Low Temperature Detector for Underground Nuclear and Particle Researches (Neutrino-less ββ Decay)

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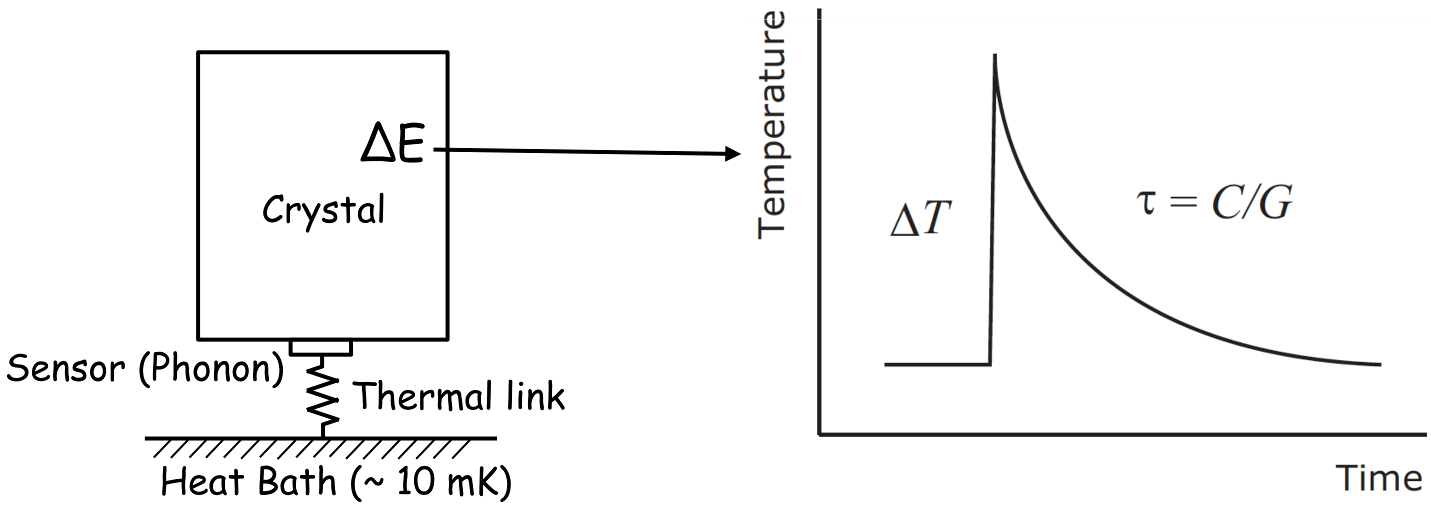
Bolometer

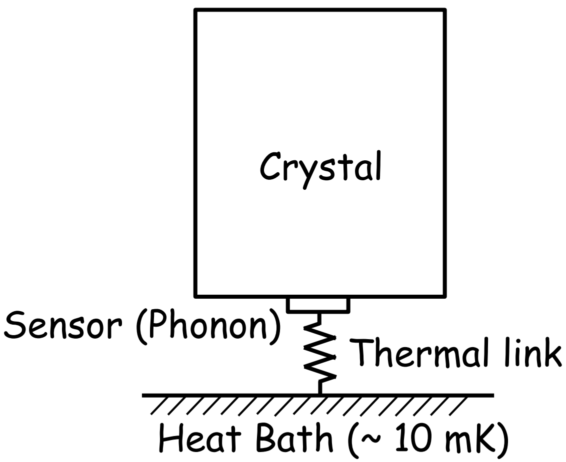
$$\Delta T(t) = \frac{E}{C} e^{-\frac{t}{\tau}} \qquad C_r(T) = \frac{12}{5}\pi^4 k_B N_A \left(\frac{T}{T_D}\right)^3$$

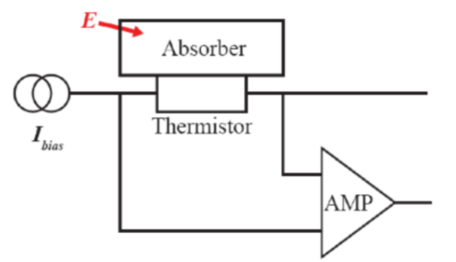


- Calorimetric measurement of heat signals **at mK temperatures**
  - **Energy absorption ➔ Temperature increase**
  - **Good Energy resolution ; expected.**

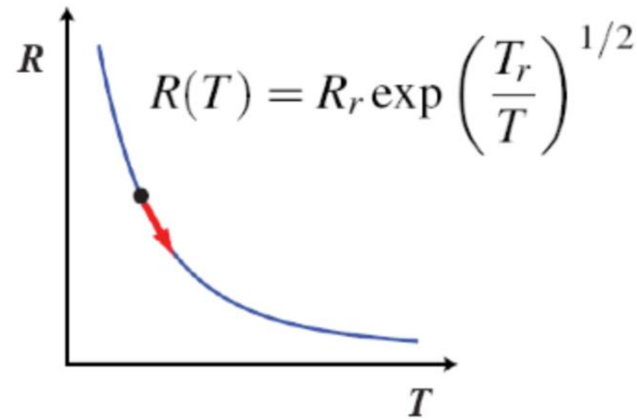
- Choice of thermometers to measure temperature increase
  - **Thermistors (NTD Ge)** CUORE, CUPID (some options)
  - TES (Transition Edge Sensor) Light detector, CRESST
  - **MMC (Metallic Magnetic Calorimeter)** AMoRE, LIMINEU
  - KID (Kinetic Inductance Device) CALDER, Ishidoshiro (Tohoku)
  - etc.

NTD-Ge as Temperature Sensor





<Current bias and read voltage >

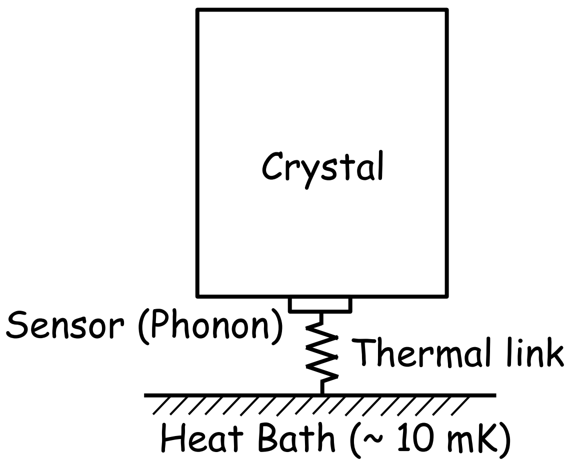


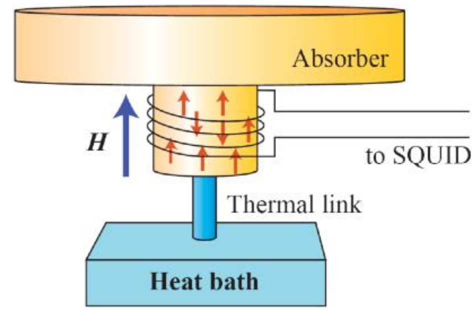
Changing MΩ ~ 100MΩ by temperature change

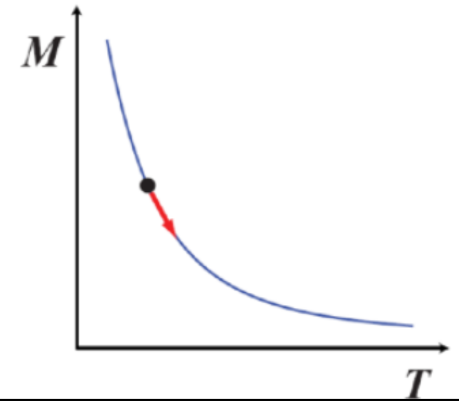
Properties of NTD-Ge

- 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







<u>Process of detecting signal</u>

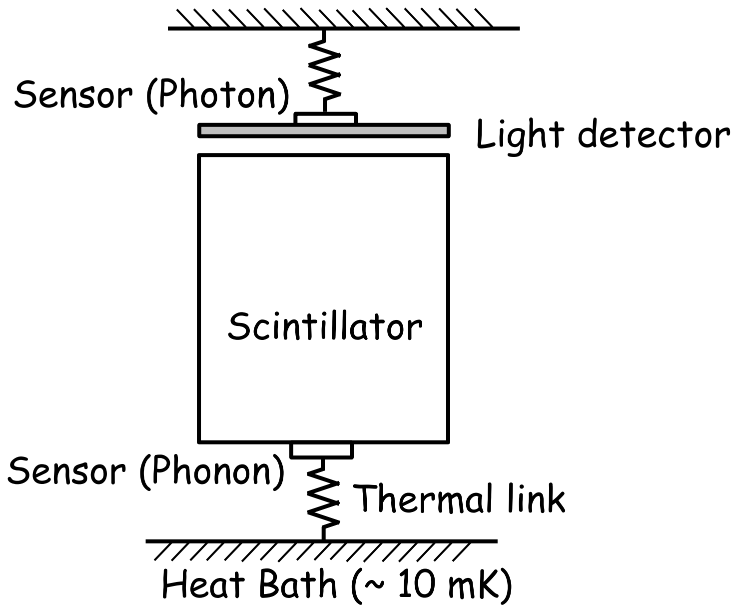
① Energy absorption in a crystal
② Phonon and photon generation
③ Temperature increase
④ Magnetization of MMC decrease
⑤ SQUID pickup the magnetization change

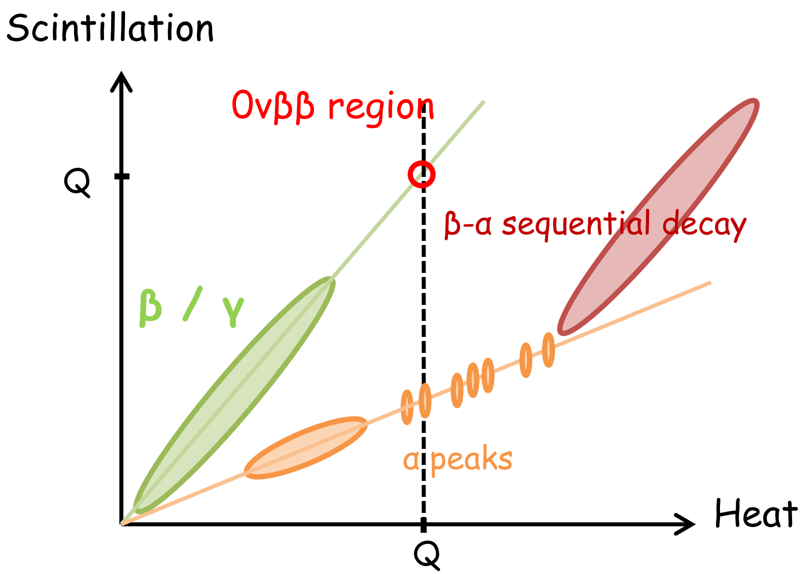
<u>Properties of MMC</u>

- 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 + **<u>Relatively fast</u>**
- **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"

Scintillating Bolometer for 0νββ study

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

CUORE Upgrade : CUPID

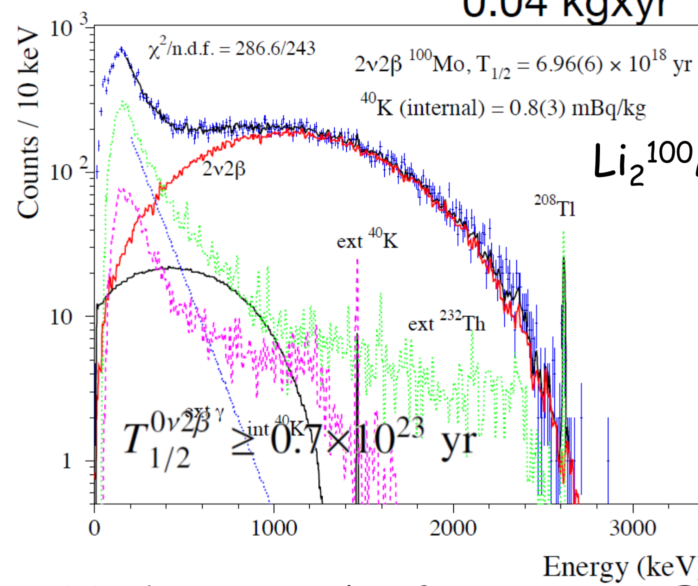
Tommy O'Dnell, Talk in DBD18

- 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

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

Main crystal, Ge wafer cryogenic light detector readout by NTDs

0.04 kgxyr



$Li_2{}^{100}MoO_4$

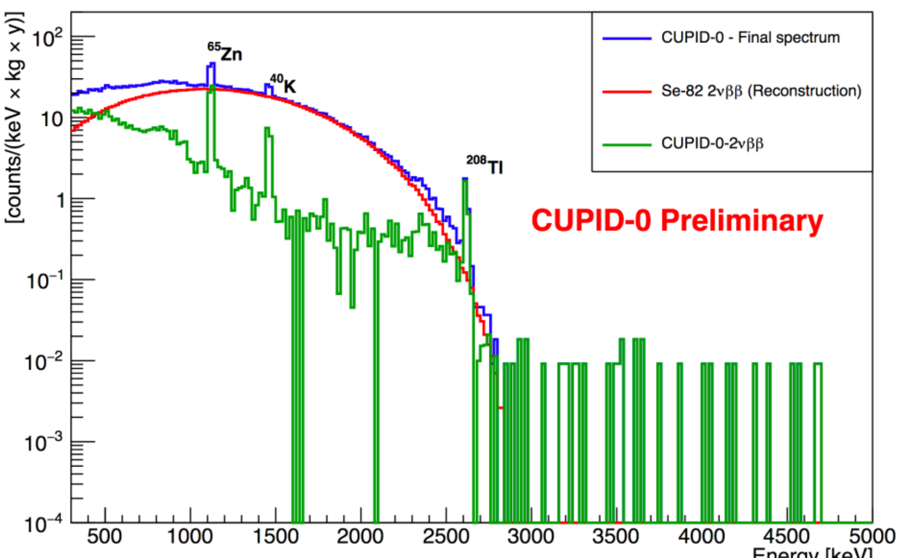
BB-decay results from LUMINEU

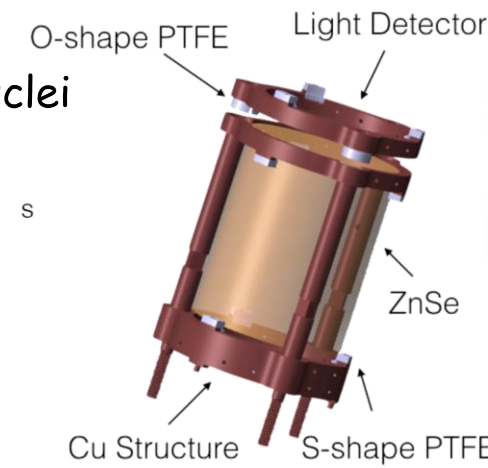
CUORE Upgrade : CUPID

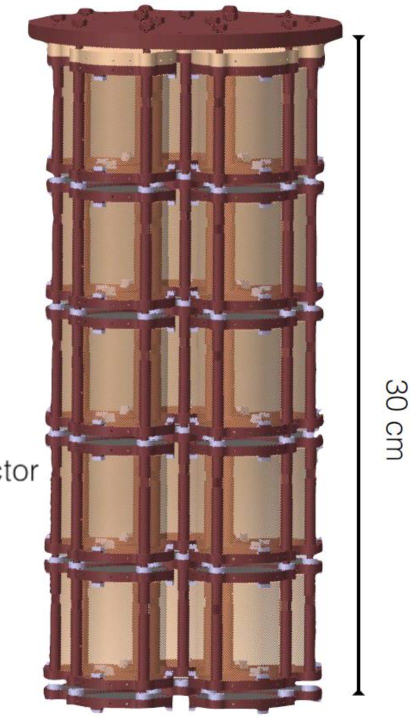
- CUPID (Cuore Upgrade with Particle ID)
  - Option1 : Scintillating-Bolometer (Zn^{82}Se / Li$_2$^{100}MoO$_4$)
  - Option2: TeO$_2$ + Light-detector (PI by Cherenkov photon)

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 → $N_{\beta\beta}$ = 3.8x10^{25} ββ nuclei







s

$T_{1/2}(^{82}Se \rightarrow ^{82}Kr) > 4.0 \cdot 10^{24}$ yr @ 90C.L.

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

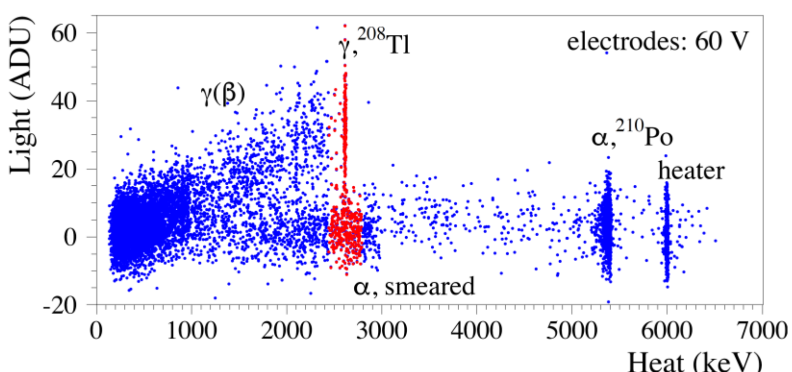
CUORE Upgrade : CUPID

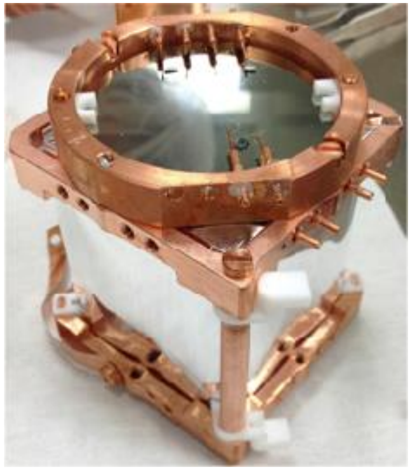
- CUPID (Cuore Upgrade with Particle ID)
  - Option1 : Scintillating-Bolometer ($Zn^{82}Se$ / $Li_2{}^{100}MoO_4$)
  - Option2: TeO_2 + Light-detector (PI by Cherenkov photon)

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





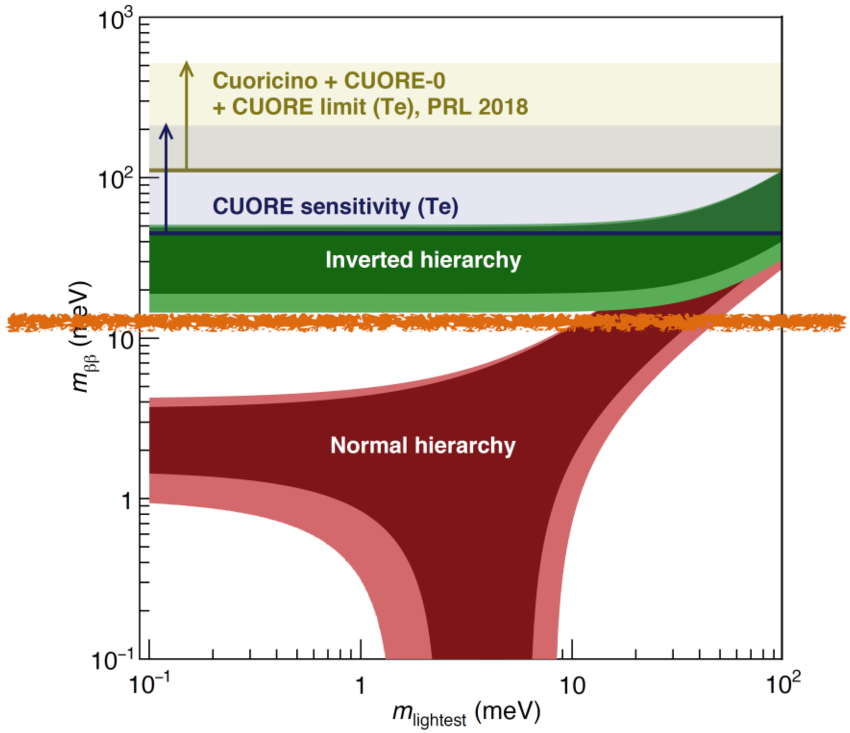
99.9% α event rejection with >95 % signal acceptance

CUORE Upgrade : CUPID

Tommy O'Dnell, Talk in 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)

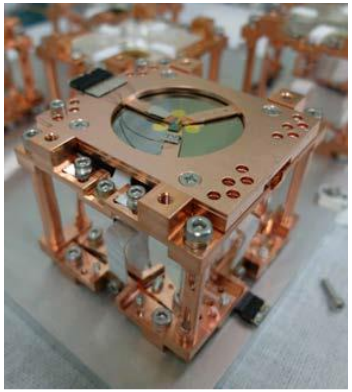
- Baseline target isotope is ^{100}Mo embedded in $LiMoO_4$ scintillating bolometers
- Viable alternative is ^{130}Te embedded in TeO_2 instrumented with advanced cryogenic light detectors



AMoRE Advanced Mo based Rare process Experiment

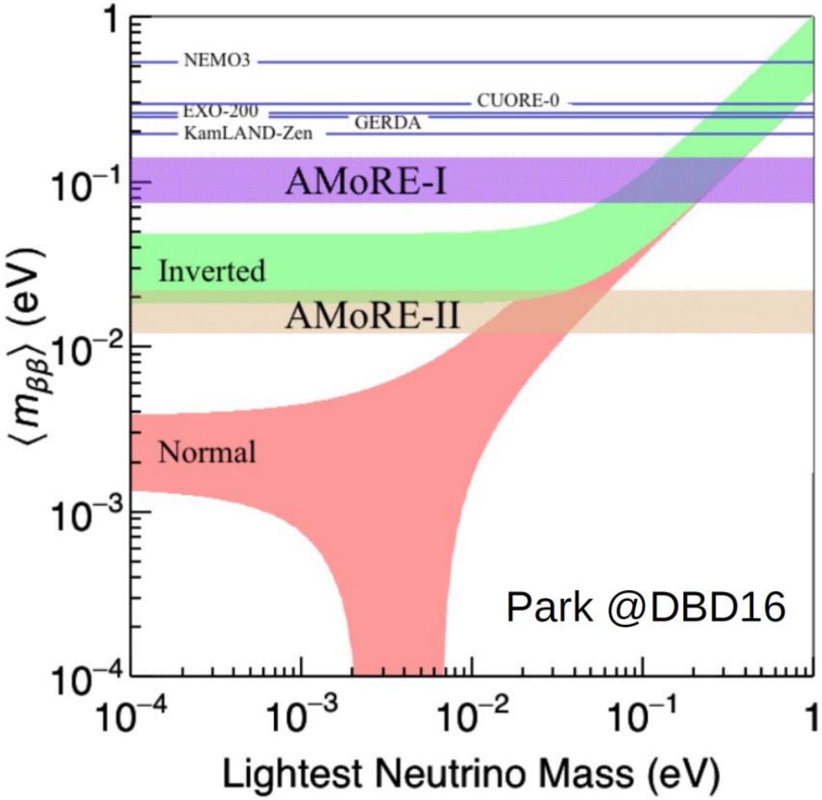
Yong-Hamb Kim, LTD-17@Kurume & talk in DBD18

- Site: YangYang Underground (Korea, Depth 700m)
- Detector: $^{40}Ca^{100}MoO_4$ Scinti-Bolometer
  - ^{40}Ca (expensive) ➔ Another Crystal ?, Li or Na



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

- Phonon sensor : MMC



AMoRE-Polot -2017
- 1.8kg, $T^{0\nu}_{1/2} > 3 \times 10^{24}$ year,
- $m_{\beta\beta} < 300\sim900$ meV

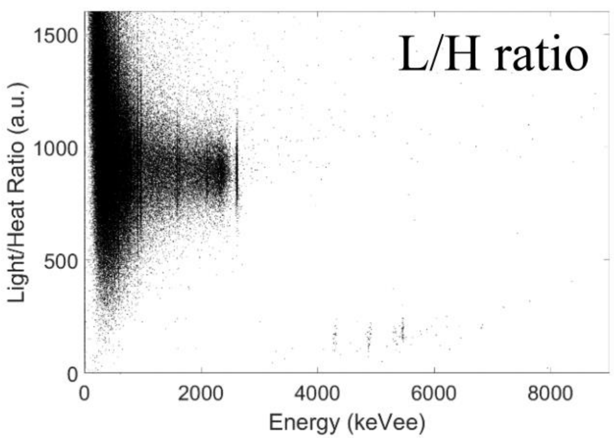
AMoRE-I 2017-2019
- 5kg, 10^{-3} cts/(keV·kg·y)、70-140meV

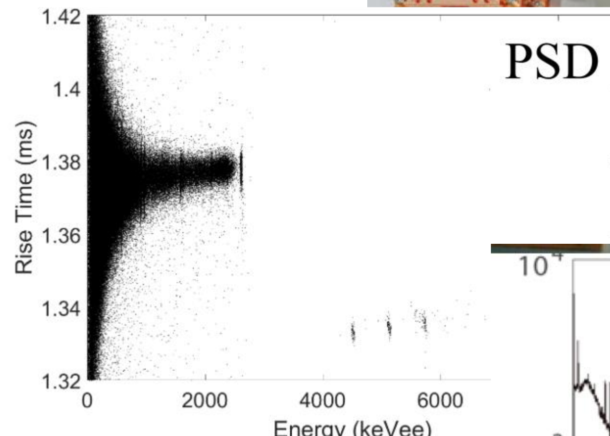
AMoRE-II 2020-2025@New Lab.
- 200kg, BG=10^{-4} cts/(keV·kg·y)
- Final goal : $m_{\beta\beta} < 12\text{-}20$ meV
  ($T^{0\nu}_{1/2} > 1.1 \times 10^{27}$ year)

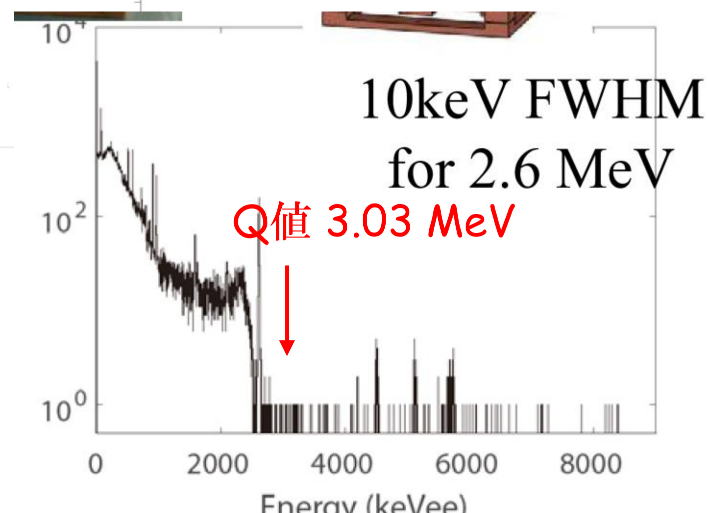
AMoRE Experiment

- AMoRE Status (^{100}Mo)
  - Installing at YangYang Underground Lab. in Korea
  - AMoRE Pilot (5 crystal)
  - Total mass ~ 1.8 kg

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







Particle ID：Highly resolving

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

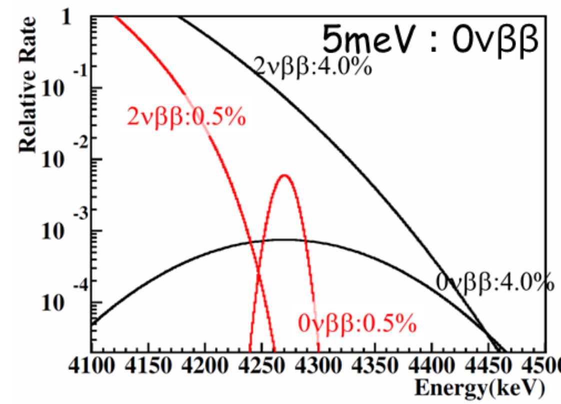
Development for Ca Bolometer

- Future development for CANDLES project

Background Candidates for CaF_2

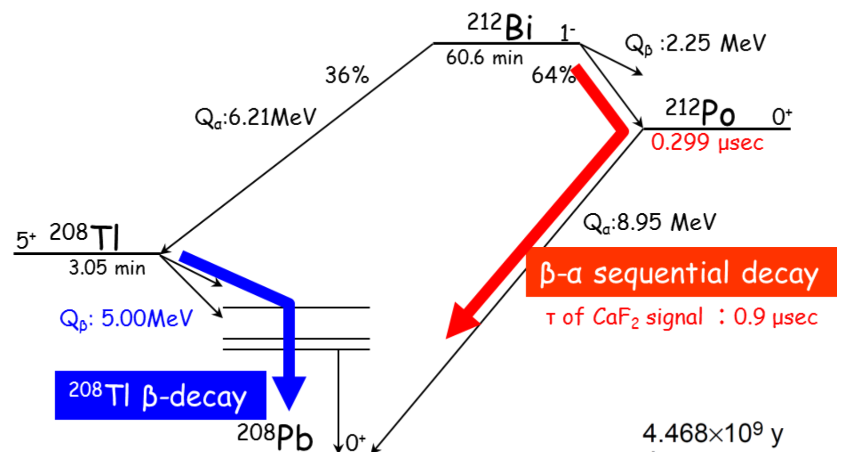
- Tail of $2\nu\beta\beta$ spectrum
  - Improving energy resolution

Scintillator → Bolometer

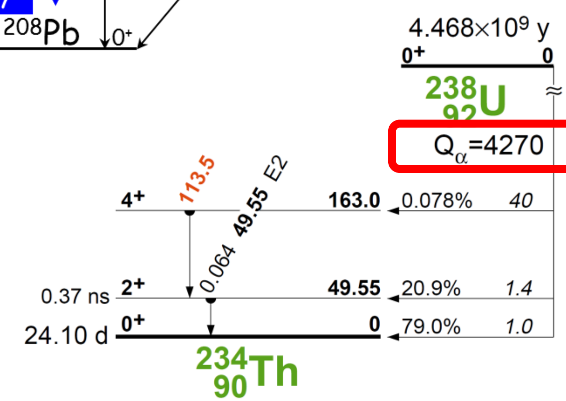


- ^{48}CaXX internal radioactivities
  - Th-chain (β-α sequential decays) → Bolometer
  - Th-chain (^{208}Tl)
    → Segmentation, Multi-crystal
  - Environmental neutrons
    - Improving resolution ＋Multi-crystal

Possible to further reduce
the BG by developing Bolometer



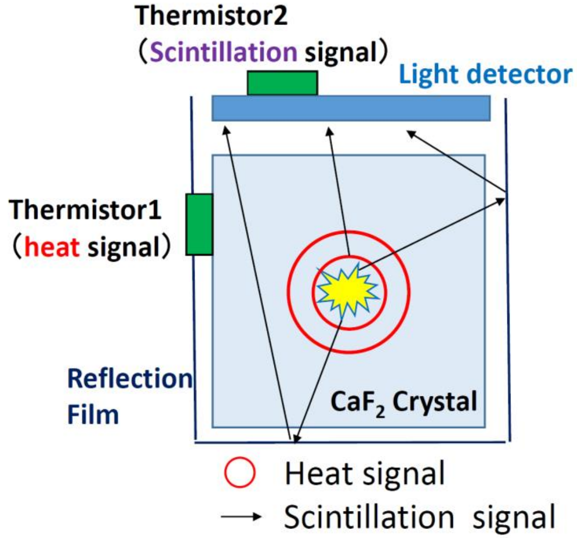
- But... new BG candidate
  - Q value of ^{48}Ca : 4267.98(32) keV   @ arXiv:1308.3815
  - Q-value of ^{238}U (α-decay) ： 4270 keV
    Impossible to avoid
    → required particle ID

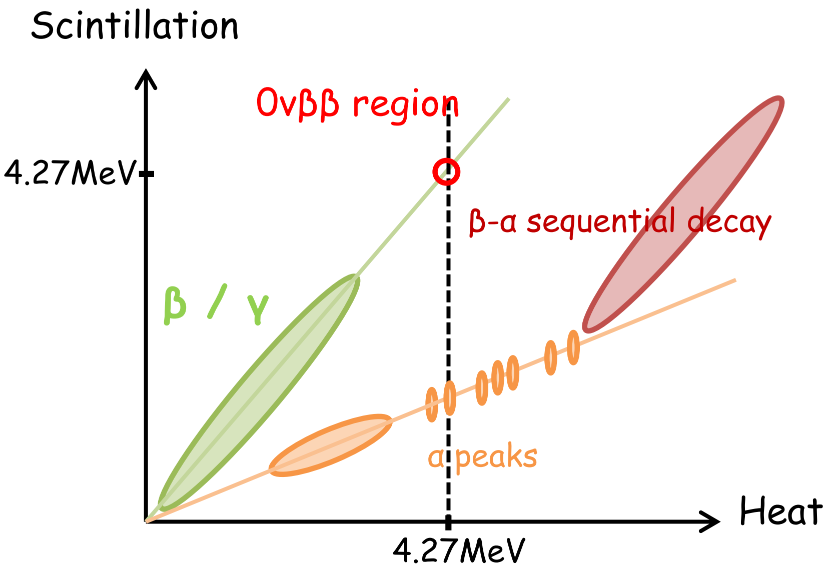


→ Developing CaF_2 Scintillating Bolometer

CaF_2 Scintillating Bolometer

- The technique (scintillating bolometer) was already established,
  - CRESST-II ($CaWO_4$), **AMoRE ($CaMoO_4$) :** Ca crystal
  - CaF_2(Eu) scintillating bolometer was also demonstrated.
    Ref; NIMA386 (1997) 453, small size (~ 0.3 g) of CaF_2(Eu)





- Simultaneous measurement both heat and scintillation enables to identify the particle types (α/β particle ID)
- It is possible to reject alpha decay events of ^{238}U
  - Q-value; 4.27MeV = Q-value of ^{48}Ca 0νββ

➔ Chance to achieve "BG free measurement"

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
Senser	NTD-Ge	NTD-Ge	MMC
Light detector	Si-PD	Ge wafer	Ge wafer

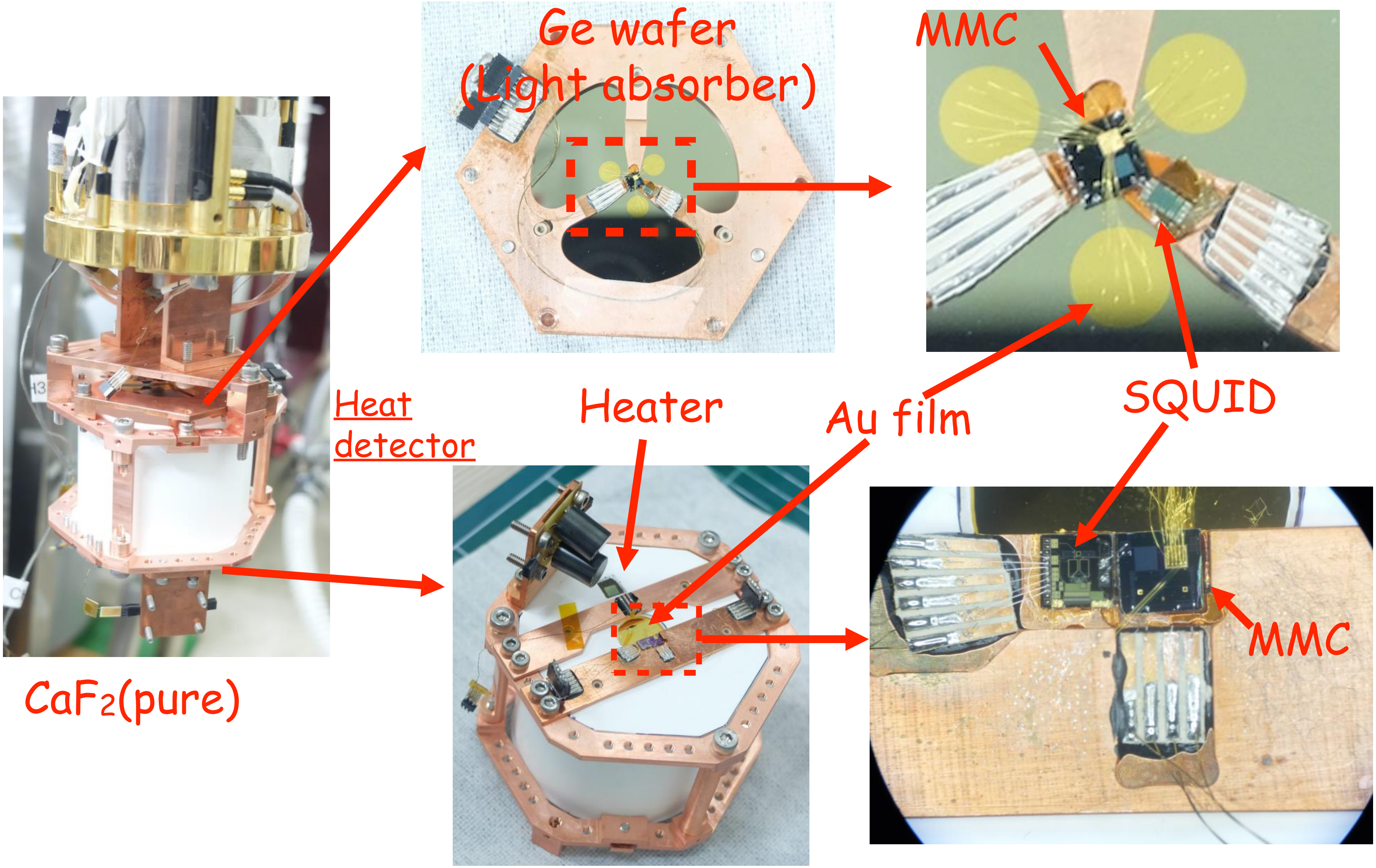
⇧ Our R&D

- Unique points of our R&D
  - Undoped CaF2 crystal
    - Radio-pure crystal is available ← developed by CANDLES project
    - Large light output at low temperature
  - MMC (Metallic Magnetic Calorimeter) as sensors

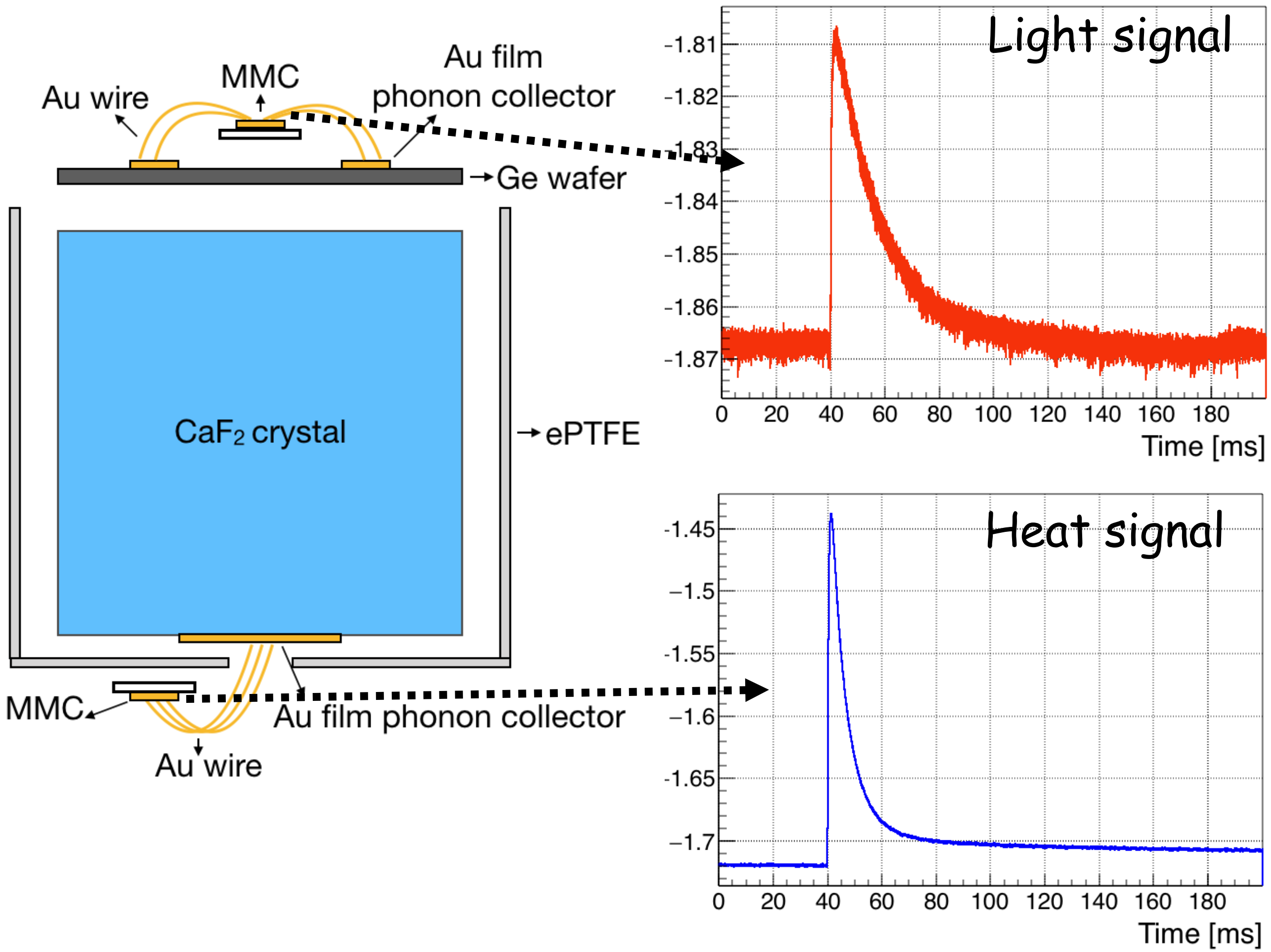
Development for CaF_2 Bolometer

- 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**
  - **Sei Yoshida**

CaF_2 Scintillating Bolometer Setup

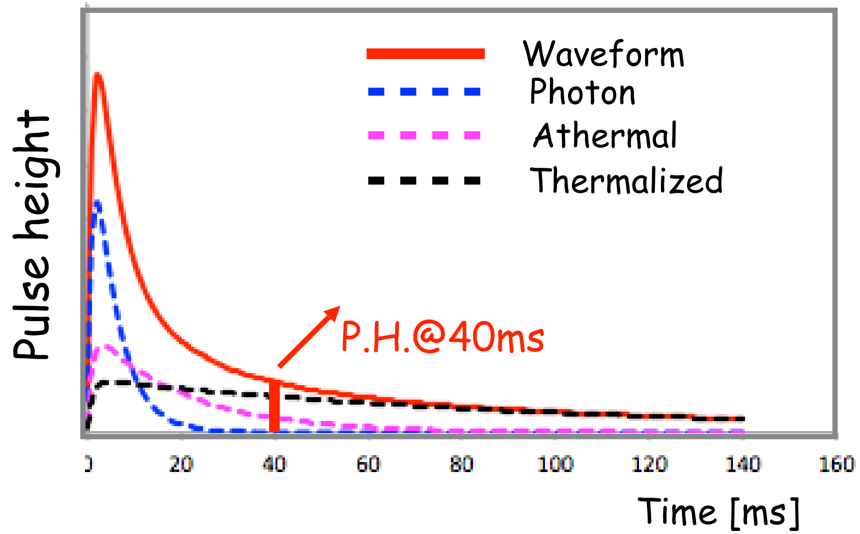


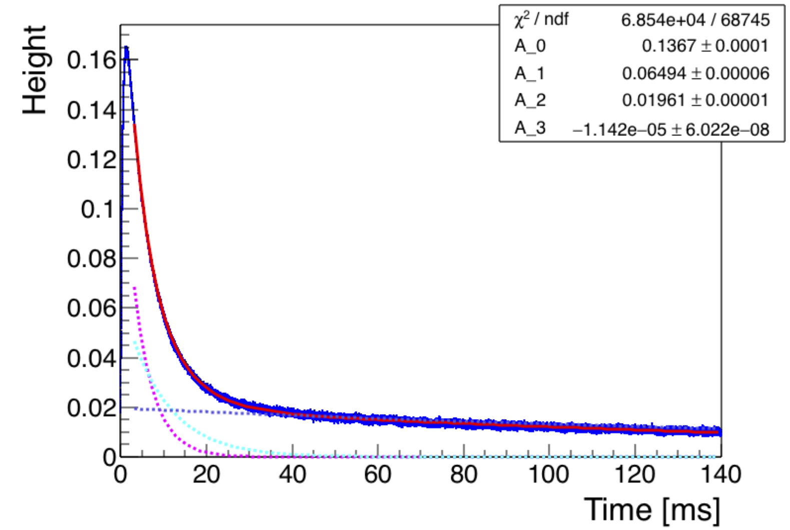
Signals from CaF_2 Bolometer



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

Heat Signal (Energy)





τ_{D0} = 4.6 ms, τ_{D1} = 9.6ms, τ_{D2} = 257ms

· Heat signals have three components of photon, athermal and thermalized parts.

Photon part

The emission spectrum of CaF_2 has a peak in the ultra-violet (UV) region (285nm)

As the refraction index of CaF_2 and Au have almost same value at 285nm, most photons reaching the Au film are absorbed. Therefore, some photon are measured as the heat signal.

Athermal part

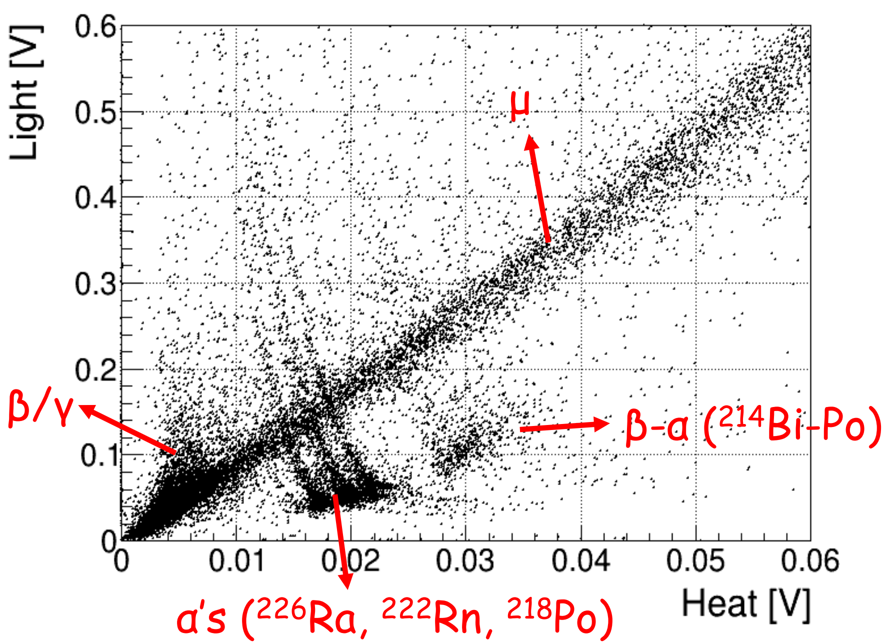
After particle absorption in the crystal, high energy phonons are initially generated, and they are immediately down-converted to lower energy phonons which is called athermal phonons. Some athermal phonons are transmitted into gold film. They can scattered by conduction electrons in the gold film and deposit their energy to conductive electrons.

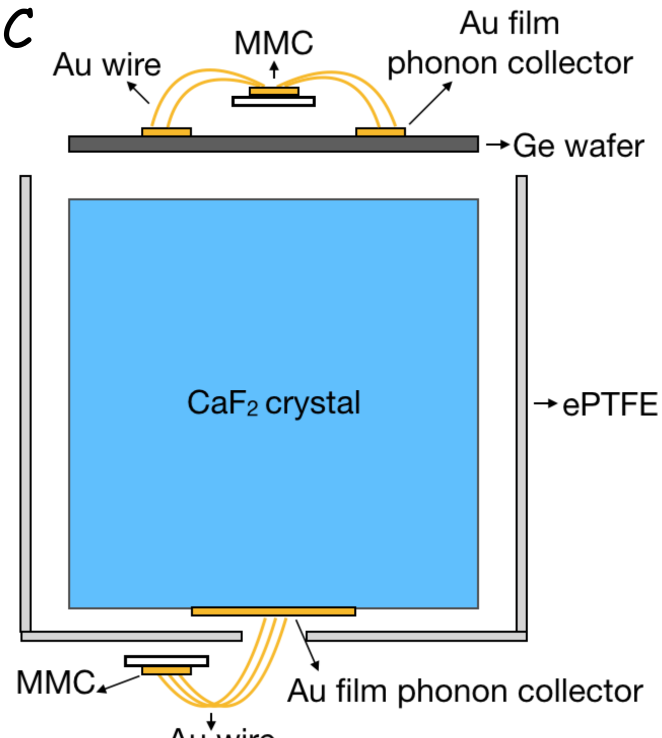
Thermalized part

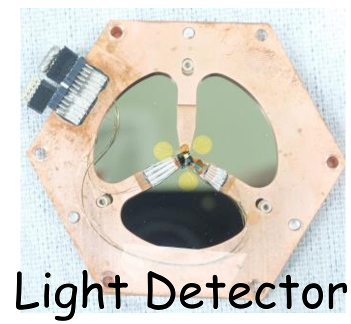
The remaining athermal phonons in the crystal are down-converted to a thermal phonon distribution described thermodynamic equation.

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



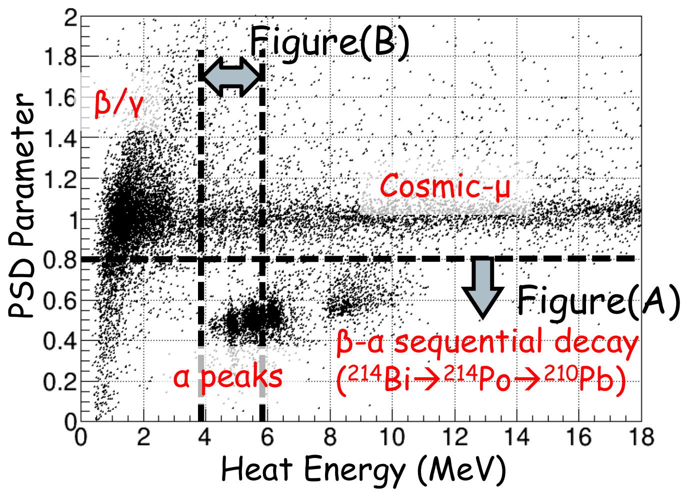


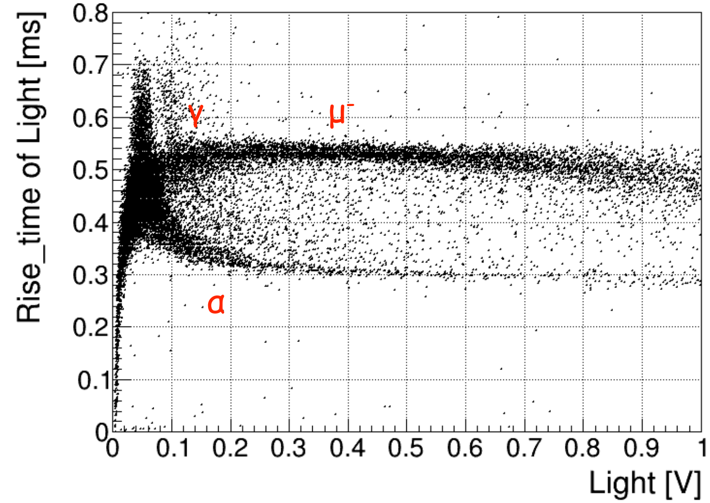


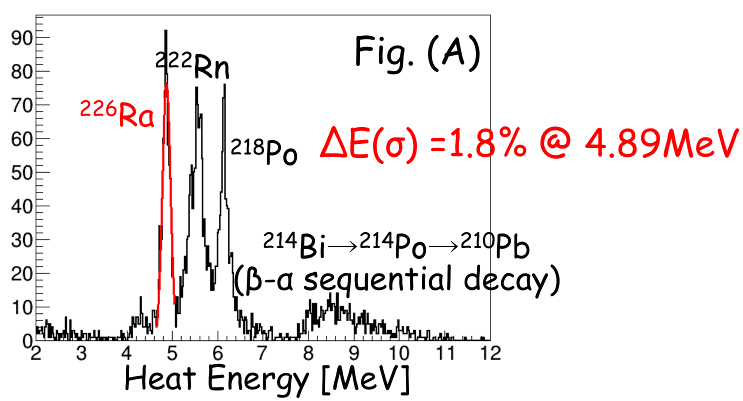
- Problem
  - UV scintillation of CaF_2 is absorbed on Au-deposit for heat signal. There is position dependence of scintillation absorption. ➔ make worse E-resolution.

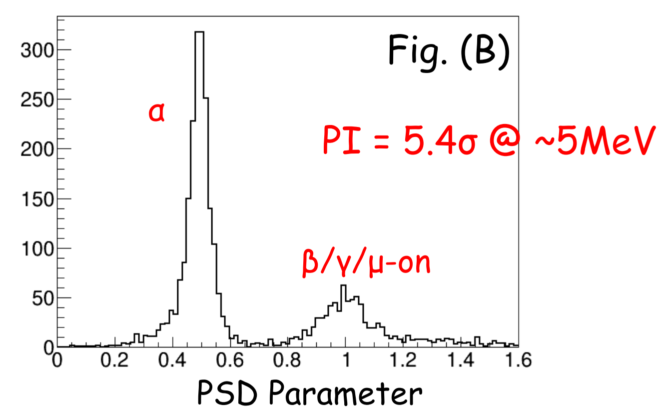
Resolution and Discrimination

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



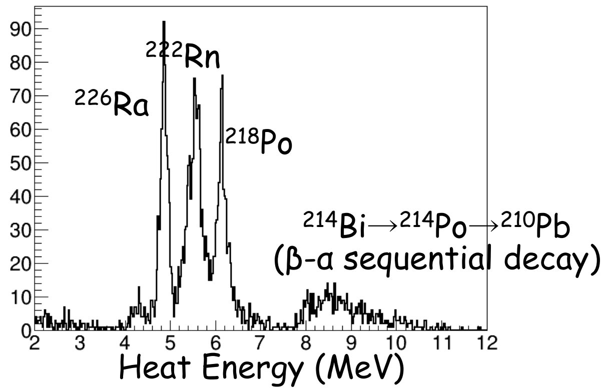


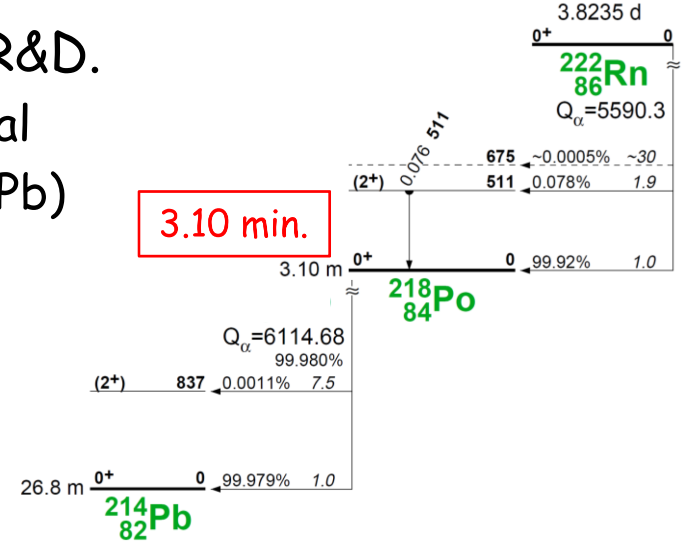


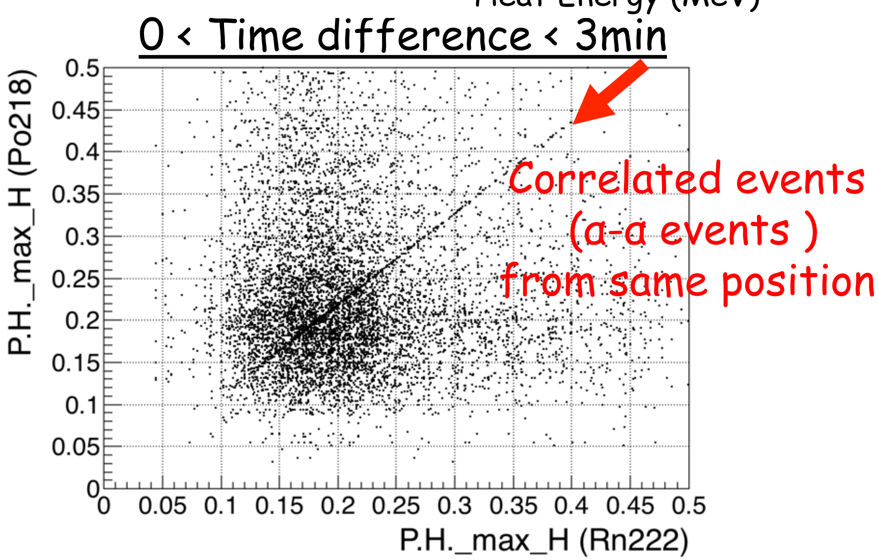


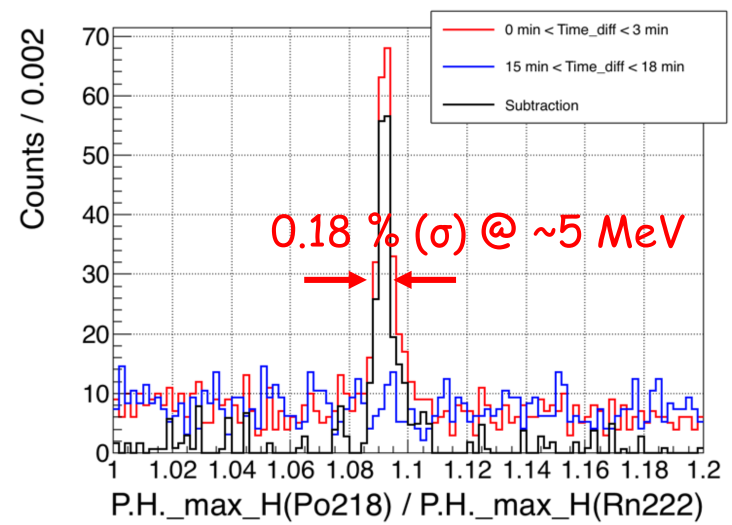
Position dependence

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







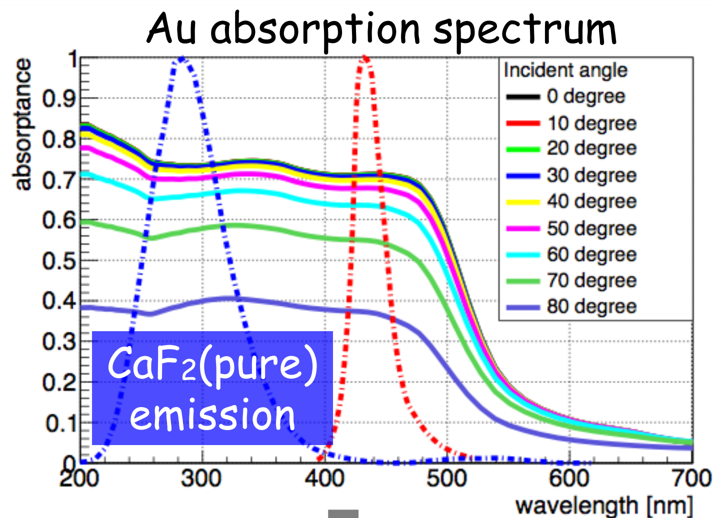


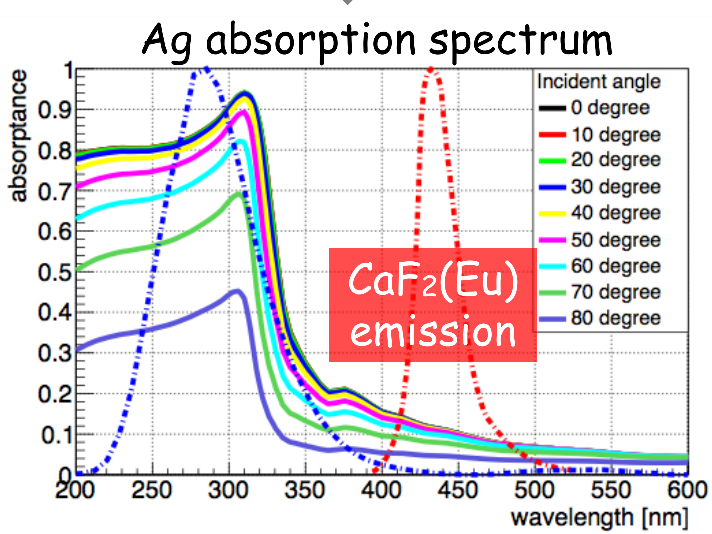
Evaluated ideal energy resolution without position dependence

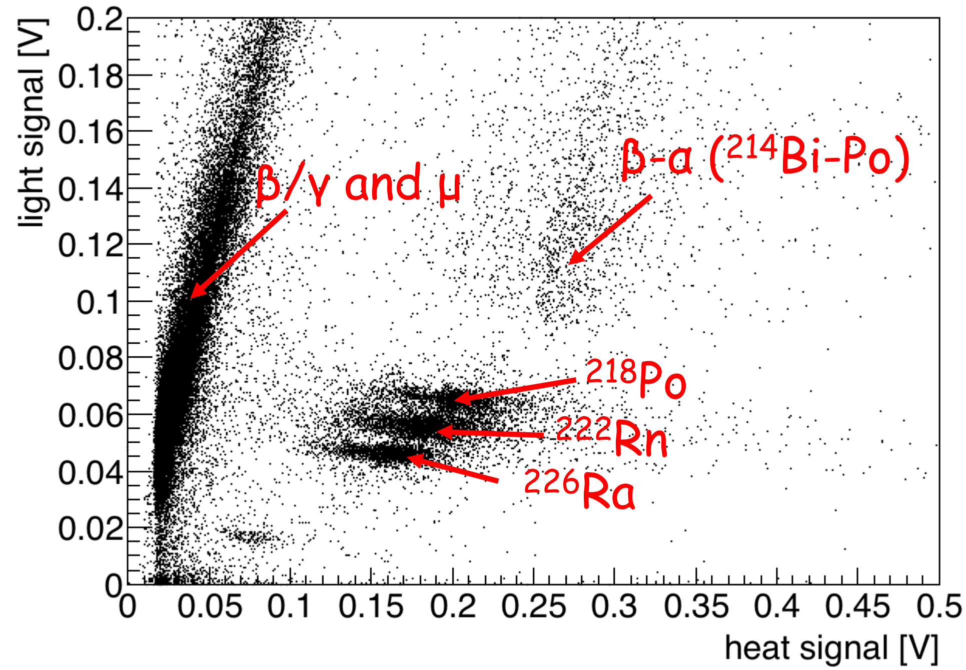
CaF_2(Eu) scintillating Bolometer

Poster by Xiaolong Li (Osaka U.)

- New trial to overcome UV absorption
  - CaF_2(Eu) +Ag-deposit instead of CaF_2(pure) + Au-deposit





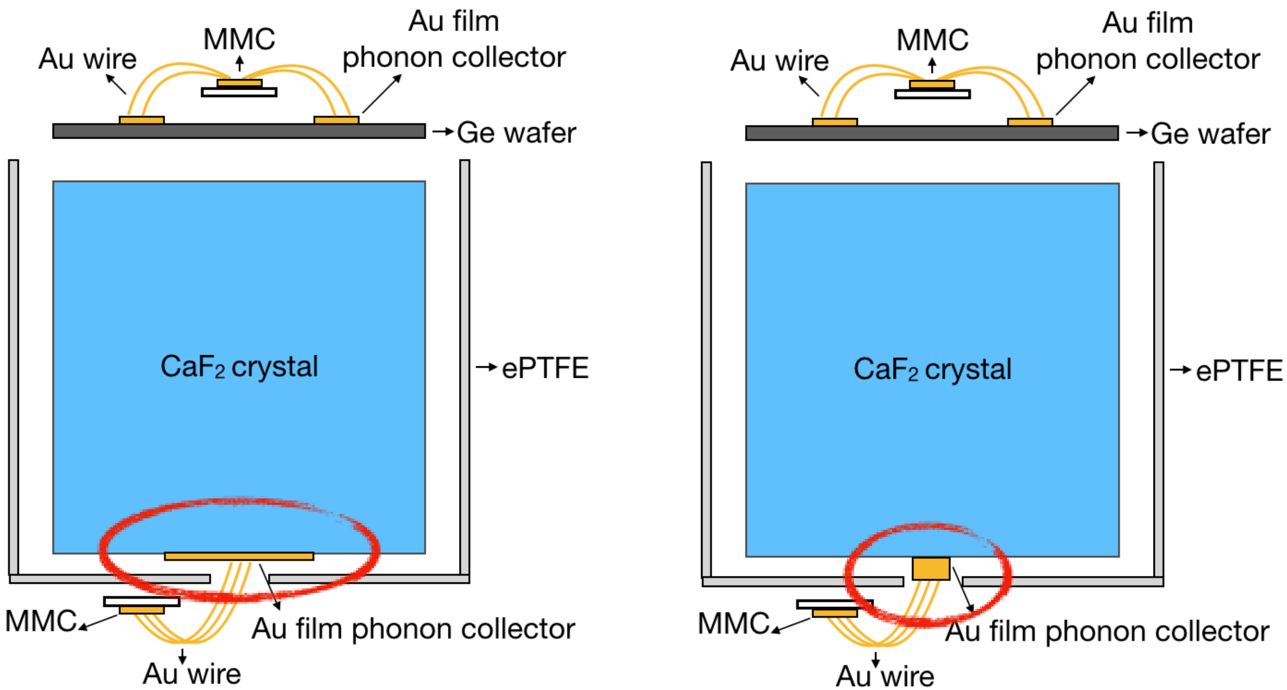


- ✓ Improved light signal properties.
- ✓ In the heat channel, peaks of α's are widely spread. (due to position dependence)
- ✓ Due to doping Eu (paramagnetic) ?
- ✓ We are now trying to understand.

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.

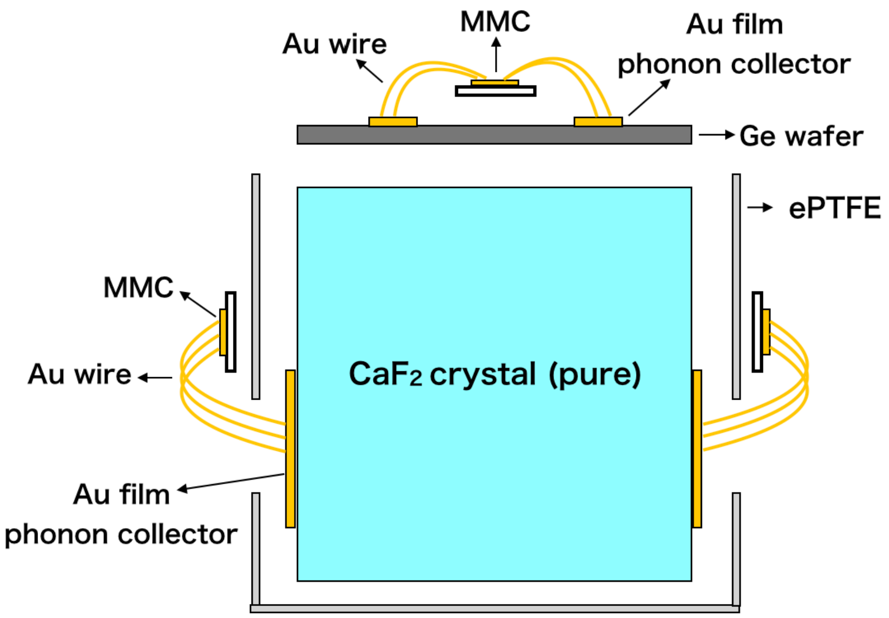
- New trial in the next step
  - CaF_2(pure) crystal with smaller but thicker Au-deposit phonon collector.
    - Smaller → reducing scintillation absorption effect
    - Thicker → increasing the strong electron-phonon interaction.



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.

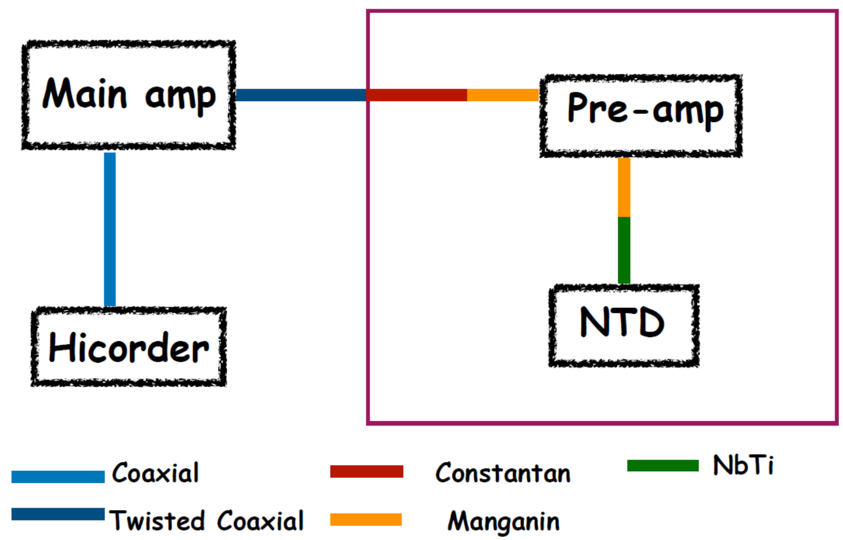
- New trial in the next step
  - CaF_2(pure) crystal with multi-phonon detector.
    - high-precision position information



R&D in Osaka

Ready

- Developing CaF_2+ NTD-Ge Scinti-Bolometer
- Transfer of 3He/first, cooling test (base temperature ~10mK) of DR was completed in September 2018.
- Confirmed the base temperature in the mixing chamber of DR ~10mK .
- Establish electrical connection from MC to main-amp box.

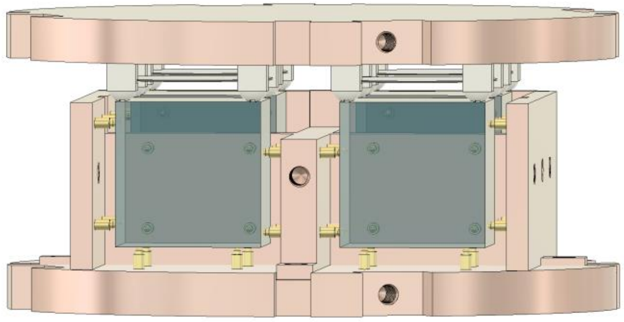


- The final bit to connect the NTD-Ge, wire bonding (Au wire)

R&D in Osaka

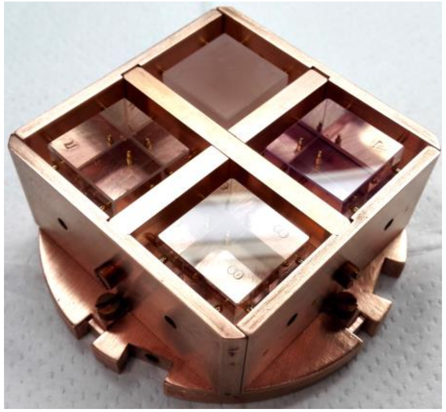
- Detector parts
  - Designed detector module consists of phonon detector and photon detector, which are fixed by copper spring pins and teflon blocks in the OFHC copper holder.

Design Drawing

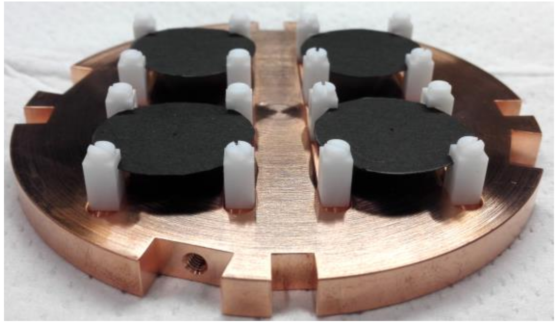


- **CaF_2 crystal**: 20×20×20 mm^3, 147mK in $Q_{\beta\beta}$ at 10mK, enough temperature rise to be detected.
- **HPGe wafer**: 22mm Φ, 200μm thickness, 13N high purity to improve energy resolution.
- **Reflector**: diffuse reflection => Teflon sheet
  specular reflection => MIRO-UV
- Each wafer and crystal is mounted with a NTD Ge thermistor for reading the signals.

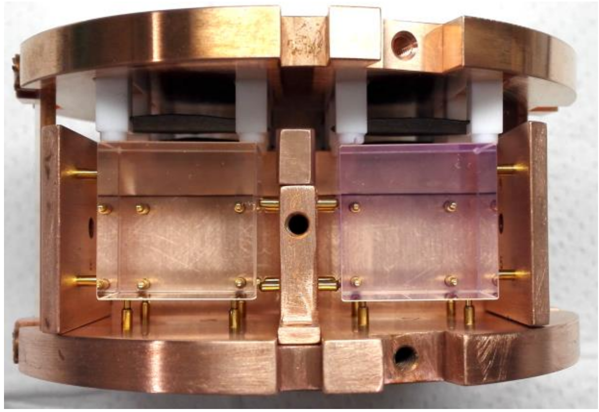
Phonon Detector Module



Photon Detector Module



Detector Combination



Bolometer with KID

Info. & Slide from Koji Ishidoshiro (Tohoku)

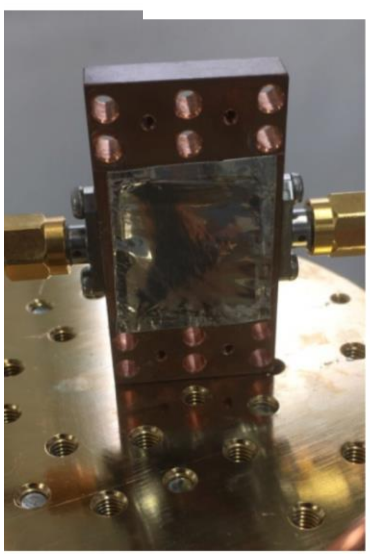
Final goal: study of MeV scale DM with superconducting target

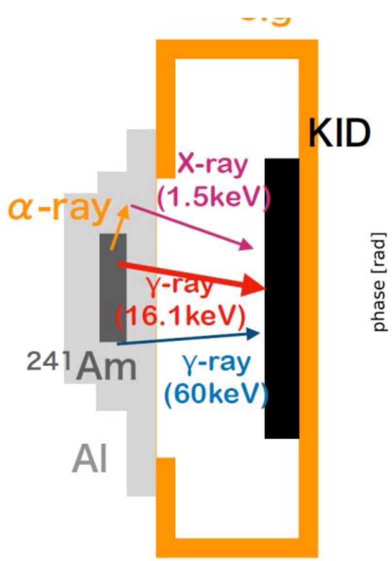
First step: KID on CaF_2

- Knowhow to develop SCD
- CaF_2 : interesting target
  - ^{19}F: sensitive to spin-dependent DM scattering
  - ^{48}Ca: 2β decay nucleus
  - Scintillation crystal: strong background reduction

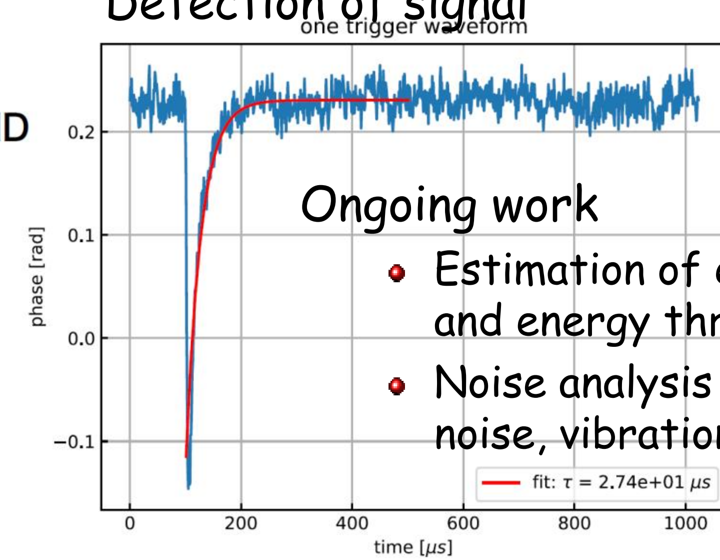
Status

- Fabrication of KID on CaF_2
- Confirmation of KID operation
  - Resonance measurement
  - Particle detection





Detection of signal



Ongoing work

- Estimation of energy resolution and energy threshold
- Noise analysis of KID (magnetic noise, vibration noise, and others)

Summary

- Bolometric measurement of temperature increase is promising technique to obtain good energy resolution, down to ~ several keV at ~MeV region.
- Scintillating bolometer wsa; good particle identification
- Some 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.