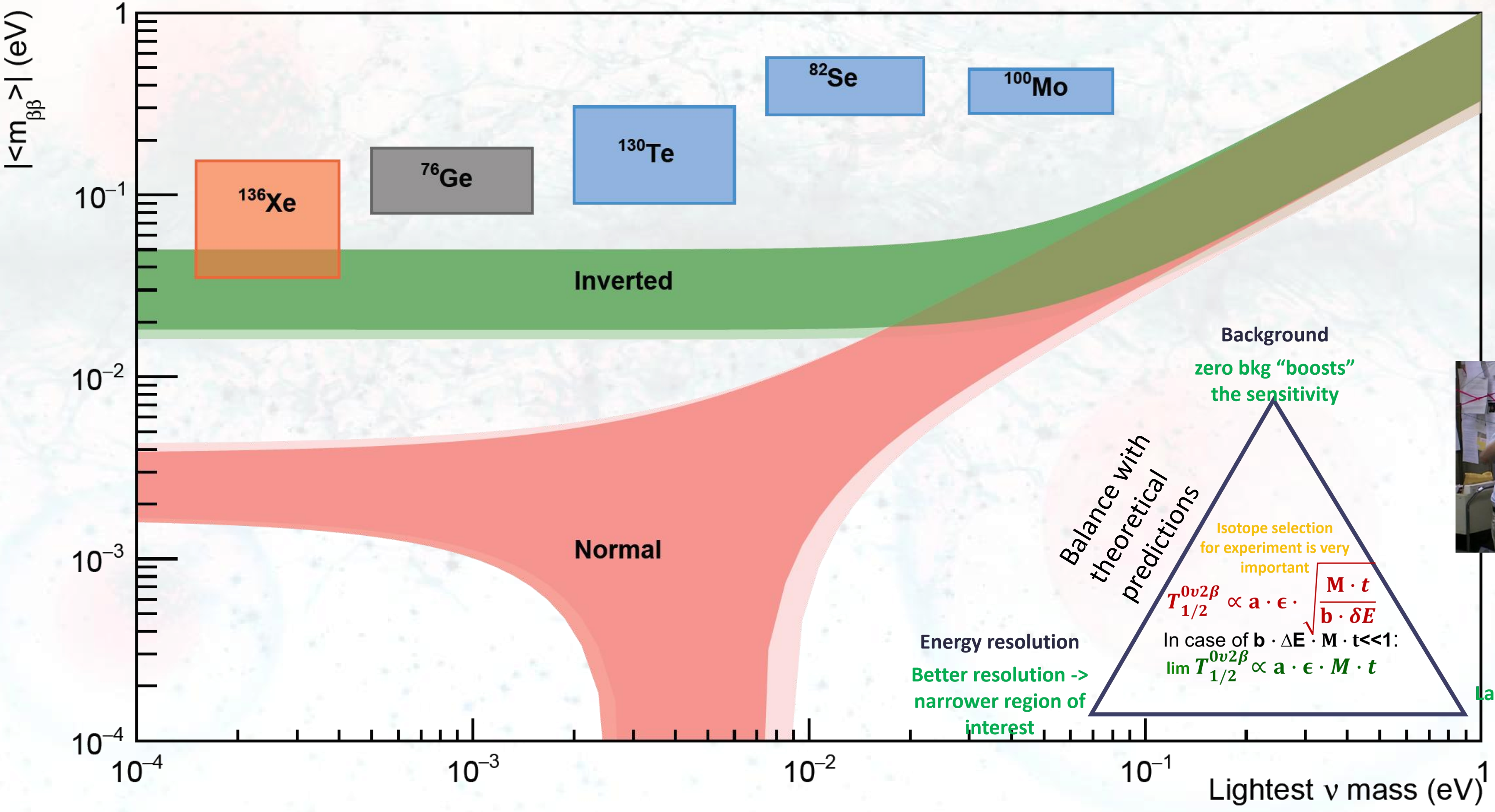
Double beta decay experiments-II

Or how it was done in past years

Current picture

I will focus more on these five best limits, but there are other experiments worth mentioning...



Background

zero bkg “boosts” the sensitivity

Balance with theoretical predictions

Isotope selection for experiment is very important

$$T^{0\nu2\beta}_{1/2} \propto \mathbf{a}\cdot\epsilon\cdot\sqrt{\frac{\mathbf{M}\cdot t}{\mathbf{b}\cdot\delta E}}$$

In case of **b** · **ΔE** · **M** · **t<<1**:

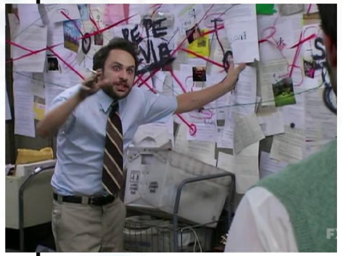
$$\lim T^{0\nu2\beta}_{1/2} \propto \mathbf{a}\cdot\epsilon\cdot M\cdot t$$

Energy resolution

Better resolution -> narrower region of interest

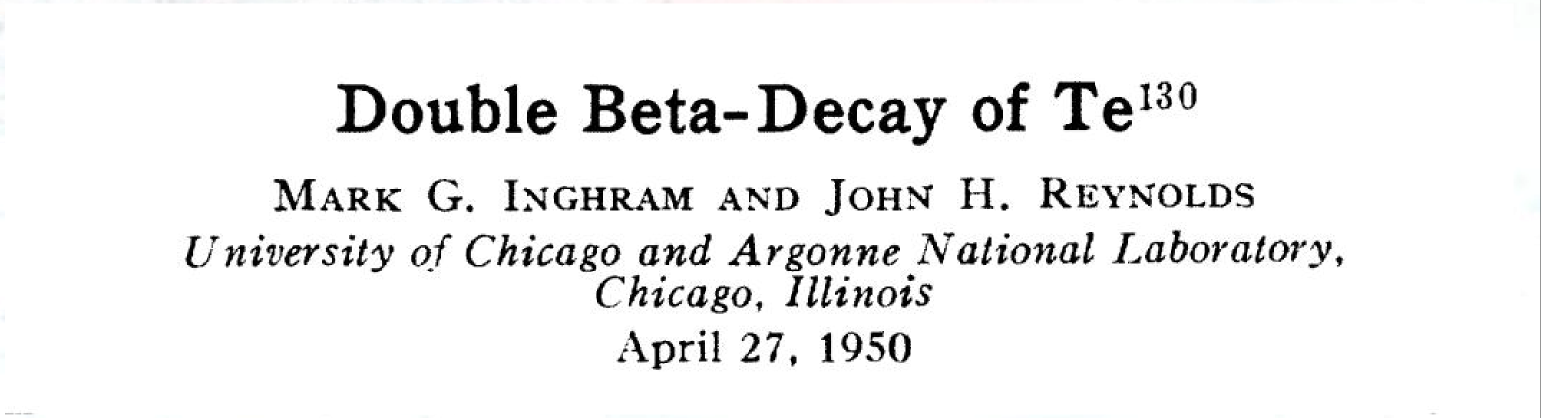
Exposure

Large masses and a lot of patience



First claims on observation

- Already in1950, Inghram and Reynolds detected the 2β decay of ^{130}Te and obtained $T_{1/2} = 1.4 \times 10^{21}$ yr.
- Method: isotopic analysis of xenon extracted from geologically old tellurium ores
- This result was initially not considered seriously, but it became clear after 15-20 yr that 2β(2v) decay was indeed observed for the first time!



Double Beta-Decay of Te^{130}

MARK G. INGHRAM AND JOHN H. REYNOLDS

University of Chicago and Argonne National Laboratory,
Chicago, Illinois

April 27, 1950

First source=detector test

- 1966: crystal scintillator
- Also enriched!
- No observation of $2\nu2\beta$, only limit
- Too much contamination in the crystals

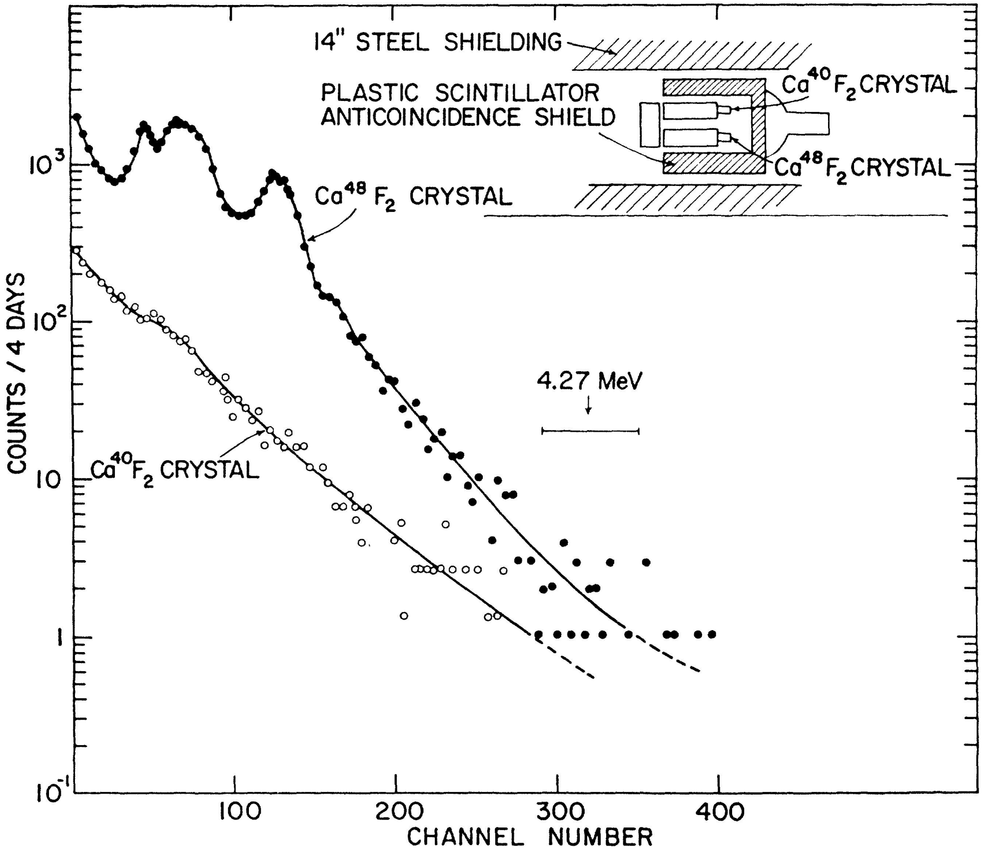


FIG. 4. Spectrum of counts seen with a crystal of $Ca^{48}F_2$ (Eu) enriched to 96.59% Ca^{48}. This run differs from that of Fig. 3 in that the Ca^{48} was repurified and a new crystal was grown. The reduced counting rate can be judged by referring to the scales of each figure. A run with a control crystal of $Ca^{40}F_2$ (Eu) is also shown for comparison.

Limits for Lepton-Conserving and Lepton-Nonconserving Double Beta Decay in Ca48
E. der Mateosian and M. Goldhaber
Phys. Rev. 146, 810

First direct observation

- Tracko-calorimetric technique
- Foil source with 14g of ^{82}Se
- TPC with magnetic field
- 7960 h of life-time

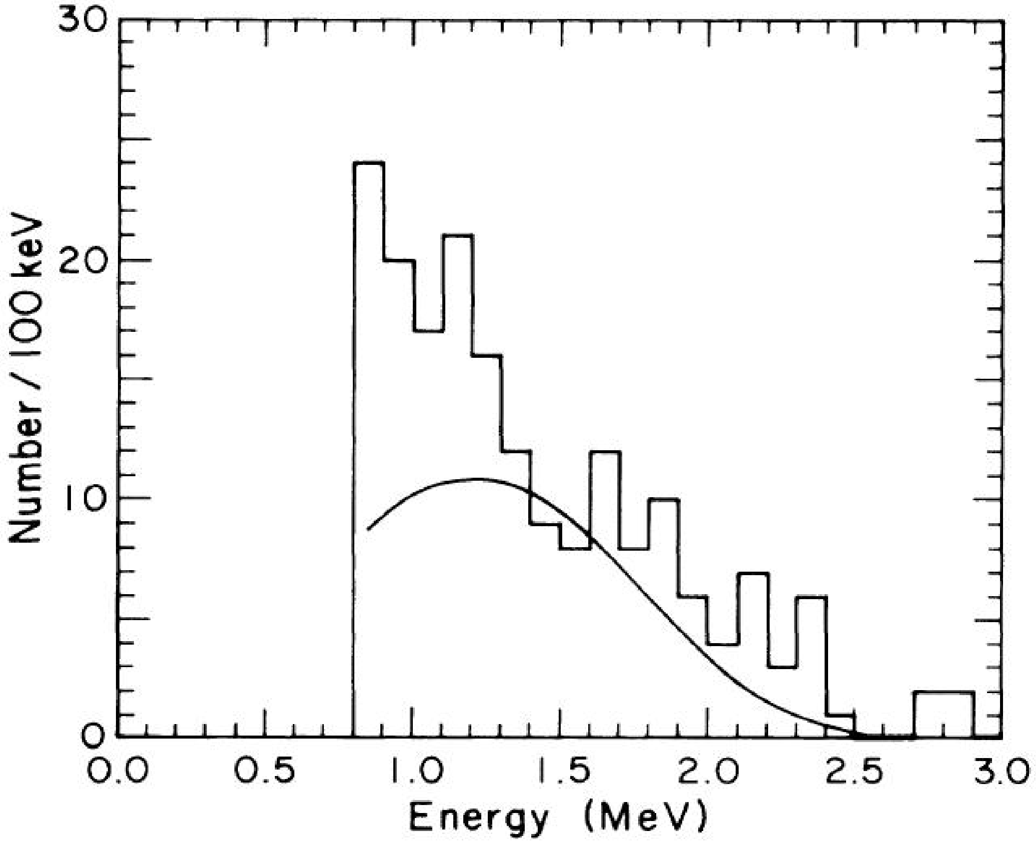


FIG. 1. The observed sum-energy spectrum of two-electron events. A threshold of 800 keV was imposed on the sum energy of the events, and a threshold of 150 keV was imposed on the single energy. The curve is the theoretical $\beta\beta(2\nu)$ sum-energy spectrum normalized to 1.1×10^{20} yr.

How far did we go..

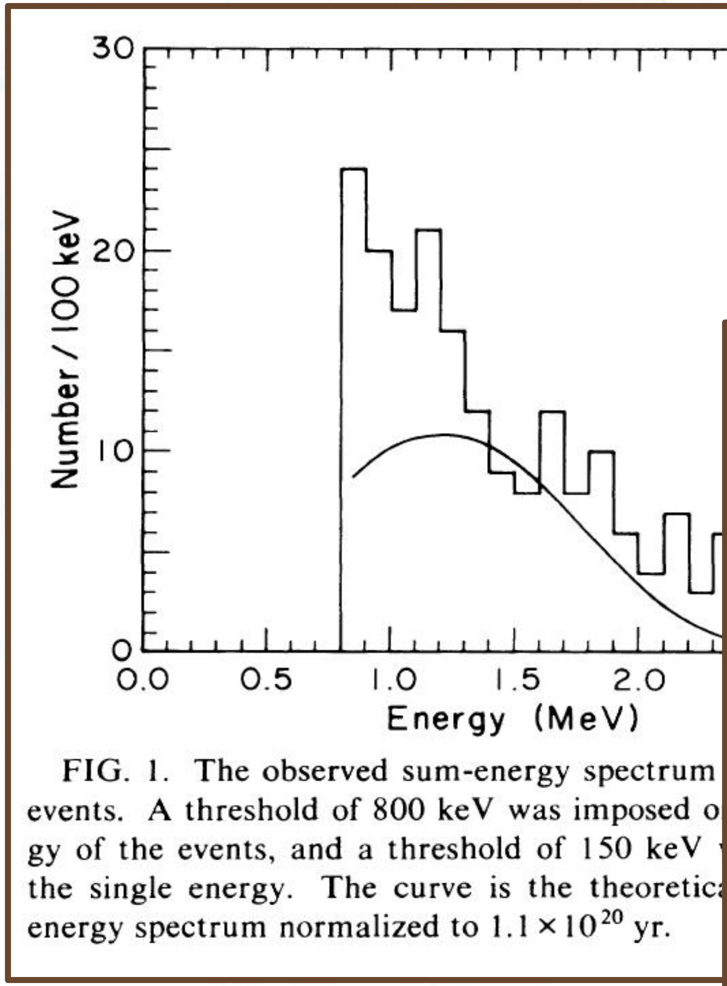
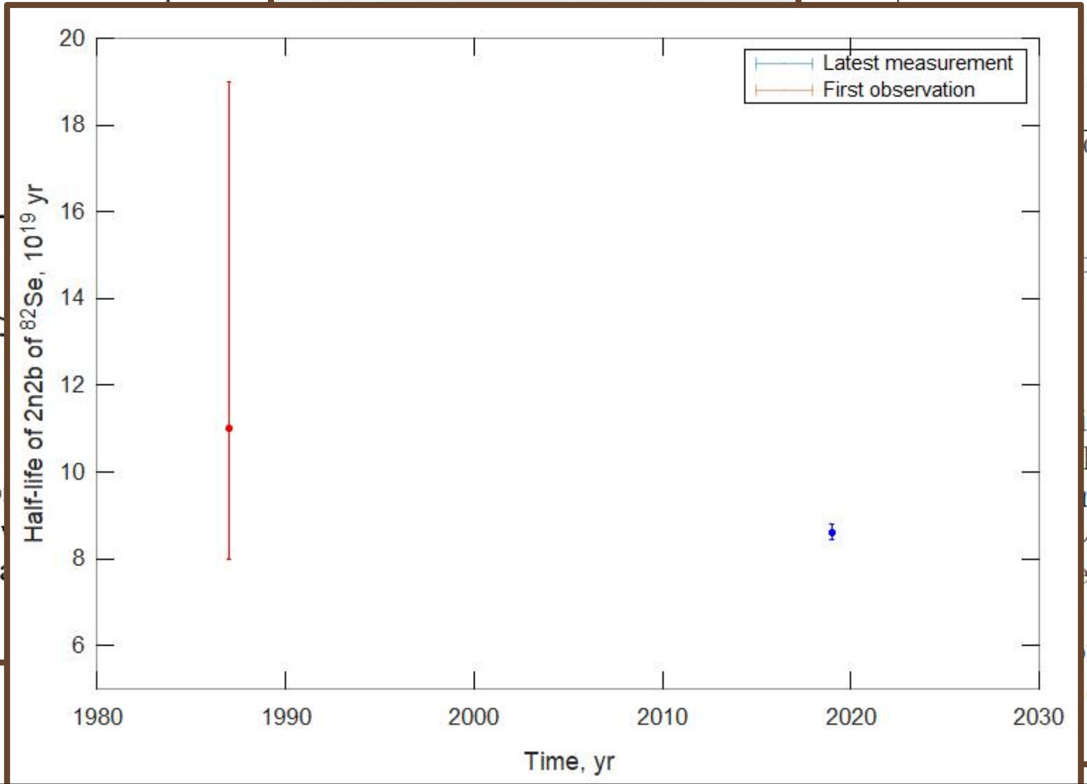
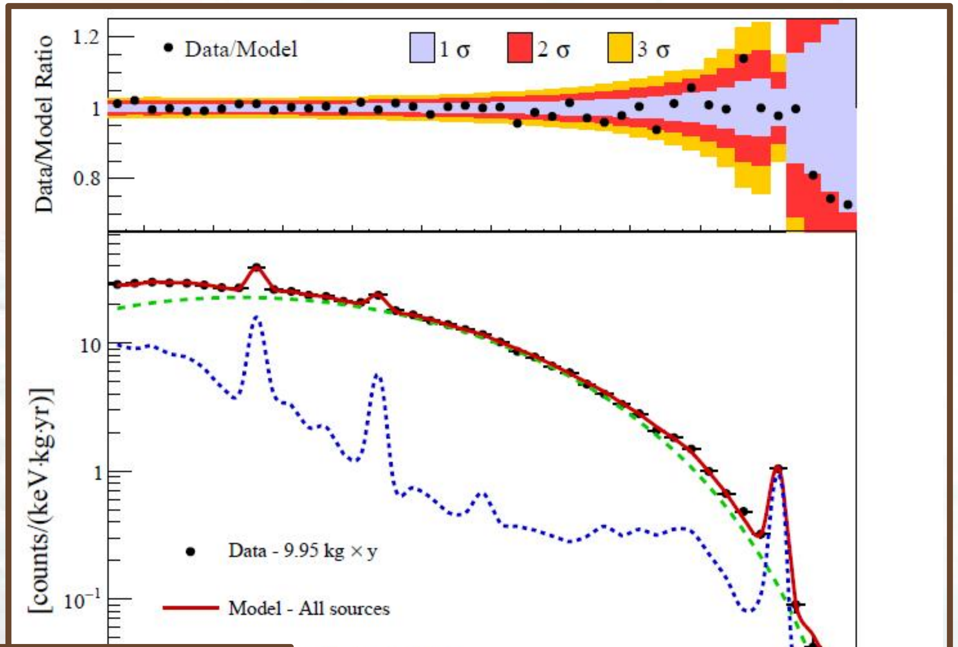


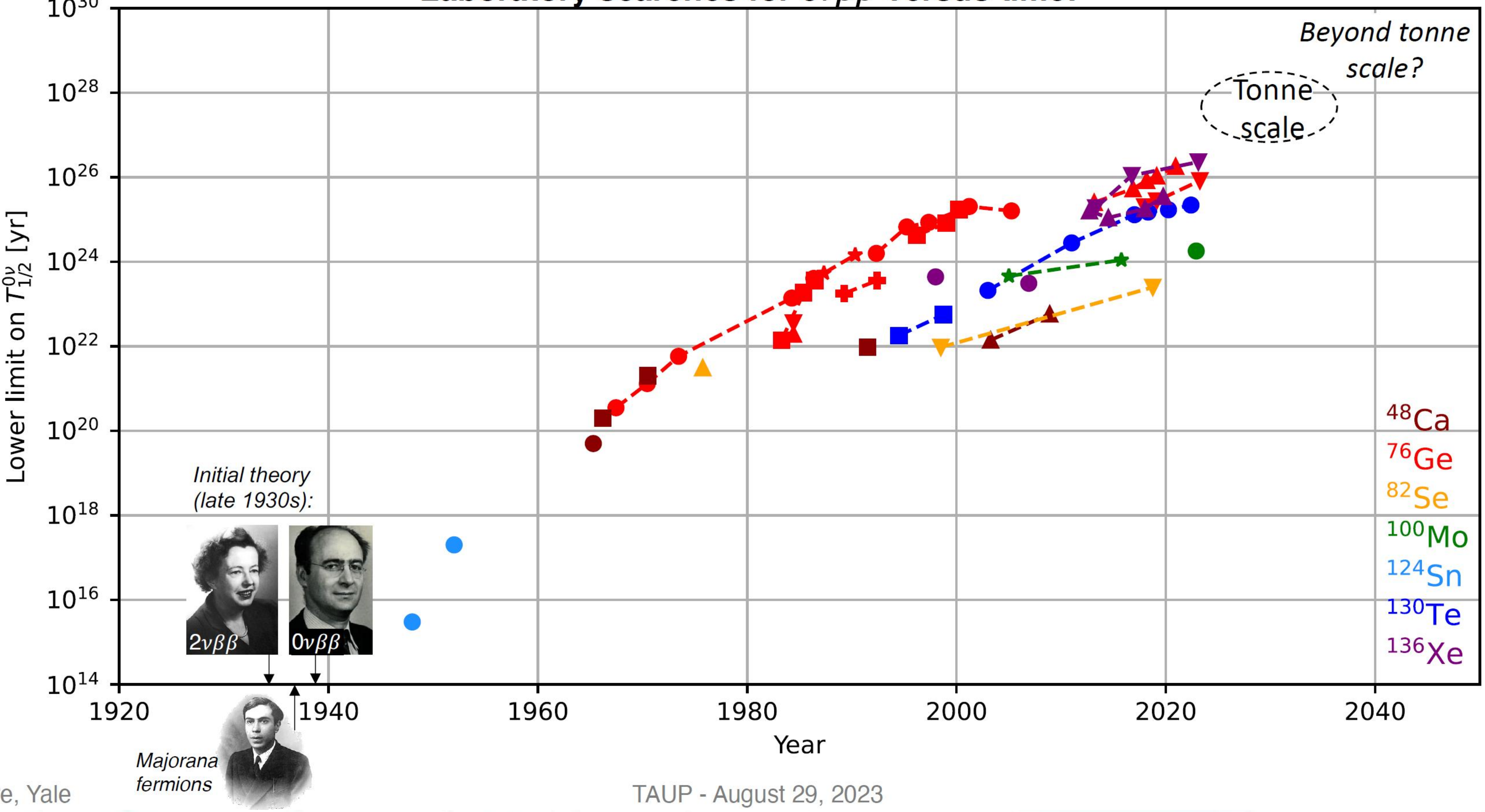
FIG. 1. The observed sum-energy spectrum
events. A threshold of 800 keV was imposed o
gy of the events, and a threshold of 150 keV
the single energy. The curve is the theoretic
energy spectrum normalized to 1.1×10^{20} yr.





pectrum of the $\mathcal{M}_{1\beta/\gamma}$ events collected by
kg×yr of Zn^{82}Se exposure (black dots).
are clearly visible over the continuum due
1116 keV, ^{40}K at 1461 keV, and ^{208}Tl at
d red line is the results of the Bayesian fit
h the SSD hypothesis for the $2\nu\beta\beta$ decay.
resents the $2\nu\beta\beta$ component, simulated as-
$\nu\beta\beta$ is SSD. The blue line is the sum of the
s. In the top panel, we show the bin-by-
counts in the experimental spectrum and
nstructed one. The corresponding uncer-
σ are shown as colored bands centered at

Laboratory searches for $0\nu\beta\beta$ versus time:



Neutrinoless double beta decay discoveries

- First discovery: 1949, 2.6σ significance with ^{124}Sn! In reality, some contamination...
- 1992-1994: background peak at 2527 keV in ^{76}Ge experiment: “Due to relevance that this peak would have in the present and future experiment on ^{130}Te, we have re-analized this spectrum in collaboration with the Neuchatel group … We found unambiguously that a peak at 2527 keV was generated … by the early saturation of amplifier number six, which was defective in the last part of the experiment”
- The most famous: “Klapdor claim” with Heidelberg-Moscow experiment

V. Tretyak:False Starts in History of Searches for 2β Decay, or Discoverless Double Beta Decay: https://doi.org/10.48550/arXiv.1112.4183

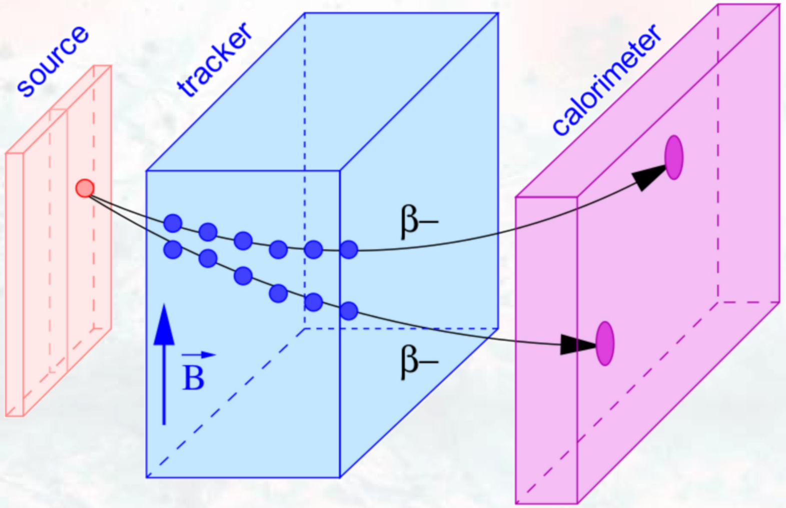
Tracko-calorimetric detector: NEMO-3

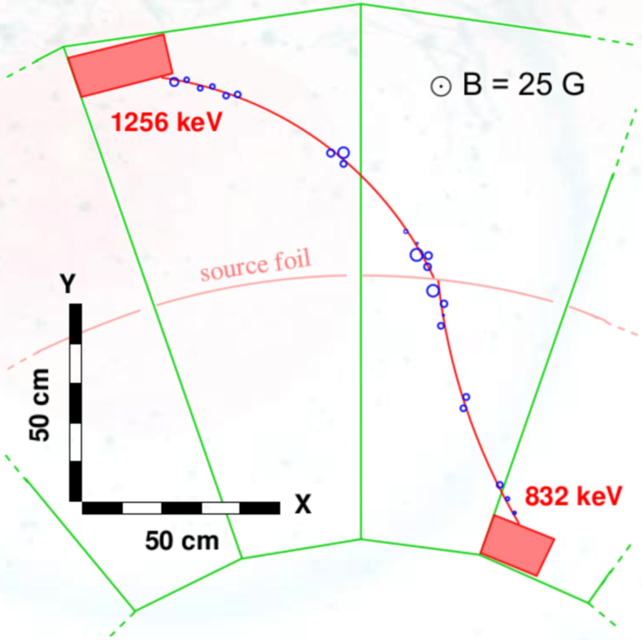
☺Reconstruction of the final state topology and particle identification

☺Precise background identification and measurement

☺Possible discrimination of mechanism behind 0νββ process

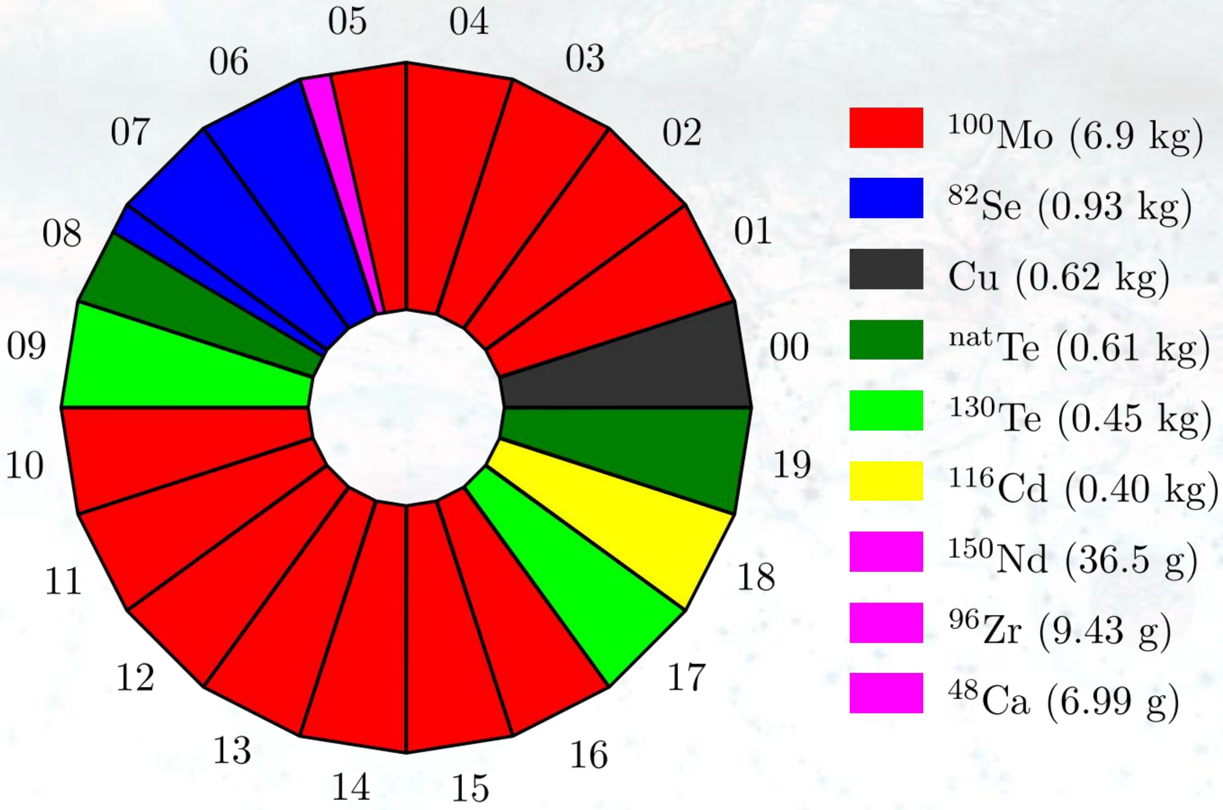
☹Limited energy resolution
Restricted exposure

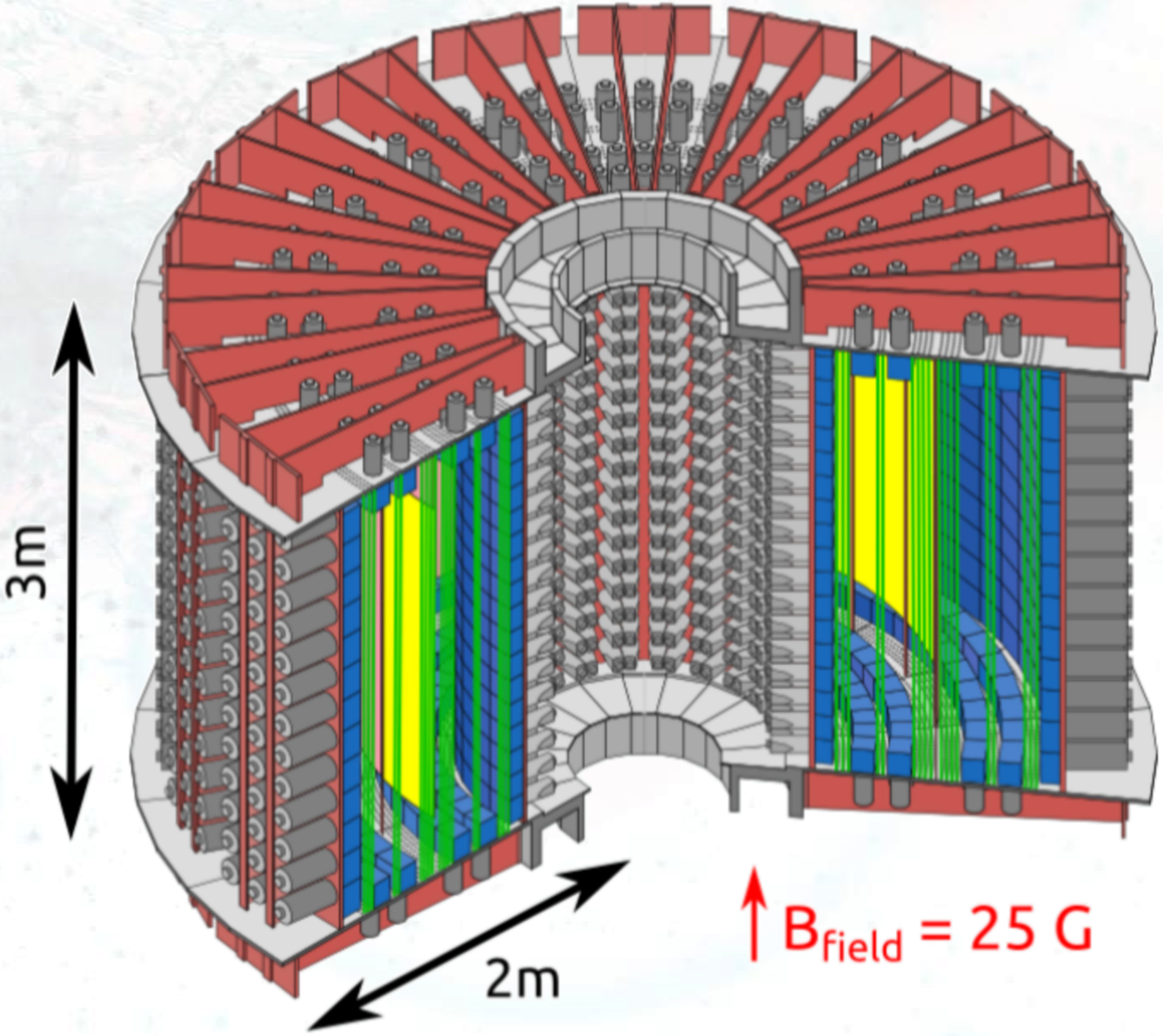




NEMO-3 strategy

- Main focus on 100-Mo, but try to collect them all!
- 7 isotopes and 8 years (2003-2011)





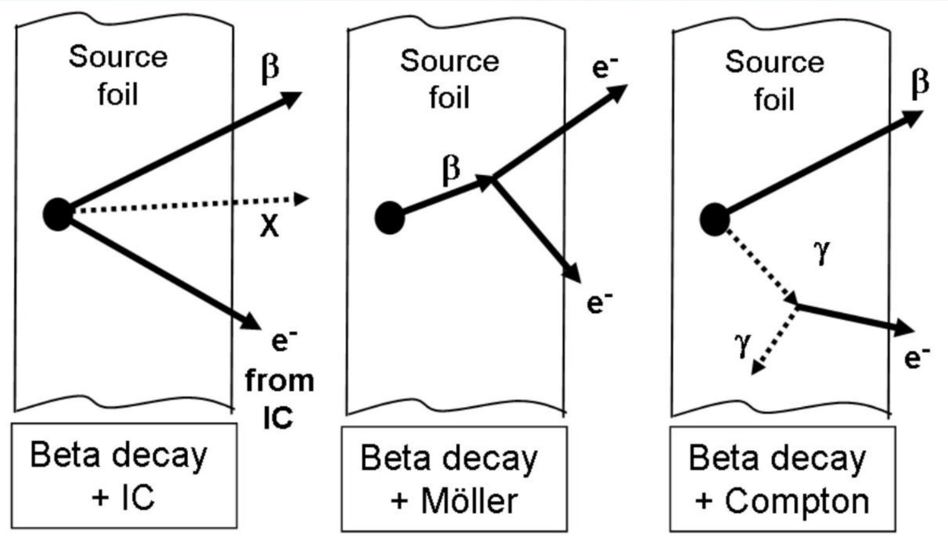
NEMO-3 detector

- Wire drift chamber: 6180 Geiger cells, σ_{vertex} = 3 mm (XY), 10 mm (Z)
- Calorimeter: 1940 polystyrene scintillators coupled with low radioactivity PMTs, FWHM ~15 % at 1 MeV
- 25 Gauss magnetic field for the charge identification
- Gamma and neutron shields, anti-radon tent

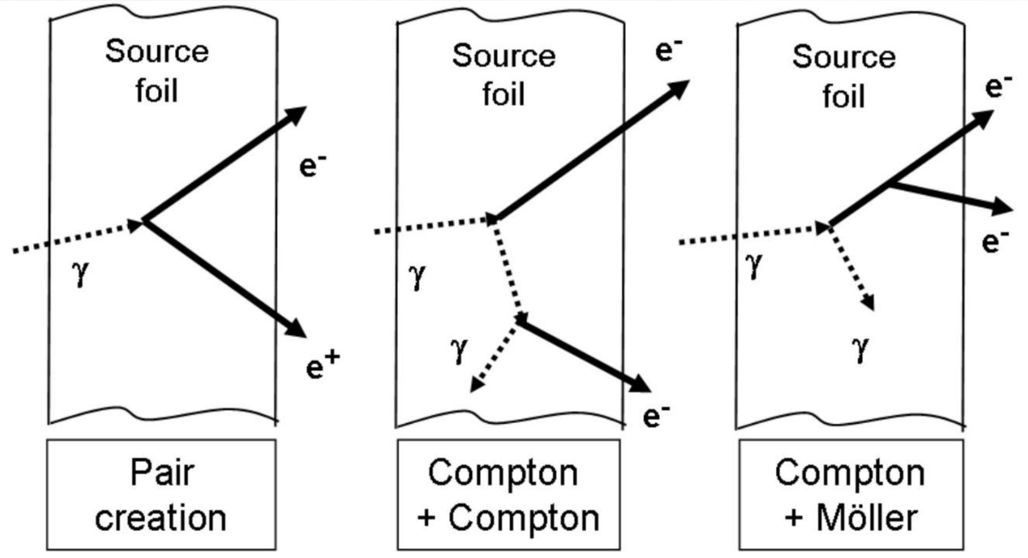
NEMO-3 backgrounds

- What can mimic the $0\nu2\beta$ tracks?

Internal bkg:
$2\nu2\beta$ tail and radioactive impurities inside the source foil

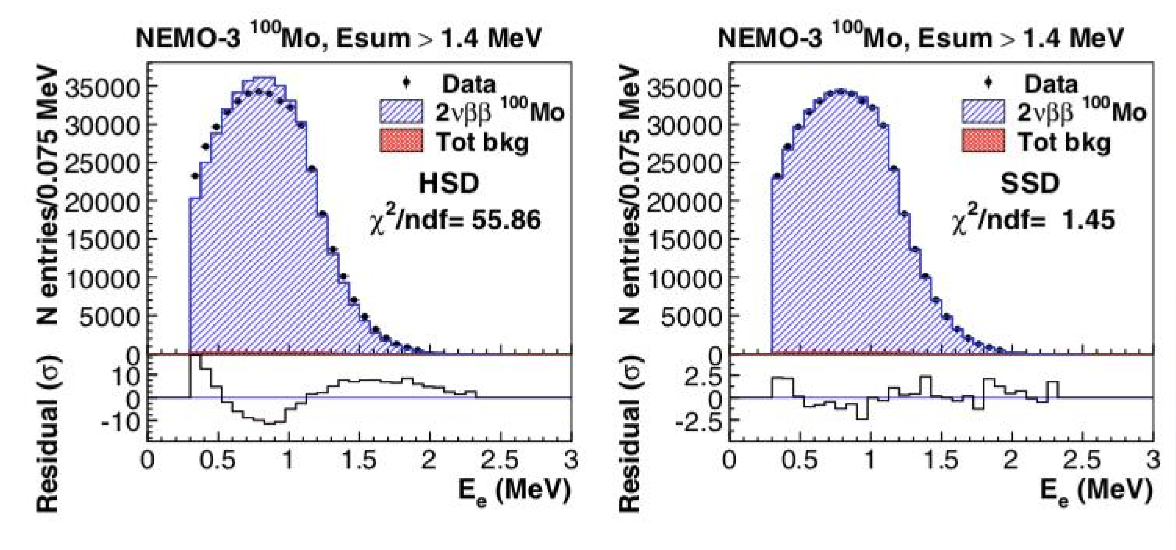


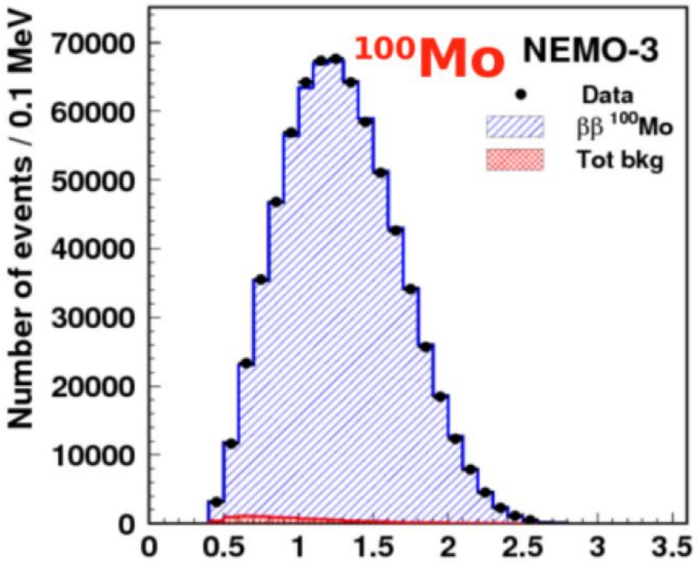
External bkg:
Radioactive impurities of the detector



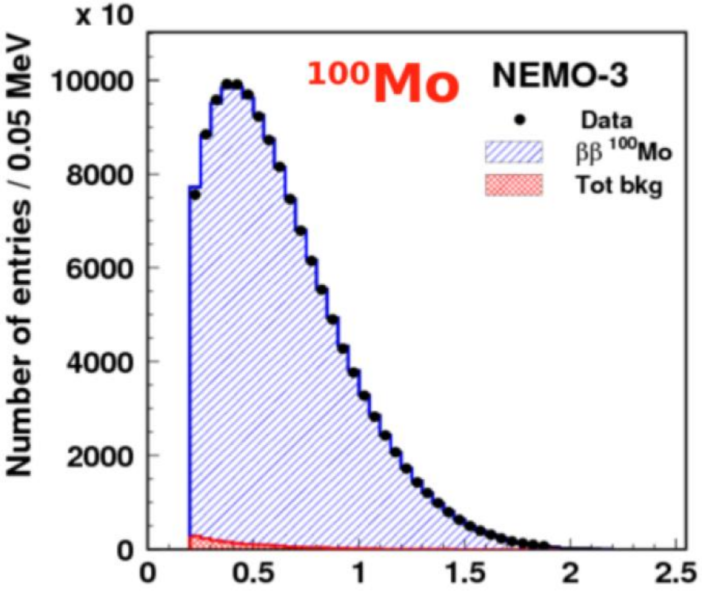
NEMO-3 results: Mo-100

- The "main" isotope
- Measurment of angular distributions
- SSD vs HSD

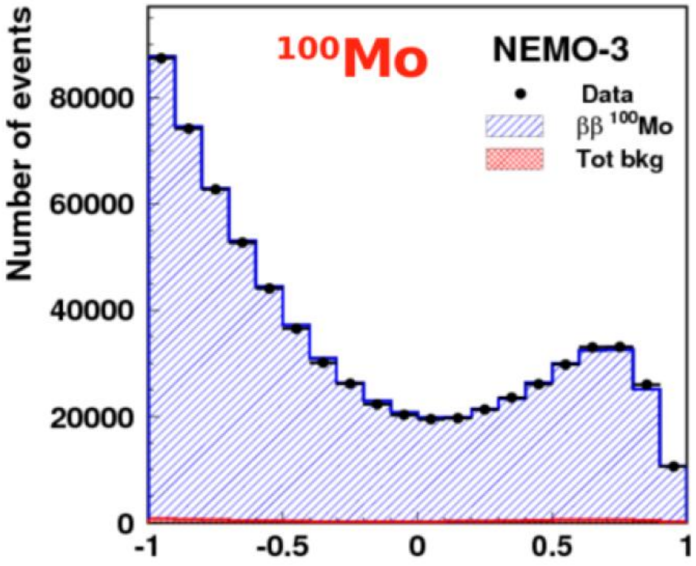




Total electron energy



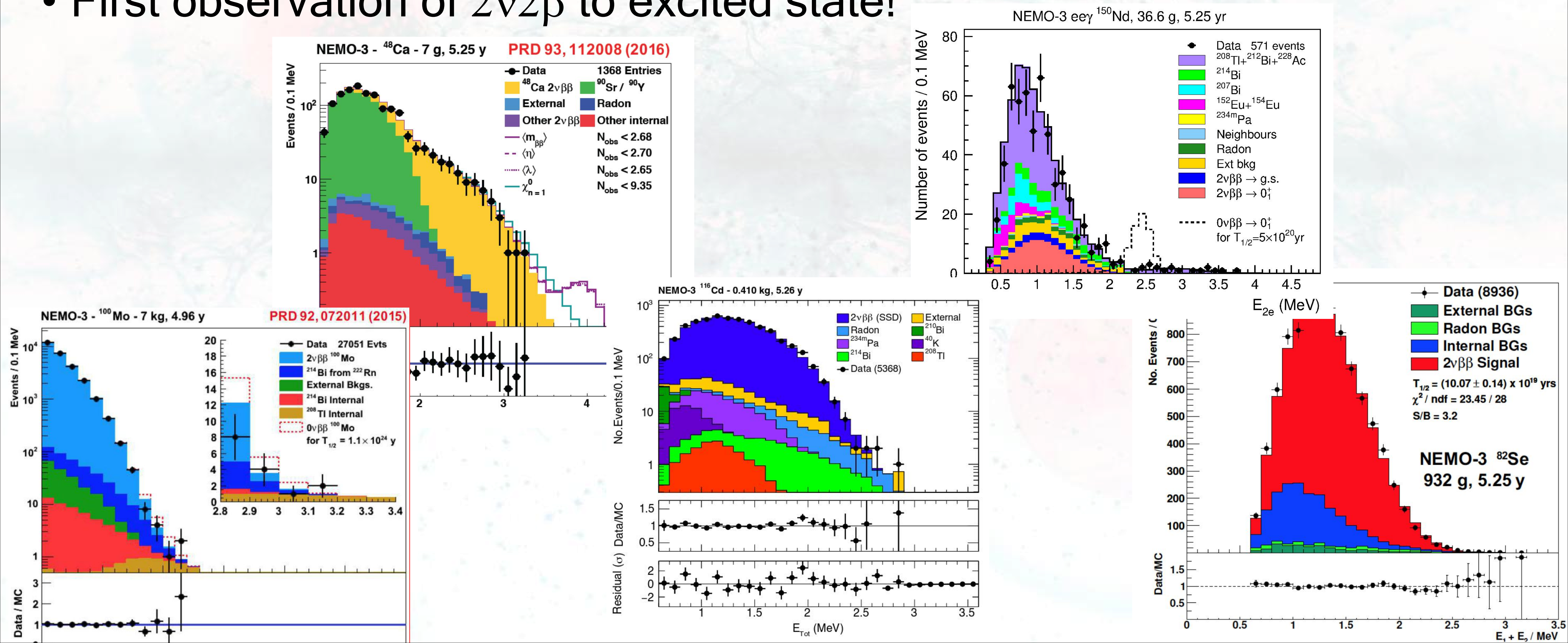
Individual electron energy



Angular distribution

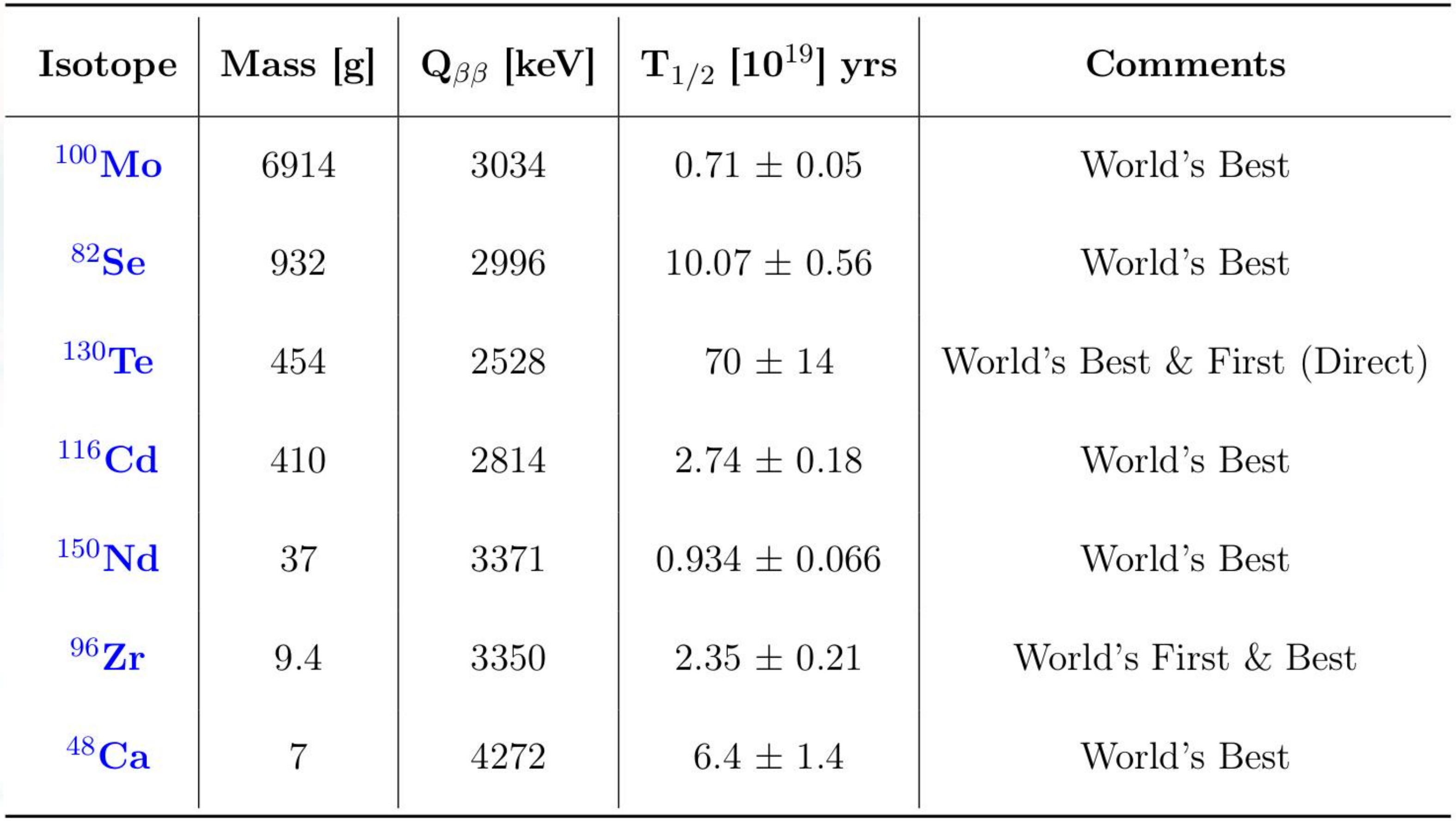
NEMO-3 results

- Best limits and precision measurements on $2\nu2\beta$ for most isotopes
- First observation of $2\nu2\beta$ to excited state!



NEMO-3 2v2β measurements

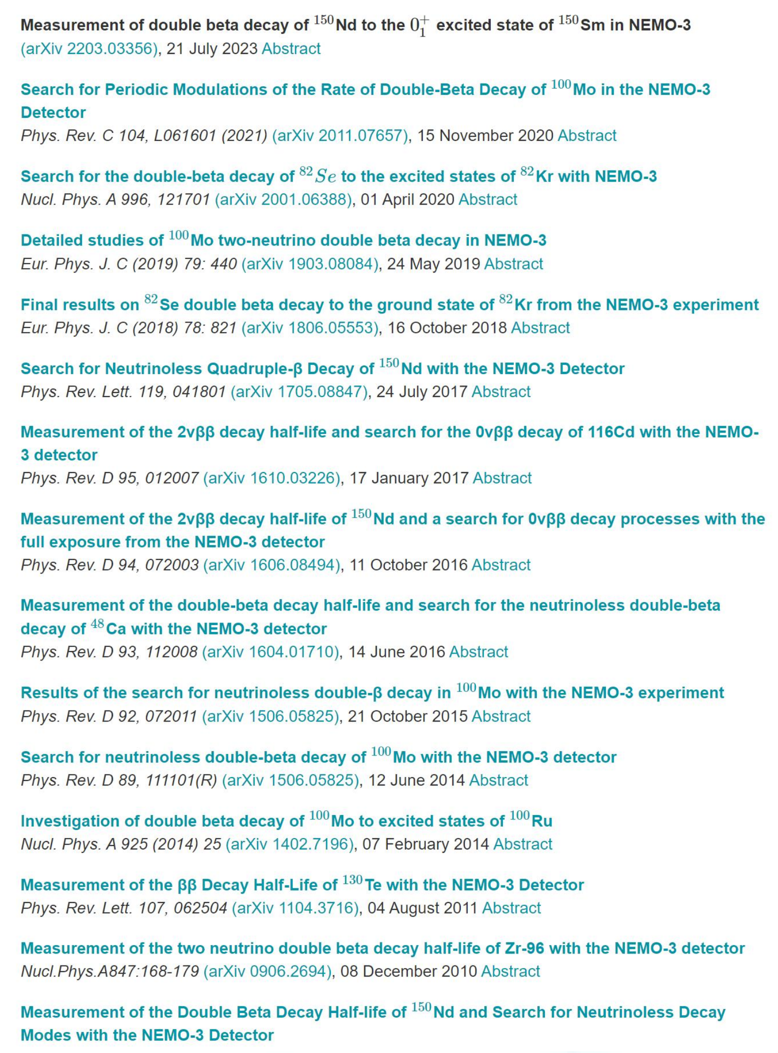
- At a time, best measurements for many isotopes, also limits on $0\nu2\beta$, limits on Majoron mode



Isotope	Mass [g]	$Q_{\beta\beta}$ [keV]	$T_{1/2}$ [10^{19}] yrs	Comments
^{100}Mo	6914	3034	0.71 ± 0.05	World's Best
^{82}Se	932	2996	10.07 ± 0.56	World's Best
^{130}Te	454	2528	70 ± 14	World's Best & First (Direct)
^{116}Cd	410	2814	2.74 ± 0.18	World's Best
^{150}Nd	37	3371	0.934 ± 0.066	World's Best
^{96}Zr	9.4	3350	2.35 ± 0.21	World's First & Best
^{48}Ca	7	4272	6.4 ± 1.4	World's Best

Status as of 2017

https://supernemo.org/publications.html



Measurement of double beta decay of ^{150}Nd to the 0_1^+ excited state of ^{150}Sm in NEMO-3
(arXiv 2203.03356), 21 July 2023 Abstract

Search for Periodic Modulations of the Rate of Double-Beta Decay of ^{100}Mo in the NEMO-3 Detector
Phys. Rev. C 104, L061601 (2021) (arXiv 2011.07657), 15 November 2020 Abstract

Search for the double-beta decay of ^{82}Se to the excited states of ^{82}Kr with NEMO-3
Nucl. Phys. A 996, 121701 (arXiv 2001.06388), 01 April 2020 Abstract

Detailed studies of ^{100}Mo two-neutrino double beta decay in NEMO-3
Eur. Phys. J. C (2019) 79: 440 (arXiv 1903.08084), 24 May 2019 Abstract

Final results on ^{82}Se double beta decay to the ground state of ^{82}Kr from the NEMO-3 experiment
Eur. Phys. J. C (2018) 78: 821 (arXiv 1806.05553), 16 October 2018 Abstract

Search for Neutrinoless Quadruple-β Decay of ^{150}Nd with the NEMO-3 Detector
Phys. Rev. Lett. 119, 041801 (arXiv 1705.08847), 24 July 2017 Abstract

Measurement of the 2vββ decay half-life and search for the 0vββ decay of 116Cd with the NEMO-3 detector
Phys. Rev. D 95, 012007 (arXiv 1610.03226), 17 January 2017 Abstract

Measurement of the 2vββ decay half-life of ^{150}Nd and a search for 0vββ decay processes with the full exposure from the NEMO-3 detector
Phys. Rev. D 94, 072003 (arXiv 1606.08494), 11 October 2016 Abstract

Measurement of the double-beta decay half-life and search for the neutrinoless double-beta decay of ^{48}Ca with the NEMO-3 detector
Phys. Rev. D 93, 112008 (arXiv 1604.01710), 14 June 2016 Abstract

Results of the search for neutrinoless double-β decay in ^{100}Mo with the NEMO-3 experiment
Phys. Rev. D 92, 072011 (arXiv 1506.05825), 21 October 2015 Abstract

Search for neutrinoless double-beta decay of ^{100}Mo with the NEMO-3 detector
Phys. Rev. D 89, 111101(R) (arXiv 1506.05825), 12 June 2014 Abstract

Investigation of double beta decay of ^{100}Mo to excited states of ^{100}Ru
Nucl. Phys. A 925 (2014) 25 (arXiv 1402.7196), 07 February 2014 Abstract

Measurement of the ββ Decay Half-Life of ^{130}Te with the NEMO-3 Detector
Phys. Rev. Lett. 107, 062504 (arXiv 1104.3716), 04 August 2011 Abstract

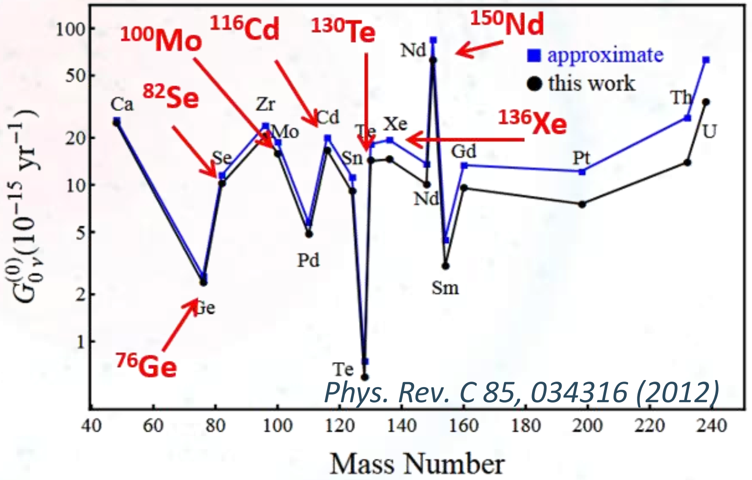
Measurement of the two neutrino double beta decay half-life of Zr-96 with the NEMO-3 detector
Nucl.Phys.A847:168-179 (arXiv 0906.2694), 08 December 2010 Abstract

Measurement of the Double Beta Decay Half-life of ^{150}Nd and Search for Neutrinoless Decay Modes with the NEMO-3 Detector

Ge-76 experiments

- ☺“Popular” approach thanks to abundance of HPGe detectors: well known and highly performant technology
- ☺Highly radiopure detectors
- ☺Made entirely from Ge, with enrichment - high mass and efficiency

- ☹ Q_{bb} =2039 keV, below end-point of natural γ radioactivity
- ☹ One of the lowest phase-space factors among popular isotopes - need to reach higher half-life limits for same sensitivity on $m_{\beta\beta}$



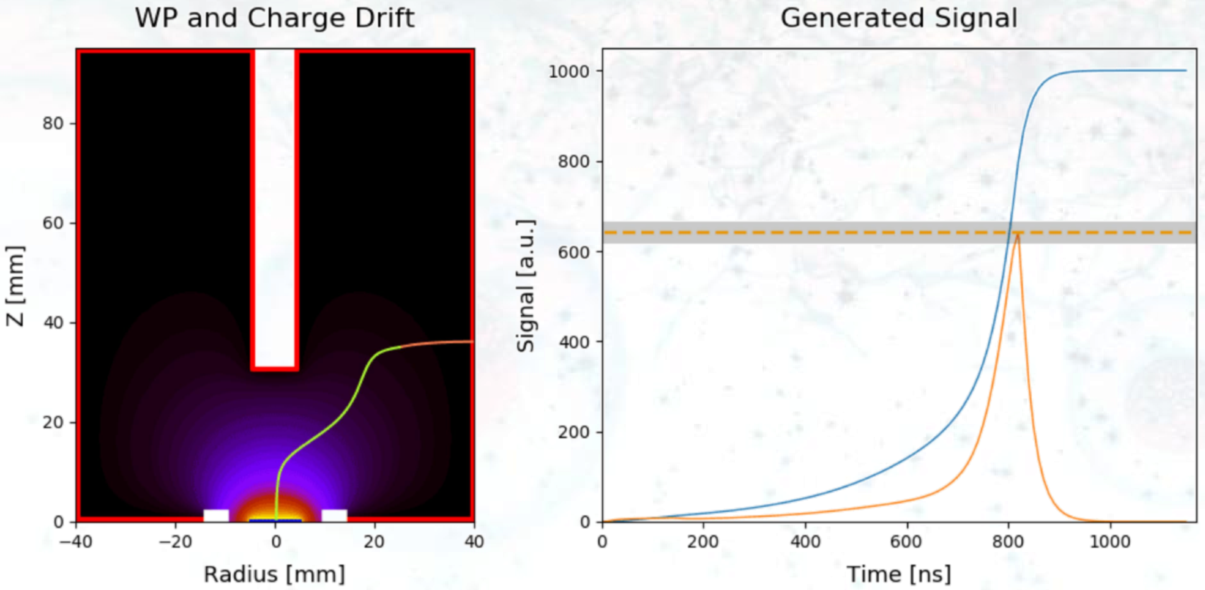
Phys. Rev. C 85, 034316 (2012)

The Search for Double Beta Decay With Germanium Detectors: Past, Present, and Future, https://doi.org/10.3389/fphy.2019.00006

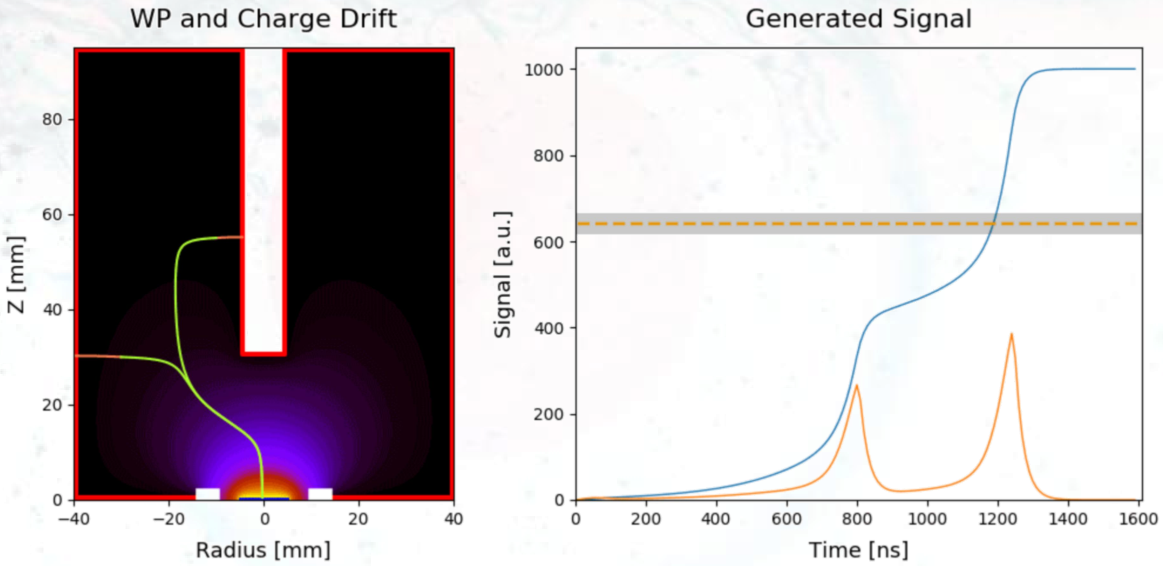
Neutrinoless Double Beta Decay with Germanium Detectors: 1026 yr and Beyond. Universe 2021, 1, 341. https://doi.org/10.3390/universe7090341

HPGe detectors

- Single-crystal semiconductor diode made from enriched Ge
- Best energy resolution on the market - 0.1% at Q_{bb}!
- Read out ionization signal – pulse shape can be used to distinguish multi-site and surface events from 2β events - single channel PSD, a big advantage!



0ν2β signal candidate (single-site)

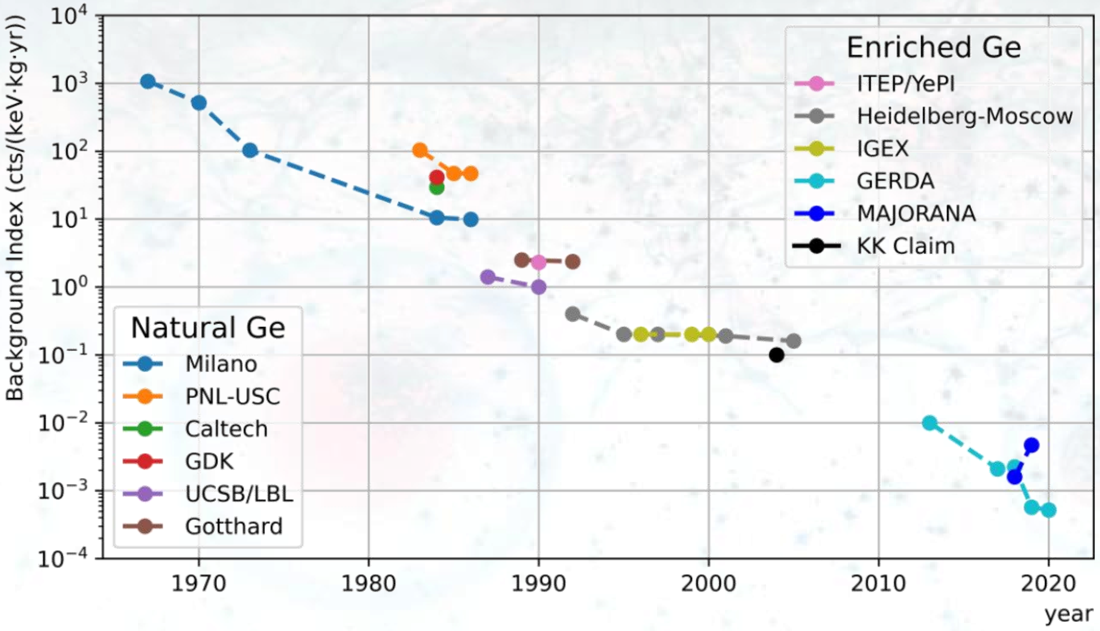


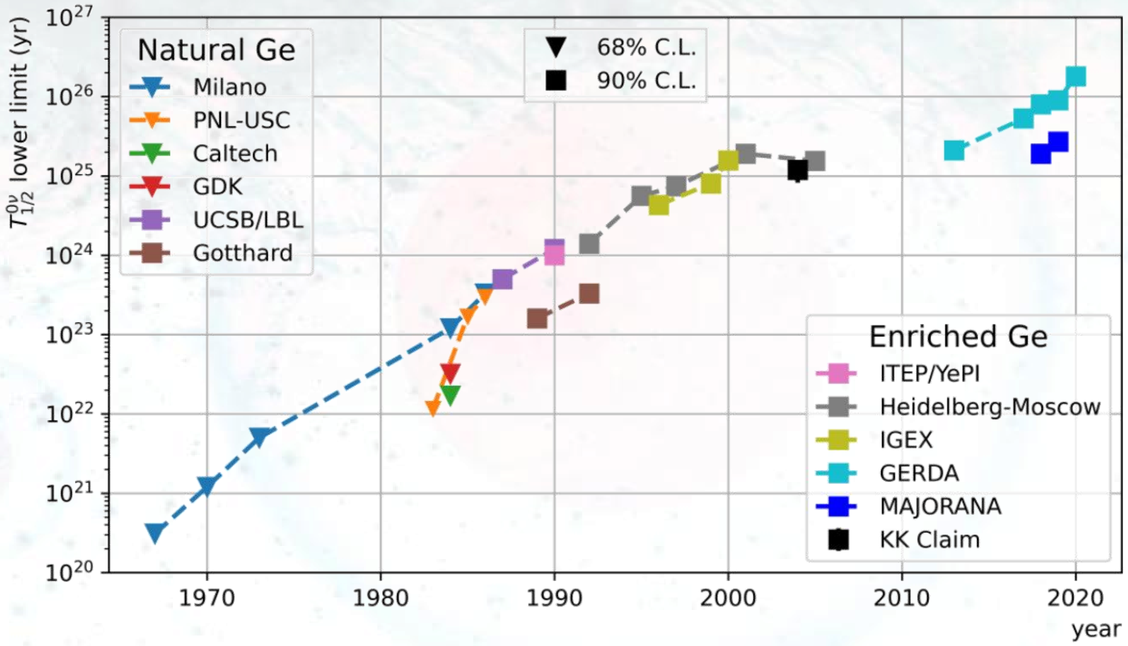
γ-background (multi-site)

Progress in Ge-76 experiments

Big technological progress during the years:

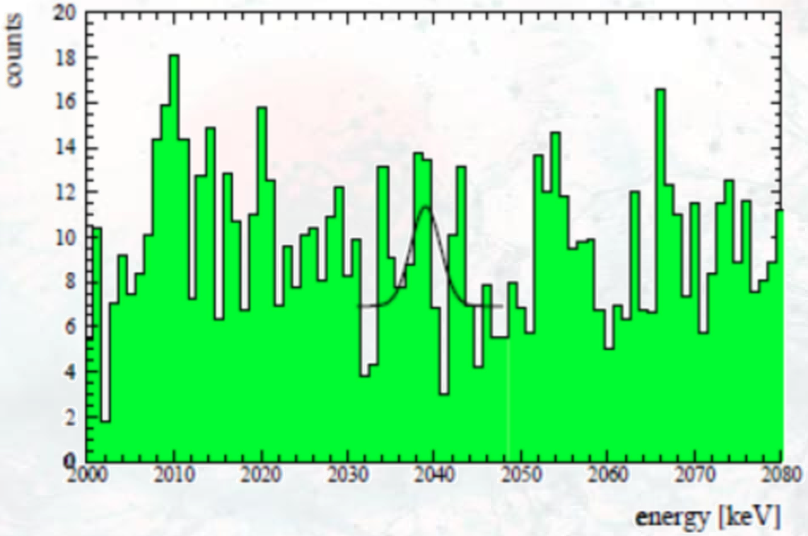
- Enrichment
- Crystal growth quality
- HPGe detectors performance, PSD methods introduction

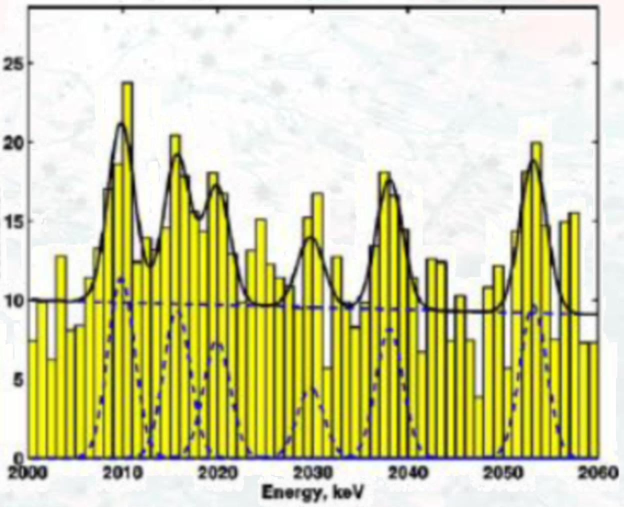


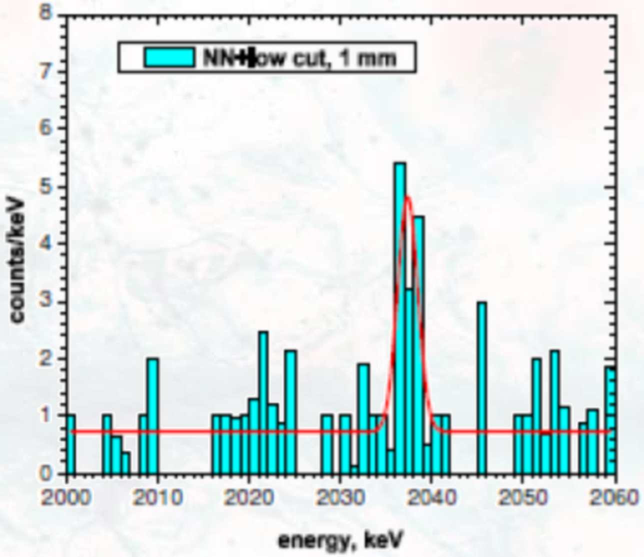


The Search for Double Beta Decay With Germanium Detectors: Past, Present, and Future, https://doi.org/10.3389/fphy.2019.00006

Claim of observation with ^{76}Ge







MPLA 16 (2001) 2409:
55.0 kg×y, no PSA,
2.2-3.1σ effect
$T_{1/2} = 1.5_{-0.7}^{+16.8} \times 10^{25}$ y

PLB 586 (2004) 198:
71.7 kg×y, no PSA,
4.2σ effect
$T_{1/2} = 1.2_{-0.5}^{+3.0} \times 10^{25}$

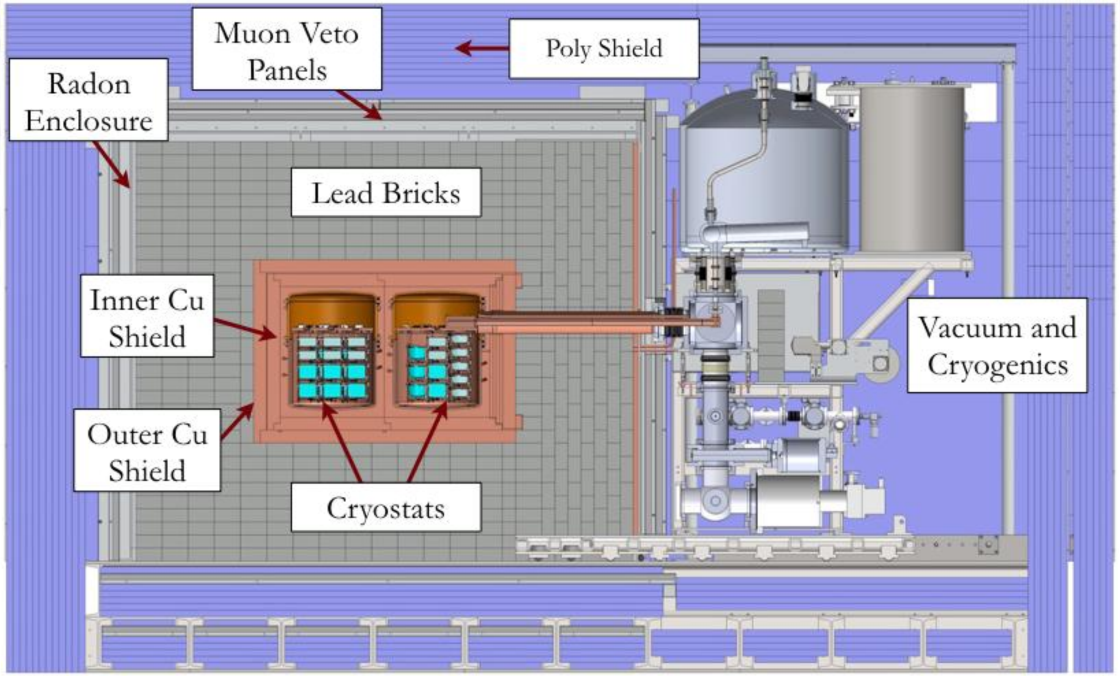
MPLA 21(2006)1547:
PSA – 2 methods,
6.2σ effect
$T_{1/2} = 2.23_{-0.31}^{+0.44} \times 10^{25}$
(final value)

Evolution of the claim in time due to reanalysis of the data.

Majorana experiment

Particular features:

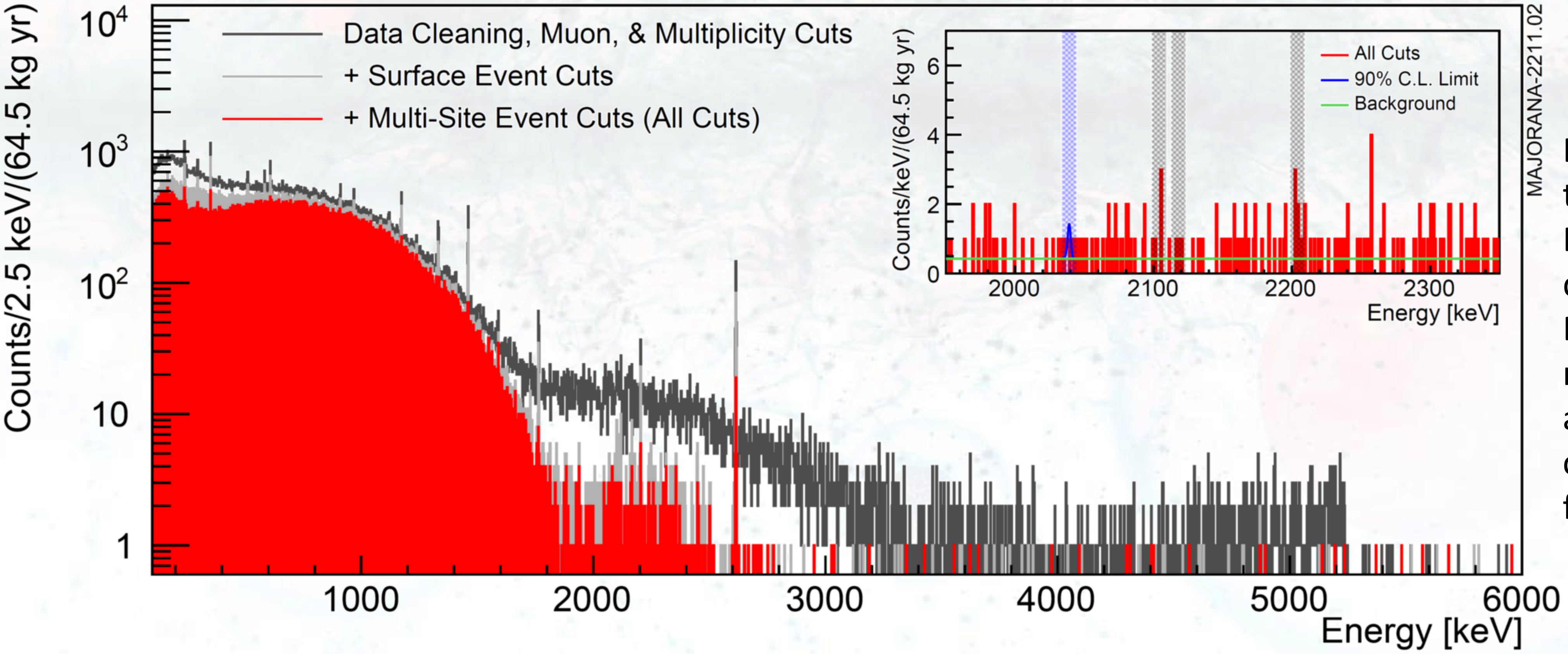
- 58 HPGe detectors, mass of 44.8 kg (14.4 kg of nat and 29.7 kg enr to 88.1%)
- Grow underground electroformed copper, machining alo underground
- Low-mass low-noise low-background electronics:
- The **best energy resolution** of any 0v2β experiment at $Q_{2\beta}$ – 2.5 keV and a low energy threshold (1 keV)



Majorana limit

$$T_{1/2} > 8.3 \times 10^{25} \text{ yr (90\% C.I.)}$$

Background index: =(6.23 ± 0.55) x 10^{-3} cts/(keV kg yr)



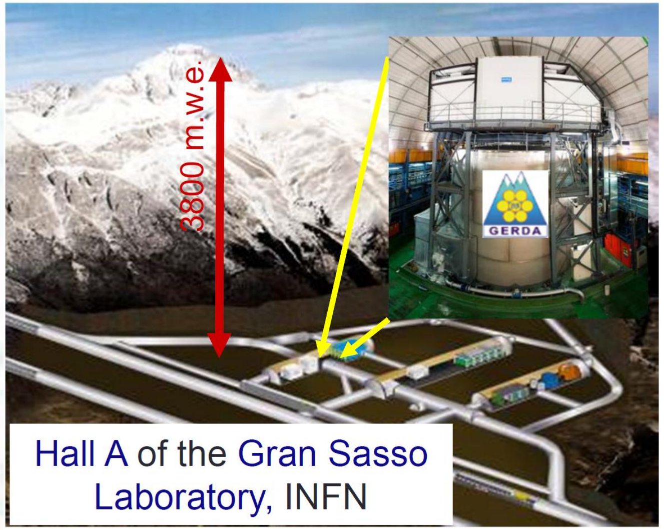
Background is higher than expected: Dominated by ^{232}Th decay chain

Evidence shows that its not from a uniform bulk activity in any component groups, but from a “hot spot”

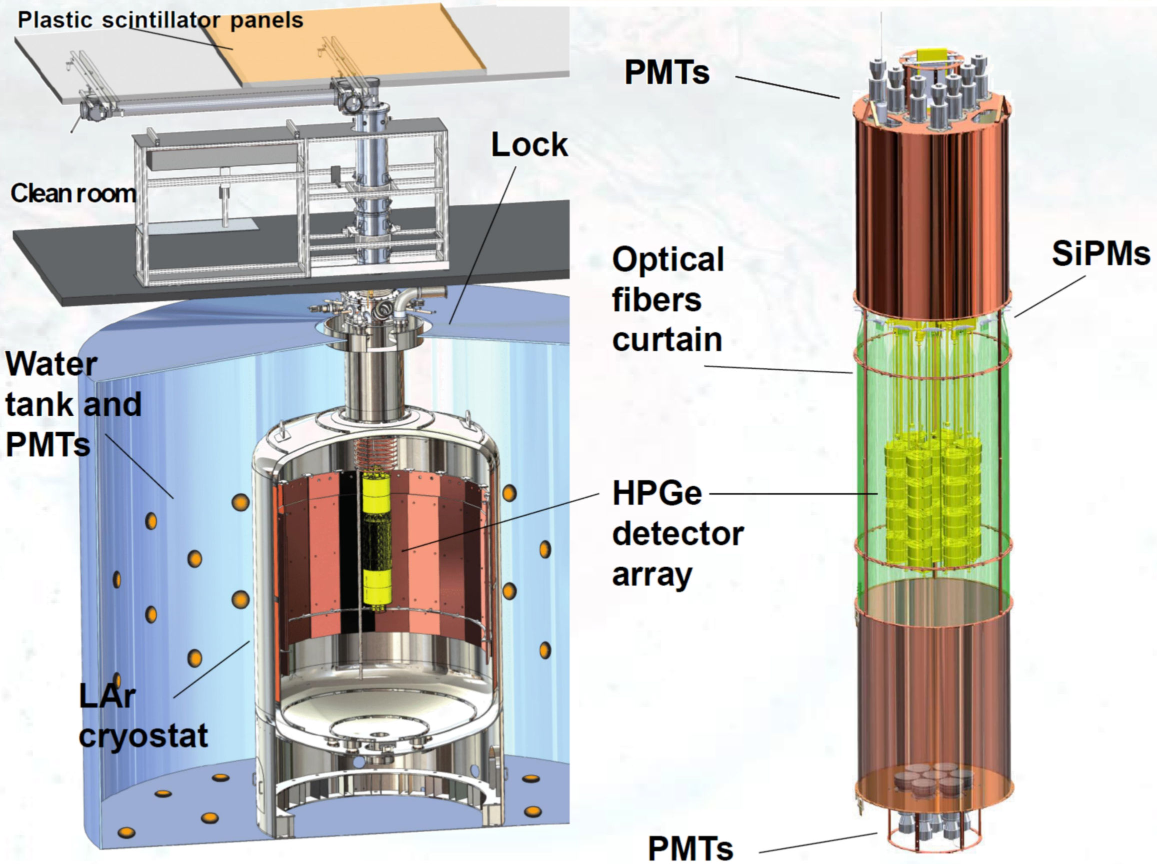
PRL 130 062501 (2023)

GERDA experiment

- GERmanium Detector Array (INFN-LNGS, Italy)
- 44.2 kg of Ge detectors
- Hybrid LAr light collection system: WLS fibers / SiPMs / PMTs
- Muon veto: water Cherenkov, scintillating panels
- Ultra radio-pure materials, small passive mass, deep underground

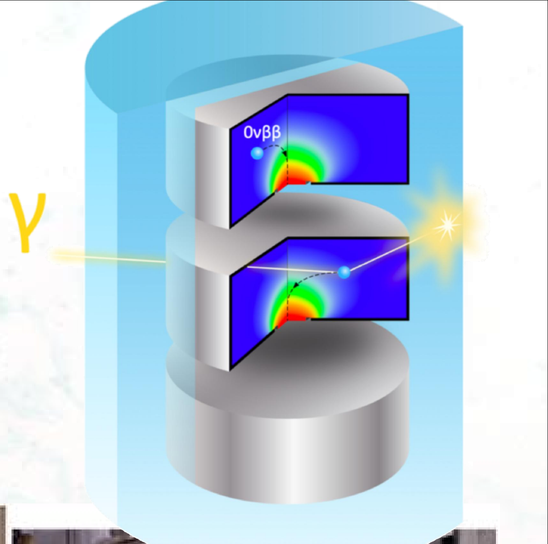


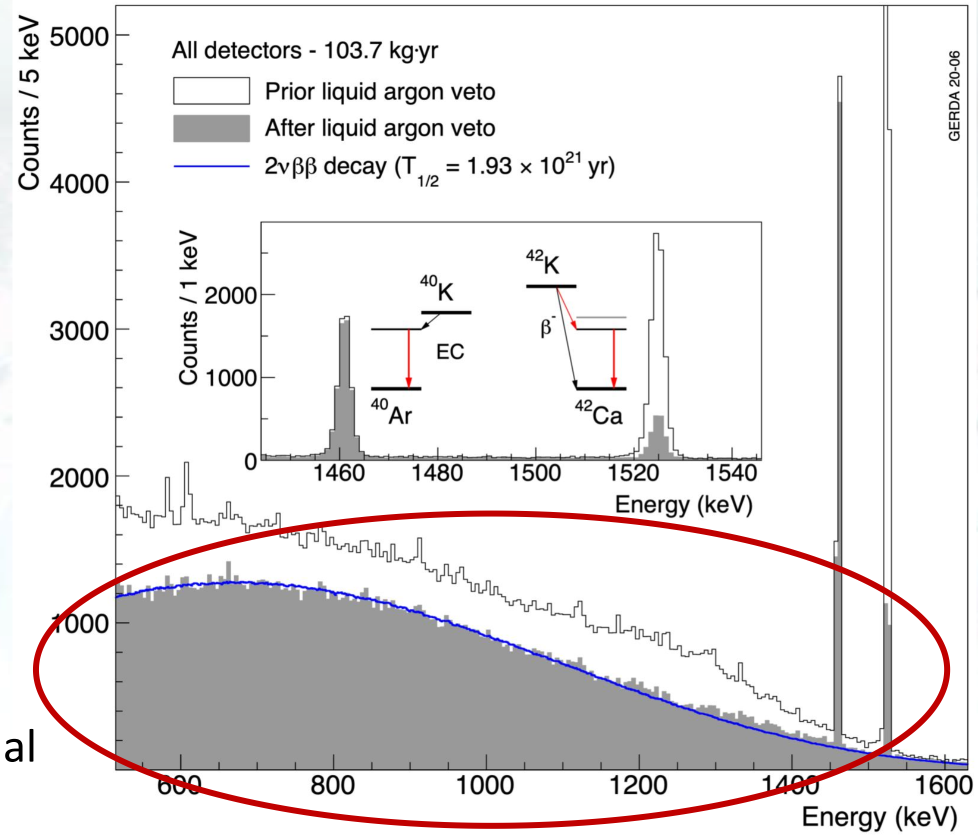
Hall A of the Gran Sasso Laboratory, INFN



LAr active veto

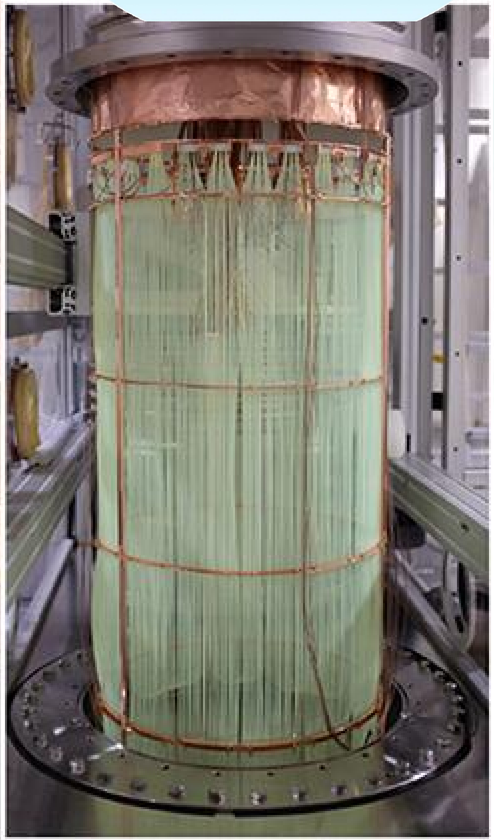
- Extremely efficient rejection of Compton events with energy deposition in LAr





Pure 2ν2β spectrum after LAr signal rejection

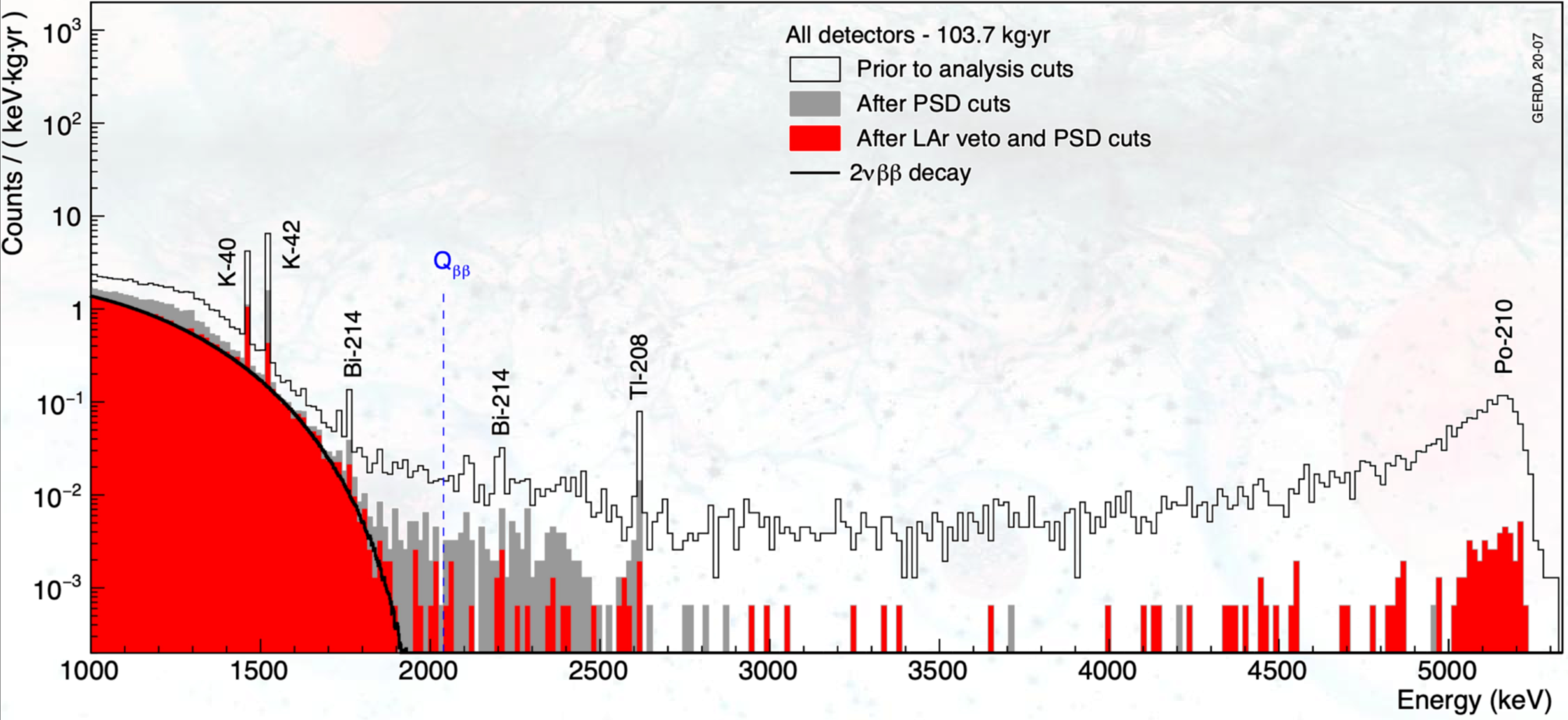
https://www.nature.com/articles/nature21717



Final result of GERDA

- **Best background index** among all experiments:

Background index: =$(5.2^{+1.6}_{-1.3})$ x 10^{-4} cts/(keV kg yr)



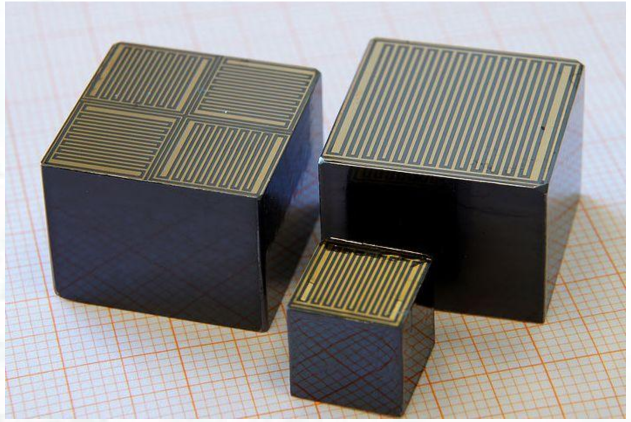
Energy resolution ~3 keV

$T_{1/2} > 1.8 \times 10^{26}$ yr at 90% C.L.

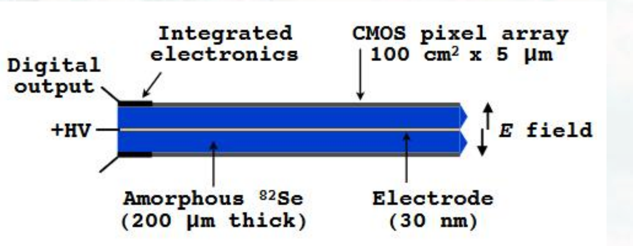
Not the strongest limit on m_{bb} mainly due to low phase space factor and limited exposure

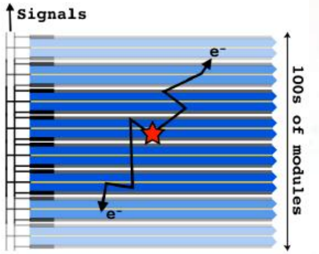
PRL 125, 252502 (2020)

R&Ds with solid state detectors



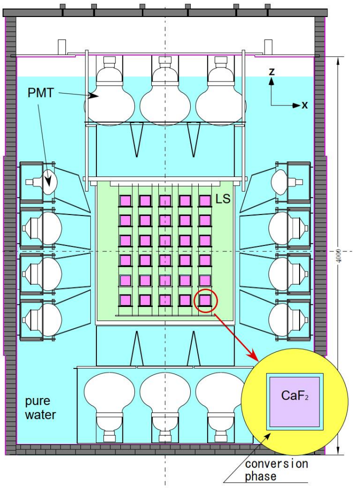
COBRA **CdZnTe detector technology**
- Several 2β isotopes – ^{116}Cd most promising
- Demonstrator: 64x1 cm^3 detectors
- Recent upgrade: 9x 2x2x1.5 cm^3 detectors





JINST 12 (2017) P03022

SELENA: **Amorphous ^{82}Se x-ray detectors (0.2 mm thick)**
- Stack to achieve high density, high mass array
- 5 µm pixel size gives full track reconstruction
- Very promising for background control



CANDLES: CaF$_2$ crystal scintillators
- Limited energy resolution, 350 g of ^{48}Ca

Liquid scintillator detectors

☺Experience and know-how from neutrino oscillation experiments

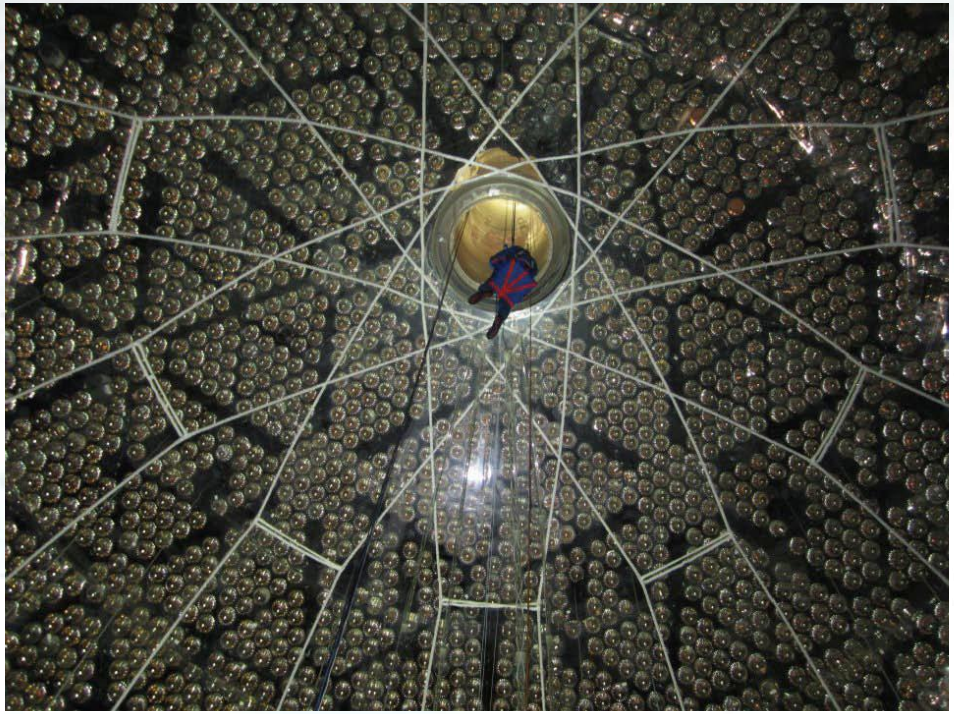
☺136-Xe in focus: reasonable $Q_{\beta\beta}$, gas is easy to handle in large amount - both for enrichment and detctor

☺The easiest scalability among all the DBD experiments

☺Nice feature: measurements before/after isotope loading - important for background evaluation

☹Caveat: large energy resolution - $2\nu2\beta$ background is dominant

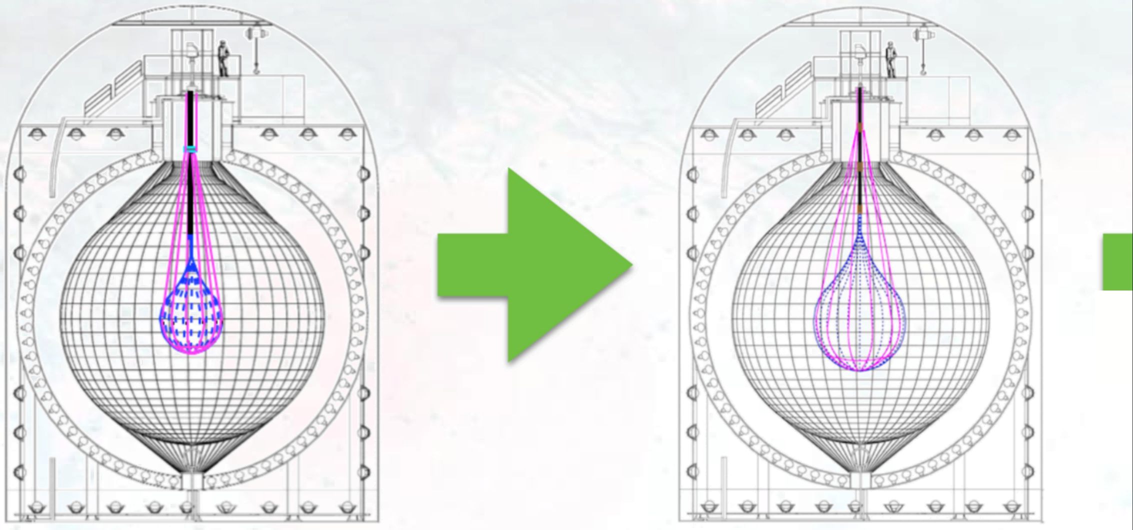
☹Good for limits, worse discovery

Kamland-ZEN

- Enriched Xenon diluted (3 wt%) in liquid scintillator exploiting the existing KamLAND detector with the addition of a nylon balloon
- Soluble to LS more than 3 wt%, easily extracted
- ^{136}Xe On-off
- Energy resolution: – 4.5%@Qbb
- Single event position –
  Vertex resolution 15 cm/√E(MeV)
- Backgrounds:
  - $2\nu\beta\beta$ decay of ^{136}Xe
  - Xe-LS, IB and outer-LS radioactive impuritities
  - Cosmogenic: muon-spallation
  - Solar neutrino ES

Past **Present**



KamLAND-Zen 400

Nylon balloon R 1.54 m

Xenon 320 − 380 kg

KamLAND-Zen 800

Nylon balloon R 1.90 m

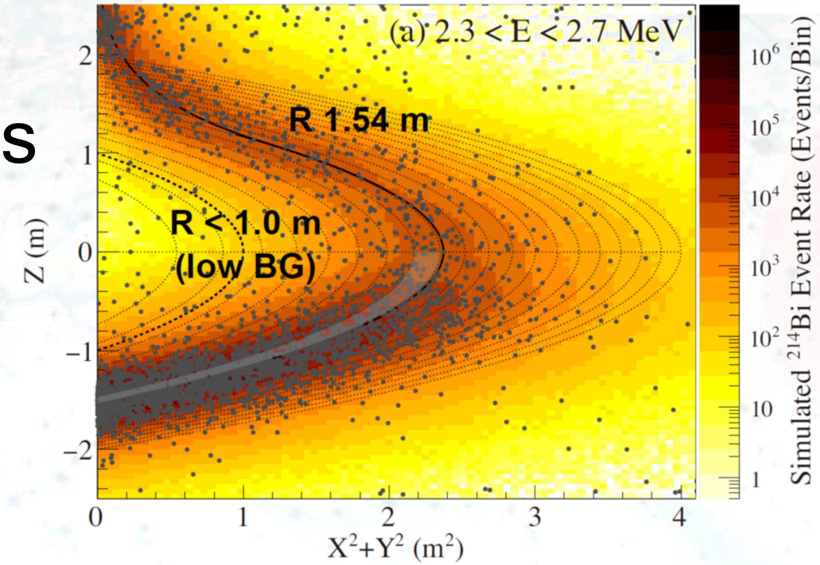
Xenon 745 kg

Nylon baloon: background improvement

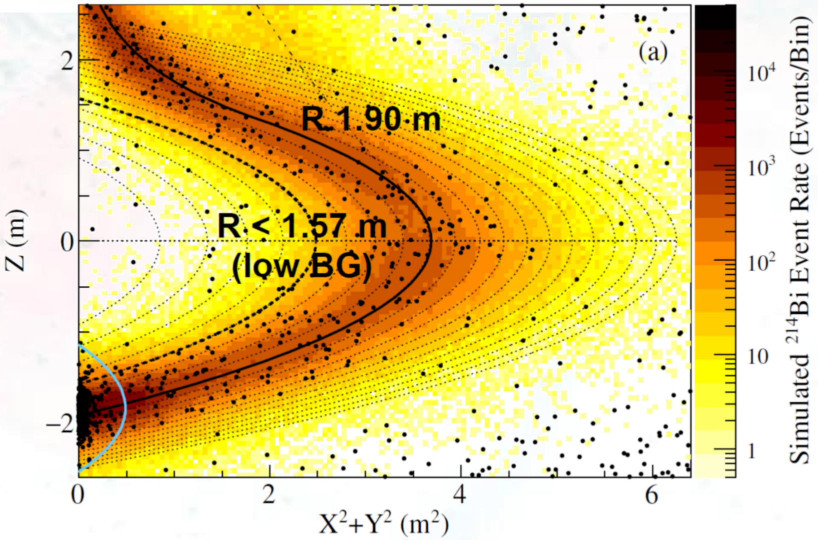
- Increase of sensitive volume by factor 3!
- ×10 reduction of IB ^{214}Bi
- Good example of radiopurity requirements

KamLAND-Zen 400

KamLAND-Zen 800



sensitive volume : R < 1.0 m

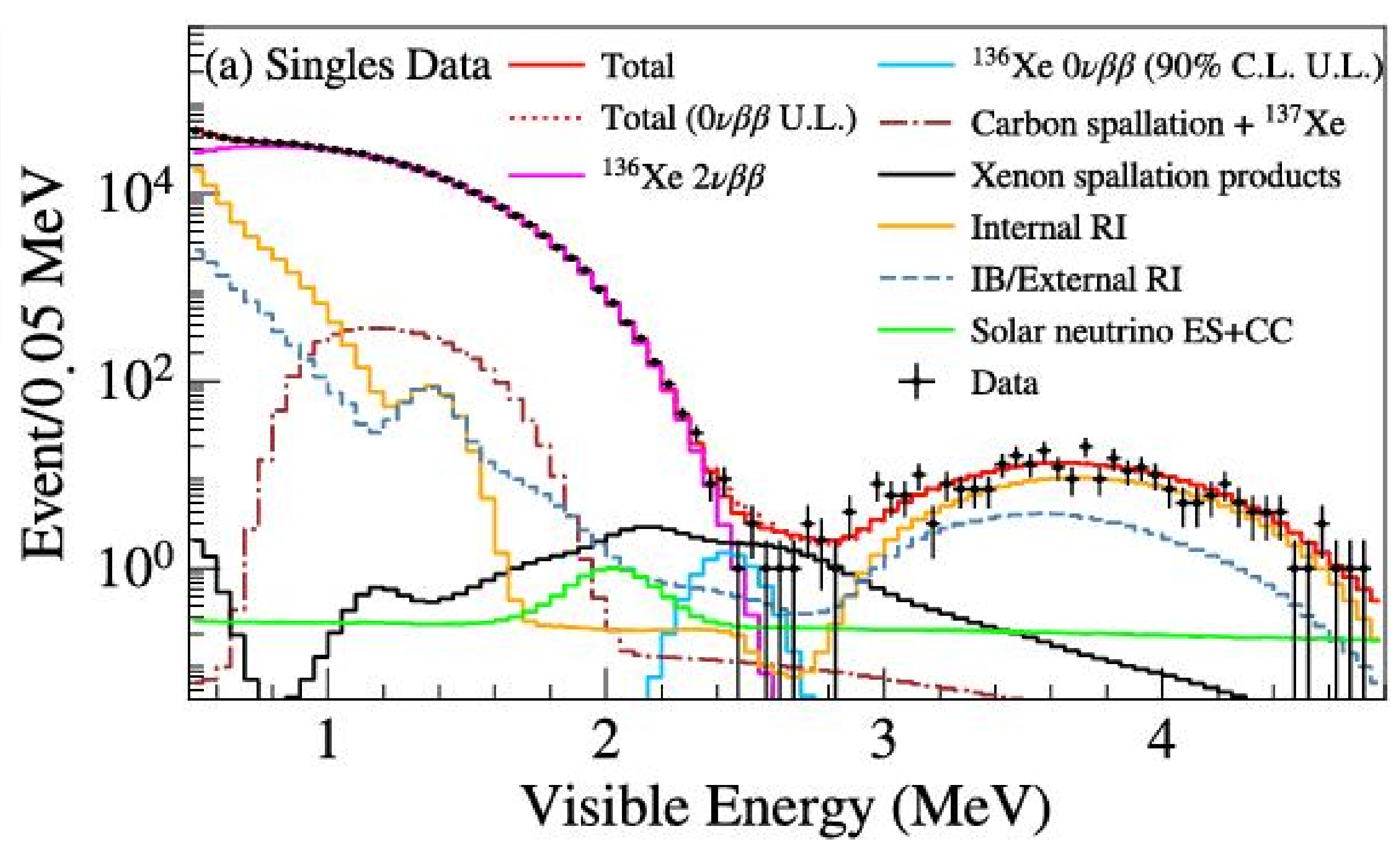


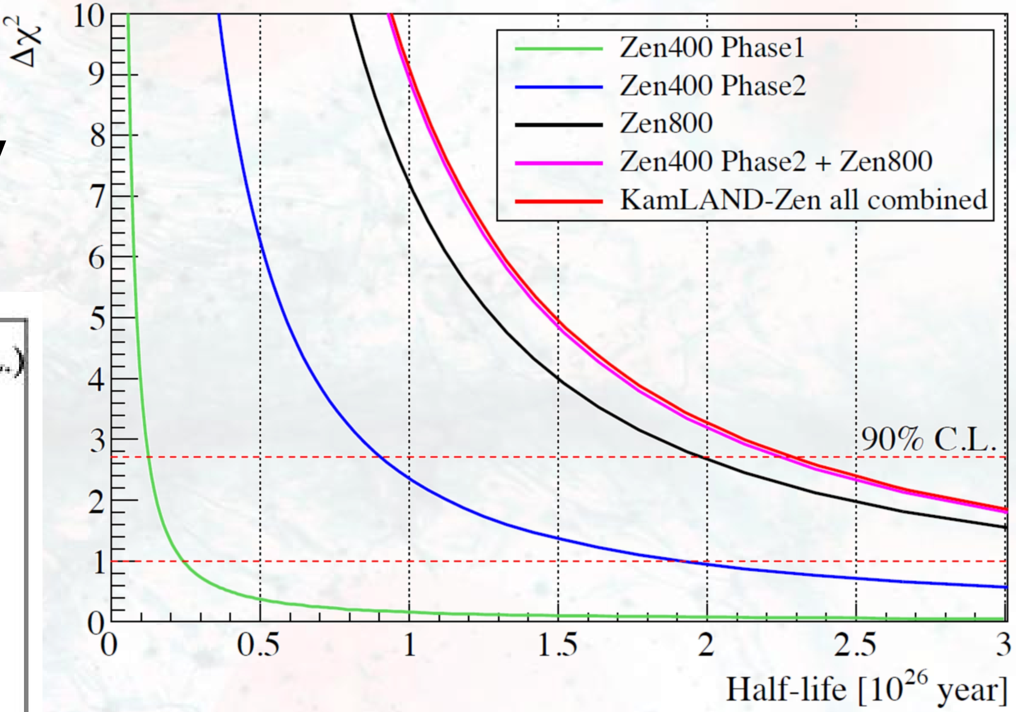
sensitive volume : R < 1.57 m

> ×3 sensitive volume !!

KamLAND-Zen final results

- Exposure: 970 kg×yr
- Best limit on $m_{\beta\beta}$ sensitivity: 36-156 meV





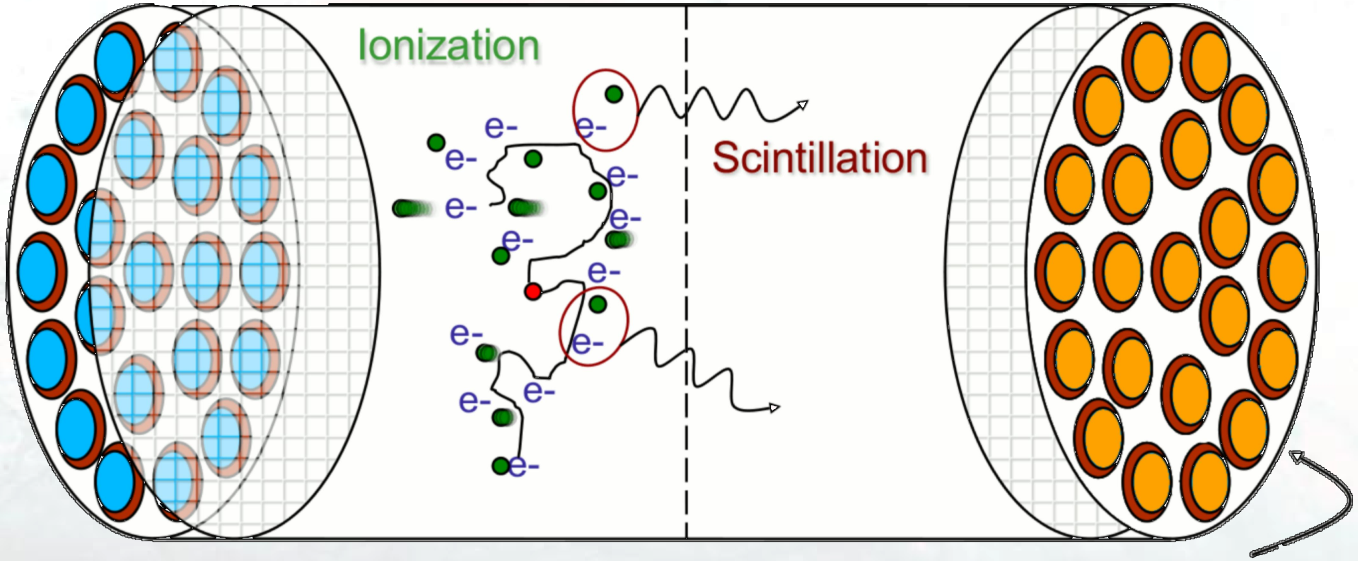
$$T^{0\nu}_{1/2} > 2.3 \times 10^{26}\ \mathrm{yr}$$

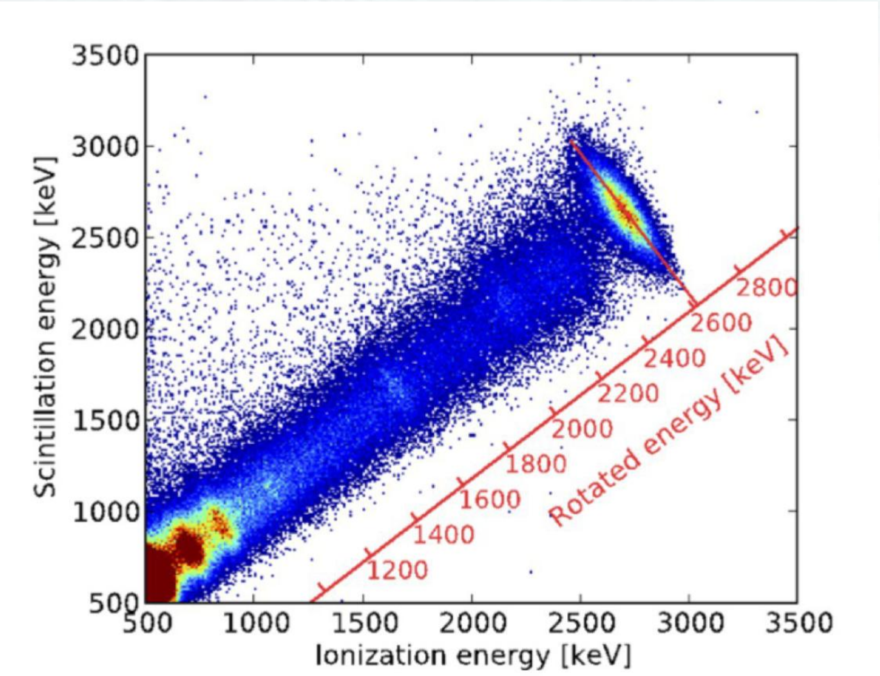
EXO-200

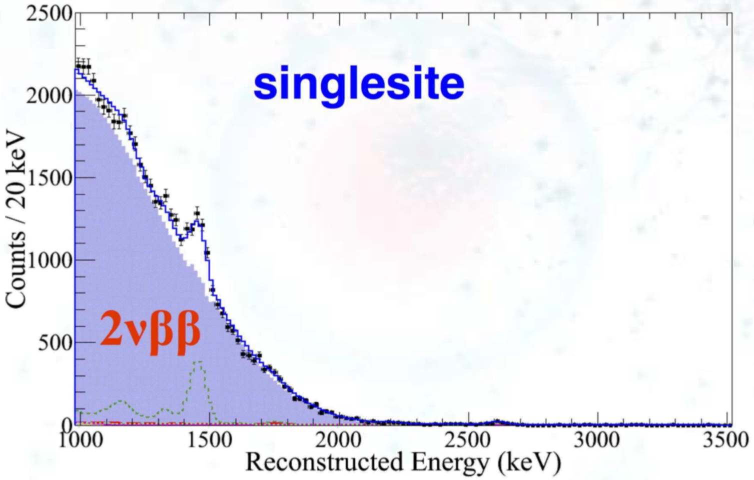
- Enriched liquid ^{136}Xe TPC
- First to detect $2\nu2\beta$ of ^{136}Xe

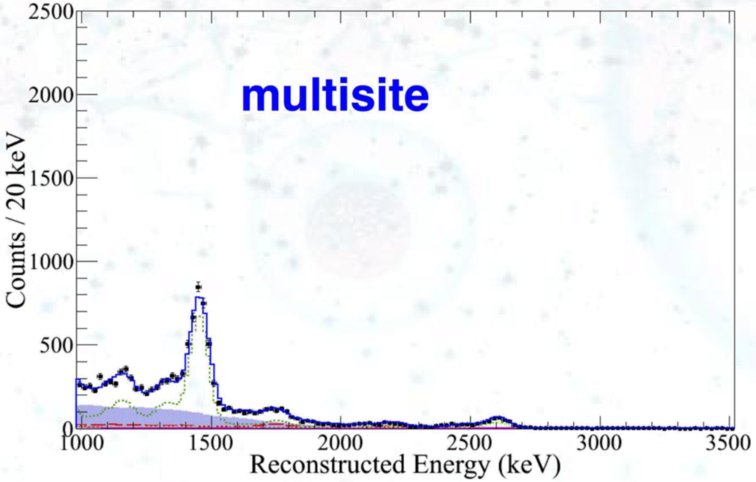
Discrimination between:

- **Multi-site (MS)** (background)
- **Single-site (SS)** (including signal events)



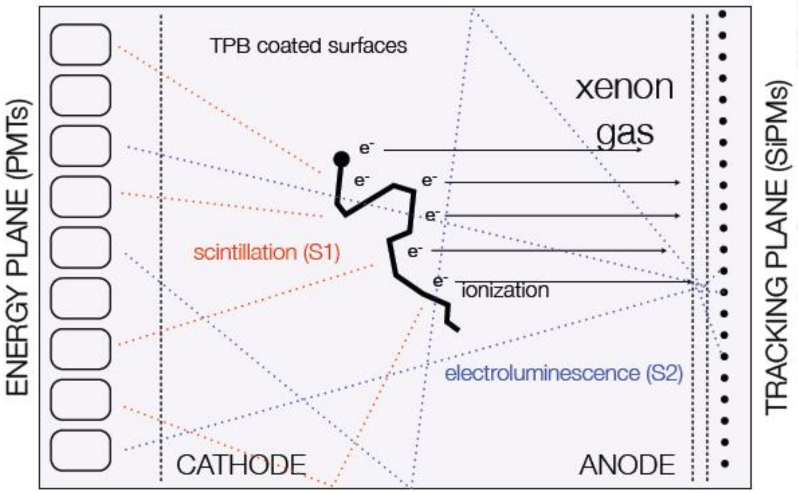


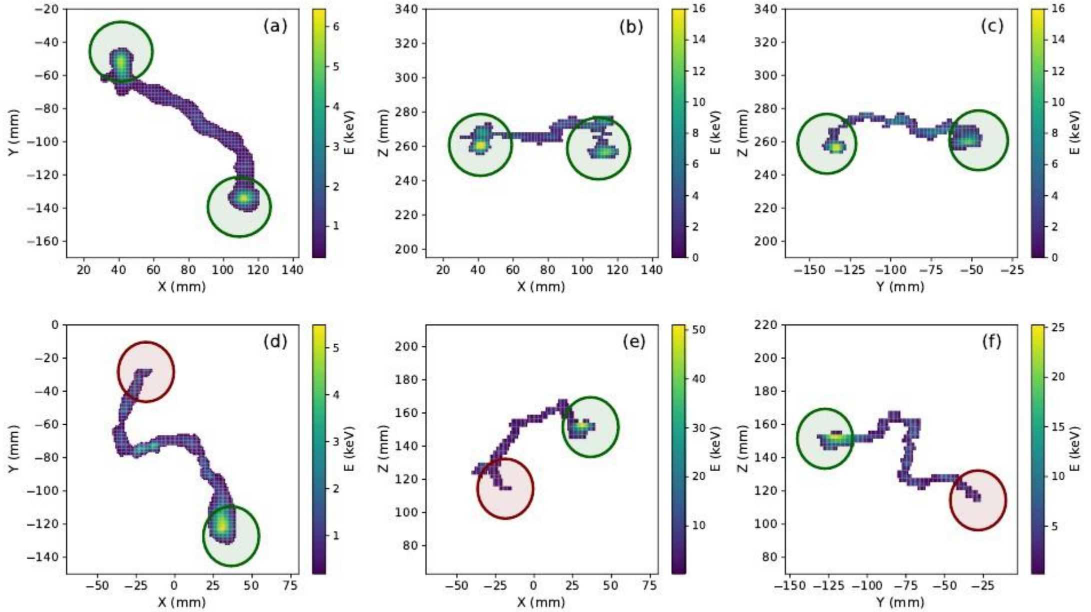




NEXT

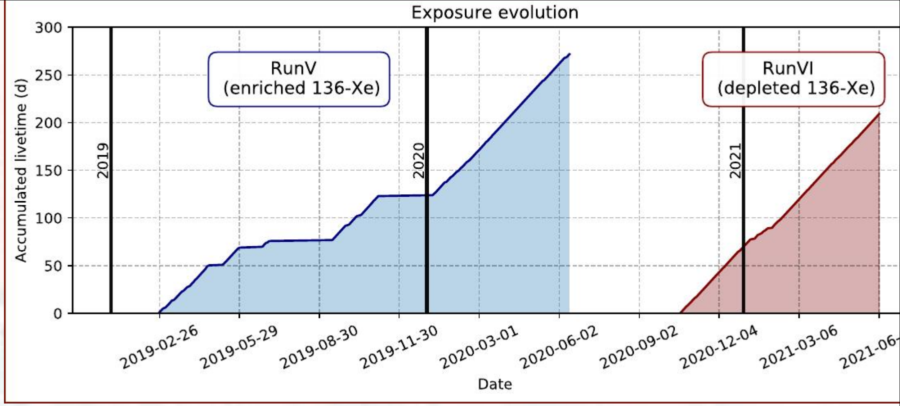
- **High pressure (10-15 bar) enriched Xe TPC**
  - Primary scintillation ($t_0 \rightarrow z$ coordinate)
  - Electroluminescence for en. res. (PMT plane) and for tracks (SiPM plane)
  - **ΔE < 1% FWHM** in the ROI (< 25 keV)
  - Very clear topological signature

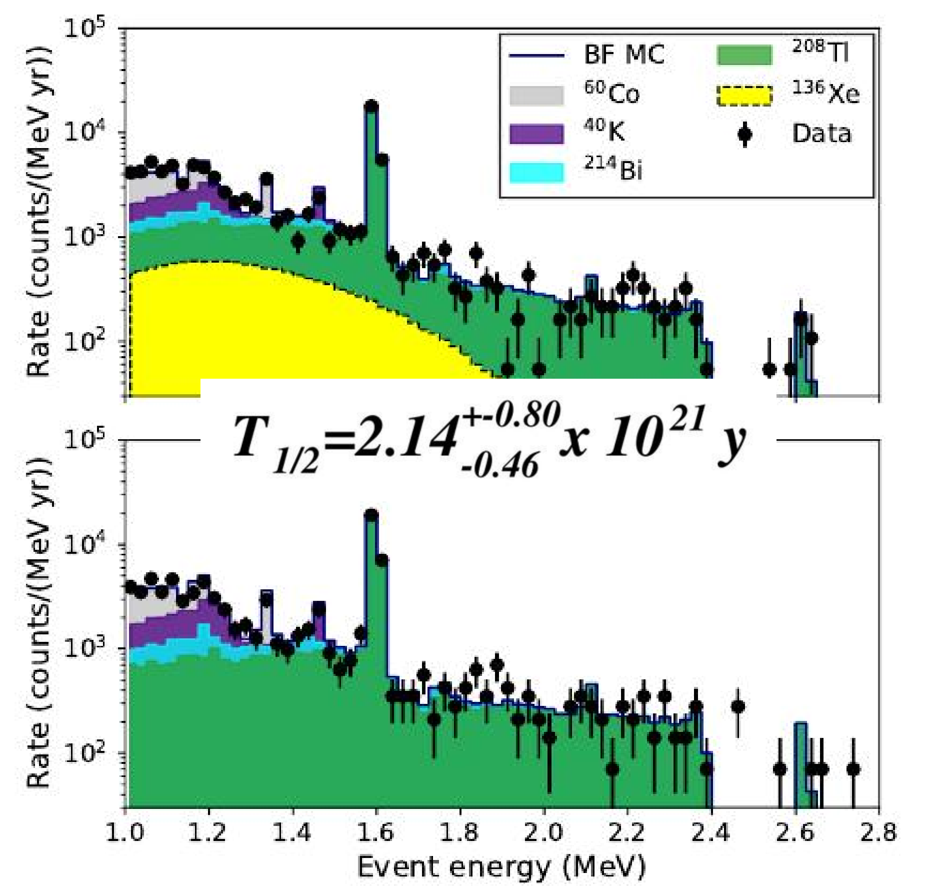




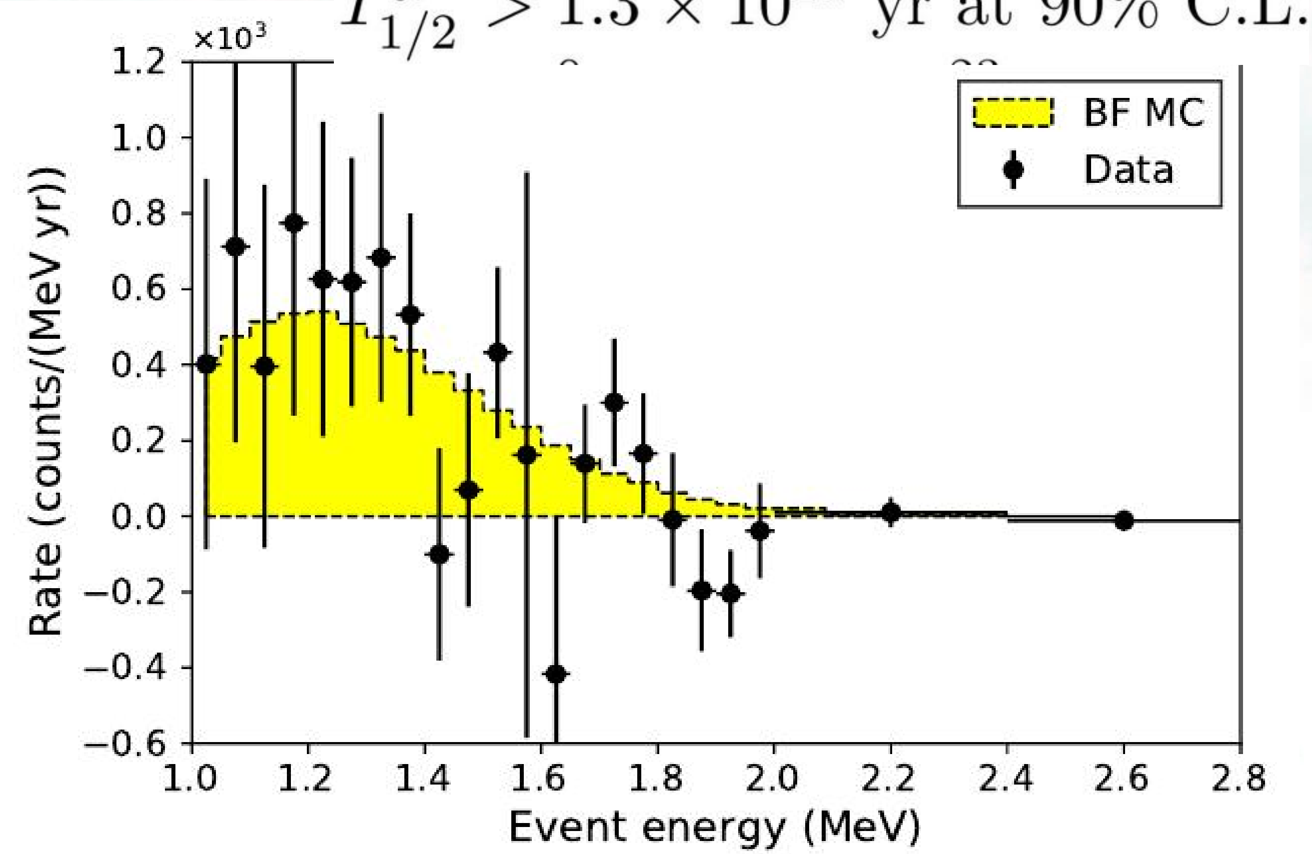
NEXT: on/off runs

- Measurements with enriched and depleted Xe
- Low exposure, but principle demonstrated - next phase NEXT-100 starting





$T_{1/2}=2.14^{+-0.80}_{-0.46}\, x\ 10^{21}\ y$

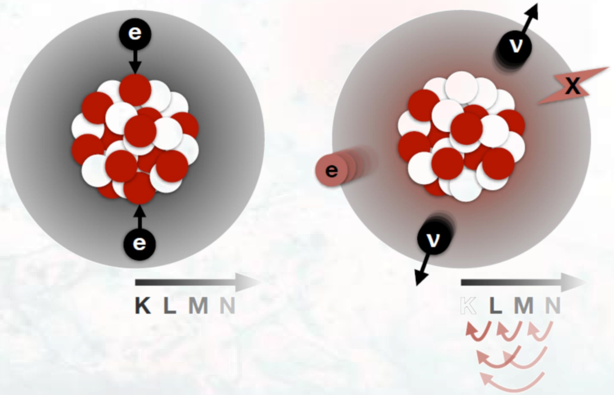


$$T^{0\nu}_{1/2} > 1.3 \times 10^{24} \text{ yr at } 90\% \text{ C.L.}$$

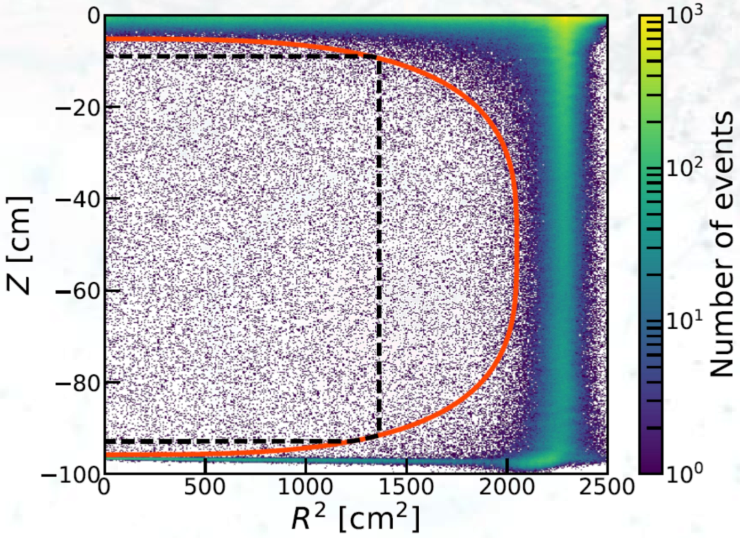
Phys.Rev.C 105 (2022) 5, 055501

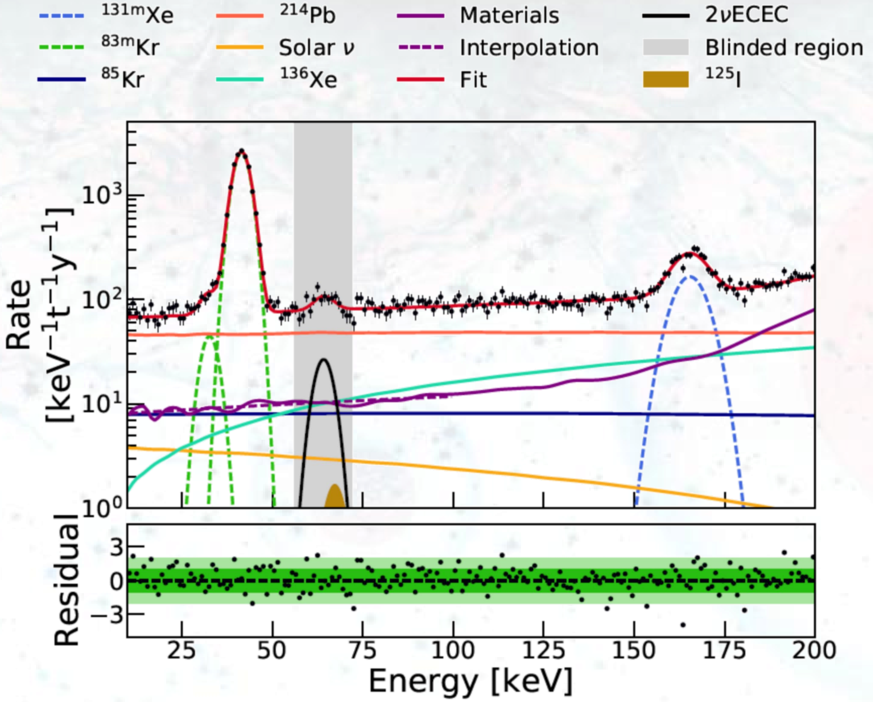
XENON-1t: observation of ECEC

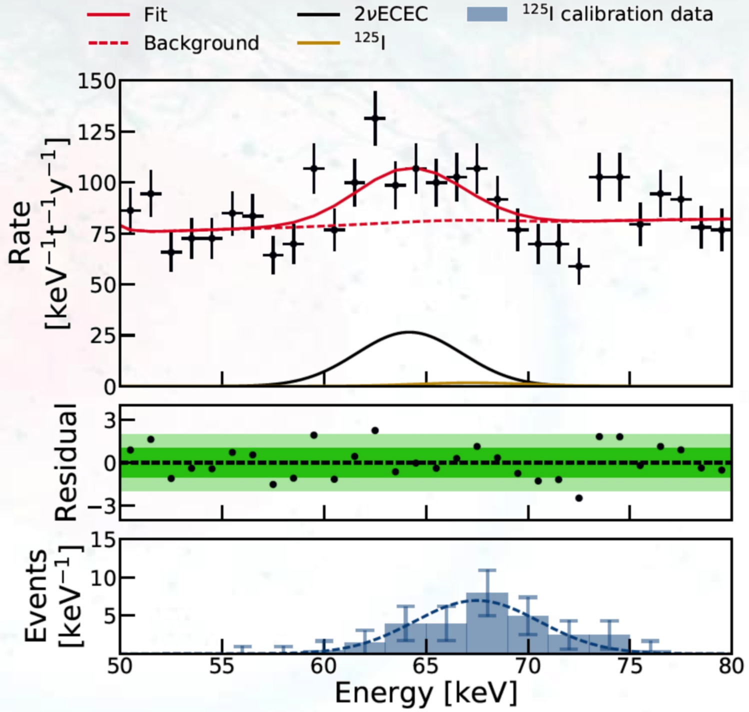
- Detector built for Dark Matter searches with Xe TPC
- 3.2 t of natural Xe, ^{124}Xe for ECEC



$$T_{1/2}^{2\nu\mathrm{ECEC}} = (1.8 \pm 0.5_{\mathrm{stat}} \pm 0.1_{\mathrm{sys}}) \times 10^{22}\ \mathrm{y}$$







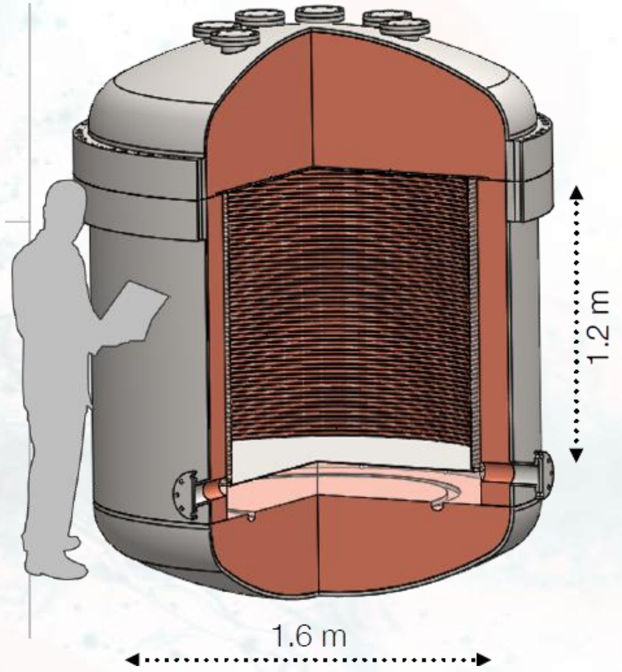
Nature 568, p.532-535, 2019

Other projects with Xe

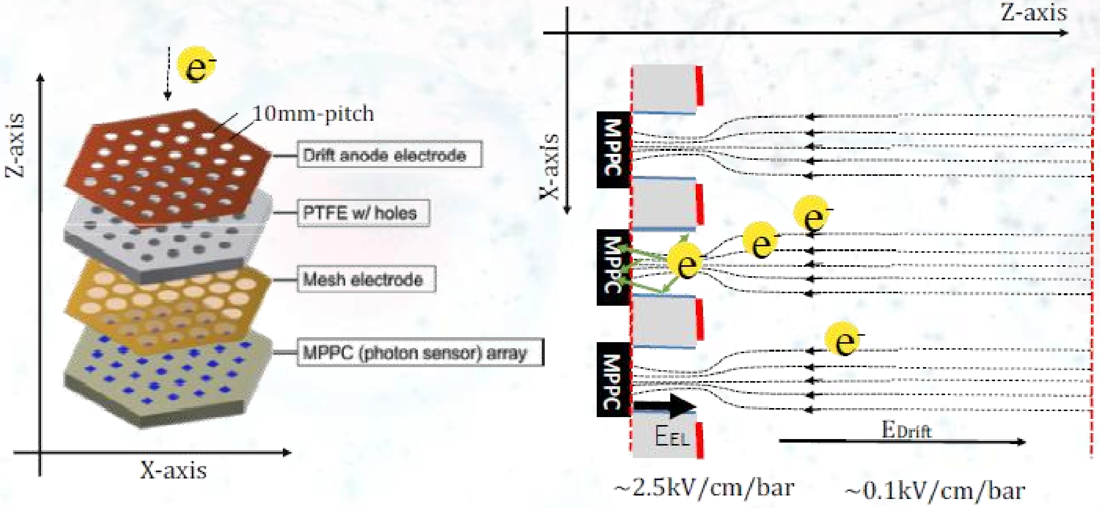
TPCs with variants:

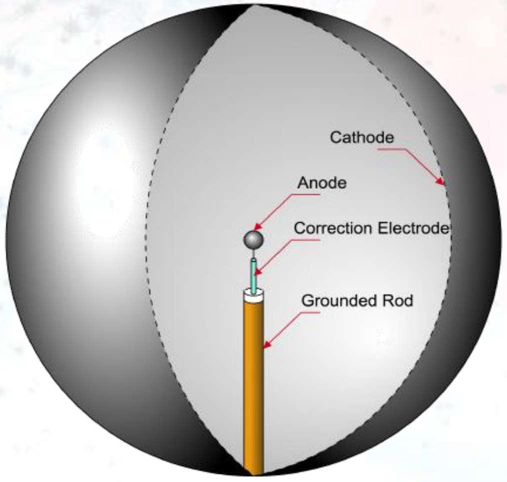
- PANDA-X-III – electron collection
- AXEL – electroluminescence (EL)
- R2D2: high pressure spherical/cylindrical TPC

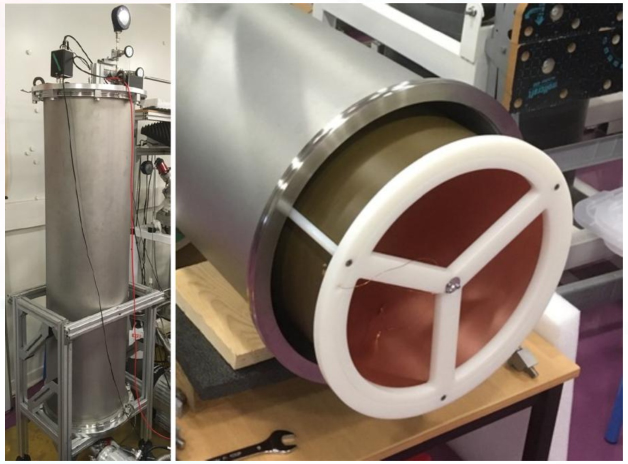
PANDA-X-III



Electroluminescence Light Collection Cell
(ELCC)







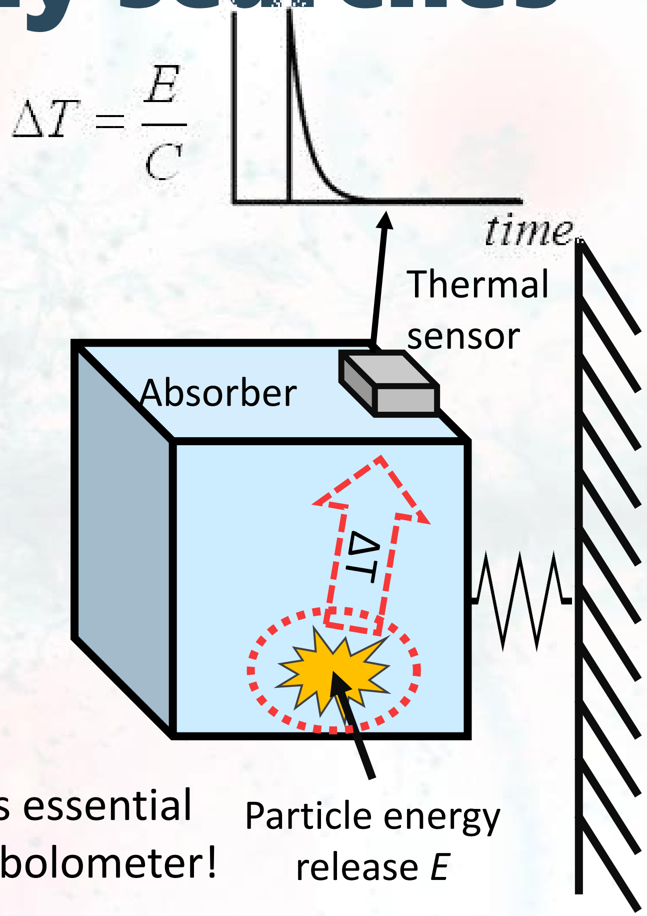
Bolometers for double beta decay searches

- Measurement of radiation via temperature change
- Requires very low temperatures of operation to detect this change (~10-100 mK)
- The change itself is defined by heat capacity and released energy:

$$\Delta T = \frac{E}{\boxed{C}}$$

$$\boxed{C_r(T)} = \frac{12\pi^4}{5} N_A k_b \left(\frac{T}{\Theta_D}\right)^3$$

Debye law for dielectrics

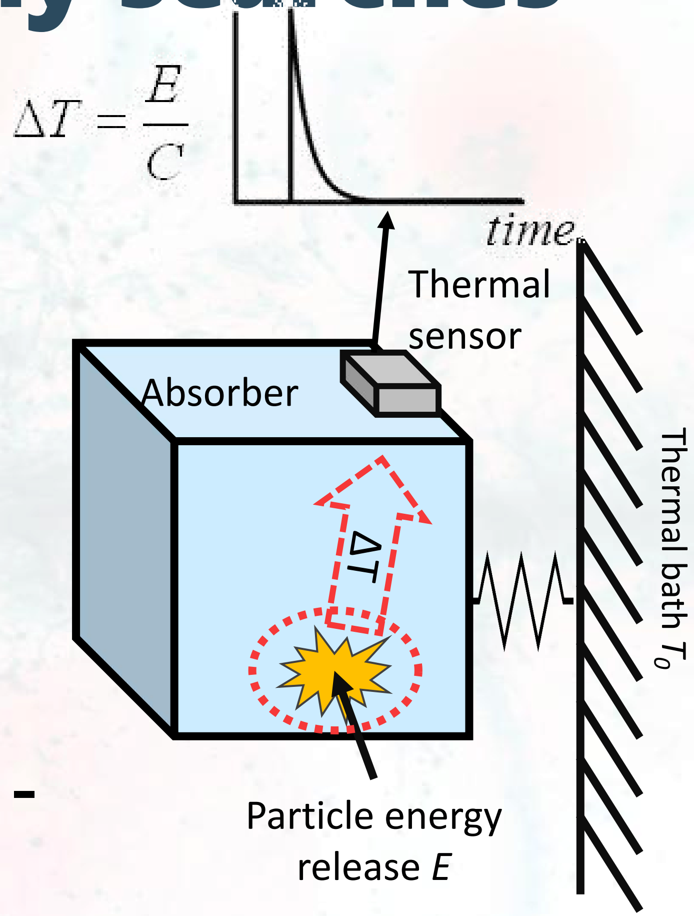


Low heat capacity is essential for building a good bolometer!

Bolometers for double beta decay searches

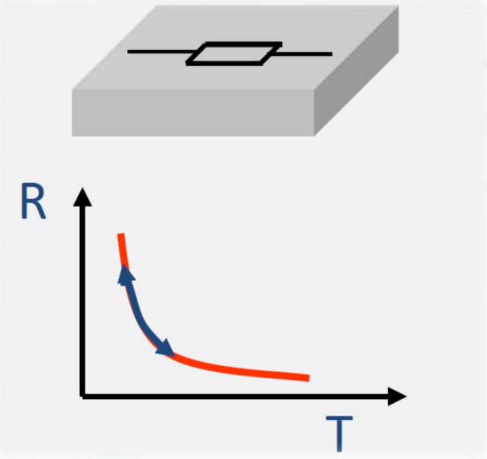
- ☺High energy resolution
- ☺Flexibility in the absorber materals
- ☺Advanced technologies for particle identification
- ☺Scalable through arrays

- ☹Slow detectors (depending on sensor type)
- ☹Detector size restricted by the size of the cryostat - scaling is not obvious

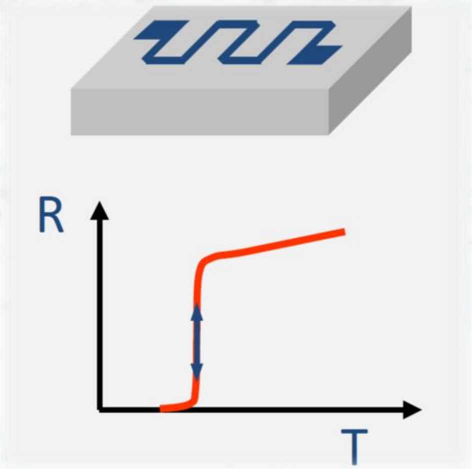


Typical sensors

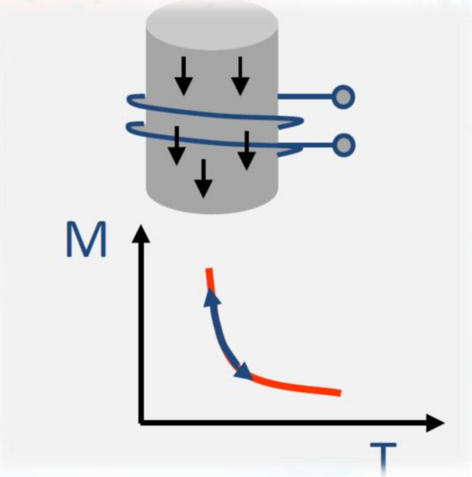
- What do we need?
- Large change of “X” parameter depending on temperature
- Low heat capacity (absorber is dominant)
- Speed of signal depends on the type of phonons we are sensitive to



Neutron Transmutation Doped sensors



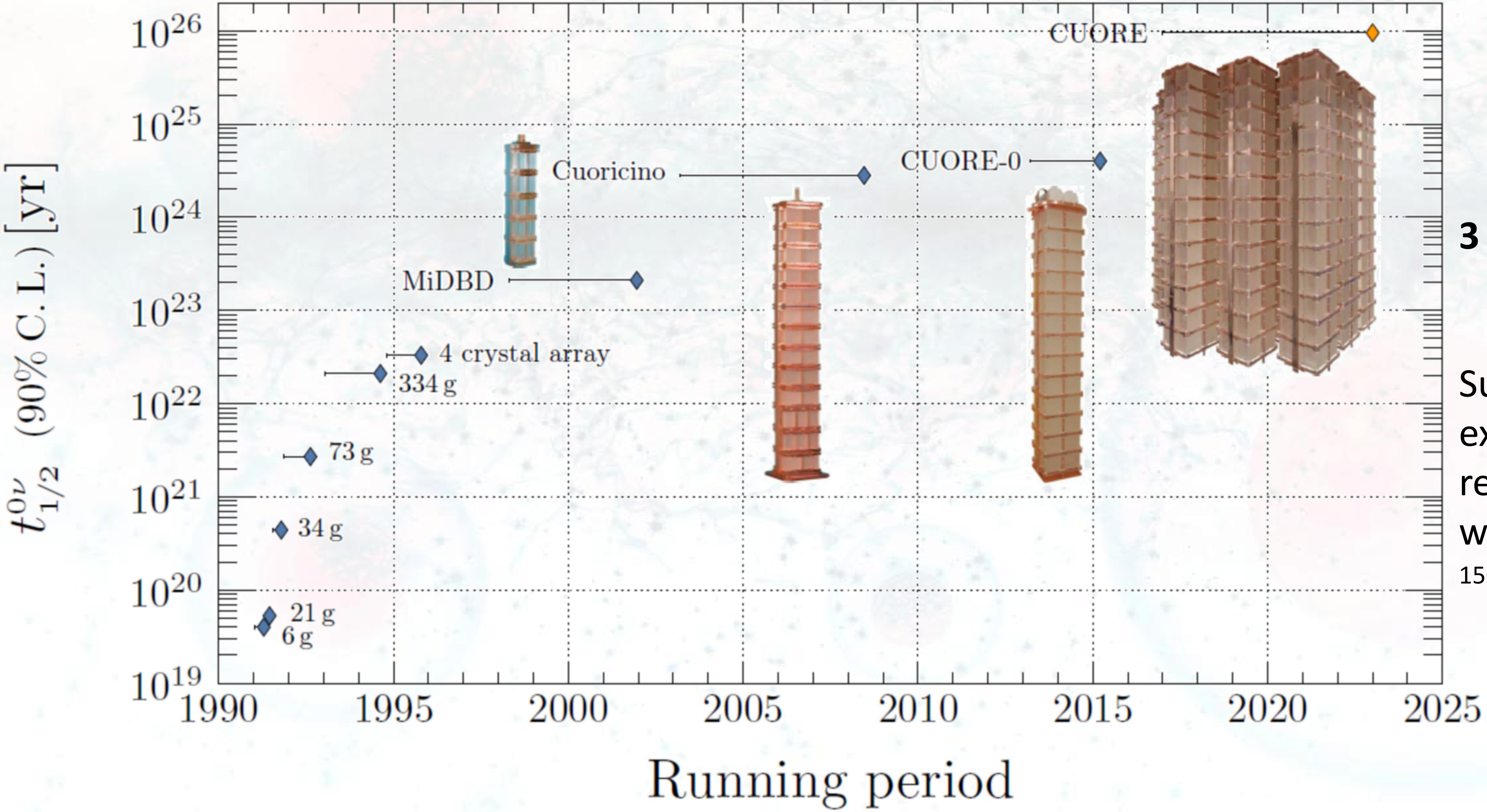
Transition Edge sensors



Metallic Magnetic Calorimeters

From 6g to 1t

- Significant progress since 1990 in cryogenic detectors: stability, size, performance, reproducibility

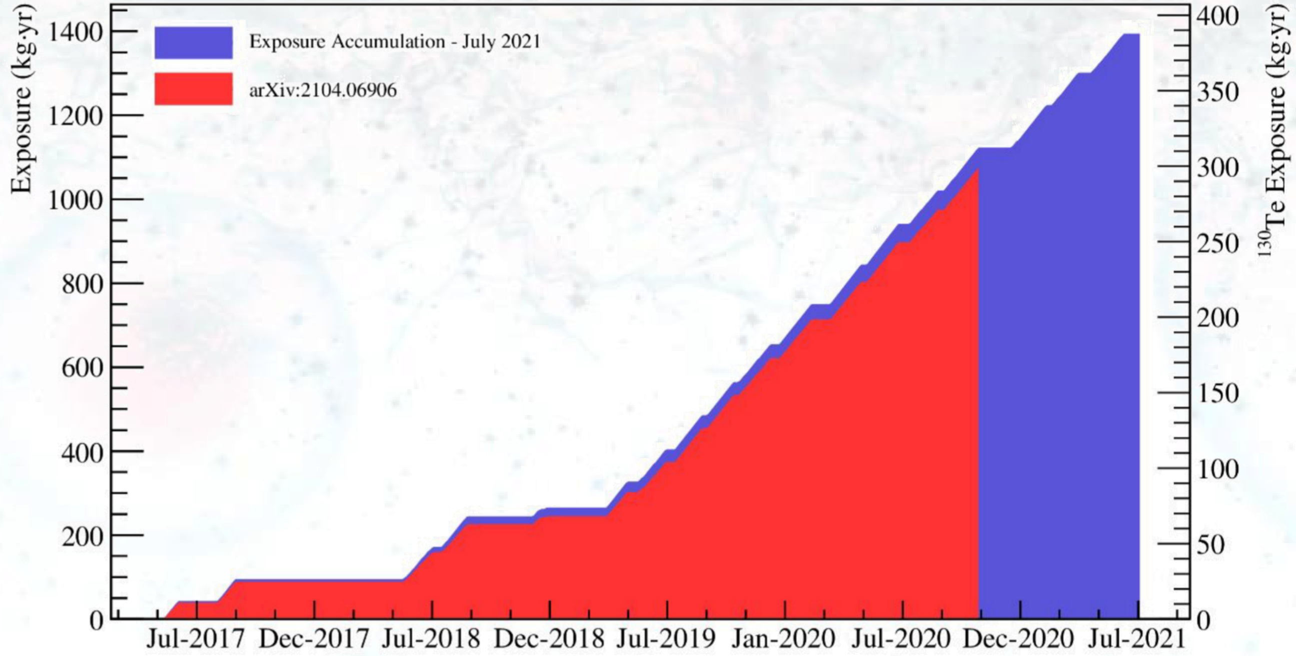


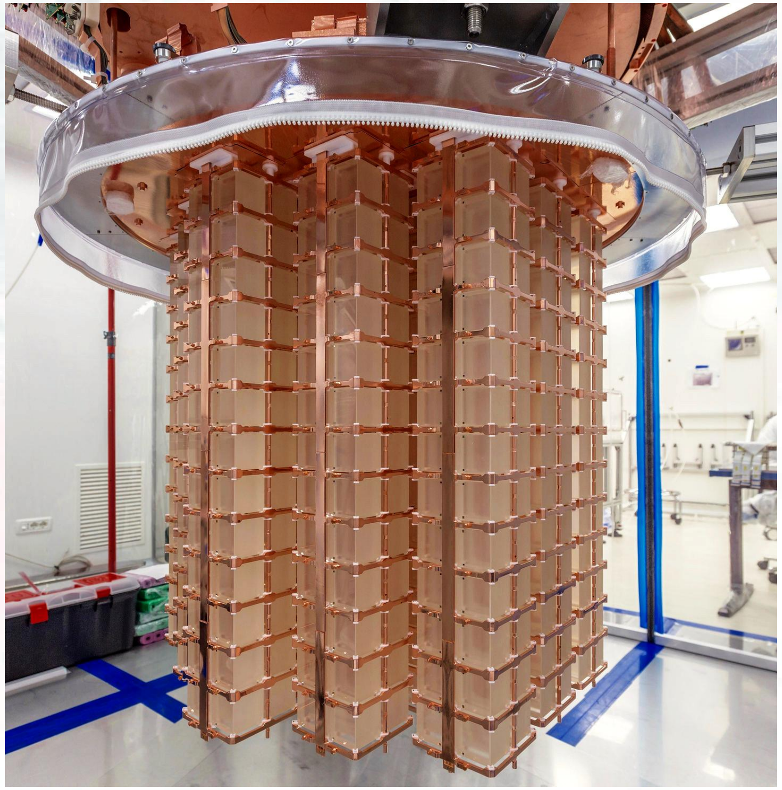
3 out of 5 leading results

Suitable to study 7/9 experimental relevant isotopes - with the 2 remaining (^{96}Zr, ^{150}Nd) being investigated

CUORE: the largest bolometric experiment

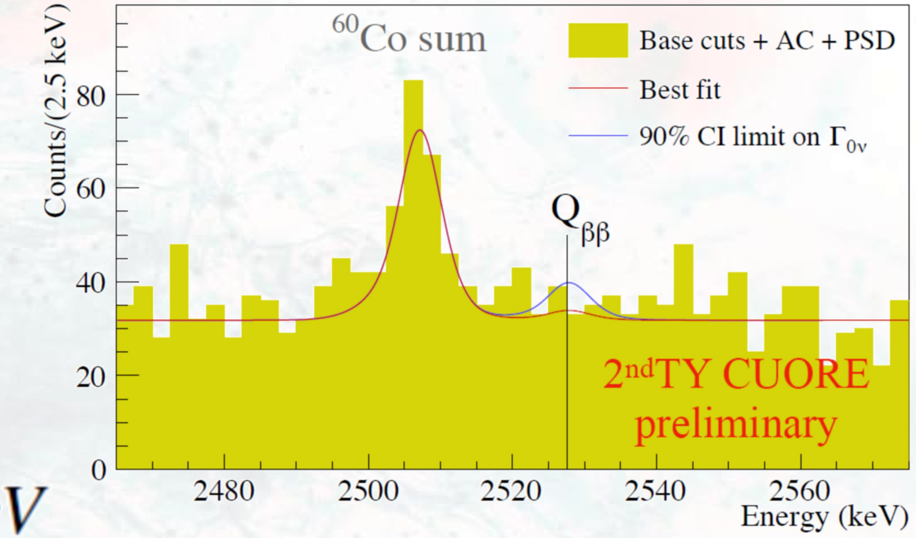
- **CUORE:** the Cryogenic Underground Observatory for Rare Events
- **First ton scale** array of cryogenic calorimeters: **988 TeO_2 crystals** (0.75 kg each)
- CUORE cryogenic facility is an unprecendented techological challenge, which is now **taking data in steady and reliable conditions**





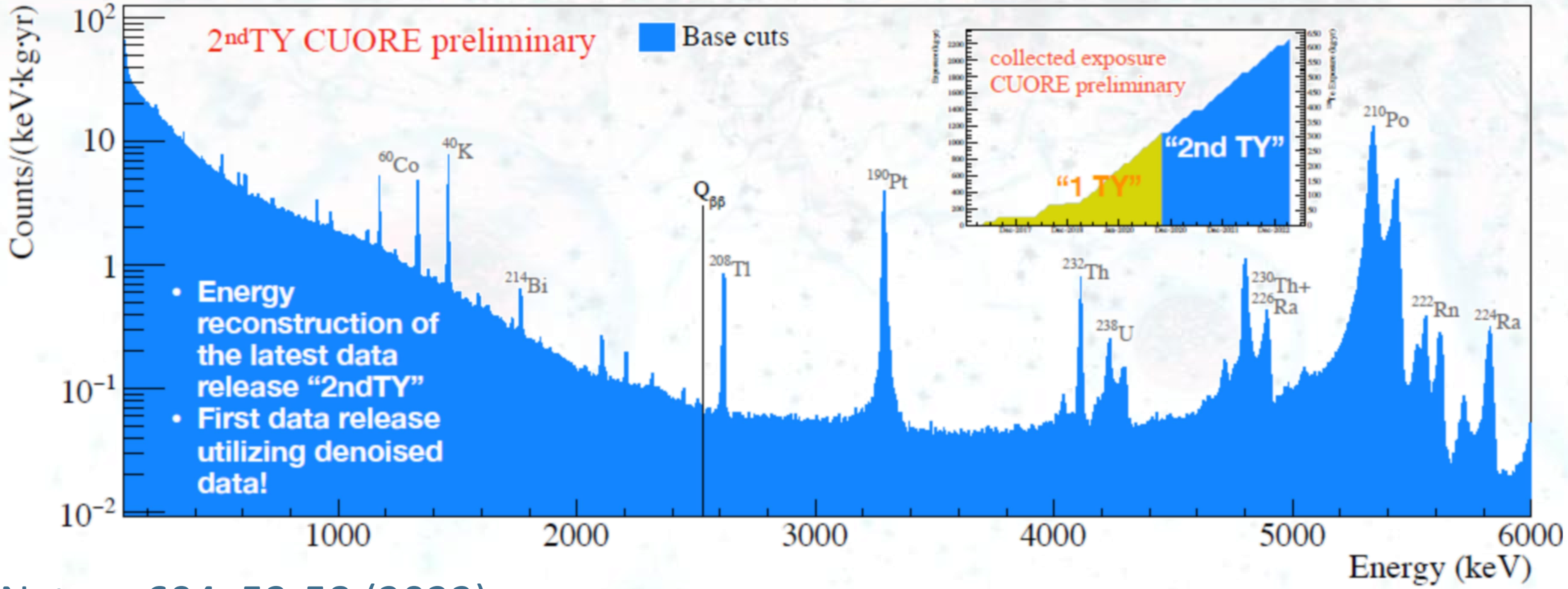
CUORE: the largest bolometric experiment

- Analyzed exposure: 2023 kg×yr
- $\Delta E_{\beta\beta}$=7.3±0.4 keV at ROI (0.3%)
- BI=1.30(3) × 10^{-2} counts/kev/kg/yr

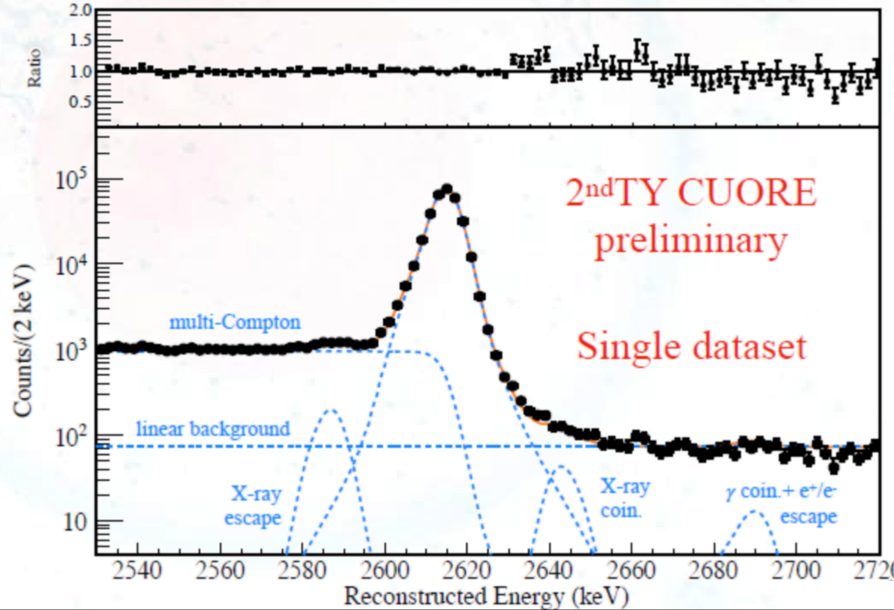


Half-life limit: $T^{0\nu}_{1/2} > 3.33 \times 10^{25}\, yr$ (90% C.I.)

Effective Majorana mass limit: $m_{\beta\beta} < 75 - 255\, meV$



- **Energy reconstruction of the latest data release "2ndTY"**
- **First data release utilizing denoised data!**



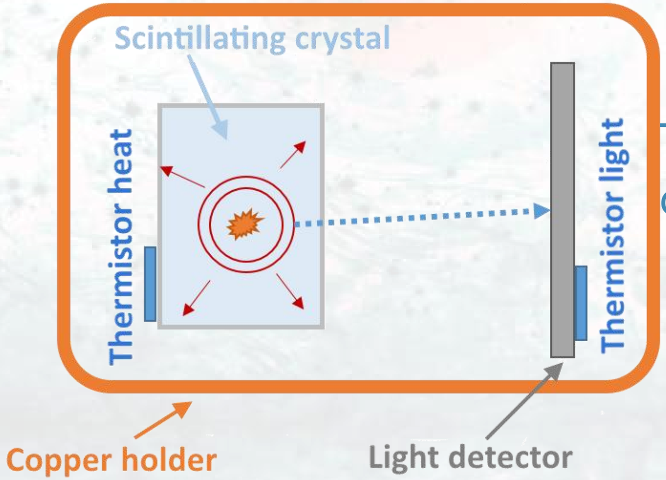
Nature 604, 53-58 (2022)

Particle discrimination with bolometers

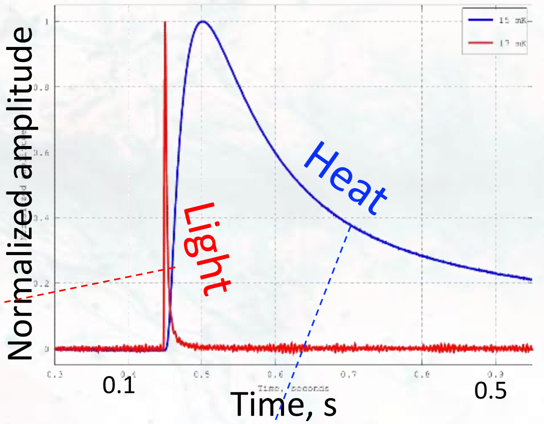
- Scintillation:

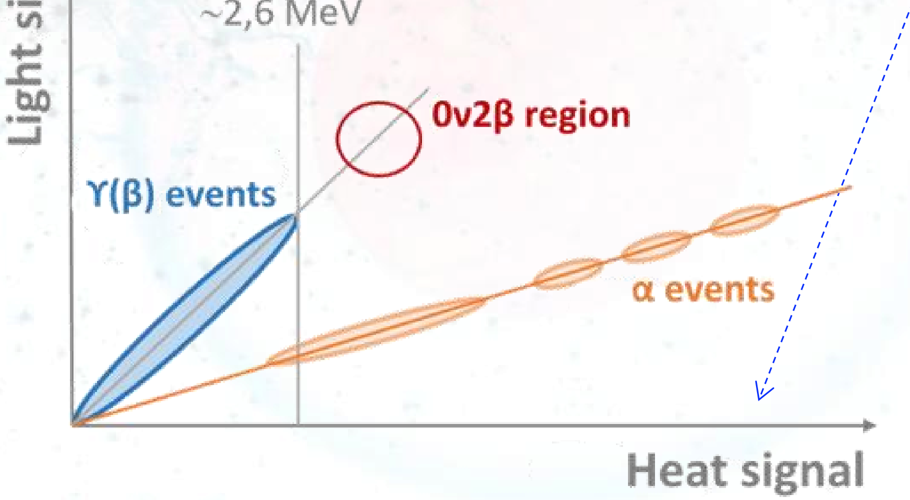
- Alphas and nuclear recoils emit in general a different amount of light with respect to beta/gamma of the same energy

- Particle **discrimination using light for** α rejection



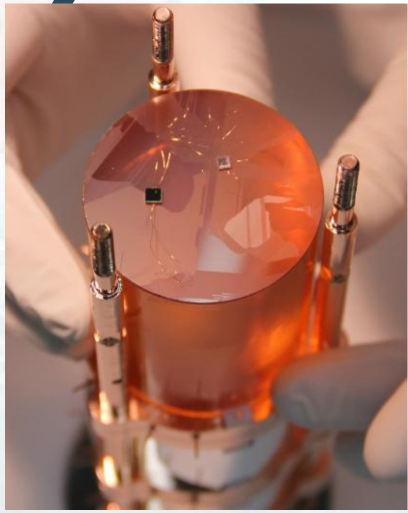
Typical signal**: 0.1 mK/MeV**, converted to **0.1-0.2 mV/MeV**

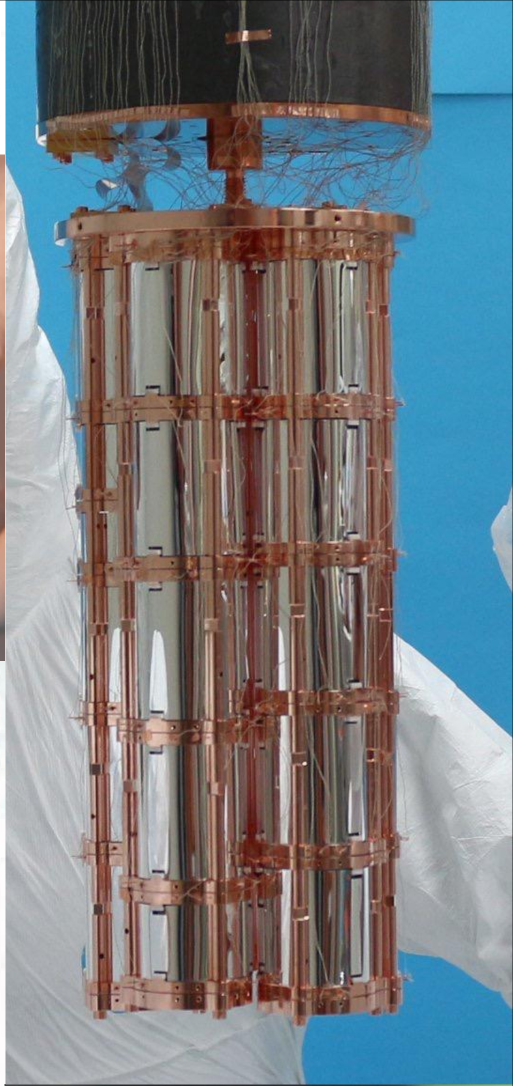


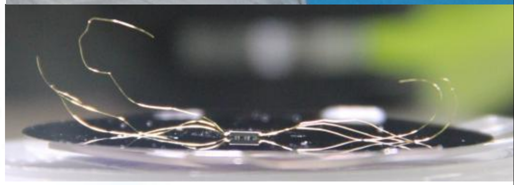


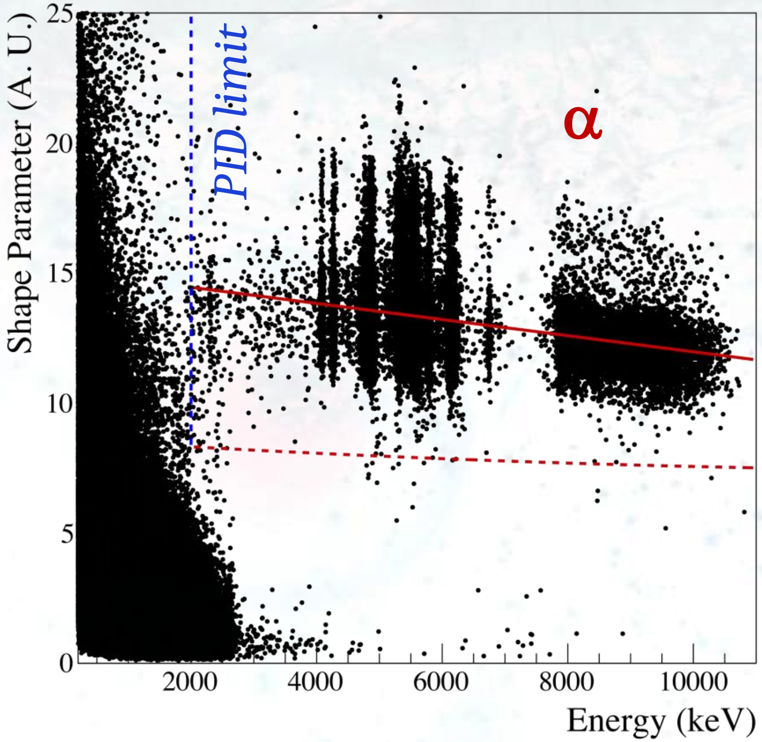
CUPID-0 demonstrator (^{82}Se)

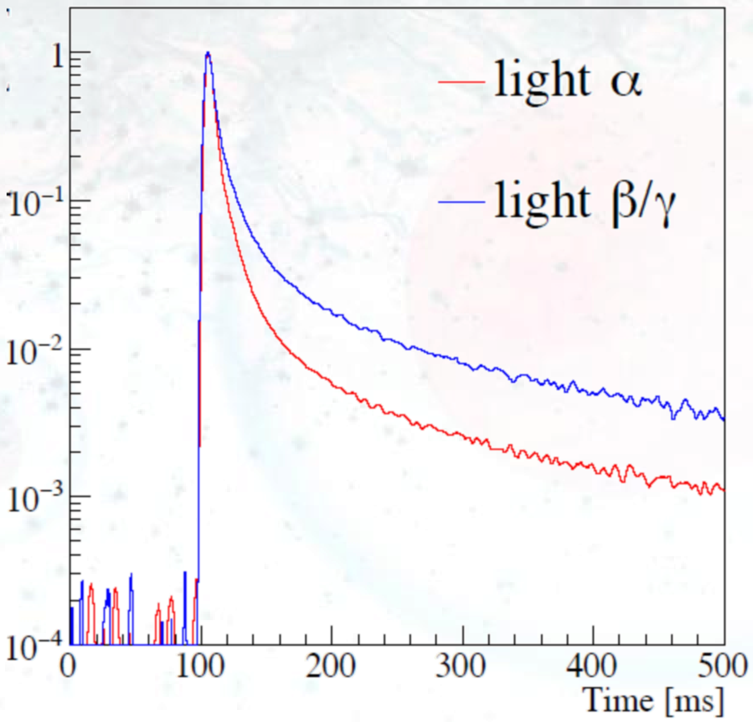
- The first pilot experiment for CUPID with scintillating bolometers in LNGS
- 95% enriched Zn^{82}Se bolometers (**5.17 kg of ^{82}Se, $Q_{\beta\beta}$=2998 keV**)









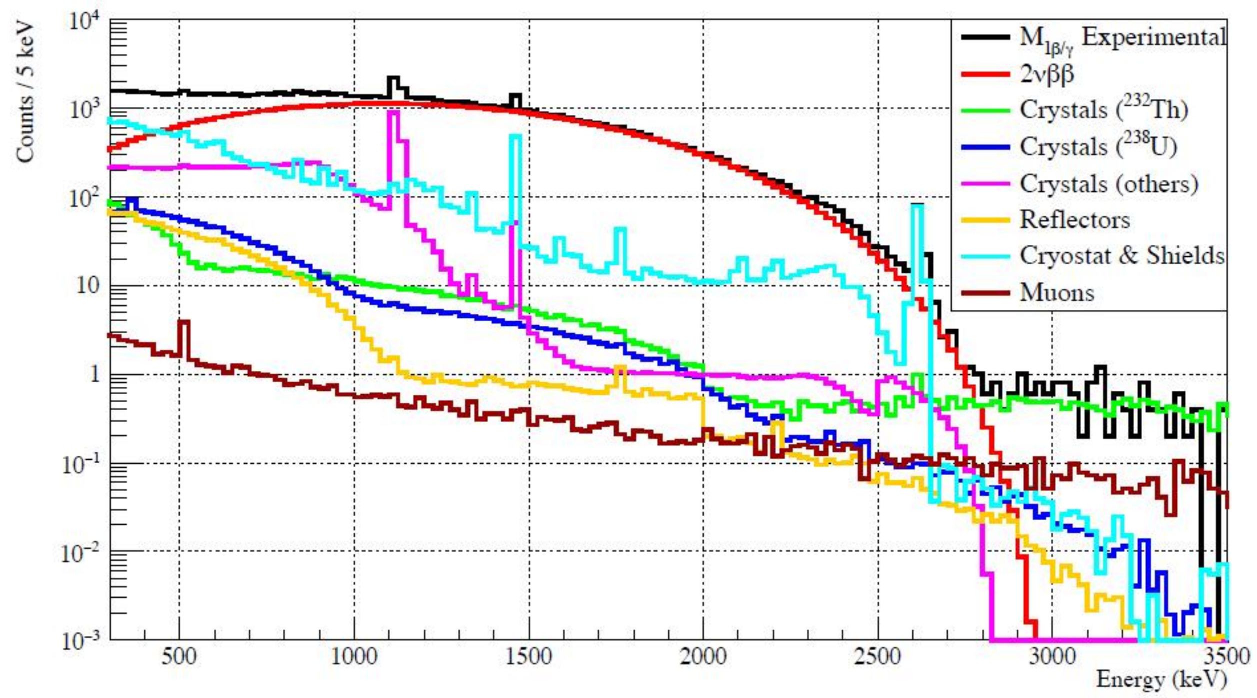


EPJC (2018) 78:428

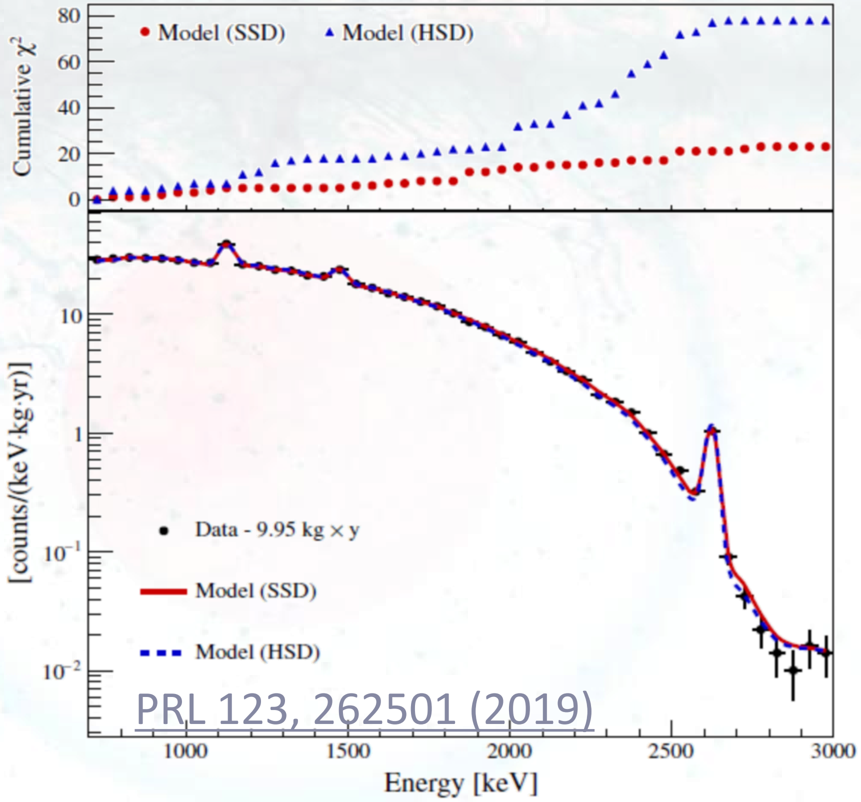
CUPID-0 results

FWHM @ $Q_{\beta\beta}$=(20.05 ± 0.34) keV

- Successfull demonstration of advantages of dual-readout technique
- High scientific potential: best limit on 0n2b, most precise measurement of ^{82}Se $2\nu2\beta$, CPT violation search, SSD vs HSD, excited states



$$T^{2\nu}_{1/2} = [8.60 \pm 0.03(\text{stat})^{+0.19}_{-0.13}(\text{syst})] \times 10^{19}\ \text{yr}$$



PRL 123, 262501 (2019)

*

CUPID-0 results

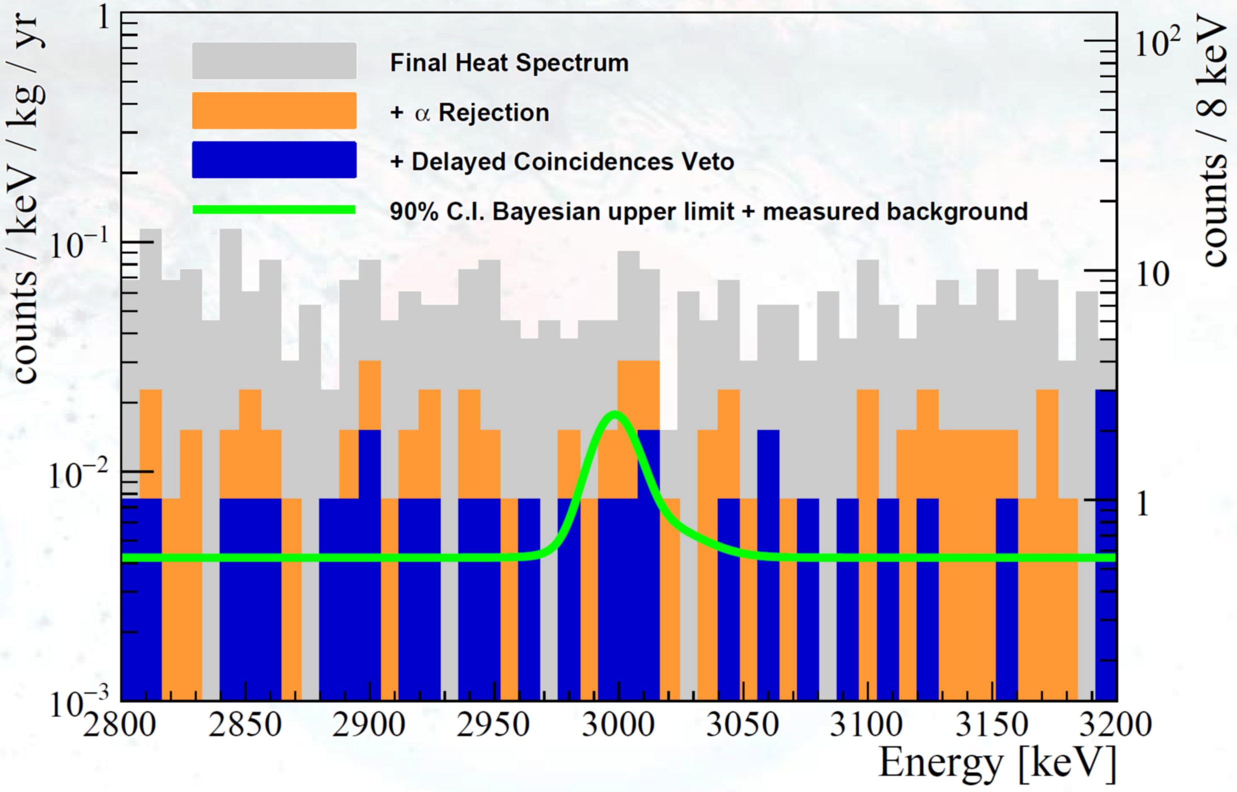
FWHM @ $Q_{\beta\beta}$=20.05 ± 0.34 keV

- Successfull demonstration of advantages of dual-readout technique
- High scientific potential: best limit on 0n2b, most precise measurement of ^{82}Se $2\nu2\beta$, CPT violation search, SSD vs HSD, excited states

$$T^{0\nu}_{1/2} > 4.6 \times 10^{24} yr\ (90\%\ C.I.\ limit)$$

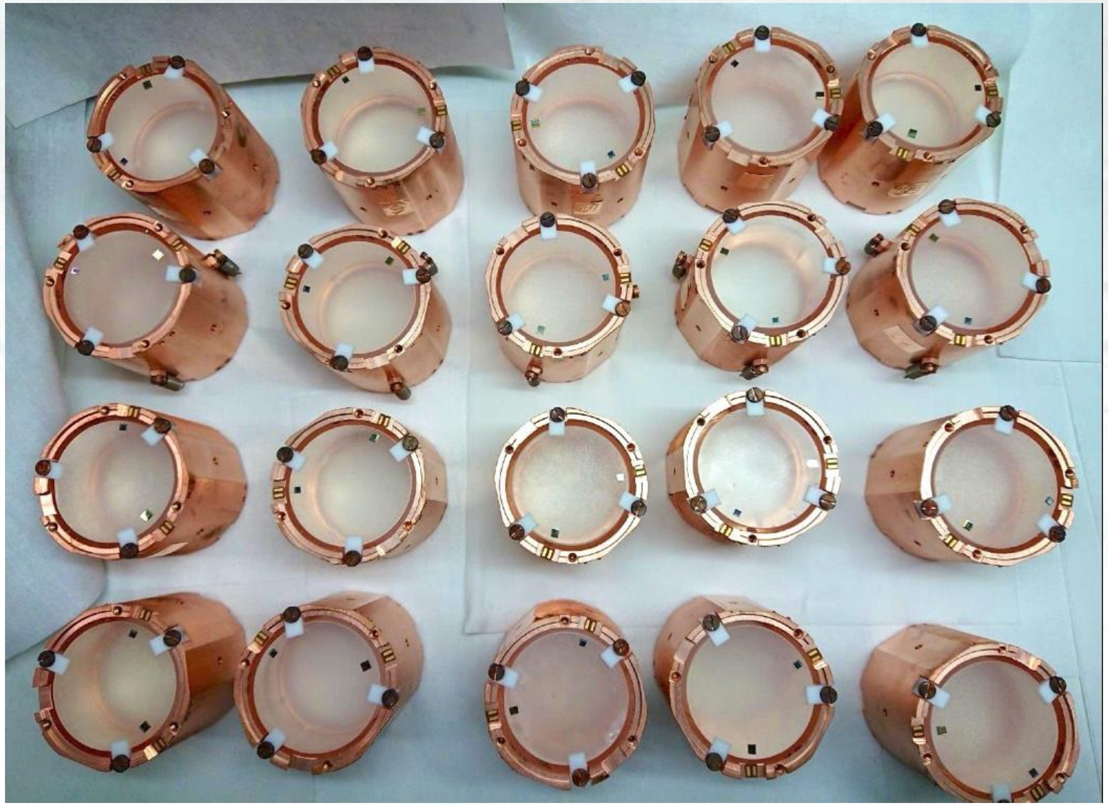
$$m_{\beta\beta} < 263\text{-}545\ \text{meV}$$

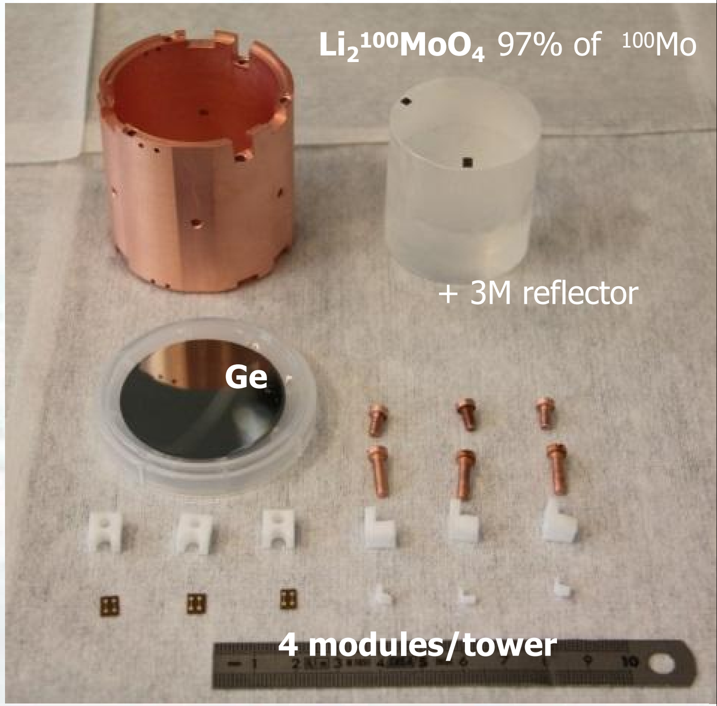
PRD 100, 092002 (2019)
PRL 123, 262501 (2019)
EPJC 79, 583 (2019)
EPJC 81, 722 (2021)



CUPID-Mo

- $Li_2{}^{100}MoO_4$ scintillating crystals - high energy resolution and radiopurity, array of 20 modules at LSM
- **Total of 2.26 kg of ^{100}Mo, $Q_{\beta\beta}$ = 3034 keV**

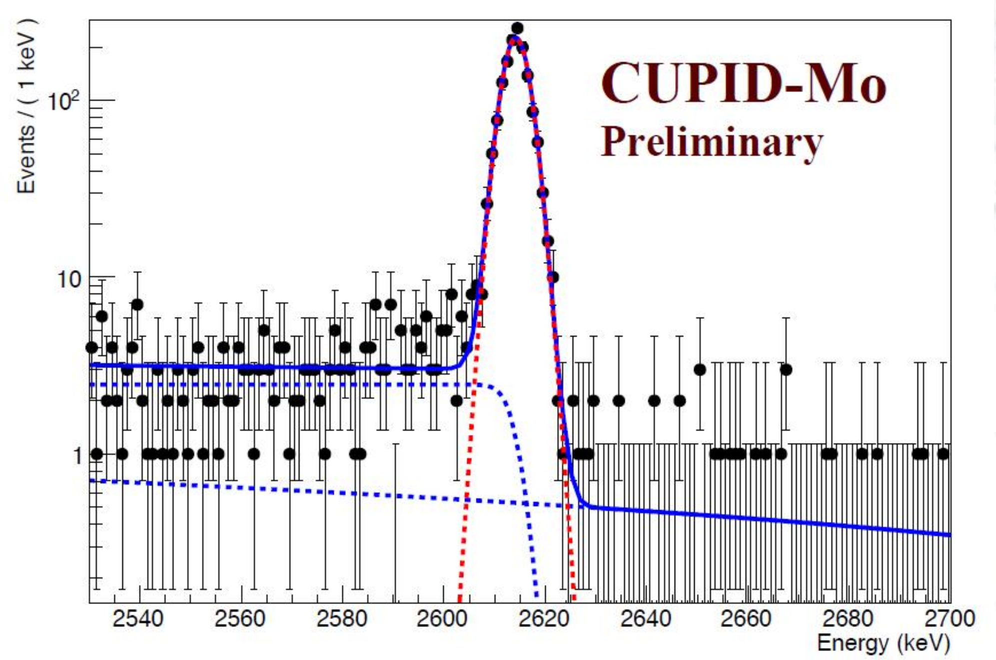


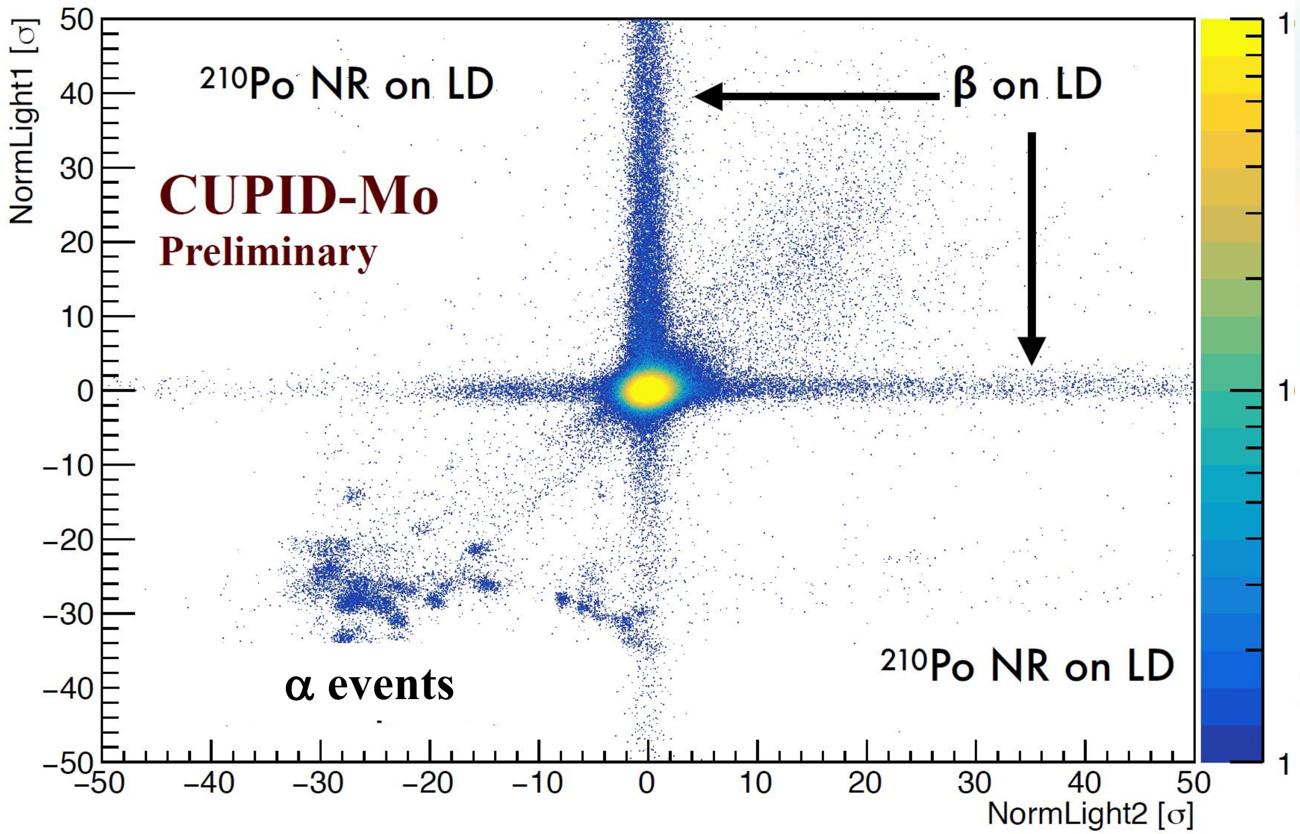


EPJC 80, 44 (2020)

CUPID-Mo features

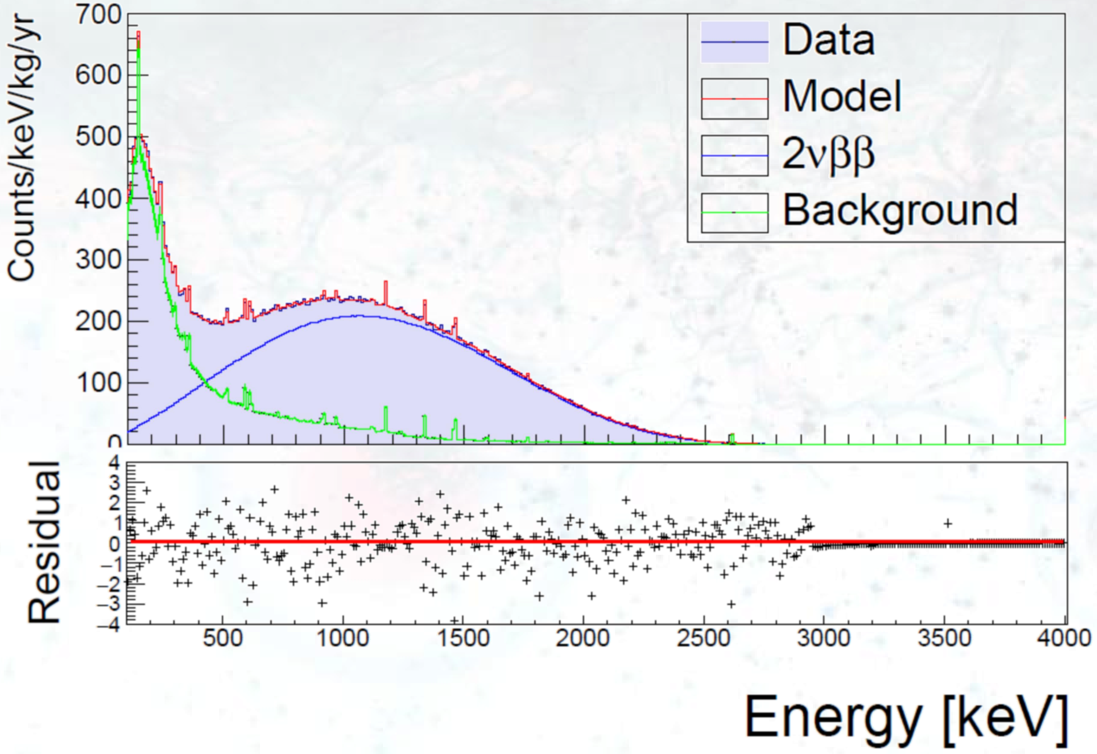
- Excellent internal radiopurity of crystals: ^{210}Po and U/Th well within CUPID requirements
- Anticoincidence, light yield and pulse shape cuts applied for background reduction
- **FWHM @ $Q_{\beta\beta}$=(7.38 ± 0.35) keV**

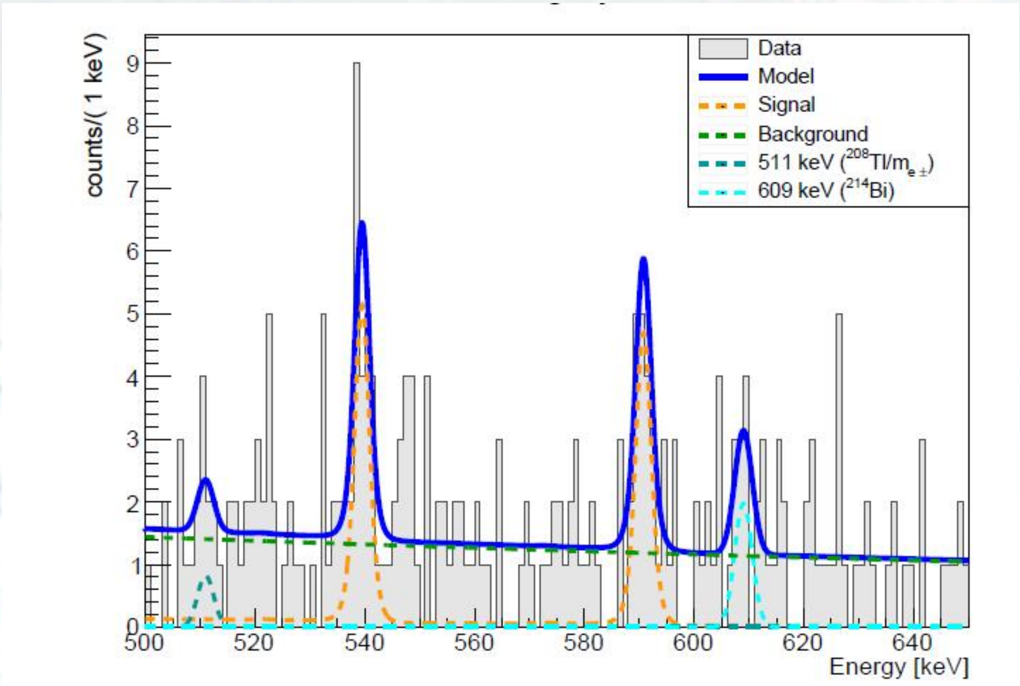




CUPID-Mo results

- Excellent performance and radiopurity - **chosen for ton-scale experiment**
- Best limit on ^{100}Mo $0\nu2\beta$ half- life, the most precise measurement of ^{100}Mo $2\nu2\beta$ and excited states





Energy, keV

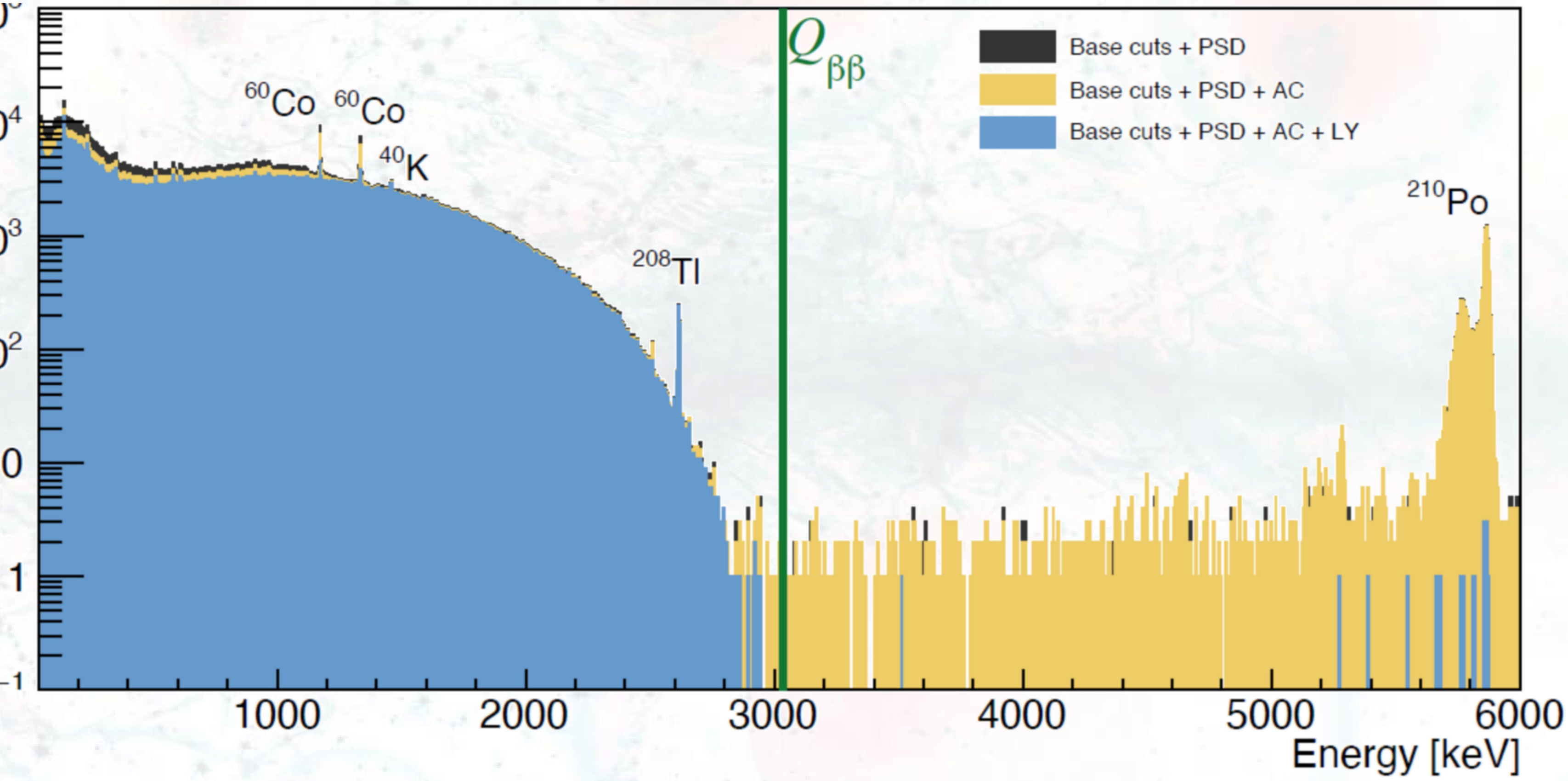
CUPID-Mo results

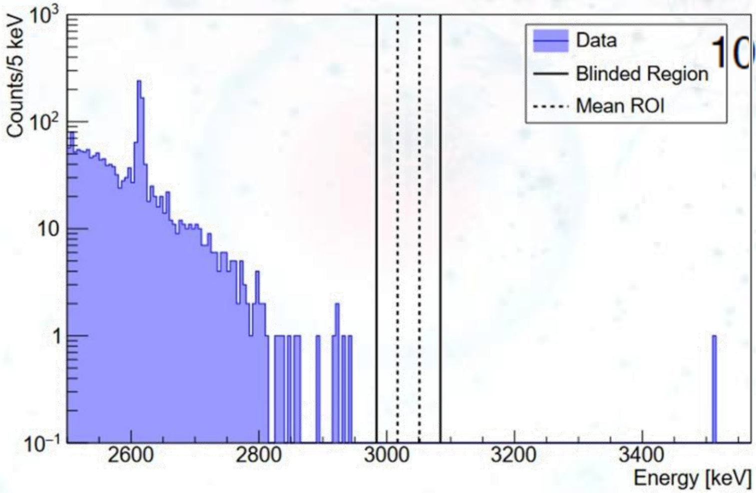
$T^{0v}_{1/2} > 1.8 \quad 10^{24} yr$

(90% C. I. limit)

$m_{\beta\beta}$<280-490 meV

1.5 kg×yr

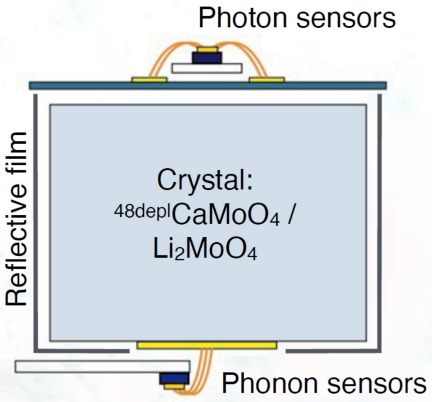


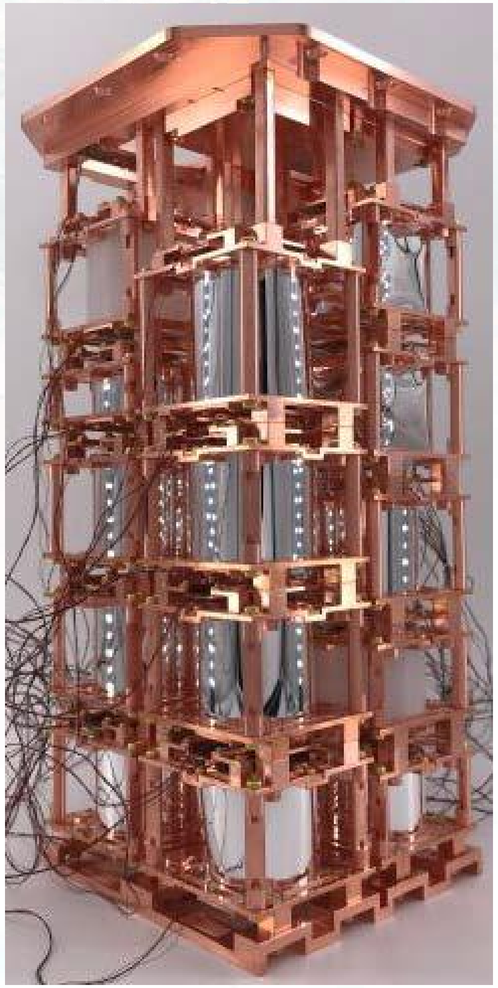


PRL 126, 181892 (2021)
JINST 16 (2021) P03032
EPJC 80, 44 (2020)
EPJC 80, 674 (2020)

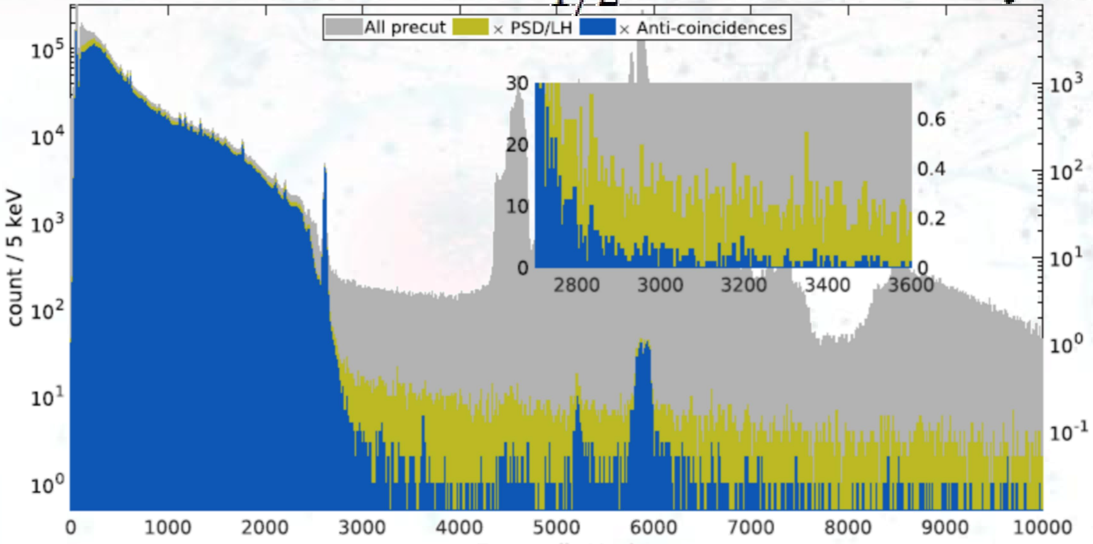
AMoRE-I

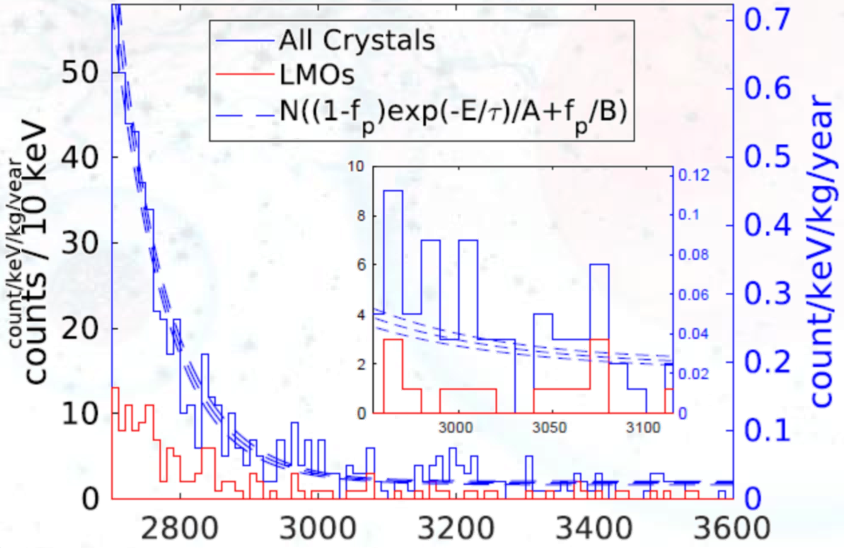
- Exploiting ^{100}Mo with $CaMoO_3$ and $LiMoO_3$ scintillating bolometers, total mass of ^{100}Mo - 3 kg
- MMC sensors for both heat and light
- Background = 0.032 ± 0.003 counts/keV/kg/year
- New most stringent limit on $T_{1/2}$ for ^{100}Mo





$$T^{0\nu}_{1/2} > 3.4 \times 10^{24} \text{ years at } 90\% \text{ C.L.}$$

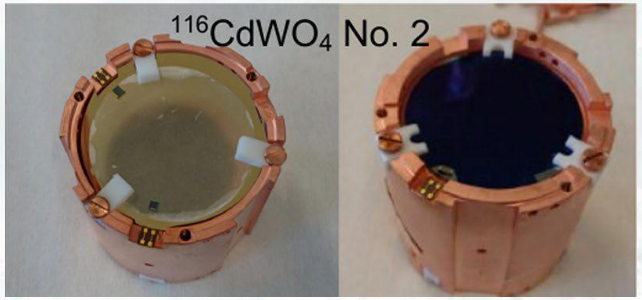


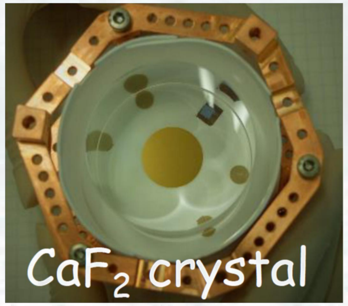


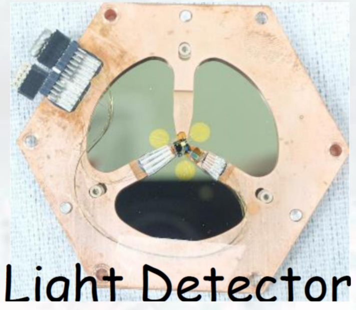
Result of AMoRE I KIM Hanbeom TAUP2023, University of Vienna, Austria

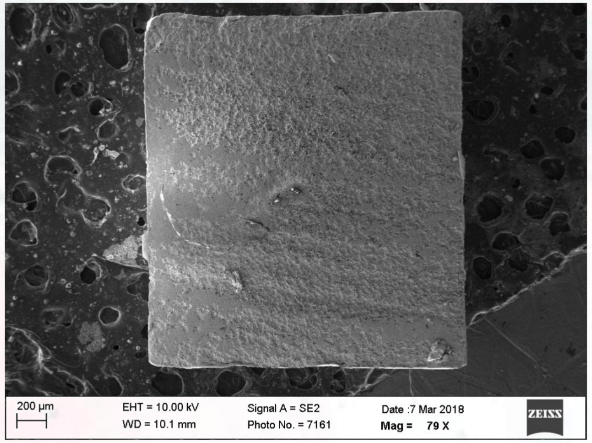
R&Ds with cryogenic detectors

- ^{116}Cd, ^{48}Ca: scintillating bolometers, single detector tests, high contamination of the crystals
- ^{124}Sn bolometers: microcalorimeter prototype, tin pest problem for scaling

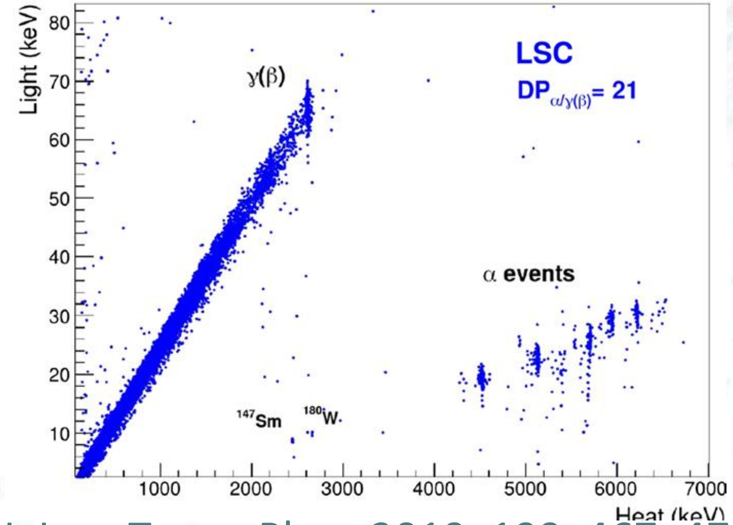




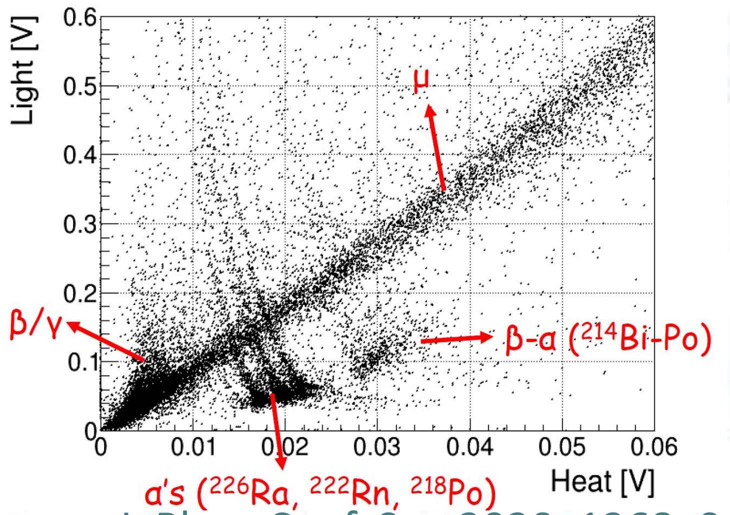




(a) Sn-Bi sample (S11)



[J. Low Temp. Phys. 2019, 199, 467–474]



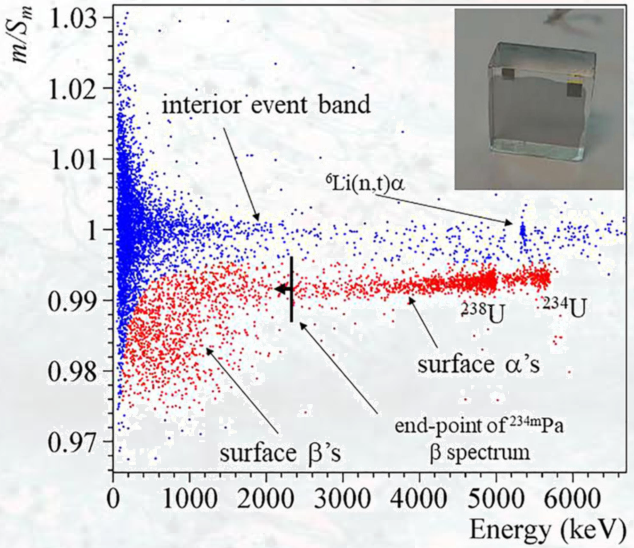
[J. Phys. Conf. Ser. 2020, 1268, 012132]

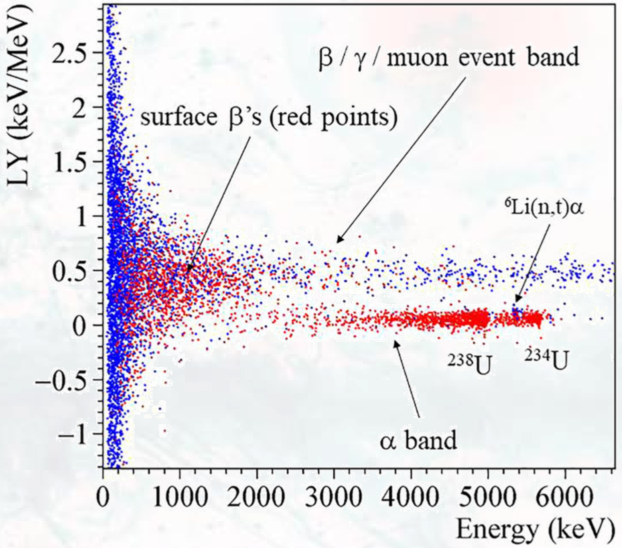
^{150}Nd, ^{96}Zr: project started, no proof of concept yet

R&Ds with cryogenic detectors

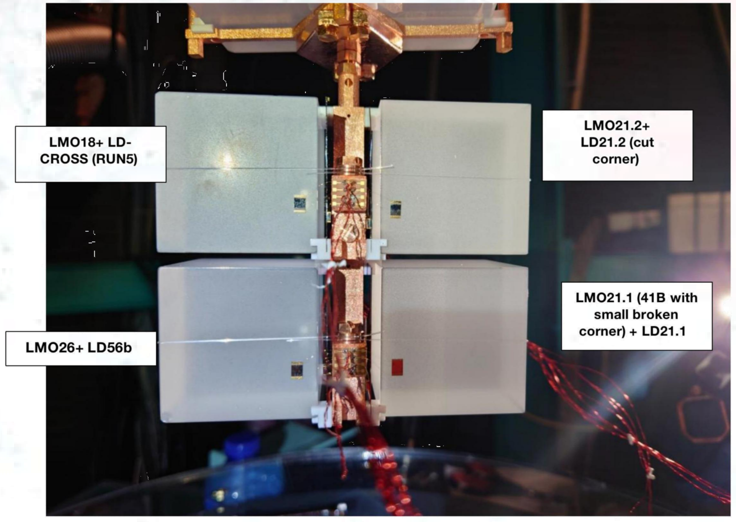
^{100}Mo: background rejection methods for ton-scale:

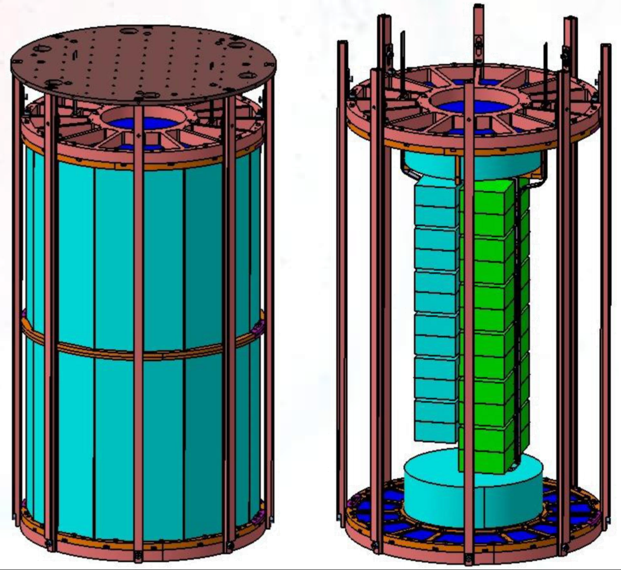
- CROSS: single-channel surface sensitive detectors





- Bingo: geometrical bkg reduction, cryogenic veto, enhanced light detectors





Summary

- Last decade was definetely fruitful for DBD experiments
- Zero-background approach desired for next generation
- We understand well which sensitivities are reachable
- A lot of technological developments on the table
- Scaling is ongoing...