Results and Prospects of KamLAND-Zen

The 2023 Fall Meeting of the Division of Nuclear Physics of the American Physical Society and Physical Society of Japan

Neutrinoless Double-Beta Decay Workshop

December 1, 2023

Itaru Shimizu (Tohoku University)

KamLAND-Zen Collaboration

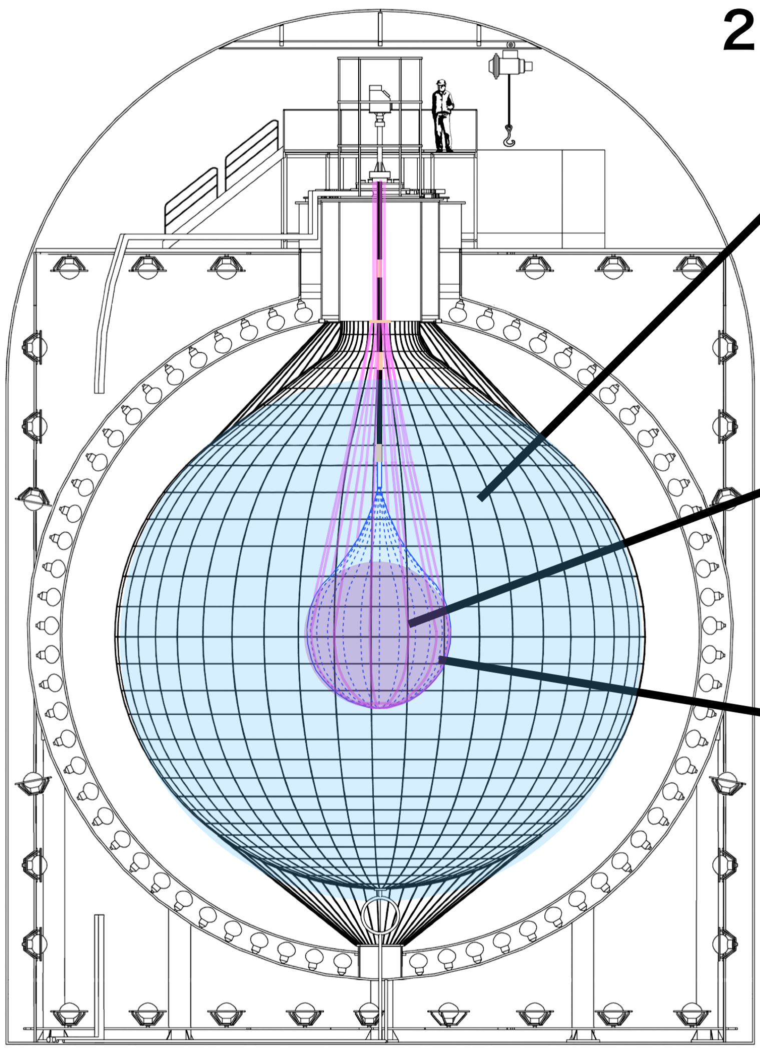
~50 physicists work on this project

Collaboration meeting in September, 2023

KamLAND-Zen

Zero Neutrino Double Beta

Kamioka underground
KamLAND detector



2-type of liquid scintillator

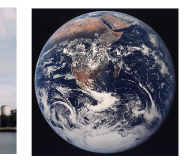
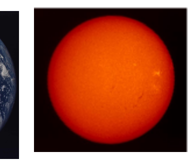
1000-ton pure liquid scintillator

U, Th < 10^{-17} g/g

745 kg Xe-loaded liquid scintillator (91% enrichment)

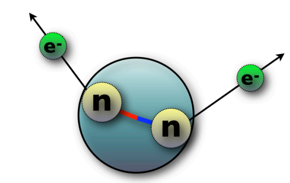
inner balloon (IB)

2002− KamLAND

reactor, geo, solar neutrino observation

2011− KamLAND-Zen



double beta decay measurement ($0\nu\beta\beta$ search)

2019− Xe increase, cleaner balloon

Advanced neutrino research utilizing
ultra-low background environment

Why Xe?

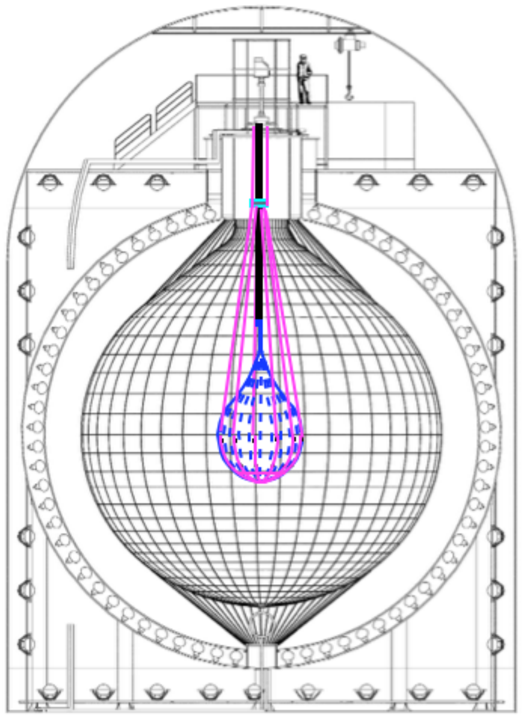
- Isotopic enrichment (centrifugal) established
- Gas purification is possible
- Soluble to LS more than 3 wt%, easily extracted
- Slow $2\nu\beta\beta$ requires modest energy resolution

competing exp.	Xe
EXO-200	200 kg
KamLAND-Zen	**745 kg**

largest amount of ^{136}Xe !!

Upgrade of KamLAND-Zen

Past



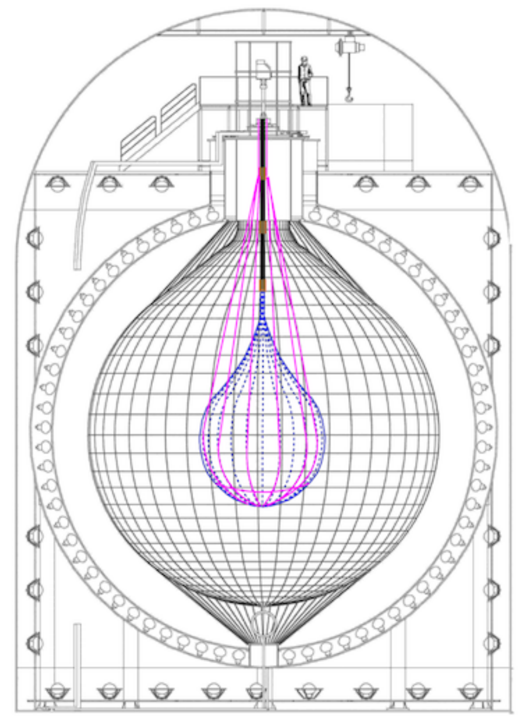
KamLAND-Zen 400

Nylon balloon R 1.54 m

Xenon 320 − 380 kg

world top performance

Present



KamLAND-Zen 800

Nylon balloon R 1.90 m

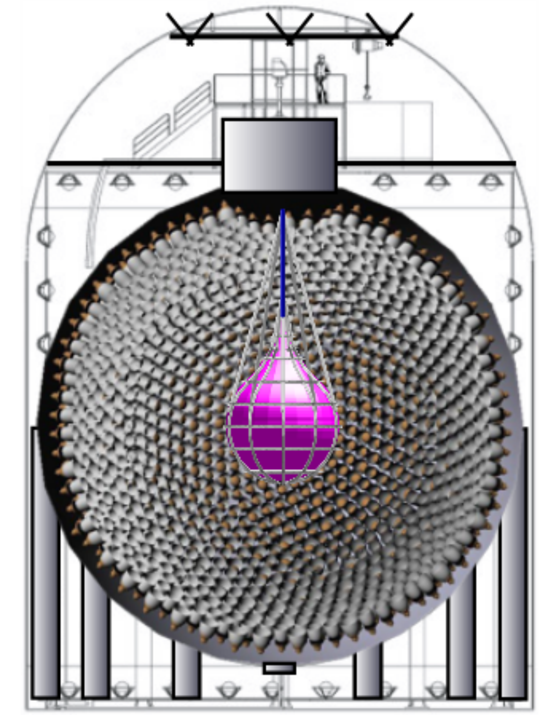
Xenon 745 kg

target $\langle m_{\beta\beta} \rangle$ ~ **40 meV**

reduced radioactive BG

demonstration of scalability

Future



KamLAND2-Zen

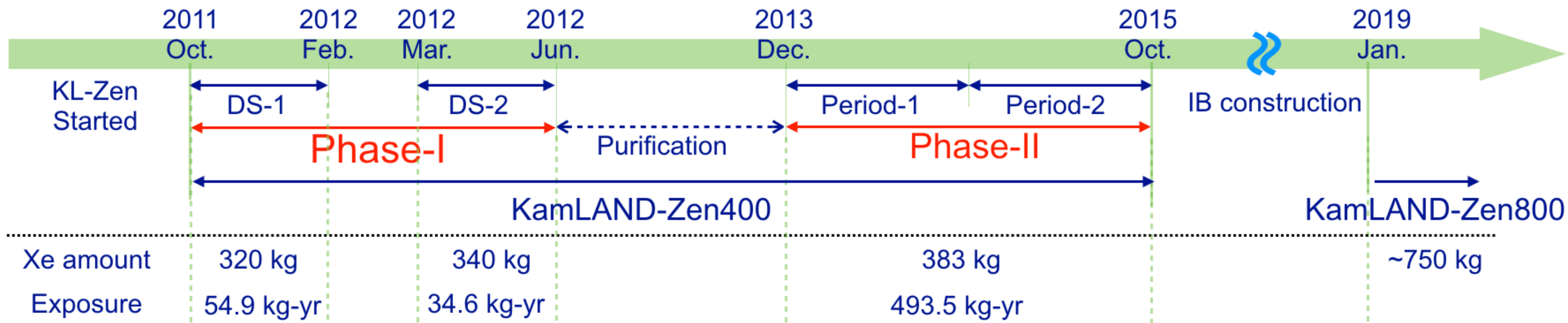
Xenon 1 ton

target $\langle m_{\beta\beta} \rangle$ ~ **20 meV**

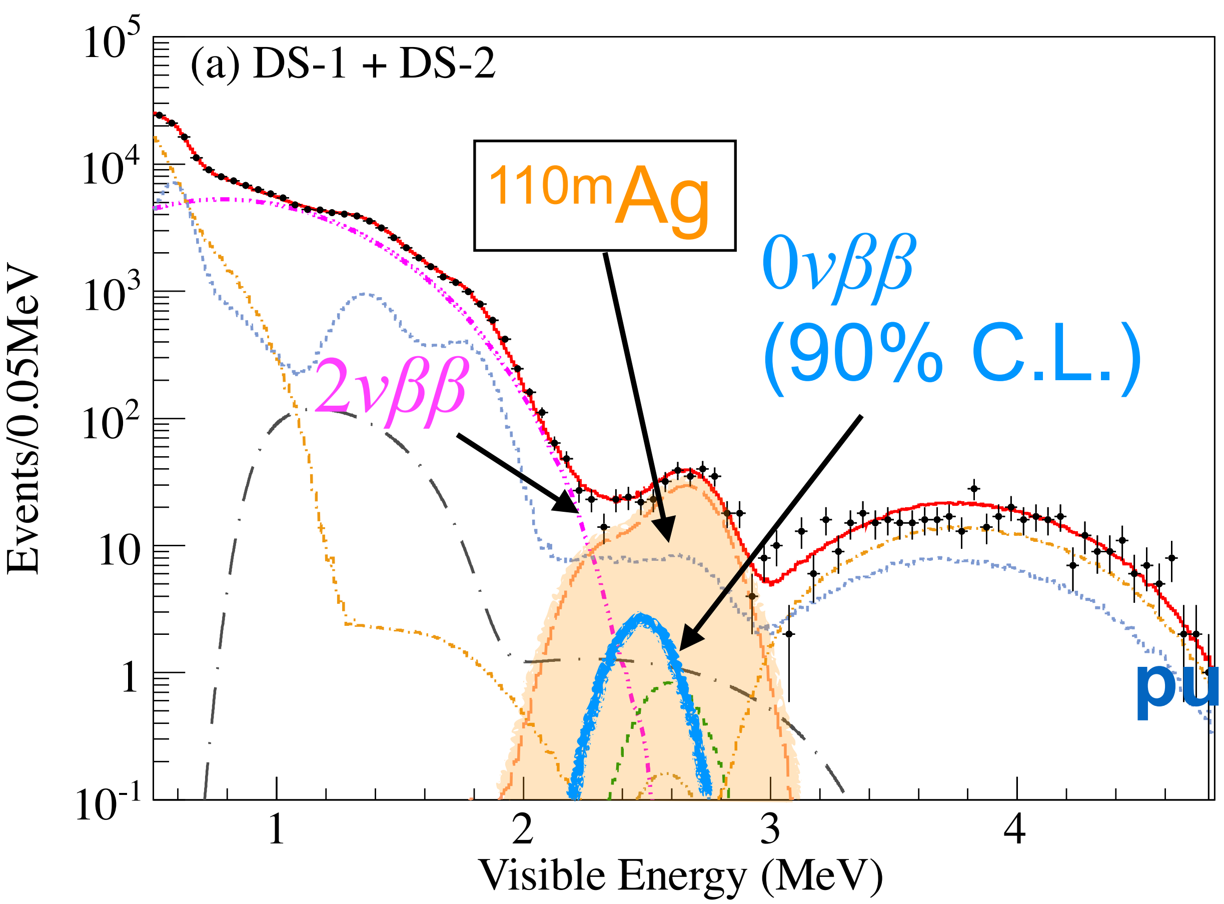
high light yield

better performance

KamLAND-Zen 400



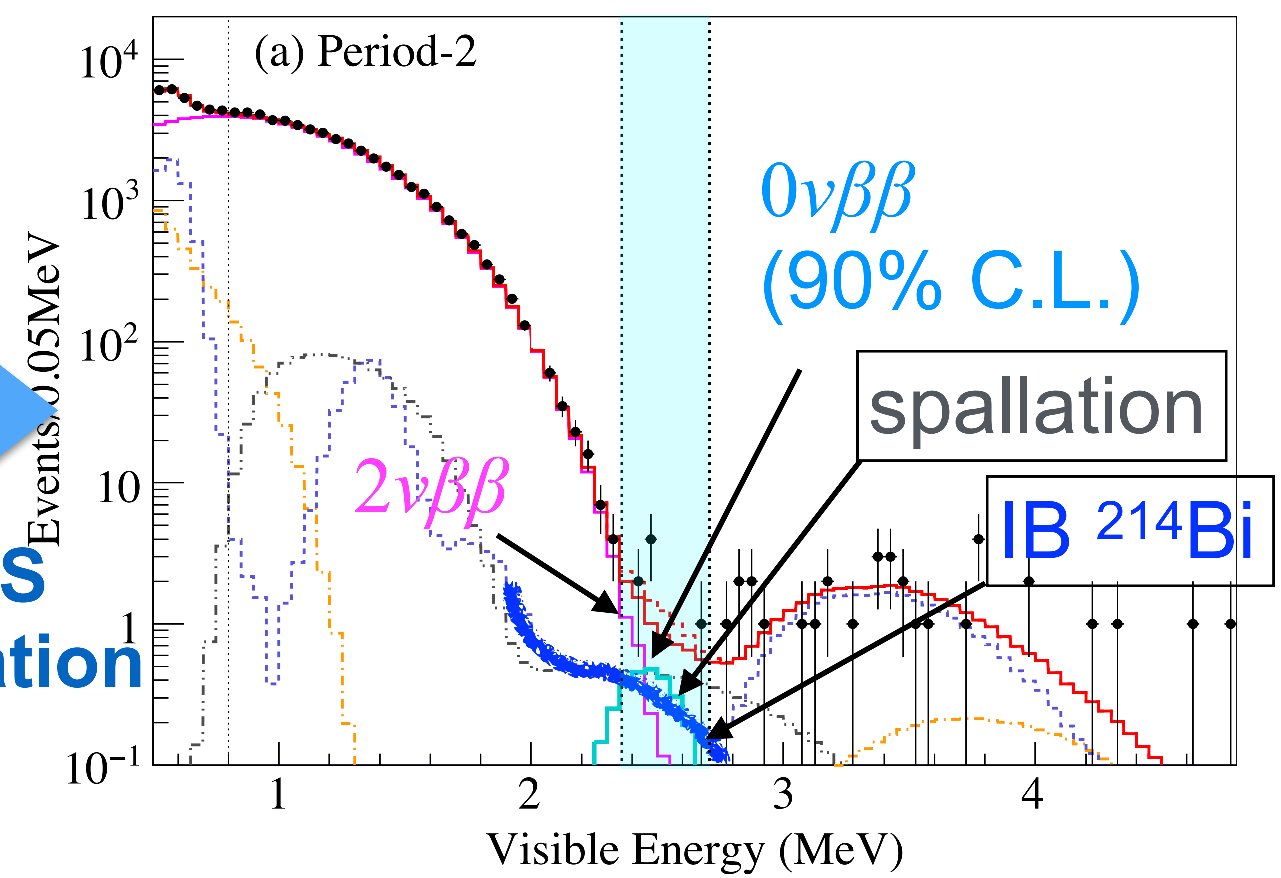
Phase-I (R < 1.35 m)



dominant BG from ^{110m}Ag

Xe-LS purification

Phase-II (R < 1 m)



No ^{110m}Ag

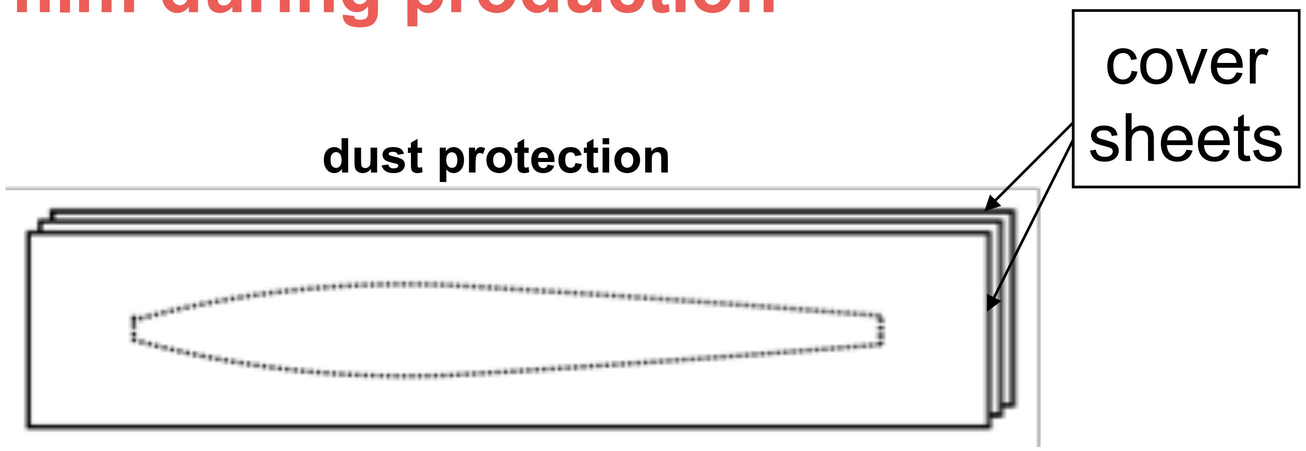
→ need to reduce other BGs

Improved Production Method

KamLAND-Zen 400

KamLAND-Zen 800

dust may be attached to the film during production



newly introduced

- goggle
- laundry twice a day
- welding machine
- more neutralizer
- cover sheet

…

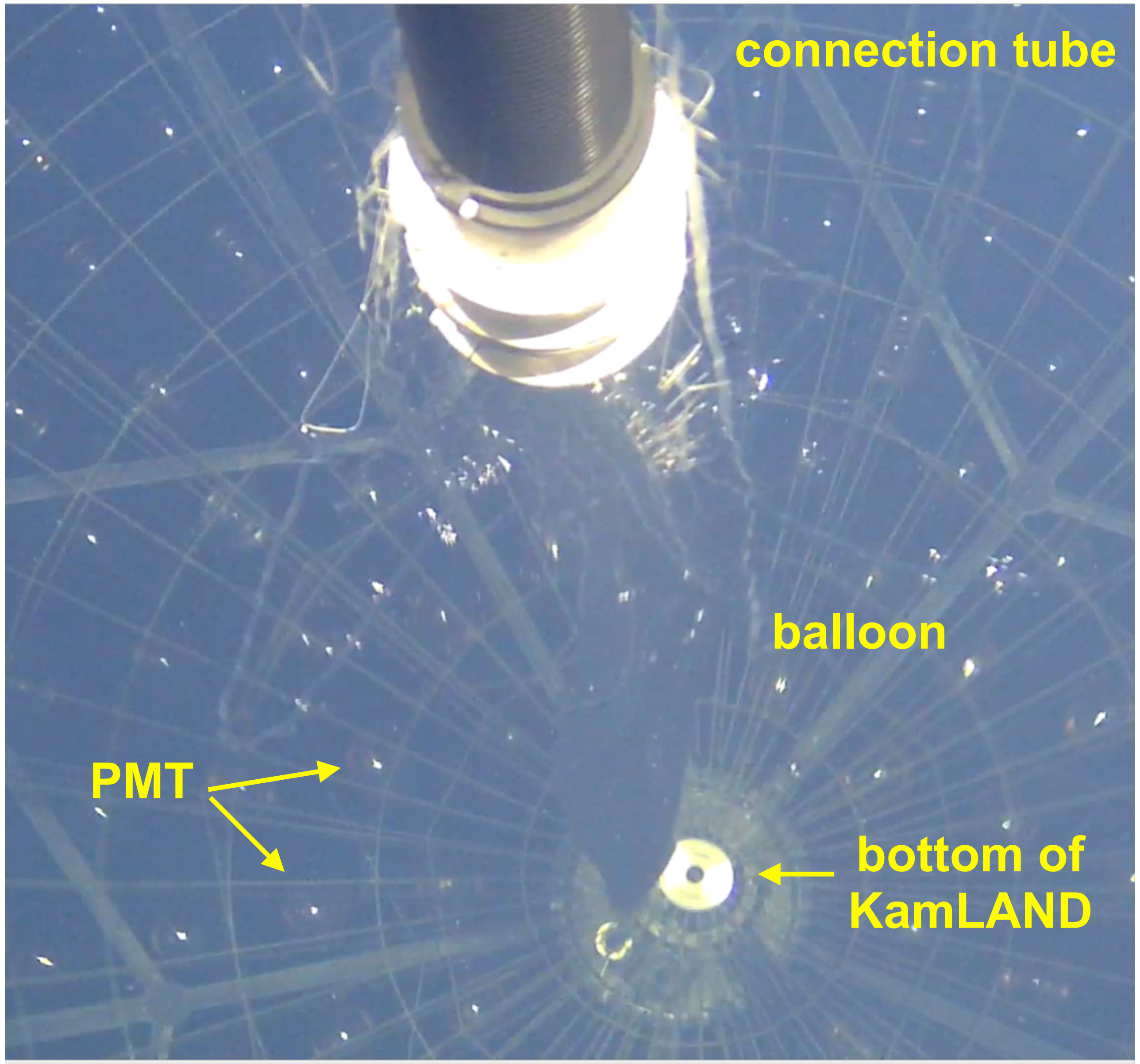
Balloon Production Work

Balloon Installation

Balloon installation completed and started LS filling on May 10, 2018

top of the detector

detector inside view



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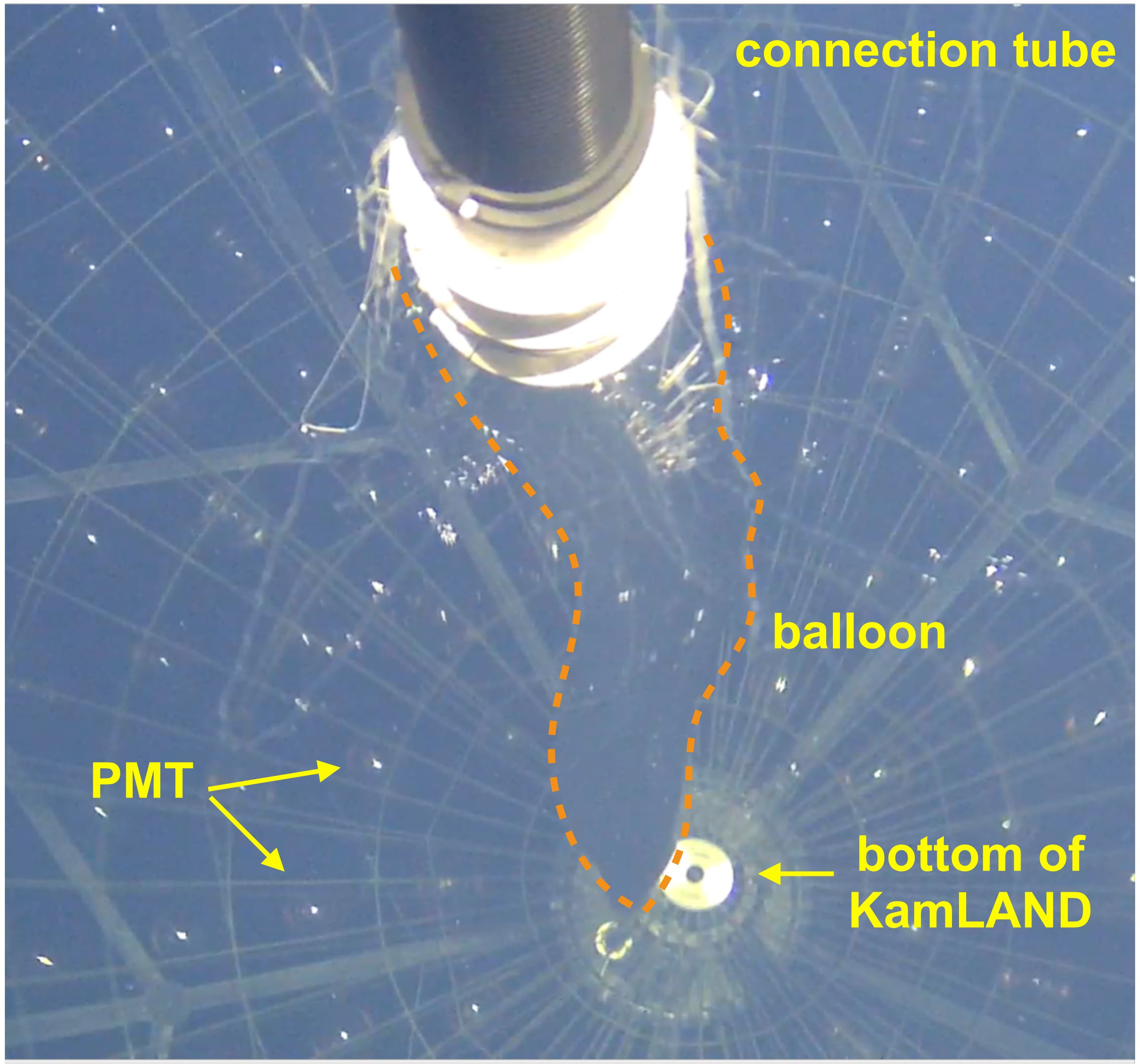
top of the detector

detector inside view



Balloon Installation

Balloon Installation

Background from Inner Balloon (IB)

Zen 400 Phase-II

^{238}U : 5×10^{-11} g/g

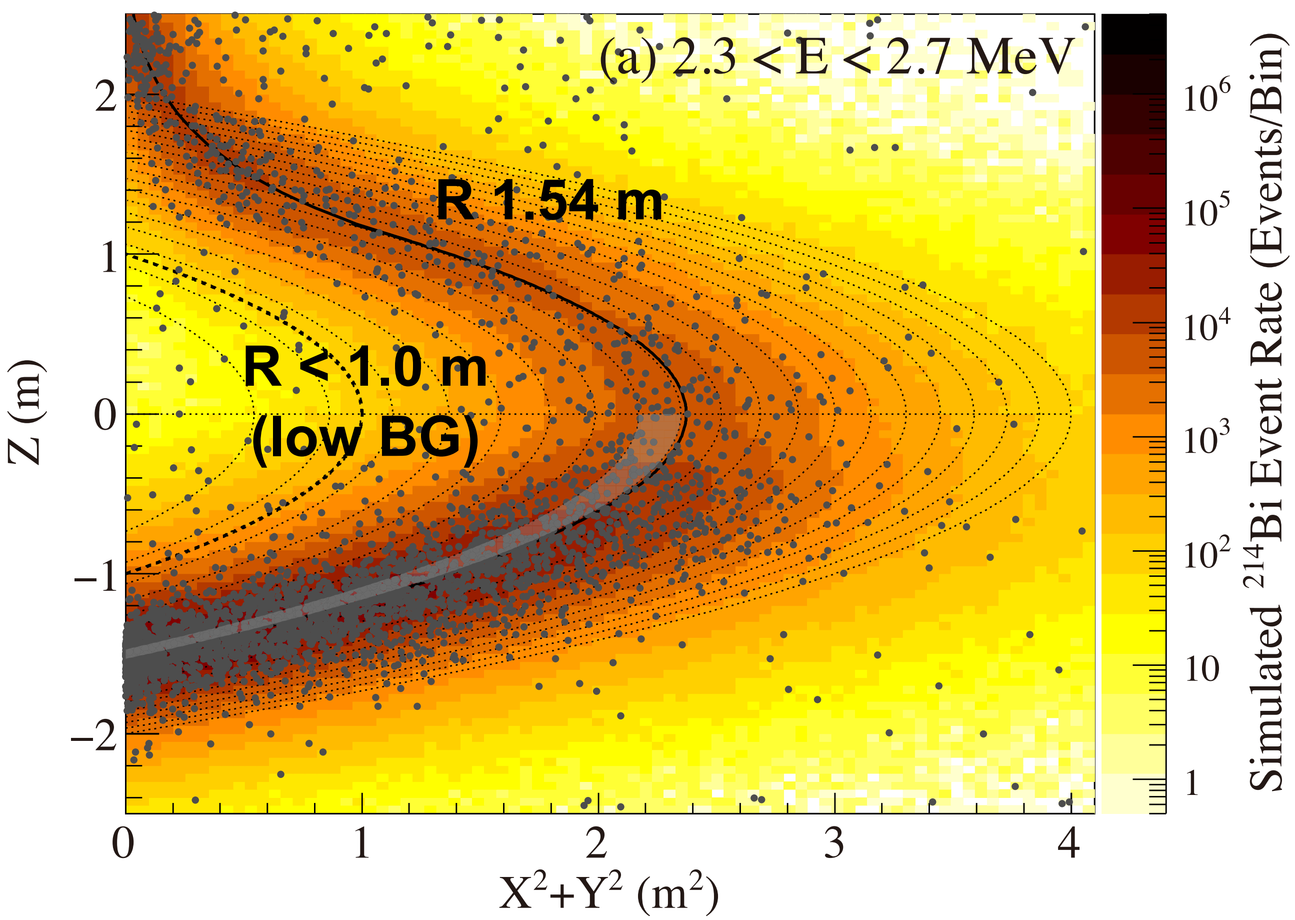
^{232}Th : 3×10^{-10} g/g

Zen 800

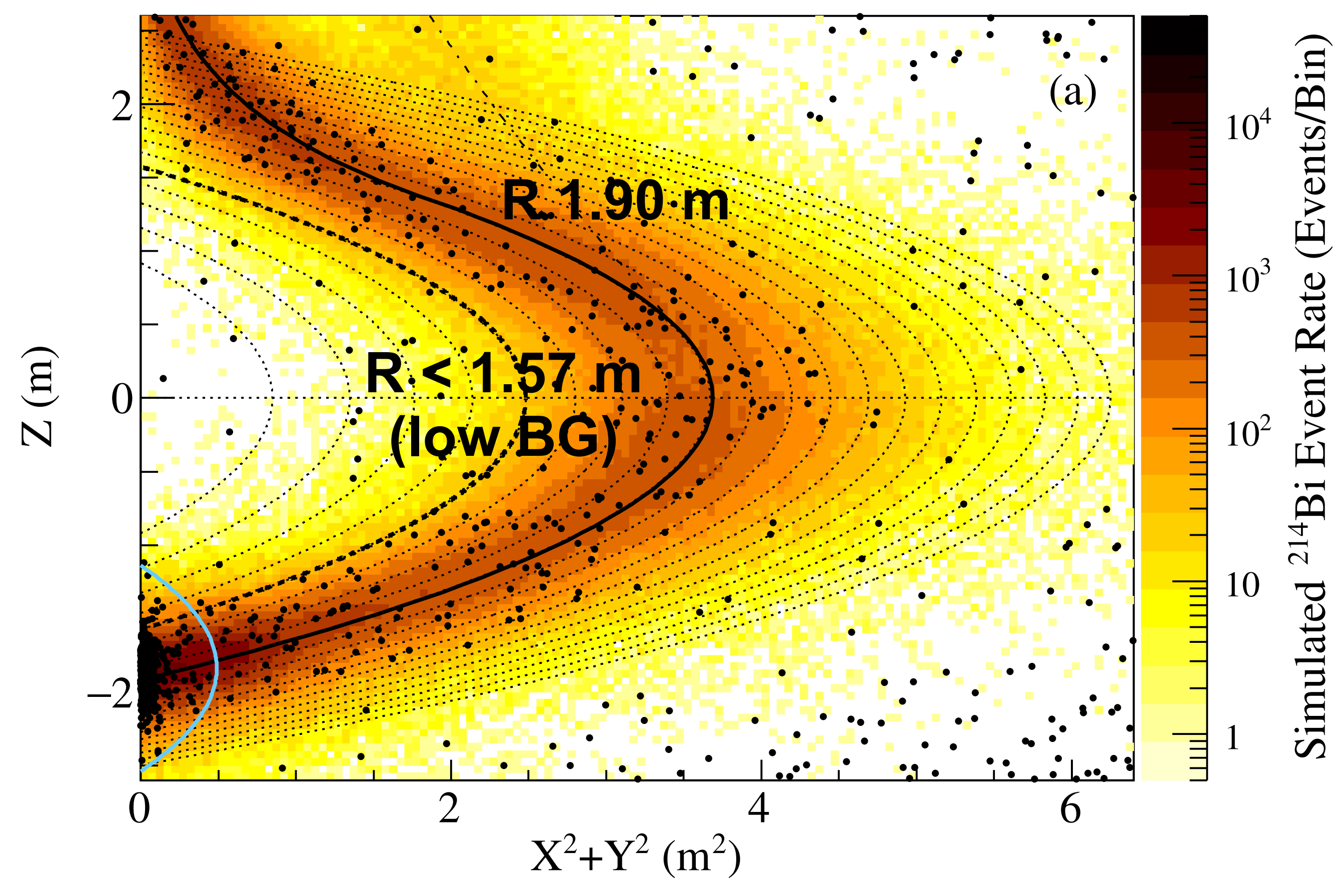
^{238}U : ~3×10^{-12} g/g

^{232}Th : ~4×10^{-11} g/g

×10 reduction of IB ^{214}Bi



sensitive volume : R < 1.0 m

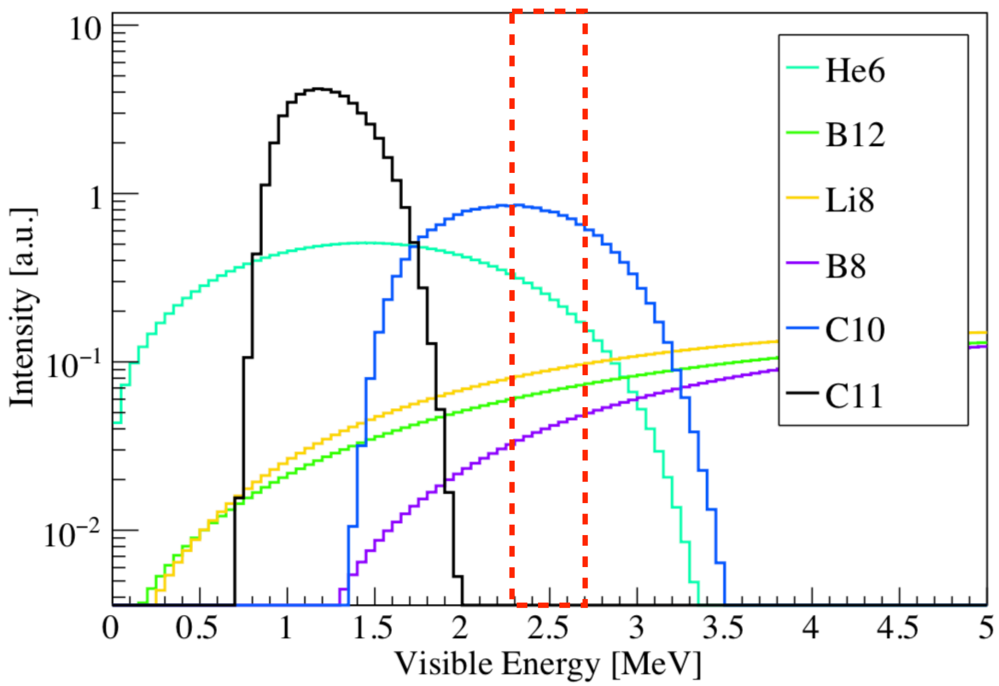


sensitive volume : R < 1.57 m

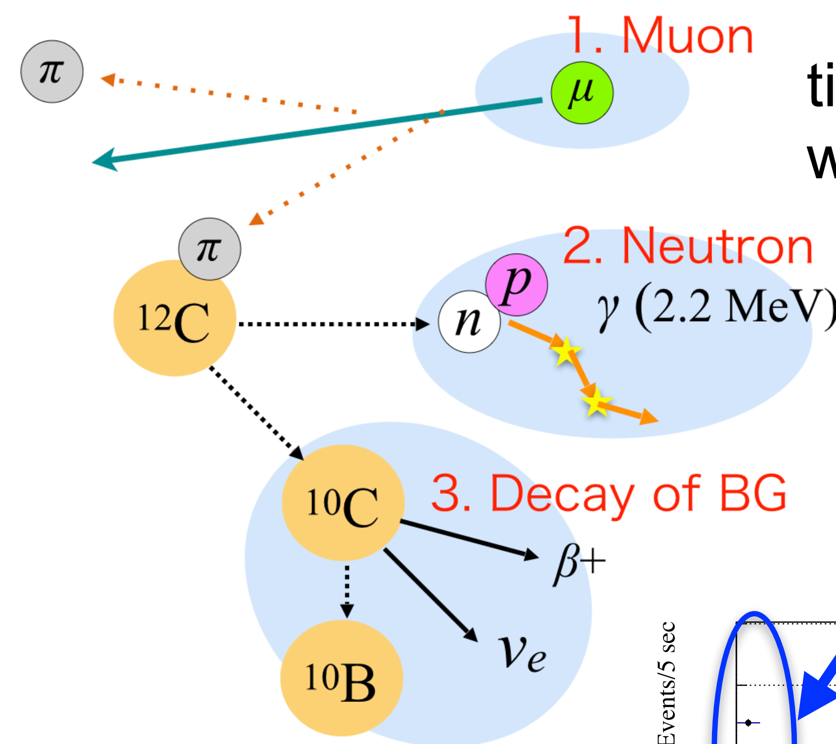
> ×3 sensitive volume !!

Short-lived Spallation Products

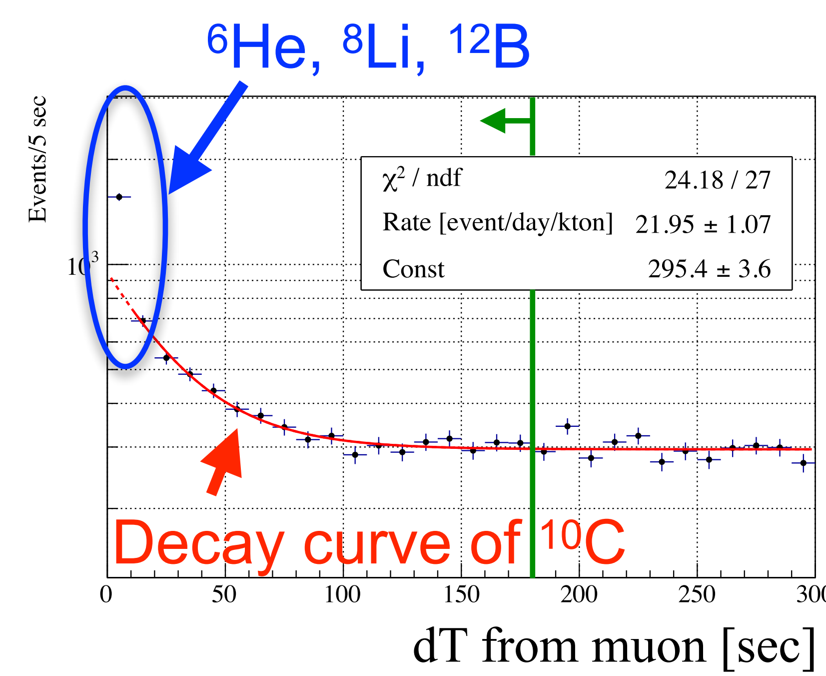
carbon spallation products



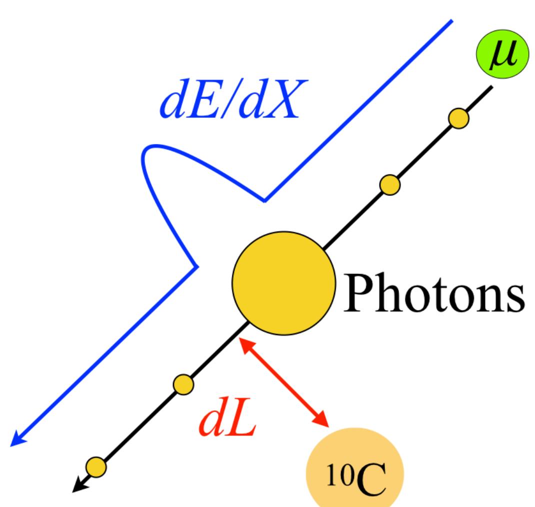
Triple coincidence tagging (dT, dR)



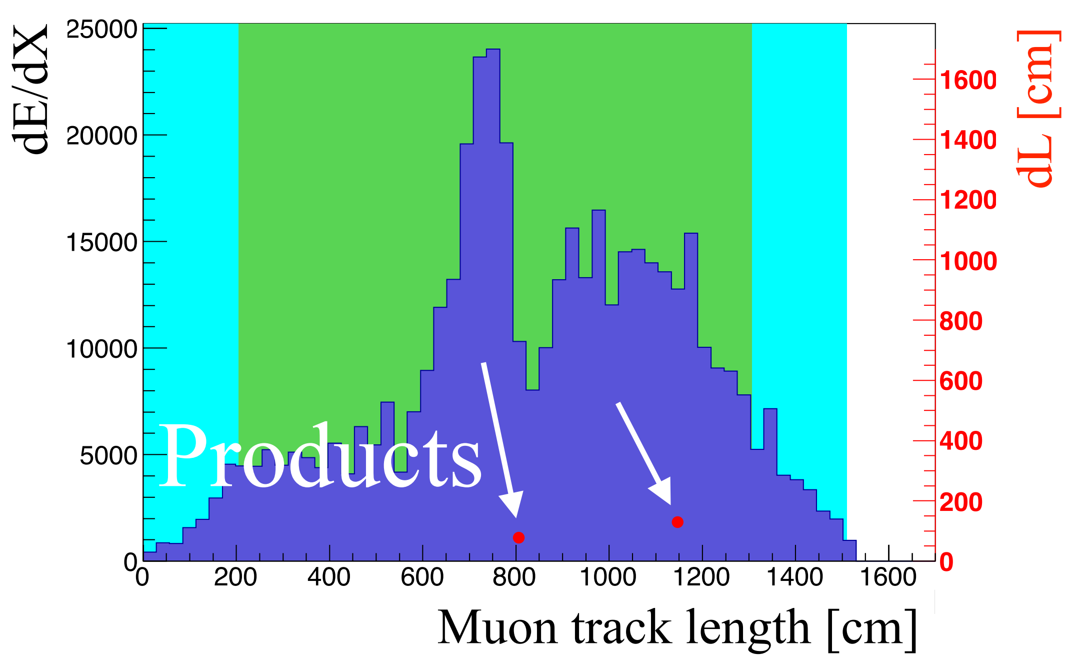
time and space correlation with muon and neutrons



Shower tagging (dE/dX, dL)



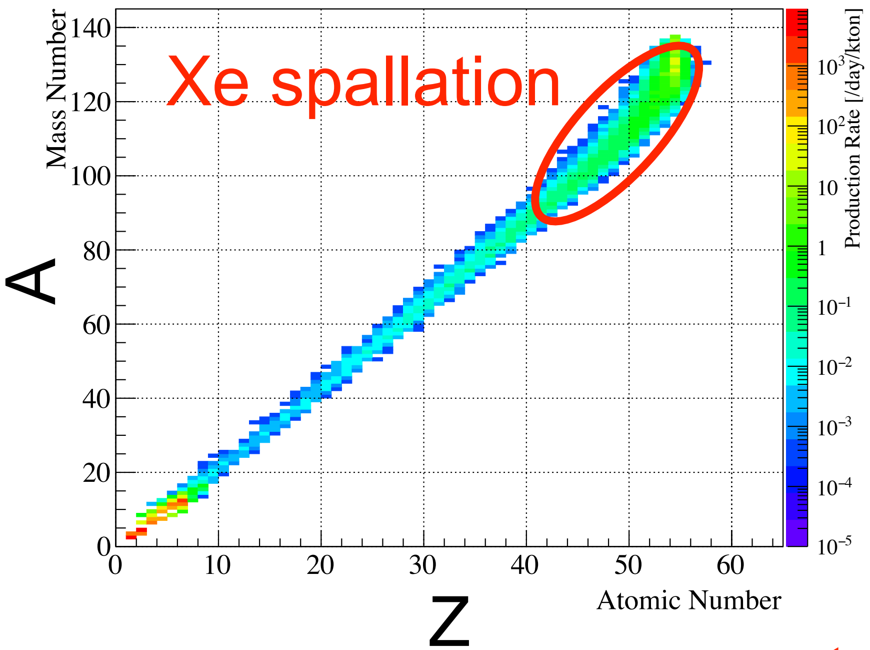
space correlation with muon shower



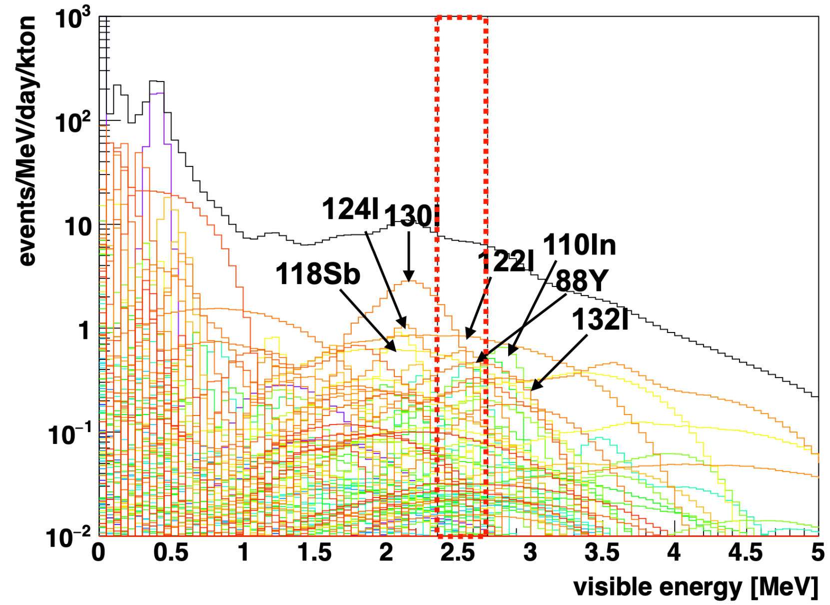
carbon spallation products
> 95% rejection efficiency

Long-lived Spallation Products

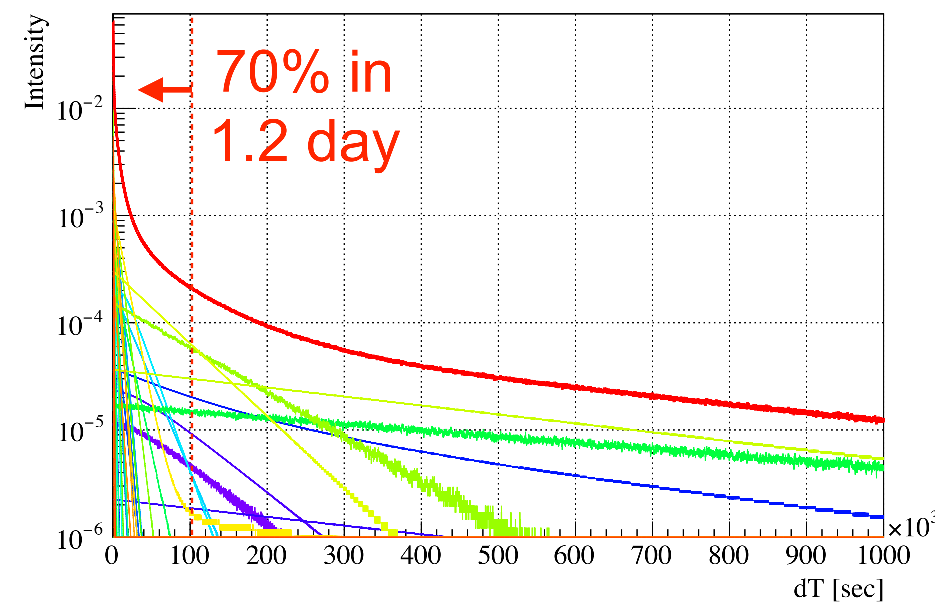
production yield



energy spectrum



time difference from muon

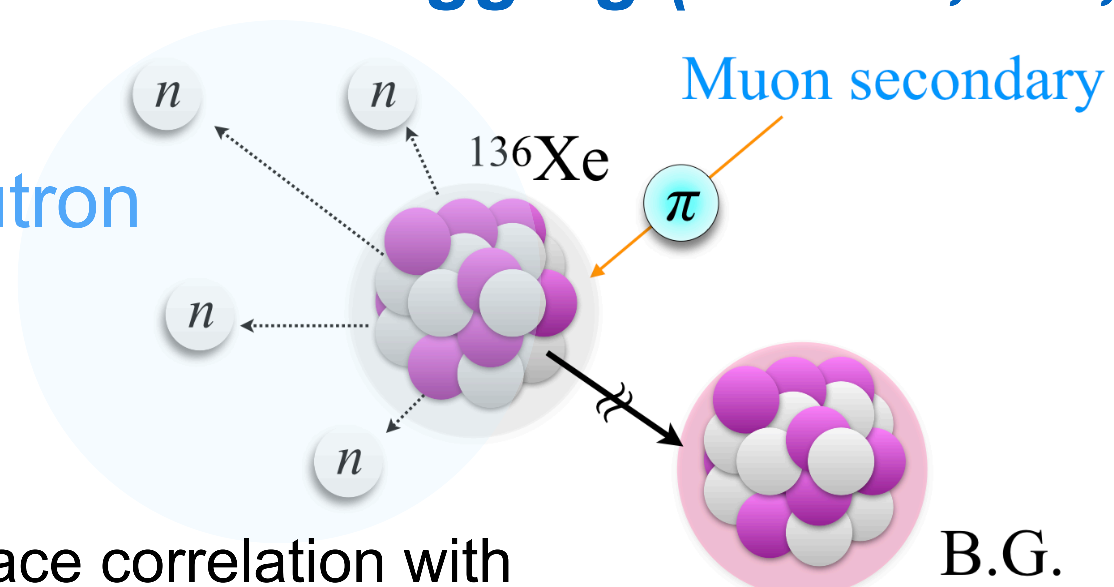


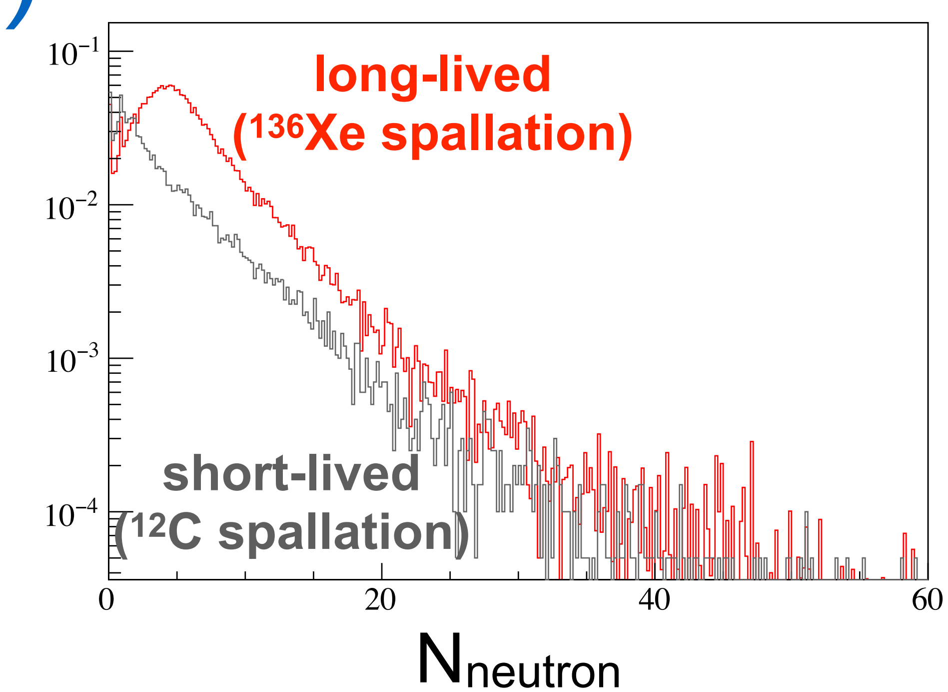
rate in ROI : 0.082 events/day/Xe-ton

need long-time veto

Likelihood-based tagging ($N_{neutron}$, dR, dT)

dense neutron cluster





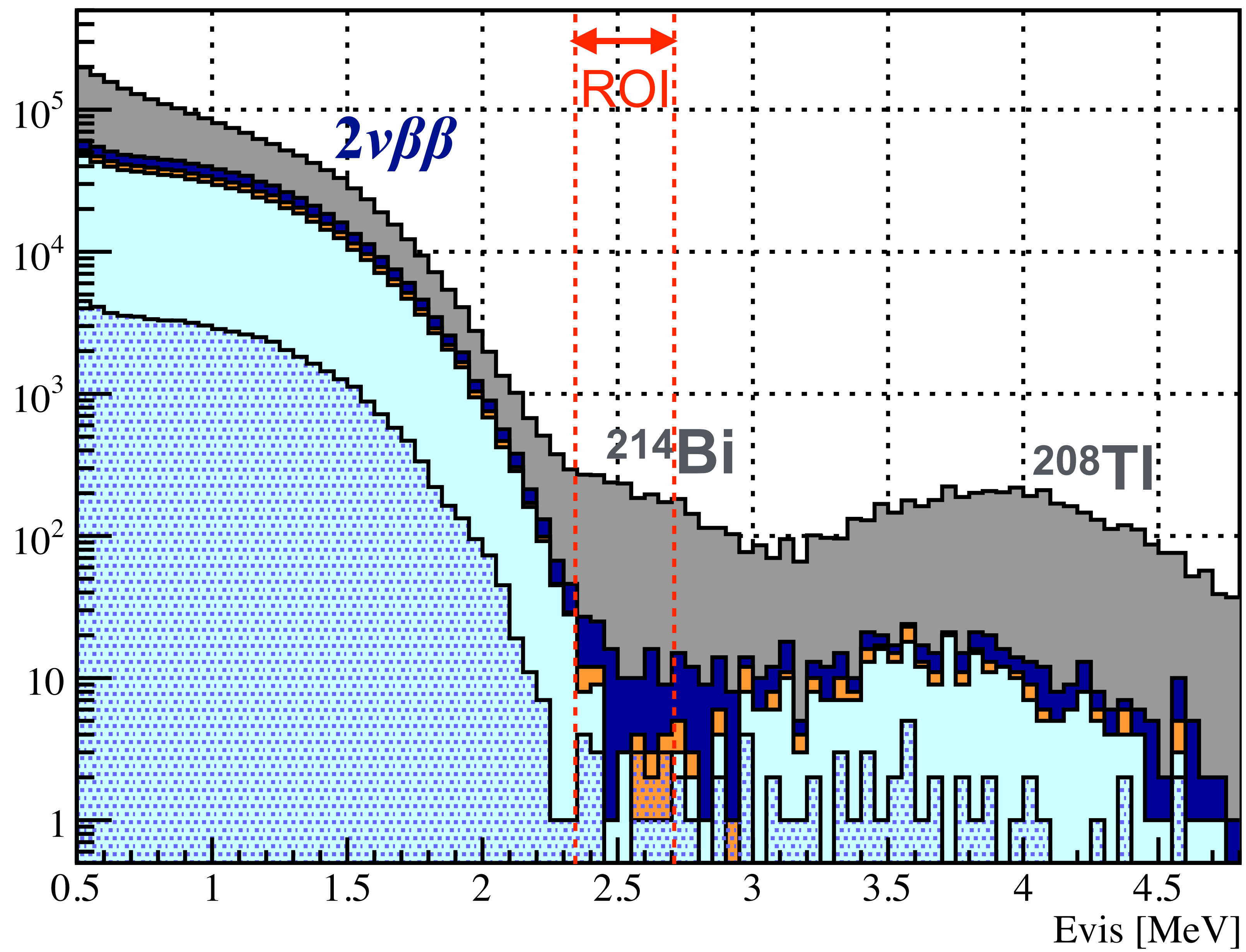
time and space correlation with muon and multiple neutrons

xenon spallation products ~40% rejection efficiency

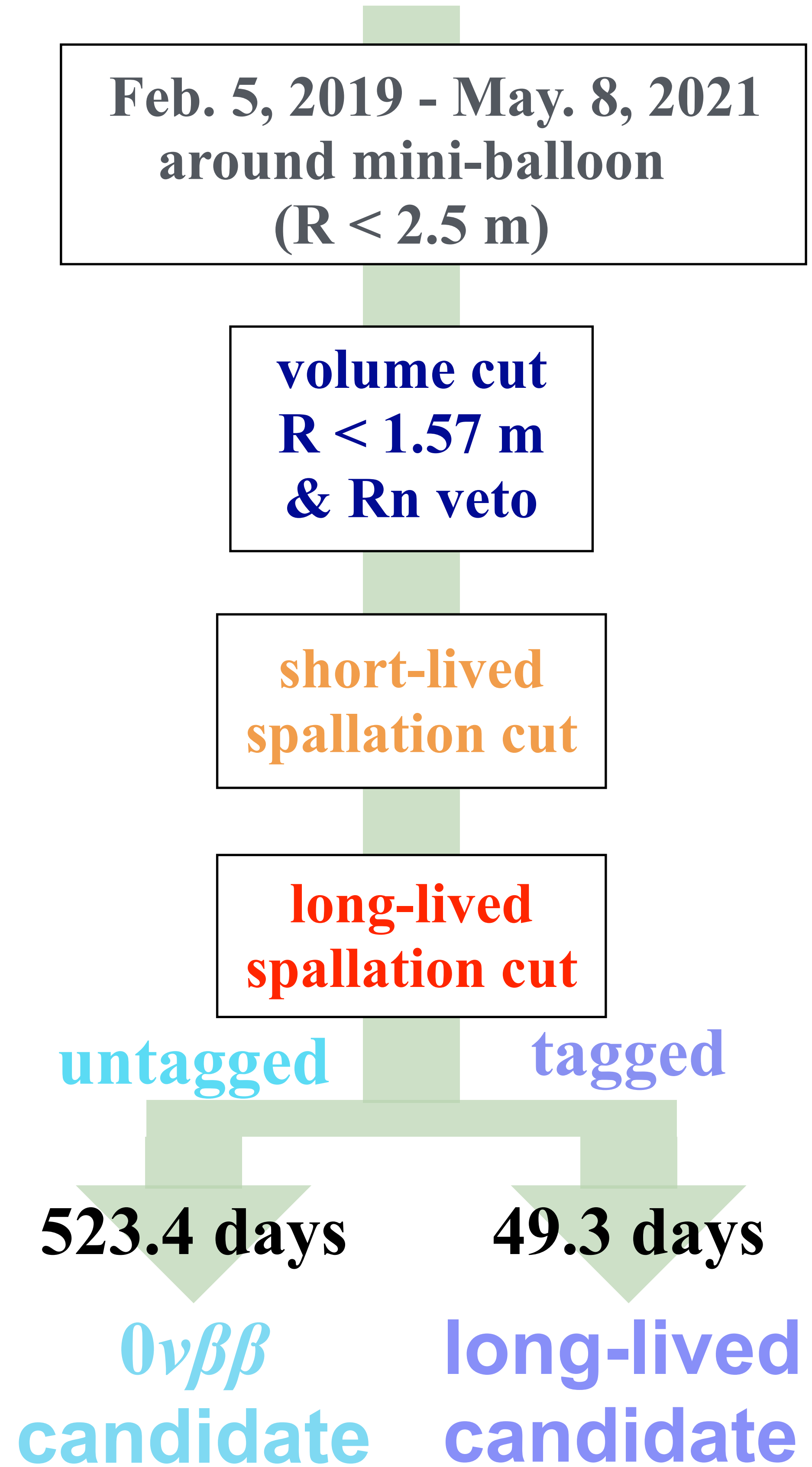
Event Selection

ββ isotope ^{136}Xe **90.85% enriched** $Q_{\beta\beta}$ = 2458 keV

745 kg Xe in all volume Feb. 5, 2019 - May 8, 2021



Two energy spectra (0νββ, long-lived) are fitted simultaneously



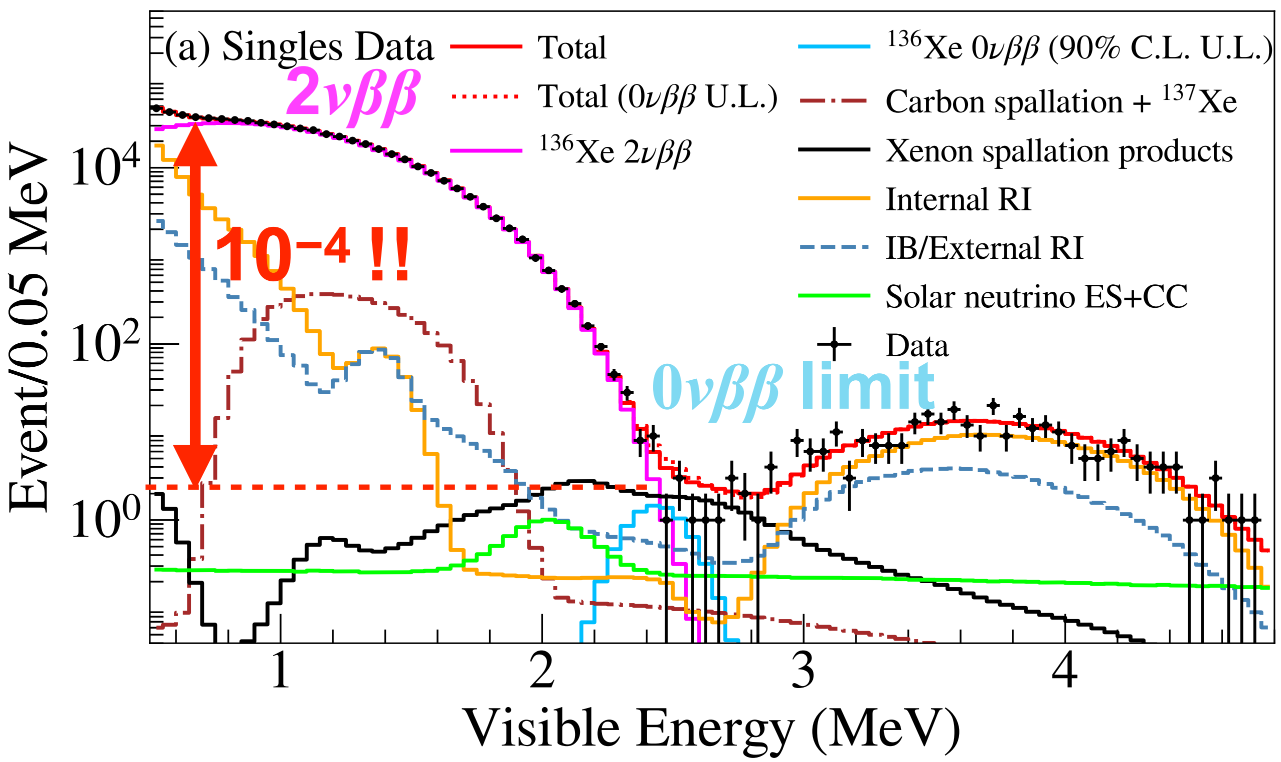
Fit to Energy Spectra for 0νββ

0νββ candidate

(sensitive to 0νββ signal)

523.4 days livetime

R < 1.57 m

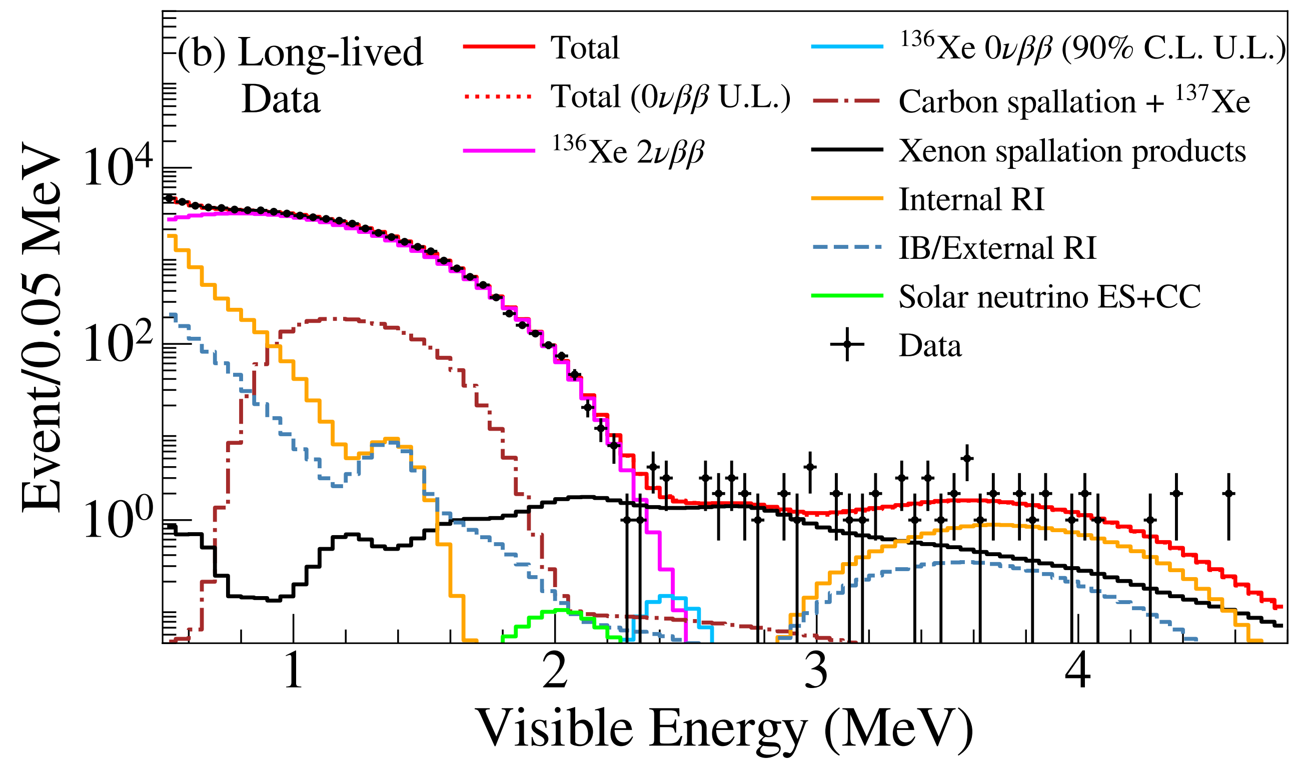


long-lived candidate

(Long-lived BG constraint)

49.3 days livetime

R < 1.57 m



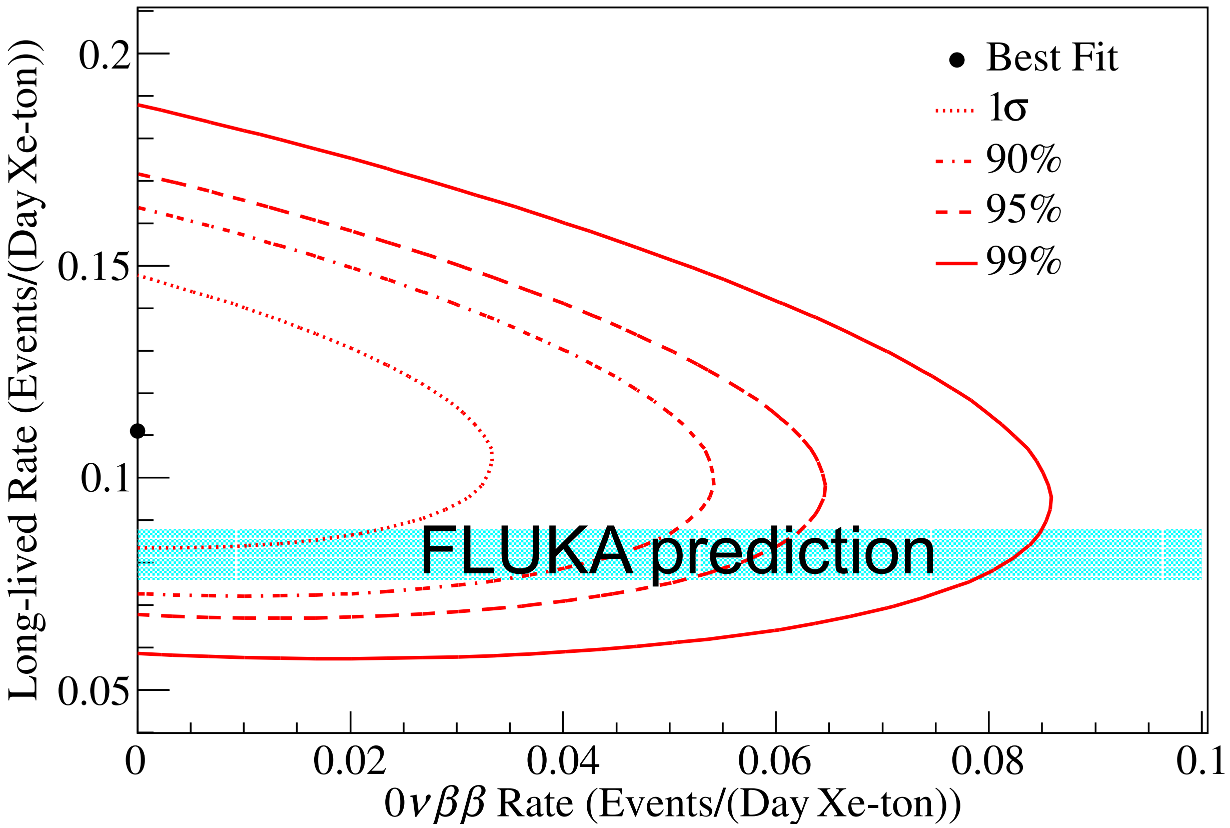
0νββ best-fit : **0 event**

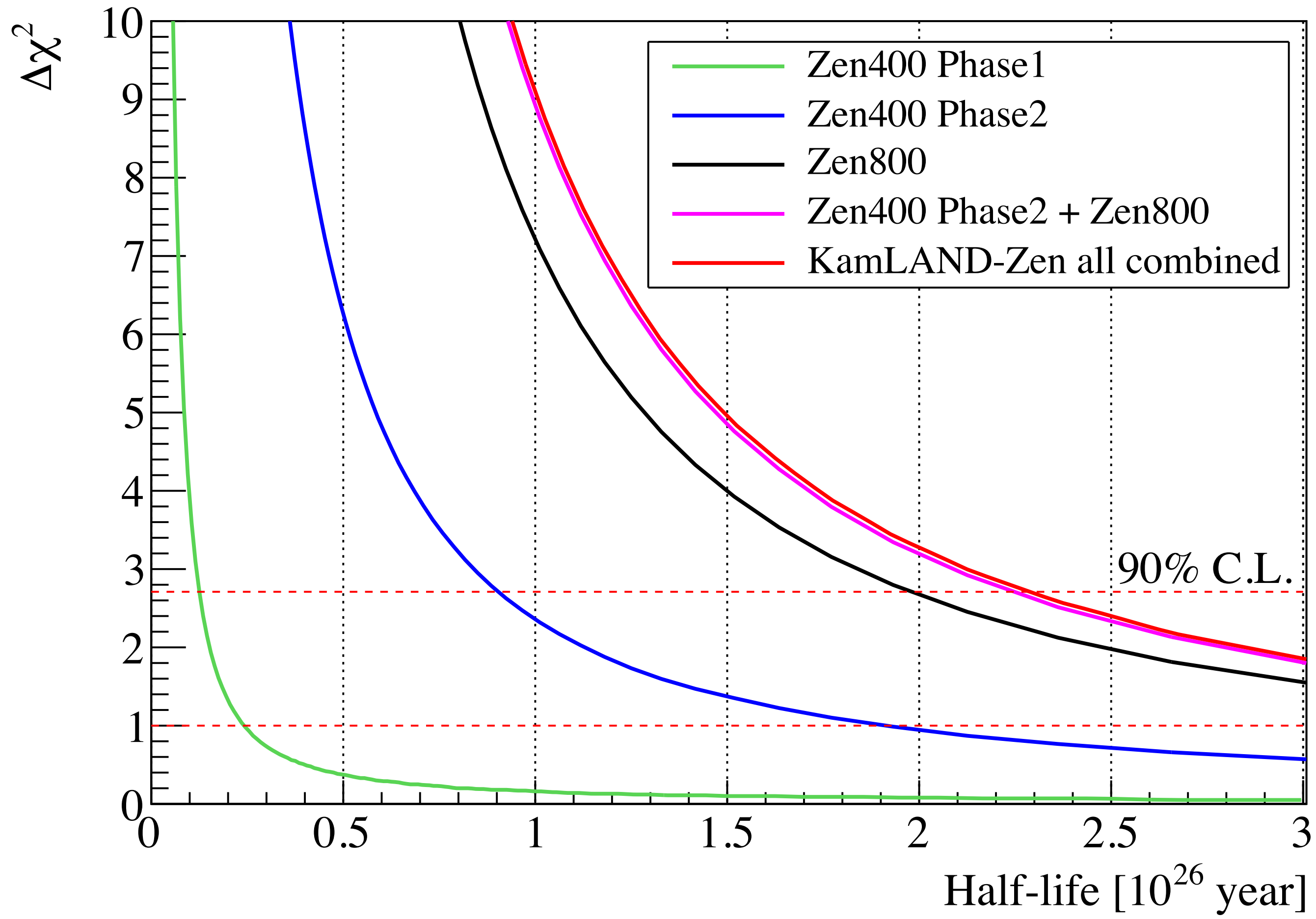
upper limit : **< 7.9 event** at 90% C.L.

No positive signal, but we obtained a stringent upper limit

^{136}Xe 0νββ Decay Half-life

(0ν rate, Long-lived BG rate)





Long-lived BG rate in 2.35-2.70 MeV = 0.111 ± 0.019 events/day/Xe-ton

(FLUKA = 0.082 ± 0.006 events/day/Xe-ton)

Long-lived BG rate was measured

<u>Half-life limit at 90% C.L.</u>

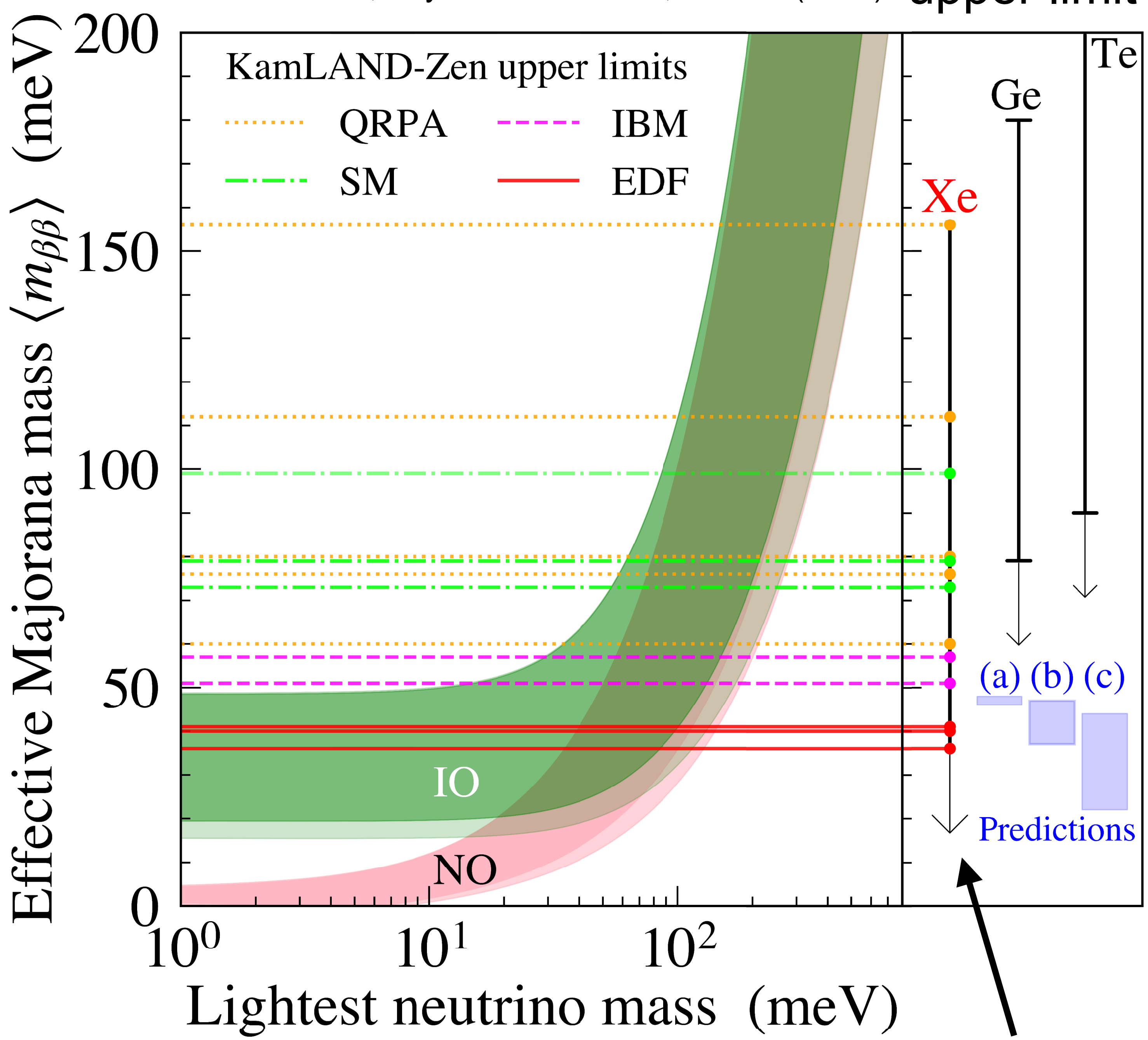
Zen 400	$T^{0\nu}_{1/2} > 0.9 \times 10^{26}$ yr
Zen 800	$T^{0\nu}_{1/2} > 2.0 \times 10^{26}$ yr
Combined	$T^{0\nu}_{1/2} > 2.3 \times 10^{26}$ yr

Limits on ^{136}Xe half-life are improved (~2 times better than previous)

Limits on Neutrino Mass

90% C.L. upper limit

S. Abe et al., Phys. Rev. Lett. 130, 051801 (2023)



Xe (KamLAND-Zen) is the leading experiment !

KamLAND-Zen (^{136}Xe)

$\langle m_{\beta\beta} \rangle$ < 36-156 meV

NME calculations assuming g_A ~ 1.27

QRPA

- J. Terasaki, Phys. Rev. C **102**, 044303 (2020).
- J. Hyvärinen and J. Suhonen, Phys. Rev. C **91**, 024613 (2015).
- F. Šimkovic, V. Rodin, A. Faessler, and P. Vogel, Phys. Rev. C **87**, 045501 (2013).
- M. T. Mustonen and J. Engel, Phys. Rev. C **87**, 064302 (2013).
- D.-L. Fang, A. Faessler, and F. Šimkovic, Phys. Rev. C **97**, 045503 (2018).

SM

- L. Coraggio, A. Gargano, N. Itaco, R. Mancino, and F. Nowacki, Phys. Rev. C **101**, 044315 (2020).
- A. Neacsu and M. Horoi, Phys. Rev. C **91**, 024309 (2015).
- J. Menendez, A. Poves, E. Caurier, and F. Nowacki, Nucl. Phys. A **818**, 139 (2009).

IBM

- F. F. Deppisch, L. Graf, F. Iachello, and J. Kotila, Phys. Rev. D **102**, 095016 (2020).
- J. Barea, J. Kotila, and F. Iachello, Phys. Rev. C **91**, 034304 (2015).

EDF

- N. L. Vaquero, T. R. Rodríguez, and J. L. Egido, Phys. Rev. Lett. **111**, 142501 (2013).
- J. M. Yao, L. S. Song, K. Hagino, P. Ring, and J. Meng, Phys. Rev. C **91**, 024316 (2015).
- T. R. Rodríguez and G. Martínez-Pinedo, Phys. Rev. Lett. **105**, 252503 (2010).

Decay rate → proportional to (neutrino mass)^2

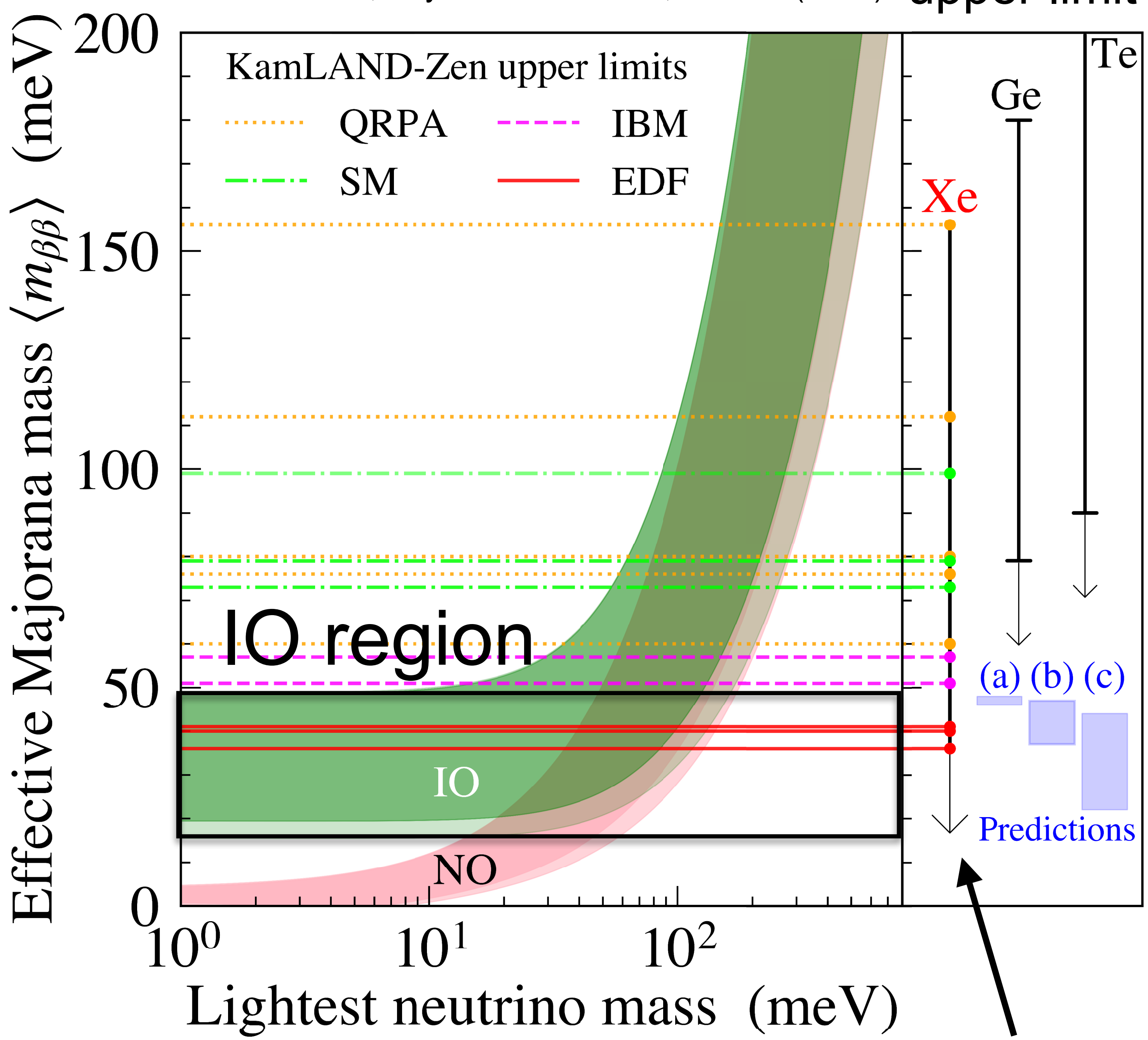
$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)|M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

PSF NME

Limits on Neutrino Mass

S. Abe et al., Phys. Rev. Lett. **130**, 051801 (2023)

90% C.L. upper limit



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$\langle m_{\beta\beta} \rangle$ < 36-156 meV

NME calculations assuming $g_A \sim 1.27$

QRPA
- J. Terasaki, Phys. Rev. C **102**, 044303 (2020).
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- F. Šimkovic, V. Rodin, A. Faessler, and P. Vogel, Phys. Rev. C **87**, 045501 (2013).
- M. T. Mustonen and J. Engel, Phys. Rev. C **87**, 064302 (2013).
- D.-L. Fang, A. Faessler, and F. Šimkovic, Phys. Rev. C **97**, 045503 (2018).

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- L. Coraggio, A. Gargano, N. Itaco, R. Mancino, and F. Nowacki, Phys. Rev. C **101**, 044315 (2020).
- A. Neacsu and M. Horoi, Phys. Rev. C **91**, 024309 (2015).
- J. Menendez, A. Poves, E. Caurier, and F. Nowacki, Nucl. Phys. A **818**, 139 (2009).

IBM
- F. F. Deppisch, L. Graf, F. Iachello, and J. Kotila, Phys. Rev. D **102**, 095016 (2020).
- J. Barea, J. Kotila, and F. Iachello, Phys. Rev. C **91**, 034304 (2015).

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- N. L. Vaquero, T. R. Rodríguez, and J. L. Egido, Phys. Rev. Lett. **111**, 142501 (2013).
- J. M. Yao, L. S. Song, K. Hagino, P. Ring, and J. Meng, Phys. Rev. C **91**, 024316 (2015).
- T. R. Rodríguez and G. Martínez-Pinedo, Phys. Rev. Lett. **105**, 252503 (2010).

Decay rate ⟶ proportional to (neutrino mass)^2

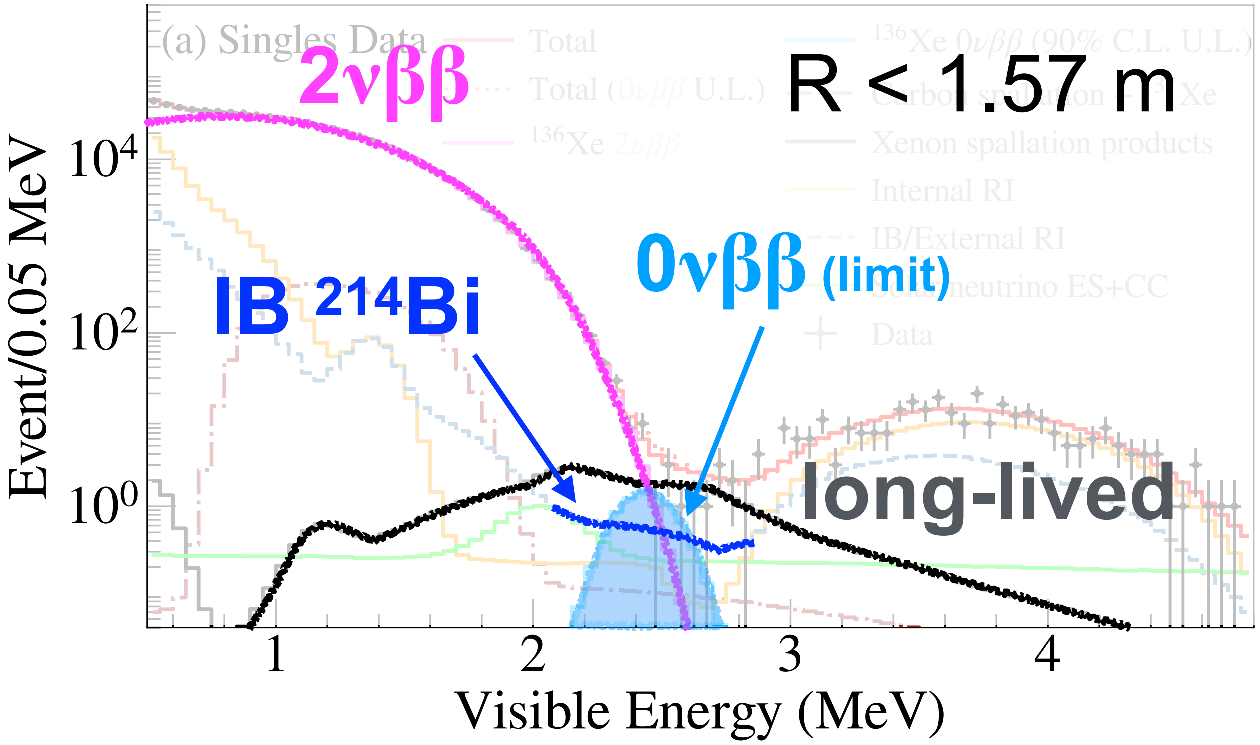
$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)|M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

PSF NME

First search in the inverted ordering (IO) region

Future Prospects

Background Measures in Future



current status

Search sensitivity will be limited by the backgrounds from **2νββ** and **long-lived spallation**

ROI event (2.35 < E < 2.70 MeV)

2νββ	**11.98**
RI in Xe-LS	0.98
RI in IB	**3.06**
solar ν	1.65
long-lived	**12.52**

measures in future

energy resolution tail → **light yield increase**

detector upgrade plan : **KamLAND2-Zen**

RI decay in film → **scintillation balloon**

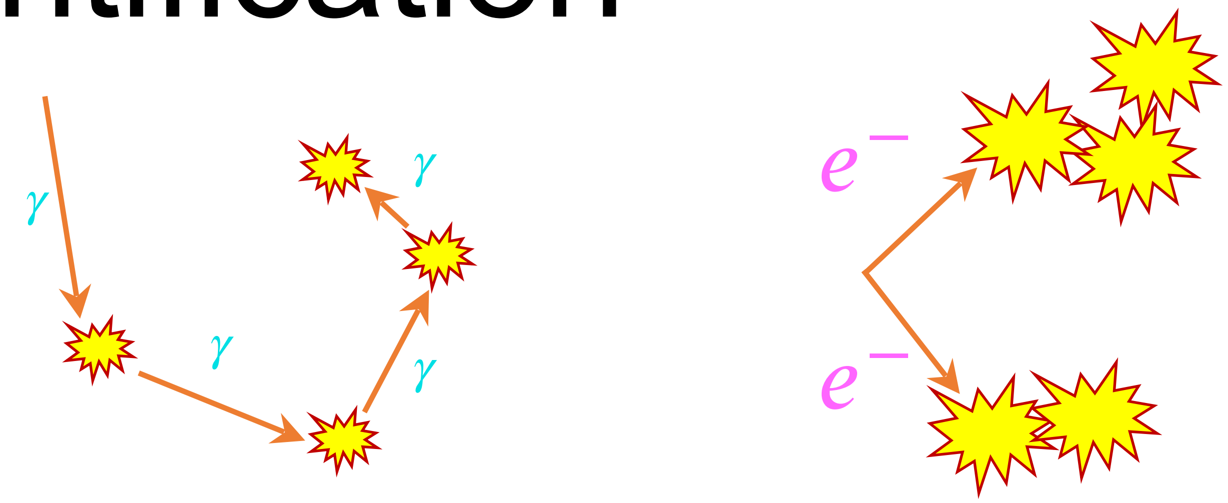
gamma or positron background
→ **particle identification**

spallation tagging with neutrons
→ **new electronics**

Particle Identification

Most of long-lived background decays with ~MeV gamma-rays

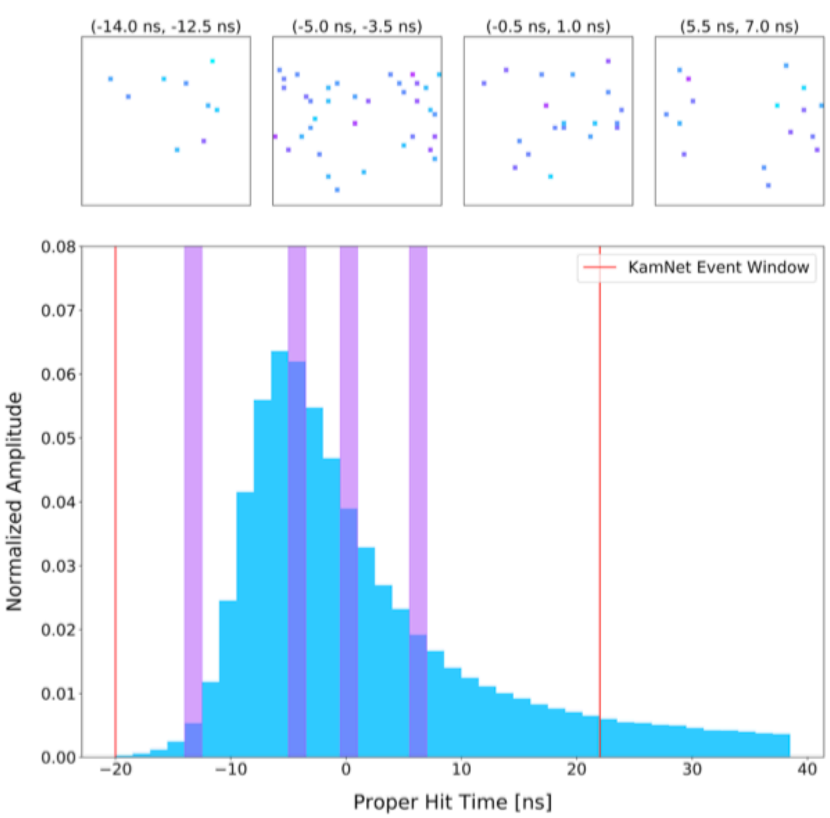
→ energy deposits spread over ~10 cm distances



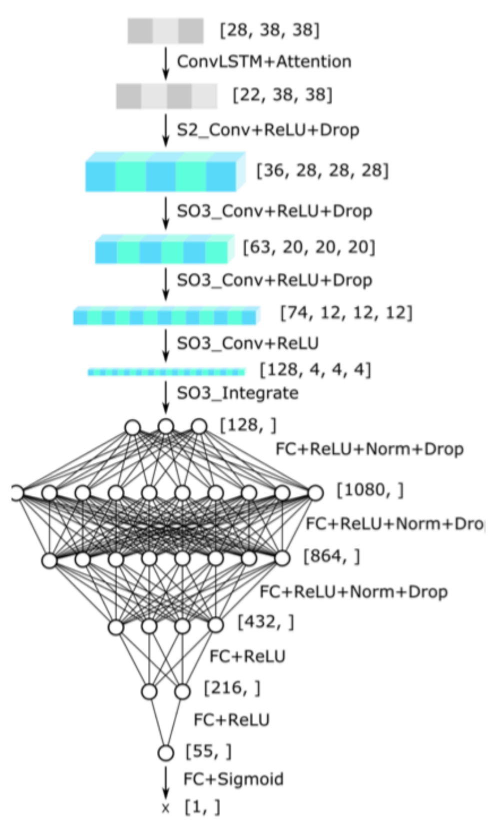
KamNET

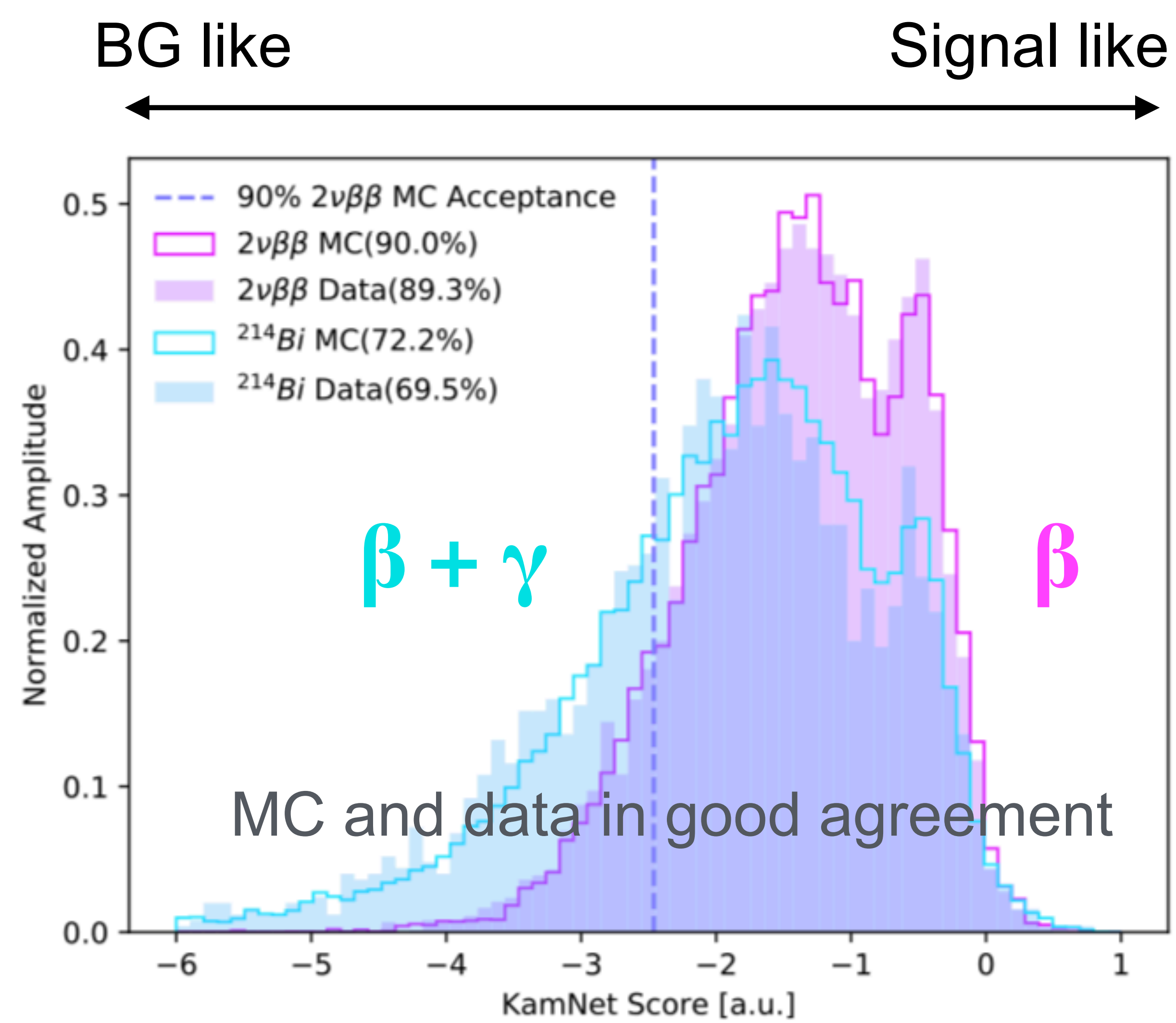
Deep neural network for KamLAND-Zen

Time series of theta-phi hit map



Spherical CNN



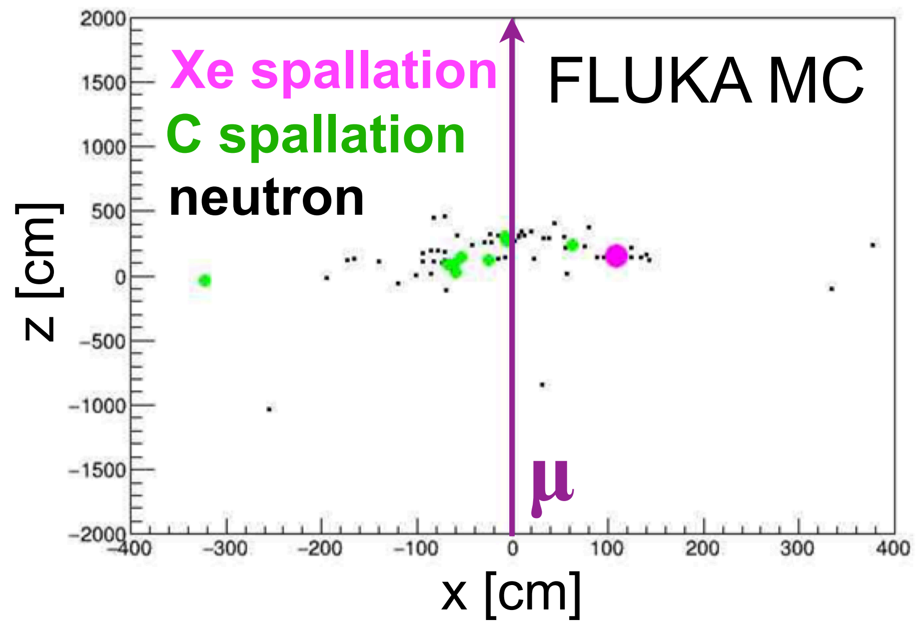


A. Li et al., Phys. Rev. C **107**, 014323 (2023)

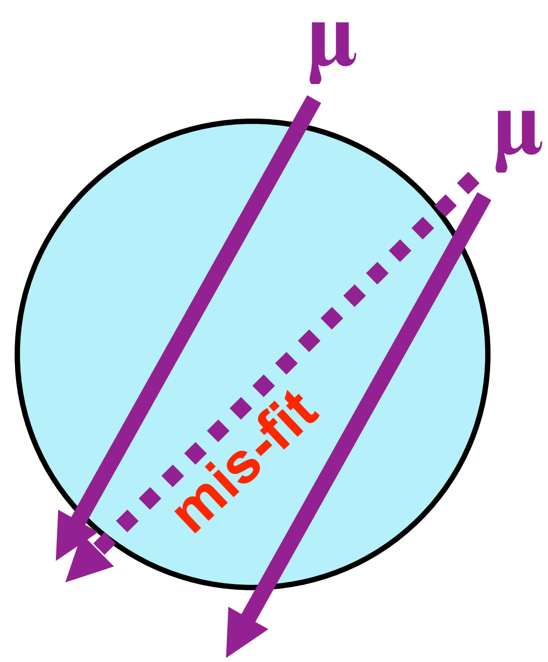
MC shows KamNET rejects ~27% of long-lived background

Tagging of Long-lived Spallation Products

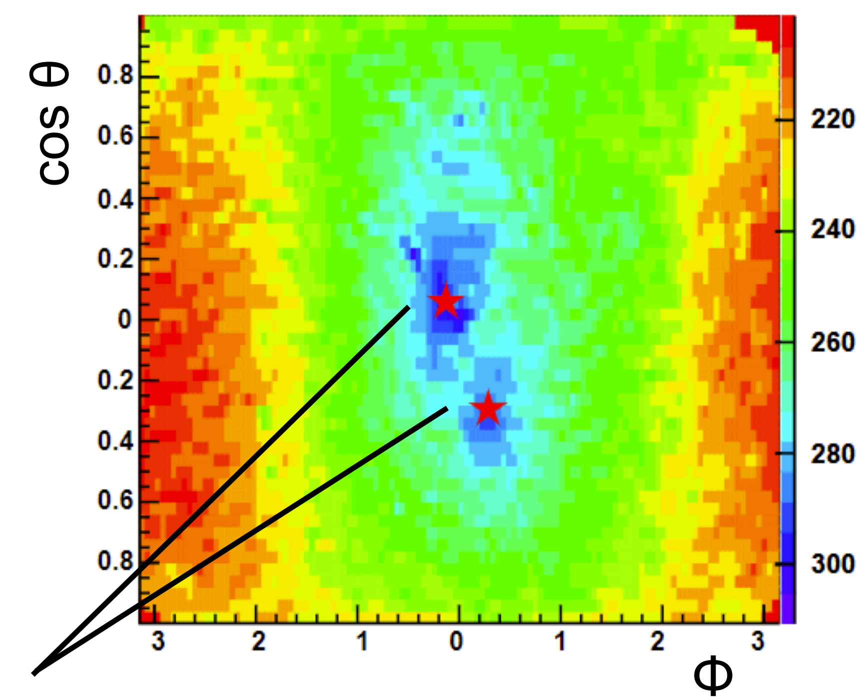
<u>Machine leaning</u>



<u>muon bundle fitter</u>



T map of PMTs



find multi-tracks

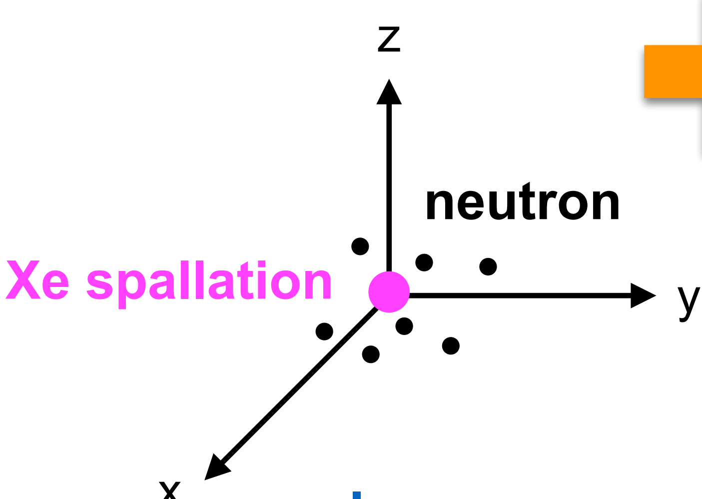
PointNet (neural network for point cloud)

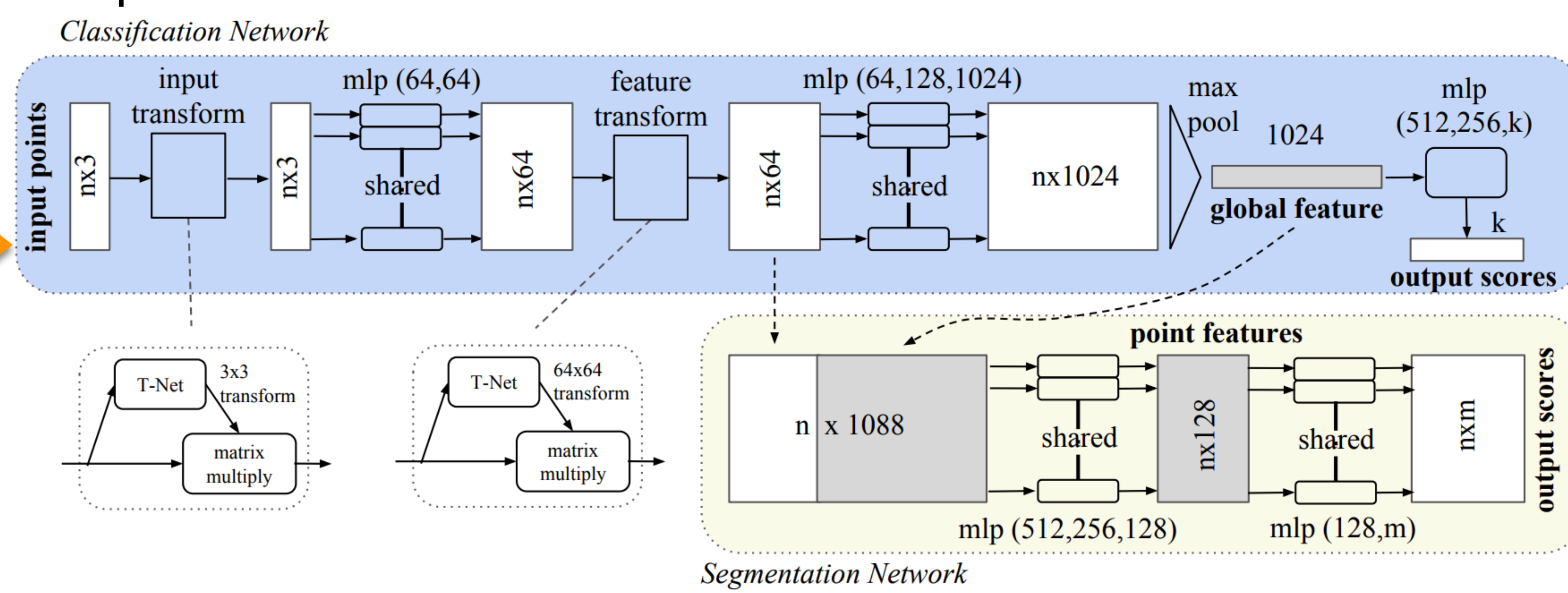
https://arxiv.org/pdf/1612.00593.pdf

identification of neutrons by Xe spallation

input points

neutron vertices in ΔR < 160 cm

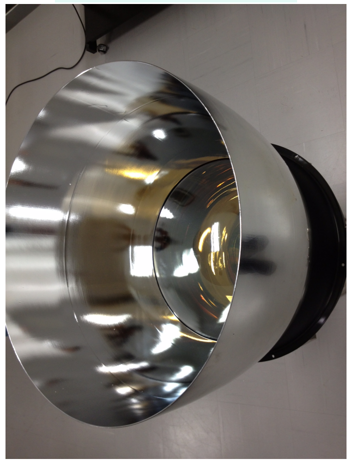




Improvement of long-lived spallation tagging is ongoing

R&D for KamLAND2-Zen

Mirror



High Q.E. PMT

x1.9

Light Collection Eff.

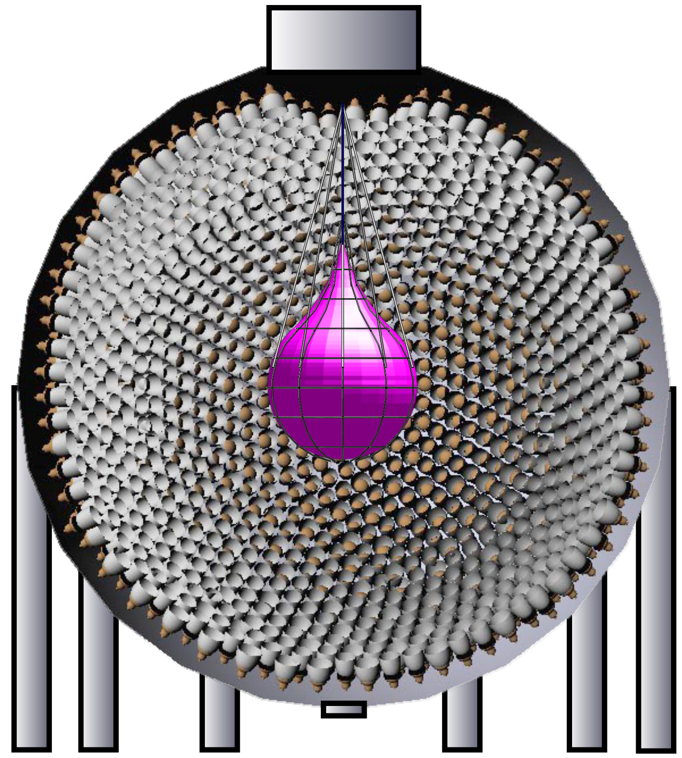
> **x1.8**

New liquid scintillator **x1.4**

σ_E @ Q-value = 4% → 2%

→ 2νββ BG reduction ~ **1/100 !**

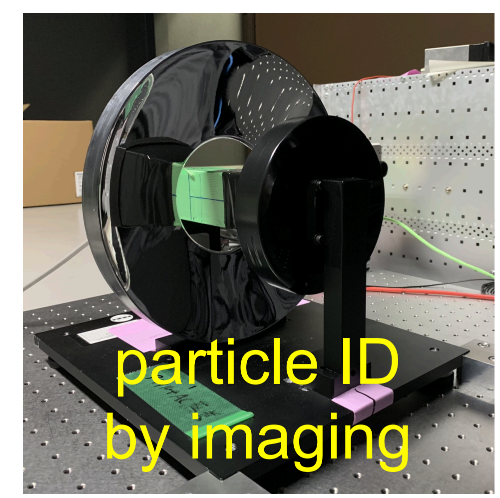
1000 kg enriched Xe



State-of-the-art electronics

more neutron tagging efficiency
→ long-lived BG reduction

Imaging device



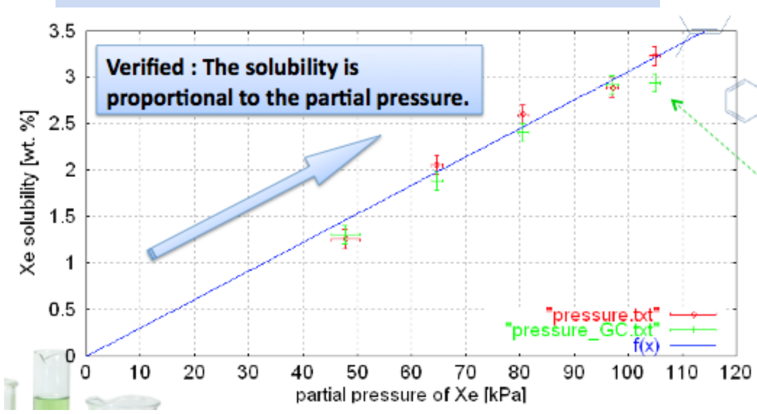
e⁻ / gamma identification
→ long-lived BG reduction

Scintillation balloon

(PEN film)

IB ^{214}Bi BG reduction
→ 100% fiducial volume

Pressurized Xe-LS

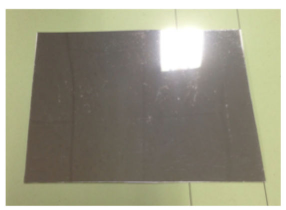


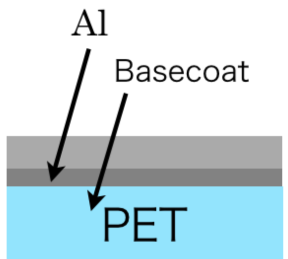
Xe / electron ratio increase
→ solar neutrino BG reduction

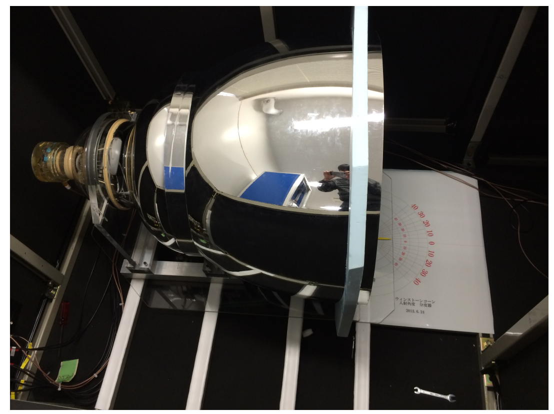
Light Yield Increase by Mirror

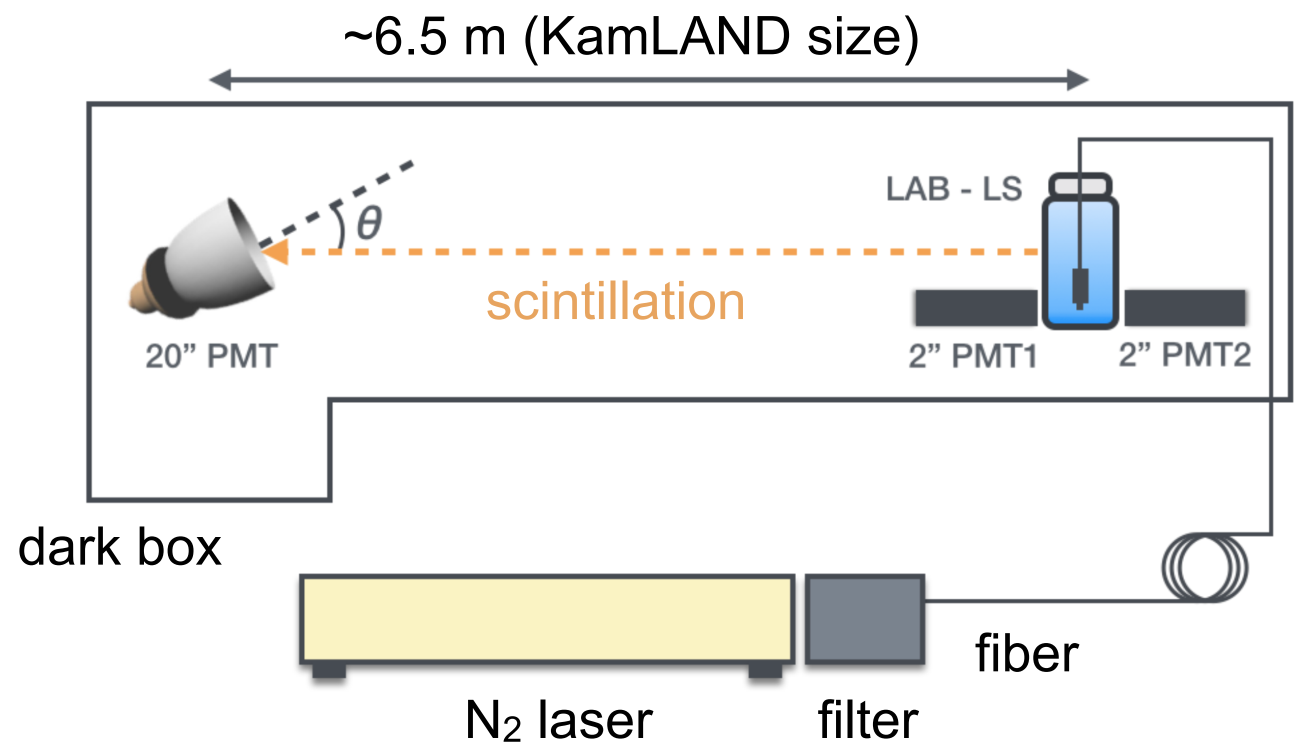
aluminum + PET mirror with high reflectivity

mirror sample

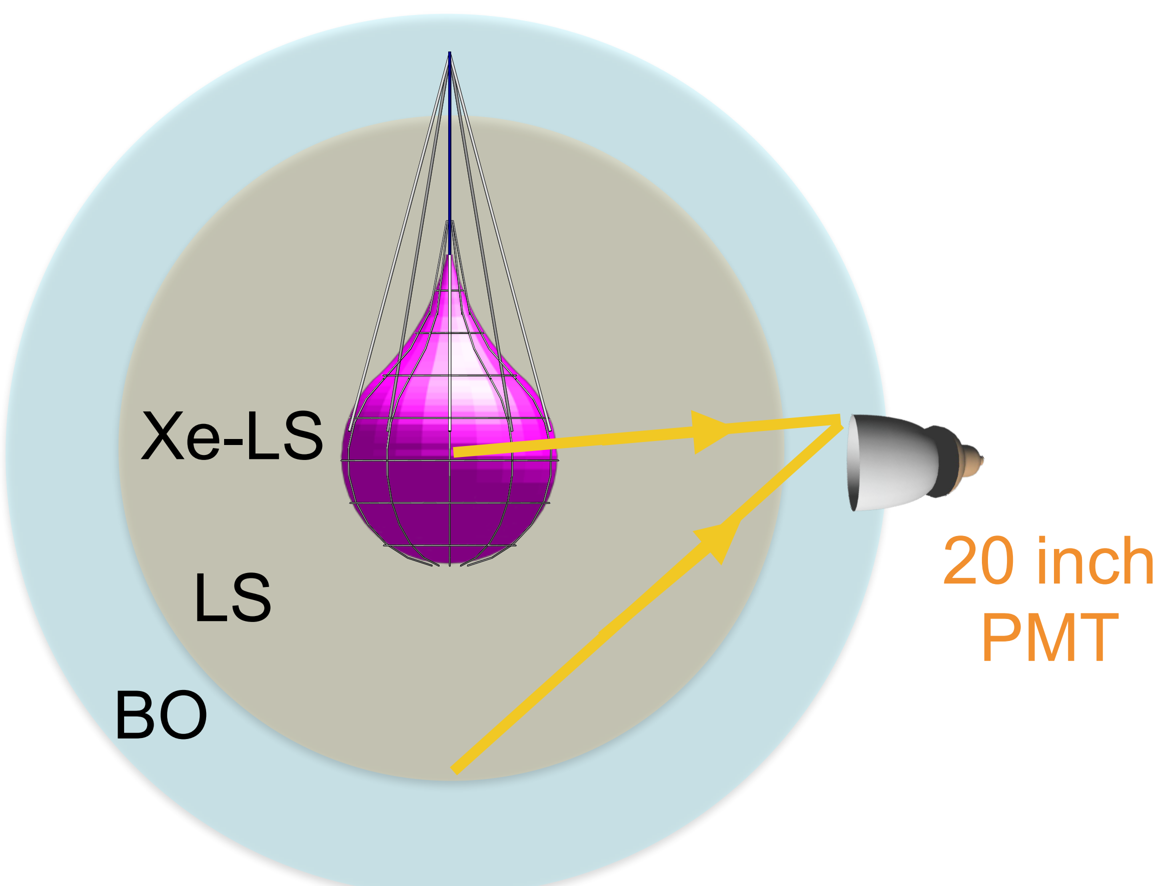




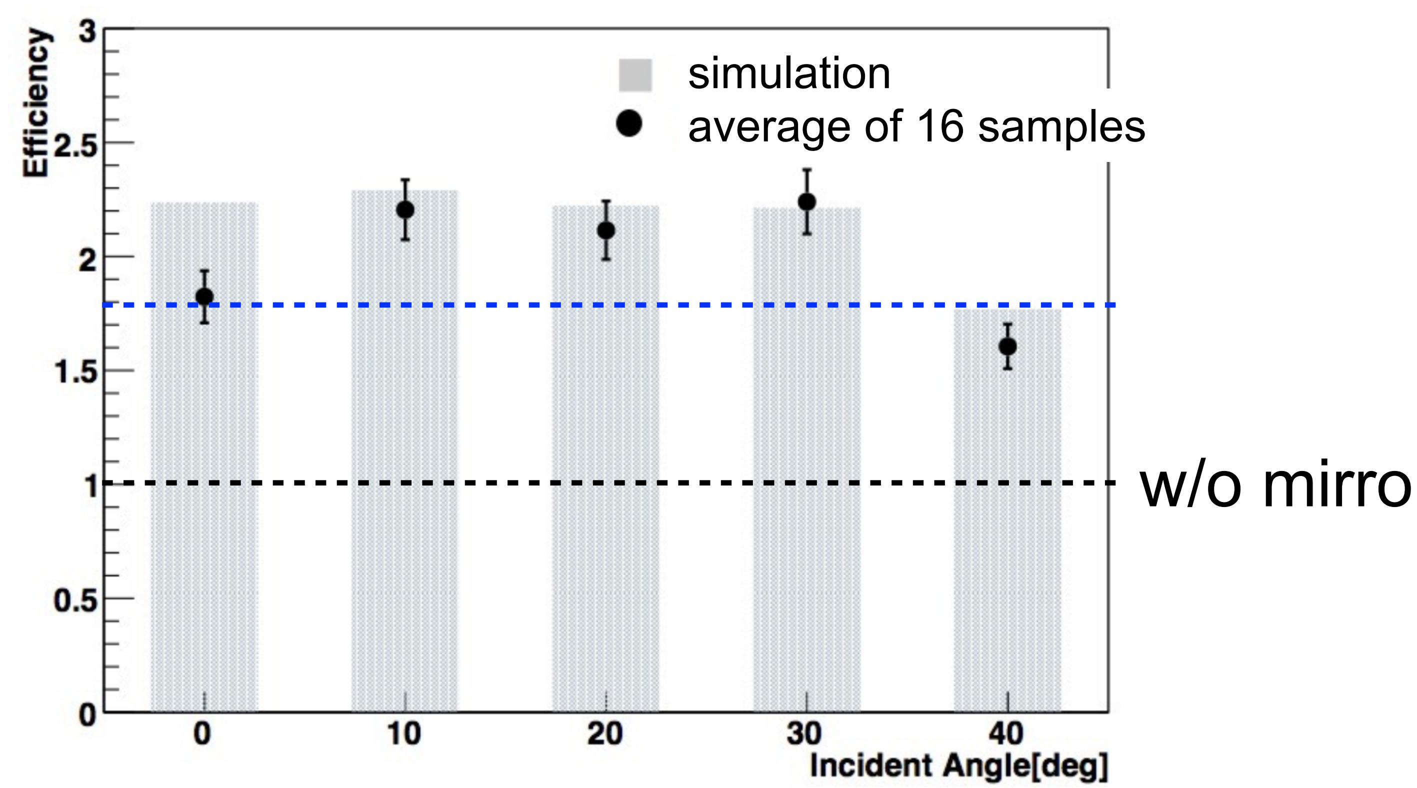




KamLAND2-Zen



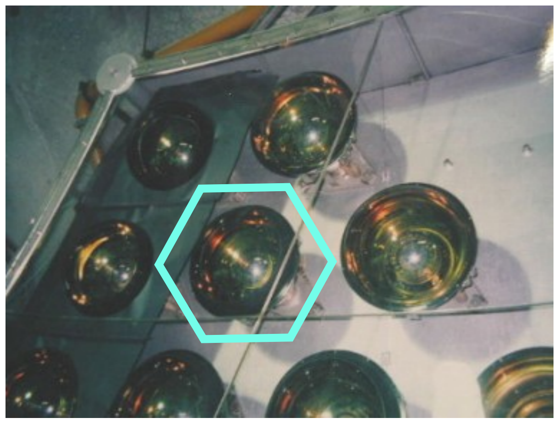
LS : 13 m diameter

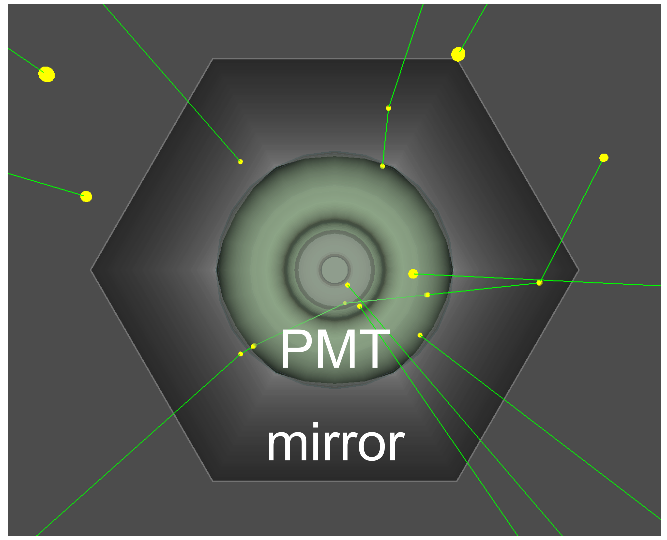


~1.8 times increase of light yield

Mirror Shape Optimization

20 inch PMT
coverage 34%





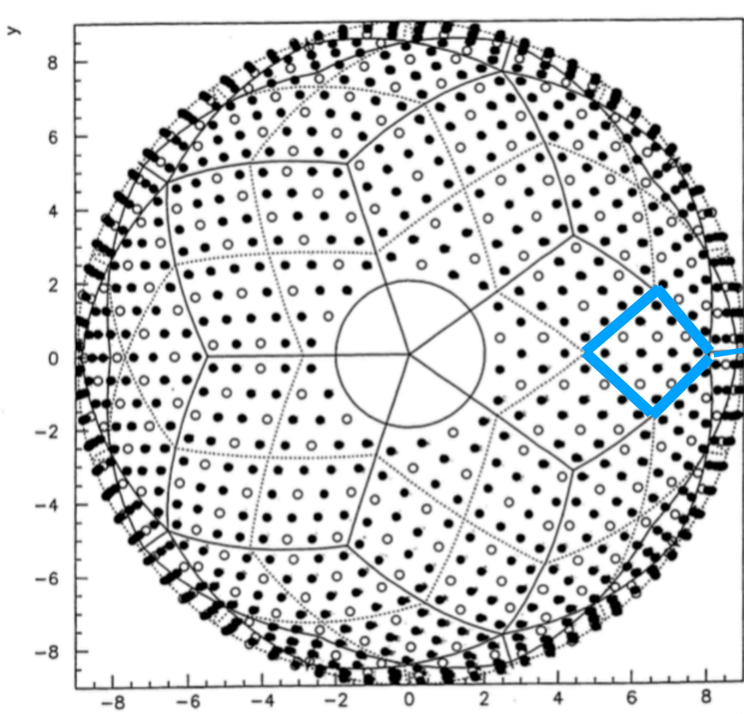
light yield ~ photo-coverage

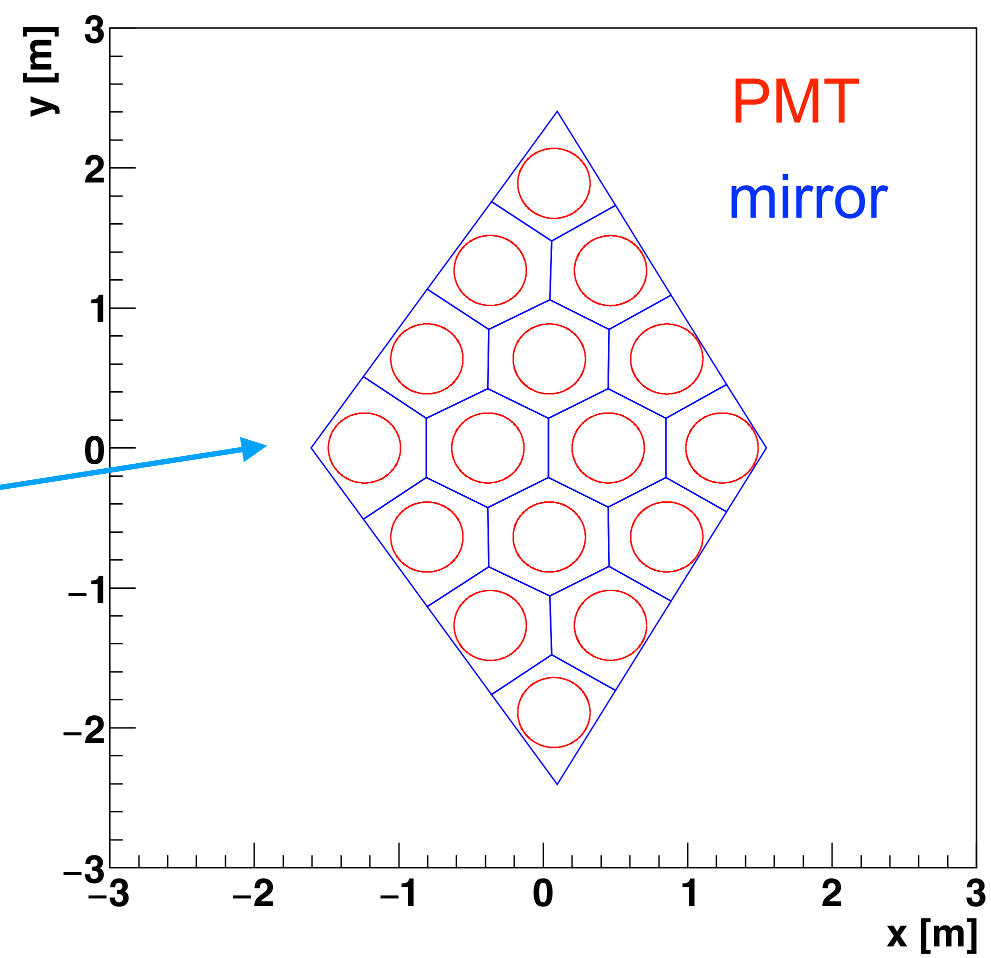
polygon entrance → circle exit

flexible shape construction was achieved by G4TessellatedSolid method in Geant4

further reduction of gap between mirrors

top view of KamLAND





mirror shape
in 4 × 4 face

4 hexagons
10 pentagons
2 squares

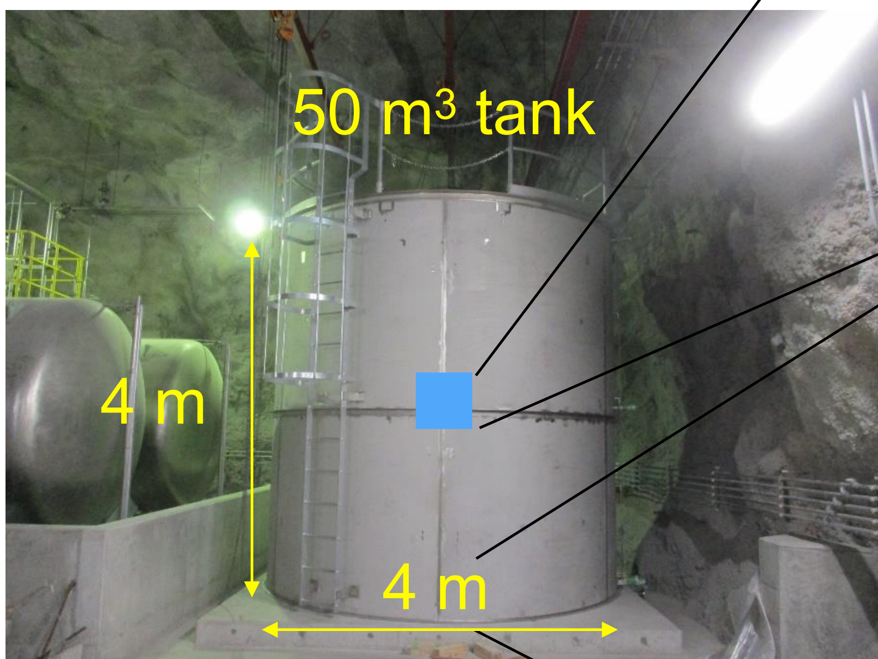
PMT with mirror

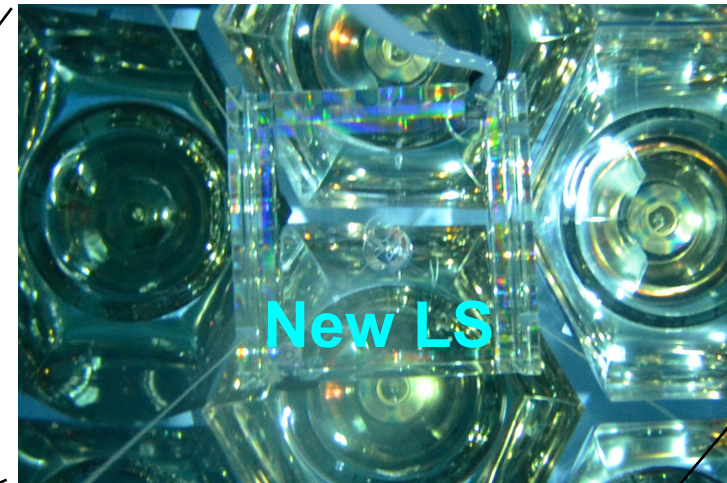
↓

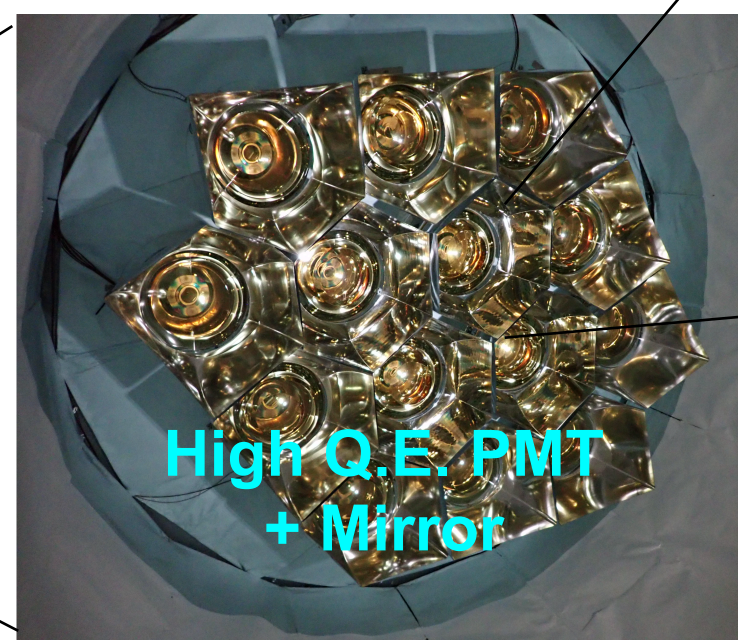
coverage ~ 100%

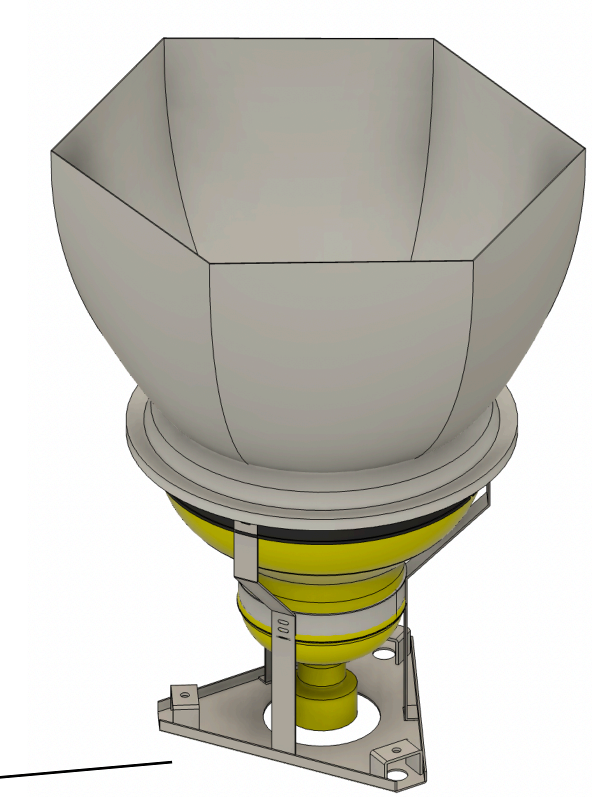
KamLAND2 Prototype

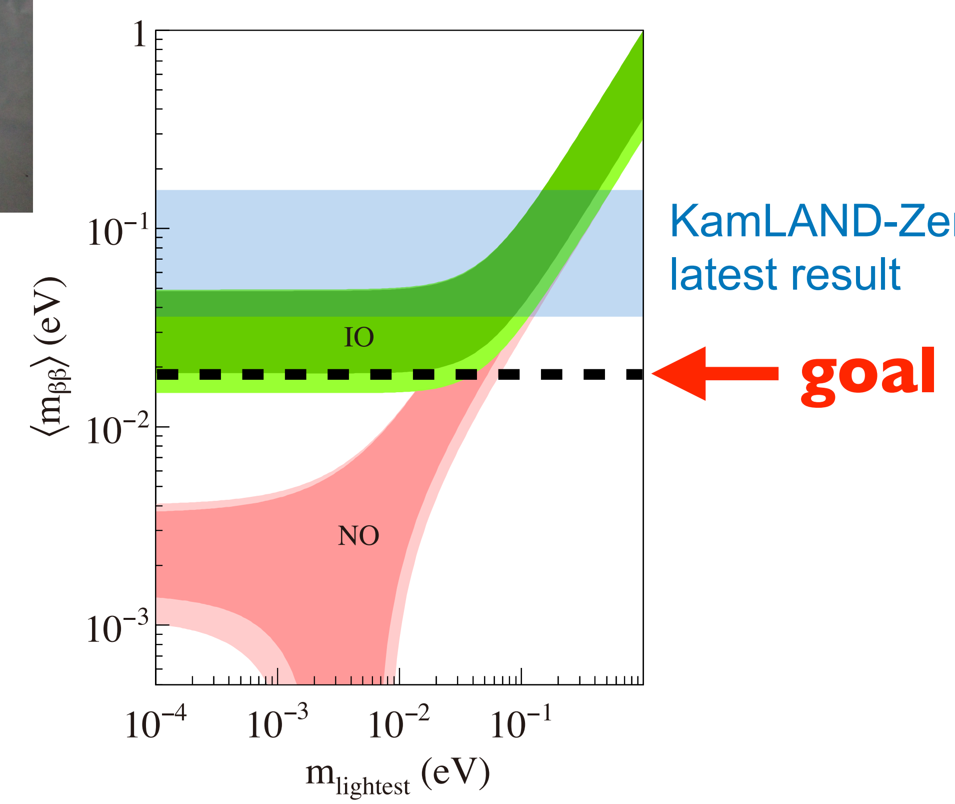
KamLAND2 prototype











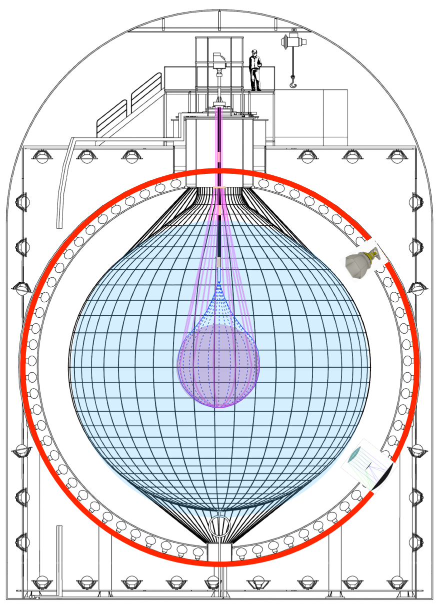
High performance of KamLAND2 will be demonstrated with the prototype detector

KamLAND2-Zen will cover the IO region

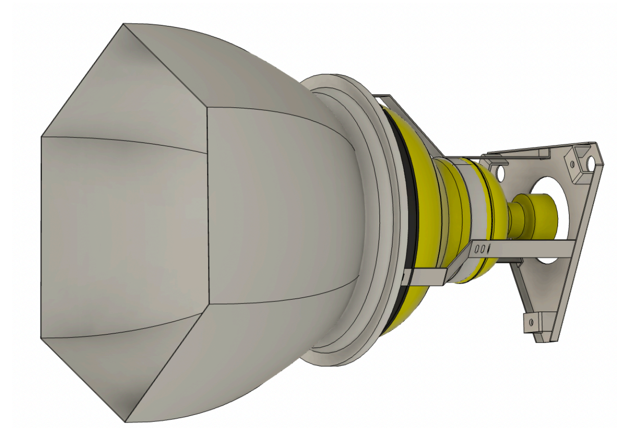
target $\langle m_{\beta\beta} \rangle$ ~ **20 meV / 5 year**

Imaging Device

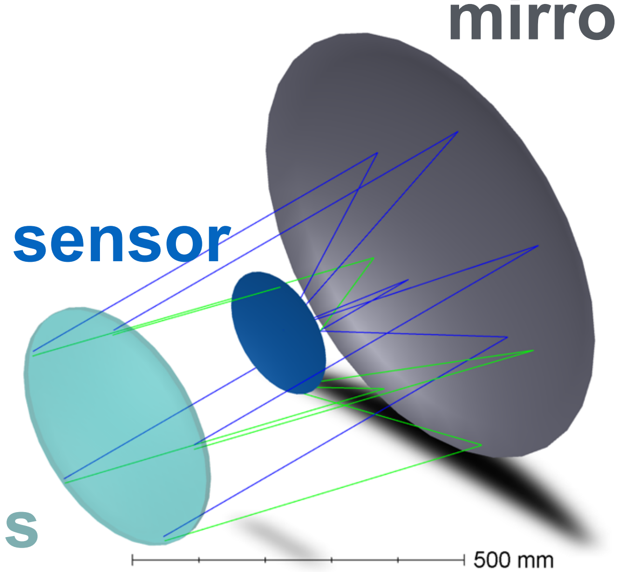
KamLAND with imaging device



PMT
x ~1800

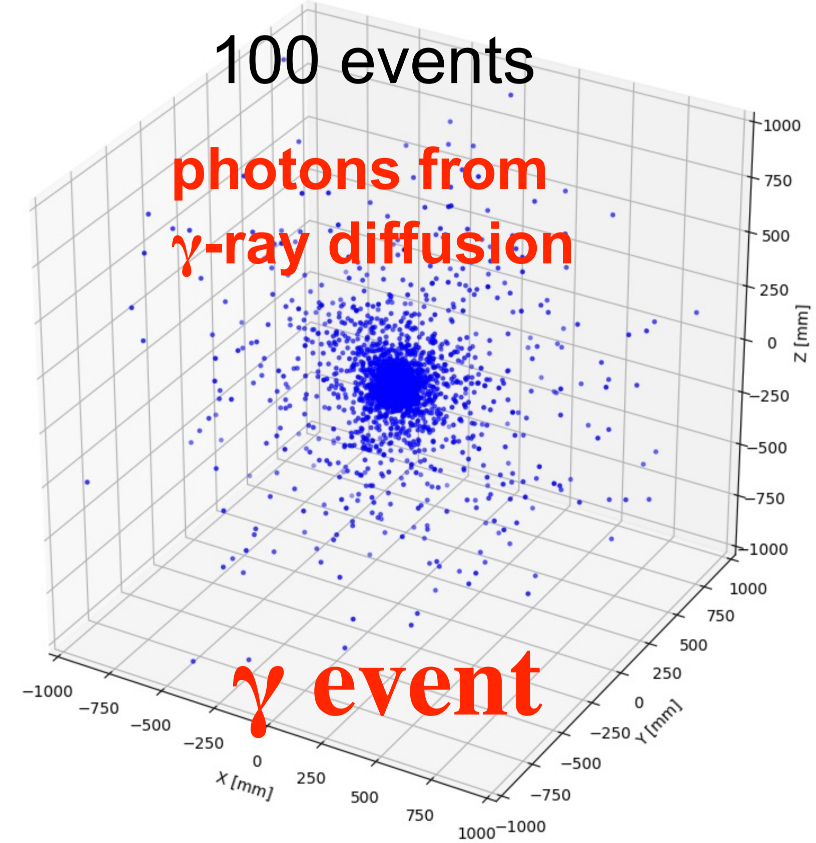


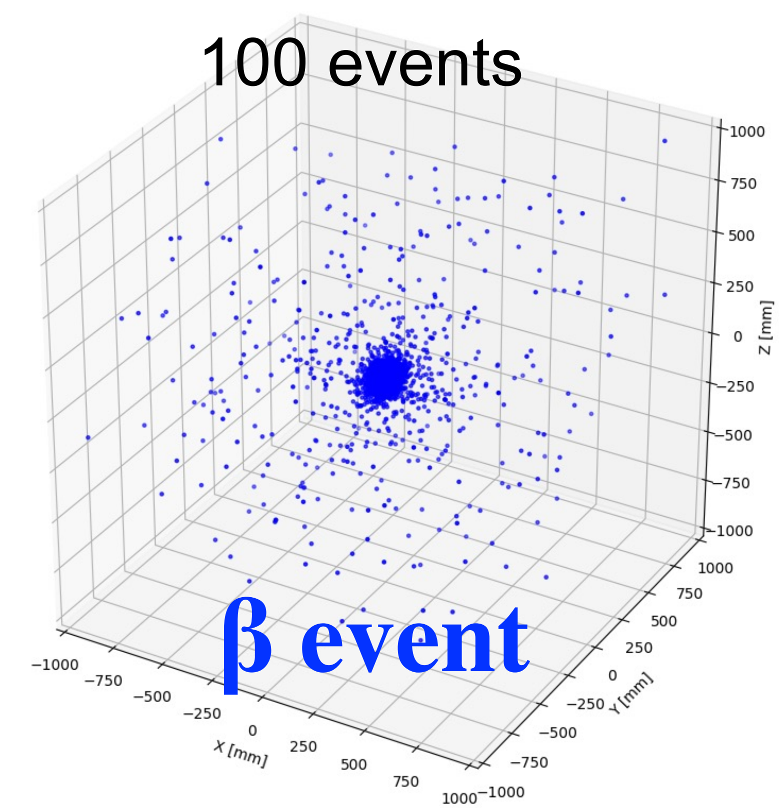
Imaging device x ~100



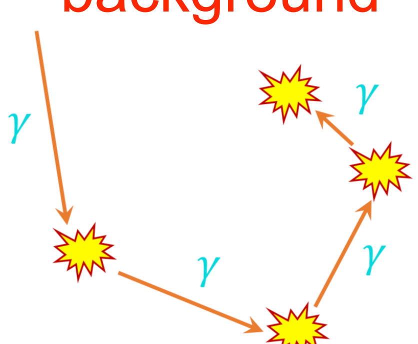
~0.3 p.e. / sensor

imaging

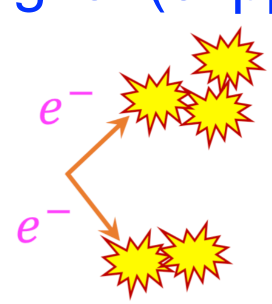




γ event
background



β event
signal ($0\nu\beta\beta$)



Large difference in spread of photon emission

→ Particle identification

background rate **< 1/10**

Photo Sensor

Design of optical system

- large half angle of view : > 20°
- large depth of field : ± 2 m
- large photon collection efficiency
- resolution < 3 cm (real image)
- lens and spherical mirror in oil

design optimized by Zemax

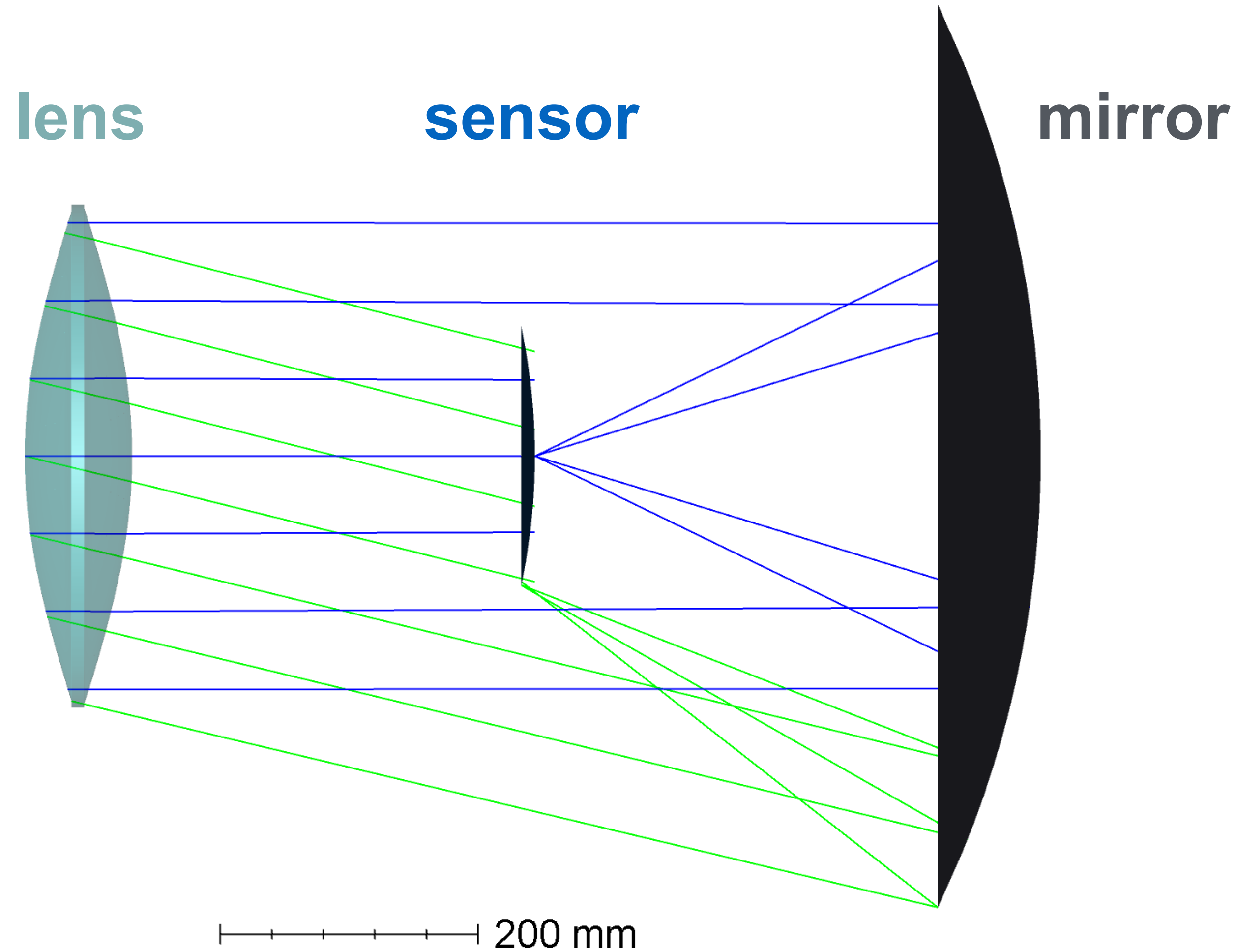


photo sensor size **~20 cm**

with **1 mm** position resolution

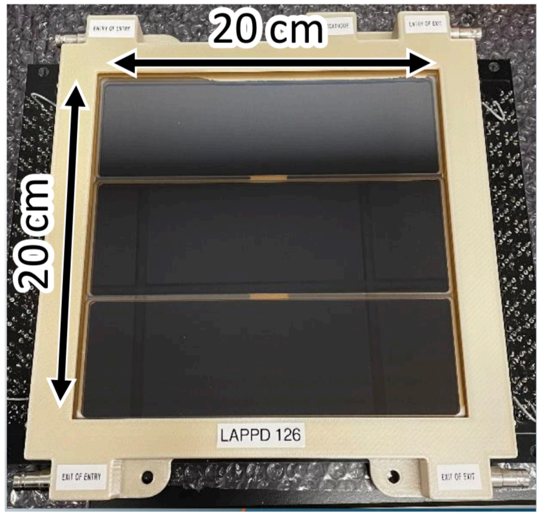
LAPPD is the best candidate

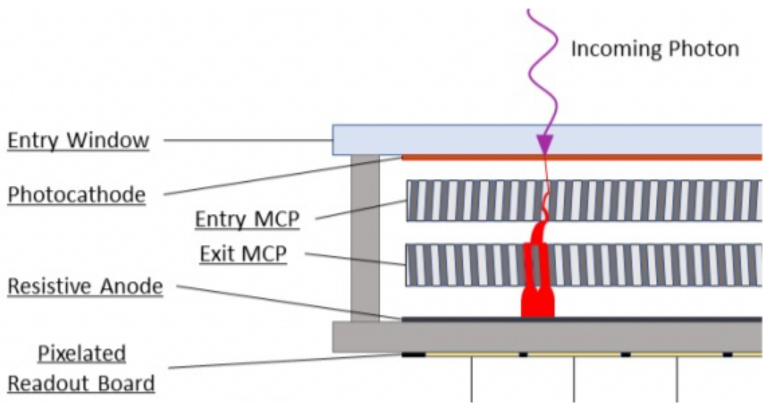
large sensitive area 20 cm × 20 cm

high quantum efficiency ~30% @ 365 nm

high position resolution ~1.3 mm

high time resolution for single p.e. ~50 ps





Test of photo sensor performance is ongoing

Summary

- Neutrinoless double-beta decays provide an important probe for physics beyond the Standard Model.

- Results from KamLAND-Zen were presented.

KamLAND-Zen limits on $0\nu\beta\beta$ at 90% C.L.

KamLAND-Zen 400	$T^{0\nu}_{1/2} > 0.9 \times 10^{26}$ yr
KamLAND-Zen 800	$T^{0\nu}_{1/2} > 2.0 \times 10^{26}$ yr
Combined	**$T^{0\nu}_{1/2} > 2.3 \times 10^{26}$ yr**
	↓
NME calculations assuming $g_A \sim 1.27$	**$\langle m_{\beta\beta} \rangle$ < 36-156 meV**

First probe of the inverted mass ordering region!

- R&D for KamLAND2-Zen is ongoing aiming at a test of inverted neutrino mass ordering.