17th International Workshop on Low Temperature Detectors

LTD17

July 17-21, 2017
Kurume, Fukuoka, Japan

Low temperature detectors for neutrinoless double beta decay experiments (LTDs for 0νββ)

Yong-Hamb Kim

김용함 (金容菡)

ibs 기초과학연구원 Institute for Basic Science

KRISS 한국표준과학연구원 Korea Research Institute of Standards and Science

Thank

Oliviero Cremonesi
INFN, Sezione di Milano Bicocca
Stefano Dell'Oro
Virginia Tech.
Andrea Giuliani
CNRS/CSNSM, Orsay
Stefano Pirro
INFN-LNGS
Sei Yoshida
Osaka Univ.

for sharing their presentation materials and helpful discussions.

Goal of my presentation

I try to explain

- Importance of 0νββ process in physics
- What we do with LTDs for 0νββ searches covering basics only.

I will not go in details of the latest results of the projects.

Outline

- Intro
  - 0νββ & ν
  - Detection sensitivities
- LTDs for 0νββ
  - Sensors & detection technologies
  - LT 0νββ projects
- Summary

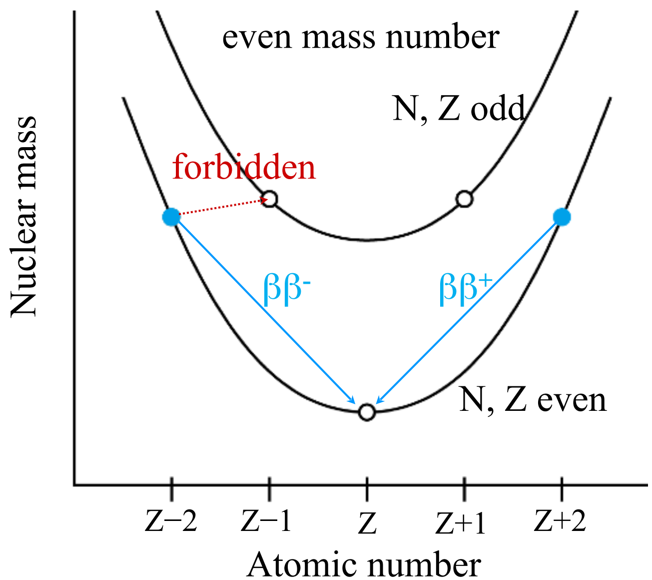
0νββ and ν (brief intro.)

- 0νββ decay can only happen if neutrinos are massive Majoanana particles (own anti-particles).
  - ✓ fundamental understanding 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.
  - ✓ Leptogenisis ?
  - ✓ New physics ?

Double beta decay

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

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



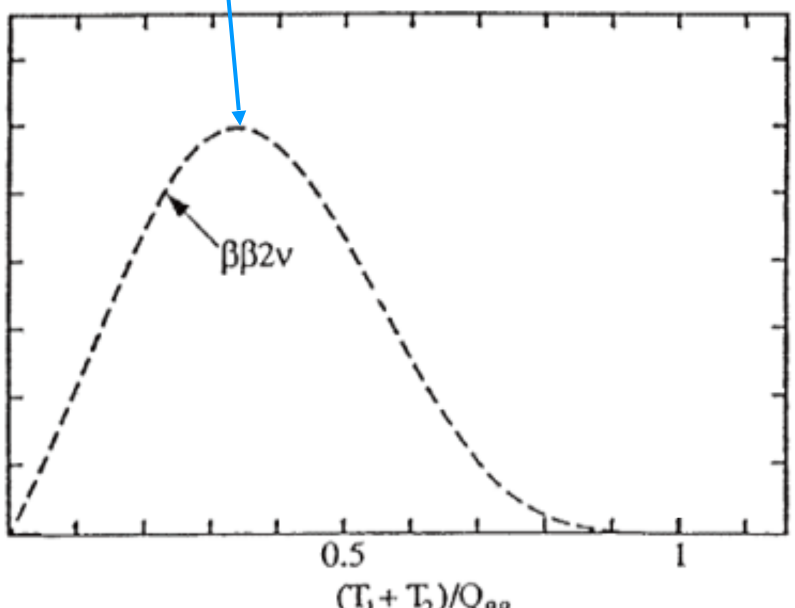
ββ-decay nuclei with Q > 2 MeV	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow {}^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow {}^{76}Se$	2.040	7.8
$^{82}Se \rightarrow {}^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow {}^{96}Ru$	3.350	2.8
$^{100}Mo \rightarrow {}^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow {}^{110}Cd$	2.013	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

Double beta decay w. & wo. ν emission

2ν mode

- A conventional
- 2nd order weak process in NP

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



Double beta decay w. & wo. ν emission

2ν mode

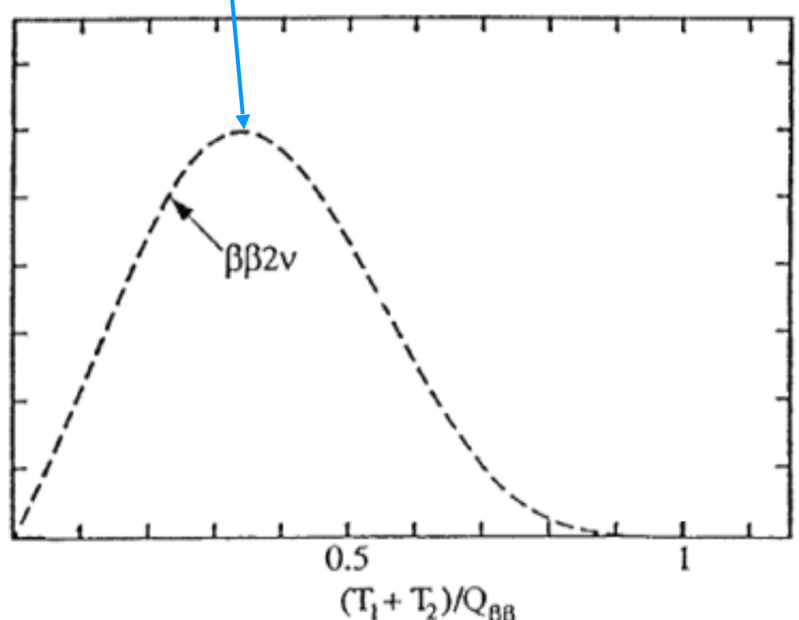
- A conventional
- 2nd order weak process in NP

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

0ν mode

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

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



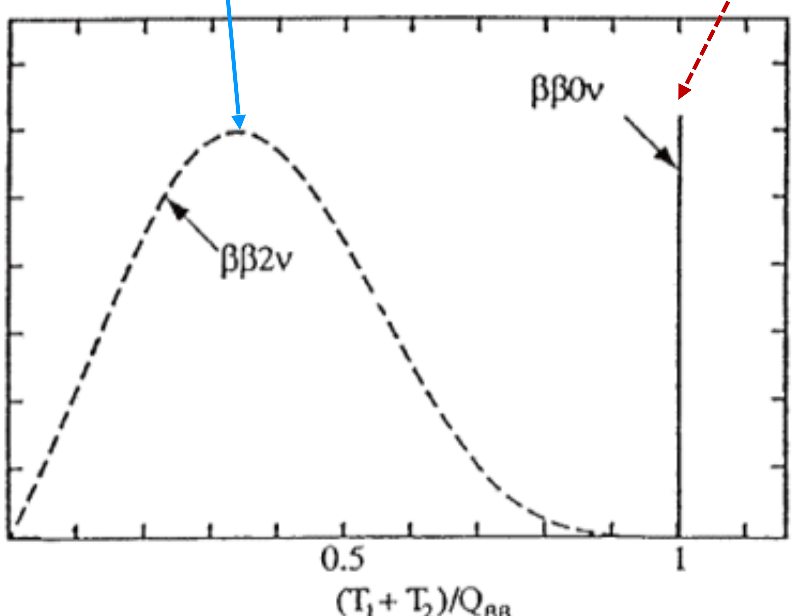
Double beta decay w. & wo. ν emission

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

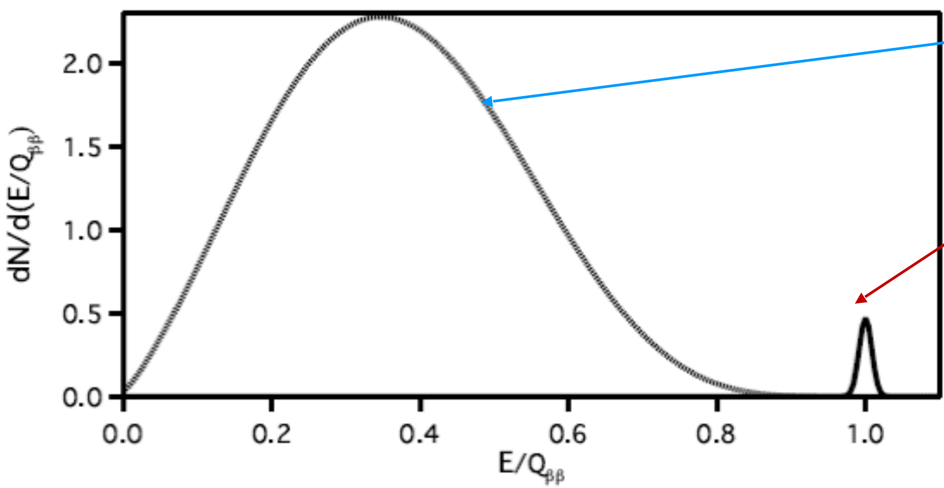
M.Goeppert-Mayer, Phys. Rev. 48 (1935) 512

- ✓ 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: $T_{1/2}$(U, Th) : 10^{10} y ~ $T_{Universe}$ (the age of the Universe)
- ✓ $T_{1/2}(2\nu\beta\beta)$: ~ 10^{10} $T_{Universe}$

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

- ✓ The possibility of **neutrinos-less decay** was discussed in 1937
- ✓ Now, we want to look for a process with $T_{1/2}(0\nu\beta\beta)$: $10^{16\sim18}$ $T_{Universe}$

Neutrinoless double beta decay (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 of neutrinos ($1/T_{1/2}^{0\nu} \propto m_\nu^2$)
- Lepton number violation

0νββ 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 (~ Q^5),

Atomic phys.

✓ **$|M_{0\nu}|$** : Nuclear matrix element. Nuclear physics

Hard to calculate. Uncertain by ~2 times

$m_{\beta\beta}$: Effective neutrino mass, where the interesting physics (in particle) lies.

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

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

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

Evolve in time with m_i & E

↓

ν oscillation

Neutrino mixing, mass, and 0νββ

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_{m1}\\ \nu_{m2}\\ \nu_{m3}\end{pmatrix}$$

weak interaction eigenstate

mass eigenstate

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

Evolve in time with m_i & E

ν oscillation

Effective ββ mass

$$\langle m_{\beta\beta}\rangle = \sum_i^3 U_{ei}^2 m_i$$

virtual ν exchange

ν mass in other measurement

m of ν_e from β end-point

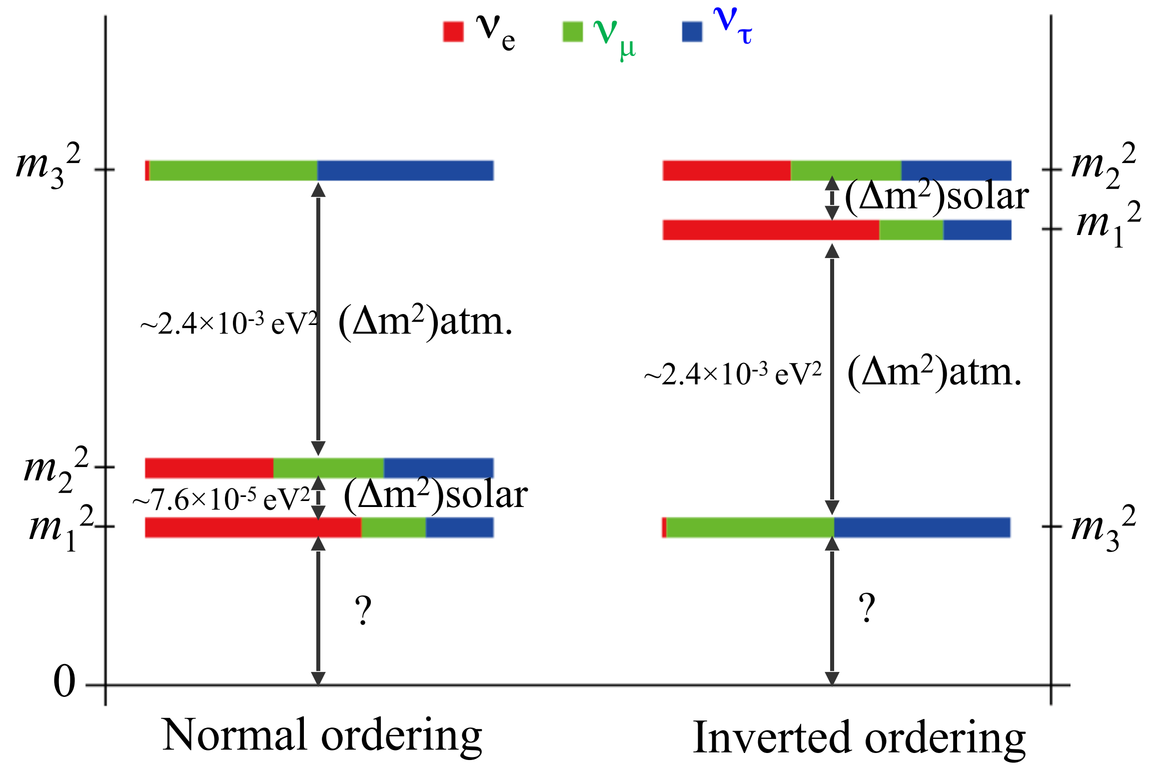
$$m_\beta = \sqrt{\sum_i^3 |U_{ei}|^2 m_i^2}$$

real ν emission

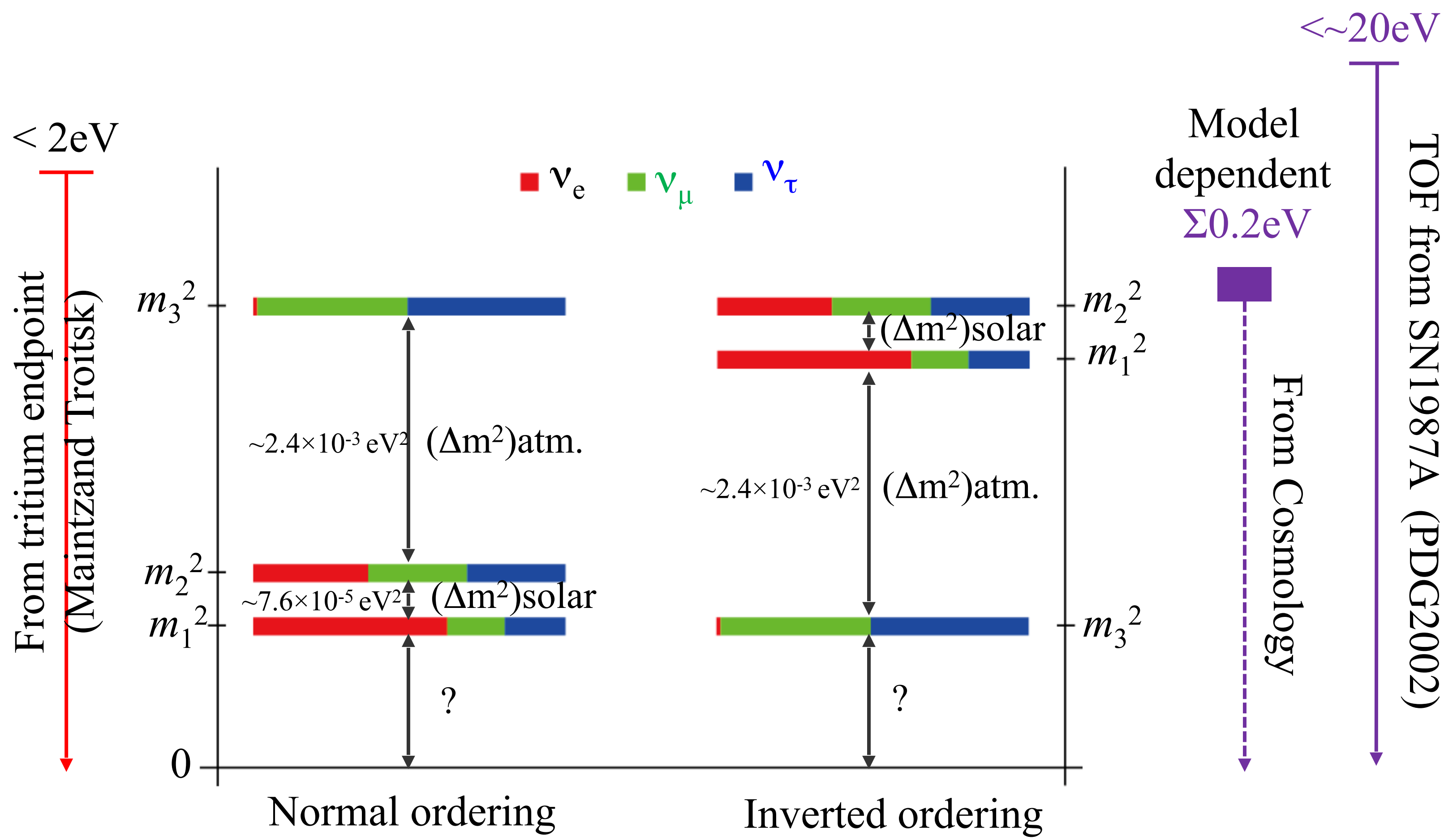
cosmology

$$\sum = \sum m_i$$

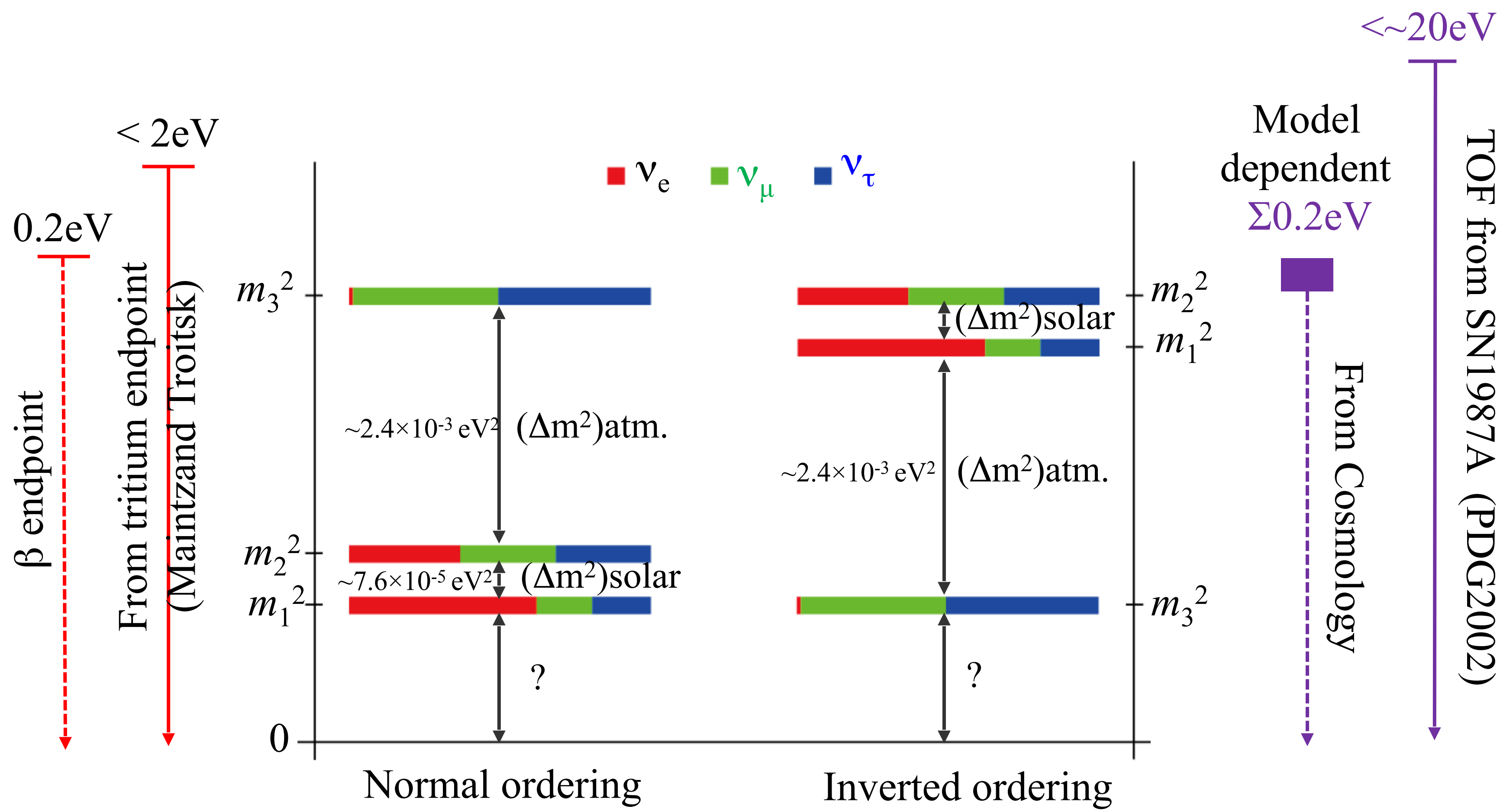
Present knowledge of ν mass pattern & scale



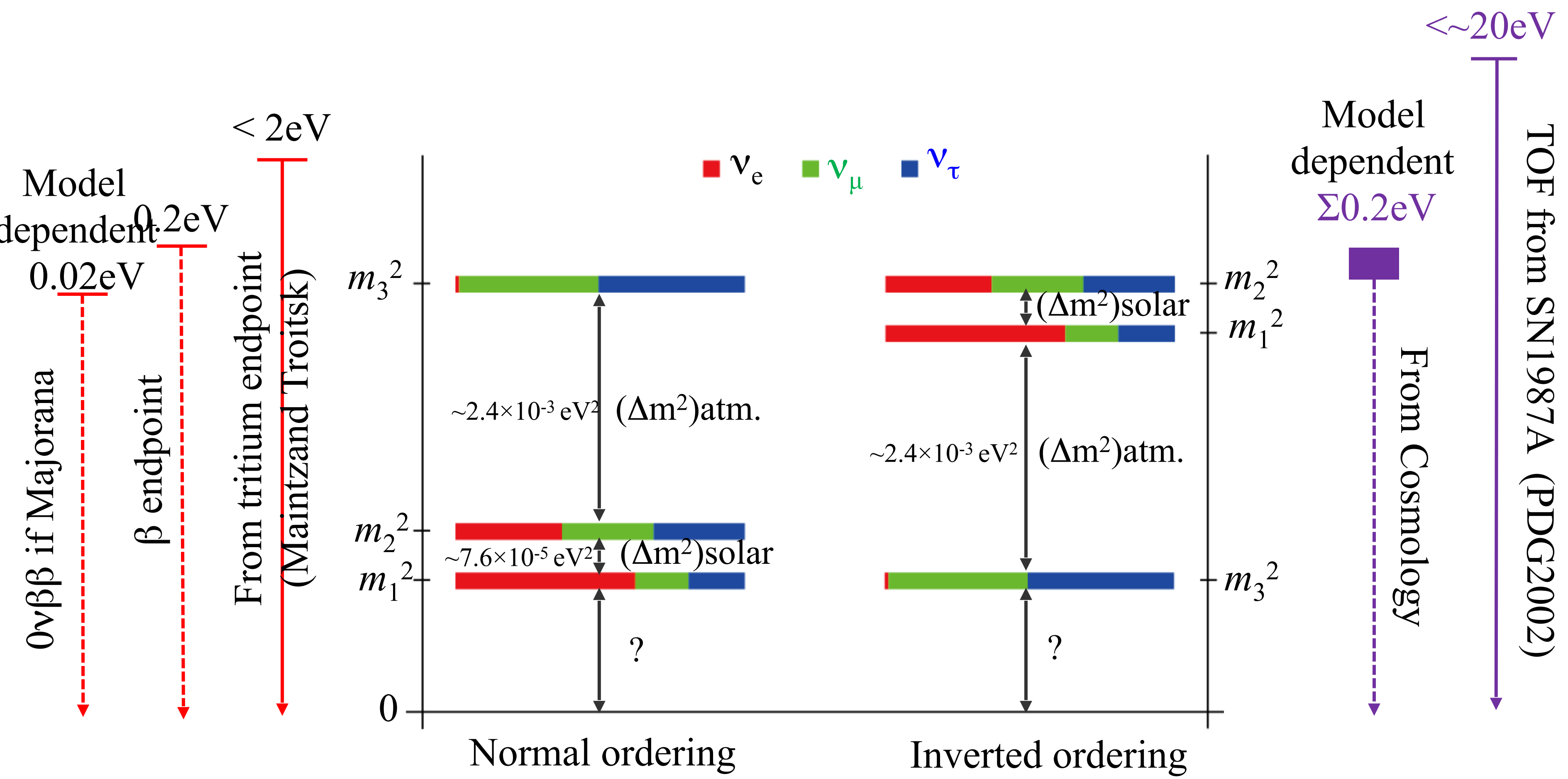
Present knowledge of ν mass pattern & scale



Present knowledge of ν mass pattern & scale



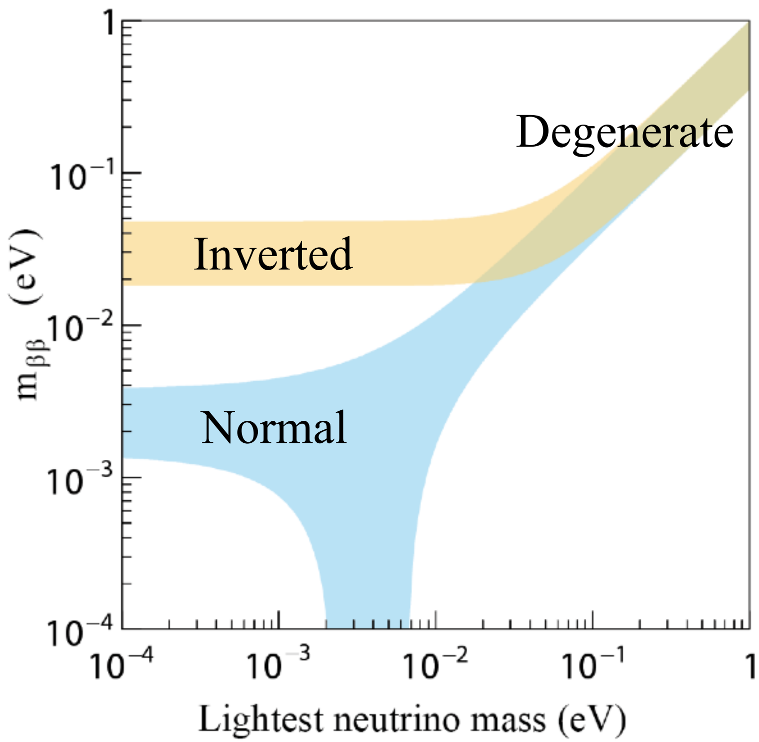
Present knowledge of ν mass pattern & scale



0νββ sensitivity region: "usual" plot

$$m_{\beta\beta} = \left| \sum U_{ei}^2 m_i \right|$$

Parameters with known, limit and unknown values



90% CL with parametersfrom
Faessler et al., JPG39, 124006 (2012)

$$1/T_{1/2}^{0\nu} \propto m_{\beta\beta}^2$$

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

- ✓ The mass hierarchy (ordering) matters.
- ✓ The lightest m_i also matters.

Physics uncertainties after 0νββ discovery

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

$$\Gamma_{0\nu} = G_{0\nu} \left| M_{0\nu} \cdot \eta \right|^2$$

η : physics processes leading to Lepton number violation.

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

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

✓ **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,
  - Light ν exchange, Heavy ν exchange,
  - R-parity violating susy,
  - Mechanisms with RHC, Majorons, etc.
- Model dependent $M_{0\nu}$ (NME) complication

Physics uncertainties after 0νββ discovery

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

$$\Gamma_{0\nu} = G_{0\nu} \left| M_{0\nu} \cdot \eta \right|^2$$

η : physics processes leading to Lepton number violation.

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

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

- ✓ **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,
  - Light ν exchange, Heavy ν exchange,
  - R-parity violating susy,
  - Mechanisms with RHC, Majorons, etc.
- Model dependent $M_{0\nu}$ (NME) complication

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

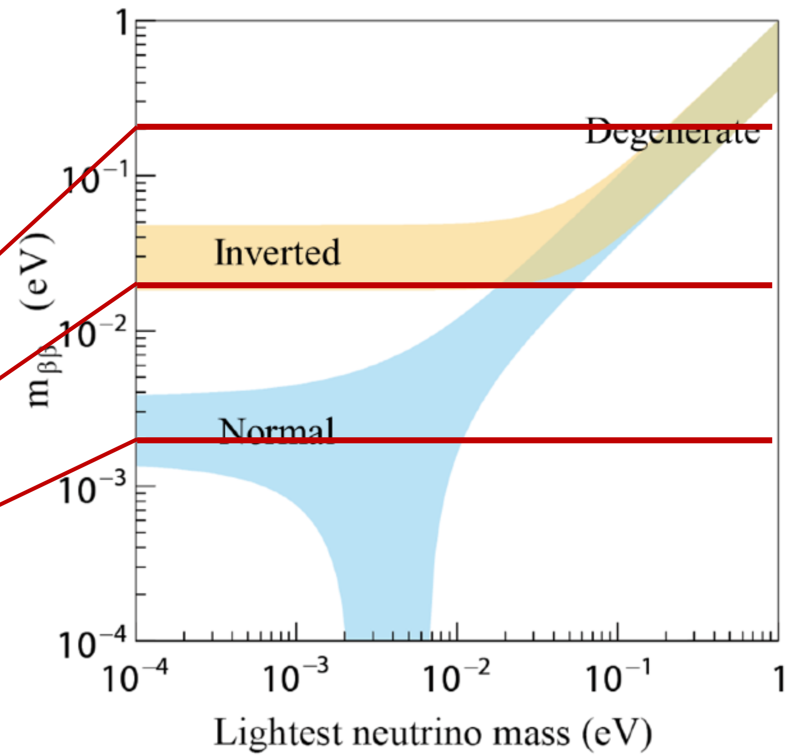
Theorists claim

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

Detection Sensitivities

0νββ decay rates: Simplified

Half life (years)	Decays in 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



Very rare!
Background matters.

Experimental Sensitivity of $T_{1/2}$ ($0\nu\beta\beta$)

For sizeable background case:

Detection Efficiency

Isotopic Abundance

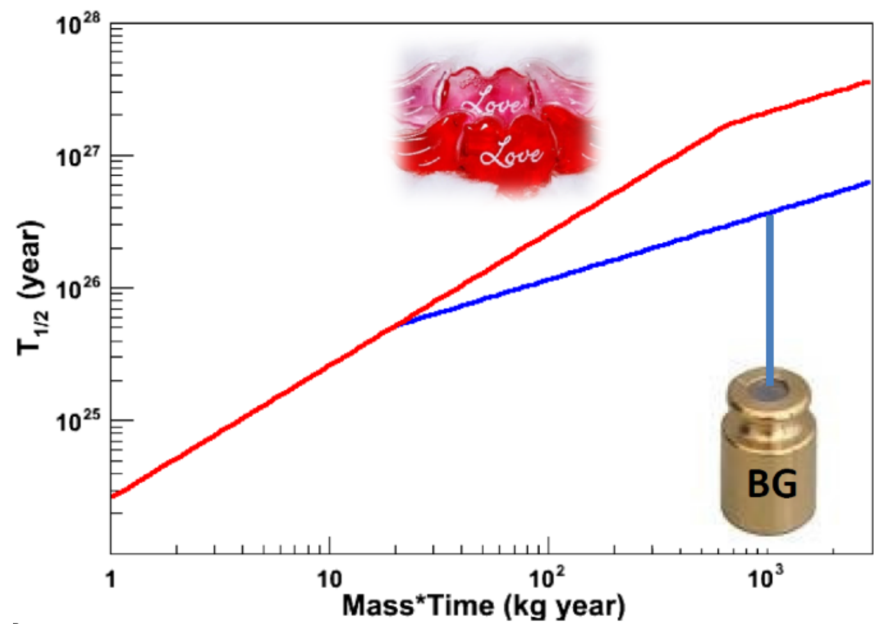
Detector Mass

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

Atomic mass

Background level (count/keV kg year)

Energy Resolution



For “zero background” case:

(Expected background events in ROI < 1 for given $M \times$ time)

$$T_{1/2}^{0\nu}(\exp) = (\ln 2) N_a \frac{a}{A} \varepsilon \frac{M \cdot \text{time}}{n_{CL}}$$

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, Not very practical to increase sensitivity $T_{1/2}$
- ✓ Smaller ΔE : Better energy resolution ← detector tech.
- ✓ Bkg. : Minimize background events in ROI
  - Underground facility
  - Rn control
  - Neutrons, Long-lived cosmogenics
  - Natural occurring radioactive materials (U Th)
  - Environmental gammas
  - ββ(2ν) signals, energy and timing resolution needed
  - Active discrimination method (PSD, H/L ratio, Cherenkov)

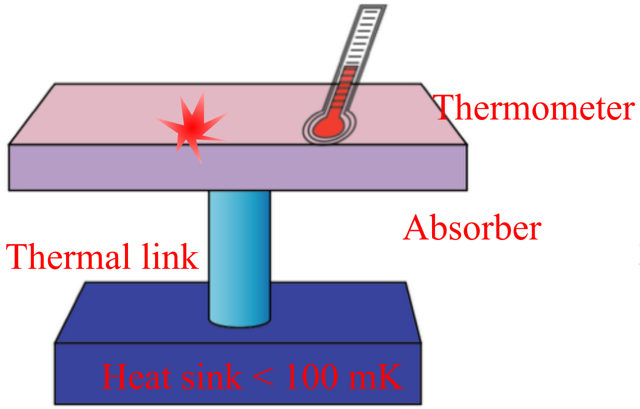
LTDs for $0\nu\beta\beta$ search

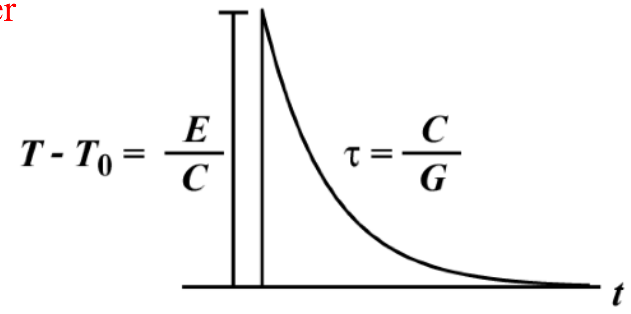
Sensors & Detection Technologies

Low Temperature Detectors

"Calorimetric measurement of heat signals at mK temperatures"

Energy absorption ➔ Temperature



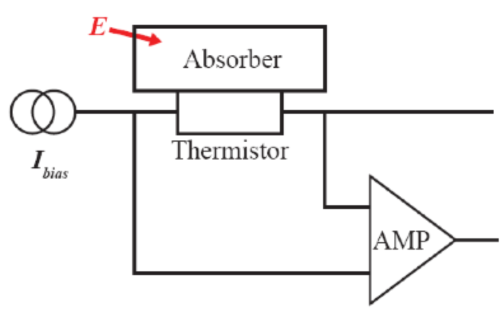


Choice of thermometers for 0νββ searches

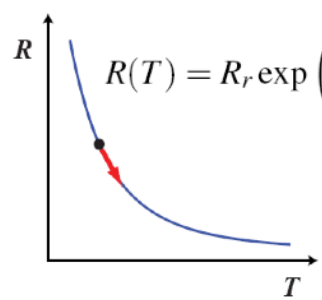
- **Thermistors (NTD Ge)** CUORE, CUPID
- TES (Transition Edge Sensor) Light detector
- **MMC (Metallic Magnetic Calorimeter)** AMoRE, LUMINEU
- KID (Kinetic Inductance Device) CALDER
- etc.

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 >



$$R(T) = R_r \exp\left(\frac{T_r}{T}\right)^{1/2}$$

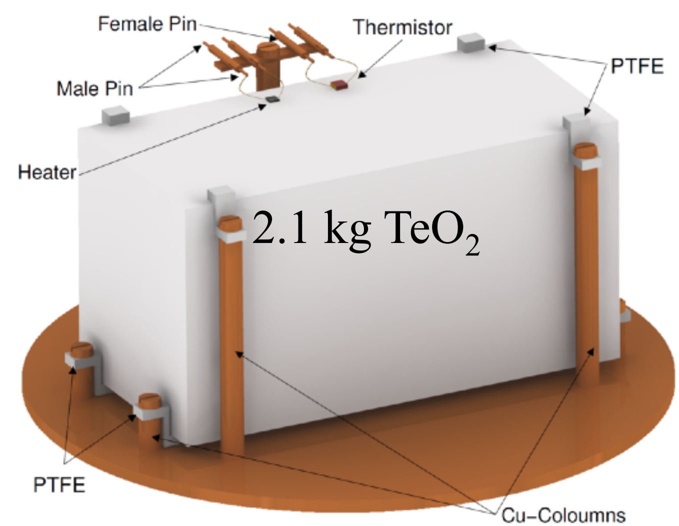


fig. from Cardani et al arXiv.1106.0568

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
- More wires & materials needed for SQUIDs and MMCs,

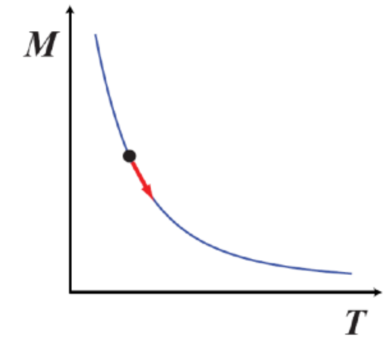
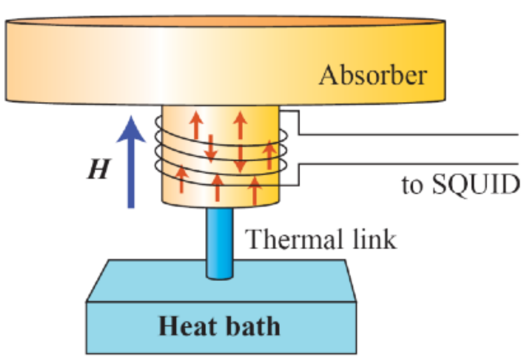
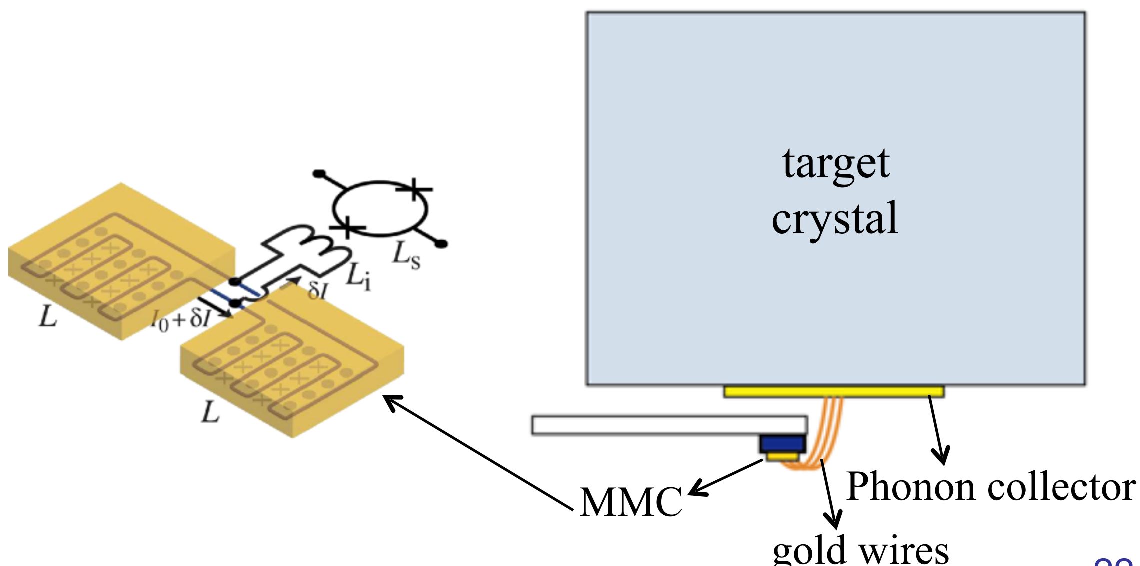


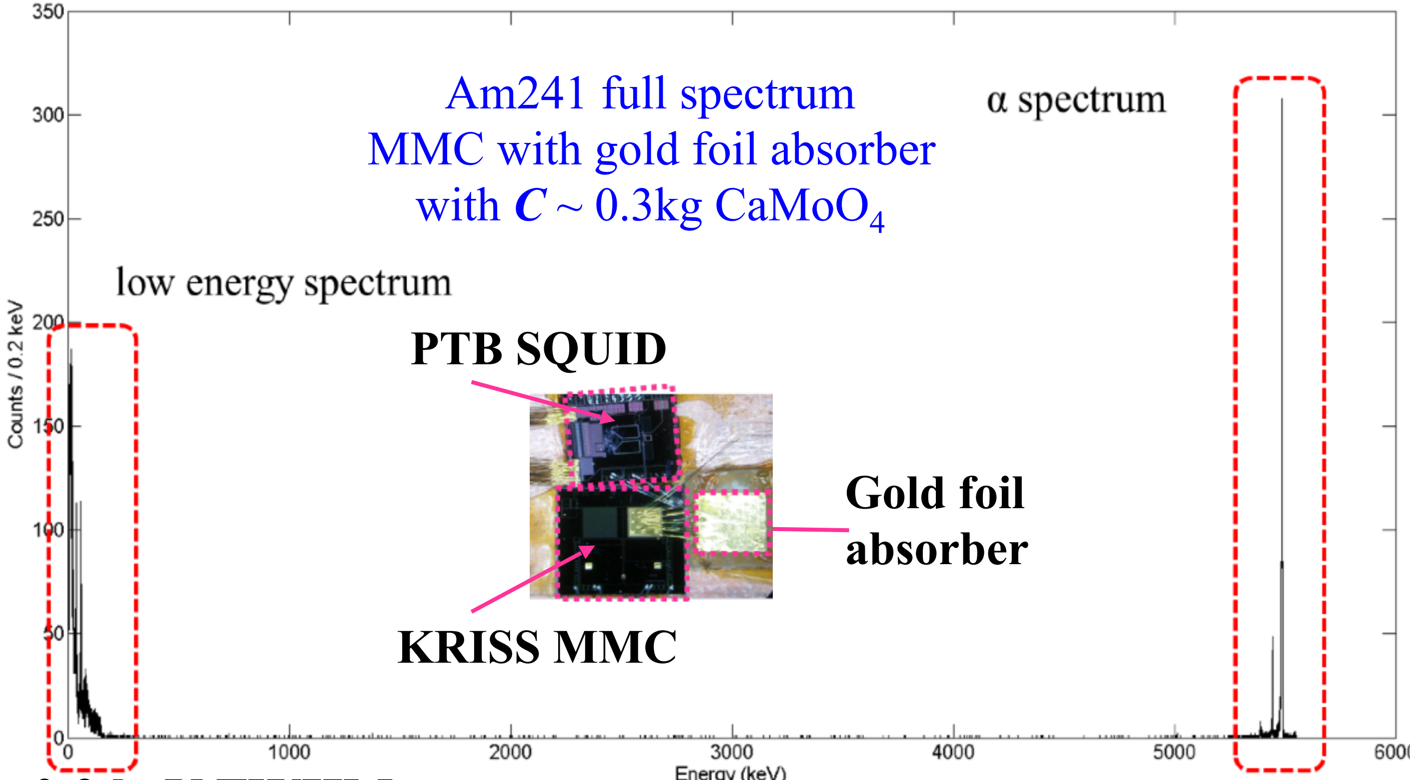
fig. from SY Oh et al SuST 2017





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.**
- ✓ **NTD Ge thermistors also have similar performance.**

Resolution matters.

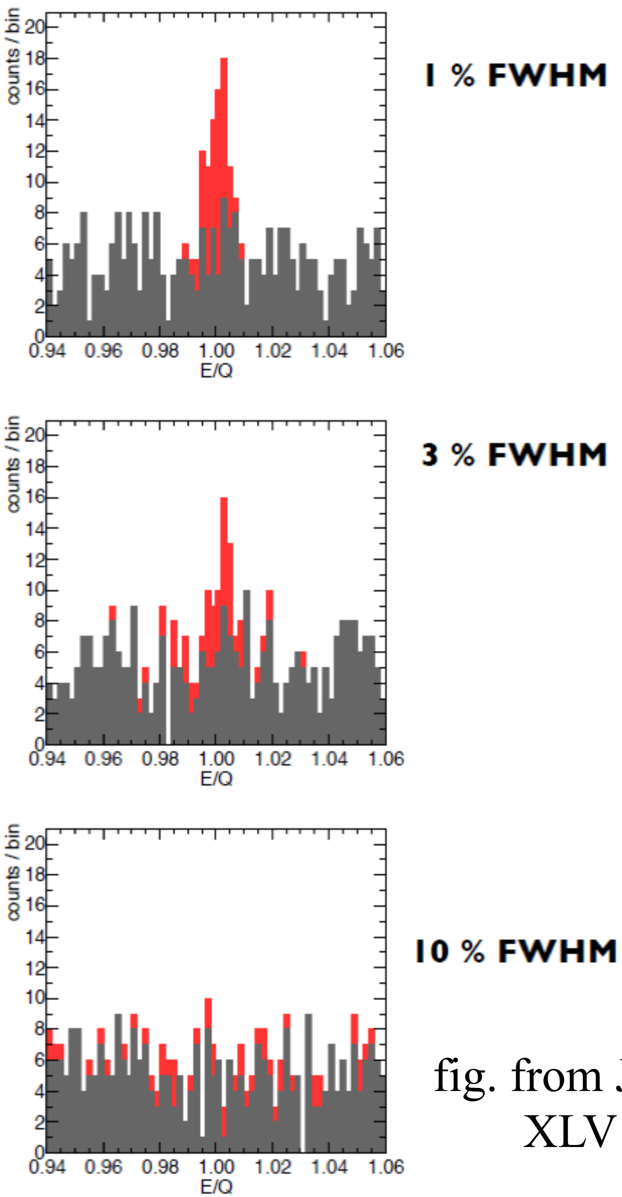


fig. from JJ Gomez-Cadenas
XLV meeting 2017

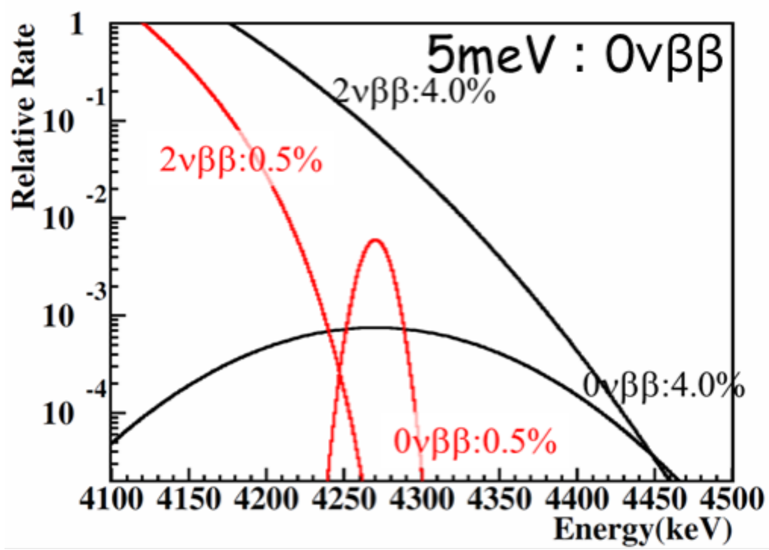
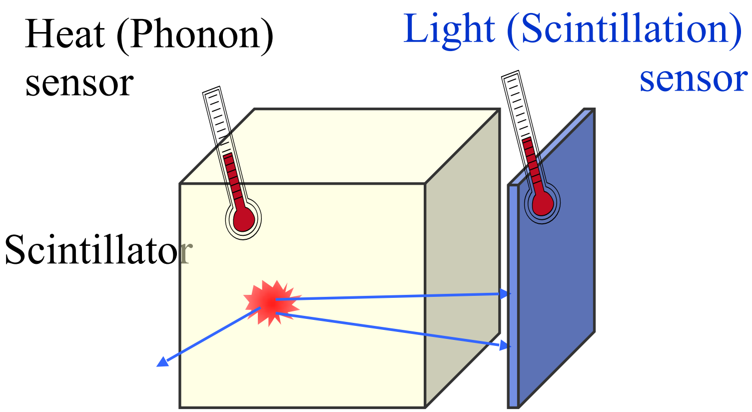


fig. from S. Yosihda Osaka Univ.

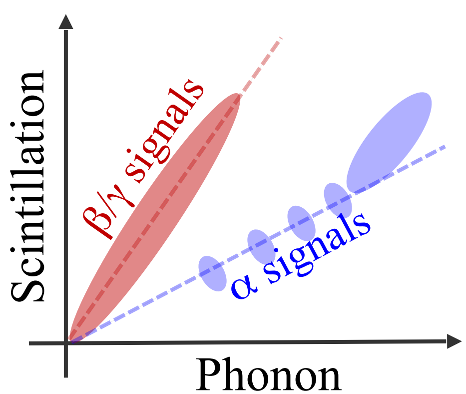
In the case of an ideal shielding with no source of background, ββ(2ν) can overwhelm ββ(0ν) with poor ΔE

Simultaneous phonon-scintillation detection

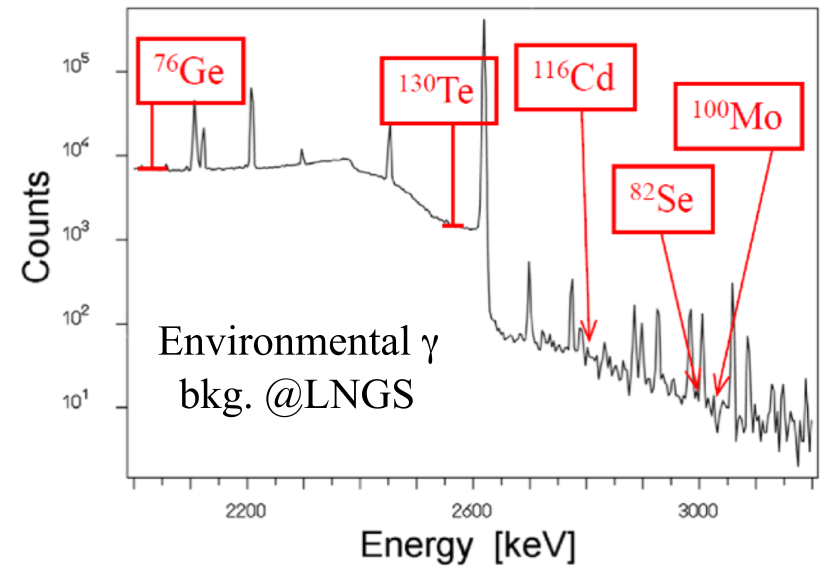
✓ Scintillating crystal as target material
➔ Active bkg. Rejection



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



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

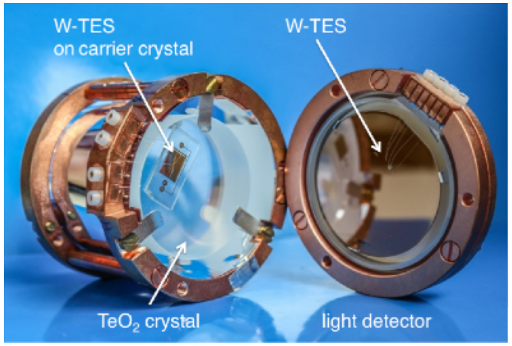


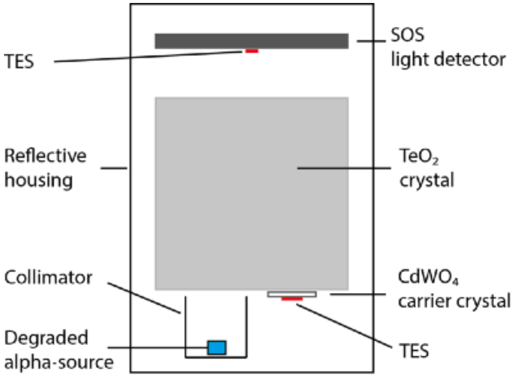
from S. Pirro' talk in DBD Shanghai 2017

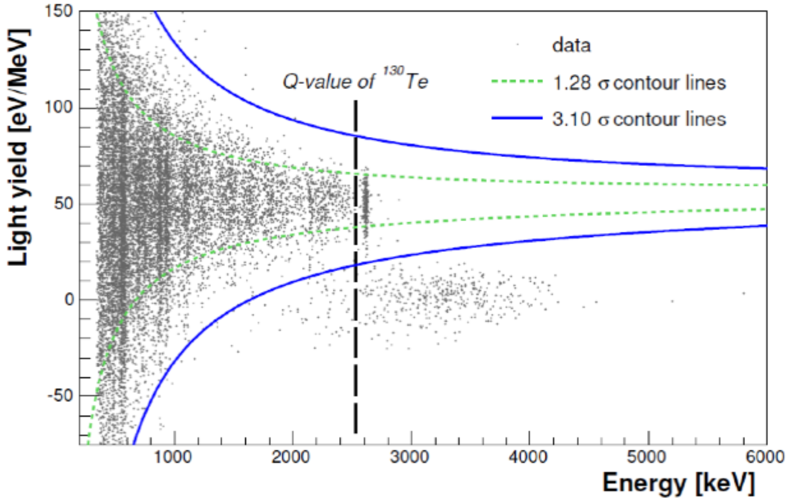
Use of Cherenkov light

- ✓ TeO_2 does not scintillate, but MeV electrons (not alphas) produce Cherenkov light in TeO_2 .
- ✓ ~ 300 eV visible photons are emitted at $Q_{\beta\beta}$ (Tabarelli et al, app 2010)

< TeO_2 in a CRESST setup >

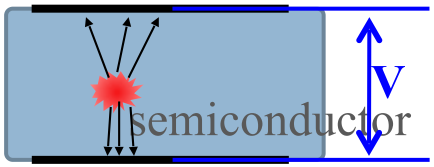






from Schaeffner, et. al, app (2015)

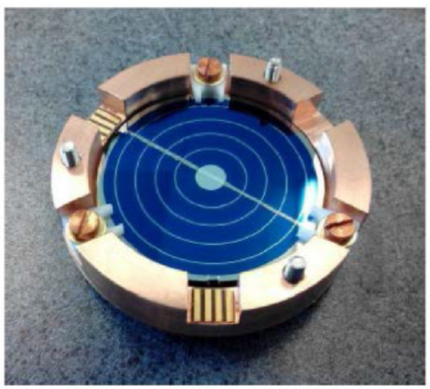
Light detector with phonon amplification

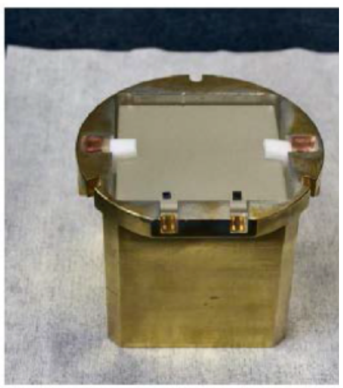


$$\Delta T = E/C$$

$$E = E_0 + E_{Luke} = E_0(1 + eV/\varepsilon)$$

Light sensor



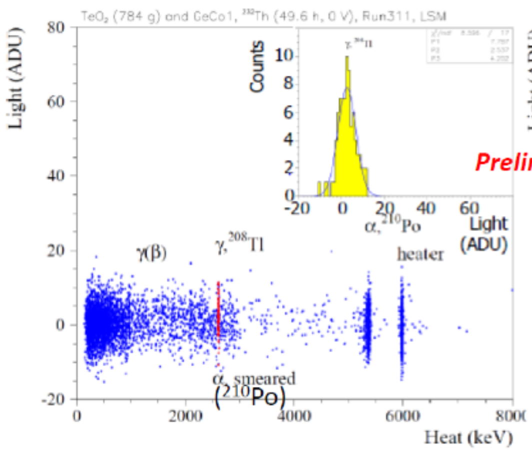


GeCo1 has also been tested coupled to a natural TeO_2 crystal (784 g) at a working temperature of 17 mK

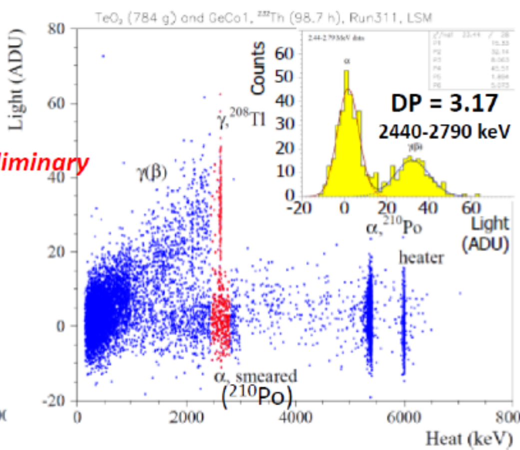
This test has been performed in Laboratoire Souterrain de Modane (LSM, France)

α/β separation

Neganov-Luke voltage = 0 V



Neganov-Luke voltage = 60 V (optimum performance)



from A, Giuliani' talk in DBD Shanghai 2017

LT $0\nu\beta\beta$ Projects

- ✓ This is a short introduction for LT $0\nu\beta\beta$ searches.
- ✓ One should refer relevant talks and posters for details.
- ✓ The summary may not cover all of those $0\nu\beta\beta$ project using LTDs.

30 years of 0νββ searches @LNGS

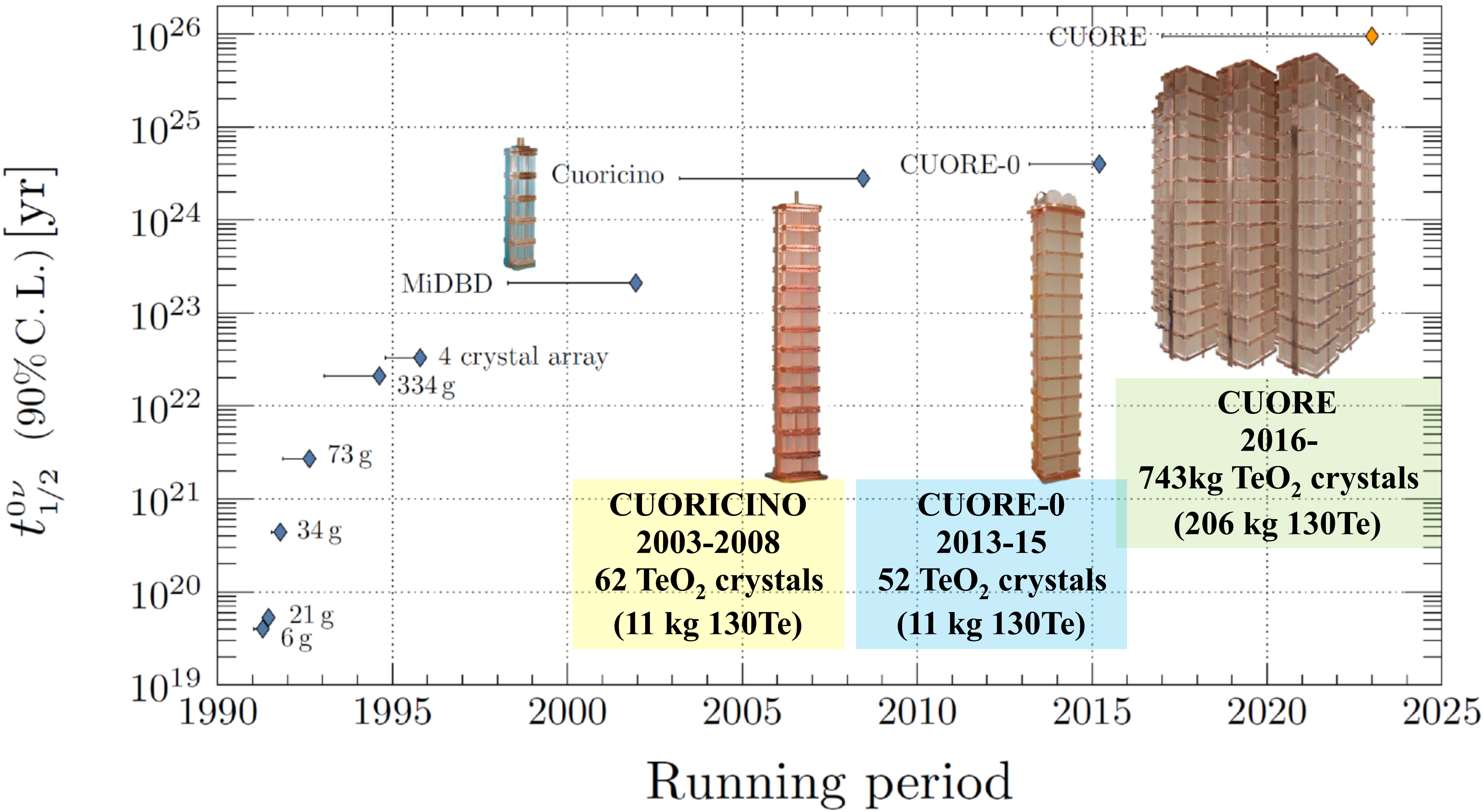


fig. from S. Dell'Oro' talk in DBD Shanghai 2017

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

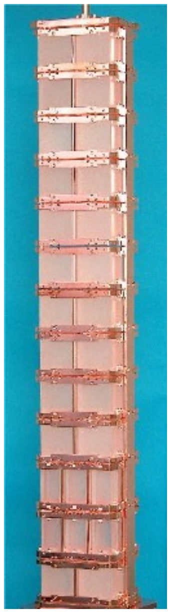
- ✓ Q = 2528 keV (between ^{208}Tl line (2615 keV) and its Compton edge)
- ✓ Large natural abundance : 34.2%

TeO_2 crystals

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

From CUORICINO, To CUORE, & ..

CUORICINO



CUORE-0

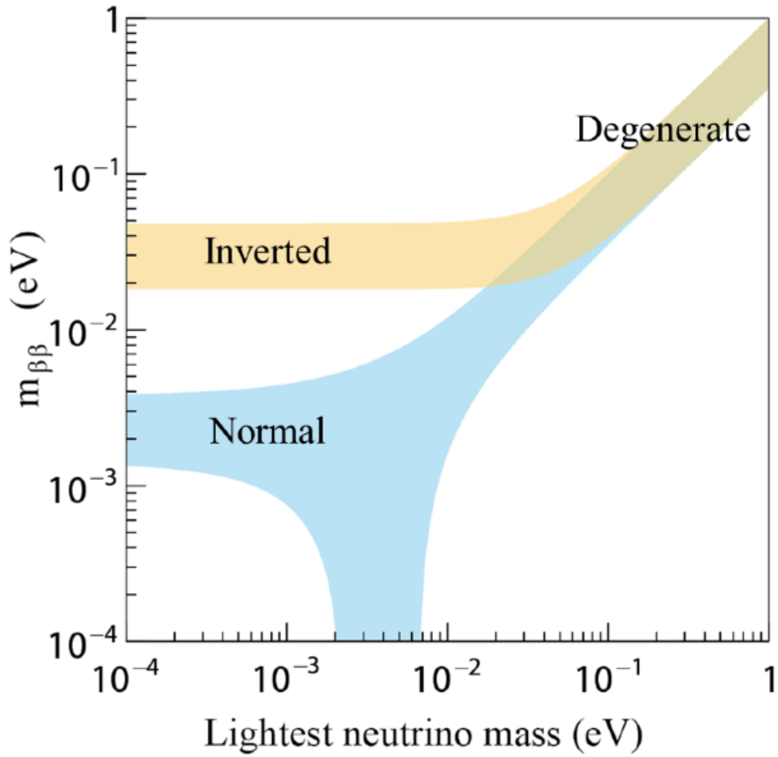
CUORE

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

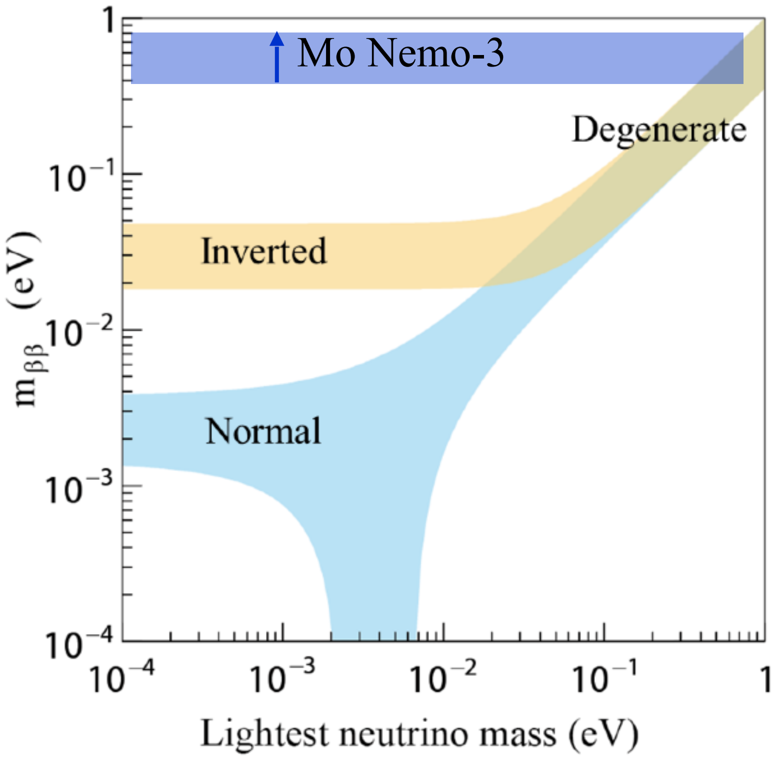
CUORE-0
2013-15
52 TeO_2 crystals
(10.9 kg ^{130}Te)
$T_{1/2} > 4\times10^{24}$ y

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

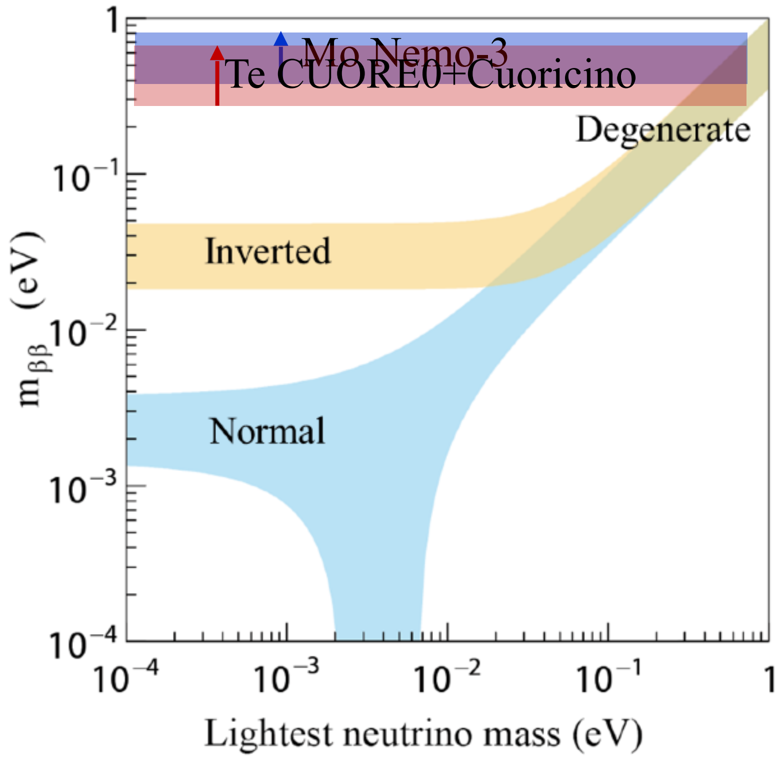
Present $m_{\beta\beta}$ limits



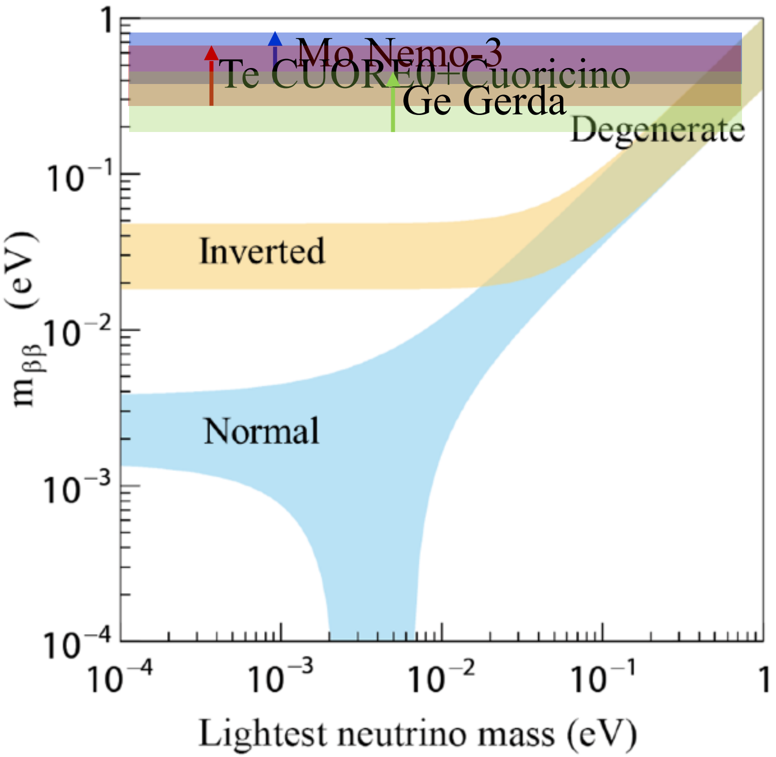
Present $m_{\beta\beta}$ limits



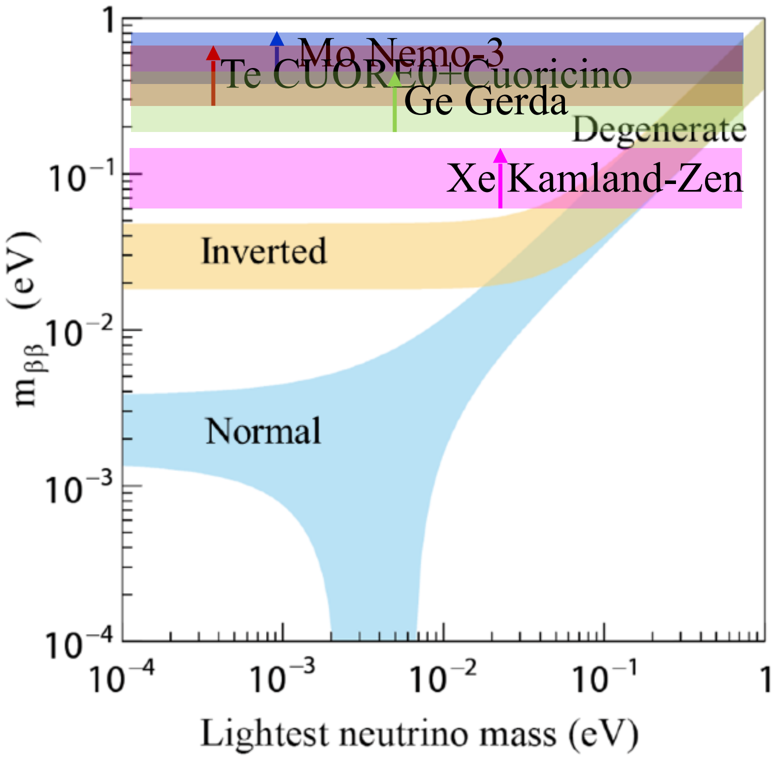
Present $m_{\beta\beta}$ limits



Present $m_{\beta\beta}$ limits



Present $m_{\beta\beta}$ limits



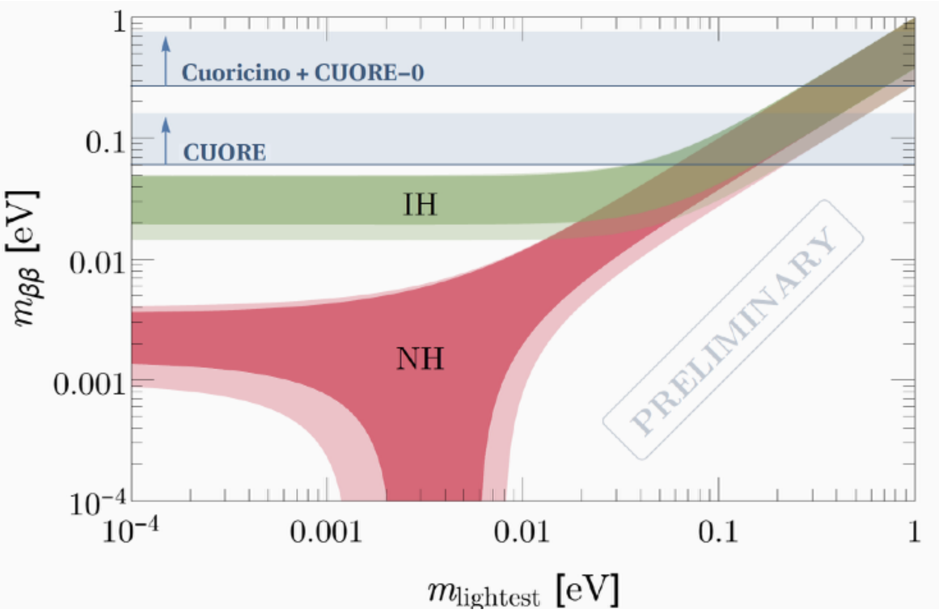
CUORE goal

Bkg.: 0.01 count/keV/kg/y

Resol.: 5 keV FWHM

5-year run: $T_{1/2}(0\nu) > 9\times10^{25}$ y (exclusion, 90% CL)
$\sim 4\times10^{25}$ y (3σ discovery potential)
$m_{\beta\beta} <$ (60-160) meV

CUORE will continue with CUPID.



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

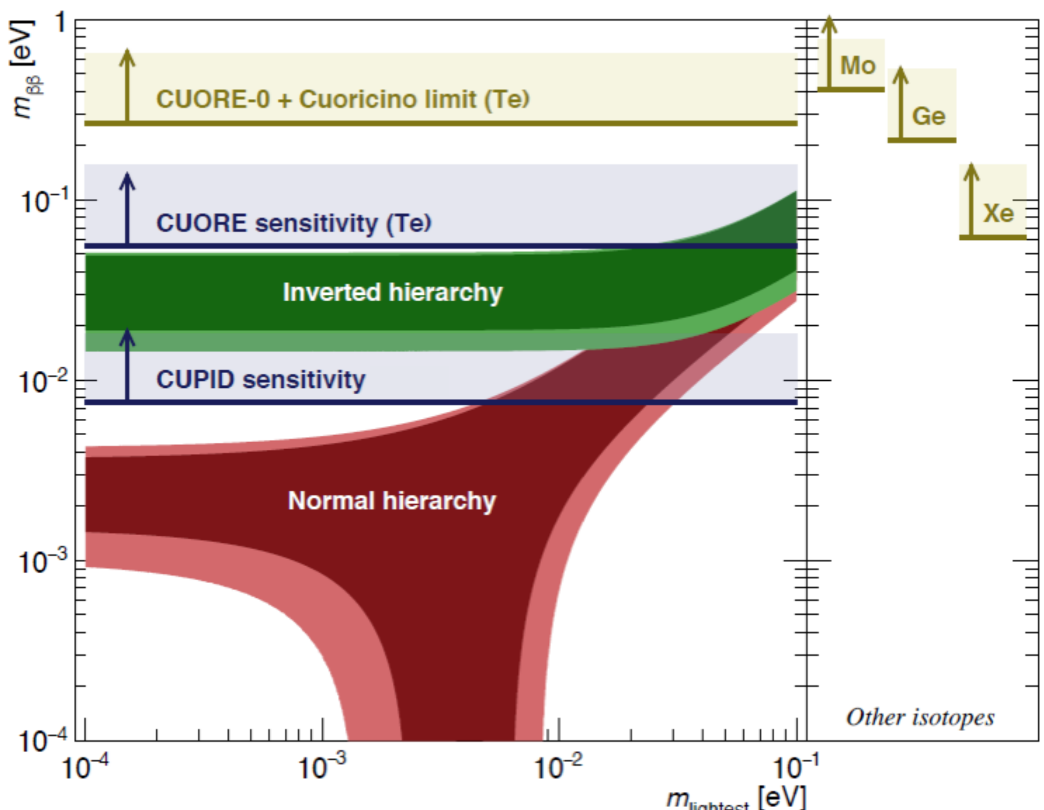
CUPID: Cuore Upgrade with Particle ID

^{130}Te, ^{82}Se, ^{100}Mo: each in ton scale

Bkg.: 0.1 count/keV/ton/y

Resol.: < 10 keV FWHM

CUORE infra structure



from M Vignati' talk in DBD Osaka 2016

R&D toward CUPID

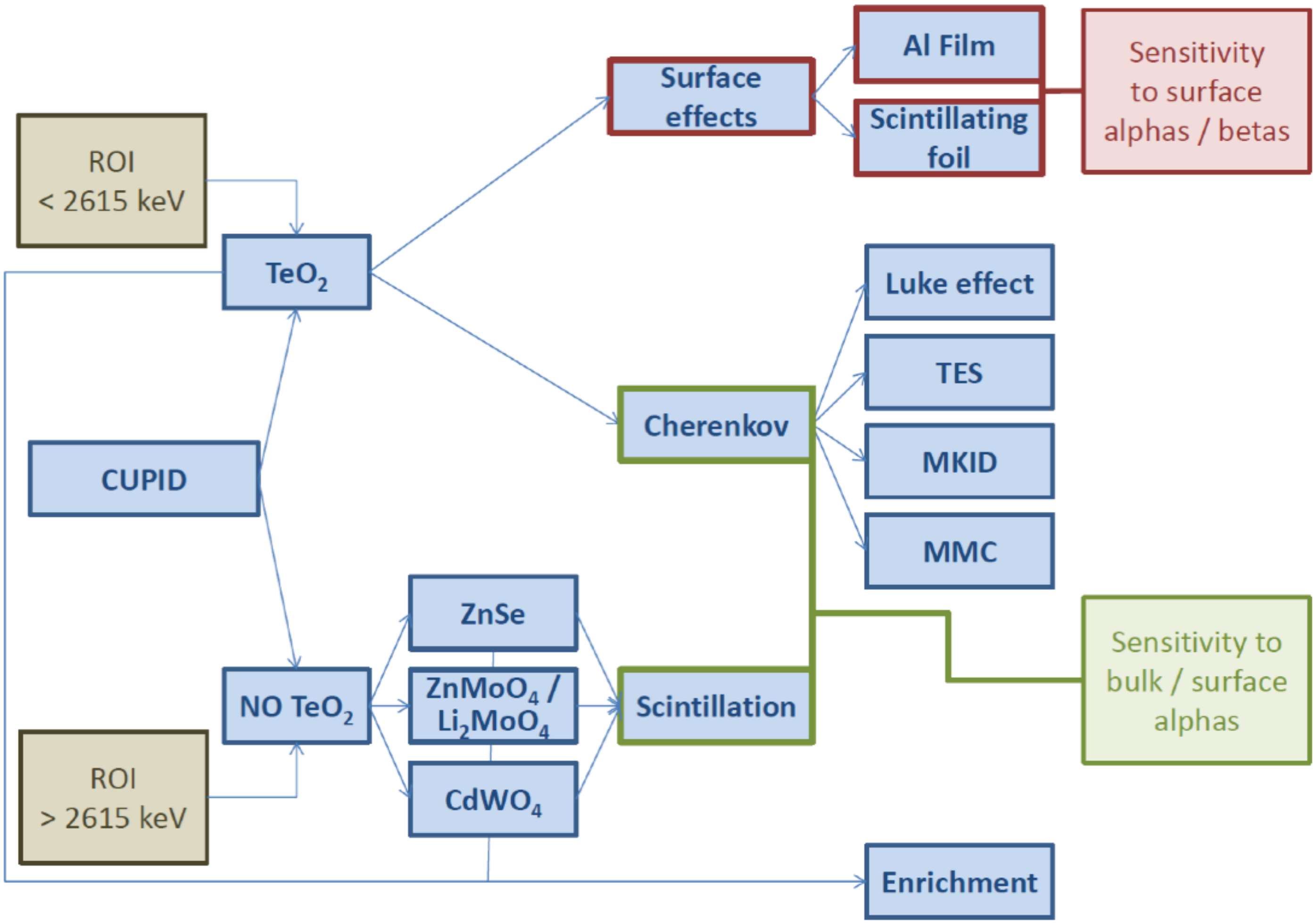


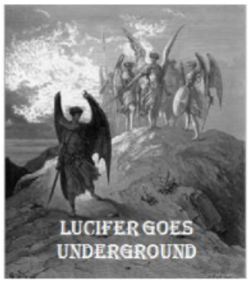
FIG. 1: Scheme of the R&D detector activities for CUPID

from arXiv:1504.03612

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

Lucifer

LUCIFER Low-background Underground Cryogenics Installation For Elusive Rates



demonstrator

isotope: ^{82}Se, ^{100}Mo, ^{116}Cd

material: ZnSe, $ZnMoO_4$, $CdWO_4$

technique: scintillating bolmeter

^{82}Se

✓ Q = 2995 keV > ^{208}Tl line (2615 keV)

✓ Natural abundance: 9.2%

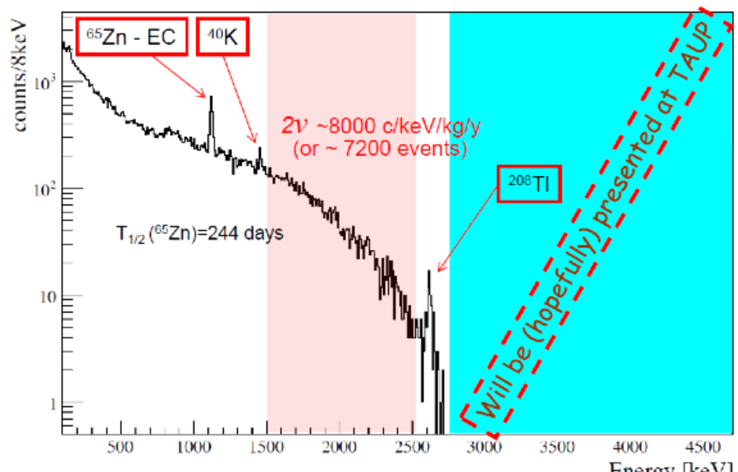
ZnSe scintillates at LT.

From 2016 this activity is funded by INFN under the INFN-CUPID Project. For this reason, LUCIFER is called now CUPID-0 the first demonstrator in view of CUPID.

Fully mounted CUPID-0 detector

from S. Pirro' talk in DBD Shanghai 2017

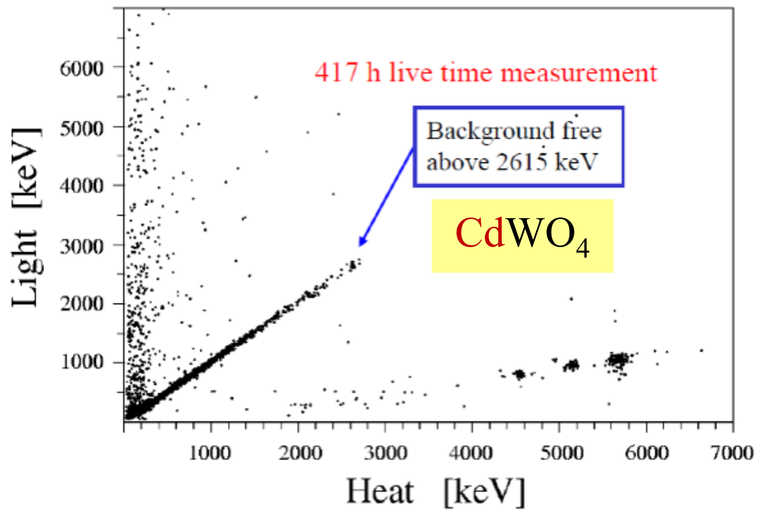
Background Spectrum



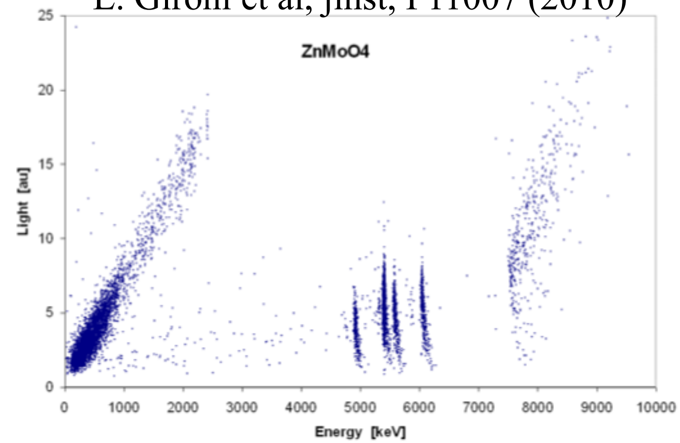
NO other lines (e.g. ^{214}Bi) are (yet) visible in the spectrum !!!

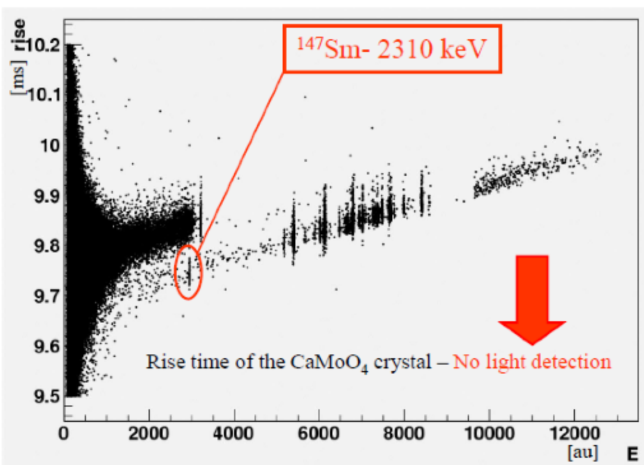
The β/γ background in the ROI *is not yet completely evaluated* since some of the fundamental cuts (delayed ^{212}Bi α-line, anti-coincidences, linearization of shape parameters are not yet fully operative and debugged)

R&D with many scintillating crystals

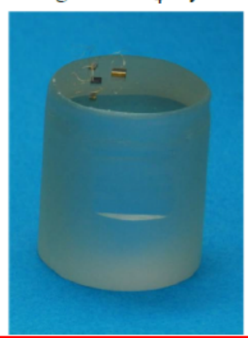


L. Gironi et al, jinst, P11007 (2010)





120 g $CaMoO_4$ crystal

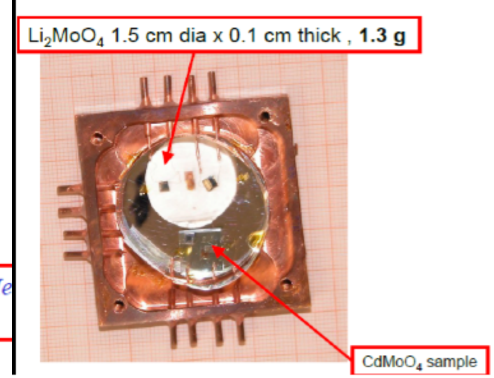


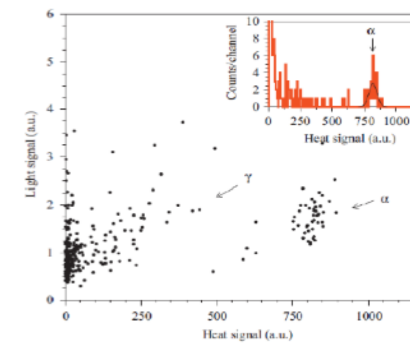
Luca Gironi, *Nucl. Instr. And Me*
A 617 (2010) 478

Nuclear Instruments and Methods in Physics Research A 613 (2010)
Contents lists available at ScienceDirect
Nuclear Instruments and Methods in Physics Research A
journal homepage: www.elsevier.com/locate/nima

First test of Li_2MoO_4 crystal as a cryogenic scintillating bolometer

O.P. Barinova, F.A. Danevich, V.Ya. Degoda, S.V. Kirsanova, V.M. Kudovbenko, S. Pirro, V.I. Tretyak



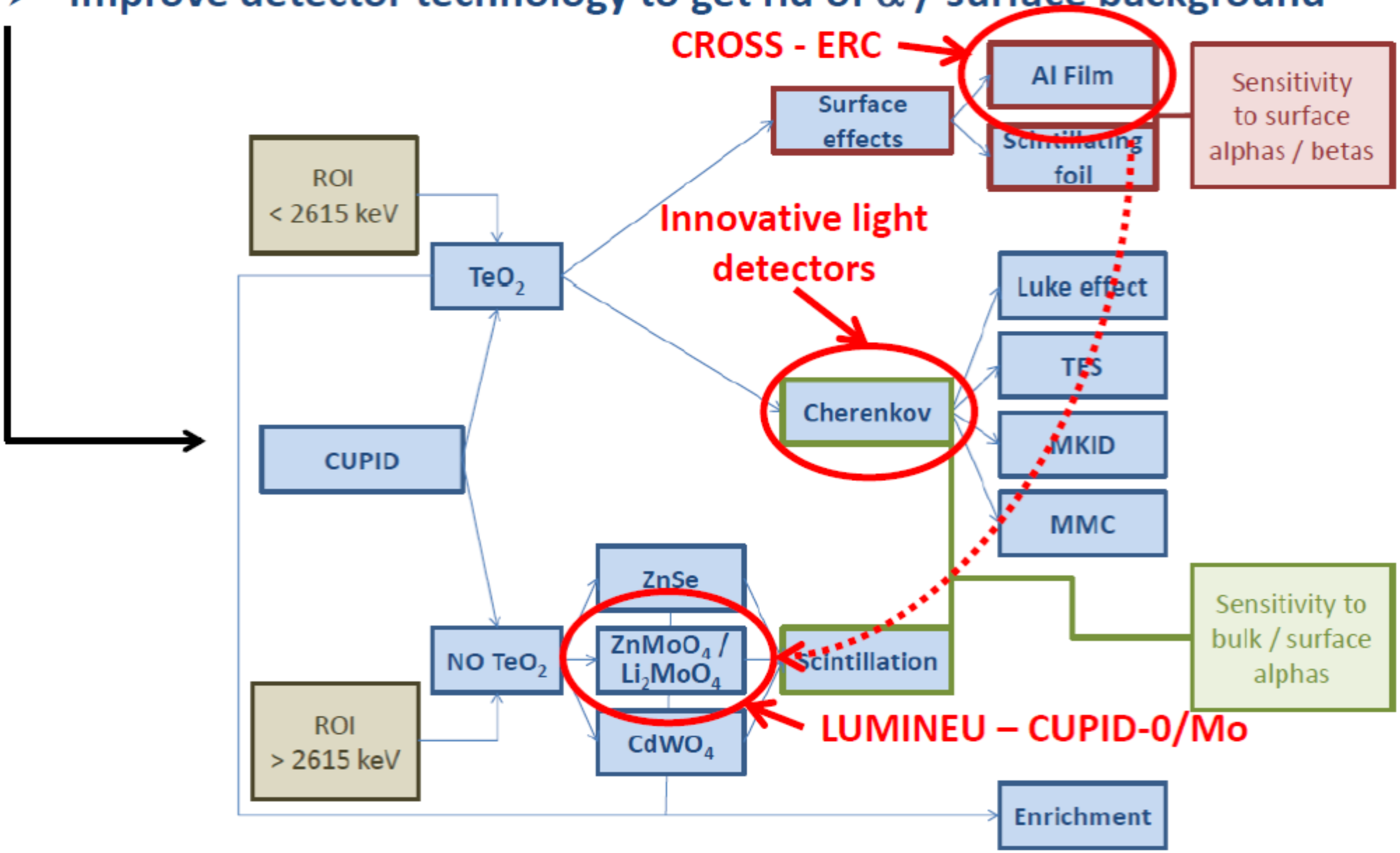


from S. Pirro' talk in DBD Shanghai 2017

CUPID-pilot experiment

Follow-up to CUORE with background improved by a factor 100

- Reduce / control background from materials and from muon /neutrons
- Optimize the enrichment-purification-crystallization chain
- **Improve detector technology to get rid of α / surface background**



from A, Giuliani' talk in DBD Shanghai 2017

CUPID-Mo (←LUMINEU)

^{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

$ZnMoO_4$: Initial choice

Li_2MoO_4 : Selected for a pilot experiment

$Li_2{}^{100}MoO_4$

Multiple tests with **natural and enriched crystals** (2014-2017) in LSM and LNGS with outstanding results in terms of: *http://arxiv.org/abs/1704.01758*

Reproducibility	→	excellent performance uniformity
Energy resolution	→	**~ 4-6 keV FWHM** in RoI
α/β separation power	→	**> 99.9 %**
Internal radiopurity	→	**< 5 – 10 μBq/kg in ^{232}Th, ^{238}U; < 5 mBq/kg in ^{40}K**

→ Compatible with $b \leq 10^{-4}$ [counts/(keV kg y)]

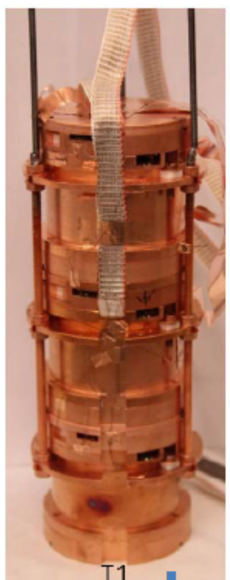
Temperature readout

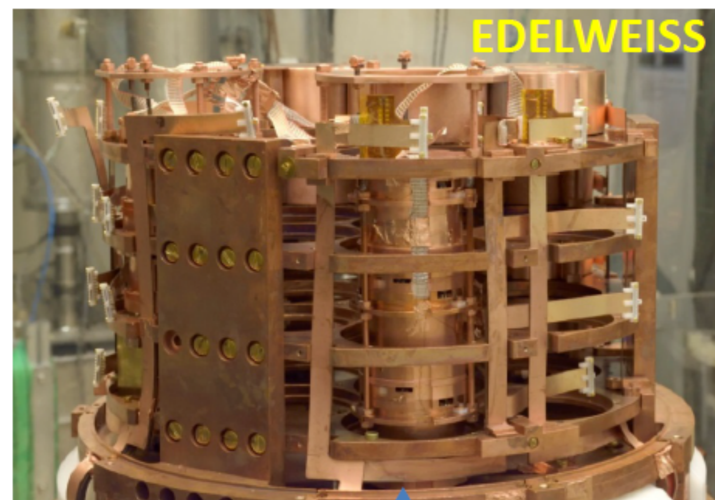
↓

NTD Ge thermistors

+

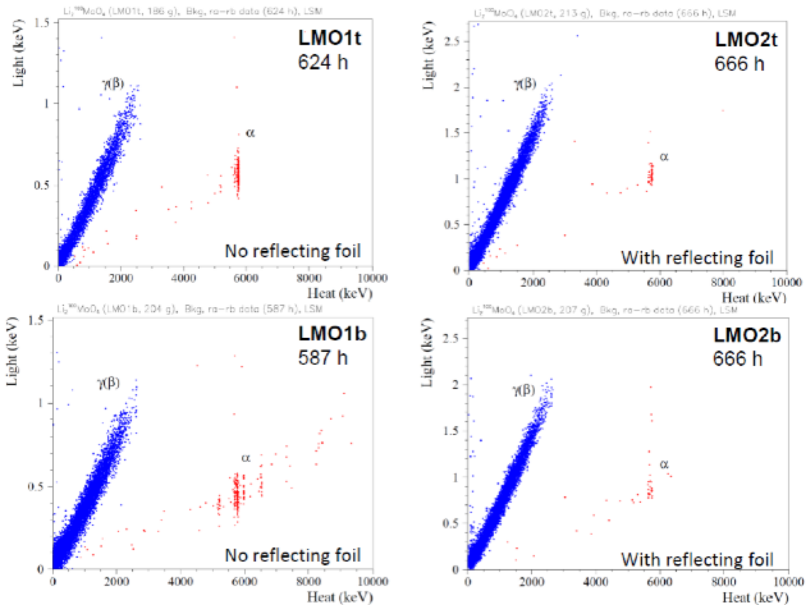
EDELWEISS Cold JEFT

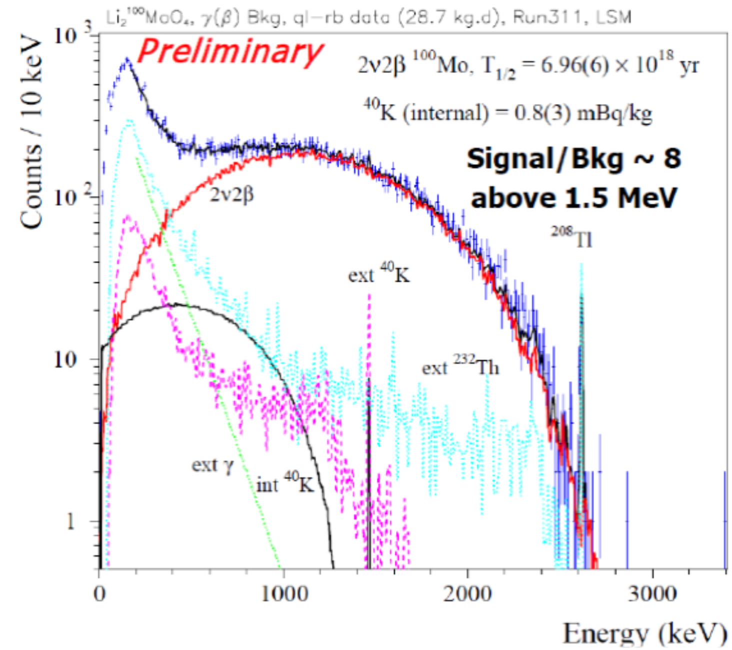




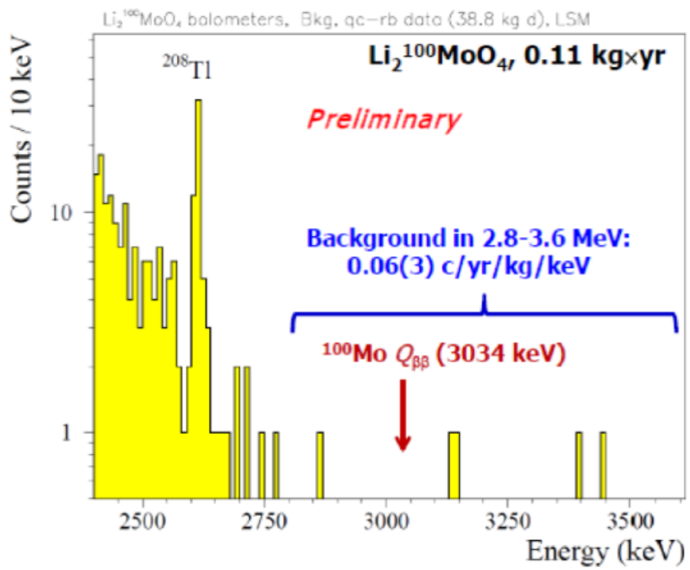
CUPID-Mo performance

99.9% α rejection with **> 99 % β acceptance**





$T_{1/2}(2\nu) = (6.96\pm0.06)\times10^{18}$ y



$T_{1/2}(0\nu) < 0.67 \times10^{23}$ y

$T_{1/2}(0\nu) < 1.1 \times10^{24}$ y from Nemo-3

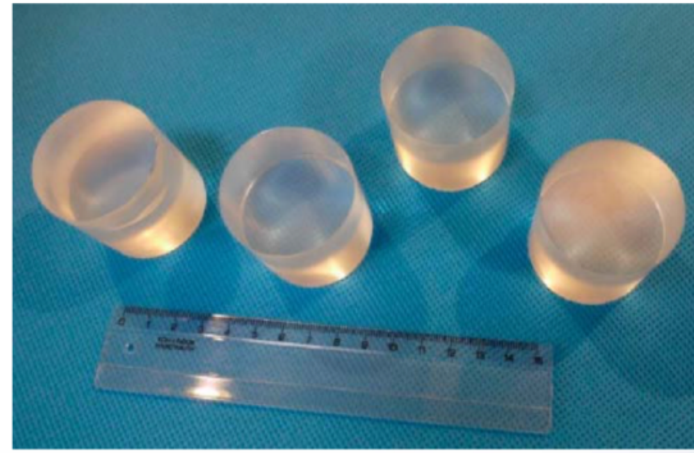
from A, Giuliani' talk in DBD Shanghai 2017

CUPID-Mo begins

CUPID-0/Mo Phase I (20 crystals):

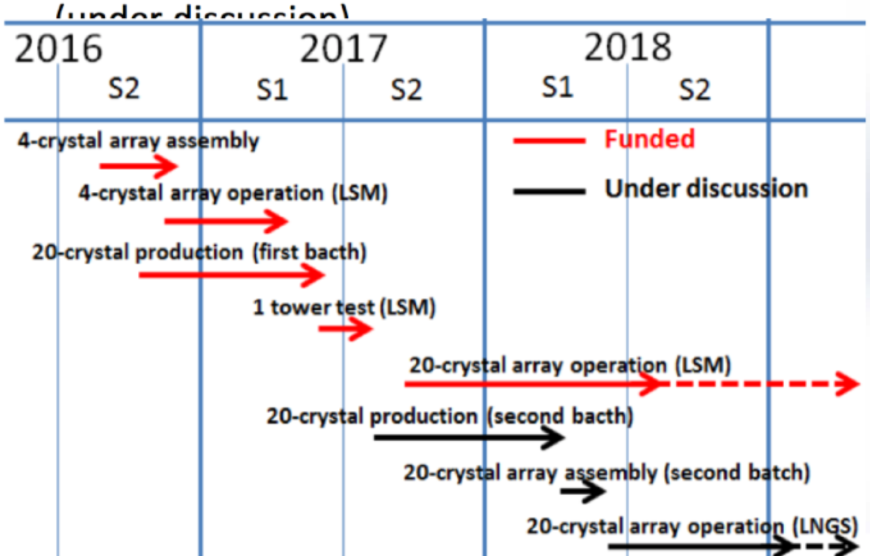
- **20 ^{100}Mo-enriched (97%) Li_2MoO_4 presently in LSM** (∅44×45 mm, 0.21 kg each; 4.18 kg total) ⇒ 2.34 kg of ^{100}Mo (1.37×10^{25} ^{100}Mo nuclei)
- **20 Ge light detectors** (∅44×0.175 mm)+SiO
- **EDELWEISS set-up** @ LSM (France)

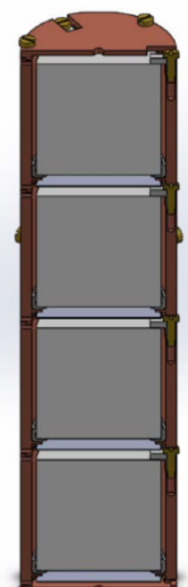
START DATA TAKING: December 2017

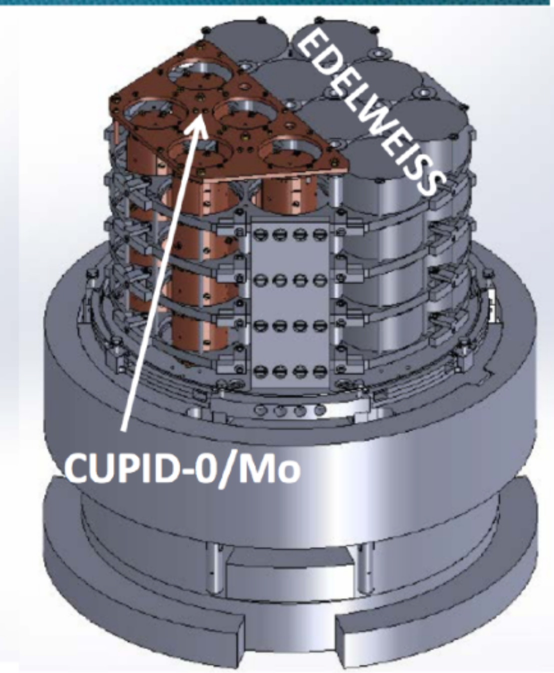


CUPID-0/Mo Phase II (20+20 - or more - crystals):

- At least additional **20 $Li_2{}^{100}MoO_4$**
- **CUPID-0 set-up in hall A** @ LNGS (Italy) (under discussion)







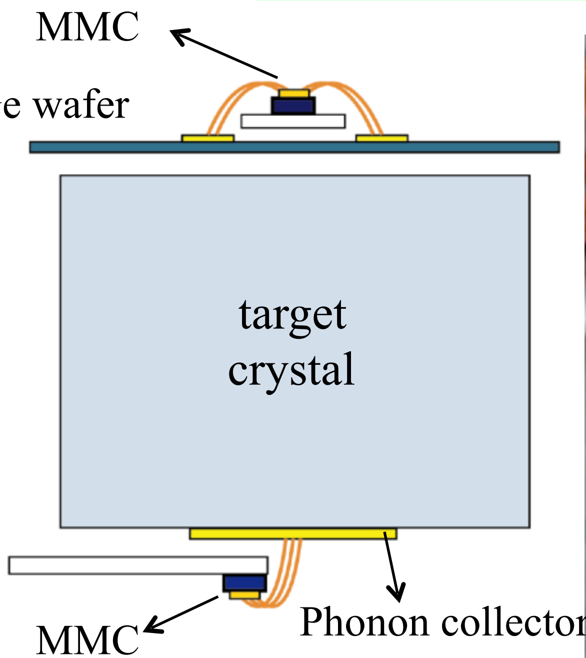
from A, Giuliani' talk in DBD Shanghai 2017

The AMoRE Project

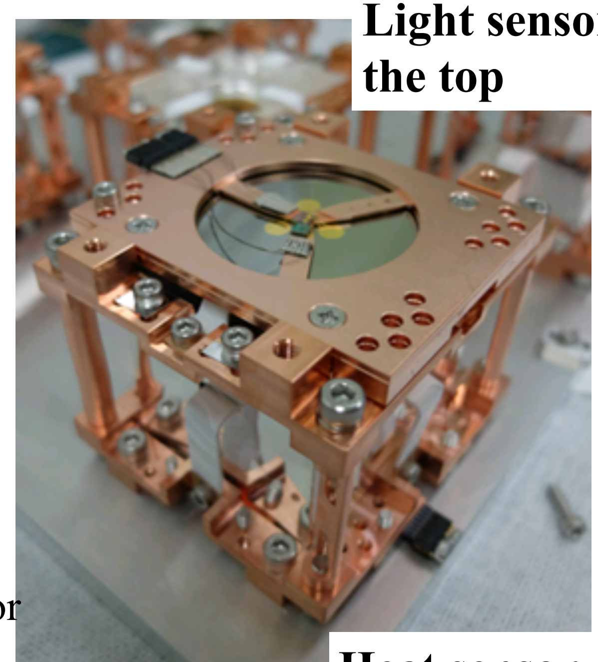
AMORE: ‘Love’ in Italian

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

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



Light sensor at the top



Heat sensor at the bottom

AMoRE

^{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

$Li_2{}^{100}MoO_4$, $Na_2{}^{100}MoO_4$: Possible option for AMoRE-II

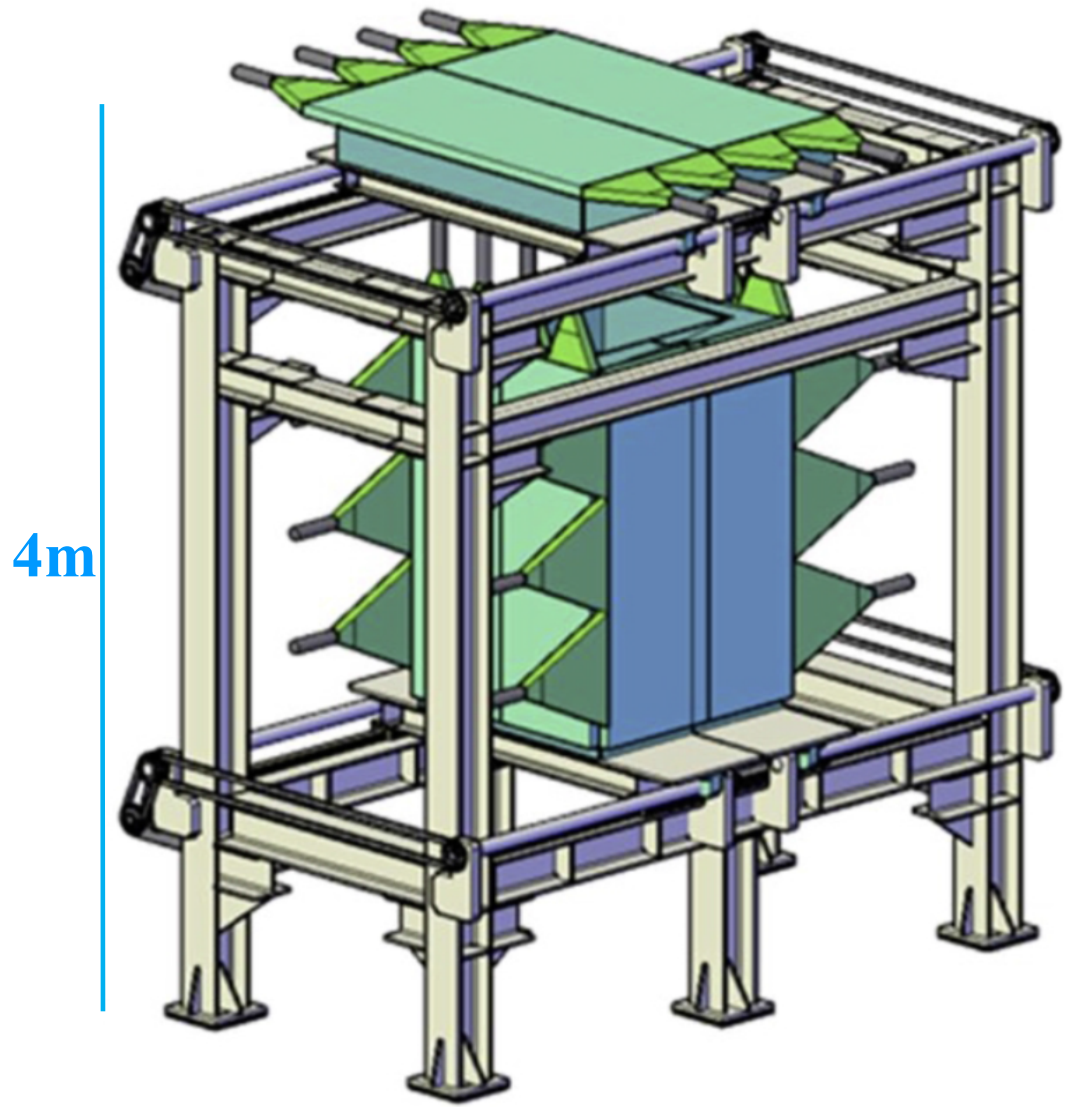
Schedule of the AMoRE project

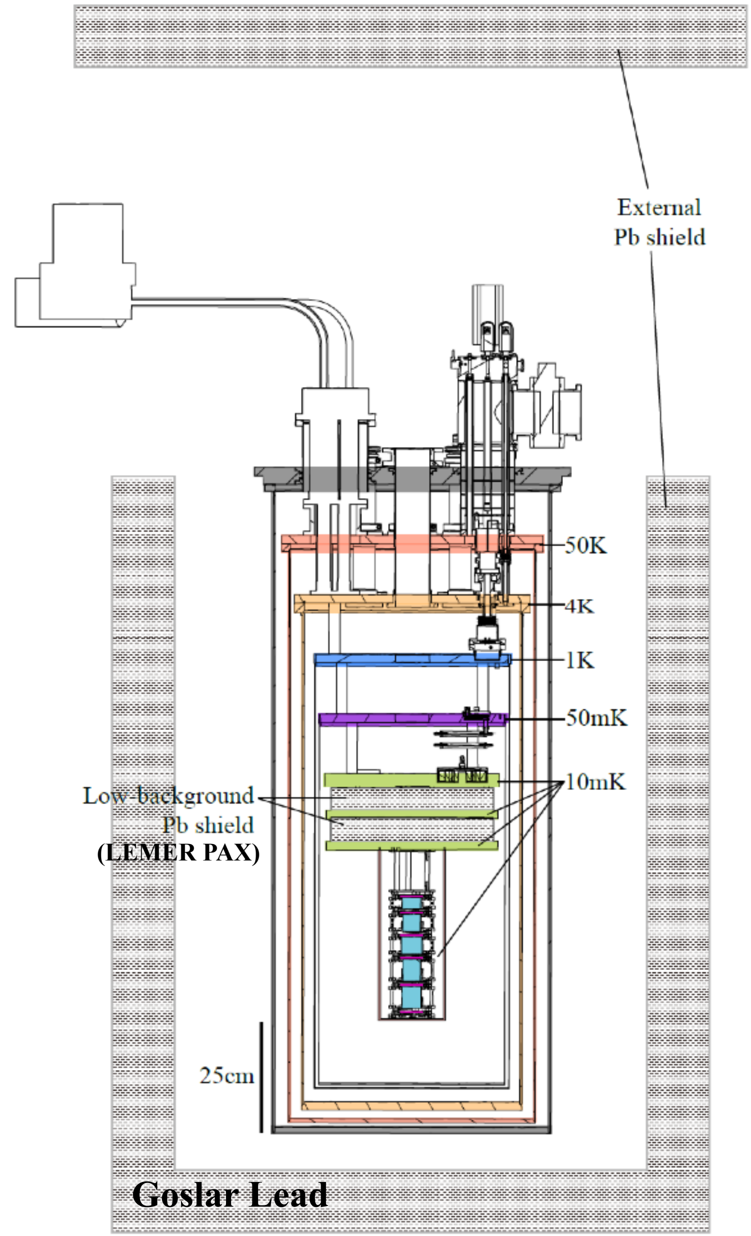
- MMC technology for heat and light measurement
- Crystal: $^{40}Ca^{100}MoO_4$, doubly enriched scintillating crystals (Pilot & I)

  For Phase II: $X^{100}MoO_4$ (X: Li, Na, ^{40}Ca, Zn or Pb)
- Zero background condition in ROI
- Shield: Lead (Pilot, I), Water (II)
- Location: Y2L (Pilot, I) and a new deeper place (ARF at Handuk)

	Pilot	Phase I	Phase II
Mass	1.8 kg	~5 kg	~200 kg
MMC Channel	12	28-36	1000
Required background (ckky)	0.01	0.001	0.0001
Sensitivity($T_{1/2}$) (year)	$\sim 10^{24}$	$\sim 10^{25}$	$\sim 5\times 10^{26}$
Sensitivity($m_{\beta\beta}$) (meV)	380-720	120-230	17-32
Location	Y2L	Y2L	ARF
Schedule	2017	2018-2019	2020-2022

Shields & Cryostat for AMoRE Pilot & I

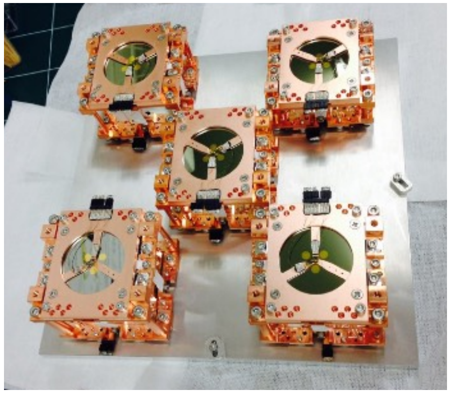


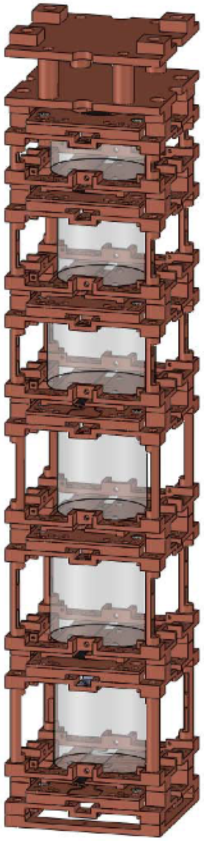


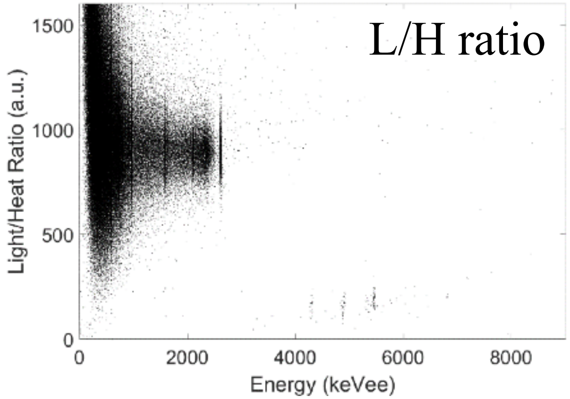
AMoRE pilot : 5 + 1 crystals

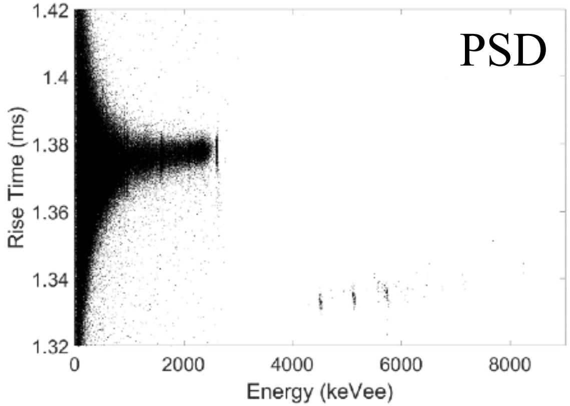
All are installed in a dry dilution refrigerator in Y2L.

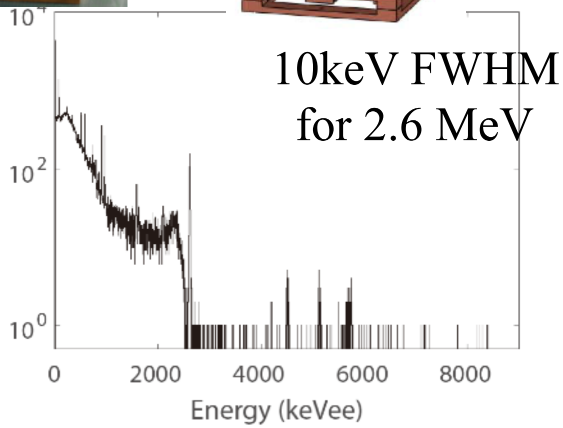
Recently added another crystals: total mass ~ 1.8 kg





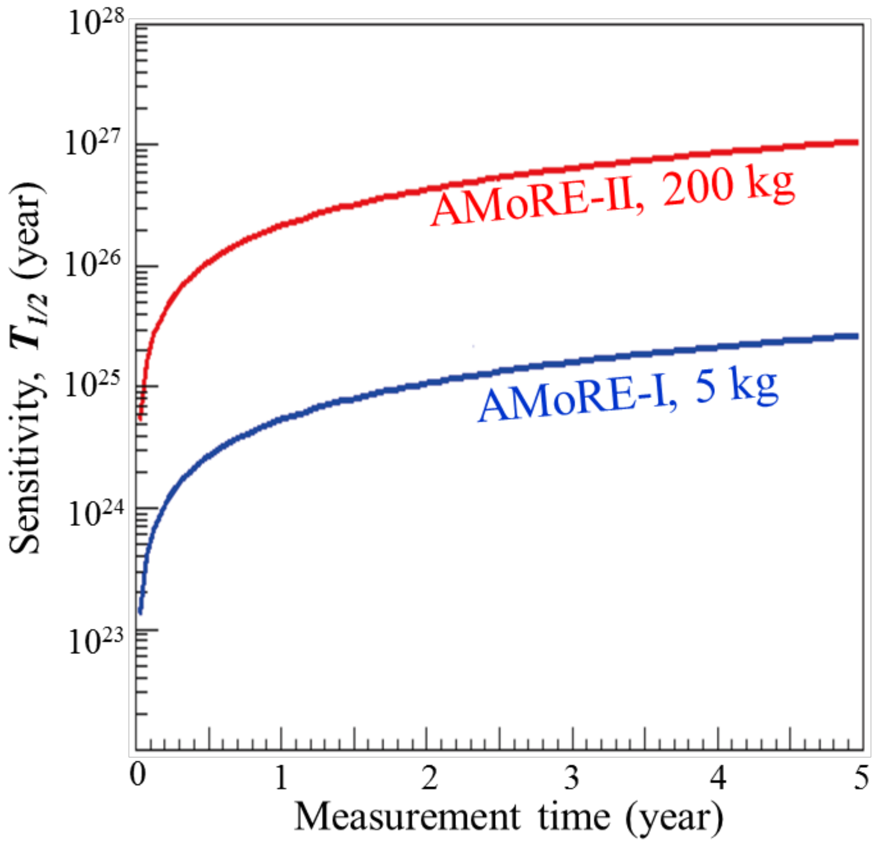


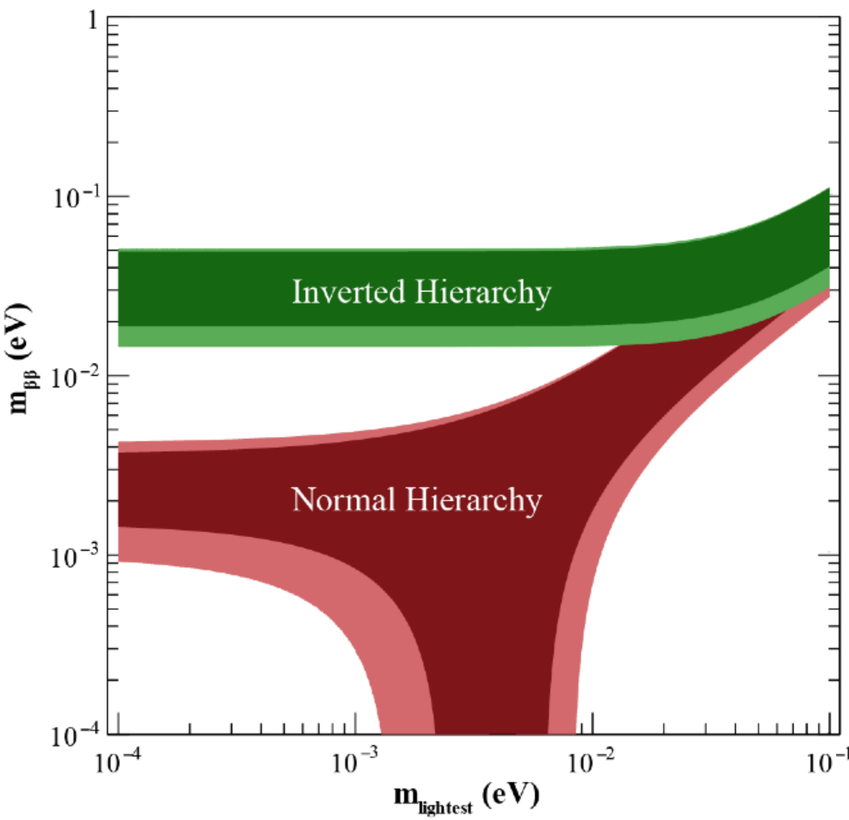




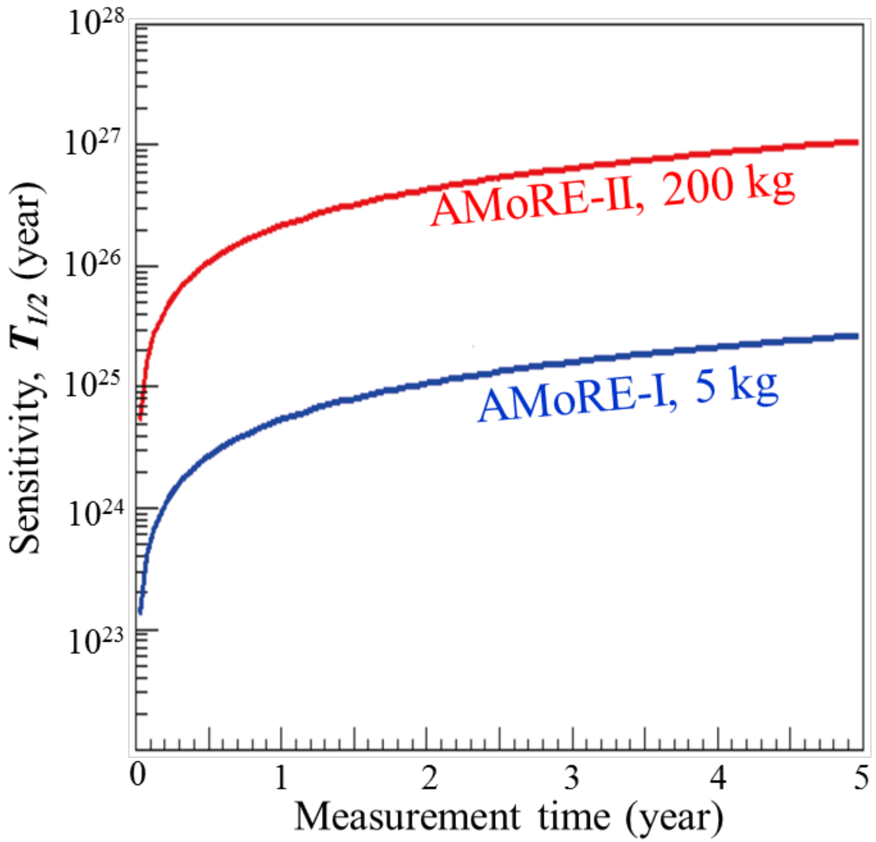
no muon-veto applied

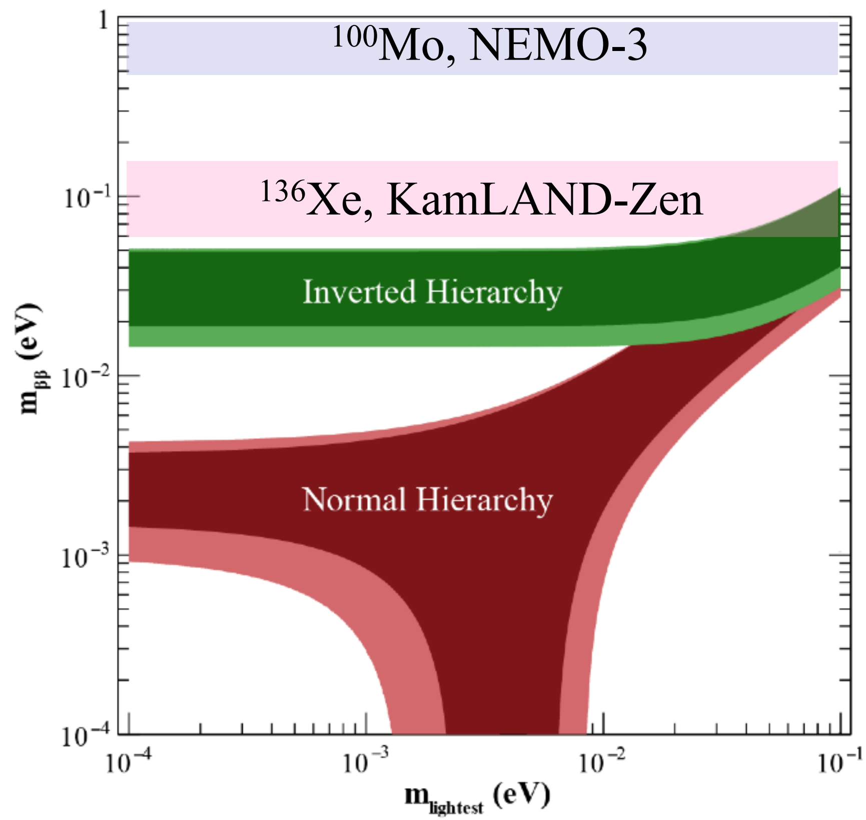
AMoRE Sensitivity



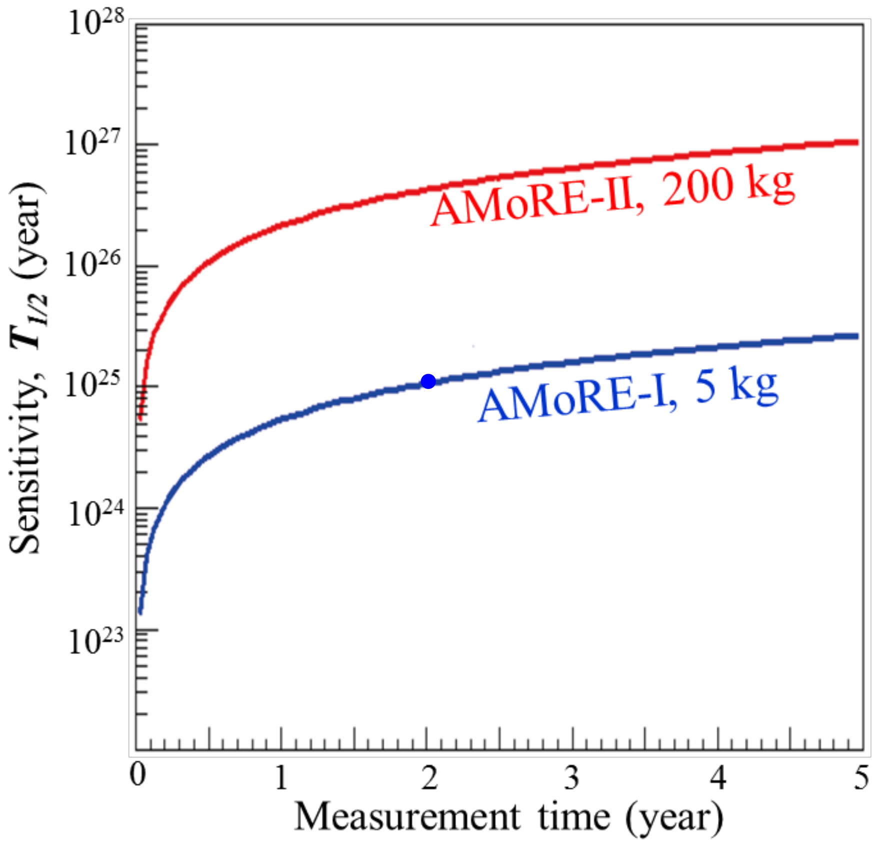


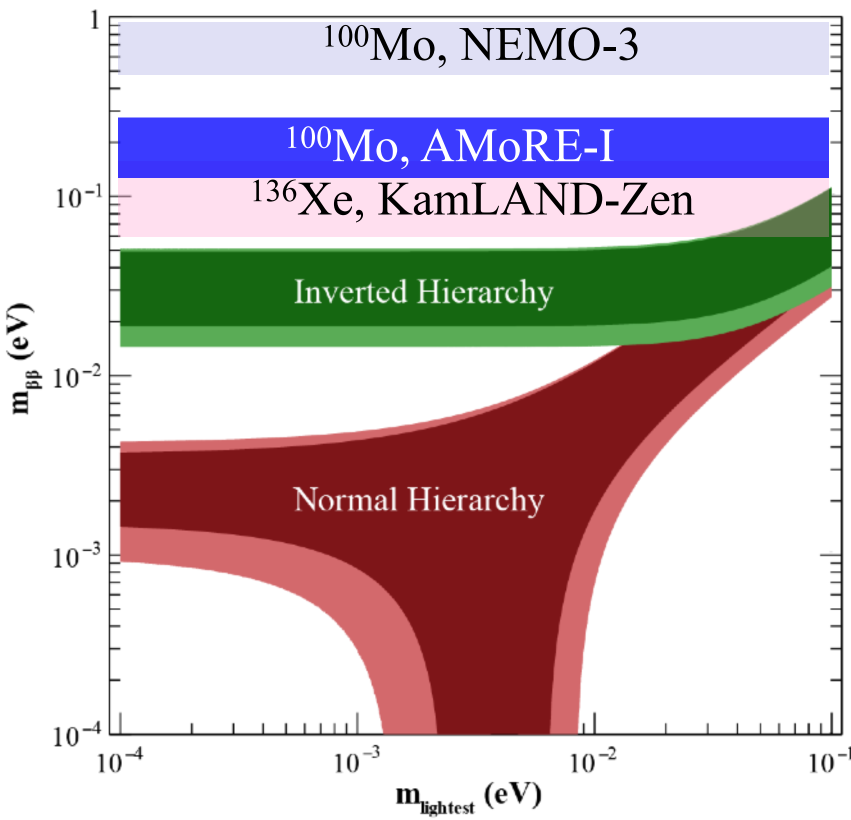
AMoRE Sensitivity



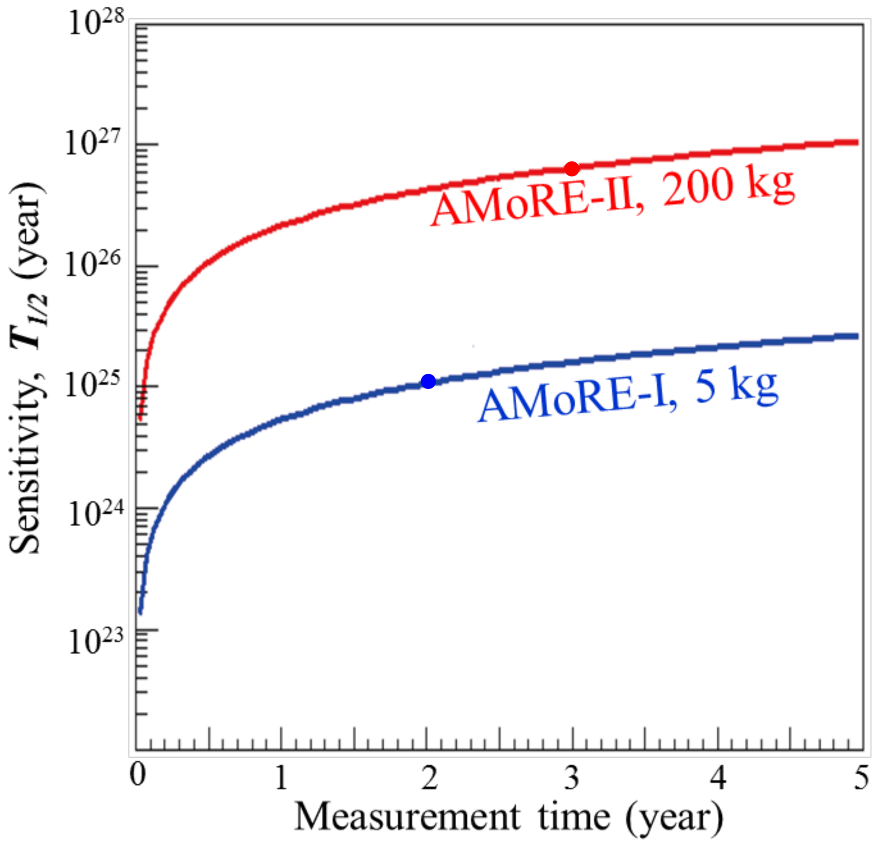


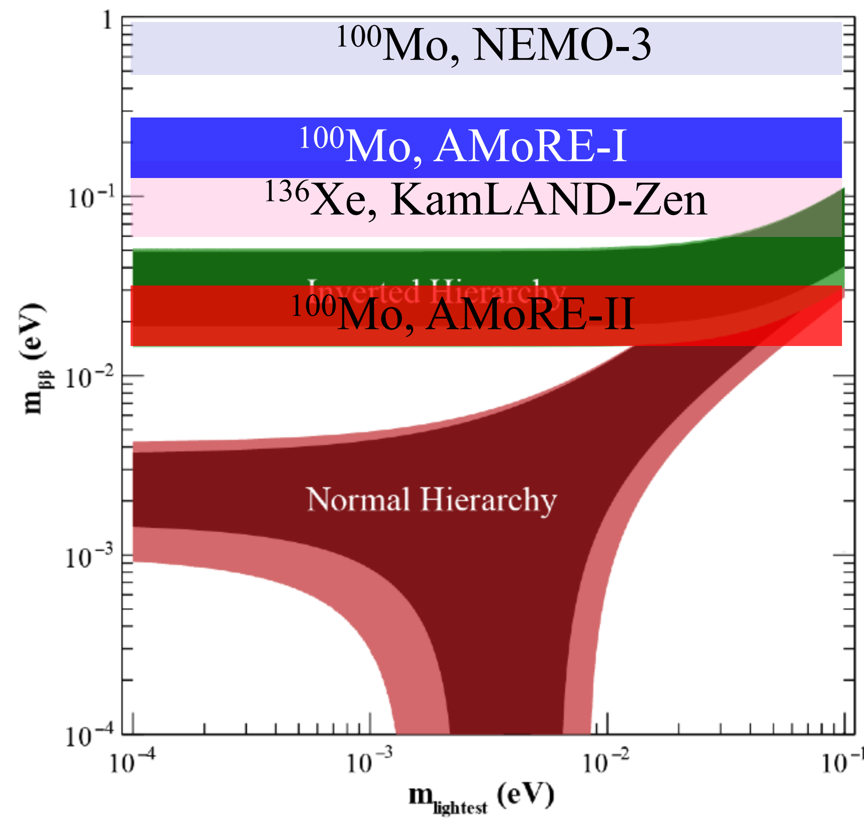
AMoRE Sensitivity





AMoRE Sensitivity

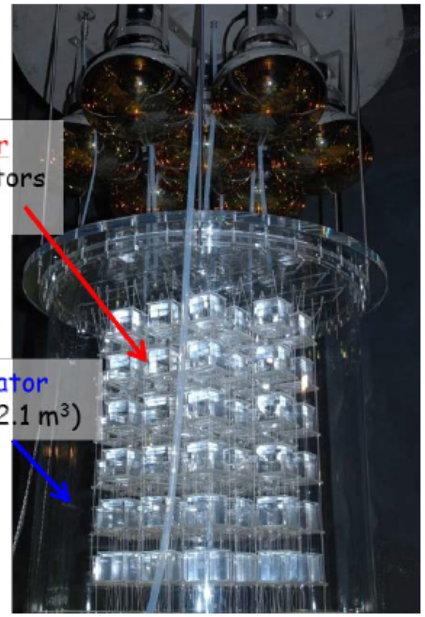




CANDLES experiment

Highest Q-valued

- CANDLES is the project to search for 0νββ decay of ^{48}Ca ($Q_{\beta\beta}$ = 4.27 MeV)
- The CANDLES-III detector is currently installed in Kamioka Underground.

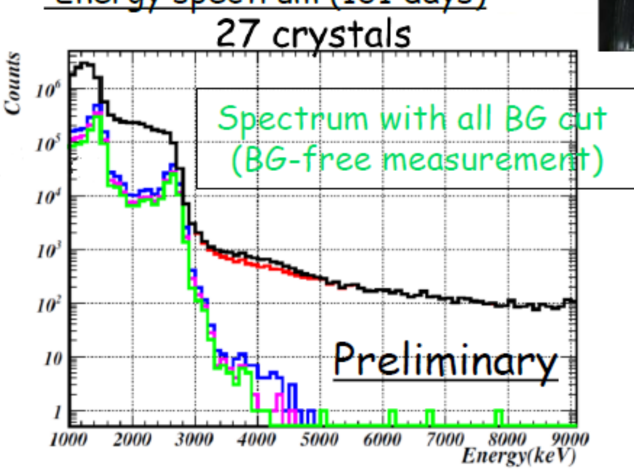


- CaF_2 Module
  - CaF_2(Pure) ; 96 Crystal → 305 kg
  - WLS Phase ; 280 nm → 420 nm
    - Thickness ; 5 mm
    - Mineral Oil + bis-MSB (0.1 g/L)

4π Active shield

- Liquid Scintillator (LS)
  - 1.37 m ϕ x 1.4 m height
  - Volume ; 2.1 m³ (1.65 ton)
  - Composition
    - Solvent ; Mineral Oil(80%) + PC(20%)
    - WLS's ; PPO (1.0g/L) + bis-MSB (0.1g/L)
- PMTs + Light pipe
  - 13 inch (Side) ; x 48
  - 20 inch (Top and Bottom) ; x 14
  - Reflector Film : reflectivity ~93%

Physics run in 2016 ~
Energy spectrum (131 days)



- Toward "Background Free Measurement"
  - Designed the shields → finished the construction.
    - Lead Bricks (10 ~ 12 cm thick)
    - Boron loaded sheet

Installed in 2016

  - Number of BG after shield installation estimated
    - Rock : 0.34±0.14 event/year
    - Tank : 0.4±0.2 event/year

LT-CANDLES

^{48}Ca

✓ Q = 4271 keV. The highest Q

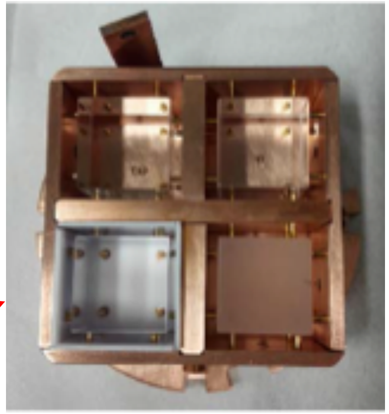
✓ Natural abundance : 0.187%

CaF_2 , CaF_2(Eu)

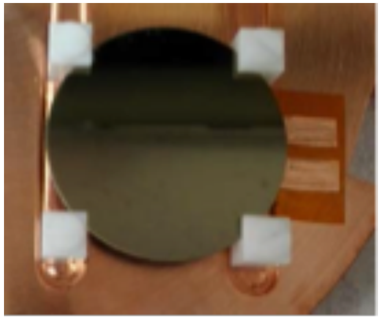
2 cm cube of CaF_2 for the first try with NTD Ge thermistors in Osaka University.

Fridge and measurement system were developed in Uinv. of Tokyo

Detector holder



Light detector (Ge wafer)

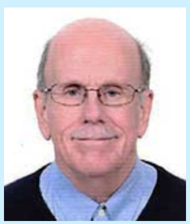


Importance of 0νββ process in physics

- 0νββ search is the direct test of ν for massive Majoanana particles
- The 0νββ decay rate ($1/T^{0\nu}$) is closely related to the mass of neutrinos.
- The 0νββ decay can only happen if Lepton number conservation is violated.

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

Prof. Steve Olsen, a particle physicist (former spokesperson of Belle) :



Yong-Hamb, you seem too modest about 0νββ goals. If, indeed, you see a signal that would be the "discovery of the century" or " biggest breakthrough in particle physics since quarks" or something of that scale.

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.
- ✓ Many $0\nu\beta\beta$ projects exist using tech. other than low temperature.

  Not just competing with, but try to help each other
- ✓ The (LT) $0\nu\beta\beta$ community has been supportive to second movers like AMoRE.

Thank you for your attention.