입자검출기워크샵 2026 (Particle Detector Workshop 2026)

Feb 6 – 7, 2026
Science Culture Center, IBS HQ

Enter

Magnetic microcalorimeters for astroparticle physics applications

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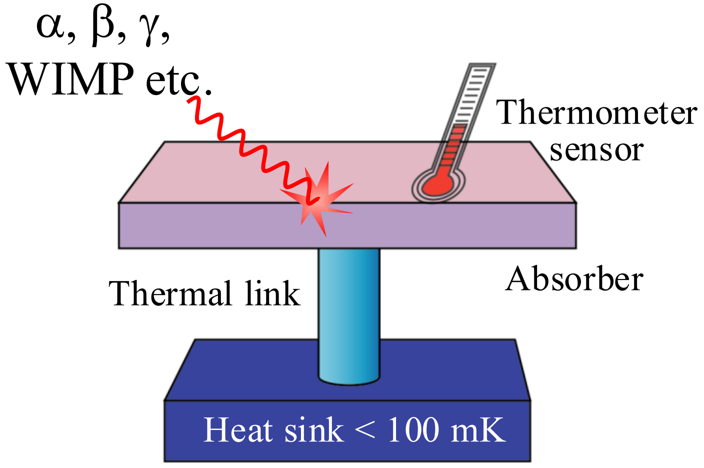
ibs 기초과학연구원 Institute for Basic Science

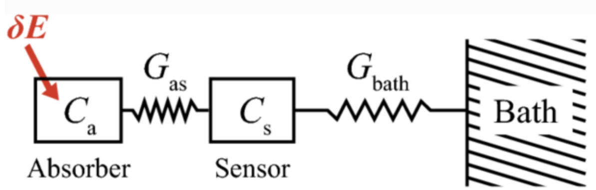
CENTER FOR UNDERGROUND PHYSICS

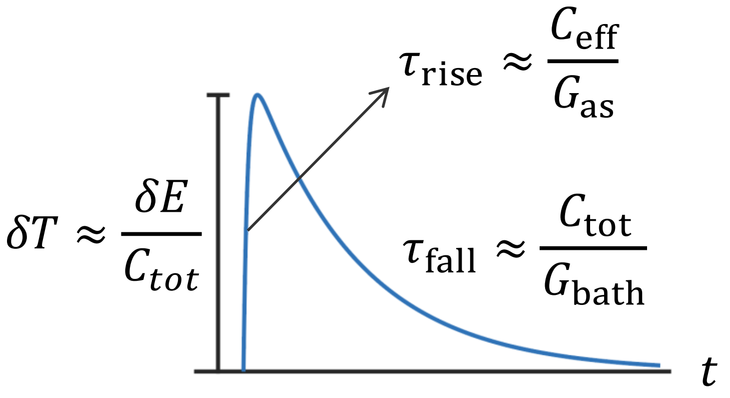
Low Temperature Detectors (저온검출기)

(Low-temperature equilibrium thermal detectors)

Energy absorption ➔ Heat (Temperature)







- Measurement of the energy ***E*** as a temperature rise
- Temperature pulse with decay time
- Very low temperature (10–300 mK)
  Small ***C*** → Large **Δ*T***
  Low noise

Sensor technology

Choice of detector sensors (superconducting detectors)

- **Thermistors (doped Ge, Si)**
- **TES (Transition Edge Sensor)**
- **MMC (Metallic Magnetic Calorimeter)**

- **STJ (Superconducting Tunneling Junction)**
- **KID (Kinetic Inductance device)**
- **Superconducting nanostrip detectors**
- **etc.**

➔ Currently used as sensors for equilibrium thermal detectors measuring the temperature increase due to the energy input

➔ Have great sensitivities for low threshold detection

What to measure with LTDs

<For more info, refer LTD conferences>

Area	Measure	Topics
Astronomy & Cosmology	CMB, submm, X-ray, γ-ray	Inflation, Dark energy, neutrino mass, Star/Galaxy formation, Black holes, ...
Quantum information	Optical, IR	Quantum computing, key distribution, communication, …
Material science, Biology	X-ray, neutrals	EPMA, Synchrotron, …
Security, Nuclear materials	THz, X-ray, γ-ray, alpha, beta, neutron,	Concealed weapons, Nuclear materials, Forensics, …
Atomic, Nuclear physics	X-ray, γ-ray, alpha, beta, neutron,	QED test, EBIT, Rare decays, Forbidden beta spec, muonic (kaonic) atoms, …
Particle physics	Dark matter, neutrinos, X-ray, optical,	Dark matter, CEνNS, ν mass, sterile ν, axion, $0\nu\beta\beta$, ...

Signal and noise in semiconductor detectors

Signal ~ N

- For Si, $E_{gap} = 1.1$ eV
- Number of e-h created

$$N = \frac{E}{W} \neq \frac{E}{E_{gap}}$$

- For Si, $W \sim 3.7$ eV measures only 30% of energy (E)
- The rest (phonons)
→ heat generation

Noise ~ δN

- the generation of e-h pairs is not statistically independent

$$\delta N \neq \sqrt{N}$$

- Fano factor, $f \sim 0.11$ for Si

$$\delta N = \sqrt{f \cdot N}$$

- $\frac{\delta E}{E}\text{(FWHM)} = \frac{2.355\sqrt{fWE}}{E} \approx \frac{\textbf{120 eV}}{\textbf{6000 eV}}$

Intrinsic resolution of thermal detectors

"A naïve concept in thermodynamic energy fluctuations"

- Thermal Energy of a detector with heat capacity C at temperature T : $\sim CT$

- Average energy per carrier (phonons, electrons, etc) : $\sim k_B T$

  $k_B T = 1.38\times10^{-23}$ (J/K) T = 8.6×10^{-6} eV (at 100 mK) < 10 μeV

- Number of carriers $N \sim CT / k_B T$

- Statistical thermal noise due to thermal energy fluctuation

$$(\Delta E)_{FWHM} \sim 2.355 \cdot k_B T\,(N)^{1/2} = 2.355 \cdot (k_B T^2 C)^{1/2}$$

~ 0.3 eV with 0.2mm×0.2mm×10μm gold at 100 mK (0.3 fJ/K)

~ 100 eV with 6cm×6cm×6cm Ge at 20 mK

Best ΔE achieved with LTDs

(measured with TFN & thermometer noise)

Measured energy resolution of 6 keV x-rays from ^{55}Fe source

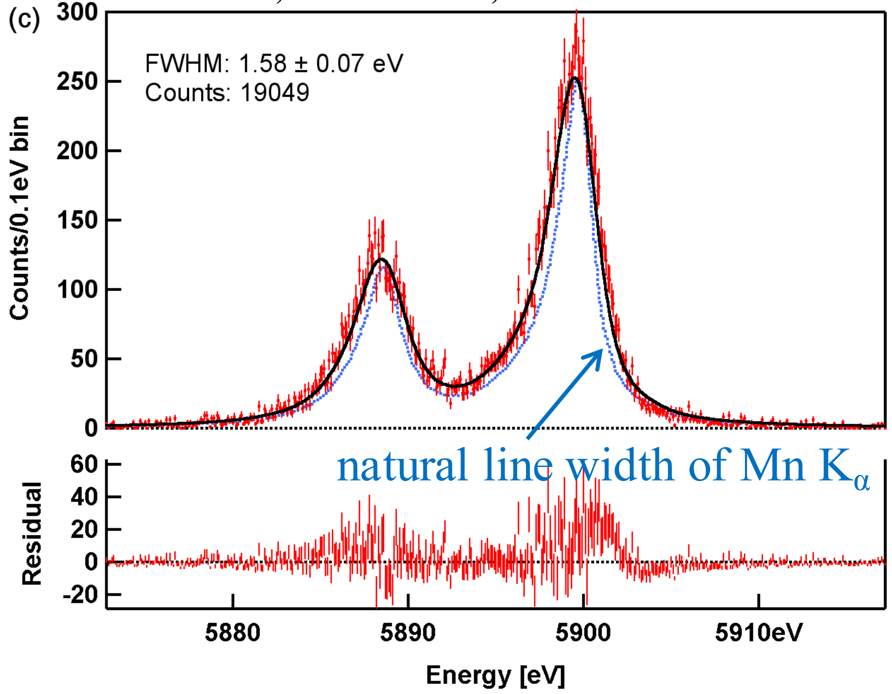
detector resolution

- Thermistors (doped Si) :
  $(\Delta E)_{FWHM}$ = 3.2 eV
  2009, NASA GSFC

- Transition edge sensors :
  $(\Delta E)_{FWHM}$ = 1.6 eV
  2011, NASA GSFC

- Magnetic micro-calorimeters :
  $(\Delta E)_{FWHM}$ = 1.3 eV
  2024, Heidelberg U., KIT

<Smith et al., 2011 at LTD14, with TES at NASA GSFC>

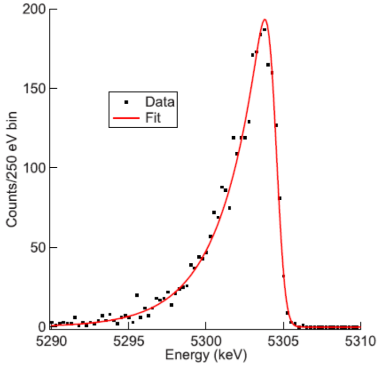


natural line width of Mn K_α

natural line width:
e.g. uncertainty principle: $\Delta E \Delta t > \frac{\hbar}{2}$

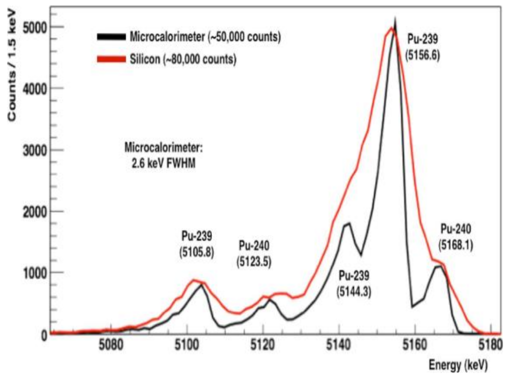
Alpha spectrometers (external source)

^{210}Po



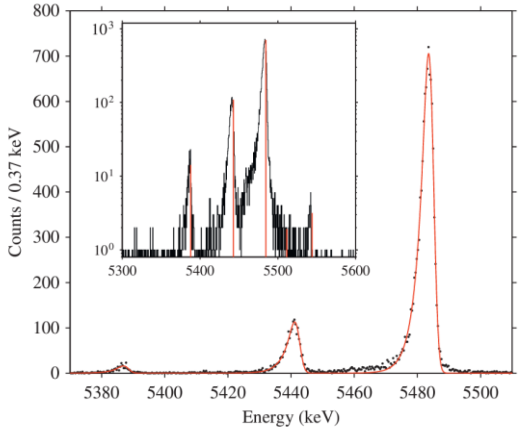
<2009 NIST>
1.1 keV FWHM

$^{229}Pu + ^{240}Pu$



<2011 LANL>
2.6 keV FWHM

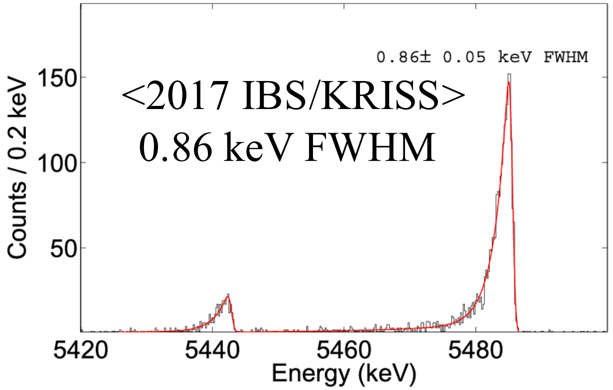
^{241}Am



<2013 KRISS>
1.2 keV FWHM

Measured broadening of thermal detectors
for alpha spectrometry

➔ **straggling on the source + detector resolution**



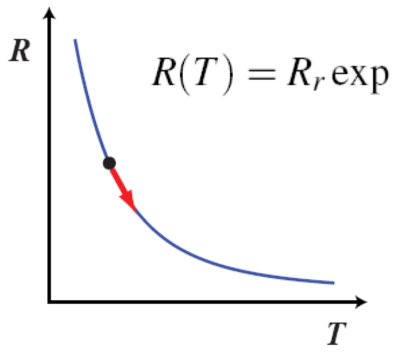
<2017 IBS/KRISS>
0.86 keV FWHM

"Best resolution achieved with an alpha source"

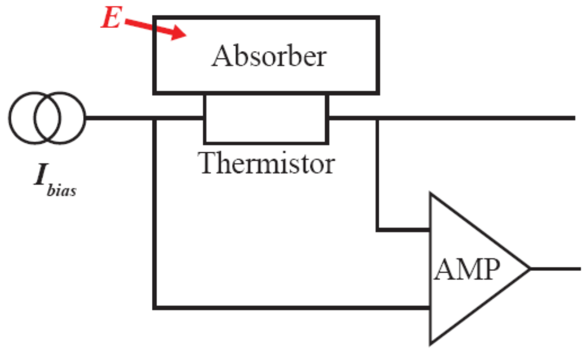
Sensor technologies

Thermistors

- Doped semiconductors
  - Neutron transmutation 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



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



<Current bias and read voltage >

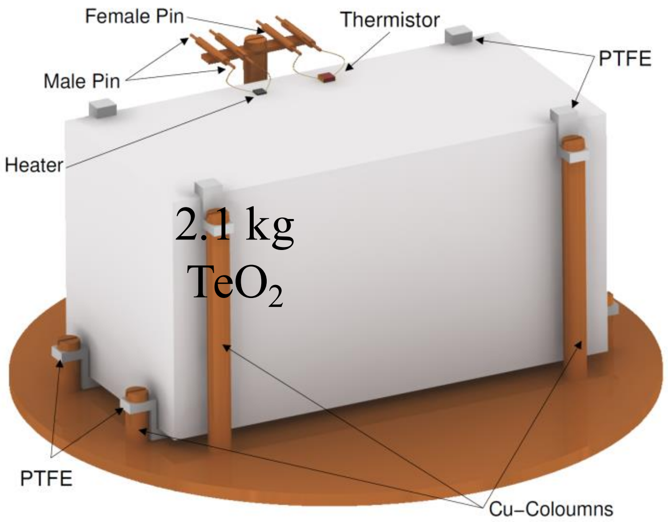
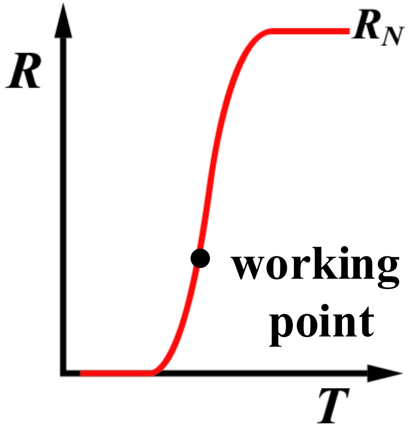
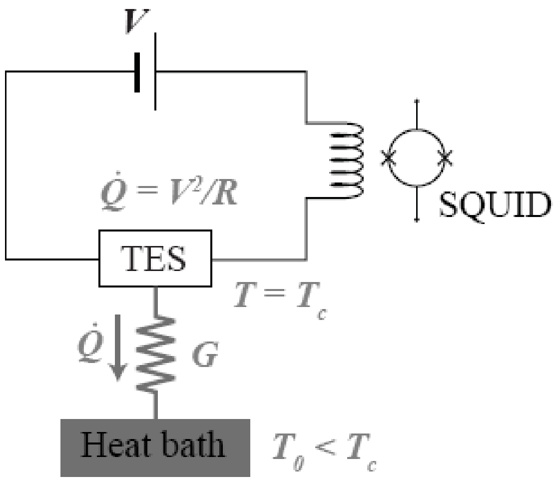


fig. from Cardani et al arXiv.1106.0568

Transition Edge Sensor (TES)

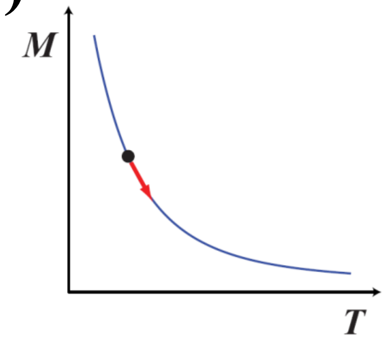
- Superconducting strip at T_c
  - Elemental superconductors: Ti, Ir, W
  - Proximity bilayers: Mo/Au, Mo/Cu, Al/Ag, Ir/Au, Ir/Pt, etc.
- R_N : 10 mΩ ~1 Ω
- Readout: SQUID
- High energy resolution + Low energy threshold + Fast + MUX
- Limited linearity and limited dynamic range, Absorber selective (or chip carrier)



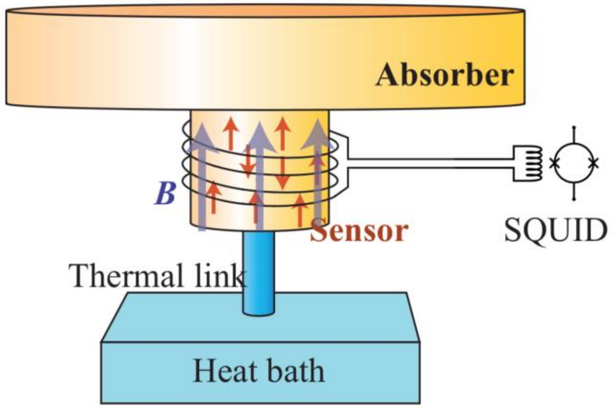


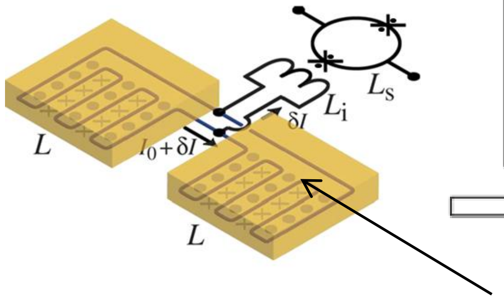
Magnetic microcalorimeter (MMC): Short intro

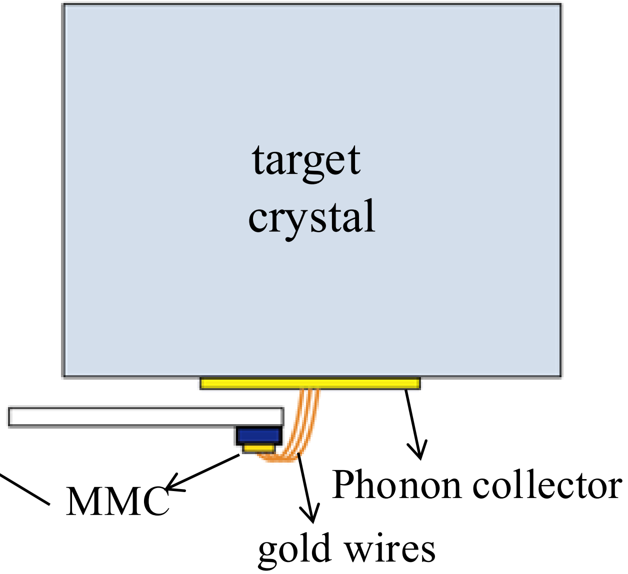
(also called Metallic Magnetic Calorimeter)



- Paramagnetic alloy in a magnetic field
  Au:Er(300-1000 ppm), Ag:Er(300-1000 ppm)
  → Magnetization variation with temperature
- Metal host → Fast thermalization
- Measurement: Superconducting circuit with SQUID readout
- High energy+time resolution, Good linearity, Large dynamic range, No bias heating, Absorber friendly, etc.



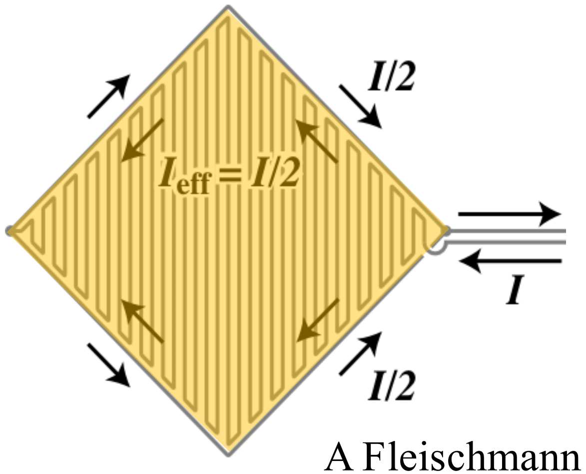




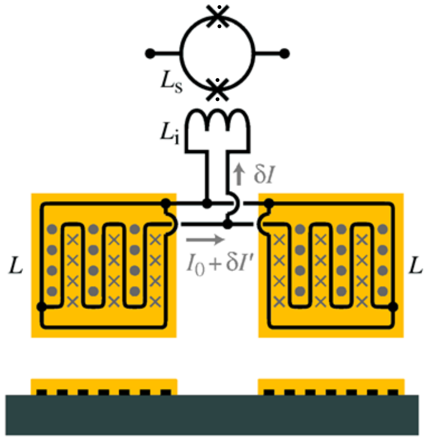
How MMC works

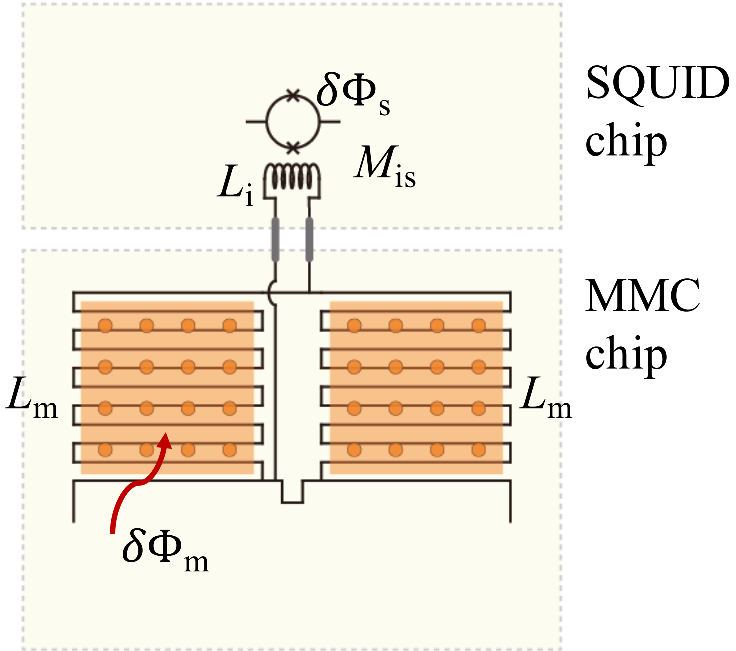
Meander-shaped superconducting coil

“Field generation” & “Signal pickup”



A Fleischmann et al. 2005





$$\delta\Phi_s = M_{is}\delta I$$
$$= M_{is}\frac{\delta\Phi_m}{L_m + 2(L_i + L_{wire})}$$

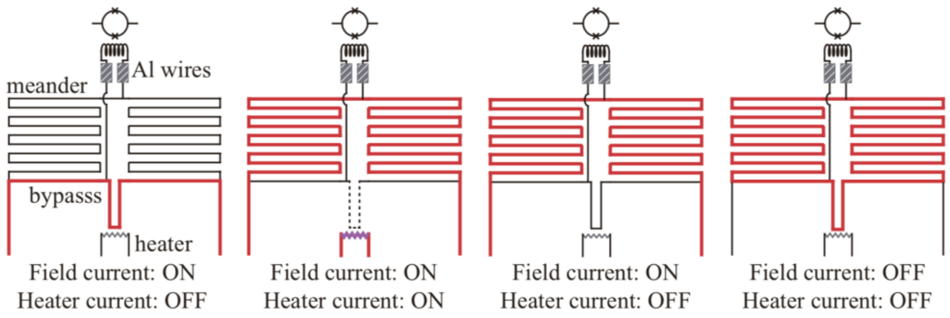
$$\delta\Phi_m = g\delta m$$
$$= g\frac{dm}{dT}\delta T = g\frac{dm}{dT}\frac{\delta E}{C_{tot}}$$

“All calculable”

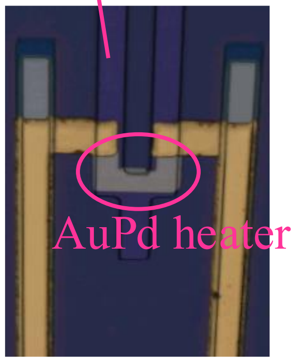
- No heat dissipation
- No need for sensor biasing
- Smaller magnetic cross-talk
- Easier to fabricate
- Reduced pickup of magnetic Johnson noise

Persistent current injection

Heat-pulse switch



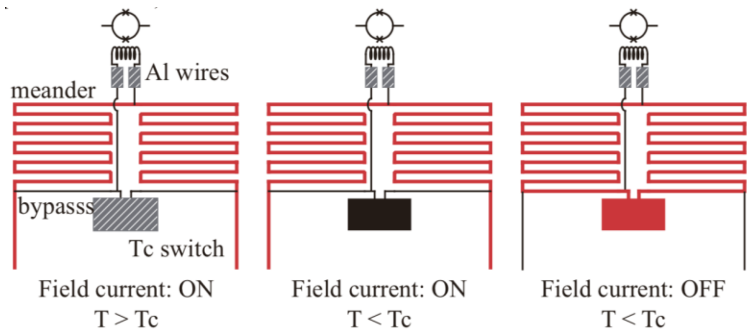
Nb bypass

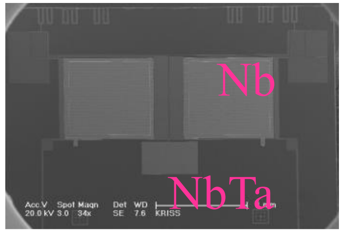


At T < T_c (Nb)

1. Field current On
2. Heat pulse On
3. Heat pulse Off
4. Field current Off

Temperature switch





SR Kim, et al., SUST (2019)

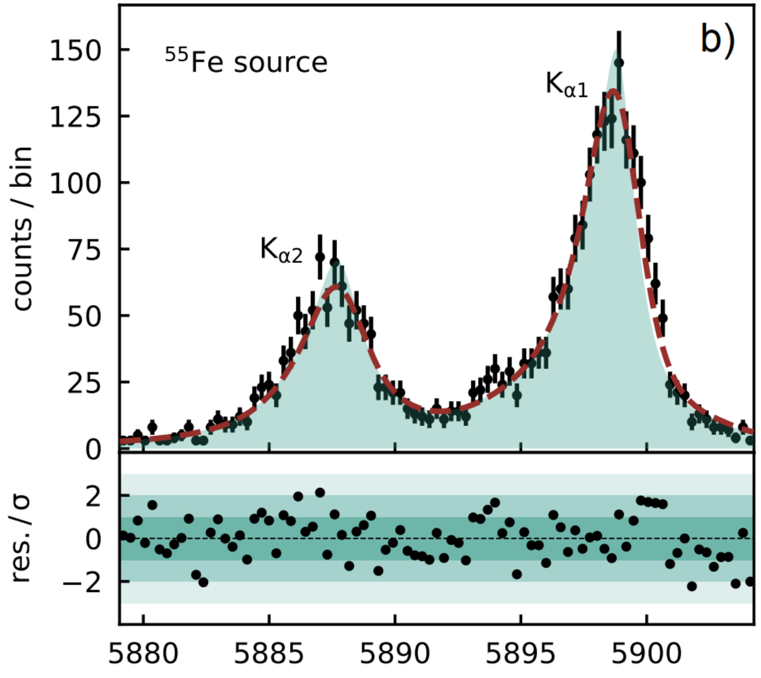
From T_c (Switch) < T < T_c (Nb)

1. Field current On
2. Cool **T < T_c (Switch)**
3. Field current Off

On-chip persistent current: Typically up to 100 mA

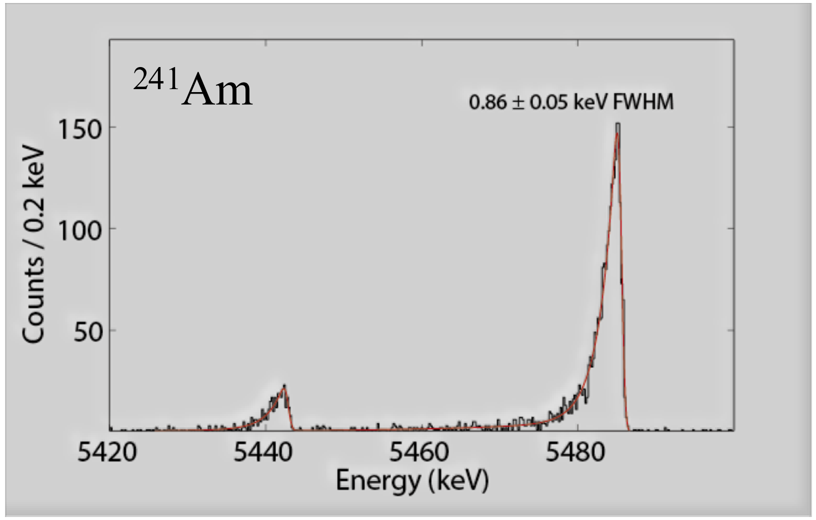
Best resolutions have been achieved with MMCs

1.25 eV FWHM for 6 keV X-rays
New update at LTD20
Heidelberg (KIP) & KIT



M Krantz, et al., APL (2024)

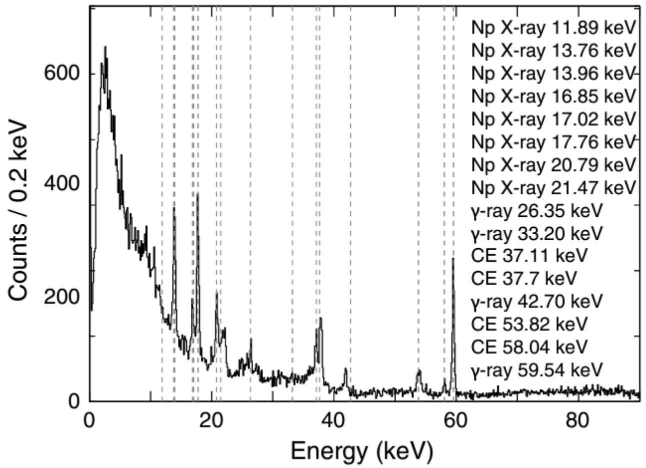
0.9 keV FWHM for 5.5 MeV α-rays
(IBS/KRISS)

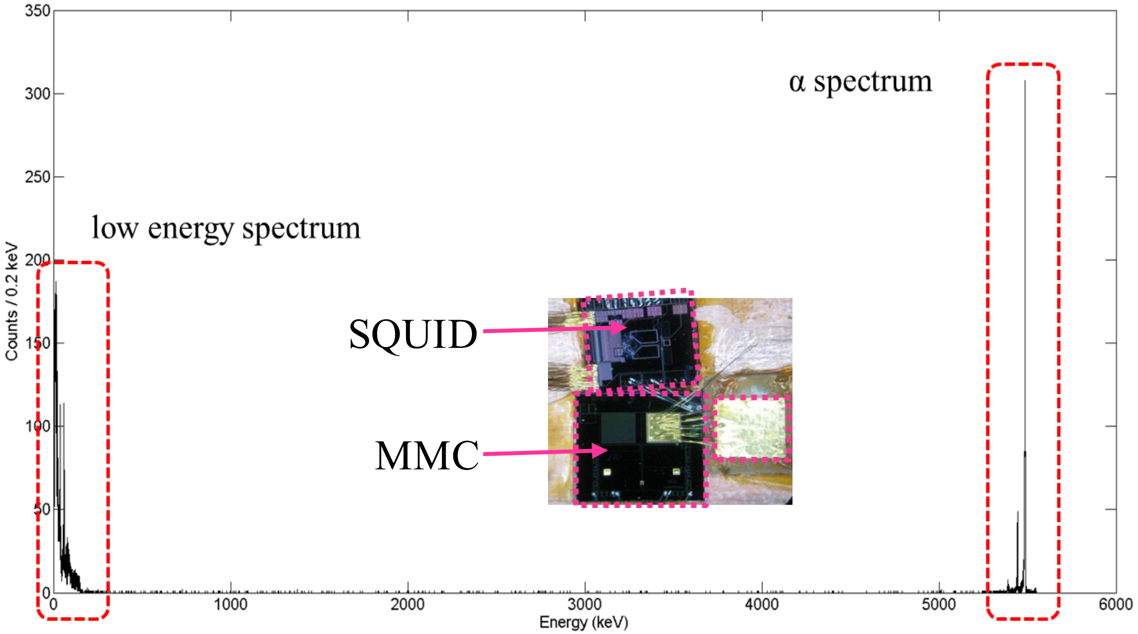


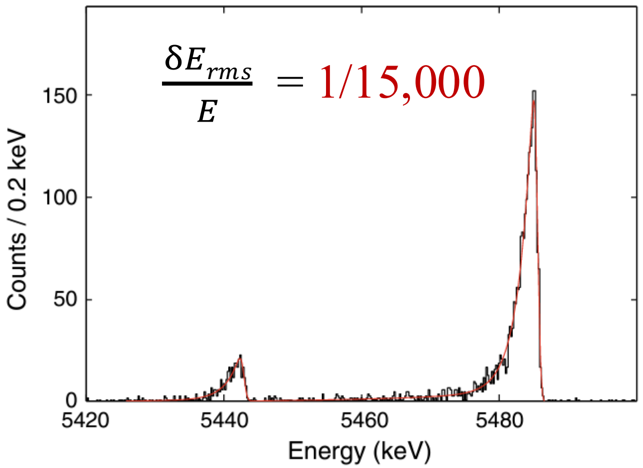
I Kim, et al., SUST (2017)

Sensor performance (fabricated at IBS)

“Superior dynamic range with high resolution”







H Kim, et al., EPJP (2023)

I Kim, et al., SUST (2017)

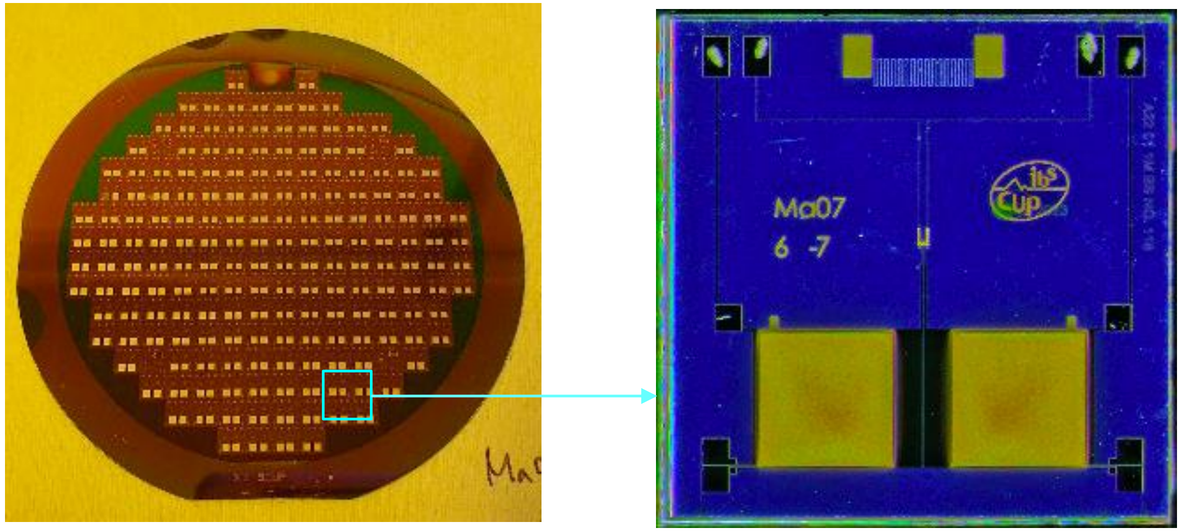
0.3 keV FWHM
for 60keV γ

0.9 keV FWHM Gaussian width
for 5.5MeV α

Low and high energy spectrum can be measured in the same time with high resolution.

Mass production of the sensors

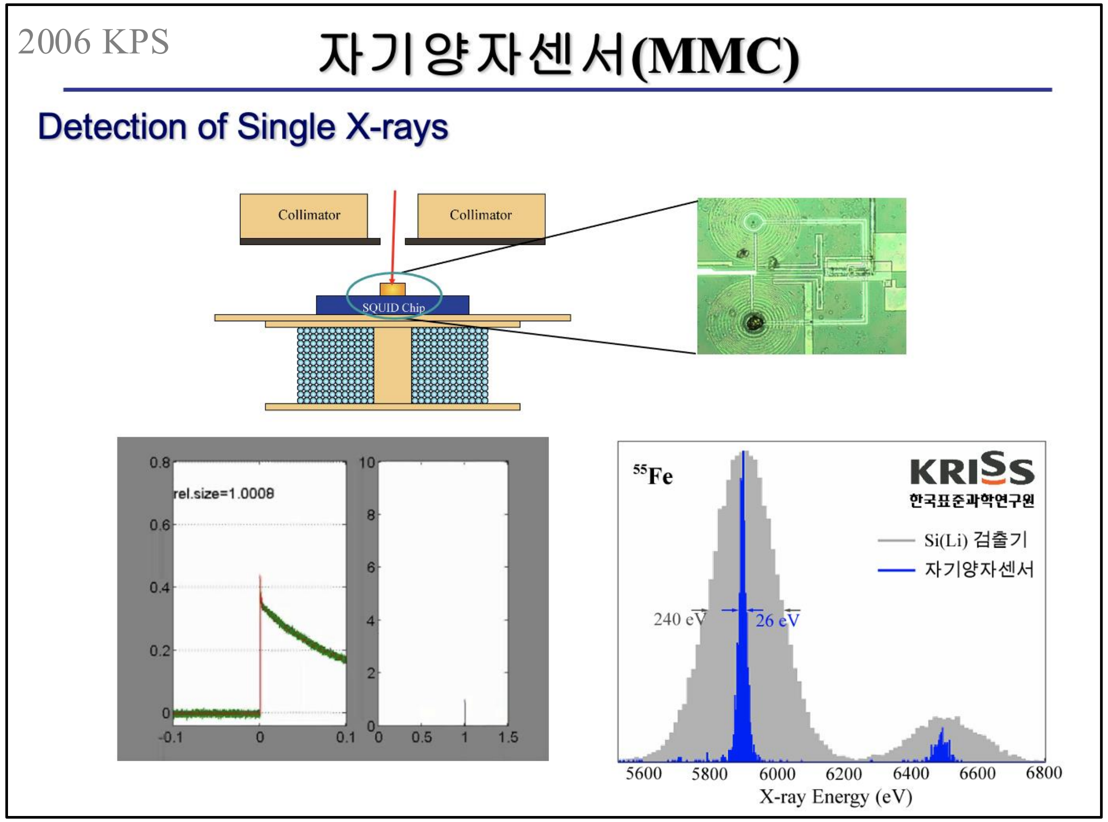
MMC production at IBS

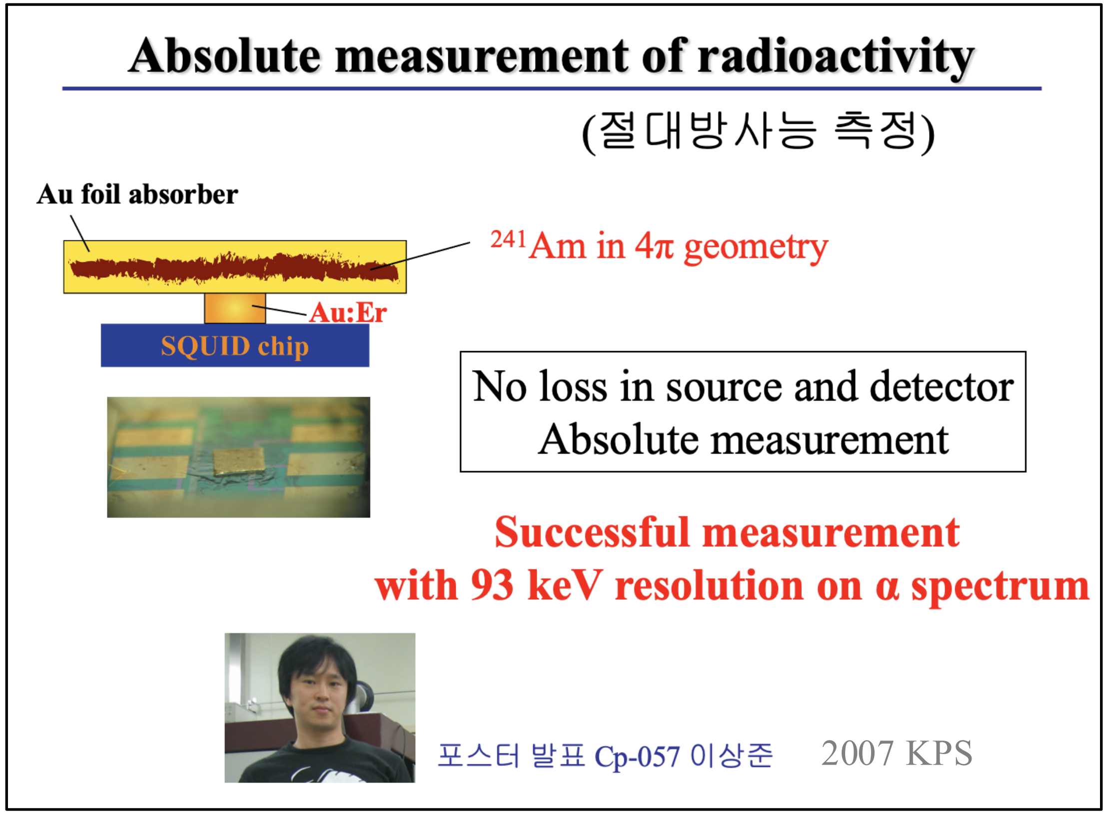


A fabrication batch can produce 100 ~ 200 working sensors.

Early Detector R&Ds in Korea

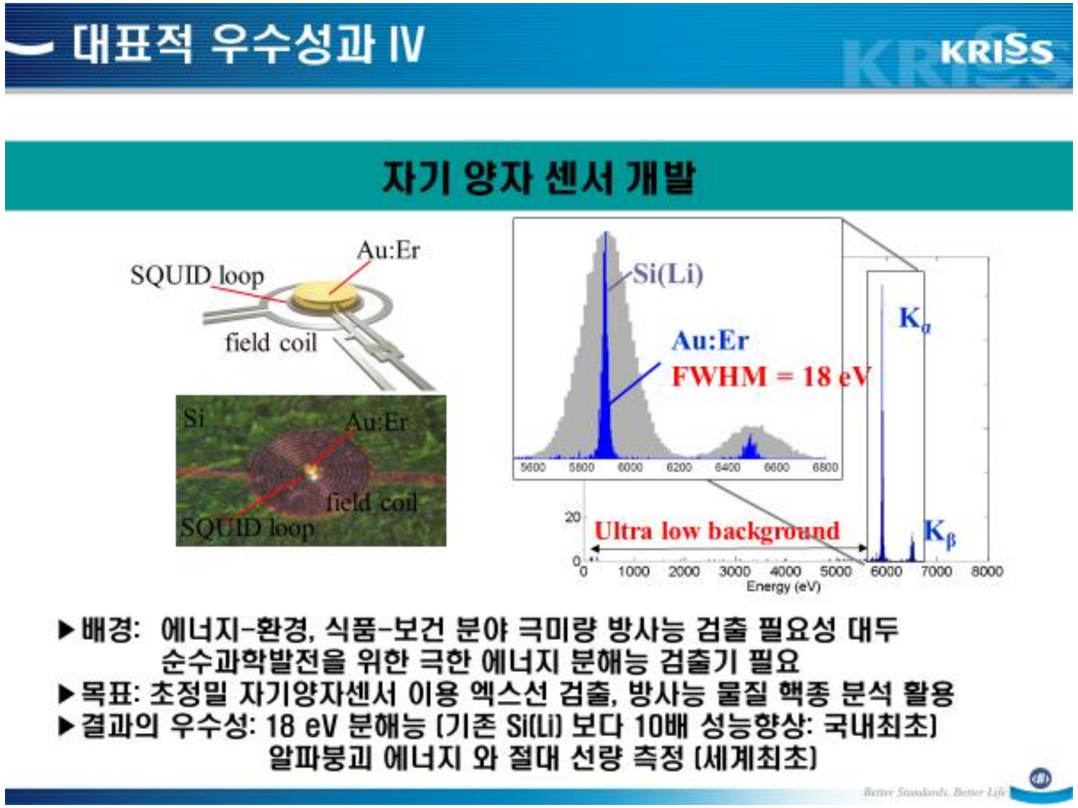
Early MMC developments in Korea





KRISS LTD projects

- Development of high-resolution detectors



KRISS Internal Project (2006~2008)

- Development of novel measurement science utilizing quantum phenomena

➔ Detector R&Ds for astroparticle physics

External gov project (2009~2013)

- Radionuclide analysis

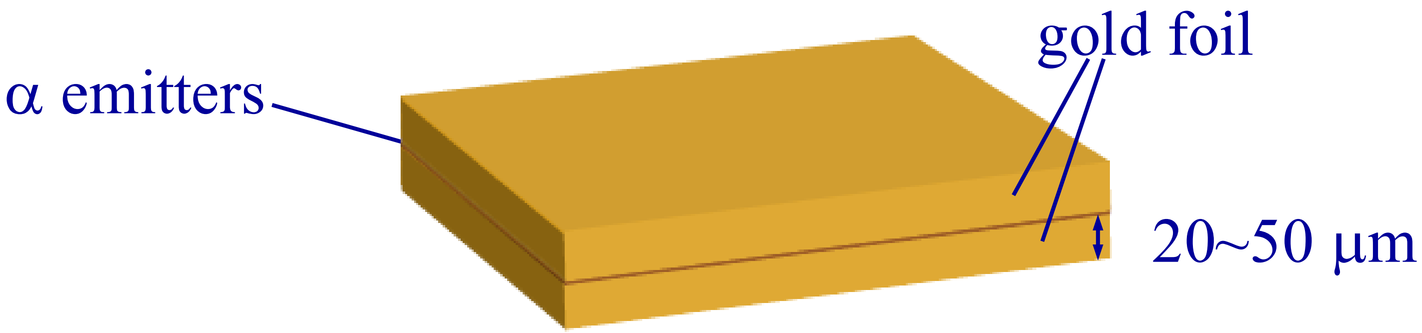
An NRF project was initiated.

High-resolution detection and fabrication methods were established during these periods.

LTD applications in Korea

Decay Energy Spectroscopy (DES)

Alpha (beta) decay in 4π metal absorber



Concept for DES
(decay energy spectroscopy)

Alpha decay energy (Q)

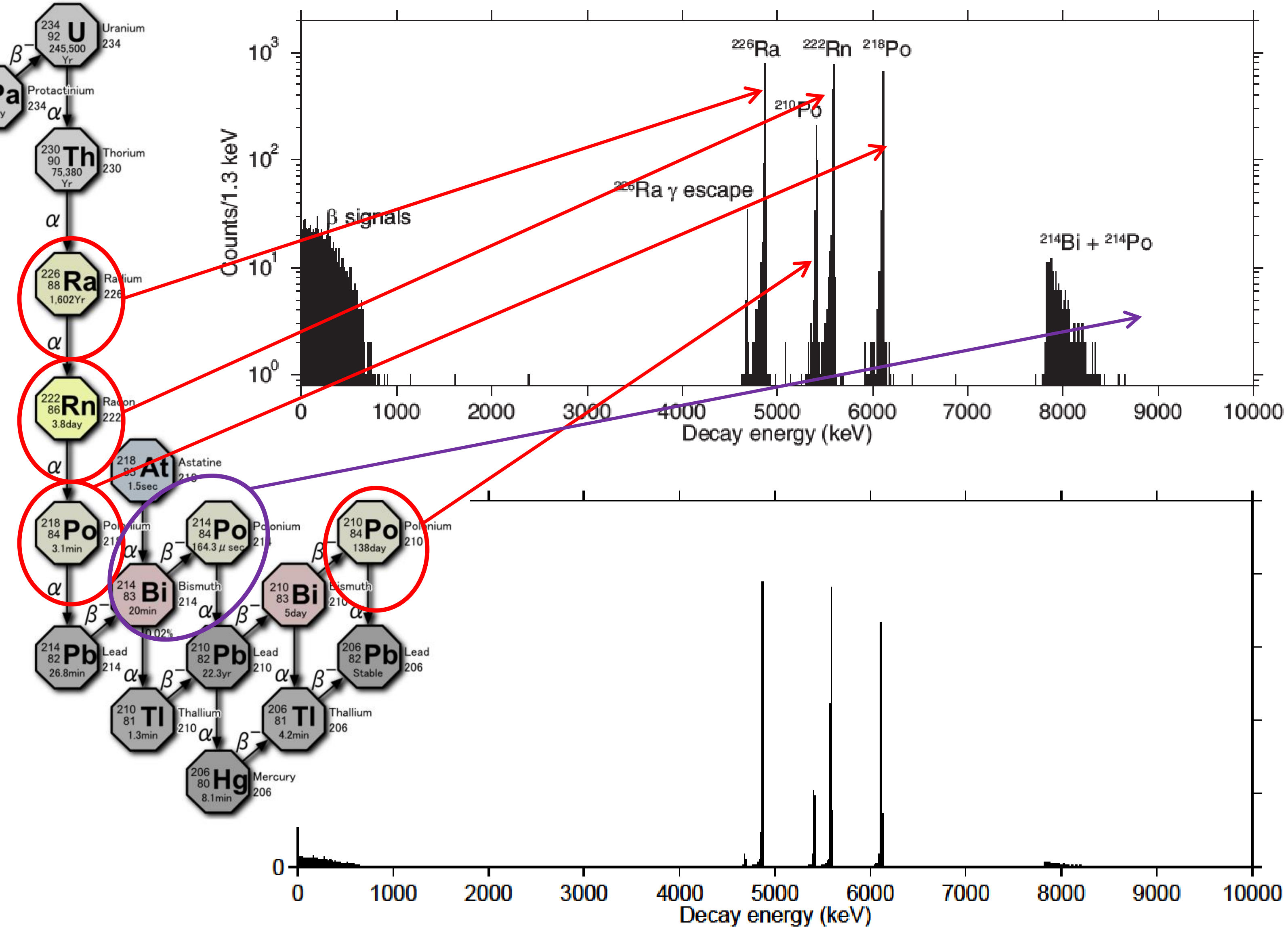
Alpha particle
Recoil
ce., γ, x, Auger electron

➔ Heat generation

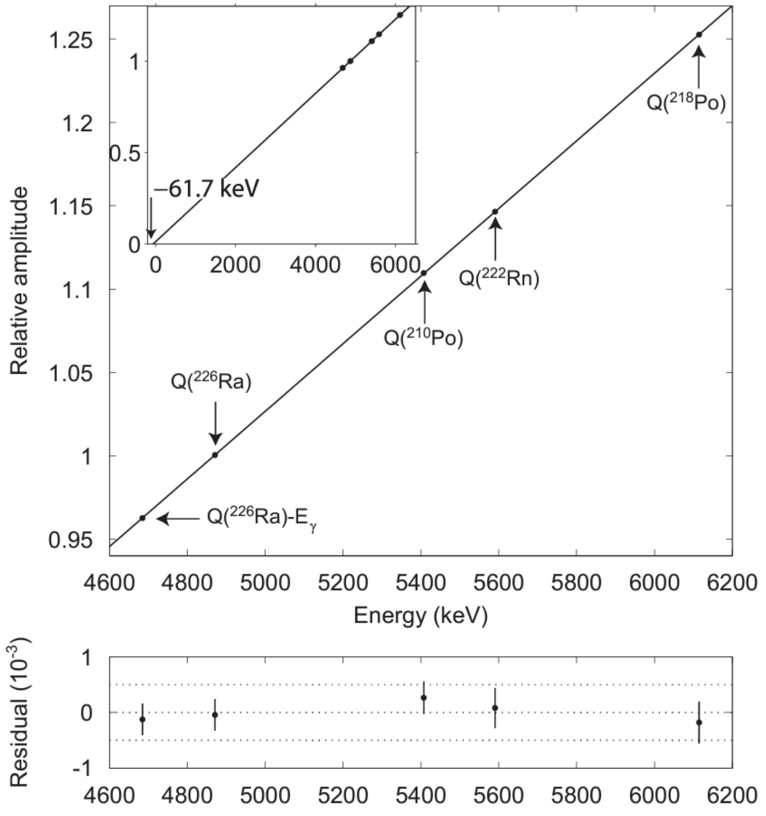
"Low emission probabilities for high energy photons and electrons"

1. No energy loss in source and detector
2. No count loss

Full DES of ^{226}Ra



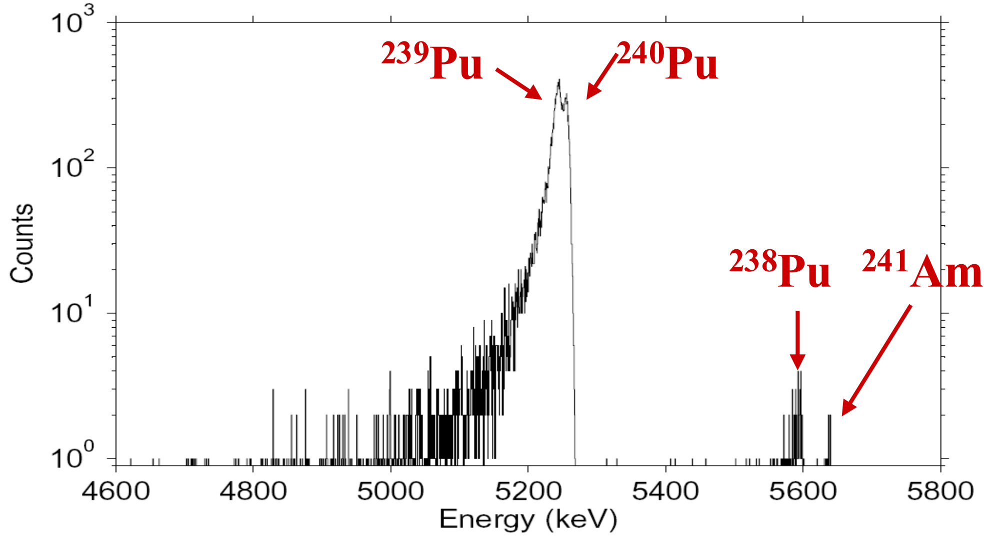
Yong-Sik Jang, 2011



Pu isotopes

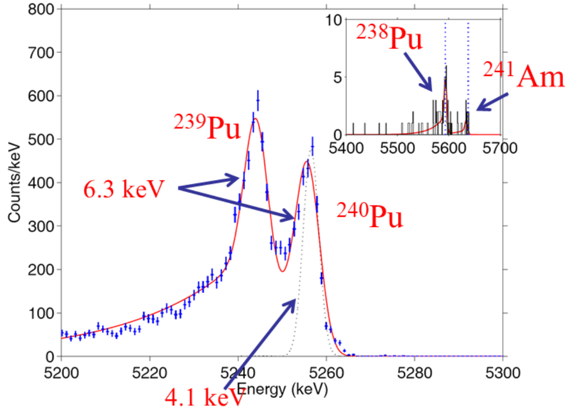
	^{239}Pu	^{240}Pu
$T_{1/2}$	2.411e4 y	6561 y
Q (keV)	5244.5	5255.8
alpha (keV,%)	5105.5, 11.9 5144.3, 17.1 5156.5, 70.8	5123.7, 27.1 5168.2, 72.8

DES from plutonium solutions

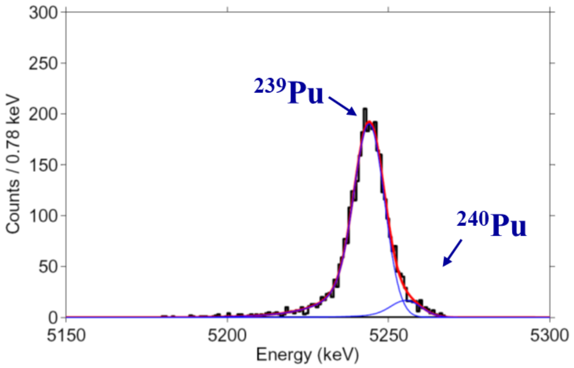


2011 KRISS

$$\frac{\text{Activity}(^{240}\text{Pu})}{\text{Activity}(^{239}\text{Pu})} = 0.99$$



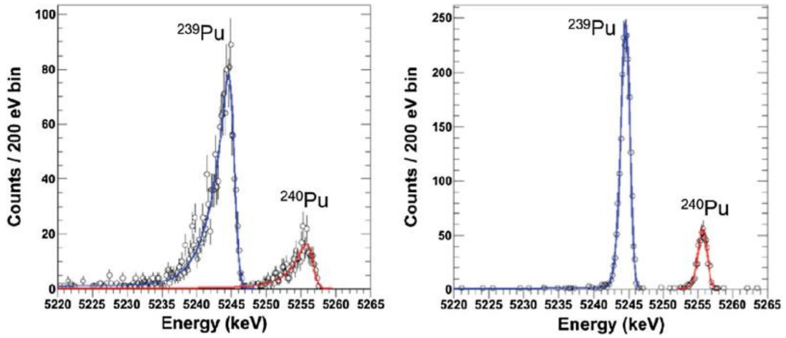
$$\frac{\text{Activity}(^{240}\text{Pu})}{\text{Activity}(^{239}\text{Pu})} = 0.087$$



DES projects in US & EU

- LANL&NIST: DES using TES

LANL 2016



- EURAMET: funded European project (PTB, CEA, etc.)

Annex I: List of running EMPIR projects of 2017 call expected to start in 2018

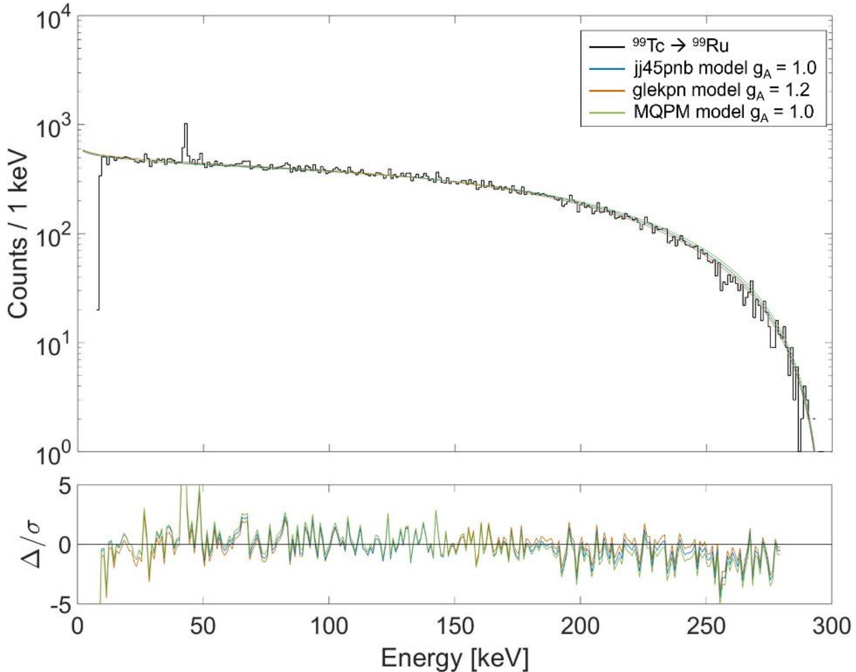
17FUN01	BeCOMe	Light-matter interplay for optical metrology beyond the classical spatial resolution limits
17FUN02	MetroMMC	Measurement of fundamental nuclear decay data using metallic magnetic calorimeters
17FUN03	USOQS	Ultra-stable optical oscillators from quantum coherent and entangled systems
17FUN04	SEQUOIA	Single-electron quantum optics for quantum-enhanced measurements
17FUN05	PhotOQuant	Photonic and Optomechanical Sensors for Nanoscaled and Quantum Thermometry
17FUN06	SIQUST	Single-photon sources as new quantum standards

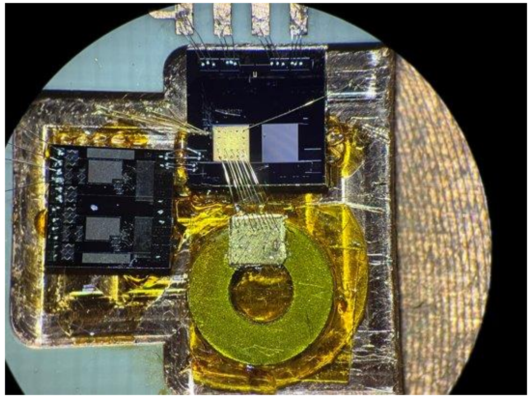
Non-unique second-forbidden β decay in ^{99}Tc

DES for ^{99}Tc beta spectrum measurement

The g_A-value investigation for non-unique second-forbidden β decay in ^{99}Tc

Model	g_A^{eff}	sNME [fm^3]	χ^2_ν	*p*-value
sNME(c)				
glekpn	1.070 $^{\pm 0.078}$	0.068 $^{\pm 0.001}$	0.99998	0.4889
jj45pnb	1.035 $^{\pm 0.040}$	0.065 $^{\pm 0.003}$	0.99992	0.4887
MQPM	1.033 $^{\pm 0.026}$	0.059 $^{\pm 0.005}$	0.99985	0.489
sNME(f) (Best fit)				
glekpn	1.172 $^{\pm 0.067}$	-0.069 $^{\pm 0.001}$	0.99999	0.4884
jj45pnb	1.043 $^{\pm 0.033}$	-0.071 $^{\pm 0.003}$	0.99976	0.4895
MQPM	0.997 $^{\pm 0.038}$	-0.068 $^{\pm 0.007}$	0.99917	0.4921





gA-EXPERT

Theory group

NATURAL RESOURCES INSTITUTE FINLAND

UNIVERSITY OF JYVÄSKYLÄ

Experiment group

Institute for Basic Science

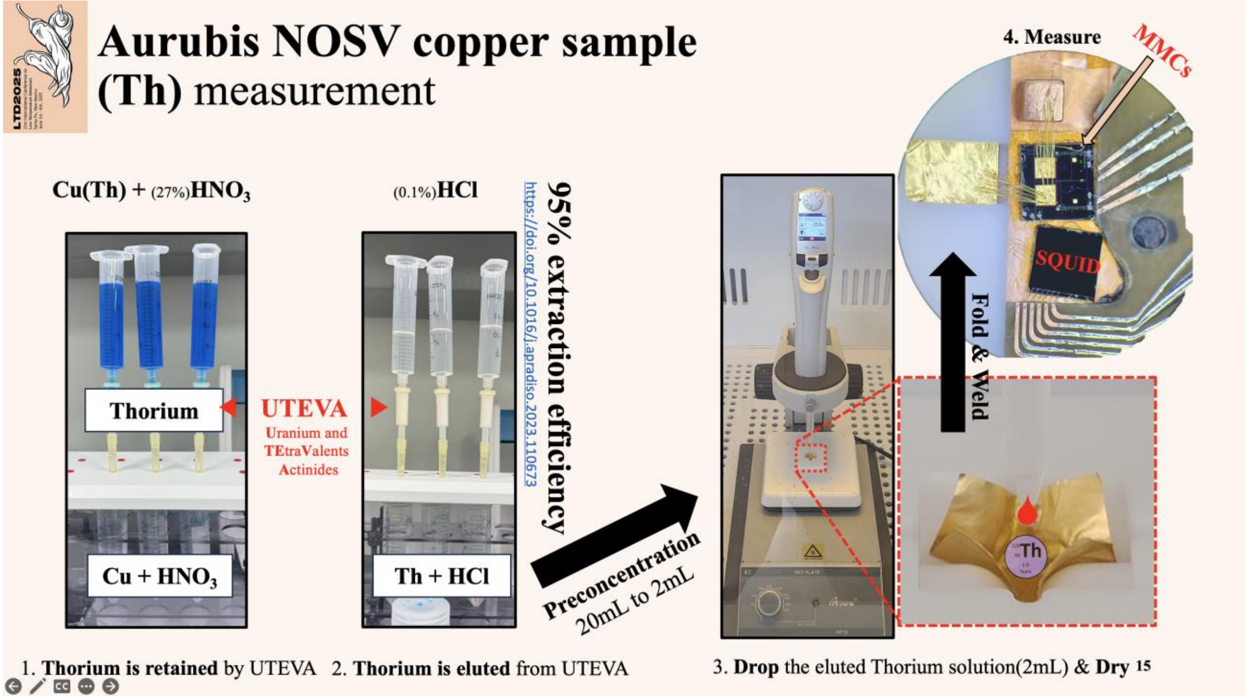
Lawrence Livermore National Laboratory

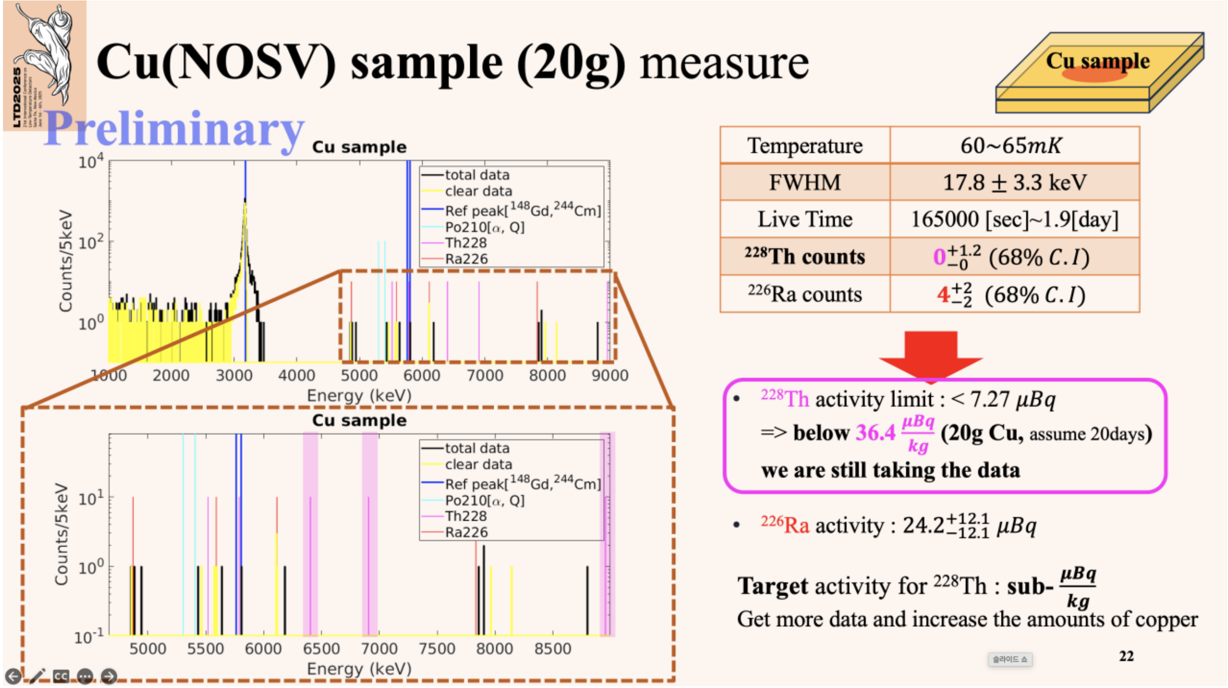
Radio impurity measurement in pure materials

Radioactivities of ^{228}Th and ^{226}Ra in Cu
- One of the significant background sources in rare event search experiments.
- Hard to measure quantitatively.

Cu sample (20g) to measure ^{228}Th

<Slides from Jongseok Chung' LTD talk 2025>





MMCs for astroparticle physics

- Search for neutrinoless double beta decay
  - Majorana or Dirac? Lepton number conservation?
  - Neutrino mass

We do in Korea

- Precise end-point measurement of beta decay spectrum
  - Model independent measurement of neutrino mass

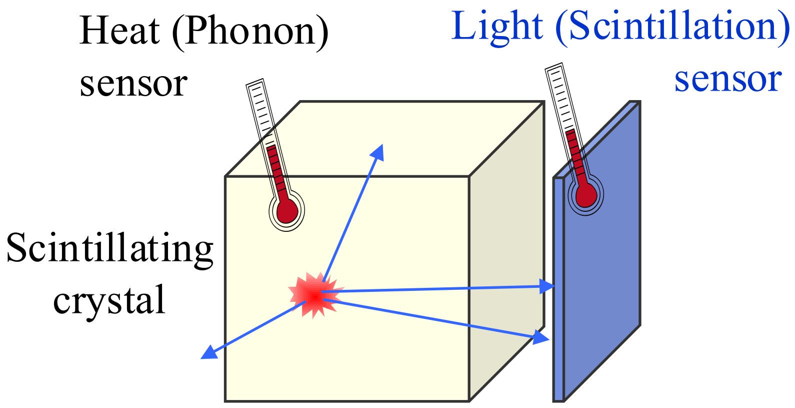
- Direct dark matter detection
  - Low mass region, LEE?

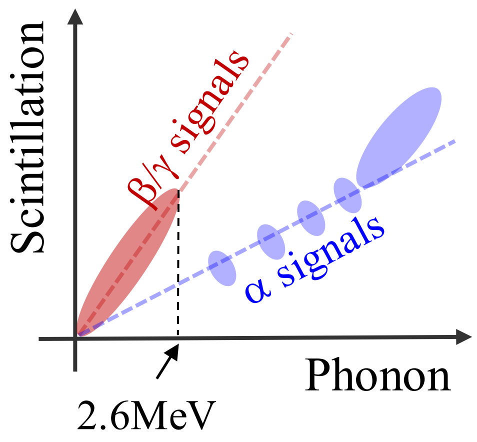
- keV-scale sterile neutrinos?

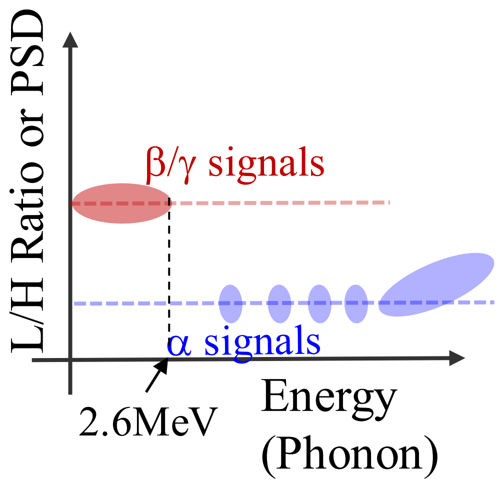
LTD (MMC) applications in Korea

Neutrinoless double beta decay ($0\nu\beta\beta$)
(AMoRE)

Signals from scintillating crystals







Target absorber: Dielectric crystal with high Debye temperature

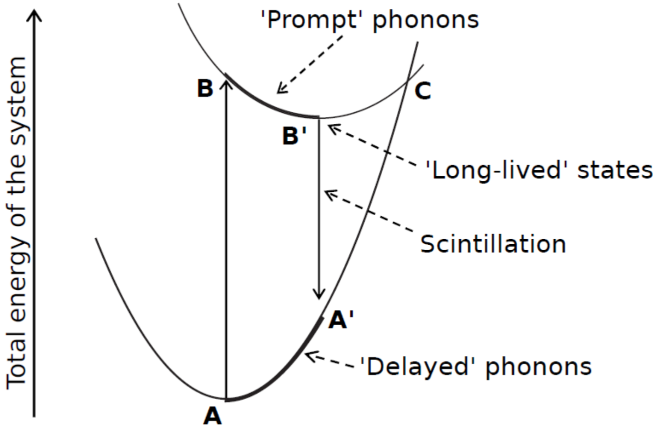
→ High energy resolution detection

Scintillating crystal

→ Simultaneous detection for heat and light signals

→ Active background rejection for heat-light ratios

→ Pulse shape difference from non-instantaneous scintillation processes at low temperatures



J. Low Temp. Phys. **215**, 237 (2024)

AMoRE Project Searching for $0\nu\beta\beta$ decay of ^{100}Mo

^{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
- ✓ Scintillation crystal in the form of $X_aMo_bO_c$ (XMO)

$^{48depl}Ca^{100}MoO_4$: enriched ^{100}Mo and depleted ^{48}Ca

: Selected for a pilot and AMoRE-1

: High T_D = 446 K, Large scintillation yield

$Li_2{}^{100}MoO_4$: Selected for AMoRE-II

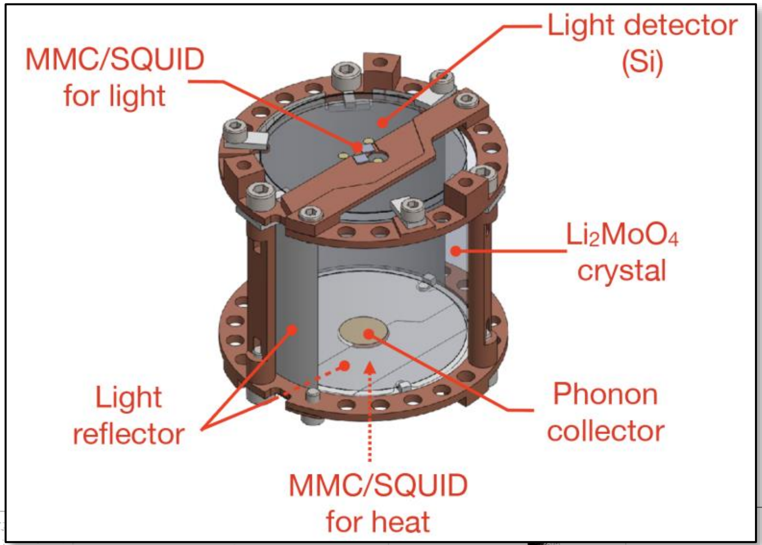
: Moderate: T_D = 316 K

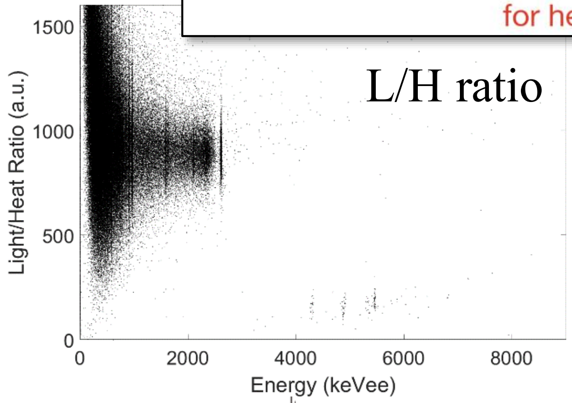
: Relatively low scintillation yield

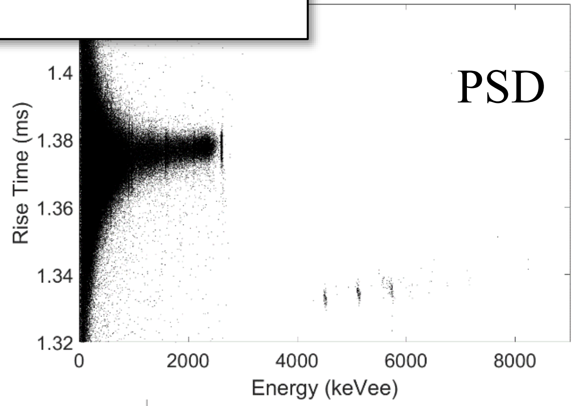
: Hygroscopic

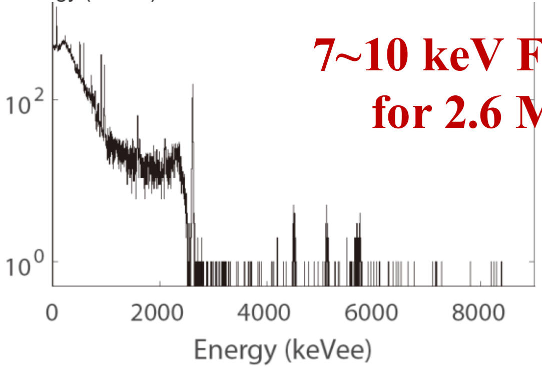
: Easy to grow crystals, low cost → Mass production

: Low internal background (surface α…)



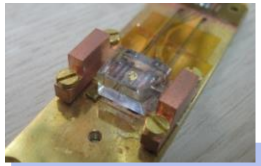






7~10 keV FWHM for 2.6 MeV

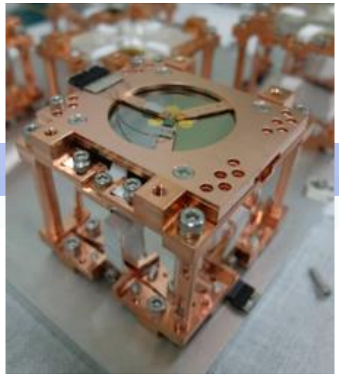
AMoRE Detector Progress



First CMO (4g)
2009

CMO (216 g)
2011

Phonon collector
(high resolution)
2012

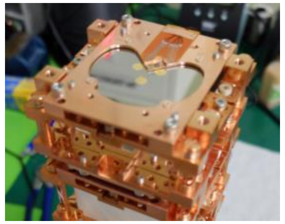


Single module
Heat+Light
2014

Underground Exp.

AMoRE-Pilot
2015 - 2018

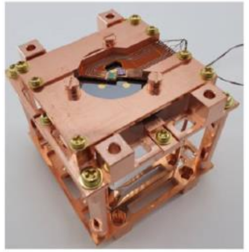
6 CMOs

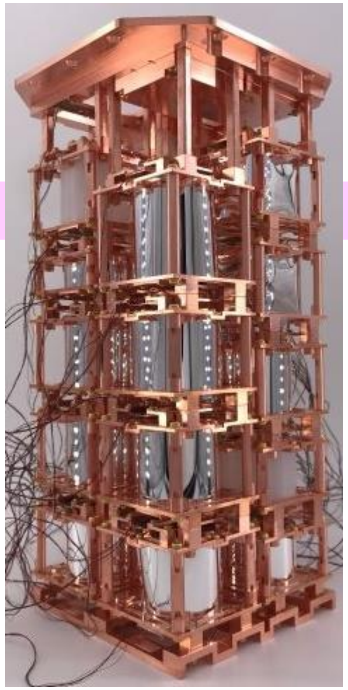


EPJC 2019

AMoRE-I
2020 - 2023

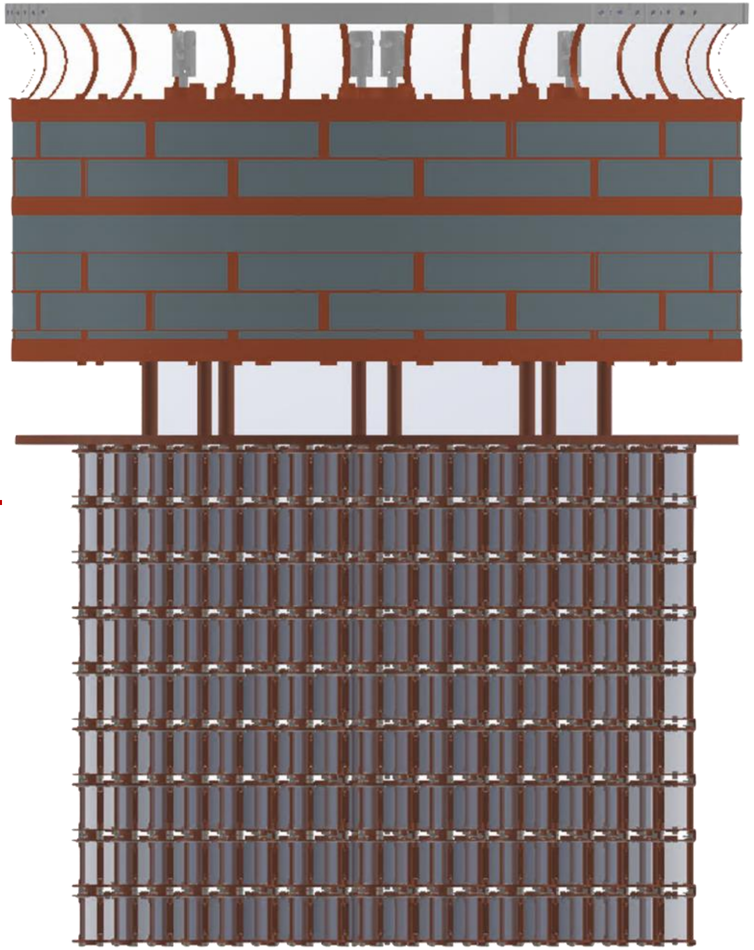
13 CMOs
+ 5 LMOs





PRL 2025

AMoRE-II
2025/26 -



~ 360 XMOs

AMoRE from very scratch

Lab space at Y2L before renovation

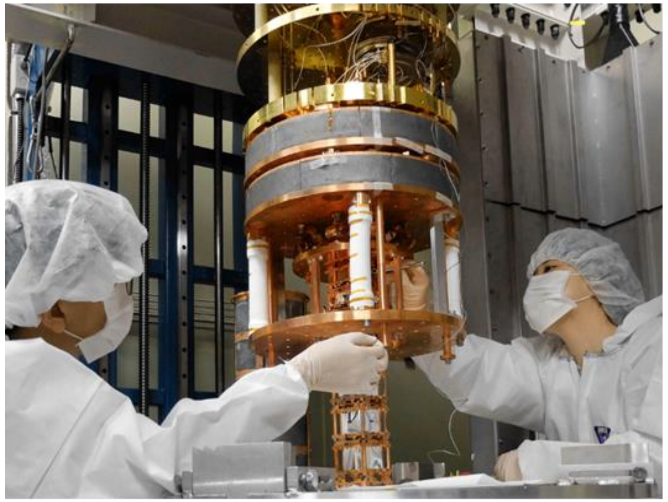
DARK & HUMID
July 2014

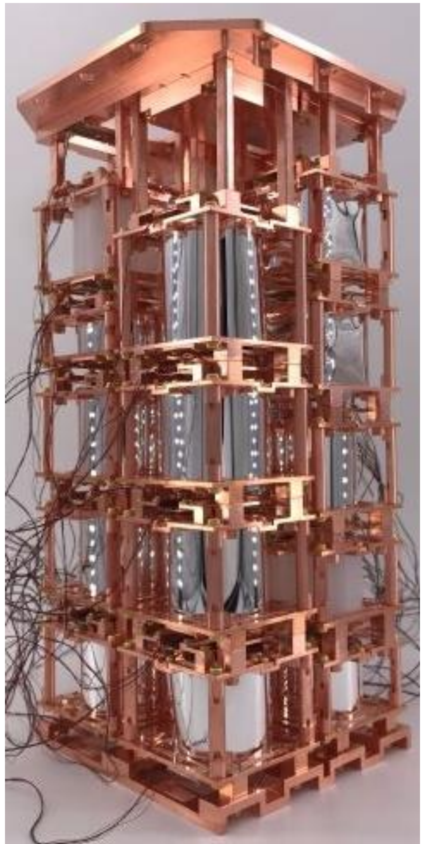
December 2014

Gantry system in a Clean lab

July 2015: Mano & AMoRE-Pilot

Jan 2017: Pilot Run-5 for 6 CMOs





AMoRE-I: 2020~23

AMoRE-I Result: $T_{0\nu\beta\beta} > 2\times10^{24}$ yr
(Most stringent limit for ^{100}Mo)

AMoRE-II overview

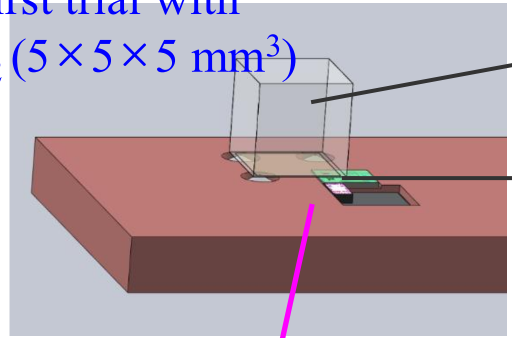
Significant progress and new results will come.

Analysis for 10-day 2×10^7 β events

Other Projects and R&Ds

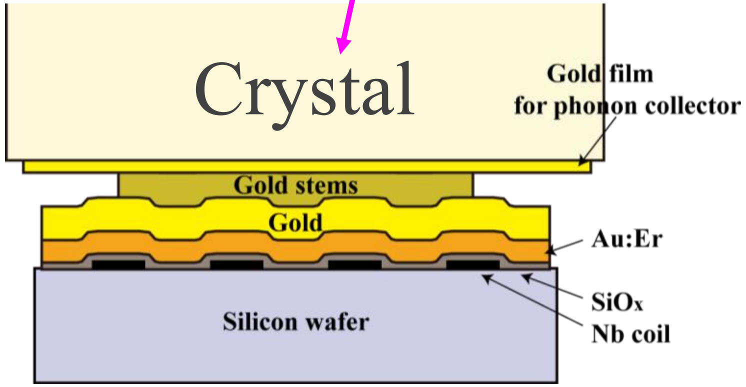
Low threshold detectors for DM detection

First trial with
CaF_2 ($5\times5\times5$ mm^3)

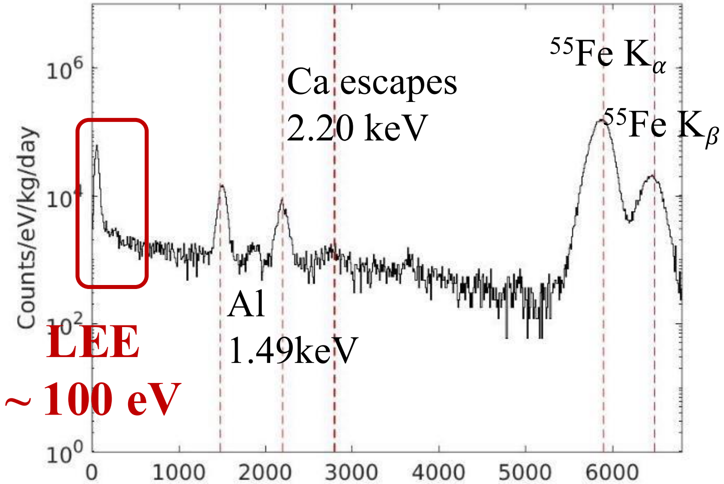


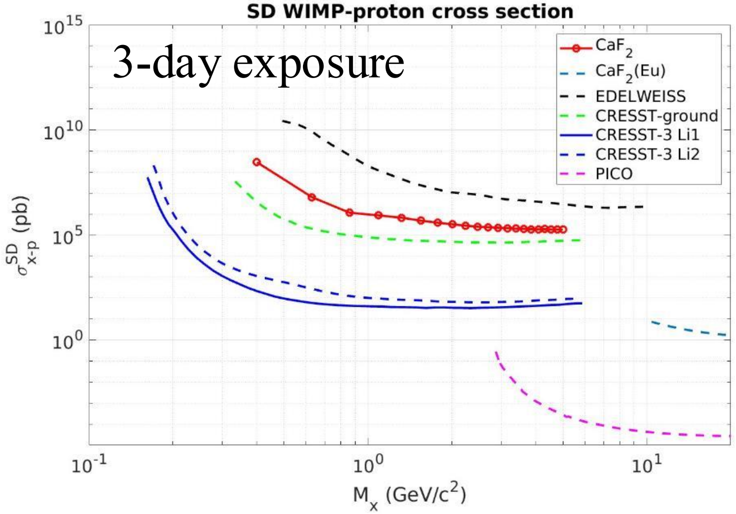
Choices: LiF, **CaF_2** (SD)
$CaMoO_4$, Sapphire, Diamond (SI)

MMC



Metallic contact:
→ 80 μs Rise-Time
~ 50 eV Threshold (5σ)

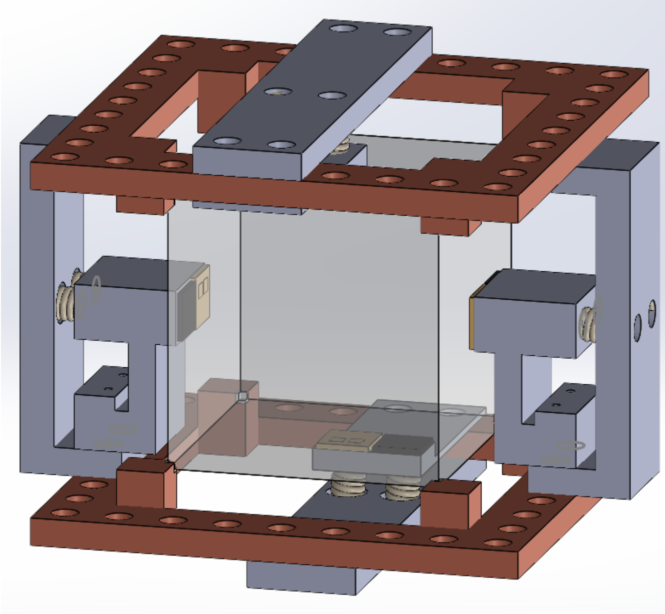




DH Kwon
ASC2024

New design with quadruple MMCs for LiF ($2\times2\times2$ cm^3)

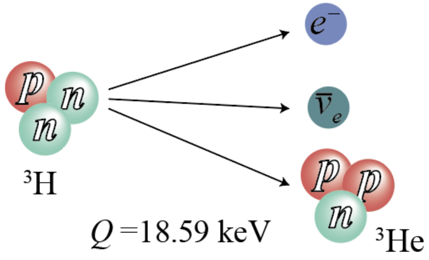
to minimize Low Energy Excess
to reconstruct the event location



Lab scale experiment for keV sterile neutrinos

LiFE-SNS: LiF Experiment for keV Sterile Neutrino Search

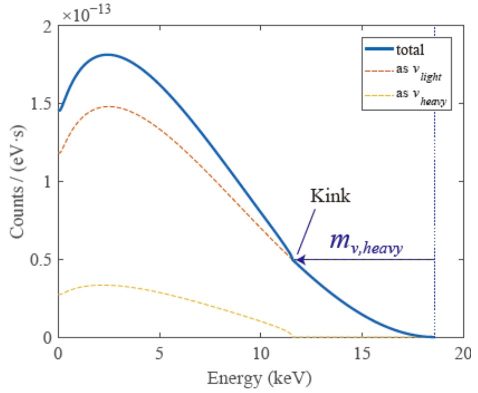
β decay of ^{3}H



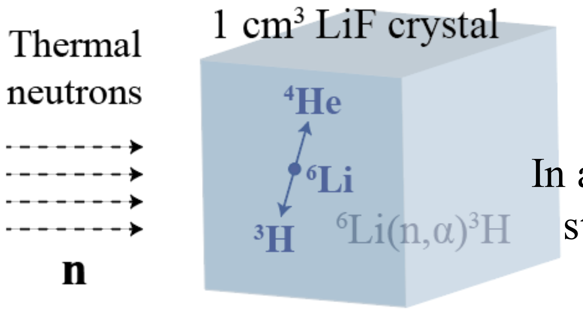
Q =18.59 keV
$T_{1/2}$ = 12.32 y

Possible mixing

$$\nu_e = \cos\theta\,\nu_{light} + \sin\theta\,\nu_{heavy}$$
$$\nu_s = -\sin\theta\,\nu_{light} + \cos\theta\,\nu_{heavy}$$



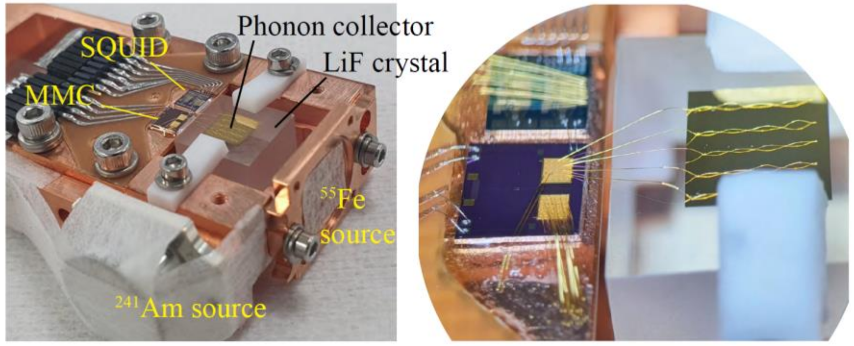
^{3}H production in LiF



Thermal neutrons in a ^{6}Li target
Mean free path: 2.3 mm in LiF with 7.6% ^{6}Li

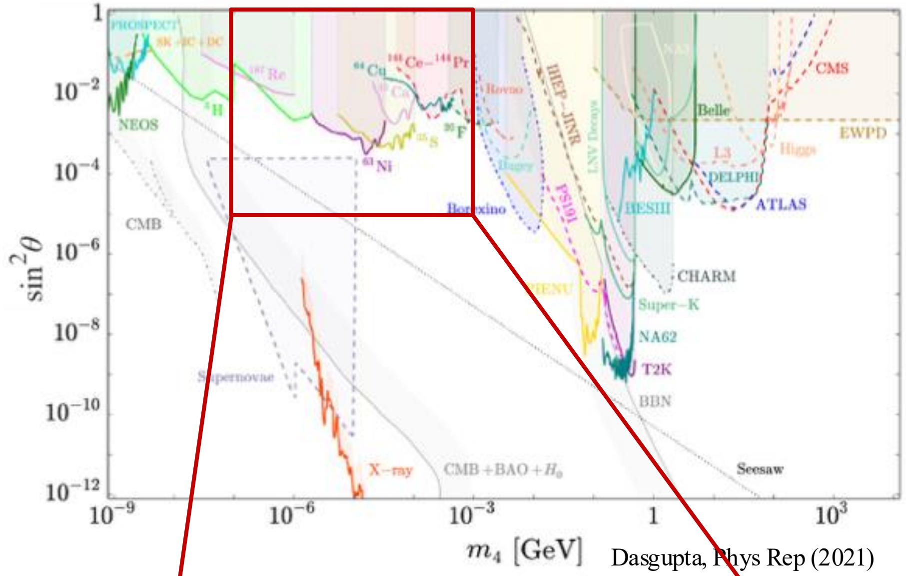
One week at the KRISS source storage
➔ ~ 20 Bq/cm^3

arXiv:2602.05161

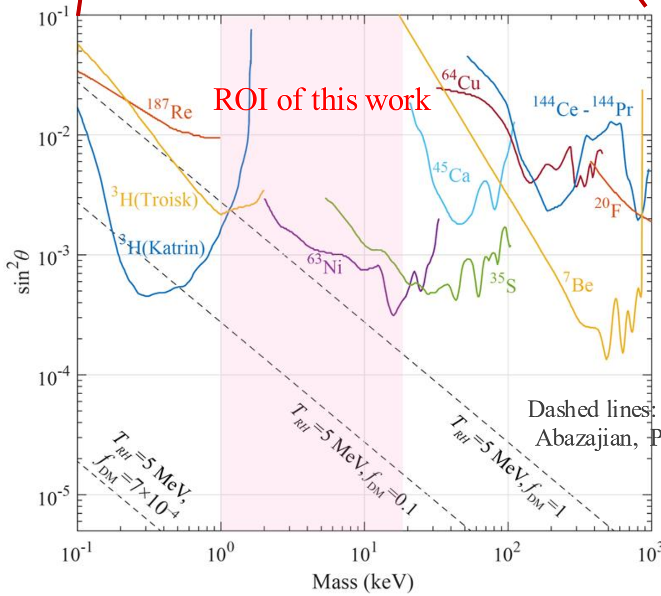


LiF + MMC for LiFE-SNS

Current limit for $\sin^2\theta$ and m_s



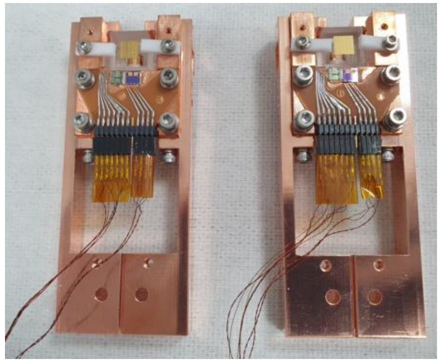
Dasgupta, Phys Rep (2021)

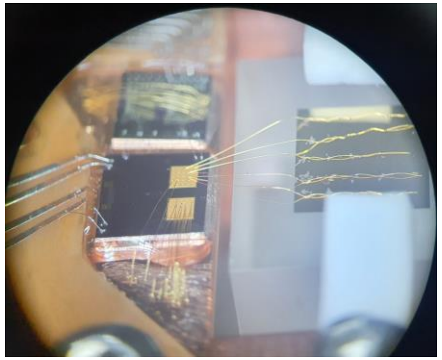


Dashed lines: LRT model
Abazajian, PRD (2023)

LiFE-SNS Phase1: two setups

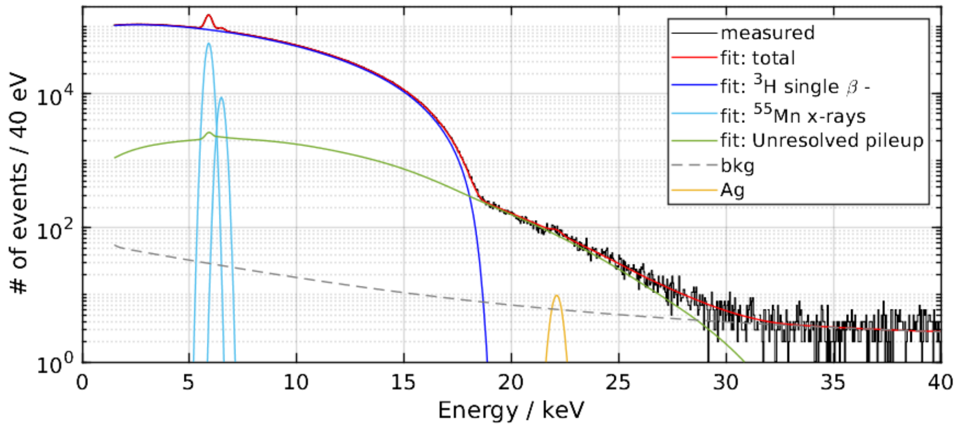
- Two detector modules: LiF(^{3}H) + MMC
- An internal ^{55}Fe source is employed on each crystal.
- The setups are attached to a dry DR surrounded by a Pb shield at the Daejeon HQ lab.
- Two-stage temperature control system with $\Delta T_{rms} \sim 0.5\ \mu K$
- Data taking period: May~Dec/2024

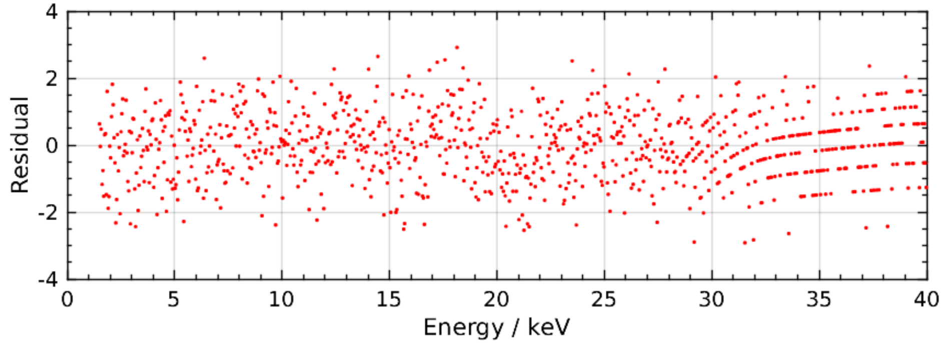




Yong Chang Lee, SNU

Analysis with 10-day 2×10^7 β events





✓ $\chi^2/NDF = 996.1/954$ in the analysis range 1.5~40 keV

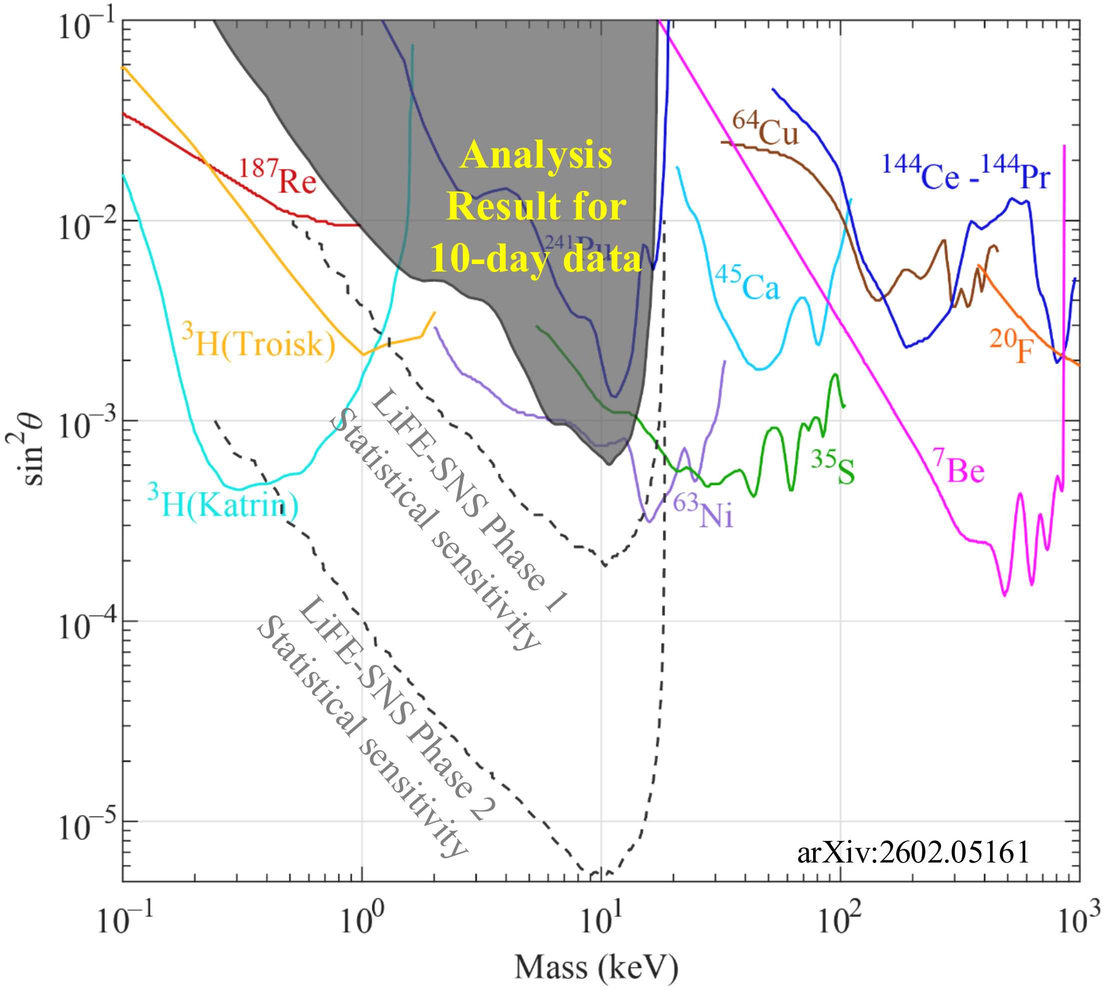
➔ Good agreement between the measured and expected values.

➔ We can activate the routine for sterile branch search.

Analysis result and expected limit (LiFE-SNS)

The null hypothesis is preferred from 10-day data.

Current best limit in the 10 keV region



LiFE-SNS Phase 1: measurement completed

- 2 detectors × 35 Bq × 4 month: 0.8 B β events
- Aboveground measurement
- **$\sin^2\theta$ sensitivity:**
  - **~ 6×10^{-4} found with only 1/20 data**
  - **Most stringent limit near 10 keV region**
  - ~ 2×10^{-4} expected (analysis result will come soon)
- Further systematics are being investigated

LiFE-SNS Phase 2

- When low systematic error is confirmed.
- 100 detectors × 100 Bq × 3 year
- $\sin^2\theta$ sensitivity: ~ 5×10^{-6}
- Underground measurement

Stay tuned for the signal from LiFE-SNS

Summary

Summary

- LTDs (MMCs) using superconducting sensor tech have great performance and applications in many aspects of science.
- Excellence in energy resolution, timing resolution, linearity, and dynamic range.
- The detector technology is open to any new projects and institutions.
- **A small- or large-scale experiment can be constructed to achieve the given objective.**

Stay tuned to us !

We have studied little parts of the topics.

Area	Measure	Topics
Astronomy & Cosmology	CMB, submm, X-ray, γ-ray	Inflation, Dark energy, neutrino mass, Black holes, ...
Quantum information	Optical, IR	Quantum computing, key distribution, communication, …
Material science, Biology	X-ray, neutrals	EPMA, Synchrotron, …
Security, Nuclear materials	THz, X-ray, γ-ray, alpha, beta, neutron,	Concealed weapons, nuclear materials, Forensics, …
Atomic, Nuclear physics	X-ray, γ-ray, alpha, beta, neutron,	QED test, EBIT, Rare decays, Forbidden beta spec, muonic (kaonic) atoms, …
Particle physics	Dark matter, neutrinos, X-ray, optical,	Dark matter, CEνNS, ν mass, axion, sterile ν, **0νββ**, ...

- ✓ **Sensor techs are well established.**
- ✓ **Cryogenics can be affordable.**
- **LTDs have been applied only to select topics in Korea.**
- **New ideas, tests, and questions are very welcome.**