Neutrino physics with low temperature detectors

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Outline

- **Bolometric detectors**
  - Definition and working principle of bolometers
  - Thermal sensors
  - Particle identification in bolometers
  - Advantages and applications
- **Neutrino physics with bolometers**
  - Big questions about neutrinos
  - Coherent elastic neutrino-nucleus scattering
  - Direct neutrino mass measurement
  - Double beta decay
- **Conclusions**

Bolometers: definition and history

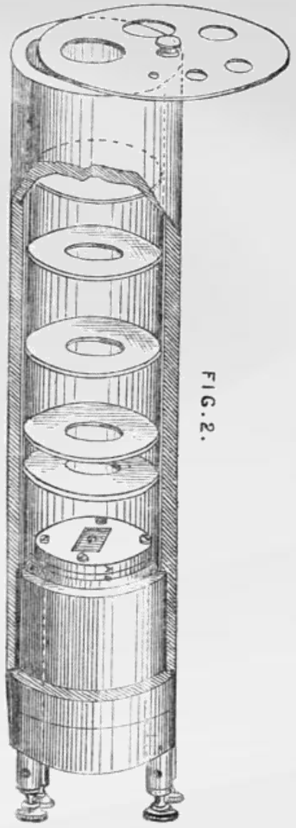
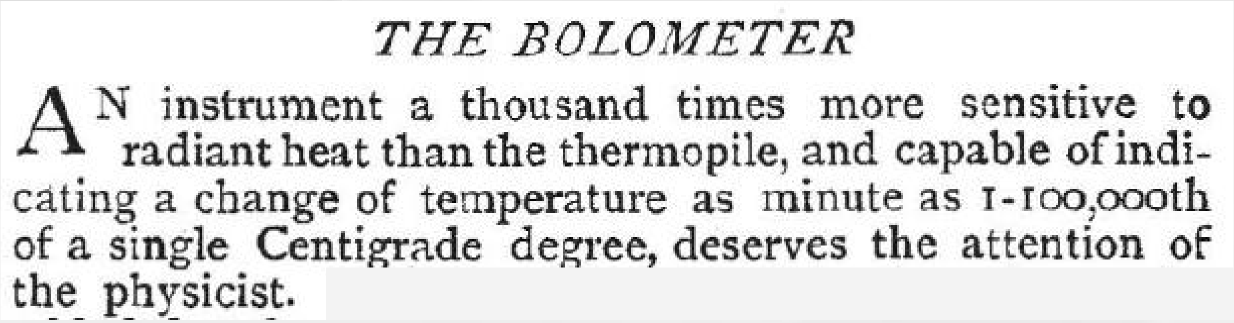


FIG. 2.

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


THE BOLOMETER

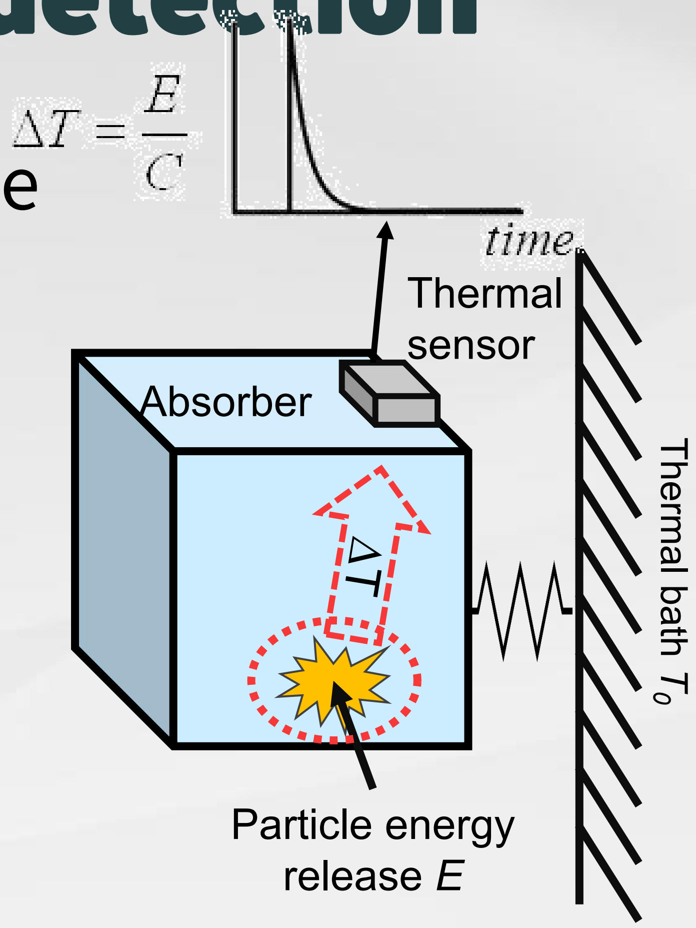
AN instrument a thousand times more sensitive to radiant heat than the thermopile, and capable of indicating a change of temperature as minute as 1-100,000th of a single Centigrade degree, deserves the attention of the physicist.

- 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

- 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:



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

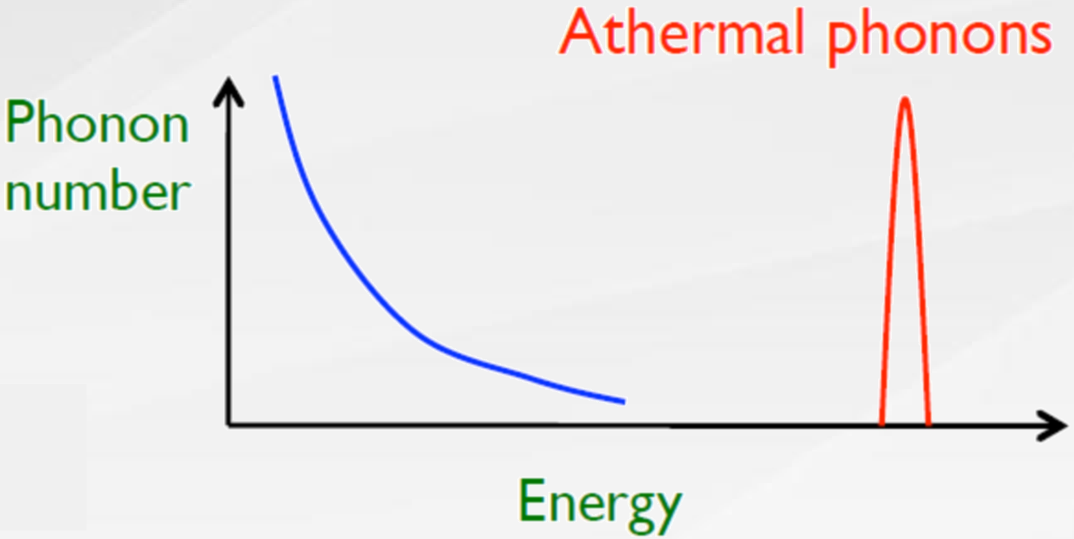
$$C_r(T) = \frac{12\pi^4}{5} N_A k_b \left(\frac{T}{\Theta_D}\right)^3$$

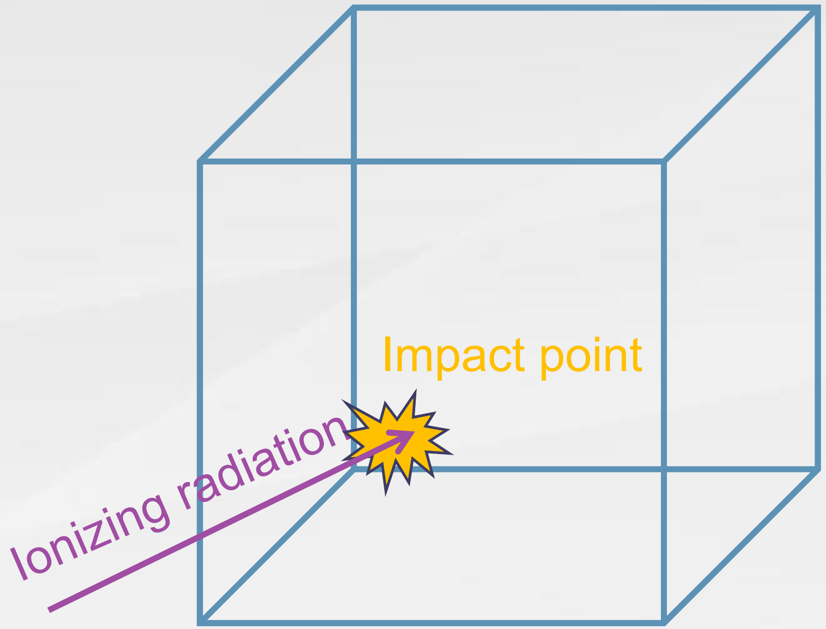
Debye law for dielectrics

Low heat capacity is essential for building a good bolometer!

Phonon propagation

- Initial high-energy phonons:
  - Very short pathlength
  - Degrade very quickly

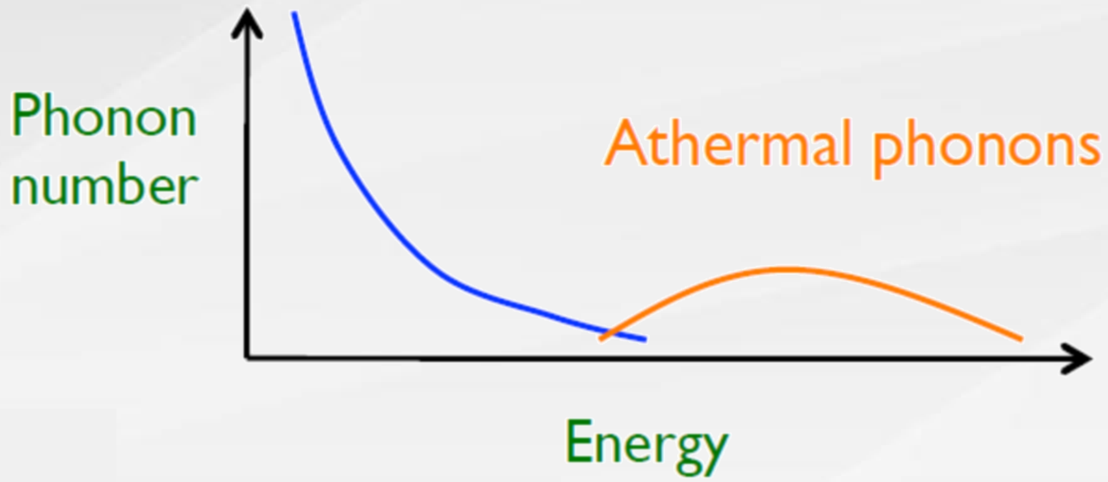


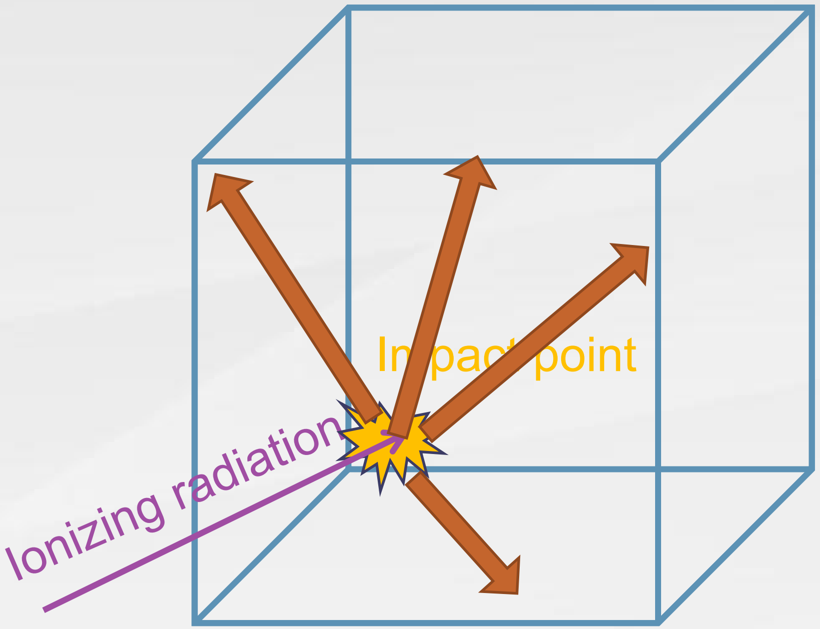


Position dependence through the pulse shape

Phonon propagation

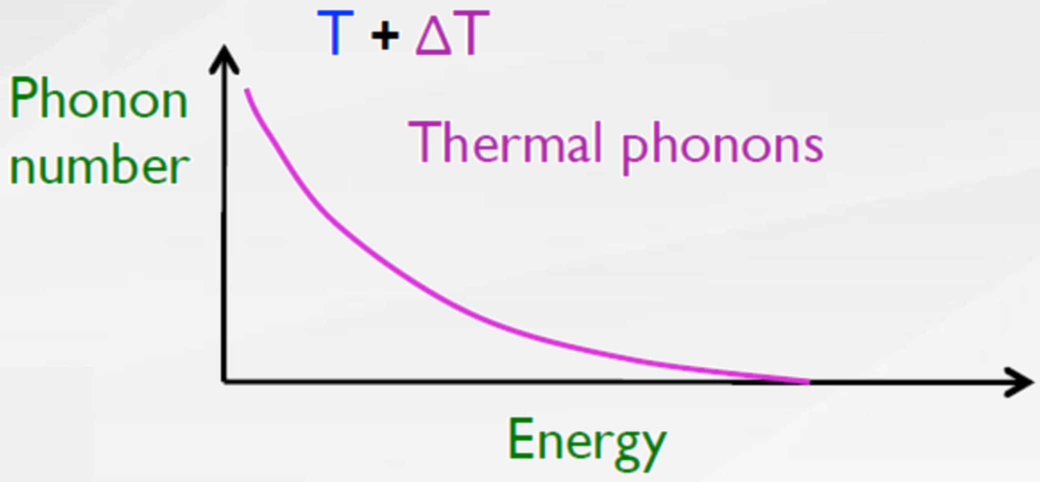
- Ballistic phonons
    - Longer lifetime (ms)
    - Path>detector size
    - Degrade through scattering on surfaces (mostly)

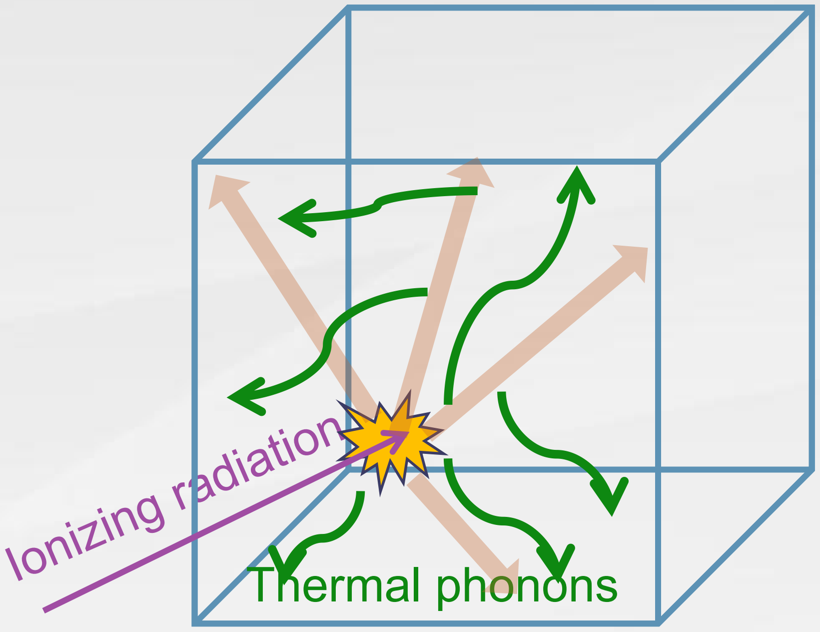




Phonon propagation

- Thermal phonons:
  - Thermalization time=C/G
  - Only energy is measured, all other features are washed out





Slow (~ms)
The most reliable energy measurement

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

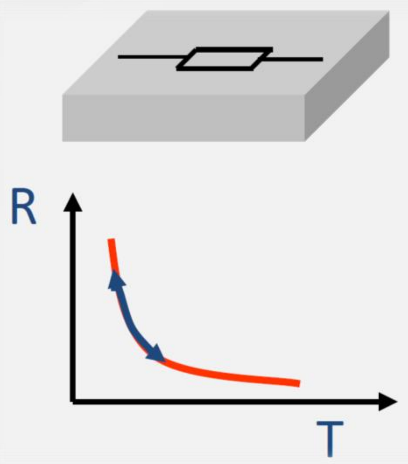
- Other mechanisms to be taken into account:
  energy losses in the detector volume, external noise sources

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

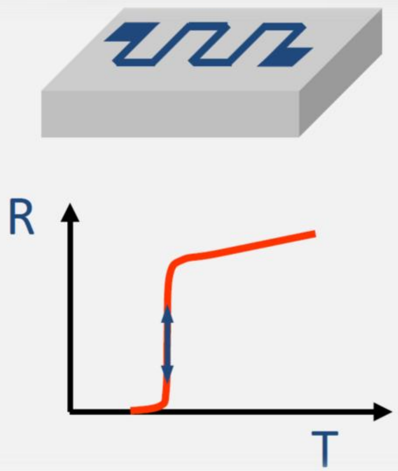
Thermal sensors

Typical sensors

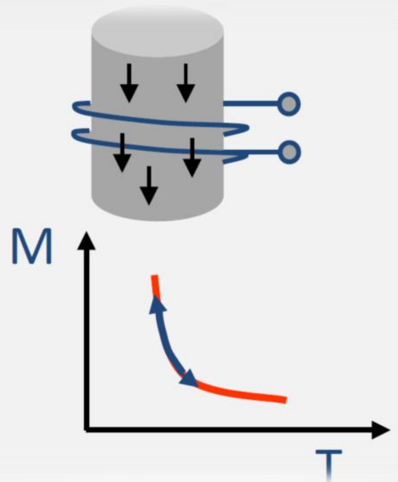
- What do we need?
- Large change of “X” parameter depending on temperature
- Low heat capacity (absorber is dominant)
- Speed of signal depends on the type of phonons we are sensitive to



Neutron Transmutation Doped sensors



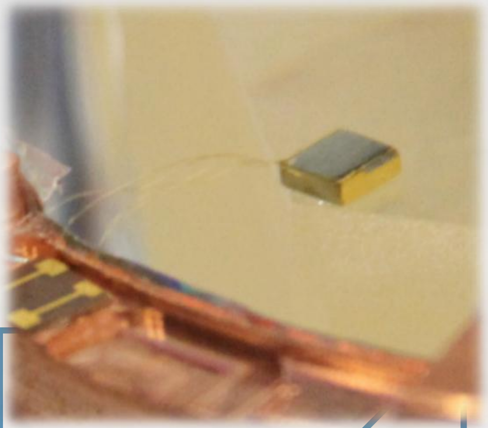
Transition Edge sensors



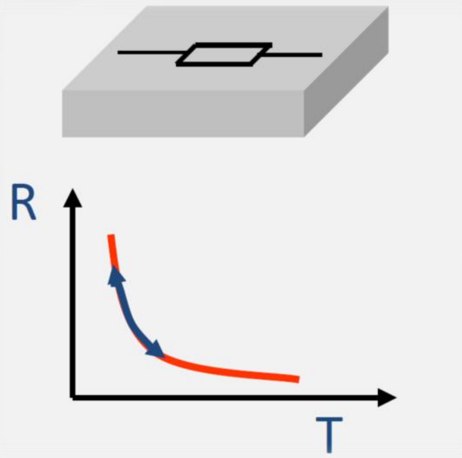
Metallic Magnetic Calorimeters

Neutron Transmutation Doped sensors

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

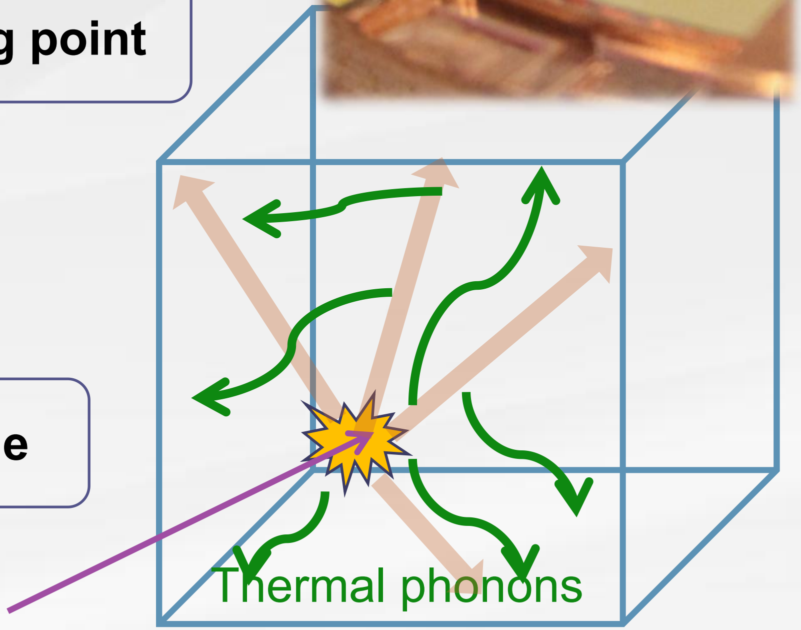


1-10 ~ MOhms at working point



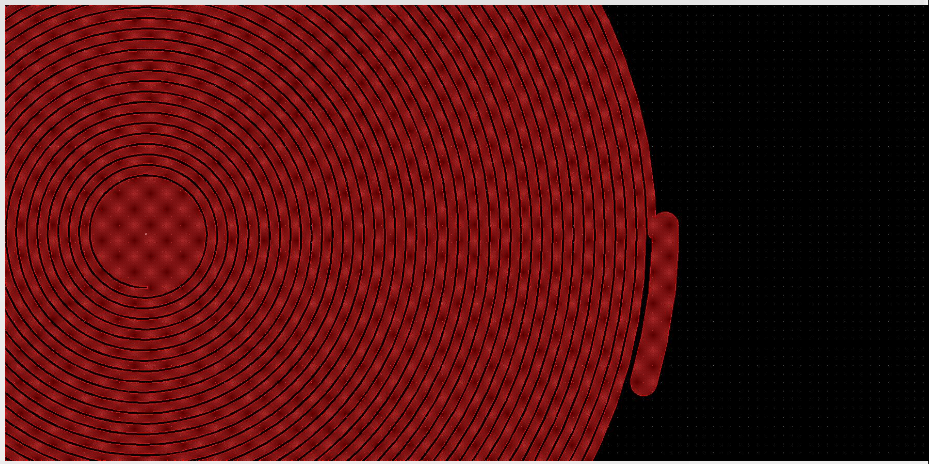
Neutron Transmutation Doped sensors

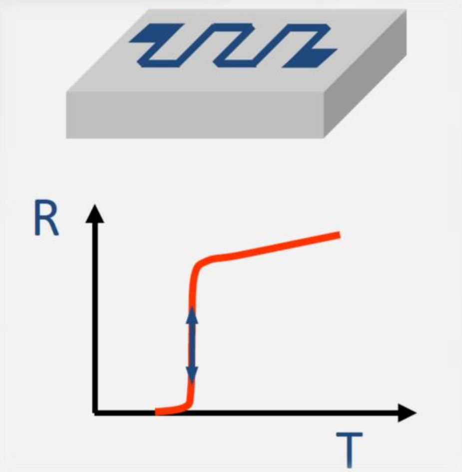
Slow sensors, thermal regime



Transition Edge sensors

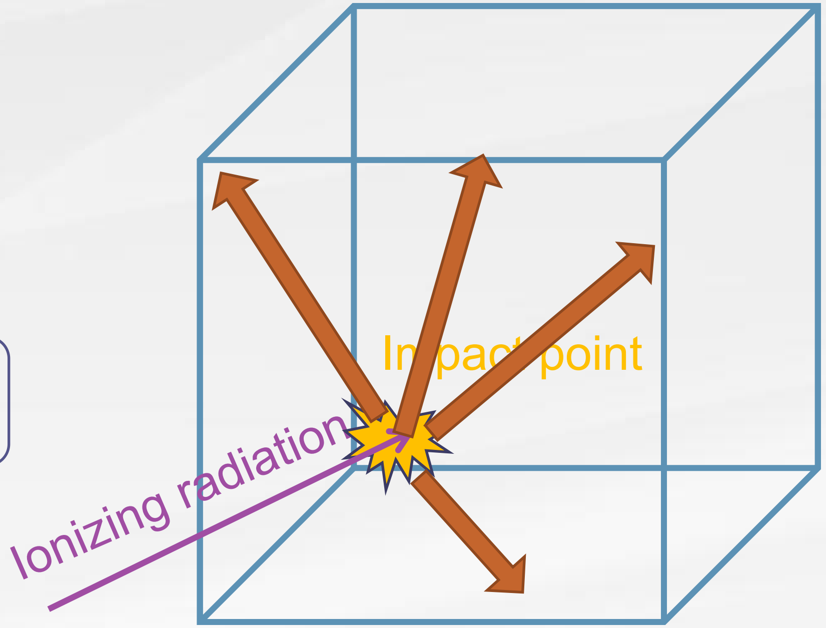
- Exploiting superconducting transition
- Materials: Mo/Cu Mo/Au Ir/Au Ti/Au W....
- SQUIDs generally required for read-out



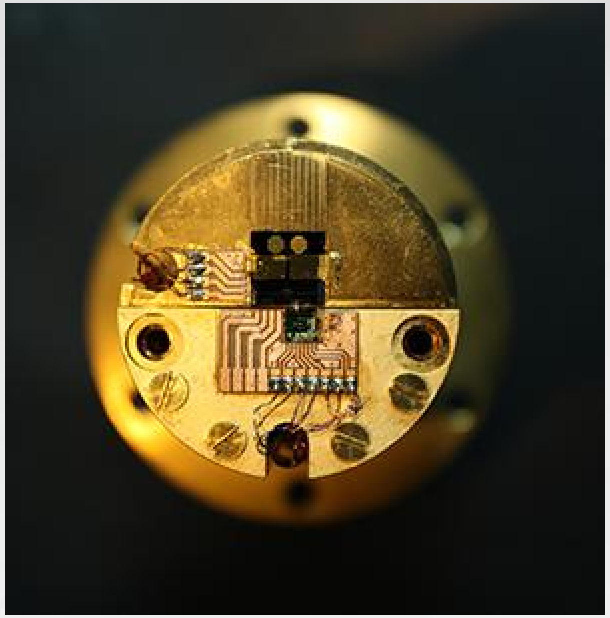


Transition Edge sensors

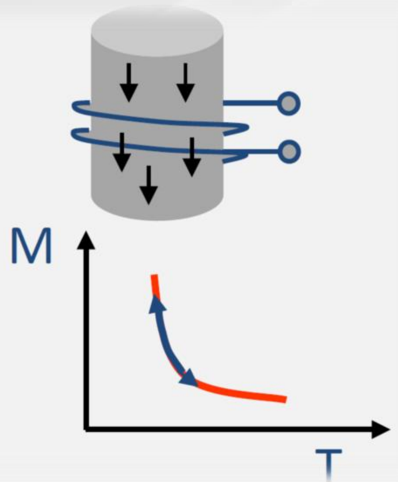
Fast sensors, athermal regime



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

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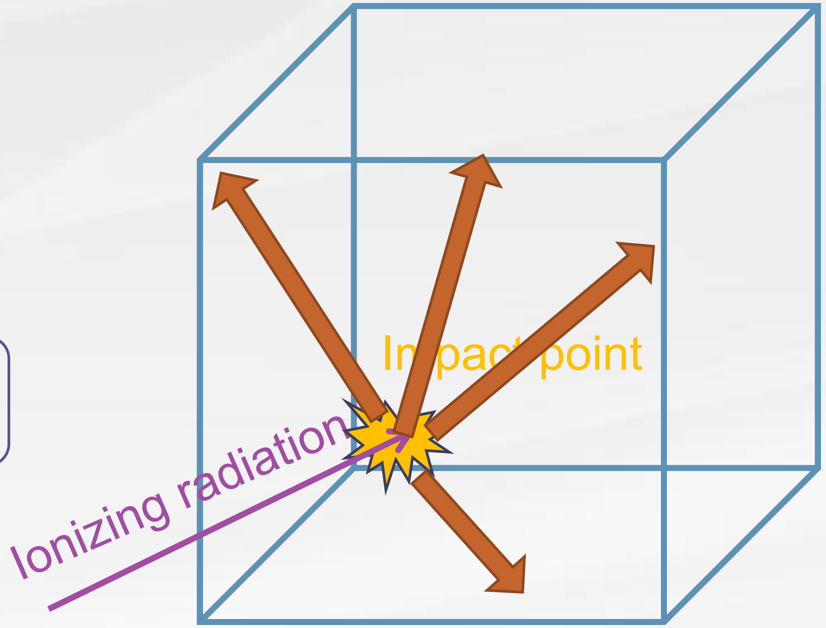
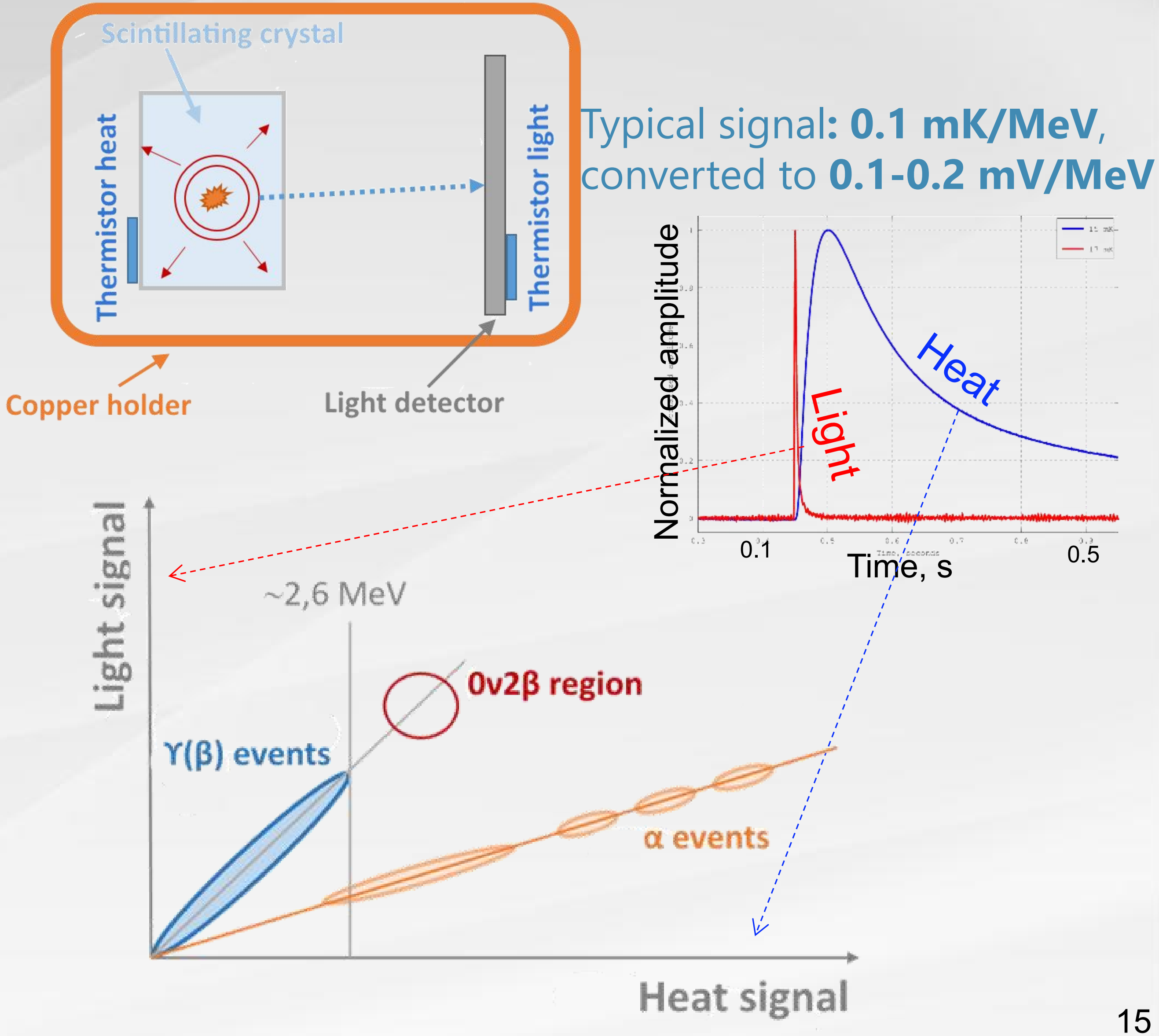


Particle identification with bolometers

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

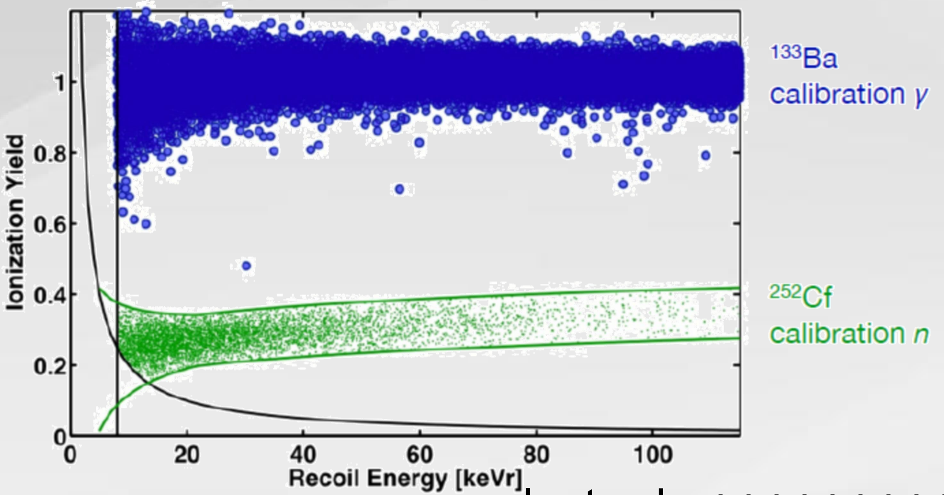
Typical signal: **0.1 mK/MeV**, converted to **0.1-0.2 mV/MeV**

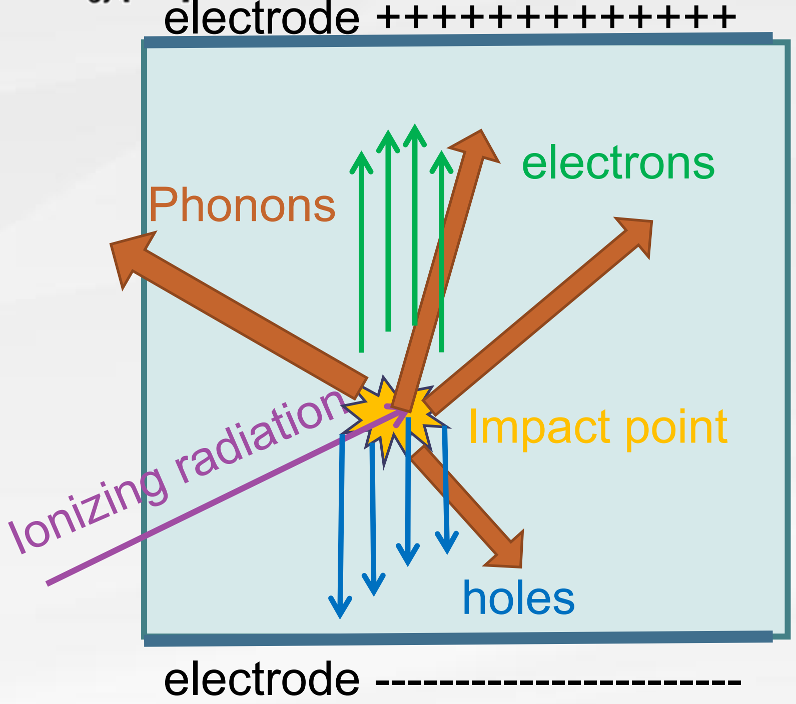


Particle discrimination with bolometers

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



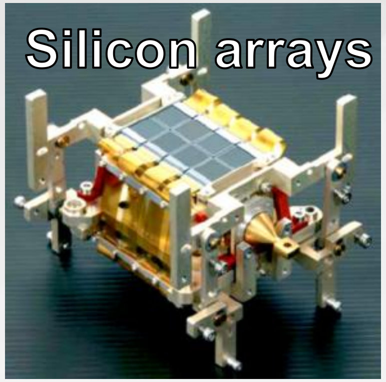


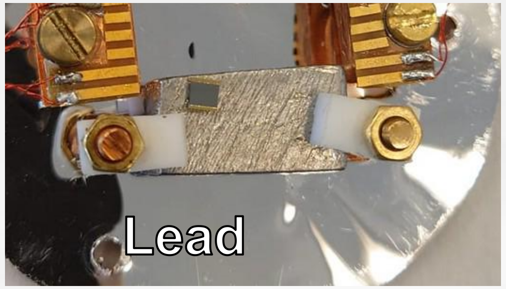
Advantages and applications

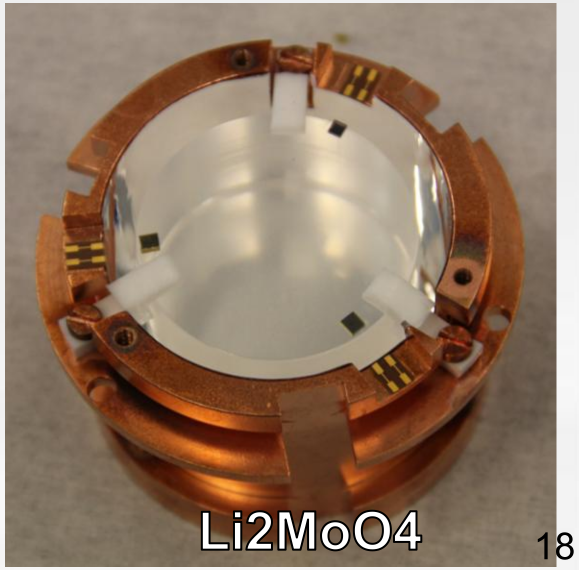
Bolometers are

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



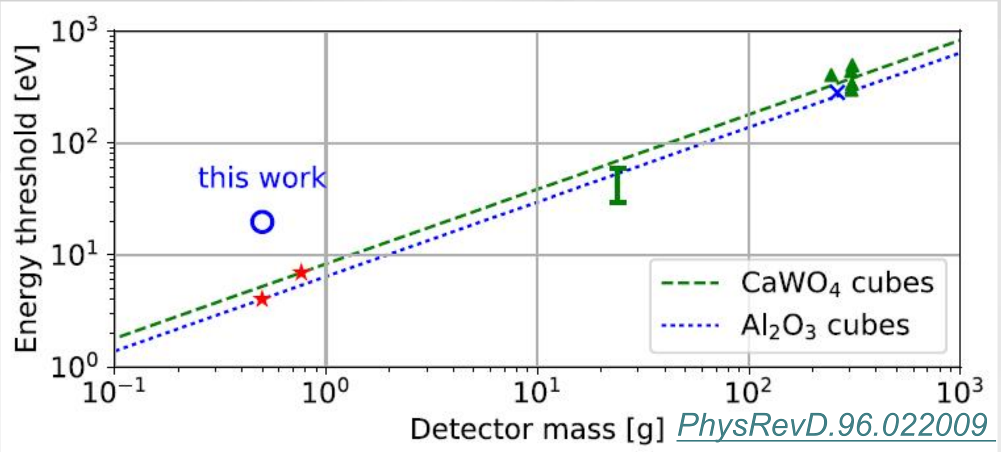




Bolometers are

Very flexible in:

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

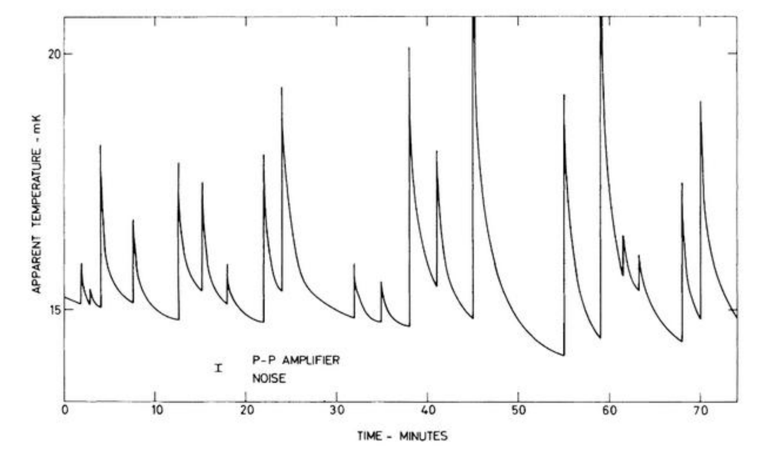


PhysRevD.96.022009

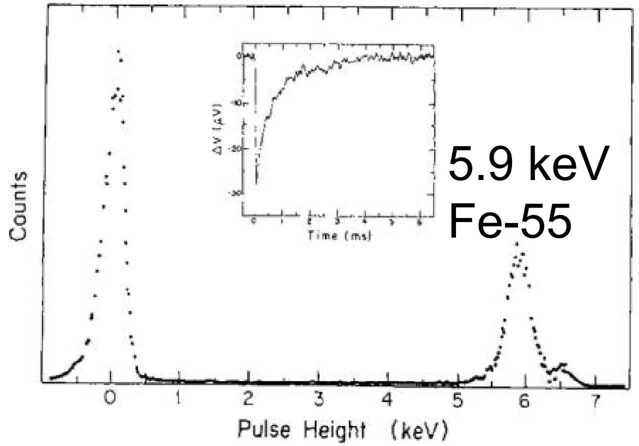
Experimental tests of a single-photon calorimeter for x-ray spectroscopy

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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Are there any disasdvantages?

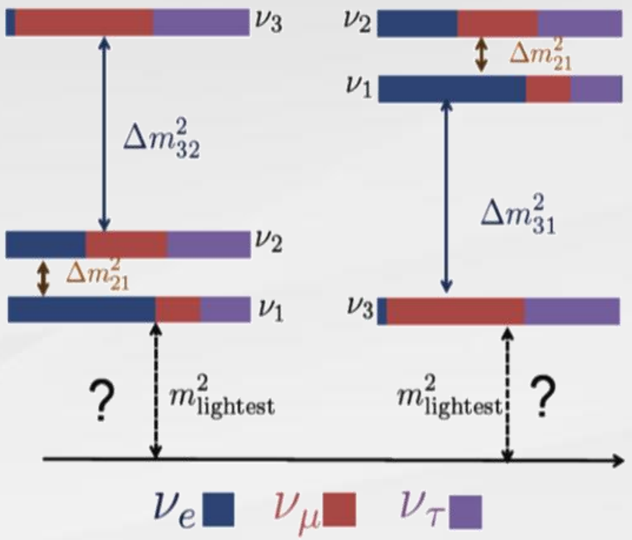
- Relatively slow detectors (especially large devices)
- Require complex infrastructure for stable operation
- Restricted volume (by size of cryostat)
- Large masses through arrays - a lot of electronics channels!

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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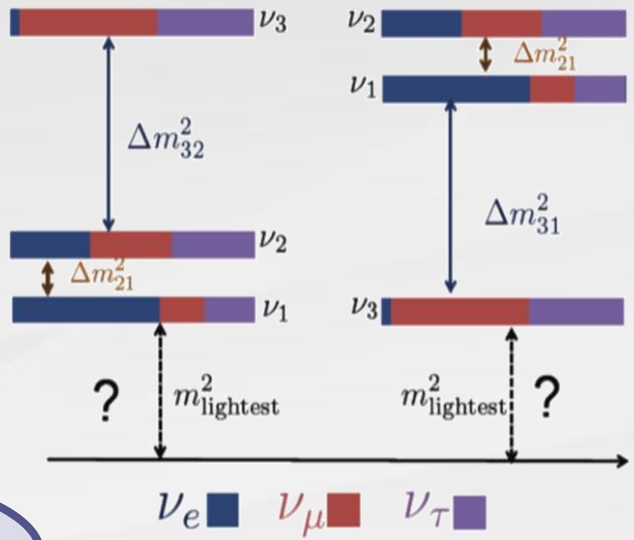

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Direct m_β mass measurement

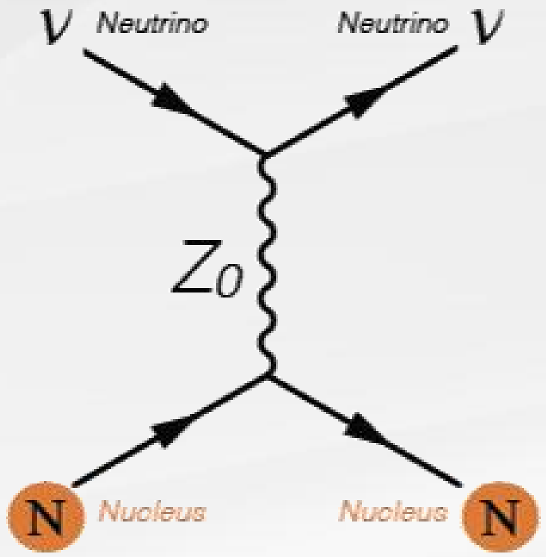
Double beta decay searches

CEνNS

Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)

CEνNS

- Largest neutrino cross section at low energies by few orders of magnitude: process within the SM, 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



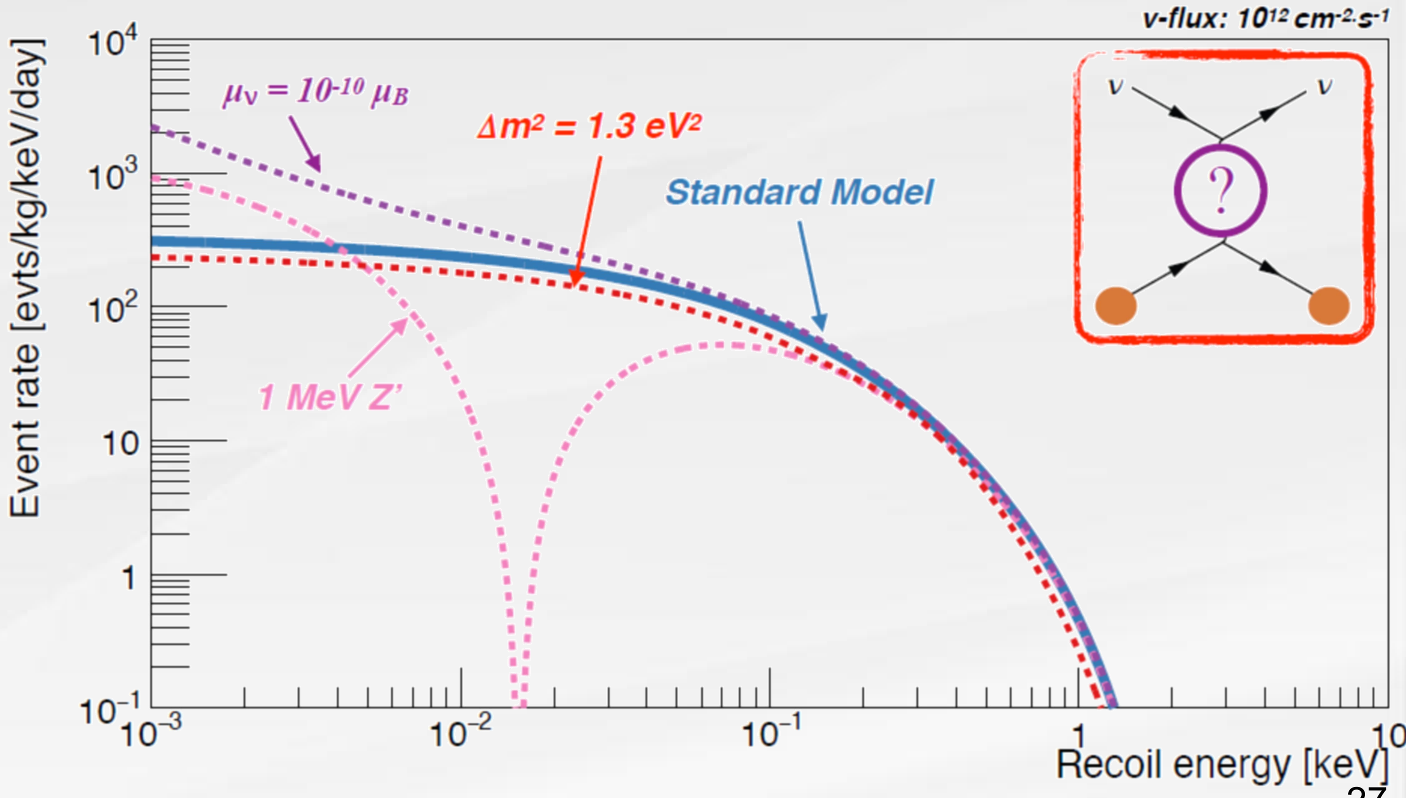
arXiv:2203.07361

CEνNS

- Low-energy source: reactor neutrinos
- 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

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

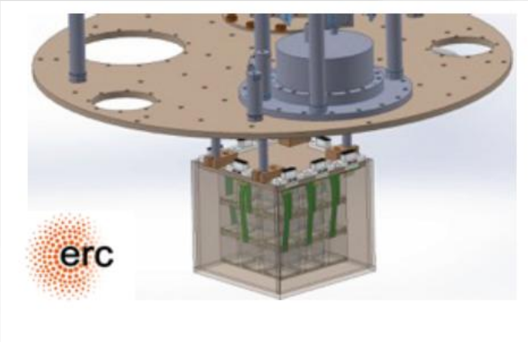
$$Q_w = N - Z(1 - 4\sin^2\theta_w)$$



CEνNS experiments

- One of the main challenges: background reduction
- Experience adopted from dark matter experiments:

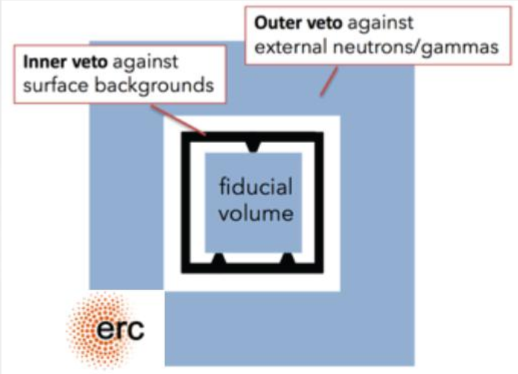
Ricochet



30 g Ge and Zn crystals
1 kg in total

Nuclear recoil identification down to O(10) eV threshold

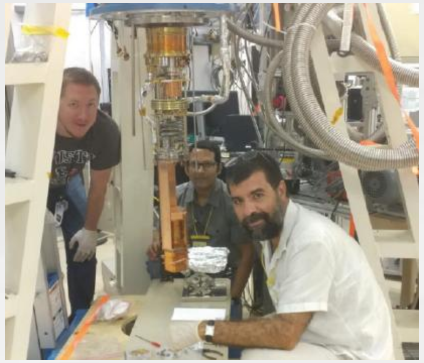
NuCLEUS



~1 g $CaWO_4$ and Al_2O_3 crystals
1st phase 10g, then 1 kg in total

Outer and inner **vetos**

MINER



Use Ge detector in HV mode

Passive and active **shielding**

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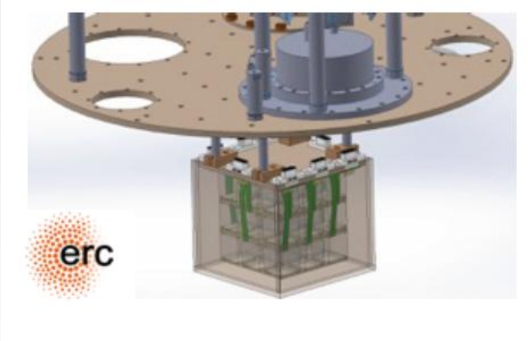

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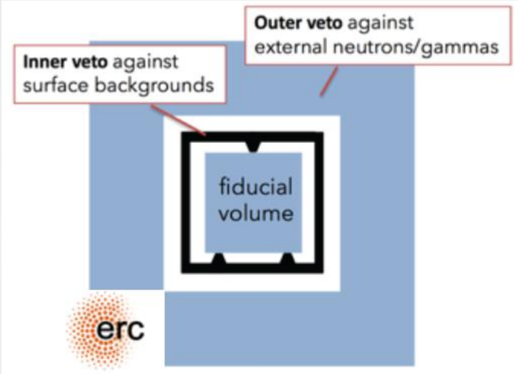

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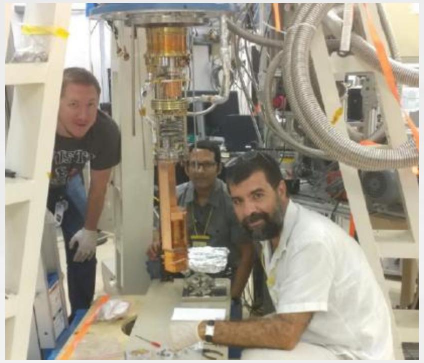


Use Ge detector in HV mode

Passive and active **shielding**

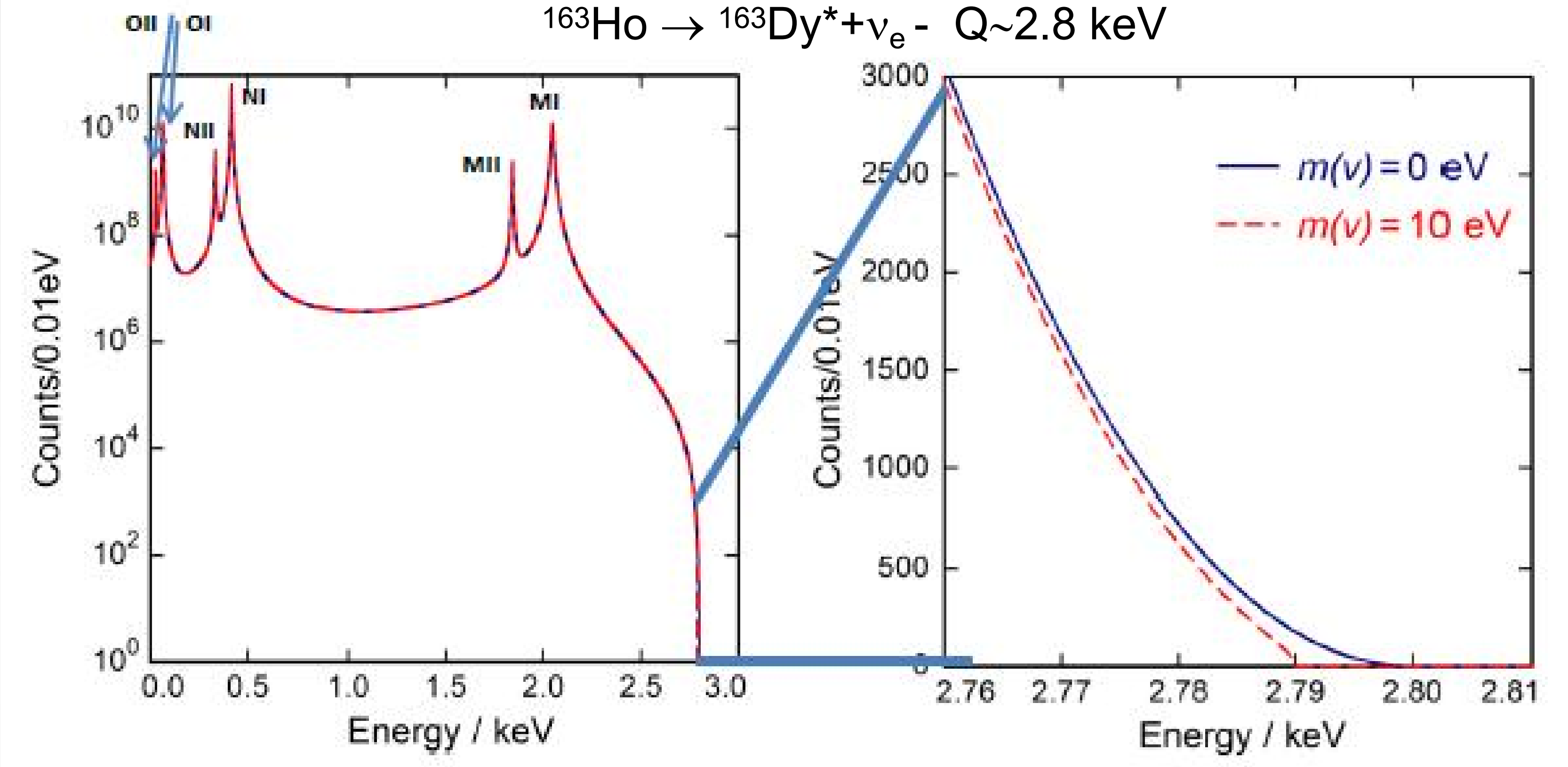
Stay tuned for the results in coming years!

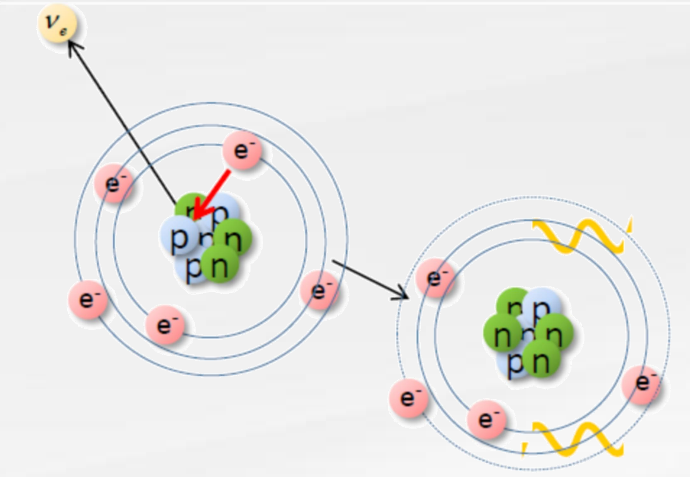
Direct neutrino mass measurements

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~2.8 keV



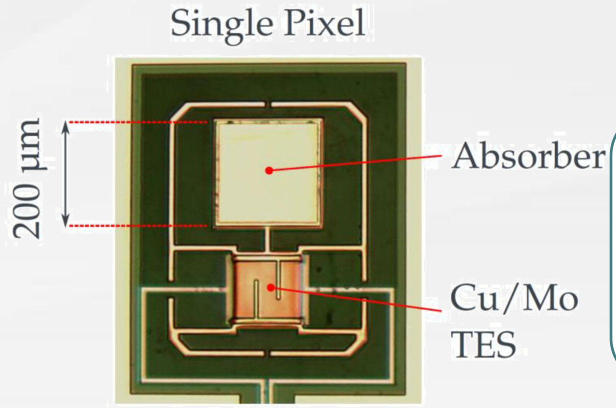


$T_{1/2}$=4570 yr

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

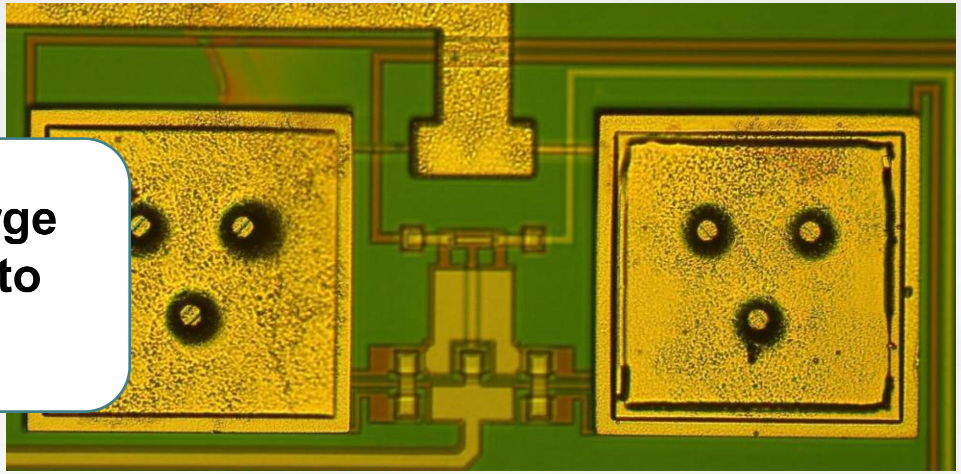
HOLMES



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

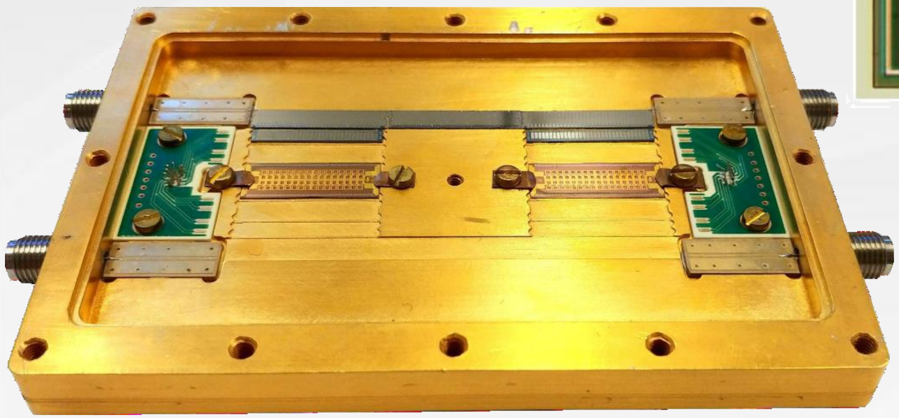
ECHo

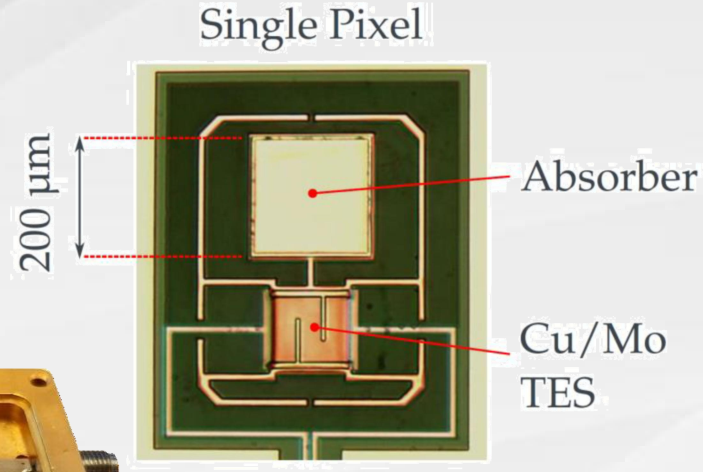
MMC

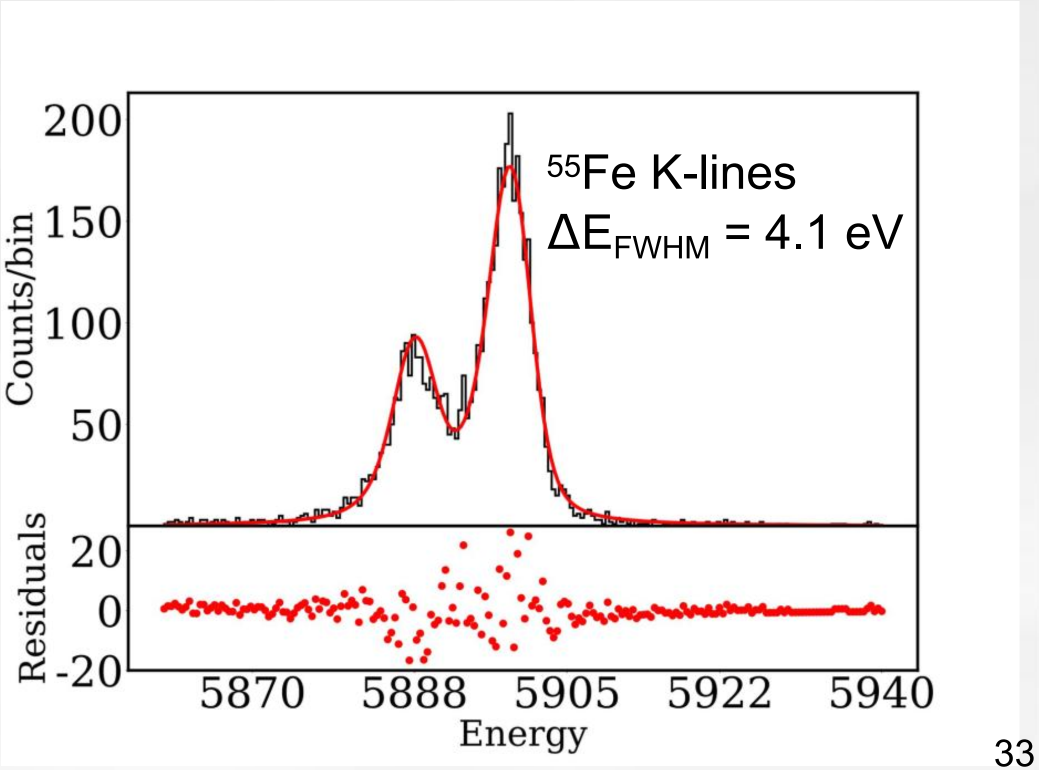


Experiments with ^{163}Ho

- Array of transition edge sensors calorimeters
- reliable performance demonstrated without ^{163}Ho
- Multiplexed readout demonstrated

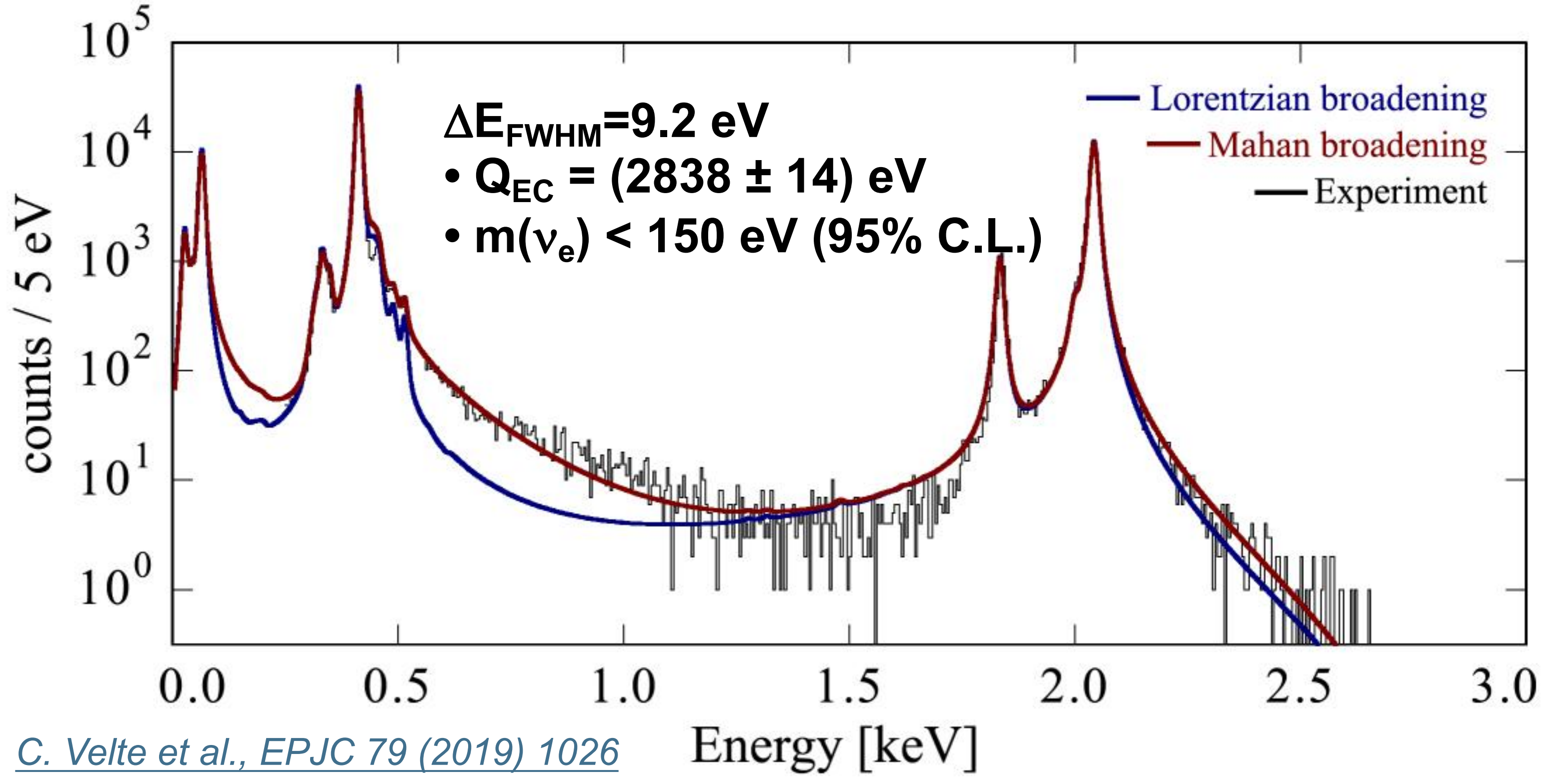




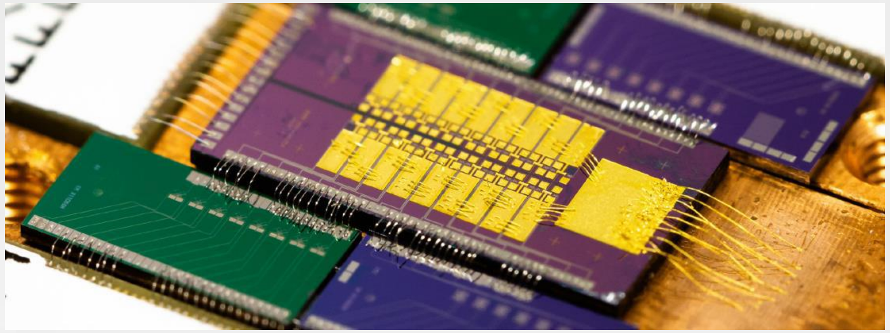


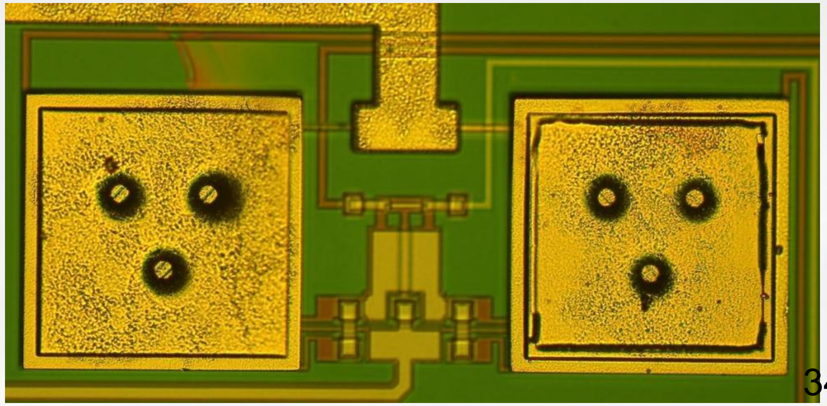
Experiments with ^{163}Ho

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



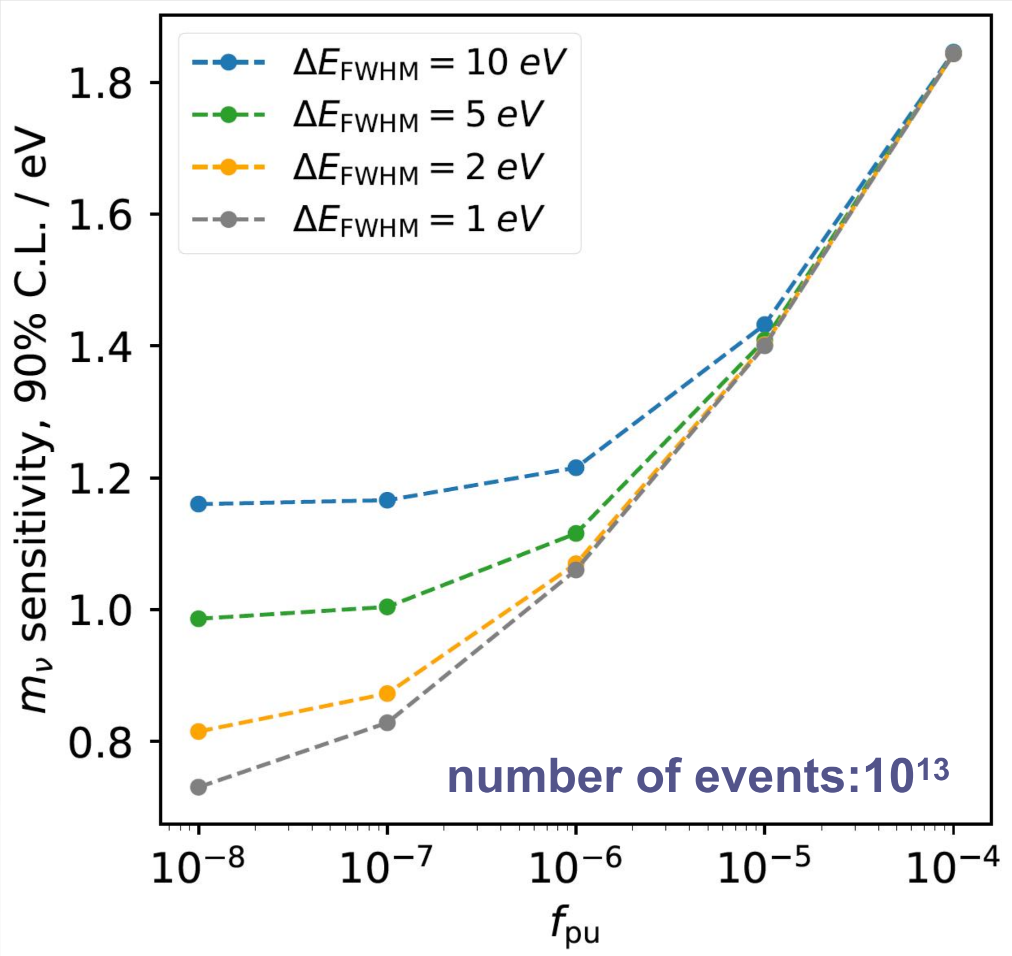
C. Velte et al., EPJC 79 (2019) 1026





Prospects

Near future:



Neutrino mass determination with ^{163}Ho ECHo & HOLMES, L. Gastaldo Neutrino 2022

Prospects

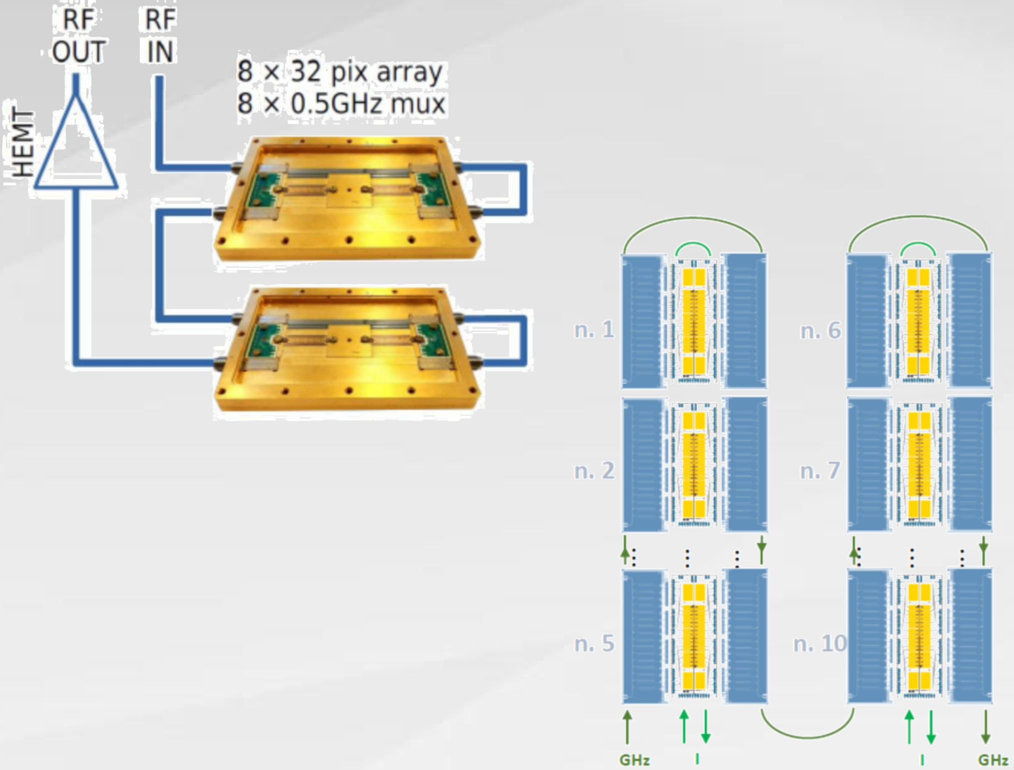
Final experiments:

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

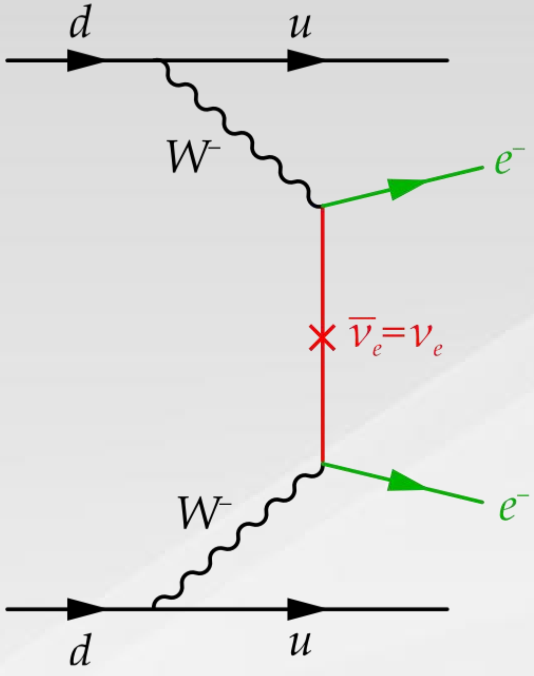
The determination of the electron neutrino mass with ^{163}Ho is complementary to the deterermination with ^{3}H

Neutrino mass determination with ^{163}Ho ECHo & HOLMES, L. Gastaldo Neutrino 2022

Neutrinoless double beta decay

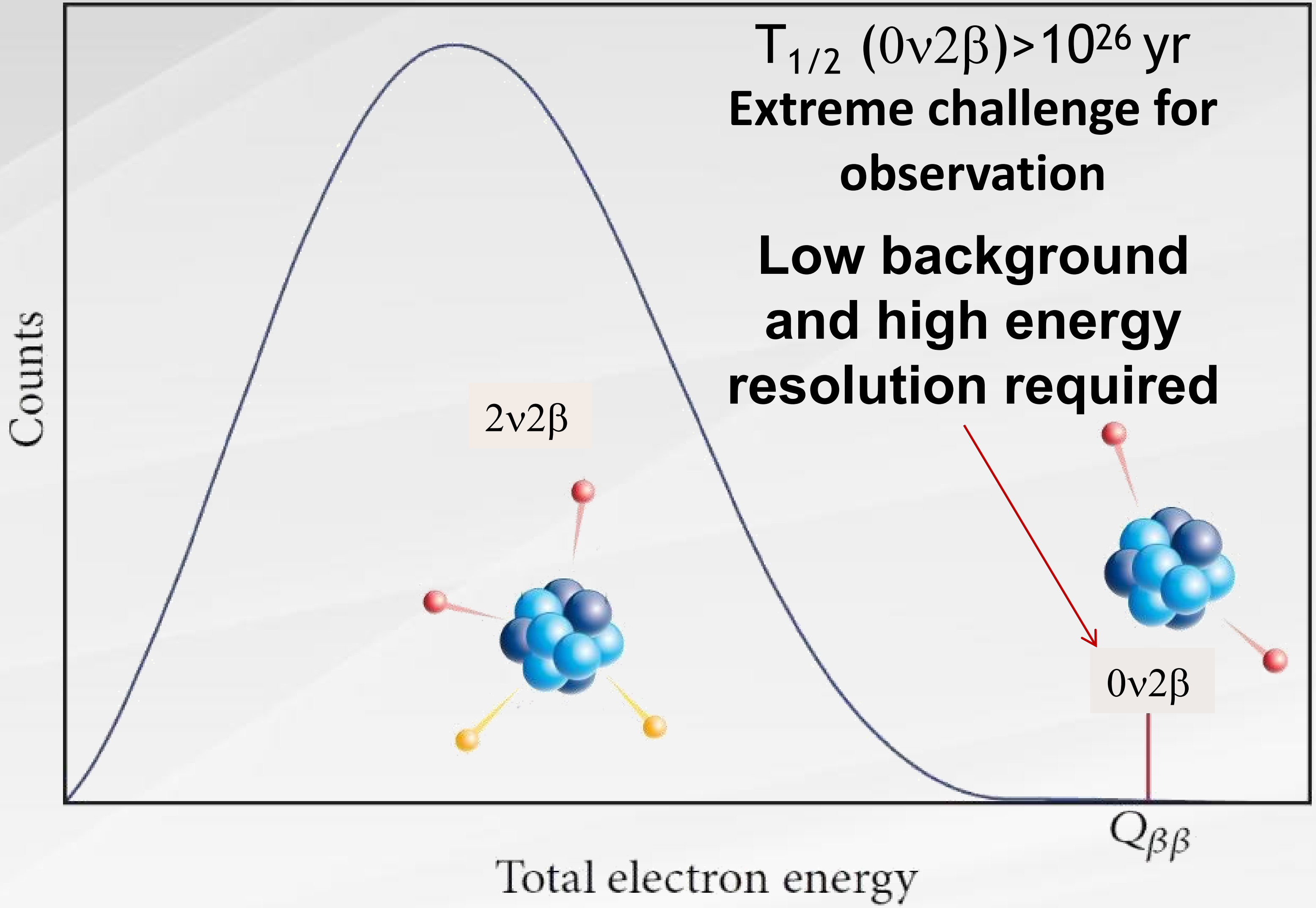
Neutrinoless double beta decay

$(A,Z) \rightarrow (A,Z+2) + 2e^-$



Fixes neutrino mass scale

Total lepton number violation →
new physics beyond SM

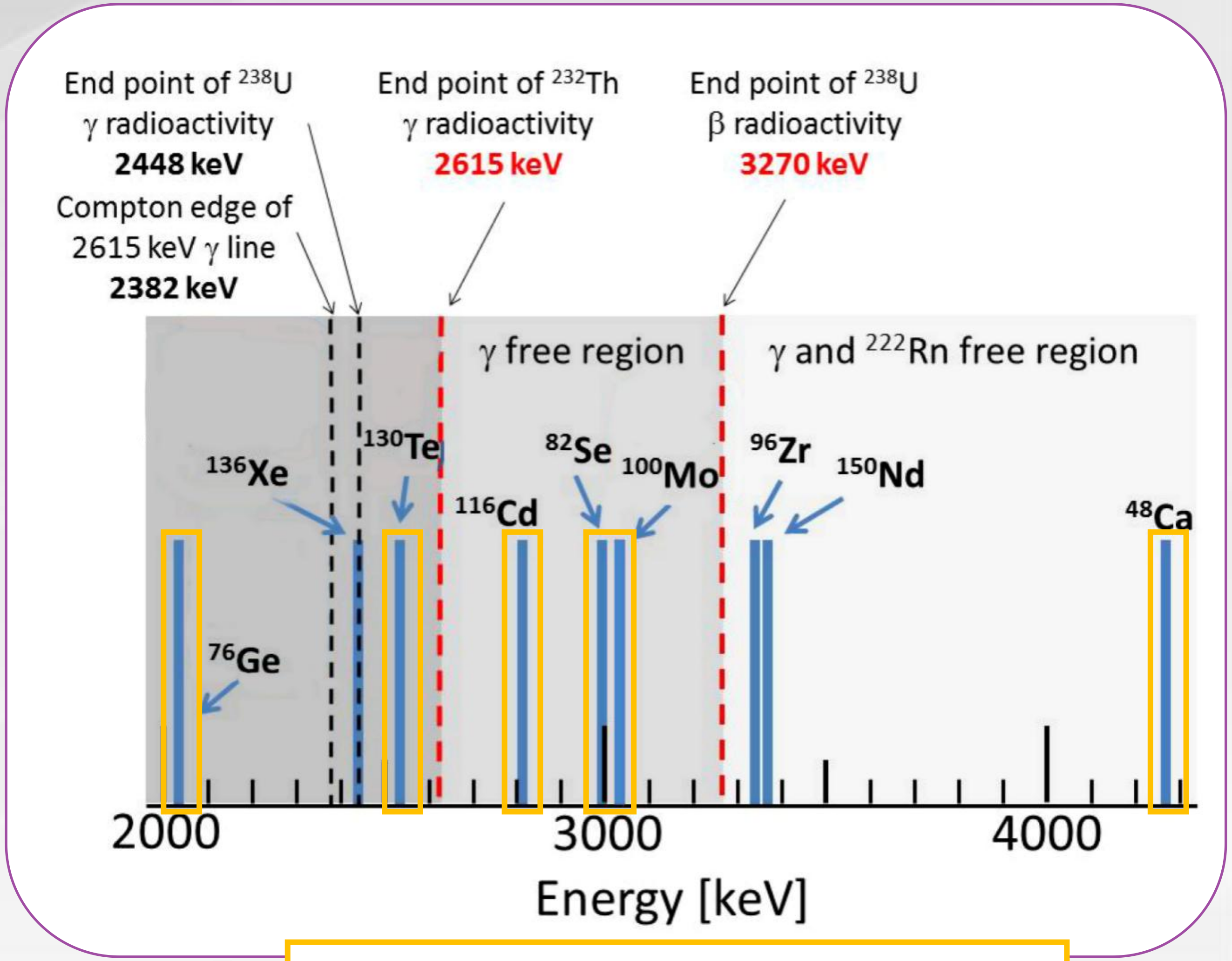


0ν2β decay candidates

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

Experimental requirements:

- Isotopic abundance and/or large scale enrichment
- High $Q_{\beta\beta}$ → 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

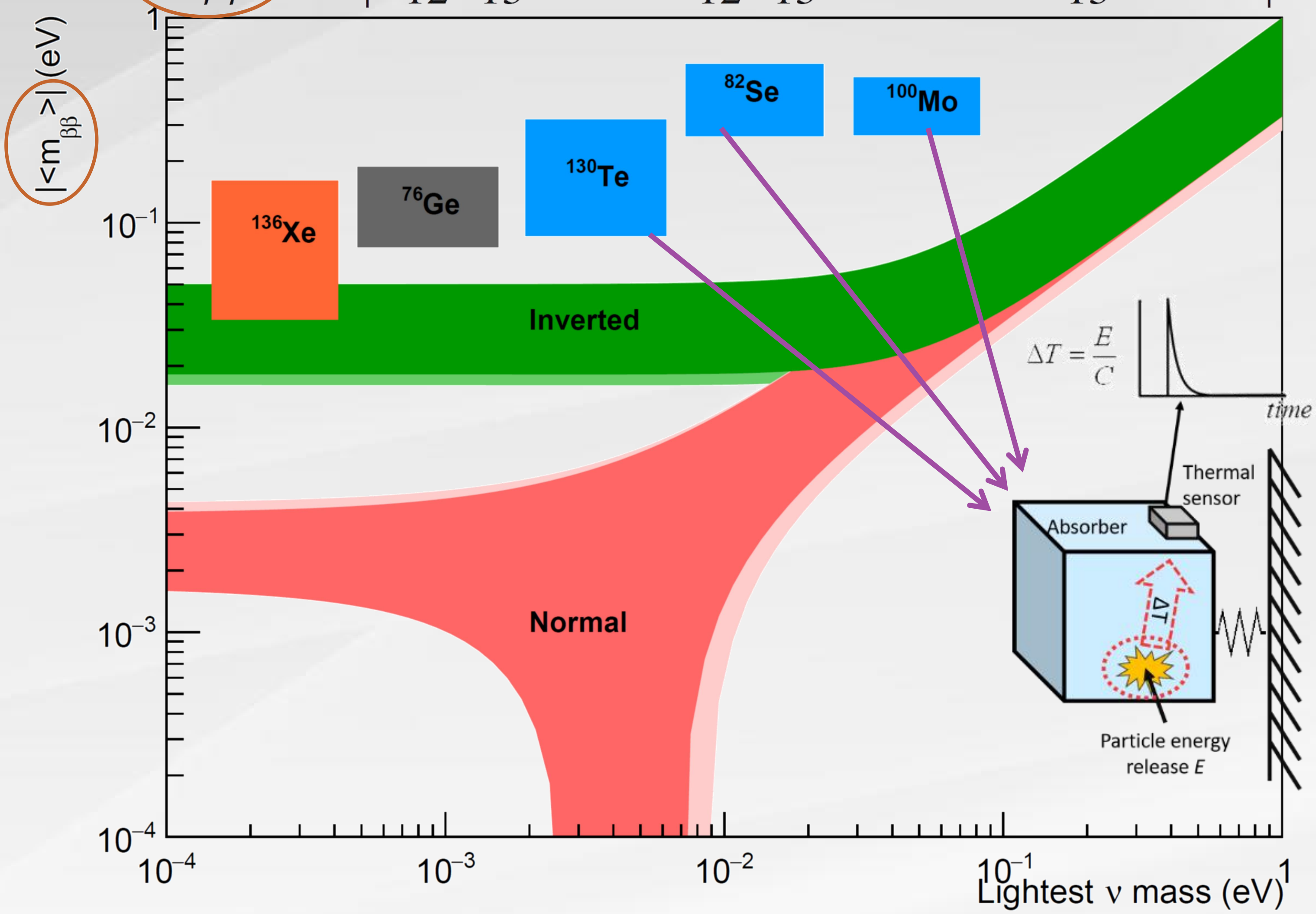
$$(T_{1/2}^{0\nu2\beta})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2 \frac{m_{\beta\beta}^2}{m_e^2}$$

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

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

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

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



Status of current searches

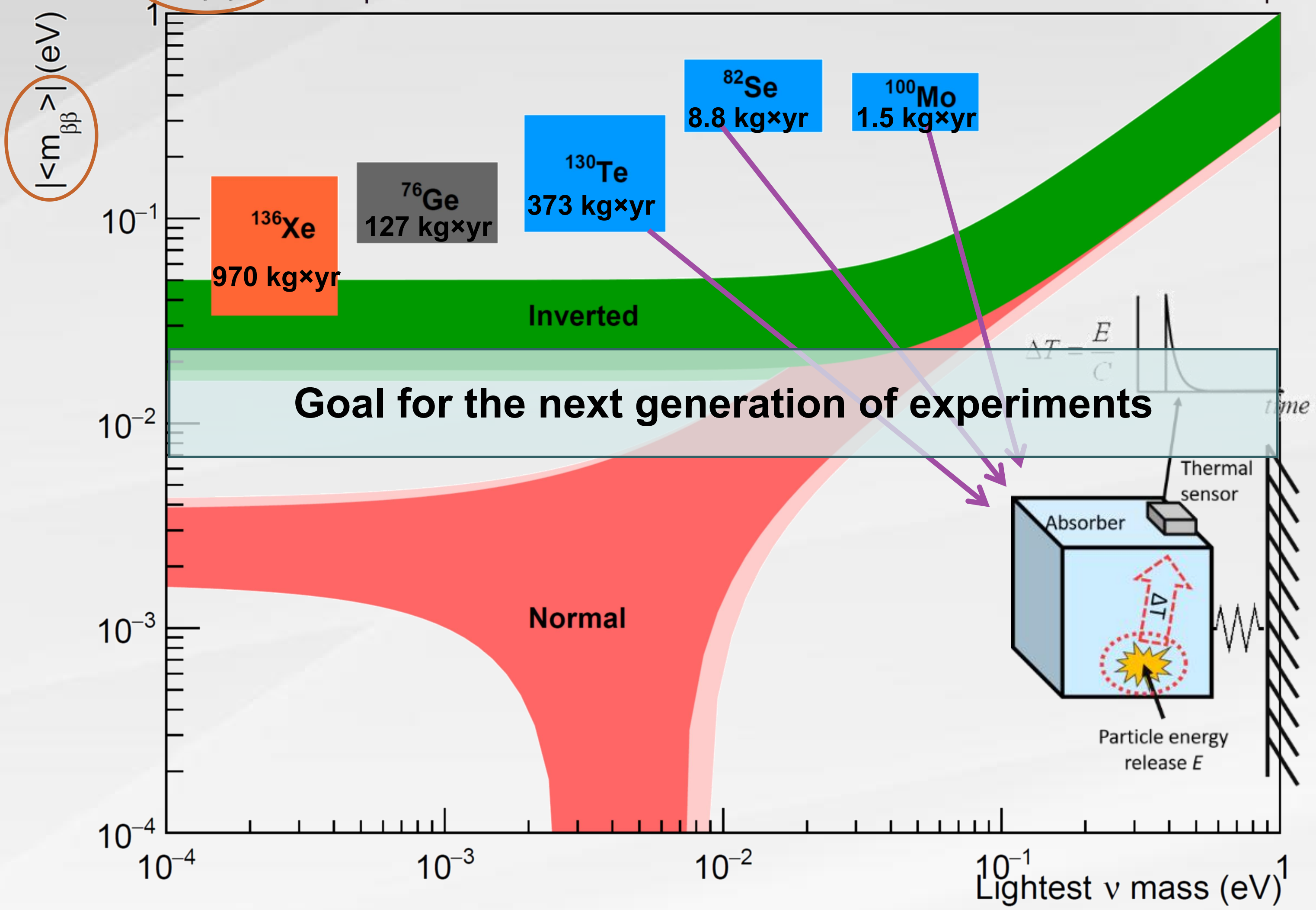
$$(T^{0\nu2\beta}_{1/2})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2 \frac{m^2_{\beta\beta}}{m^2_e}$$

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

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

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

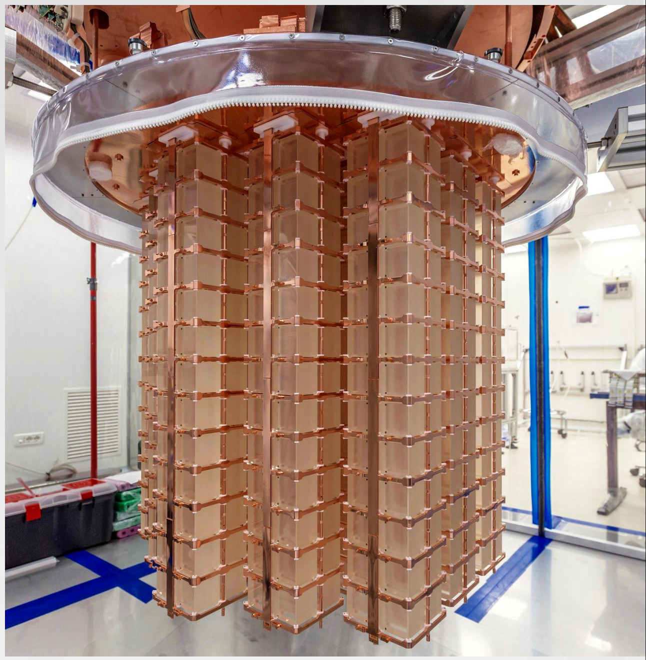
$$|m_{\beta\beta}| = |c^2_{12}c^2_{13}m_1 + s^2_{12}c^2_{13}m_2e^{i\alpha} + s^2_{13}m_3e^{i\beta}|$$

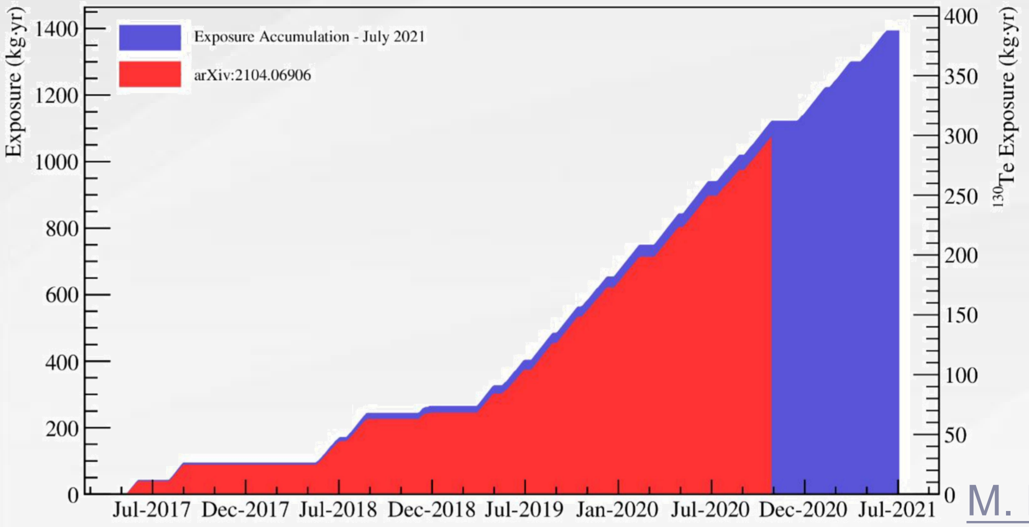


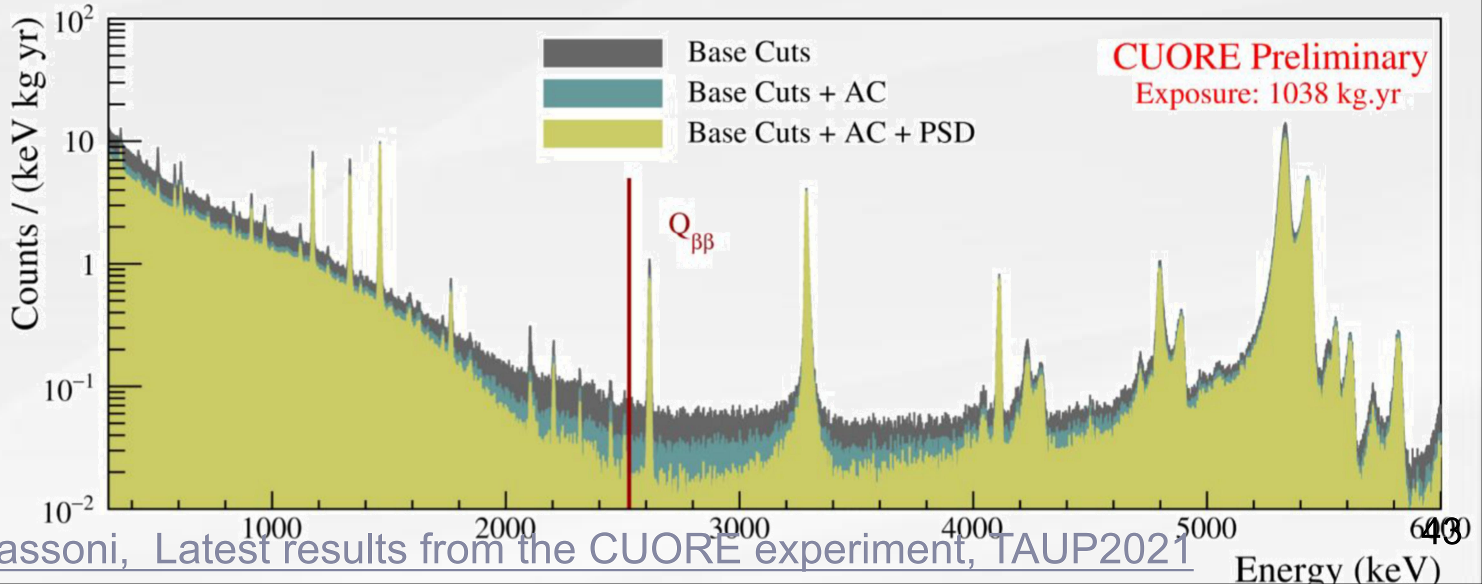
Demonstrators and large experiments

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**







M. Biassoni, Latest results from the CUORE experiment, TAUP2021

CUPID: past and future

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

CUPID: past and future

CUPID-Mo

CUPID demonstrators:
a rejection with light
Best limits on
^{100}Mo and ^{82}Se 0ν2β

CUPID-0

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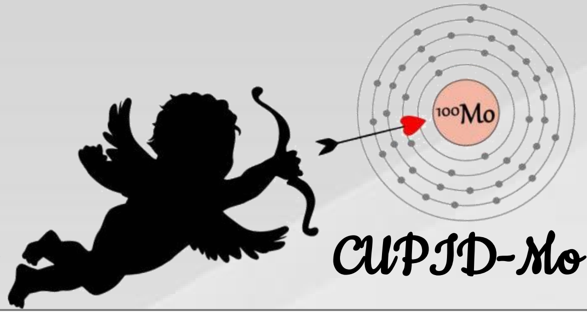
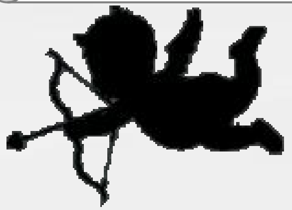
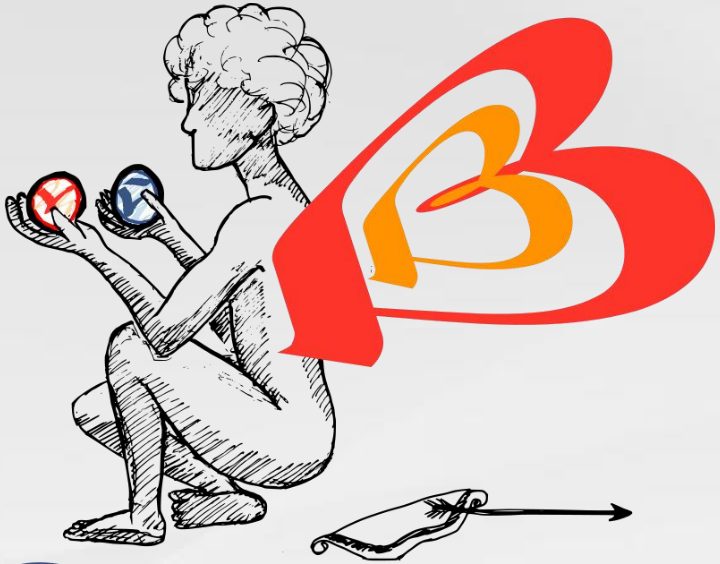


CUPID demonstrators:
a rejection with light
Best limits on
^{100}Mo and ^{82}Se 0ν2β



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



CUPID

New demonstrators for
deeper investigations of
normal mass ordering

BINGO

CROSS

Neutrinoless double β decay

Superconductivity

CUPID: past and future

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

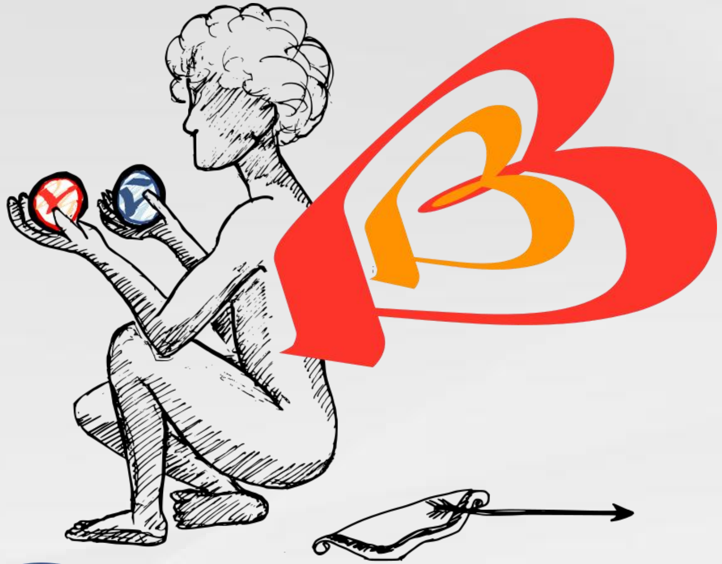
CUPID-Mo

CUPID demonstrators:
a rejection with light
Best limits on
^{100}Mo and ^{82}Se 0ν2β

CUPID-0

Phase II

New demonstrators for
deeper investigations of
normal mass ordering



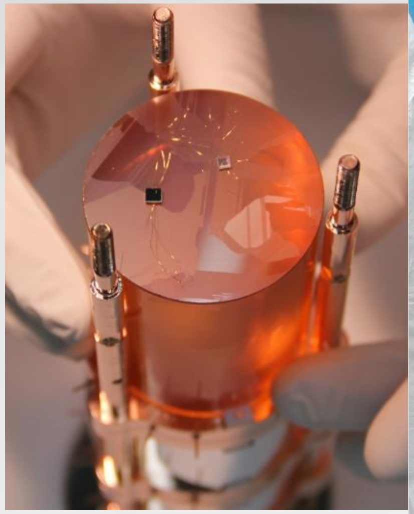
CUPID

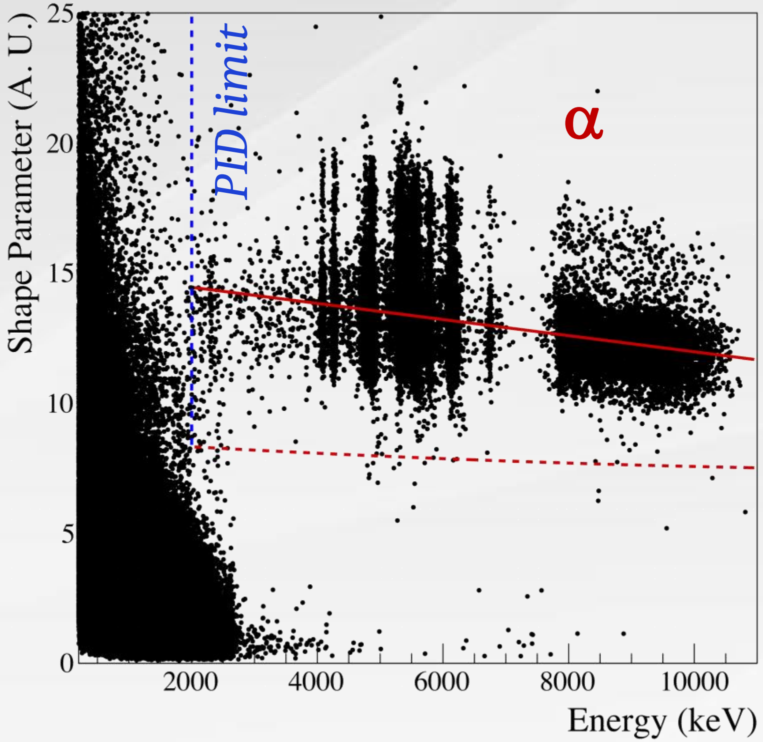
BINGO

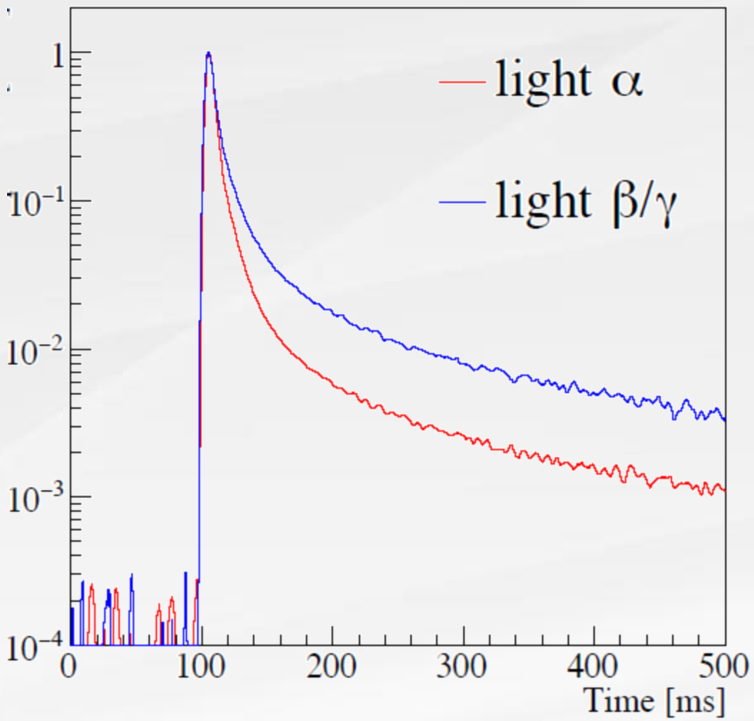
CROSS

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**)





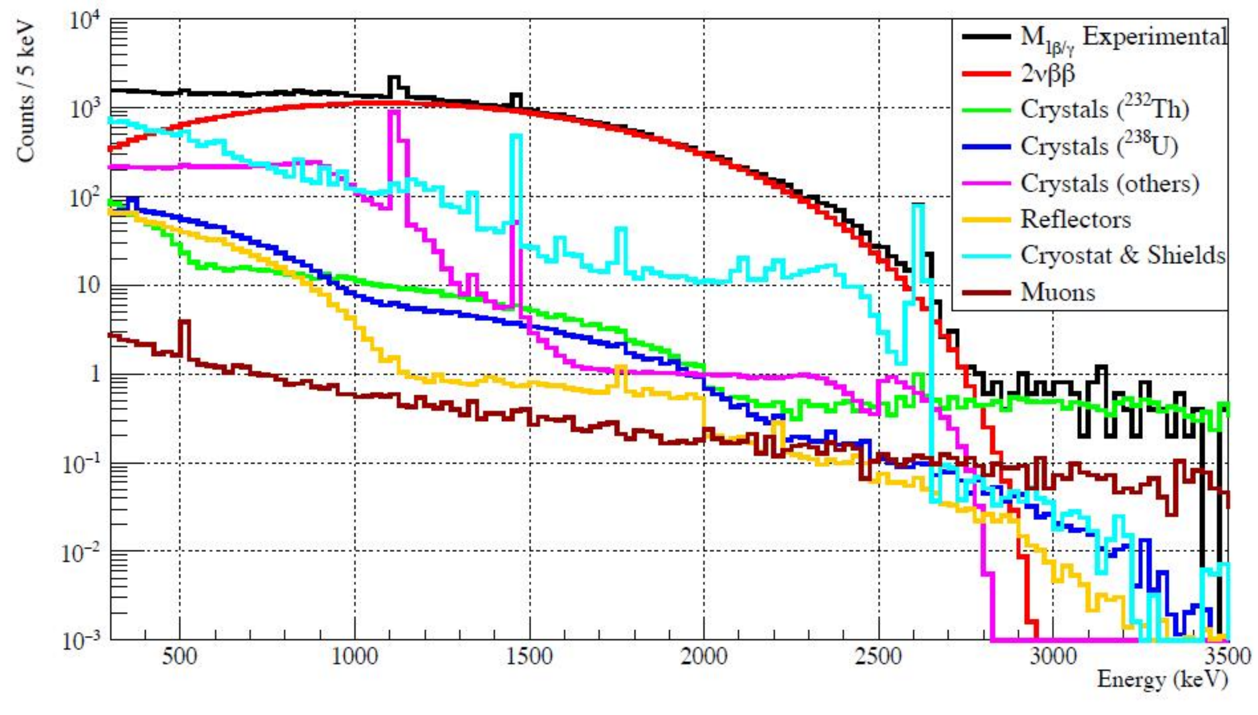


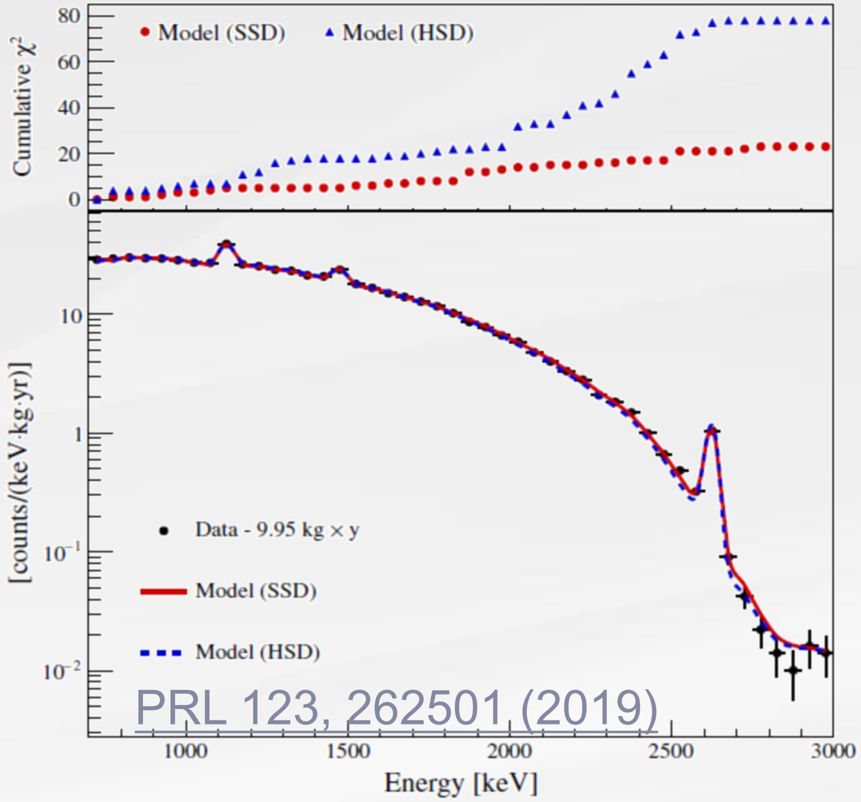
EPJC (2018) 78:428

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





PRL 123, 262501 (2019)

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

*

CUPID-0 results

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

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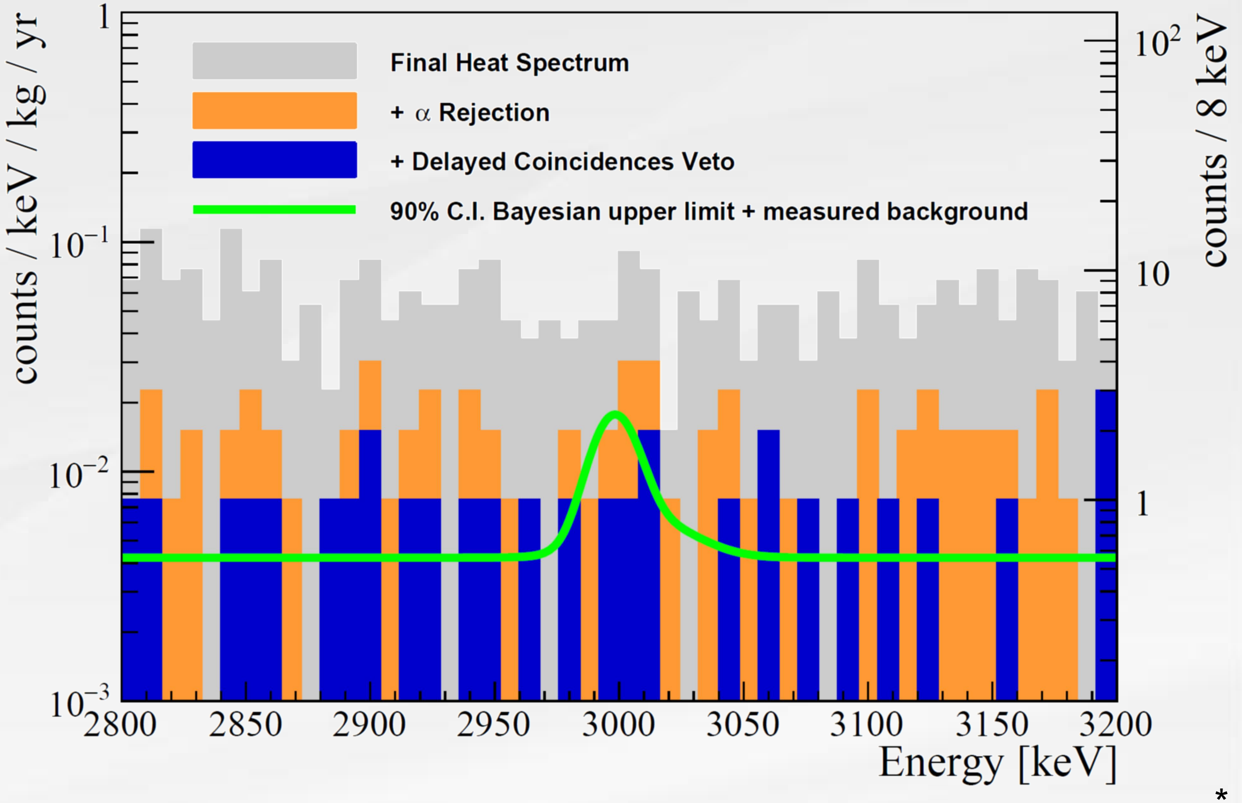
- High scientific potential: best limit on 0n2b, most precise measurement of ^{82}Se $2\nu2\beta$, CPT violation search, SSD vs HSD, excited states

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

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

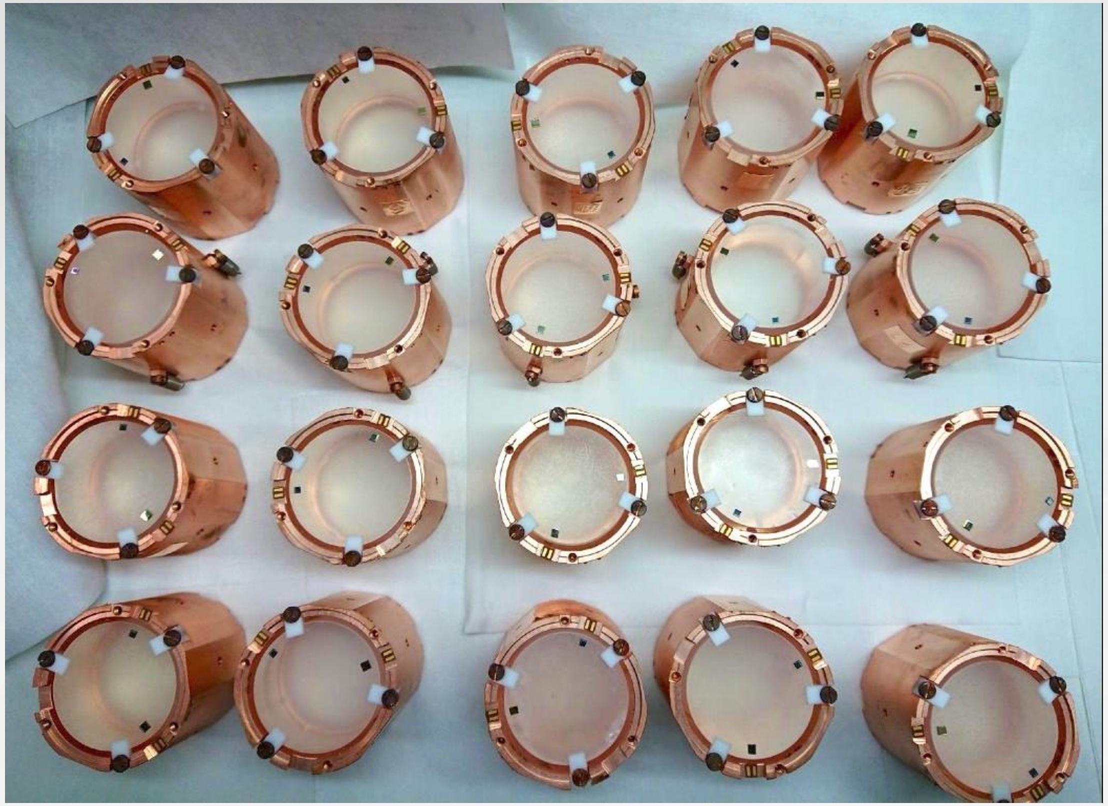
[PRD 100, 092002 (2019)](#)
[PRL 123, 262501 (2019)](#)
[EPJC 79, 583 (2019)](#)
[EPJC 81, 722 (2021)](#)

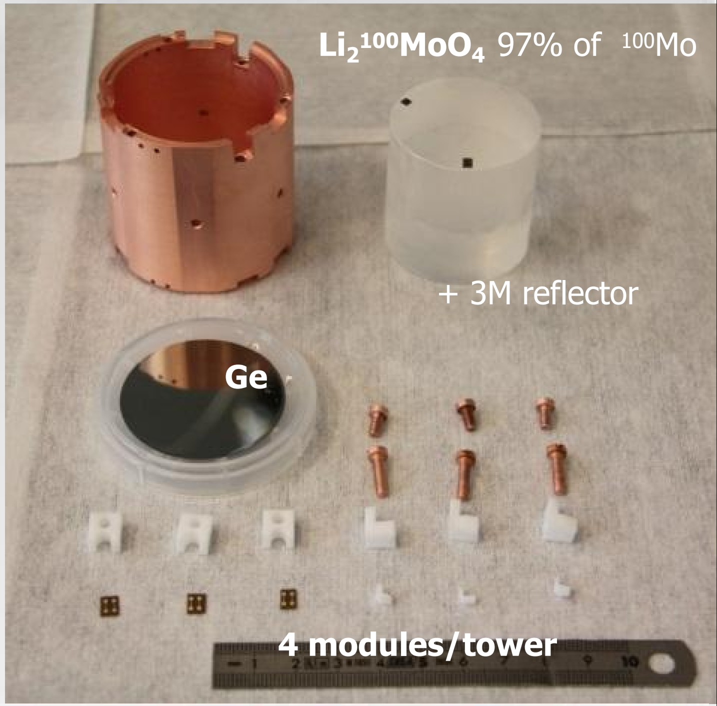


*

CUPID-Mo

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

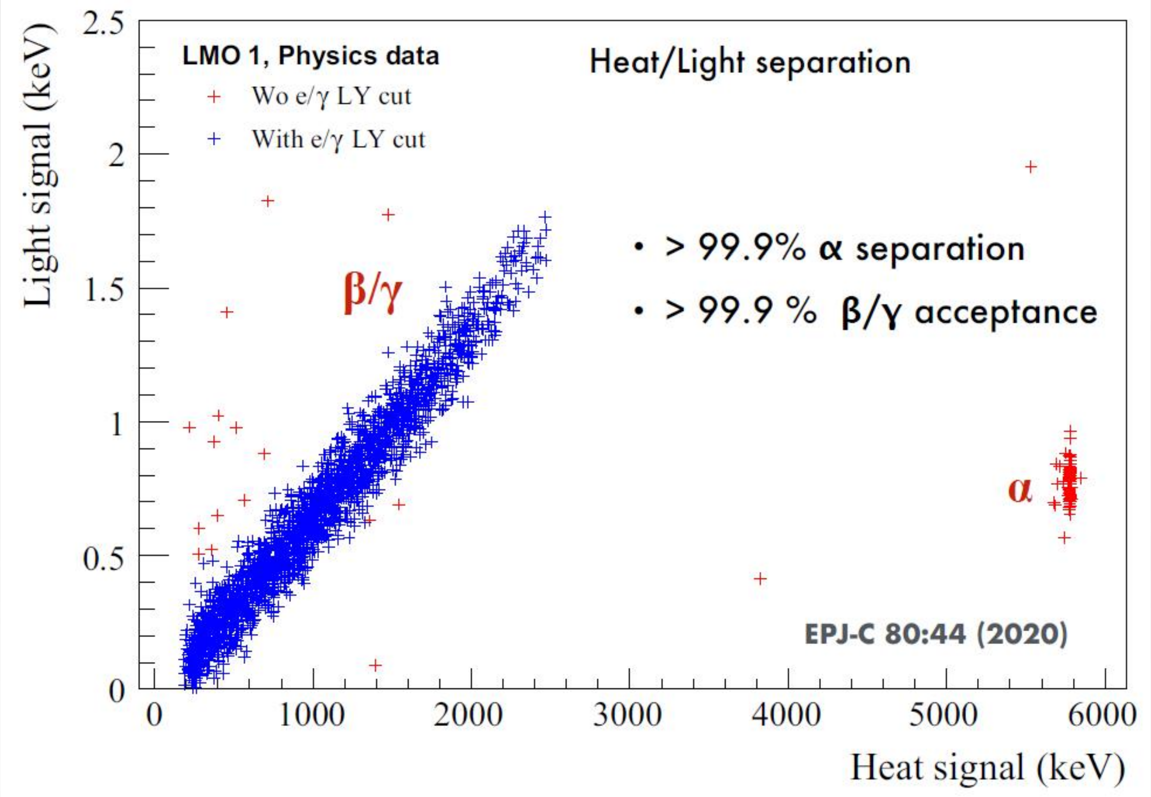


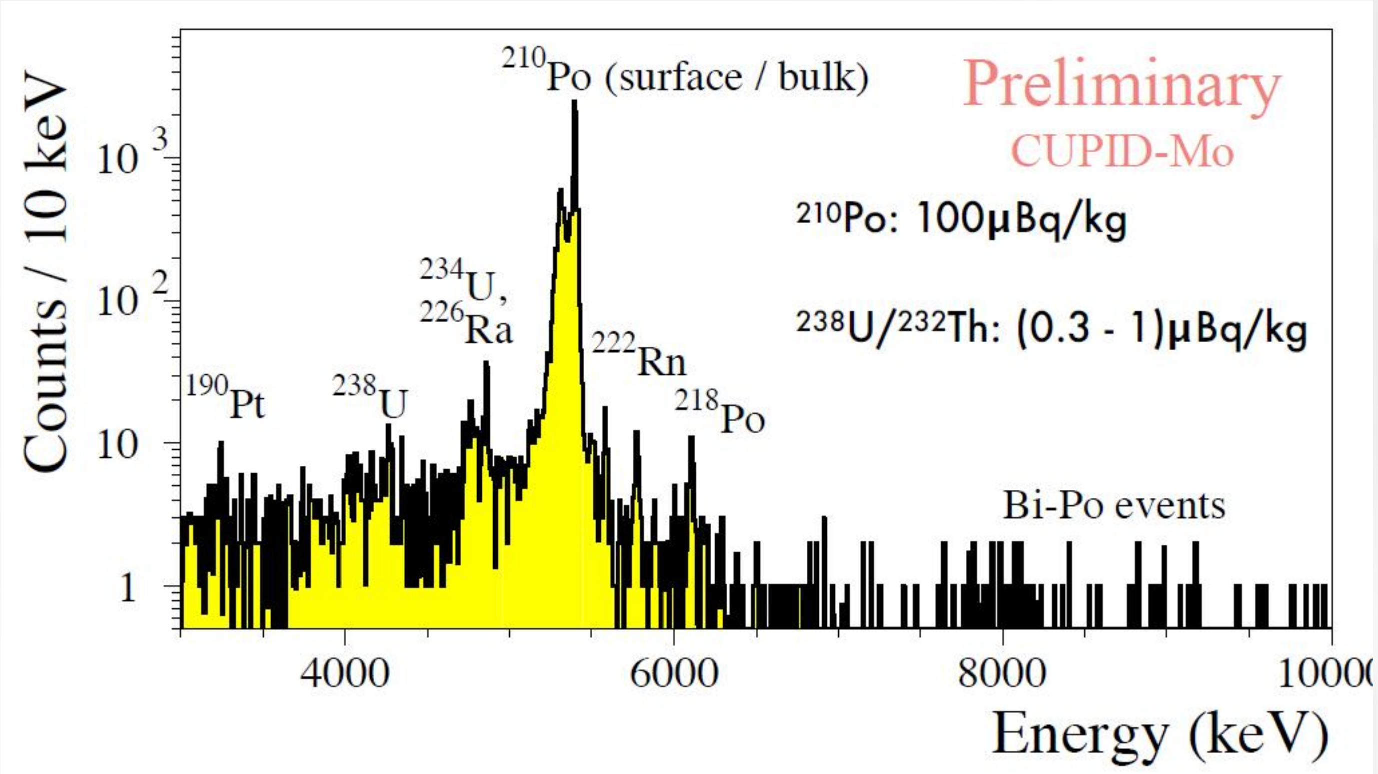


EPJC 80, 44 (2020)

CUPID-Mo features

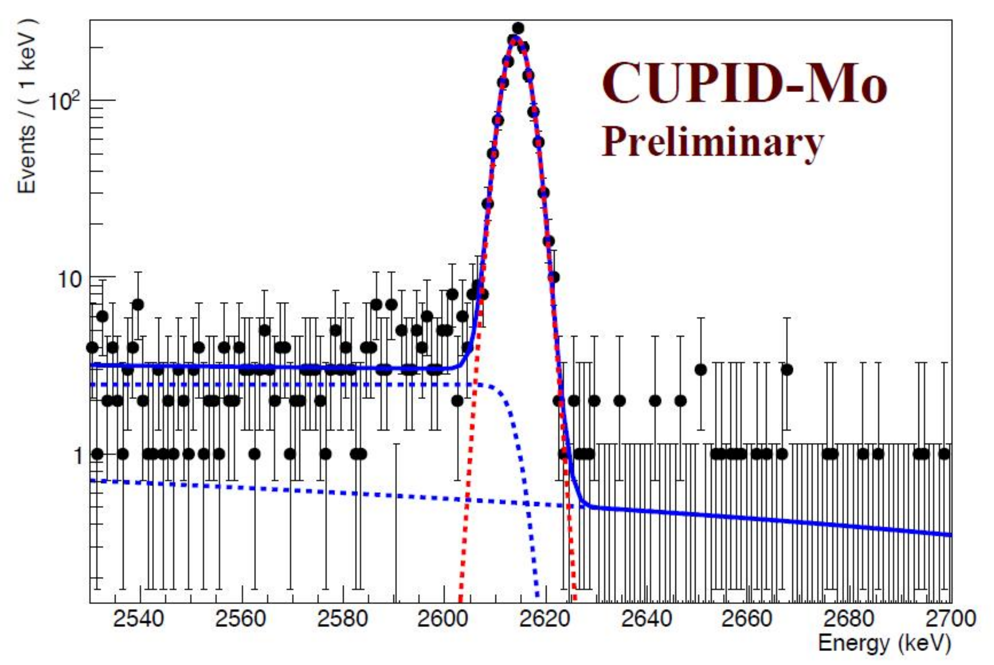
- Excellent internal radiopurity of crystals: ^{210}Po and U/Th well within CUPID requirements

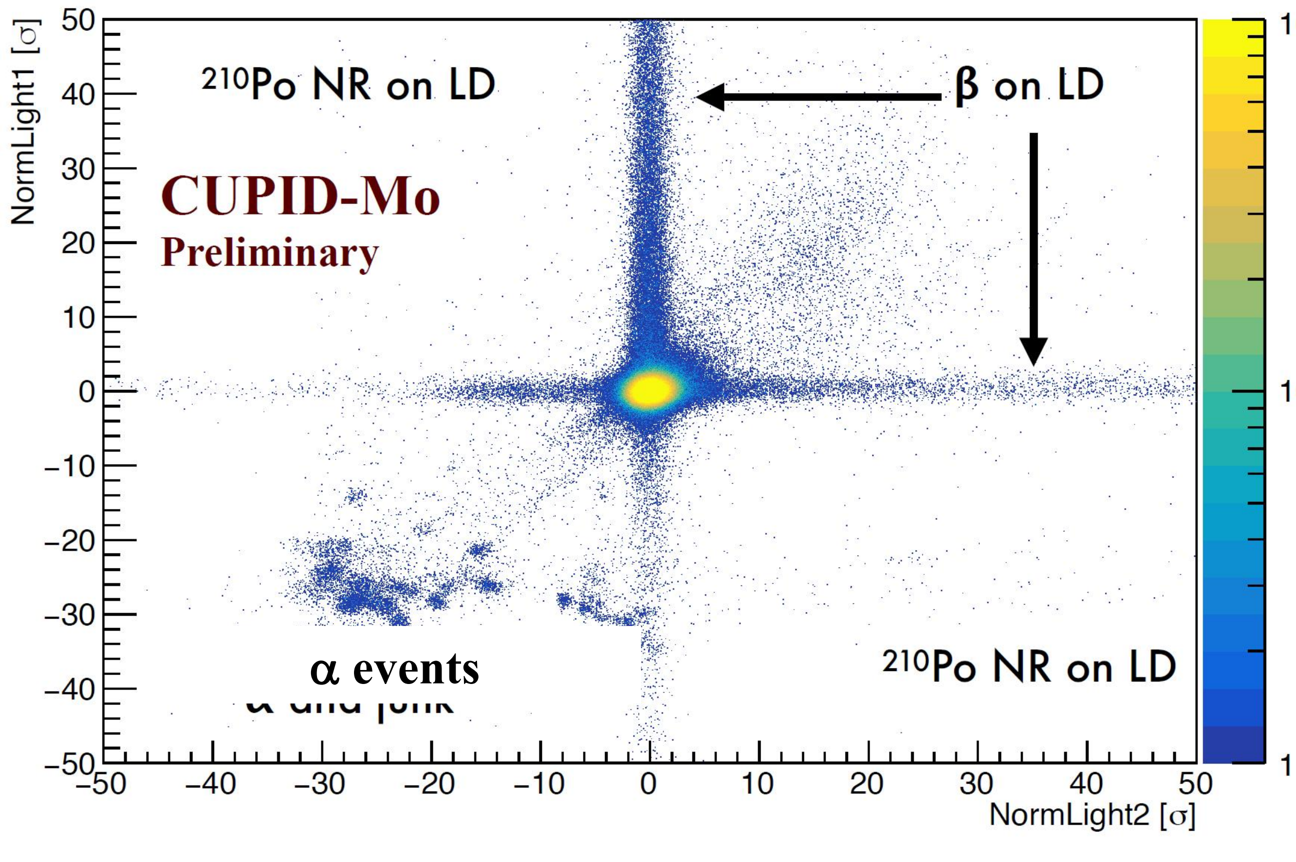




CUPID-Mo features

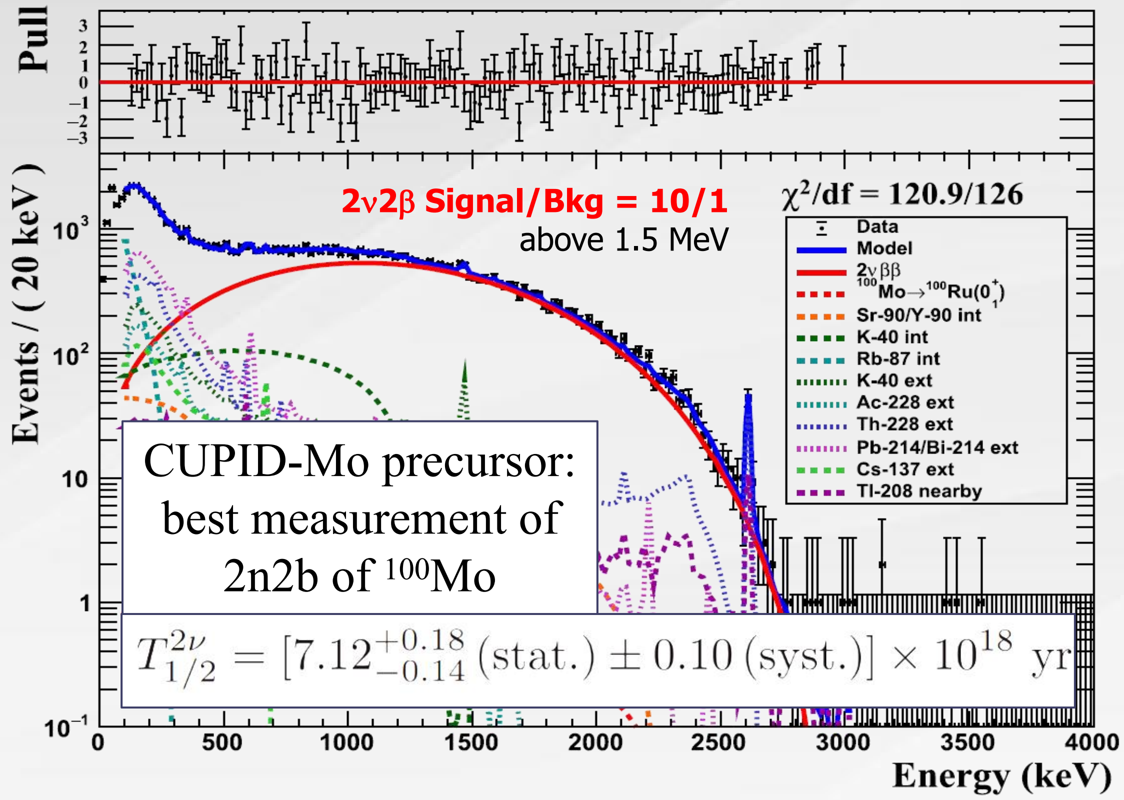
- Excellent internal radiopurity of crystals: ^{210}Po and U/Th well within CUPID requirements
- Anticoincidence, light yield and pulse shape cuts applied for background reduction
- **FWHM @ $Q_{\beta\beta}$=(7.38 ± 0.35) keV**

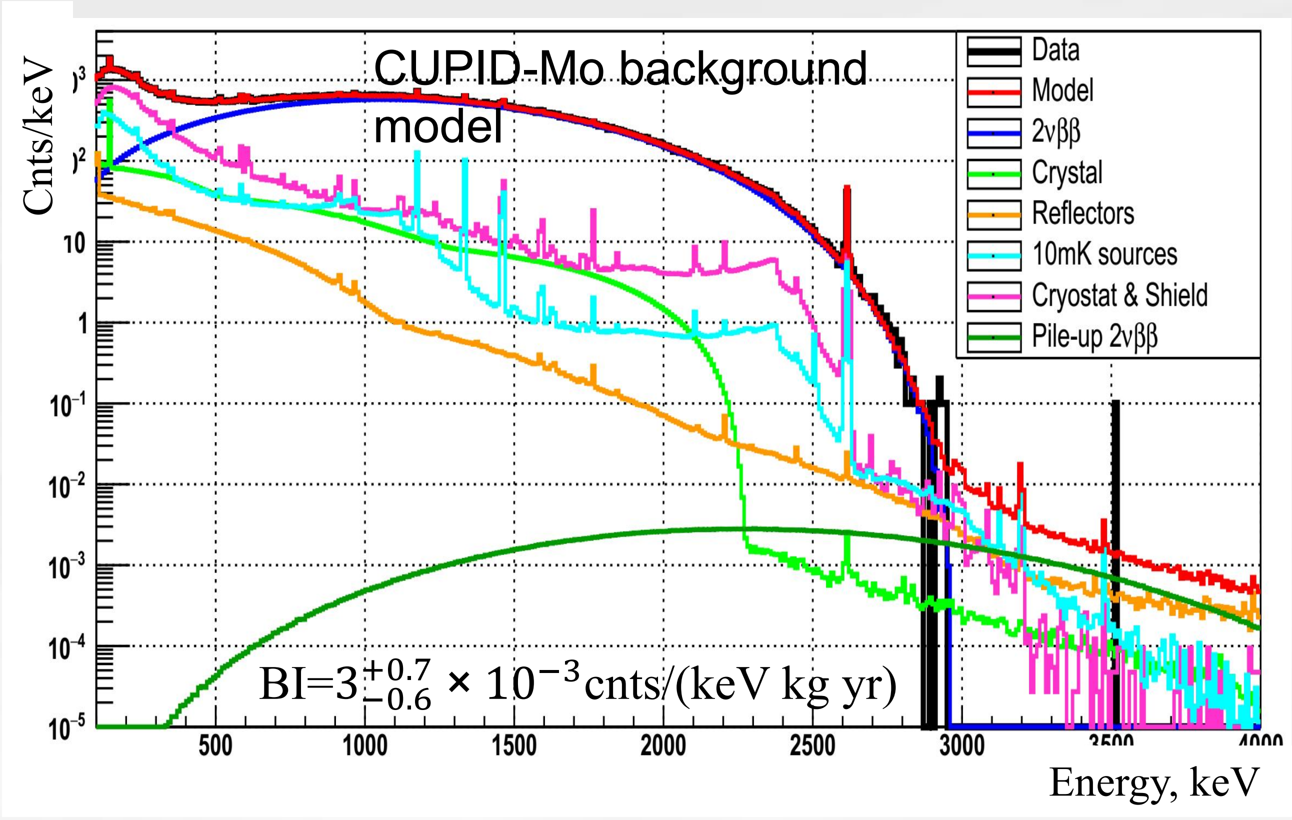




CUPID-Mo results

- 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 $2\nu2\beta$ (new results are expected from full CUPID-Mo) and excited states





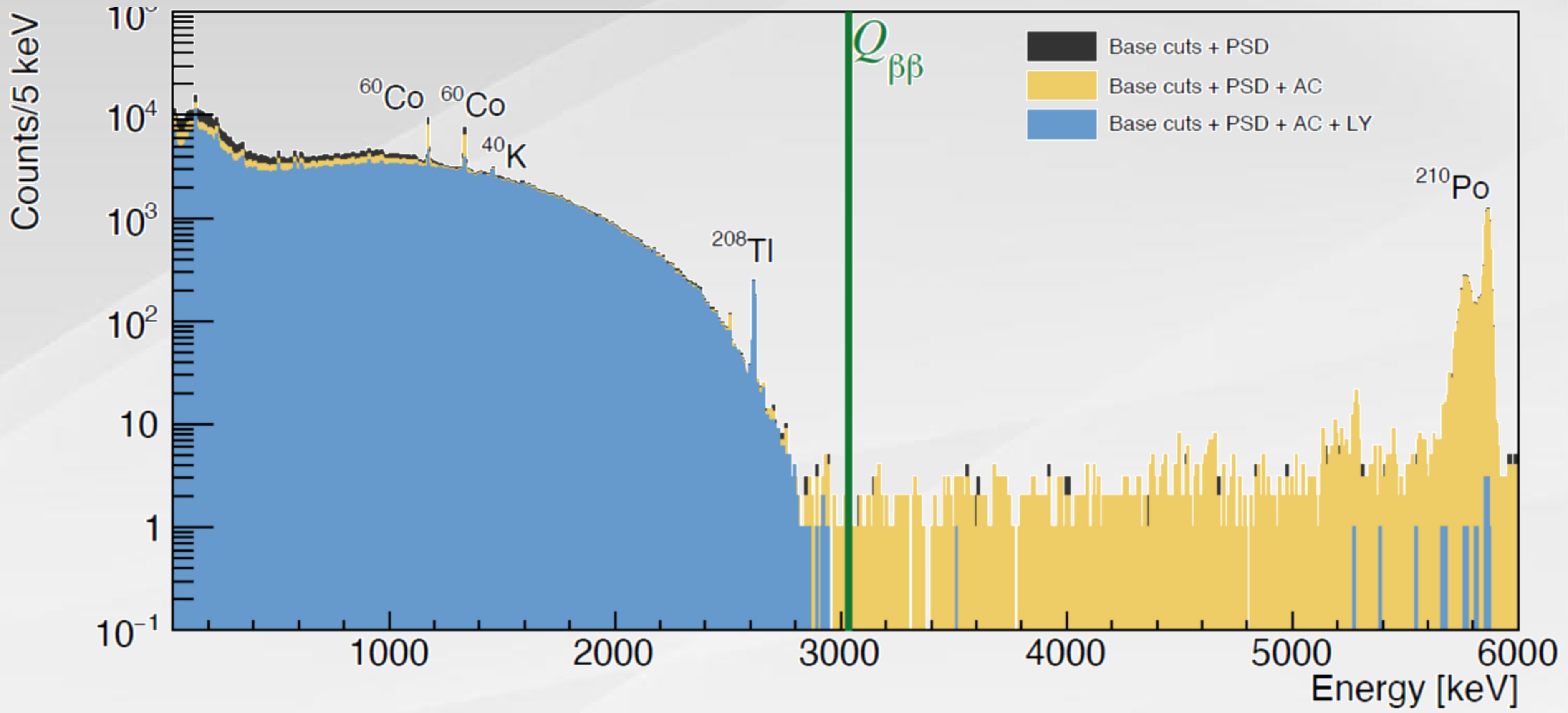
CUPID-Mo results

$T_{1/2}^{0v} > 1.8 \times 10^{24} yr$

(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

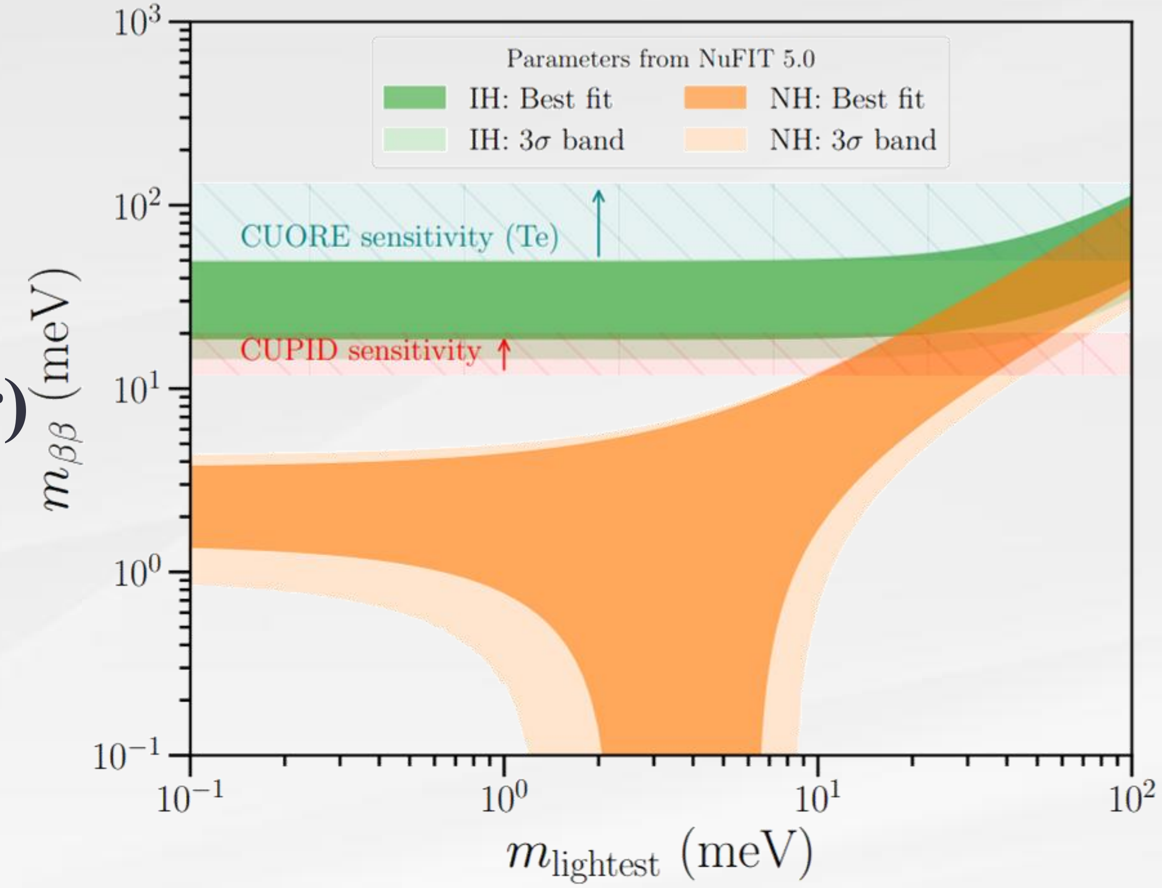
- **$Li_2{}^{100}MoO_4$ scintillating bolometers**
- α rejection using light signal
- Enrichment > 95%
- 1596 crystals and 240 kg of ^{100}Mo
- FWHM <10 keV at $Q_{\beta\beta}$ (3034 keV)

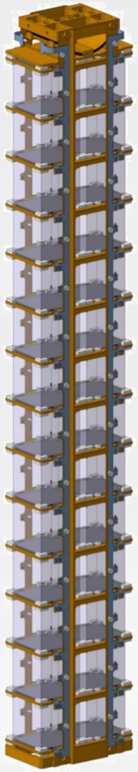
Background goal: 10^{-4} cnts/(keV kg yr)

Discovery sensitivity at 3σ:

$T_{1/2}(^{100}Mo) = 10^{27}$ yr

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





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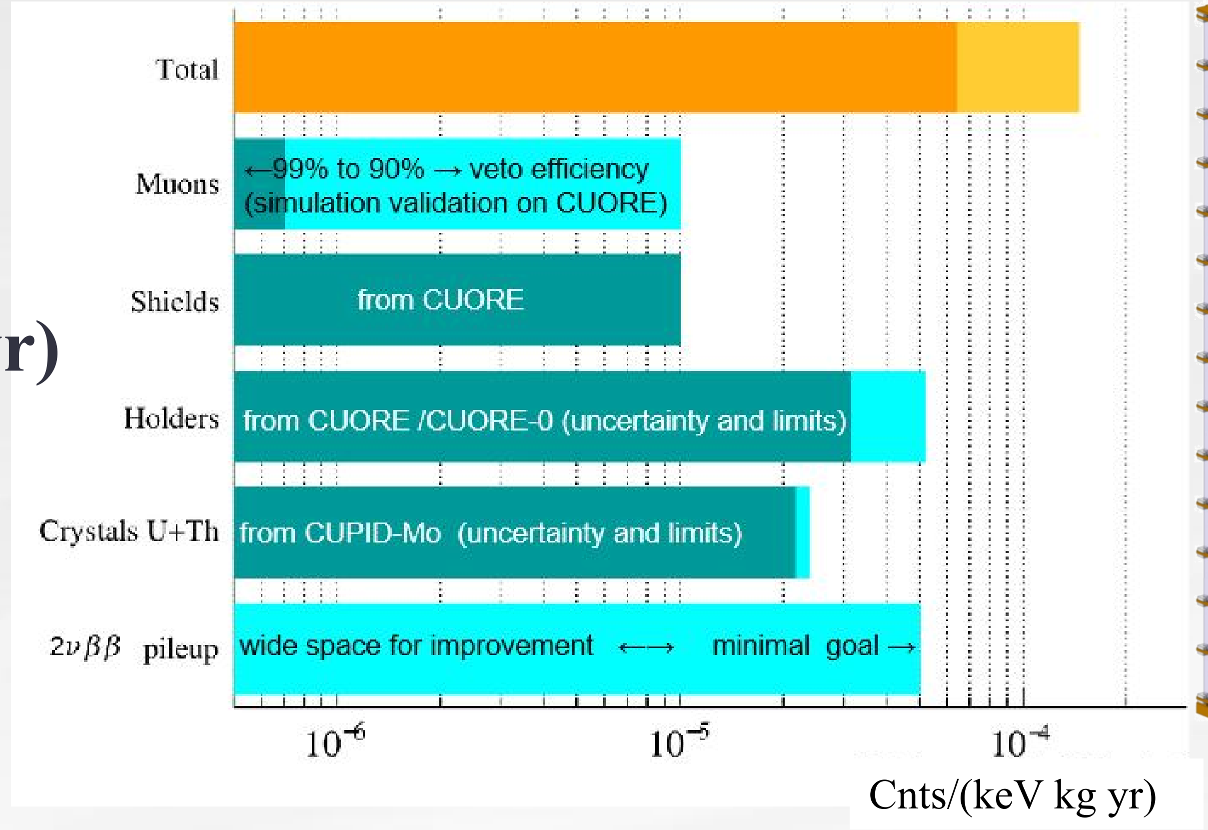
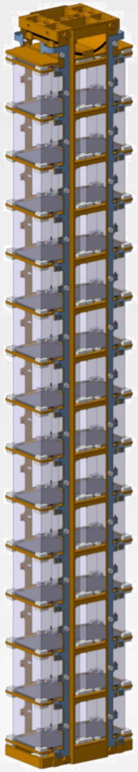
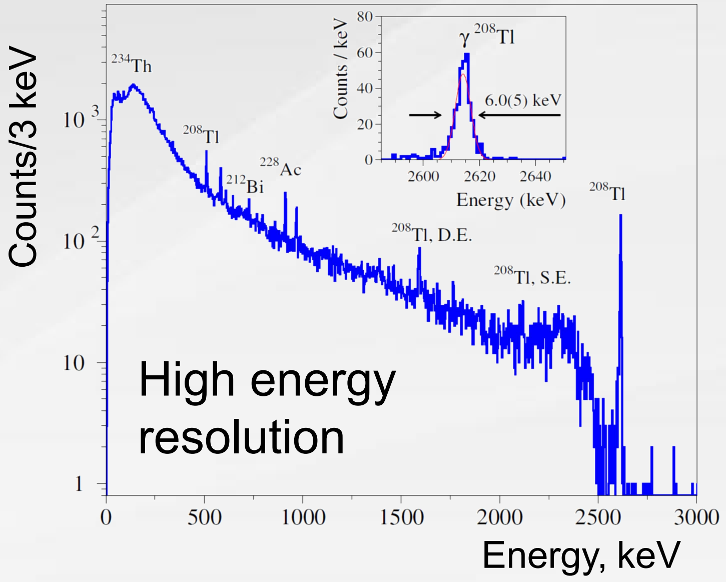


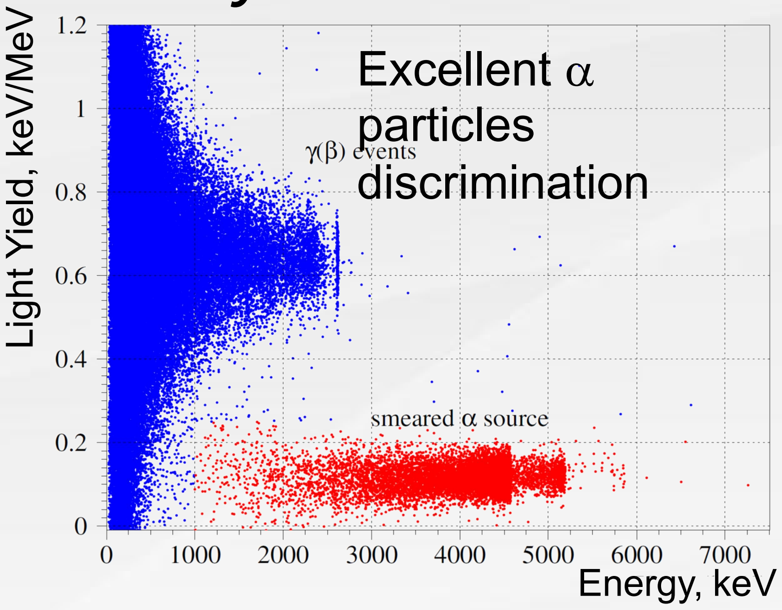


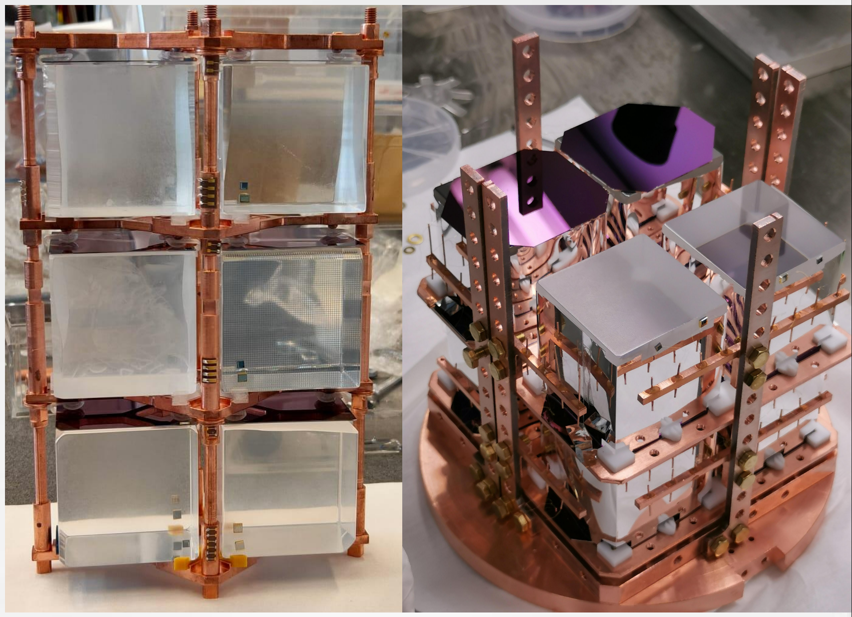
CUPID: R&D

- Series of cryogenic tests at LNGS and LSC performed to define the final **structure of CUPID**
- Maximally effective use of experimental space
- Studies of pile-up rejection: both synthetic and induced pulses used for analysis

[Eur. Phys. J. C (2021) 81: 104](#)
[JINST 16 (2021) P02037](#)
[arXiv:2011.11726](#)
[arXiv:2202.06279](#)

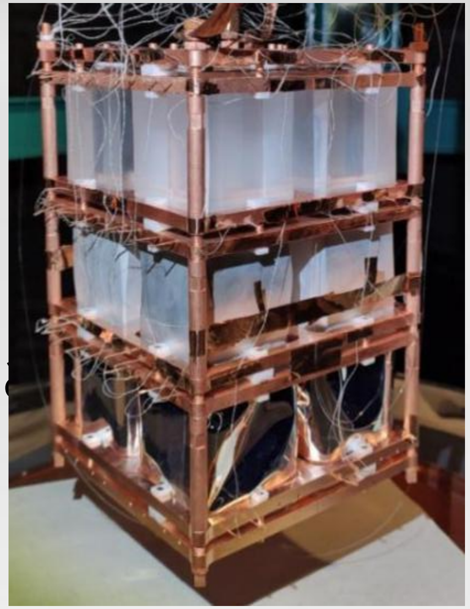


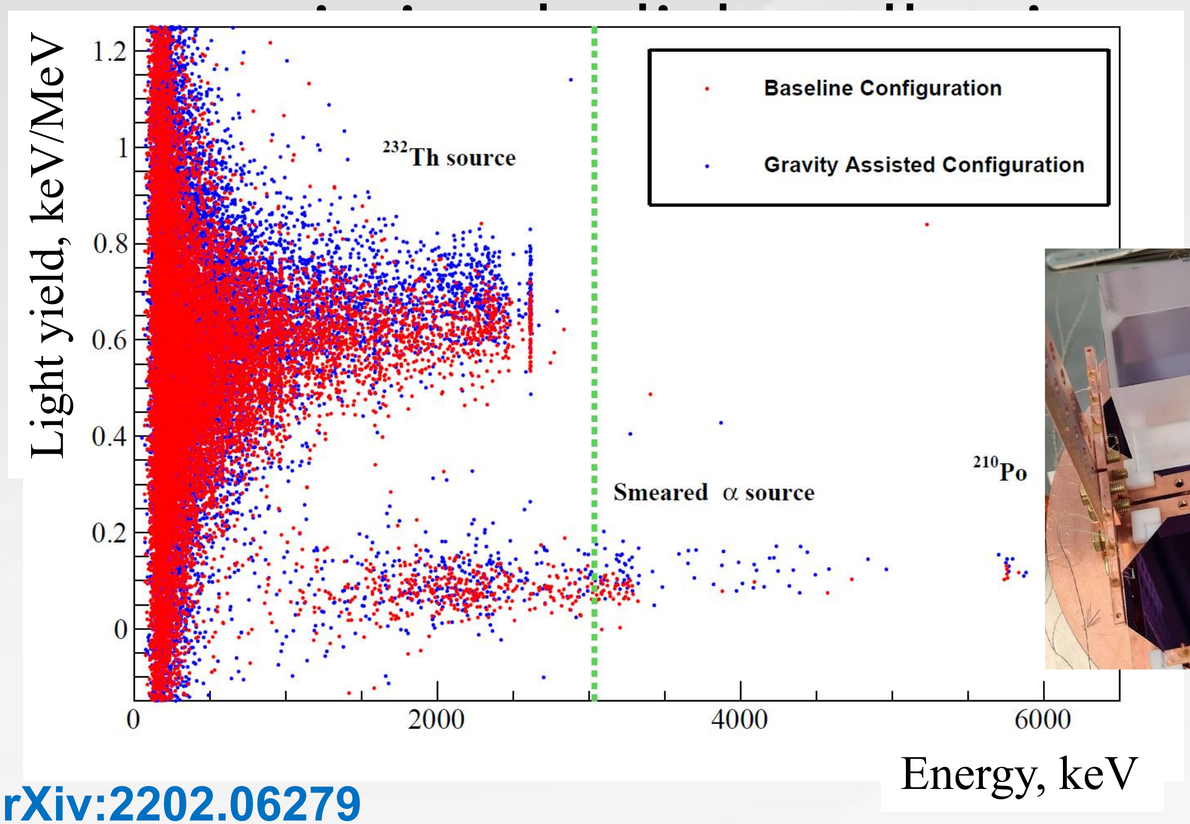


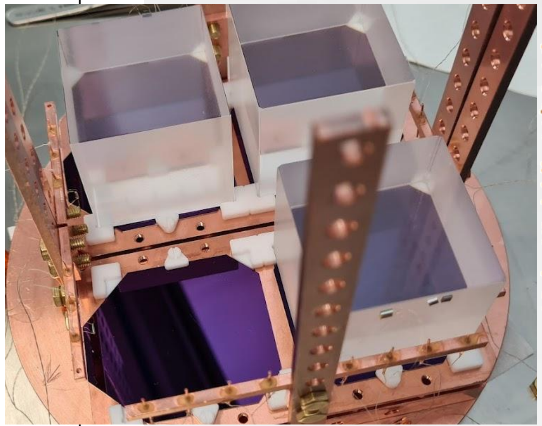


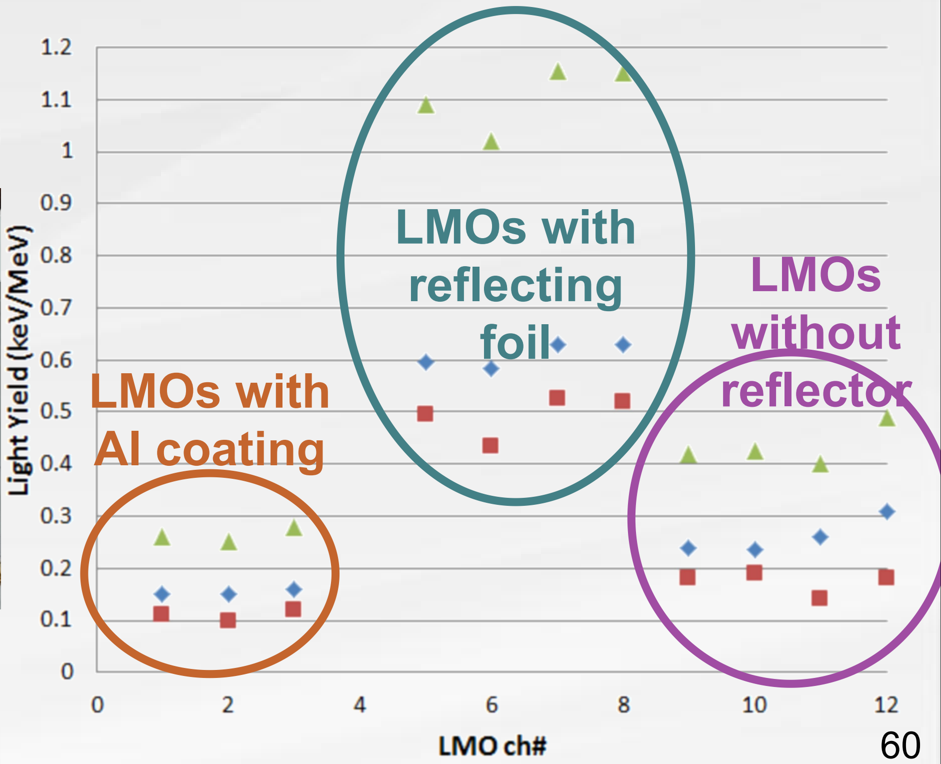
CUPID: light collection studies

- Light yield comparison leads to rejection of reflecting foil - lower background with sufficient light yield for α discrimina
- Optimisation of the detector structure







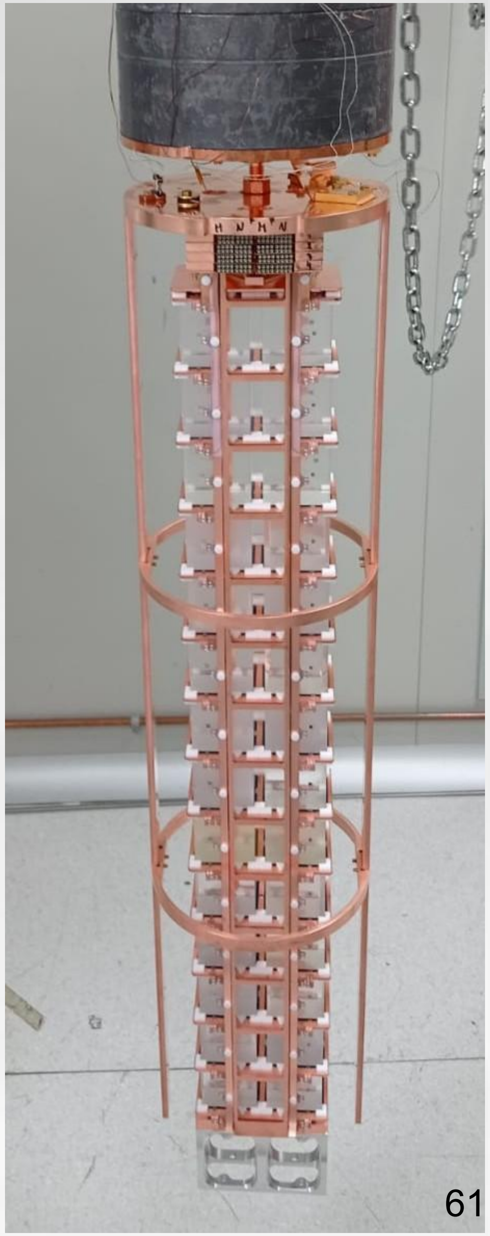


arXiv:2202.06279

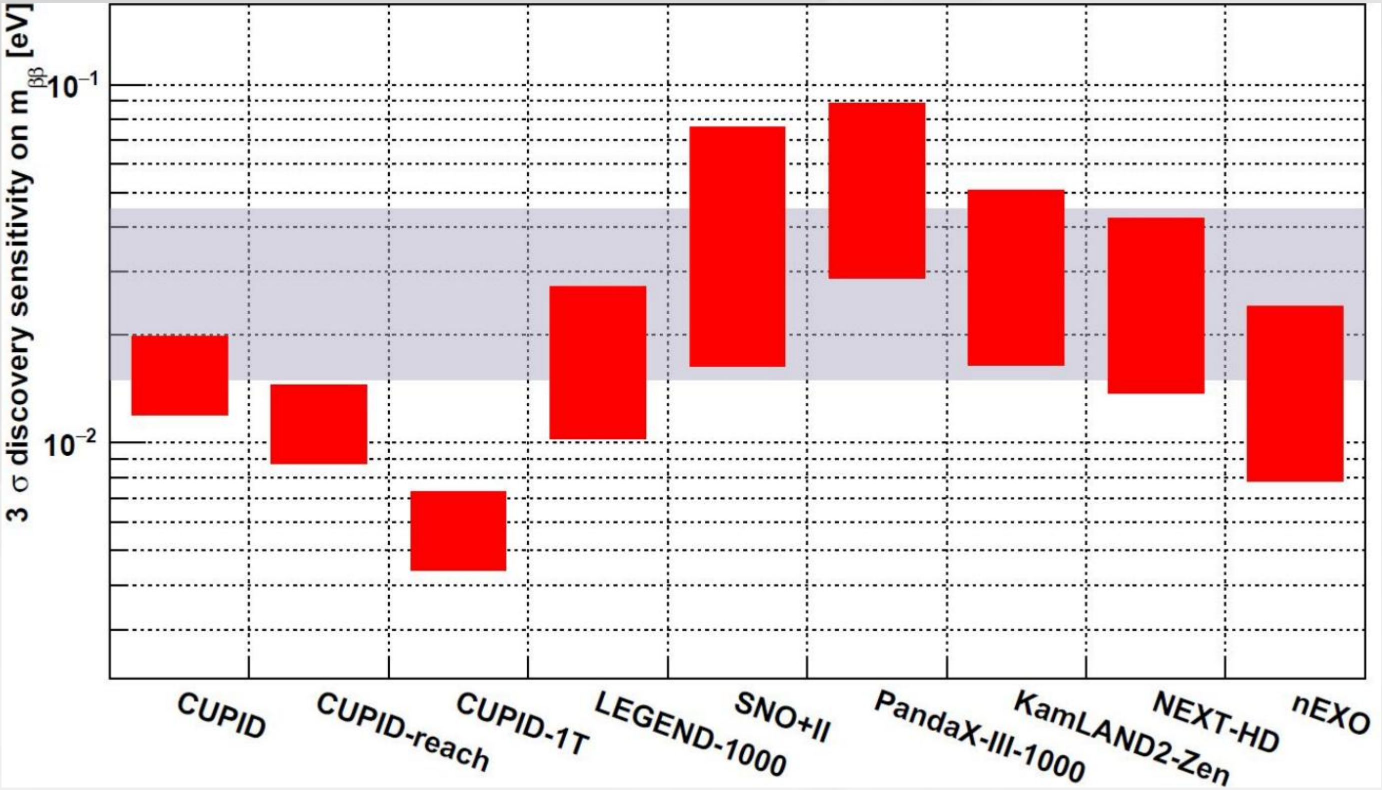
CUPID: single tower measurement

- The tower with 28 crystals and 30 light detectors is being measured in the cryostat at LNGS
- Validation of the CUPID detector structure and performance

- Analysis is ongoing: results coming soon

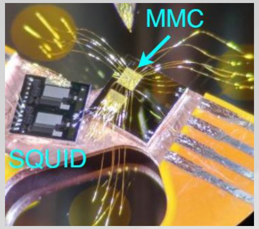


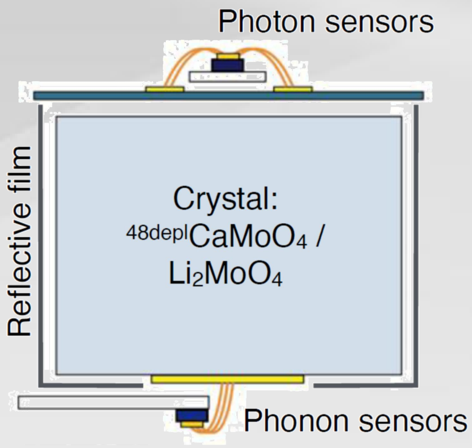
CUPID sensitivity

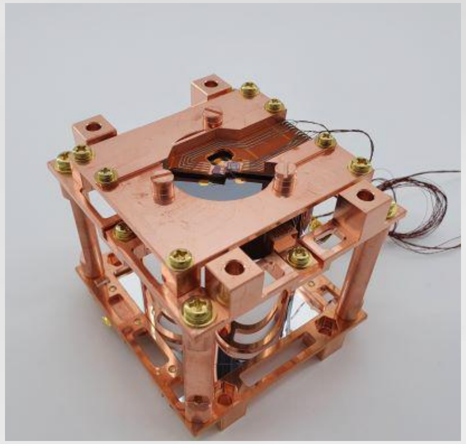


- CUPID: Exactly what we start building: **10^{-4}** cnts/keV/kg/yr
- CUPID-reach: improvements before construction: **$2{\times}10^{-5}$** cnts/keV/kg/yr
- CUPID-1T: 1 ton ^{100}Mo in new cryostat: **$5{\times}10^{-6}$** cnts/keV/kg/yr

AMoRE





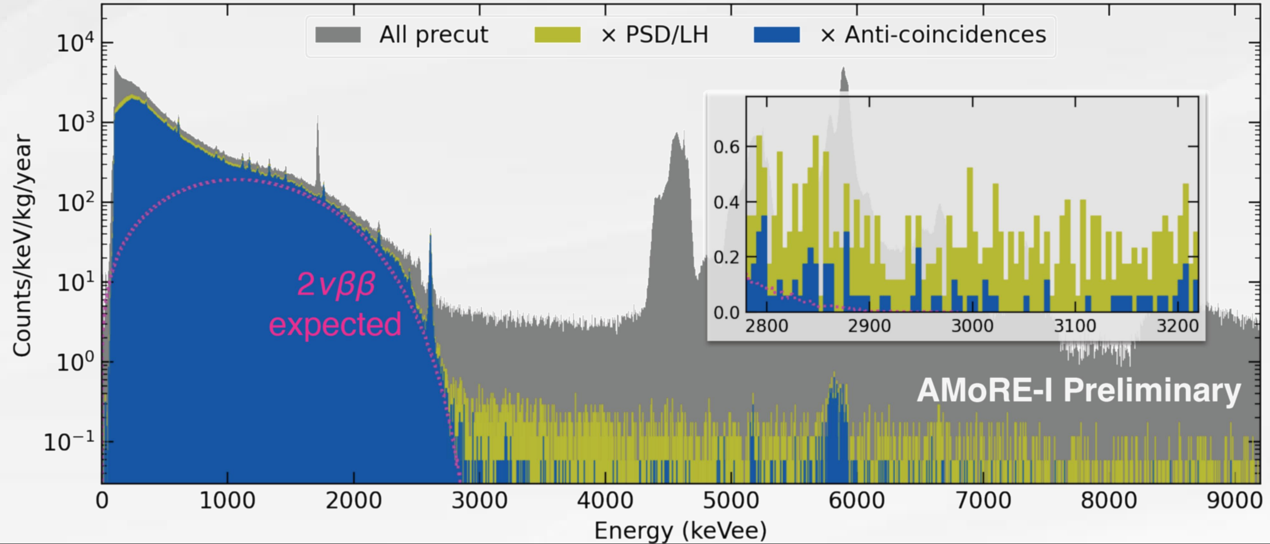


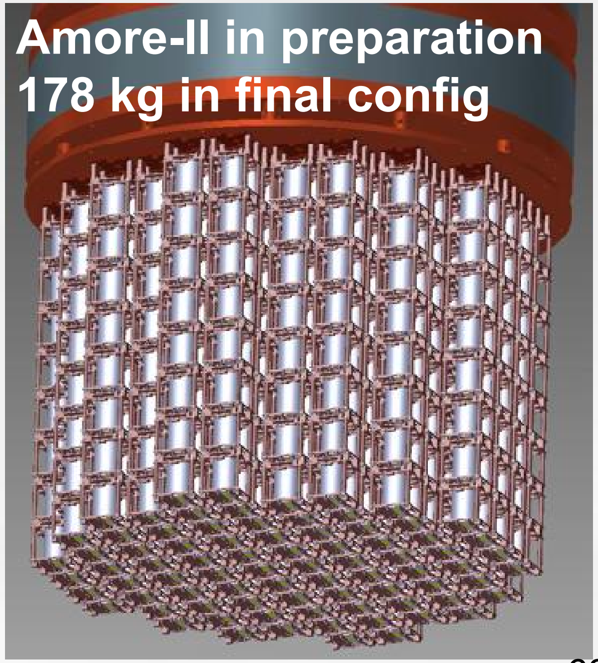
- Metallic magnetic calorimeter (MMC) + SQUID:

-Fast signal timing: a few millisecond rise-time for phonon signals at mK

-Low random coincidence background

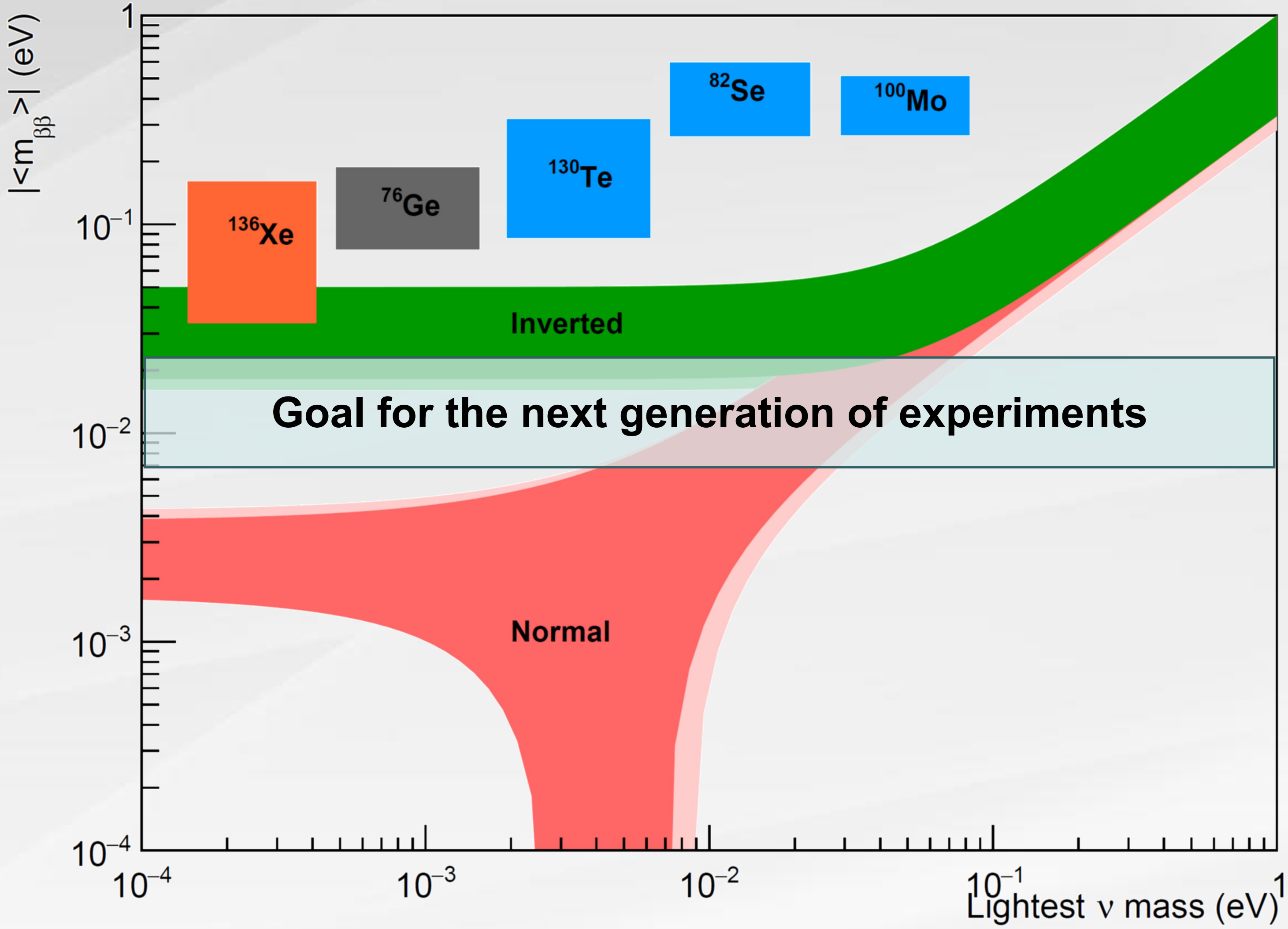
-Energy resolution ~ 10 keV FWHM at 2.6 MeV





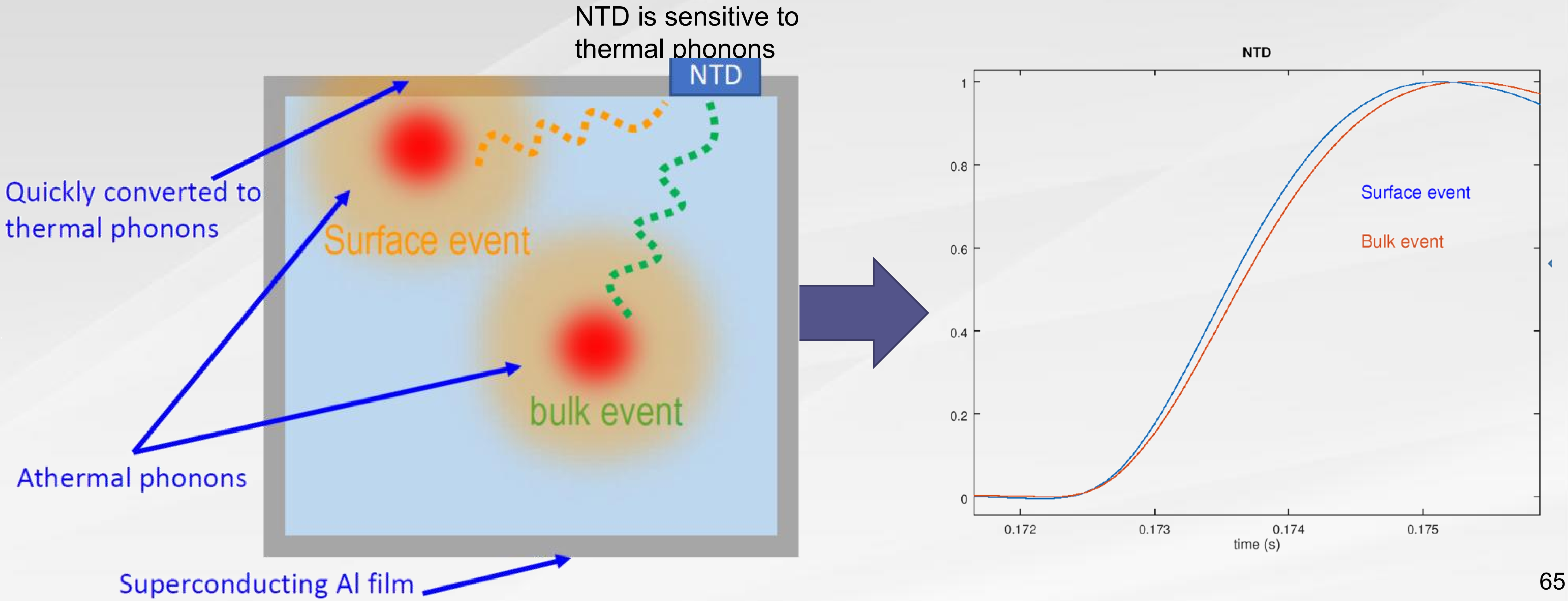
R&D and future projects

- 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)



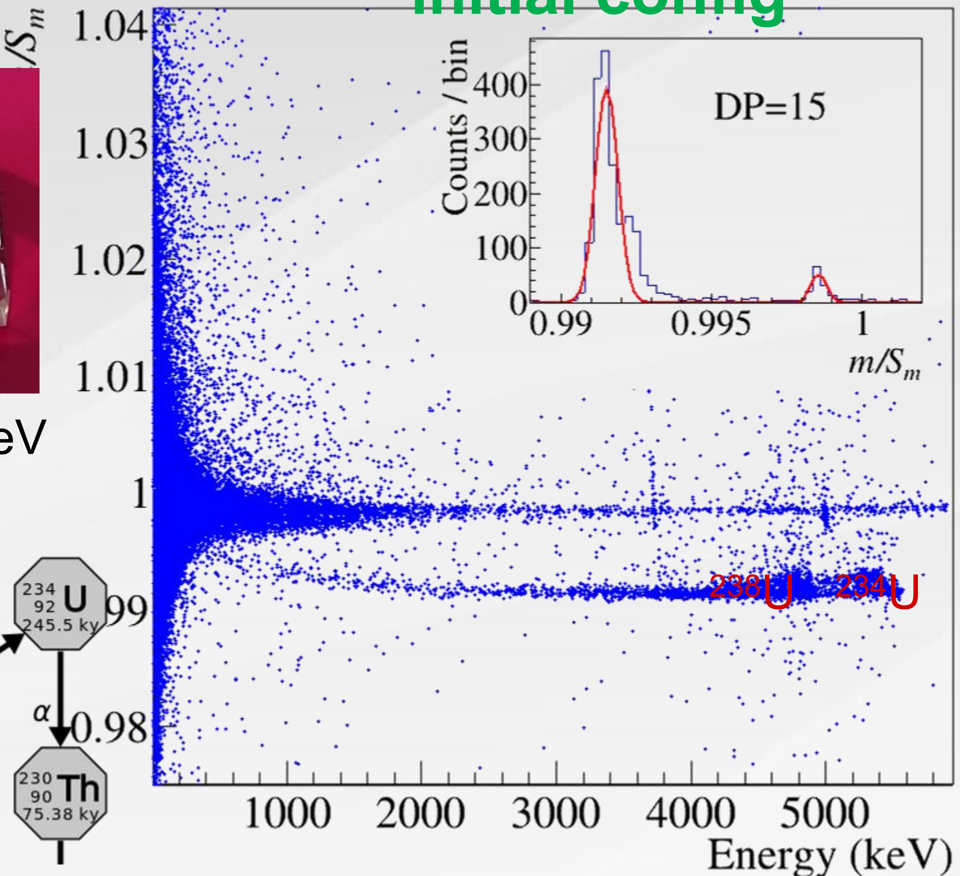
CROSS prototypes: coating tests

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

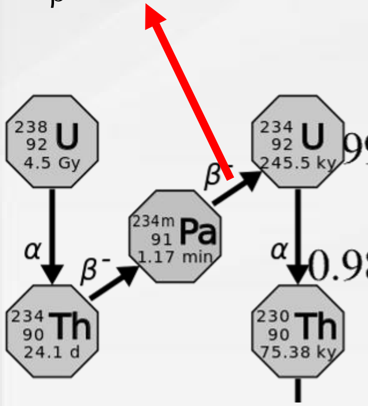
- Prototypes are tested in aboveground tests (IJCLab) with coating on one face, irradiated by a U source

HEP 2020, 018 (2020)

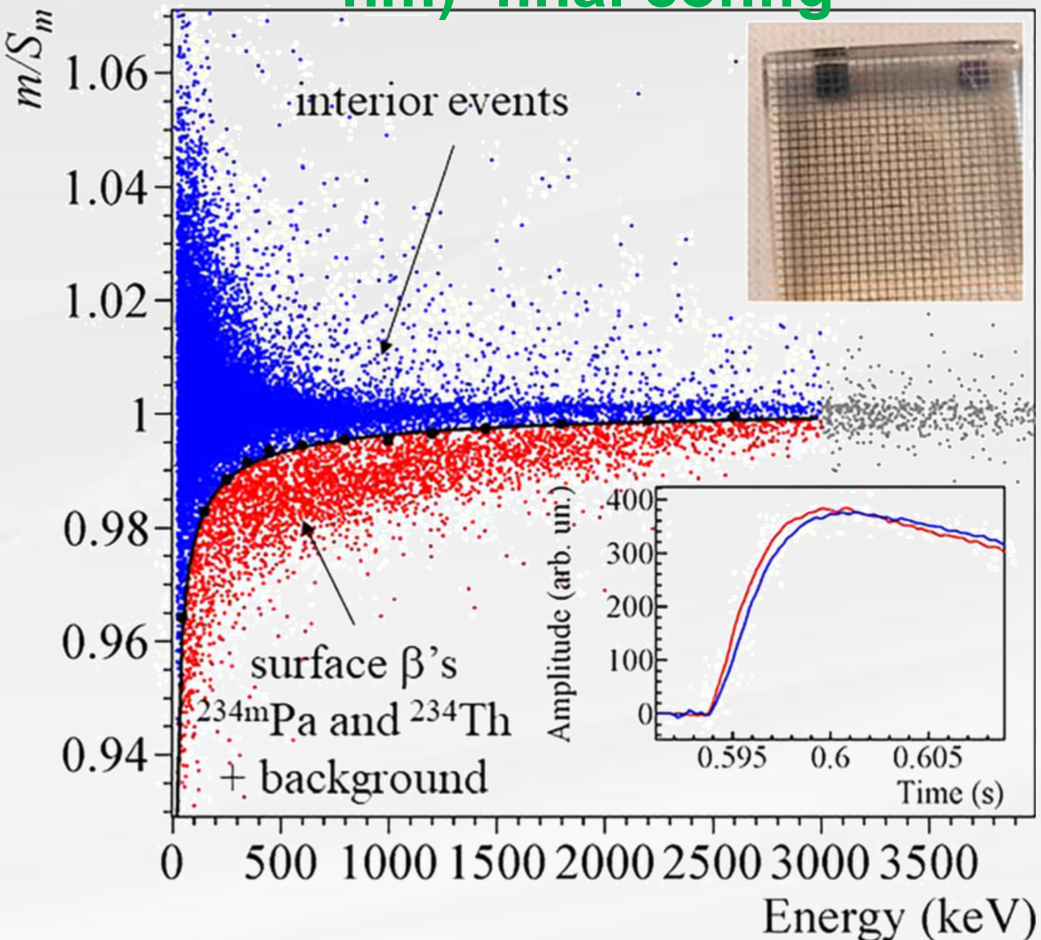
Aluminum (10um) layer: initial config



Q_β= 2.2 MeV

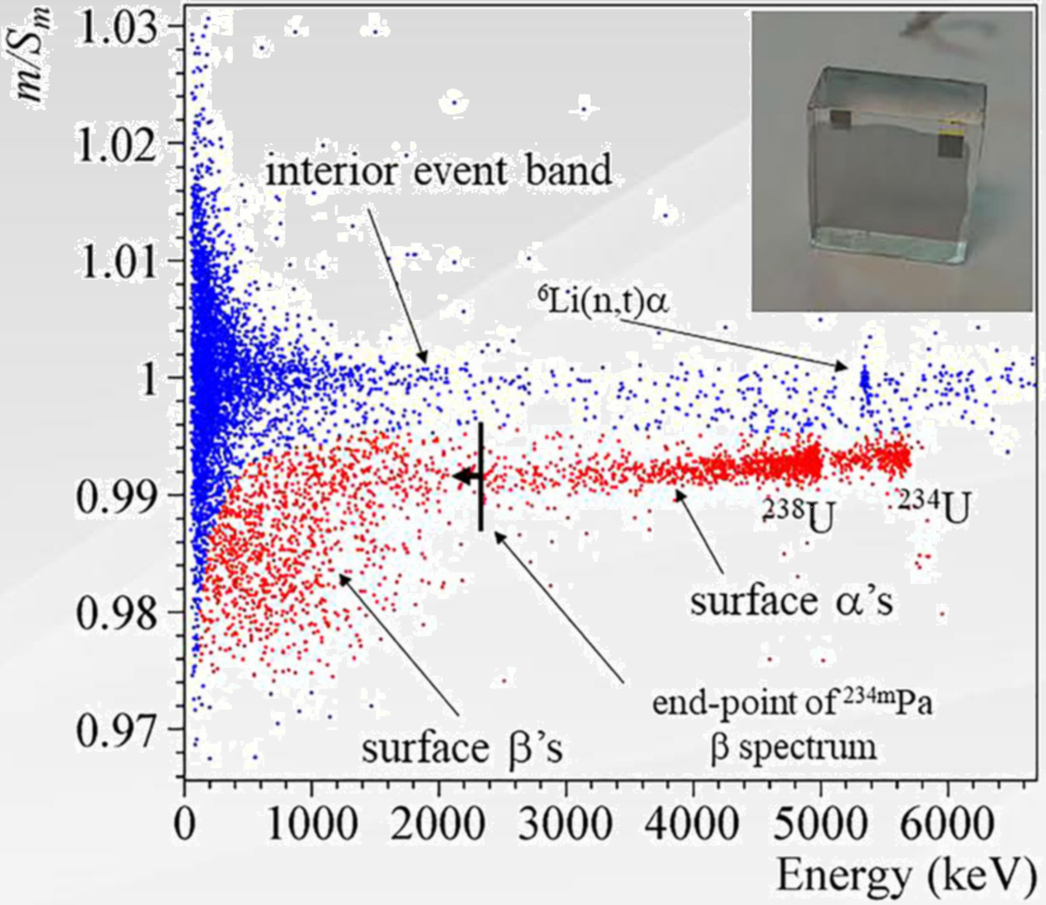


Palladium (10nm)-Aluminum (100 nm) final config

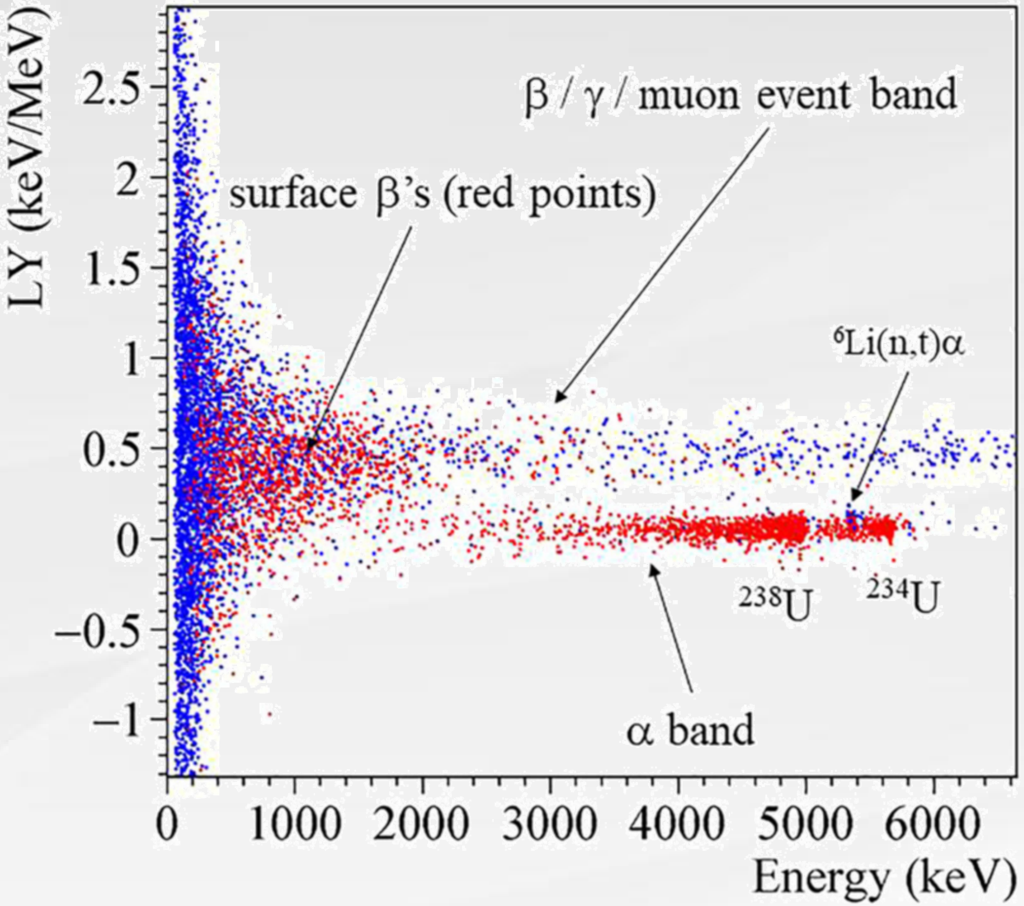


CROSS prototypes

CROSS technology: single read-out



CUPID technology: dual read-out



Appl. Phys. Lett 118, 184105 (2021)

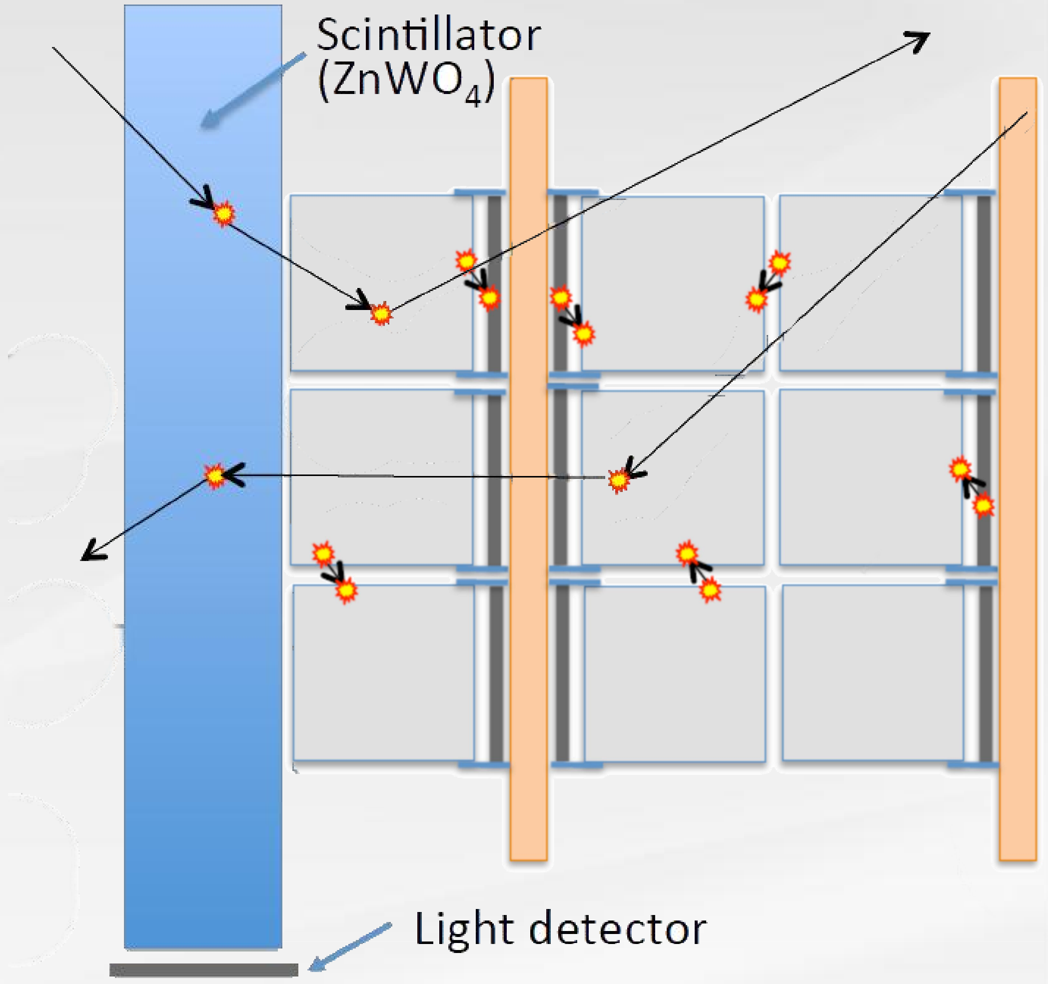
Cross: prospects

- Compications faced with surface coating technology when scaling the detectors size: R&D phase reengaged
- In the meanwhile: LSC facility used for joint CROSS-CUPID-BINGO measurements
- In preparation: 42 $Li_2{}^{100}MoO_4$ cubic (45^3 mm) crystals + 20 CUPID-Mo crystals: **6.6 kg of ^{100}Mo**
- With BI=10^{-3} cnts/keV/kg/yr and 2 yr livetime: $T_{1/2}$ limit ~ 2×10^{25} yr, **$m_{\beta\beta}$ ~(86-149) meV**

BINGO experiment: gamma bkg reduction

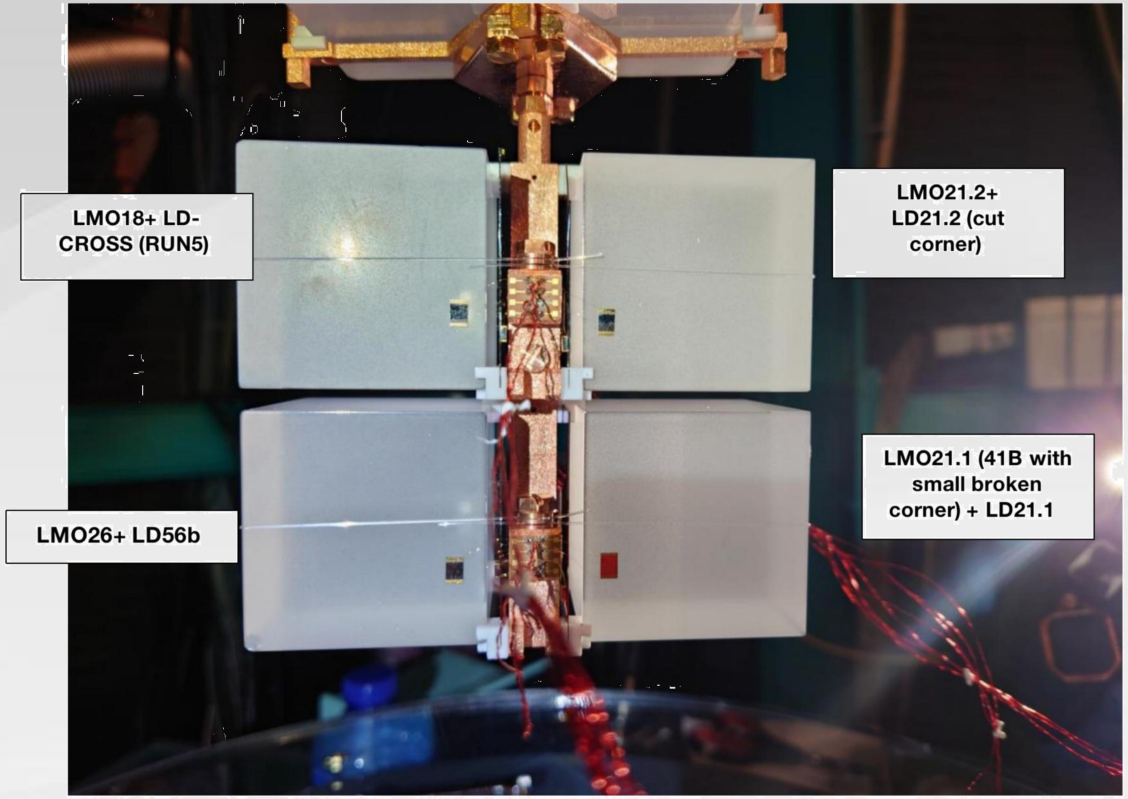
- Surface events discrimination: detectors will “see” only active elements
- Internal **active veto**: BGO scintillators, bolometric light read-out
- Light detectors with **Neganov-Luke technology** to reach 10 eV rms baseline
- Both Li_2MoO_4 and TeO_2 compounds

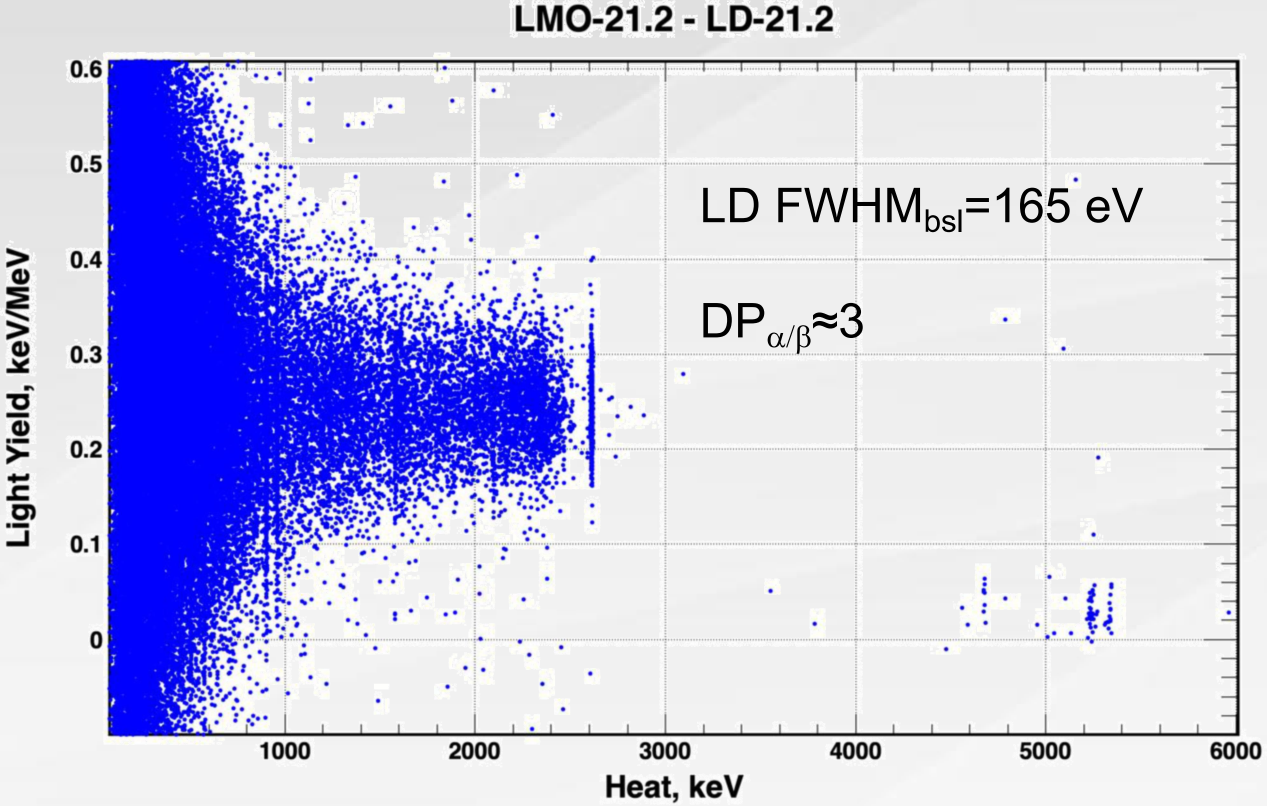
Goal for bkg index in ROI:
~10^{-5} cnts/keV/kg/yr

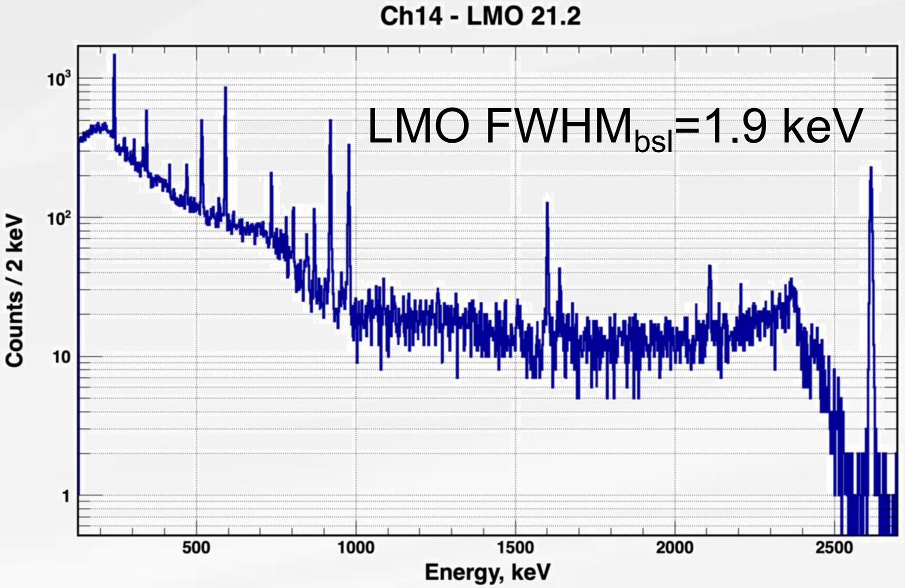


BINGO prototypes

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

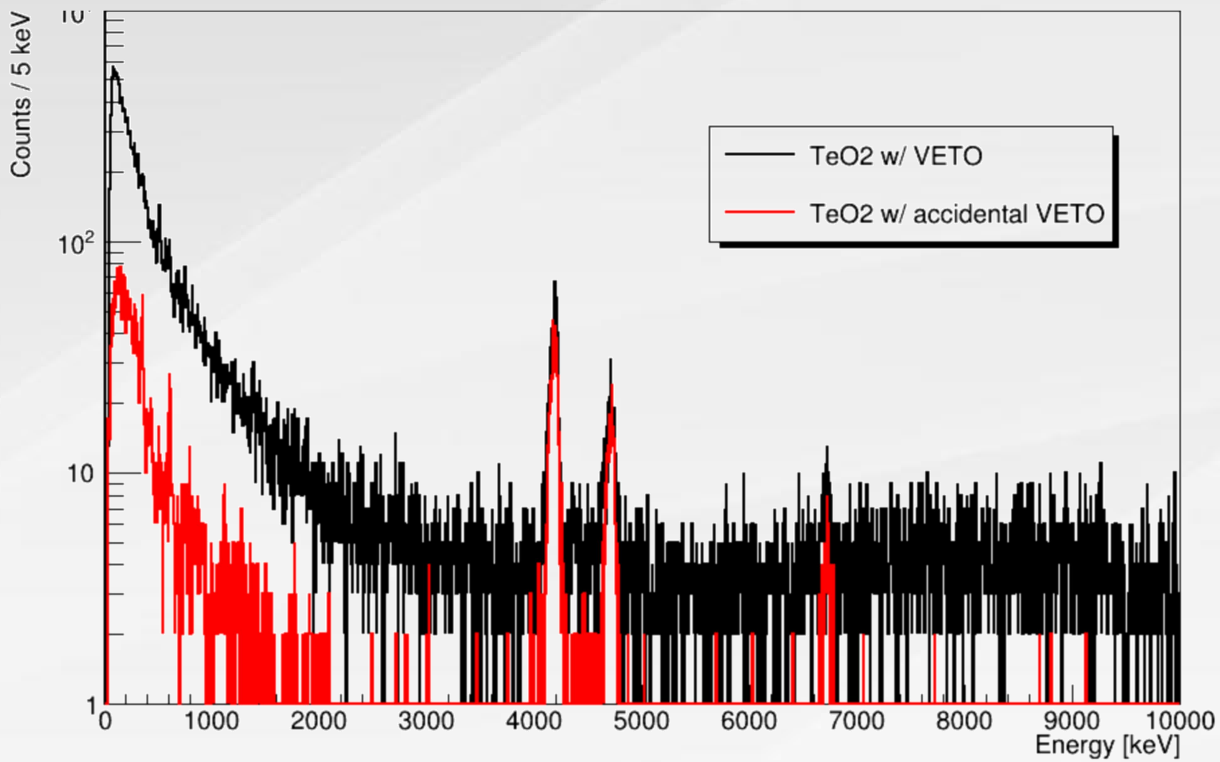






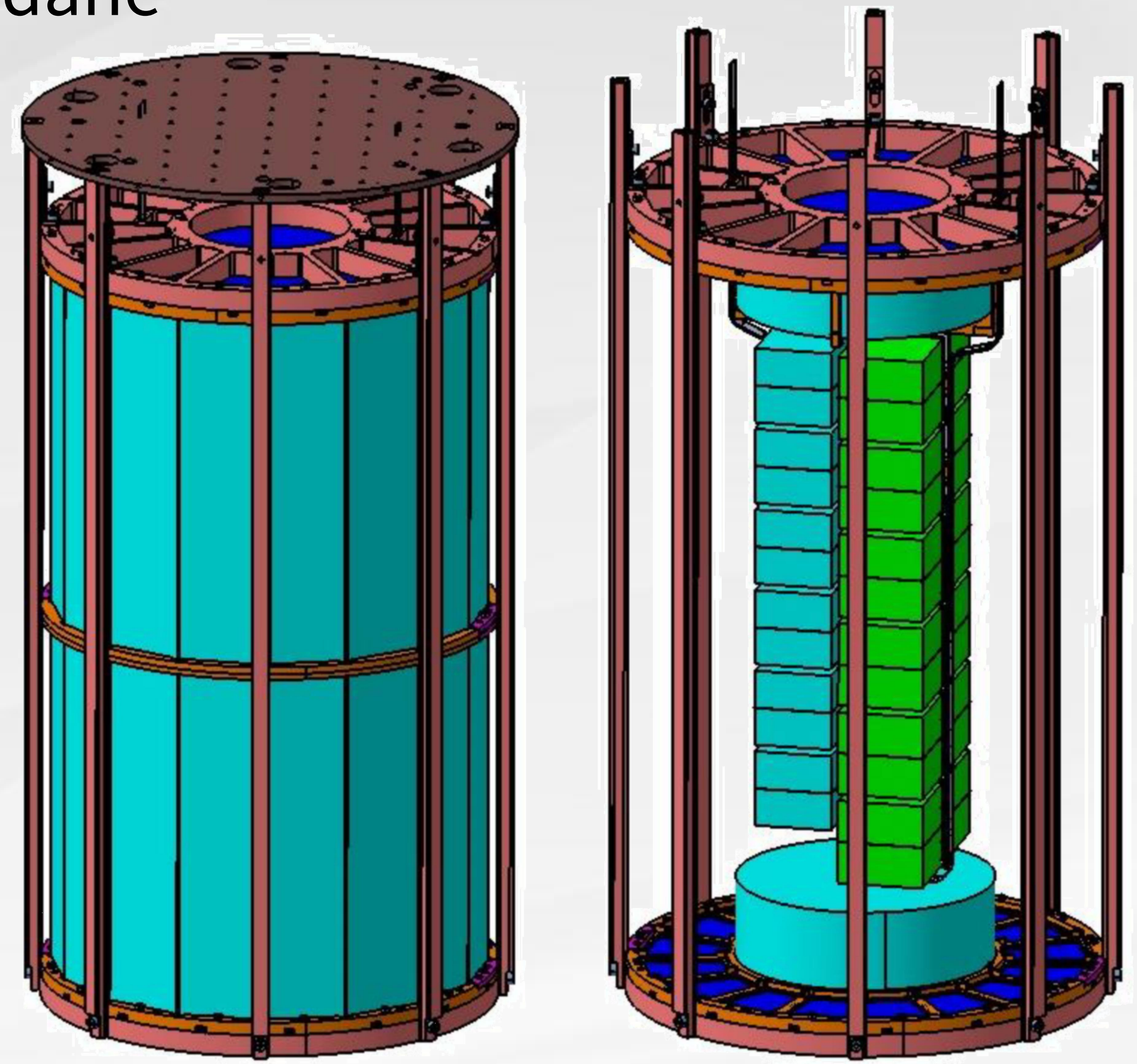
BINGO prototypes:veto

- First test with large BGO crystals and LD detecors for coincidence studies
- Efficiency/threshold study performed



BINGO demonstrator

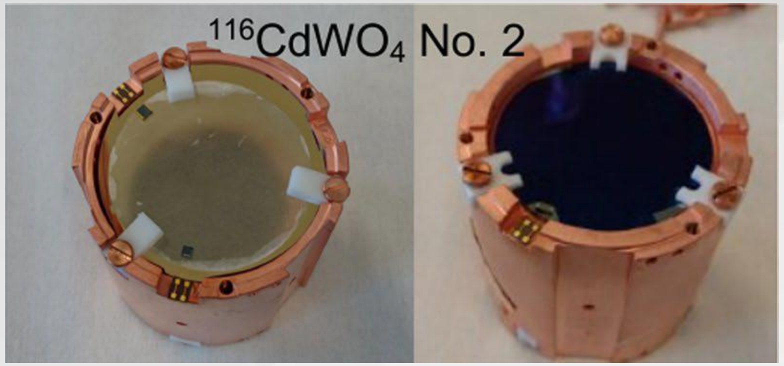
- MINI-BINGO will be installed in Modane Underground Laboratory
- 2x12 crystal towers (LMO+TeO)
- Crystals will see nothing else that is not active

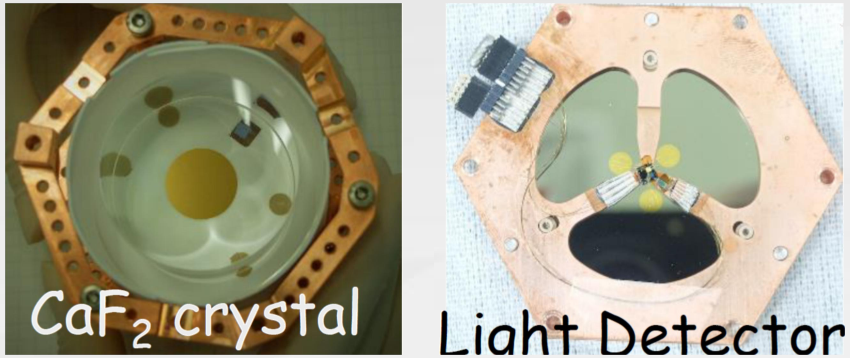


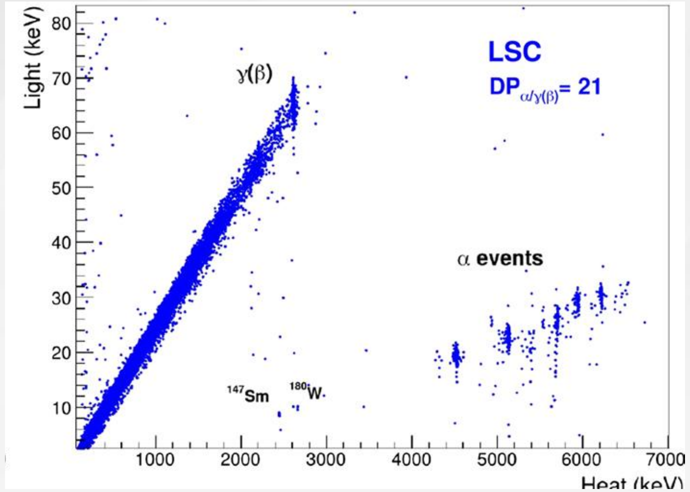
Scale high enough to demonstrate $b \leq 10^{-4}$ cnts/keV/kg/yr in 1 yr data taking

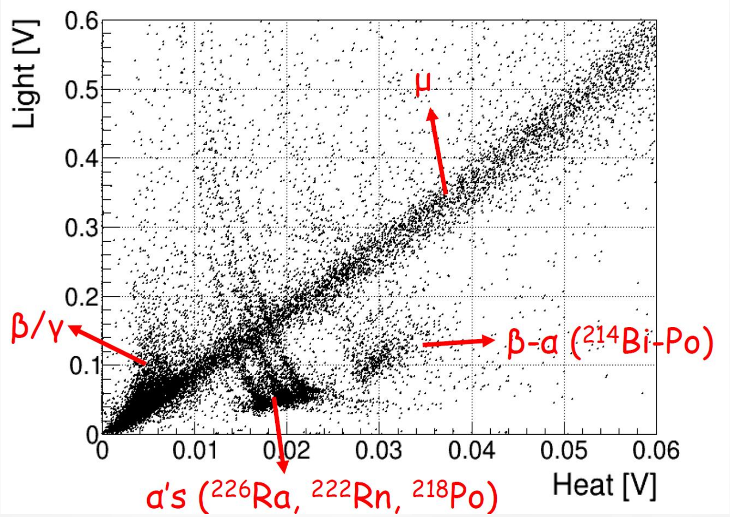
^{116}Cd, ^{48}Ca scintillating bolometers

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









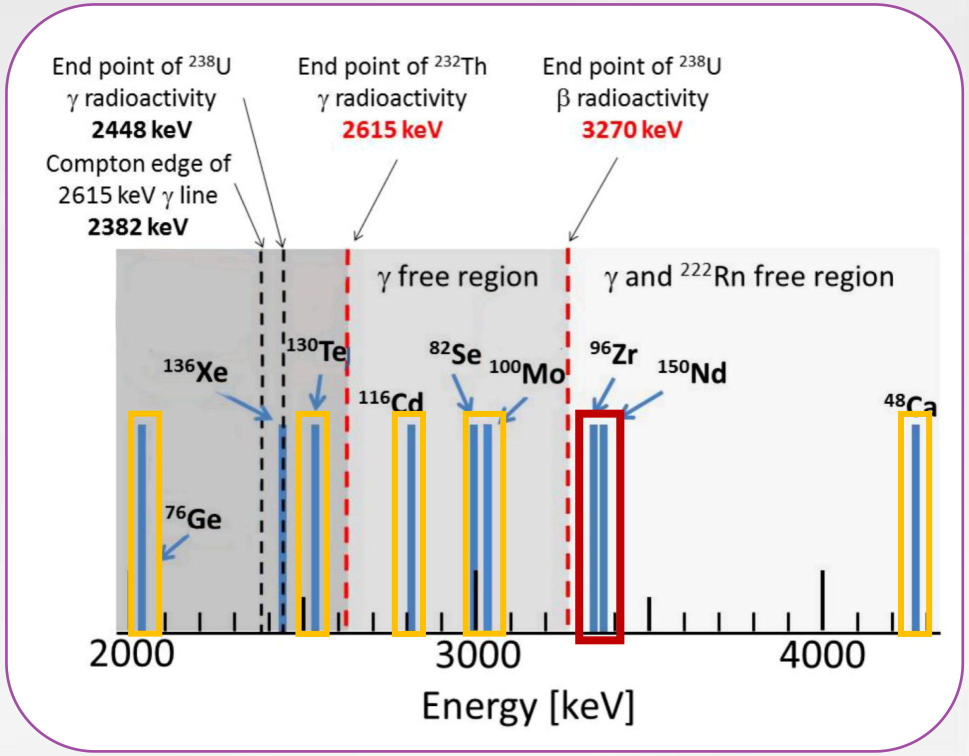
TINY experiment proposal

Starting Grant

- Two Isotopes for Neutrinoless double beta decaY search

- Development of **easy to reproduce detector technology** for highly sensitive searches for $0\nu2\beta$ with **^{96}Zr and ^{150}Nd**

- R&D followed by an underground demonstrator on a small scale

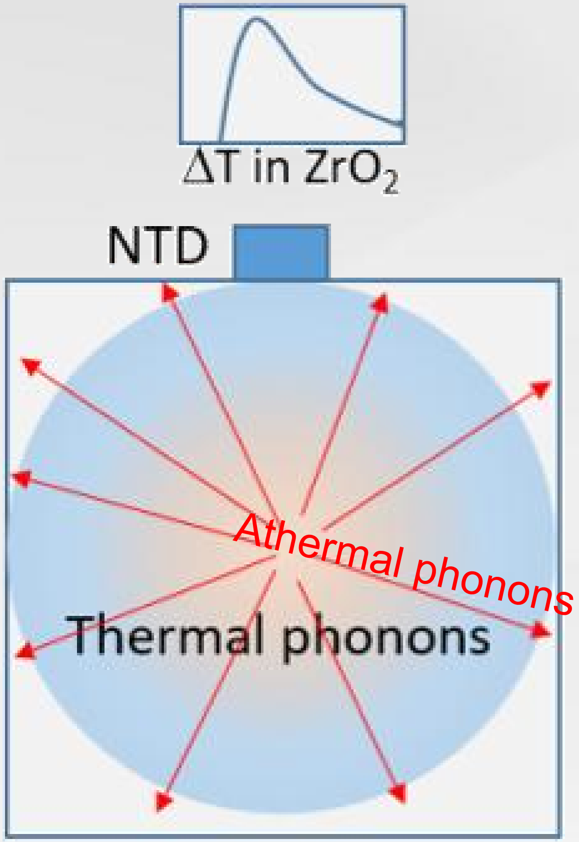


TINY EXPERIMENT

TINY detectors: Zr

- Low risk
- Medium risk
- High risk

- Crystal compounds: **ZrO_2** (75% Zr), $ZrSiO_4$ (55% Zr)
- **Scintillating bolometers** as a baseline
- **Thermal sensors** (Neutron Transmutation Doped thermistors) - robust and reproducible



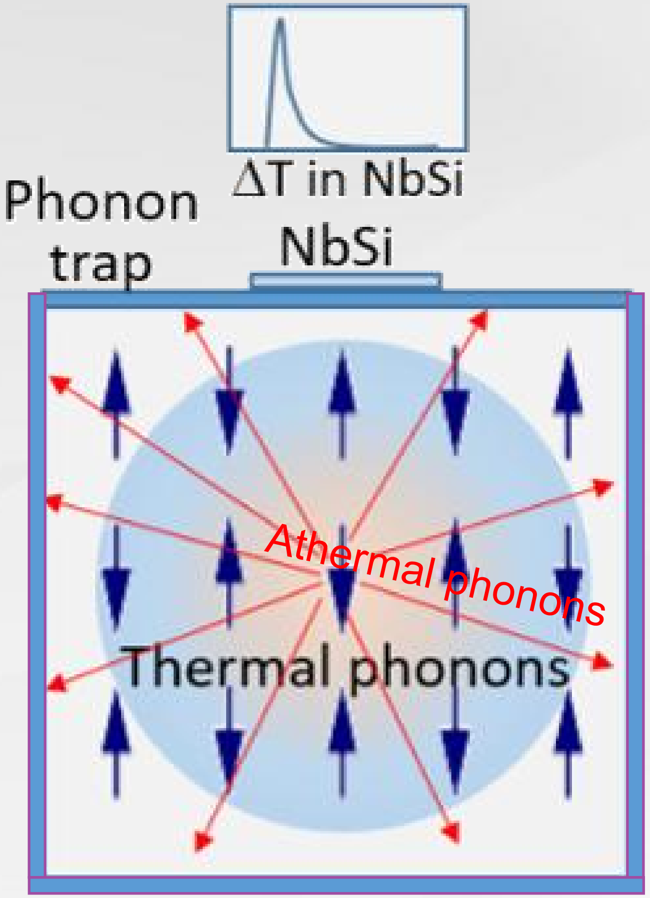
- Target energy resolution: **<10 keV FWHM at Q_{bb}**
- Target α discrimination by light: >99.9%
- First: natural crystals, then move to enriched material for demonstrator

TINY detectors: Nd

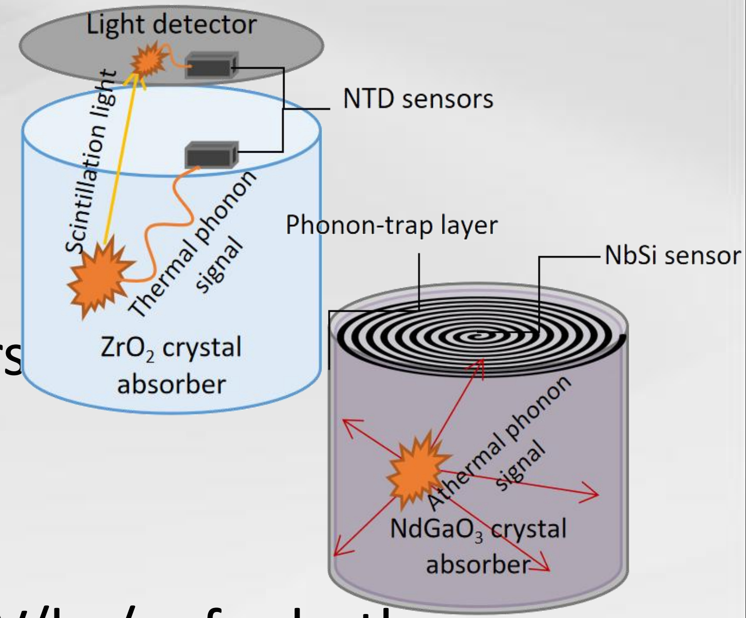
- Low risk
- Medium risk
- High risk

- Crystal compounds: **$NdGaO_3$(55%)**, NdF_3(71%)
- Proof-of-concept: **measurement of magnetic compounds** with athermal sensors
- Use large surface athermal phonon sensors (high impedance NbSi Transition Edge Sensors)

- Target energy resolution: **<20 keV FWHM at Q_{bb}**
- Particle **discrimination by the pulse-shape**
- First measurement of magnetic bolometers
- No large-scale enrichment yet



TINY final demonstrator



Baseline configuration: **array of 10 crystals**

- 5×400 g enriched **$^{96}ZrO_2$ double read-out** scintillating bolometers
- 5×400 g natural **$NdGaO_3$ single read-out** magnetic bolometers

Precision measurement of $2\nu2\beta$ spectrums

New limits in 1 year of measurements and background 10^{-3} cnts/keV/kg/yr for both:

Isotope	NEMO-3		TINY	
	Exposure, kg×yr	Present limits, yr	Exposure, kg×yr	Present limits, yr
^{96}Zr	0.031	9.2×10^{21}	1.4	**2×10^{24}**
^{150}Nd	0.191	2×10^{22}	0.062	**5.7×10^{22}**

*J. Argyriades et. al., Measurement of the two neutrino double beta decay half-life of Zr-96 with the NEMO-3 detector, Nucl.Phys.A847:168-179 (2010)
J. Argyriades et al., Measurement of the double-β decay half-life of ^{150}Nd and search for neutrinoless decay modes with the NEMO-3 detector, Phys. Rev. C 80, 032501 (2009)

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!

Backups

Bolometers are

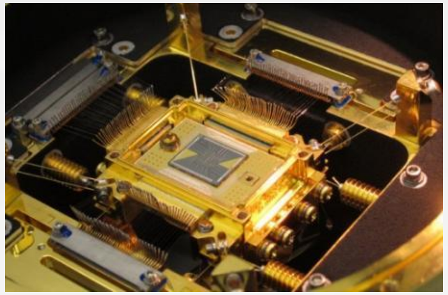
As a consequence of two previous ponts, bolometers are very flexible in applications:

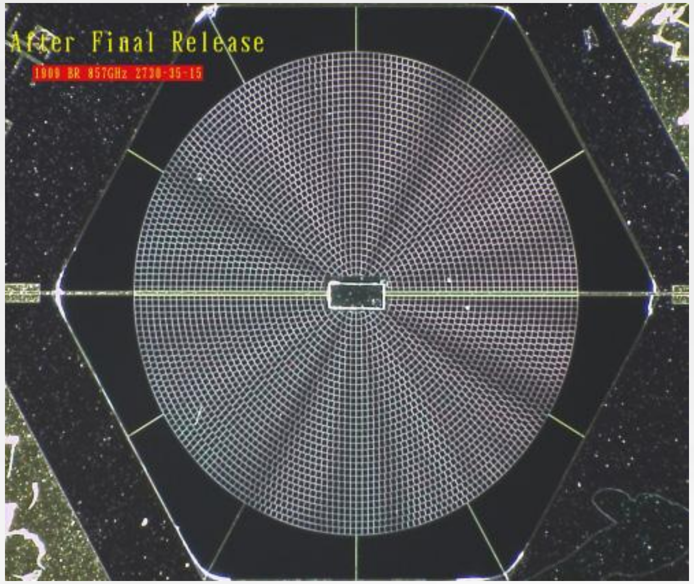
- Astronomy, astrophysics and cosmology

Examples:

High Frequency Instrument (HFI) in Plank experiment
52 spider-web bolometers based on NTD Ge thermistors T ~ 0.1 K

SXS instrument on ASTRO-H mission
HgTe asborbers on **Si thermistors**
6×6 channels - 7 eV FWHM in 0.3-12 keV





Bolometers are

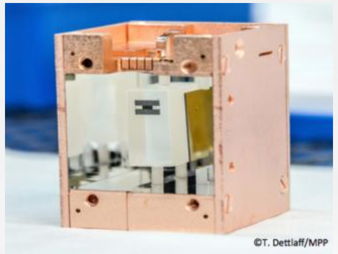
As a consequence of two previous ponts, bolometers are very flexible in applications:

- Dark matter: search for WIMPs, axions and other exotic particles

Examples:

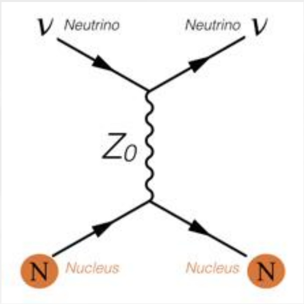
- **EDELWEISS and SuperCDMS with Ge ionizing bolometers**
- **CRESST with $CaWO_4$ scintillating bolometers**

➢ Low energy threshold (≤ 100 eV)
➢ Low raw background
➢ Electron/nuclear recoil discrimination
➢ Large exposures



Cryogenic equipment

- Past: liquid bath cryostats
- Now: pulse-tube cryostats



Background sources and isotope choice

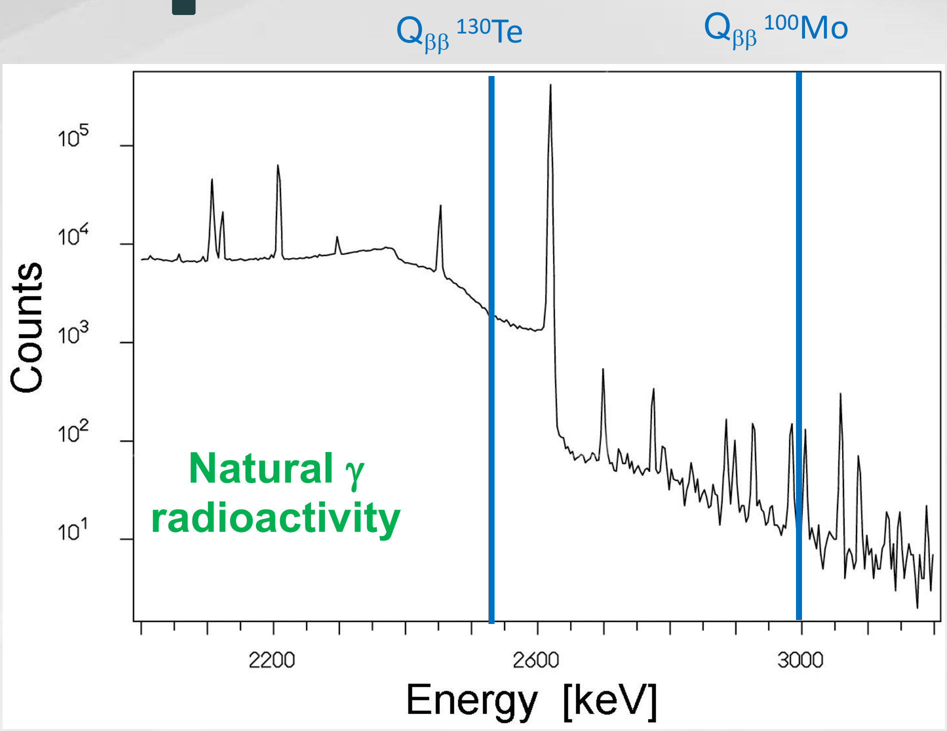
- Cosmic muons, neutrons
- Environmental γ's, α's and β's
- 2ν2β decay

Underground lab
Radiopurity
Shielding

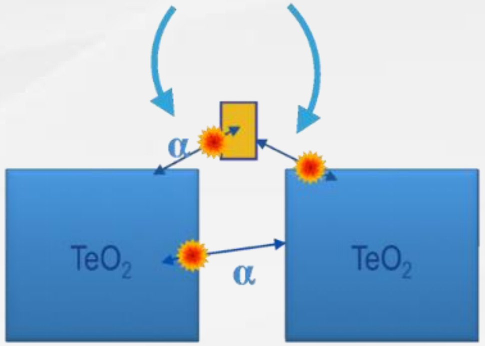
High energy resolution (**bolometers**)

Choose **high $Q_{\beta\beta}$-value** (> 2.6 MeV) isotopes

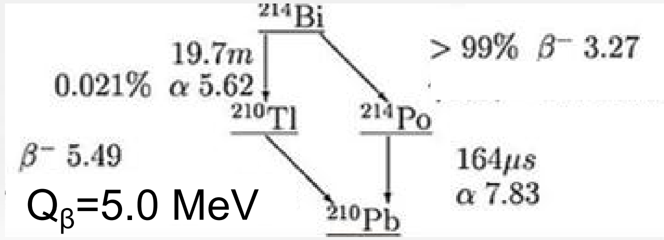
Develop **advanced bolometers** with particle and impact-point identification



Energy degraded α events

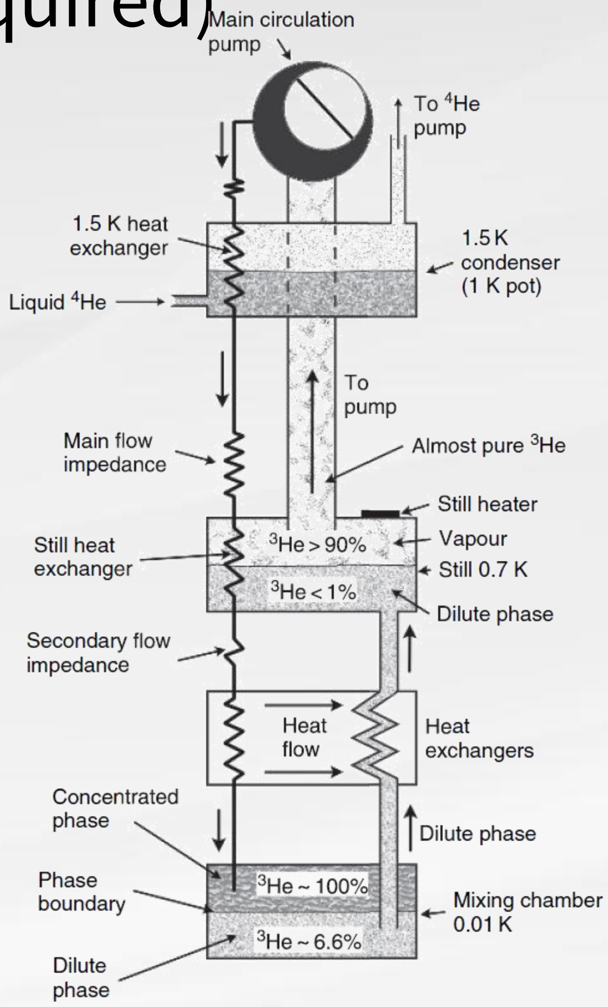


High energy β decays



Dilution unit cryostats

- Allow to stay at low temperatures stably for indefinite amount of time
- Modern closed-circuit cryostats (no cryoliquids required) are cost-efficient
- Scalable: biggest one so far is CUORE cryostat



CUPID-0 background

Several cuts applied:

- Selecting only particle signals:

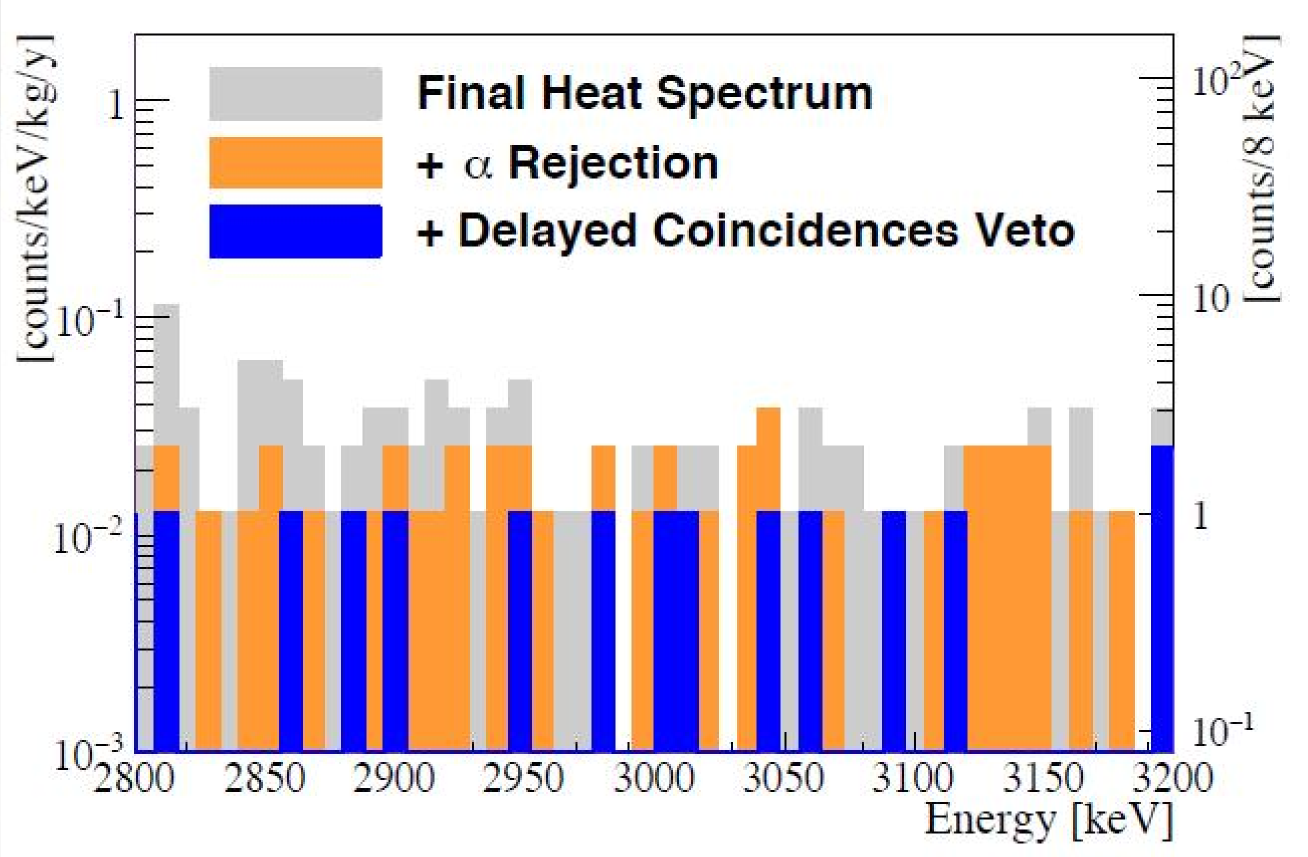
⇒ 3.2×10^{-2} cnts/(keV kg yr)

- Selecting only β/γ:

⇒ 1.3×10^{-2} cnts/(keV kg yr)

- Removing ^{208}Tl events:

⇒ 3.5×10^{-3} cnts/(keV kg yr)

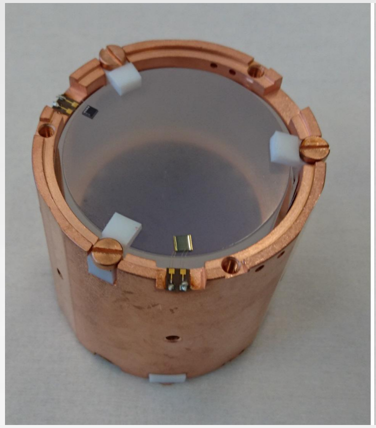


Important insights for design of the next generation experiment

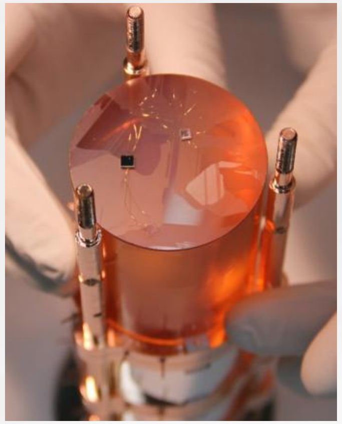
Choice for CUPID

- Both demonstrators have shown excellent perspectives for double beta decay searches with scintillating bolometers: high efficiency, background rejection in ROI, good energy resolution

- Few features pushed the choice towards $Li_2{}^{100}MoO_4$:

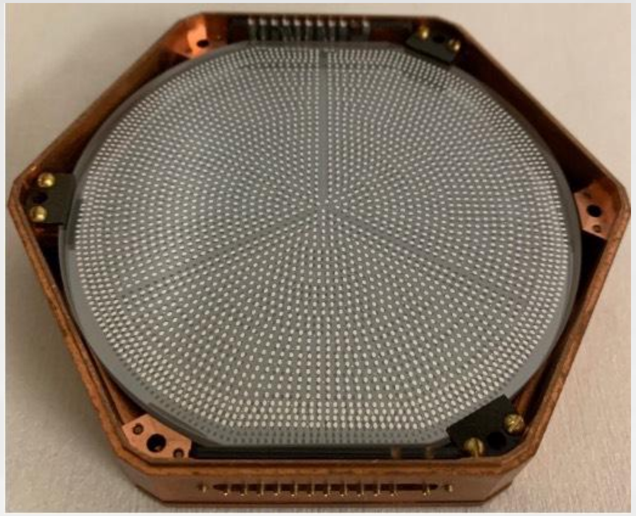


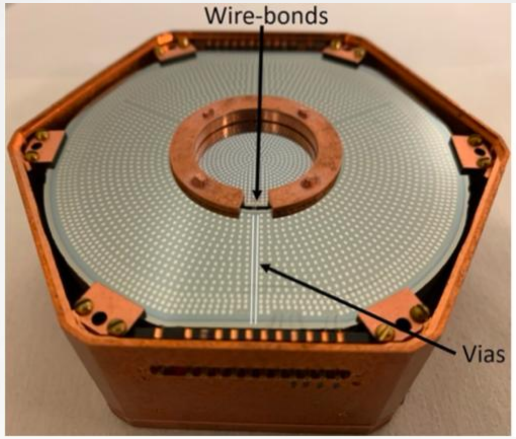
  - Higher energy resolution (7.4 vs 20 keV)
  - Excellent radiopurity (ZnSe crystals have much higher U\Th contamination, ~30 times)
  - Easier crystal growth



CENNS experiments: MINER

- Full cryogenic active veto: 25g Ge target detectors with 2.5 cm (4 Pi)active Ge with 200 eV threshold
  - Back. reduction about 10
- Hybrid Ge detector: ER/NR discrimination demonstrated at the few keV scale
- Low threshold 100g sapphire detectors:
  - Demonstrated 100 eVnr threshold with position sensitivity





R. Mahapatra et al., NIMA 853 (2017) 53

CENNS experiments: Ricochet

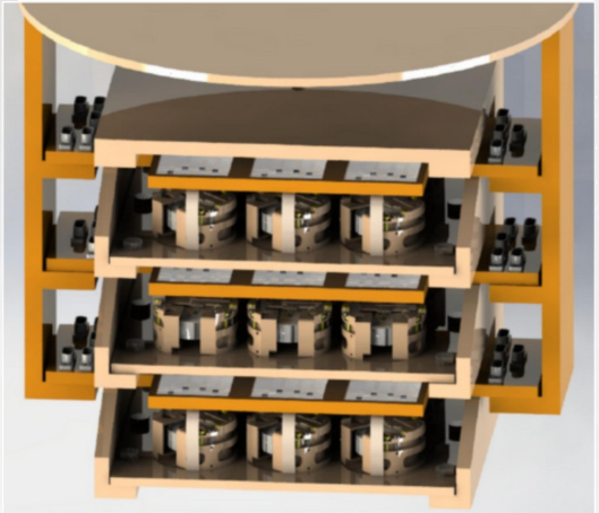
- Cosmic reduced by overburden (15 m w.e.)
- Pushing for particle identification down to 100 eV

3x3x3 CryoCube

1kg payload

integrated HEMT readout

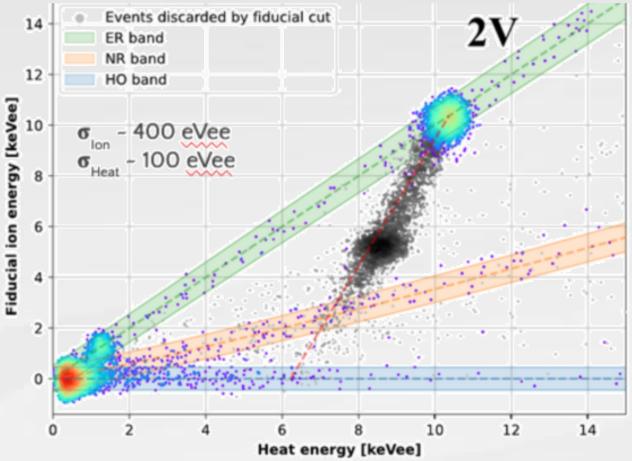
To be delivered starting mid-2022



Alternating 15mK/1K layers

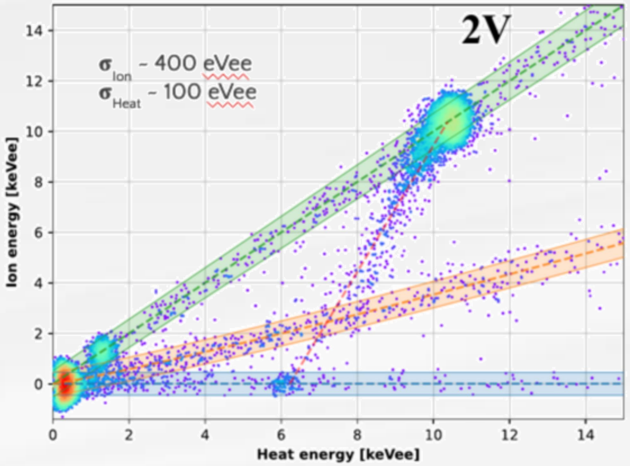
27 x 38g Ge crystals
with NTDs and electrodes
2 optimized designs (COMSOL)
Ongoing validation of the performances.

FID 38



Using FET electronics

PL 38

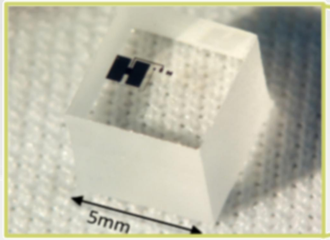


Misiak PhD Thesis
Salagnac & al: arXiv:2111.12438

CENNS experiments: NuCLEUS

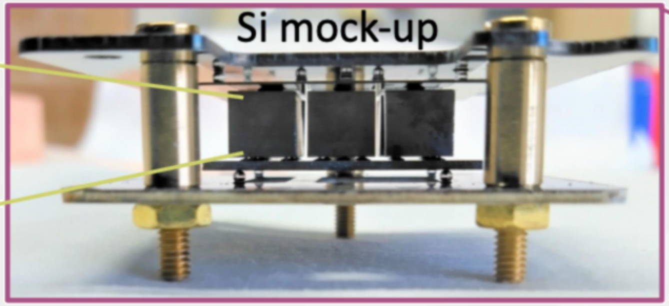
- Al_2O_3 prototype with threshold ~ 20 eV
- Outer and inner vetos for bkg rejection

Target crystals:
Two 3x3 arrays with a total mass of 6g ($CaWO_4$) + 4g (Al_2O_3)



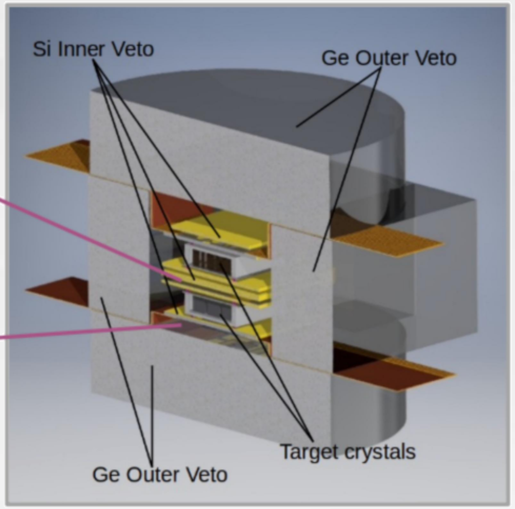
- ✓ Production of detector arrays
- Next steps: testing & cutting

Inner veto: TES-instrumented holder
to reject surface backgrounds and holder-related events



- ✓ Mechanical and thermal test with mock-up
- Next steps:
  - Replacement of 2nd wafer with *beaker* for a 4π-coverage
  - detector operation in inner veto

Germanium outer veto
for active γ/n background rejection



- ✓ Design finished
- ✓ Ongoing prototype test

CENNS experiments: NuCLEUS

- Al_2O_3 prototype with threshold ~ 20 eV
- Outer and inner vetos for bkg rejection

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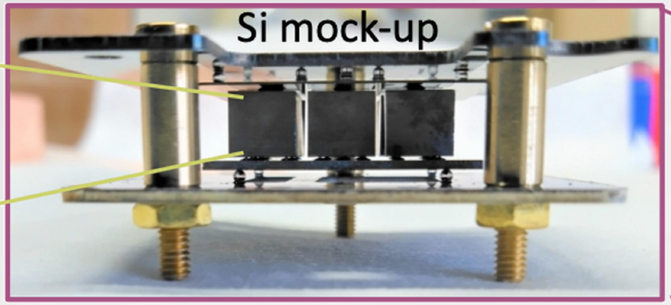

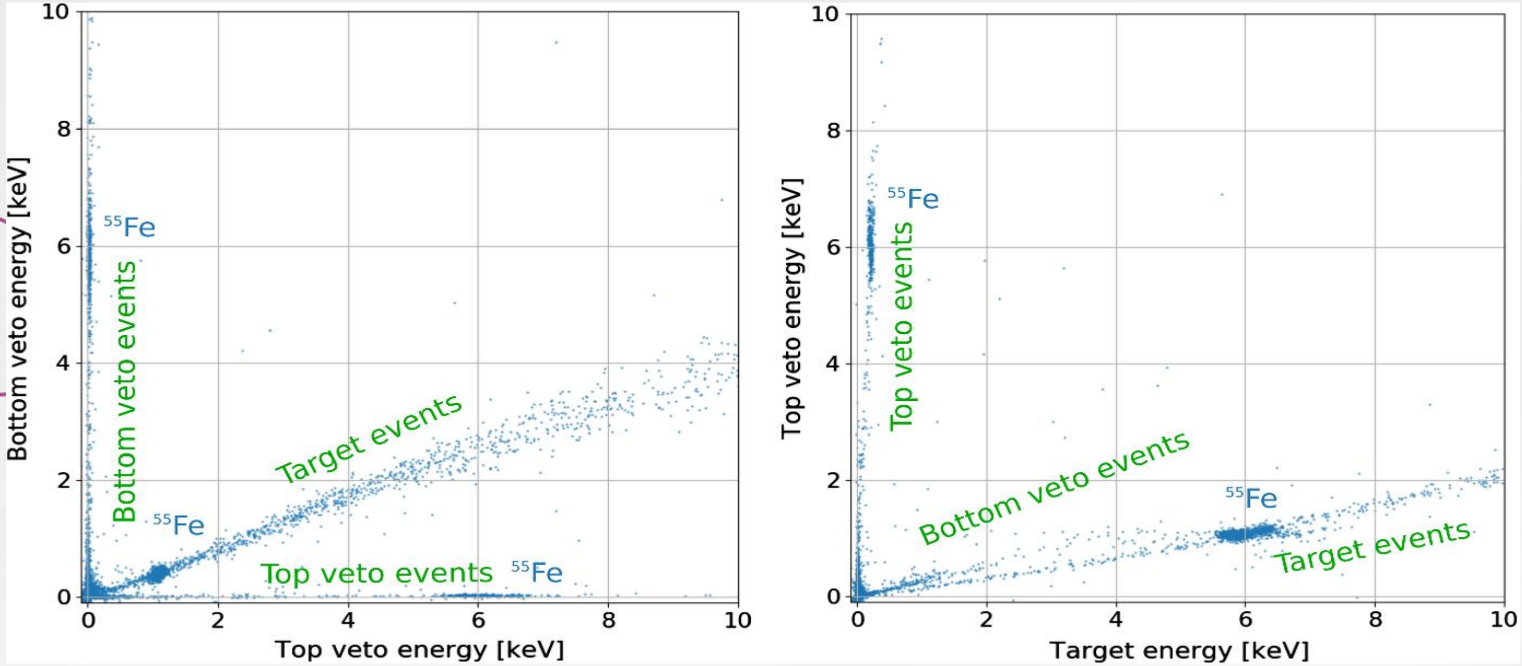

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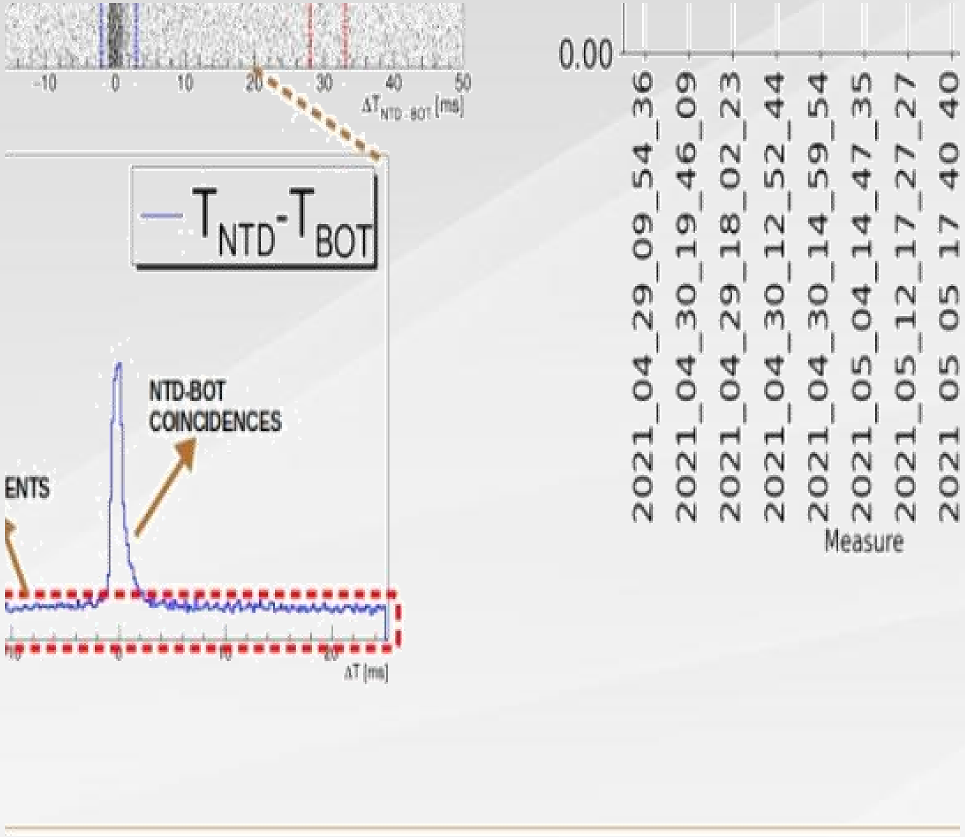
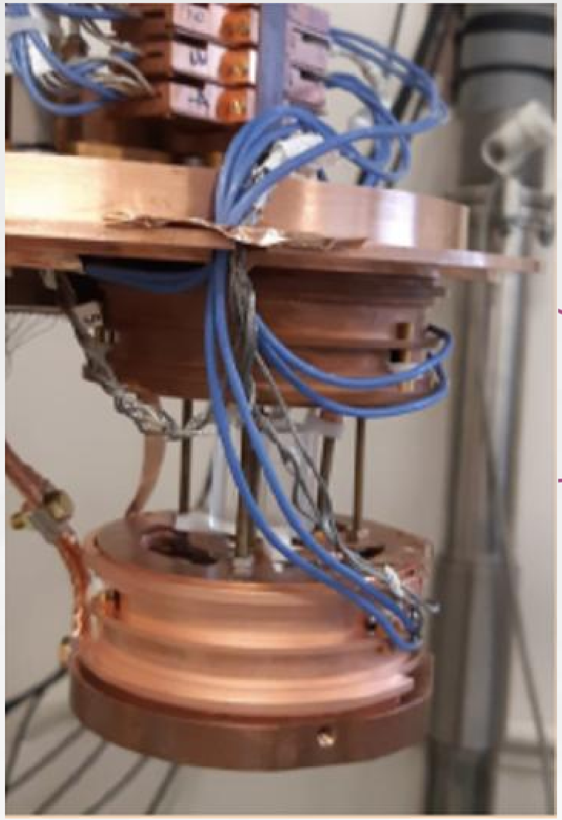
J Low Temp. Phys. 199, 433–440 (2020)

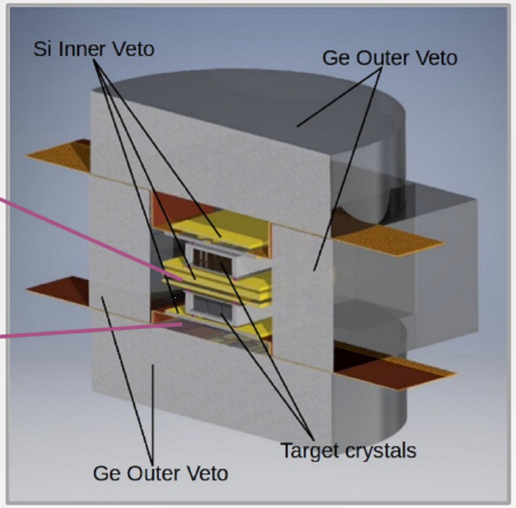
CENNS experiments: NuCLEUS

- Al_2O_3 prototype with threshold ~ 20 eV
- Outer and inner vetos for bkg rejection





Germanium outer veto for active γ/n background rejection



- ✓ Design finished
- ✓ Ongoing prototype test

CENNS: the signature

- df

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

DBD bolometers measurements worldwide

Underground cryogenic facilities for DBD:

- **Italy: LNGS, 3 cryostats**
- **Spain: LSC, 1 cryostat**
- **France: LSM, 1 cryostat (to be installed)**
- **Korea, Y2L: 1 cryostat**

0ν2β decay rate

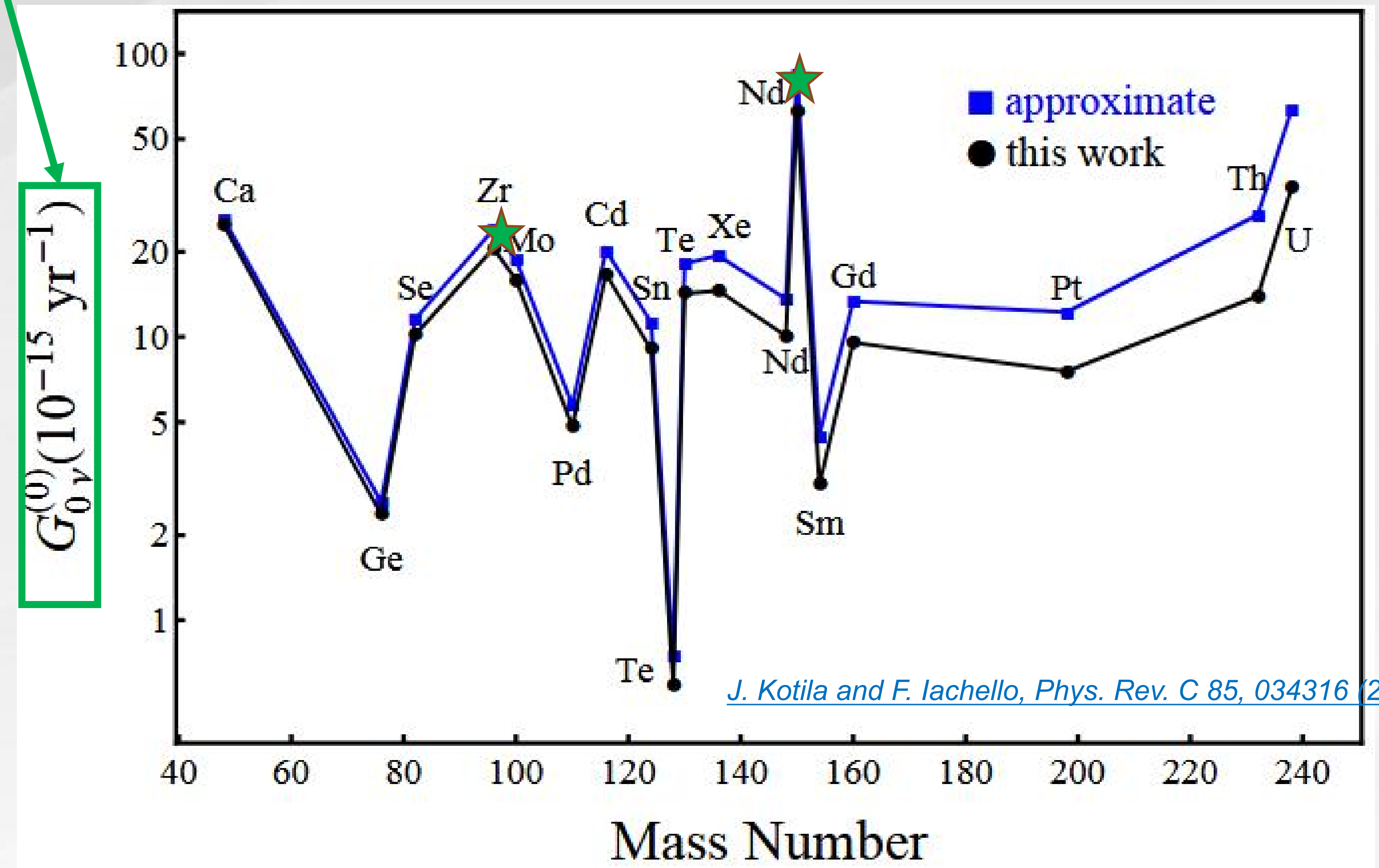
$$(T_{1/2}^{0\nu2\beta})^{-1} = G(Q,Z)\, g_A^4 |NME|^2 \langle m_{\beta\beta}\rangle^2$$

Effective Majorana mass - the unknown

Phase space factor

Observable

Process is allowed in 35 nuclei → **only few are interesting** for experiments



TINY experiment: study of $2\nu2\beta$

- Nuclear spectroscopy with high precision
- NME calculations quality verification

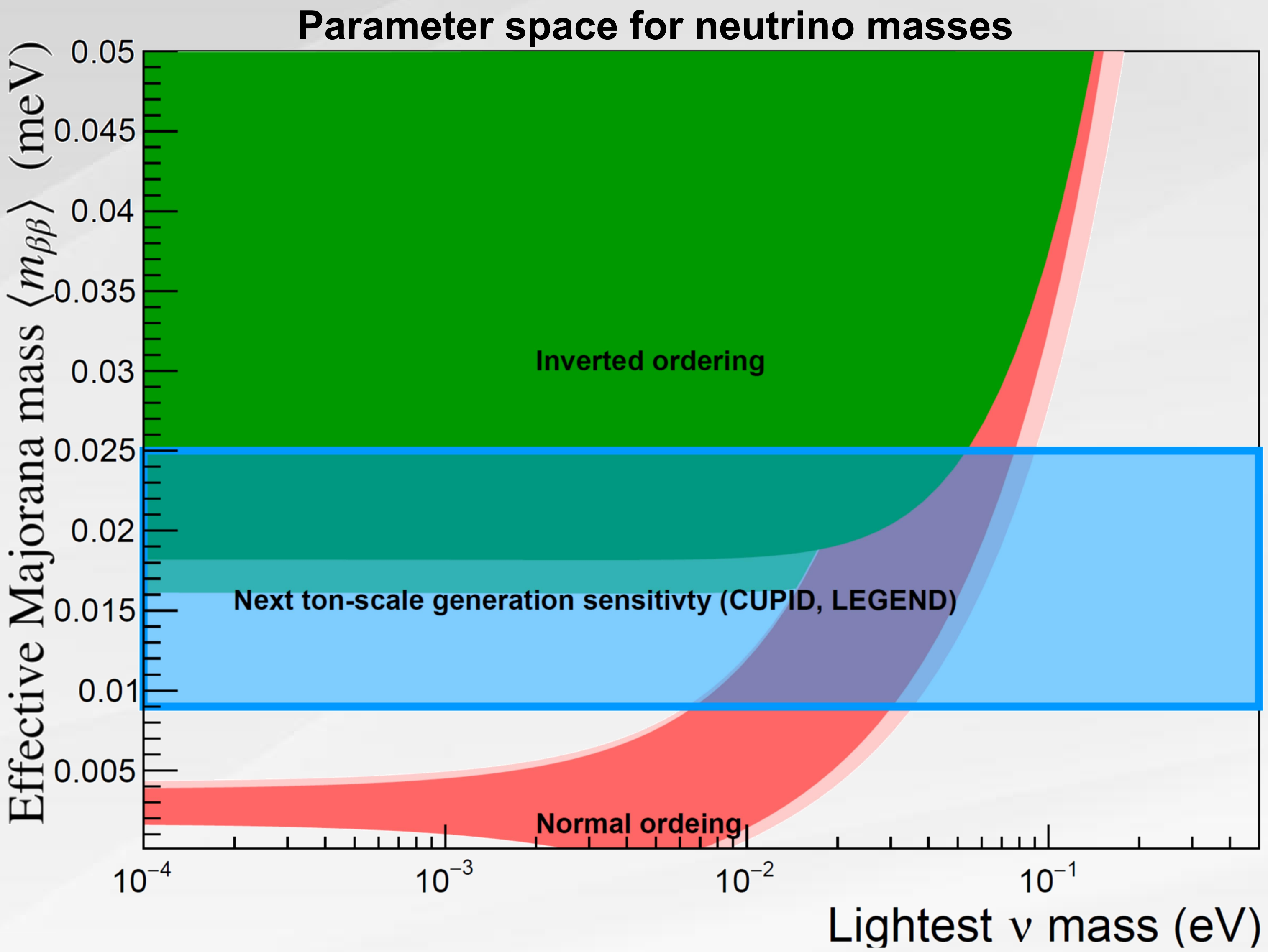
Isotope	Exposure NEMO-3, kg×yr	Previously measured $2\nu2\beta$ events	Exposure TINY, kg×yr	Amount of decays in TINY demonstrator
^{96}Zr	0.031	453	1.425	**~215700**
^{150}Nd	0.191	2214	0.062	**~14700**

Application of TINY technology on a large scale

- Estimation
  is done for existing
  cryogenic facility -
  CUPID experiment

- Significant improvement
  in sensitivity with
  the same volume thanks
  to high $Q_{\beta\beta}$

- Perfect timing: ready for
  after CUPID measurements

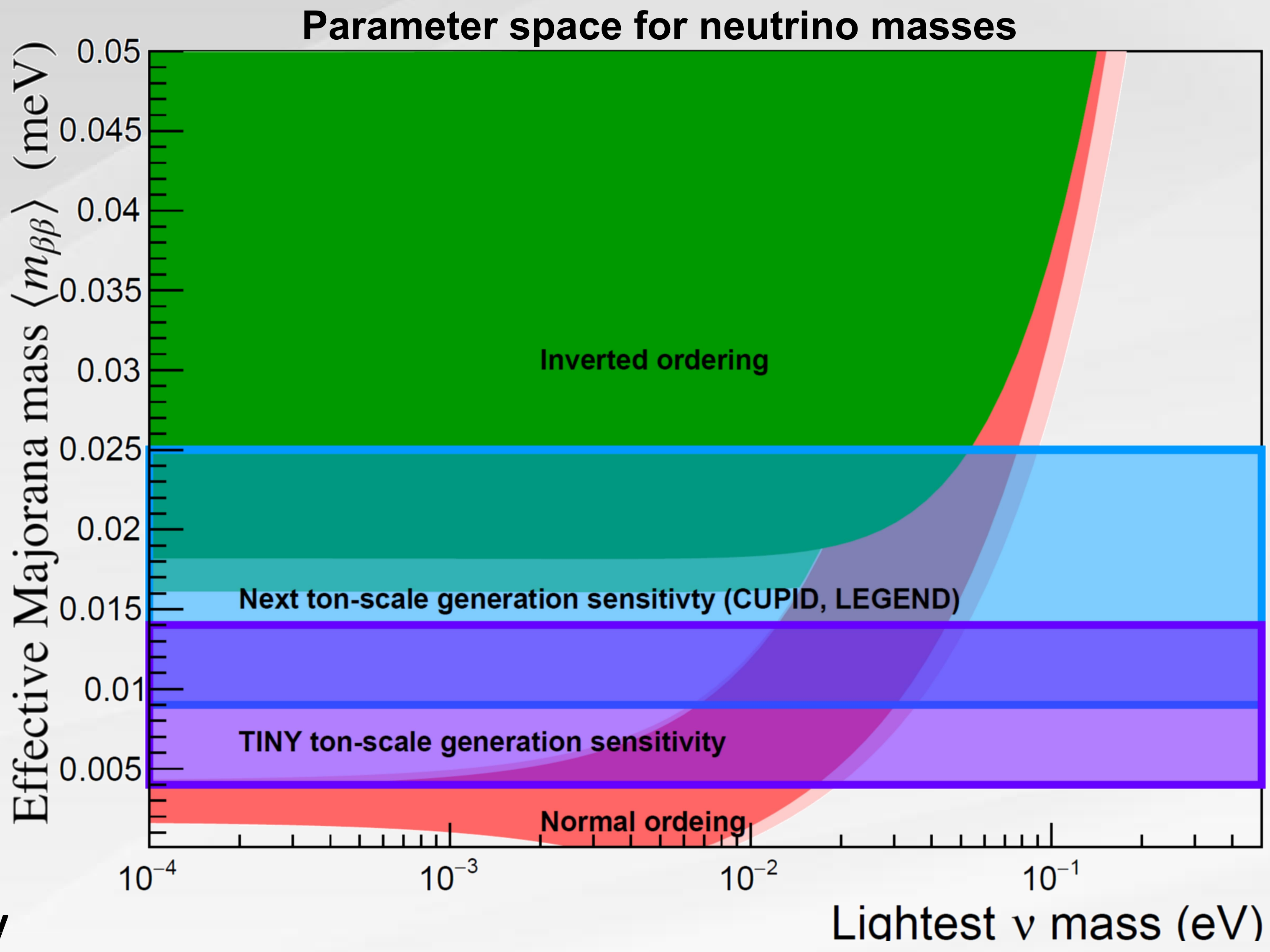


Application of TINY technology on a large scale

- Estimation
  is done for existing
  cryogenic facility -
  CUPID experiment

- Significant improvement
  in sensitivity with
  the same volume thanks
  to high $Q_{\beta\beta}$

- Timely project: technology
  ready after CUPID is concluded



CENNS: outlook

- After the first observation in 2017, interest is growing in precision measurements
- An exciting physics program to investigate:
  - physics beyond the SM
  - non standard neutrino interactions
  - studies of neutrino background for dark matter searches

- Stay tuned for the results in coming years!