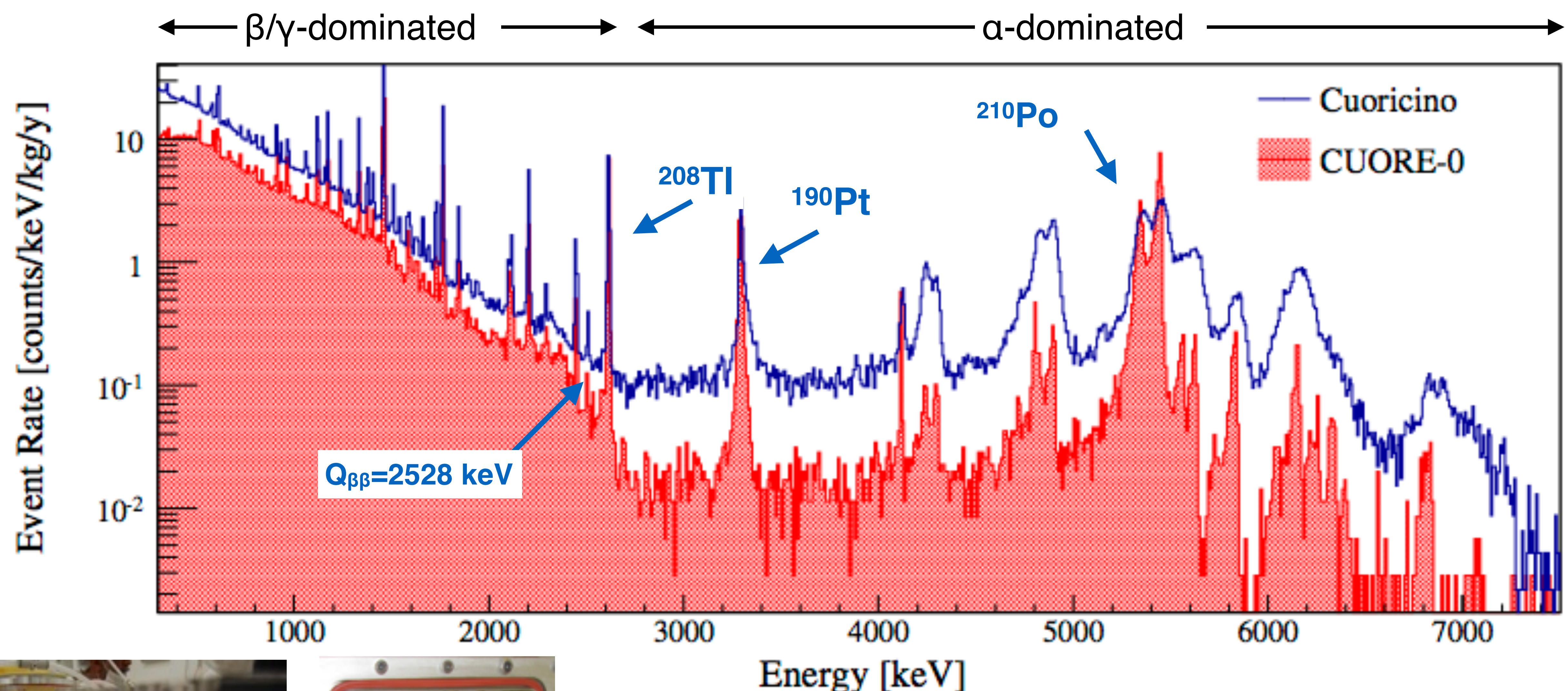


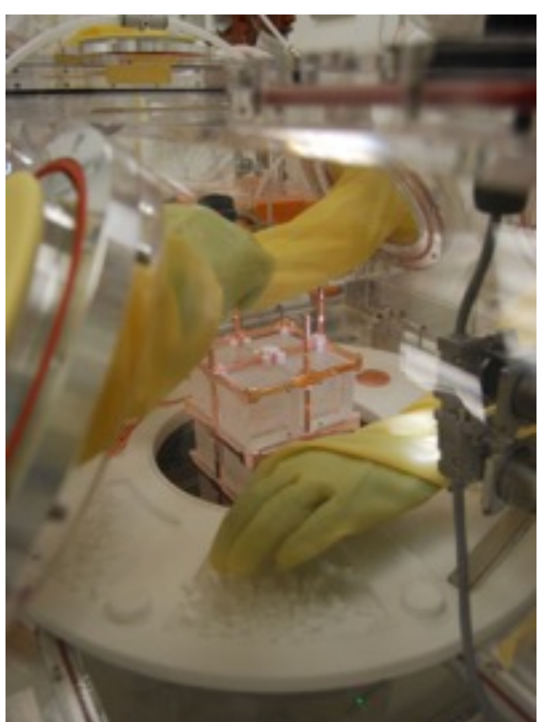


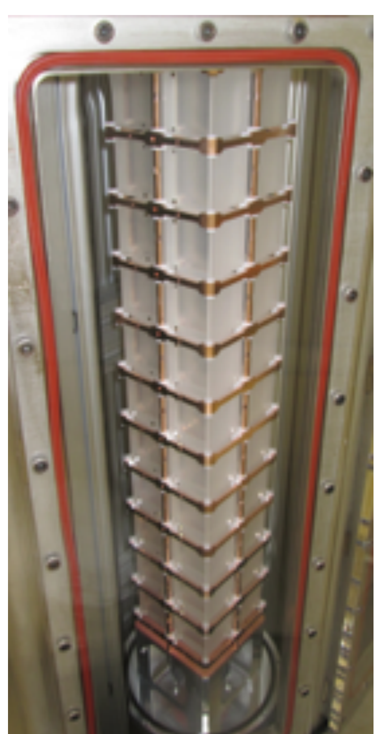


- The raw tellurium metal and the TeO_2 powder were assayed using high-purity germanium detectors and ICPMS, showing $<2 \times 10^{-10}$ g/g (90% C.L.) in ^{232}Th and ^{238}U
- The structure made of copper that supports the crystals constitutes the largest inactive mass that is closest to the detectors.
- Copper on frames, columns and shield were machined from NOSV copper by Aurubis
- Surface cleaning was developed at the Legnaro National Laboratories (Italy).

CUORE-0 background reduction



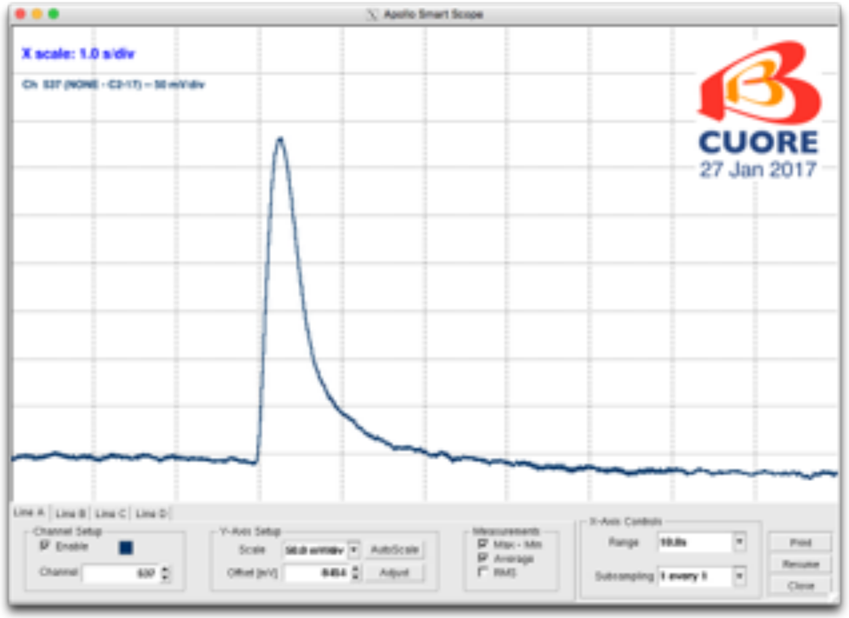




	$0\nu\beta\beta$ region ($c \cdot keV^{-1} \cdot kg^{-1} \cdot yr^{-1}$)	2700-3900 keV * ($c \cdot keV^{-1} \cdot kg^{-1} \cdot yr^{-1}$)
CUORICINO ε = 83%	0.169 ± 0.006	0.110 ± 0.001
CUORE-0 ε = 81%	0.058 ± 0.004	0.016 ± 0.001

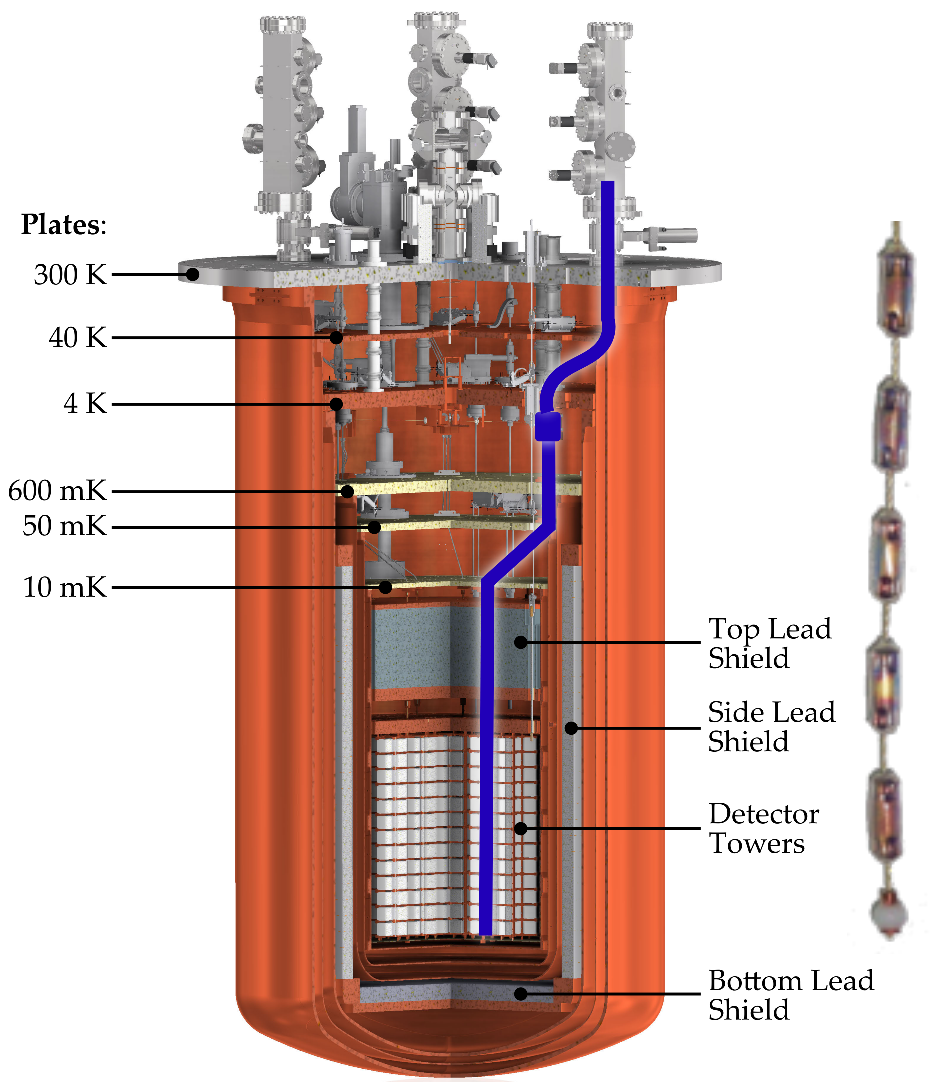
CUORE detector installation, cooldown and first pulses

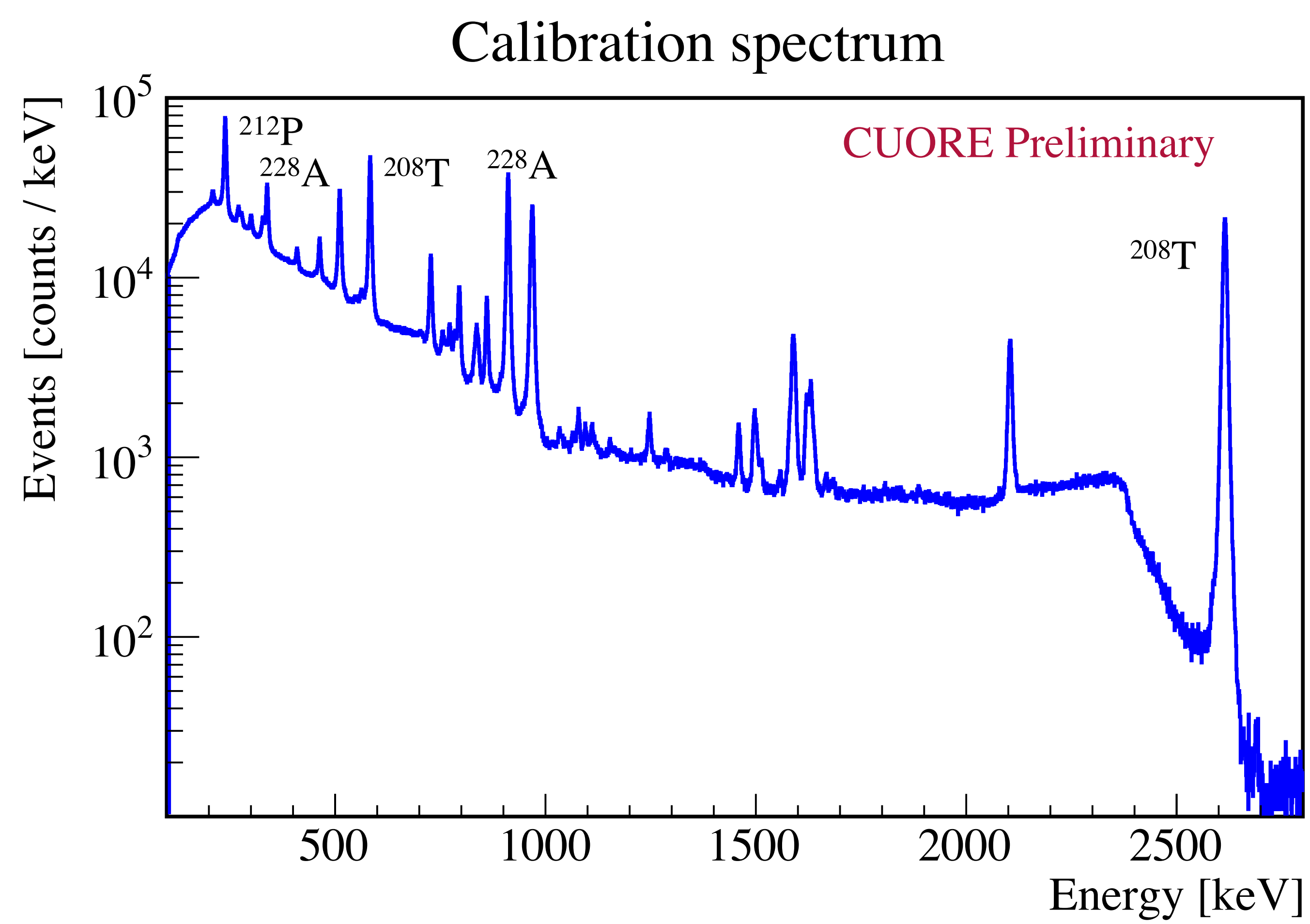
All detector towers installed inside the cryostat, it took about 1 month

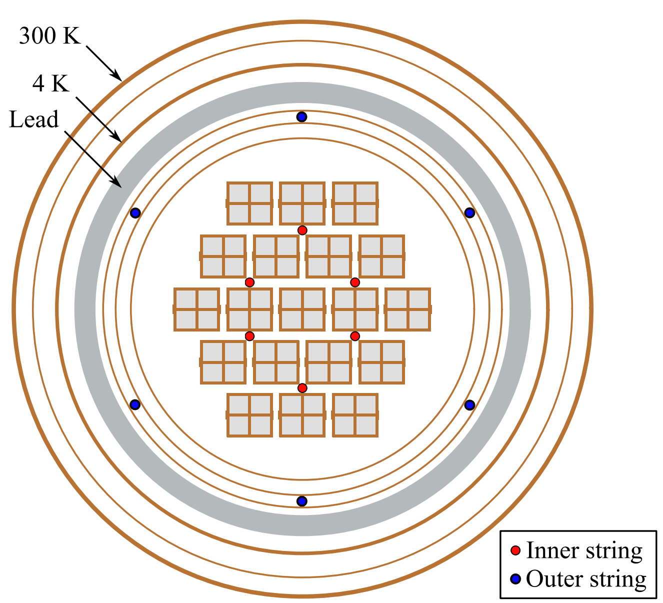


- Custom-made clean room flushed with Rn-free air (Rn<0.1 Bq/m^3, typically 5 mBq/m^3)
- Dec 2016: Cooldown to 4K: 22 days
- Jan 2017: noise mitigation @ 4K
- Jan 2017 cooldown to base: 3 days
- Lowest temperature reached: 6.7 mK
- First detector pulses: Jan 27, 2017

CUORE calibration spectrum

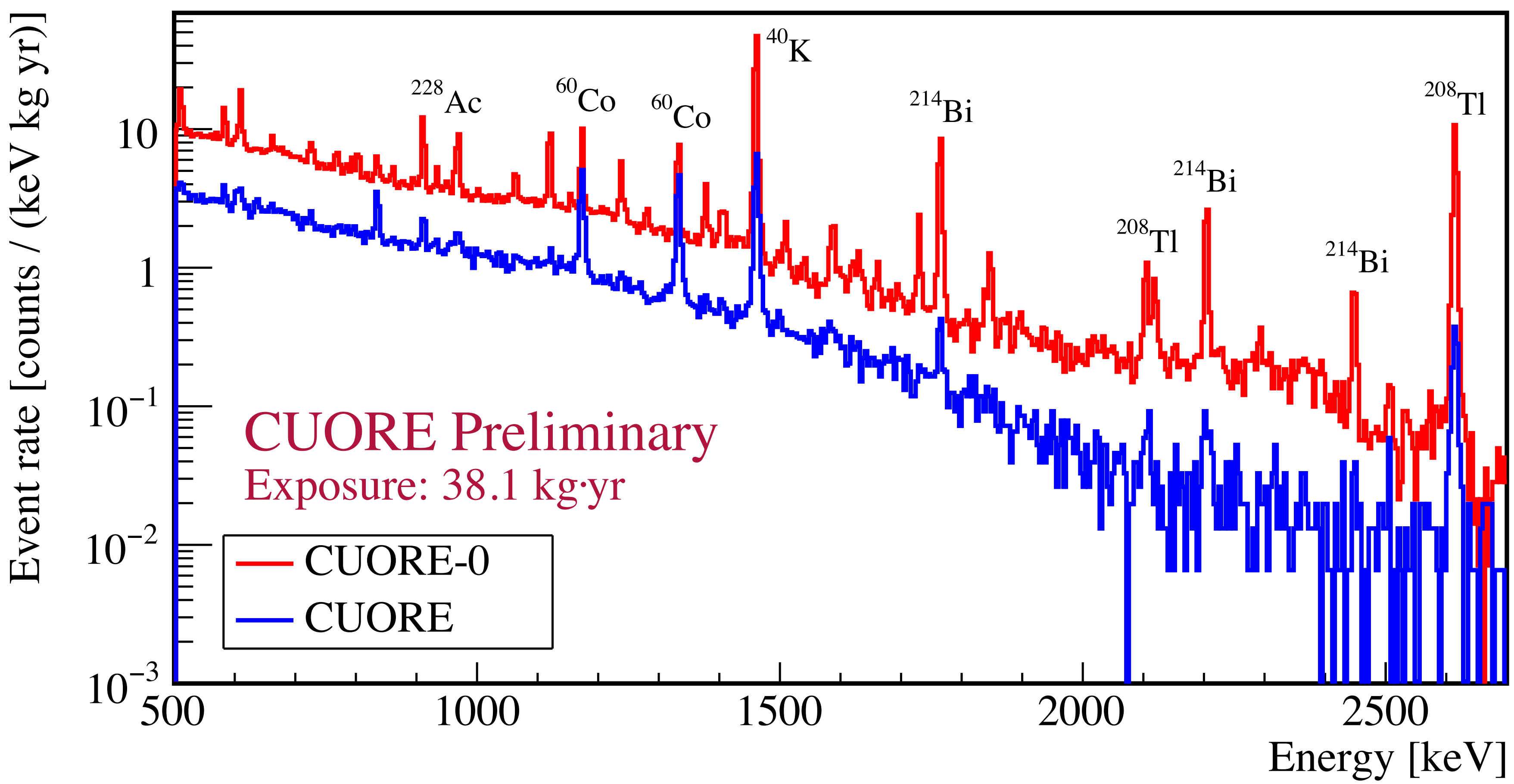






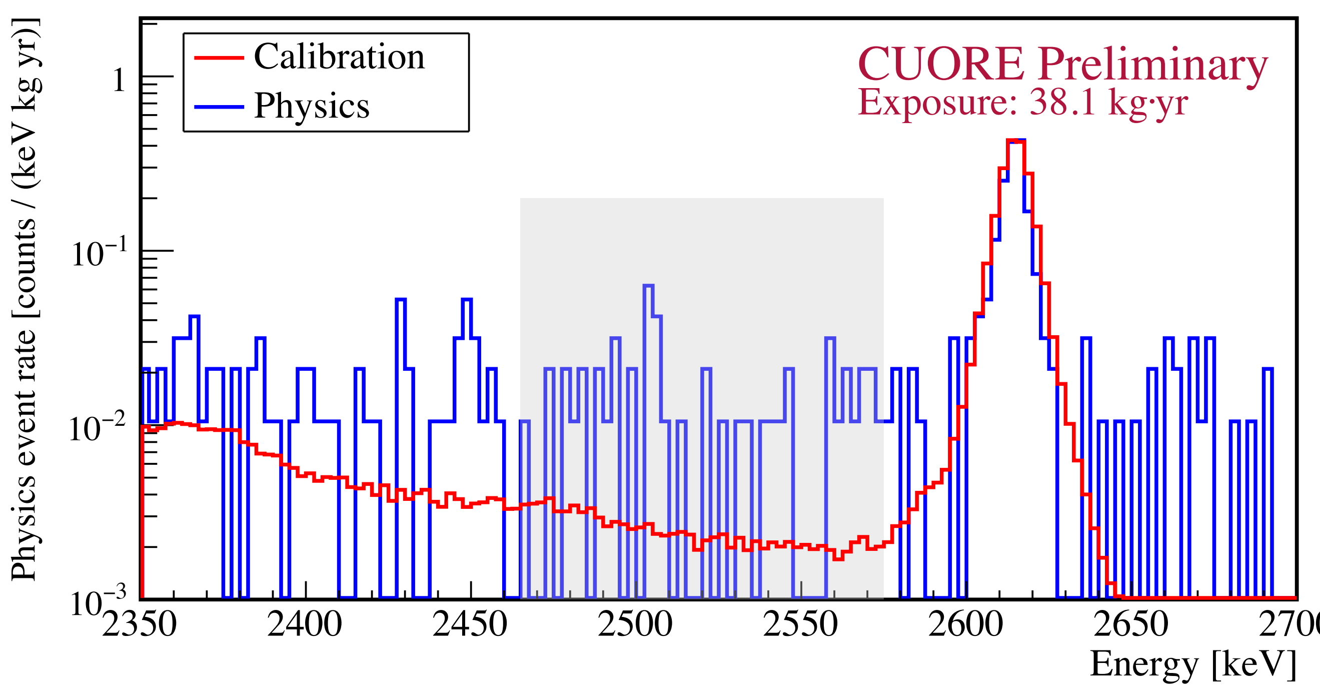
- ^{232}Th calibration spectrum from all CUORE detector array
- 12 kevlar strings are lowered through a series of tubes inside the cryostat
- 6 outer strings provide aprox. 20 Bq.
- 6 inner strings provide about 4 Bq.

CUORE background spectrum

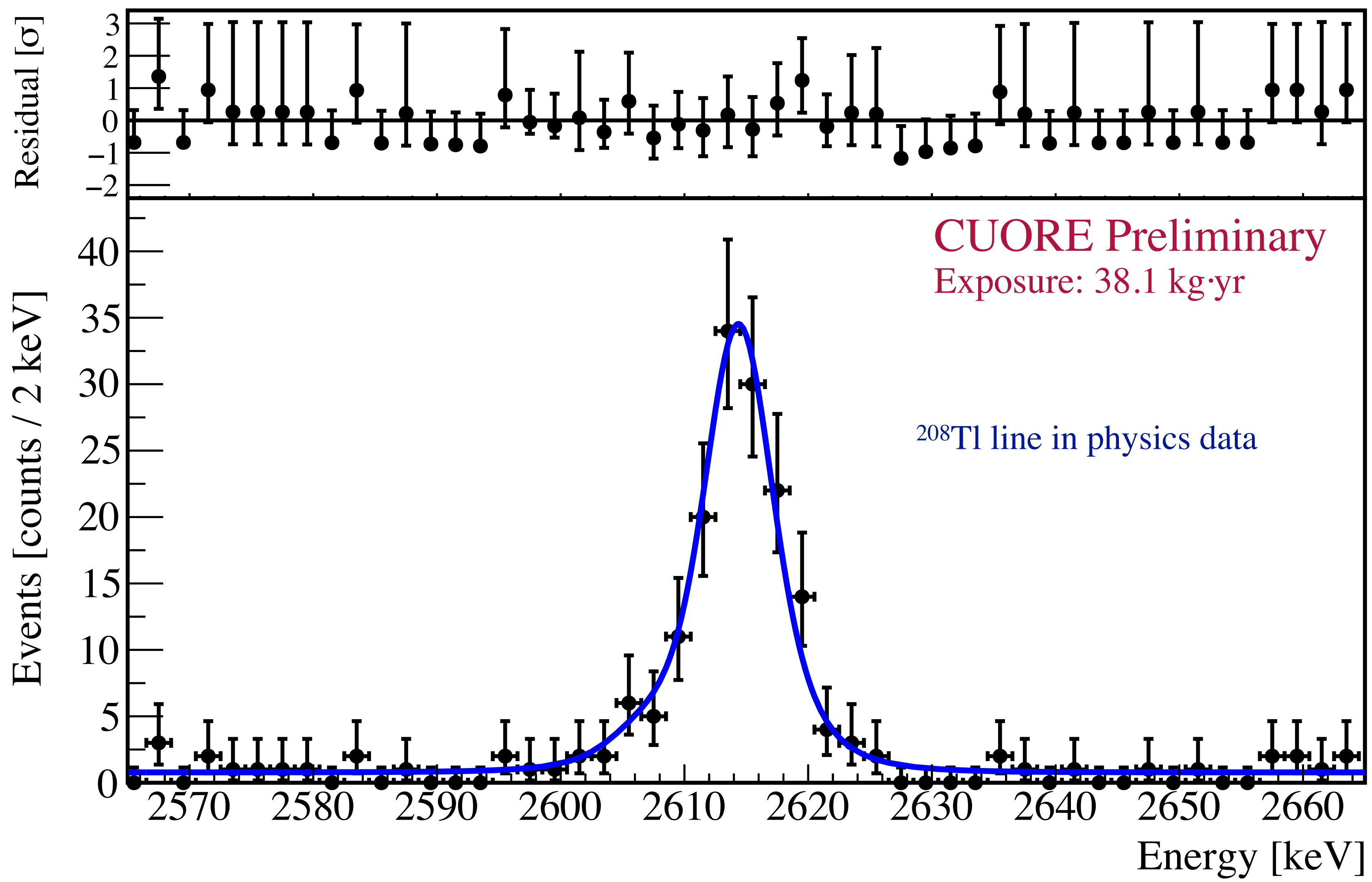


- Reduction of backgrounds in the gamma region, as expected from cleaner CUORE cryostat
- Spectrum consistent with background model

- Background in ROI dominated by alpha particle events
- Next generation experiment will require to tag or eliminate this background



CUORE energy resolution

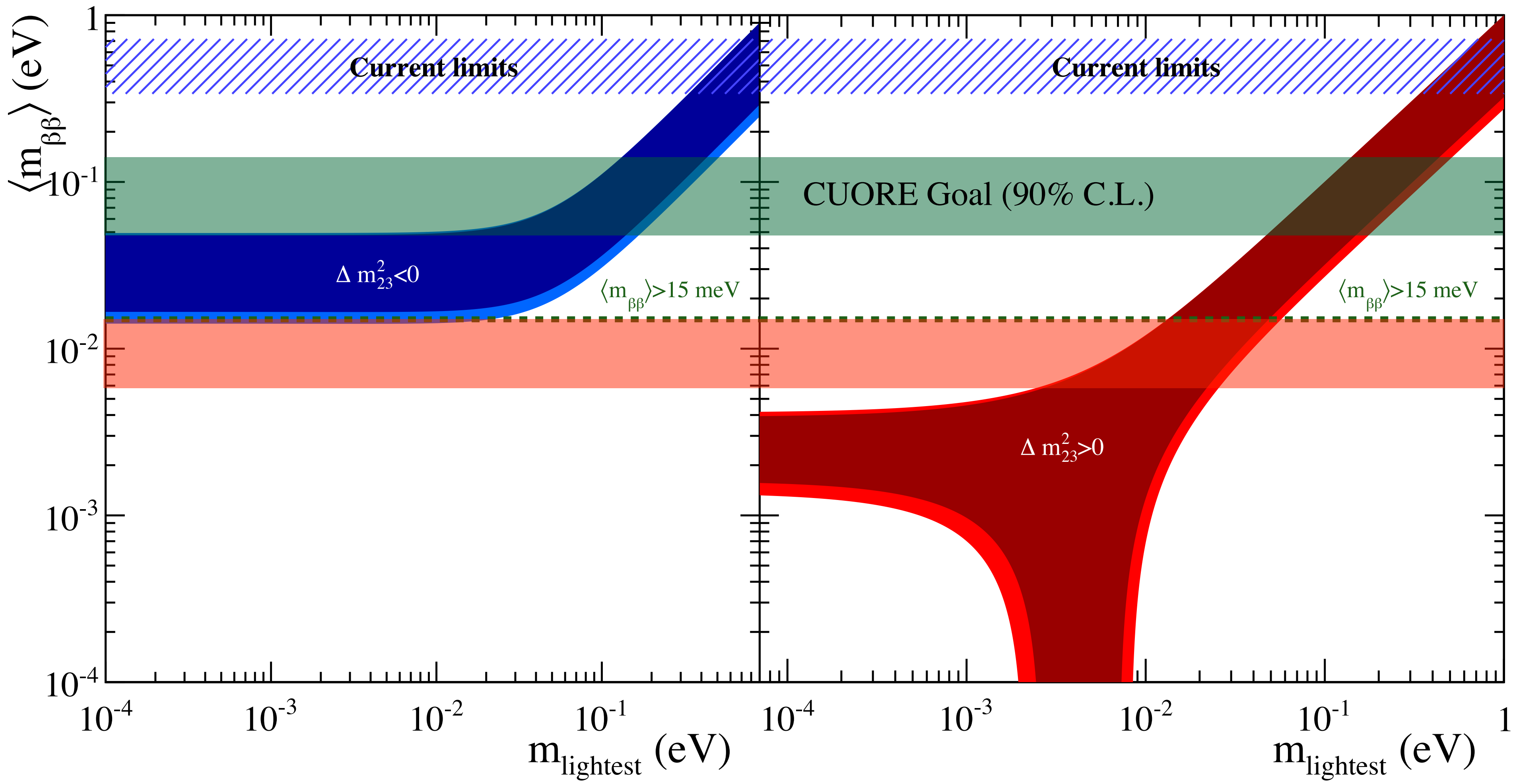


- Energy resolution from physics data:
  7.9 ± 0.6 keV FWHM
- Physics data from 899 (90%) of channels (so far)
- Noise reduction and analysis improvements ongoing

What is CUPID?

Next-generation bolometric tonne-scale experiment based on CUORE design

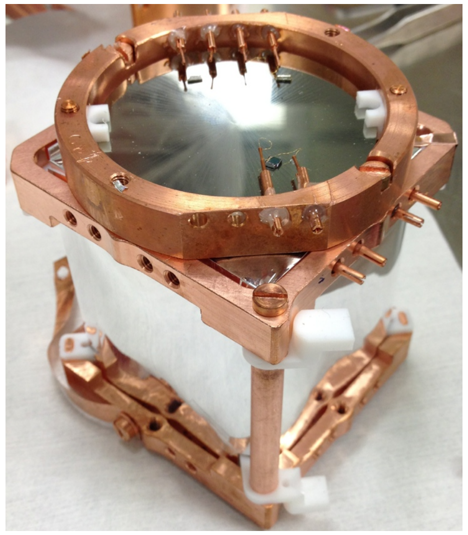
- 988 enriched (90%) crystals, particle identification with light detection
- Sensitivity to cover IH region
  - Reduce backgrounds to 0.1 events / (ton-year)
  - 99.9% α rejection @ >90% signal efficiency
  - 5 keV FWHM resolution
  - Half-life sensitivity (2-5)x10^{27} years in 10 years (3σ)
  - $m_{\beta\beta}$ sensitivity of 6-20 meV (3σ)



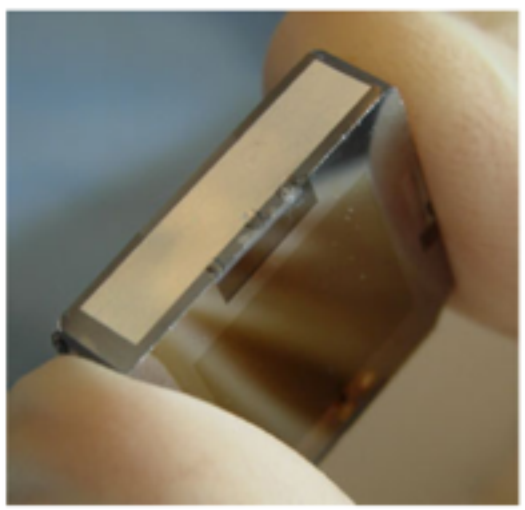
CUPID Interest Group arXiv:1504.03612 & arXiv:1504.03599

The path to reach sensitivity goal

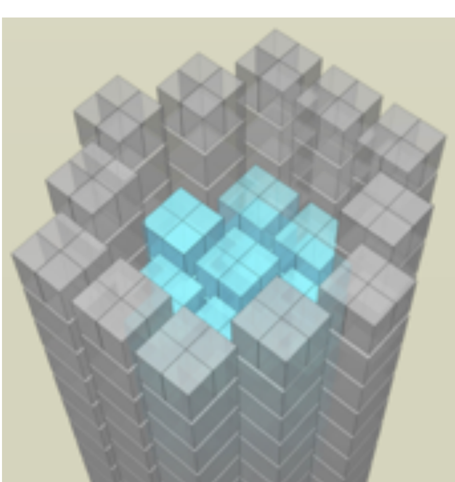
Particle ID

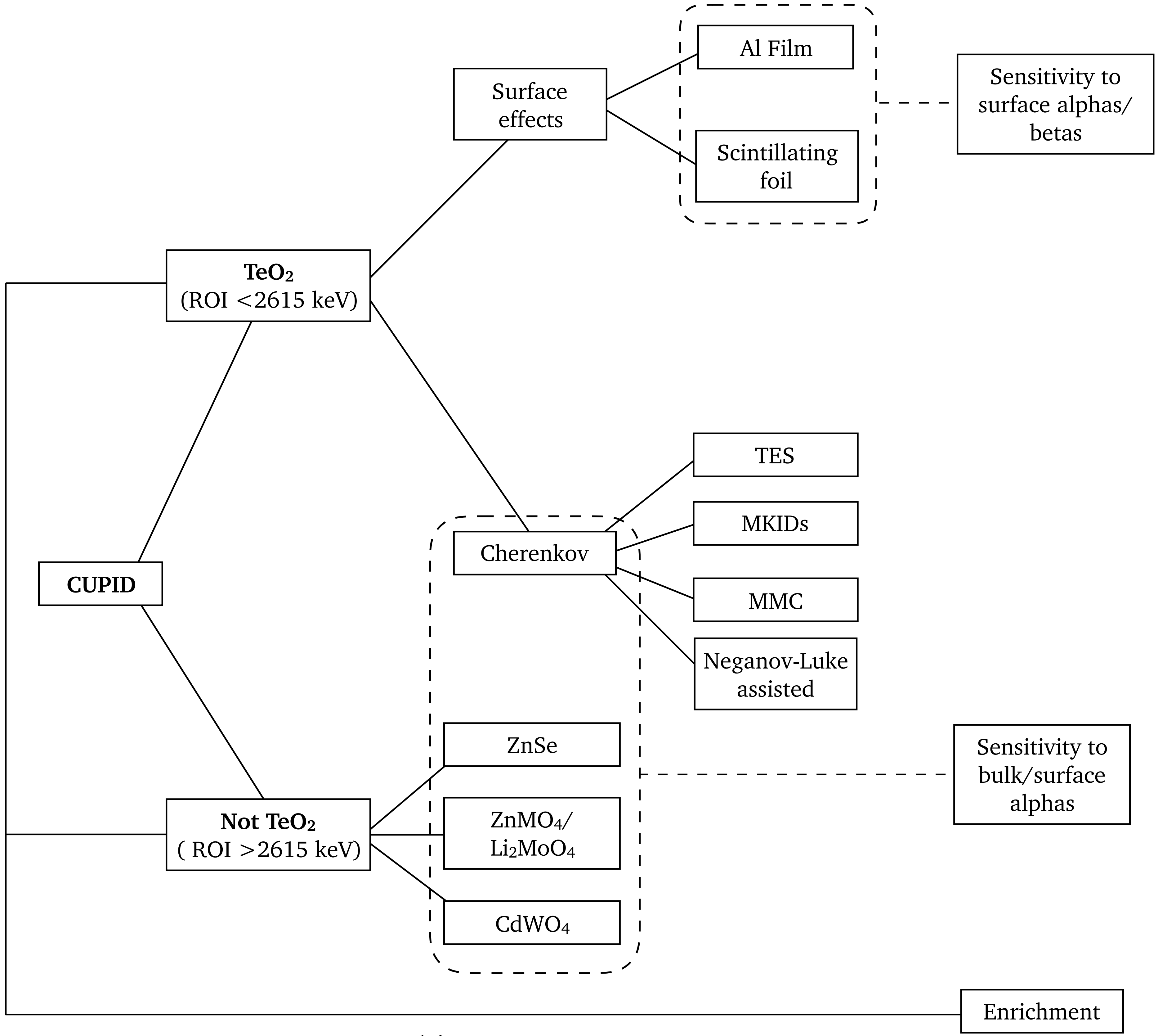


Aluminum film



Te-130 enrichment

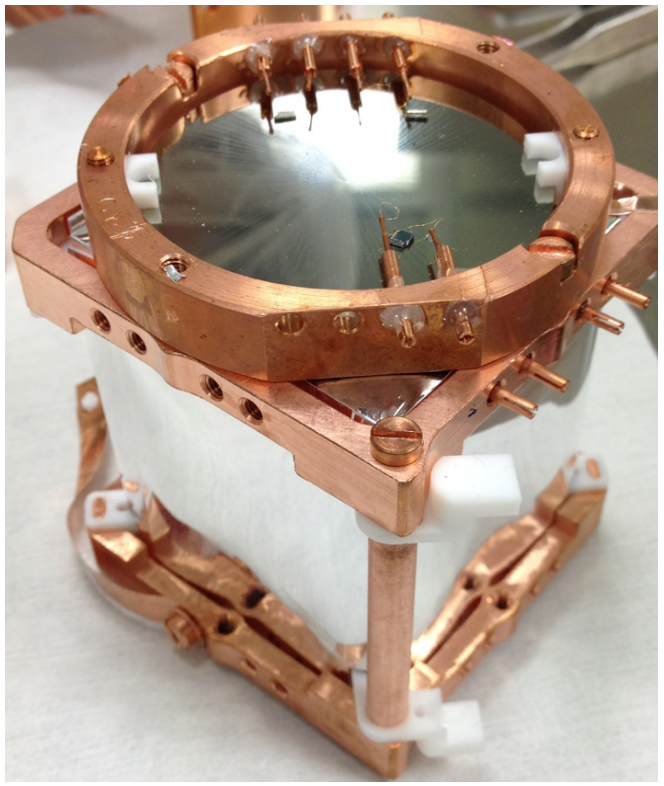


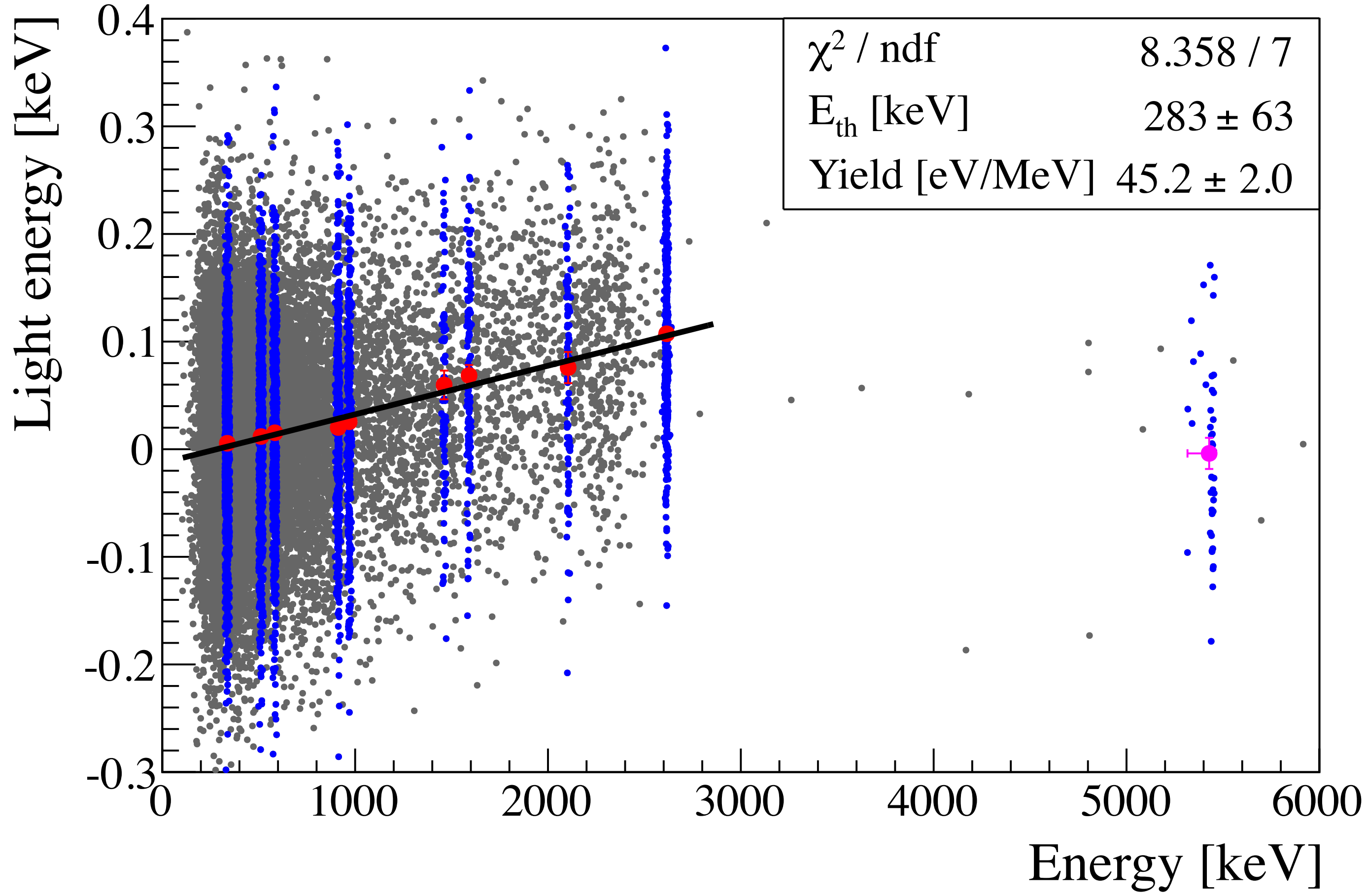


CUPID Interest Group arXiv:1504.03612 & arXiv:1504.03599

Particle ID via a the Light channel

Cherenkov light from a full 750g TeO_2 crystal





Casali et al. Eur. Phys. J. C75 (2015), 1, 12

101± 3.4 eV of light for a β/γ event with energy 0νββ value

R&D on improved light detectors currently ongoing:
TES, MKIDs, Neganov-Luke assisted, MMCs

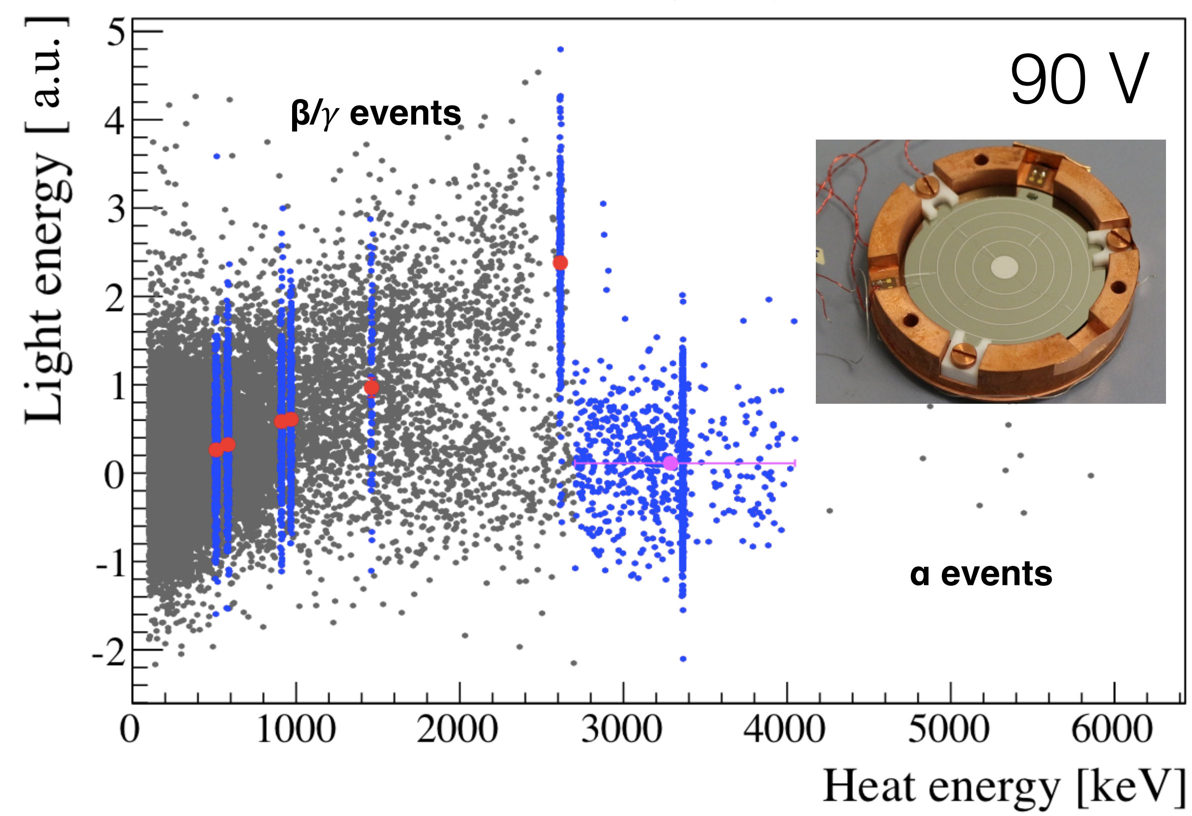
We need to discriminate between α and β/γ at 5σ, ie 99.9% rejection α's with 90% efficiency.
For a light yield of 100 eV implies resolution need of better than 20eV.

Neganov-Luke Amplification within CUPID R&D

$$E_{tot} = \left(1 + \frac{eV_{NL}}{\epsilon}\right) \cdot E$$

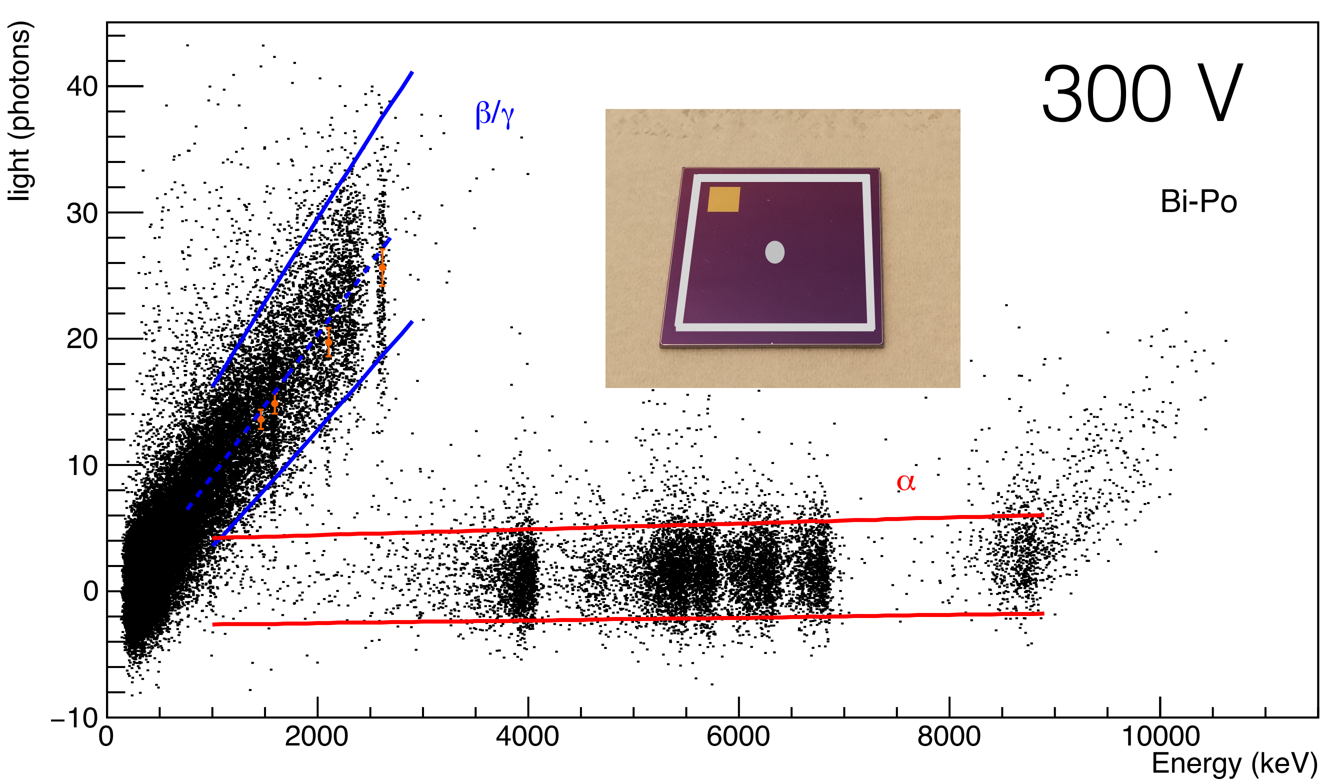
ϵ = Energy required to create electron-hole pair.
E = Energy of incident γ / photon.

L. Pattavina et al., J. Low Temp. Phys. (2016) 184:286-291



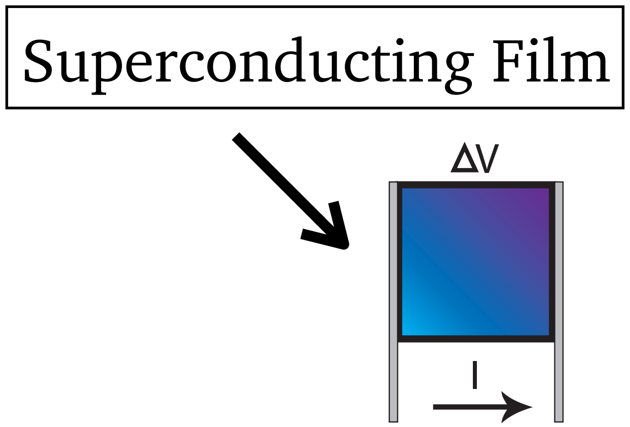
- Detector has Al interleaved electrodes, similarly made for EDELWEISS
- 5cm diameter, 180 μm thick, with a Ge-NTD sensor and Neganov-Luke amp.
- On top of 750g TeO_2 crystal
- Electrodes biased up to 300 V (factor of 5x amplification) with no worsening of baseline noise.

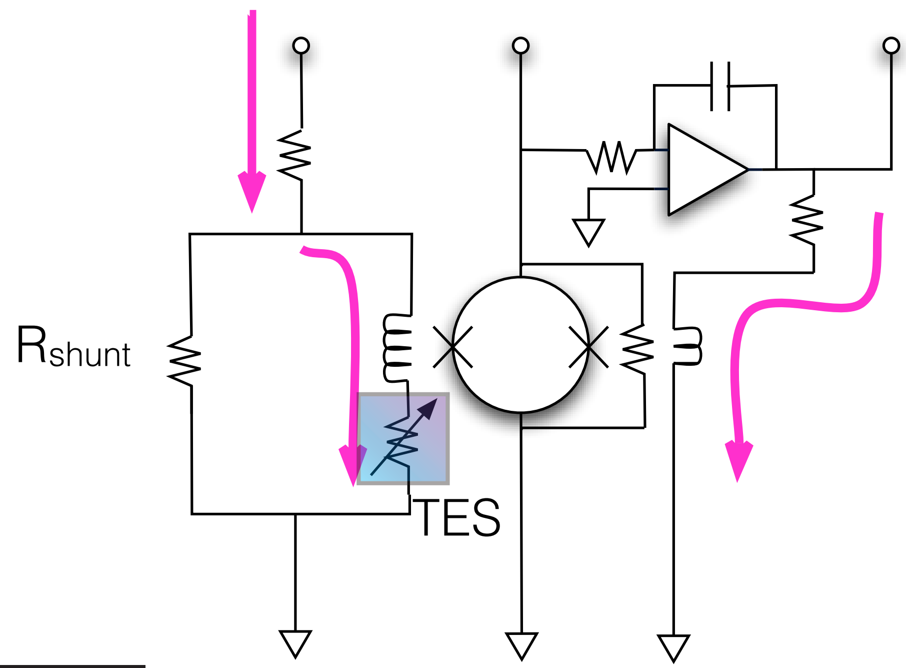
L. Gironi et al., Phys. Rev. C 94, 054608 (2016)

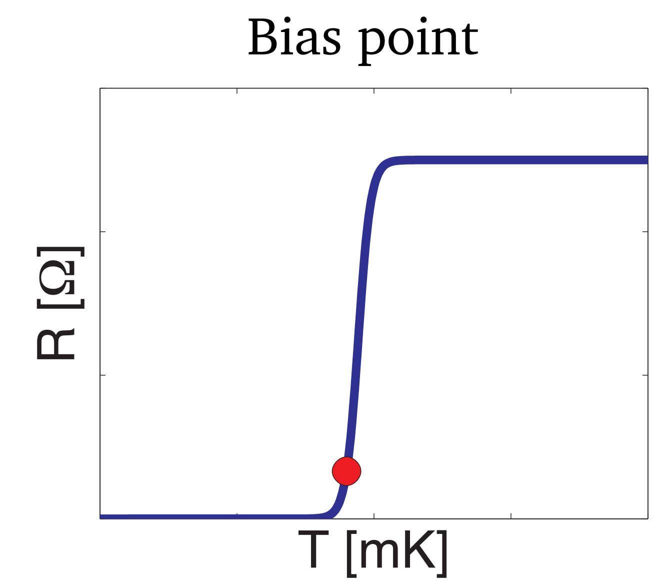


- 20 x 20 mm^2 silicon slab, 625 μm thick
- Central dot is biased with 300V
- Square electrode on perimeter is GND.
- Light detector 1.7 mm from a 1 cm^3 TeO_2 crystal
- Crystal surrounded by VM2000 (3M) reflecting foil, bottom covered with Al tape.
- Sources: ^{232}Th on surfaces and outside.

Transition Edge Sensors







$$\Delta E_{\mathrm{rms}} = \sigma_E \approx \sqrt{\frac{4k_B T^2 C_{\mathrm{tot}}}{\alpha}\sqrt{\frac{\beta+1}{2}}},$$

C_{tot} = C_{bolo} ($\sim T^3$) + C_{TES} ($\sim T$) + C_{other} (e.g. caused by impurities in the crystal)

K.D. Irwin, Appl. Phys. Lett. Vol. 66, 1998 (1995)

$$\alpha \equiv \frac{T}{R}\frac{dR}{dT}$$

β: determined by thermal conductivity between the TES and absorber/heat-bath

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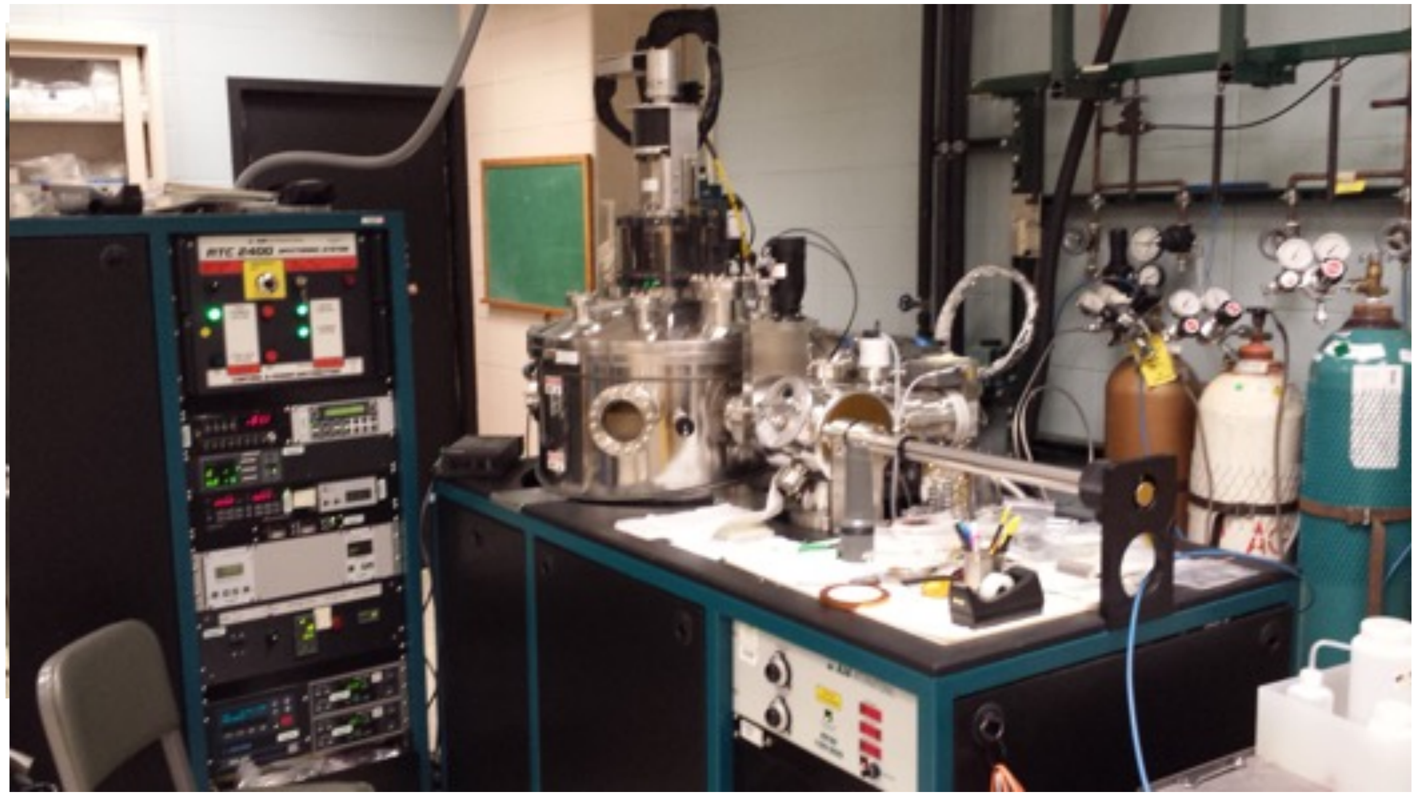
Low Tc TES fabrication:

- W-TES may be possible through ion implantation
- Grow W-alpha phase for Low Tc
- Or we can utilize superconducting bilayers as TES (proximity effect)
- Minimize # TES and SQUIDs on detector
- SQUIDs can be readout in arrays al large as up to 10,000

Superconducting films fabrication

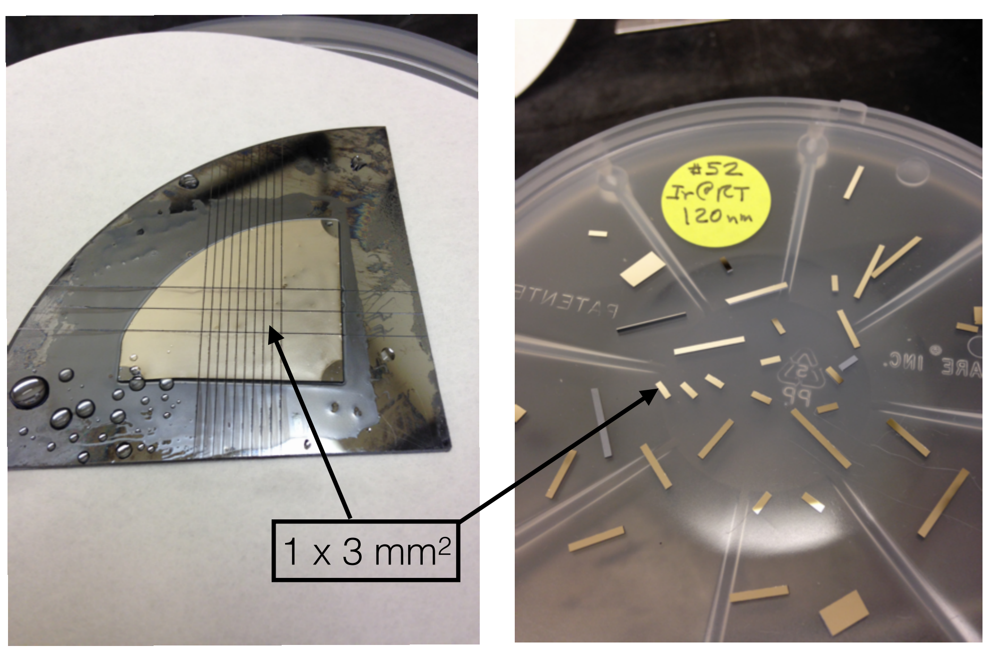
Collaborating at ANL with C. Chang, V. Novosad, T. Polakovic, G. Wang and V. Yefremenko

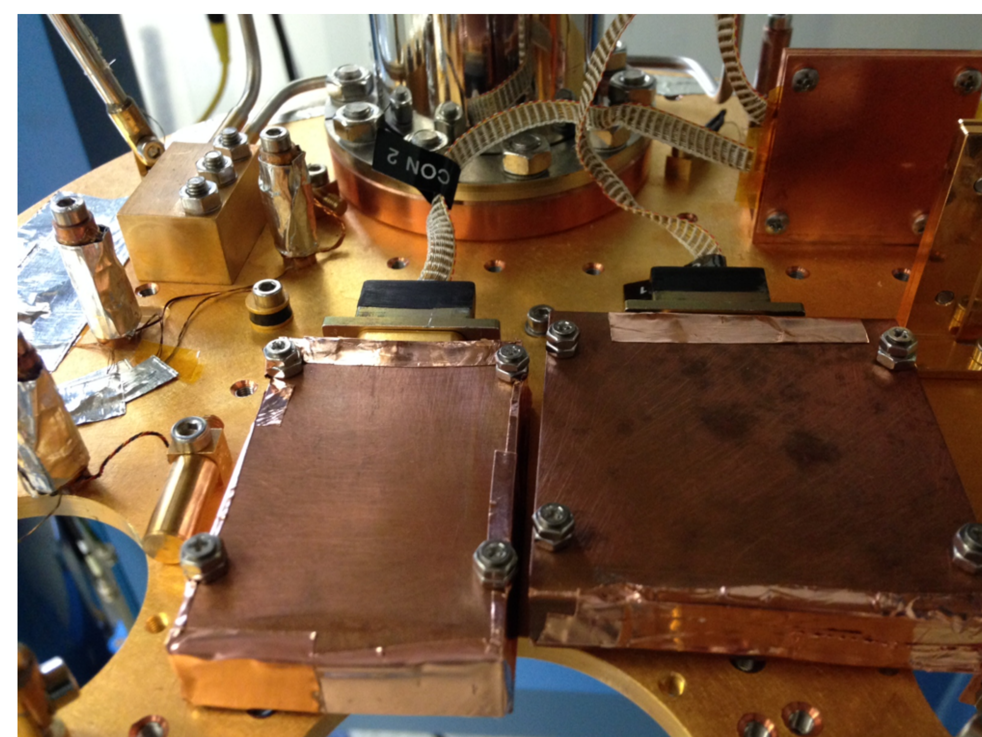
Cryogen free DR and Co-60 thermometry down to ~7mK



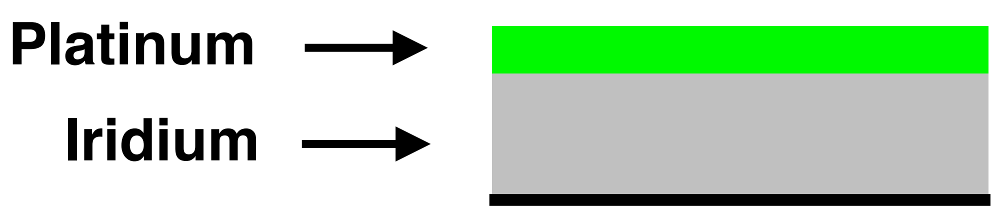
At ANL with sputtering chamber on the back

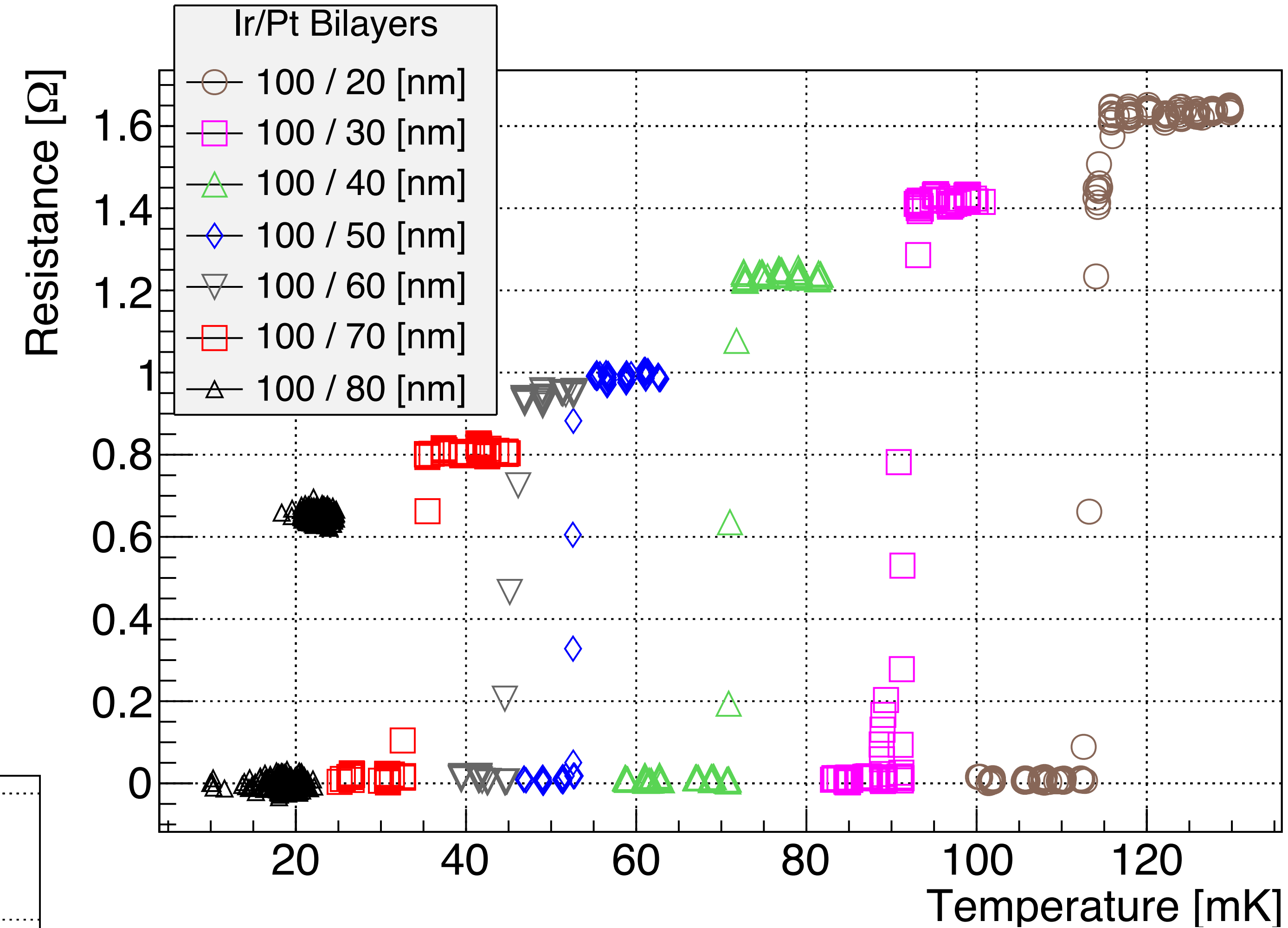
Iridium bilayers

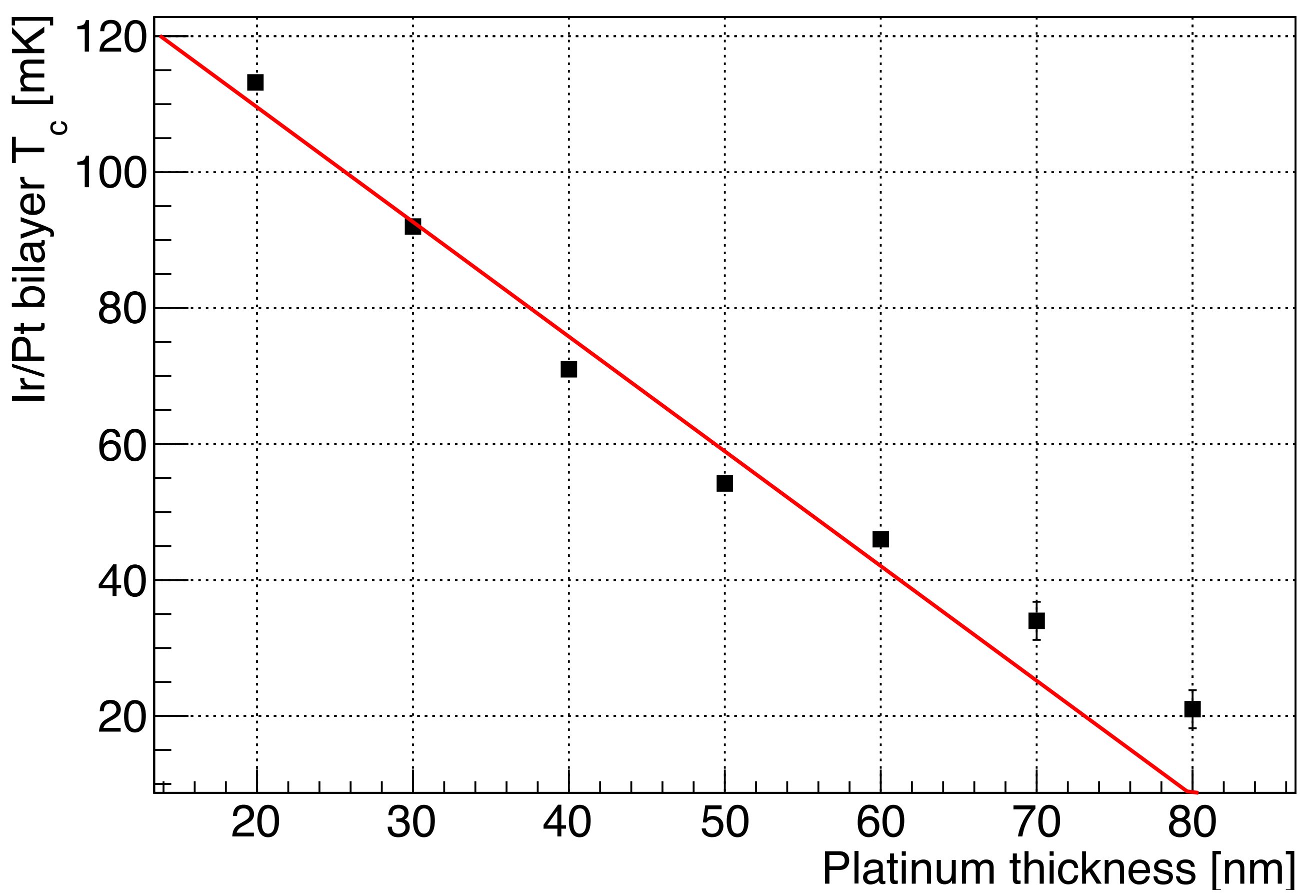




T_c suppression in Iridium/Platinum Bilayers

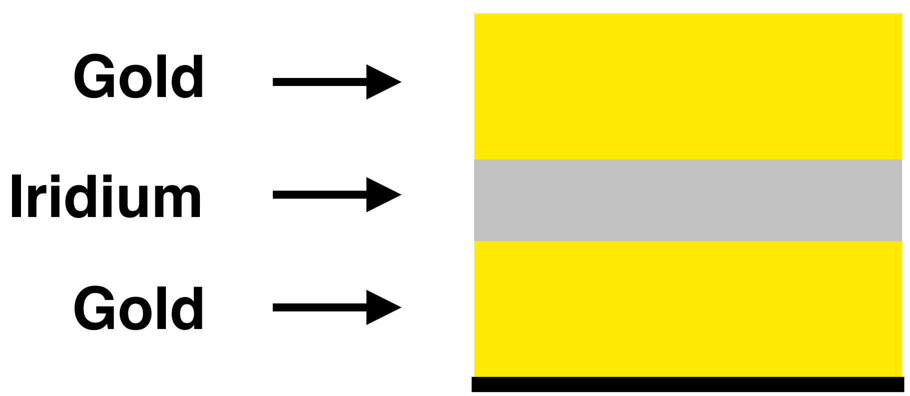


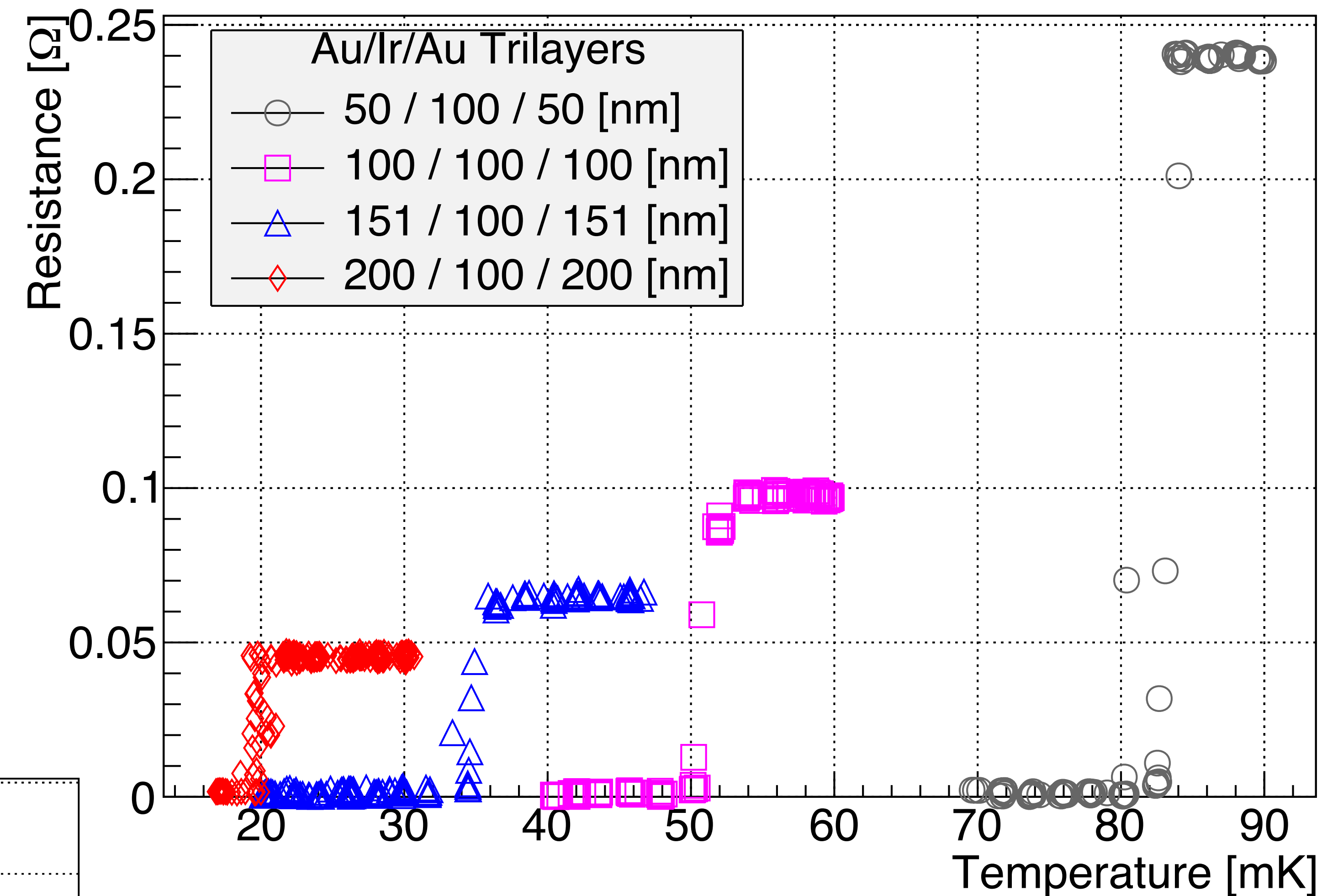


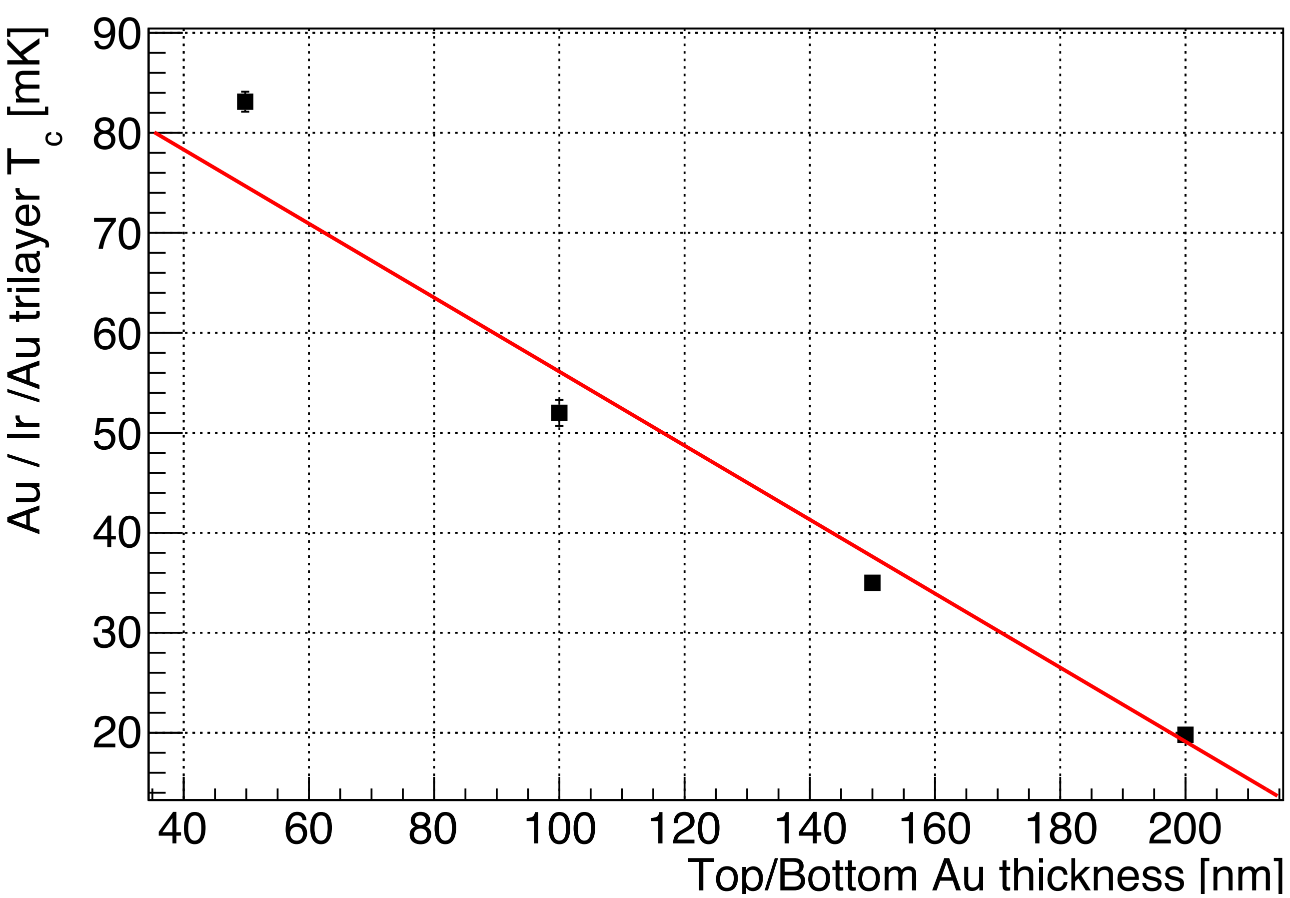


- We found 2 recipe solutions for fabrication of Low T_c TES
- Films fabricated at and in collaboration with Argonne National Lab.
- Sputtering at room temperature allows for a scalable solution

T_c suppression in Gold/Iridium/Gold Trilayers







- We found 2 recipe solutions for fabrication of Low T_c TES
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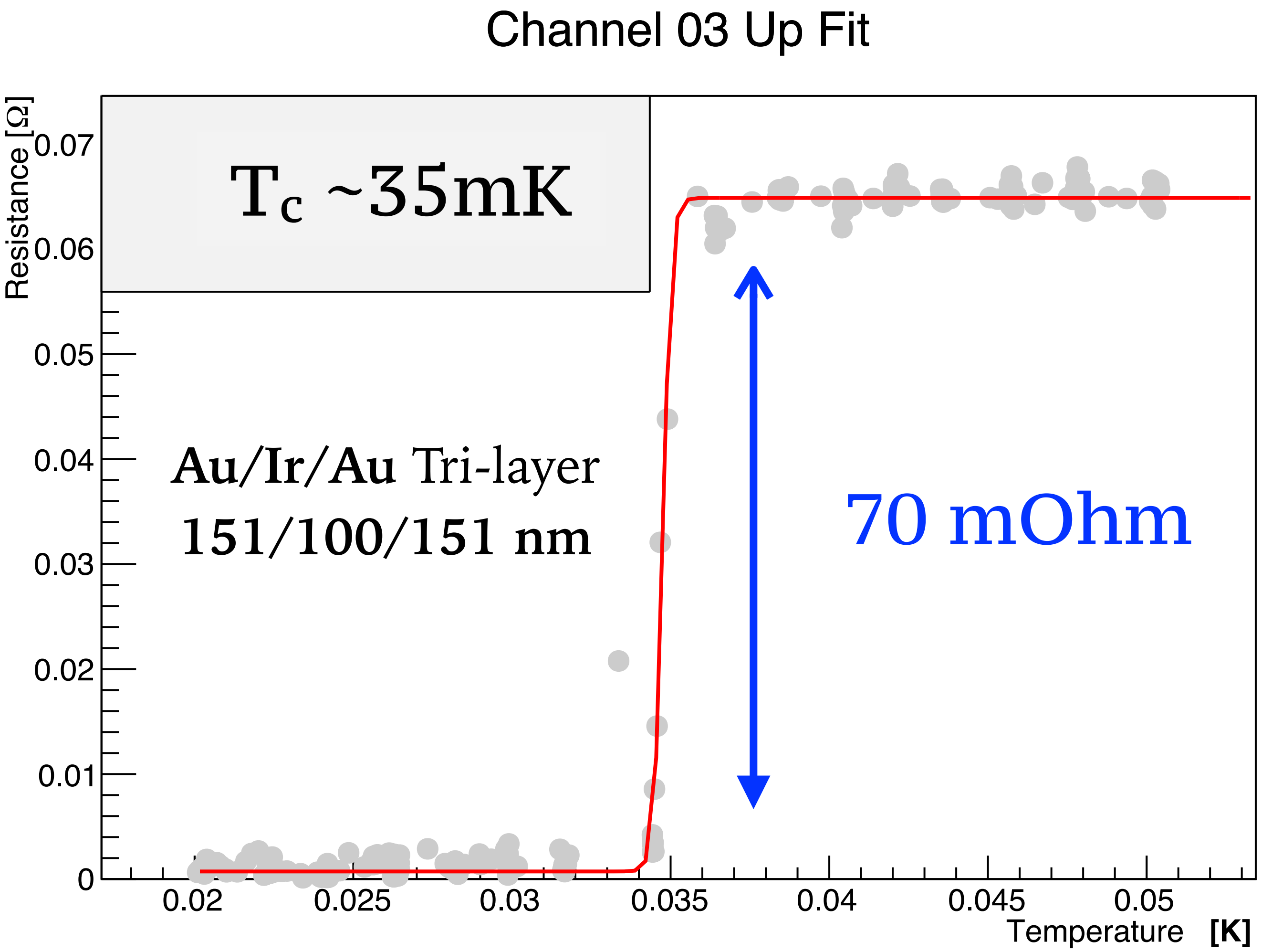
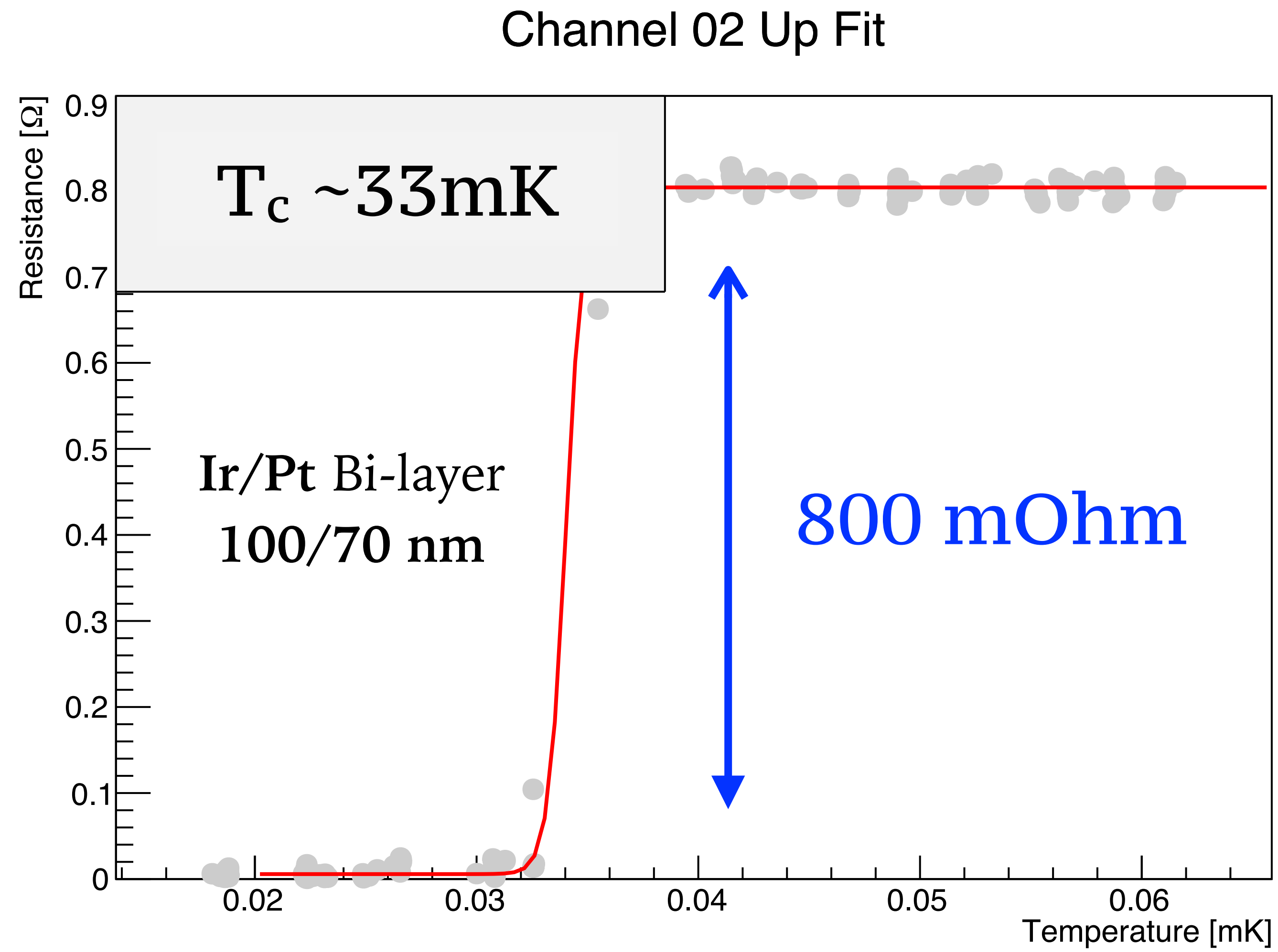
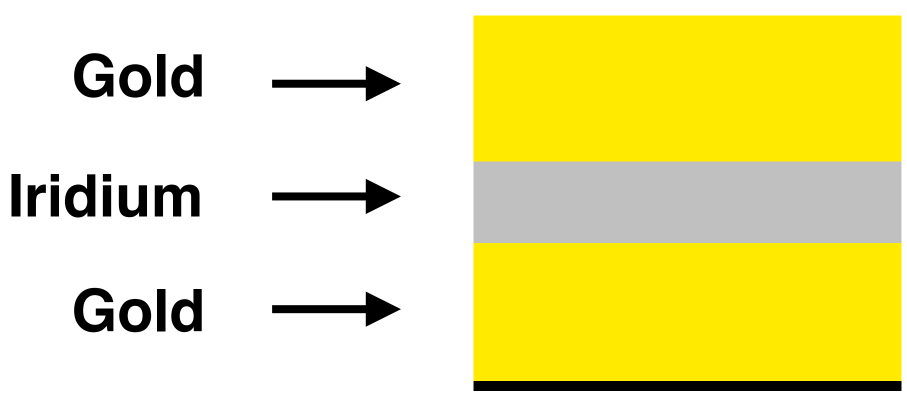
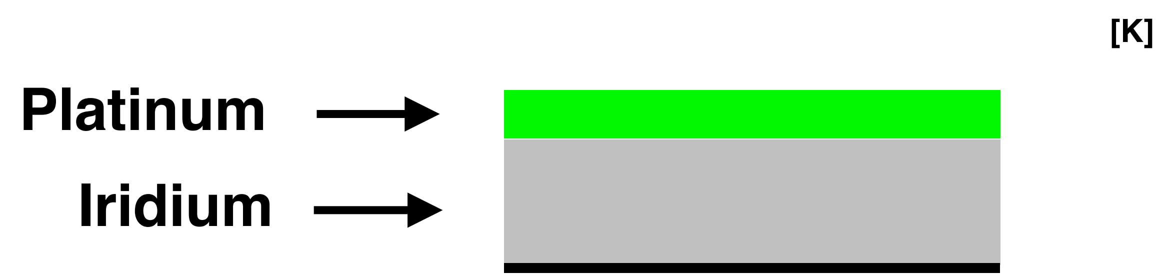
- Sputtering at room temperature allows for a scalable solution

Ir/Pt: A new promising bilayer for low T_c TES



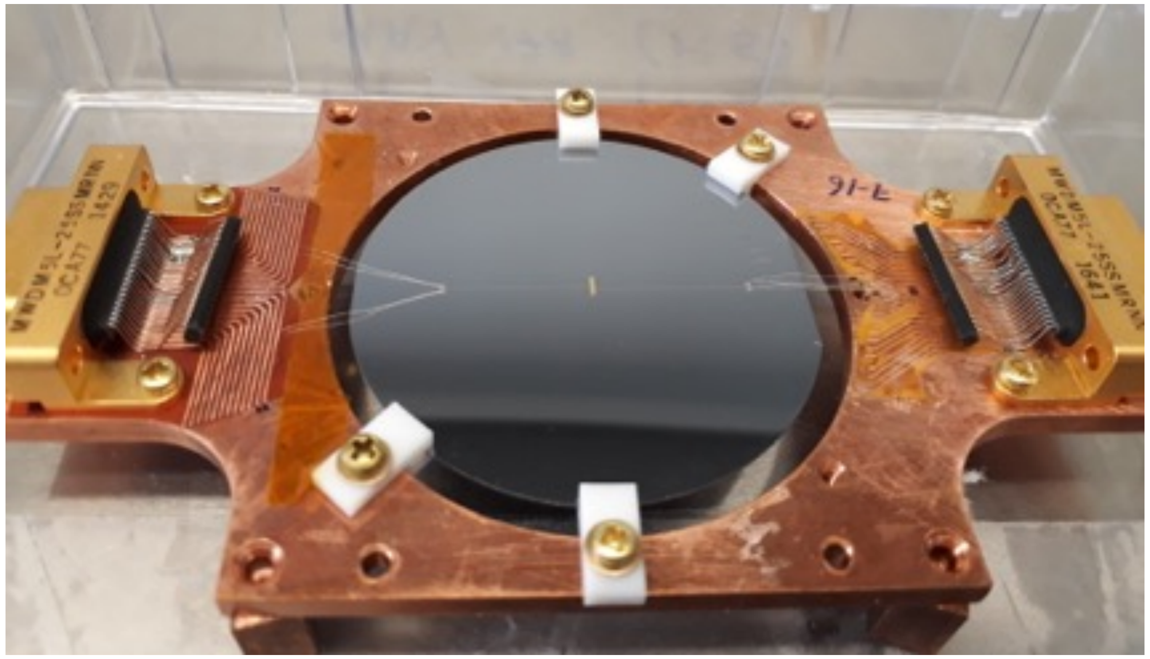




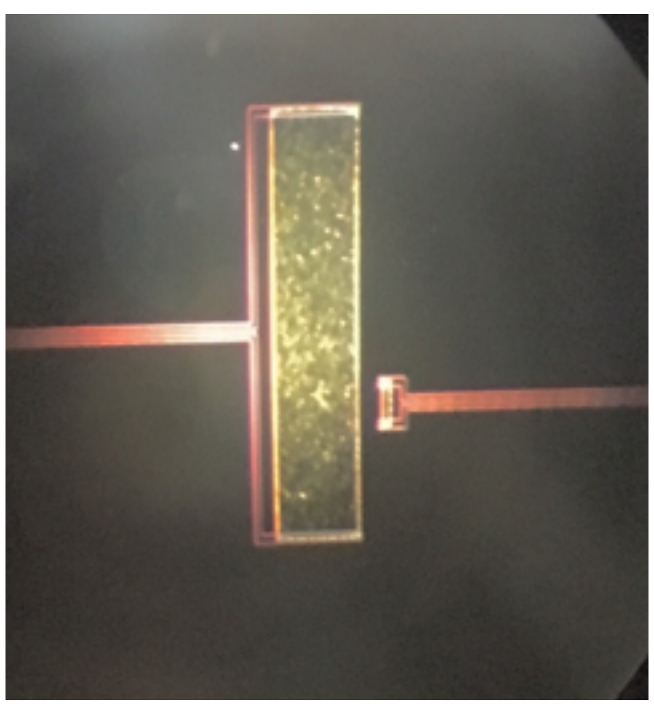


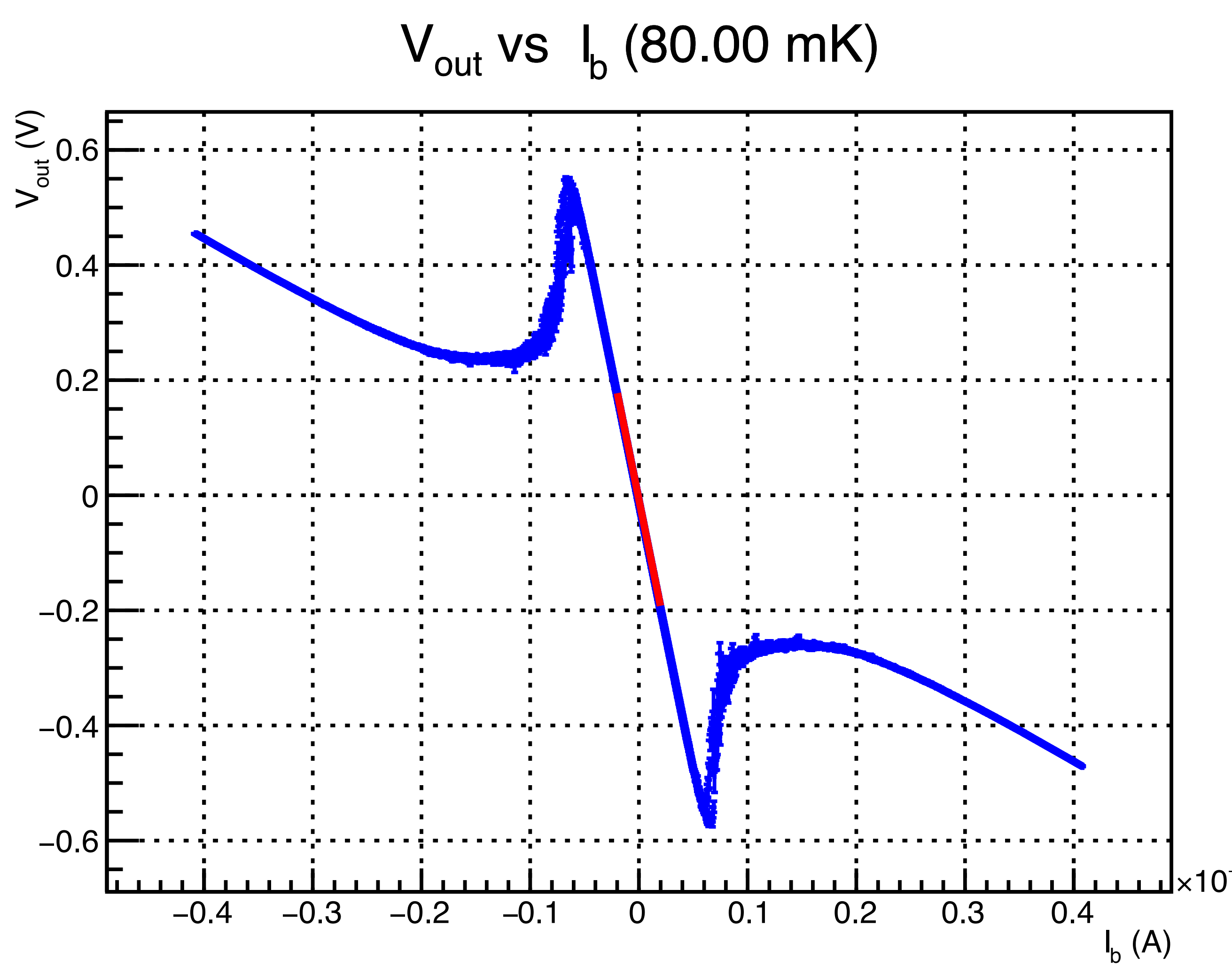
Normal Resistance of Ir/Pt is ~10x Au/Ir/Au for similar Tc

From films to TES on 2 inch diameter Si wafer



- Ir/Au TES on 2 inch wafer sputtered at room temperature
- Tc consistent with that obtained with films
- AC current bias using Magnicon squid with a local Nb can on squid
- Working on noise mitigation, measurement of Gep and testing of Ir/Pt towards using lower Tc recipes found on films already

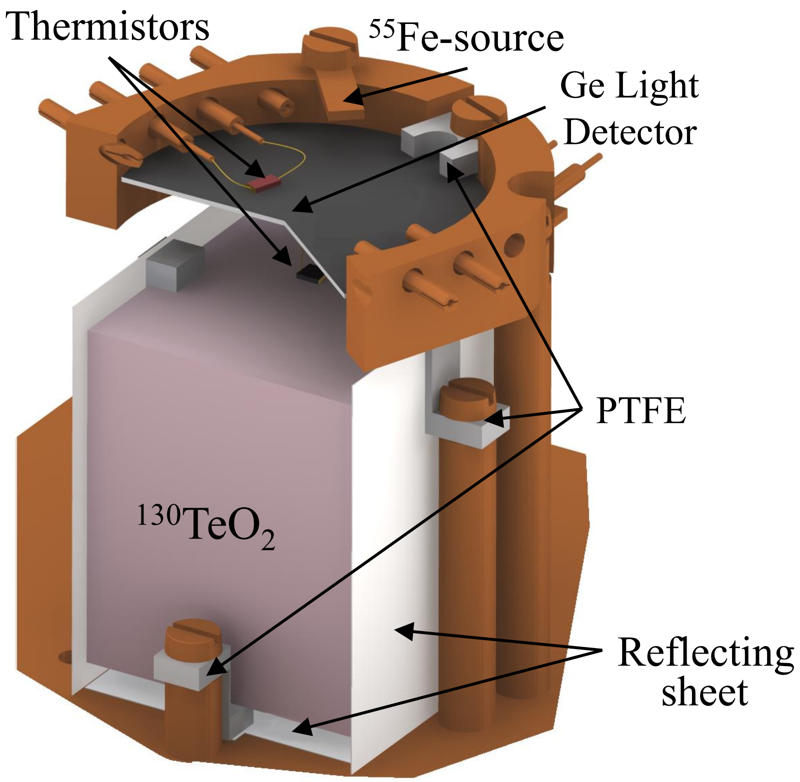




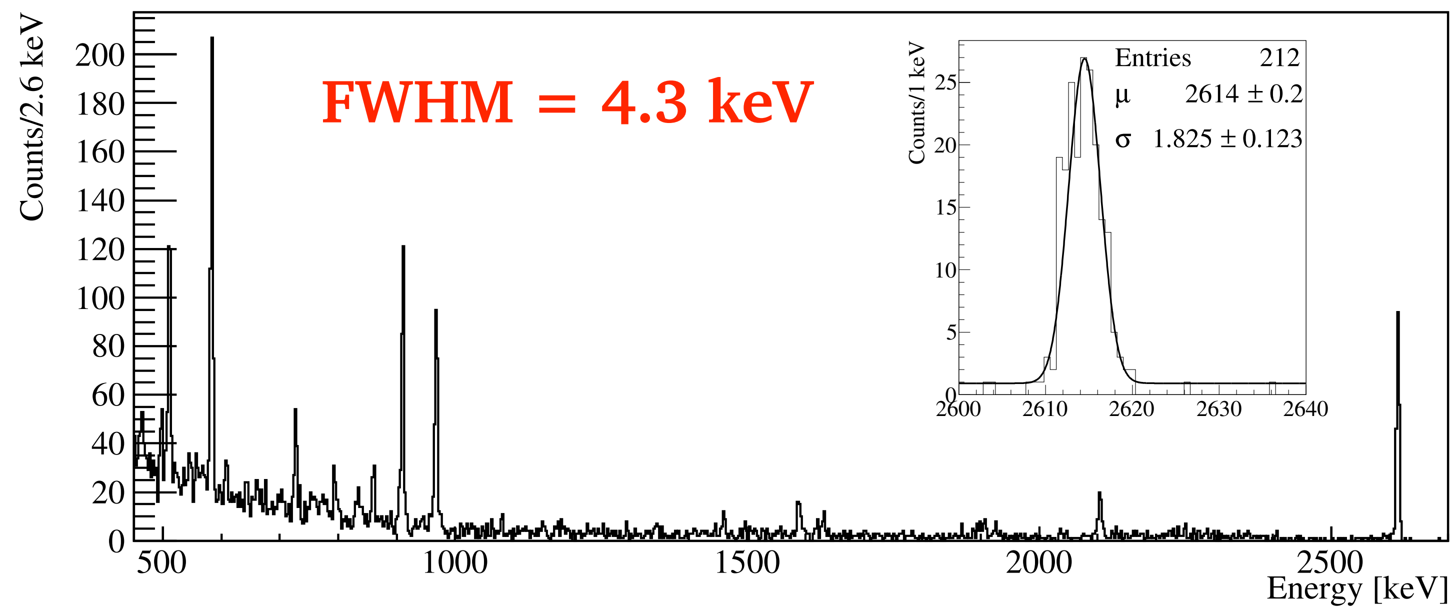
Enriched TeO_2 bolometers with PID

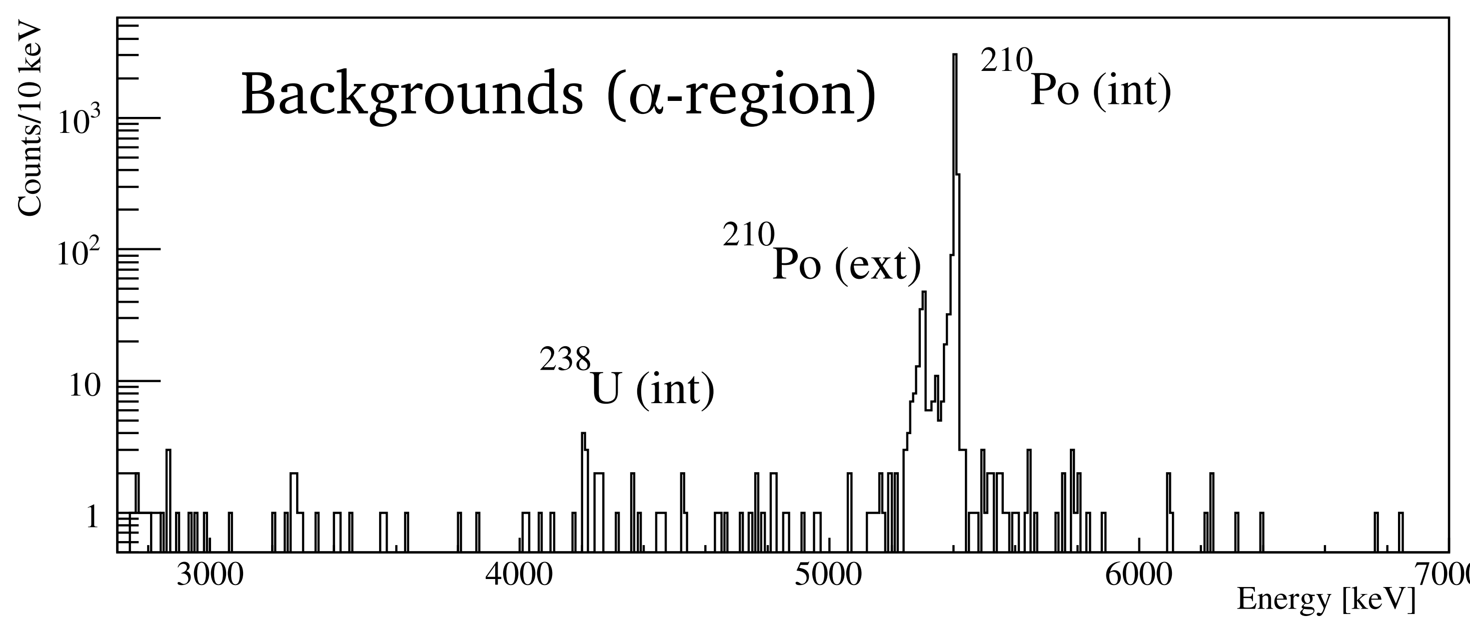
First results of performance of a large (36x38x52 mm³) TeO_2 crystals in which Cherenkov light is used for Particle Identification (PID).

- 92% enriched ^{130}Te crystals, 435g each, produced at SICCAS in a similar way to CUORE crystals but starting with an enriched ^{130}Te powder.



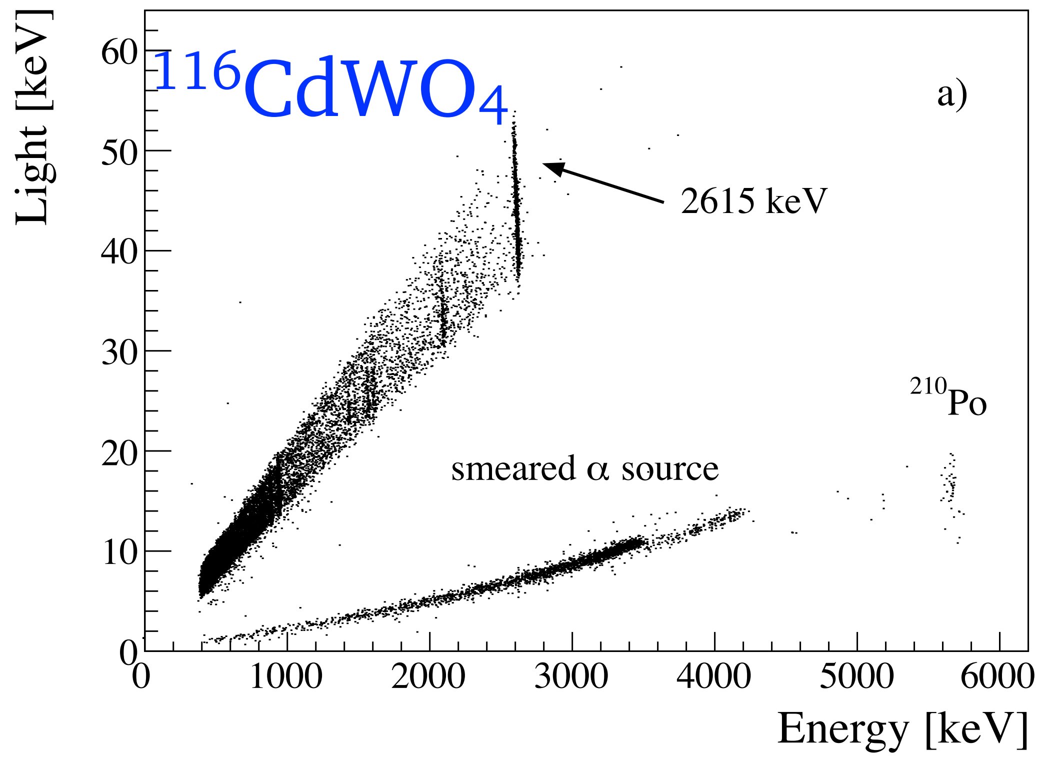
Chain	Nuclide	$^{130}TeO_2$-1 [μBq/kg]	$^{130}TeO_2$-2 [μBq/kg]
^{232}Th	^{232}Th	<4.3	<4.8
	^{228}Th	<2.3	<3.1
^{238}U	^{238}U	7.7 ± 2.7	15.1 ± 4.4
	^{234}U	<6.3	<5
	^{230}Th	<5.7	<3.8
	^{226}Ra	<2.3	<3.1
	^{210}Po	3795 ± 60	6076 ± 88

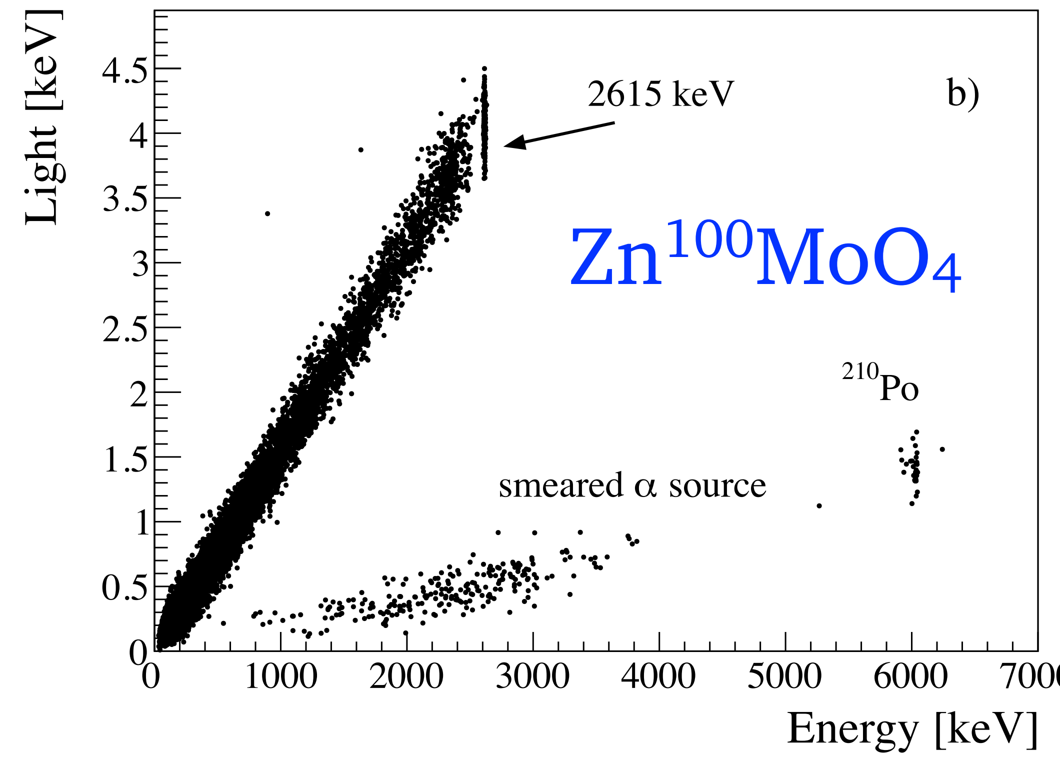


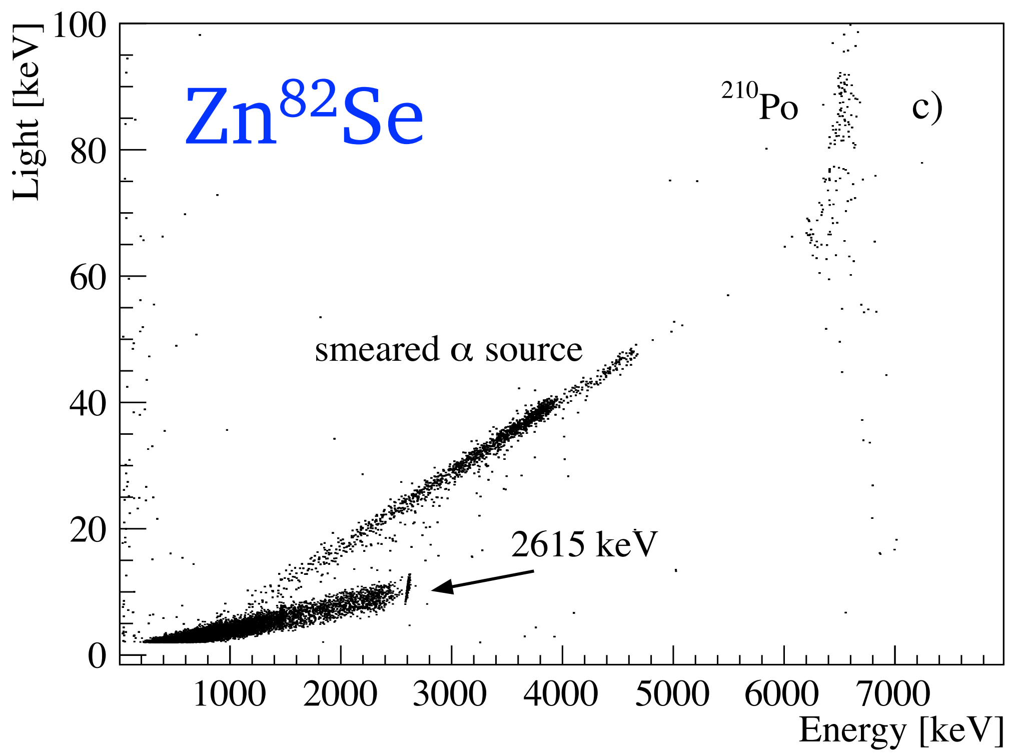


D.R. Artusa et al., Phys. Lett. B 767 (2017) 321b 329

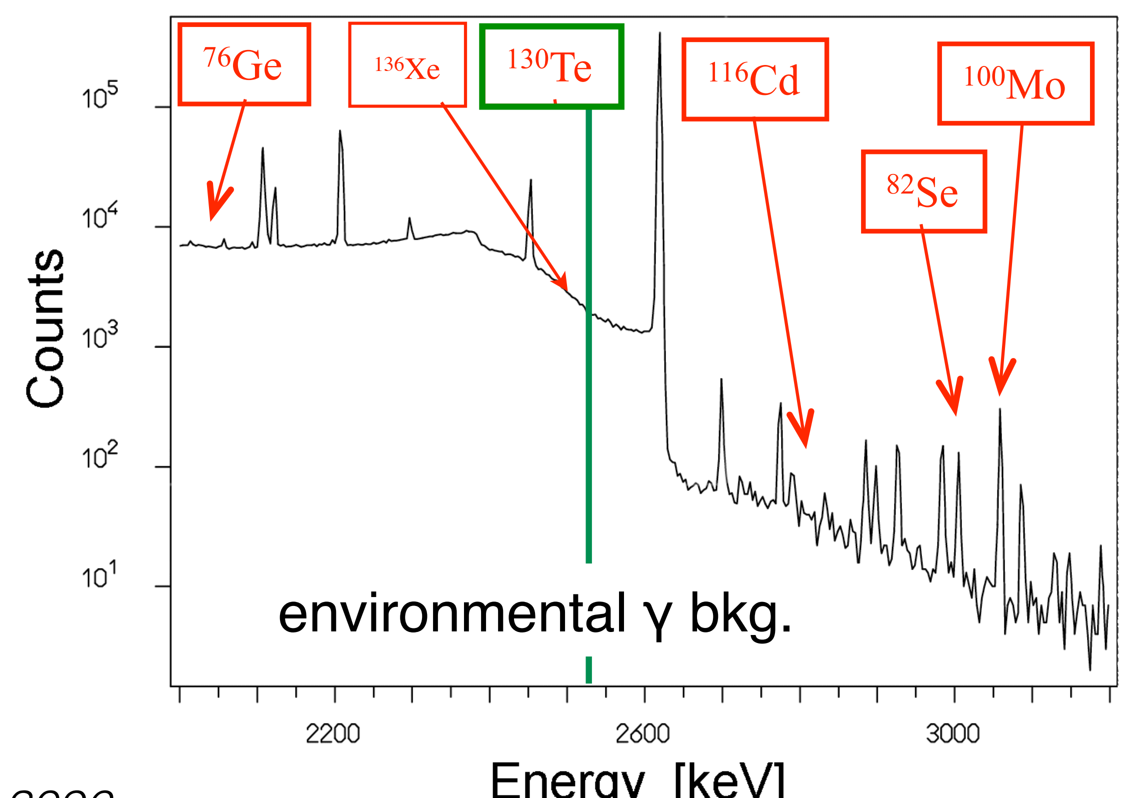
Scintillating crystals







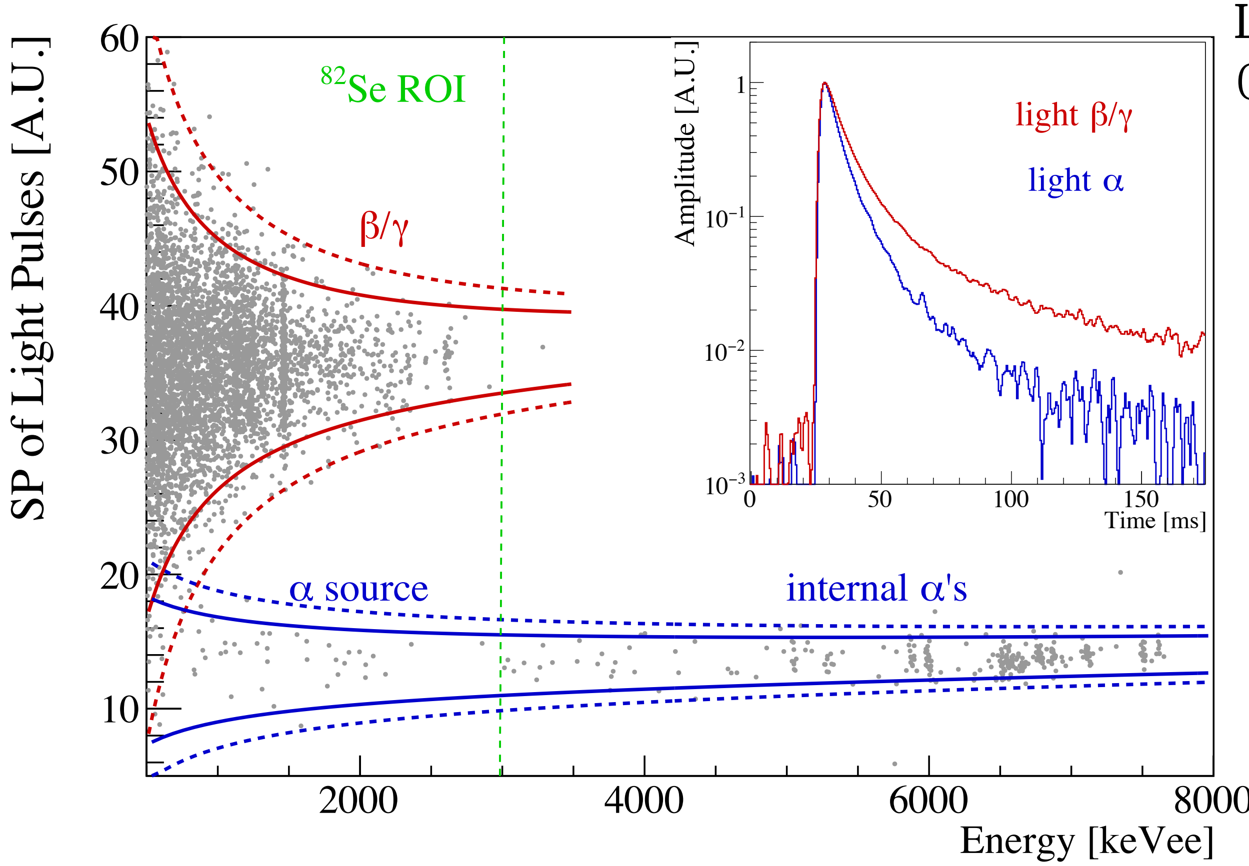
Cuore Collab. Eur. Phys. J. C74 (2014) 10, 3096

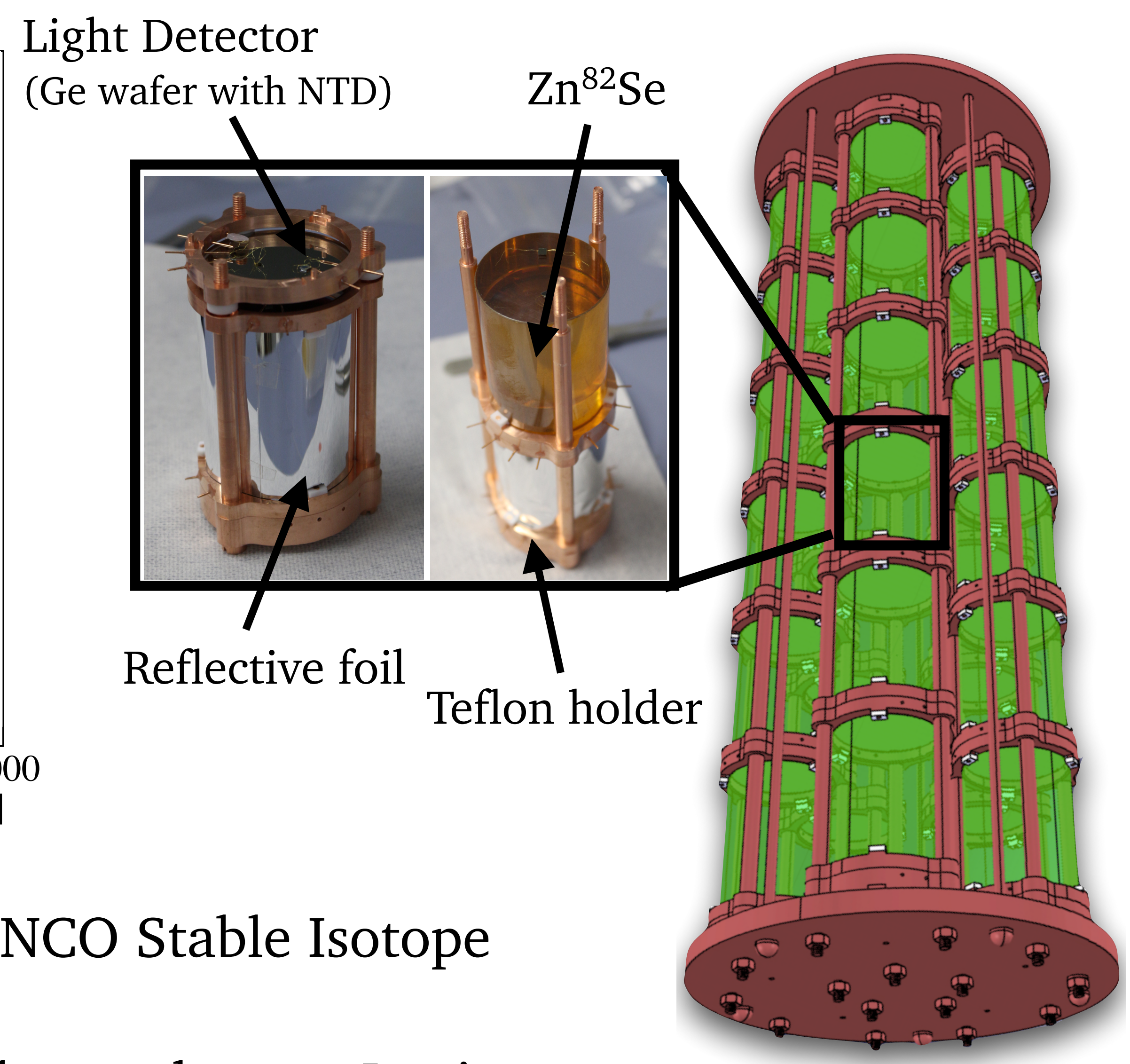


Advances in HEP, Vol 2013 (2013), Article ID 237973

CUPID-0: First array of $Zn^{82}Se$ bolometers

- 22 enriched $Zn^{82}Se$ ($Q_{\beta\beta}$=2996 keV) bolometers to 95% (400g each) + 2 not enriched
- 5 towers, total mass ~11 kg (5.3 kg ^{82}Se)
- Goal to demonstrate a background of 10^{-3} count/keV/kg/y and energy resolution of 10 keV in ROI.



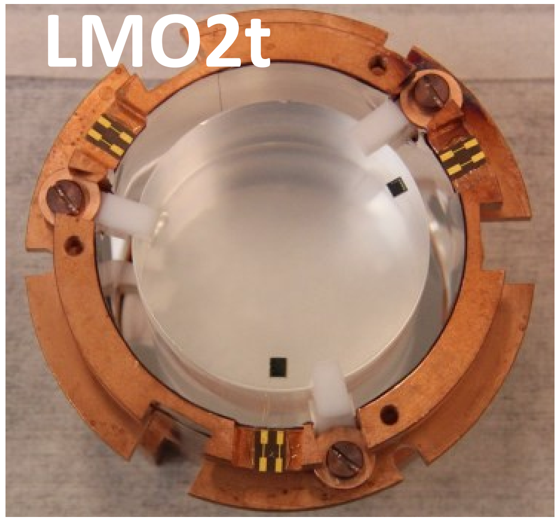


- The ZnSe powder was enriched at URENCO Stable Isotope Group in the Netherlands.
- The $Zn^{82}Se$ synthesis and crystal growth was done at Institute for Scintillation Materials (ISMA) in Kharkov, Ukraine.

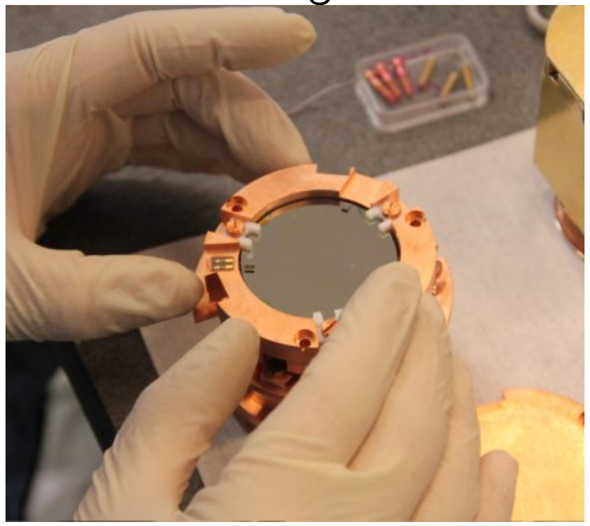
D.R. Artusa et al., Eur. Phys. J. C (2016) 76:364

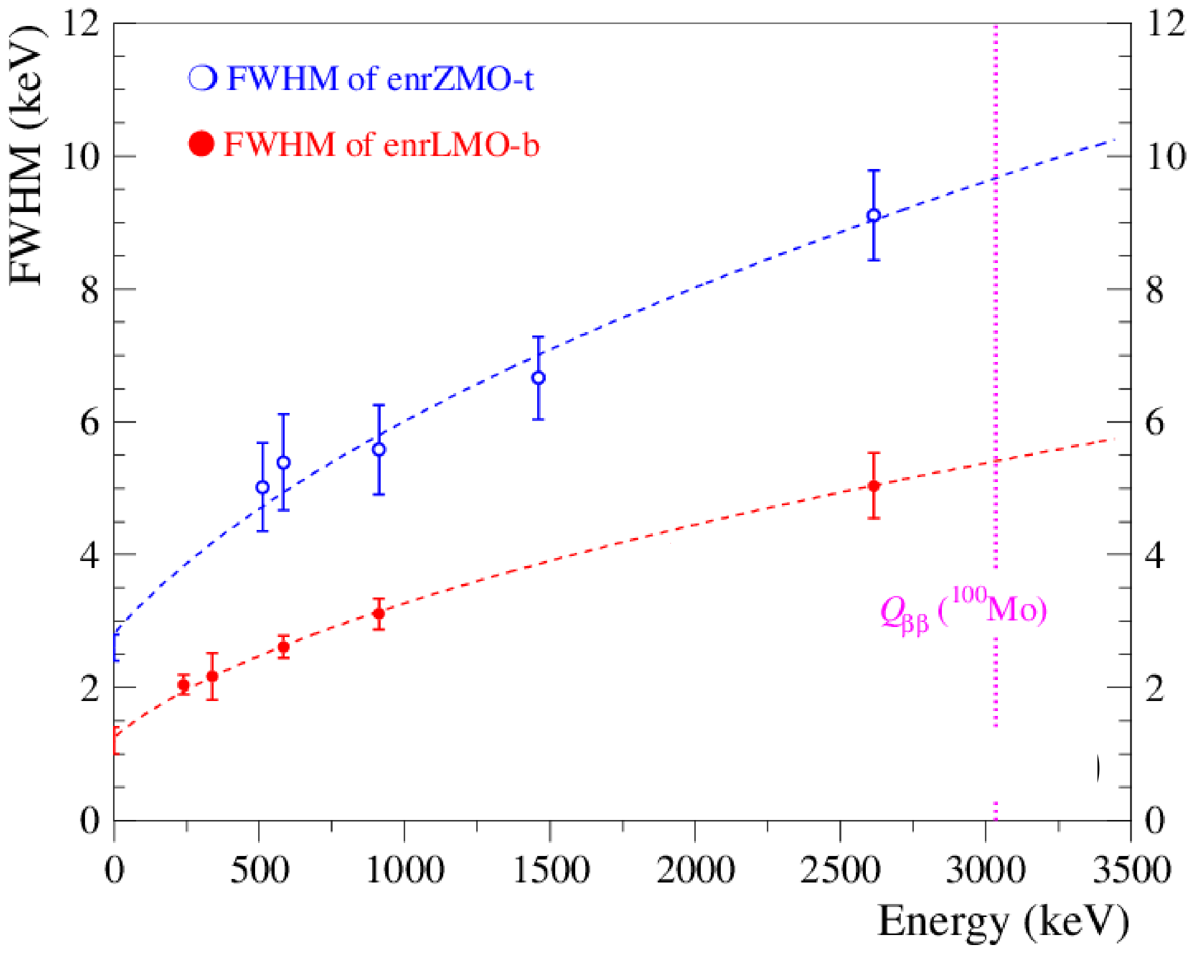
CUPID-Mo

- Four $Li^{100}MoO_4$ (LMO) bolometers were operated at LSM (Modane underground lab, France)
- Excellent energy resolution on heat channel (see Figure), good radiopurity and easy crystallization
- Successful test of performance of 4 enriched $Li^{100}MoO_4$ (LMO) using the EDELWEISS cryostat, electronics and DAQ
- CUPID-0/Mo is a 20 detector demonstrator is being planned and data taking is expected to start at early 2018.



Light detector





arXiv:1603.08049v2

Summary

1. CUORE-0 was a successful demonstration of the low-background techniques that we have applied to CUORE.

2. CUORE has been commissioned and is currently in data-taking phase

3. CUPID is a next generation $0\nu\beta\beta$ decay search experiment aiming at a zero-background (0.1 events/ton-year) with a sensitivity to $m_{\beta\beta}$<20 meV to cover IH.

4. We have a vigorous R&D program aimed to demonstrate this sensitivity on the timescale of 2-3 years:

   (a) CUORE has demonstrated the cryogenic technology

   (b) Scalable and low T_c TES technology is a promising sensor for CUPID. Other sensor technologies are also being developed such as MKIDs (CALDER).

   (c) Neganov-Luke amplification with a Ge-NTD has already been demonstrated as a viable light detector technology, using 2 enriched ^{130}Te crystals, 435g each.

   (d) Enrichment and crystal production of ^{130}Te: a promising starting point.

   (e) Scintillating bolometer R&D proceeding with pilot experiments, including CUPID-0

The CUORE collaboration

cuore.lngs.infn.it

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