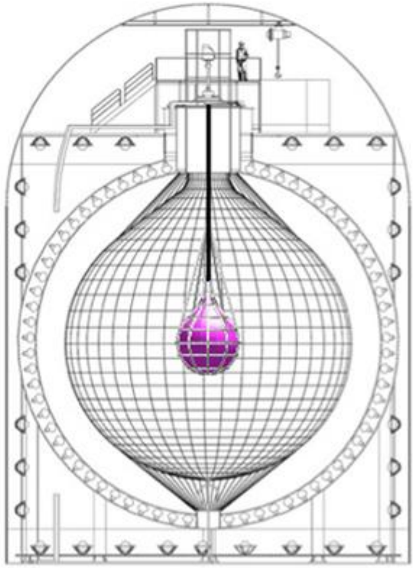
KamLAND-Zen

Coping with decreasing PMT-gains in a ^{136}Xe $0\nu\beta\beta$-decay experiment

NNV symposium, 2019-11-01

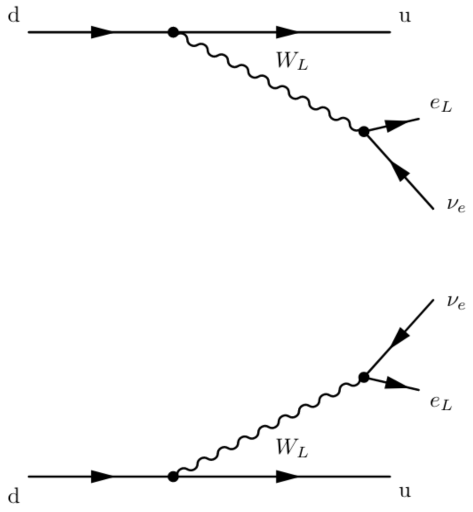
Bouke Jung (bjung@nikhef.nl)

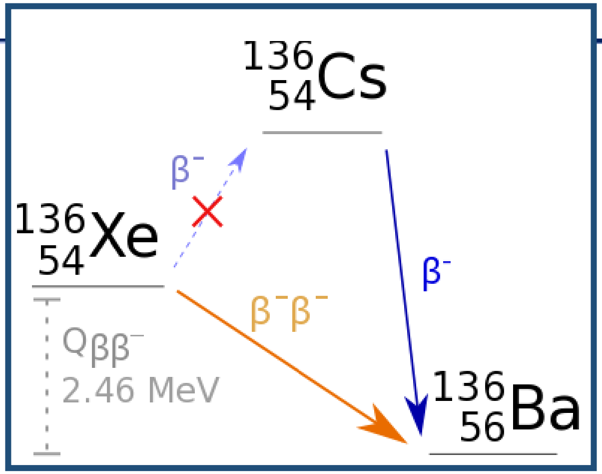


ββ-decay

Two modes:

I. 2vββ-decay
   - $(A,Z) \longrightarrow (A,Z+2) + 2e^- + 2\overline{\nu}_e$
   - SM process: $T_{1/2}$ ~10^{19} -10^{24} yr





ββ-decay

Two modes:

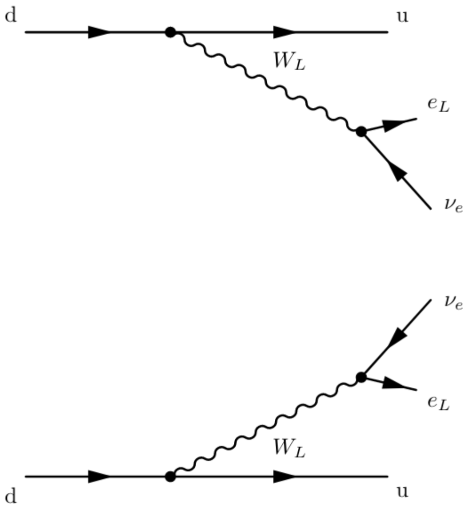
I. 2νββ-decay

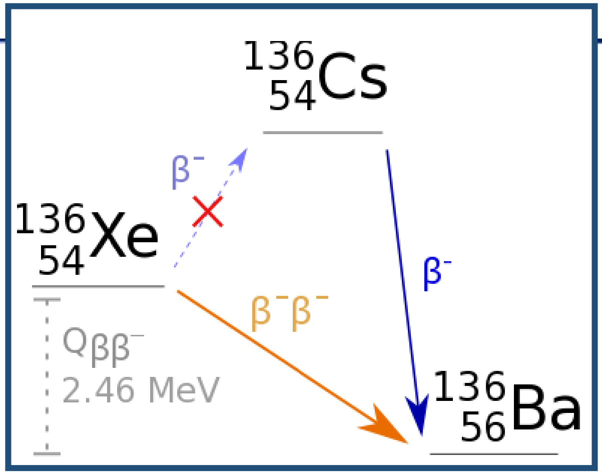
- $(A,Z) \longrightarrow (A,Z+2) + 2e^- + 2\overline{\nu}_e$
- SM process: $T_{1/2} \sim 10^{19}$ -10^{24} yr

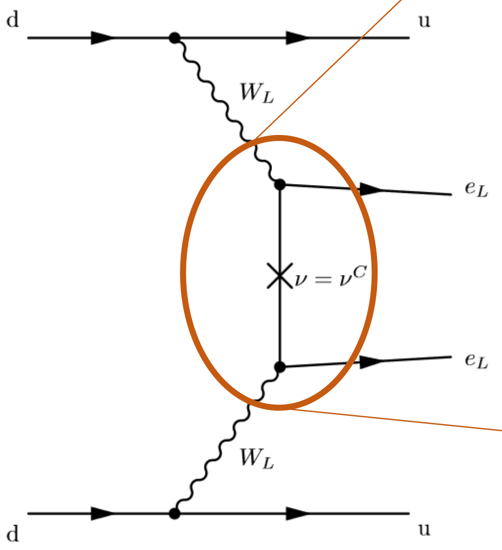
II. 0νββ-decay

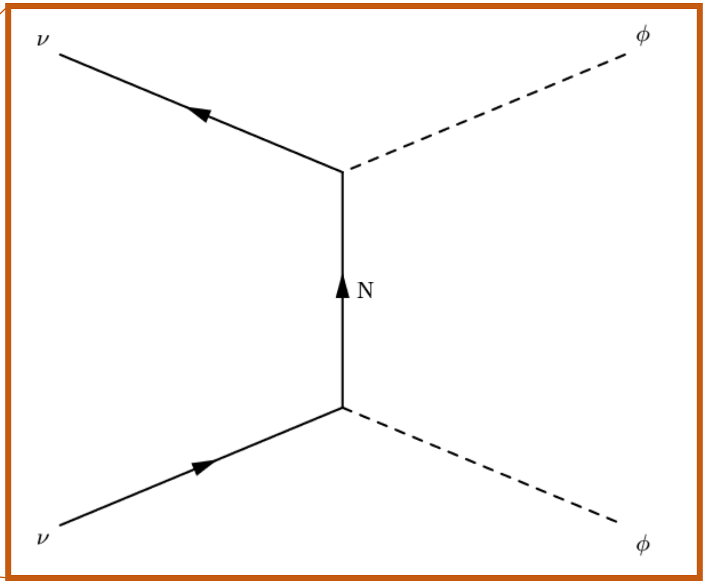
- $(A,Z) \longrightarrow (A,Z+2) + 2e^-$
- BSM, **L-violating**
- **Majorana neutrino**

- If observed:
  →**Necessarily** implies Majorana-ν
  (black-box theorem)



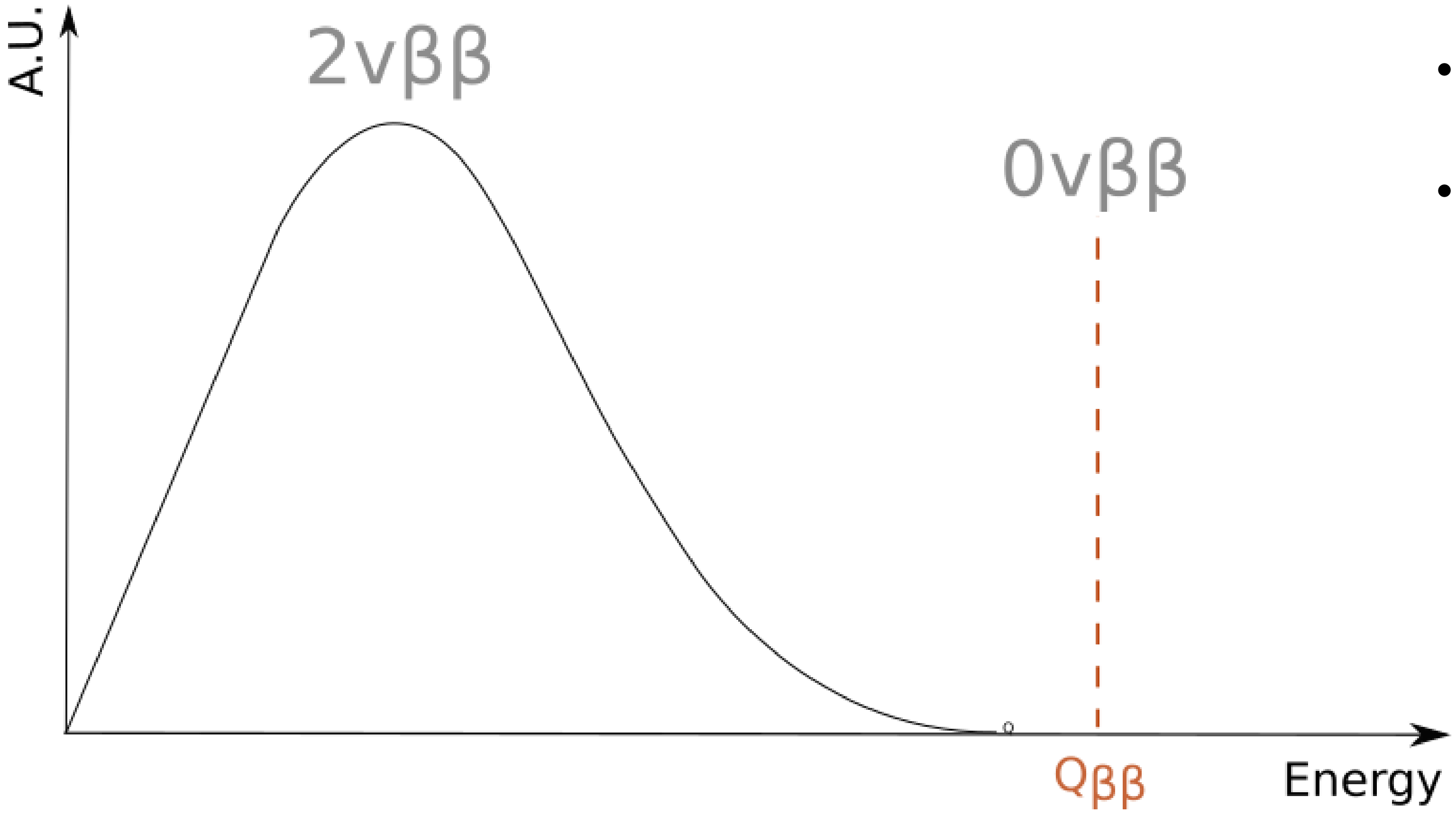






Seesaw (I) Mechanism

Experimental signature



- Nuclear recoil negligible
- Measure of energy *necessary* & *sufficient*
  i. Continuous 2ν-spectrum
  ii. 0ν-spike @ $Q_{\beta\beta}$

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \left|M^{0\nu}\right|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right|$$

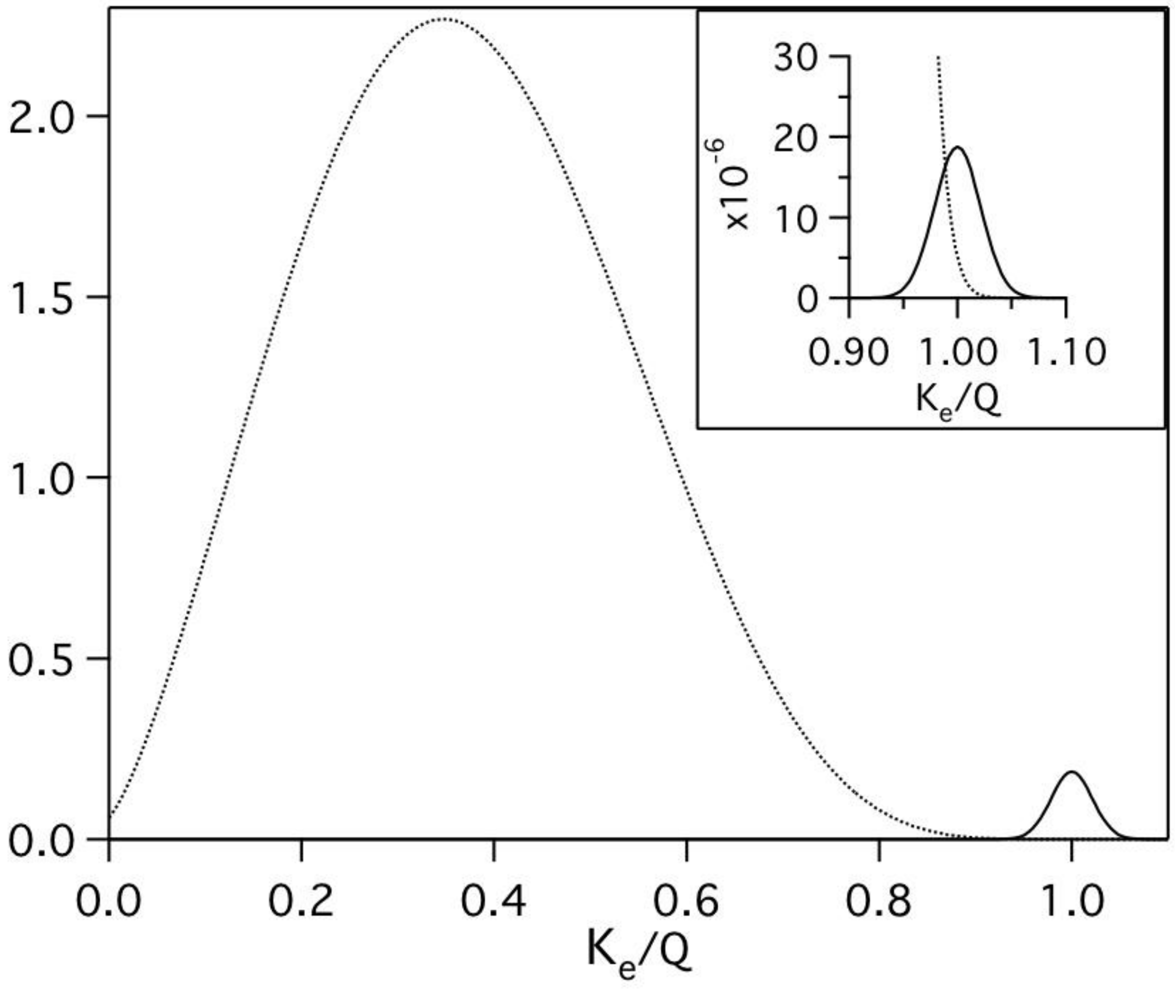
Experimental considerations

- Experimental sensitivity:

$$S(m_{\beta\beta}) \propto \left(\frac{1}{G^{0\nu}|M^{0\nu}|^2}\right)^{1/2}\left(\frac{c\Delta E}{\epsilon^2 M t}\right)^{1/4}$$

- Five ingredients:
  1. Energy resolution
  2. Isotope choice
  3. Background levels
  4. Detection efficiency
  5. Exposure

Only protection
against **2νββ intrinsic BG**



Steven R. Elliot and Petr Vogel. - **Annu. Rev. Nucl. Part. Sci.52(2002)**

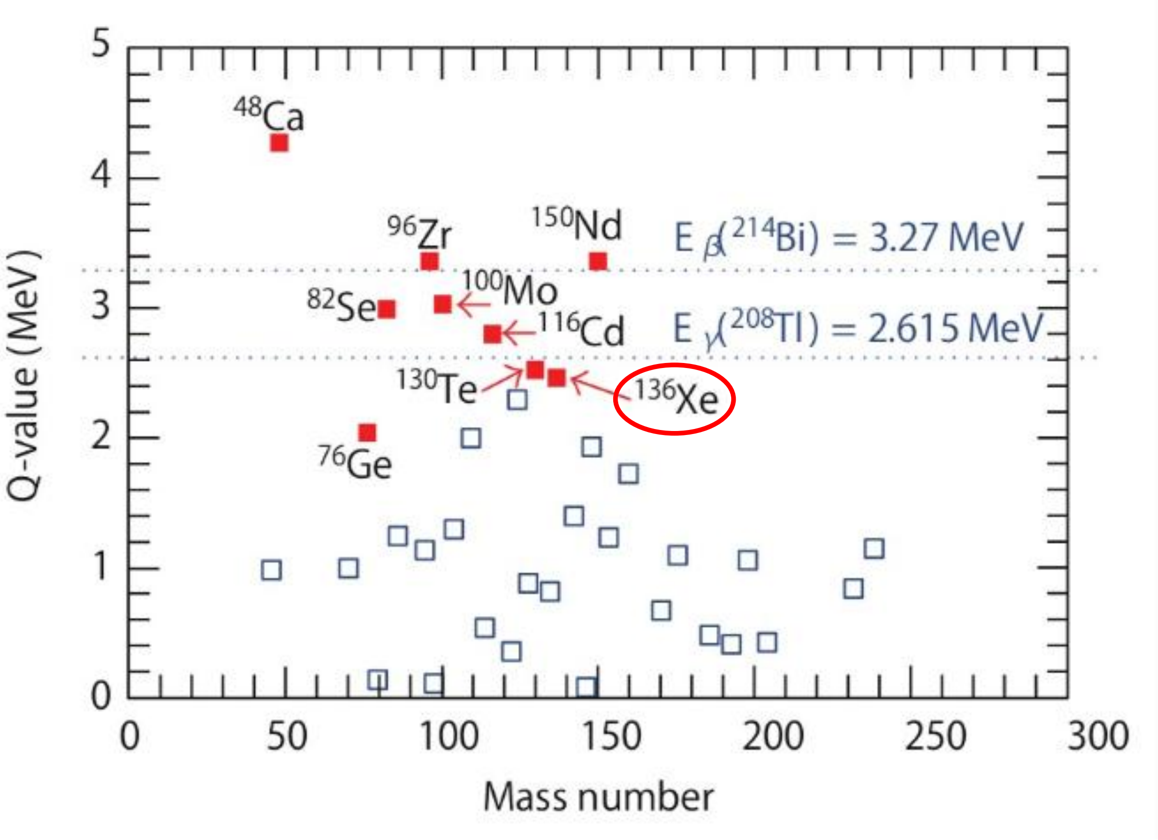
Experimental considerations

- Experimental sensitivity

$$S(m_{\beta\beta}) \propto \left(\frac{1}{G^{0\nu}\,|M^{0\nu}|^2}\right)^{1/2}\left(\frac{c\Delta E}{\epsilon^2 Mt}\right)^{1/4}$$

- Five ingredients:
  1. Energy resolution
  2. Isotope choice
  3. Background levels
  4. Detection efficiency
  5. Exposure

i.	High Q-value
ii.	Ease of enrichment
iii.	High isotopic abundance
iv.	Large target mass



Matsuda Sayuri, Doctoral thesis (2014)

KamLAND-Zen

Japan
- Tohoku University, RCNS
- University of Tokyo, Kavli IPMU
- Osaka University
- Tokushima University
- Kyoto University

US
- University of California, Berkeley
- University of Tennessee
- Triangle University Nuclear Laboratory
- University of Washington
- Massachusetts Institute of Technology
- Virginia Tech
- University of Hawaii
- Boston University

Netherlands
- Nikhef, University of Amsterdam

Currently ~50 people worldwide

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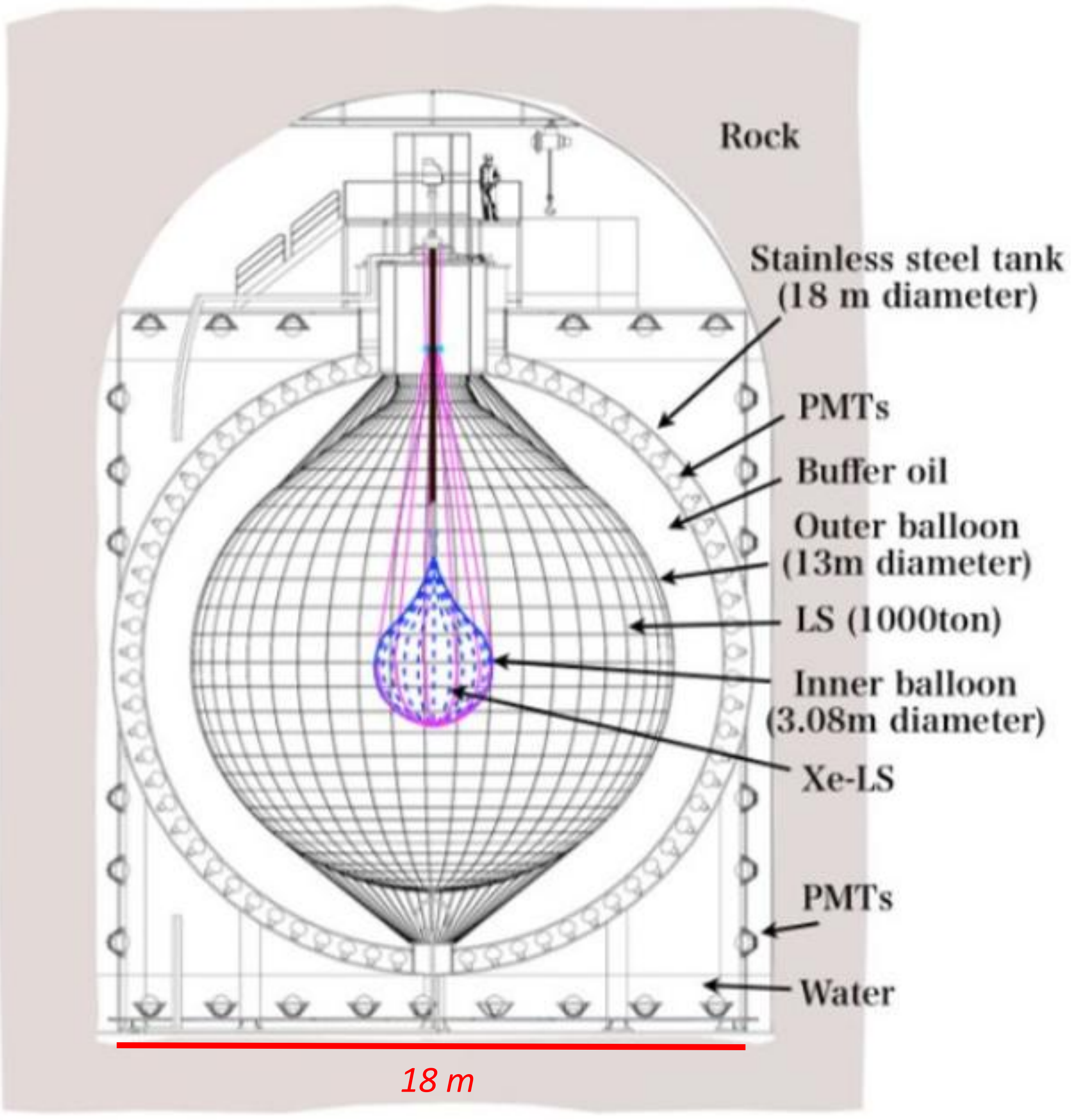


KZ collaboration, PoS NEUTEL2017

^{136}Xe

- Noble gas
- Centrifugal enrichment (to 90% !)
- $Q_{\beta\beta}$ = 2459 keV
  → Above most ^{238}U and ^{232}Th low-E backgrounds
  → Below ^{208}Tl (3198-5001 keV)

Advantages

I. Full active thick shielding
II. In-situ purification
III. Great scalability
IV. Diverse physics targets
   - 0νββ, ν-osc., geo-ν, astro-ν, …

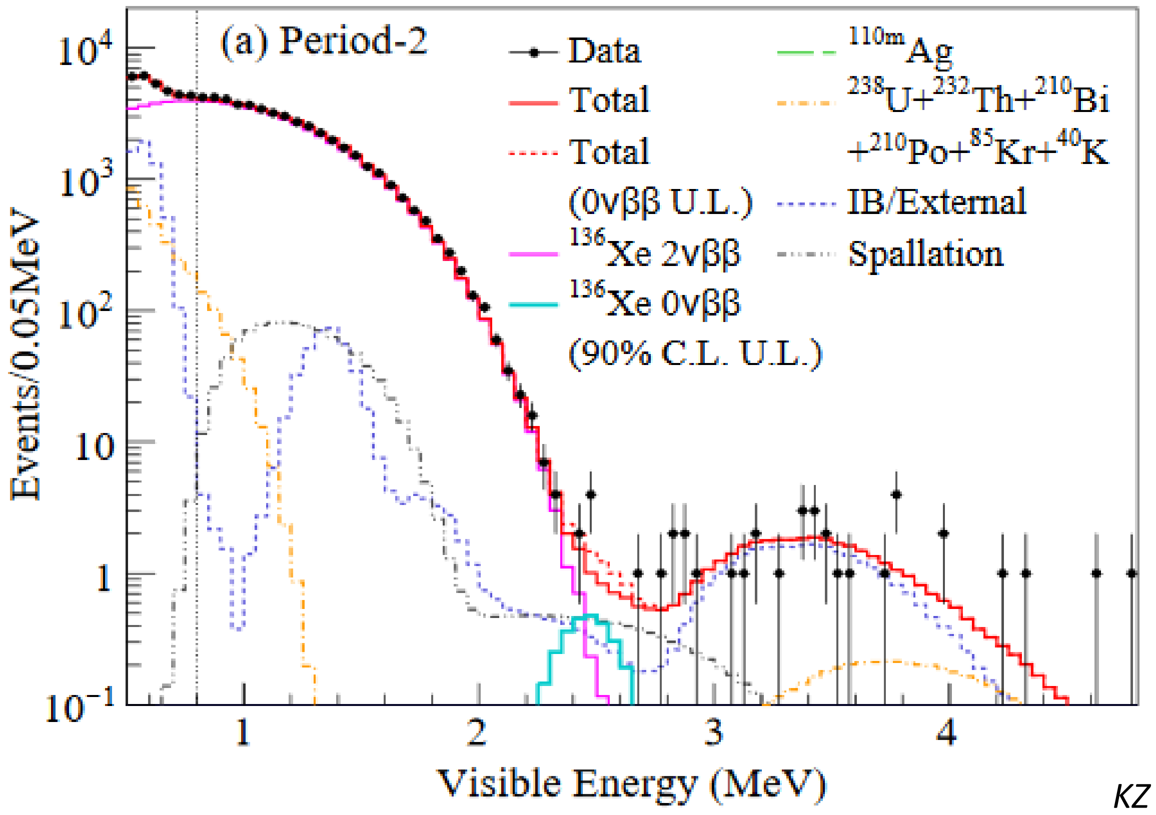
90% enriched ^{136}Xe (3 wt%)

- Phase-I → 320kg
- Phase-II → 380kg
- Zen-800 → 745kg (NEW!)

Phase-II

- First to reach $T_{1/2} > 10^{26}$ yr
- First to reach $m_{\beta\beta} < 100$ meV !

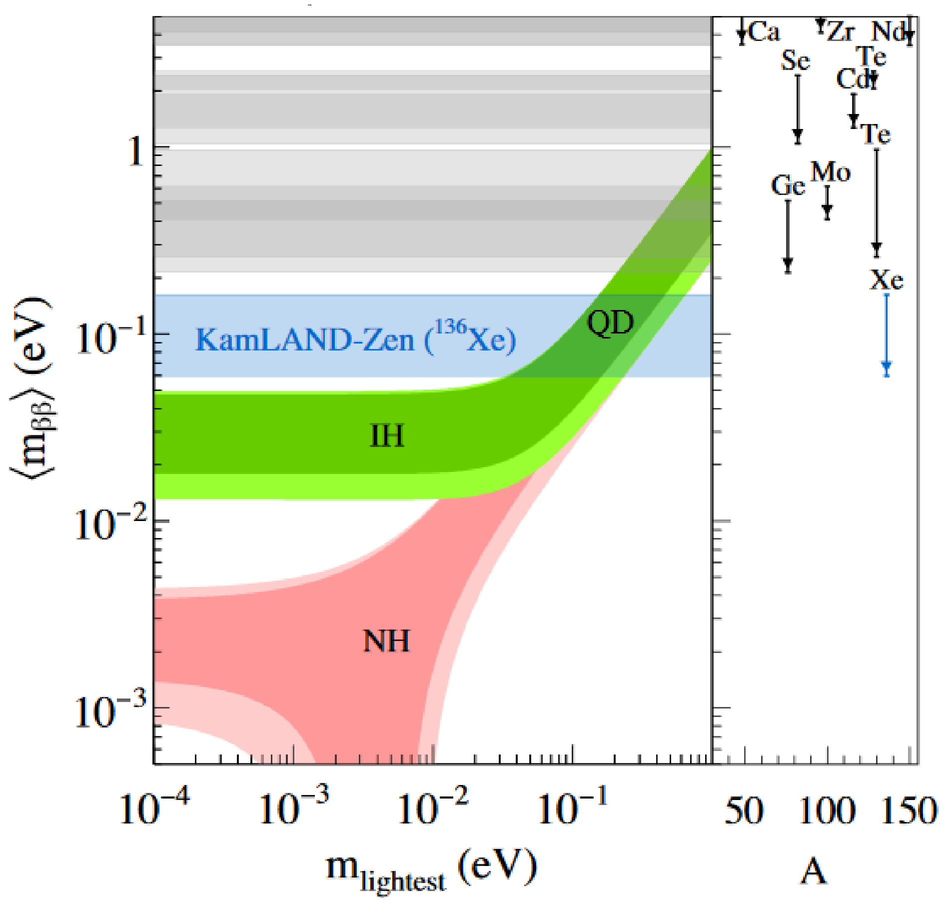
- Muon spallation products (e.g. ^{10}C,^{12}B) and 2νββ currently dominant BG



504 kg-yr exposure

$$T_{1/2}^{0\nu} > 1.07 \times 10^{26}\ \mathrm{yr}$$

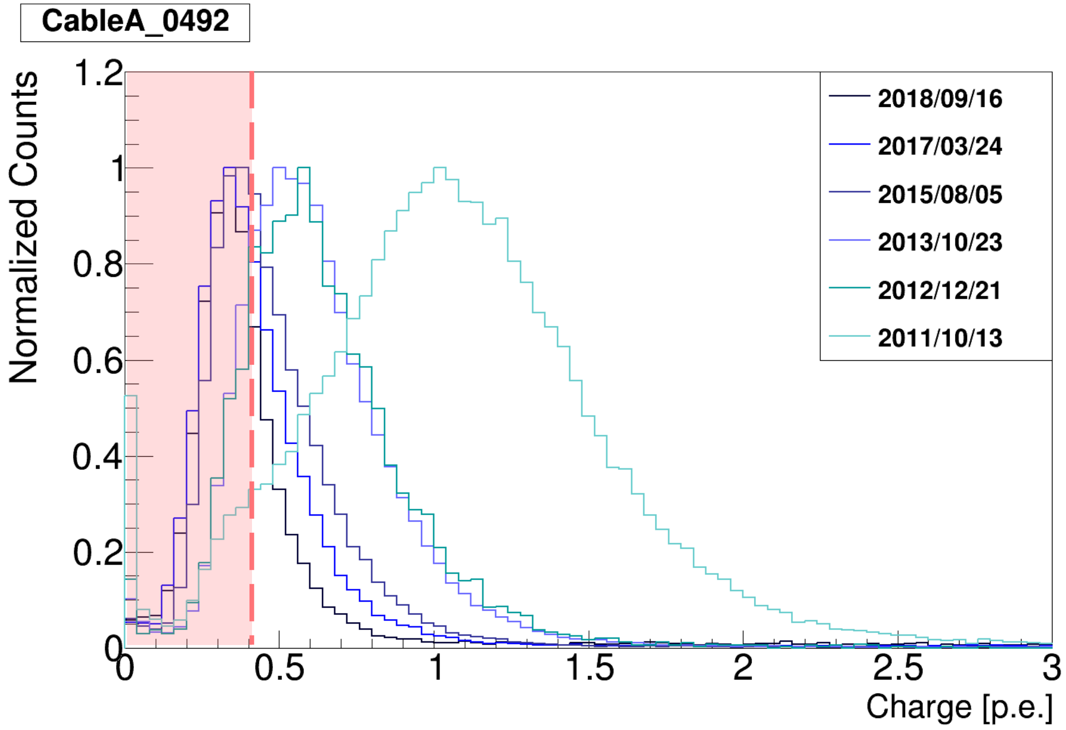
$$\langle m_{\beta\beta} \rangle < (61 - 165)\ \mathrm{meV}$$



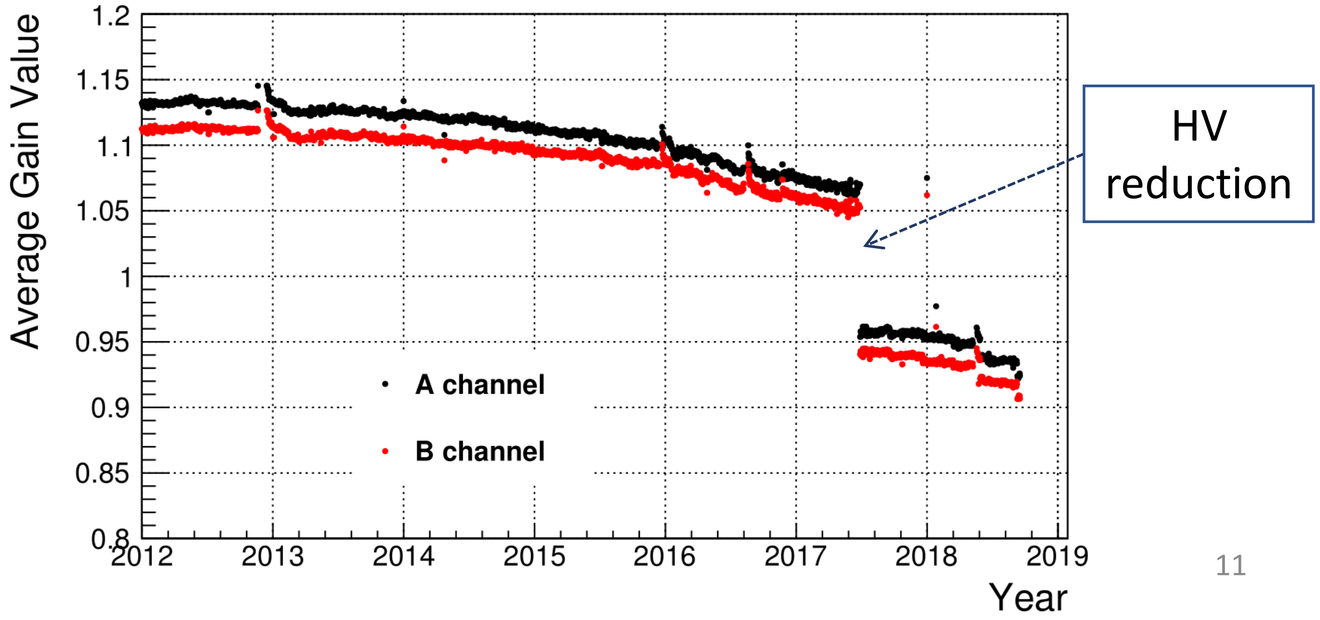
KZ collaboration (2016), **arXiv:1605.02889**

Detector status

- Decreasing PMT gains:
    - Charge distributions shift to lower Q
    - # masked PMTs ↑
    - Energy resolution worsens
    - Intrinsic BG ↑

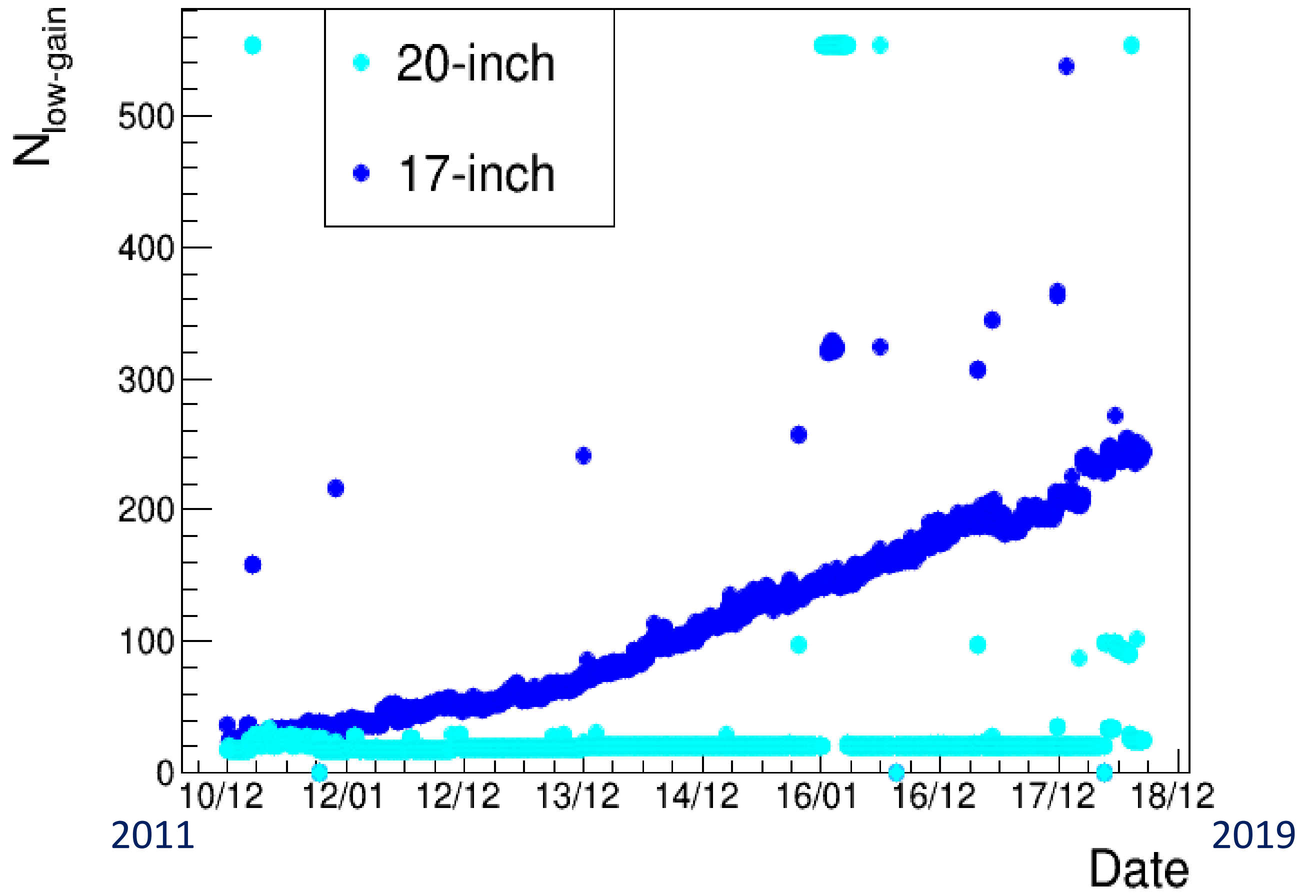


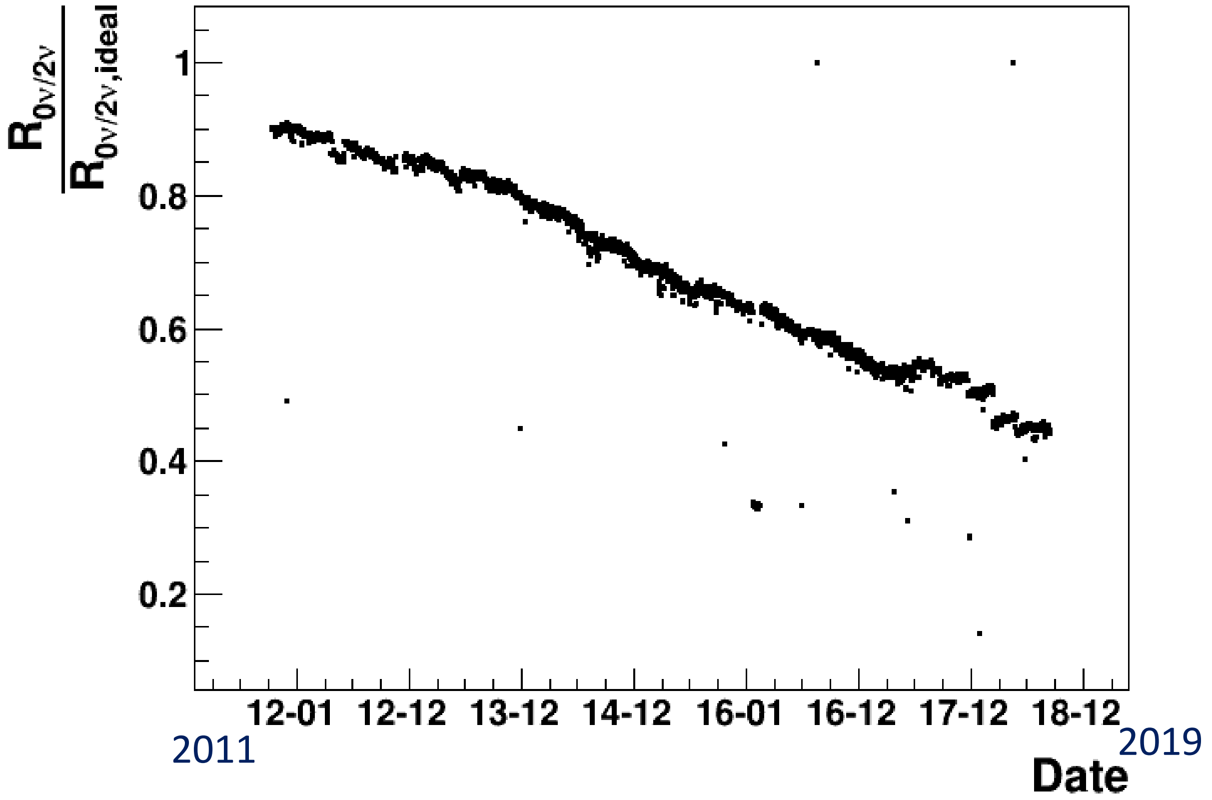
- Causes
    - Short-circuit in bleeder
    - HV reductions



Masked PMTs

- Currently ~250 PMTs masked and increasing…





- Huge effects on discrimination power!

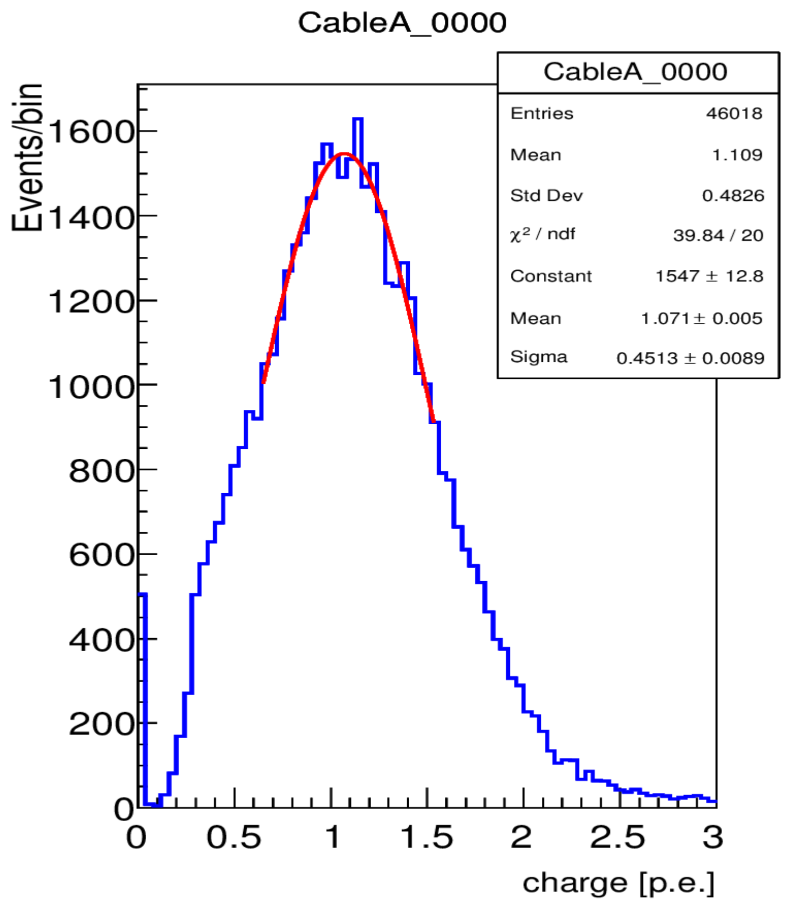
$$R_{0\nu/2\nu} \propto \left(\frac{\Delta E}{Q_{\beta\beta}}\right)^{-5.8}$$

A solution: new gain estimation

- Higher charge events should remain visible above threshold
- Find a way to fit 2 p.e. (or >2 p.e.) peaks

- Similar to standard approach:
  1. Collect charge histograms for each PMT
  2. Fit the >1 p.e. peaks
  3. Extract the gain

- But: very different considerations!
  - What model?
  - Data selection?
  - …



New PMT response function

- Ideal PMT response + BG:

Photocathode response

$$S_{ideal}(q) = \sum_{n=1}^{\infty} \left(\frac{\mu^n}{n!} e^{-\mu} \frac{1}{\sqrt{2\pi n \sigma^2}} e^{-\frac{(q-nQ_1)^2}{2n\sigma^2}} \right)$$

Dynode amplification

$$S_{real}(q) = \int S_{ideal}(q') B(q-q') dq'$$

$$B(q) = \frac{1-w}{\sigma_0\sqrt{2\pi}} \exp\left(-\frac{q^2}{2\sigma_0^2}\right) + w\theta(q)\alpha \exp(-\alpha q)$$

- Two types of background:

1. Pedestal (electronic noise)
2. Discrete noise (thermoemission, etc.)

Taken care of by HW discriminator + BL subtraction

E.H. Bellamy et al. (1993)

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2. Discrete noise (thermoemission, etc.)

Taken care of by
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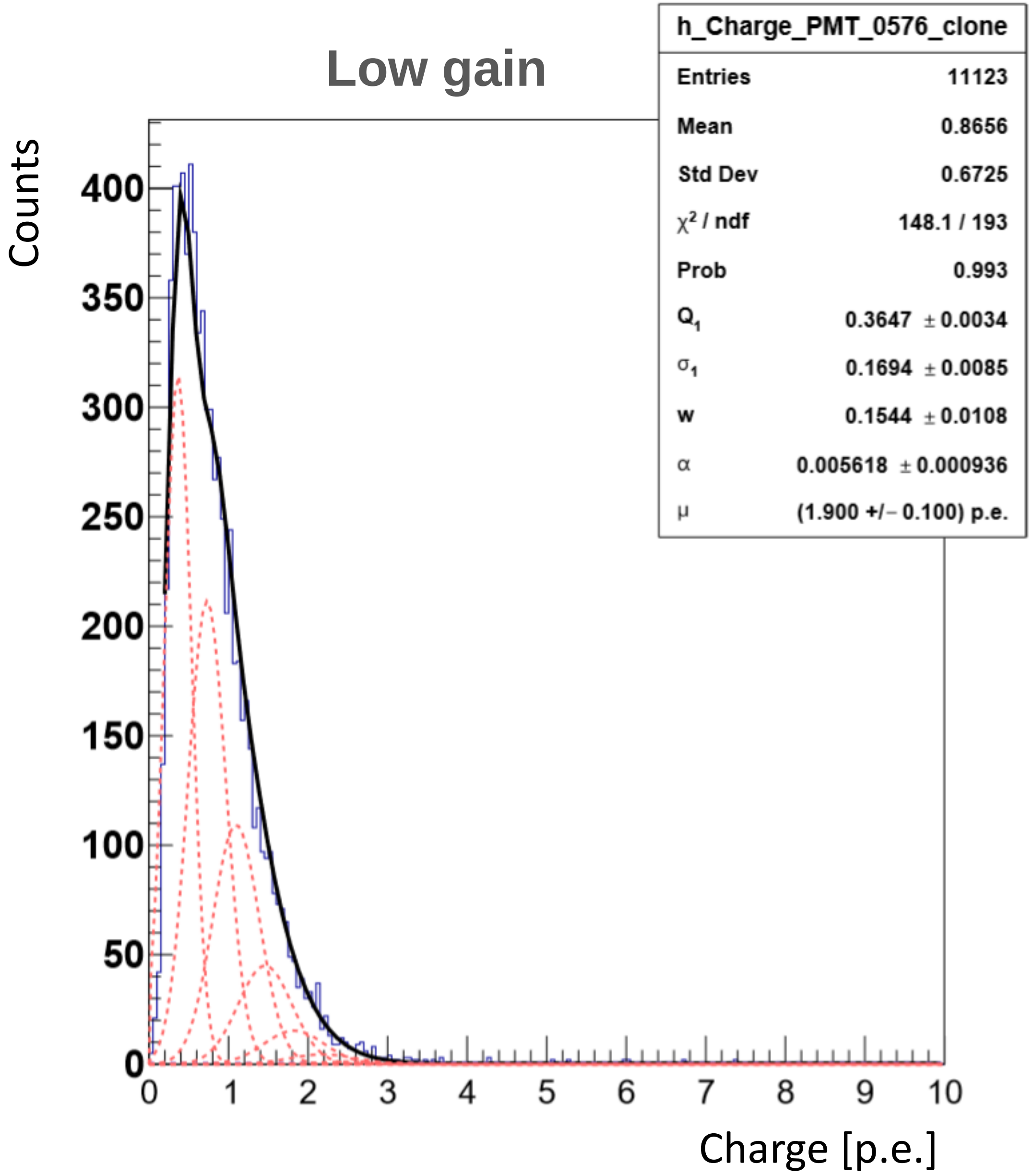
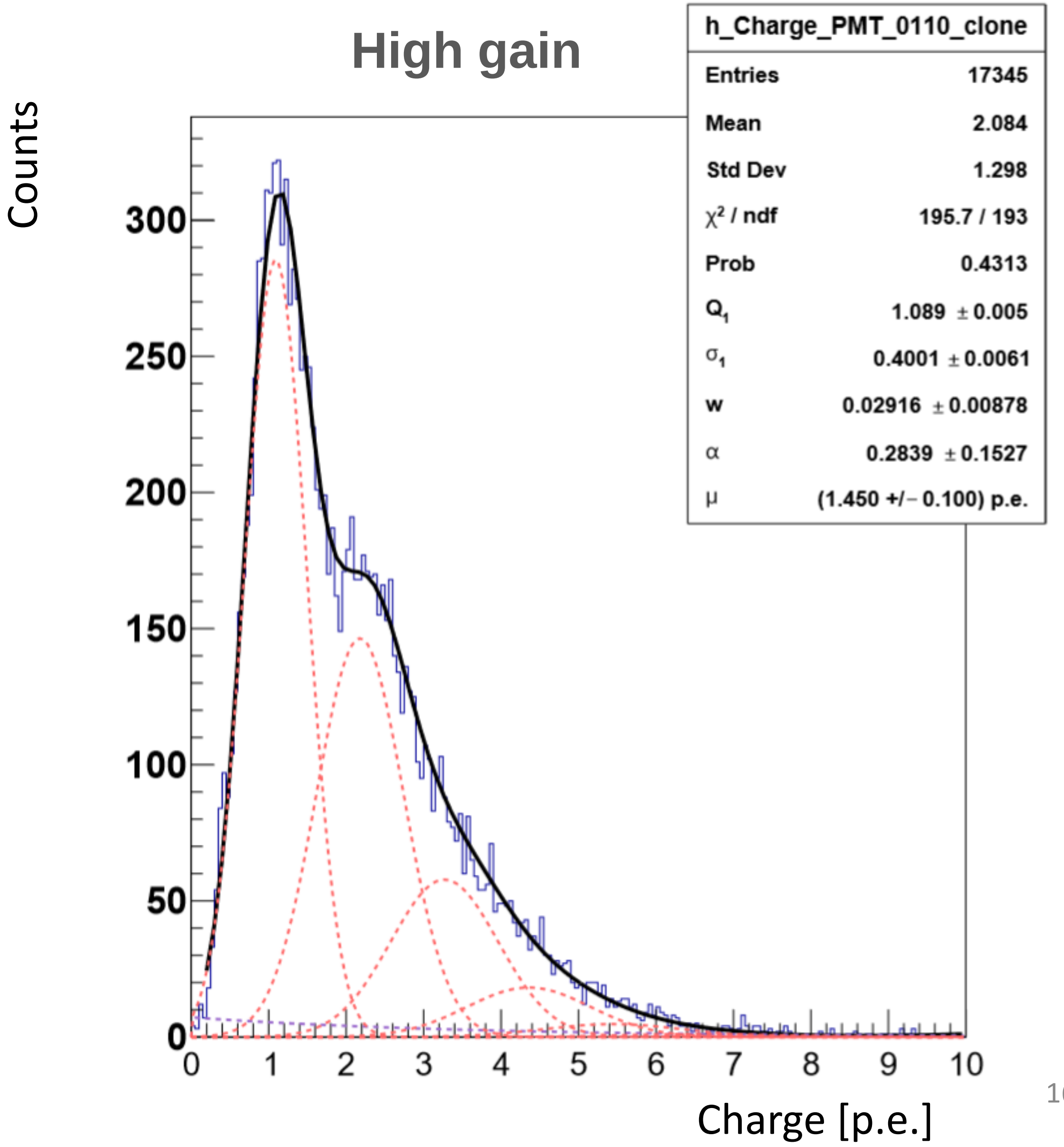
E.H. Bellamy et al. (1993)

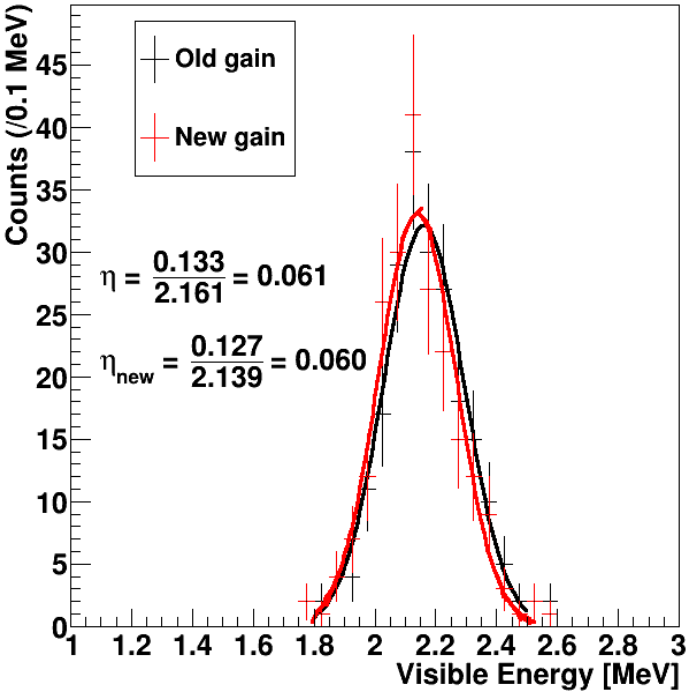
Results


Low gain
h_Charge_PMT_0576_clone
Entries 11123
Mean 0.8656
Std Dev 0.6725
χ² / ndf 148.1 / 193
Prob 0.993
Q1 0.3647 ± 0.0034
σ1 0.1694 ± 0.0085
w 0.1544 ± 0.0108
α 0.005618 ± 0.000936
μ (1.900 +/− 0.100) p.e.
Counts
Charge [p.e.]

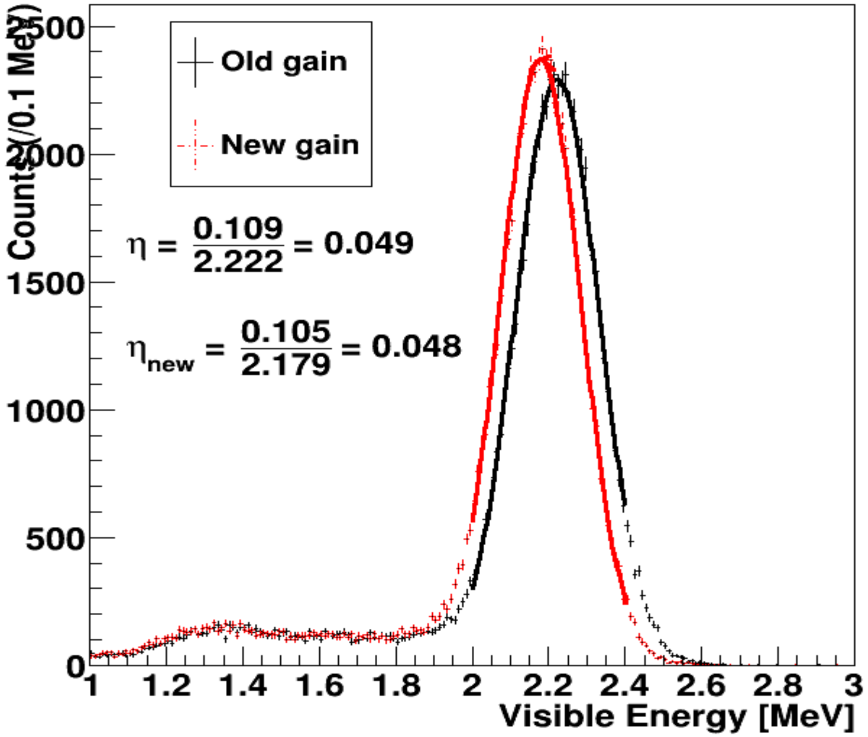

High gain
h_Charge_PMT_0110_clone
Entries 17345
Mean 2.084
Std Dev 1.298
χ² / ndf 195.7 / 193
Prob 0.4313
Q1 1.089 ± 0.005
σ1 0.4001 ± 0.0061
w 0.02916 ± 0.00878
α 0.2839 ± 0.1527
μ (1.450 +/− 0.100) p.e.
Counts
Charge [p.e.]

Prospects

- Taking p > 0.01 as criterion:
  - ~**25%** of masked PMTs **retrievable**
  - # active PMTs 1629 → 1691
- Theoretically, ~3% improvement in E-res.



- From data:
  - 60Co: 0.049 → 0.048
  - n-Capture: 0.061 → 0.060
- **2% E-res.** Improvement
  → **10% R0v/2v** improvement



In summary

- 0νββ-decay research forms an important framework for studying ν's
  - Observation **necessarily** implies Majorana-ν!
  - Important complement for understanding mass hierarchy

- KamLAND-Zen stands at the forefront of 0νββ-studies
  - **Most stringent limits** as of yet from Phase I+II
  - 800-phase ongoing as of Jan. 2019 with 40 meV target sensitivity

$$T^{0\nu}_{1/2} > 1.07 \times 10^{26}\,\mathrm{yr}$$
$$\langle m_{\beta\beta} \rangle < (61 - 165)\,\mathrm{meV}$$

- Improving E-res. necessary to counter 2νββ intrinsic BG going forward
  - Currently **E-res. is decreasing**! ← increasing # masked PMTs (~250 at present)
  - New gain estimation **may recover ~25%** of masked PMTs
    → **~2%-5% improvement E-res.**
    → **~10% decrease in relative intrinsic BG**!

  - Implementation in **energy fitter** in progress
  - Further improvements to energy fitter under investigation

Haruhiko Miyake

ありがとう
ございます！

EXTRA

Neutrino Masses

1. Dirac neutrino scheme

- Add right-chiral neutrinos

$$\mathscr{L}^{\mathrm{D}}_{\mathrm{mass}} = -m\,\overline{\nu}\,\nu = -m\left(\overline{\nu_R}\,\nu_L + \overline{\nu_L}\,\nu_R\right) = -m\,\overline{\nu_R}\,\nu_L + \mathrm{H.c.}$$

- Copy + paste SM massive fermion case

2. Majorana scheme

- Can we conjure mass without separate ν_R?
- Yes! Provided ν_L and ν_R are not independent

$$\mathscr{L}^{\mathrm{M}}_{\mathrm{mass}} = -\frac{1}{2}\,m\,\overline{\nu_L^C}\,\nu_L + \mathrm{H.c.}$$

1. Constructable from 2-comp. spinor
2. Lorentz invariant
3. Solutions to EOM satisfy rel. mom.

$\nu_L^C = C\,\nu_L^\dagger$ (= ν_R)

Neutrino Masses

1. Dirac neutrino scheme

- Add right-chiral neutrinos

$$\mathscr{L}^{\mathrm{D}}_{\mathrm{mass}} = -m\,\overline{\nu}\,\nu = -m\,(\overline{\nu_R}\,\nu_L + \overline{\nu_L}\,\nu_R) = -m\,\overline{\nu_R}\,\nu_L + \mathrm{H.c.}$$

- Copy + paste SM massive fermion case

2. Majorana scheme

- Can we conjure mass without separate v_R?
- Yes! Provided v_L and v_R are not independent

$$\mathscr{L}^{\mathrm{M}}_{\mathrm{mass}} = -\frac{1}{2}\,m\,\overline{\nu_L^C}\,\nu_L + \mathrm{H.c.}$$

$v_L^C = C\, v_L^\dagger$ ($= v_R$)

Majoranas are their own antiparticles!

$$\nu = \nu_L + \nu_L^C$$

$$\nu^C = \nu$$

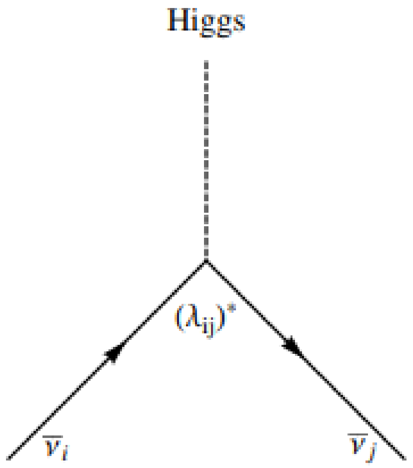
Neutrino Masses

1. **Dirac neutrino scheme**

- Add right-chiral neutrinos

$$-\mathcal{L}_m^{Dirac} = \overline{L}\,\lambda\tilde{\Phi}\,\nu_R + \text{h.c.}$$

- Copy + paste SM massive fermion case

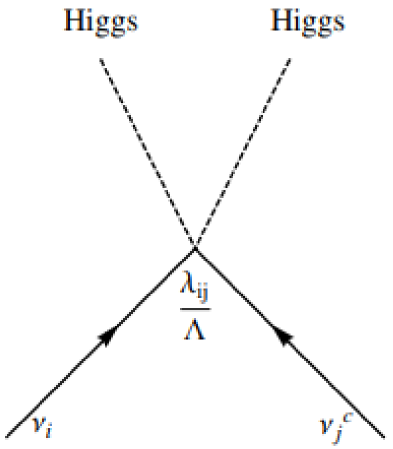


2. **Majorana scheme**

- Can we conjure mass without separate v_R?
- Yes! Provided v_L and v_R are not independent

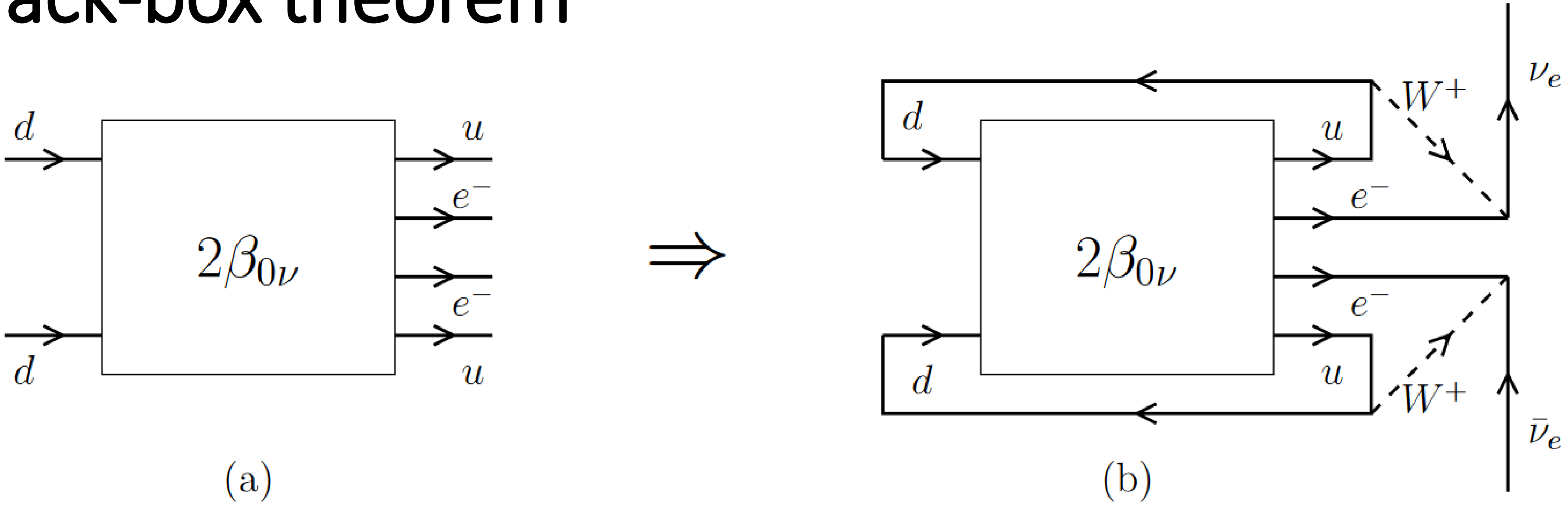
$$-\mathcal{L}_m^{Majorana} = \bar{L}\tilde{\phi}\,\alpha C\tilde{\phi}^T\bar{L}^T + h.c.,$$

$v_L^C = C\, v_L^\dagger$ $(= v_R)$



P. Hernandez (2017)

Black-box theorem



- Suppose there is a global symmetry prohibiting a Majorana mass term
- Only possible symmetry is discrete phase transformation
- This would imply that at the same time:
  - $\varphi_d - \varphi_u + \varphi_e = 0$
  - $\varphi_\nu = \varphi_d - \varphi_u + \varphi_e$

$$\varphi_\nu \neq 0$$

$$\mathcal{L}^{\mathrm{M},\nu_e}_{\mathrm{mass}} = -\frac{1}{2}\, m_{ee}\left(-\nu_{eL}^T\, \mathcal{C}^\dagger\, \nu_{eL} + \overline{\nu_{eL}}\, \mathcal{C}\, \overline{\nu_{eL}}^T\right)$$

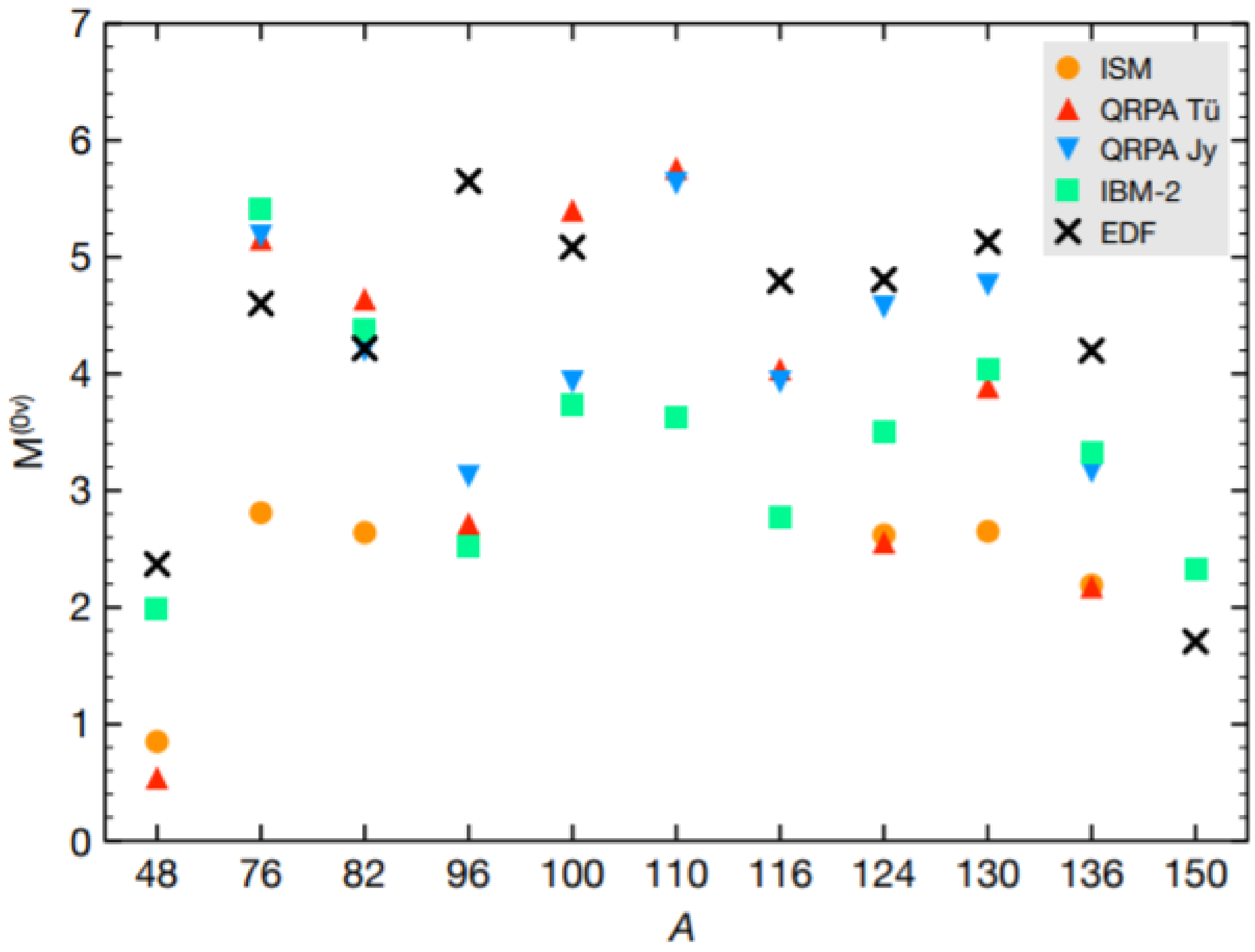
$$\nu_{eL} \to e^{i\varphi_\nu}\, \nu_{eL} \qquad \varphi_\nu \neq 0$$

$$e \to e^{i\varphi_e}\, e\,, \quad u \to e^{i\varphi_u}\, u\,, \quad d \to e^{i\varphi_d}\, d\,, \quad W^\rho \to e^{i\varphi_W}\, W^\rho$$

$$\left.\begin{array}{lll} \overline{\nu_{eL}}\,\gamma^\rho\, e_L\, W_\rho & \Rightarrow & \varphi_\nu - \varphi_e - \varphi_W = 0 \\ \overline{u_L}\,\gamma^\rho\, d_L\, W_\rho & \Rightarrow & \varphi_u - \varphi_d - \varphi_W = 0 \end{array}\right\} \Rightarrow \quad \varphi_\nu = \varphi_d - \varphi_u + \varphi_e$$

Fundamentals of Neutrino Physics and Astrophysics – A. Giunti (2007)

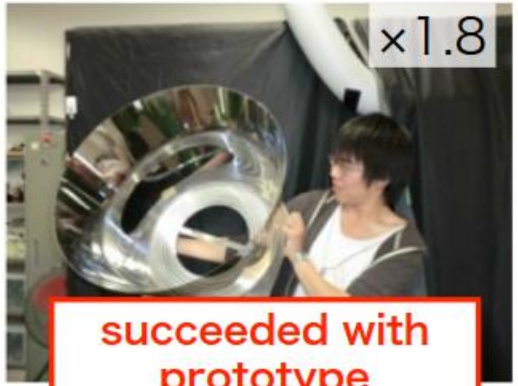
NMEs



J.J. Gómez-Cadenas and Justo Martín-Albo (2017)

R&D for KamLAND2-Zen and future

○ winston cone

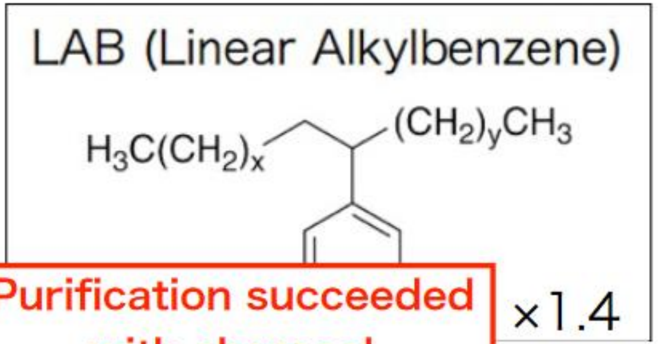


succeeded with prototype

○ HQE-PMT

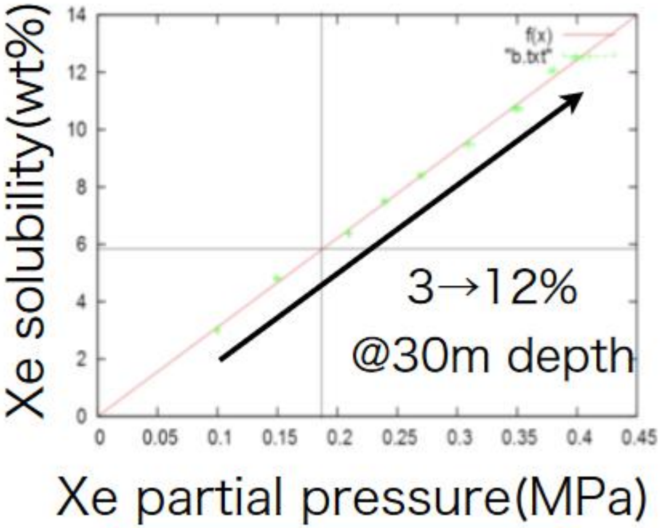
prototype in hand

○ New LAB-LS



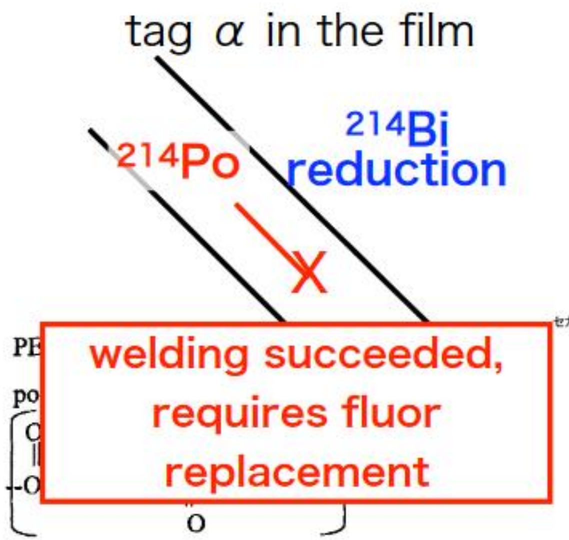
Purification succeeded with charcoal

○ denser xenon



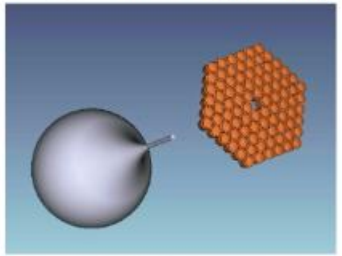
principle confirmed

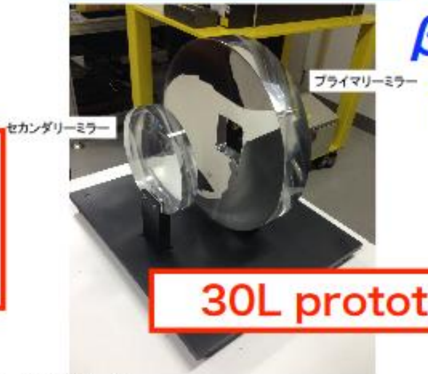
○ scintillator film



welding succeeded, requires fluor replacement

○ imaging

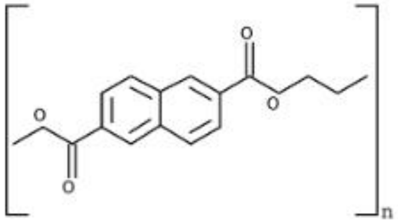




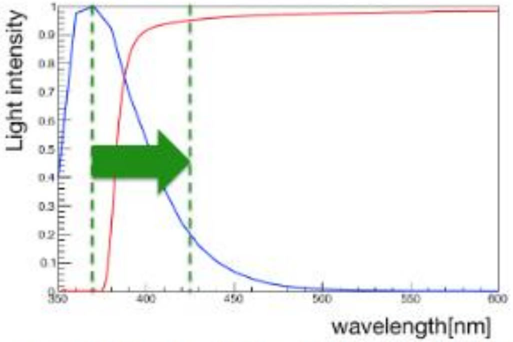
β/γ id.

30L prototype

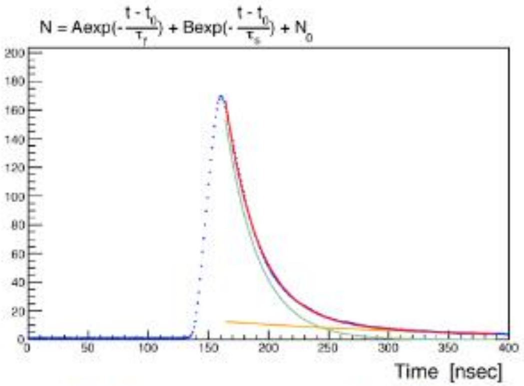
PolyEthylene Naphthalate (PEN)



η=10,500ph/MeV
λ_{PEN}=425nm
U,Th < 3 ppt



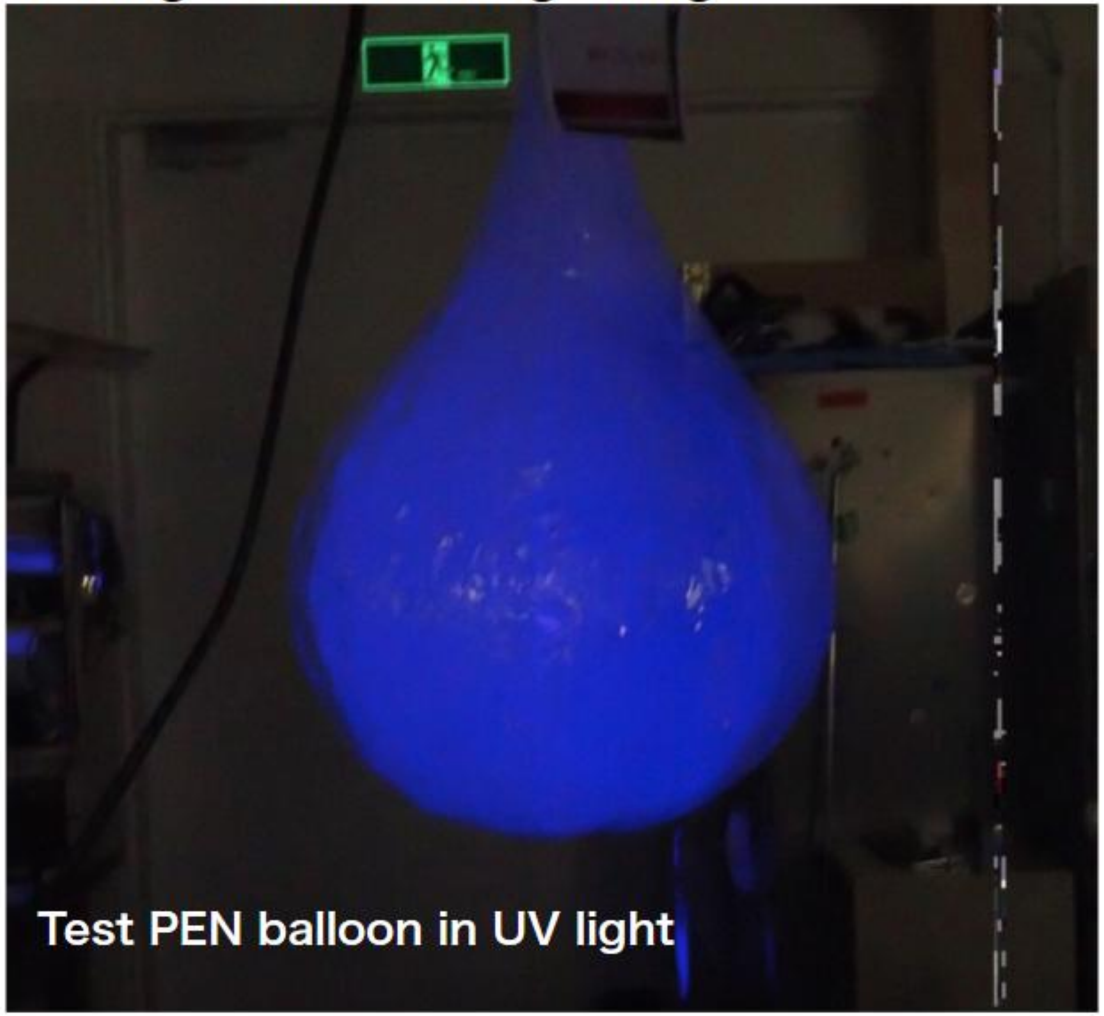
requires Bis-MSB in LS



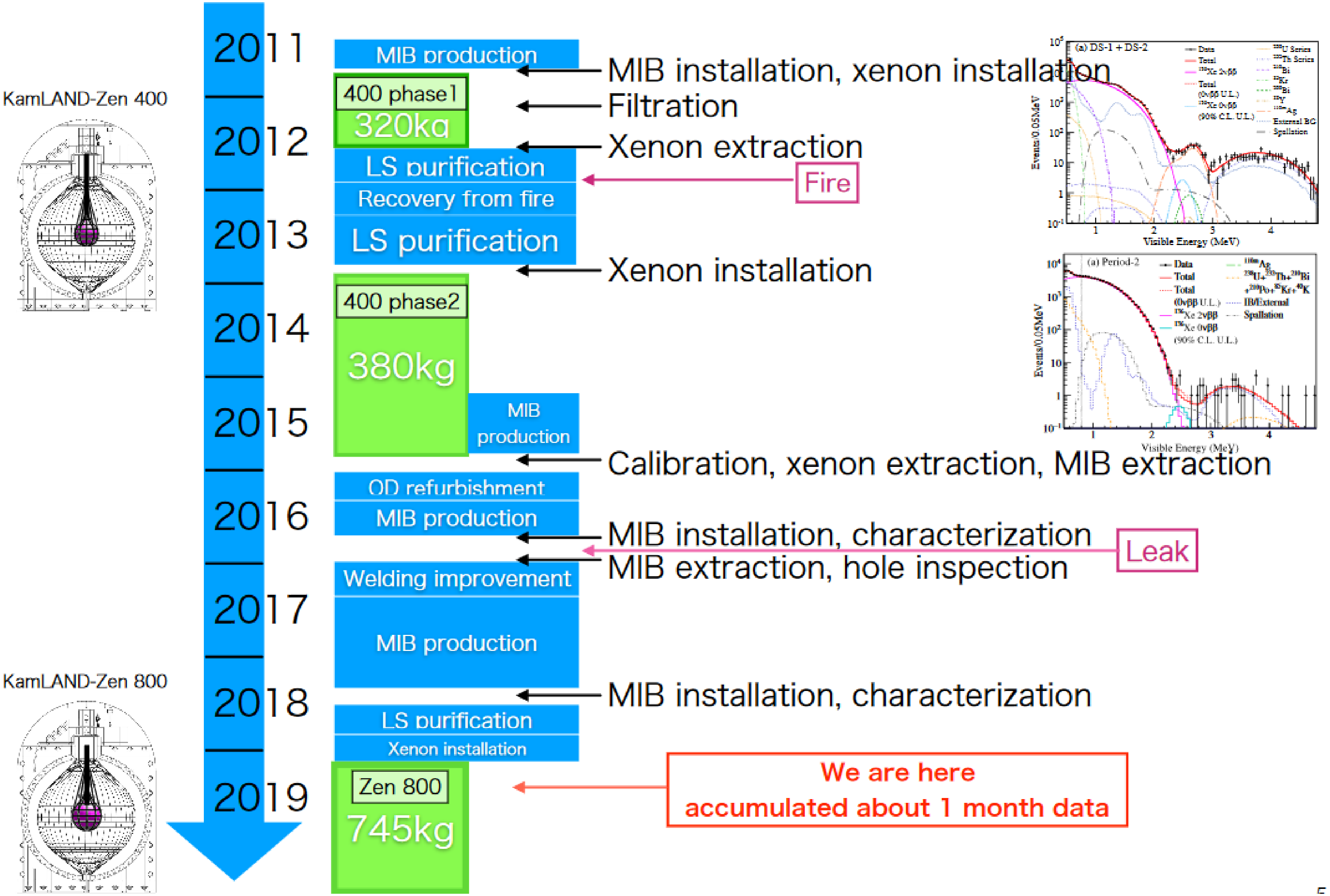
τ~27 nsec, much slower than Kam-LS 4 nsec

PSD possible

welding easier & strong enough



Timeline


KamLAND-Zen 400
KamLAND-Zen 800
2011
2012
2013
2014
2015
2016
2017
2018
2019
MIB production
400 phase1
320kg
LS purification
Recovery from fire
LS purification
400 phase2
380kg
MIB production
OD refurbishment
MIB production
Welding improvement
MIB production
LS purification
Xenon installation
Zen 800
745kg
MIB installation, xenon installation
Filtration
Xenon extraction
Fire
Xenon installation
Calibration, xenon extraction, MIB extraction
MIB installation, characterization
Leak
MIB extraction, hole inspection
MIB installation, characterization
We are here
accumulated about 1 month data
(a) DS-1 + DS-2
Events/0.05MeV
Visible Energy (MeV)
(a) Period-2
Events/0.05MeV
Visible Energy (MeV)

Schedule

installation of new electronics planned during Zen 800

2019 KamLAND-Zen 800

2020

2021

2022

2023

2024

2025

2026

2027

2028

Environmental and peripheral preparation

- Purchase enriched Xenon(200kg)
- Installation of MoGURA2
- Clean room fabrication
- Clean air system installation
- Purification system upgrade
- Light concentrator production
- Large balloon production

KamLAND upgrade

No observation

- Purchase HQE-PMT
- LS drain
- Expansion of entrance
- PMT replacement/mirror attachment
- Large balloon installation
- Refurbishment of N2 system
- New LS production
- LS filling
- Development of calibration system

KamLAND2 start

- Mini-balloon installation
- Xenon installation

KamLAND2-Zen start

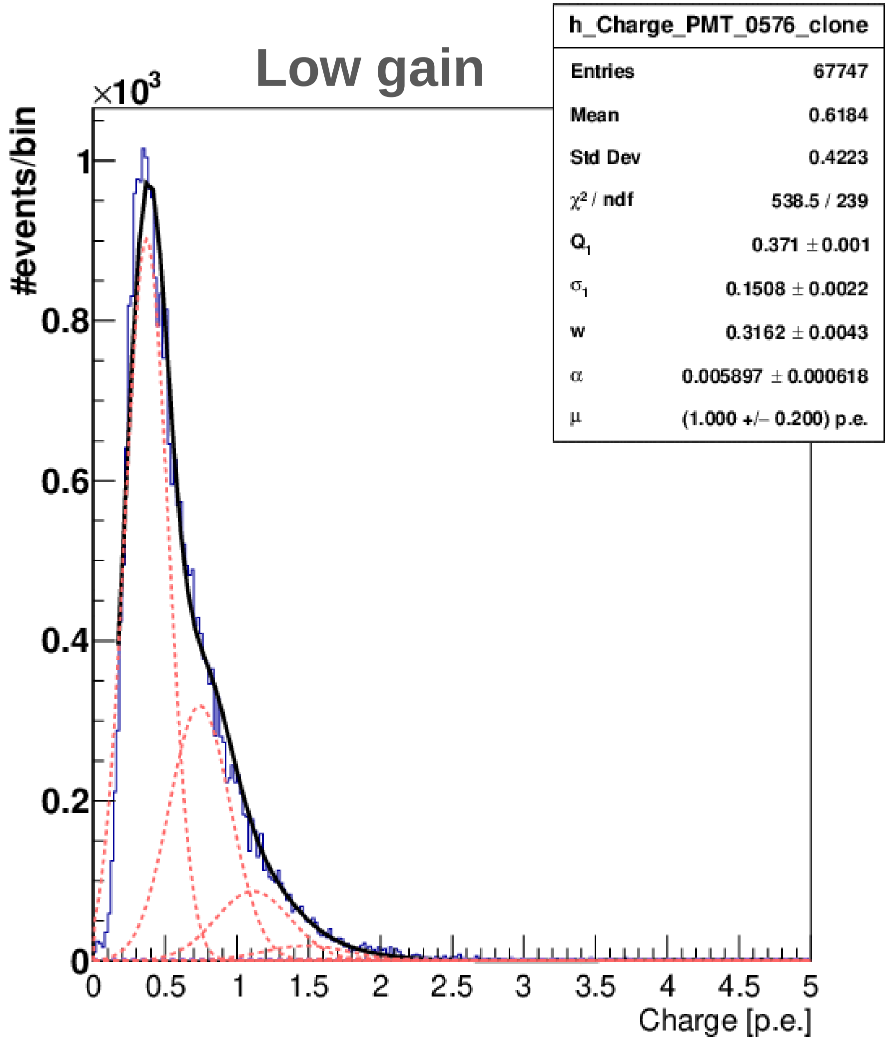
Geo-neutrino observation

Investigation of Majorana nature

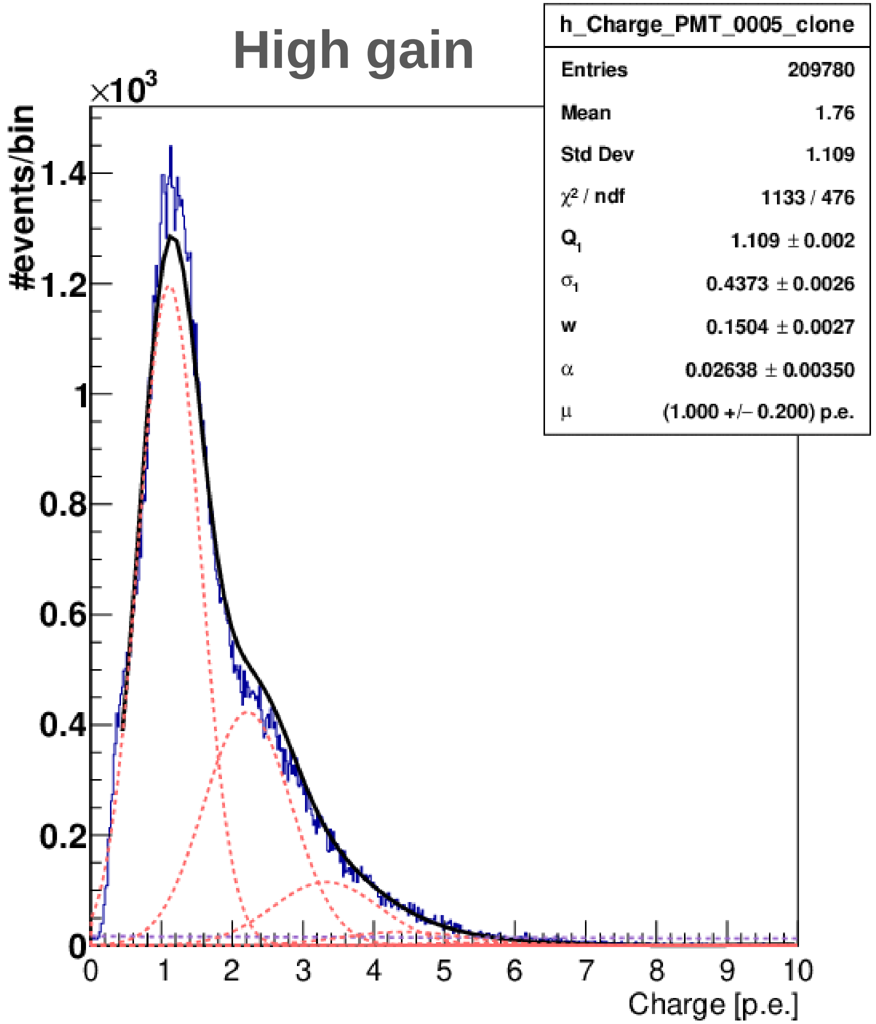
Expected charge

$$S_{ideal}(q) = \sum_{n=1}^{\infty}\left(\frac{\mu^n}{n!}e^{-\mu}\frac{1}{\sqrt{2\pi n\sigma^2}}e^{-\frac{(q-nQ_1)^2}{2n\sigma^2}}\right)$$

Low gain



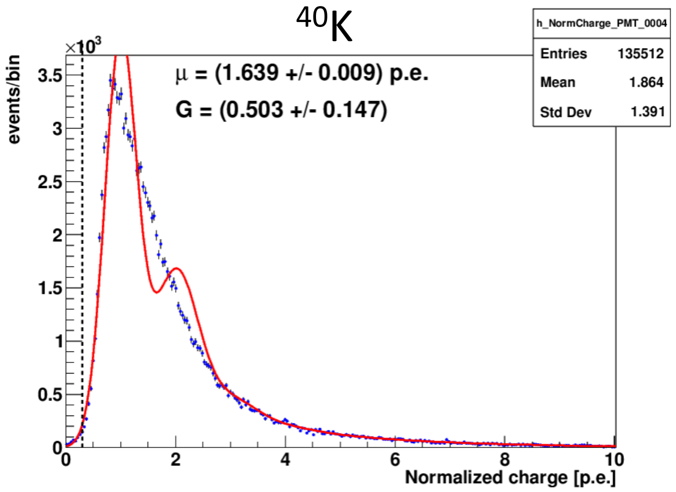
High gain



Data selection procedure

- Expected charge **μ very hard to constrain**
  - Can use only use in-situ data
  - Light and charge yield not controlable…

- Two options:
  1. Very careful event type selection + occupancy
     - Sufficient run-by-run statistics close to PMTs (^{40}K, ^{208}Tl)
     - Incidence angle selection
     - μ from occupancy: $\mu \equiv -\ln\left(P_{\mathrm{no-hit}}\right)$



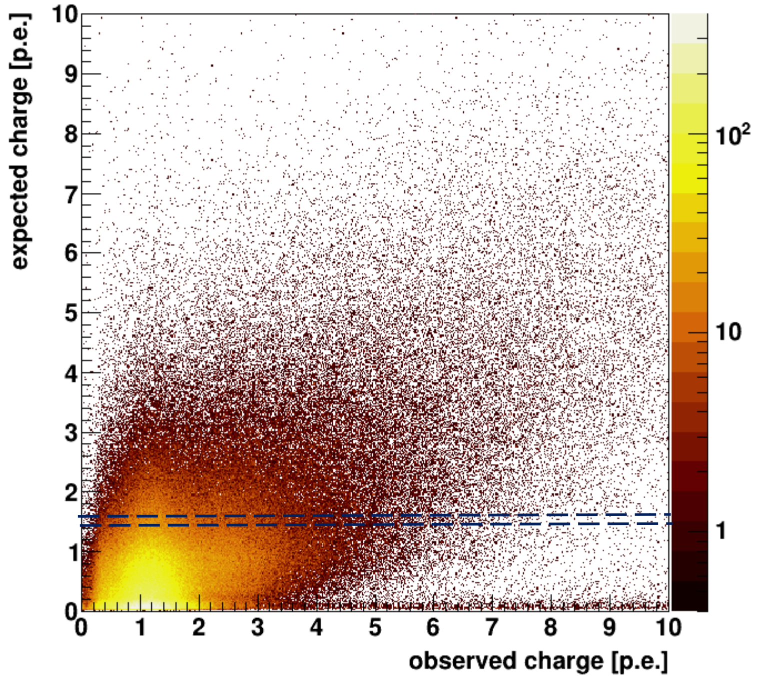
  2. Estimate μ from distance to PMTs and light attenuation factors:

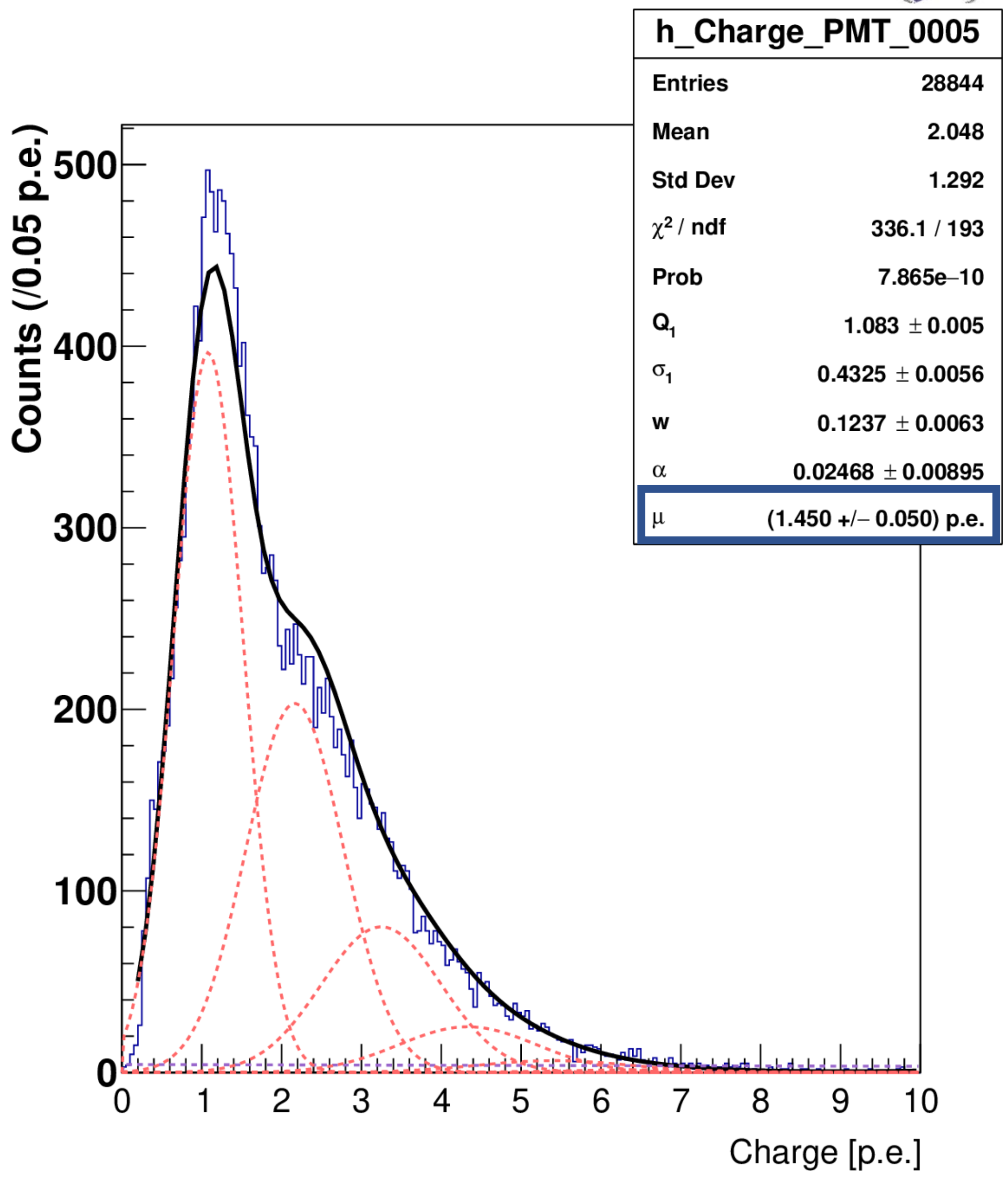
$$\mu_i = \sum_m Q_m^{\mathrm{observed}} \cdot \left(\frac{\tilde{Q}_i^{\mathrm{expected}}}{\sum_n \tilde{Q}_n^{\mathrm{expected}}} \right)$$

$$\tilde{Q}_i^{\mathrm{expected}} = \eta_i \xi_i \frac{\cos\left(\theta_i\right)}{L_i^2} e^{-L_i/\lambda}$$

(Q,μ)-mapping

- Charge distributions for gain fitting selected from projection ranges in (Q,μ)-maps
  - Central projection value varied from 1.0 p.e. to 2.5 p.e.
  - Width varied from 0.05 p.e. to 0.3 p.e.
  - $N_{entries}$ > 10.000 counts





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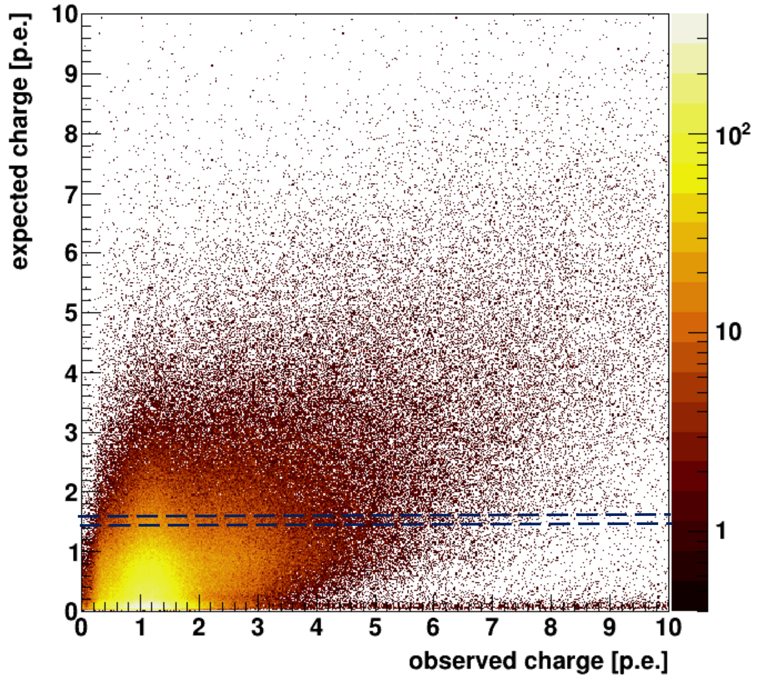

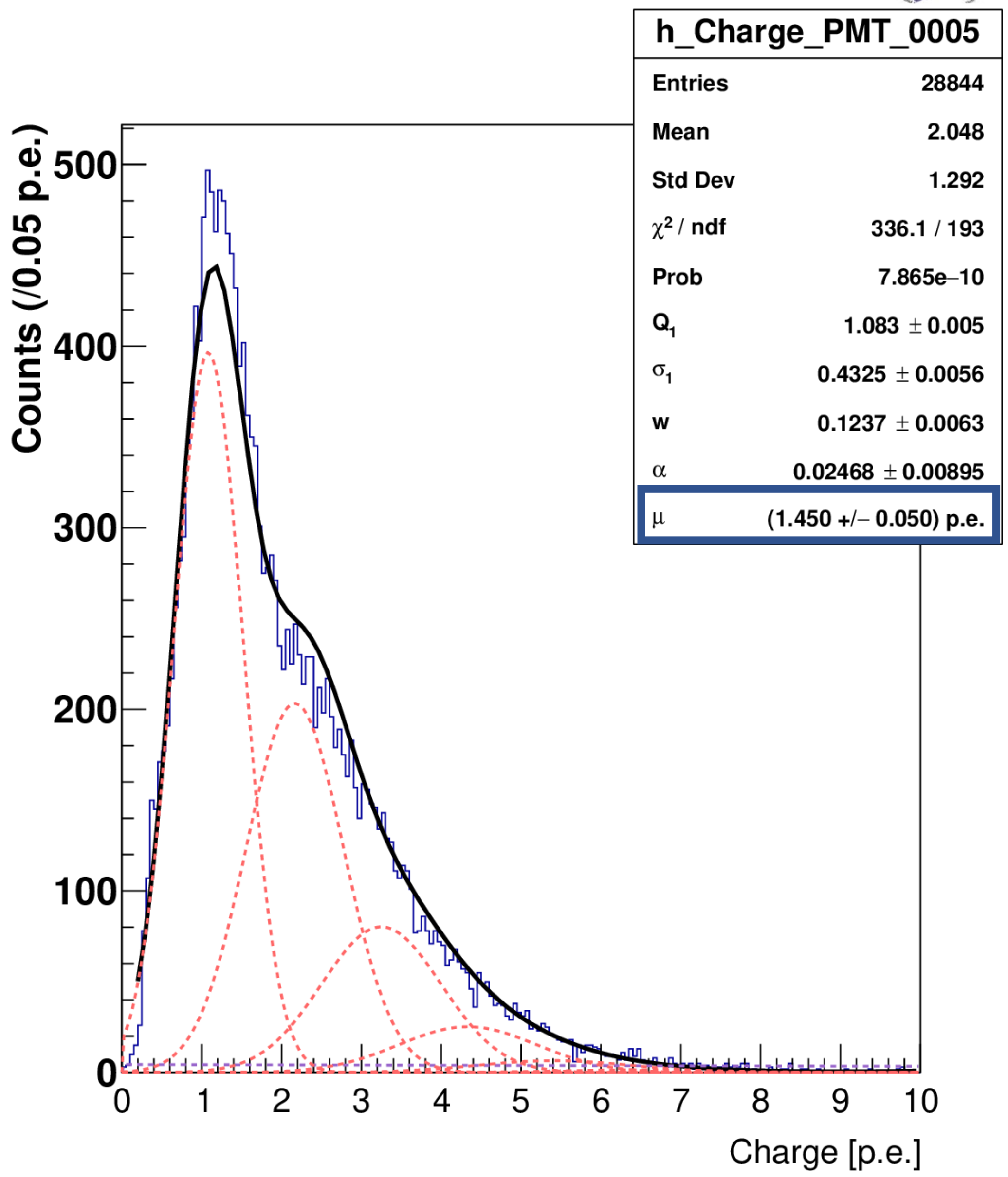

Current work (by Haruhiko Miyake)

- Implement new gain estimation in energy estimator

- Event Energy found through MLE
  - Includes no-hit probabilities

weight by **charge** distribution

weight by **timing** distribution

$$L = \prod_{i \in \mathrm{hit}} \left(P_i^{\mathrm{hit}} P_i^{\mathrm{charge}} P_i^{\mathrm{time}} \right) \times \prod_{i \in \mathrm{no\text{-}hit}} P_i^{\mathrm{no\text{-}hit}}$$

hit probability for a PMT actually hit

no-hit probability for a PMT actually no-hit

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  - Currently assume detection <u>in</u>efficiency (ε_n) = 0 for n ≥ 2
  - Not sufficient for low-gain PMTs!
    → Fit $\varepsilon_n(\mu)$ for all PMTs

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hit probability for a PMT actually hit

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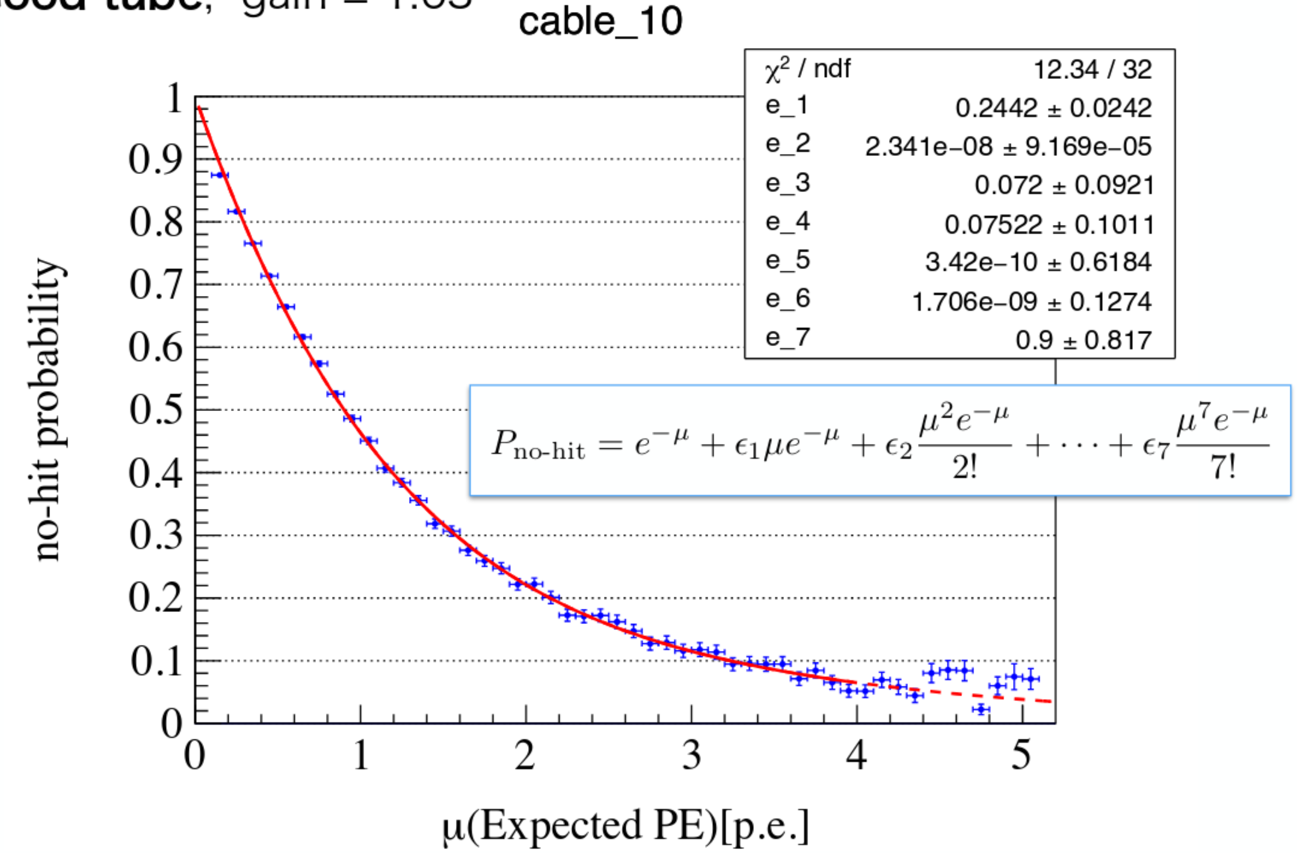
ε n : detection **in**efficiency for n p.e.

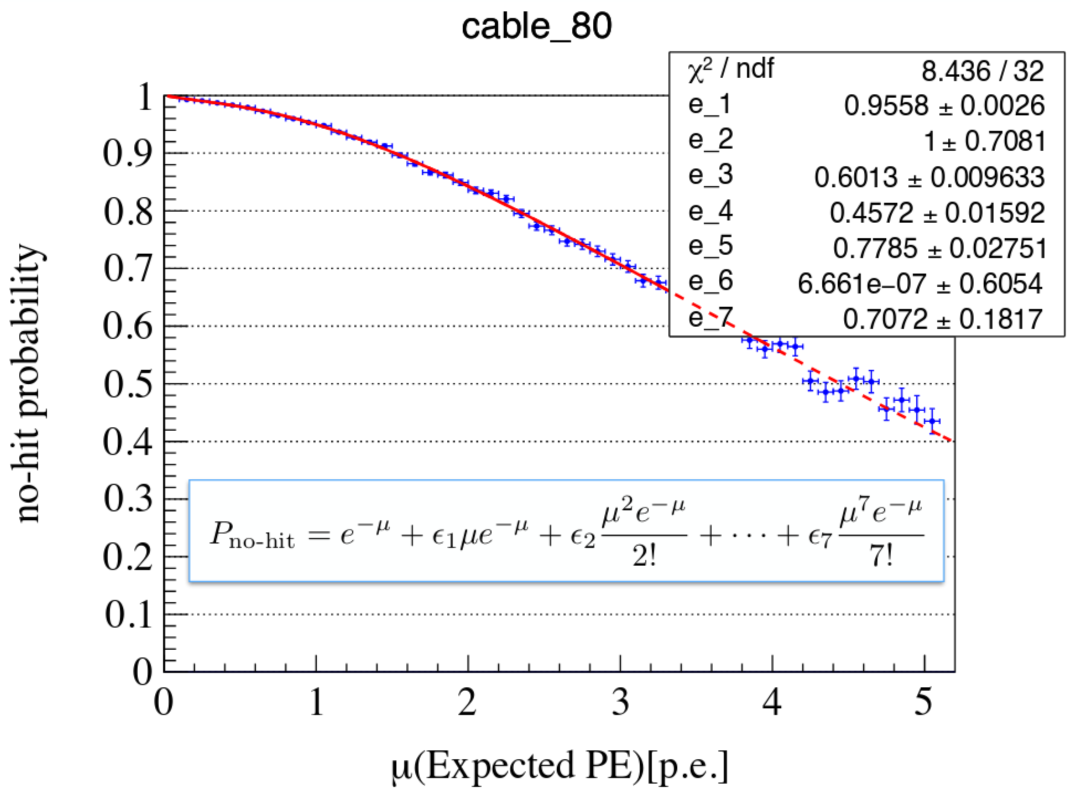
$$P_{\text{no-hit}} = P_0 + \epsilon_1 P_1 + \epsilon_2 P_2 + \epsilon_3 P_3 + \cdots$$

Current work (by Haruhiko Miyake)

Good tube, gain = 1.03



Low-gain tube, gain = no value (failed to estimate)



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- Event Energy found through MLE
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  - Currently assume detection **in**efficiency (ε_n) = 0 for n ≥ 2
  - Not sufficient for low-gain PMTs! → Fit $\varepsilon_n(\mu)$ for all PMTs
  - Inclusion of $\varepsilon_n(\mu)$ -fit improves E-res. in low-E region
  - But not in higher-E region
  - Work in progress:
    - Apply *differential weights* for signal events compared to background

Performance Summary

	New (1274 ch)	New (1110 ch)	Old (1110 ch)
^{137}Cs (661 keV)	9.75 +/- 0.05 %	10.19 +/- 0.06 %	10.44 +/- 0.05 %
^{60}Co (2505 keV)	5.94 +/- 0.05 %	6.63 +/- 0.02 %	5.17 +/- 0.01 %