Present Status of Low Temperature Detector for Neutrino-less ββ Decay

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Detector E-Resolution

Widely used radiation detector

- ☐ Scintillator

Photon

（例） NaI(Tl) Scintillator

Scintillation photons　4.2×10^4 photons/MeV

Resolution（ΔE @1 MeV）　~ several tens keV

- ☐ Semiconductor

Ionization

（例） HPGe detector

Electron-hole pair　E_{gap}~2 eV ➔ 5×10^5 pairs/MeV

Resolution（ΔE @1 MeV）　2~3 keV

Energy resolution is determined by statistical fluctuation of quantum (and fano-factor).

How about Phonon？

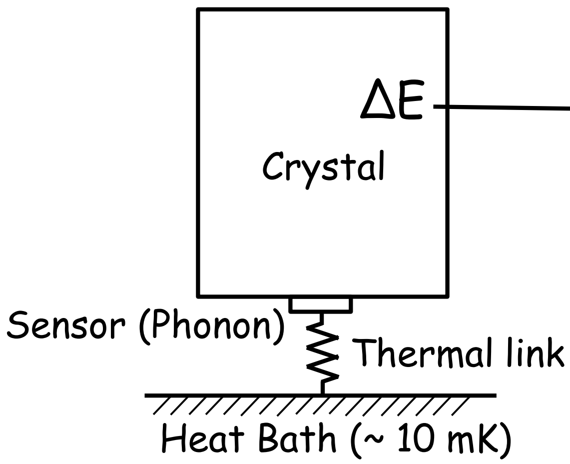
At 1 K under thermal equilibrium, mean energy of phonons $k_B T$ ~ 80 μeV

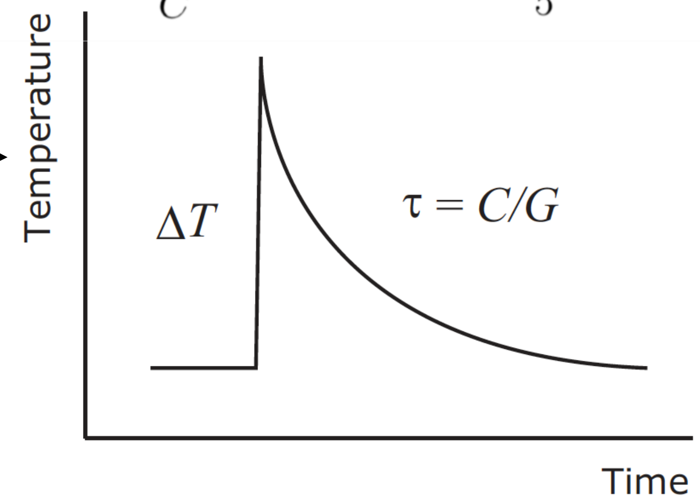
At Debye temperature ~ 100 meV

➔ Phonon detector (Bolometer)

Bolometer

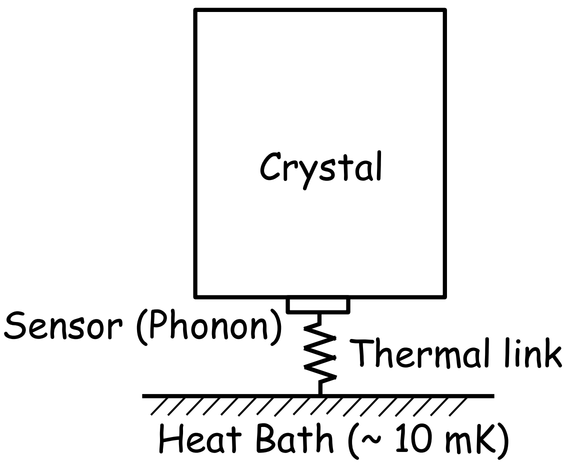
$$\Delta T(t) = \frac{E}{C} e^{-\frac{t}{\tau}} \qquad C_r(T) = \frac{12}{5}\pi^4 k_B N_A \left(\frac{T}{T_D}\right)^3$$

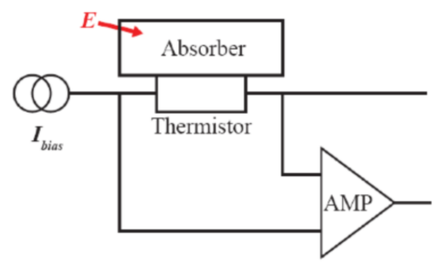




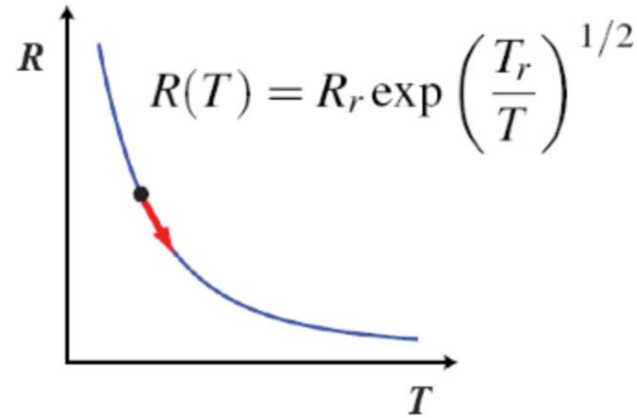
- Calorimetric measurement of heat signals **at mK temperatures**
  - **Energy absorption ➔ Temperature increase**
  - **Good Energy resolution ; expected.**
- Choice of thermometers to measure temperature increase
  - **Thermistors (NTD Ge)** CUORE, CUPID (some options)
  - TES (Transition Edge Sensor) Light detector, CRESST
  - **MMC (Metallic Magnetic Calorimeter)** AMoRE, LIMINEU
  - KID (Kinetic Inductance Device) CALDER
  - etc.

NTD-Ge as Temperature Sensor





<Current bias and read voltage >

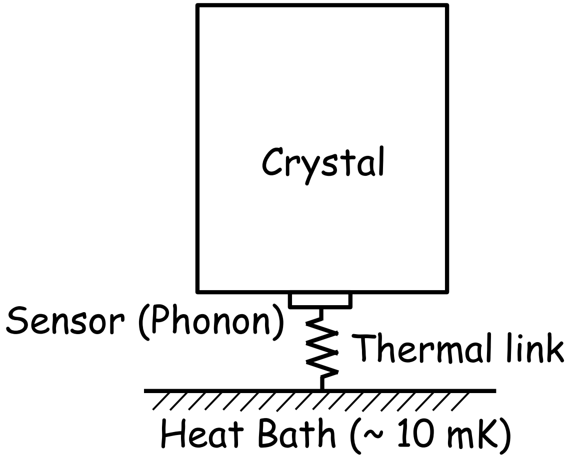


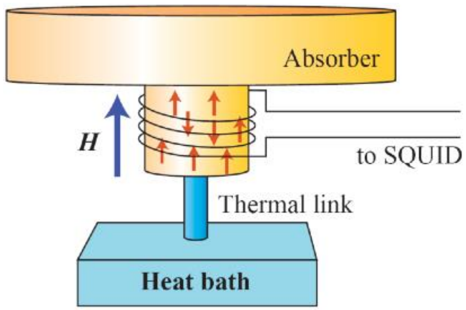
Changing MΩ ~ 100MΩ by temperature change

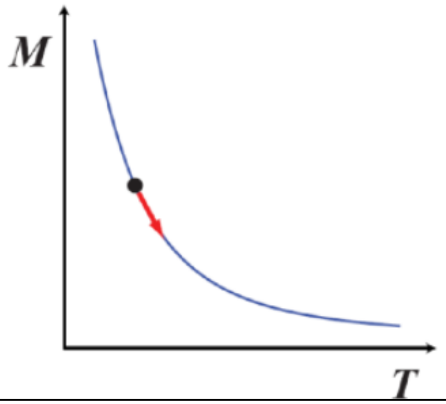
Properties of NTD-Ge

- Doped semiconductors
  - Neutron transmuted doped (NTD) Ge thermistors
- 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**

MMC as Temperature Sensor







Process of detecting signal

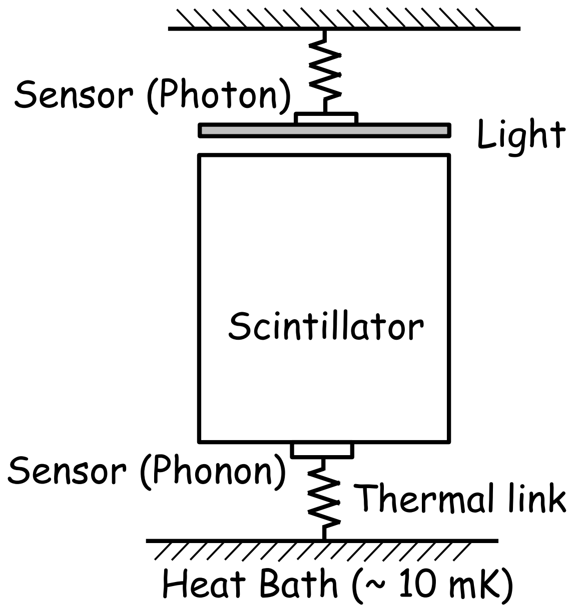
① Energy absorption in a crystal
② Phonon and photon generation
③ Temperature increase
④ Magnetization of MMC decrease
⑤ SQUID pickup the magnetization change

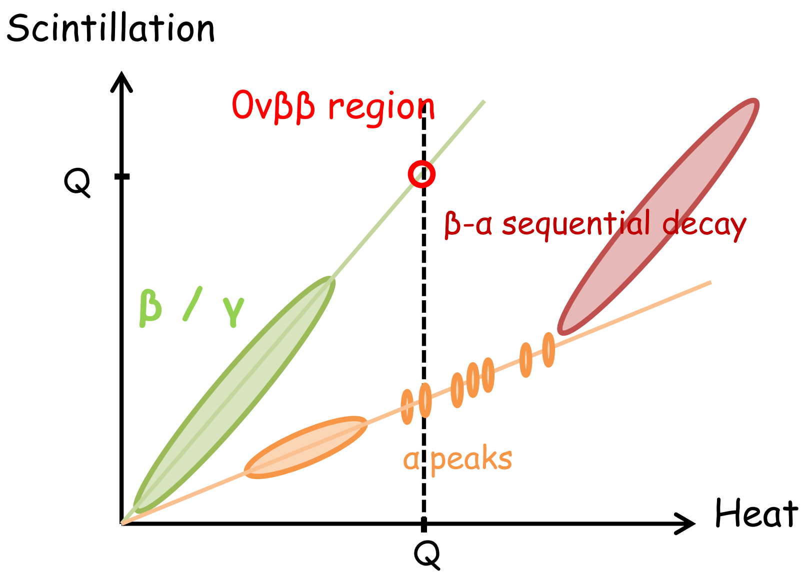
Properties of MMC

- 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**

Scintillating Bolometer

- The technique (scintillating bolometer) was already established,
  - CRESST-II ($CaWO_4$), LUMINEU, Lucifer, CUPID, AMoRE ($CaMO_4$)





- Simultaneous measurement both heat and scintillation enables to identify the particle types (α/β particle ID)
- It is possible to reject alpha decay events, also β-α sequential events

➔ Chance to achieve "BG free measurement"

Bolometer Detector for 0νββ study

- COURE Experiment ; Running experiment

CUORE

Info. from official website https://cuore.lngs.infn.it/

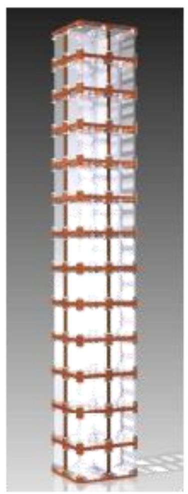
- Site：Gran Sasso (Italy) ~3600 m.w.e
- Target： 741 kg TeO_2 (~206 kg ^{130}Te), 988 crystals in 19 towers
  - Natural abundance of ^{130}Te; 34 %, $Q_{\beta\beta}$ = 2528 keV
- Temperature Sensor：NTD-Ge Thermistor
- Operated at ~10 mK. Energy resolution ~0.2% FWHM

	Cuoricino	CUORE-0	CUORE
^{130}Te mass (kg)	11	11	206
Background (c/keV/kg/y) @ 2528 keV	0.17	0.05	0.01
E resolution (keV) FWHM @ 2615 keV	7	5–6	5
$\langle m_{\beta\beta} \rangle$ (meV) @ 90% C.L.	300–710	200–500	40–90

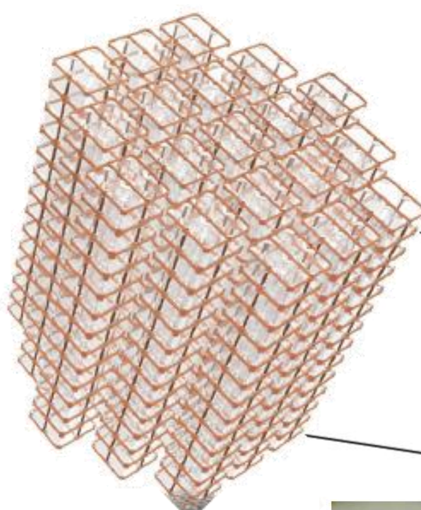
Excellent ΔE

History

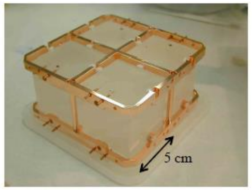
Cuoricino
2003–2008
11 kg ^{130}Te

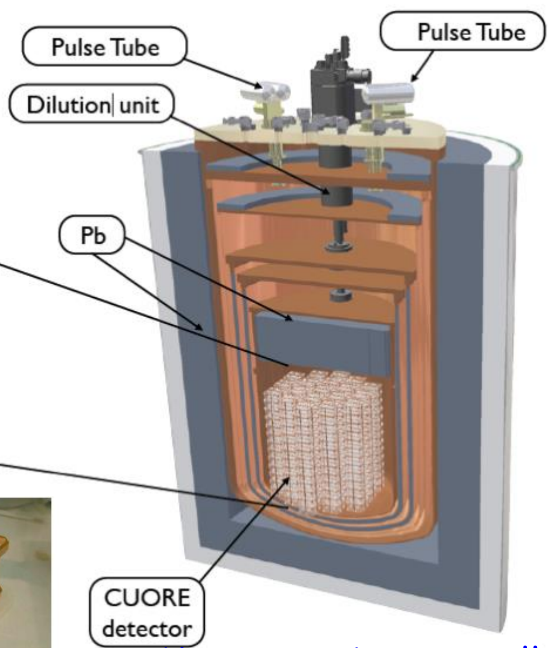


CUORE-0
2012–2014
11 kg ^{130}Te



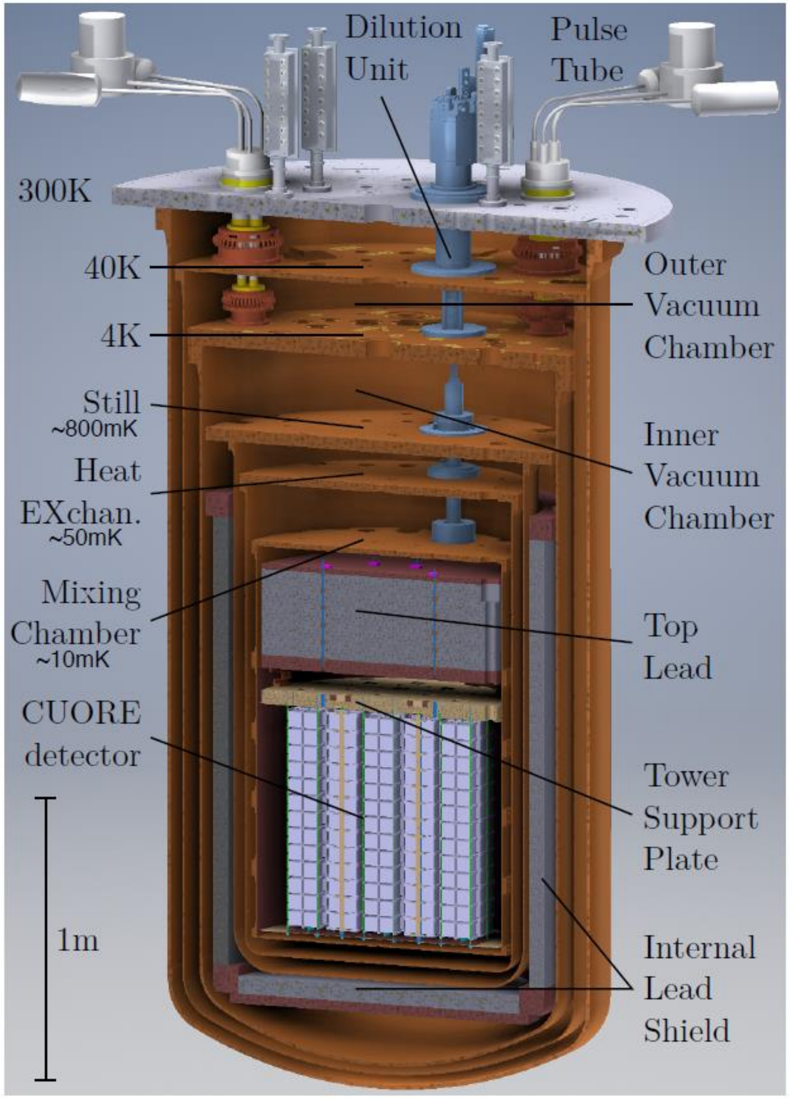
CUORE
2013–2018
206 kg ^{130}Te





Monster Cryostat !!

CUORE; ton-scale @mK facility



Cryogenics ***93****, 56-65 (2018).*

- Powerful dilution refrigerator
  - cooling power: 5 μW at 10 mK
- Precooled by 4 pulse tubes
- Cryogenic stages and loads:
  - 13 tonnes < 4 K
  - 5 tonnes < 50 mK
  - 1500 kg @ 10 mK (detectors + materials)
- Experimental volume ~1 m^3
- Cooldown time ~ 1 month
- External Shielding:
  - 18 cm polyethylene + 2 cm borated material
  - 30 cm lead

Results of CUORE

Phys. Rev. Lett. 124, 122501 (2020)

- Data taking started in Spring 2017
  - ~ 1000 kg x year exposure of Te
- First result from CUORE-0 dataset:
  - 372.5 kg x year
  - Likelihood model
    - flat continuum (BI) + ^{60}Co (rate + position)

- No evidence for 0νββ decay

$$T_{1/2}^{0\nu} > 3.2 \times 10^{25}\ \mathrm{yr}\ (90\%\ \mathrm{C.I.})$$

- Interpretation in context of light Majorana neutrino exchange

$$m_{\beta\beta} < 75 - 350\,\mathrm{meV}$$

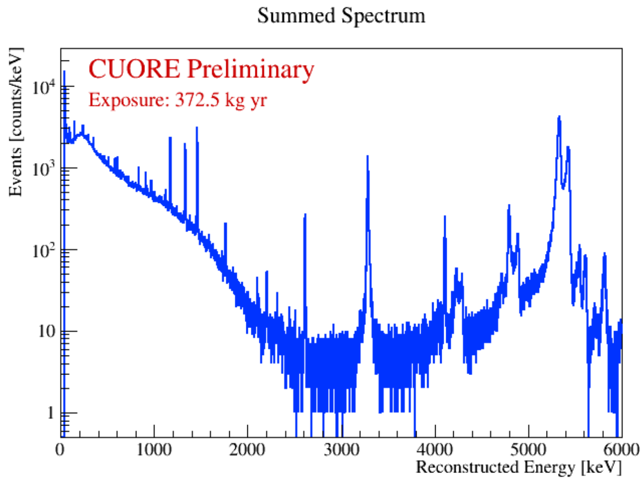
Detector Performance Parameters

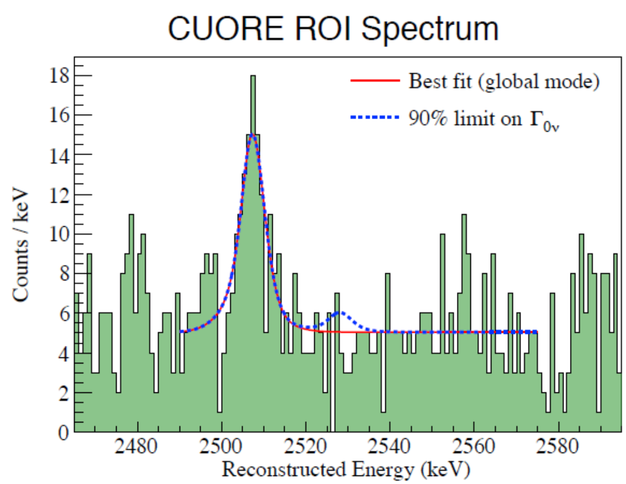
Background Index

$$(1.38 \pm 0.07) \times 10^{-2} \mathrm{cnts}/(\mathrm{keV} \cdot \mathrm{kg} \cdot \mathrm{yr})$$

Characteristic FWHM ΔE at $Q_{\beta\beta}$

$$7.0 \pm 0.3\ \mathrm{keV}$$





Scintillating Bolometer for 0νββ study

- CUORE and CUPID
- AMoRE
- Development of CaF_2 Scinti.-Bolometer

CUORE Upgrade : CUPID

Tommy O'Dnell, Talk in DBD18

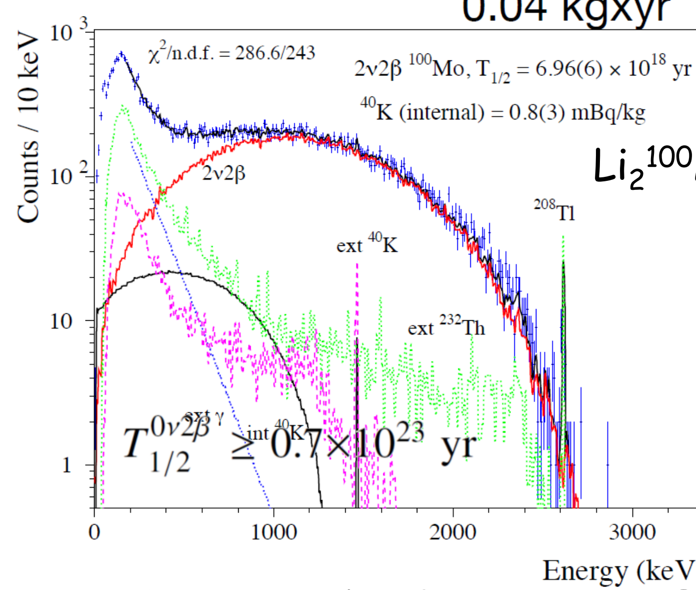
- CUPID (CUORE Upgrade with Particle ID)
  - Option1: Scintillating-Bolometer ($Zn^{82}Se$ / $Li_2{}^{100}MoO_4$)
  - Option2: TeO_2 + Light-detector (PI by Cherenkov photon)
- LMO crystal
  - ^{100}Mo (Q-value: 3034 keV)
  - Enrichment to ~97%
  - Seminal R&D from LUMINEU project
  - Possible to grow large, high purity, high optical quality LMO crystals

CUPID-Mo Prototype

Eur. Phys. J. C (2017) 77:785

Main crystal, Ge wafer cryogenic light detector readout by NTDs

0.04 kgxyr



$Li_2{}^{100}MoO_4$

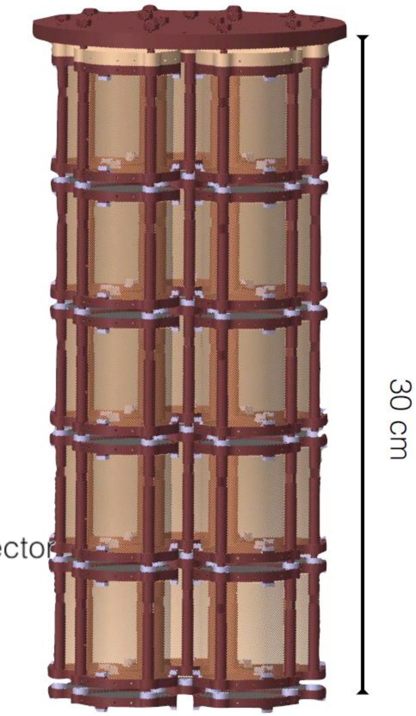
BB-decay results from LUMINEU

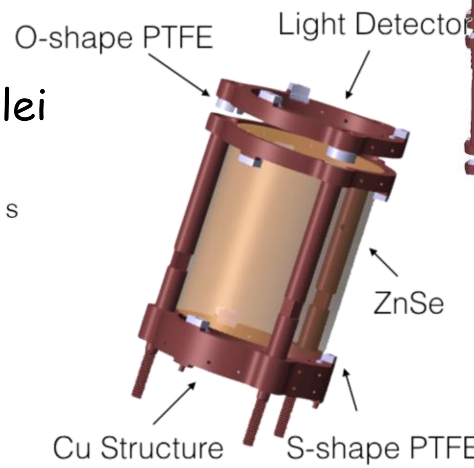
CUORE Upgrade : CUPID-0

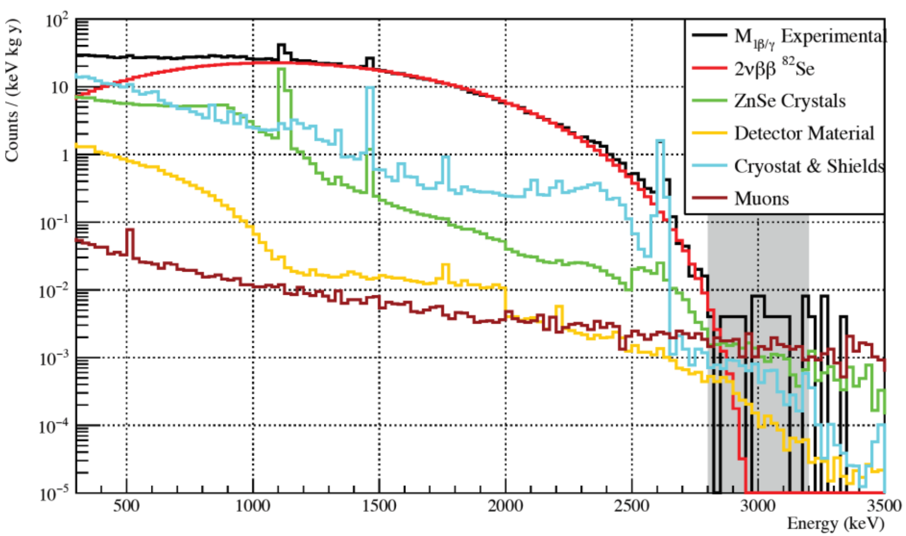
- CUPID (Cuore Upgrade with Particle ID)
  - Option1 : Scintillating-Bolometer ($Zn^{82}Se$ / $Li_2{}^{100}MoO_4$)
  - Option2: TeO_2 + Light-detector (PI by Cherenkov photon)

Luca Pattivina, Talk in DBD18

- $Zn^{82}Se$
  - Q-value: 2998 keV
  - CUPID-0 Se demonstrator now operating at LNGS
  - 26 bolometers (24 enr. + 2 nat) arranged in 5 towers
    - 10.5 kg of ZnSe
    - 5.17 kg of ^{82}Se → $N_{\beta\beta}$ = 3.8×10^{25} ββ nuclei







$T_{1/2}(^{82}Se \rightarrow {}^{82}Kr) > 4.0\cdot10^{24}$ yr @ 90C.L.

$m_{\beta\beta} < (290\text{-}596)^1$ meV

Eur. Phys. J. C 79, 583 (2019)

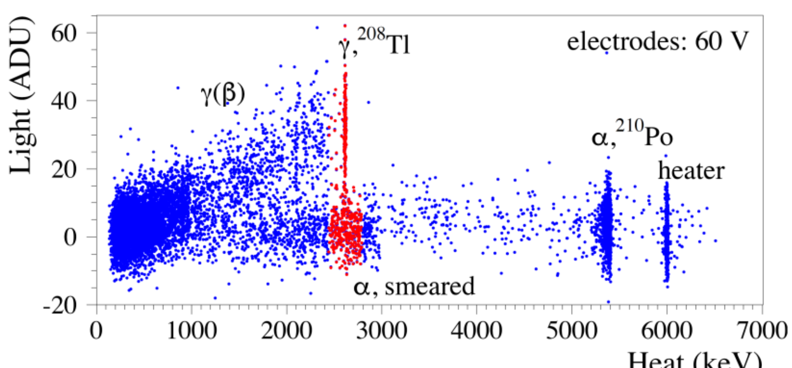
CUORE Upgrade : CUPID

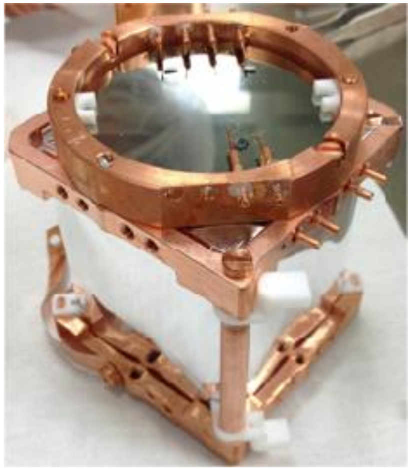
- CUPID (Cuore Upgrade with Particle ID)
  - Option1 : Scintillating-Bolometer ($Zn^{82}Se$ / $Li_2{}^{100}MoO_4$)
  - Option2: TeO_2 + Light-detector (PI by Cherenkov photon)

Tommy O'Dnell, Talk in DBD18

- TeO_2 + Cherenkov photon
  - Q-value: 2527 keV
  - R&D to discriminate electron/alpha events based on Cherenkov light
  - Low threshold bolometric light detectors
  - Light detector thermometry (standard NTD-Ge)
    - TES and KIDs are being investigated

Phys. Rev. C **97** 032501 2018





99.9% α event rejection with >95 % signal acceptance

CUORE Upgrade : CUPID

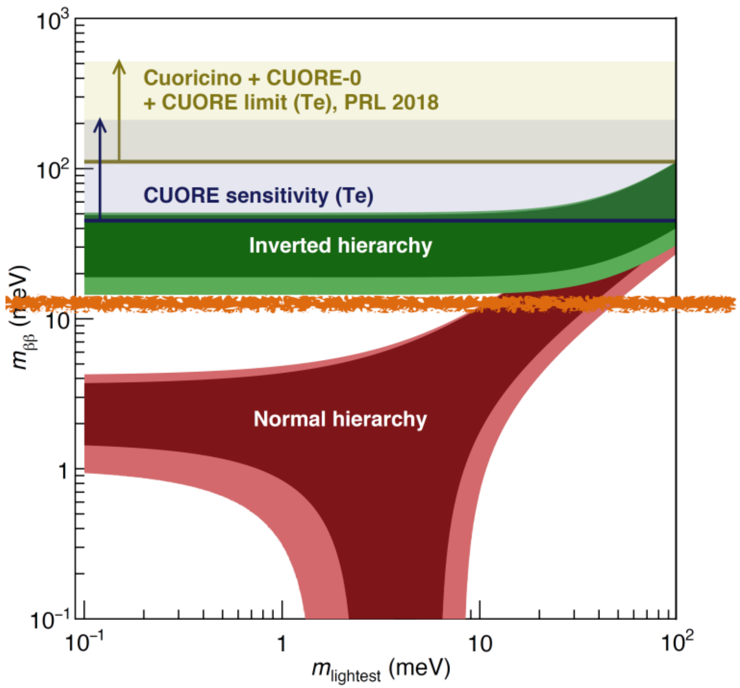
Tommy O'Dnell, Talk in Neutrino2020

- CUPID (Cuore Upgrade with Particle ID)
  - Option1 : Scintillating-Bolometer (Zn^{82}Se / $Li_2{}^{100}MoO_4$)
  - Option2: TeO_2 + Light-detector (PI by Cherenkov photon)

- Baseline target isotope is ^{100}Mo embedded in $LiMoO_4$ scintillating bolometers

<u>Proposed Design of CUPID</u>

Parameter	CUPID Baseline
Crystal	$Li_2{}^{100}MoO_4$
Detector mass (kg)	472
^{100}Mo mass (kg)	253
Energy resolution FWHM (keV)	5
Background index (counts/(keV·kg·yr))	10^{-4}
Containment efficiency	79%
Selection efficiency	90%
Livetime (years)	10
Half-life exclusion sensitivity (90% C.L.)	1.5×10^{27} y
Half-life discovery sensitivity (3σ)	1.1×10^{27} y
$m_{\beta\beta}$ exclusion sensitivity (90% C.L.)	10–17 meV
$m_{\beta\beta}$ discovery sensitivity (3σ)	12–20 meV

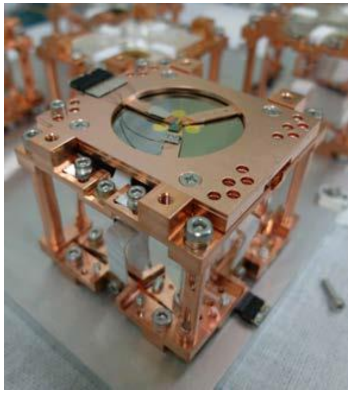


AMoRE Advanced Mo based Rare process Experiment

Yong-Hamb Kim, LTD-17@Kurume & talk in TAUP2019

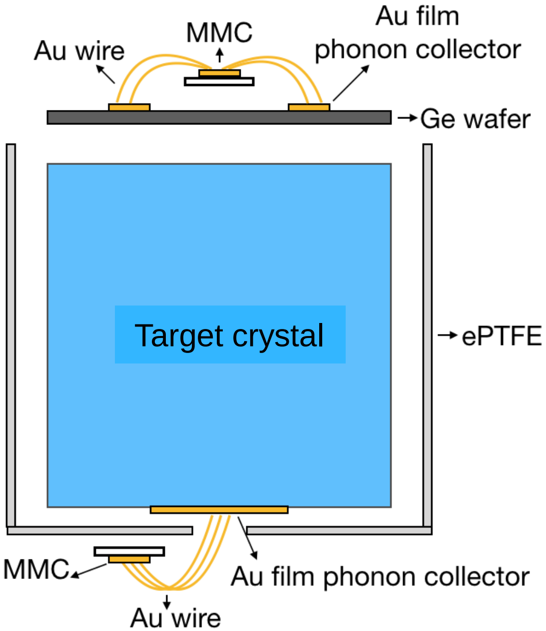
- Site: YangYang Underground (Korea, Depth 700m)
- Detector: $^{40}Ca^{100}MoO_4$ Scinti-Bolometer
  - ^{40}Ca (expensive, delivery problem)

    ➔ Another Crystal ?, Li or Na



- ββ Isotope: ^{100}Mo (Q = 3034 keV, 9.63%)
  - using enriched ^{100}Mo, and ^{40}Ca (depleted ^{48}Ca)

- Phonon sensor: MMC
  - Fast time response; ~ mili-sec. rising
  - Decay constant (thermalized) ~100 msec
  - Excellent PI & ΔE



AMoRE-Polot -2018
- 1.9 kg of ^{100}Mo
- target sensitivity $T^{0\nu}_{1/2} > 3 \times 10^{24}$ year,
- $m_{\beta\beta}$ < 300~900 meV

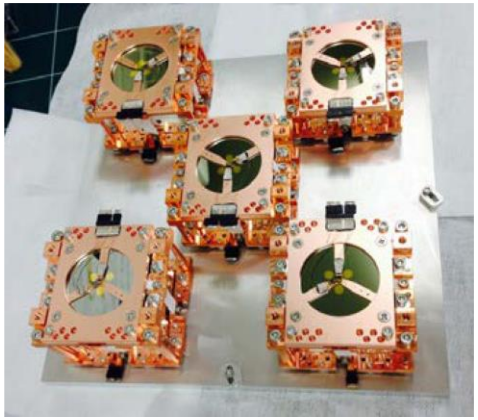
AMoRE-I 2019 ~
- 6.1 kg, 10^{-3} cts/(keV·kg·y)、70-140 meV

Status of AMoRE Experiment

- First Results from the AMoRE-Pilot

  The European Physical Journal C 79, 791 (2019)

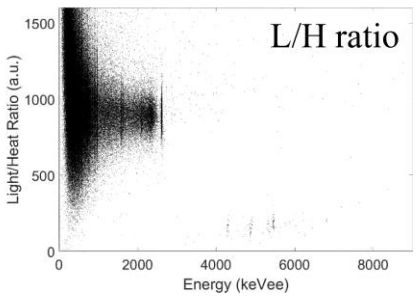
  - $^{48depl.}Ca^{100}MoO_4$ Crystals (1.9 kg)
  - Exposure ; 111 day x kg

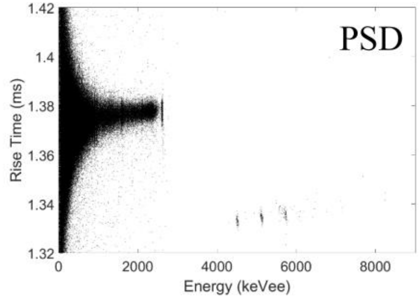


Particle ID : Highly resolving

Not only Heat/Light ratio, but also timing properties of signal

Yong-Hamb Kim, LTD-17@Kurume & talk in DBD18

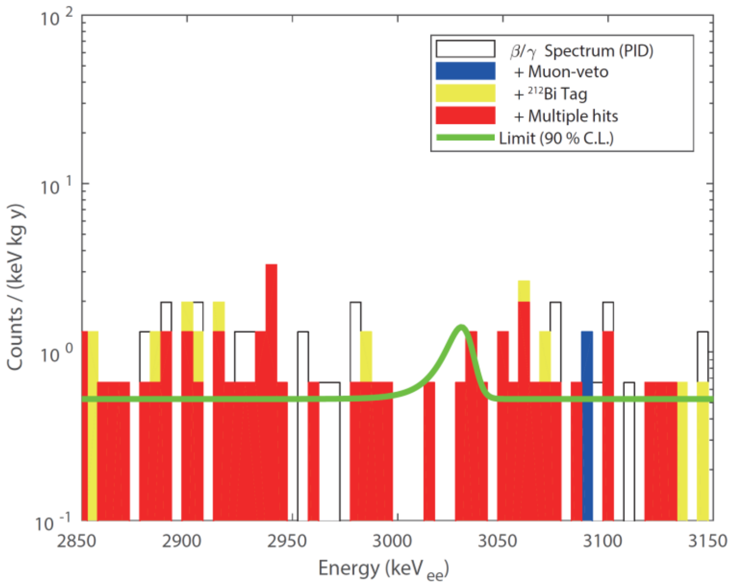




$T_{1/2} > 9.5 \times 10^{22}$ year (90% C.L.)

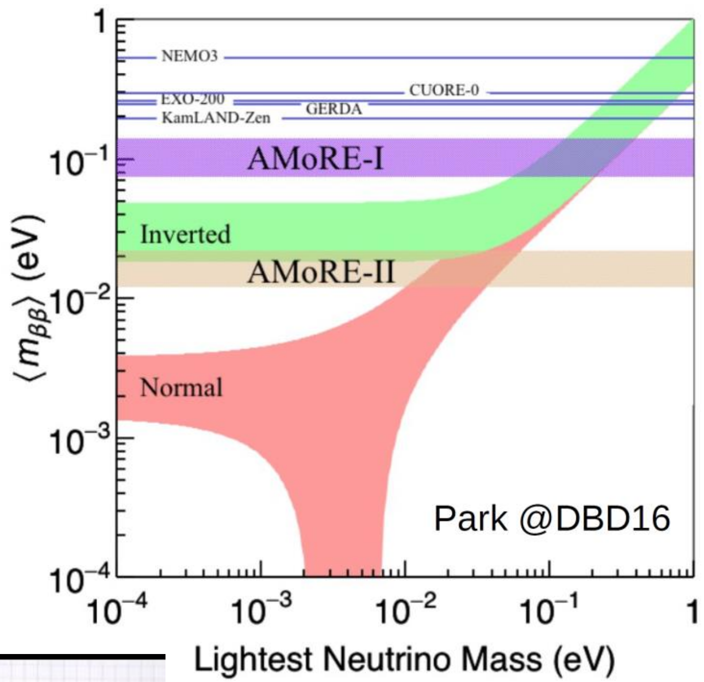
1.1×10^{24} year (by NEMO-3)

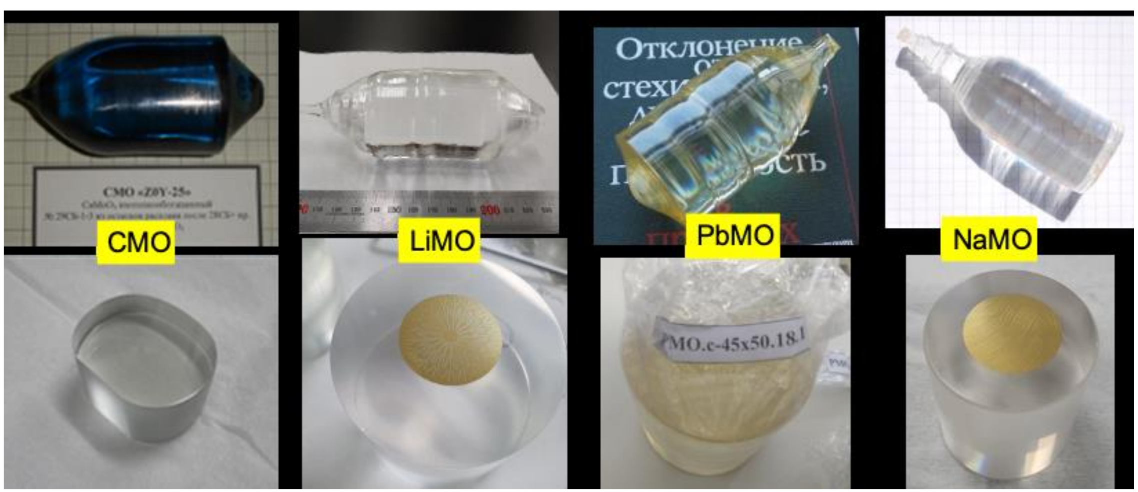
1.4×10^{24} year (by CUPID-Mo)



Future Prospects of AMoRE

	AMoRE-Pilot	AMoRE-I	AMoRE-II
Mass [kg]	1.9	~6.1	~200
Channels	12	36	~1000
BKG goal [ckky]	0.01	0.001	0.0001
Sensitivity [year]	~10^{24}	~10^{25}	~5×10^{26}
Sensitivity [meV]	380 to 640	120 to 200	17 to 29
Location	Y2L	Y2L	Yemilab
schedule	2017 to 2018	2019~	2021~





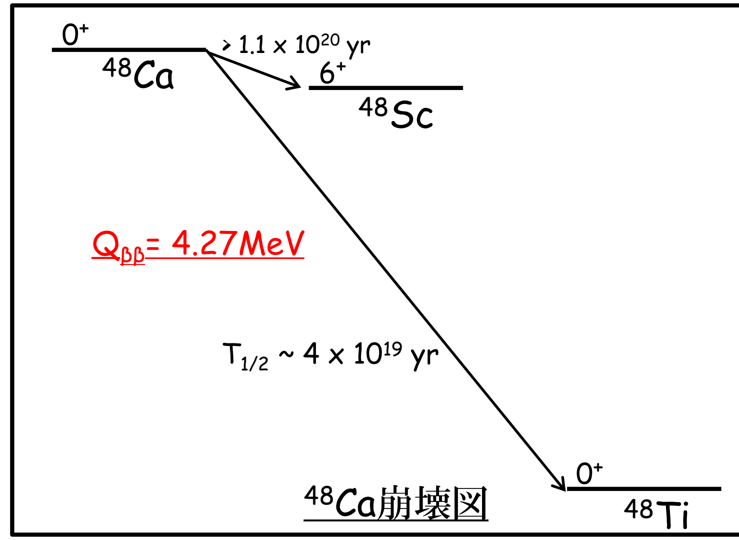
JINST 15 C08010 (2020)

Development for Ca Bolometer

- Future development for CANDLES project

^{48}Ca for ββ Isotope

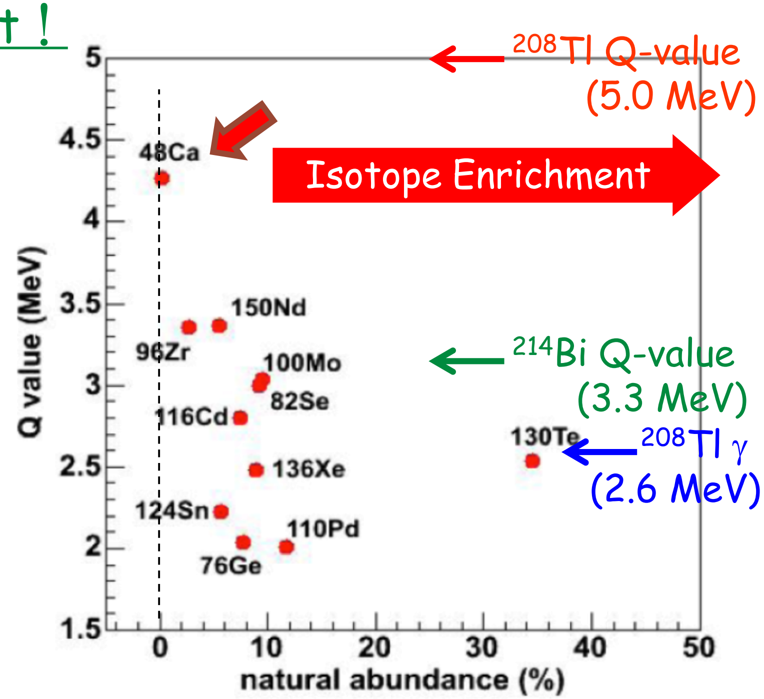
- ^{48}Ca isotope
  - Highest Q-value (4.27MeV)
    - ➔ Large phase space factor
    - ➔ Low background
      - γ-ray ; 2.6 MeV (^{208}Tl)
      - β-ray ; 3.3 MeV (^{214}Bi)



  - Chance to realize
    the Background Free Measurement !

$$\langle m_\nu \rangle \propto T_{0\nu}^{-1/2} \propto (1/ M \cdot T_{live})^{1/2}$$

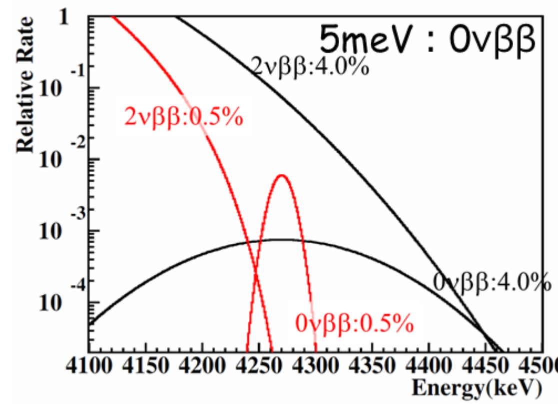
  - Small natural abundance (0.187 %)
- However,
  - Chance to improve the sensitivity by the enrichment without scale-up.
  - Low risk to increase BG origins



Background Candidates for Ca-Bolometer

- Tail of 2νββ spectrum
  - Improving energy resolution

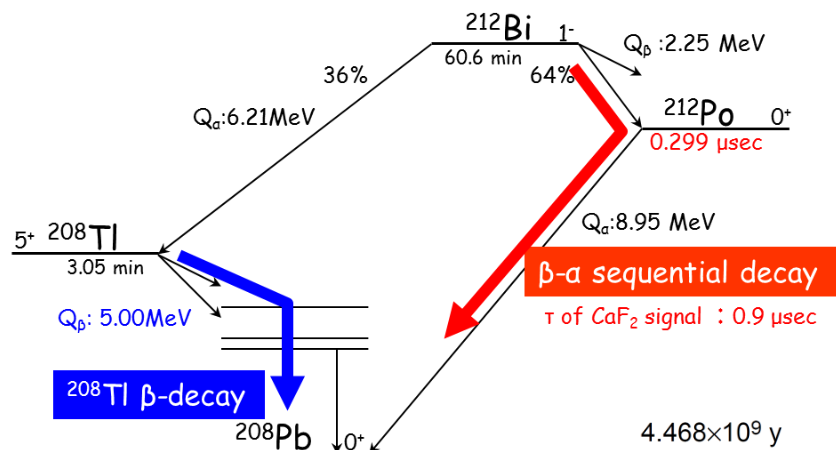
    Scintillator → Bolometer



- ^{48}CaXX internal radioactivities
  - Th-series (β-α sequential decays) → Bolometer
  - Th-series (^{208}Tl)

    → Segmentation, Multi-crystal
  - Environmental neutrons
    - Improving resolution + Multi-crystal

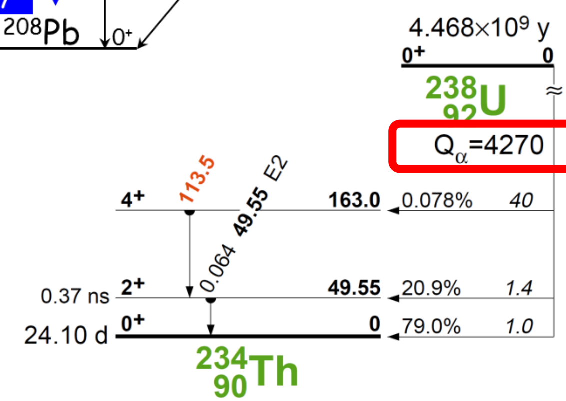
Possible to further reduce
the BG by developing Bolometer



- But... new BG candidate
  - Q value of ^{48}Ca : 4267.98(32) keV @ arXiv:1308.3815
  - Q-value of ^{238}U (α-decay) : 4270 keV

    Impossible to avoid

    ➔ required particle ID



➔ <u>Developing CaF_2 Scintillating Bolometer</u>

CaF_2 Scintillating Bolometer

- History of CaF_2 Scintillating Bolometer R&D

Year	1992	1997	2017
Purpose	DBD	DM	DBD
Crystal	CaF_2 (Eu) (Eu :0.01～0.07%)	CaF_2(Eu) (Eu :0.30%±0.08)	CaF_2(pure)
Mass	2.5 g	300 mg	312 g
Sensor	NTD-Ge	NTD-Ge	MMC
Light detector	Si-PD	Ge wafer	Ge wafer

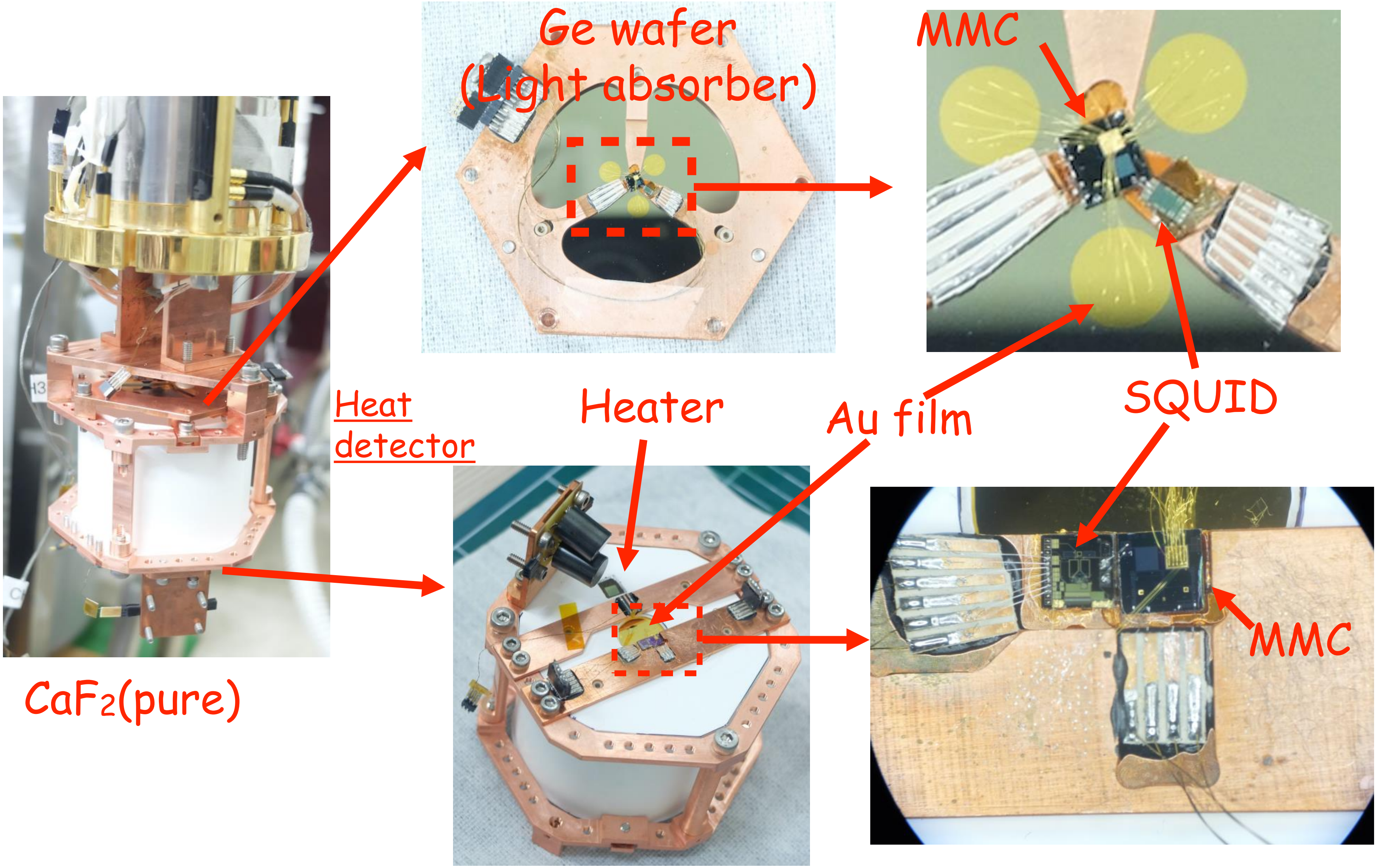
⇧ Our R&D

- Unique points of our R&D
  - Undoped CaF_2 crystal
    - Radio-pure crystal is available ← developed by CANDLES project
    - Large light output at low temperature
  - MMC (Metallic Magnetic Calorimeter) as sensors

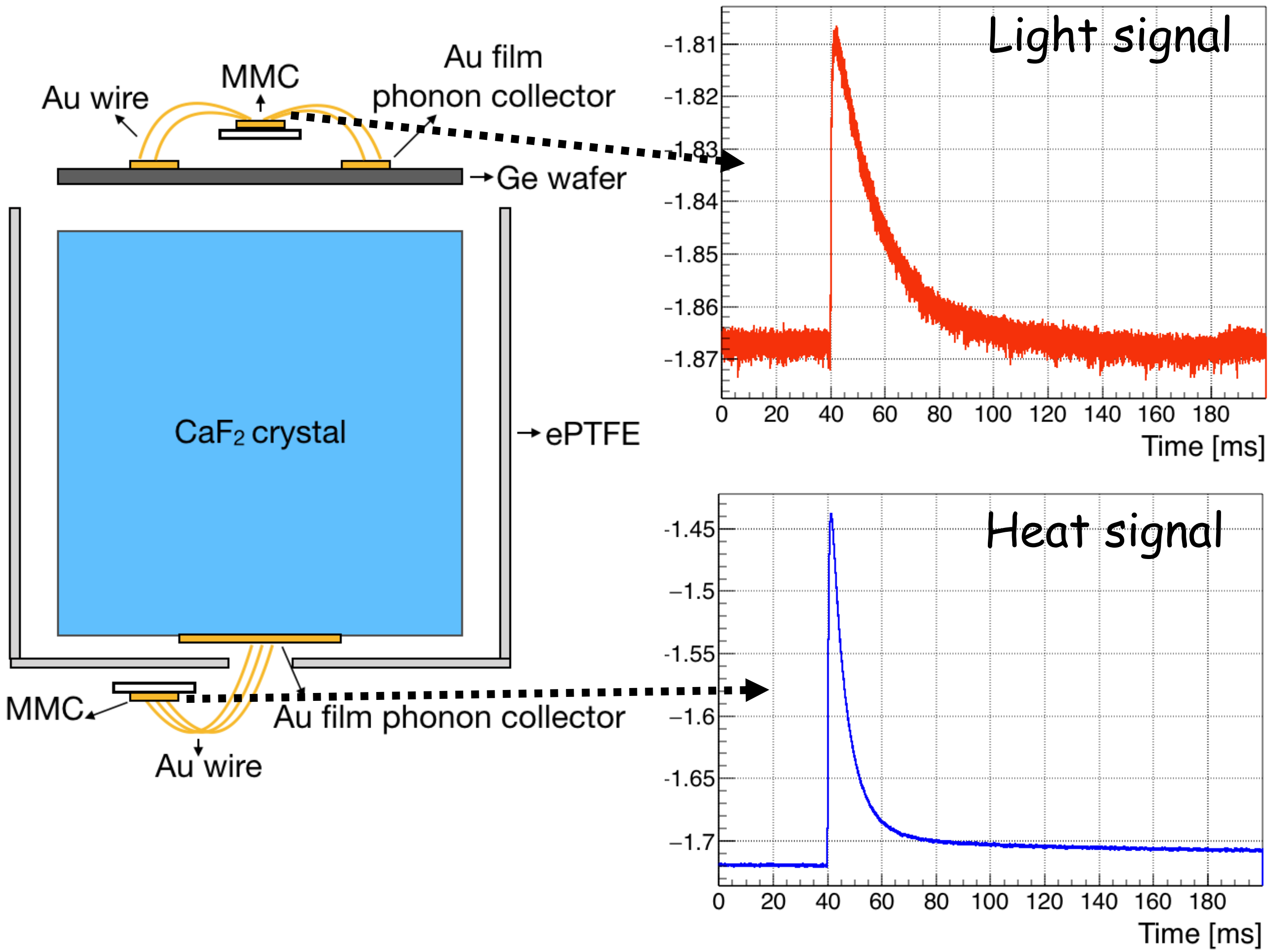
Development for CaF_2 Scinti.-Bolometer

- Collaborative research with Korean colleague
  - **Yong-Hamb Kim (IBS & KRISS)**
  - **Minkyu Lee (KRISS)**
  - **Inwook Kim**
  - **Do-Hyoung Kwon**
  - **Hyejin Lee**
  - **Hye-Lim Kim**
- Sub-Group of CANDLES (Osaka)
  - **Konosuke Tetsuno**
  - **Xialoang Lee**
  - **Saori Umehara**
  - **Tadafumi Kisimoto**
  - **Sei Yoshida**

CaF_2 Scintillating Bolometer Setup



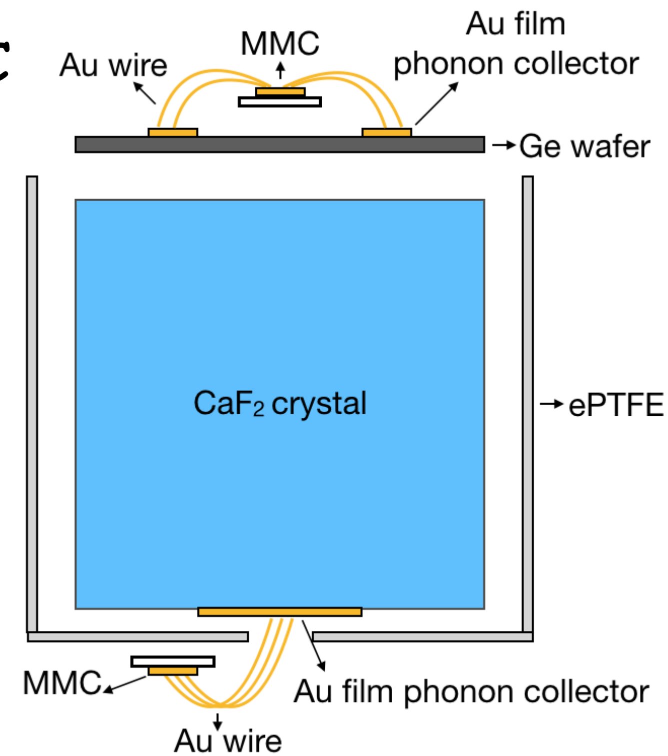
Signals from CaF_2 Bolometer

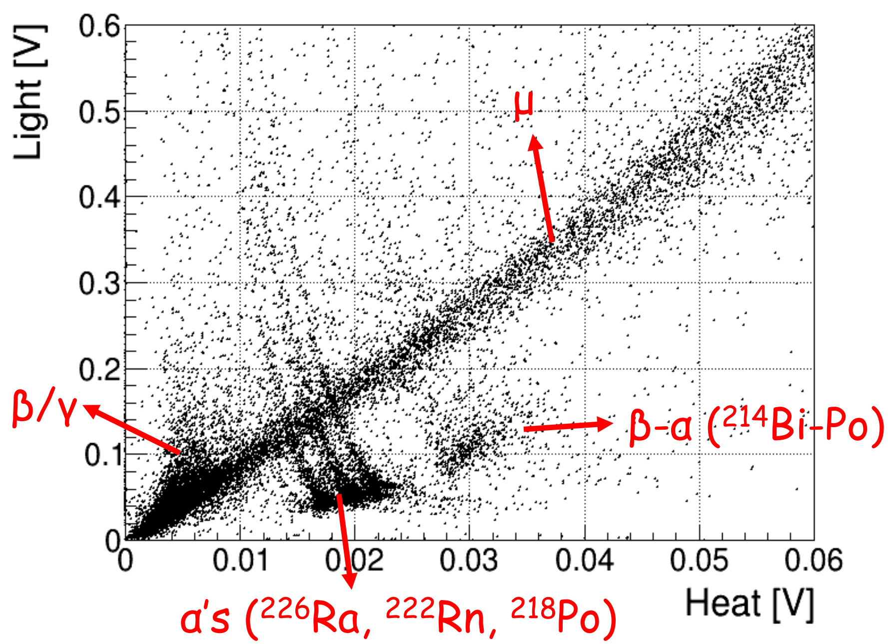


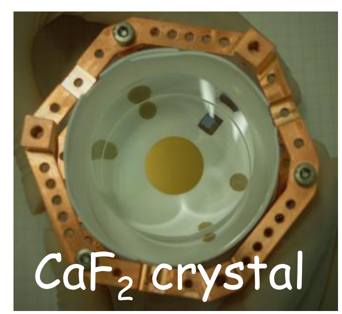
- The rise time ; ~ 0.7ms.
- The decay time ; ~ 8ms, ~ 200 msec

CaF_2(pure) Scintillating Bolometer

- First Challenge using CaF_2(pure) and MMC
  - Crystal: CaF_2(pure)
    - Volume: 300g (5cmφ×5cm)
    - Emission peak : 280nm
    - Light output: 25,000 photons/MeV



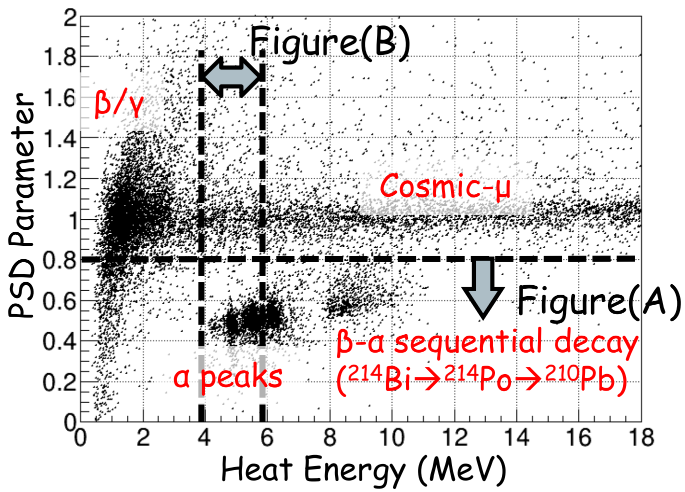


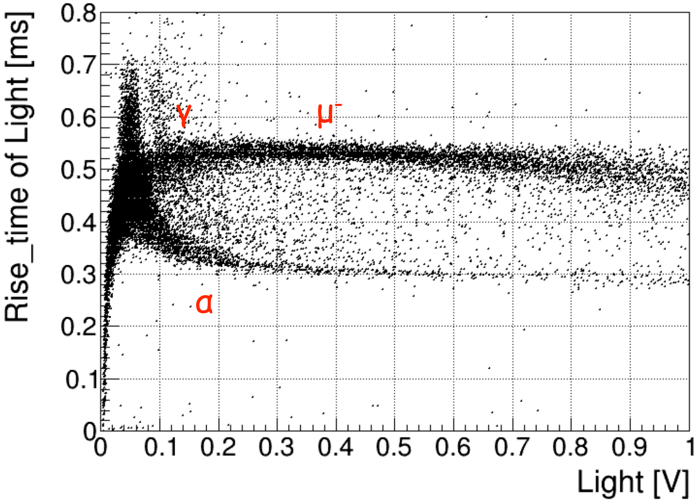


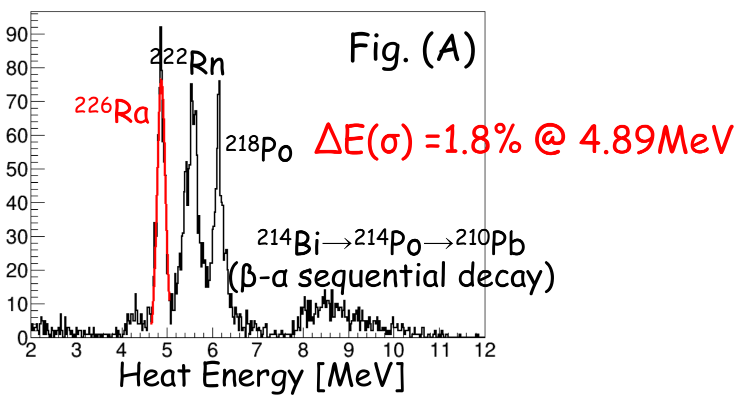
- Problem
  - UV scintillation of CaF_2 is absorbed on Au-deposit for heat signal. There is position dependence of scintillation absorption. ➔ make worse E-resolution.

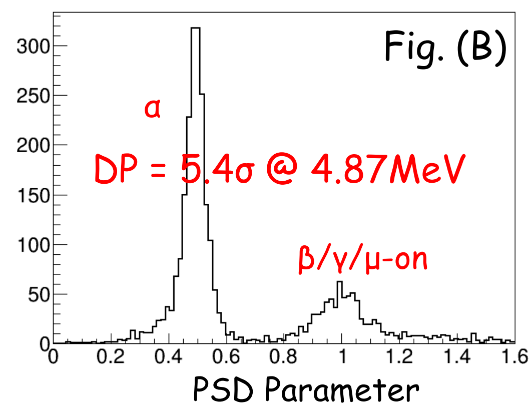
Resolution and Discrimination

- The rising/decay time of signal depend on particles.
- define PSD parameter
  - Heat/Light ratio
  - Rising/Decaying time of both signals



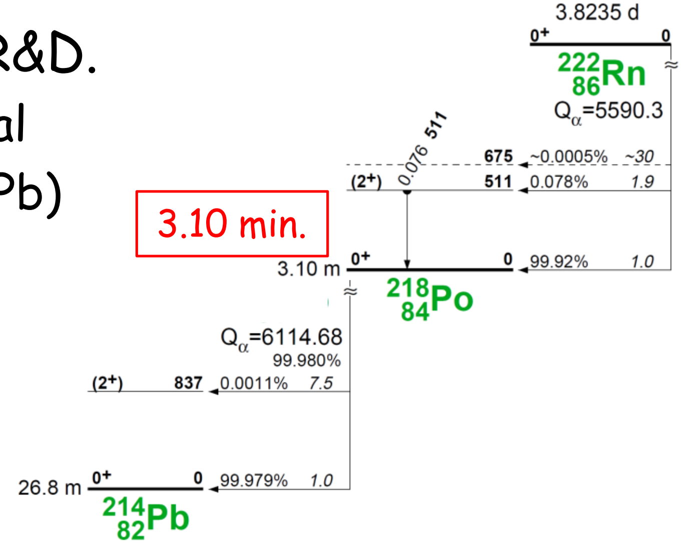


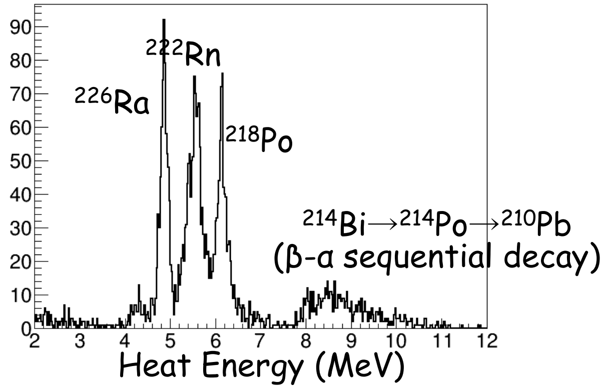


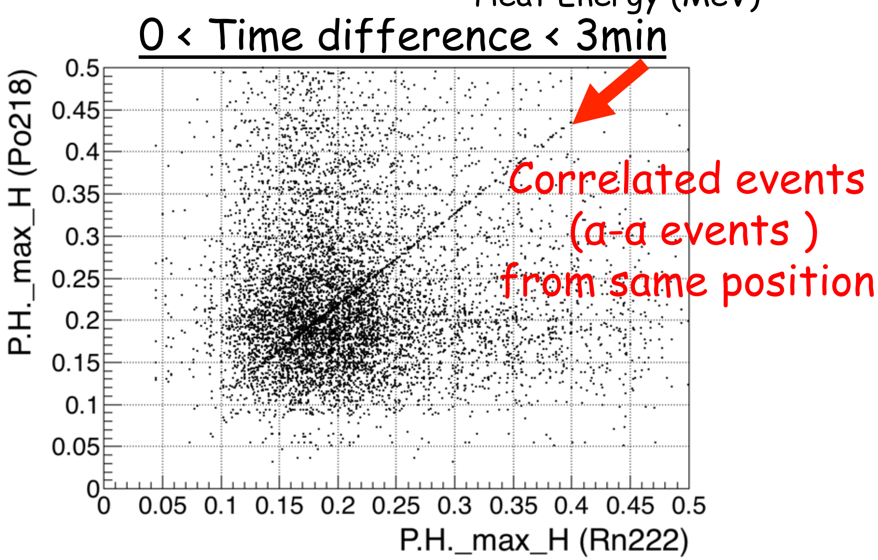


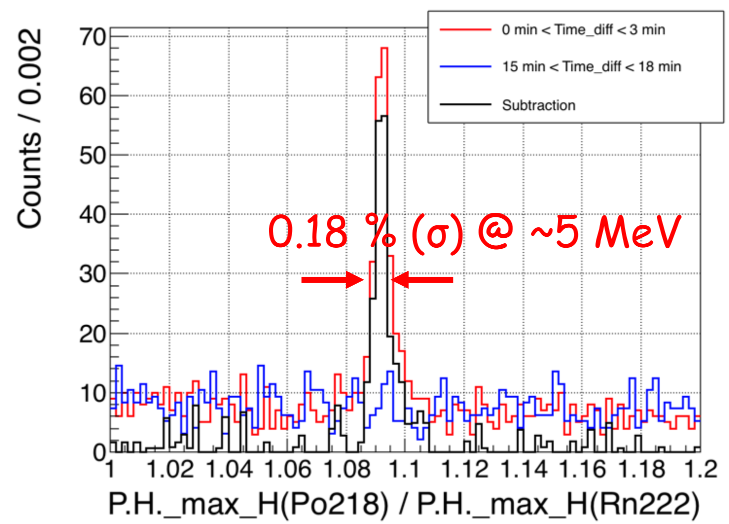
Position dependence

- We use contaminated CaF_2 crystal for R&D.
  - ~ 30 mBq of ^{226}Ra (U-chain) within crystal
  - Delayed coincidence ($^{222}Rn \rightarrow {}^{218}Po \rightarrow {}^{214}Pb$)



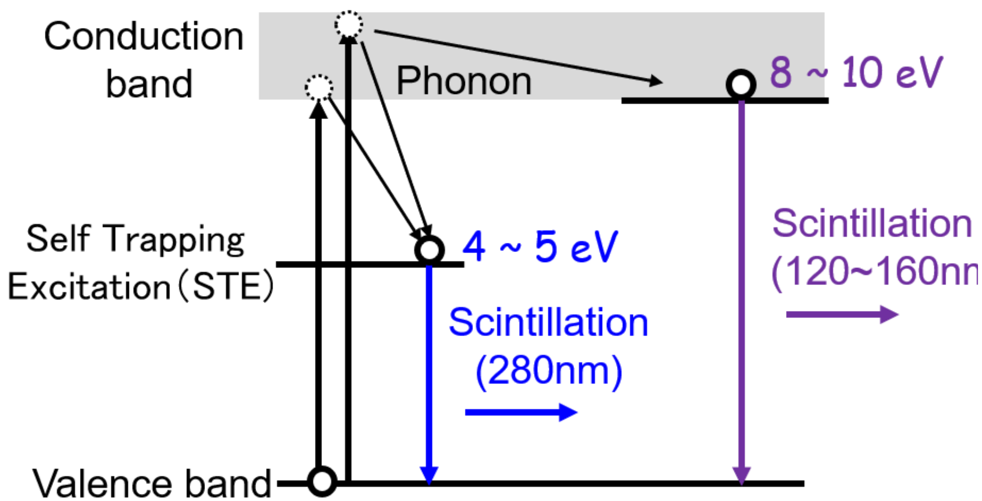


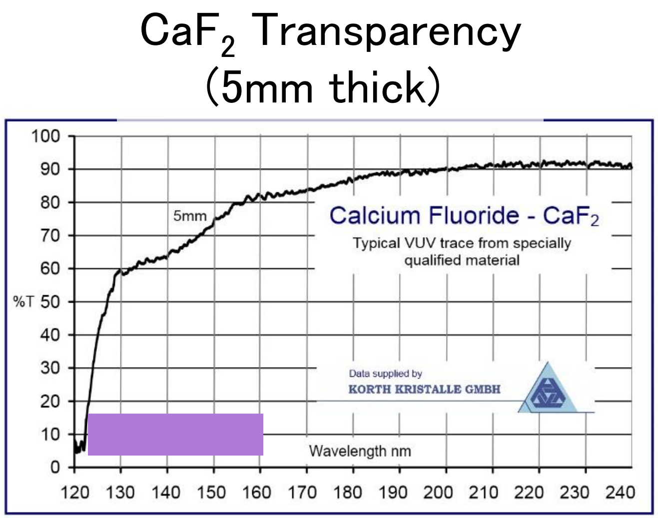




Evaluated ideal energy resolution without position dependence

Position dependence of Light Signal





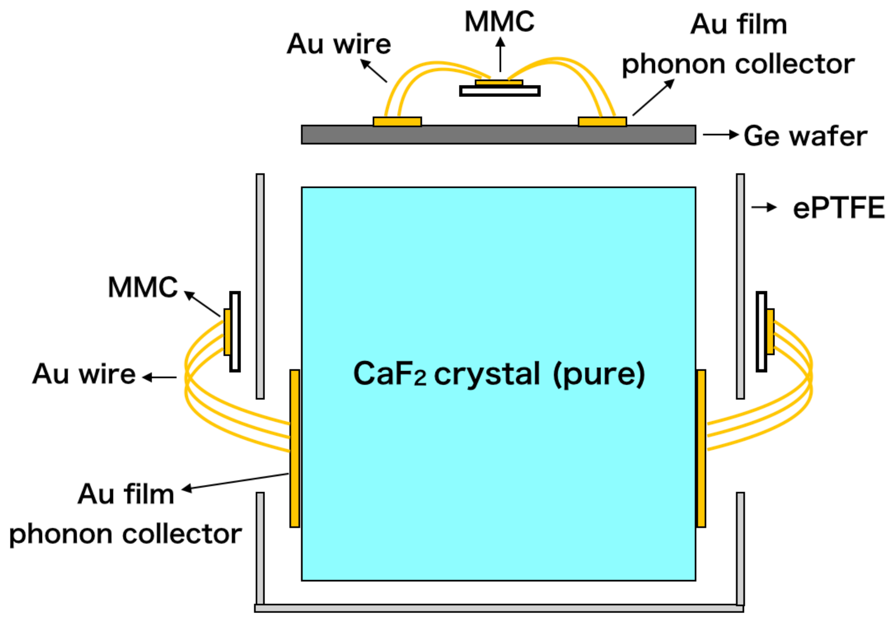
- CaF_2(pure) crystal has a conduction band at 8~ 10 eV in addition to 4~5 eV [Ref.].
- Large amount of VUV light (120 ~ 160 nm) may be emitted in the case of α-particles, having a large energy loss density. In the CaF2 crystal, the attenuation length of VUV light is about 5 mm, so VUV is detected only in the event near the LD.

[Reference] J. Birth et al., Phys. Rev. B41.3291

Prospects for the development

- Improving E-resolution of CaF_2(pure) scintillating bolometer
  - Radio-pure CaF_2(pure) crystal had been developed.
  - Doping Eu may affect phonon propagation in CaF_2 crystal.

- New trial in the next step
  - CaF_2(pure) crystal with multi-phonon detector.
    - high-precision position information



Summary

- Bolometric measurement of temperature increase is promising technique to obtain good energy resolution, down to ~ several keV at ~MeV region.

- Scintillating bolometer has; good particle identification

- Experiments are on going
  - CUORE → CUPID
  - AMoRE

- Scintillating bolometer of undoped CaF_2 was firstly demonstrated, and evaluated performance of detector.
  - $\Delta E(\sigma)$ = 1.8 % @ ~ 5MeV, not good due to position dependence.
  - PID ~5σ separation (undoped CaF_2) , 10σ (CaF_2(Eu))
  - $\Delta E(\sigma)$ = 0.18 % @ ~ 5MeV w/o position dependence

- We will start to develop Ca bolometer in Osaka.
  - using NTD-Ge, first → another sensor.

In Future

- To explore normal ordering region, down to ~ several meV, multi-ton scale scintillating bolometer facility will be required.
  - Cooling power of dilution refrigerator, ~ several mW@100 mK
  - Increasing number of crystal ; ~ a few to several 1000 crystals
  - readout sensors → readout cables ; 10000 of cables ?
- Very important to reduce incoming heat flow to cold stage.
  - Multiplex readout system should be developed for reducing number of readout cables (heat flow) by frequency domain readout system.