Low Temperature Detector Development
for
Underground Researches

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Development of low temperature detector with highly sensitive astro-particle physics research

D02

【Member】

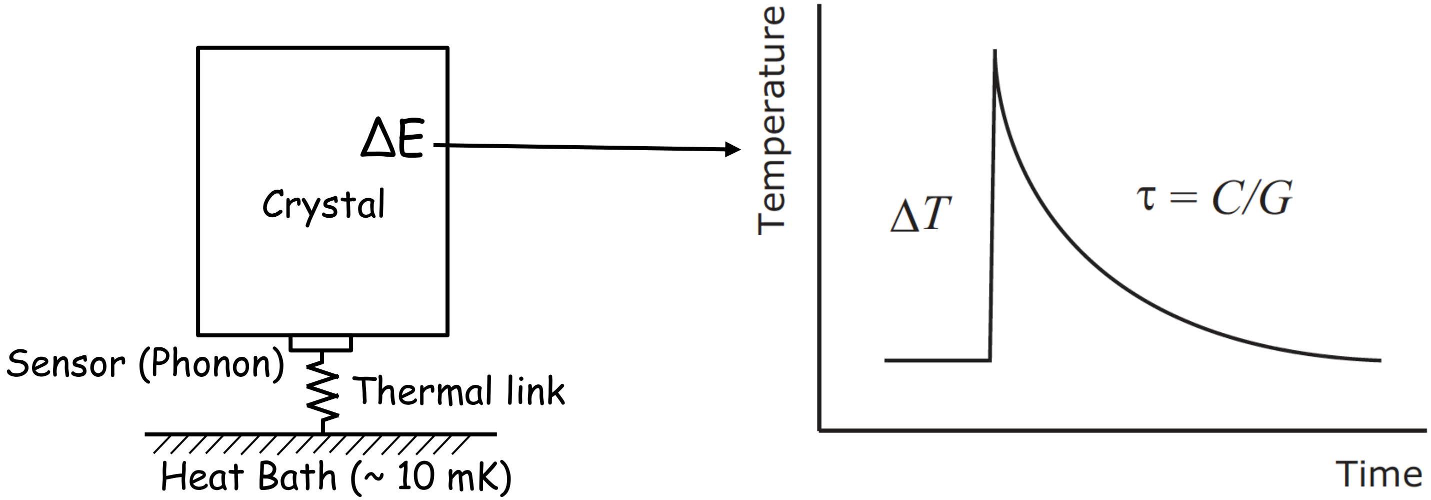
Sei Yoshida(Osaka): Low temp. detector for 0νββ decay
Y. Kishimoto (Tohoku): Low-temp. & high-magnetic field cavity
K.Ishidoshiro (Tohoku): Low temp. detector for DM search
S. Mima (NICT): Development of superconducting sensor

Development for Ca Bolometer

- Future development for CANDLES project

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.

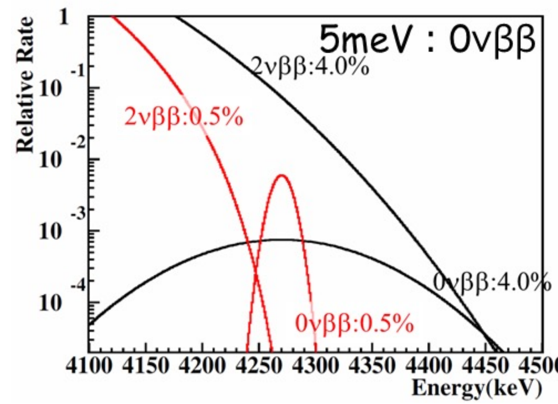
Background Candidates for CaF_2

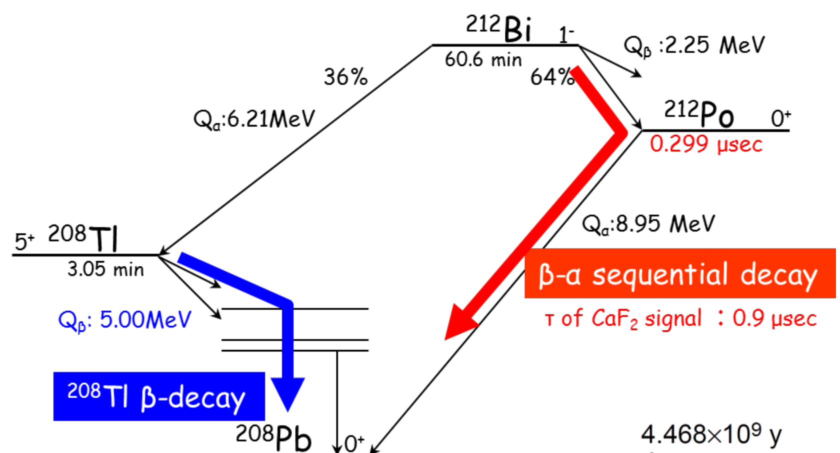
- Tail of $2\nu\beta\beta$ spectrum
  - Improving energy resolution

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



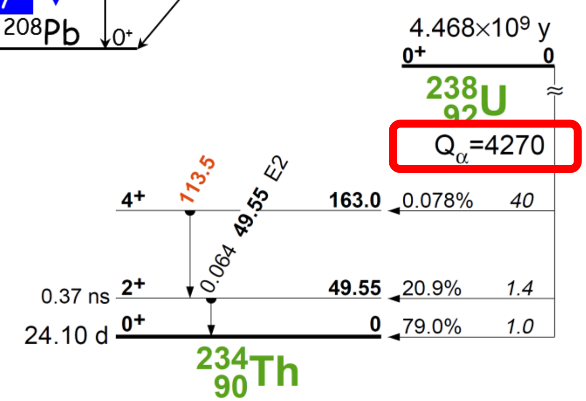


- But... new BG candidate
  - Q value of ^{48}Ca : 4267.98(32) keV @ arXiv:1308.3815
  - Q-value of ^{238}U (α-decay) ： 4270 keV

    Impossible to avoid

    ➔ required particle ID

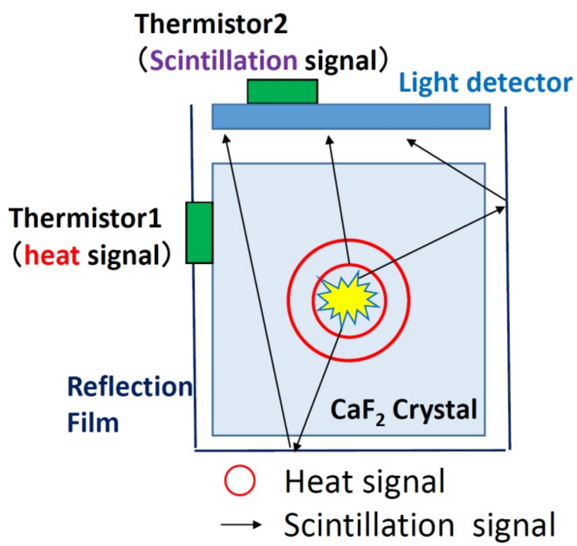
➔ Developing CaF_2 Scintillating Bolometer

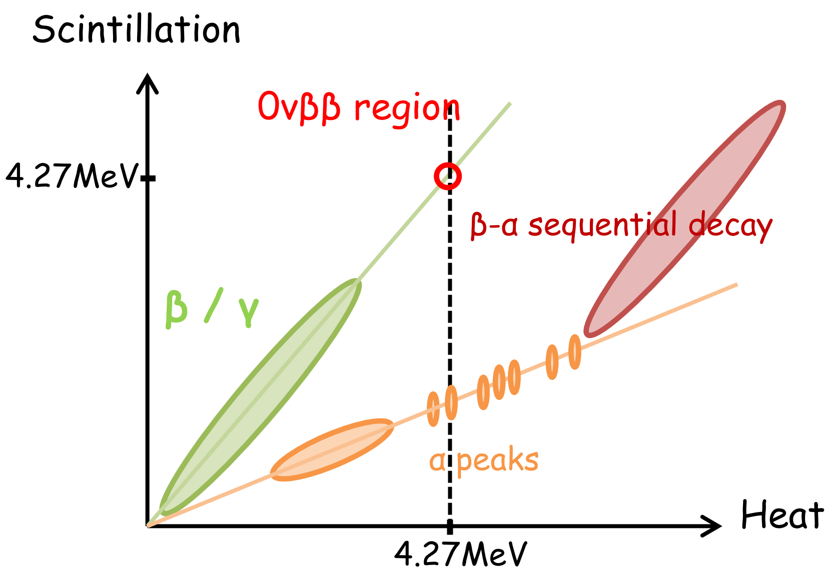


CaF_2 Scintillating Bolometer

- 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
  - Un-doped CaF_2 crystal
    - Radio-pure crystal is available ← developed by CANDLES project
    - Large light output at low temperature
  - MMC (Metallic Magnetic Calorimeter) as sensors

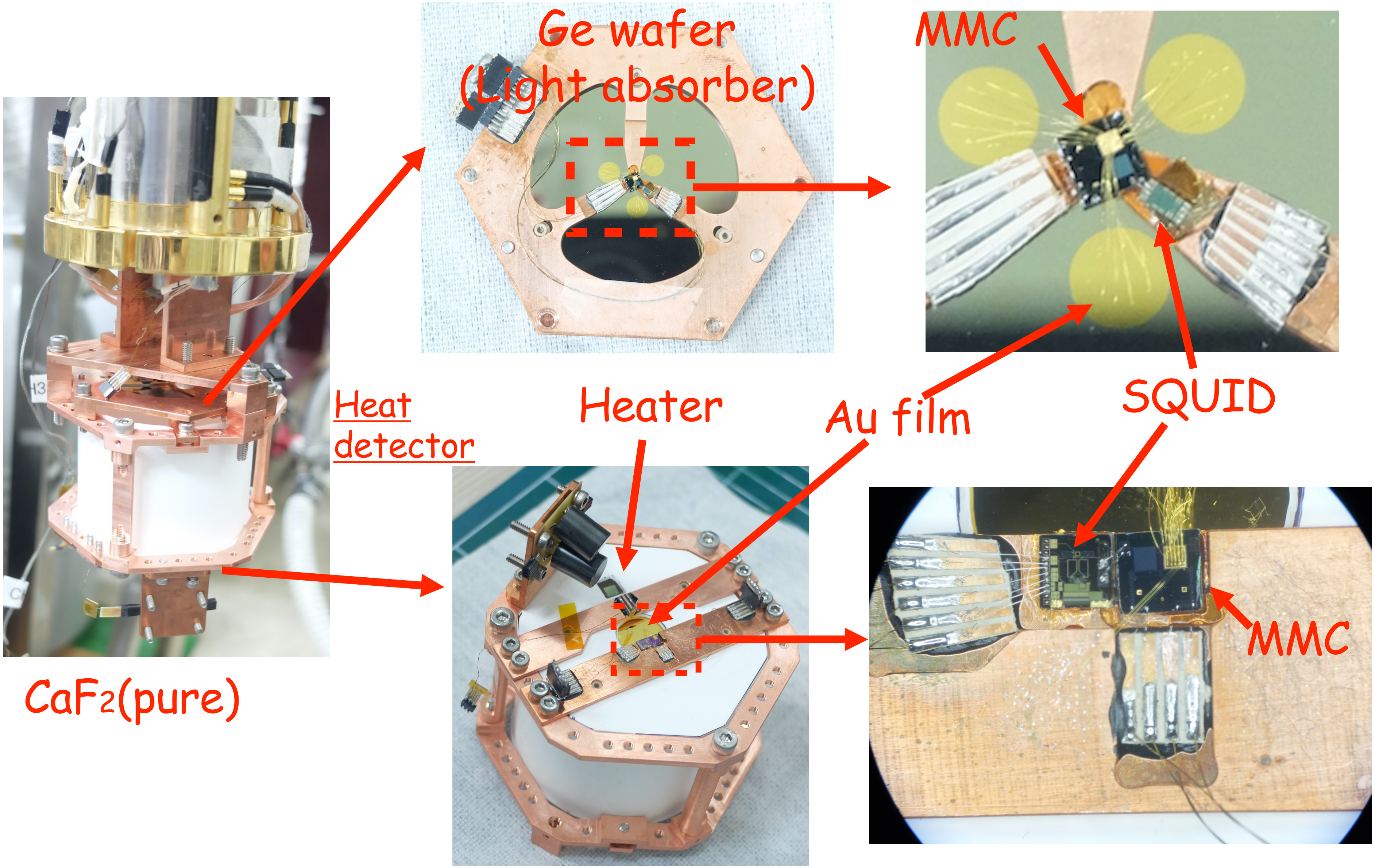
Development for CaF_2 Scintillating Bolometer with MMC

- Collaborative research with Korean colleague

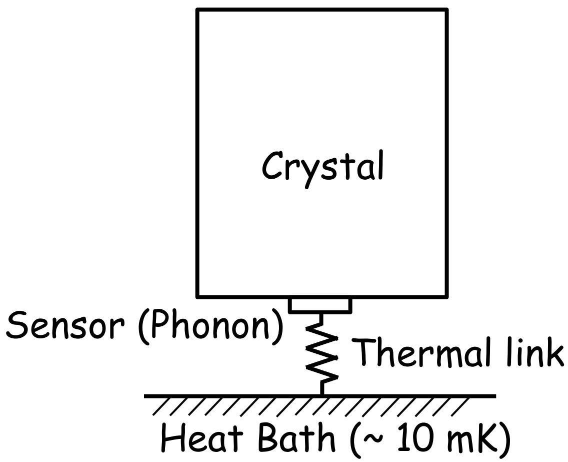
  Yong-Hamb Kim (IBS & KRISS)
  Minkyu Lee (KRISS)
  Inwook Kim
  Do-Hyoung Kwon
  Hyejin Lee
  Hye-Lim Kim

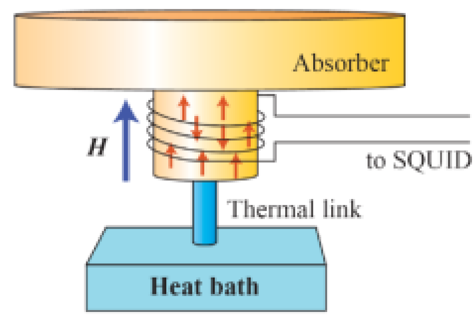
- Sub-Group of CANDLES (Osaka)

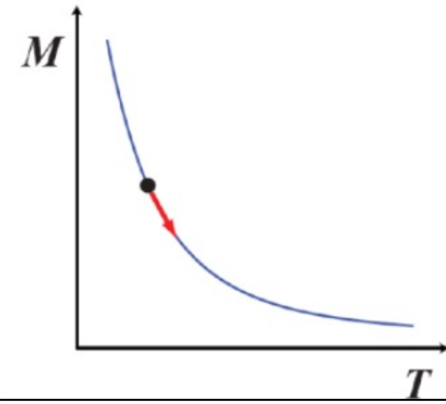
CaF_2 Scintillating Bolometer Setup



MMC as Temperature Sensor







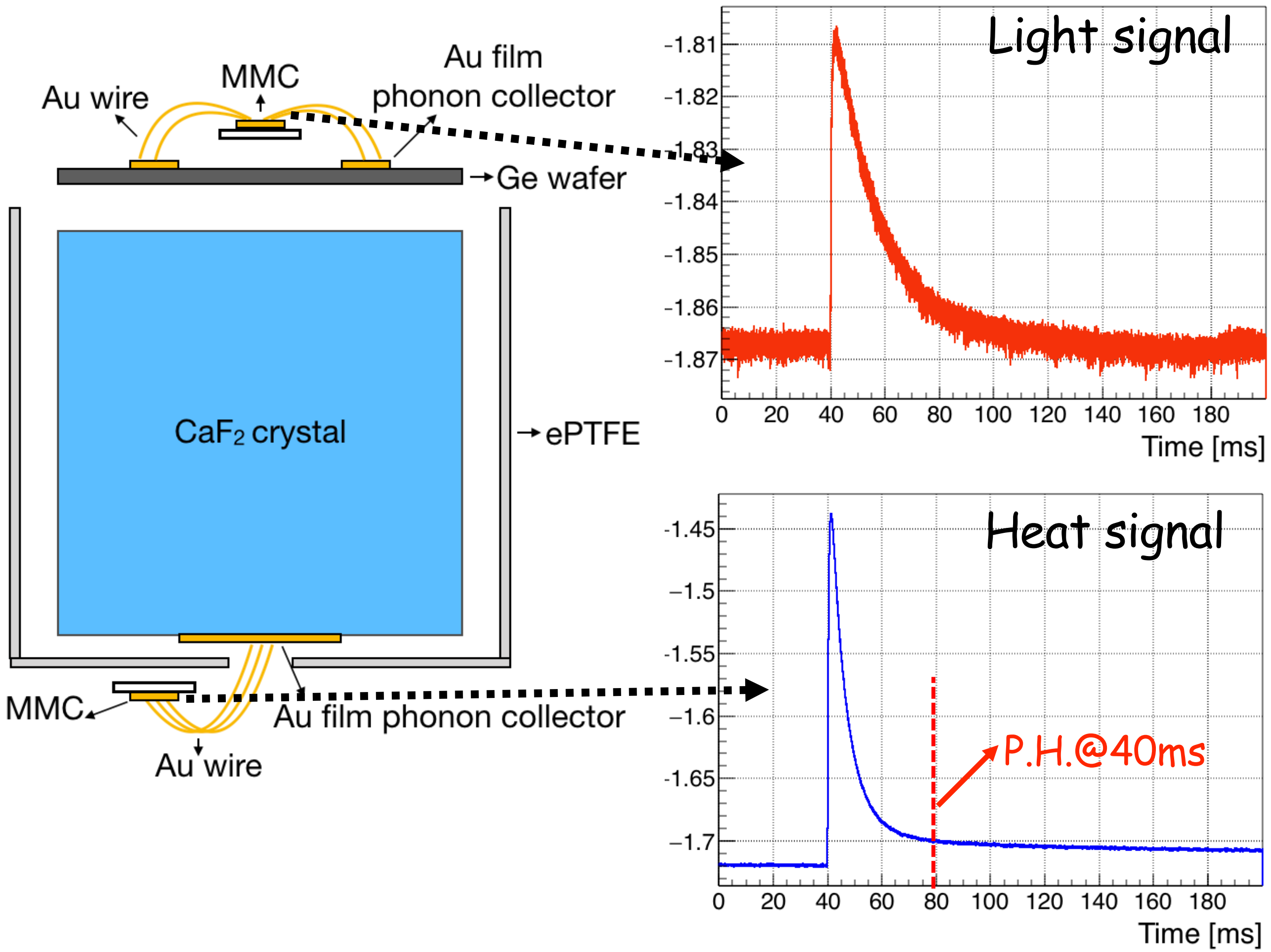
Process of detecting signal

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**

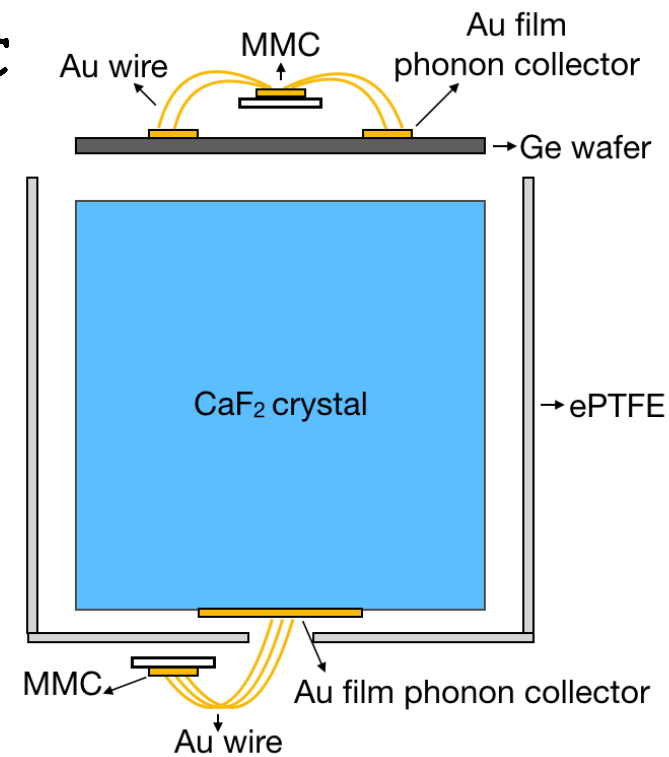
Signals from CaF_2 Bolometer

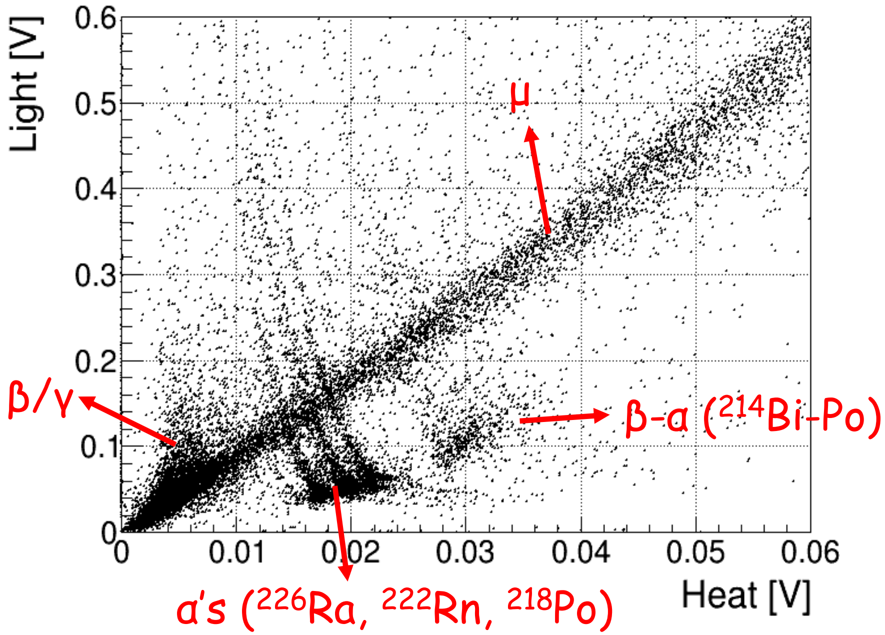


- The rise time ; ~ 0.7ms.
- The decay time ; ~ 8ms, ~ 200 msec

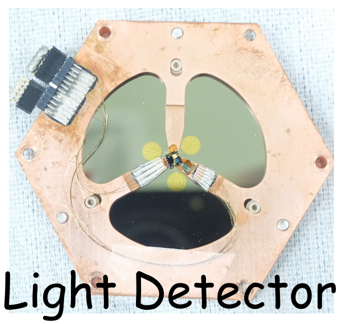
CaF_2(pure) Scintillating Bolometer

- 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






CaF_2 crystal


Light Detector

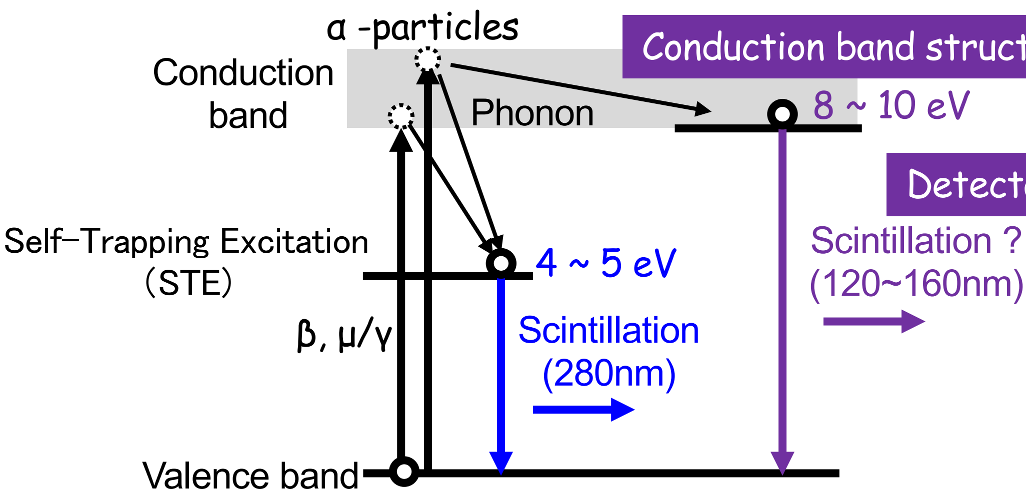
- Problem
  - UV scintillation of CaF_2 is absorbed on Au-deposit for heat signal. There is position dependence of scintillation absorption. ➔ make worse E-resolution.

CaF_2 Scintillating-Bolometer開発

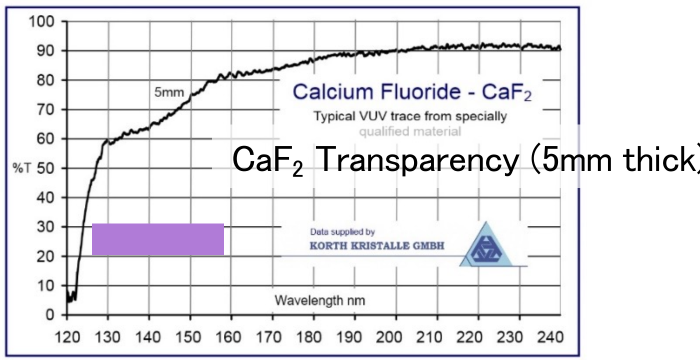
- Problem：Light yields of α-ray events distribute widely.
  - There is a fluorescent component with extremely high attenuation.

Conduction band structure @ 8 ~ 10 eV

Ref. ; J. Birth et al., Phys. Rev. B41 (1990) 3291



Detectable only in the vicinity of the light detector



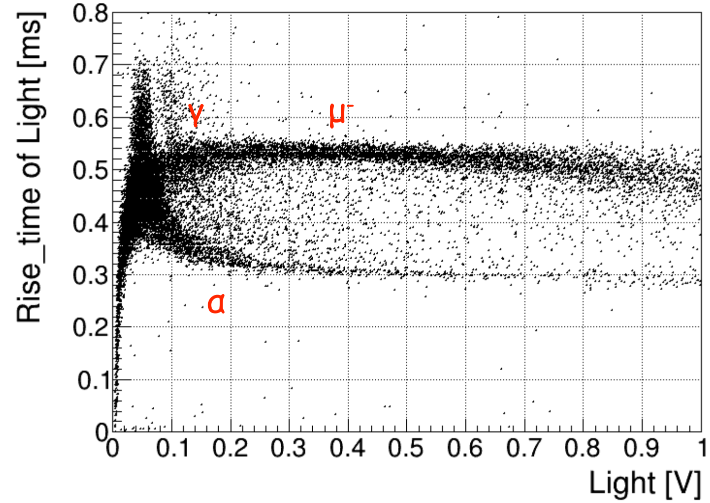
- Scintillation light with very short wavelength ?
  - Attenuation in CaF_2 crystal（Transparency ~ worse below 200 nm）
  - Absorbed on the PTFE reflector（It was OK for UV light of 280 nm ）

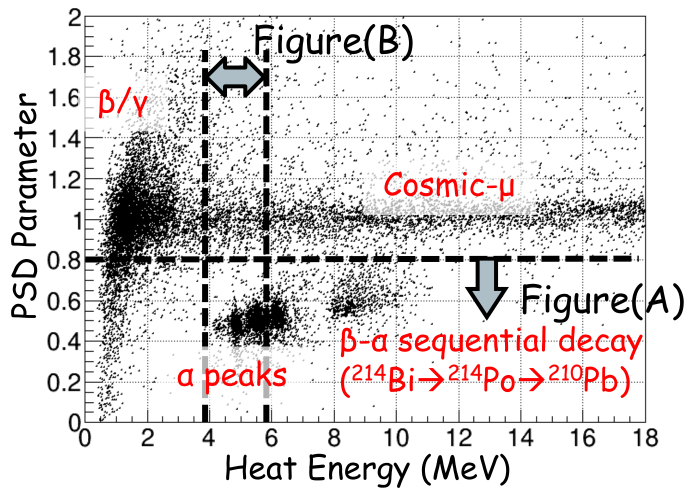
So far, the experimental data is well understandable (no contradictions)

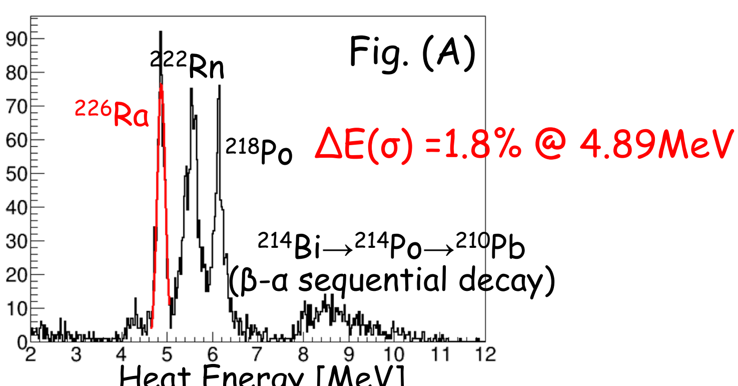
- Experimental check
  - Scintillation counting with TPB wavelength shifter (VUV → visible light)
  - (Emission wavelength measurement)

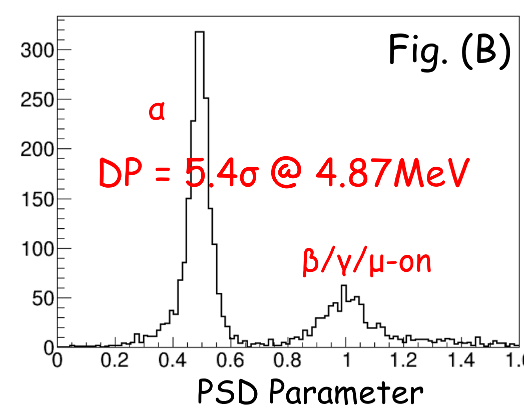
Resolution and Discrimination

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



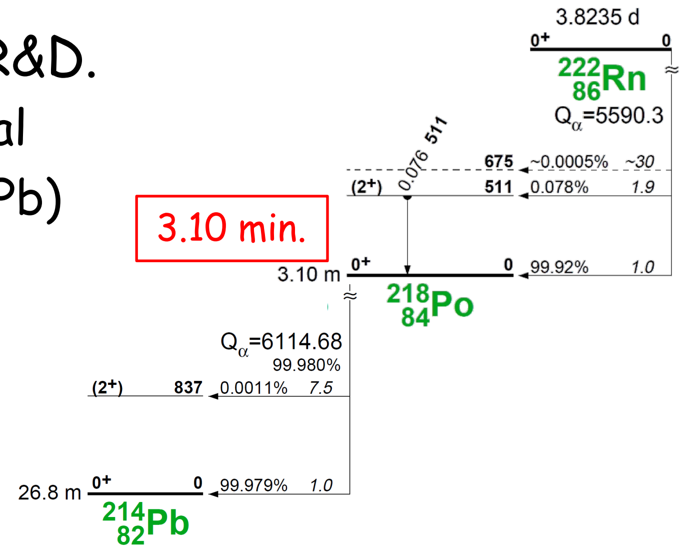


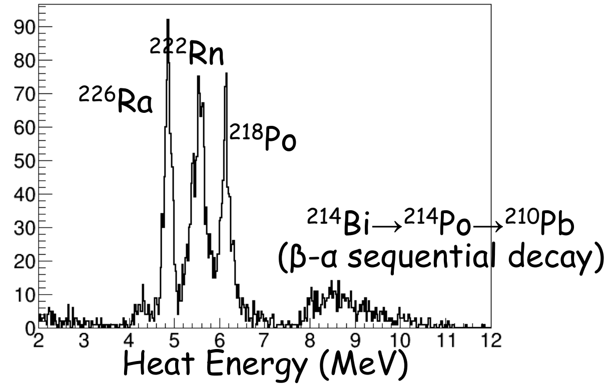




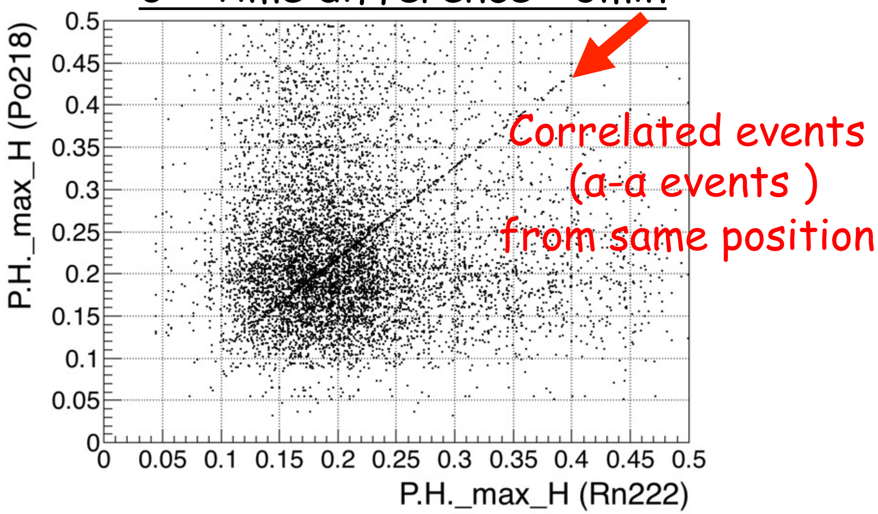
Position dependence

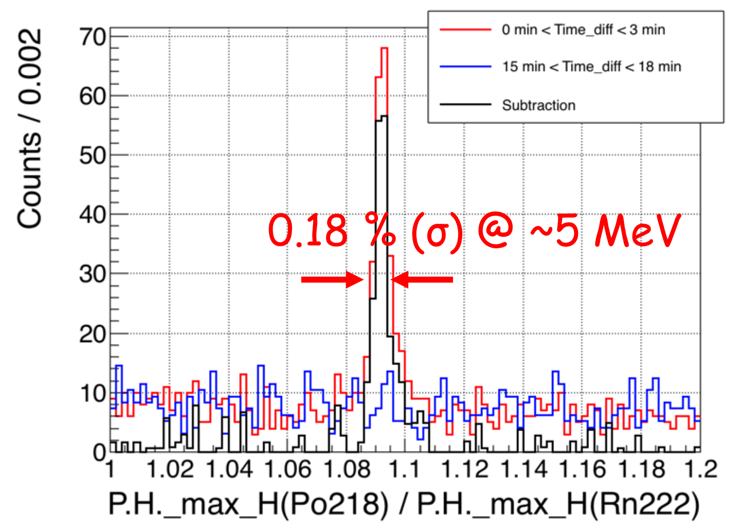
- We use contaminated CaF_2 crystal for R&D.
  - ~ 30 mBq of ^{226}Ra (U-chain) within crystal
  - Delayed coincidence ($^{222}Rn \rightarrow {}^{218}Po \rightarrow {}^{214}Pb$)





0 < Time difference < 3min





Evaluated ideal energy resolution without position dependence

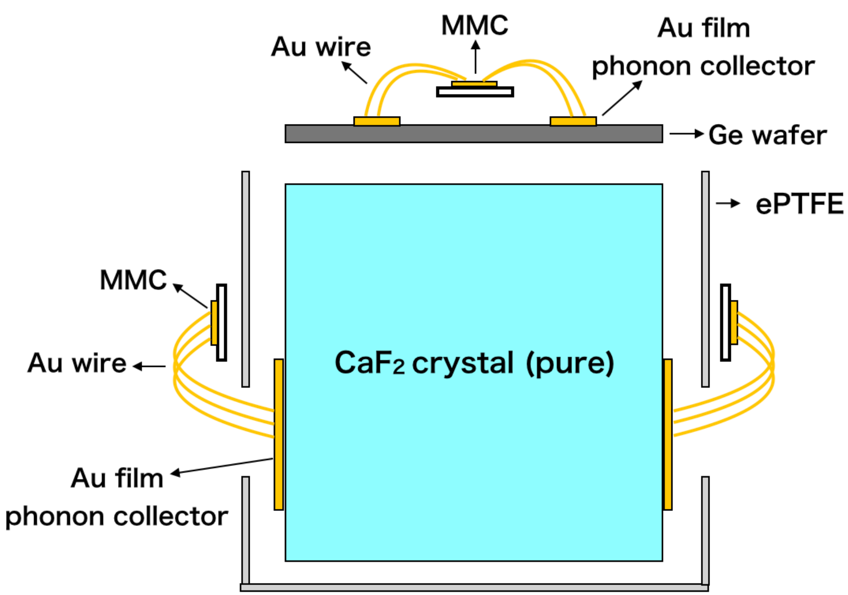
Design for the next trial

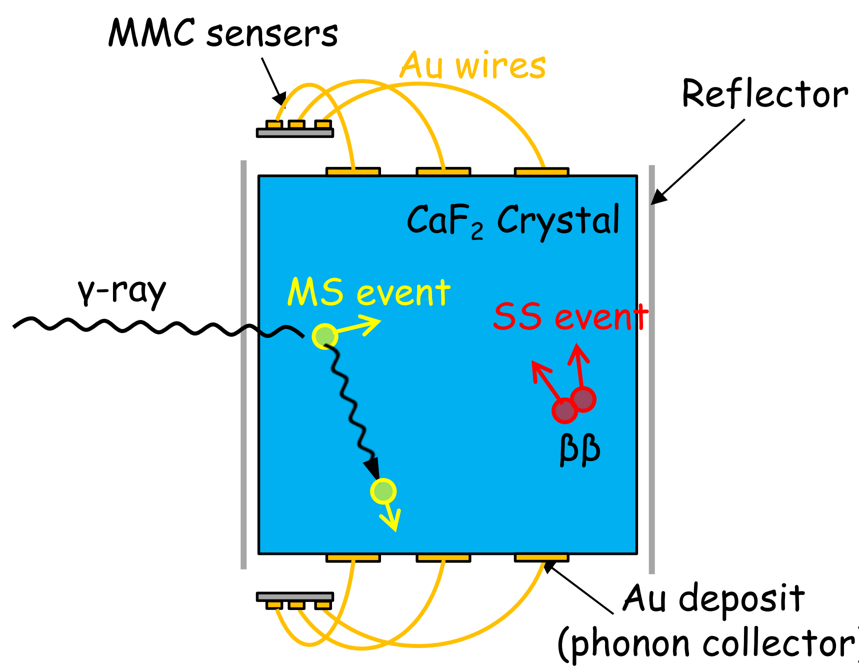
- Improving E-resolution of CaF_2(pure) scintillating bolometer
  - Radio-pure CaF_2(pure) crystal had been developed.

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

    ➔ *Good energy resolution of phonon signal*

    ➔ Discriminate single site event and multi-site event ?





Low temperature detector for dark matter searches

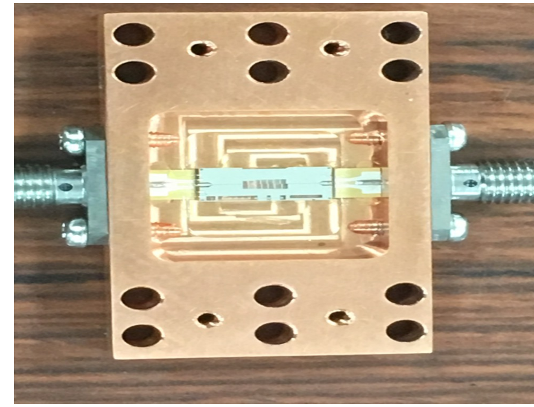
- <u>Development of KID of CaF_2</u> / ZrO_2 substrates*
- CryoLab at Kamioka
- TES for the detection of ECEC decay of ^{112}Sn*

* discussed in Poster Session

Bolometer with KID on CaF_2

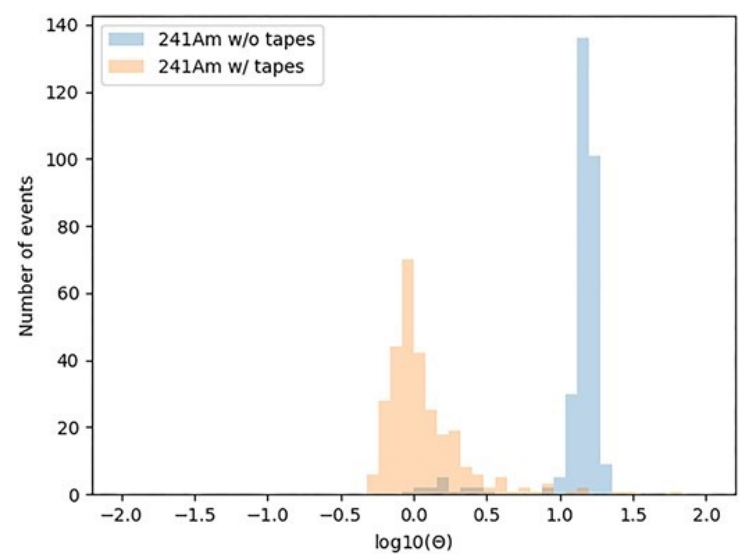
Koji Ishidoshiro (Tohoku)

- Motivation
  - Searching for low mass WIMPs at ~MeV mass range
- Methodology
  - Substrate = WIMPs target (Direct detection)
  - Si substrate → CaF_2 substrate
    - 19-F : sensitive target for SD-WIMPs
    - Future development for scintillating-bolometer to discriminate between electron and nuclear recoils
  - Al target → Energy threshold ~10 eV



KID mounted on CaF2 substrate

- Results
  - PTEP2023, Issue 10, October 2023, 103H02
    - ^{241}Am source irradiation
    - Detection of
      - γ-ray events (59.5 keV) with masking tape
      - α-ray events (5.49 MeV) without tape
    - Verification of the resonance of a LEKID on the CaF_2 substrate and the capability of phonon-mediated particle detection



Summary

- Bolometric measurement of temperature increase is promising technique to obtain good energy resolution, down to ~ several keV at ~MeV region.
- Scintillating bolometer ; good particle identification
- Scintillating bolometer of undoped CaF_2 was firstly demonstrated, and the performance of detector was evaluated.
  - $\Delta E(\sigma)$ = 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 are developing next design of Ca bolometer in Osaka univ..