IFIRSE, ICISE Webinar 2020

October 29th 2020

Energy resolution of CANDLES detector for studying neutrino-less double beta decay of ^{48}Ca

Bui Tuan Khai

RCNP, Osaka University

(on behalf of the CANDLES collaboration)

CONTENTS

1. Introduction
2. CANDLES experiment
3. 2νββ & Energy resolution
4. Error in charge measurement
5. Photon Counting
6. Results and Discussion
7. Possibility for Photon Counting

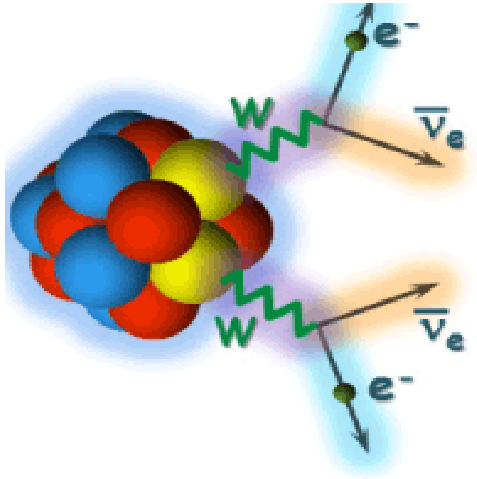
CONTENTS

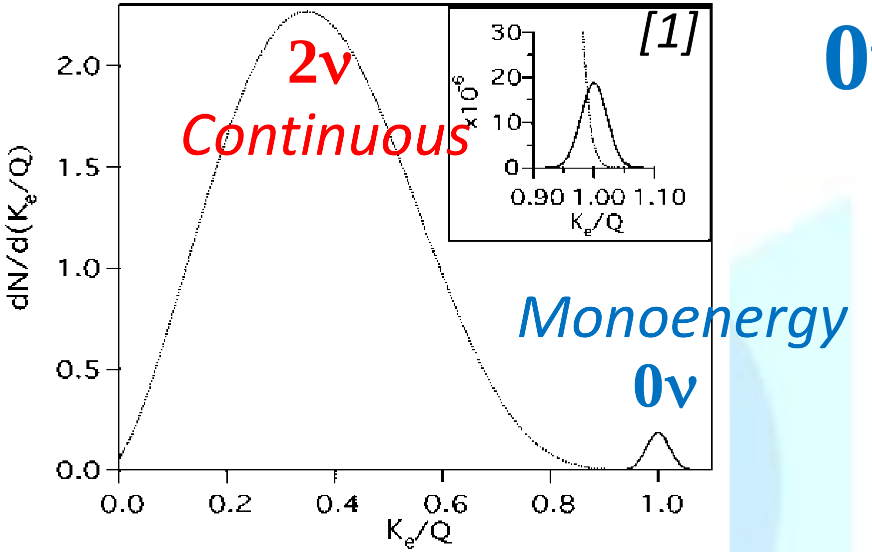
1. Introduction
2. CANDLES experiment
3. $2\nu\beta\beta$ & Energy resolution
4. Error in charge measurement
5. Photon Counting
6. Results and Discussion
7. Possibility for Photon Counting

Double Beta Decay (DBD)

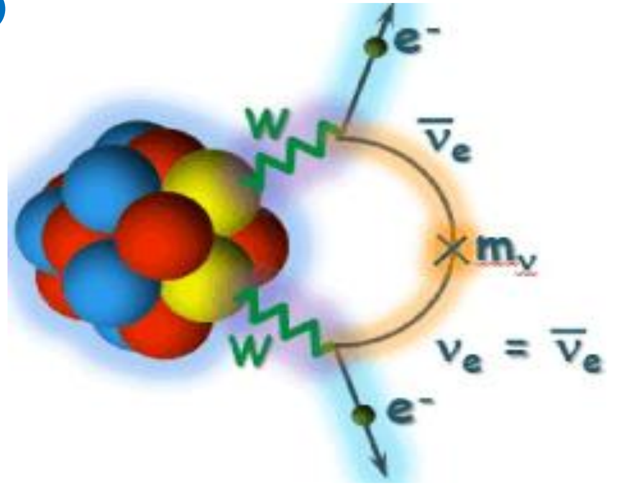
[1] Ann.Rev.Nucl.Part.Sci.52:115

$2\nu\beta\beta$





$0\nu\beta\beta$



- Obtained in >10 isotopes
- $T^{2\upsilon}_{1/2}$ = 10^{18}~10^{20} yr
- Rare, under standard model (SM)

- No observation
- $T^{0\upsilon}_{1/2}$ > 10^{26} yr (KamLAND-Zen)
- Extremely rare!

❖ <u>Physics of **0νββ decay**:</u>

➢ Neutrino mass from the $\mathbf{T^{0\nu}_{1/2}}$

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}\left|\langle m_{\beta\beta}\rangle^2/m_e^2\right||M^{0\nu}|^2$$

➢ Nature of neutrino: Majorana or Dirac?

➢ Lepton number not conserved (ΔL=2)

⇒ New physics beyond SM

0νββ experiment with ^{48}Ca

✓ **Highest $Q_{\beta\beta}$ 4.27 MeV**

- Large phase space factor
- Far from BKG (γ: 2.6 MeV; β: 3.3 MeV)

⇒**Aim for background-free measurement**

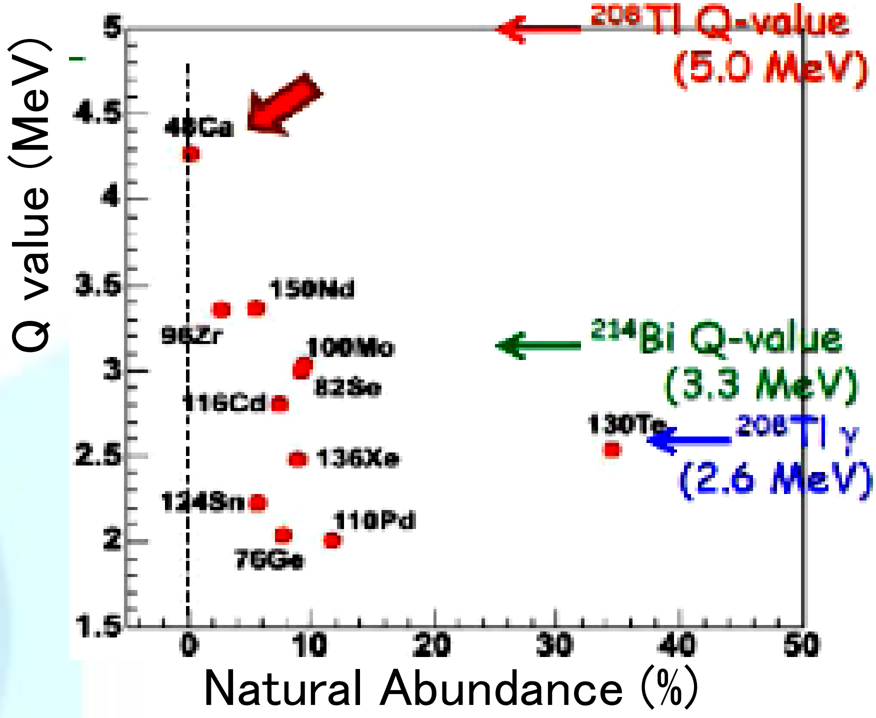
☒ **Low abundance**

- Natural abundance: <0.2 %
- Separate isotopes: expensive

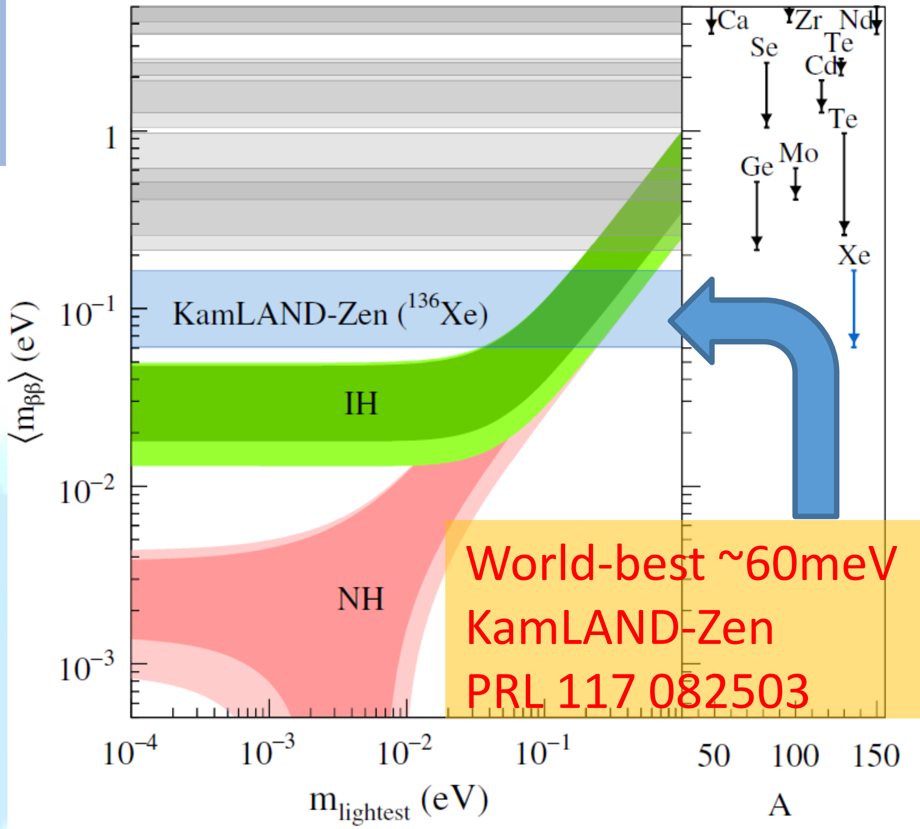
⇒**Cost-effective enrichment**

❑**Energy Resolution** $T^{0\nu}_{1/2} \propto (N_{BKG} \cdot \Delta E)^{-1/2}$

⇒ Improve sensitivity



0νββ experiment with ^{48}Ca



✓ **Highest $Q_{\beta\beta}$ 4.27 MeV**

- Large phase space factor
- Far from BKG (γ: 2.6 MeV; β: 3.3 MeV)

⇒**Aim for background-free measurement**

☒ **Low abundance**

- Natural abundance: <0.2 %
- Separate isotopes: expensive

⇒**Cost-effective enrichment**

❑**Energy Resolution**

⇒ Improve sensitivity

❖Current: above IH $m_{\beta\beta}$≈60meV

⇒ Aim for below IH ($m_{\beta\beta}$≈20meV)

⇒ Final: below NH ($m_{\beta\beta}$≈1meV)

Future CANDLES
- Enrichment (~600kg ^{48}Ca)
- High resolution (bolometer)
- Low background

CONTENTS

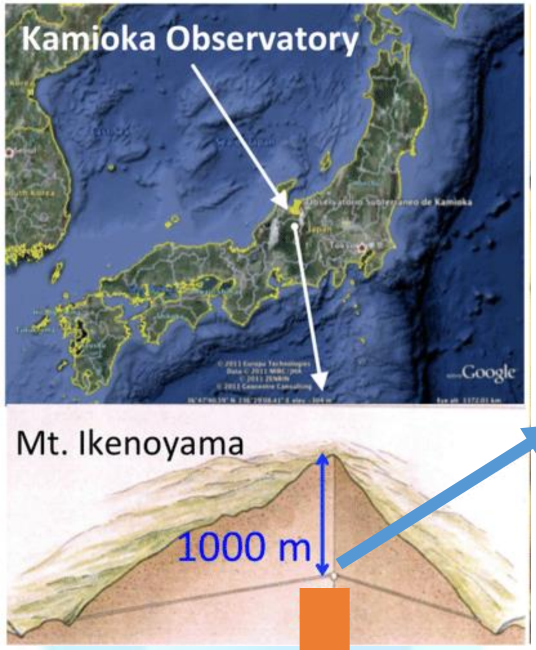
1. Introduction
2. CANDLES experiment
3. $2\nu\beta\beta$ & Energy resolution
4. Error in charge measurement
5. Photon Counting
6. Results and Discussion
7. Possibility for Photon Counting

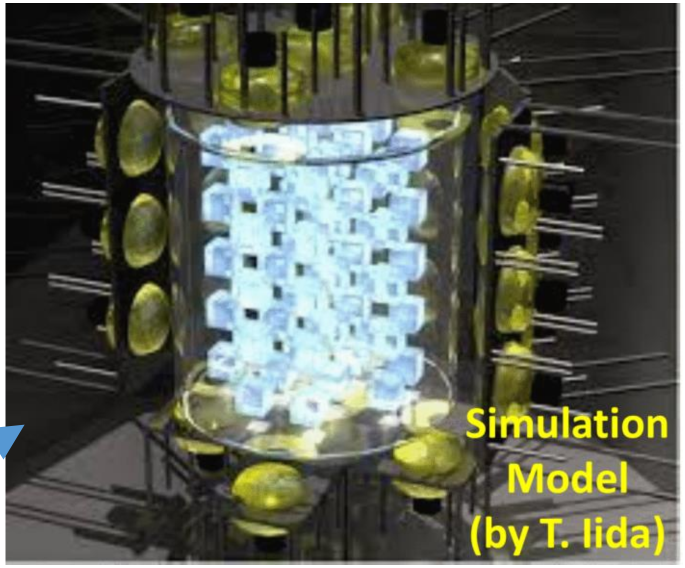
CANDLES experiment

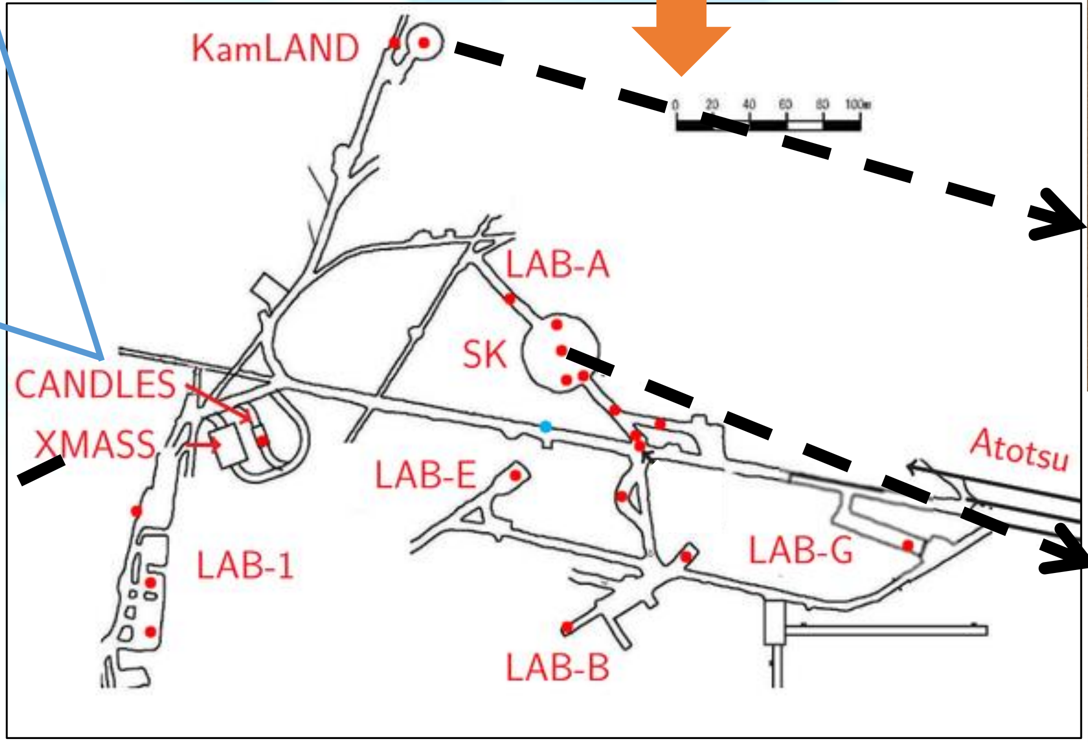
- To observe $0\nu\beta\beta$ of ^{48}Ca
- Set up @ Kamioka (2700m.w.e depth)

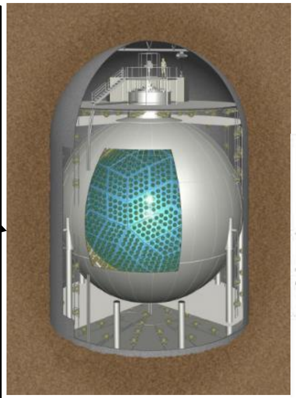
CANDLES

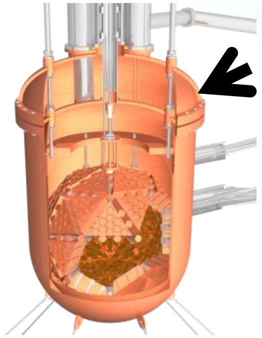
CAlcium fluoride for studies of **N**eutrino and **D**ark matters by **L**ow **E**nergy **S**pectrometer





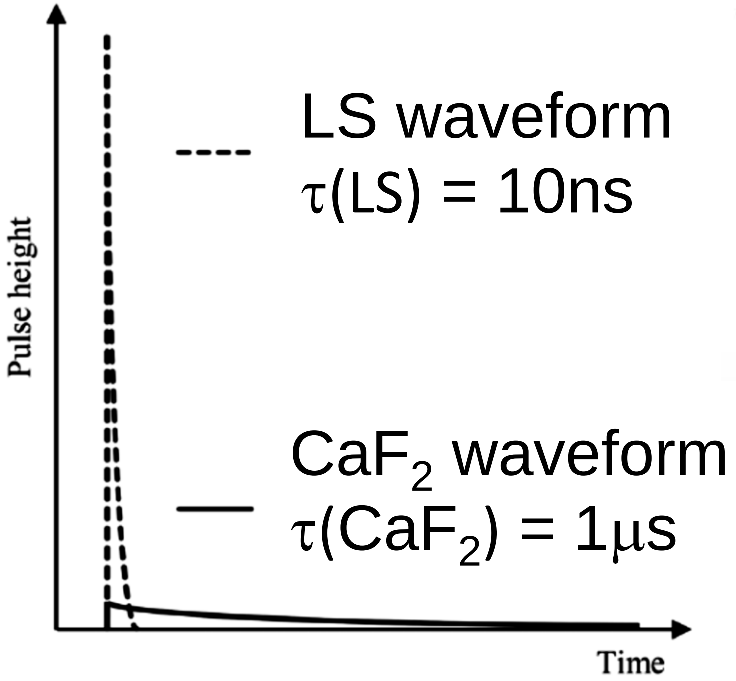


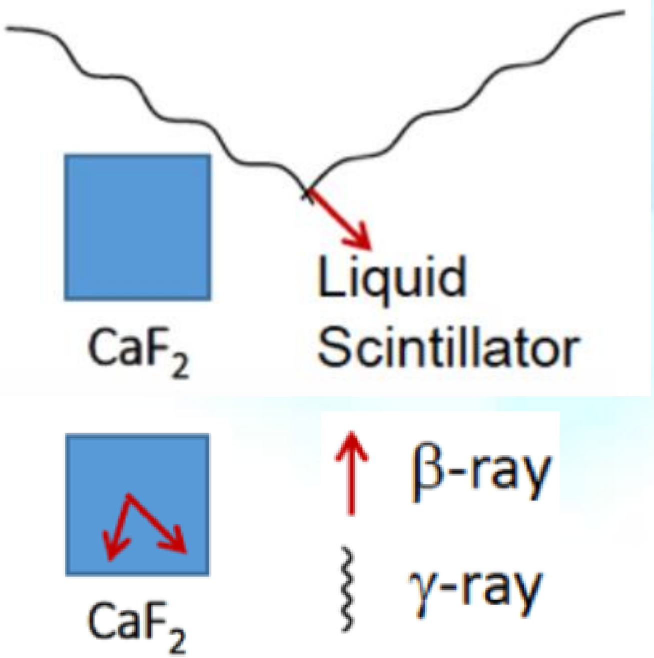


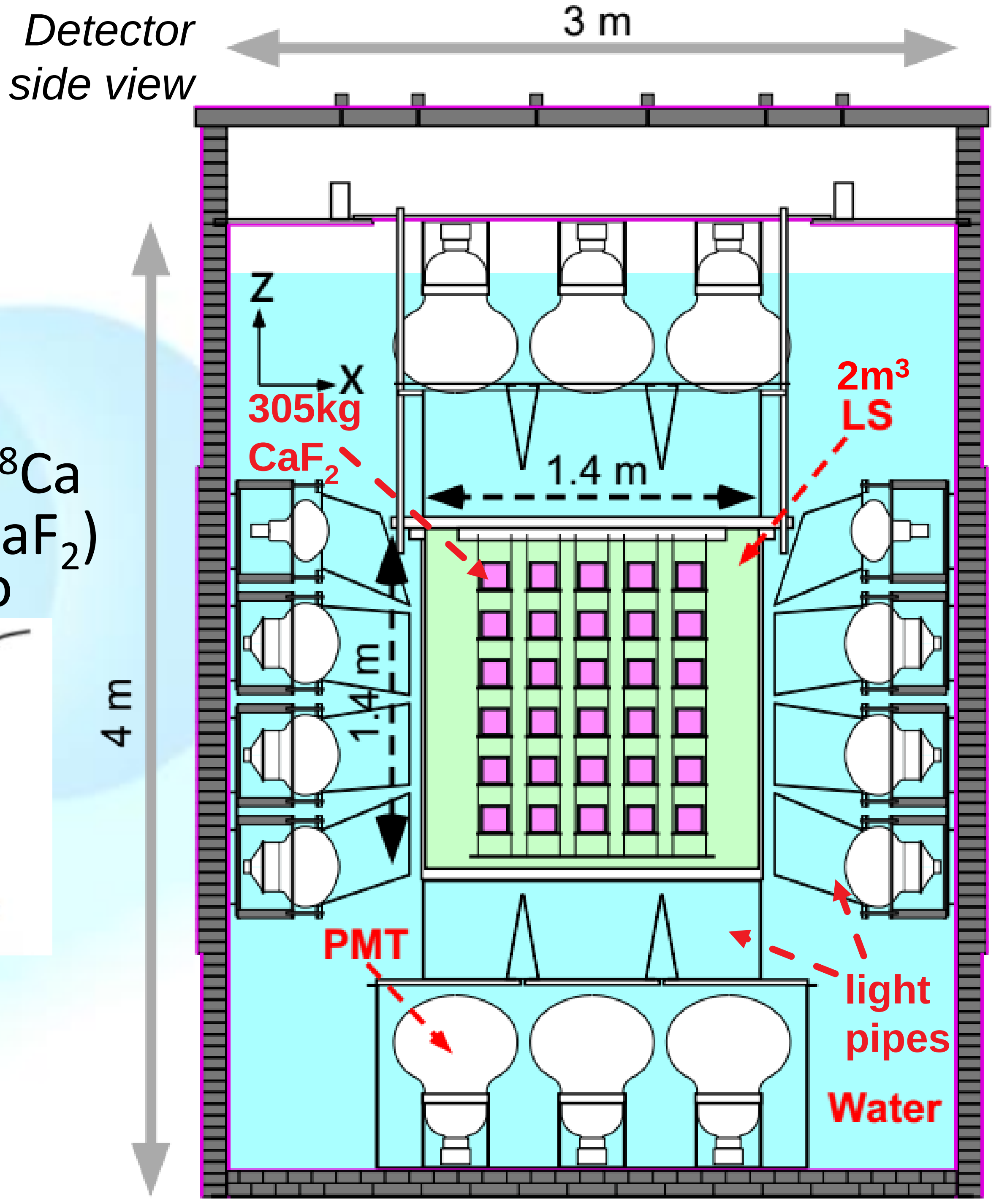


CANDLES experiment

- To observe $0\nu\beta\beta$ of ^{48}Ca
- Set up @ Kamioka (2700m.w.e depth)
- CANDLES consists of:
  - 96 CaF_2(nat.): detector + source $\Rightarrow$ 350g ^{48}Ca (305kg CaF_2)
  - Liquid scintillator (LS): 2m^3, 4π active veto

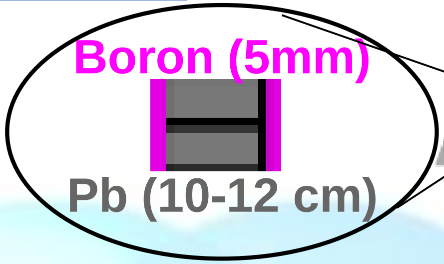


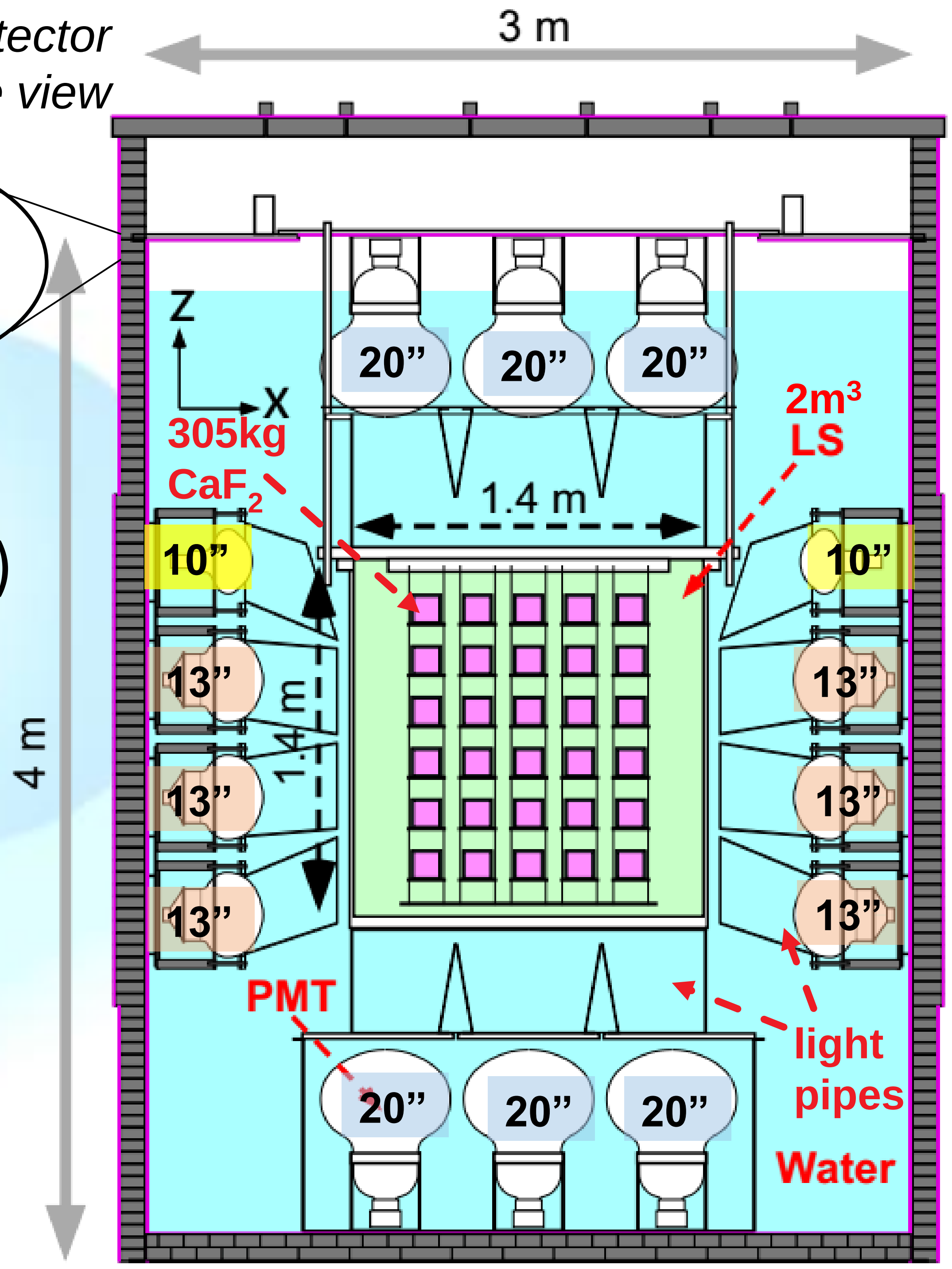




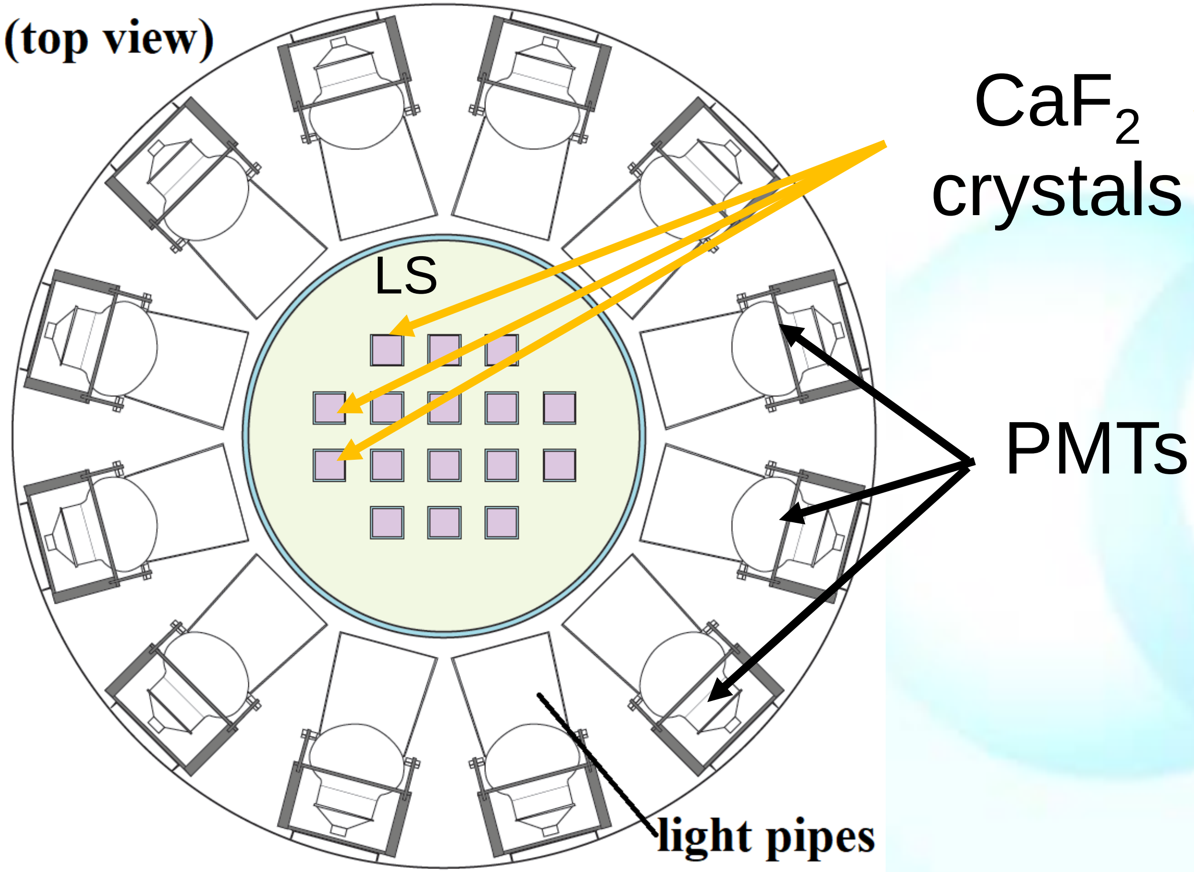
CANDLES experiment

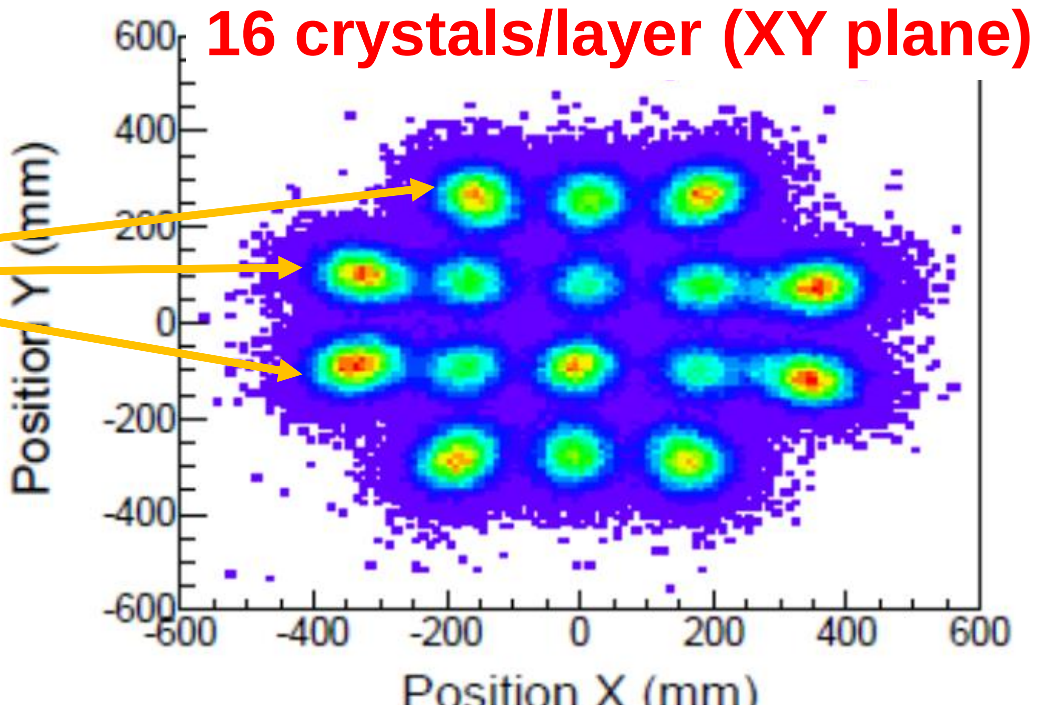
- To observe $0\nu\beta\beta$ of ^{48}Ca
- Set up @ Kamioka (2700m.w.e)
- CANDLES consists of:
  - 96 CaF_2(nat.): detector + source ⇒ 350g ^{48}Ca (305kg CaF_2)
  - Liquid scintillator (LS): $2m^3$, 4π active veto
  - 62 PMTs surrounding:
    - 10-inch(x12), 13-inch(x36), 20-inch(x14)
    - each PMT waveform is recorded
  - Water passive shield $4m^h \times 3m^\phi$
  - Passive shielding (**Pb**+**Boron**) outside/inside

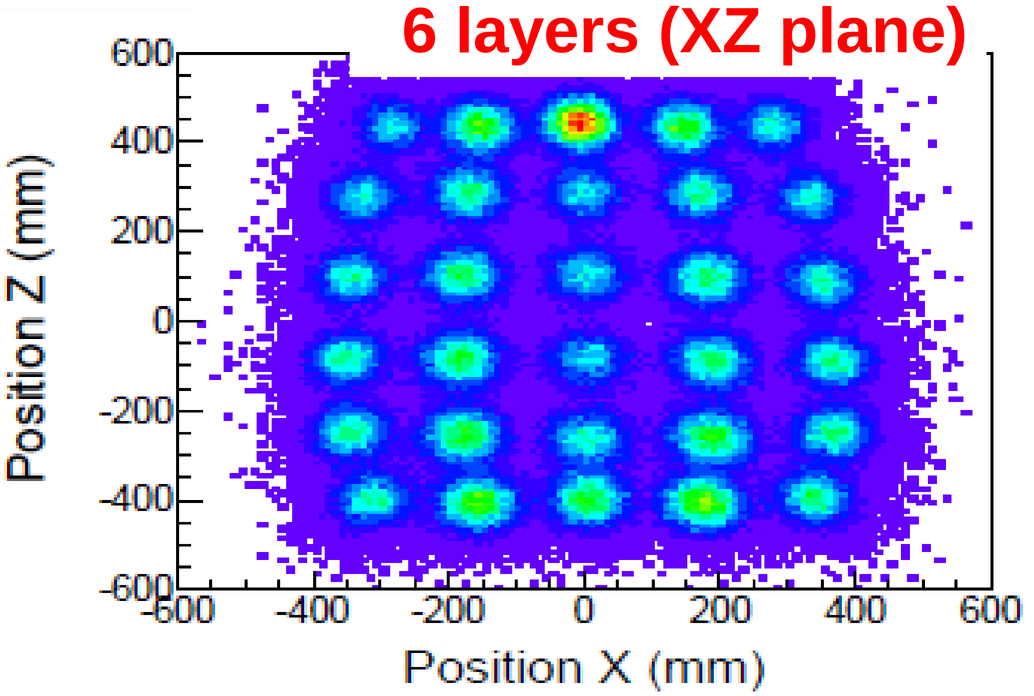




Position Reconstruction







- 96 crystals: 6 layers x 16 crystals/layer

$\Rightarrow$ different in Light yield and contamination

$\Rightarrow$ In analysis, check each crystal

$\Rightarrow$ Using photoelectrons in 62 PMTs to relocate event position

DAQ system in CANDLES

Developed by SHIMAFUJI, JAXA, RCNP

µTCA® DAQ system

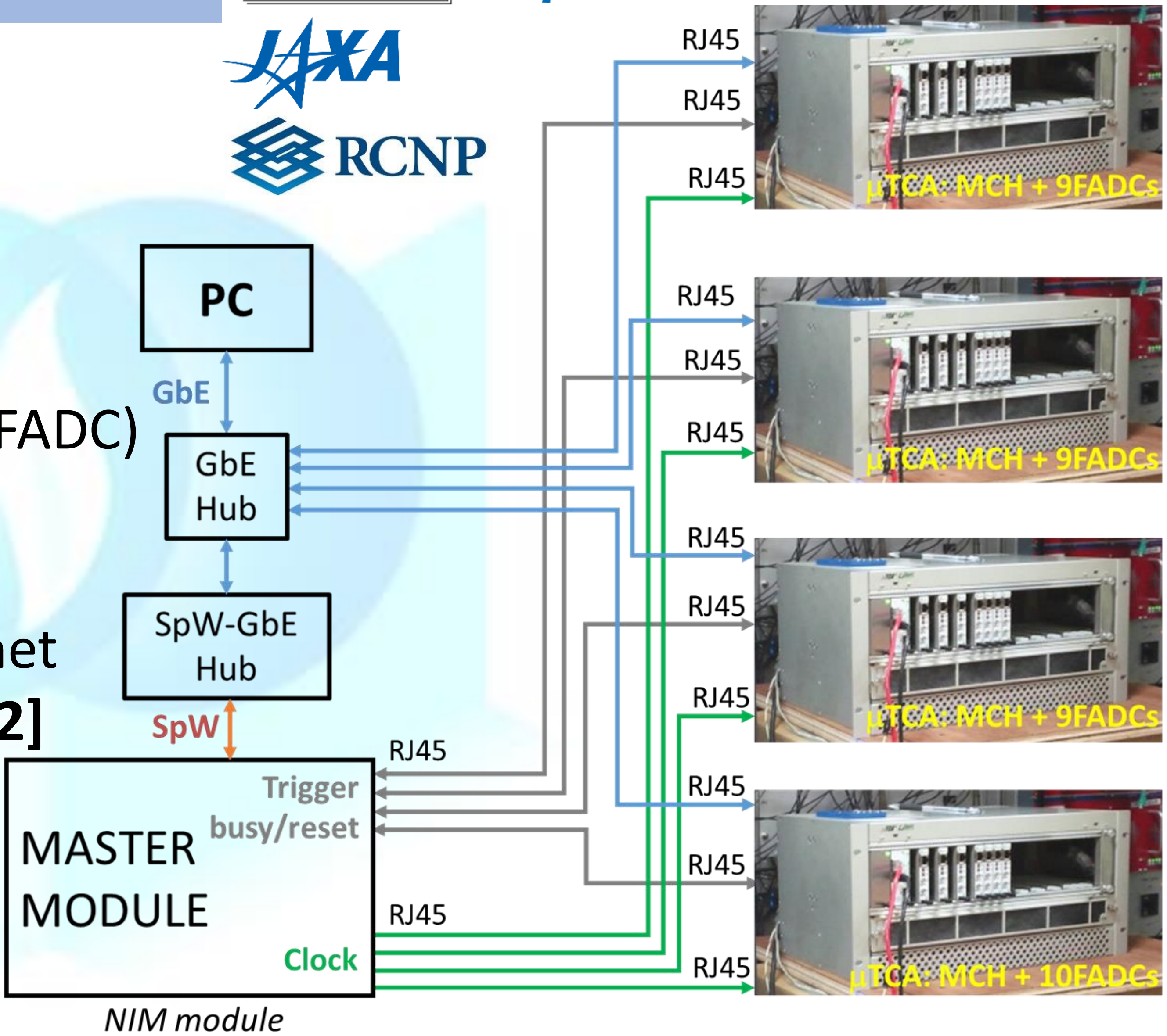
- Using **500MHz-8bit-8buffers** FADCs
- Record ~9µsec waveform:
  - First 768 ns, record 2ns/sample
  - Latter sum every 64ns
- 74 FADC channels: divided in 4 crates
- Each crate: 1 MCH + 9or10 FADCs (2Chs/FADC)
- Master Module: synchronize modules
- Main trigger: CaF_2-like events **[1]**
- PC ↔ FADC: SpaceWire ↔ GigabitEthernet
- Software framework: DAQ-Middleware **[2]**

DAQ performance in daily data taking**[3]**:

- Data size: ~50kB/event

⇒@current trigger rate of 10cps, negligible dead-time($<10^{-6}$)

⇒Max speed 100cps (5MB/s)



[1] T. Maeda et al. IEEE TNS 62:1128
[2] K. Suzuki et al. IEEE TNS 62:1112
[3] B. T. Khai et al. IEEE TNS 66:1174

CANDLES

CAlcium fluoride for studies of Neutrino and Dark matters by Low Energy Spectrometer

35 members, 7 institutes
6 members, 2 institutes

Institute for Basic Science
KRISS Korea Research Institute of Standards and Science

← More about us

Some publications

[0νββ] arxiv:2008.09288 (for PRD)
[0νββ] PRC 78:058501
[0νββ] Nucl. Phys. A 730:215

[DAQ] IEEE TNS 66:1174
[DAQ] IEEE TNS 62:1122
[DAQ] IEEE TNS 62:1128

[Detector] NIMA 986:164727
[Detector] Astropart. Phys.100:54
[Detector] NIMA 705:1
[Detector] NIMA 601:282

[Enrich] J. Nucl. Sci. Tech. 55:1473
[Enrich] Austin Chromatogr. 3:1040
[Enrich] J. Chroma. 1415:67
[Enrich] PTEP 2015:053C03
[Enrich] PTEP 2015:033D03

大阪大学 OSAKA UNIVERSITY

RCNP

Nomachi, Masaharu
Kishimoto, Tadafumi
Umehara, Saori
Takemoto, Yasuhiro
Takihira, Yukichi
Matsuoka, Kenji
Tetsuno, Kounosuke
Yoshida, Sei
Shokati Mojdehi Masoumeh
Li, Xiaolong
Temuge Batpurev
Bui Tuan Khai
Lee Ken Keong
Yamamoto, Kohei
Miyamoto, Koichiro
Iga, Tomoki

UNIVERSITY OF FUKUI

Tamagawa, Yoichi
Ogawa, Izumi
Nakajima, Kyohei
Tozawa, Masashi
Ikeyama, Yuta
Ozawa, Kenta
Matsuoka, Kohei
Araki, Yusuke
Hirota, Ayumu
Kawashima, Yusuke

大阪産業大学 OSAKA SANGYO UNIVERSITY

Hazama, Ryuta
Pannipa Noithong
Anawat Rittirong

筑波大学 University of Tsukuba

Iida, Takashi

徳島大学 Tokushima University

Fushimi, Ken-ichi

THE WAKASA WAN ENERGY RESEARCH CENTER

K. Suzuki

SAGA UNIVERSITY

O. Hideaki

ILT Institute for Laser Technology

T. Shigeki

CONTENTS

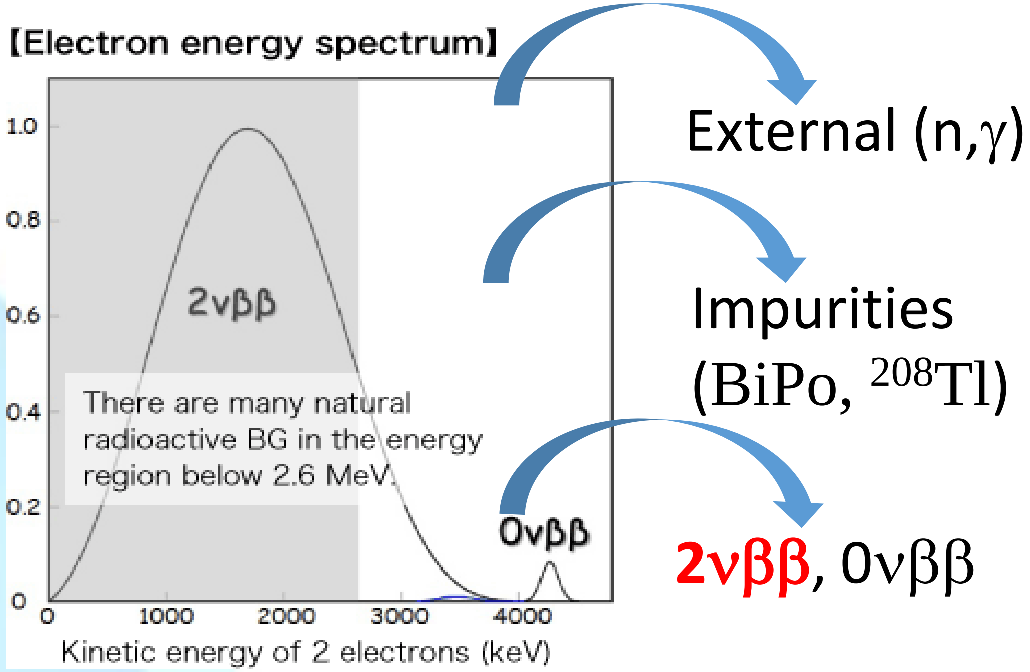
1. Introduction
2. CANDLES experiment
3. $2\nu\beta\beta$ & Energy resolution
4. Error in charge measurement
5. Photon Counting
6. Results and Discussion
7. Possibility for Photon Counting

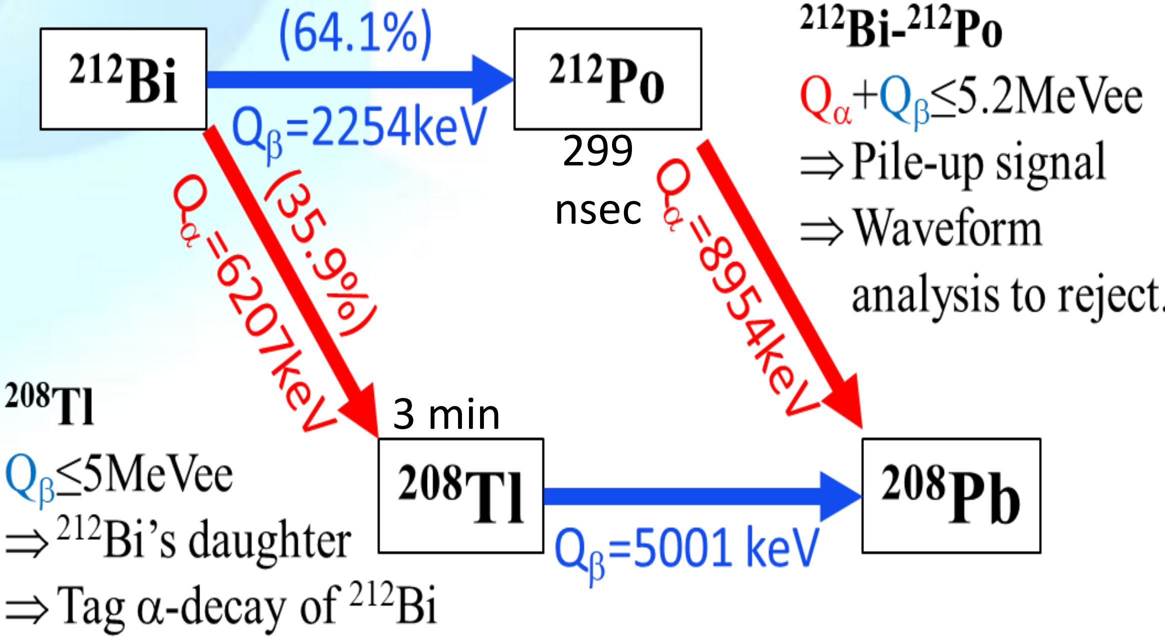
Background in CANDLES

- Background at $Q_{\beta\beta}$ of ^{48}Ca:
- ○ *Most background: removed by active shielding*
- ○ <u>External (n,γ)</u>: passive shielding (Pb,B)
- ○ <u>Impurities background</u>:
  - ▪ $^{212}Bi^{212}Po$ sequential decay: pile-up event

    ⇒Waveform analysis
  - ▪ ^{208}Tl β-decay: remove by tagging preceding α-decay

    ⇒ tagging efficiency (DAQ + Analysis)
- ○ 2νββ: not reduced by above methods





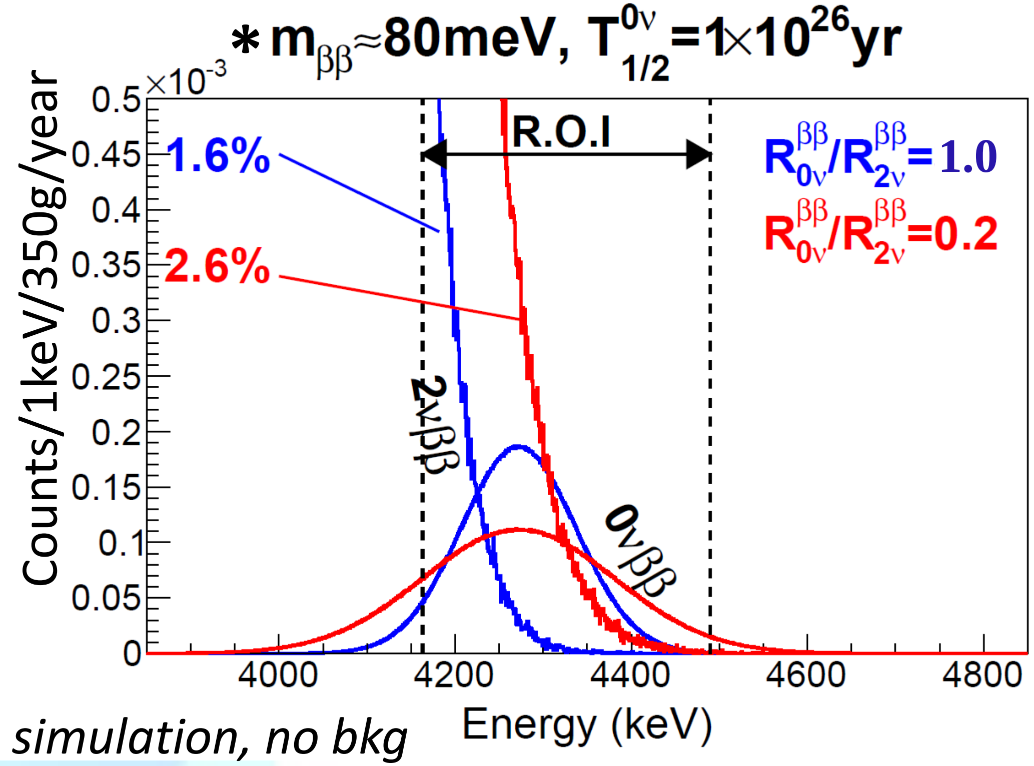
2νββ in CANDLES

- 2νββ: irremovable background
- Proportional to M(^{48}Ca)
- ~600kg of ^{48}Ca in future

⇒ huge 2νββ background

- To distinguish 2νββ and 0νββ

⇒Must improve energy resolution.



simulation, no bkg

*close to world-best ~60meV

*NME(EDF)=2.37 [PRL 105, 252503 (2010)]

- Ideal case, resolution = statistical fluctuation of number of p.e.
- Current setup:

⇒at $Q_{\beta\beta}$(4272keV): $\sigma_{p.e.} \approx$ **1.6%**

- Current resolution:

  σ_E=**2.6%** > $\sigma_{p.e.}$

⇒Other fluctuation(s) make energy resolution worse!

*σ_E = 2.6%, reported in T. Ohata Dthesis (2018)

Energy Resolution

Energy resolution depends on:

1. Statistical fluctuation

- Mainly from fluctuation of number of p.e.

⇒ • Light yield (cooling detector)
  • Photon collection (light pipes)

2. Detector stability

- Temperature and high-voltage
- Monitor during data taking

3. Crystal dependence [Ref]

Numbers of scintillation photons from different crystals are different.

⇒ Calibration for each crystal

⇒ Small fluctuation (0.3% at 2.6 MeV)

4. Error in charge measurement

Research motivation:

- Improve energy resolution.

⇒ Study the error of charge measurement in CANDLES III

[Ref] T. Ohata DThesis O.U. (2018)

CONTENTS

1. Introduction
2. CANDLES experiment
3. 2νββ & Energy resolution
4. Error in charge measurement
5. Photon Counting
6. Results and Discussion
7. Possibility for Photon Counting

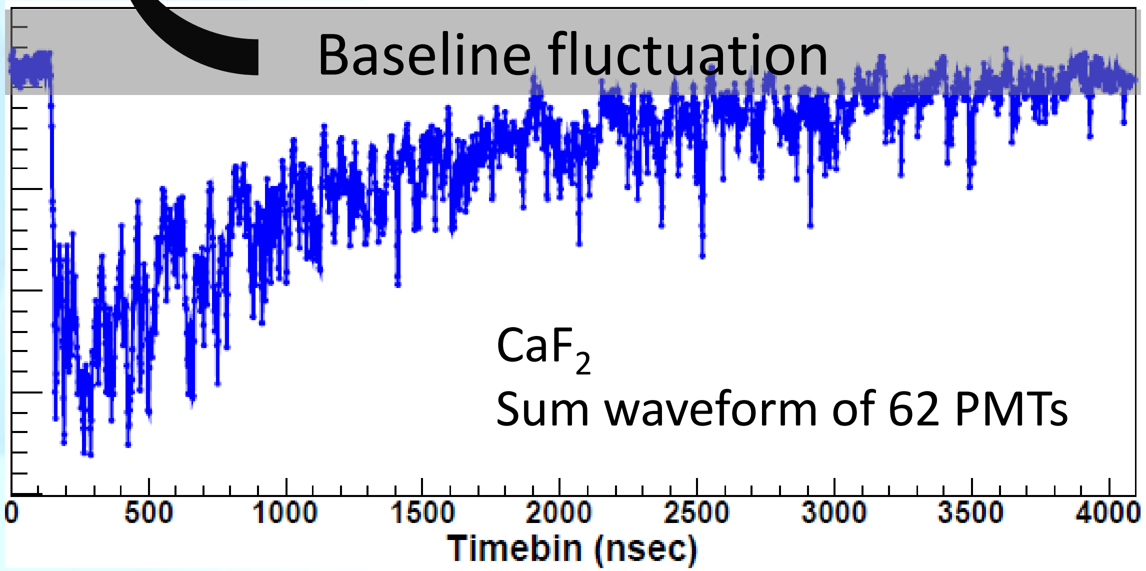
Error in charge measurement

- σ_E=2.6% > $\sigma_{p.e.}$=1.6%

- CaF_2 has a long decay constant 1μsec
- To calculate the energy, signal integration of 4μsec

⇒Baseline fluctuation can be accumulated

- Dark Current in PMTs
- Noises in baseline
- Digitization error
- ….?



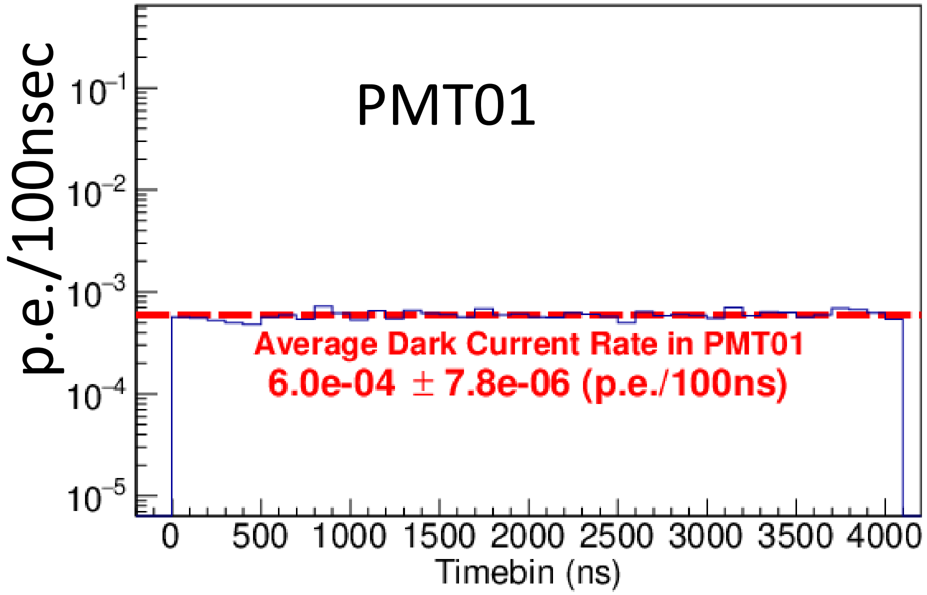
- Possible fluctuations in a long interval:
  - Dark Current in PMTs
  - Noises in baseline
  - Digitization error (resolution of FADC)

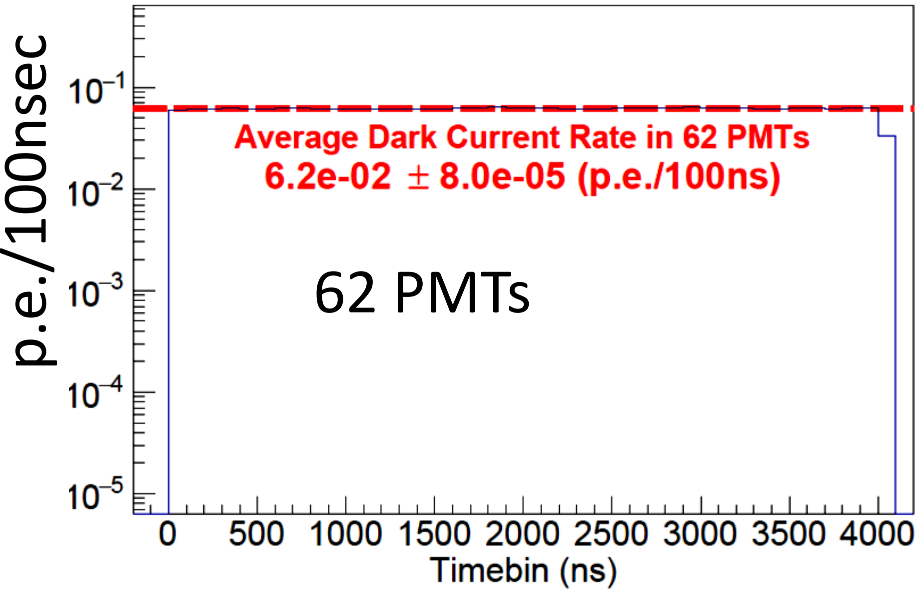
⇒Study the above fluctuations to identify the problem

CONTENTS

1. Introduction
2. CANDLES experiment
3. 2νββ & Energy resolution
4. Error in charge measurement
    a. Dark Current
    b. Noise in baseline
    c. Digitization Error
5. Photon Counting
6. Results and Discussion
7. Possibility for Photon Counting

Dark Current (& Small Scint. Light)

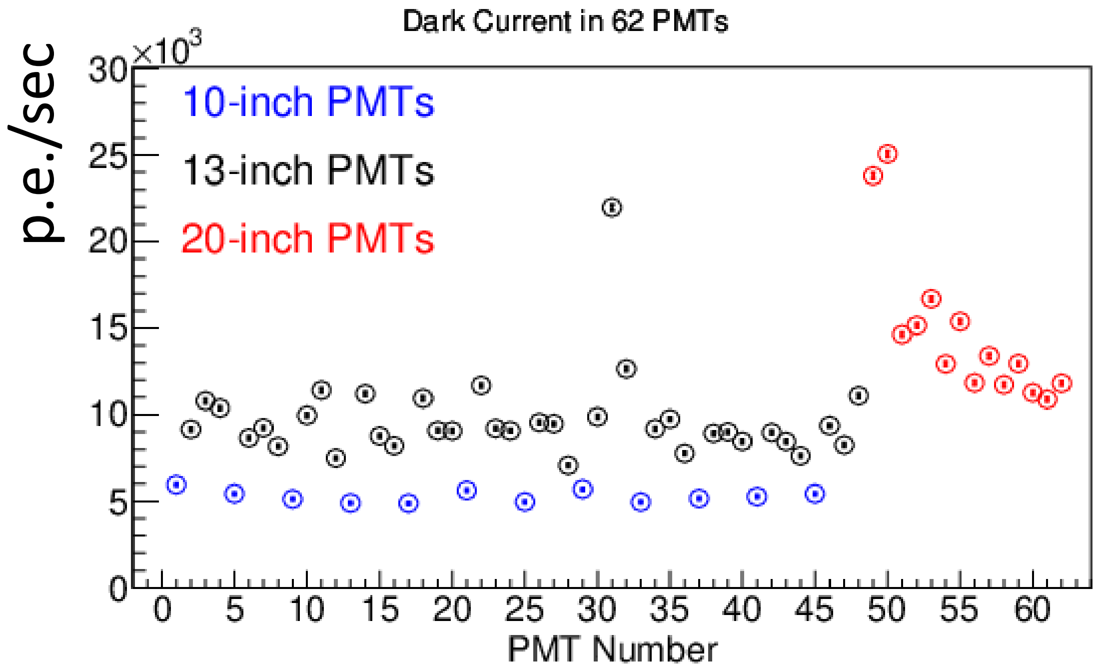




- Dark Current affects statistically on the energy resolution.
- Dark Currents in every 100ns of each PMT are counted.

$\Rightarrow$ Sum dark current in 62 PMTs to estimate the effect in the CaF_2 waveform.

Dark Current (& Small Scint. Light)



- Dark Current affects statistically on the energy resolution.
- Dark Currents in every 100ns of each PMT are counted.

⇒ Sum dark current in 62 PMTs to estimate the effect in the CaF_2 waveform.

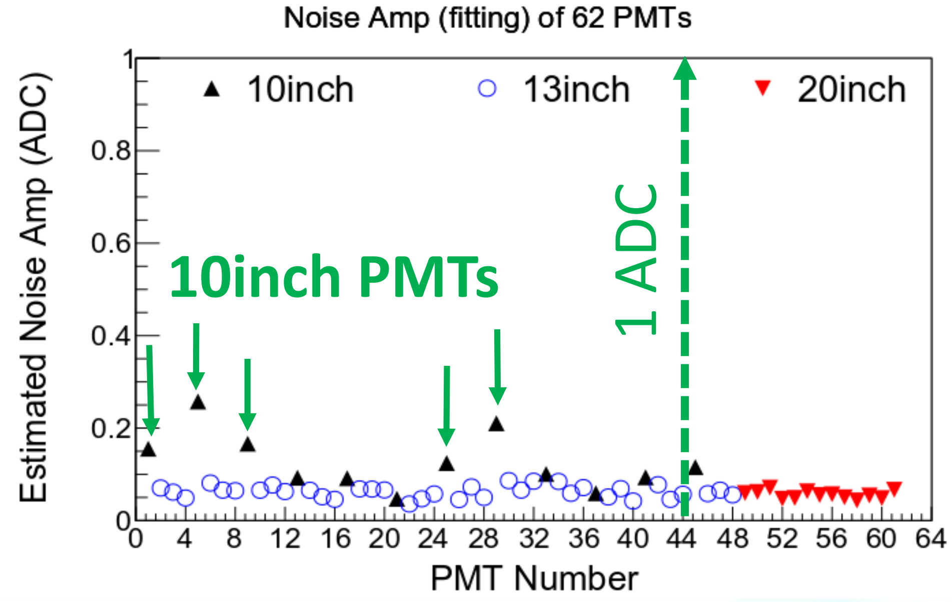
- Dark current rate of 10-inch PMTs are the lowest ones.
- The dark current fluc. of 62 PMTs in 4000ns integration: **~1.6 p.e.**
- **<u>Fluctuation of dark current is negligibly small</u>**:

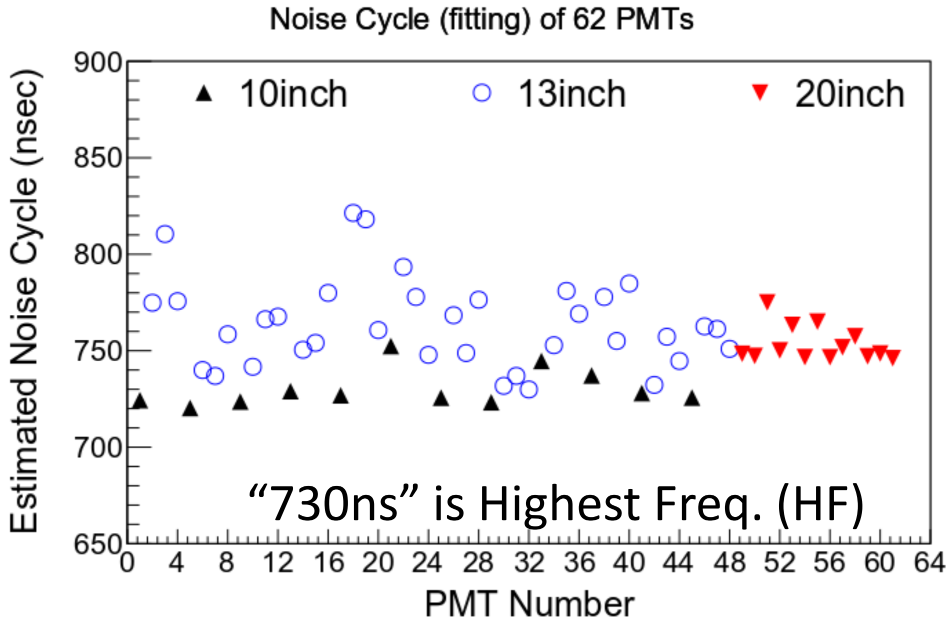
  at Q-value, **$\sigma_{DC}/Q = 0.04\%$**

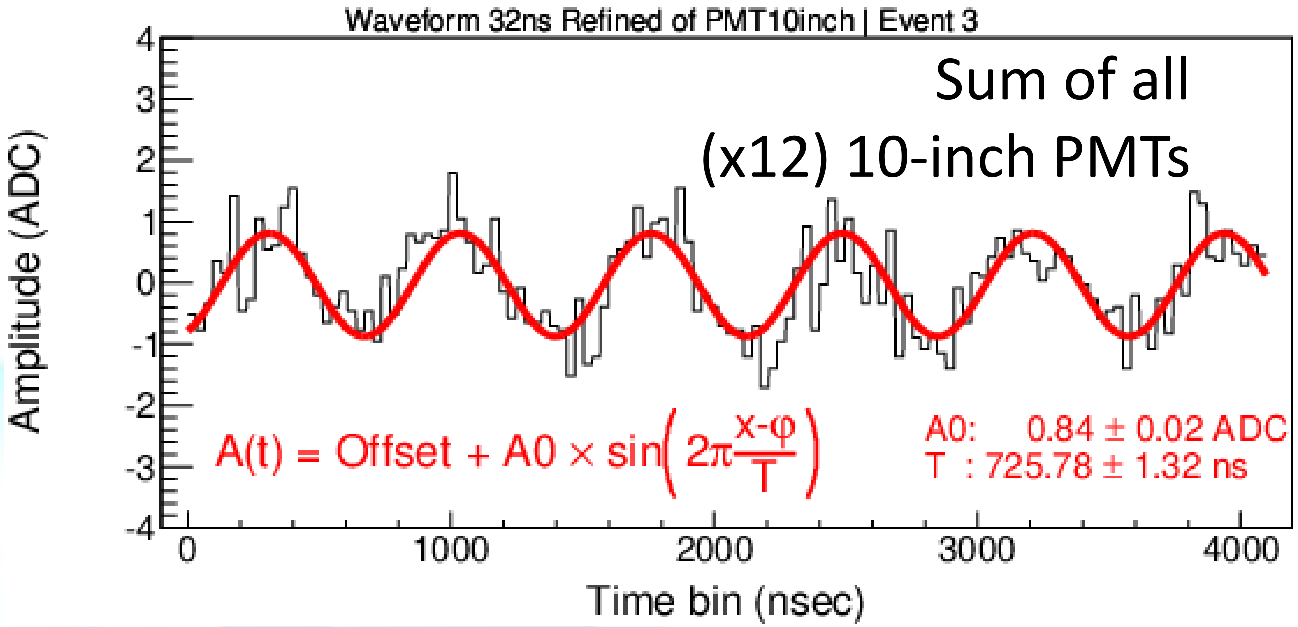
CONTENTS

1. Introduction
2. CANDLES experiment
3. 2νββ & Energy resolution
4. Error in charge measurement
   a. ~~Dark Current~~
   b. Noise in baseline
   c. Digitization Error
5. Photon Counting
6. Results and Discussion
7. Possibility for Photon Counting

Noise in Baseline







- Fit the baseline of each PMT (sine-wave)

⇒get the amplitudes and cycles of noises

⇒Highest amplitudes in Five 10-inch PMTs

⇒Similar noise cycles in these PMTs

⇒Sum all 10-inch PMTs to check the noise

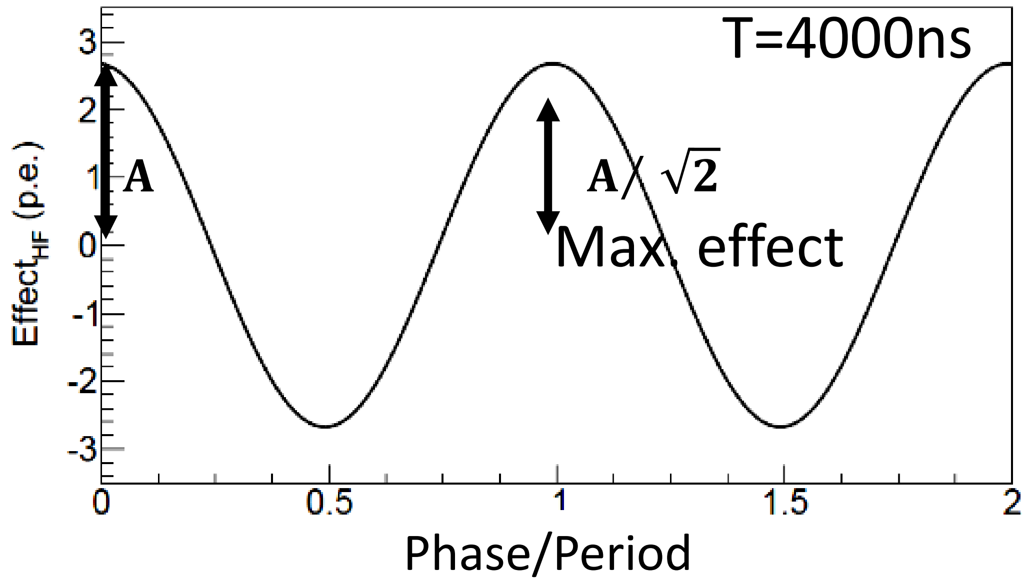
- In sum baseline of 10-inch PMTs (x12):

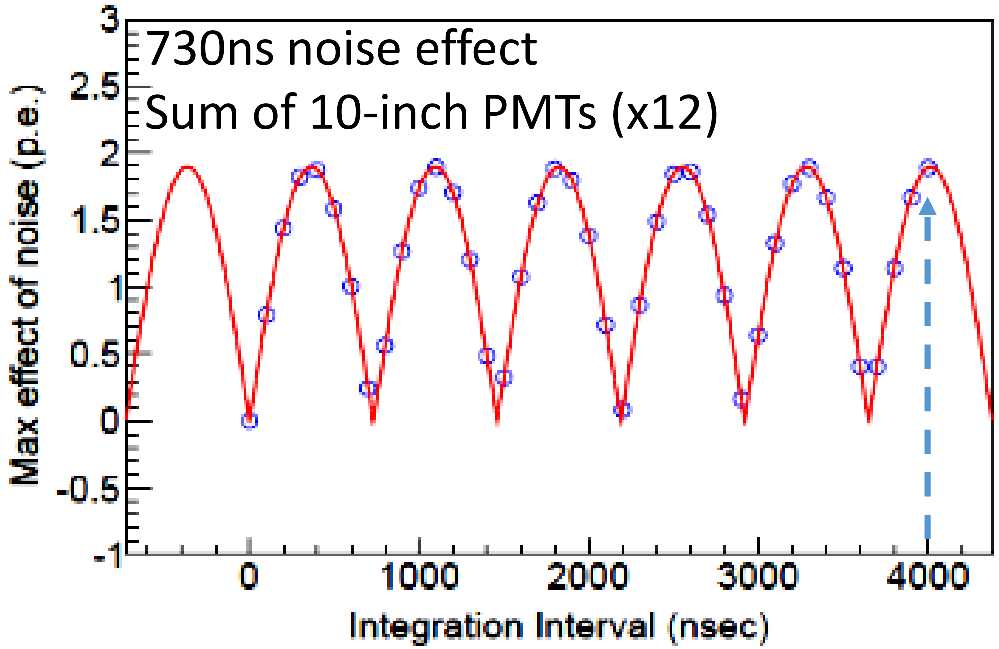
○ Cycle 730 ns (1.3-1.4 MHz)

○ Amplitude ~0.73 ADC (3mV)

⇒Amplitude < 1 ADC even sum up 12 PMTs

Noise in Baseline





- Noise effect in an interval T is

⇒a function of phase ($\int_0^T \sin(x+\varphi)\,dx$)

- Phase factor is random in CaF_2 waveform. (difficult to estimate)

⇒Estimate the max effect at each interval

⇒At T=4000ns, effect is about $\sigma_{noise} \leq 2$p.e.

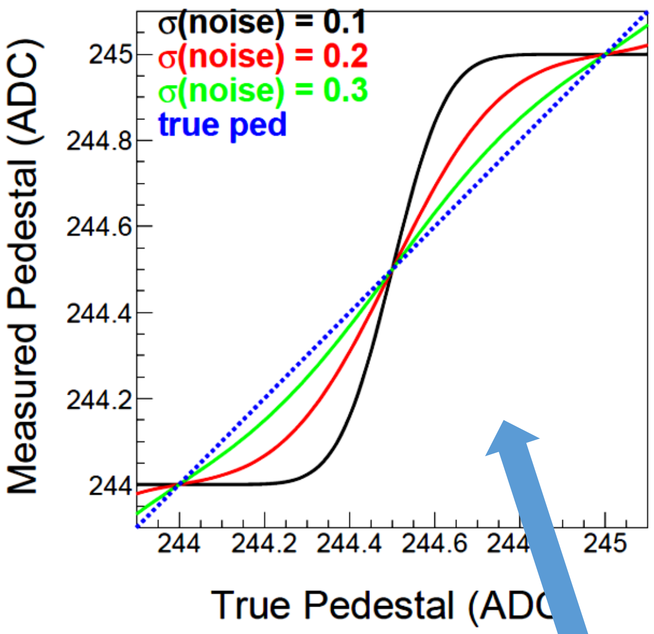
⇒$\sigma_{noise}/Q \leq 0.05\%$ (still negligible)

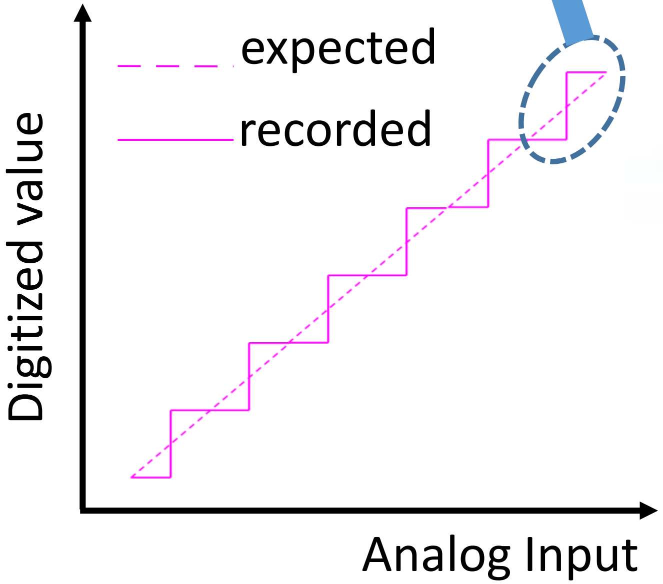
CONTENTS

1. Introduction
2. CANDLES experiment
3. 2νββ & Energy resolution
4. Error in charge measurement
   a. ~~Dark Current~~
   b. ~~Noise in baseline~~
   c. Digitization Error
5. Photon Counting
6. Results and Discussion
7. Possibility for Photon Counting

Digitization Error

We are using ADCs:
*ADC0850DL, Texas Ins.
*ENOB=7.5bits @ 125MHz





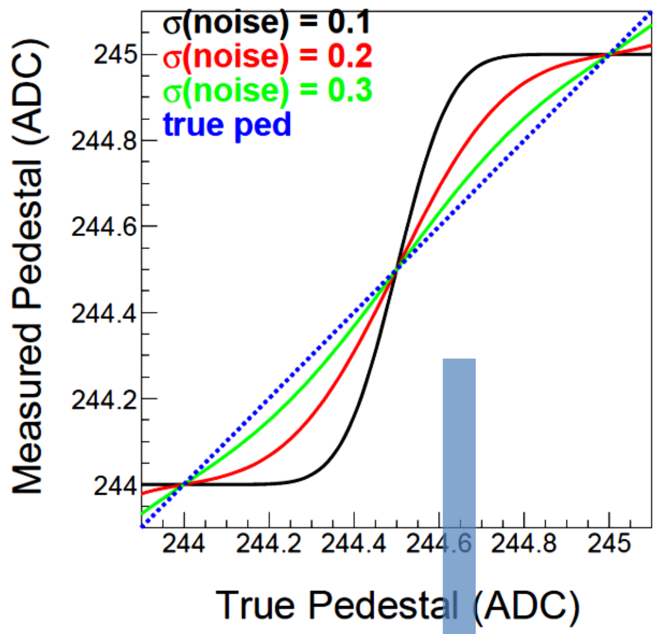
Digitization error (DE):

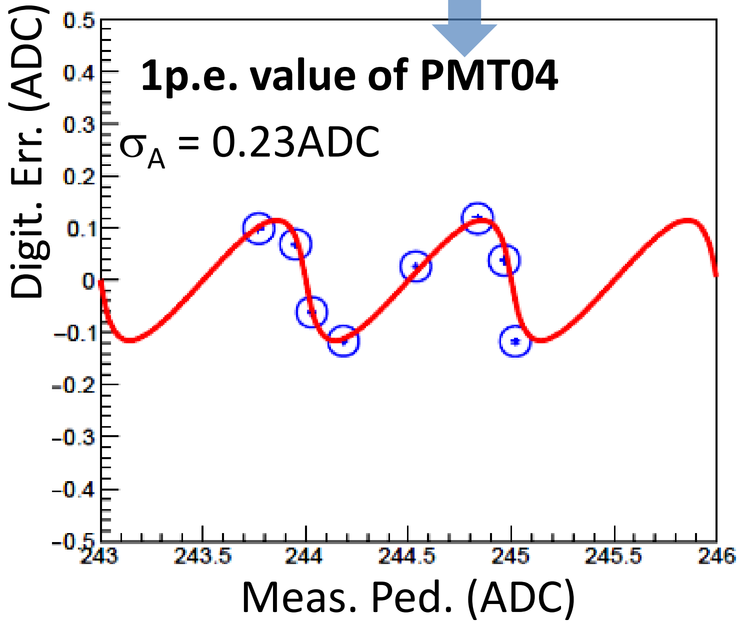
- Difference between measured pedestal and true pedestal (b/c of LSB)
- **As a function of pedestal**
- Calculate charge:

⇒**Accumulated in signal integration**

Digitization Error

We are using ADCs:
*ADC0850DL, Texas Ins.
*ENOB=7.5bits @ 125MHz





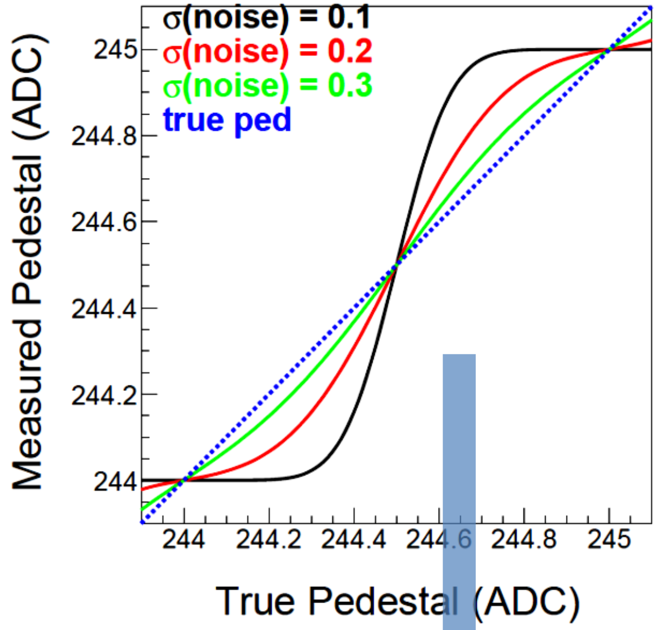
Digitization error (DE):

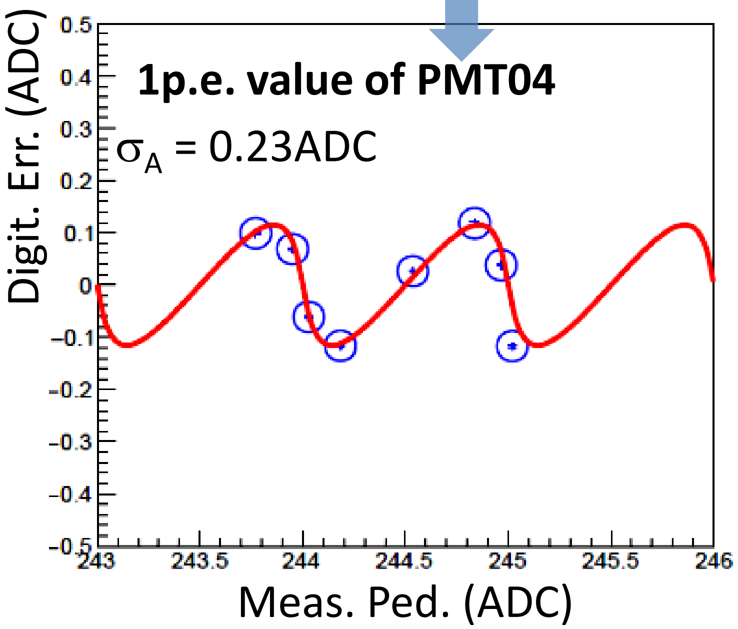
- Difference between measured pedestal and true pedestal (b/c of LSB)
- **As a function of measured pedestal**
- Calculate charge: $\sum(\mathrm{Ped} - \mathrm{Signal}[i])$

$\Rightarrow$**Accumulated in signal integration**

Digitization Error

We are using ADCs:
*ADC0850DL, Texas Ins.
*ENOB=7.5bits @ 125MHz

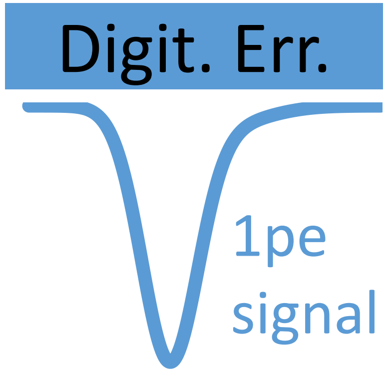


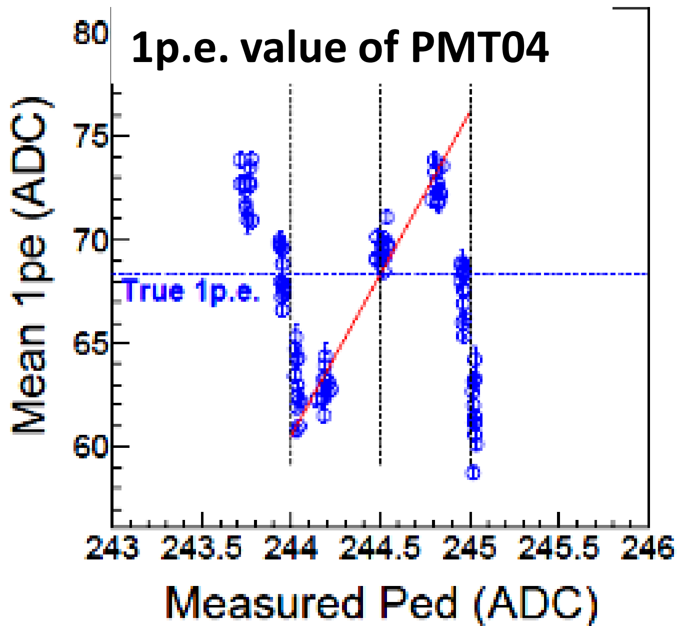


Digitization error (DE):

- Difference between measured pedestal and true pedestal (b/c of LSB)
- **As a function of measured pedestal**
- Calculate charge: $\sum(\mathrm{Ped} - \mathrm{Signal}[i])$

$\Rightarrow$ **Accumulated in signal integration**





- In 1p.e. signal:

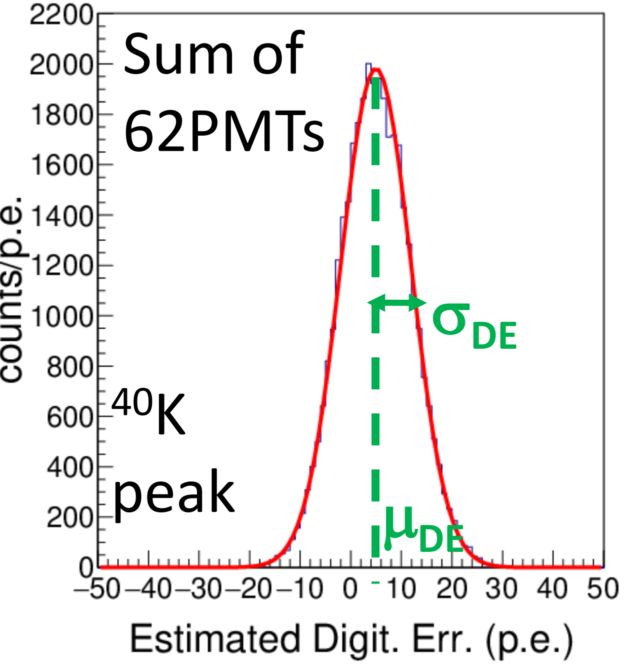
$\Rightarrow$ DE accumulated by the width

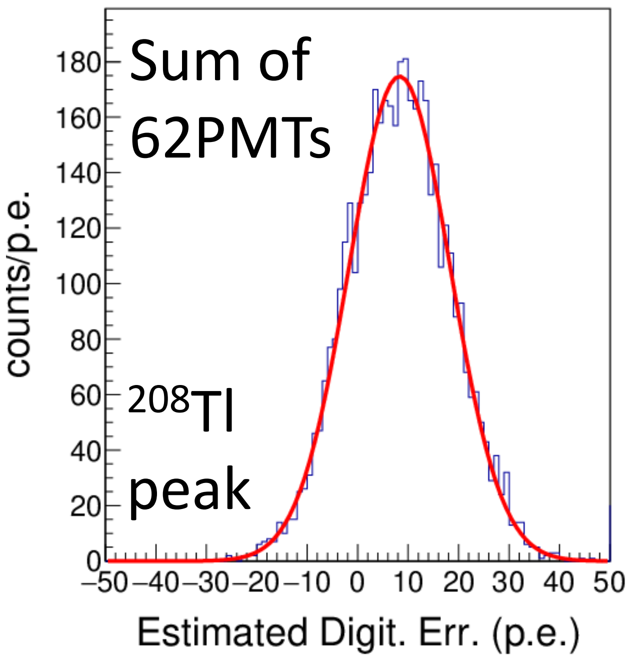
$\Rightarrow$ Estimate as a function of ped.

- Signal contains many 1p.e.

$\Rightarrow$ **Digitization error in each PMT can be estimated using: <u>Number p.e.</u> & <u>Pedestal</u>**

Digitization Error





- From experimental data,

⇒number of p.e. and pedestal

⇒Estimate the digitization error on the energy spectrum (^{40}K & ^{208}Tl)

- From the Digitization Error dist.,
  - μ_{DE} affects peak position
  - σ_{DE} affects energy resolution

- Fluctuations of DE at different peaks are estimated:
  - ^{40}K (1.46MeV), $\sigma_{DE}/E = 0.6\%$
  - ^{208}Tl (2.6MeV), $\sigma_{DE}/E = 0.4\%$

⇒At Q-value, **σ_{DE}/Q is small**

Error in charge measurement (review)

- Several sources of fluctuations were checked
- However,
  - Dark Current ($\sigma_{DC}/Q_{\beta\beta}$) ⇒ negligible
  - Baseline Noise ($\sigma_{noise}/Q_{\beta\beta}$) ⇒ negligible
  - Digitization Error ($\sigma_{DE}/Q_{\beta\beta}$) ⇒ small

$\Rightarrow$ I found the <u>most severe fluctuation in the baseline</u> is the <u>pedestal uncertainty</u>.

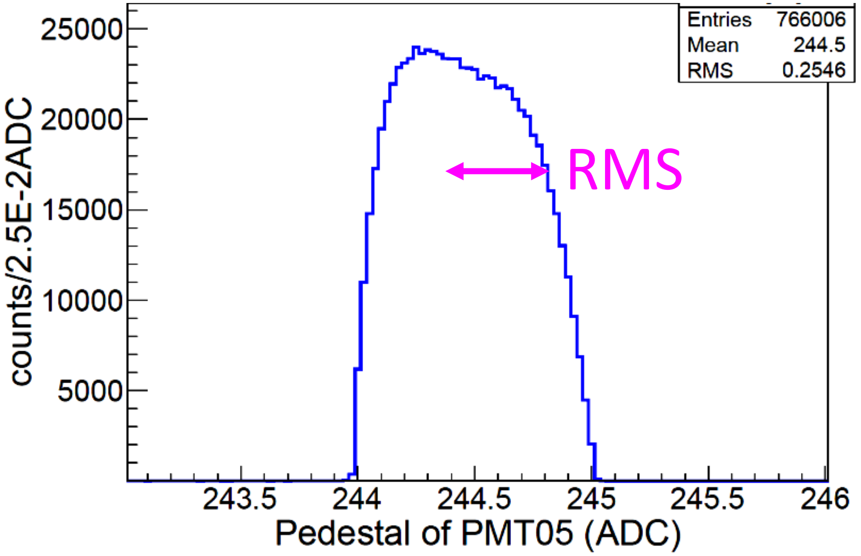
CONTENTS

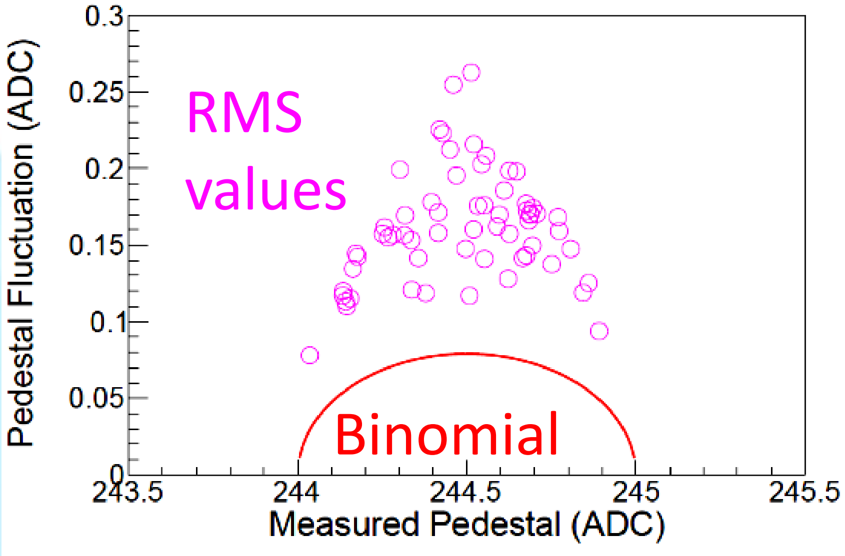
1. Introduction
2. CANDLES experiment
3. 2νββ & Energy resolution
4. Error in charge measurement
5. Photon Counting
6. Results and Discussion
7. Possibility for Photon Counting

~~a. Dark Current~~
~~b. Noise in baseline~~
~~c. Digitization Error~~
d. Pedestal Uncertainty

Pedestal Uncertainty

Event-by-event distribution





- In this research, the pedestal of each PMT is calculated using first 40 bins
- Ideally, binomial fluctuation below LSB

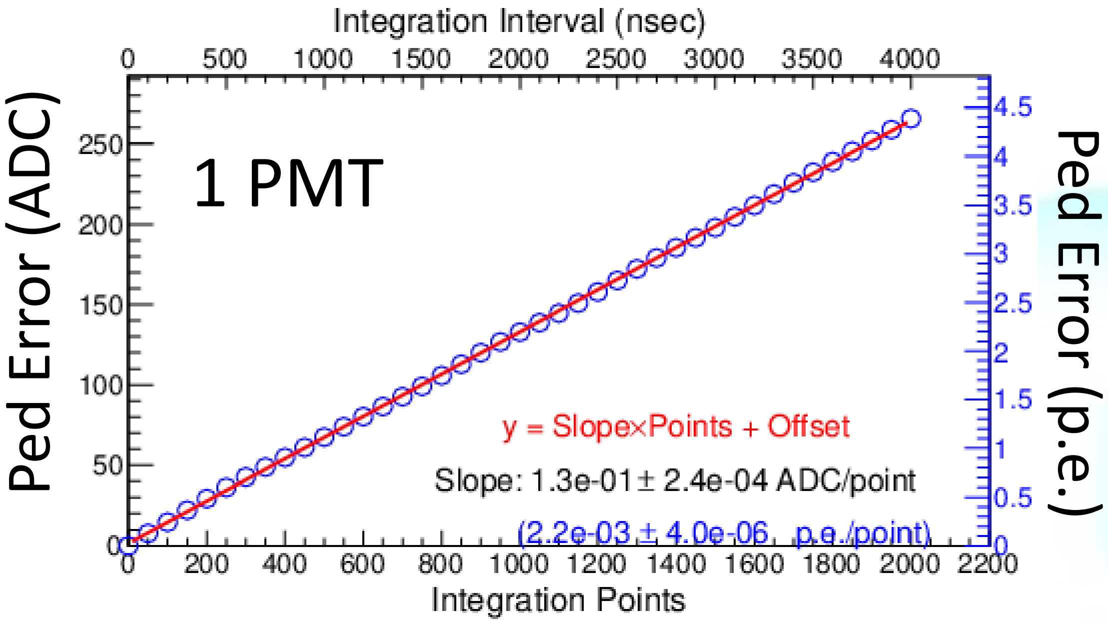
- Due to the noise in every PMT

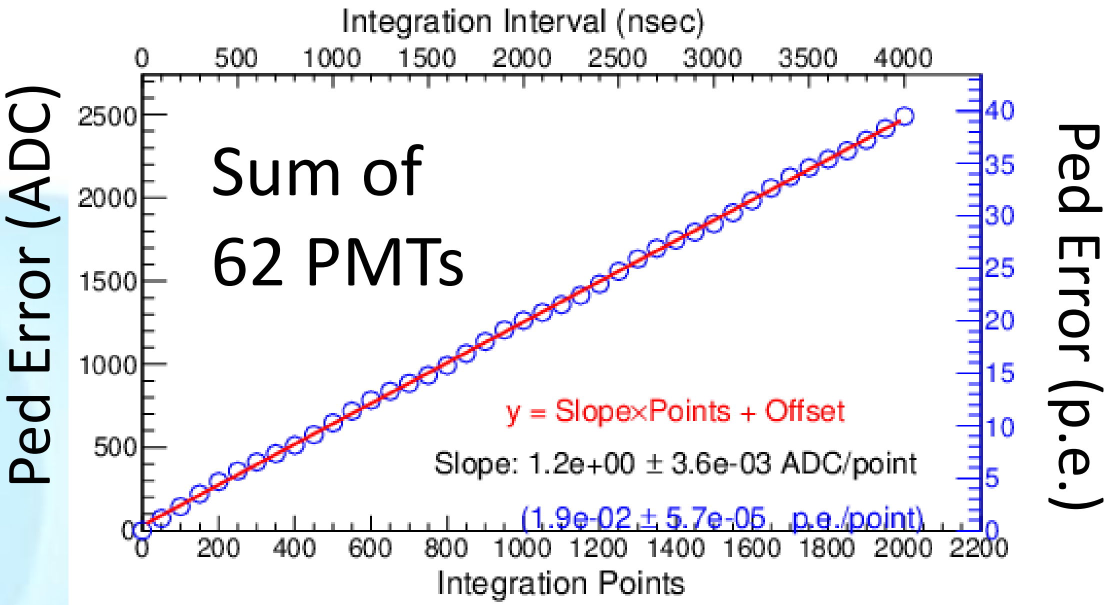
$\Rightarrow$The pedestal uncertainty is about 2 times larger than the binomial one.

$\Rightarrow$Study pedestal uncertainty at **zero-energy signal**

Pedestal Uncertainty

*Signal Integration = N×Ped - Σ_i^NSignal[i]





- In Signal Integration, the pedestal uncertainty is accumulated at every data point*.

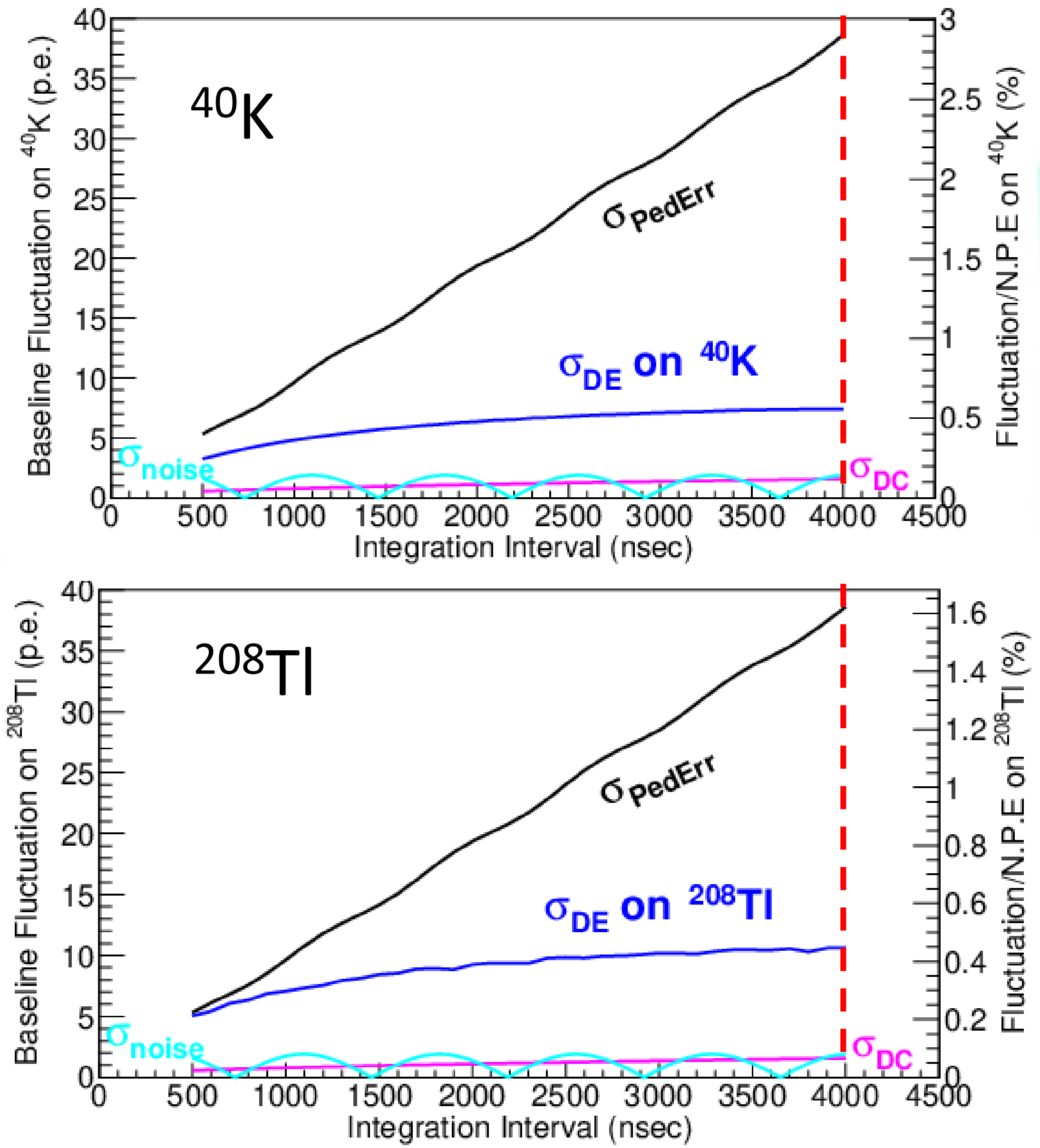
$\Rightarrow$Accumulated Fluc = N x σ_{PedErr}

$\Rightarrow$The accumulated fluctuation is linearly proportional to number of data points

- In case we sum up many PMTs, it is more severe effect.
- For 62 PMTs, integration interval of 4000 ns, the accumulated fluctuation is σ_{PedErr} = 38.6 p.e. or $\sigma_{PedErr}/Q_{\beta\beta}$ = 1%
- Compare $\sigma_{p.e.}/Q_{\beta\beta} \approx 1.6\%$

$\Rightarrow$ **σ_{PedErr} causes a severe fluctuation**

SUMMARY of fluctuations



Full integral (4000 nsec)	^{40}K peak (1460 keV)	^{208}Tl peak (2614 keV)	^{48}Ca Q-value (4272 keV)
σ_{PedErr} : Ped Error (σ_{PedErr}/N_{pe})	38.6 p.e. (2.9 %)	38.6 p.e. (1.6 %)	38.6 p.e. (1.0 %)
σ_{DE} : Digit. Err. (σ_{DE}/N_{pe})	7.3 p.e. (0.6 %)	10.4 p.e. (0.4 %)	(small)
σ_{noise} : 730ns noise (σ_{HF}/N_{pe})	≤2 p.e. (≤ 0.15 %)	≤2 p.e. (≤ 0.08 %)	≤2 p.e. (≤ 0.05 %)
σ_{DC} : Dark Current (σ_{DC}/N_{pe})	1.6 p.e. (0.1 %)	1.6 p.e. (0.06 %)	1.6 p.e. (0.04 %)

- Fluctuations from Dark Current, Noise, Digitization Error and Pedestal uncertainty are estimated as functions of integration interval.

⇒**Fluctuation from Pedestal Uncertainty (σ_{PedErr}) is the most severe**

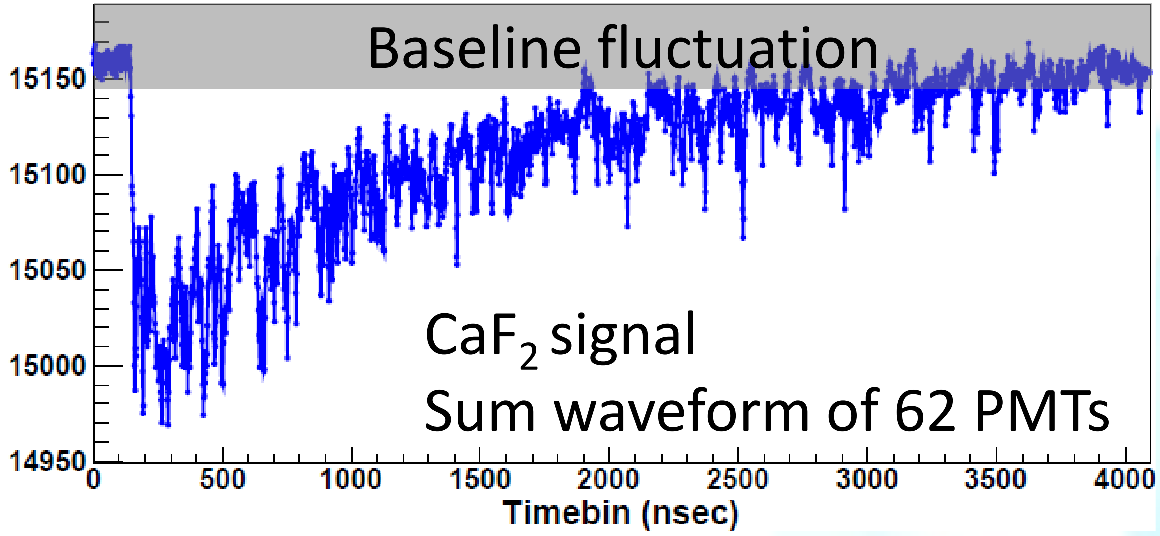
⇒Signal integration to get energy ⇒ **not good**

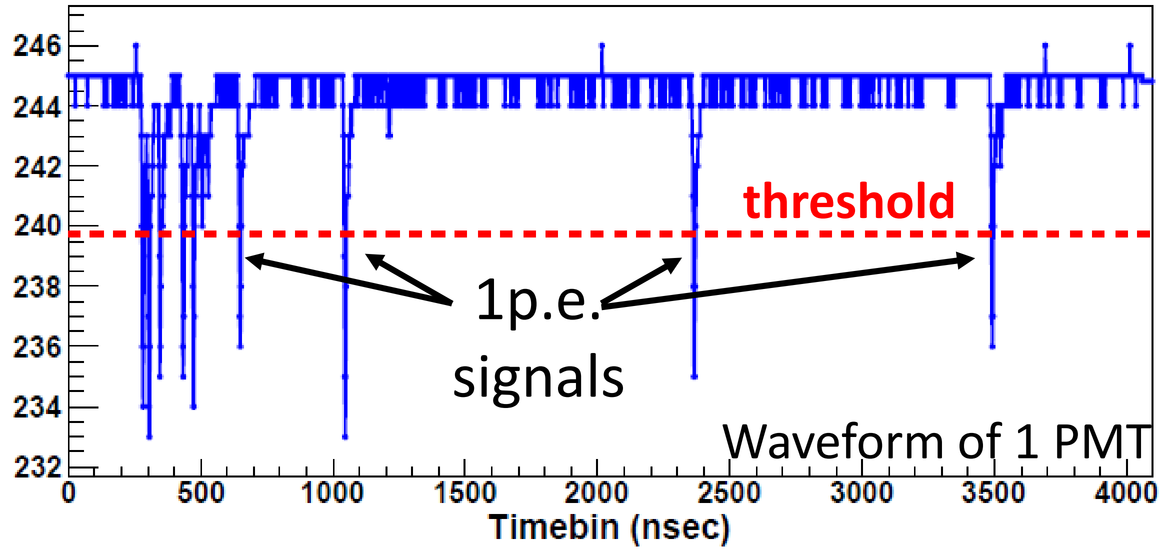
⇒**Need another method to get energy**

CONTENTS

1. Introduction
2. CANDLES experiment
3. 2νββ & Energy resolution
4. Error in charge measurement
5. Photon Counting
   a. Motivation
   b. Measurement
   c. Analysis
6. Results and Discussion
7. Possibility for Photon Counting

Photon Counting: Motivation





SIGNAL INTEGRATION

- The baseline fluctuations: severe
- In current analysis, signal integration is used

⇒Baseline fluctuations are accumulated

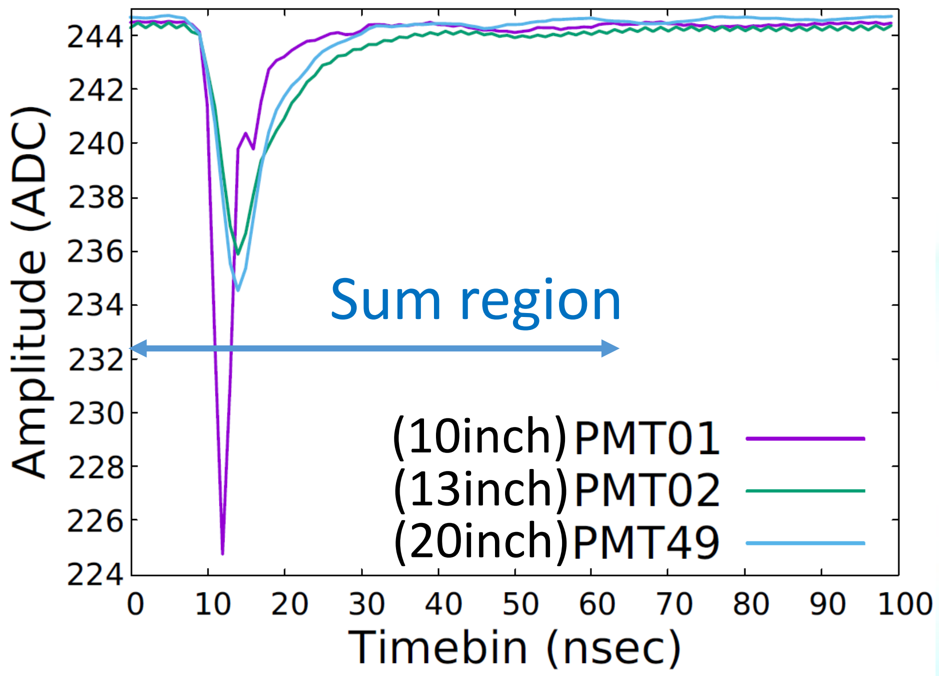
PHOTON COUNTING

- Setting threshold
- Count p.e. in each PMT

⇒ No integration

⇒ Avoid baseline fluctuation

Photon Counting: Measurement

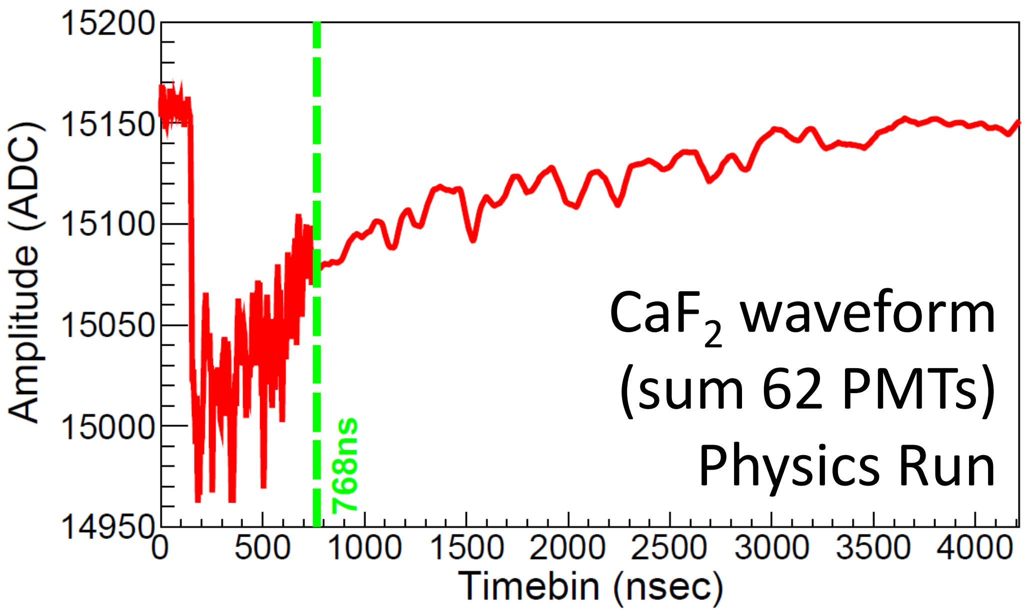


- Waveform of CANDLES:
  - First 768 ns, 2ns/sample
  - Latter sum every 64 ns.
- The 1p.e. width is short (<50ns)
- If 1p.e. arises after 768 ns, it is difficult to see it.

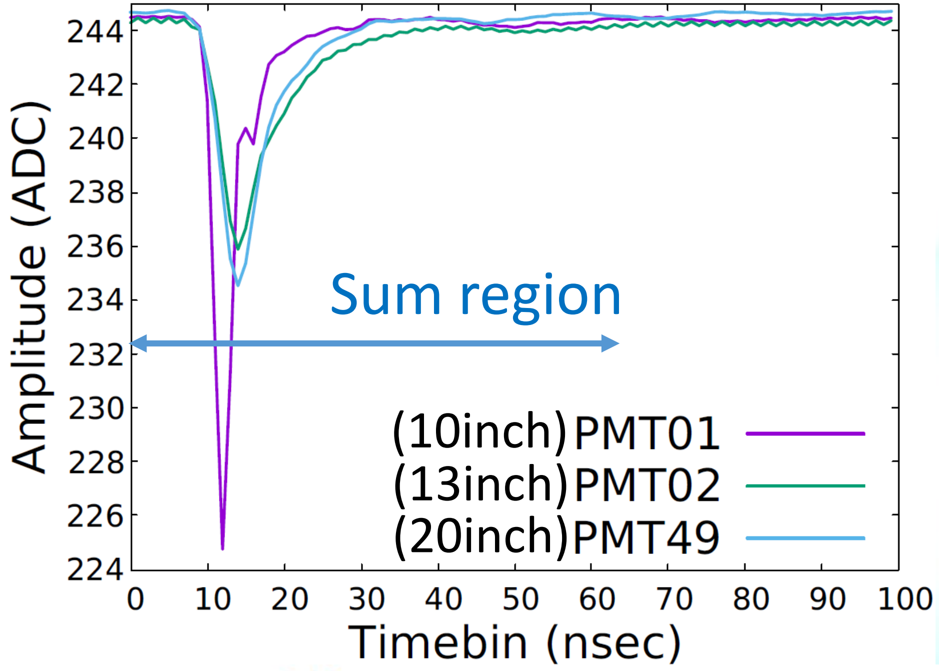
⇒Need to modify the DAQ software

- After modification, data size x3 times larger.

	Physics Run	Photon Count
Size	~50kB/event	**~150kB/event**
Waveform interval	~9μsec	**~4.2μsec**



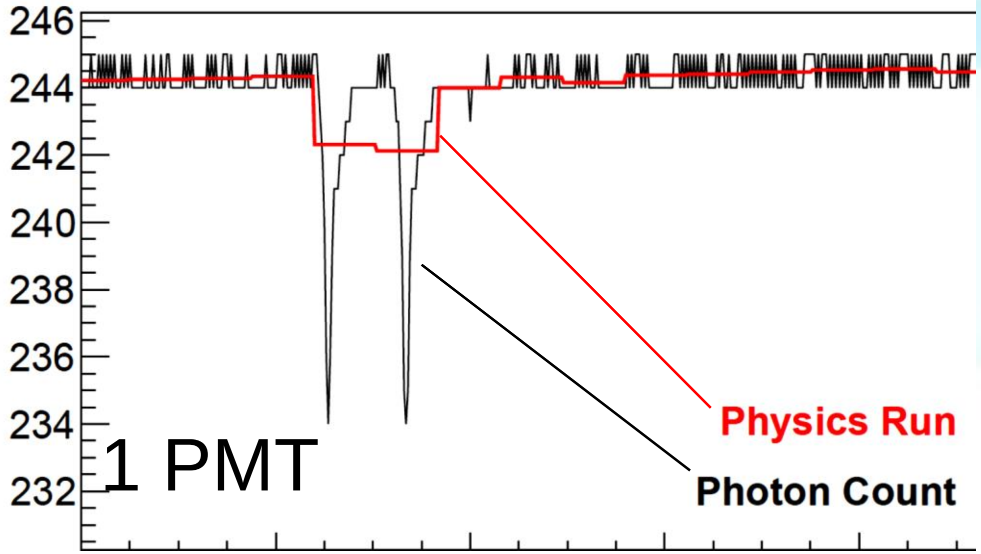
Photon Counting: Measurement

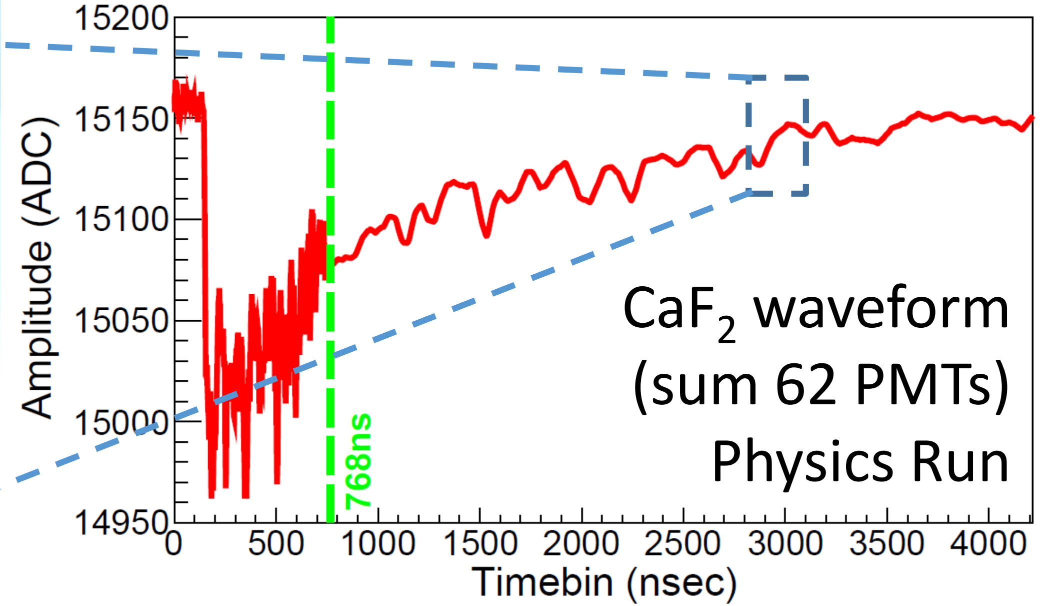


- Waveform of CANDLES:
  - First 768 ns, 2ns/sample
  - Latter sum every 64 ns.
- The 1p.e. width is short (<50ns)
- If 1p.e. arises after 768 ns, it is difficult to see it.

⇒Need to modify the DAQ software

- After modification, data size x3 times larger.





Photon Counting: Measurement

- Maximize 2 nsec means extend a lot of data size in event buffer of FADCs

- Size/event is 3 times larger

⇒The readout time/event is ~20msec

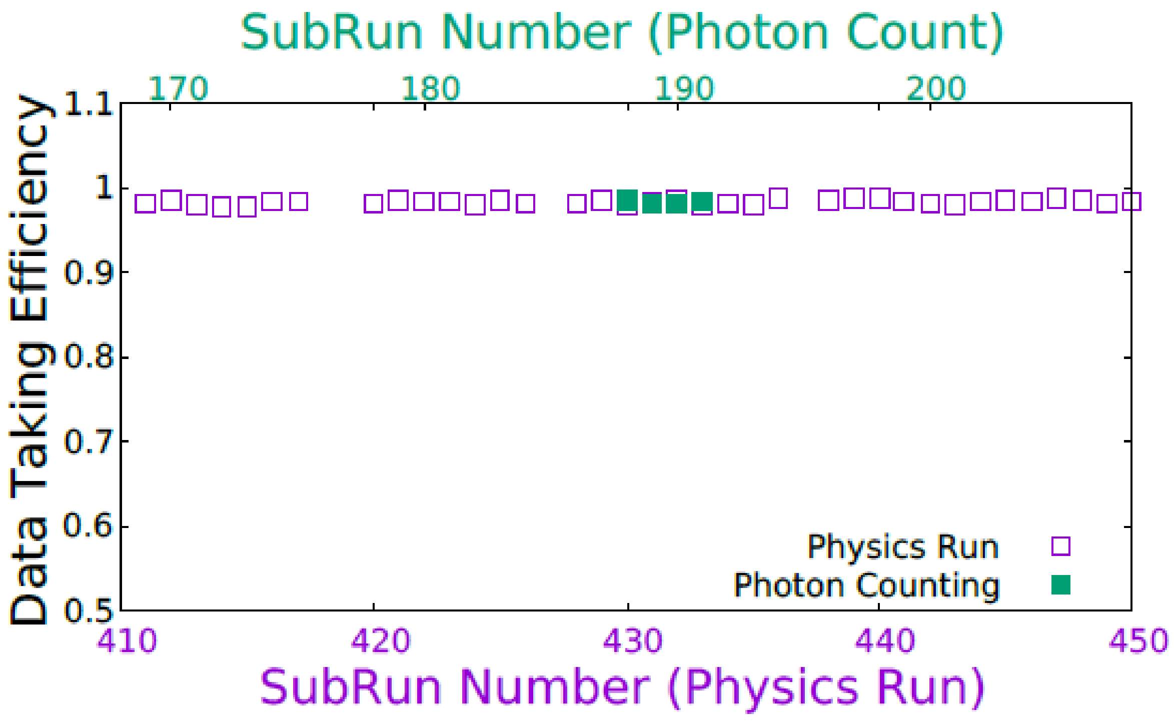
⇒X2 times longer than the Physics Run

⇒Estimate the data taking efficiency.

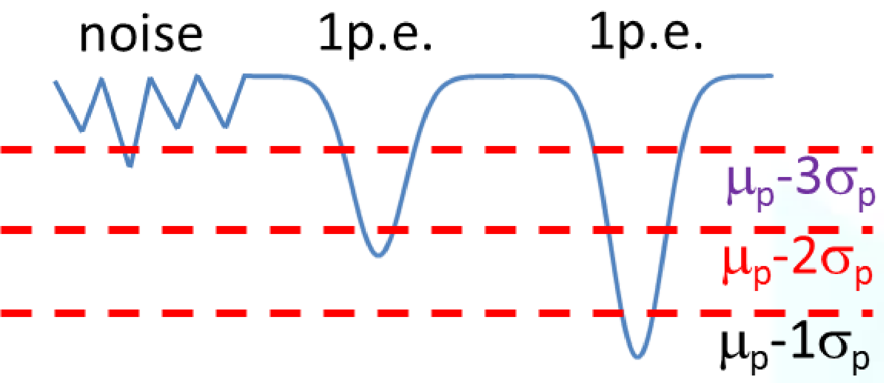
- Data taking efficiency = $N_{record}/N_{incident}$

⇒Thanks to our development of DAQ system (with 8 event buffers)

⇒Acquire ~100% data taking efficiency



Photon Counting analysis: Threshold

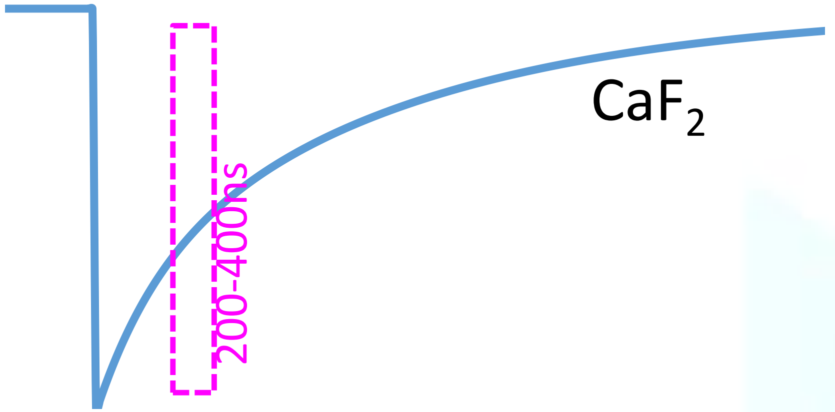


μ_p: mean of 1p.e. pulse height dist.
σ_p: rms of 1p.e. pulse height dist.

- In photon counting, a threshold is set to count the photoelectrons.
- If it is set too low: noises are counted as p.e.
- If it is set too high: we may lose p.e. when counting.
- Three thresholds μ_p-1 σ_p, μ_p-2 σ_p and μ_p-3 σ_p are used to test
- Check the separation of 1p.e. from baseline

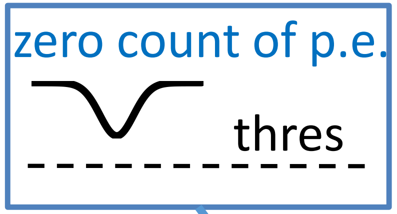
⇒**The threshold for photon counting μ_p-2 σ_p**

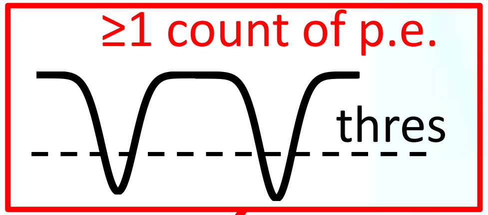
Photon Counting analysis: Threshold

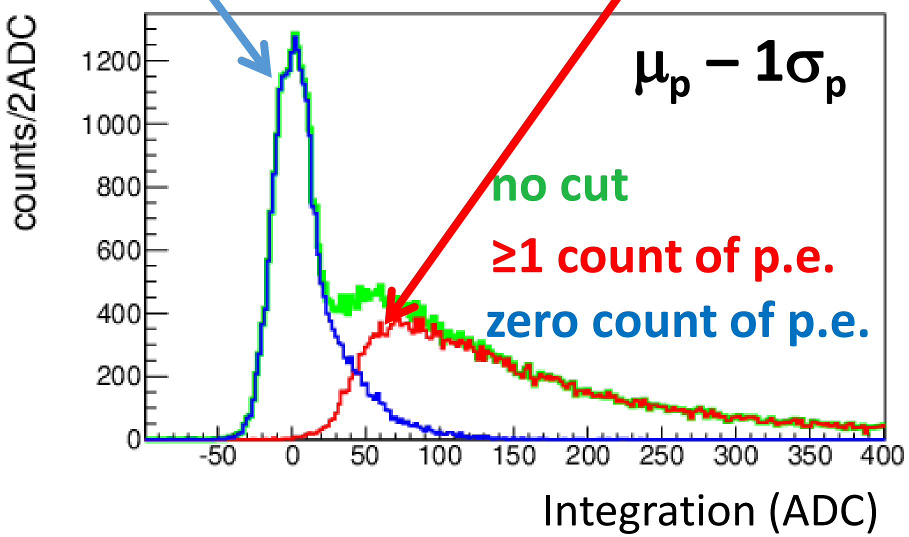


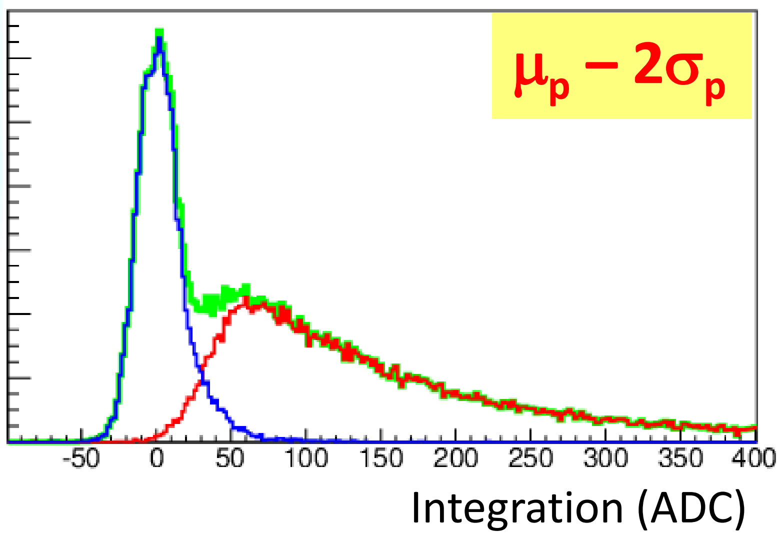
- In photon counting, a threshold is set to count the photoelectrons.
- If it is set too low: noises are counted as p.e.
- If it is set too high: we may lose p.e. when counting.
- Three thresholds μ_p-1 σ $_p$, μ_p-2 σ $_p$ and μ_p-3 σ $_p$ are used to test
- Check the separation of 1p.e. from baseline

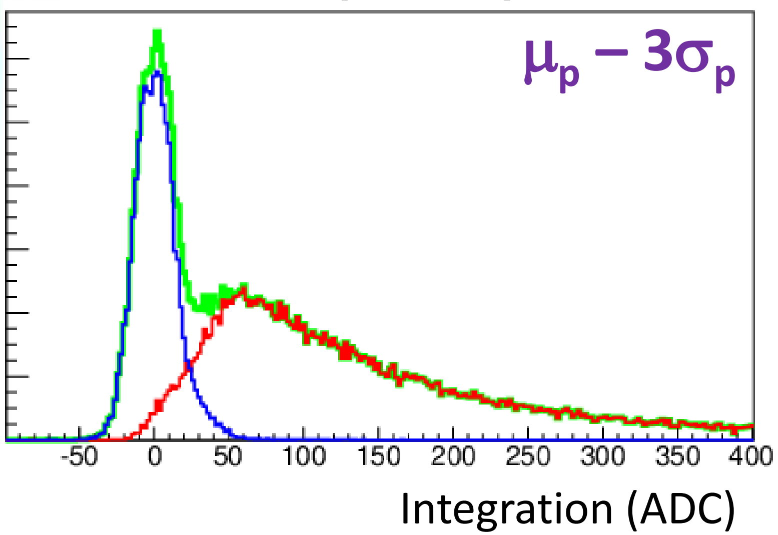
⇒The threshold for photon counting μ_p-2 σ $_p$



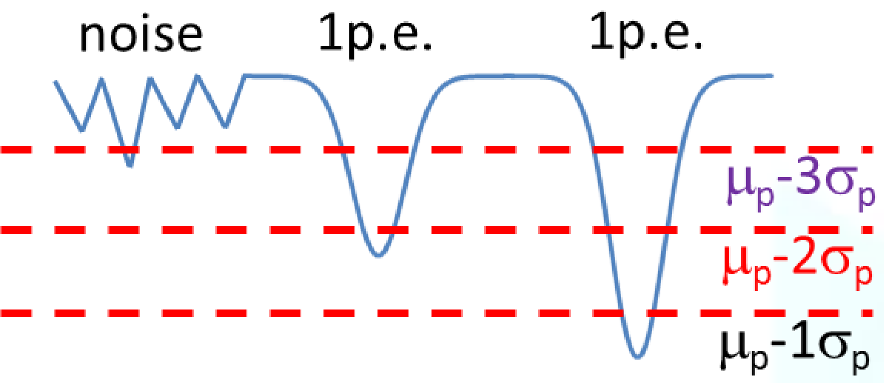








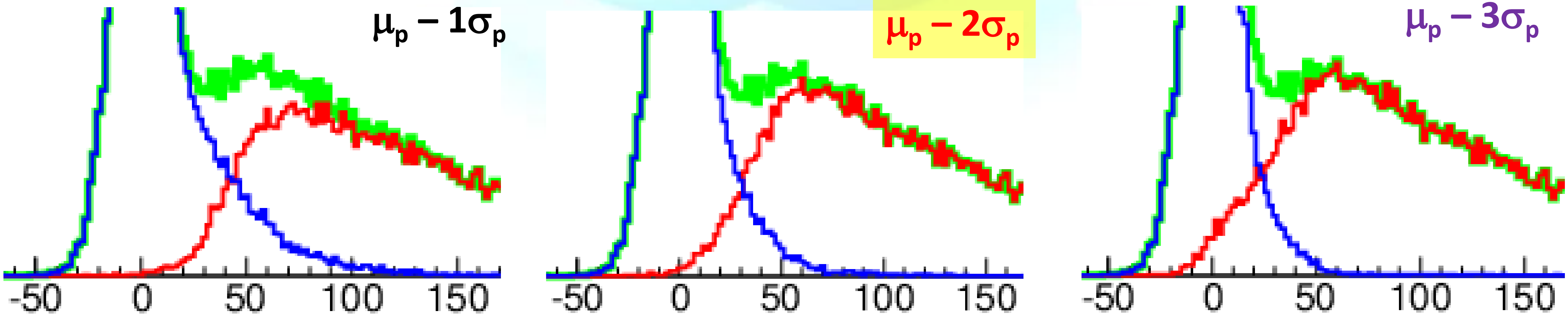
Photon Counting analysis: Threshold



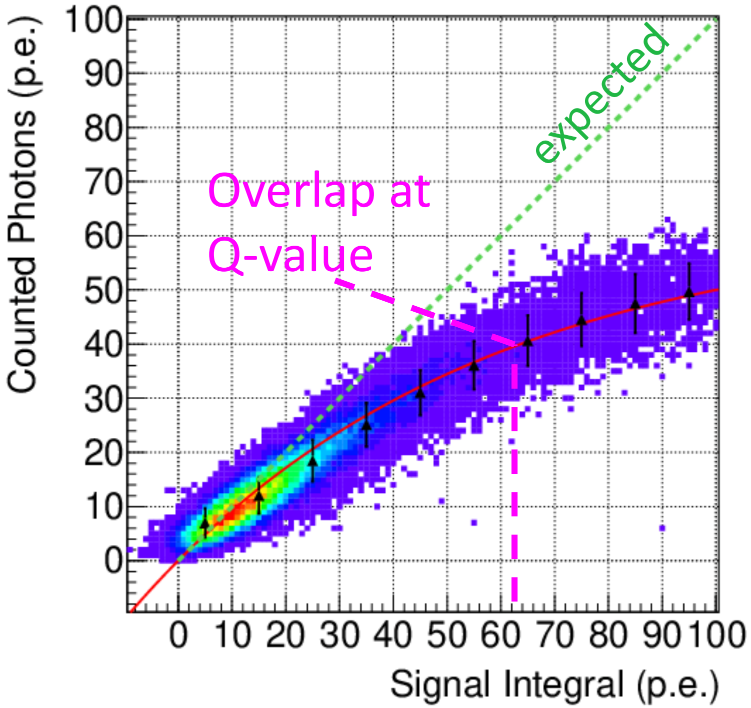
μ_p: mean of 1p.e. pulse height dist.
σ_p: rms of 1p.e. pulse height dist.

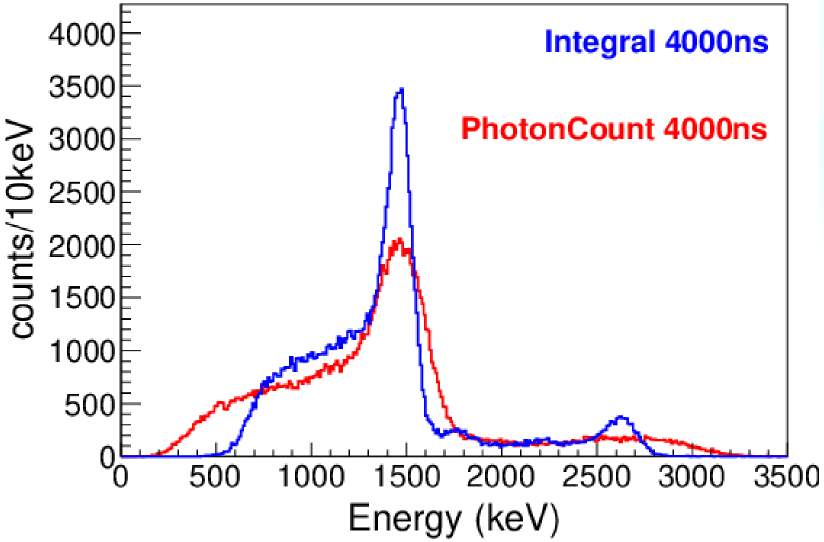
- In photon counting, a threshold is set to count the photoelectrons.
- If it is set too low: noises are counted as p.e.
- If it is set too high: we may lose p.e. when counting.
- Three thresholds μ_p-1 σ_p, μ_p-2 σ_p and μ_p-3 σ_p are used to test
- Check the separation of 1p.e. from baseline

⇒**The threshold for photon counting μ_p-2 σ_p**



Overlap of 1p.e. signals





- Many 1p.e. signals overlap

⇒forming into a multi p.e. signal (2p.e., 3 p.e., etc.)

- With simple photon counting, a multi p.e. signal is counted as 1 p.e. signal.

⇒Miss photoelectrons in counting

⇒Bad energy resolution.

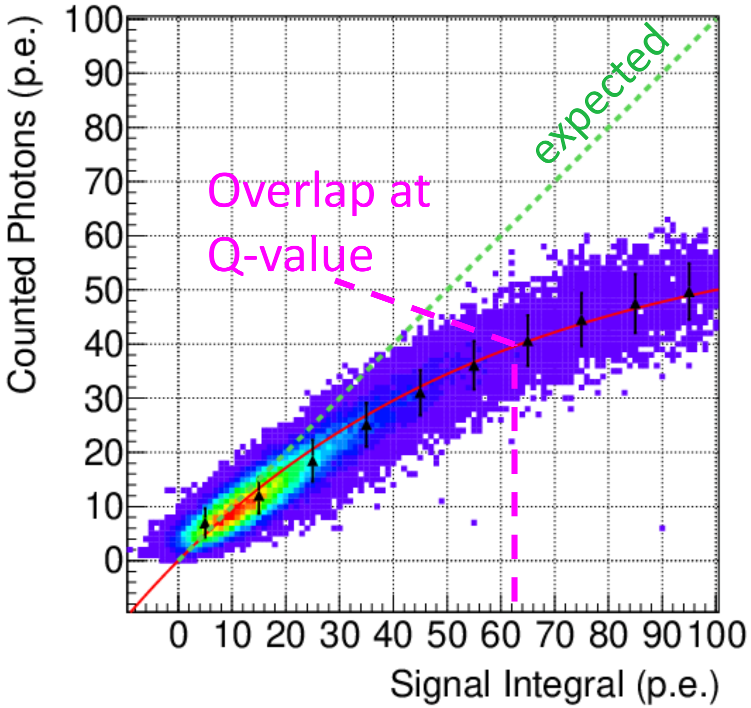
- In average, each PMT detects ~62p.e. at $Q_{\beta\beta}$

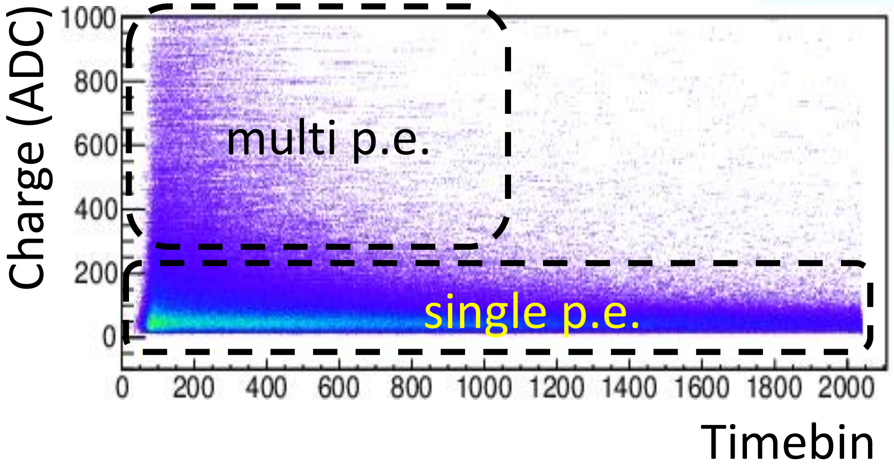
⇒Overlap is serious at Q-value!

- The multi p.e. are found at the rising edge of the waveform.

⇒Introduce an alternative method named "Partial Photon Counting".

Overlap of 1p.e. signals





- Many 1p.e. signals overlap

⇒forming into a multi p.e. signal (2p.e., 3 p.e., etc.)

- With simple photon counting, a multi p.e. signal is counted as 1 p.e. signal.

⇒Miss photoelectrons in counting

⇒Bad energy resolution.

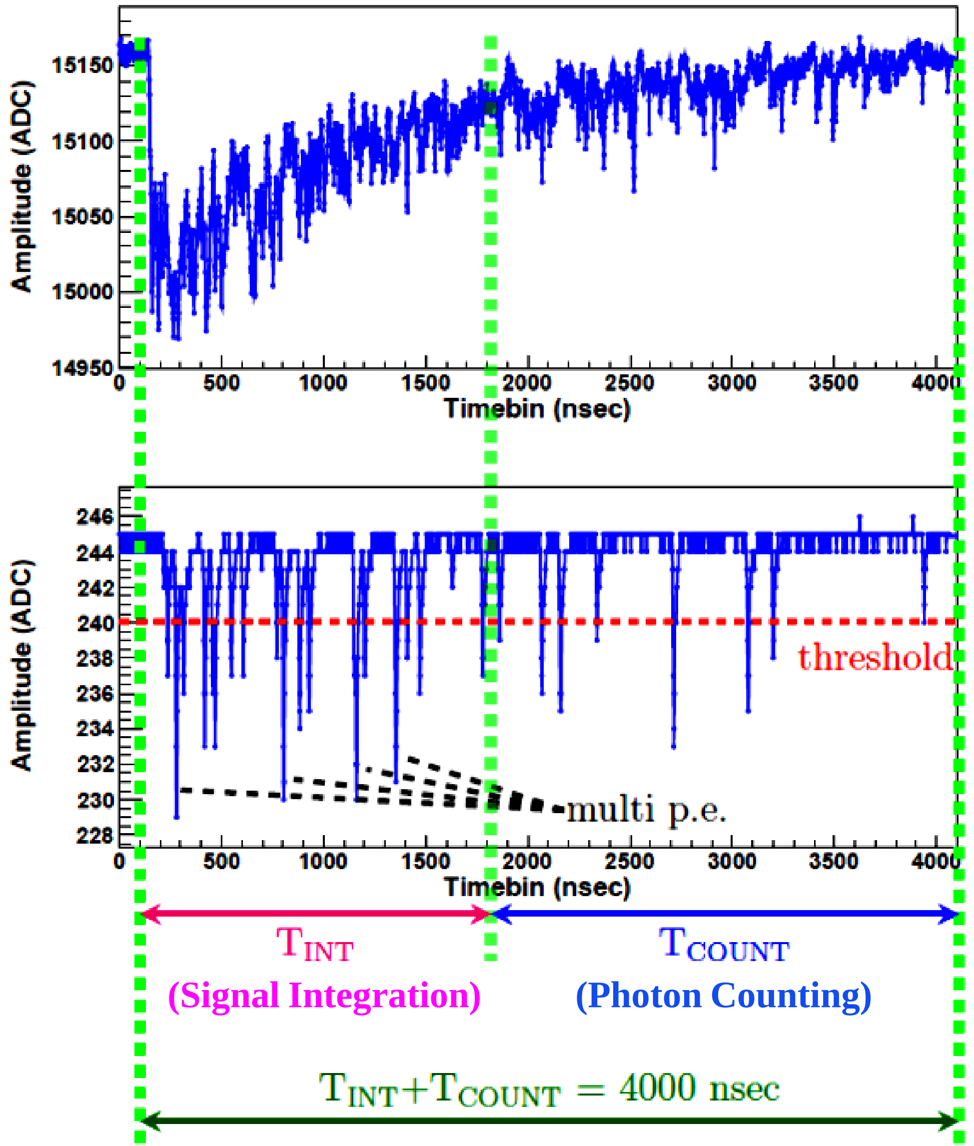
- In average, each PMT detects ~62p.e. at $Q_{\beta\beta}$

⇒Overlap is serious at Q-value!

- The multi p.e. are found at the rising edge of the waveform.

⇒Introduce an alternative method named "Partial Photon Counting".

Partial Photon Counting (PPC)



Divide the waveform each PMT into 2 areas:

– The 1st area (near rising edge):

⇒ many multi p.e.

⇒ Signal integral to avoid the lost of p.e.

– The 2nd area (near the tail):

⇒ not so many multi p.e.

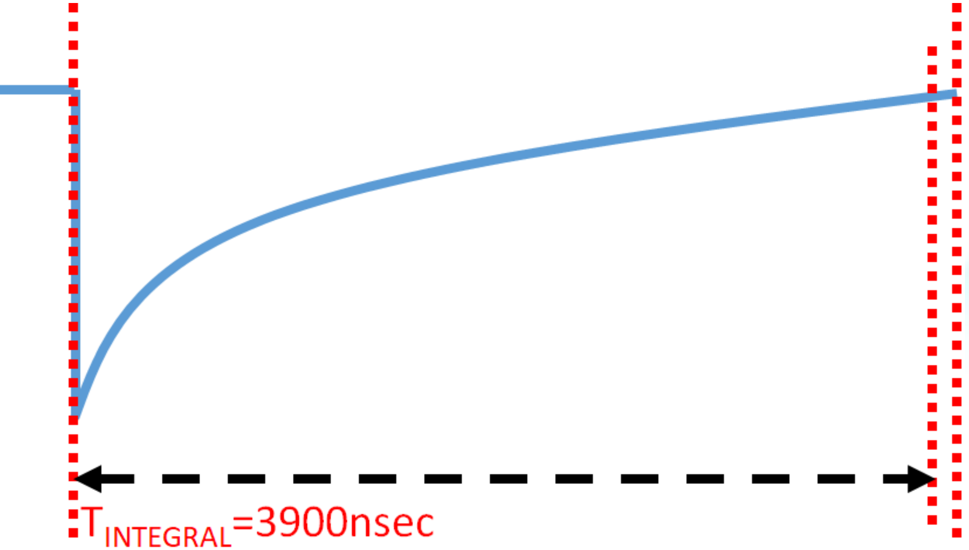
⇒Photon counting to avoid pedestal fluc.

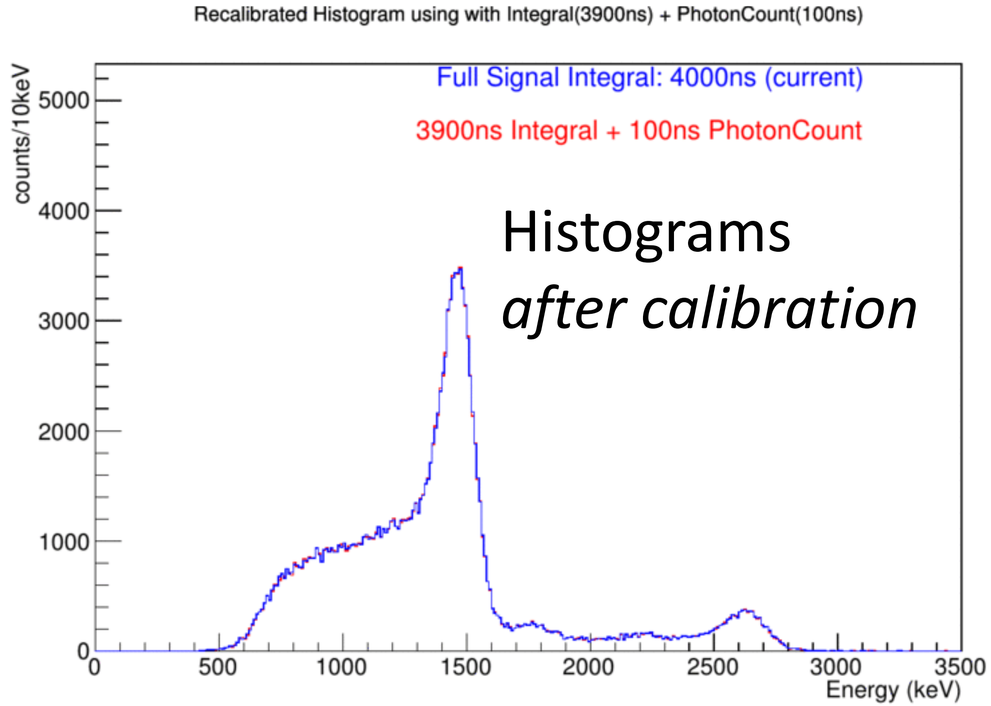
- In my research

⇒$T_{INTEGRAL} + T_{COUNT} = 4000ns$

⇒Check different mixtures of integration and photon counting

Partial Photon Counting (PPC)





Divide the waveform each PMT into 2 areas:

− The 1st area (near rising edge):

⇒ many multi p.e.

⇒ Signal integral to avoid the lost of p.e.

− The 2nd area (near the tail):

⇒ not so many multi p.e.

⇒ Photon counting to avoid pedestal fluc.

- In my research

⇒ $T_{INTEGRAL} + T_{COUNT}$ = 4000ns

⇒ Check different mixtures of integration and photon counting

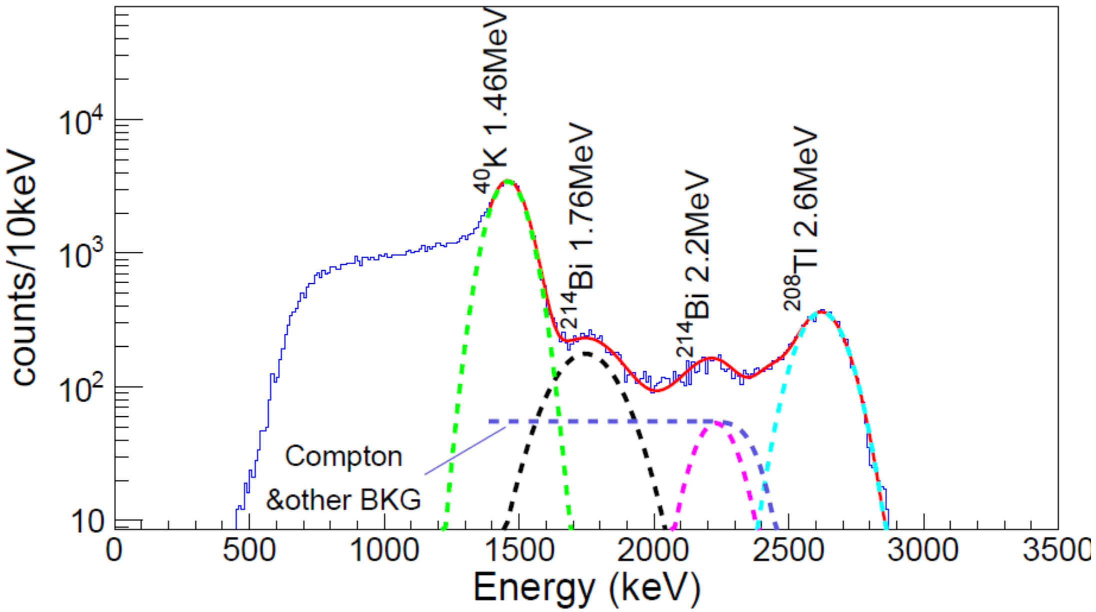
Partial Photon Counting (PPC): Result

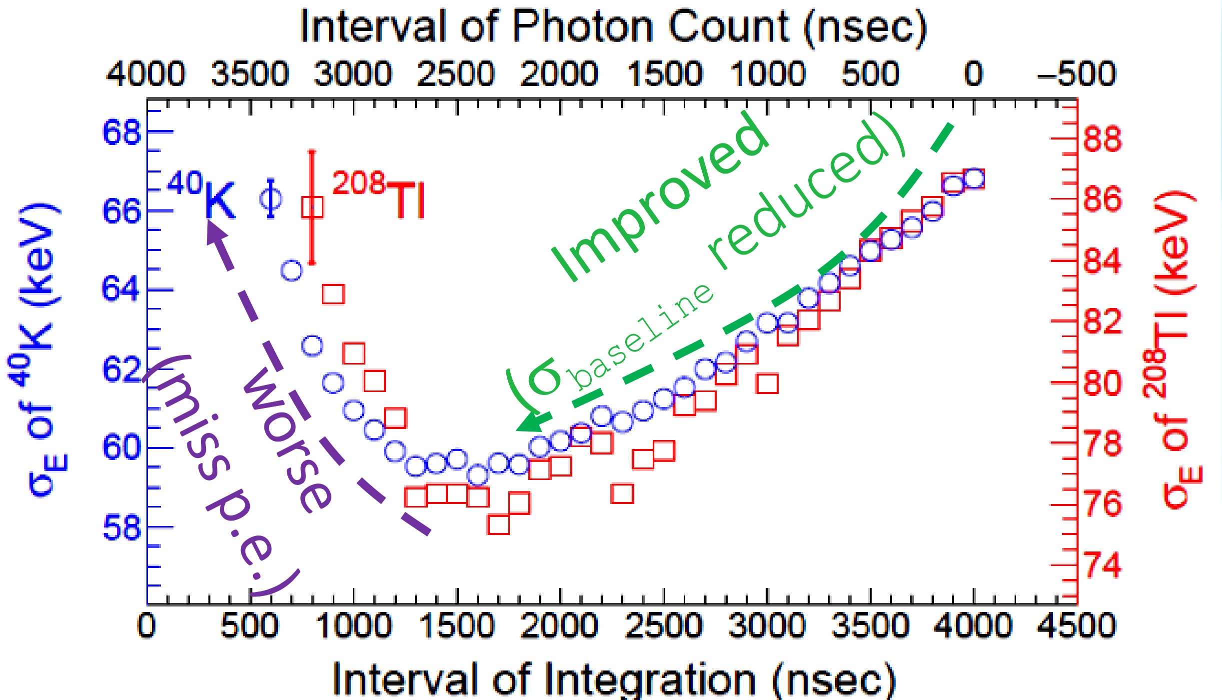
Evaluate the energy resolution at 1460keV (^{40}K) and 2614.5keV (^{208}Tl) for each histogram

⇒ Resolution: a function of signal integral gate

⇒The resolution is improved:

- $\sigma_E/E(^{40}K)$:~4.5% to ~4.0%
- $\sigma_E/E(^{208}Tl)$:~3.3% to ~2.9%





Gaussian of ^{208}Tl (impurities in crystal)

Gaussian of ^{214}Bi (impurities in crystal)

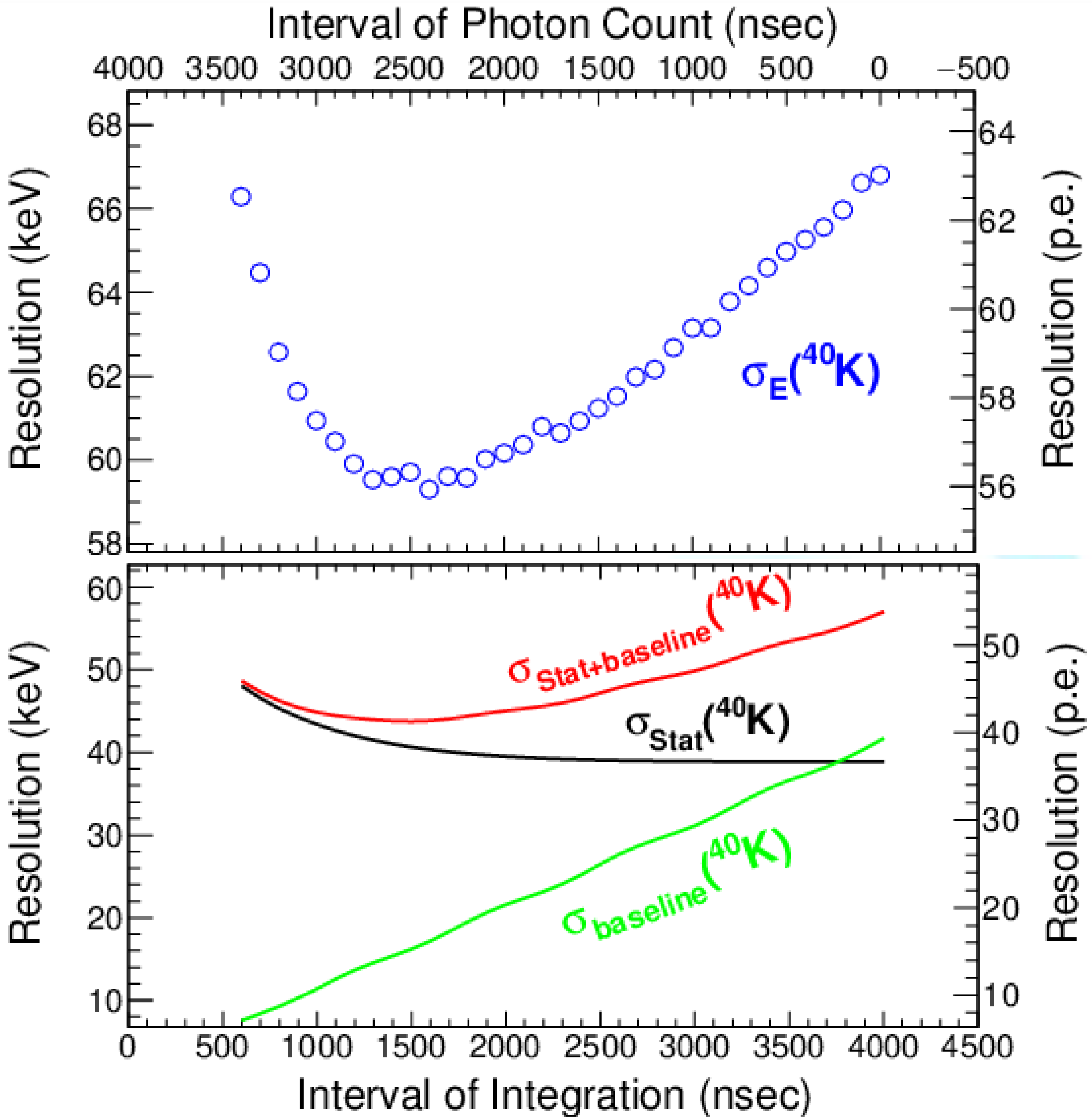
Gaussian of ^{40}K (impurities in PMTs)

Error function as Compton background

CONTENTS

1. Introduction
2. CANDLES experiment
3. $2\nu\beta\beta$ & Energy resolution
4. Error in charge measurement
5. Photon Counting
6. Results and Discussion
7. Possibility for Photon Counting

Results & Discussion



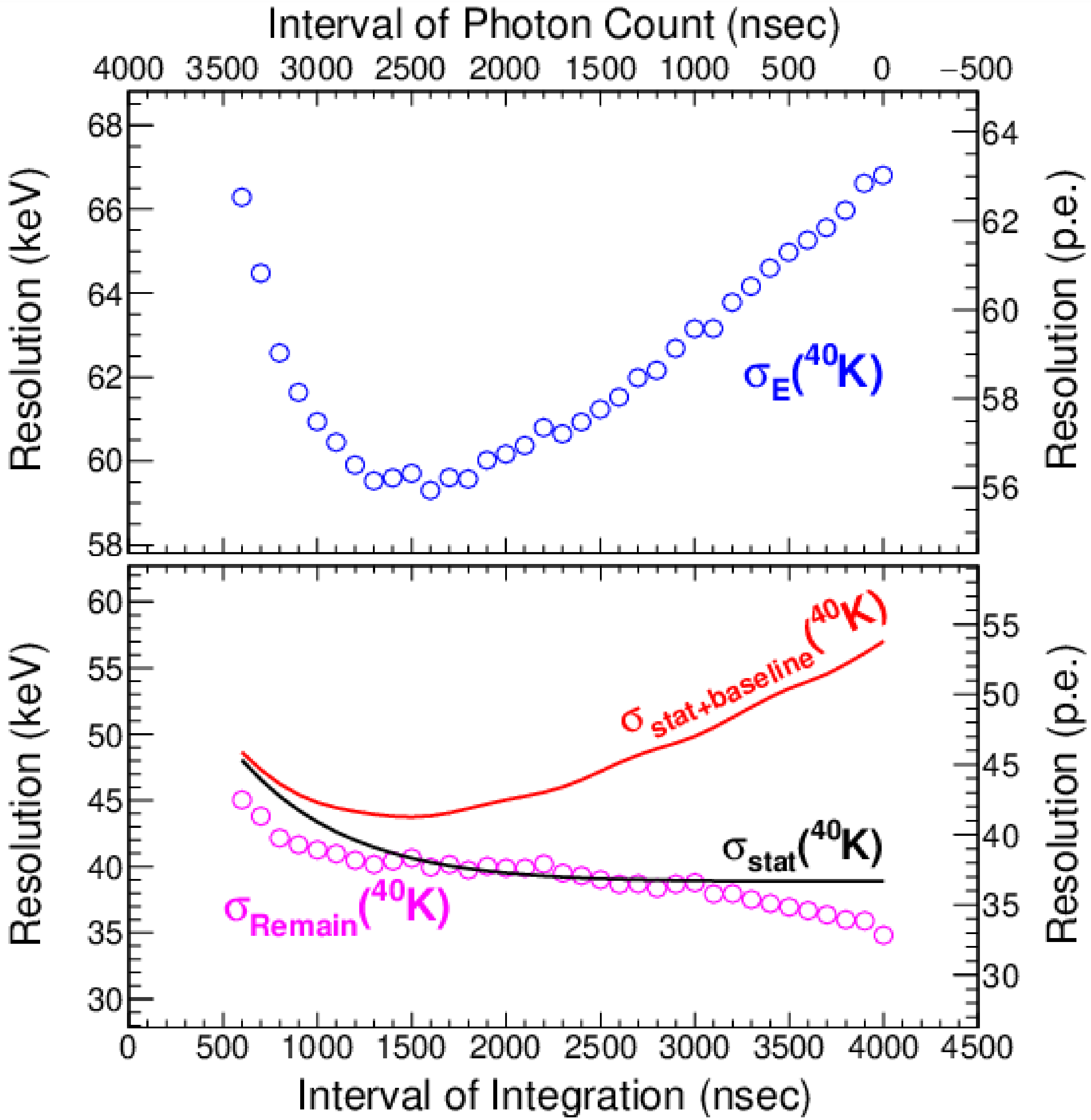
Obtained resolution at ^{40}K (σ_E)

(1) Baseline Fluc. = $\sqrt{\mathbf{PedErr}^2 + \mathbf{DE}^2}$

(2) Statistical Fluc. (estimated)

(3) Stat+Baseline = $\sqrt{(1)^2+(2)^2}$

Results & Discussion



Obtained resolution at ^{40}K (σ_E)

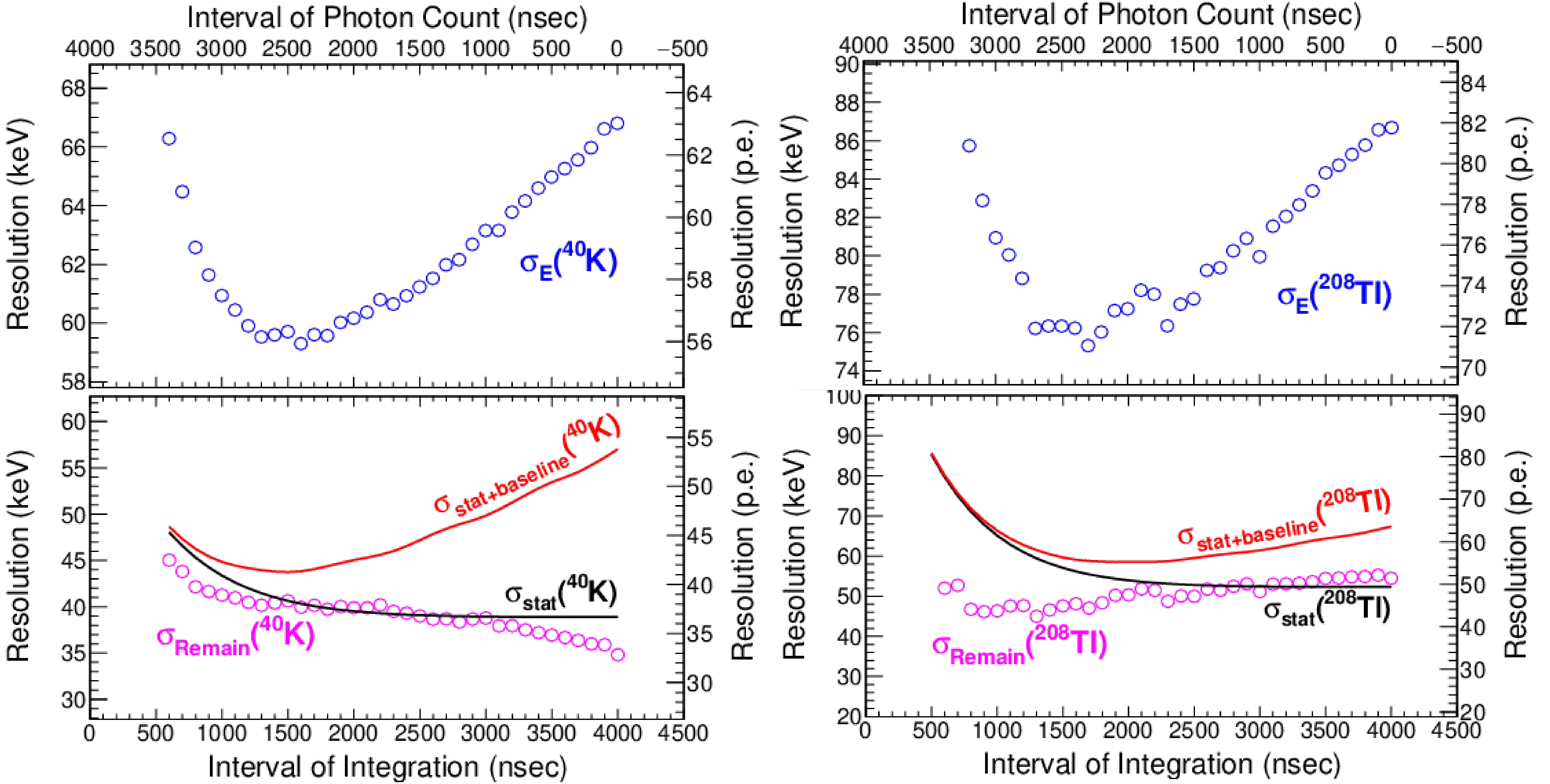
(1) Baseline Fluc. = $\sqrt{\mathbf{PedErr}^2 + \mathbf{DE}^2}$

(2) Statistical Fluc. (estimated)

(3) Stat+Baseline = $\sqrt{(1)^2 + (2)^2}$

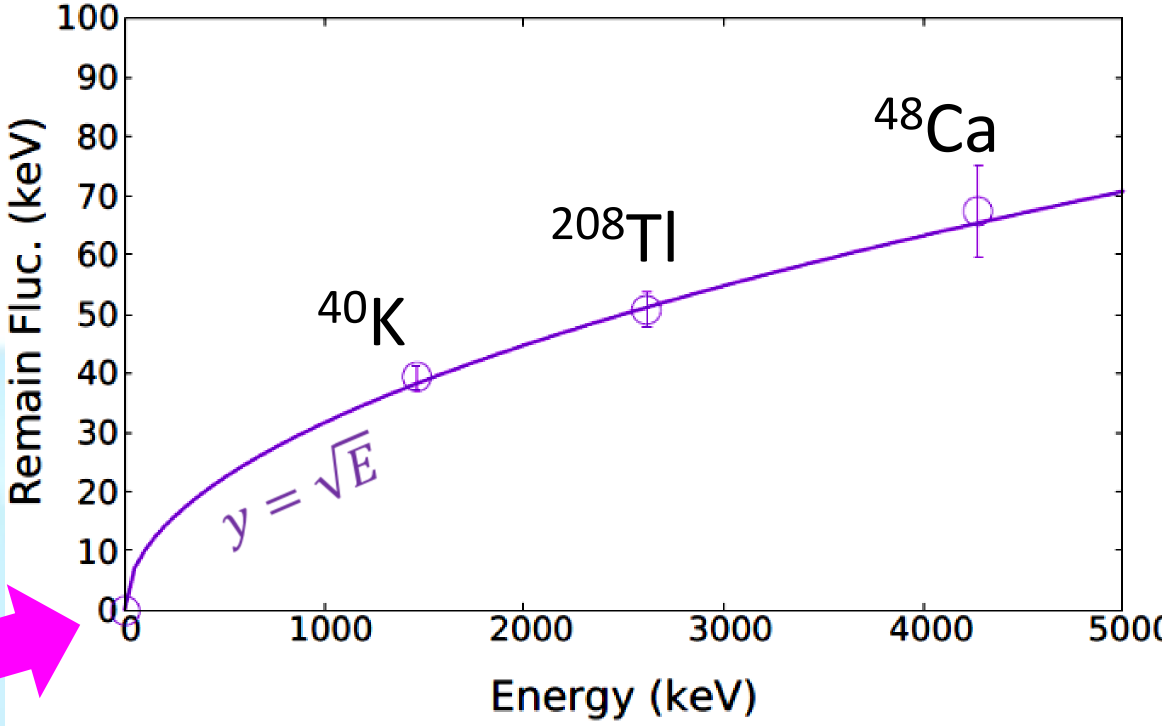
(4) Remain Fluc. = $\sqrt{\sigma_E^2 - (1)^2 - (2)^2}$

Results & Discussion



Results & Discussion

	^{40}K peak (1460 keV)	^{208}Tl peak (2614 keV)
σ_E (resolution)	66.8 keV	86.7 keV
$\sigma_{p.e.}$ (statistical)	38.9 keV	52.3 keV
σ_{Base} (Baseline fluc.)	41.7 keV	42.5 keV
(Remain Fluc.)	34.8 keV	54.5 keV

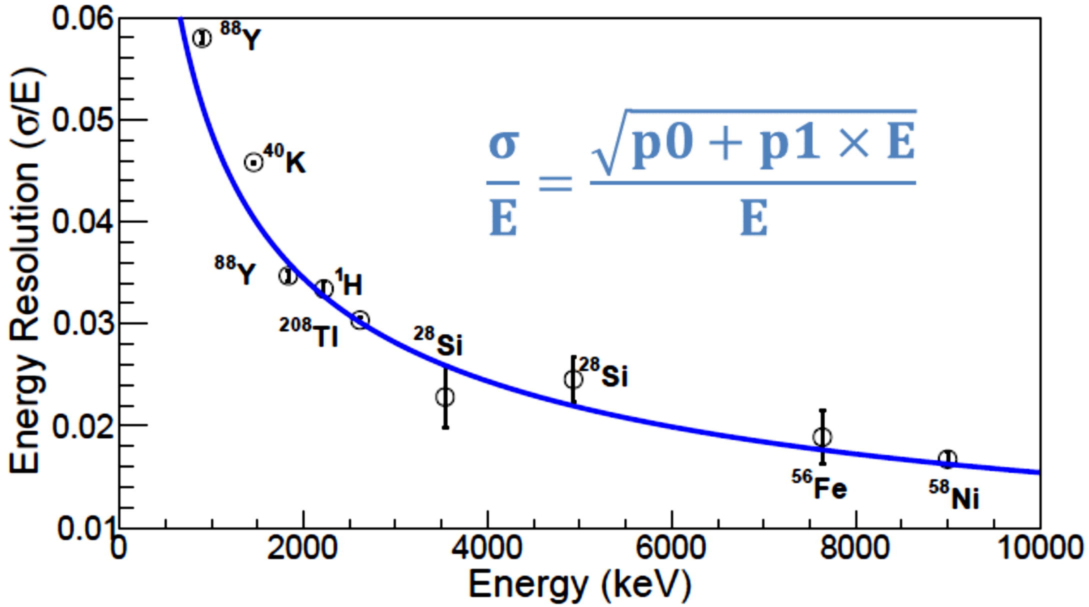


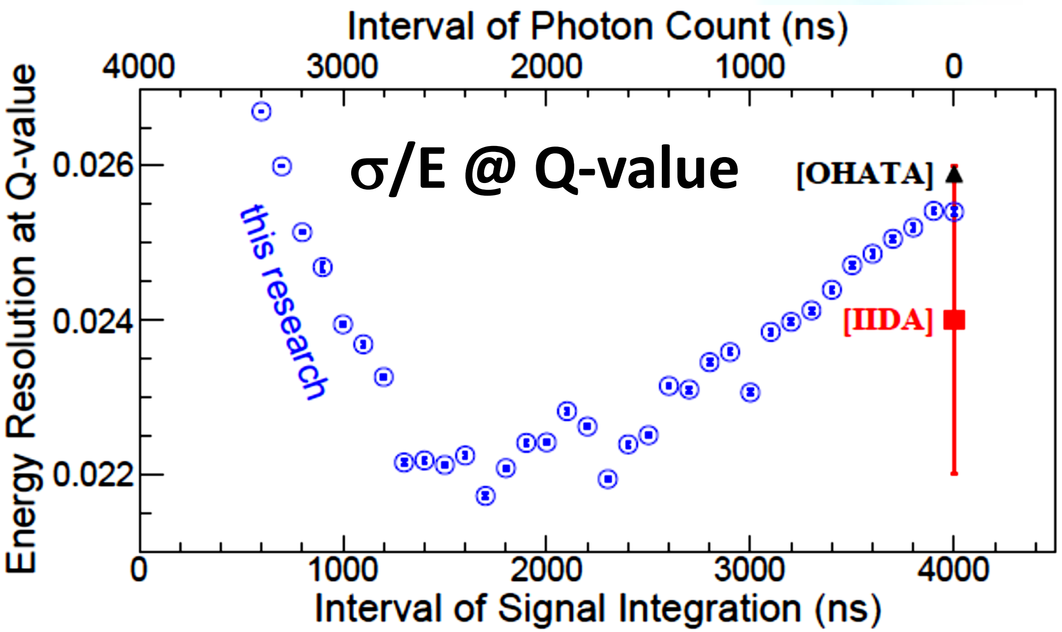
- Study the energy resolution at 1460keV (^{40}K) and 2614.5keV (^{208}Tl)

⇒The baseline fluctuation can explain the tendency of improved resolution

- There is still remaining fluctuation:
  - independent with the integration interval
  - depends on the energy (assuming)

Results & Discussion





- Estimate the resolution at Q-value

⇒ need a fitting equation

- Considering all fluctuations in my study, fluctuations can be divided in 2 groups:
  - Depending on the energy *Statistical fluctuation, digitization error, remaining fluctuation*
  - Independent with the energy *pedestal error*
- The fitting function is:
- Apply this equation on the energy resolutions of CANDLES **⇒ Good fitting**
- The obtained result at ^{48}Ca is consistent with the result obtained in prev. researches (at $T_{INTEGRAL}$ = 4000ns).

⇒The resolution of ^{48}Ca is improved to 2.2%

Results & Discussion

- In previous research*, the sensitivity of of ^{48}Ca was estimated as:
  - ❑ 93 non-enriched crystals of CaF_2(pure)
  - ❑ T = 129.5 days
  - ❑ $\sigma_E/Q_{\beta\beta}$ = **2.6%** (Full Integration)

current sensitivity for $0\nu\beta\beta$ with **Full Integration**

$0.44–0.50 \times 10^{23}$ yr, 90% C.L.

- In current CANDLES, $2\nu\beta\beta$ is not dominant

⇒ The sensitivity in $0\nu\beta\beta$ search is proportional to $(\sigma_E)^{-1/2}$

- In the same conditions, if σ_E is improved, the sensitivity is increased by a factor $\sqrt{\sigma_{\text{Full Integration}}/\sigma_{\text{Partial Photon Count}}}$

⇒ The sensitivity of CANDLES with $\sigma_E/Q_{\beta\beta}$ = **2.2%** is improved by = 1.09

- If the energy resolution can be improved to 2.2%

⇒ the sensitivity can be improved to

expected sensitivity for $0\nu\beta\beta$ with **PPC method**

$0.48–0.55 \times 10^{23}$ yr, 90% C.L.

*T. Ohata, Doctor Thesis, Osaka University (2018)

SUMMARY (1)

- Resolution is important in studying $0\nu\beta\beta$ for CANDLES
- The current $\boldsymbol{\sigma_E/Q_{\beta\beta}}$=**2.6%** **>** $\boldsymbol{\sigma_{p.e.}/Q_{\beta\beta}}$=**1.6%**
- Pedestal fluctuation (σ_{PedErr}) makes the resolution worse.

⇒This fluctuation is negligible with short decay constant (PLS, LS)

⇒For CaF_2 in CANDLES, it is large fluctuation ($\boldsymbol{\sigma_{PedErr}/Q_{\beta\beta}}$ **=1%**)

⇒My research goal: reduce σ_{PedErr} to improve resolution of CANDLES

⇒ Introduce "**partial photon counting**".

⇒The energy resolution is improved.

- The energy resolution at Q-value is expected to be improved to **2.2%**

⇒With this improvement, the sensitivity can be **<u>1.09 times improved</u>**.

SUMMARY (2)

- CANDLES faces a large baseline fluctuation, which can be reduced by "partial photon counting" (PPC)
- PPC requires a lot of data space for daily data taking

$\Rightarrow$ ~40 GB/day $\rightarrow$ ~120 GB/day

$\Rightarrow$ In the next step, DAQ improvements (software and firmware) to reduce the data size

$\Rightarrow$ Energy calibration, resolution at $Q_{\beta\beta}$, long measurement…

CONTENTS

1. Introduction
2. CANDLES experiment
3. $2\nu\beta\beta$ & Energy resolution
4. Error in charge measurement
5. Photon Counting
6. Results and Discussion
7. Possibility for Photon Counting

CaF_2 at low temperature + photon counting

- In the future generations:
  CANDLES plans to introduce the bolometer detector*

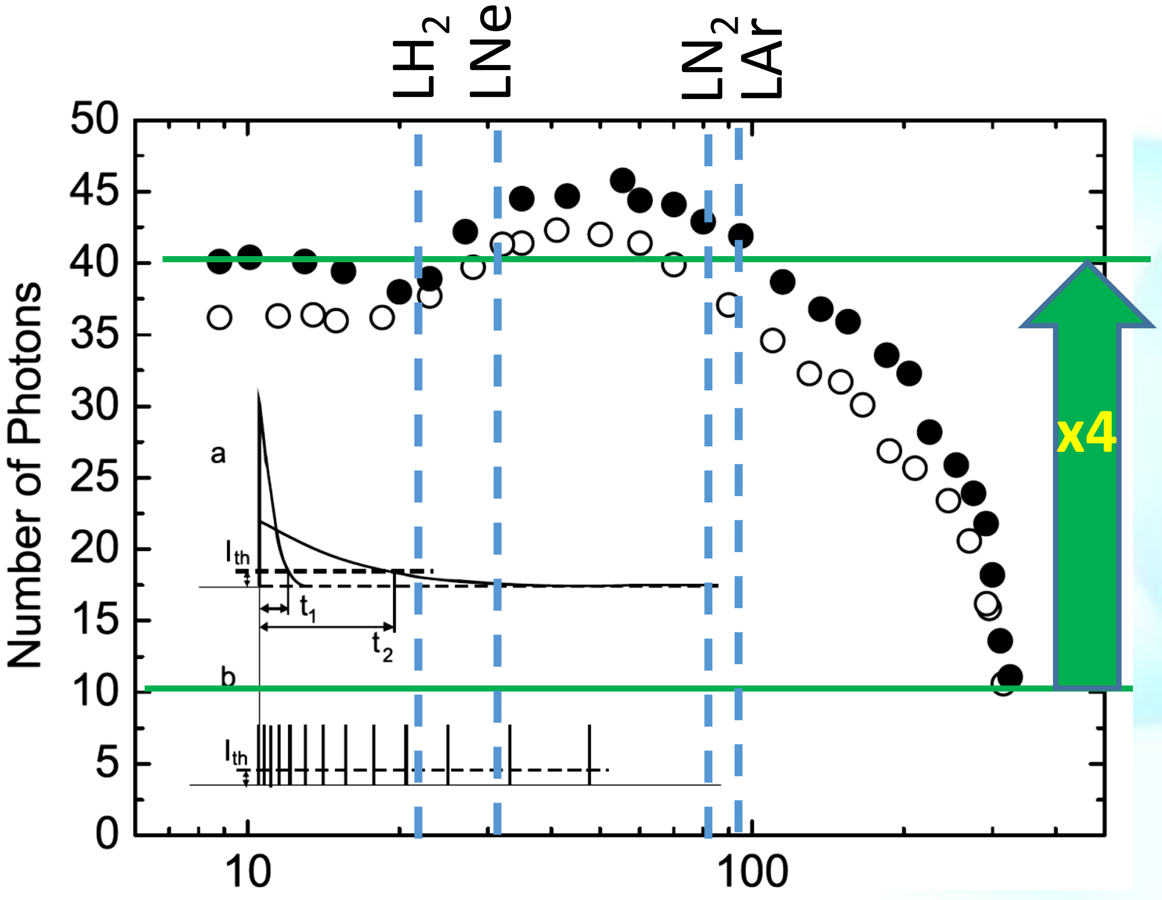
⇒to improve energy resolution and sensitivity

- Before going to bolometer detector,
  We still have a possibility to improve detector resolution with CaF_2(pure) at low temperature + photon counting

⇒Discussion in next slides

*Temperature: in the order of 10mK

CaF_2 at low temperature + photon counting

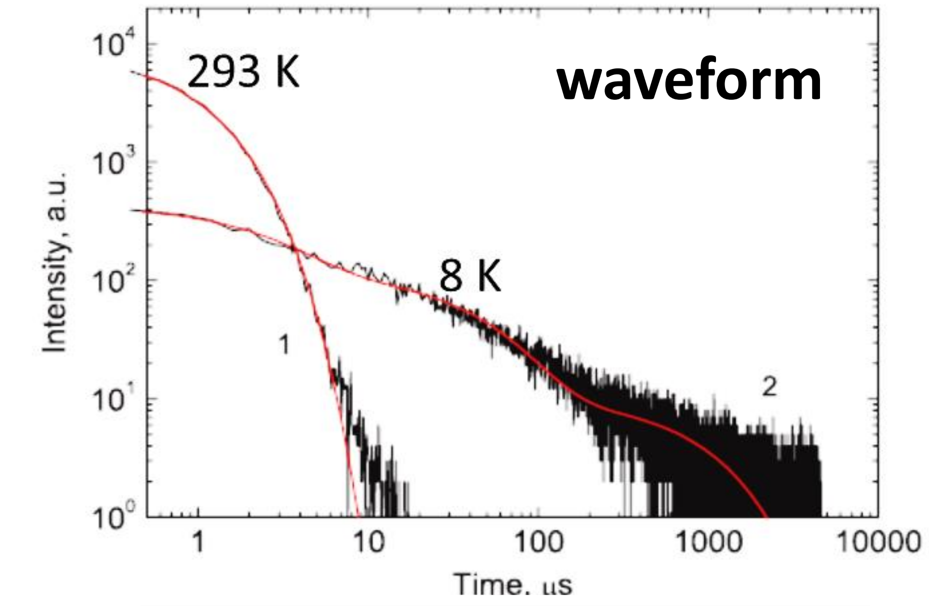


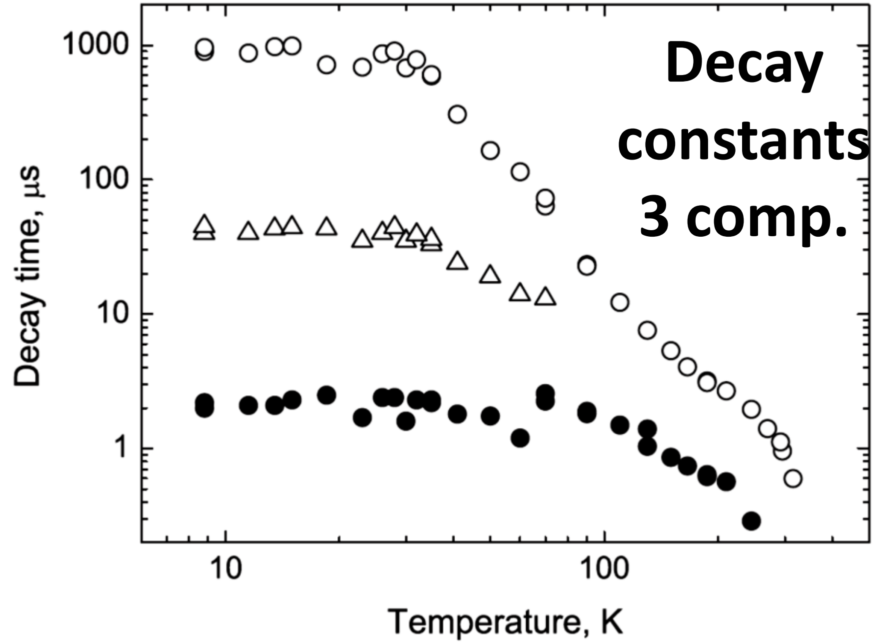
- At temperature ≤ 100 K, Light output is increased x4 times.
- The statistical fluctuation can be improved x2 times: ~1.6% → ~ 0.8%.
- Cooling machines or Liquefied gas (LAr, LN_2, LNe, LH_2)

[ref] V.B.Mikhailik et al., NIMA, v.566, n.2, 2006.
https://doi.org/10.1016/j.nima.2006.06.063

[*]assume Q.E. is not changed

CaF_2 at low temperature + photon counting





However, …

- At cryogenic temperature, the waveform is extended, τ_{decay} : ~1μsec $\rightarrow$ ~40μsec.
- If we use signal integral: a huge $\sigma_{baseline}$
- Roughly check p.e. rate (p.e./ns):
  - 293K, N = 3838, τ = 1μsec $\Rightarrow$ ~3.8p.e./ns
  - <30K, N = 15352, τ = 40μsec $\Rightarrow$ ~0.4p.e./ns

$\Rightarrow$Less p.e. rate; less overlapping prob.

$\Rightarrow$Photon counting can work!

$\Rightarrow$Avoid the baseline fluctuation

$\Rightarrow$Energy resolution can be much better compared to the current detector

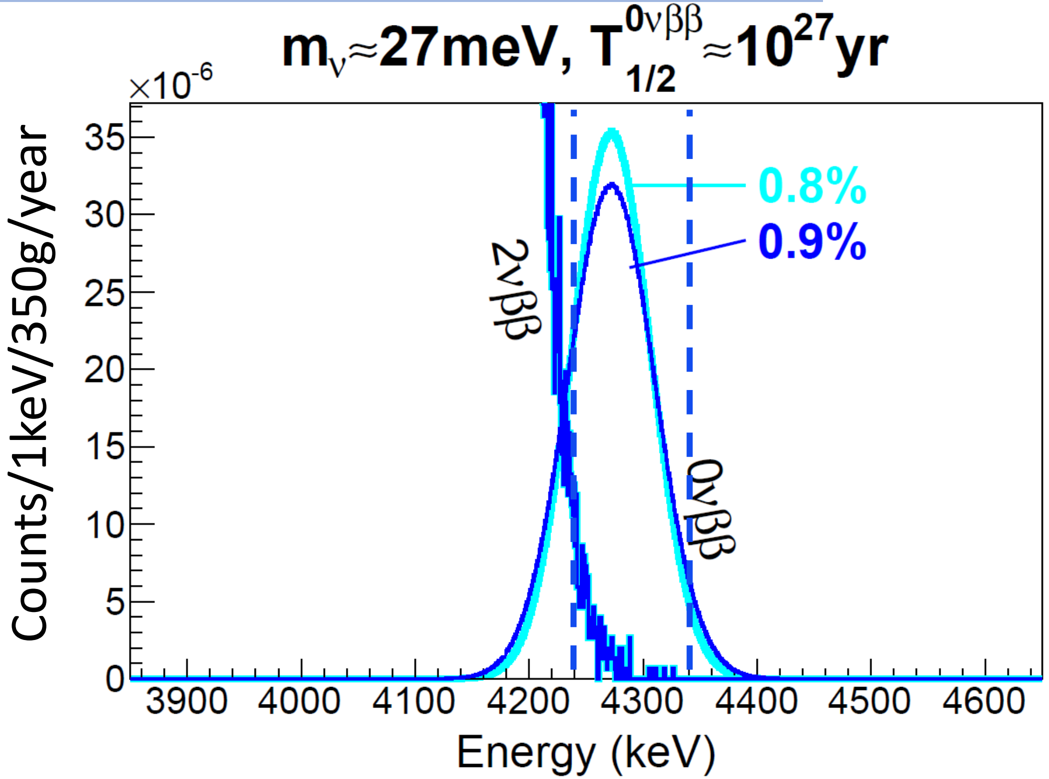
CaF_2 at low temperature + photon counting

- The world best sensitivity is reported KamLand-Zen: $m_{\beta\beta} \approx$ 61-165meV (*) (above IH region)
- With CaF_2(pure) low temp. + photon counting

We may achieve $\sigma/Q_{\beta\beta}$ = 0.9%-1.1%(**)

- With this resolution @ $Q_{\beta\beta}$, we may achieve much improved sensitivity:
  $m_{\beta\beta} \approx$ 27-118 meV ($\sigma/Q_{\beta\beta}$ = 0.9%)
  $m_{\beta\beta} \approx$ 80-240 meV ($\sigma/Q_{\beta\beta}$ = 1.1%)

⇒ Can be close to (or better than) the current world-best limit of $m_{\beta\beta}$



(**) not consider environmental background

(*) due to different NME values
(**) stat. + dark current + remain

SUMMARY (3)

- I discussed CaF_2(pure) at low temperature + Photon Counting.

⇒Can use liquefied gas or cooling machine

⇒ σ /E at Q-value (expected) $\approx$ 0.9-1.1%

⇒The resolution is promising to achieve a better sensitivity for CANDLES experiment


CANDLES
Collaboration Meeting
2016. 10. 30. at Osaka University
Thank you very much !!

BACK UP

0νββ experiment with ^{48}Ca

✓ **Highest $Q_{\beta\beta}$ 4.27 MeV**

- Large phase space factor
- Far from BKG (γ: 2.6 MeV; β: 3.3 MeV)

⇒**Aim for background-free measurement**

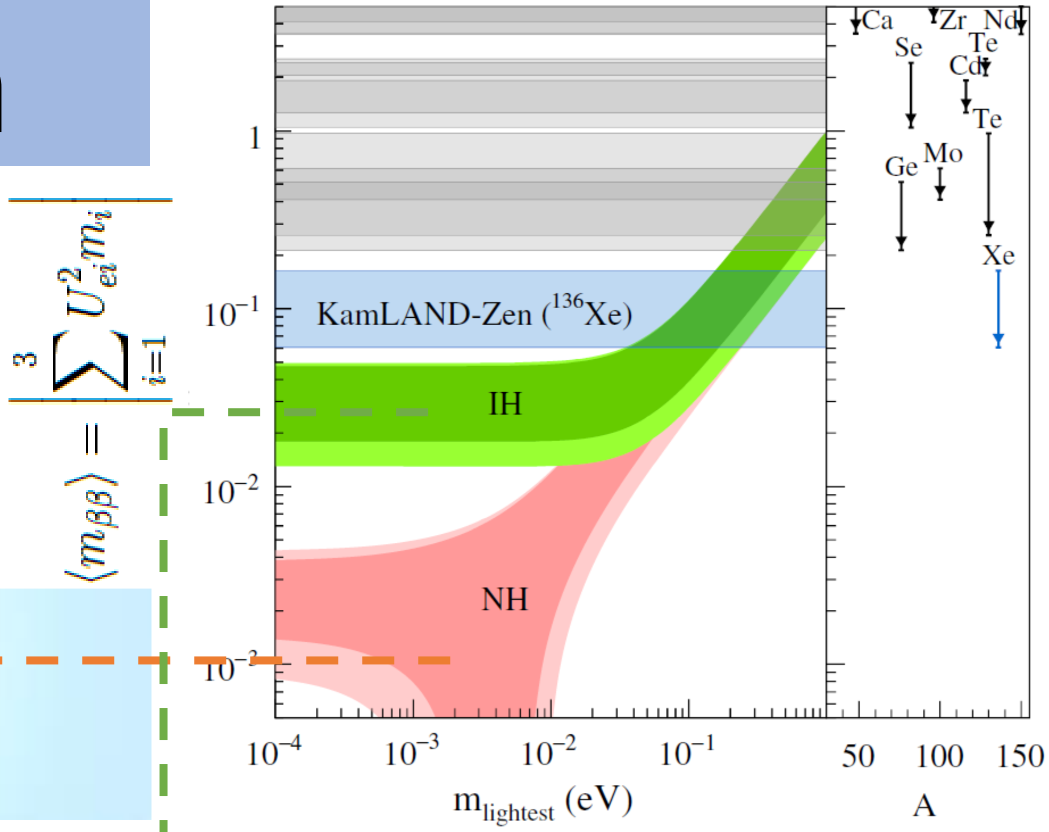
☒ **Low abundance**

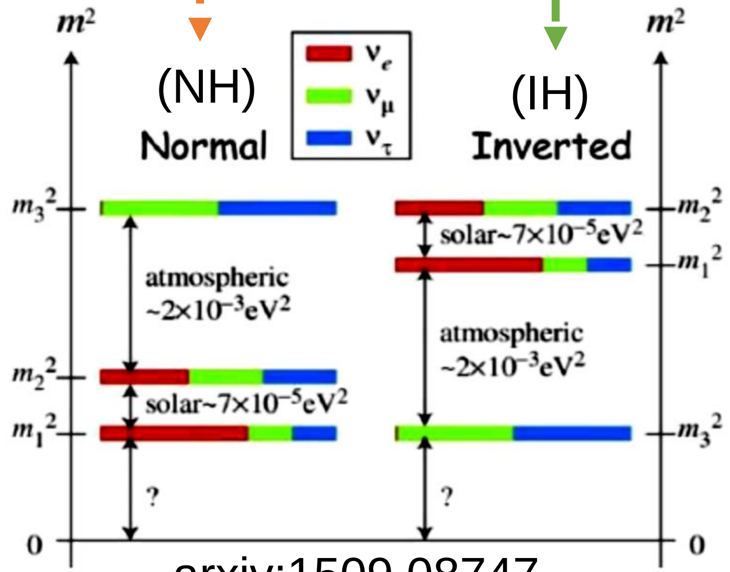
- Natural abundance: <0.2 %
- Separate isotopes: expensive

⇒**Cost-effective enrichment**

❑**Energy Resolution**

⇒ Improve sensitivity





arxiv:1509.08747

- m_1, m_2, m_3: mass eigenstates
- Hierarchy is unknown
- 2 possible hierarchies:

(NH): $m_1 < m_2 < m_3$

(IH): $m_3 < m_1 < m_2$

Detector upgrade

2009	: Setup CANDLES-III detector at Kamioka	
2011 Mar.	: Introduce energy calibration system with ^{88}Y source	
2012 Mar.	: Introduce light pipes	$\Rightarrow$ light collection efficiency
2014 Mar.~Sep.	: Magnetic Cancelation coil	$\Rightarrow$ photoelectrons collection efficiency
	& Cooling system	$\Rightarrow$ increase light yield
2015 Apr.	: Passive shielding (Pb+B)	$\Rightarrow$ reduce (n,γ) background (later)

Detector upgrade

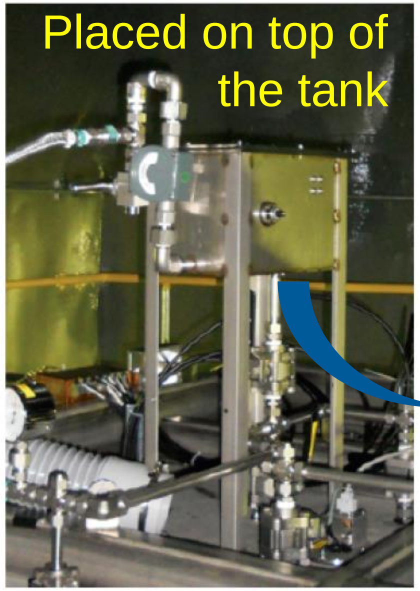
2009 : Setup CANDLES-III detector at Kamioka

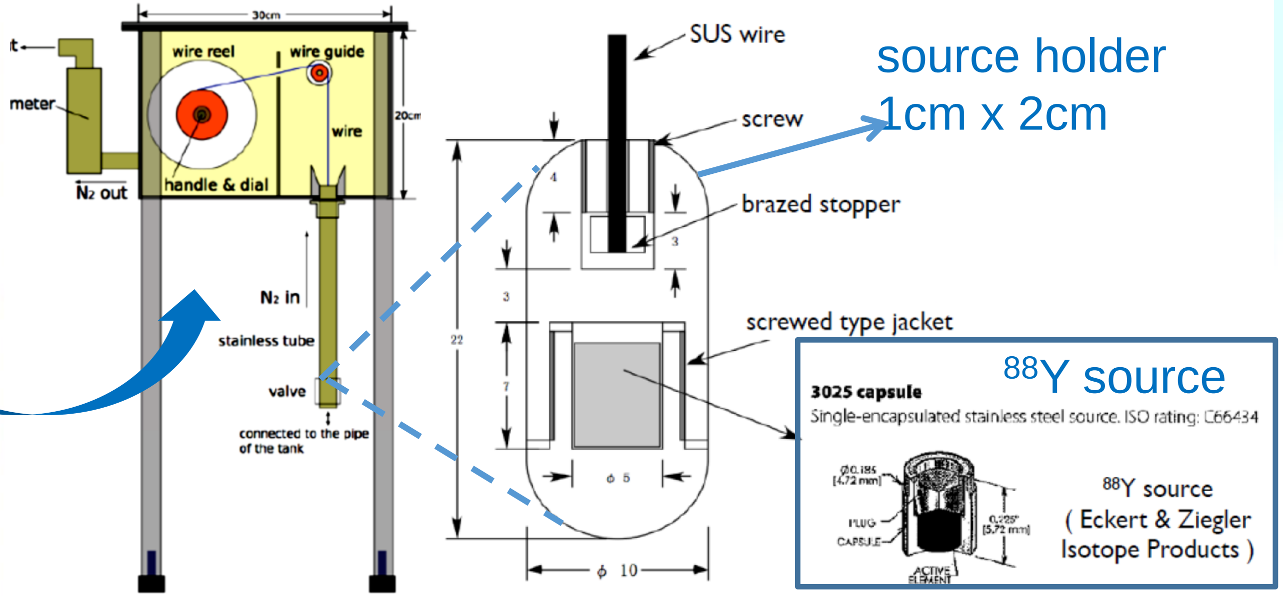
2011 Mar. : Introduce energy calibration system with ^{88}Y source

2012 Mar. : Introduce light pipes ⇒ light collection efficiency

2014 Mar.~Sep. : Magnetic Cancelation coil ⇒ photoelectrons collection efficiency
& Cooling system ⇒ increase light yield

2015 Apr. : Passive shielding (Pb+B) ⇒ reduce (n,γ) background (later)



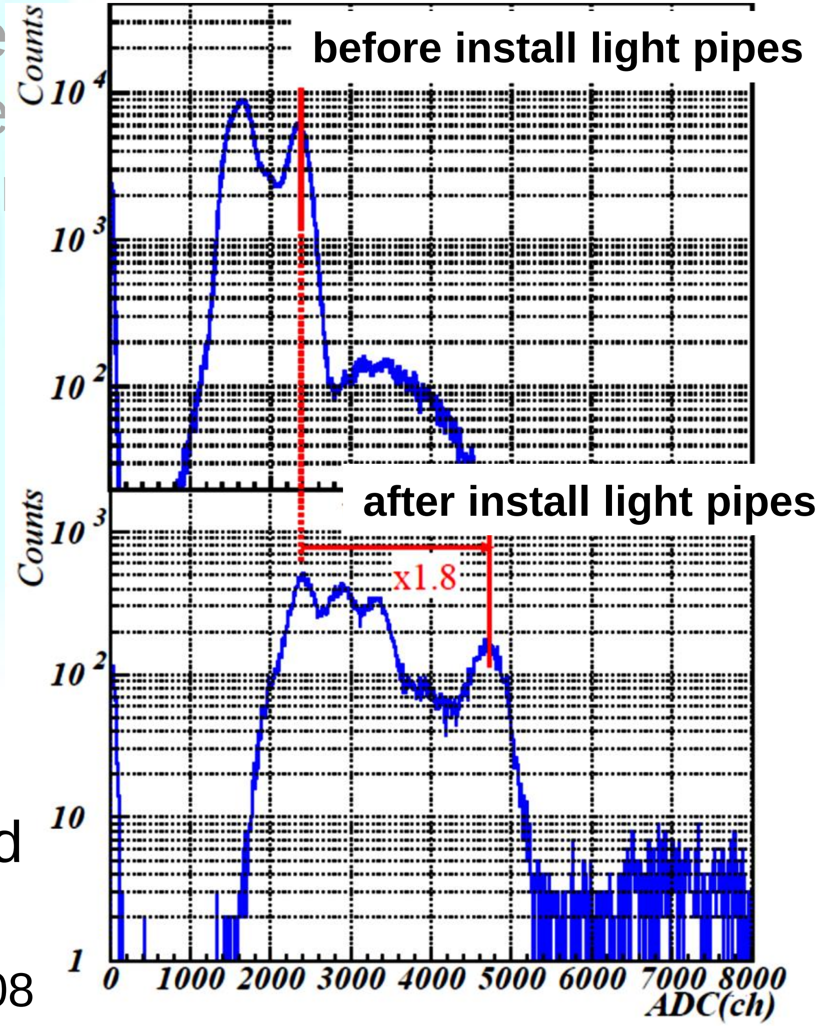


A box designed for:

- No (contaminated) air leakage inside our detector
- Easily adjust source position vertically to calibrate each crystal
- Small-size source (mm scale)

Detector upgrade

2009 : Setup CANDLES-III detector at Kamioka
2011 Mar. : Introduce energy calibration system with ^{88}Y source
2012 Mar. : Introduce light pipes ⇒ **light collection efficiency**
2014 Mar.~Sep. : Magnetic Cancelation coil ⇒ photoele
& Cooling system ⇒ increase
2015 Apr. : Passive shielding (Pb+B) ⇒ reduce (



Spectrum of α-decays (Th-chain)

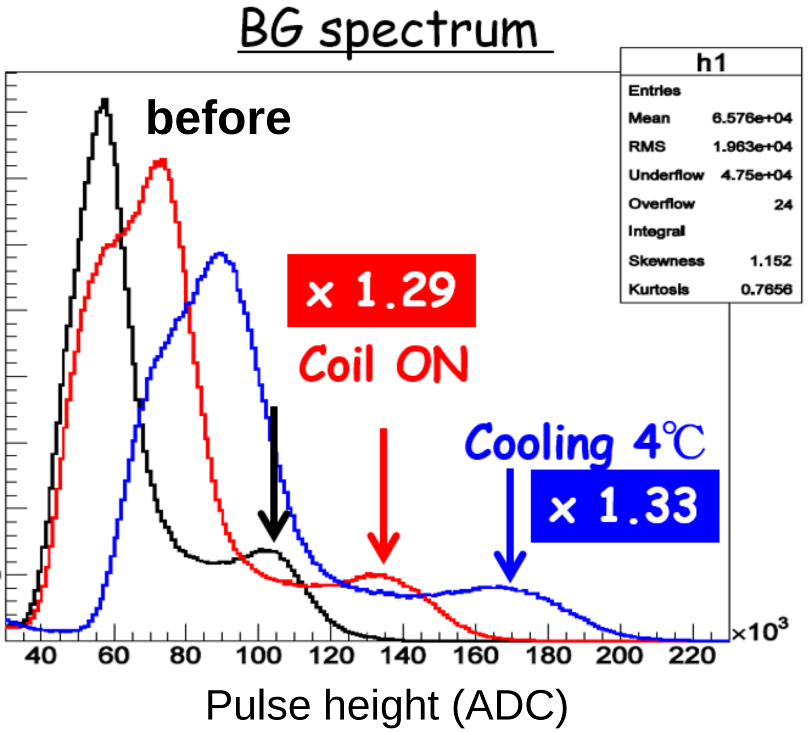
After installing light pipes,

photoelectrons x1.8 times increased

EPJ Web of Conferences 66:08008

Detector upgrade

2009	: Setup CANDLES-III detector at Kamioka
2011 Mar.	: Introduce energy calibration system with ^{88}Y source
2012 Mar.	: Introduce light pipes ⇒ light collection efficiency
2014 Mar.~Sep.	: Magnetic Cancelation coil ⇒ photoelectrons collection efficiency
	& Cooling system ⇒ increase CaF_2 light yield
2015 Apr.	: Passive shielding (Pb+B) ⇒ reduce (n,γ) background (later)



Geomagnetic field affects photoelectron collection in PMTs

⇒ Magnetic cancellation coil around detector

⇒ Photoelectrons x1.29 times increased

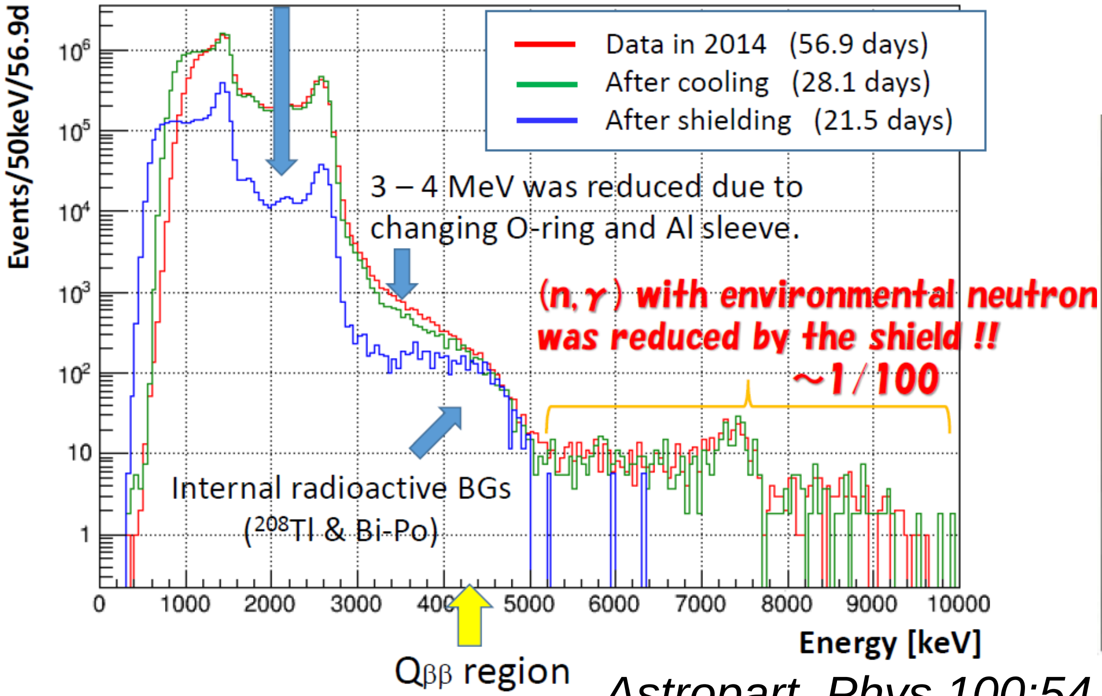
CaF_2's light yield increases at low temperature

⇒ Cool all crystals to 4°C degree

⇒ Light yield x1.33 times increased

Detector upgrade

2009 : Setup CANDLES-III detector at Kamioka
2011 Mar. : Introduce energy calibration system with ^{88}Y source
2012 Mar. : Introduce light pipes ⇒ light collection efficiency
2014 Mar.~Sep. : Magnetic Cancelation coil ⇒ photoelectrons collection efficiency
& Cooling system ⇒ increase CaF_2 light yield
2015 Apr. : Passive shielding (Pb+B) ⇒ reduce (n,γ) background
(reduced x100 times for E>5MeV)

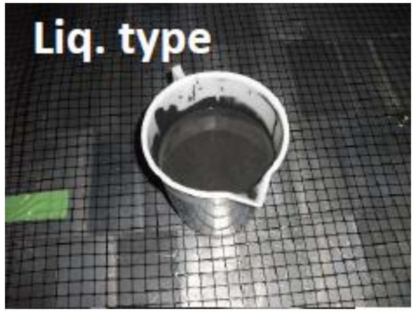


Astropart. Phys.100:54

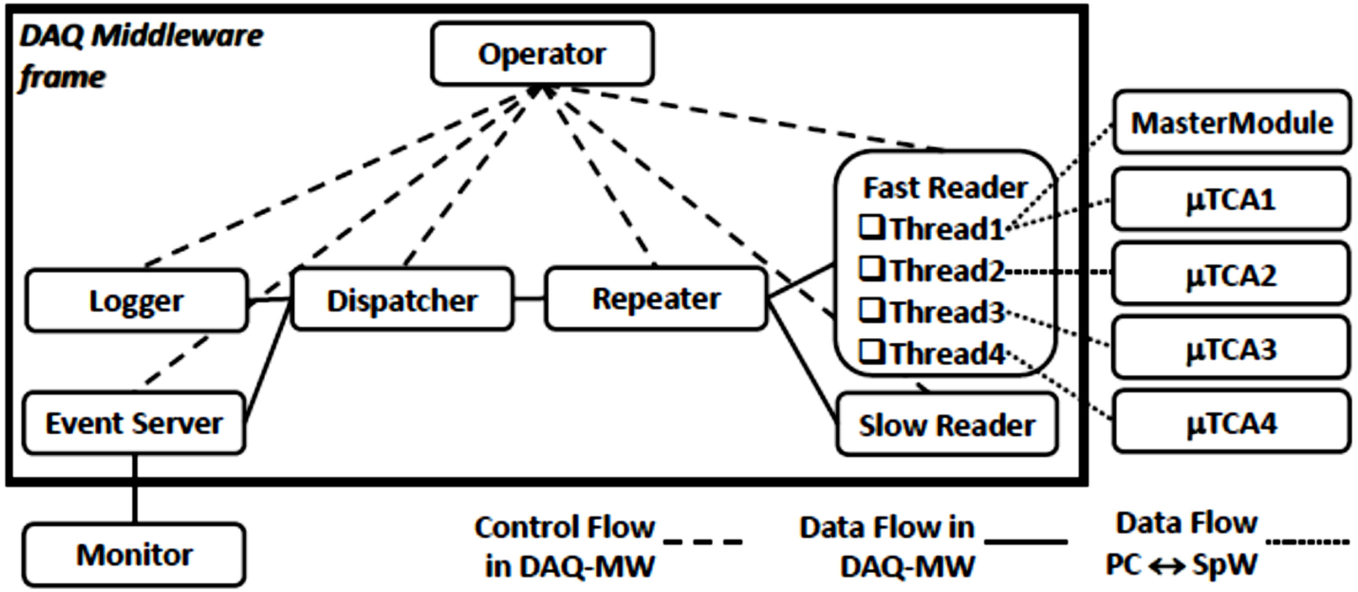
Pb blocks for shielding γ-rays

Boron for shielding neutron

B_4C 40% wt silicone rubber (surrounding)

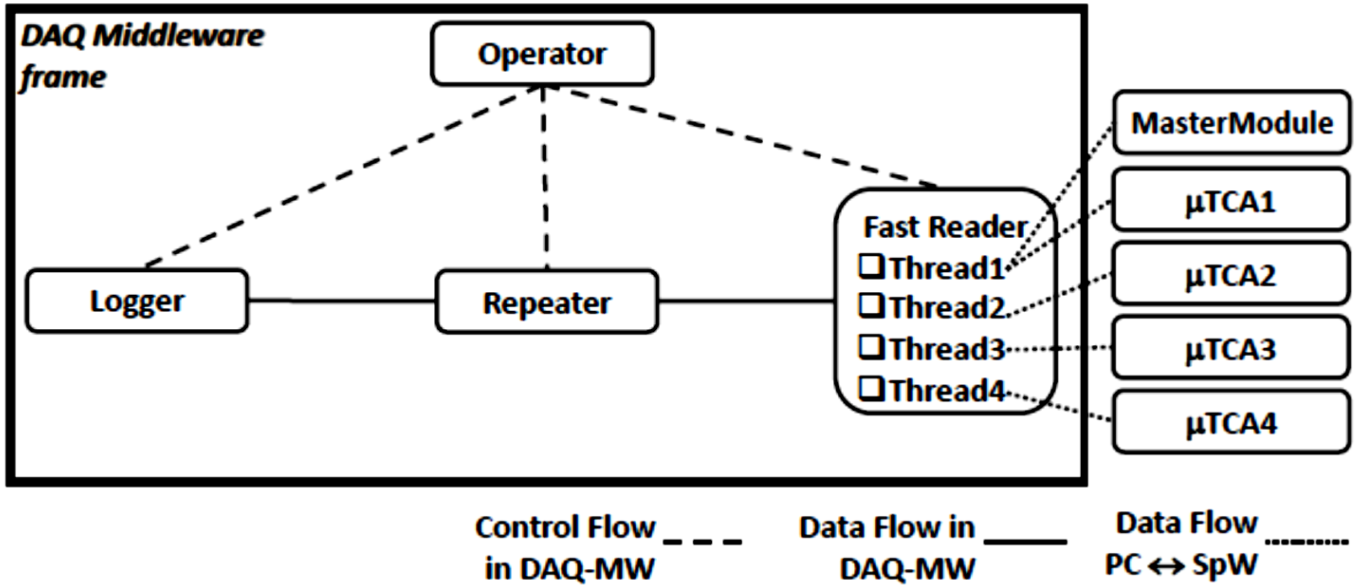


Liquid type for tank's bottom



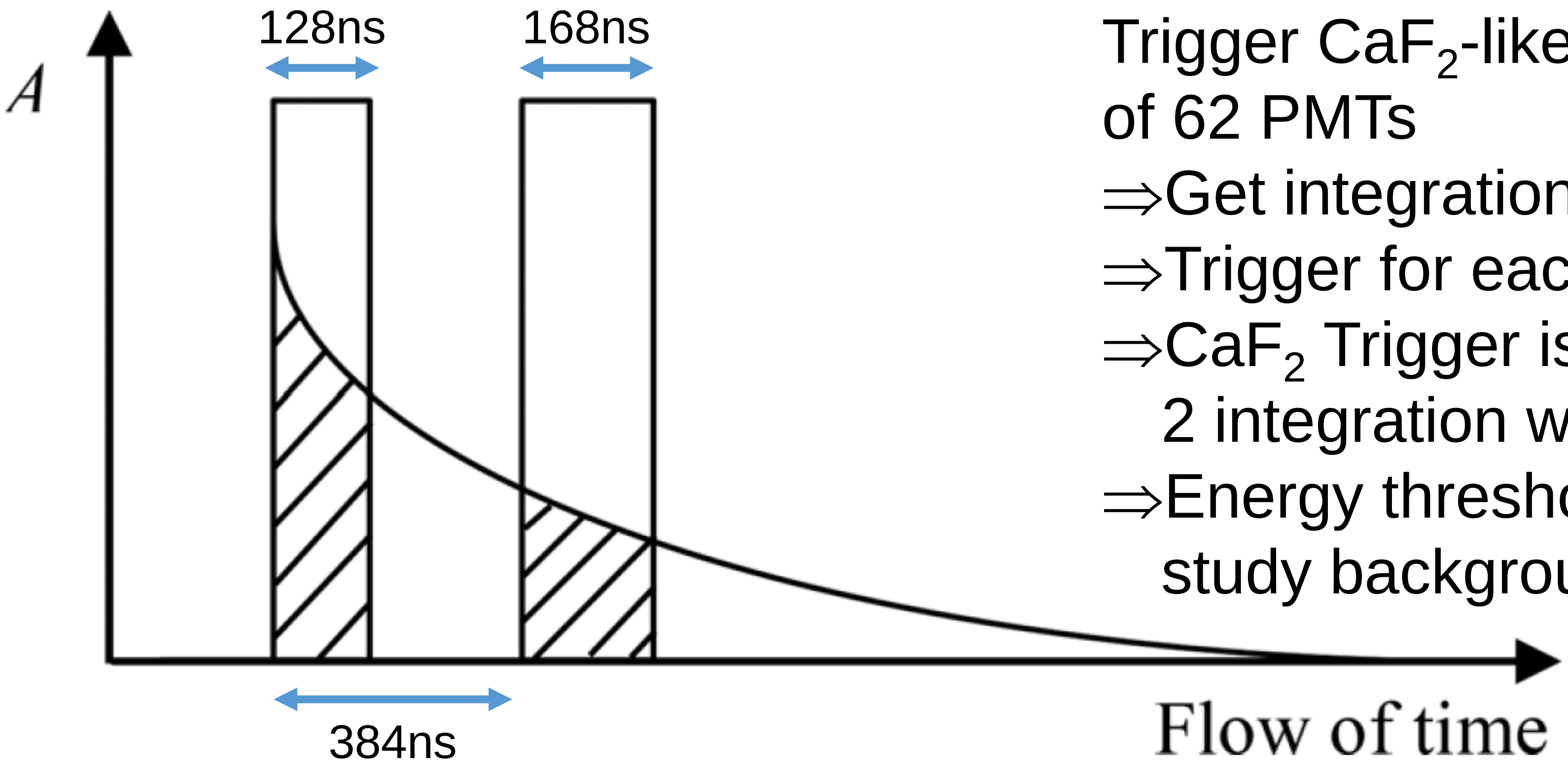
(a) DAQ Middleware for Physics Run

DAQ-Middleware for Physics Run

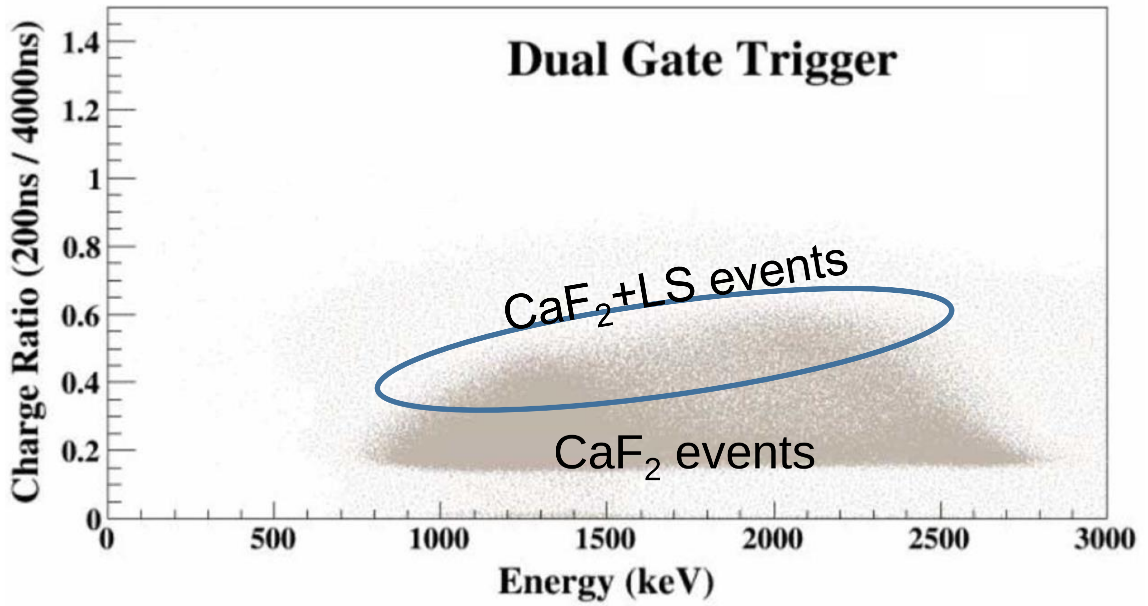


(b) DAQ Middleware for Photon Counting

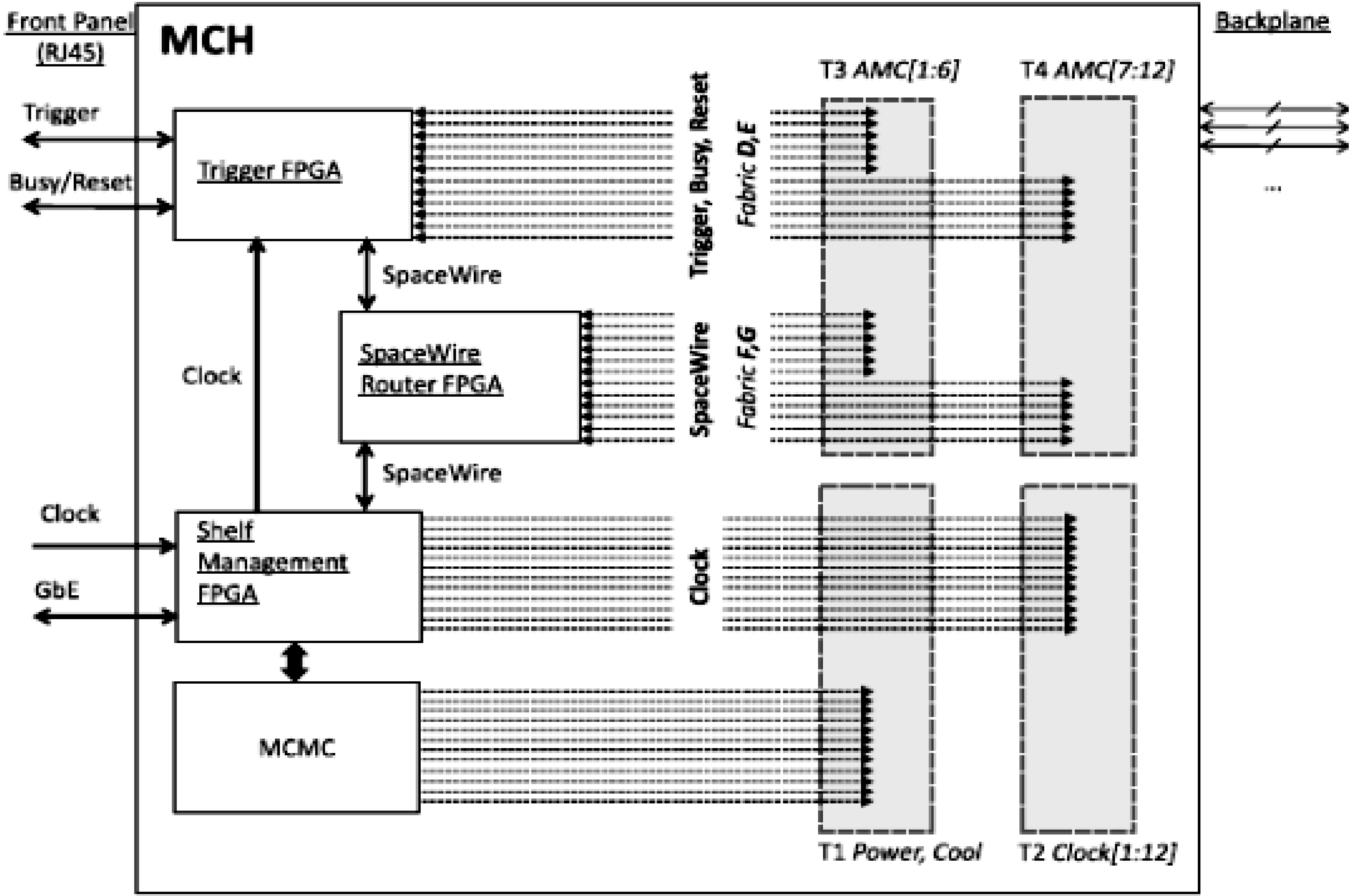
DAQ-Middleware for Photon Counting



Trigger CaF_2-like events using the analog sum of 62 PMTs
⇒Get integrations in 2 different time windows
⇒Trigger for each integration
⇒CaF_2 Trigger is delayed coincidence of these 2 integration windows
⇒Energy threshold: ~800 keV (enough to study background in CANDLES)



CaF_2+LS event may be an accidental trigger
⇒Further PSD is needed to remove it


Front Panel (RJ45)
MCH
Backplane
Trigger
Busy/Reset
Trigger FPGA
T3 AMC[1:6]
T4 AMC[7:12]
Trigger, Busy, Reset
Fabric D,E
SpaceWire
SpaceWire Router FPGA
Clock
SpaceWire
Fabric F,G
SpaceWire
Clock
Shelf Management FPGA
GbE
Clock
MCMC
T1 Power, Cool
T2 Clock[1:12]
...

To FADCs

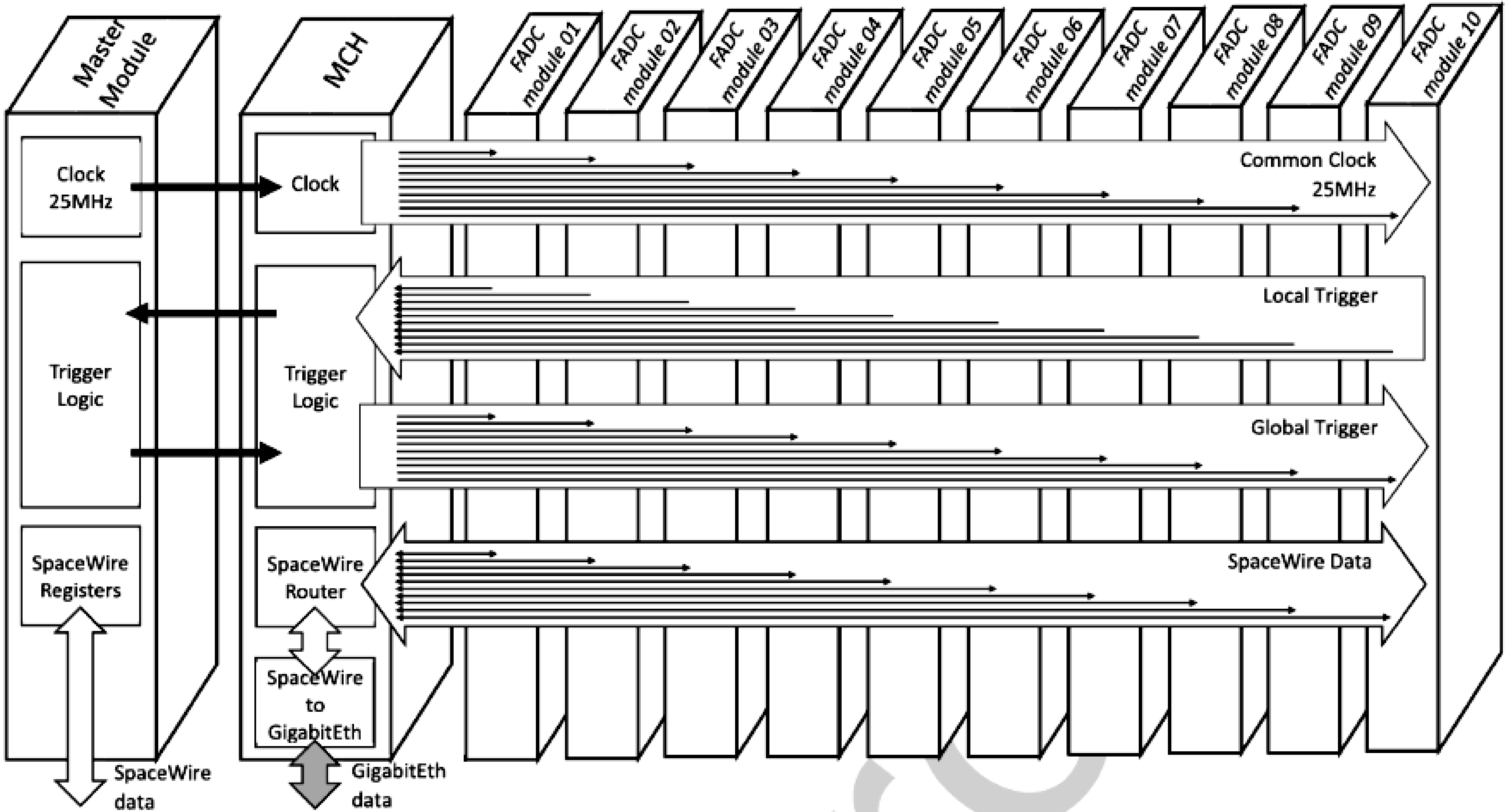


Fig. 4. Triple-star network in μTCA crate. The first star is used to connect the trigger module with the AMC-FADC modules. The second star is used for common clock distribution. The final star is used to connect the SpaceWire router with the AMC-FADCs.

●新DAQシステムの使用モジュール

Module	Manufacturer	FPGA logic	FPGA development
μTCA	Uber Ltd.		
MCH	Shimafuji	SpW-GbE[i] interface Clock distribution	by Shimafuji
		SpaceWire Router	Open IP[ii] by Shimafuji
		Trigger Controller for CANDLES	by Osaka University
AMC-FADC	Shimafuji	FADC control	by RCNP,[iii] Osaka University
		SpaceWire	Open IP[ii] by Shimafuji

[i] SpW-GbE: The acronyms "SpW" and "GbE" are used in this paper to indicate "SpaceWire" and "Gigabit-Ethernet", respectively.
[ii] Open IP: The FPGA's intellectual property core is publicly available.
[iii] RCNP: Research Center for Nuclear Physics

MasterModule

MicroTCA crate

AMC-FADC

MCH