ONLINE

5-9

Universe Evolution and Matter Origin

Session Organizer: TAKEUCHI Yuji, Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Associate Professor

0νββ Searches with Low-Temperature Thermal Calorimeters

Yong-Hamb Kim
Center for Underground Physics
Institute for Basic Science

CENTER FOR UNDERGROUND PHYSICS

ibS 기초과학연구원 Institute for Basic Science

Outline

1. $0\nu\beta\beta$ physics
2. Low-Temperature Thermal Calorimeters for $0\nu\beta\beta$ experiments
3. The AMoRE project
4. R&D challenges for LT $0\nu\beta\beta$ searches

0νββ and ν (brief intro.)

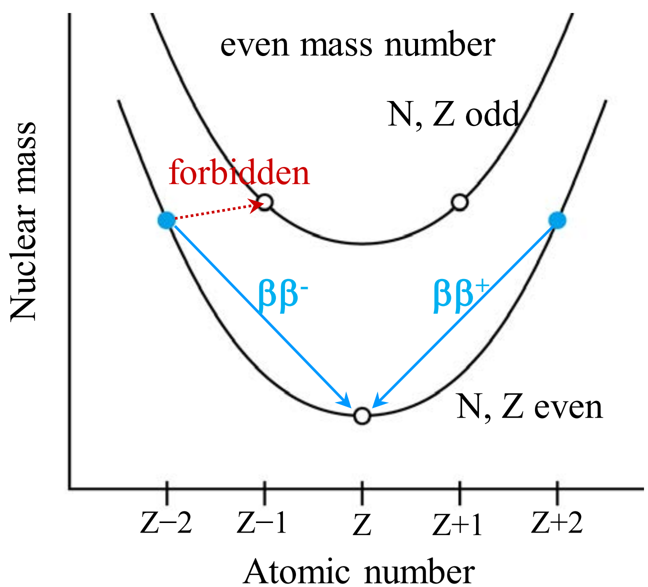
- 0νββ decay can only happen if neutrinos are massive Majoanana particles (own anti-particles).
  - ✓ fundamental understanding of particle physics
  - ✓ 0νββ search is the only practical technique to answer.
- The 0νββ decay rate ($T^{0\nu}$) is closely related to the mass of neutrinos.
  - ✓ Most sensitive measurement method (if Majorana particle)
- The 0νββ decay can only happen if Lepton number conservation is violated.
  - ✓ New physics beyond the standard model

Double beta decay

$$(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$$

35 0νββ nuclei are found.

- 2nd order weak process
- ββ(2ν) decay is detectable if 1st order β decay is not allowed.



ββ-decay nuclei with Q > 2 MeV	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow {}^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow {}^{76}Se$	2.040	7.8
$^{82}Se \rightarrow {}^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow {}^{96}Ru$	3.350	2.8
$^{100}Mo \rightarrow {}^{100}Ru$	3.034	9.7
$^{110}Pd \rightarrow {}^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow {}^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow {}^{124}Ge$	2.228	5.8
$^{130}Te \rightarrow {}^{130}Xe$	2.528	34.2
$^{136}Xe \rightarrow {}^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow {}^{150}Sm$	3.367	5.6

Double beta decay w. & wo. ν emission

2ν mode

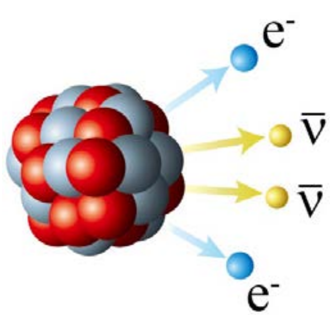
- A conventional
- 2nd order weak process in NP

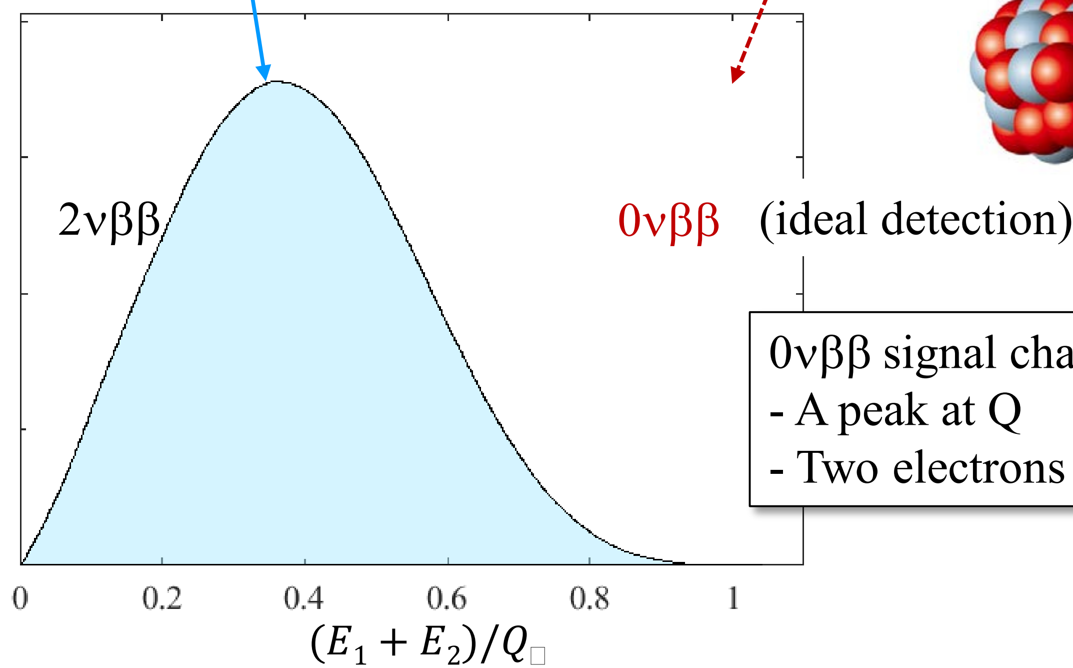
$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$$

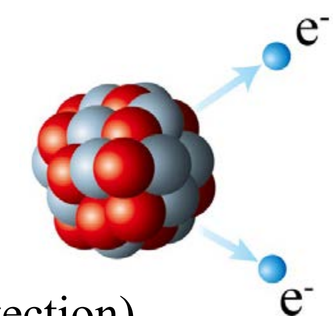
0ν mode

- A hypothetical process only if $m_\nu \neq 0$, $\bar{\nu} = \nu$, $|\Delta L| = 2$

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

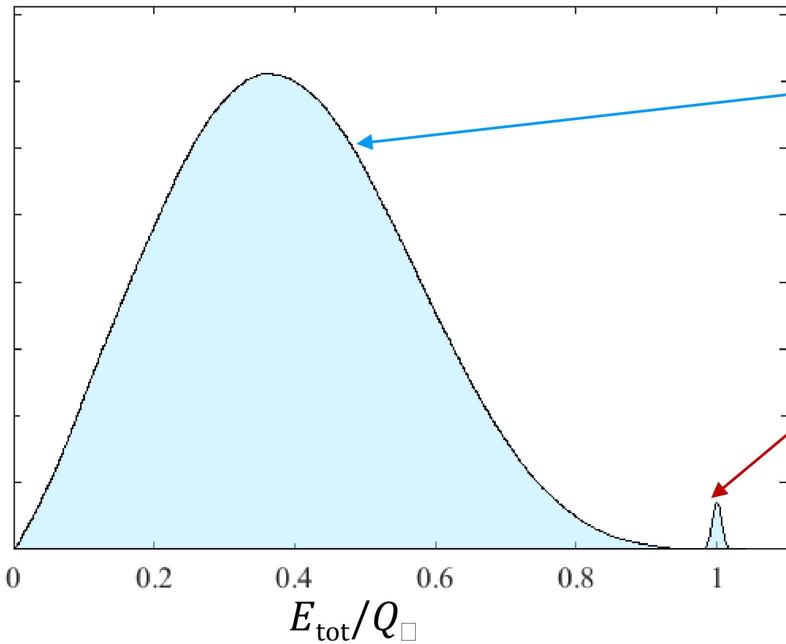






0νββ signal characteristics
- A peak at Q
- Two electrons from vertex

Search for 0νββ



Double Beta Decay with two neutrinos

$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$$

Double Beta Decay with no neutrino

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

0νββ discovery answers

- Majorana ($\nu = \bar{\nu}$) particles not Dirac ($\nu \neq \bar{\nu}$)
- Mass scale of neutrinos ($1/T_{1/2}^{0\nu} \propto m_\nu^2$)
- Lepton number violation

$0\nu\beta\beta$ decay rate

$$\Gamma_{0\nu} = 1/T_{1/2}^{0\nu} = G_{0\nu}\left|M_{0\nu}\right|^2 m_{\beta\beta}^2$$

<standard process>

- ✓ **$G_{0\nu}$** : Phase space factor: Calculable
  Atomic physics

- ✓ **$|M_{0\nu}|$** : Nuclear matrix element: Uncertain by 2~3 times,
  Nuclear physics

- ✓ **$m_{\beta\beta}$** : Effective neutrino mass: Interesting
  Particle physics

$0\nu\beta\beta$ Experiments

Methods	Isotopes
Loaded Liquid Scintillators	^{130}Te: SNO+, JUNO ^{136}Xe: KamLAND-Zen
Ge semiconductors	^{76}Ge: GERDA, Majorana Demonstrator LEGEND, CDEX
TPCs (liquid, gas)	^{136}Xe: EXO200, nEXO NEXT PandaX-III, R2D2
Low-temperature thermal calorimeters	^{48}Ca: CANDLES-LT R&D ^{82}Se: CUPID-0 ^{100}Mo: AMoRE, CUPID-Mo, CUPID ^{130}Te: CUORE
Tracking chambers	^{82}Se: SuperNEMO
Inorganic scintillators	^{48}Ca: CANDLES

Common strategies to increase sensitivity

$$T_{1/2}^{0\nu} \propto \sqrt{\frac{M \cdot \mathrm{time}}{\mathrm{bkg} \cdot \Delta E}}$$

<background case>

$$T_{1/2}^{0\nu} \propto M \cdot \mathrm{time}$$

<background-free case>

- ✓ Increase *M* : Large detector mass, Enriched ββ elements ← budget
- ✓ Increase 'time' : up to a few years
- ✓ Smaller ΔE : Better energy resolution ← detector tech. LT thermal calorimeters
- ✓ Bkg. : Minimize background events in ROI
  - Underground facility (w. controls on Rn, n, dust, long-lived cosmogenics)
  - Radio-assay equipment and protocols
    - Controls on natural occurring radioactive materials (U, Th, etc.)
  - In-situ bkg. identification
    - Alphas, gammas, ββ(2ν), μ- and n- induced, ν-e scatterings
    ← PSD, Heat/L or Charge/L detection, Veto, Shield, Topology, ΔE, Δt
  - Etc.

LT thermal calorimeters

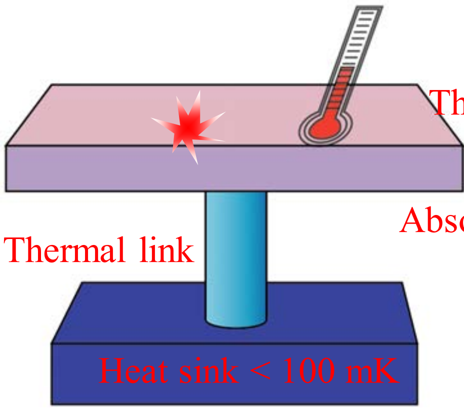
LTDs for $0\nu\beta\beta$ search

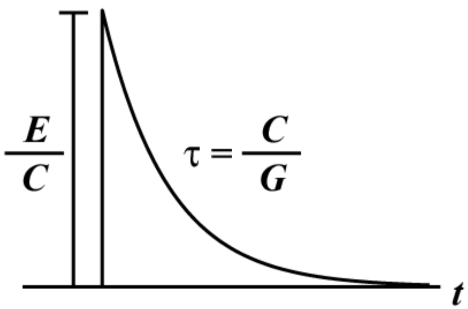
Sensors & Detection Technologies

Low Temperature Thermal Calorimeters

"Calorimetric measurement of heat signals at mK temperatures"

Energy absorption → Temperature





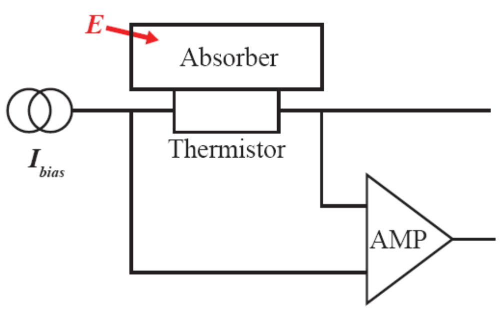
$$T - T_0 = \frac{E}{C} \qquad \tau = \frac{C}{G}$$

Choice of thermometers for 0νββ searches

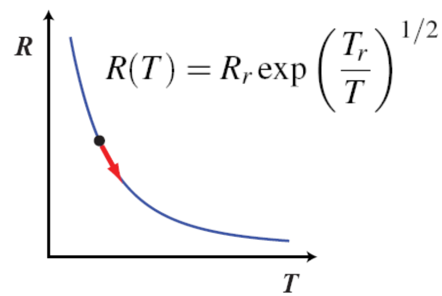
- **Thermistors (NTD Ge)** CUORE, CUPID
- **MMC (Metallic Magnetic Calorimeter)** AMoRE CANDLES-LT
- TES (Transition Edge Sensor) Light detector
- KID (Kinetic Inductance Device) CALDER
- etc.

Thermistors

- Doped semiconductors
  - Neutron transmuted doped (NTD) Ge thermistors
  - Ion implantation doped Si thermistors
- *R(T)* : 1 MΩ ~100 MΩ
- Readout: (cold) JFET
- High resolution + High linearity + Wide dynamic range + Absorber friendly
- Require very low bias current(sensitive to micro-phonics and electromagnetic interference), Slow response



<Current bias and read voltage >



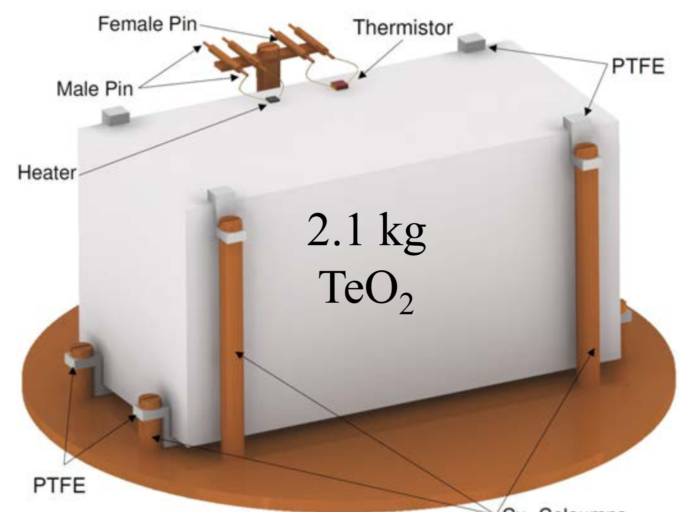
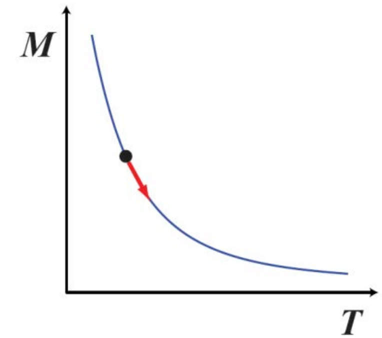
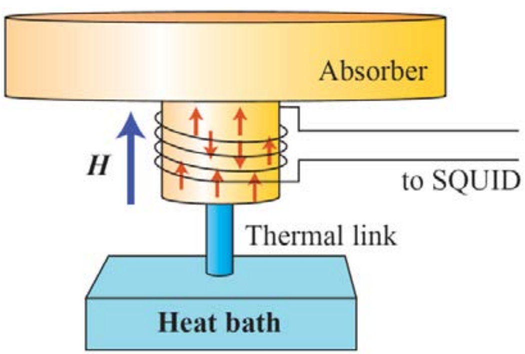


fig. from Cardani et al arXiv.1106.0568

Metallic Magnetic Calorimeter (MMC)



- Paramagnetic alloy in a magnetic field
  Au:Er(300-1000 ppm), Ag:Er(300-1000 ppm)
  → Magnetization variation with temperature
- Readout: SQUID
- High resolution + High linearity + Wide dynamic range + Absorber friendly + No bias heating + Relatively fast + MUX
- More wires & materials needed for SQUIDs and MMCs



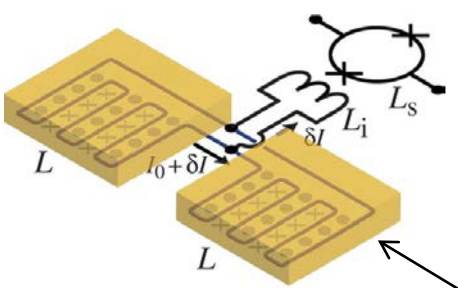
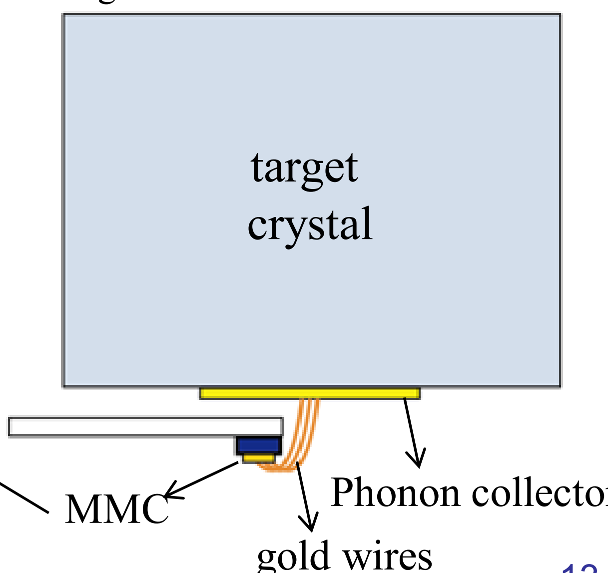
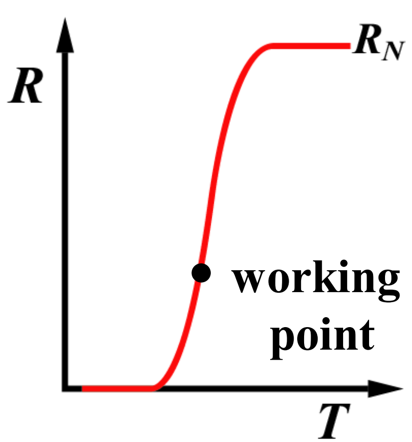


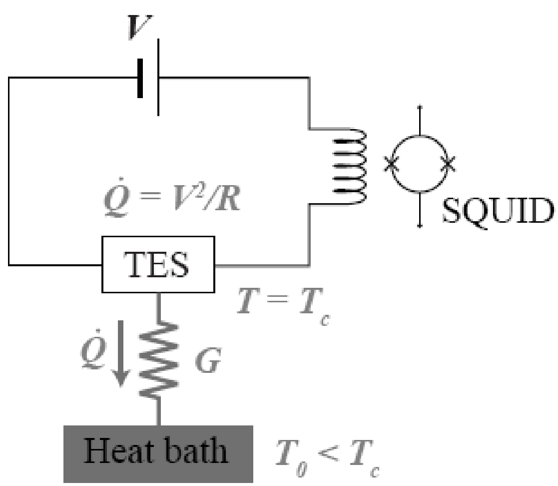
fig. from SY Oh et al SuST 2017



Transition Edge Sensor (TES)

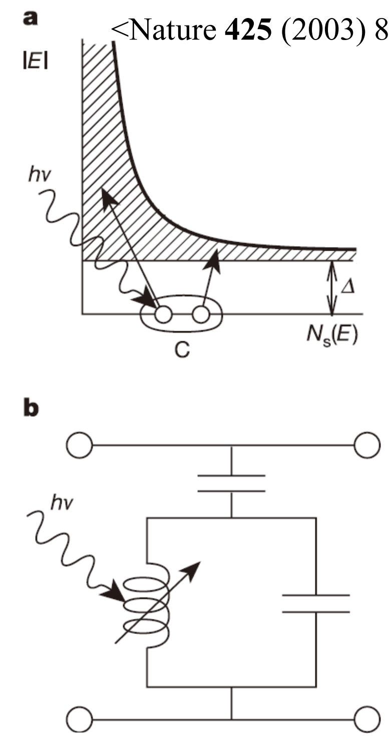
- Superconducting strip at T_c
  - Elemental superconductors: Ti, Ir, W
  - Proximity bilayers: Mo/Au, Mo/Cu, Al/Ag, Ir/Au, Ir/Pt, etc.
- R_N : 10 mΩ ~1 Ω
- Readout: SQUID
- High energy resolution + Low energy threshold + Fast + MUX
- Limited linearity and limited dynamic range, Absorber selective (or chip carrier)



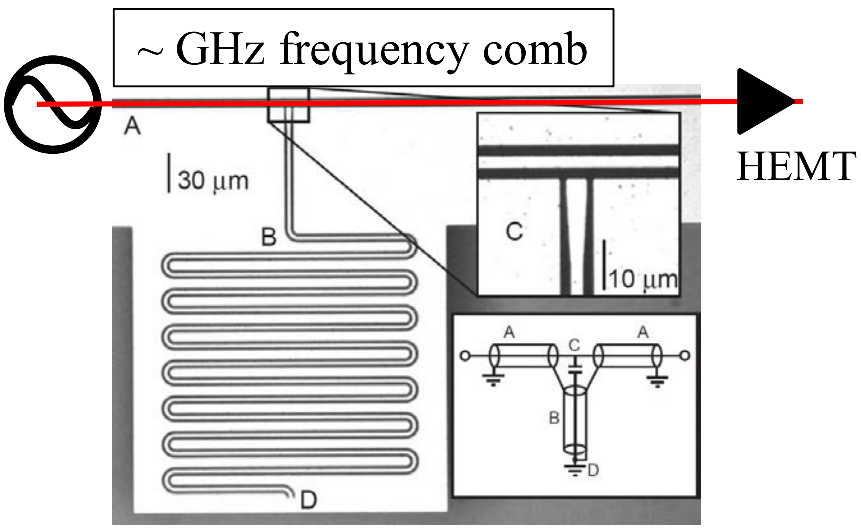


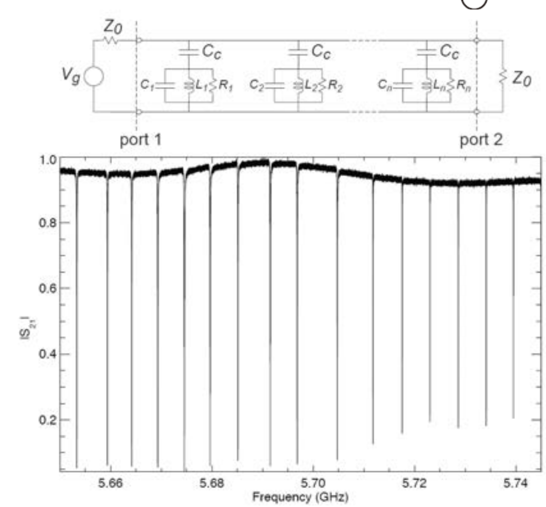
Kinetic Inductance Detectors

<Nature **425** (2003) 817 >



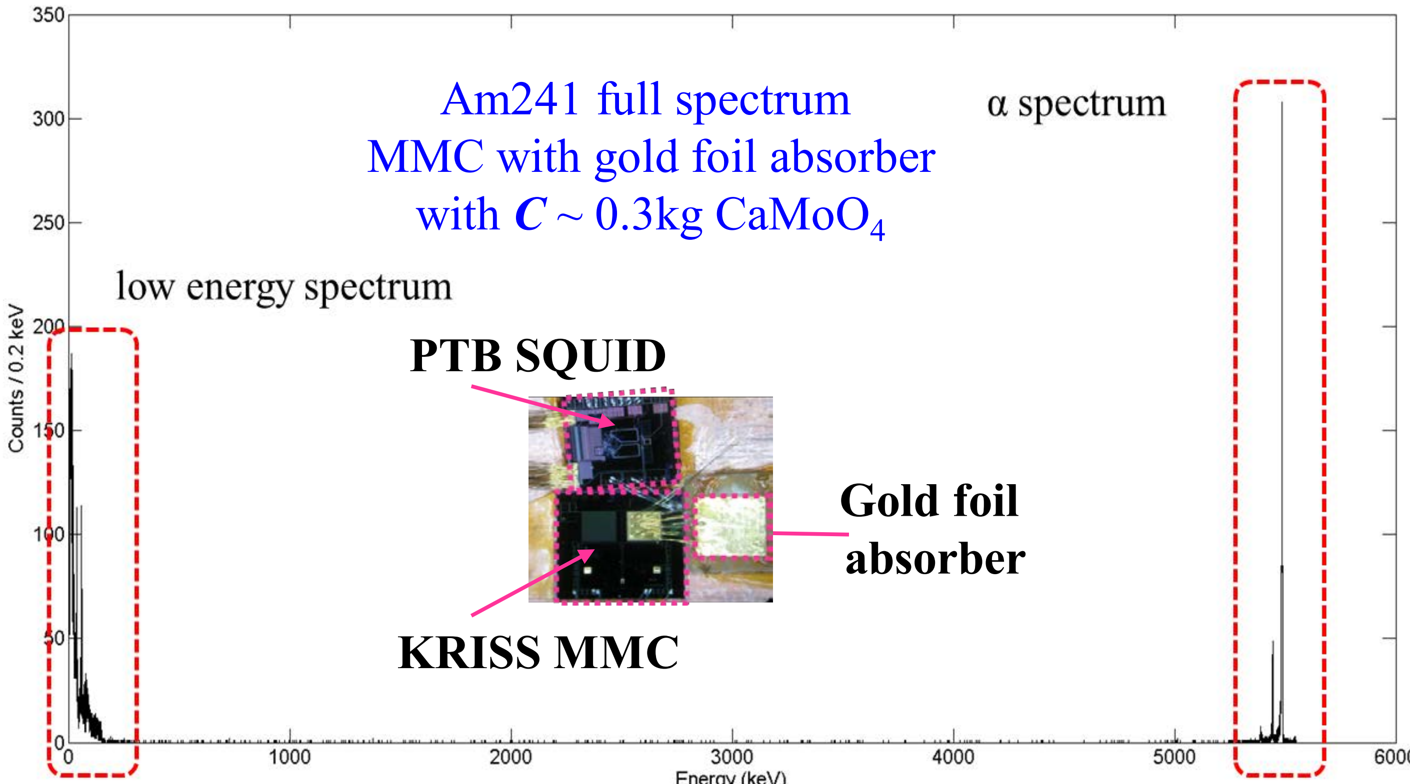
- Pair breaking superconducting detector:
  Quasiparticles are electron-like excitations in superconductors from breaking Cooper pairs
- Superconductor as the inductor in a LC resonance circuit
- Breaking pairs changes the Kinetic inductance
- Easy to MUX (on one chip)
- Non-equilibrium detector





Sensor performance (example)

"Superior dynamic range with high resolution"



0.3 keV FWHM for 60keV γ

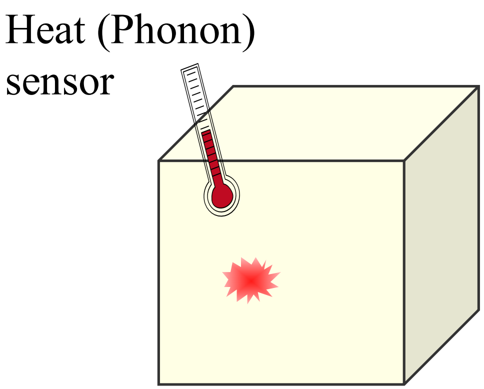
0.9 keV FWHM Gaussian width for 5.5MeV α

- ✓ **A test result with an MMC.**
- ✓ **NTD Ge thermistors also have similar performance.**

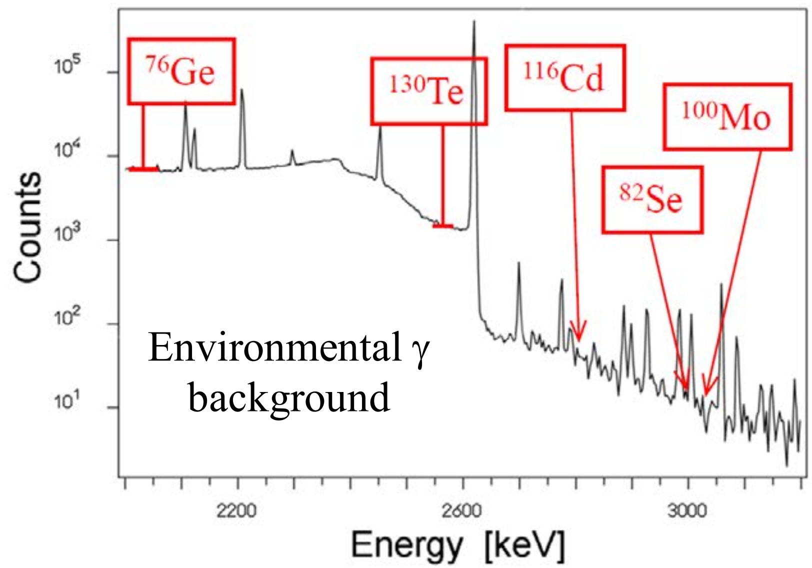
High resolution detection of heat signals

✓ Crystal target
- Many DBD nuclei can be used when found in a crystal form

✓ Many ββ nuclei test
✓ $Q_{\beta\beta}$ > 2.6 MeV possible for ^{48}Ca, ^{82}Se, ^{100}Mo, etc.
➔ Low env. γ bkg.

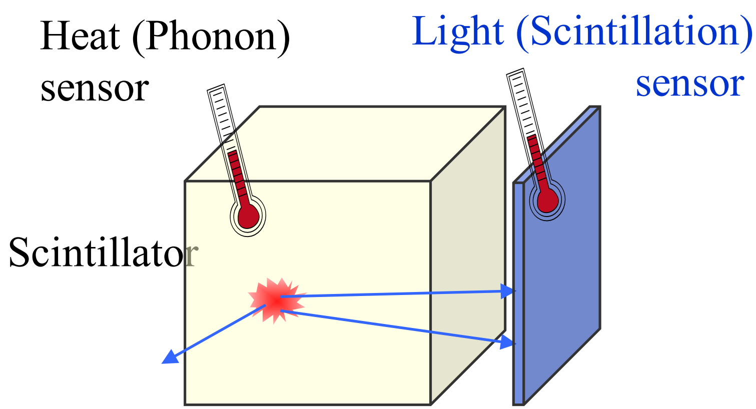


TeO_2 Li_2MoO_4 $CaMoO_4$
$CdWO_4$ ZnSe, CaF_2 etc.

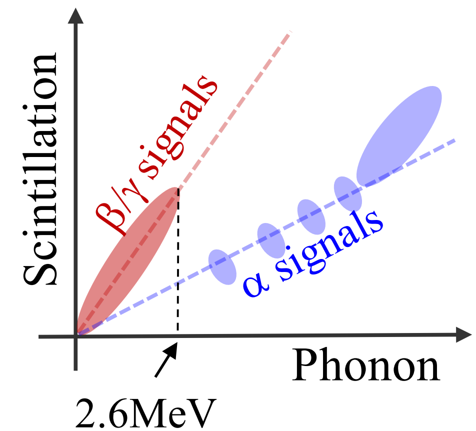


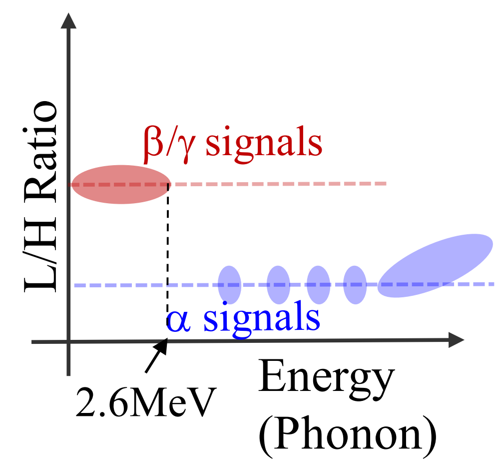
Simultaneous phonon-scintillation detection

✓ Scintillating crystal as target material



Li_2MoO_4 $CaMoO_4$
$CdWO_4$ ZnSe, CaF_2 etc.





Scintillating crystal ➔
Active bkg. Rejection
using **L/H ratio and PSD**

LT $0\nu\beta\beta$ Projects

- ✓ This is a short introduction for LT $0\nu\beta\beta$ searches.
- ✓ The summary may not cover all of those $0\nu\beta\beta$ project using LTDs.

$0\nu\beta\beta$ Experiments

Methods	Isotopes
Loaded Liquid Scintillators	^{130}Te: SNO+, JUNO ^{136}Xe: KamLAND-Zen
Ge semiconductors	^{76}Ge: GERDA, Majorana Demonstrator LEGEND, CDEX
TPCs (liquid, gas)	^{136}Xe: EXO200, nEXO NEXT PandaX-III, R2D2
Low-temperature thermal calorimeters	^{48}Ca: CANDLES-LT R&D ^{82}Se: CUPID-0 ^{100}Mo: AMoRE, CUPID-Mo, CUPID ^{130}Te: CUORE
Tracking chambers	^{82}Se: SuperNEMO
Inorganic scintillators	^{48}Ca: CANDLES

30 years of 0νββ searches @LNGS

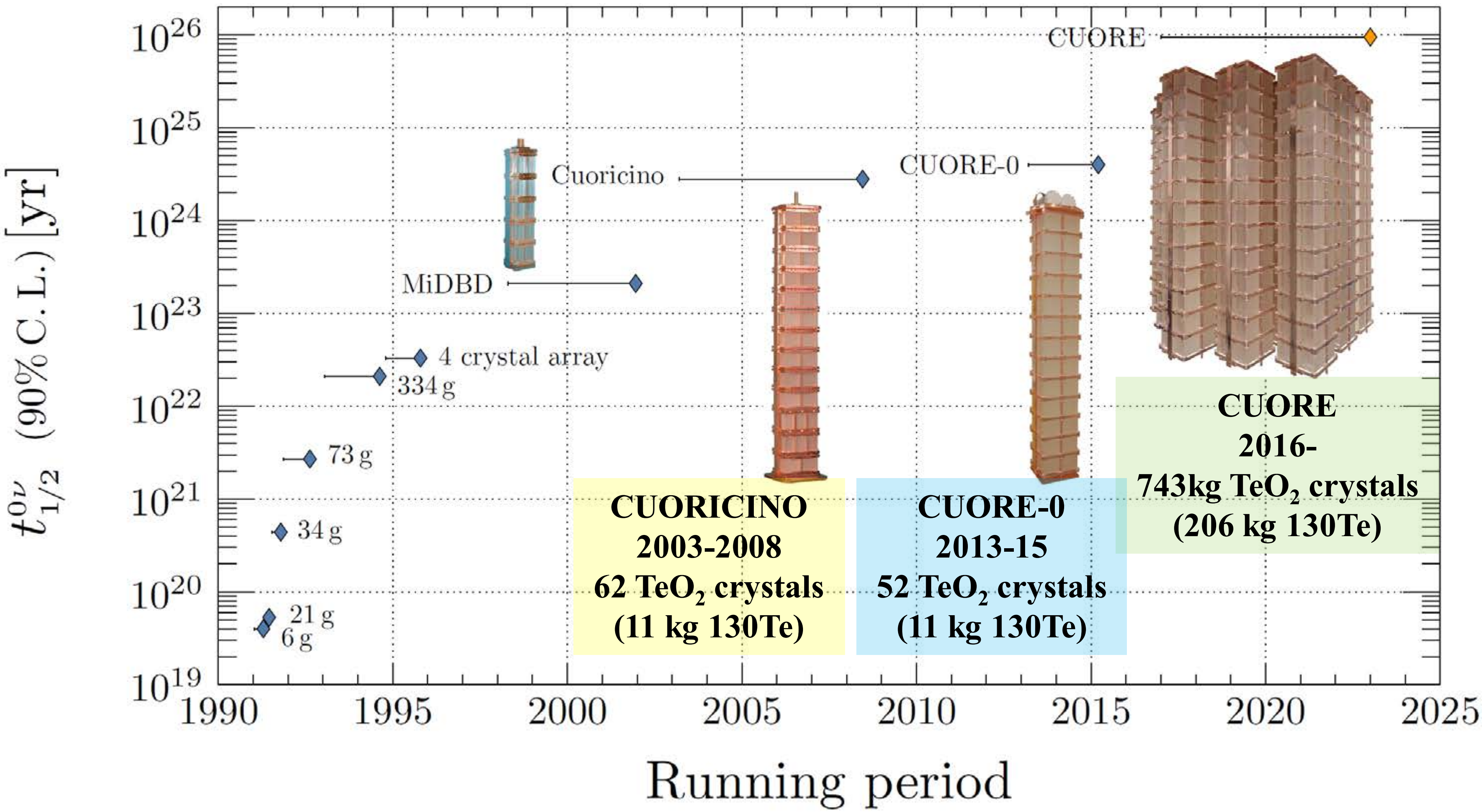


fig. from S. Dell'Oro' talk in DBD Shanghai 2017

TeO_2 for ^{130}Te

ββ-decay nuclei with Q > 2 MeV	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Ru$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Cd$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Ge$	2.228	5.8
$^{130}Te \rightarrow ^{130}Xe$	2.528	34.2
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

^{130}Te

- ✓ Q = 2528 keV (between ^{208}Tl line (2615 keV) and its Compton edge)
- ✓ Large natural abundance : 34.2%

TeO_2 crystals

- ✓ Debye Temp. ~ 230 K
- ✓ High crystal quality can be achieved.
- ✓ Low radio contaminants
- ➢ Do not scintillate → Particle ID not allowed

From CUORICINO, To CUORE, & ..

CUORICINO

CUORE-0

CUORE

CUORICINO
2003-2008
62 TeO_2 crystals
(11 kg ^{130}Te)
$T_{1/2} > 2\times10^{24}$ y

CUORE-0
2013-15
52 TeO_2 crystals
(10.9 kg ^{130}Te)
$T_{1/2} > 4\times10^{24}$ y

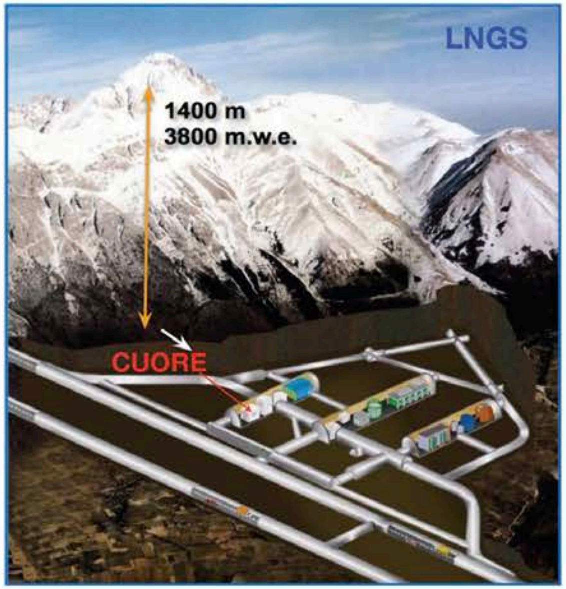
CUORE
2016-
743kg TeO_2 crystals
(206 kg ^{130}Te)

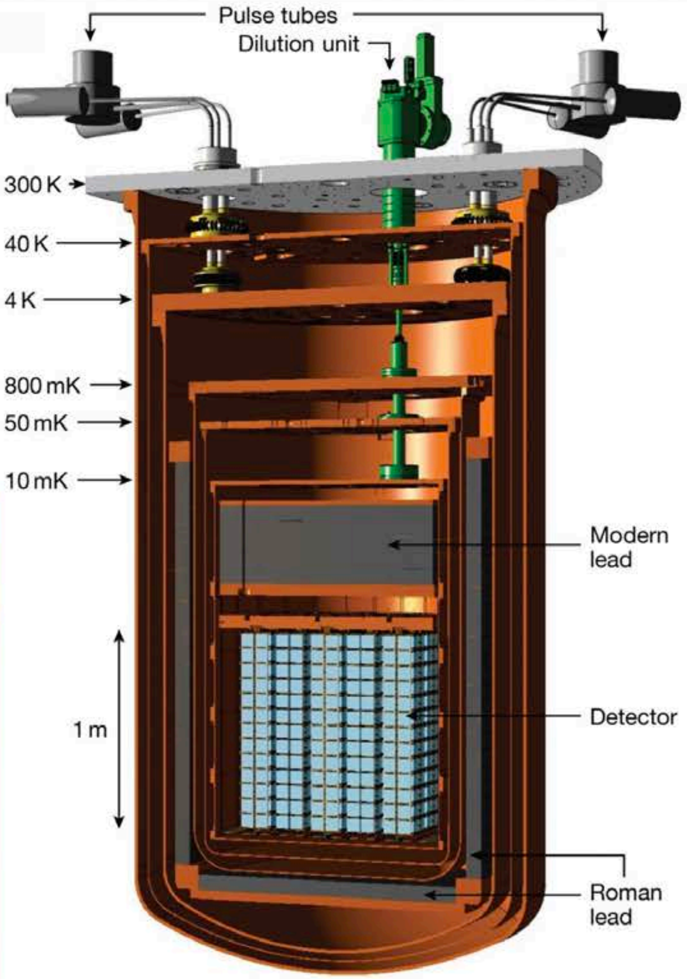
CUORE Tech for 0νββ search wih LTD

<I.Nutini ν-2022>

* **Low temperature** and **low vibrations**
  TeO_2 detectors operated as calorimeters at ~10 mK stable
  - Multistage cryogen-free cryostat. Nested vessels at decreasing temperature. Cooling systems: Pulse Tubes and Dilution Unit
    - Mass to be cooled < 4K: ~ 15 tons (IVC volume and Cu vessels, Roman Pb shield)
    - Mass to be cooled < 50 mK: ~ 3 tons (Top Pb shield, Cu supports and TeO_2 detectors)
  - Mechanical vibration isolation: Reduce energy dissipation by vibrations

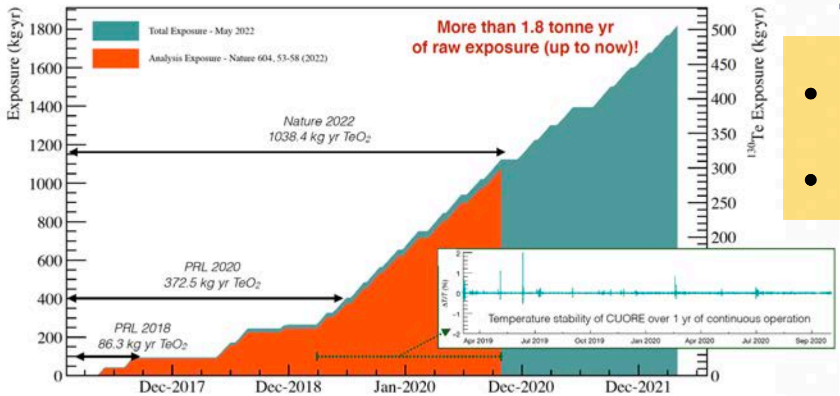
* **Low background**
  - Deep underground location
  - Strict radio-purity controls on materials and assembly
  - Passive shields from external and cryostat radioactivity
  - Detector: high granularity and self-shielding





Dell'Oro S. et al., Cryogenics 102, 9, (2019) https://doi.org/10.1016/j.cryogenics.2019.06.011
Adams D. et al. (CUORE collaboration), Prog.Part.Nucl.Phys. 122 (2022) 103902, https://doi.org/10.1016/j.ppnp.2021.103902

CUORE Result (^{130}Te 0νββ) <I.Nutini ν-2022>



- CUORE aims to collect 3 t·yr of TeO_2
- CUPID is the follow up.

Total e

1038.4 kg yr TeO_2, 288 kg yr ^{130}Te

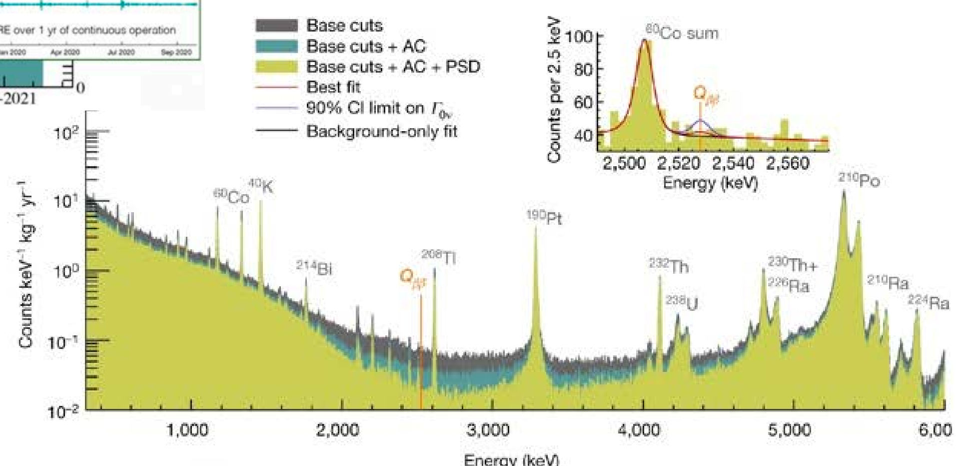
Selection efficiencies: 92.4(2)%

^{130}Te $Q_{\beta\beta}$= 2527.5 keV

Reconstructed energy resolution at $Q_{\beta\beta}$:

7.8(5) keV FWHM

ROI background index (B)
~ 1.49(4) × 10^{-2} c/(keV·kg·yr)

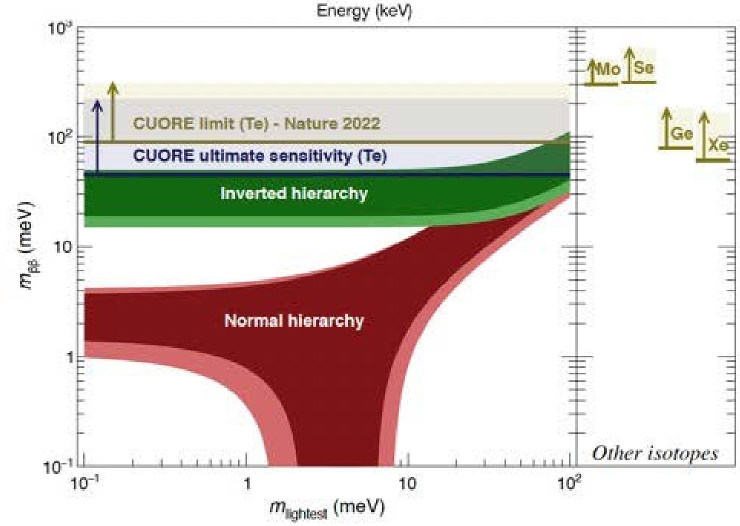


0νββ analysis

Half-life limit for 0νββ in ^{130}Te (90%C.I. including syst.)

$T_{0\nu}^{1/2}$ (^{130}Te) > 2.2 x 10^{25} yr

$m_{\beta\beta}$ < 90 - 305 meV



Evoluion from CUORE to CUPID

CUORE: Cryogenic Underground Observatory for Rare Events

CUPID: CUORE Upgrade with Particle IDentification

CUORE
743kg TeO_2 crystals
(206 kg ^{130}Te)

- Successful ton scale DBD at 10 mK
- No particle ID
- NTD

CUPID0
$Zn^{82}Se$ (5.17kg ^{82}Se)

- ZnSe Scintillating crystal
- Q = 2995 keV
- Successful partile ID with light detectors
- NTD

CUPID-Mo
$Li_2{}^{100}MoO_4$ (2.26kg ^{100}Mo)

- Li_2MoO_4 Scintillating crystal
- Q = 3.34 keV
- Good resolution, Particle ID
- Low background, easy to grow
- NTD

CUPID
$Li_2{}^{100}MoO_4$
(240kg ^{100}Mo)

- Li_2MoO_4 Scintillating crystal
- ^{100}MoEnrichment > 95%
- NTD

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

Fully mounted CUPID-0 detector to a wet DR in LNGS

^{82}Se

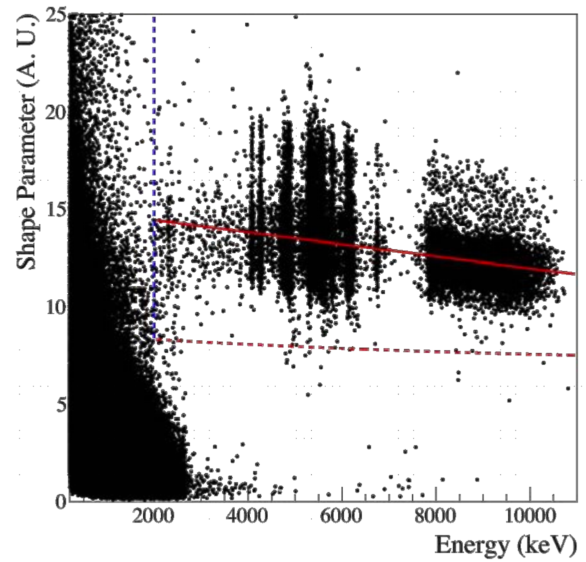
- ✓ Q = 2995 keV > ^{208}Tl line (2615 keV)
- ✓ Natural abundance: 9.2%

ZnSe scintillates at LT.

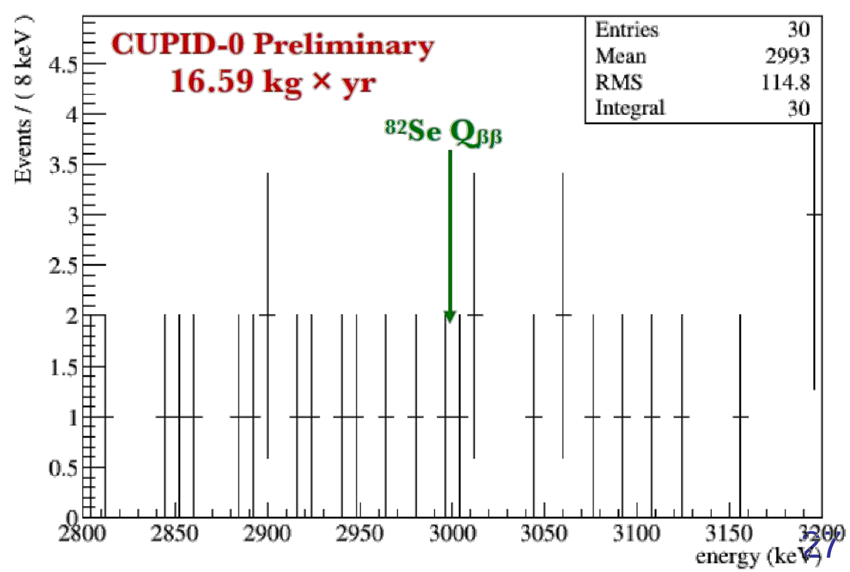
$T_{1/2} > 4.7 \times 10^{24}$ y (90% C. I. limit)

$m_{\beta\beta} < 276\text{-}570$ meV

Pulse shape of light signals



<L.Pagnanini ν-2022>



CUPID-Mo

^{100}Mo

✓ Q = 3034 keV > ^{208}Tl line (2615 keV)

✓ Natural abundance : 9.7%

✓ $T_{1/2}$ (2ν) = 7.1×10^{18} y: the largest ββ decay rate

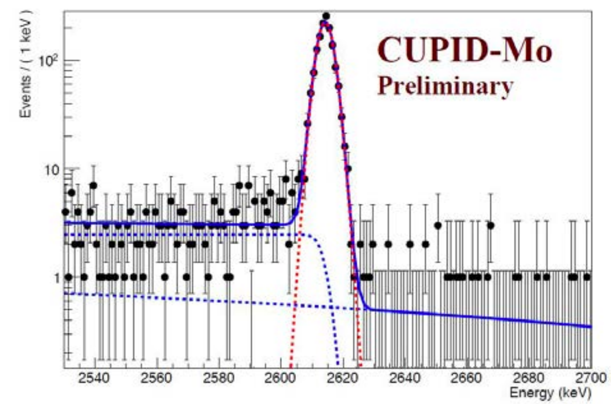
Li_2MoO_4 : Scintillating molybdates, Selected

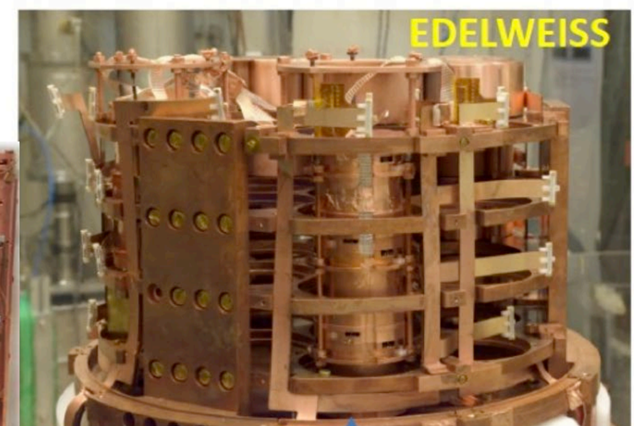
NTD Ge, Cold JFET

EDELWEISS cryostat

<A.Zolotarova ν-2022>

7.4 keV FWHM at Q



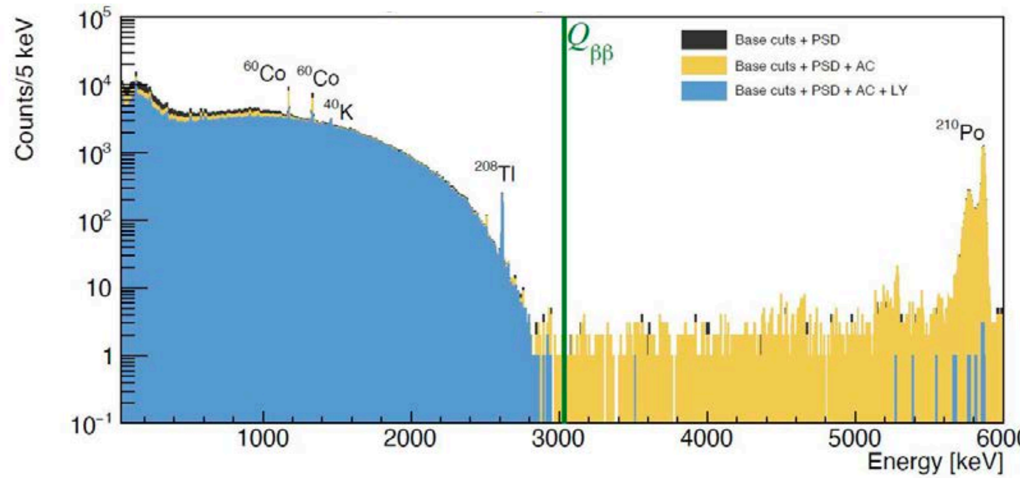


CUPID-Mo Results

$T_{1/2}(0\nu) > 1.8 \times 10^{24}$ y (90% C. I. limit)

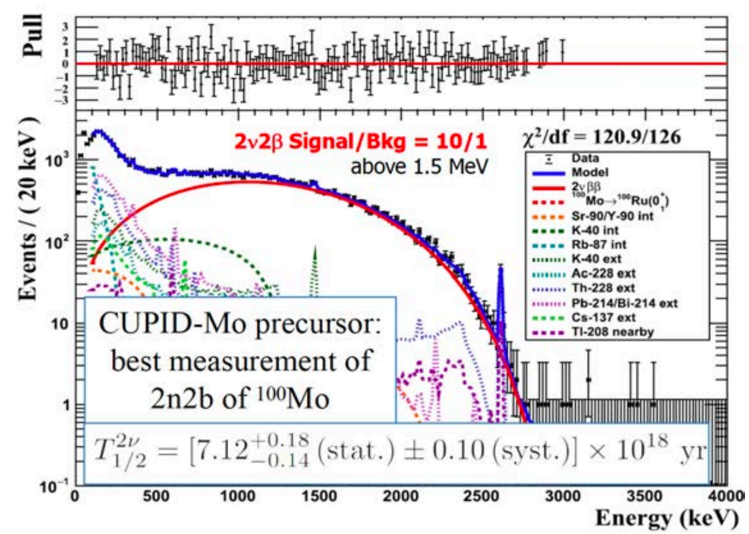
$m_{\beta\beta} < 280\text{-}490$ meV

<A.Zolotarova ν-2022>



- ✓ Best limit on ^{100}Mo $0\nu\beta\beta$ half- life

- ✓ The most precise measurement of ^{100}Mo $2\nu\beta\beta$

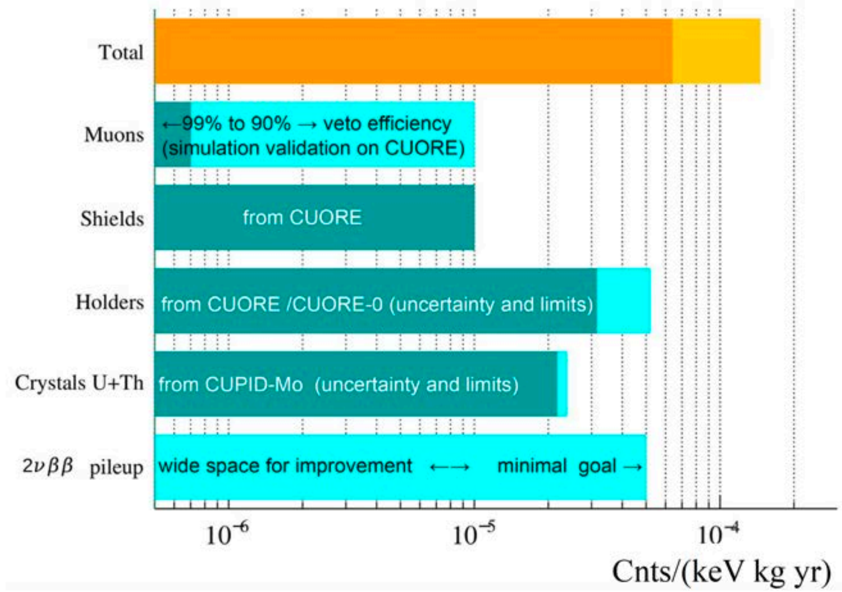


Yong-Hamb Kim

CUPID

<A.Zolotarova ν-2022>

- Heat-Light detection: $Li_2{}^{100}MoO_4$ + NTD
- Particle Identification
- ^{100}Mo Enrichment > 95%
- 1596 crystals and 240 kg of ^{100}Mo
- FWHM <10 keV at Q (3034 keV)
- CUORE cryostat

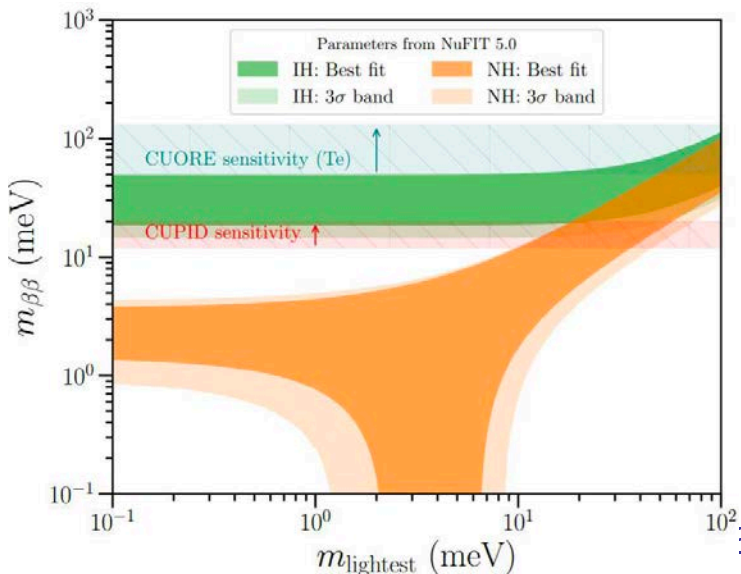


Background goal: 10^{-4} ckky

Discovery sensitivity at 3**σ**:

$T_{1/2}(^{100}Mo\ 0\nu\beta\beta) = 10^{27}$ year

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



AMoRE

AMoRE: Advanced Mo-based Rare process Experiment

^{100}Mo

- ✓ Q = 3034 keV > ^{208}Tl line (2615 keV)
- ✓ Natural abundance : 9.7%
- ✓ $T_{1/2}$ (2ν) = 7.1 × 10^{18} y: the largest ββ decay rate

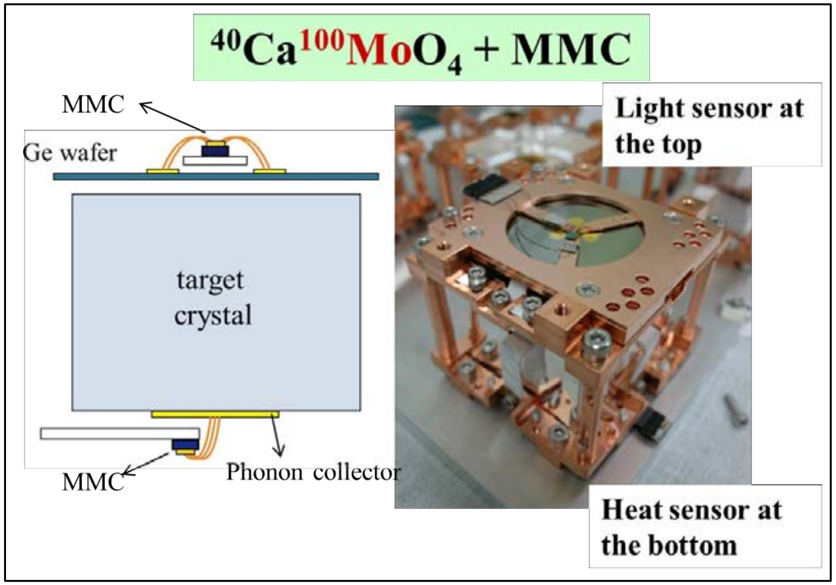
$^{40}Ca^{100}MoO_4$: enriched ^{100}Mo and depleted ^{48}Ca

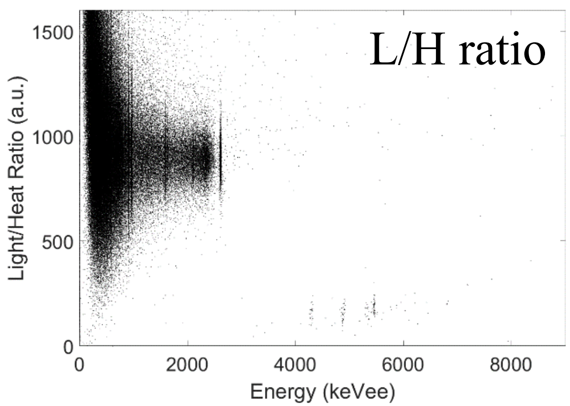
: Selected for a pilot and AMoRE-1'

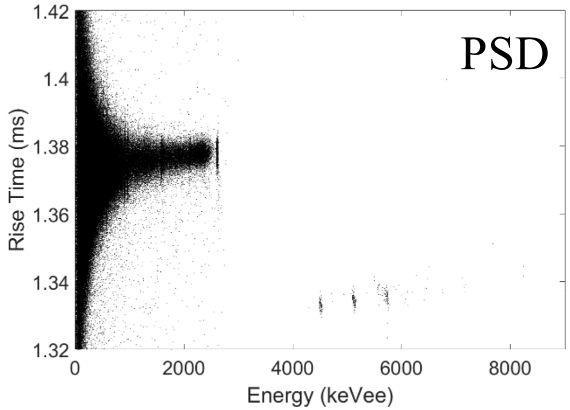
: High Debye temperature: T_D = 438 K

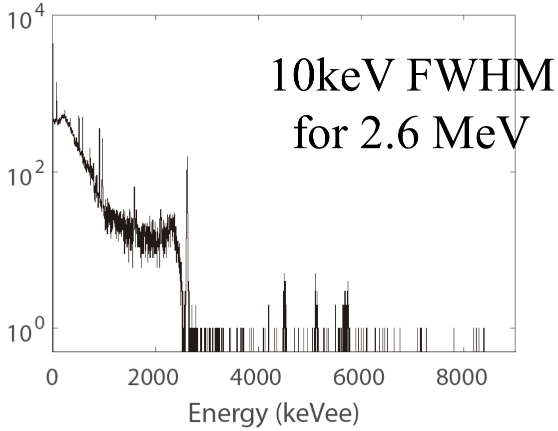
$Li_2{}^{100}MoO_4$: Selected for AMoRE-II

MMC for heat and light detection

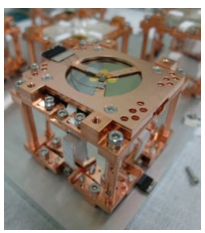






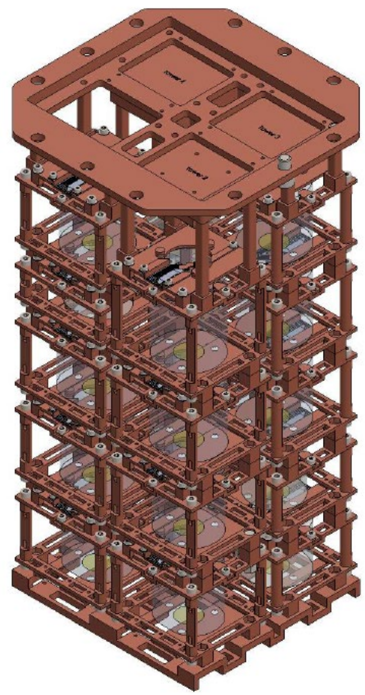


AMoRE Progress



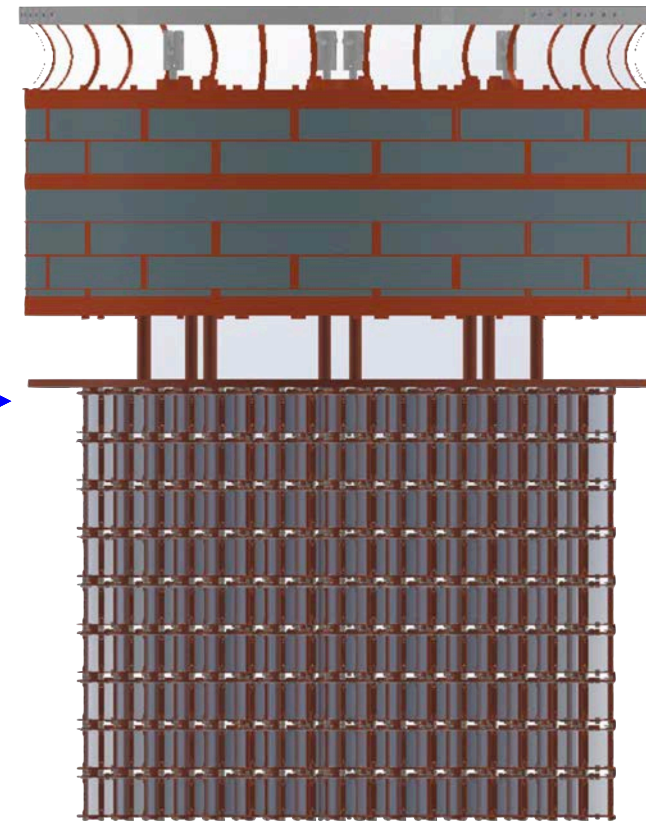
Single module

AMoRE-Pilot
- 2018



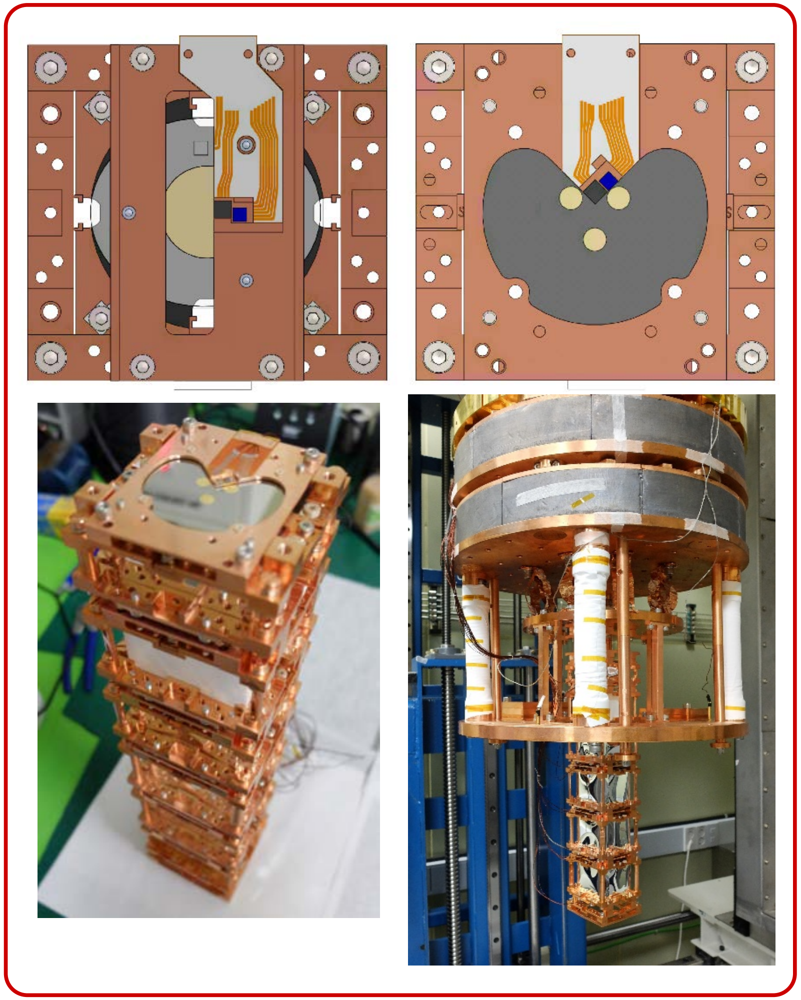
AMoRE-I

Now

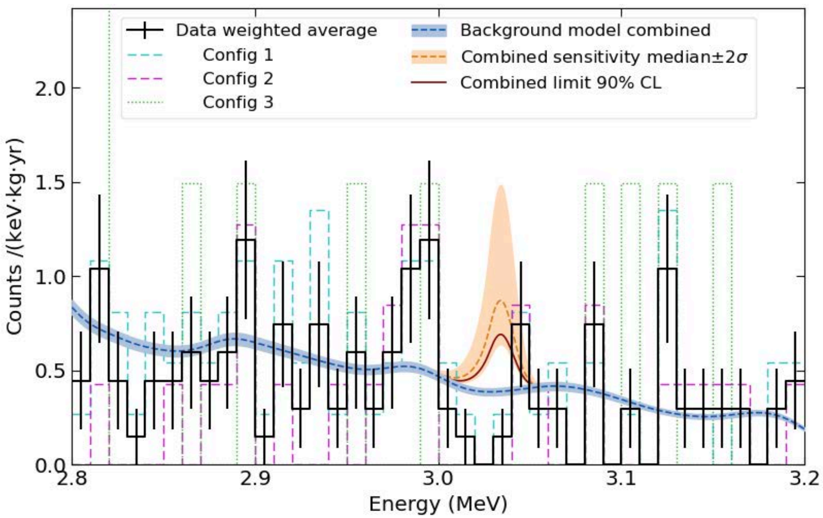


AMoRE-II
Being prepared

AMoRE Pilot result

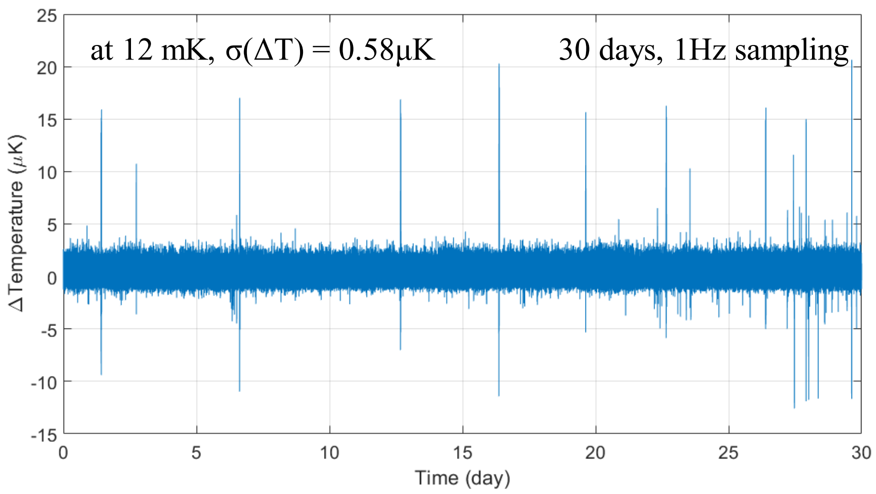


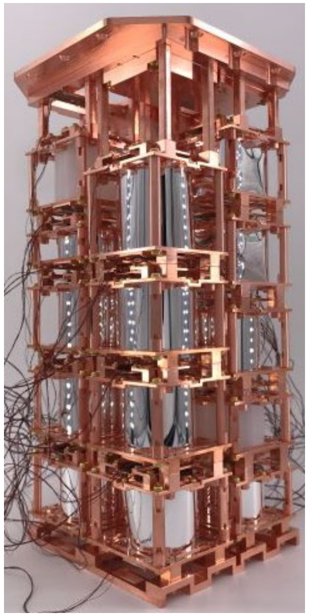
- $^{48depl}Ca^{100}MoO_4$: 6 crystals 1.9 kg (0.9kg ^{100}Mo)
- Proof of the AMoRE detection principle
- Understanding of the background components & reduction of them.
- Background level of ~0.5 ckky at 2.8-3.2 MeV
  - n-induced γ, Internal bkg, rock/air-radon γ
  - Internal background— arXiv:2107.07704
- $T_{1/2}(0\nu) > 3.2\times10^{23}$ years at 90% CL.

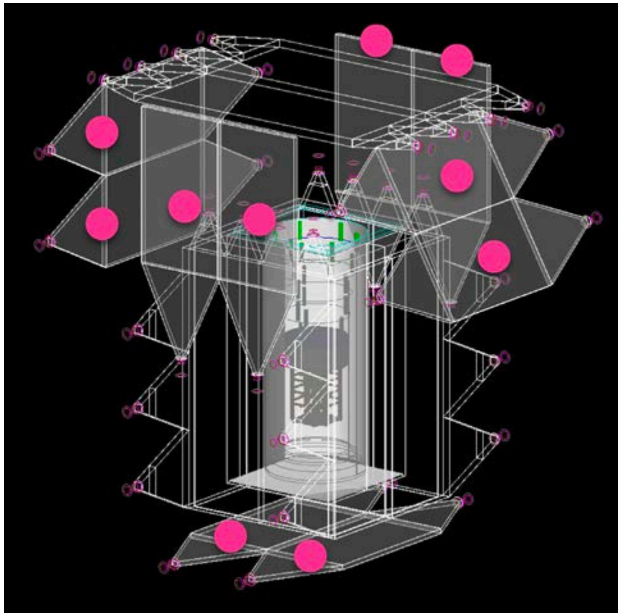


AMoRE Pilot → AMoRE-I

- 18 crystals: 13 $^{48depl}Ca^{100}MoO_4$ (4.58 kg) + 5 $Li_2{}^{100}MoO_4$ (1.61 kg)
- Total crystal mass 6.19 kg (3.0 kg ^{100}Mo)
- MMC sensor: Au:Er ➔ Ag:Er
- Using same cryostat + two stage temperature control: $\langle \Delta T \rangle < 1$ μK
- Shielding enhancements:
  - Outer Pb: 15 ➔ 20 cm; neutron shields
  - boric acid silicon + more PE / B-PE
  - More muon counter coverage
  - More supply of Rn-free air.

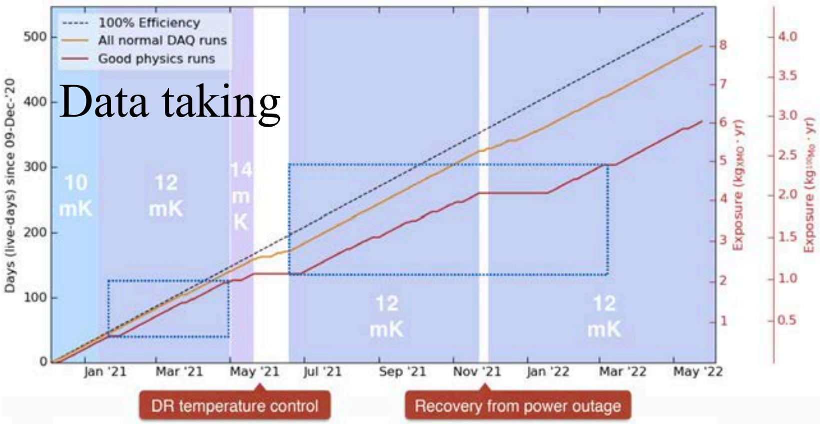


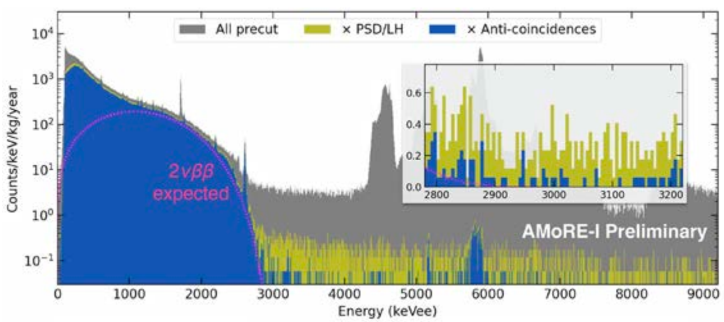


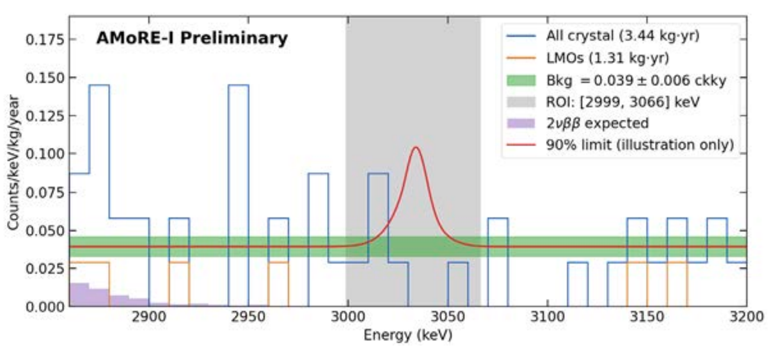


AMoRE-I (Preliminary) Results

<YM Oh ν-2022>







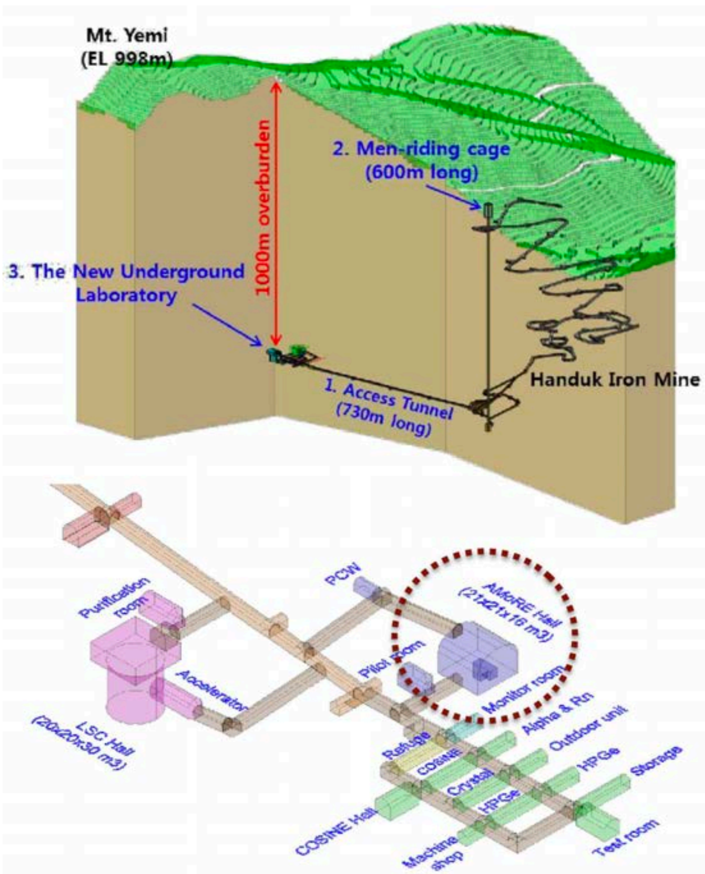
- Data taking (Science) started Dec./2020
- Data for 1.67 kg ^{100}Mo exposure is analyzed.
- To be continued till 2023.

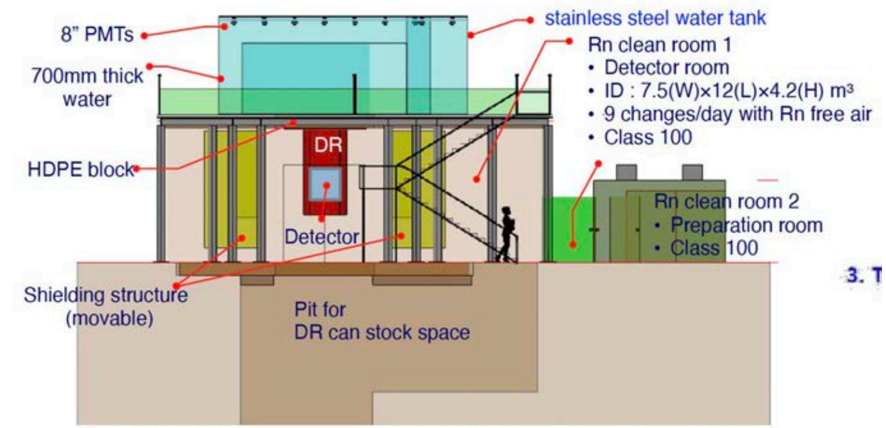
- 10 – 30 keV FWHM@2.6MeV (15 keV average)

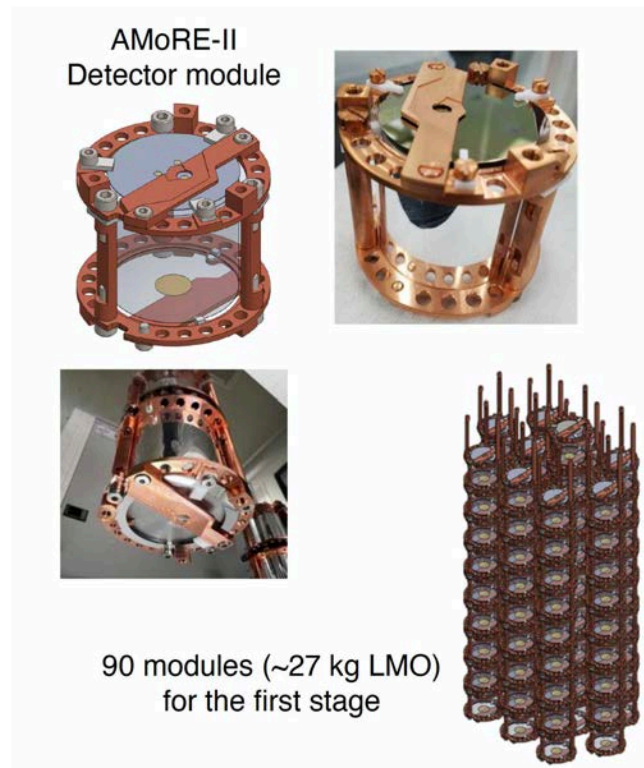
$$T_{1/2}(0\nu) > 1.2 \times 10^{24} \text{ y (90\% CL.)}$$
with 1.67 kg ^{100}Mo exposure

AMoRE-II in prepration

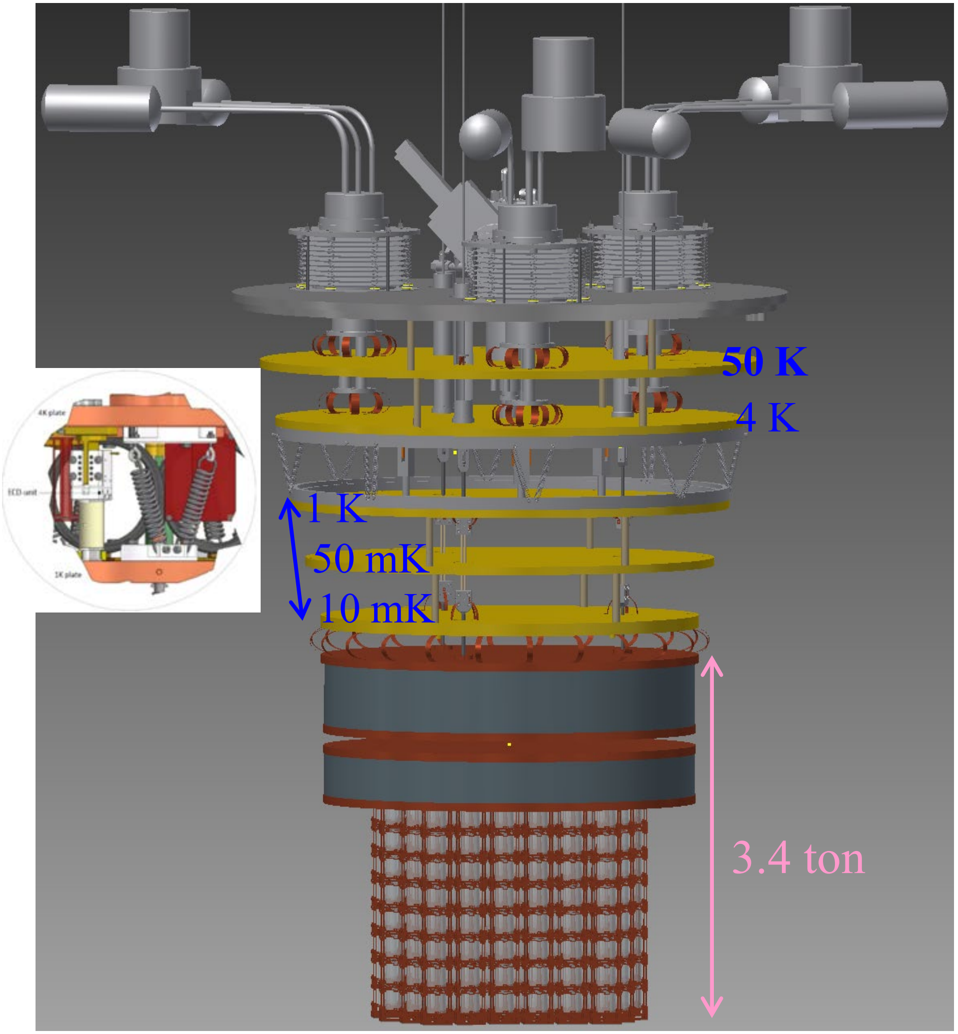
- In a new underground lab (Yemilab)
- With new cryostat and new shields







AMoRE-II Cryogenics

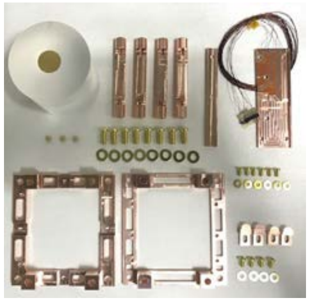


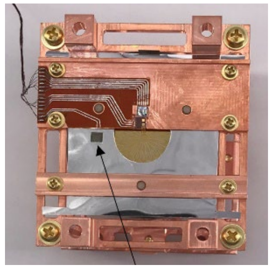
- Three PTRs (PT420 RM)
- Dilution refrigerator (delivered)
  - 5.4 mK base temperature
  - 7 uW at 10 mK

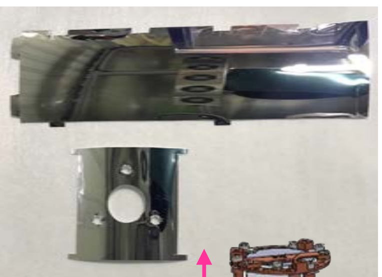
- Spring Suspended Still with Eddy Current Damper
- Independent holding structure for detector tower

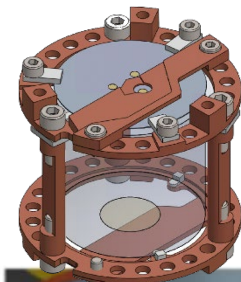
- 1 m diameter M.C plate
- 26 cm thick inner Pb shield
- 450 detector towers
- $Li^{100}MoO_4$ (~ 100 kg ^{100}Mo at final stage)

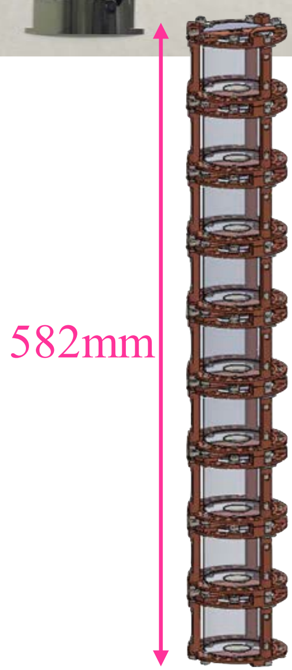
AMoRE-II from chips to the house

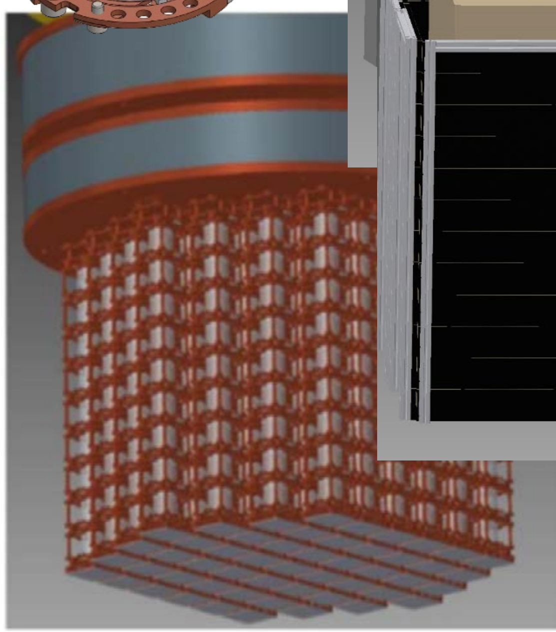


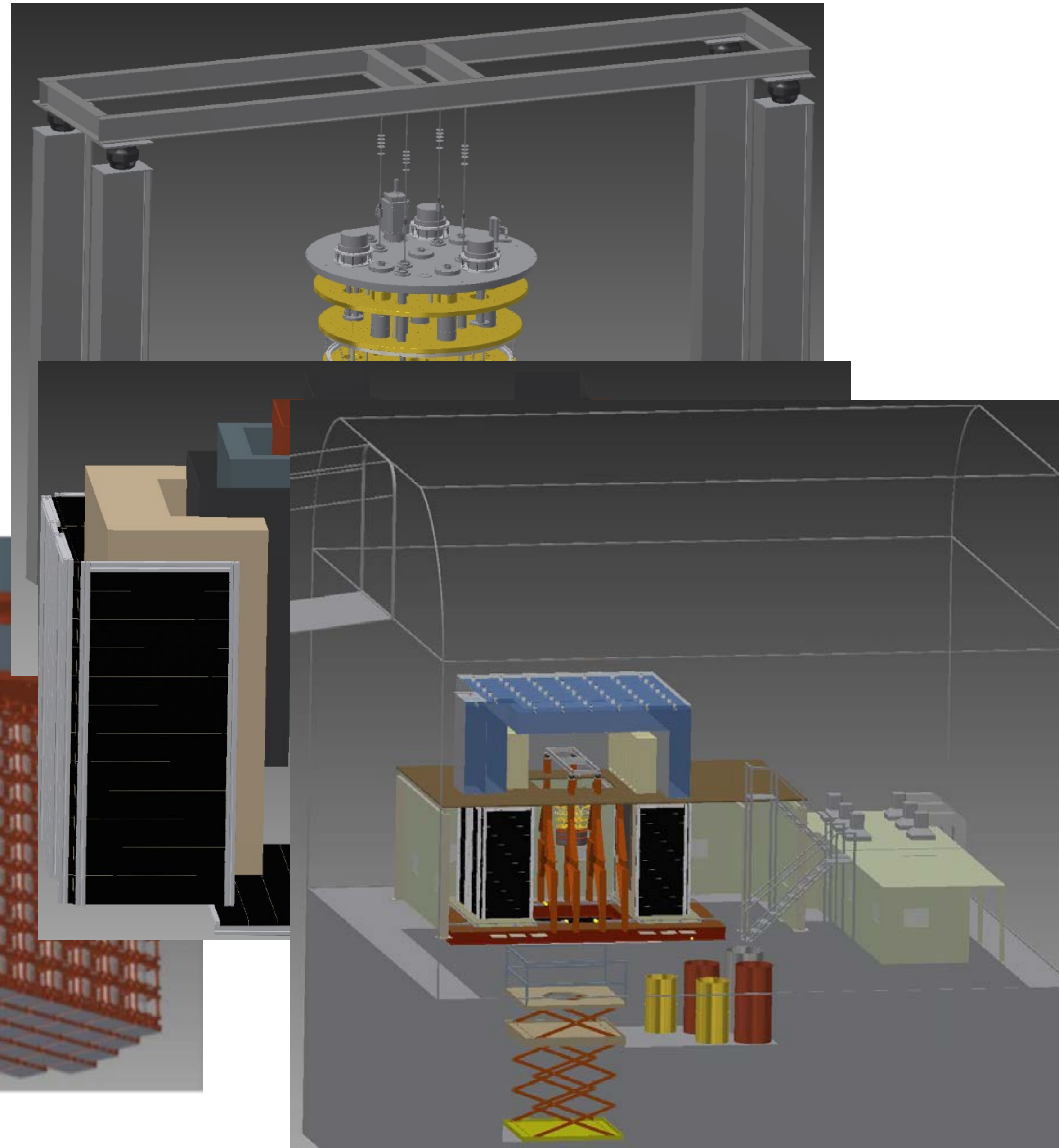




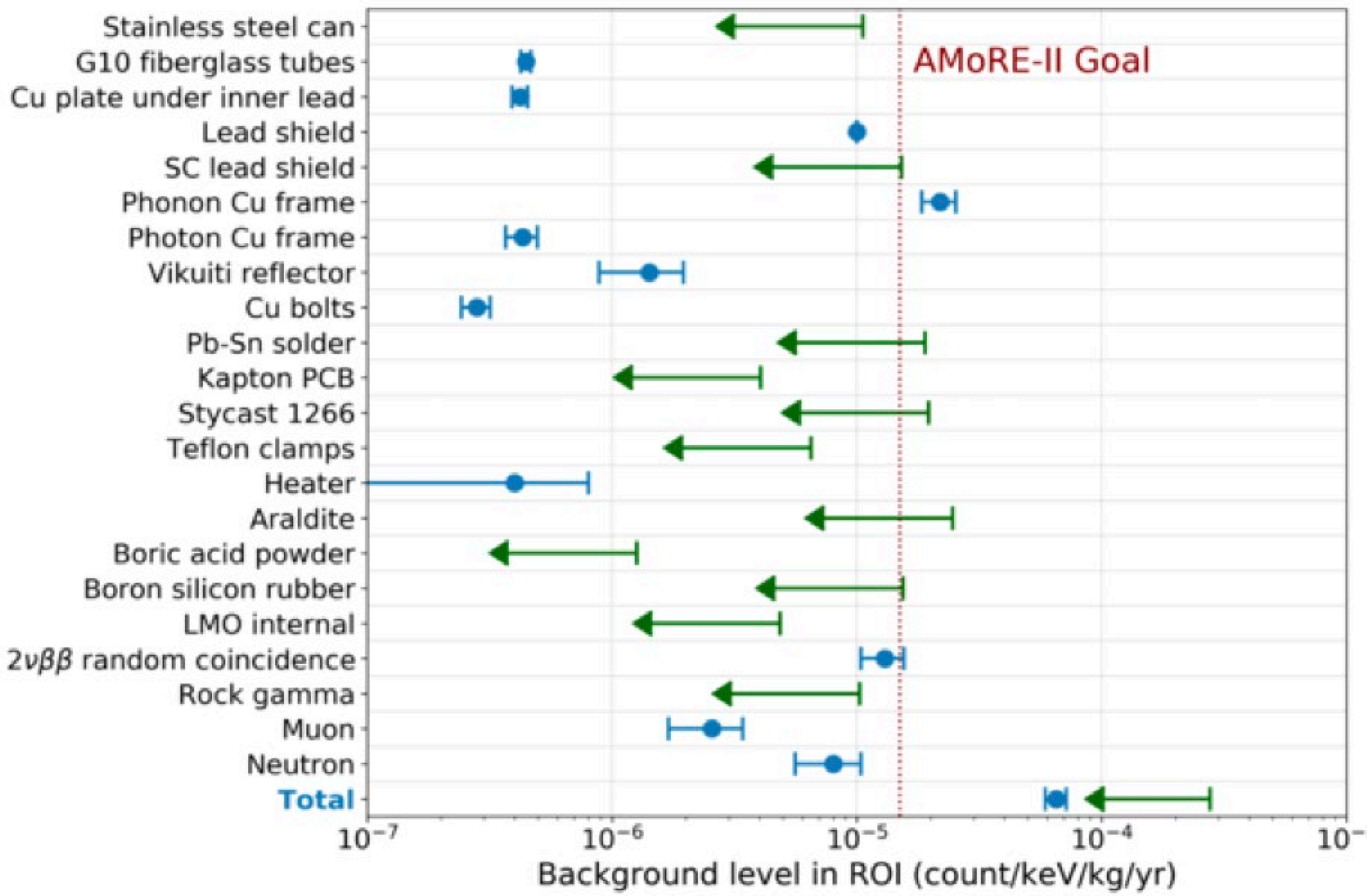




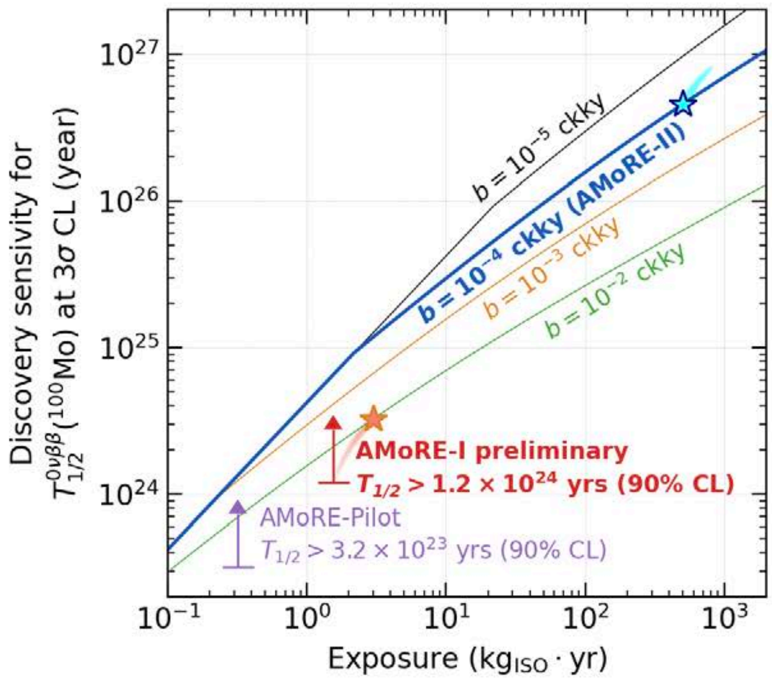


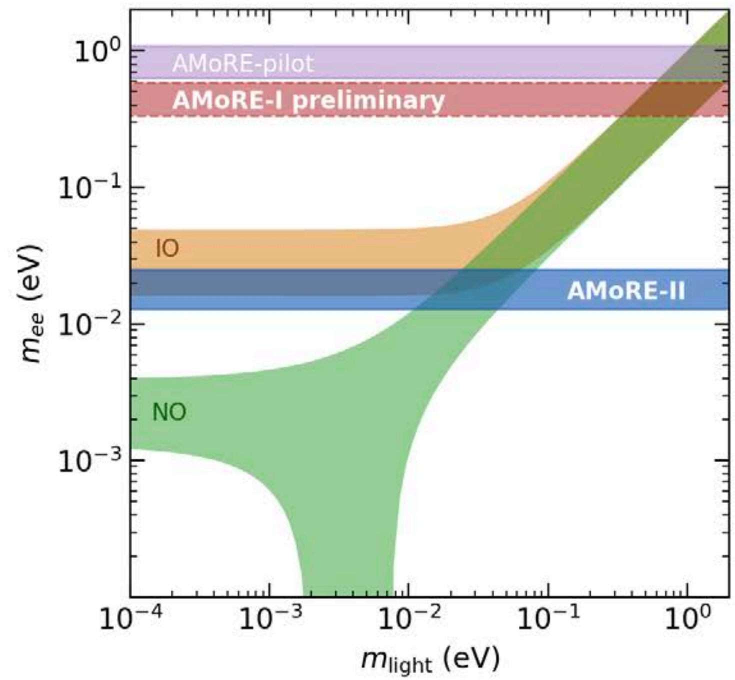


AMoRE-II Background budgets



AMoRE-II goals





- AMoRE-II for $T > \sim 5 \times 10^{26}$ years by 100 kg of ^{100}Mo × 5 years running.
- Reduction of background level down below 10^{-4} ckky.

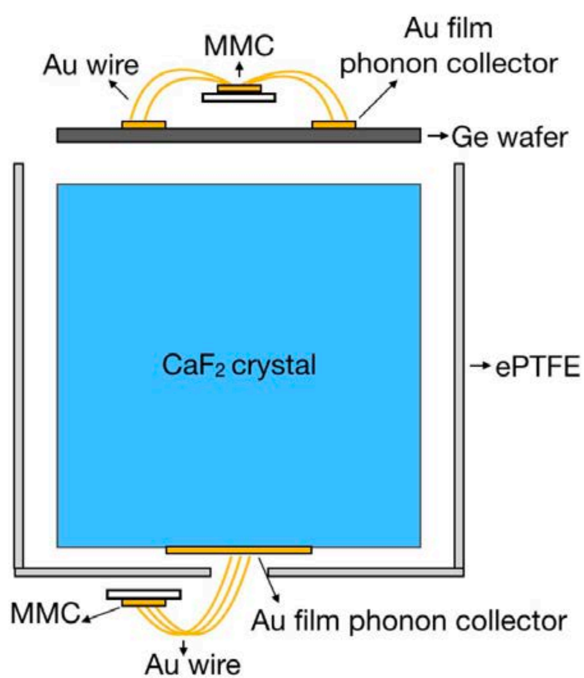
CANDLES-LT

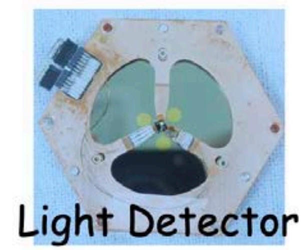
^{48}Ca

- ✓ Q = 4271 keV. The highest Q
- ✓ Natural abundance : 0.187%

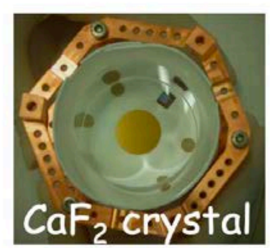
CaF_2 , CaF_2(Eu)

Low Temp. R&D : Osaka Univ. + IBS/KRISS

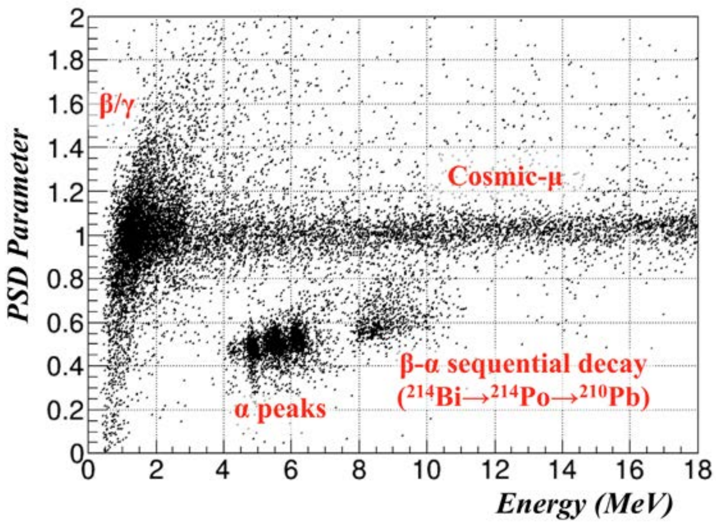




Ge wafer(2 inch) as scintillation absorber



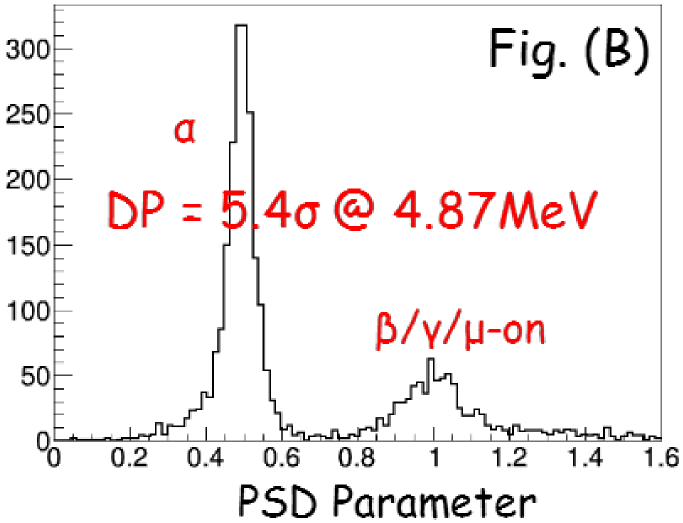
Heat & Light detection with CaF_2



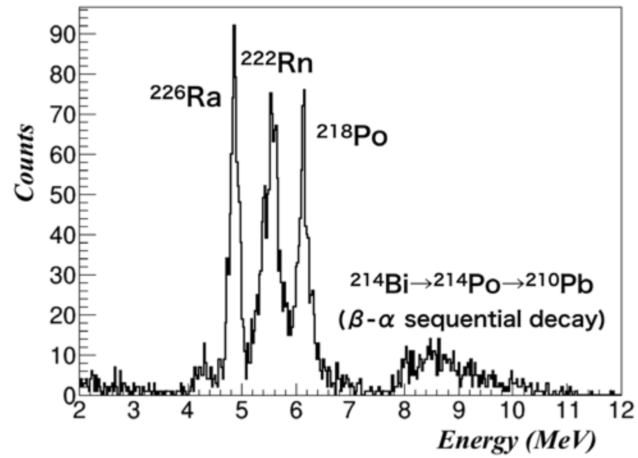
Tetuno 2020 J Phys Conf. 1468 012132

- Promissing demostration for heat-light detection with MMCs from CaF_2 crystals at 10-20 mK
- Clear particle identifcation

- Poor energy resolution due to position dependence



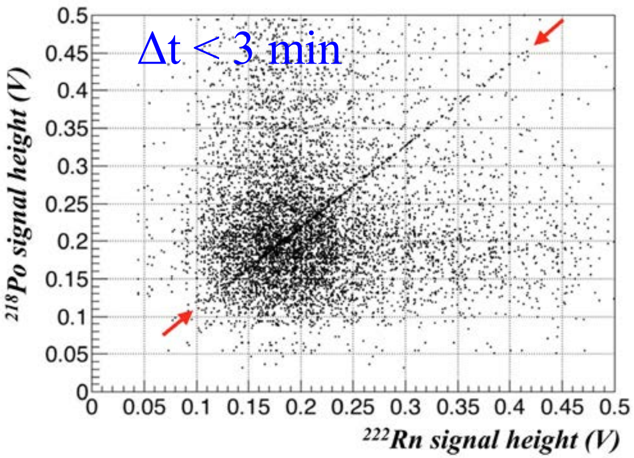
<CANDLES-LT>

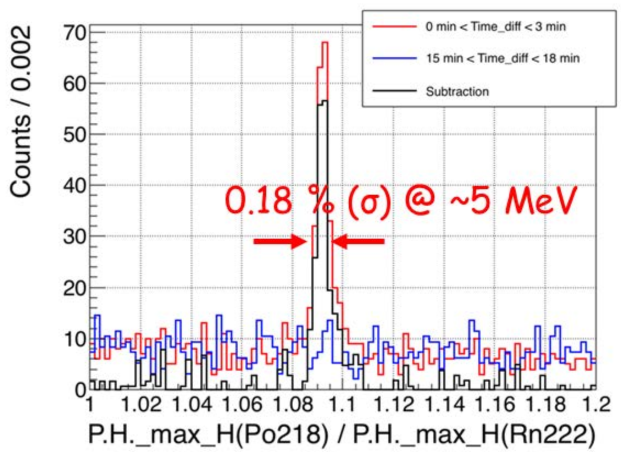


Heat & Light detection with CaF_2

30 mBq of ^{226}Ra (U-chain) within an R&D crystal

Delayed coincidence (^{222}Rn → ^{218}Po → ^{214}Pb)





<CANDLES-LT>

- High resoltuion with position dependence correction
- Further R&D should continue.

R&D challenges

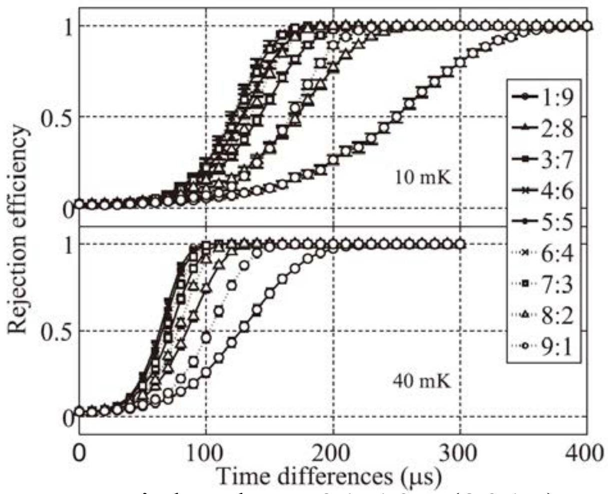
Technical tasks and challenges

- ✓ Unresolved pileups.
- ✓ Single-site event selection.
- ✓ Resolve position dependence (for fast sensors)
- ✓ Multiplexing capability

Unresolved pileups of ^{100}Mo 2νββ signals

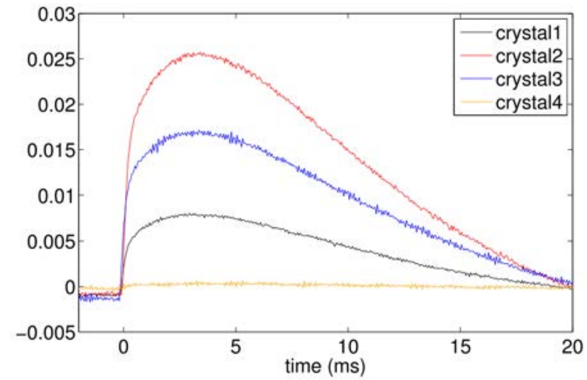
- 1 kg ^{100}Mo → ~20 mBq of 2νββ $T_{1/2}(2\nu\beta\beta\ ^{100}\mathrm{Mo}) > 7.1\times10^{18}$ year
- Timing resolution for pileup rejection:
  ~ 40 μs for 10^{-5} ckky in a Ø50×50 LMO (in most conservative way)

With heat-signal rise-time only.
120 μs at 10 mK, 60 μs at 40 mK



Astroparticle Phys. 91:105 (2017)

Light signals: τ_{fast}~200 μs
→ ~ 100 μs rejection possibility

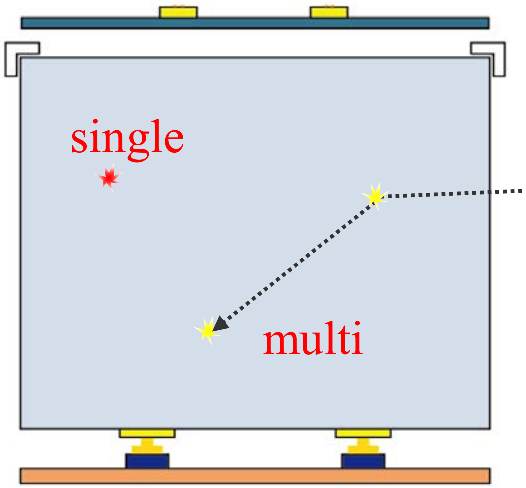


- Should improve τ of light (heat) signals
- Likelihood pileup rejections should be implemented.

Yong-Hamb Kim

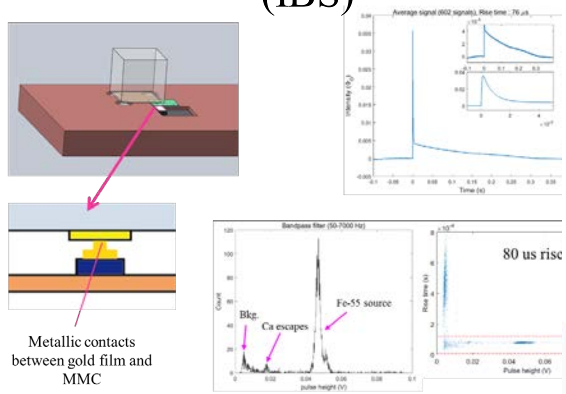
R&D proposal to multi-site event rejection

fast light signals

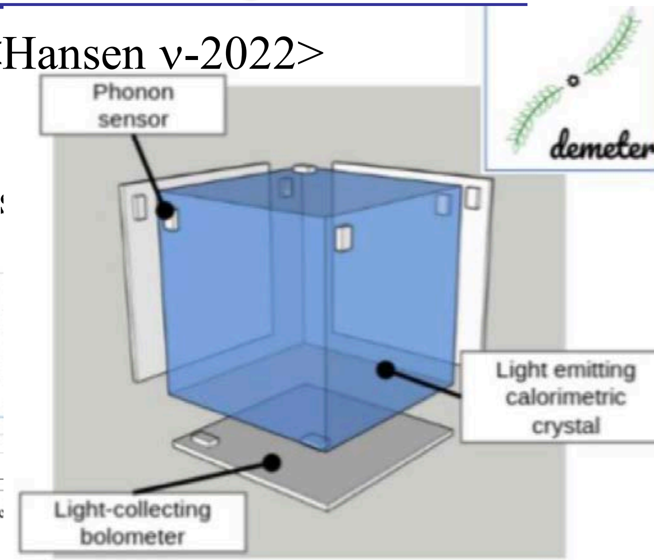


fast phonon signals

R&D result for fast heat signals
(IBS)

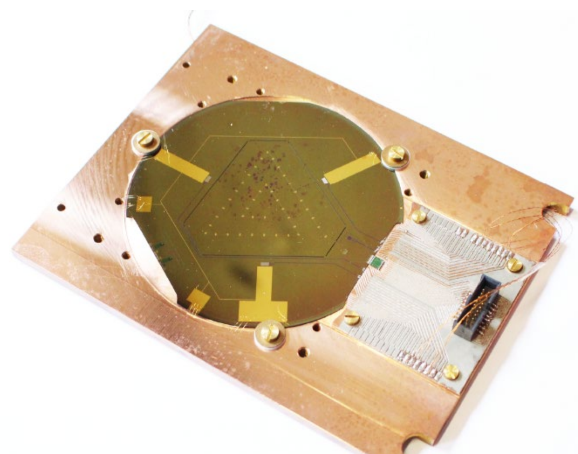


<Hansen ν-2022>



DEMETER focuses on both phonon and photon reconstruction at the crystal scale to provide physics information & background identification to large scale detectors like CUPID-1T.

- Fast heat & light signals.
- Finite phonon speed: ~10^5 cm/s
- PSD with time dependence can be studied.



R&D setup for fast phonon-photon signals: 30 us rise time (Heidelberg)

SWOT for LT Detectors in 0νββ search

Strengths
- ✓ High energy resolution
- ✓ Particle ID
- ✓ Proven technology

Weaknesses
- ✓ Surface effect
- ✓ Unresolved pileups
- ✓ Bkg from copper
- ✓ Number of channels

Opportunities
- ✓ Use of Cherenkov light
- ✓ New crystal targets
- ✓ Single-site selection
- ✓ Multiplexing
- ✓ Possible collaboration

Threats
- ✓ Isotope production
- ✓ Crystal growing
- ✓ Purification

Closing remarks

- ✓ $0\nu\beta\beta$ search projects with LT detectors are well established experiments.
- ✓ The technology provides promising performance in energy resolution, background reduction method, and scalability of the detector size.
- ✓ Those LT projects aim to investigate $0\nu\beta\beta$ process in many nuclei.

Stay tuned !