Search for Invisible Particles at GRANDE

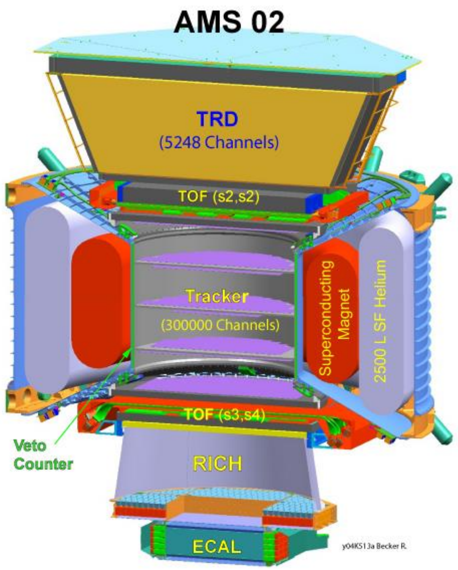
On behalf of the KAPAE & GRANDE Collaboration

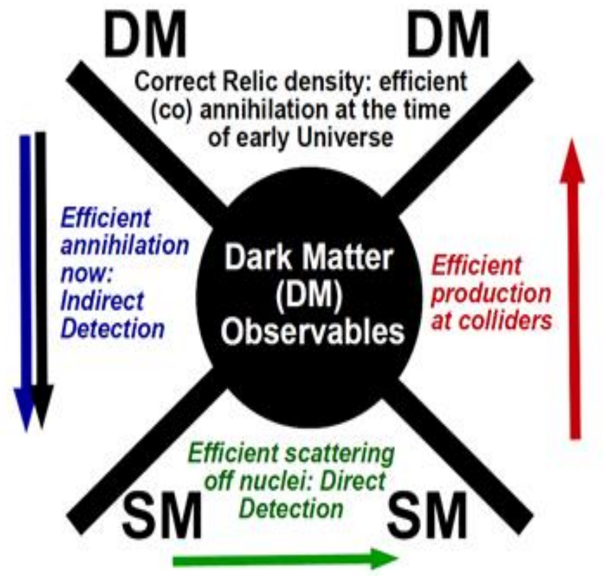
Speaker: Hong Joo Kim

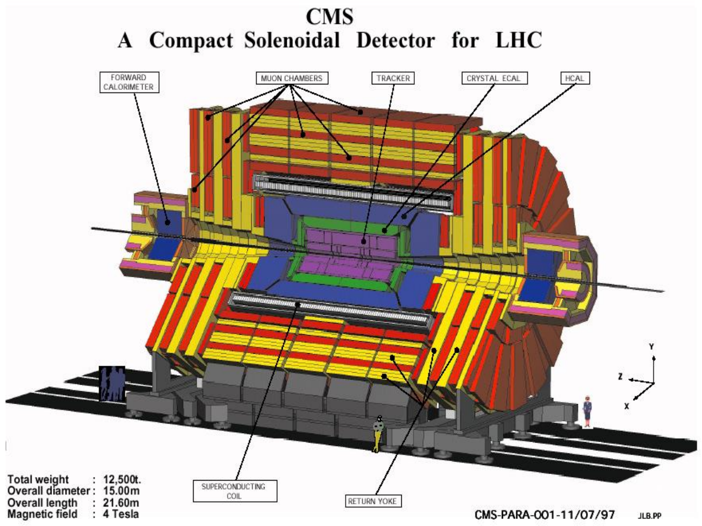
Center for High Energy Physics (CHEP)

Department of Physics, Kyungpook National University

Why universe is dark?







Dark Sector Search

- WIMP
- SUSY
- Axion
- Dark photon

……..

?????

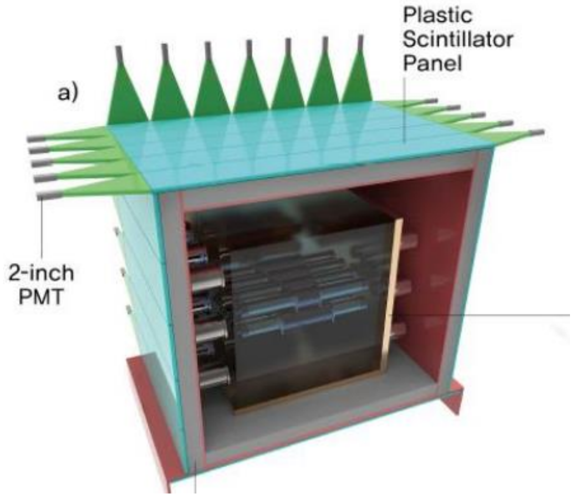
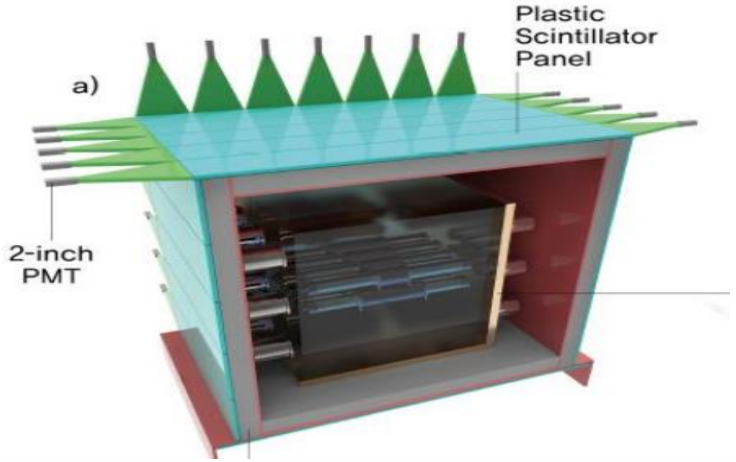
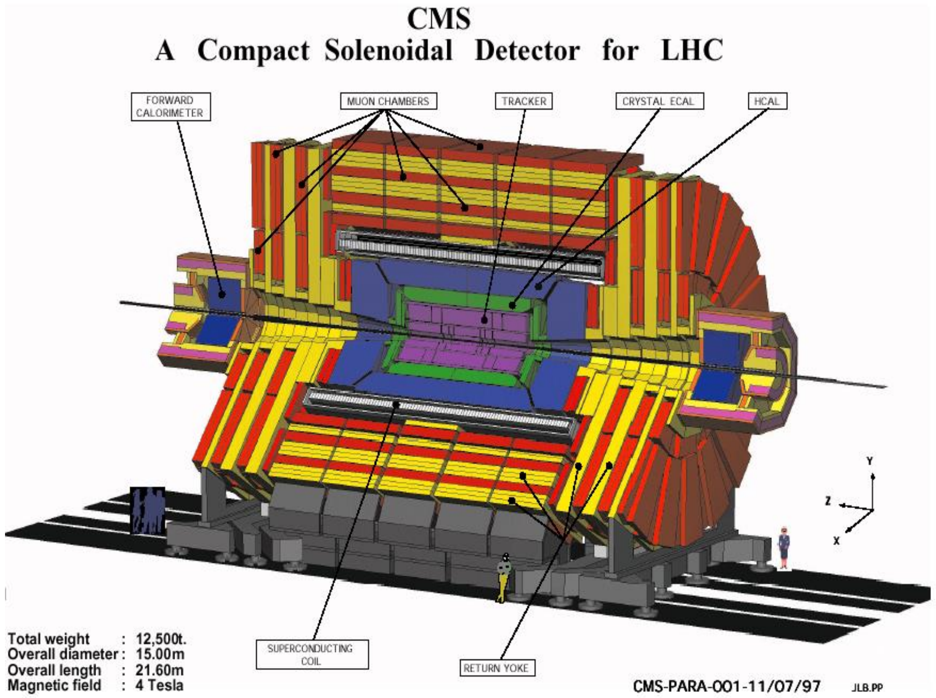
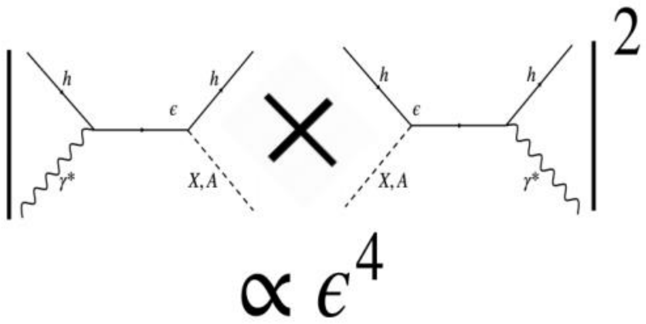


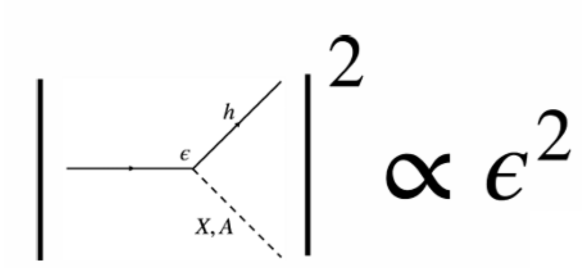
Table top scale for dark sector search?





Radioactive sources for Dark Sector Search : E<1 MeV





Appearance Exp.
Accelerator, Reactor
~10^{24} POT
→ ε ~10^{-6}

Disappearance Exp.
Radioactive source
~$10^{12\text{-}14}$ Decay
→ ε ~$10^{-6\sim7}$

Advantage

- ❑ Decay process: Coupling is proportional to ε^2 not ε^4 (Accelerator, Reactor)
- ❑ Tabletop-scale experiment (much lower cost)
- ❑ Source-detector technique (radioactive doping in fast scintillator)
- ❑ Time-delayed coincidence method to eliminate backgrounds in the case of isomeric states
- ❑ Underground experiment with Cu, Pb shielding

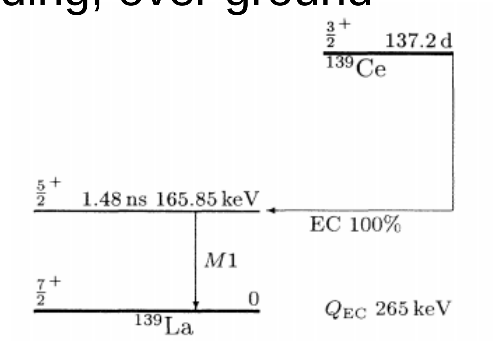
Limitation

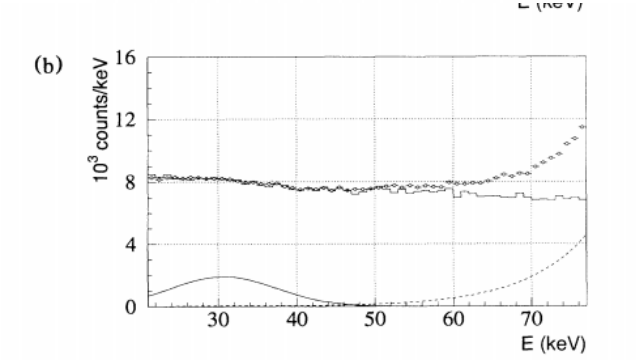
- ❑ Low mass only (typically =< 1 MeV due to detector costs)
- ❑ Activity limitations

Tabletop experiments with radioactive source?

- Background is too high

No shielding, over ground





$$\Gamma_a/\Gamma_\gamma < 1.21 \times 10^{-6} \text{ at the } 95\%$$

Mass of hadronic axion > 26.7 keV by 95%CL

M.Minowa et al, Phys. Rev. Lett. 71, 4120

- Background is the serious issue
- Detector is too thin for ~ MeV gamma

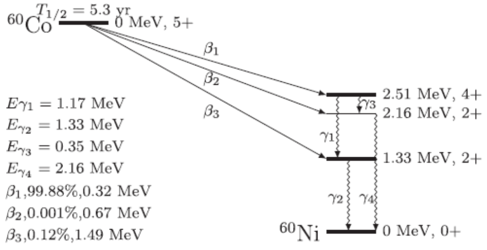
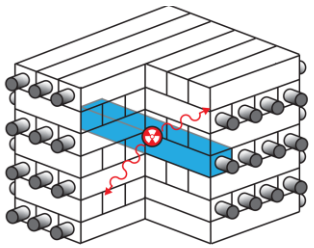
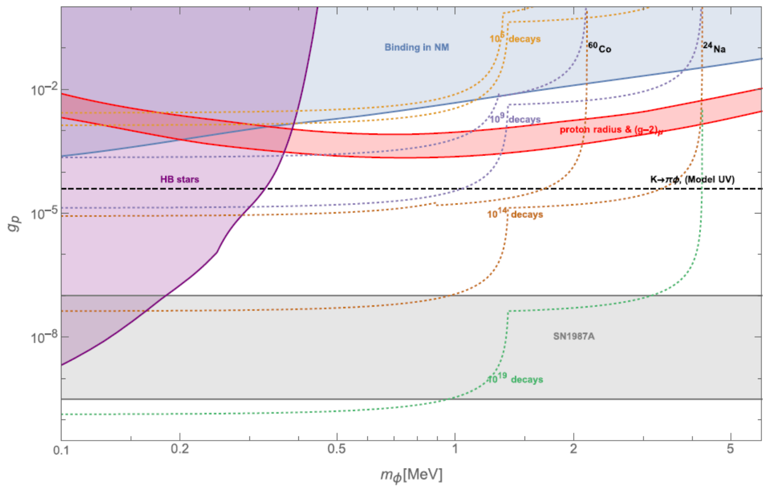


FIG. 2. Decay scheme of ^{60}Co.



INVISIBLE DECAY MODES IN NUCLEAR GAMMA CASCADES PHYS. REV. D **99,** 035025 (2019)



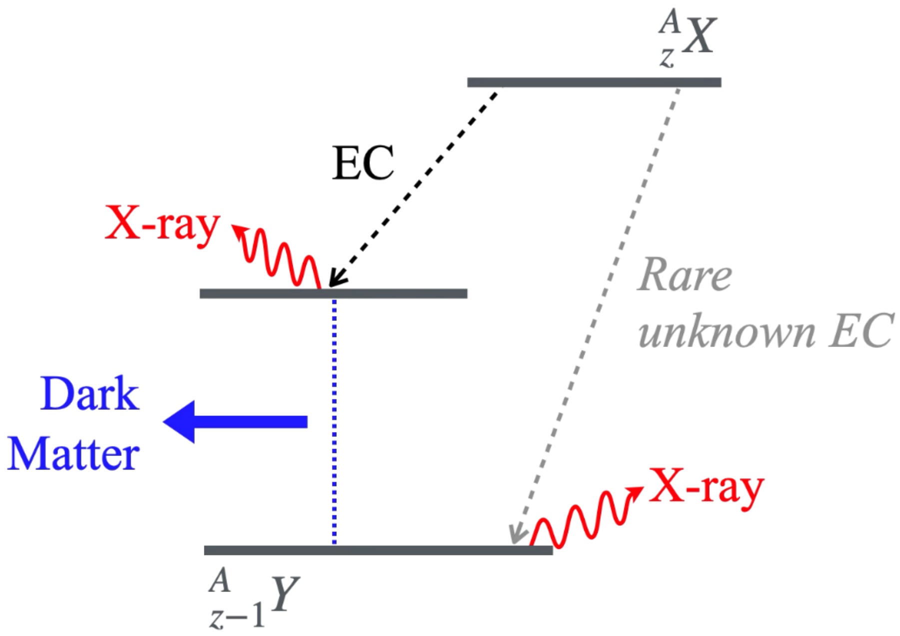
When experimentalist meets theorist

PHYSICAL REVIEW LETTERS **133,** 232501 (2024)

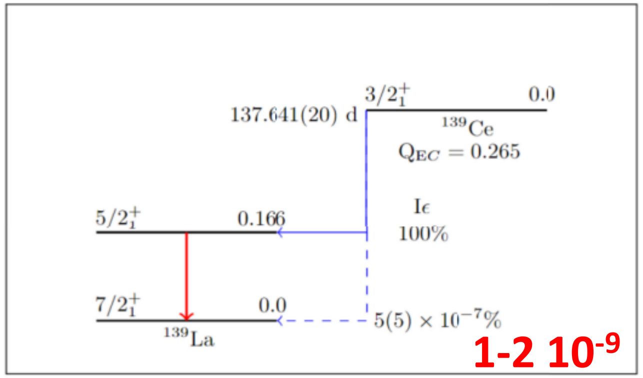
Constraints for Rare Electron-Capture Decays Mimicking Detection of Dark-Matter Particles in Nuclear Transitions

Aagrah Agnihotri[*] and Jouni Suhonen[†]
University of Jyväskylä, Department of Physics, P.O. Box 35, FI-40014 Jyväskylä, Finland

Hong Joo Kim[‡]
Department of Physics, Kyungpook National University, Daegu 41566, Republic of Korea



Major possibilities for dark matter particle searches through EC transitions



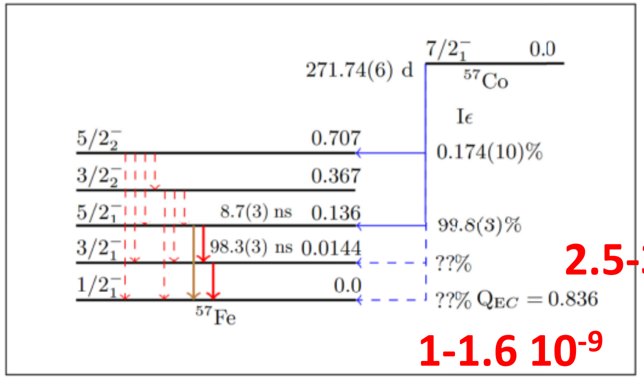
#1

M1 $5/2^+_1 \rightarrow 7/2^+_1$: 165.86 keV

→ K_α X-ray: ~33 keV

Easiest case

Search for 33 keV X-ray only



2.5-3.3 10^{-8}

#1

M1 $5/2^-_1 \rightarrow 3/2^-_1$: 122.06 keV

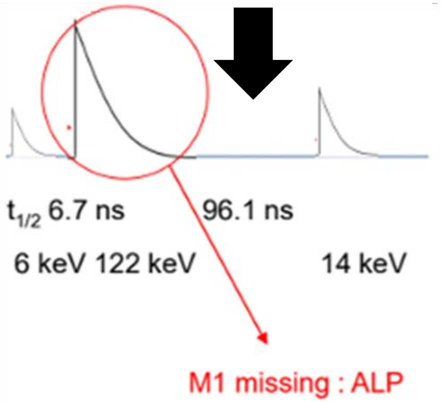
→ M1 $3/2^-_1 \rightarrow 1/2^-_1$: 14.4 keV

→ K X-ray: ~6 keV

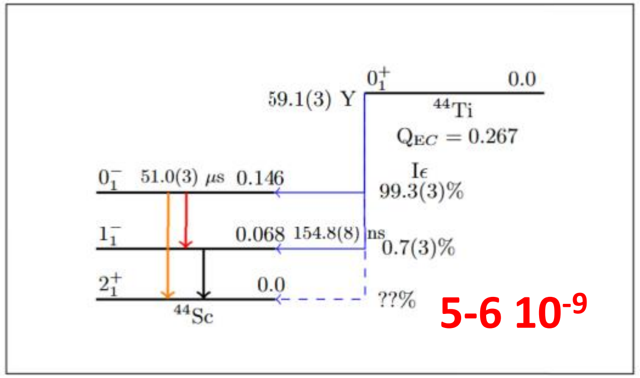
#2

E2 $5/2^-_1 \rightarrow 1/2^-_1$: 136.47 keV

→ K X-ray: ~6 keV



CeBr$_3$:T1^{44}
CeBr$_3$:Co^{57}
CeBr$_3$:Ce^{139}



#1

M1 $0^-_1 \rightarrow 1^-_1$: 78.33 keV

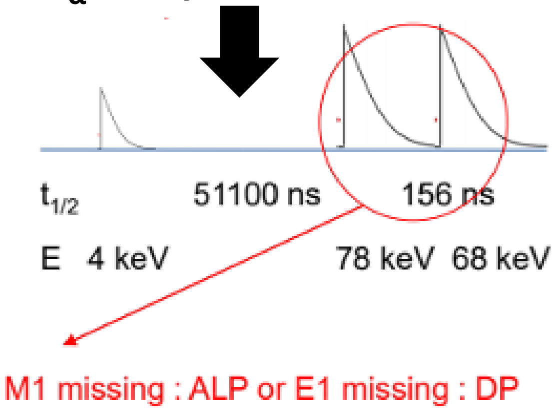
→ E1 $1^-_1 \rightarrow 2^+_1$: 67.87 keV

→ K_α X-ray: 4 keV

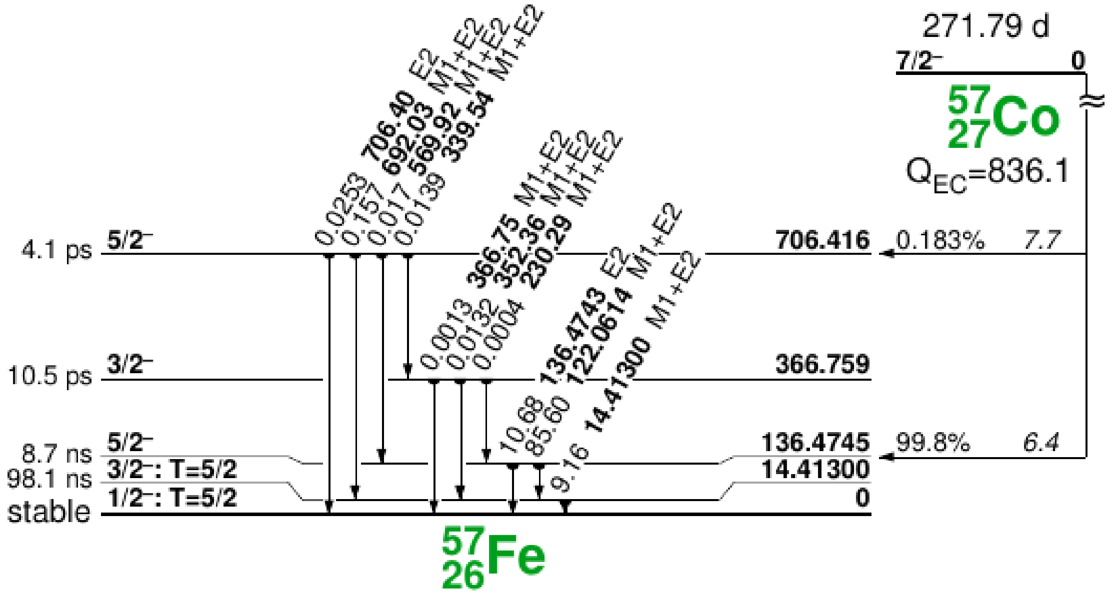
#2

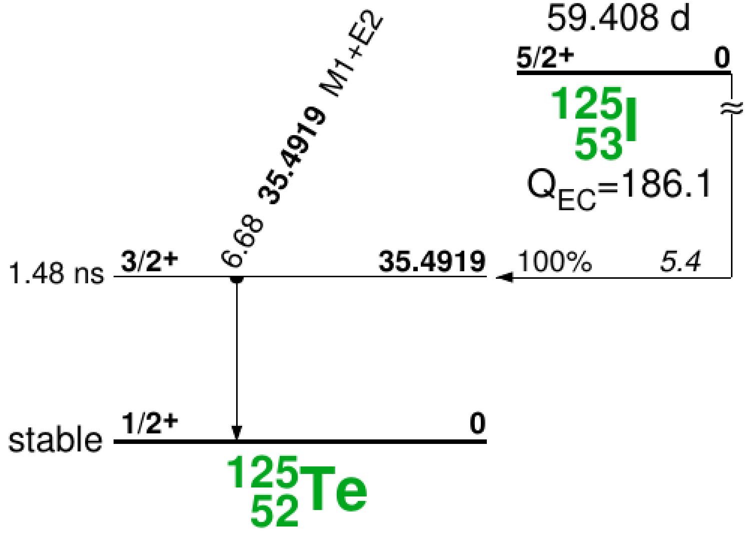
M2 $0^-_1 \rightarrow 2^+_1$: 146.212 keV

→ K_α X-ray: 4 keV



Limitation of Co-57 and new candidate





Even if branching ratio is 0.15%, 692 keV gamma will escape if BGO thickness is not enough and it create unwanted background signals.

It will have a 35.5 keV gamma + 30 keV X-ray that 30 keV X-ray only will be ALP or anapole signal.
Theoretical calculation of EC to ground state is necessary.

GRANDE

(Global Rare Anomalous Nuclear Decay Experiment)

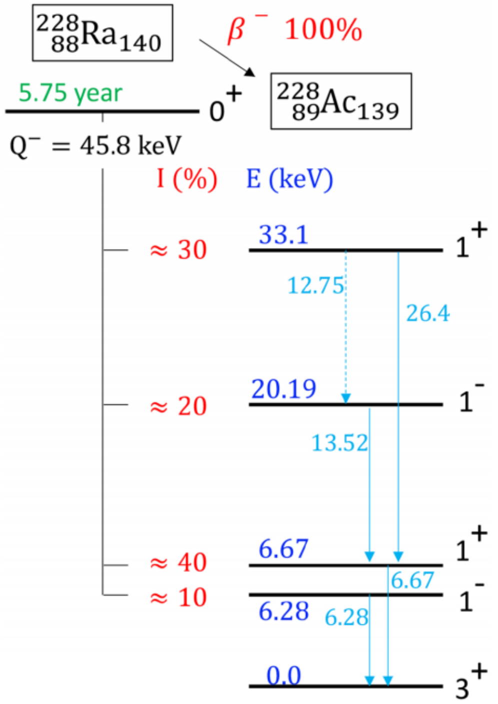
GRANDE Collaboration (5 countries, 9 institution, 17 members)

- H.J. Kim, N.T. Luan, D.W. Jeong, J.Y. Cho, J.Y. Lee, L. Truc (Kyungpook National University, KOREA)
- M.H. Lee (Center for Underground Physics, IBS, KOREA)
- J.H. So (Yemi operation center, IBS, KOREA)
- J. Suhonen, A. Agnihotri (University of Jyväskylä, Finland)
- J. Kaewkhao (Nakhon Pathom Rajabhat University, Thailand)
- S. Kothan (Chiangmai University, Thailand)
- M. Haroon, S. Khan (Kohat University of Science and Technology, Pakistan)
- F. Qayyum, M. A. Program, G. Rooh (Adbul Wali Khan University Mardan, Pakistan)
- I. Gkialas (University of the Aegean, Greece)

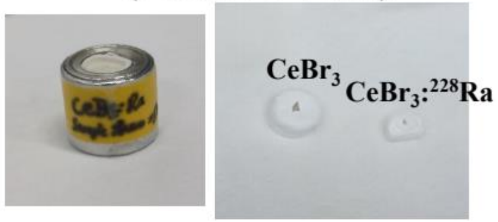
Scope of the GRANDE

- ❑ Experiment setup at the Yemi Underground Lab with low-background Cu+Pb shielding
- ❑ Radioactive source embedded in a crystal scintillator
  ($CeBr_3$: fast, high light yield, low background)
- ❑ 4π VETO with BGO
- ❑ Aiming for extremely low background condition
- ❑ Measurement of Rare EC process, rare beta, and alpha decay and searching for new particles.

Radioactive source doped crystal scintillators?



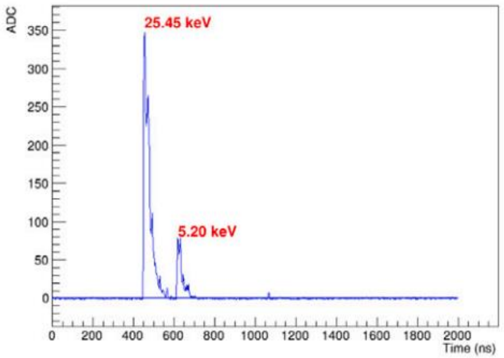
(5 mm × Φ 7 mm)

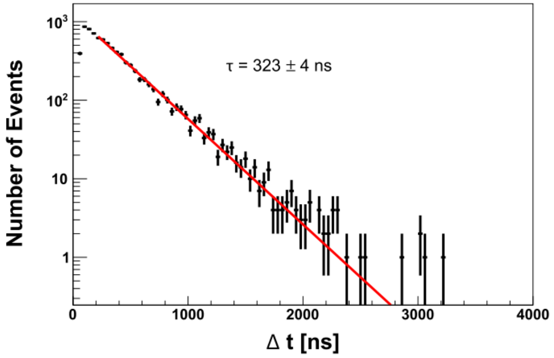


Encapsulated $CeBr_3$:^{228}Ra

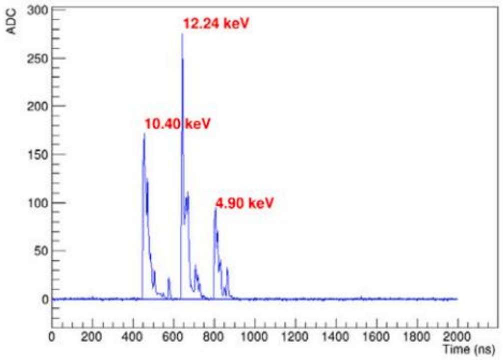
Measurement of New Ac-228 Isomers Using a Ra-228 doped CeBr3

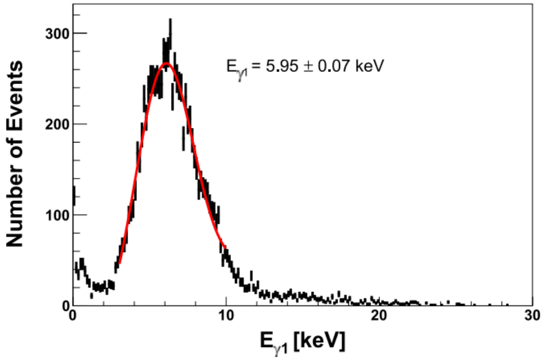
D.H. Lee et al, Radiation Physics and Chemistry 238 (2026) 113148





(a)





Low energy gamma (X-ray), beta and internal conversion can be measured efficiently.

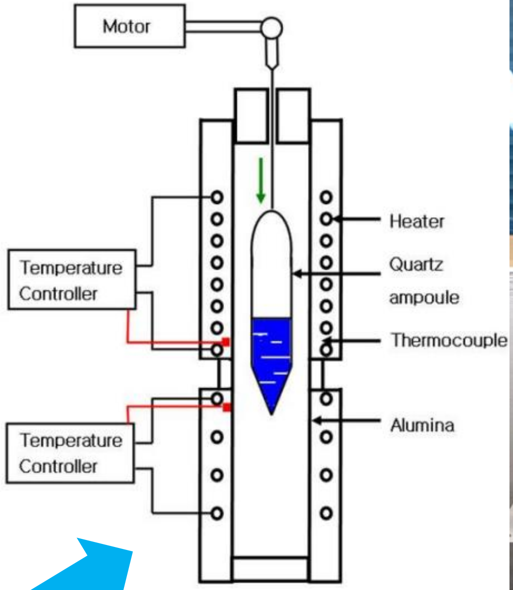
Radioactive source doped $CeBr_3$ crystal growth

Rad. Source in Solution

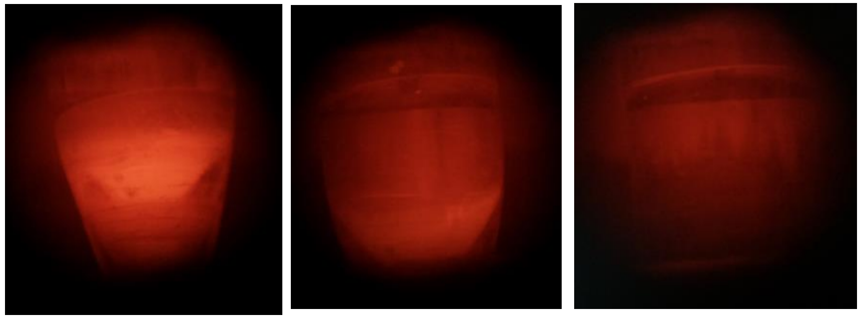
Rad. ampoule coating (under vacuum)

Fail process (dehydrate) (solved)

"home-made" Bridgman furnace

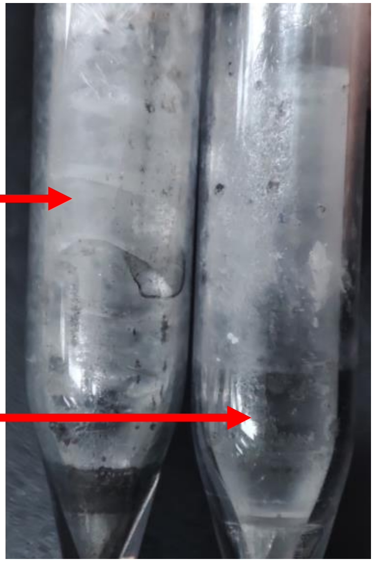


Realtime camera assistant interface monitor monitoring and changing growth rate



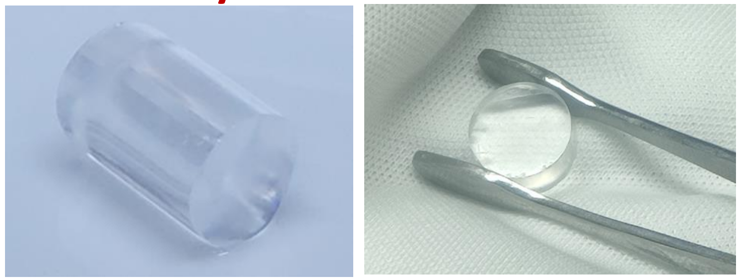
#Early
Dirty ampoule
Bad cracks

#NOW
#Optimized
Clean
No cracks
Long



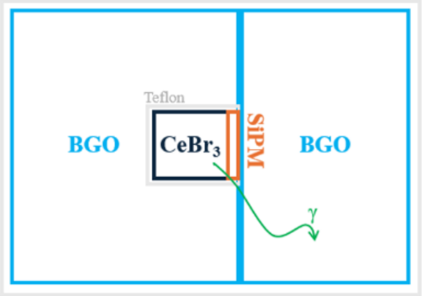
Cutting

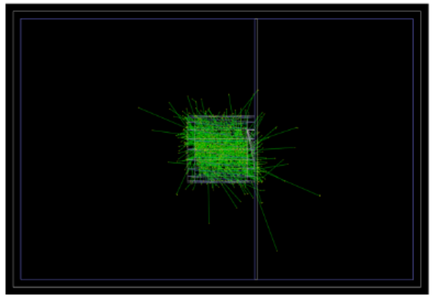
Crystal

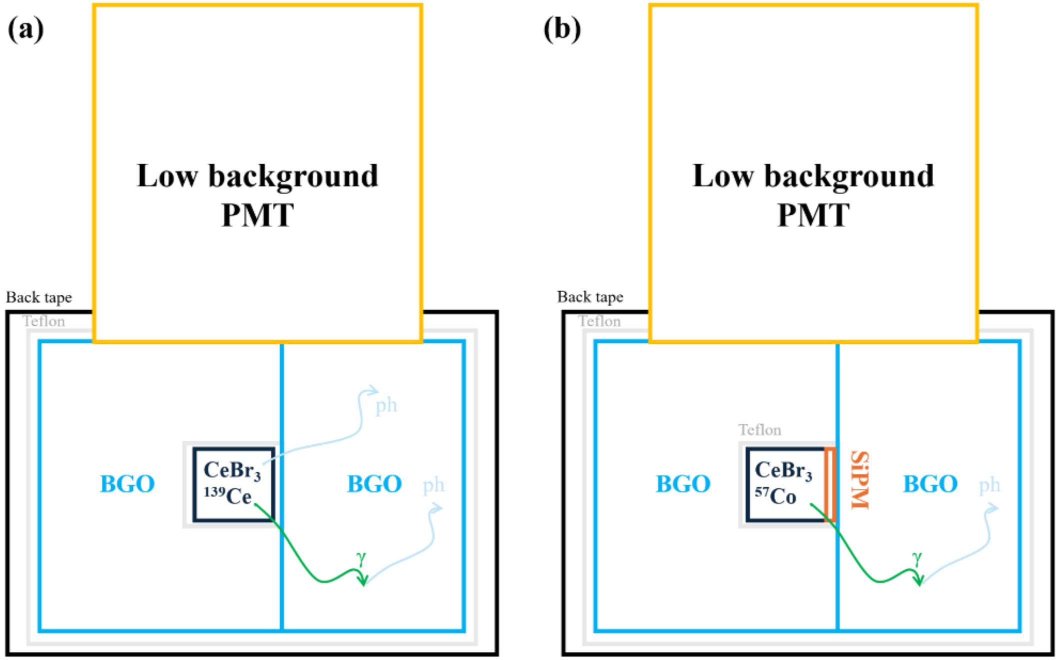


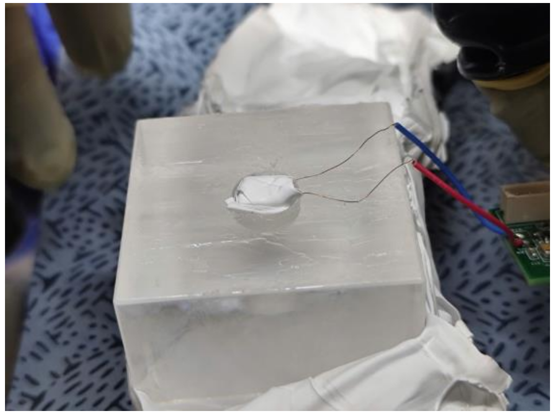
Source-as-Detector Experiment

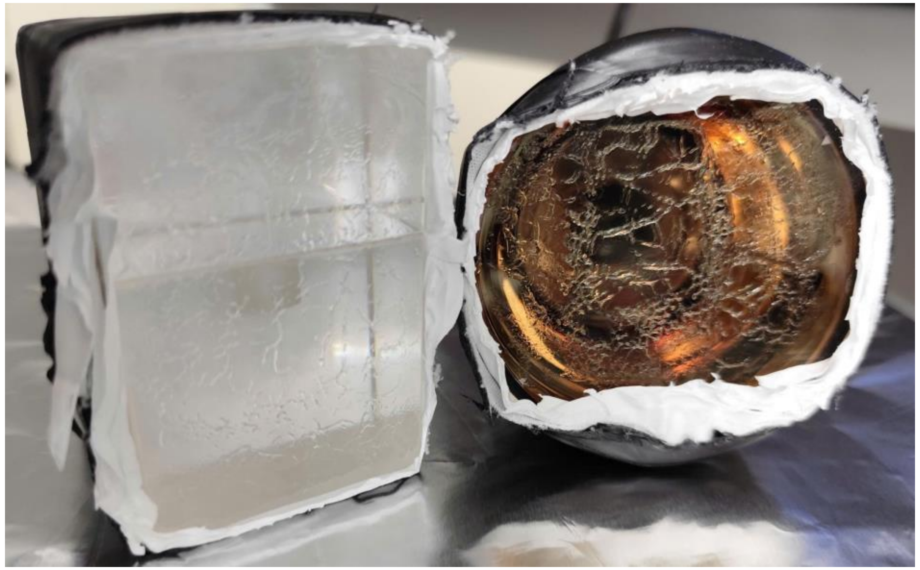
$CeBr_3$ advantages : Fast decay time, high light yield, good energy resolution
Disadvantages : very hygroscopic, internal background?





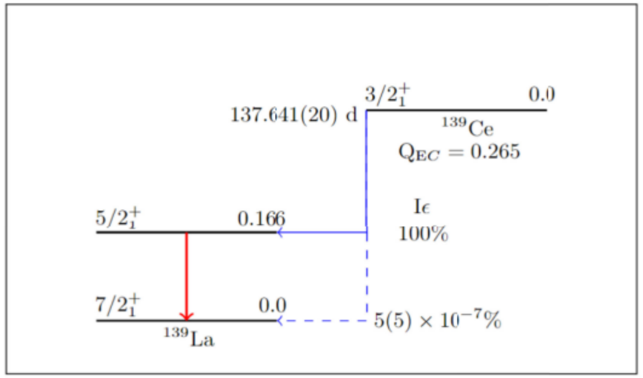






Phoswich detector

1st experiment using ^{139}Ce Source



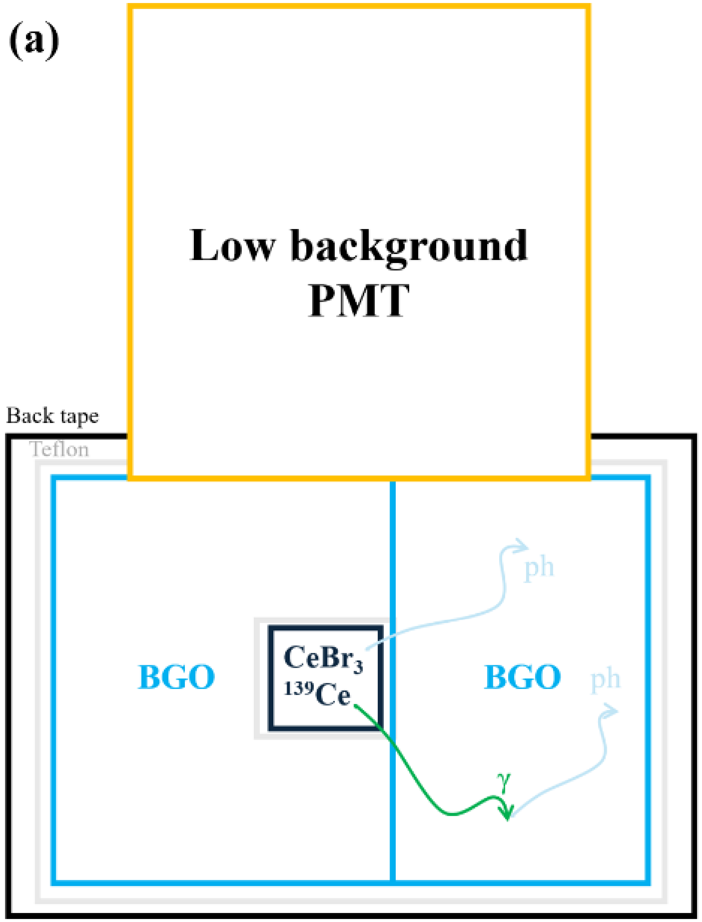
#1

M1 $5/2^+_1$ → $7/2^+_1$: 165.86 keV

→ K_α X-ray: ~33 keV

Easiest case

Search for single X-ray



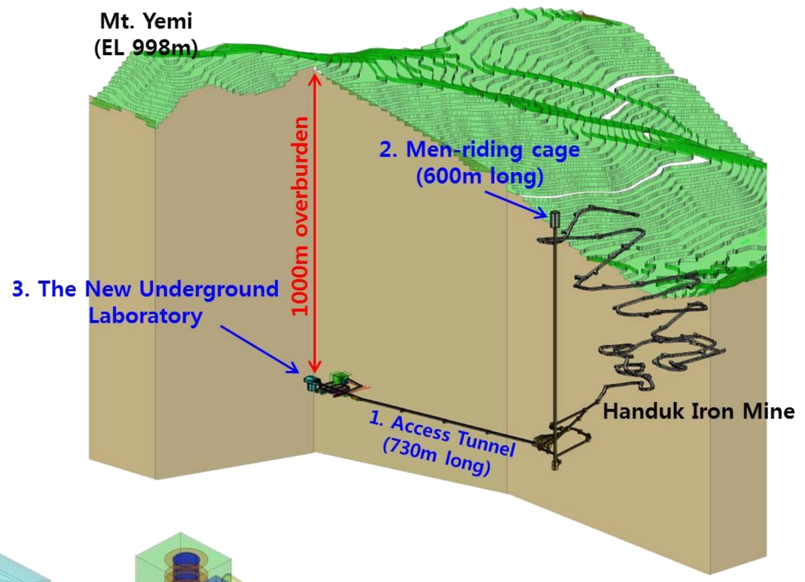
Phoswich detector

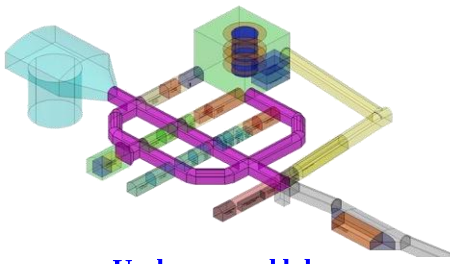
Yemi Underground Laboratory (Center for Underground Physics)

- **COSINE Dark matter search**
- **AMoRE 0ν ββ experiment**
- **Rare decay experiment (KAPAE-II, GRANDE)**

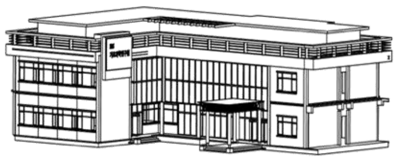
Future possibility

- **k-Ton LSC for DB, solar ν**
- Rare decay search with HPGe
- **Ton scale DB exp.**
- **Dark photon exp.**
- **New dark matter search**
- **New idea with new detector!**

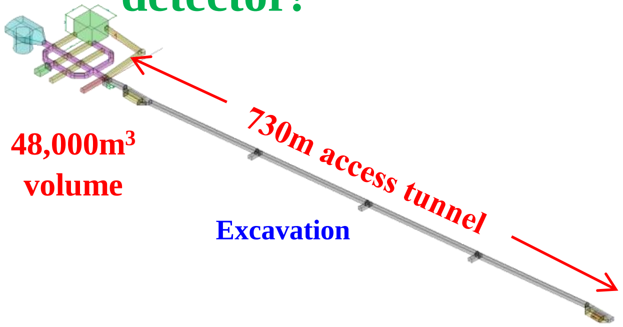




Underground lab



Surface office/lab



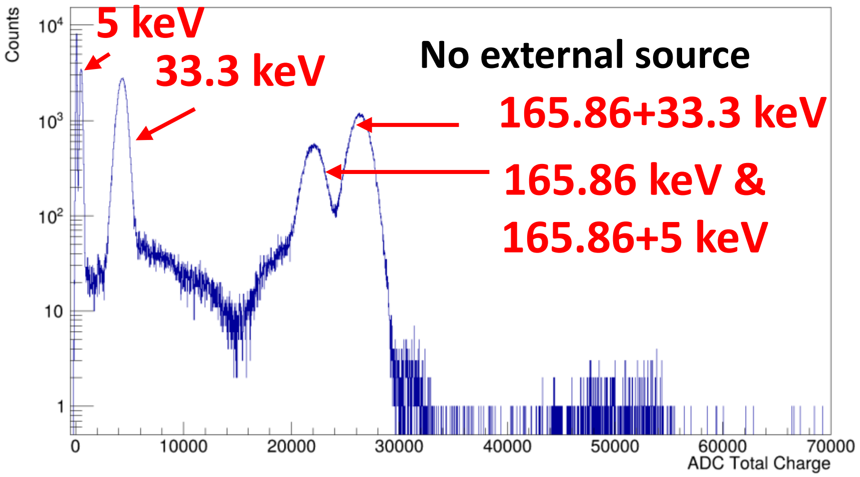
Excavation

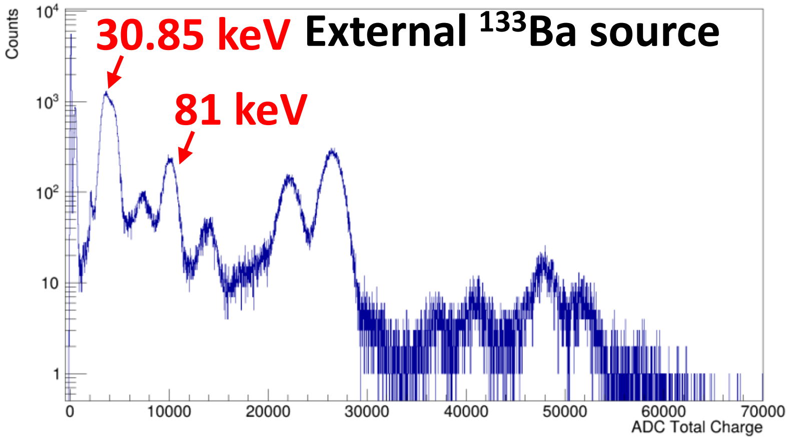
Experiment using ^{139}Ce Source

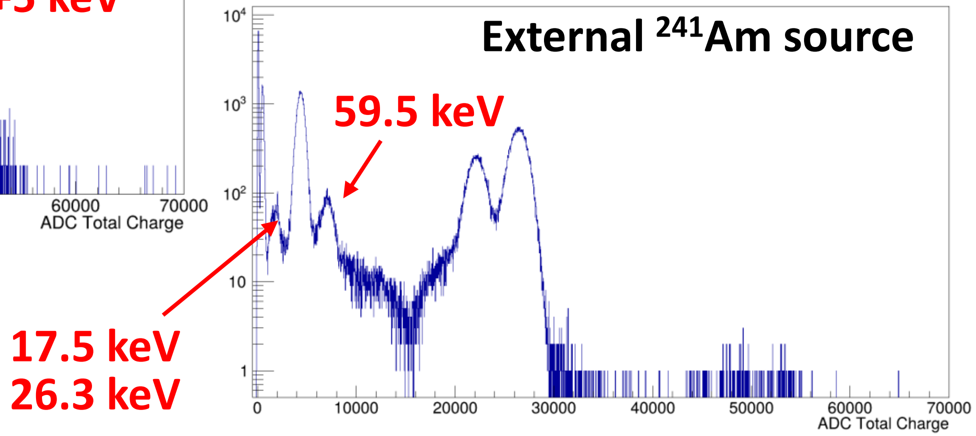
- Yemi Underground lab. with 15cm Pb shielding.
- Super bi-alkali PMT 12669SEL (High quantum efficiency, low background)
- Notice 500-MHz flash Analog to Digital Converter
- Caen High Voltage Supplier
- PC with 18Tb storage
- Data rate ~20 kHz

Running 5 month without problem!
No degradation of CeBr3 crystal

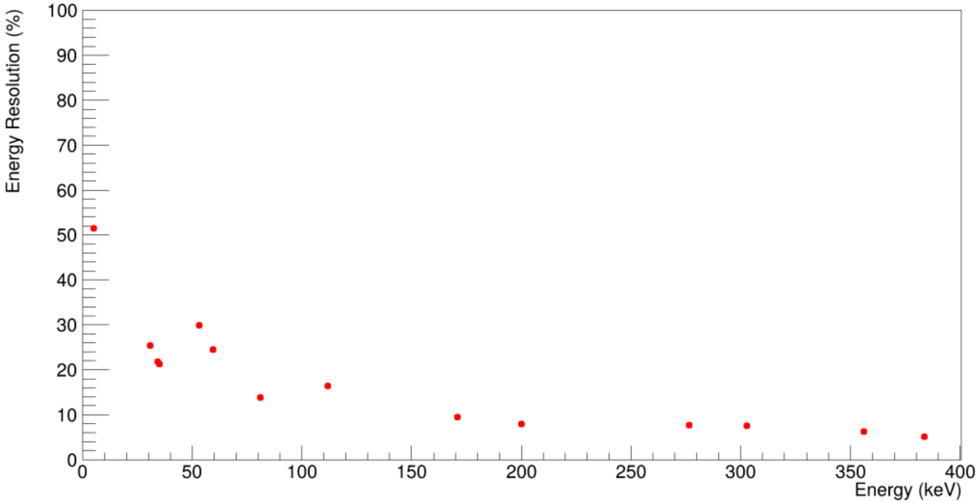
$CeBr_3$:^{139}Ce

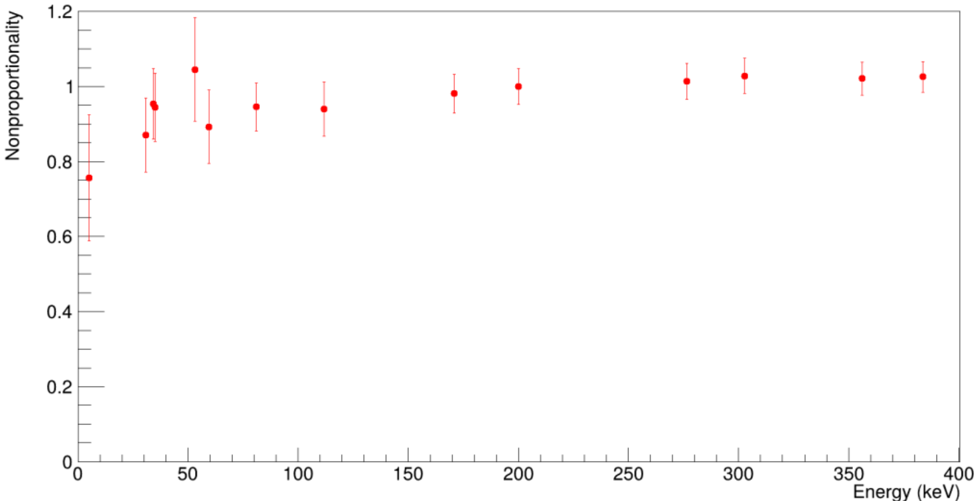




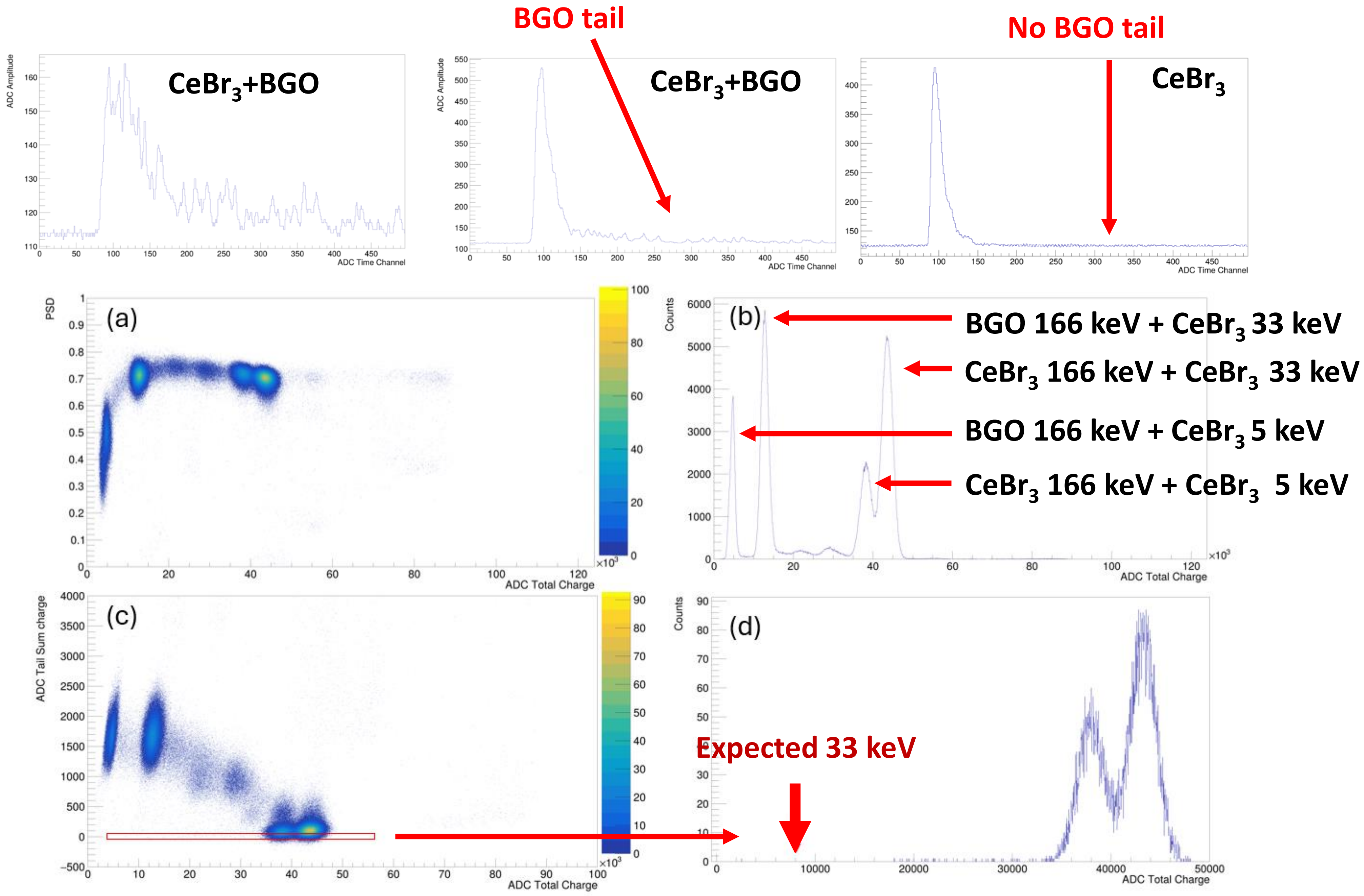


Isotope	Energy (keV)
^{139}Ce	5
	33.
	170
	200
^{241}Am	59.5
^{133}Ba	30.85
	35.1
	53.15
	81
	111.85
	276.4
	302.85
	356.02
	383.85



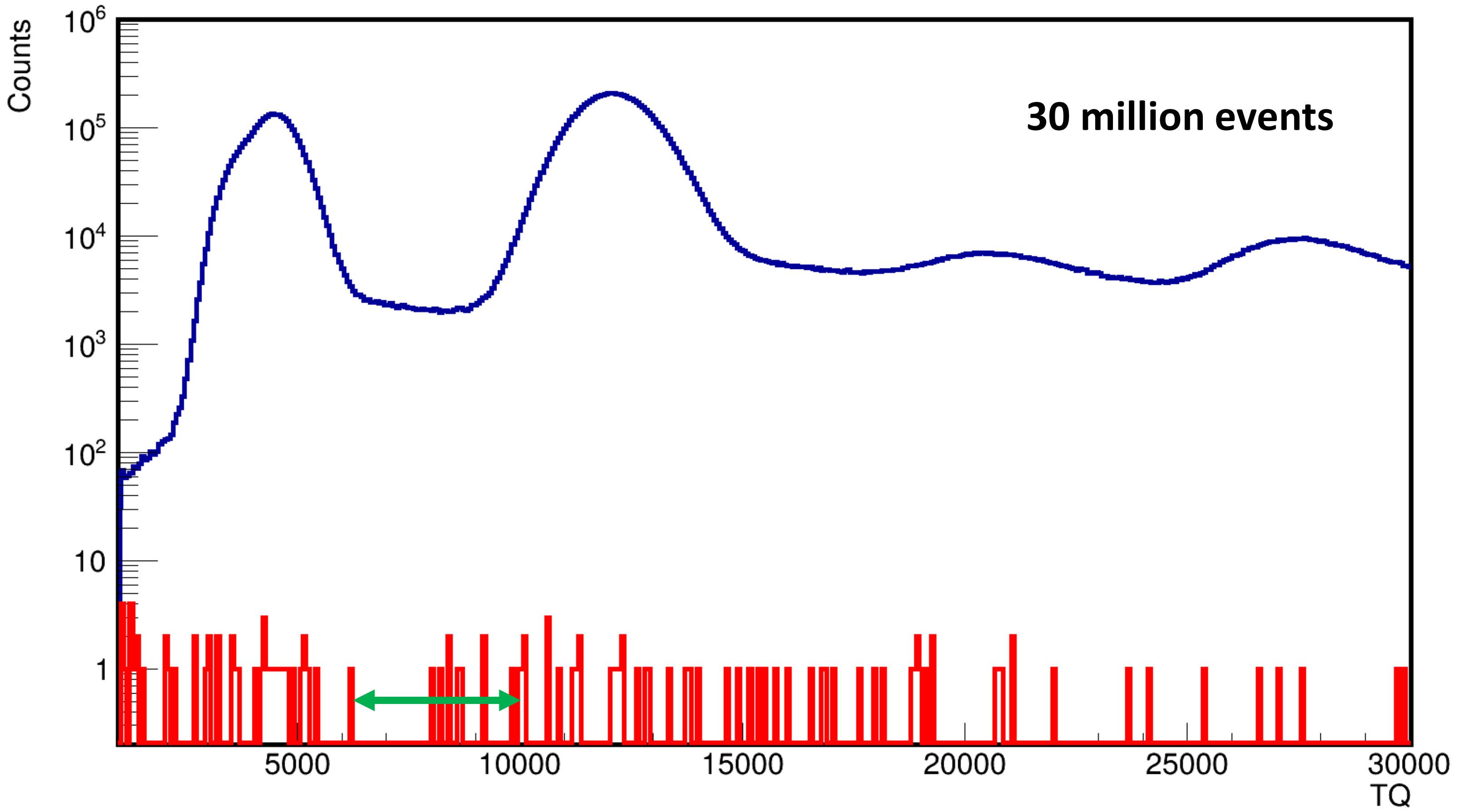


$CeBr_3$:^{139}Ce + BGO veto



$CeBr_3$:^{139}Ce + BGO veto

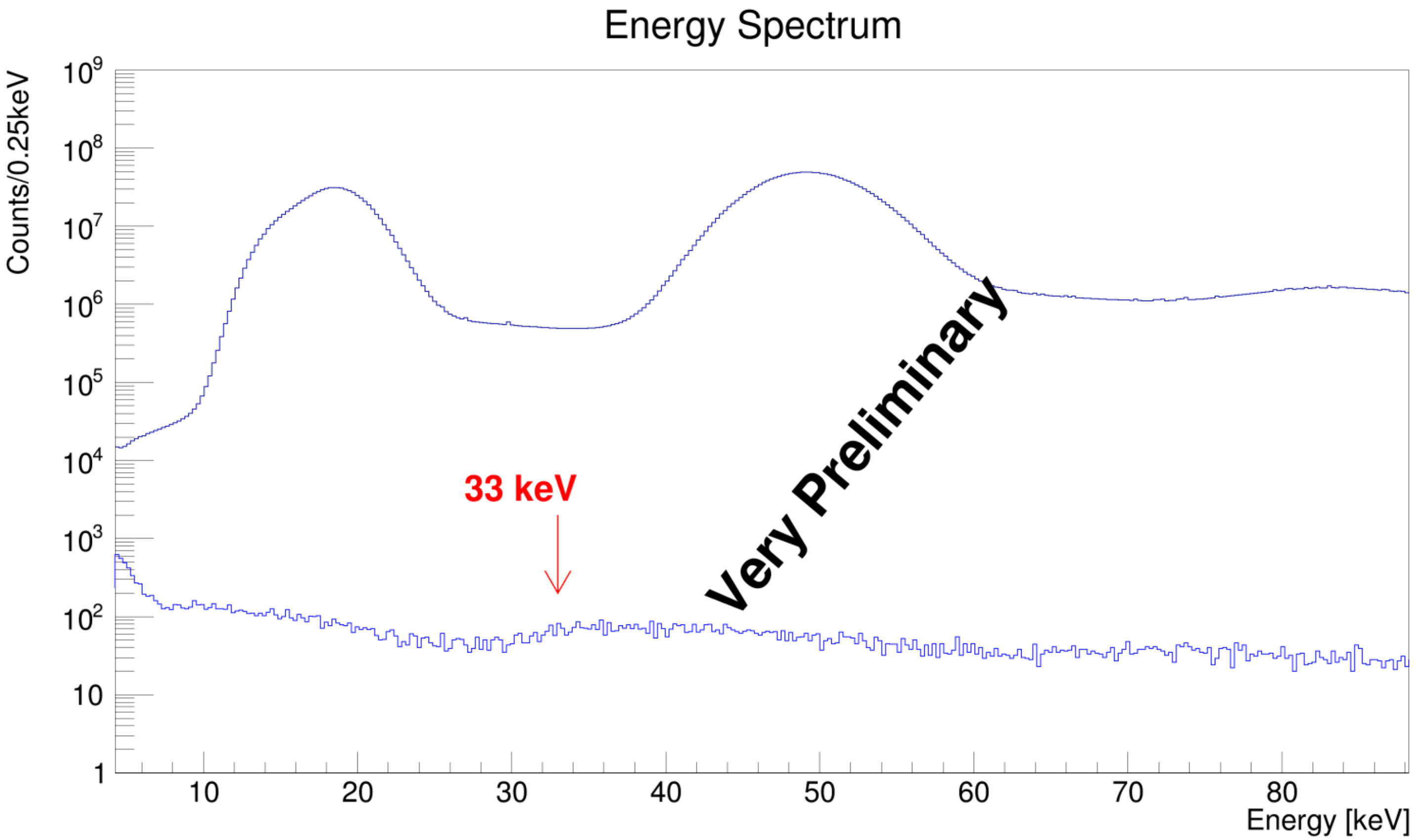
- 2 million events → reach 1×10^{-6}
- 30 million events → reach 4×10^{-7}

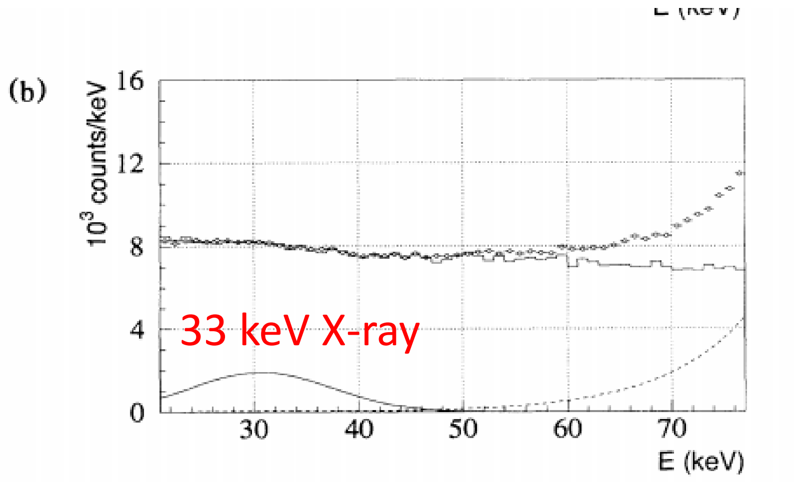


8000 -> 33 keV (20% FWHM energy resolution)

$CeBr_3$:^{139}Ce + BGO veto

- Very preliminary results with 10 billion events (5 month data taking)
- 200 times lower background than M. Minowa's experiment

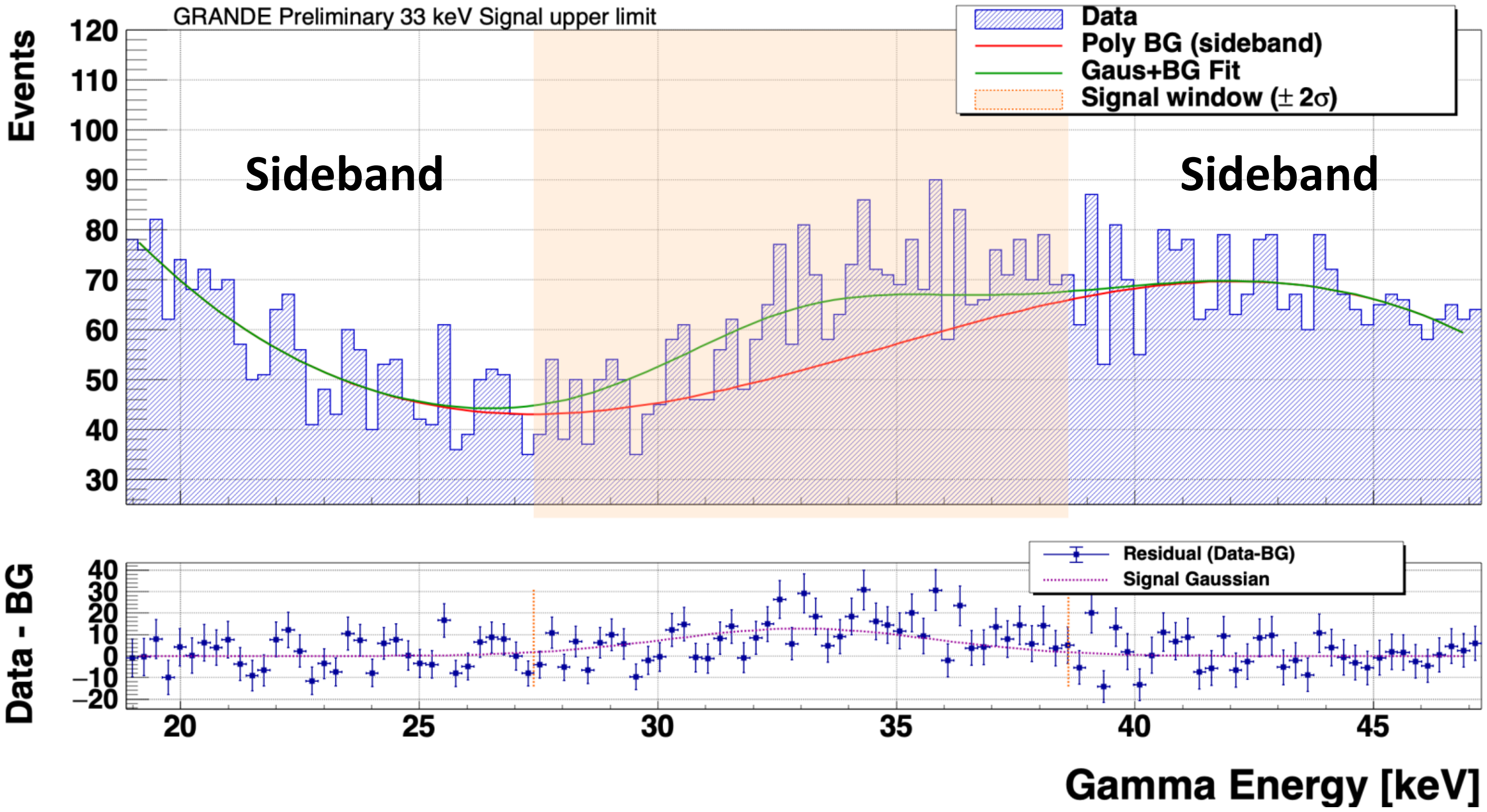




$$\Gamma_a/\Gamma_\gamma < 1.21 \times 10^{-6} \text{ at the } 95\%$$

Mass of hadronic axion > 26.7 keV by 95%CL
M.Minowa et al, Phys. Rev. Lett. 71, 4120

Preliminary Branching ratio upper limit of ^{139}Ce



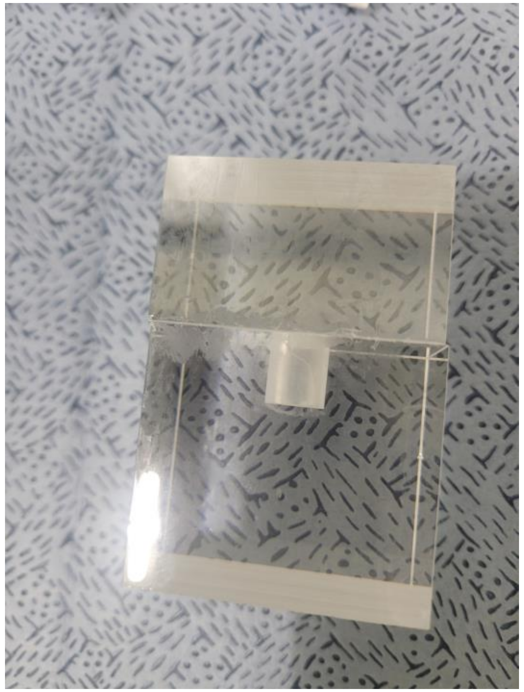
- **Signal window:** 33 keV, $\pm 2\sigma$ region
- **Sideband:** 33 keV, $\pm 5\sigma$ region, excluding the signal window ($\pm 2\sigma$) with 3rd-order polynomial
- **Branching ratio upper limit:** 1.1×10^{-8}(90% C.L.) Preliminary
- **Previous experiment** $\Gamma_a/\Gamma_\gamma < 1.21 \times 10^{-6}$ at the 95%

Background signals due to 166 keV gamma escape from BGO since it is only 2 cm thickness.

Upgrade of $CeBr_3$:^{139}Ce experiment with KAPAE-II

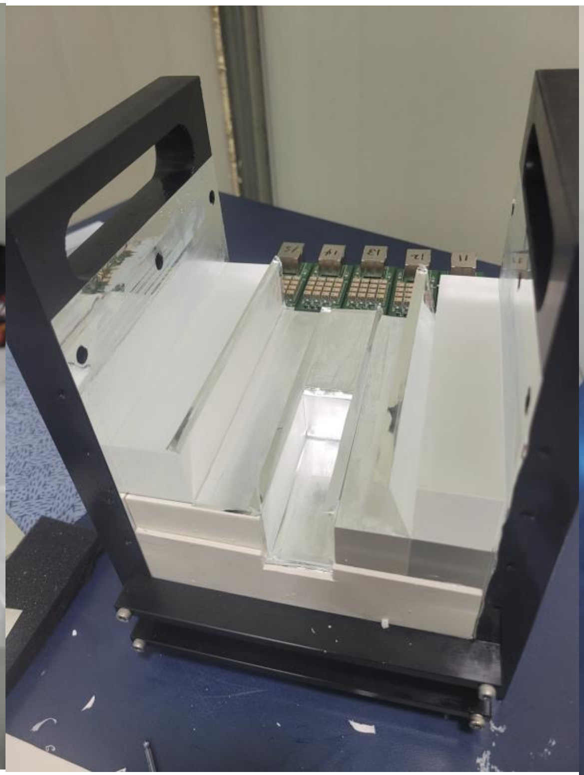
Phoswitch to KAPAE-II
1. BGO thickness is only 2.0cm (166 keV γ leak) -> 6cm for KAPAE-II setup
2. Phoswitch does not give a perfect separation between CeBr3 and BGO signal

Phoswitch setup



KAPAE-II Setup

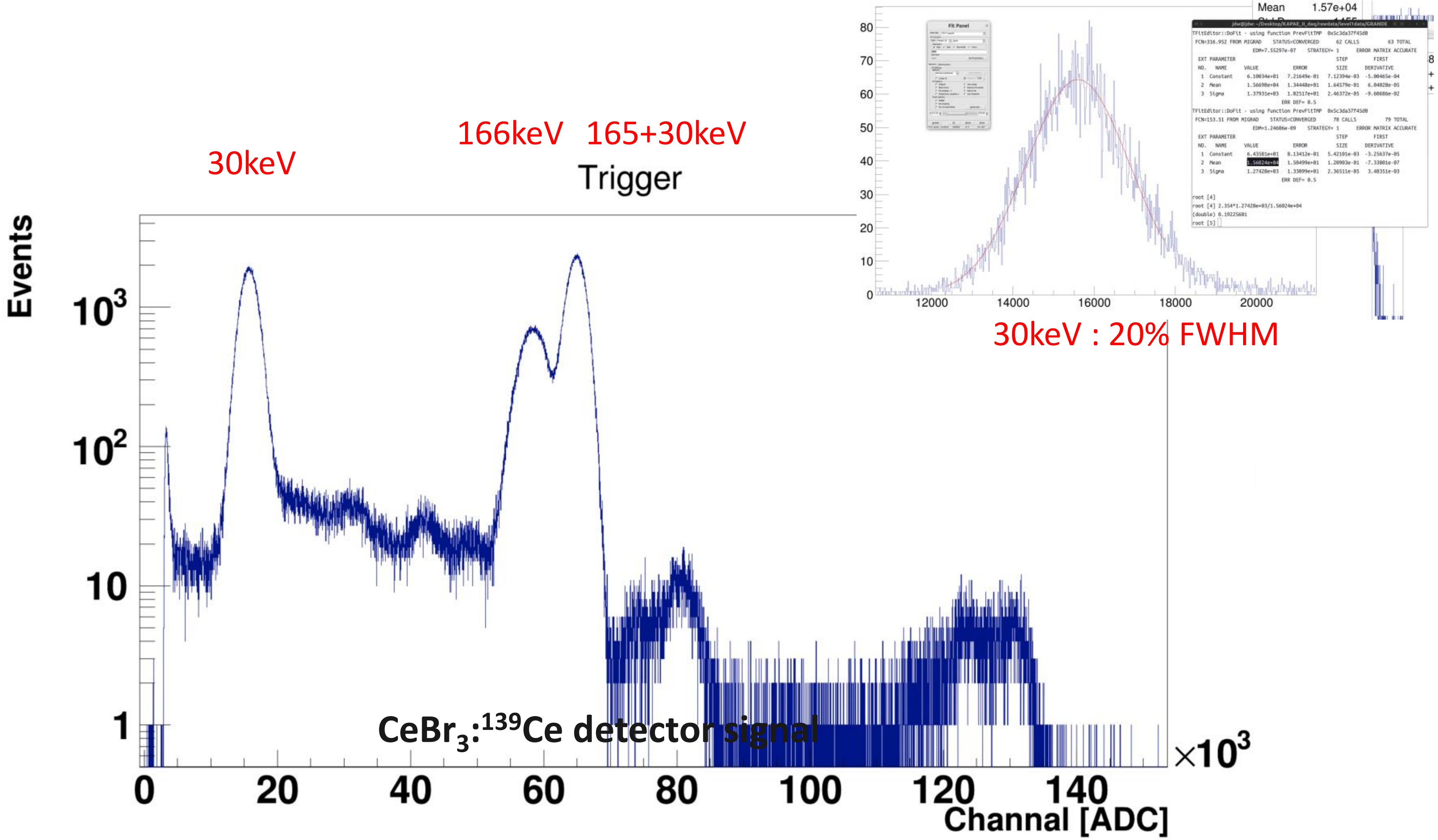
^{139}Ce experiment with KAPAE-II Setup



$CeBr_3$:^{139}Ce Crystal with SiPM connection

^{139}Ce experiment with KAPAE-II Setup : CeBr3 signal

Data just started Oct 17, 2025 and will be continue for 6 month



Summary and Prospect

- Radioactive sources are good for the Tabletop experiments wit low budget.

- Search for the exotic dark matter search and extremely rare nuclear EC transition measurement will be performed with GRANDE.

- Source-Detector technique is used with $CeBr_3$ doped with radio-active source.

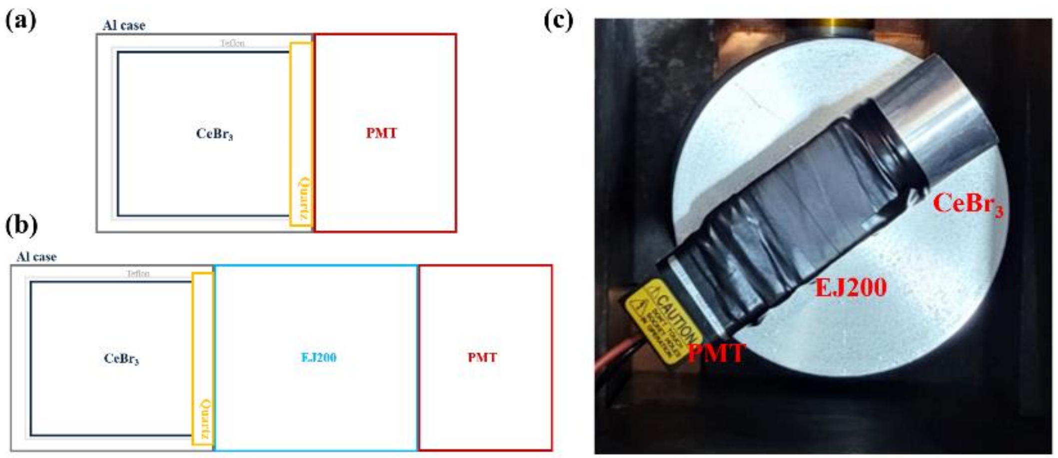
- To reduced external radio-active background, 4p BGO veto is used and experiment is on going at Yemi underground laboratory in Cu and Pb shielding.

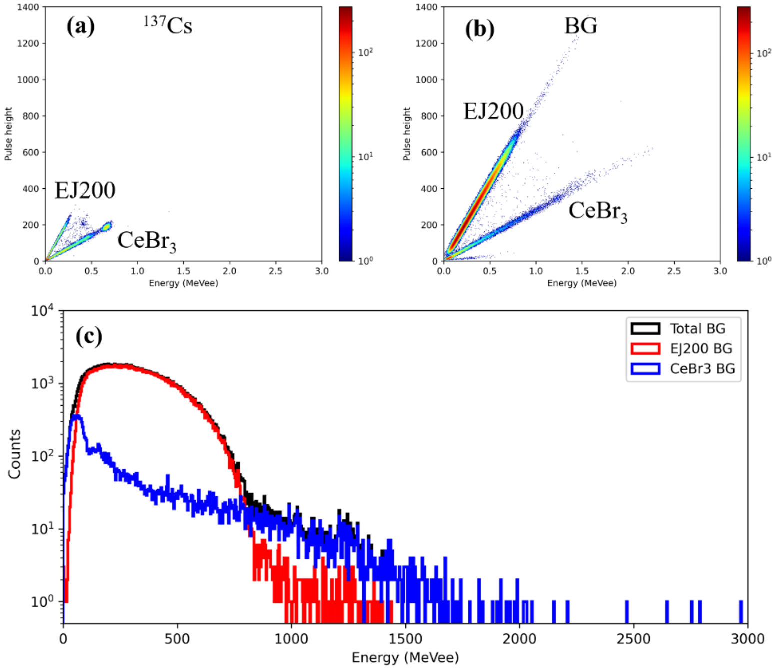
- Missing gamma study with ^{139}Ce, ^{125}I and ^{44}Ti of EC M1/E1/E2 transition, exotic dark matter search of ALP, dark photon and anapole will be performed in GRANDE.

- Are there any new theoretical motivation at E < 1MeV for new particle searches related with invisible particles such as new bosonic particle?

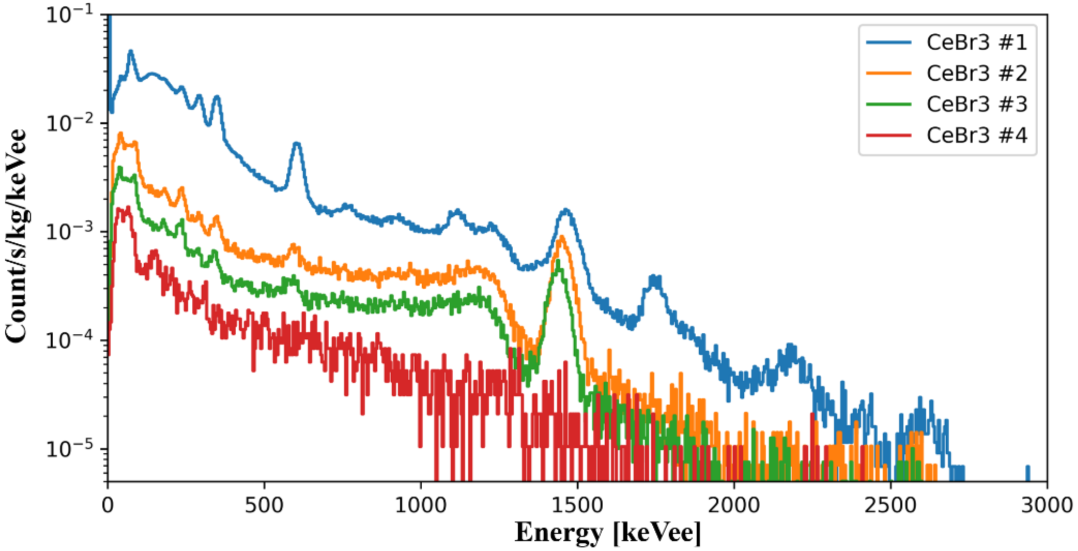
Thank You !

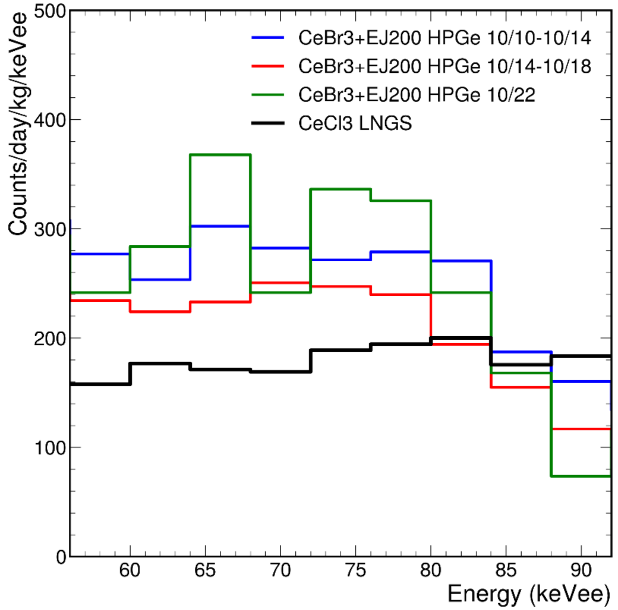
Pure 1" $CeBr_3$ internal background @ Yemi





Good background condition @ Yemi





The Gran Sasso National Laboratory (LNGS) of the INFN (Italy)
P Belli et al., J. Phys. G: Nucl. Part. Phys. 38 (2011) 015103 (15pp)

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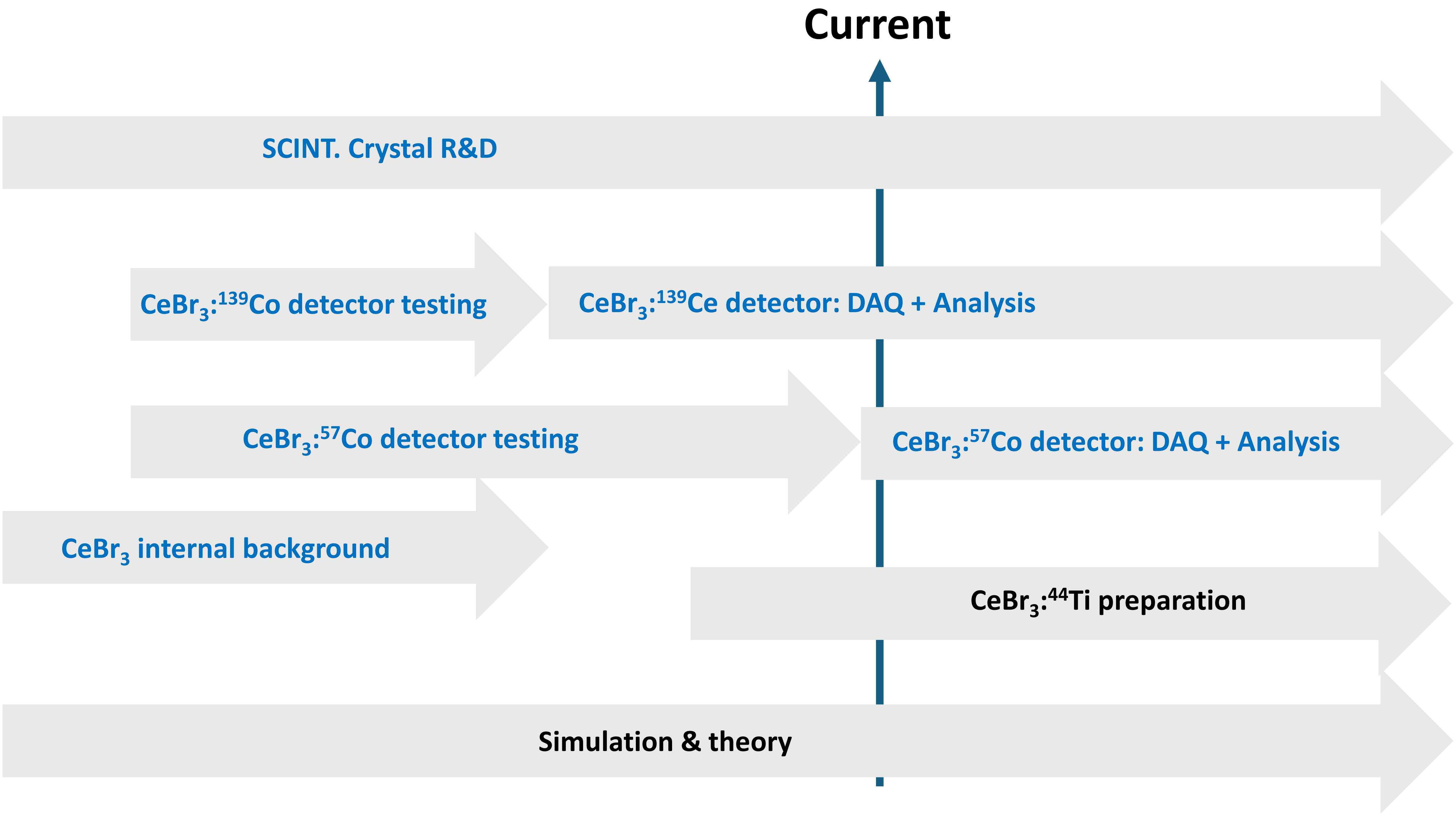
Current
SCINT. Crystal R&D
$CeBr_3$:^{139}Co detector testing
$CeBr_3$:^{139}Ce detector: DAQ + Analysis
$CeBr_3$:^{57}Co detector testing
$CeBr_3$:^{57}Co detector: DAQ + Analysis
$CeBr_3$ internal background
$CeBr_3$:^{44}Ti preparation
Simulation & theory