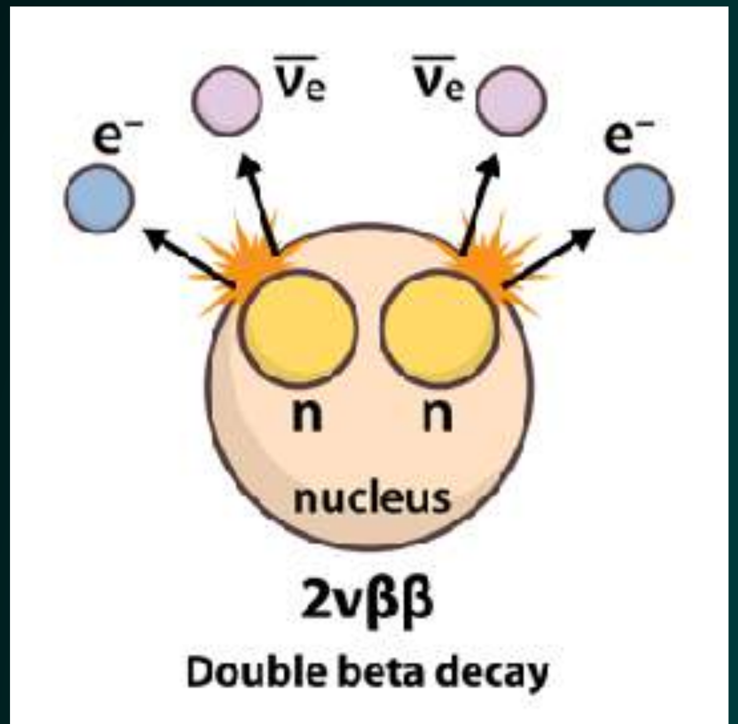
57th Rencontres de Moriond 2023

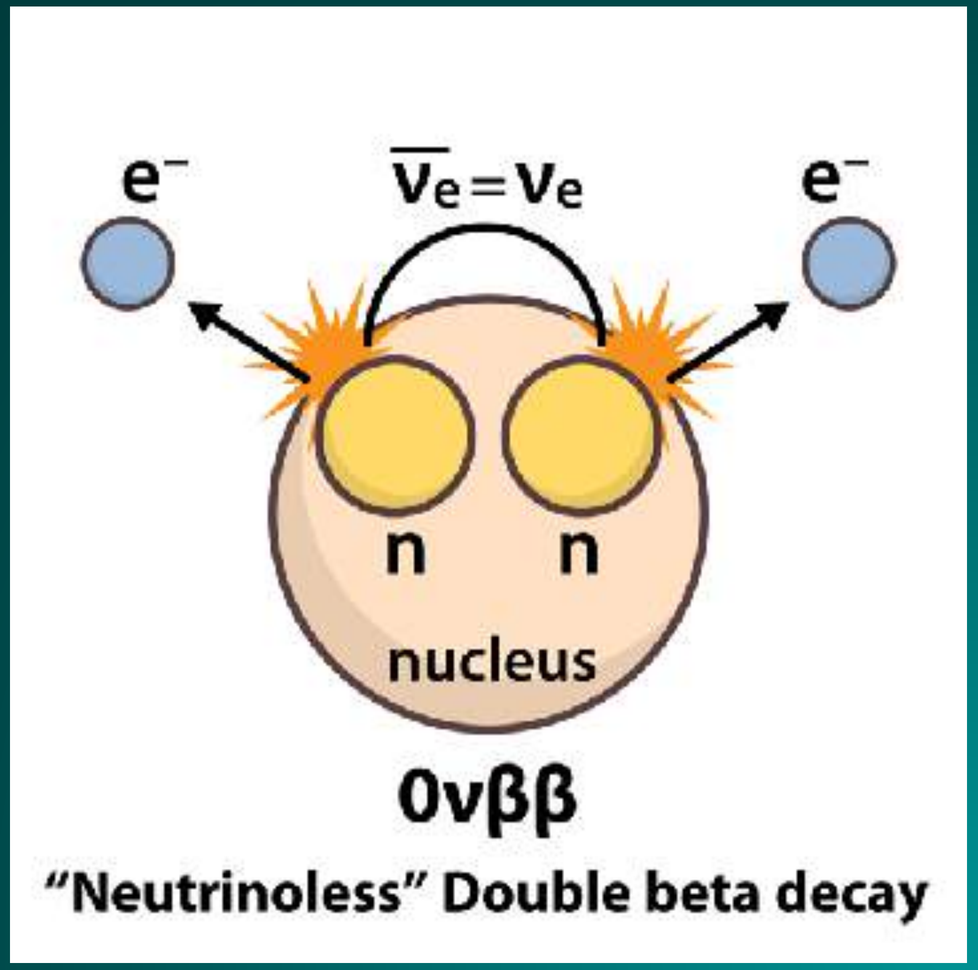
EW session Mar. 19

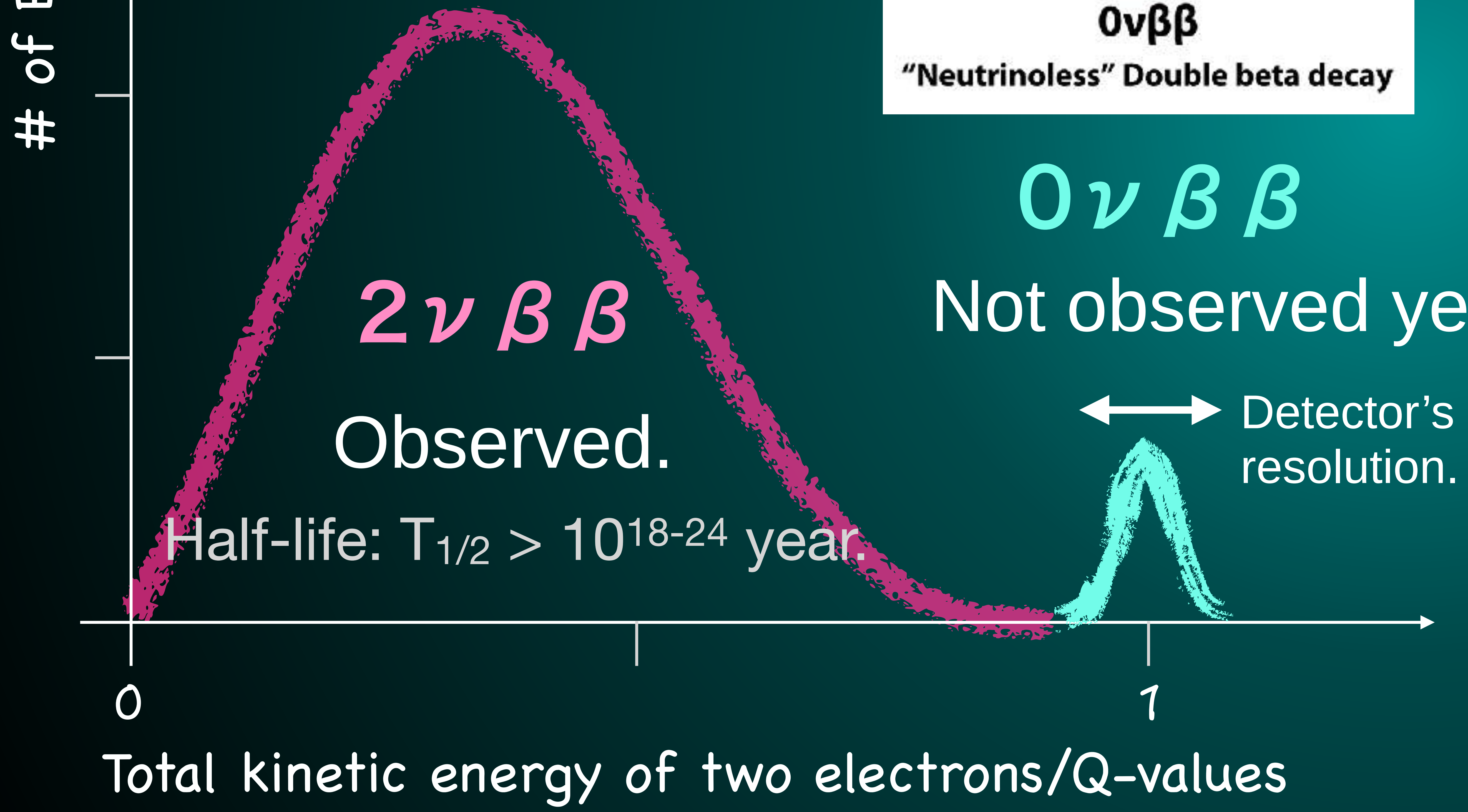
KamLAND-Zen

Hideyoshi Ozaki,
for KamLAND-Zen collaboration
RCNS Tohoku university

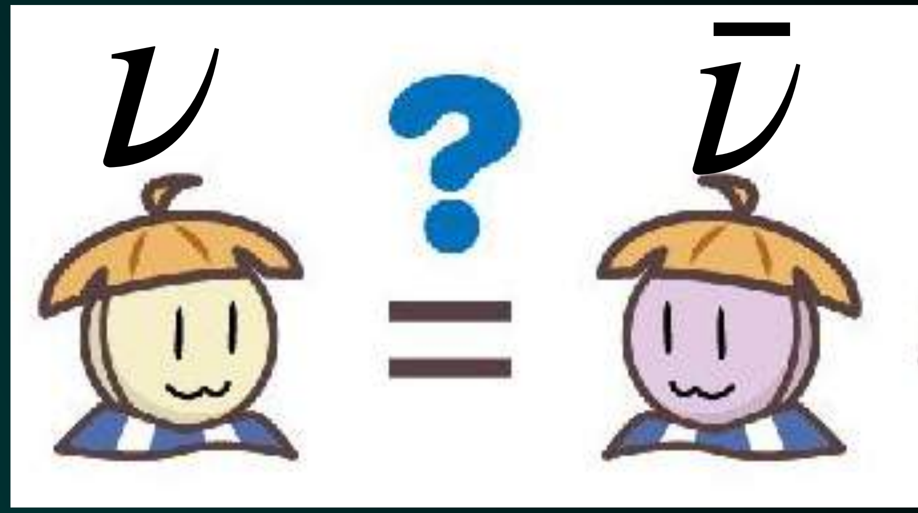
Neutrinoless double-beta decay







Are neutrinos Majorana particles?



Observation of $0\nu\beta\beta$ decay:

- Lepton number violation.
- Proof of Majorana neutrinos.

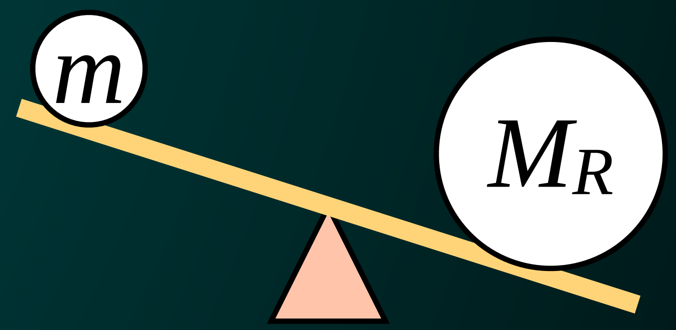
ν_L, ν_R, N_L, N_R

Too heavy to observe .

Majorana neutrino is key for

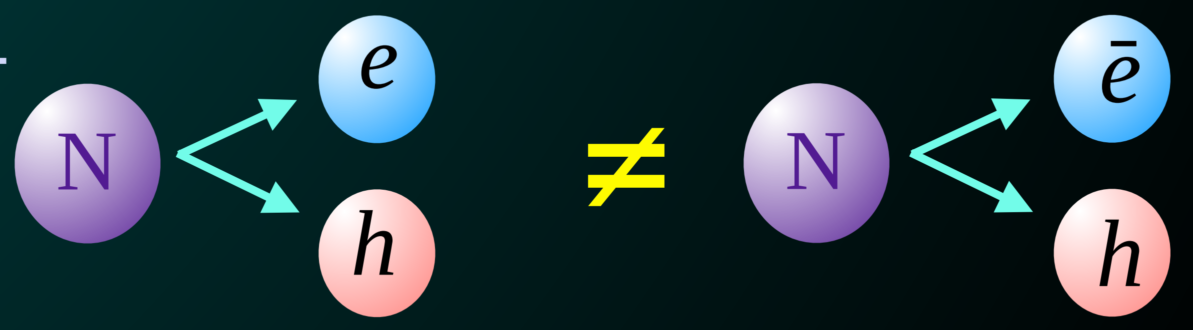
$$m \sim \frac{m_D}{M_R}$$

Seesaw mechanism



and

Matter dominant universe (via Leptogenesis).



0νββ experiment

Assuming 3-gen of neutrinos and light Majorana ν exchange,

Observable **Effective Majorana mass**

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(g_{A,\mathrm{eff}}/g_A)^4|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

Large model uncertainty.

$$\langle m_{\beta\beta}\rangle = |\Sigma_i U_{ei}^2 m_{\nu_i}|$$

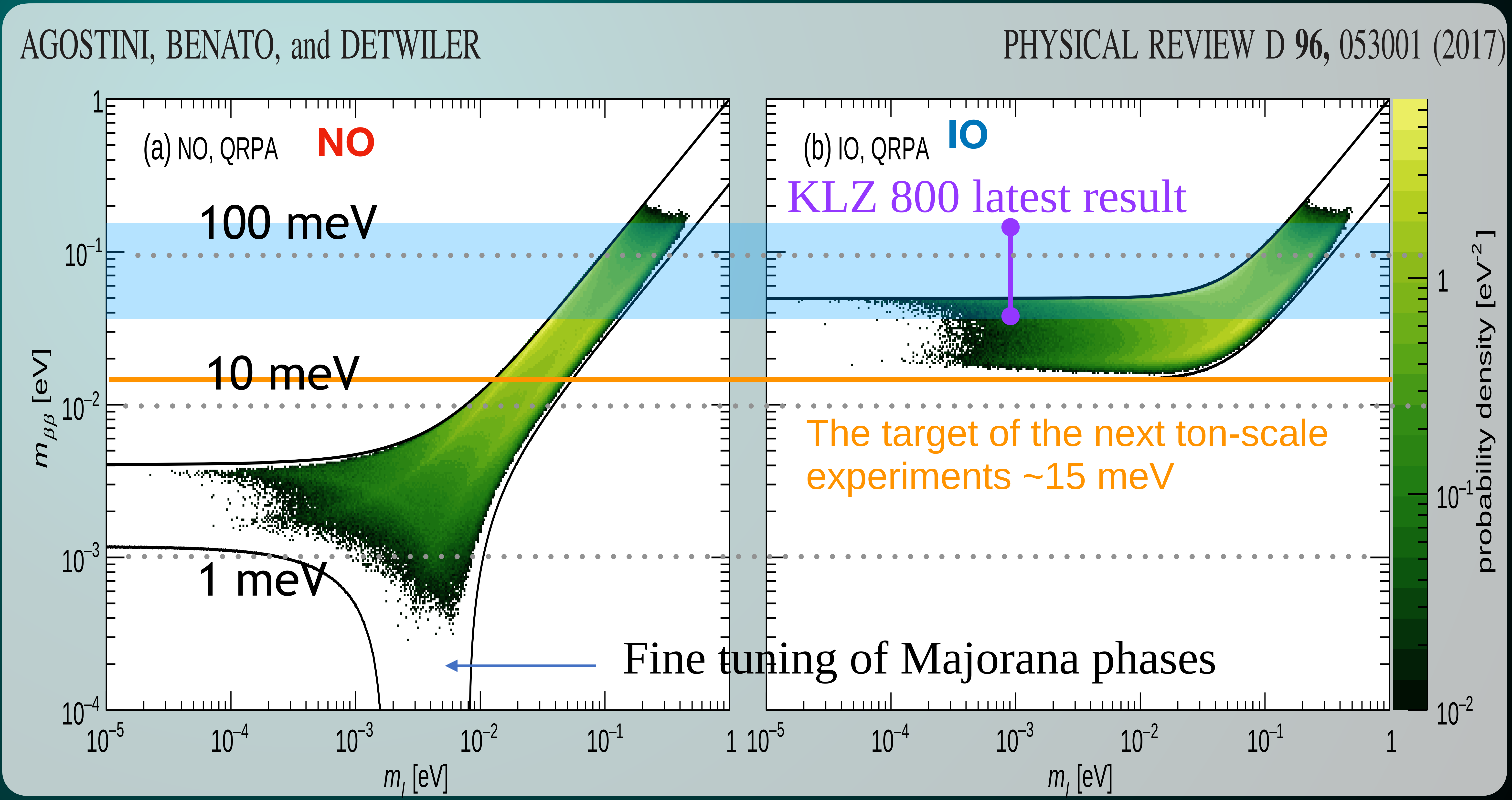
Half-life sensitivity : $T^{0\nu}_{1/2} \propto \begin{cases} \sqrt{\dfrac{M \times t}{B \times \Delta E}} & \text{(w/ BG)} \\ Mt & \text{(w/o BG)} \end{cases}$

M … Mass, t … observation time, B … BG rate, ΔE … energy resolution

Requirement for the experiment

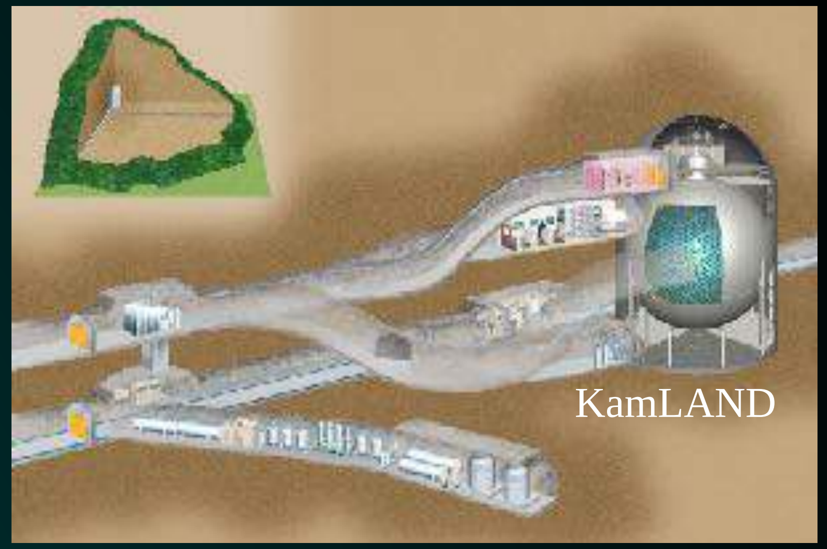
1. Large isotope mass
2. No (low) background
3. High energy resolution

KLZ deployed the largest amount of ββ nuclei.

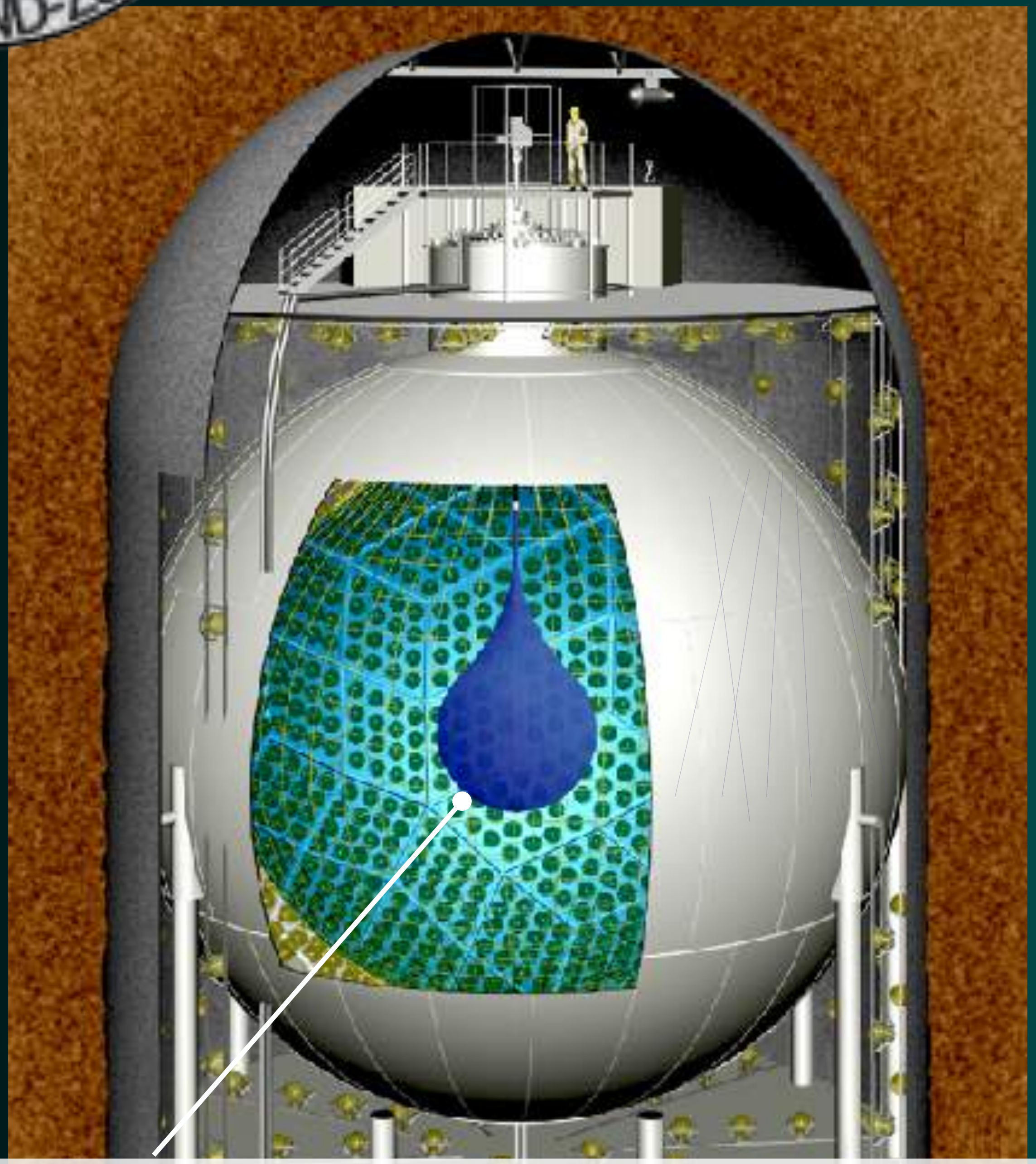


KamLAND-Zen

Located 1,000 m (2,700 m w.e.) underground in Mt. Ikenoyama, Japan.



- The largest amount of ββ nuclei.
- Low BG by distillation and filtration of both LS and Xenon.
- Pure LS as an active shielding for external BGs.
- Source on/off option and so on…



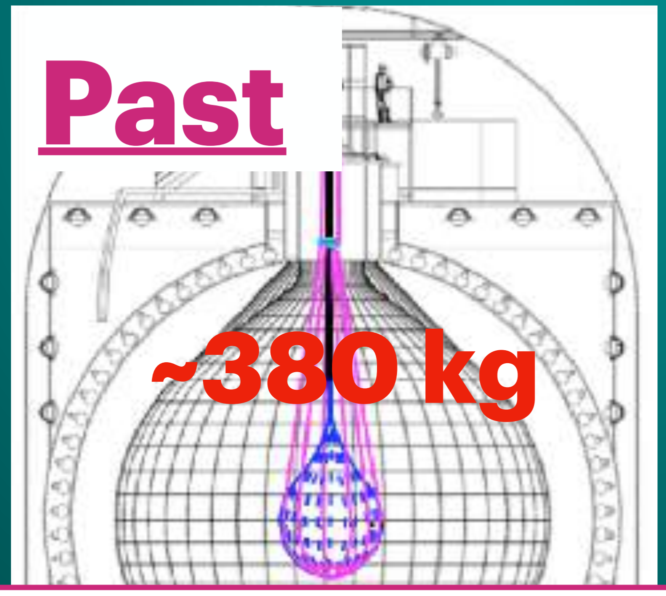
Xe-LS		LS	
Decane	82%	D12	80%
PC	18%	PC	20%
PPO	2.4 g/L	PPO	1.4 g/L
Xe	~3.1 wt%		

RI in XeLS:
^{238}U ~ 1.5×10^{-17} g/g,
^{232}Th ~ 3×10^{-16} g/g

Resolutions:
ΔE ~ 6.7%/ √E(MeV)
ΔX ~13.7 cm/ √E(MeV)

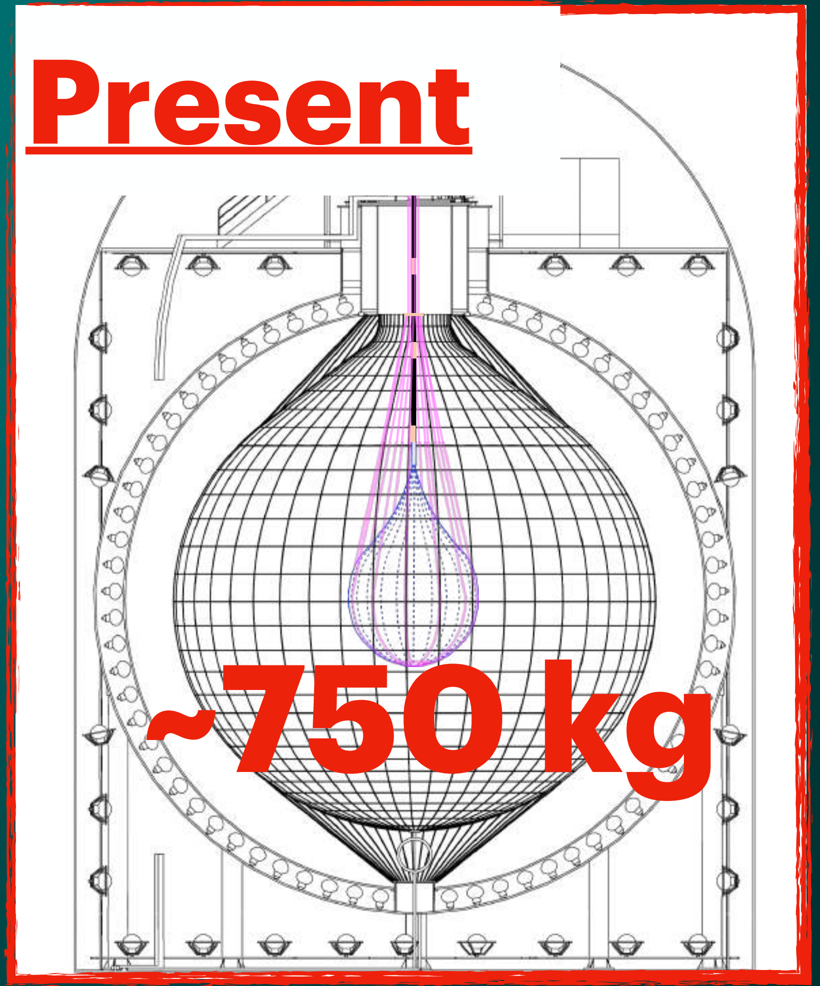
Demonstrated scalability!!

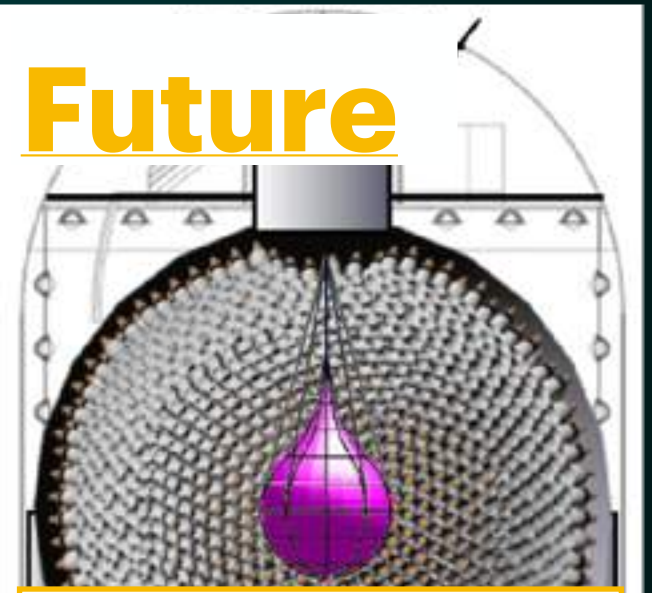
Duration: 2011 ~ 2015



Phase I + Phase II:
$T_{1/2} > 1.07 \times 10^{26}$ yr (90% C.L.)
Phys. Rev. Lett. 117, 082503

Duration: 2019~





Target:
$T_{1/2} > 2 \times 10^{27}$ yr

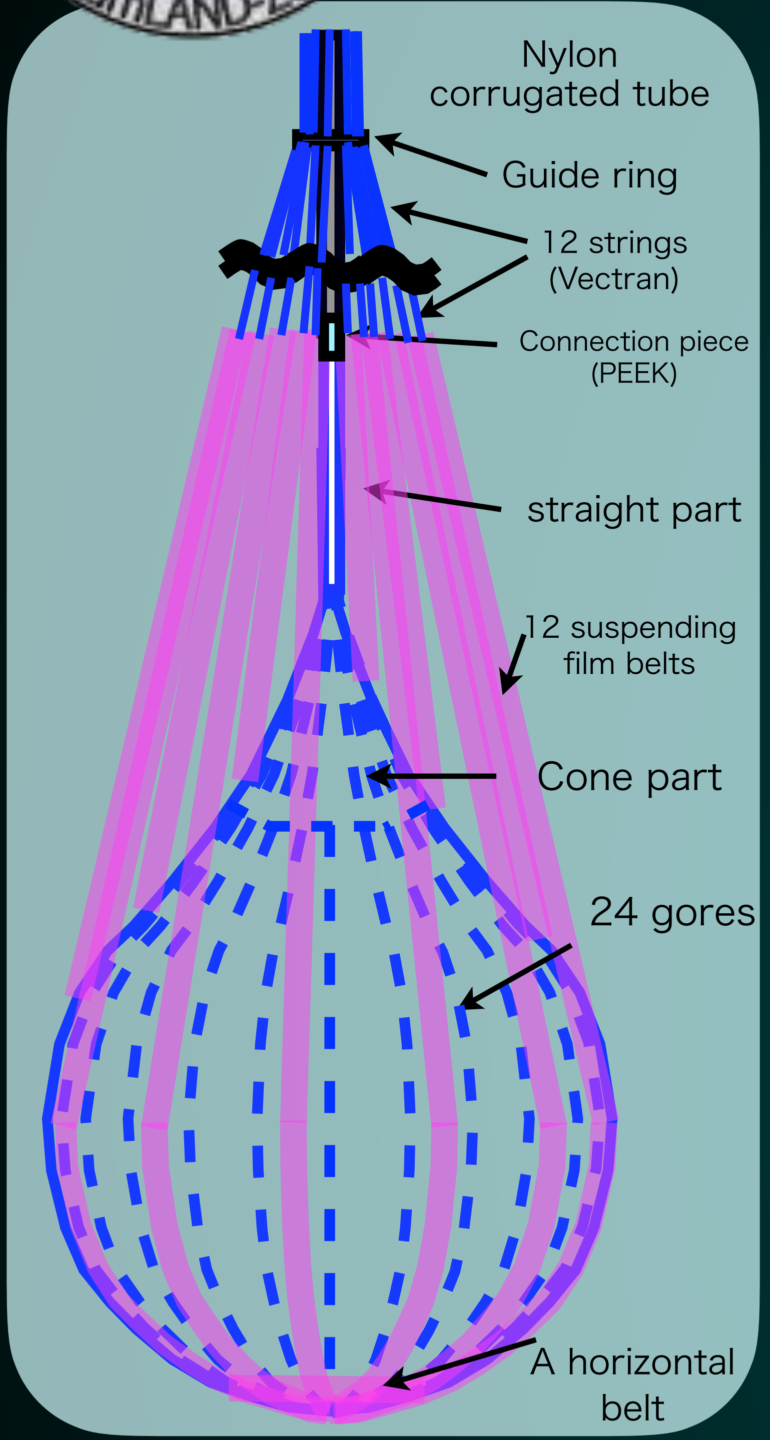
KamLAND-Zen 400:
- Mini-balloon Radius = 1.54 m
- Xenon mass = 320 ~ 380 kg

KamLAND-Zen 800:
- Mini-balloon Radius = 1.90 m
- Xenon mass = 745±3 kg

KamLAND2-Zen:
- Xenon mass ~ 1ton
- Aiming at 100% Photocoverage

Zen 800 construction

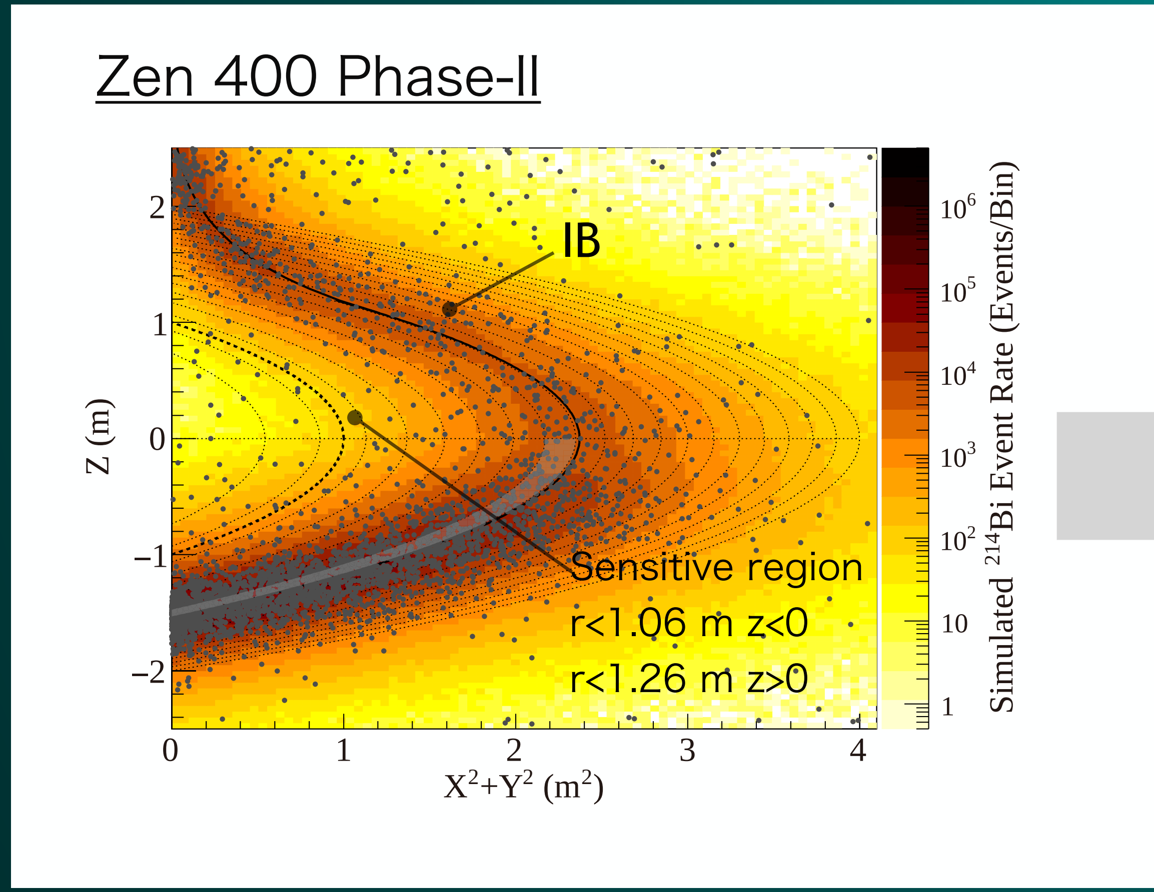
The KamLAND-Zen collaboration
et al 2021 *JINST* **16** P08023

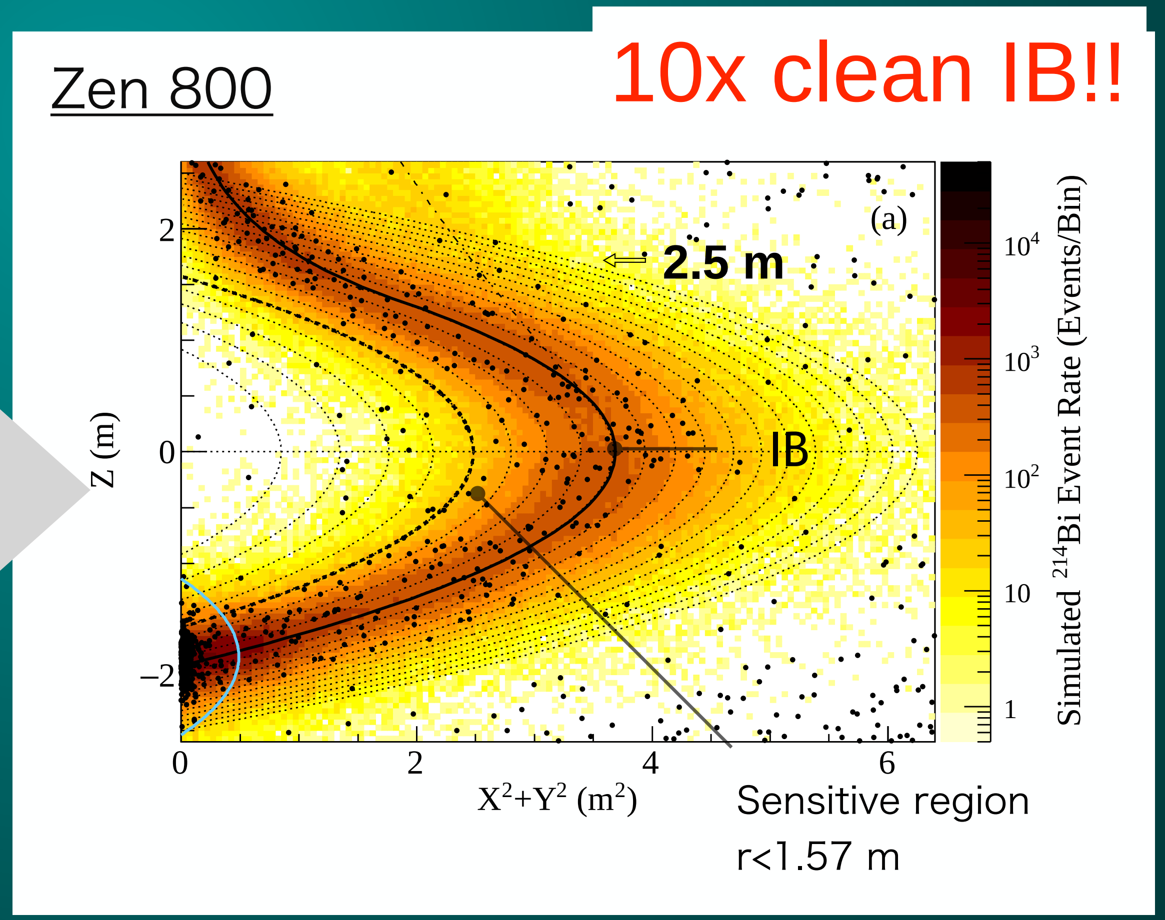


Inner-ballon fabrication in the cleanest level cleanroom, Sendai.

Contamination comes from workers.

Fresh clean suit, goggles, double gloves, cover films, anti-static, etc



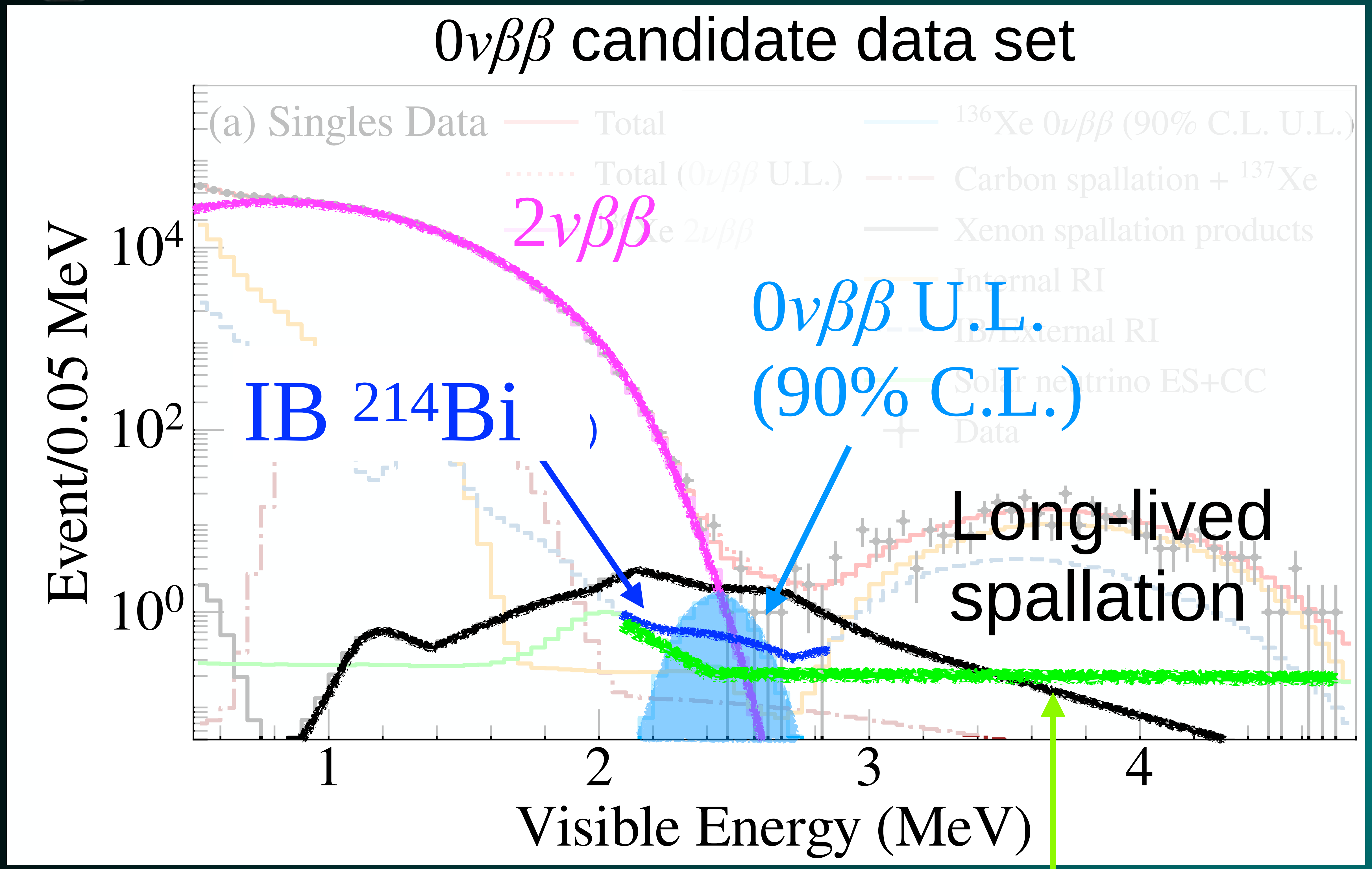


^{110m}Ag, ^{137}Cs, and ^{134}Cs were not detected from the Zen800 IB.

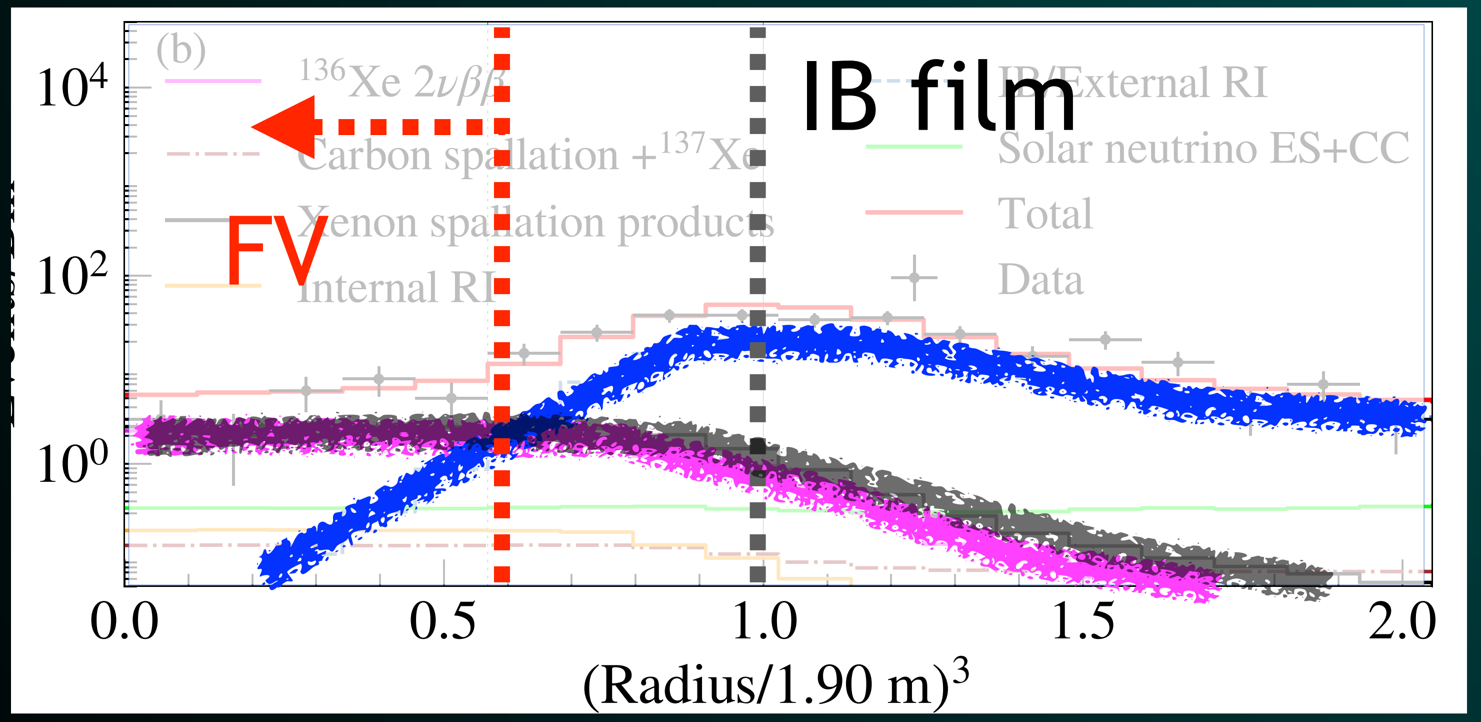
	U-238 (g/g)	Th-232 (g/g)	V (m3)
Zen400 Phase-II	~5×10^{-11}	~3×10^{-10}	16.7
	~1/10	~1/10	~x2
Zen800	~3×10^{-12}	~4×10^{-11}	30.5

Achieved >3x highly sensitive volume!

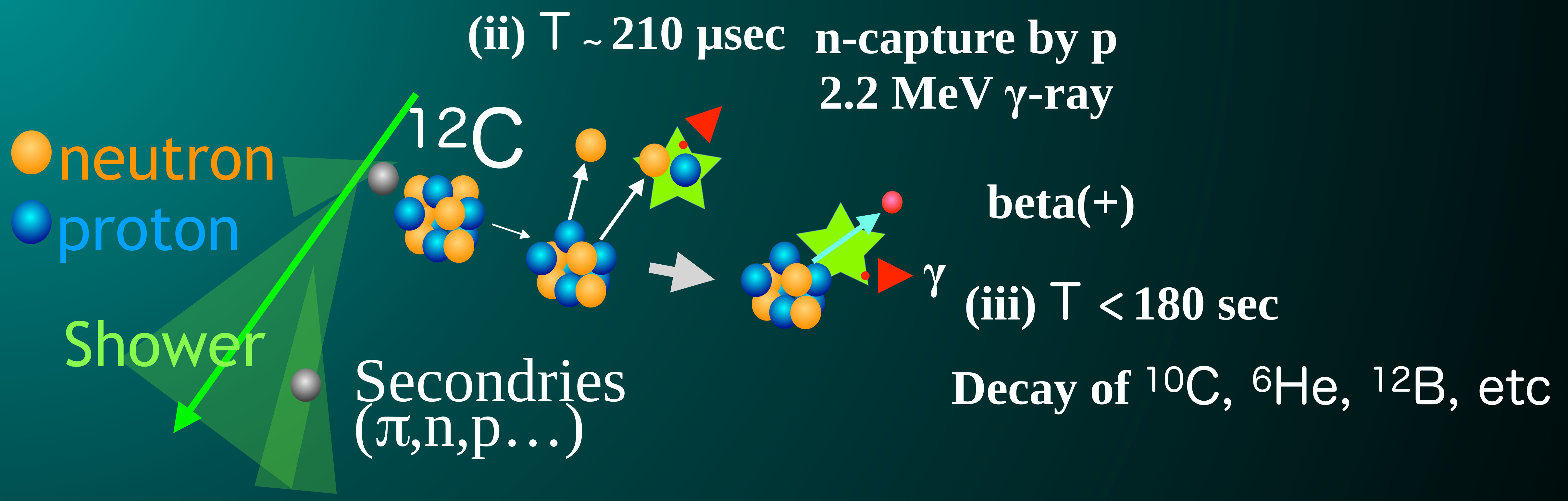
Backgrounds in KLZ



Solar neutrino's electron scattering



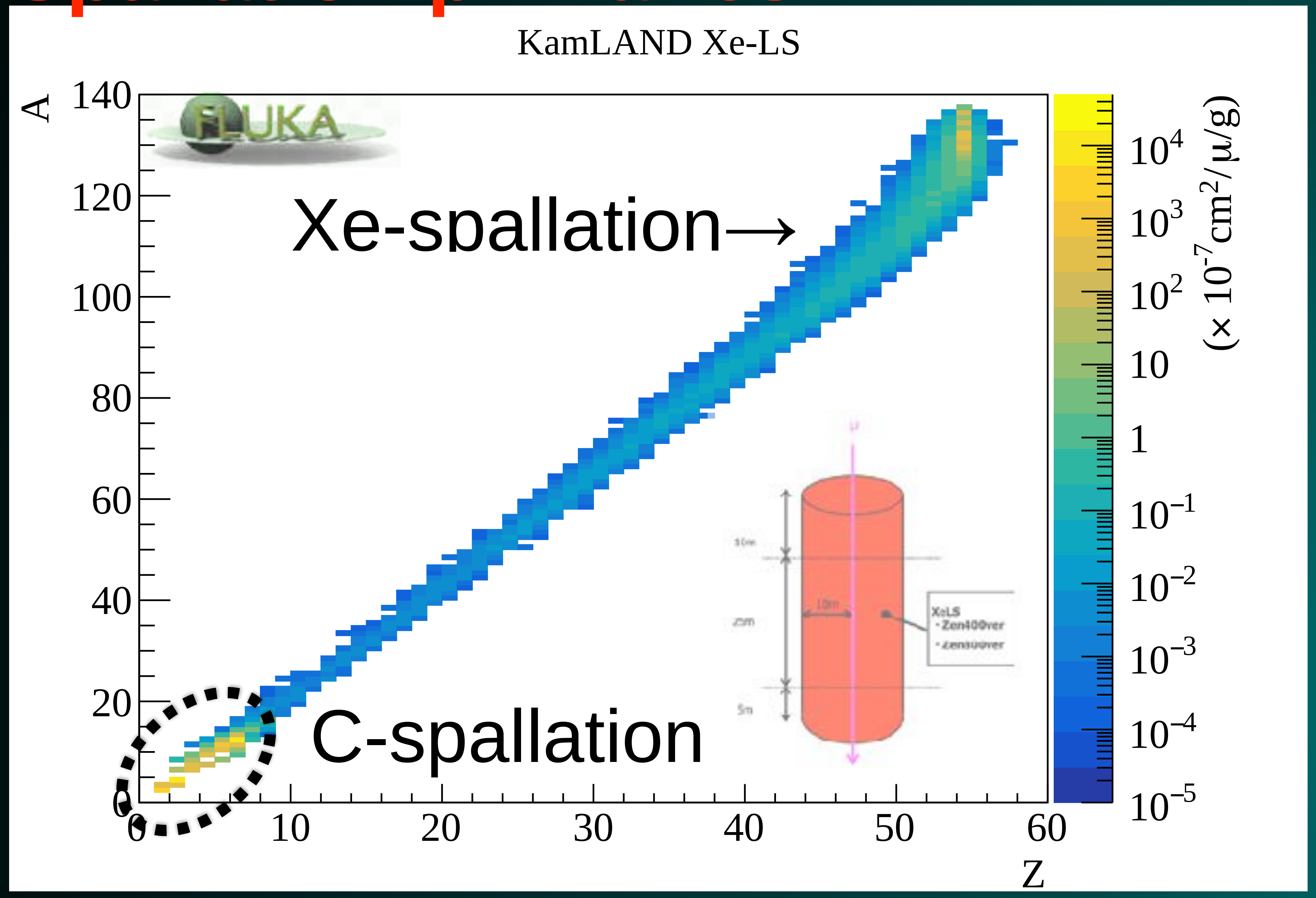
1. Radioactive Impurities (RI)
   - RI from detector (PMT, aclinic panel…) **Shielded by outer-LS**
   - Contamination in XeLS and outer-LS **Negligibly small!**
   - Contamination in/on inner-balloon (IB) → ^{214}Bi
2. Cosmic-ray muon spallation
   - C-12 spallation **Tagged by triple coincidence and shower LH.**
   - Xenon spallation (Long-lived) **Major BG(next page)**



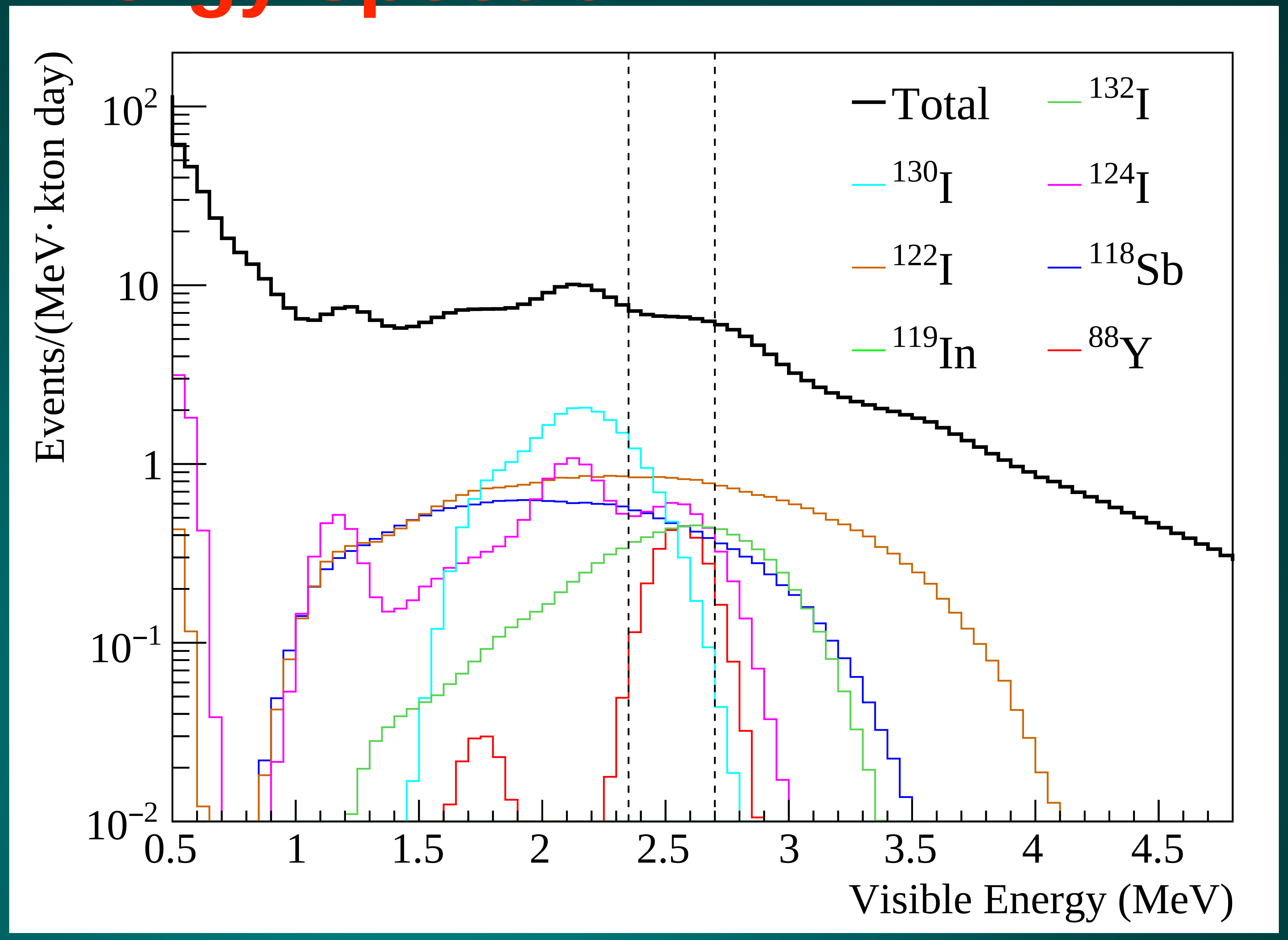
3. Neutrinos
   - Reactor anti-neutrinos **Tagged by delayed coincidence!**
   - Solar neutrino's electron scattering

Long-lived spallation products arxiv.2301.09307

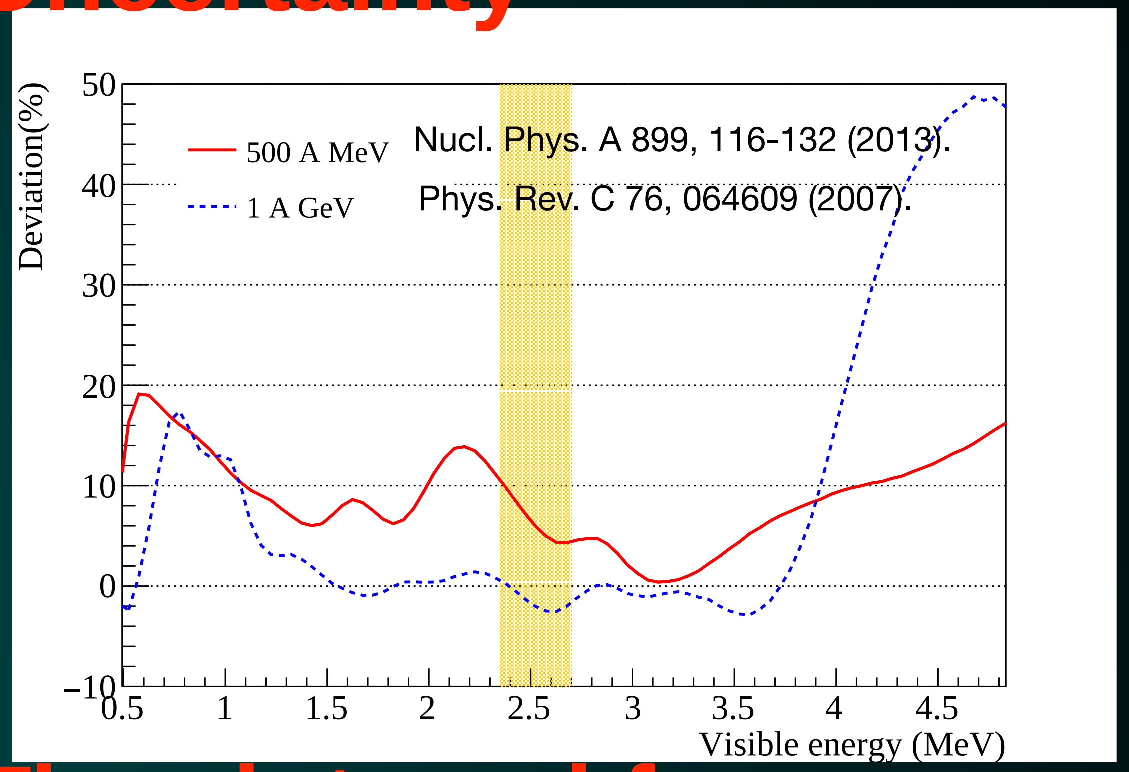
Spallation primaries



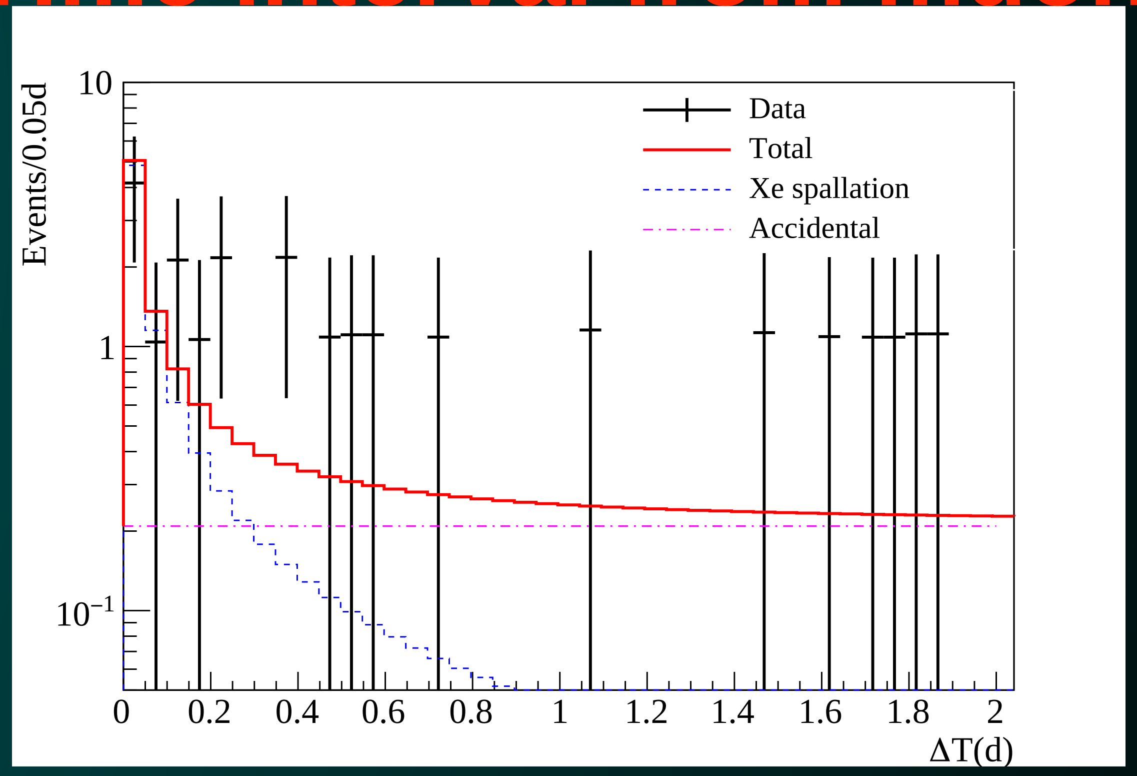
Energy spectrum

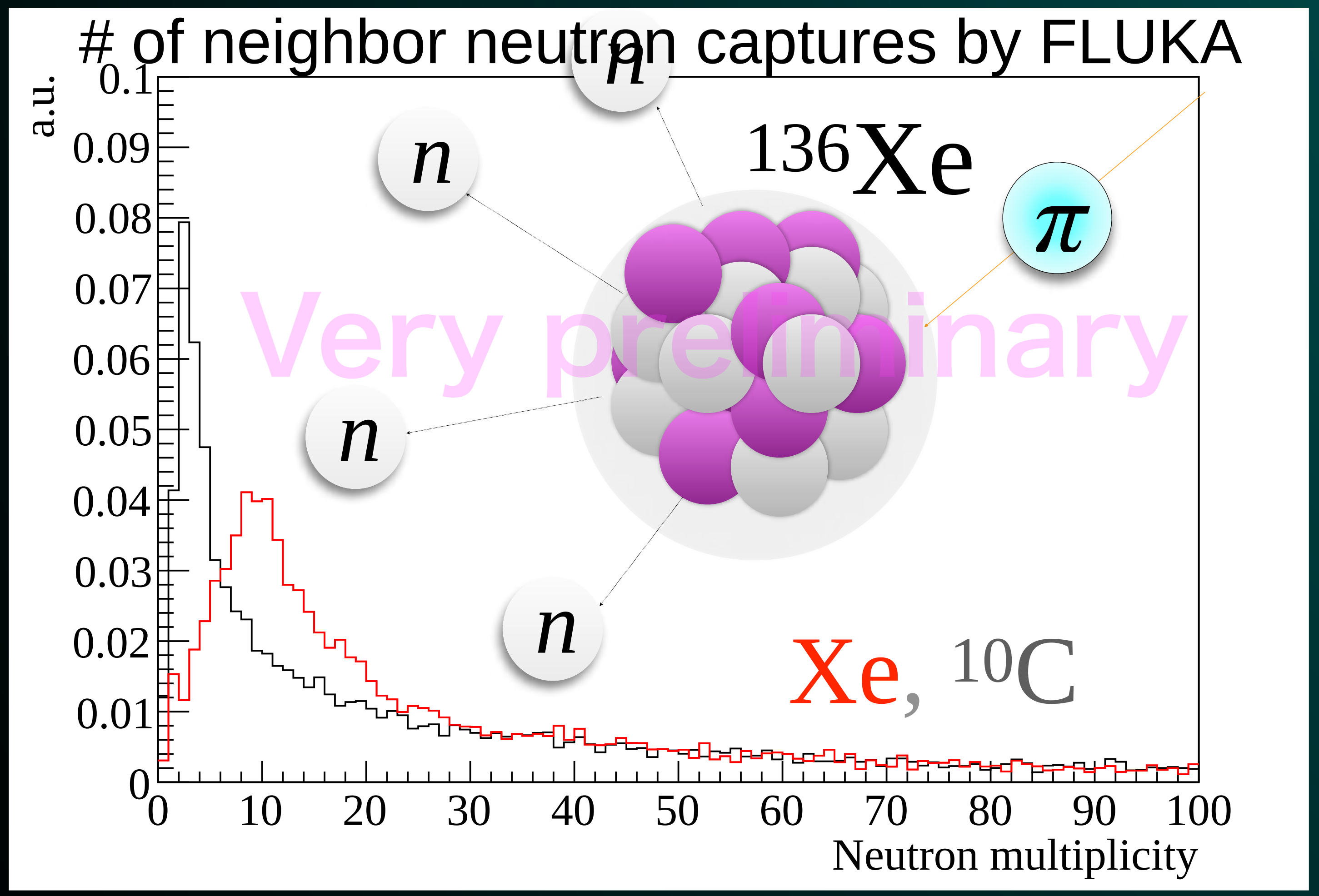


Uncertainty



Time interval from muon

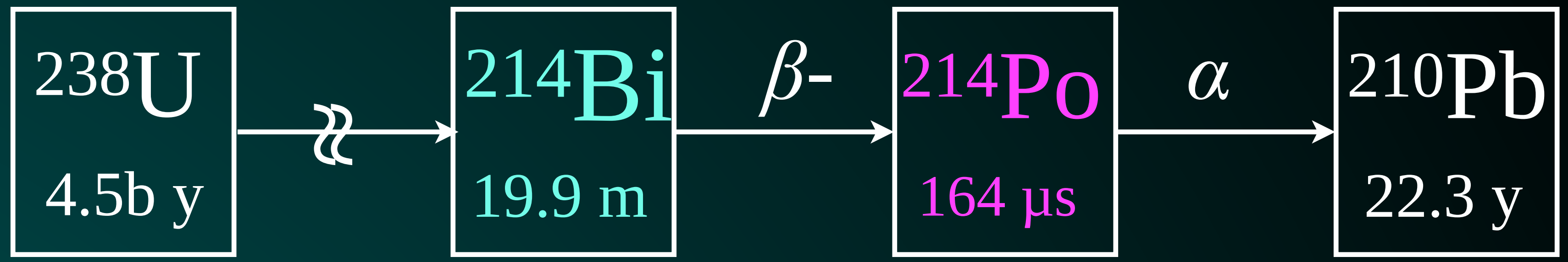




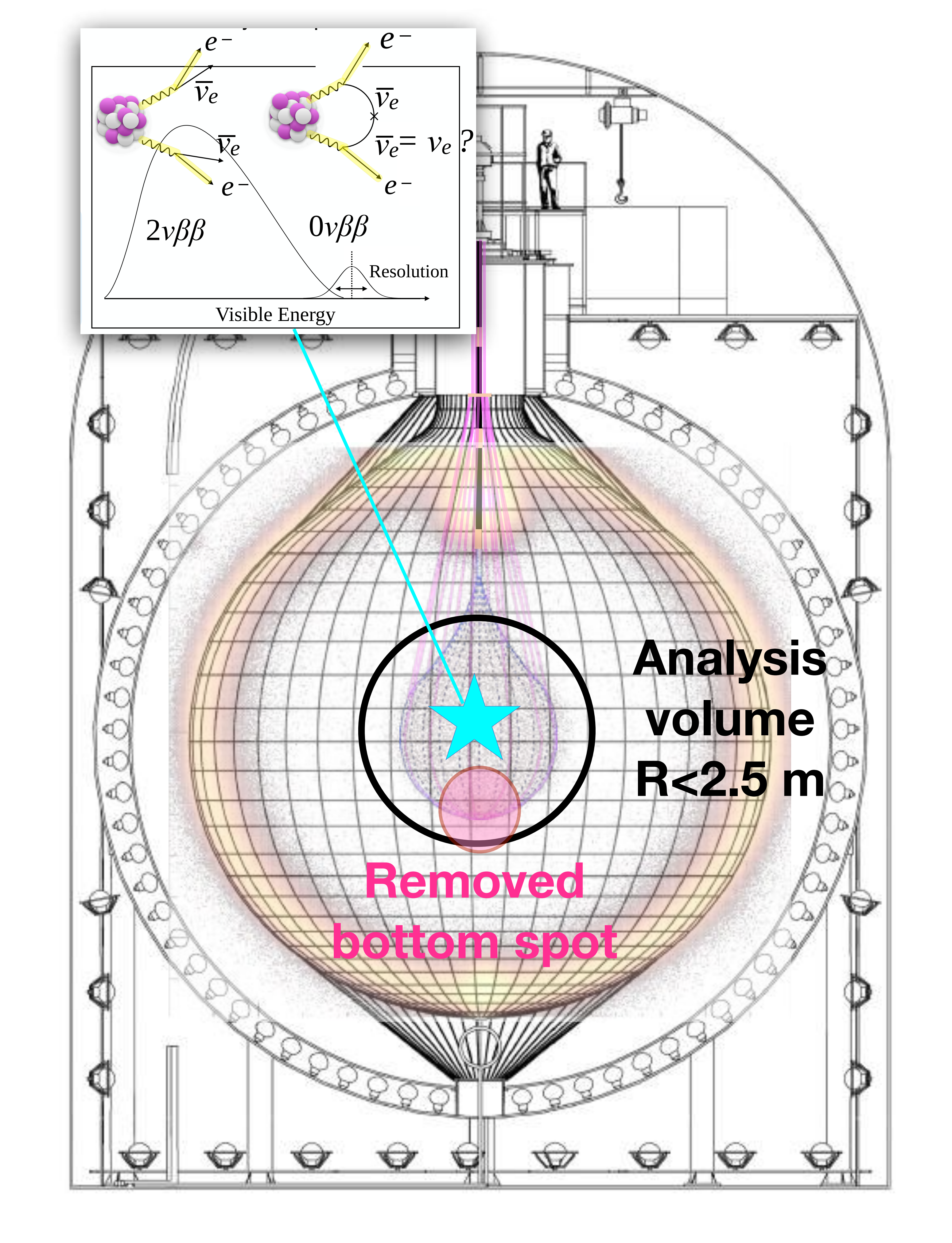
- FLUKA for primary products, then G4 & ENSDF for their daughters.
- Expected event rate: 0.082 event/(day*Xe-ton*ROI$_{(2.35\text{-}2.70\ \mathrm{MeV})}$).
- Long-lives and high neutron multiplicities.
- We developed a likelihood tag (N-multiplicity,dR,dT) with ~40% efficiency.

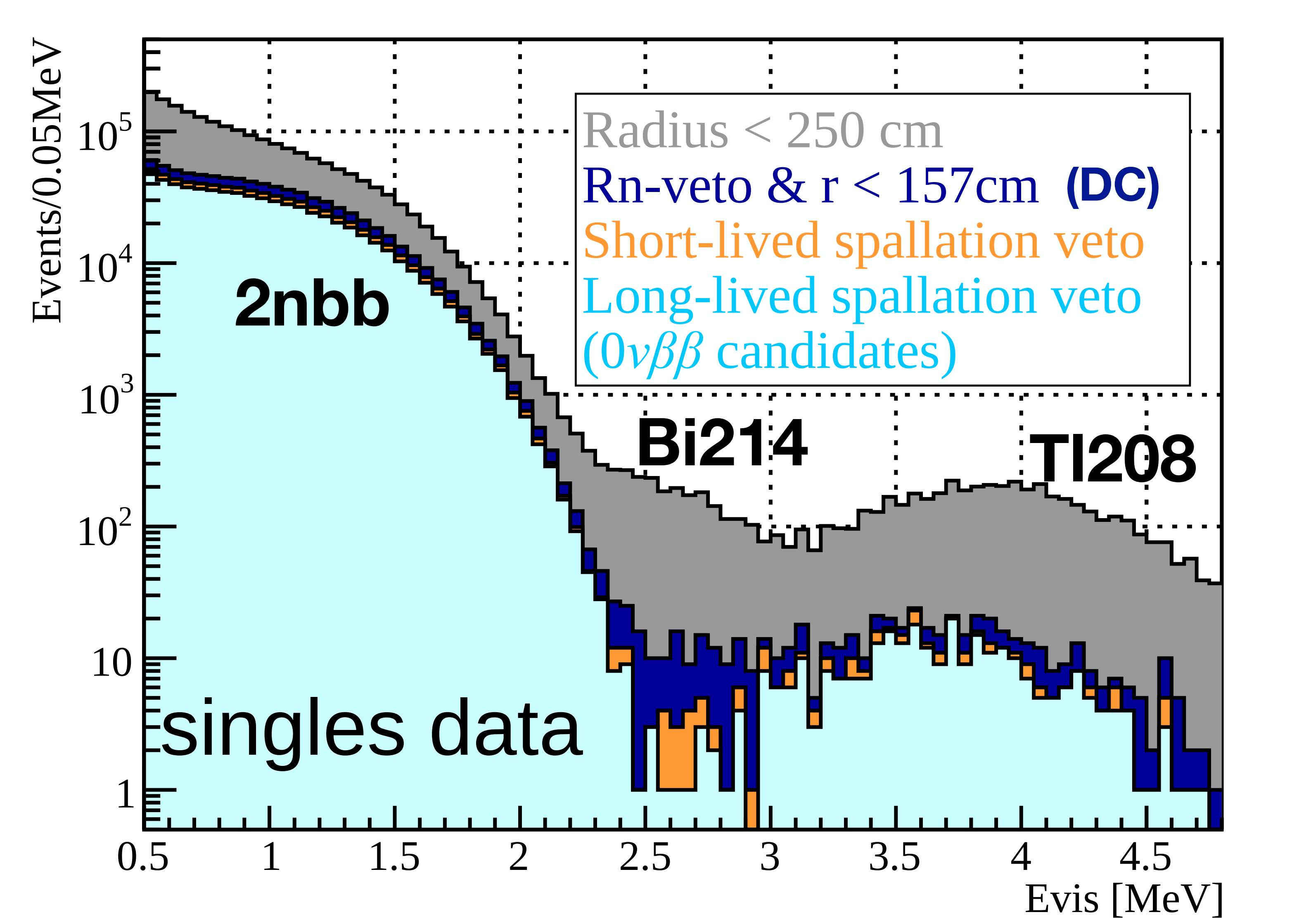
Data analysis

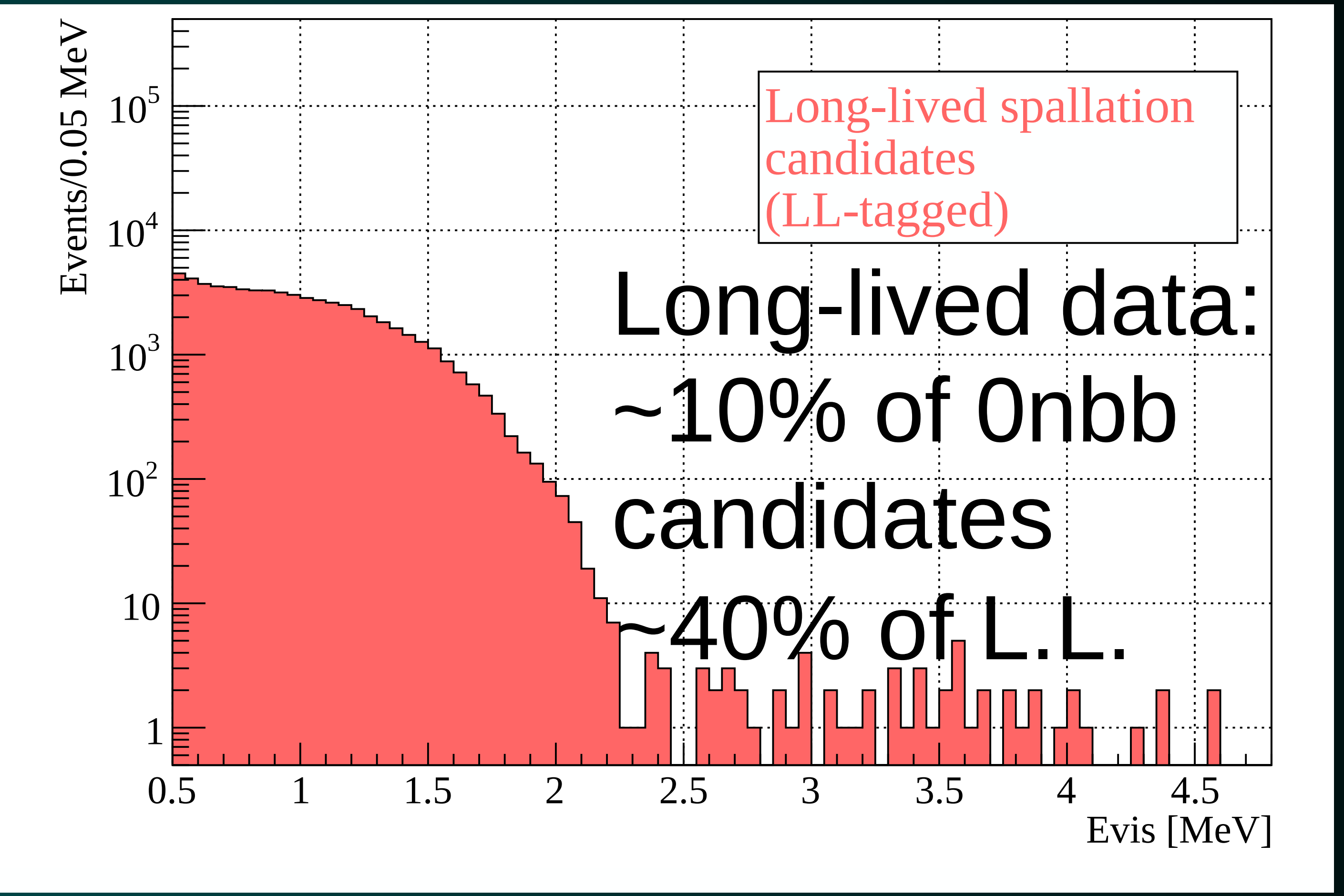
Delayed coincidence tag technique:



Bi-214 tag efficiency ~100% for XeLS and ~50% for IB surface.

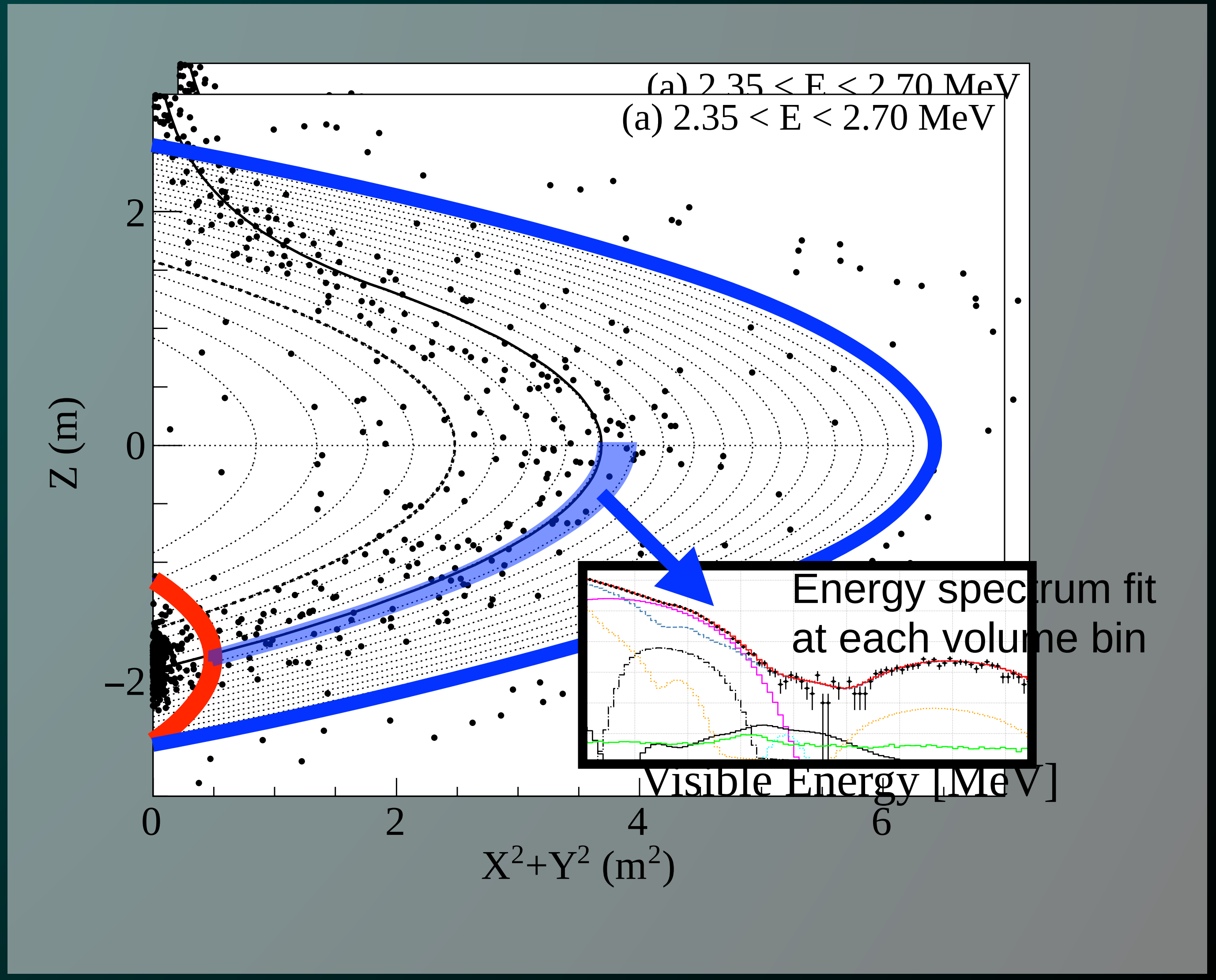






Divided dataset into "singles data" (SD) and "Long-lived data" (LD).

- The simultaneous fitting of
  - 86 energy bins,
  - 40 equal-volume bins,
  - 3 time-period bins,
  - SD and LD bins.



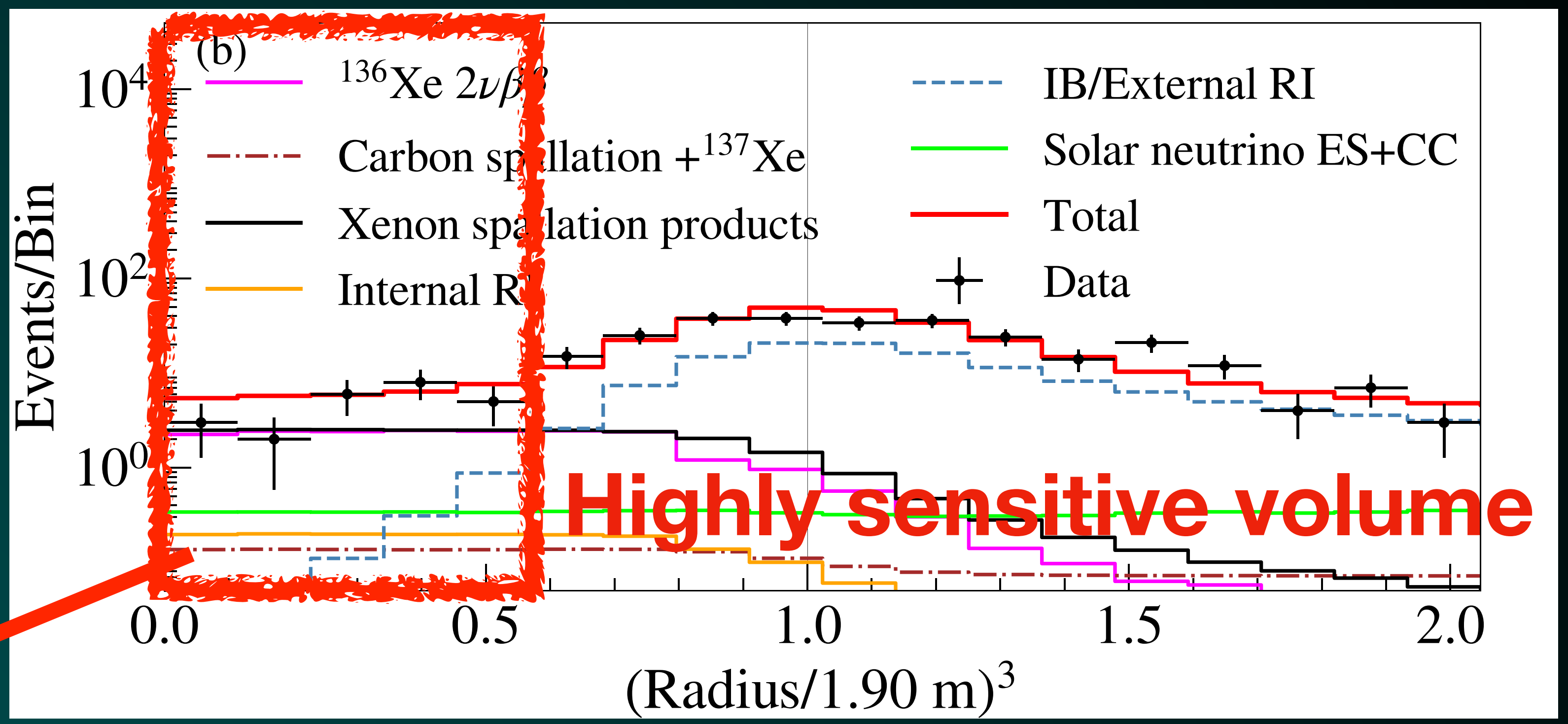
Performed 2D scan of 0vββ rate and LL rate.

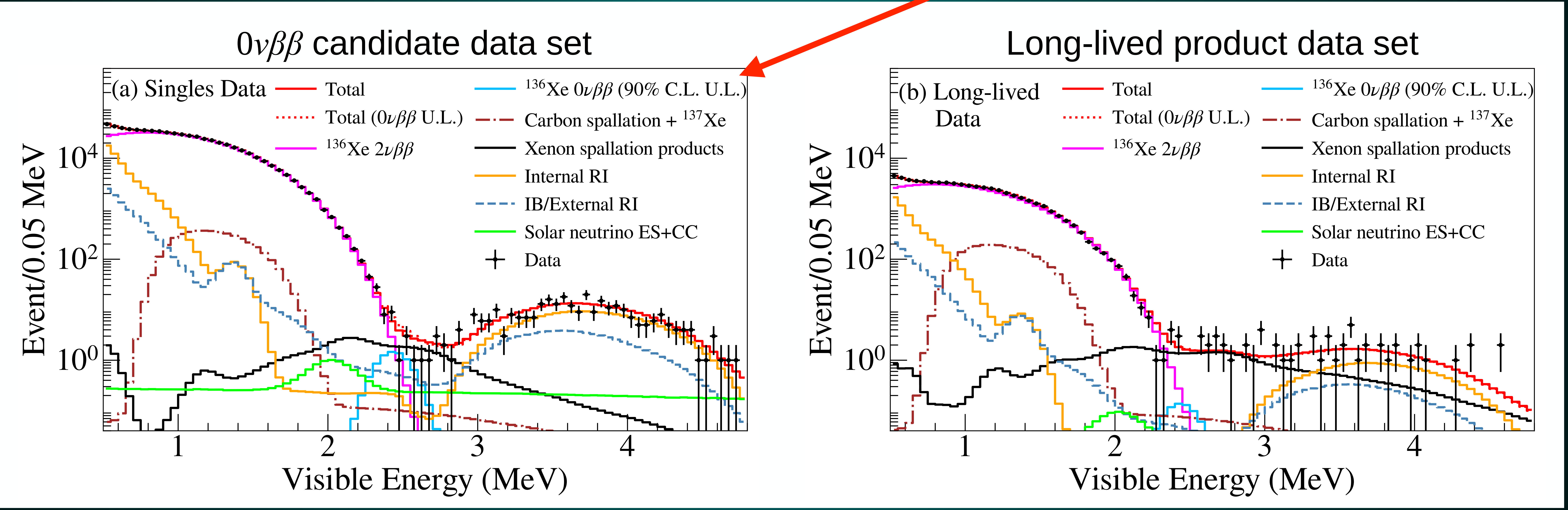
- The ratio of single events to DC events is high at the bottom. Something big enough to absorb alpha-ray?

Energy spectrum in Zen800

- livetime : 523 days(left) and 49 days for the LL dataset(right).

~1 ton*year exposure for all volume





The best fit of the 0νββ rate was 0
0νββ upper limit # of events was 7.9 (90% C. L.).

Obtained limit by KLZ800 : $T^{0\nu}_{1/2} > 2.0 \times 10^{26}$ year (90% C.L.)

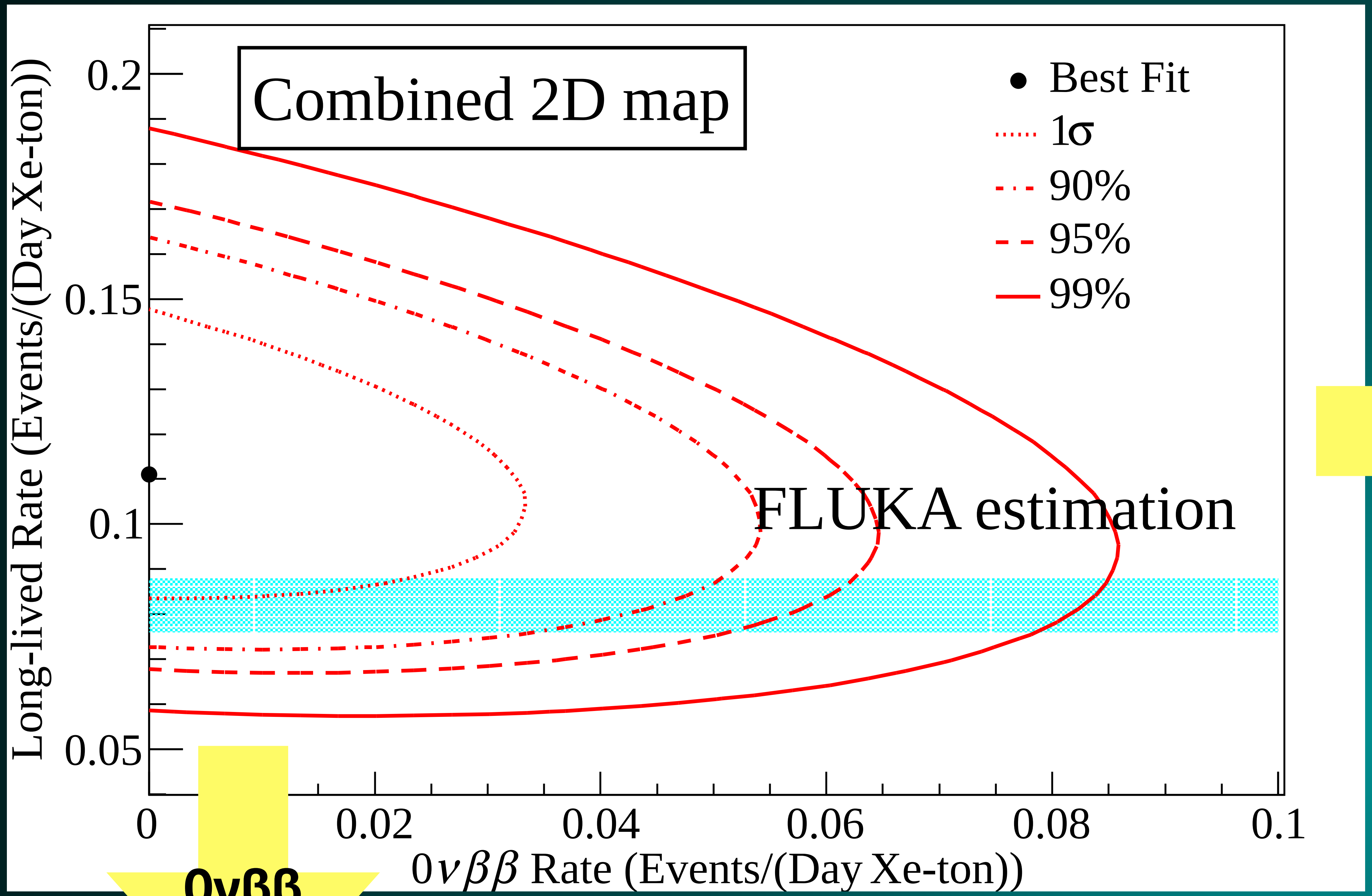
sensitivity: $T^{0\nu}_{1/2} > 1.3 \times 10^{26}$ year.
prob.~24%

Alternative methods

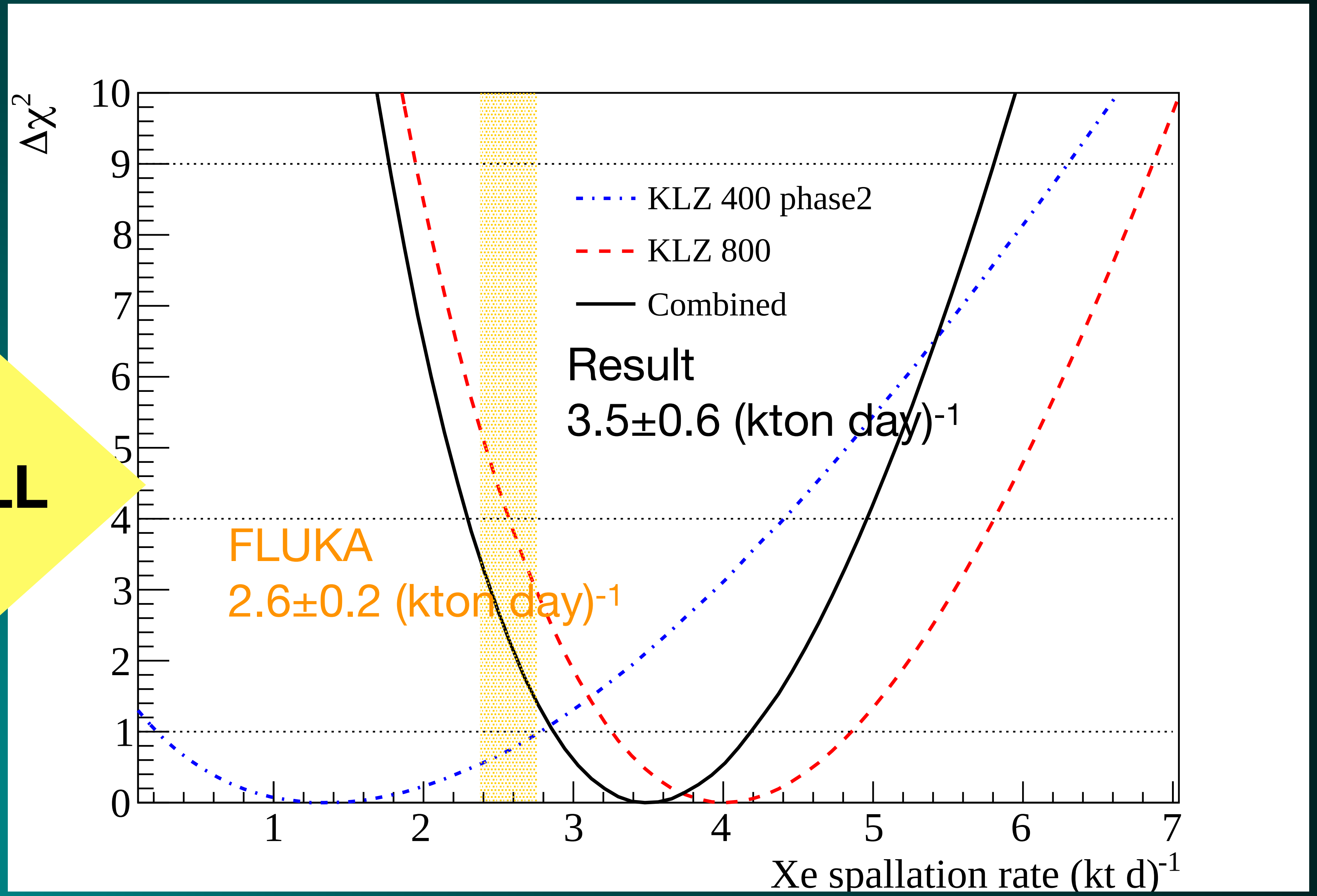
Bayesian limit: $T^{0\nu}_{1/2} > 2.1 \times 10^{26}$ year. FC : $T^{0\nu}_{1/2} > 2.3 \times 10^{26}$ year.

⇒ **Phys. Rev. Lett. 130, 051801**

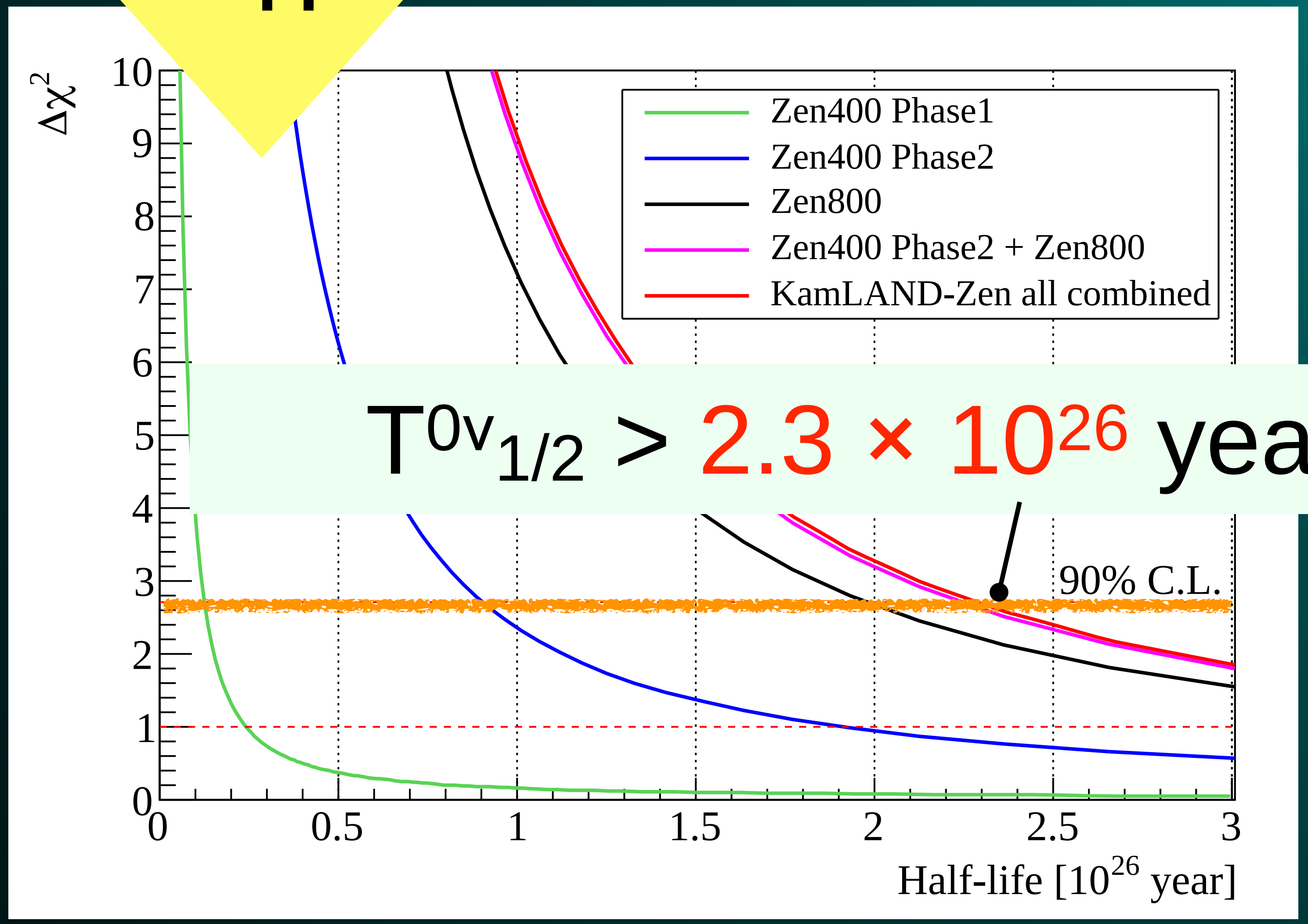
KamLAND-Zen combined result



LL



0νββ



$T^{0\nu}_{1/2} > 2.3 \times 10^{26}$ year.

- Reanalyzed Zen400 dataset.
- Combined in 2D ΔLLH map.
- Measured the LL background rate.
- 2x better half-life limit!

Obtained limit : $T^{0\nu}_{1/2} > 2.3 \times 10^{26}$ year (90% C.L.)

sensitivity: $T^{0\nu}_{1/2} > 1.5 \times 10^{26}$ year.
prob.~23%

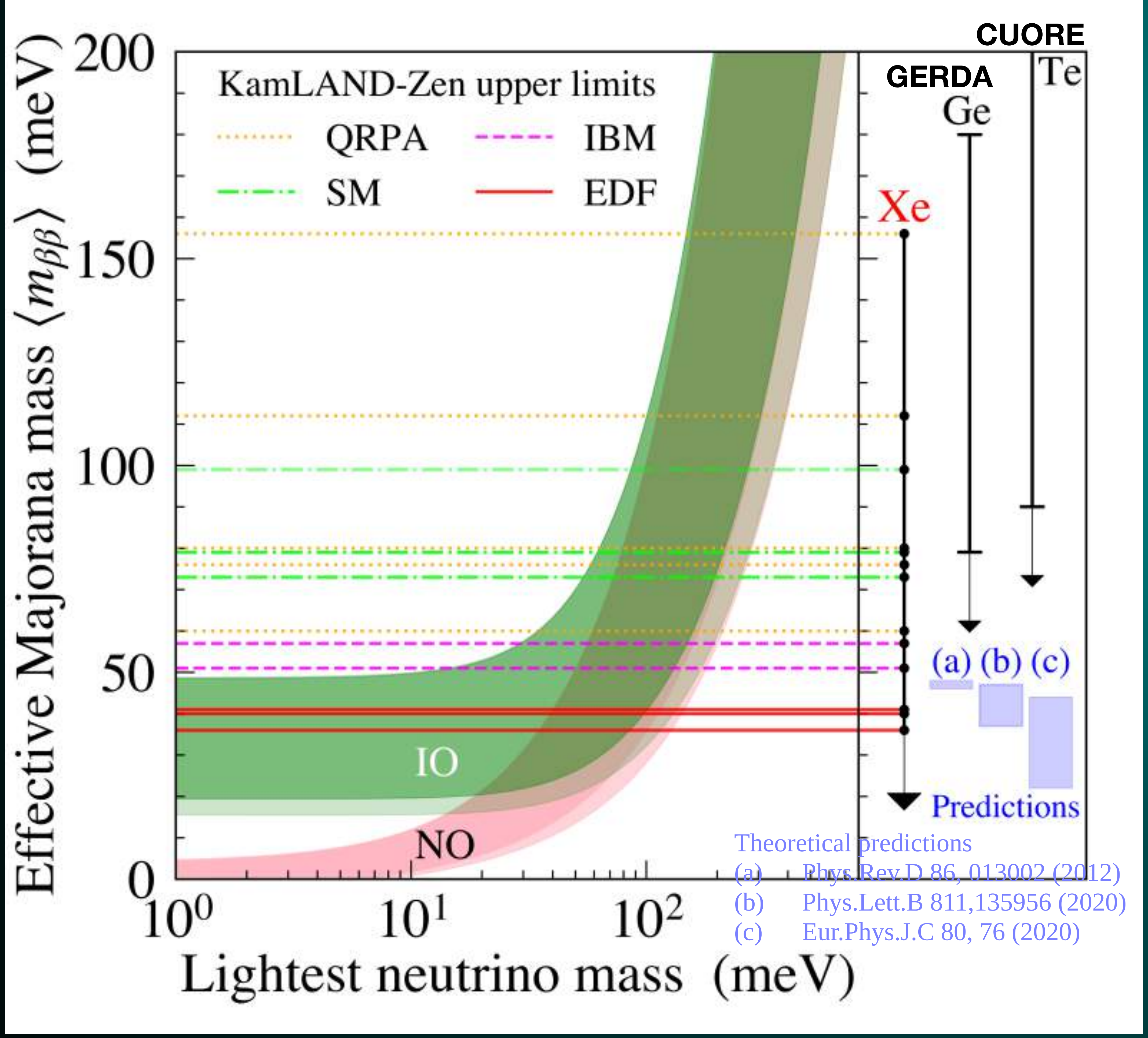
⇒ **Phys. Rev. Lett. 130, 051801**

Upper limit to $m_{\beta\beta}$

Nuclear Matrix Elements (NMEs)

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(g_{A,\text{eff}}/g_A)^4|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

g_A = 1.27, following NMEs



Quasi-particle Random Phase Approximations

* Phys.Rev.C 102, 44303(2020)
* Phys.Rev.C 91, 024613(2015)
* Phys.Rev.C 87, 045501(2013)
* Phys.Rev.C 87, 064302(2013)
* Phys.Rev.C 97, 045503(2018)

Interacting boson models

* Phys. Rev. D 102, 095016(2013)
* Phys. Rev. C 91, 034304(2015)

Shell models

* Phys. Rev. C 101, 044315(2020)
* Phys. Rev. C 91, 024309(2015)
* Phys. Rev. A 818, 139 (2009)

Energy density functional theory

* PRL 111, 142501(2013)
* Phys. Rev. C 91, 024316(2015)
* PRL 105, 252503 (2010)

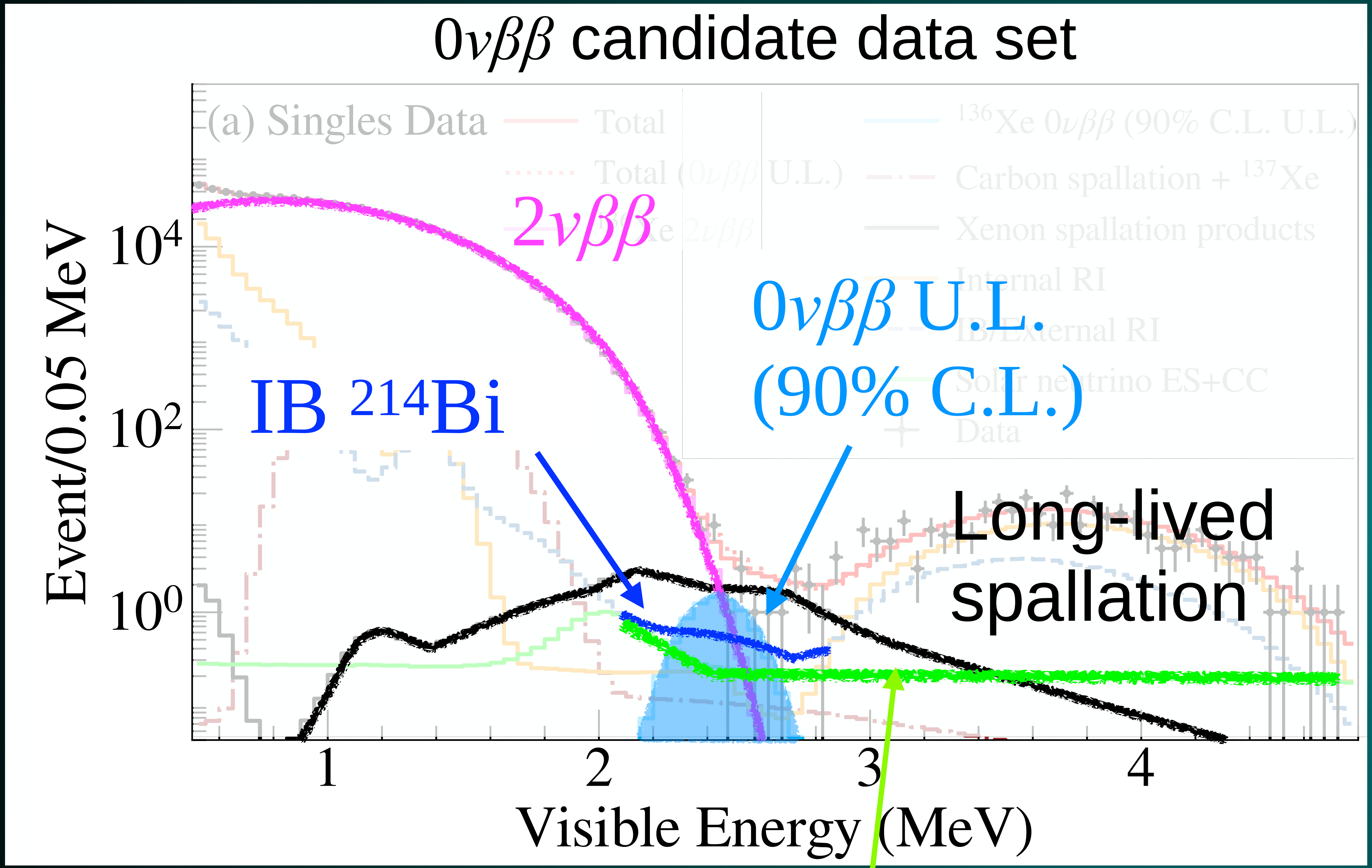
$\langle m_{\beta\beta}\rangle$ translated with upper NMEs

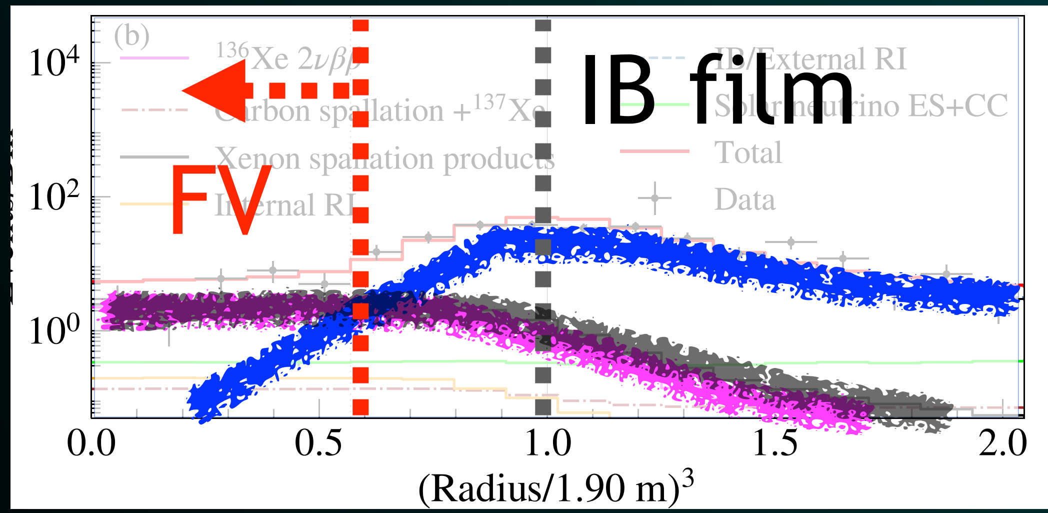
$$\langle m_{\beta\beta}\rangle < 36\text{–}156 \text{ meV} \quad (90\% \text{ C.L.}).$$

We are the first in the world to test the IO band below 50 meV !

⟹ **Phys. Rev. Lett. 130, 051801**

Background summary





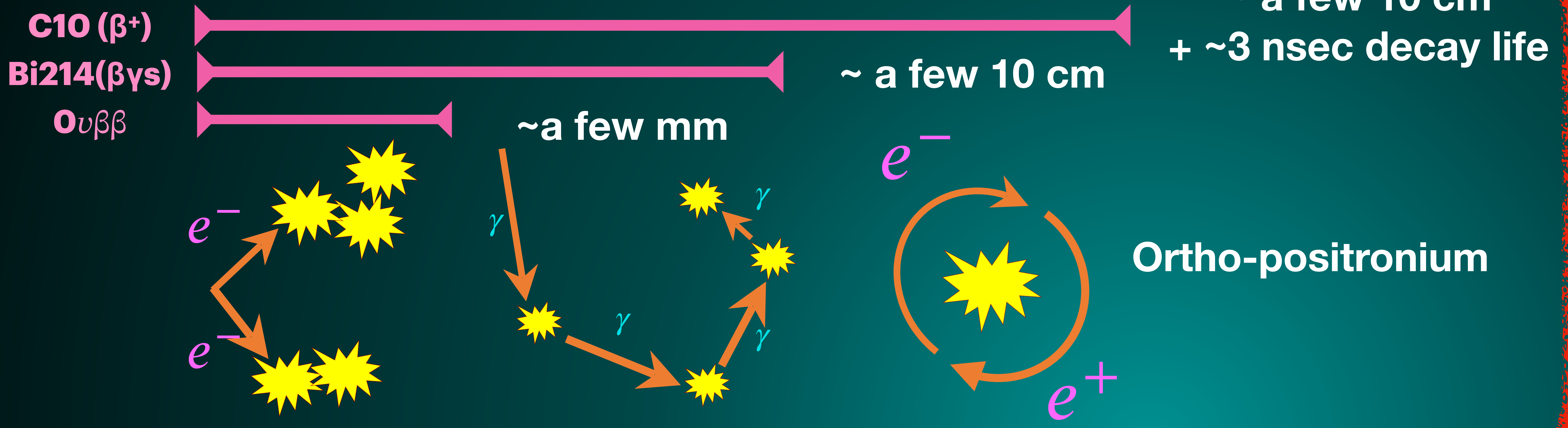
Solar neutrino
electron scattering

Background	Best-fit Frequentist	Best-fit Bayesian
$^{136}Xe\ 2\nu\beta\beta$	11.98	11.95
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
^{232}Th series	0.01	0.01
Neutrino interactions		
^{8}B solar $\nu\ e^-$ ES	1.65	1.65
Spallation products		
Long-lived	12.52	11.80
^{10}C	0.00	0.00
^{6}He	0.22	0.21
^{137}Xe	0.34	0.34

Gamma and/or positron backgrounds
⟹ PID is a key technology for the future.

Particle identification

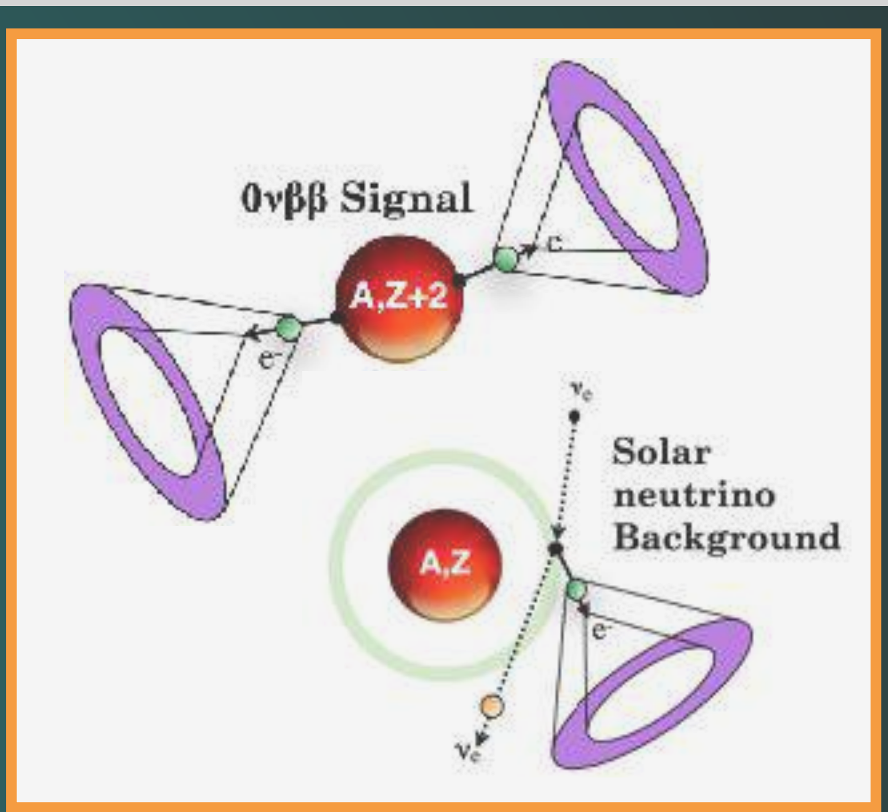
β/γ(β+) discrimination



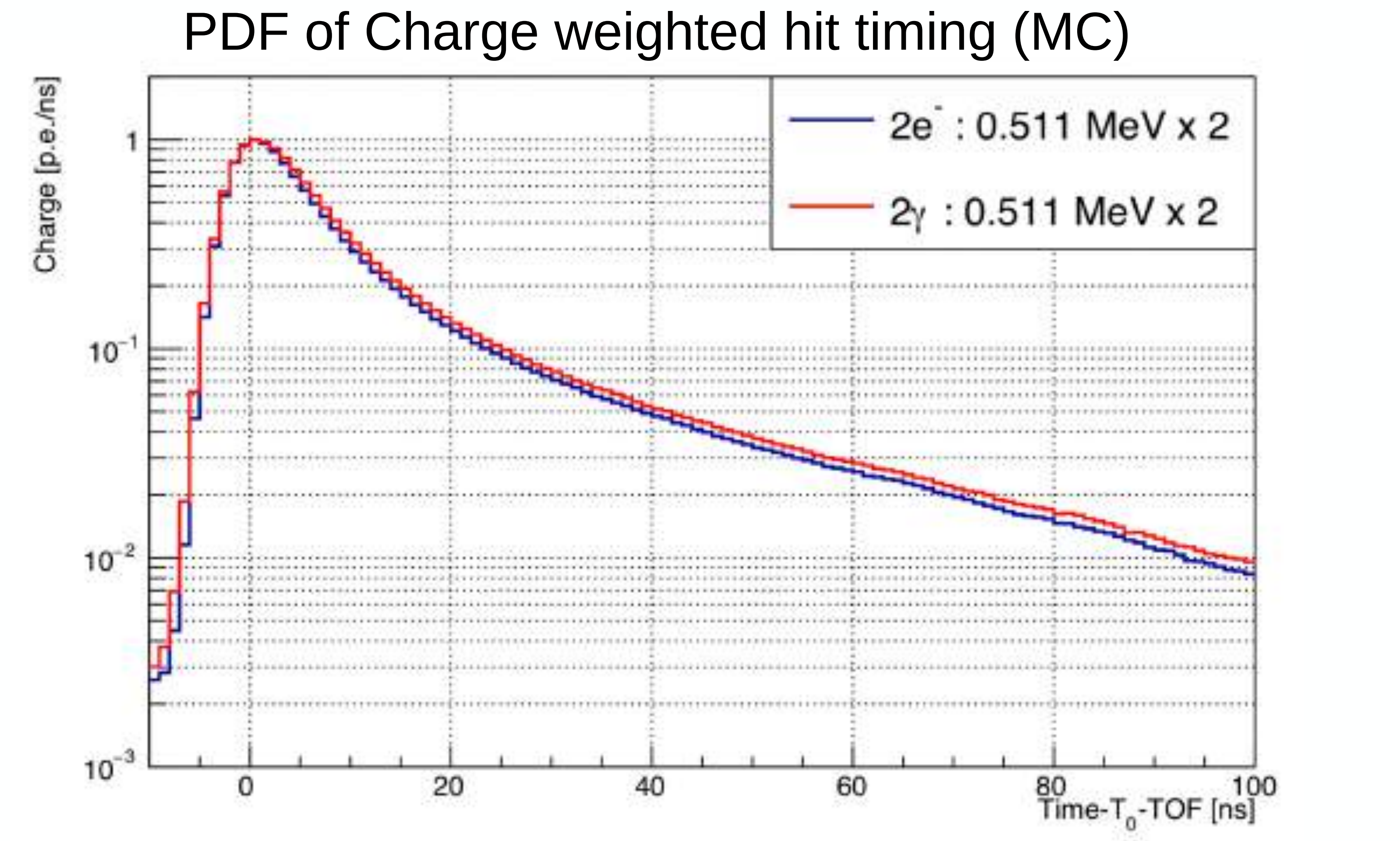
Ortho-positronium

Too hard for KLZ800, Future task …

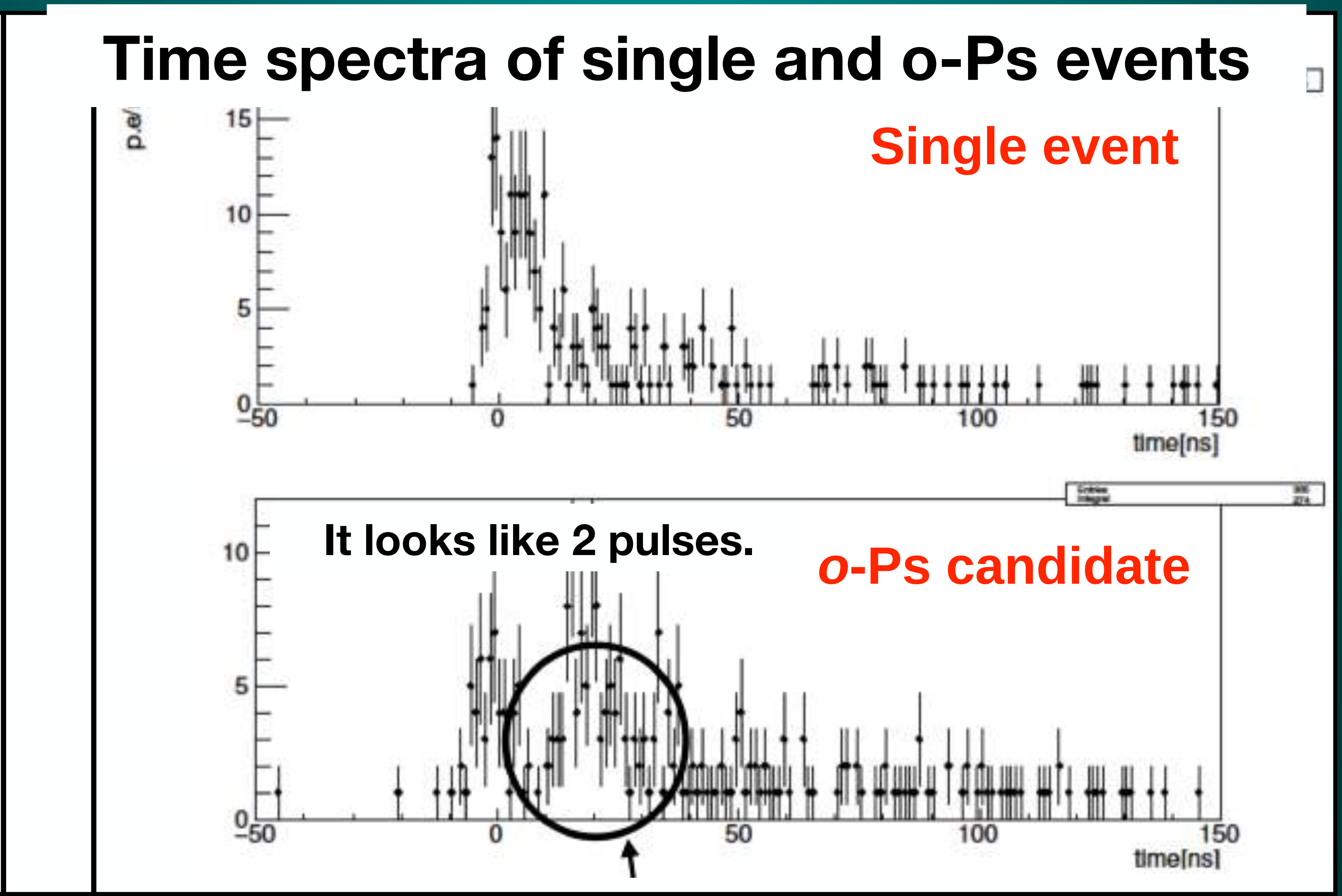
Cherenkov light detection



To discriminate solar-nu's ES.



Time spectra of beta and gamma events



We developed two β/γ rejection NNs.

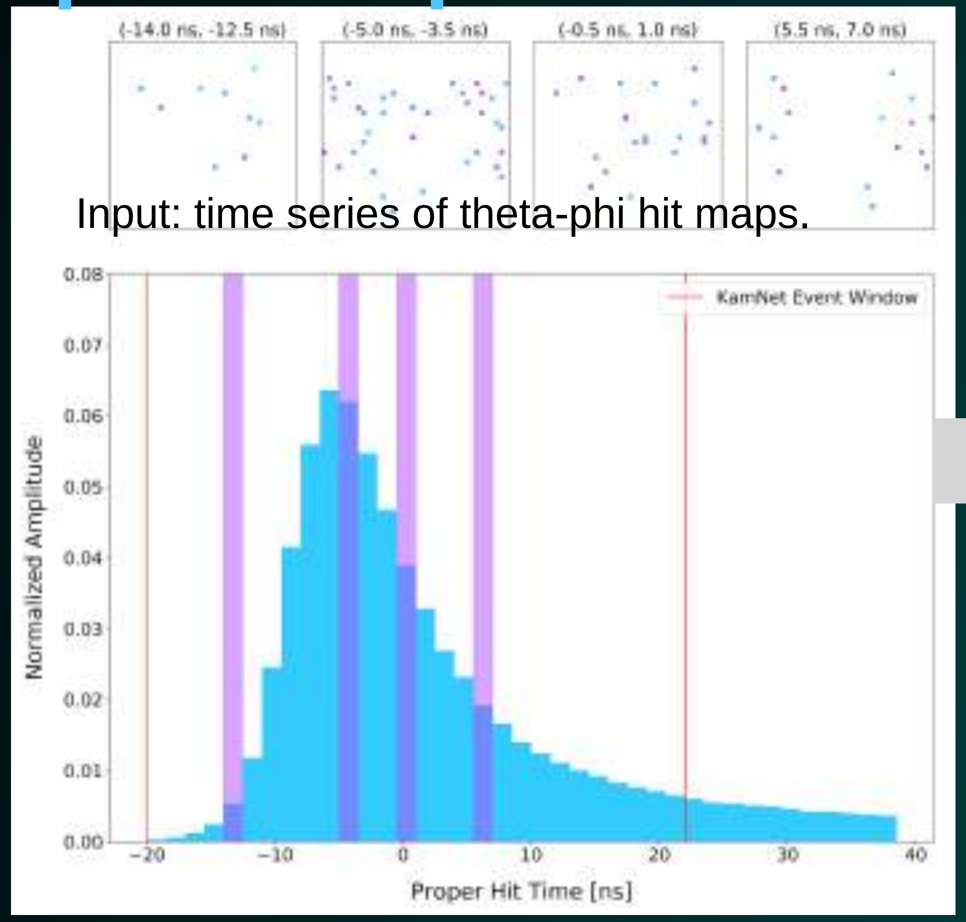
RNN for Zen400
… Simple but strong for 1D time-spectrum data.

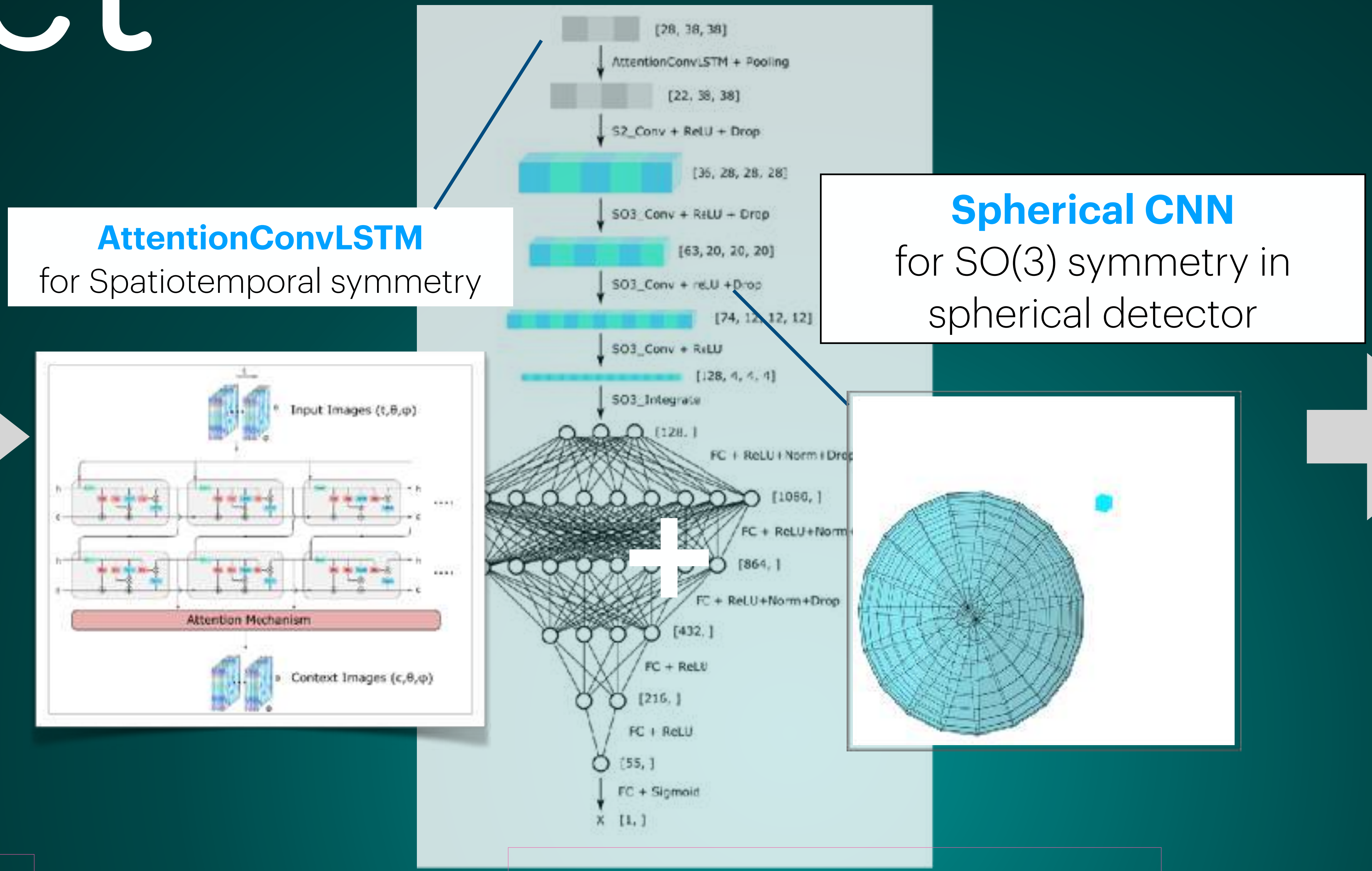
KamNet for Zen800
… Maximal information extraction for spherical LS detector.

KamNet

Phys. Rev. C 107, 014323 (2023) GitHub: https://github.com/aobol/KamNet.git

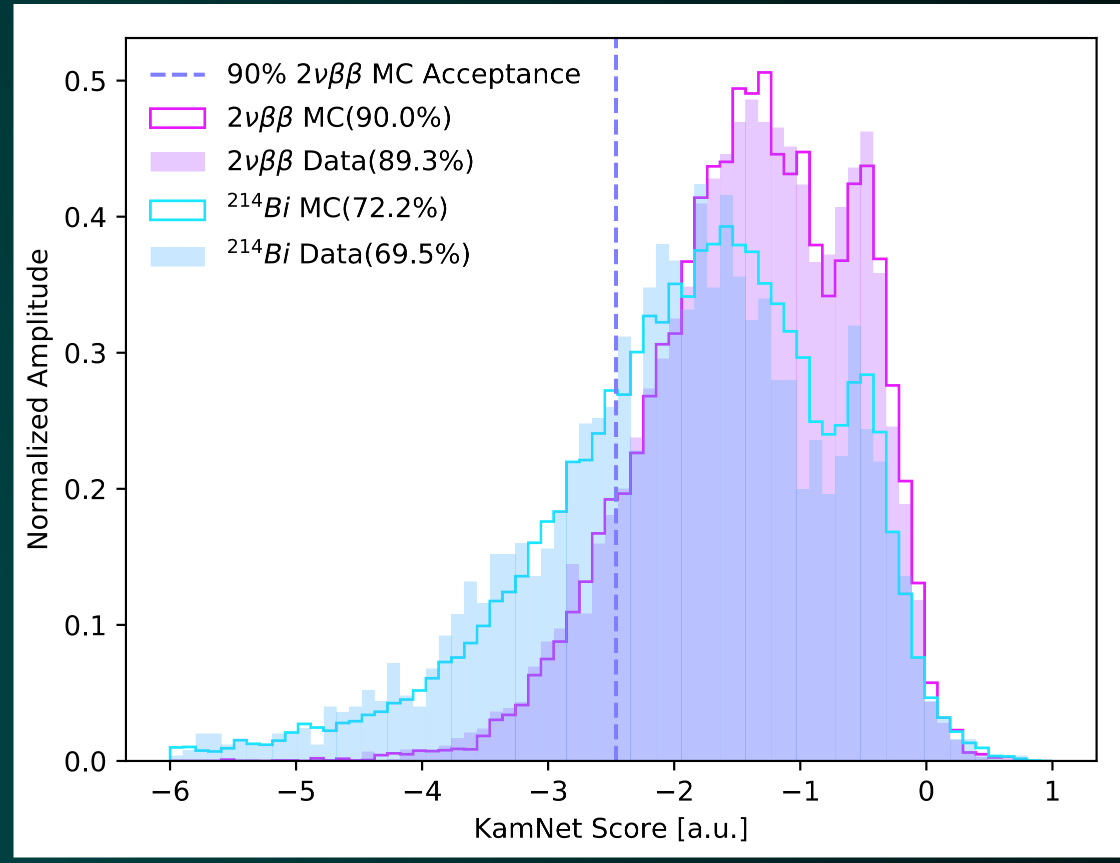
Spatiotemporal Data





KamNet Score

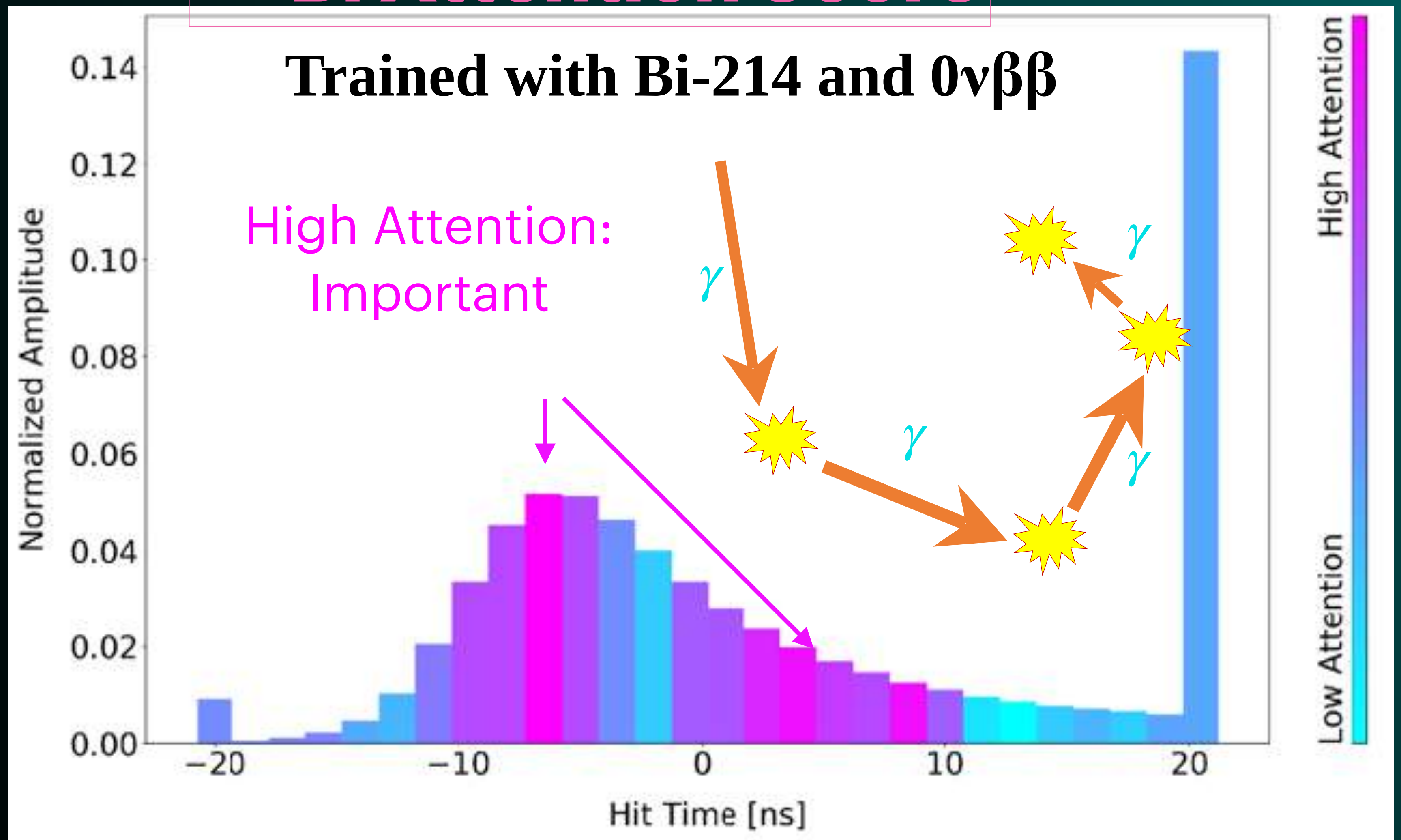
BG like ⟷ SG like



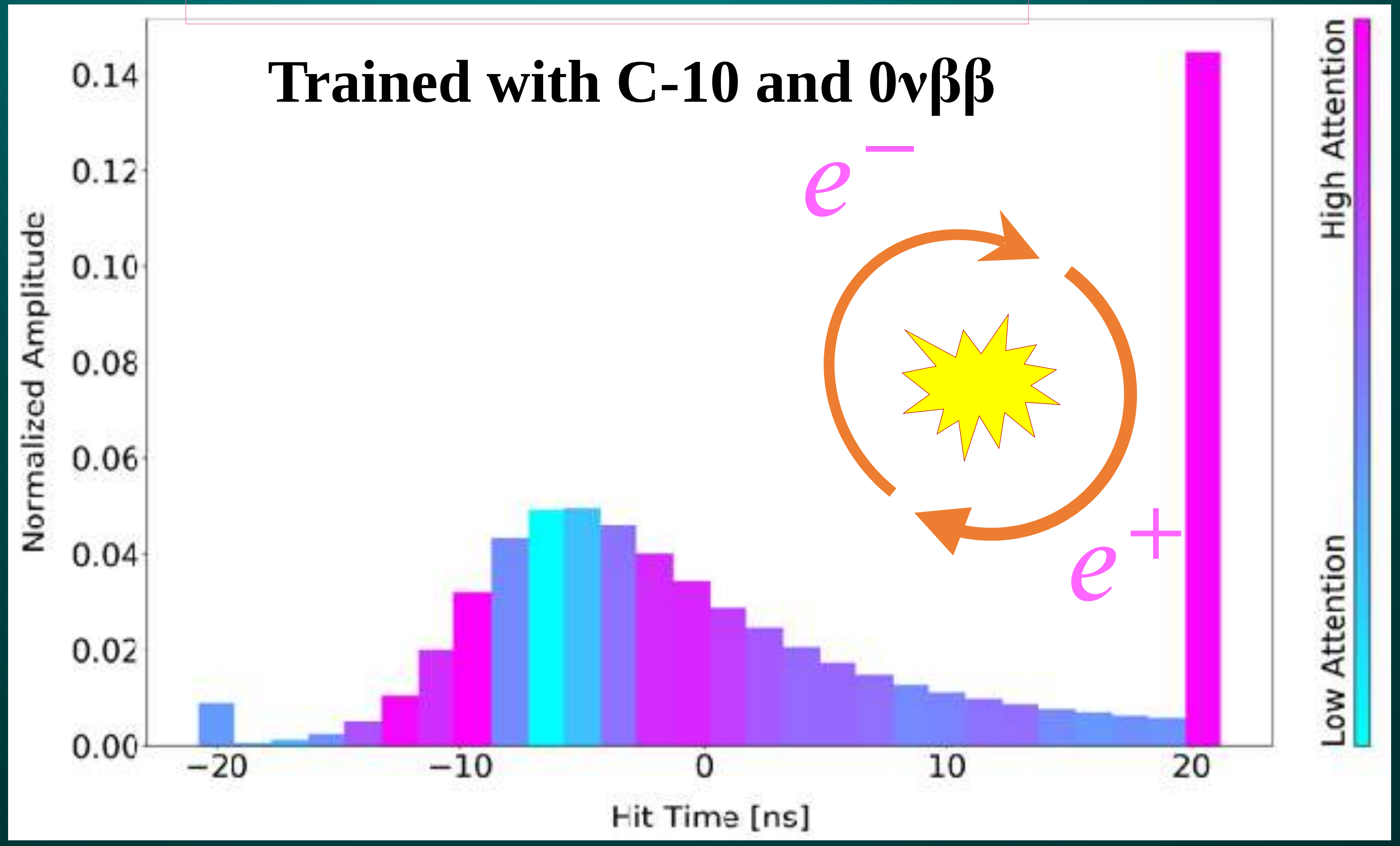
The data and MC were in good agreement!

Interpretability

^{214}Bi Attention Score

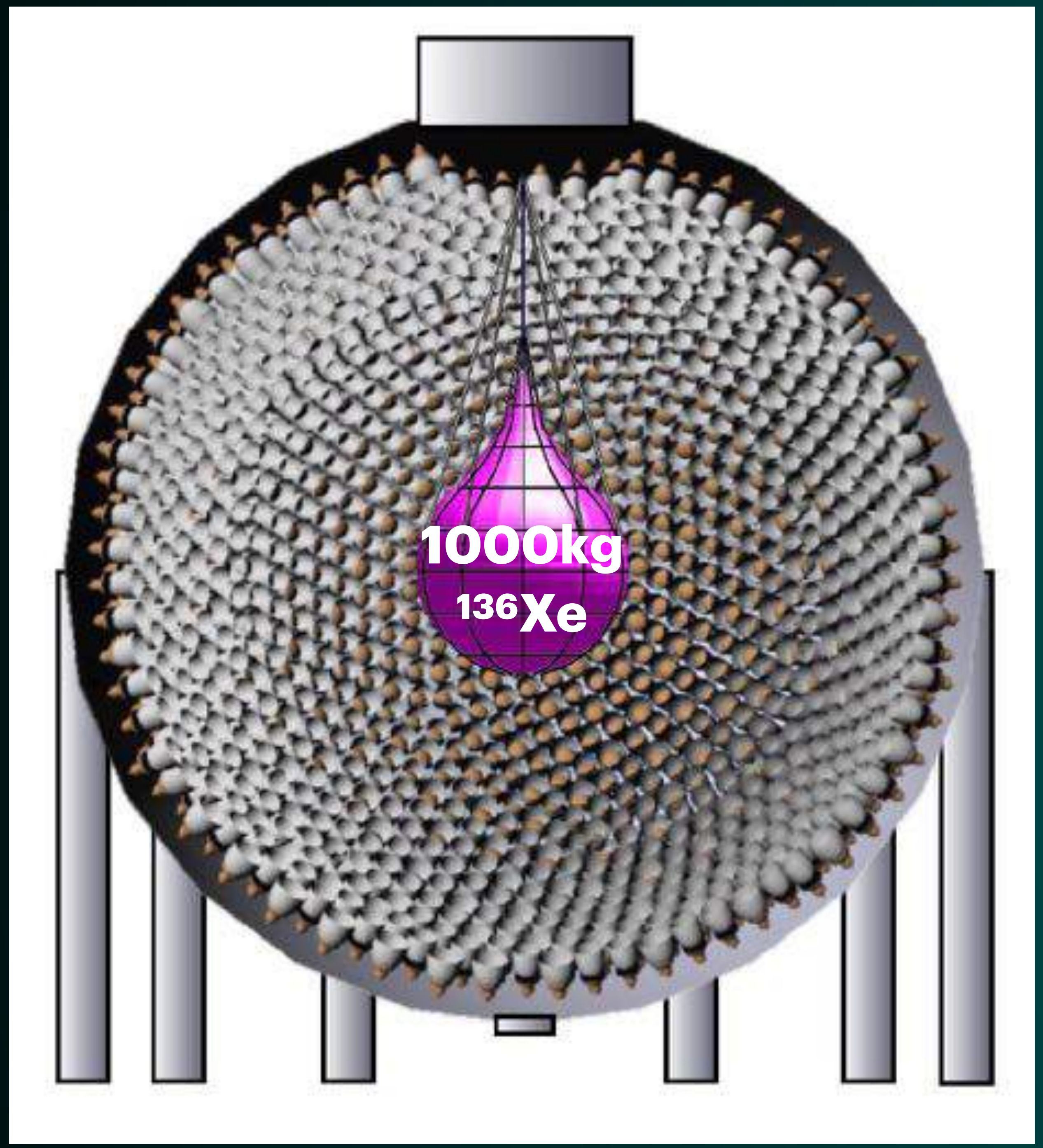


^{10}C Attention Score



- While accepting 90% of $0\nu\beta\beta$ events, KamNet rejects ~27% of LL backgrounds and ~59% of film backgrounds.
- We can see that the ML highlights which time slice with attention score.

KamLAND2-Zen



Light collection with Winston Cones (x1.8)
High light yield scintillator (x1.4)
High QE 20" PMTs (x1.9)

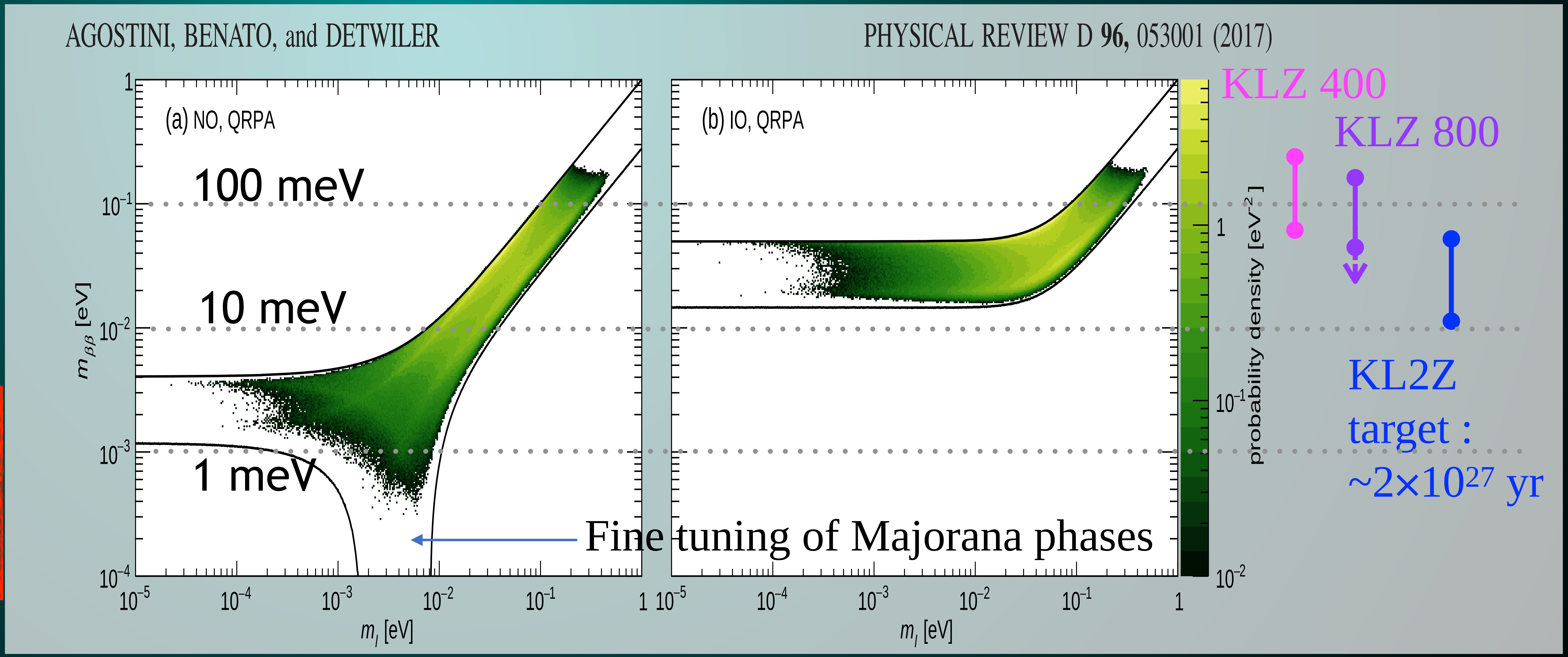
~5x light yield

4% ⇒ 2% energy resolution @ Q-value

- Reduce background events of 2νββ to ~1/100.
- Greatly improve PID power!

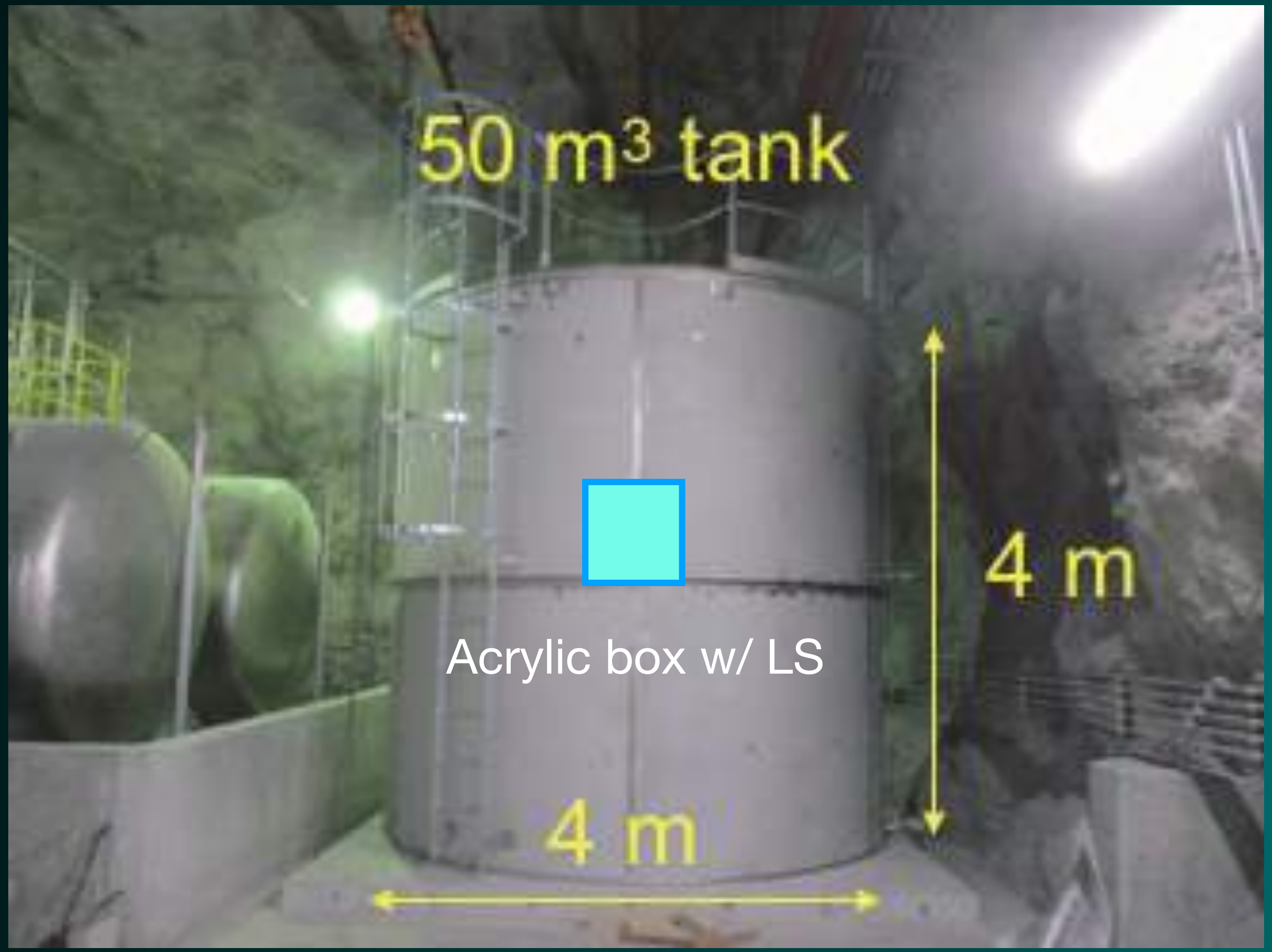
R&Ds are ongoing.

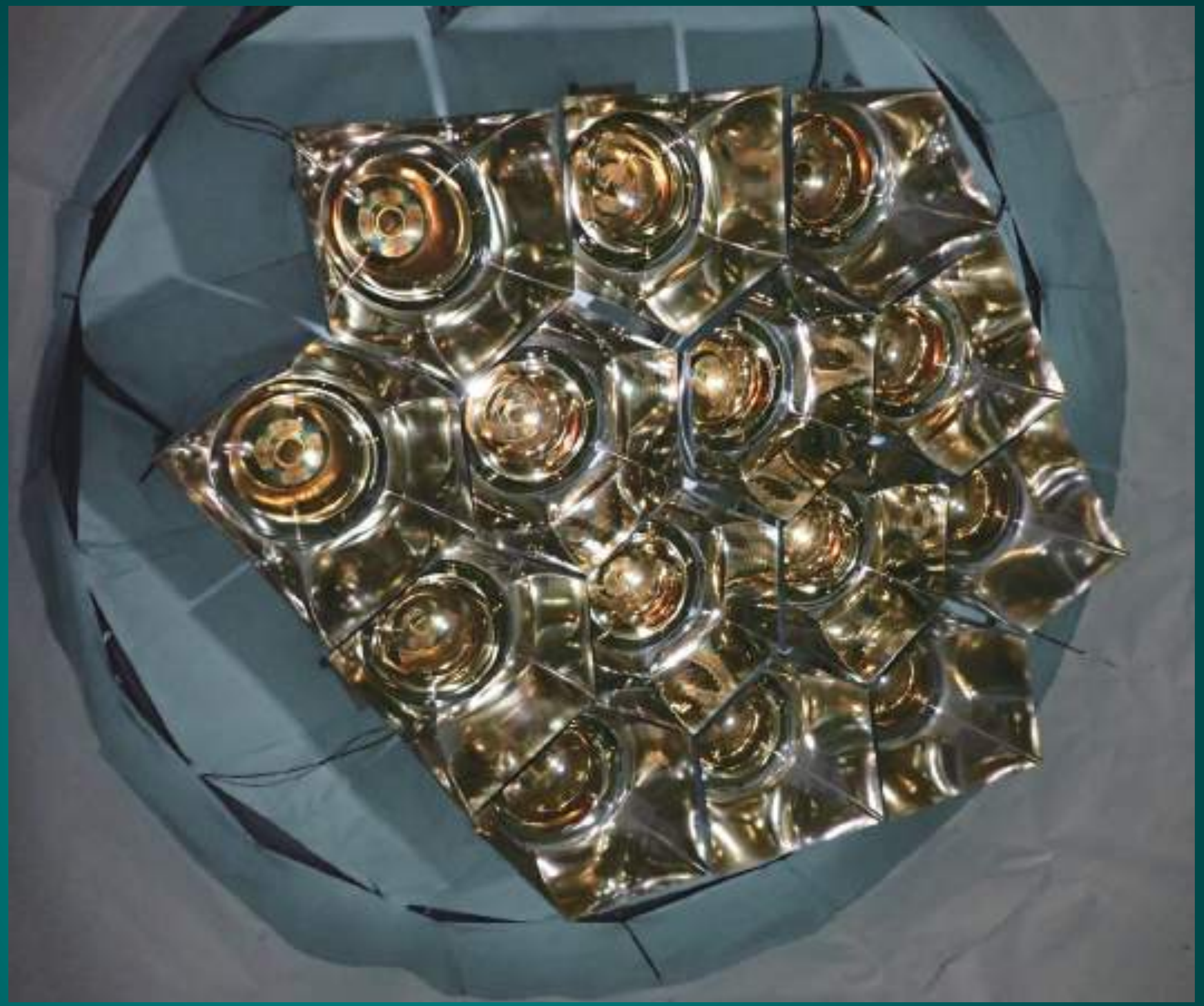
+ PID by o-Ps in XeLS, High pressurized XeLS, RI in Bis-MSB…

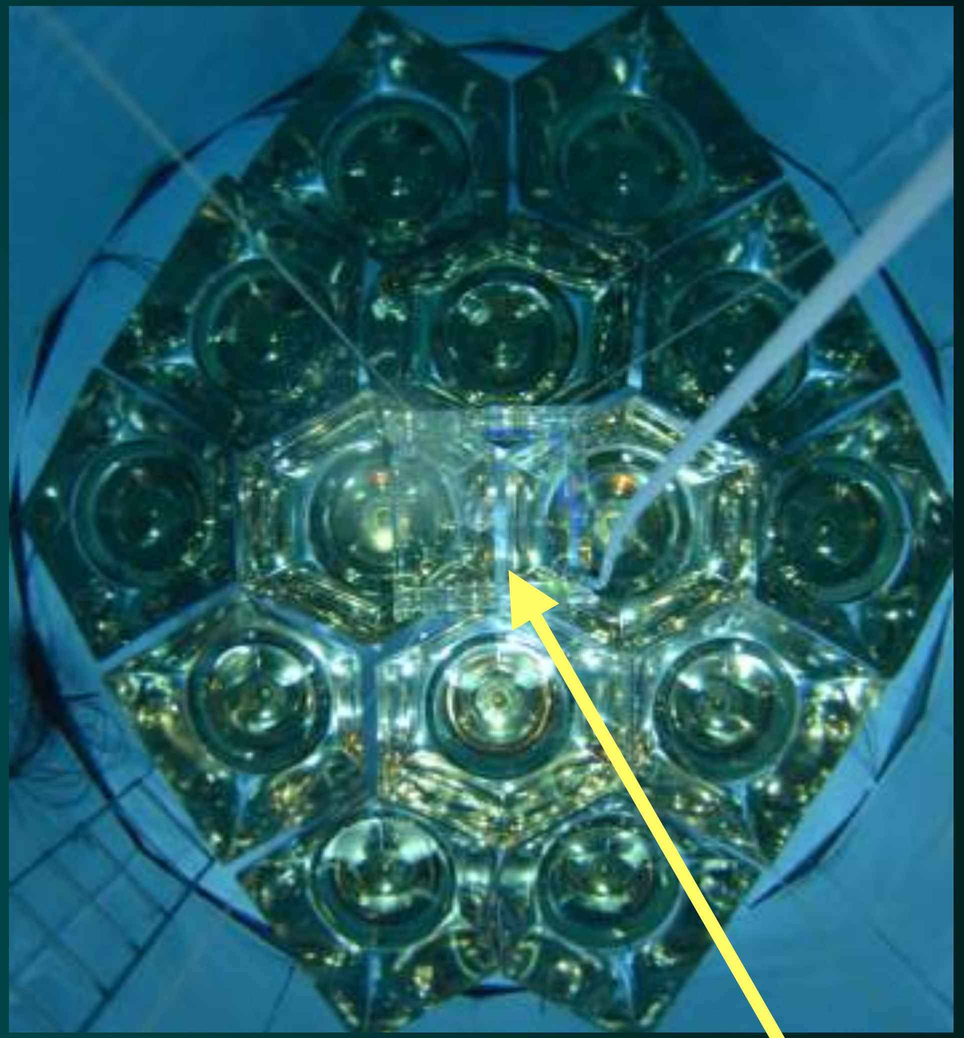


Goal: covering the IO region!
Half-life: 2x10^{27} yr.
<$m_{\beta\beta}$>~20 meV in 10 years.

KamLAND2-Zen: prototype







Acrylic box w/ LS.

The performance demonstration in a 50 m^3 tank is ongoing.

- ✔ High QE PMT.
- ✔ Light collecting mirror.
- ✔ Pure-water and acrylic box w/ LAB LS.
- ✔ New electronics and DAQ system.
- ✔ LED light and source calibration.

Source calibration.

Summary

- The latest results of the 0νββ search with KamLAND-Zen were reported.
  - $T^{0\nu}_{1/2} > 2.3 \times 10^{26}$ year (90% C.L.)
  - $\langle m_{\beta\beta} \rangle < 36$–$156$ meV (90% C.L.)
- New analysis techniques were developed.
  - Muon spallation of Xe nucleus and its day-scale tag.
  - ML for PID in spherical LS detector (KamNet).
- R&D toward KamLAND2-Zen is ongoing.

KamLAND(-Zen) Collaboration