Status of the AMoRE experiment searching for neutrinoless double beta decay of ^{100}Mo

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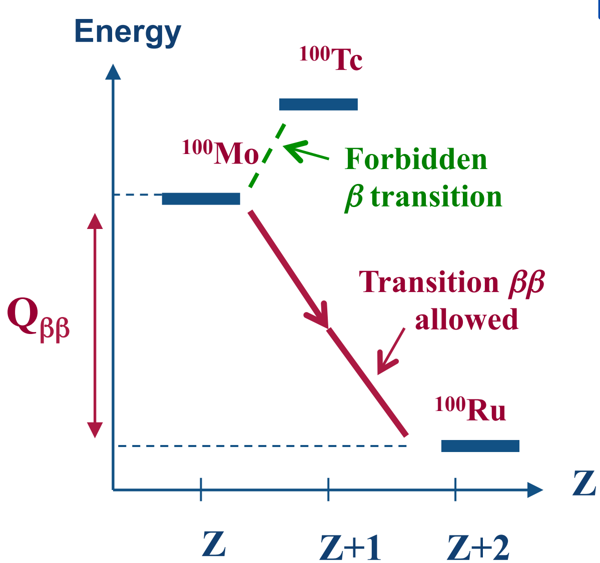
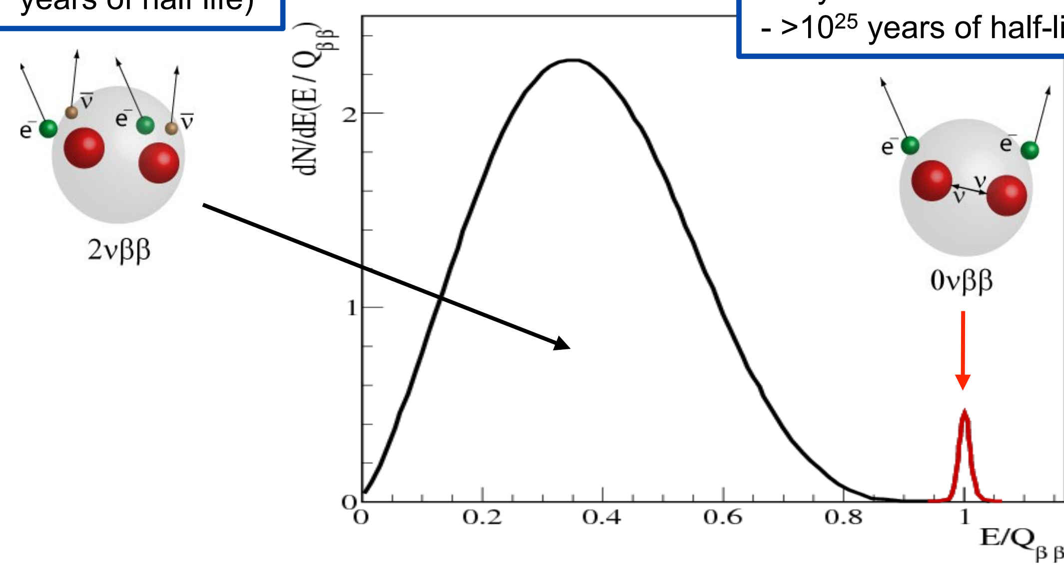
Neutrinoless double beta decay of ^{100}Mo

The goal of the AMoRE (**A**dvanced **Mo**-based **R**are process **E**xperiment) project is to search for neutrinoless double beta decay ($0\upsilon\beta\beta$) of ^{100}Mo using Mo-based scintillating crystals and low-temperature sensors.



$2\nu\ \beta\beta$ decay
- 2^{nd} order beta decay
- Rare nuclear decay
- ($>10^{18}$ years of half life)

$0\nu\ \beta\beta$ decay
- Massive neutrino
- Majorana particle
- Beyond the SM model
- $>10^{25}$ years of half-life



$(Z, A) \rightarrow (Z+2, A) + 2e^- + 2\text{anti-}\nu_e$ ($\Delta L = 0$, conserved)
$(Z, A) \rightarrow (Z+2, A) + 2e^-$ ($\Delta L = 2$, violated)

AMoRE Collaboration

Advanced Mo based Rare process Experiment

8 countries, 18 Institutes, ~90 collaborators

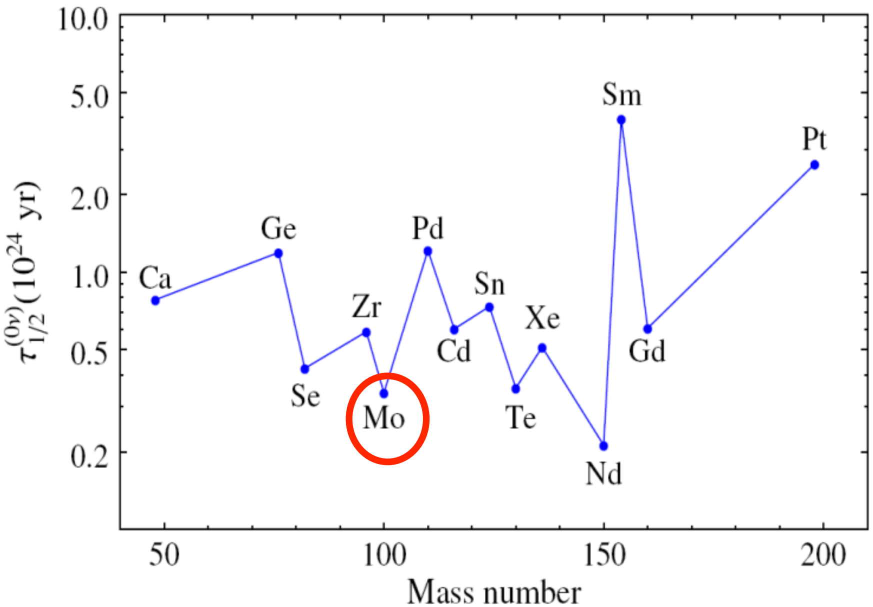
Choice of ^{100}Mo

Candidates	$Q_{\beta\beta}$(MeV)	N.A. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

Phys. Rev. C 53, 695 (1996)

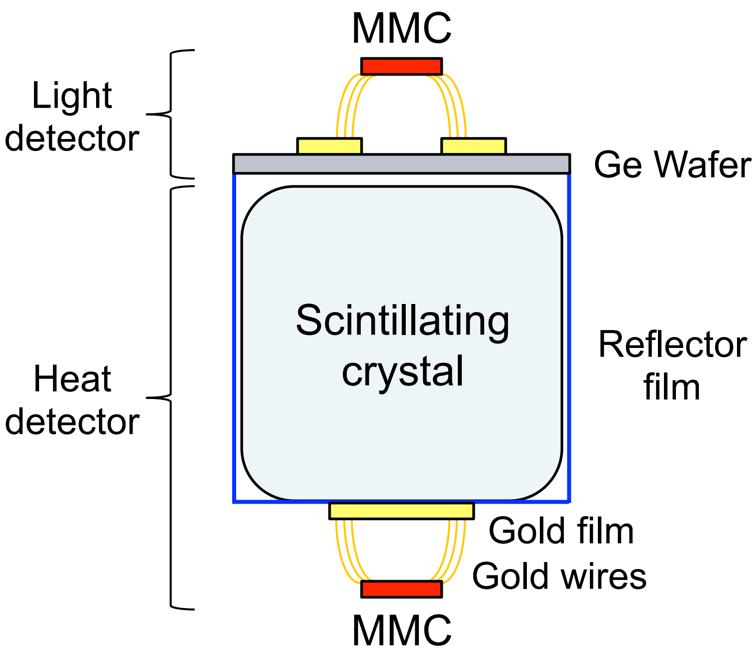
- High Q-value (3.034 MeV)
- High natural abundance (9.6 %)
- Relatively short theoretically predicted half-life (0νββ)

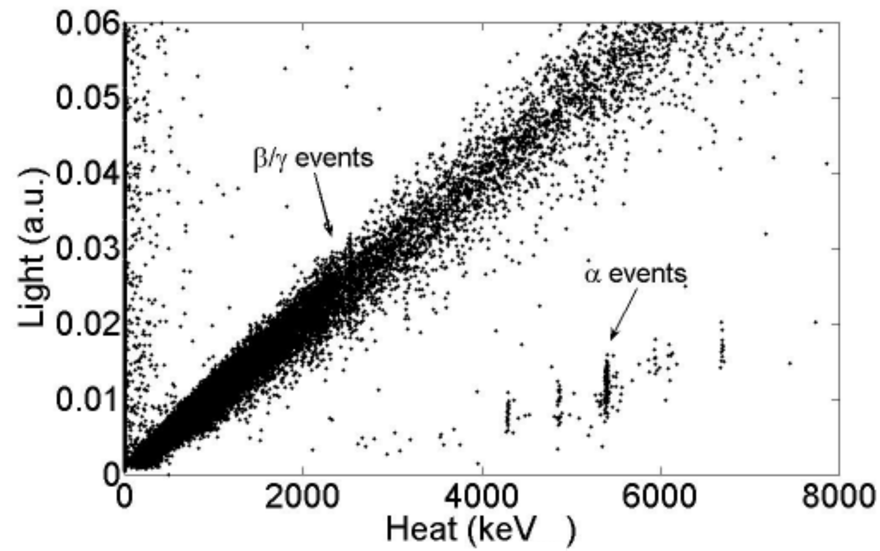
Phys. Rev. Lett. 109, 042501 (2012)



Detector concept

$^{40}Ca^{100}MoO_4$ (enriched ^{100}Mo, depleted ^{48}Ca) or other Mo-based scintillating crystal used as source and detector
+ Metallic Magnetic Calorimeter (MMC, low temperature sensor)





"Source = detector" approach
- ➢ High detection efficiency
- ➢ High energy resolution

MMCs
- ➢ Fast response, high energy resolution, wide operating temperatures

Simultaneous measurement of heat and light
- ➢ Particle discrimination for rejection of α-induced background

AMoRE sensitivity to $0\nu\beta\beta$

Sizeable background case

$$T_{1/2}^{0\nu}(\exp) = (\ln 2) N_A \frac{a}{A} \varepsilon \sqrt{\frac{Mt}{b\Delta E}}$$

- Isotopic Abundance (a)
- Detection Efficiency (ε)
- Detector Mass (M)
- Measurement time (t)
- Energy Resolution (ΔE)
- Background rate (b)
- Atomic mass (A)
- Sensitivity to half-life of 0νββ ($T_{1/2}^{0\nu}$)

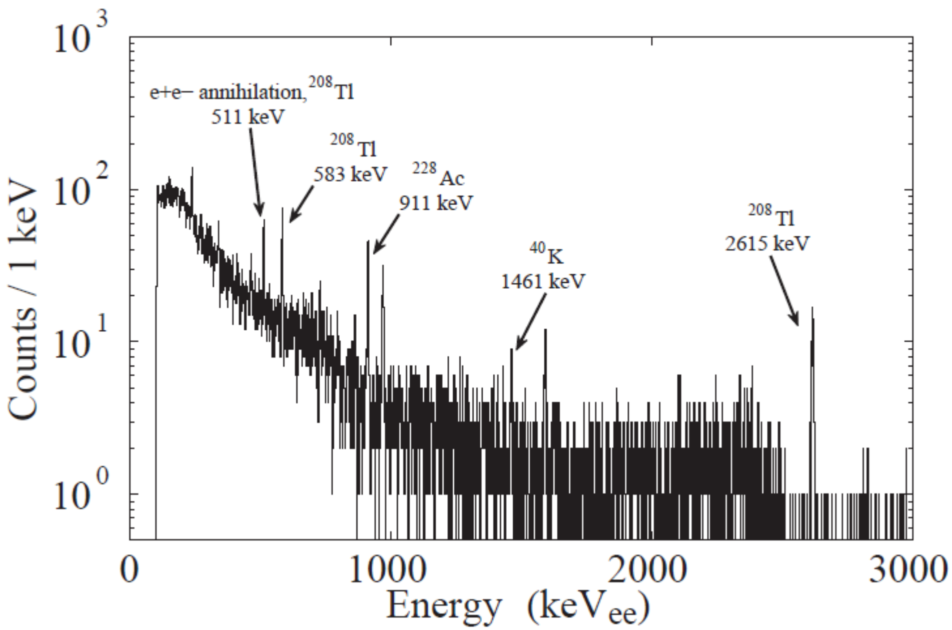
"Zero" background case

$$T_{1/2}^{0\nu}(\exp) = (\ln 2) N_A \frac{a}{A} \varepsilon M t$$

AMoRE project towards "zero"-background conditions:

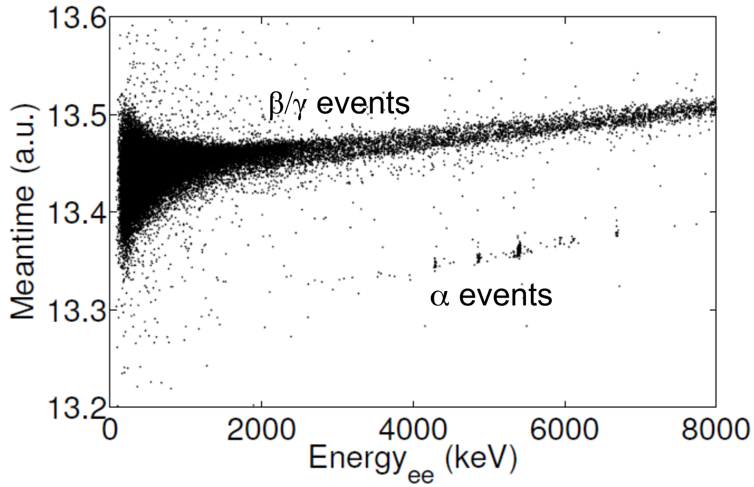
- Reduction of the background
  - α-background rejection with particle discrimination (heat and light measurement)
  - less than 0.001% of depleted ^{48}Ca (natural abundance: 0.157%, $Q_{\beta\beta}$=4.271 MeV)
  - low levels of internal and external backgrounds
- High energy resolution with MMCs
- High detection efficiency with "source = detector" approach
- Detector mass
  - enrichment of ^{100}Mo above 95%

Above-ground measurements (with a wet dilution refrigerator)

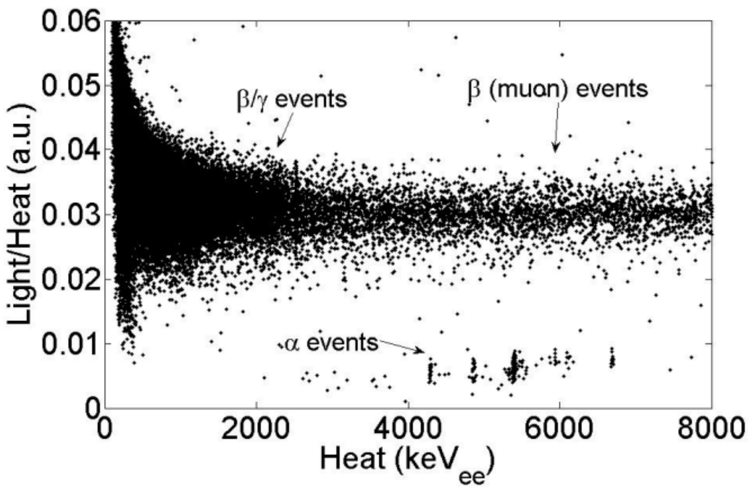


- Energy spectrum obtained with a ^{232}Th source at 10 mK
- FWHM energy resolution: 8.7 keV @ 2.6 MeV (Region of interest: 3.034 MeV)

Pulse shape discrimination from heat signals



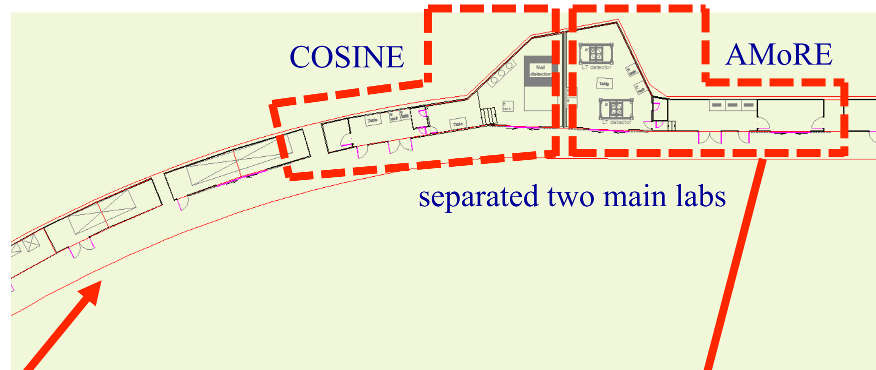
Particle discrimination by light-heat ratio

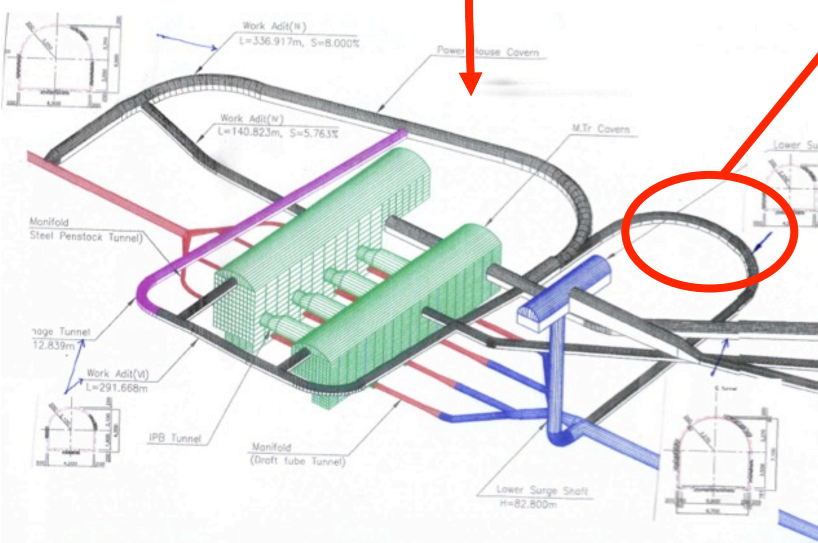


Yangyang underground laboratory (Y2L, South Korea)

Yangyang pumped storage Power Plant
Minimum vertical depth : 700 m
Access to the lab by car : around 2 km

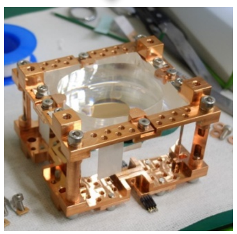
Experiments
- COSINE : dark matter search experiment
- AMoRE-Pilot (followed by AMoRE-I)

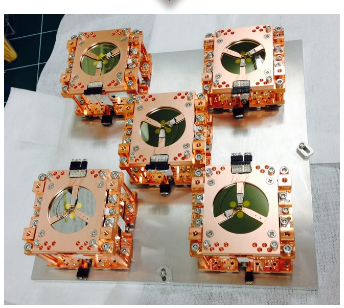




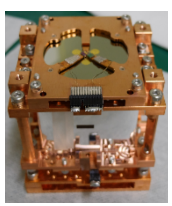
AMoRE-Pilot detector configuration

Six $^{40}Ca^{100}MoO_4$ crystals (from 0.2kg to 0.4kg each, for a total of ~1.8kg)
Each crystal module has a heat detector and a light detector



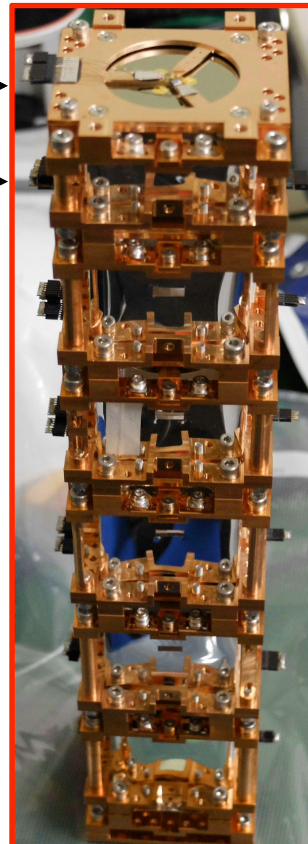


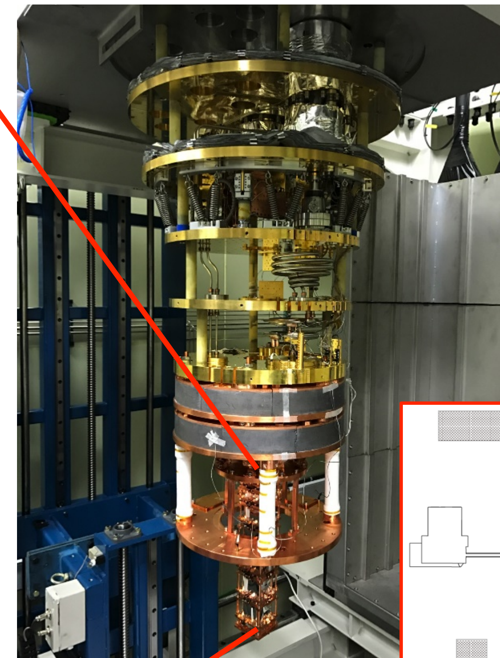
6th crystal added in Run-5

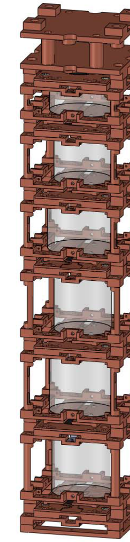


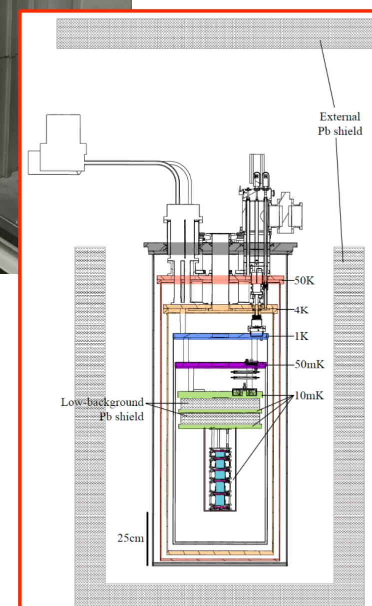
Light detector

Heat detector





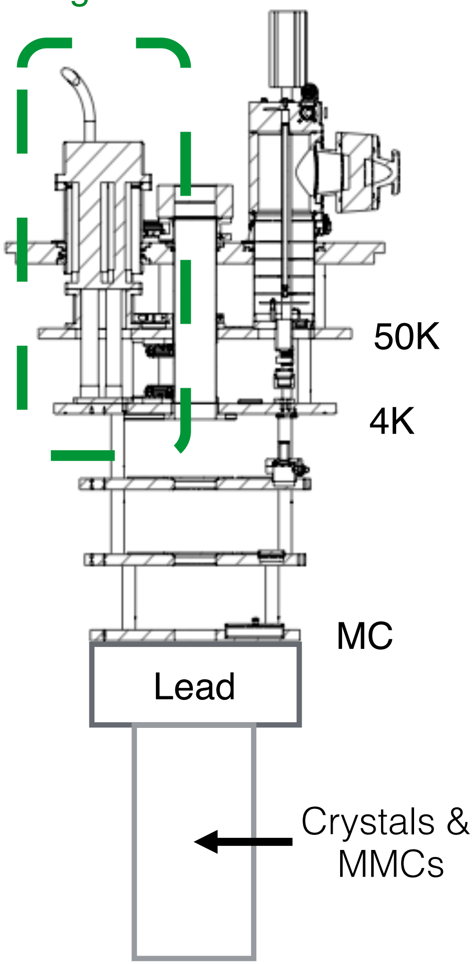




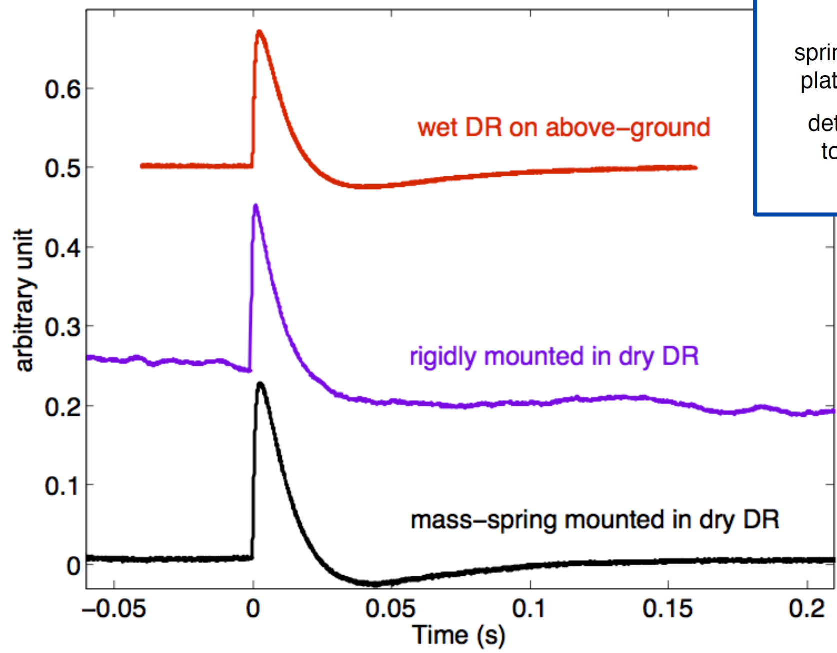
Operating temperatures as low as 8 mK reached using a Cryogen Free Dilution Refrigerator (CFDR)

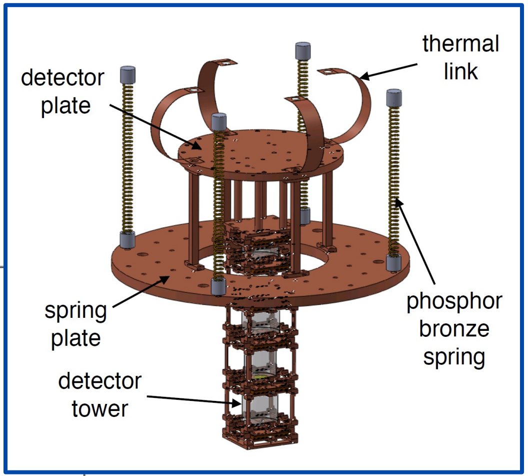
Vibration from the pulse tube refrigerator

The pulse tube refrigerator (PTR) of the cryostat generates mechanical vibration which turns into heat noise and disturbs the baseline



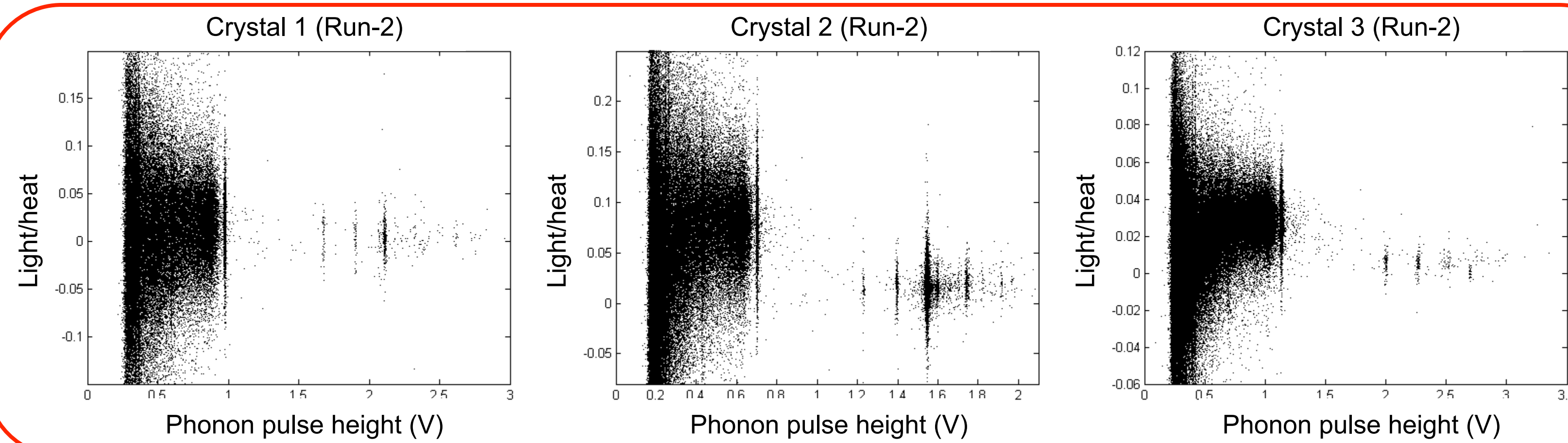
Mass spring (MS) damper was installed in Run-4 to reduce the vibration noise



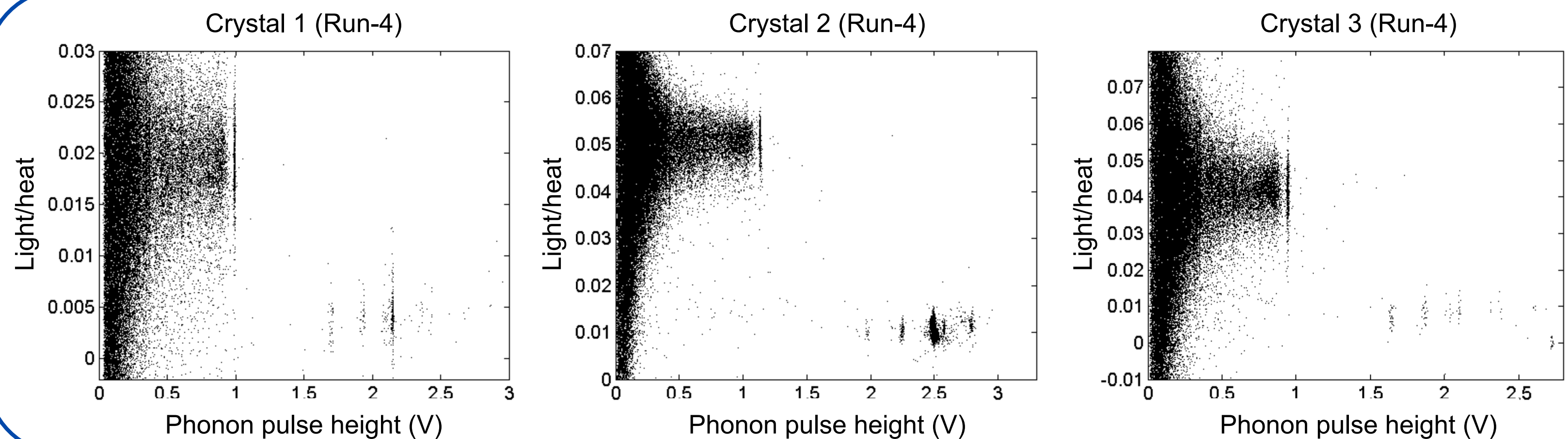


Comparison of light/heat ratio between Run-2 and Run-4

Run-2



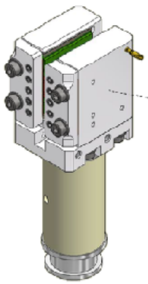
Run-4

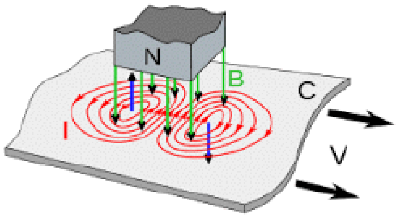


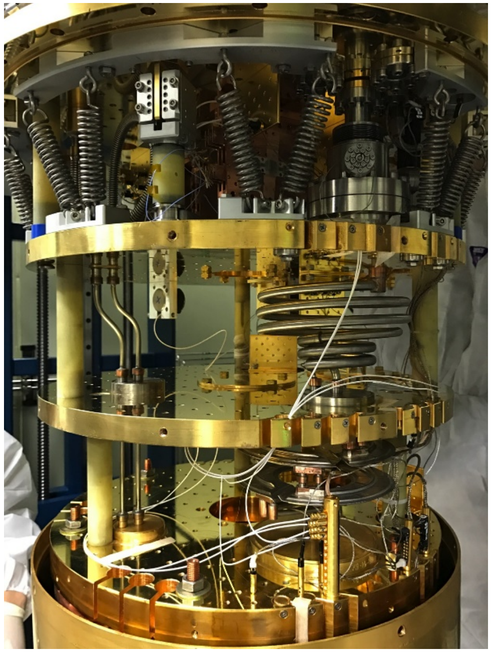
Large improvement of the light/heat ratio thanks to the reduction of vibration noise in the photon channels

Setup upgrade for Run-5

Spring suspended still (SSS) with Eddy current dampers
Designed by Leiden Spin Imaging (Netherlands)



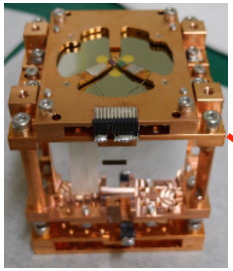


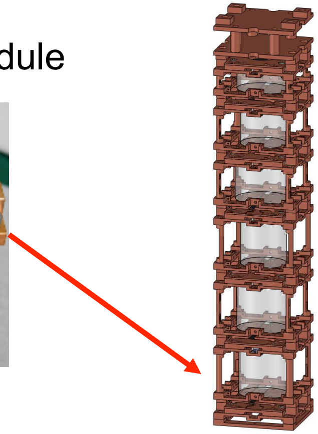


4K

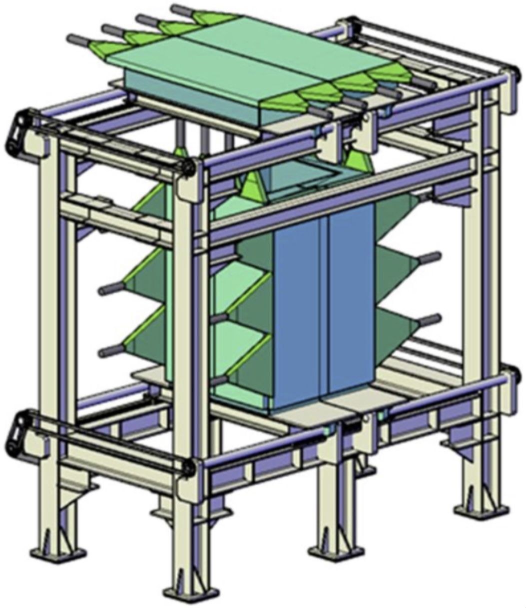
Still

6th detector module





Muon veto system

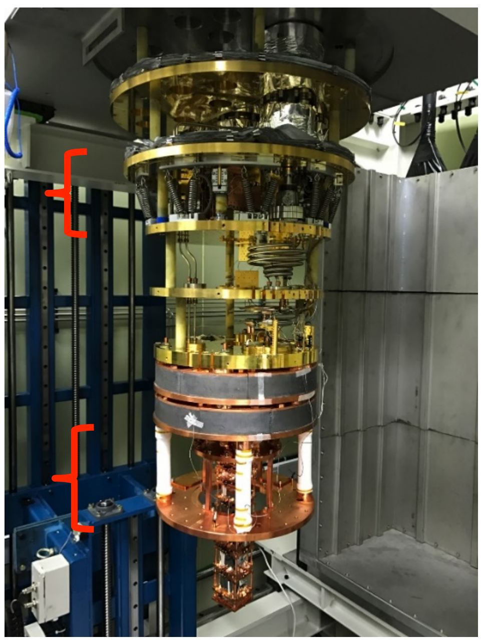


Current status of AMoRE-Pilot

- Four Pilot runs have been completed from summer 2015 to late 2016 with five $^{40}Ca^{100}MoO_4$ crystals
- Operating temperatures 10 mK – 30 mK
- Currently, Run-5 is running with 6 crystals (total mass ~1.8 kg) and two vibration damping systems

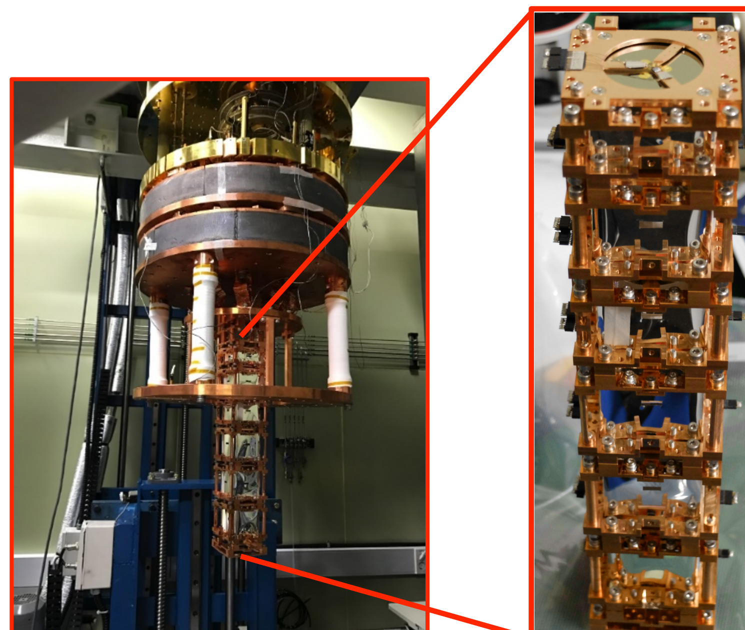
Two vibration dampers were installed

Spring Suspended Still (SSS) damper [Eddy currents]

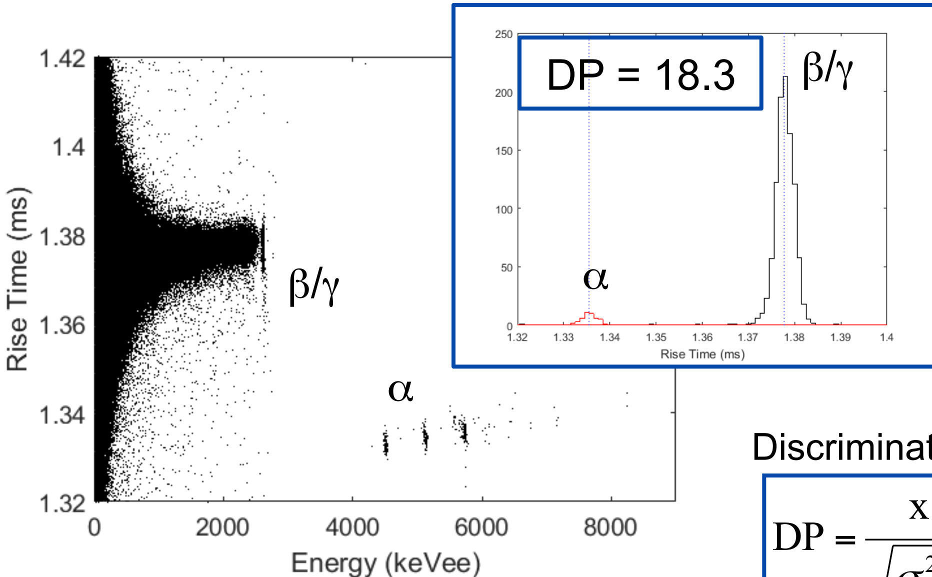


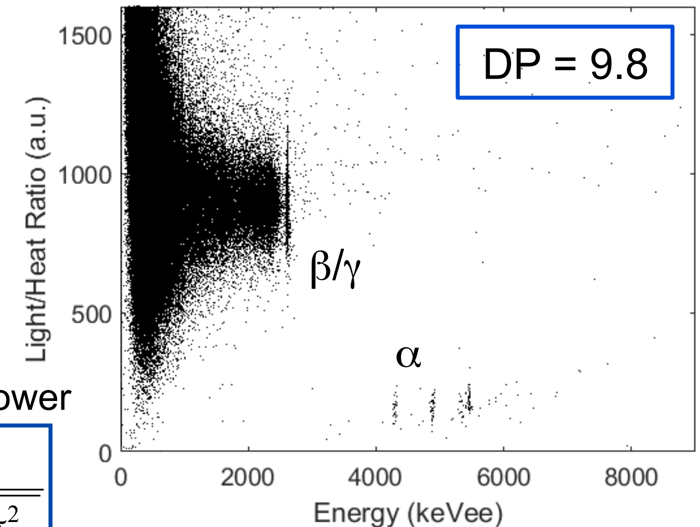
Mass Spring (MS) damper

12 detector channels
(6 heat detectors + 6 light detectors)



Detector performance in Run-5 (preliminary)



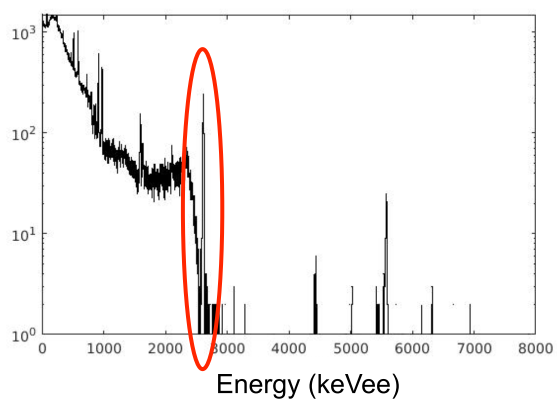


Discrimination Power

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

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

β/γ and α particles can also be distinguished using the light/heat ratio



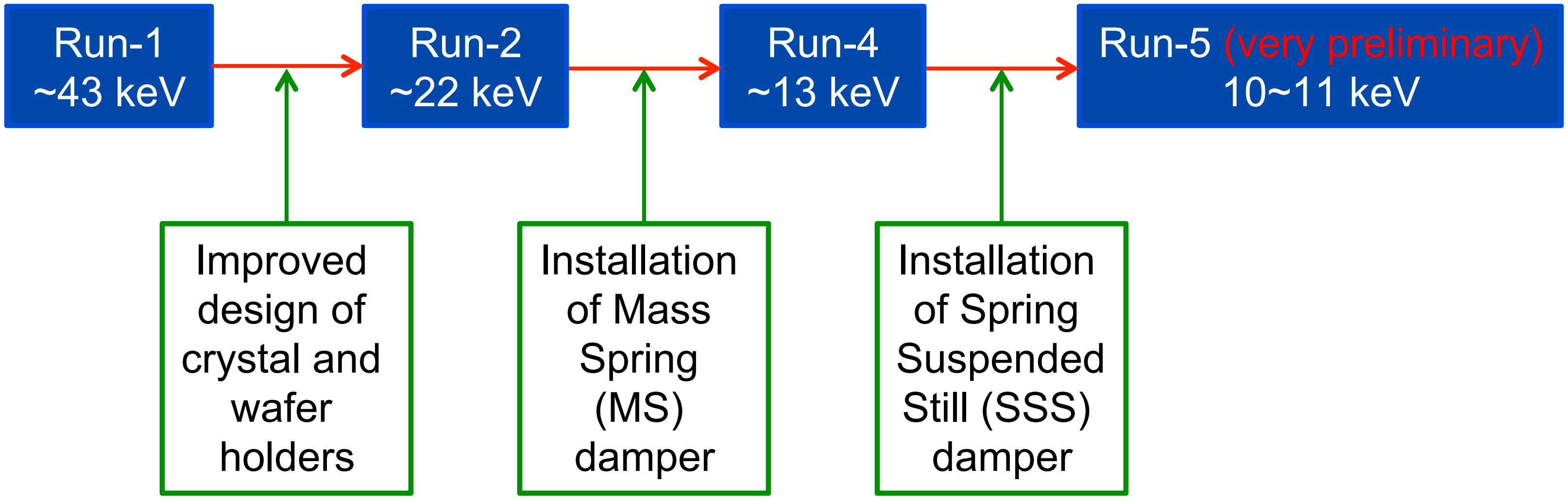
FWHM Energy resolution at 2.615 MeV :
10~11 keV

no muon veto applied

Energy resolution throughout the Pilot runs

The energy resolutions have been significantly improved throughout the different runs

FWHM energy resolution @ 2.615 MeV
averaged over the detector modules

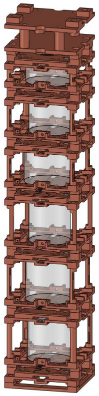


Run-5 : Baseline energy resolutions (FWHM @ 0 MeV) are now about 3~5 keV

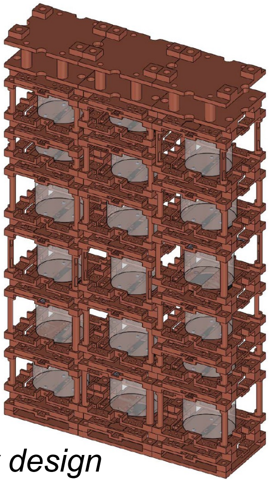
AMoRE phases and schedule

- AMoRE-I at Y2L (same cryostat as Pilot), with $CaMoO_4$ crystals + a few others (ZMO, LMO, …)
- AMoRE-II at a new, larger laboratory (ARF), $X^{100}MoO_4$ crystals (X = Li, Na, ^{40}Ca, Zn or other)

AMoRE-Pilot
~1.8 kg
2016-2017

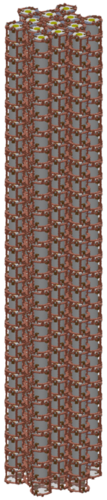


AMoRE-I
5~6 kg
2018~



Preliminary design

AMoRE-II
200 kg
2020~



Preliminary design

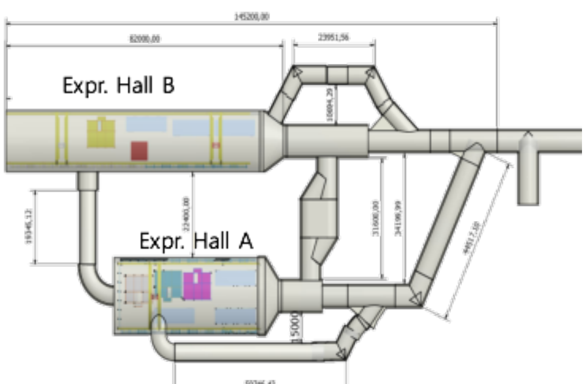
	Pilot	AMoRE-I	AMoRE-II
Mass	1.8 kg	~5 kg	~200 kg
Channels	12	36	1000
Background (counts/keV/kg/year)	0.01	0.001	0.0001
Sensitivity($T_{1/2}$) (year)	$\sim 10^{24}$	$\sim 10^{25}$	$\sim 5\times 10^{26}$
Sensitivity(m_{ee}) (meV)	380-720	120-230	17-32
Location	Y2L	Y2L	ARF (new lab)
Schedule	2016-2017	2018-2019	2020-2022

Site for Astroparticle Research Facility (ARF)

Handeok Iron Mine, Jeongseon

- ARF will be located at the Handeok mine
- Contract signed at the end of 2016
- Construction will start in late 2017

Preliminary design of Underground Laboratory



Plan for two experimental halls (total area ~2000 m^2) under 1100 m below surface

Overview

- AMoRE searches for neutrinoless double beta decay ($0\upsilon\beta\beta$) of ^{100}Mo using Mo-based scintillating crystals and MMC sensors
- Throughout the different AMoRE-Pilot runs, several setup upgrades allowed us to reduce the vibration noise, which improved the energy resolution and particle discrimination powers (PSD, light/heat)
- Run-5 is currently running with 6 crystals (total mass ~1.8 kg), two vibration damping systems, and a muon veto system
- After some more tests, data taking will be carried out for several months this year

Thank you