公募研究：「高感度0vββ探索のための高圧XeLSの開発研究」
Open call research : R&D of High-pressurized XeLS for high sensitive search for 0vββ

Xenon-loaded liquid scintillator for KamLAND-Zen

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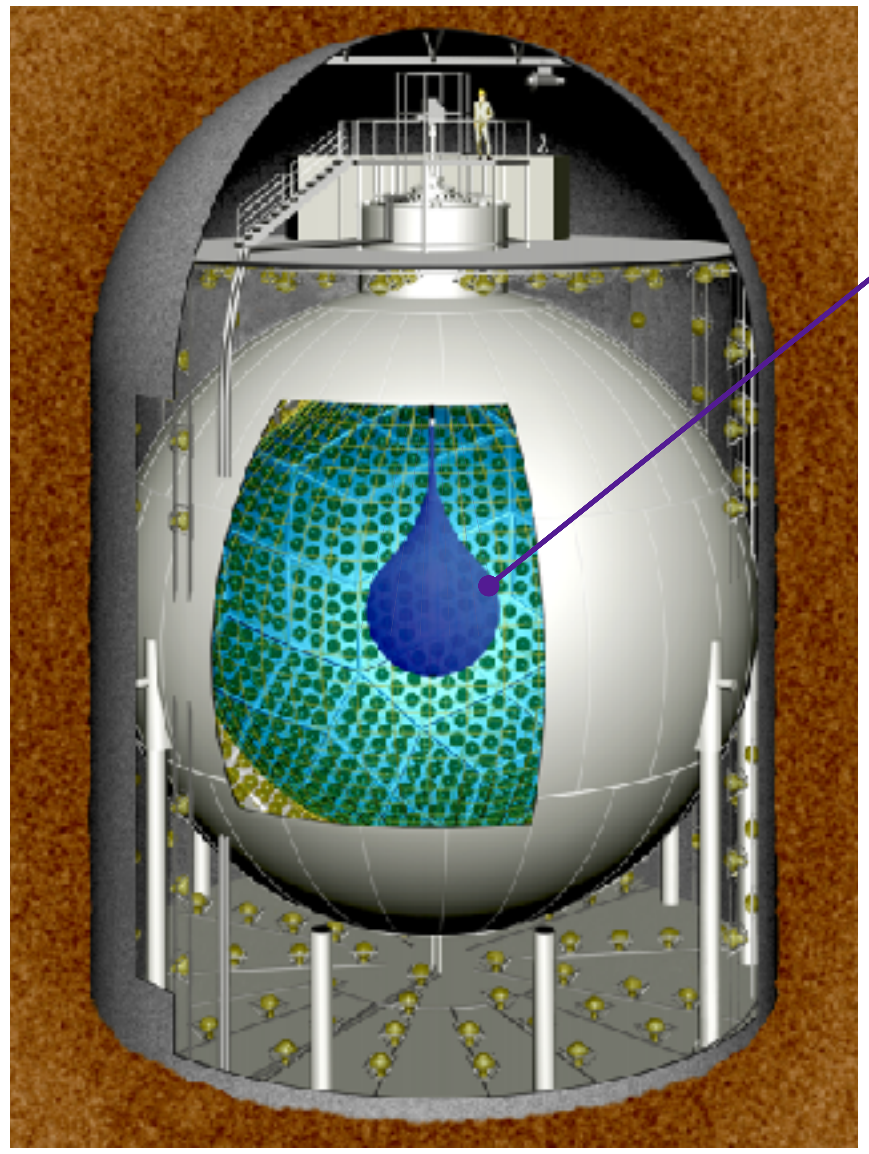
Unraveling the History of the Universe and Matter Evolution with Underground Physics (UGAP2024)

KamLAND-Zen

Zero neutrino double beta decay search,
Xenon

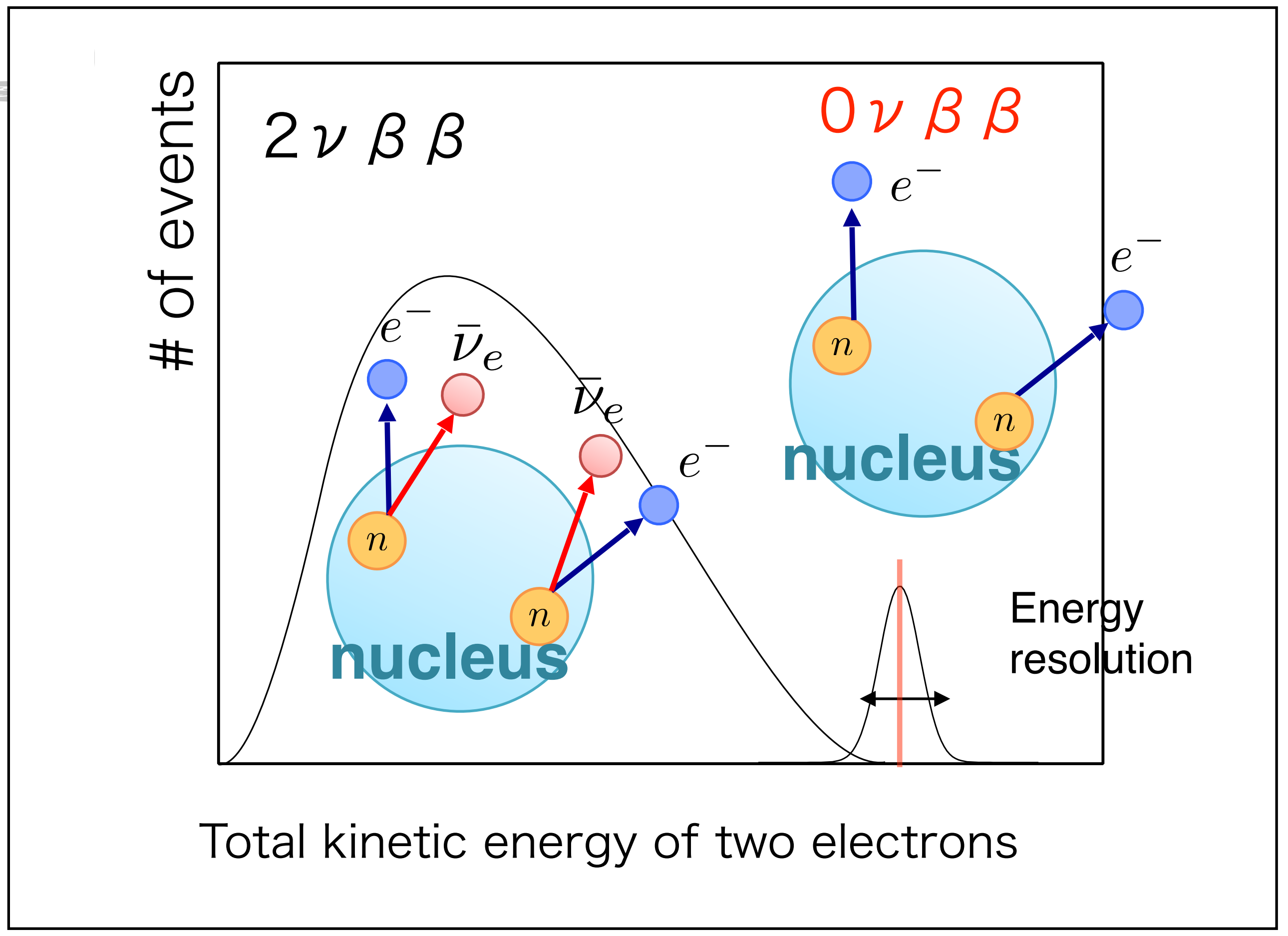


Next plan : KamLAND2-Zen

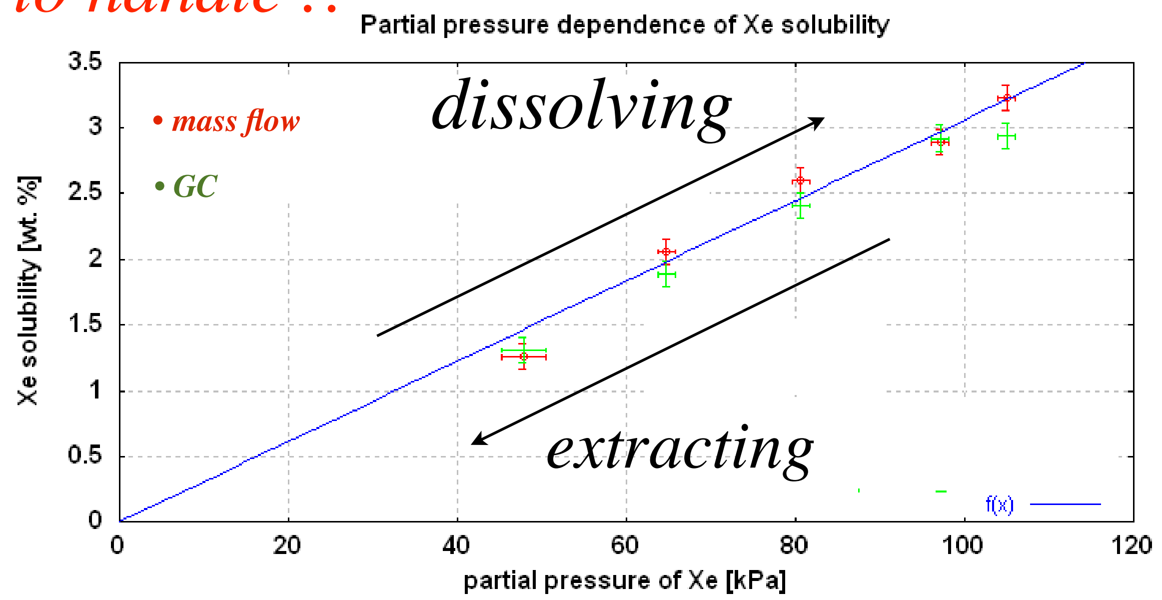
Xenon-136 loaded LS

Huge mass! **Easy to handle!** **Low BG!**

- Soluble into LS by ~3 weight%
- A large mass of Xe with high isotope enrichment
  - 745±3 kg of Xe enriched with ^{136}Xe by ~91wt%
- Purification by distillation
  RI in XeLS: ^{238}U ~ 1.5×10^{-17} g/g, ^{232}Th~3×10^{-16} g/g
- High Q-value: 2.46 MeV (Low BG @ KamLAND)
- Long ^{136}Xe 2νββ decay half-life ~2.×10^{21} years



Easy to handle !!



Xe solubility follows Henry's law.

High light yield (x5)

- HQE PMT
- Improvement in LS
- Mirror for PMT

Other upgrades

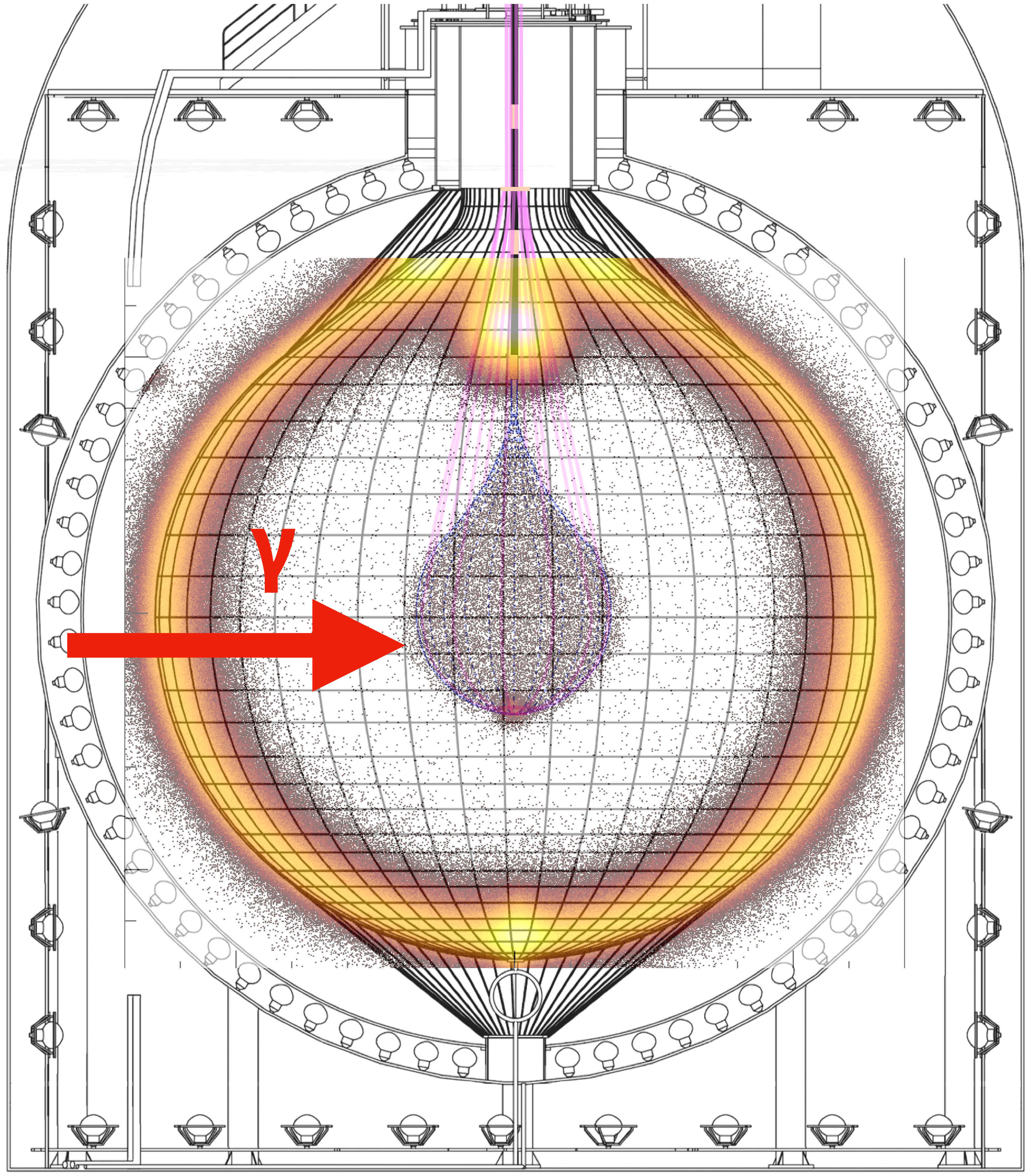
- New electronics
- Scintillation balloon
- Imaging camera
- High-pressurized XeLS

Towards KamLAND2-Zen!
What are the requirements for XeLS?

Xenon-loaded LS

Xe-LS	
Decane(D10)	82%
PC	18%
PPO	~2.4 g/L
Xe	~3.1 wt%

KamLAND-LS	
Dodecane(D12)	80%
PC	20%
PPO	~1.4 g/L

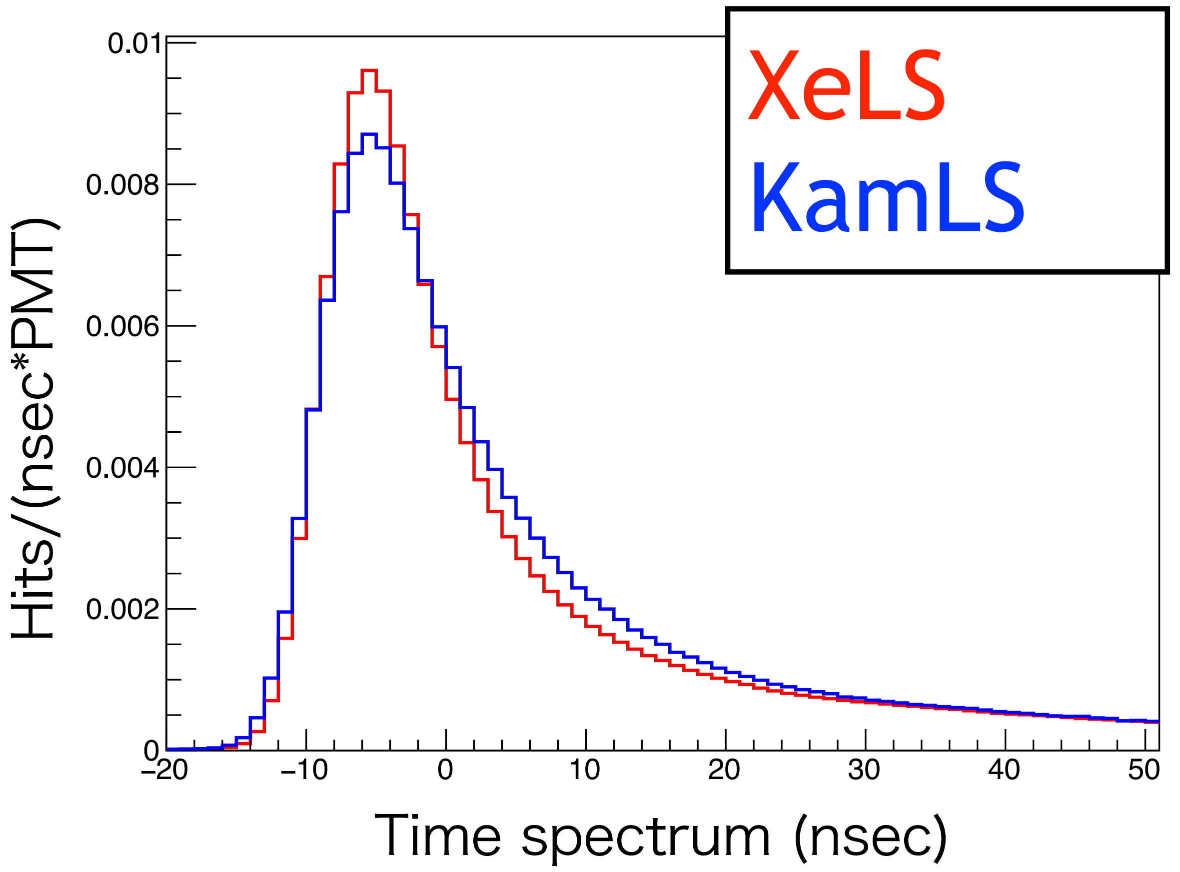


Old requirement for XeLS

- Light yield is equivalent to KamLAND LS. (→High PPO concentration)
- Density is equivalent to KamLAND LS (D12 → D10).
- Capable of dissolving a large amount of Xe (aiming to retain Xe in a small region, R<2 m).

New requirement (To be studied)

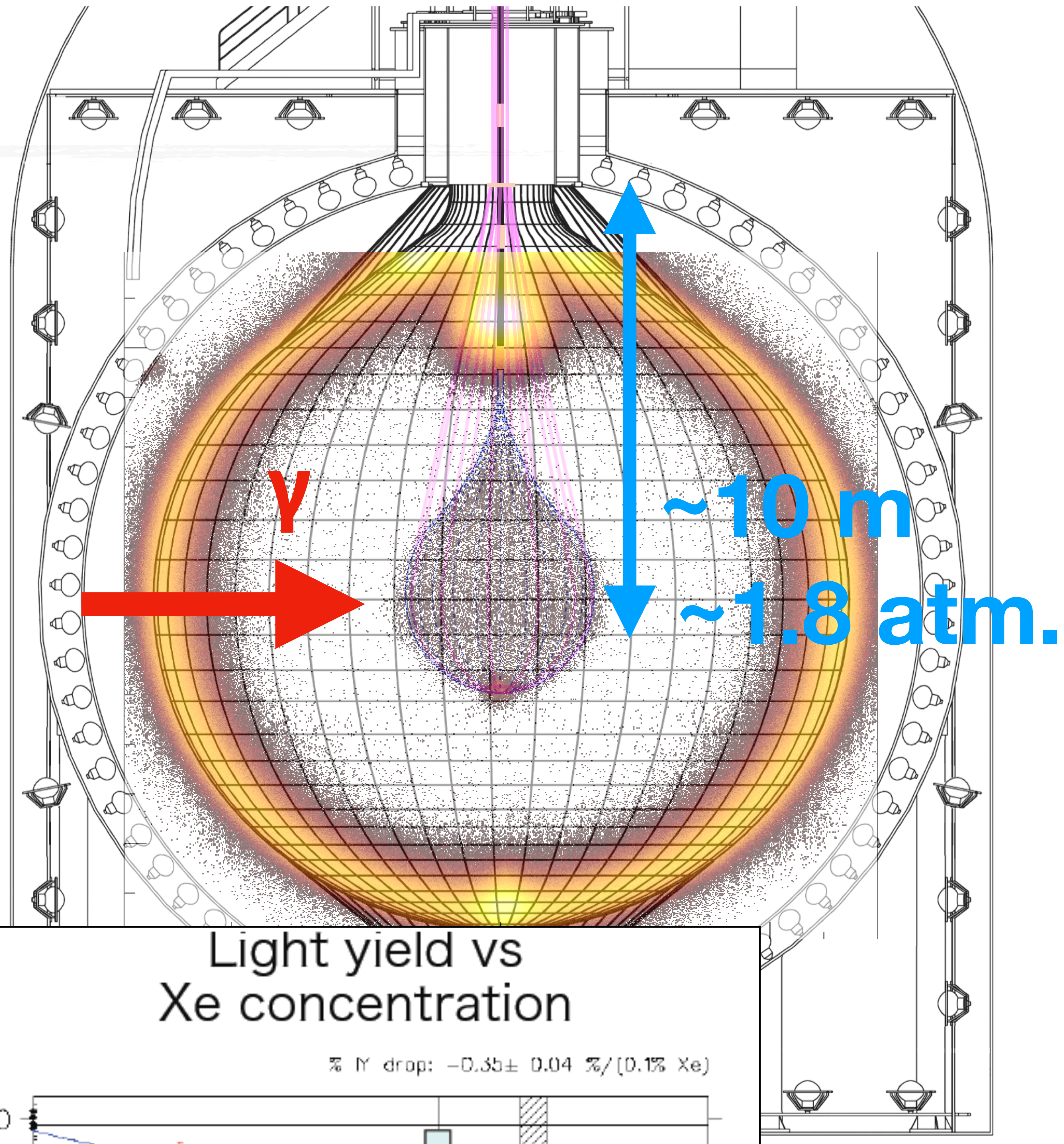
- Is a higher light yield possible? (to reduce 2νββ.)
- How to remove new long-lived backgrounds with XeLS?
  - Are there any XeLS with less Xe spallation BG?
  - Are there any XeLS capable of Particle Identification (PID)?



High-pressurized (HP) XeLS

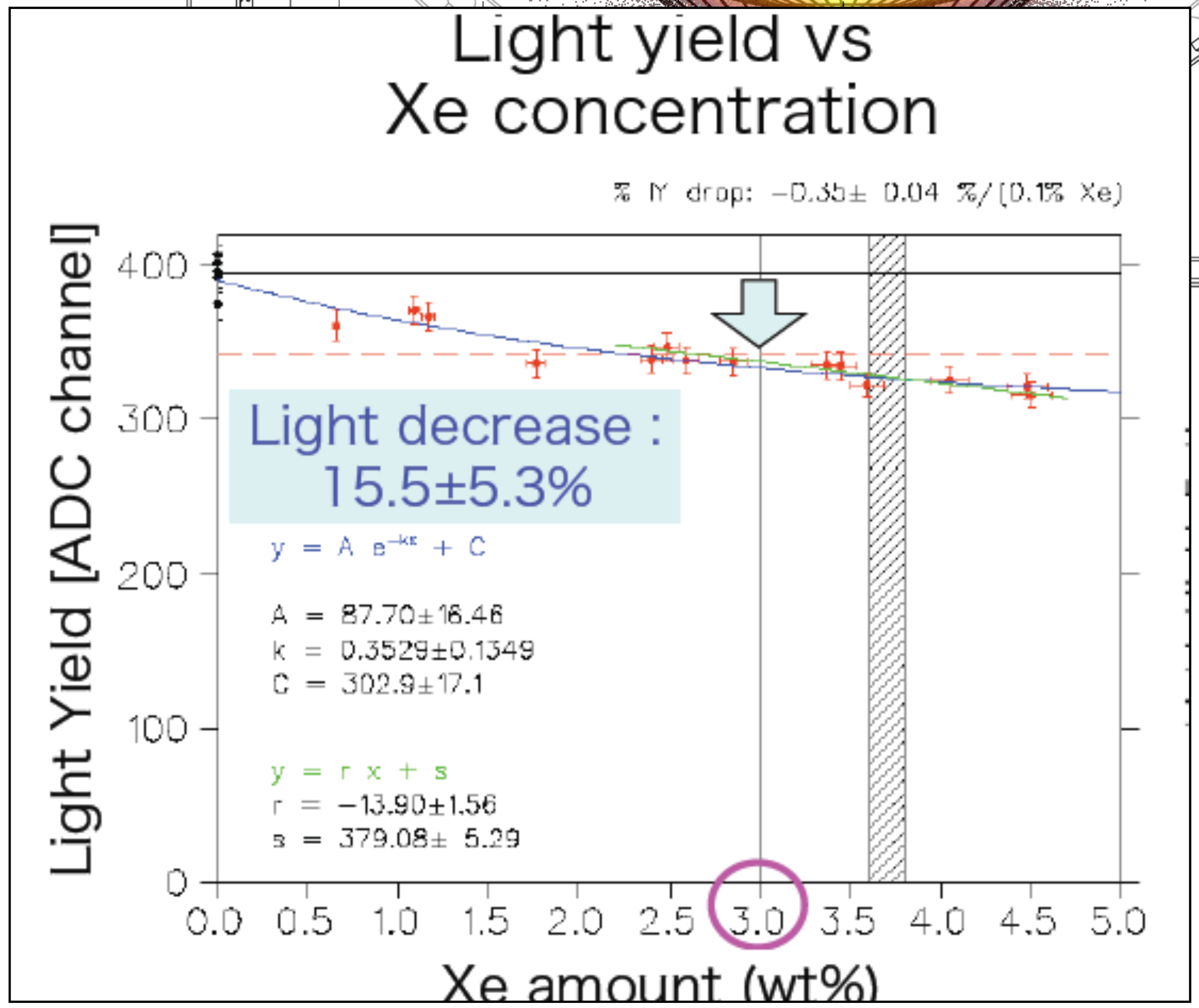
Merit of high-pressurized XeLS

- It is possible to dissolve a large amount of Xe in a small area, R<2 m.
  - This can reduce the background per Xe from solar neutrinos and RIs in the detector.
- Already pressurized to approximately 1.8 atmospheres (atm).



Demerit/Challenging of high-pressurized XeLS

- Quenching; dissolving xenon leads to a reduction in light yield.
  - > Is it possible to suppress quenching?
- The difference in density may also be a problem.



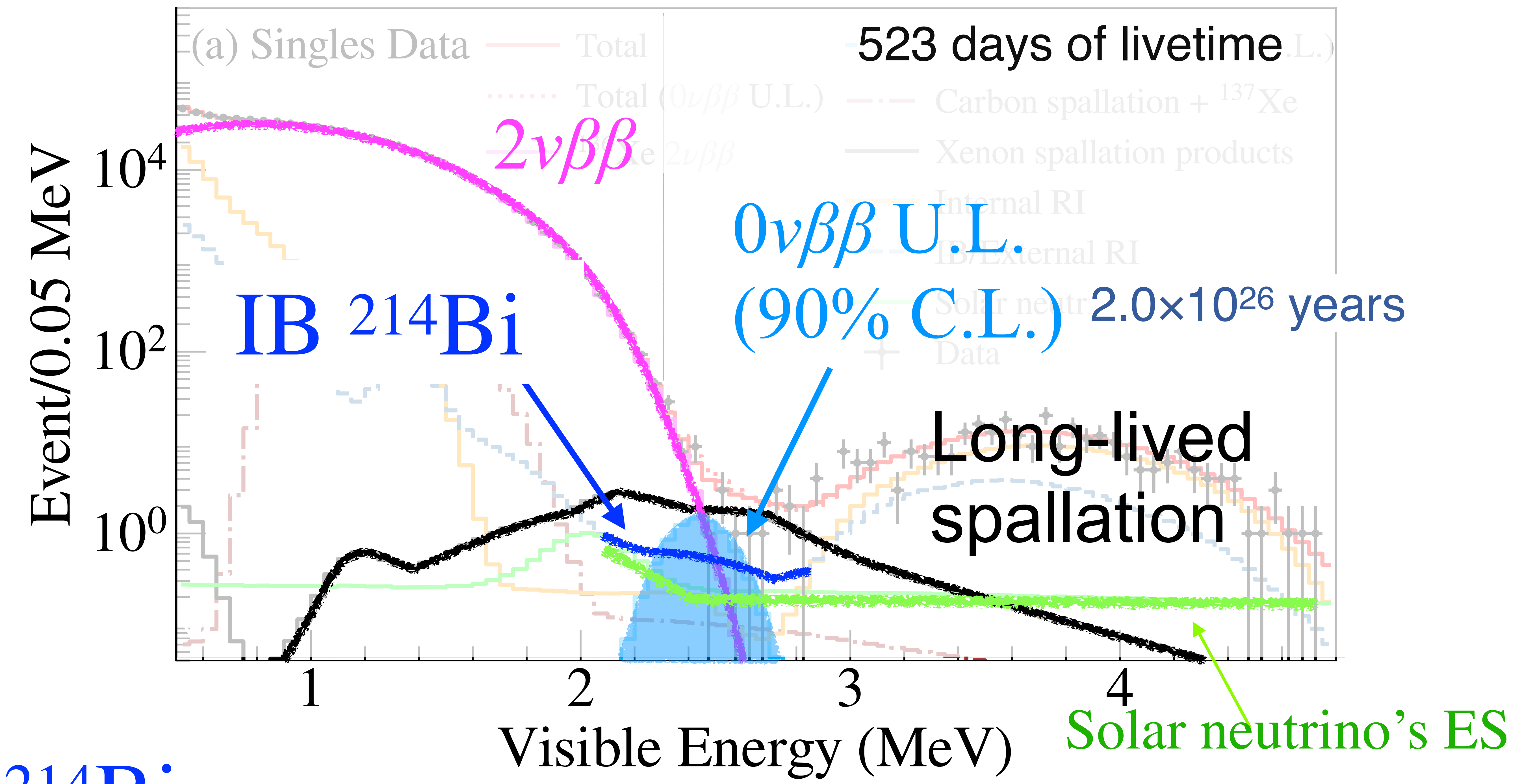
- Investigated potential of the HP XeLS.

Backgrounds in KamLAND-Zen

Phys. Rev. Lett. **130**, 051801 (2023)

- Sensitivity is significantly dependent on BG.

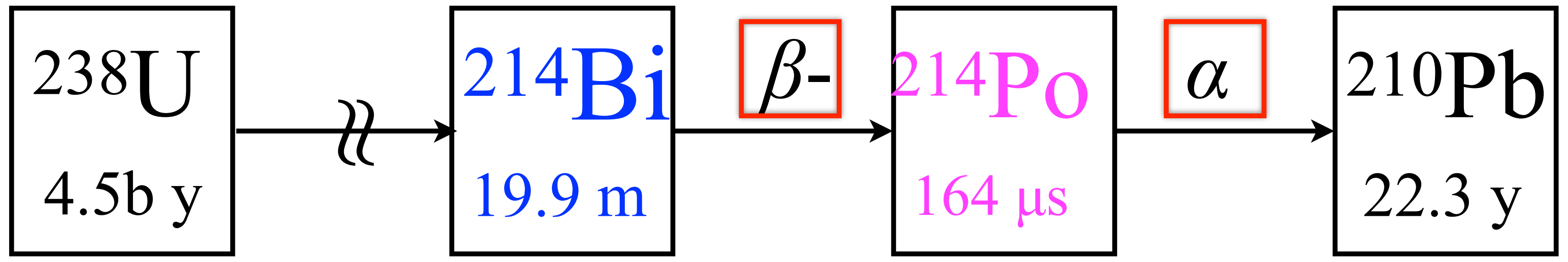
$0\nu\beta\beta$ candidate data set

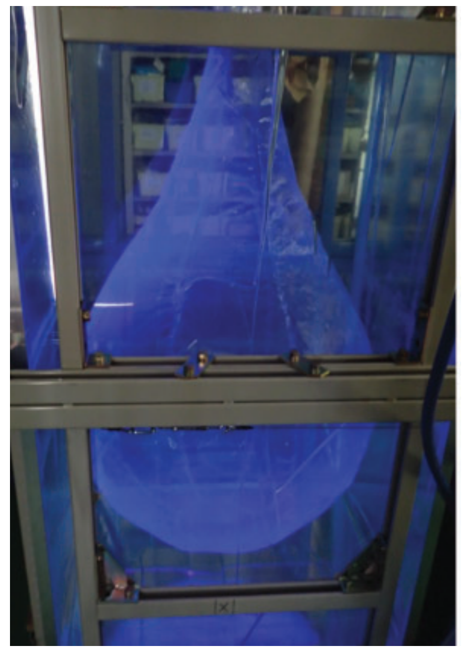


Background	Best-fit Frequentist	Best-fit Bayesian	
^{136}Xe $2\nu\beta\beta$	11.98	11.95	1st
Residual radioactivity in Xe-LS			
^{238}U series	0.14	0.09	
^{232}Th series	0.84	0.87	
External (Radioactivity in IB)			
^{238}U series	3.05	3.46	3rd
^{232}Th series	0.01	0.01	
Neutrino interactions			
^{8}B solar ν e^- ES	1.65	1.65	4th
Spallation products			
Long-lived	12.52	11.80	~1st
^{10}C	0.00	0.00	
^{6}He	0.22	0.21	
^{137}Xe	0.34	0.34	

IB ^{214}Bi

- Assuming the Bi-214 background is resolved using a scintillation balloon.





$2\nu\beta\beta$ - An increase in light yield is necessary.
-> Investigated via measurement!

L.L. - Investigated the requirements for XeLS using Simulation and Neural Networks!

Solar-ν - Reduction can be achieved with High-pressurization!

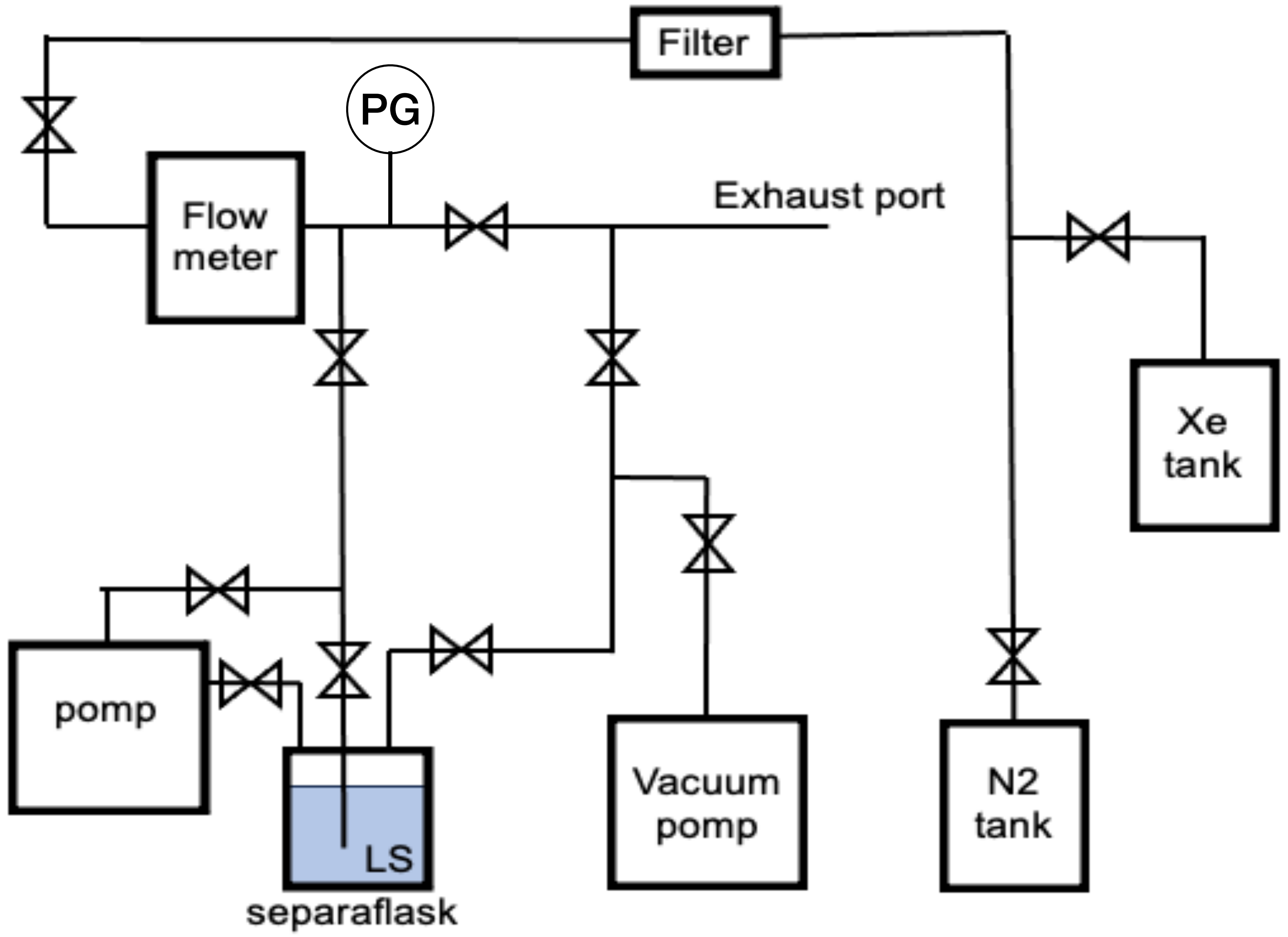
$2\nu\beta\beta$

~Study on light yield~

Light yield measurement

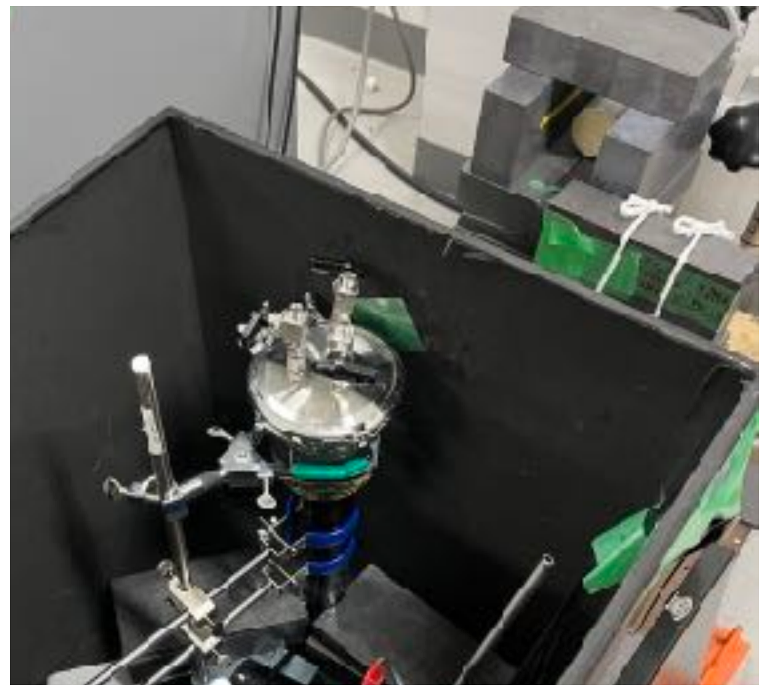
for Watanabe-san
(M2 student)

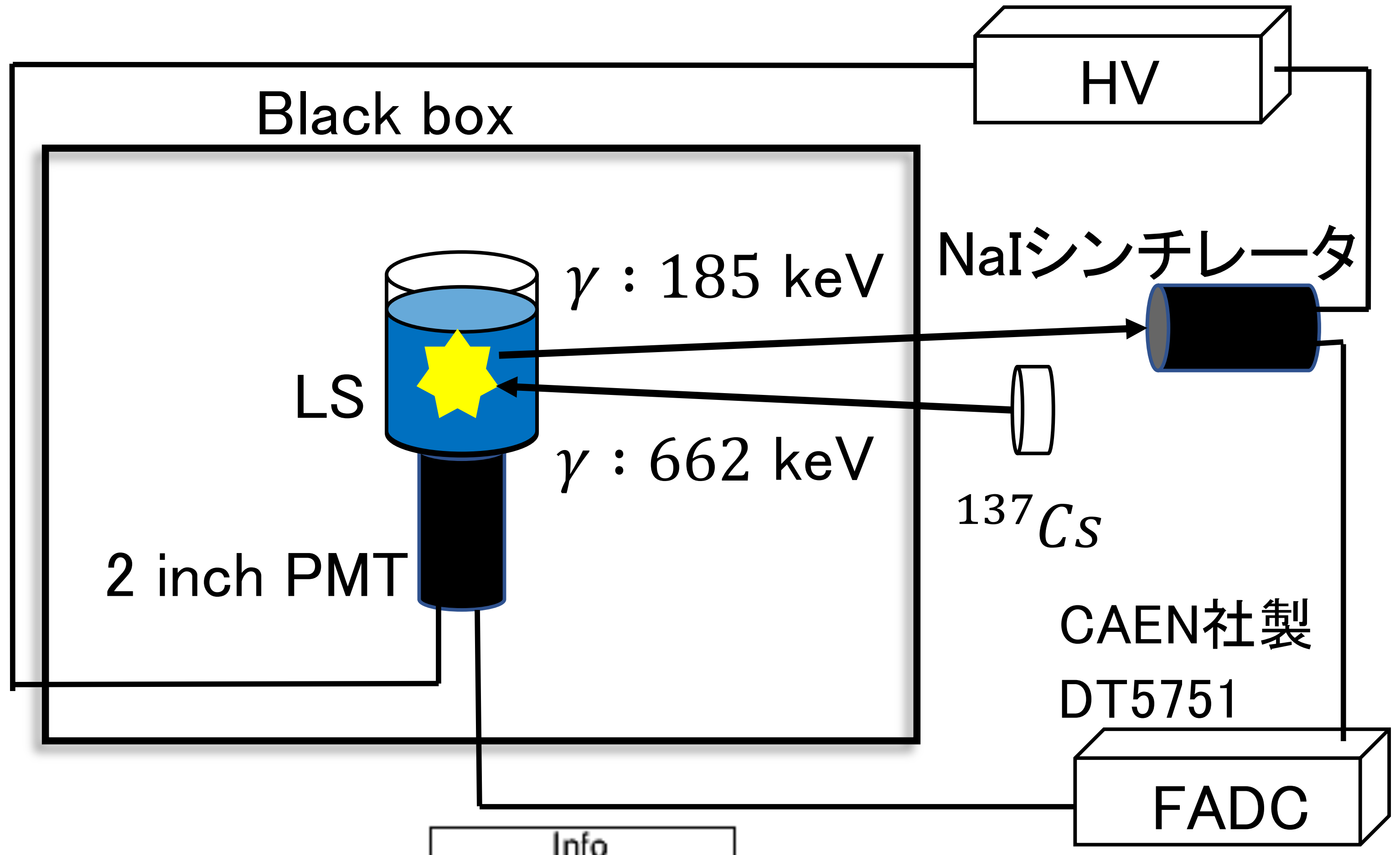
Xe installing system was made.

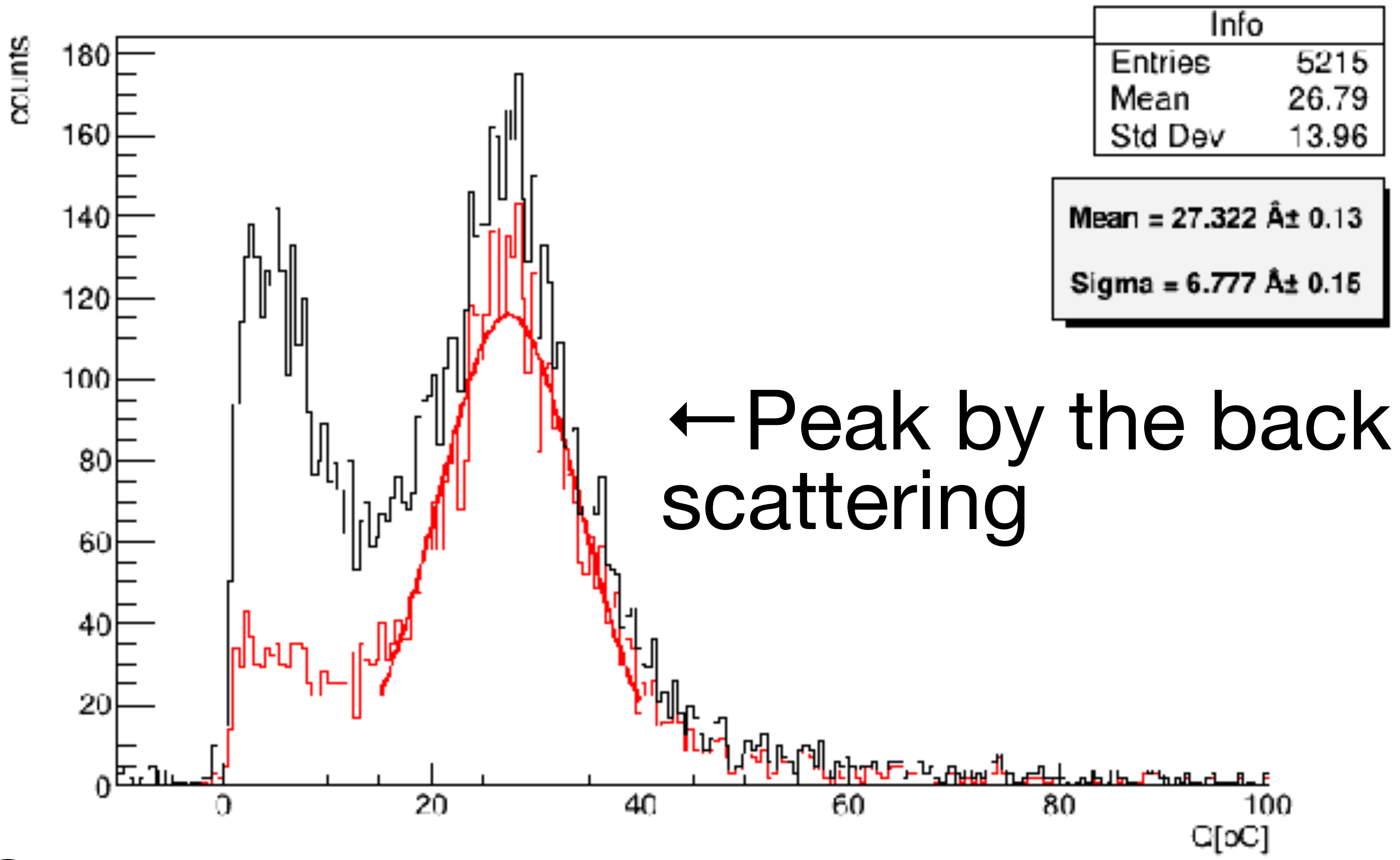


- How to make XeLS / HPXeLS.
  - N2 bubbling
  - Vacuuming
  - Xe installing (with pressure)

Light yield measurement system







←Peak by the back scattering

Compared the observed charge amounts at the peaks with KamLAND LS.

XeLS : Light yield measurement

for Watanabe-san
(M2 student)

My naive and stupid idea : Xe is also scintillator, so wavelength shifter for UV will be effective.

Did not work well …

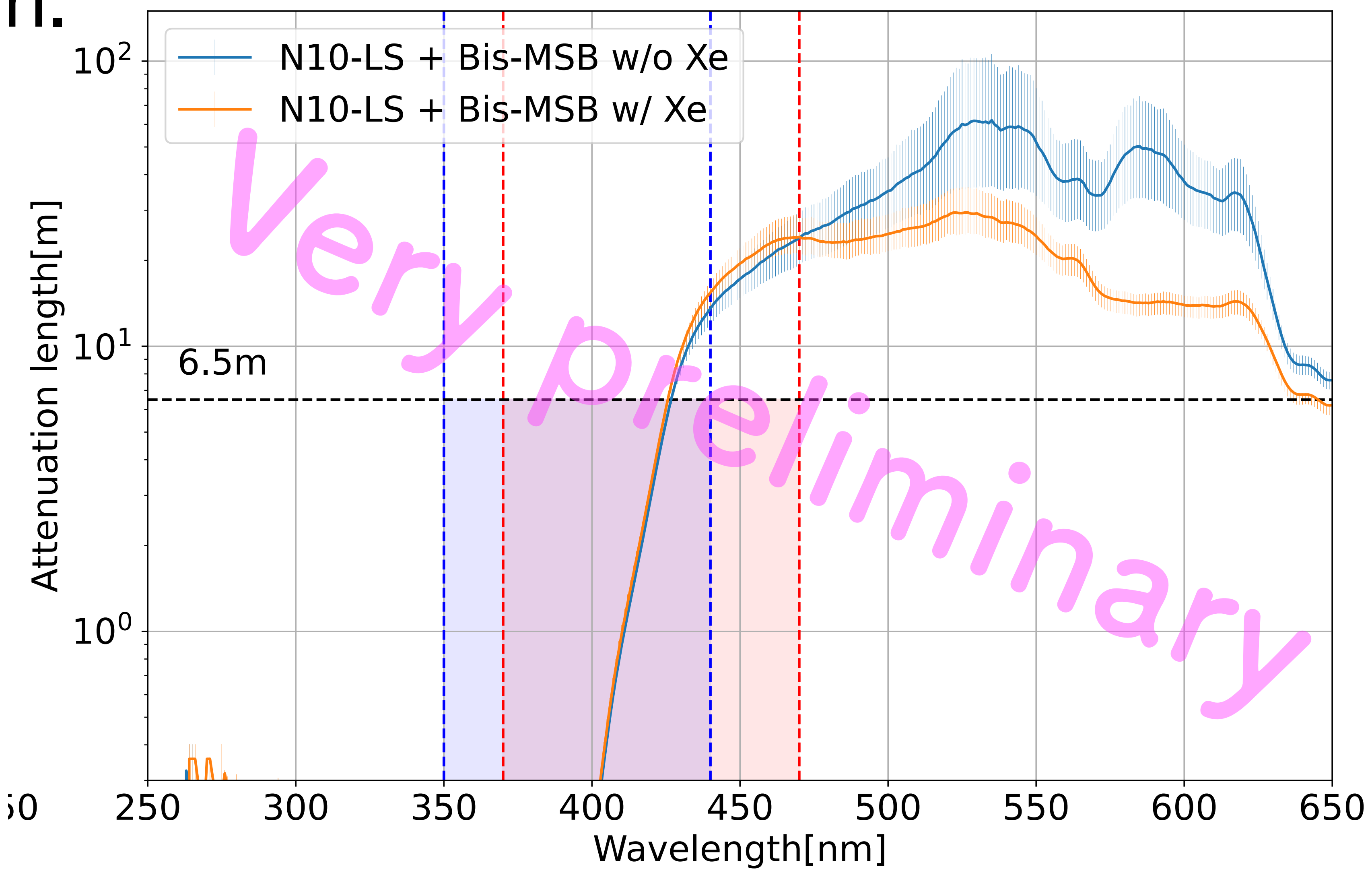
The scintillation mechanism by the formation of excimers involving two molecules, is considered to be highly sensitive to impurities.

- p-Terphenyl … Light yield at 1 atm was comparable to the current XeLS, but worse at 2 atm. Very slow time spectrum.
- PTB (1,1,4,4-Tetraphenyl-1,3-butadiene) … Light yield was not enough.

The current conclusion is …

- Increase PPO up to ~2.7 g/L.
- Using WS : Bis-MSB to shift the wavelength towards the higher wavelength side (~450 nm) makes KamLAND-LS and XeLS more transparent (LS).
- ~x1.4 light yield will be achieved for XeLS at 1atm. (~10% less for HPXeLS)

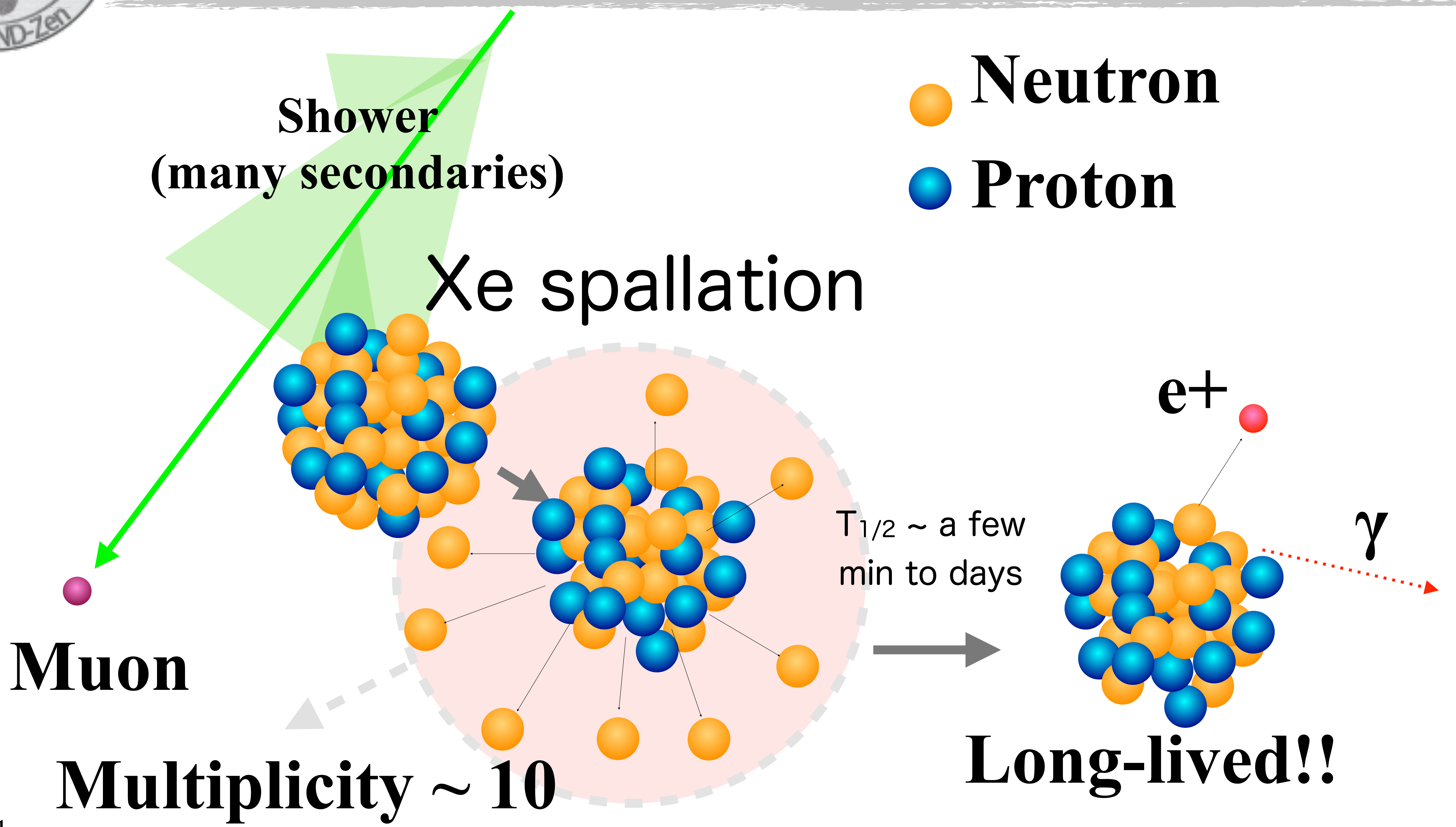
From watanabe-san's thesis.

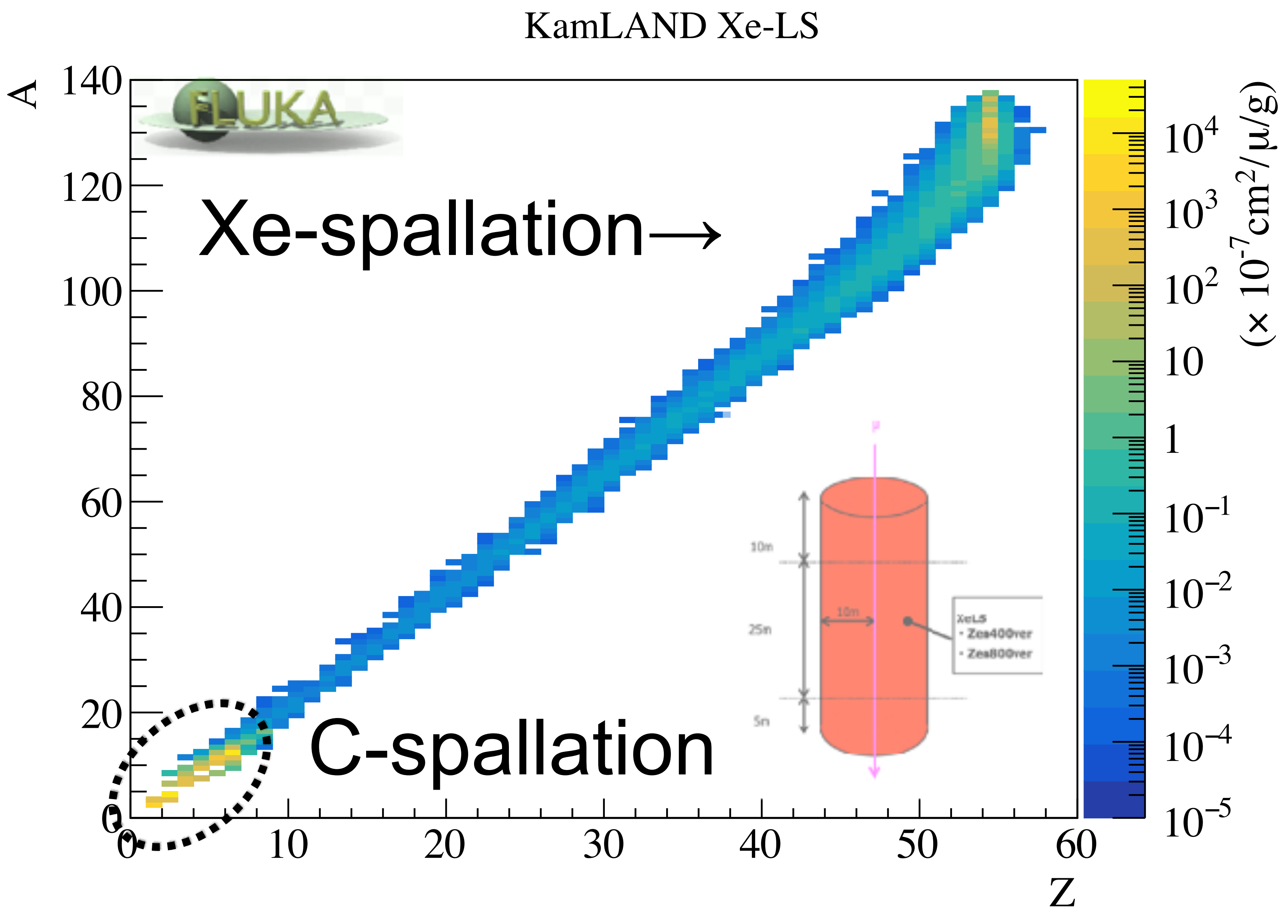


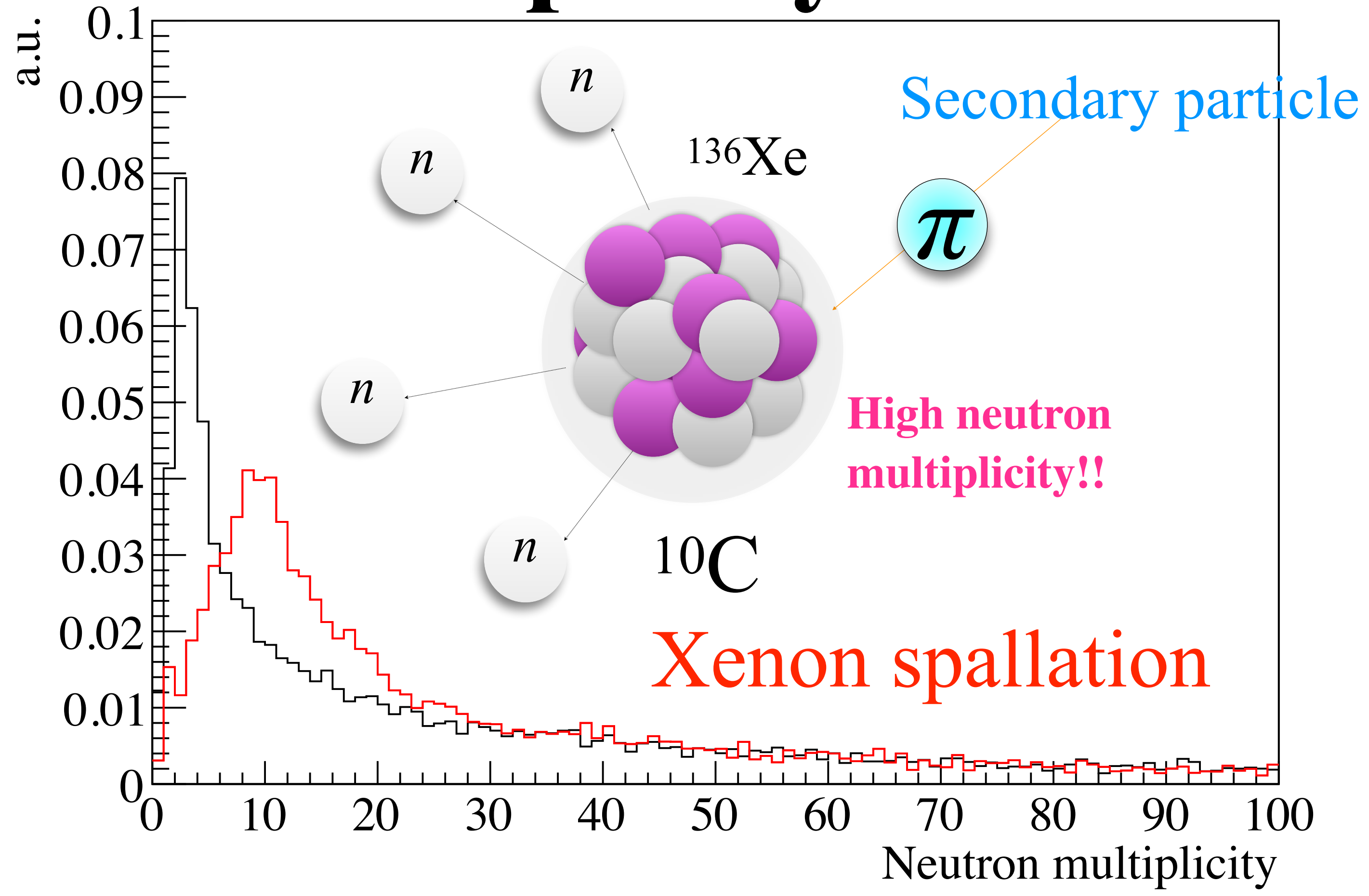
(b) N10-LS+Bis-MSB

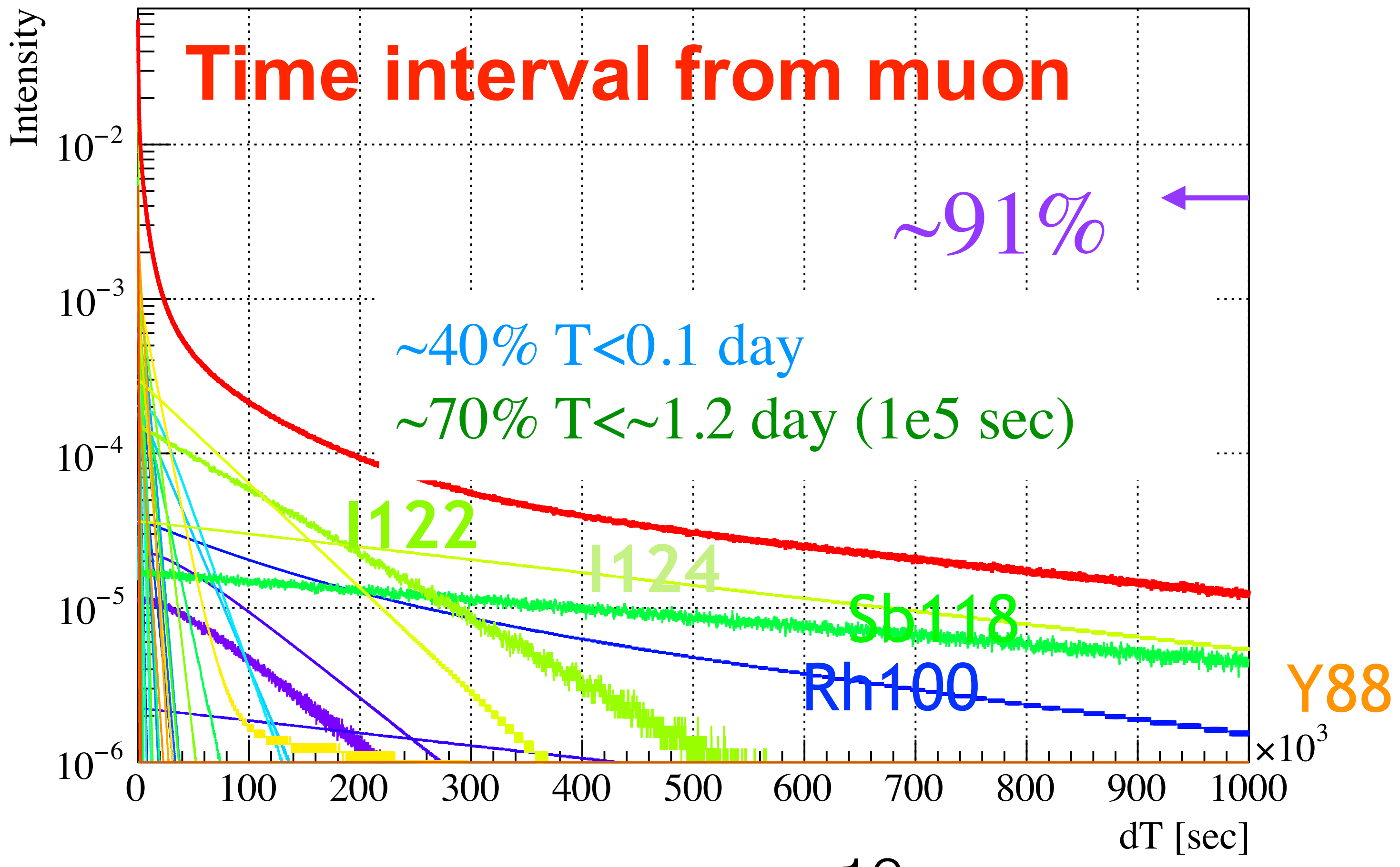
Long-lived background
~Study on simulation and neural networks~

Modeling Muon Spallation (Long-lived background)









- FLUKA for primary products, then Geant4 with ENSDF for their daughters.
- Checked LL background of HP XeLS!!

FLUKA simulation result

- FLUKA 2023.3.1

Unit: 10^{-6} (day*kg Xe)$^{-1}$

Isotope	XeLS	HP XeLS (2 atm)
^{8}He	11	6
^{9}Li	115	56
^{12}B	1150	573
^{12}N	25	12
^{8}Li	958	465
^{8}B	284	138
^{9}C	38	20
11Be	83	40
^{10}C	511	248
^{6}He	607	294
^{11}C	26134	13027

Very preliminary

Unit: 10^{-6} (day*kg Xe)$^{-1}$

Isotope	XeLS	HP XeLS
Y-88	0.59	0.59
Nb-90	1.07	1.26
Tc-96	0.99	1.05
Rh-98	1.51	1.56
Rh-100	1.88	1.84
Ag-104	2.94	3.02
In-107	2.86	2.87
In-108	4.28	4.08
In-110	4.95	5.06
Sn-109	3.01	3.02
Sb-113	7.27	7.39
Sb-114	8.95	9.26
Sb-115	16.08	15.99
Sb-116	11.90	11.97

Isotope	XeLS	HP XeLS
Sb-118	8.50	8.33
Sb-124	1.21	1.25
Te-115	3.16	3.10
Te-117	10.80	10.95
I-119	12.30	12.37
I-120	14.94	14.95
I-122	29.94	29.62
I-124	39.67	40.47
I-130	36.54	36.68
I-132	12.69	12.99
I-134	6.48	6.79
Xe-121	11.87	11.71
Cs-125	6.36	6.06
Cs-126	7.14	7.05
Cs-128	10.15	10.15

Very preliminary

HP XeLS has less C spallation per Xe.

HP XeLS has almost same amount of LL background.

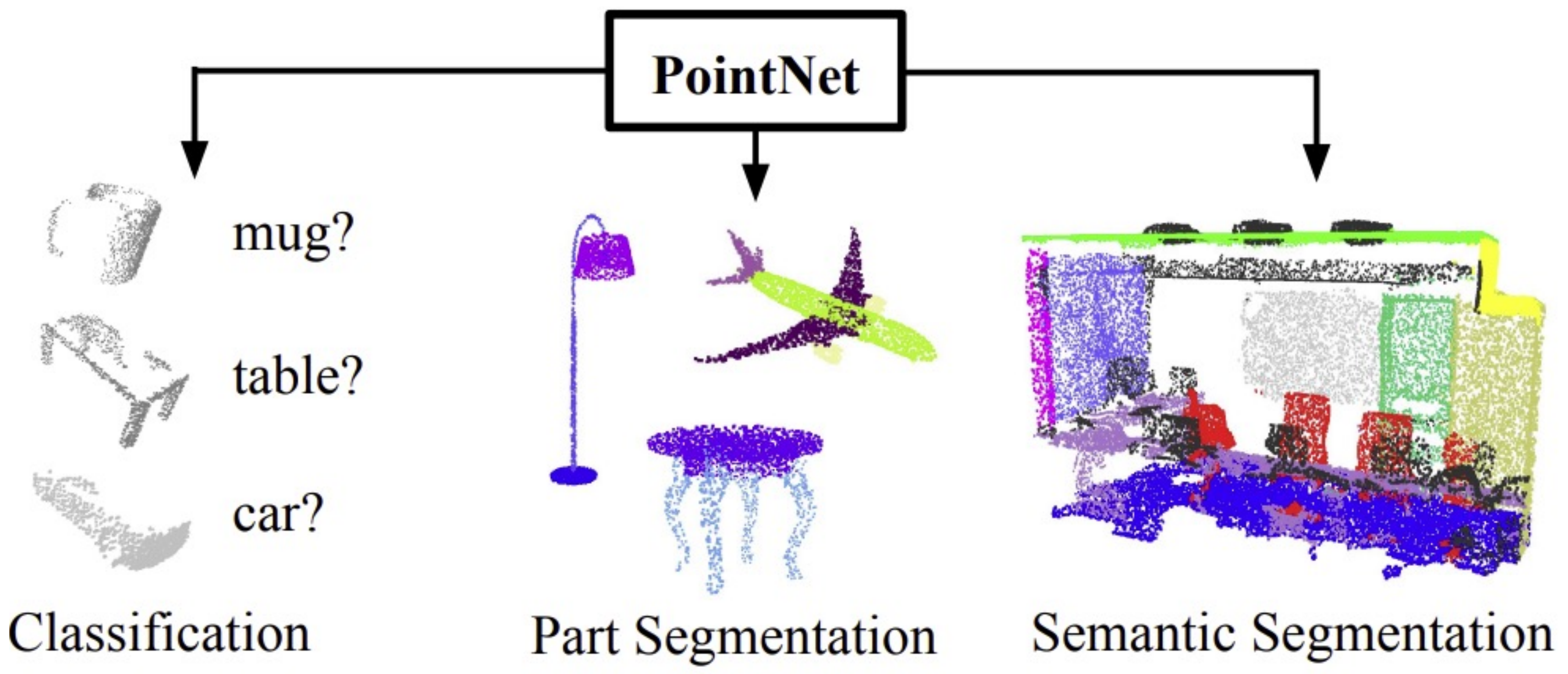
What about the removal (tag efficiency) of long-lived backgrounds?

PointNet for LL tag ~ Modeling Muon Spallation ~

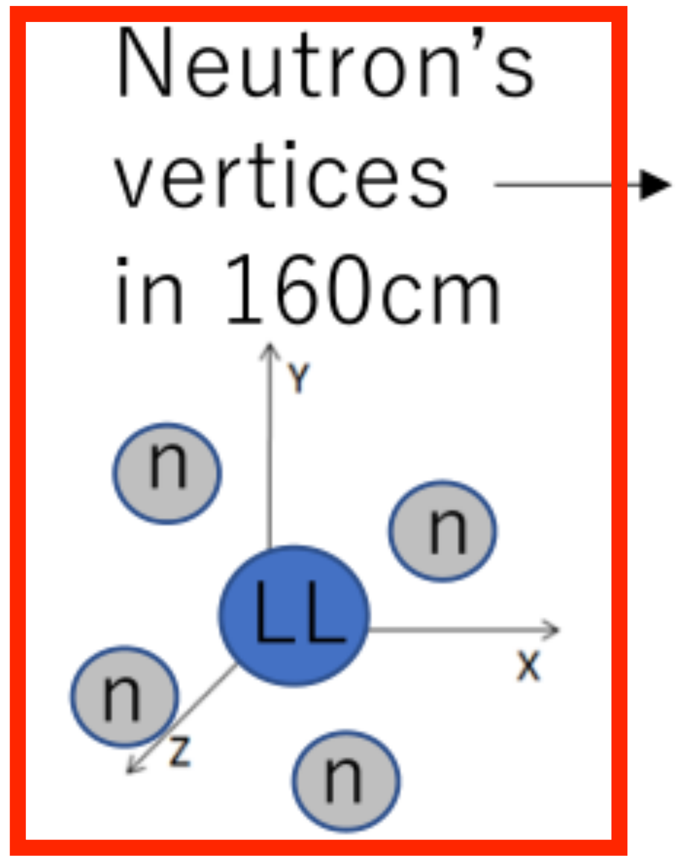
for Goto-san
(M2 student)

PointNet

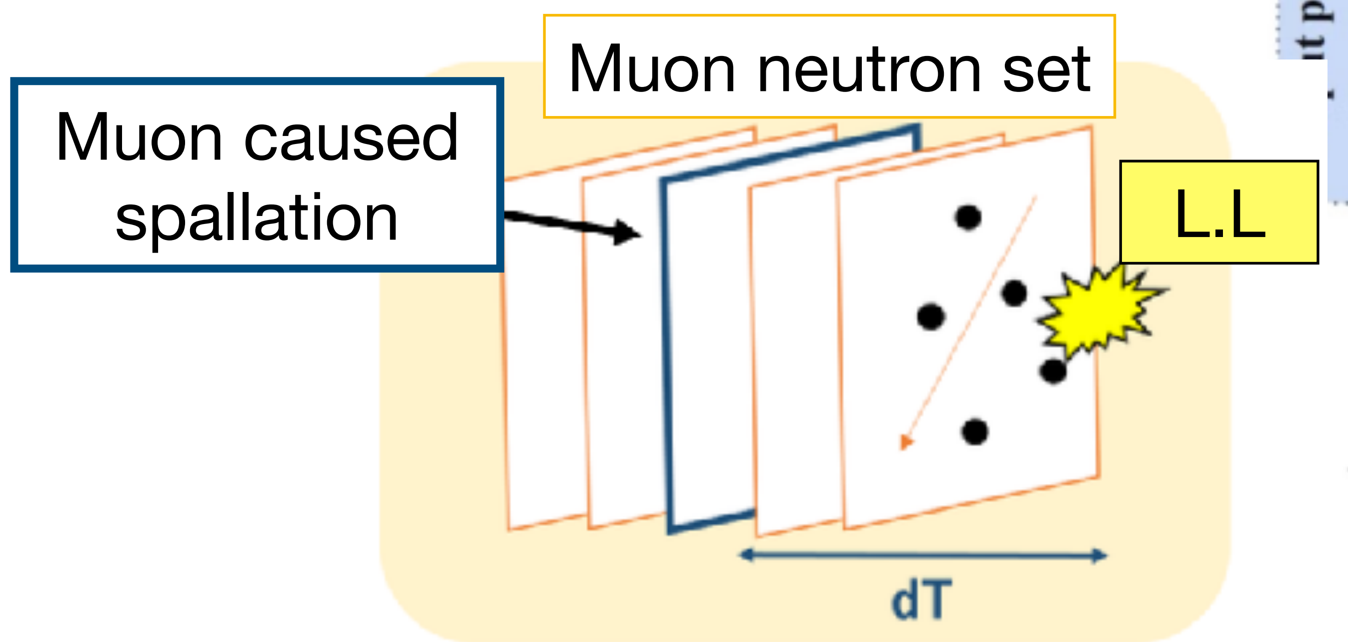
- PointNet: Efficient 3D point cloud processing for object classification and segmentation.
- ex) Used to segment LiDAR (Light Detection and Ranging) Data.
- Long-lived tag using neutrons and muon.



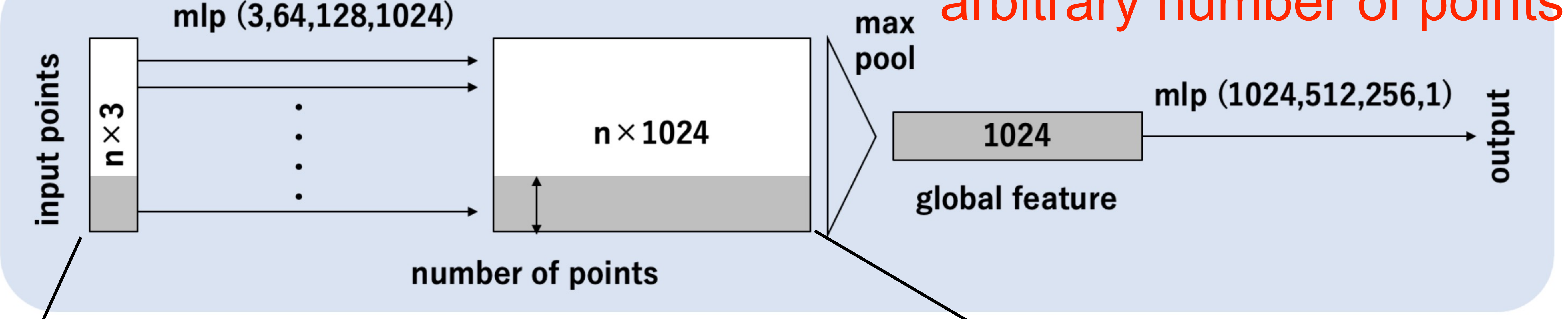
Data structure (neutrons + dT from muon)

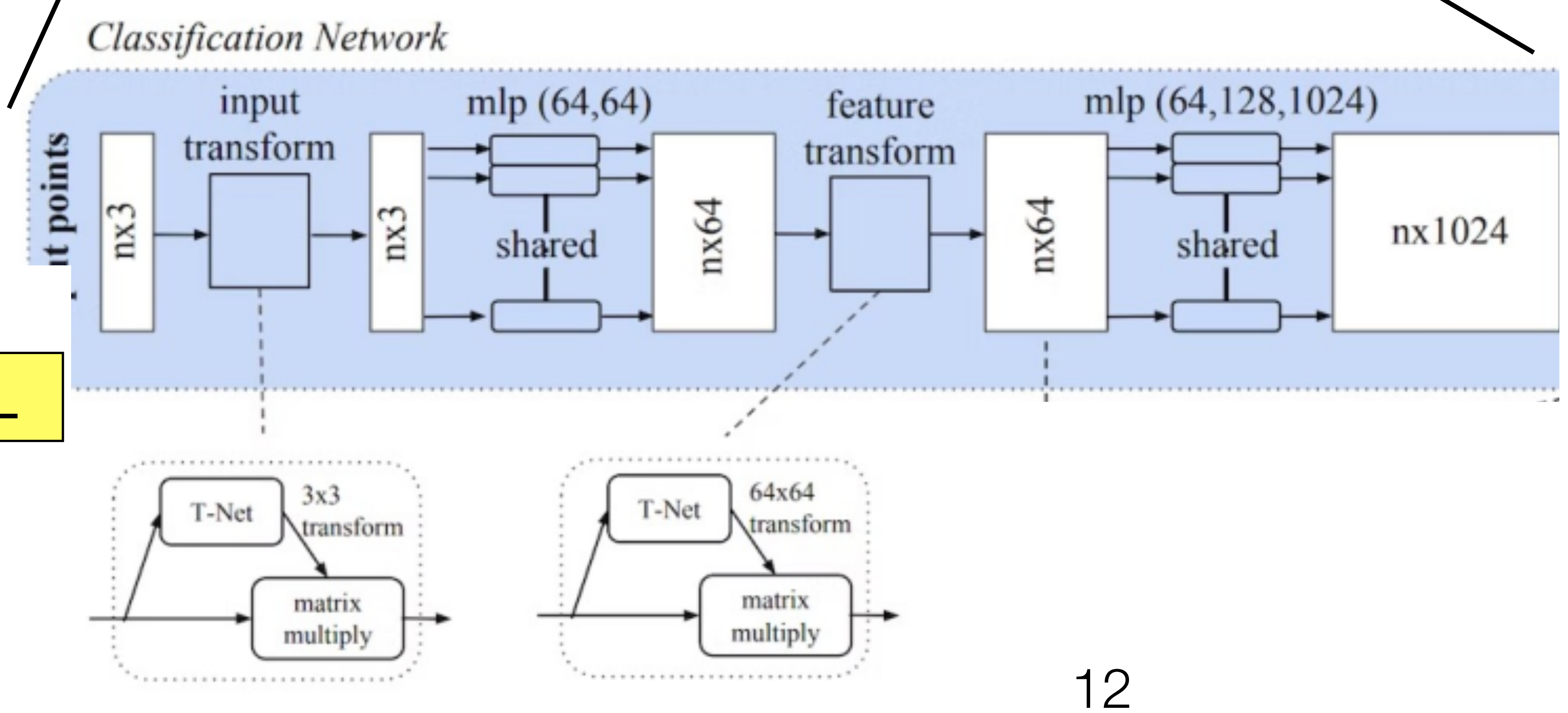


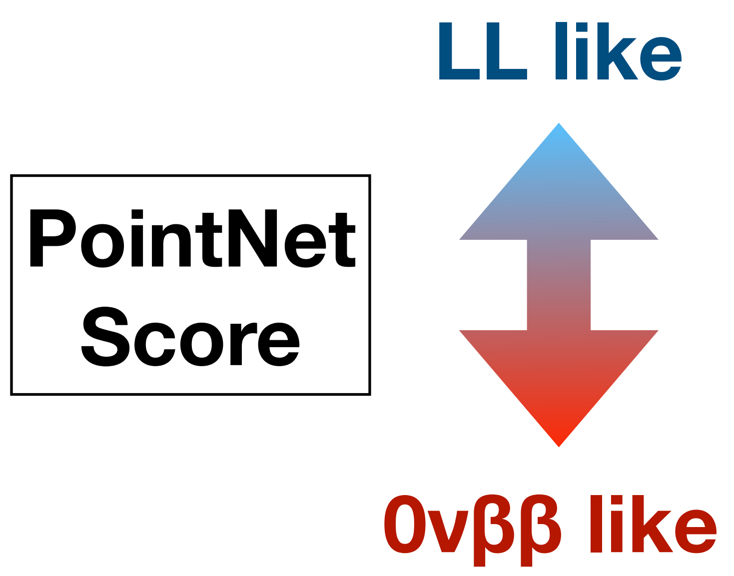
+ dT



Improved to process arbitrary number of points!





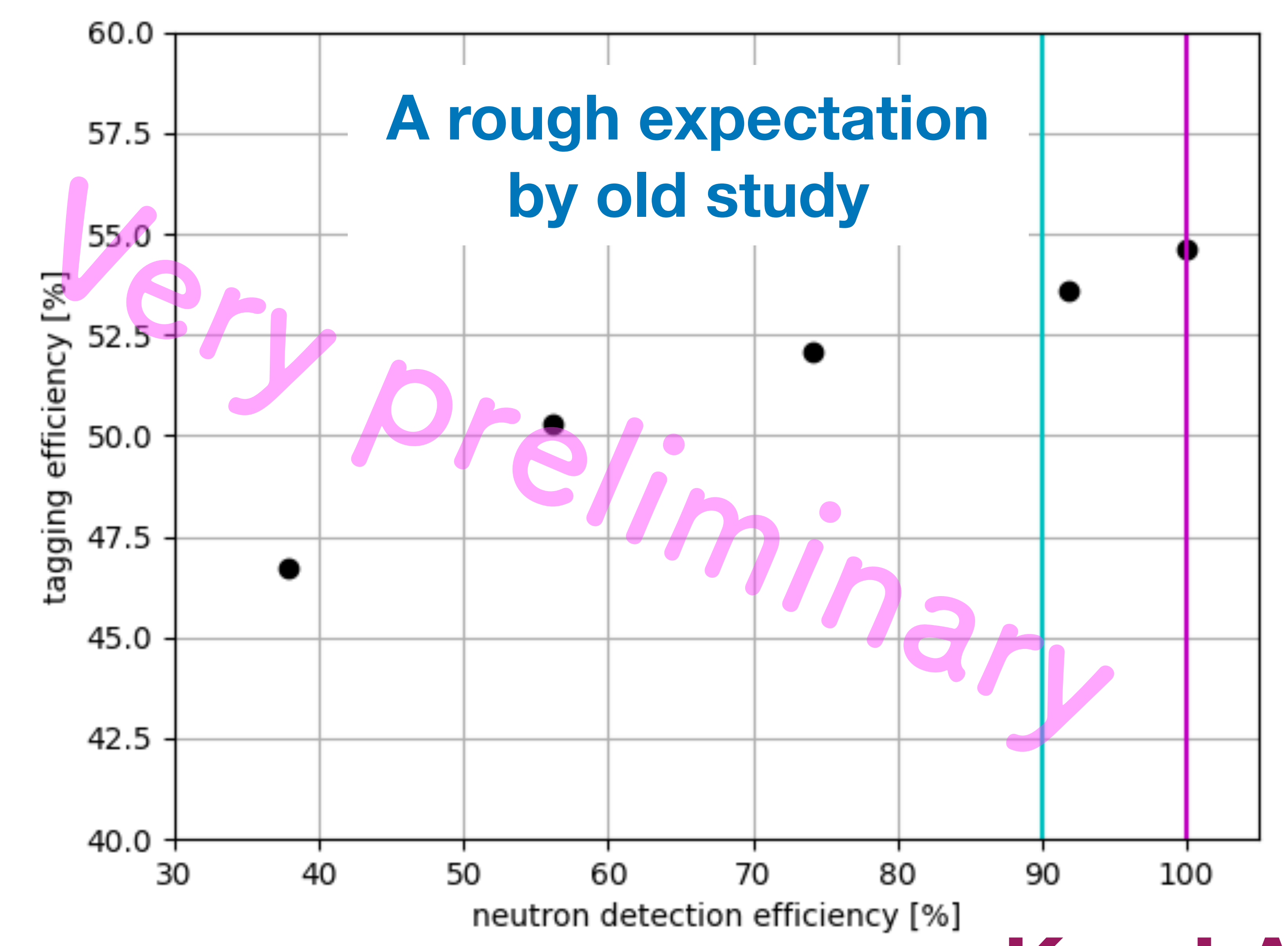


- Developed a Long-Lived (LL) tag using neural networks!
- It maximizes the use of information by neutrons compared to traditional likelihood methods!!

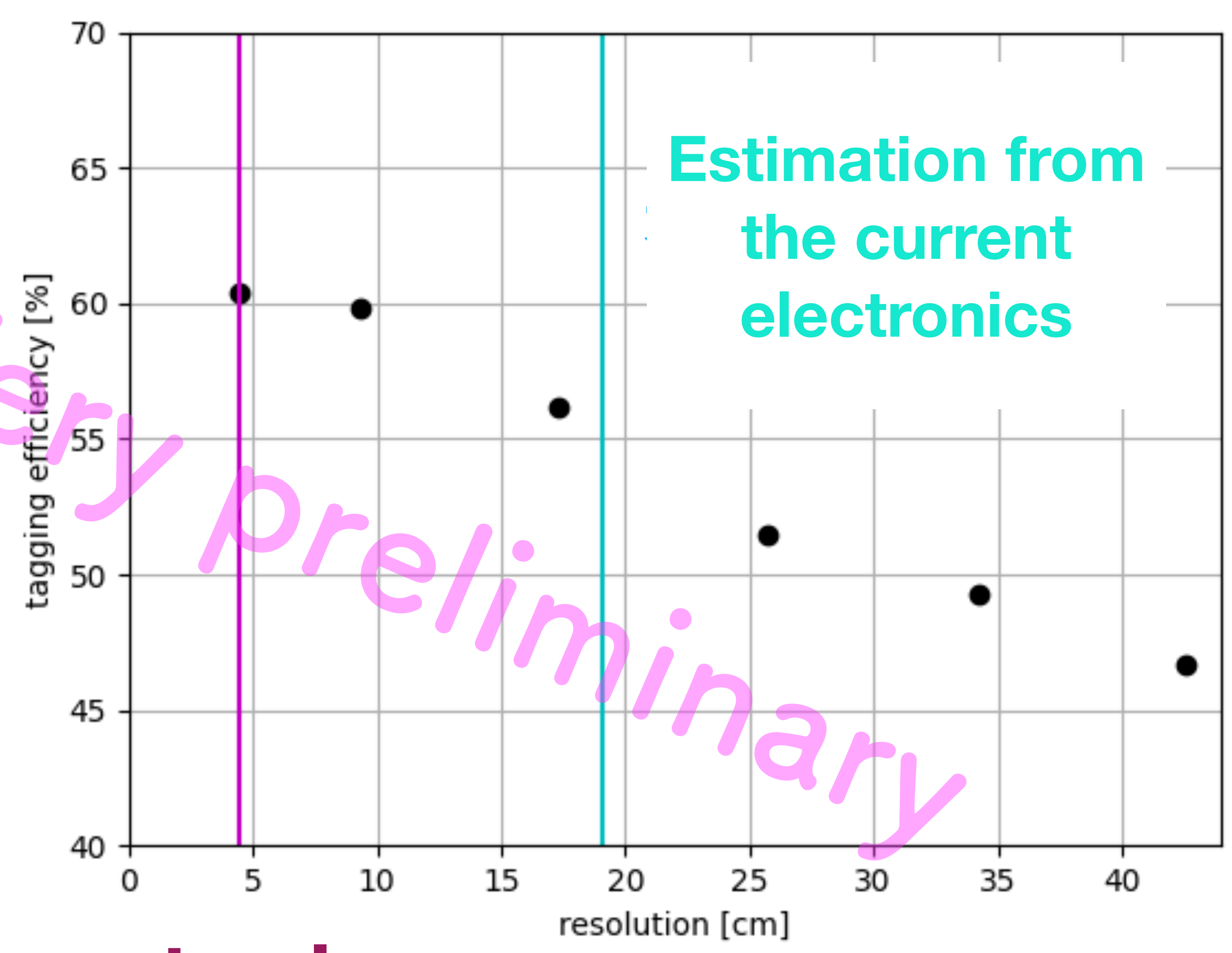
PointNet for LL tag : performance

for Goto-san (M2 student)

Tag efficiency vs neutron efficiency



Tag efficiency vs neutron vertex resolution



KamLAND2-Zen's target value

from Goto-san's thesis

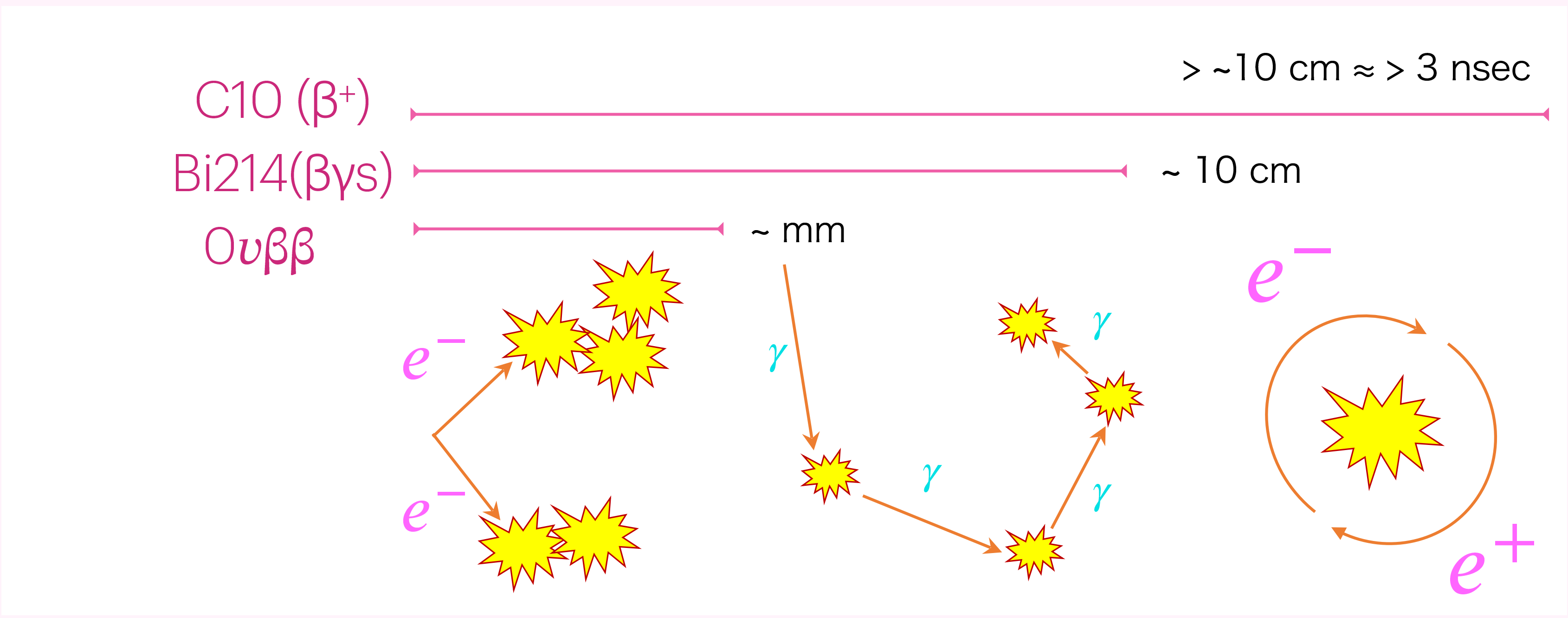
- For Zen800, an improvement in removal efficiency of 1.1 times compared to the current Likelihood methods (with a 10% signal sacrifice).
- In the case of 2Zen, an ideal scenario achieves a removal efficiency of ~65%!!
- In HPXeLS, assuming the Zen800 case, the removal efficiency is 1.3 times that of normal XeLS. (Because of less C-spallation, which interferes with the LL tagging.)

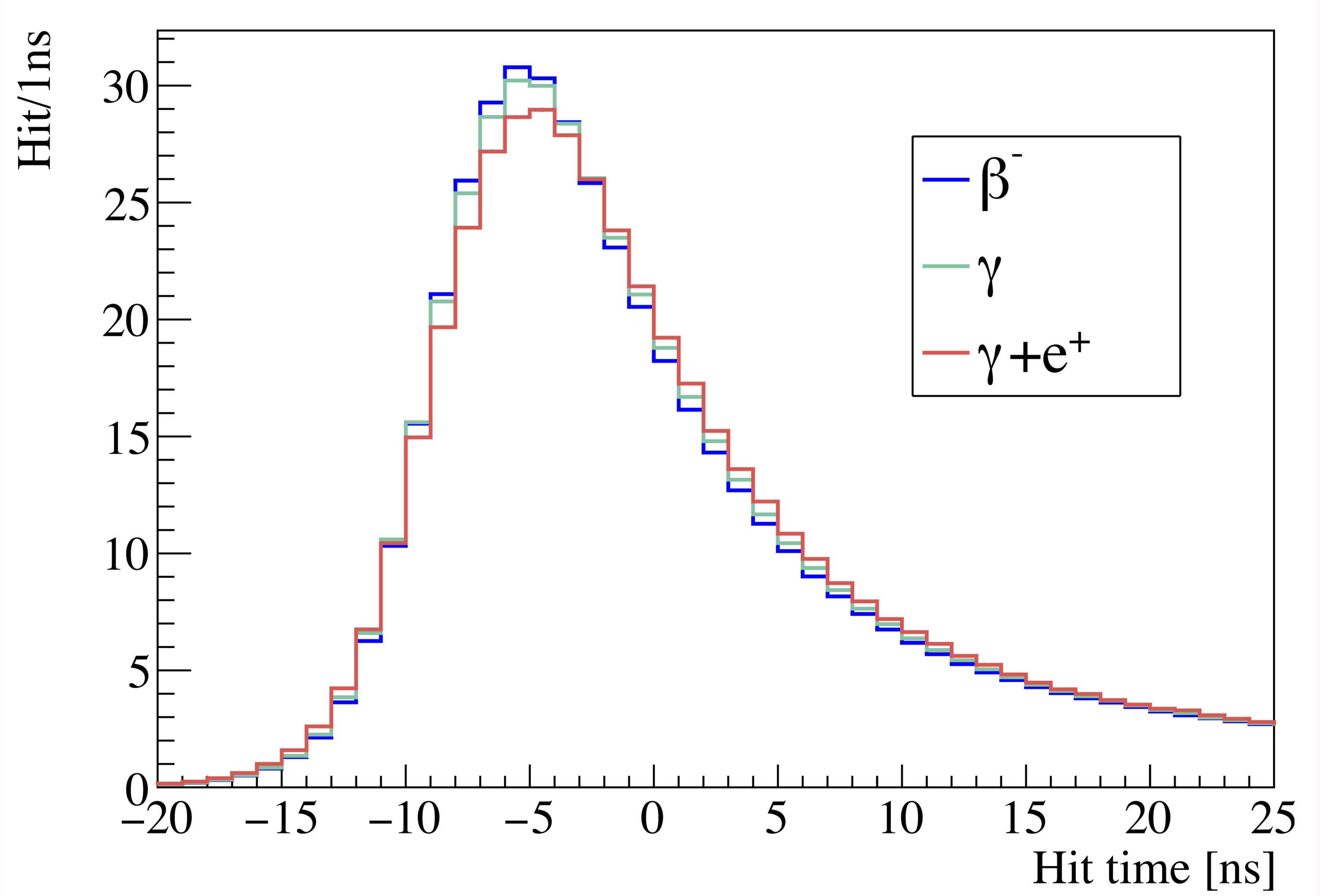
Particle Identification (PID) for LL veto

- Almost all LL backgrounds decay with gamma or(and) positron emission!! (by FLUKA and ENSDF study.)

- KamLAND-Zen utilizes event spread and positronium formation lifetimes for particle identification (PID) between β and γ/β+ discrimination at the ML.

β/γ(β+) discrimination

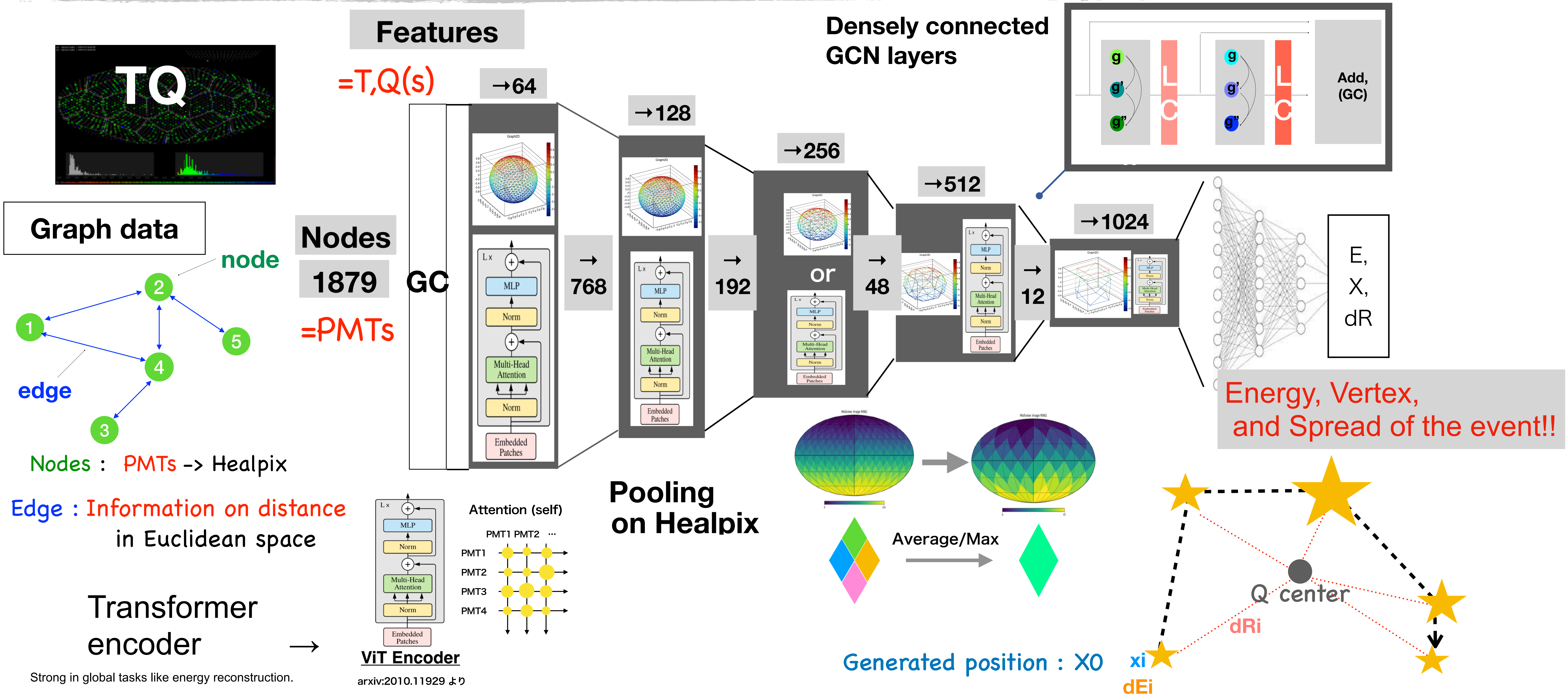




Event spread and oPs formation time delays are subtle features in pulse shapes.

PID tool to reduce the long-lived backgrounds (γ/β+) in KamLAND-Zen / KamLAND2-Zen was necessary for the evaluation of XeLS and other upgrades!

GNN (and Transformer) fitter



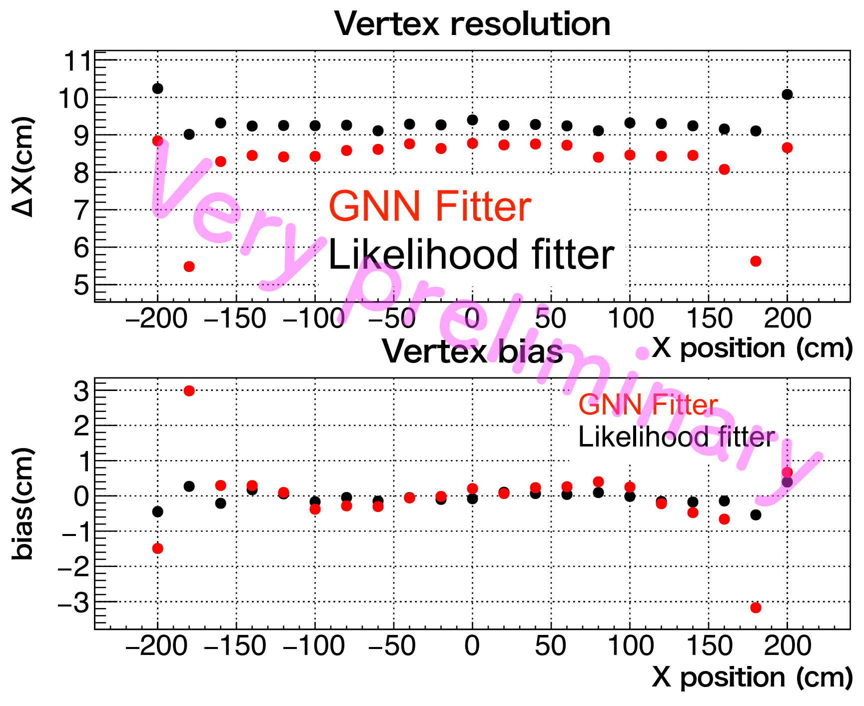
Developed a NN that simultaneously performs event reconstruction and Particle Identification (PID) !

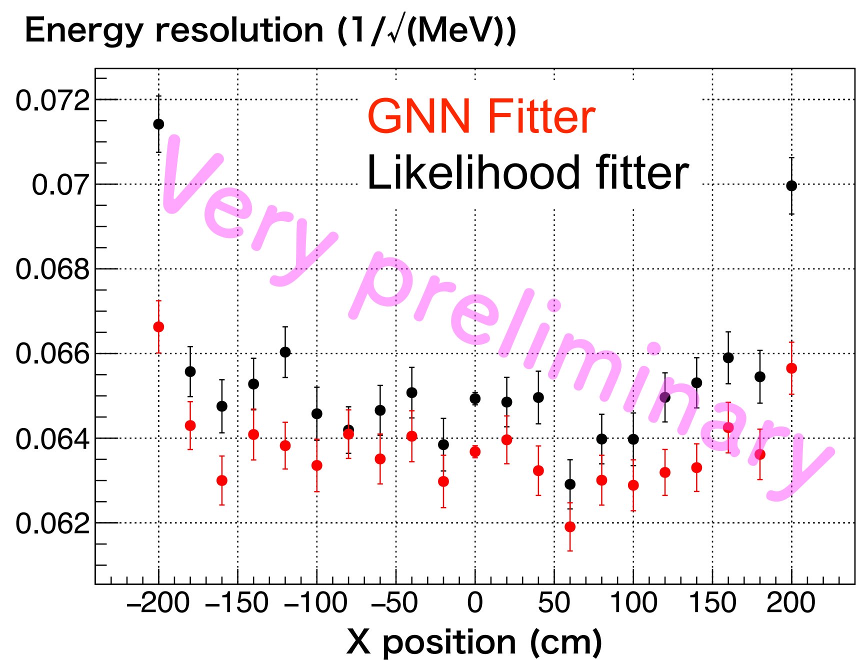
Charge center position: $x = \frac{\Sigma dE_i * x_i}{\Sigma dE_i}$

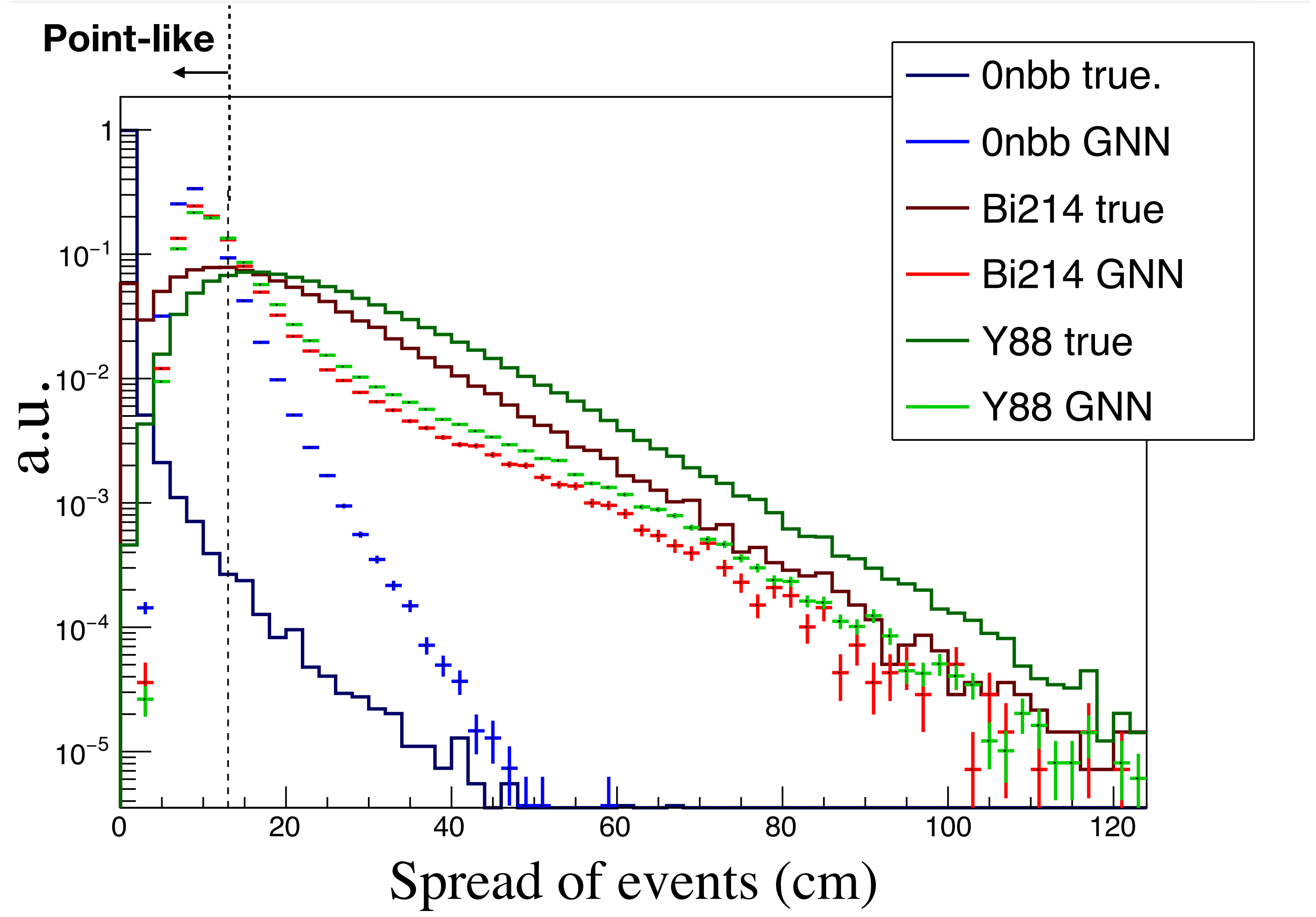
Charge weighted spread of event: $dR = \frac{\Sigma dE_i * dR_i}{\Sigma dE_i}$

GNN fitter : Performance

- Energy and vertex resolution, as well as PID performance of KL2-Zen like detector were confirmed through a simplified Geant4 simulation (without mirror effects).
  - Energy resolution : ~2% and Vertex resolution : ~3 cm for β @ 2.46MeV.
  - 72% PID efficiency was achieved!!







Distribution of event spread. $0\nu\beta\beta$events are point-like, while ^{214}Bi and Y88 spread due to γ.

Efficiency at 10% signal sacrifice.

	KLZ800	KL2-Zen (ToyMC)
$0\nu\beta\beta$	0.10	0.09
Xe spallation	0.29	0.72
^{214}Bi in XeLS	0.28	0.66
^{10}C	0.39	0.81
^{137}Xe	0.11	0.15
^{214}Bi on IB	0.55	0.89

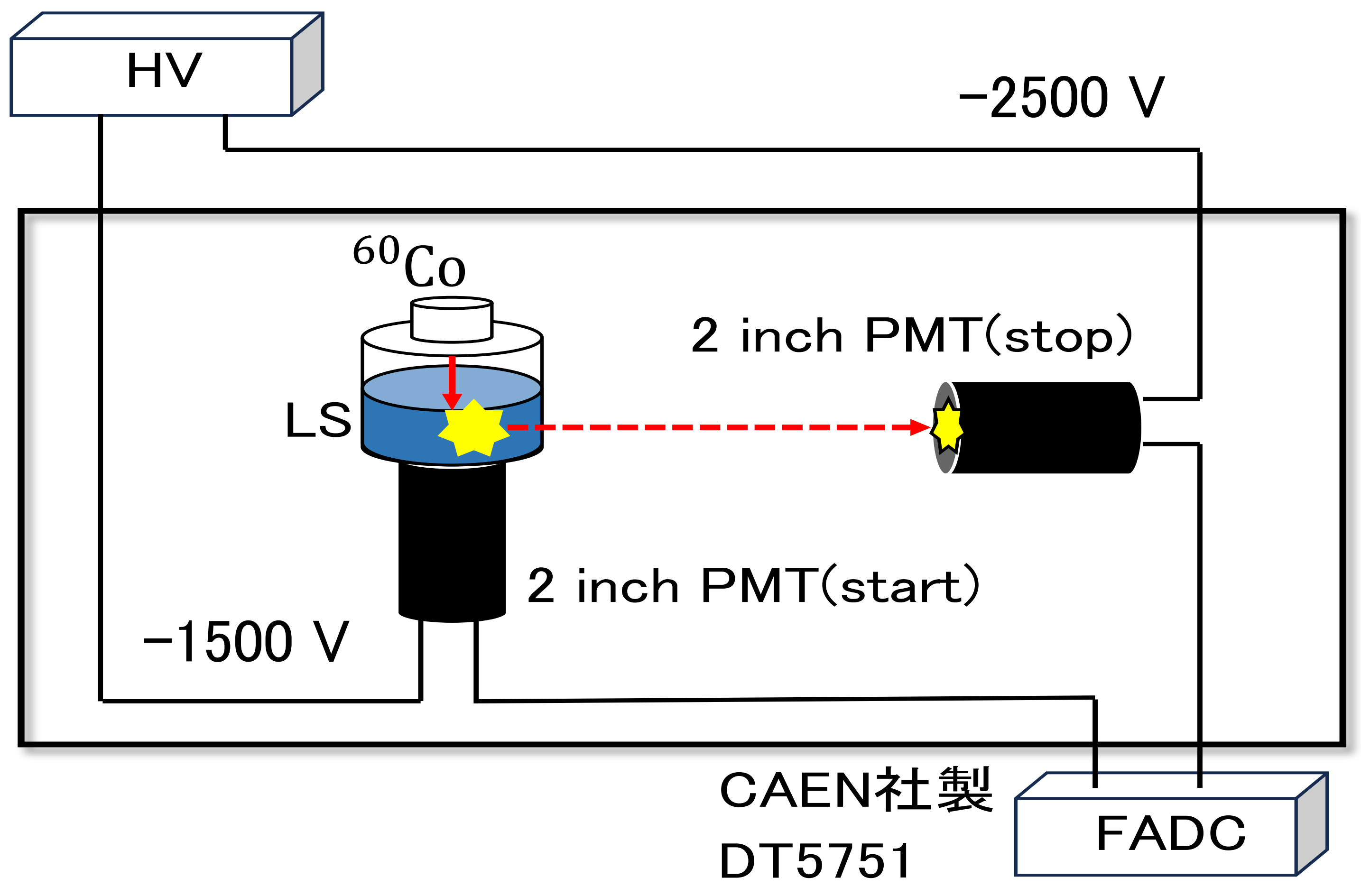
Very preliminary

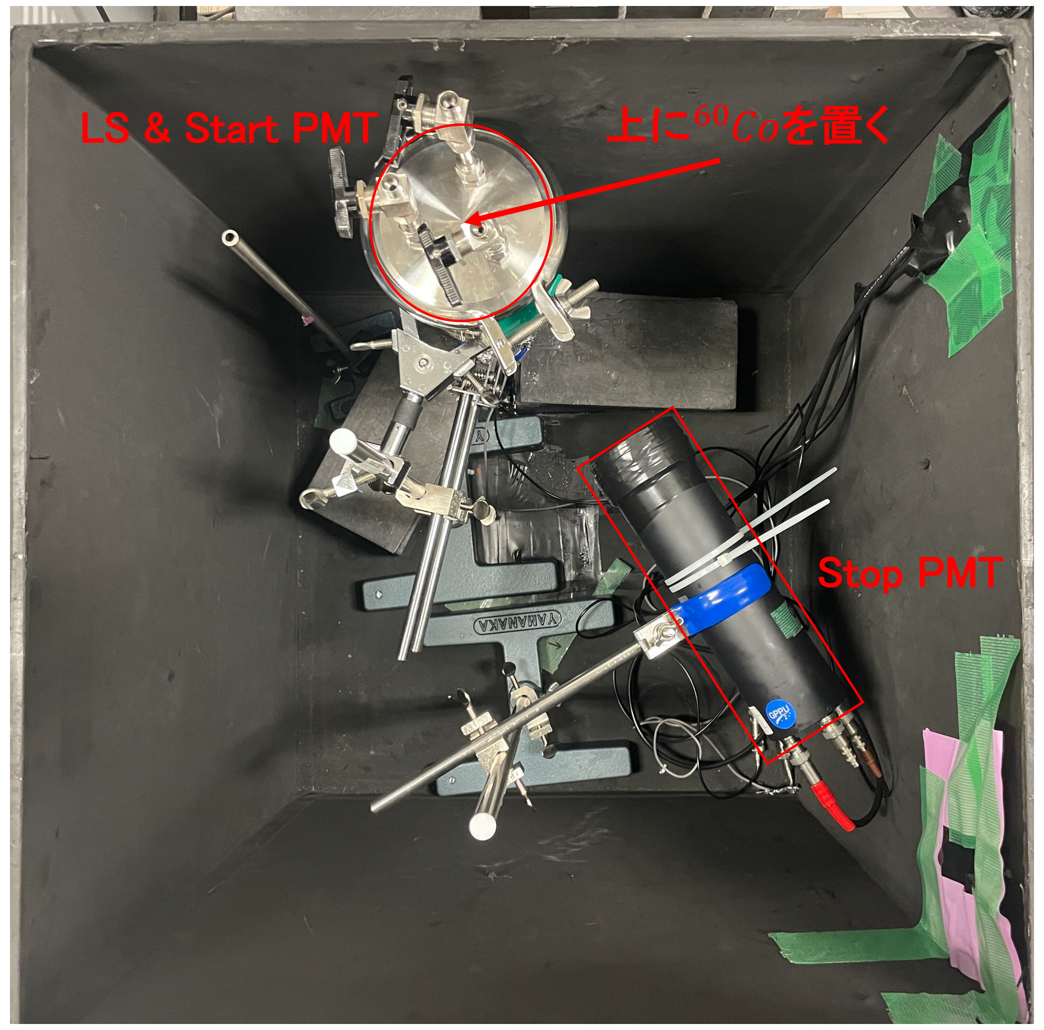
- GNN fitter offers direct sensitivity predictions!!
- Simulation with Mirror and new XeLS are under processing!!

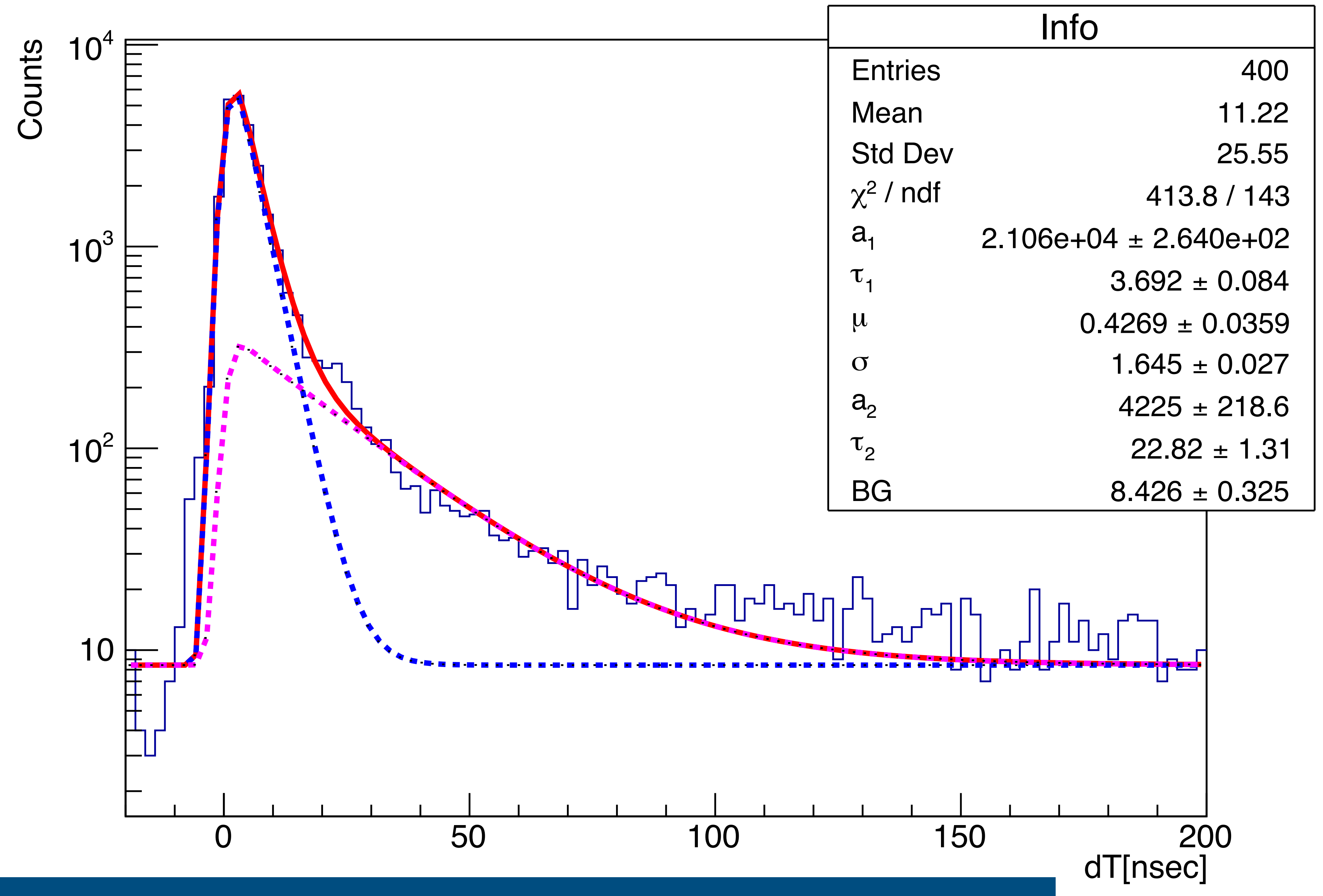
XeLS : Time spectrum measurement

for Watanabe-san
(M2 student)

Setup of the scintillation time measurement using ^{60}Co source







	τ1 (sec)	τ2 (sec)	A_τ2/A_τ1
XeLS w/o Xe	4.06 ± 0.12	18.5 ± 1.4	0.167 ± 0.017
XeLS (Bis+PPO)	3.74 ± 0.12	18.2 ± 1.3	0.196 ± 0.018
HPXeLS (2 atm)	3.69 ± 0.08	22.8 ± 1.3	0.201±0.011

→The scintillation timing coefficients for XeLS and HPHeLS have been measured for the first time!

→Used as input for simulations to investigate the impact on PID performance.

Summary

- Developed N.N. methods to remove Xe spallation BG (LL) in next-generation large LS detectors (KamLAND2-Zen).
  - Provided comprehensive evaluation metrics for XeLS, HPXeLS, and other upgrades.
- Developed measurement system for time spectra and light yield in various XeLS and high-pressurized XeLS.
- Todo: Evaluate XeLS and HPXeLS with the developed N.N. tool since the input for the simulation has been measured.