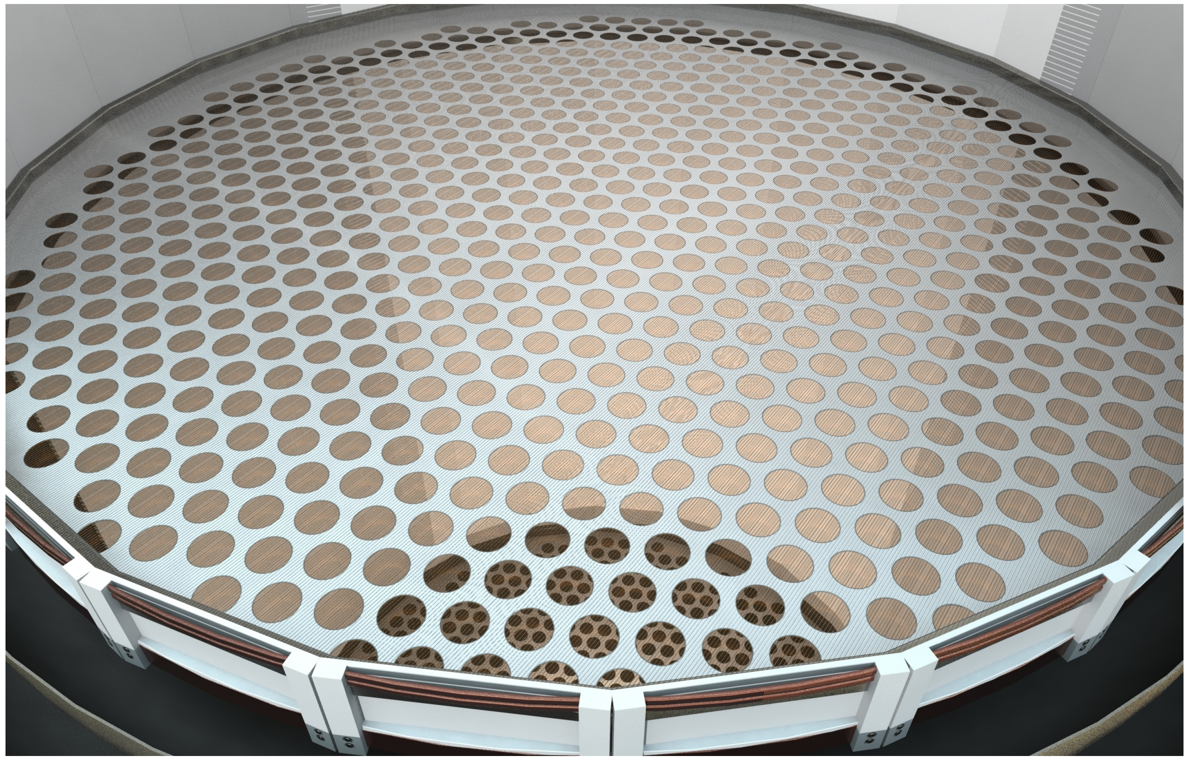
Photosensors for XLZD

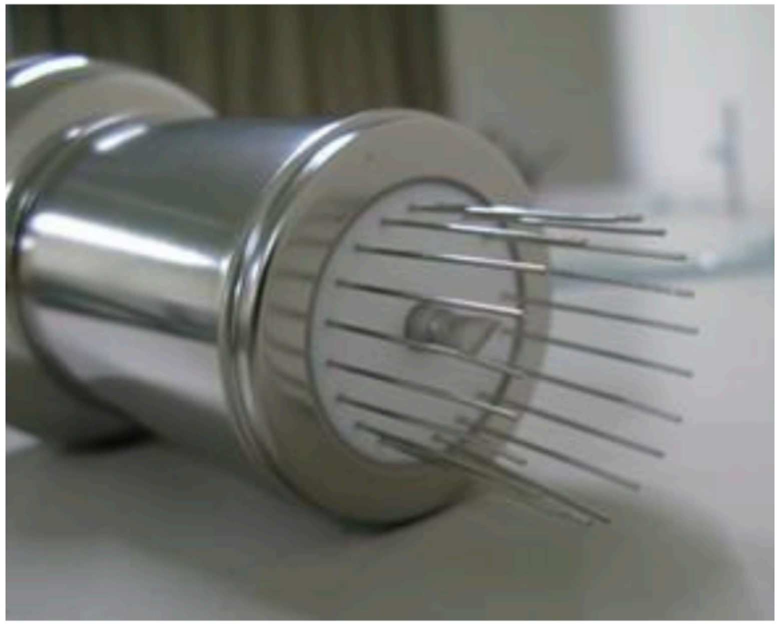


XLZD collaboration meeting
July 2, 2025 LNGS

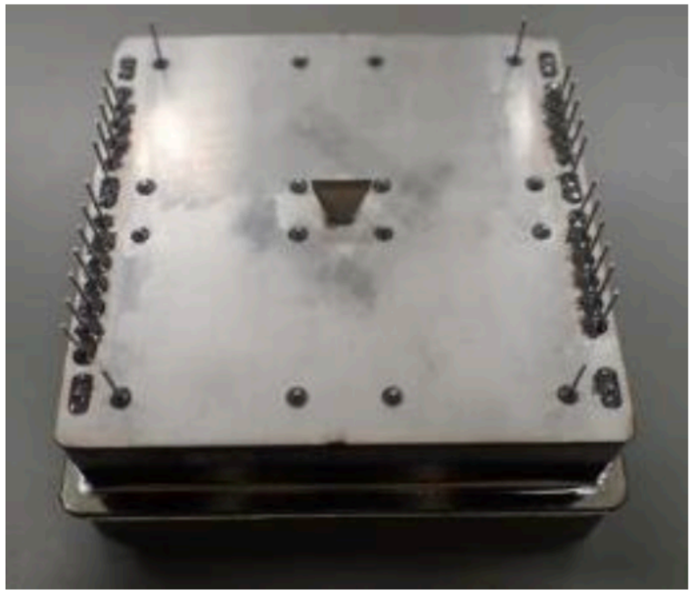
Laura Baudis (UZH), Masaki Yamashita (U Tokyo), Shingo Kazama (Nagoya U) for the photosensor group

PMT options

- R11410-21/22, 3'' diameter



- R12699-406-M4, 2'' square



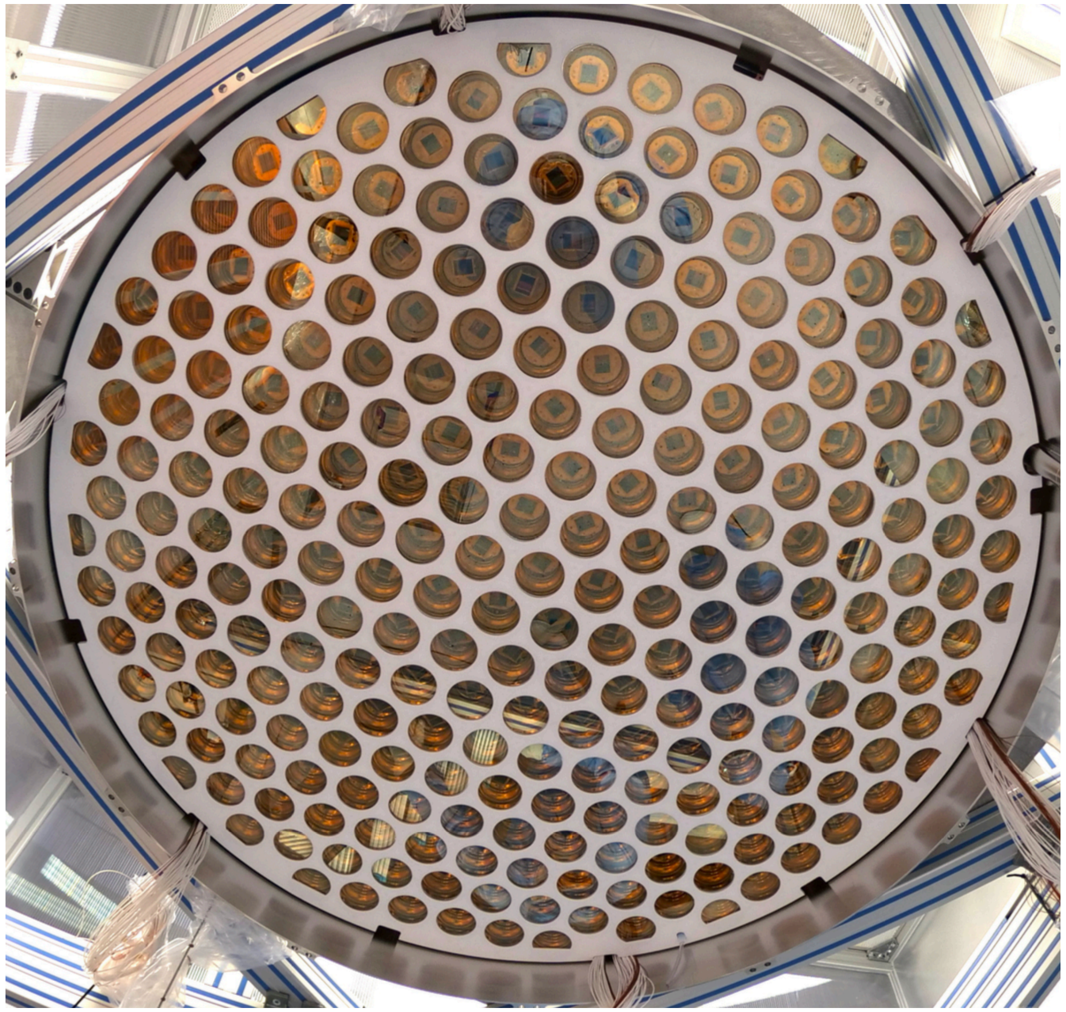
PMT main parameters

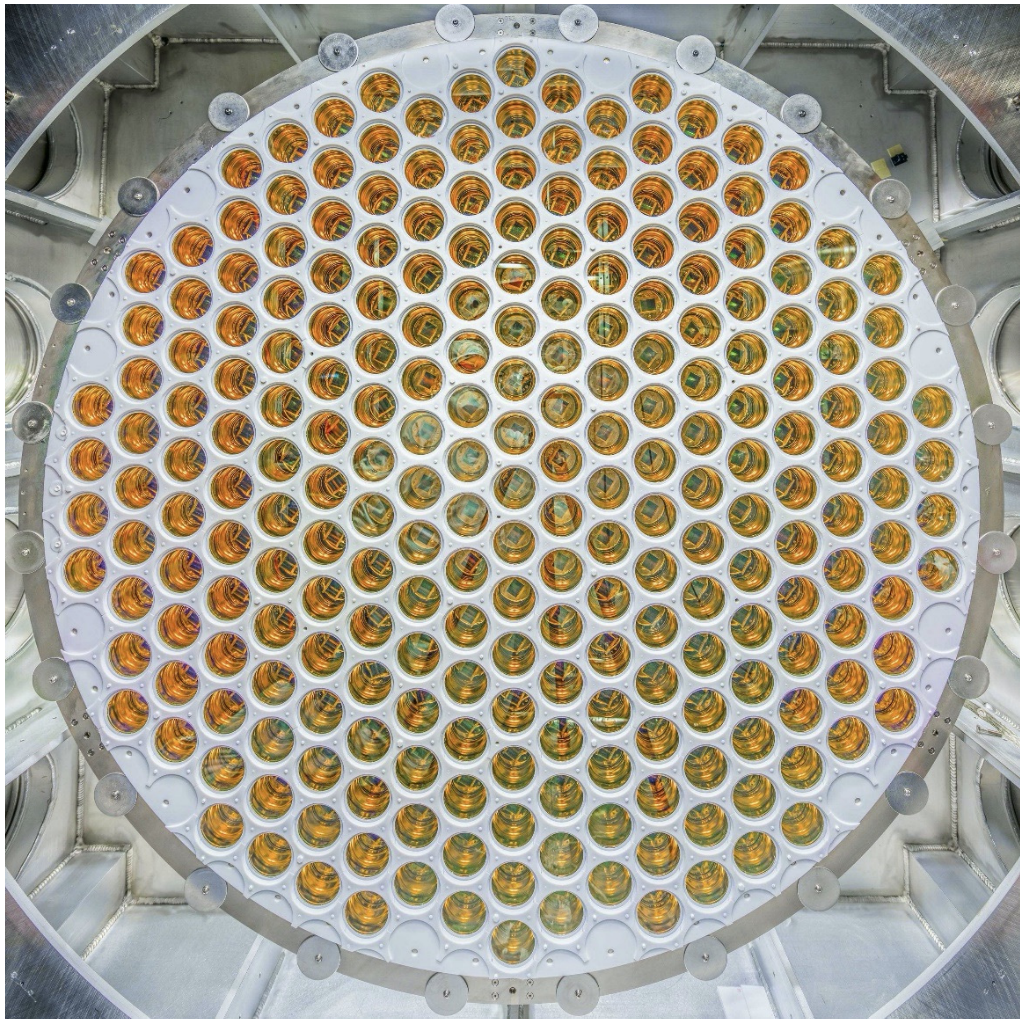
Parameter		R11410-21	R13111	R12699-406-M4	Unit
Spectral Response		160 to 650			nm
Window Material		Synthetic Silica			-
Photocathode	Material	Bialkali			-
	Minimum Effective Area	Φ64	Φ70	48.5 x 48.5	mm
Dynode	Structure	Box & Linear-focused		Metal channel dynode	-
	Number of Stages	12		10	-
Number of Anode		1		4	-
Stem		Ceramic	Metal with glass beads		-
Maximum Supply Voltage	Between Anode and Cathode	1750		1100	V
Maximum Pressure-resistance (Gauge)		0.3	0.2	0.5	MPa
Quantum Efficiency at 175 nm (Typ.)		32.5	28	33	%
Gain (Typ.)		5.0×10^6	7.5×10^6	1.5×10^6	-
Time Response (Typ. *1 Max.)	Anode Pulse Rise Time	5.5	6*1	1.2	ns
	Electron Transit Time	46	50*1	5.9	ns
	Transit Time Spread (FWHM)	9	3.5*1	0.41	ns
Dark Counts Rate at 25°C (Typ.)		4000	1500	No spec	s^{-1}

Table provided by Hamamatsu, for internal use only

R11410 PMTs

- Baseline photosensor for XLZD: design book arXiv:2410.17137
- **Efforts to reduce their overall activity** (e.g., reduce radioactivity of the stems)





Motivation

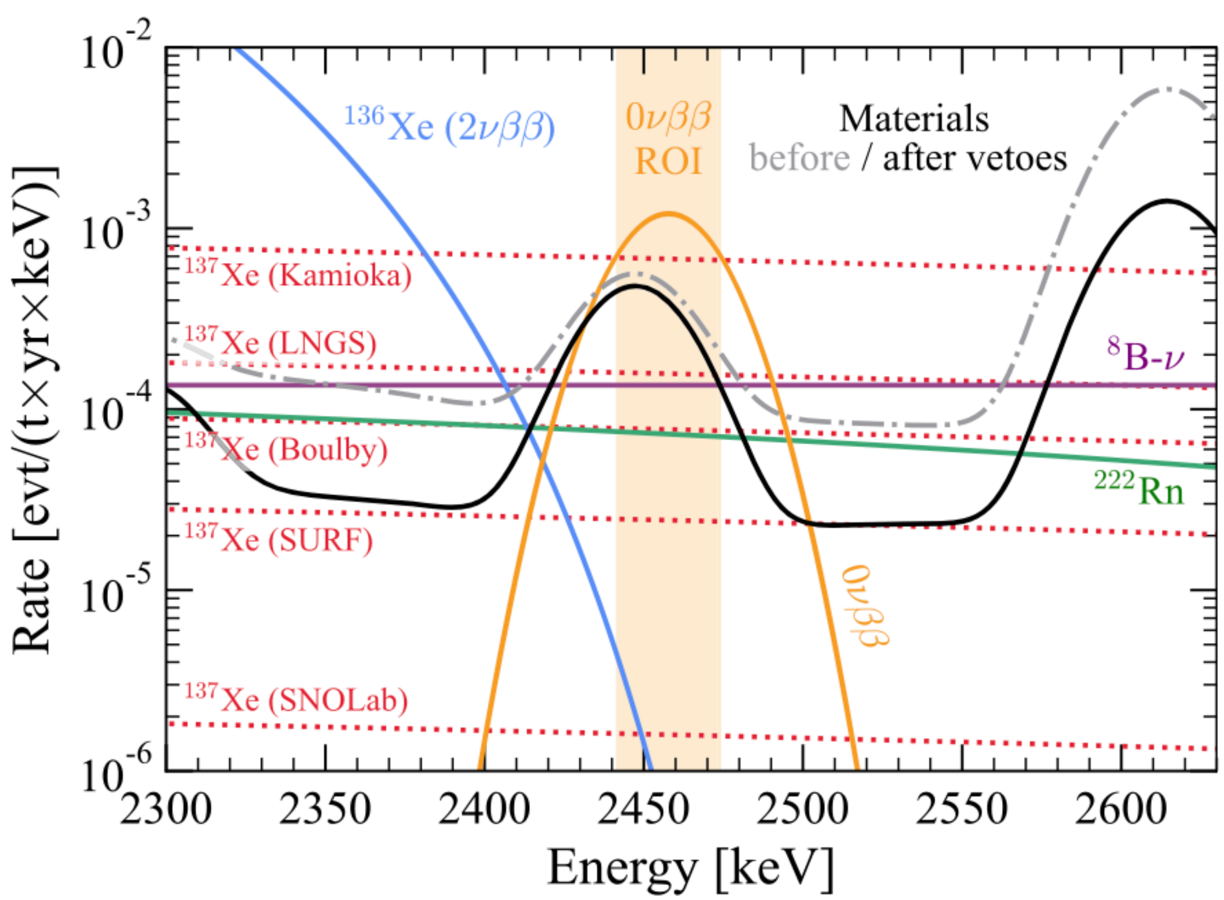
- TPC PMTs and cryostat dominate the materials background contribution
- Especially relevant for the $0\nu\beta\beta$-decay search

XLZD double beta decay study, Journal of Physics G, 2025

^{214}Bi events

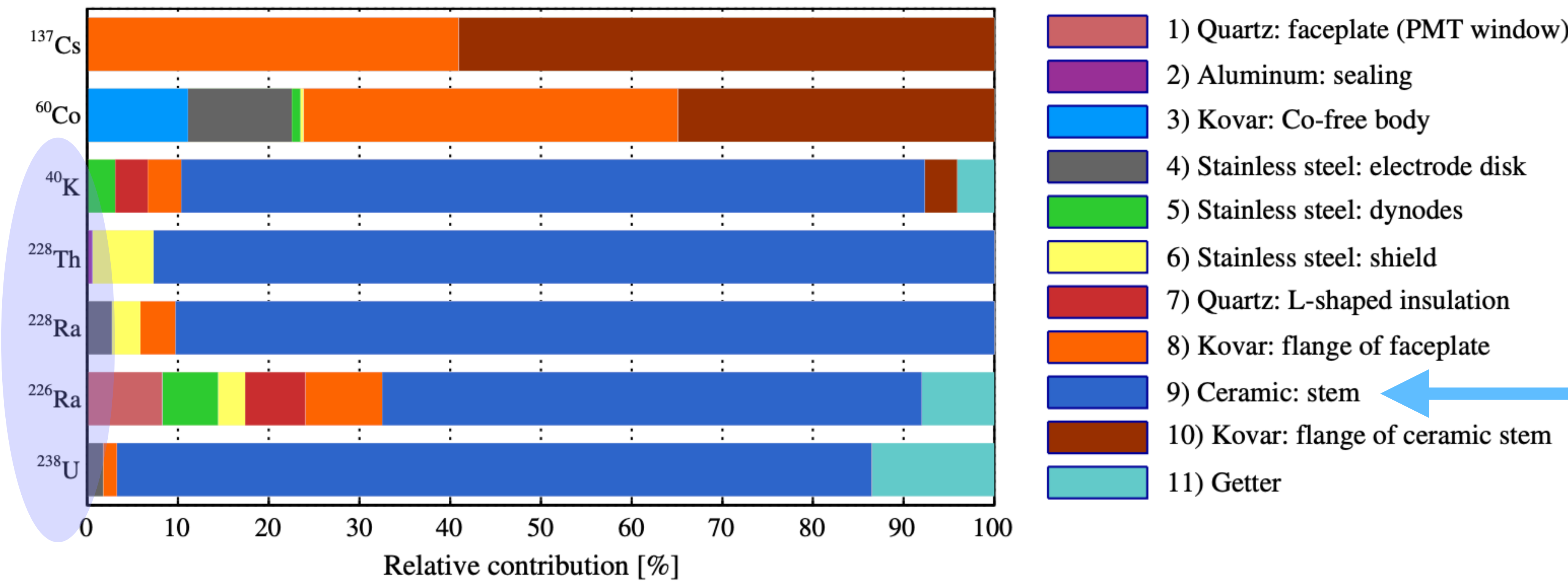
Component	LZ (967 kg × 1000 d) Nominal	LZ (967 kg × 1000 d) Reduced	XLZD (8.2 t × 10 years) Projected
TPC PMTs	2.95	0.98	0.61
PMT structures	2.75	0.54	0.33
Field-cage resistors	2.46	0	0
Internal sensors	1.81	0.22	0.14
PMT bases	1.52	0.39	0.24
Cryostat	1.26	0.82	0.51
PMT cables	1.01	0.16	0.10
Field-cage rings	0.97	0.40	0.25
OD tank supports	0.73	0	0
OD foam	0.71	0	0
Skin PMTs	0.69	0.06	0.04
Other skin parts	0.68	0.05	0.03
Other components	3.56	1.42	0.88
Total	21.10	5.05	3.15

Sensitivity estimate for XLZD (60 t active)

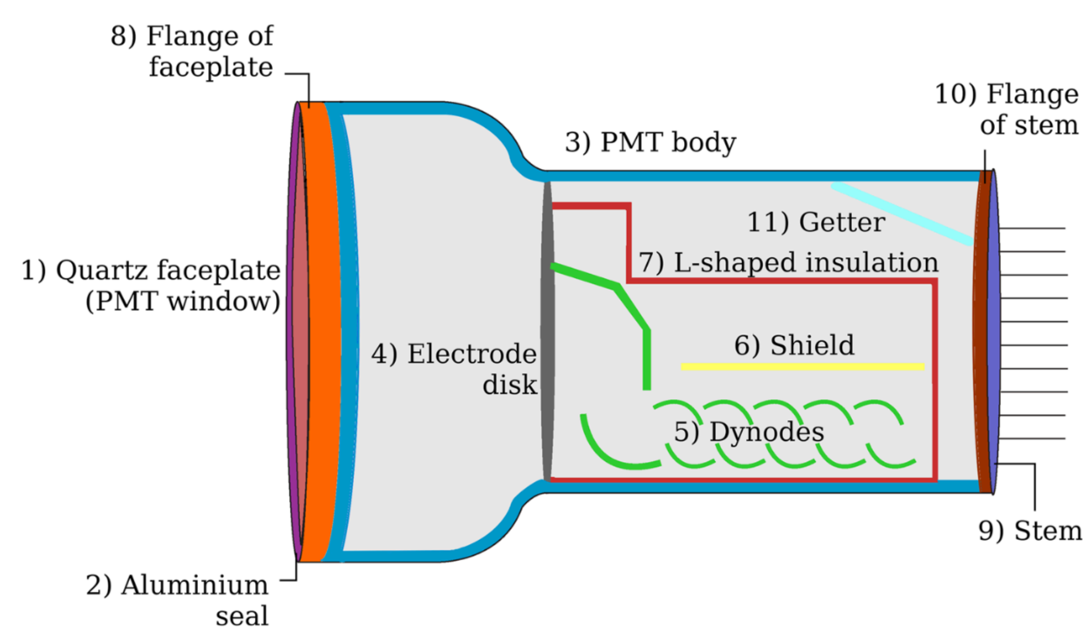


Motivation

- The main ^{238}U, ^{226}Ra, ^{228}Ra, ^{228}Th, ^{40}K contributions: **from the stems**



Eur. Phys. J. C 75, 546 (2015)

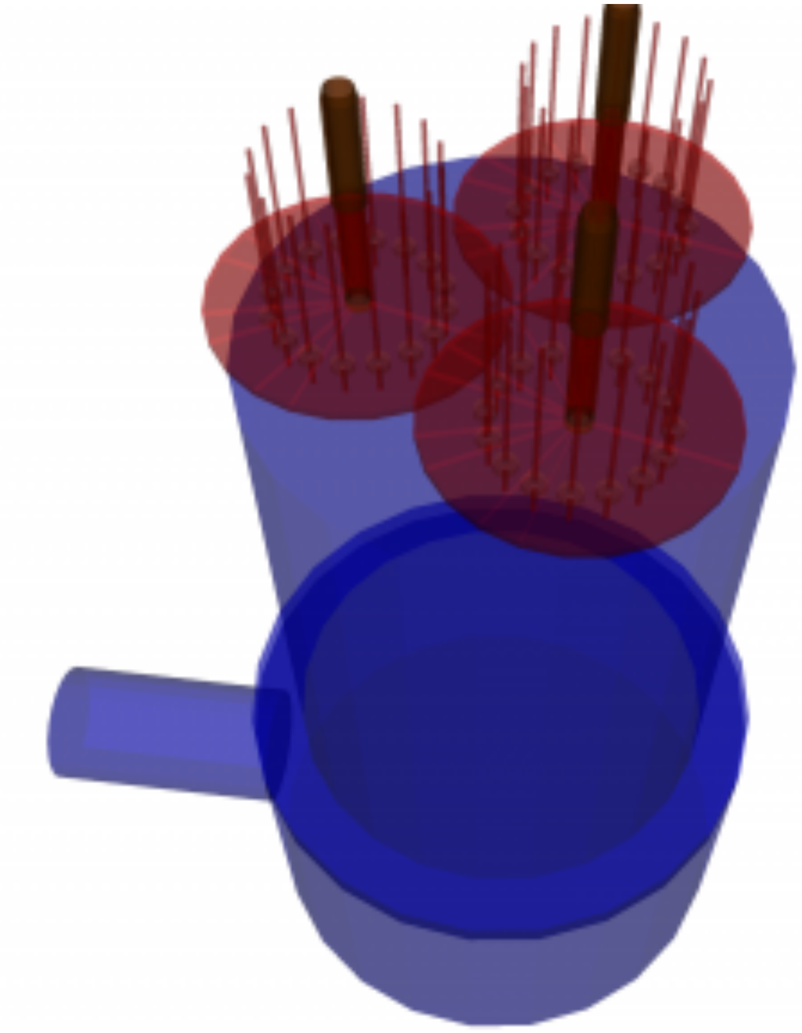


R11410 PMT stems

- **Several versions screened with Gator at LNGS**
  - Low-activity glass stems
  - Refined metal stems with glas beads
  - XENONnT stems (2015)

Low-activity glass stems

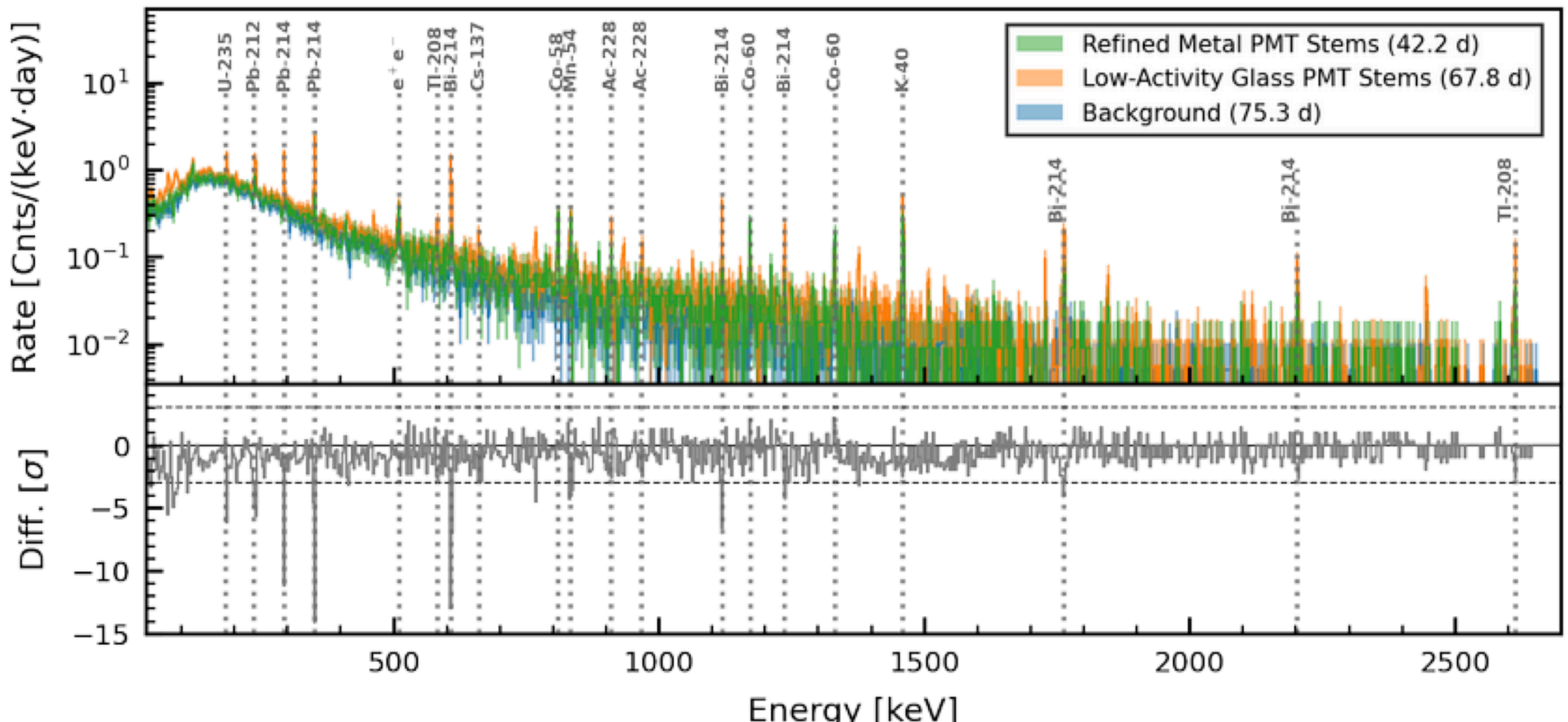
Refined metal stems



Geant4 model

R11410 PMT stems

- **Several versions screened with Gator at LNGS**
  - Low-activity glass stems (67.8 d)
  - Refined metal stems (42.2 d)
  - XENONnT stems (2015)



Refined metal stems

Low-activity glass stems

Analysis by Alex Bismark, UZH

R11410 PMT stems

- **Several versions screened with Gator at LNGS**
  - Low-activity glass stems (67.8 d)
  - Refined metal stems (42.2 d)
  - XENONnT stems (2015)

Refined metal stems

Low-activity glass stems

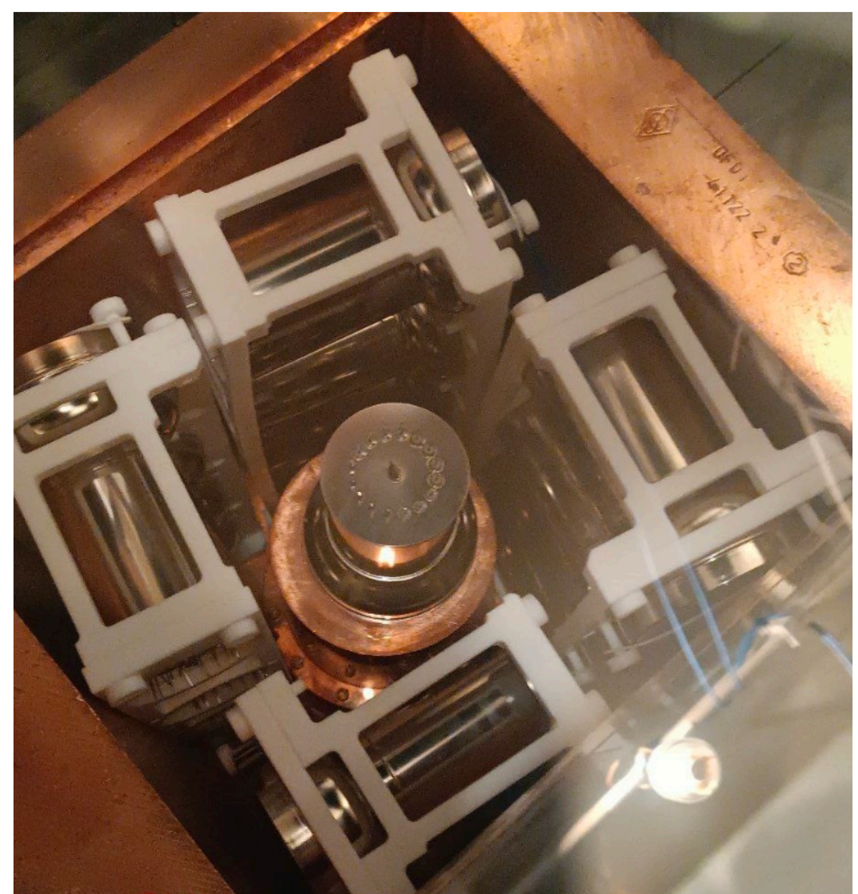
A [mBq/stem]	^{238}U	^{226}Ra	^{228}Ra	^{228}Th	^{235}U	^{60}Co	^{40}K	^{137}Cs
Refined metal stems	<6.01	<0.18	<0.35	<0.28	<5.05	0.08(2)	0.9(3)	<0.06
Glass stems	<4.81	1.11(7)	0.27(8)	<0.45	<6.3	<0.09	1.6(3)	<0.08
XENOnT stems	<18.4	1.0(3)	<0.81	<0.79	0.46(11)	0.34(5)	1.9(6)	<0.40

Analysis by Alex Bismark, UZH

New R11410* PMT units

- **Screened with Gator at LNGS**
  - Eight units placed in 2 PTFE holders; 67 days (after data cleaning)
  - Sixteen units placed in 4 PTFE holders; 30.7 days (run ongoing)
  - Background run with PTFE holders: 57.5 days

Eight units



Sixteen units

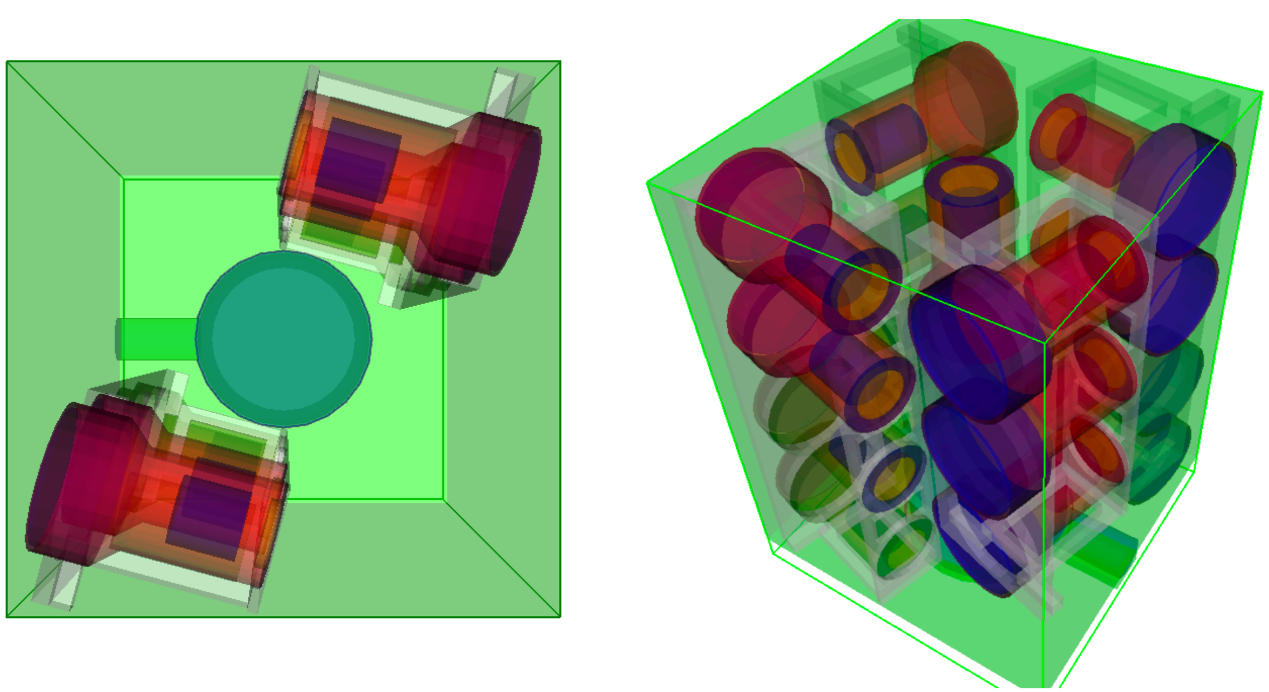
Francesco Piastra, UZH

*R17317

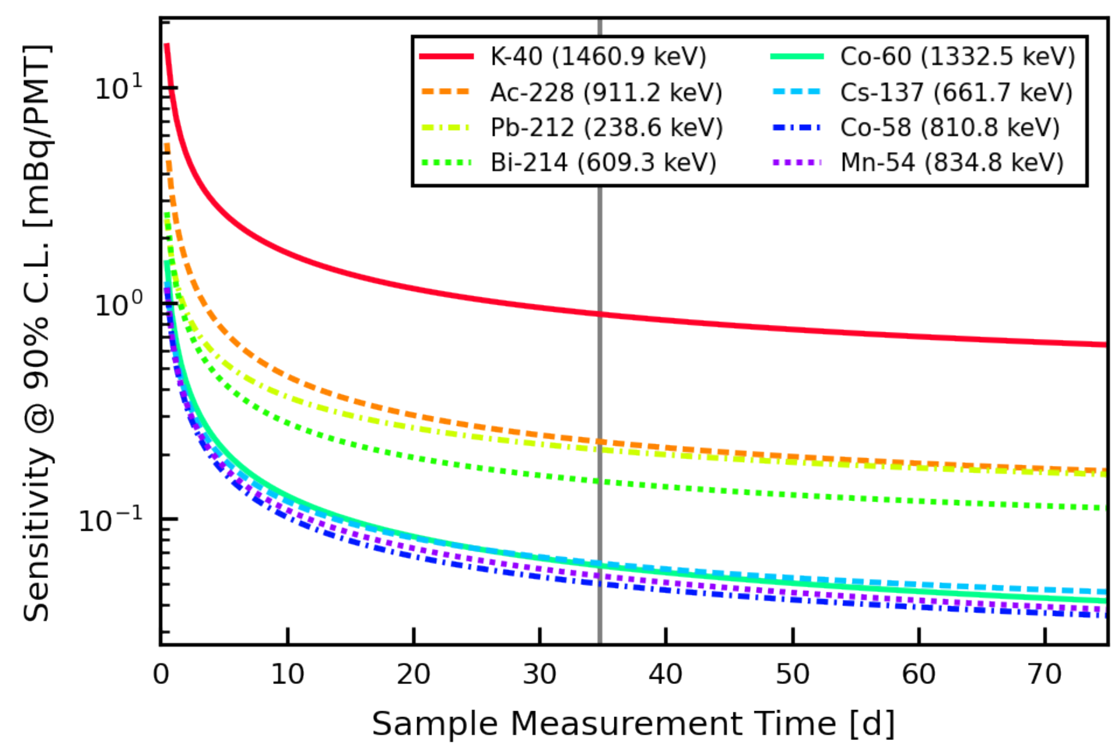
New R11410* PMT units

- **Screened with Gator at LNGS**
  - Eight units placed in 2 PTFE holders; 67 days (after data cleaning)
  - Sixteen units placed in 4 PTFE holders; 30.7 days (run ongoing)
  - Background run with PTFE holders: 57.5 days

MC simulations



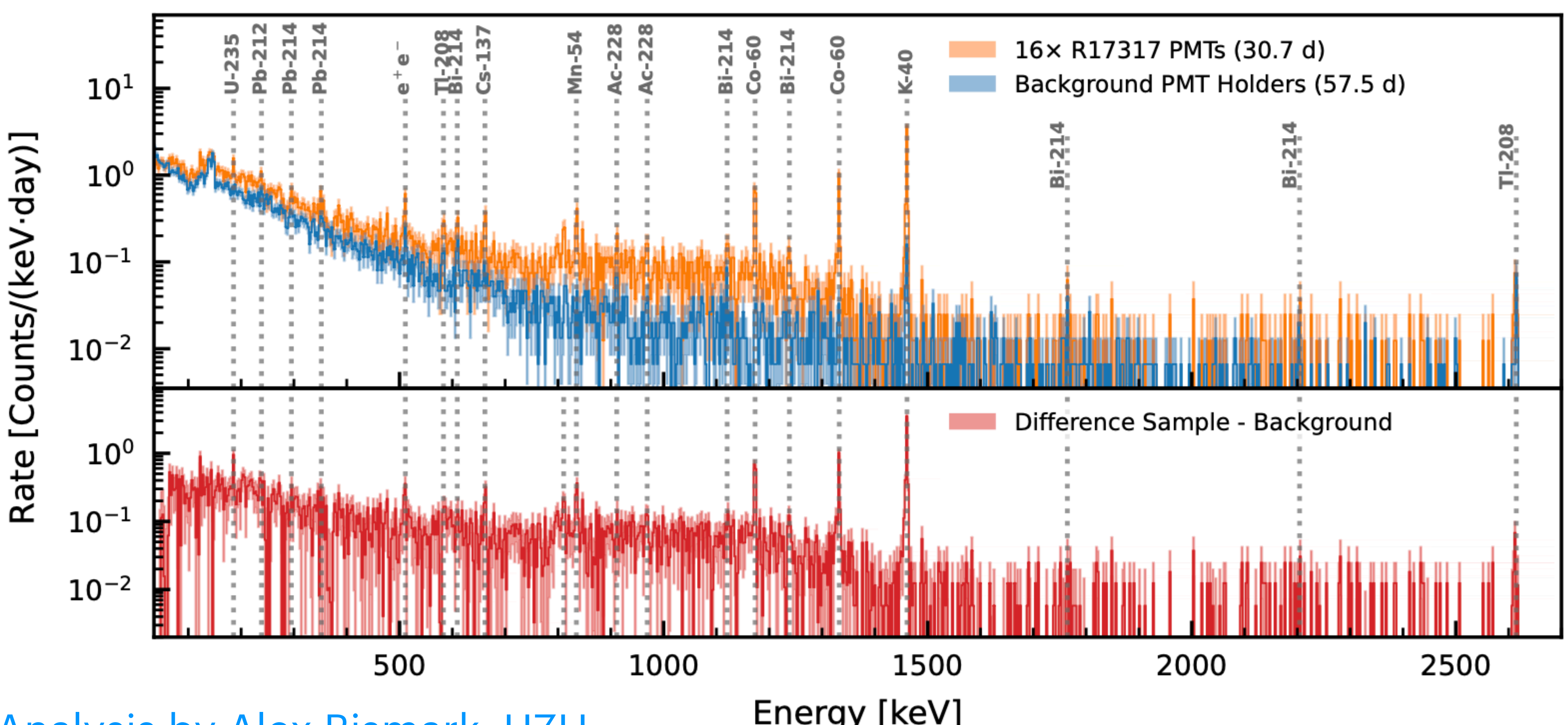
Sensitivity versus time



MC + analysis by Alex Bismark, UZH

New R11410* PMT units

- **Screened with Gator at LNGS**
  - Eight units placed in 2 PTFE holders; 67 days (after data cleaning)
  - Sixteen units placed in 4 PTFE holders; 30.7 days (run ongoing)
  - Background run with PTFE holders: 57.5 days



Analysis by Alex Bismark, UZH

New R11410* PMT units

- **Screened with Gator at LNGS**
  - Eight units placed in 2 PTFE holders; 67 days (after data cleaning)
  - Sixteen units placed in 4 PTFE holders; 30.7 days (run ongoing)
  - XENONnT PMTs (180 units, see EPJ-C 82, 2022)

A [mBq/PMT]	^{238}U	^{226}Ra	^{228}Ra	^{228}Th	^{235}U	^{60}Co	^{40}K	^{137}Cs
8 Units	<11.0	<0.40	<0.50	<0.37	<0.31	0.31±0.04	11.8±1.4	<0.19
16 Units	<6.0	<0.21	<0.42	<0.24	0.14±0.06	0.33±0.04	11.1±1.4	0.09±0.03
XENONnT PMTs	9±2	0.47±0.02	0.47±0.07	0.46±0.02	0.4±0.1	1.05±0.03	14.2±0.5	<0.14

Analysis by Alex Bismark, UZH

Preliminary results from 30.7 days

Nomenclature and further steps

- PMT with metal stem with glass beads: **new name R17317**
- **Further planned reduction in radioactivity** See 2020 JINST 15 P09027
  - Photocathode with highly pure K used for XMASS (R13111)
  - Glass beads with low-radioactivity glass used for XMASS (R13111)
  - Material provided by XMASS when R13111 were produced

R11410-21 and R17317

R11410-21 and R17317

R13111

^{39}K-rich Photocathode

- Most of the ^{40}K in R10789 comes from the photocathode material
- Chemicals used to make photocathode material contain potassium, which contains ^{40}K with a natural abundance of 117 ppm
- ^{39}K enriched material was used to make the photocathode
- ^{40}K in a material reduced to ~1/100

Samples	^{226}Ra	^{238}U (^{234}Th)	^{210}Pb	^{228}Ra	^{40}K	^{60}Co
without enrichment	< 82	$< 3.0 \cdot 10^4$	$< 8.8 \cdot 10^4$	$< 3.4 \cdot 10^2$	$(1.0 \pm 0.1) \cdot 10^7$	$< 9.9 \cdot 10^2$
with enrichment	$< 2.2 \cdot 10^2$	$< 1.3 \cdot 10^3$	$< 8.9 \cdot 10^3$	$< 1.9 \cdot 10^2$	$(8.4 \pm 0.4) \cdot 10^4$	< 52

uBq/g HPGe measurement with 20g material

μBq/PMT	^{226}Ra	^{238}U	^{228}Ra	^{40}K	^{60}Co
R13111 in 2015	$(3.8 \pm 0.7)\cdot 10^2$	$<1.6 \cdot 10^3$	$(2.9 \pm 0.6)\cdot 10^2$	$<1.4 \cdot 10^3$	$(2.2 \pm 0.5)\cdot 10^2$
R13111 in 2016	$(4.4 \pm 0.6)\cdot 10^2$	$<1.4 \cdot 10^3$	$(2.0 \pm 0.6)\cdot 10^2$	$(2.0 \pm 0.5) \cdot 10^3$	$(1.3 \pm 0.4)\cdot 10^2$
R11410-21(XENON1T) [15]	$(5.2 \pm 1.0)\cdot 10^2$	$<1.3 \cdot 10^4$	$(3.9 \pm 1.0)\cdot 10^2$	$(1.2 \pm 0.2) \cdot 10^4$	$(7.4 \pm 1.0) \cdot 10^2$
R11410-10(PandaX) [3]	$<7.2\cdot 10^2$	—	$<8.3\cdot 10^2$	$(1.5 \pm 0.8) \cdot 10^4$	$(3.4 \pm 0.4) \cdot 10^3$
R11410-10(LUX) [19]	$<4.0\cdot 10^2$	$<6.0 \cdot 10^3$	$<3.0 \cdot 10^2$	$<8.3 \cdot 10^3$	$(2.0 \pm 0.2) \cdot 10^3$

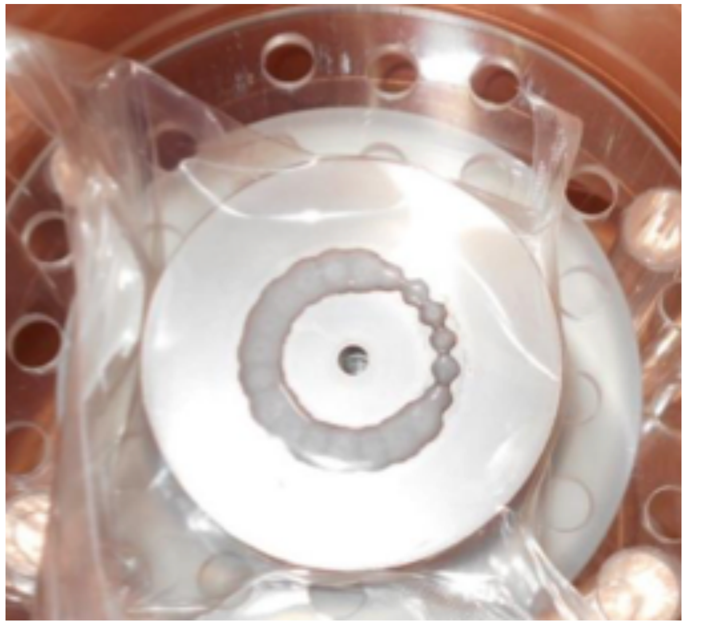
Glass beads used for Stem

K. Abe et al. 2020 JINST 15 P09027

- High purity reagents were obtained from Kojundo Chemical Laboratory Ltd.
- The milling process uses ceramic tools (ceramic balls and a ceramic pot). We provide high purity ceramic materials for them.

Table 2. Results of HPGe measurements for the glass-bead-related materials. The unit is μBq/g. Errors quoted are purely statistical. See the text for the systematic error.

Samples	component ratio [%]	^{226}Ra	^{238}U (^{234}Th)	^{210}Pb	^{228}Ra	^{40}K	^{60}Co
SiO_2 5N grade	64	< 11	$< 1.5 \cdot 10^2$	$< 1.1 \cdot 10^3$	< 13	$< 1.5 \cdot 10^2$	< 4.4
B_2O_3 4N5 Grade	3	< 45	$< 1.8 \cdot 10^2$	$< 4.6 \cdot 10^2$	< 44	$< 4.5 \cdot 10^2$	< 12
$Na_2B_4O_7$ 4N5 Grade	24	$(1.8 \pm 0.6) \cdot 10^2$	$< 3.9 \cdot 10^2$	$< 1.3 \cdot 10^3$	< 74	$< 1.1 \cdot 10^3$	< 25
$Al(OH)_3$ 4N grade	9	< 25	$< 2.3 \cdot 10^2$	$< 1.5 \cdot 10^3$	< 42	$< 2.0 \cdot 10^2$	< 7.6
Sum		36 ± 15	$< 1.3 \cdot 10^2$	$< 6.5 \cdot 10^2$	< 19	$< 2.6 \cdot 10^2$	< 6.6
Glass after synthesis		12 ± 4	57 ± 26	< 61	< 9.4	$(1.5 \pm 0.5) \cdot 10^2$	< 2.5
Glass after milling		24 ± 5	< 97	< 99	17 ± 4	$(1.3 \pm 0.6) \cdot 10^2$	< 4.0
Glass beads		< 15	< 72	$< 1.9 \cdot 10^2$	< 9.7	$(1.7 \pm 0.7) \cdot 10^2$	< 2.0
R10789 glass beads		$(8.1 \pm 0.1) \cdot 10^2$	$(3.3 \pm 0.6) \cdot 10^2$	$< 4.1 \cdot 10^2$	$(1.4 \pm 0.1) \cdot 10^2$	$(1.4 \pm 0.1) \cdot 10^3$	< 2.3



Glass 0.765 g/PMT HPGe measurement @ Kamioka

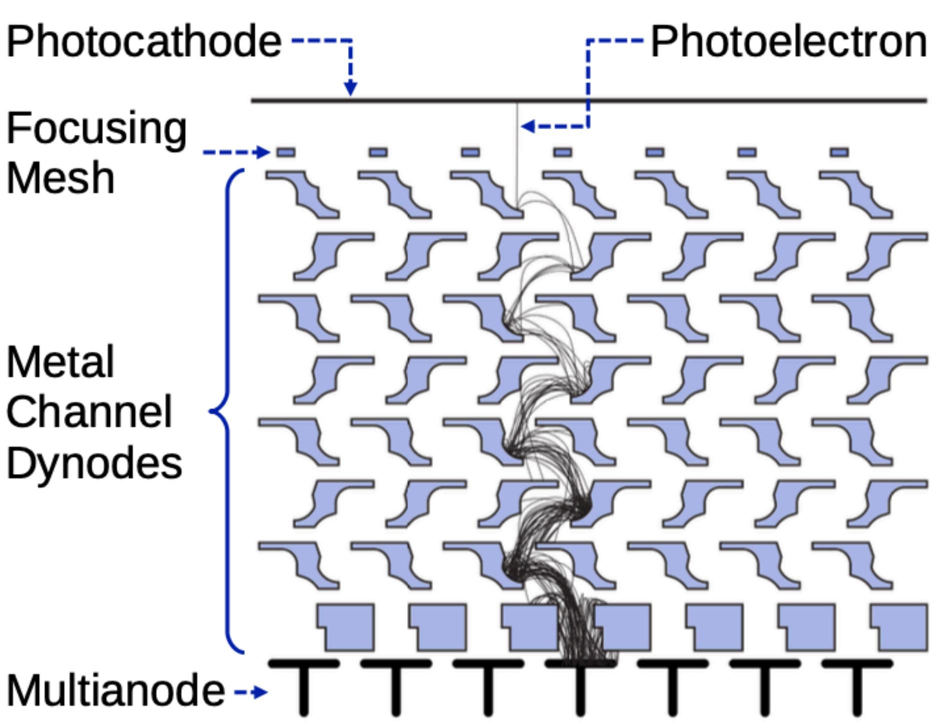
A [mBq/PMT]	^{238}U	^{226}Ra	^{228}Ra	^{228}Th	^{235}U	^{60}Co	^{40}K	^{137}Cs
R17317	0.25(4)	0.34(1)	0.015(3)	0.015(2)		$<0.9\times10^{-3}$	0.65(2)	
R13111	**<0.055**	**<0.011**	**<0.01**	**<0.0074**		**$<1.5\times10^{-3}$**	**0.13(5)**	

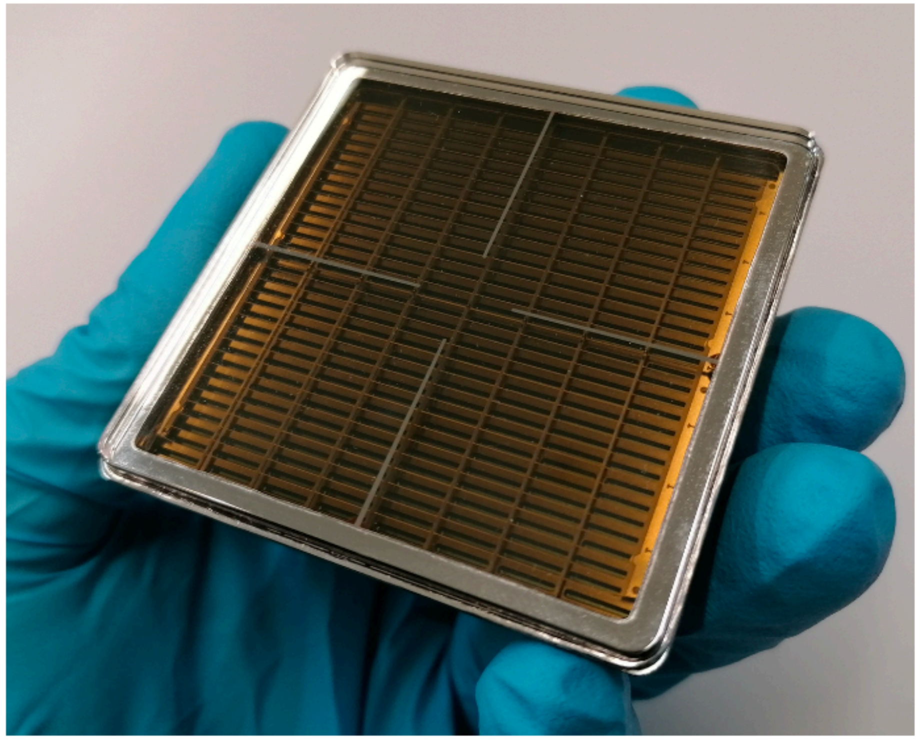
Production of 3" PMTs

- **Lead time: 9 months ARO**
  - then, 50 PMTs per month
  - if we aim for 2500 units (this includes contingency, 2364 in the DB):
  - 58 months ~ 4.8 years
- Lead time does not include screening of materials (+ 1 year?)
- **Assume we place the orders in early 2027**
  - production would start late 2027 (9 months ARO)
  - 2027 + 6 years!
  - this scenario assumes we do not reuse LZ and nT PMTs
- **Visit Hamamatsu November 2024 (Laura, Masaki, Masatoshi, Shingo)**
  - Discussion on 3’’ PMT, 2’’ square PMT, SiPM
  - **Hamamatsu agreed to use R13111 technologies for XLZD**

The 2" square PMT

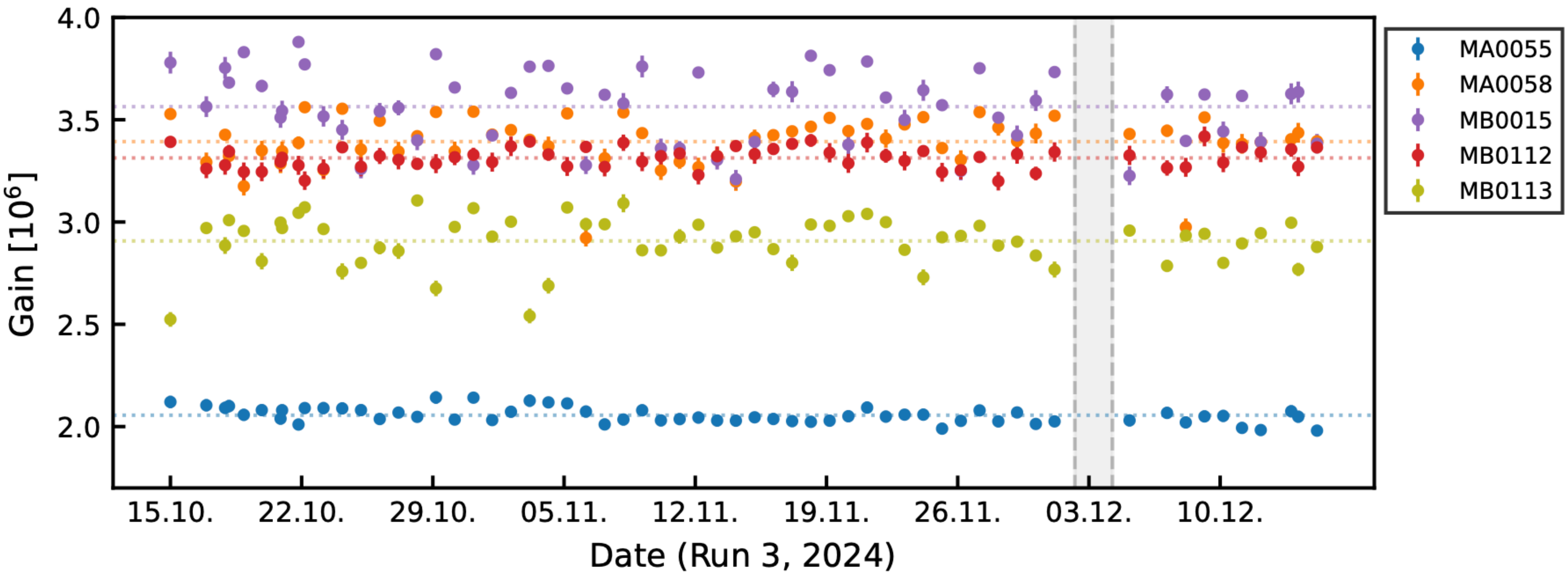
- **Characterisation in LXe (MarmotX) and in a 2-phase TPC (Xams)**
  - 2506.04844: UZH and Nikhef (Alex, Maxi, Marijke)
  - screening with Gator (Alex)
- Leakage issue around the pins (Hamamatsu aims to solve within 2025)





The 2" square PMT

- Long-term gain stability measurements in MarmotX



2506.04844

The 2" square PMT

- Comparison with the 3" unit

	R12699-406-M4	R11410-21
Dimensions (longitudinal / lateral)	14.8 mm / 56 mm [11]	114 mm / 77.5 mm [31]
Packing density	75.0 %	61.8 %
Dynode structure	Metal channel [11]	Box & linear-focused [31]
Number of dynode stages	10 [11]	12 [31]
Quantum efficiency at 175 nm	33 % [11]	32.5 % [31]
Operation voltage (nominal / max.)	1000 V / 1100 V [11]	1500 V / 1750 V [31]
Gain (T_{room})	$(3.3 \pm 0.7) \cdot 10^6$	$(8.4 \pm 2.3) \cdot 10^6$ [15]
SPE resolution (gain $\sim 2 \cdot 10^6$, T_{room})	(37 ± 3) %	(30 ± 3) % [21]
Dark count rate (> 1/4 PE)	(0.4 ± 0.2) Hz/cm^2	(1.4 ± 0.7) Hz/cm^2 [21]
Time response (RT / transit time / TTS)	1.2 / 5.9 / 0.41 ns [11]	5.5 / 46 / 9 ns [31]
Separable afterpulse rate	(1.1 ± 0.2) %/PE	(8.6 ± 2.2) %/PE [21]

2506.04844

The 2" square PMT

- Screening results

ID	Sample Description	Mass [g/PMT]	Livetime Sample / Background [d]	Units	Notes
0	Initial model (2× R12699-406-M4)	2×104	41.7 / 73.7	mBq/cm^2	Full PMT volume Glass bead region only
1	Improved LRI metal (2× R12699-406-M4/NG)	2×104	47.8 / 73.7	mBq/cm^2	Full PMT volume Glass bead region only
2	Improved LRI glass (3× R12699-406-M4/NG)	3×104	40.8 / 32.2	mBq/cm^2	Full PMT volume Glass bead region only
3	R8520-06-Al (XENON100)	Various	Various	mBq/cm^2	From [33]
4	R11410-21 (XENONnT)	Various	Various	mBq/cm^2	From [9]

ID	^{238}U	^{226}Ra	^{228}Ra	^{228}Th	^{235}U	^{60}Co	^{40}K	^{137}Cs	^{54}Mn	^{58}Co
0	< 0.260	0.026(4)	< 0.028	< 0.023	< 0.008	0.055(5)	1.47(16)	< 0.005	< 0.006	< 0.005
	< 0.376	0.028(4)	< 0.031	< 0.023	< 0.011	0.064(6)	1.78(19)	< 0.006	< 0.007	< 0.006
1	< 0.294	0.023(4)	< 0.023	< 0.015	< 0.009	0.0036(16)	1.45(15)	< 0.005	0.0070(15)	0.0103(18)
	< 0.425	0.026(4)	< 0.026	< 0.018	< 0.012	0.0041(18)	1.76(19)	< 0.006	0.0086(19)	0.012(2)
2	< 0.404	< 0.015	< 0.022	< 0.017	< 0.010	0.0057(17)	1.29(14)	< 0.006	0.0068(17)	0.0055(15)
	< 0.621	< 0.017	< 0.025	< 0.020	< 0.013	0.007(2)	1.57(17)	< 0.008	0.008(2)	0.0067(18)
3	< 3.569	< 0.067	< 0.140	0.071(17)	< 0.159	0.144(10)	2.86(18)	< 0.024	–	–
4	0.28(6)	0.0146(6)	0.015(2)	0.0143(6)	0.012(3)	0.0326(9)	0.441(16)	< 0.004	–	–

2506.04844

Production of 2" PMTs

- **Lead time: 5 months ARO**
  - then, 70 PMTs per month
  - if we aim for 3750 units (this includes contingency, xxxx needed):
  - 58 months ~ 4.8 years
- Lead time does not include screening of materials

- **Mixed option: 3-inch PMTs bottom, 2-inch PMTs top**
  - production can proceed in parallel, as production lines are different
  - we would likely gain ~ **two years**

Other considerations

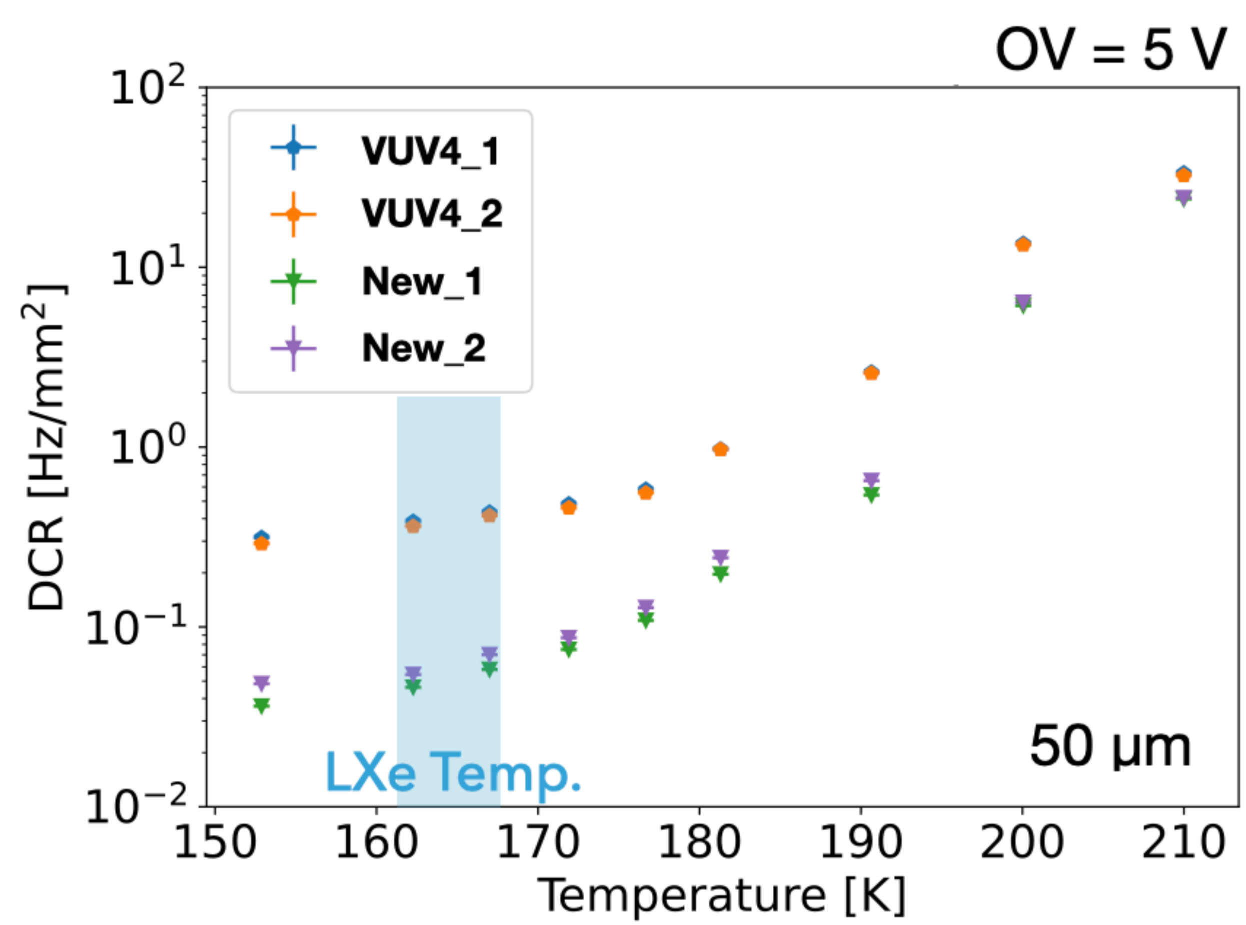
- LXe test of the 16 units with new stems: where, when?
- Can we reuse LZ and nT PMTs (but higher radioactivity)? We need detailed MC studies (and also see how many good PMTs are left after 2028)
- Quartz fluorescence backgrounds? (arXiv:2505.08067)

  → Comparison of fluorescence properties for different grades of quartz glass is ongoing
- Base design: compare LZ, XENONnT designs, decide on any required improvements (linearity, radioactivity, etc)
  - See also talk by Alessandro Razeto (re: cold electronics)
- Cables, connectors
- Support structures

SiPMs: Dark Count

- At LXe T: huge DC rate is mainly due to the band-to-band tunnelling effect
- Developed VUV SiPMs with decreased avalanche electric field to suppress the tunnelling effect
- Managed to decrease DCR of VUV4 SiPMs by a factor of 5 - 8
- Reached DCR of O(0.01) Hz/mm²
  → Hamamatsu is currently developing new SiPMs ("VUV5") with further reduced DCR

SiPM	VUV 4	New VUV SiPM	
Operation Voltage	40-50 V	80-100 V	
Active Area	3×3 mm²		
Number of pixels	14400		6400
Pixel size	50×50 µm²		100×100 µm²
Fill factor	58%	74%	>> 74 %

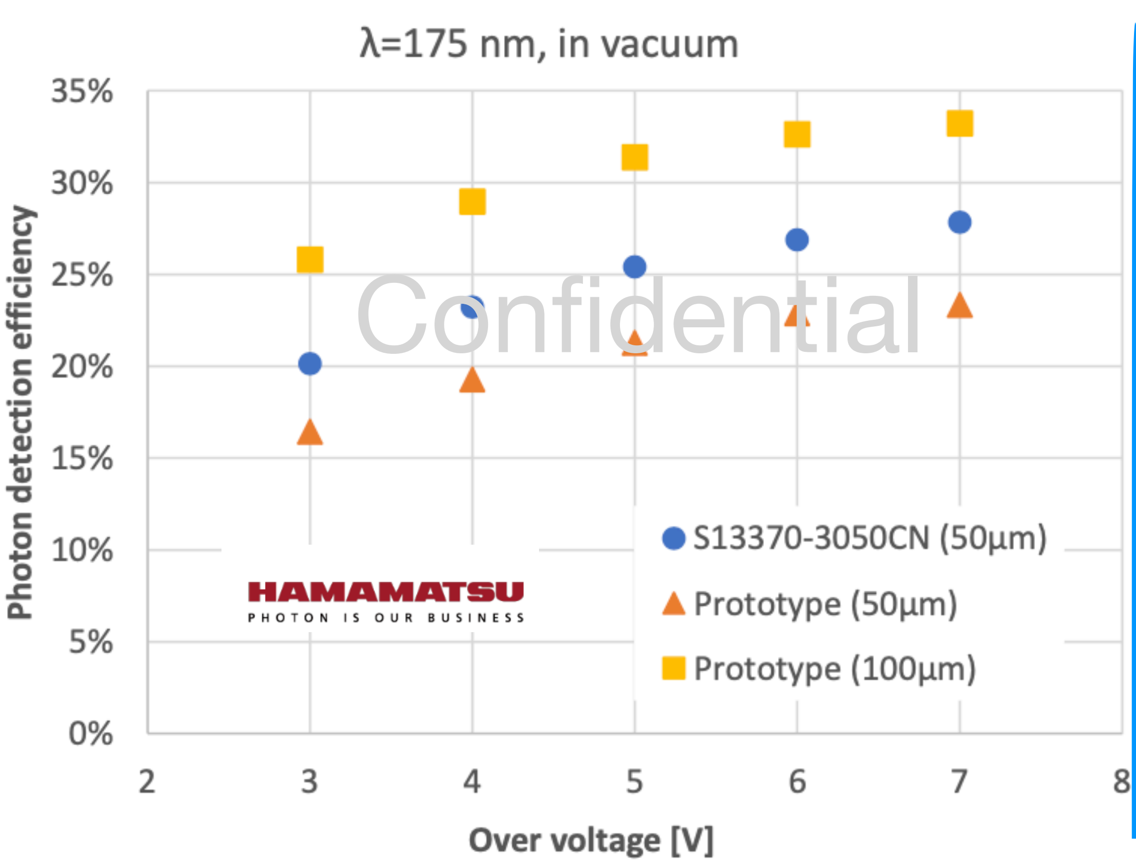


SiPMs: PDE & RI

- Reducing DCR worsens PDE; can be compensated for with optimised fill factor
  → New SiPMs: PDE > 30% depending on over-voltage

- Concerning RI: Hamamatsu currently develops new VUV SiPMs with TSV chips
  → No ceramic packaging

- VUV5 = “lower DCR” + “better PDE” + “lower RI”



To achieve low RI,
we mounted TSV chips on a substrate made of low RI material.

Si package

- *Pros* : Low RI characteristics
- *Cons* : Difficult to handle because a substrate to mount a Si package is required

CoF package

*CoF = chip on film

- *Pros* : Low cost, Design flexibility
- *Cons* : Lower RI properties than Si

The end

Hamamatsu visit, November 2024

Additional slides

3" PMT screening

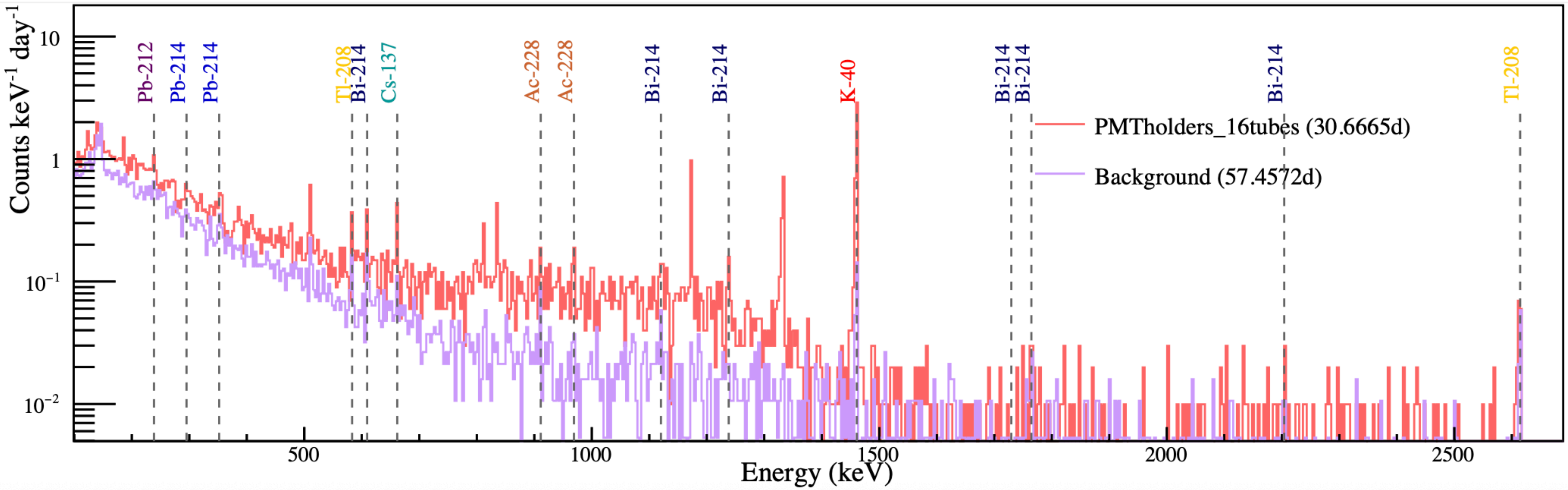
16 PMTs

	This work	Eight R17317 PMTs	XENONnT PMT sc
^{238}U	< 6.0	< 11.0	9 ± 2
^{226}Ra	< 0.21	< 0.40	0.47 ± 0.02
^{228}Ra	< 0.42	< 0.50	0.47 ± 0.07
^{228}Th	< 0.24	< 0.37	0.46 ± 0.02
^{235}U	0.14 ± 0.06	< 0.40	0.4 ± 0.1
^{60}Co	0.33 ± 0.04	0.30 ± 0.04	1.05 ± 0.03
^{40}K	11.1 ± 1.3	11.8 ± 1.4	14.2 ± 0.5
^{137}Cs	0.09 ± 0.03	< 0.19	< 0.14
^{54}Mn	0.08 ± 0.03	0.18 ± 0.04	–
^{58}Co	0.06 ± 0.02	0.12 ± 0.03	–

Isotope	Energy (keV)	Line BR	Effic	BRxEffic
^{234}Th	92.6	0.0433	0.00466	0.000202
^{235}U	185.72	0.572	0.0134	0.00765
^{212}Pb	238.632	0.436	0.0115	0.00500
^{214}Pb	295.224	0.184	0.0117	0.00215
^{228}Ac	338.32	0.114	0.0115	0.00132
^{214}Pb	351.932	0.356	0.0114	0.00404
^{208}Tl	583.187	0.3054	0.00798	0.00244
^{214}Bi	609.312	0.4549	0.00837	0.00381
^{137}Cs	661.657	0.8499	0.00915	0.00778
^{54}Mn	834.838	0.999746	0.00831	0.00830
^{46}Sc	889.271	0.99984	0.00758	0.00757
^{228}Ac	911.196	0.262	0.00656	0.00172
^{228}Ac	968.96	0.159	0.00660	0.00105
^{214}Bi	1120.29	0.1491	0.00634	0.000945
^{46}Sc	1120.54	0.99987	0.00676	0.00676
^{60}Co	1173.23	0.9985	0.00666	0.00665
^{60}Co	1332.49	0.9998	0.00621	0.00621
^{58}Co	810.775	0.99	0.00820	0.00812
^{40}K	1460.88	0.1055	0.00626	0.000660
^{214}Bi	1764.49	0.1531	0.00533	0.000816
^{208}Tl	2614.51	0.3584	0.00372	0.00133

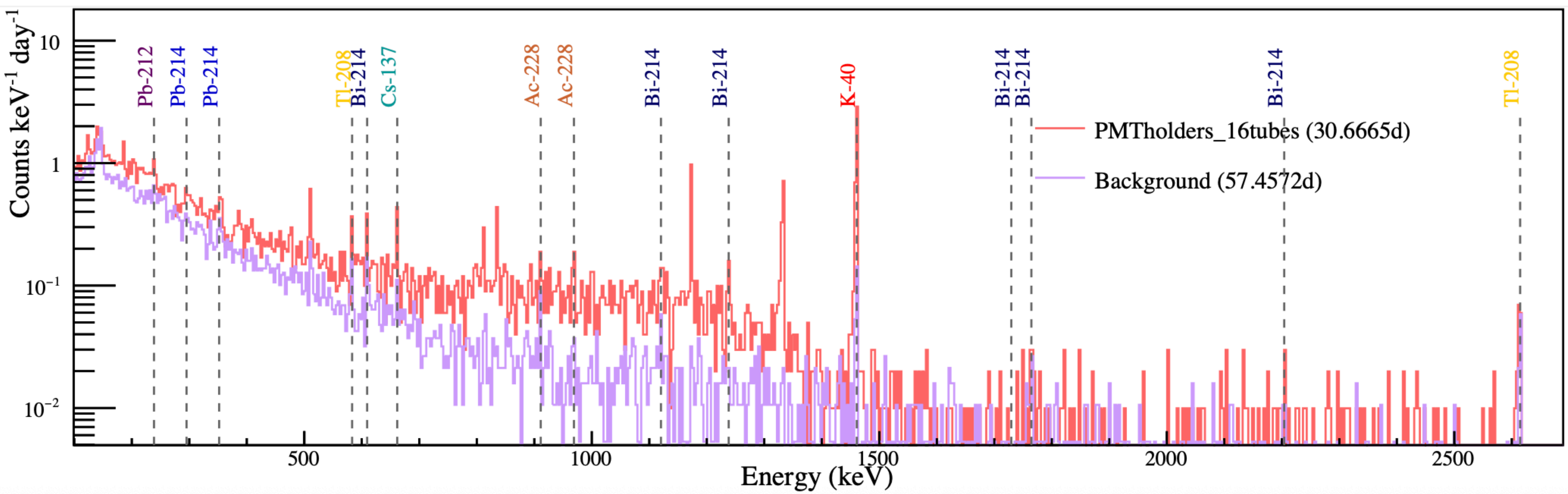
3" PMT screening

16 PMTs



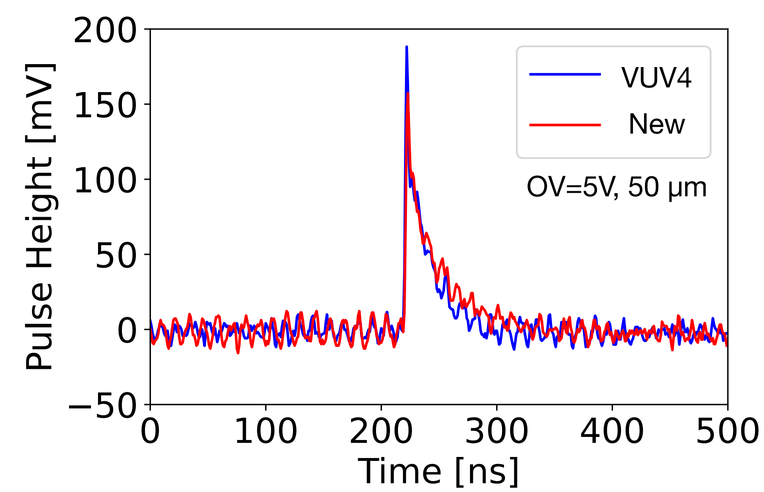
3" PMT screening

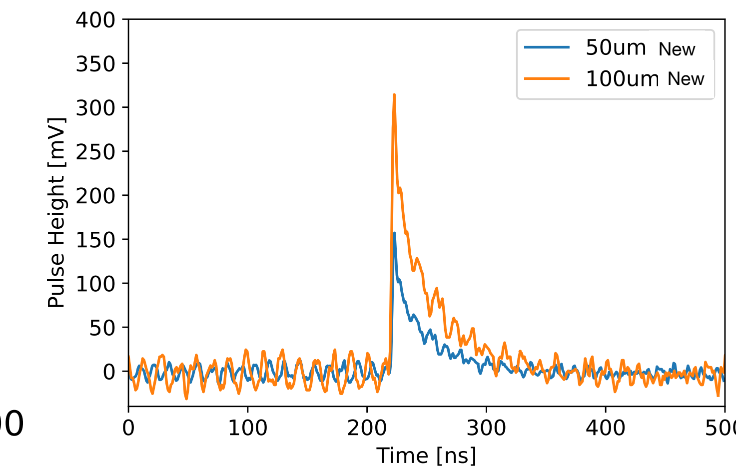
16 PMTs



Single-Photon Responses

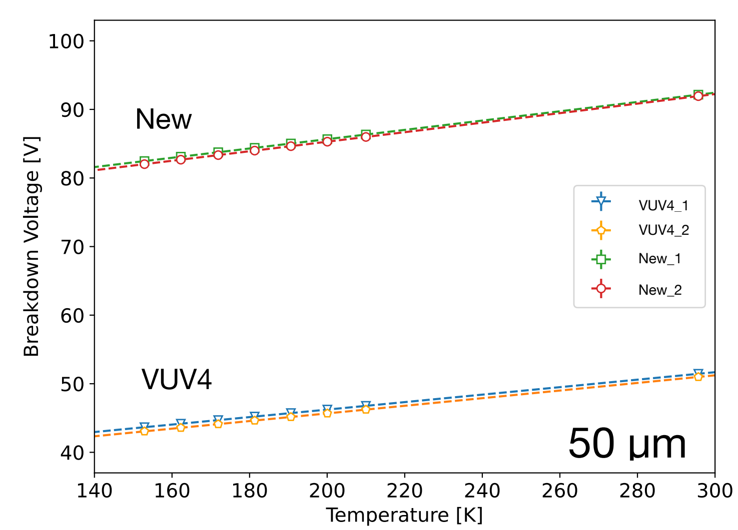
	Over-voltage	VUV-4 50 µm	New 50 µm	New 100 µm
breakdown voltage @ 165 K [V]		44.4	83.4	84.4
1pe Gain [×10^6]	3 V	1.0	0.6	1.6
	5 V	1.7	1.0	2.6
	7 V	2.4	1.4	3.6

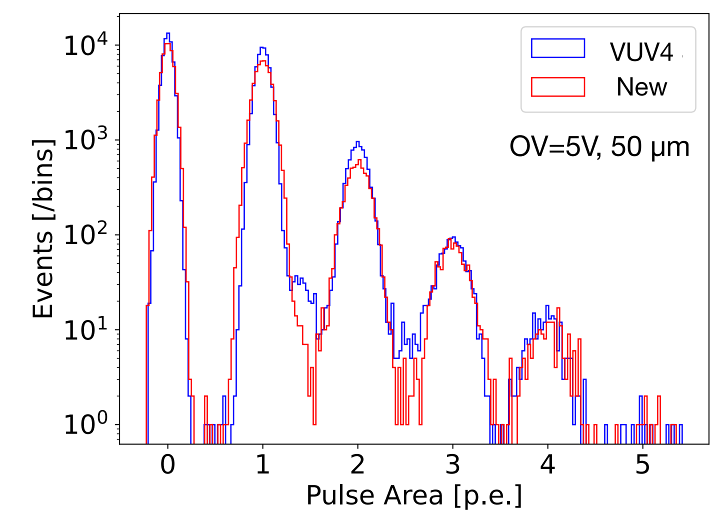




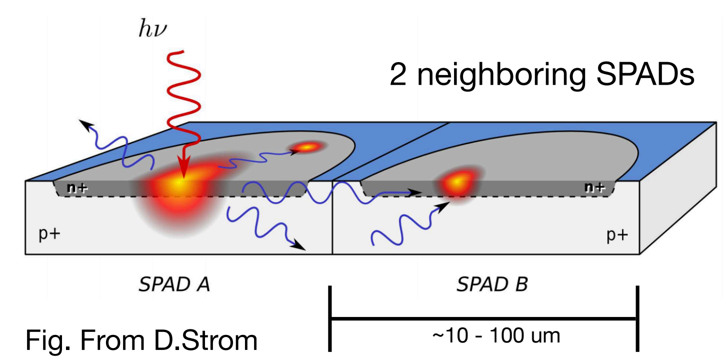
Changes w.r.t. the original SiPM

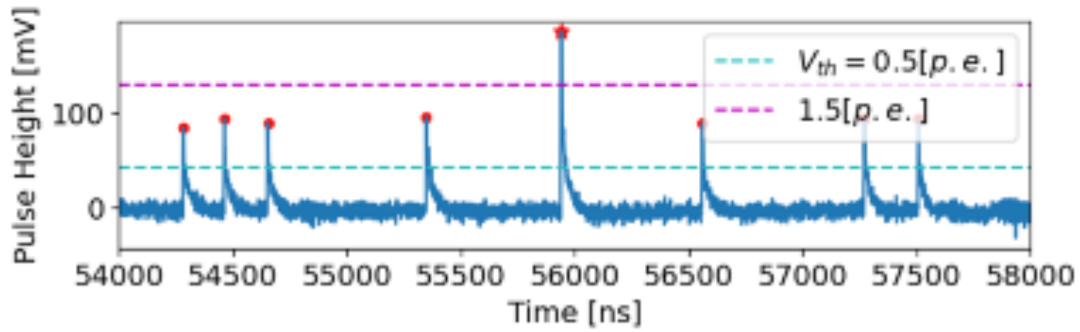
- No significant changes in waveform shapes
- Breakdown voltage increased by 40 V
- 1PE gain becomes smaller at the same OVs, but it still has ~10^6 gain





Cross-talk Probability



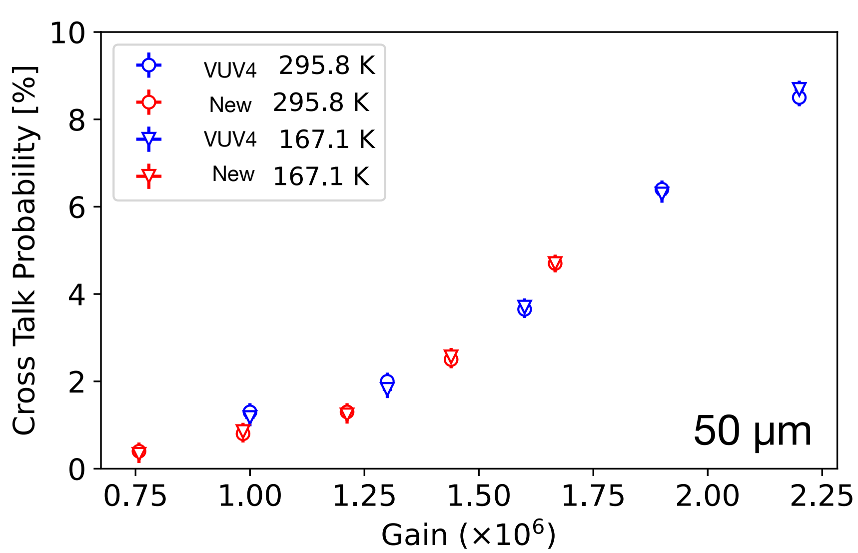


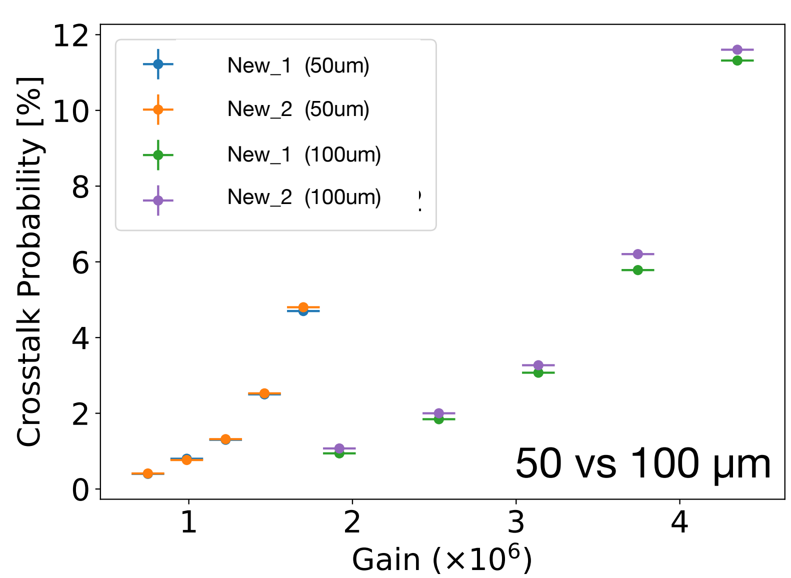
$$R_{CT} = \frac{N_{>1.5pe}}{N_{>0.5pe}}$$

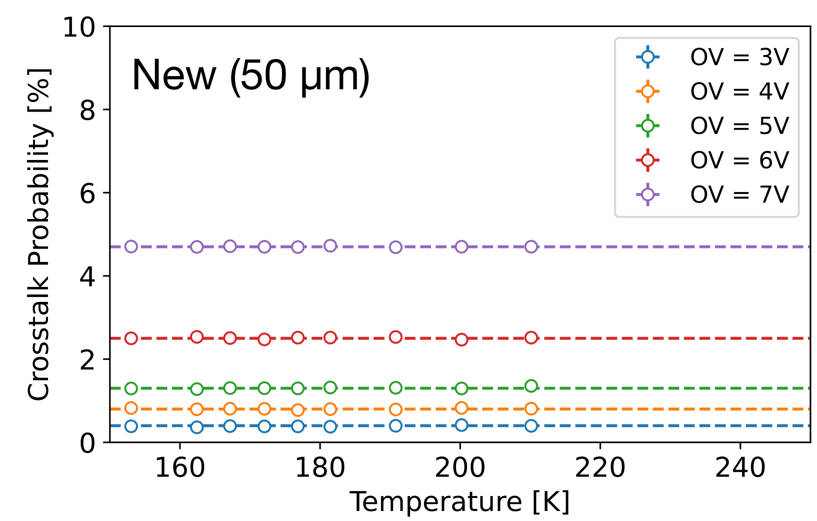
•As expected, cross-talk probability for VUV4 and new SiPMs is almost the same at the same 1PE gain.

•SiPM with a100 um pixel has a smaller cross-talk probability because it has a larger active area (smaller chance for infrared photons to propagate to nearby SPADs.)

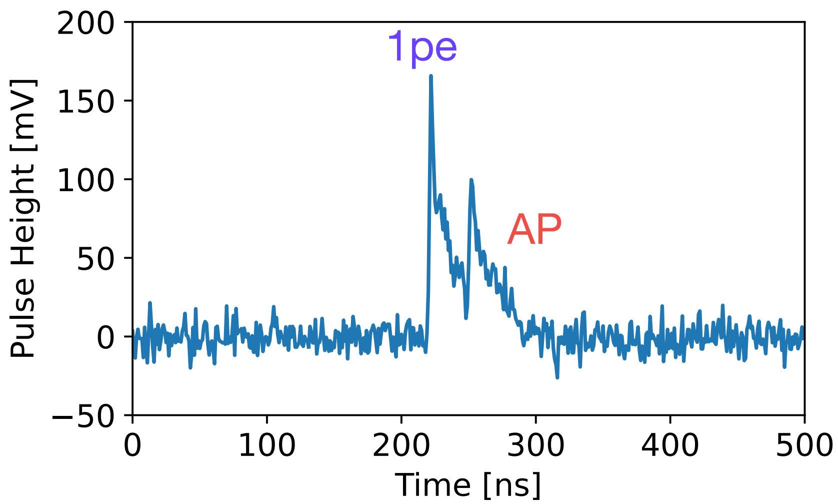
•No significant temperature dependence was observed.

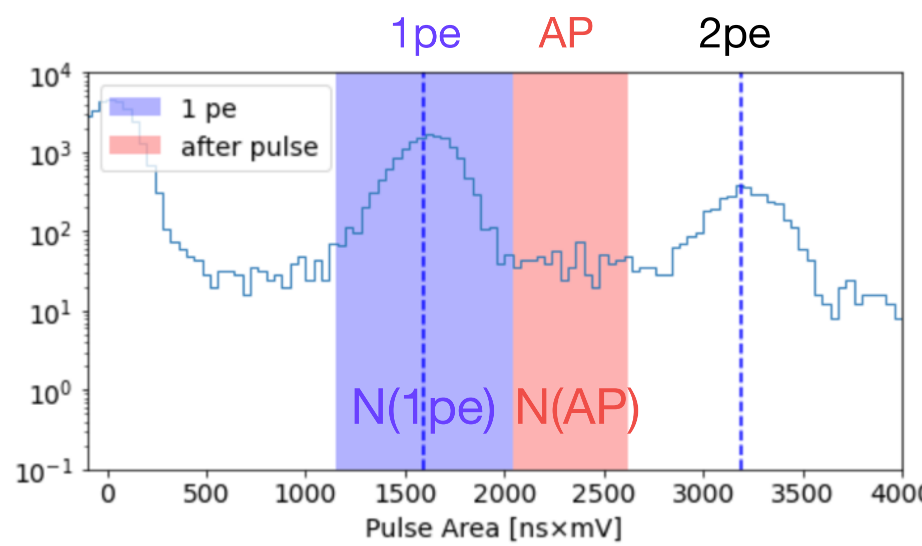




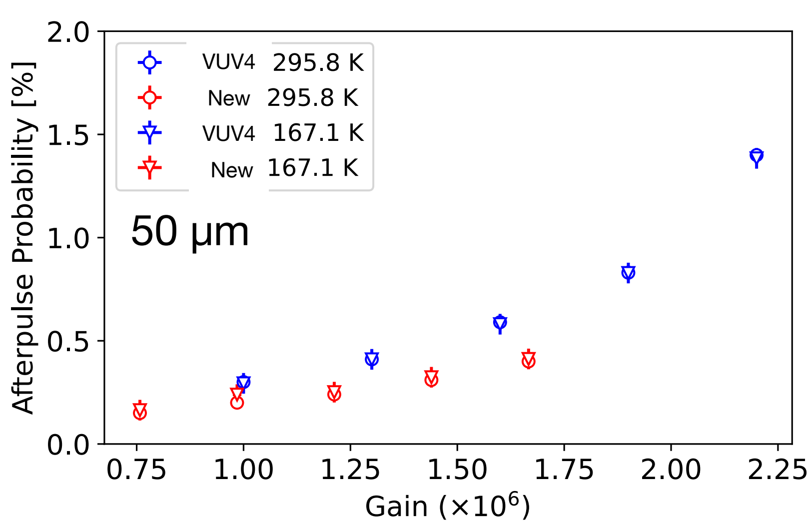


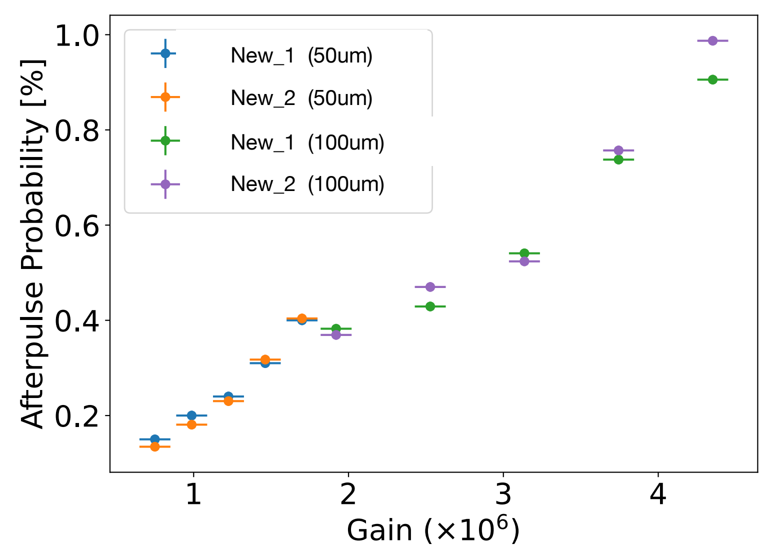
Afterpulse Probability





Afterpulse probability in this study is defined by N(AP) / N(1pe)





- AP probability for new SiPMs is smaller at the same 1PE gain, probably due to smaller dope concentration.
- 100 μm pixel has a bit smaller AP probability
- No significant temperature dependence was observed.