Neutrino physics with low temperature detectors

Anastasiia ZOLOTAROVA, CEA-Saclay, Irfu/DPhP

Bolometers: definition and history

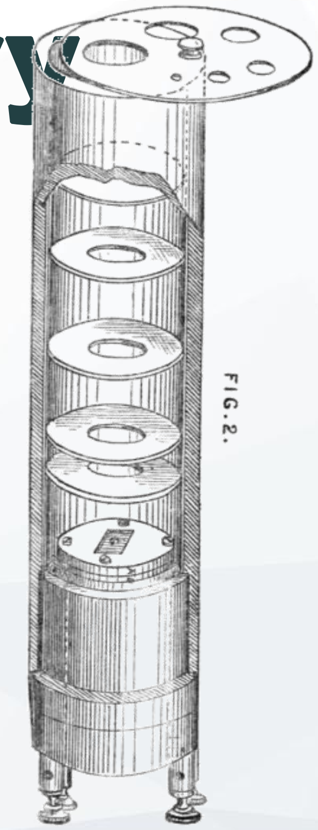


FIG. 2.

- Name comes from greek βολος : ray
- Defined in 1880 by Samuel P. Langley

THE BOLOMETER

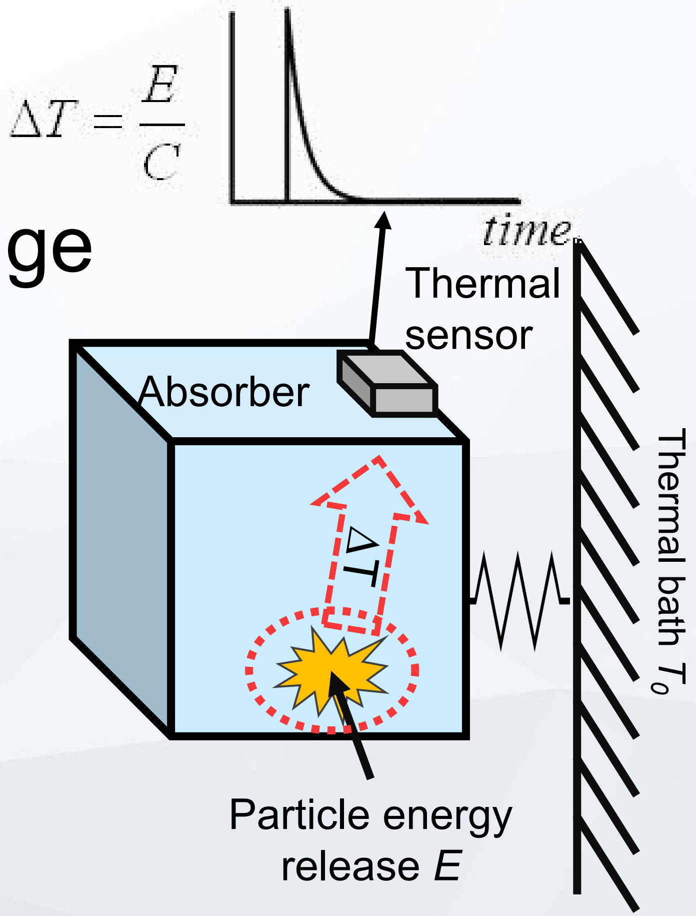
AN instrument a thousand times more sensitive to radiant heat than the thermopile, and capable of indicating a change of temperature as minute as 1-100,000th of a single Centigrade degree, deserves the attention of the physicist.

- First device was used to measure the intensity of solar radiation at various wavelengths
- Measurements at ambient temperature
- Sensitivity **$\Delta T \sim 10^{-5}$ K**

S. Langley, The bolometer
Nature, 25, 14-16, 1882

Modern bolometers for particle detection

- Very different picture today:
- Measurement of radiation via temperature change
- Requires very low temperatures of operation to detect this change (~10-100 mK)



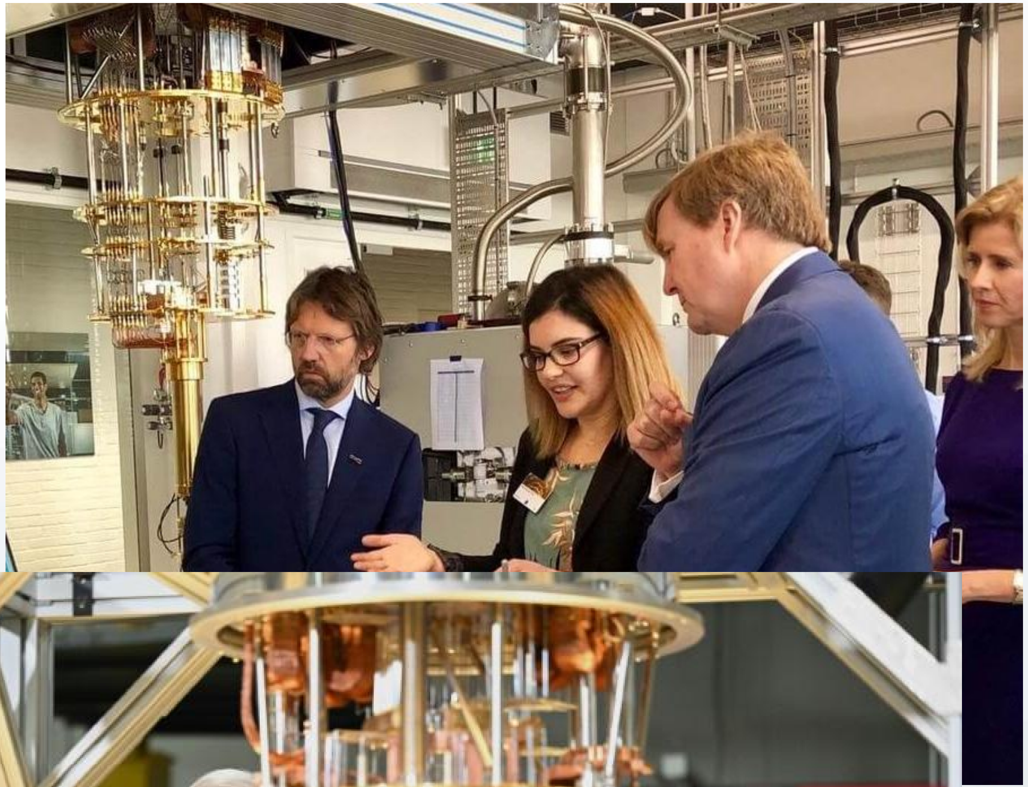
Modern bolometers for particle detection

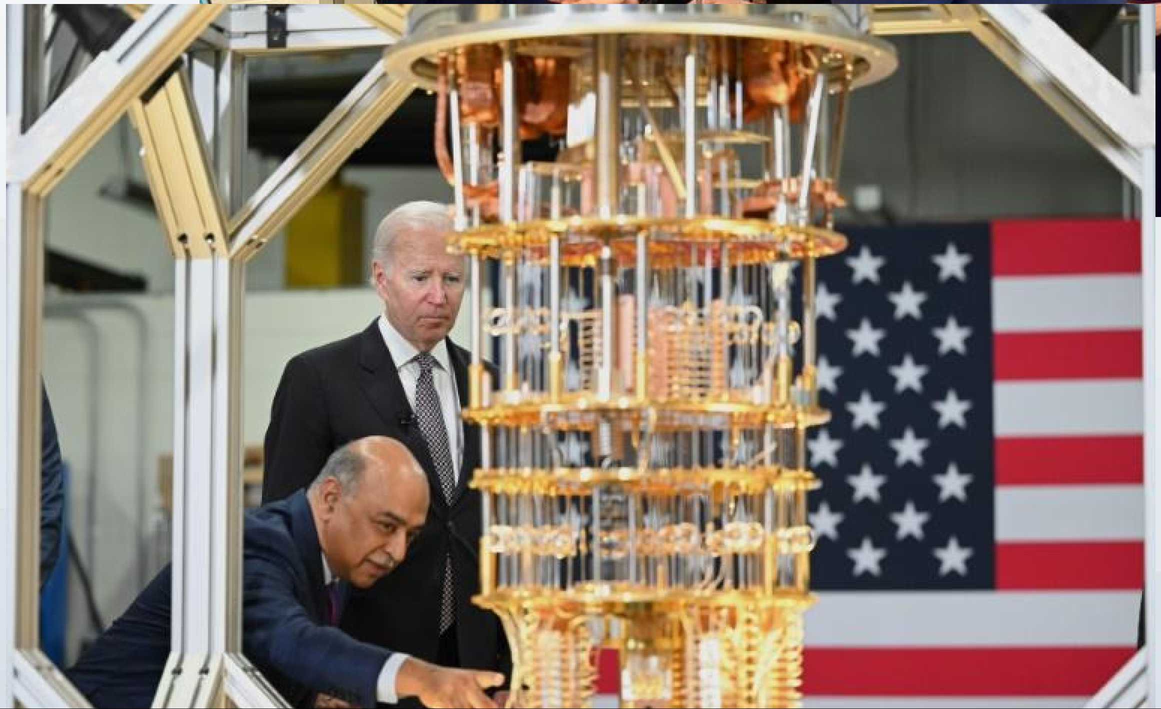
Cryostats:

- Huge progress in past 20 years: from liquid He bath to pulse-tube cryostats

- Large progress in available experimental space

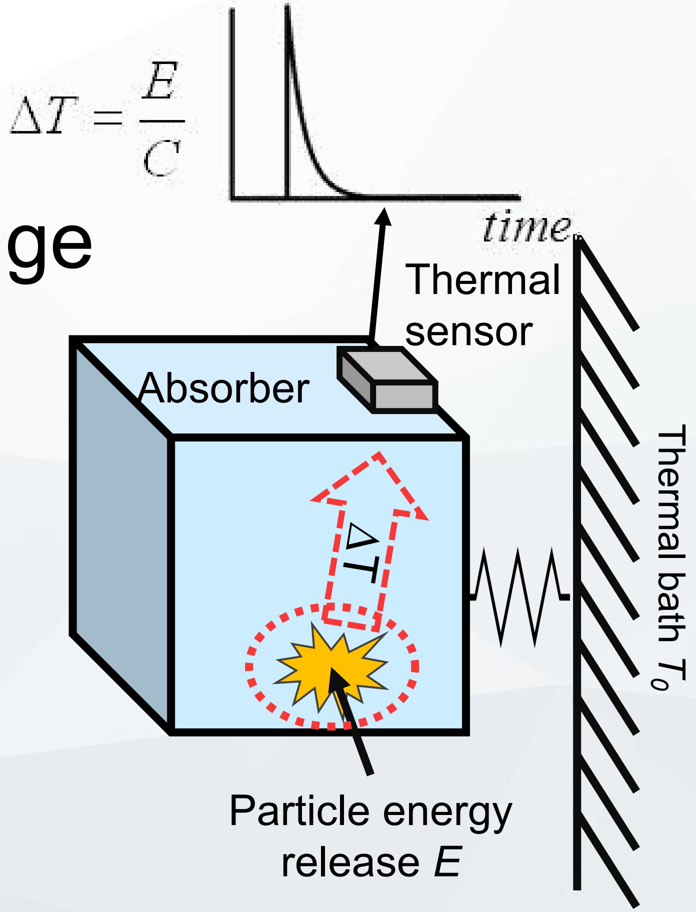
- Thanks to big interest in qubits - larger market!





Modern bolometers for particle detection

- Very different picture today:
- 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:



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

Low heat capacity is essential for building a good bolometer!

Debye law for dielectrics

Energy resolution

- Internal energy resolution:

$$\Delta E_{int} = \sqrt{N} \cdot k_B T = \sqrt{k_B C(T) T^2}$$ ~ few eV for macrobolometers

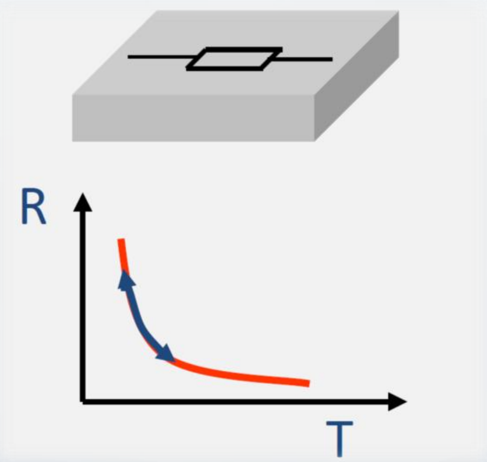
- Other mechanisms to be taken into account:
  energy losses in the detector volume, external noise sources

- Typical energy resolution strongly depends on size of the bolometer, ranges from eV to keV

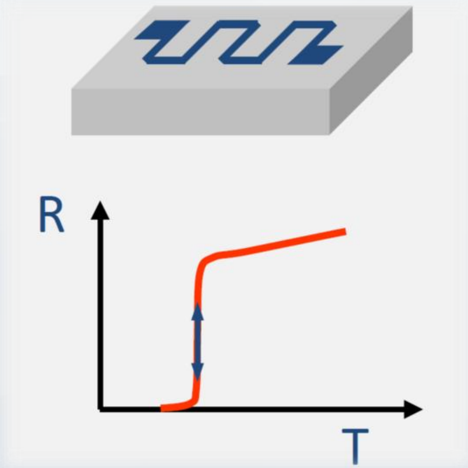
Thermal sensors

Typical sensors

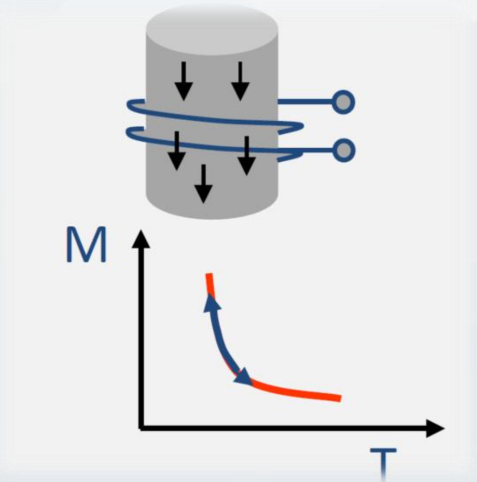
- What do we need?
- Large change of “X” parameter depending on temperature
- Low heat capacity (absorber is dominant)
- Speed of signal depends on the type of phonons we are sensitive to



Neutron Transmutation Doped sensors



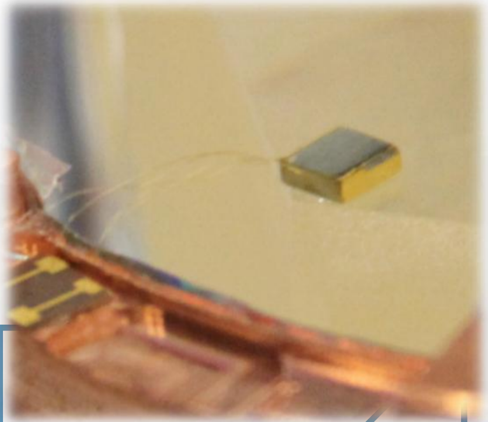
Transition Edge sensors



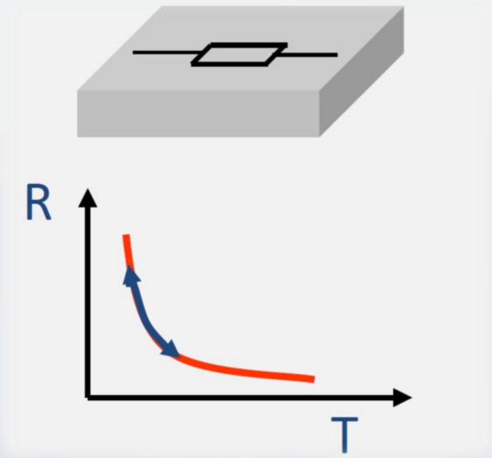
Metallic Magnetic Calorimeters

Neutron Transmutation Doped sensors

- Produced by irradiation of Ge crystal with thermal neutrons
- Good reproducibility for big amounts of sensors
- Temperature dependence: $R = R_0 exp\left(\frac{T_0}{T}\right)^{1/2}$

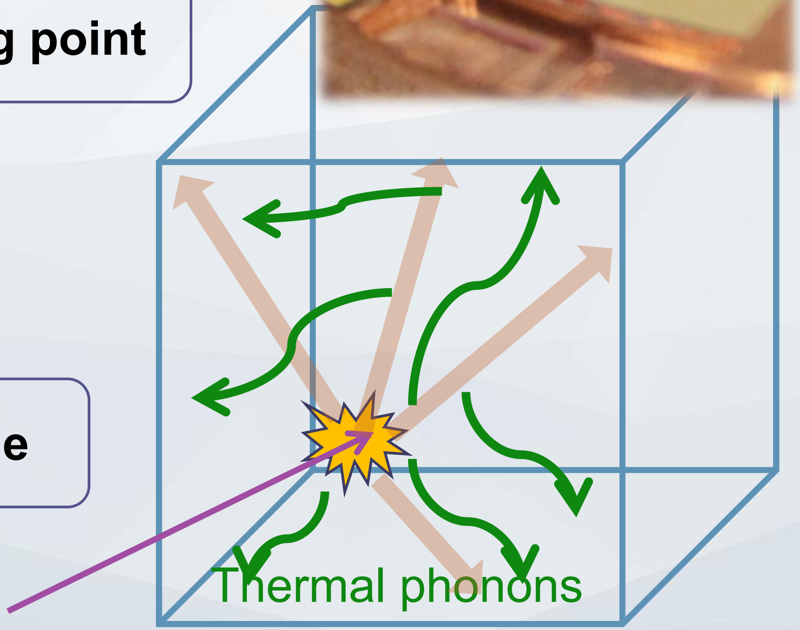


1-10 ~ MOhms at working point



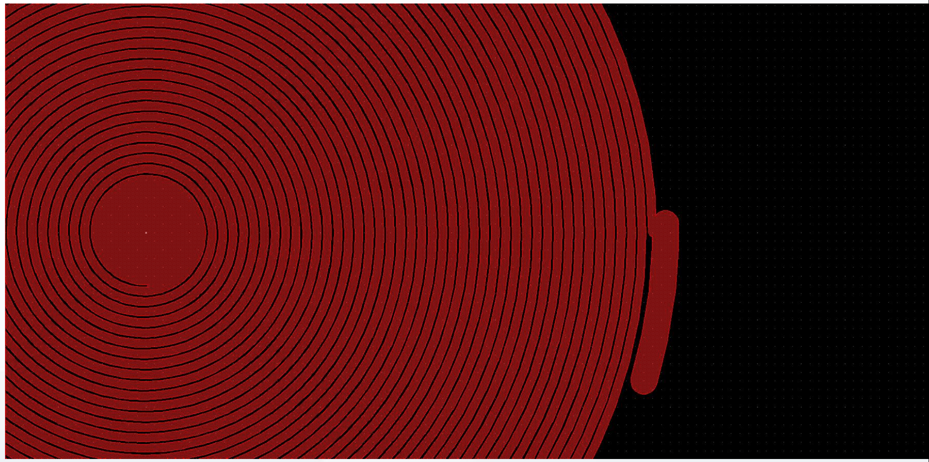
Neutron Transmutation Doped sensors

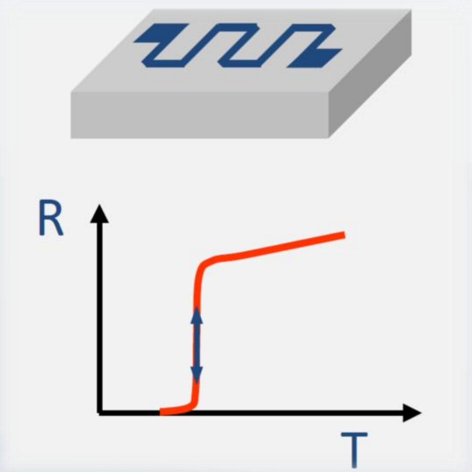
Slow sensors, thermal regime



Transition Edge sensors

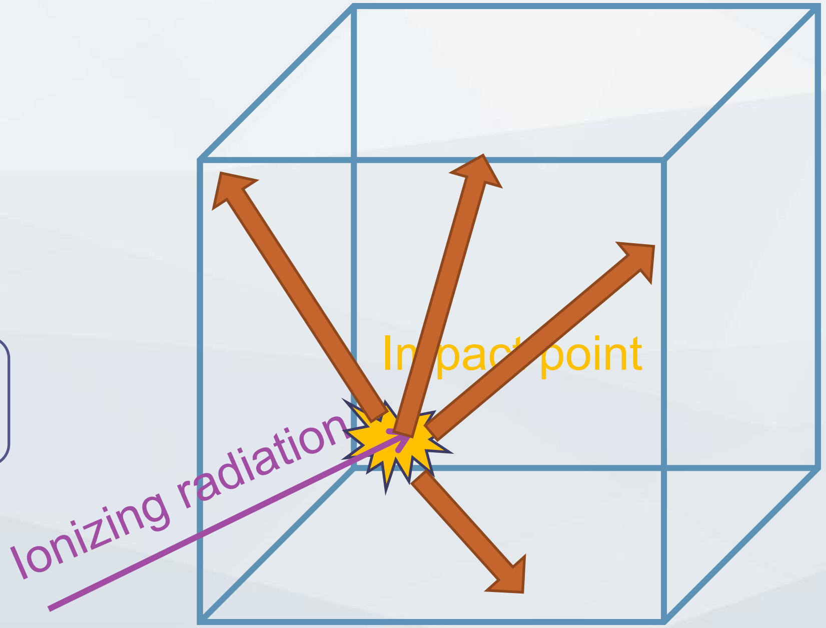
- Exploiting superconducting transition
- Materials: Mo/Cu Mo/Au Ir/Au Ti/Au W....
- SQUIDs generally required for read-out





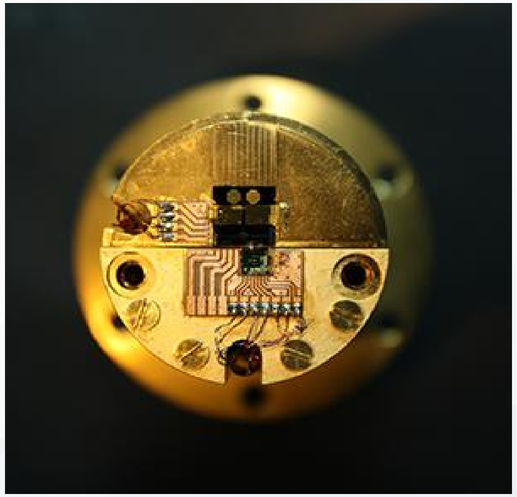
Transition Edge sensors

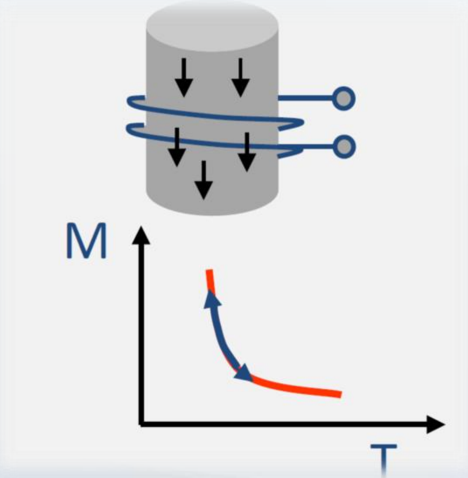
Fast sensors, athermal regime



Metallic Magnetic Calorimeters

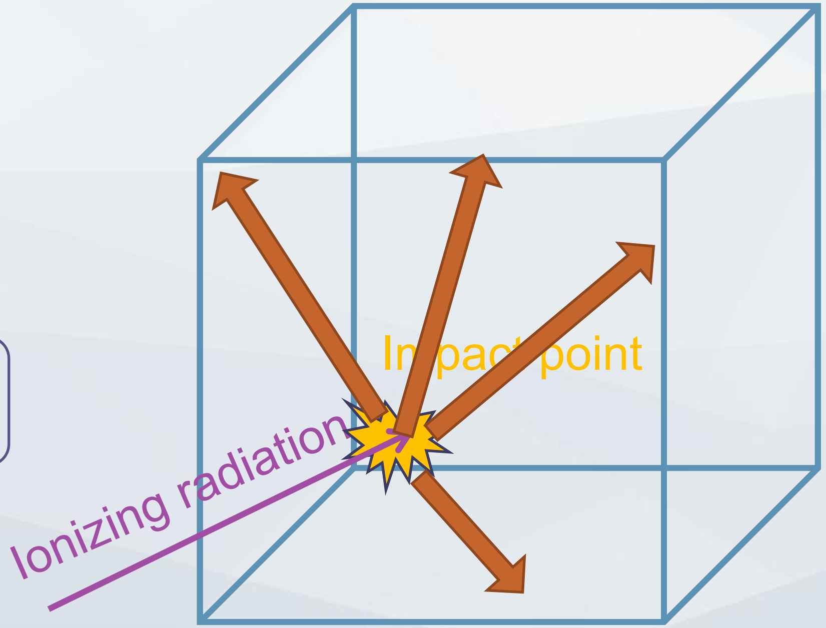
- Magnetization of material changes with temperature
- SQUIDs generally required for read-out
- no dissipation in the sensor
- no galvanic contact to the sensor





Metallic Magnetic Calorimeters

Fast sensors, athermal regime



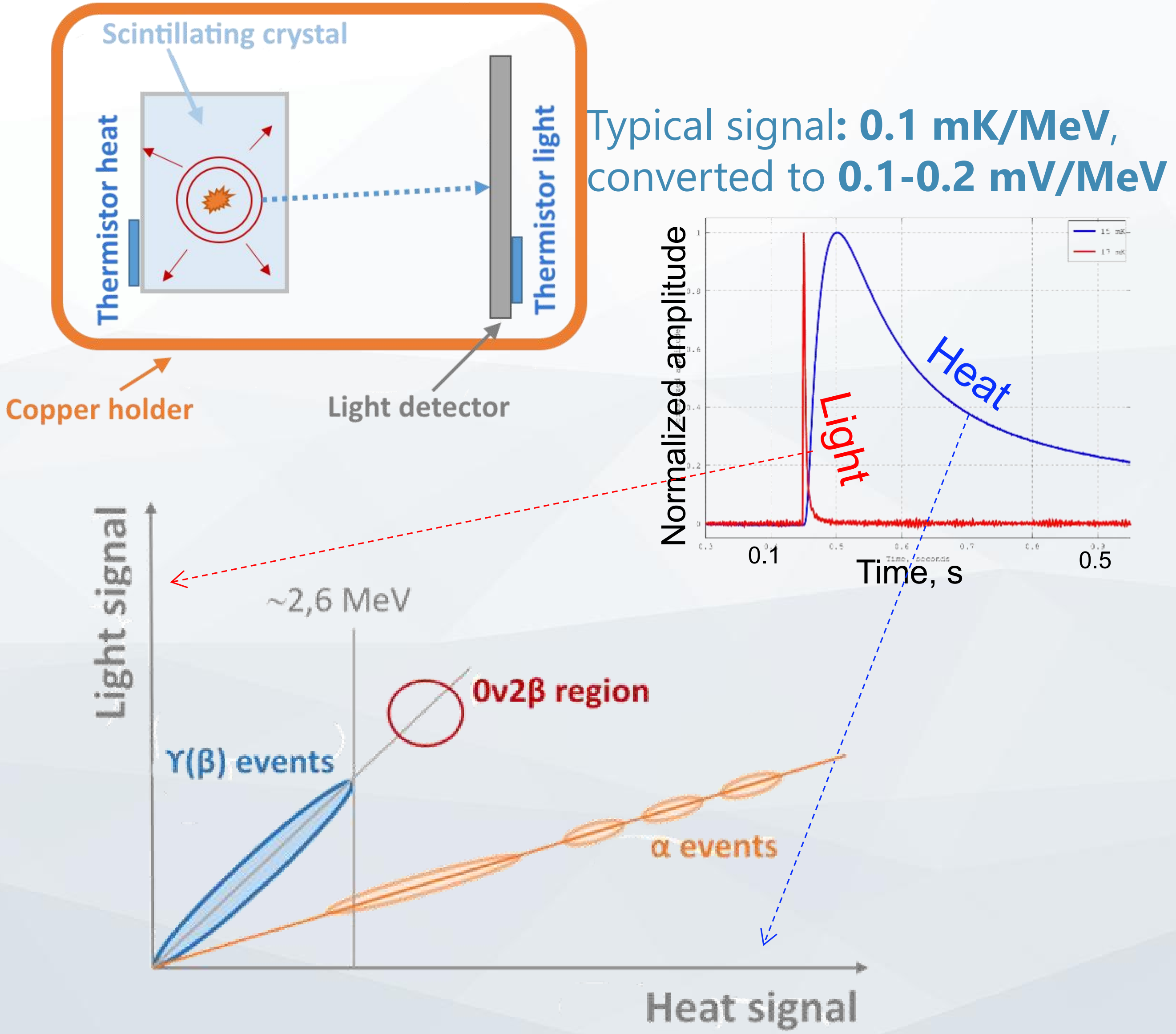
Particle identification with bolometers

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

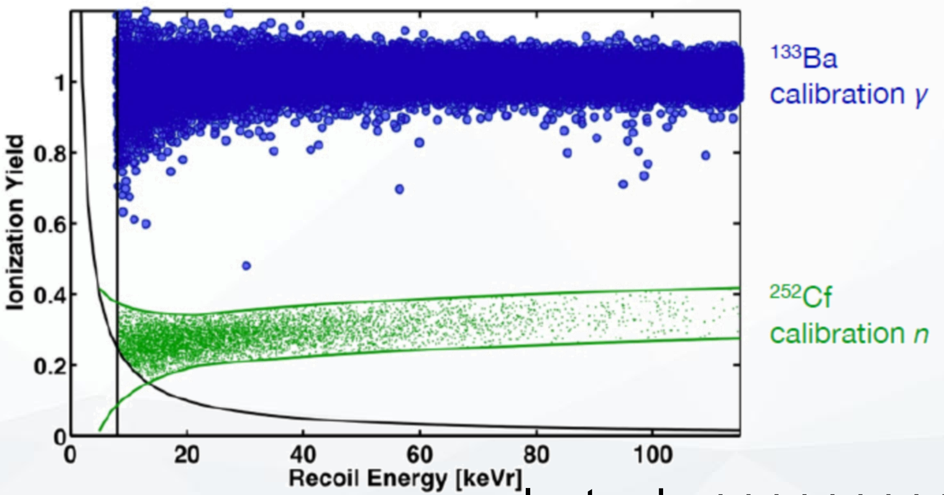
- Particle **discrimination using light for α** rejection

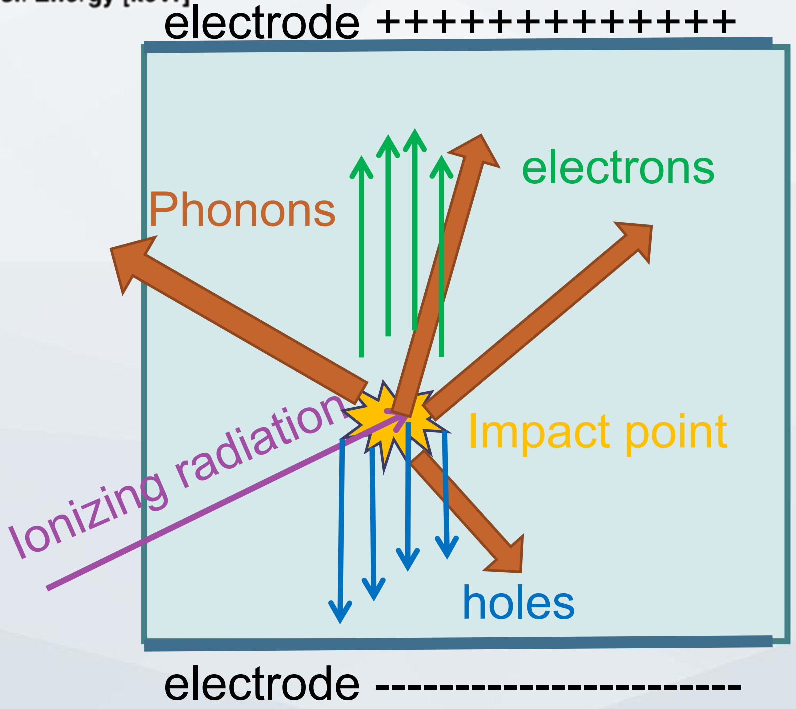


Particle discrimination with bolometers

Ionisation:

- Nuclear recoils produce less charge with respect to same energy electron recoils induced by beta/gamma.
- Add a charge readout to the phonon readout
- Excellent method to discriminate nuclear recoils from electron recoils

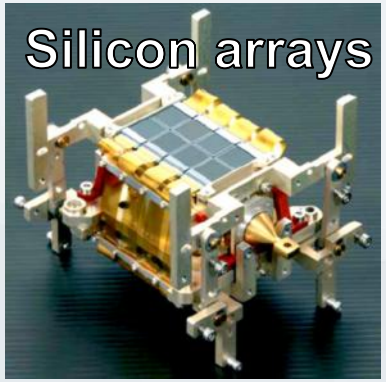


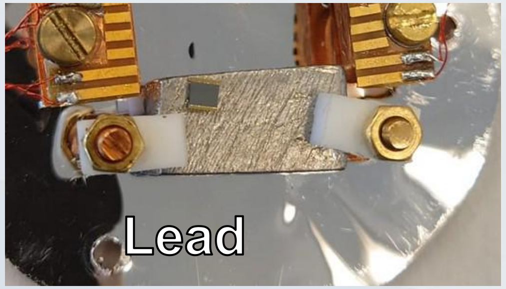


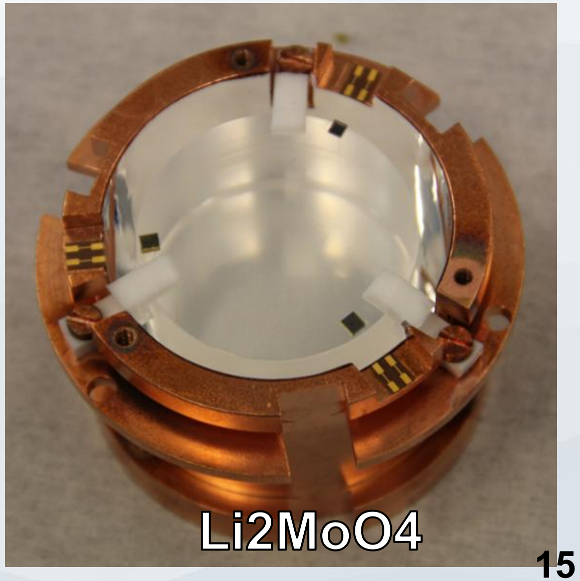
Bolometers are

Very flexible in:

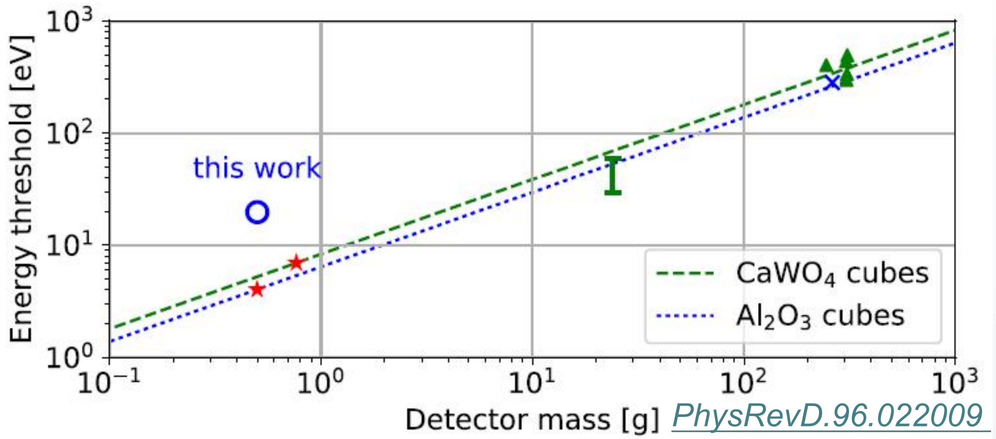
- Materials - you need sufficiently high Debye temperature and non-magnetic material for a good absorber
- The studied isotope can be embedded into the detector







Bolometers are



PhysRevD.96.022009

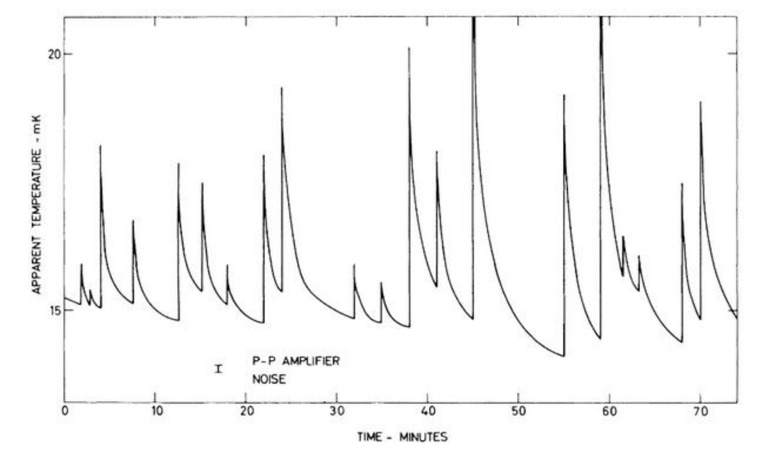
Very flexible in:

- Energy ranges!
- This depend on the absorber size, sensors, etc.
- From infrared to X-rays and particle detection

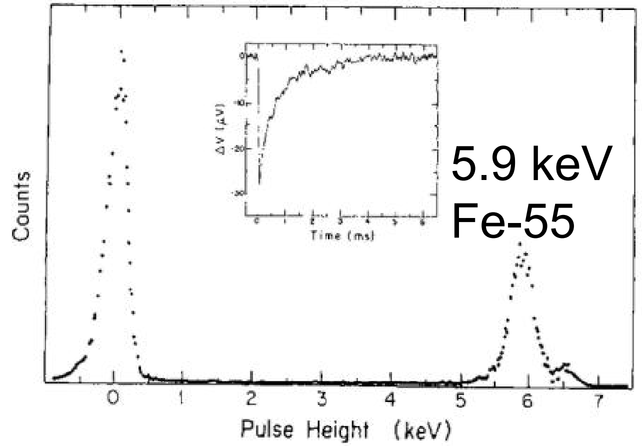
Experimental tests of a single-photon calorimeter for x-ray spectroscopy

Journal of Applied Physics **56**, 1263 (1984); https://doi.org/10.1063/1.334130

D. McCammon
Physics Department, University of Wisconsin, Madison, Wiscor
S. H. Moseley, J. C. Mather, *and* R. F. Mushotzky
Goddard Space Flight Center, Greenbelt, Maryland 20771



First energy spectrum with a low temperature calorimeter, 1984



Bolometers are

As a consequence of two previous points, bolometers are very flexible in applications:

- Cosmology, astronomy and astrophysics
- Dark matter searches
- **Neutrino physics studies**
- Material science
- Nuclear and atomic physics
- Recent: quantum computing

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- Material science
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- Recent: quantum computing

Are there any disasdvantages?

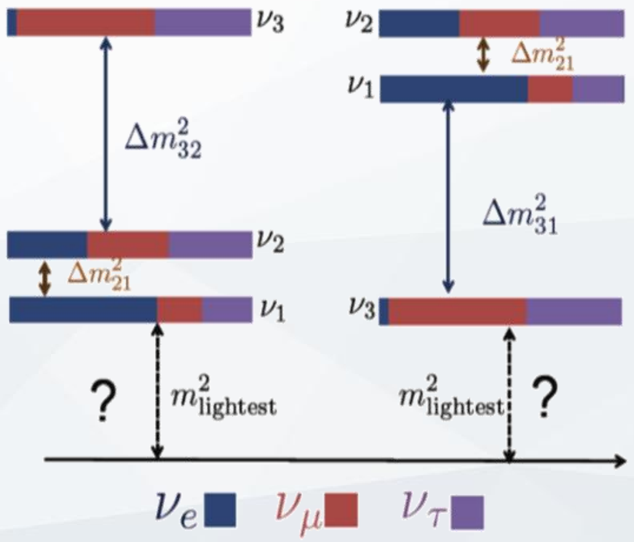
- Relatively slow detectors (especially large devices)
- Require complex infrastructure for stable operation
- Restricted volume (by size of cryostat)
- Large masses through arrays - a lot of electronics channels!

Neutrino physics: big questions

Big questions about neutrinos

We know that neutrinos are “outliers” - SM doesn’t include massive neutrinos (defined by oscillations)

What we need to find out?



- **Neutrino absolute masses**
- **Neutrino mass ordering**
- **Neutrino nature:** Majorana ($\upsilon = \bar{\upsilon}$) or Dirac ($\upsilon \neq \bar{\upsilon}$)
- **New physics beyond the SM**

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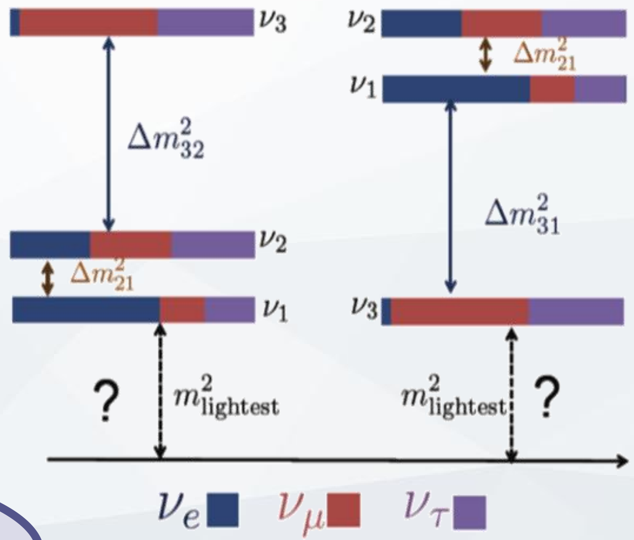
Direct m_β mass measurement

Double beta decay searches

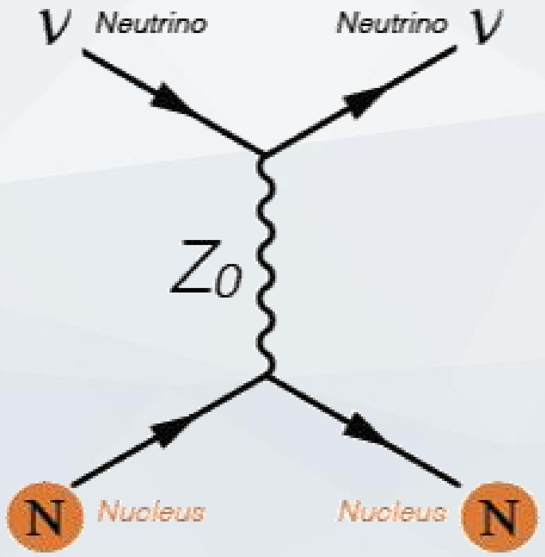
CEνNS



Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)

CEνNS

- Largest neutrino cross section at low energies by few orders of magnitude: process within the SM, predicted in **1974**, first detected by COHERENT collaboration in **2017**
- Low-energy and high precision measurements required for further investigations:
  - – Low energy test of SM
  - – Physics beyond SM
  - – n magnetic moment
  - – Non standard n interaction
  - – Z’ boson



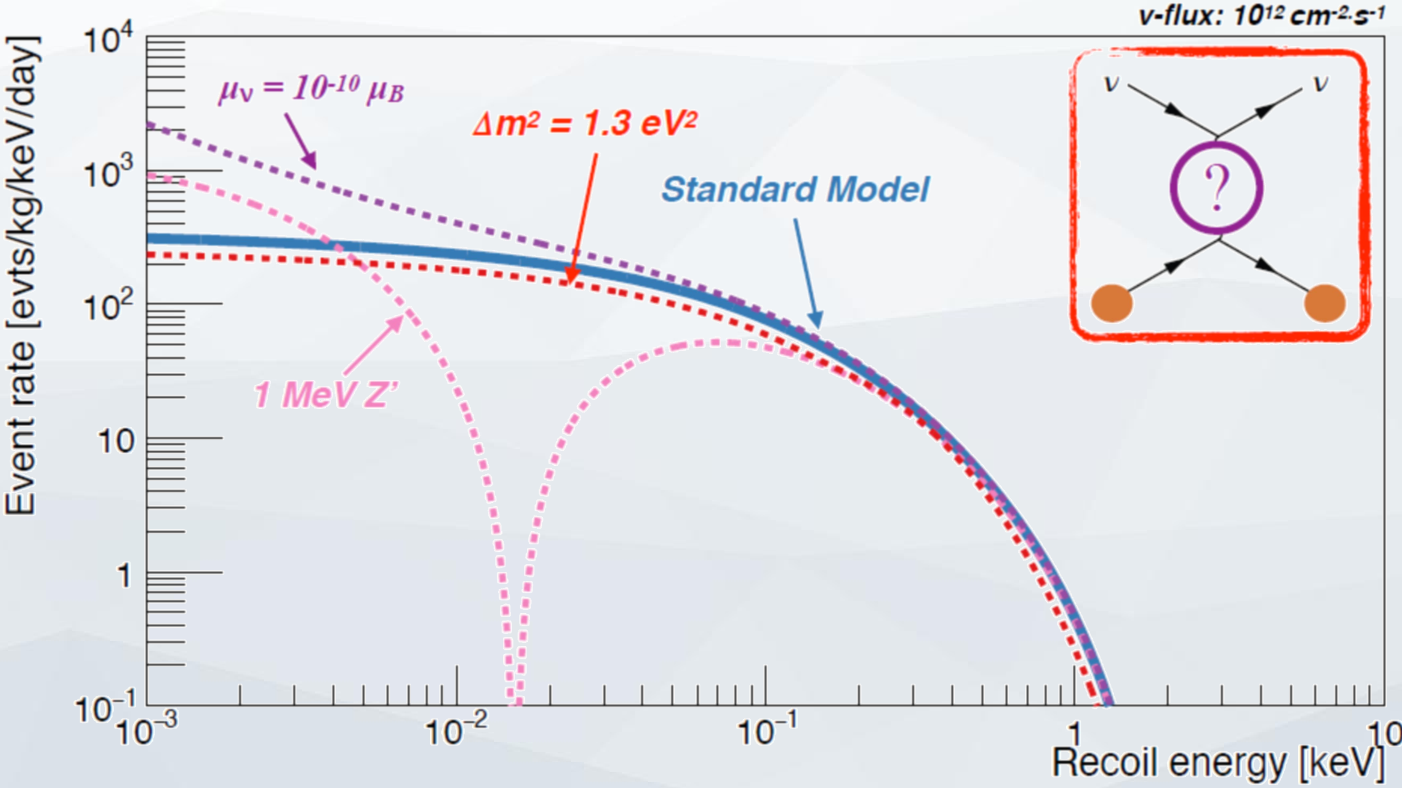
CEνNS

- Low-energy source: reactor neutrinos

$$\frac{d\sigma(E_\nu, E_r)}{dE_r} = \frac{G_f^2}{4\pi} Q_w^2 m_N \left(1 - \frac{m_N E_r}{2E_\nu^2}\right) F^2(E_r)$$

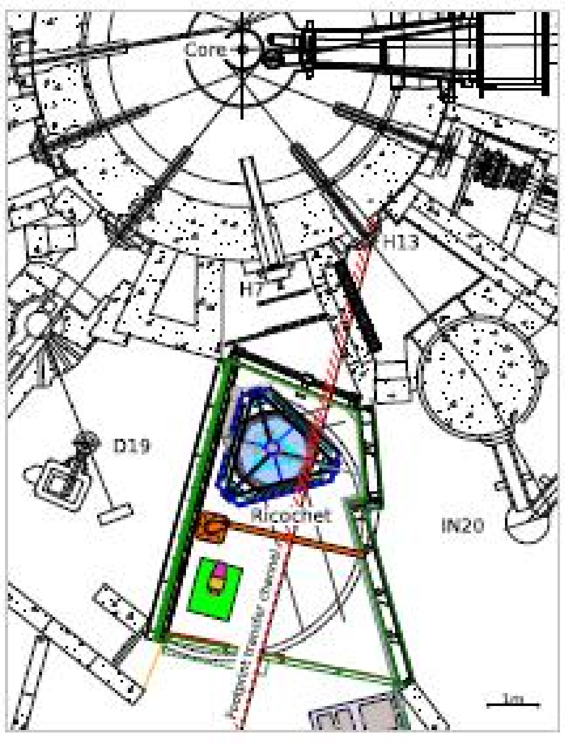
$$Q_w = N - Z(1 - 4\sin^2\theta_w)$$

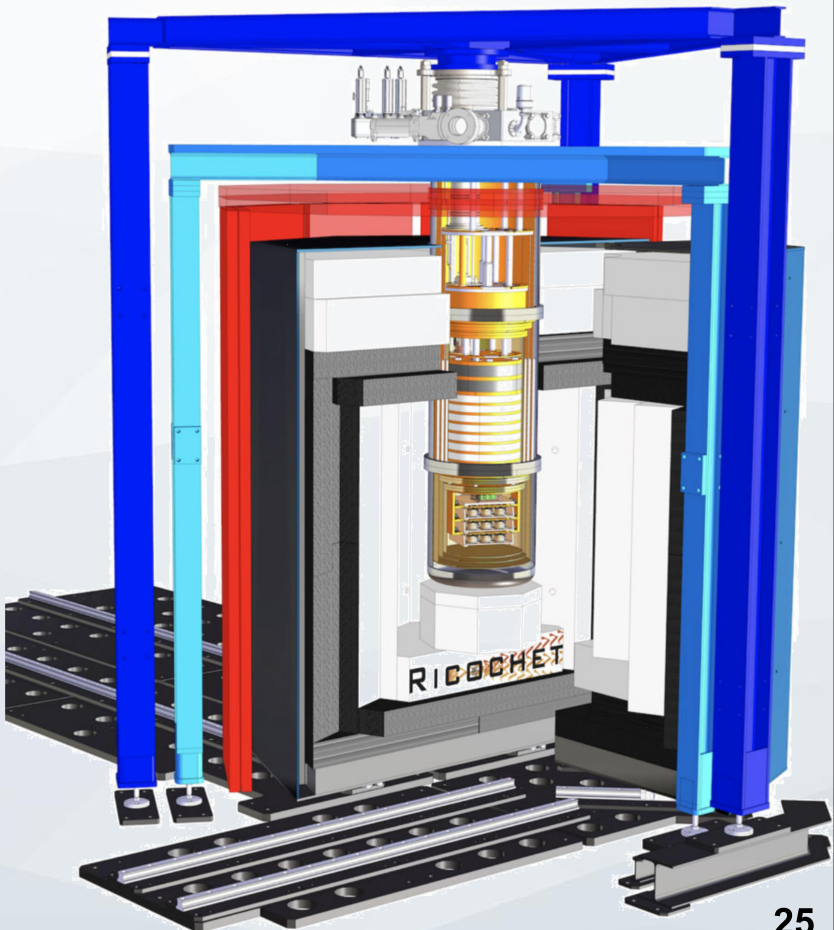
- Few tens of events per day and per kg of detector material expected
- **O(10 eV)** theshold required
- Challenge within the reach for bolometric detector technology



CENNS experiments: Ricochet

- Ge (heat+ionisation) and Zn (heat only) crystals,1 kg in total
  Nuclear recoil identification <100 eV
- ILL Research reactor in France
  Cosmic reduced by overburden (15 m w.e.)





C. Augier, et al, Eur. Phys. J. C 83 (2023) 20

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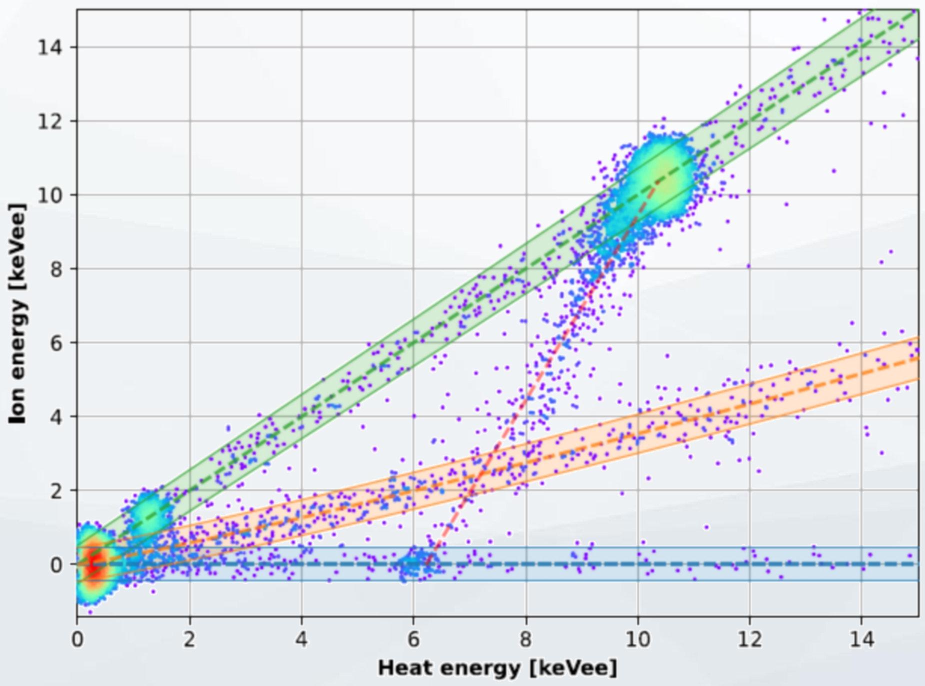
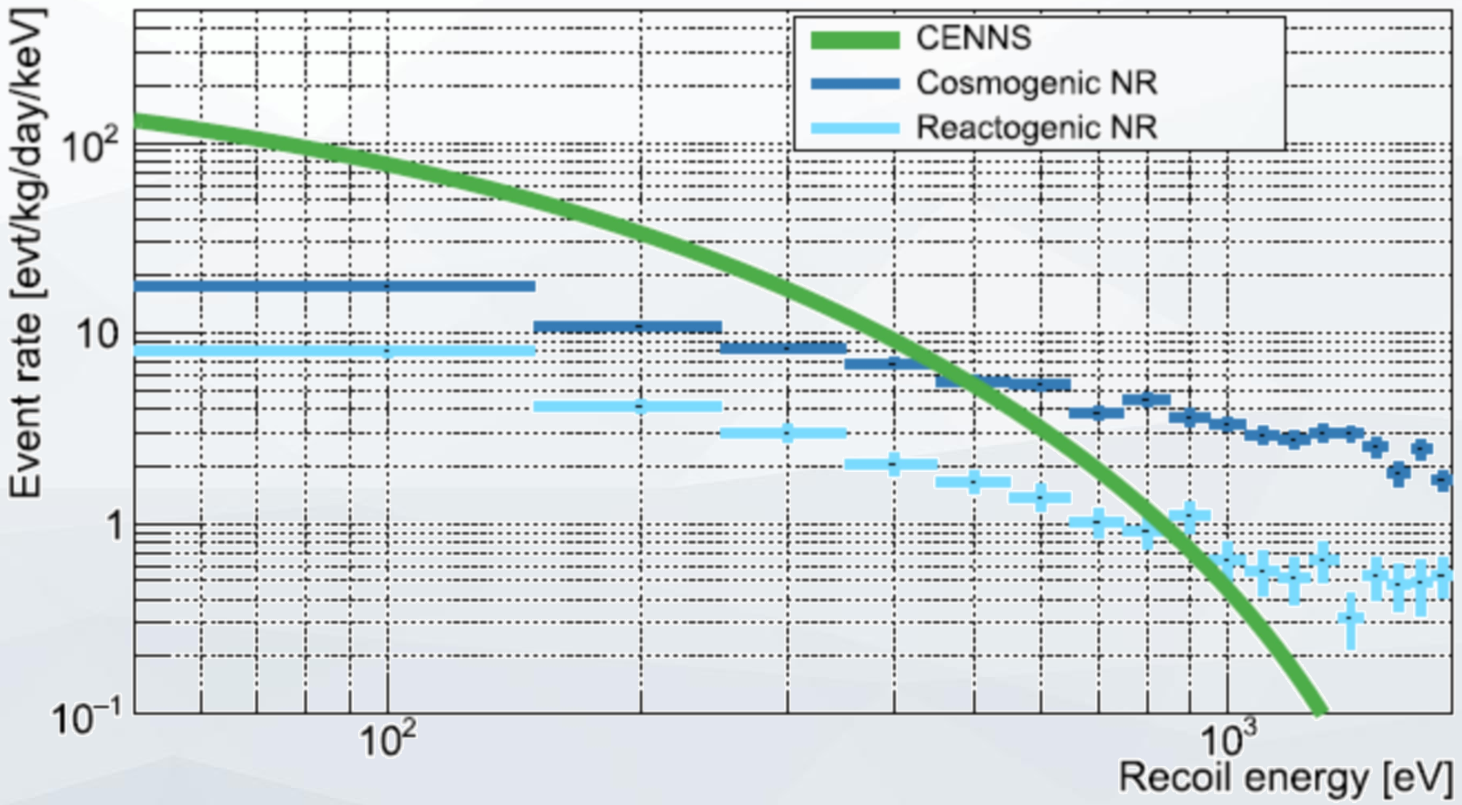


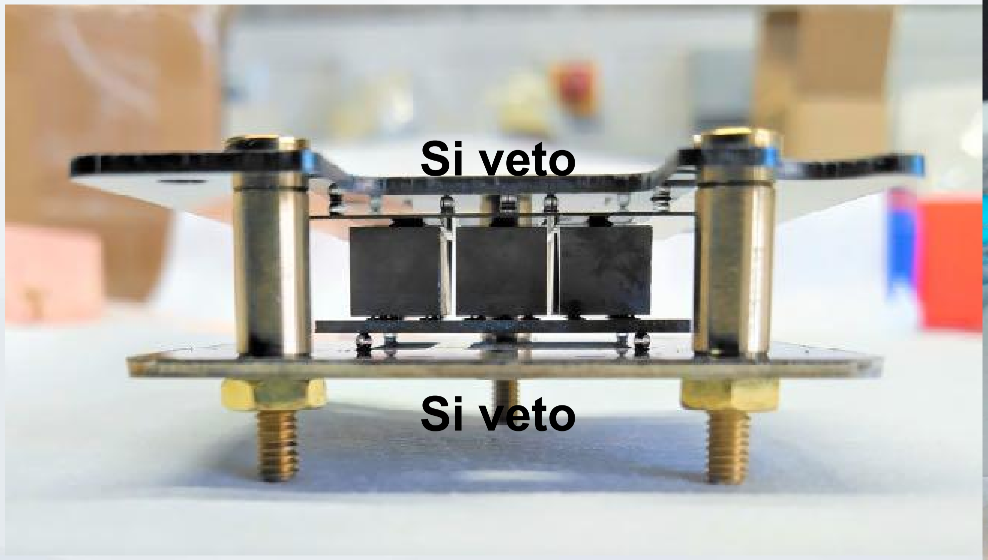


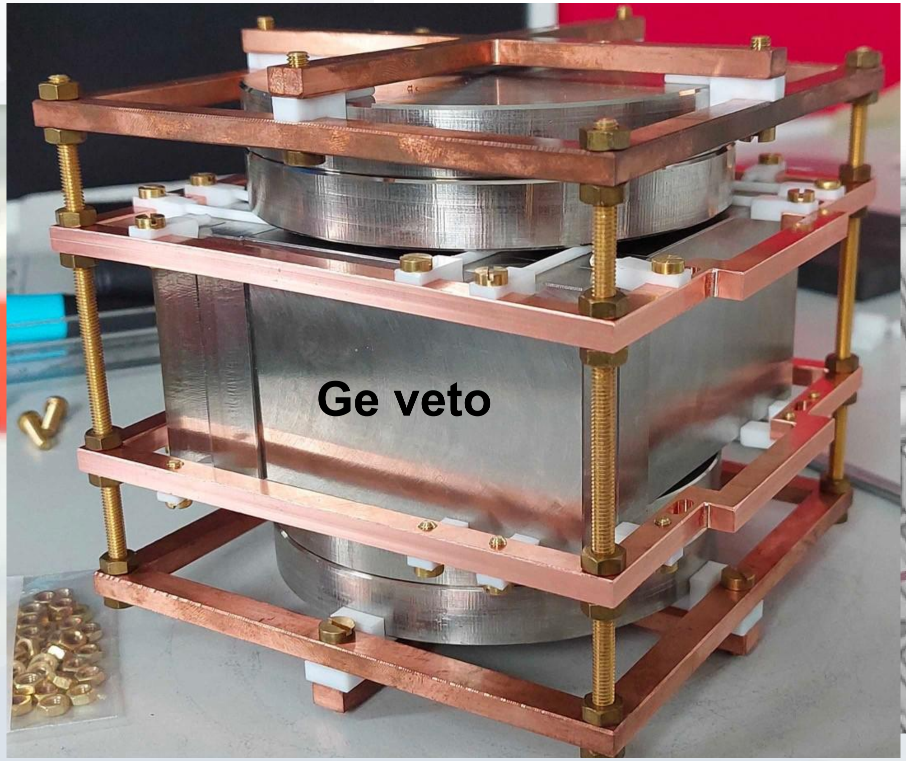
Datataking at reactor site starting in 2024!

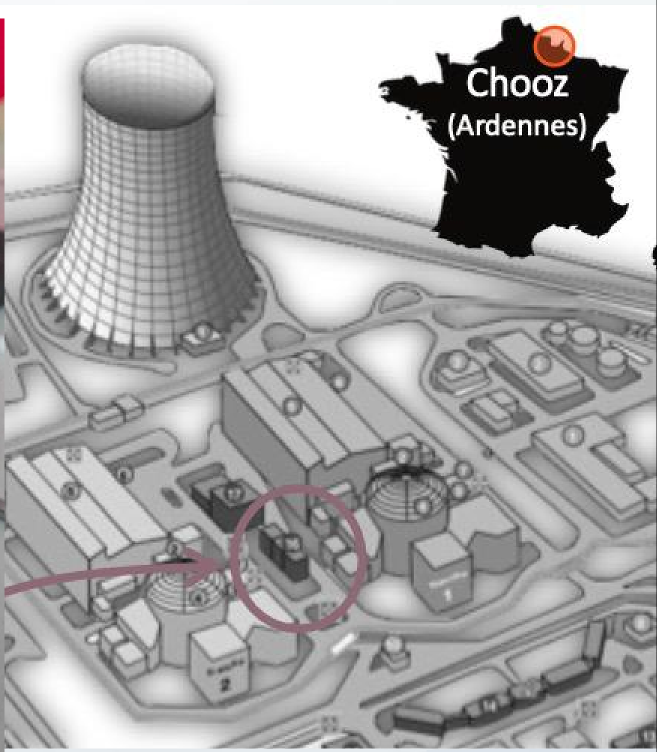
C. Augier, et al, Eur. Phys. J. C 83 (2023) 20

CENNS experiments: NuCLEUS

- Neutrino target: 9 Al_2O_3 (4 g) and 9 $CaWO_4$ (6 g) crystals
- 20 eVnr threshold, outer and inner vetos for bkg rejection
- Neutrino source: Chooz nuclear plant







G. Angloher et al., Eur. Phys. J. C, 79 (2019) 1018

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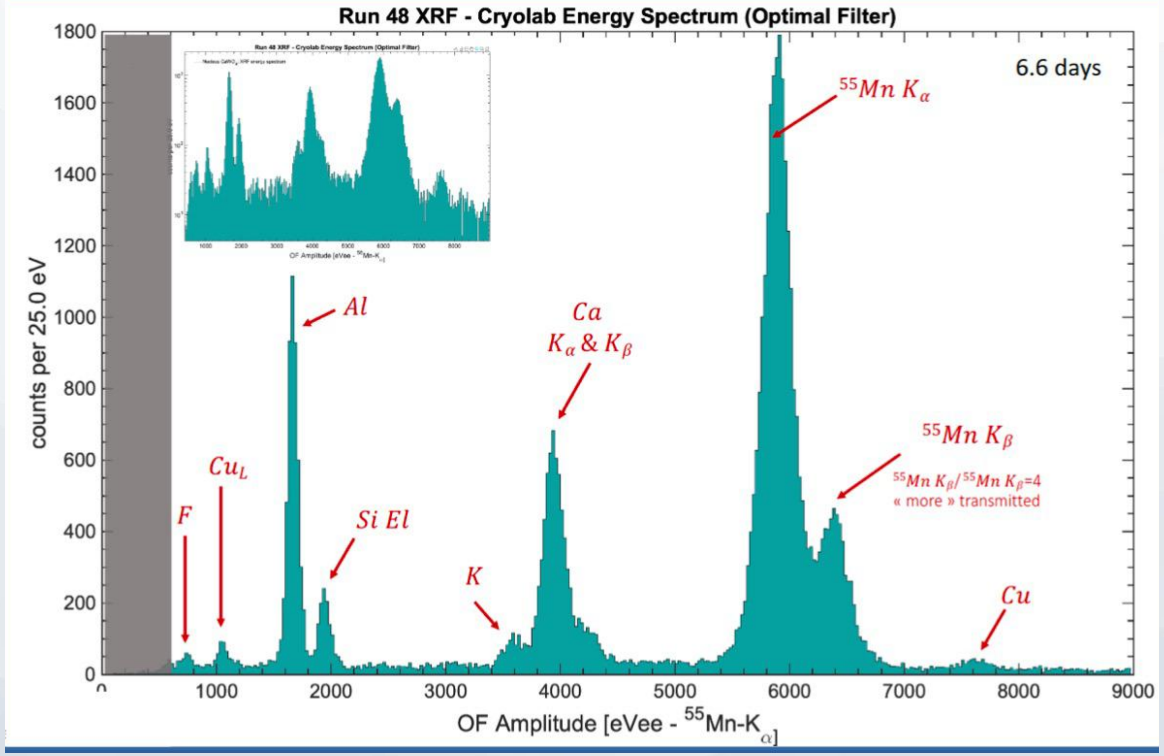
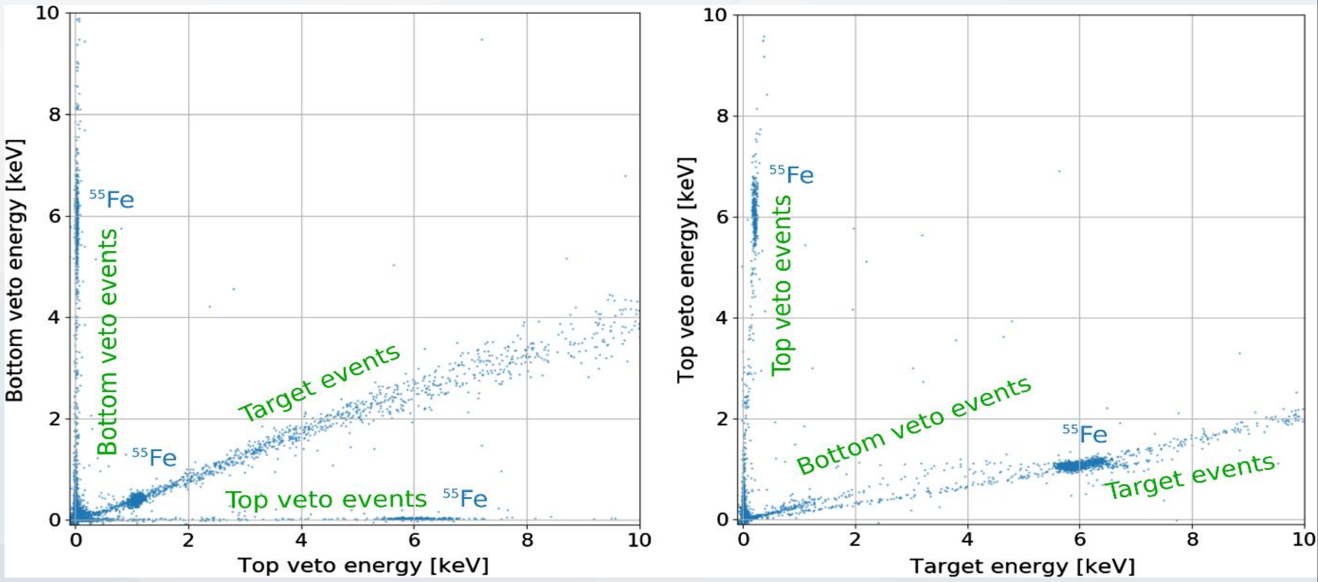




First neutrino run at Chooz in 2024/2025!

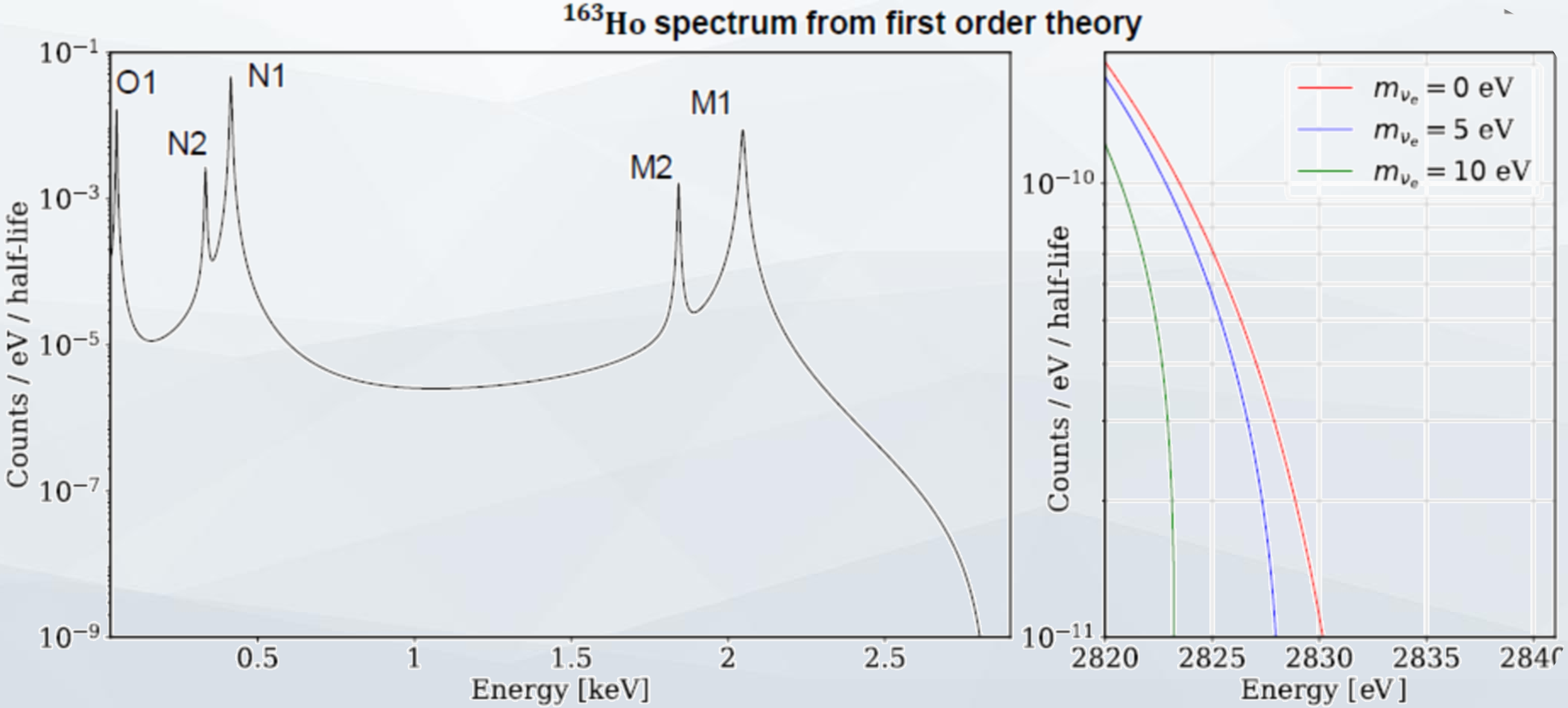
G. Angloher et al., Eur. Phys. J. C, 79 (2019) 1018

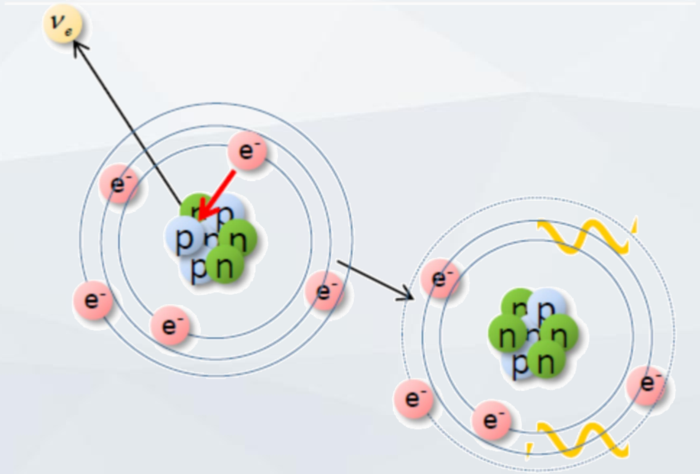
Direct neutrino mass measurements

Direct neutrino mass measurements

- **Model-independent measurement**: kinematics
- High-precision measurement of end-point of β spectrum (or EC)
- Good energy resolution and efficiency is needed -> bolometers

$^{163}Ho \rightarrow {}^{163}Dy^{*} + \nu_e$ - $Q \sim 2.8$ keV



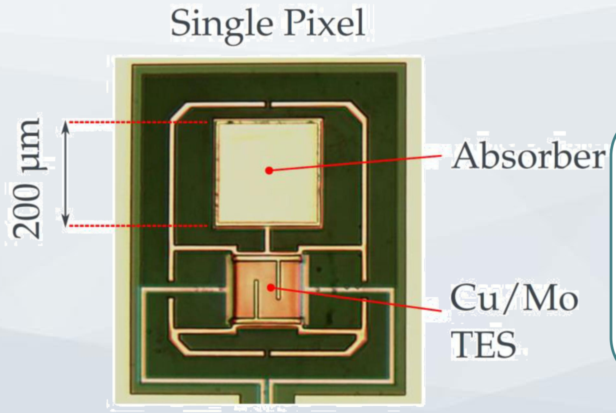


$T_{1/2}$=4570 yr

Experiments with ^{163}Ho

- Required activity in the detectors :
  Final experiment $>10^6$ Bq $>10^{17}$ atoms
- Precision characterization of the endpoint region $E_{FWHM} < 3$ eV
- Background level $< 10^{-6}$ events/det/day

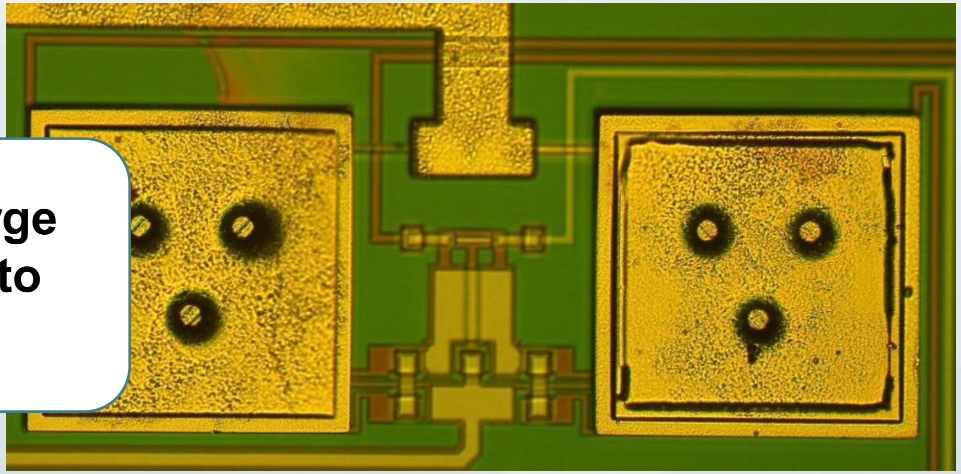
HOLMES



Both experiments use large arrays and multiplexing to limit pile-ups

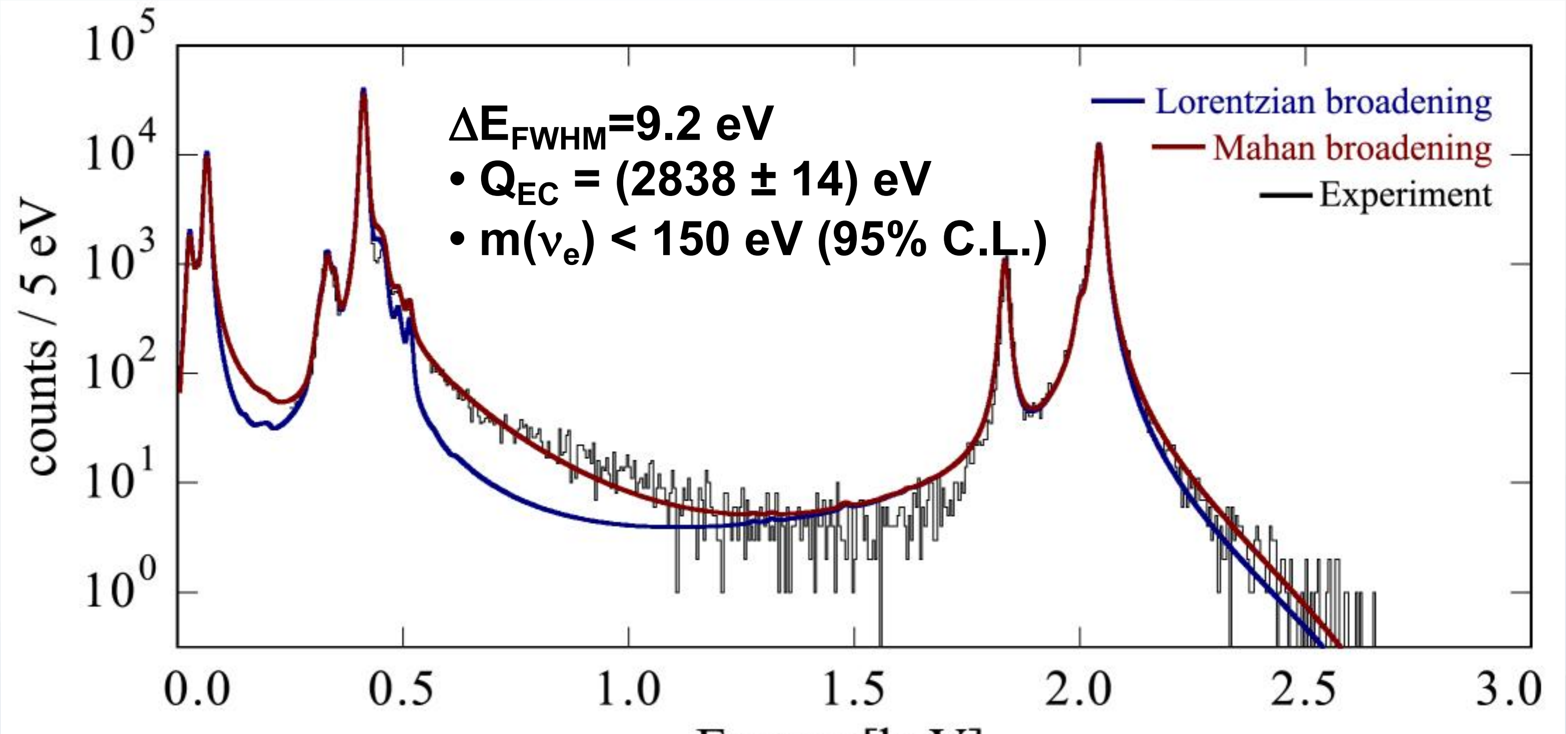
ECHo

MMC

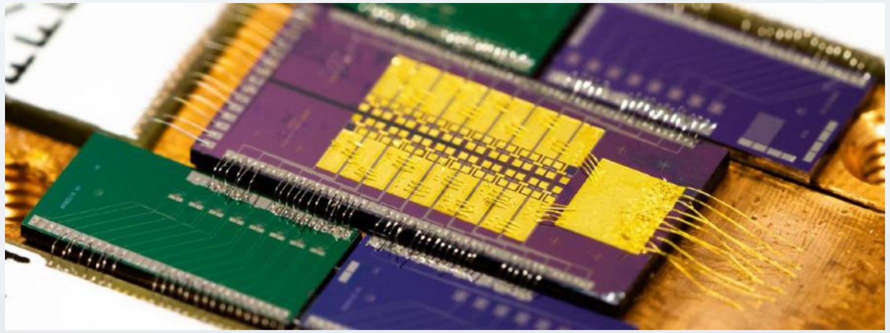


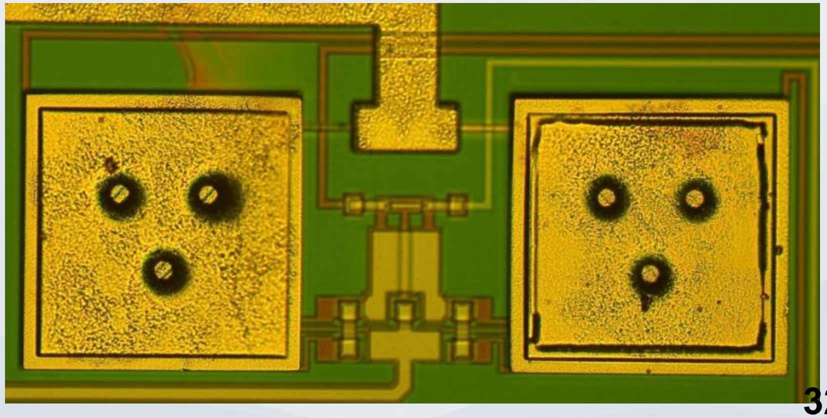
Experiments with ^{163}Ho

- Metallic magnetic calorimeters
- Reliable performance with ^{163}Ho implanted (Ag and Au): 0.2 Bq
- Parallel readout tested



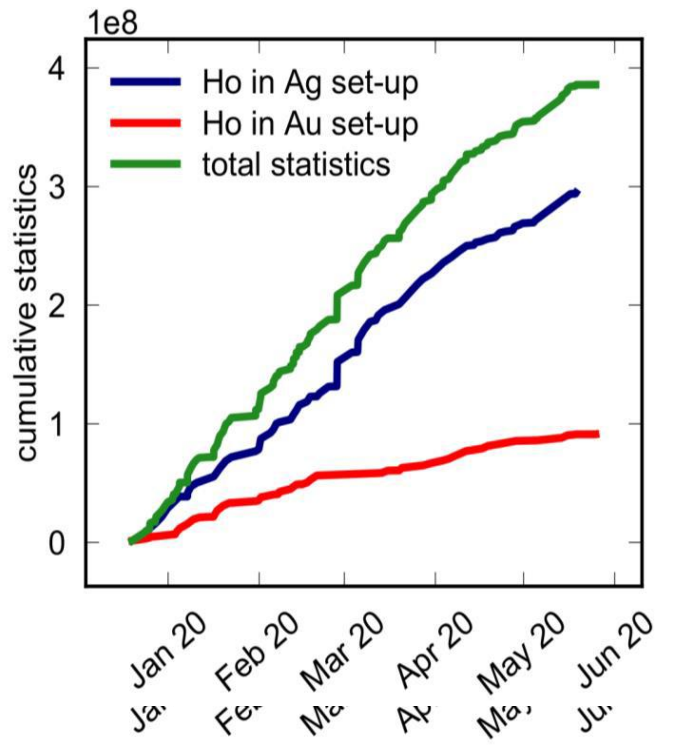
C. Velte et al., EPJC 79 (2019) 1026

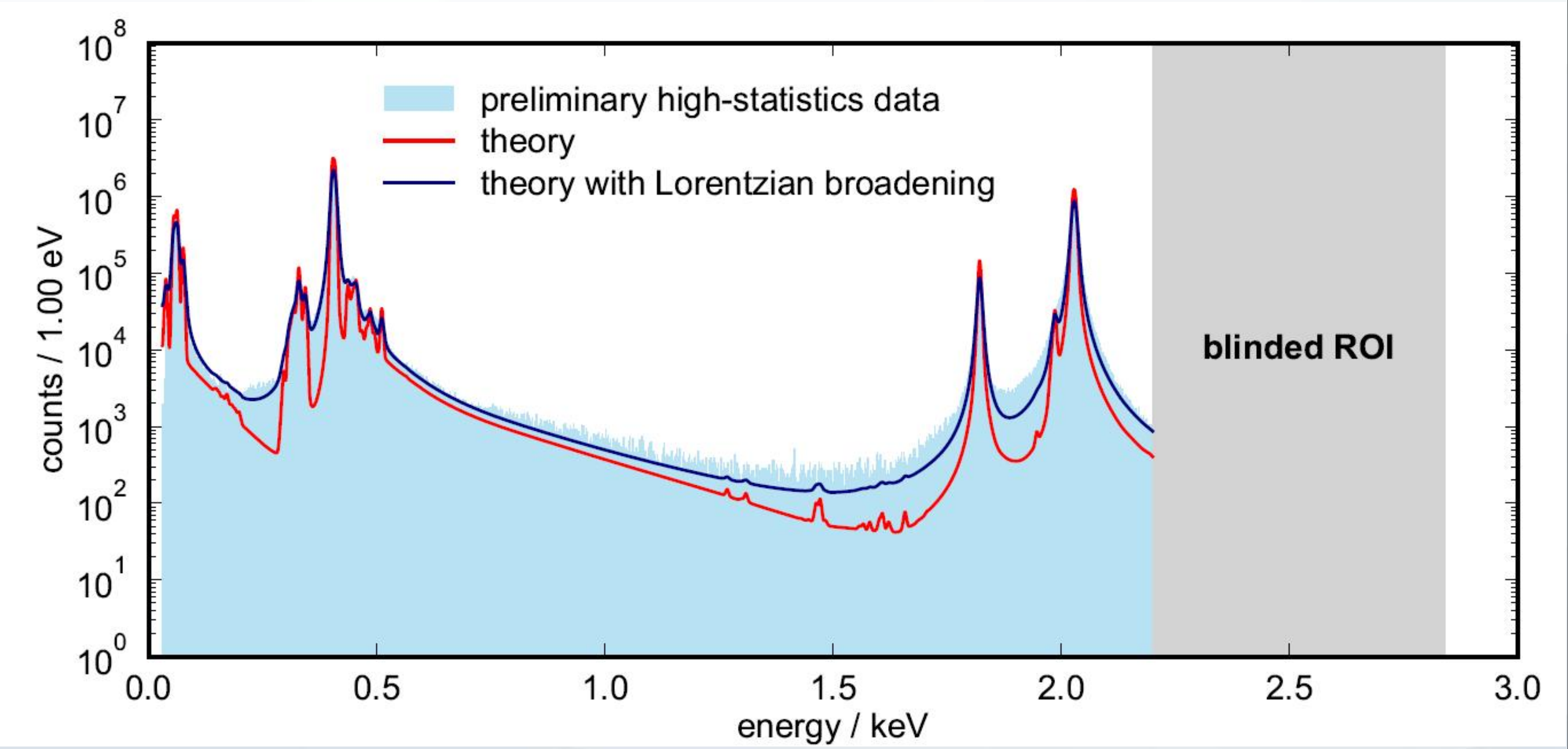




ECHo-1k spectrum

- Fraction of data corresponding to 6 x10^7 events acquired with detectors having ^{163}Ho

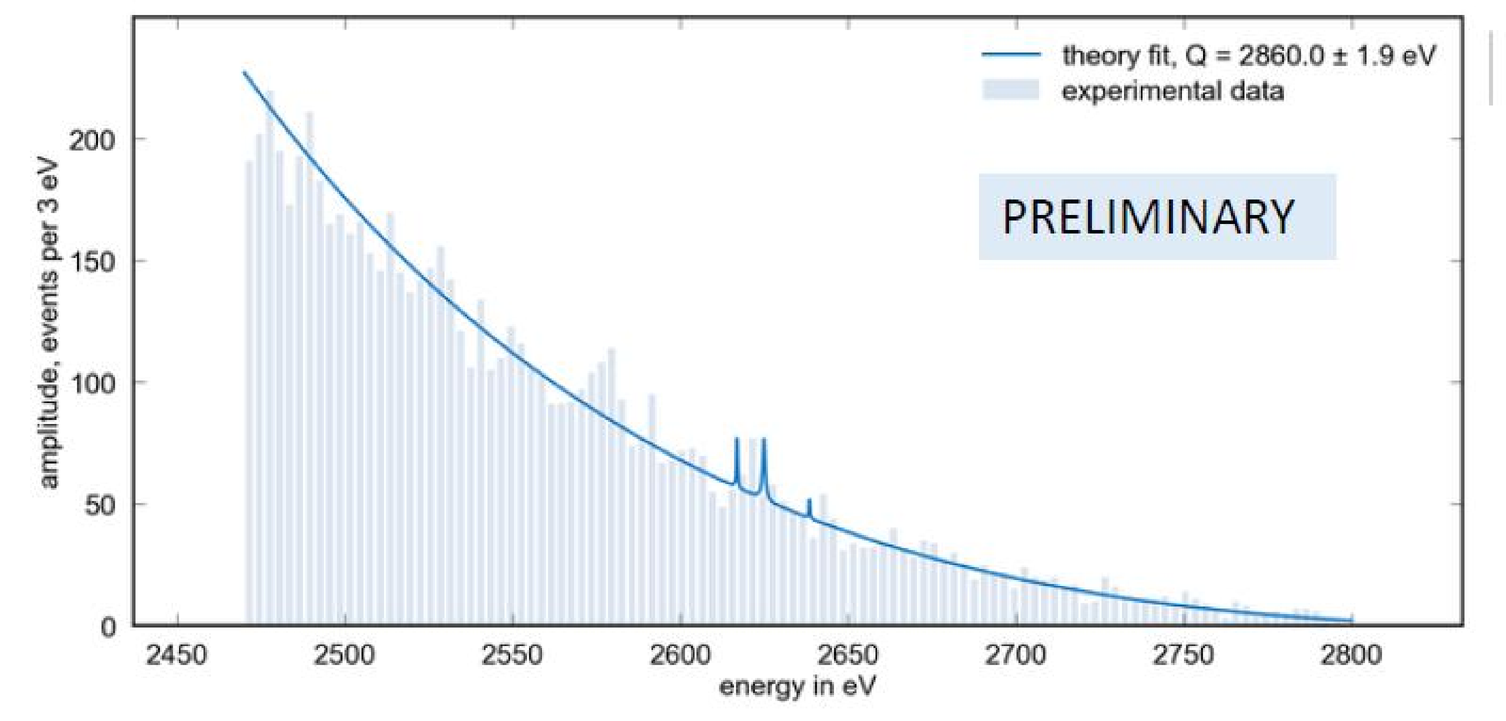


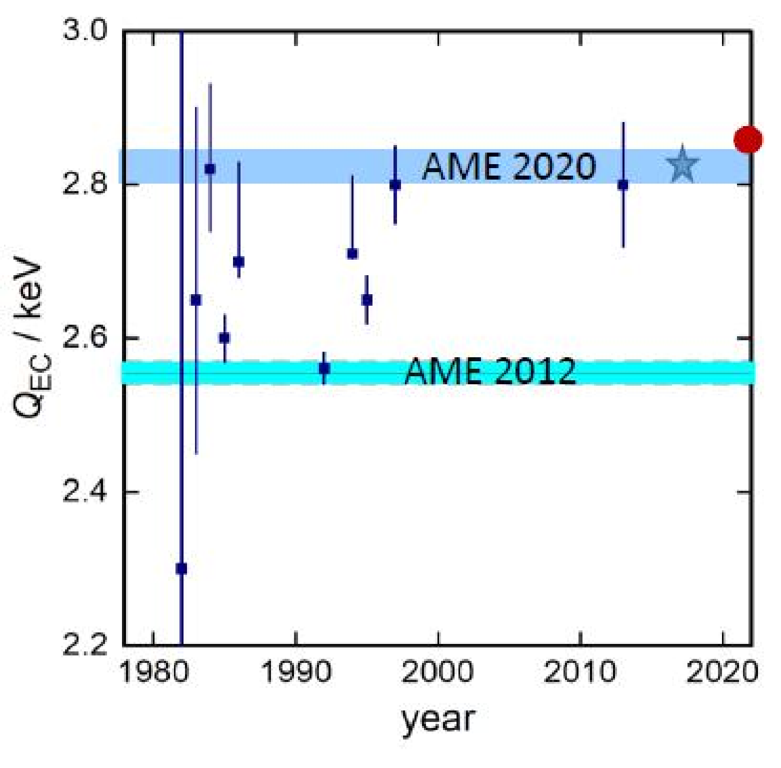


M. Braß et al., Phys. Rev. C 97 (2018) 054620,
M. Braß M. W. Haverkort, New J. Phys. 22 (2020) 093018
M. Merstorf et al, arXiv:2307.13812 [physics.atom-ph]

ECHo-1k spectrum

- Determination of Q_{EC} by fitting the spectrum using:
- Brass & Haverkort theory
- Flat background

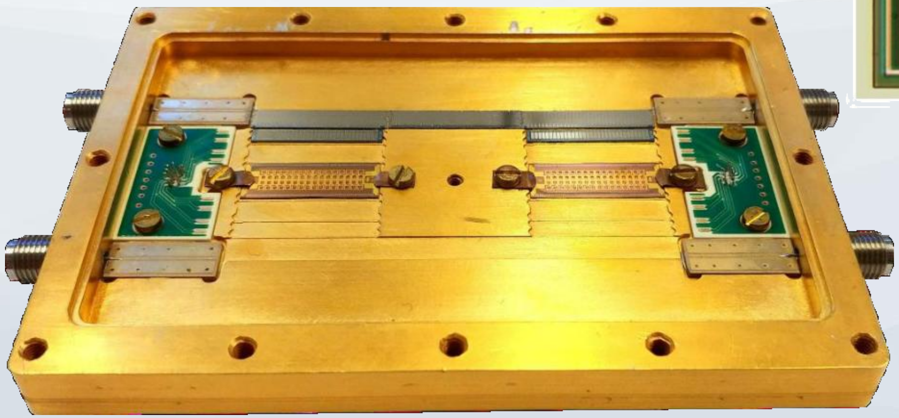


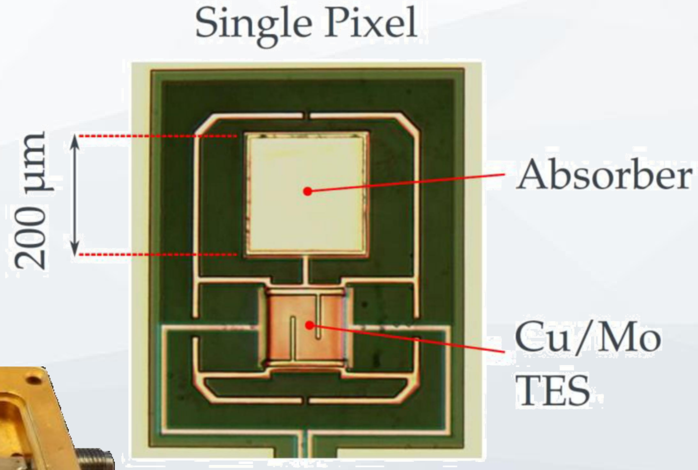


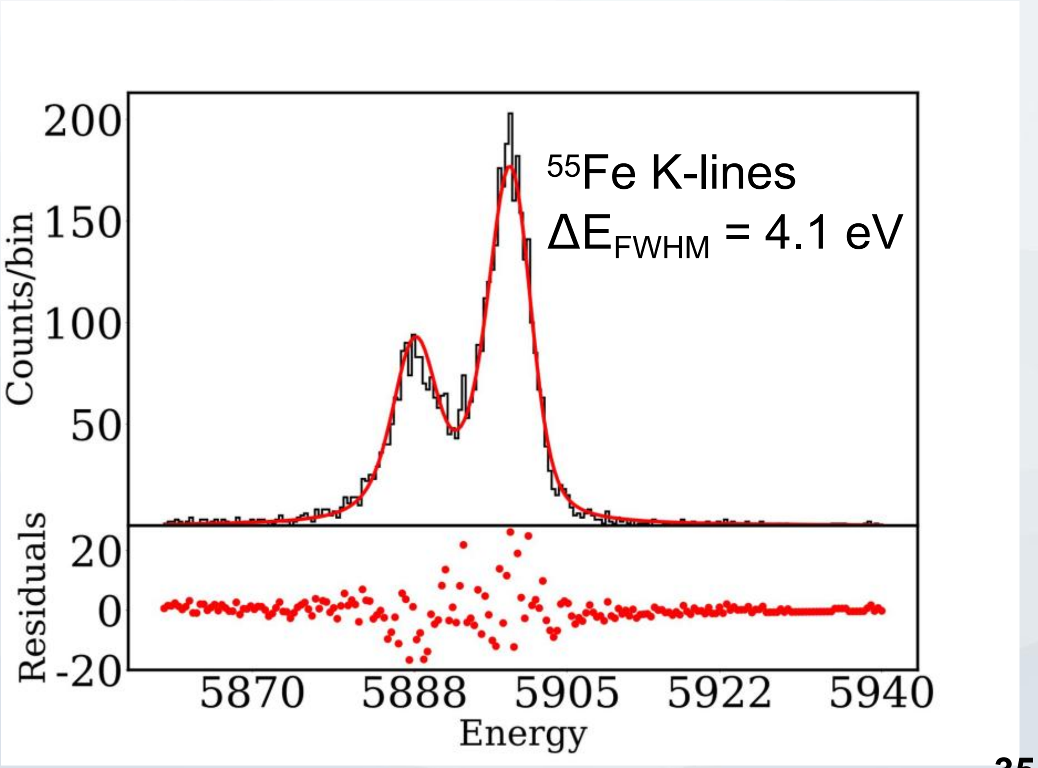
$Q_{EC} = (2860 \pm 2_{stat} \pm 5_{syst})$ eV

Experiments with ^{163}Ho

- Array of transition edge sensors calorimeters, $\Delta E \sim 1$ eV
- Microwave multiplexed readout
- Reliable performance demonstrated without ^{163}Ho



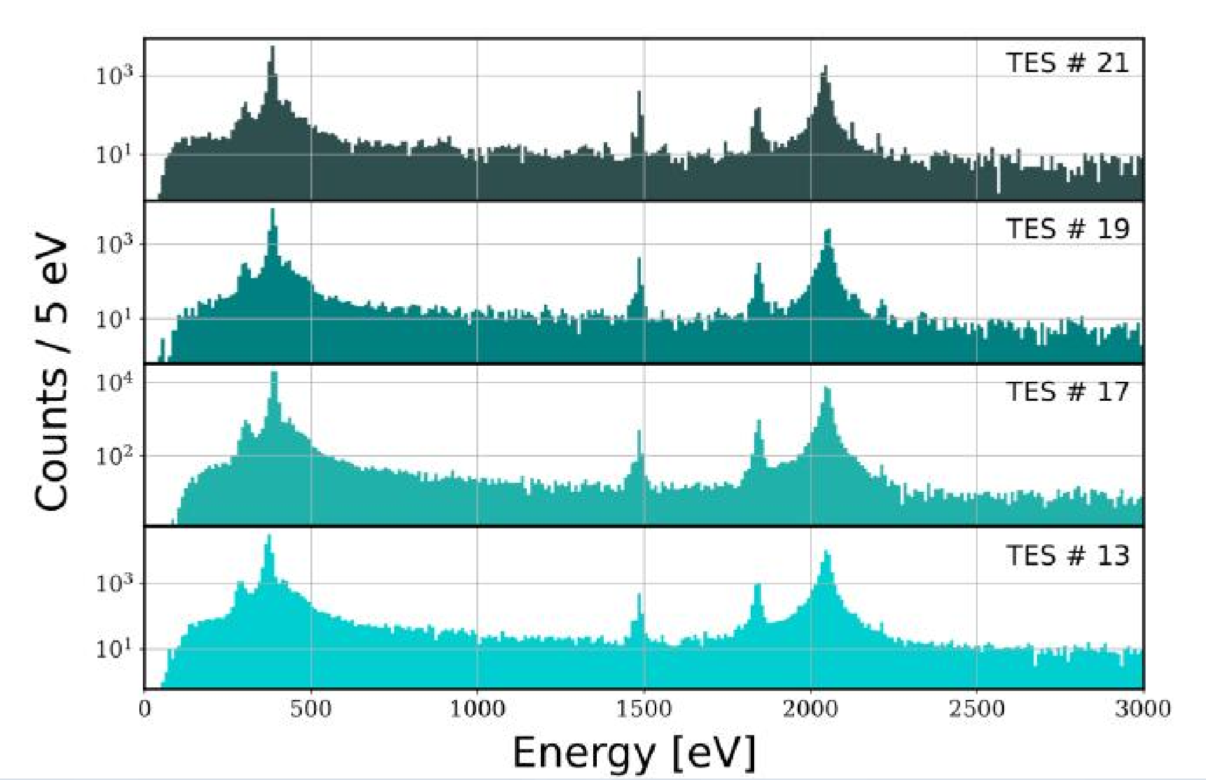


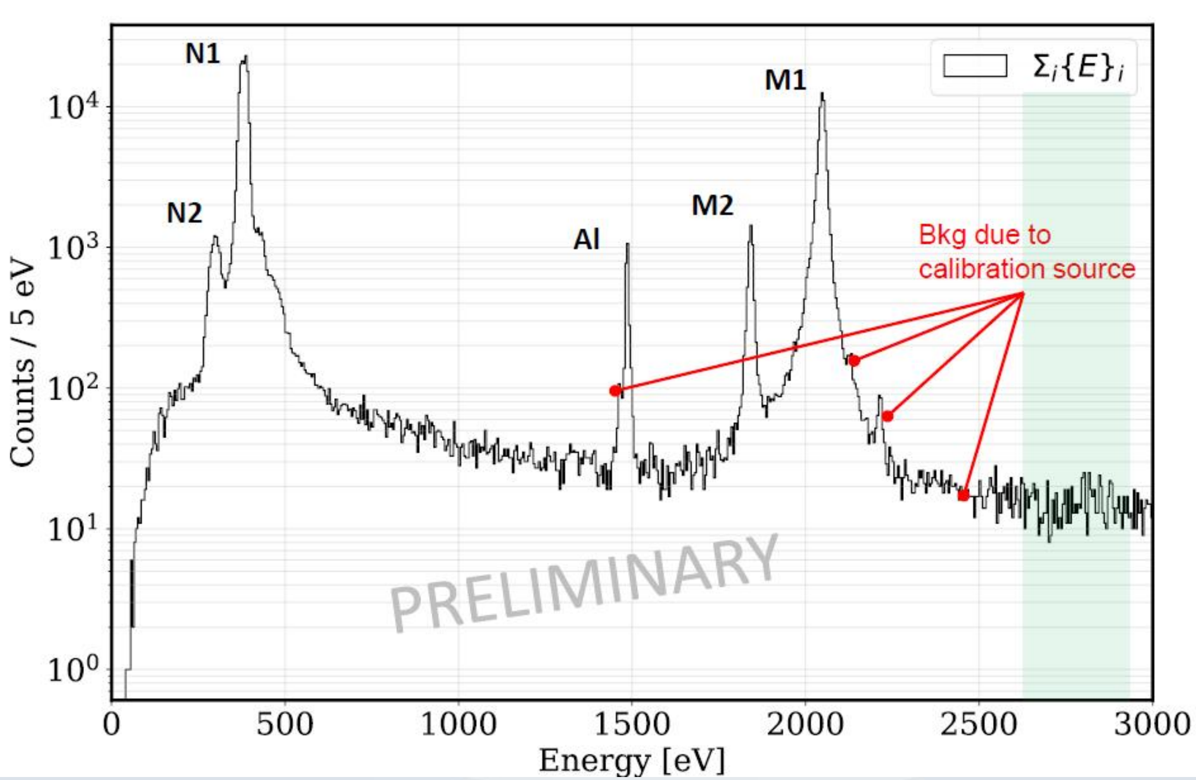


Experiments with ^{163}Ho

- Array of transition edge sensors calorimeters
- Microwave multiplexed readout
- First run with Ho implantation! ΔE = 6 ÷ 8 eV @6 keV

Expected first limit on neutrino mass is ~10 eV





Prospects

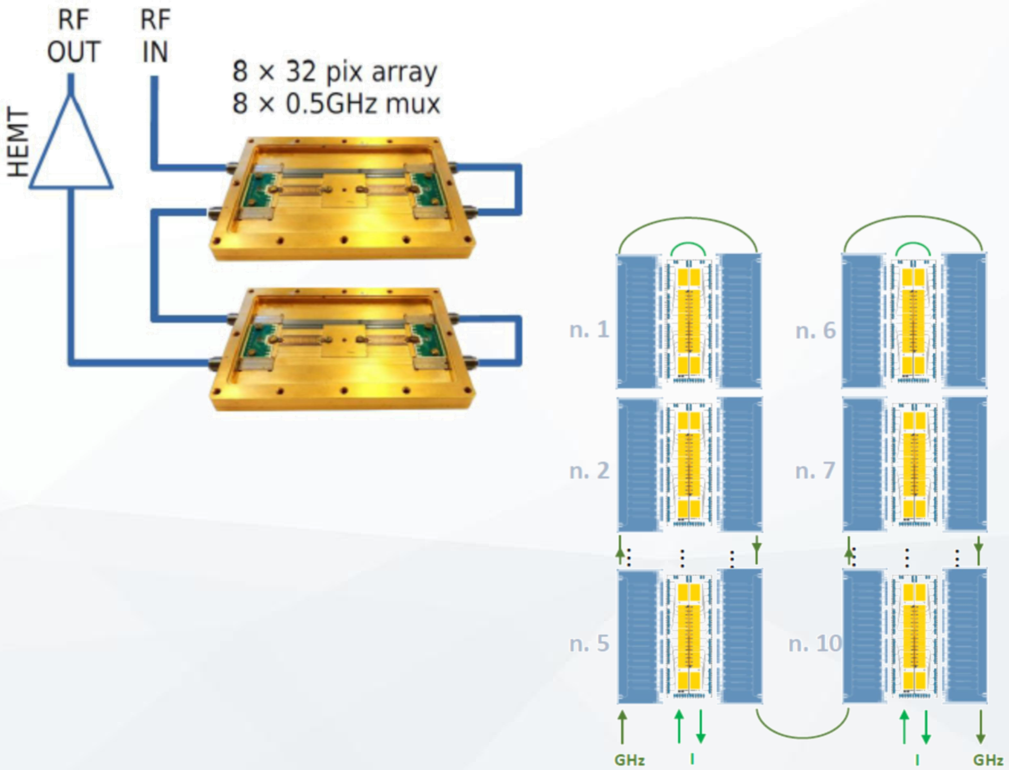
Final experiments:

Holmes:

- 1000 channels
- Activity per pixel: 300 Bq

ECHo-100K:

- 12000 channels
- Activity per pixel: 10 Bq



The goal is to achieve sensitivity near <0.2 eV with measurement of >10^{16} decays

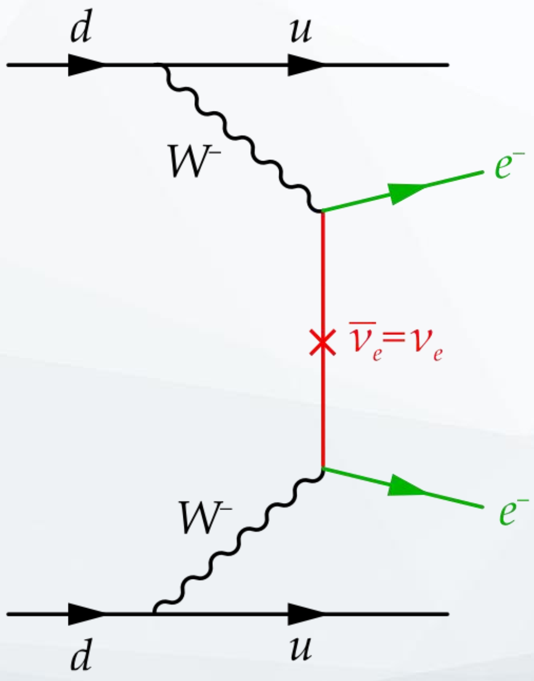
The determination of the electron neutrino mass with ^{163}Ho is complementary to the detererrmination with ^{3}H

F. Mantegazzini et al., NIM A 1055 (2023) 168564

Neutrinoless double beta decay

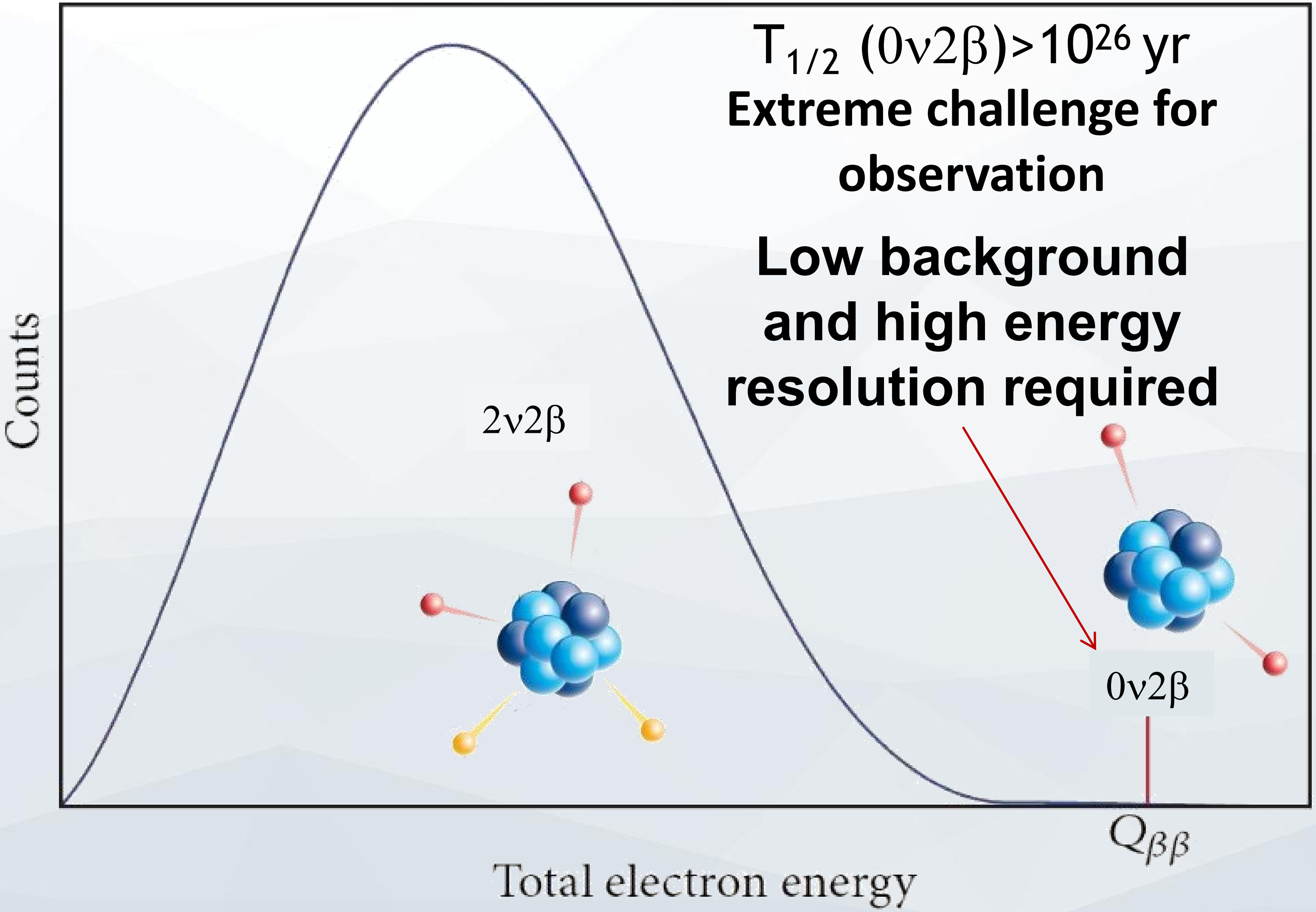
Neutrinoless double beta decay

(A,Z) → (A,Z+2) + 2e⁻



Fixes neutrino mass scale

Total lepton number violation →
new physics beyond SM

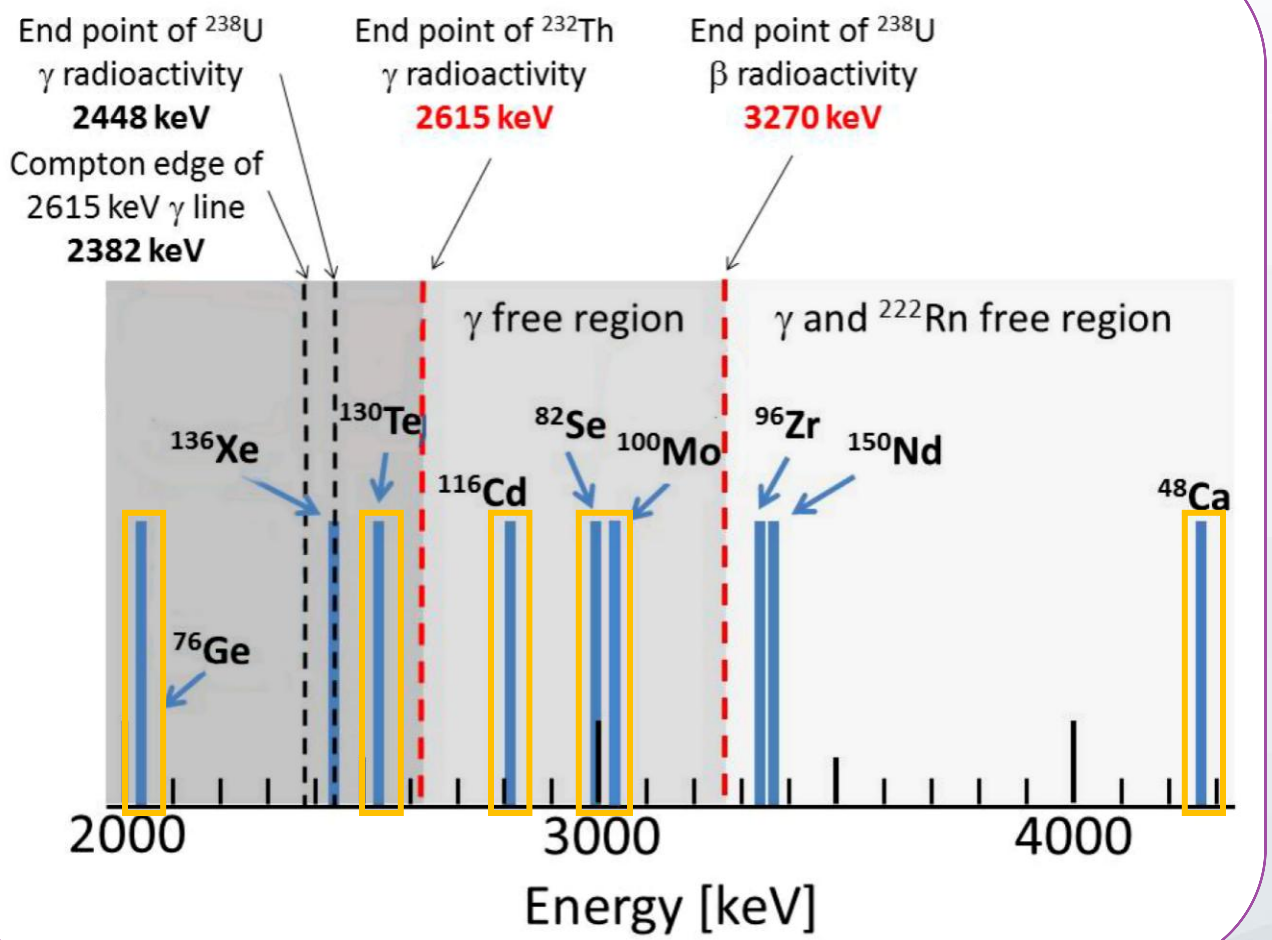


0ν2β decay candidates

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

Experimental requirements:

- Isotopic abundance and/or large scale enrichment
- High $Q_{\beta\beta} \rightarrow$ lower background level in ROI and higher $0\nu2\beta$ decay rate
- **Minimum two isotopes** should be measured: for observation and confirmation



Bolometric detectors technology applicable for most of candidates!

Status of current searches

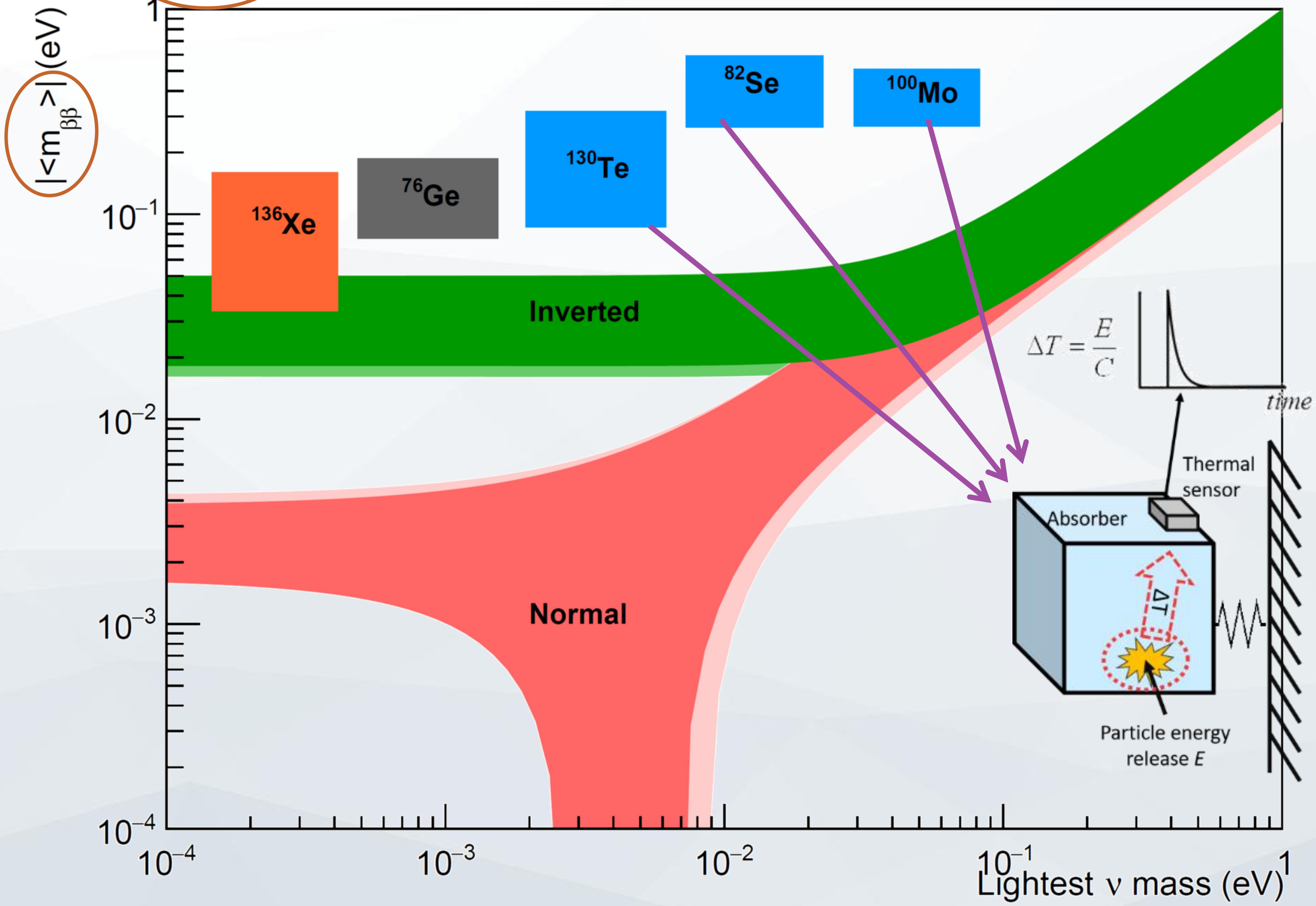
$$(T_{1/2}^{0\upsilon 2\beta})^{-1} = G^{0\upsilon}(Q,Z)\,|M^{0\upsilon}|^2 \frac{m_{\beta\beta}^2}{m_e^2}$$

$$\lim T_{1/2}^{0\upsilon 2\beta} \propto \mathbf{a} \cdot \epsilon \cdot \sqrt{\frac{\mathbf{M} \cdot t}{\mathbf{b} \cdot \delta E}}$$

In case of **b** · Δ**E** · **M** · **t<<1**:

$$\lim T_{1/2}^{0\upsilon 2\beta} \propto \mathbf{a} \cdot \epsilon \cdot M \cdot t$$

$$|m_{\beta\beta}| = |c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{i\alpha} + s_{13}^2 m_3 e^{i\beta}|$$



Status of current searches

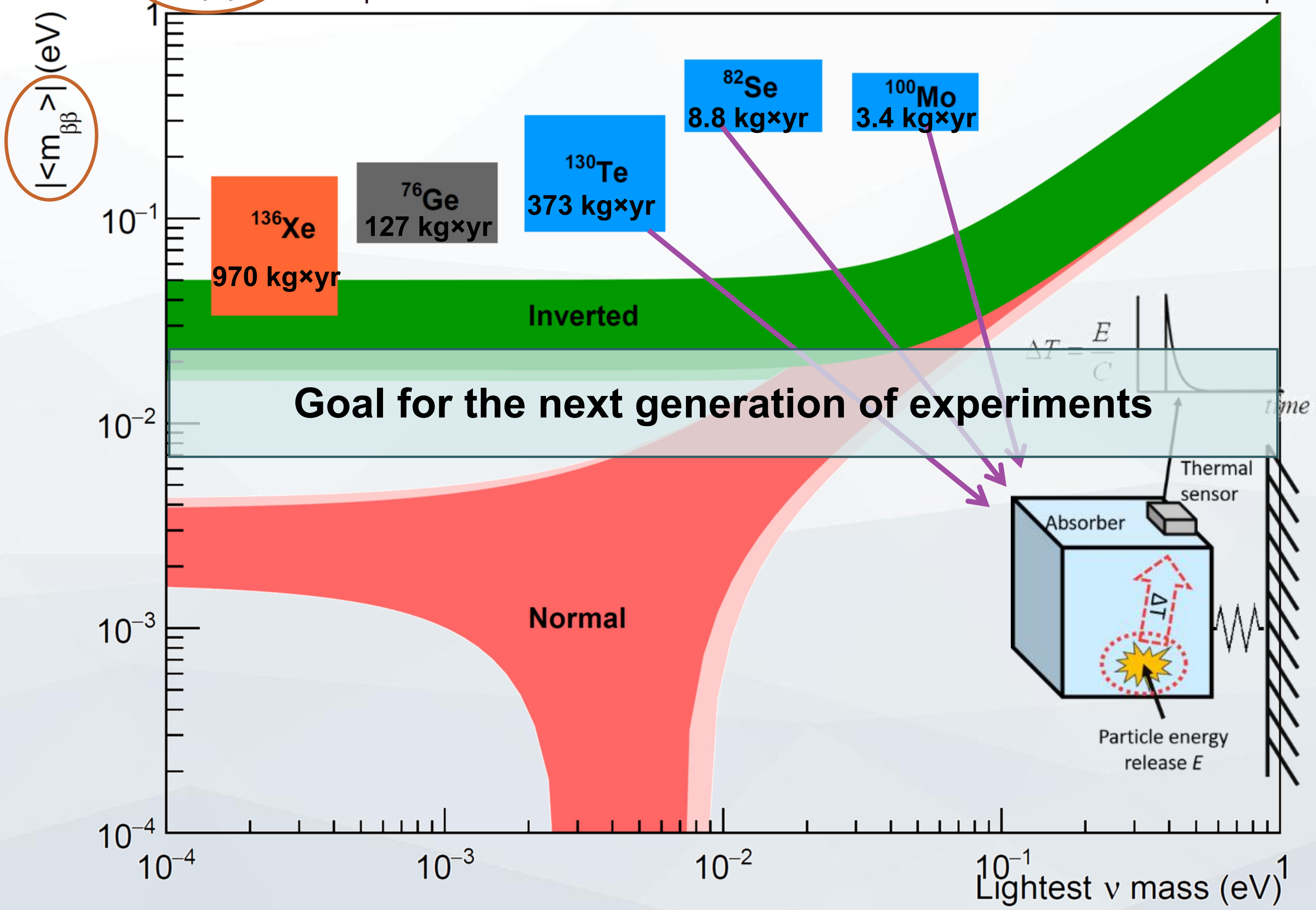
$$(T_{1/2}^{0\nu 2\beta})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2 \frac{m_{\beta\beta}^2}{m_e^2}$$

$$\lim T_{1/2}^{0\nu 2\beta} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$$

In case of $b \cdot \Delta E \cdot M \cdot t \ll 1$:

$$\lim T_{1/2}^{0\nu 2\beta} \propto a \cdot \epsilon \cdot M \cdot t$$

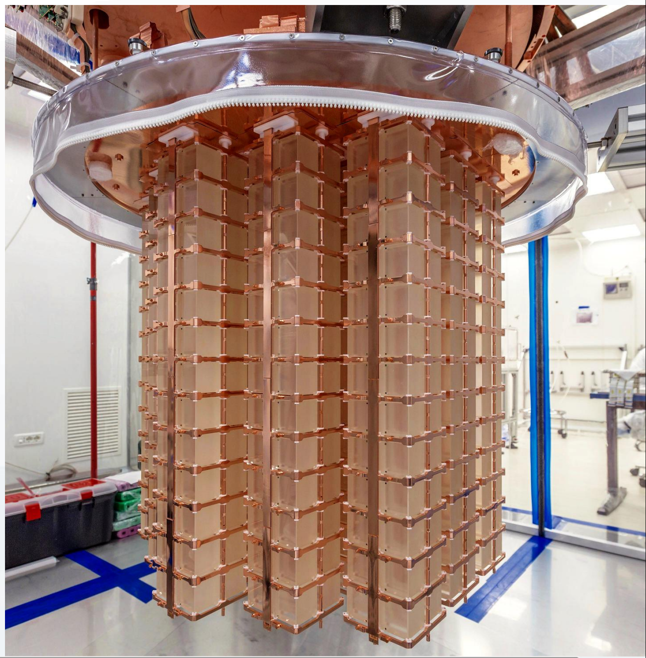
$$|m_{\beta\beta}| = |c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{i\alpha} + s_{13}^2 m_3 e^{i\beta}|$$



Demonstrators and large experiments

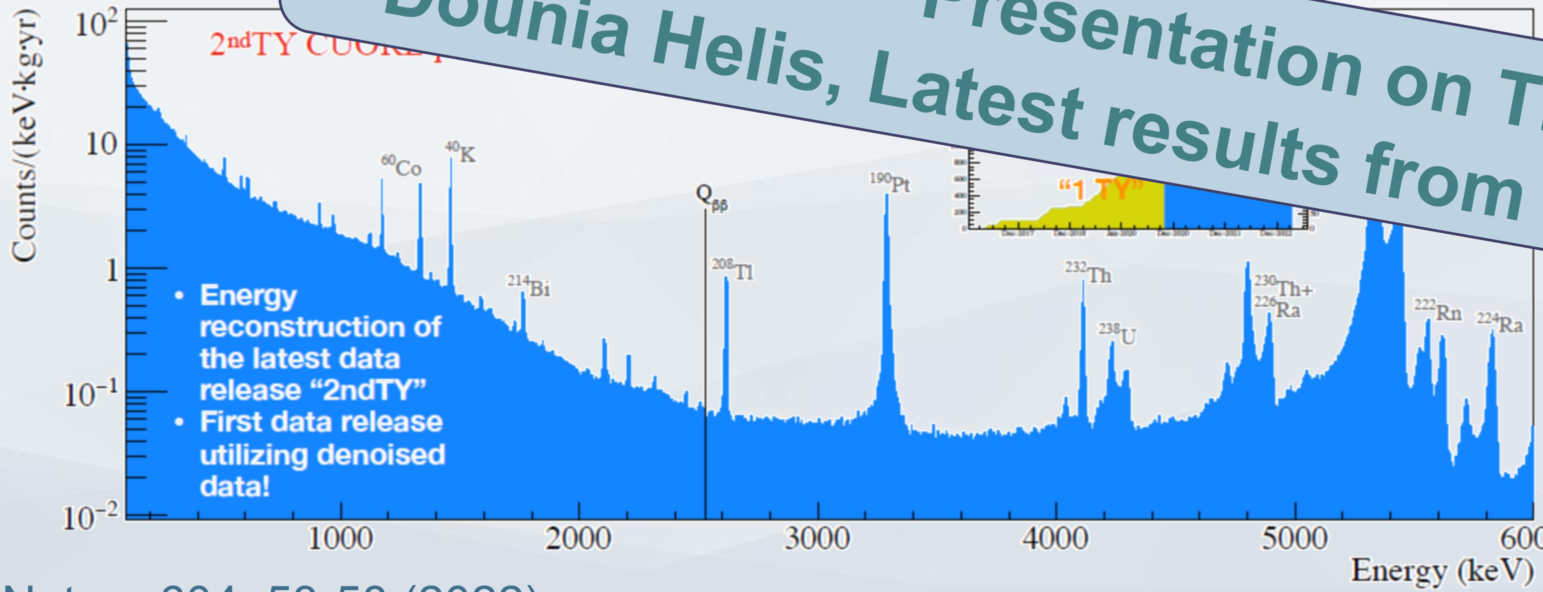
CUORE: the largest bolometric experiment

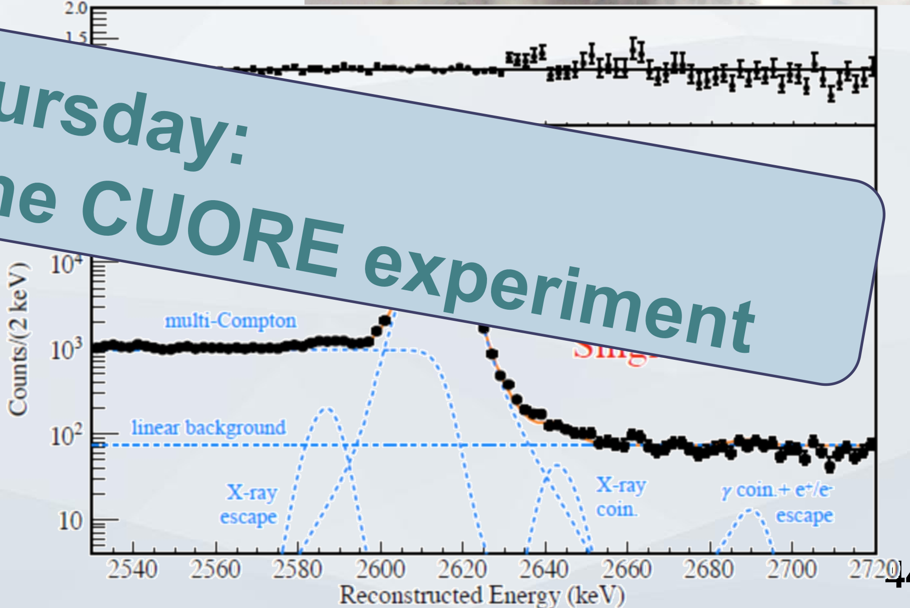
- Cryogenic Underground Observatory for Rare Events
- **First ton scale** array of cryogenic calorimeters: **988 TeO_2 crystals** (0.75 kg each)
- $\Delta E_{\beta\beta}$=7.3±0.4 keV at ROI



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

E... limit: $m_{\beta\beta} < 75 - 255\, meV$



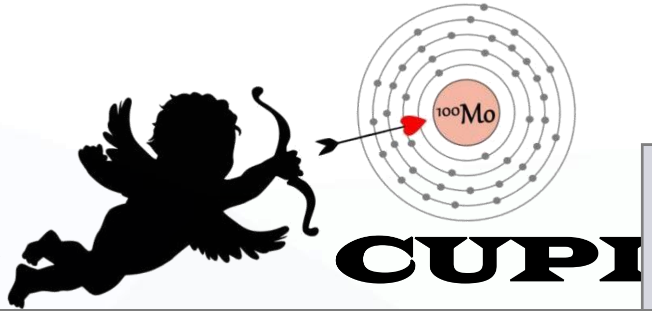


Presentation on Thursday: Dounia Helis, Latest results from the CUORE experiment

Nature 604, 53-58 (2022)

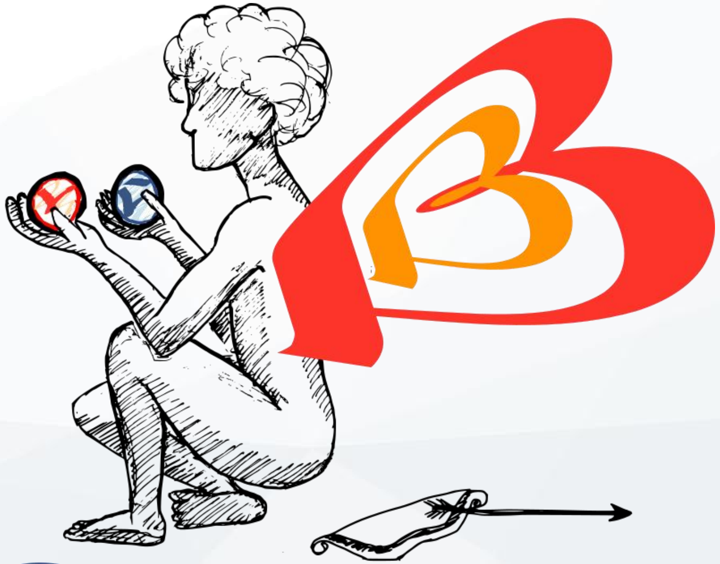
CUPID: past and future

CUORE: first ton-scale
DBD experiment at 10 mK
No particle ID



CUPID demonstrators:
a rejection with light
Best limits on
^{100}Mo and ^{82}Se $0\nu2\beta$

CUPID-0



CUPID

Phase II

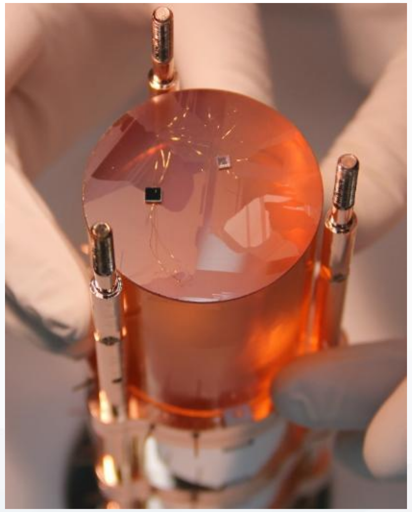
New demonstrators for
deeper investigations of
normal mass ordering

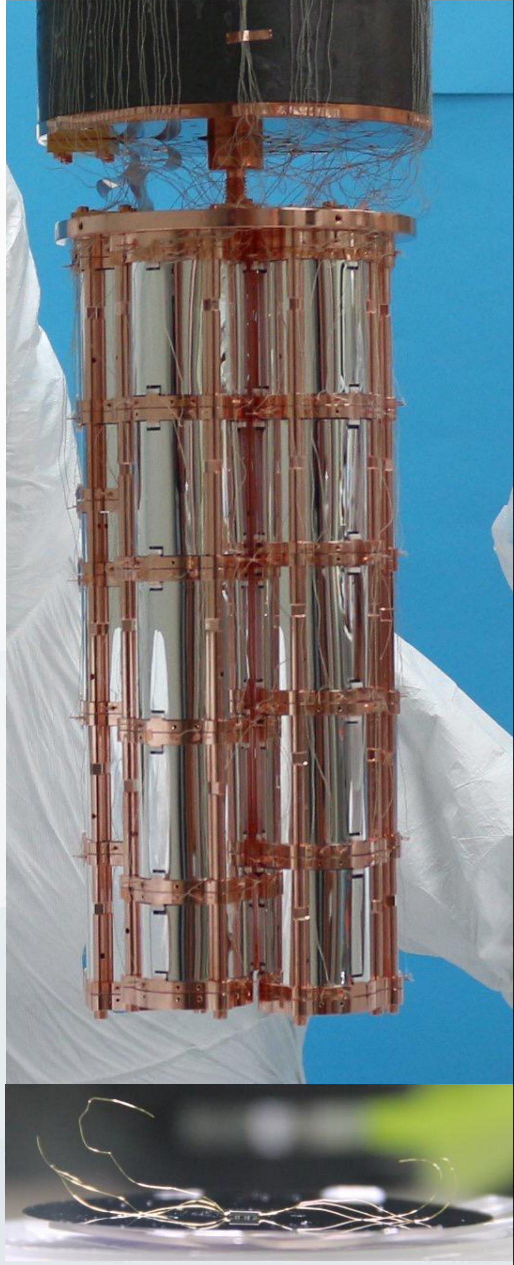
BINGO

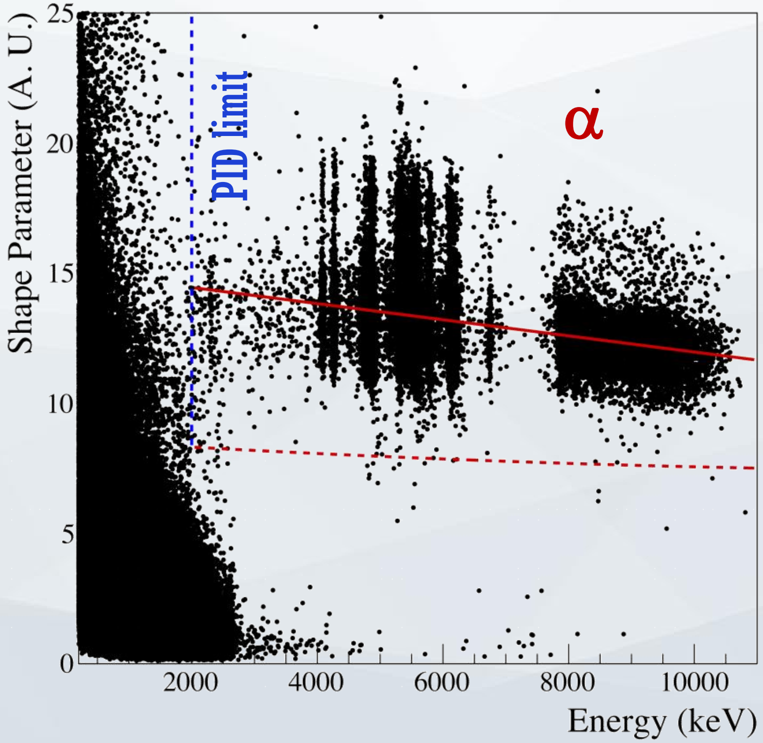
CROSS

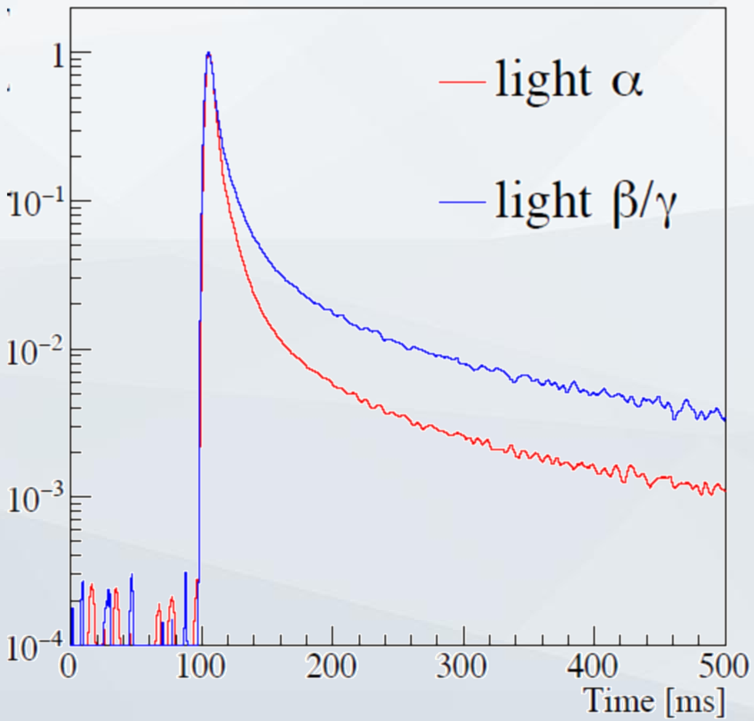
CUPID-0 demonstrator (^{82}Se)

- 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**)







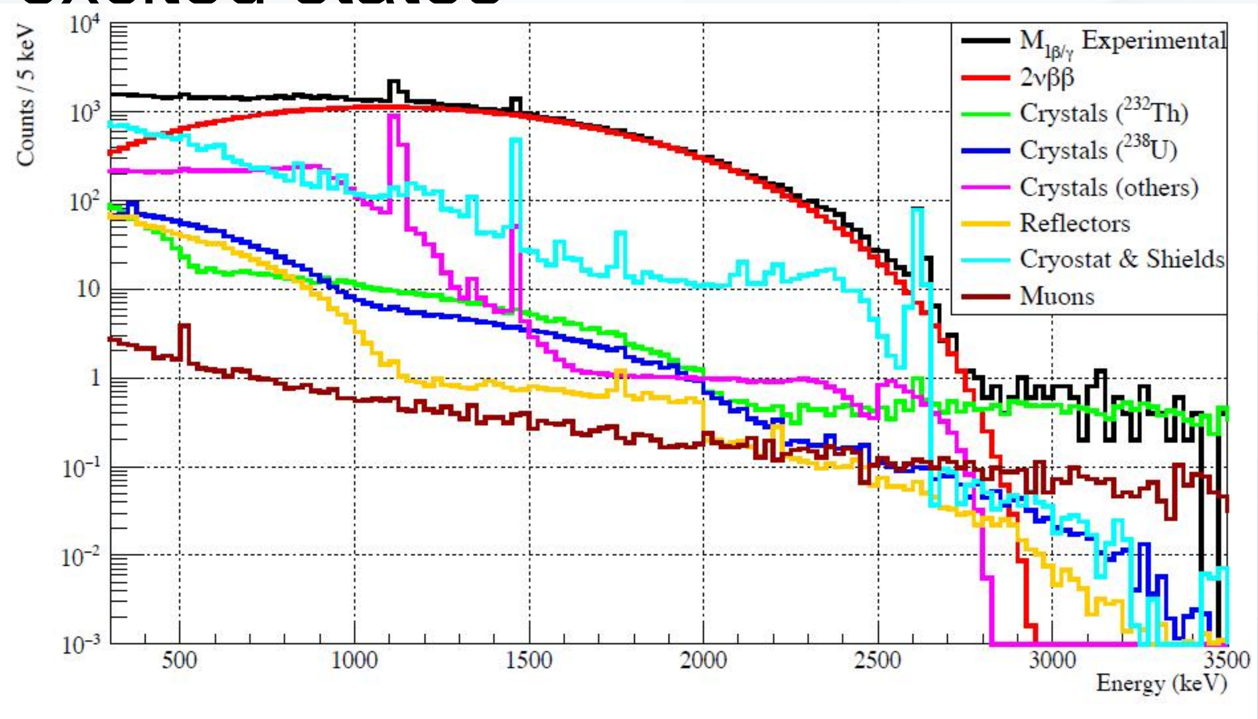


EPJC (2018) 78:428

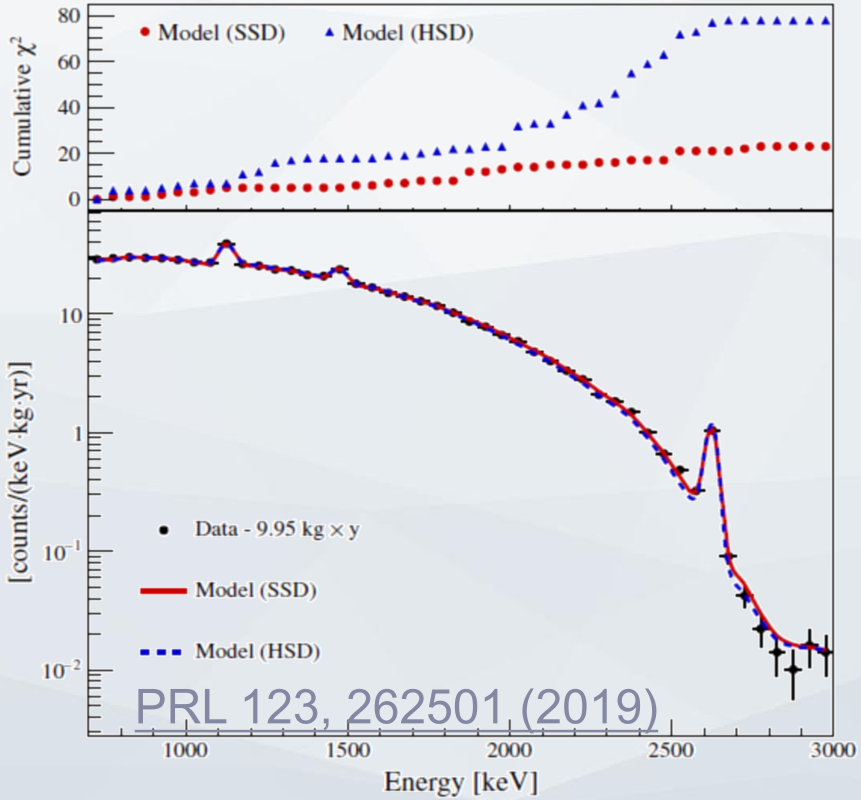
CUPID-0 results

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

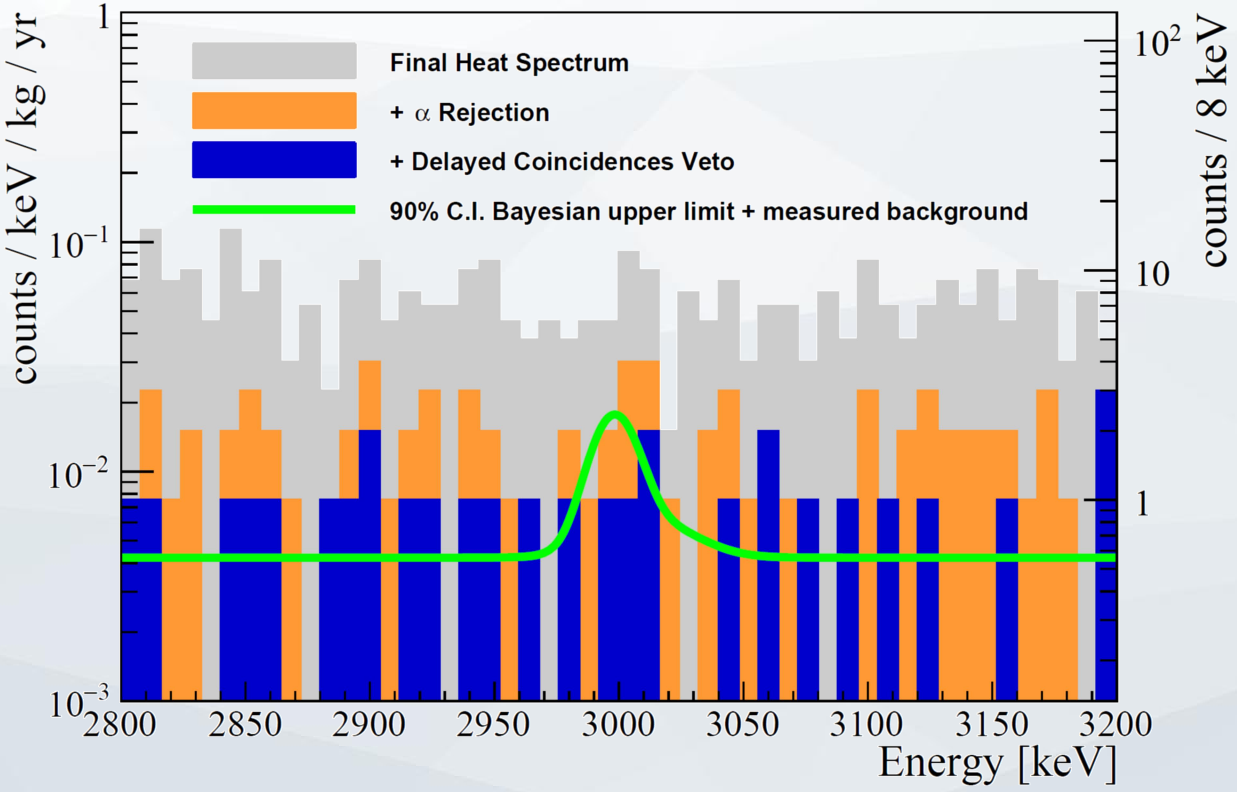
FWHM @ $Q_{\beta\beta}$=(20.05 ± 0.34) keV

- 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

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

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

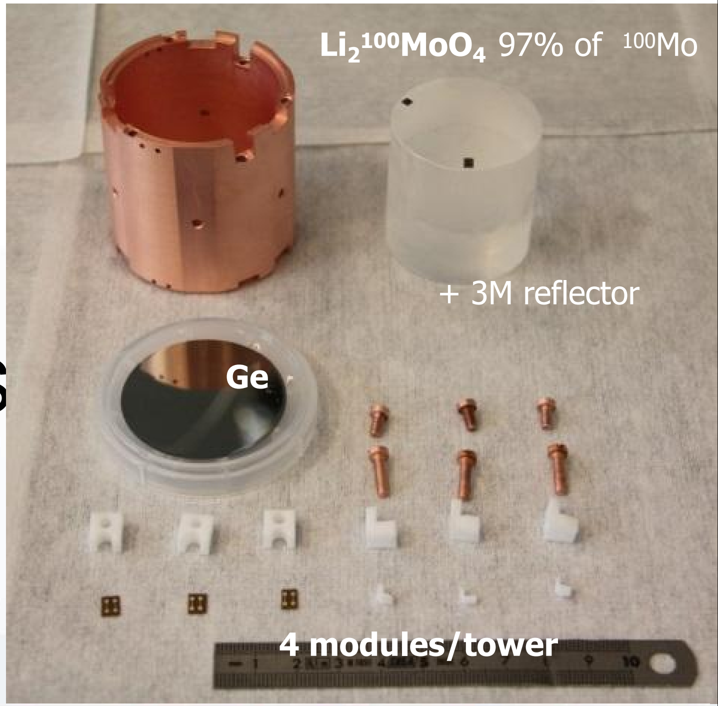
PRD 100, 092002 (2019)
PRL 123, 262501 (2019)
EPJC 79, 583 (2019)
EPJC 81, 722 (2021)

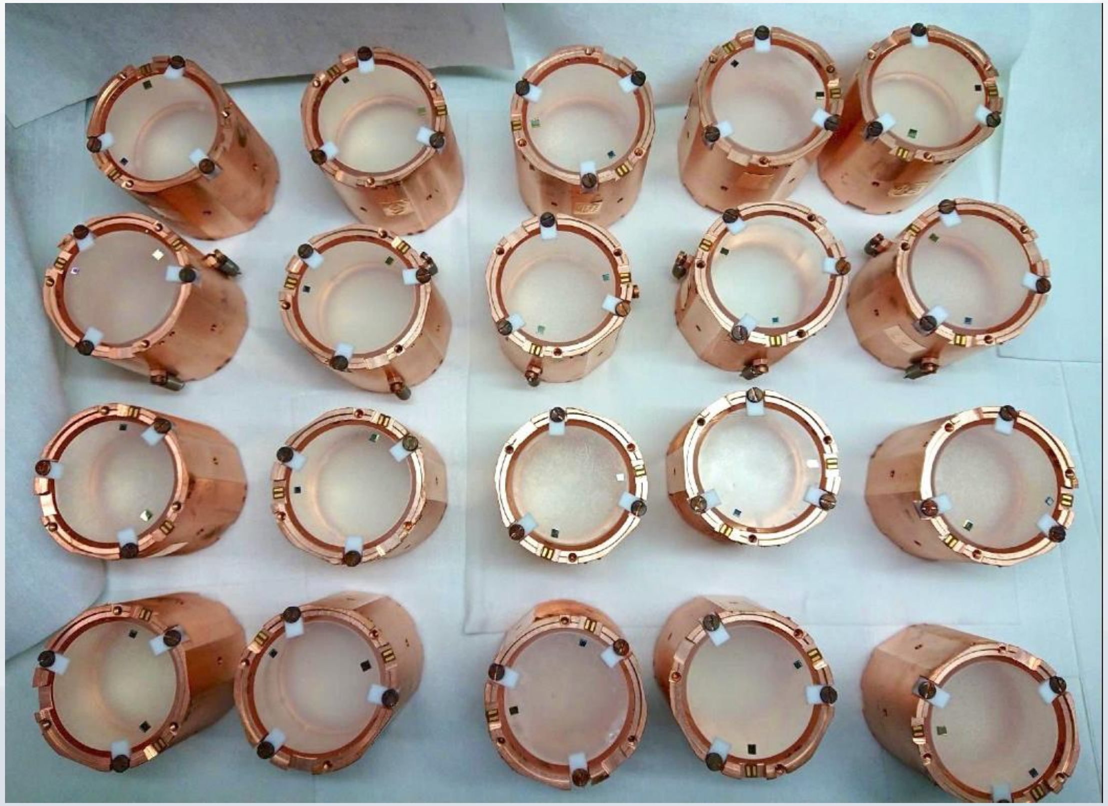


*

CUPID-Mo

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

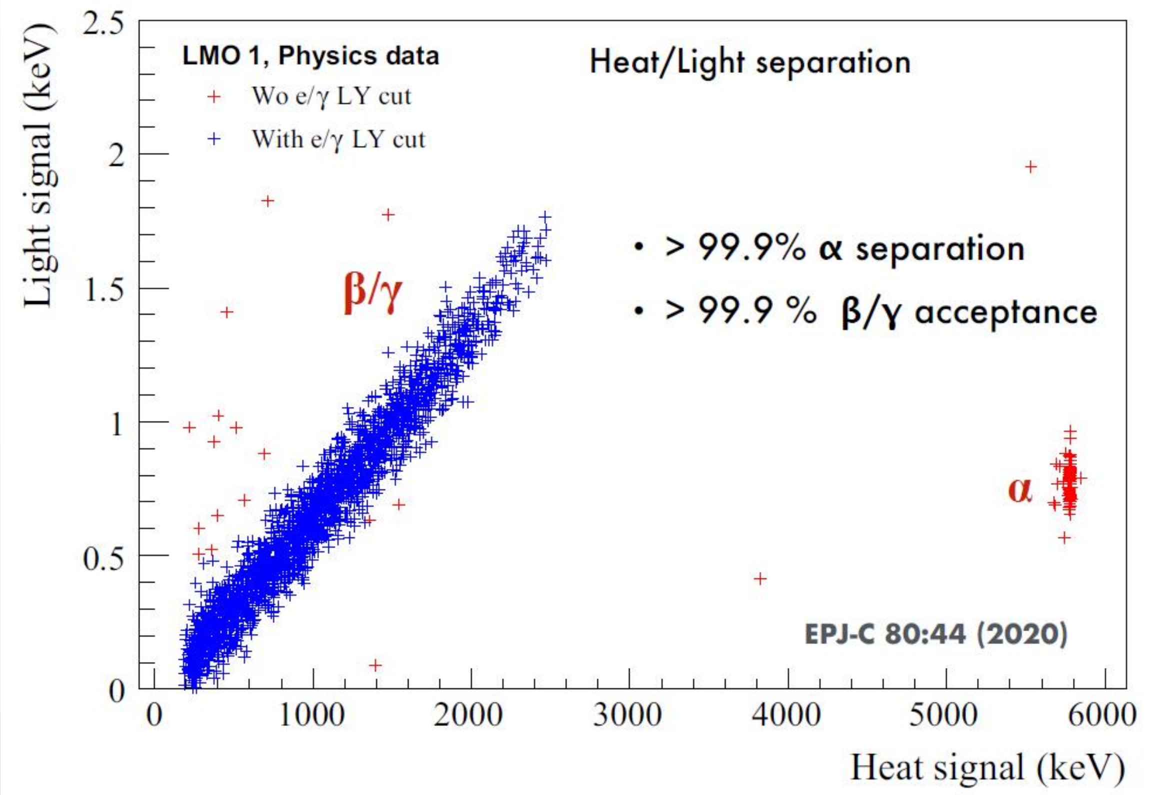


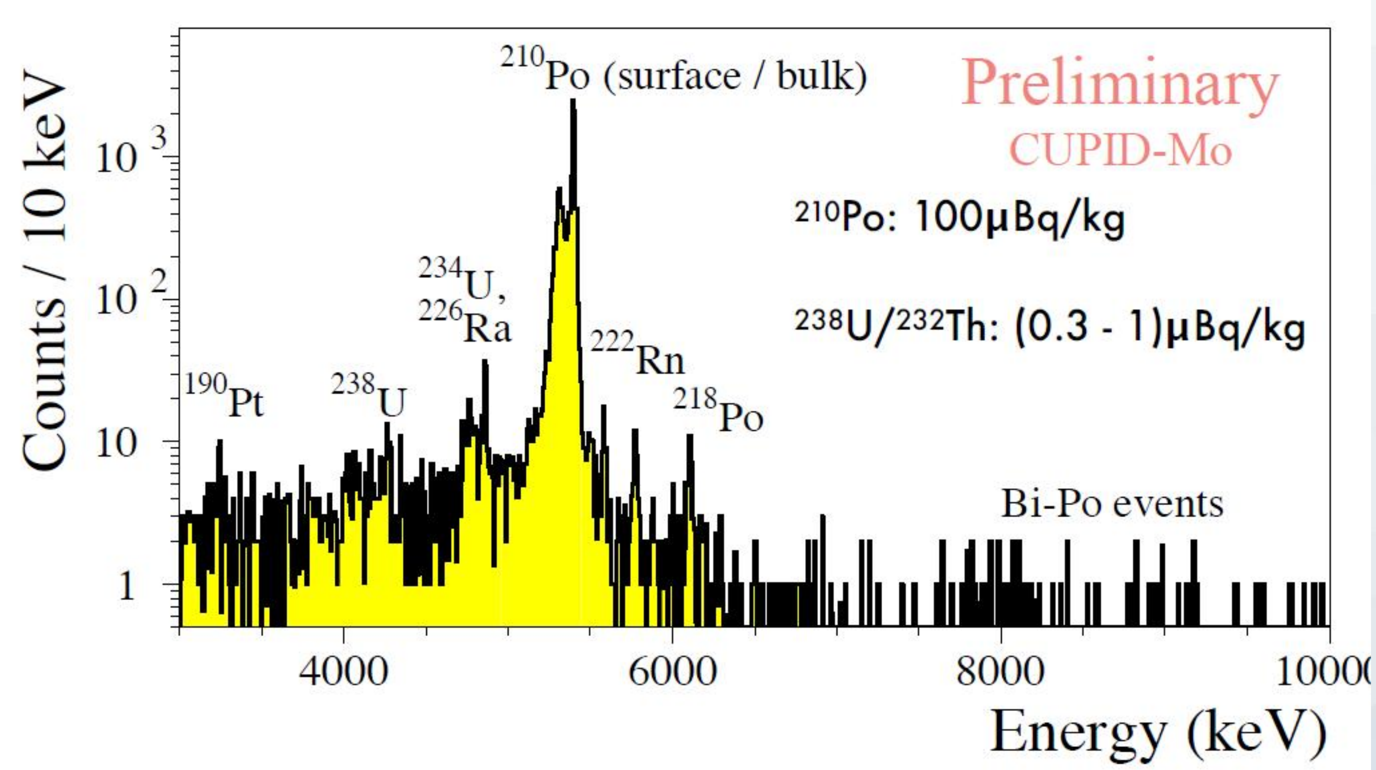


EPJC 80, 44 (2020)

CUPID-Mo features

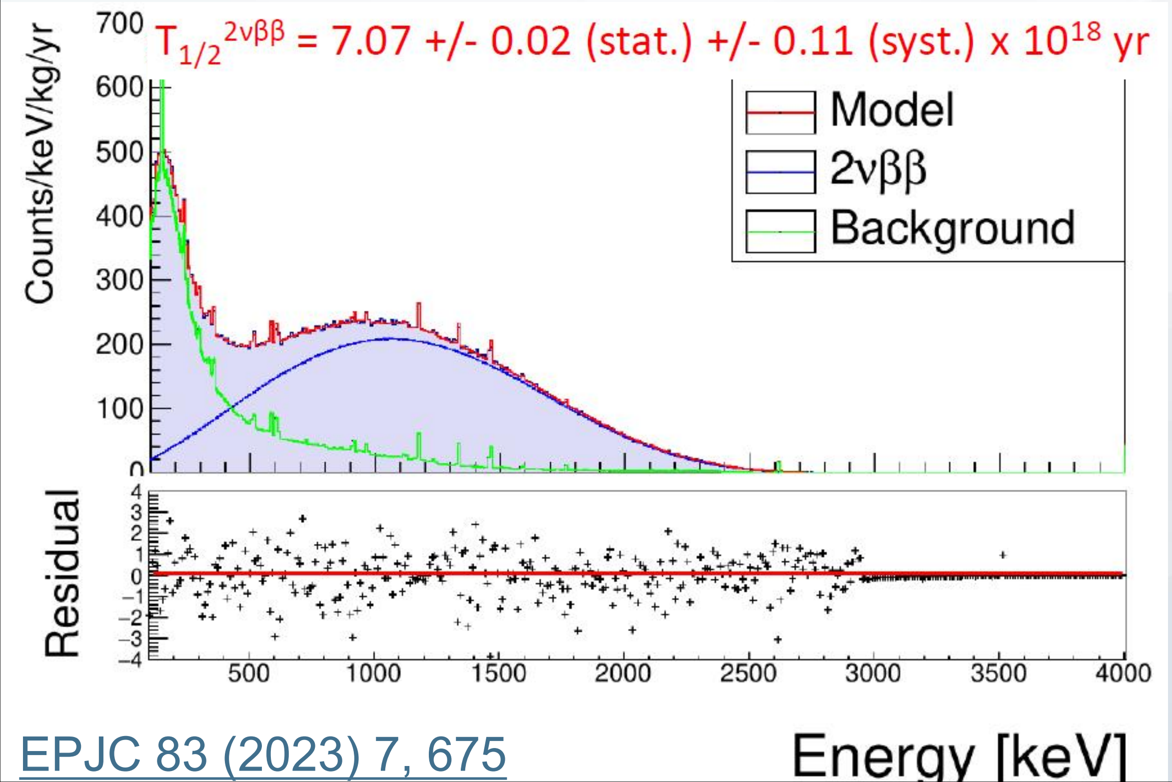
- Excellent internal radiopurity of crystals: ^{210}Po and U/Th well within CUPID requirements

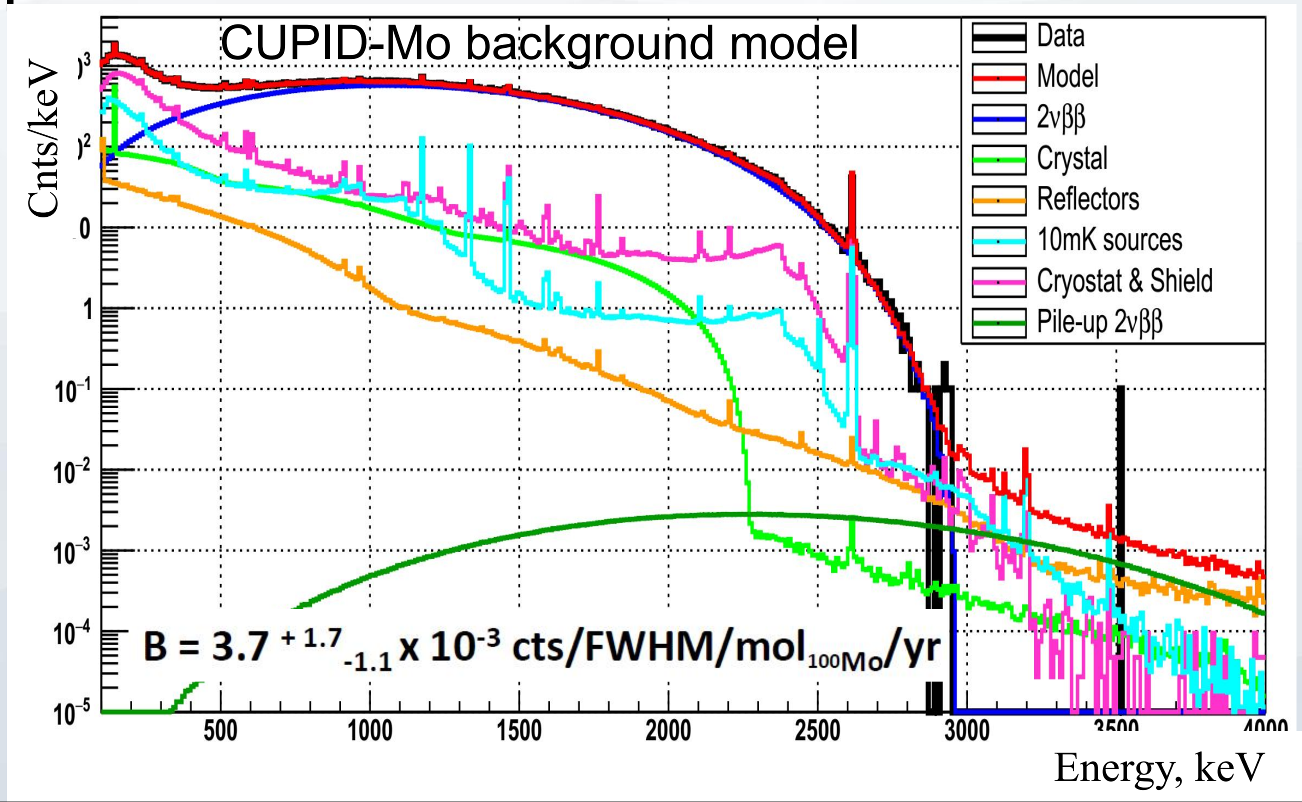




CUPID-Mo results

- 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
- Best background in bolometric experiment

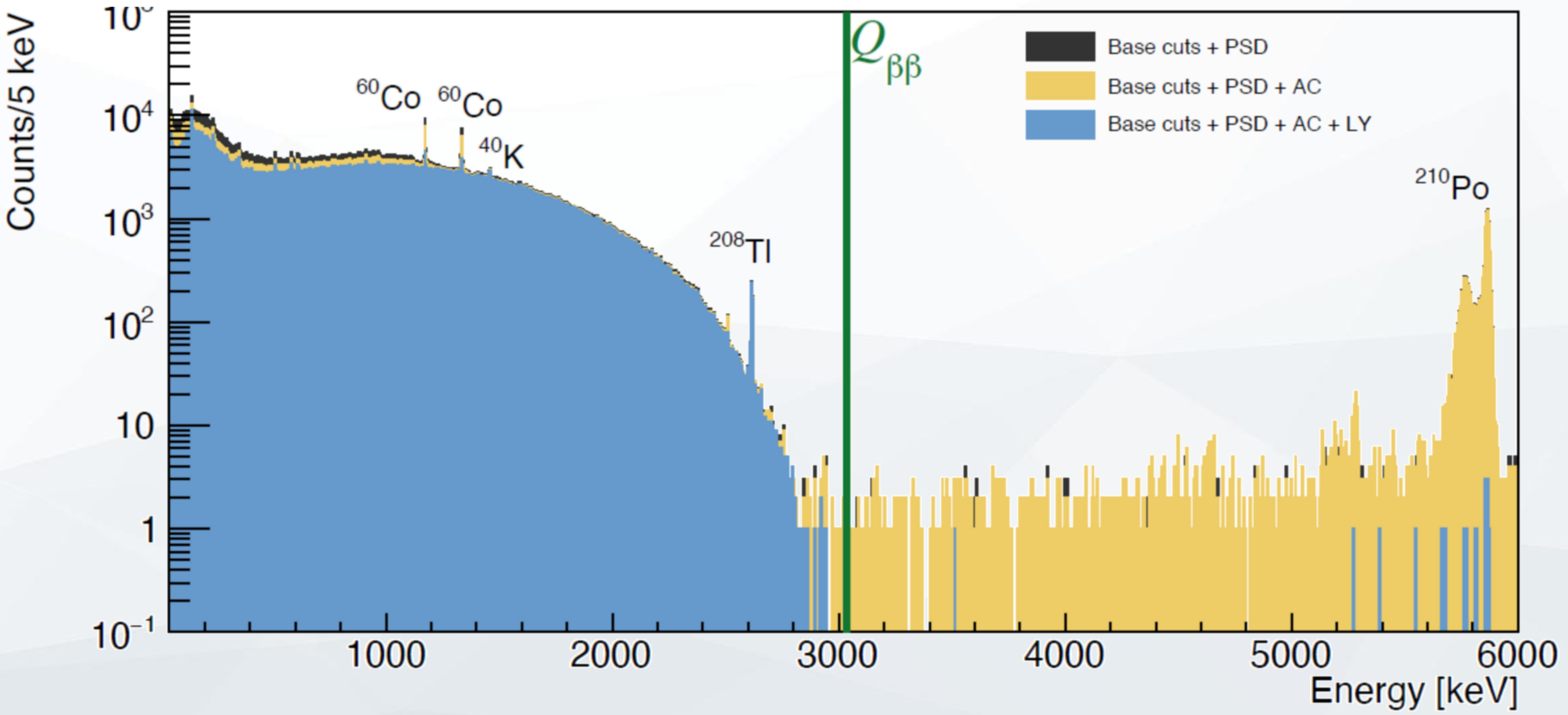




EPJC 83 (2023) 7, 675

CUPID-Mo results

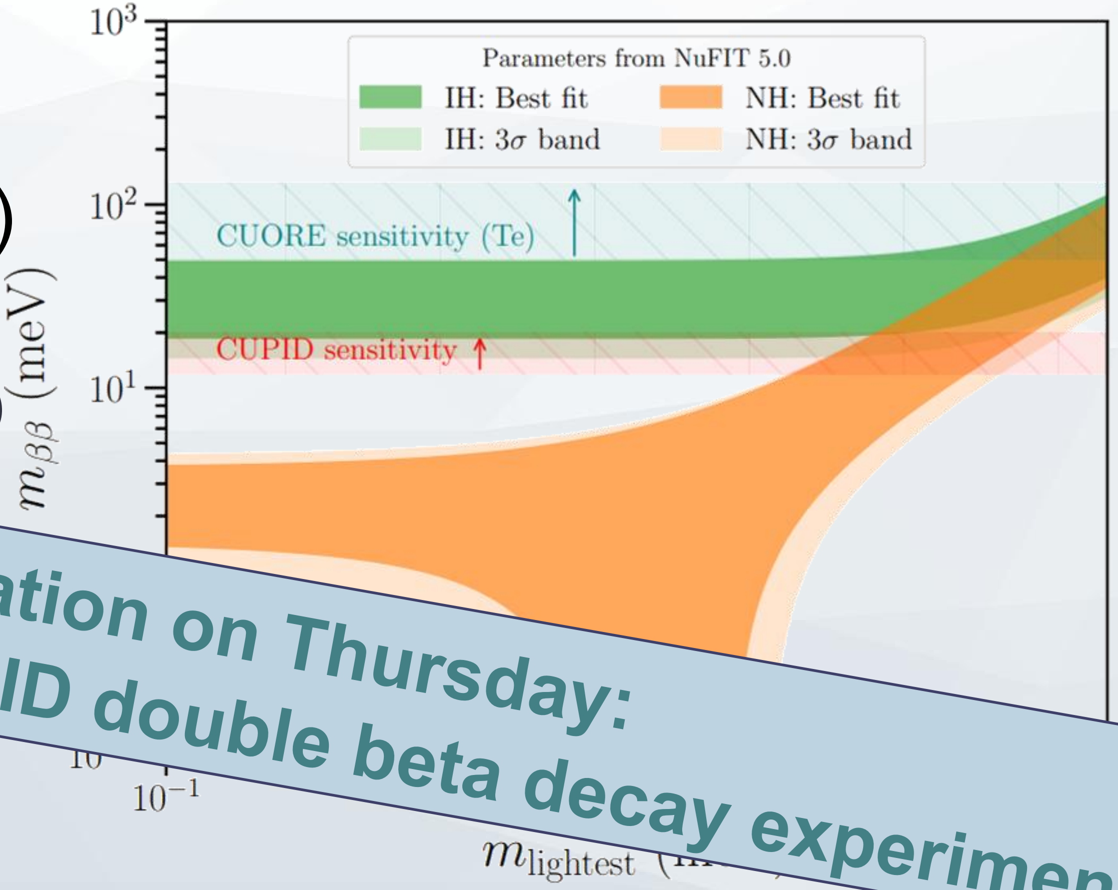
$T^{0v}_{1/2} > 1.8 \times 10^{24} yr$
(90% C. I. limit)
$m_{\beta\beta}$<280-490 meV
1.5 kg×yr

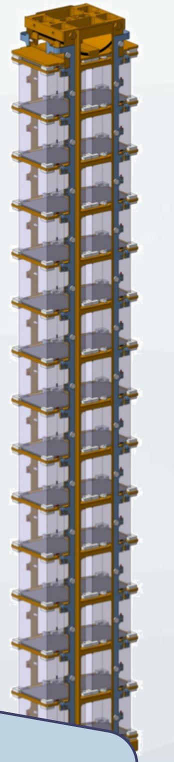


PRL 126, 181892 (2021)
JINST 16 (2021) P03032
EPJC 80, 44 (2020)
EPJC 80, 674 (2020)

CUPID: baseline

- **$Li_2{}^{100}MoO_4$ crystals**
- Ge Neganov-Trofimov-Luke light detectors
- Enrichment > 95%
- 1596 crystals and 240 kg of ^{100}Mo
- FWHM <10 keV at $Q_{\beta\beta}$ (3034 keV)





Backgrou… el: 10^{-4} cnts/(keV kg yr)

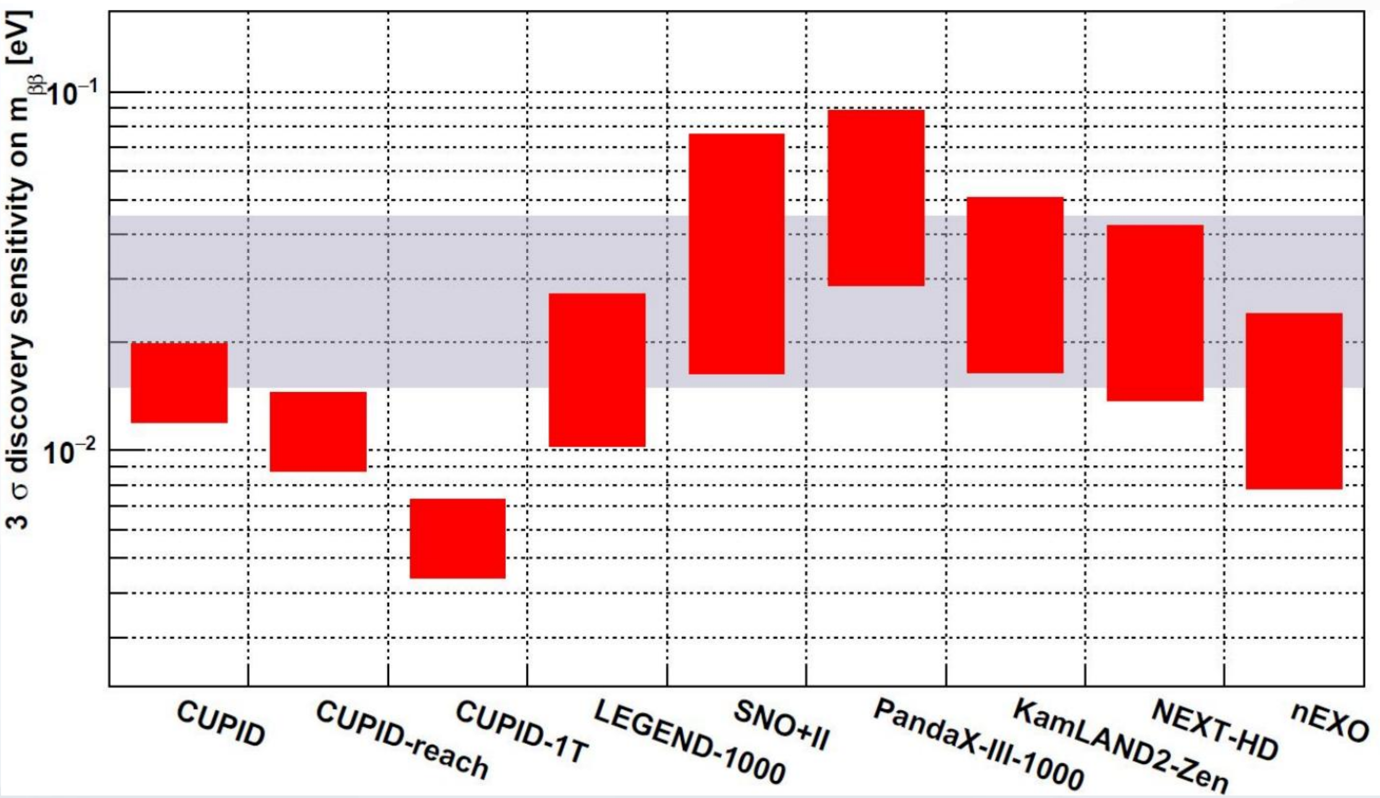
Dis…

$T_{1/2}$(…

$m_{\beta\beta}$ ~12-20 meV

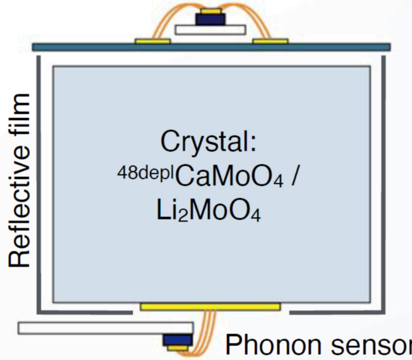
Presentation on Thursday:
Chiara Capelli, The CUPID double beta decay experiment

CUPID sensitivity



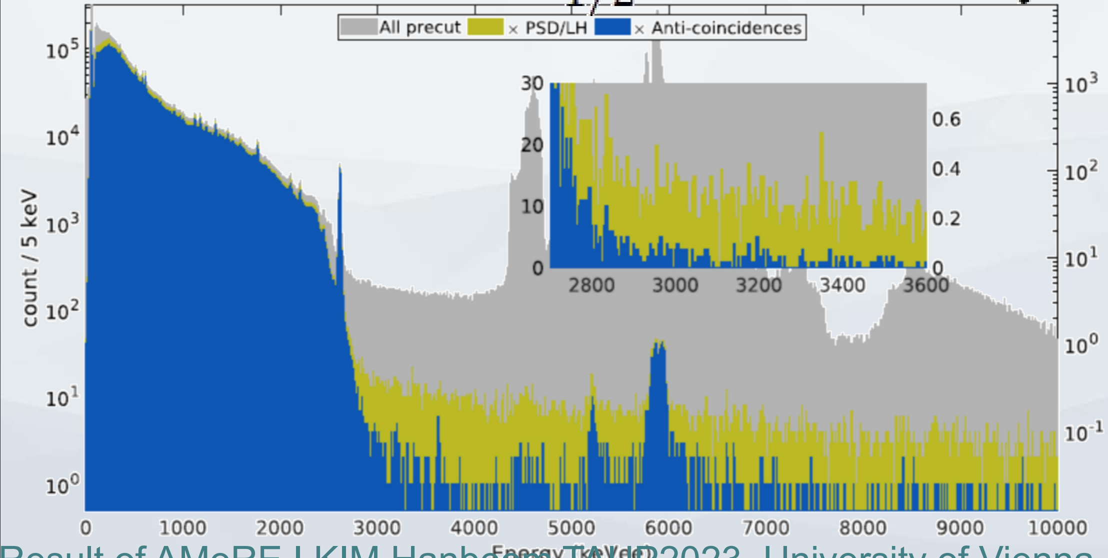
- CUPID: Exactly what we start building: **10^{-4}** cnts/keV/kg/yr
- CUPID-reach: improvements in same cryostat: **2×10^{-5}** cnts/keV/kg/yr
- CUPID-1T: 1 ton ^{100}Mo in new cryostat: **5×10^{-6}** cnts/keV/kg/yr

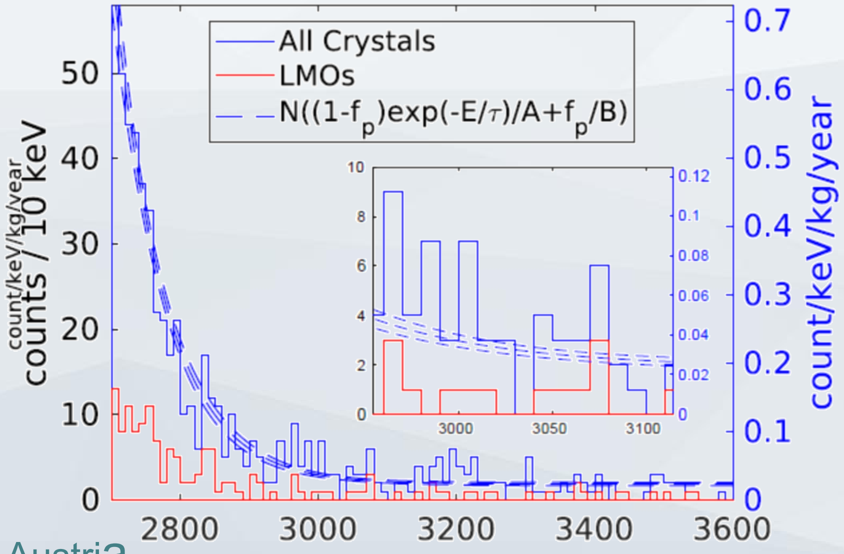
AMoRE-I

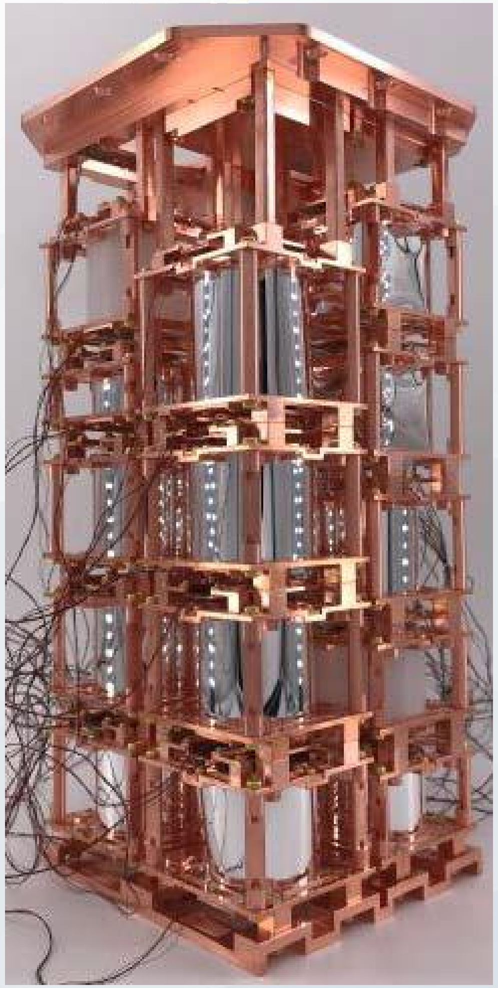


- Exploiting ^{100}Mo with $CaMoO_3$ and $LiMoO_3$ scintillating bolometers, total mass of ^{100}Mo - 3 kg
- MMC sensors for both heat and light
- Background = 0.032 ± 0.003 counts/keV/kg/year
- New most stringent limit on $T_{1/2}$ for ^{100}Mo

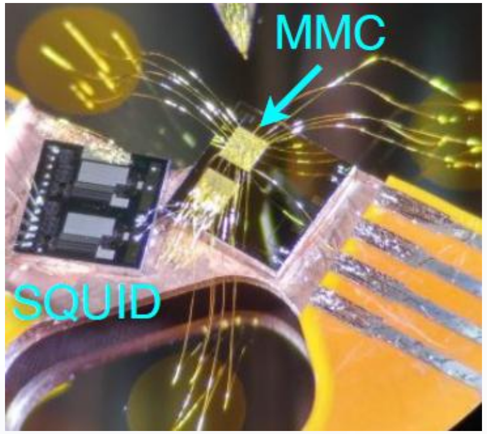
$$T^{0\nu}_{1/2} > 3.4 \times 10^{24} \text{ years at 90\% C.L.}$$

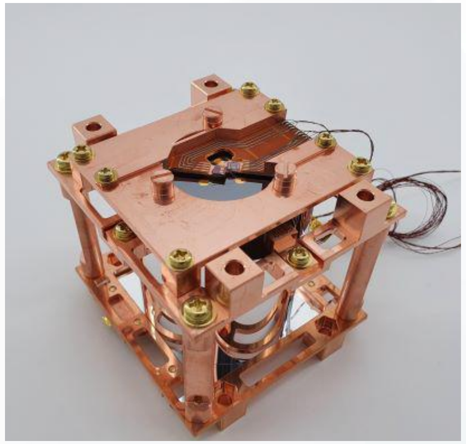






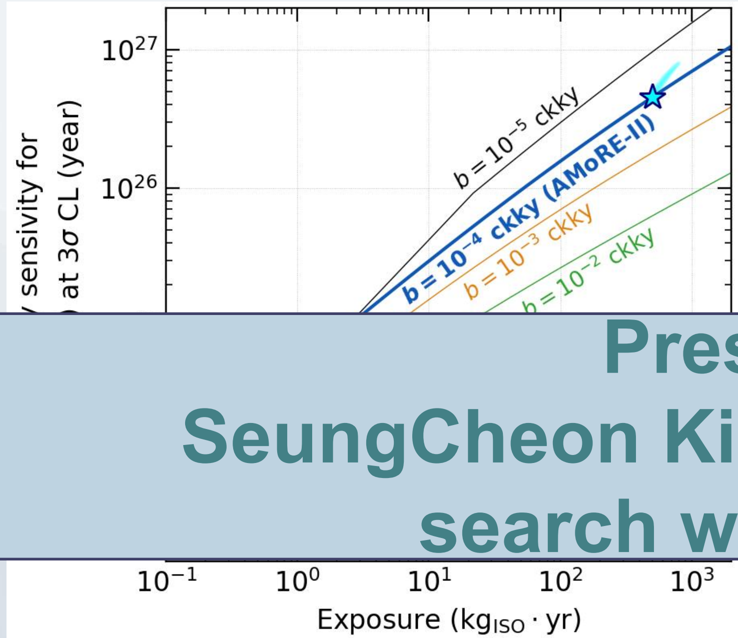
AMoRE-II

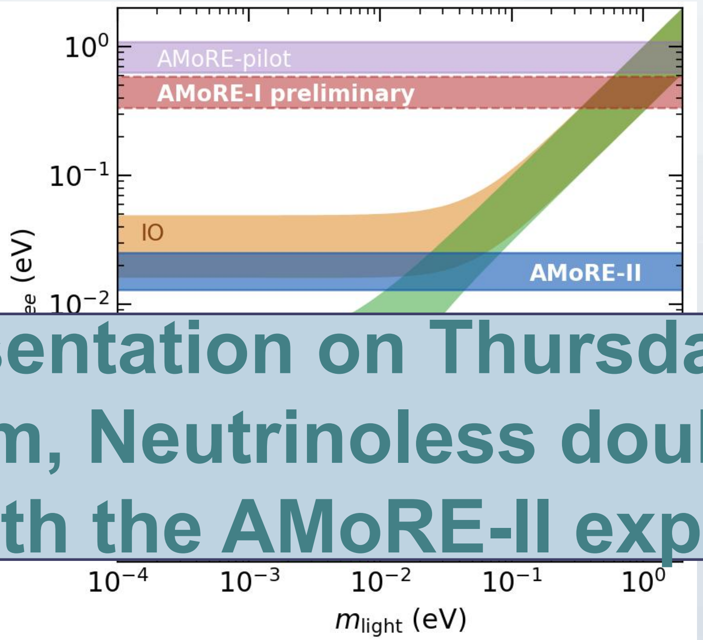


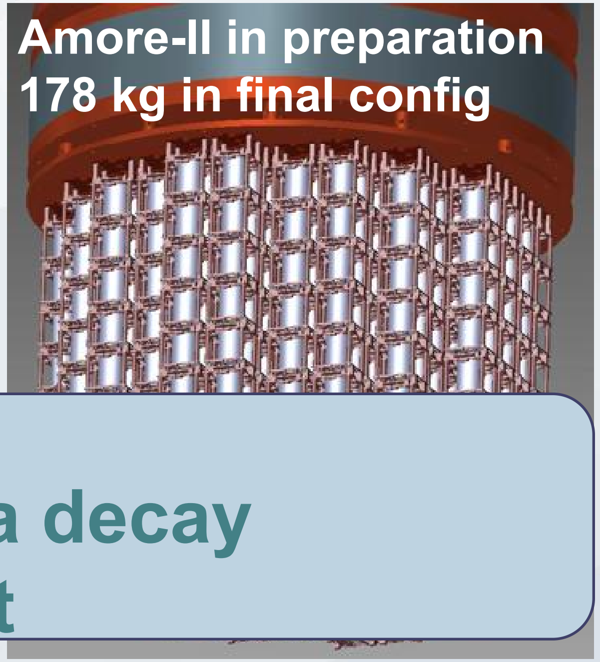


- Metallic magnetic calorimeter (MMC) + SQUID:

- Fast signals: few milliseconds rise-time:
- Thanks to this, no big problem with pile-ups
- Energy resolution ~ 10 keV FWHM at 2.6 MeV



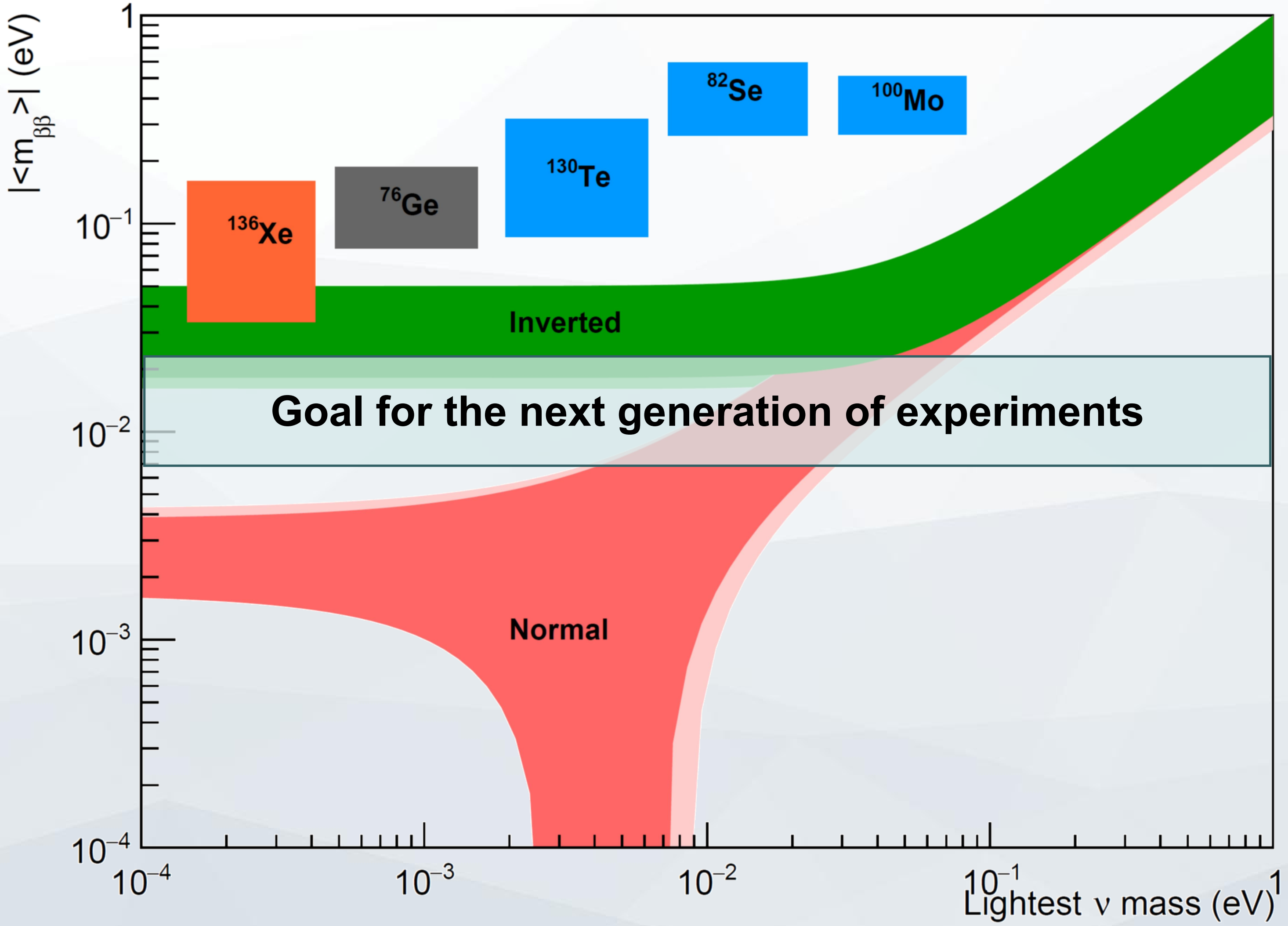




Presentation on Thursday:
SeungCheon Kim, Neutrinoless double beta decay search with the AMoRE-II experiment

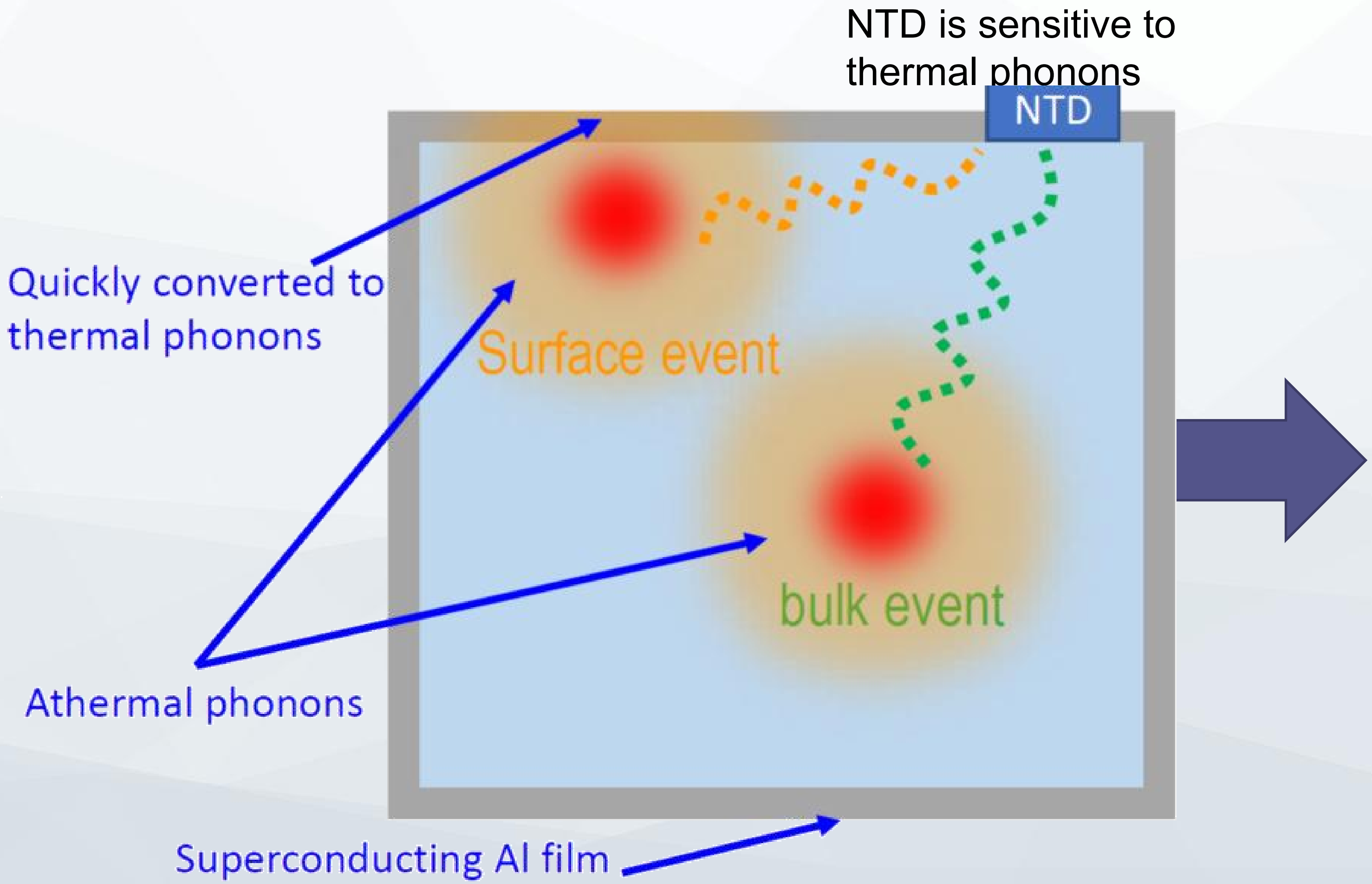
R&D and future projects

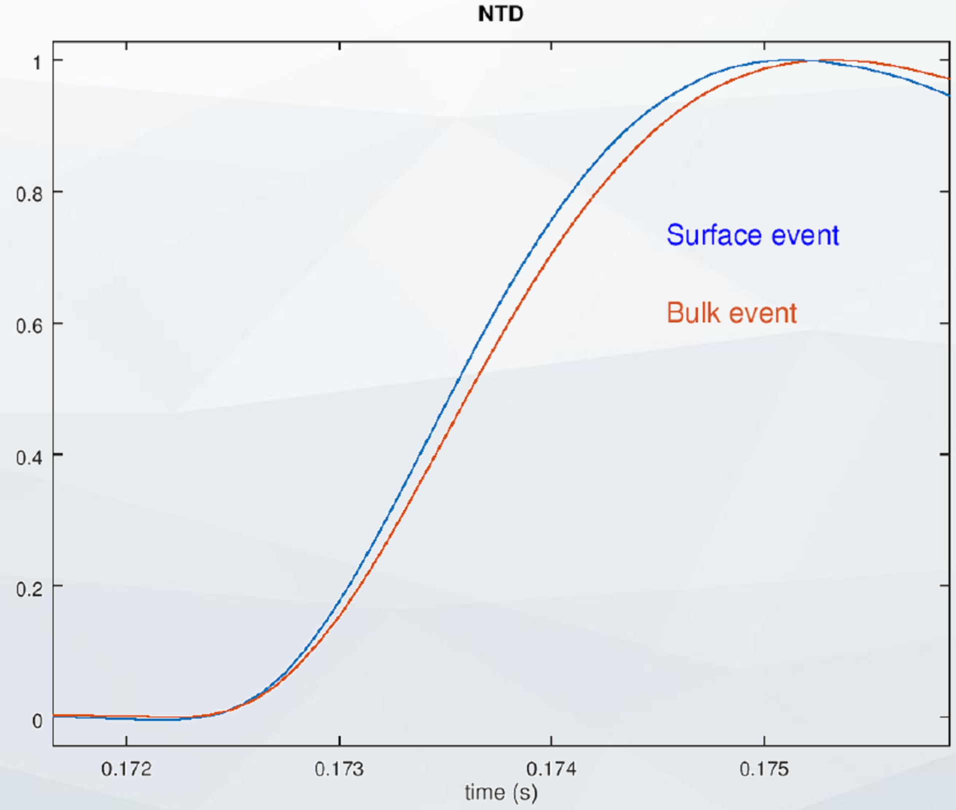
- Which improvements can be done “at reach” for sensitivity increase?
- Background rejection and reduction
- New PID methods
- Other isotopes?



CROSS technology: surface sensitivity

- Bolometers coated with metal films to identify near-surface events (No light detector is needed and advanced particle ID)





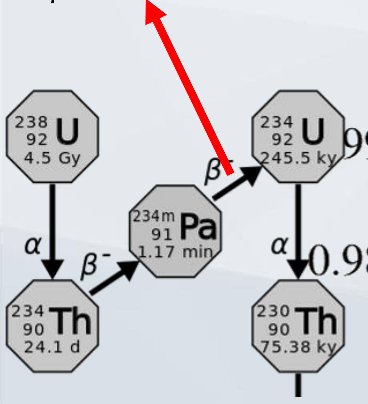
CROSS prototypes: coating tests

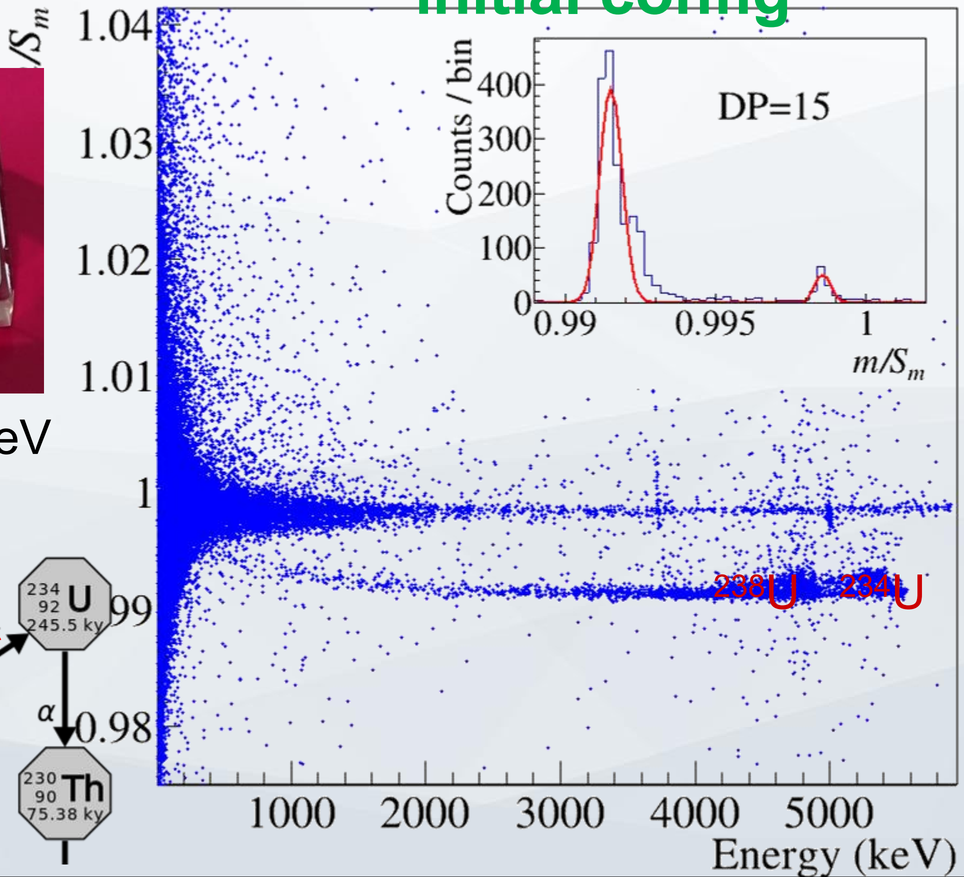
$$DP = \frac{|\mu_{\beta/\gamma} - \mu_{\alpha}|}{\sqrt{\sigma^2_{\beta/\gamma} + \sigma^2_{\alpha}}}$$

- Prototypes are tested in aboveground tests (IJCLab) with coating on one face, irradiated by a U source

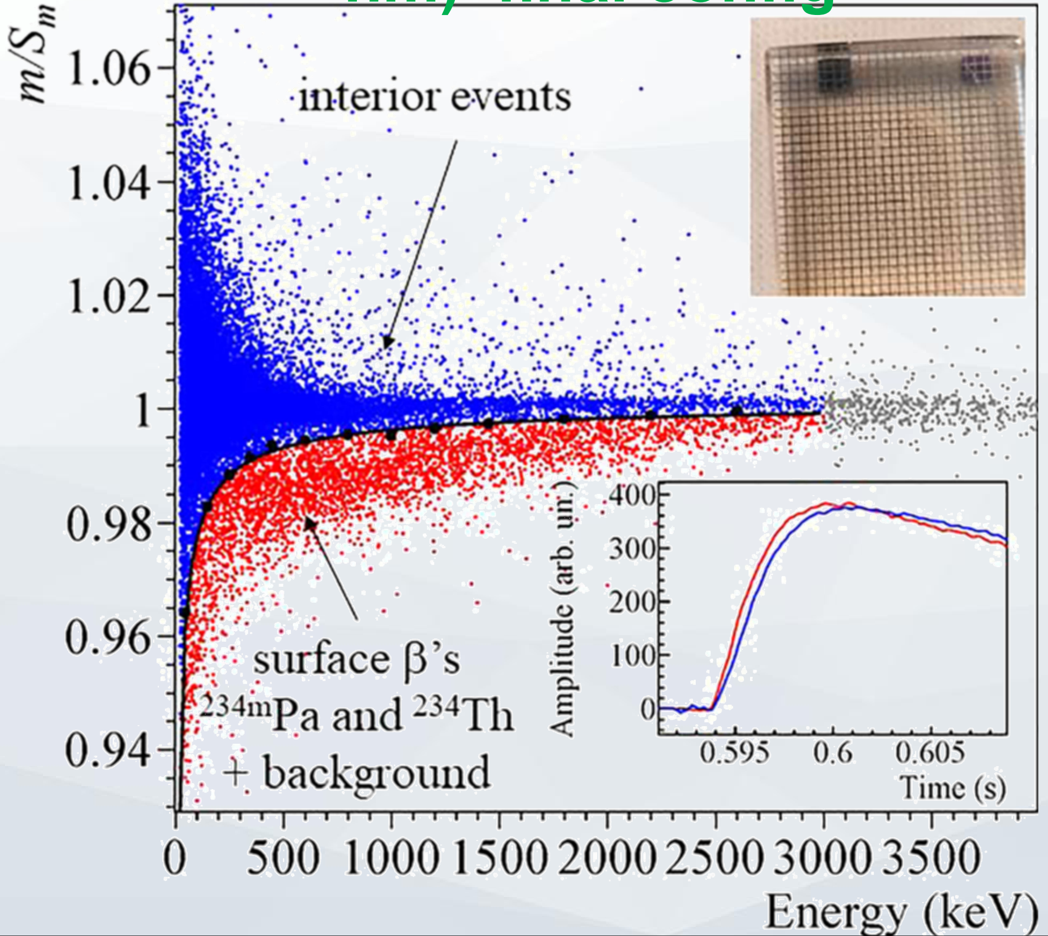
HEP 2020, 018 (2020)

Aluminum (10um) layer: initial config



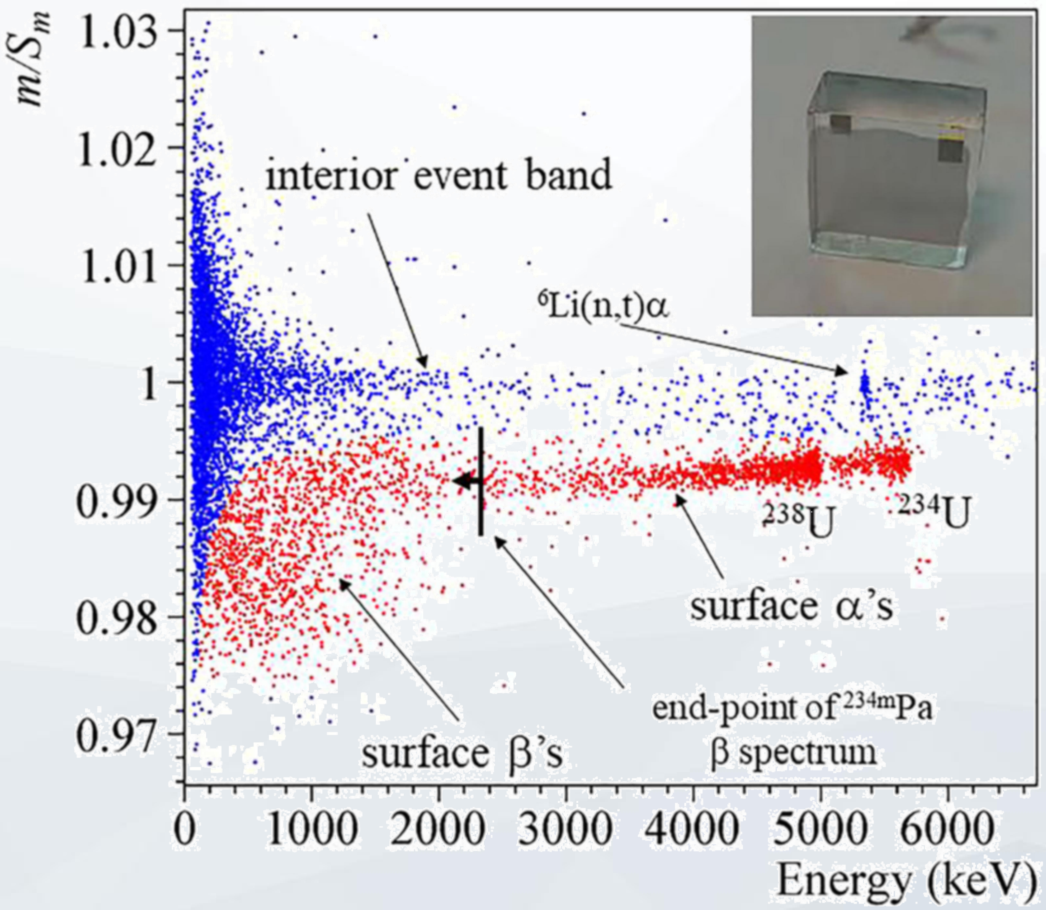


Palladium (10nm)-Aluminum (100 nm) final config

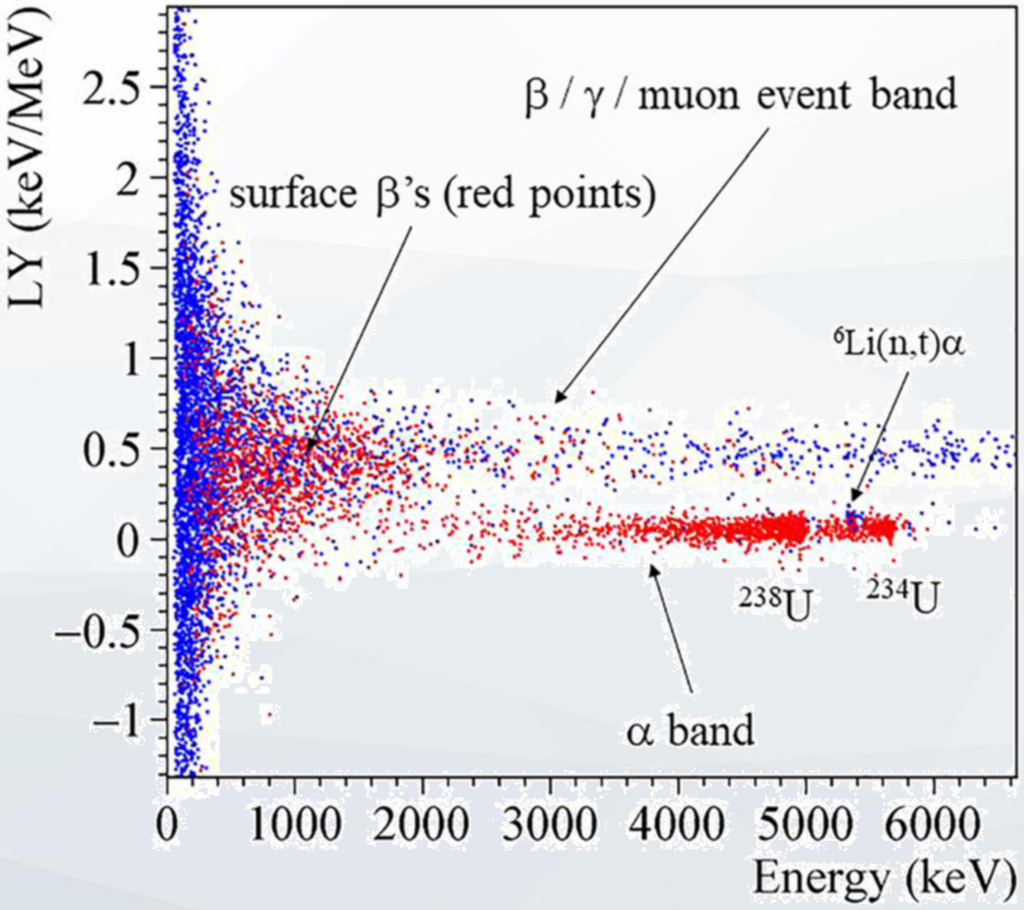


CROSS prototypes

CROSS technology: single read-out

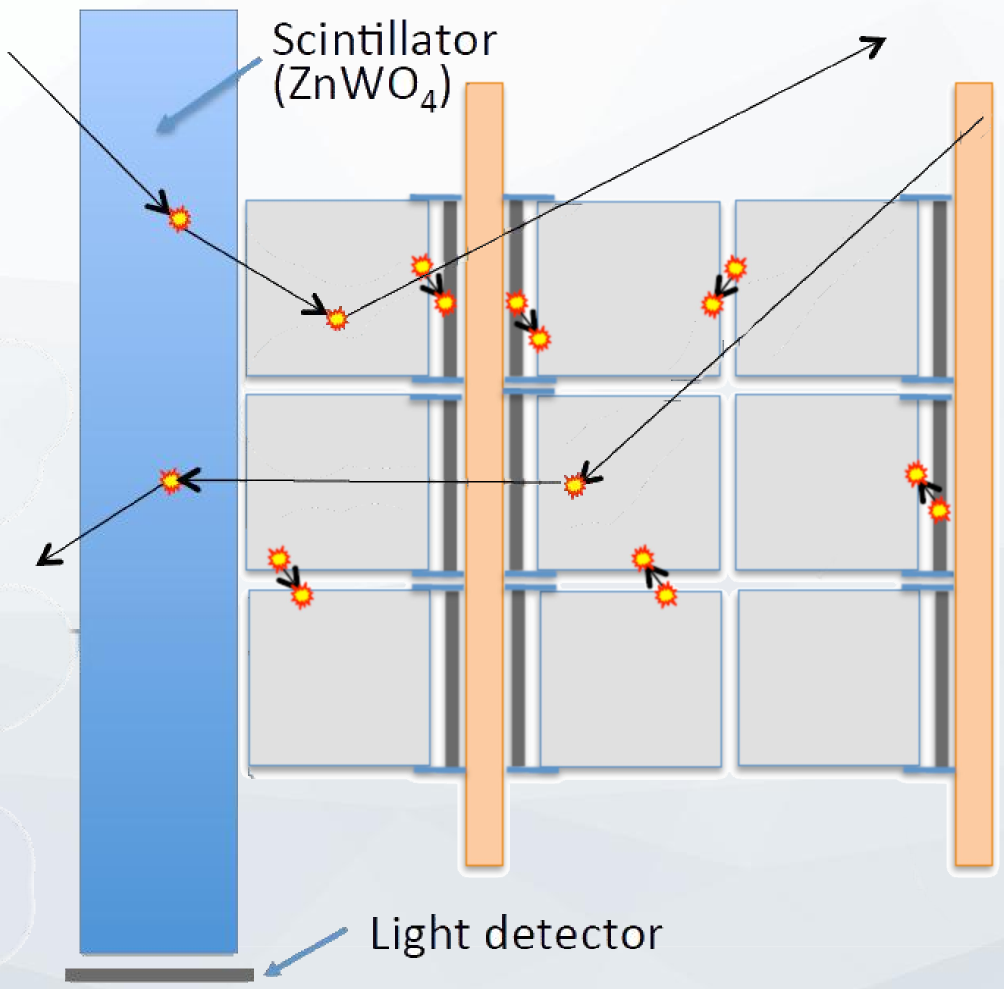


CUPID technology: dual read-out



BINGO experiment: gamma bkg reduction

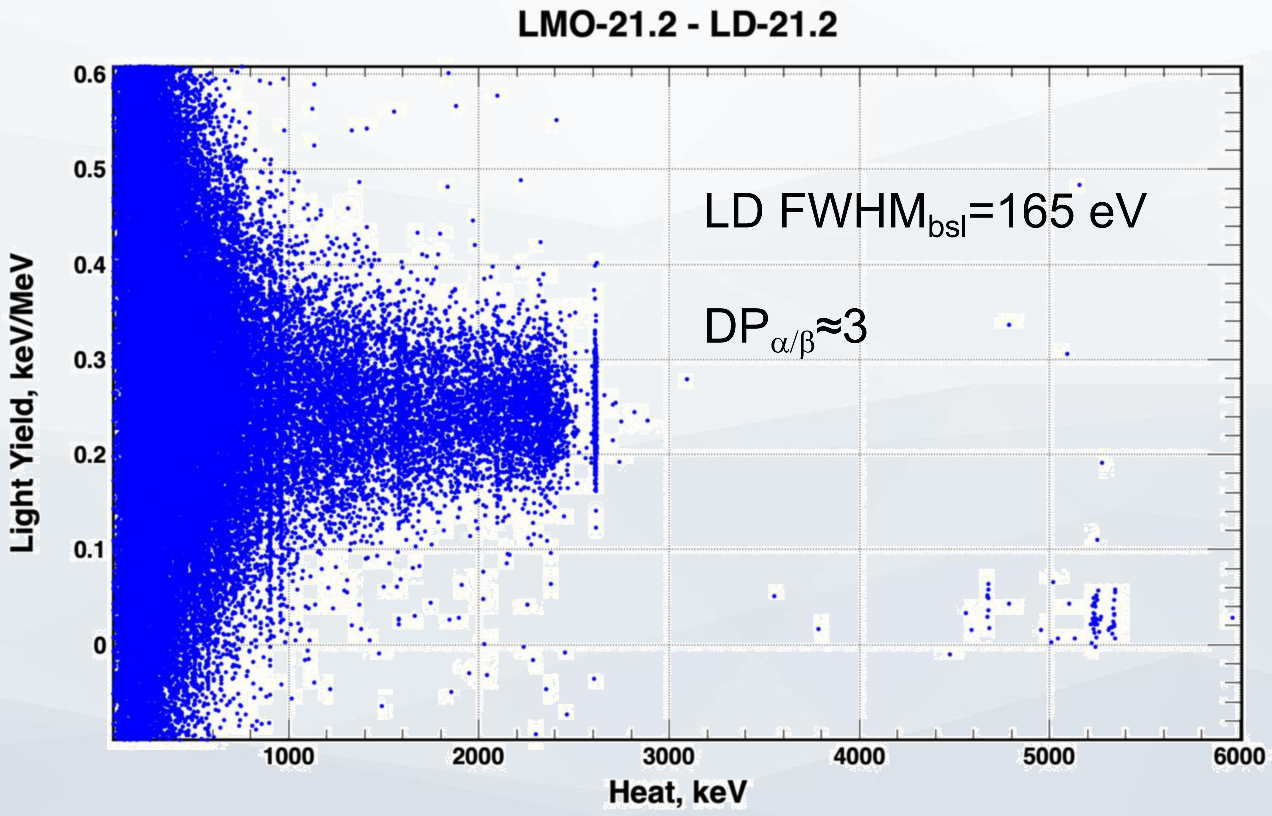
- Surface events discrimination: detectors will “see” only active elements
- Internal **active veto**: BGO scintillators, bolometric light read-out
- Light detectors with **Neganov-Luke technology** to reach 10 eV rms baseline
- Both Li_2MoO_4 and TeO_2 compounds



Goal for bkg index in ROI:
~10^{-5} cnts/keV/kg/yr

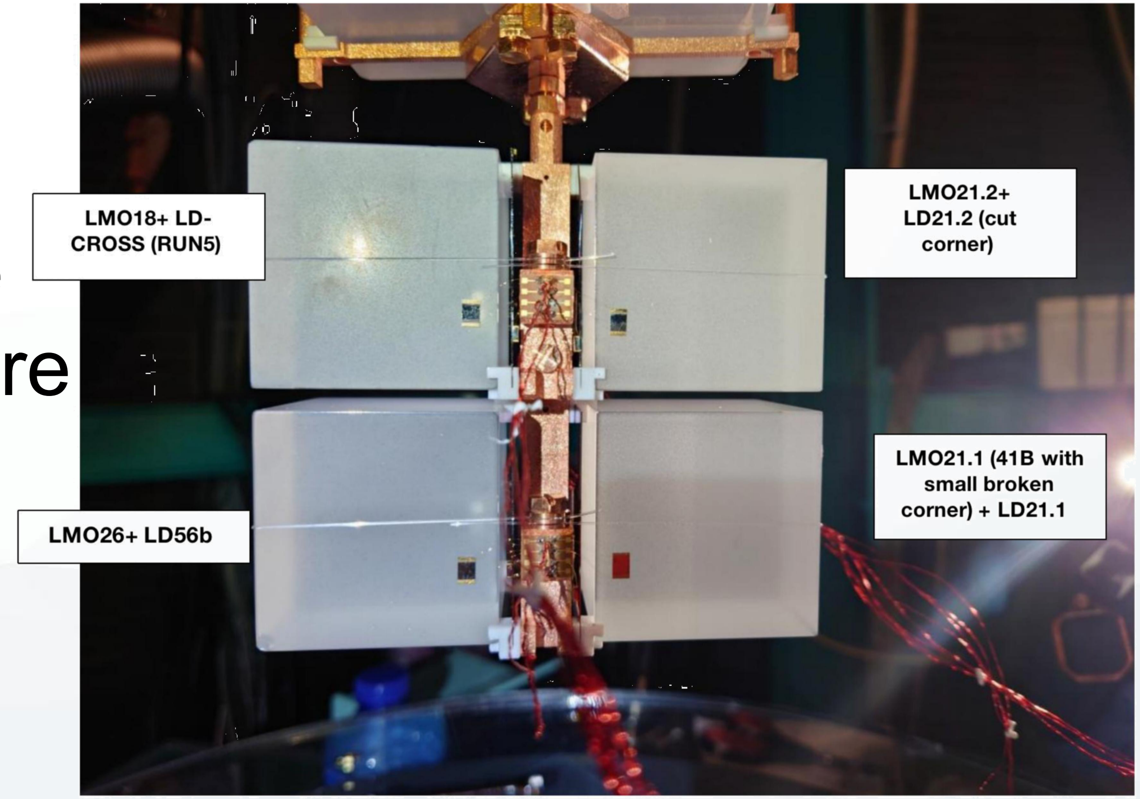
BINGO prototypes

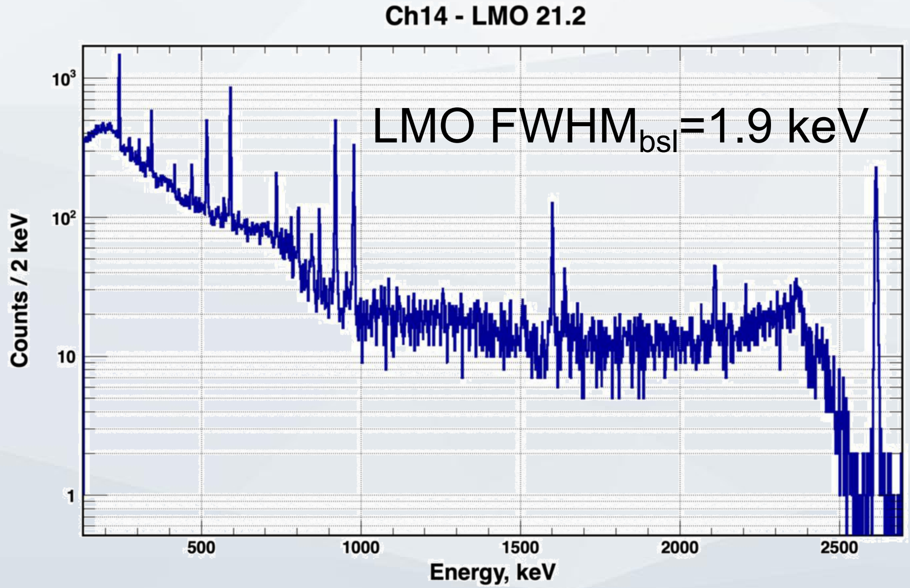
- New nylon wire assembly structure validated: detector performances are satisfactory



LD $FWHM_{bsl}$=165 eV

$DP_{\alpha/\beta} \approx 3$



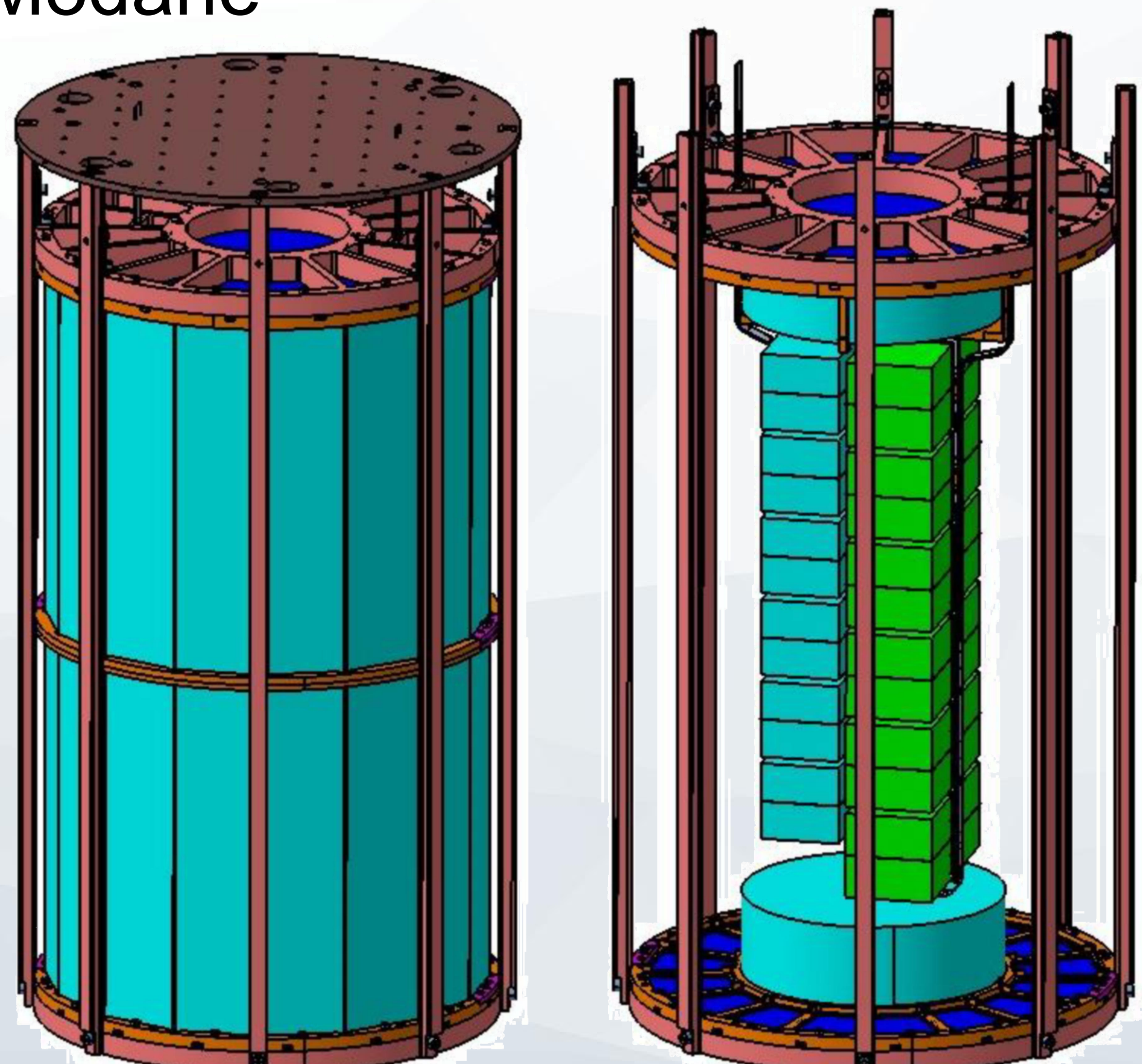


LMO $FWHM_{bsl}$=1.9 keV

BINGO demonstrator

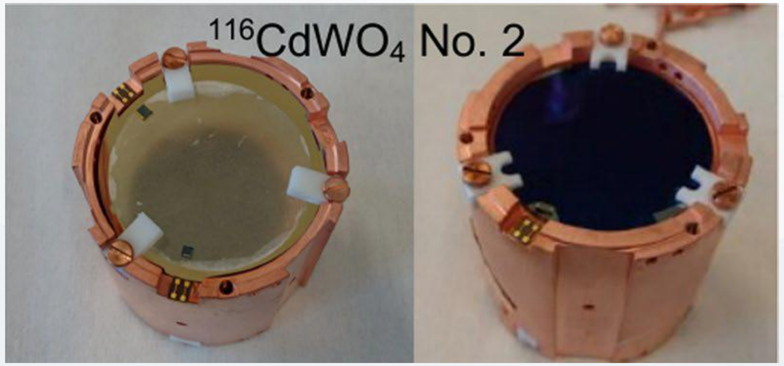
- MINI-BINGO will be installed in Modane Underground Laboratory
- 2x12 crystal towers (LMO+TeO)
- Crystals will see nothing else that is not active

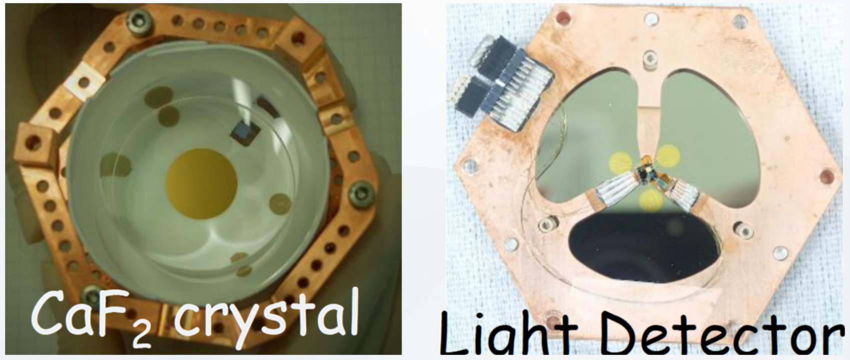
Scale high enough to demonstrate
$b \leq 10^{-4}$ cnts/keV/kg/yr
in 1 yr data taking

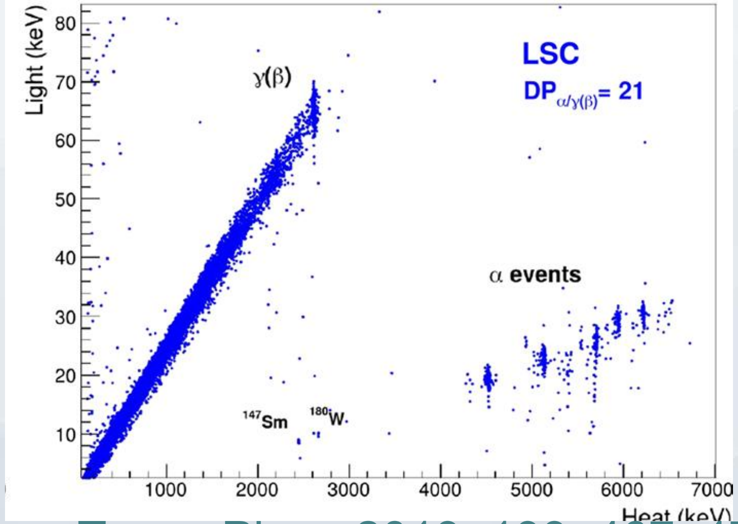


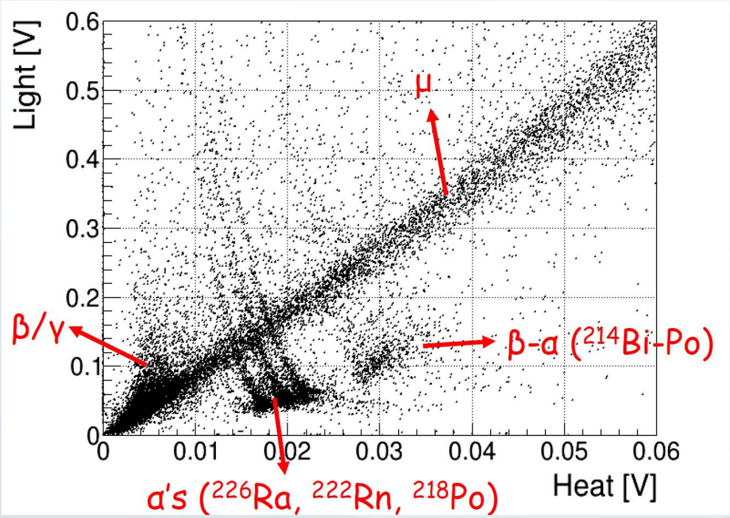
^{116}Cd, ^{48}Ca scintillating bolometers

- R&D tests performed on small scale with promising performance and particle discrimination capability









J. Low Temp. Phys. 2019, 199, 467–474

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

Conclusions

- Low temperature detectors have evolved enormously in last ~20 years and have wide range of applications now
- Particle identification capability, materials flexibility, high energy resolution allow to reach unprecedented sensitivities
- Powerfull tool for neutrino physics - major advancement are expected on scale of next 10 years

Stay tuned!