新学術領域研究 ニュートリノフロンティアの融合と進化

平成28～29年度 公募研究
「精密飛行時間測定によるニュートリノレス二重ベータ崩壊探索の新手法の開発」

Research of a new TOF method for neutrino-less double beta decay search

K. Matsuoka

(KMI, Nagoya University)

Nov. 30, 2016

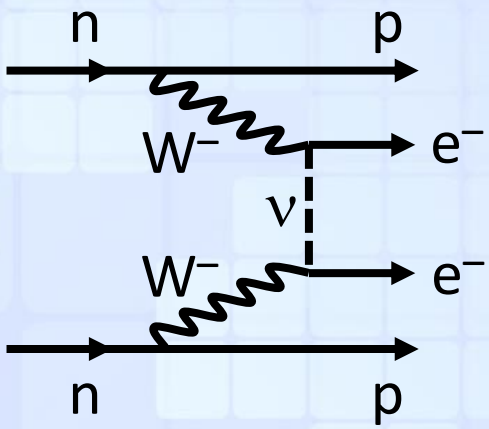
Neutrino Frontier Workshop 2016 @ 山代温泉

Contents

- Brief introduction of neutrino-less double beta decay
- A new concept of experimental approach for neutrino-less double beta decay search
- Preliminary study with Monte Carlo simulation
- Summary

Neutrino-less double beta decay

$(\mathrm{A}, \mathrm{Z}) \rightarrow (\mathrm{A}, \mathrm{Z}+2)^{++} + 2\mathrm{e}^{-}$



- Lepton number violation
- Majorana neutrino
- Access to the absolute neutrino mass scale
- Neutrino mass hierarchy
- …

Phase space factor Particle physics

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}|M^{0\nu}|^2|f(m_i, U_{ei})|^2 > O(10^{24-25}\ y)_{\text{current limit}}$$

Nuclear matrix element

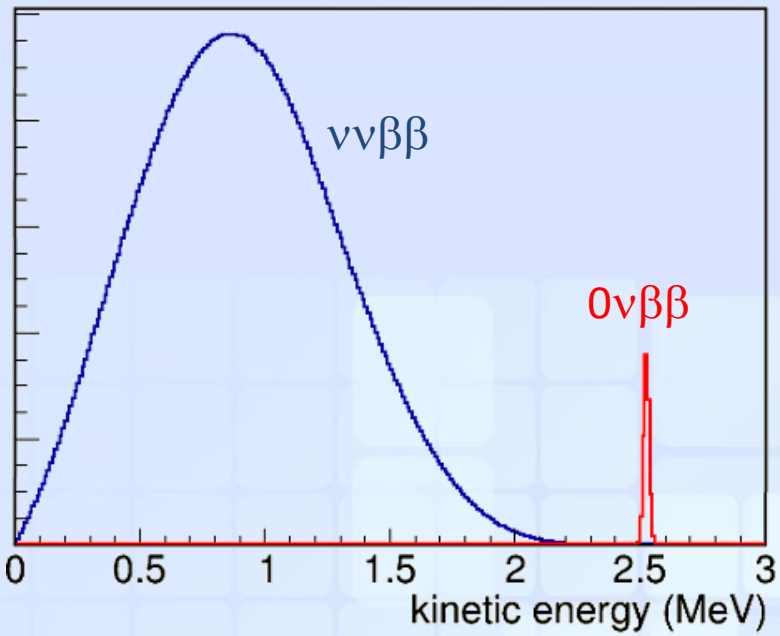
– In the case of exchange of light Majorana neutrino

$$f(m_i, U_{ei}) \equiv \frac{m_{\beta\beta}}{m_e} = \frac{1}{m_e}\left|\sum_{k=1,2,3} U_{ek}^2 m_k\right|$$

$$\simeq c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha_1} m_2 + s_{13}^2 e^{i\alpha_2} m_3$$

$m_{\beta\beta}$: Effective Majorana mass α_1, α_2: Majorana phase

Experimental signature



- Two electrons
  - back-to-back
  - from a common vertex
- Sum of their kinetic energies is equal to the Q-value

Experimental requirements

✓ Good energy resolution

✓ High efficiency

✓ Very low background

✓ Large isotope mass

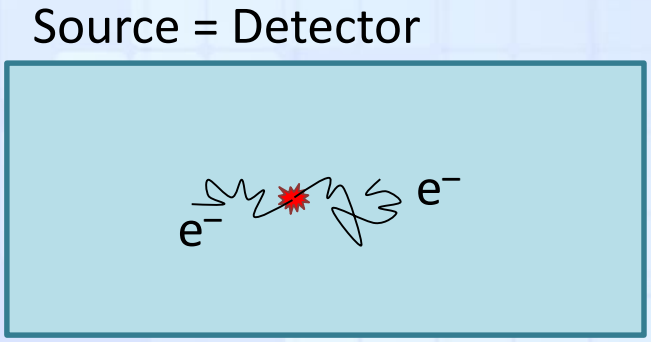
$$S^{0\nu} = \ln 2 \cdot \frac{1}{n_\sigma} \cdot \frac{x\eta N_A}{\mathcal{M}_A} \cdot \boldsymbol{\varepsilon} \sqrt{\frac{\boldsymbol{MT}}{\boldsymbol{B\Delta E}}}$$

- ε: detection efficiency
- ΔE : FWHM energy resolution [keV]
- T: measuring time [y]
- M: detector mass [kg]
- B: background level [/keV/y/kg]

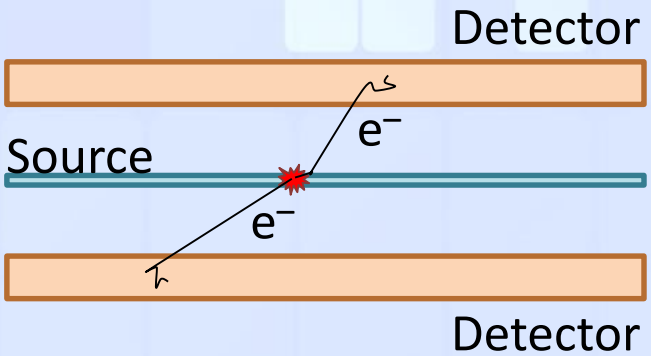
- $\mathcal{M}_A$: compound molar mass
- x: stoichiometric multiplicity of the element containing ββ candidate
- η: ββ candidate isotopic abundance
- N_A: Avogadro number
- n_σ: confidence level

Main experimental approaches

- Calorimeter
  - ☺ Large source mass
  - ☺ Very high resolution (~0.1% FWHM)



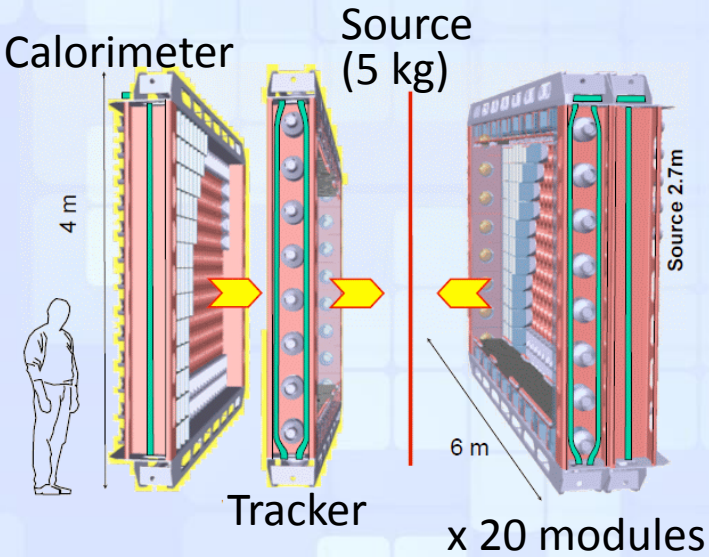
- External source
  - ☺ Event topology
  - ☺ Source replaceable
  - ☹ Smaller source mass
  - ☹ Lower energy resolution (>4%)
  - ☹ Less efficiency (~30%)

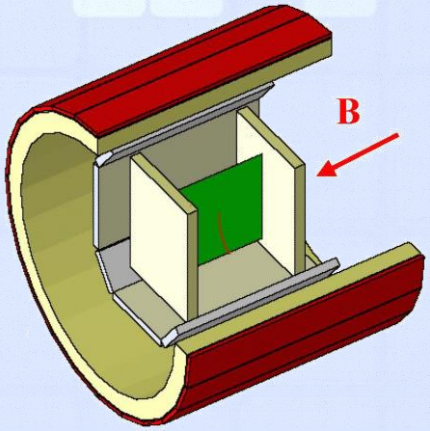


Can be improved by experimental technique

Major technique for external source

- SuperNEMO (^{82}Se or ^{150}Nd)
  - Measure the energy of the two electrons by the plastic scintillator + PMT.
    - ΔE = 4% FWHM, $\varepsilon \sim 30\%$
  - Reconstruct the event topology by the drift chamber etc.
- DCBA (^{150}Nd)
  - Reconstruct the momentum of the two electrons by the drift chamber in B-field, and calculate the energy.
    - ΔE = 6% FWHM, $\varepsilon \lesssim 30\%$
- MOON (^{100}Mo or ^{82}Se or ^{150}Nd)
  - Measure the electron energy by the scintillator + PMT (ΔE = 6% FWHM)
  - Measure the position by the scintillating fiber + PMT.





Possible to improve ΔE and ε with another different technique?

A new idea for external source

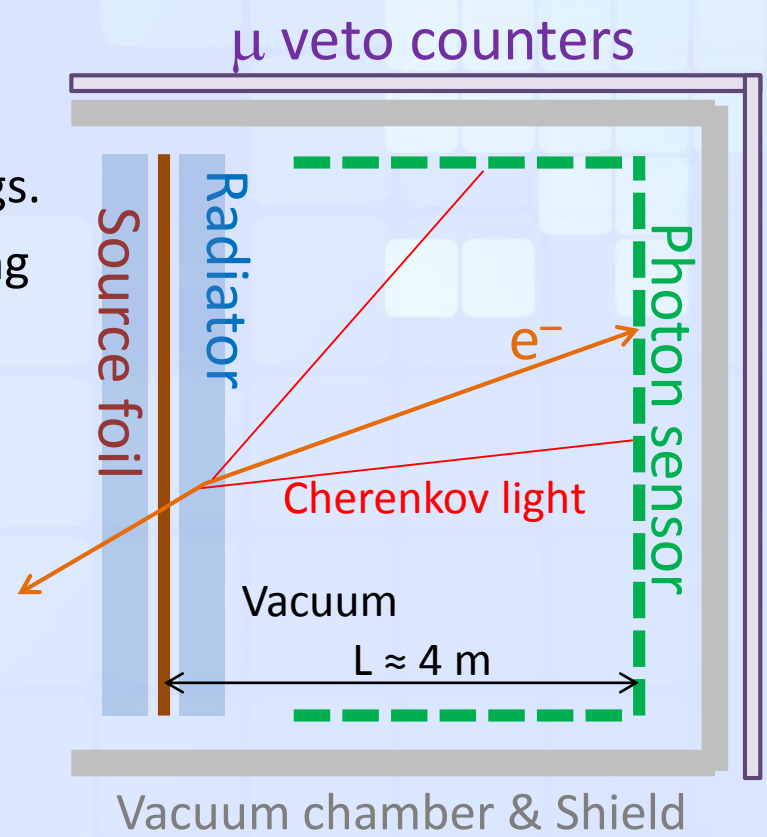
- Reconstruct the kinetic energy by measuring the velocity β:

$$E = \frac{m_e}{\sqrt{1-\beta^2}} - m_e$$

- Measure β from TOF of the electron
  1. Calculate the vertex $(x_0, y_0, 0; t_0)$ from Cherenkov photon hit positions and timings.
  2. Identify the electron hit position and timing $(x, y, L; t)$ where the electron emit Cherenkov light in the sensor window.
  3. Calculate $\beta c = \frac{\sqrt{(x-x_0)^2+(y-y_0)^2+L^2}}{t-t_0}$

$$\Delta\beta = \frac{\beta^2 c}{L}\Delta t$$

  - Need a good time resolution
  - and a long flight length.
  - Lower Q-value source is better.



Advantage compared to the other external source experiments

- Vacuum → Expect no background except $\nu\nu\beta\beta$
- Possible to achieve $\Delta E \sim$ a few %
  - ^{130}Te (Q = 2.527 MeV, β = 0.9576)
    - 25 keV (FWHM) at 2.5 MeV → σ_β = 0.00037 and σ_t = 5.4 ps for L = 4 m
  - ^{154}Sm (Q = 1.215 MeV, β = 0.8895)
    - 12 keV (FWHM) at 1.2 MeV → σ_β = 0.00077 and σ_t = 12.9 ps for L = 4 m

  * Photon sensor of the best time resolution: MCP-PMT ($\sigma_t \sim$ 30 ps)
- Better efficiency than 30% could be achieved.

[Disadvantage]

- Large vacuum chamber

  → Scalability similar to the other experiments

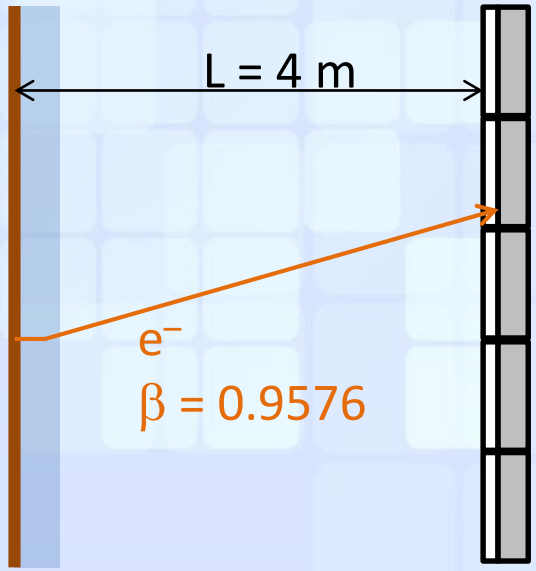
technically

Monte Carlo simulation (all-too-easy way)

out of consideration of cost

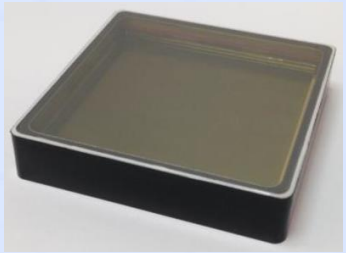
- Construct the detector only with the existing technologies.
  - A kind of the first trial; no optimization yet for the detector, analysis etc.
  - However every important parameter is included.
  - No background except the $\nu\nu\beta\beta$ decay and the PMT dark noise.
  - Primary electrons are generated at the center and normal to the source in this simulation and there is no sensor on the side walls (as the coding is still on the way).

^{130}Te (10 x 10 m^2 x 100 μm)
62.4 kg (η = 33.8%)
Q = 2.527 MeV



Optical film (0.6 mm thick)
n = 1.53, 1.02 g/cm^3

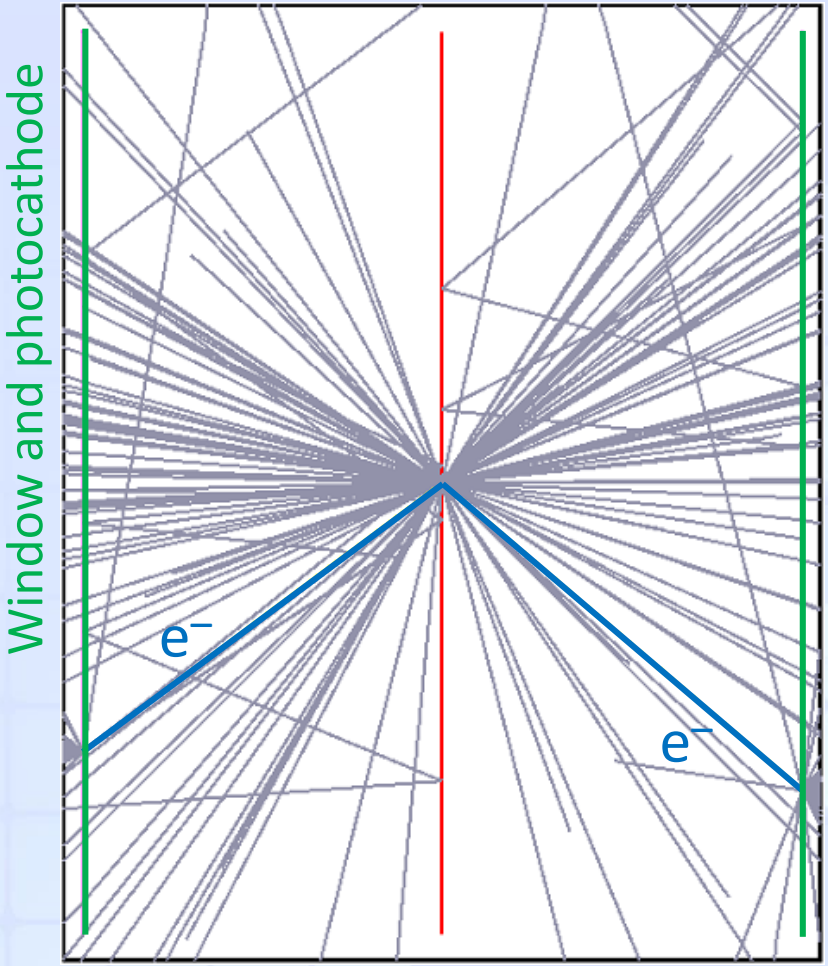
Array of 2-inch MCP-PMTs (single anode)
Δt = 30 ps for single photons
Peak QE = 33% at 280 nm (High-QE UV)
Collection efficiency = 60%
Photocoverage = 79.6%
Dark rate = 30 Hz/cm^2



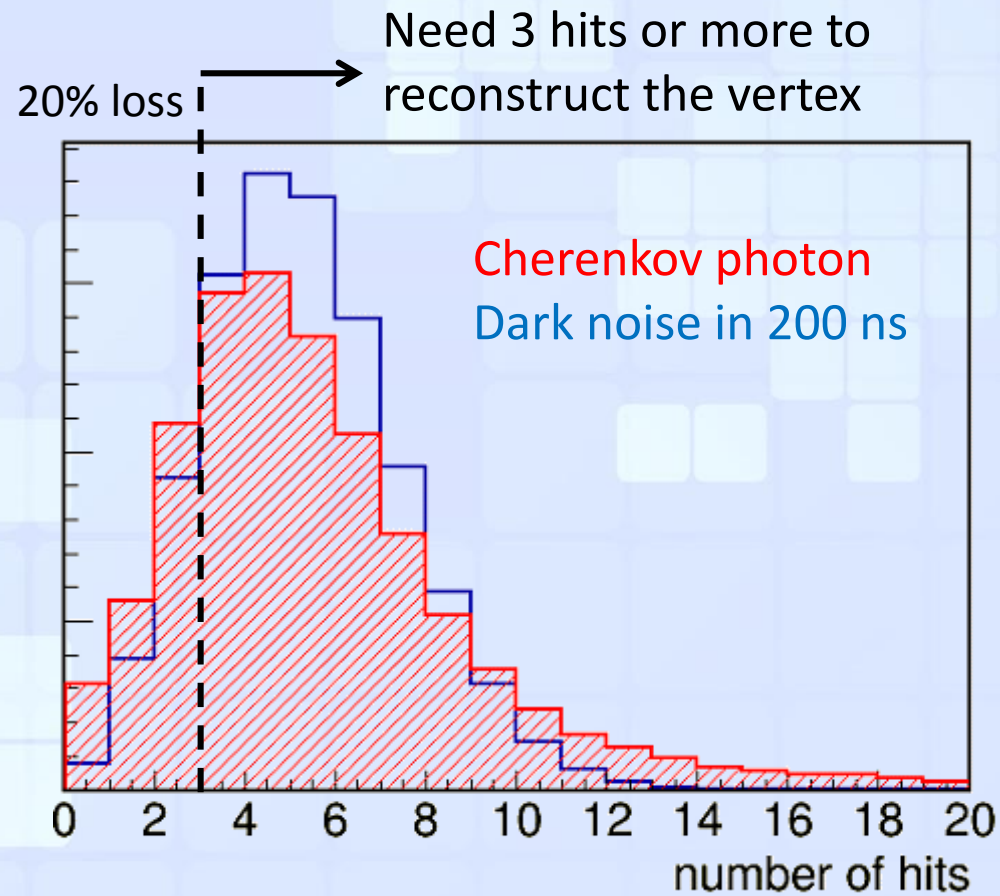
PHOTONIS
PLANACON®

0νββ MC simulation

MC event display

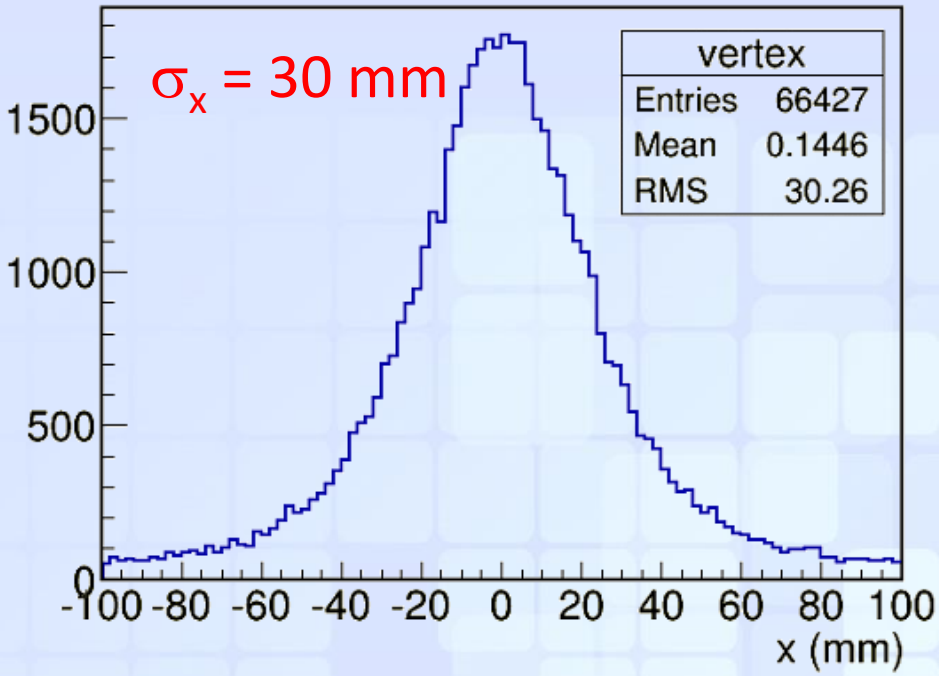


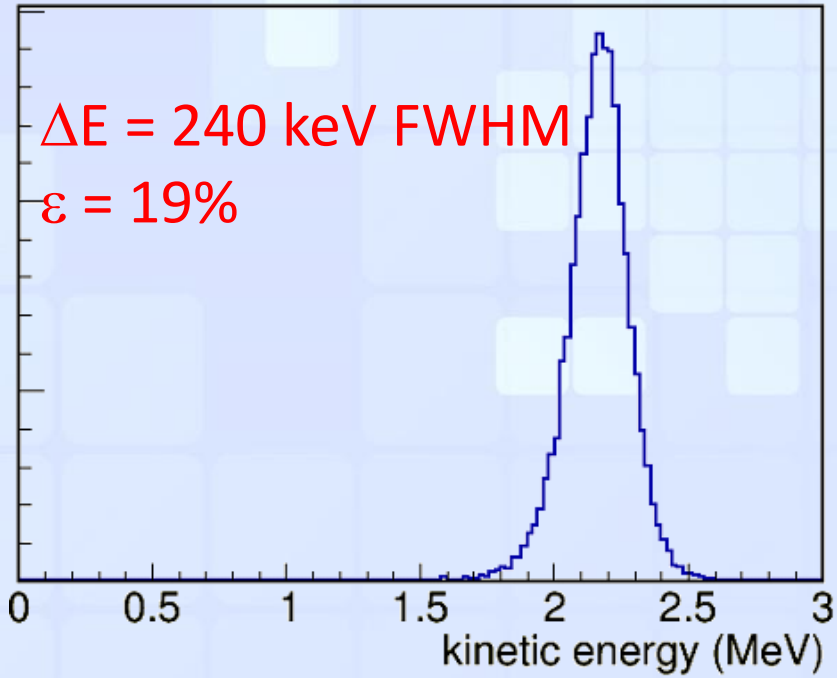
Generated Cherenkov photons ~ 80 / film



Reconstruction (0νββ MC)

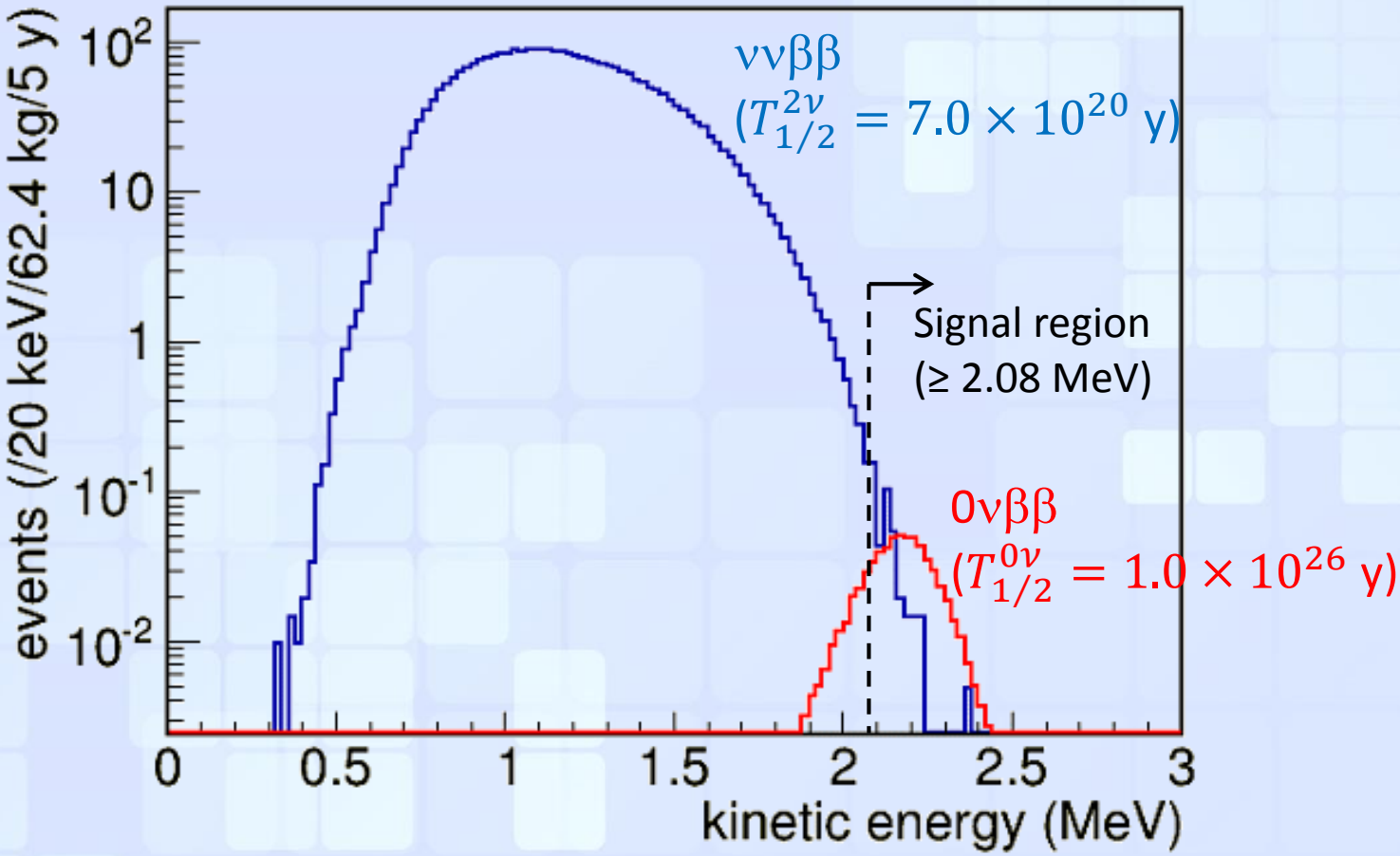
- Vertex reconstruction
- Energy reconstruction





ΔE is dominated by
the sensor time resolution

Spectrum (MC)



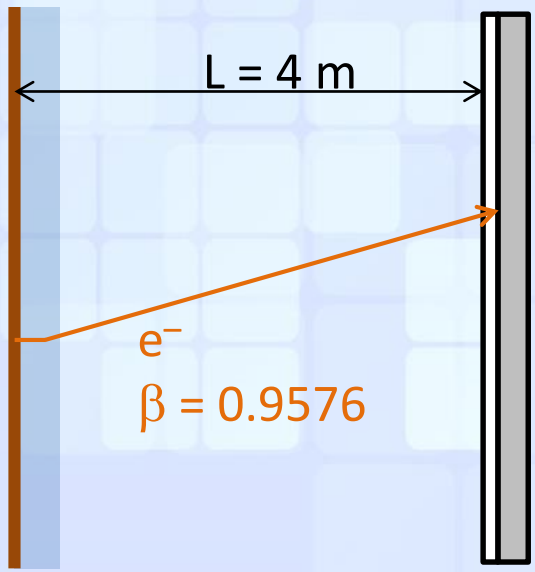
$S^{0\nu} = 4.8 \times 10^{25}$ y

MC simulation (challenging option)

with realistic cost

- Given that I can realize a novel photon sensor in my mind.
  - It will be very low-cost and be feasible to construct the large scale detector.
- The other conditions in MC are the same as the previous one.

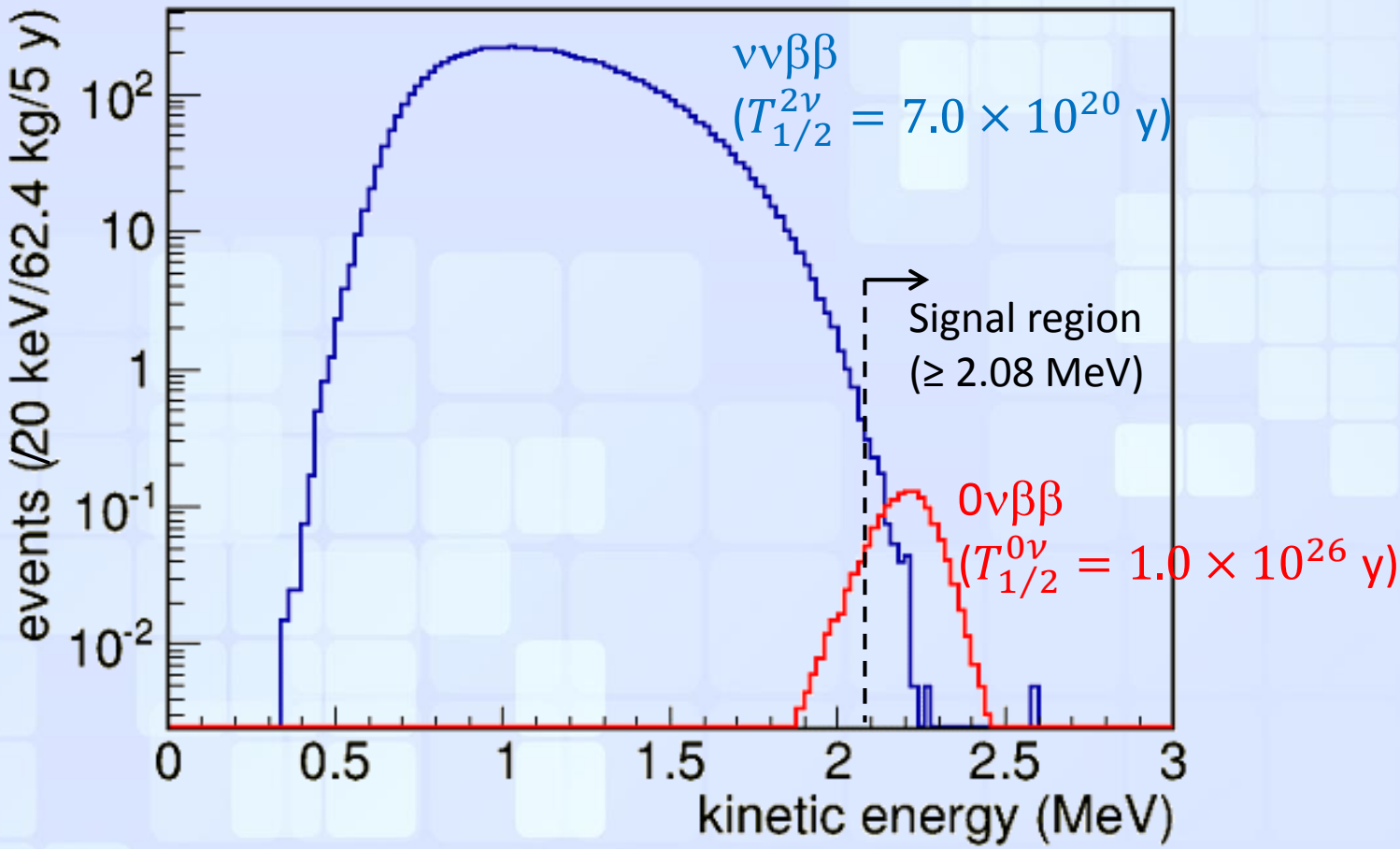
^{130}Te (10 x 10 m^2 x 100 μm)
62.4 kg (η = 33.8%)
Q = 2.527 MeV



Optical film (0. mm thick)
n = 1.53, 1.02 g/cm^3

A novel photon sensor in my mind
Δt = 20 ps for single photons
Peak QE = 33% at 280 nm (High-QE UV)
Collection efficiency = 80%
Photocoverage = 100%
Dark rate = 30 Hz/cm^2
Will be very low-cost

Spectrum (MC, challenging option)



ΔE = 200 keV FWHM

ε = 42%

$S^{0\nu} = 8.0 \times 10^{25}$ y

Competitive to the other experiments?

S. Dell'Oro et al., Advance in High Energy Physics, 2016, 2162659.

Experiment		Technique	M [kg]	Exposure [kg y]	FWHM at Q [keV]	B [counts /keV/kg/y]	$S^{0\nu}$ 90% CL [10^{25} y]
CUORE	^{130}Te	Bolometer	741	1030	5	0.01	9.5
SNO+	^{130}Te	LScintillator	2340	3980	270	0.0002	9
SuperNEMO	^{82}Se	Ext. source	100	500	120	0.01	10
This exp. (MC)	^{130}Te	TOF	62.4	312	200	0.000015	8

Very preliminary

Competitive to the other experiments?

S. Dell'Oro et al., Advance in High Energy Physics, 2016, 2162659.

Experiment		Technique	M [kg]	Exposure [kg y]	FWHM at Q [keV]	B [counts /keV/kg/y]	$S^{0\nu}$ 90% CL [10^{25} y]
CUORE	^{130}Te	Bolometer	741	1030	5	0.01	9.5
SNO+	^{130}Te	LScintillator	2340	3980	270	0.0002	9
SuperNEMO	^{82}Se	Ext. source	100	500	120	0.01	10
This exp. (MC)	^{130}Te	TOF	62.4	312	200	0.000015	8

Very preliminary

YES

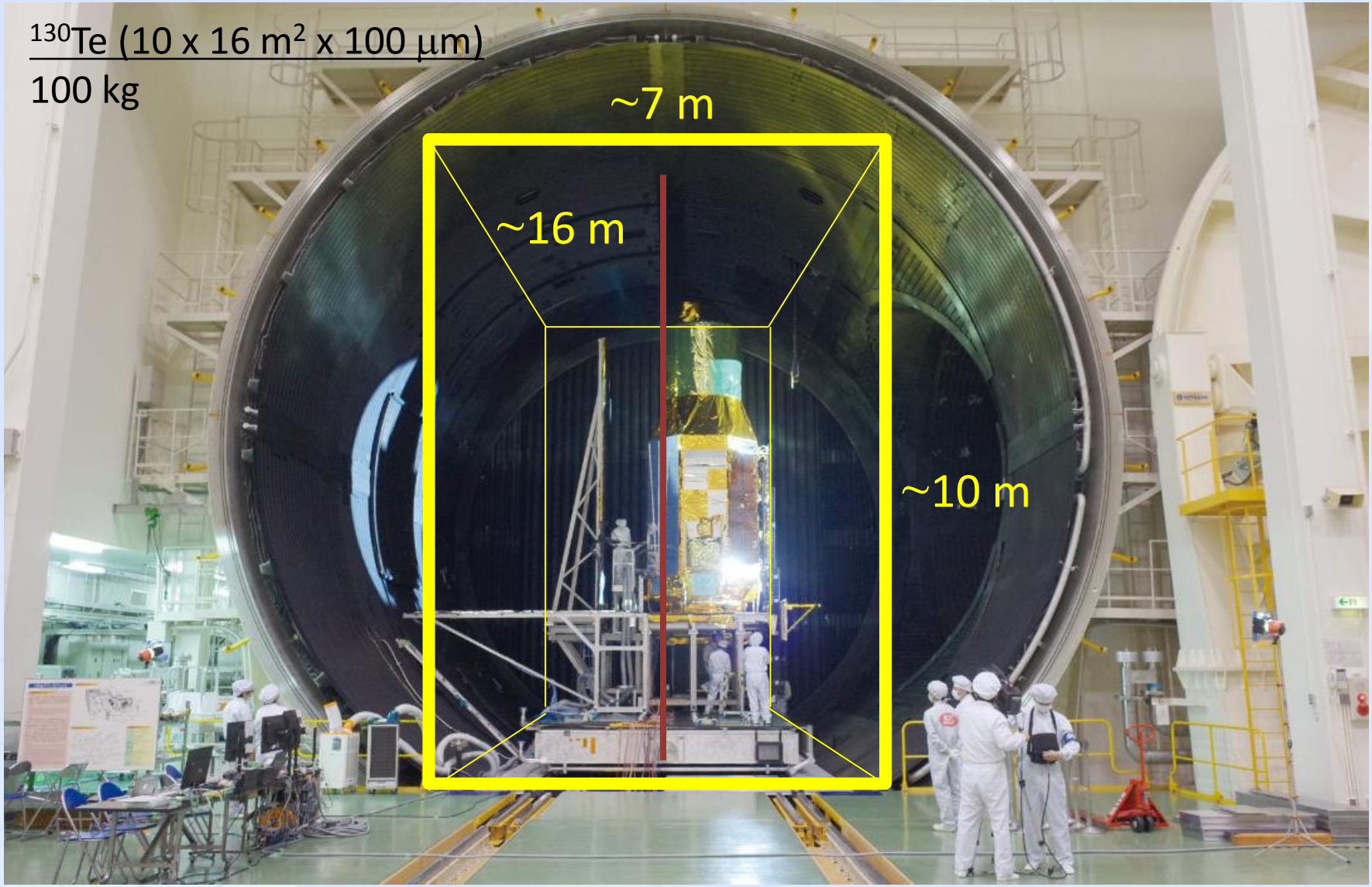
Just buy the components, but the cost will be comparable to SuperKEKB.

or

Develop the novel photon sensor of much low cost.

However a breakthrough idea is necessary after those next generation experiments.

Something like this



Space chamber in JAXA

Summary

- “Everyone wants to find a neutrino-less double beta decay.”
- The new technique with TOF is encouraging.

- To do
  - (I have just started this study, all from scratch.)
  - Proof of principle of this new TOF technique with a small prototype (four MCP-PMTs) using cosmic rays.
  - Monte Carlo simulation for optimization of the detector and analysis.
  - Background estimation.
  - Choose the best isotope for this experiment.
  - Development of a novel photon sensor. (no difficulty involved)