KamLAND-Zen Status and Future Prospects

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On Behalf of the KamLAND-Zen Collaboration

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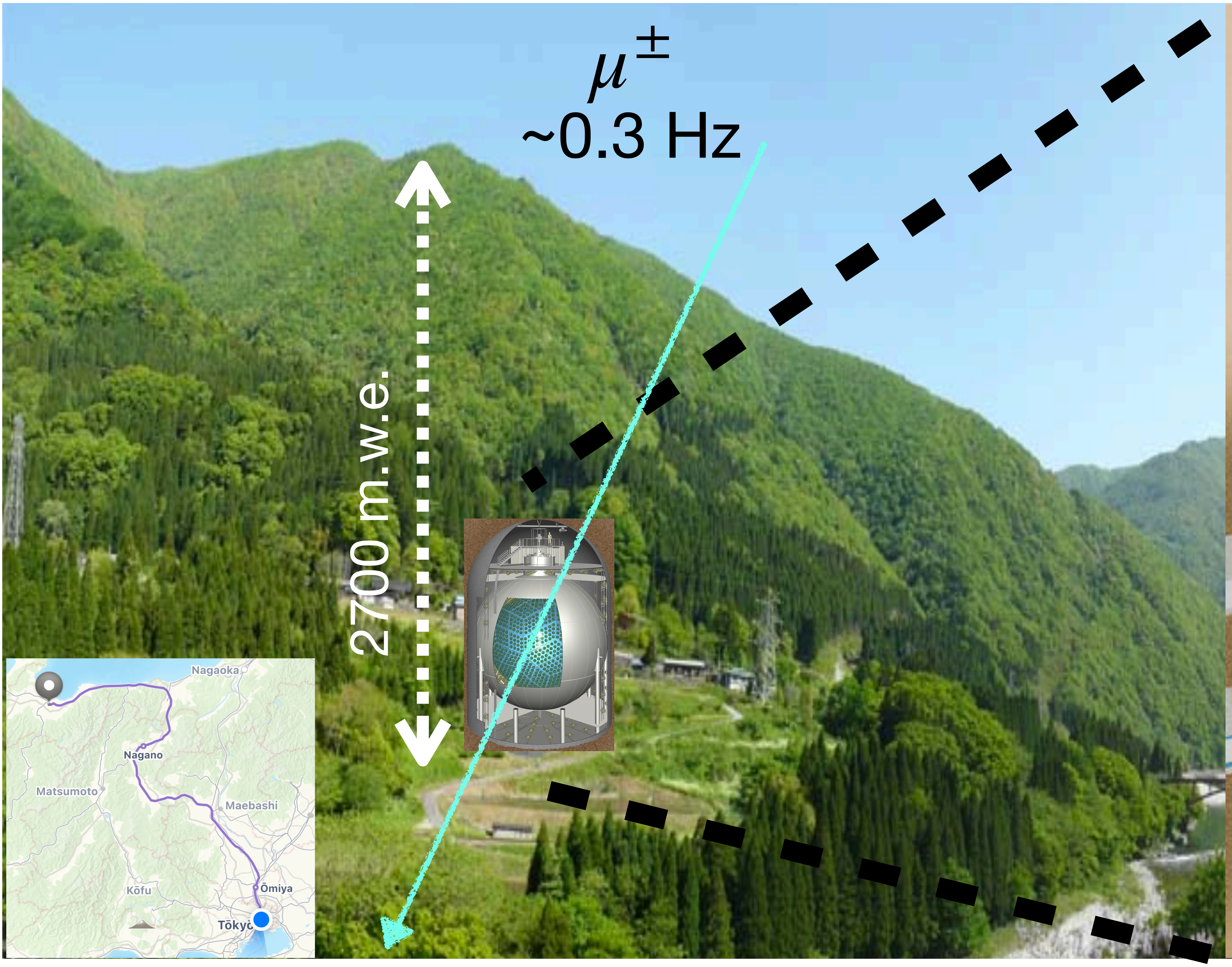
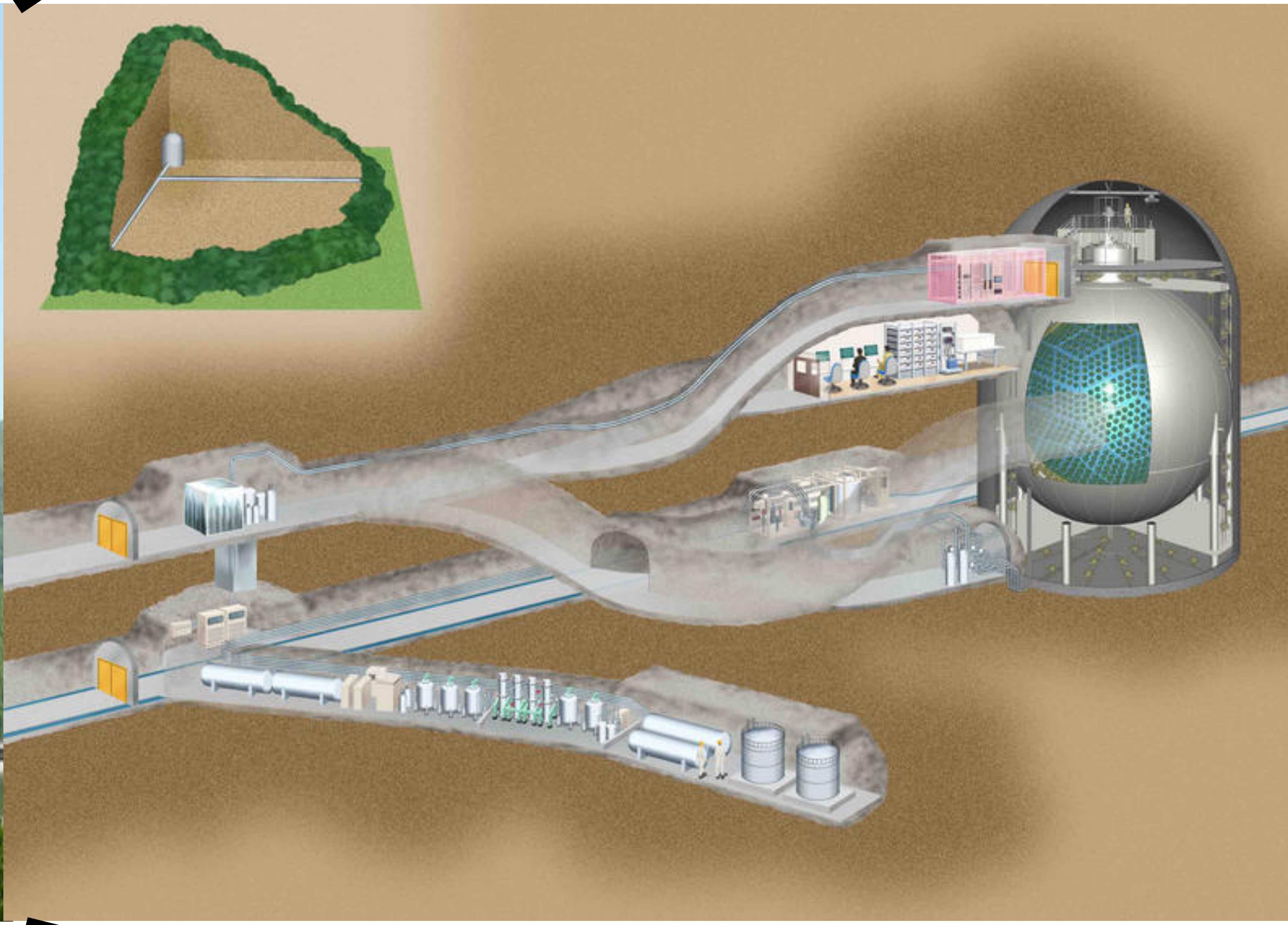
KamLAND-Zen Collaboration Meeting March 2025 @Miyagi, Japan

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
UNIVERSITY of HAWAI'I
VT VIRGINIA TECH.
BU BOSTON UNIVERSITY
Nikhef

KamLAND = Kamioka Liquid Scintillator $\bar{\nu}_e$ Detector

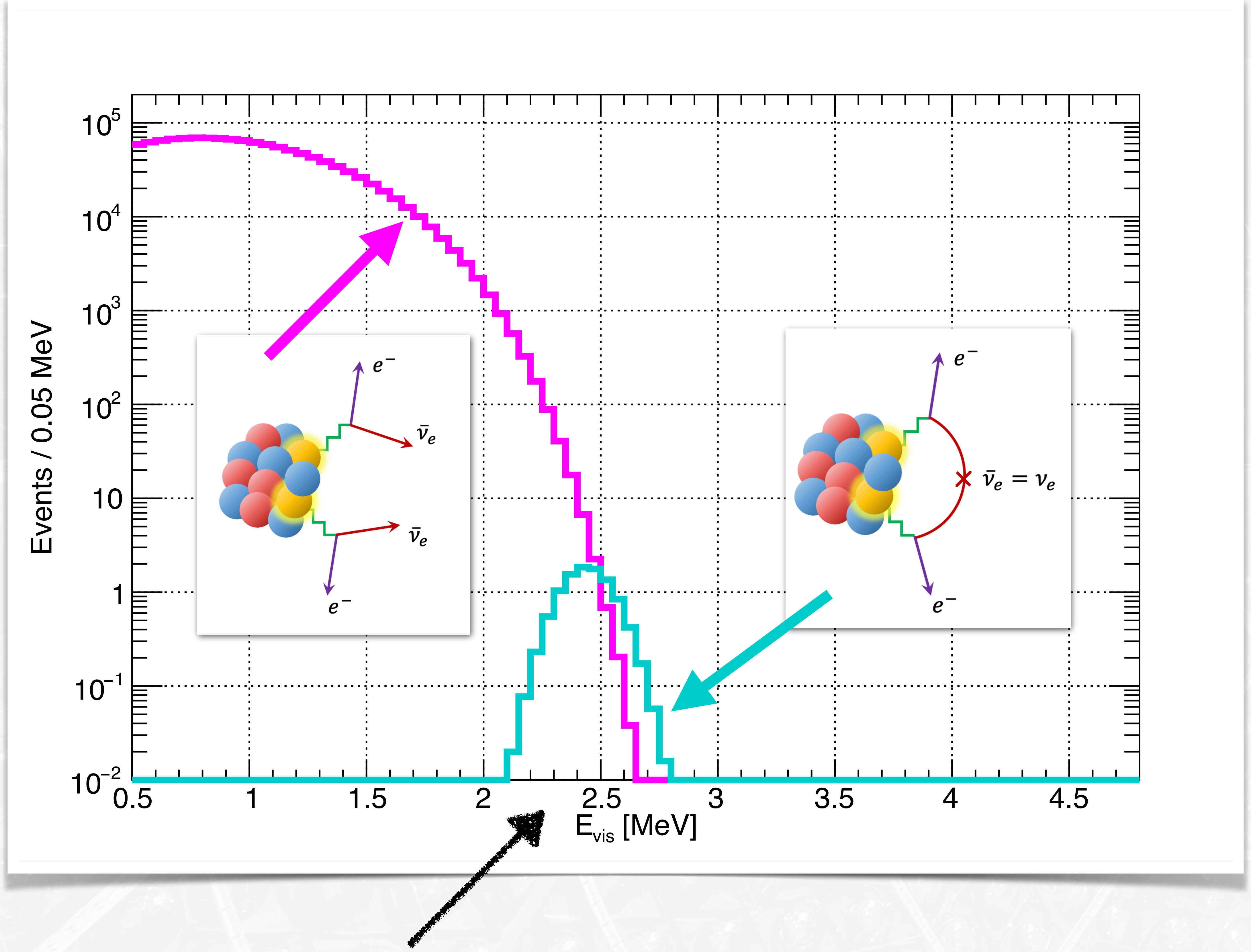




1 kton detector originally built for reactor neutrino detection

From KamLAND to KamLAND-Zen

^{136}Xe Double Beta Decay - Candidate for Neutrinoless Double Beta Decay



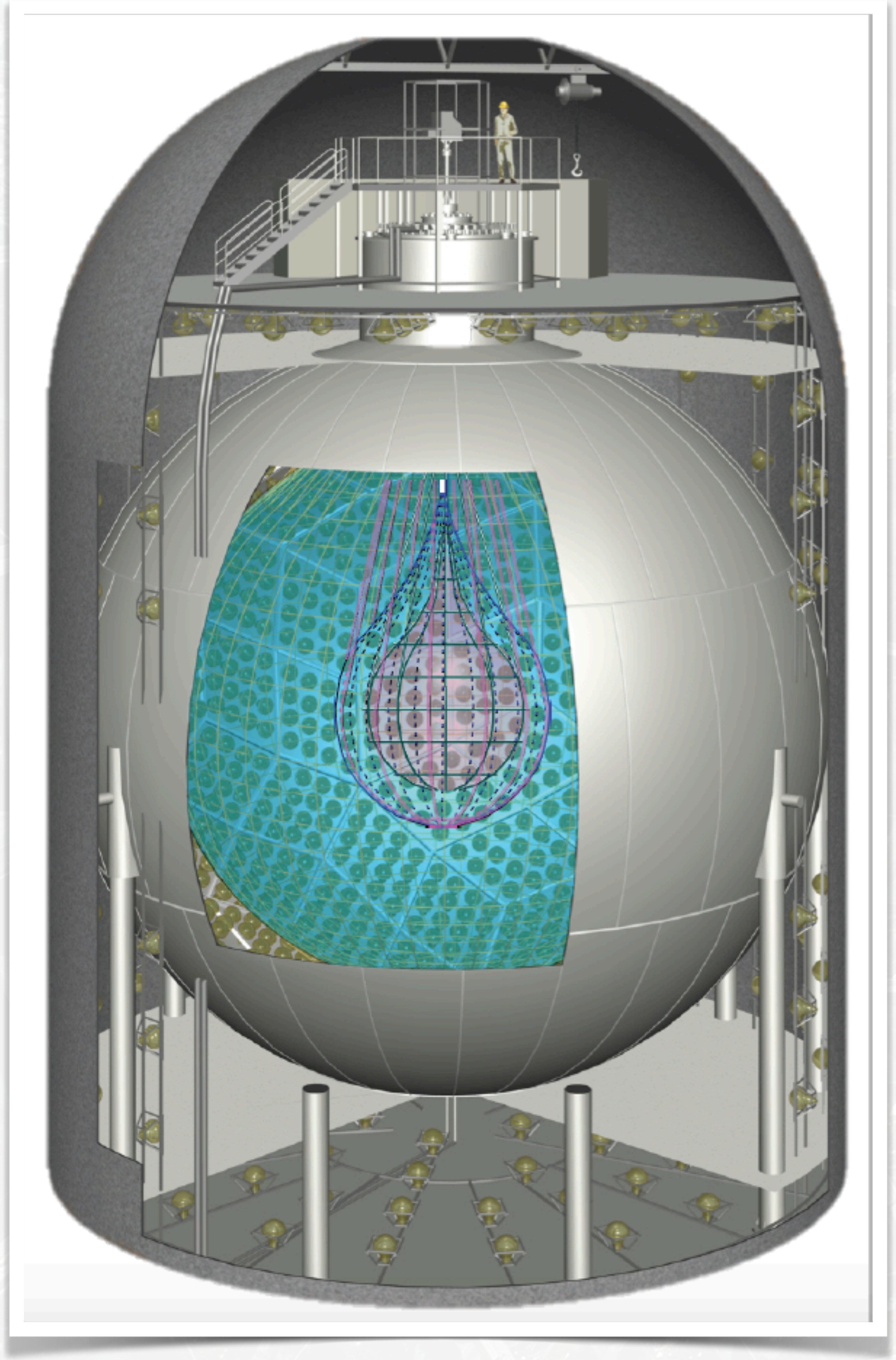
- Xenon as a noble gas
- Capable of being highly enriched
- Can be dissolved directly into liquid scintillator (LS)
- Clean, recoverable, reusable

$Q_{\beta\beta}(^{136}\text{Xe}) = 2.458$ MeV

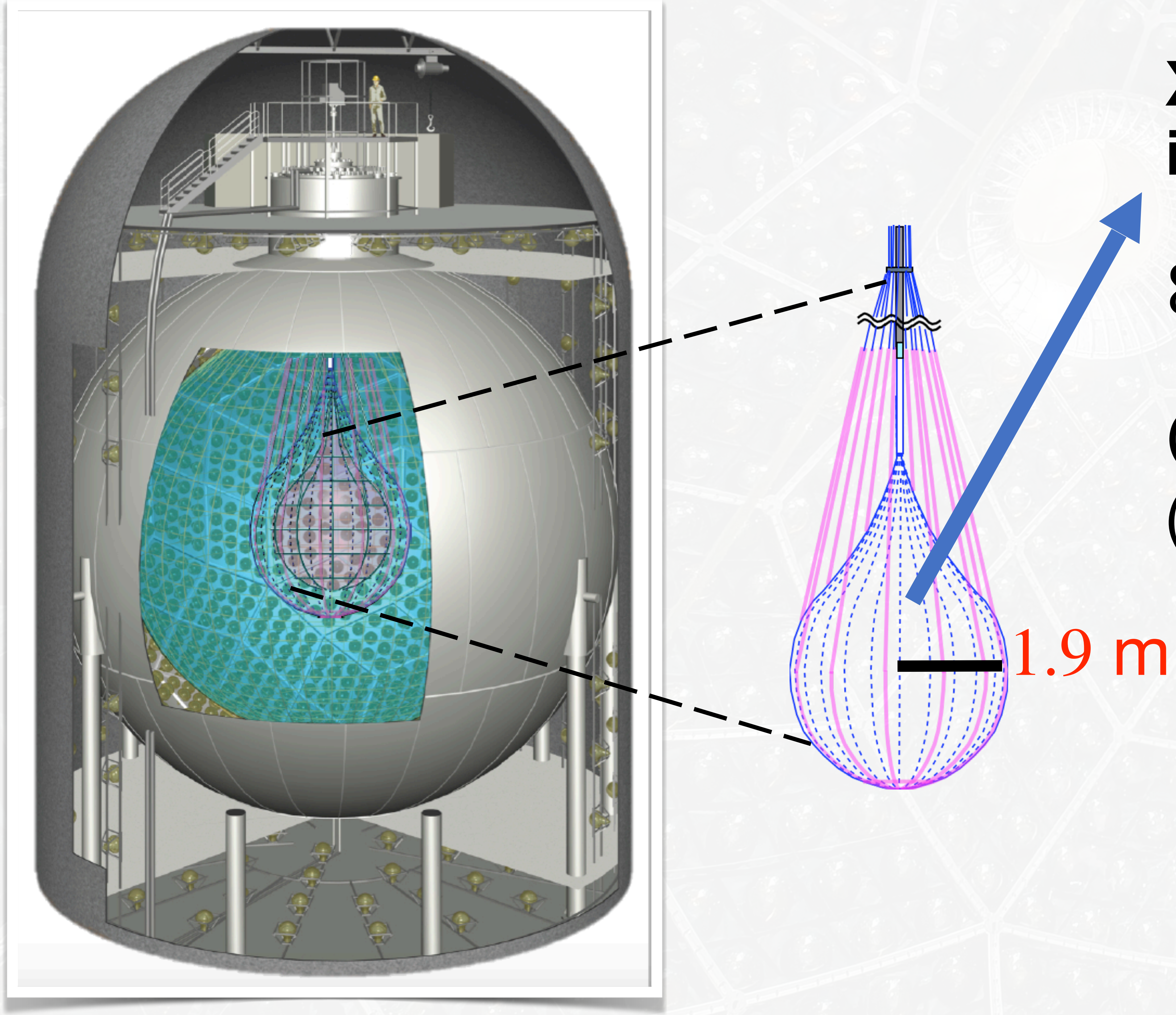
($2\nu\beta\beta$ endpoint appears larger here due to detector response)

Poster 2/441
So Young Jeon

Turning KamLAND into a $0\nu\beta\beta$ Detector



Turning KamLAND into a $0\nu\beta\beta$ Detector

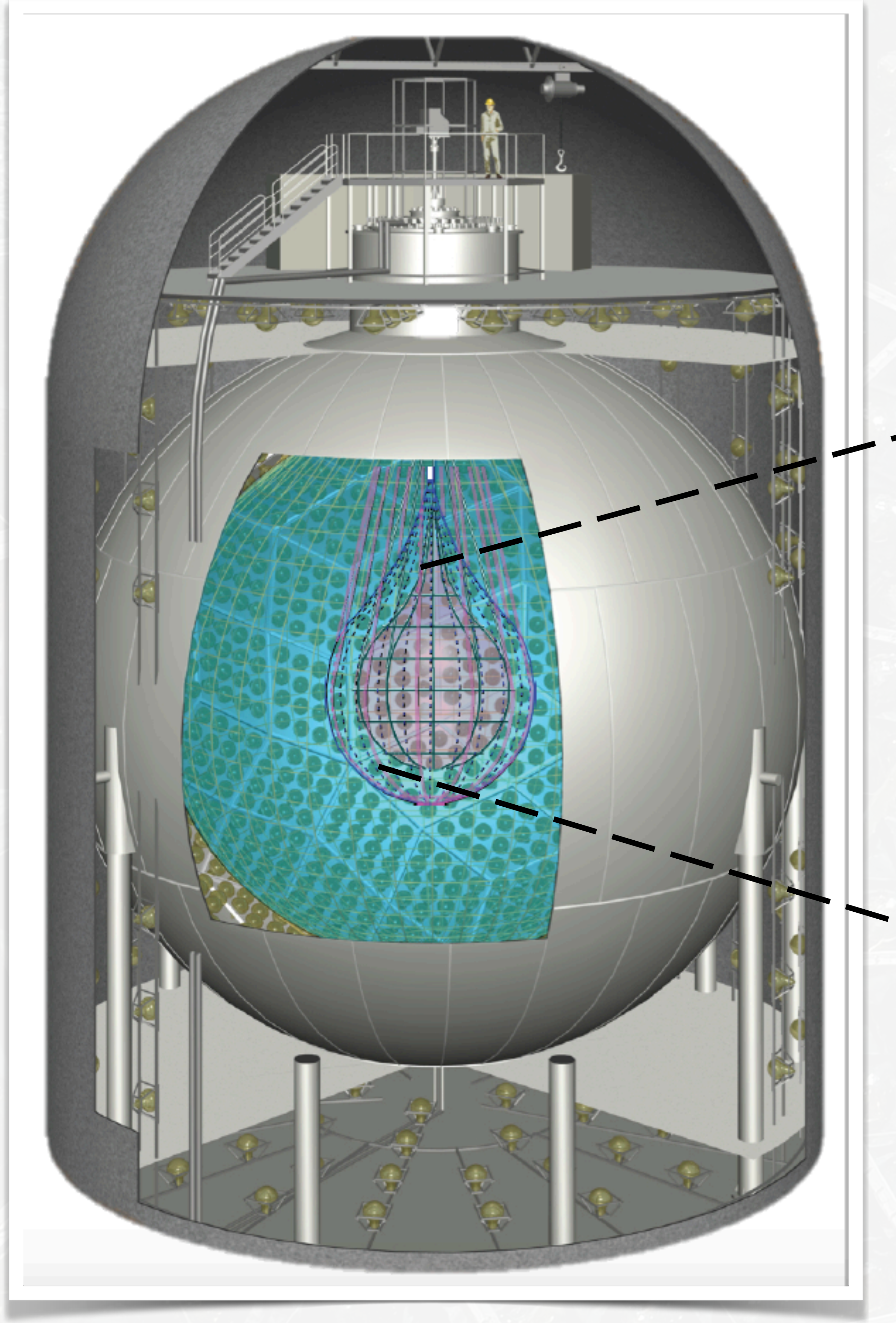


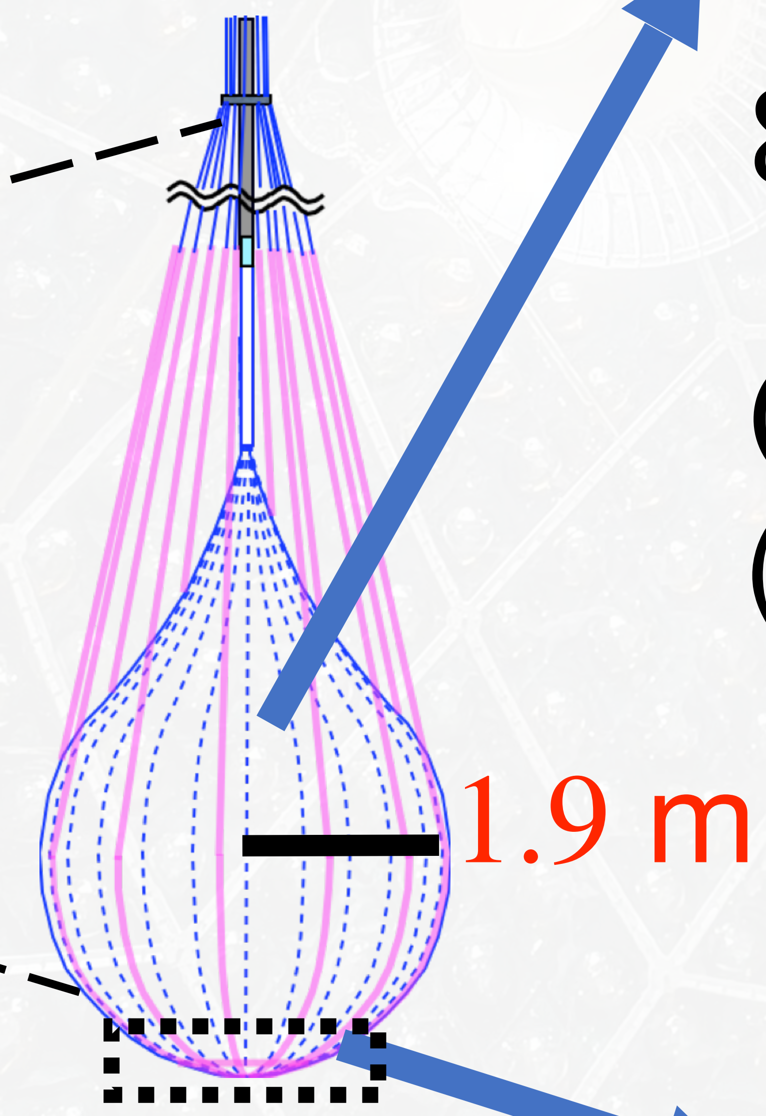
Xenon Liquid Scintillator inside Inner Balloon

$82\,\%$ Decane + $18\,\%$ Pseudocumene + 2.4 g/L PPO

(3.13 ± 0.01)%weight with 745 kg xenon gas ($90.85\,\%$ ^{136}Xe)

Turning KamLAND into a $0\nu\beta\beta$ Detector





Xenon Liquid Scintillator inside Inner Balloon

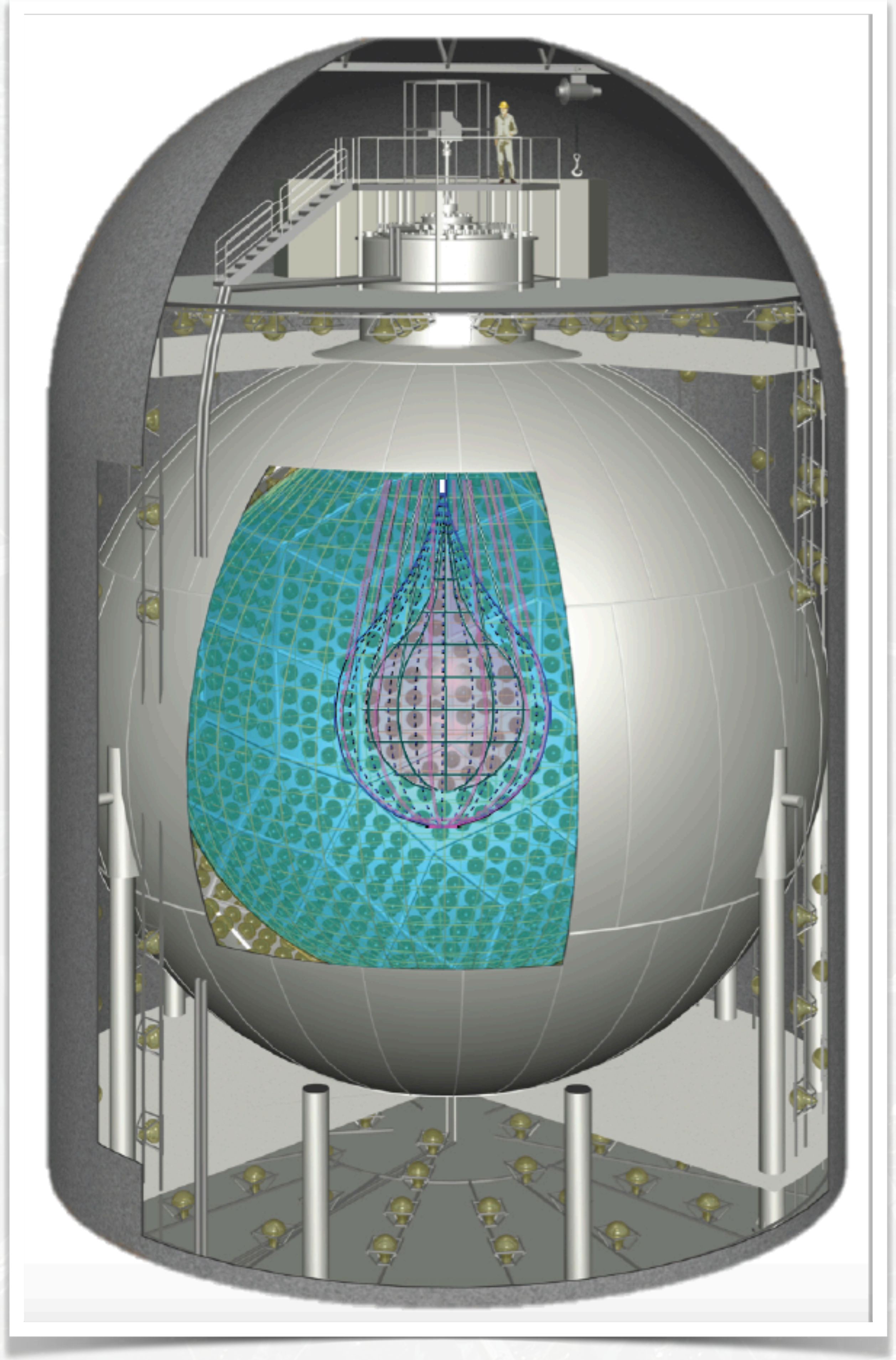
$82\,\%$ Decane $+\,18\,\%$ Pseudocumene $+\,2.4$ g/L PPO

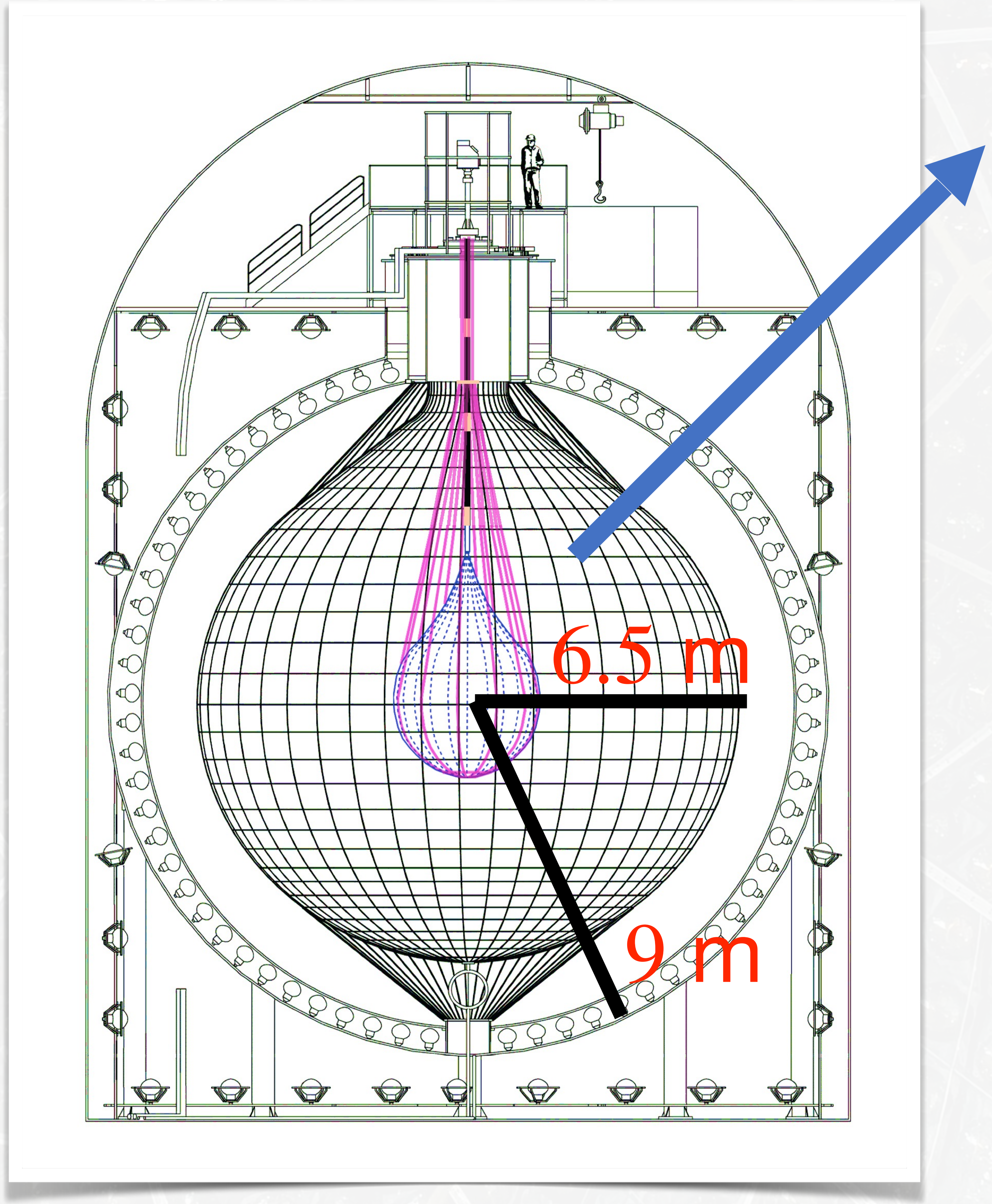
(3.13 ± 0.01)%weight with 745 kg xenon gas ($90.85\,\%$ ^{136}Xe)

Inner Balloon Film

$25\,\mu$m Nylon Film

Turning KamLAND into a $0\nu\beta\beta$ Detector

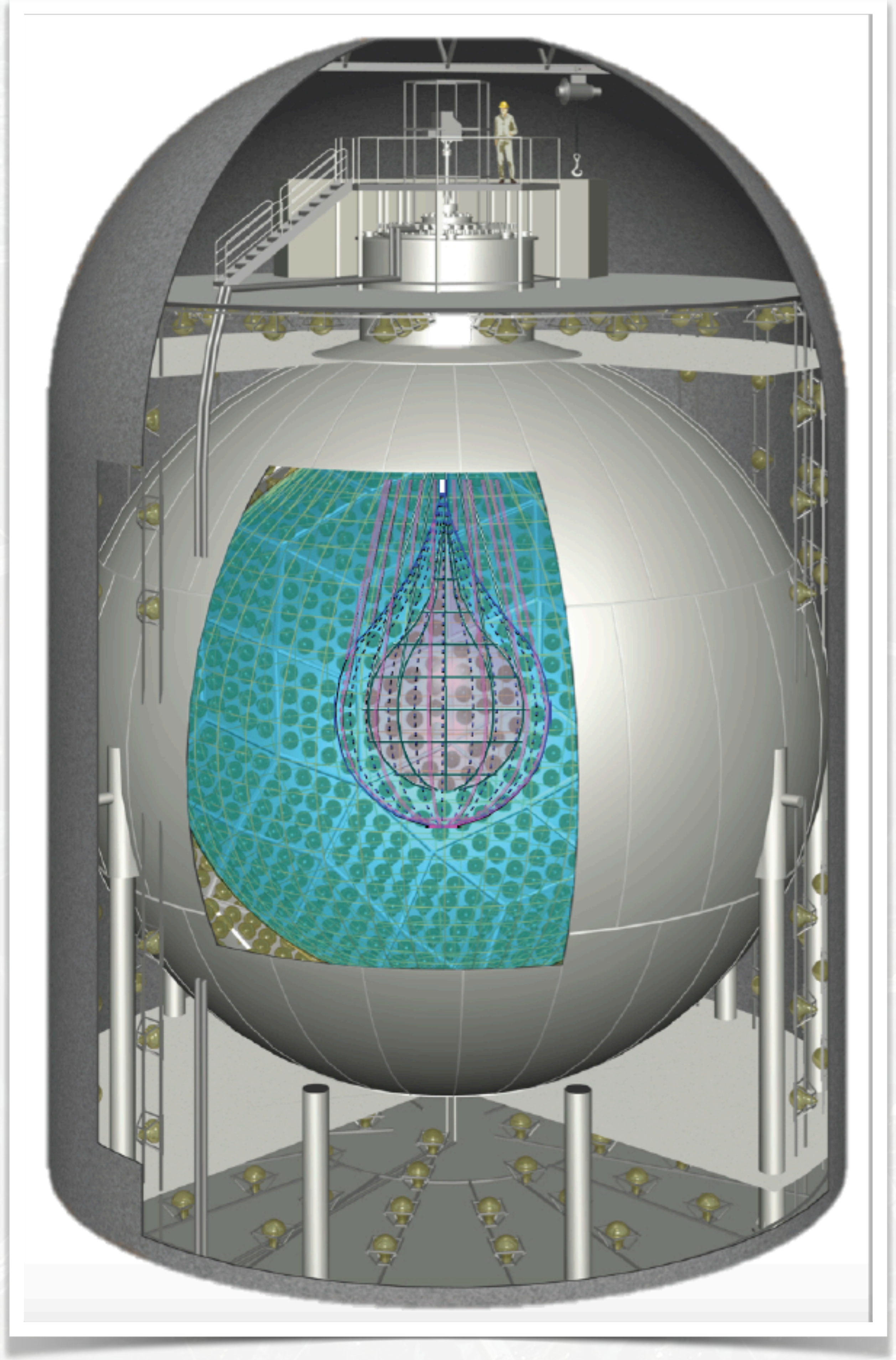


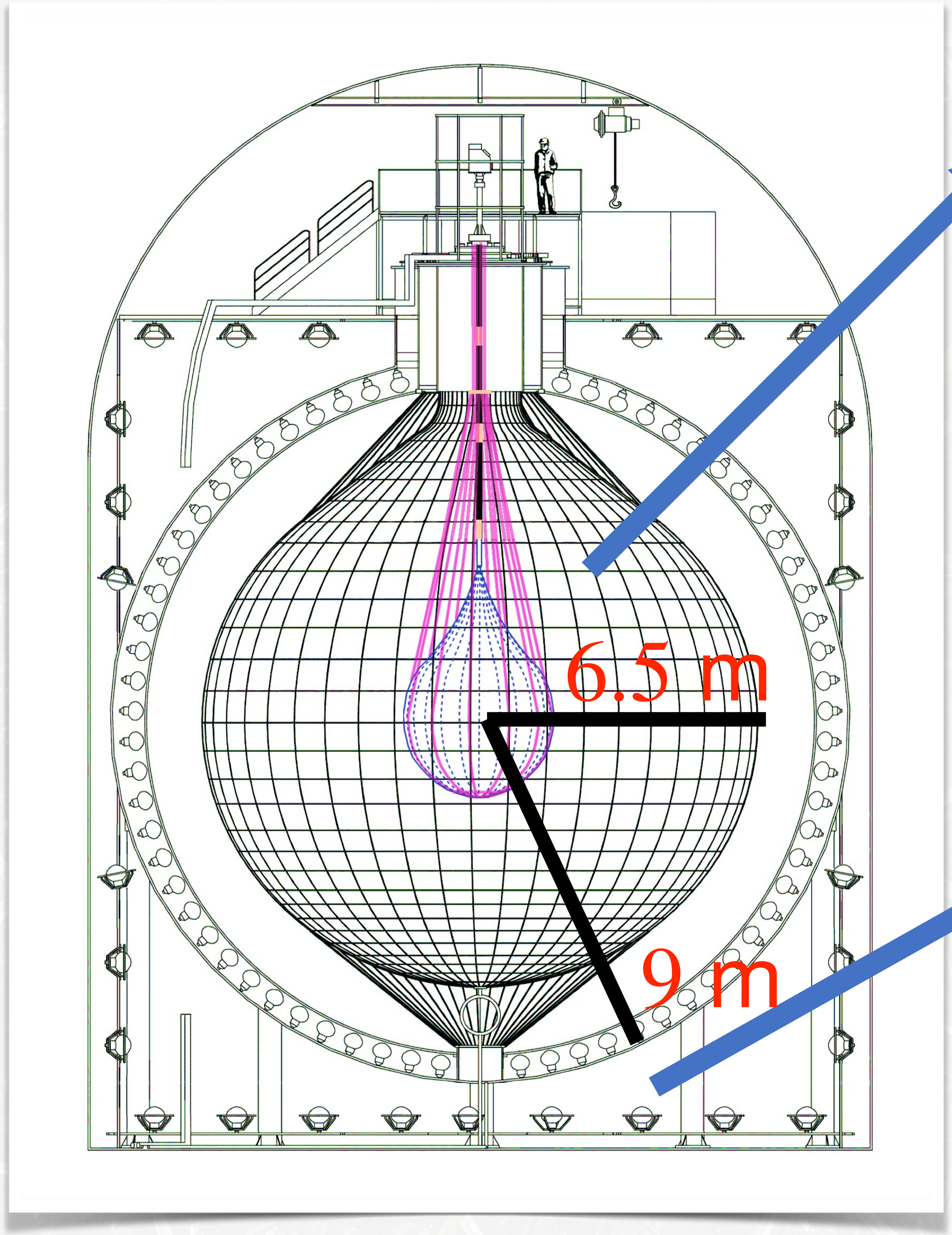


KamLAND Liquid Scintillator

1 kton liquid scintillator
made of $80\,\%$ dodecane
+ $20\,\%$ pseudocumene
+ 1.36 g/L PPO

Turning KamLAND into a $0\nu\beta\beta$ Detector





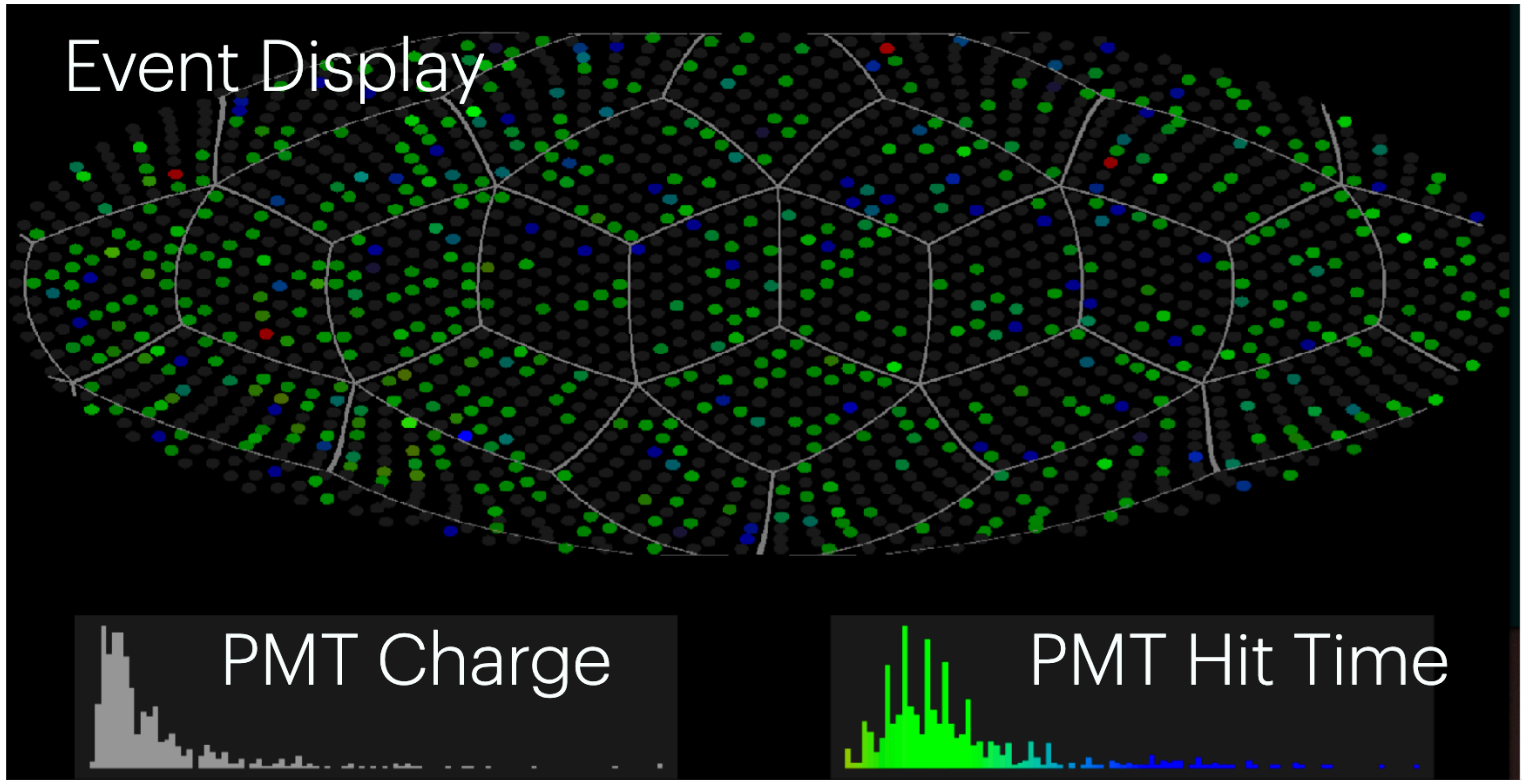
KamLAND Liquid Scintillator

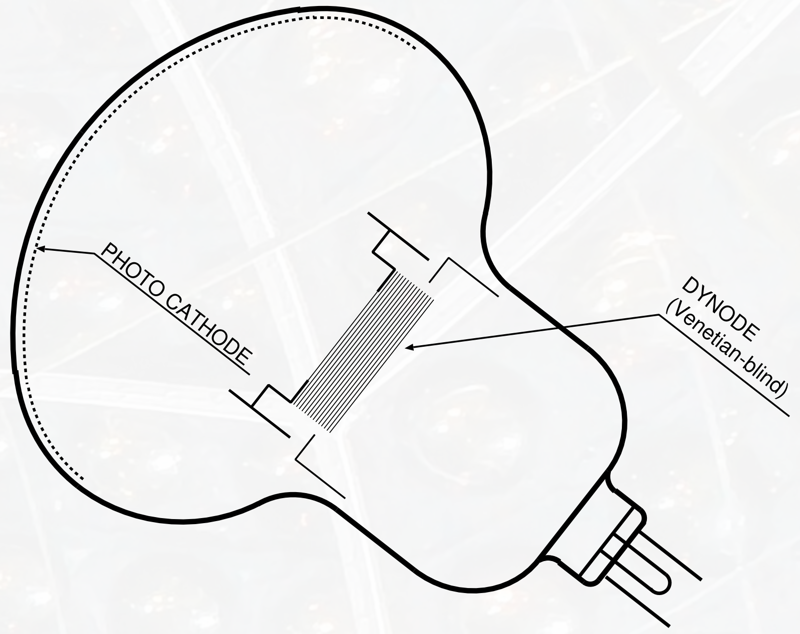
1 kton liquid scintillator made of 80 % dodecane + 20 % pseudocumene + 1.36 g/L PPO

Water Cherenkov (Veto) Detector

3.2 kton water for muon veto

Turning KamLAND into a $0\nu\beta\beta$ Detector





Light Yield =
500 photoelectrons / MeV

Photo-Multiplier-Tubes (PMTs) =
17“(1325) + 20“(554)

Resolutions

Energy $\rightarrow \frac{\sigma_E}{E} \sim$ 6.7% / $\sqrt{E}$ [MeV]

Vertex $\rightarrow \frac{\sigma_R}{E} \sim$ 13.7 cm / $\sqrt{E}$ [MeV]

PMT
Charge
Timing
Occupancy
...

→

Event Reconstruction
Vertex (x,y,z)
(visible) Energy
Particle Identification

KamLAND-Zen *Timeline*

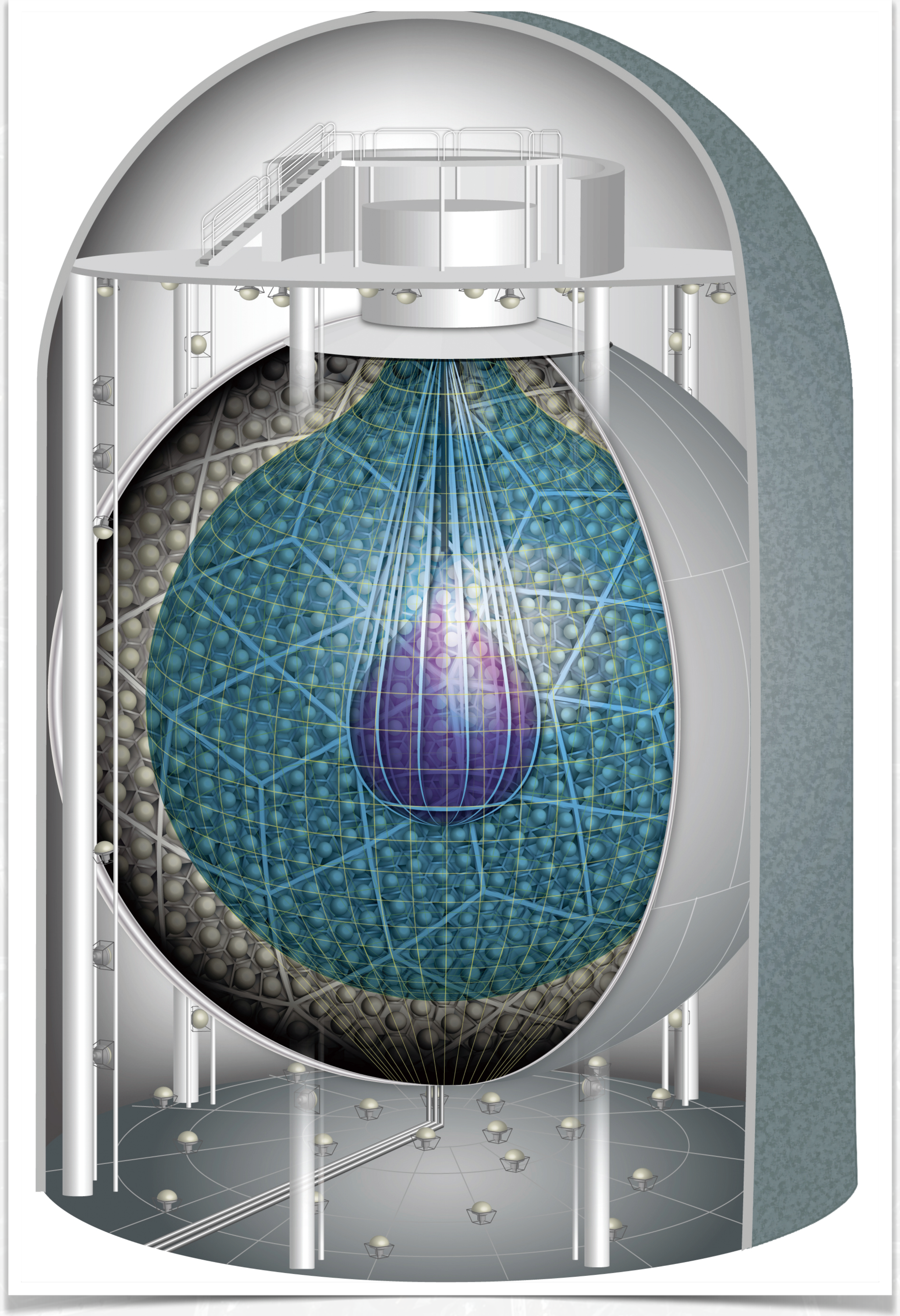
2011 – 2012: KL-Zen 400 Phase-I — $89.5 \cdot \mathbf{kg} \cdot \mathbf{yr}$

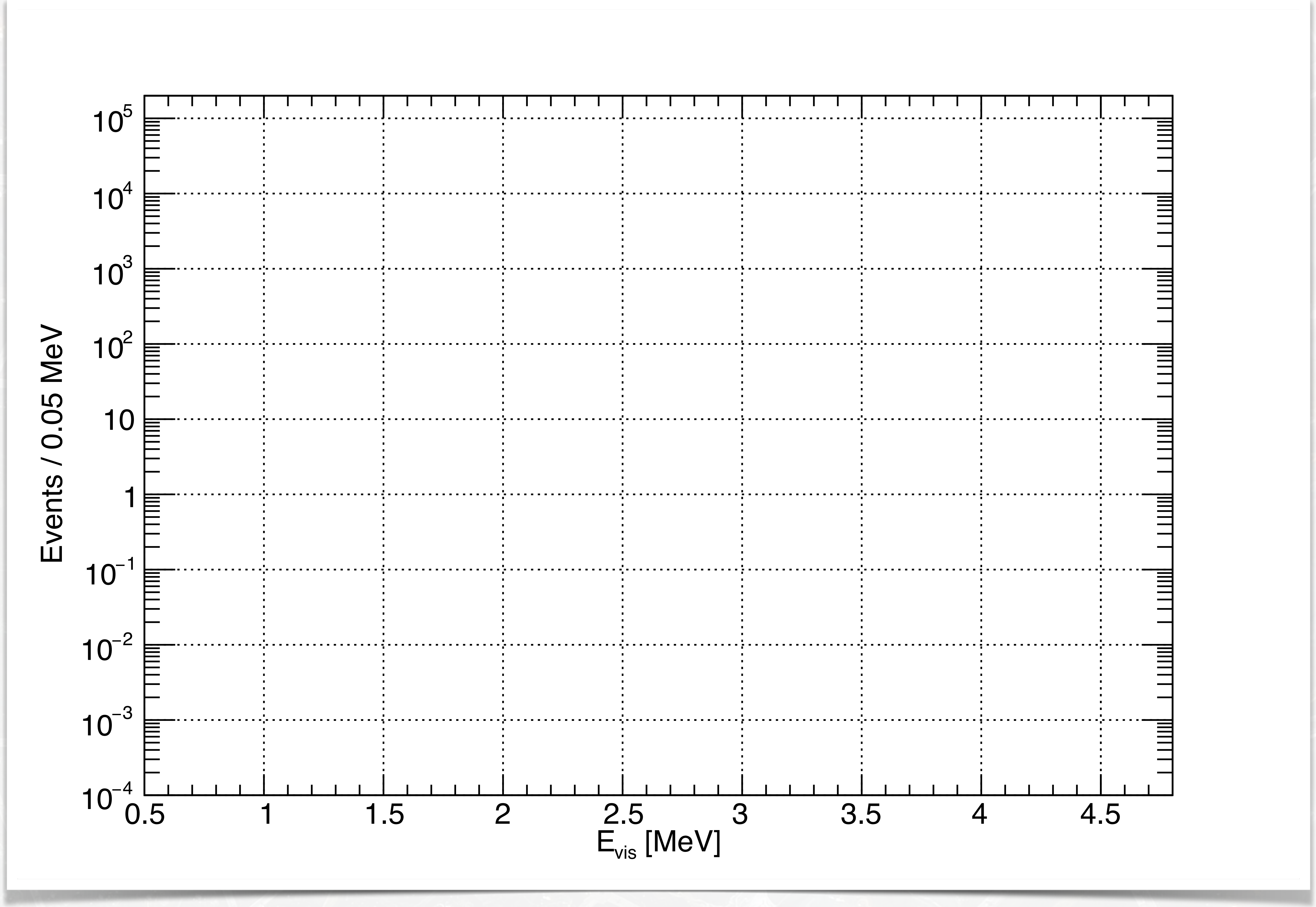
2013 – 2015: KL-Zen 400 Phase-II — $493.5 \cdot \mathbf{kg} \cdot \mathbf{yr}$

2019 – 2024: KL-Zen 800 Phase-III — $2097 \cdot \mathbf{kg} \cdot \mathbf{yr}$

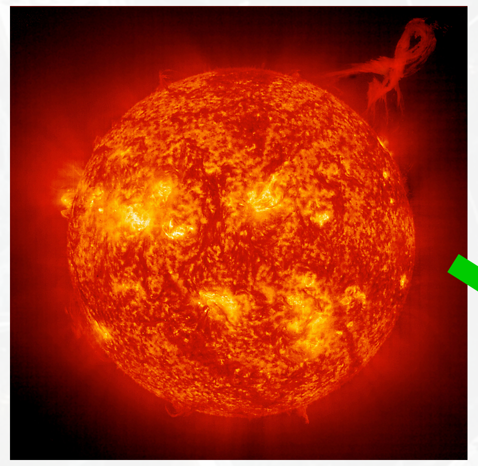
Now: KL2-Zen Construction — DAQ → 2028

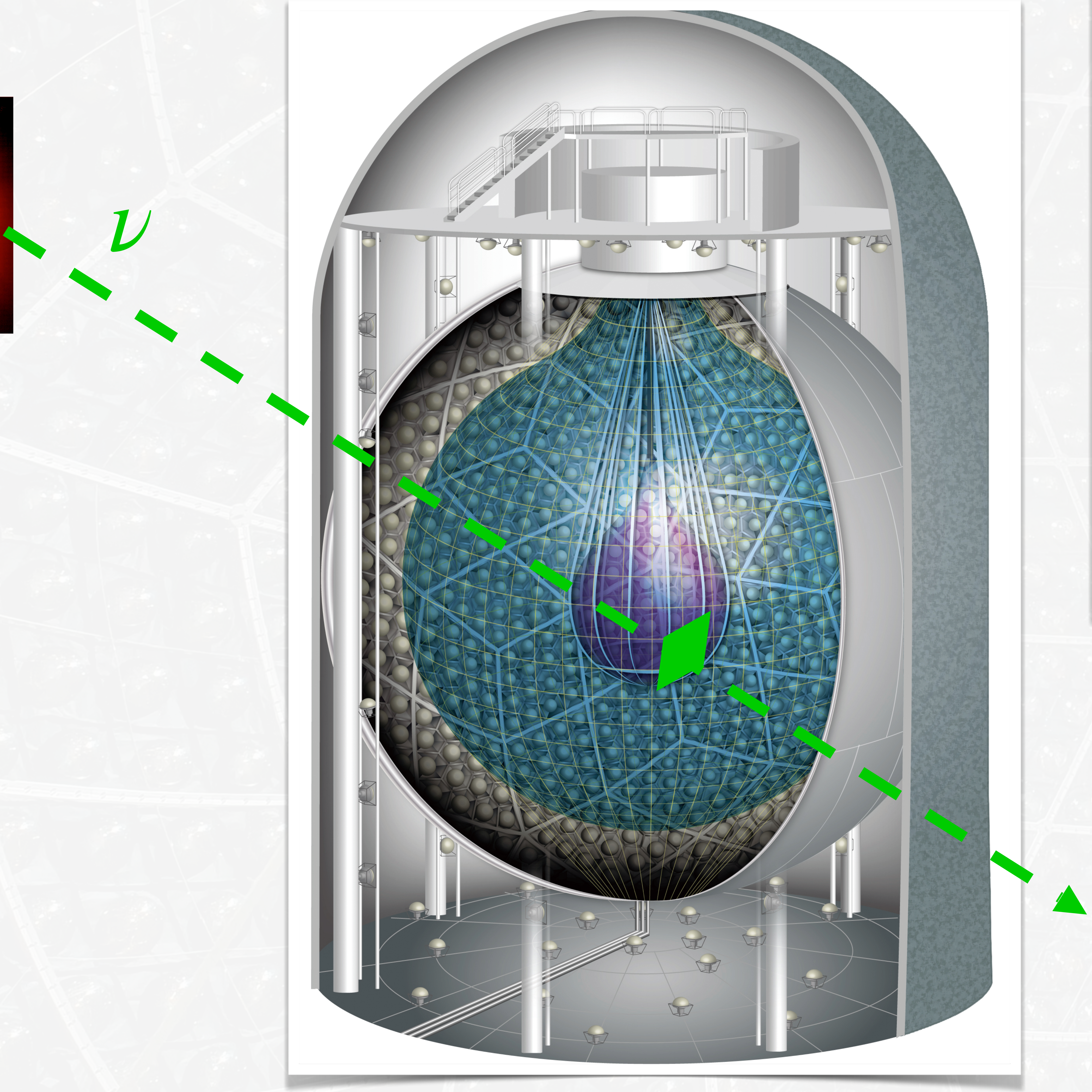
$0\nu\beta\beta$ Backgrounds

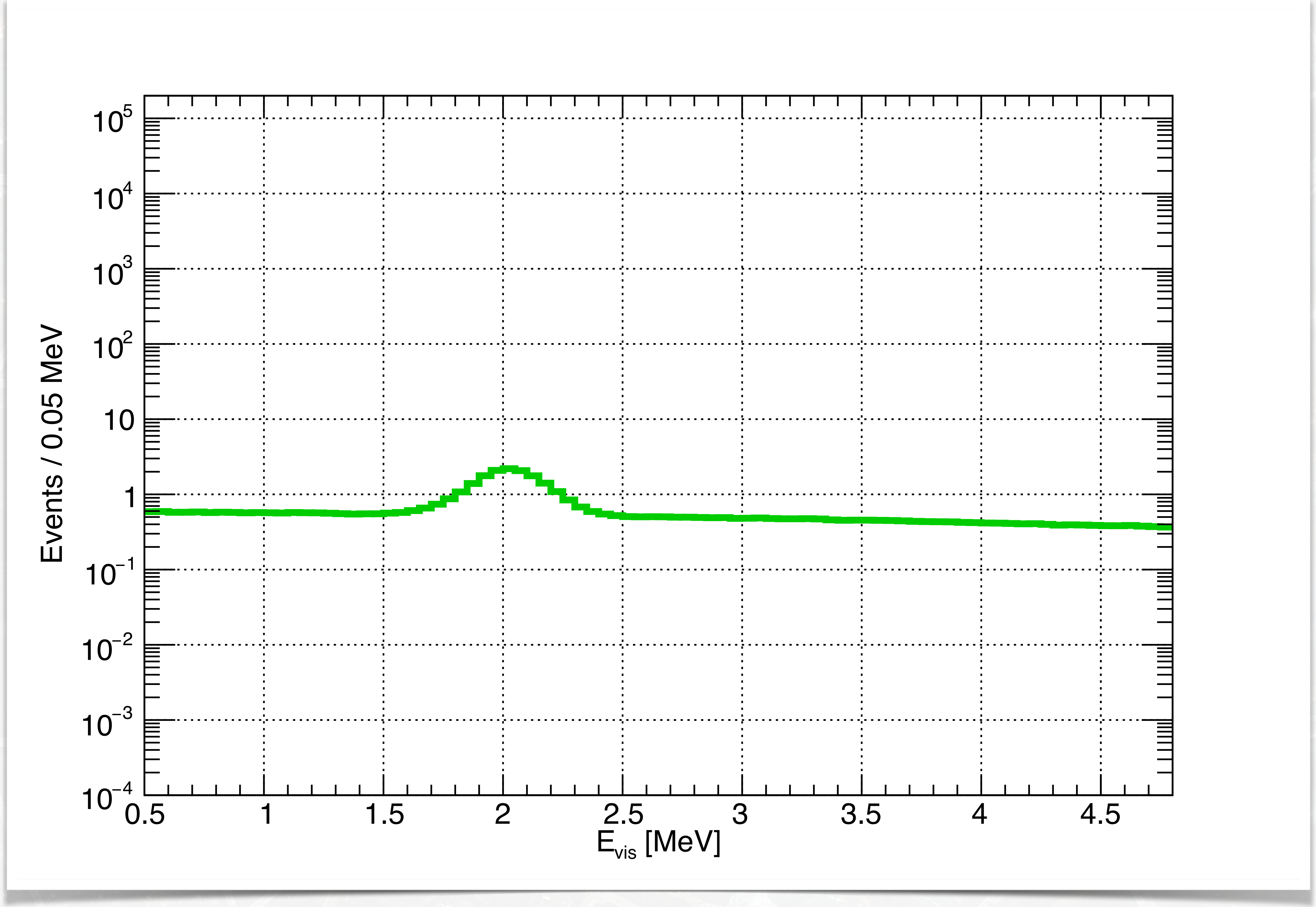




$0\nu\beta\beta$ Backgrounds

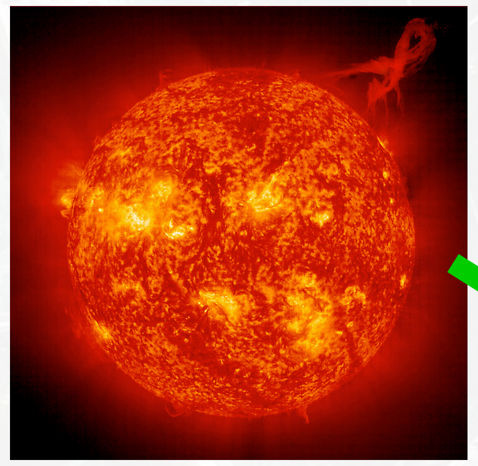


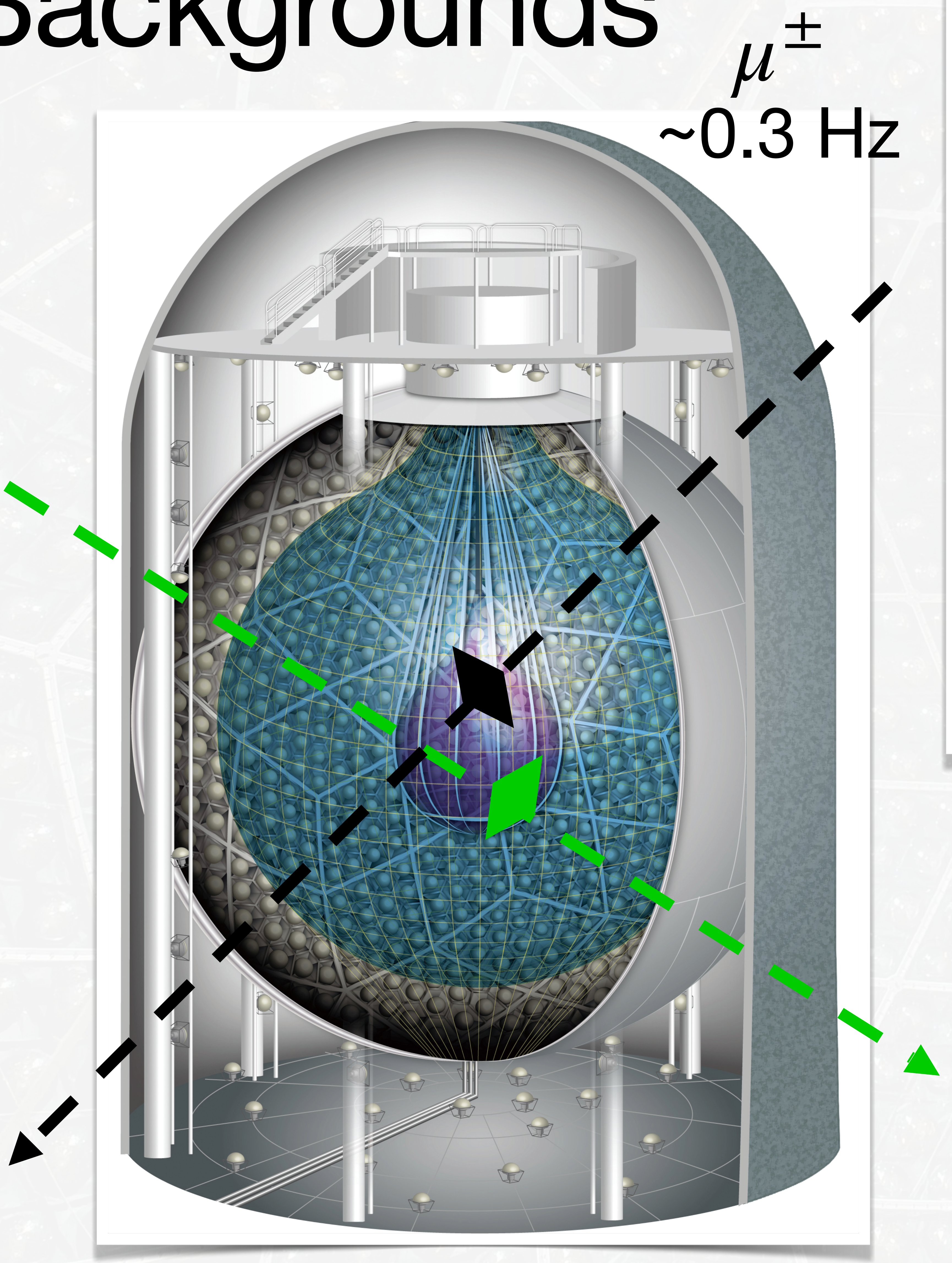


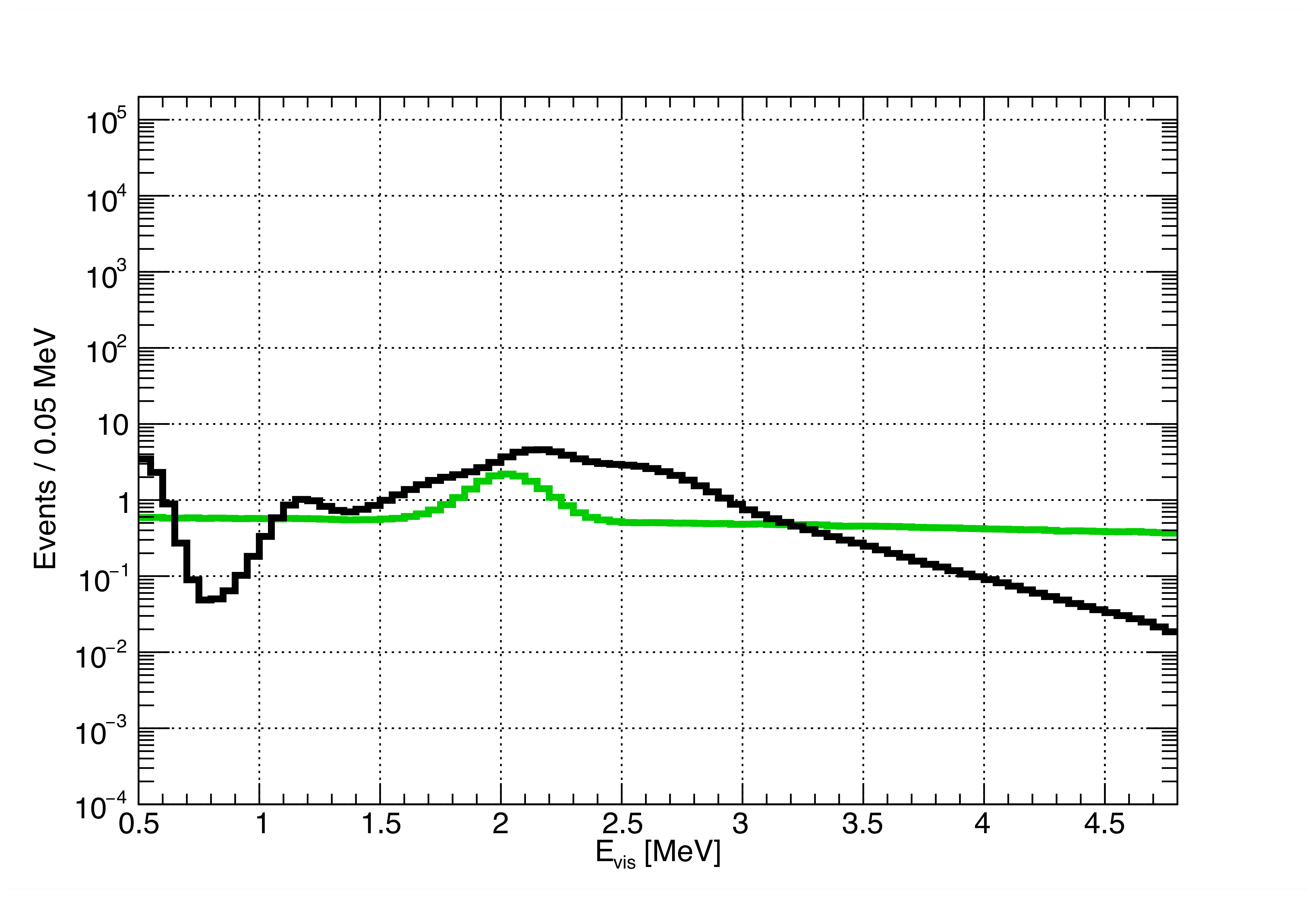


- **Solar Neutrino Interactions (ES+CC)**

$0\nu\beta\beta$ Backgrounds

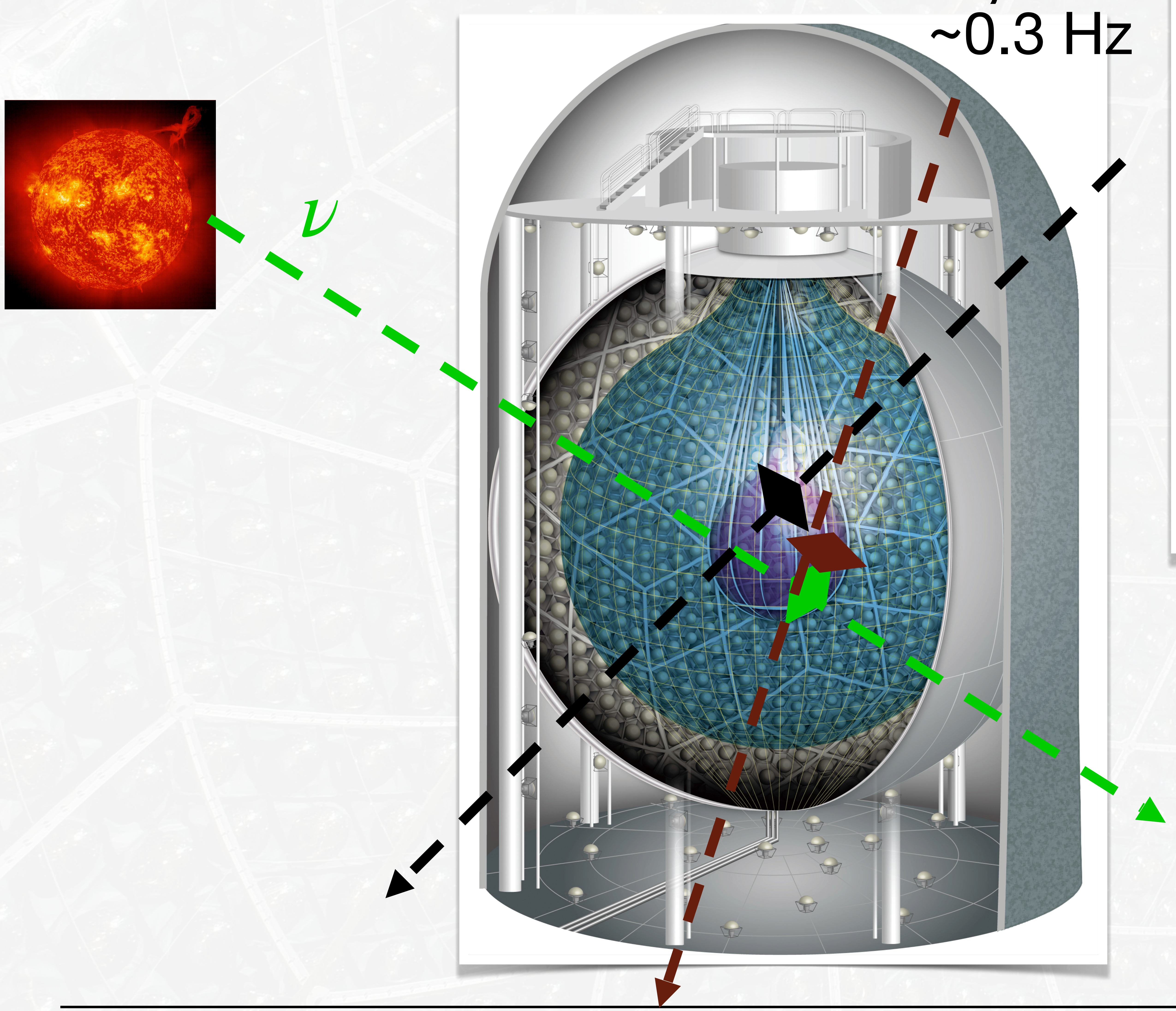


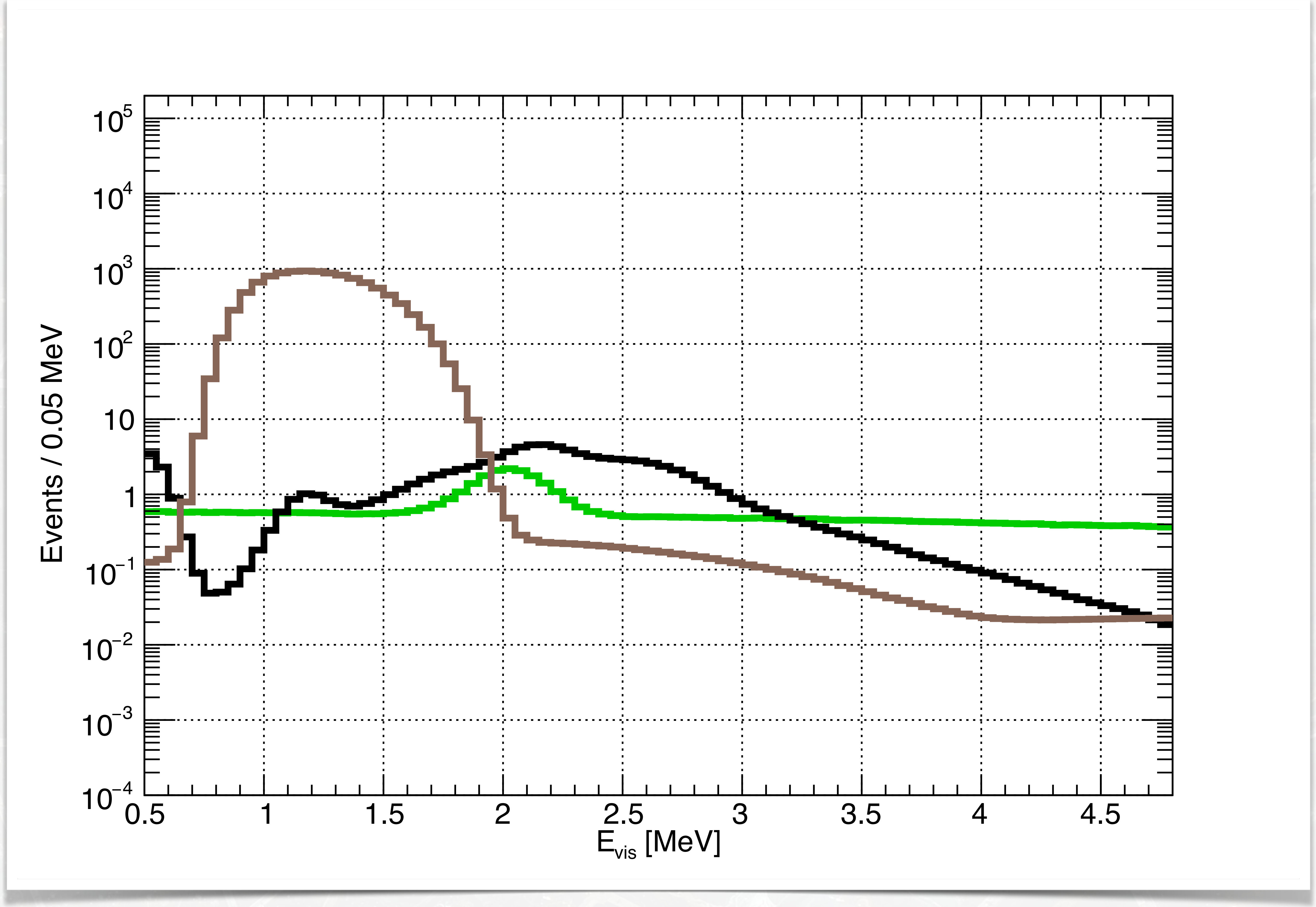




- **Solar Neutrino Interactions (ES+CC)**
- **Cosmogenics Xenon Spallation Products**

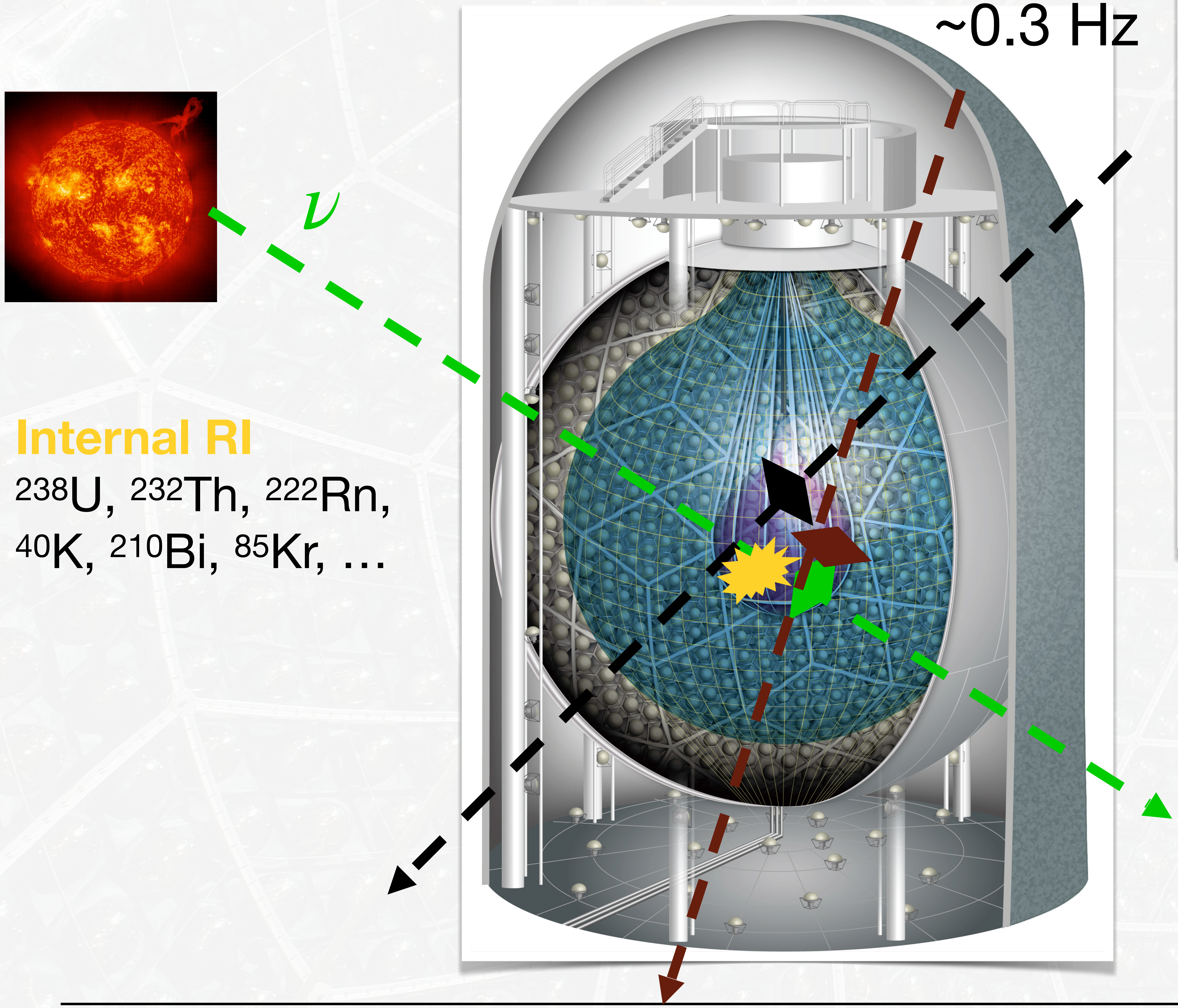
$0\nu\beta\beta$ Backgrounds





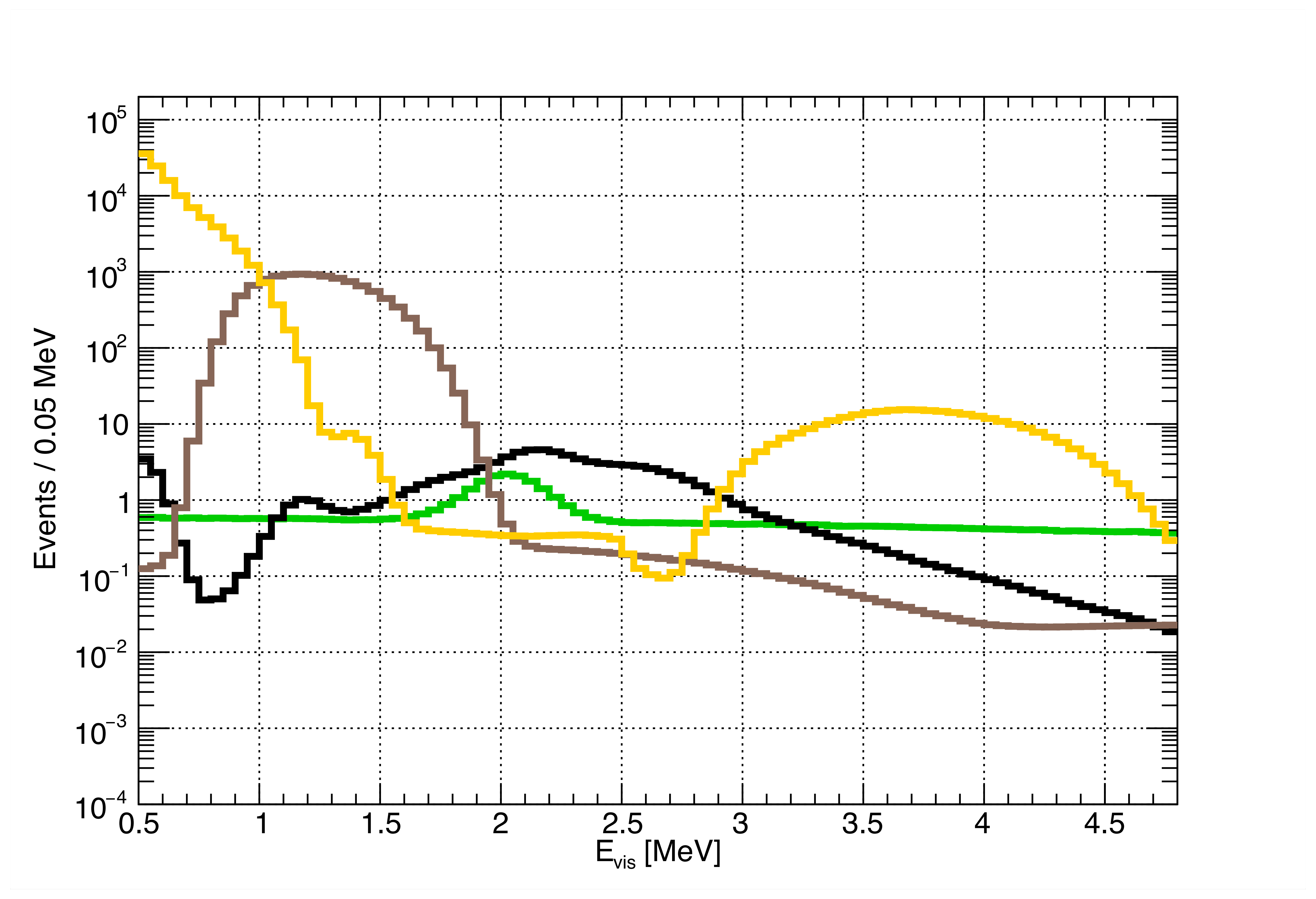
- Solar Neutrino Interactions (ES+CC)
- Cosmogenics Xenon Spallation Products
- Cosmogenics Carbon spallation Products

$0\nu\beta\beta$ Backgrounds



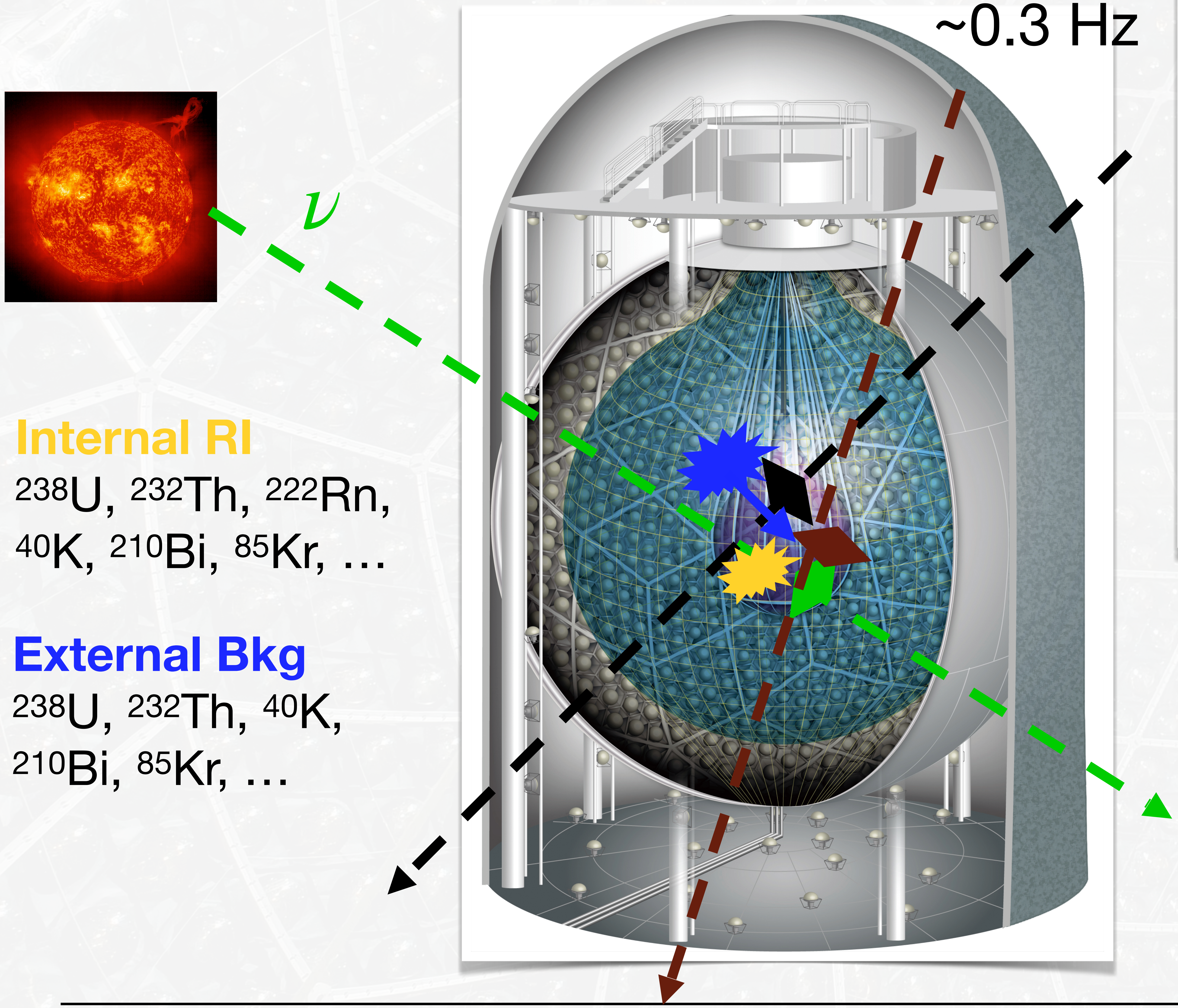
Internal RI

^{238}U, ^{232}Th, ^{222}Rn, ^{40}K, ^{210}Bi, ^{85}Kr, …



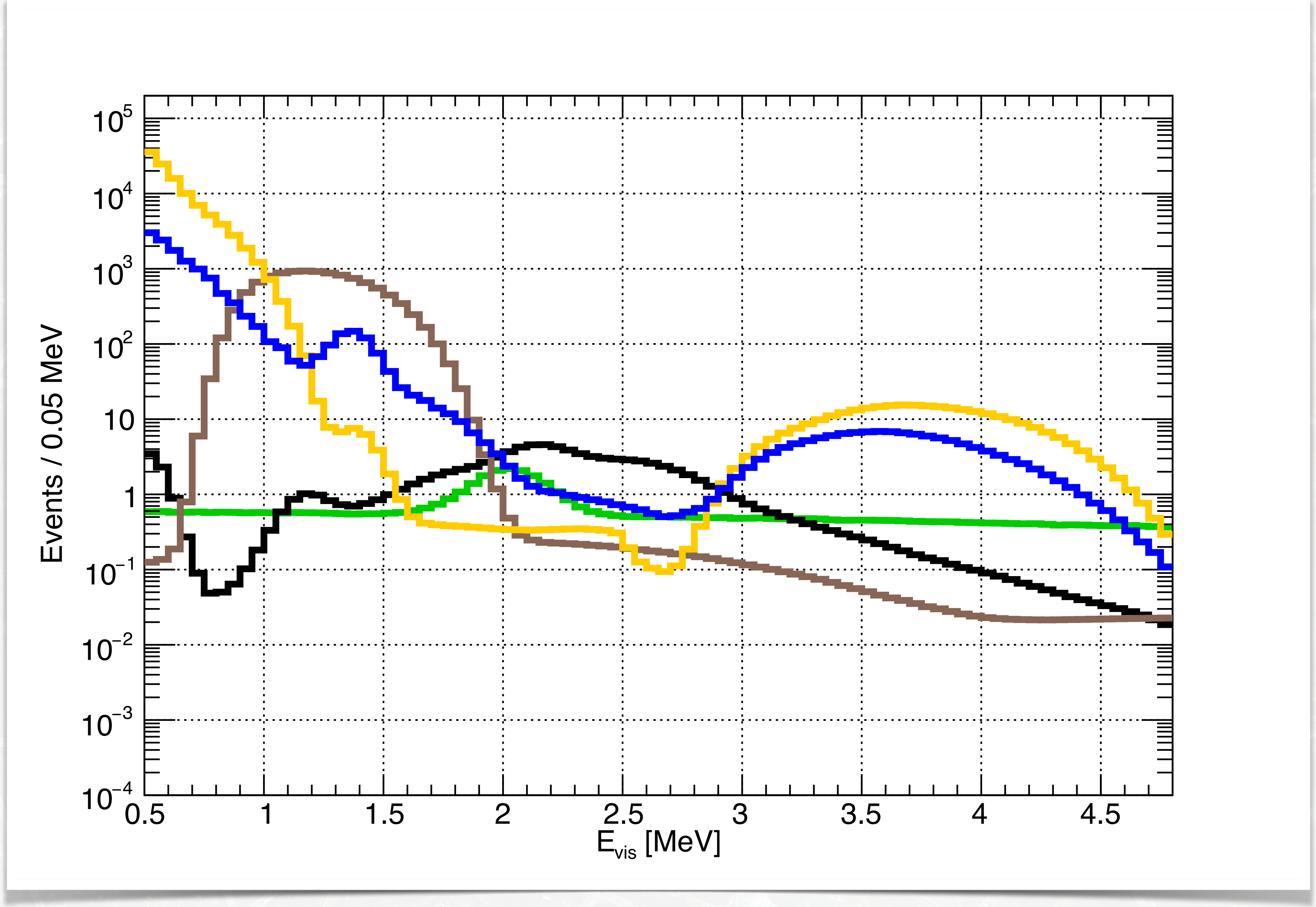
- **Solar Neutrino Interactions (ES+CC)**
- **Cosmogenics Xenon Spallation Products**
- **Cosmogenics Carbon spallation Products**
- **Internal XeLS Radioactive Impurities (RI)**

$0\nu\beta\beta$ Backgrounds



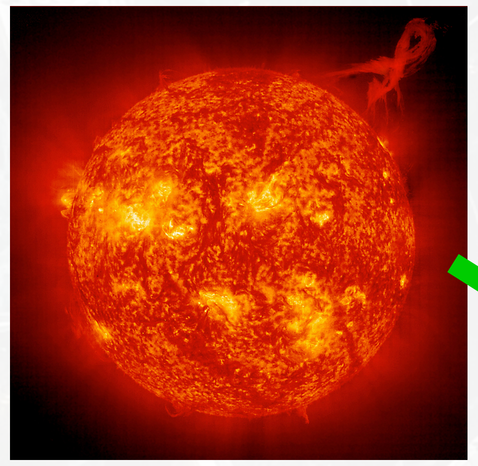
Internal RI
^{238}U, ^{232}Th, ^{222}Rn, ^{40}K, ^{210}Bi, ^{85}Kr, …

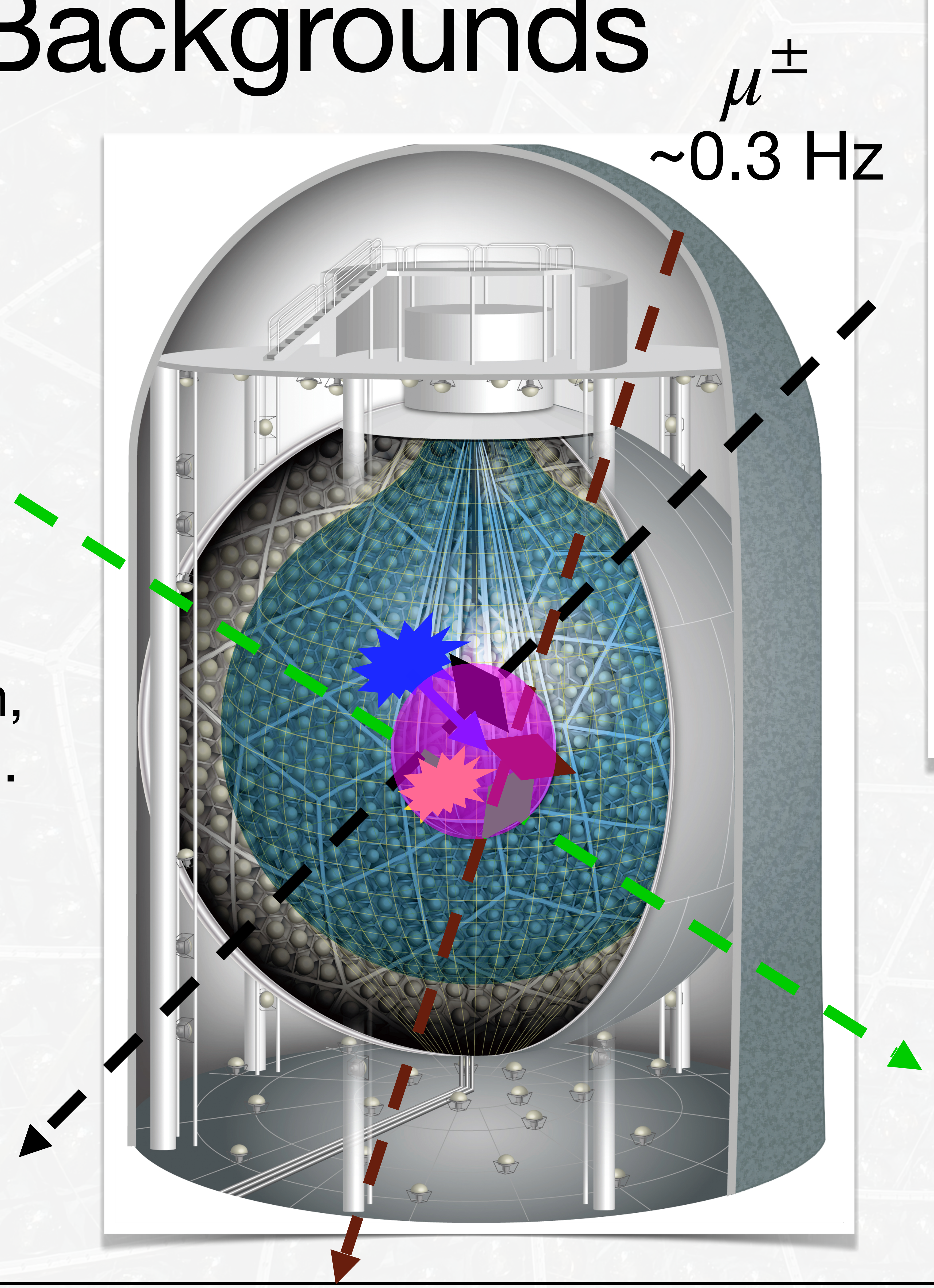
External Bkg
^{238}U, ^{232}Th, ^{40}K, ^{210}Bi, ^{85}Kr, …

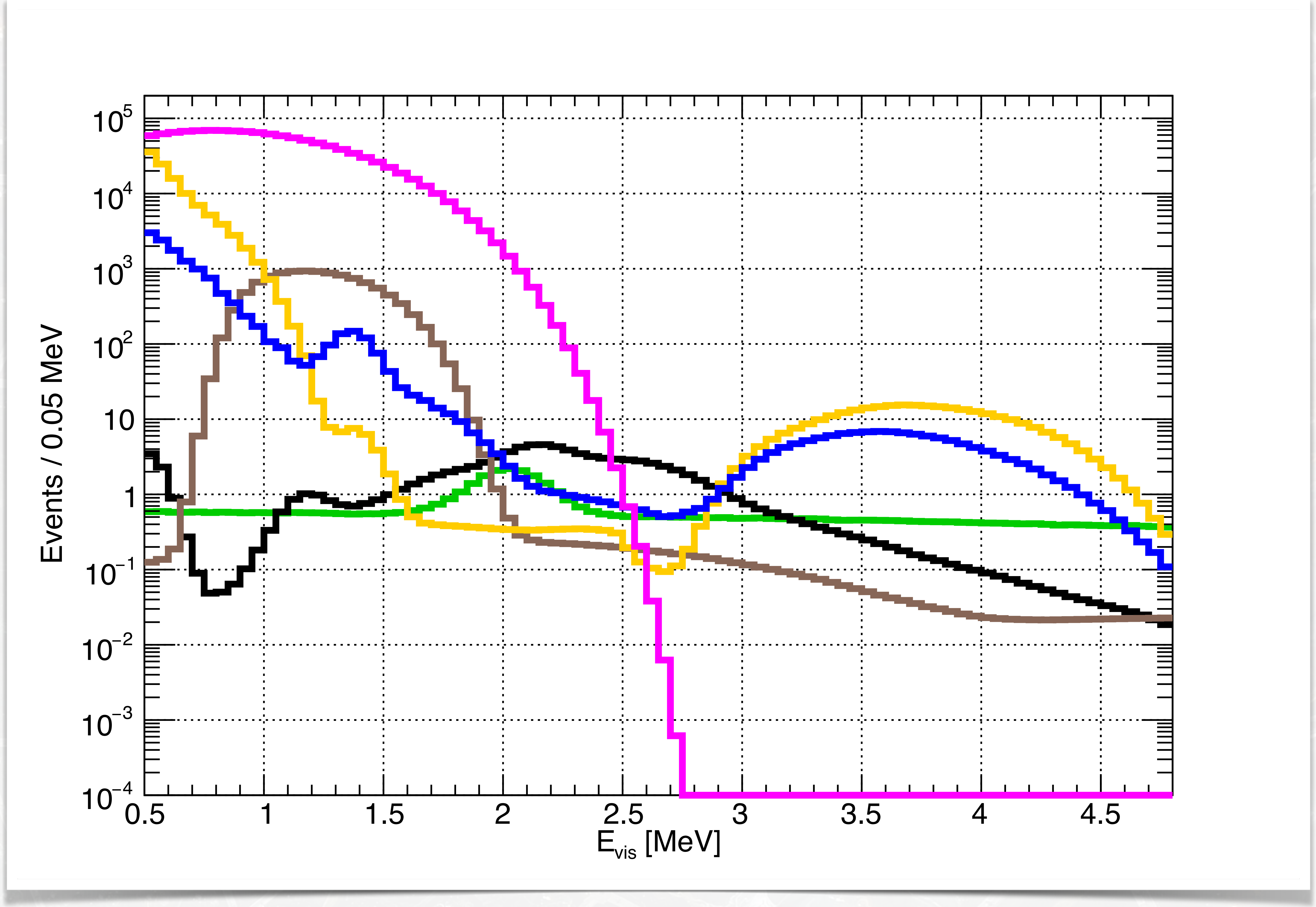


- **Solar Neutrino Interactions (ES+CC)**
- **Cosmogenics Xenon Spallation Products**
- **Cosmogenics Carbon spallation Products**
- **Internal XeLS Radioactive Impurities (RI)**
- **External to XeLS from IB + KamLAND-LS**

$0\nu\beta\beta$ Backgrounds







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External Bkg

^{238}U, ^{232}Th, ^{40}K, ^{210}Bi, ^{85}Kr, …

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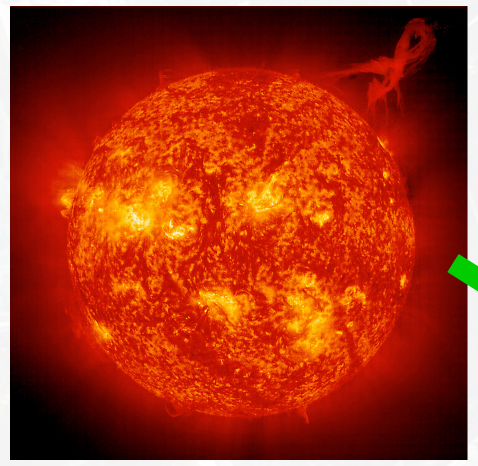
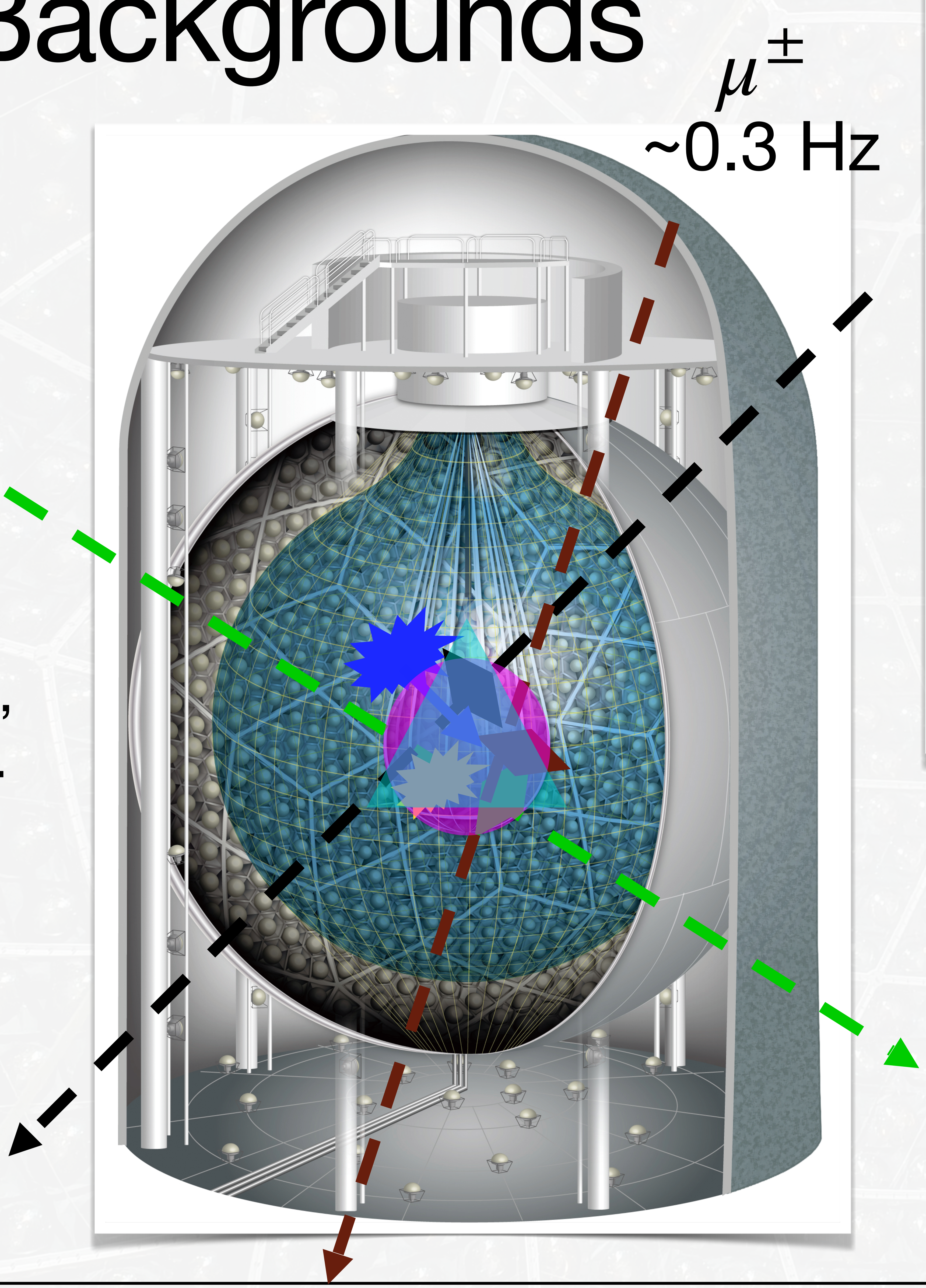
- **External to XeLS from IB + KamLAND-LS**
- **^{136}Xe $2\nu\beta\beta$ (source bkg)**

$0\nu\beta\beta$ Backgrounds



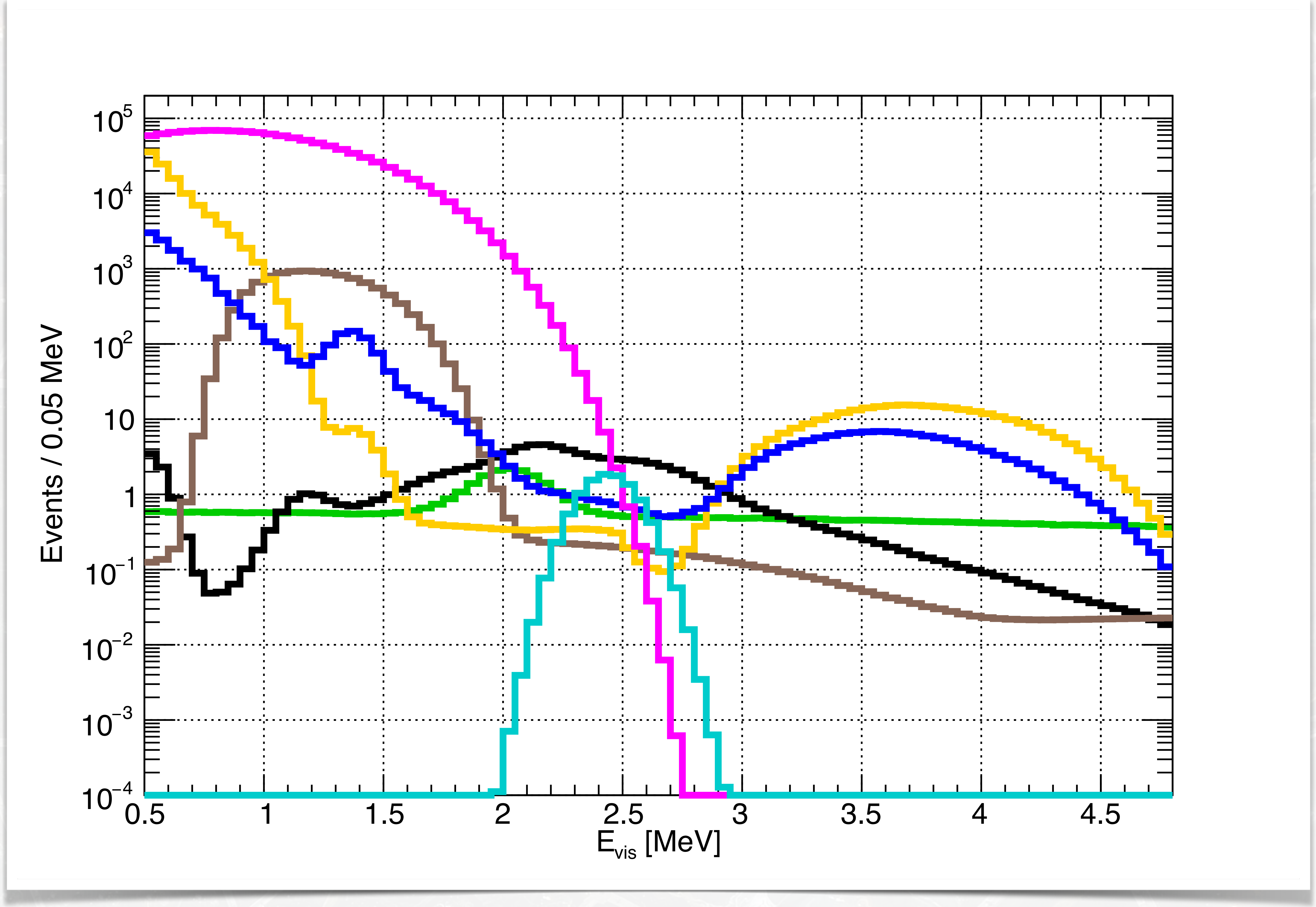


Internal RI

^{238}U, ^{232}Th, ^{222}Rn, ^{40}K, ^{210}Bi, ^{85}Kr, …

External Bkg

^{238}U, ^{232}Th, ^{40}K, ^{210}Bi, ^{85}Kr, …



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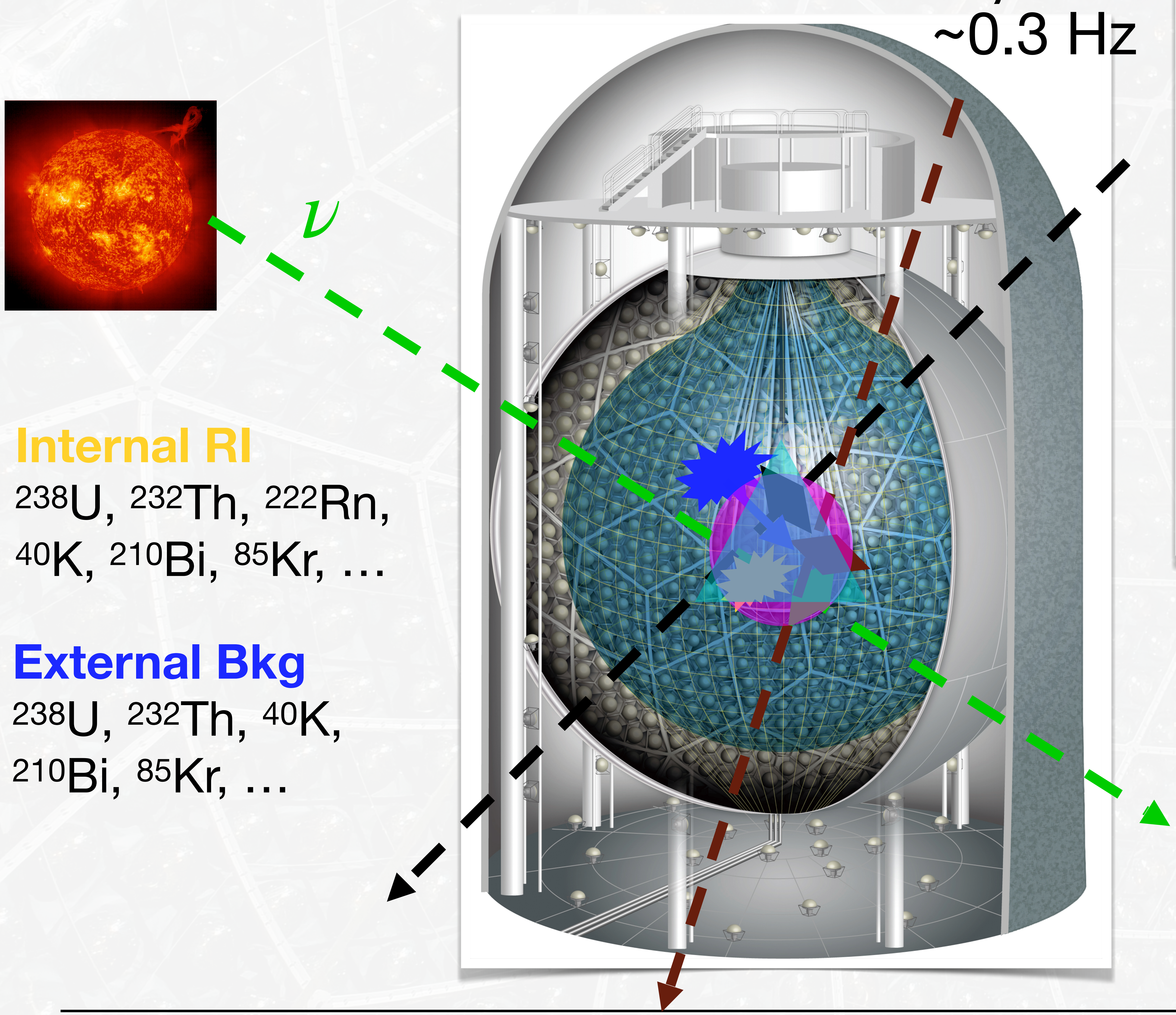
- **^{136}Xe $0\nu\beta\beta$**

$0\nu\beta\beta$ Backgrounds



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External Bkg

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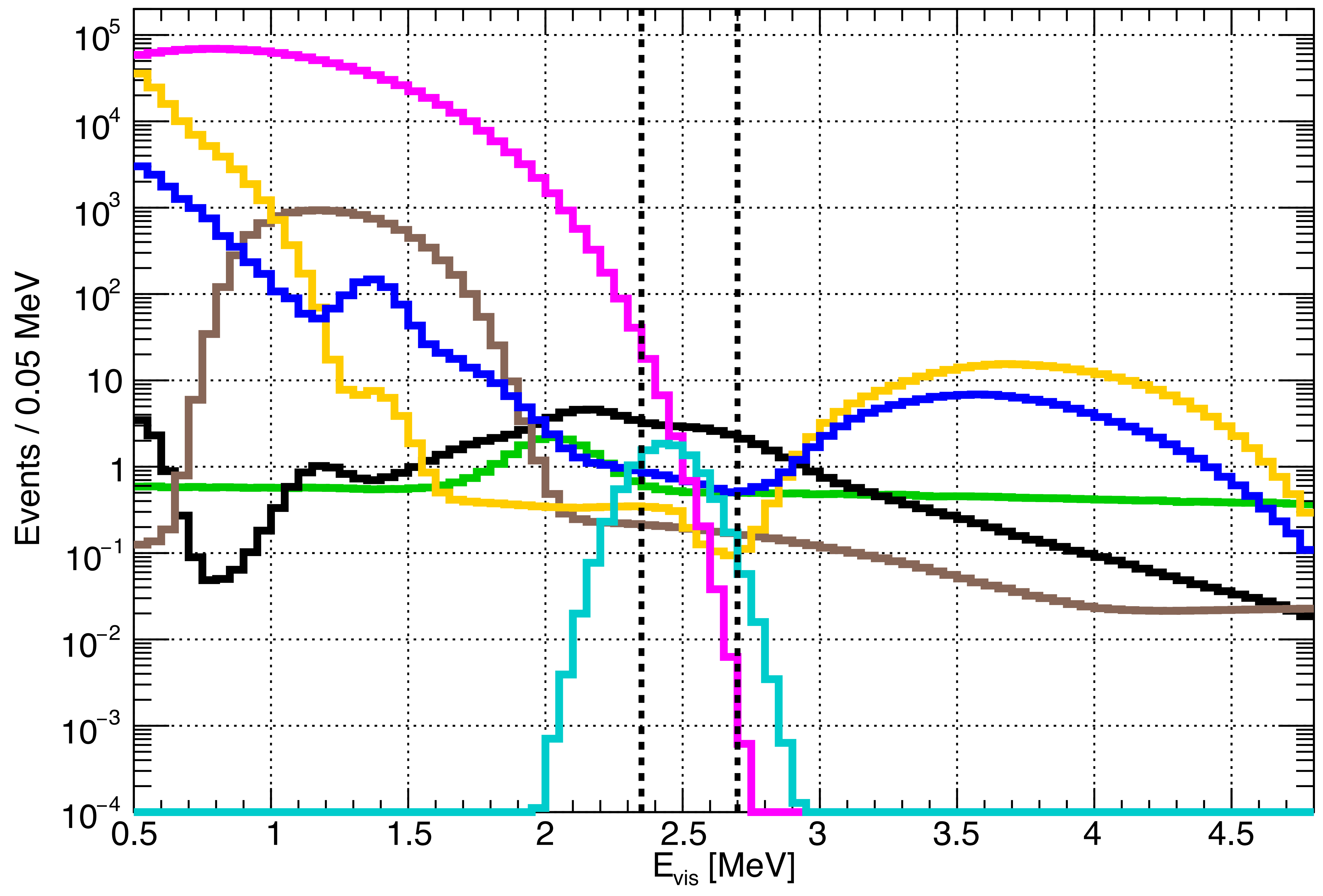
Region-of-Interest (ROI) = 2.35..2.70 MeV



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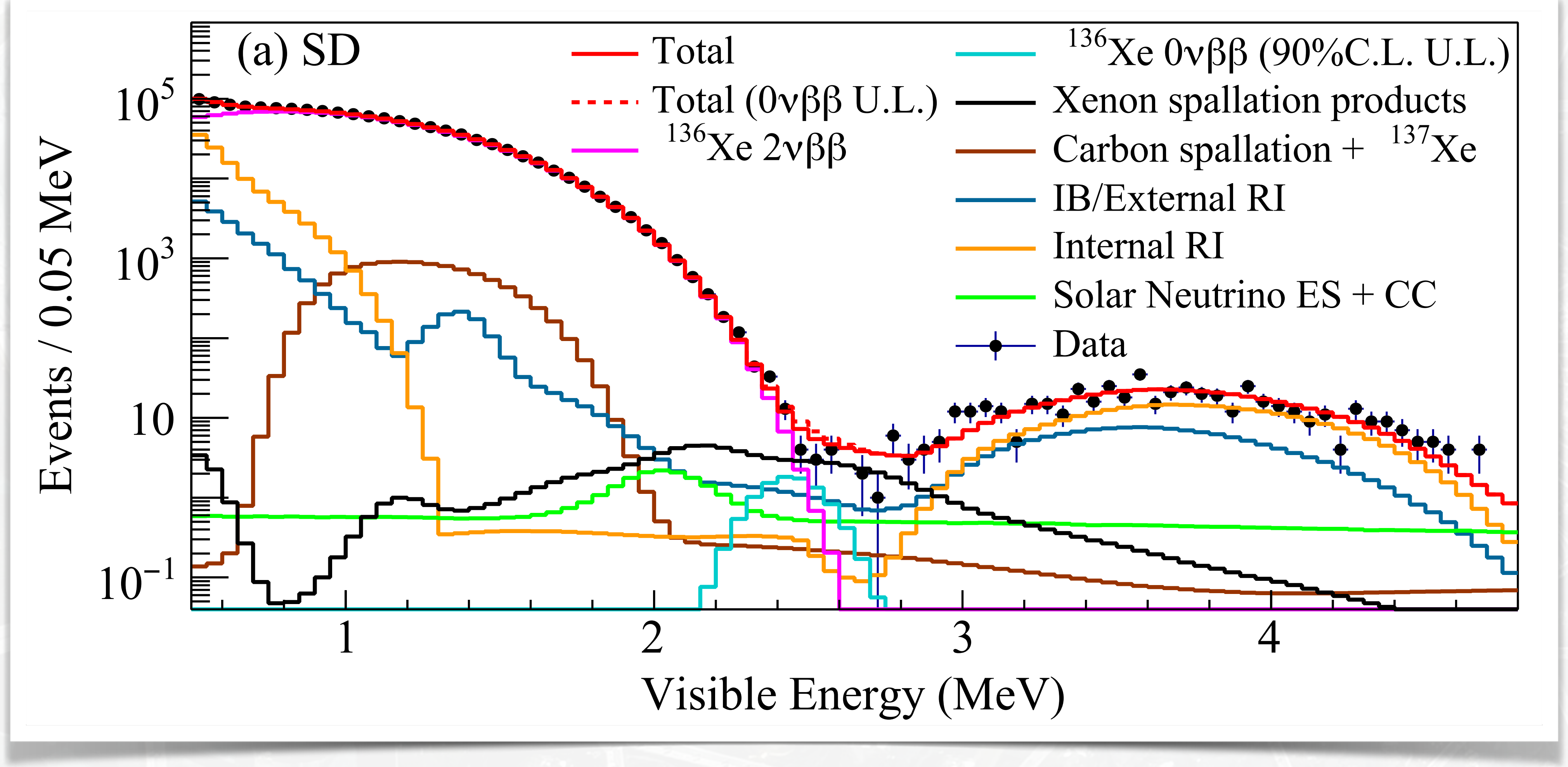
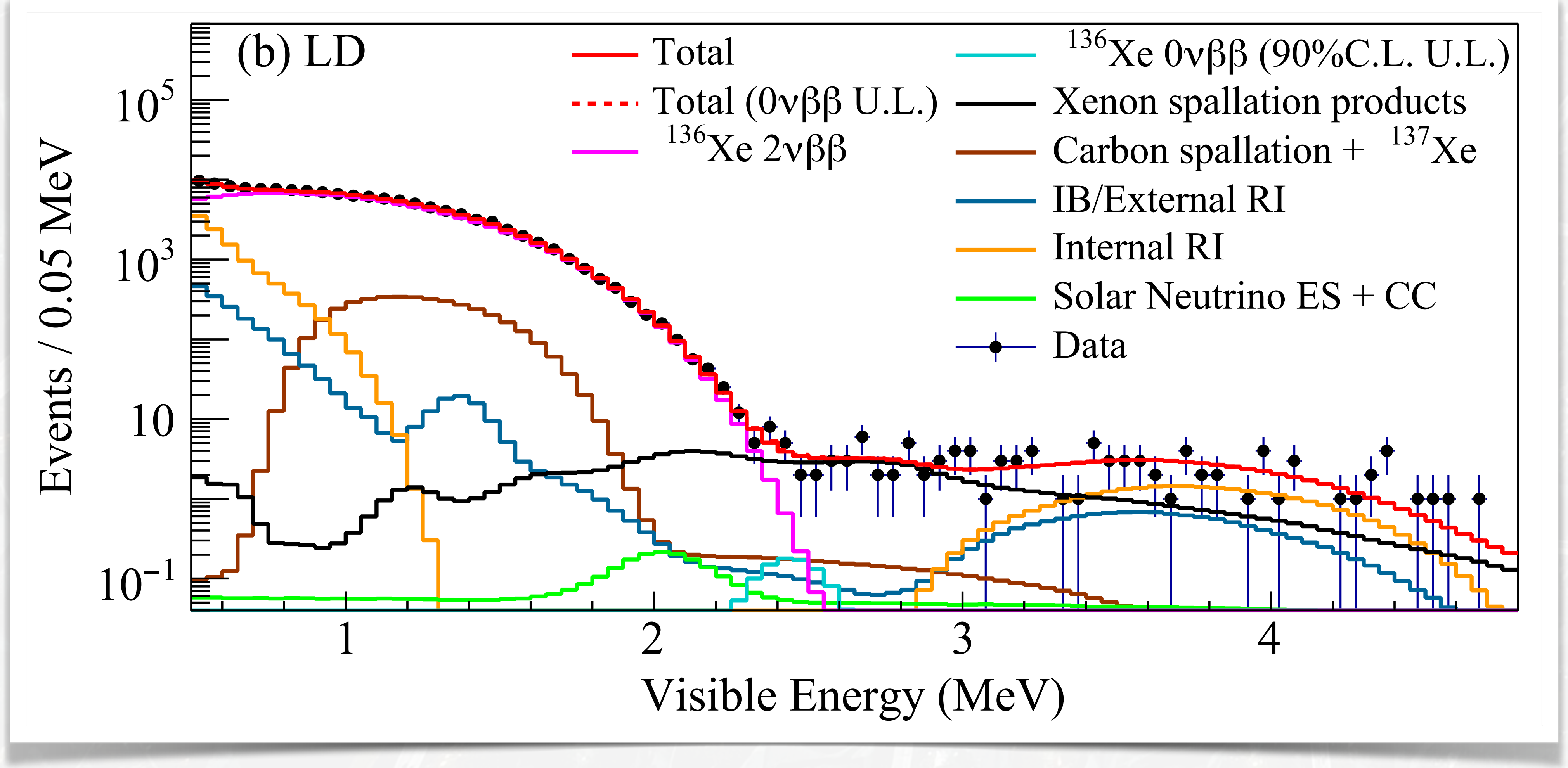
- **^{136}Xe $2\nu\beta\beta$ (source bkg)**
- **^{136}Xe $0\nu\beta\beta$**

Spectral Analysis

Singles Data (SD) $E \sim 90\,\% \sim 1131$ days



Long-Lived Data (LD) $E \sim 10\,\% \sim 111$ days



SD = Untagged/ Singles Data $\rightarrow 90\,\%$ Exposure

LD = Long-Lived TaggedData with isotope $\tau \geq 100$ sec

Analysis Range

$[0.5,4.8]$ MeV for R < 250 cm

Exposure = $2.1 \cdot$ ton $\cdot$ year of ^{136}Xe

Plots show $R < 157$ cm

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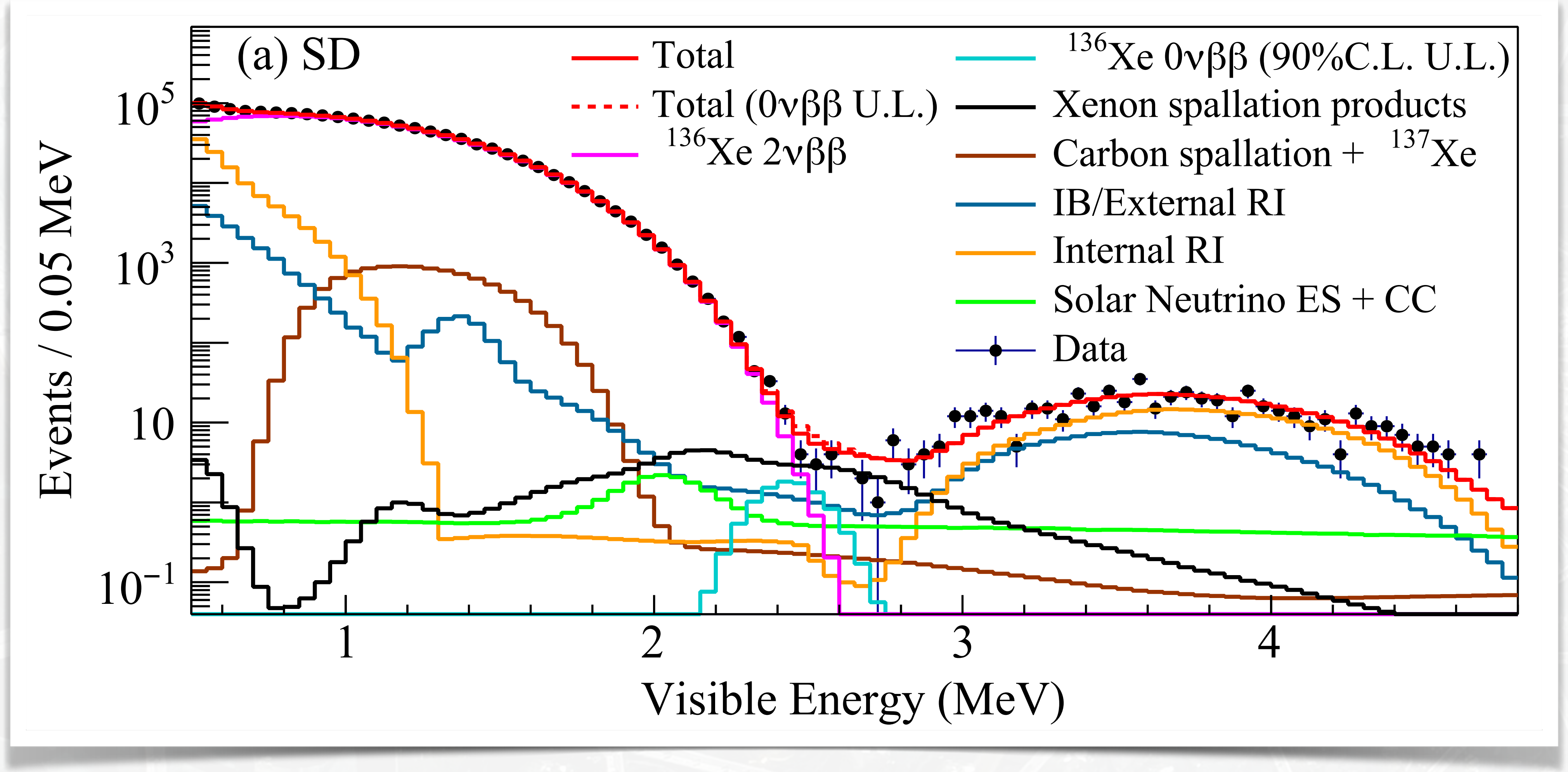
Singles Data (SD) $E \sim 90\,\% \sim 1131$ days



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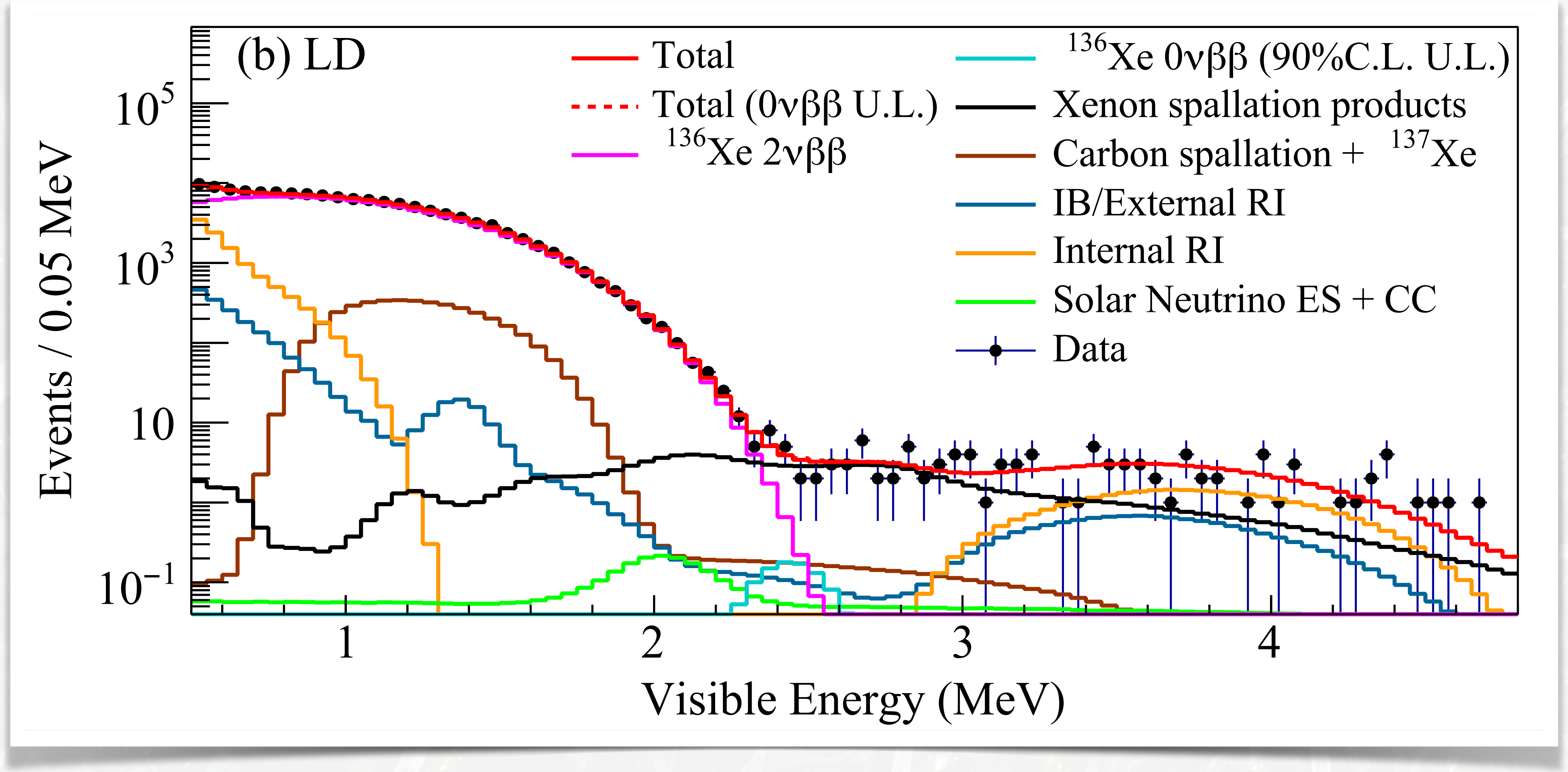

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Analysis Range

[0.5,4.8] MeV for R < 250 cm

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Plots show $R < 157$ cm

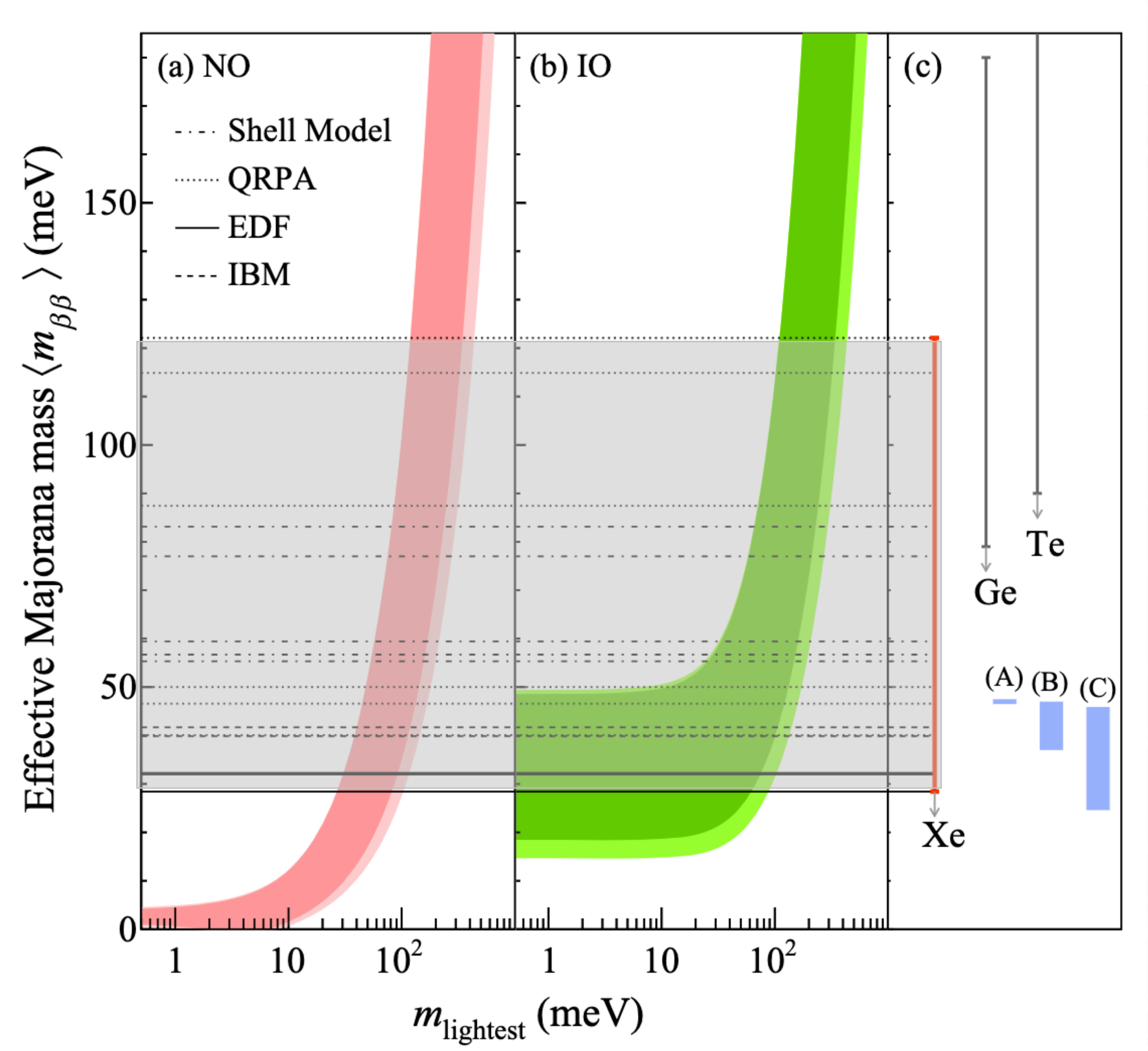
$$T_{1/2}^{0\nu\beta\beta} > 3.8 \times 10^{26} \text{ years}$$

(Combined KLZ-400 + 800 based on **Wilks**)

We also performed **Feldman-Cousins** and **Bayesian** Calculations → consistent

Phys. Rev. Lett. **135**, 262501

Results for Effective Majorana Mass



Model	Ref.	$M^{0\nu}$	$\langle m_{\beta\beta} \rangle$ [meV]
QRPA	8	1.11, 1.18	122, 115
EDF	11	4.77	28.4

Shell model

[1] J. Menéndez, J. of Phys. G **45**, 014003 (2018).
[2] M. Horoi and A. Neacsu, Phys. Rev. C **93**, 024308 (2016).
[3] L. Coraggio, A. Gargano, N. Itaco, R. Mancino, and F. Nowacki, Phys. Rev. C **101**, 044315 (2020).
[4] L. Coraggio *et al.*, Phys. Rev. C **105**, 034312 (2022).

QRPA

[5] M. T. Mustonen and J. Engel, Phys. Rev. C **87**, 064302 (2013).
[6] J. Hyvärinen and J. Suhonen, Phys. Rev. C **91**, 024613 (2015).
[7] F. Šimkovic, A. Smetana, and P. Vogel, Phys. Rev. C **98**, 064325 (2018).
[8] D.-L. Fang, A. Faessler, and F. Šimkovic, Phys. Rev. C **97**, 045503 (2018).
[9] J. Terasaki, Phys. Rev. C **102**, 044303 (2020).

EDF

[10] T. R. Rodríguez and G. Martínez-Pinedo, Phys. Rev. Lett. **105**, 252503 (2010).
[11] N. L. Vaquero, T. R. Rodríguez, and J. L. Egido, Phys. Rev. Lett. **111**, 142501 (2013).
[12] L. S. Song, J. M. Yao, P. Ring, and J. Meng, Phys. Rev. C **95**, 024305 (2017).

IBM

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

Theoretical model

(A) K. Harigaya, M. Ibe, and T. T. Yanagida, Phys. Rev. D 86, 013002 (2012)
(B) T. Asaka, Y. Heo, and T. Yoshida, Phys. Lett. B 811, 135956 (2020).
(C) K. Asai, Eur. Phys. J. C 80, 76 (2020)

$$\left(T_{1/2}^{0\nu2\beta}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2 m_{\beta\beta}^2$$

$$\left\langle m_{\beta\beta} \right\rangle < 28 \ldots 122 \text{ meV}$$

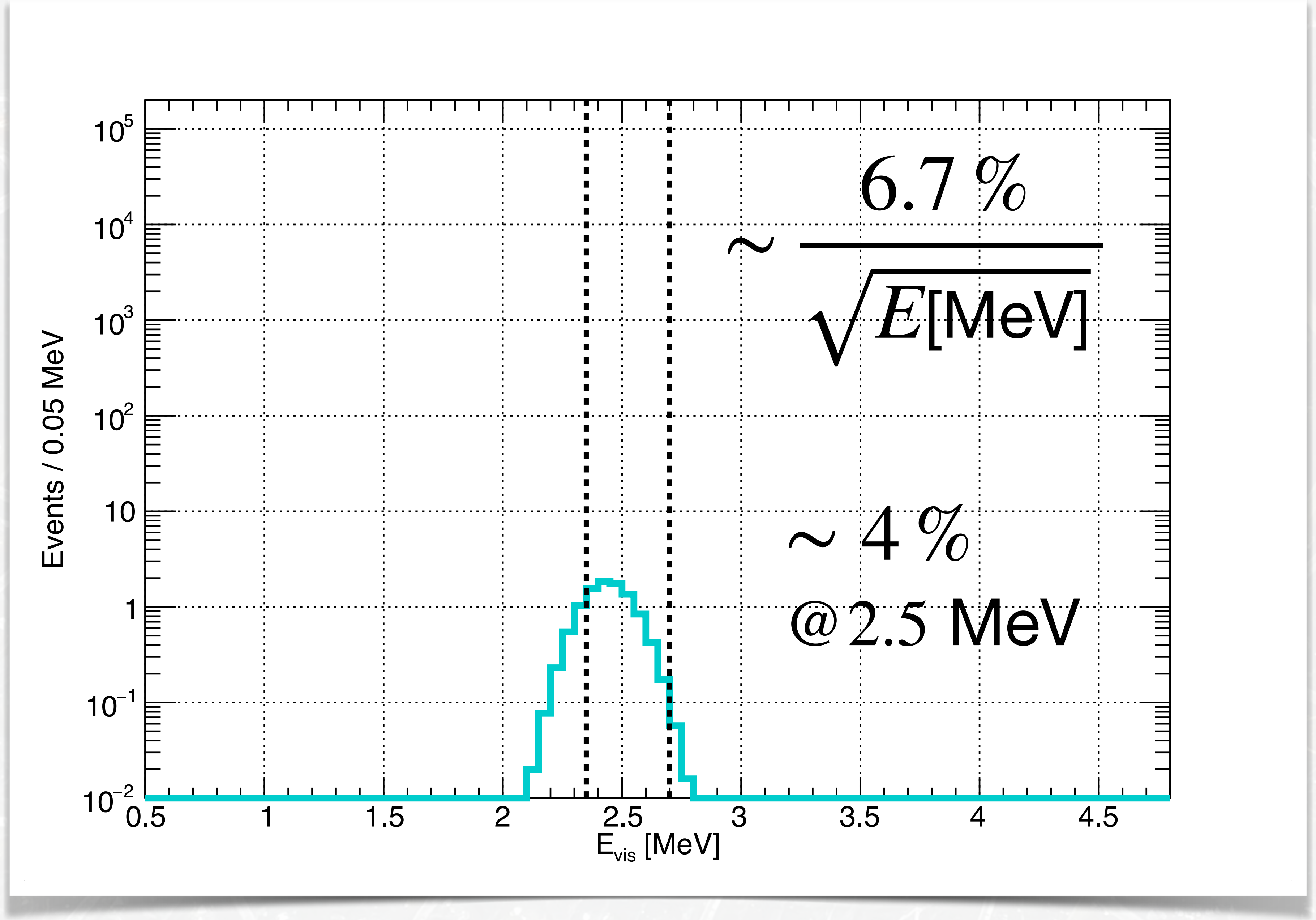
From KamLAND-Zen to KamLAND2-Zen

- **KamLAND-Zen 800: Feb. 5, 2019 – Jan. 12, 2024**
- **Decommisioning started in 2024 while KL2Z construction in 2025**

Poster 2/260
Nanami Kawada-san

Towards KL2-Zen → Top Backgrounds in ROI

ROI $2.35\,..\,2.70$ MeV in R < 157 cm

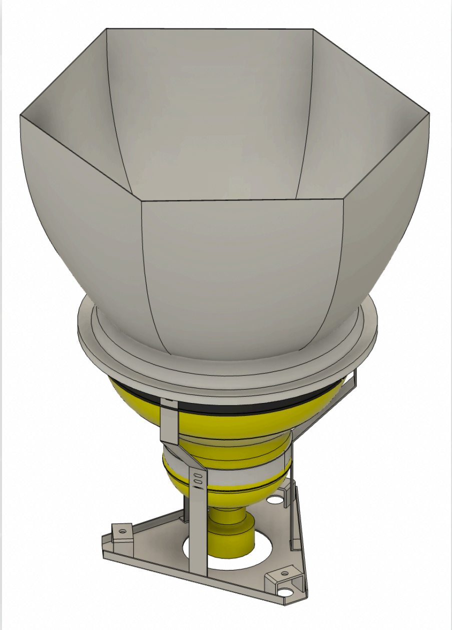


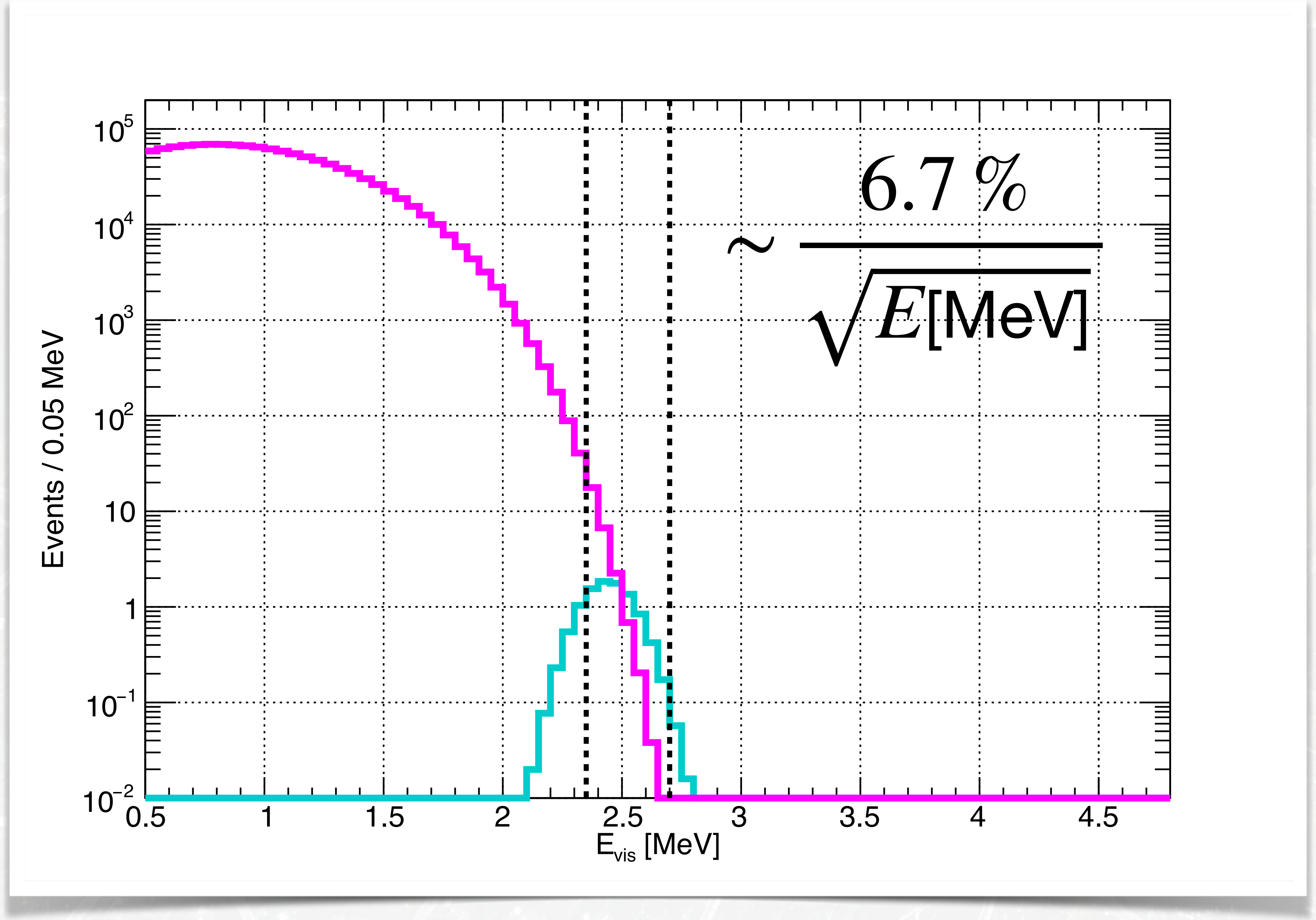
Towards KL2-Zen → Top Backgrounds in ROI

ROI $2.35\,..\,2.70$ MeV in R < 157 cm

$2\nu\beta\beta \rightarrow 47\ \%$

Energy resolution tail
→ increase light yield
→ increase collection





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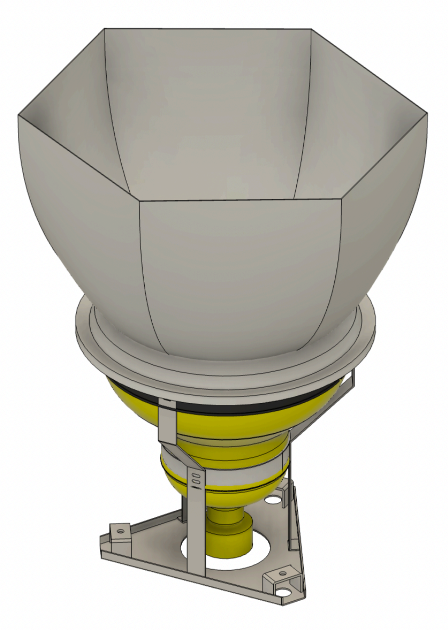
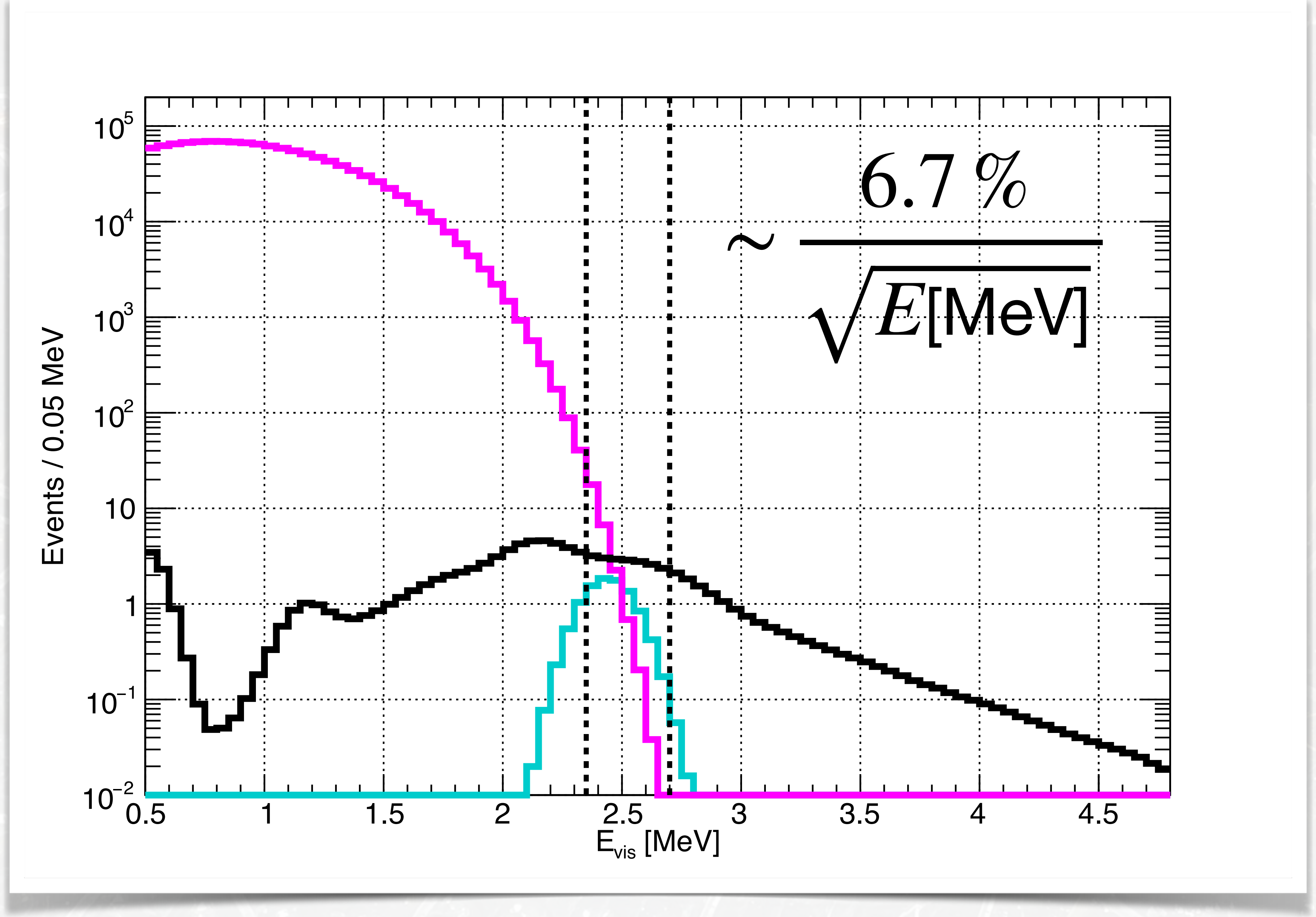
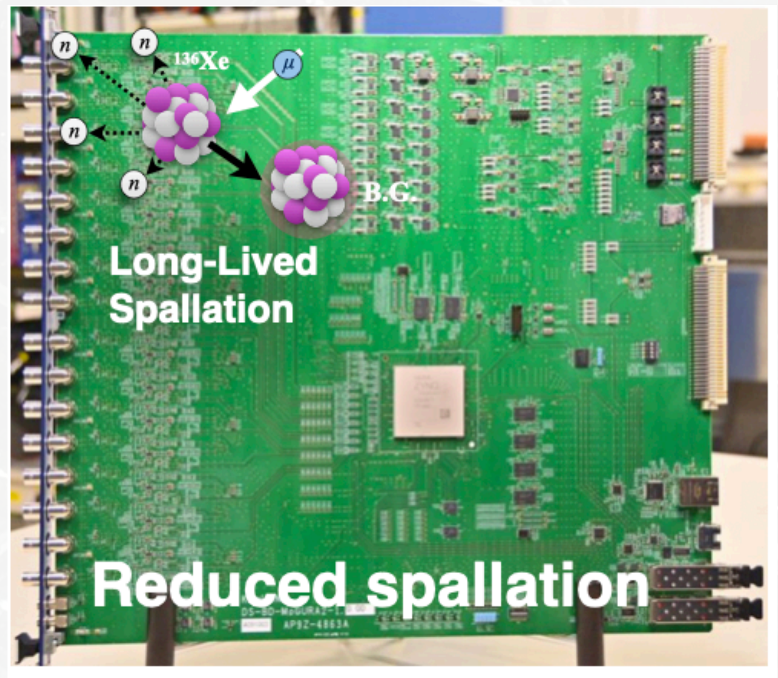




Long-Lived → $33\,\%$

→ New Electronics
→ Spallation Tagging
→ Deadtime free

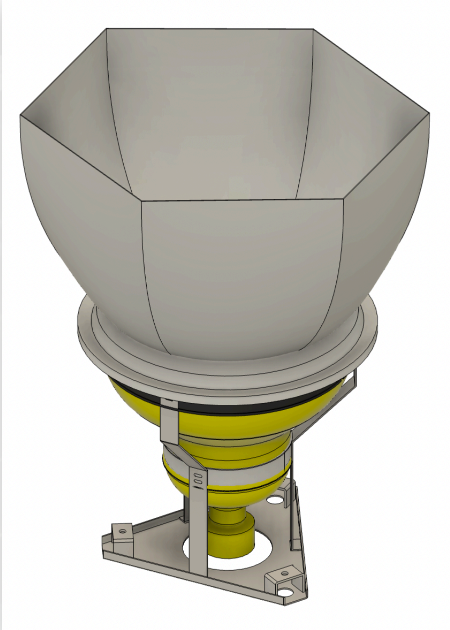


Towards KL2-Zen → Top Backgrounds in ROI

ROI $2.35 \ldots 2.70$ MeV in R < 157 cm

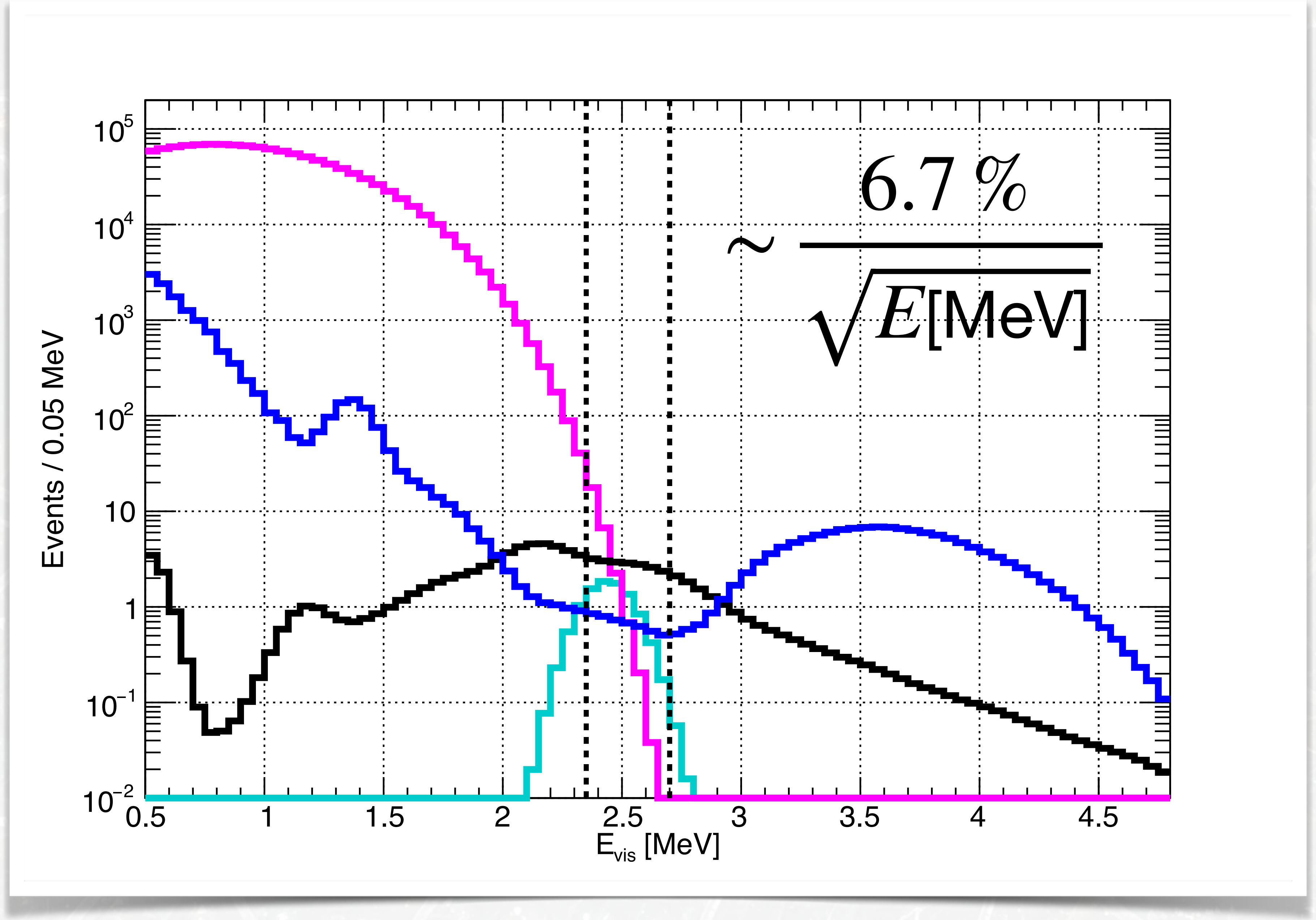
$2\nu\beta\beta \rightarrow 47\,\%$

Energy resolution tail
→ increase light yield
→ increase collection



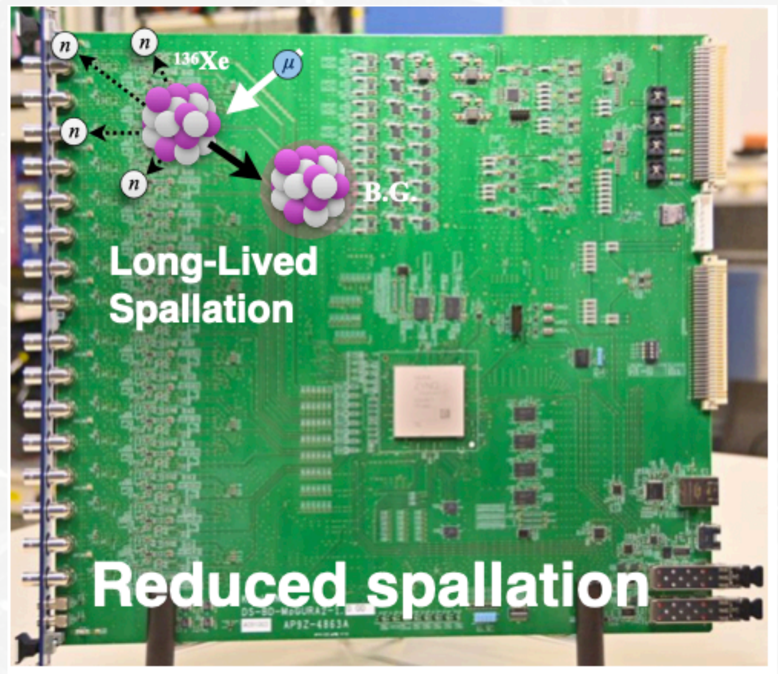
RI in IB → $11\,\%$

→ Scintillating Balloon
→ Reduce Background



Long-Lived → $33\,\%$

→ New Electronics
→ Spallation Tagging
→ Deadtime free



Towards KL2-Zen → Top Backgrounds in ROI

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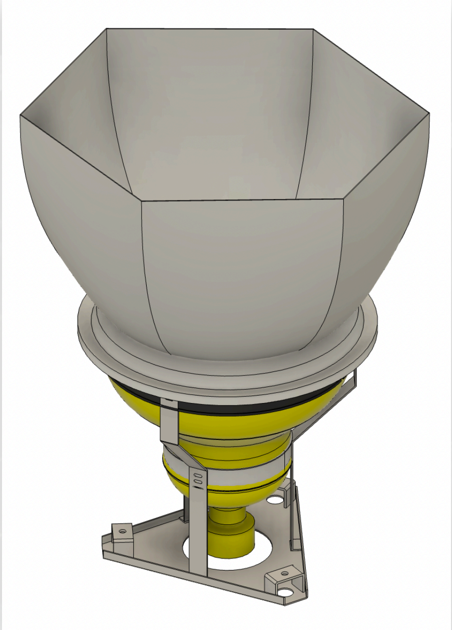
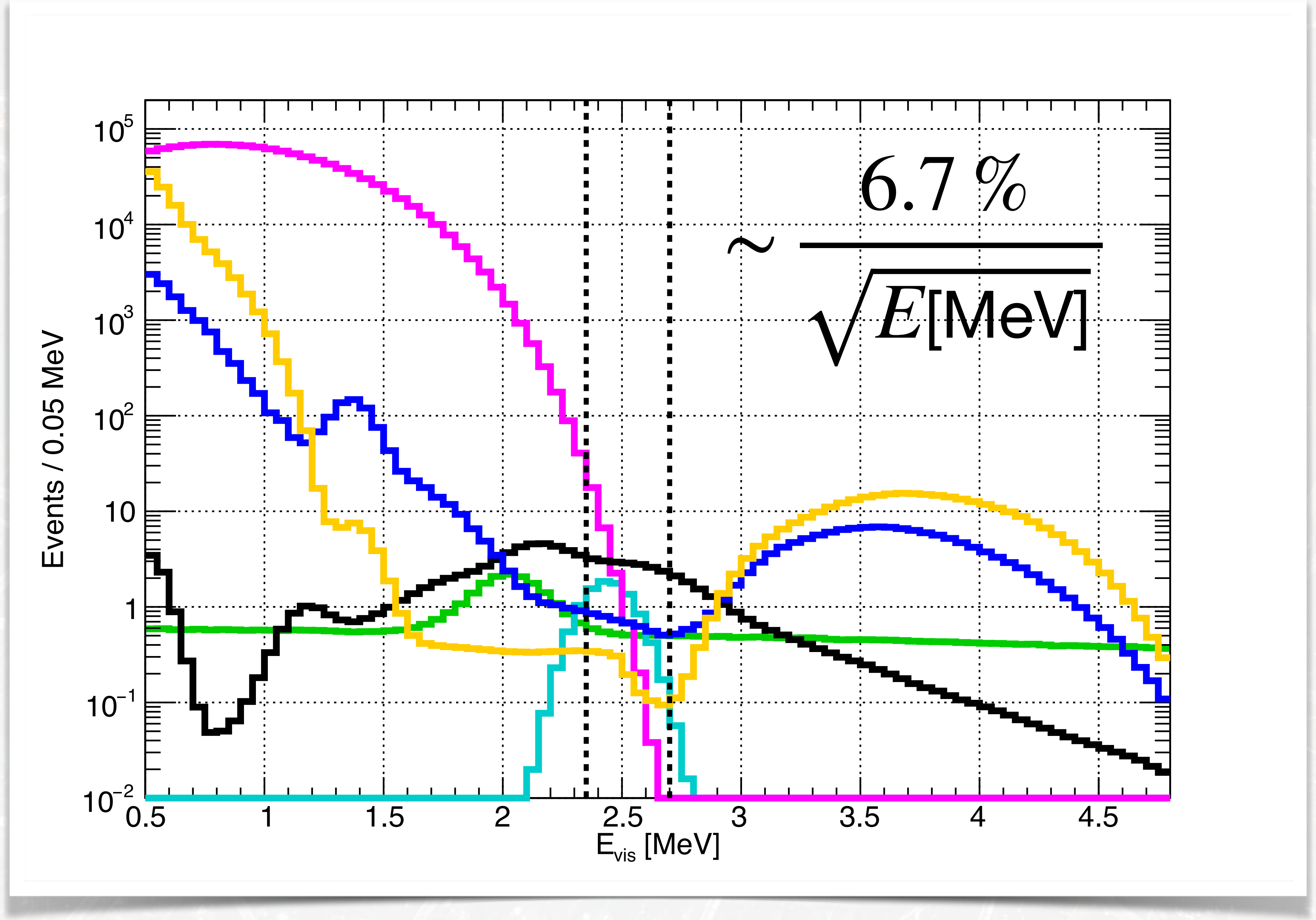


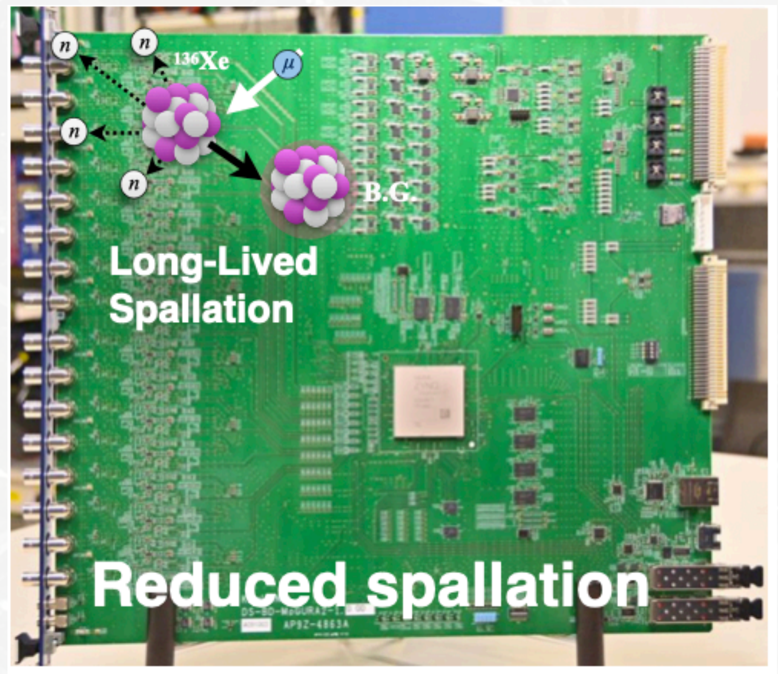


Long-Lived → $33\,\%$

→ New Electronics

→ Spallation Tagging

→ Deadtime free



RI in IB → $11\,\%$

→ RI in XeLS → $2\,\%$

→ Solar ν → $6\,\%$

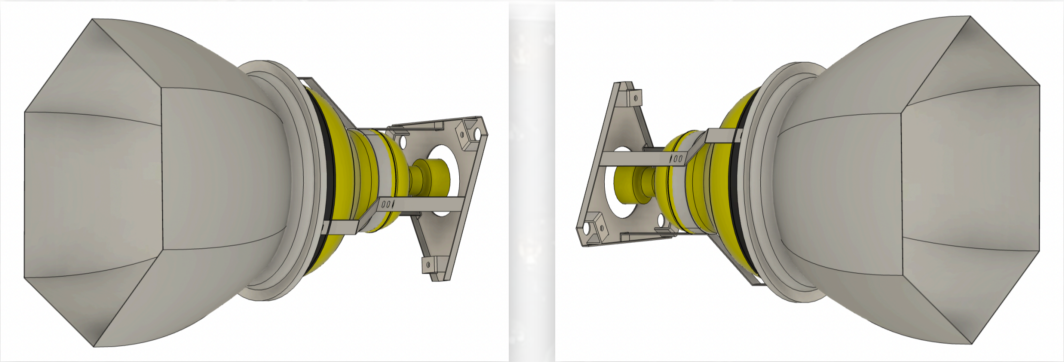
Poster 2/368
Ö.P.

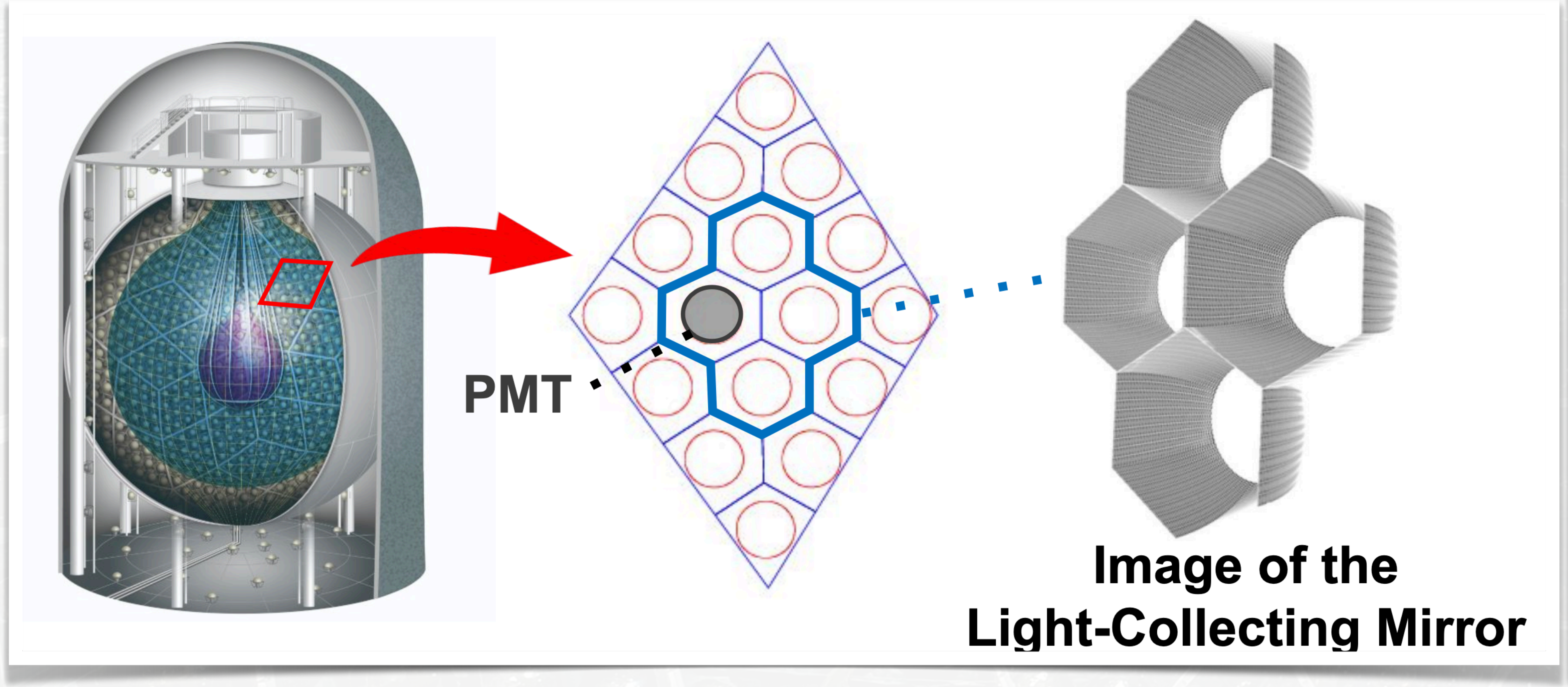
→ Scintillating Balloon

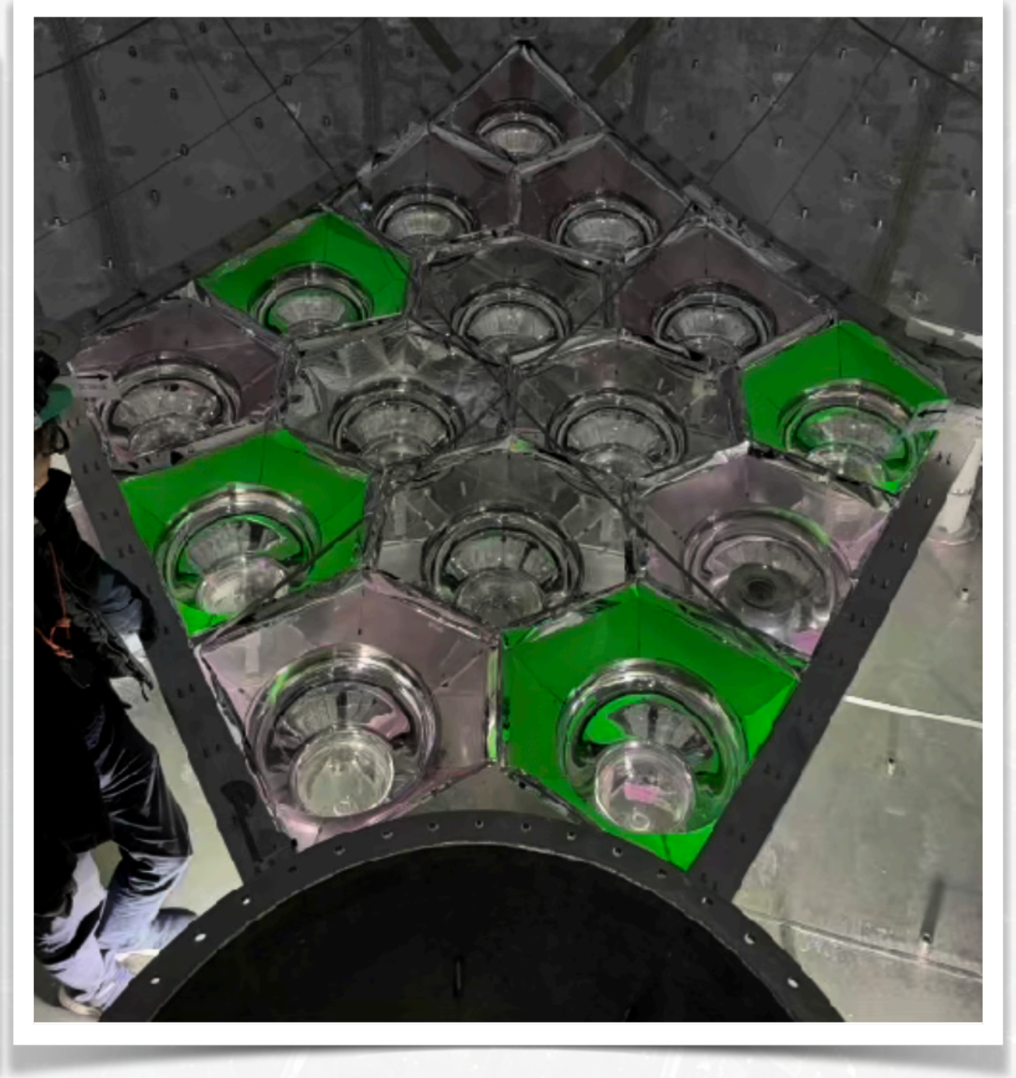
→ Reduce Background

Light Collection

Winston Cone Approach

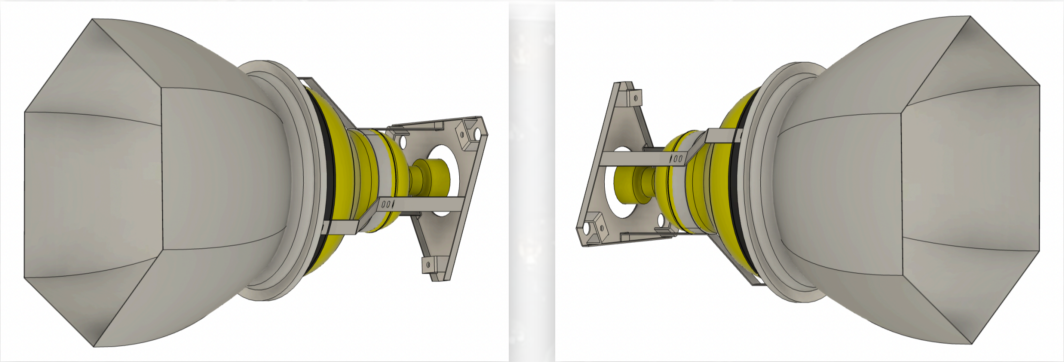




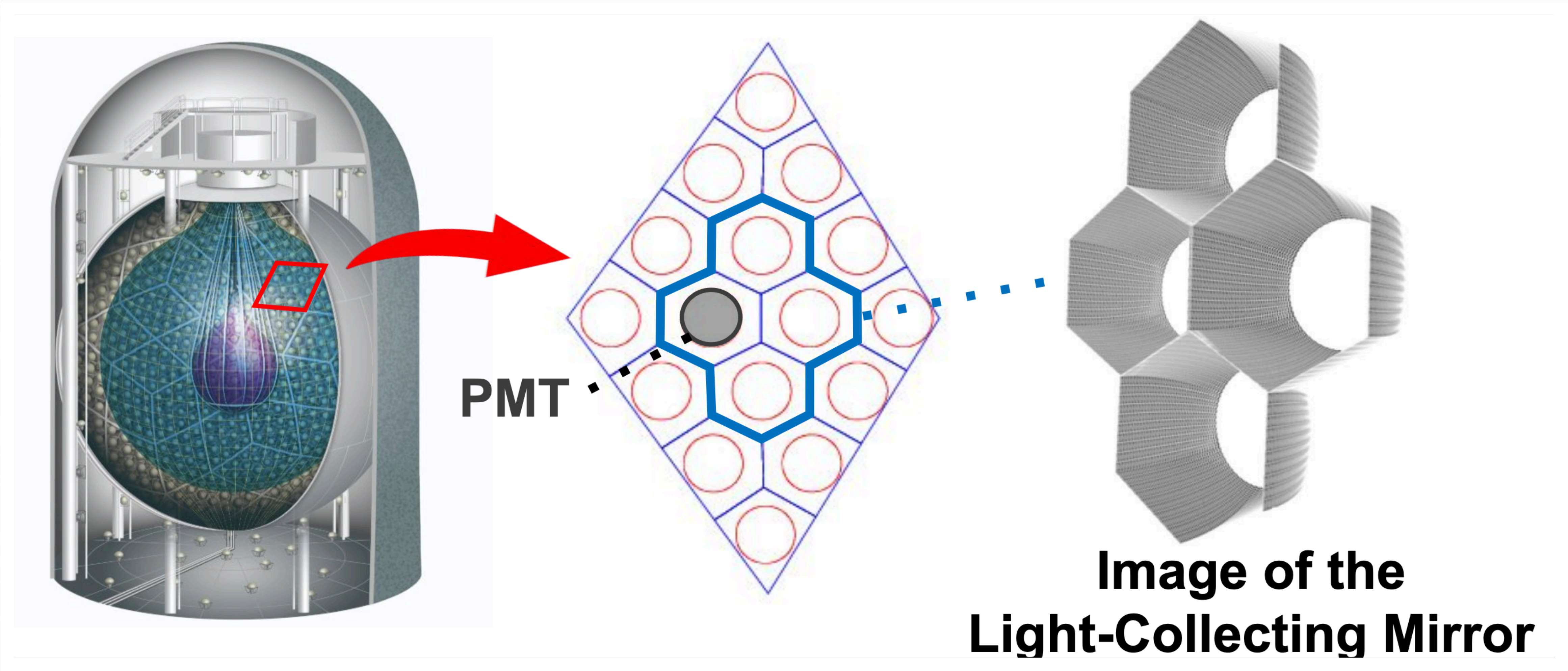


Light Collection

Winston Cone Approach



polyethylene-terephthalate

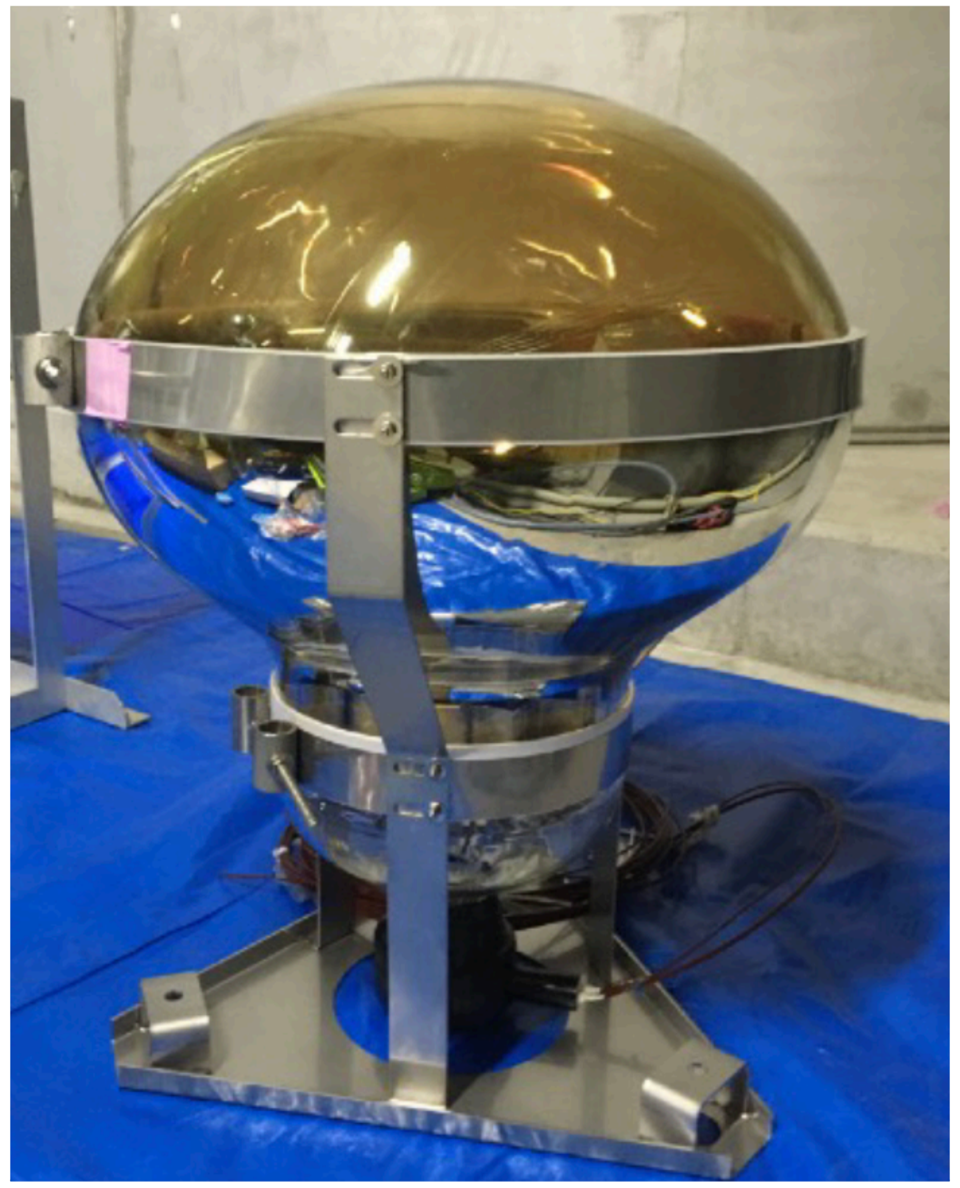


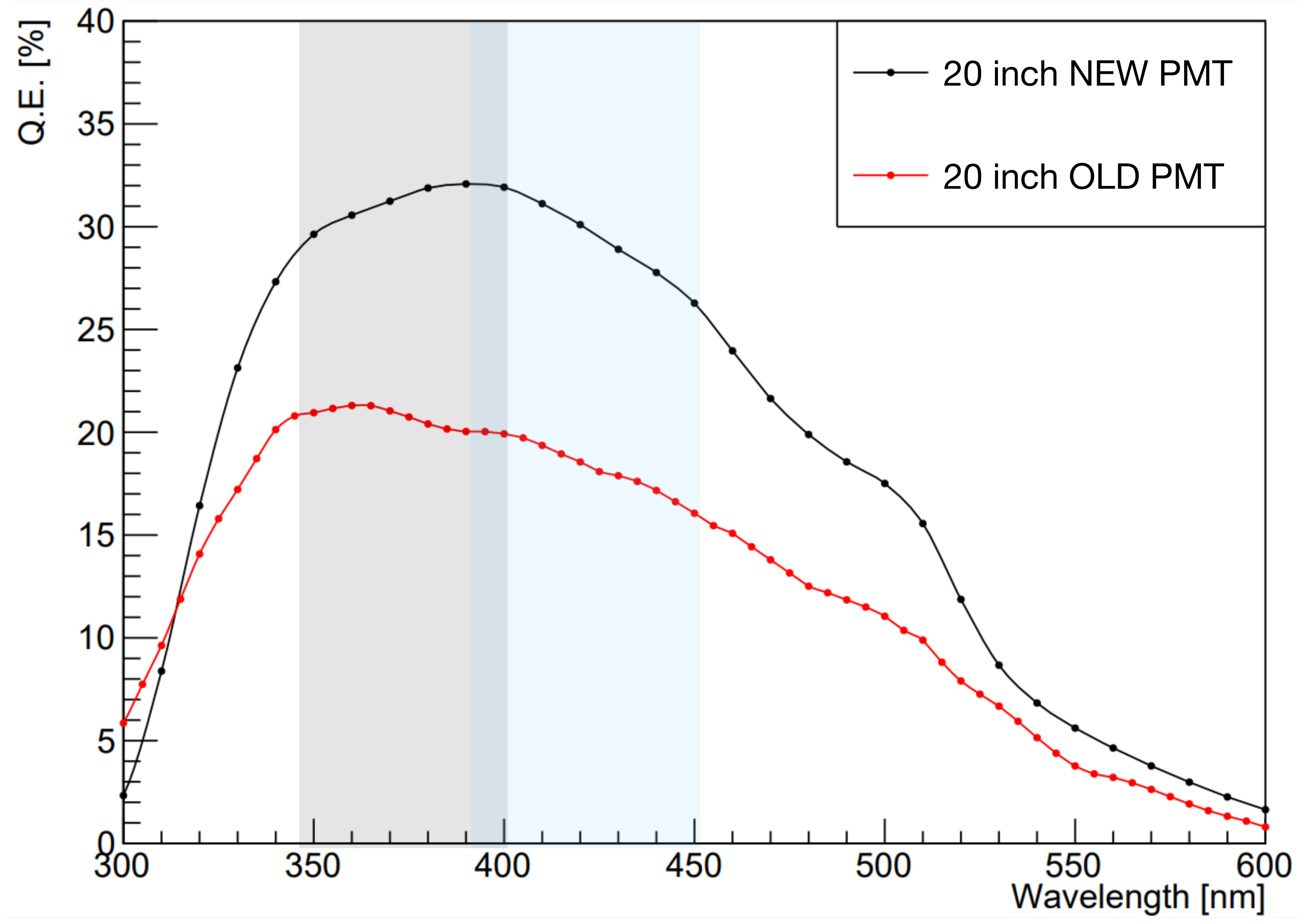
$$\text{Efficiency Factor} = \frac{\text{\#P.E. w/ Mirror}}{\text{\#P.E. w/o Mirror}} =$$

→ 1.8 times more light

PMT Performance

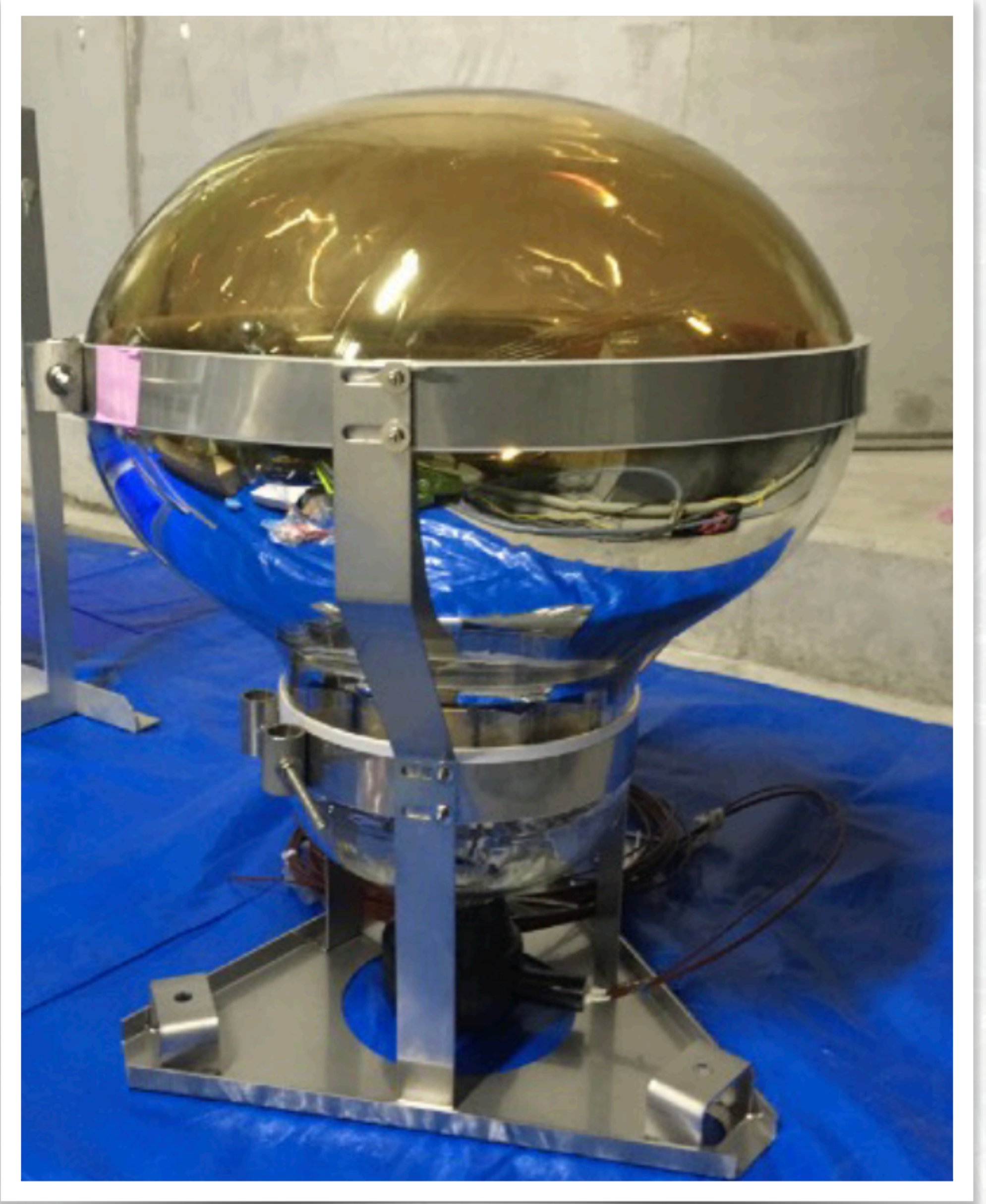
~1879 20 inch PMTs (R12860-03LXA)

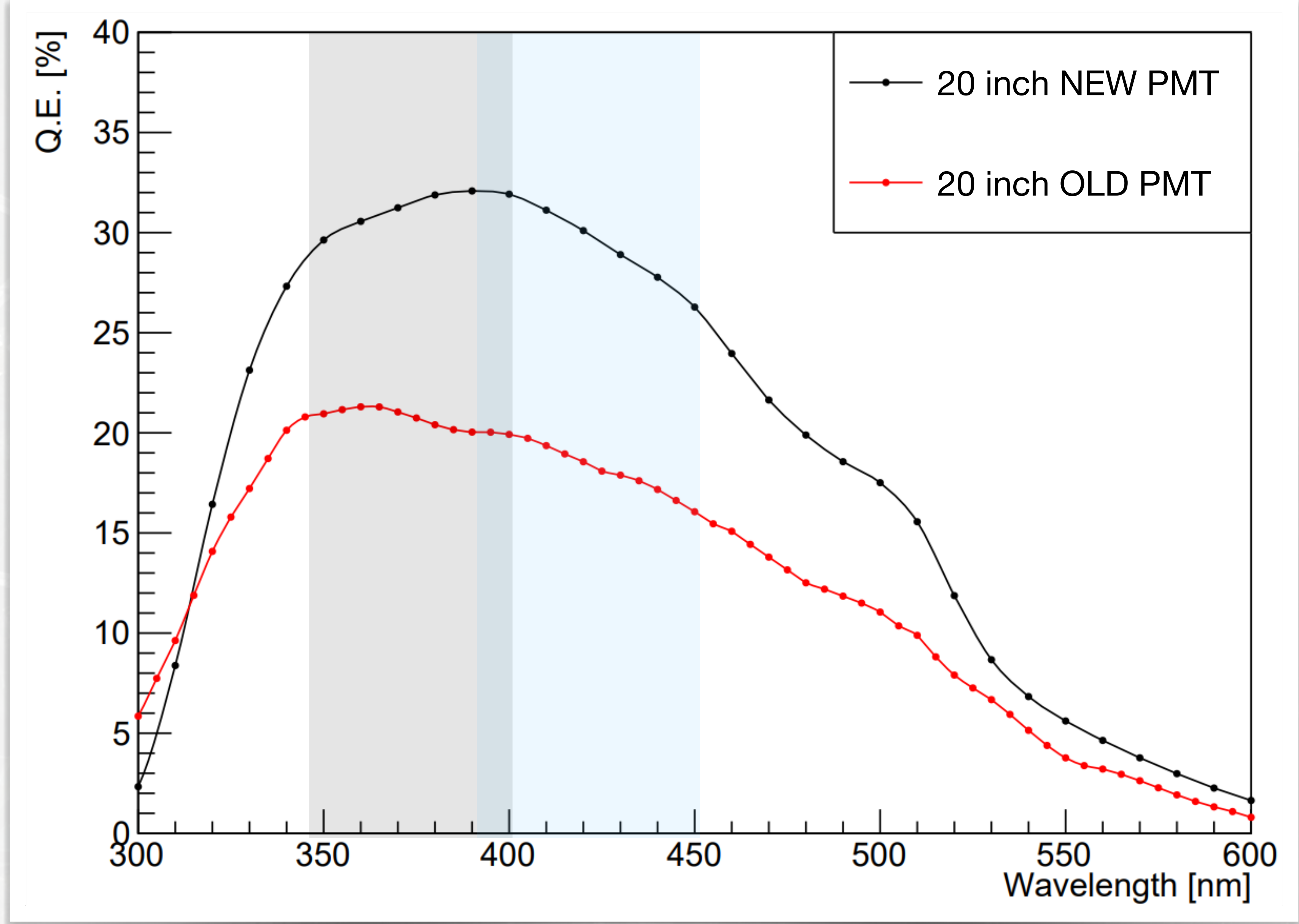




PMT Performance

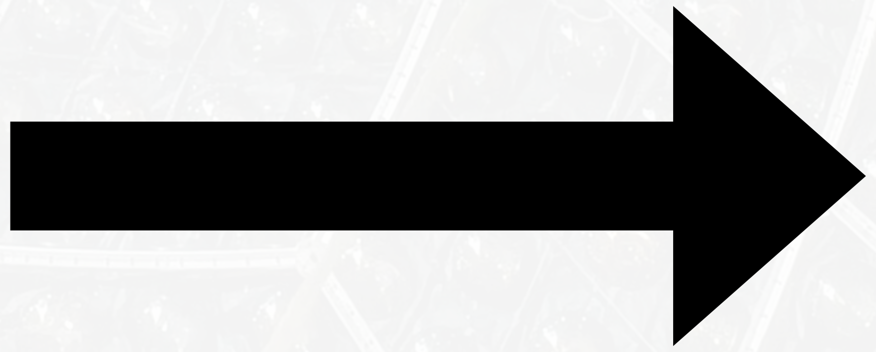
~1879 20 inch PMTs (R12860-03LXA)





PMT	20 inch NEW	20 inch OLD
QE @ 400 nm	~32 %	~20 %
Dark Pulse Rate [kHz]	8	22
Time Transit Spread [ns]	2.4	7.7

$$\text{Efficiency Factor} = \frac{\text{Q.E. New}}{\text{Q.E. Old}} =$$



~ 1.9 times more QE

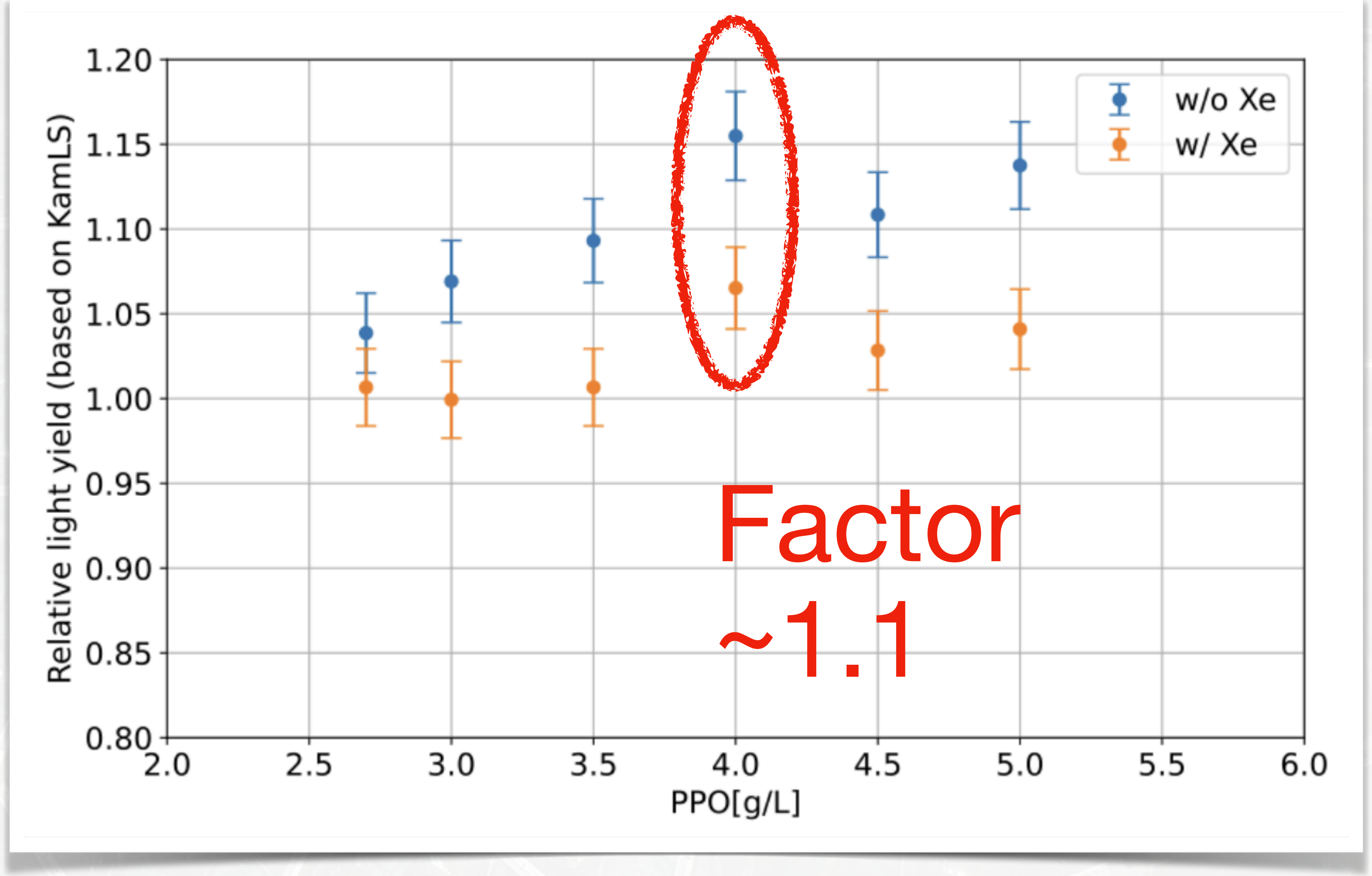
Fluor + Wavelength Optimization

More PPO + add 1,4-Bis(2-methylstyryl)benzene (secondary)

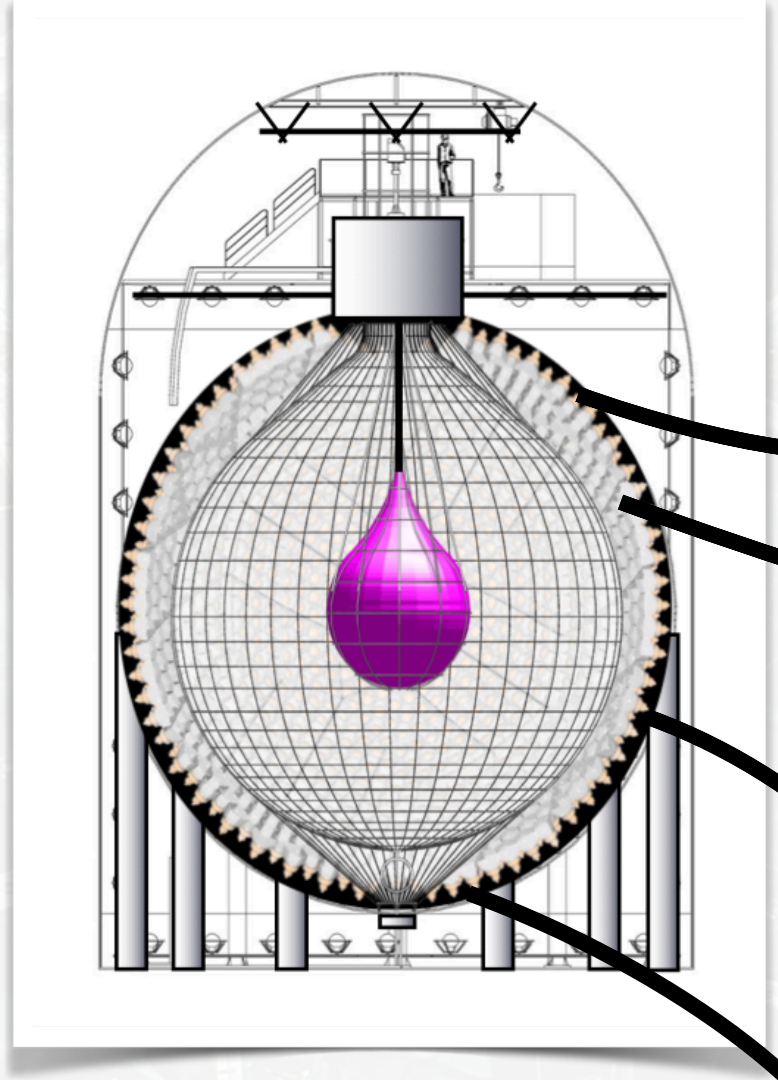
- Optimization of the PPO concentration in KamLS and XeLS

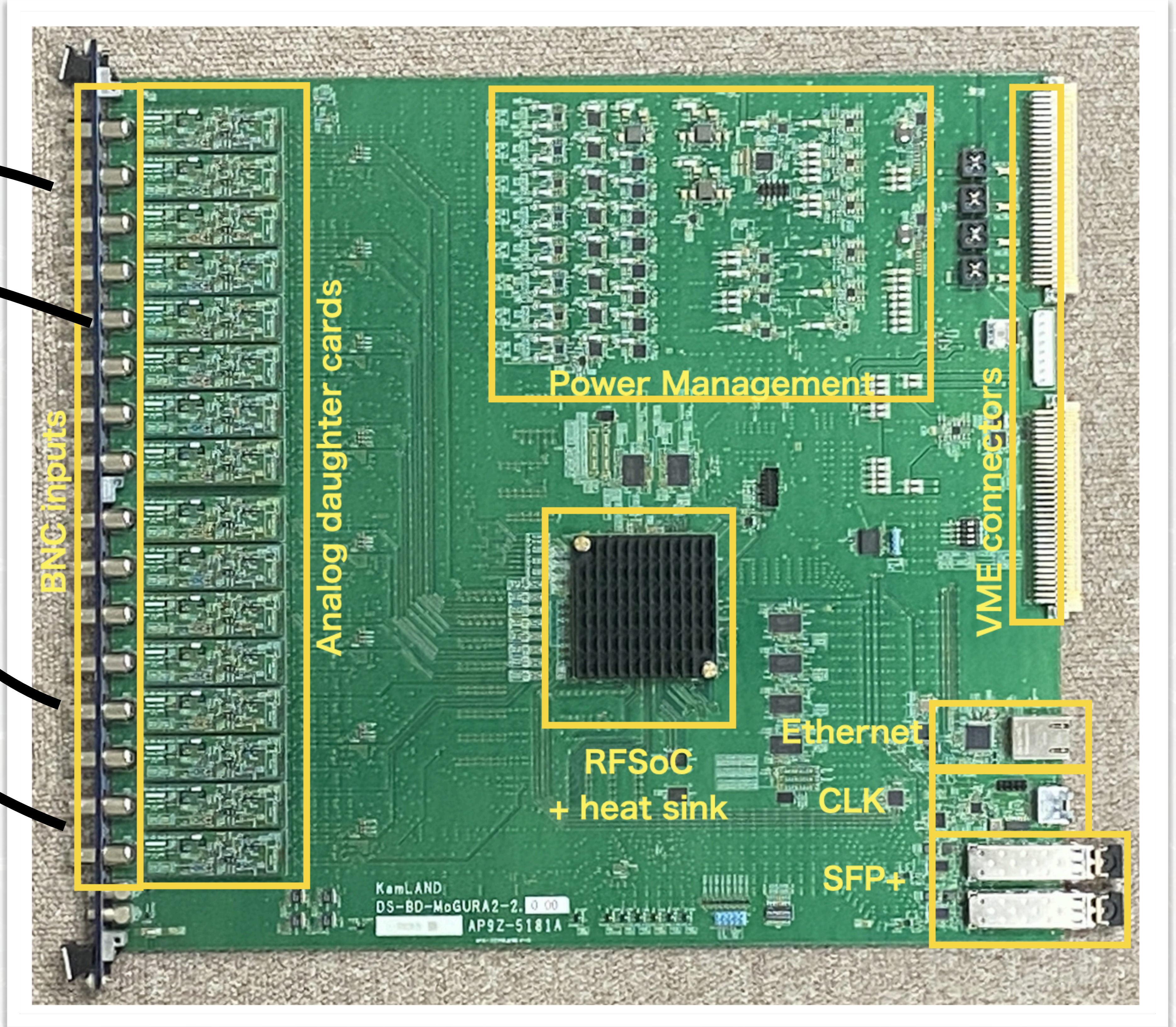
- Use bis-MSB (~ 15 mg/L) to shift emission peak from 360 to 400 nm (QE window)

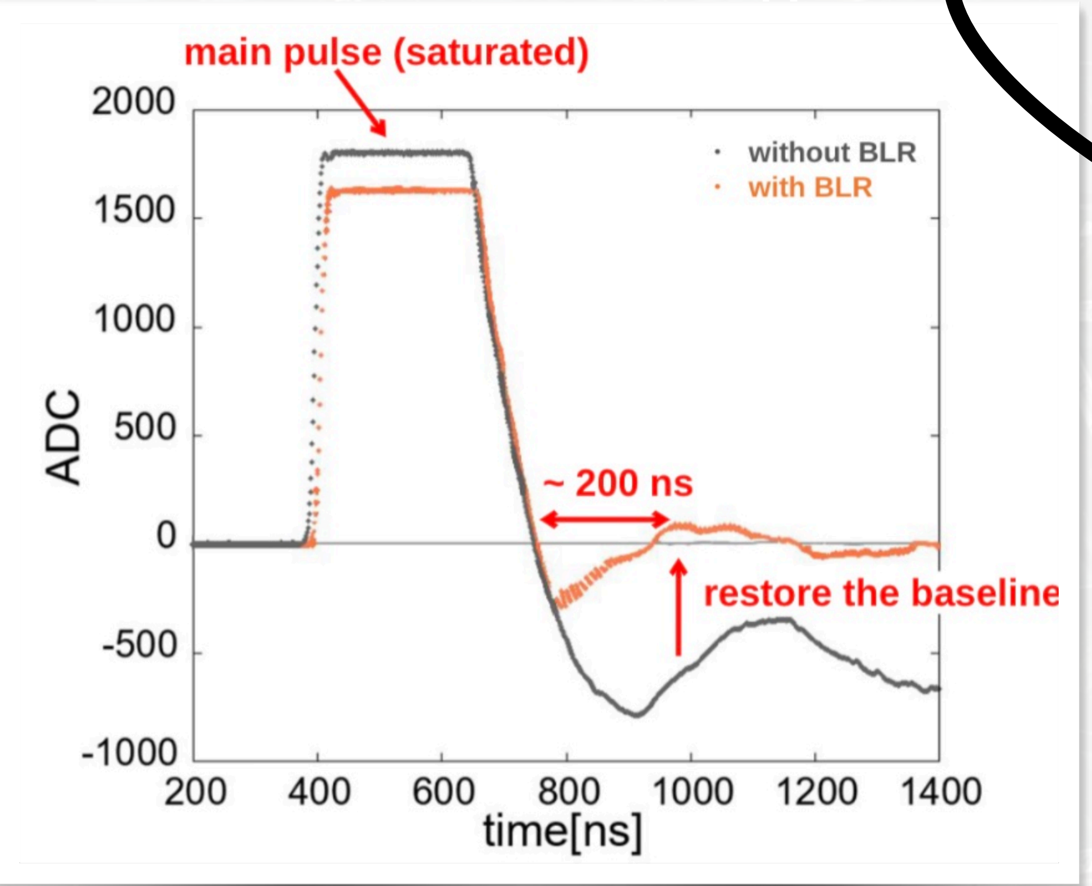
	PPO old	PPO at maximum light yield
KamLS	1.36 g/L	1.50 g/L
XeLS	2.40 g/L	4.00 g/L



Readout Electronics (MoGURA2)







Radio Frequency System-on-a-chip (RFSoC)—based readout

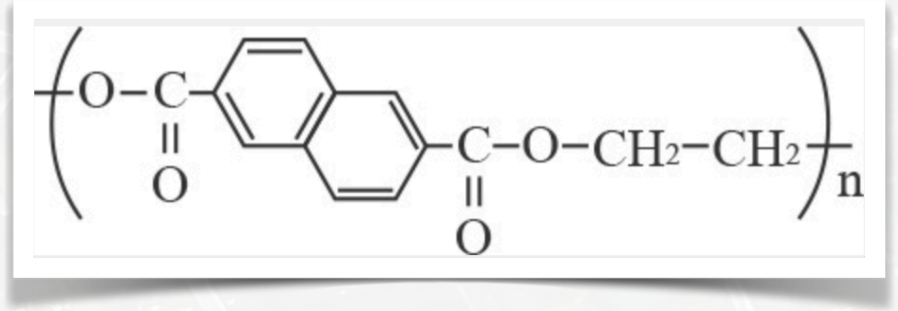
The Analog Front-End conditions the PMT waveforms to feed the signal into the RFSoC-ADC

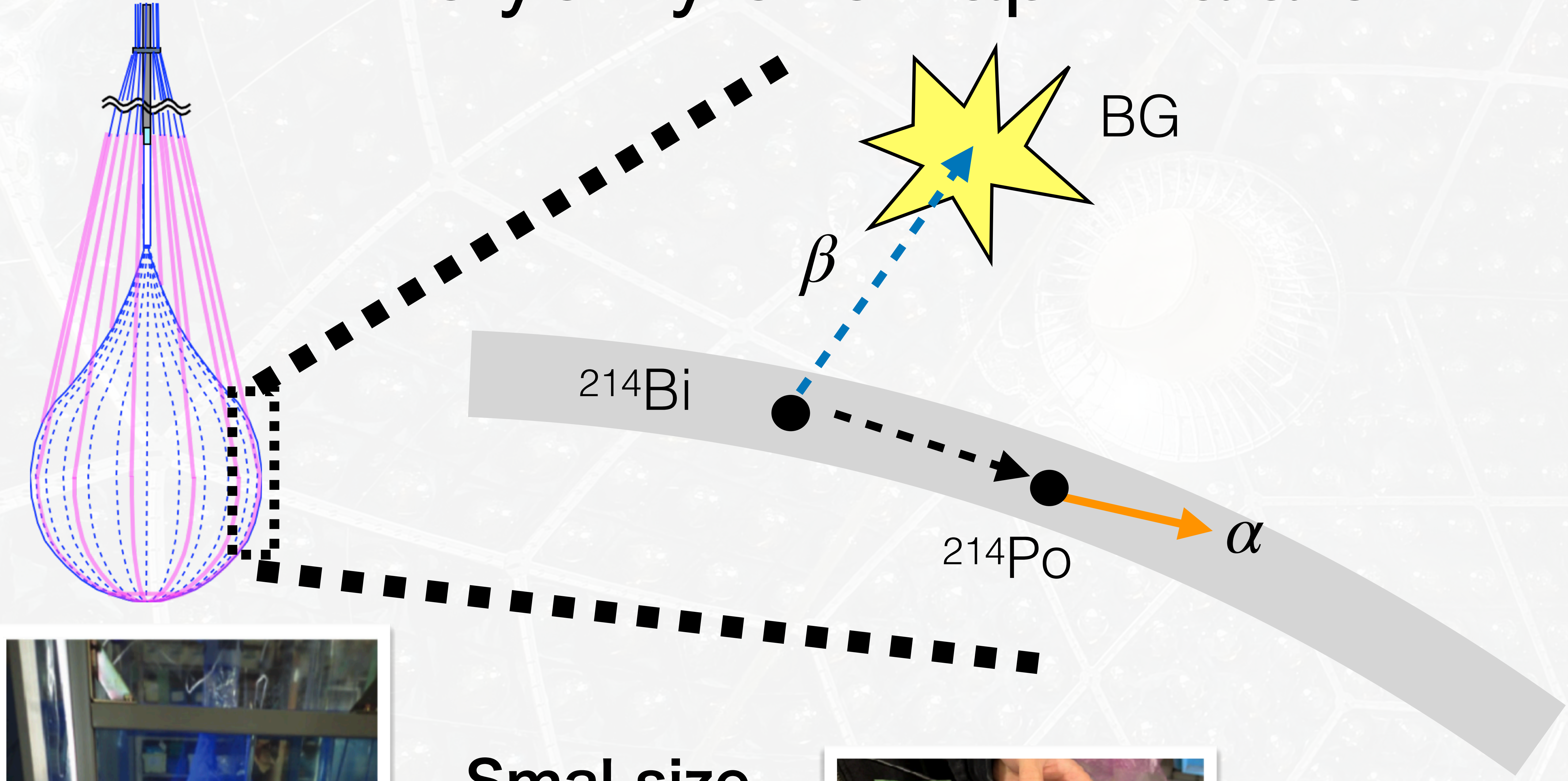
Zero-deadtime electronics to improve spallation neutron tagging
→ Short- and Long-Lived Tagging

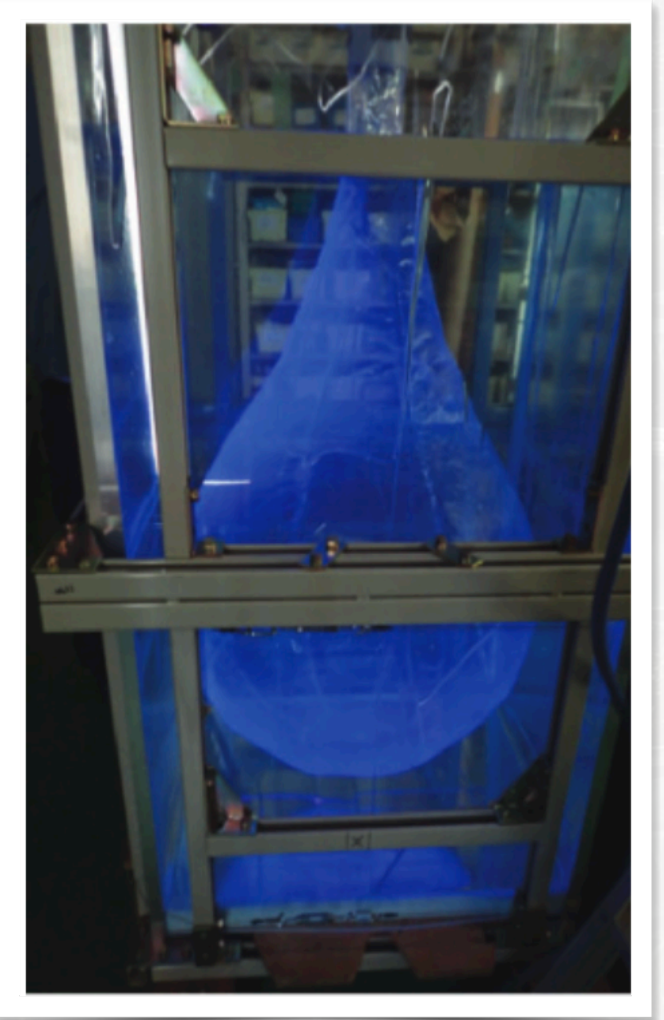
Improve Tagging Efficiencies (n, LL)

Scintillating Balloon → PEN

PEN = Polyethylene naphthalate



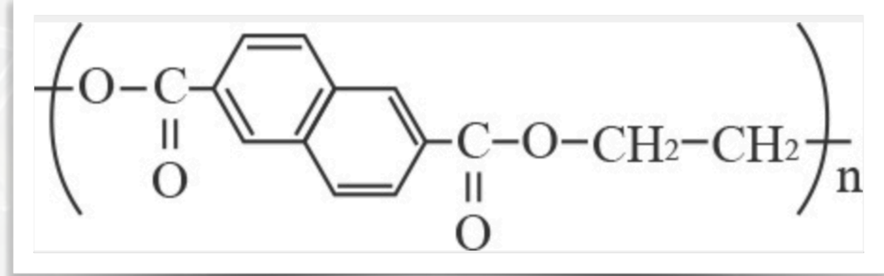




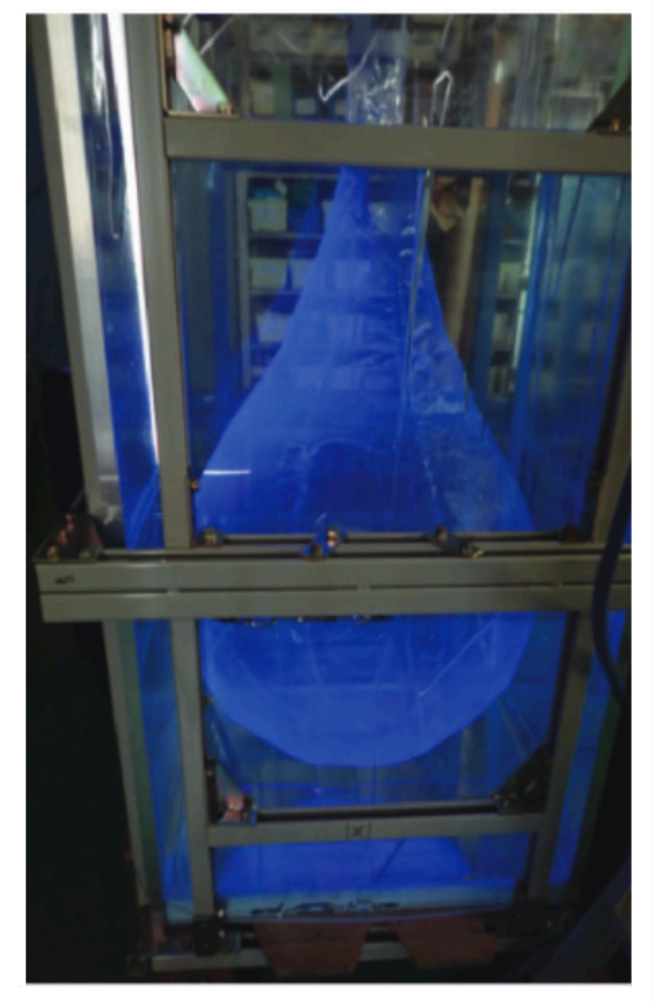
Smal size prototype balloon (In water + UV light)

Scintillating Balloon → PEN

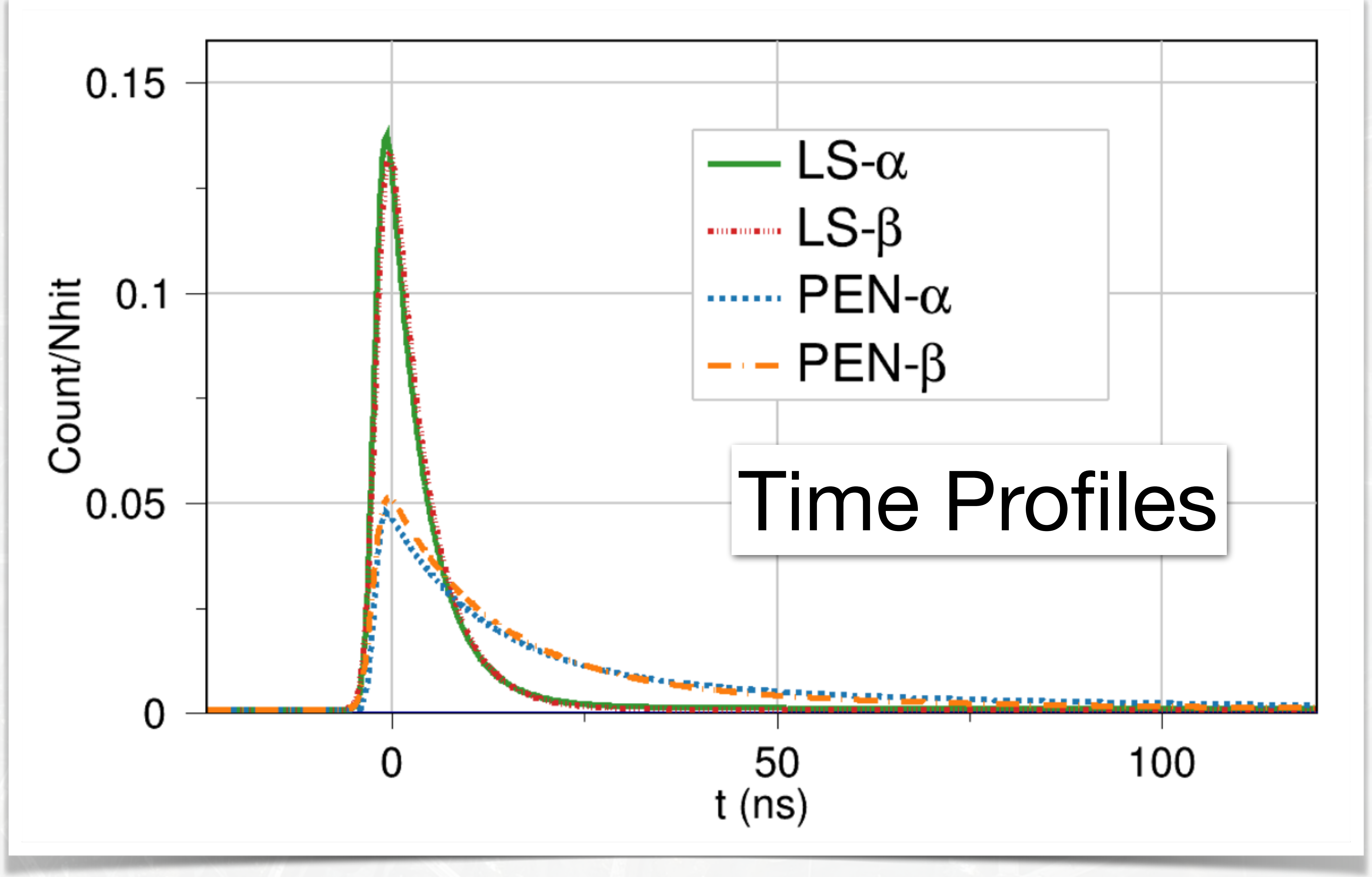
PEN = Polyethylene naphthalate



Distinguish LS (XeLS,KamLS) and IB
(despite $> 99\,\%$ Bi-Po Efficiency)
→ Powerful

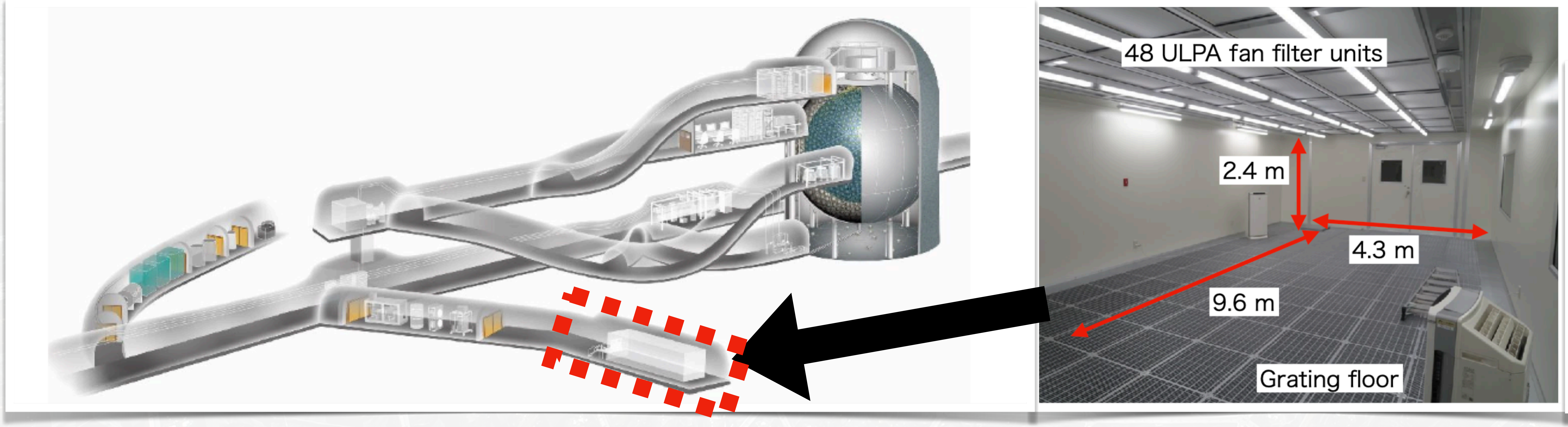


Smal size prototype balloon (In water + UV light)



KERNEL — Clean Lab

KERNEL = Kamioka Extremely Rare phenomena and Neutrino research Lab



„Cleanest“ Category

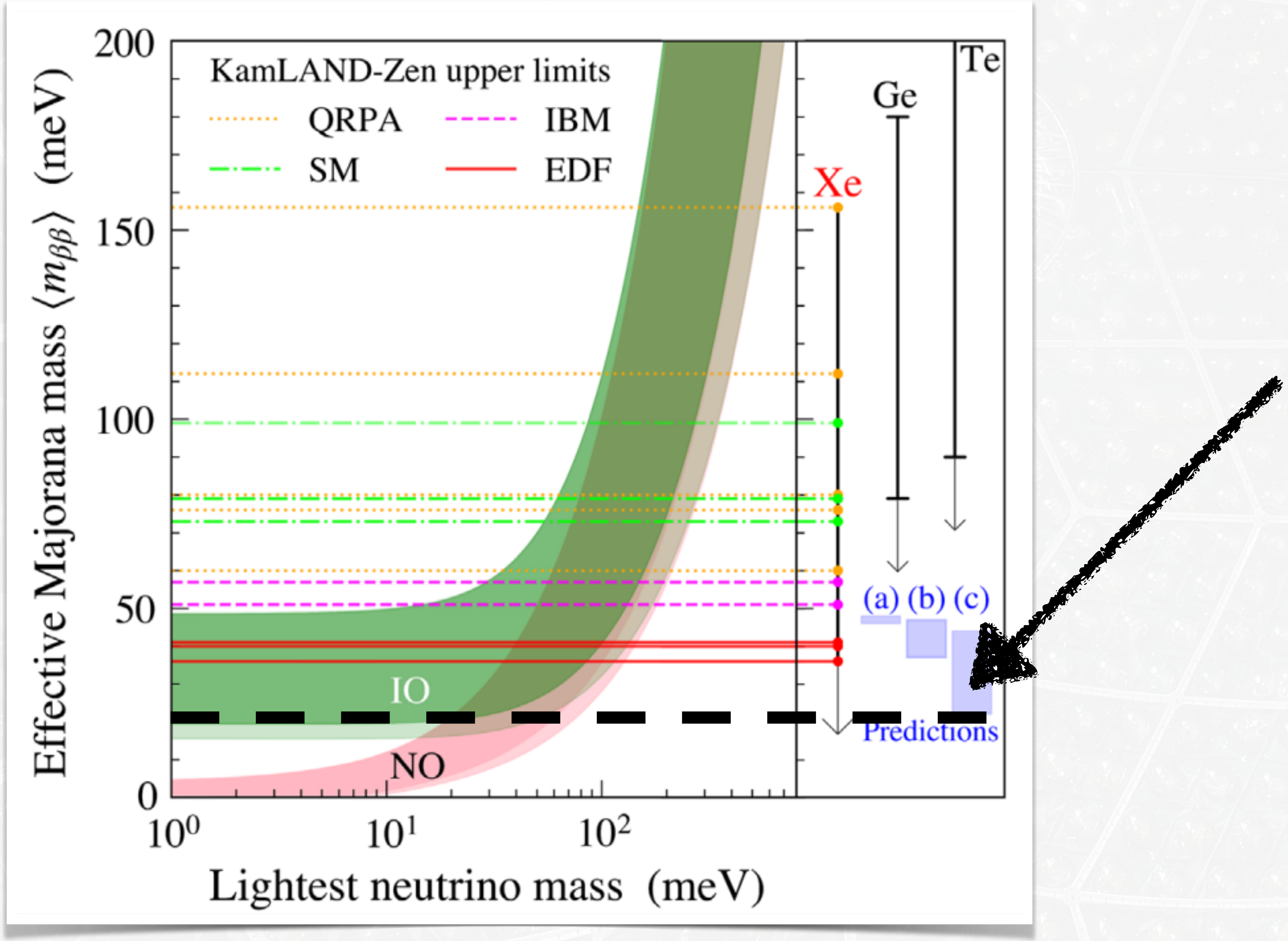
ISO14644-1	0.5 µm [particles/m³]	0.1 µm [particles/m³]
Class 8	3,520,000	
Class 7	352,000	
Class 6	35,200	1,000,000
Class 5	3,520	100,000
Class 4	352	10,000
Class 3	35	1,000
Class 2	0	100
Class 1	0	10

- Super Clean Room (ISO14511-1 Class 1)
- Depth = 1km from top of mountain
- For development of ultra-low-radioactivity materials

APPLICATIONS

- Fabrication and cleaning of detector components
- High-purity metal refining

KamLAND2-Zen Target $0\nu\beta\beta$ Half-Life

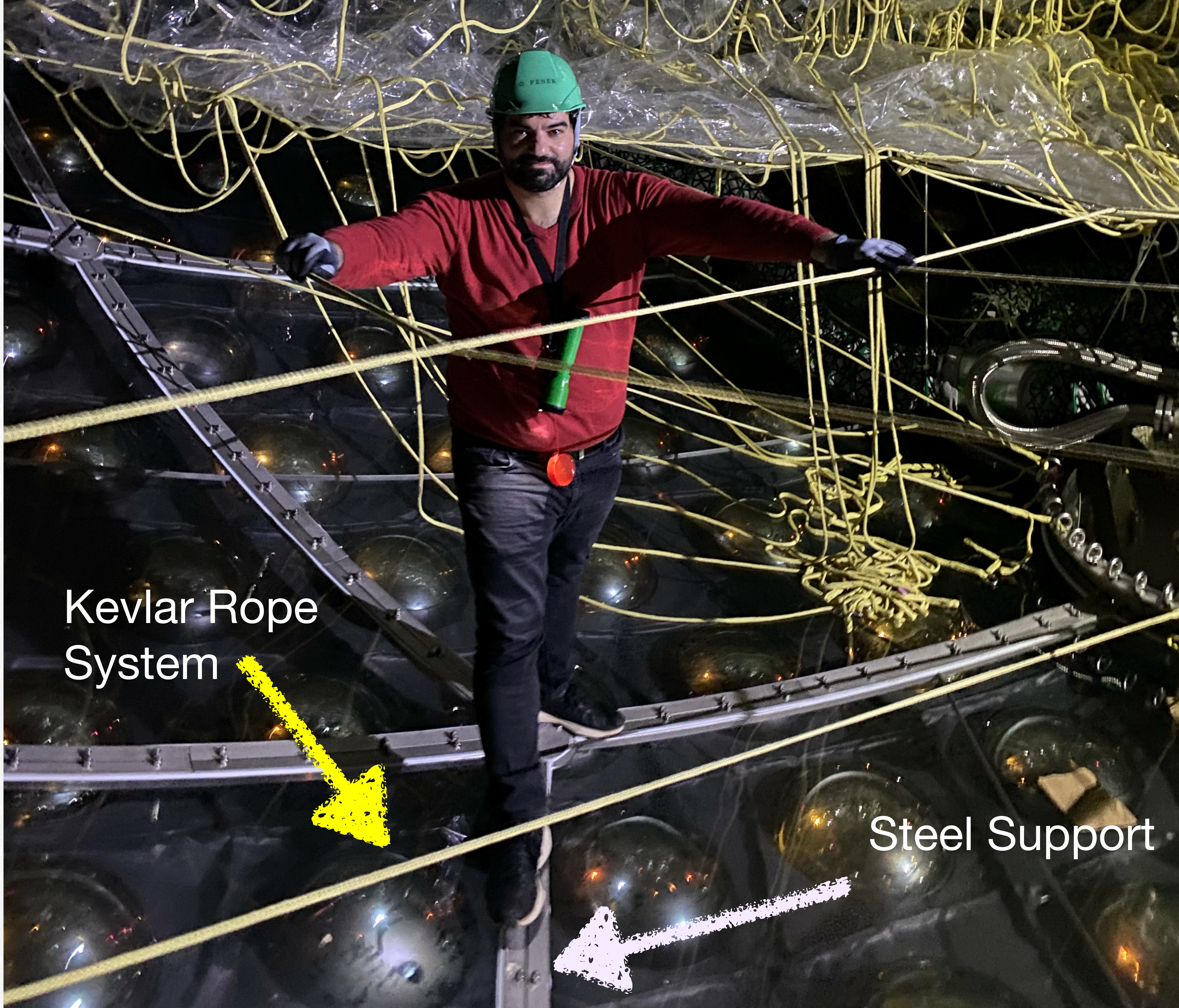


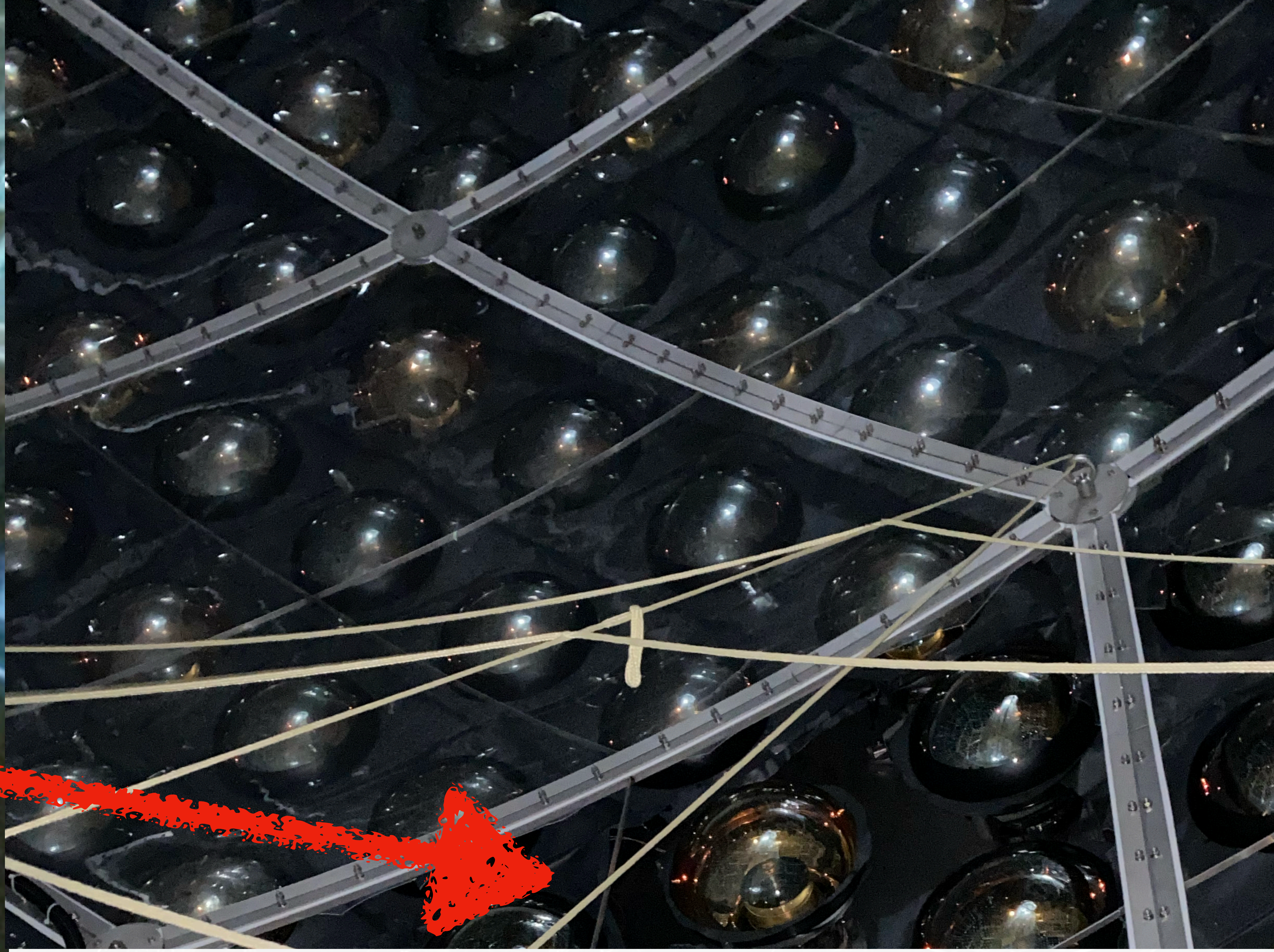
- Energy Resolution $4\,\% \rightarrow 2\,\%\,@2.458$ MeV
- Cover IO region almost completely (NME precision)
- Target mass limit $\left\langle m_{\beta\beta} \right\rangle \sim 20$ meV / 5 Years
- Target half life limit for 5 Years $T > 2 \times 10^{27}$ years (90% C.L.)

KamLAND2-Zen → Construction

Entering the detector

Use this chance to make a photo





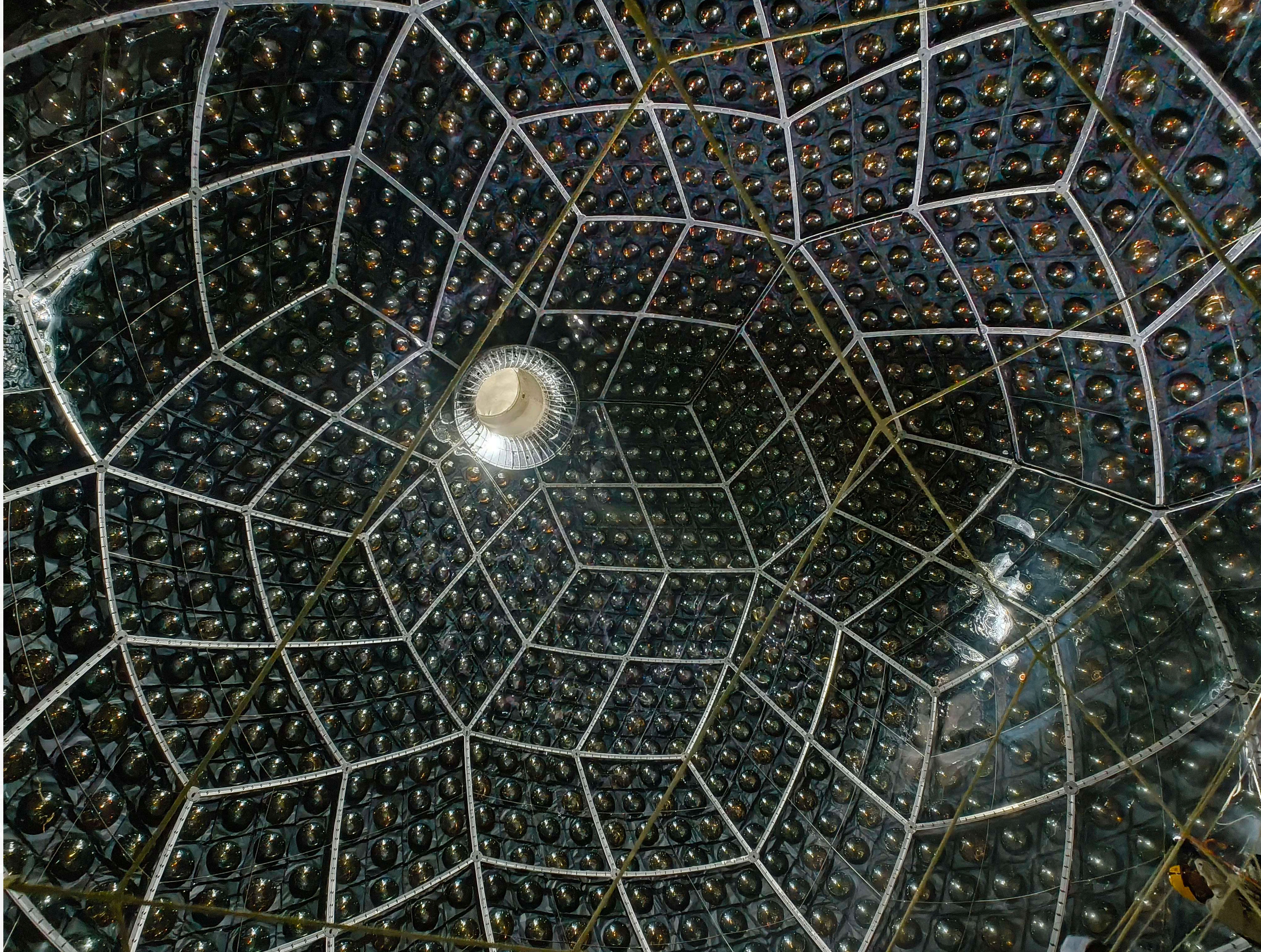
First acrylic plate removal campaign ~2025

Outer balloon removal campaign ~ 2025

Outer balloon „watch“

Poster 2/488
Natsu Obata-san

Inner view without balloon

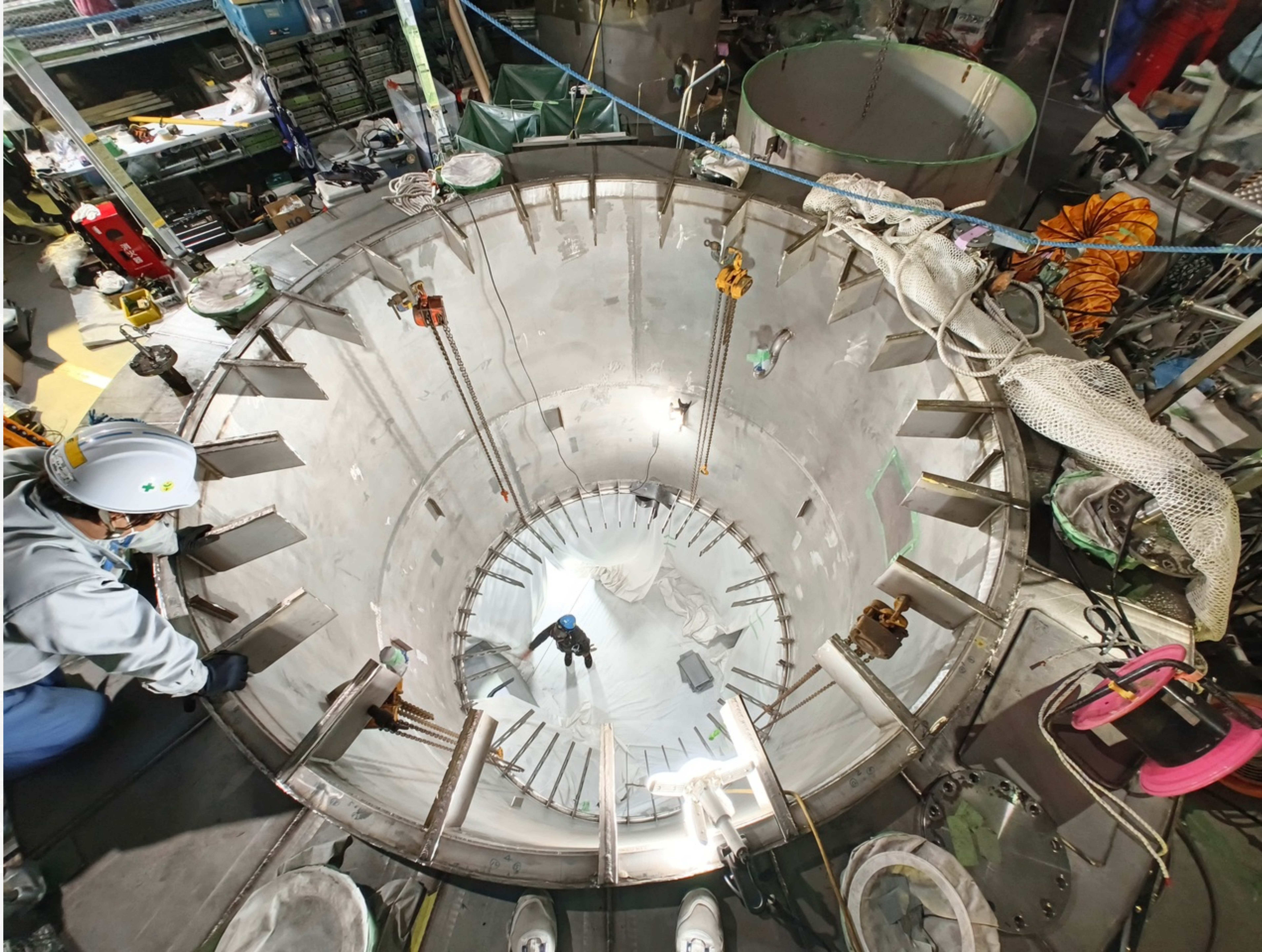


PMT disassembling ~2025-2026

PMT transport

Destroying PMTs

Detector completely emptied

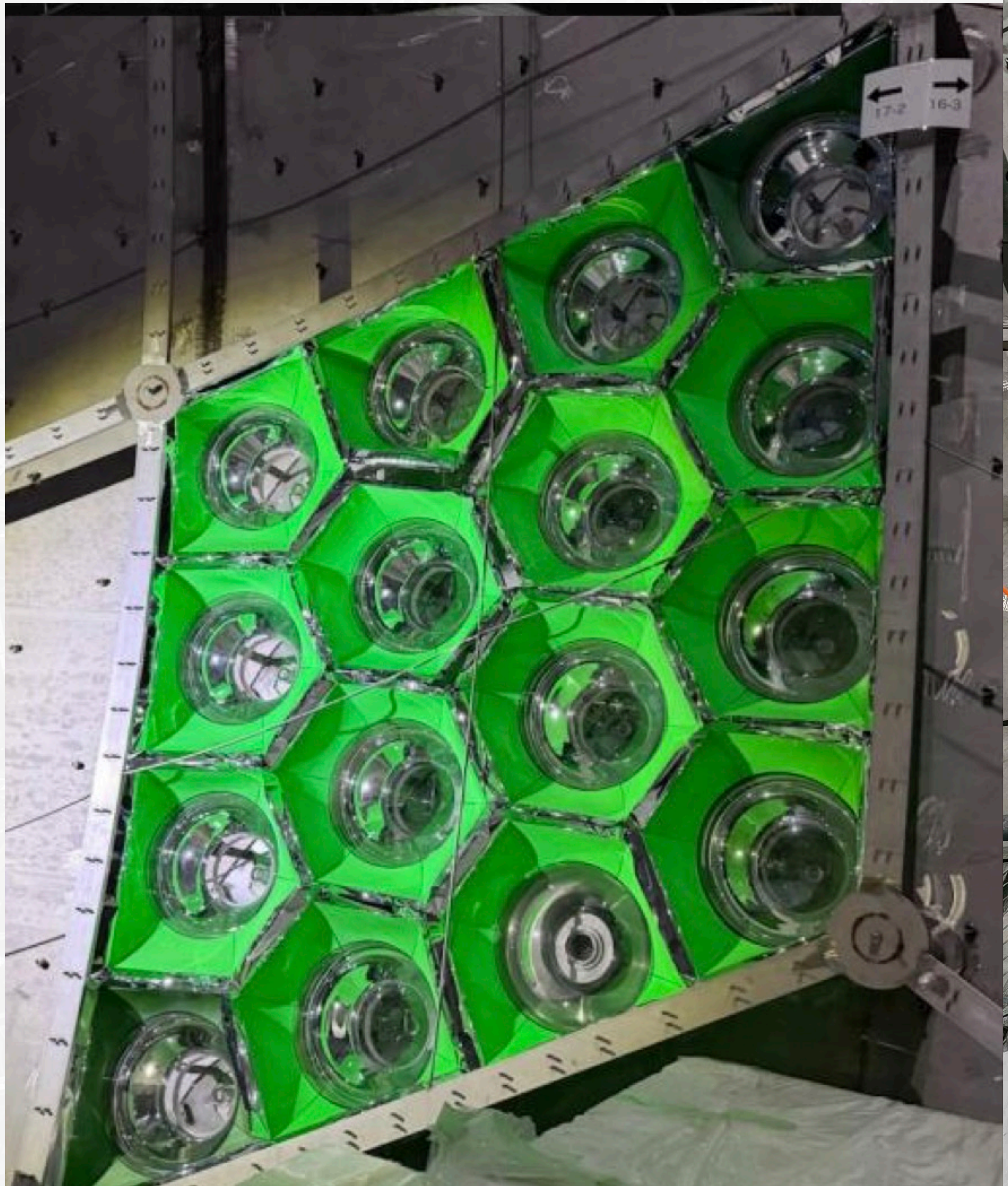


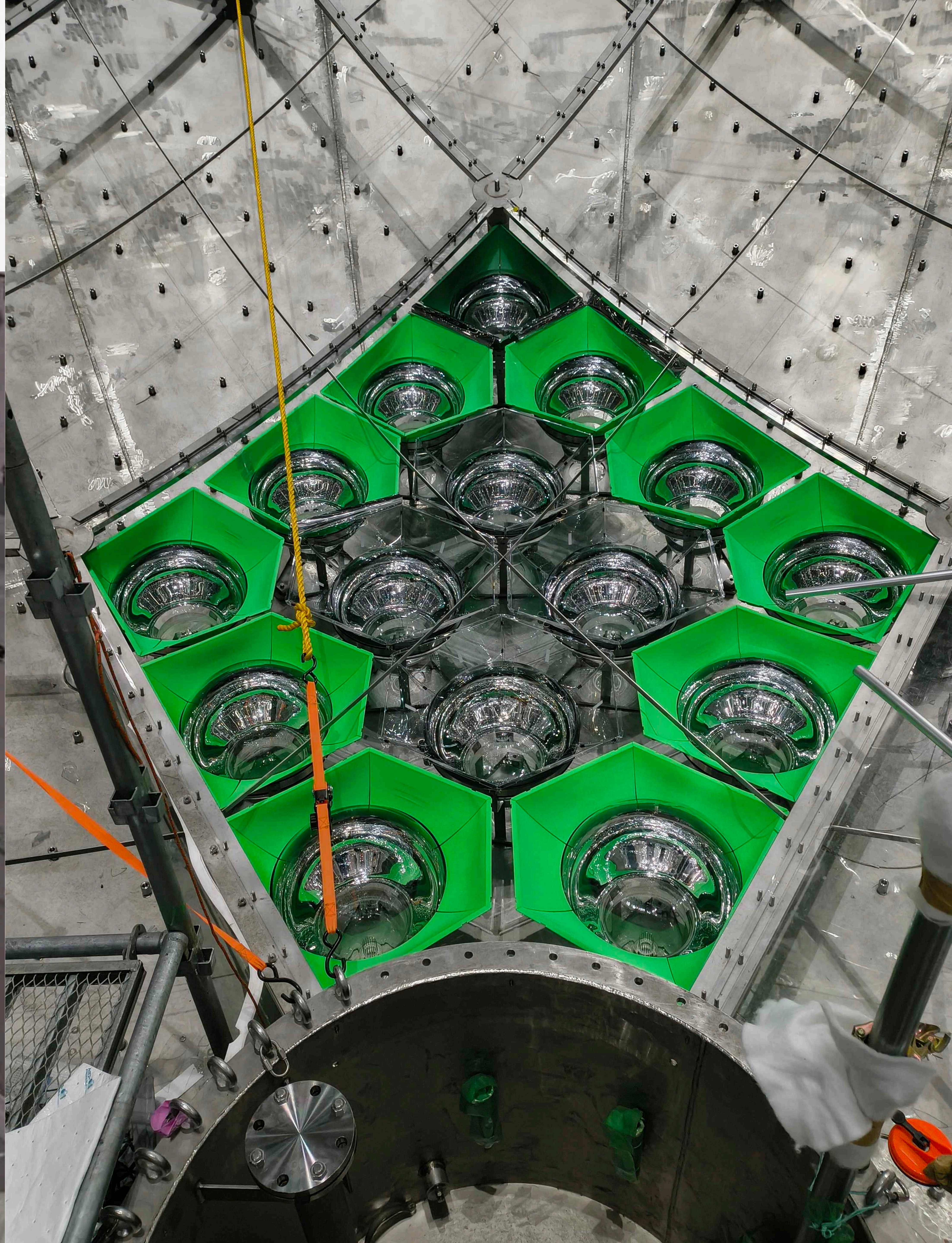
360° view incl. mock-up

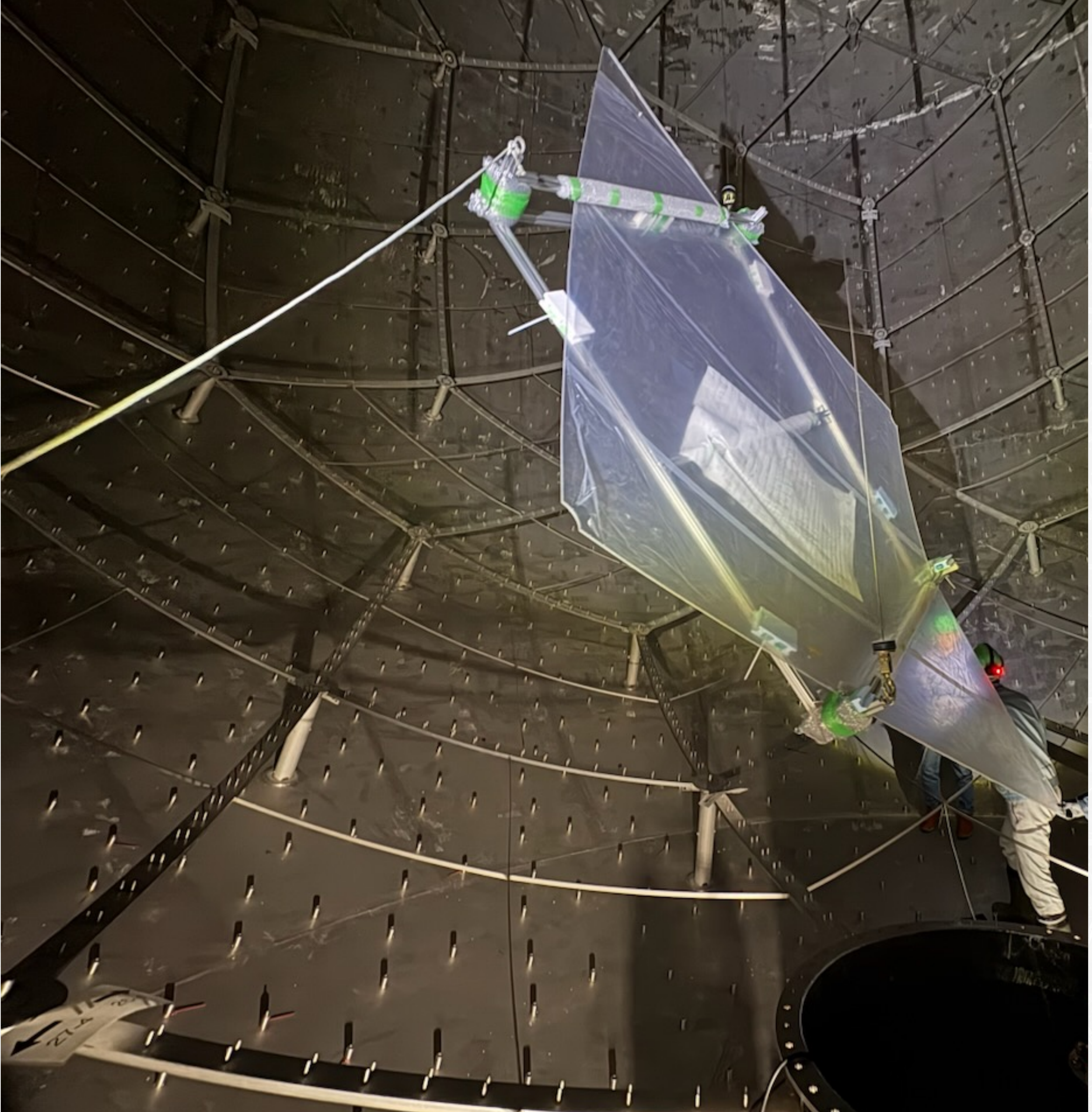
Mock-up installation

Mock-up installed

Different diamond locations







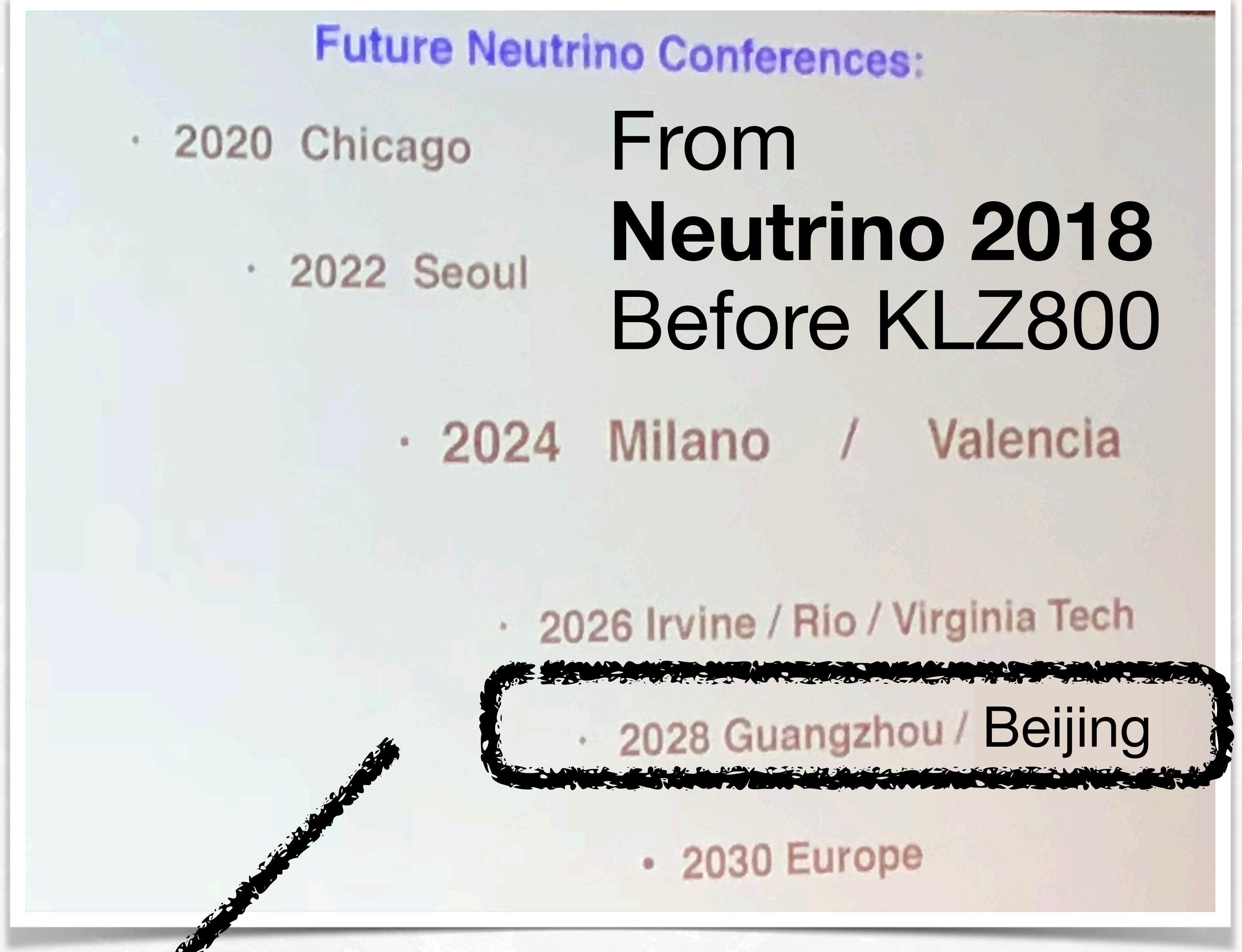
Installing new acrylic plates

Summary and Outlook

- KamLAND-Zen demonstrated that Xenon-loaded liquid scintillator can scale to leading sensitivity
- KamLAND2-Zen keeps that scalable isotope source but upgrades the detector response around it
- Construction is underway to allow us to push beyond 10^{27} years

Summary and Outlook

- KamLAND-Zen demonstrated that Xenon-loaded liquid scintillator can scale to leading sensitivity
- KamLAND2-Zen keeps that scalable isotope source but upgrades the detector response around it
- Construction is underway to allow us to push beyond 10^{27} years
- Main DAQ Start 2028 (Fiscal Year 2027)



… Nu 2028 …

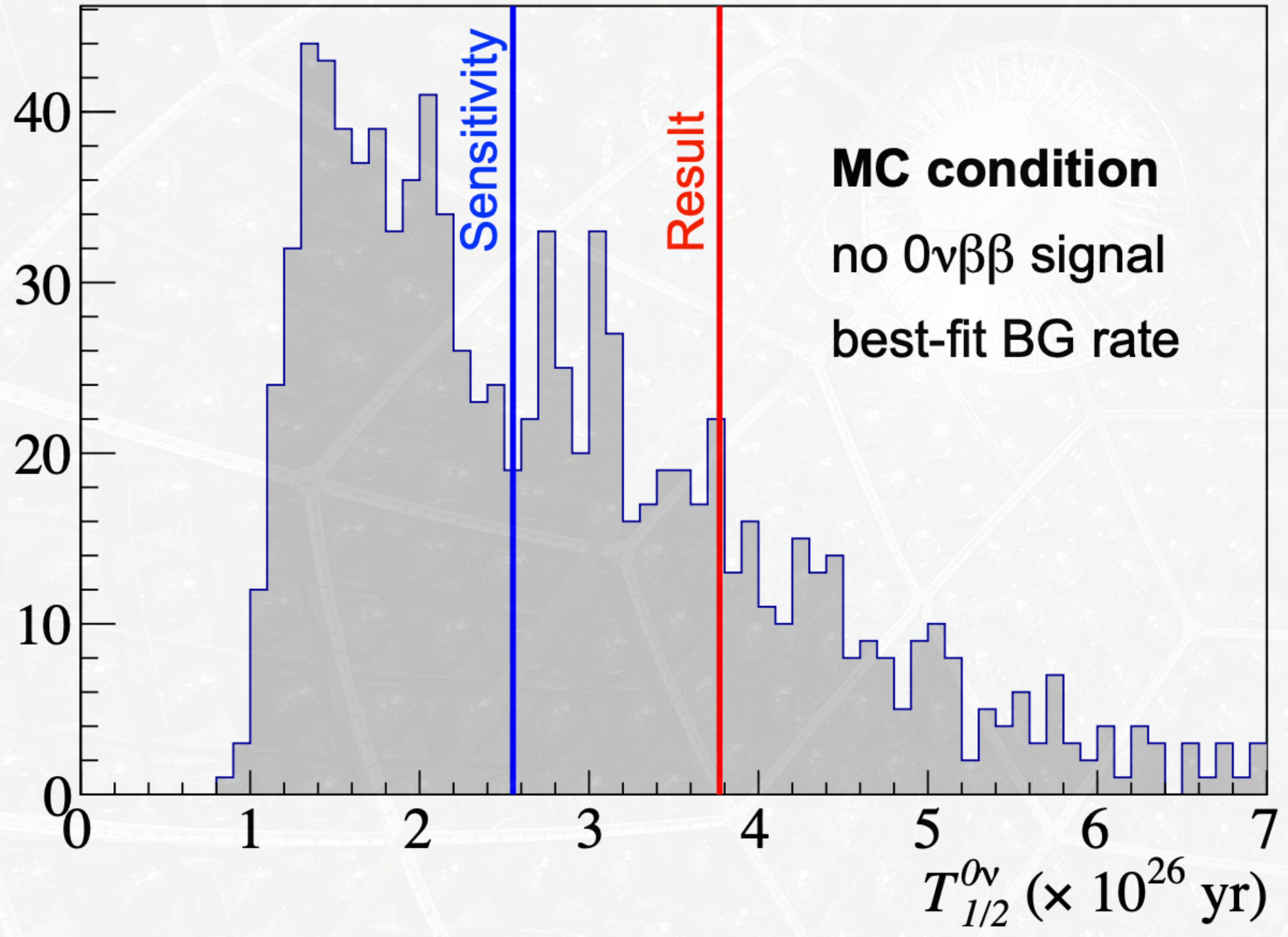
Thank You

Backup

Left intentionally blank

Sensitivity vs. Limit

distribution of 0νββ limits at 90% C.L. from Toy MC



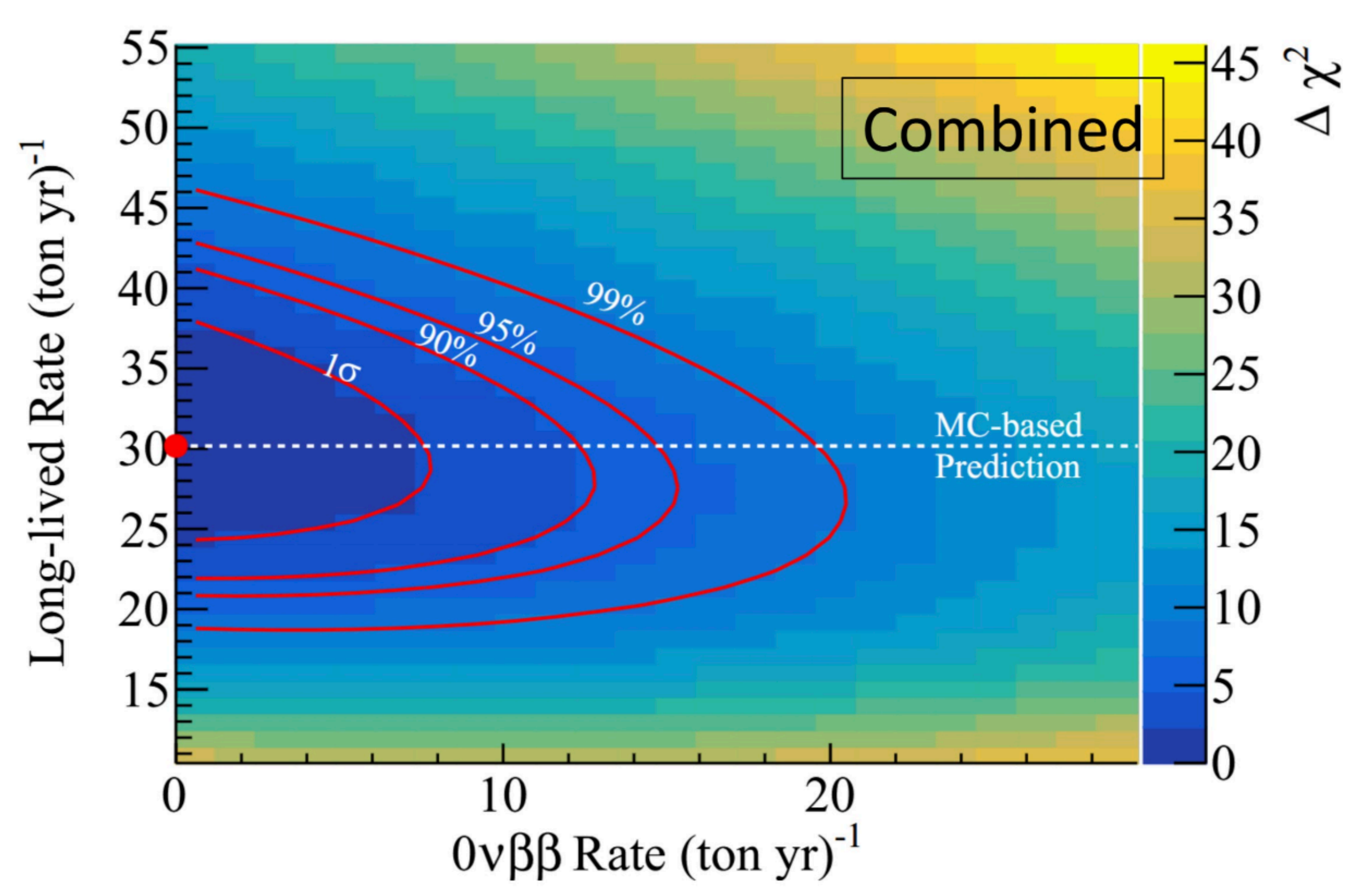
$T^{0\nu}_{1/2} > 3.8 \times 10^{26}$ yr   29% of the time

$T^{0\nu}_{1/2} > 2.6 \times 10^{26}$ yr   50% of the time

Sensitvity checked by MC assuming best-fit BG rate

Many Thanks to Itaru Shimizu

KLZ-400 + KLZ-800 Combined Fit



Combining $\Delta\chi^2$ Profiles of KLZ-400 and KLZ-800

Many Thanks to Haruhiko Miyake

RFSoC vs. Conventional

RFSoC

Versus

FPGA-plus-ADC
with
TCP logic core

⟷

Overkill in terms of raw performance but price difference not very high

HV System

Needs high-speed serial links between FPGA and **external ADCs**

Increase of heat dissipation

≫ cooling issue ≪

ΔPrice not high proceed with RFSoC to reduce heat generation and relax requirements on the cooling

HV and Front-End Electronics will be integrated
in E-hut
→ Heat Dissipation strong requirement

Many Thanks to Koji Ishidoshiro

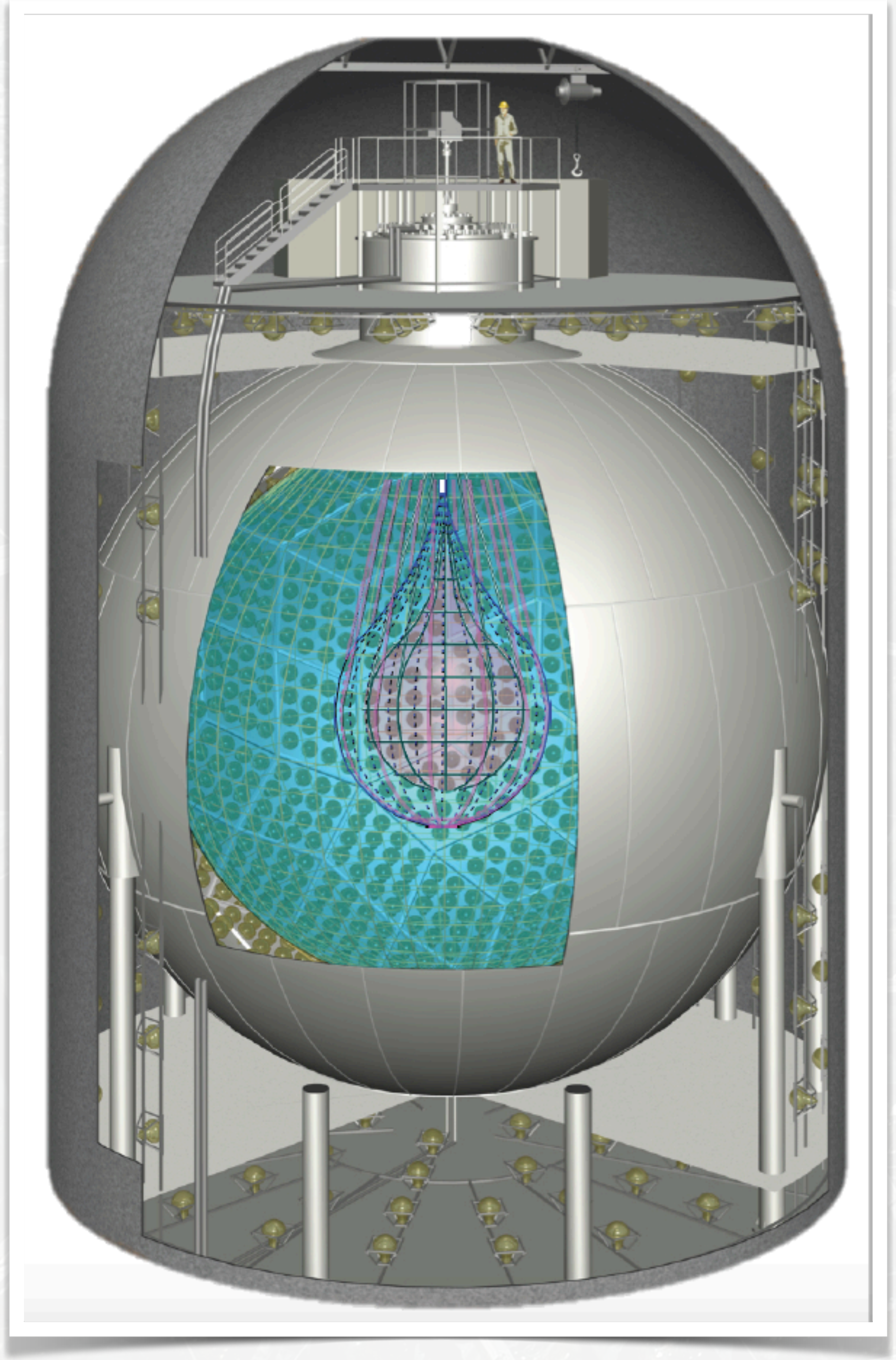
Status on the Liquid Scintillators

- No calibrations planned for the XeLS

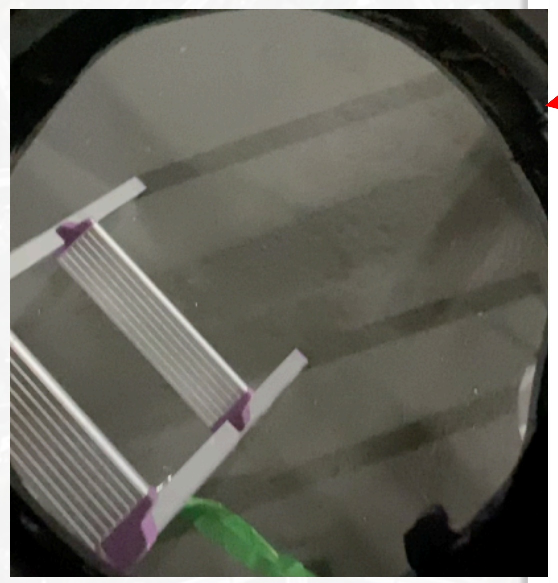
- Ongoing
  PPO increase linked to budget situation
  Reduction of U/Th
  Consequences of adding bis-MSB
  → Re-emission from larger balloon might impact event reconstruction
  → Mis-reconstruction effect has to be marginal

Many Thanks to Yasuhiro Kishimoto

Turning KamLAND into a $0\nu\beta\beta$ Detector

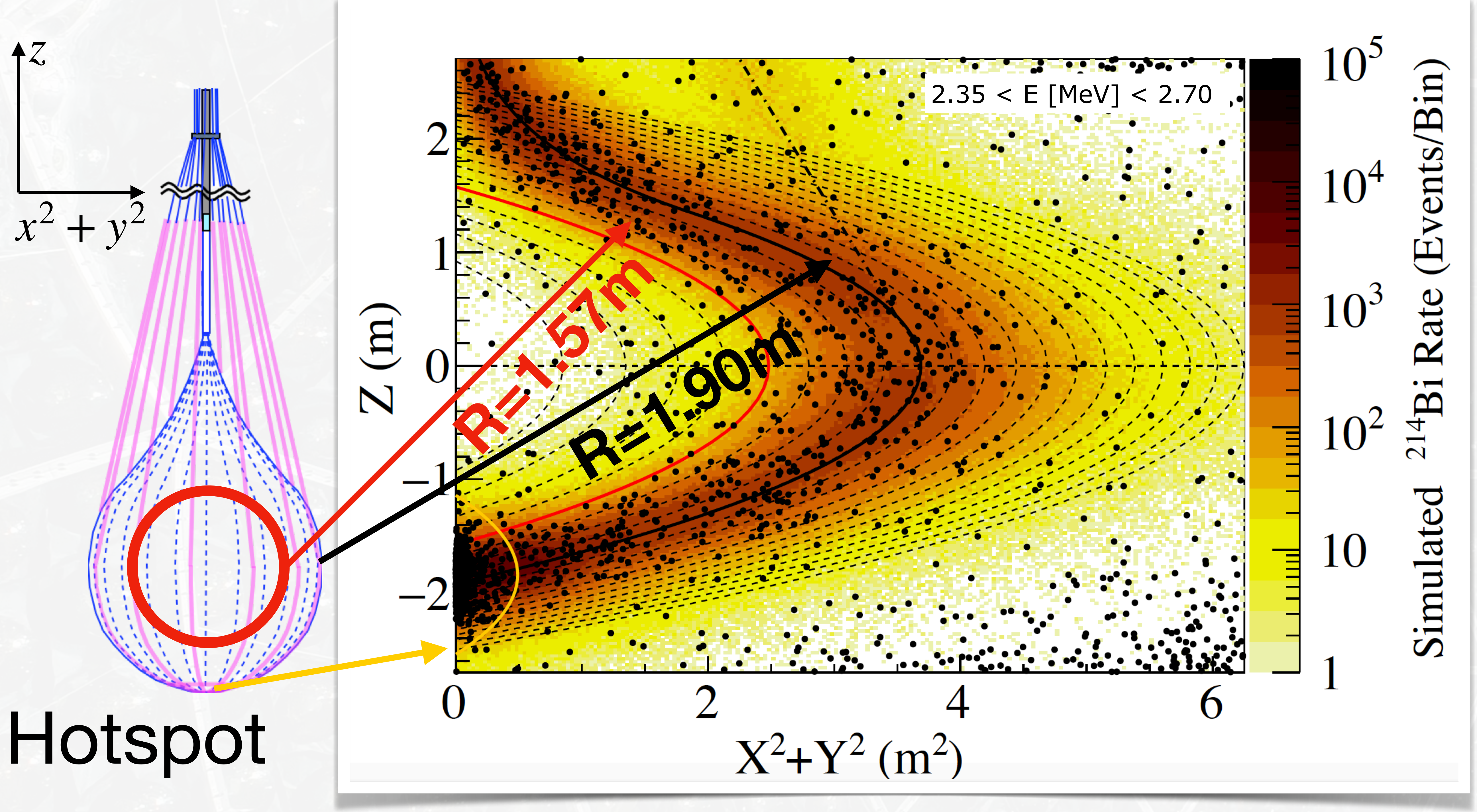


Inner
Top View



Inner View

Selection Cuts



Fiducial Volume R<2.5m
+ hotspot and deadtime removal

μ and μ + dT < 2 ms veto

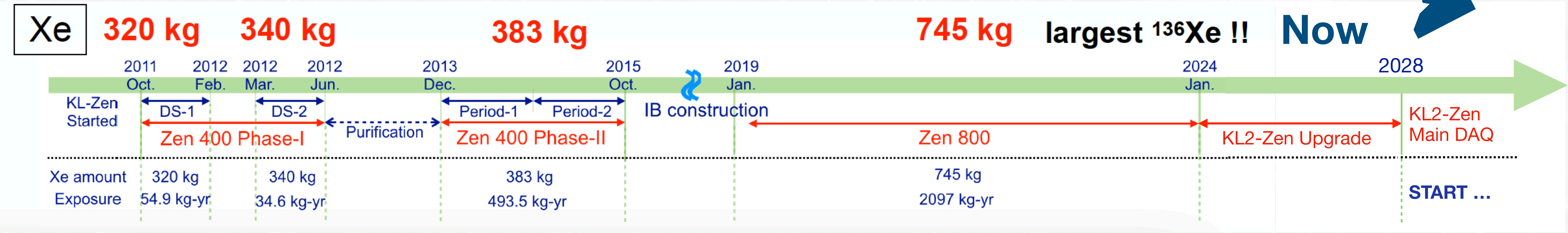
Bi-Po veto —> delayed coincidence
(prompt Bi, delayed Po <=> 2 Pulse)
—> (dt,dr) = (1.9 ms, 1.7m)

Reactor nu and e+ and nH gamma veto

Bad Reco Veto (bad vertex-time-charge)

Analysis Data
Long-Lived Data (LD) = Classified as Muon Spallation products with $\tau \geq 100$ sec
Singles Data (SD) = not LD classified Data $\rightarrow 90\,\%$ Exposure

KamLAND-Zen *Timeline*



Zen 400 Phase-I

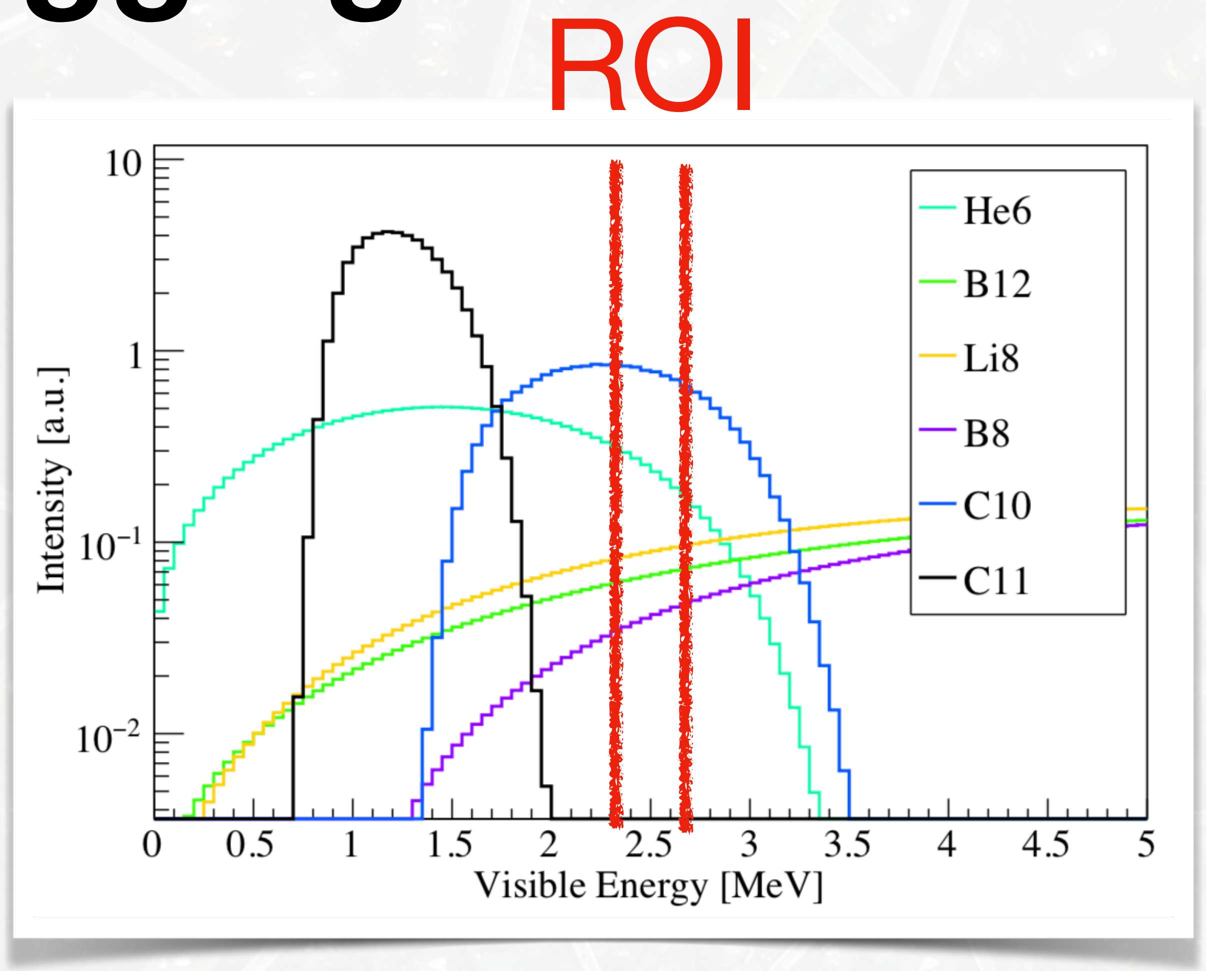
Zen 400 Phase-II

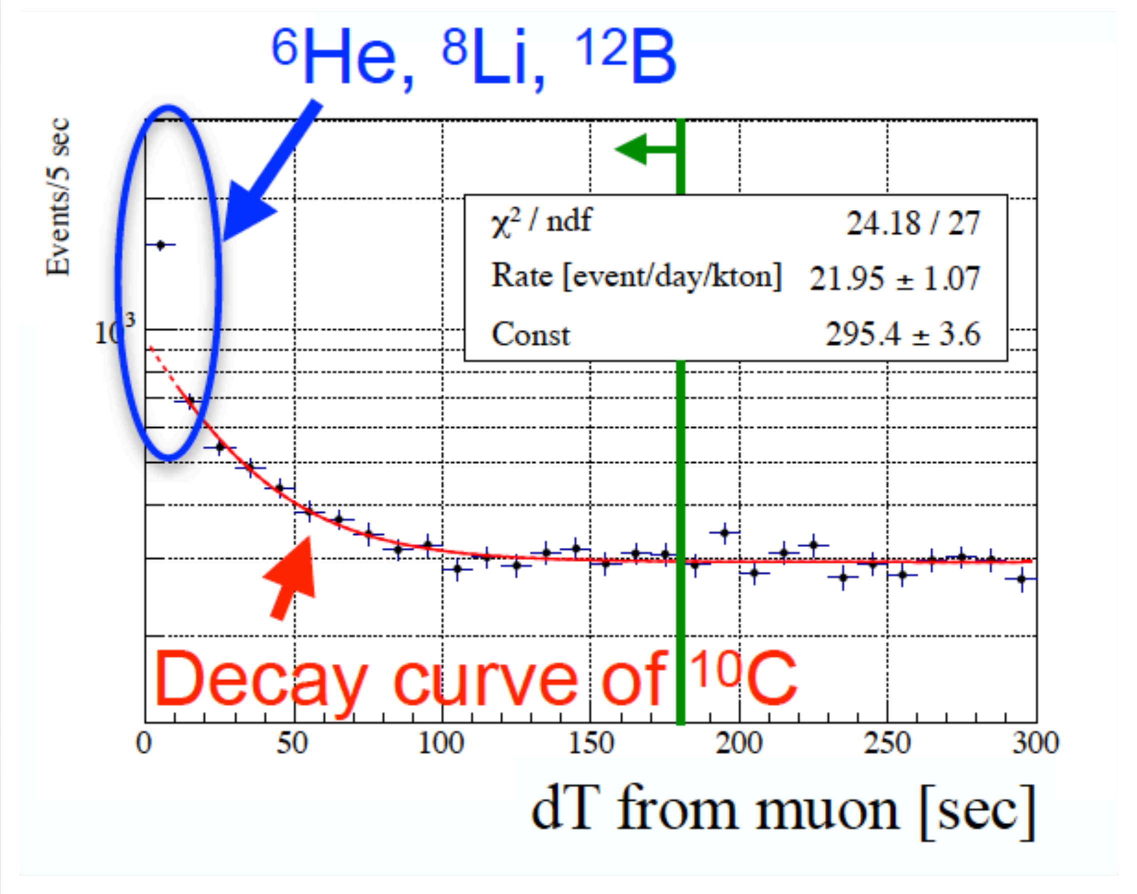
Zen 800

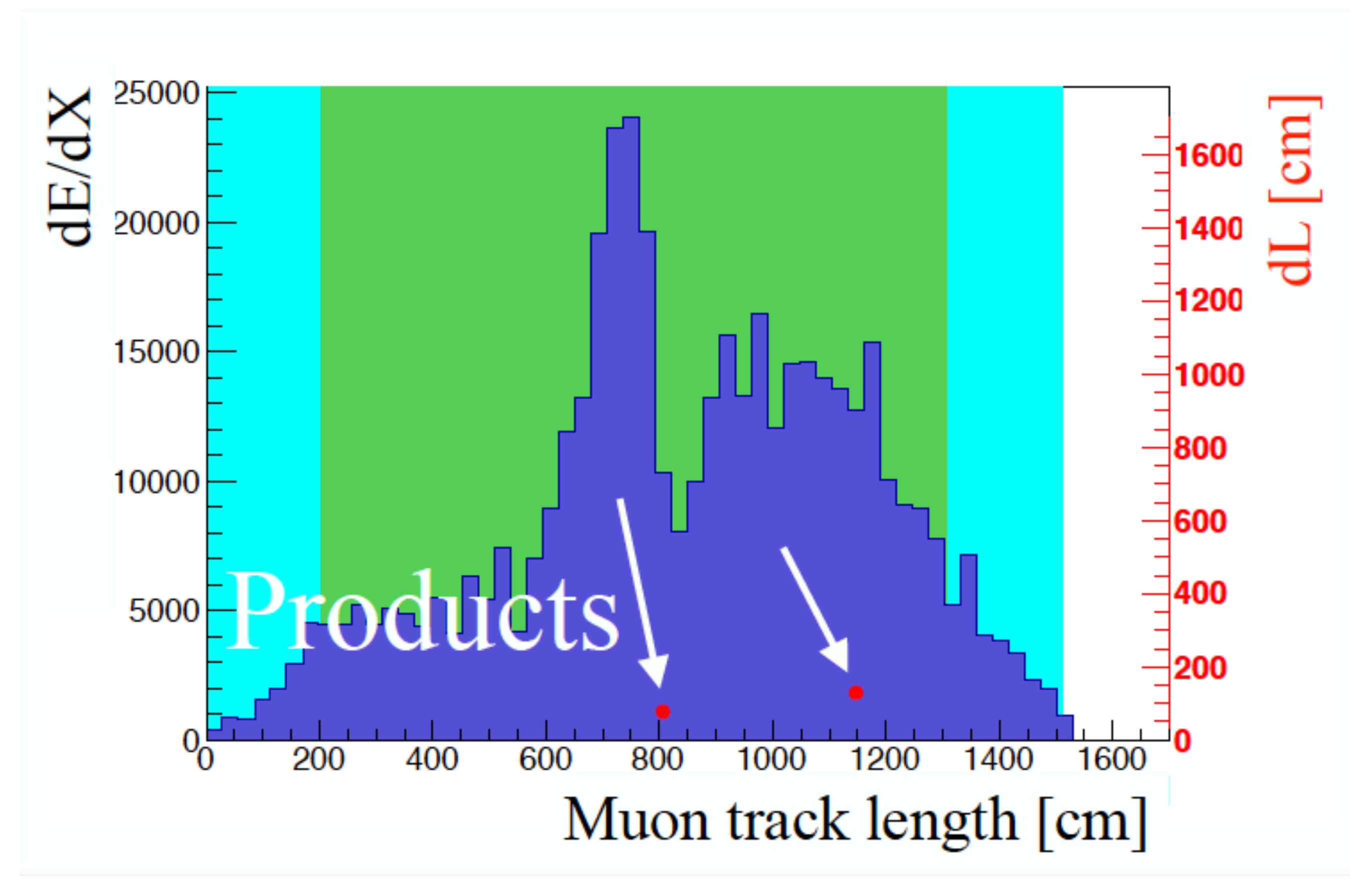
Analysis Preparation I

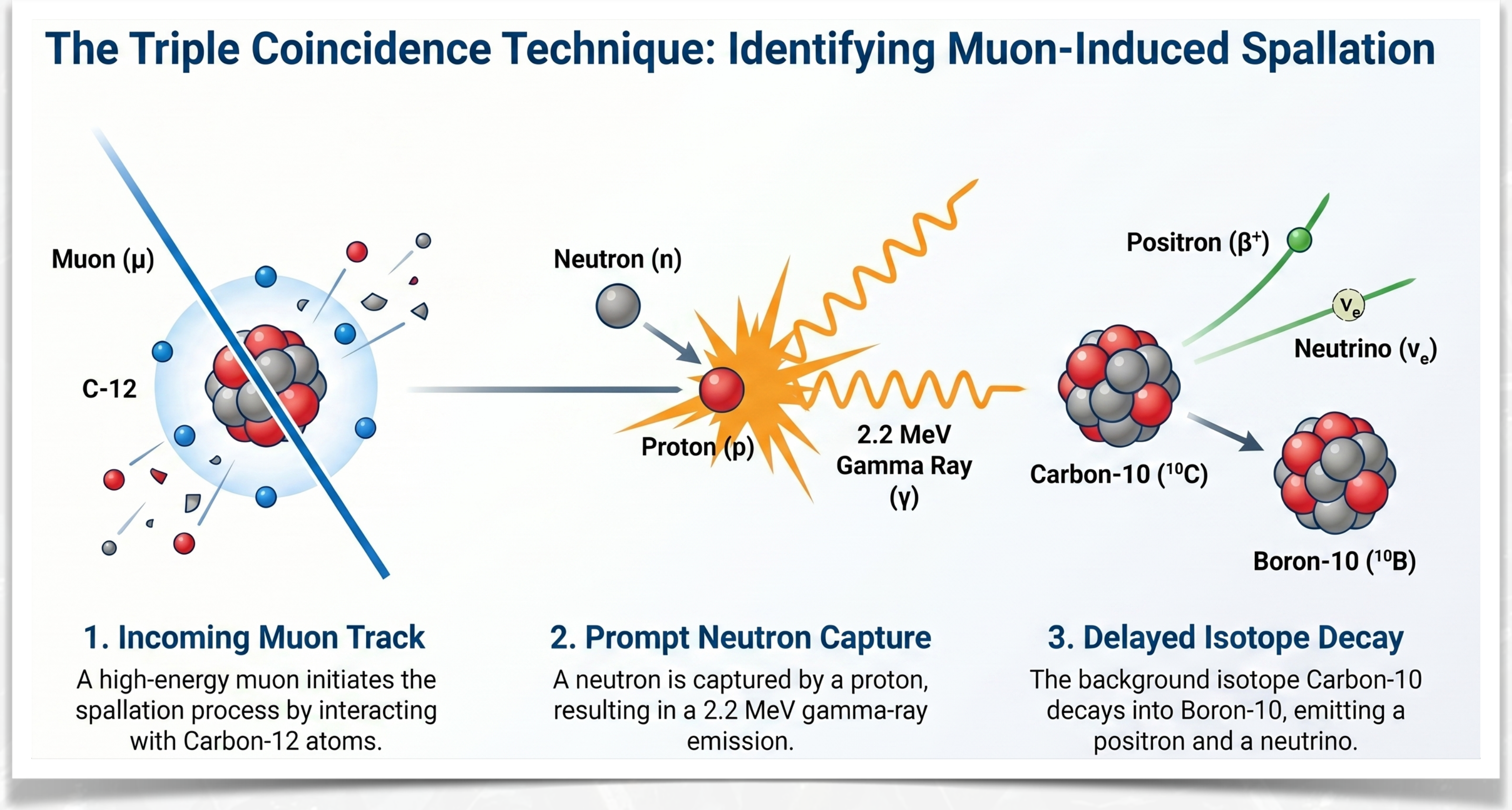
Short-Lived Tagging

	$\tau_{1/2}$	Q (MeV)
^{8}He	119.1 ms	10.7 (β^-)
^{9}Li	178.3 ms	13.6 (β^-)
^{12}B	20.2 ms	13.4 (β^-)
^{12}N	11.0 ms	17.3 (β^+)
^{8}Li	839.9 ms	16.0 (β^-)
^{8}B	770 ms	18.0 (β^+)
^{9}C	126.5 ms	16.5 (β^+)
^{11}Be	13.8 s	11.5 (β^-)
^{10}C	19.29 s	3.65 (β^+)
^{6}He	806.7 ms	3.51 (β^-)
^{11}C	1221.8 s	1.98 (β^+)
n	207.5 μs	2.223(cap.γ)



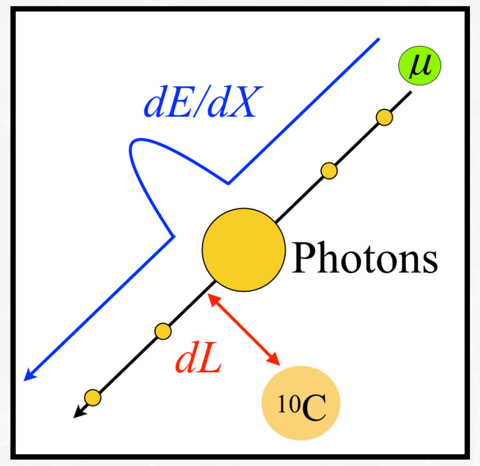






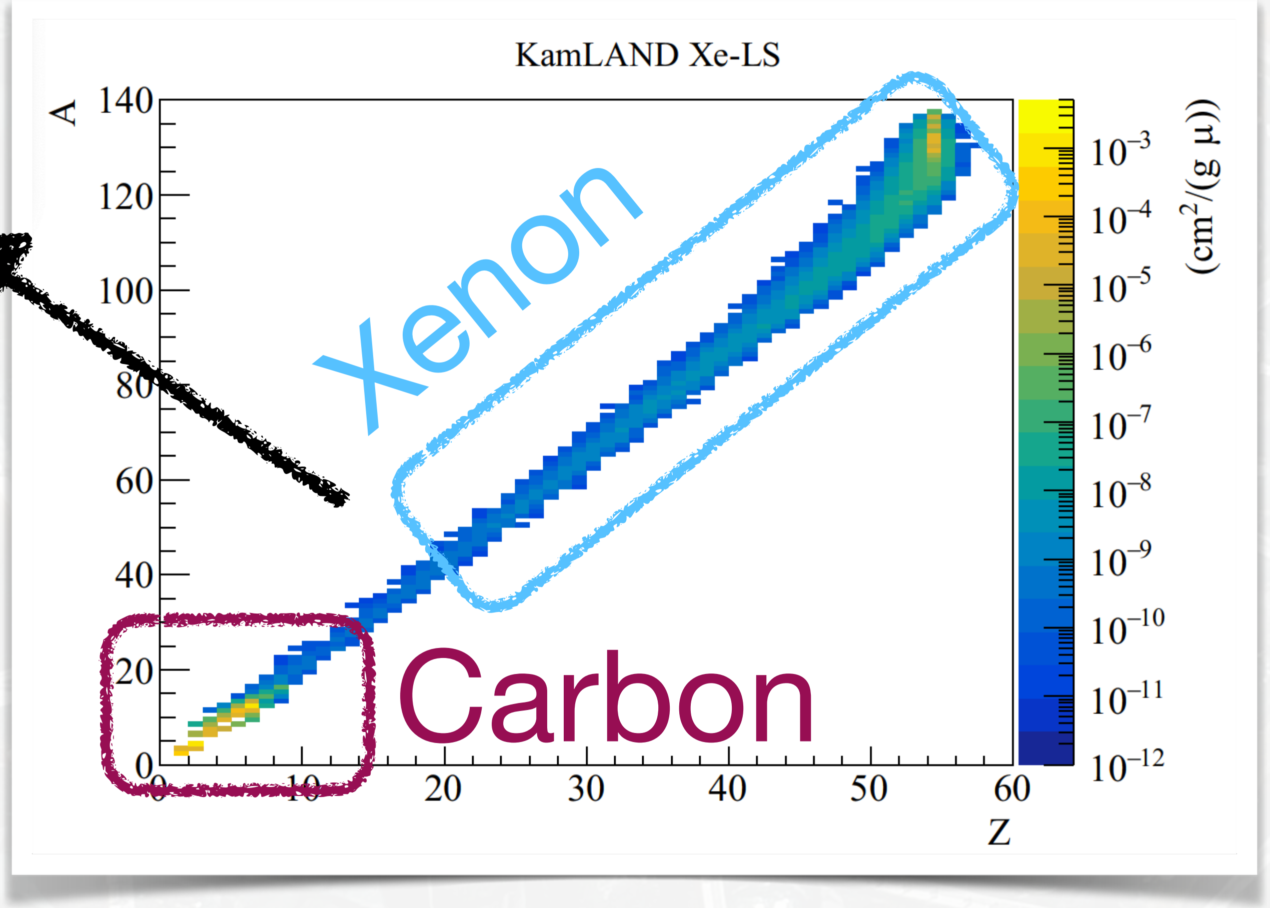
- Triple Coincidence Tagging = space + time correlation of n with muons
- Lifetime veto efficiency —> 100% for τ>100s (when $\tau(^{10}$C) = Flat)
- Carbon spallation products rejection efficiency > 95%

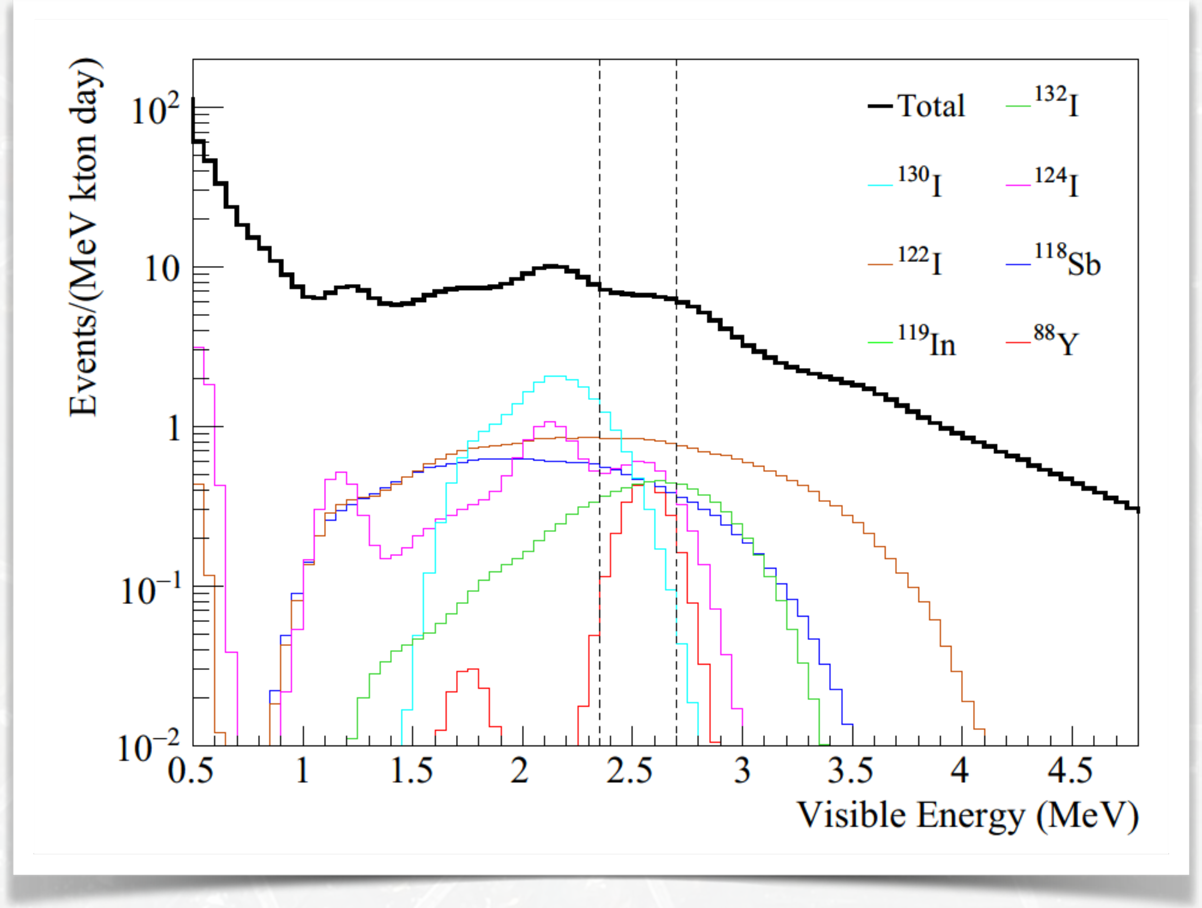
- Muon shower correlation <=> Energy Loss vs. Distance of Spallation Product to Muon Track

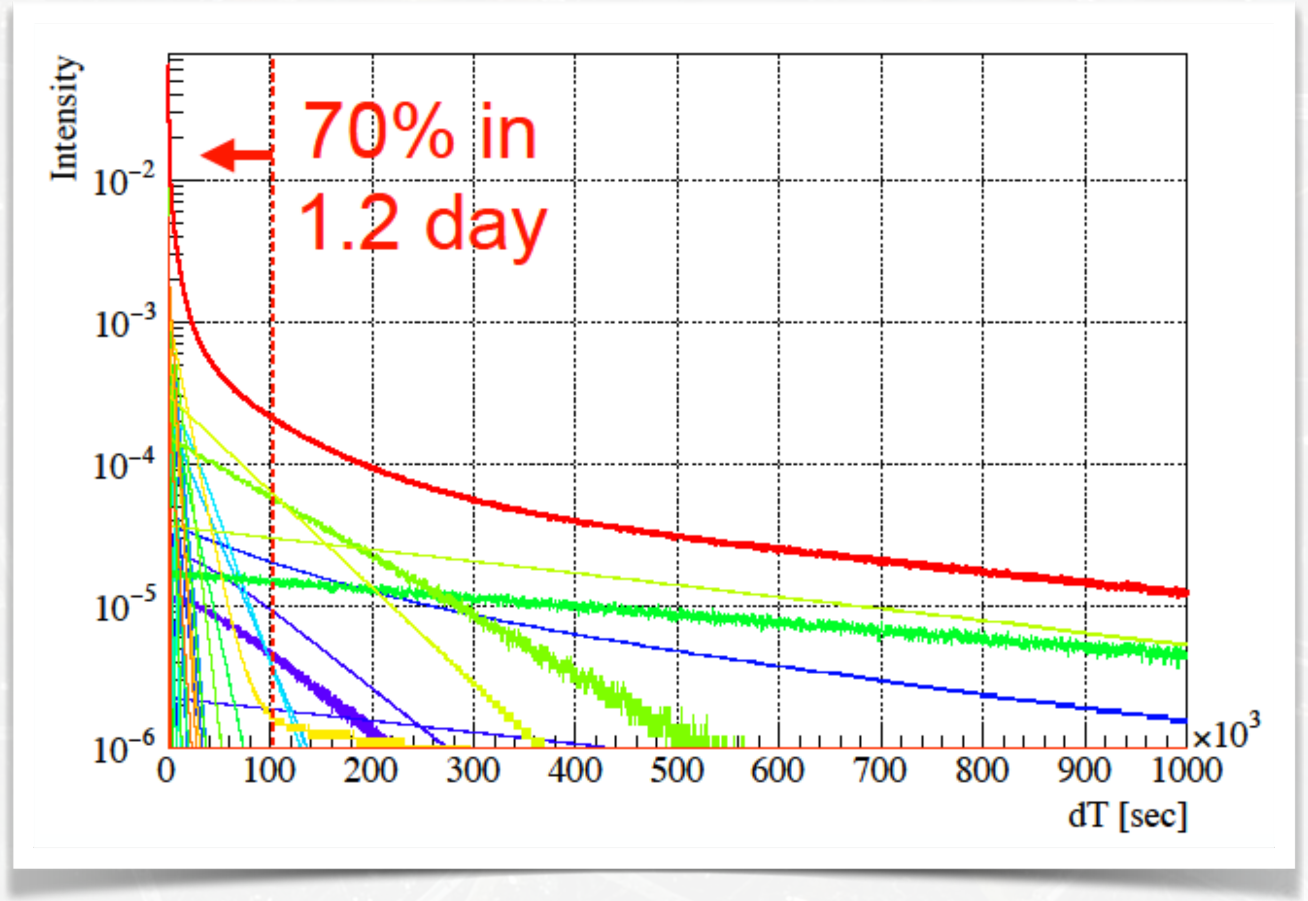


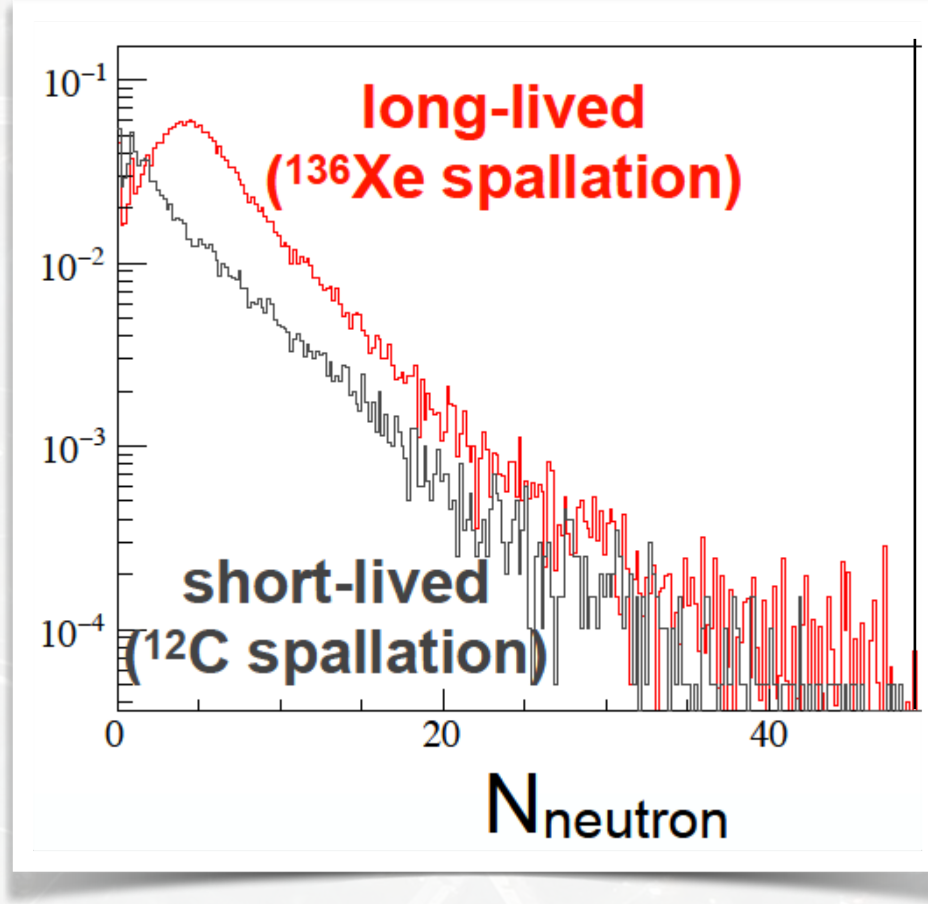
Analysis Preparation II

Long-Lived Tagging









- Likelihood-based tagging
  —> uses space-time information of muons with Neutrons wrt spallation isotopes and its lifetimes

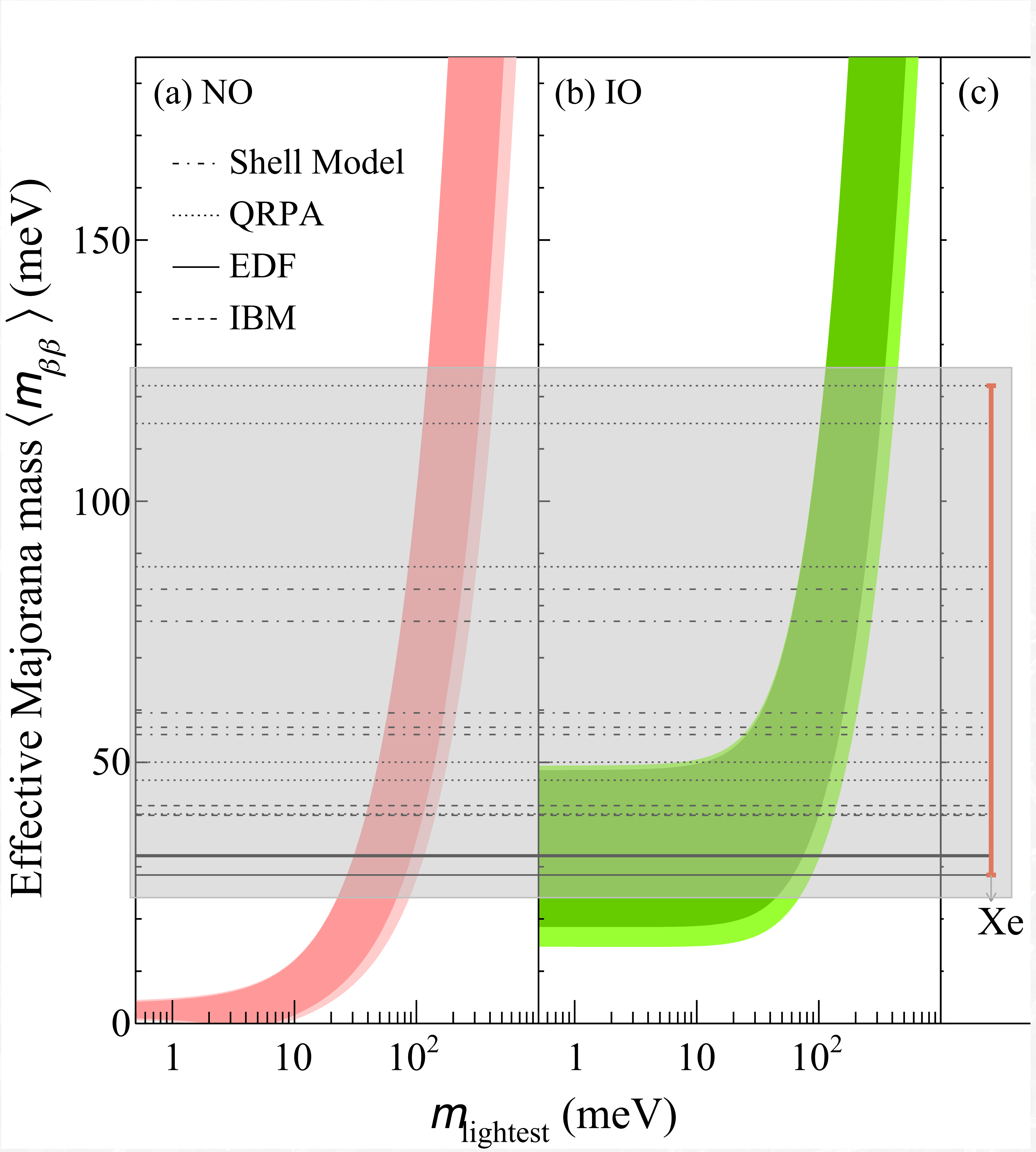
- Construct tagging variable based on Three-dim. Likelihood function $LKL(N_n, dR_n, dT)$

- Rejection Efficiency for Xe spallation products (47±9)%

Long time veto required

$N_n^{S.Lived} < N_n^{L.Lived}$

Results for Effective Majorana Mass



	Ref.	$M^{0\nu}$	$\langle m_{\beta\beta} \rangle$ (meV)
Shell model	[34]	2.28, 2.45	59.4, 55.3
	[35]	1.63, 1.76	83.1, 77.0
	[36, 37]	2.39	56.7
QRPA	[38]	1.55	87.4
	[39]	2.91	46.6
	[40]	2.71	50.0
	[41]	1.11, 1.18	122, 115
	[42]	3.38	40.1
EDF theory	[43]	4.20	32.3
	[44]	4.77	28.4
	[45]	4.24	32.0
IBM	[46]	3.25	41.7
	[47]	3.40	39.9

Shell model

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QRPA

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EDF

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IBM

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[14] F. F. Deppisch, L. Graf, F. Iachello, and J. Kotila, Phys. Rev. D **102**, 095016 (2020).

Theoretical model

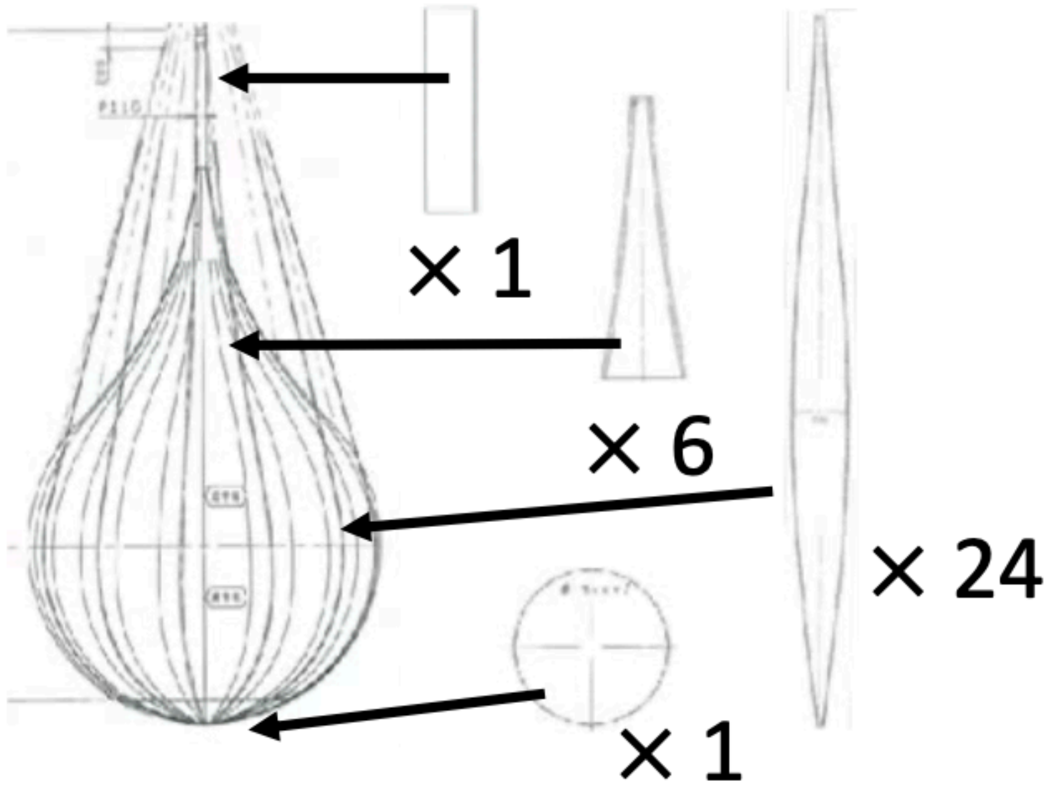
(A) K. Harigaya, M. Ibe, and T. T. Yanagida, Phys. Rev. D 86, 013002 (2012)
(B) T. Asaka, Y. Heo, and T. Yoshida, Phys. Lett. B 811, 135956 (2020).
(C) K. Asai, Eur. Phys. J. C 80, 76 (2020)

$$\left(T_{1/2}^{0\nu 2\beta}\right)^{-1} = G^{0\nu} \left| M^{0\nu} \right|^2 m_{\beta\beta}^2$$

$$\left\langle m_{\beta\beta} \right\rangle < 28\ldots122 \text{ meV}$$

Mini-Balloon Fabrication in Sendai (2017 - 2018)

All work performed inside a Class 1 clean room in Sendai



① Film Washing

② Seam Welding

③ He leak test + repairs

④ Folding

⑤ Packaging

Many Thanks to Chris Grant

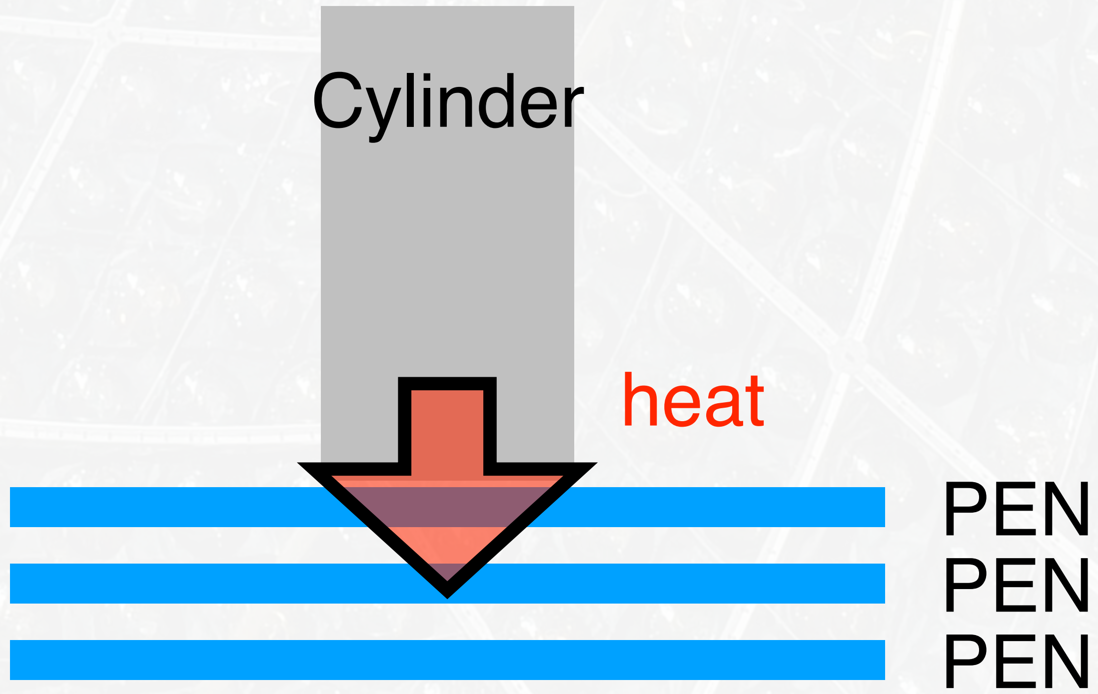
PEN film study around 2019

S.Obara et al., Prog. Theor. Exp. Phys. **2019**, 073H01 (DOI: 10.1093/ptep/ptz064)

- Basic tests were conducted to understand the characteristics of PEN film.
- **Heat welding**
  - Same welding machine as production of KamLAND-Zen 800 balloon
  - Same PEN film is sandwiched as glue for welding line
  - Force gauge tests were done

  →The strength of the film after welding appears to be sufficient.

- **Problems**
  - The tested PEN film is no longer available because of the company's situation.
  - Level of radioactive impurity did not achieve the requirement.
  - Many holes were found around the welding line. The method for repairing the holes was unclear. PEN film did not stick with the glue used to repair nylon balloon.

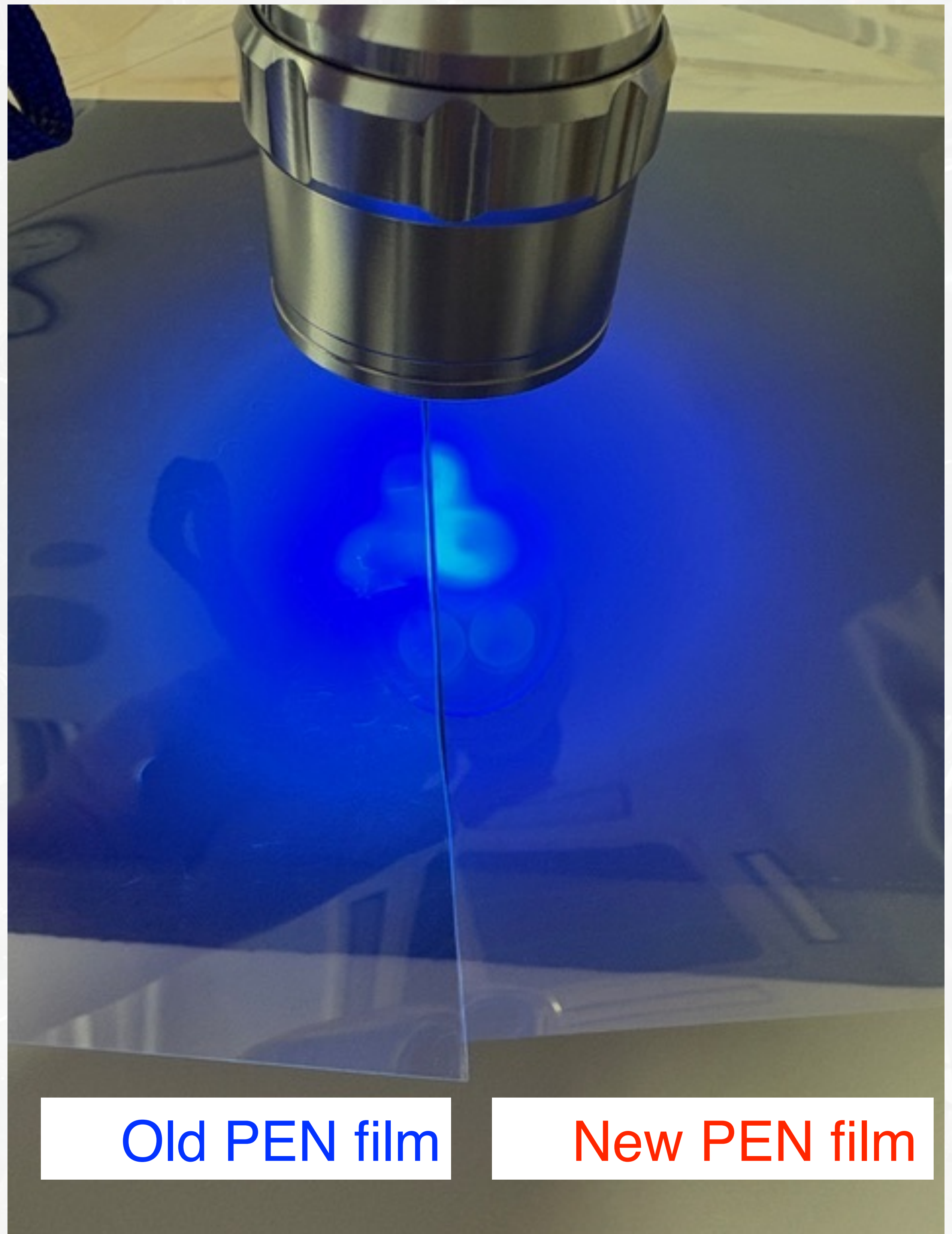


Many Thanks to Hiroko Watanabe

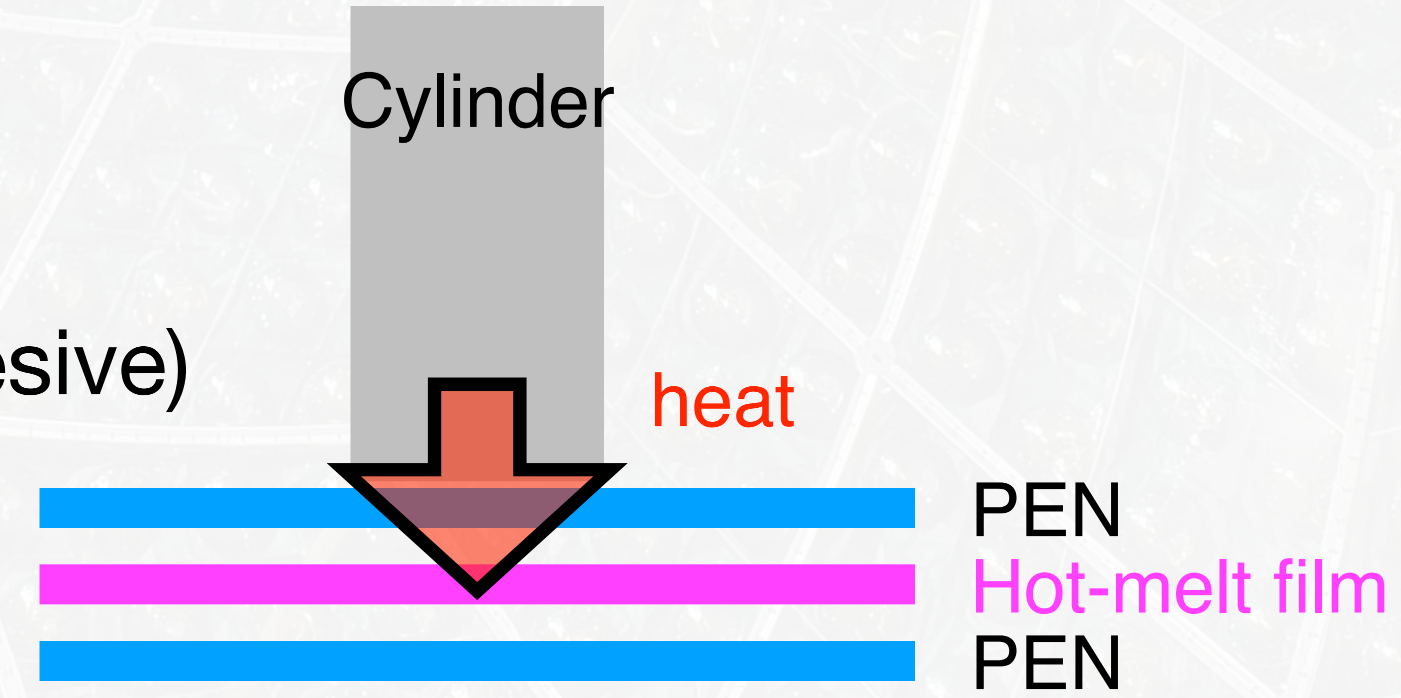
Recent updates

- We could get PEN film supply from another company. The level of the radioactive impurity is acceptable!
- Basic characteristics tests are ongoing (e.g. light yield, transparency, Xe-gas transmission rate etc.)
- **Heat welding**
  - New method: we found that **hot-melt film** works well as glue for welding.

- PEN has high melting point (265-280 degree C). High temperature can cause holes around the welding line.
- "Hot-melt film" melts at 105-120 degree C. Hopefully less number of holes around the welding line.



Polyester-based hot melt adhesive (thermoplastic adhesive)



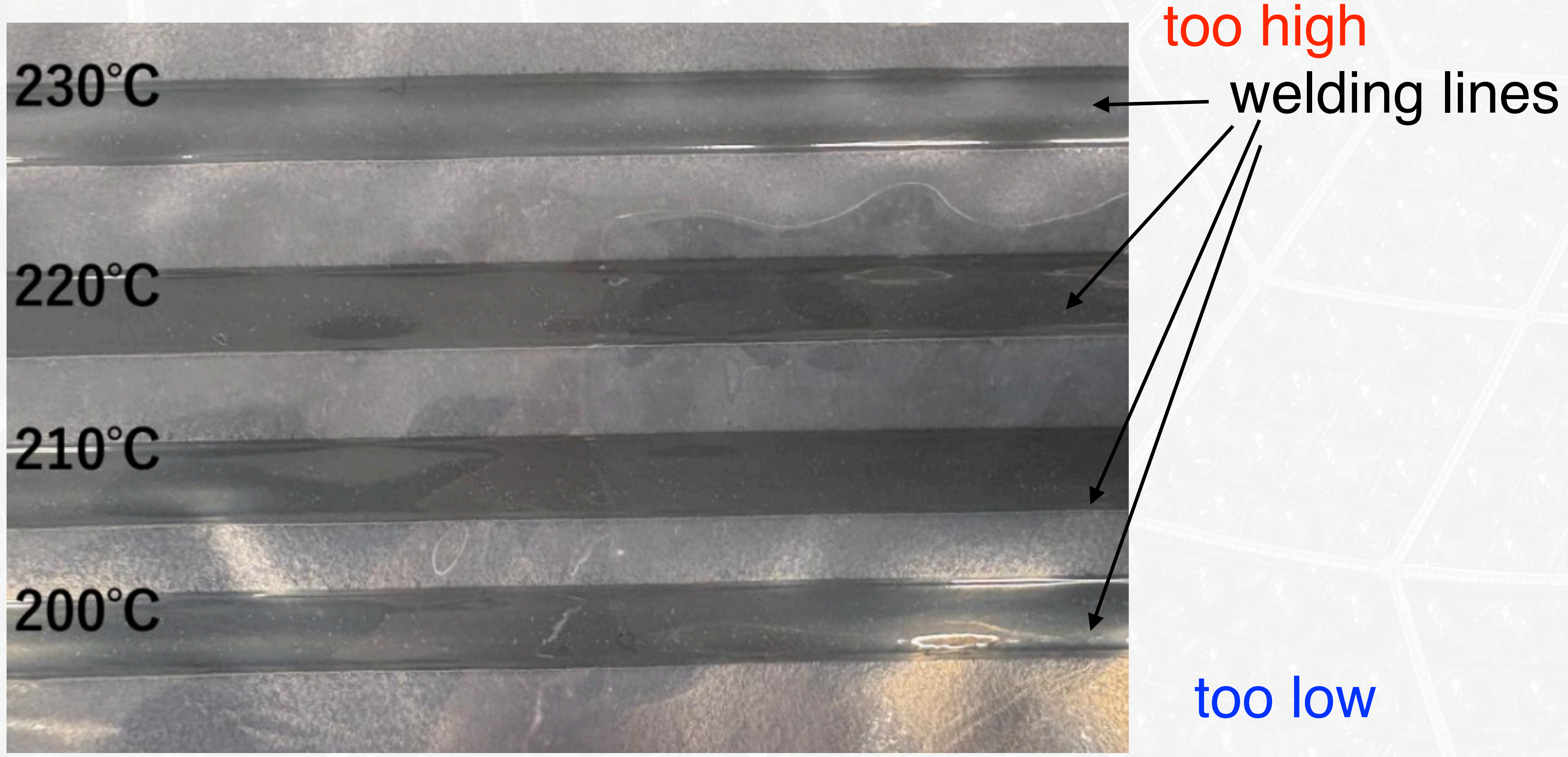
Many Thanks to Hiroko Watanabe

Recent updates

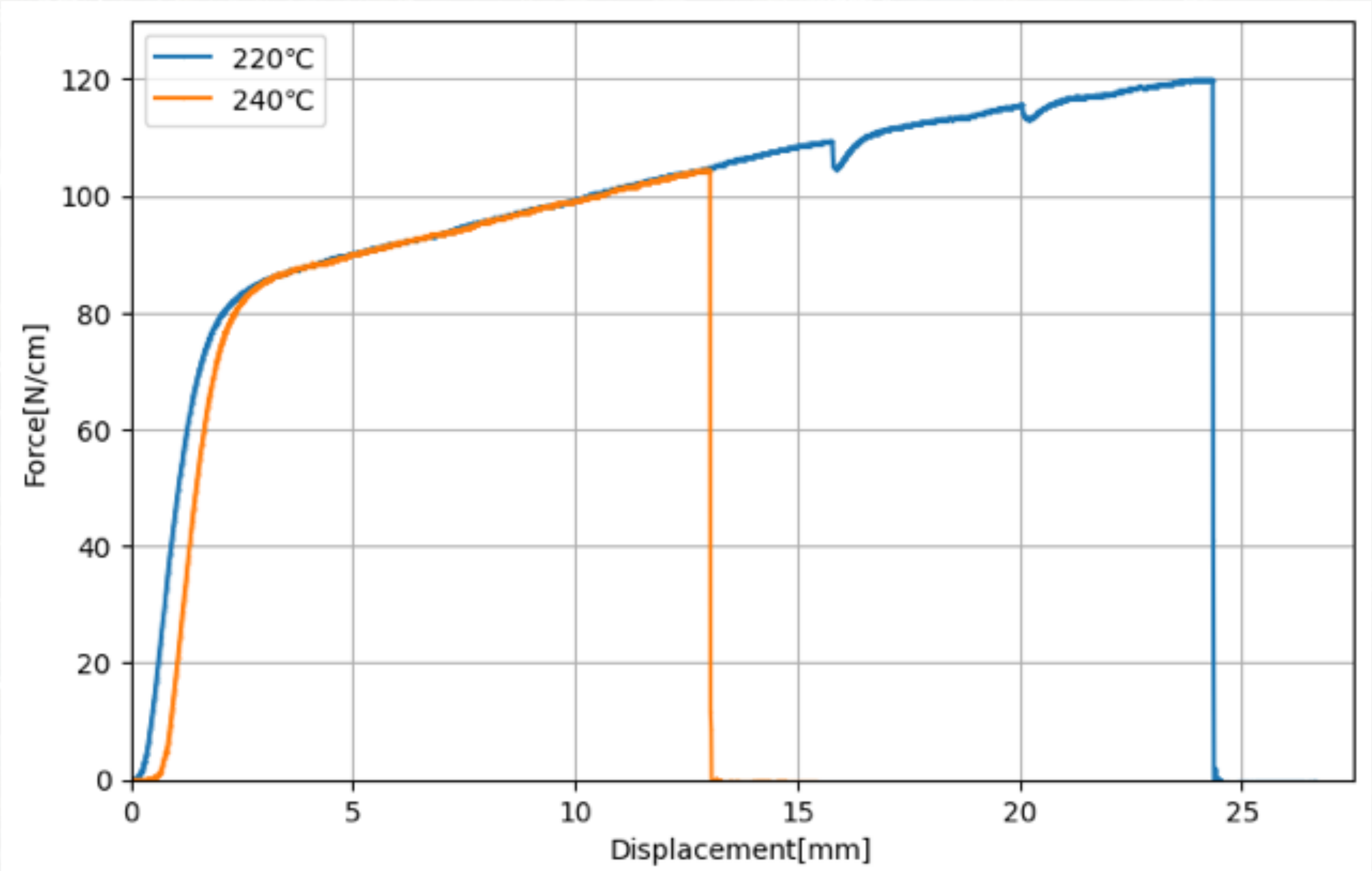
- Tested:
  - Hot-melt film has chemical compatibility with liquid scintillator.
  - Weld line strength: Maintained above requirement post-LS soaking.
  - There is negligible leakage from the weld line!
  - Some types of hot-melt film have very high RI impurities.
- Ongoing test:
  - Fixing the type of hot-melt film regarding welding quality & RI
  - Investigating PEN film's surface treatments for enhanced transmittance

Many Thanks to Hiroko Watanabe

parameter check



Strength test



Improved PMTs (R12860-03LXA) KamLAND2-Zen

New 20” (50.8cm) High Quantum Efficiency (HQE) PMTs are being used for KamLAND2-Zen.

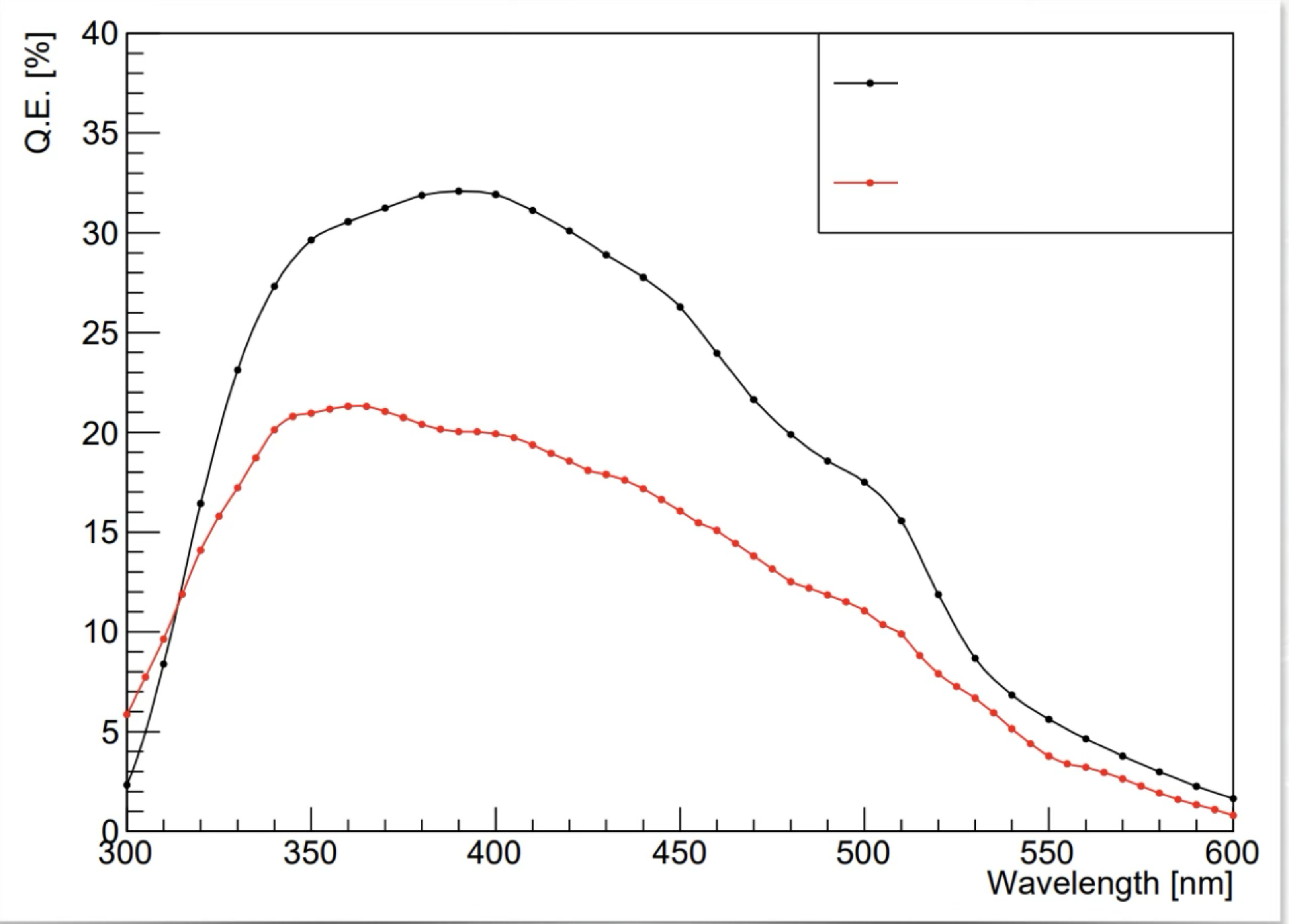
Datasheet link

Type No.	Diameter (mm) / (inch)	Minimum effective area (mm)	Surface area Min. (cm^2)	Surface area Typ. (cm^2)	Dynode Structure	Dynode Number of stages	Weight (g)
R12860	508 / 20	ϕ460	2120	2600	**Box & Line**	10	approx. 8000

Type No.	Luminous (2856 K) Min. (μA/lm)	Luminous (2856 K) Typ. (μA/lm)	Radiant at 420 nm Typ. (mA/W)	Blue sensitivity index (CS 5-58) Min.	Blue sensitivity index (CS 5-58) Typ.	Quantum efficiency at 390 nm Typ. (%)	Luminous (2856 K) Typ. (A/lm)	Radiant at 420 nm Typ. (A/W)	Gain Typ.	Applied voltage for typical gain Typ. (V)
R12860	40	80	90	10.0	12.0	**30%**	800	9.0×10^5	1.0×10^7	2000

Dark current (After 30 min storage in darkness) Typ. (nA)	Dark current Max. (nA)	Dark count (After 15 hours storage in darkness) Typ. (s^{-1})	Dark count Max. (s^{-1})	Time response Rise time Typ. (ns)	Time response Electron transit time Typ. (ns)	Time response Transit time spread (FWHM) Typ. (ns)	Single photo-electron (Peak to valley ratio) Min.	Single photo-electron Typ.	Pulse linearity at 2 % Deviation Typ. (mA)	Pulse linearity at 5 % Deviation Typ. (mA)	Type No.
500	1000	20 000	80 000	6.0	95	**2.4ns**	1.5	**2.8**	20 (100)	40 (150)	R12860

+ improved dark count rate (8kHz compared to 22kHz) and charge resolution



The collection efficiency was also measured to be ~95%.

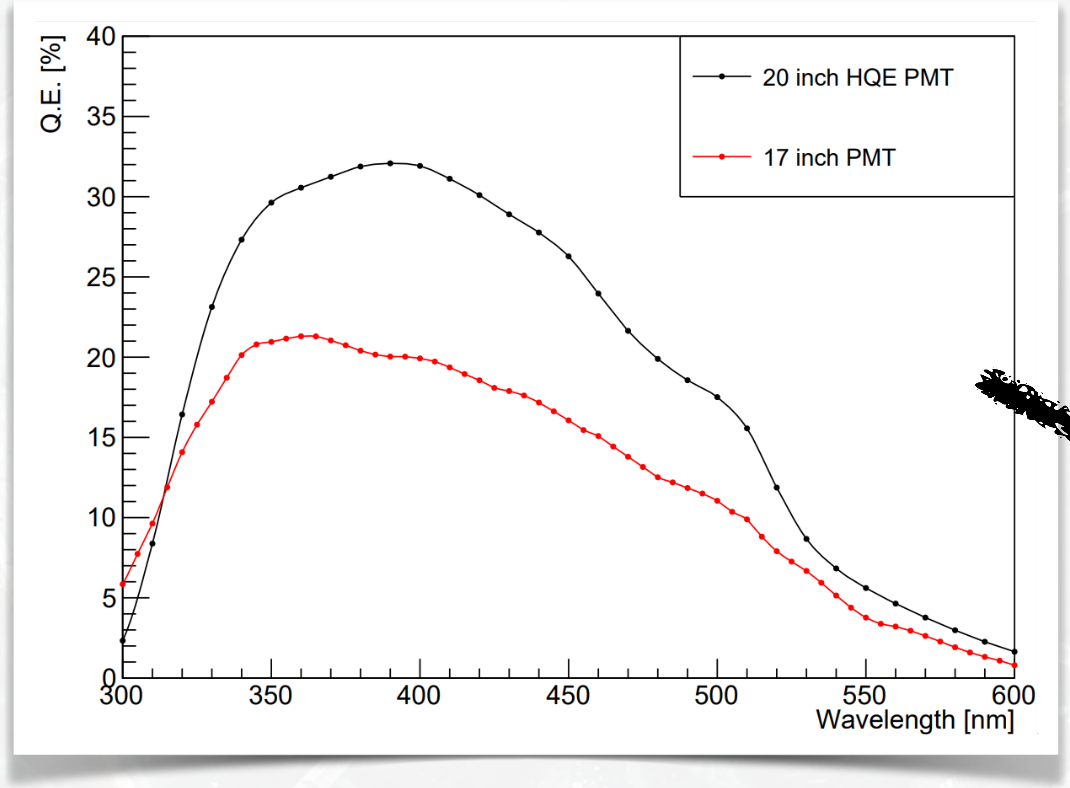
IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC). IEEE, 2021.

New HQE PMTs will collect 1.9x the photons **enhancing energy resolution** & **lower TTS** will help with positional reconstruction and background reduction.

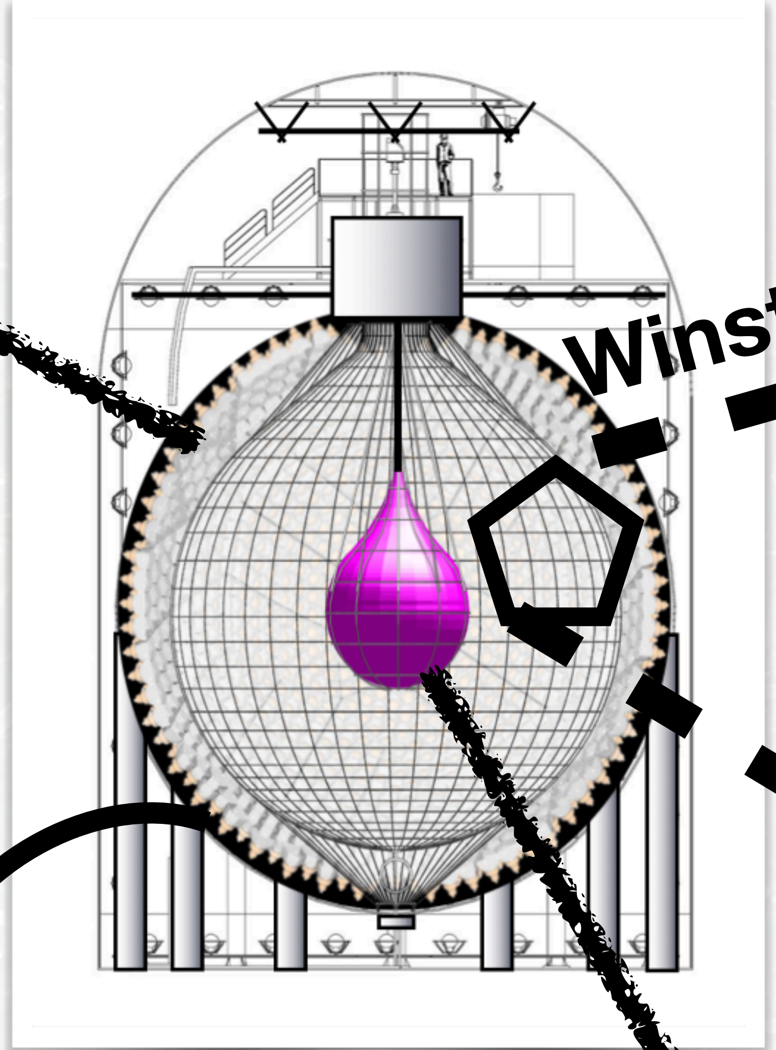
Many Thanks to Spencer N. Axani

KamLAND2-Zen

New 20“ PMTs

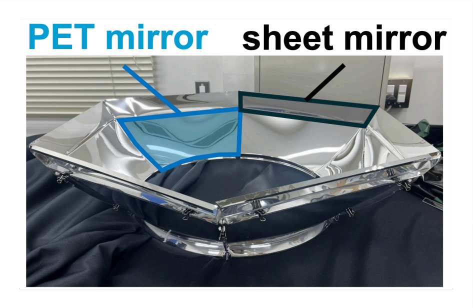


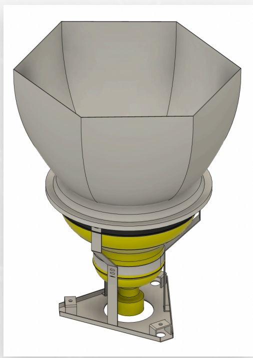
Significantly Enhanced
Quantum Efficiencies **x1.9**

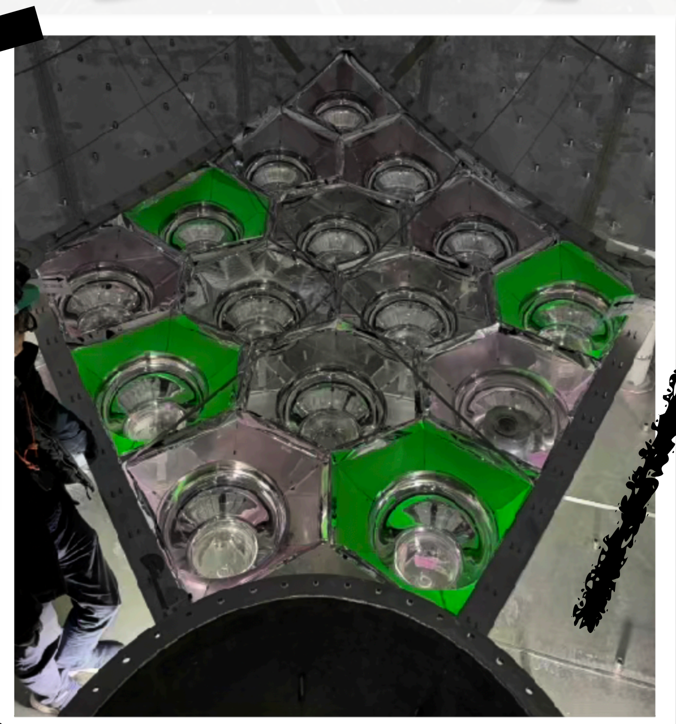


>x1.8

Winston Cones

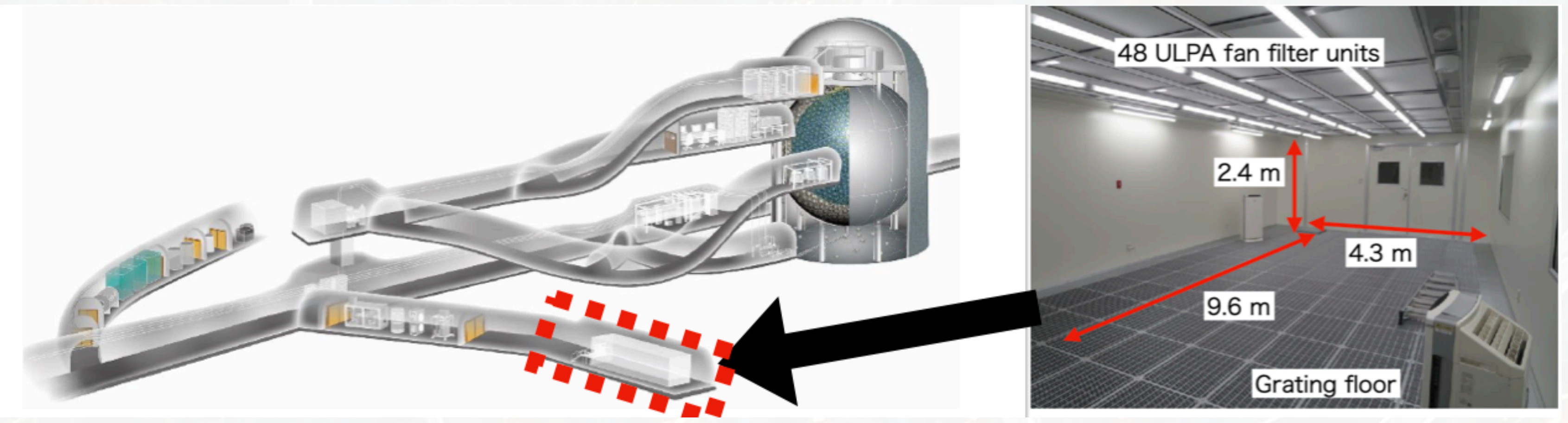






KERNEL = Kamioka
Extremely Rare
phenomena and
Neutrino research Lab

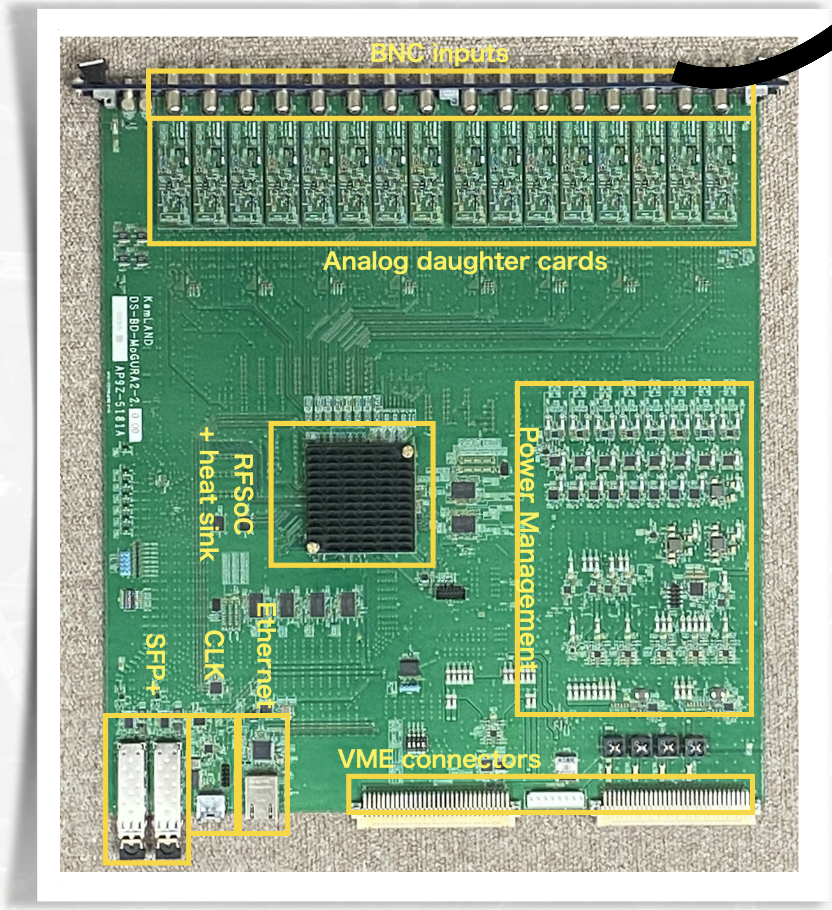
KERNEL = Class 1 Clean Lab



PPO optimization (=increase) towards
achieving maximum light yield in
KamLAND-LS and Xenon-LS

Add bis-MSB to reach optimal match of
Emission + High QE window

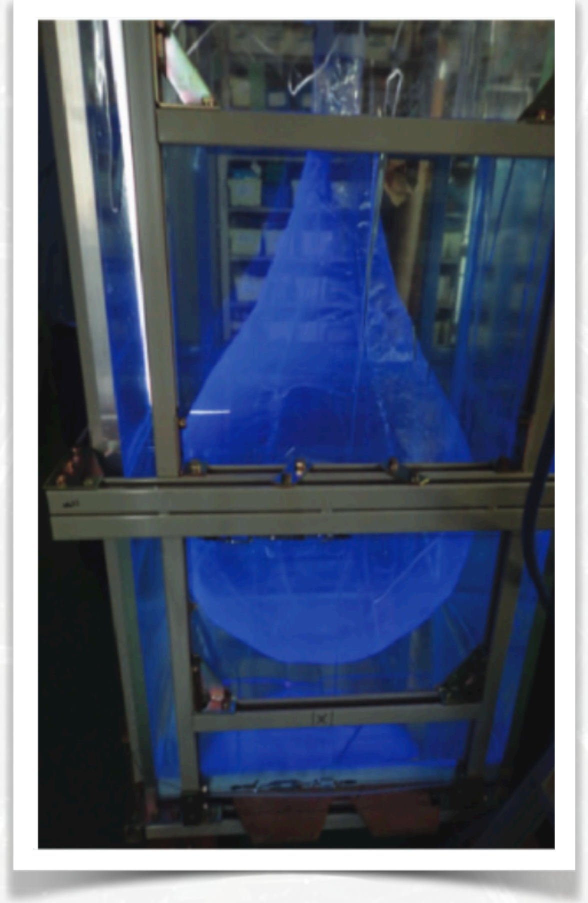
Readout Electronics



MoGURA2 is
the Radio
Frequency
System-on-a-
chip (RFSoC)

Low noise front end to
extract smaller pulses

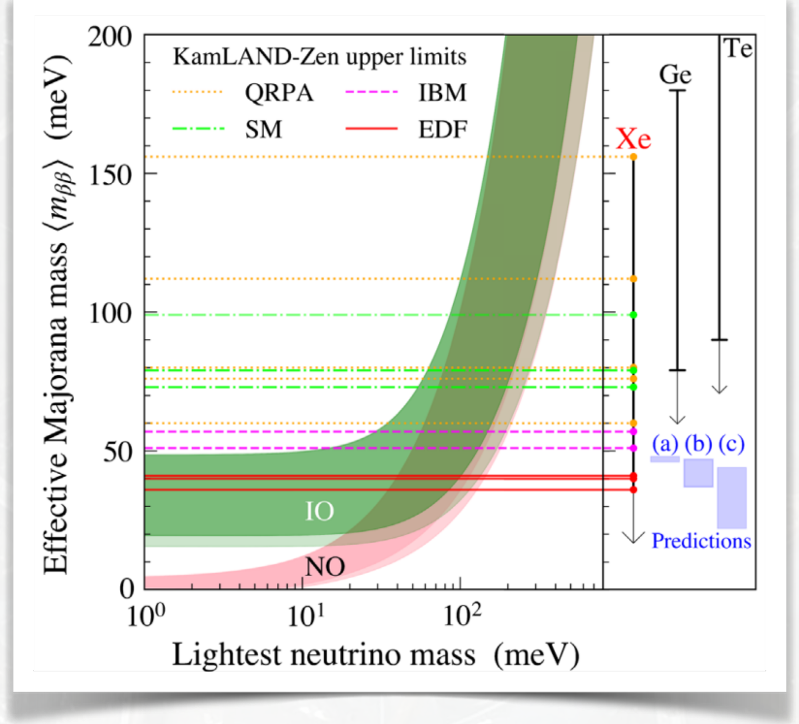
Streaming DAQ



PEN Balloon

Smal size
prototype
baloon
(In water
+ UV light)

Sensitivity



Energy Resolution
(Feeding in all
improvements)
4% —> 2% @ 2.458 MeV

Cover IO region
completely

Target mass sensitivity
$\langle m_{\beta\beta} \rangle \sim 20$ meV / 5 Years

Target Half Life for 5 Years
$T > 2 \times 10^{27}$ Years

Main DAQ Start 2028
(FY 2027)