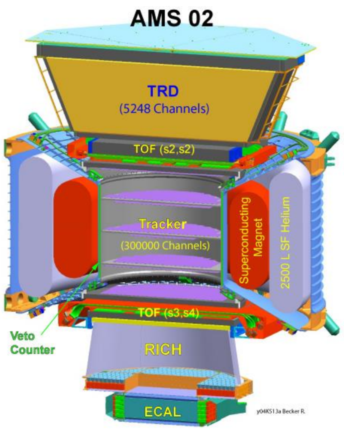
Searching for Exotic Dark Matter Searches using Radioactive Source at Underground
Lecture-1 : KAPAE

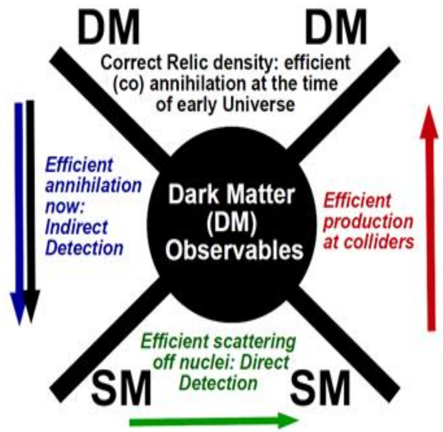
H.J.Kim (Kyungpook National Univ.)

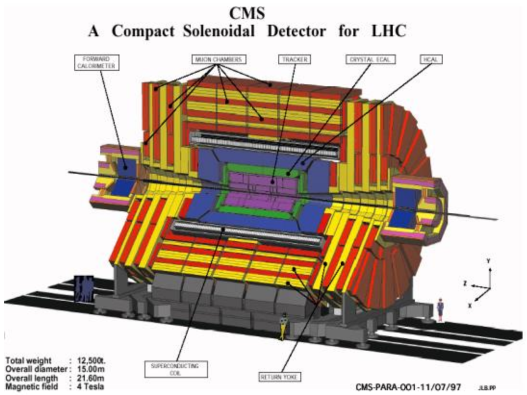
CNPR Workshop 2025: Neutrinos and Physics beyond the Standard Model

Oct 24-27, Chonnam National University

Why universe is dark?





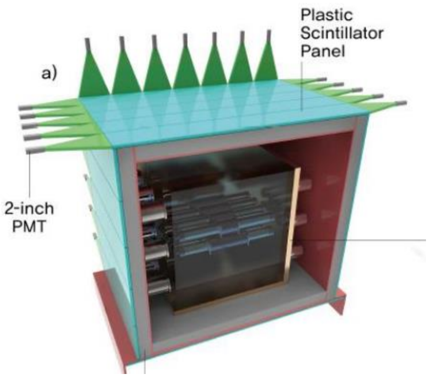


Dark Sector Search

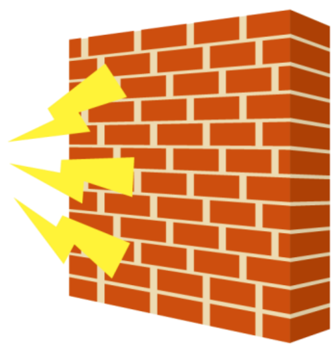
- WIMP
- SUSY
- Axion
- Dark photon

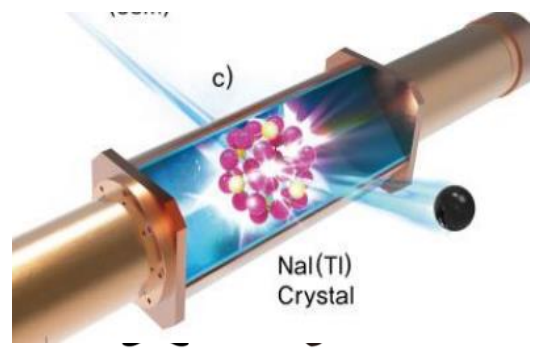
……..

?????



Smaller scale for dark sector search?



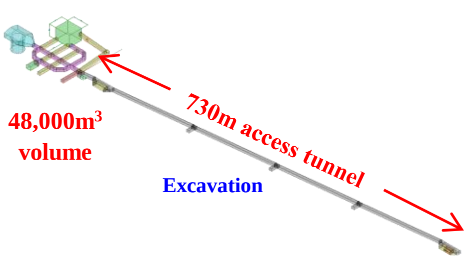


Yemi Underground Laboratory (Center for Underground Physics)

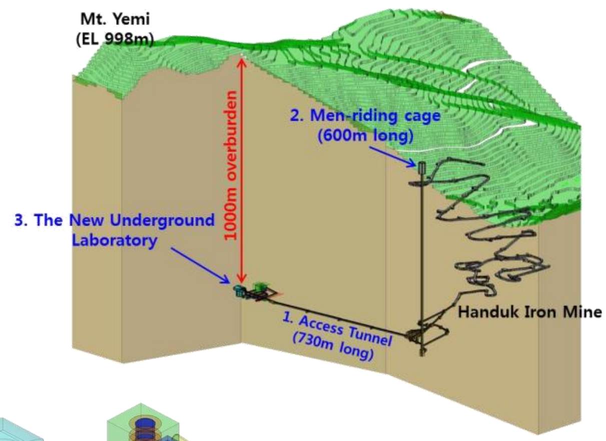
- COSINE Dark matter search
- AMoRE $0\nu\ \beta\beta$ experiment
- Rare decay experiment
  (KAPAE-II, GRANDE)

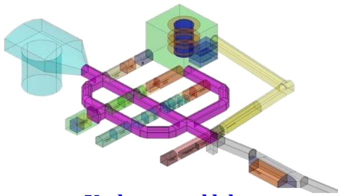
Future possibility

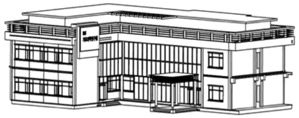
- nEye for DB, solar ν
- Rare decay search with HPGe
- Ton scale DB exp.
- Dark photon exp.
- New dark matter search
- New idea with new detector!



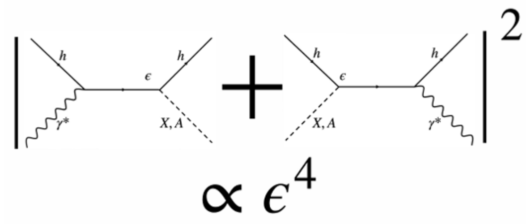
Excavation



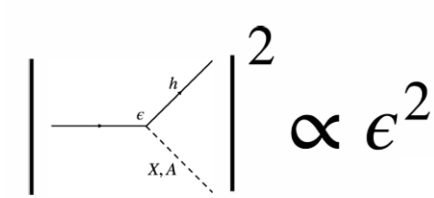

Underground lab


Surface office/lab

Radioactive sources for Dark Sector Search



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



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

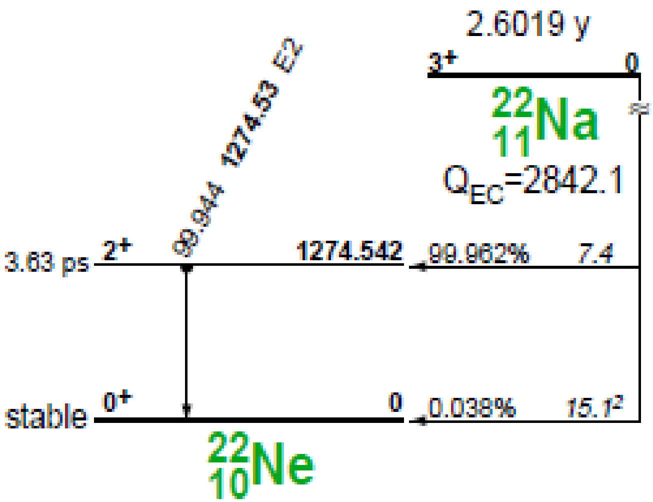
Advantage

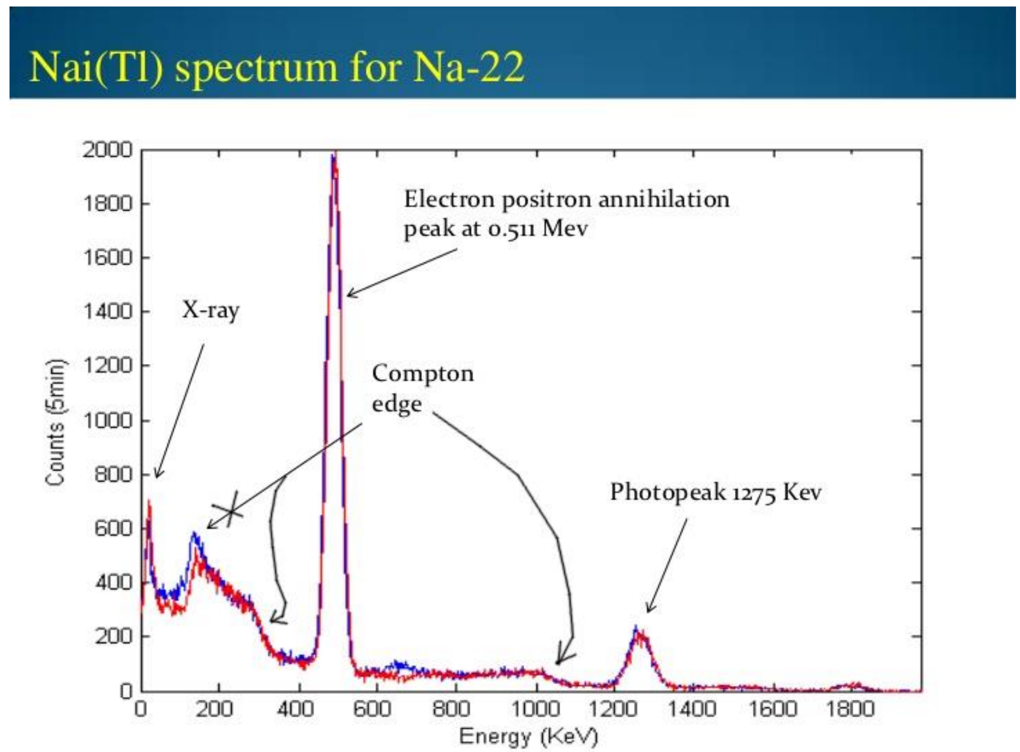
- ❑ Decay process: Coupling is **proportional to ε^2** not ε^4 (Accelerator, Reactor)
- ❑ Tabletop-scale experiment (**much smaller and lower cost**)
- ❑ Deep underground with Cu, Pb shielding

Limitation

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

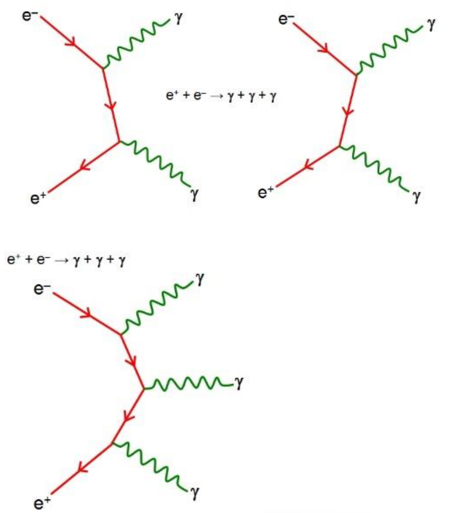
Na-22 Radioactive source

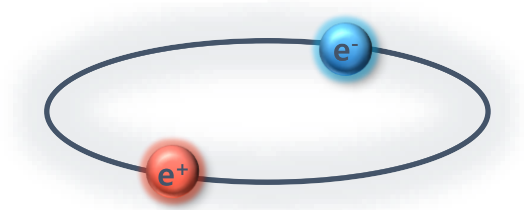




Introduction

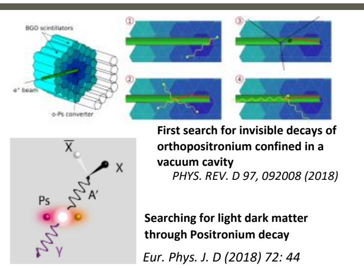
- KNU Advanced Positronium Annihilation Experiment (KAPAE)





Electron-Positron Pair

Physics



- Rare decay, QED verification
- New particle searches

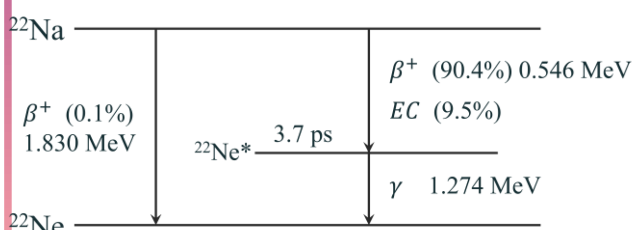
Application

- **P**ositron **E**mission **T**omography (PET)

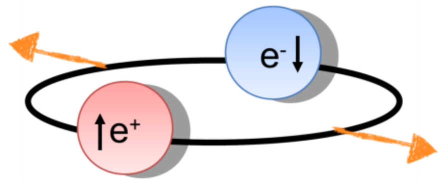
e+e- annihilations with 1.02 MeV, 10^{10-14} events possible : Intensity frontier !

Introduction

Positronium (Ps)



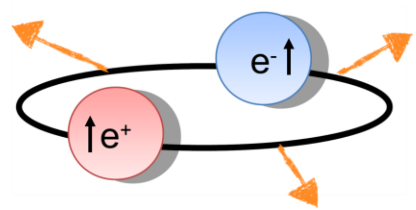
p-Ps (Spin singlet state)



$|0,0\rangle = (\uparrow\downarrow - \downarrow\uparrow)/\sqrt{2}\ \}\ s = 0$

p-Ps $\rightarrow 2\gamma(, 4\gamma, \ldots)$

o-Ps (Spin triplet state)



$$\left.\begin{array}{l} |1,1\rangle = \uparrow\uparrow \\ |1,0\rangle = (\uparrow\downarrow + \downarrow\uparrow)/\sqrt{2} \\ |1,-1\rangle = \downarrow\downarrow \end{array}\right\} s = 1$$

o-Ps $\rightarrow 3\gamma(, 5\gamma, \ldots)$

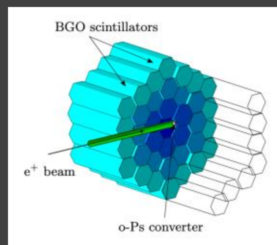
para-Positronium (p-Ps)

- The ground state l = 0, s = 0
- C = $(-1)^{l+s}$ = +1
- Photon C = $(-1)^n$
  - Decay = even photons (2, 4, 6, ...)
- Life time = 125 ps

ortho-Positronium (o-Ps)

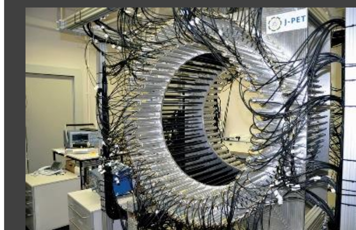
- The ground state l = 0, s = 1
- C = $(-1)^{l+s}$ = -1
- Photon C = $(-1)^n$
  - Decay = odd photons (3, 5, ...)
- Life time = 142 ± 0.02 ns

Introduction : Positronium Experiments



- Invisible decay study
- Plastic + BGO + PMT
- o-Ps totally Invisible : 2.1×10^{-7}

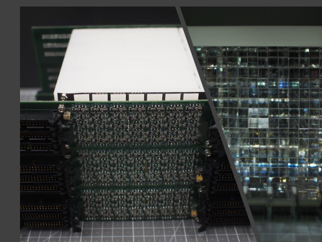
ETH Zurich (Switzerland)



- CP, CPT study
- Plastic + PMT

- Plastic + SiPM (ver. II)

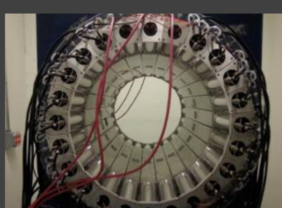
J-PET (Poland)
The Jagiellonian University



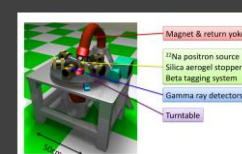
- BGO + SiPM
- Rare decay
- C, CP, CPT study
- Invisible decay search

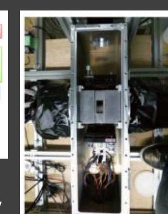
KAPAE (Korea)
Kyungpook Nat'l Univ.

- CPT study
- NaI + PMT



APEX (U.S.A.)
Triangle Universities Nuclear Laboratory



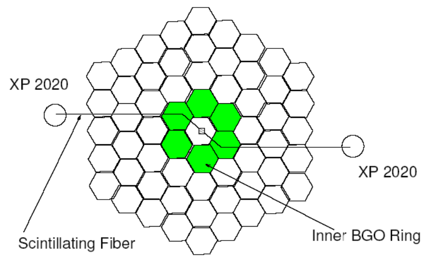


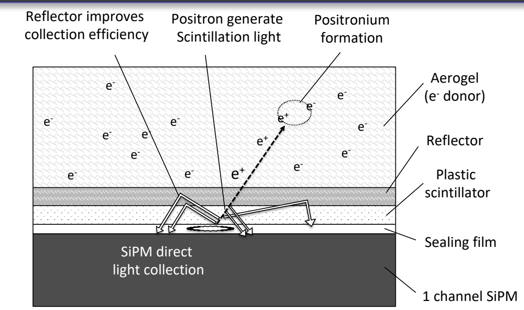
- CP & CPT study
- Plastic + NaI + PMT

ICEPP (Japan)
Univ. of Tokyo

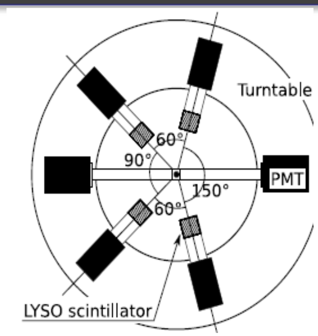
KAPAE novel design concept

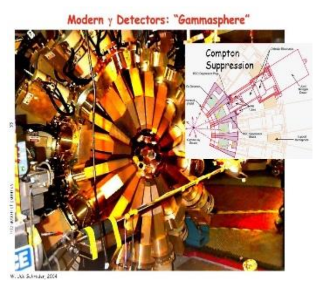
Improvement over other experiment : Better e+ tagging, Higher activity (1uCi -> 10uCi), High DAQ

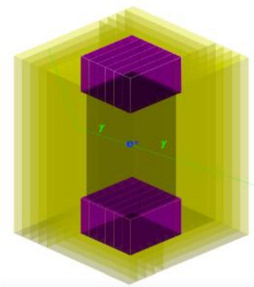


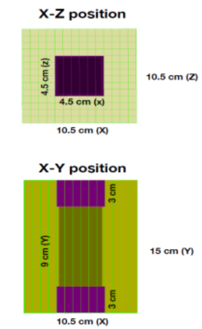


KAPAE-I : compact (10x10x15cm) & fine segmentation (200 crystals) for QED test (Since 2017)

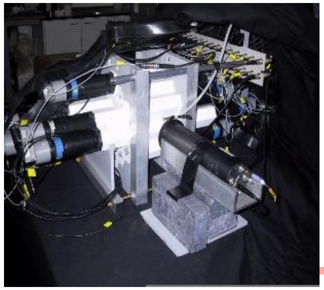


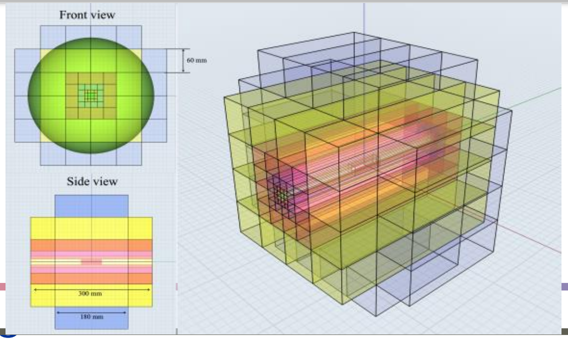






KAPAE-II :(30x30x30cm) & less segmentation for new particle search (Since 2020)





Introduction : KAPAE-I physics

QED Symmetry violation search

1. C violation : Best limit ~10^{-6} – 10^{-7}
- $Br(o\text{-}Ps \rightarrow 4\gamma / o\text{-}Ps \rightarrow 3\gamma) < 2.6 \times 10^{-6}$ at 90% CL
- $Br(p\text{-}Ps \rightarrow 3\gamma / p\text{-}Ps \rightarrow 2\gamma) < 2.8 \times 10^{-6}$ at 68% CL
- $Br(p\text{-}Ps \rightarrow 5\gamma / p\text{-}Ps \rightarrow 2\gamma) < 2.7 \times 10^{-7}$ at 90% CL

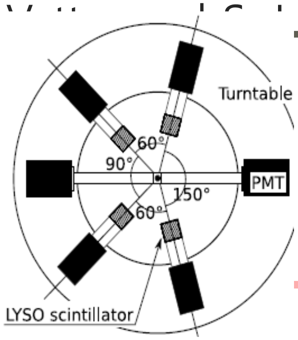
2. CP violation : : Best limit ~10^{-3}

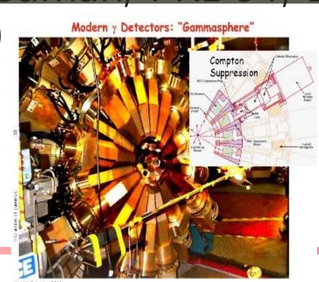
$C_{CP} = 0.0013 \pm 0.0022$
T. Yamazaki et. al, Phys. Rev. Lett. 104, 083401 (2010)

3. CPT violation : Best limit ~10^{-3}

$C_{cpt} = 0.0026 \pm 0.0031$

P. A. V... and S. J. Freedman, PRL 91, 26...003)

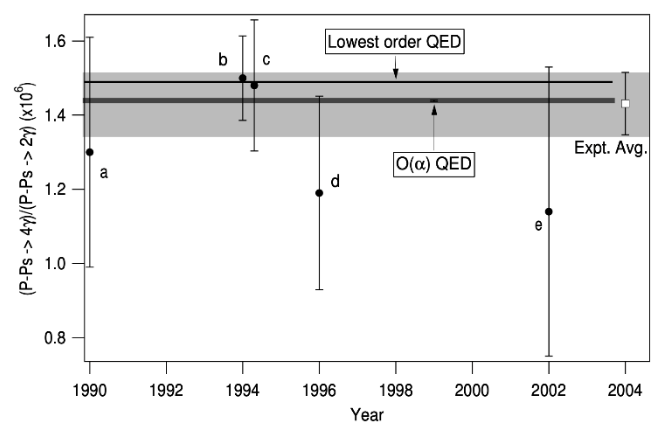




High order QED

1. p-Ps → 4 γ : Best results : 26 events
$R(p\text{-}Ps \rightarrow 5\gamma / 2\gamma) =$
$[1.30 \,.) \pm 0.26(stat.) \pm 0.16(syst.)] \times 10^{-6}$
S. Adachi et al., PRL 65, 2634 (1990)

2. o-Ps → 5 γ : Best results : 1 events
$R(o\text{-}Ps \rightarrow 5\gamma / 3\gamma) =$
$[2.2\ ^{+2.6}_{-1.6}(stat.) \pm 0.5(syst.)] \times 10^{-6}$
T. Matsumoto et al, PRA 54, 1947 (1996)



Introduction : KAPAE-II physics

- Totally Invisible Exotic Decay (Mirror world, Extra dimensions, Mili-charged Particle, etc)

Milli-charged particles

- The grand unified theory (GUT) model
- Electric charge particles ("shadow" photon <<<< e)

$$\Gamma(o\text{–}Ps \to X\bar{X}) = \frac{\alpha^5 Q_X^2 m_e}{6} \cdot k \cdot F(\frac{m_X^2}{m_e^2})$$

Extra dimensions

- k > 2.7 TeV

$$\text{o}\text{–}Ps \to \gamma^* \to \text{ additional dimension(s)}$$

$$\text{Br} = \frac{9\pi}{4(\pi^2-9)} \cdot \frac{1}{\alpha^2} \cdot \frac{\pi}{16}\left(\frac{m_0 - Ps}{k}\right)^2 \approx 3 \times 10^4 \left(\frac{m_0 - Ps}{k}\right)^2$$

Mirror world

- The mirror universe model
- Vibration of o-Ps and mirror o-Ps

$$\text{Br}(\text{o}\text{–}Ps \to \text{ invisible}) = \frac{2(2\pi\varepsilon f)^2}{\Gamma^2 + 4(2\pi\varepsilon f)^2}$$

3×10^{-5} at 90% C.L.

A.Badertsher et. al,
PRL 124 101803 (2020)

Searching for Ps-> Invisible : 2x10^{-8}

A.Badertsher et. al,
PHYS. REV. D 95, 032004 (2007)

Introduction : KAPAE-II physics

- Partially Invisible Exotic Decay (Axion Like Particle (ALP), Dark Photon, Dark Z, etc)

Axion Like Particle
PDG 2024: Best limit : ~10^{-4} - 10^{-6}

A^0 (Axion) Searches in Positronium Decays

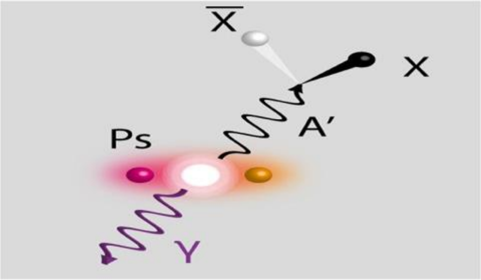
Decay or transition of positronium. Limits are for branching ratio.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4.4 \times 10^{-5}$	90	[1] BADERT...	02	CNTR	$o\text{-Ps} \rightarrow \gamma X_1 X_2$, $m_{X_1}+m_{X_2} \leq$ 900 keV
$<2 \times 10^{-4}$	90	MAENO	95	CNTR	$o\text{-Ps} \rightarrow A^0 \gamma$ m_{A^0}=850–1013 keV
$<3.0 \times 10^{-4}$	90	[2] ASAI	94	CNTR	$o\text{-Ps} \rightarrow A^0 \gamma$ m_{A^0}=30–500 keV
$<2.8 \times 10^{-5}$	90	[3] AKOPYAN	91	CNTR	$o\text{-Ps} \rightarrow A^0 \gamma$ $(A^0 \rightarrow \gamma\gamma)$, $m_{A^0} < 30$ keV
$<1.1 \times 10^{-6}$	90	[4] ASAI	91	CNTR	$o\text{-Ps} \rightarrow A^0 \gamma$, $m_{A^0} < 800$ keV
$<3.8 \times 10^{-4}$	90	GNINENKO	90	CNTR	$o\text{-Ps} \rightarrow A^0 \gamma$, $m_{A^0} < 30$ keV
$<(1\text{–}5) \times 10^{-4}$	95	[5] TSUCHIAKI	90	CNTR	$o\text{-Ps} \rightarrow A^0 \gamma$, m_{A^0} = 300–900 keV
$<6.4 \times 10^{-5}$	90	[6] ORITO	89	CNTR	$o\text{-Ps} \rightarrow A^0 \gamma$, $m_{A^0} < 30$ keV
		[7] AMALDI	85	CNTR	Ortho-positronium
		[8] CARBONI	83	CNTR	Ortho-positronium

Dark Photon

- Light vector particle

$p-Ps \rightarrow \gamma XX$



J. Perez-Rıos, S. T. Love Eur. Phys. J. D (2018) 72: 44

Dark Z

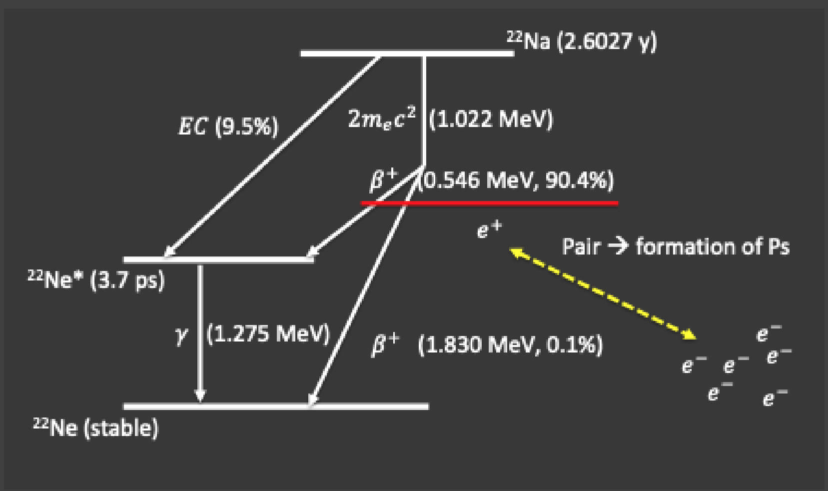
- Light vector particle

$p-Ps,\ o-Ps \rightarrow \gamma$

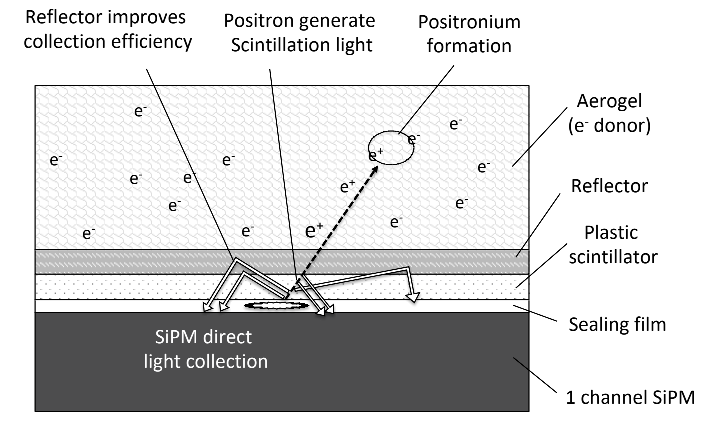
JUNG, LEE, and YU, *Phys. REV. D (2022)* 105, 095023

Introduction : KAPAE trigger

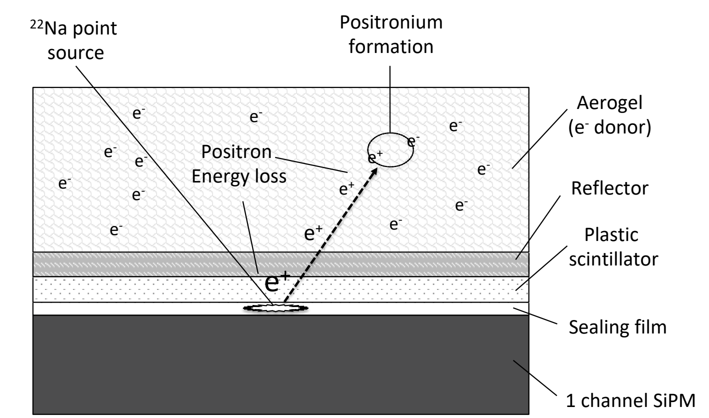
- Positronium = Electron + Positron
  - Positron → β^+ decay (^{22}Na)
  - Electron → aerogel
- Trigger signal
  → Plastic scintillator (PS)



Generation of trigger signal

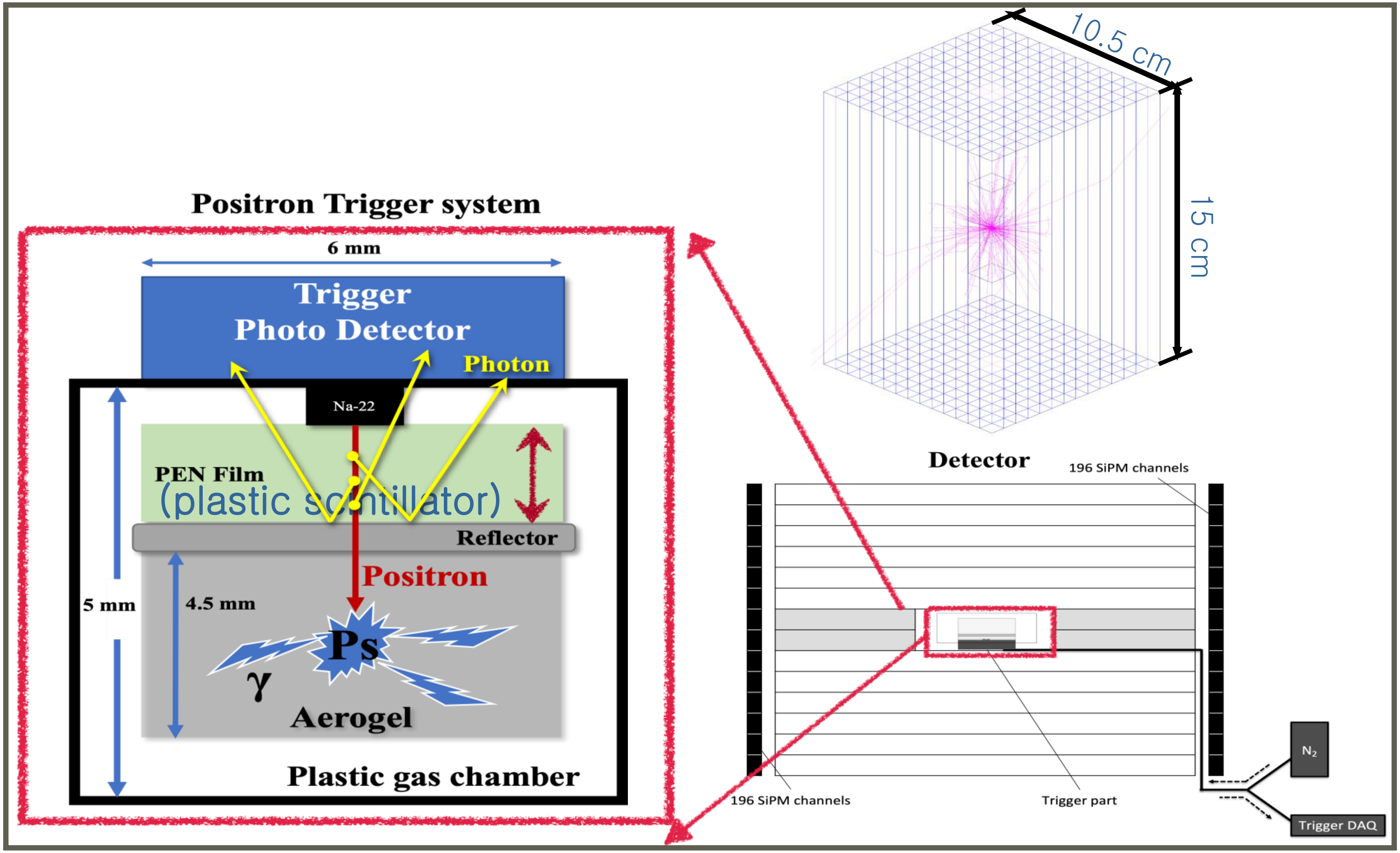


Positronium formation in aerogel



Trigger signal : e+ and 1.275 MeV coincidence trigger

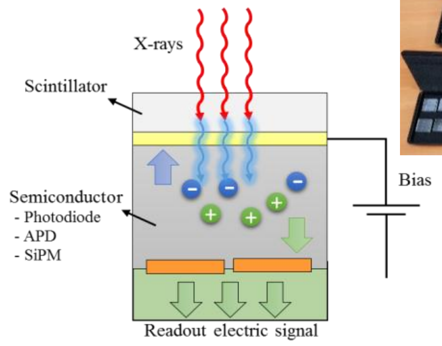
KAPAE-I : Design concept

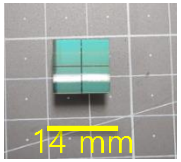


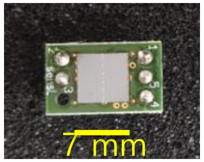
H.J.Kim, KNU

KAPAE-I : Detector design

- Customized Na-22 radioactive sources
  1 μCi, 2 μCi, 5 μCi (KRISS)
- 100 channel of 2x2 SiPM (400 channel)
- 7x7 mm SiPM for trigger
- 100 um of PEN film for trigger (optimized
- PreAMP + 65Mhz FADC : Notice Korea



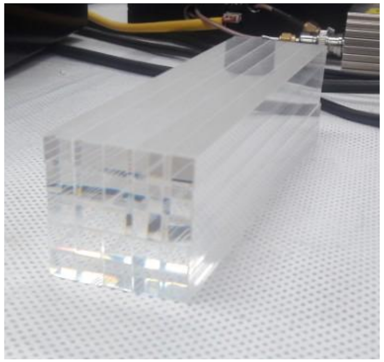


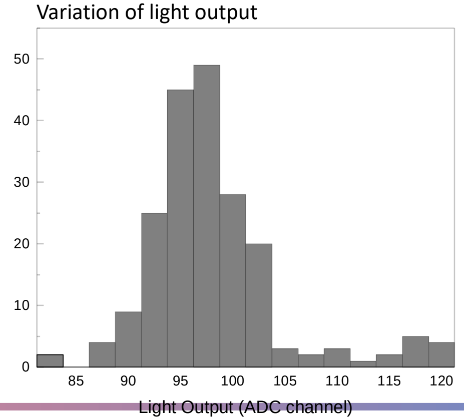


SiPM

- Bismuth germinate (BGO) scintillators
- Nikolaev Institute of Inorganic Chemistry(NIIC) in Russia
- 196 BGOs (7.5 x 7.5 x 150 mm^3)
- ^{137}Cs radiation source by coupling with PMT to confirm that the performance

Crystal scintillator





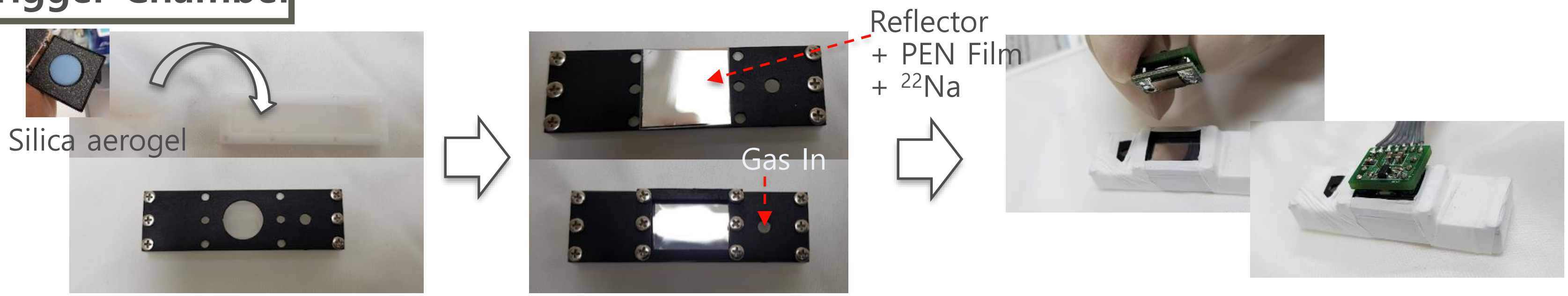
KAPAE-I : Hermetic detector assembly

KNU KYUNGPOOK NATIONAL UNIVERSITY

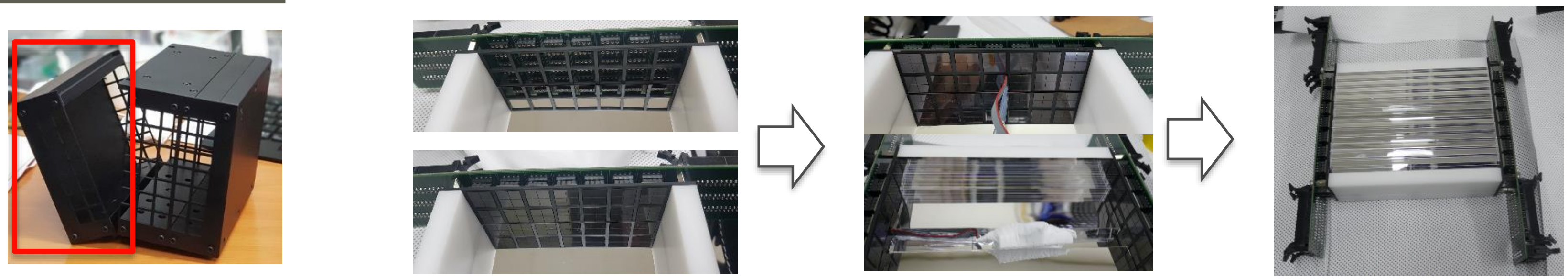
Partial assembly

- Partial assembly of 4 x 14 BGO array

Trigger Chamber



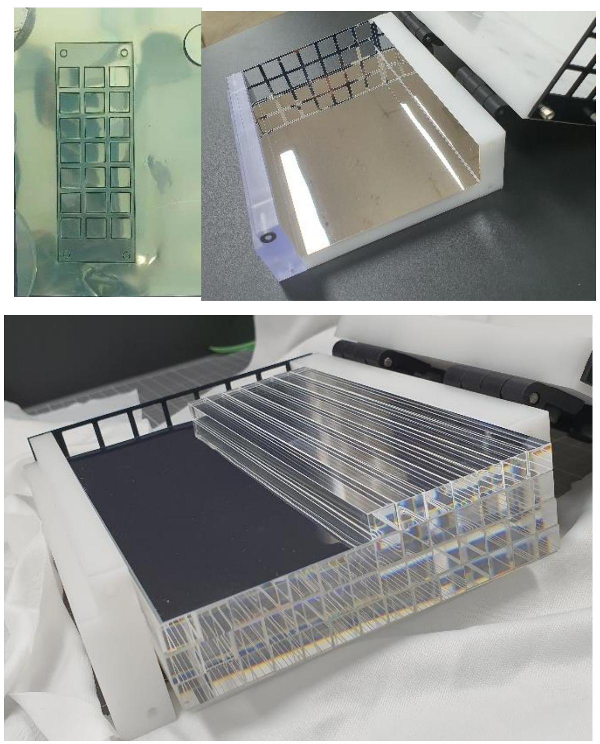
Partial assembly

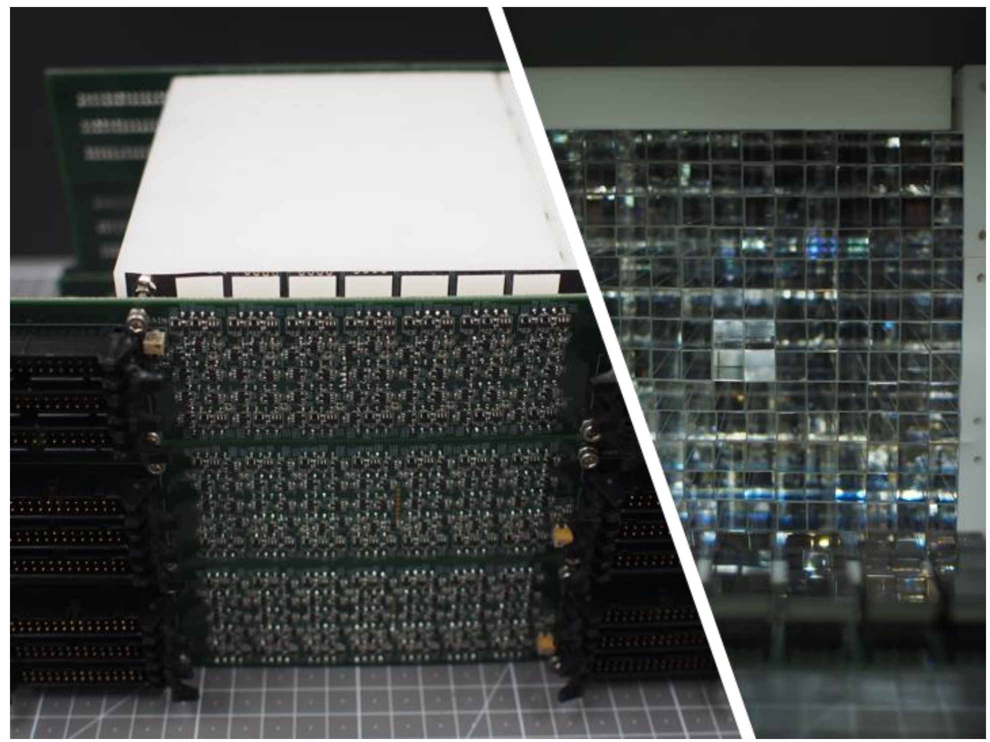


KAPAE-I : Full detector

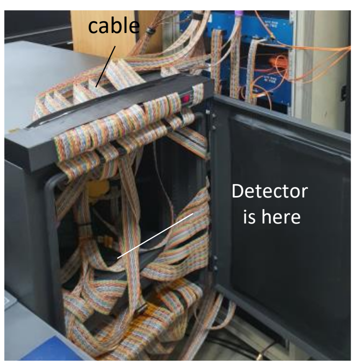
Full Detector assembly

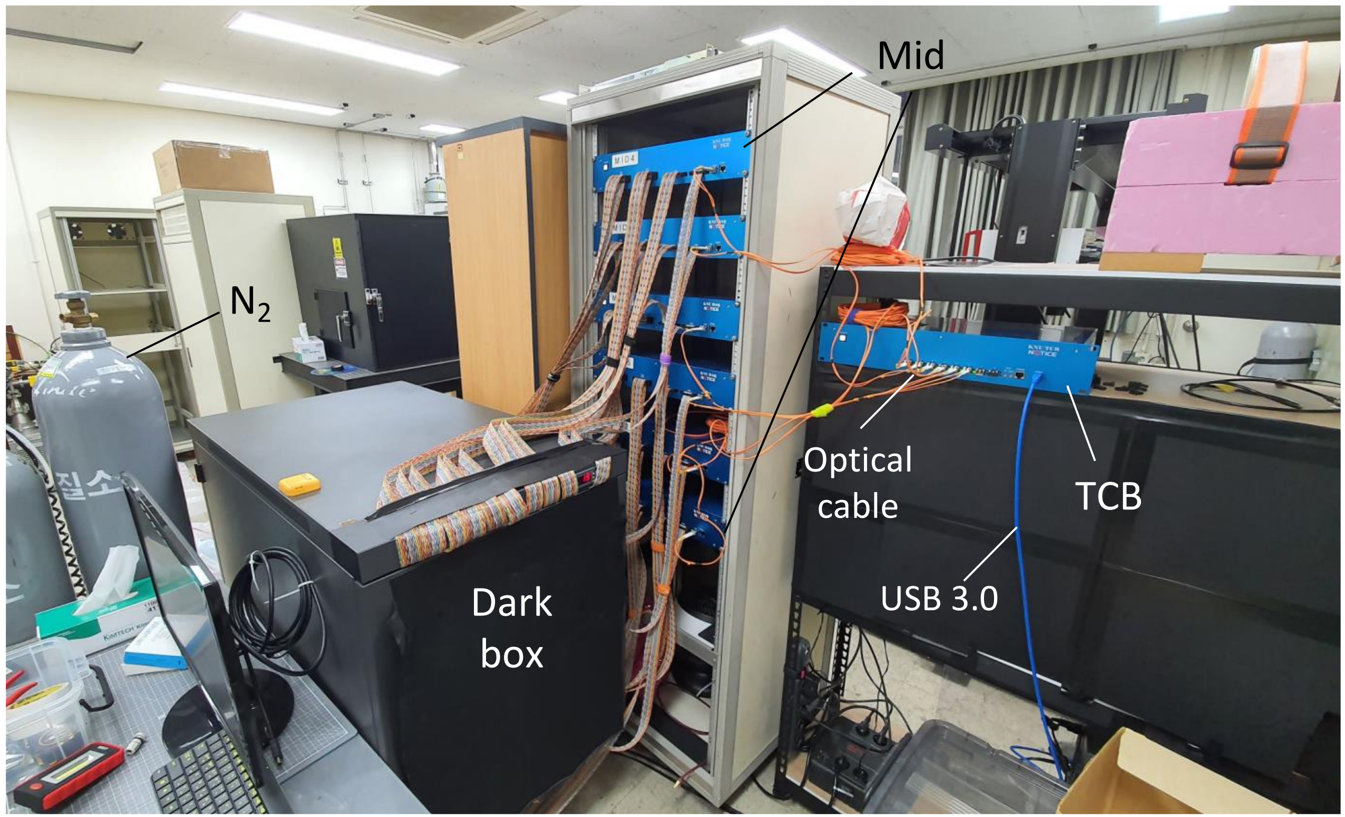
- Mockup + Partial → modify frame & full assembly





KAPAE-I :Detector setup and electronics

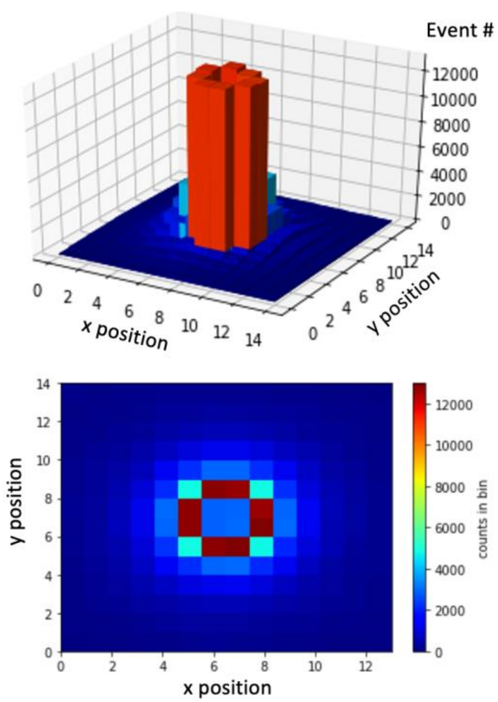




Entire hermetic detector system

KAPAE-I : Data

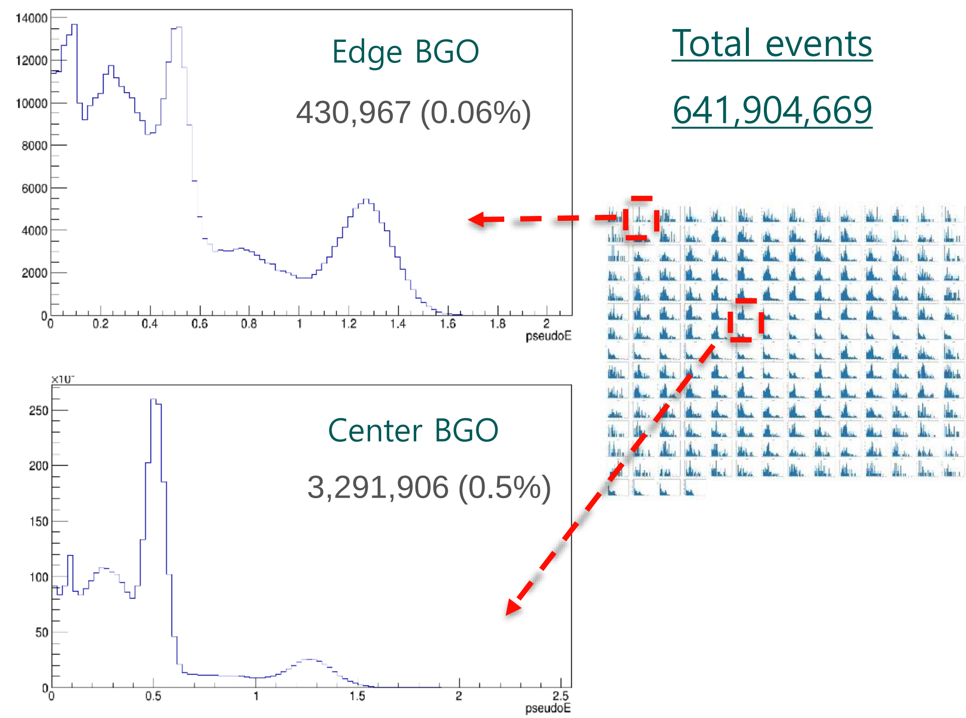
Event distributions of BGO location



3D & 2D graph

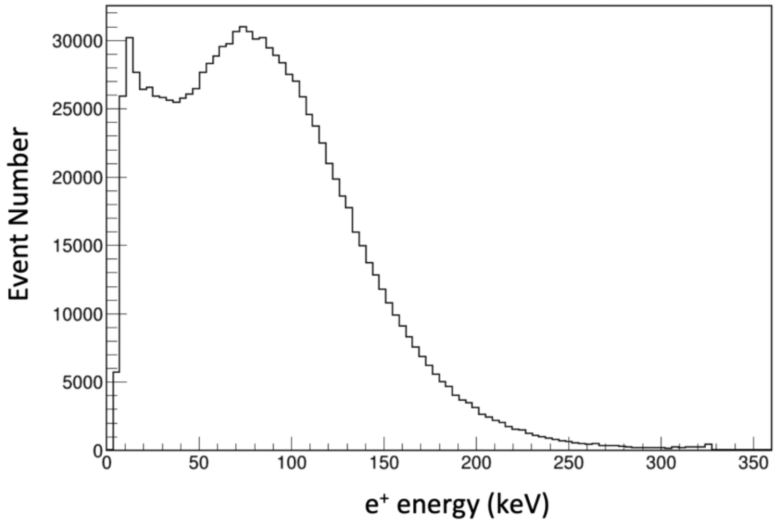
Total events

641,904,669



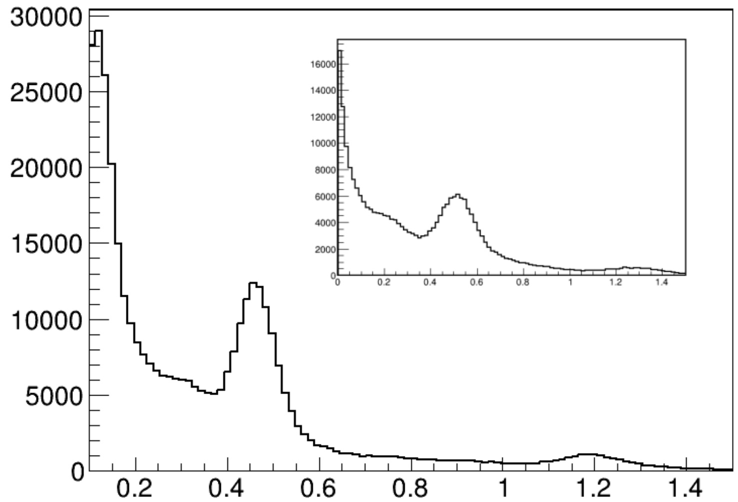
Energy spectrum at different locations

KAPAE-I : Data



- Positron trigger signal

  - DAQ firmware (Max rate = 2.5×10^4 Hz)

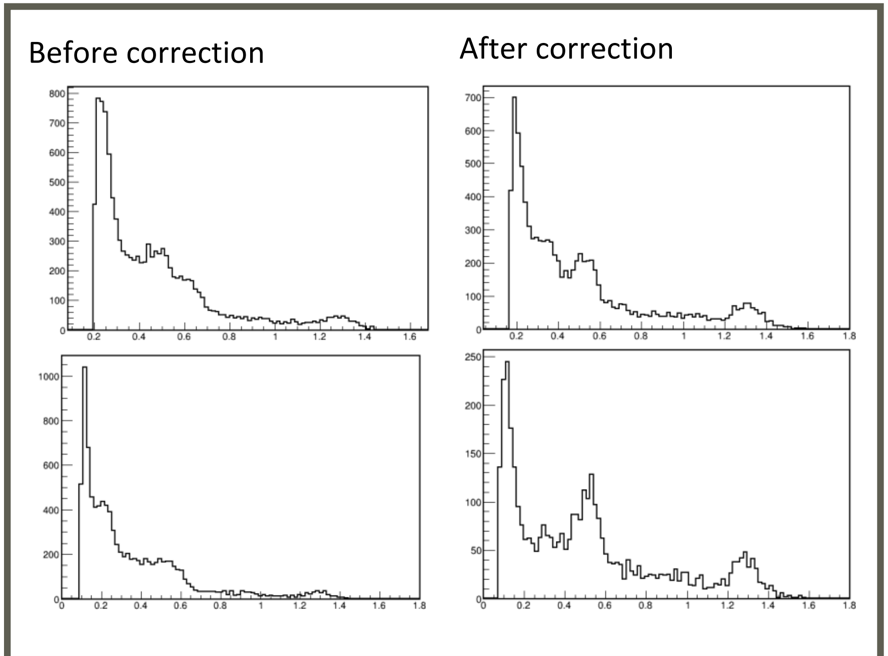


- BGO gamma signal

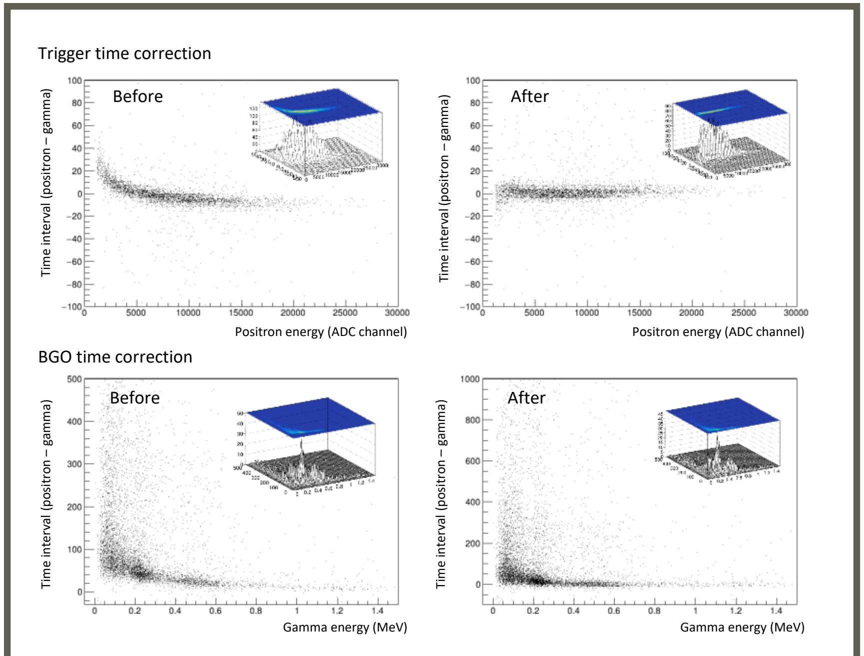
  - ER 20 ~ 35 % at 511 keV (FWHM)

KAPAE-I : Data analysis

- Adding adjacent BGO energy (ER 63% → 33%)
  - Optical crosstalk, Light leak due to misalignment (will be upgraded after finding a reason)
- BGO Left (ER 33%) + Right (ER 38%) → BGO Total (ER 26%) → Correction (ER 25%)
- Leading edge time discrimination → Time walk correction



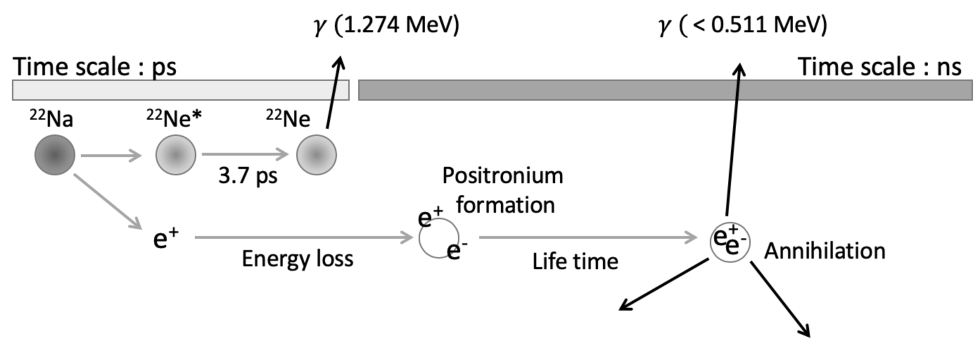
Energy correction



Time walk correction

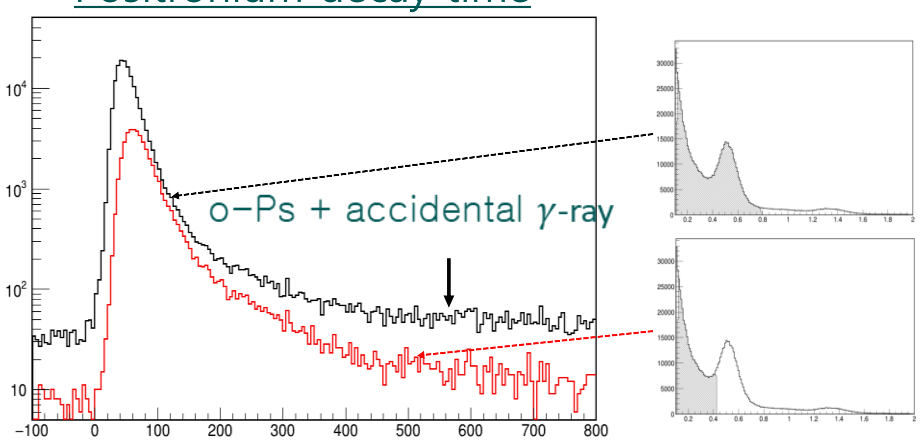
KAPAE-I

- Time data → Cut parameters for o-Ps (142 ns)
- Time resolution → positron trigger signal vs. 1.274 MeV gamma signal - 3.54 ns

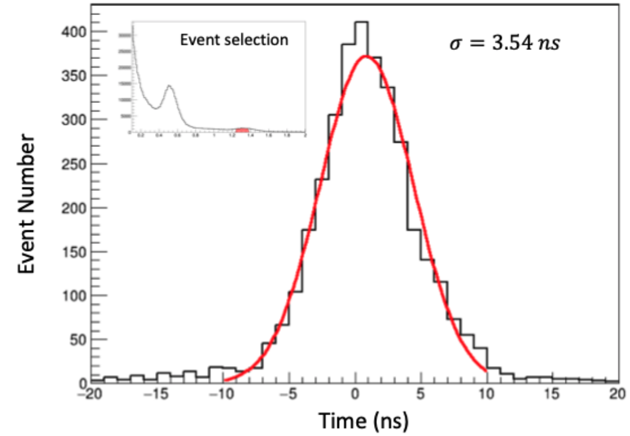


Timeline

Positronium decay time



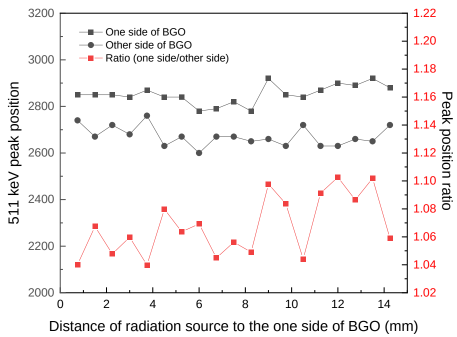
Trigger vs. 1.274 MeV

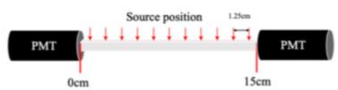


KAPAE-I : Data analysis

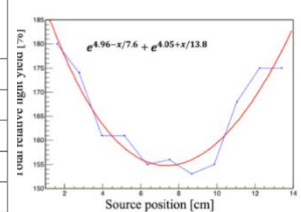
KNU KYUNGPOOK NATIONAL UNIVERSITY

- Position reconstruction
- Z position cannot be distinguished → XY projection position reconstruction
- Kinematic fit will be used if we fail to reconstruct Z position

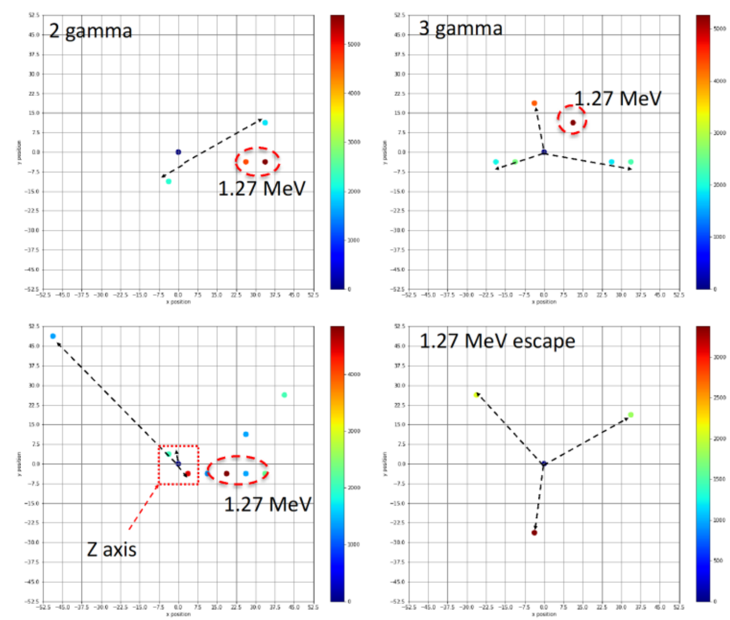




	Source position [cm]	ADC mean [channel]	Energy resolution [%]	Relative light output [%]
Teflon	1.25	5361.01	19	100
	13.75	4178.89	18	77.95
VM2000	1.25	5788.33	17	100
	13.75	5731.43	17	99.02
Without Reflector	1.25	947.39	16	100
	13.75	889.35	15	93.87



Attenuation length test



Track reconstruction

H.J.Kim, KNU

KAPAE-II Physics

Invisible decay of positronium study

1st experiment : p-PS : 2025

Partial invisible decay of p-Ps
- p-Ps to Gamma + X
- Dark photon, Dark Z

Total invisible decay of p-Ps
- p-Ps to X
- Mirror world

2nd experiment : o-PS : 2026

Partial invisible decay of o-Ps
- Axion like particle and other light boson

Total invisible decay of o-Ps
- Axion like particle and other light boson
- Milli-charged particle
- Extra-dimensions

KAPE-II p-Ps motivation

Dark photon - partial invisible

$$\Gamma_{Ps\to\gamma X\overline{X}} = 4|\Psi_{Ps}(0)|^2 (v_{rel}\sigma_{e^+e^-\to\gamma X\overline{X}})_{v\to 0}$$

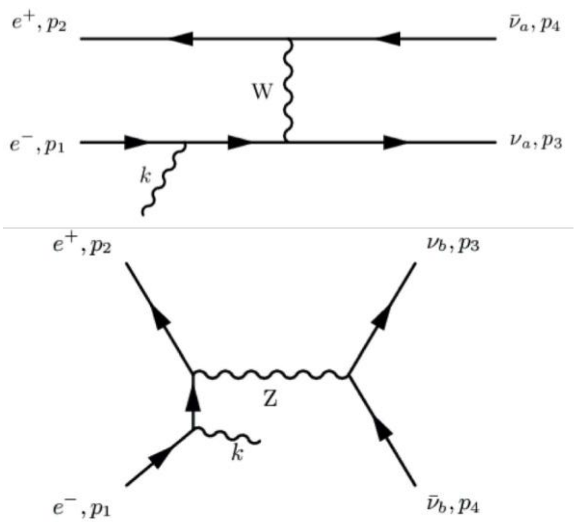
$|\Psi_{Ps}(0)|^2$: *Theelectrondensityforasingleatom*

v_{rel}: *Relativevelocity*

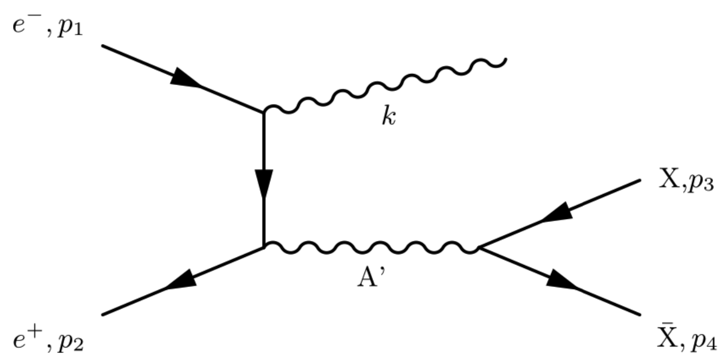
Standard model background

$Br(p-Ps\to\gamma\nu\overline{\nu})\approx 4.3\times 10^{-24}$

$Br(p-Ps\to\gamma X\overline{X})\lesssim 10^{-10}(\epsilon\simeq 10^{-6}, m_{A'} = 10-500\,\mathrm{keV})$ [ref*]



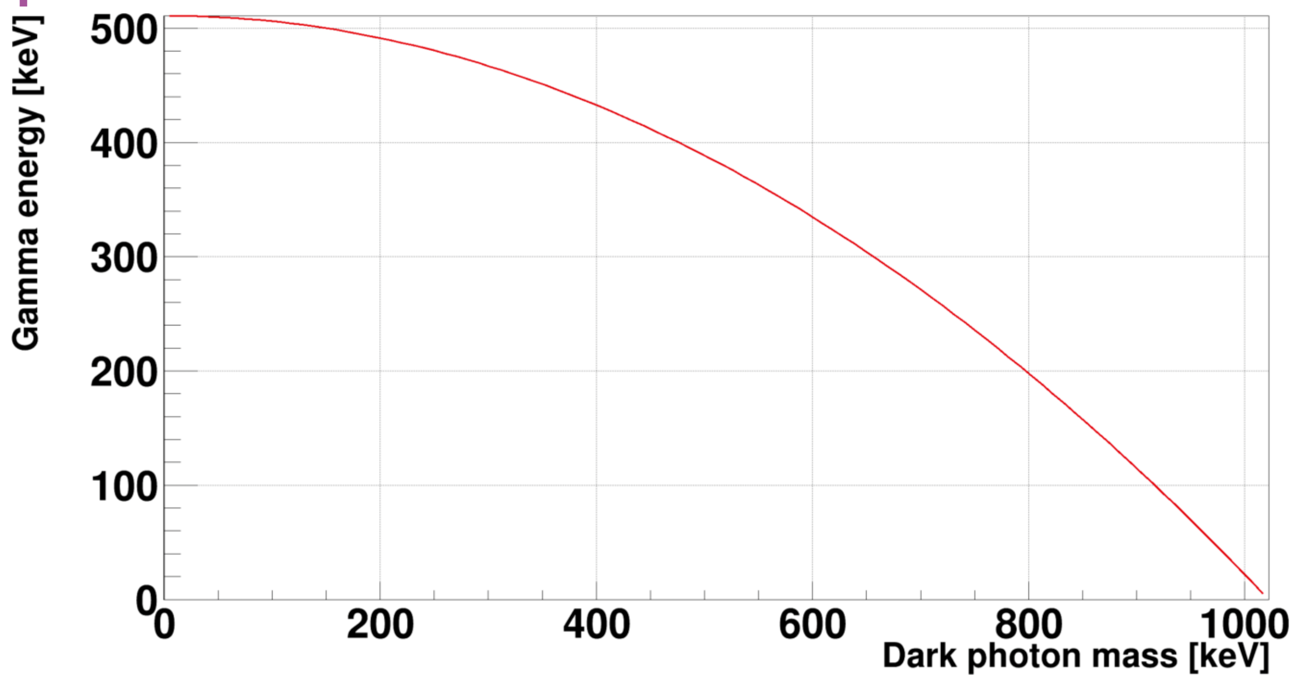
A new model for which no experimental upper limit on the branching ratio has been reported.



*[J. P´ erez-R´ ıos and S. T. Love, "Searching for light dark matter through positronium decay," The European Physical Journal D, vol. 72, pp. 1–5, 2018]

KAPAE-II : Eg vs Mdp

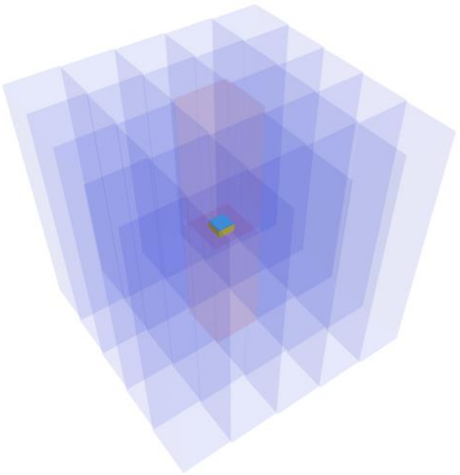
Dark photon - partial invisible

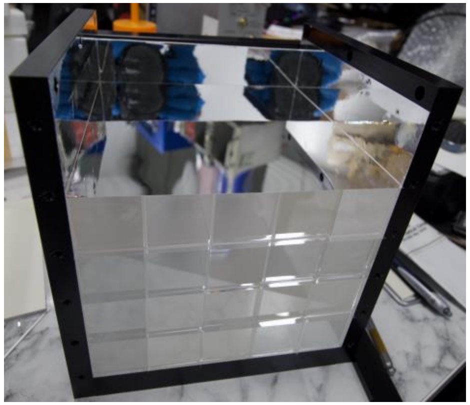


$$E_\gamma = m_e\left[1-\left(\frac{m_{A'}}{2m_e}\right)^2\right]$$

- E_γ: Emitted Gamma energy
- $m_{A'}$: Dark photon mass
- m_e: Electron mass

KAPAE-II : Detector Design



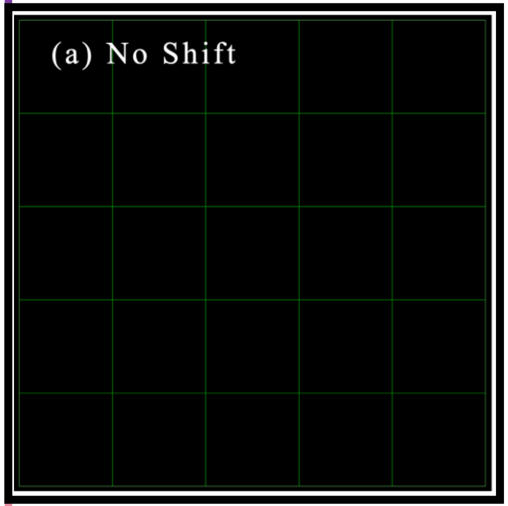


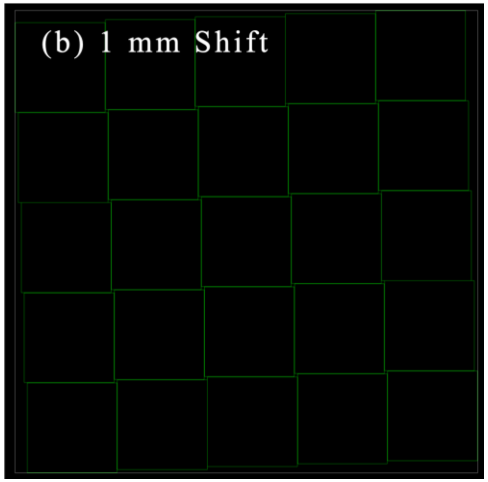
- Bigger size, **less channel (27)**
- 30 x 30 x 150 mm^3 BGO
- 5 x 5 array **150 x 150 x 150 mm^3**
- **Reduced dead area**
- **Underground cryogenic operation**
- p-Ps **invisible decay**
- o-Ps invisible decay (next step)

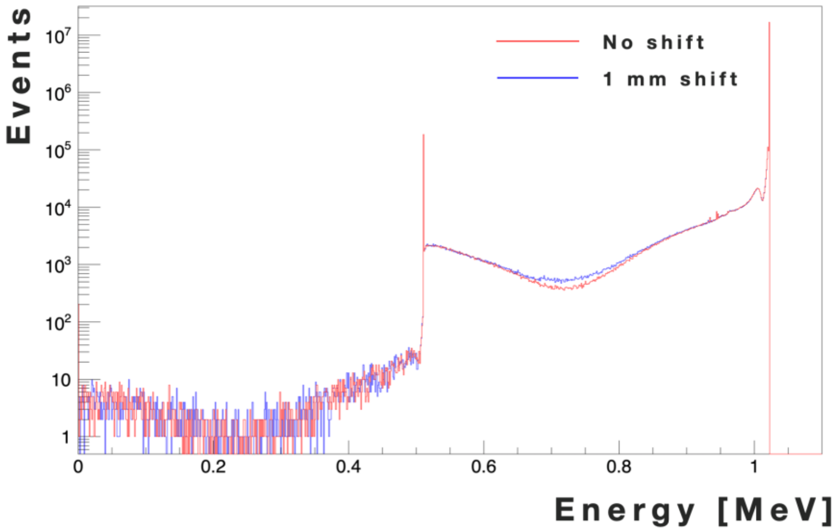
Dongwoo Jeong, Hyeoungwoo Park, and H.J. Kim. "Development of the KAPAE II Detector for New Particles Search in Positronium Decay". In: Acta Phys. Pol. A (2024).

KAPAE-II : Detector Design

Geant4 simulation for design







Investigation of the effect of a uniform lattice structure on the escape of 511 keV gamma rays.
Based on the comparison results, the effect was determined to be negligible, and the “No Shift” design was adopted.

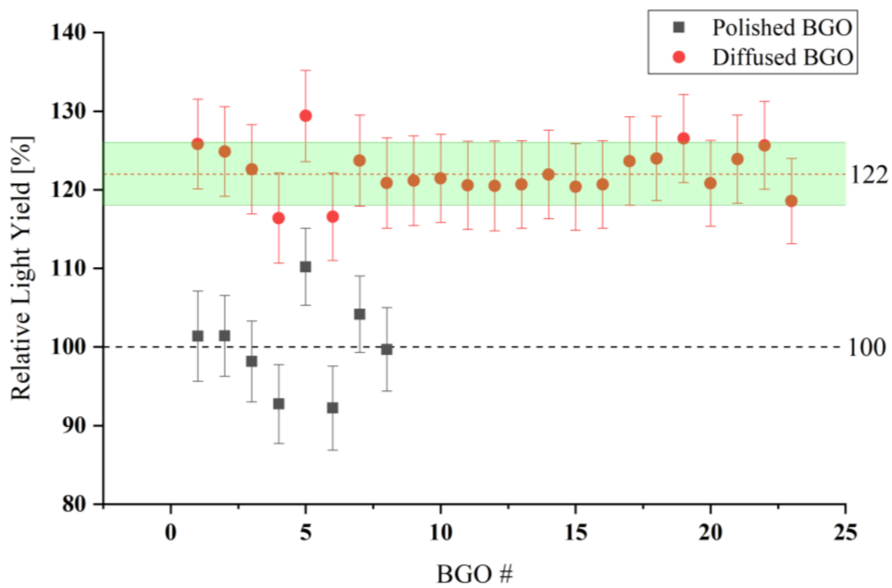
KAPAE-II : Detector Design

BGO crystal scintillator

Out of 26 BGO scintillation crystals, 2 endcap crystals were excluded due to size difference, and 1 was used as a reference. Therefore, 23 barrel-type crystals were tested.

Detector Design

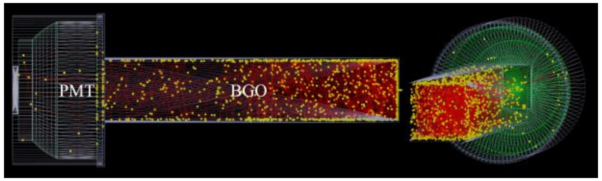
Light collection efficiency



The average light yield of **polished BGO crystals** was normalized to **100%**.

Simulation results

bulk attenuation length [m]	Light collection efficiency [%] Polished	Diffused	Light improvement [%]
1	18.5	24.6	32.9
2	32.9	41.6	26.4
3	43.1	52.3	21.3
4	50.5	59.6	18.0
5	56.2	64.8	15.3



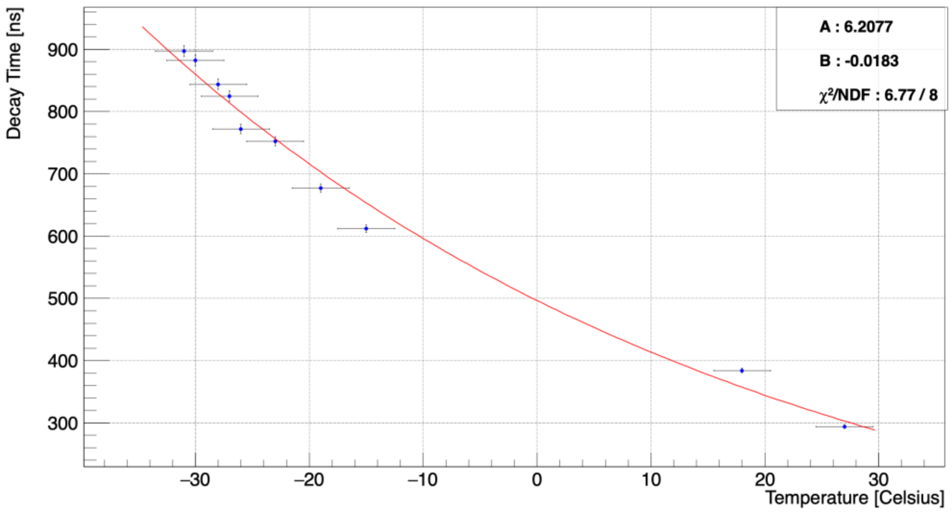
Our results show a significant improvement in energy resolution, achieving an average of 10.8% at 662 keV, compared to the previously reported 15% in other studies. (detail in backup slide)

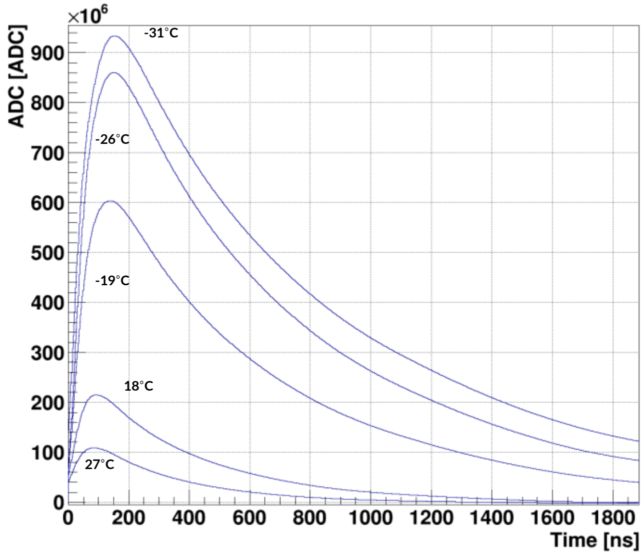
D.W. Jeong et al. "Optimization of Scintillation Light Collection Efficiency in BGO Crystals with Surface Diffusion for Enhanced Sensitivity in the KAPAE". In: IEEE Transactions on Nuclear Science (2025)

KAPAE-II : Detector Design

BGO decay time

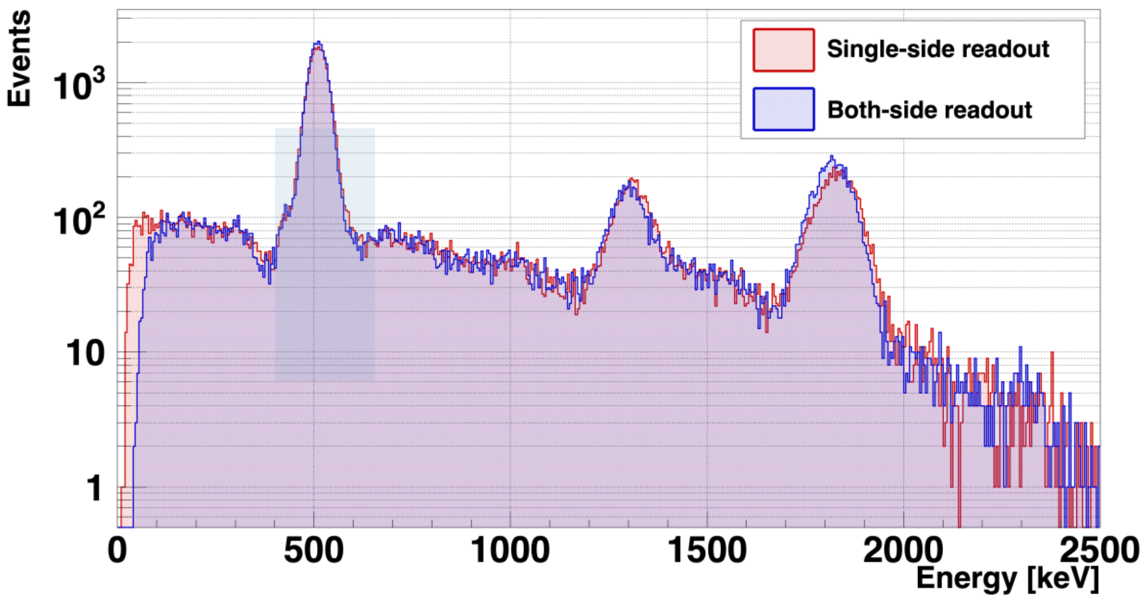
- The decay time of a BGO crystal increased from 300 ns at room temperature to 789 ns at -26 °C[Ref*].
- The decay time was fitted with the exponential function; $decaytime = e^{(A+B\times temp)} = e^{(6.2-0.018\times temp)}$.





KAPAE-II :Detector Design

Readout configuration



Single-side readout

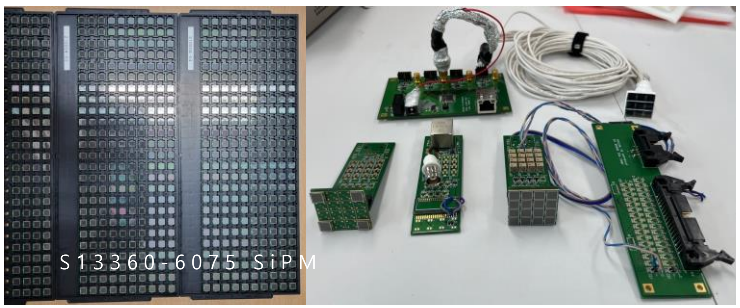
Both-side readout

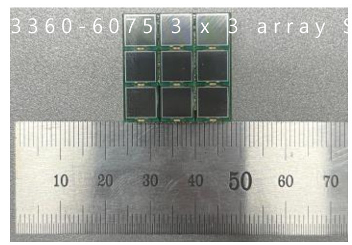
The **single-side readout showed 12%** resolution, and after calibration, the **both-side readout gave 11.2%**. Considering increased calibration errors with more channels, the gain was minimal, so a **single-sided readout was chosen.**

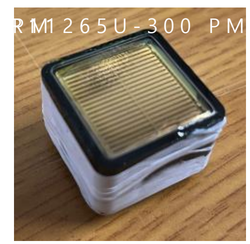
KAPAE-II : Detector Design

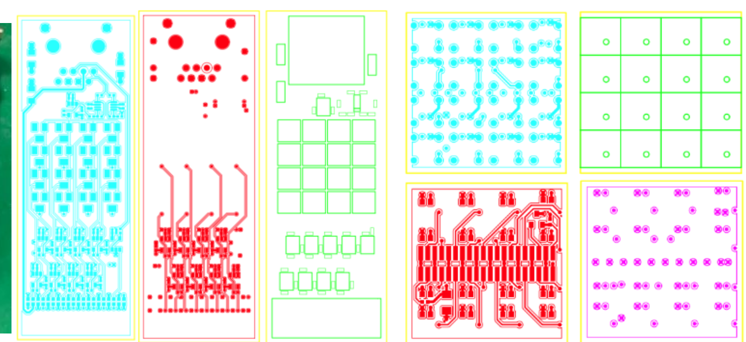
- R11265U-300 PMT energy resolution 16.5 % @ 511 keV
- S13360-6075 3 x 3 array SiPM energy resolution 15.1 % @ 511 keV
- S13360-6075 4 x 4 array SiPM energy resolution 14.8 % @ 511 keV

Photodetector



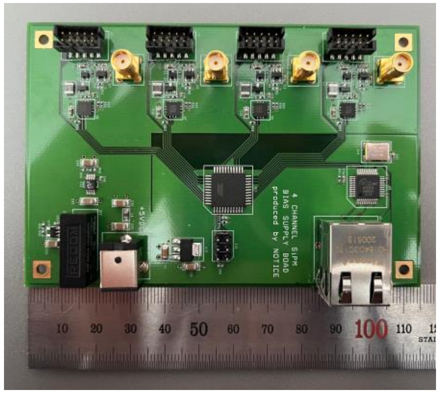




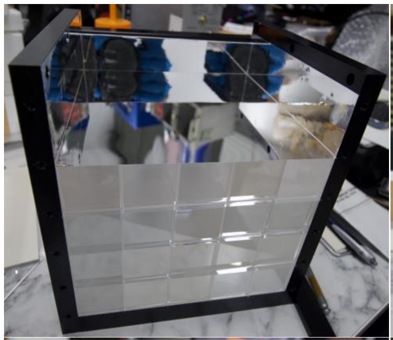
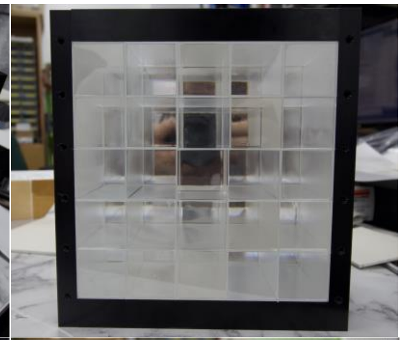


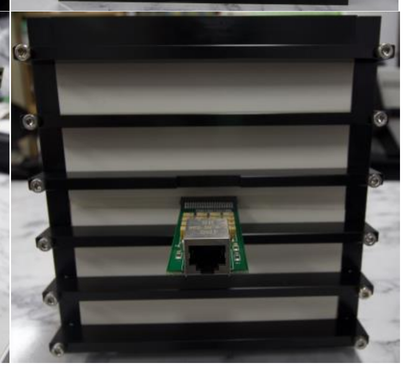
KAPAE-II : DAQ

- Multiplicity trigger (PEN + BGO)
- Waveform data
- Charge data
- Real-time pedestal correction
- Pulse shape information (peak time, mean time, pulse height, TDC time)
- 12-bit ADC, 62.5 MHz, 1.3 ns TDC
- Customized by Notice

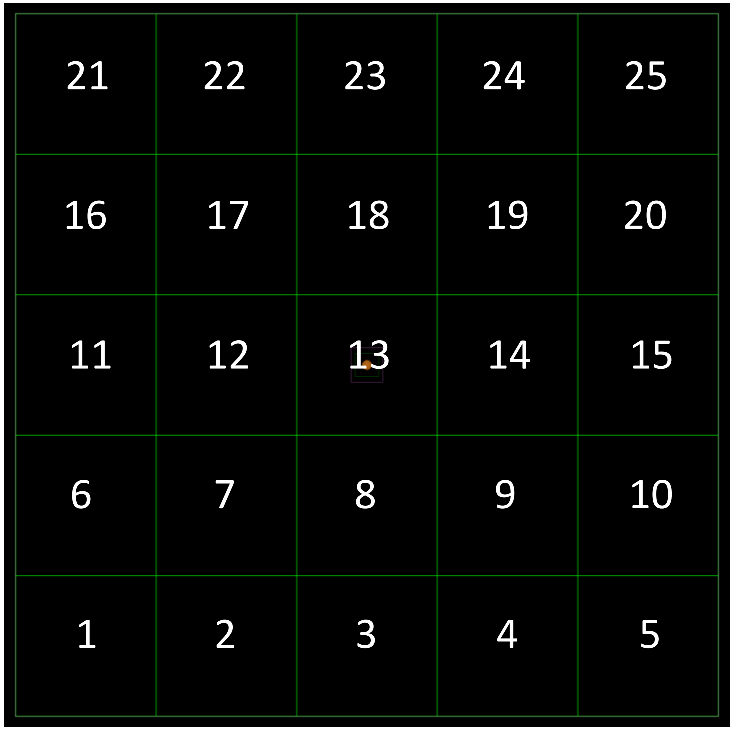


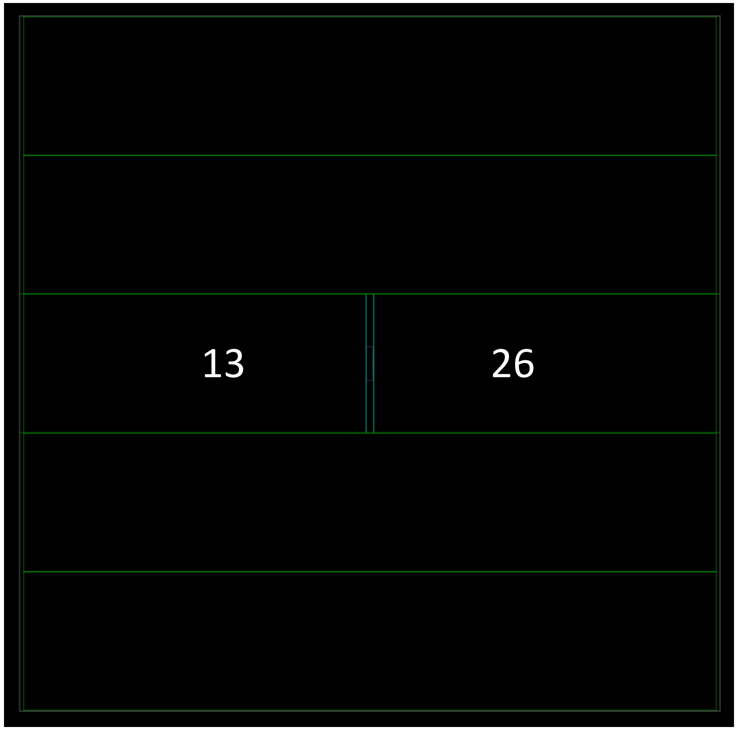
KAPAE-II : Detector assembly

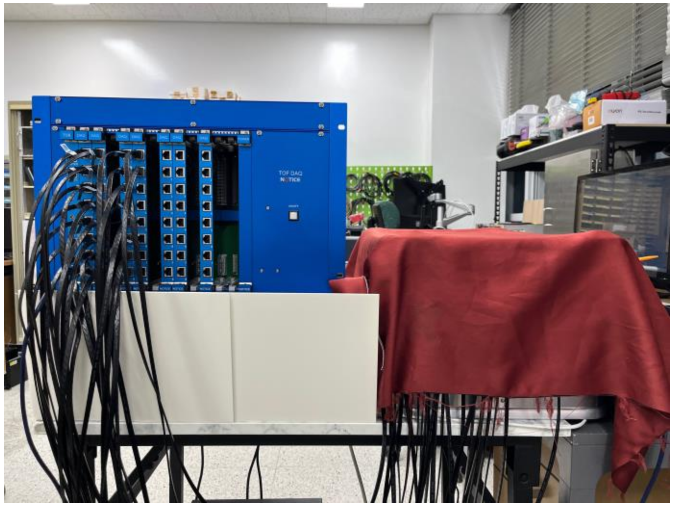

KAPAE-II : Detector mapping





KAPAE-II : Overground test

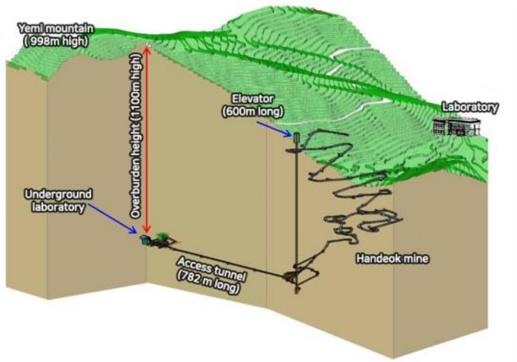
Room temperature installation

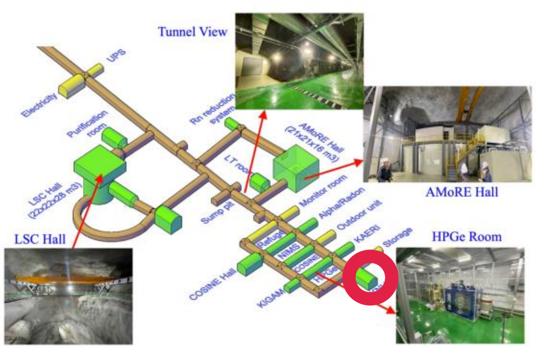


Rapid cooling chamber

Assembled detector

KNU lab at Yemi Underground lab.

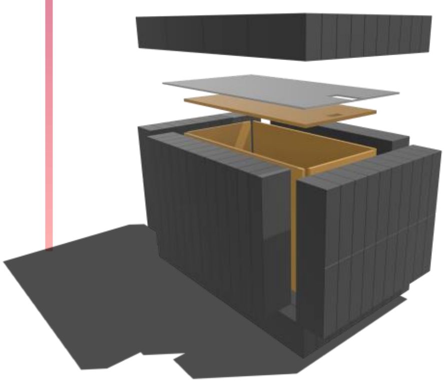


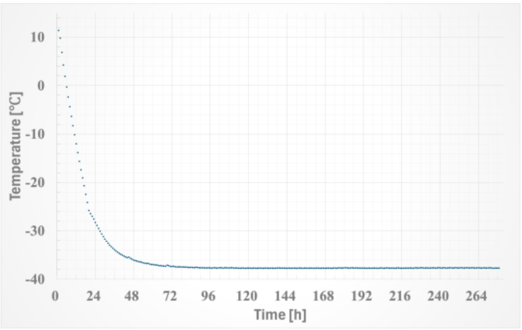


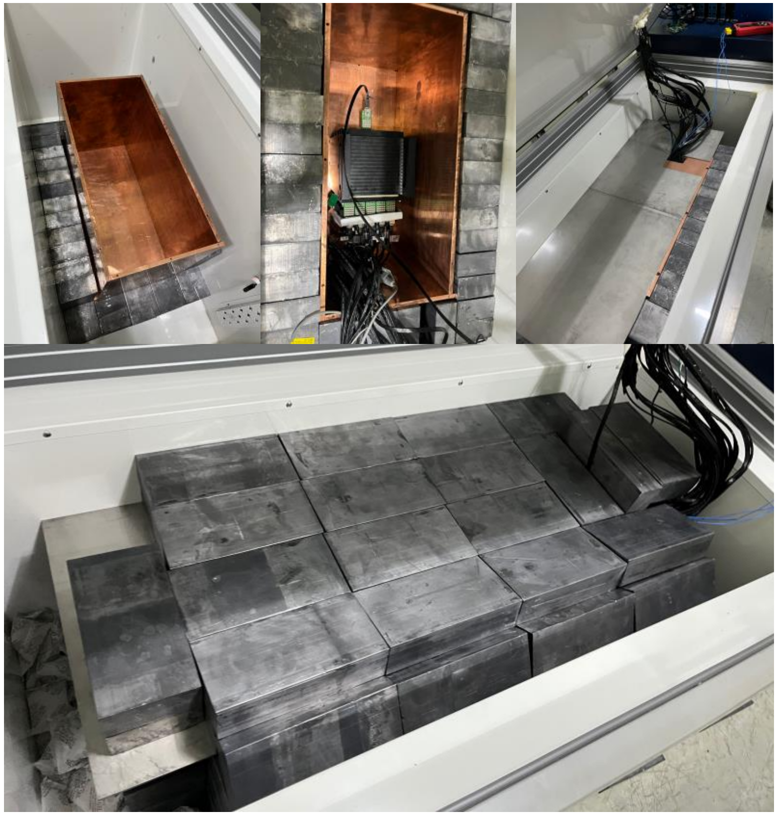
Yemi-Lab
KNU Experimental hall

KAPAE-II : Yemi lab installation

- The detector, copper case, and lead shielding were installed in the Yemi underground lab.
- The total shielding structure measures 500 × 800 × 600 mm³, with 100 mm thick lead and oxygen-free copper.
- Cryogenic operation at −37.5 °C was stabilized after 3 days and maintained within ±0.5 °C for 19 days.

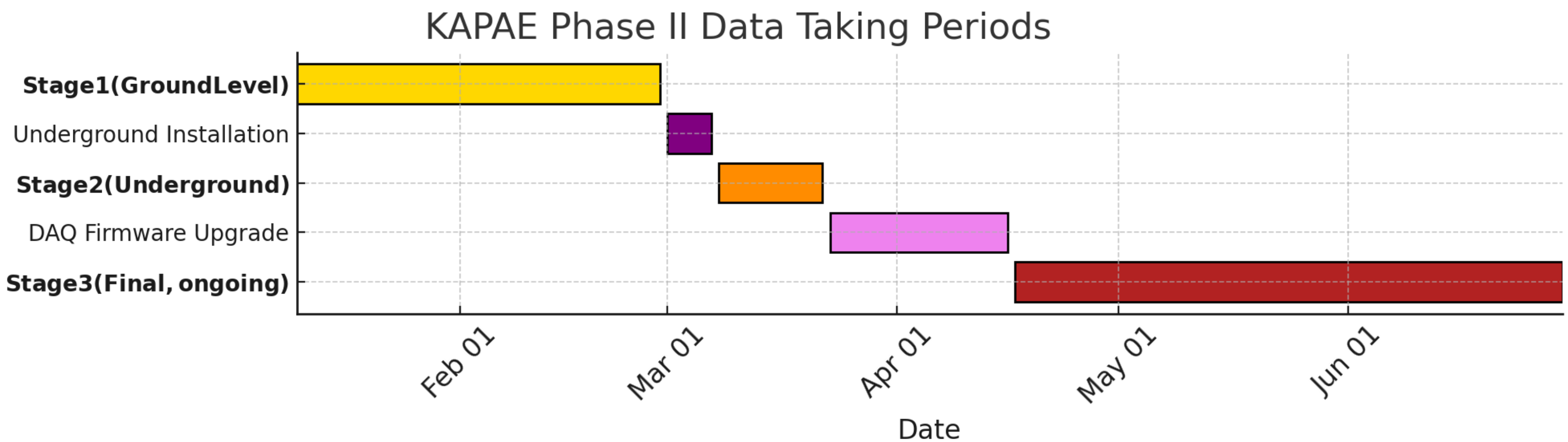




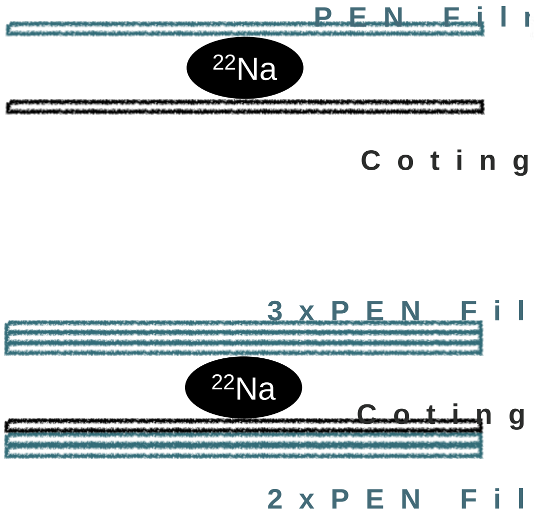


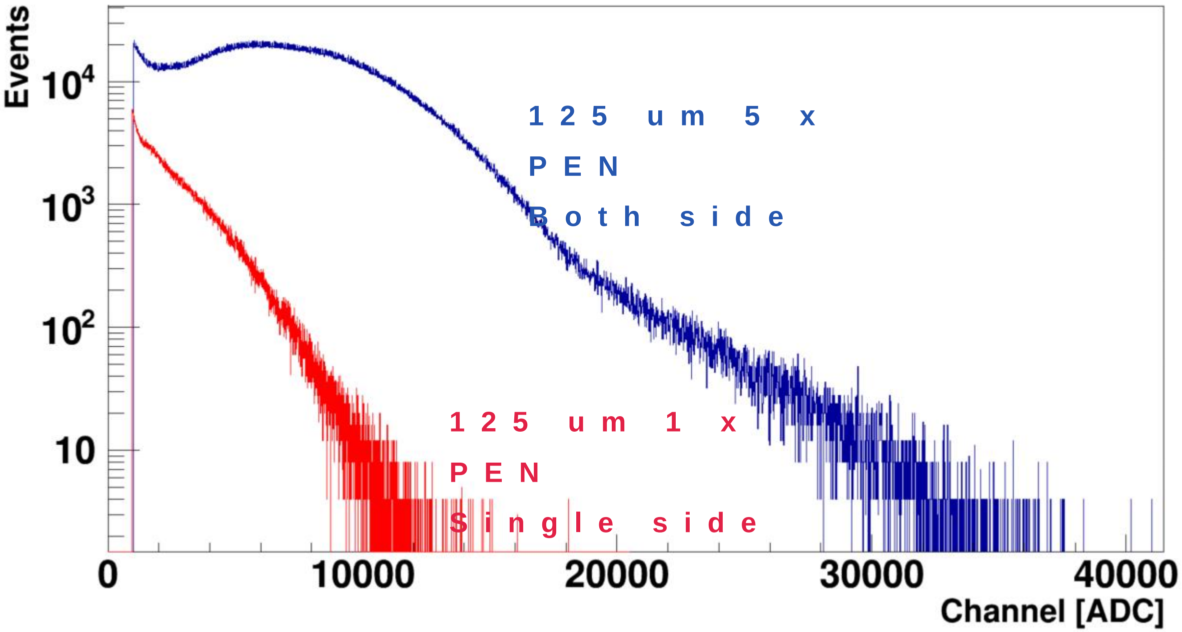
KAPAE-II : Data taking

- Ground level data : 2025 Jan. 10 - Mar. 01
- Underground installation : 2025 Mar. 02 - Mar. 06
- Underground data : 2025 Mar. 07 - Mar. 24
- DAQ system upgrade : 2025 Mar. 25 - Apr. 16
- Data taking : 2025 Apr. 17 – Oct. 16 **(6 month)**



KAPAE-II : e+ trigger signal

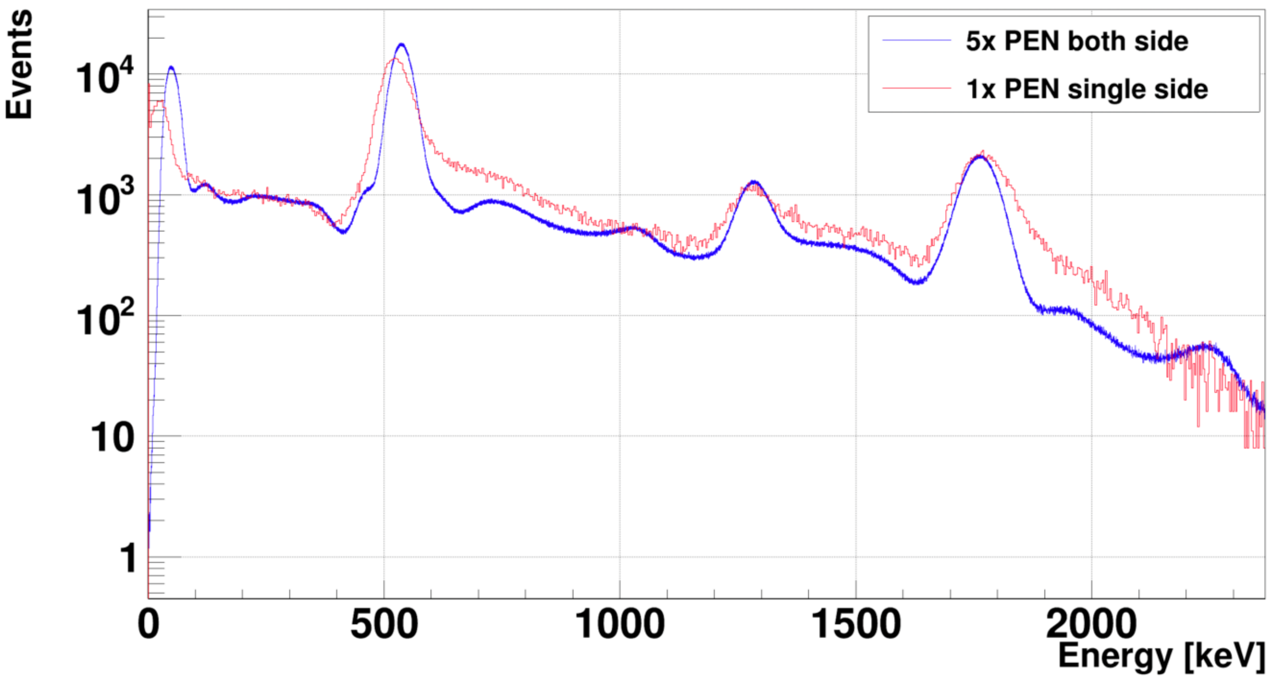




KAPAE-II : Results

- *D.W. Jeong et al. "Optimization and characterization of detector and trigger system for a KAPAE design". In: Nucl. Instrum. Methods Phys. Res. A 989 (2021), p. 164941. issn: 0168-9002.*

Impact of the positron trigger on BGO channels

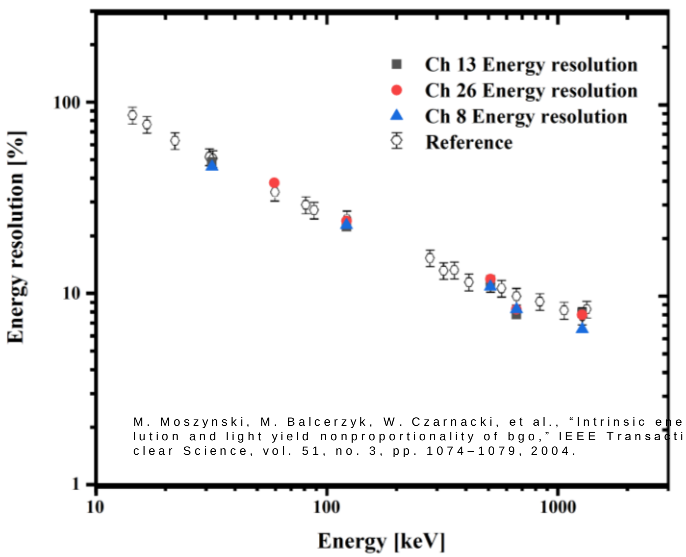


The right side of the tail of the full peak is due to positron energy deposition.

KAPAE-II : Results

Detector BGO energy spectrum

Energy [keV]	Room temperature Average FWHM [%]	-37°C Average FWHM [%]
511	14.8 ± 1.6	11.7 ± 1.5
1274	7.9 ± 0.8	6.5 ± 0.5



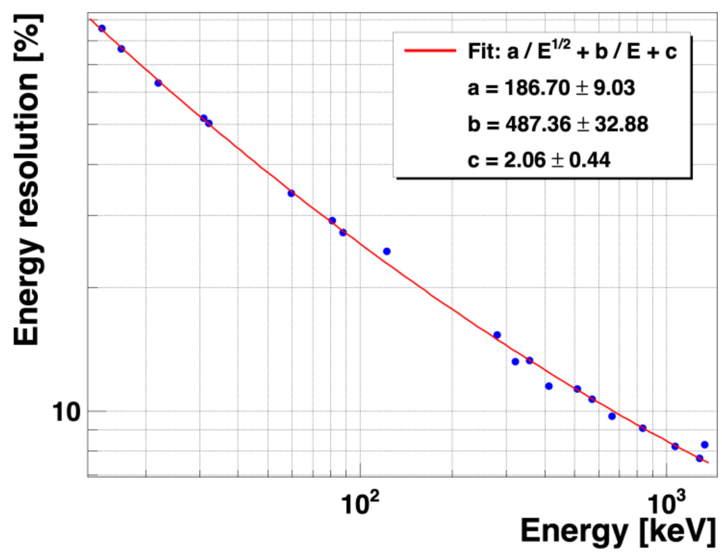
M. Moszynski, M. Balcerzyk, W. Czarnacki, et al., “Intrinsic energy resolution and light yield nonproportionality of bgo,” IEEE Transactions on Nuclear Science, vol. 51, no. 3, pp. 1074–1079, 2004.

$$\frac{\sigma_E}{E}(\%FWHM) = \frac{a}{\sqrt{E}} + \frac{b}{E} + c$$

a: Statistical fluctuation contribution

b: Instrumental contribution (noise, pedestal, etc.), relatively energy-independent

c: Systematic contribution (calibration errors, non-uniformity, non-linearity), energy-independent

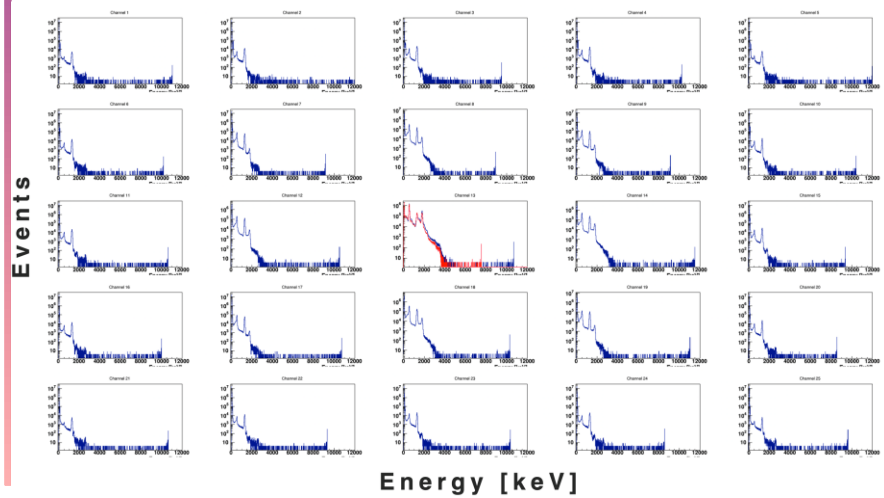


H.J.Kim, KNU

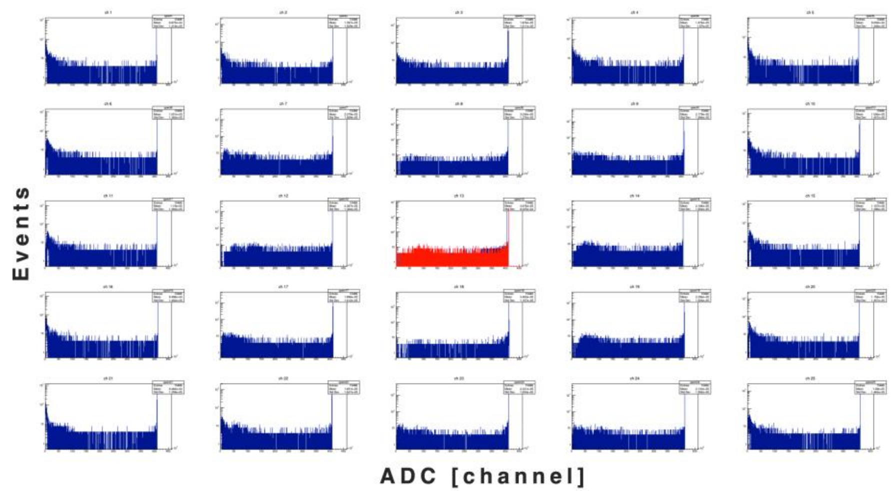
KAPAE-II : Results

Ground level energy spectrum

Ground with source

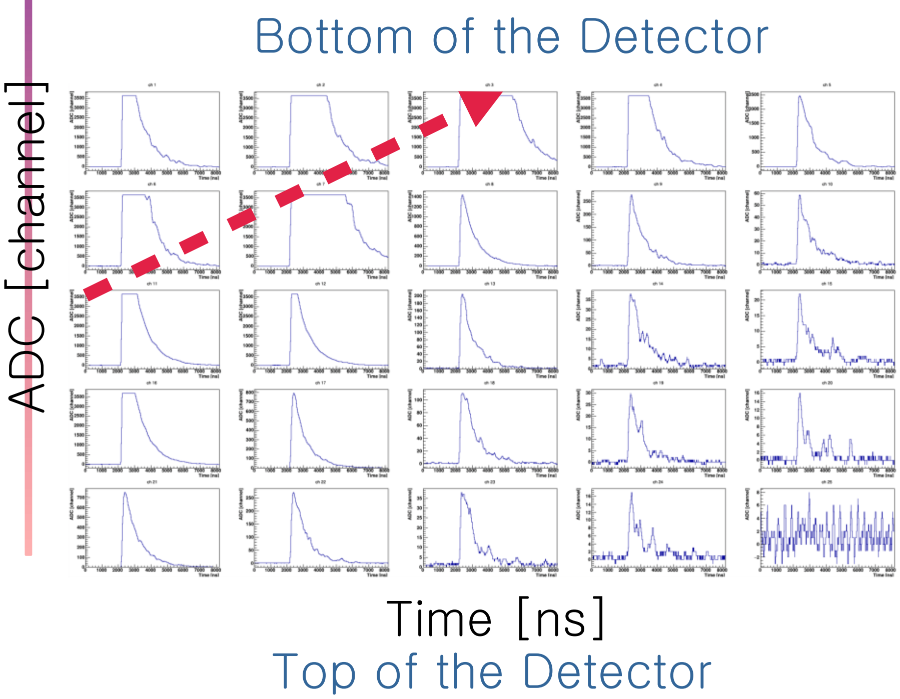


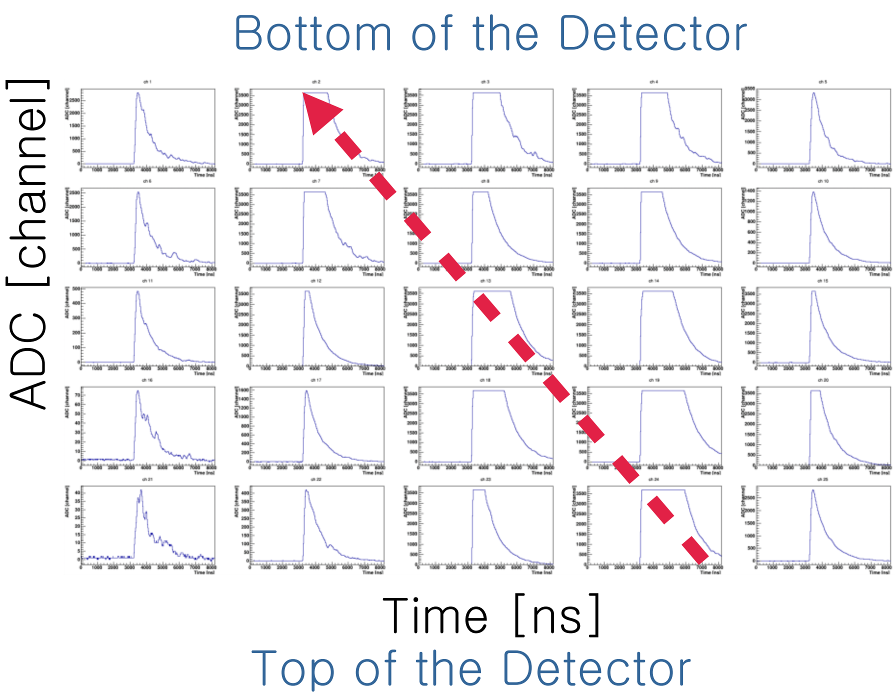
Ground without source : 0.06 Hz with coincidence trigger



KAPAE-II : Results

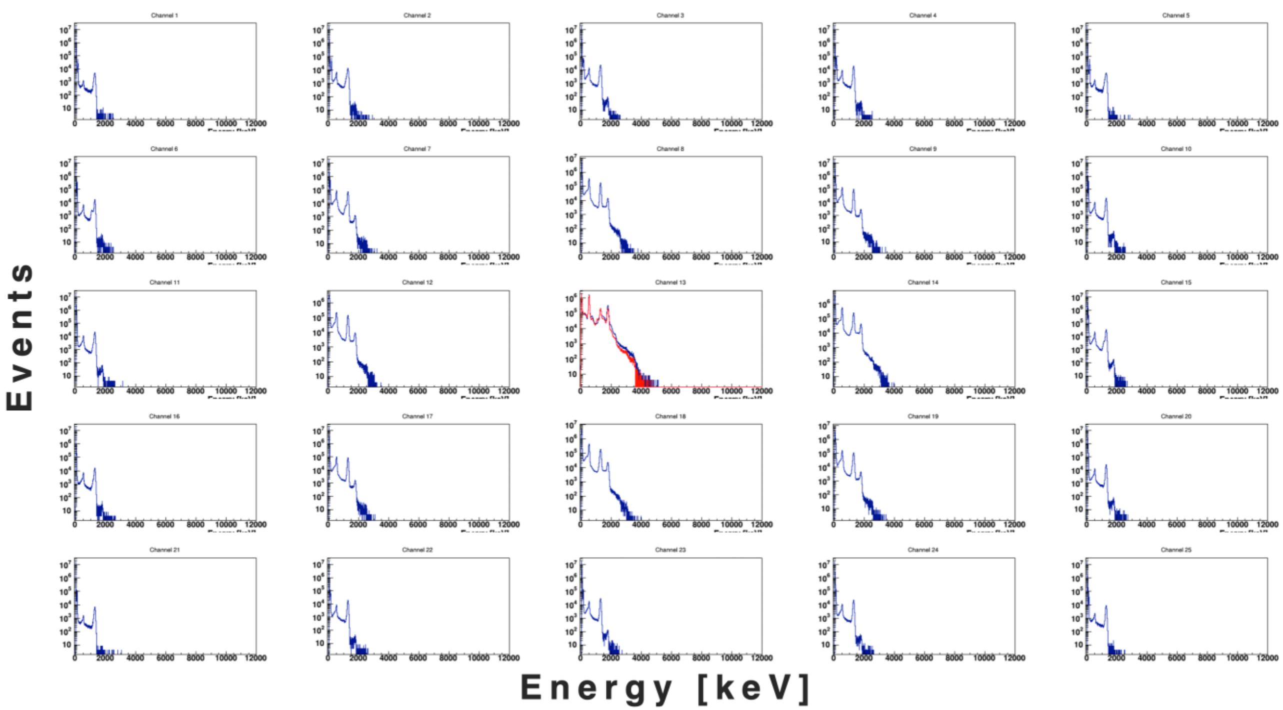
Ground level high energy background waveform

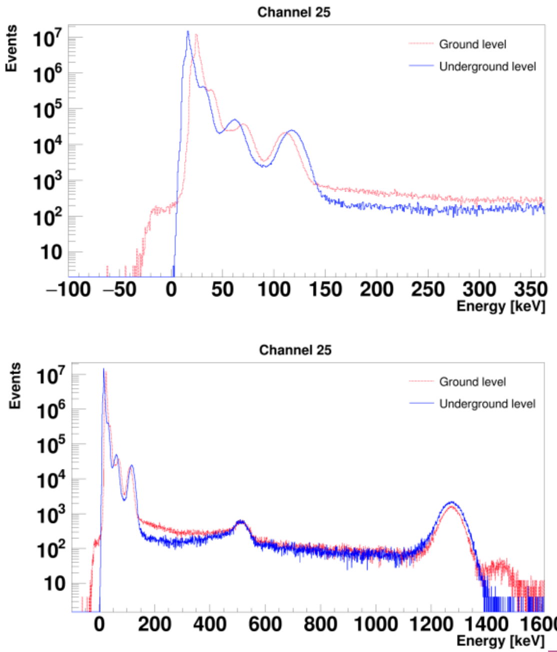




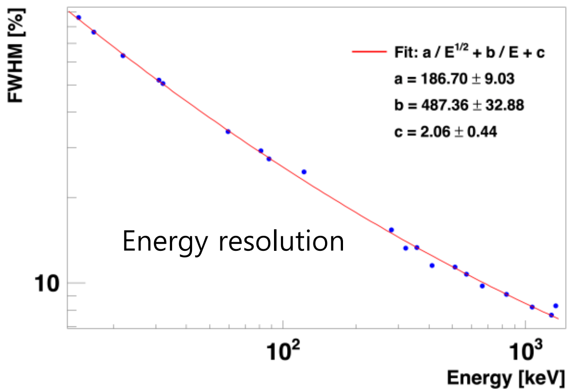
KAPAE-II : Results

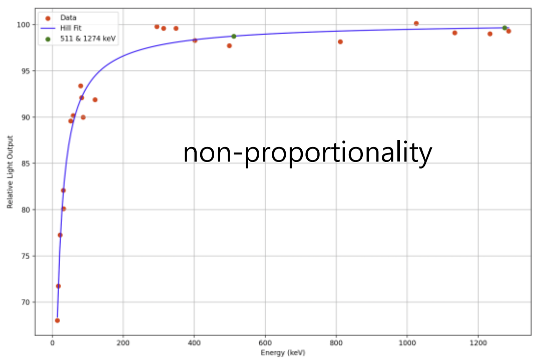
Underground energy spectrum

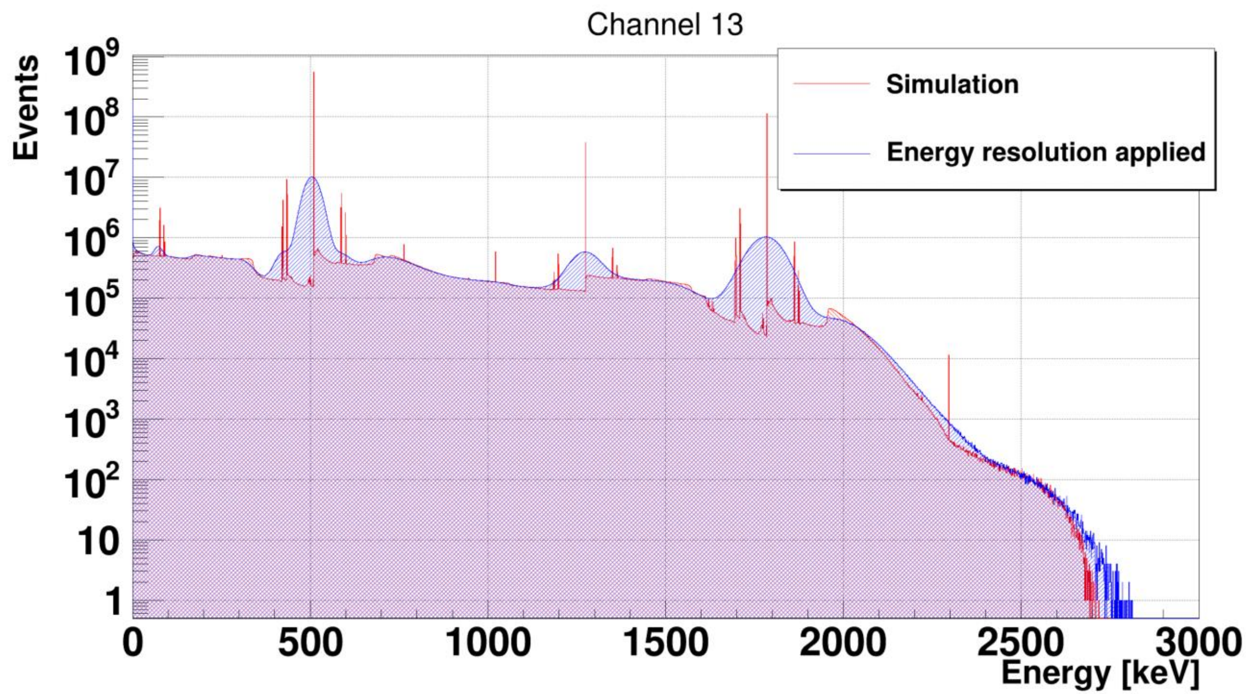




KAPAE-II : Simulation results

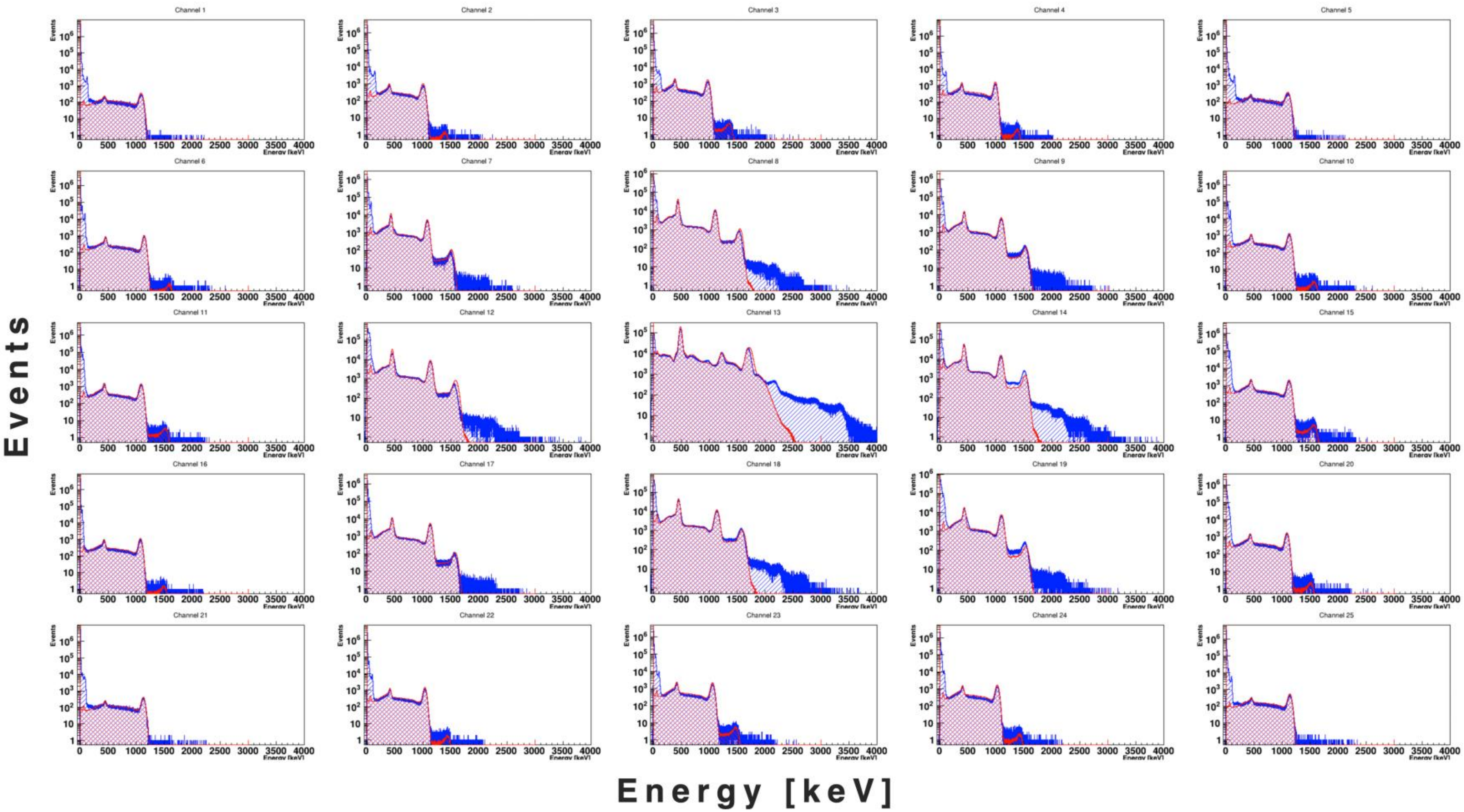




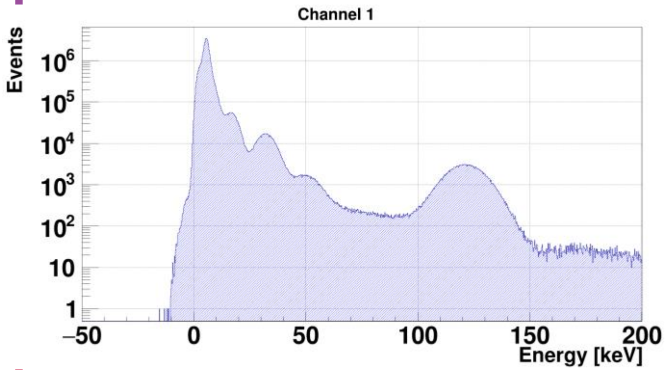


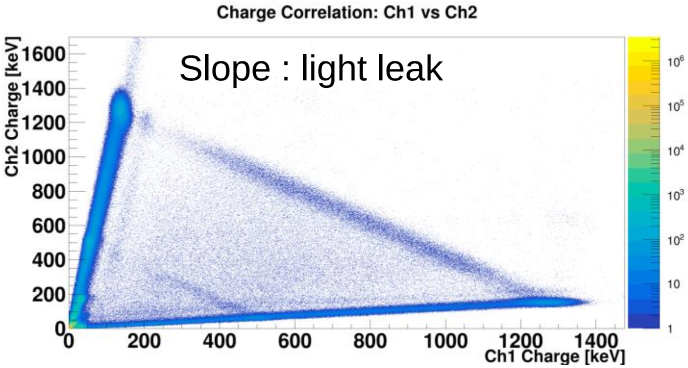
KAPAE-II : Results

Simulation (red) vs Underground (blue)

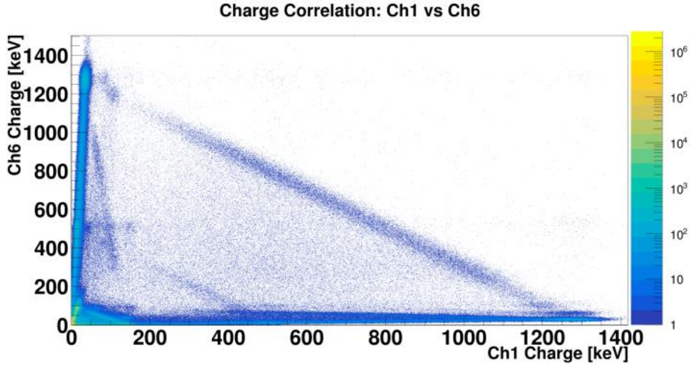


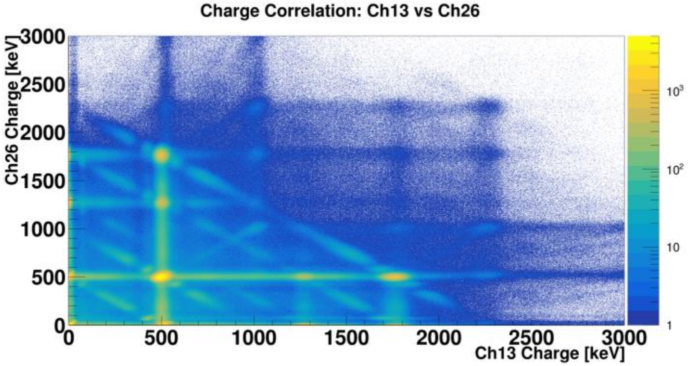
KAPAE-II : Light leak issue



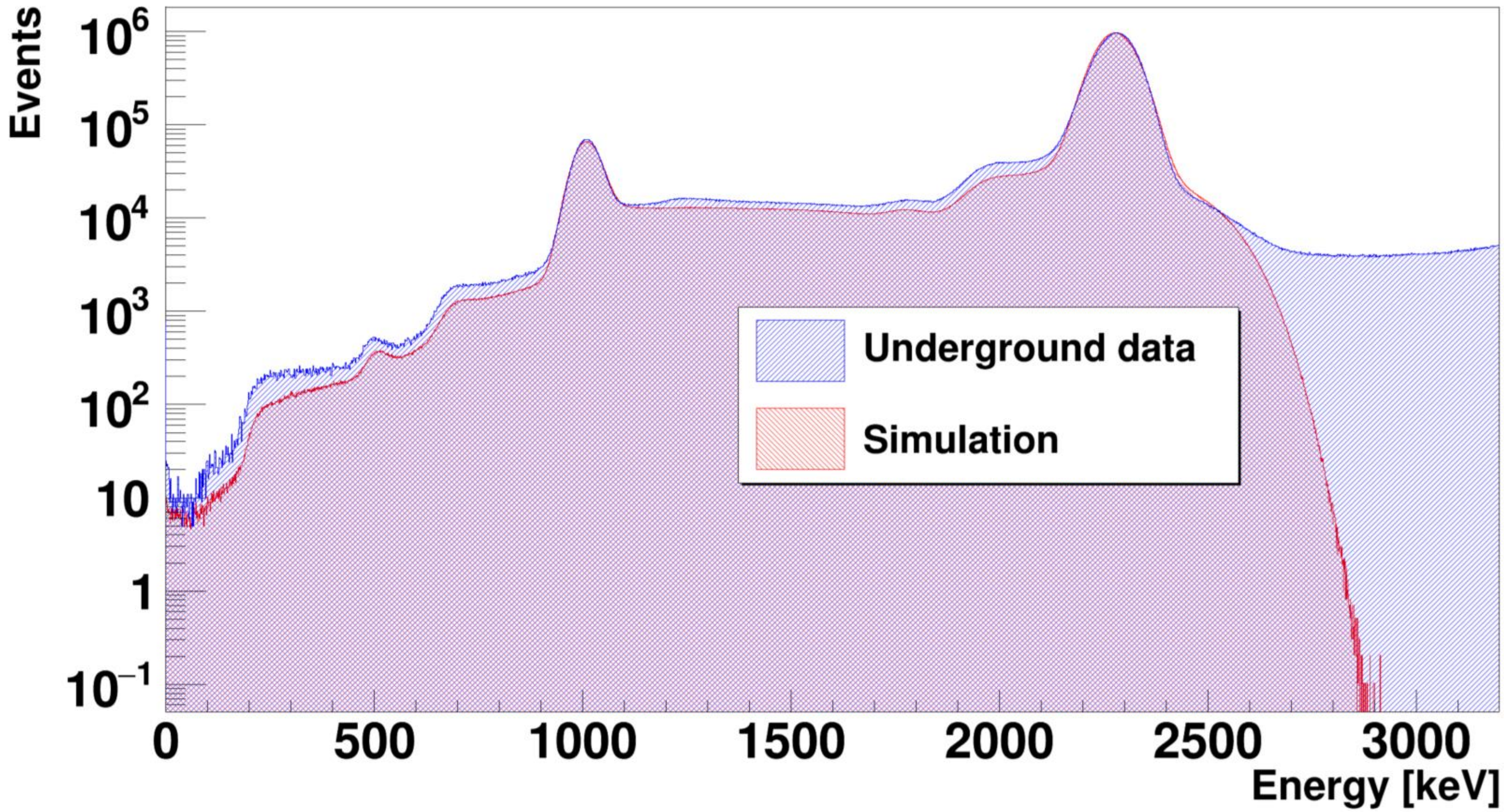


Energy ✕ (1 - light leak) calibration



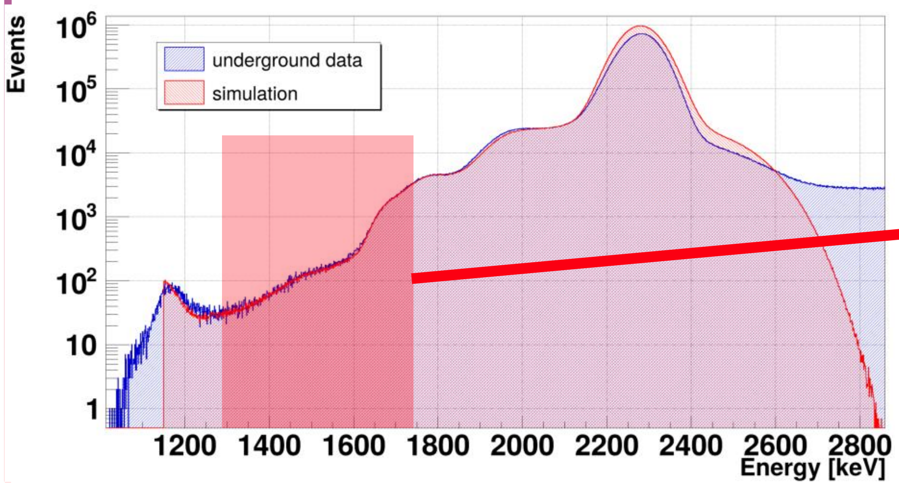


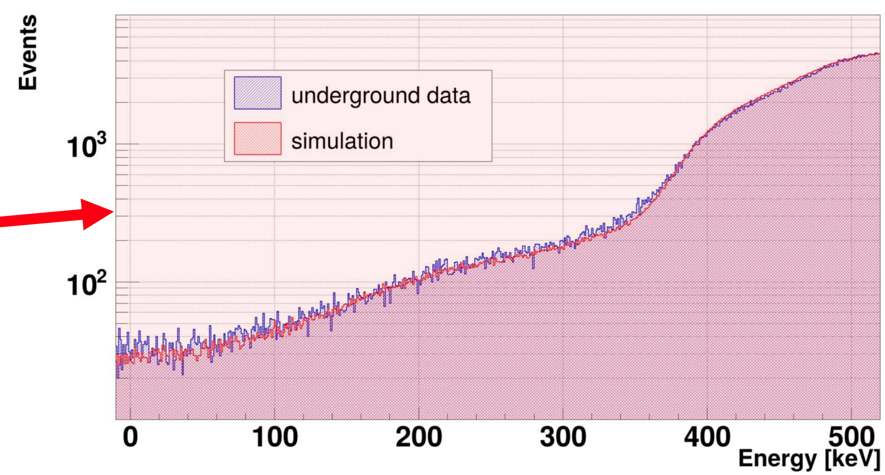
KAPAE-II : Comparison with data & MC



KAPAE-II : Energy distribution

Total energy distribution with 1275 keV gamma selection

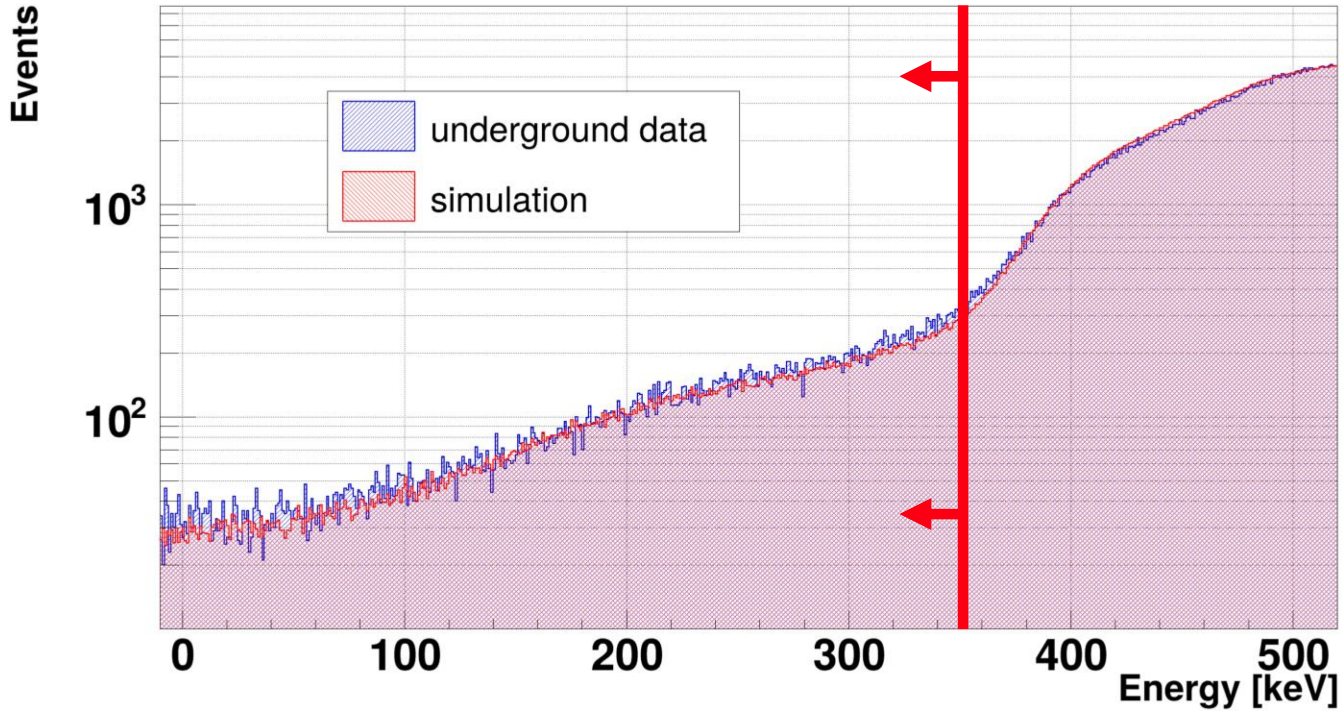




H.J.Kim, KNU

KAPAE-II : Results

Total energy distribution with 1275 keV gamma selection



KAPAE-II : Expected sensitivity

- Trigger rate: ~11 kHz
  → Energy cut (63%): ~7.2 kHz
  → Pileup rejection (expectation 94%): ~6.8 kHz

- 1 day (1D) of continuous data taking
  → ~5.9 × 10^8 events

- 75 days (75D) of continuous data taking → ~4.4 × 10^{10} events

$$Expected\ Sensitivity = \frac{1.28 \times \sqrt{N_{BG}}}{N_{total}} = \frac{1.28 \times \sqrt{R_{BG} \times N_{total}}}{N_{total}}$$
$$= \frac{1.28 \times \sqrt{R_{BG} \times 4.4 \times 10^{10}}}{4.4 \times 10^{10}}$$

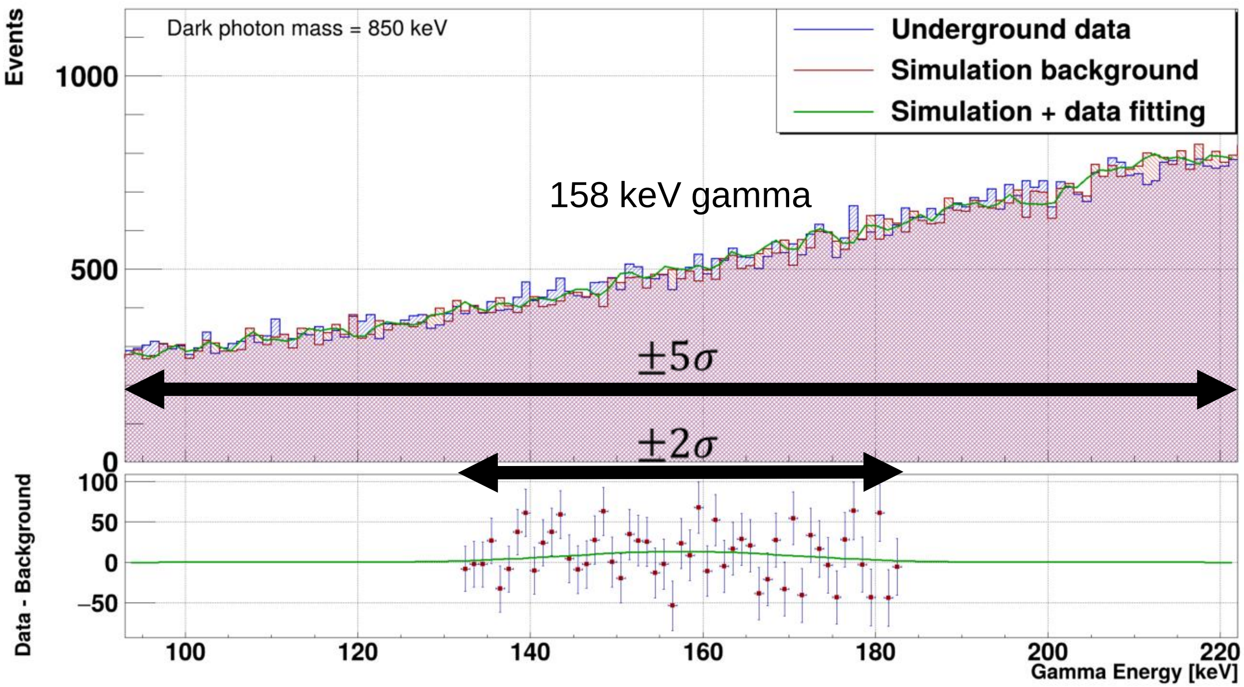
- N_{BG}: Number of background events
- N_{total}: Number of total data ~ 4.4 × 10^{10} events
- R_{BG}: Background event rate (fraction relative to the total events)
- $1.28 \times \sqrt{N_{BG}}$: Using the Gaussian approximation, this represents the 90% C.L. upper limit, corresponding to the number of additional signal events required above the background to achieve 90% confidence.

R_{BG}

Gamma energy (Dark photon mass) [keV]	Background rate	Expectation sensitivity (1D)	Expectation sensitivity (75D)
0 (1022)	9.4×10^{-6}	1.6×10^{-7}	1.9×10^{-8}
50 (970)	2.0×10^{-5}	2.3×10^{-7}	2.7×10^{-8}
100 (916)	4.0×10^{-5}	3.3×10^{-7}	3.8×10^{-8}
250 (730)	1.9×10^{-4}	7.3×10^{-7}	8.4×10^{-8}
400 (476)	2.1×10^{-3}	2.4×10^{-6}	2.8×10^{-7}
500 (149)	4.1×10^{-3}	3.4×10^{-6}	3.9×10^{-7}

KAPAE-II : Preliminary results

Branching ratio upper limit using 24 hour data

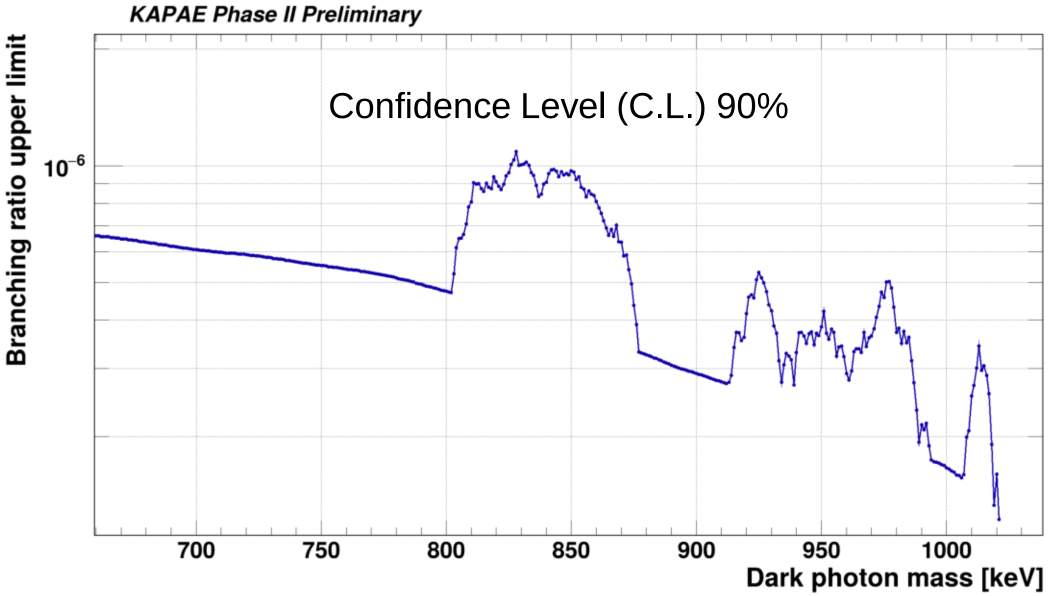


$$Upper\ limit = \frac{A_{signal} + 1.28 \times \Delta A_{signal}}{N_{total}}$$

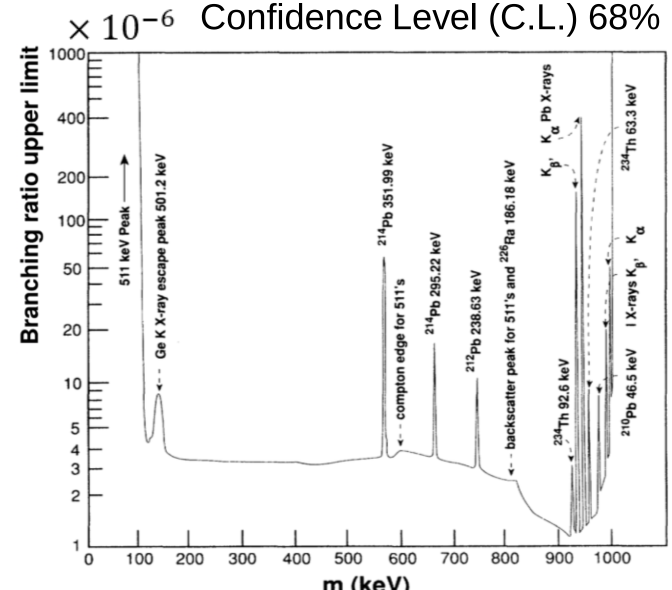
- A_{signal}: The number of signal events
  (area of the fitted Gaussian)
- ΔA_{signal}: statistical uncertainty of signal events
- N_{total}: Total number of events (24 hour, 5.9×10^{8})

KAPAE-II : Preliminary results

Branching ratio upper limit using 24 hour data



HPGe experiment
Confidence Level (C.L.) 68%



Skalsey, M., and R. S. Conti. "Search for exotic decays from low-energy e+ e− direct annihilation." Physical Review D 51.11 (1995): 6292.

Total invisible :

1.1 × 10^{-7} at 90% C.L., improving upon the previous ETH Zurich result (1.1 × 10^{-7}) .

Summary & Prospect

1. We constructed KAPAE-I detector for the QED study and KAPAE-II detector for the exotic dark matter search using positronium decay
2. The following is preliminary results and prospect with KAPAE-II p-PS mode study

Objective: Search for **total and partial invisible decays** of p-Ps, predicted in models involving dark photons and mirror dark matter.

Improvements over Phase I:
→ Enhanced positron trigger efficiency
→ Enhanced detector energy resolution
→ Minimized dead area
→ Optimized DAQ and cryogenic shielding

Design and Development: Yemi lab with a 5×5 BGO array, PEN-film positron trigger, and low-temperature operation

Branching ratio Results:
→ Upper limit of **total invisible decay** branching ratio:
· 1 days: 1.1×10^{-7} @ 90% C.L. (improvement over ETH Zurich expectation 4.3×10^{-7})
· 75 days: 10^{-8} @ 90% C.L. (Expectation)

→ Upper limit of **Partial invisible decay** branching ratio: Compared to the previous HPGe experiment
· 1 day: 10 times improvement
· 75 days: 100 times improvement (Expectation)

3. KAPAE-II o-PS mode data taking will be started from 2026 for ALP, Dark Z and mirror world search.


Thank you!