KamLAND-Zen Experiment

International Conference on the Physics of the Two Infinities

March 29, 2023

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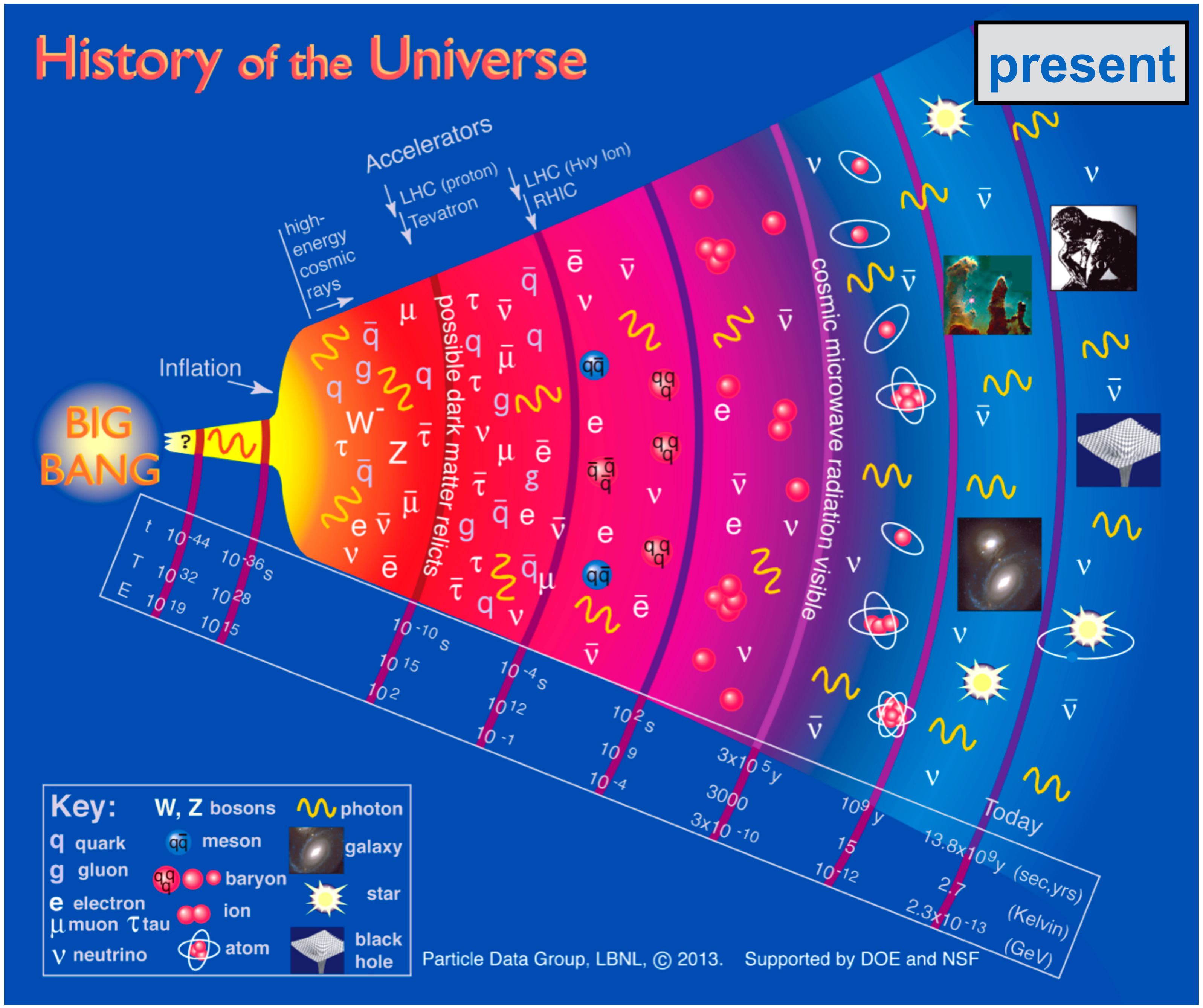
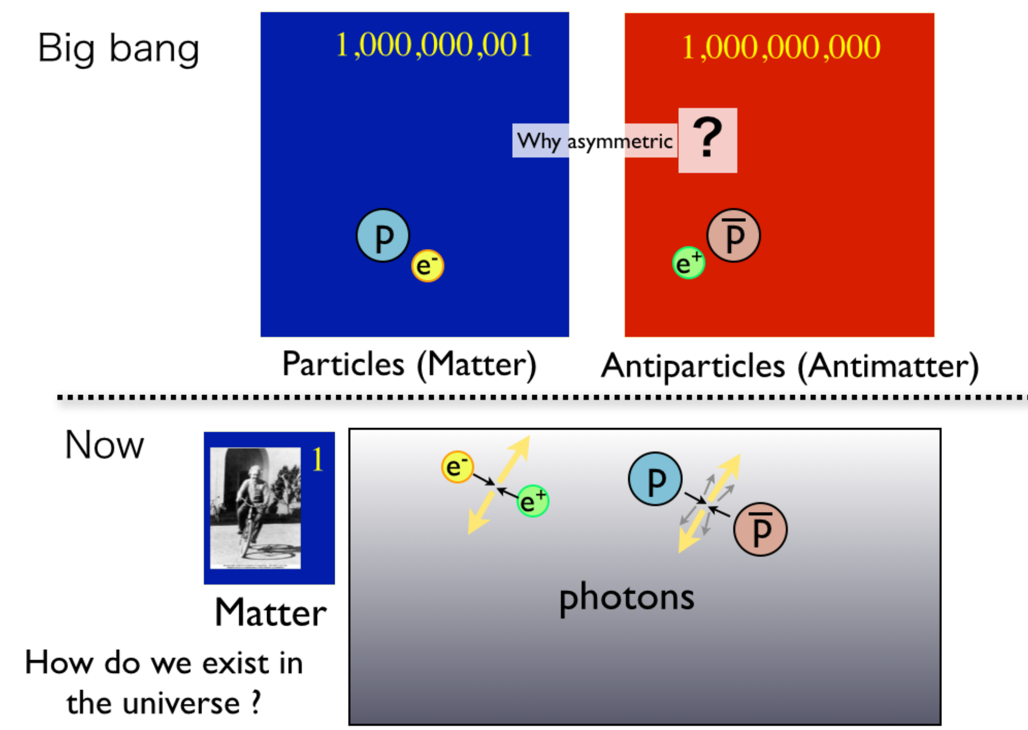
Matter Dominated Universe



- significant **asymmetry** between matter and anti-matter

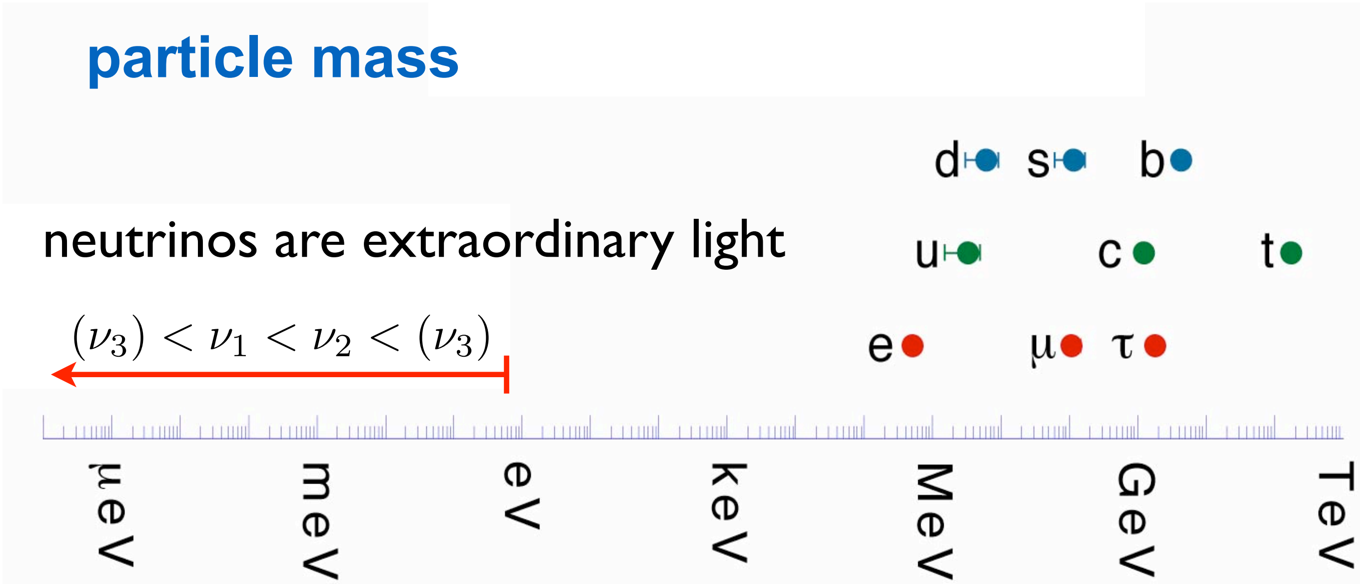


- **neutrinos** and photons are the most abundant particle

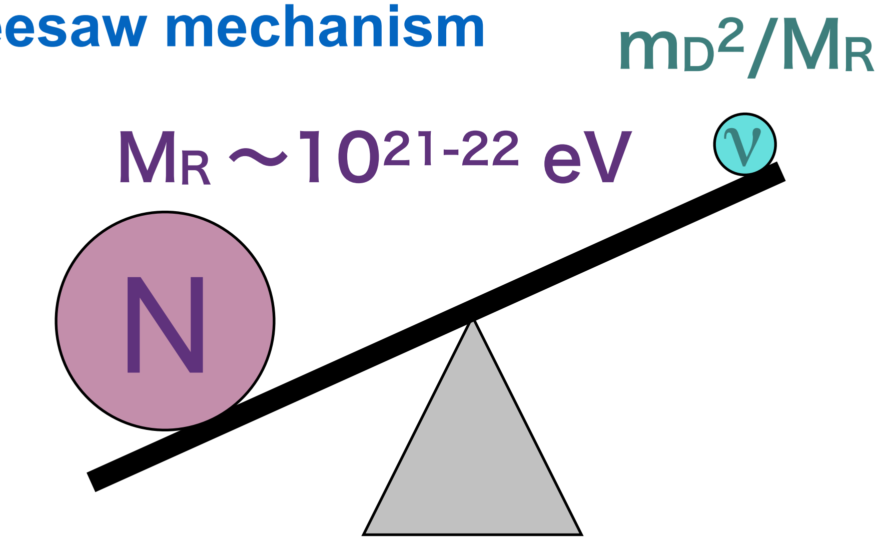
neutrinos / nucleon ~ 10^9

Neutrinos may play a key role to explain matter/anti-matter asymmetry

Light Neutrino Mass



Seesaw mechanism



Possible mass terms

Dirac mass

allowed in neutral particle

Majorana mass

$$L_{mass} = \overline{\psi_R} m_D \psi_L + \frac{1}{2}\overline{(\psi_L)^C} m_L \psi_L + \frac{1}{2}\overline{\psi_R} m_R (\psi_R)^C$$

$\nu_R \quad \nu_L$ — $\Delta L = 0$

$\nu_L \quad \bar{\nu}_L$ — $\Delta L = 2$

$\nu_R \quad \bar{\nu}_R$ — $\Delta L = 2$

lepton number violation

$$\nu = \bar{\nu}$$

Majorana neutrino

Heavy neutrino (just below GUT scale) naturally explains

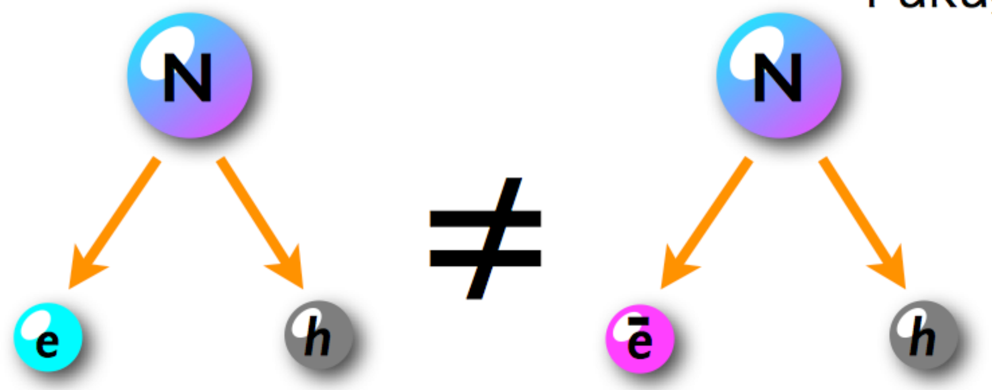
“finite but light neutrino mass”

Matter Production

<u>Leptogenesis theory</u>

Fukugita, Yanagida,'86

violation of B−L



CP-violating decay

(sphaleron) ⟶ $\frac{n_B}{s}$(observed) = $(0.88 \pm 0.02) \times 10^{-10}$

Three Sakharov conditions

- Violation of B−L. Guaranteed if neutrinos are Majorana particles.
- C and CP violation. Guaranteed if the neutrino Yukawa couplings contain physical phases.
- Departure from thermal equilibrium. Guaranteed, due to the expansion of the Universe.

A. Ibarra, Leptogenesis, INSS 2012

CP violating decay of heavy neutrino explains

"matter dominance in the universe"

Neutrinoless Double-Beta Decay

Nucleus ββ-decay emitting two electrons

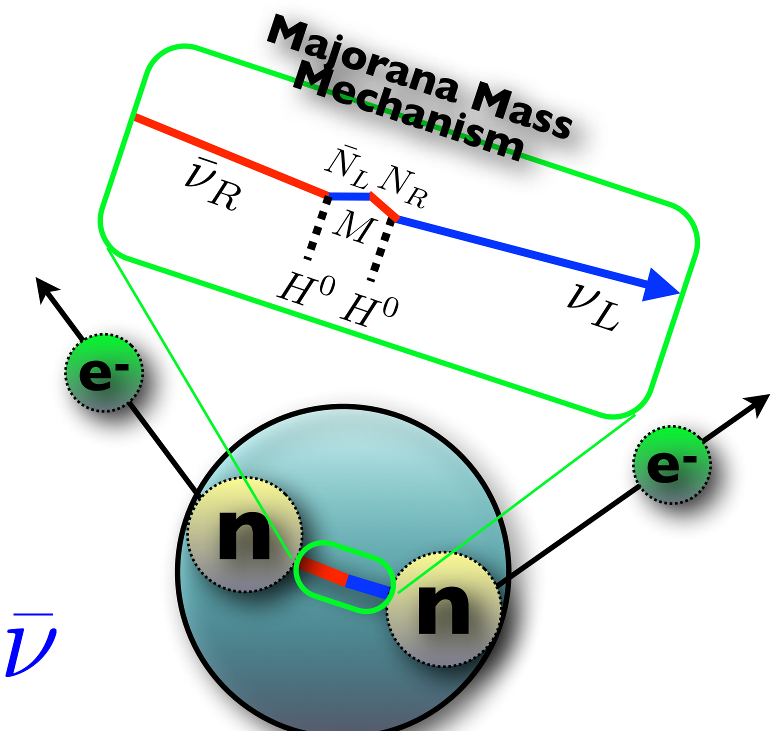
$$(Z, A) \rightarrow (Z+2, A) + 2e^-$$

lepton number violation

$\Delta L = 2$

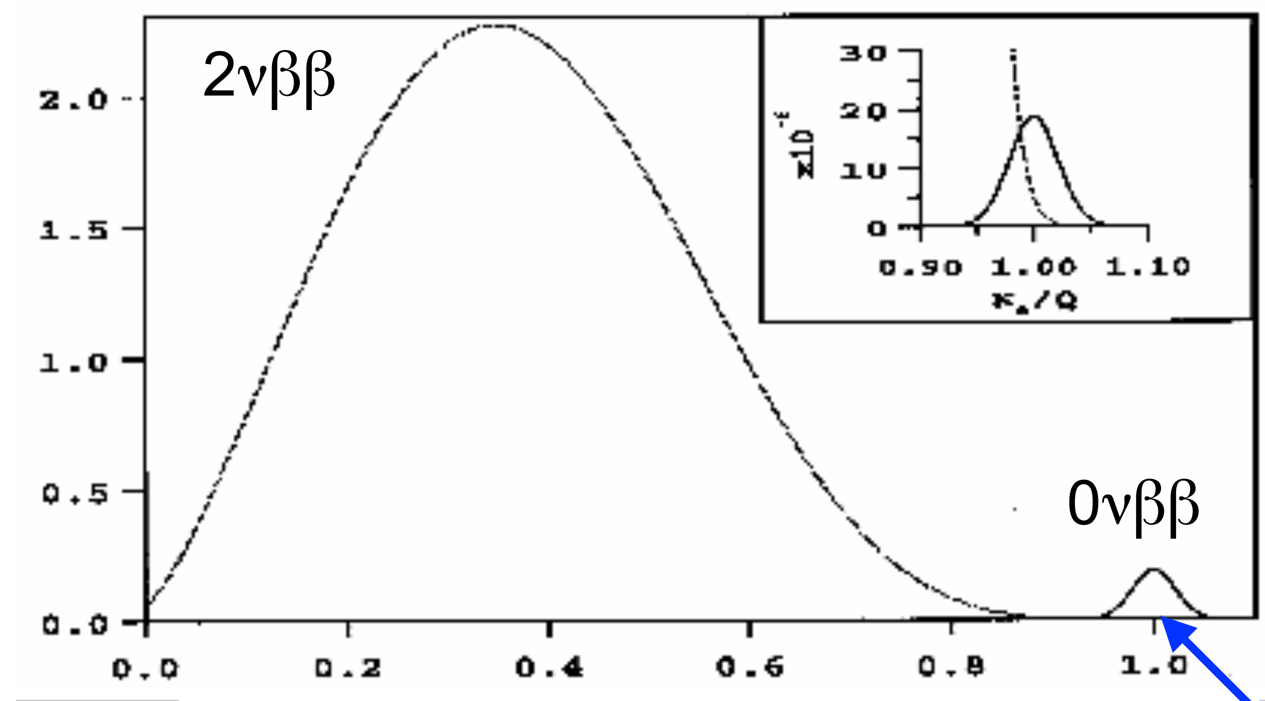
0νββ

neutrinoless double beta-decay



$$\nu = \bar{\nu}$$

Require the neutrino **Majorana nature**



sum energy for two electrons / Q

peak at Q-value

amplitude ~ $\langle m_{\beta\beta} \rangle \equiv \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$

effective neutrino mass

decay rate

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

nuclear matrix element
(nuclear physics)

phase space factor

effective neutrino mass
(particle physics)

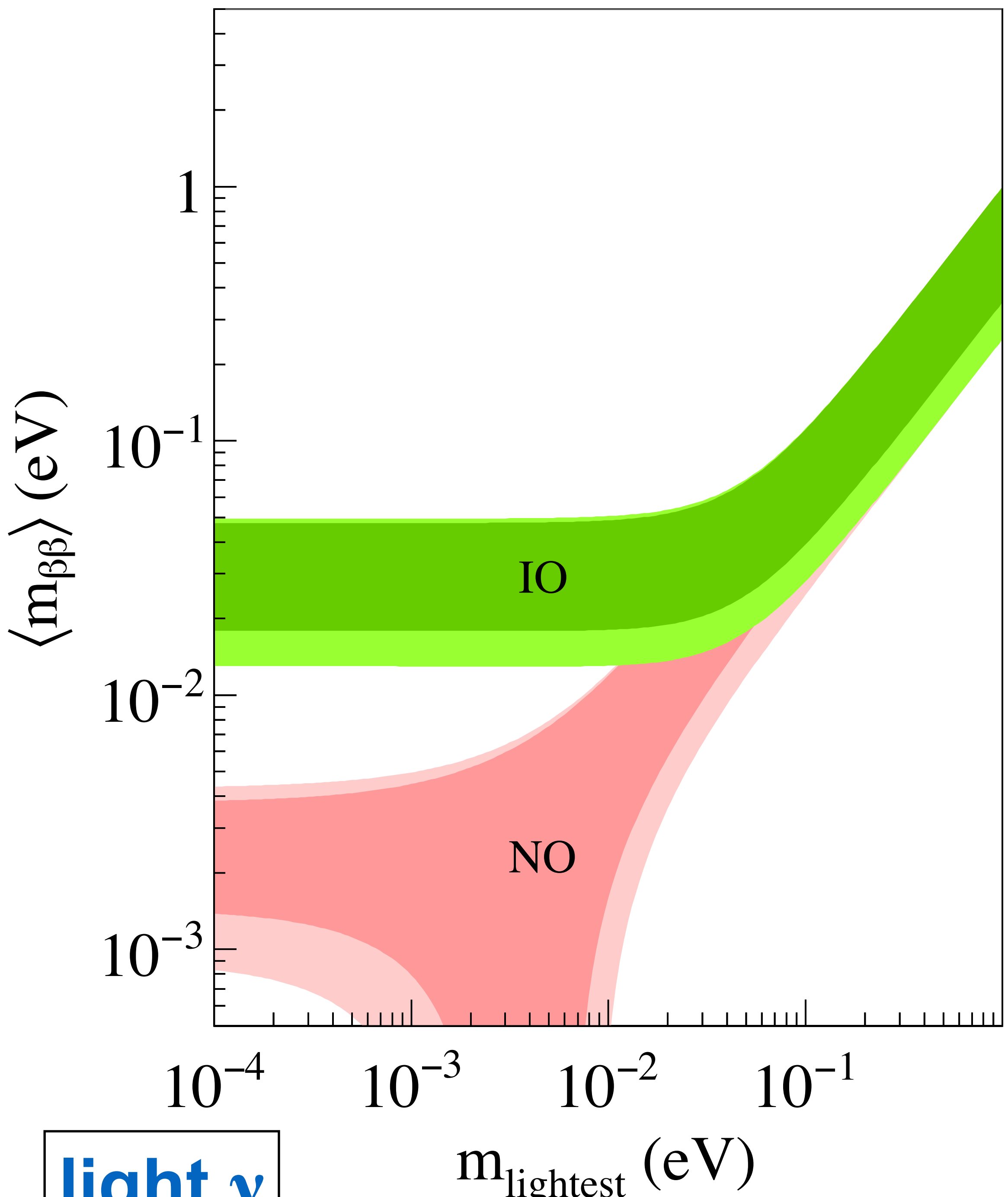
Possible contributions also from
Majoron, SUSY, right-handed current, ...

Milestone of 0νββ search

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)|M^{0\nu}|^2 \langle m_{\beta\beta}\rangle^2 \qquad \langle m_{\beta\beta}\rangle \equiv \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$

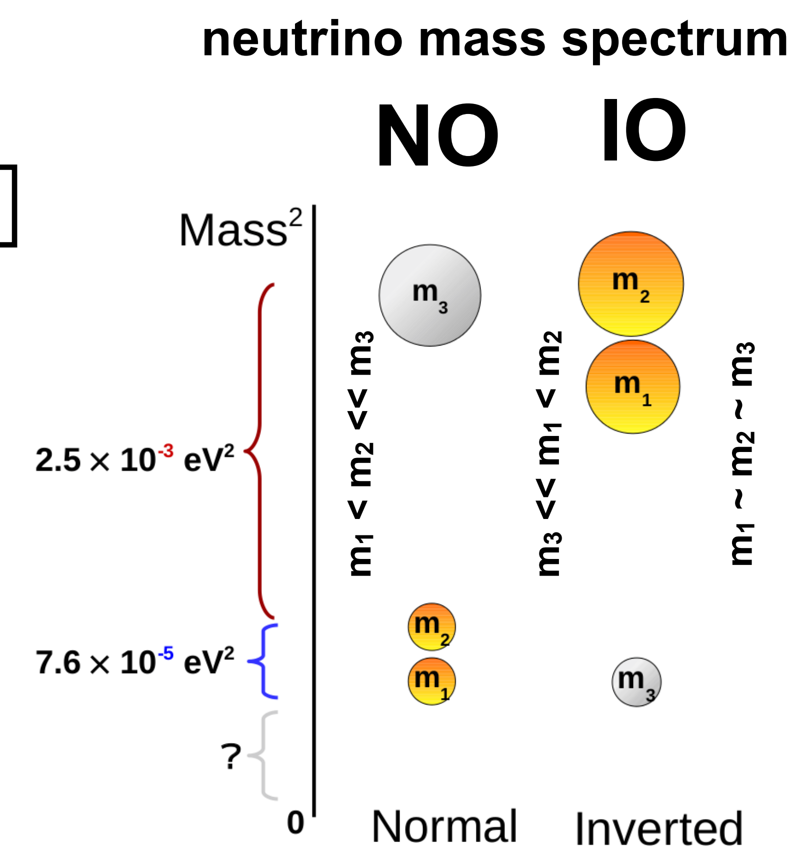
heavy ν

dark shaded: unknown CP phase only
light shaded: w/ uncertainty from oscillation parameters



light ν

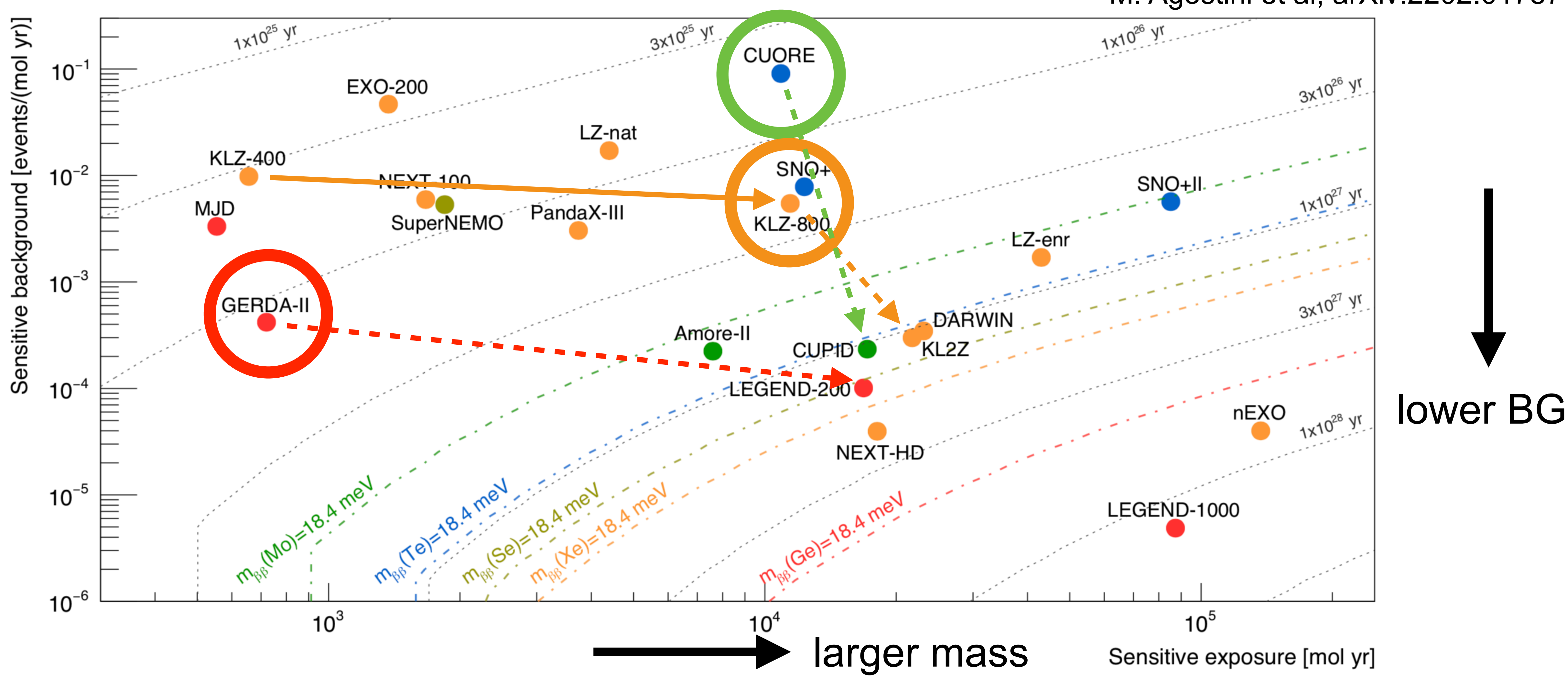
$T_{1/2}$ sensitivity	required mass
10^{25} y	10 kg
10^{26} y	100 kg
10^{27} y	1 ton
10^{28} y	10 ton
10^{29} y	100 ton



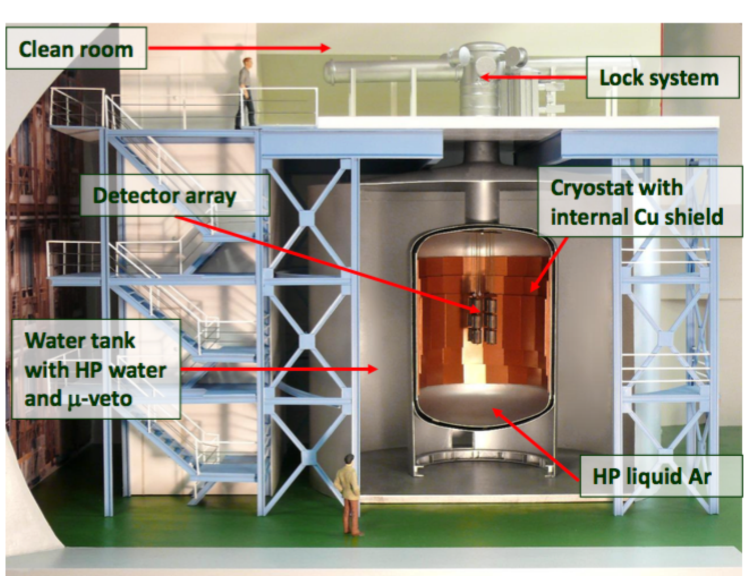
Large amount of isotope is necessary to investigate lighter Majorana ν mass

0νββ Experiments

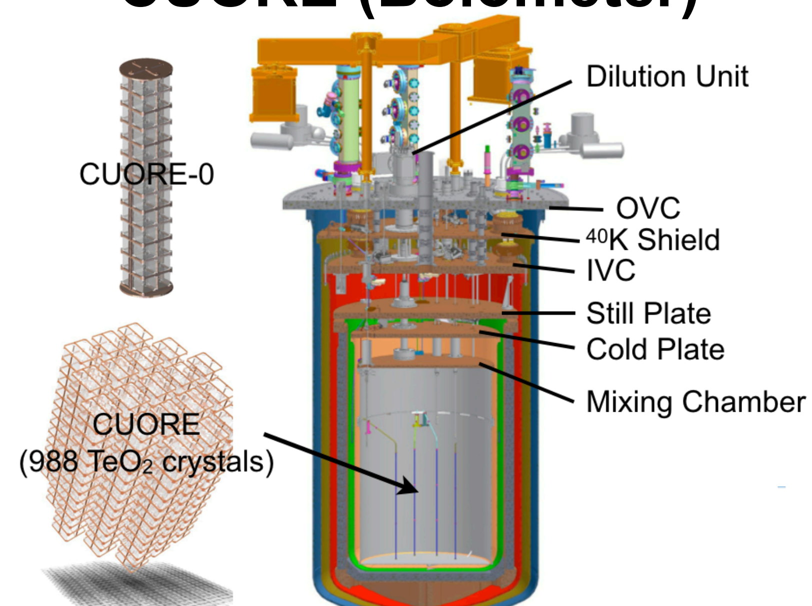
M. Agostini et al, arXiv:2202.01787



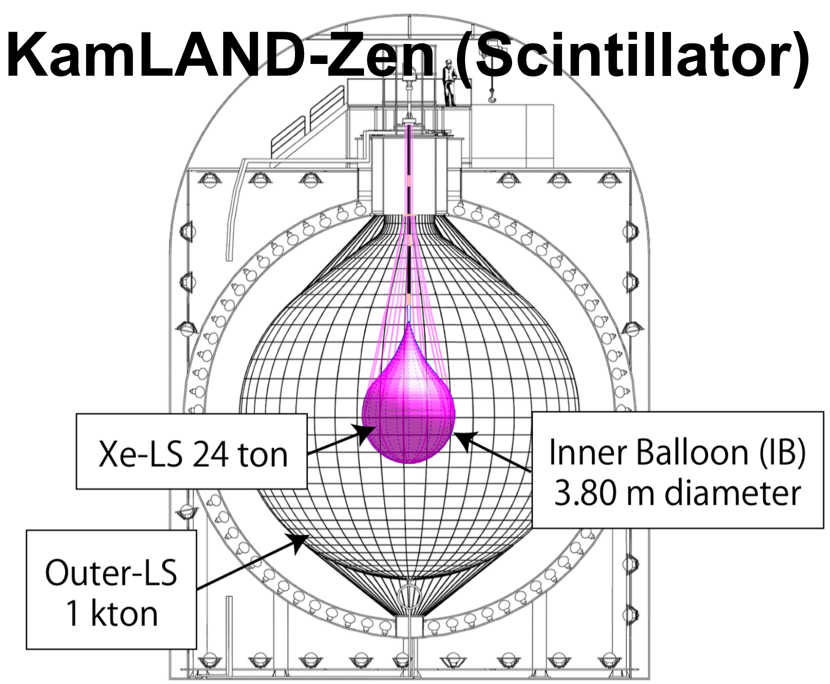
GERDA (Ge-detector)



CUORE (Bolometer)

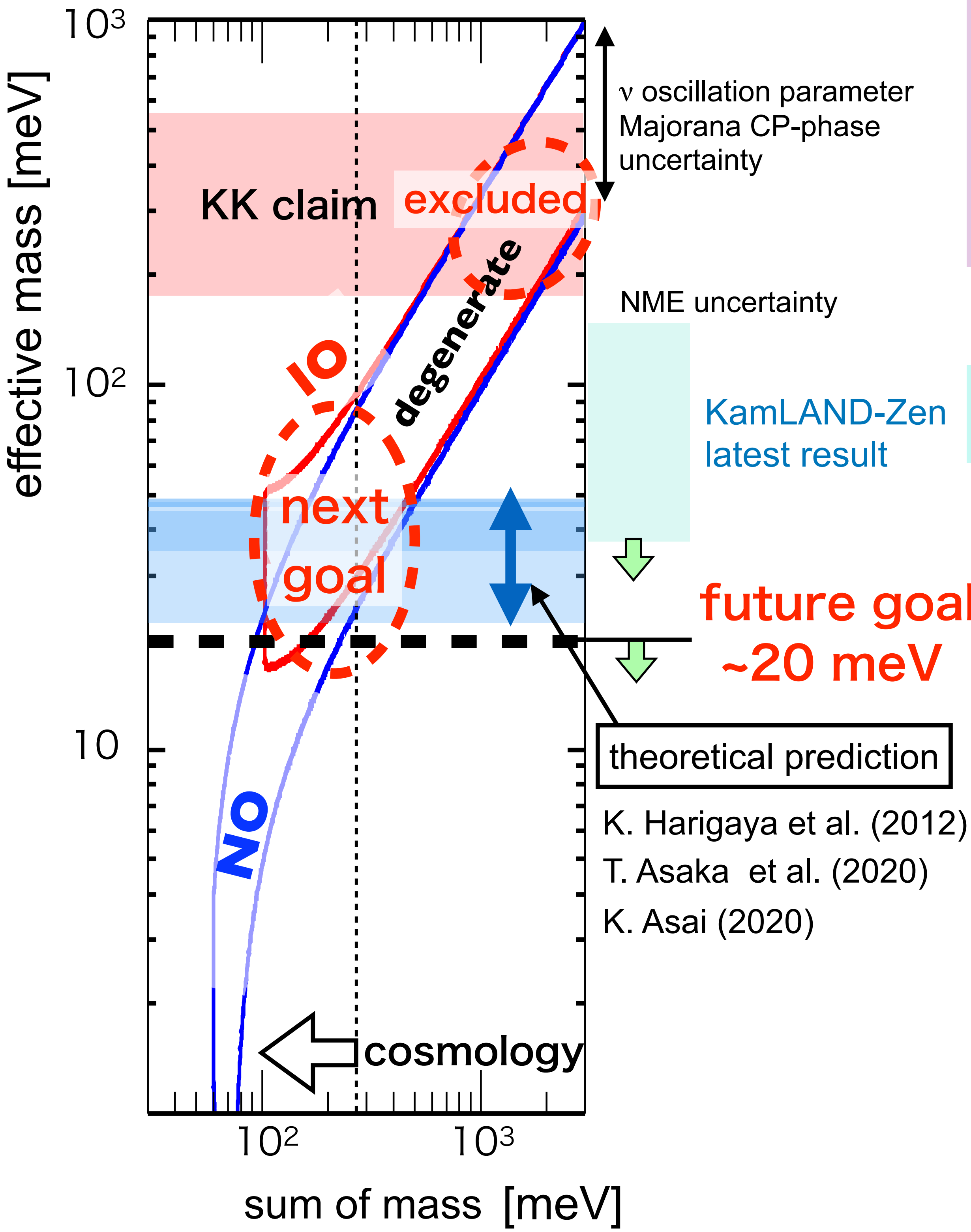


KamLAND-Zen (Scintillator)



Prospect on Neutrino Mass Search

Search target



Other exp.	on-going and future experiments
ν oscillation	SK, T2K, HK, DUNE, JUNO, …
cosmology	Planck, ACT, SPT, …
β-decay	KATRIN, Project 8

↕ **complementary**

0νββ decay	KamLAND-Zen, GERDA, CUORE, n-EXO, LEGEND, CUPID, …

Half-life **effective mass**

$$\left[T^{0\nu}_{1/2}\right]^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2$$

case 1: 0νββ signal is found

Verification of Majorana and neutrino mass scale

Mass disagreement with other experiments may indicate some contributions from new physics?

case 2: no 0νββ signal is found

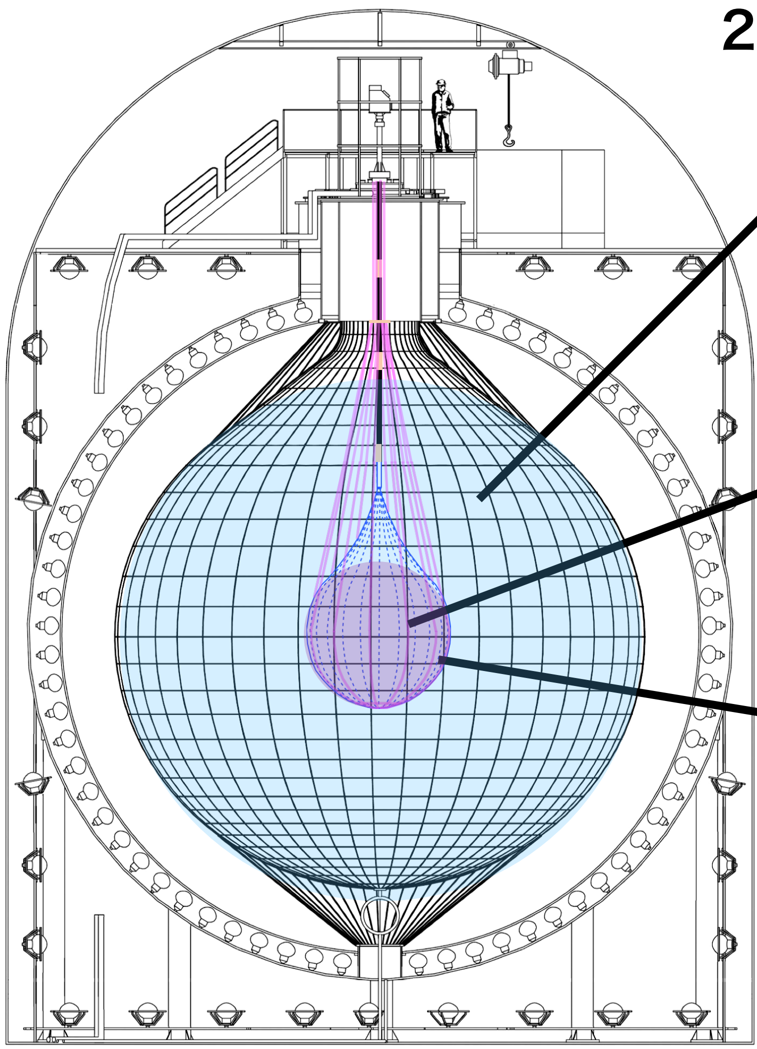
Rejection of Majorana if the mass disagrees with other experiments

KamLAND-Zen

KamLAND-Zen

Zero Neutrino Double Beta

Kamioka underground KamLAND detector



2-type of liquid scintillator

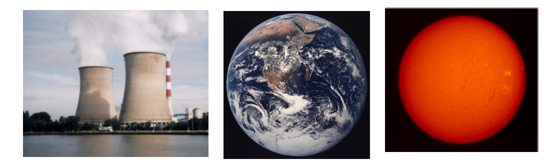
1000-ton pure liquid scintillator

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

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

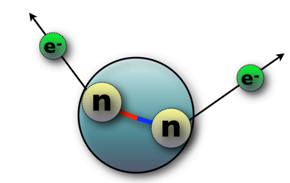
inner balloon (IB)

2002− KamLAND



reactor, geo, solar neutrino observation

2011− KamLAND-Zen



double beta decay measurement (0νββ search)

2019− Xe increase, cleaner balloon

Advanced neutrino research utilizing
ultra-low background environment

Why Xe?

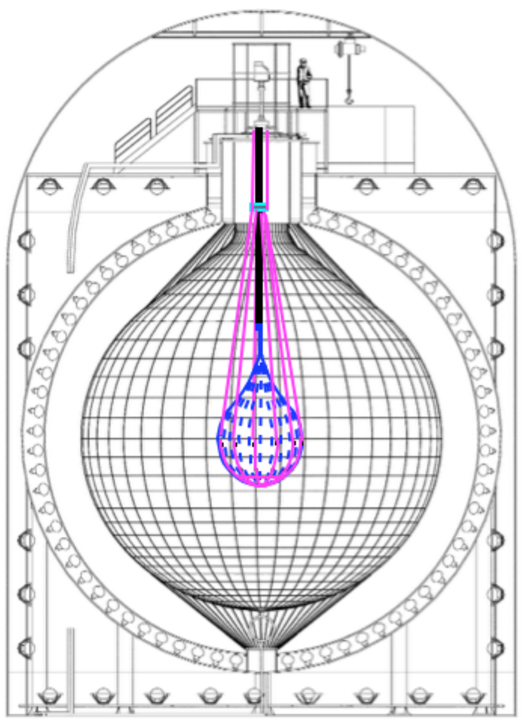
- Isotopic enrichment (centrifugal) established
- Gas purification is possible
- Soluble to LS more than 3 wt%, easily extracted
- Slow 2νββ requires modest energy resolution

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

largest amount of ^{136}Xe !!

Upgrade of KamLAND-Zen

Past



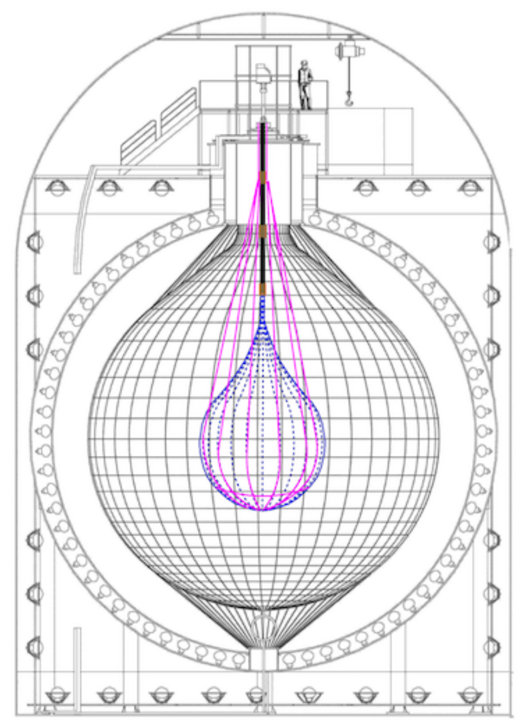
KamLAND-Zen 400

Nylon balloon R 1.54 m

Xenon 320 − 380 kg

world top performance

Present



KamLAND-Zen 800

Nylon balloon R 1.90 m

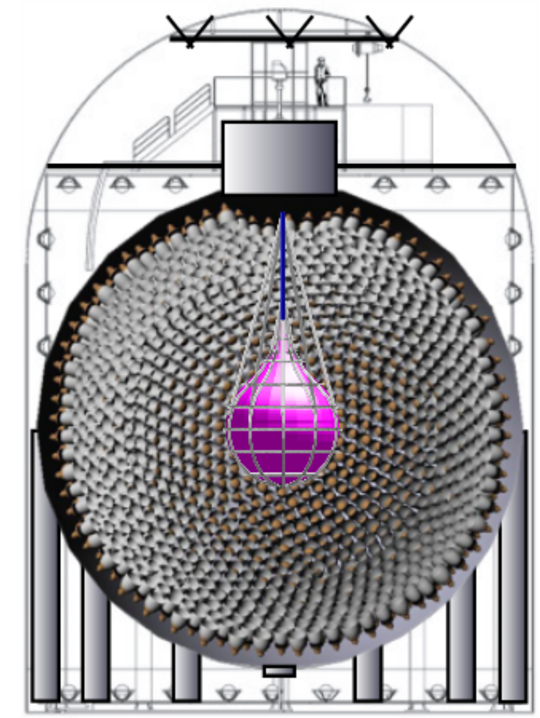
Xenon 745 kg

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

reduced radioactive BG

demonstration of scalability

Future



KamLAND2-Zen

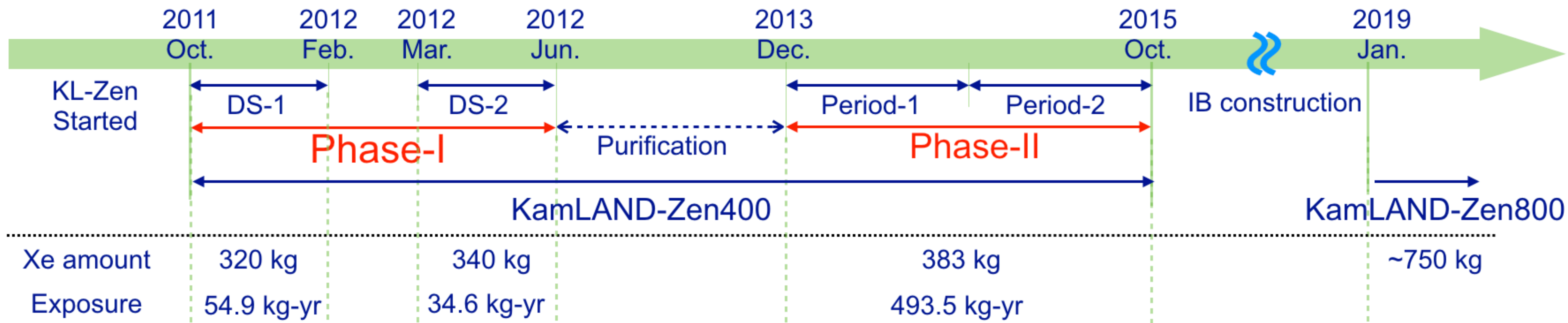
Xenon 1 ton

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

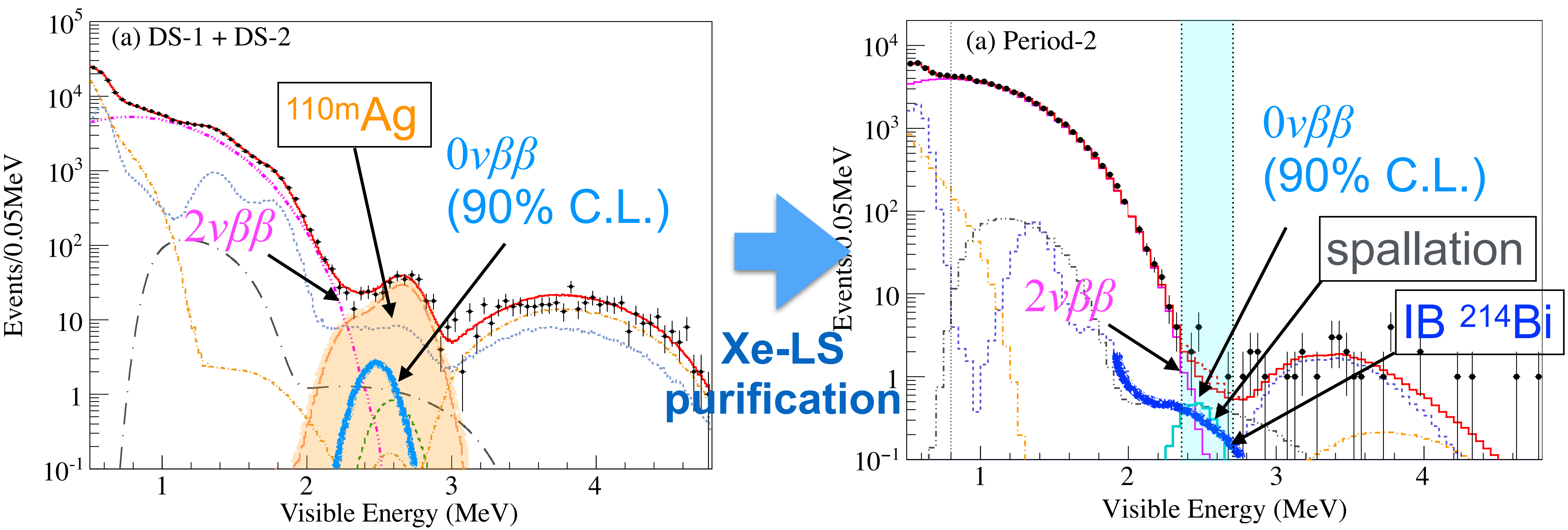
high light yield

better performance

KamLAND-Zen 400



Phase-I (R < 1.35 m) **Phase-II** (R < 1 m)



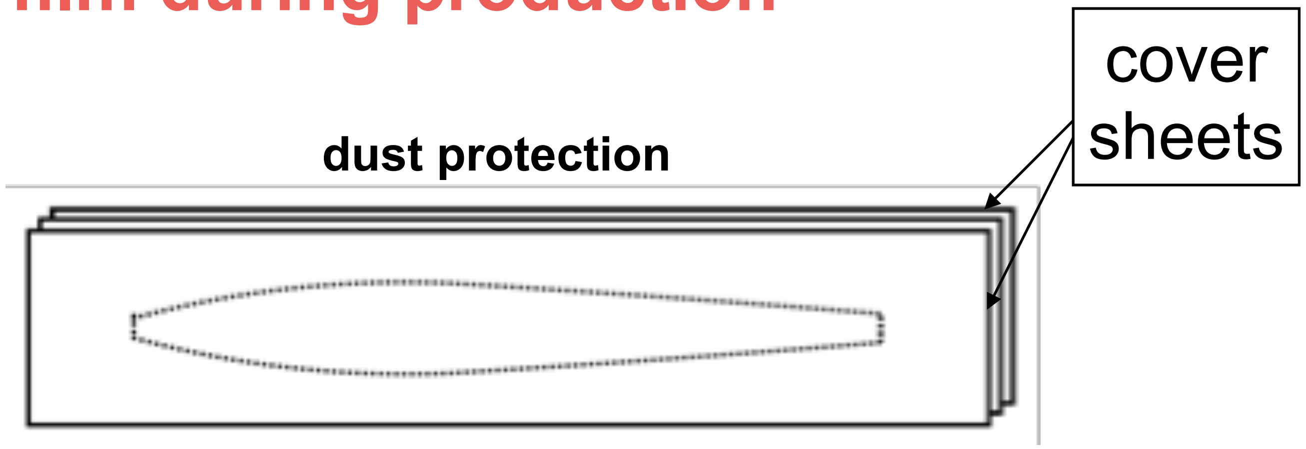
dominant BG from ^{110m}Ag

No ^{110m}Ag
→ need to reduce other BGs

Improved Production Method

KamLAND-Zen 400

dust may be attached to the film during production



KamLAND-Zen 800

newly introduced

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

…

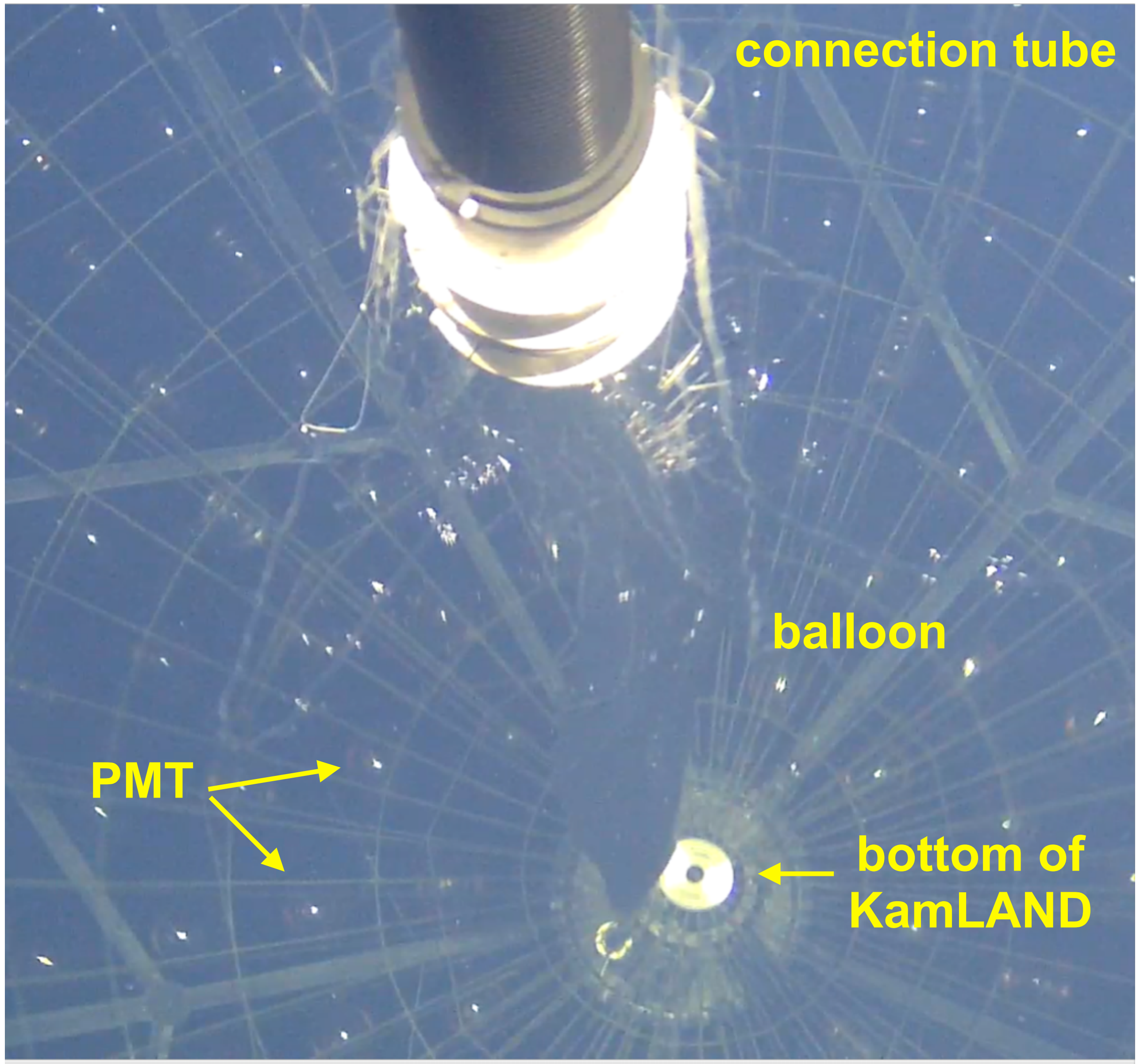
Balloon Production Work

Balloon Installation

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

top of the detector

detector inside view



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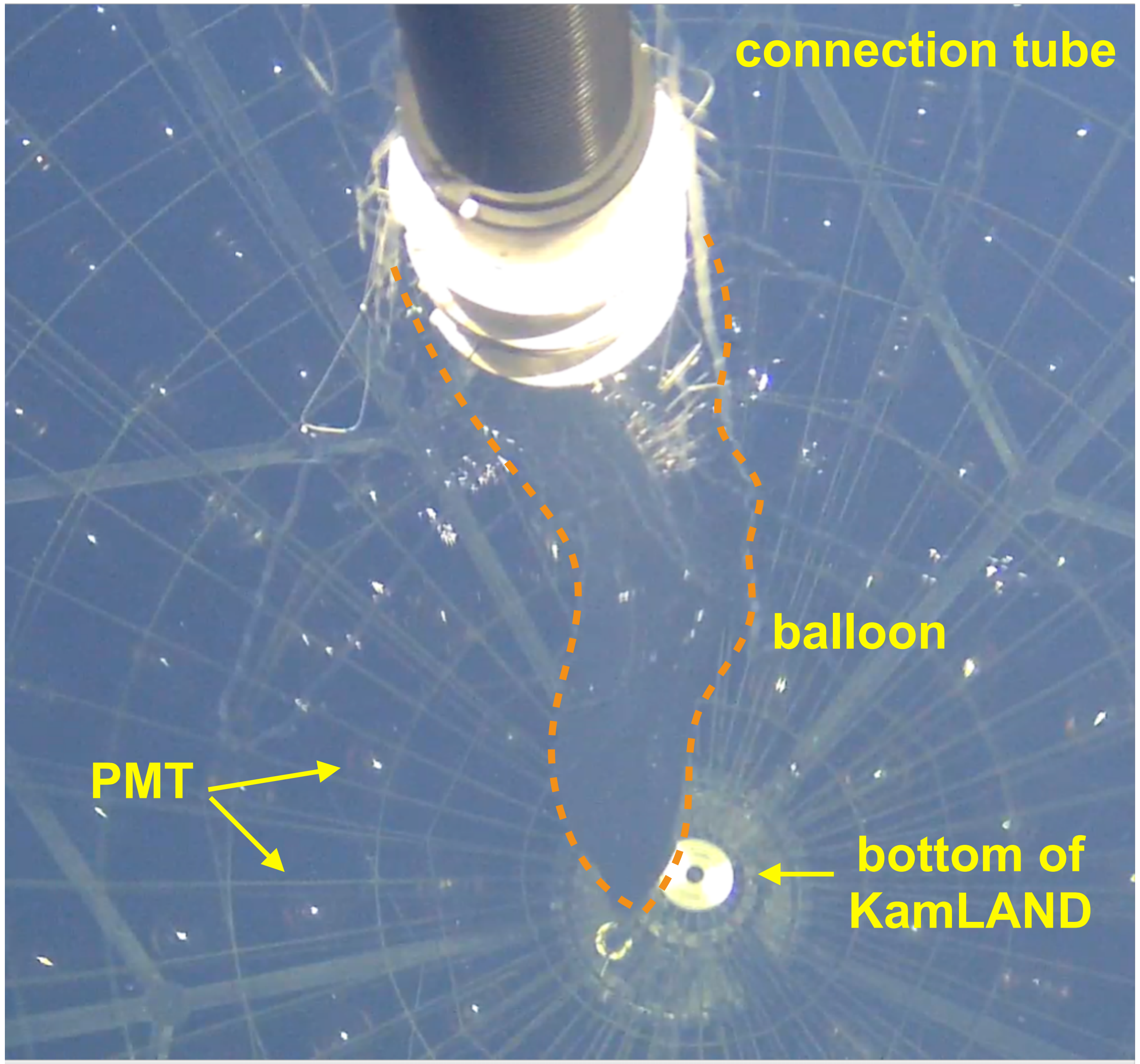


Balloon Installation

Balloon Installation

Background from Inner Balloon (IB)

Zen 400 Phase-II

^{238}U : 5×10^{-11} g/g

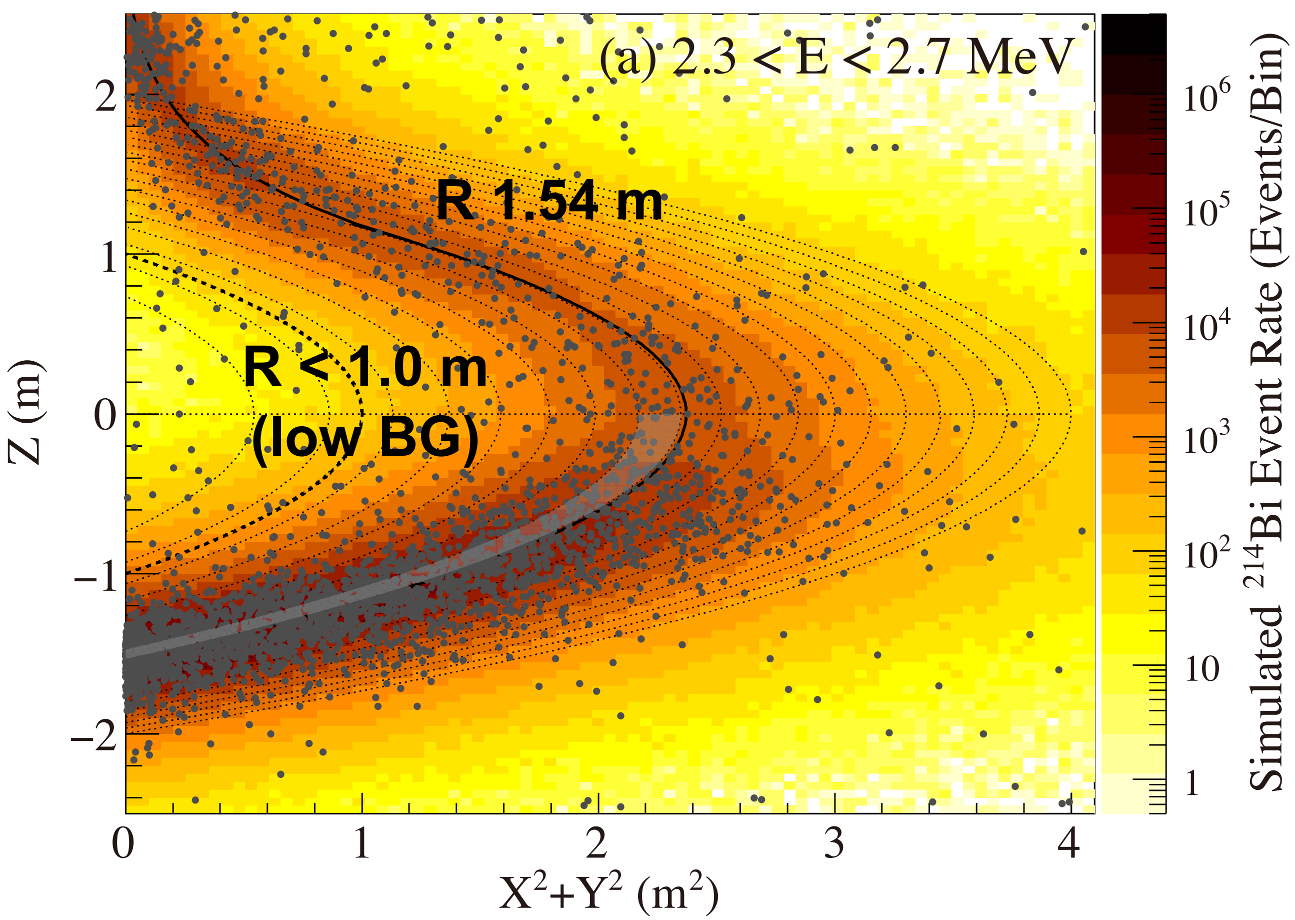
^{232}Th : 3×10^{-10} g/g

Zen 800

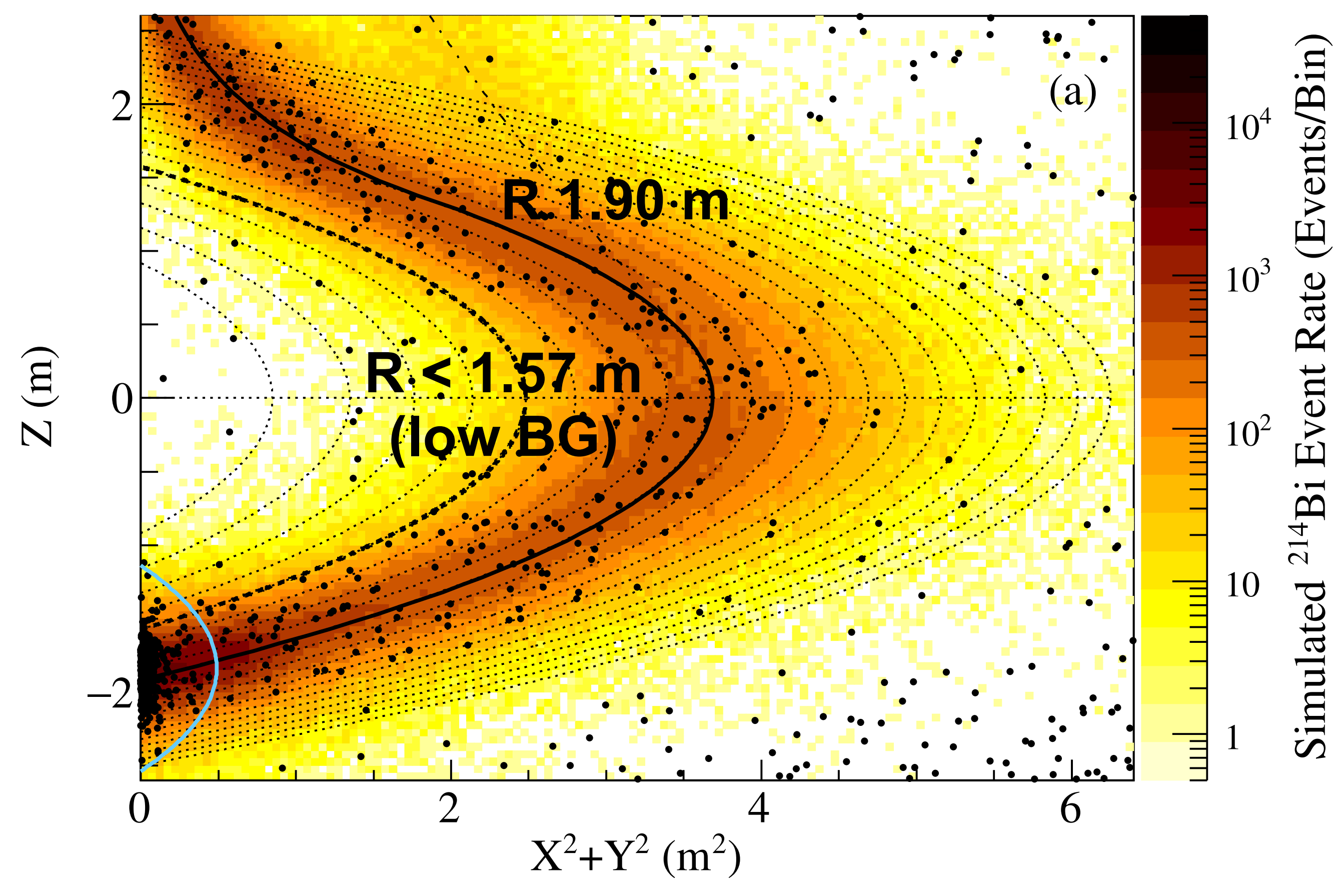
^{238}U : $\sim3\times10^{-12}$ g/g

^{232}Th : $\sim4\times10^{-11}$ g/g

×10 reduction of IB ^{214}Bi



sensitive volume : R < 1.0 m

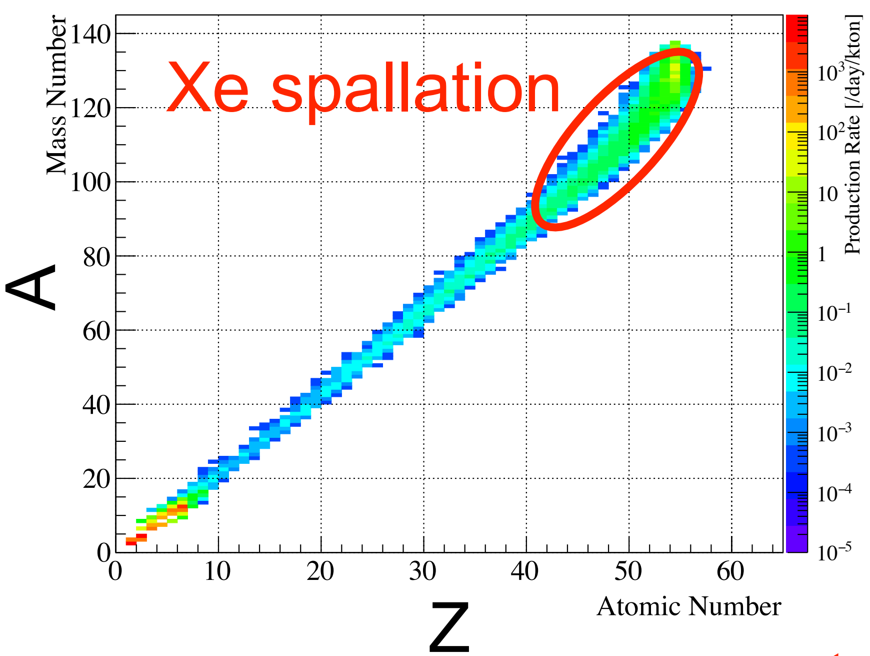


sensitive volume : R < 1.57 m

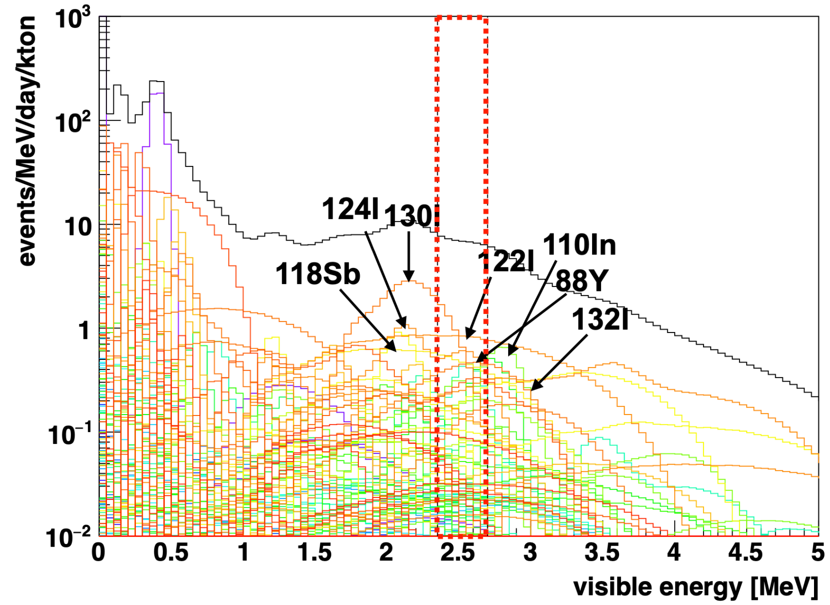
> ×3 sensitive volume !!

Long-lived Spallation Products

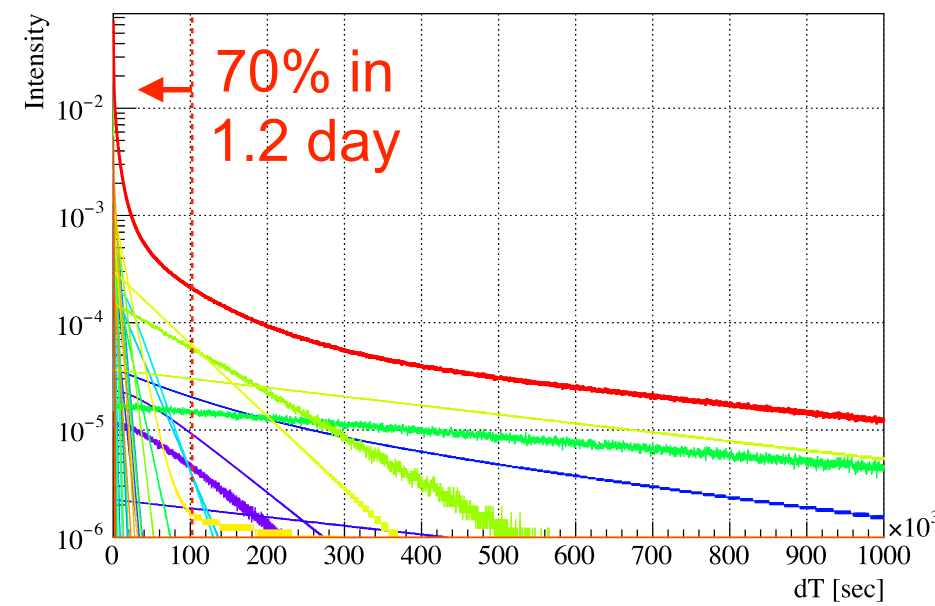
production yield



energy spectrum



time difference from muon

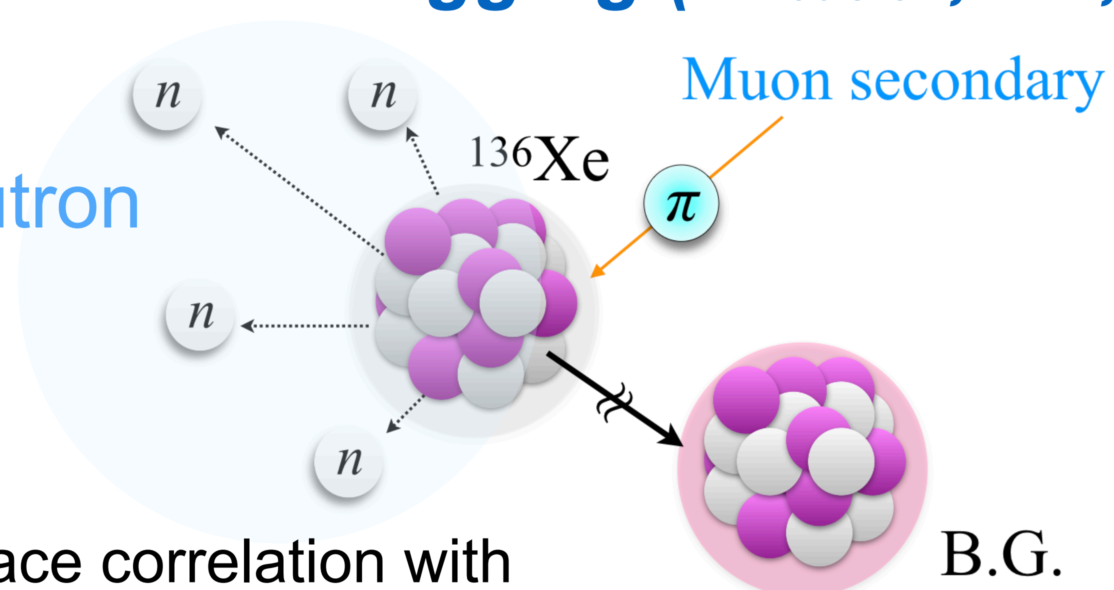


rate in ROI : 0.082 events/day/Xe-ton

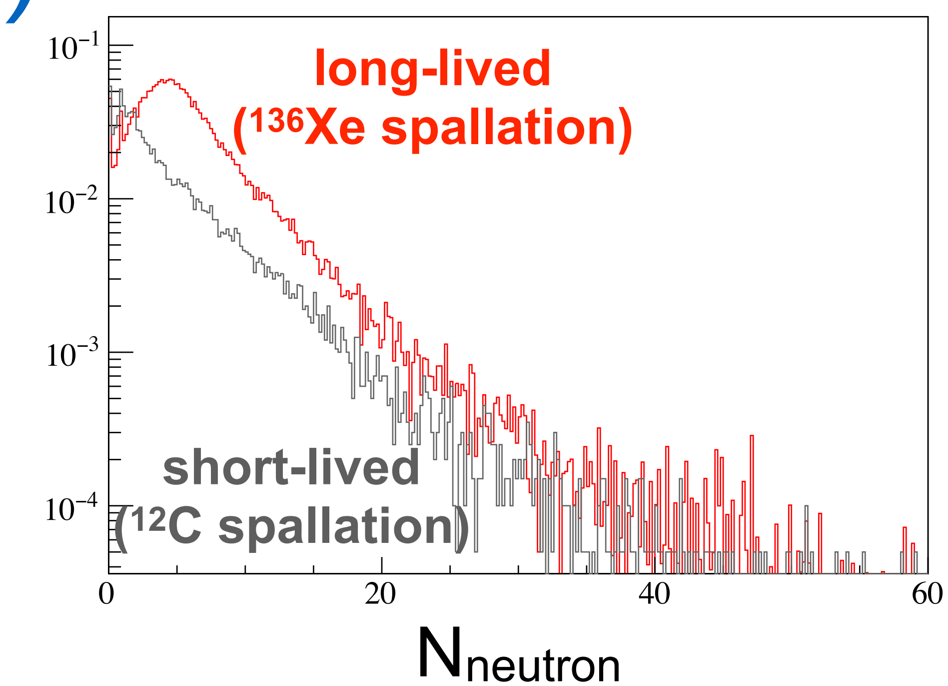
need long-time veto

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

dense neutron cluster



time and space correlation with muon and multiple neutrons

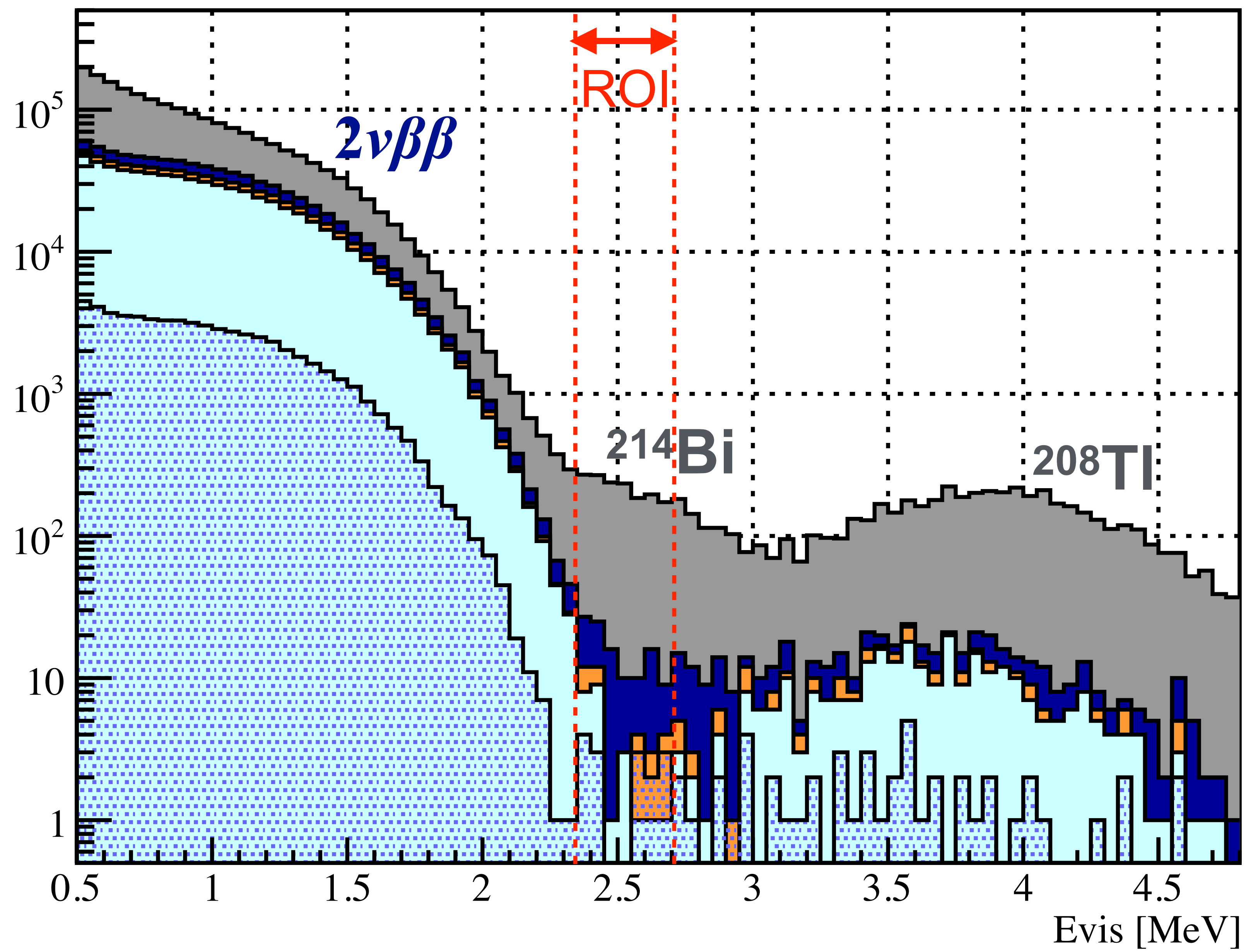


xenon spallation products ~40% rejection efficiency

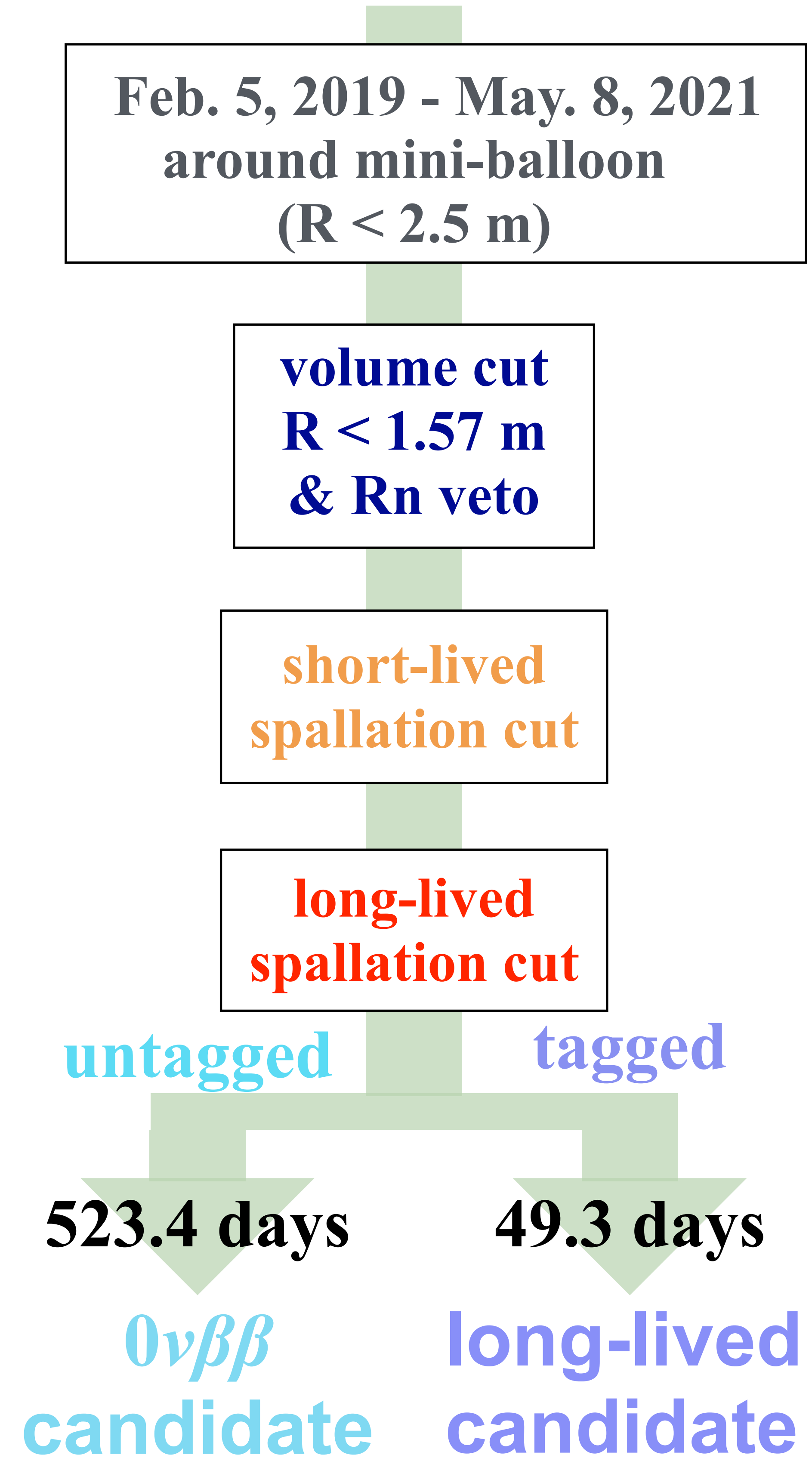
Event Selection

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



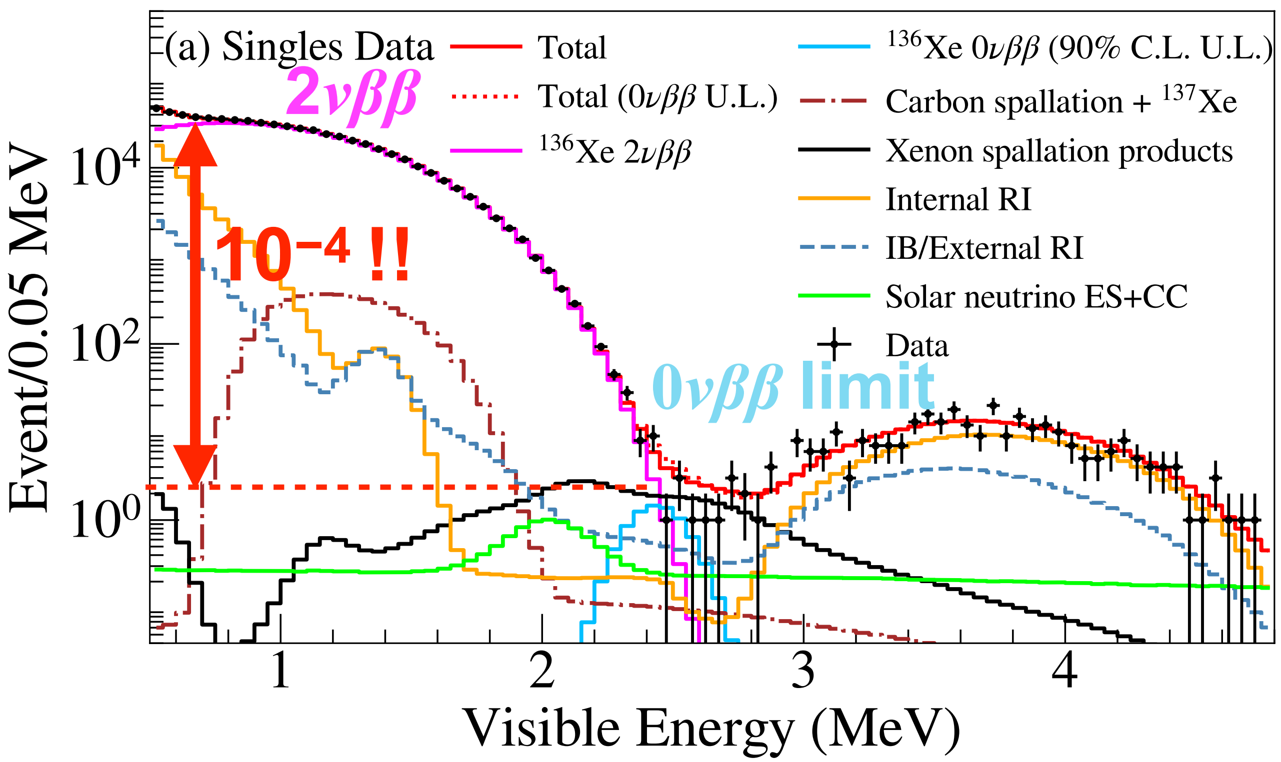
Fit to Energy Spectra for 0νββ

0νββ candidate

(sensitive to 0νββ signal)

523.4 days livetime

R < 1.57 m

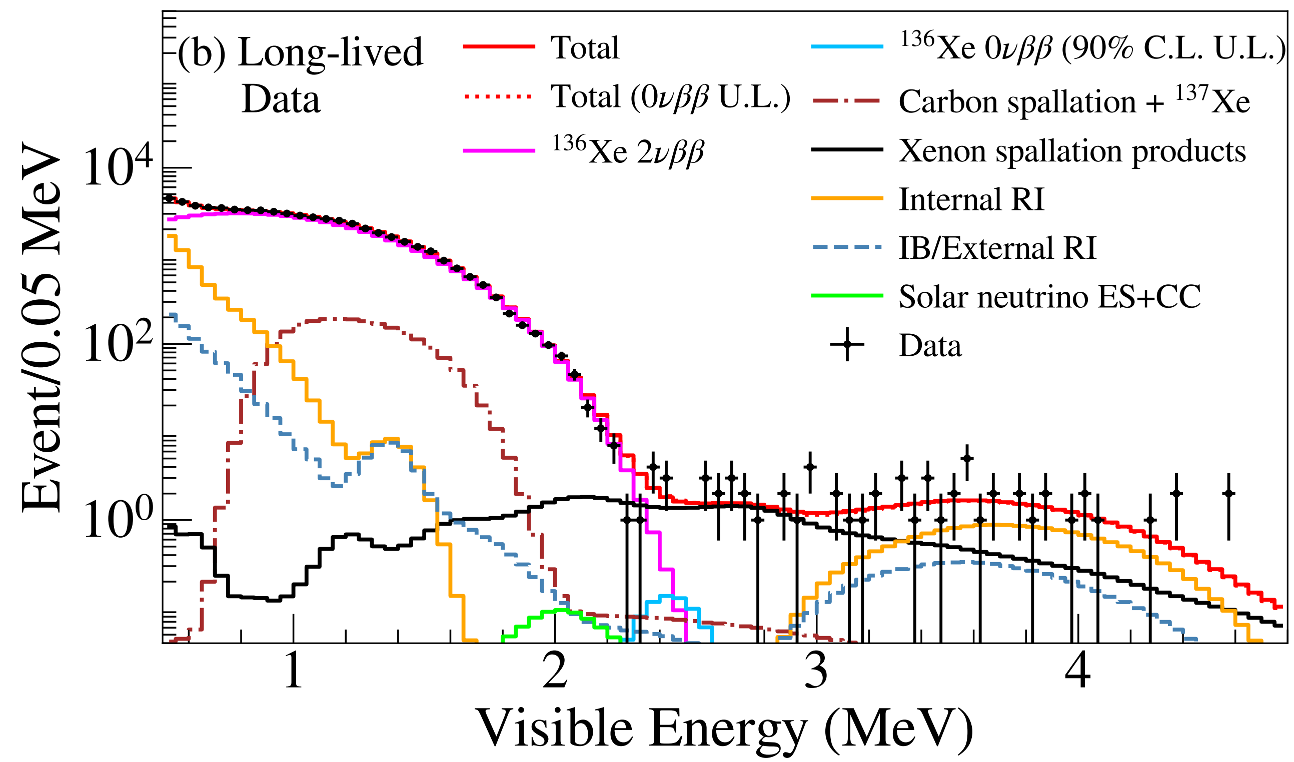


long-lived candidate

(Long-lived BG constraint)

49.3 days livetime

R < 1.57 m



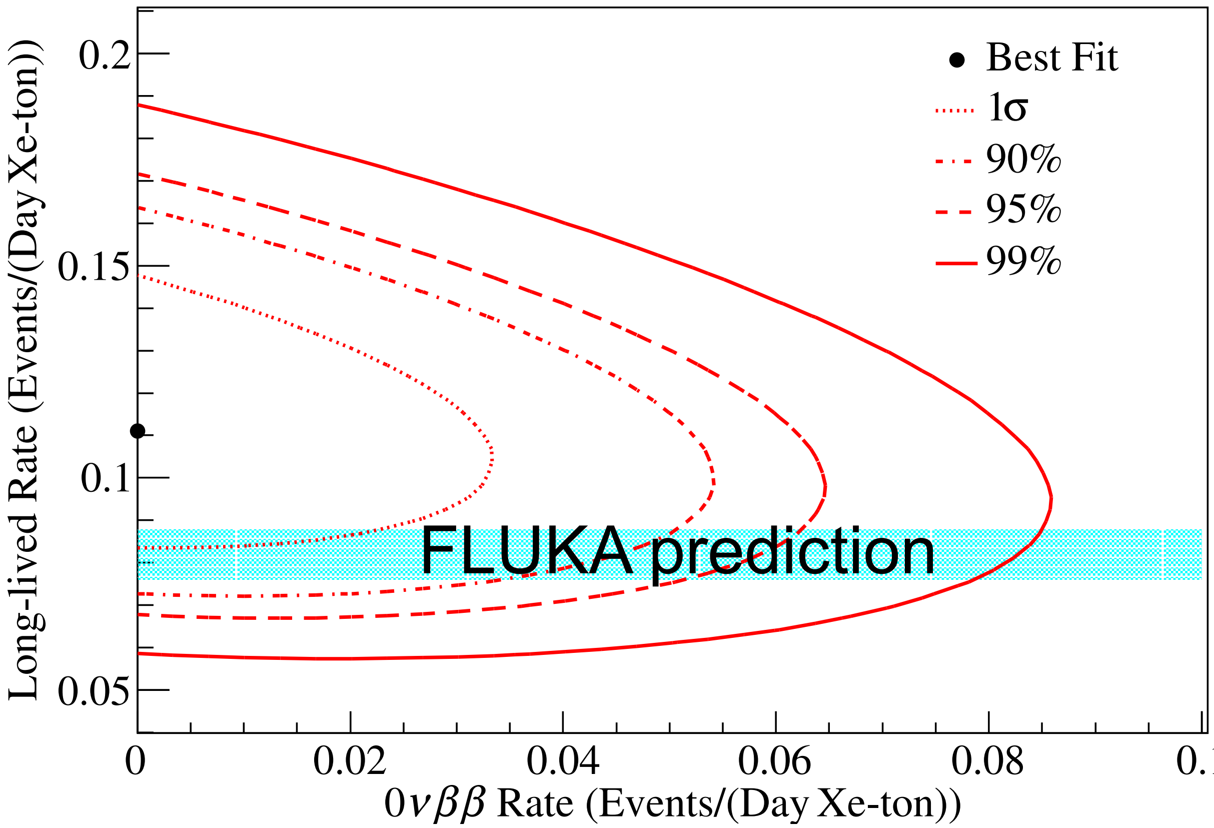
0νββ best-fit : **0 event**

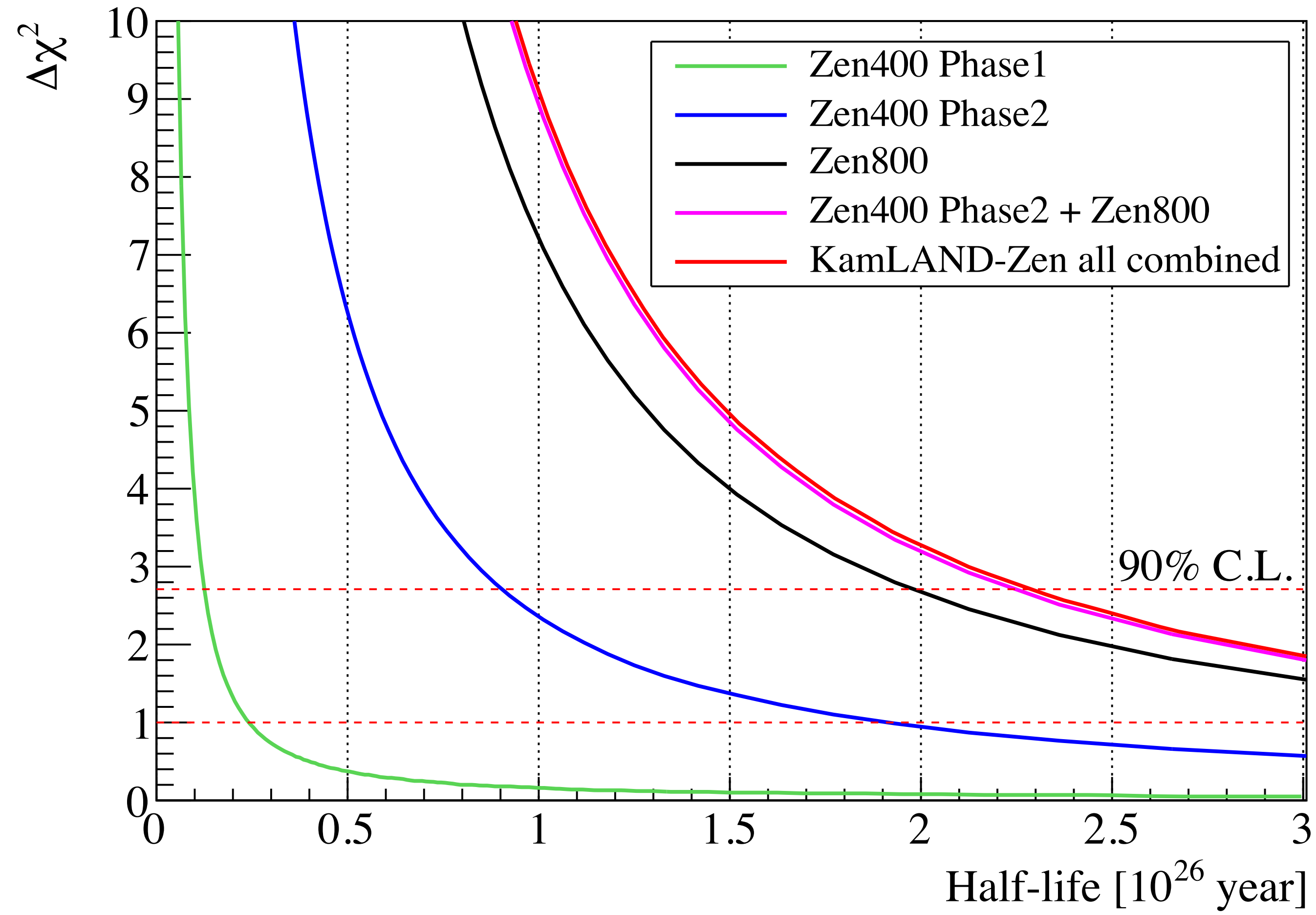
upper limit : **< 7.9 event** at 90% C.L.

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

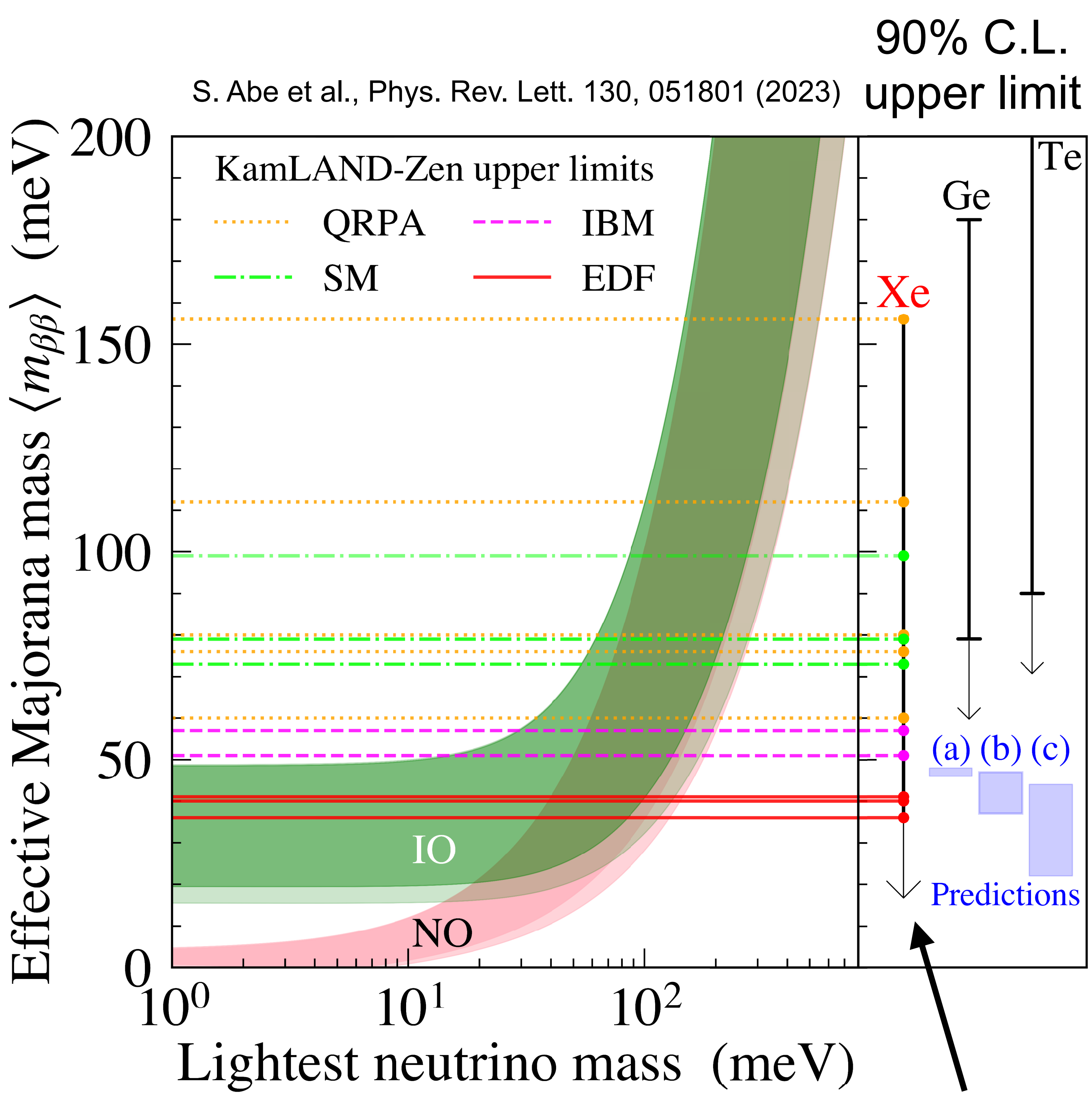
Half-life limit at 90% C.L.

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

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).

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- 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

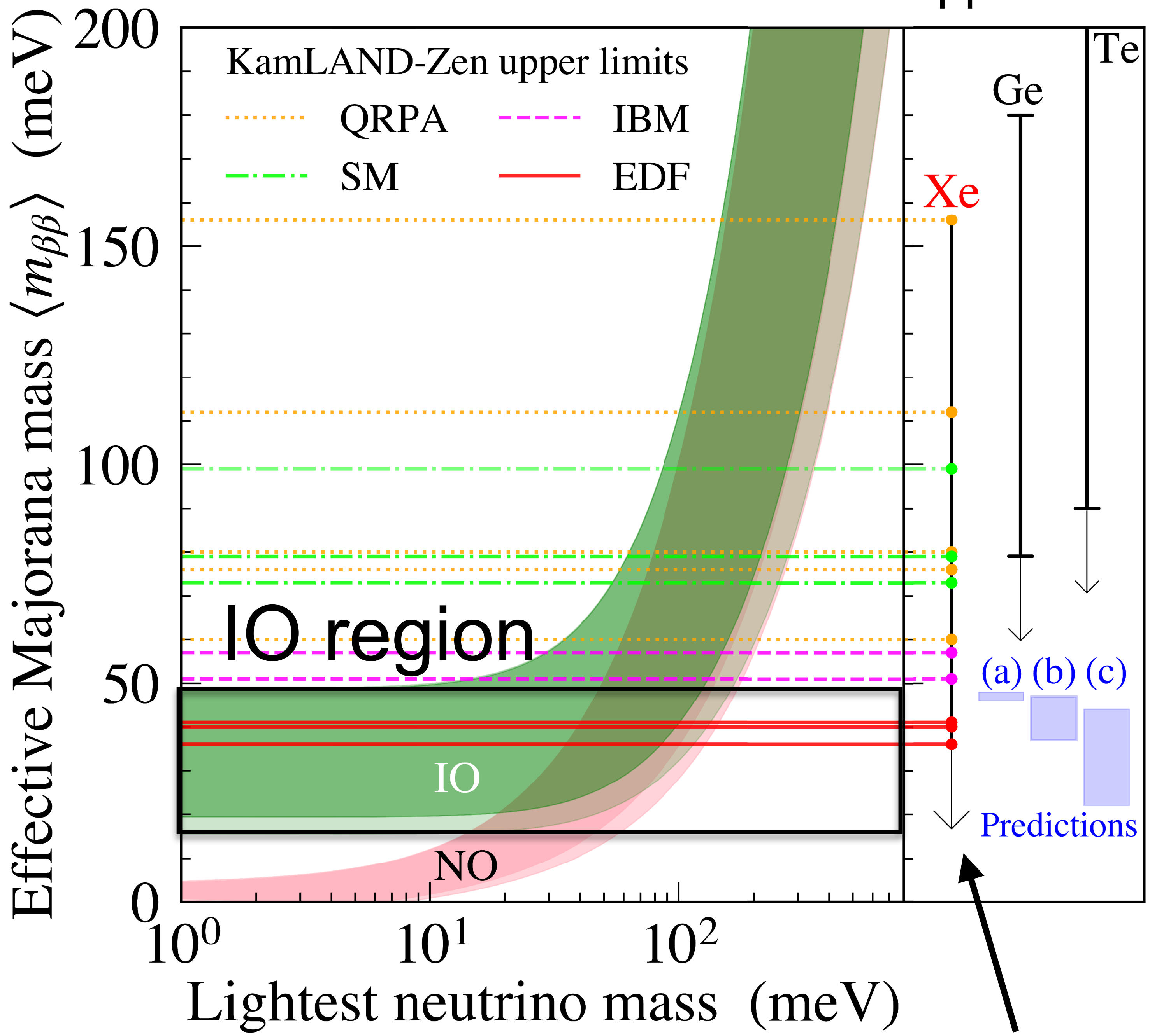
$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)|M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

PSF NME

Limits on Neutrino Mass

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

90% C.L. upper limit



KamLAND-Zen (^{136}Xe)

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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).

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).

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- J. M. Yao, L. S. Song, K. Hagino, P. Ring, and J. Meng, Phys. Rev. C **91**, 024316 (2015).
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Decay rate ⟶ proportional to (neutrino mass)^2

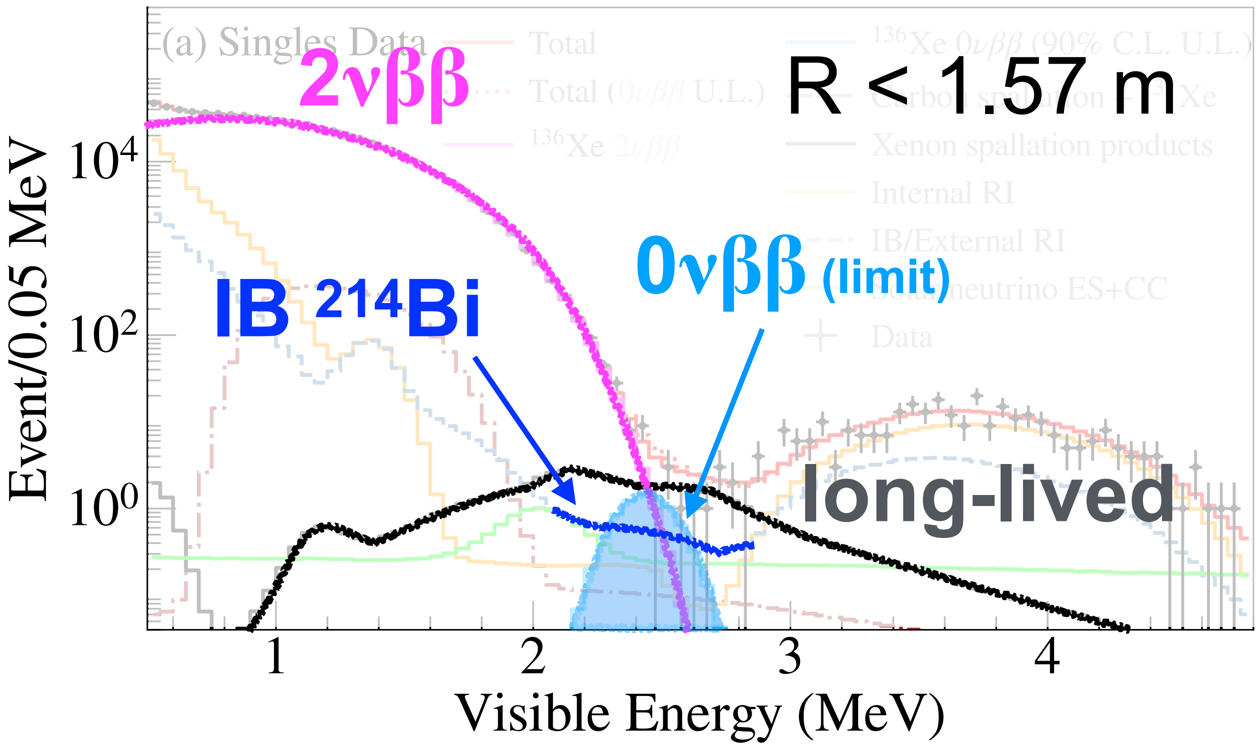
$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)|M^{0\nu}|^2 \langle m_{\beta\beta}\rangle^2$$

PSF NME

Xe (KamLAND-Zen) is the leading experiment !

First search in the inverted ordering (IO) region

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**

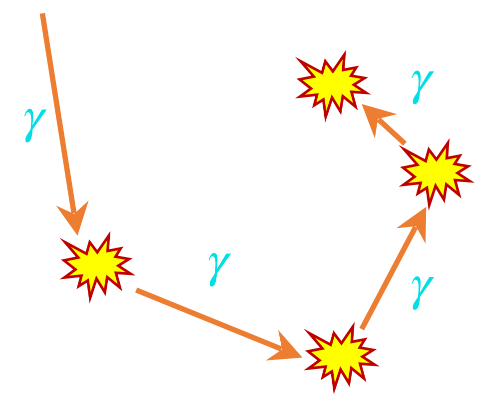
gamma or positron background → **particle identification**

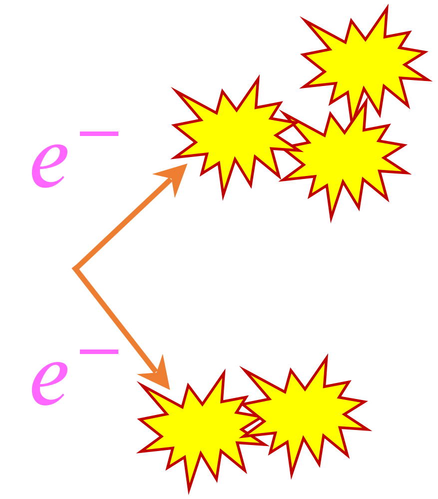
spallation tagging with neutrons → **new electronics**

Particle Identification

Most of long-lived background decays with <u>~MeV gamma-rays</u>

→ energy deposits spread over ~10 cm distances

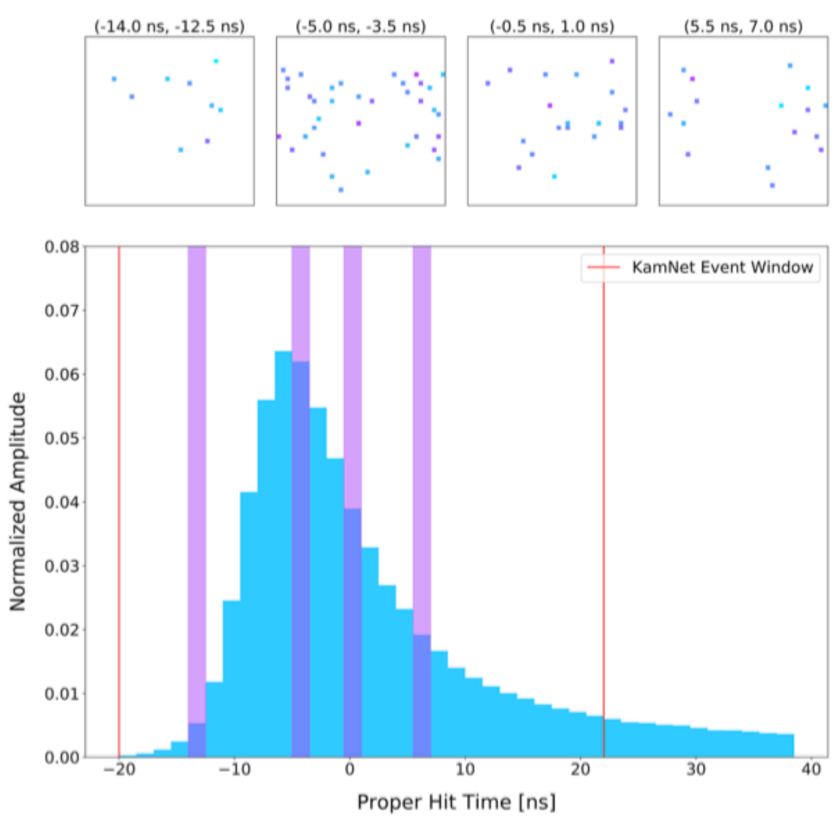




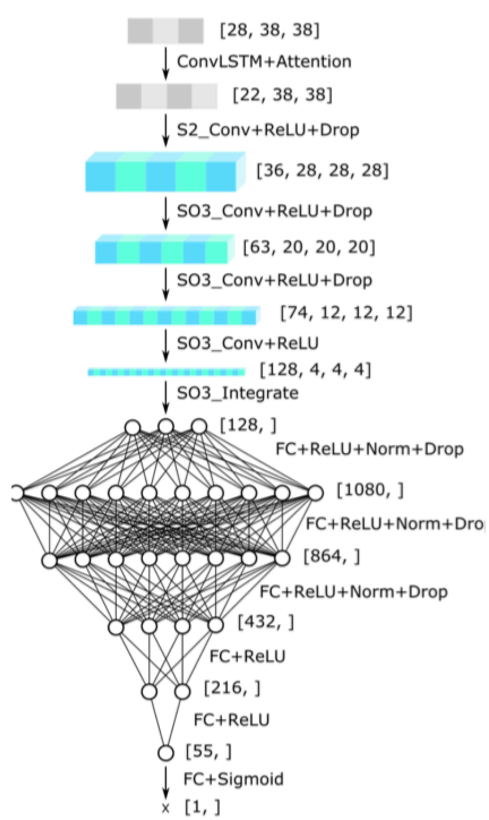
<u>KamNET</u>

Deep neural network for KamLAND-Zen

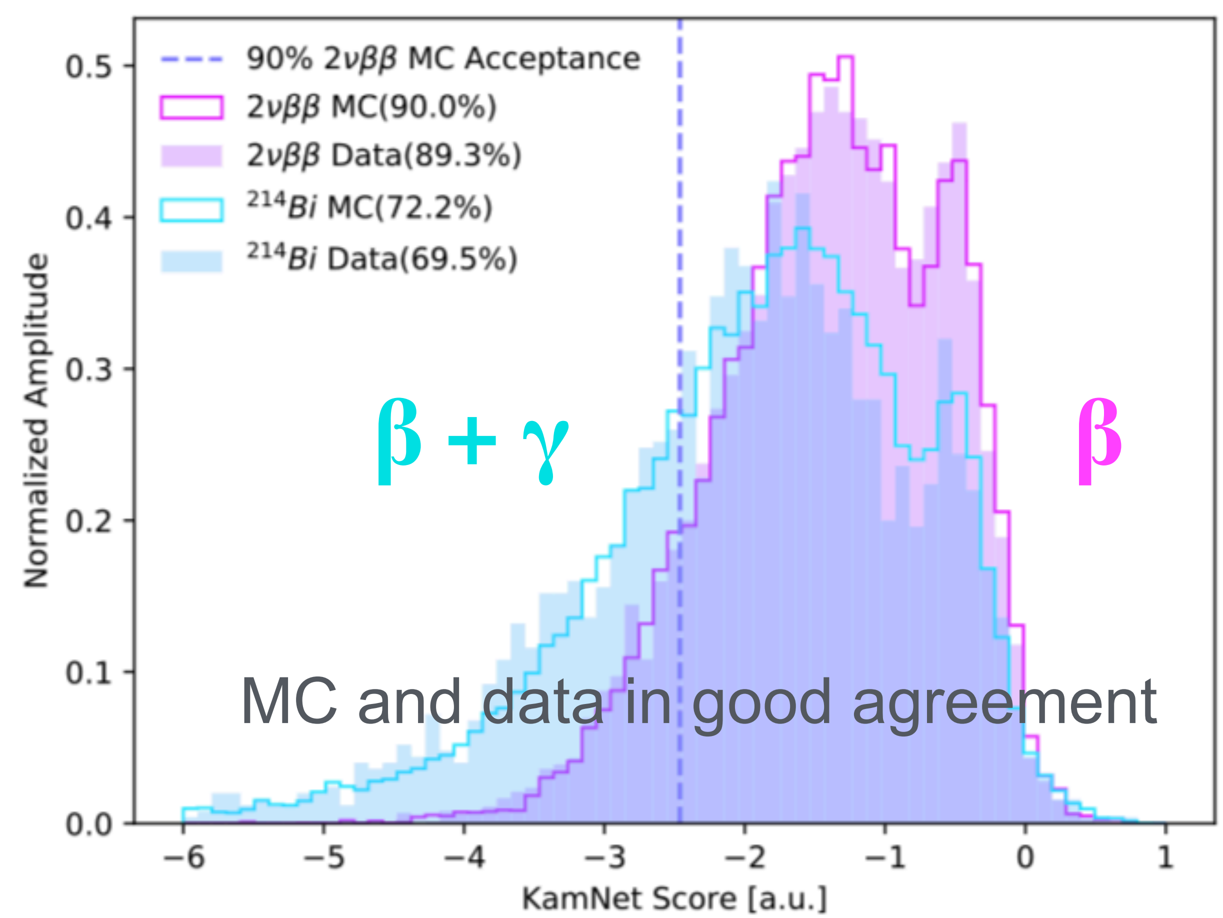
Time series of theta-phi hit map



Spherical CNN



BG like ⟷ Signal like

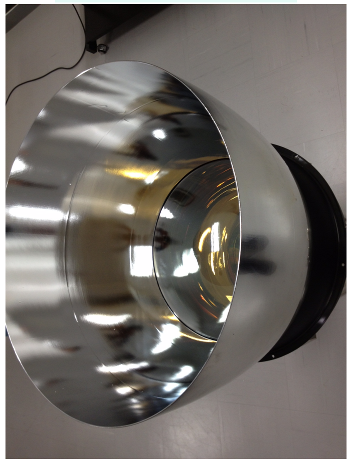


A. Li et al., Phys. Rev. C **107**, 014323 (2023)

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

R&D for KamLAND2-Zen

Mirror



High Q.E. PMT

x1.9

Light Collection Eff.

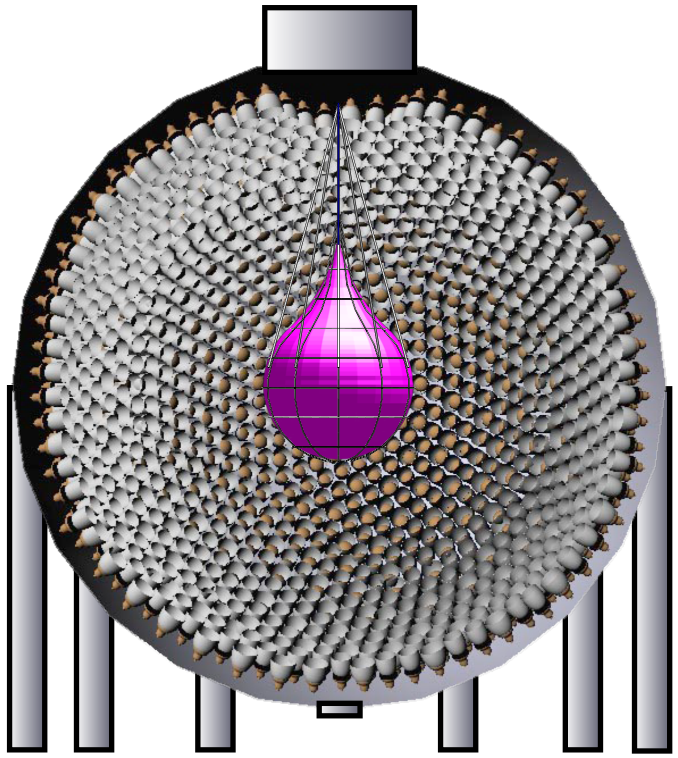
> **x1.8**

New liquid scintillator **x1.4**

σ_E @ Q-value = 4% → 2%

→ 2νββ BG reduction ~ **1/100 !**

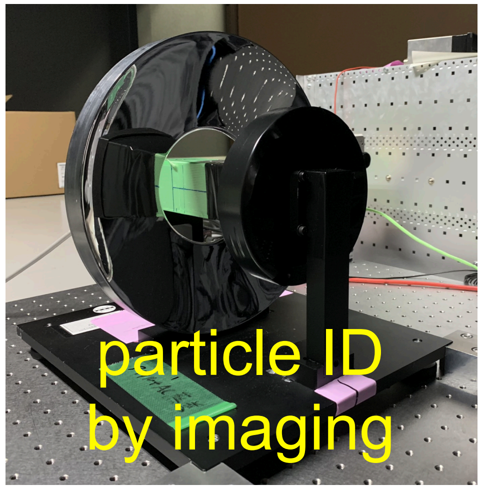
1000 kg enriched Xe



State-of-the-art electronics

more neutron tagging efficiency
→ long-lived BG reduction

Imaging device



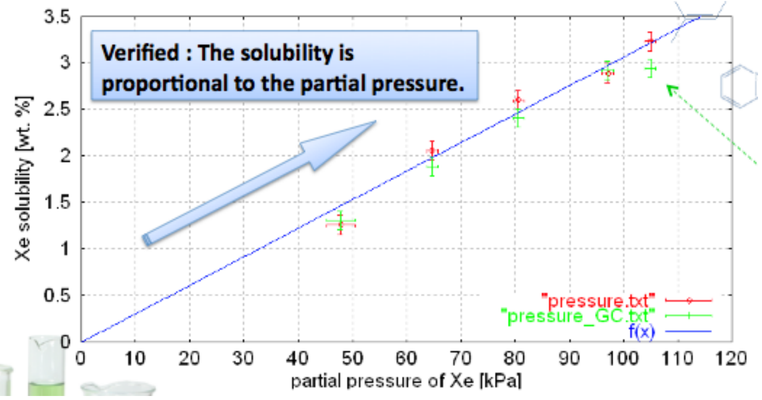
e⁻ / gamma identification
→ long-lived BG reduction

Scintillation balloon

(PEN film)

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

Pressurized Xe-LS



Xe / electron ratio increase
→ solar neutrino BG reduction

KamLAND2-Zen Prototype

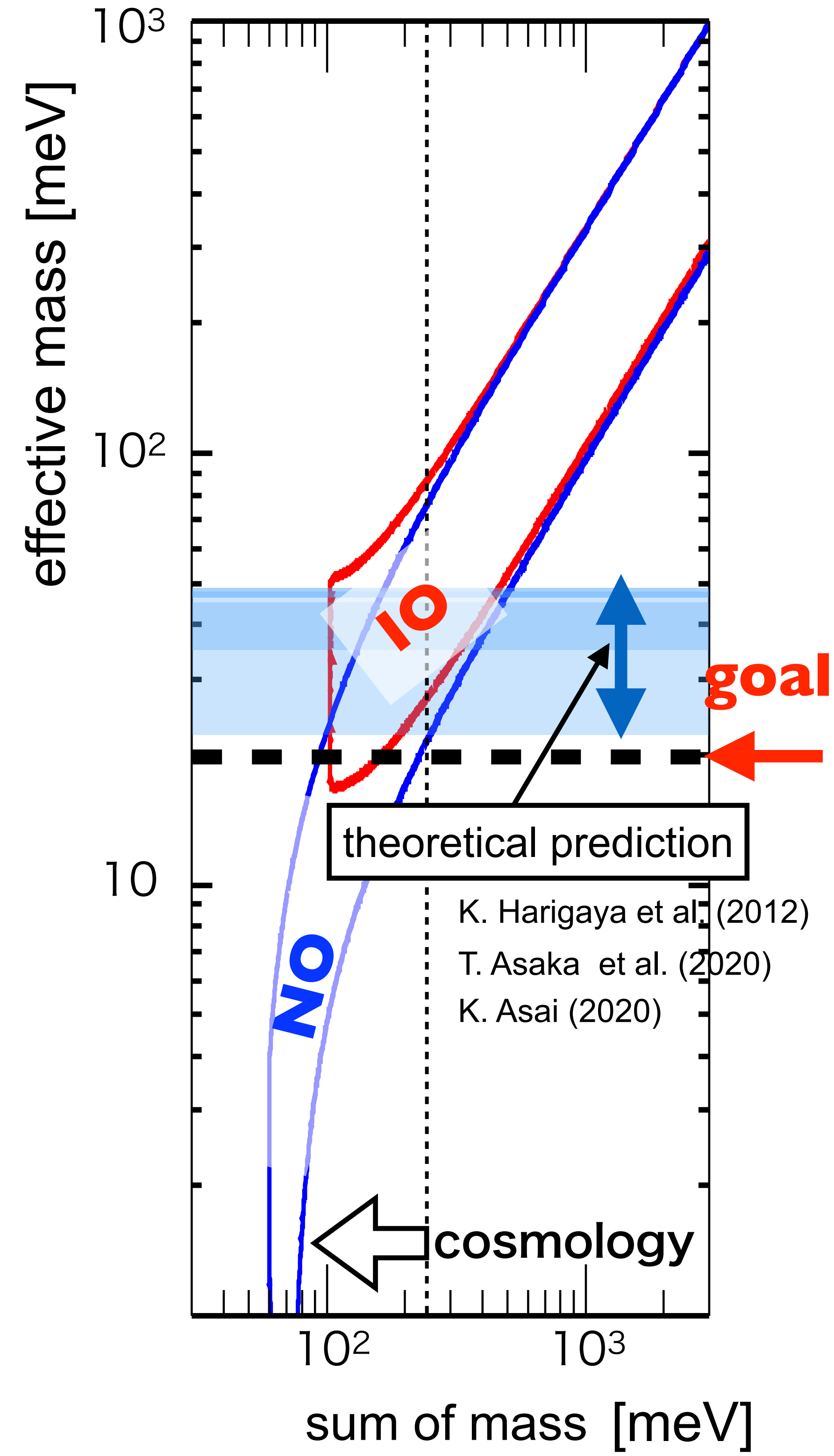
High performance of KamLAND2 will be demonstrated with the prototype detector

- **High Q.E. PMT / light collecting mirror** were installed
- **New liquid scintillator** was installed
- DAQ with **new electronics** will be performed soon

KamLAND2 prototype

inside view

KamLAND2-Zen goal



KamLAND2-Zen will cover the IO region

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

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 0νββ at 90% C.L.

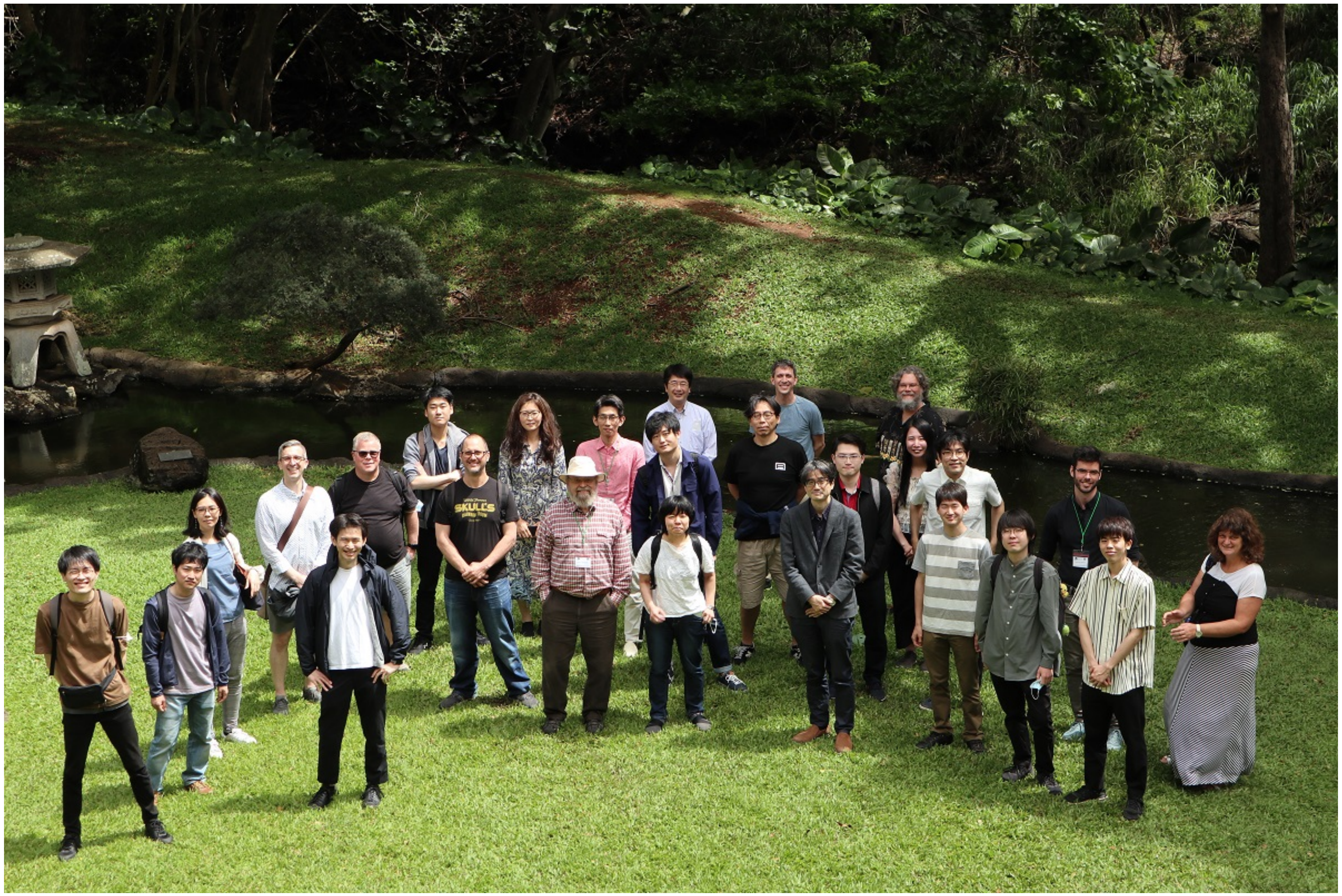
KamLAND-Zen 400	$T^{0\nu}_{1/2} > 0.9 \times 10^{26}$ yr
KamLAND-Zen 800	$T^{0\nu}_{1/2} > 2.0 \times 10^{26}$ yr
Combined	$\mathbf{T^{0\nu}_{1/2} > 2.3 \times 10^{26}}$ **yr**
	↓
NME calculations assuming $g_A \sim 1.27$	$\langle m_{\beta\beta} \rangle$ **< 36-156 meV**

First probe of the inverted mass ordering region!

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

KamLAND-Zen Collaboration

~50 physicists work on this project



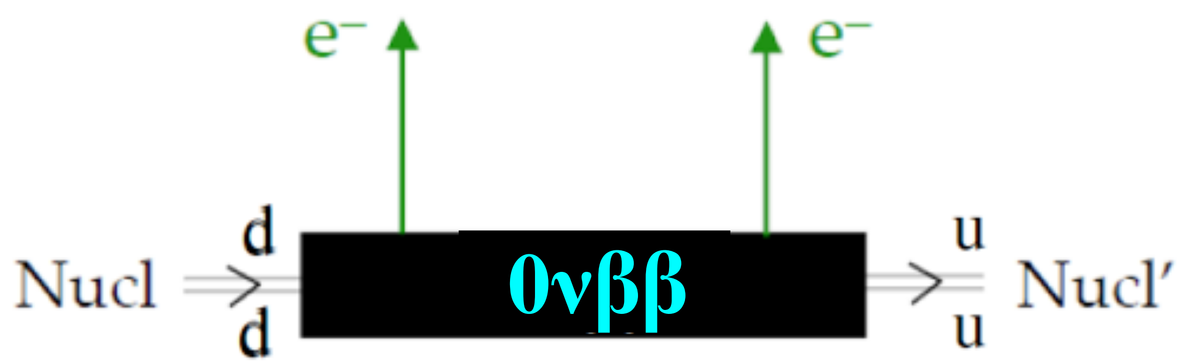
Collaboration meeting in March, 2023

TOHOKU UNIVERSITY
東京大学 THE UNIVERSITY OF TOKYO
大阪大学 OSAKA UNIVERSITY
TOKUSHIMA UNIVERSITY
BERKELEY LAB
KYOTO UNIVERSITY FOUNDED 1897
THE UNIVERSITY OF TENNESSEE KNOXVILLE
TUNL
MIT
VIRGINIA TECH.
UNIVERSITY of HAWAIʻI
BOSTON UNIVERSITY
Nikhef

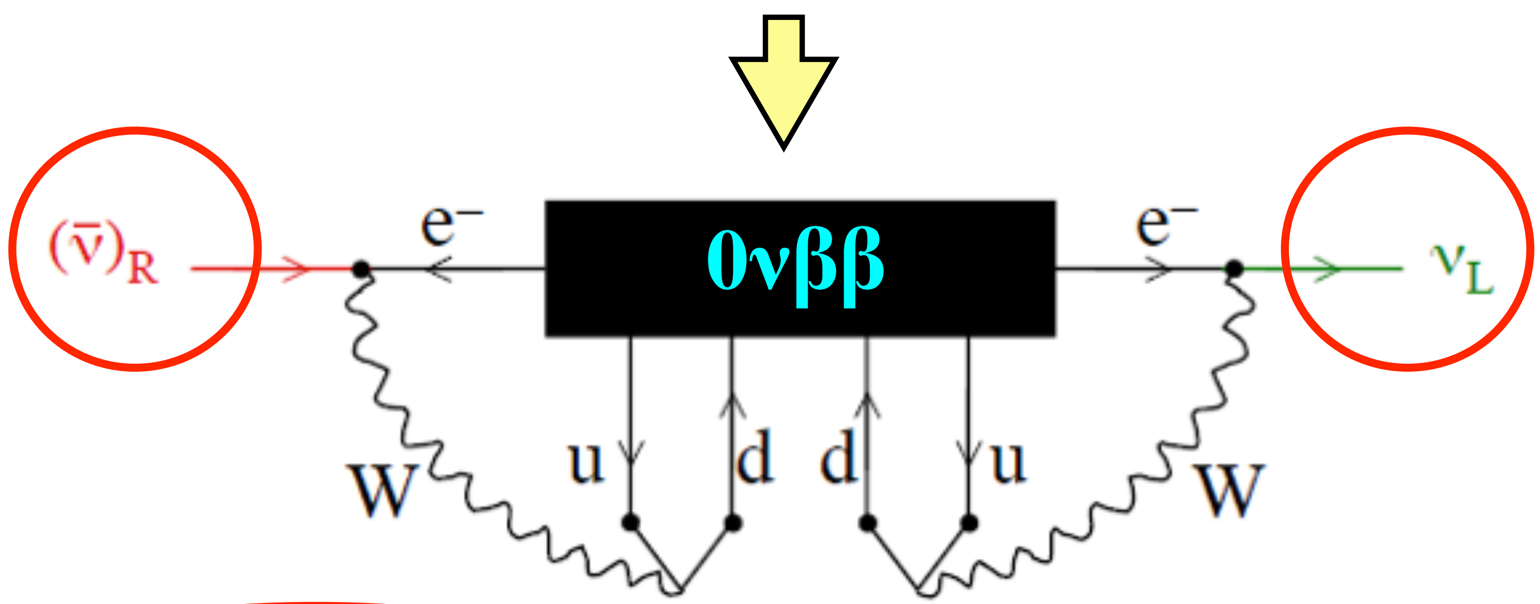
Backup

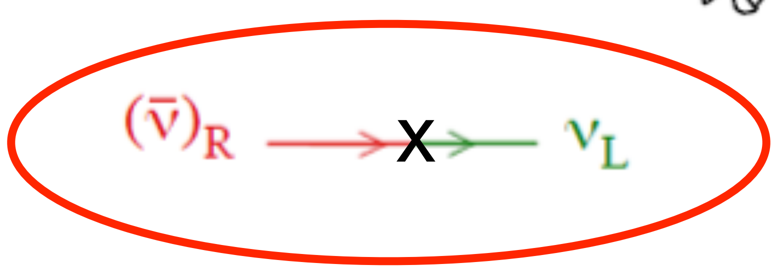
Test of Majorana Neutrino

Schechter Valle theorem



detect 0νββ emitting only 2 electrons





imply the existence of **Majorana mass term**

0νββ ⟺ $\bar{\nu} = \nu$

Milestone of 0νββ search

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)|M^{0\nu}|^2 \langle m_{\beta\beta}\rangle^2 \qquad \langle m_{\beta\beta}\rangle \equiv \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$

Phase space factor

Highly depends on target double-beta decay nuclei (larger in high Q-value)

Precisely calculated considering Coulomb distortion of the electron wave functions

uncertainty ~a few %

Phys. Rev. C 85, 034316 (2012), Phys. Rev. C 88, 037303 (2013)

Nuclear matrix element (NME)

Nuclear states needs to be modeled

Uncertainties due to approximation and dependence on nuclear modeling are large

uncertainty ~factor 2-3

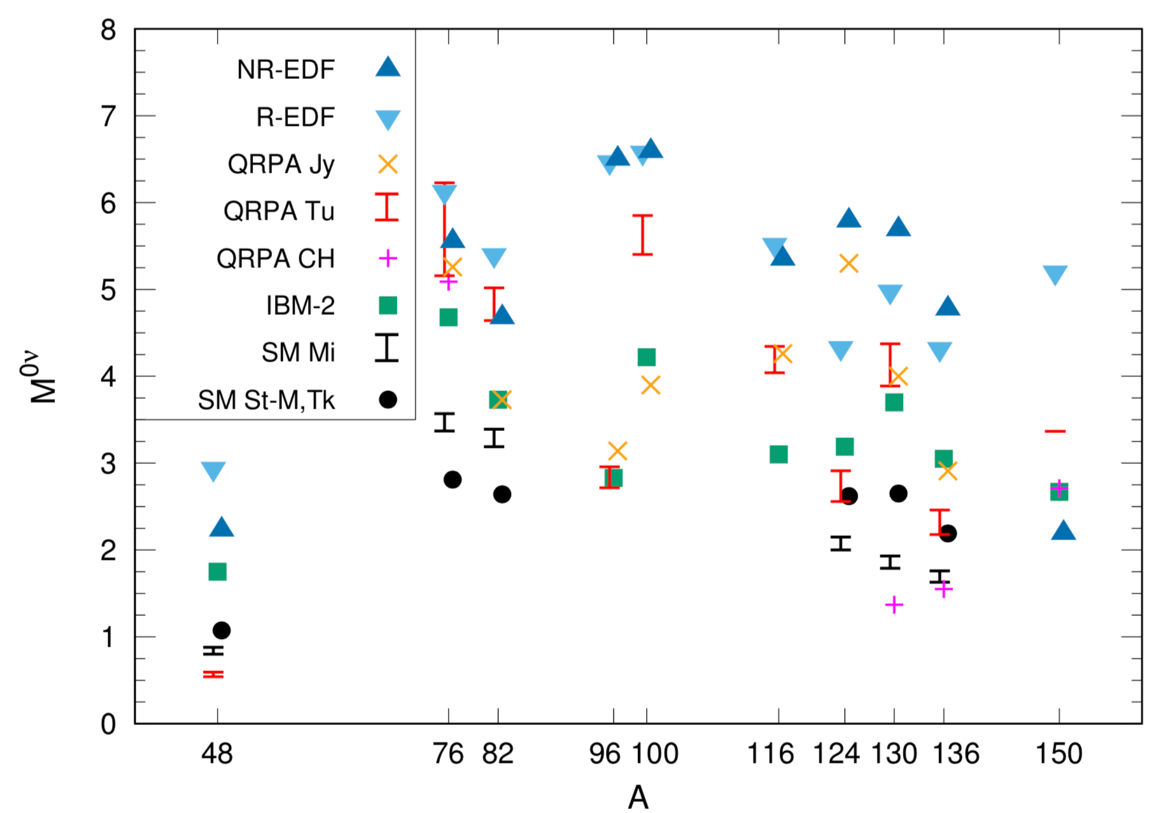
Axial-vector coupling : g_A = 1.27 (neutron)

$$|M^{0\nu}| \propto g_A^2$$

smaller value g_A ~ 1 in β-decay

no good prediction in 0νββ

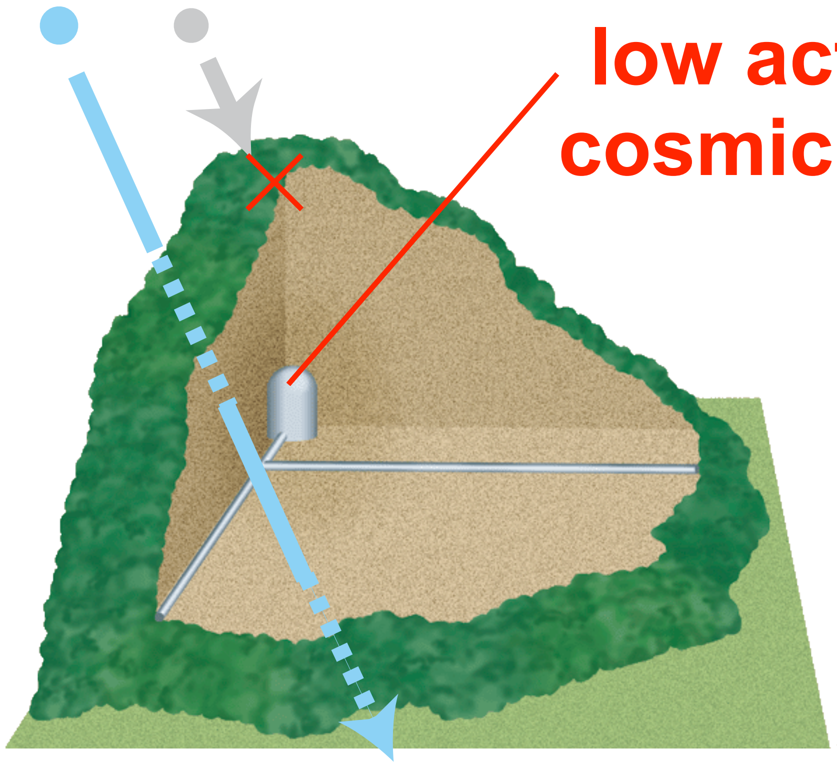
EPJ Web of Conferences **137**, 08011 (2017)



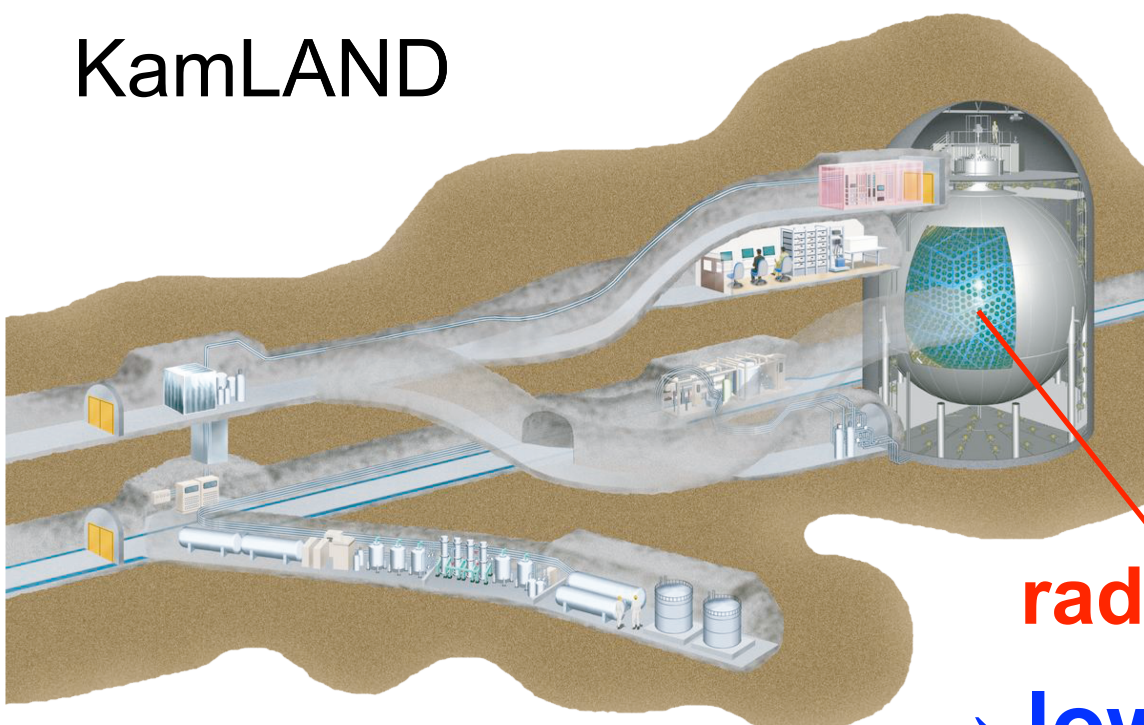
Underground Experiment

neutrino , cosmic-ray

low activation by cosmic-ray muons

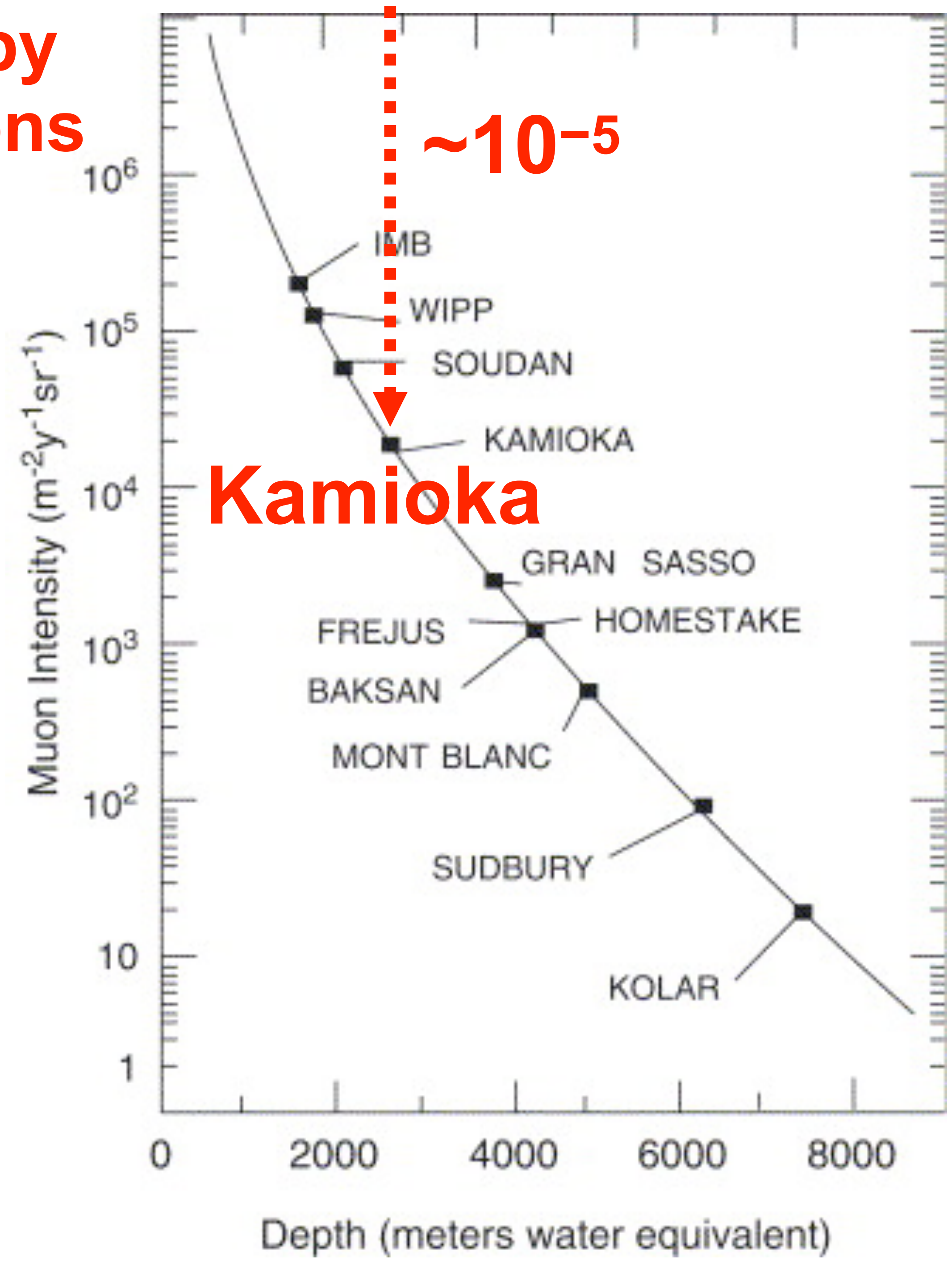


KamLAND



radiopure

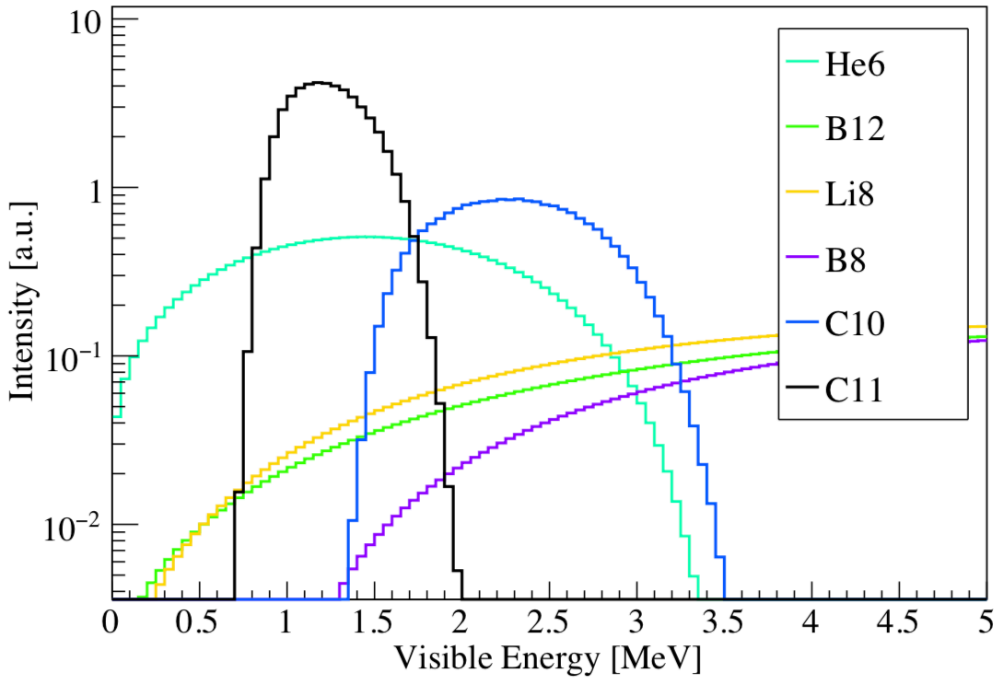
muon flux at underground sites



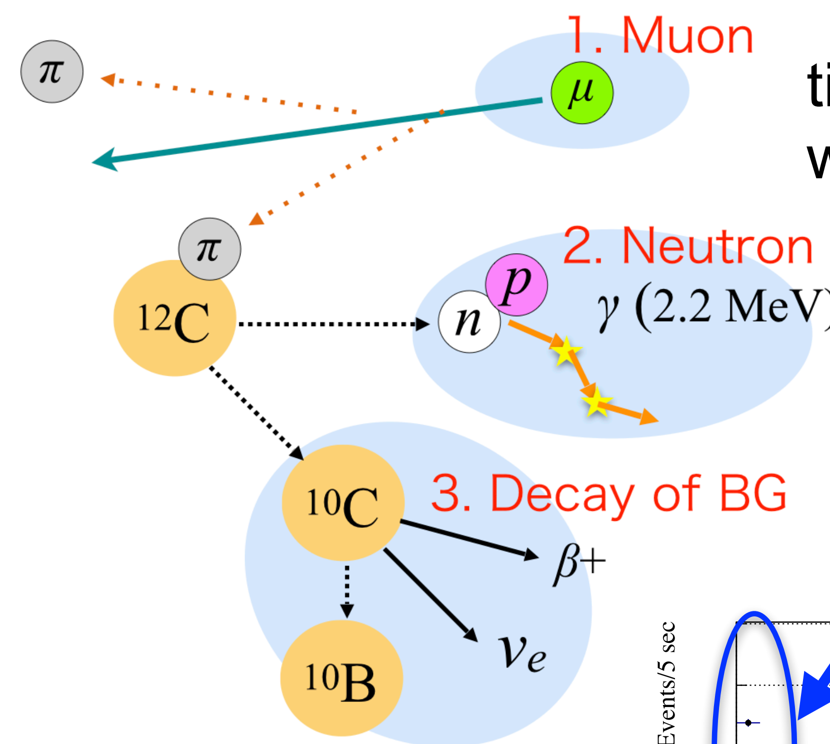
→ **low BG technique** high-purity source/shield

Short-lived Spallation Products

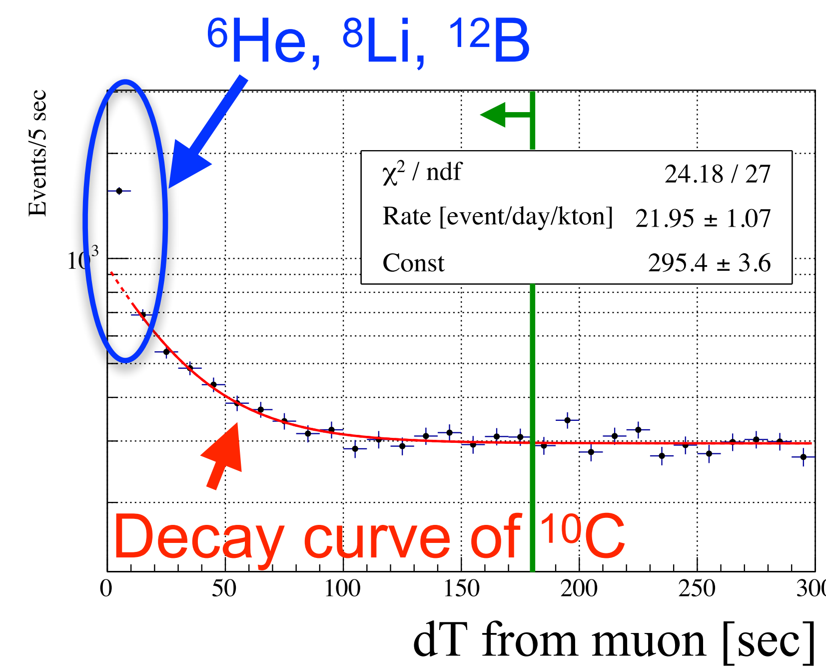
carbon spallation products



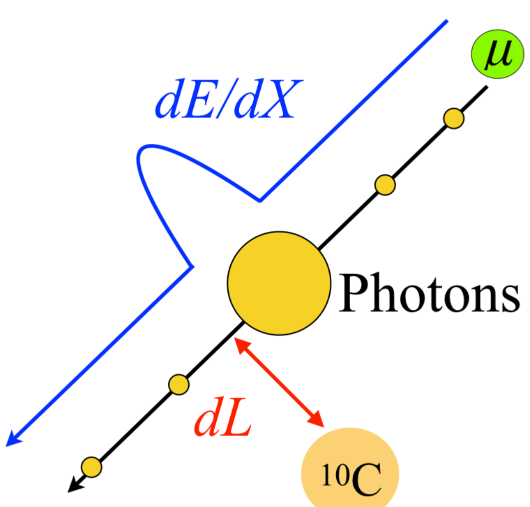
Triple coincidence tagging (dT, dR)

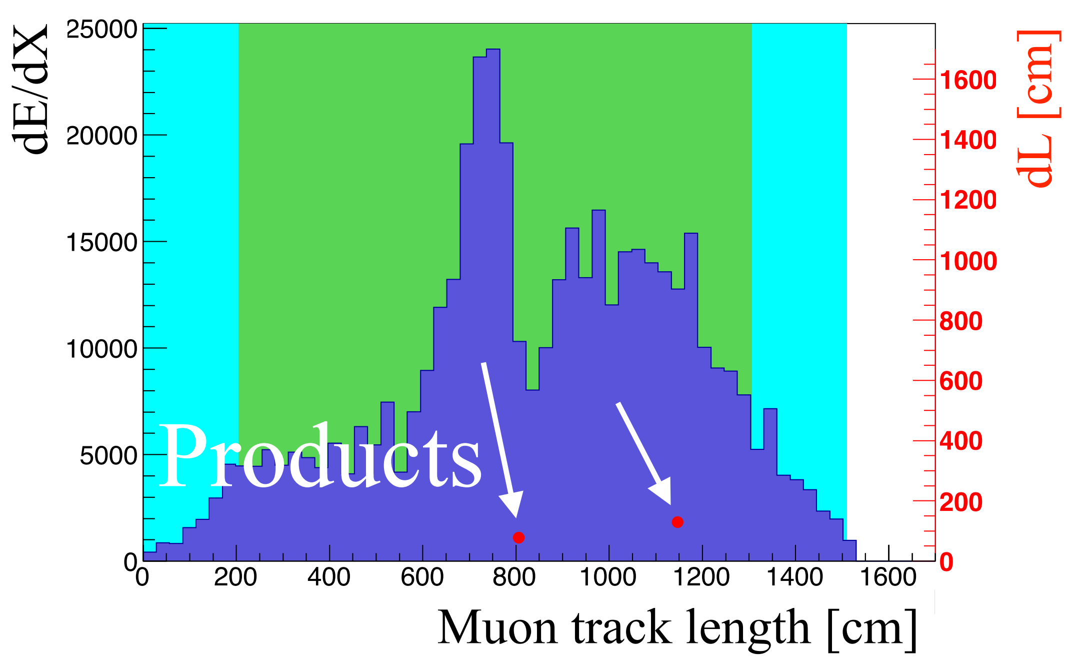


time and space correlation with muon and neutrons



Shower tagging (dE/dX, dL)





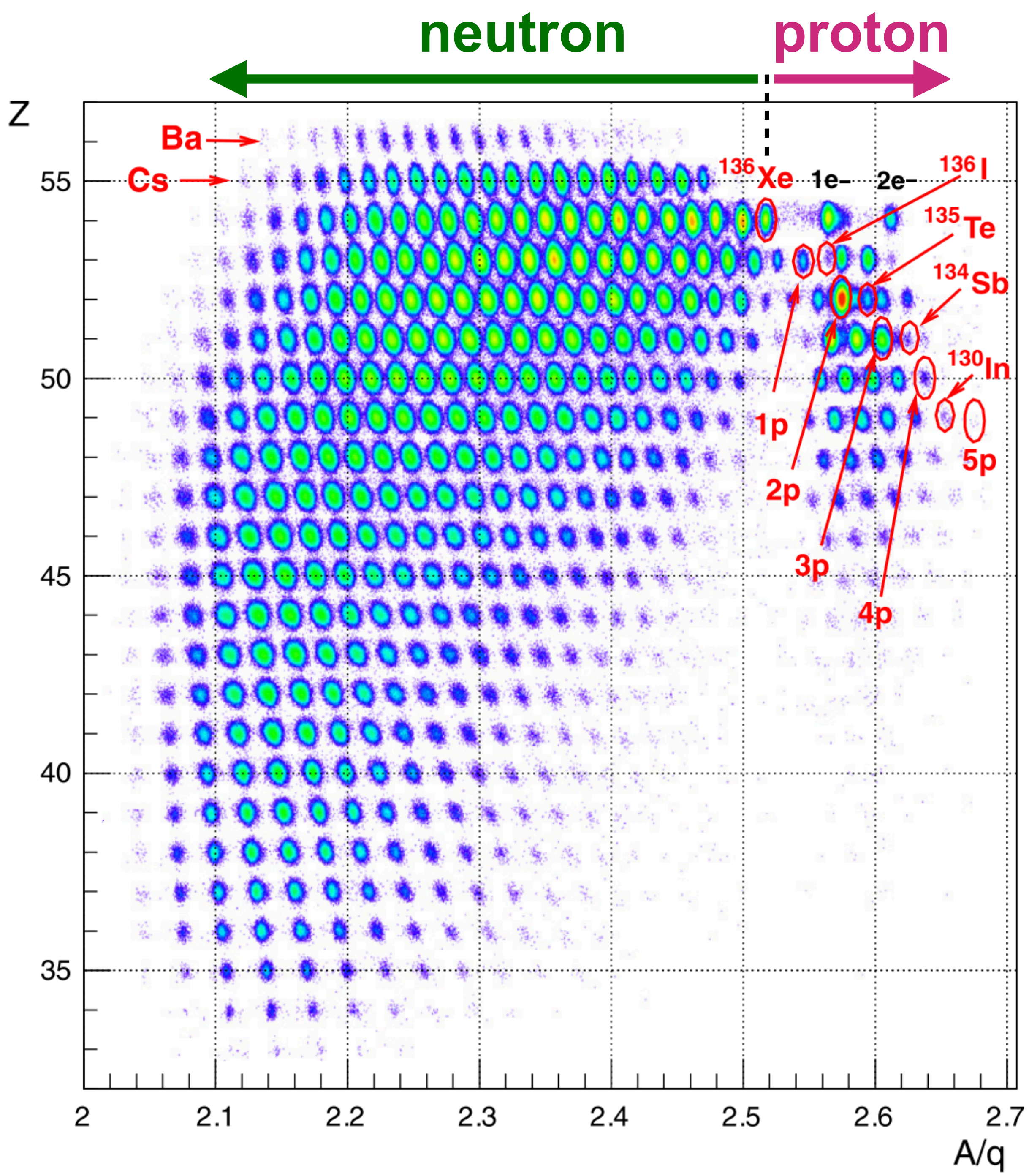
space correlation with muon shower

carbon spallation products
> 95% rejection efficiency

Proton-beam Spallation Data

p + ^{136}Xe (500 MeV/nucleon)

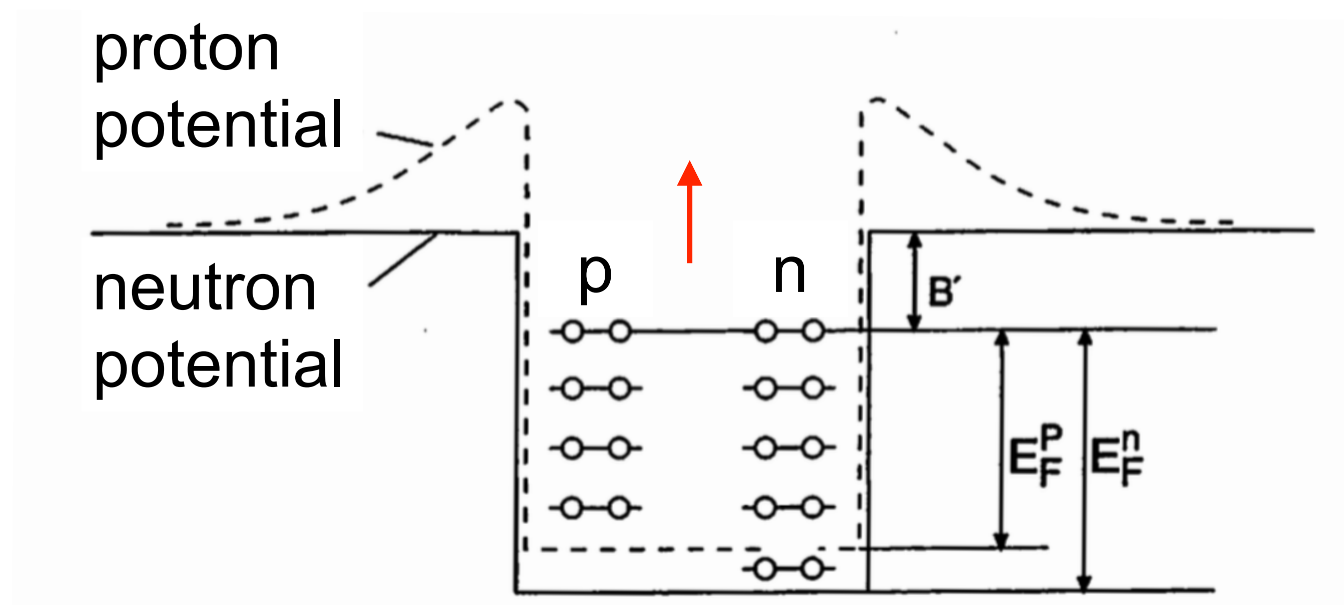
https://www.sciencedirect.com/science/article/pii/S0375947412004423?via%3Dihub



tends to emit neutrons (up to ~20)

<u>spallation reaction</u>

collisions between nucleon (cascade)
→ increase “temperature”
→ evaporation (nucleon emission)



neutron emission favored over proton emission due to the absence of the Coulomb barrier

Production Rate Estimated by FLUKA

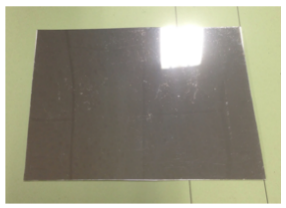
events/day/kton

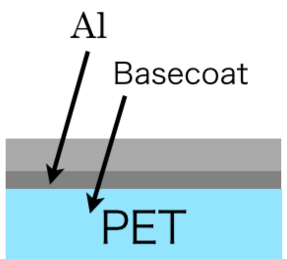
nuclei	rate_all	rate_ROI	$T_{1/2}$ (ns)
Y88	0.136	0.110	9.212E+15
Zr90m1	0.093	0.012	8.092E+08
Nb90	0.095	0.024	5.256E+13
Tc96	0.059	0.012	3.698E+14
Rh98	0.076	0.011	5.232E+11
Rh100	0.234	0.088	7.488E+13
Ag104	0.160	0.012	4.152E+12
Ag104m1	0.111	0.018	2.01E+12
In107	0.135	0.019	1.944E+12
In108	0.194	0.089	3.48E+12
In110	0.236	0.053	1.771E+13
In110m1	0.351	0.066	4.146E+12
Sn109	0.122	0.027	1.08E+12
Sb113	0.231	0.036	4.002E+11
Sb114	0.297	0.020	2.094E+11
Sb115	0.839	0.031	1.926E+12
Sb116	0.939	0.071	9.48E+11
Sb118	1.288	0.165	2.16E+11
Sb124	0.054	0.016	5.201E+15
Te115	0.124	0.012	3.48E+11
Te117	0.594	0.052	3.72E+12
I119	0.533	0.053	1.146E+12
I120	0.953	0.091	4.896E+12
I122	1.965	0.289	2.178E+11
I124	1.654	0.190	3.608E+14
I130	1.635	0.269	4.45E+13
I132	0.441	0.152	8.262E+12
I134	0.194	0.046	3.15E+12
Xe121	0.540	0.100	2.406E+12
Cs125	0.266	0.012	2.802E+12
Cs126	0.080	0.011	9.84E+10
Cs128	0.229	0.031	2.196E+11
Total	330.845	**2.427**	

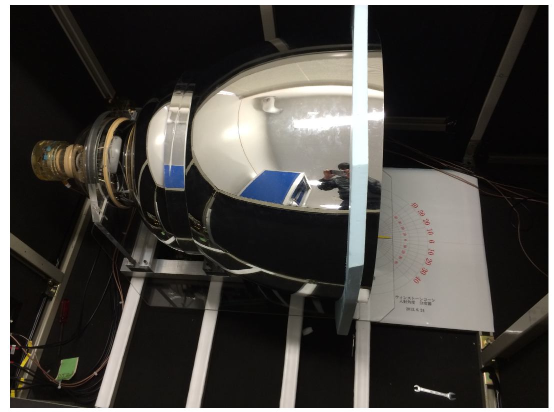
Light Yield Increase by Mirror

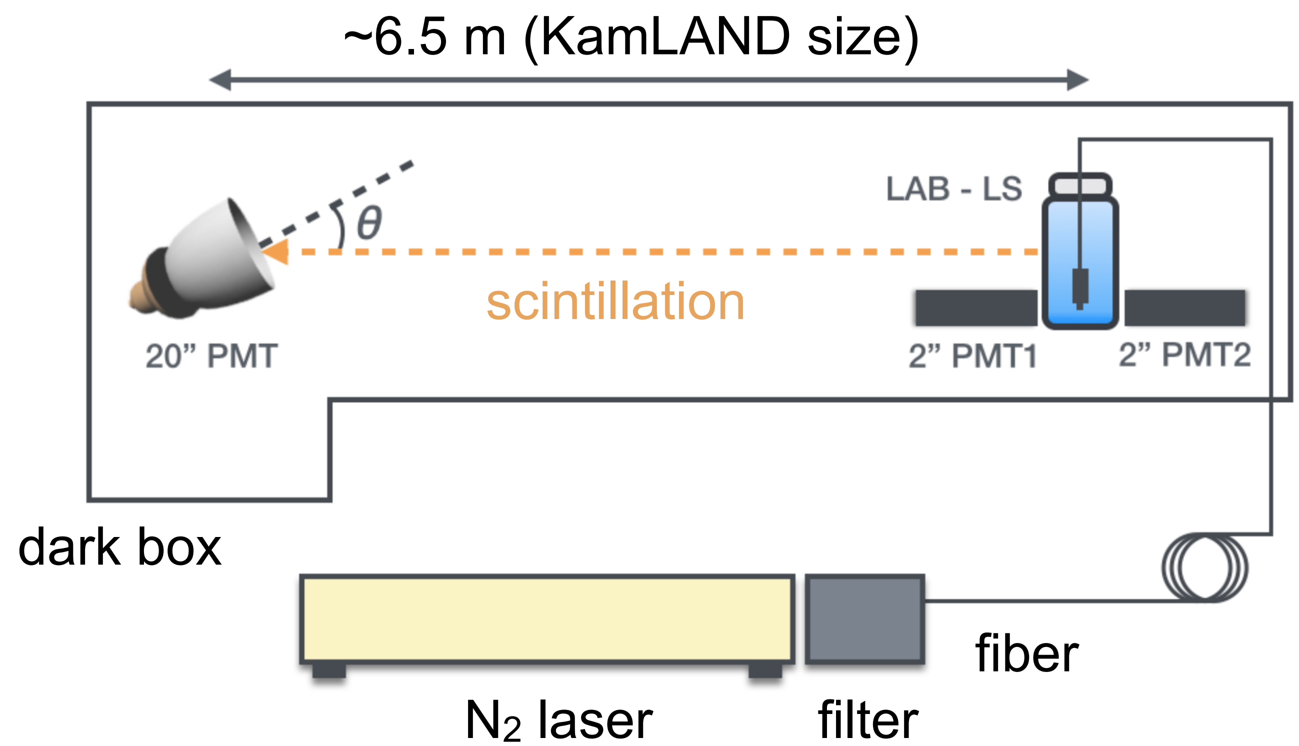
aluminum + PET mirror with high reflectivity

mirror sample

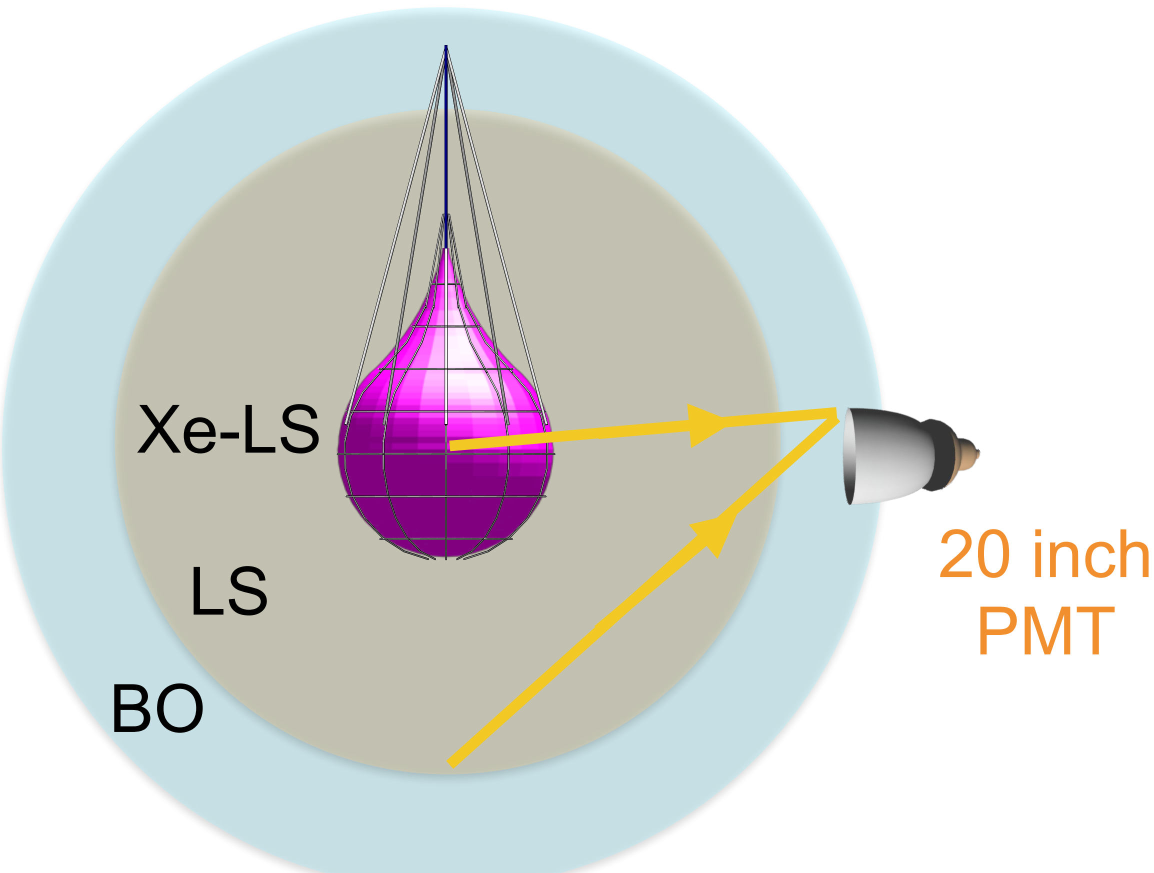


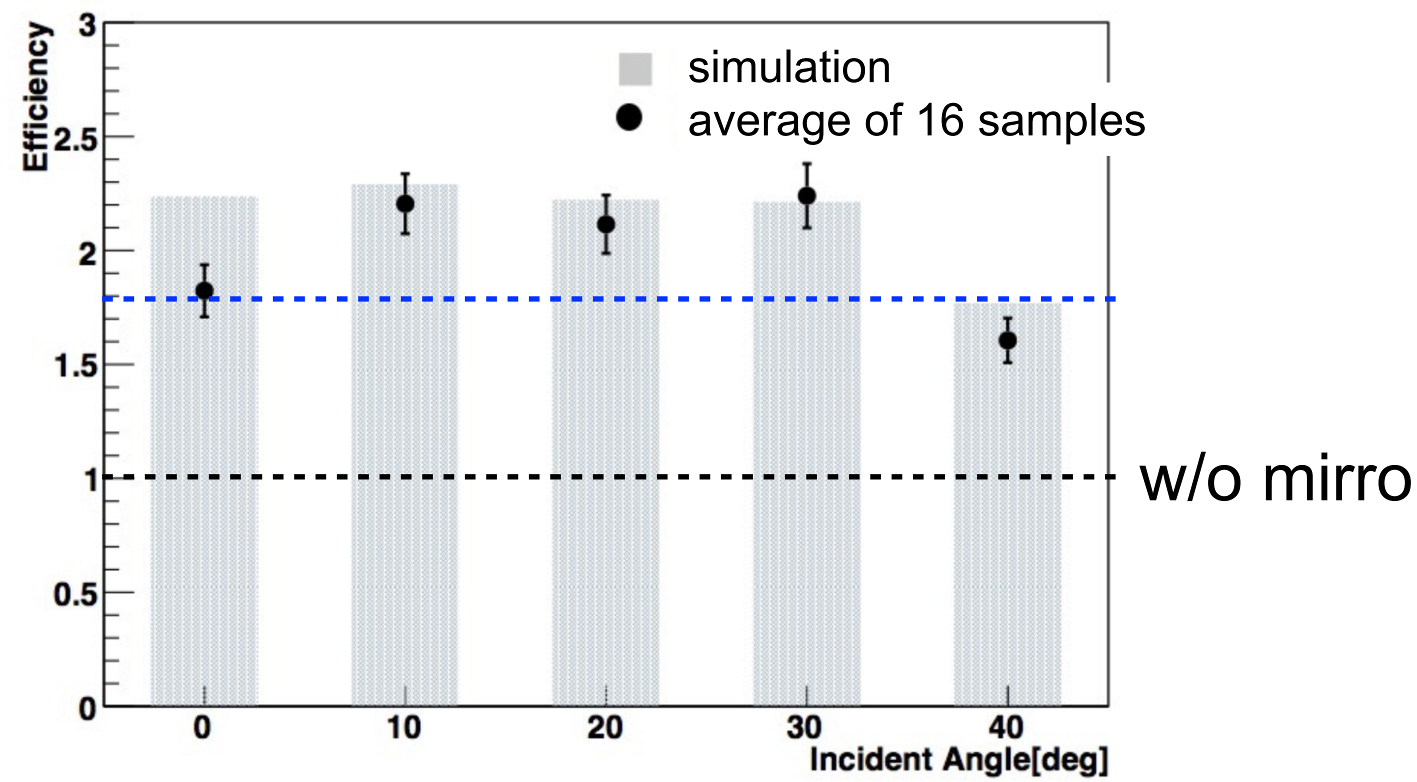






KamLAND2-Zen



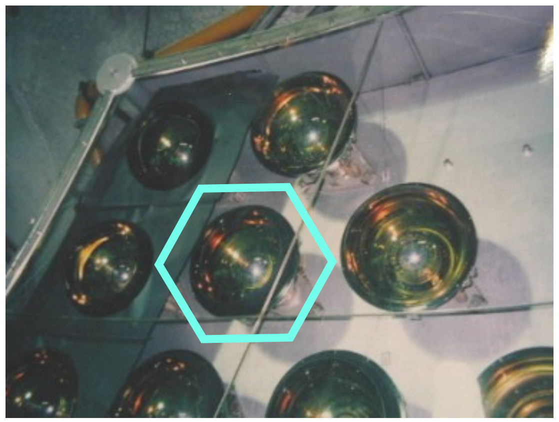


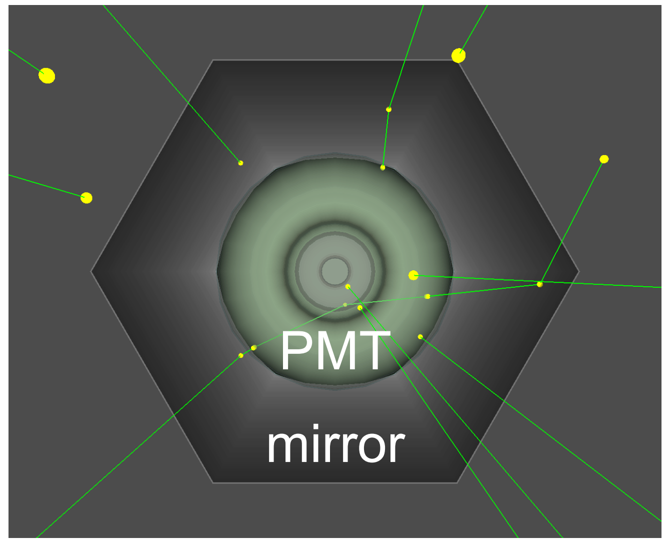
LS : 13 m diameter

~1.8 times increase of light yield

Mirror Shape Optimization

20 inch PMT
coverage 34%





light yield ~ photo-coverage

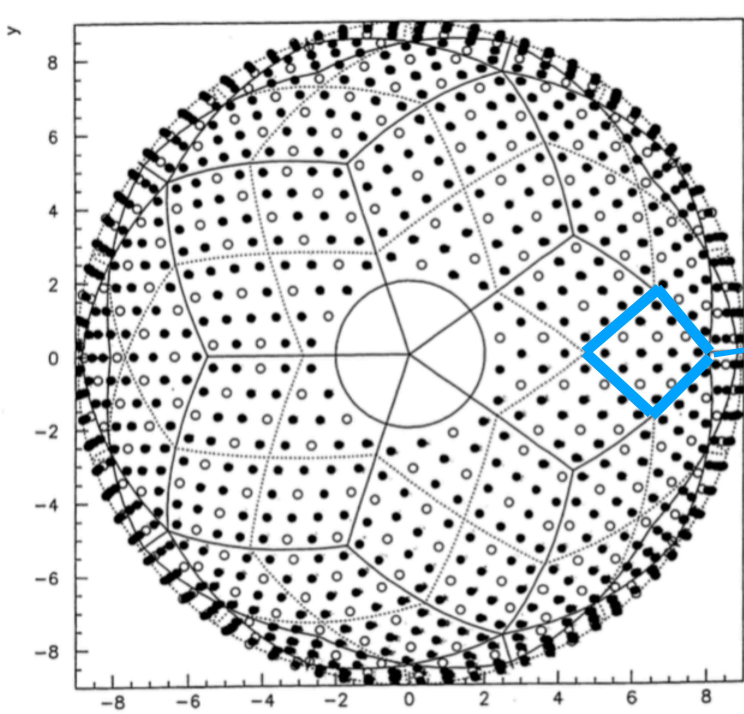
hexagon entrance → circle exit

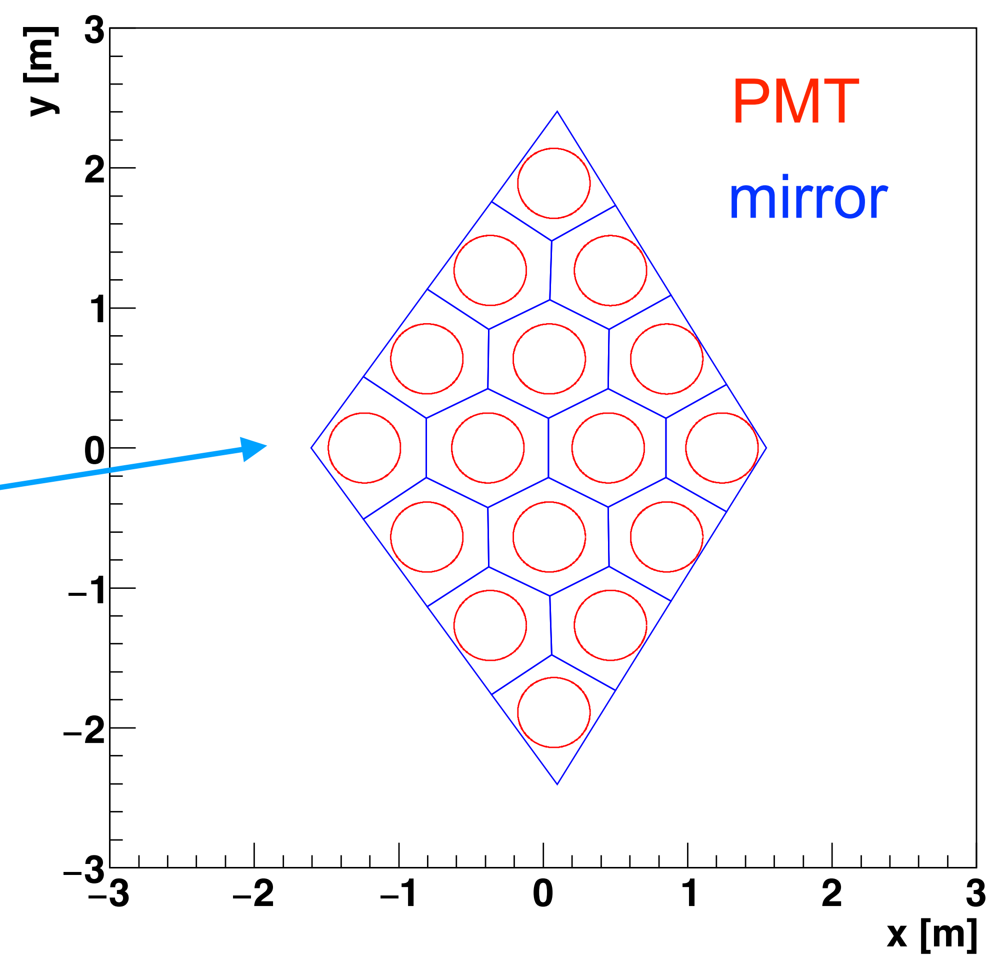
flexible shape construction was achieved by G4TessellatedSolid method in Geant4

polygon entrance → circle exit

further reduction of dead space

top view of KamLAND





mirror shape
in 4 × 4 face

4 hexagons
10 pentagons
2 squares

PMT with mirror

↓

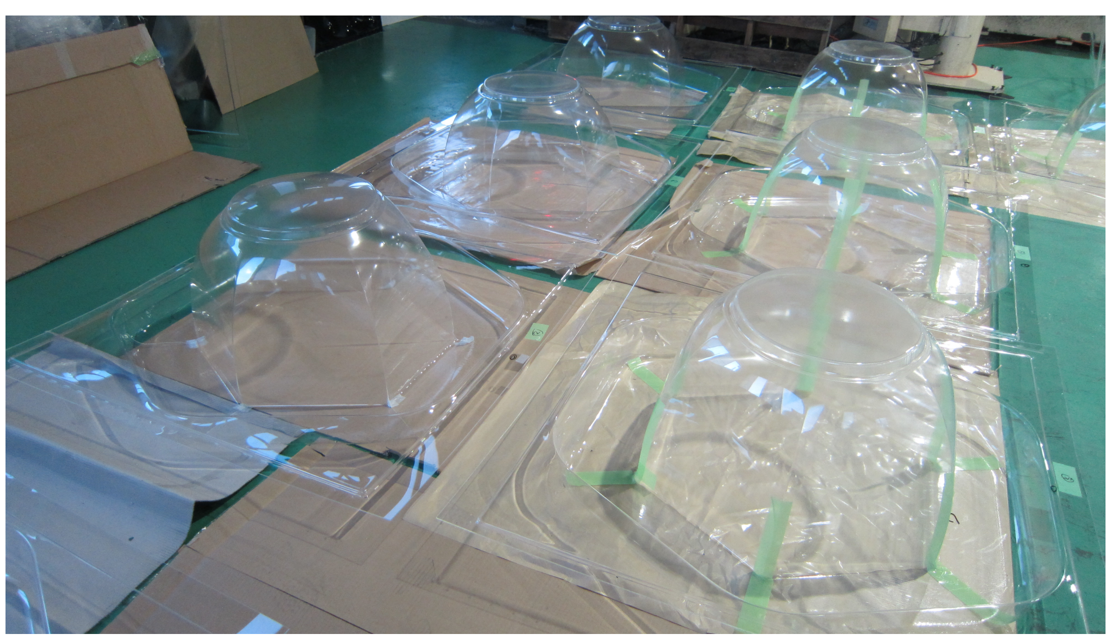
coverage ~ 100%

Mirror Production

Resin mold

↓

Shaped acrylic



↗

Aluminum vapor deposition