ibs CONFERENCES

IBS Conference on Dark World

30th October - 3rd November 2017

Lecture Building, KAIST Munji Campus, Daejeon, Korea

AMoRE 0νββ experiment

Yong-Hamb Kim (김용함)

Center for Underground Physics (CUP), IBS

On behalf of AMoRE collaboration

The AMoRE Project

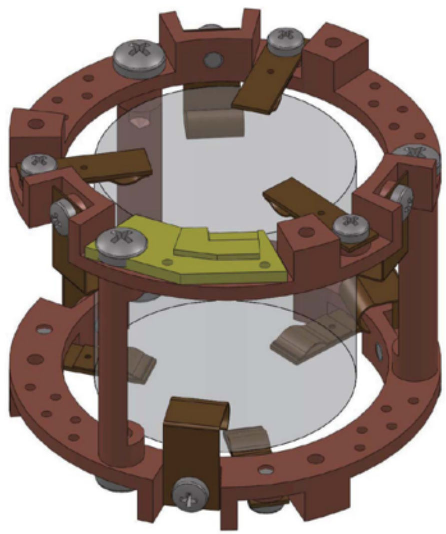
AMORE: ‘Love’ in Italian

AMORE “A cosmetic company in Korea”
Their factory is located in Daejoen.

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

to search for neutrinoless double decay of ^{100}Mo
using **cryogenic X^{100}MoO$_4$ detectors**

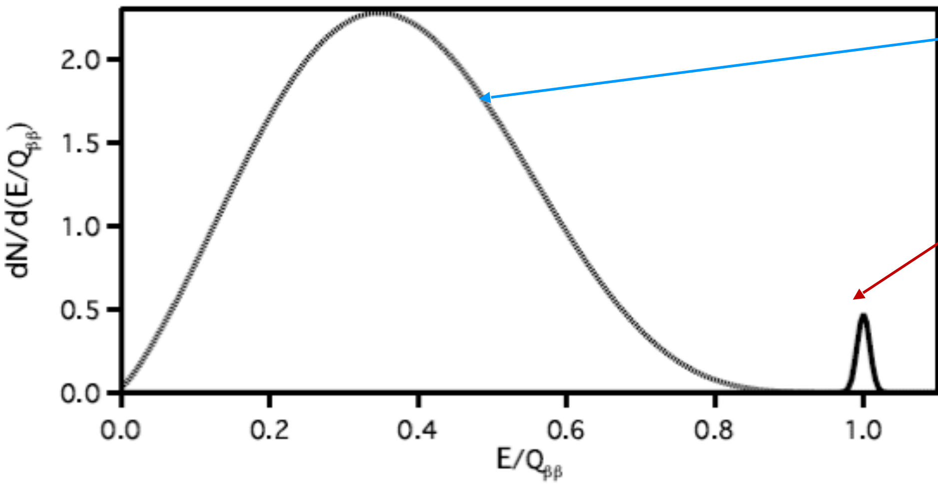
That’s AMoRE for us!



Ø4cmx4cm
CaMoO$_4$ crystal

AMoRE collaboration (since 2009)

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



Double Beta Decay with two neutrinos

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

Double Beta Decay with no neutrino

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

$0\nu\beta\beta$ discovery answers

- Majorana ($\nu = \bar{\nu}$) particles not Dirac ($\nu \neq \bar{\nu}$)
- Mass of neutrinos ($1/T^{0\nu}_{1/2} \propto m^2_\nu$)
- 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.

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

For sizeable background case:

Detection Efficiency

Isotopic Abundance

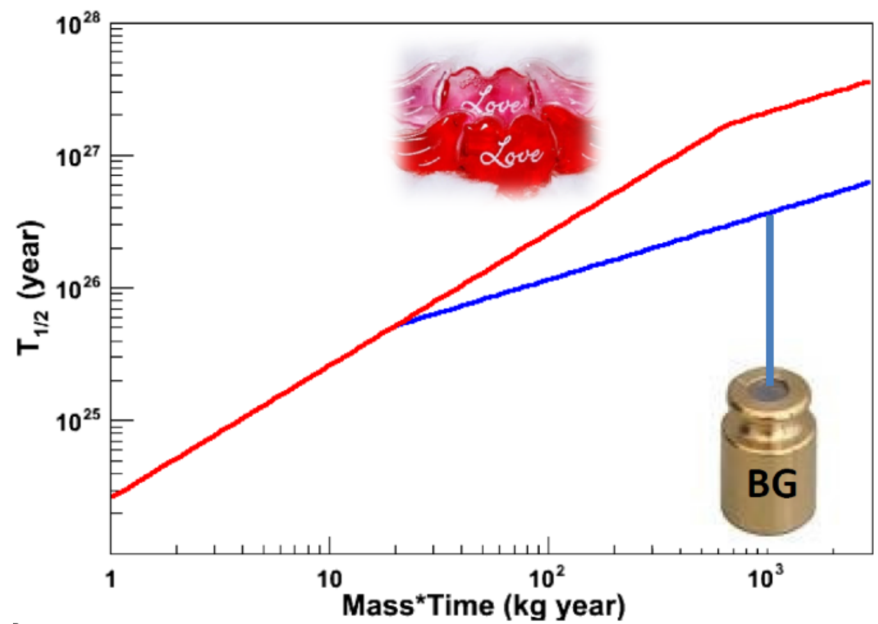
Detector Mass

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

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)

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

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
- ✓ Increase 'time' : up to a few years, Not very practical to increase sensitivity $T_{1/2}$
- ✓ Smaller ΔE : Better energy resolution
- ✓ 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)

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<background case>

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<background-free case>

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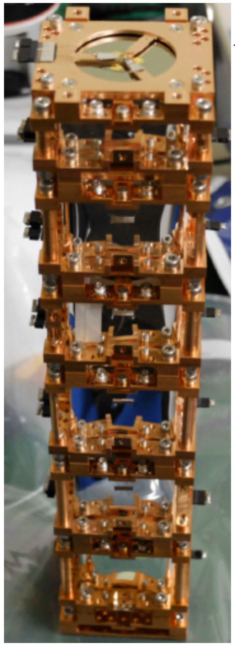
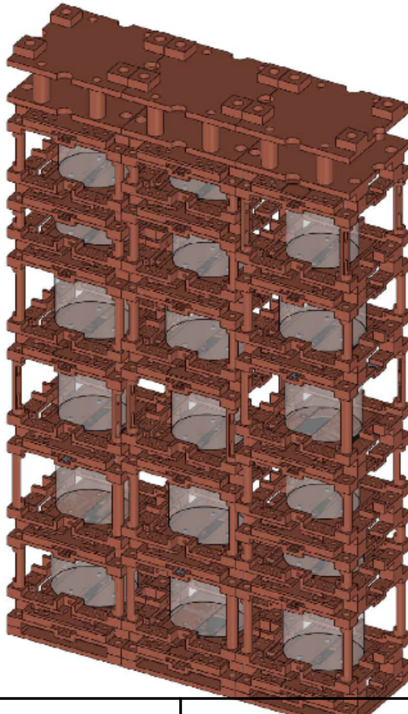
AMoRE Stage Plan

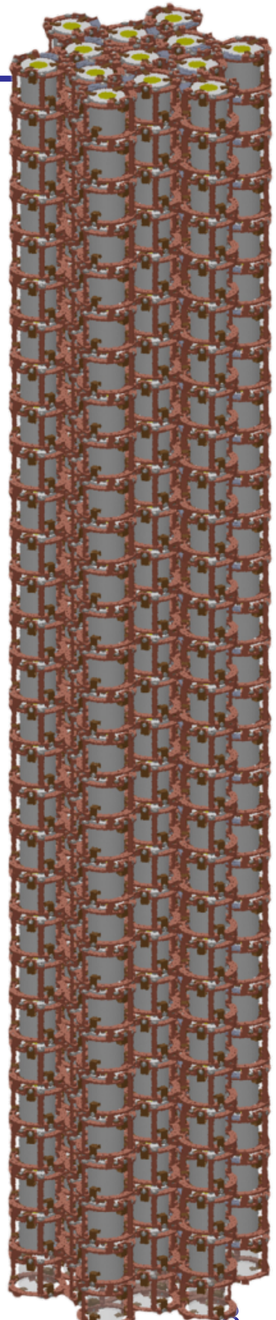


AMoRE-Pilot
1.9 kg
now~

AMoRE-1
5 kg
2018~

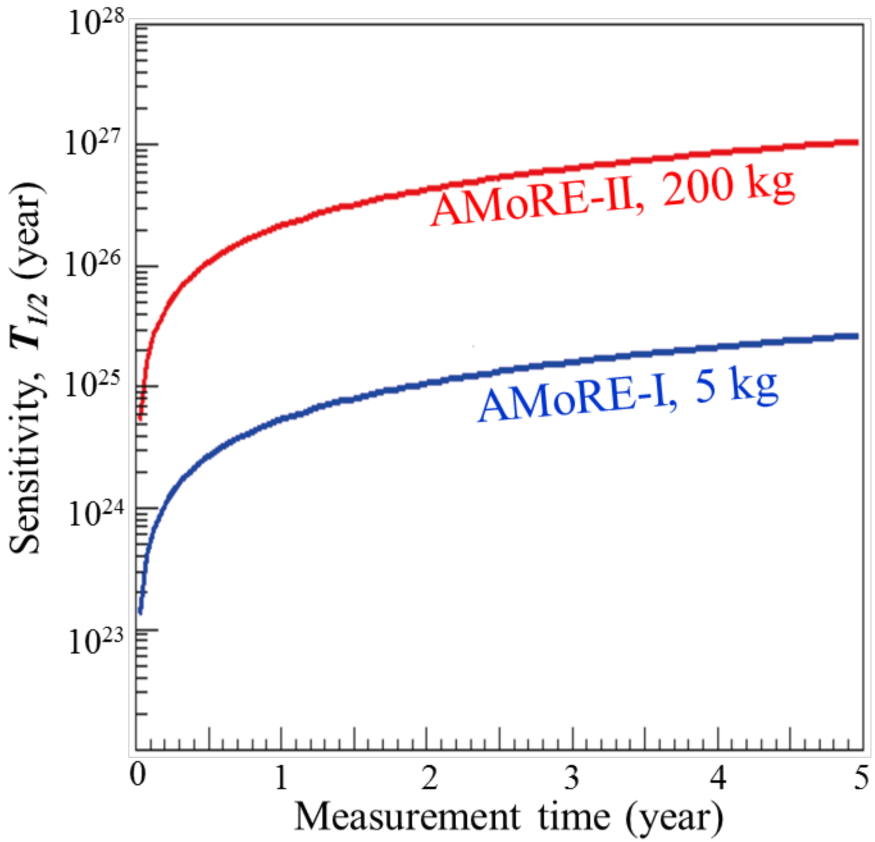


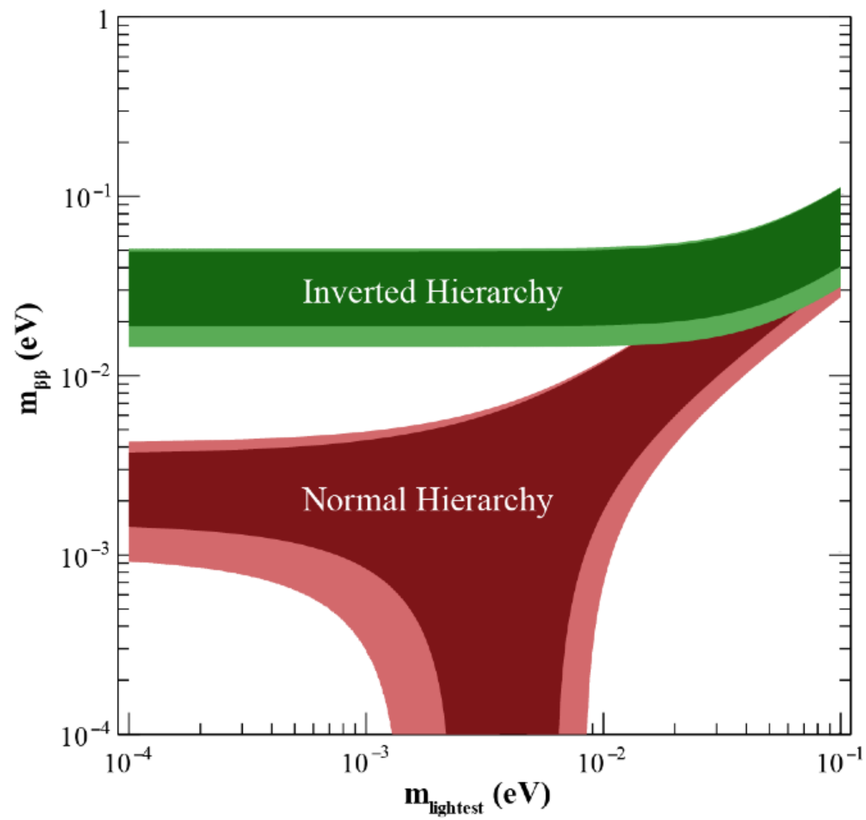
AMoRE-II
200 kg
2020~



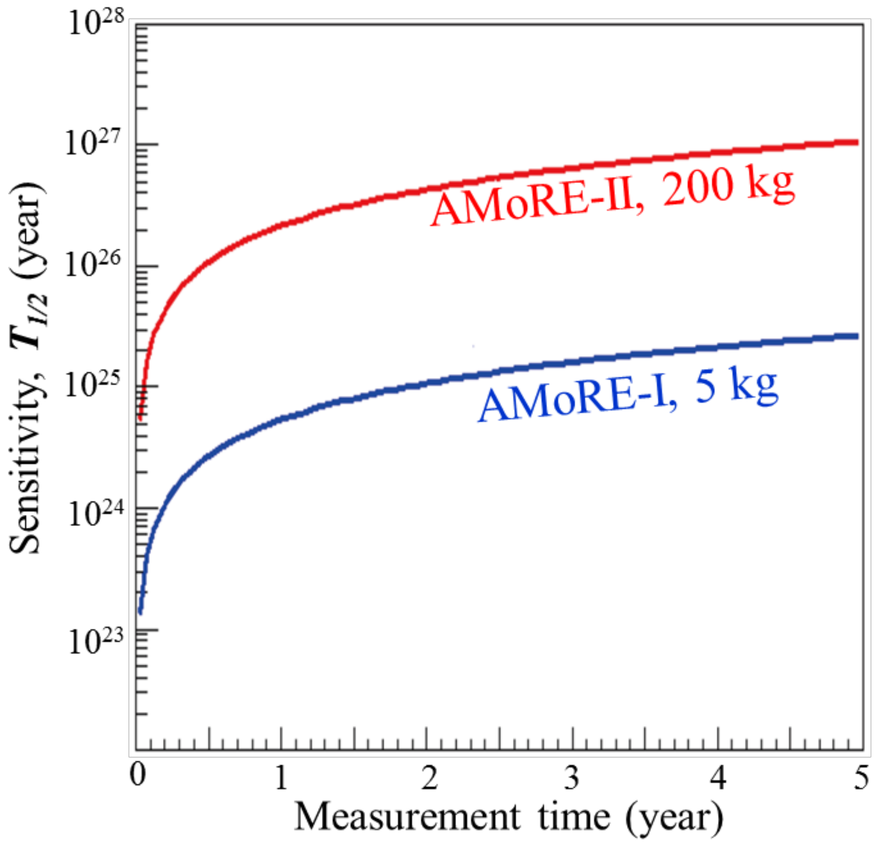
	Pilot	AMoRE-I	AMoRE-II
Mass	1.9 kg	~5 kg	~200 kg
Channels	12	36	1000
Required Bkg. (ckky)	0.01	0.001	0.0001
Sensitivity($T_{1/2}$) (year)	~10^{24}	~10^{25}	~5×10^{26}
Sensitivity(m_{ee}) (meV)	380-720	120-230	17-32
Location	Y2L	Y2L	New Lab
Schedule	2017	2018-2019	2020-2022

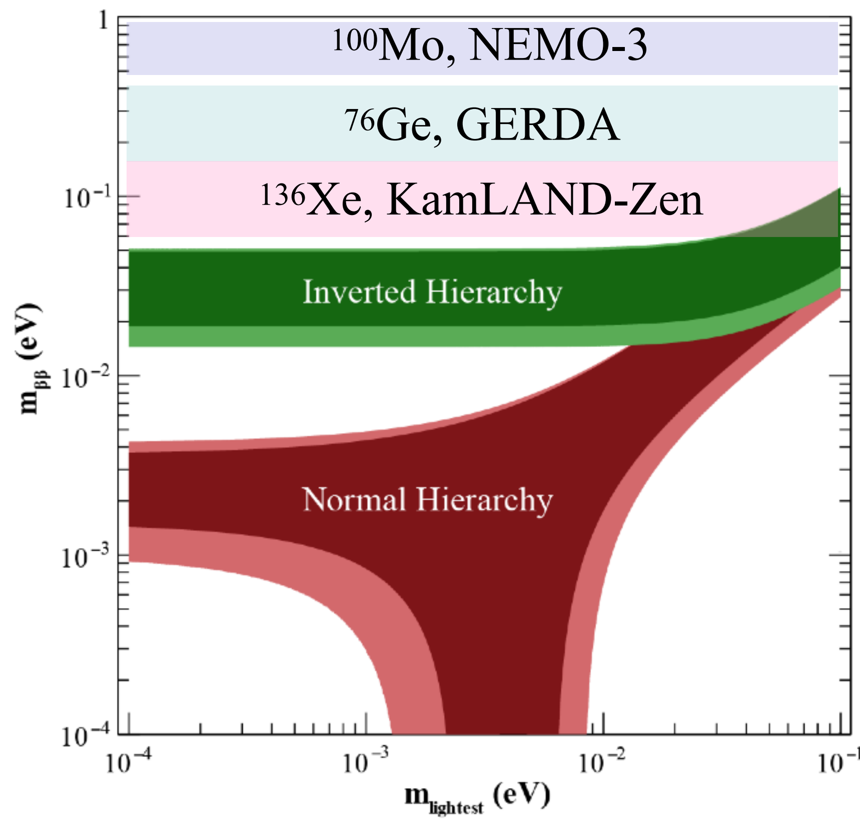
AMoRE Sensitivity



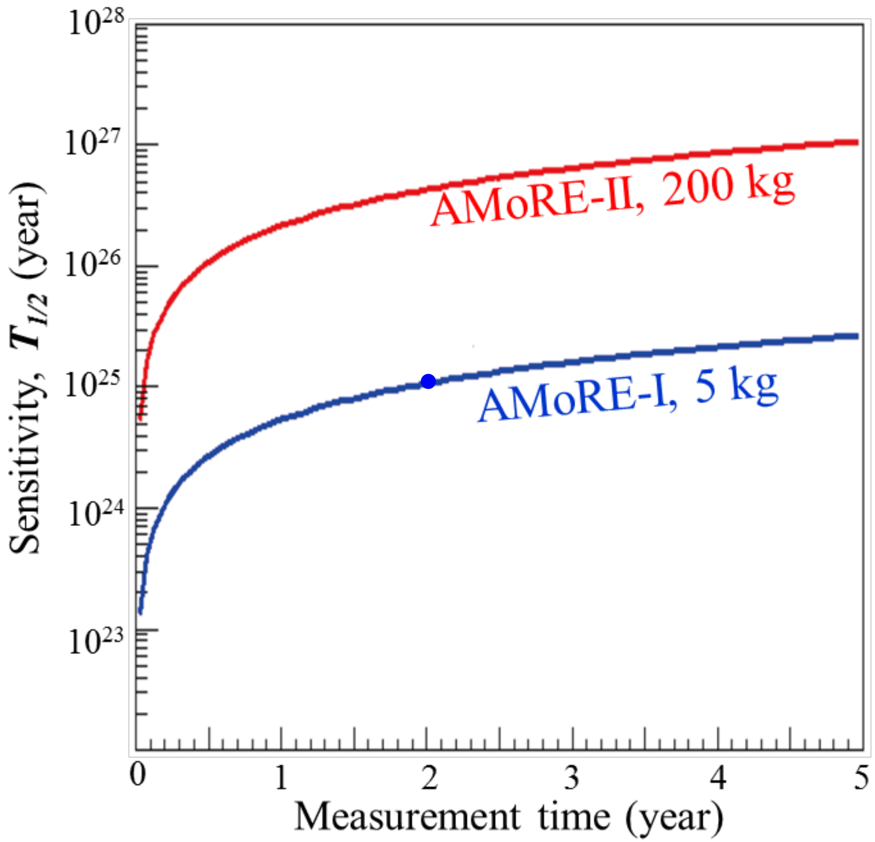


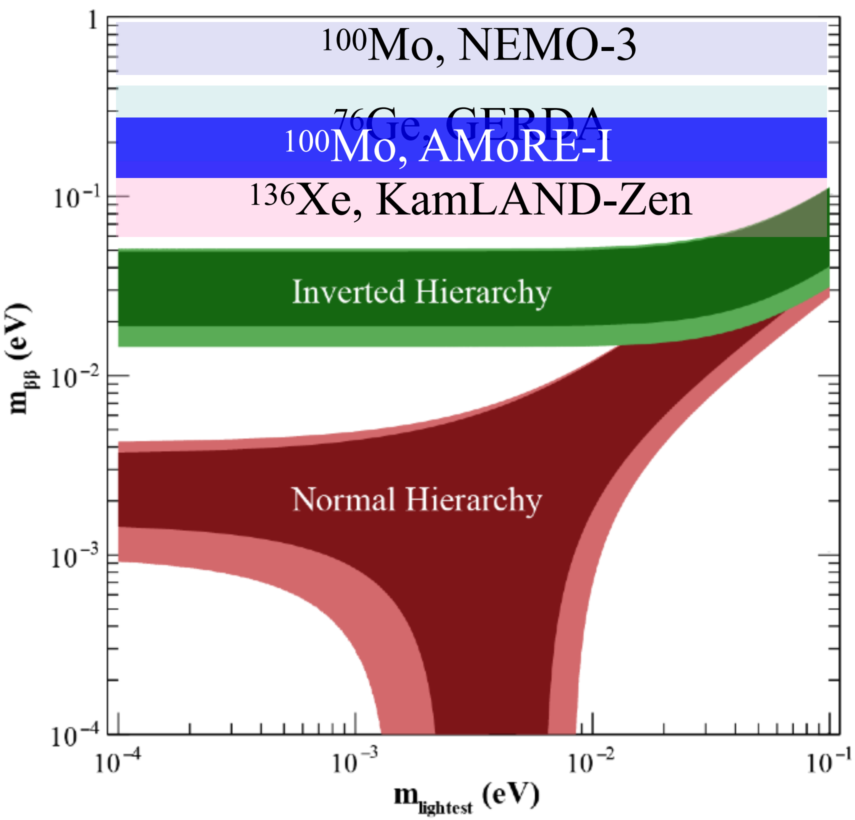
AMoRE Sensitivity



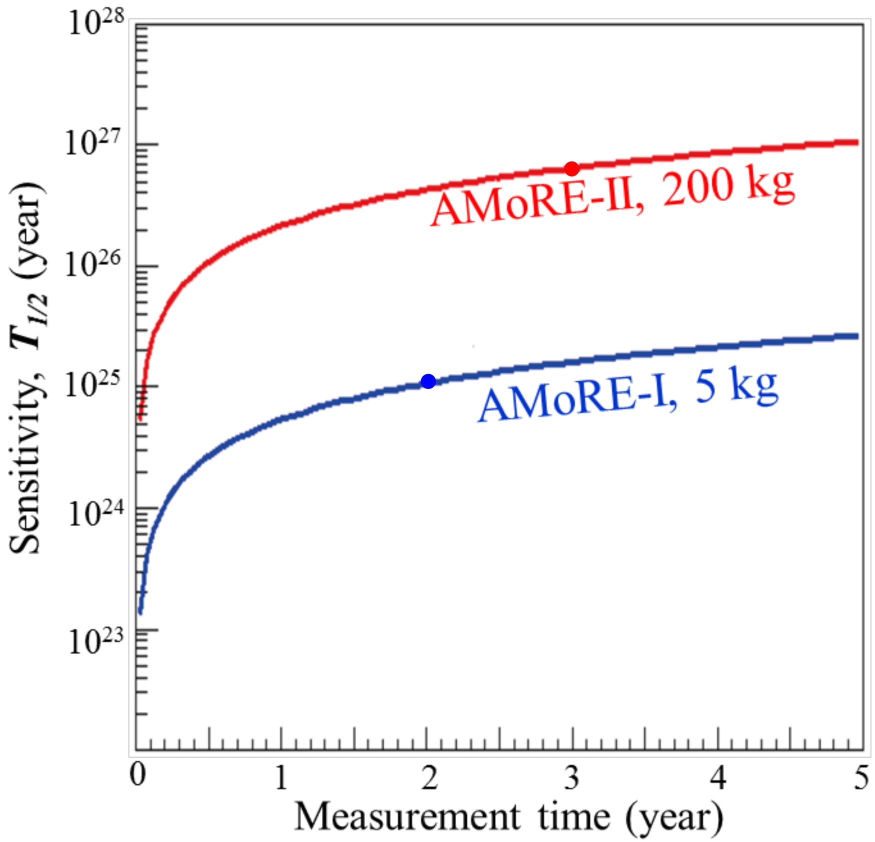


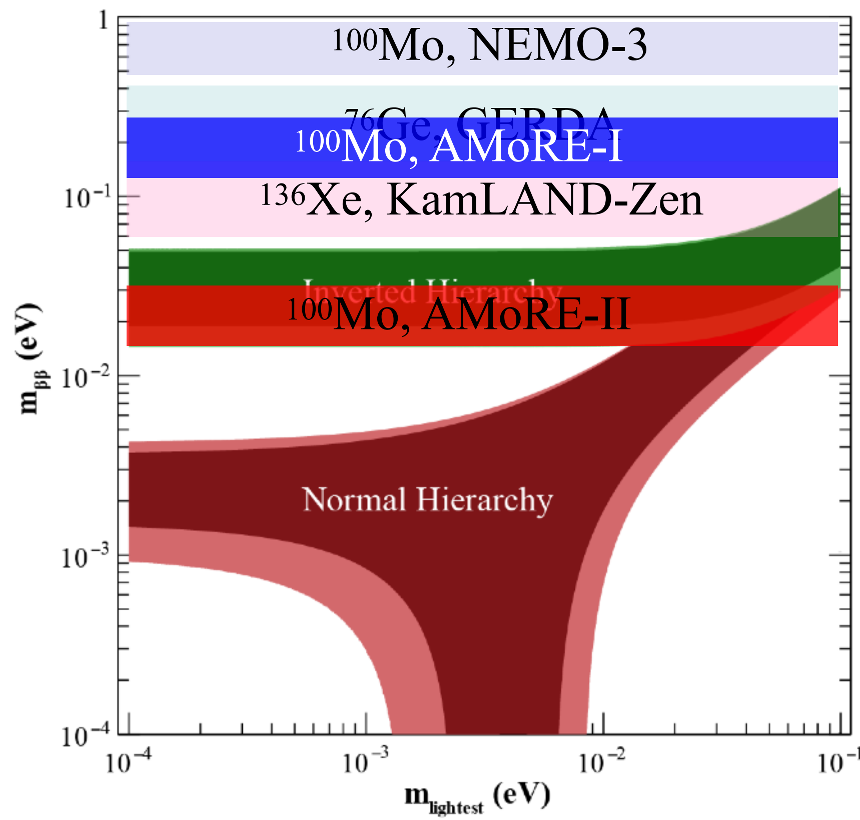
AMoRE Sensitivity





AMoRE Sensitivity

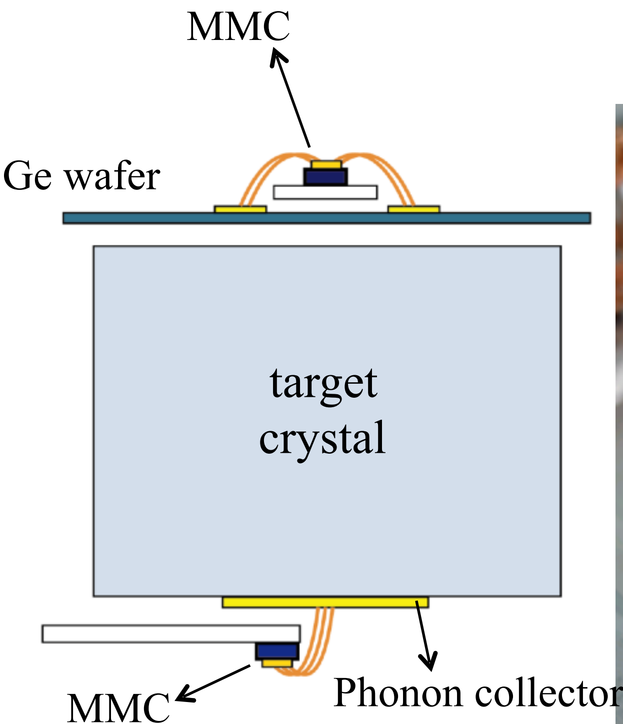


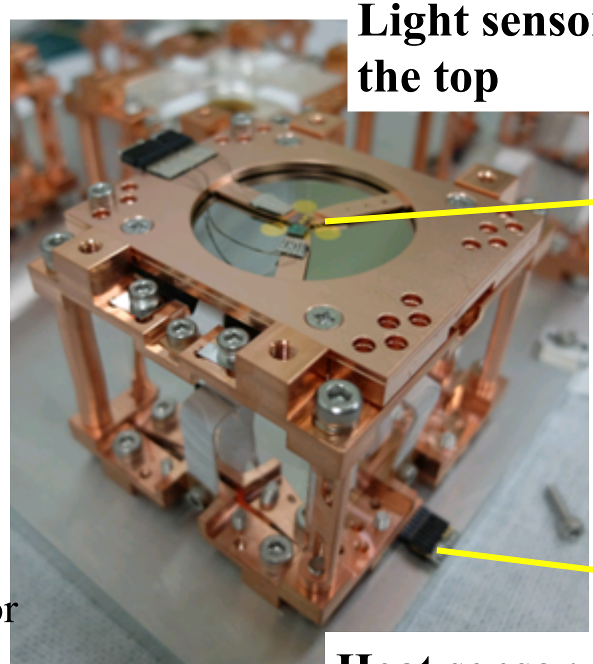


AMoRE detector module

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

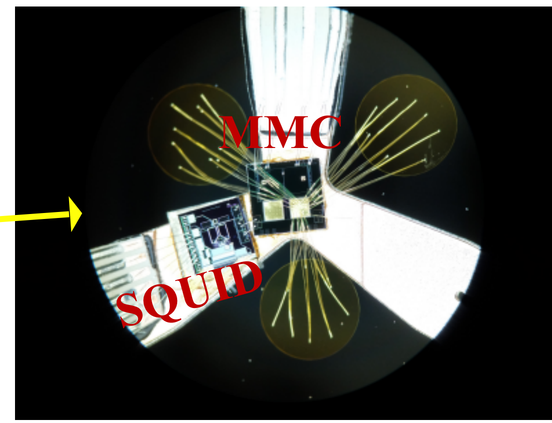
Phonon-Scintillation detection at mK

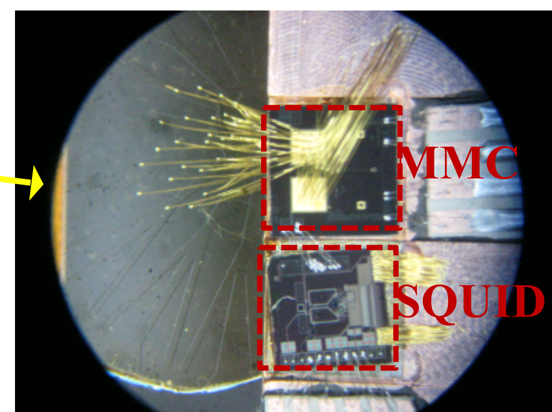




Light sensor at the top

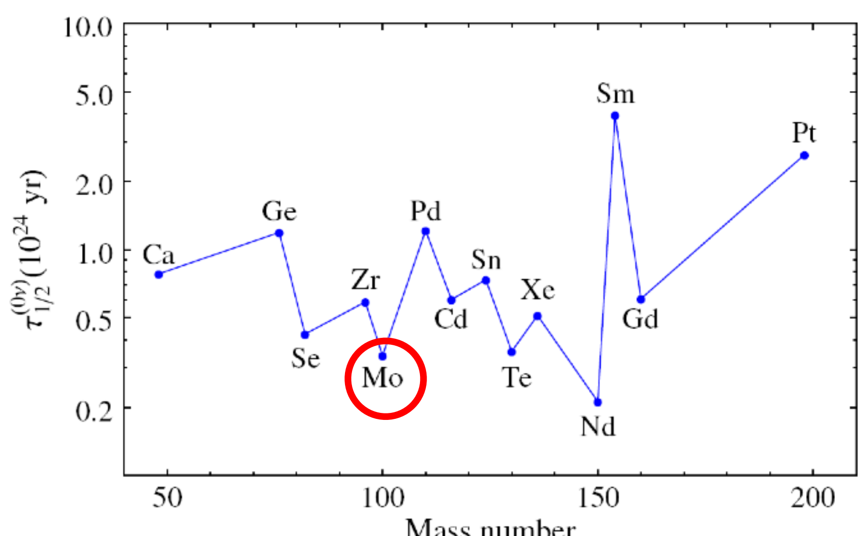
Heat sensor at the bottom





^{100}Mo is chosen for 0νββ experiment

- ^{100}Mo
  - ✓ High Q-value (ββ) of 3034.40 (12) keV.
  - ✓ High natural abundance of 9.6%
  - ✓ Relatively short half life (0νββ) expected from theoretical calculation



Barea et al., Phy. Rev. Lett. 109, 042501 (2012)

Candidate	Q (MeV)	Abund. (%)
^{48}Ca	4.271	0.19
^{76}Ge	2.040	7.8
^{82}Se	2.995	8.7
^{100}Mo	3.034	9.6
^{116}Cd	2.802	7.5
^{124}Sn	2.228	5.8
^{130}Te	2.533	34.1
^{136}Xe	2.479	8.9
^{150}Nd	3.367	5.6

$CaMoO_4$ crystals

- Scintillating crystal

  Light yield at mK : ~ 30,000 photons/MeV

- High Debye temperature: $\boldsymbol{T_D}$ = 438 K, $\boldsymbol{C} \sim (\boldsymbol{T/T_D})^3$

- ^{48}Ca, ^{100}Mo $0\nu\beta\beta$ candidates

- AMoRE Pilot uses $^{40}Ca^{100}MoO_4$:

  enriched ^{100}Mo and depleted ^{48}Ca

$^{40}Ca^{100}MoO_4$ crystals for Pilot and I

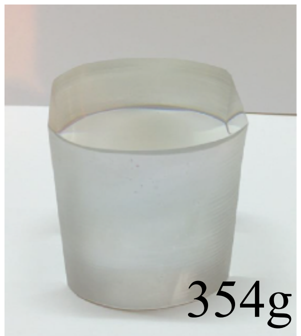
- Enrichment of ^{100}Mo (natural abundance : 9.6%)
  - Gas-centrifuge method
  - Enrichment of ^{100}Mo: ~ 95%.

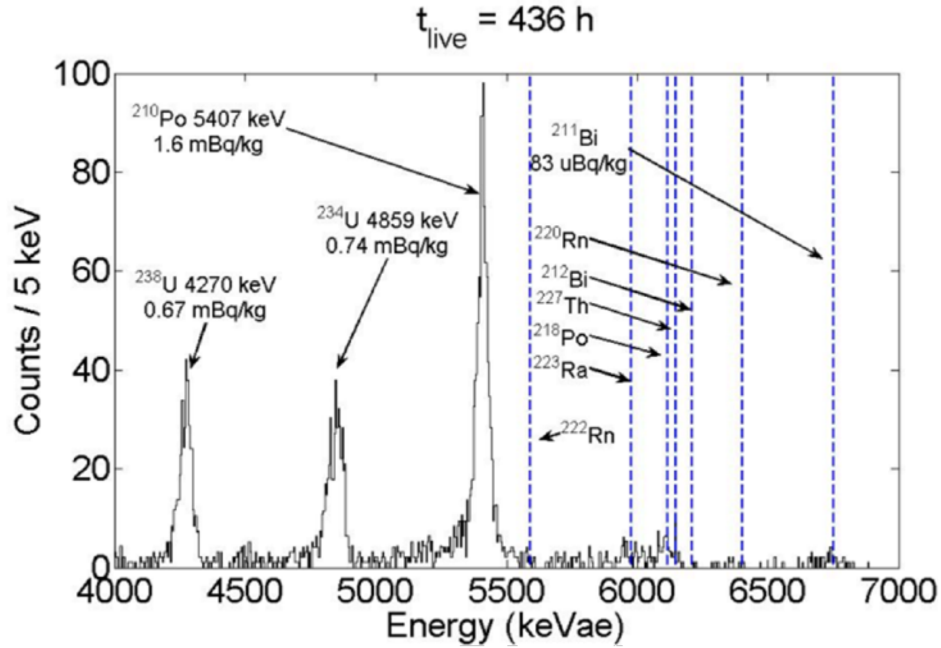
- Depletion of ^{48}Ca (natural abundance : 0.187%)
  - Electromagnetic separation
  - Composition of ^{48}Ca is less than 0.001 %.






Background for $^{40}Ca^{100}MoO_4$





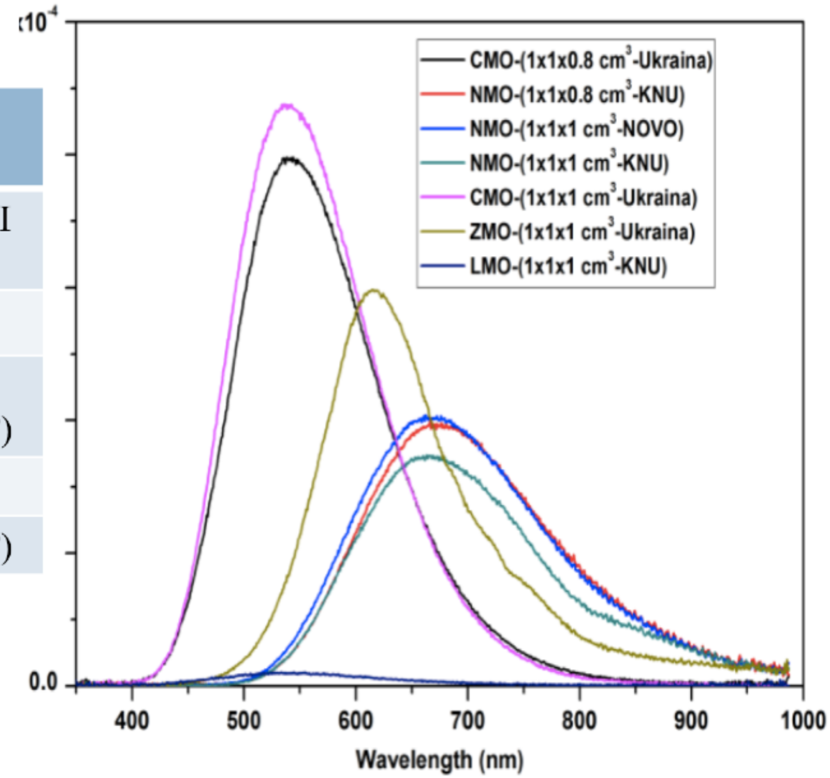
Isotopes	Activity (μBq/kg)	Specification (μBq/kg)
Bi-214 (U-238 chain)	< 18	< 100
Rn-220 (Th-232 chain)	< 14	< 50
Bi-211 (U-235 chain)	83	< 500
Total α activity	4600 (E > 4 MeV)	< 10000

Crystals for AMoRE-II

- ✓ We search for other Mo containing crystals for AMoRE-II in addition to $CaMoO_4$

Crystal	Emission (nm)	LightYield @ 10K	density	Mo Fraction	Exp
$CaMoO_4$	538	100	4.34	0.49	AMoRE-1, II (?)
$ZnMoO_4$	614	20-50	4.37	0.436	LUMINEU
Li_2MoO_4	533	5	3.03	0.562	LUMINEU AMoRE-II(?)
$PbMoO_4$	?	~10	6.95	0.269	
$Na_2Mo_2O_7$	663	~40	3.62	0.558	AMoRE-II(?)

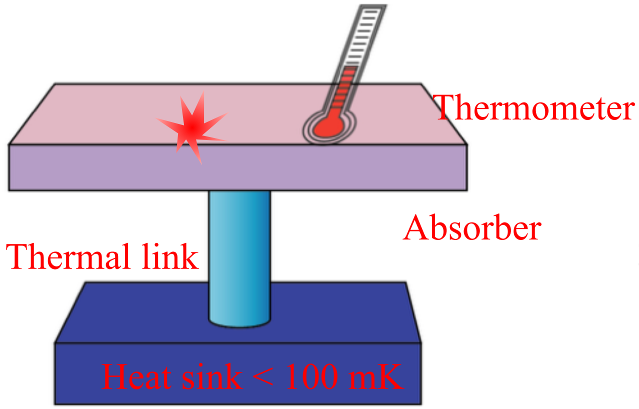
<From KNU>

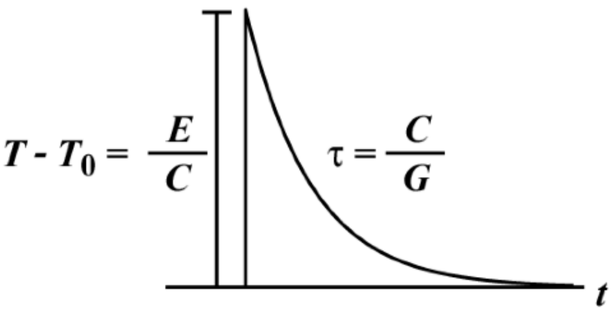


Low Temperature Detectors

"Calorimetric measurement of heat signals at mK temperatures"

Energy absorption ➔ Temperature



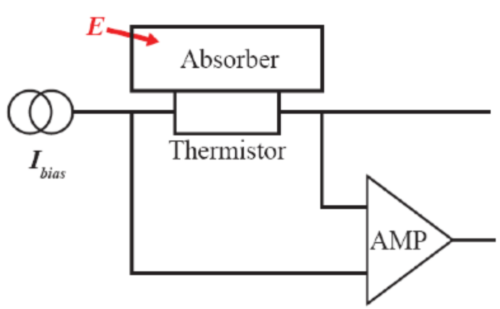


Choice of thermometers for 0νββ searches

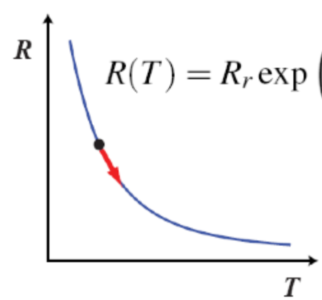
- **Thermistors (NTD Ge)** CUORE, CUPID
- TES (Transition Edge Sensor) Light detector
- **MMC (Metallic Magnetic Calorimeter)** AMoRE, LUMINEU
- KID (Kinetic Inductance Device) CALDER
- etc.

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 >



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

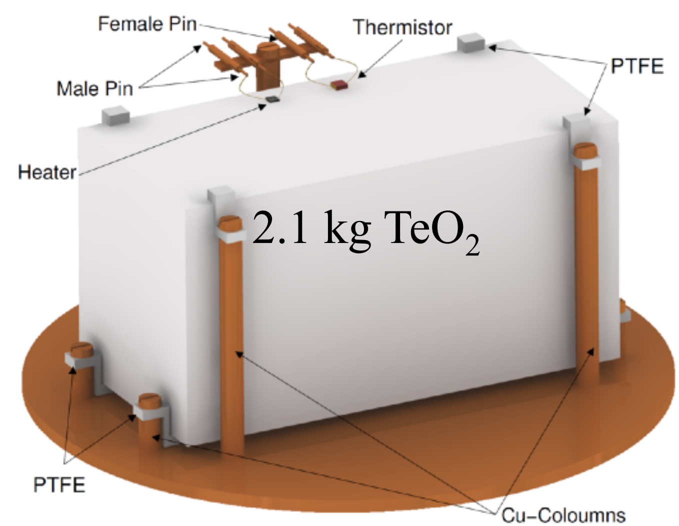
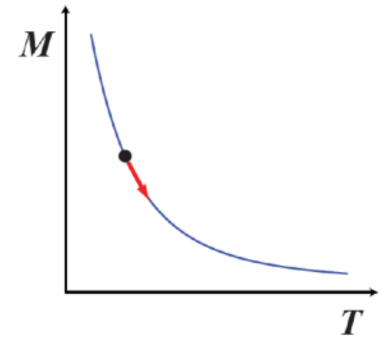
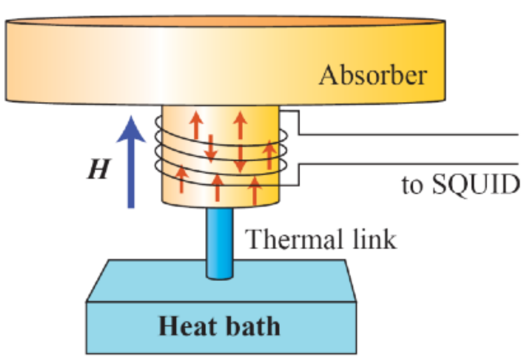


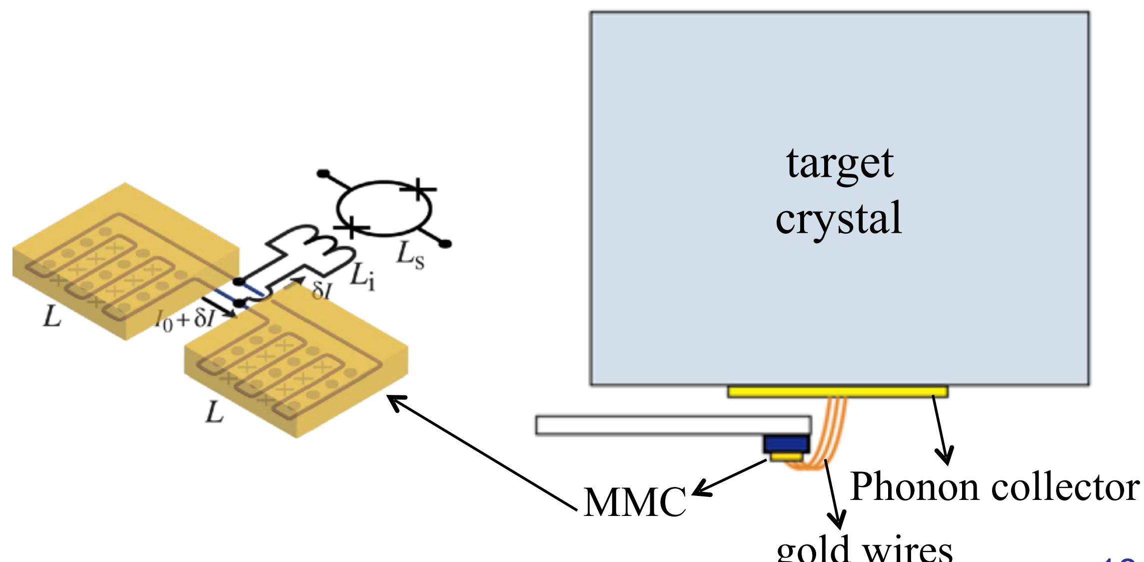
fig. from Cardani et al arXiv.1106.0568

Metallic Magnetic Calorimeter (MMC)

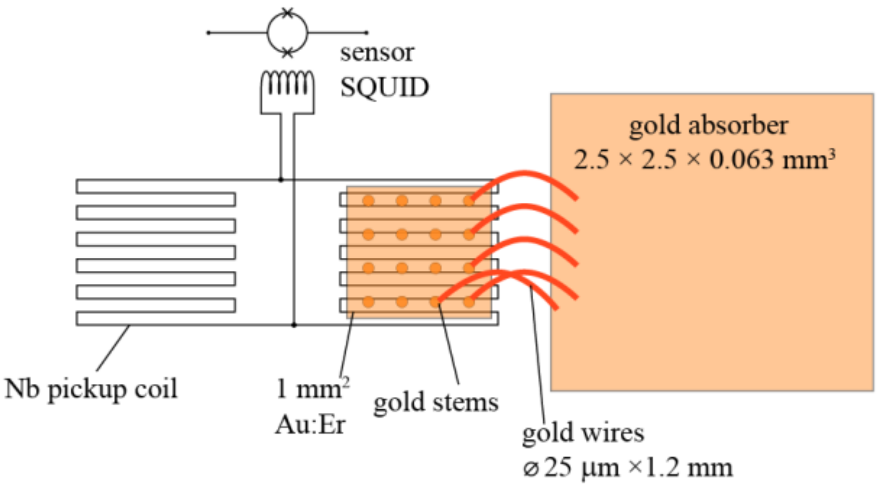
- Paramagnetic alloy in a magnetic field
  Au:Er(300-1000 ppm), Ag:Er(300-1000 ppm)
  → Magnetization variation with temperature
- Readout: SQUID
- High resolution + High linearity + Wide dynamic range + Absorber friendly + No bias heating + Relatively fast
- More wires & materials needed for SQUIDs and MMCs,

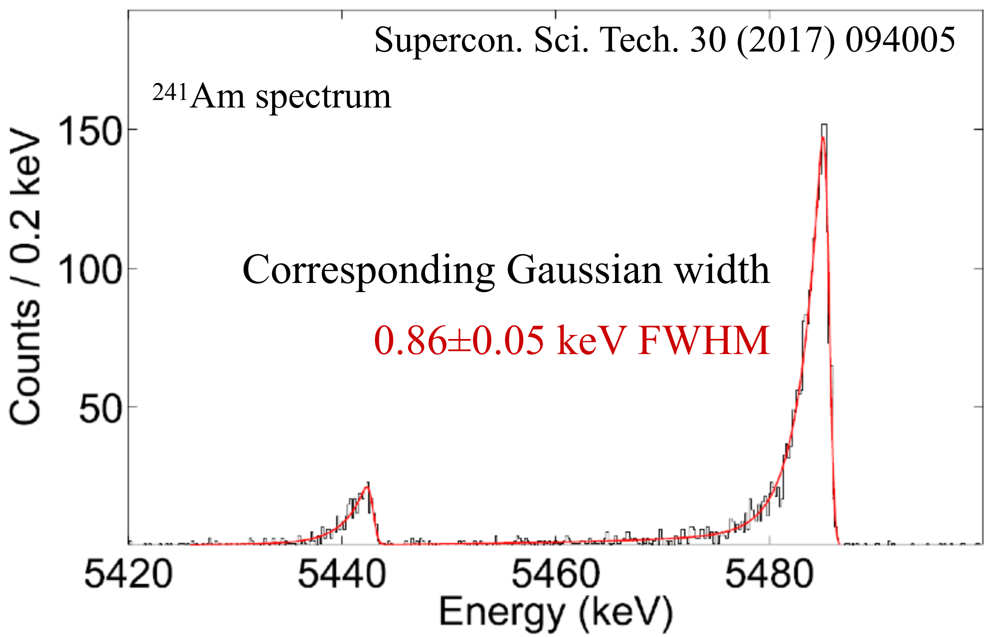




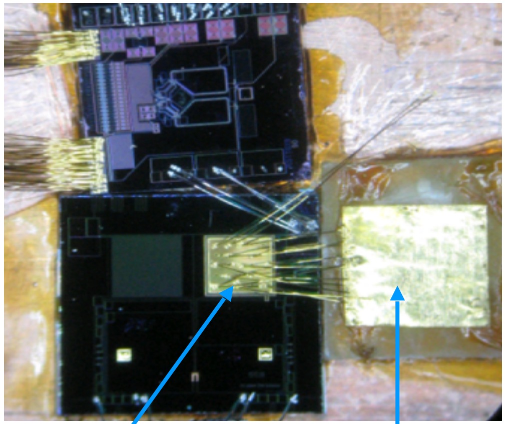


MMC provides high resolution for AMoRE





MMC fabrication: KRISS
PTB SQUID: C6XS116



Au:Er

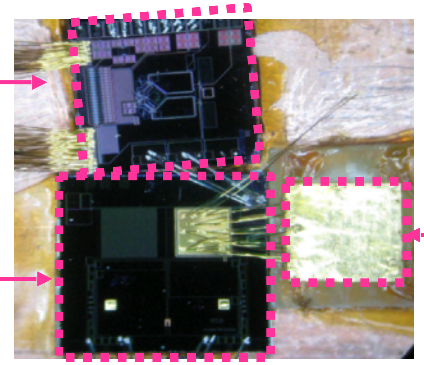
Gold foil absorber

MMC with gold foil absorber with C ~ 0.3 kg $CaMoO_4$

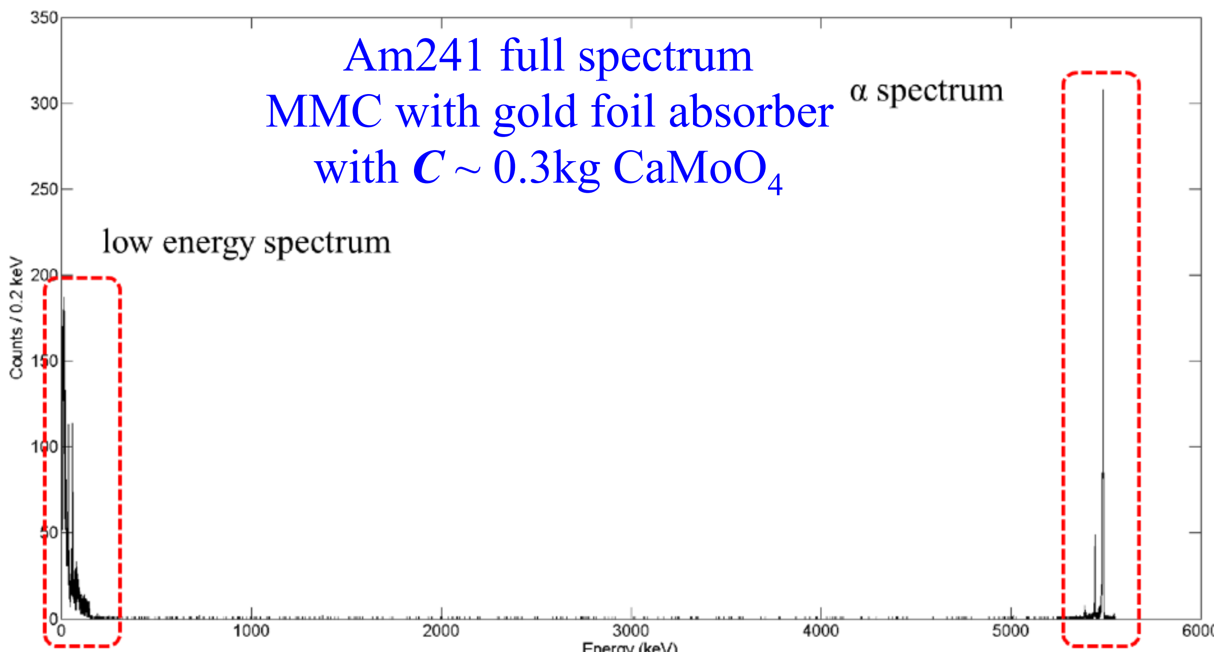
Superior dynamic range with high resolution

PTB SQUID

KRISS MMC



Gold foil absorber

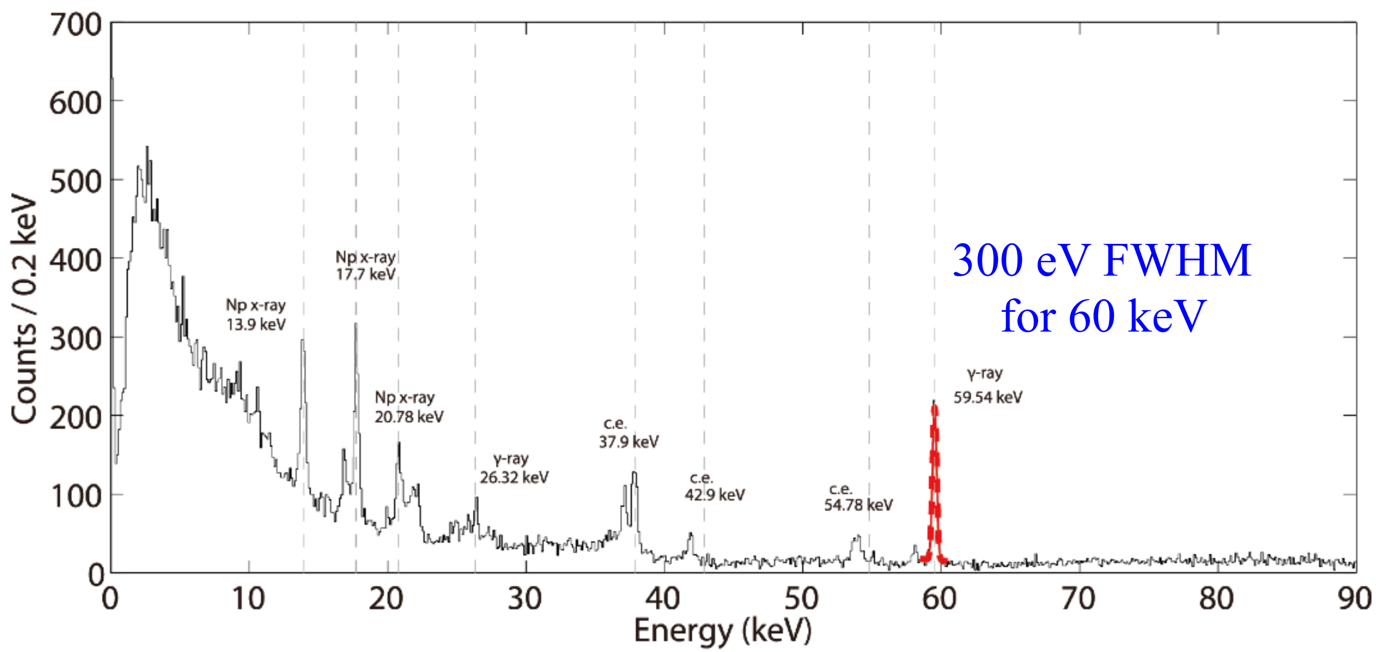


0.3 keV FWHM for 60keV γ

0.9 keV FWHM Gaussian width for 5.5MeV α

Low energy spectrum

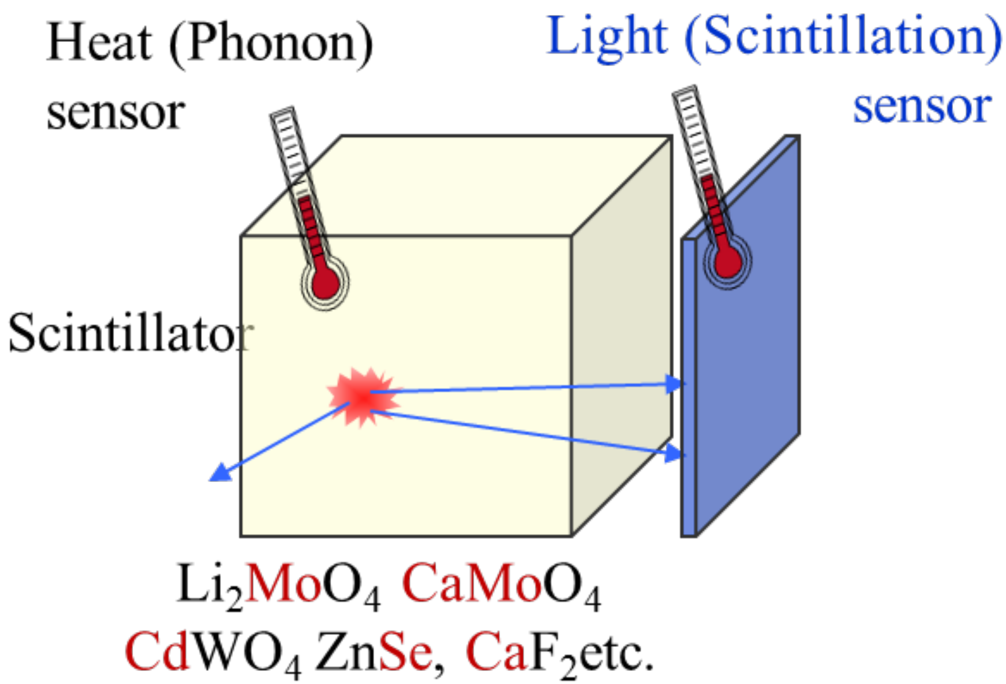
^{241}Am low energy spectrum

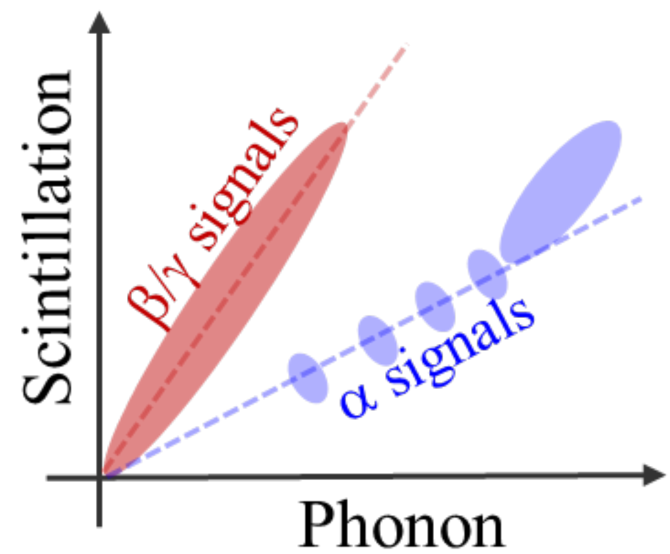


Low E. and high E. spectrum can be measured in the same time with high resolution.

→Also useful for WIMP searches

Simultaneous Heat-Light detection

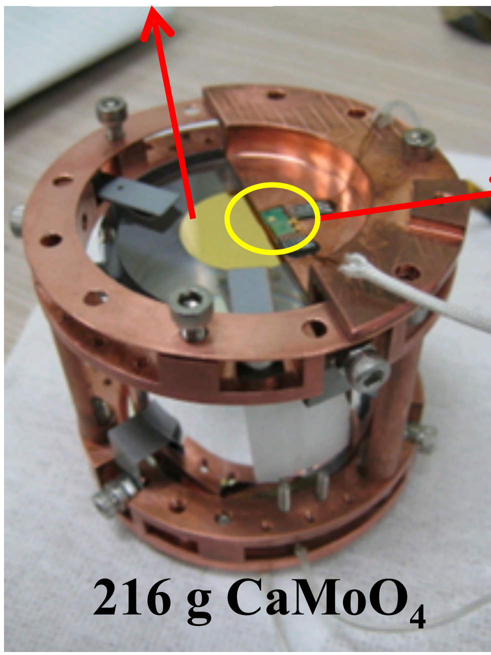




✓ Scintillating crystal as target material
➔ Active bkg. Rejection

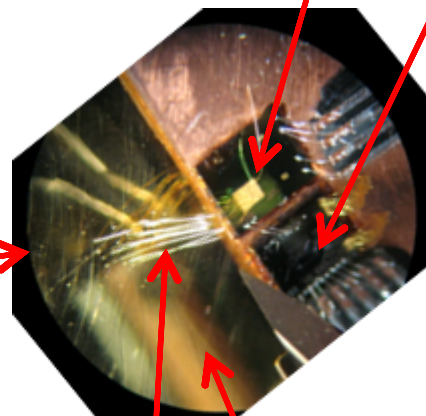
Heat(Phonon) sensor for AMoRE

Phonon collector
Patterned gold film



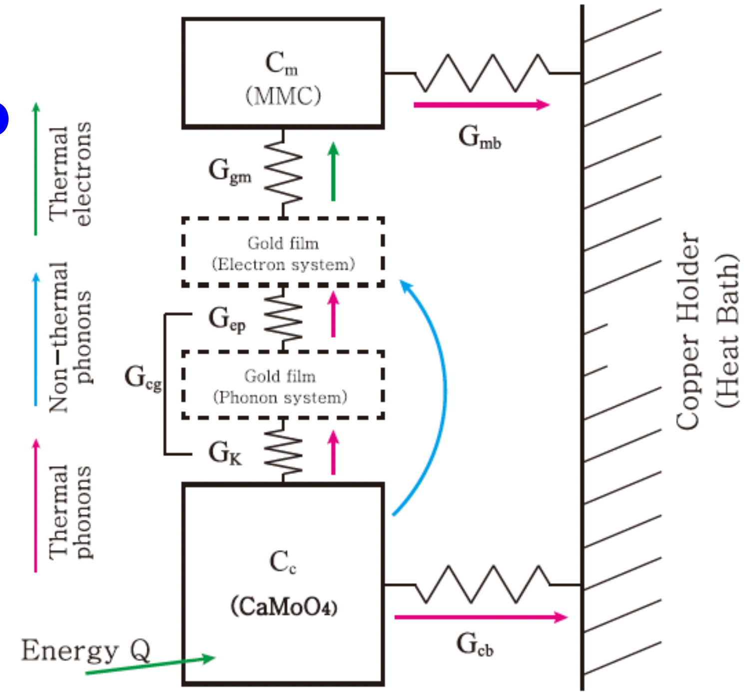
MMC

SQUID

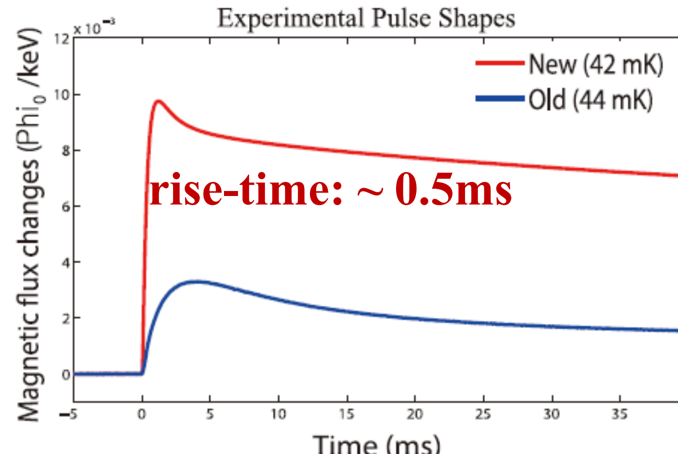


Gold film

Gold wires
(thermal connection)



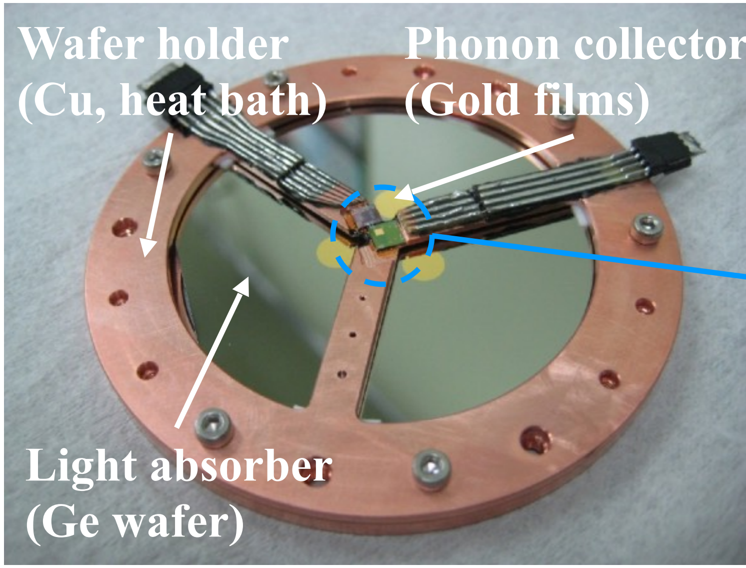
We measure both thermal and athermal phonons.

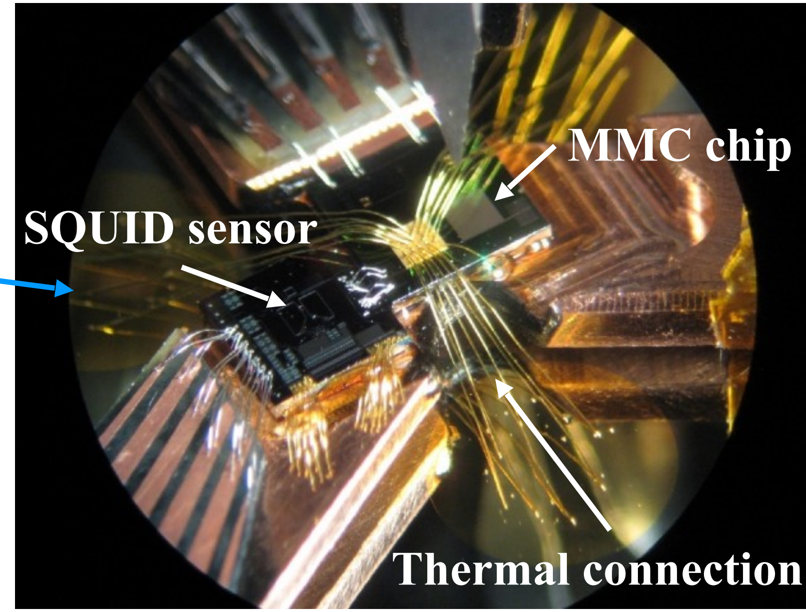


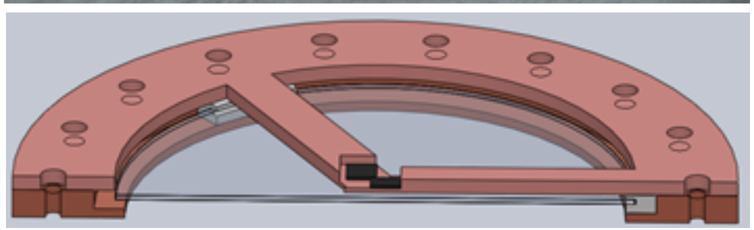
<Heat flow optimization>

Light (patchable) sensor with MMC

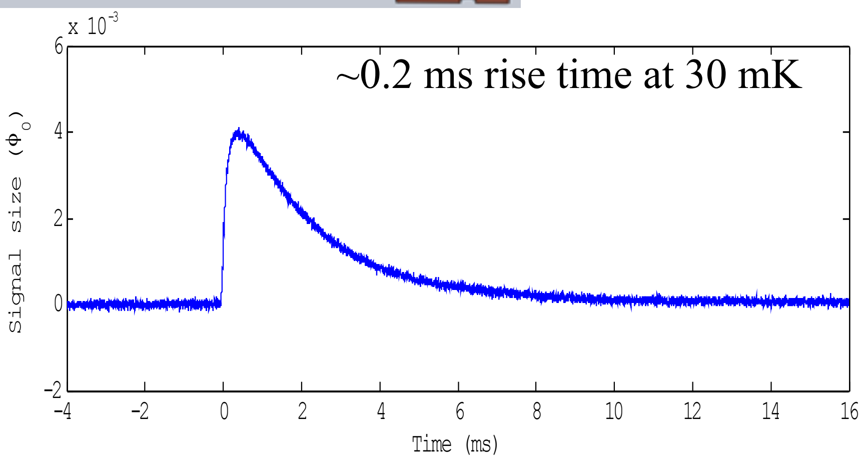
NIMA 784 (2015) 508

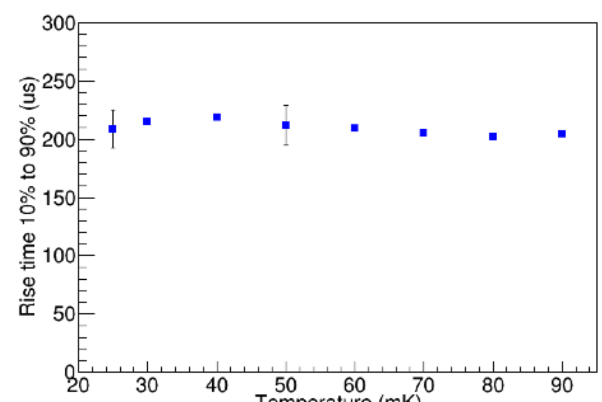






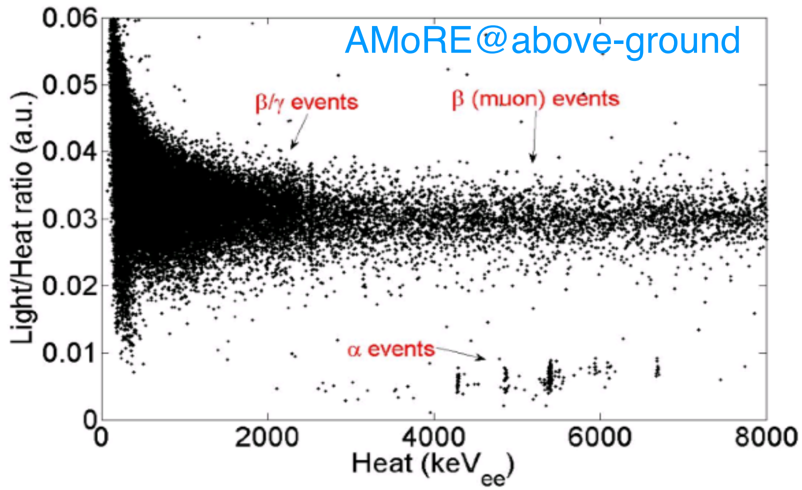
Temperature independent rise-time !

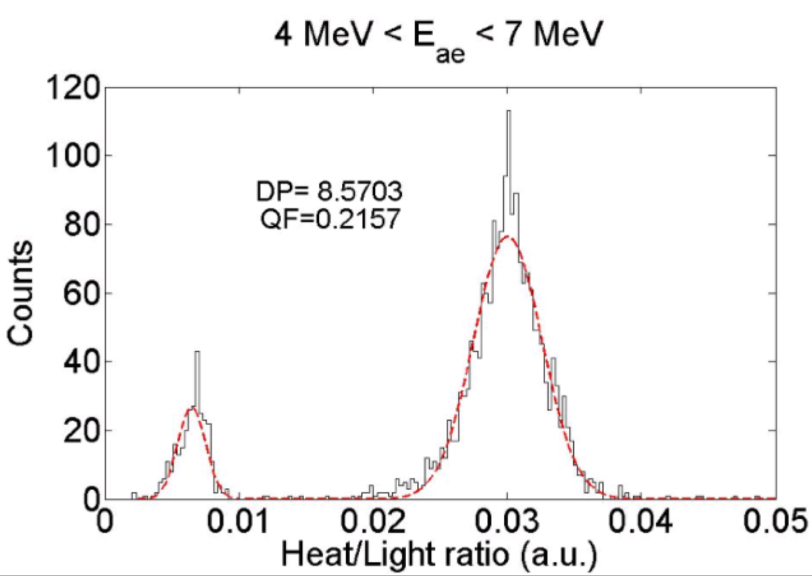




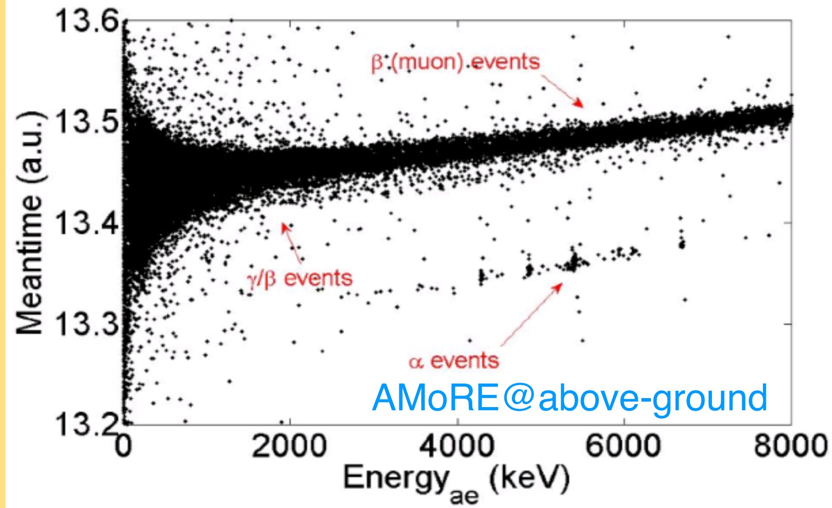
Particle discrimination

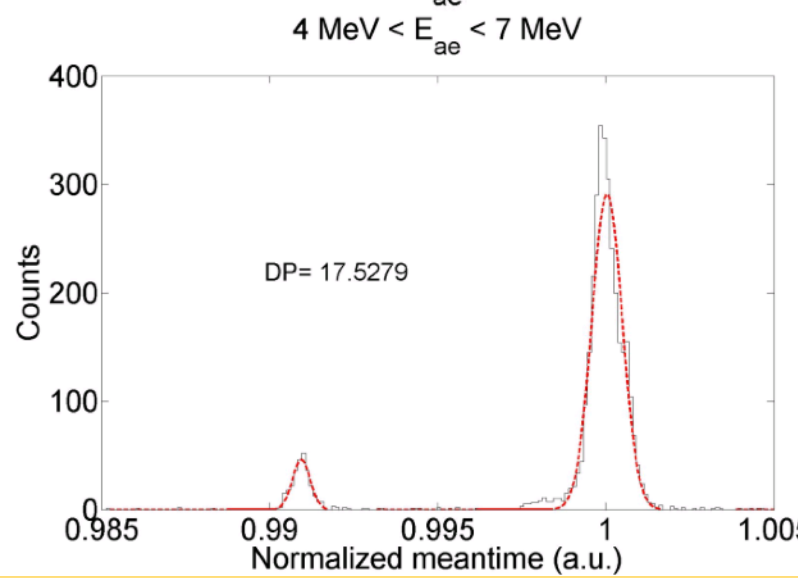
Particle discrimination by light heat ratio





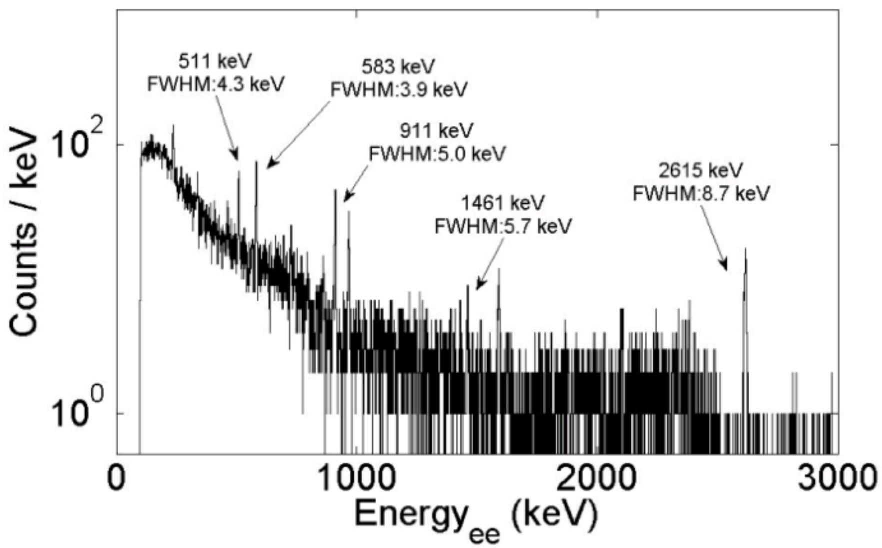
Phonon pulse shape discrimination (PSD)

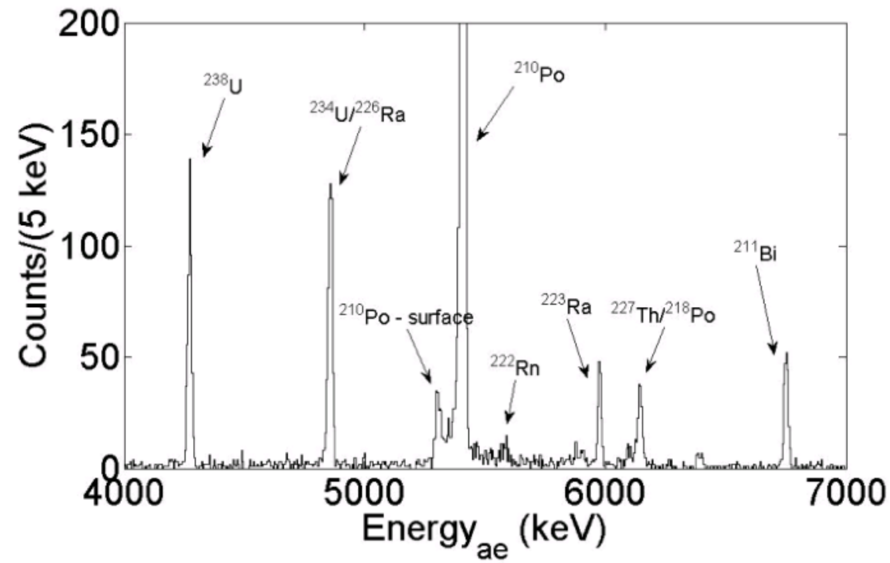




Energy spectrum (above-ground)

Electron and alpha events can be efficiently identified.





- Better than 9 keV energy resolution was obtained at 10 mK temperature.
- Internal alpha background levels of each isotopes were calculated successfully.

Energy calibration & Lineartiy

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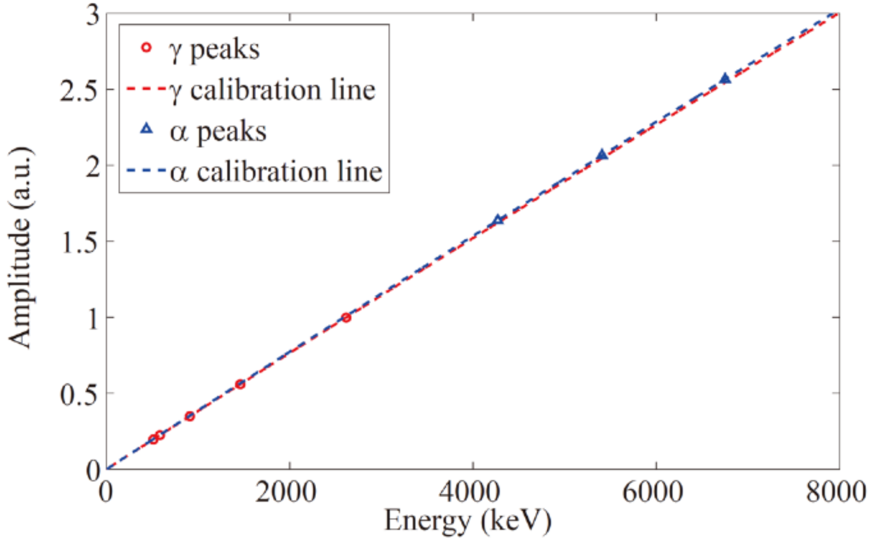
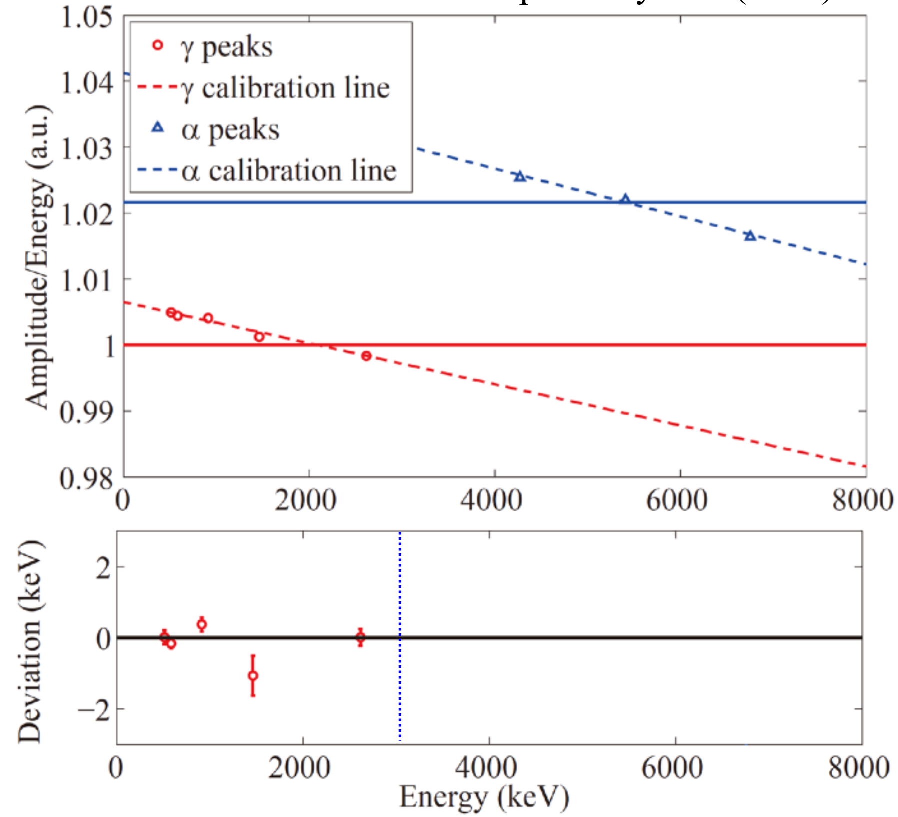
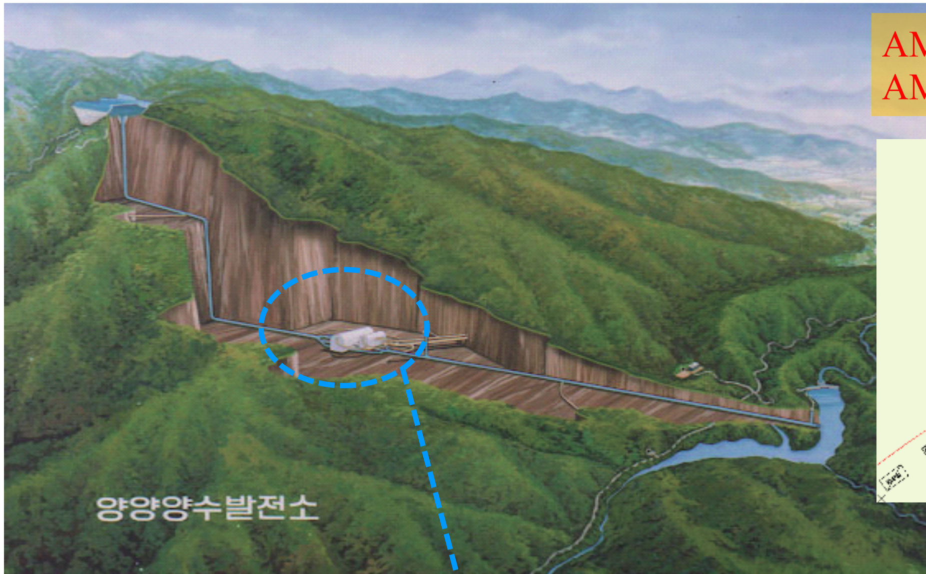


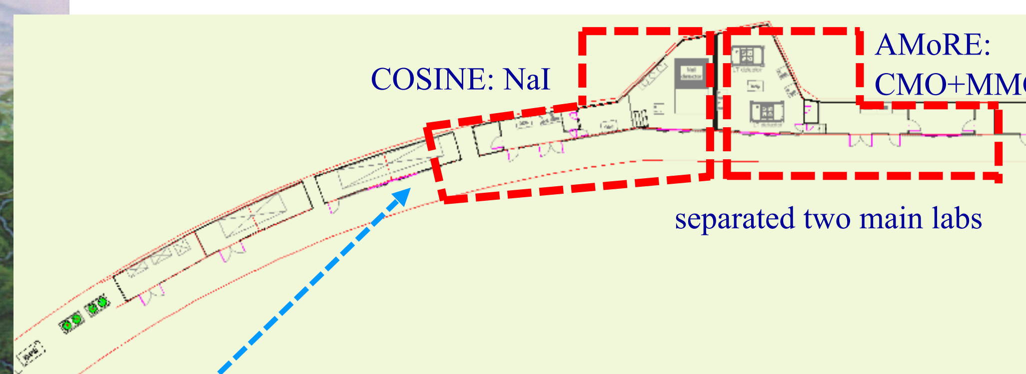


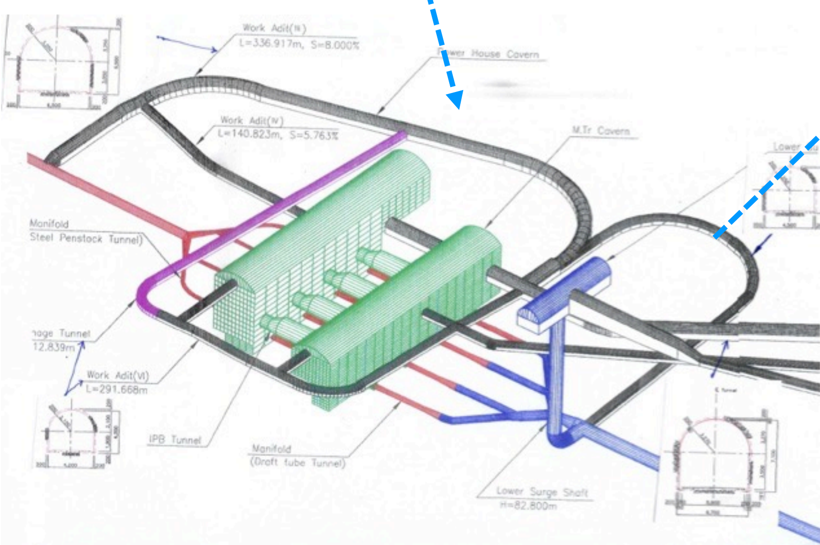
- Alpha peaks are slightly larger than gamma peaks
- A few % non-linearity was found for α and γ peaks
- Better than 1 keV calibration is expected at 3MeV with a quadratic function

YangYang Underground Laboratory (Y2L)



AMoRE-pilot and AMoRE-phase1 will be run at Y2L.
AMoRE-phase2 will be run at other place. (New underground lab.)





Yangyang pumped storage Power Plant

Minimum vertical depth : 700 m

Access to the lab by car : around 2 km

Experiments

- COSINE : dark matter search experiment
  100 kg NaI (room temperature)
- AMoRE : 0νββ decay search experiment
  1.9 kg $^{40}Ca^{100}MoO_4$ with MMC

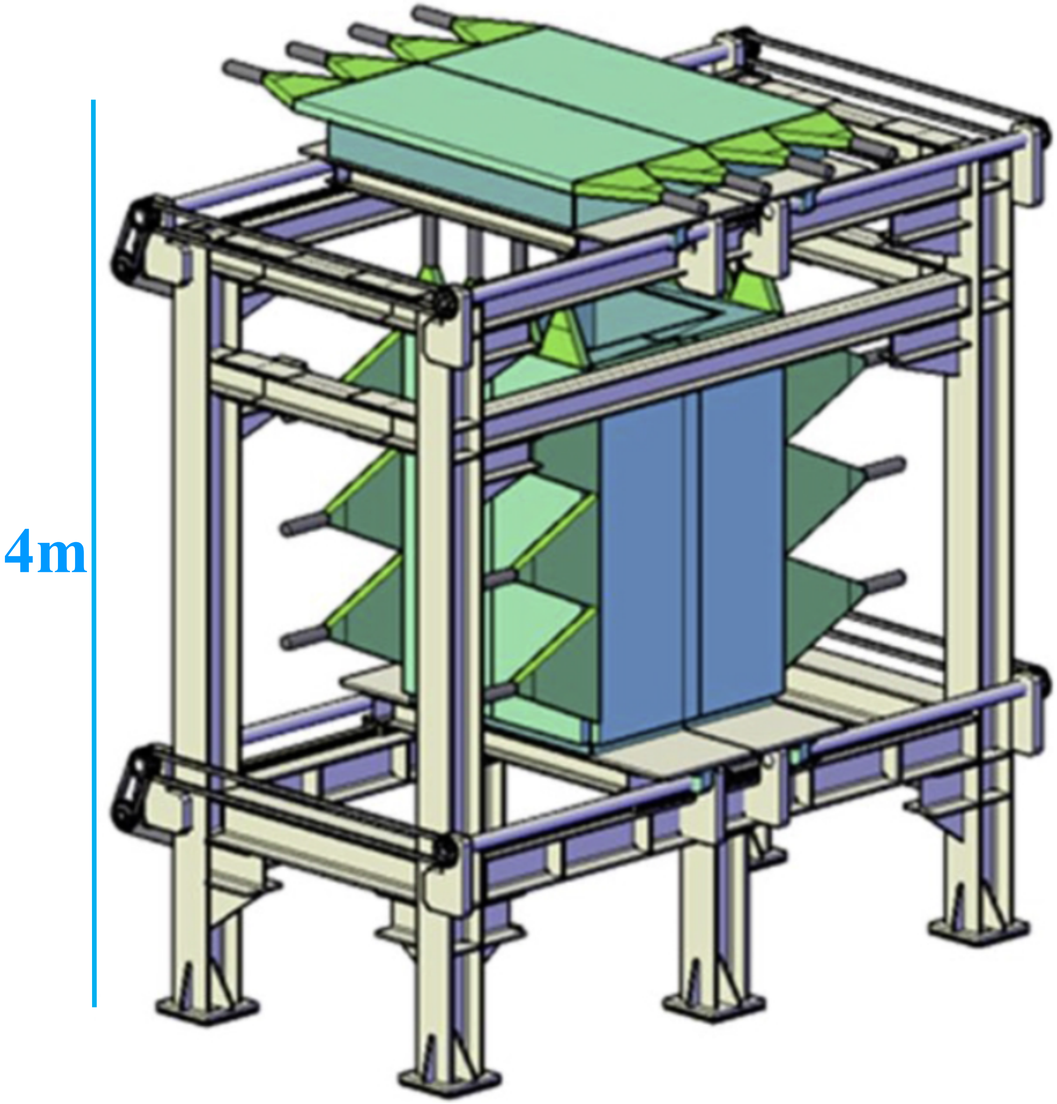
We’ve been busy at construction

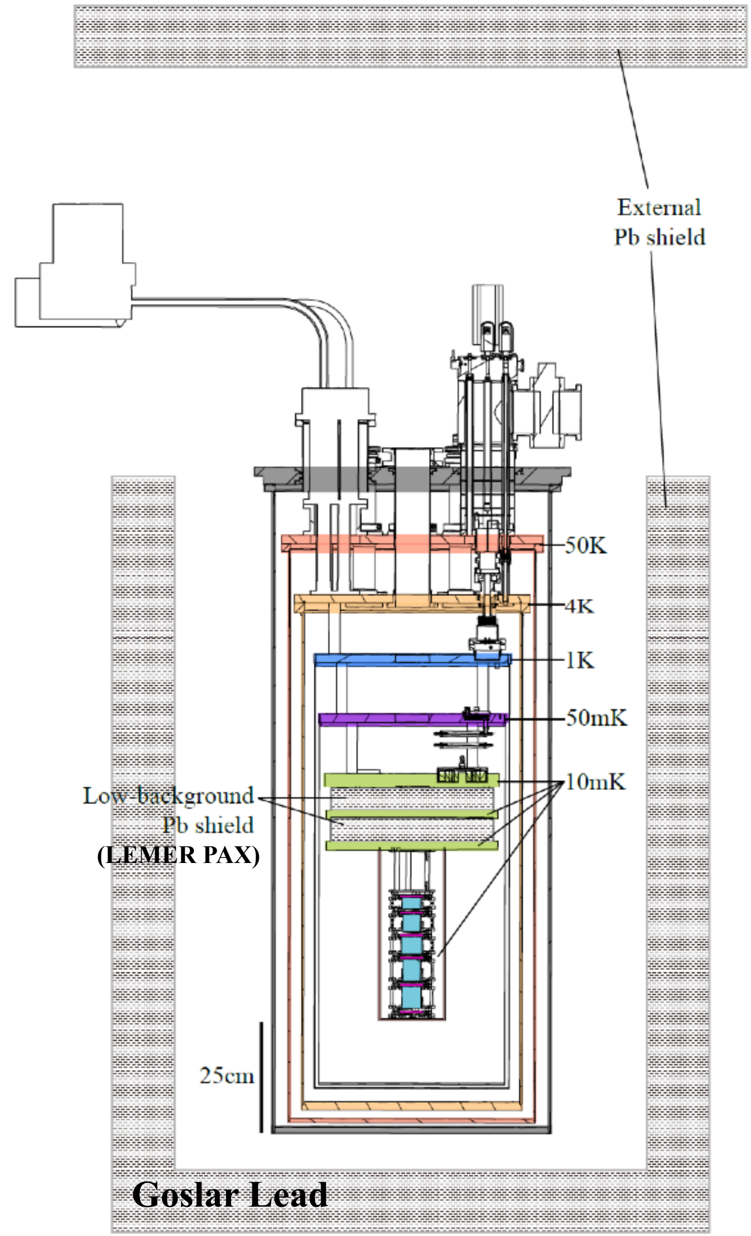

Lab space : July 2014


December 2014

July 2015


Shields & Cryostat for AMoRE Pilot & I

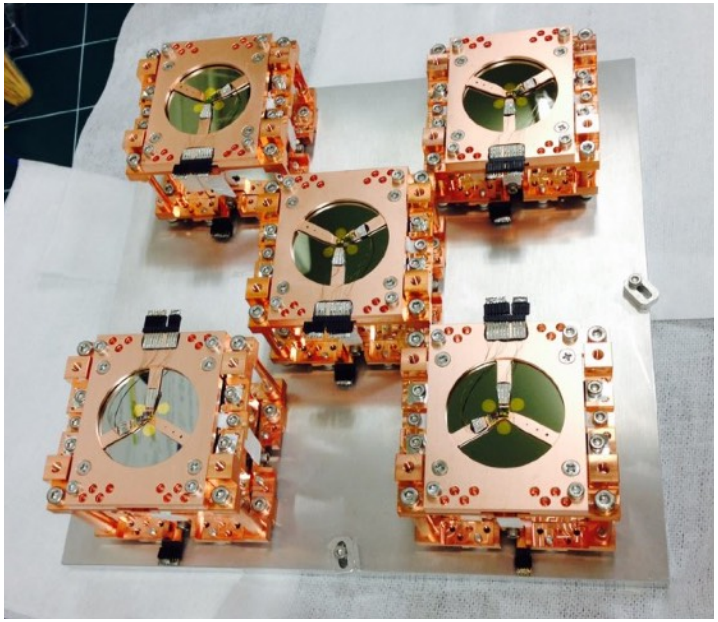


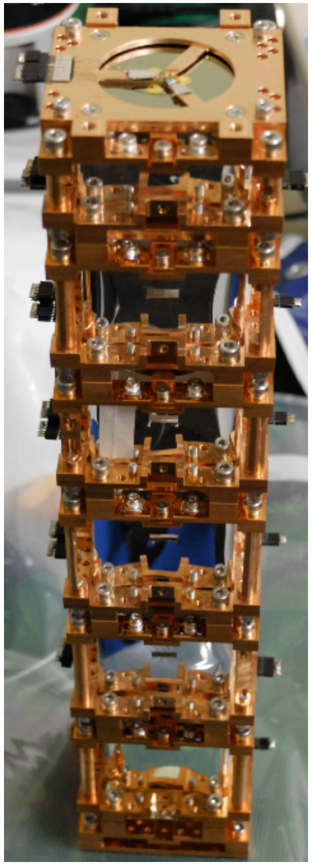


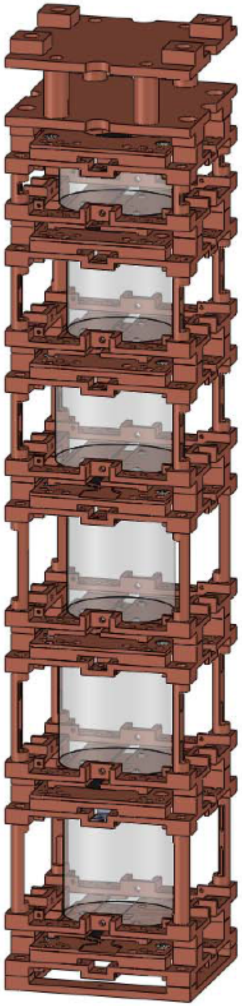
AMoRE pilot : 5 + 1 crystals

All are installed in a dry dilution refrigerator in Y2L.

Recently added another crystals: total mass ~ 1.9 kg



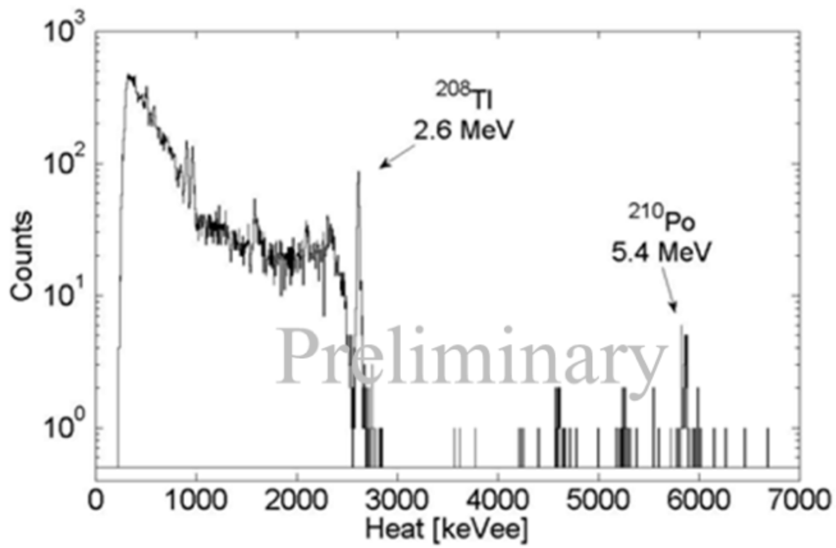




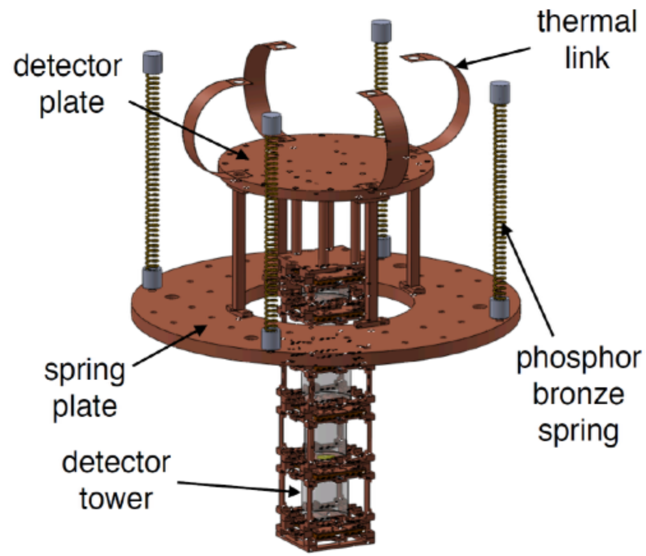
All installed and taking measurement now.

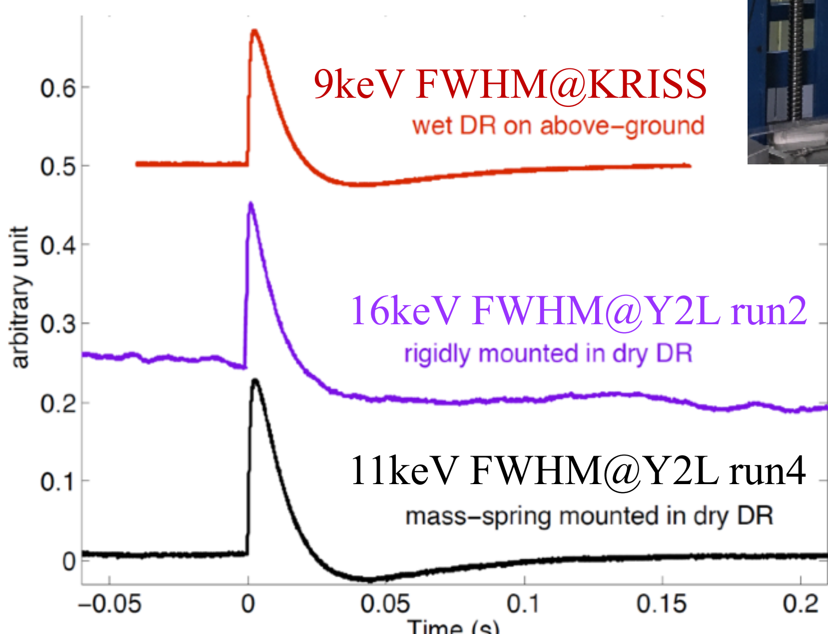
- All of the shields are mounted.
- The *dry* dil. fridge reaches 8 mK with 250kg lead & copper attached to M.C.
- We are improving noise figures now.
  - High frequency: reasonably low.
  - Low frequency: recently improved.

with an external source at 20 mK



Mass Spring Damper





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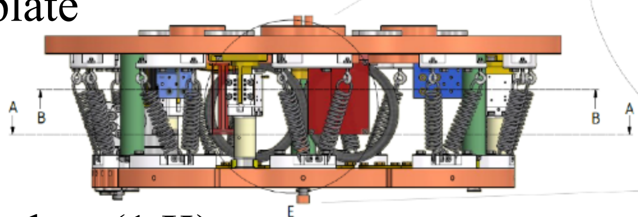
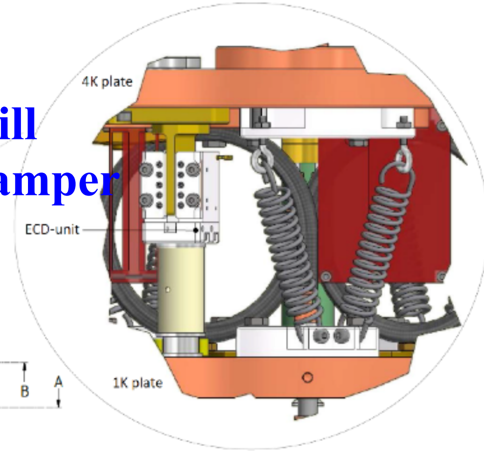
Additional Isolation between 1 K and 4 K stages

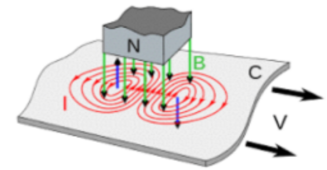
Spring Suspended Still with Eddy current damper

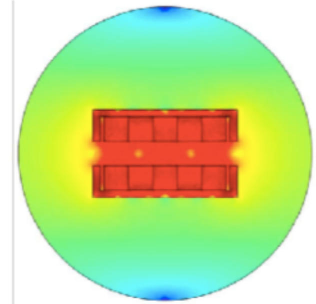
4K plate

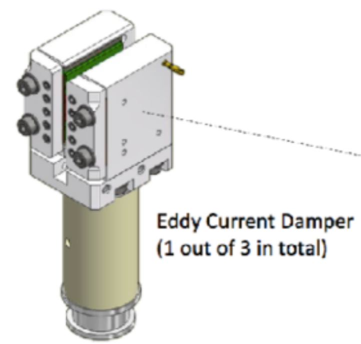


Still plate (1 K)

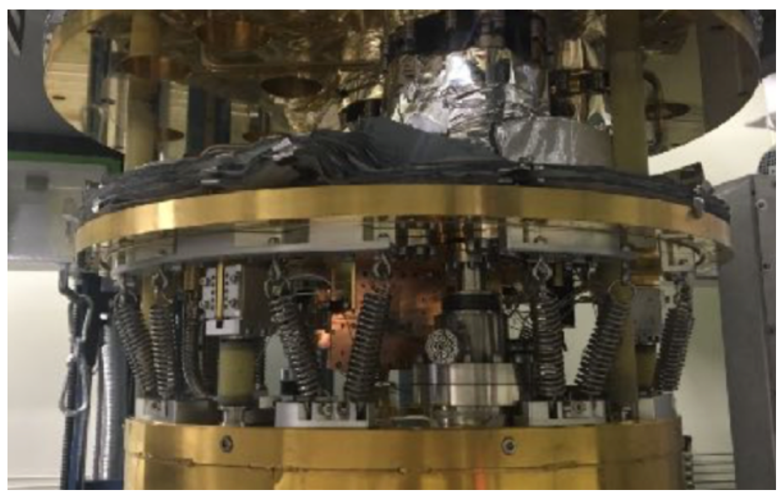








Eddy Current Damper
(1 out of 3 in total)

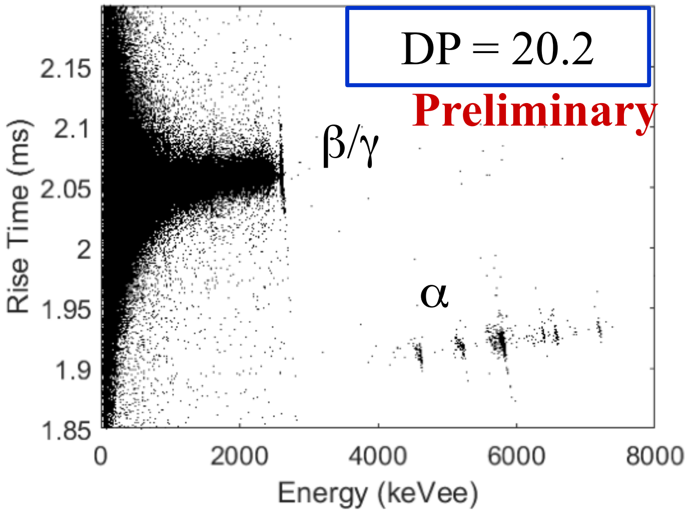


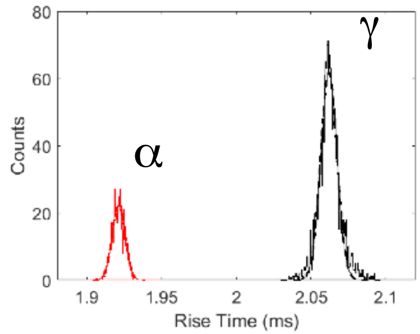
Installation completed, now back to measurement

Latest status for AMoRE Pilot

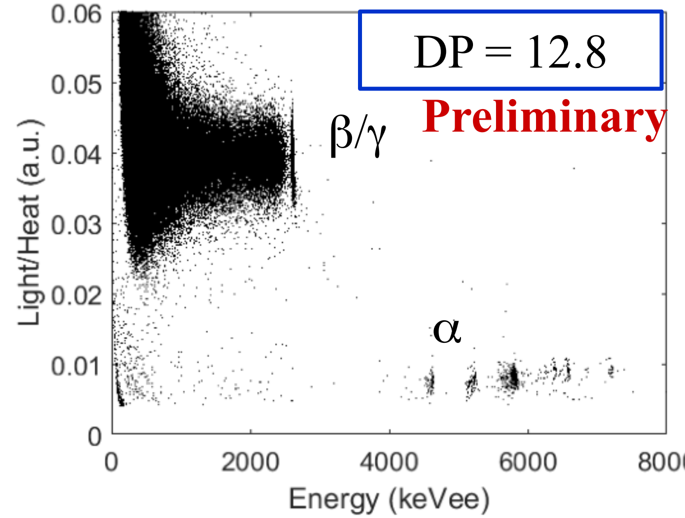
- All detector modules work currently (6 heat + 6 light).
- Energy resolution: 9 – 15 keV FWHM for 6 crystals
- Separation power
  - Pulse shape (Rise-time or Mean-time) in heat channel: 6 – 22 σ
  - Light/Heat ratio: 10 – 18 σ
- A new DAQ system is installed for 18bit 100 kS/s continuous data stream of 12 channels.
- Muon veto system has been up with 5 cm thick plastic scintillators.
- A long measurement has begun since Aug. 2017.

Particle discrimination (preliminary)





$$DP = \frac{x_{\beta/\gamma} - x_{\alpha}}{\sqrt{\sigma^2_{\beta/\gamma} + \sigma^2_{\alpha}}}$$

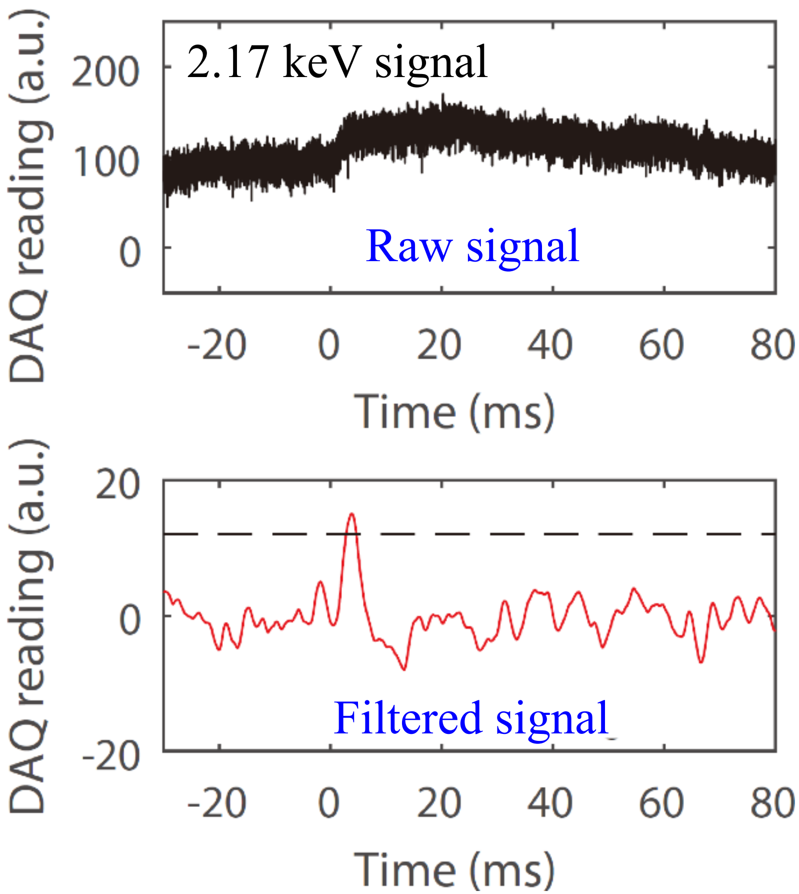


β/γ and α particles can be distinguished using pulse shape discrimination via pulse rise time or mean time

The use of the light/heat ratio for particle discrimination also shows excellent results.

Crystals	DP Light/Heat	DP Mean Time	DP Rise Time
SB28 (0.20 kg)	12.8	22.0	20.2
S35 (0.25 kg)	18.8	11.3	9.4
SS68 (0.35 kg)	16.2	6.0	5.7
SE01 (0.35 kg)	15.7	21.8	19.3
SB29 (0.40 kg)	14.1	8.6	9.8
SE02 (0.34 kg)	9.6	20.5	18.1

Low energy signals of AMoRE-Pilot



- ~2 keV threshold
- SQUID and DAQ are tuned for 3MeV (0νββ) with 12 MeV (alpha tagging) dynamic range.
- AMoRE can be a DM detector.

Upgrade plan to AMoRE-I

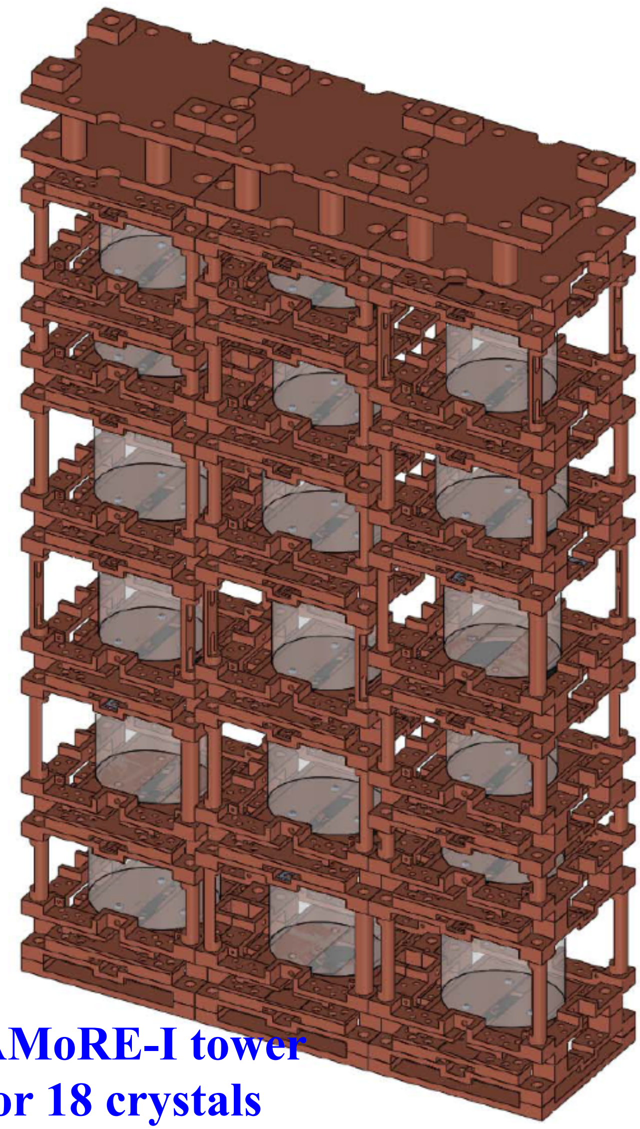
AMoRE-I:

Cryostat: The same cryostat will be used.

Crystals:
- 13 CMOs have been made.
- 1-5 CMOs and XMOs are to be prepared.
- Total: 14-18 crystals
- Total mass: 5-6 kg

Num. of channels:
- 28 ~ 36 MMC+SQUID channels

Schedule:
- Plan to begin mid. 2018
- Run for 2+ years.



AMoRE-I tower for 18 crystals

Schedule of the AMoRE project

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

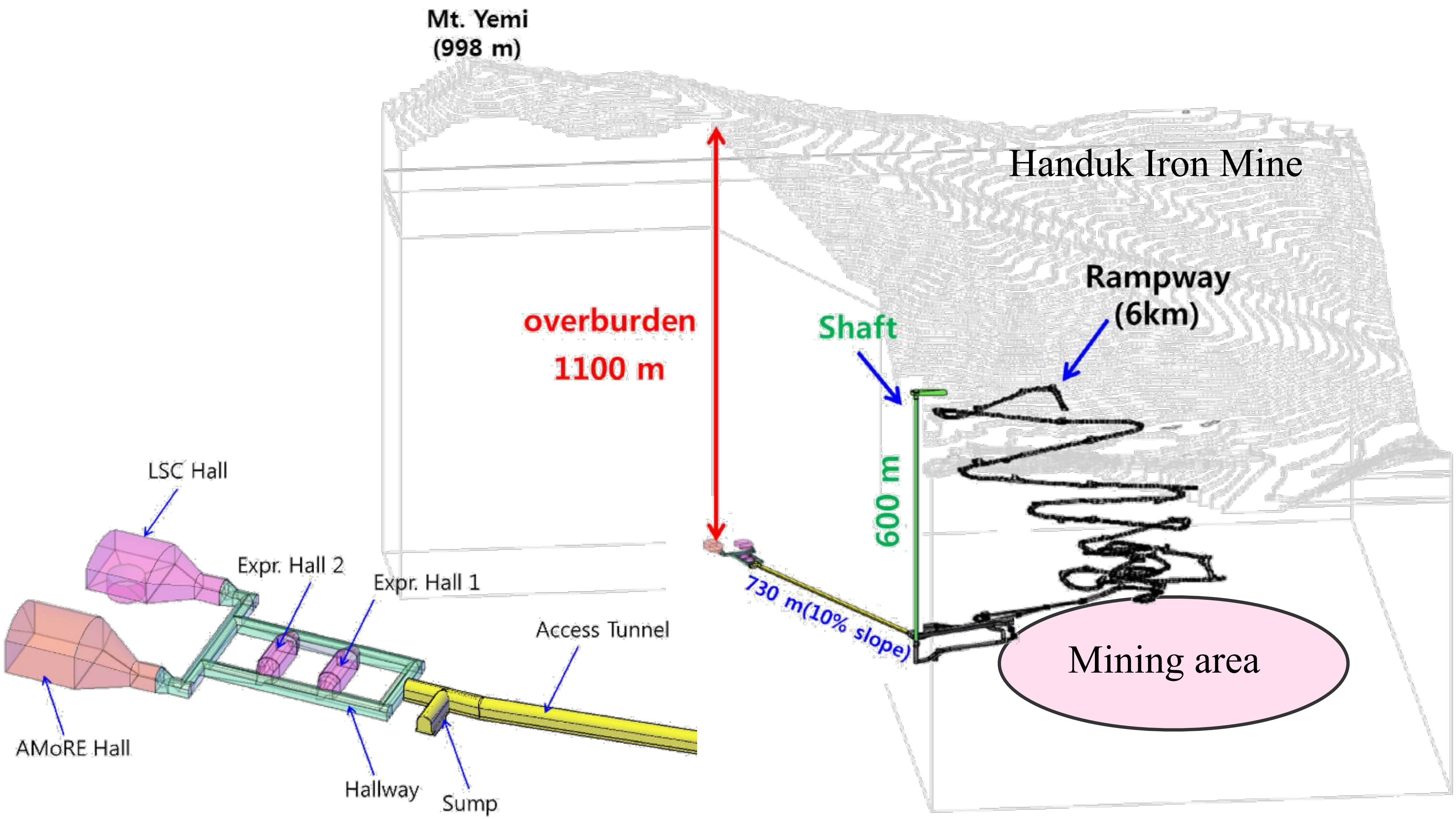
  For Phase II: $X^{100}MoO_4$ (X: Li, Na, ^{40}Ca, Zn or Pb)
- Zero background condition in ROI
- Shield: Lead (Pilot, I), Water (II)
- Location: Y2L (Pilot, I) and a new deeper place (New lab at Handuk)

	Pilot	Phase I	Phase II
Mass	1.9 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_{ee}) (meV)	380-720	120-230	17-32
Location	Y2L	Y2L	Handuk
Schedule	2017	2018-2019	2020-2022

New lab at Handuk mine

- Lab space of Y2L is limited and new excavation is not allowed.
- A new underground lab will be constructed in Handuk Iron Mine.
- Overburend:1100 m
- Access: 600m vertical elevator or 6km ramp-way + 730m tunnel
- The construction budget has been approved for elevator, tunnel, cavity and necessary utilities by 2019.

New Underground Lab in Korea



- **Total lab space : 2000 m²**

Stay tuned to us!