Discovery potential of fermionic dark matter by using the Xe Charged Current tagging in KamLAND-Zen

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Contents

KamLAND collaborations

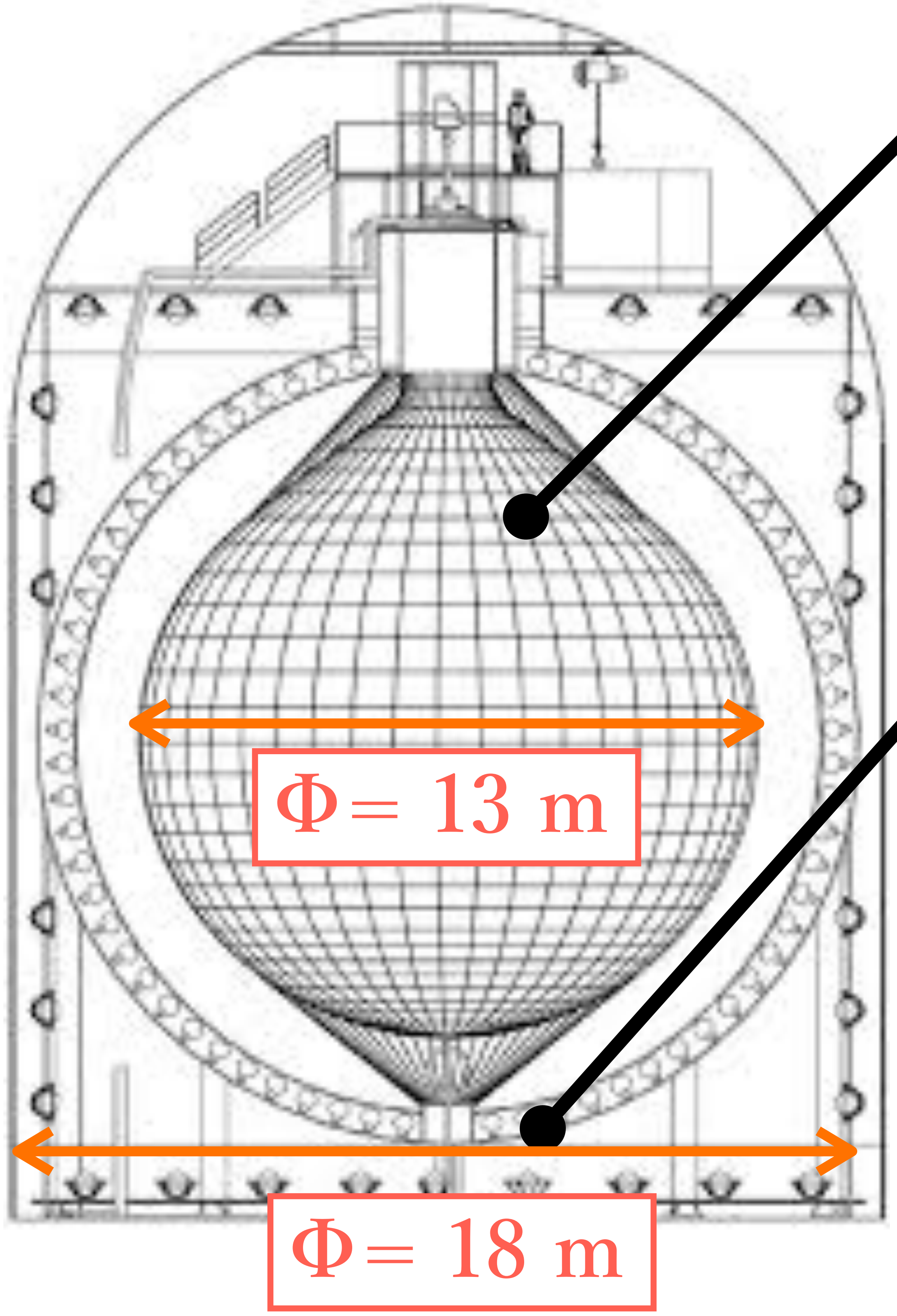
Collaboration meeting @ Hokkaido in Sep.2023
+ remote participants

> 50 physicists work on this project

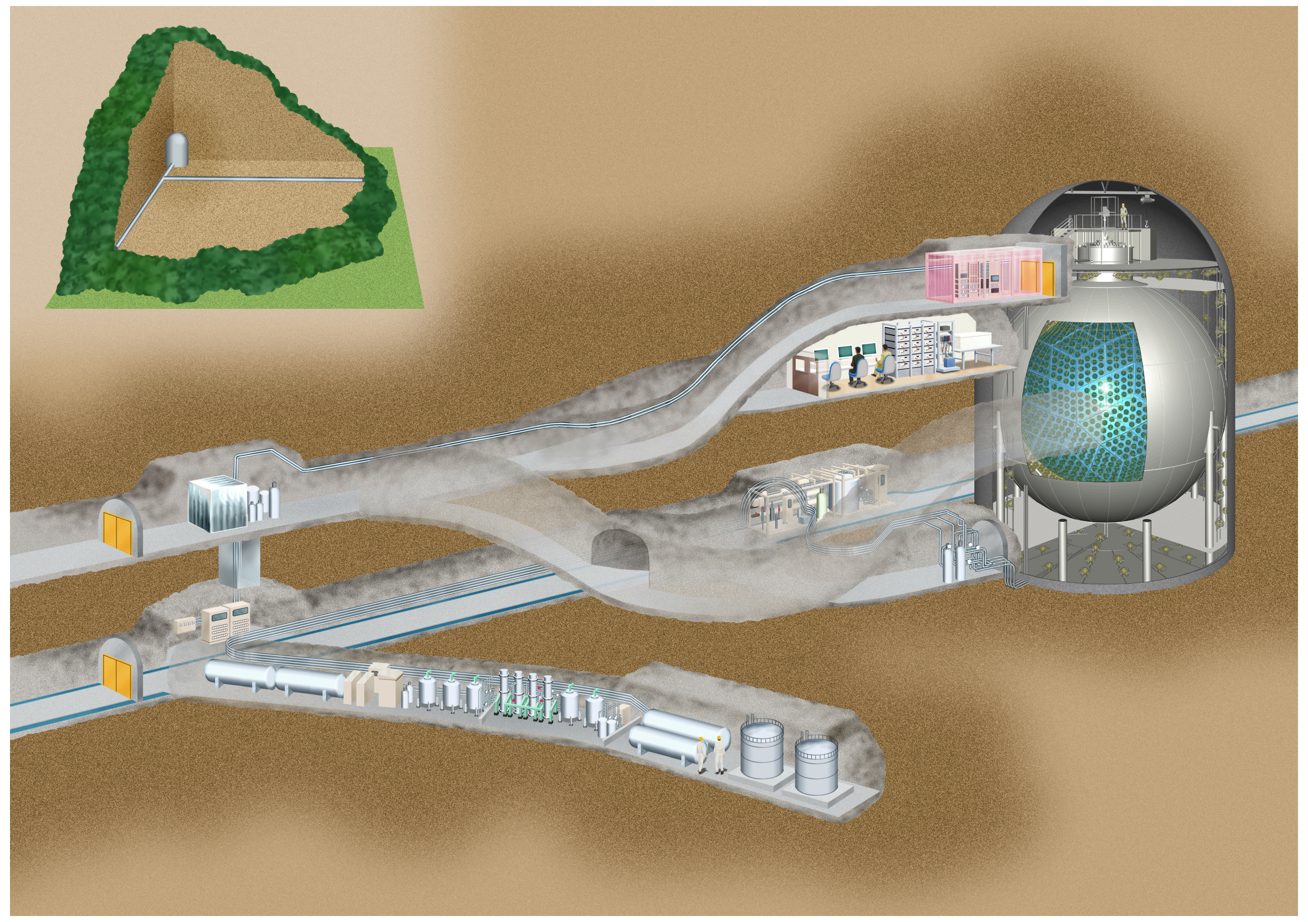
TOHOKU UNIVERSITY
東京大学 THE UNIVERSITY OF TOKYO
大阪大学 OSAKA UNIVERSITY
VIRGINIA TECH.
BERKELEY LAB
MIT
THE UNIVERSITY OF TENNESSEE KNOXVILLE
BOSTON UNIVERSITY
Nikhef
TUNL
UNIVERSITY of HAWAIʻI
TOKUSHIMA UNIVERSITY

Introduction: KamLAND detector

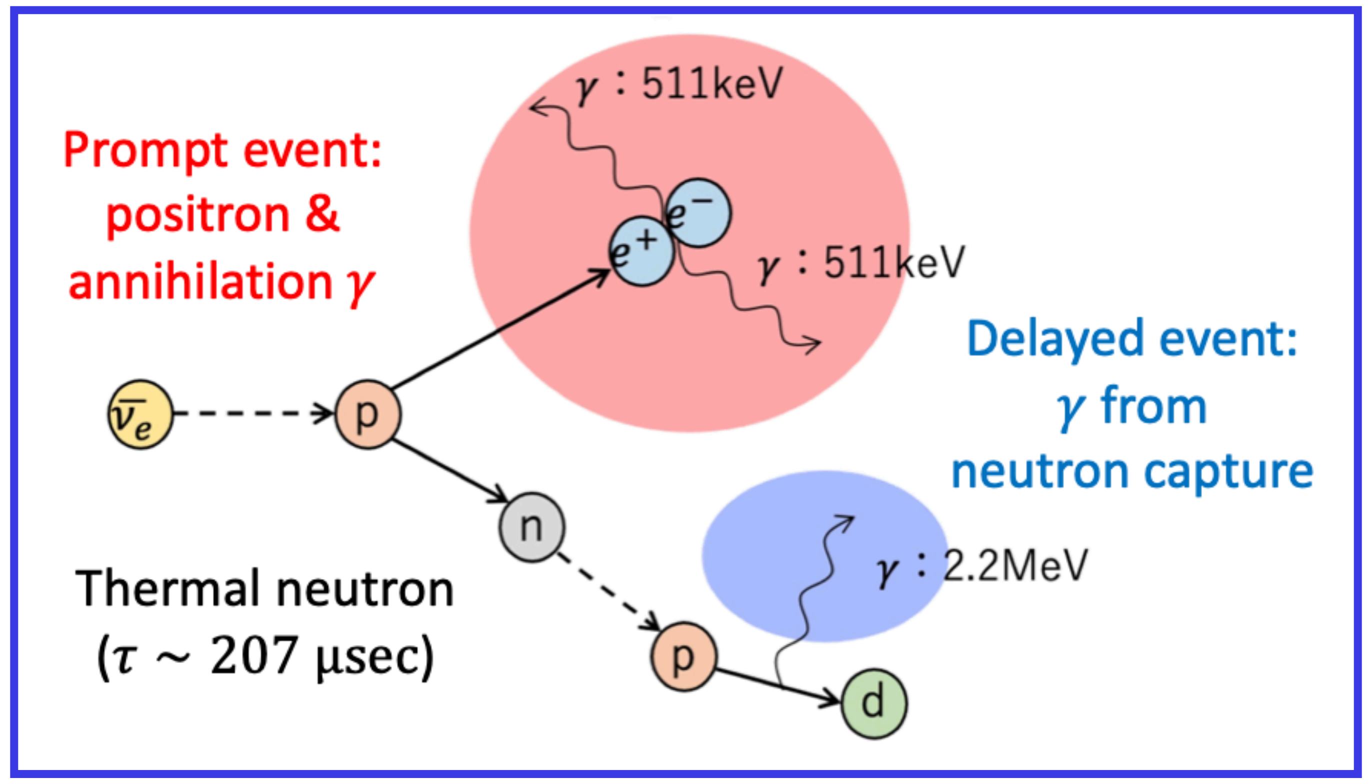
Kamioka Liquid scintillator Anti Neutrino Detector



- Inner detector (ID)
  - 1 kt Liquid scintillator (LS)
  - 1325 (17-inch) + 554 (20-inch) PMTs
  - Photo coverage 34%
  - Energy resolution 6.7 %/√E [MeV]
  - Physics observation
- Outer detector (OD)
  - 3200 t Pure water
  - 140 20-inch PMTs
  - Veto to muon

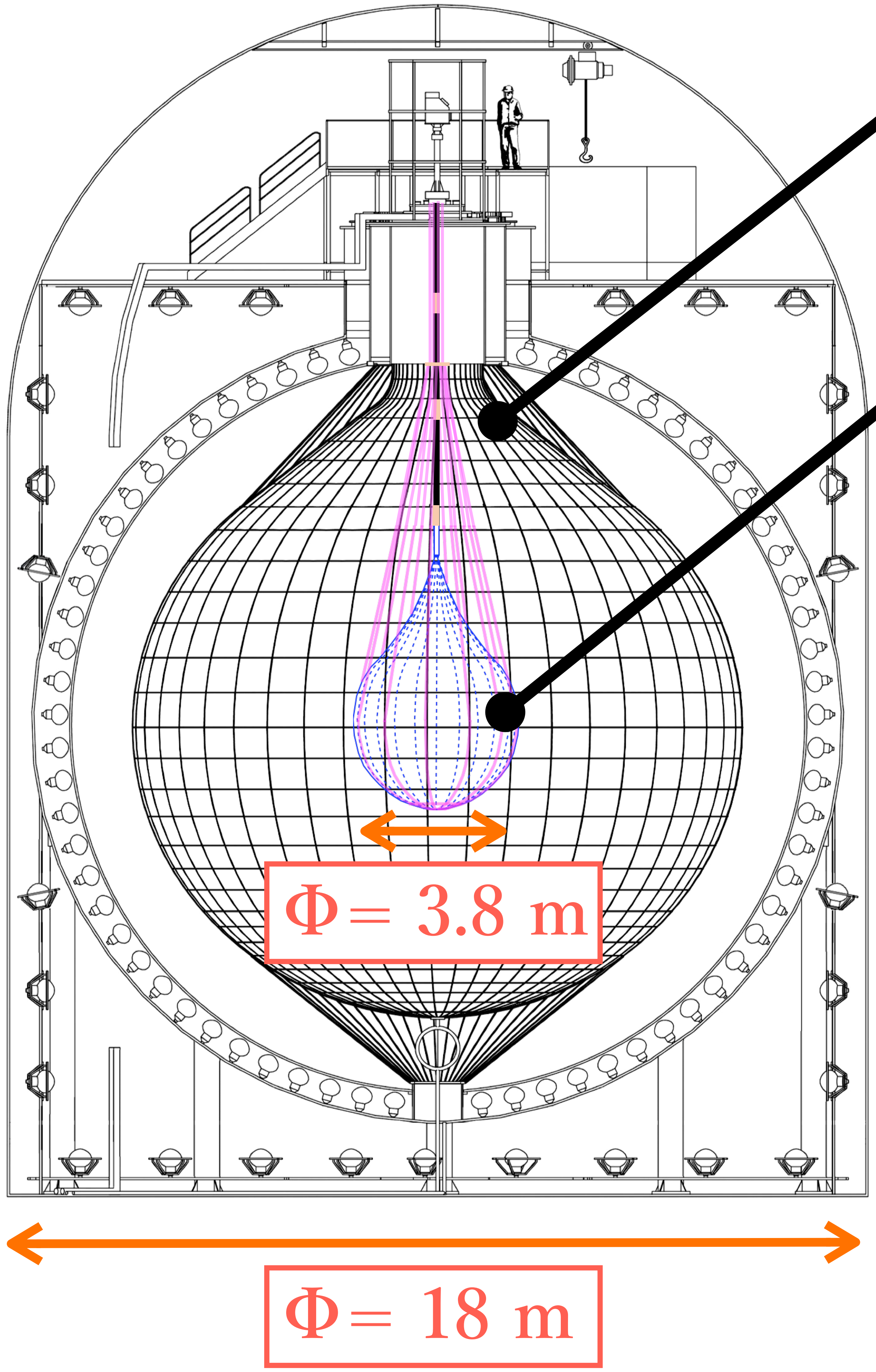


Main detection channel



Introduction: KamLAND-Zen experiment

Zero-neutrino double-beta decay search

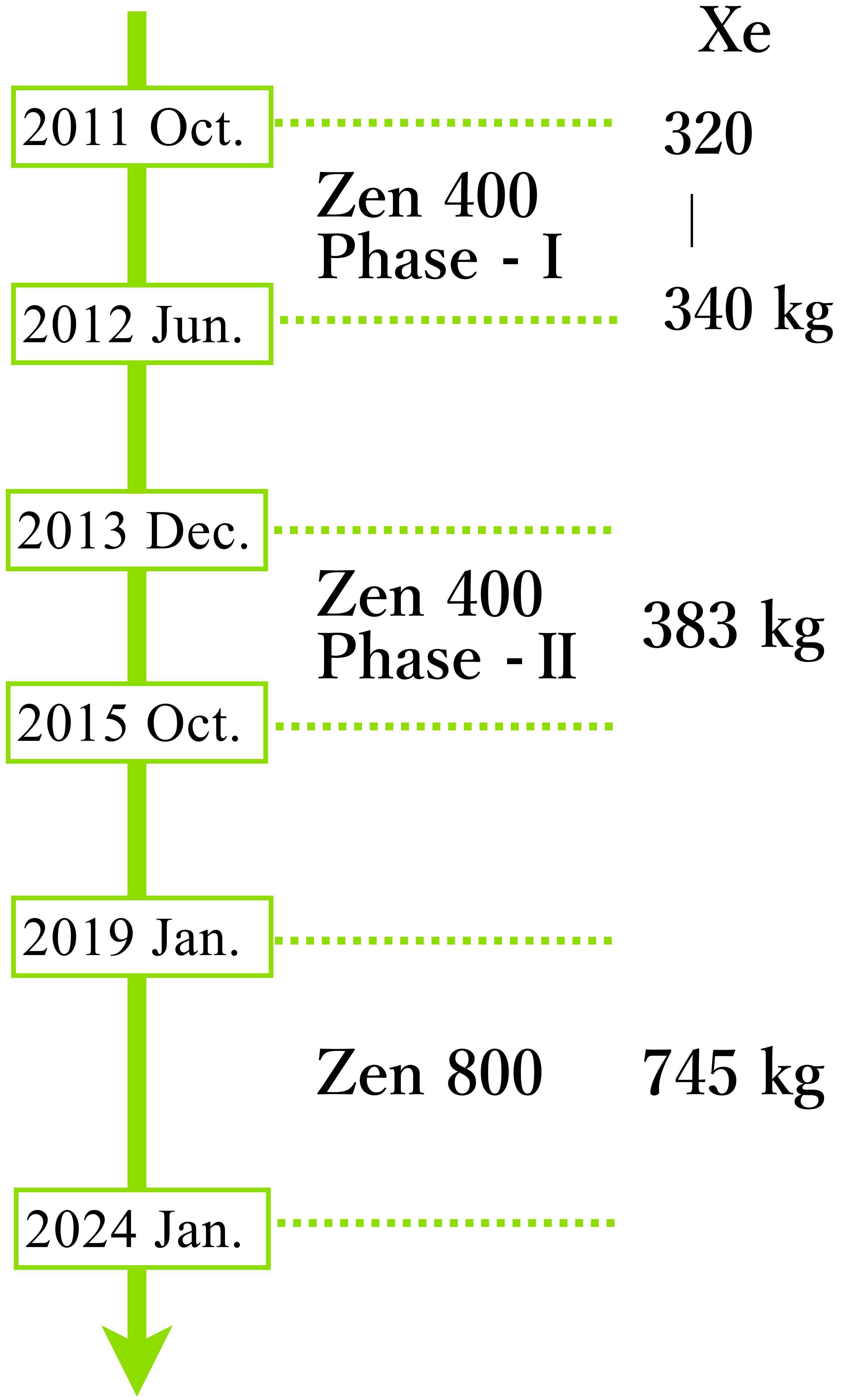


- Outer balloon
  - ~ 1k ton pure liquid scintillator
  - PC + Dodecane + PPO mixture
- Inner balloon
  - ~750 kg Xe-loaded liquid scintillator
  - ^{136}Xe is enriched to ~90%
- Feature
  - Ultra-low radioactive environment
  - ^{136}Xe liquid scintillator
    - Long $2\nu\beta\beta$ half-life
    - $0\nu\beta\beta$ Q-value: 2.46 MeV
    - Dissolved into liquid scintillator at 3%

Latest result (https://arxiv.org/pdf/2406.11438):

$T^{0\nu\beta\beta}_{1/2} > 3.8 \times 10^{26}$ yr (90% C.L.)

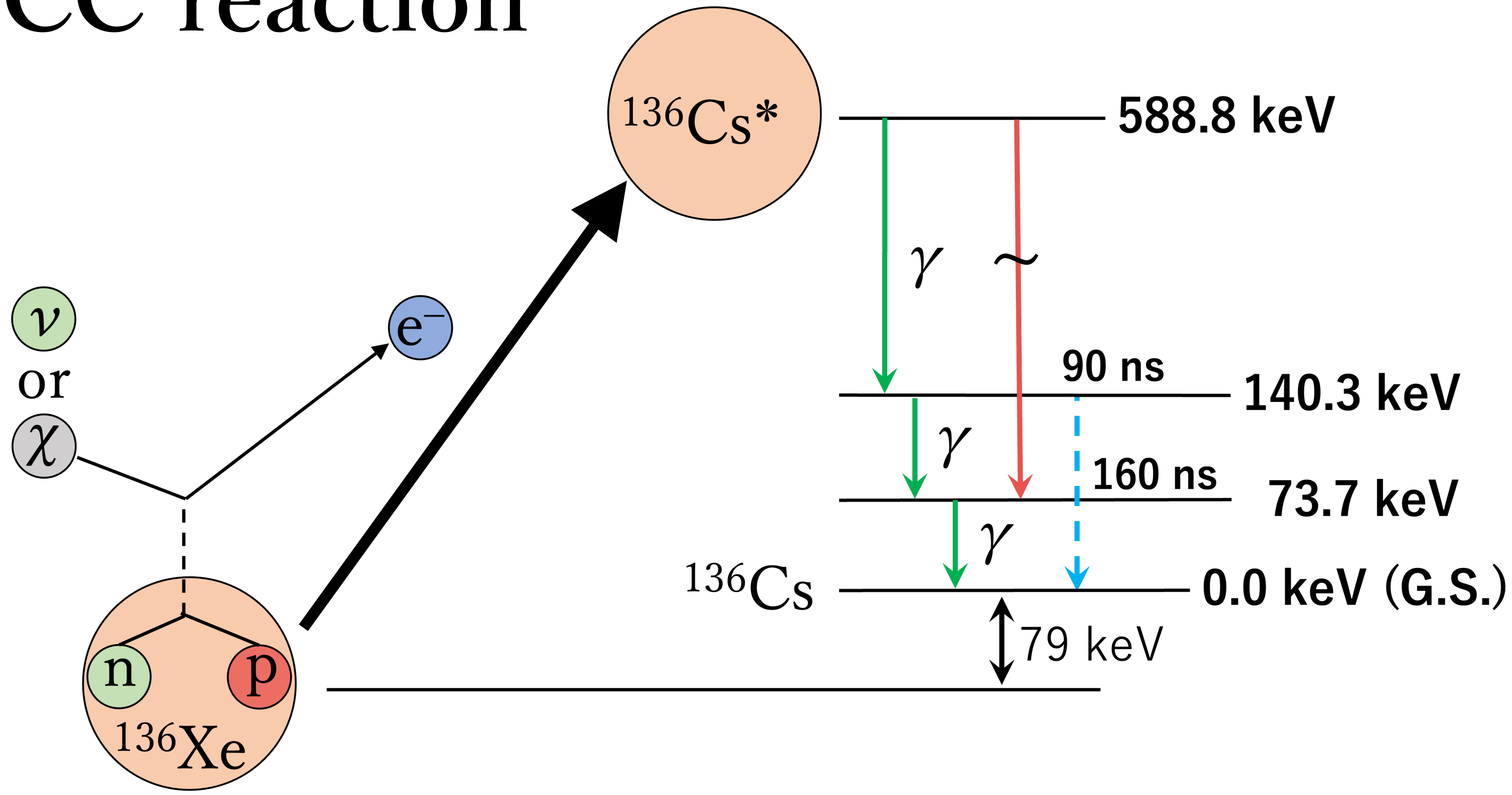
Exposure: 2.097 ton yr



Introduction: $\chi / \nu + {}^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Cs}^{*} + e^{-}$

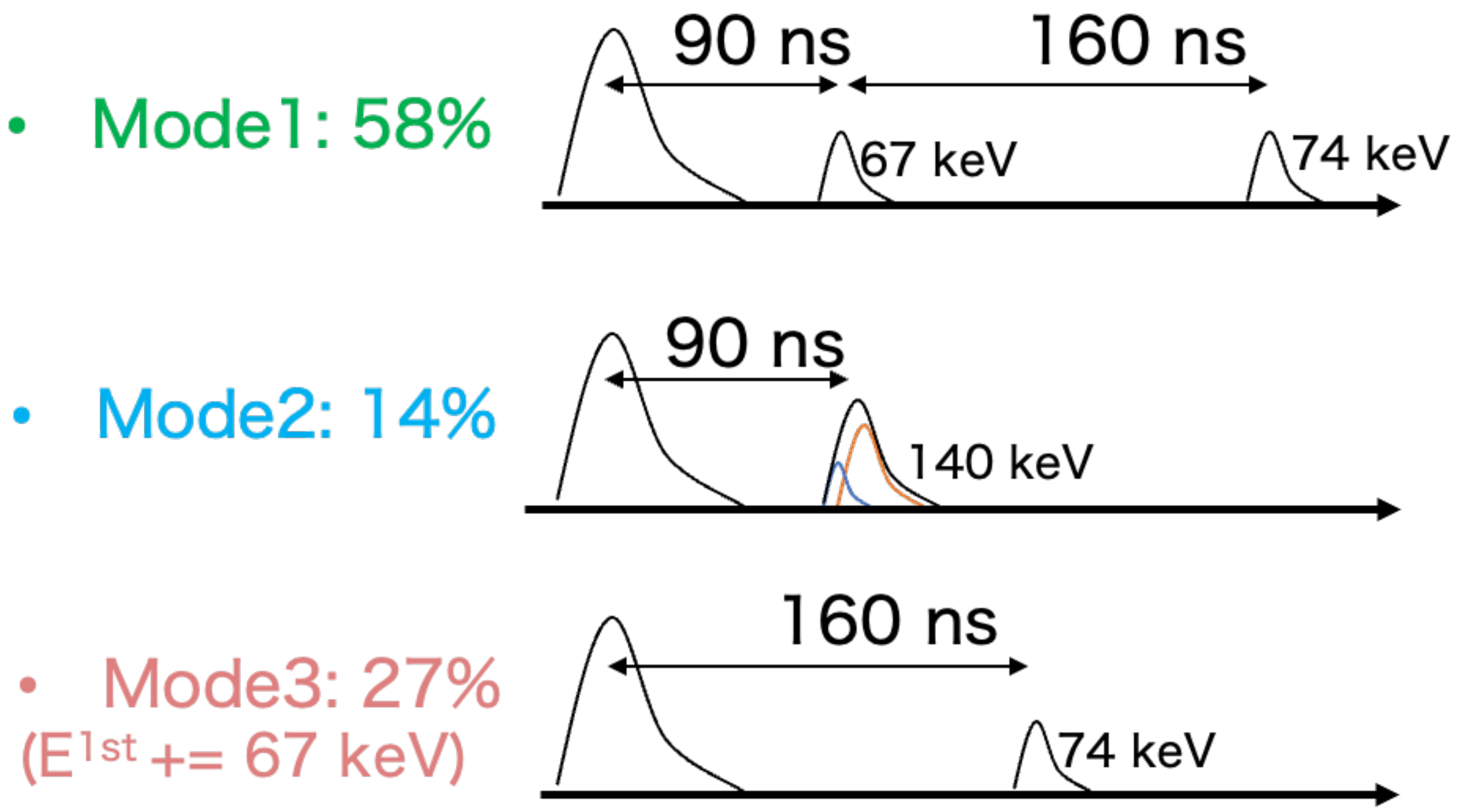
XeCC reaction

c.f. PhysRevLett.131.052502



- Feature
  - Transition to g.s. (5^+) is highly suppressed
  - Mostly goes to the excited states (1^+ state: 590 keV and 840 keV)
  - Energy threshold: 79 + 590 = 670 keV
- BG reduction by delayed coincidence
  - Low-lying isomeric state with O(100) ns lifetime observed recently
  - Double or triple coincidence

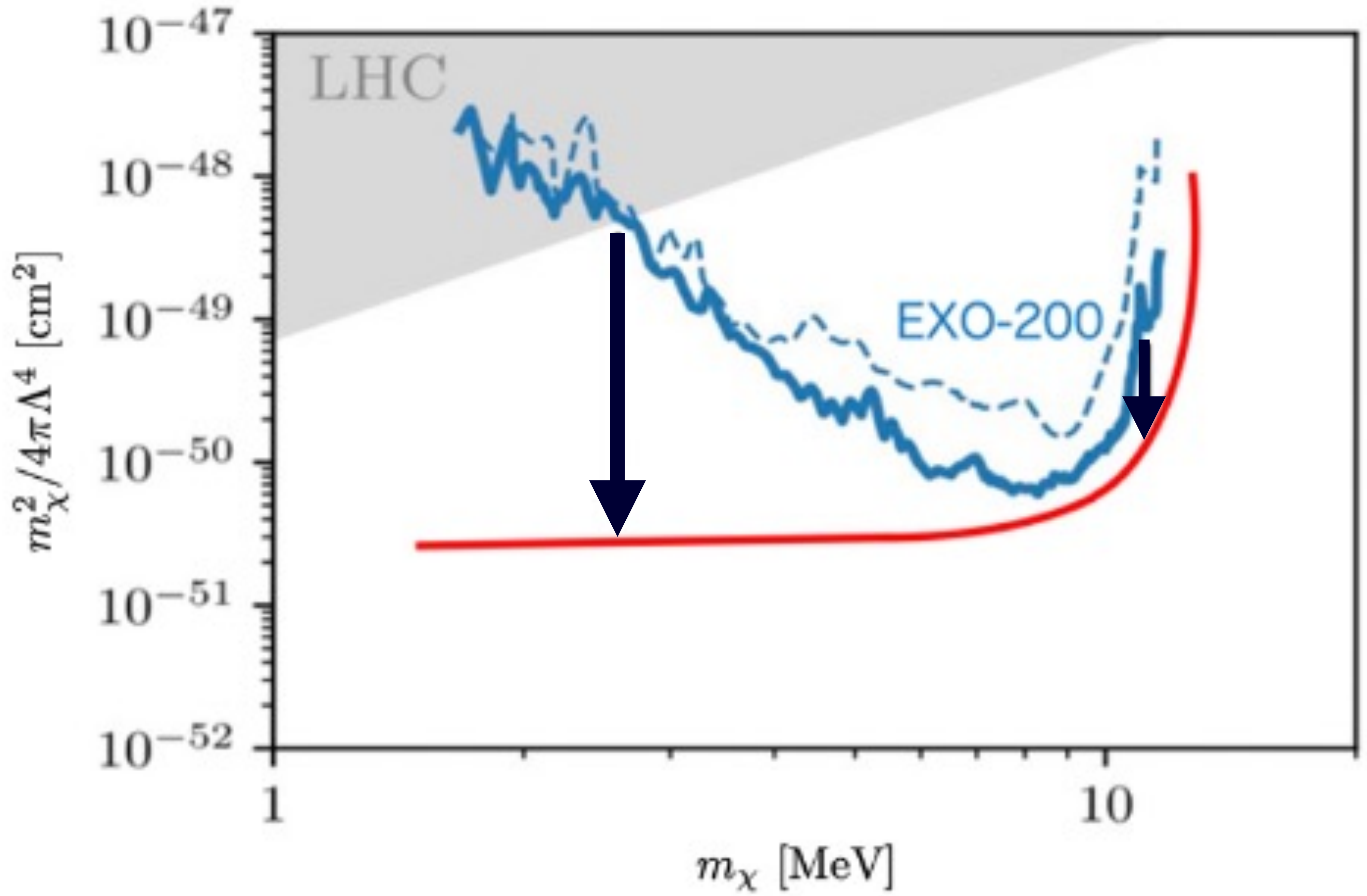
- Main observable modes



- 590 → 140 → 74 → g.s (Mode1: 58%, 90 +157 ns)
- 590 → 140 → 105 → g.s (Mode2: 14%, 90 ns)
- 590 → 422 → 314 → 74 → g.s (Mode3: 27%, 157 ns)

Introduction: $\chi / \nu + {}^{136}Xe \rightarrow {}^{136}Cs^* + e^-$

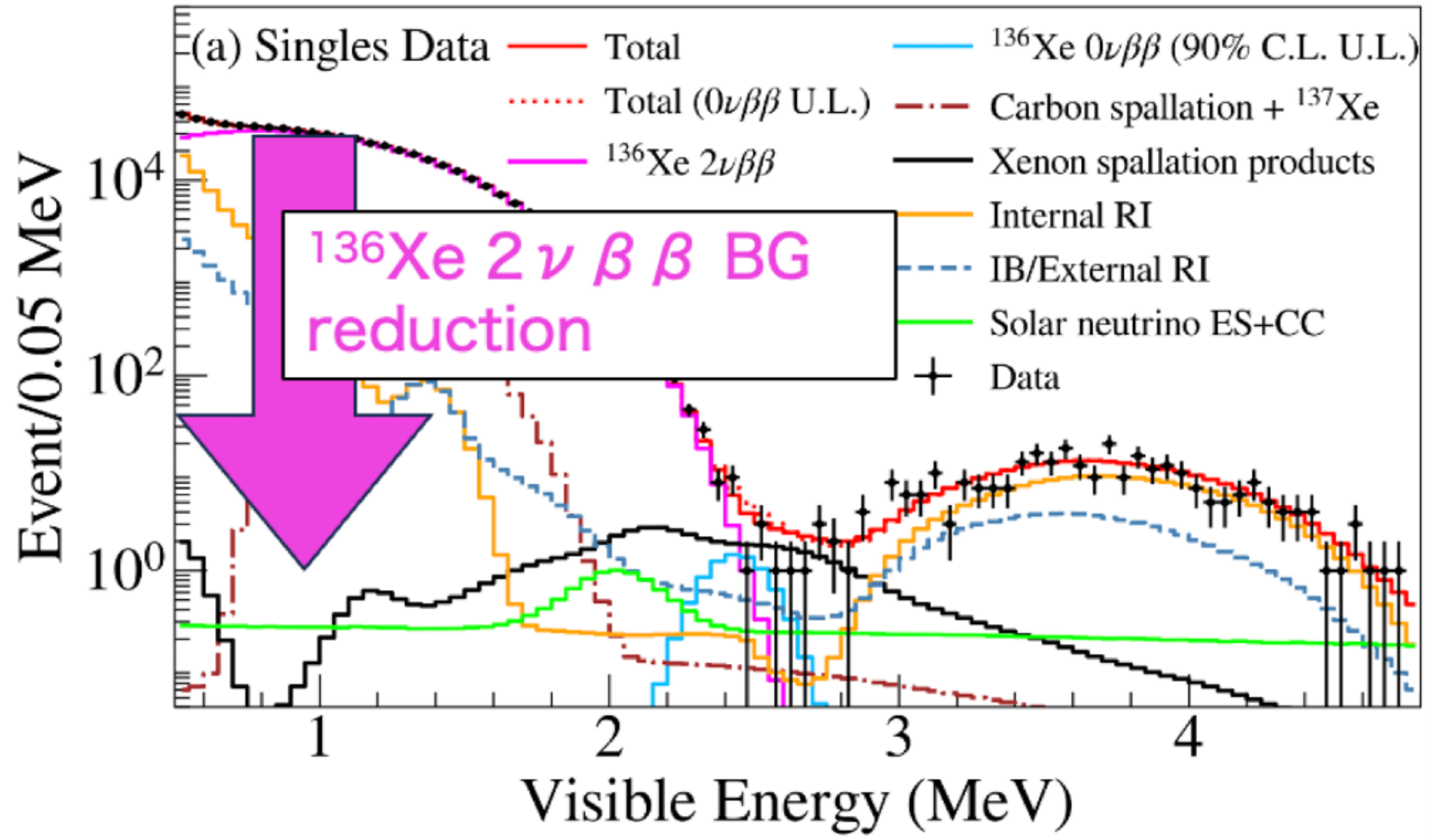
Absorption of Fermionic dark matter (FDM)



- EXO-200
  - $0\nu\beta\beta$ search experiment using ^{136}Xe TPC
  - m_χ range: 1.6 - 11.6 MeV
  - Minimum cross-section: 6×10^{-51} cm^2 at 8.3 MeV (90% C.L.)
  - Measuring recoil electron

Sensitivity is limited at low mass (visible) region due to ^{136}Xe $2\nu\beta\beta$ BGs

- KamLAND-Zen 800
  - Drastic improvement of sensitivity by using XeCC tagging method
  - Large exposure than EXO-200 (× ~ 6)



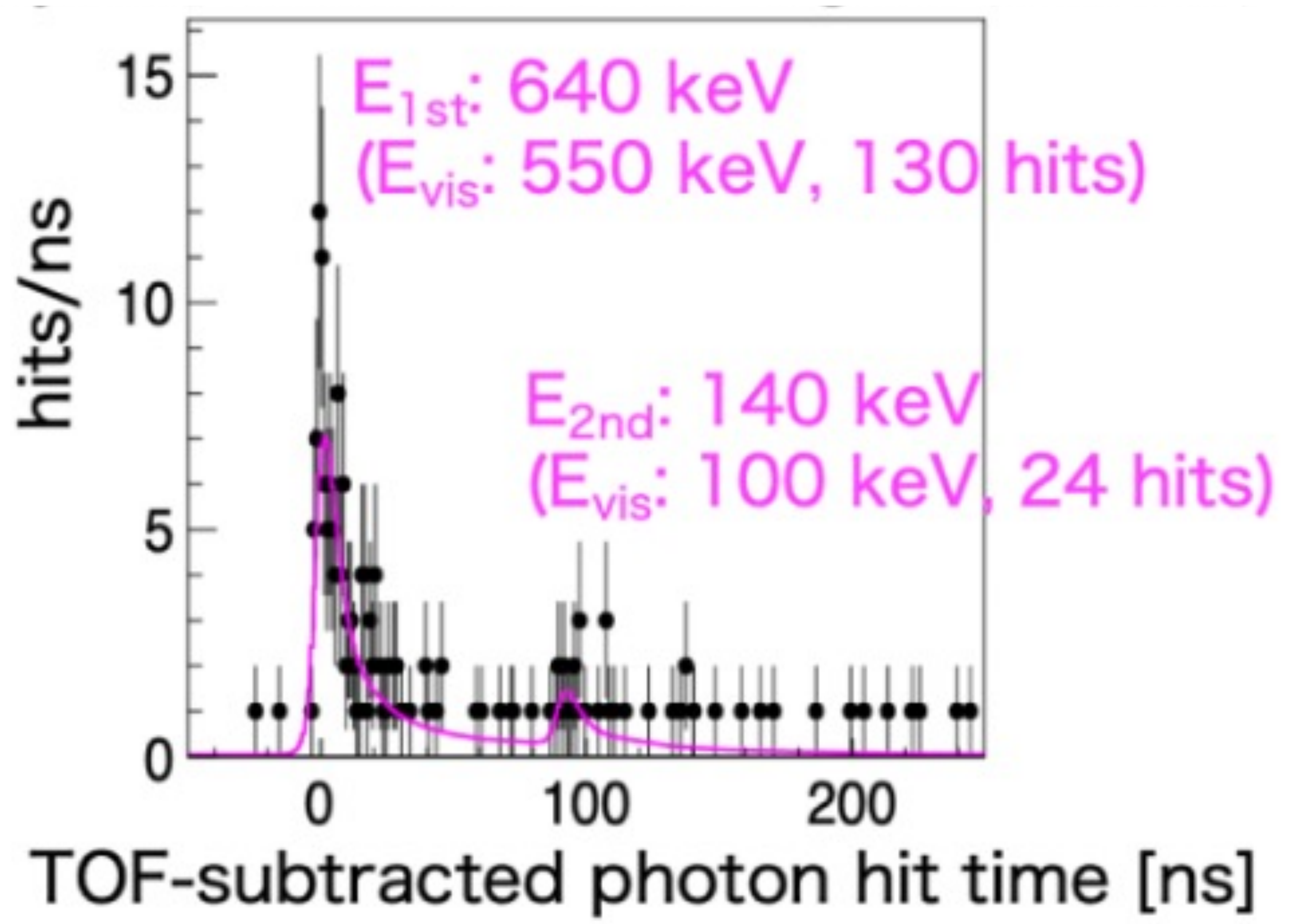
XeCC at KamLAND-Zen 800

- DAQ
  - Zen 800 period (Feb 5, 2019 - Jan 12, 2024)
  - Trigger threshold: ~ 0.3 MeV
  - Only 1st pulse can be triggered

↓

2nd & 3rd pulse can be detected if in the event window of the 1st pulse (~200 ns)

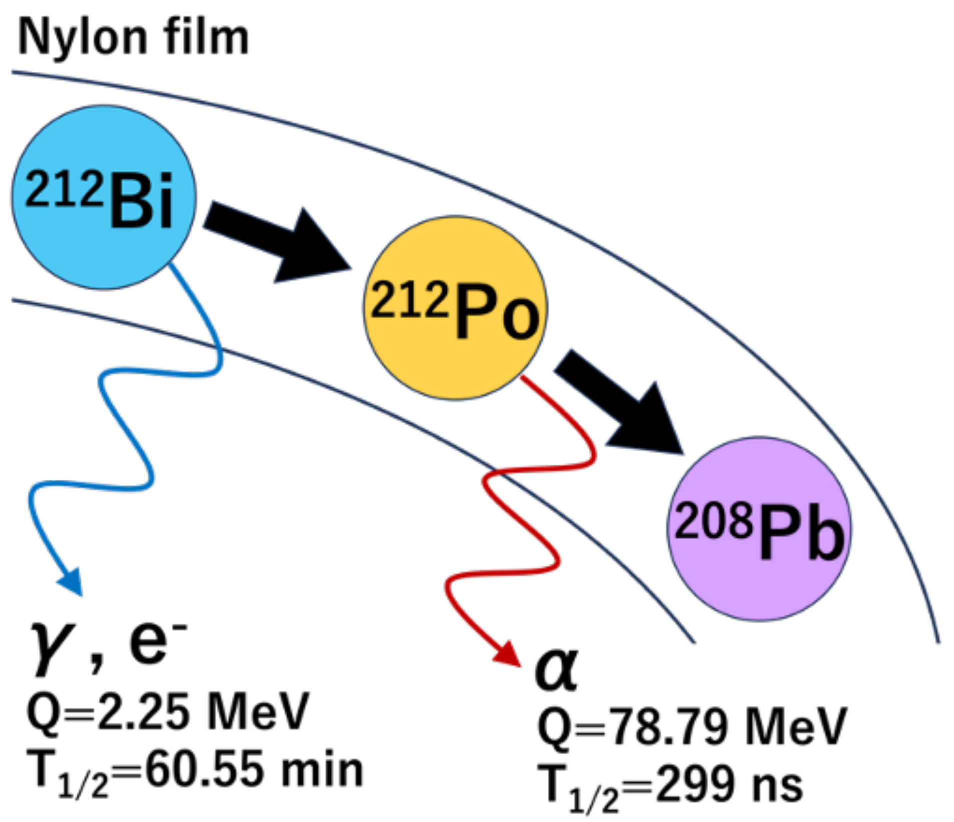
ToyMC signal (Mode 2)

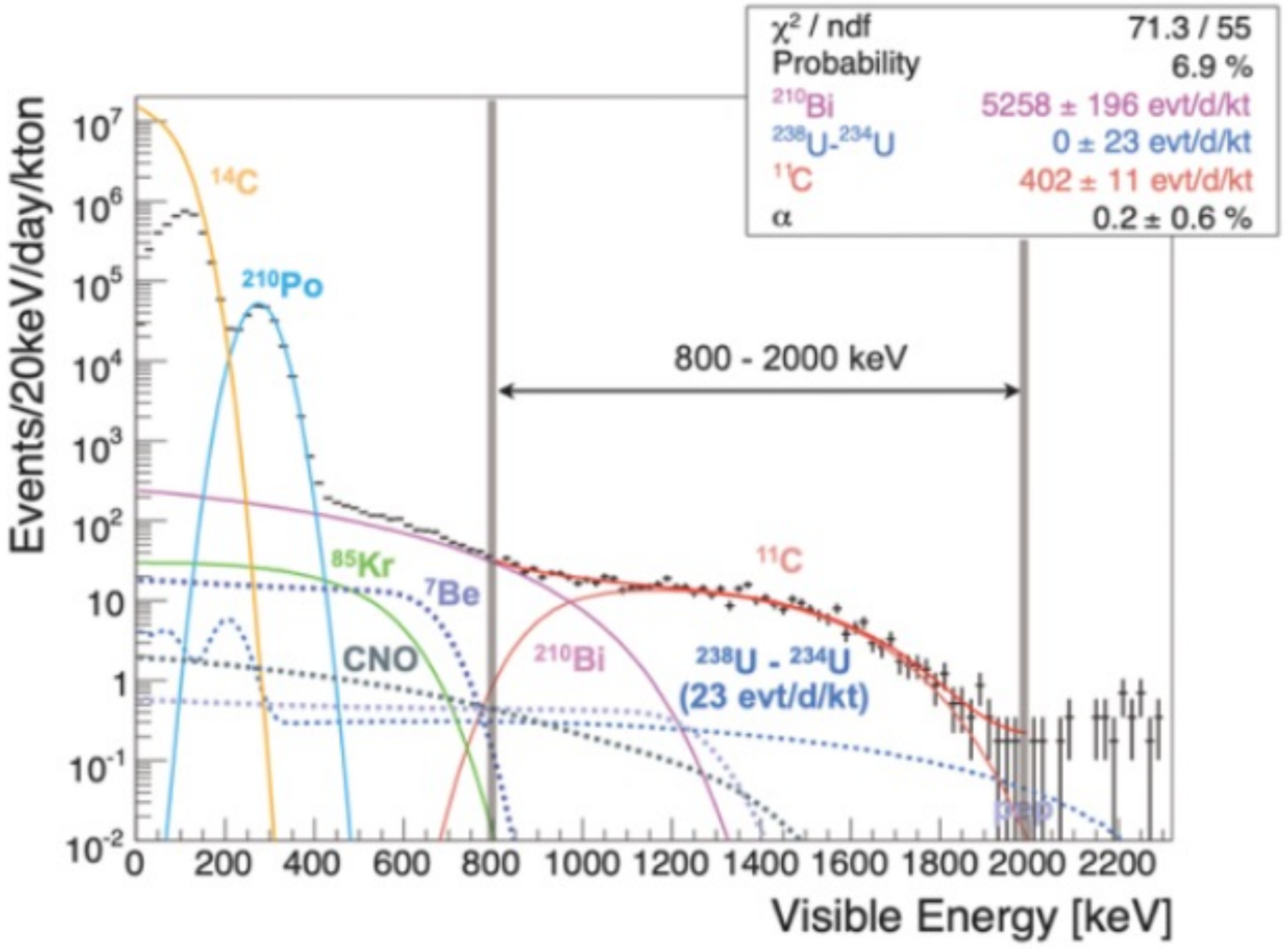


- Single vs Multi pulse discrimination
  - Double or triple pulse fitting

Potential backgrounds

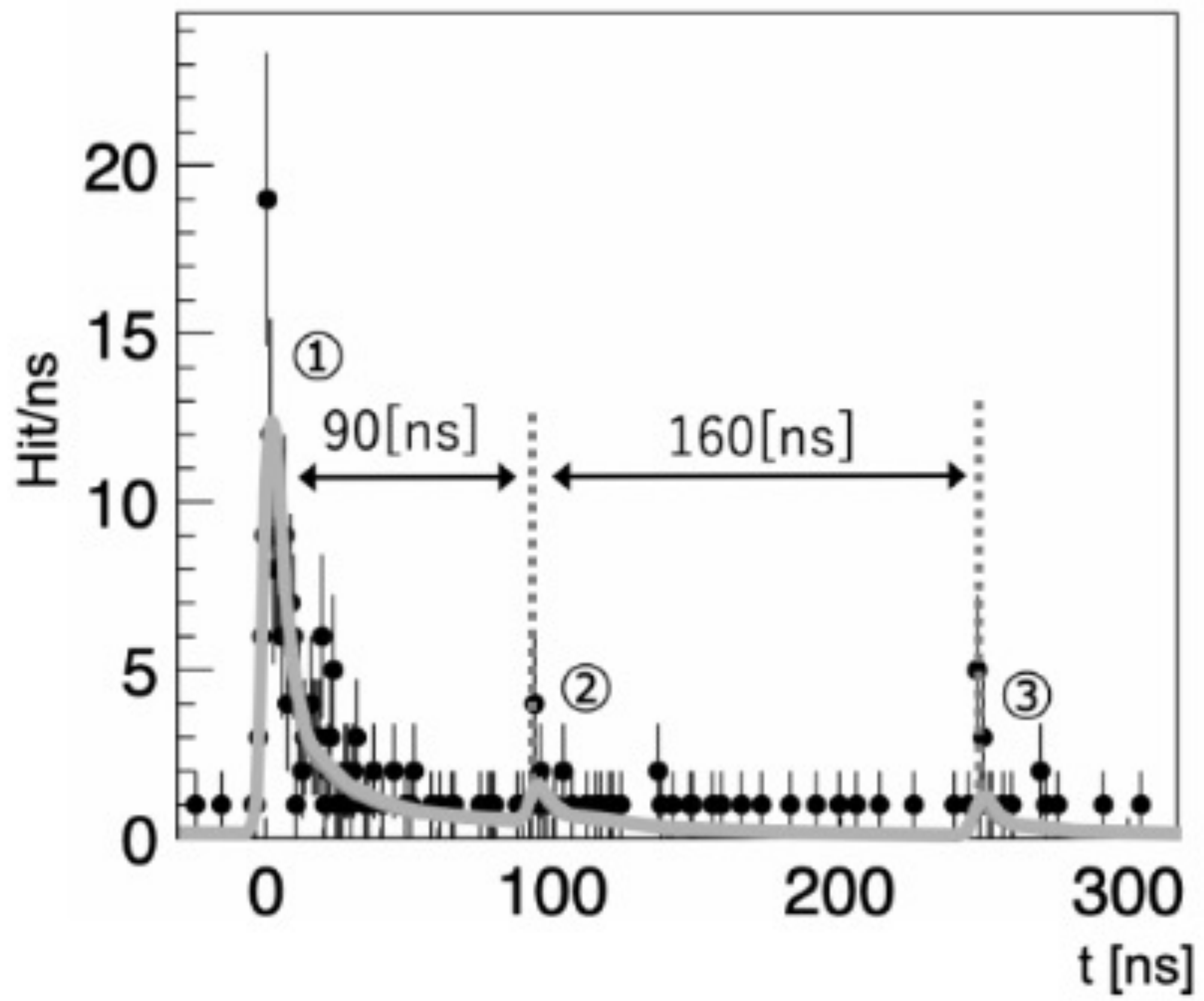
- Miss identified 2νββ
- Correlated BGs: ^{214}BiPo in nylon film
  - Fiducial volume cut for double-pulse search
- Accidental BG: ^{14}C + 2νββ
  - ^{14}C probability
    : few kHz (rate) × 200 ns (time window)
  - Vertex recon. of 2nd (or 3rd) pulses required

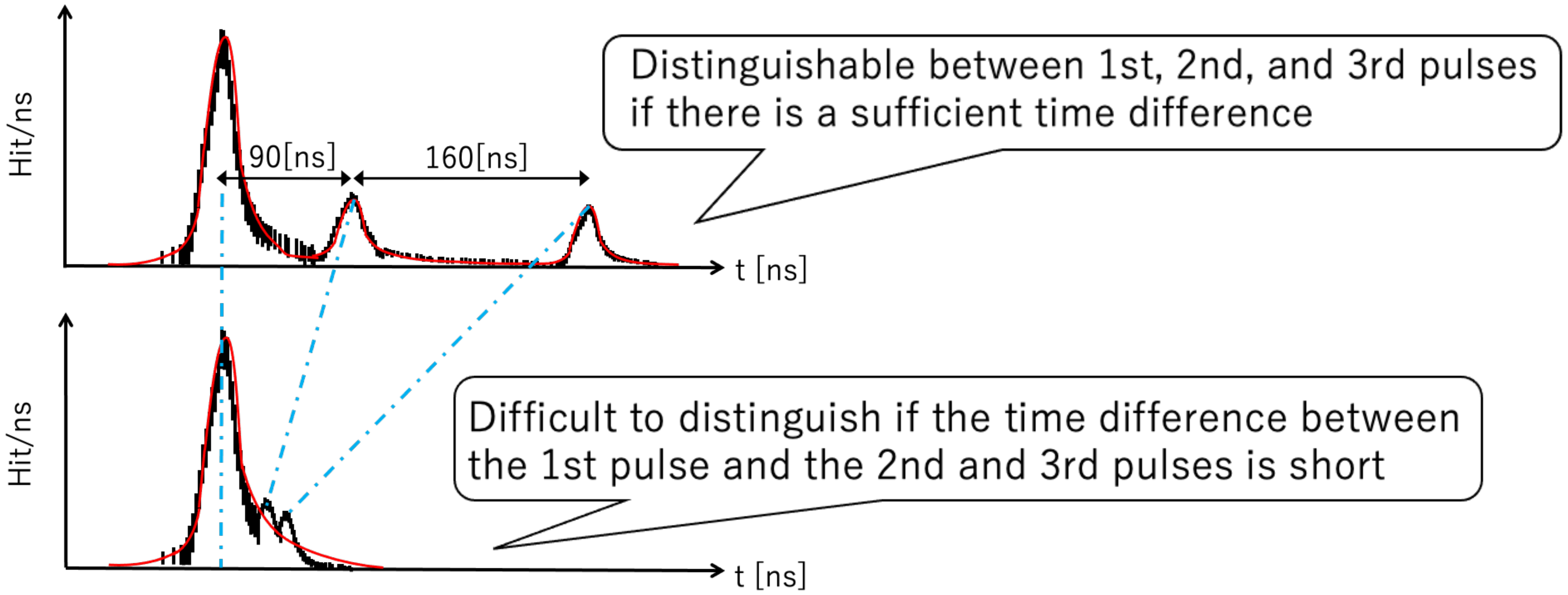




Analysis method: Triple pulse fitter

- BG source
  - Miss-identification of single pulse (2νββ) → Fitter
  - Accidental: 2νββ ＋ ^{14}C → Vertex reconstruction
  - Correlated: ^{212}BiPo → Fiducial volume cut
- Fitter development
  - Do not miss ID single-pulse and multi-pulse
  - Discriminate true multi-pulse and fake multi-pulse from accidental
  - Possibility of miss ID because of close pulse to pulse distance





- Event window: 200 ns
- Consider fluctuation (E_1, E_2, E_3, t_2, t_3)

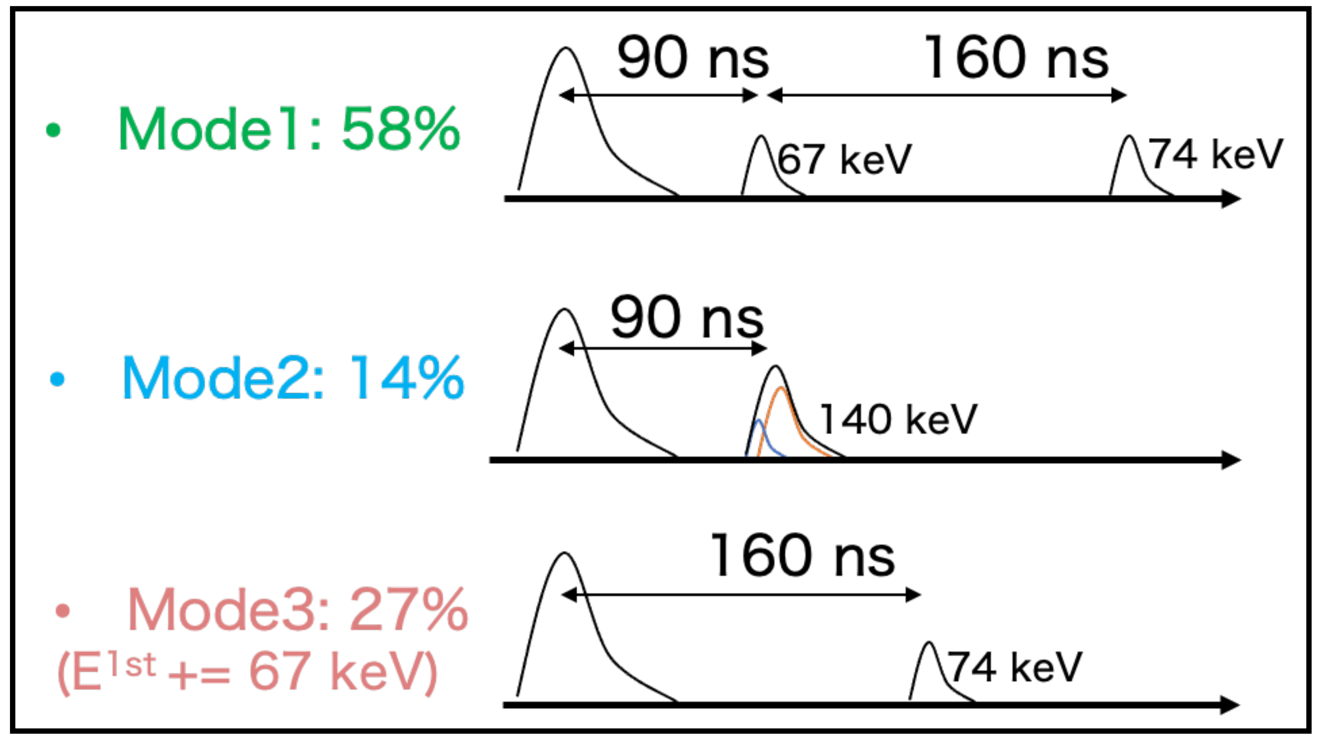
Distinguish waveforms from $\chi 2$ obtained by fitting

Efficiency estimation

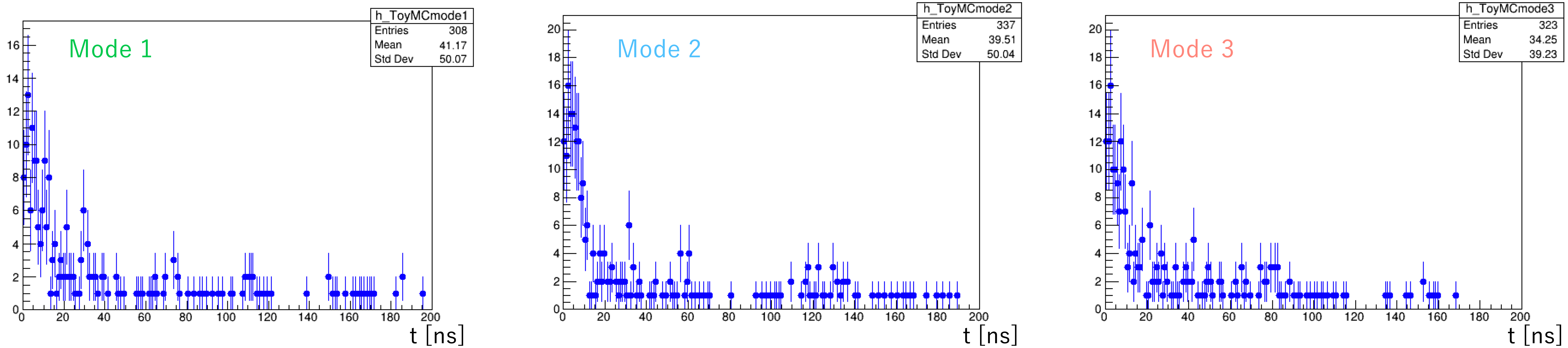
Evaluation of energy dependence of eff. by ToyMC

- Signal
  - Recoil e^- + multiple de-excited γ-ray → True multi-pulse
- Background
  - Miss-identification of single pulse by 2νββ
  - 2νββ + ^{14}C β-decay

→ Fake multi-pulse



- ToyMC conditions
  - 3 decay modes are generated based on the branching ratio
  - The number of hits has statistical fluctuation
  - Hit time depends on the lifetime of each mode (pulse-to-pulse distance is random)
  - FDM mass m_χ = 1.181(minimum) − 2.3 [MeV] (2νββ dominant region)



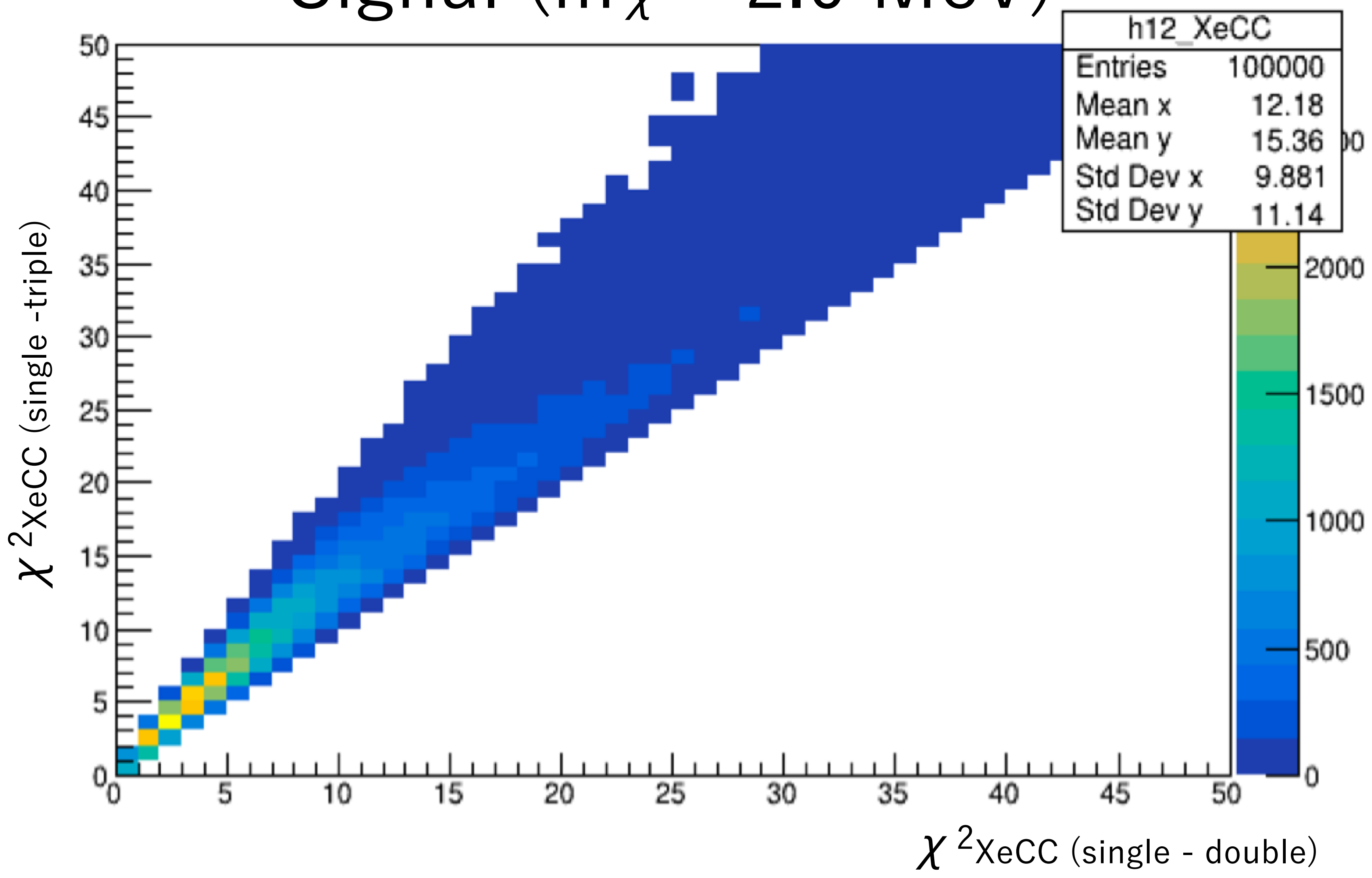
Efficiency estimation

Event selection criteria

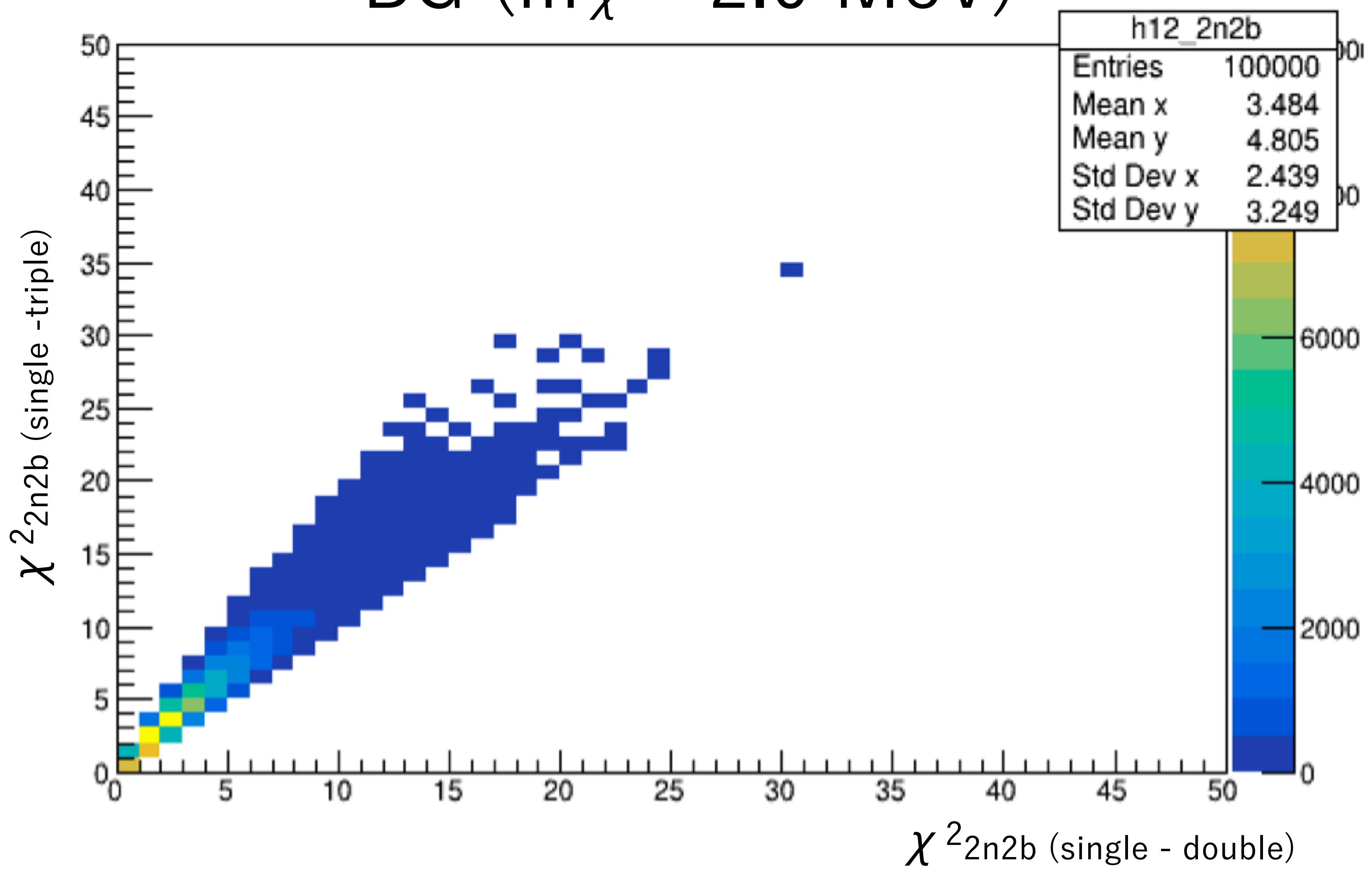
- Signal efficiency
  - Generate triple pulse (mode1) → 1pulse, 3pulse fit → get χ^2 $_{\mathrm{XeCC\ (single\ -\ triple)}}$
  - Generate double pulse (mode2 & mode3) → 1pulse, 3pulse fit → get $\chi^2_{\mathrm{XeCC\ (single\ -\ triple)}}$
- BG efficiency
  - Generate single pulse → 1pulse, 3pulse fit → get χ^2 $_{\mathrm{2n2b\ (single\ -\ triple)}}$

→ The cut threshold is optimized to maximize FoM from the obtained χ^2

Signal (m_χ = 2.0 MeV)



BG (m_χ = 2.0 MeV)

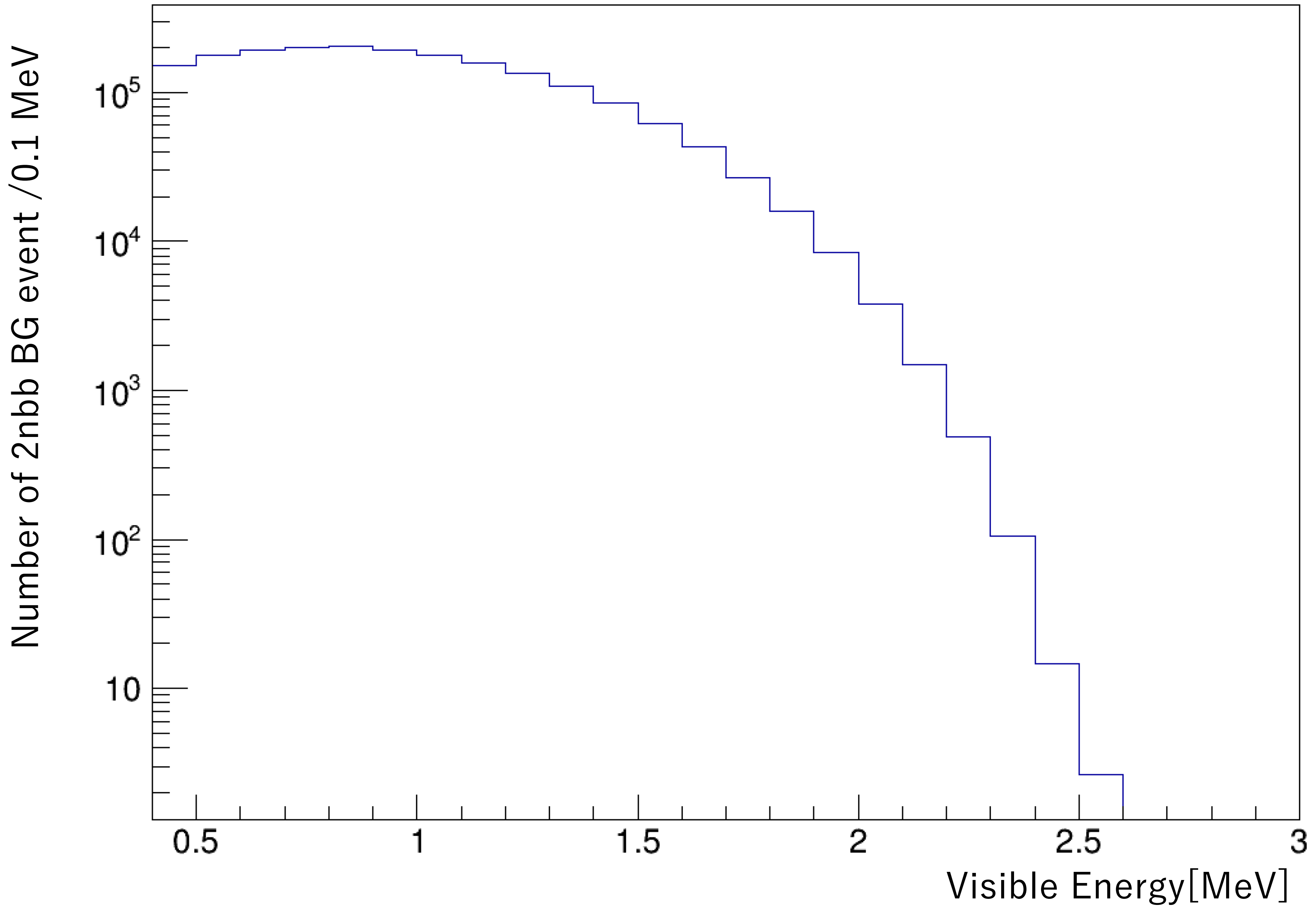


→ $\chi^2_{\mathrm{single\ -\ triple}}$ makes it easier to determine whether single or multi pulse

Efficiency estimation (2 $\nu\ \beta\ \beta$ +Accidental)

Number of BGs

- 2νββ single event generated by Monte Carlo simulation



- Total number of MC events: 3M
- $T^{2\nu}_{1/2} = 2.26 \times 10^{21}$ yr
- $N_{136Xe} = 1.261 \times 10^{29}$ /kt XeLS
- Zen-800 period = 997.1 days
- Energy resolution
  $$\frac{7.69\,\%}{\sqrt{E\ [\mathrm{MeV}]}} \rightarrow \sim 0.1[\mathrm{MeV/bin}]$$
- R < 1.6 m

- ^{14}C accidental pile-up event generated by Monte Carlo simulation
  - Decay rate = 3582 Hz

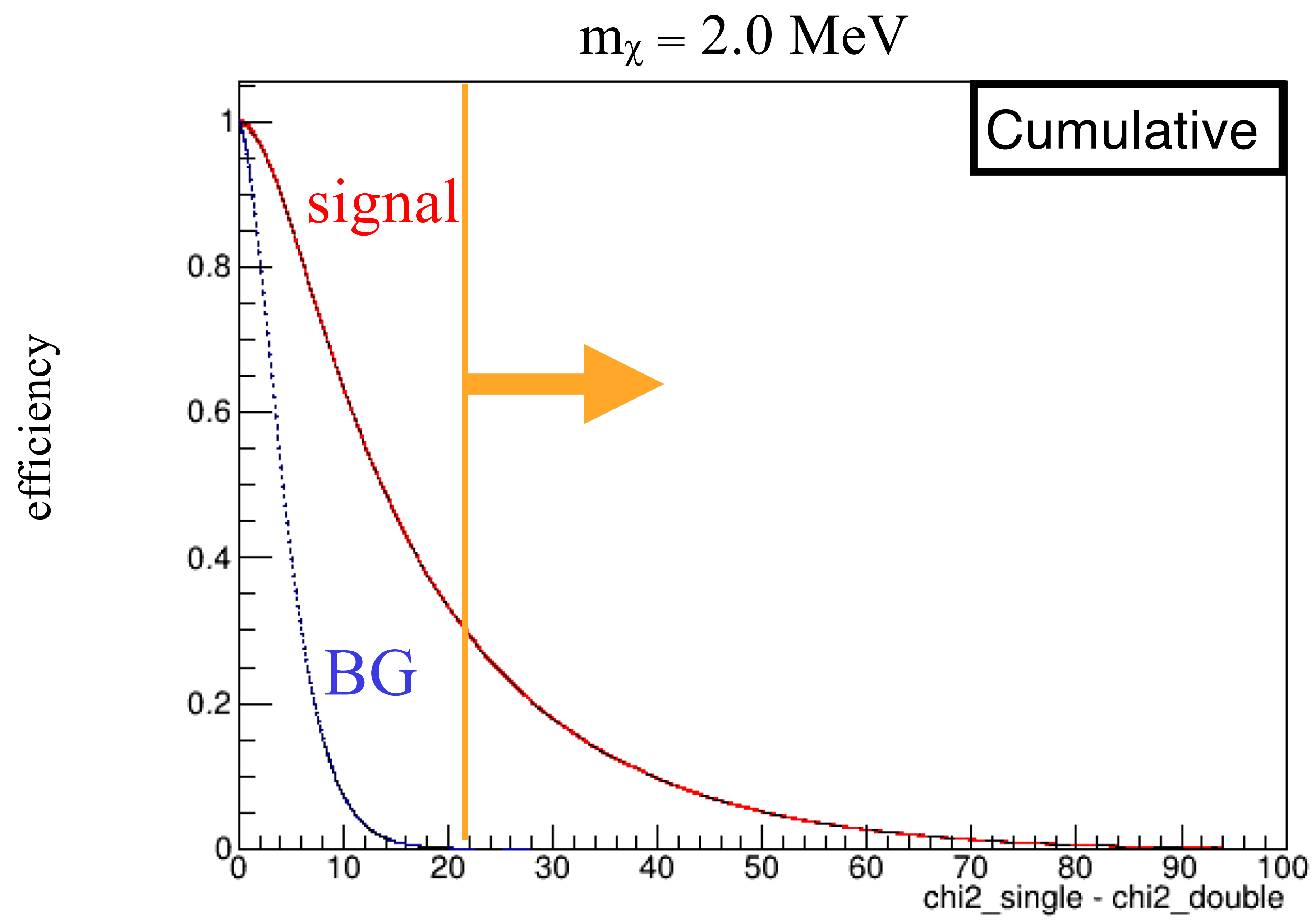
Efficiency estimation

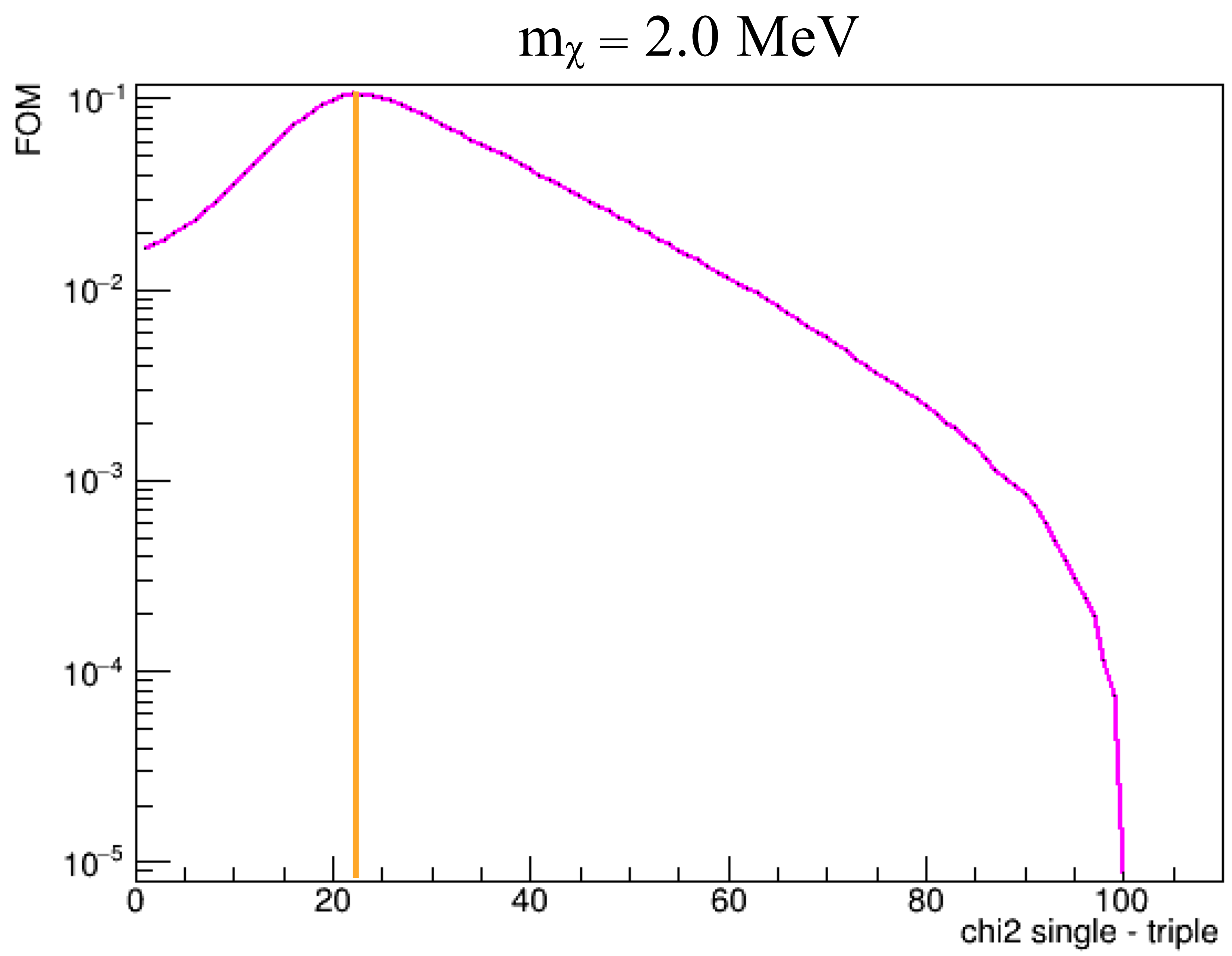
Figure of merit

$$FoM = \frac{\epsilon_{signal}}{a/2 + \sqrt{N_{BG} \cdot \epsilon_{BG} + N_{accidental}}}$$

0 signal expected FoM formula

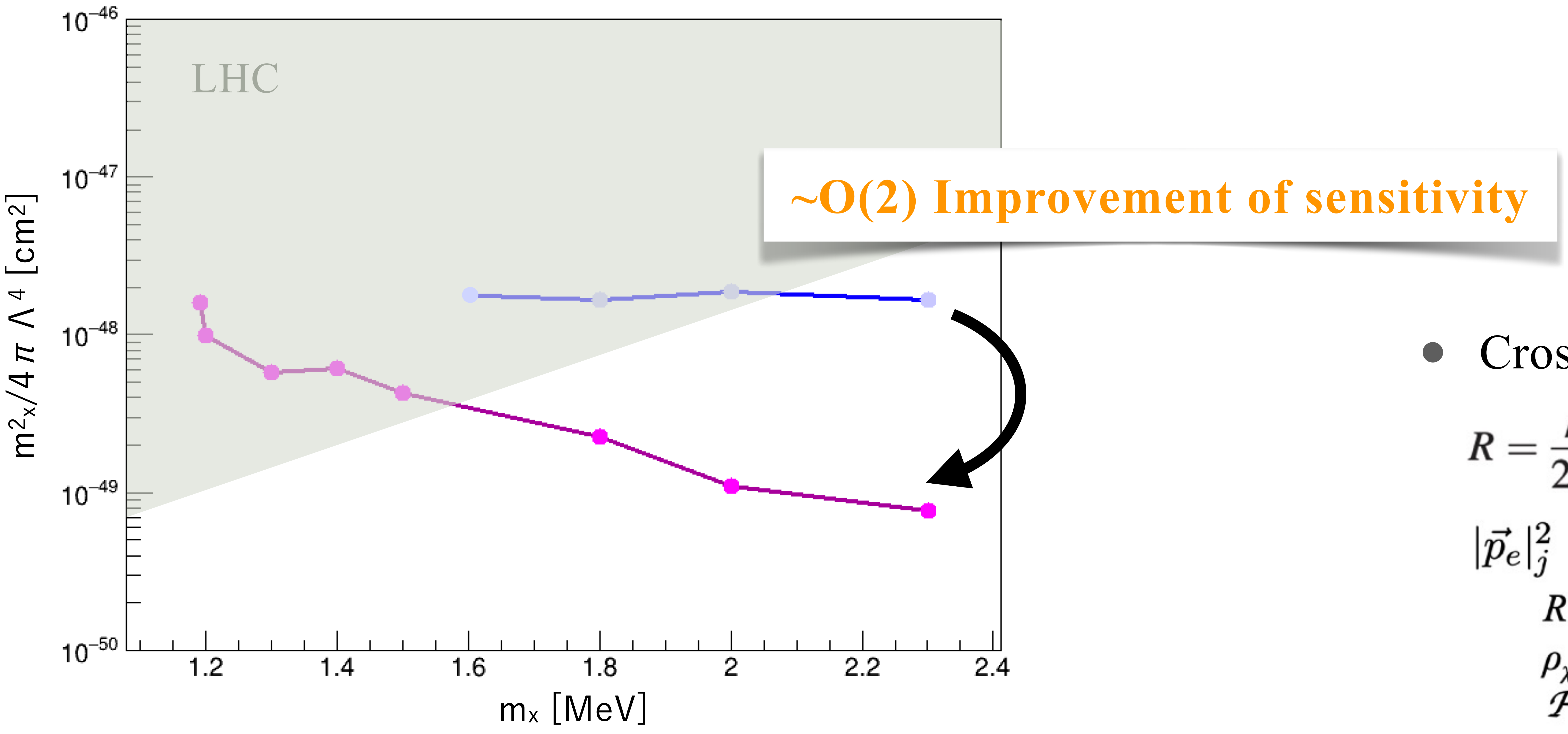
- a: significance (90 % C.L. → 1.28)
- N_{BG}: Number of 2νββ
- N_{BG}: Number of accidental pileup (2νββ + ^{14}C)





m_χ [MeV]	1.18	1.2	1.3	1.4	1.5	1.8	2.0	2.3
$\chi^2_{\text{threshold}}$	24.9	23.9	22.9	23.9	21.9	21.9	21.9	18.9
Signal eff. [%]	54.2	57.1	57.4	51.7	55.5	49.1	46.4	51.0

Discovery potential



KLZ-800 with XeCC tag; Discovery potential

EXO-200; Upper limit (90 % C.L.)

(https://journals.aps.org/prd/abstract/10.1103/PhysRevD.107.012007)

LHC; Upper limit (90 % C.L.)

- Cross section

$$R = \frac{\rho_\chi}{2m_\chi}\sum_j N_{T,j}(A_j - Z_j)\frac{|\vec{p}_e|_j^3 \mathcal{F}(Z_j+1, E_e)}{2\pi\Lambda^4(m_\chi - m^\beta_{\mathrm{th},j})}$$

$$|\vec{p}_e|_j^2 = (m^\beta_{\mathrm{th},j} - m_\chi)(m^\beta_{\mathrm{th},j} - m_\chi - 2m_e)$$

R: rate [s^{-1}]

ρ_χ: local DM mass [MeV/cm^3]

$\mathcal{F}$: Fermi function

Λ: effective energy scale

$m^\beta{}_{th}$: 79 keV + 590 keV + m_e

$T_e = m_\chi - m^\beta{}_{th}$

$$\frac{m_\chi^2}{4\pi\Lambda^4} = \frac{N_{signal}\cdot(m_\chi - m_{th})\cdot m_\chi^3}{T\cdot\epsilon\cdot\rho_\chi\cdot N_T\cdot(A-Z)\cdot p_e^3\cdot\mathcal{F}}$$

Summary

- Feasibility of XeCC detection by multi-pulse tagging in KamLAND-Zen was studied
- Tagging efficiency is better at Lighter m_χ
- Introducing the XeCC tag yields Upper Limits as strict as O(2)
- We need to mitigate accidental BG from ^{14}C
    - Vertex recon. of delayed pulse etc
- 2.5 MeV < m_χ : Analysis by electron recoil

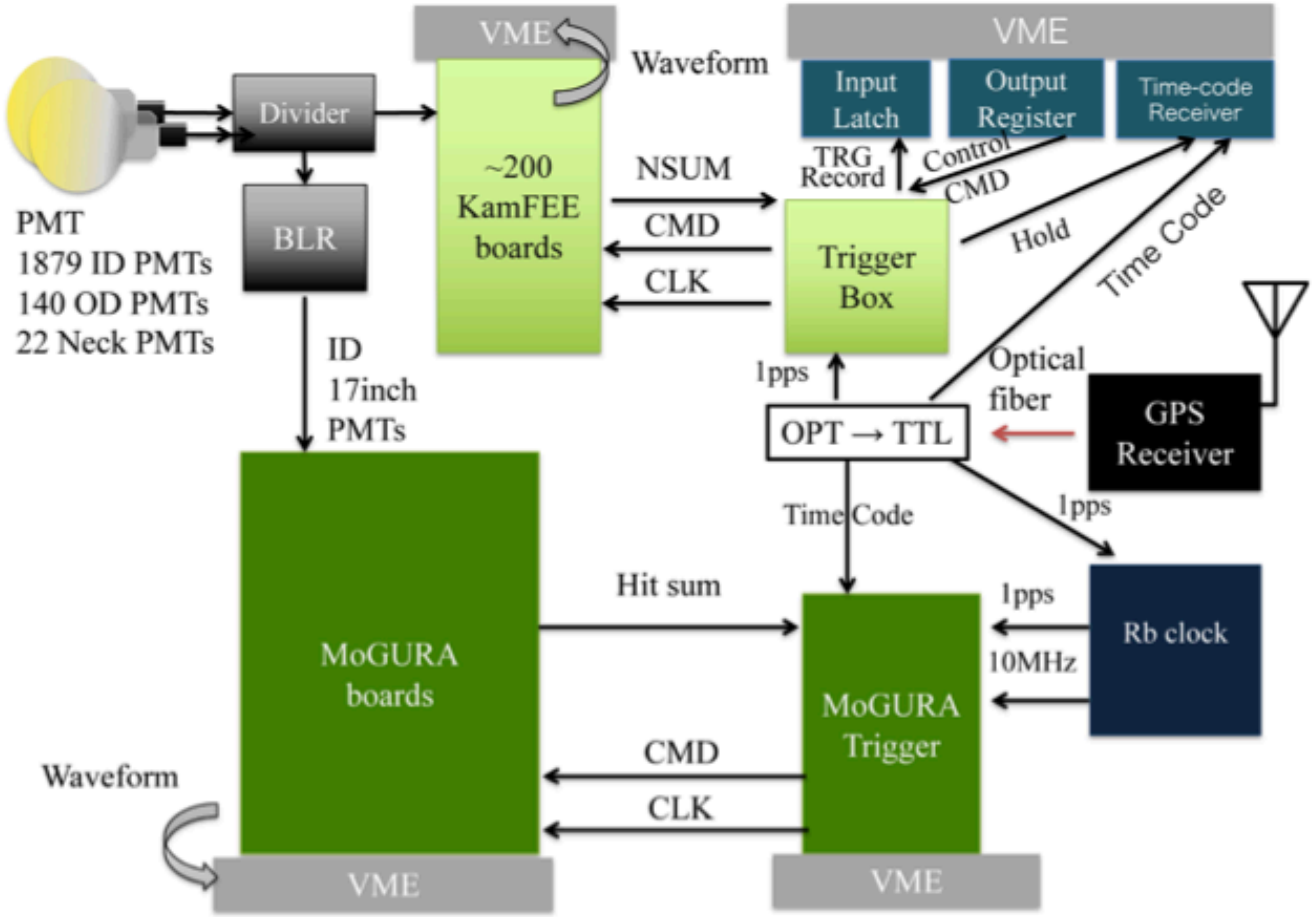
Back up

KamLAND DAQ systems

- KamFEE (KamLAND Front-End electronics)
  - Signal waveform digitized by ATWD (Analog Transient Waveform Digitizer)
    - Sample interval: ~1.5 ns
    - Number of samples per waveform: 128

→ Event window: ~200 ns

- MoGURA (Module for General-Use Rapid Application)
  - Eliminating dead time caused by high rate after pulse and overshoot after cosmic ray muons



KamFEE trigger systems

- **GPS Trigger**
  - **1PPS trigger:** A trigger without external trigger issue based on 1PPS of GPS.
  - **1PPS global acquisition trigger:** A forced DAQ trigger for all ID and OD based on 1PPS of GPS.
  - **GPS trigger:** A forced DAQ trigger issued every 32 seconds.

- **ID Nusm Trigger**
  - **ID singles trigger:** A DAQ trigger for the entire ID issued when the number of ID hits (N_{ID}) exceeds the threshold of the ID singles trigger threshold, which was set to 60 in the runs of KamLAND-Zen 800.
  - **ID prompt trigger:** A DAQ trigger for the entire ID issued when the number of ID hits (N_{ID}) exceeds the threshold of ID prompt trigger threshold, which is also 60 in KamLAND-Zen 800. Then, the DAQ accept ID delayed trigger for the variable delayed time window, which was set to $\sim$ 1.2 msec in KamLAND-Zen 800.
  - **ID delayed trigger:** A DAQ trigger for the entire ID issued when the number of ID hits (N_{ID}) exceeds the threshold of the ID delayed trigger threshold in the delayed time window.
  - **ID prescale trigger:** A DAQ trigger for the entire ID issued when the number of ID hits (N_{ID}) in the prescale time after 1PPS trigger (sim 10 msec) exceeds the threshold of the ID prescale trigger threshold.
  - **OD to ID trigger:** A DAQ trigger for the entire ID issued when one of OD Nsum triggers is issued.

- **OD Nusm trigger**
  - **OD top singles trigger:** A DAQ trigger for the entire OD issued when the number of OD top PMT hits (N_{top}) exceeds the threshold of OD top singles trigger threshold.
  - **OD middle singles trigger:** A DAQ trigger for the entire OD issued when the number of OD middle PMT hits (N_{middle}) exceeds the threshold of OD middle singles trigger threshold.
  - **OD bottom singles trigger:** A DAQ trigger for the entire OD issued when the number of OD bottom PMT hits (N_{bottom}) exceeds the threshold of OD bottom singles trigger threshold.
  - **OD global singles trigger:** A DAQ trigger for the entire OD issued when the number of entire OD PMT hits (N_{global}) exceeds the threshold of OD global singles trigger threshold.
  - **ID to OD trigger:** The DAQ trigger for the entire OD issued when one of ID Nsum triggers is issued.

Absorption cross-section (calculation)

https://arxiv.org/pdf/1908.10861