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Low-Temperature Thermal Calorimeters for 0νββ experiments

Yong-Hamb Kim (김용함 金容菡)

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

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 ($\boldsymbol{T}^{0\nu}$) 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

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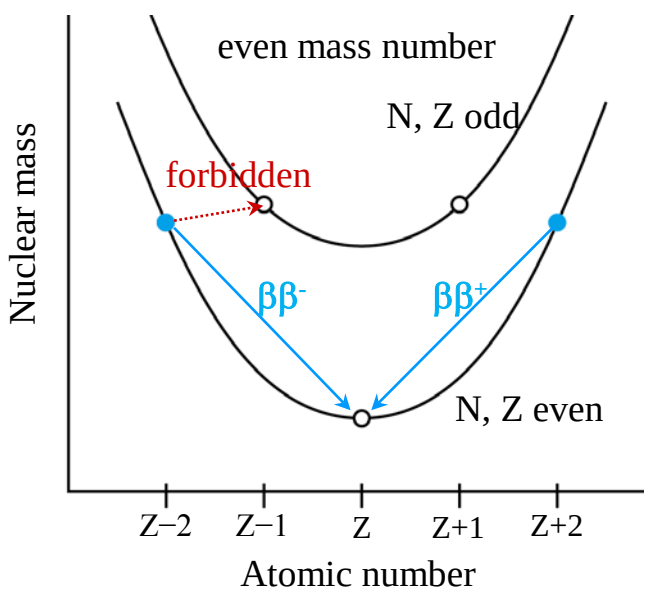
Double beta decay

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

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

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Double beta decay w. & wo. ν emission

2ν mode

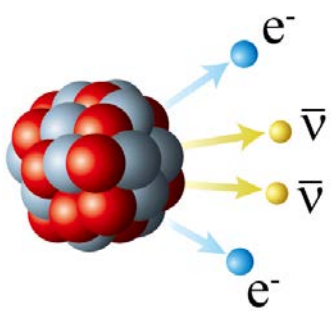
- A conventional
- 2nd order weak process in NP

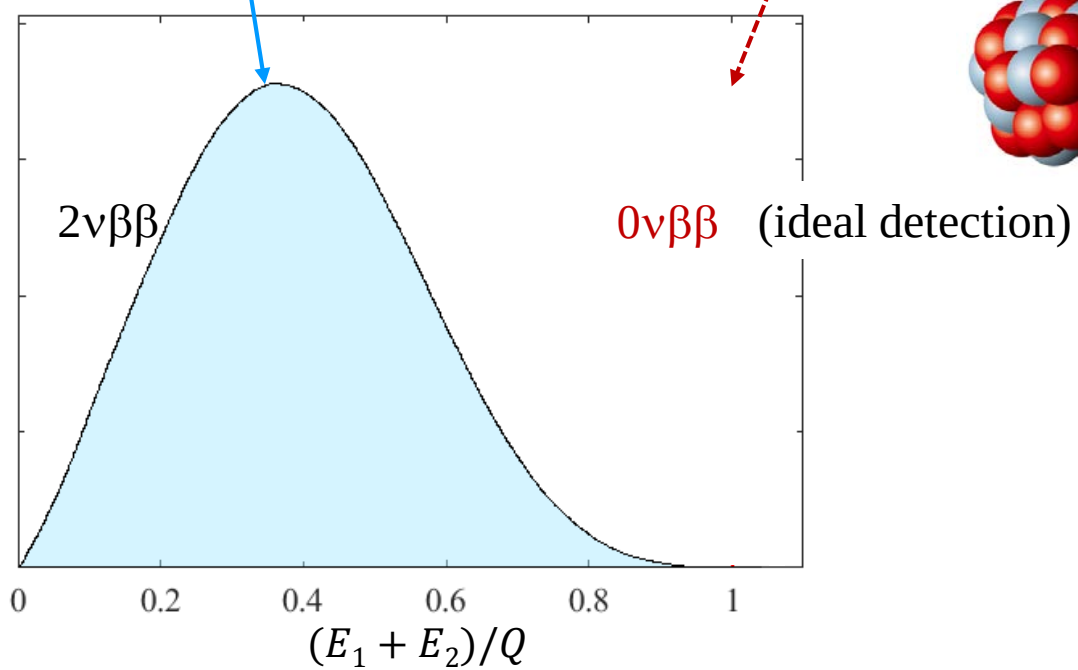
$$(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$$

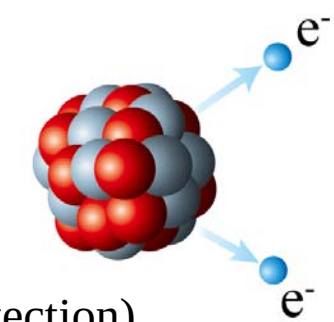
0ν mode

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

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







Some history about ββ decay

M. Goeppert-Mayer, Phys. Rev. 48 (1935) 512

- ✓ The study of nuclear structure expected that the **2 neutrino mode** would have half lives in excess of 10^{20} years

- ✓ First observed directly in 1987.
- ✓ Background: $_{1/2}$(U, Th) : 10^{10} y
- ✓ $_{1/2}(2\nu\beta\beta)$: $10^{19\sim24}$ years

E. Majorana, NuovoCimento14 (1937) 171
G. Racah, NuovoCimento14 (1937) 322

- ✓ The possibility of **neutrinos-less decay** was discussed in 1937.

W.H. Furry, Phys, Rev. 56 (1939) 1184

- ✓ Specific discussion on **ββ on Majorana theory (0νββ)**

- ✓ Now, we want to look for a process with $_{1/2}(0\nu\beta\beta)$: $\sim10^{26\sim28}$ years

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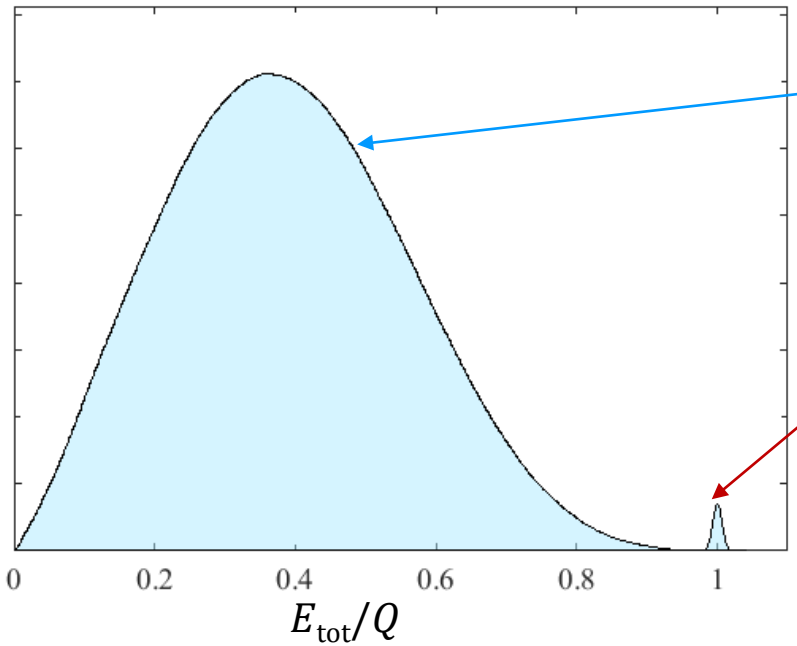
Search for 0νββ



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 ($1/{}^{0\nu}_{1/2} \propto {}^{2}_{\nu}$)
- Lepton number violation

0νββ decay rate

$$\Gamma_{0\nu} = 1 \Big/ {}^{0\nu}_{1/2} = {}_{0} \Big| {}_{0} \Big|^{2} {}^{2}_{\beta\beta}$$

<standard process>

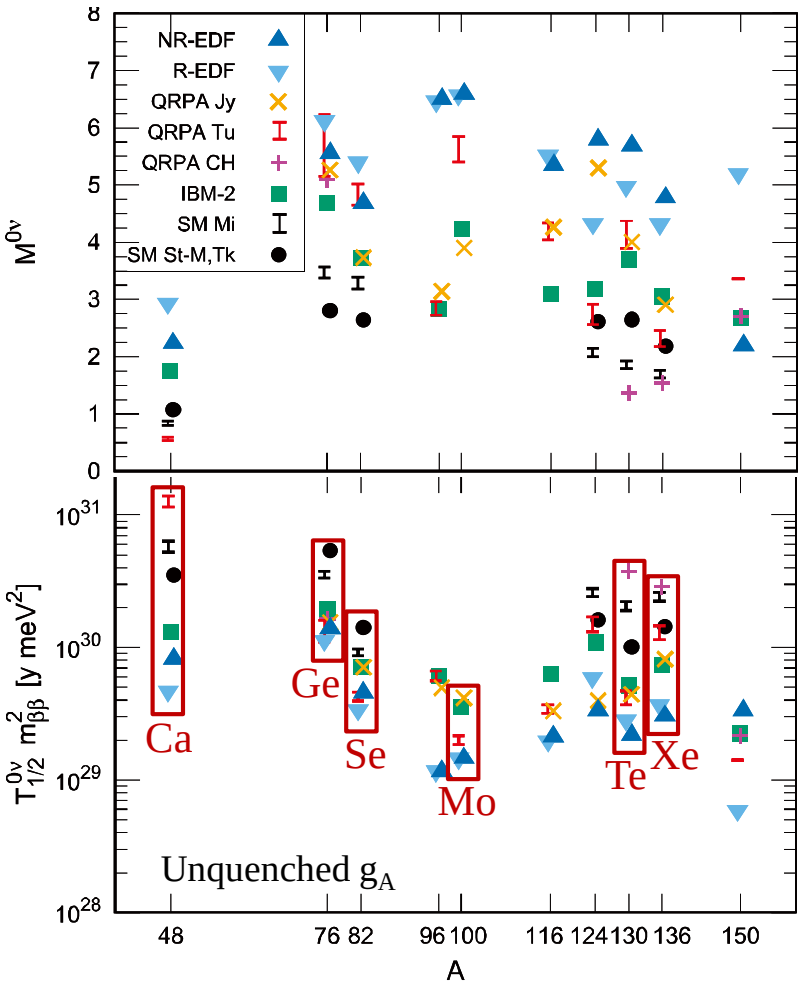
- ✓ **$G_{0\nu}$:** Phase space factor: Calculable
  Atomic physics

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

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

Model dependent NME ($M_{0\nu}$)

Engel & Menédez
Rep. Prog. Phys. **80** (2017) 046301



$$1/T^{0\nu}_{1/2} = G_{0\nu}\left|M_{0\nu}\right|^2 m^2_{\beta\beta}$$

- ✓ Model dependence: 2-3 times spread for each nucleus.

$$1/T^{0\nu}_{1/2} = G_{0\nu}\left|M_{0\nu}\right|^2 m^2_{\beta\beta}$$

- ✓ No significant isotope preference when consider detector mass.

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Another uncertainty in the standard process

g_A: Effective axial-vector coupling constant incorporated in NME

$$1/T_{1/2}^{0\nu} = G_{0\nu}\left|M_{0\nu}\right|^2 m_{\beta\beta}^2 \quad \rightarrow \quad {}^{4}_{A}G_{0\nu}\left|M_{0\nu}\right|^2 m_{\beta\beta}^2$$

Simple-minded

- ✓ $_A$ = 1.27 (no quenching for free nucleon)
  = 1 (quark)
- ✓ $_A$ is quenched in β, 2νββ, and possibly 0νββ.
  $^{eff}_A$ for 0νββ: 0.4~0.6

Effective value of g^{eff}_A on 0νββ

- ✓ Theory predictions: $^{eff}_A$ = 0.6 ~ 0.8, <Suhonen PRC 96 (2018) 05550>
  - ➔ Even with small $^{eff}_A$ values, 0νββ decay rates are reduced only by 2-6 times.
- ✓ Some theortical predictions exist quenching matters with the energy scale
  - ➔ No or less quenching might be needed on 0νββ. <Dolinski et al arXiv:1906.02723>

- ✓ Further theoretical and experiemantal studies are needed.

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Neutrino mixing, mass, and 0νββ

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_{m1} \\ \nu_{m2} \\ \nu_{m3} \end{pmatrix}$$

weak interaction eigenstate

mass eigenstate

$$|\nu_i(t)\rangle = e^{-i(E_i t - \vec{p}_i \cdot \vec{x})} \mid \nu_i(0)\rangle$$

Evolve in time with $_i$ &

↓

ν oscillation

Effective ββ mass

$$\langle \quad _{\beta\beta} \rangle = \sum^{3} \quad ^{2}$$

virtual ν exchange

Other measurables in ν mass

m of ν_e from β end-point

$$_{\beta} = \sqrt{\sum^{3} | \quad |^{2} \quad ^{2}}$$

Observational cosmology

$$\sum \quad = \sum$$

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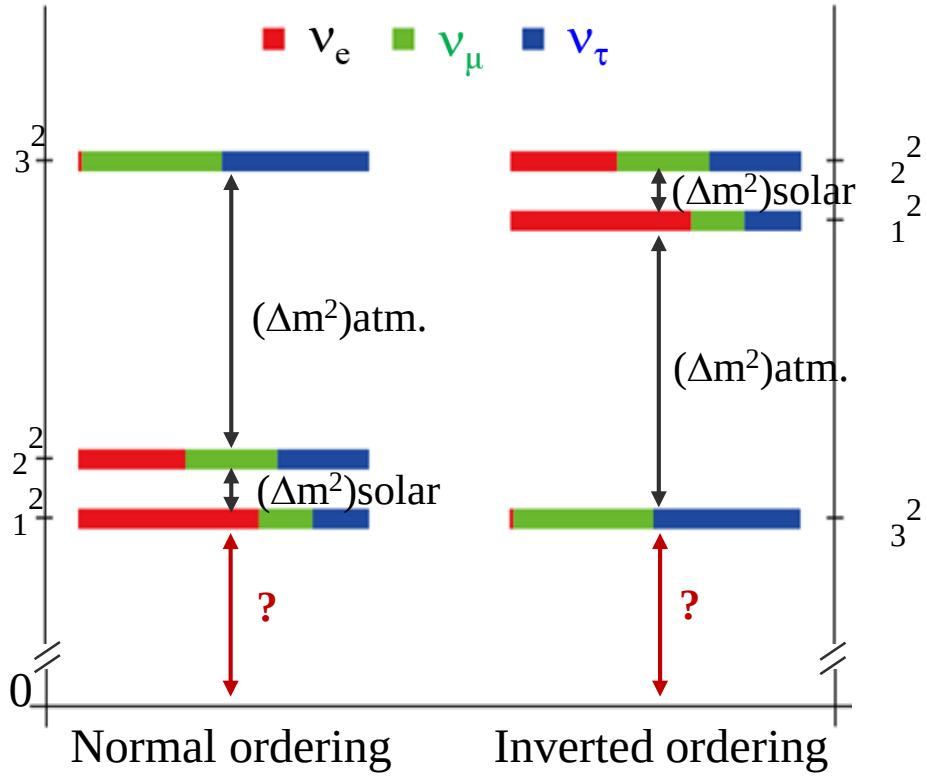
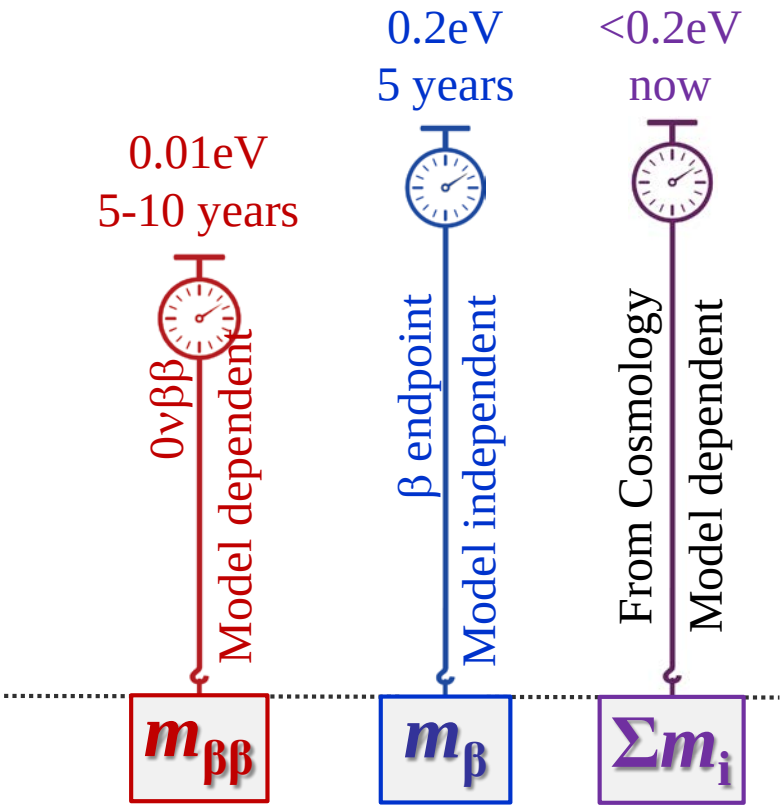
Present knowledge of ν mass pattern & scale

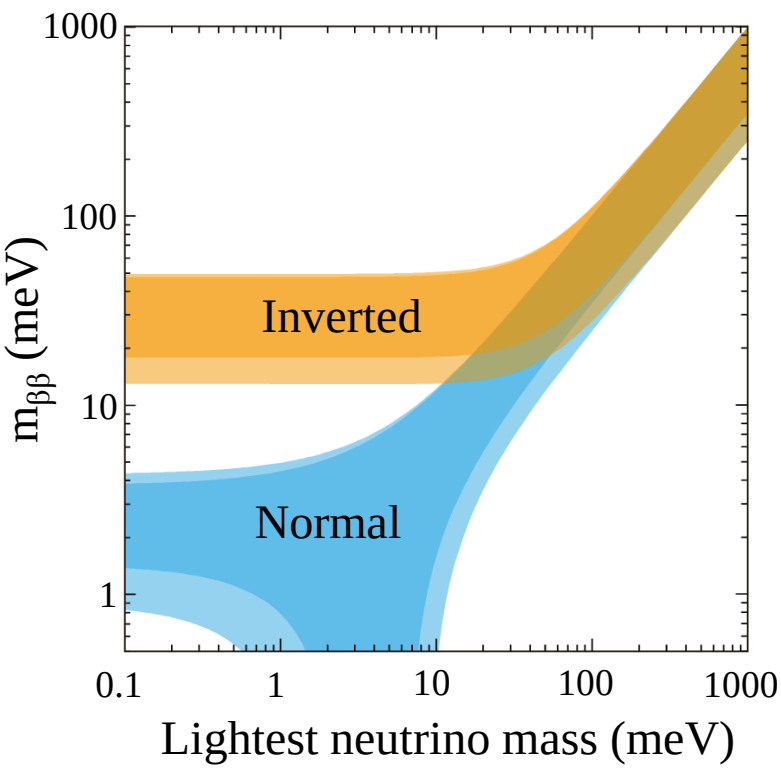




$m_{\beta\beta}$ allowed region: "usual" plot

$$_{\beta\beta} = \left| \sum \quad ^{2} \right|$$

Parameters with known, limit and unknown values



$$1/ \quad ^{0\nu}_{1/2} \propto \quad ^{2}_{\beta\beta}$$

The smaller $m_{\beta\beta}$ is the more difficult to discover $0\nu\beta\beta$.

- ✓ The mass ordering matters.
- ✓ The lightest $_{i}$ also matters.

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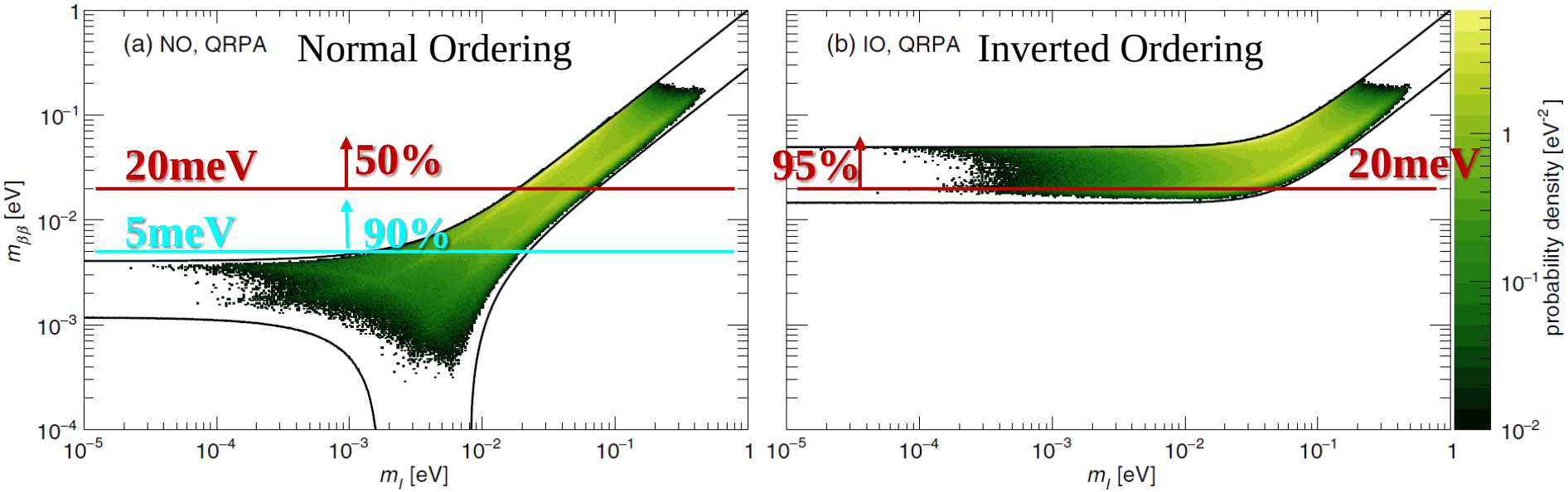
$m_{\beta\beta}$ expected region: "probable" plot

Discovery Probability Distribution <Agostini et al PRD 96 (2017) 053001>

- ✓ Global Bayesan analysis including ν osc., m_β, $m_{\beta\beta}$, and Σm_i
- ✓ Flat prior for the Majorana phases
- ✓ see also Caldwell, et al, PRD 96 (2017) 073001.



- ✓ **20 meV sensitivity ➔ 50% (NO) or 95%(IO) discovery probability**

  ➔ Clarification of mass ordering.

- ✓ **5 meV sensitivity ➔ 90% for NO**

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Physics uncertainties after 0νββ discovery

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

$$\Gamma_{0\nu} = \quad {}_0 \left| \quad {}_0 \cdot \eta \right|^2$$

η : physics processes leading to Lepton number violation.

Standard interpretation : Only light Majorana ν's lead to 0νββ

$$\Gamma_{0\nu} = \quad {}_0 \left| \quad {}_0 \right|^2 \quad {}^2_{\beta\beta}$$

- ✓ **Experimental 0νββ discovery demonstrates massive Majorana particles and Lepton number violation.**
- Other mechanisms exist leading 0νββ in the same order as light ν exchange mechanism,
  - Heavy ν exchange,
  - Mechanisms with RHC,
  - Majorons, etc.
- Model dependent $_A$ and $_{0\nu}$ (NME) complication

➔ 0νββ discovery from one nucleolus is not enough for full understanding.

- ✓ **Full understanding requires 0νββ results in serval isotopes.**
- ✓ **0νββ is not just a neutrino mass experiment.**

Detection Sensitivities

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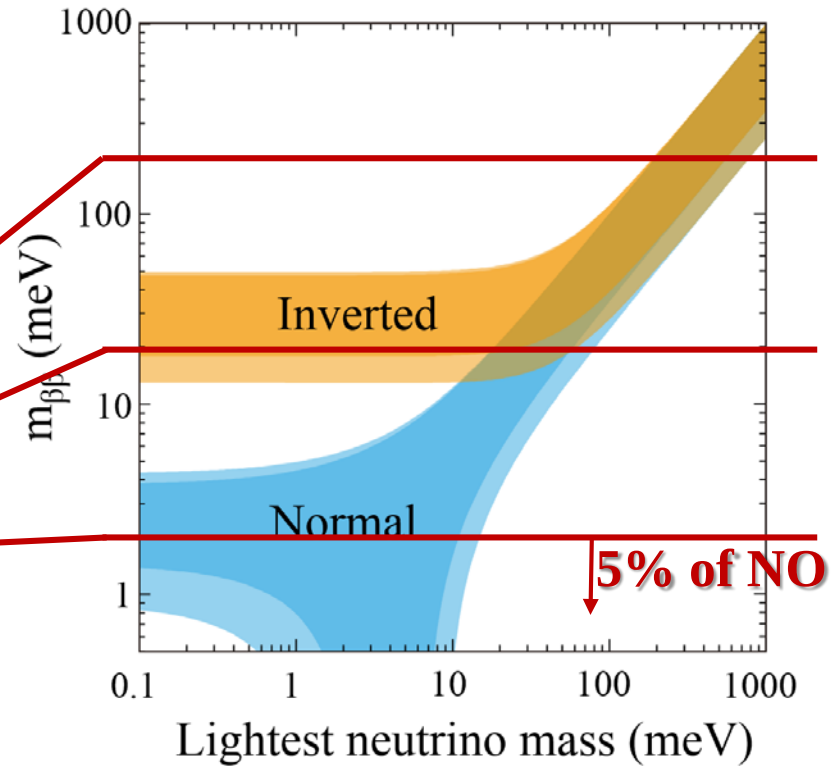
0νββ decay rates: Simple-mined

NME dependent

Half life (years)	Decays in 10 mol (1 kg ^{100}Mo) (counts/year)	ν mass scale $m_{\beta\beta}$ (meV)
5×10^{24}	1	~200
5×10^{26}	0.01	~20
5×10^{28}	0.0001	~2



Surely rare.

Matters with Bkg., ΔE, Exposure.

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Experimental Sensitivity of $T_{1/2}$ (0νββ)

For sizeable background case:

$$T_{1/2}^{0\nu}(\exp) = (\ln 2) \quad \frac{\quad}{} \varepsilon \sqrt{\frac{\quad \cdot \text{time}}{\text{bkg} \cdot \Delta}}$$

Isotopic Abundance

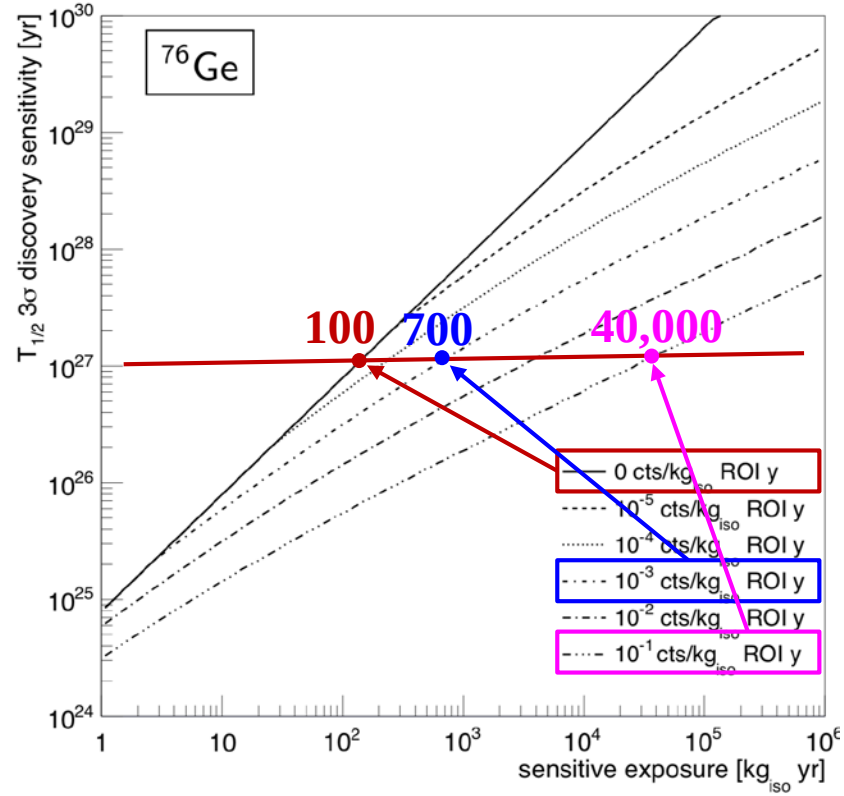
Detection Efficiency

Detector Mass

Atomic mass

Background level (count/keV kg year)

Energy Resolution



For "zero background" case:

(Expected background events in ROI < 1 for given time)

$$T_{1/2}^{0\nu}(\exp) = (\ln 2) \quad \frac{\quad}{} \varepsilon \frac{\quad \cdot \text{time}}{\quad}$$

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Common strategies to increase sensitivity

$$T_{1/2}^{0\nu} \propto \sqrt{\frac{\cdot\,\text{time}}{\text{bkg}\cdot\Delta}}$$

<background case>

$$T_{1/2}^{0\nu} \propto \cdot\,\text{time}$$

<background-free case>

- ✓ Increase : 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

Experimental approaches for $0\nu\beta\beta$

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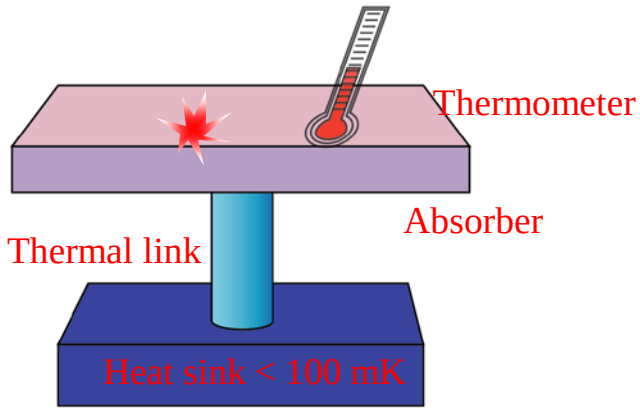
0νββ Experiments

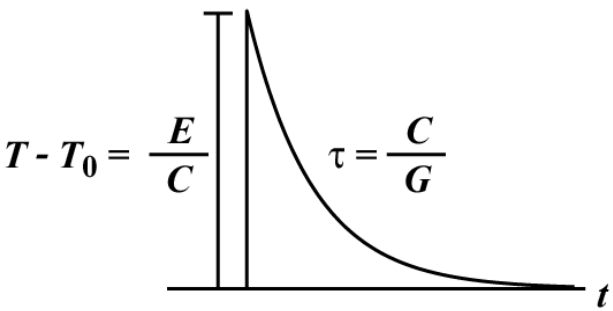
Methods	Isotopes
Loaded Liquid Scintillators	^{130}Te: SNO+ ^{136}Xe: KamLAND-Zen
Ge semiconductors	^{76}Ge: GERDA Majorana Demonstrator LEGEND
TPCs (liquid, gas)	^{136}Xe: EXO200, nEXO NEXT PandaX-III
Low-temperature thermal calorimeters	^{48}Ca: CANDLES ^{82}Se: CUPID-0 ^{100}Mo: AMoRE, CUPID-Mo ^{130}Te: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

Low Temperature Detectors

"Calorimetric measurement of heat signals at mK temperatures"

Energy absorption ➔ Temperature



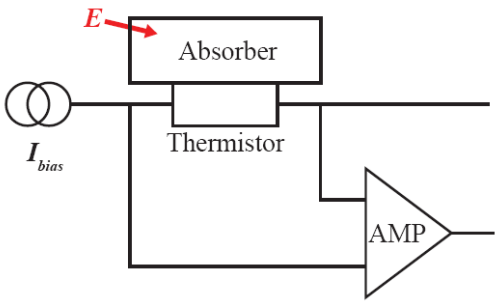


Choice of thermometers for 0νββ searches

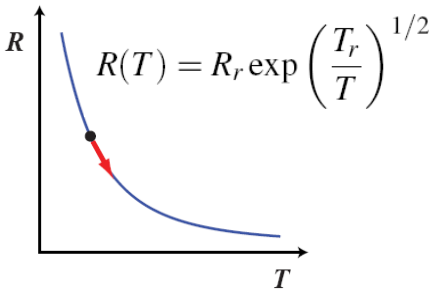
- **Thermistors (NTD Ge)** CUORE, CUPID
- TES (Transition Edge Sensor) Light detector
- **MMC (Metallic Magnetic Calorimeter)** AMoRE
- KID (Kinetic Inductance Device) CALDER
- etc.

Thermistors

- Doped semiconductors
  - Neutron transmuted doped (NTD) Ge thermistors
  - Ion implantation doped Si thermistors
- : 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 >



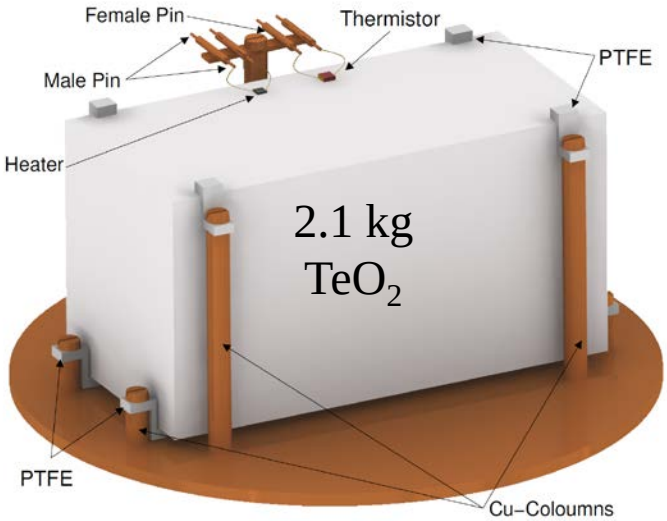


fig. from Cardani et al arXiv.1106.0568

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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
- More wires & materials needed for SQUIDs and MMCs,

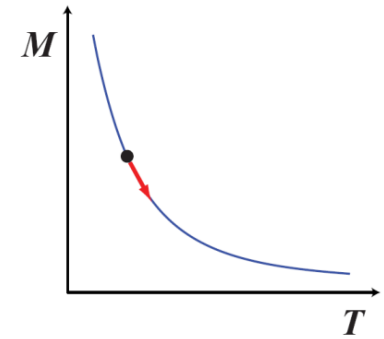
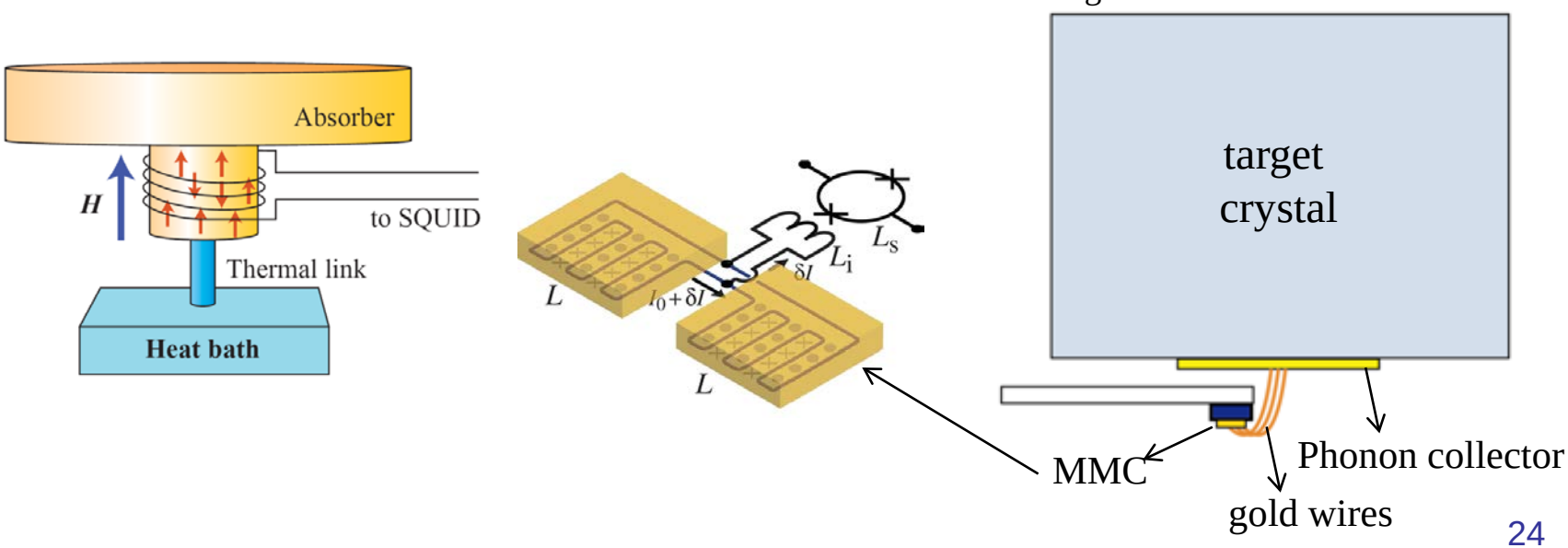


fig. from SY Oh et al SuST 2017



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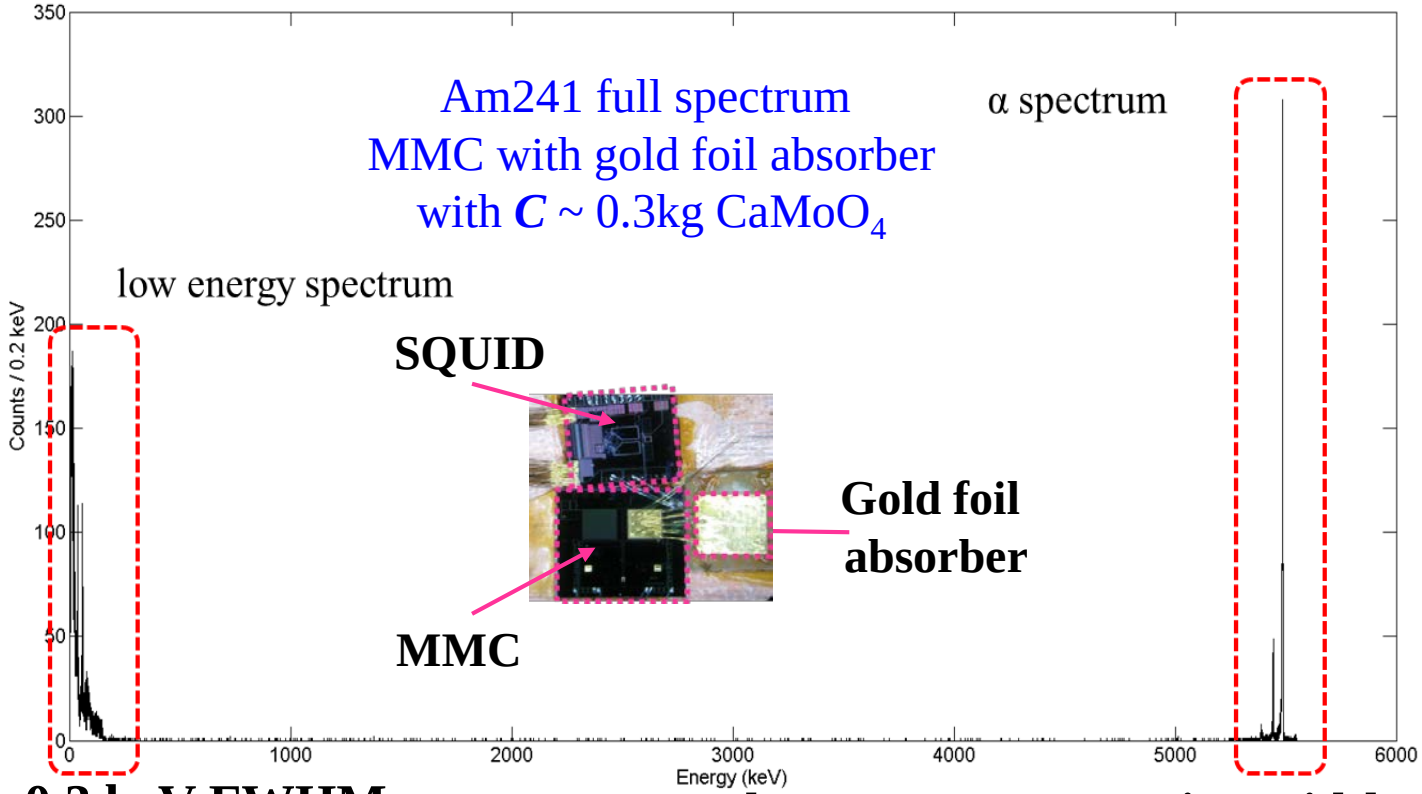
Sensor performance

"Superior dynamic range with high resolution"

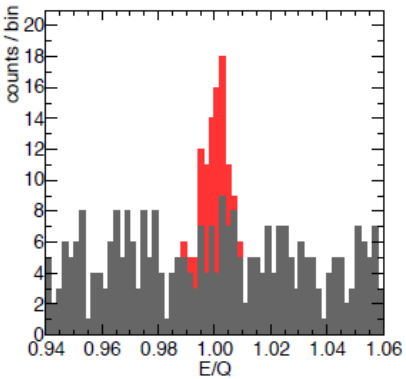


0.3 keV FWHM for 60keV γ

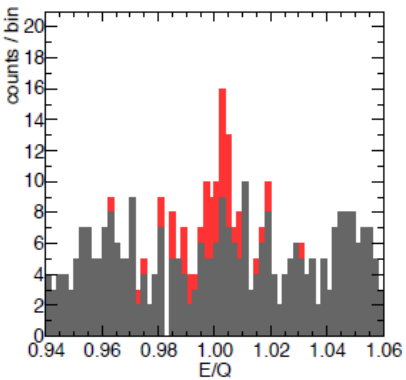
0.9 keV FWHM Gaussian width for 5.5MeV α

✓ **A test result with an MMC.**

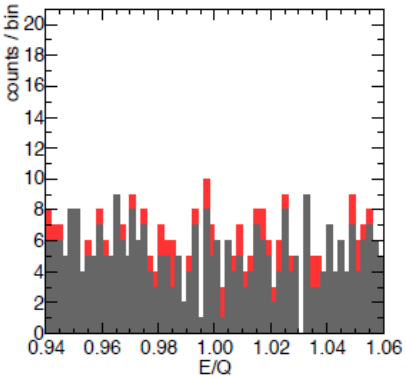
Resolution matters.



1 % FWHM



3 % FWHM



10 % FWHM

fig. from JJ Gomez-Cadenas
XLV meeting 2017

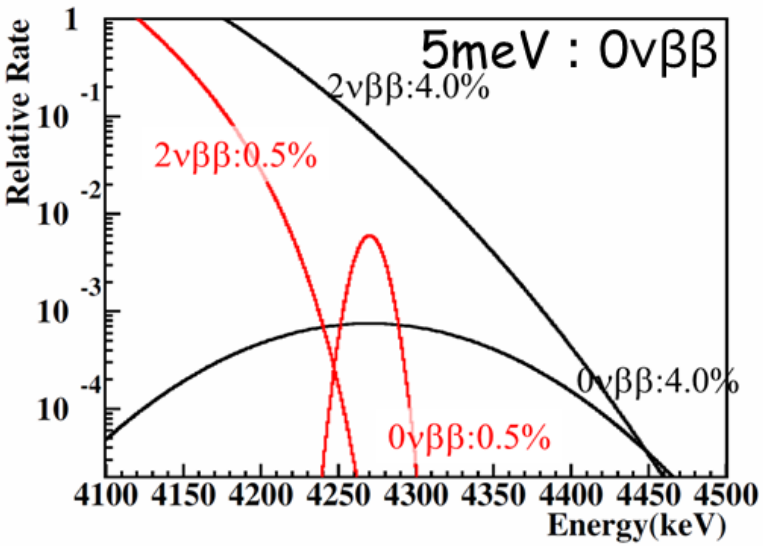


fig. from S. Yosihda Osaka Univ.

In the case of an ideal shielding with no source of background, ββ(2ν) can overwhelm ββ(0ν) with poor ΔE

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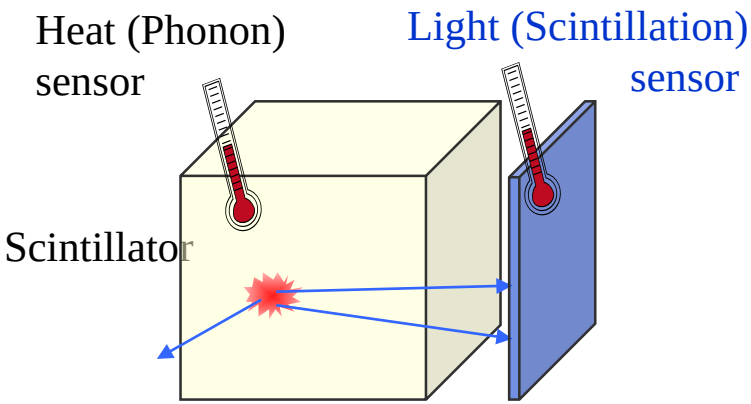
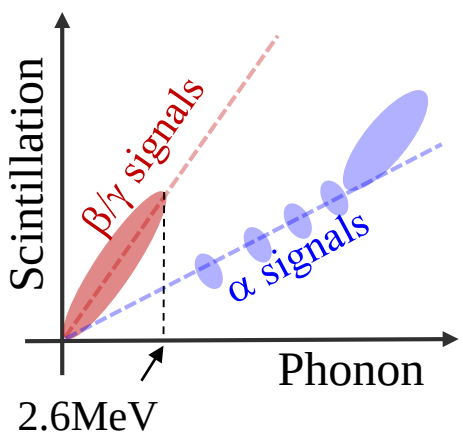
Simultaneous phonon-scintillation detection

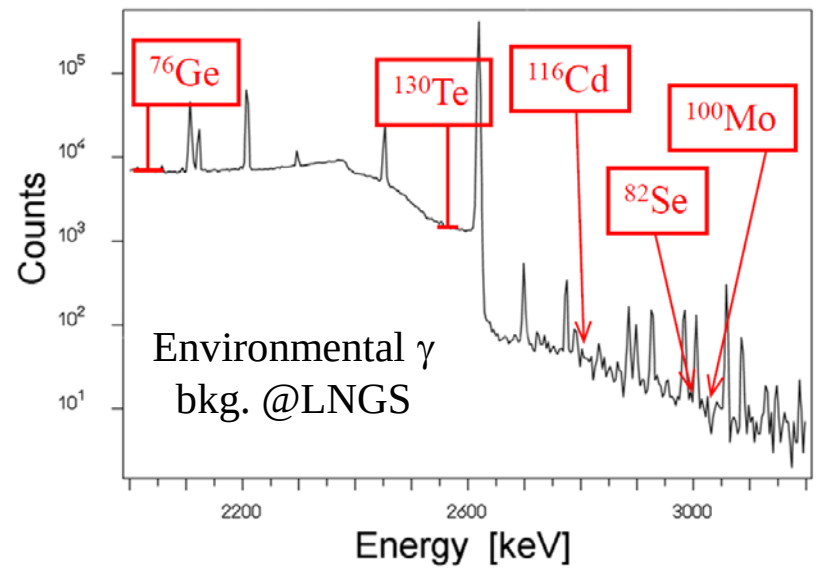
✓ Scintillating crystal as target material
➔ Active bkg. Rejection



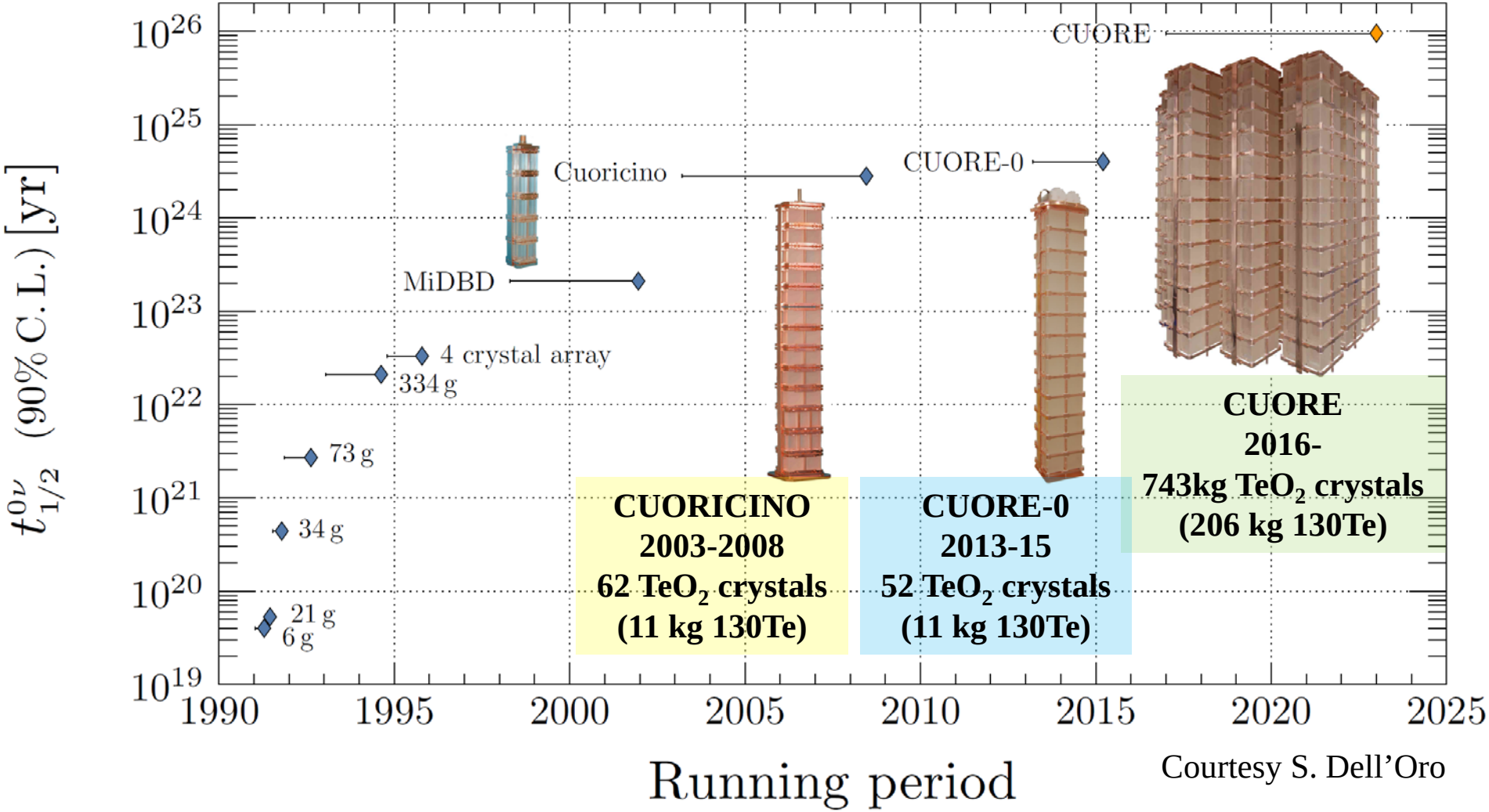
Li_2MoO_4 $CaMoO_4$
$CdWO_4$ ZnSe, CaF_2etc.



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

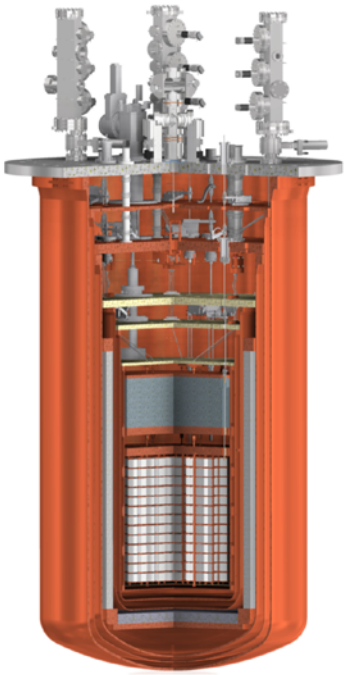


CUORE history



Courtesy S. Dell'Oro

CUORE



- **C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents
- Main objective: $0\nu\beta\beta$ in ^{130}Te
- 988 TeO_2 crystals, 5x5x5 cm^3 each
- Total mass: 742 kg TeO_2 (natural Te)
- ^{130}Te mass: 206 kg
- Crystals operated as bolometers in a cryostat capable of reaching T < 10mK

Present limit:

^{130}Te $T^{0\nu} > 3.2 \times 10^{25}$ yr w. 90% CI

$m_{\beta\beta} < 75\text{-}350$ meV

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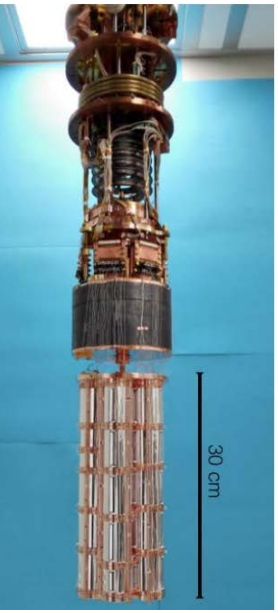
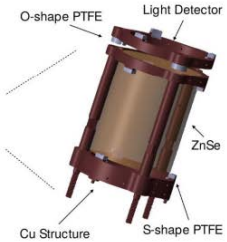
CUPID-0

CUPID: CUORE Upgrade with Particle IDentification

CUPID-0: the first demonstrator



- 26 ZnSe (24 95% enriched + 2 natural)
- ^{82}Se 0νββ decay Q-Value: 2998 keV
- 31 Ge slabs (Light Detector)
- Arranged in 5 towers -> (3.8x10^{25} ^{82}Se nuclei)

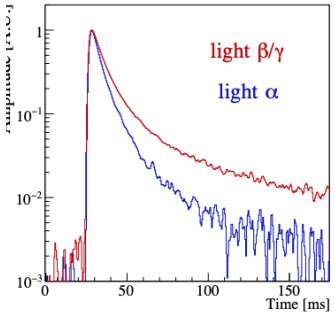


- Assembled in an underground radon free clean-room @ LNGS
- Hosted in the same CUORE-0 dilution refrigerator (Hall A)

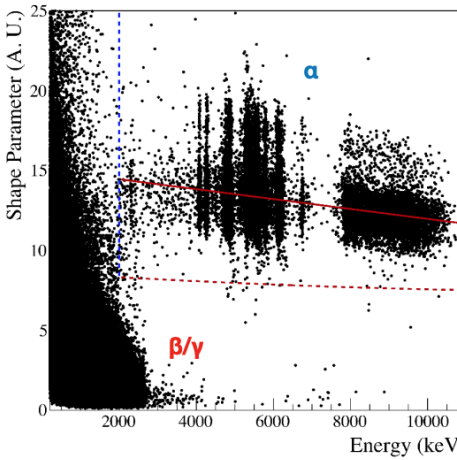
6

$$T^{2\nu}_{1/2} = [8.60 \pm 0.03(\text{stat.})\ ^{+0.17}_{-0.10}(\text{syst.})] \times 10^{19}\ \text{yr}$$

α rejection with light shape



e light signal shape depends on particle type



CUPID-0 upgrade: 2019

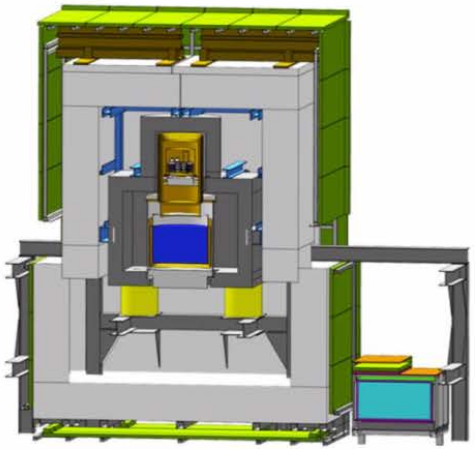
January 2019: stop data taking for a major detector upgrade:

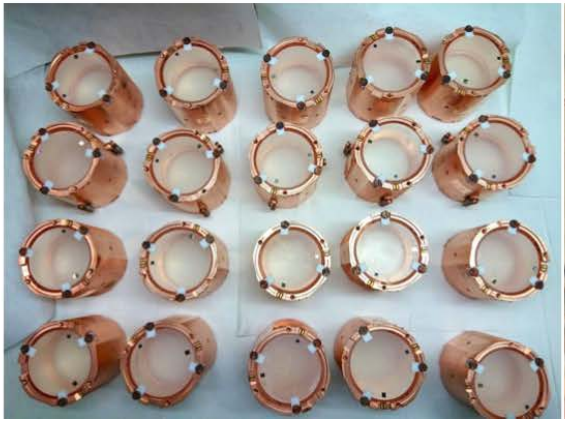
- Remove the reflective foils
- Install a new clean copper shield
- Install a muon veto

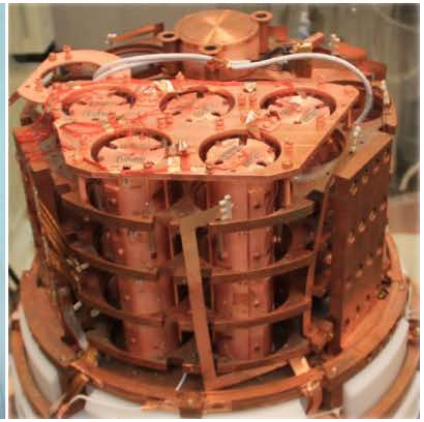
CUPID-Mo

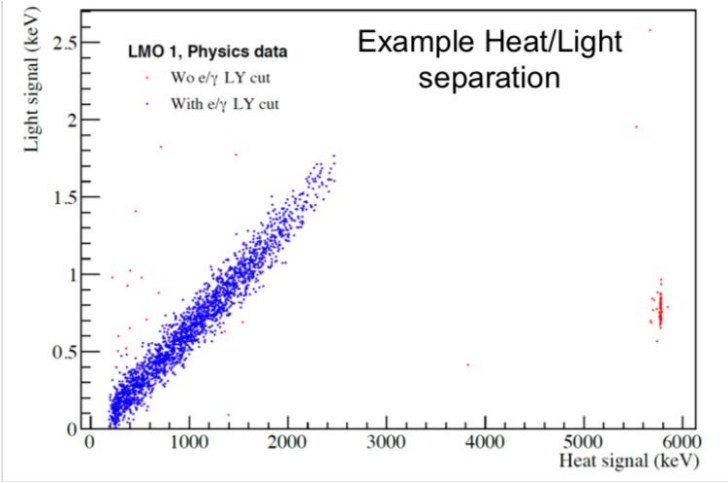
First data from the CUPID-Mo neutrinoless double beta decay experiment

Benjamin Schmidt for the CUPID-Mo Collaboration









Now: accumulated > 1 kg*yr of physics data

$T_{1/2} > 3*10^{23}$ yr at 90% C.L with
~0.5 kg*yr exposure (~0.27 kg*yr of ^{100}Mo), 81% signal acceptance

Yong-Hamb Kim

The AMoRE Project

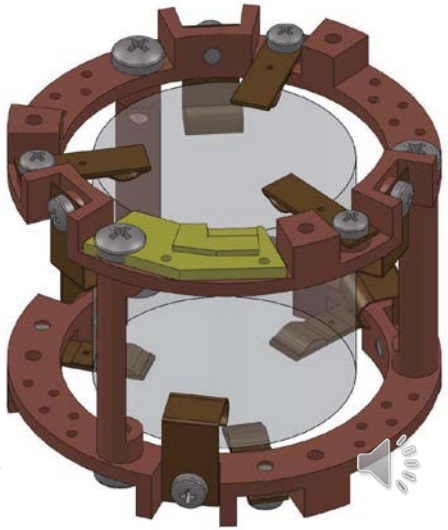
AMORE: ‘Love’ in Italian

AMORE “A cosmetic company in Korea”
Their factory is located in Daejoen.

AMoRE: **Advanced Mo-based Rare process Experiment**

to search for neutrinoless double decay of ^{100}Mo using **cryogenic $X^{100}MoO_4$ detectors**

That’s AMoRE for us!

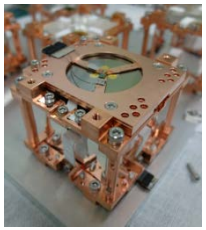


Ø4cmx4cm
$CaMoO_4$ crystal

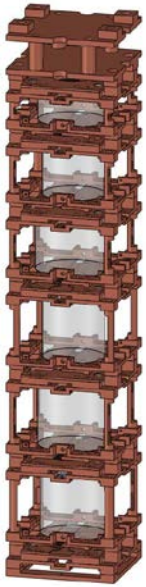
AMoRE collaboration (since 2009)

Yong-Hamb Kim

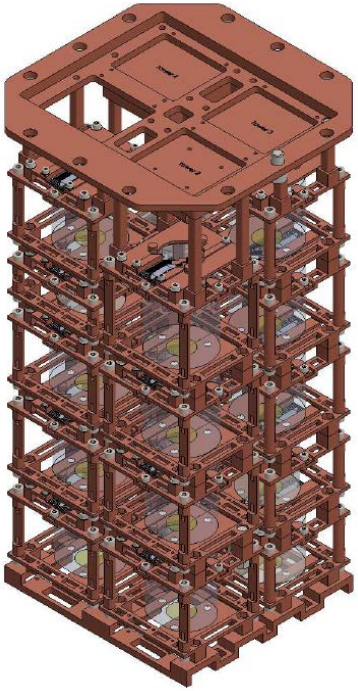
AMoRE Progress



Single module

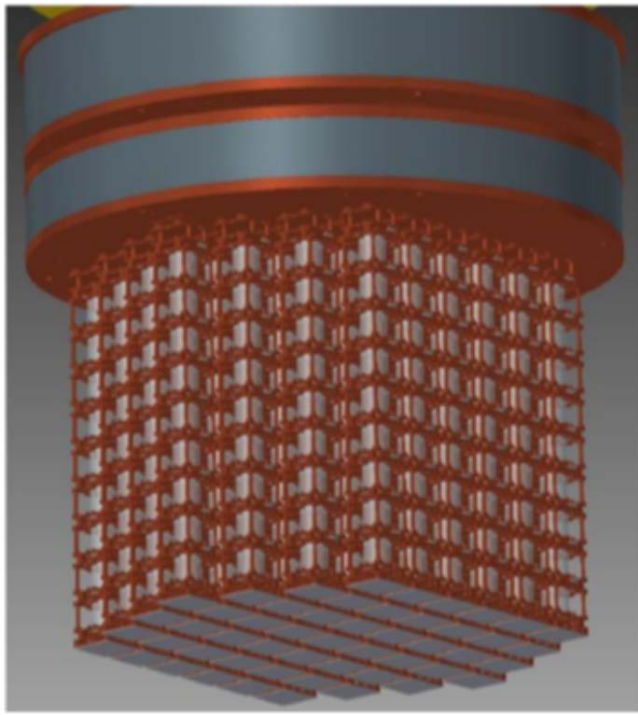


AMoRE-Pilot
- 2018



AMoRE-I

Now



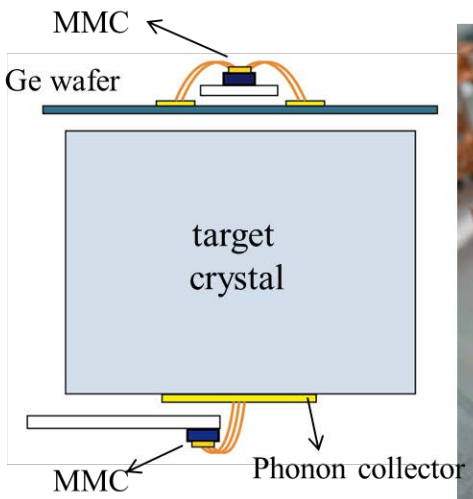
AMoRE-II
Being prepared

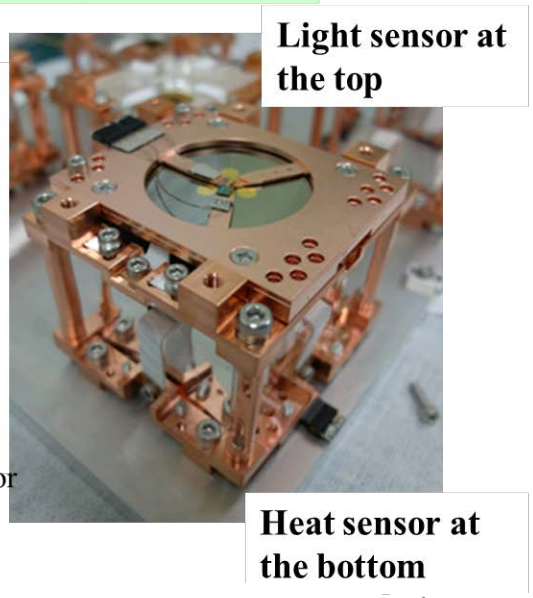
Yong-Hamb Kim

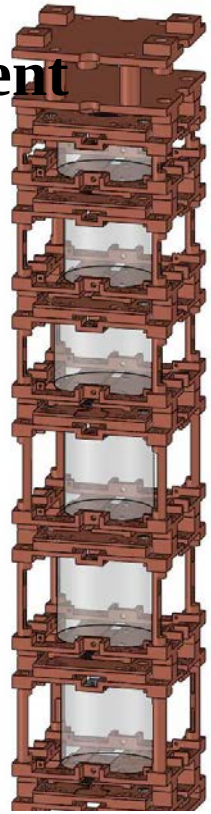
AMoRE

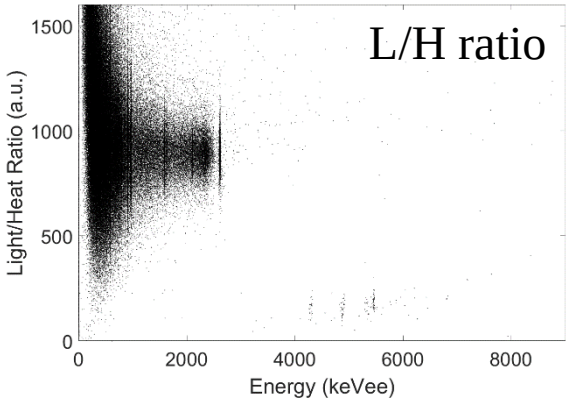
AMoRE: **Advanced Mo-based Rare process Experiment**

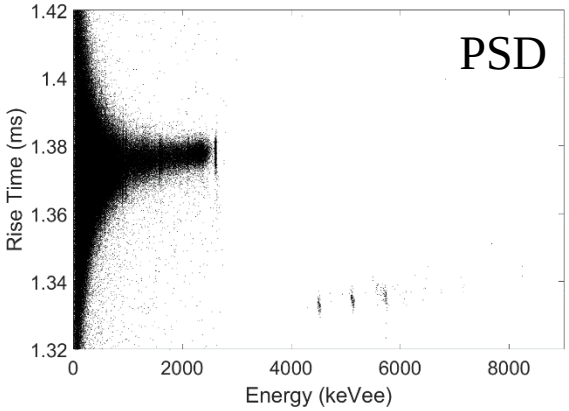
$^{40}Ca^{100}MoO_4$ + MMC

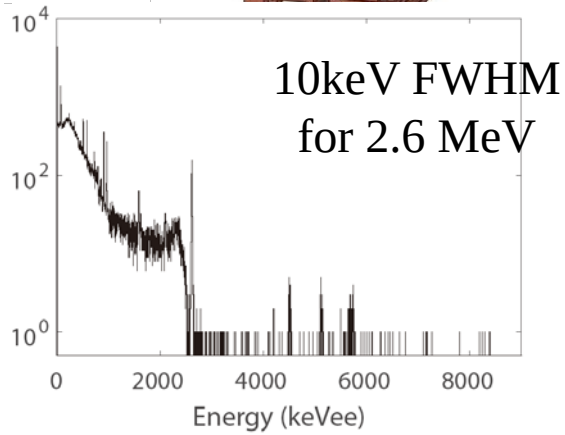




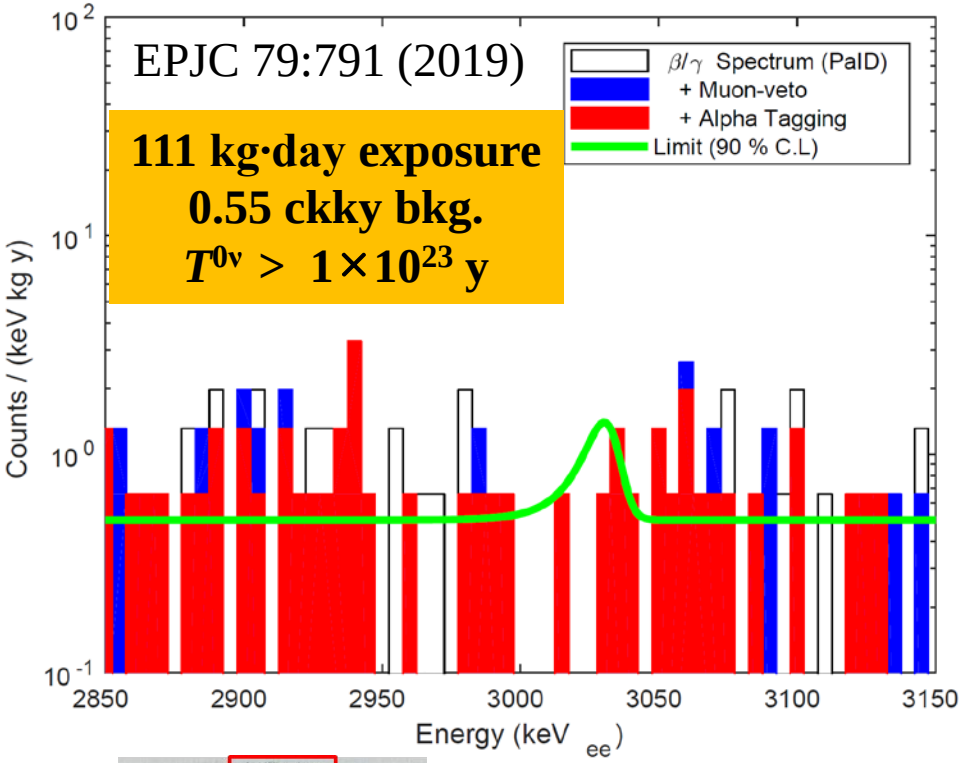


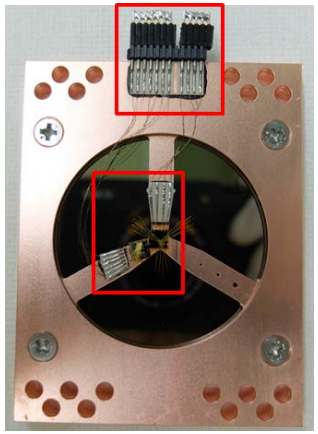






First Pilot result, + Upgrades

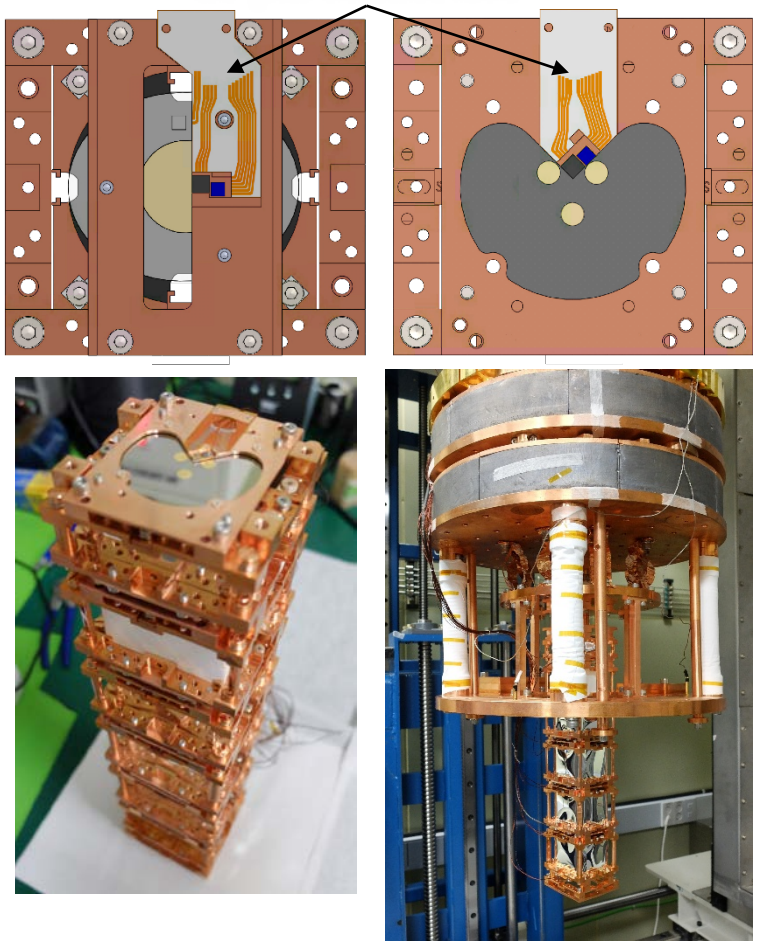




Bkg. from PCB and pin connectors

Bkg. improvement

Clean PCB (tested)
no pin connectors



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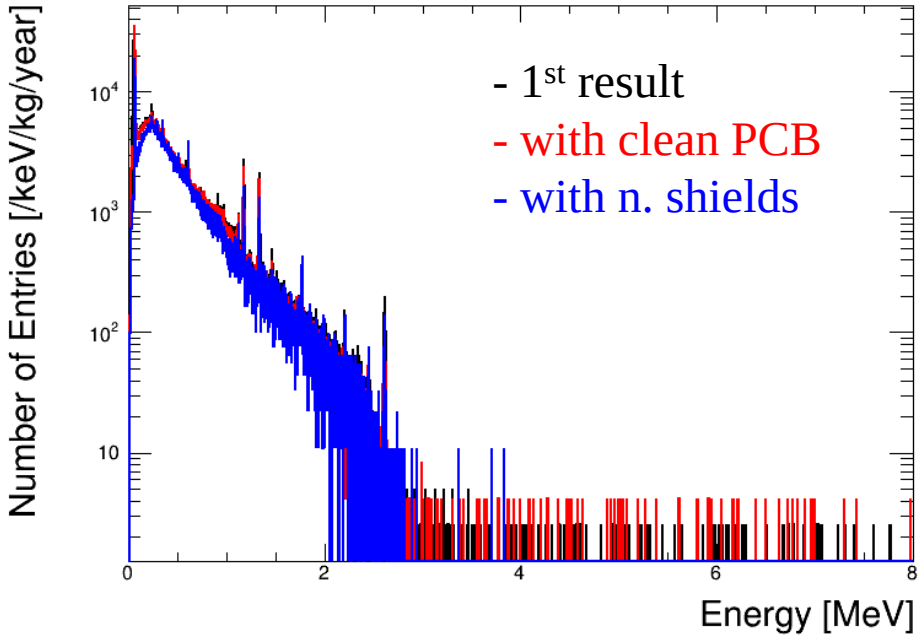
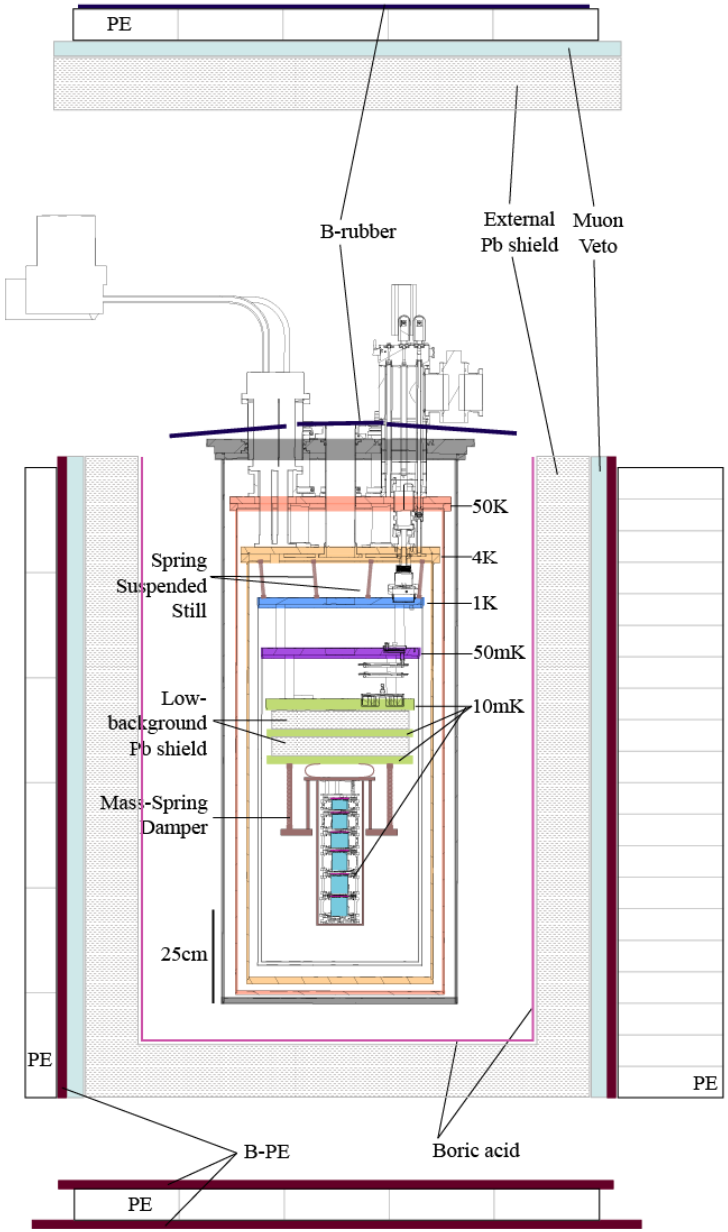
Upgrade: + Neutron shields





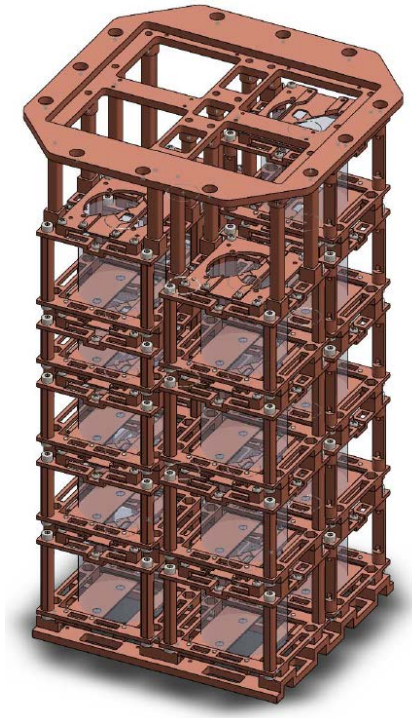
Bkg. rate reduced by 3~9 times from the 1st result.

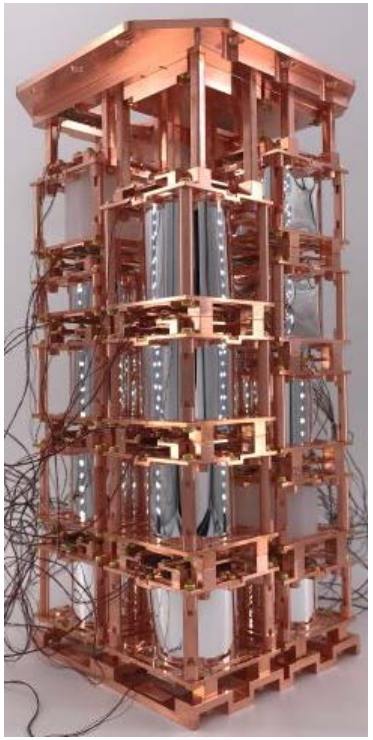
New results are to be updated.

AMoRE-I detector

- 18 crystals
  - 36 MMC channels
  - CMOs ($^{48depl}Ca^{100}MoO_4$): 13
    - 6 from Pilot (Fomos): 1.886 kg
    - 7 new crystals (Fomos): 2.696 kg
  - LMOs ($Li_2{}^{100}MoO_4$)
    - 4 (NIIC) + 1 (CUP): 1.609 kg
  - Total crystal mass 6.193 kg

  ~ 3.1 kg of ^{100}Mo





- **Science run began Dec. 2020.**

Yong-Hamb Kim

Schedule of the AMoRE project

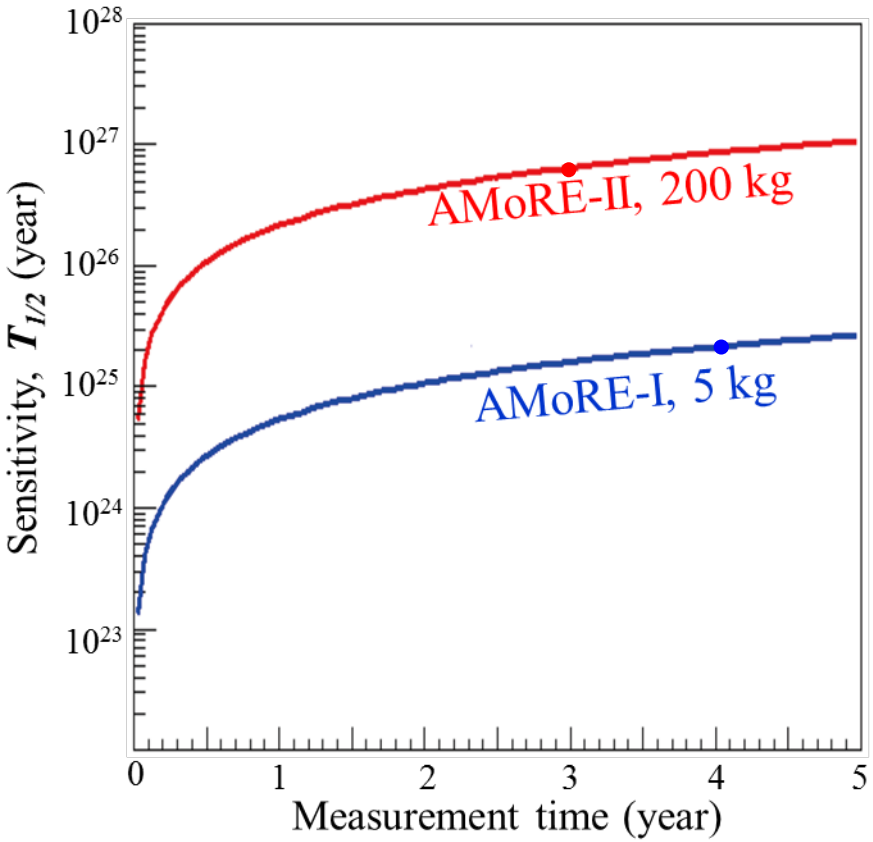
- MMC technology for heat and light measurement
- Crystal: $^{40}Ca^{100}MoO_4$, doubly enriched scintillating crystals (Pilot & I)

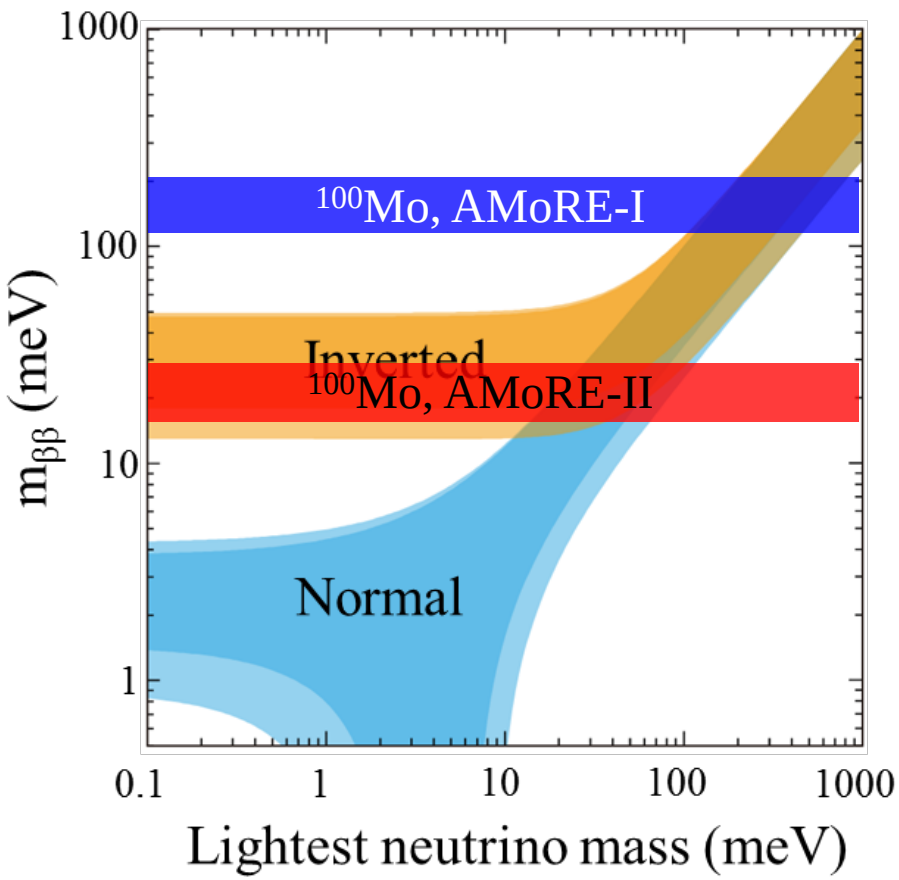
  For Phase II: $X^{100}MoO_4$ (X: Li, Na, or Pb)
- Zero background in ROI
- Location: Y2L (Pilot, I) and a new deeper place (Yemilab at Jeongsun)

	Phase I	Phase II
Mass	~6 kg	~40 (200) kg
MMC Channel	36	1000
Required background (ckky)	0.0015	0.0001
Sensitivity($\boldsymbol{T}_{1/2}$) (year)	~10^{25}	~5×10^{26}
Sensitivity($m_{\beta\beta}$) (meV)	120-200	17-29
Location	Y2L	Yemilab
Schedule	2020 ~	2022 (2023) ~

Yong-Hamb Kim

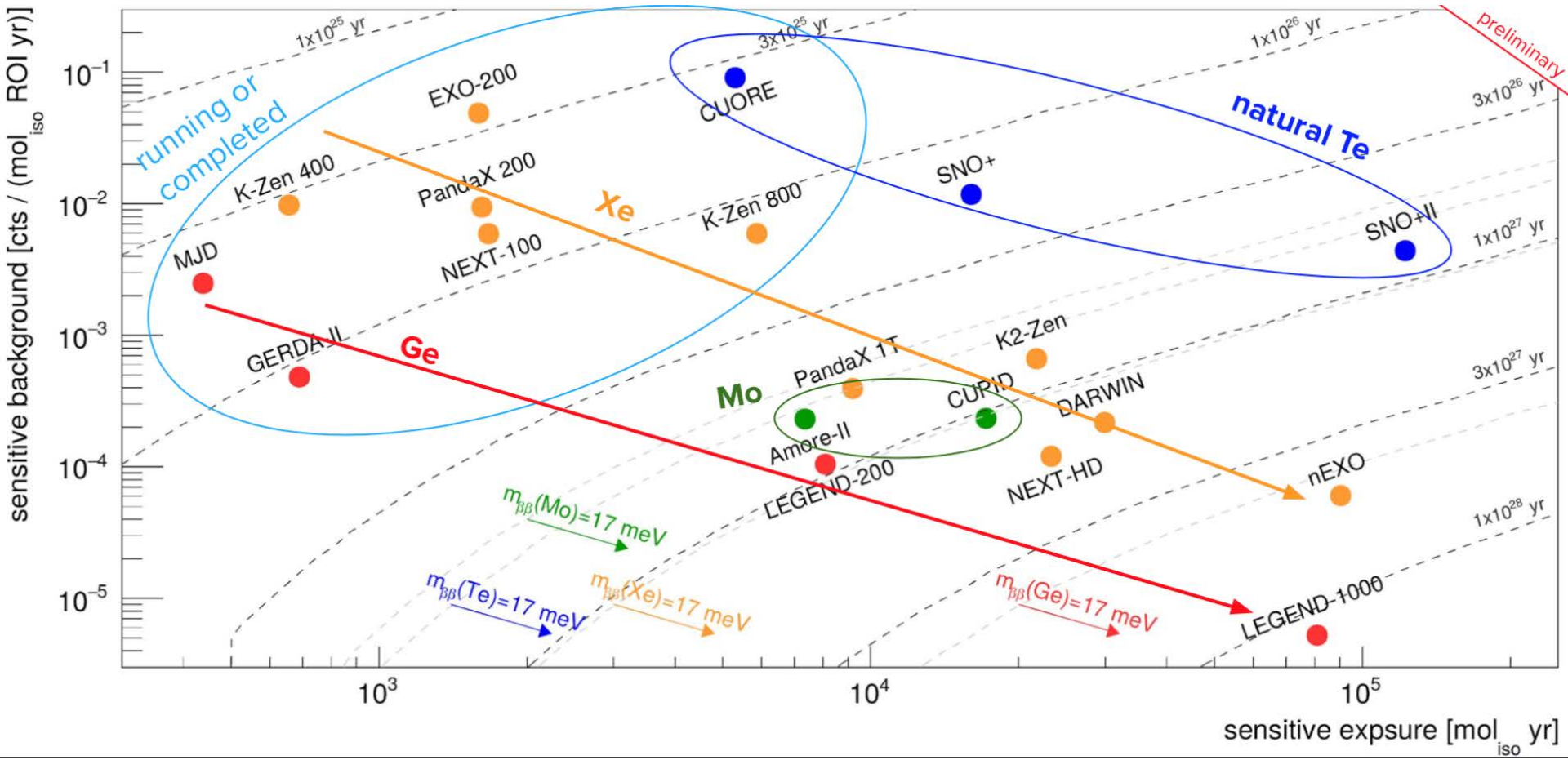
AMoRE Sensitivity





Summary

Current and future sensitivities



<M. Agostini 2019>

Summary

- **0νββ discovery is feasible in the following decade.**
- **NO does not mean no hope for 0νββ discovery. (Sensitivity should reach 20meV)**
- **It requires many experiments with various isotopes and different detection methods.**
- **0νββ search is not just a ν mass experiment but also studies firmamental understandings of particle physics.**
- **Amazing progress has been realized in many projects.**

- **AMoRE is a promising 0νββ experiment.**
- **Stay tuned to AMoRE**