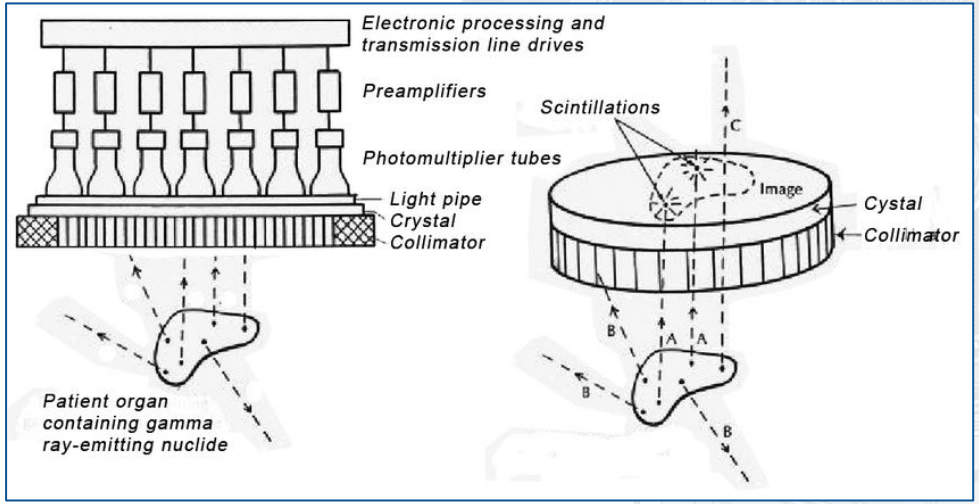
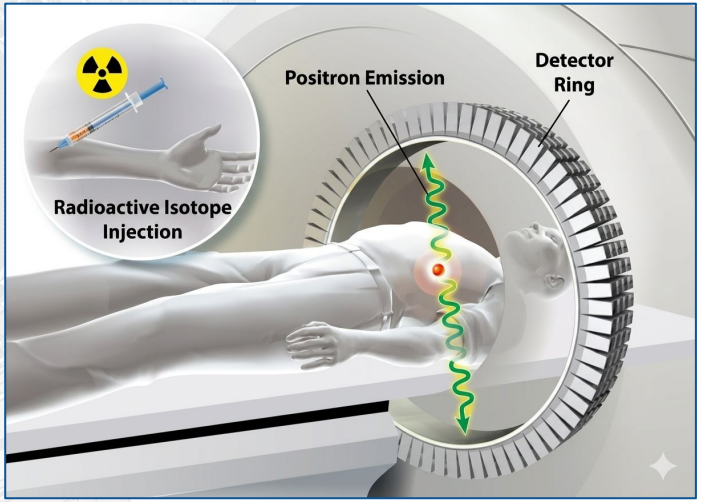
Heure Thésarde:
Development of the XEMIS2 liquid xenon Compton camera and its interface with three-gamma imaging
21/05/2026

Context :
Nuclear imaging

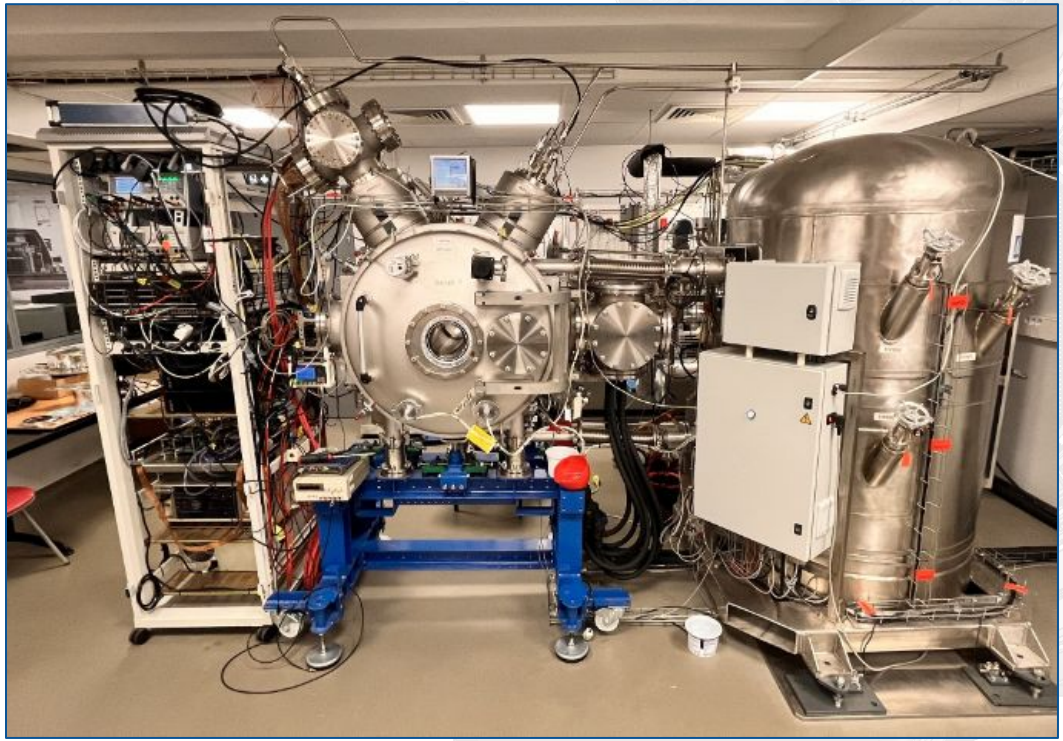
SPECT (1γ imaging)

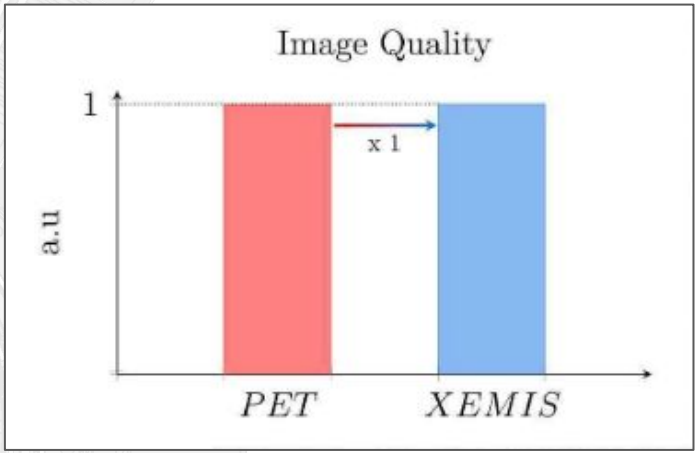


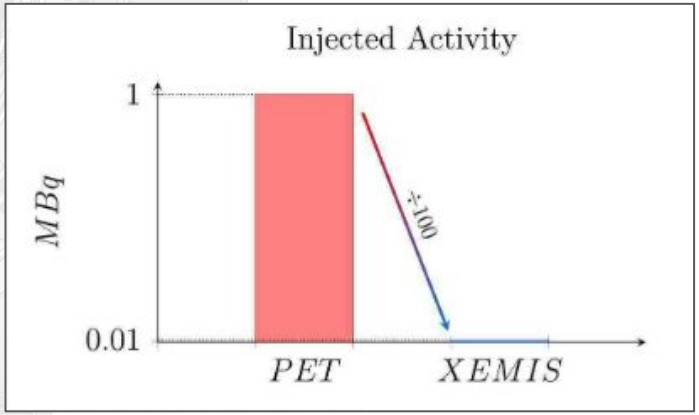
PET (2γ imaging)



XEMIS (3γ imaging)

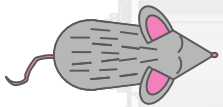






2 γ imaging (PET scan)

$$^{18}_{9}\mathrm{F} \rightarrow {}^{18}_{8}\mathrm{O} + e^{+} + \nu_e$$



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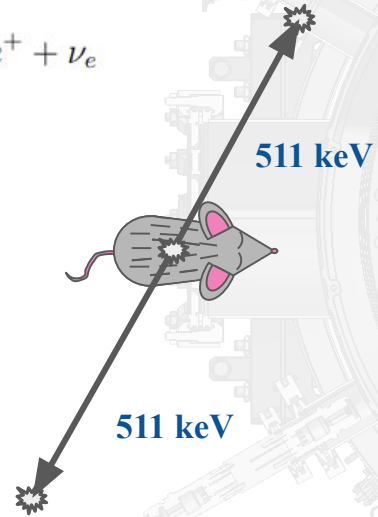

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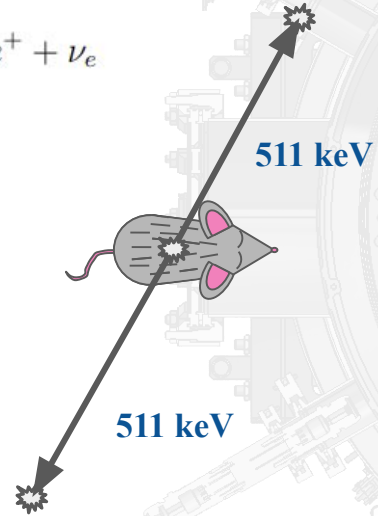

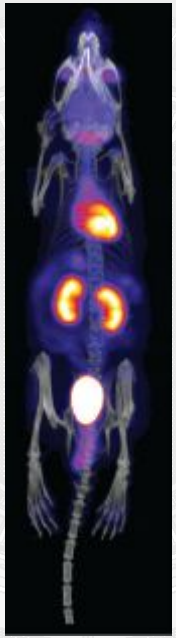

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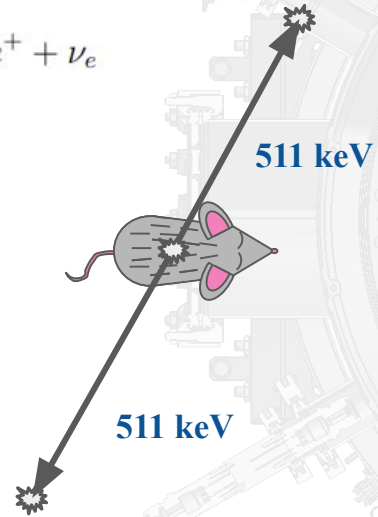
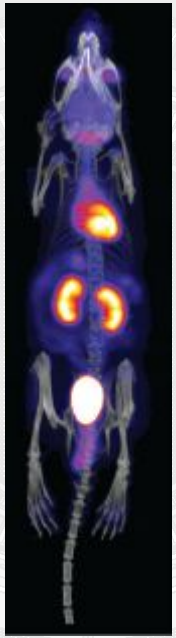
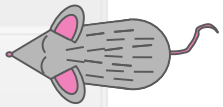




3 γ imaging (Xemis 2)

$$^{44}\mathrm{Sc} \rightarrow {}^{44}\mathrm{Ca}^{*} + e^{+} + \nu_e$$

$$^{44}\mathrm{Ca}^{*} \rightarrow {}^{44}\mathrm{Ca} + \gamma(1157keV)$$



Introduction

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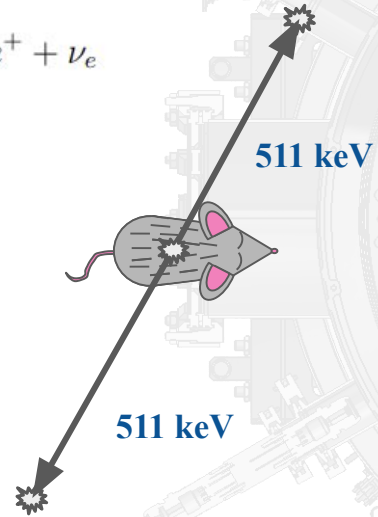

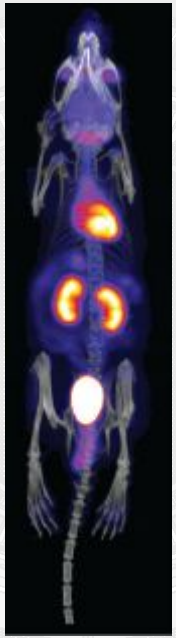

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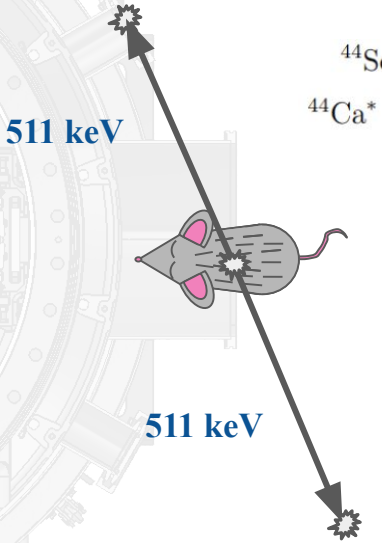

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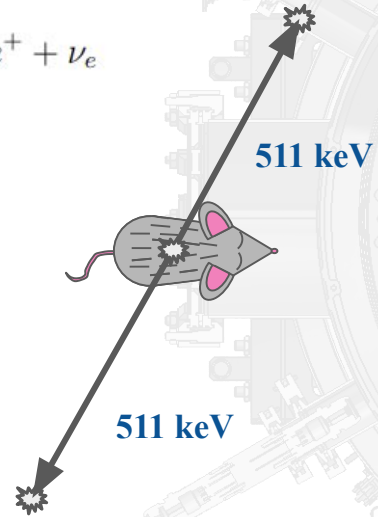

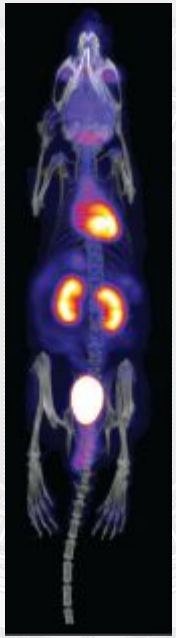

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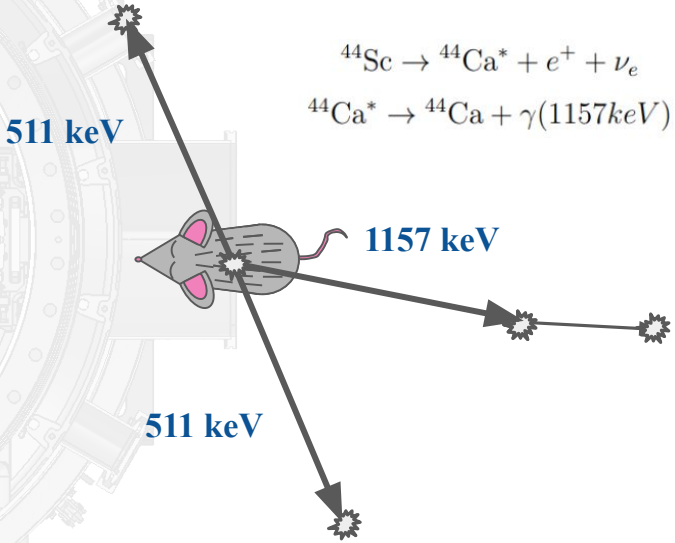

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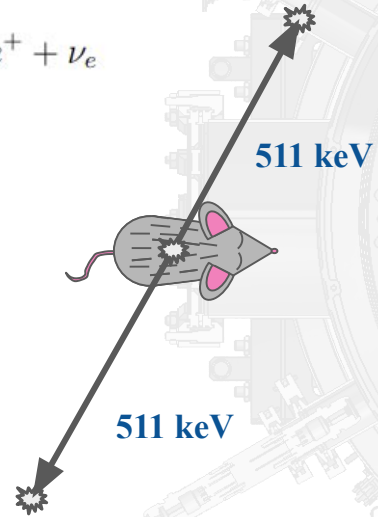

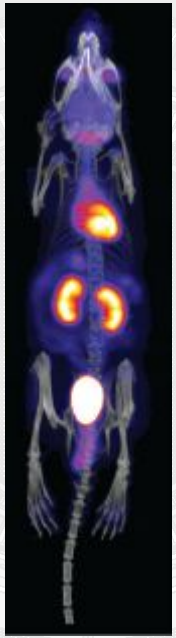

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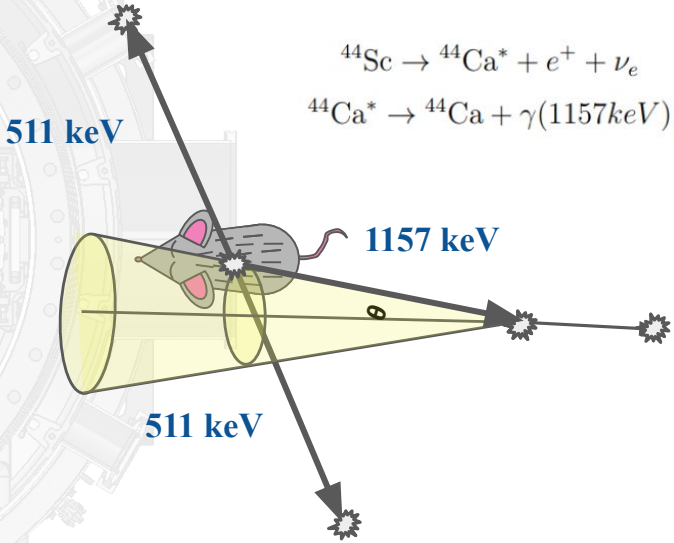
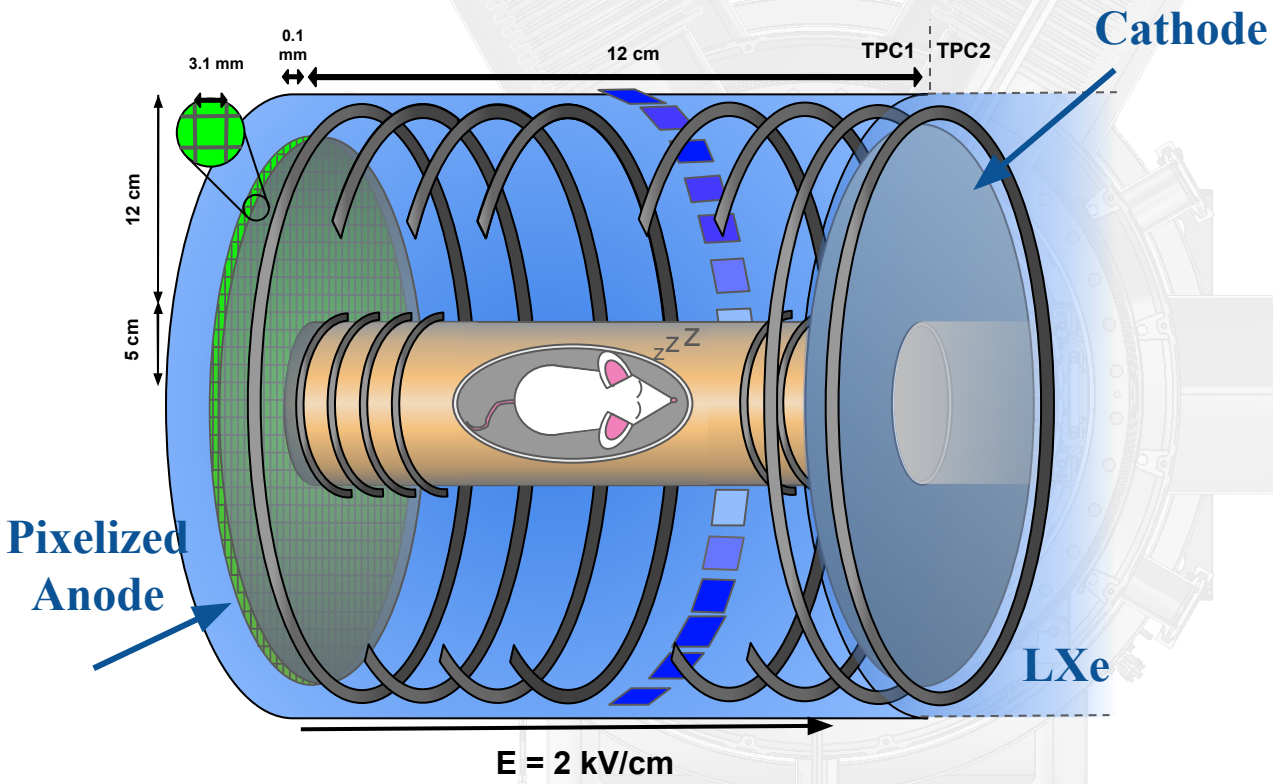


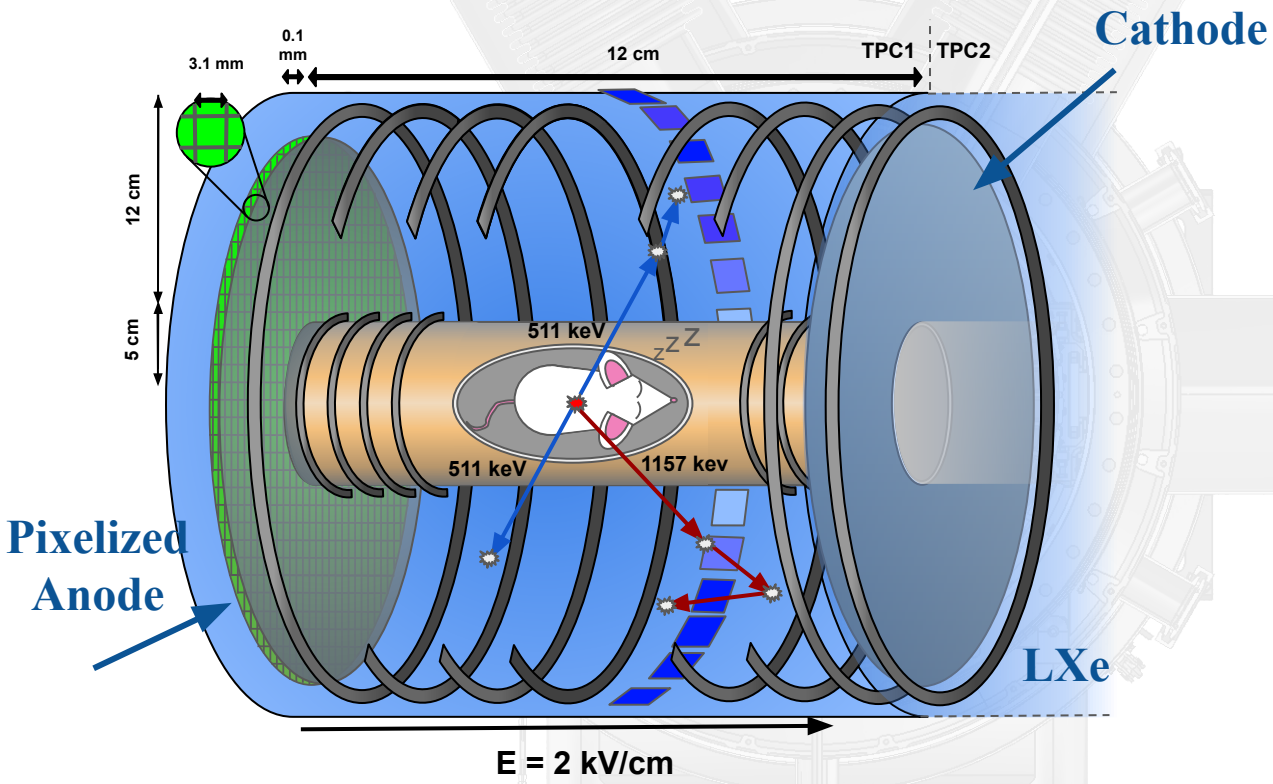
$$\theta^{C} = arccos[1 - m_e c^2 \frac{E_{dep}}{E_i(Ei - Edep)}]$$

Introduction



- 2 x 32 PMTs
- 2 x 9808 pixels
- 200 kg of LXe at -100 °C

Introduction



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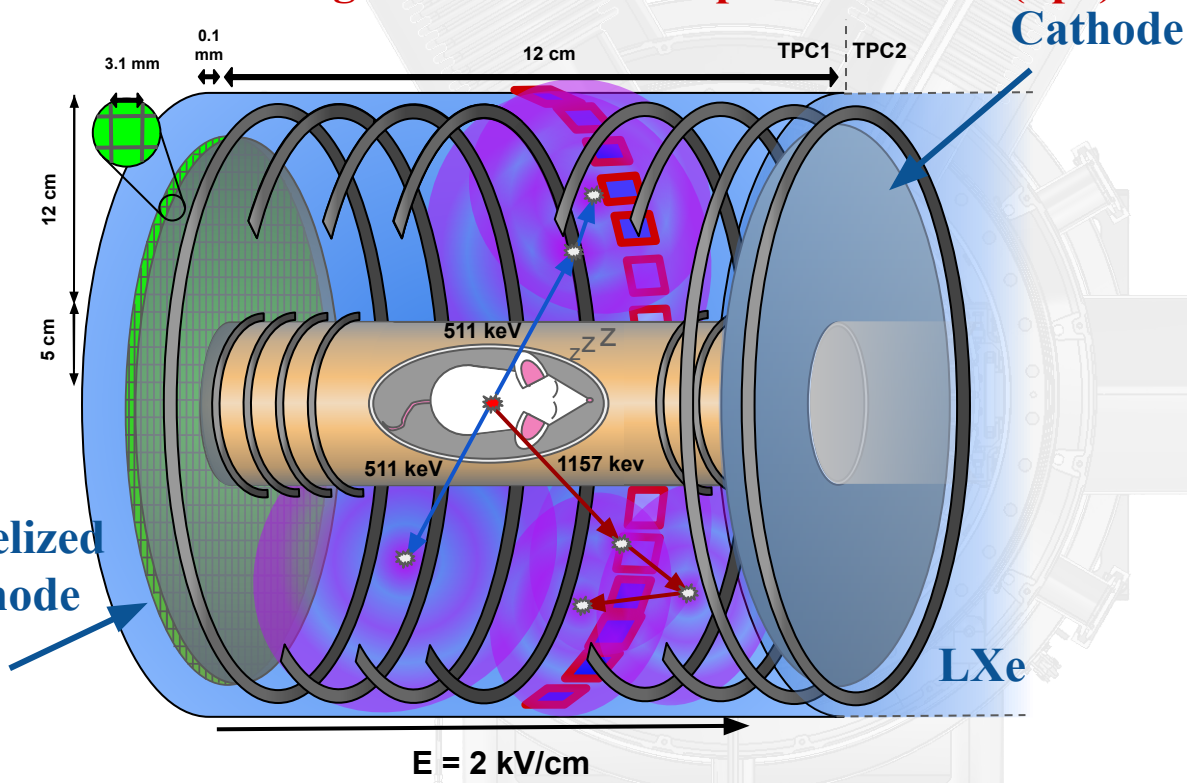
Each PMT gives a Number of photoelectron (npe)



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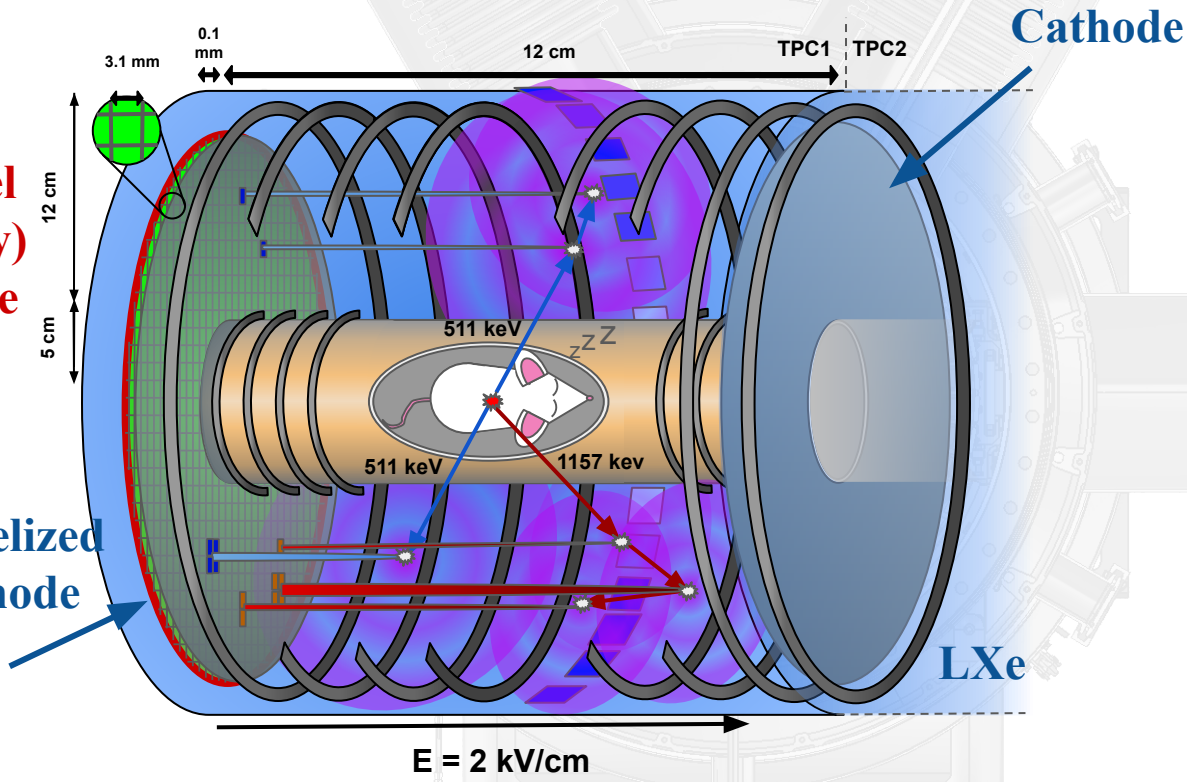
Introduction

Each pixel has an (x,y) coordinate



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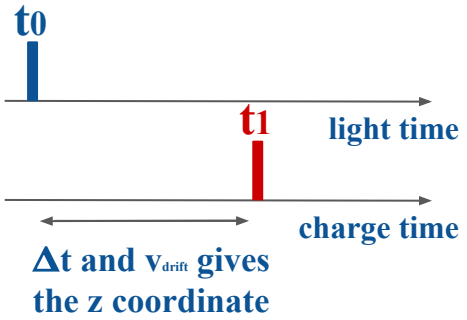

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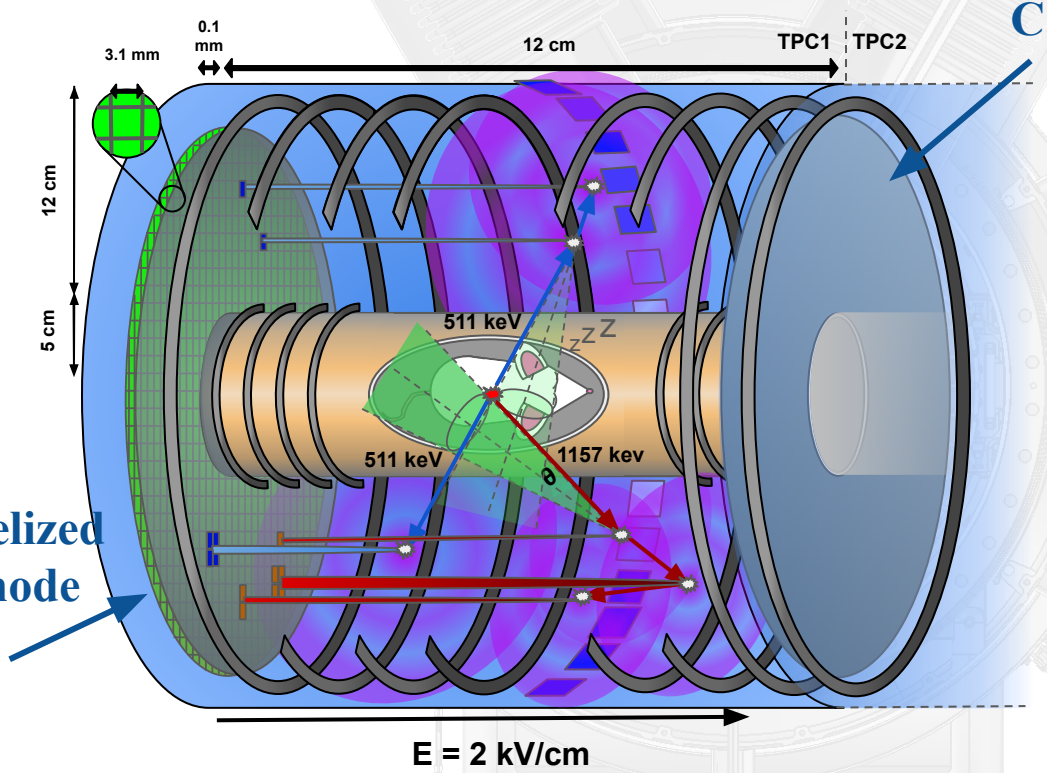


Cathode

Pixelized Anode

- 2 x 32 PMTs
- 2 x 9808 pixels
- 200 kg of LXe at -100 °C

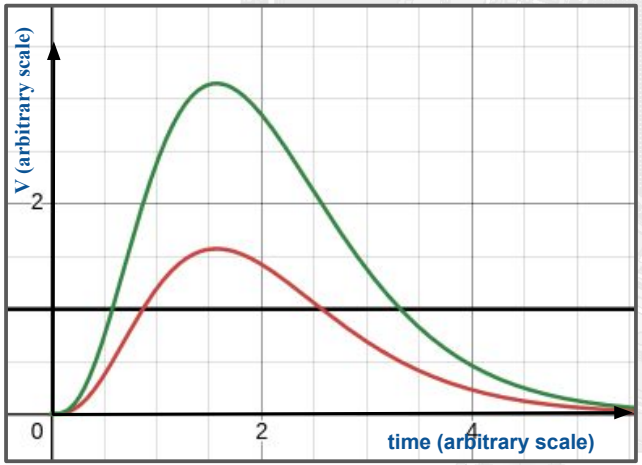
Compton Cinematics for cones reconstruction

$$\theta^C = arccos[1 - m_e c^2 \frac{E_{dep}}{E_i(Ei - Edep)}]$$

Raw Data, output of the camera

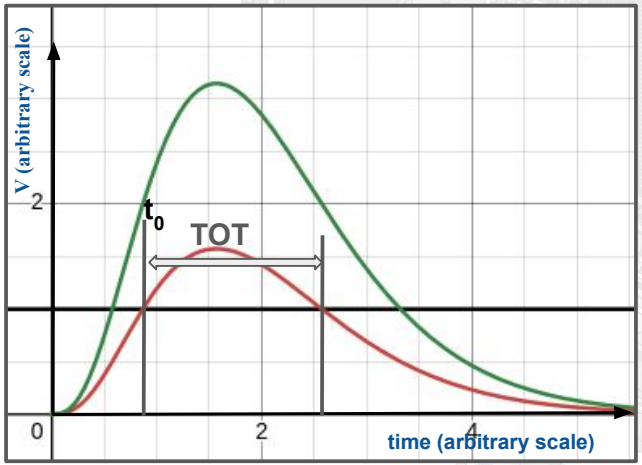
Files containing multiple signals:

- Light signals



Raw Data, output of the camera
Files containing multiple signals:

- Light signals (t_0, Time Over Threshold (TOT), PMT_{id})



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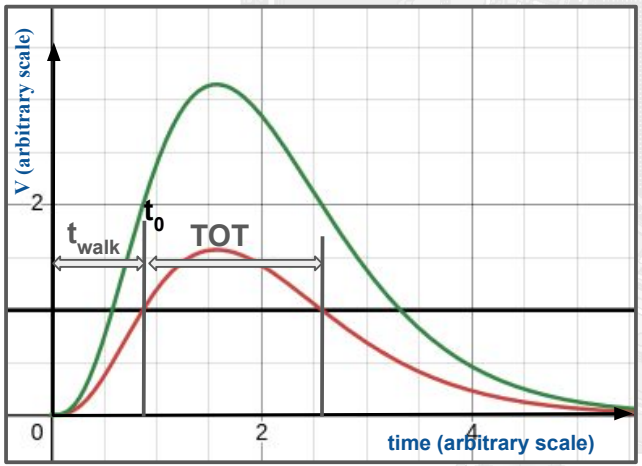
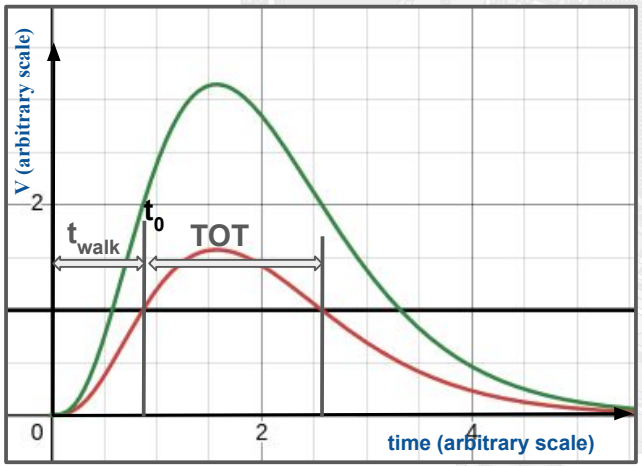


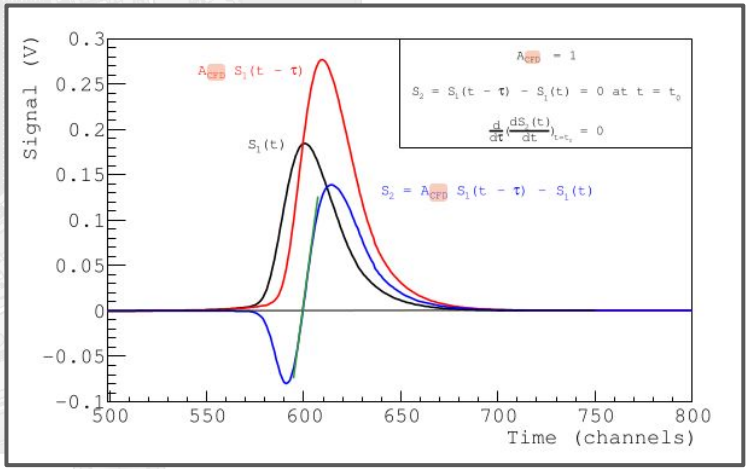
$$t_m = t_{Event} + t_{Walk}\,(TOT)\,(+\,t_{delay})$$

Raw Data, output of the camera

Files containing multiple signals:

- Light signals (t_0, Time Over Threshold (TOT), PMT_{id})
- Charge signals

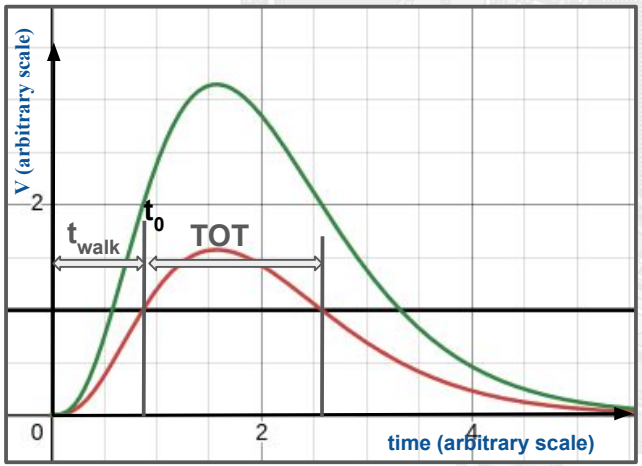


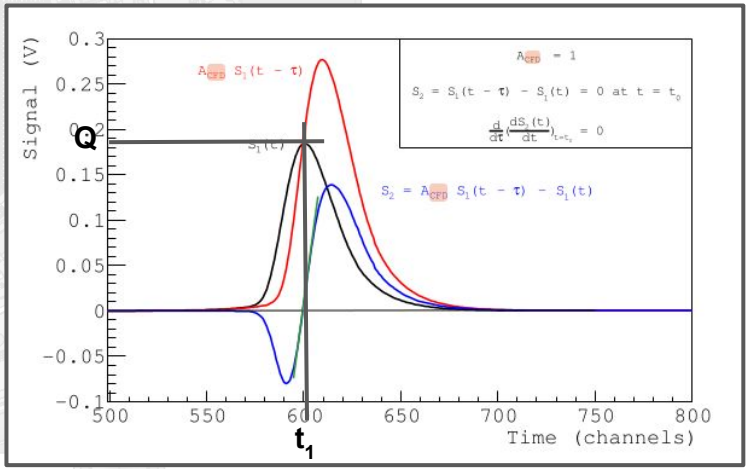


Raw Data, output of the camera

Files containing multiple signals:

- Light signals (t_0, Time Over Threshold (TOT), PMT_{id})
- Charge signals (t_1, Q, (x,y))





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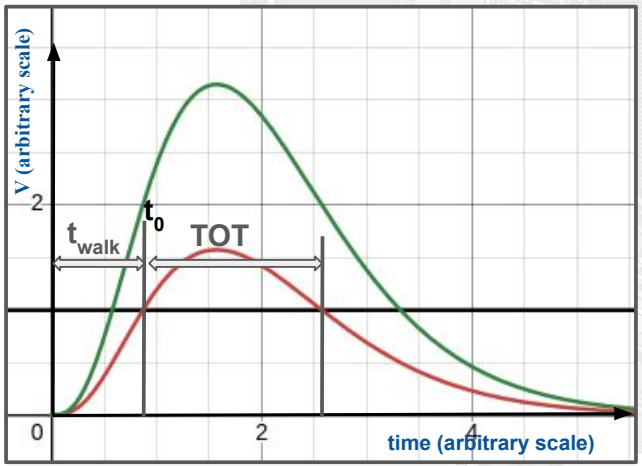
If you know v_d the drift speed of the electron in LXe you have the z coordinate => $z = v_d*(t_1 - t_0)$



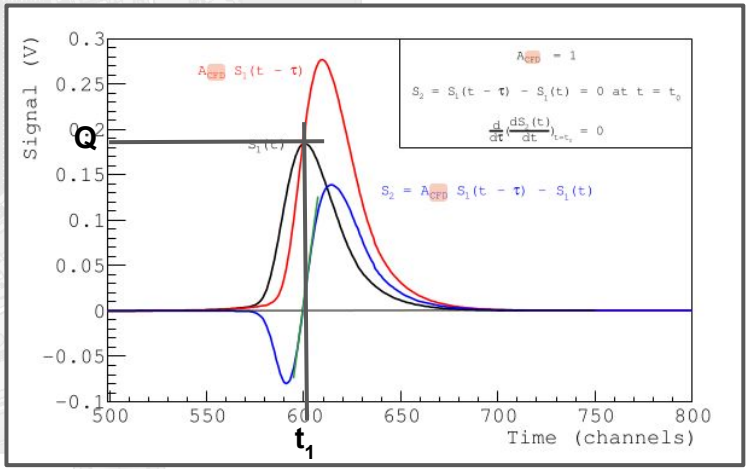
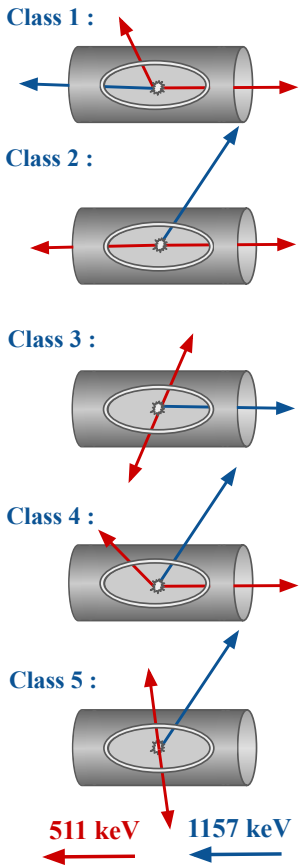


Image Algorithm Data Structure, input of the reconstruction algorithm
File containing multiple combination of interactions:

nom	times	Class	Vertex1			Vertex2			Vertex1'			Vertex2'			Energies1	Energies2	Energies3	Energies4	Weight
Class 1G511	t1	1	0	0	0	0	0	0	X_1'	Y_1'	Z_1'	X_2'	Y_2'	Z_2'	0	E1'	0	0.511 MeV	W1
Class 1G1157	t2	2	X_1	Y_1	Z_1	X_2	Y_2	Z_2	0	0	0	0	0	0	E1	0	1.157 MeV	0	W2
Class 2GLOR	t3	3	0	0	0	0	0	0	X_1'	Y_1'	Z_1'	X_2'	Y_2'	Z_2'	0	0	0	0	W3
Class 2GCOR	t4	4	X_1	Y_1	Z_1	X_2	Y_2	Z_2	X_1'	Y_1'	Z_1'	X_2'	Y_2'	Z_2'	E1	E1'	1.157 MeV	0.511 MeV	W4
Class 3G	t5	5	X_1	Y_1	Z_1	X_2	Y_2	Z_2	X_1'	Y_1'	Z_1'	X_2'	Y_2'	Z_2'	E1	0	1.157 MeV	0	W5

The classes correspond to the different types of events:
Example: 2 γ511 + 1 γ1157, 1 γ511 + 1 γ1157, etc.

As output, the algorithm provides the 3D spatial distribution of scandium: an image !



To do :

- **Light Calibration :**
  - Threshold
  - Conversion/correction curve
  - Gain
- **Charge Calibration :**
  - Zero crossing
  - Thresholds
- **Transformation from raw data to Refined data / List mode :**
  - Simultaneous charge and light acquisition
  - Light clustering
  - Light preprocessing
  - Matching light-charge
  - Gamma tagging
  - Event weighting

Goal :

- **Image reconstruction**

To do :

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  - Thresholds

Not done by me

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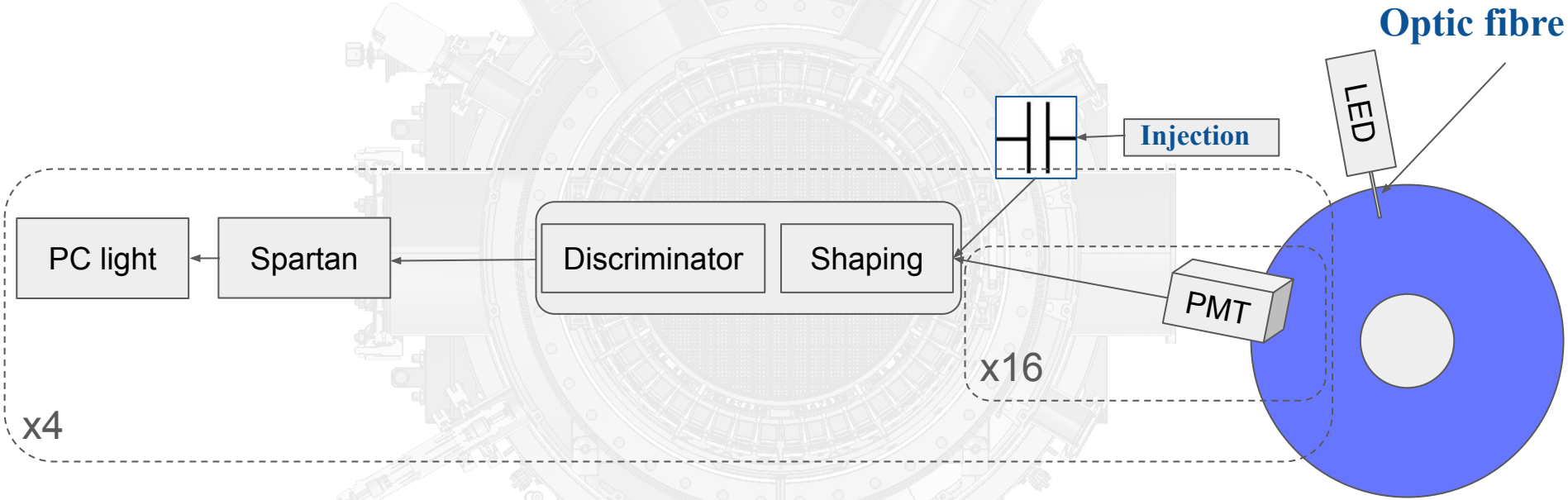
Light Calibration

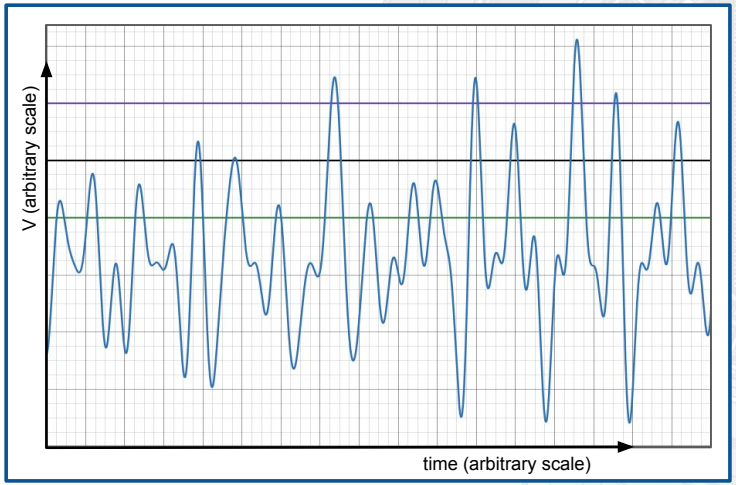
Experimental Setup :



Light Calibration

Thresholds :

The threshold is set to 1000 hit noise/s/pmt (~4σ)



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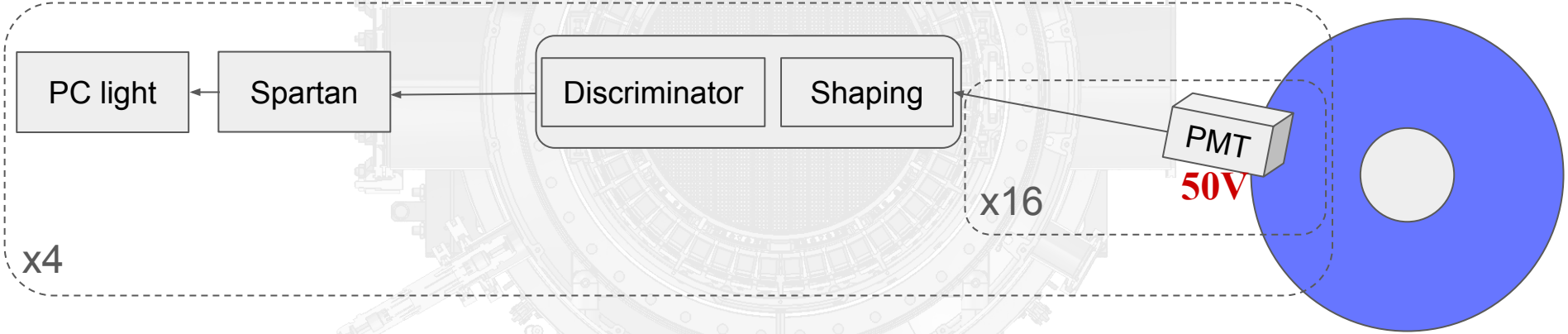

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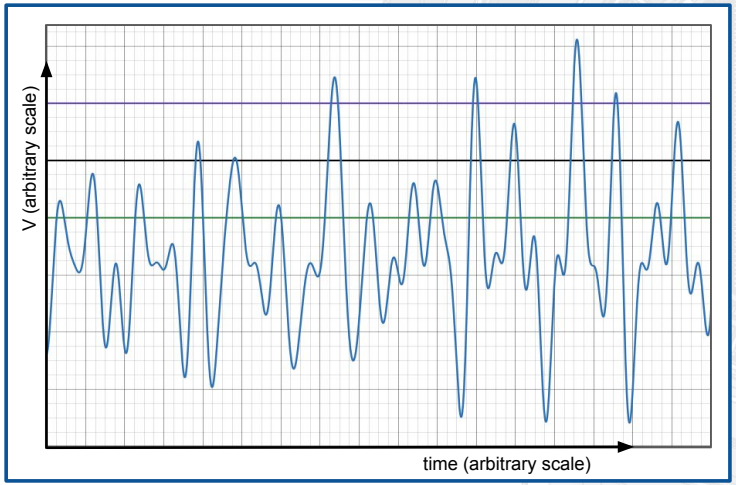

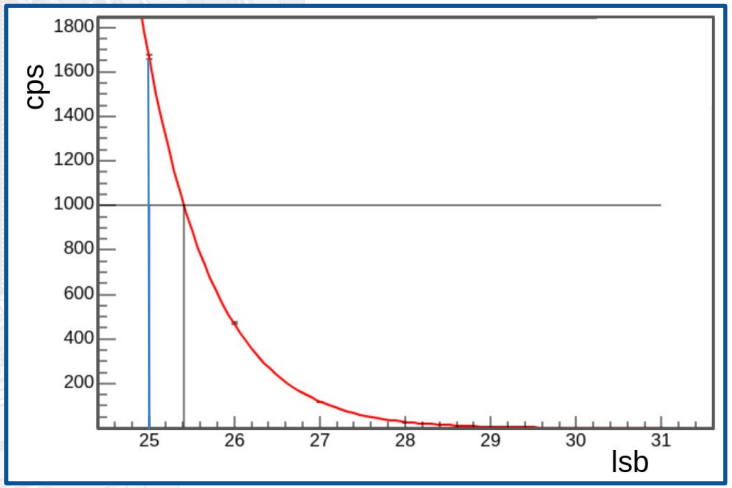

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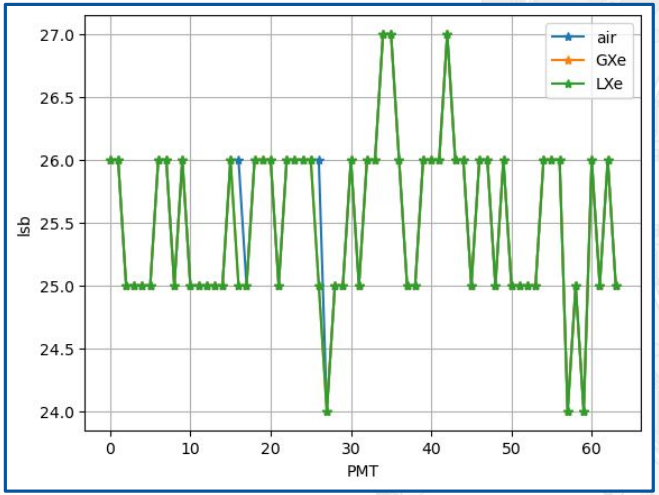
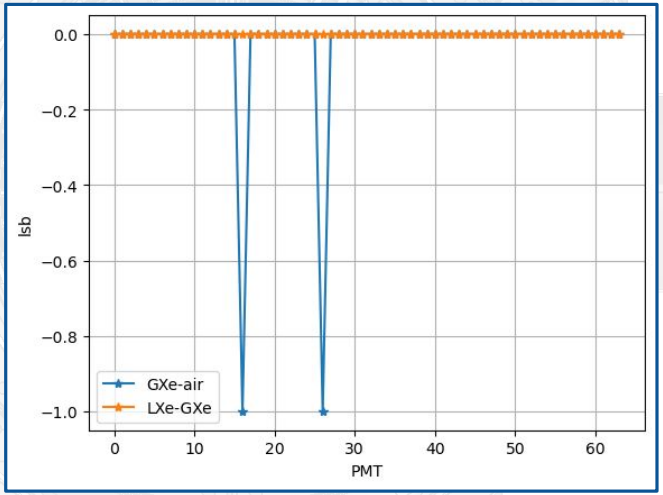
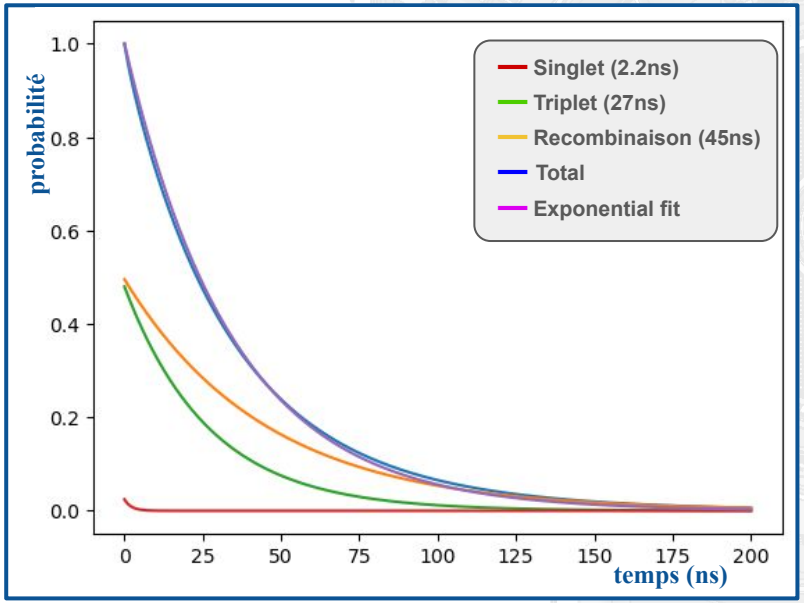




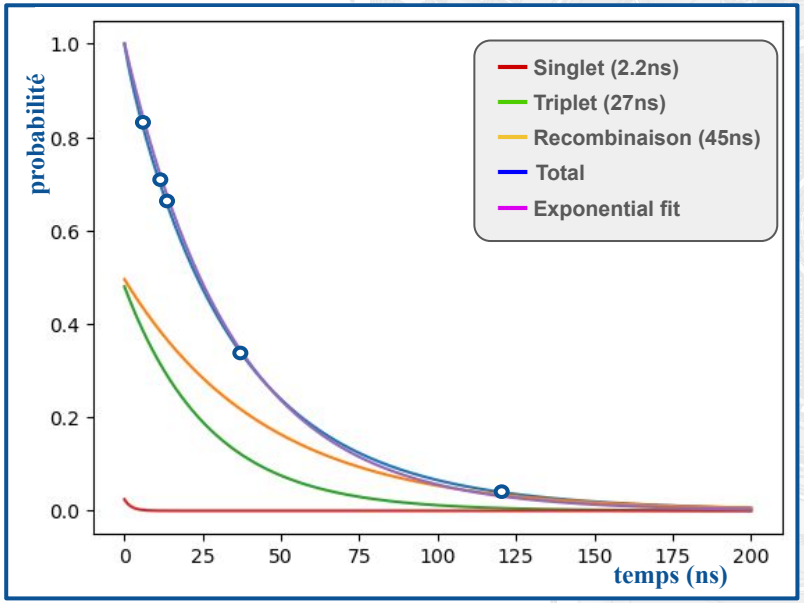
Thresholds are stable through the different stage of the experiment

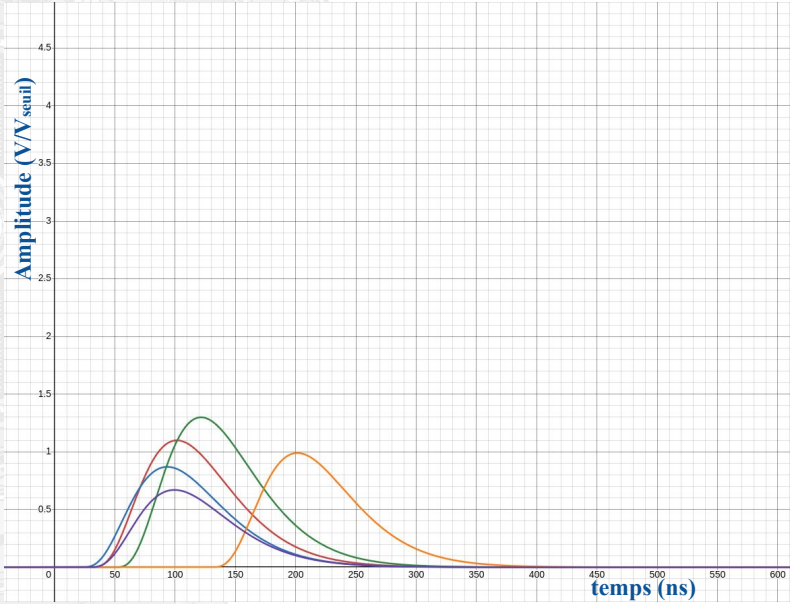
Light Calibration

Simulation (validated on experimental data):

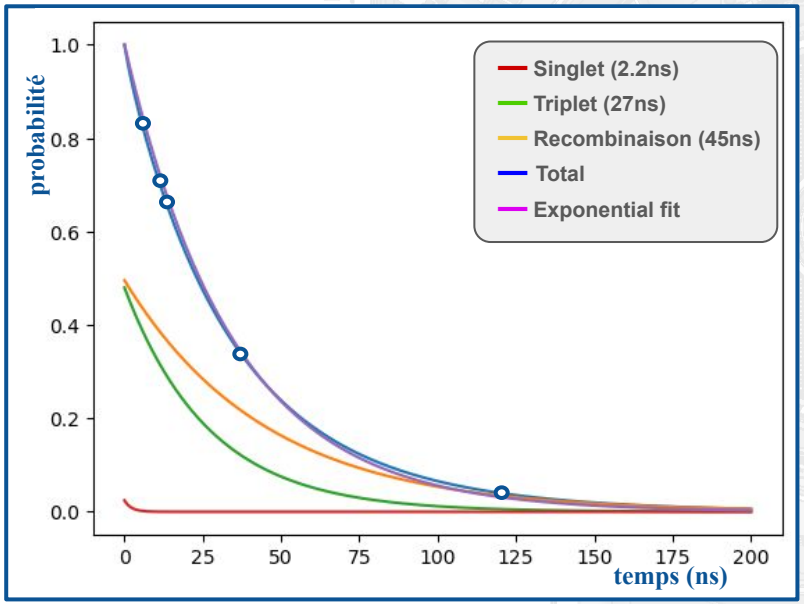


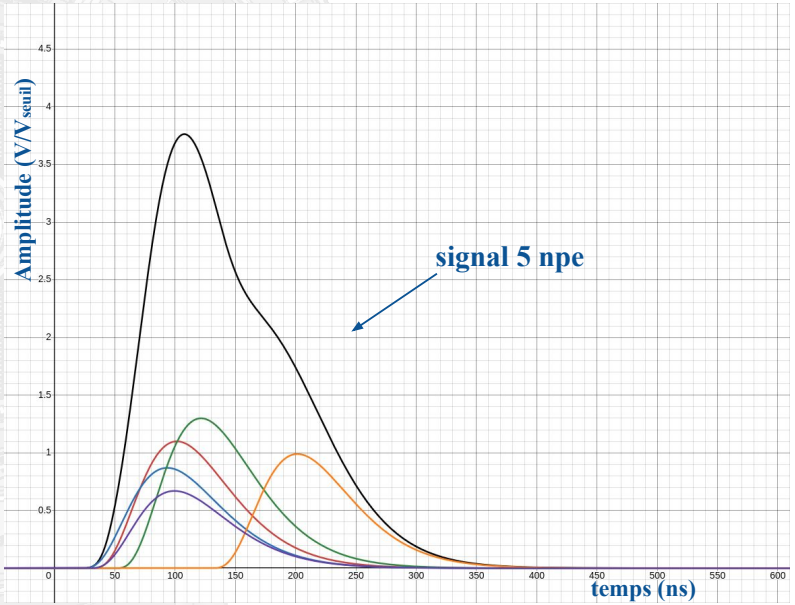
Simulation (validated on experimental data):





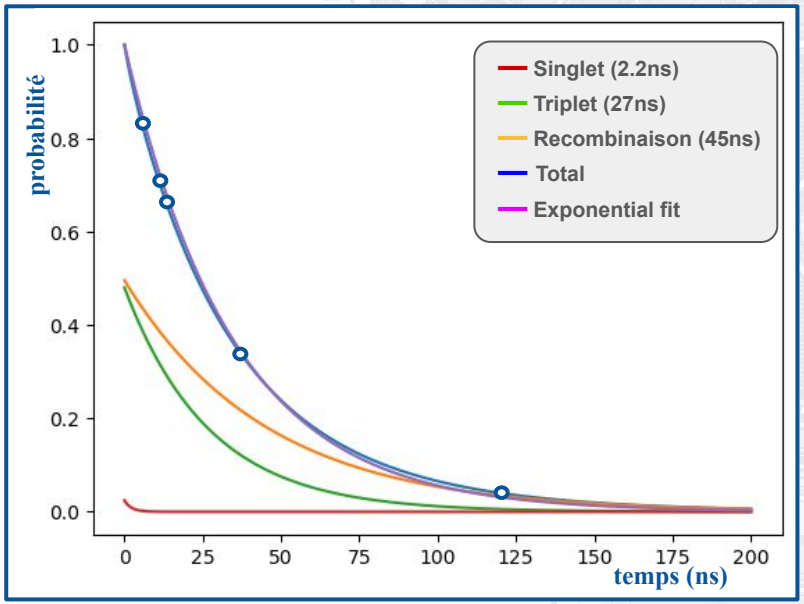
Simulation (validated on experimental data):

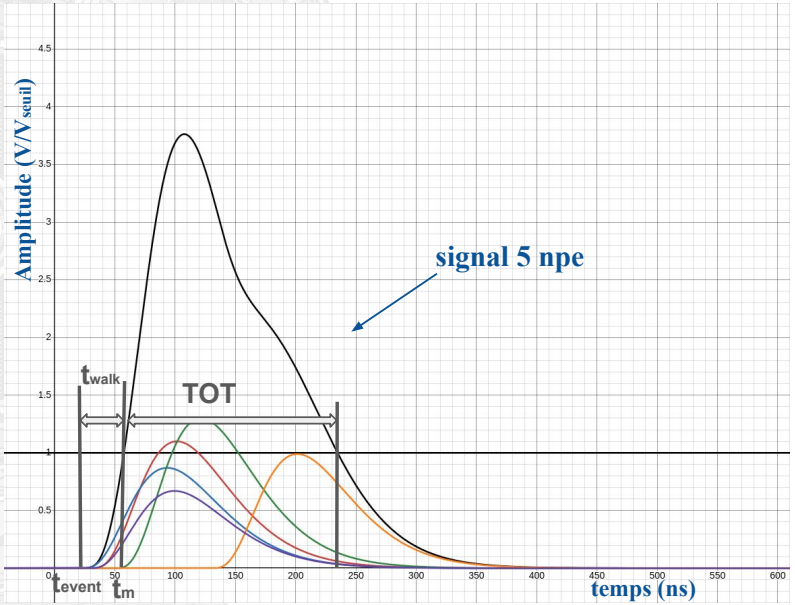




Light Calibration

Simulation (validated on experimental data):

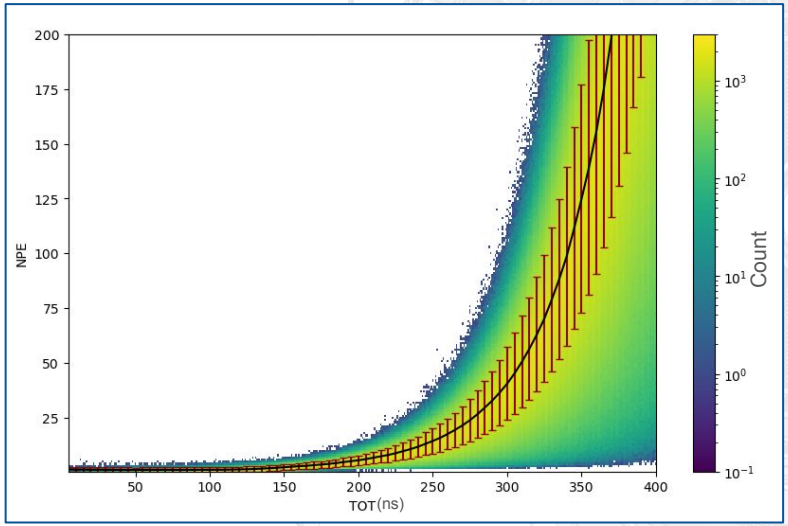




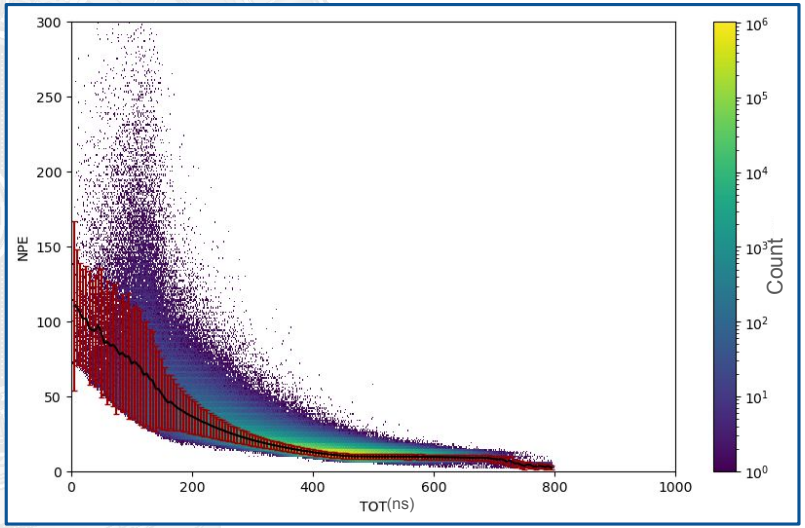
Light Calibration

Simulation :

TOT -> npe

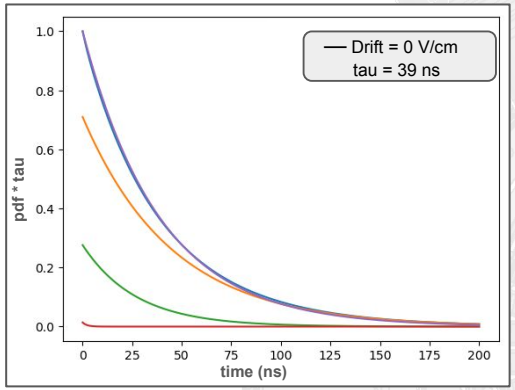


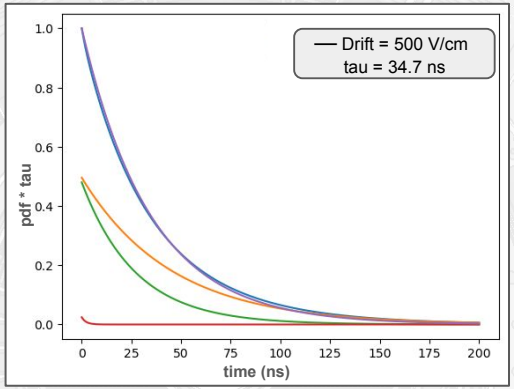
TOT -> Walk

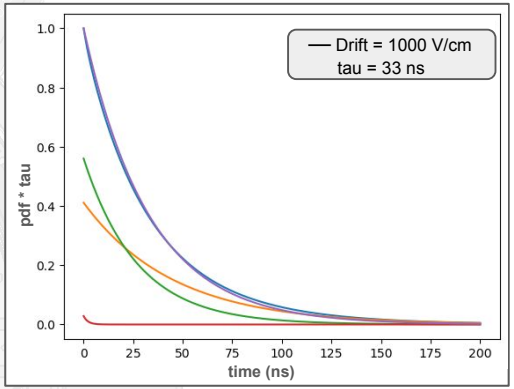


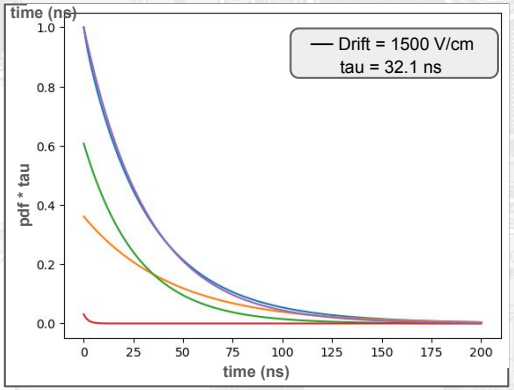
Light Calibration

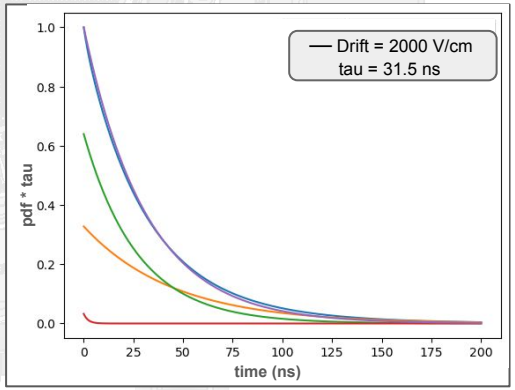
Simulation :



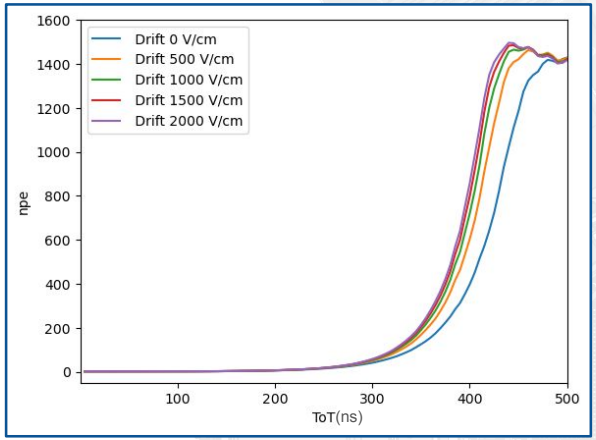


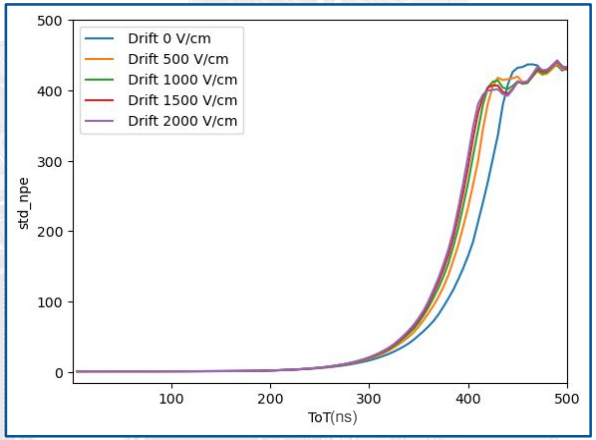


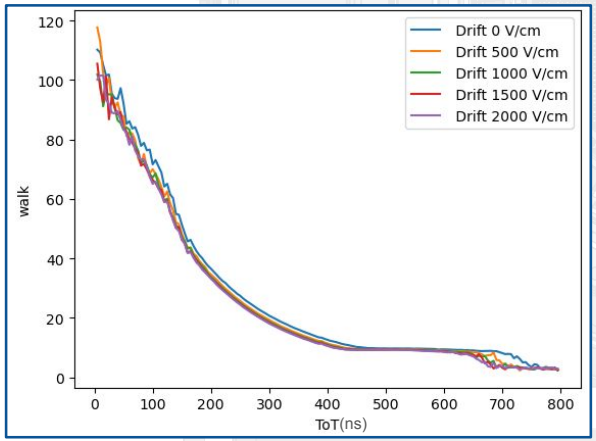


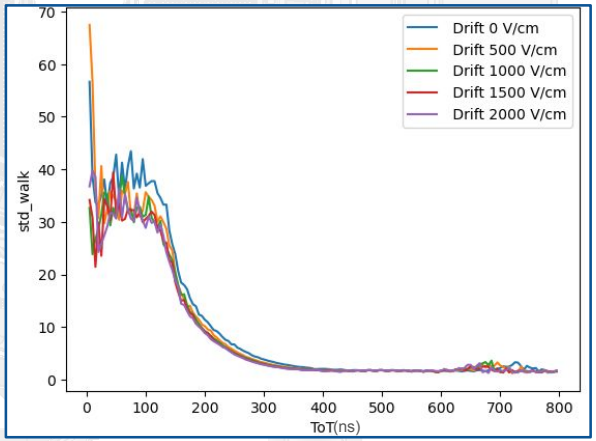


Light Calibration



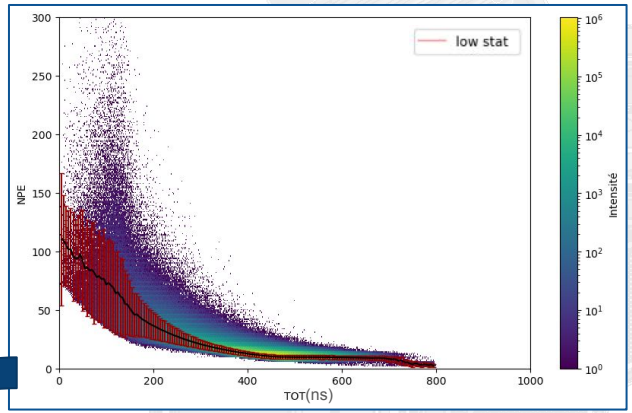


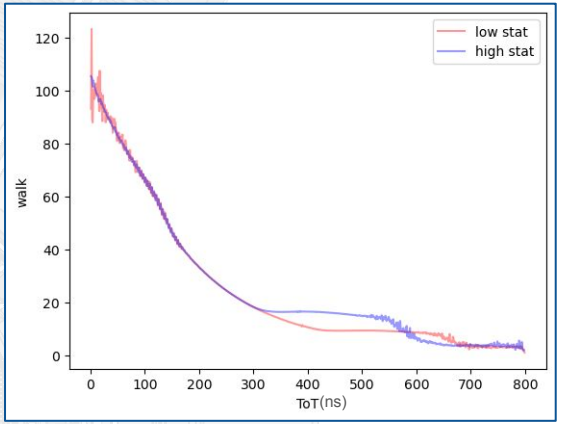




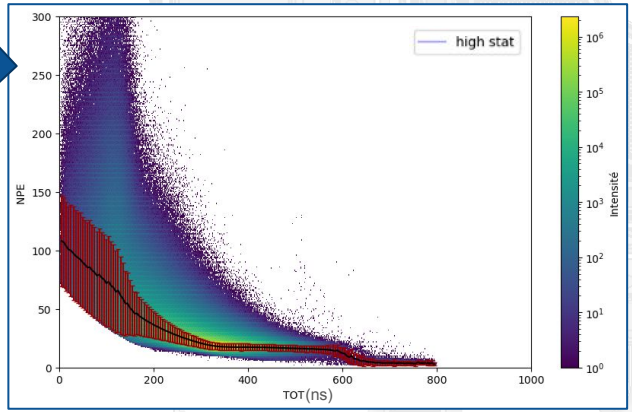
Light Calibration

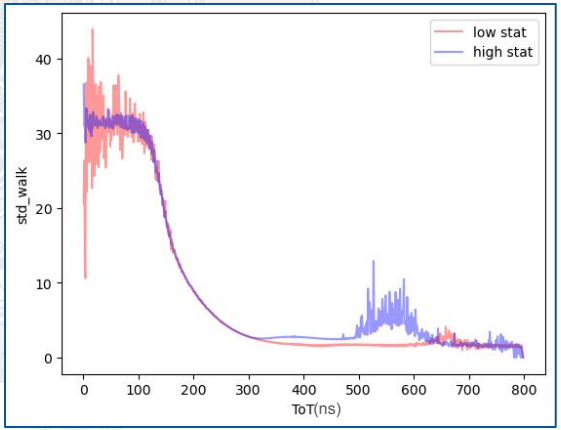
Simulation :





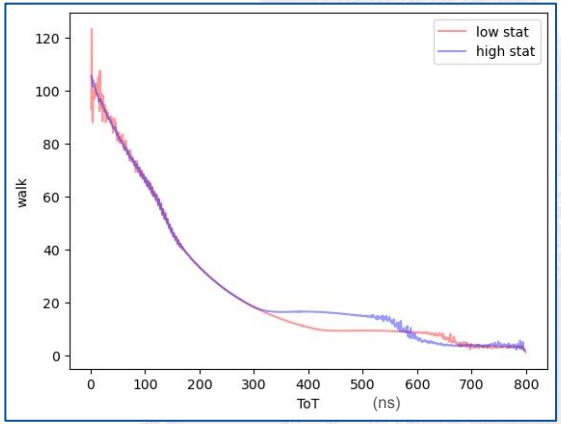
X 30 (but only from 1 to 200 npe)

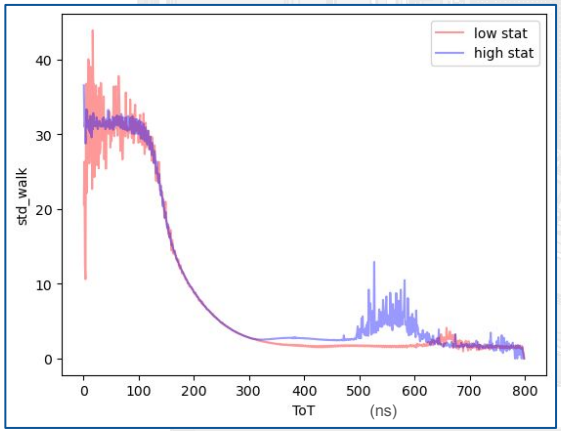




Light Calibration

Simulation :

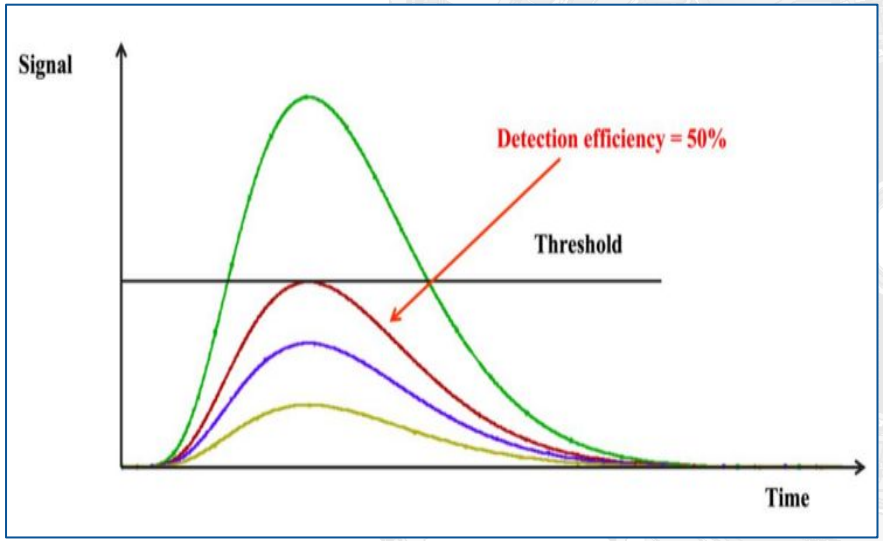




$$t_m = t_{Event} + t_{Walk}(TOT) - \langle t_{Walk} \rangle (TOT) \; (+ t_{delay})$$

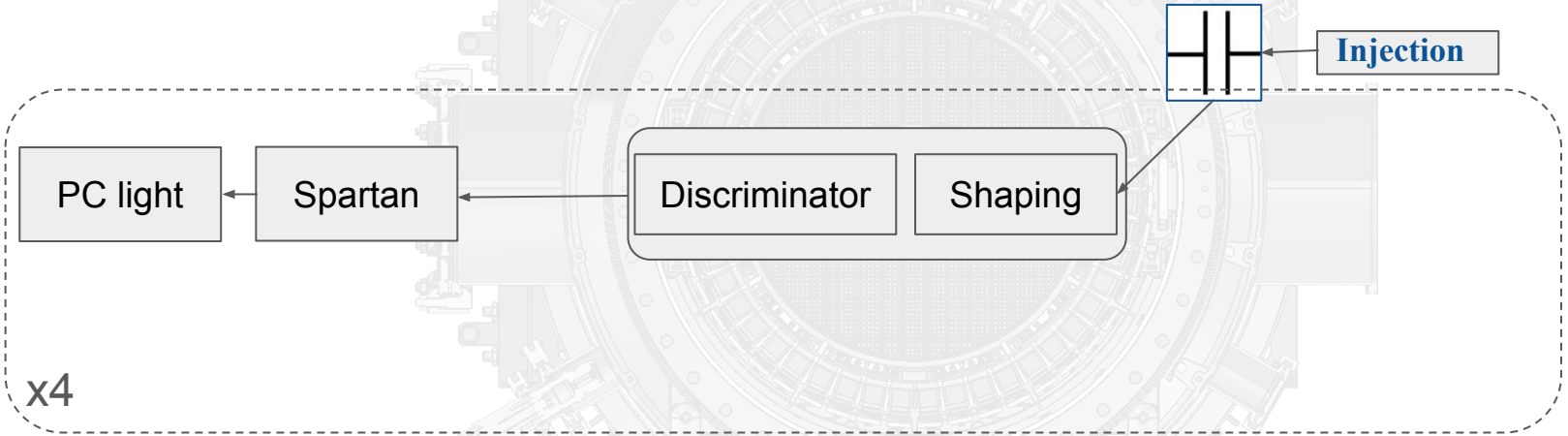
Light Calibration

Measure Th->Q :



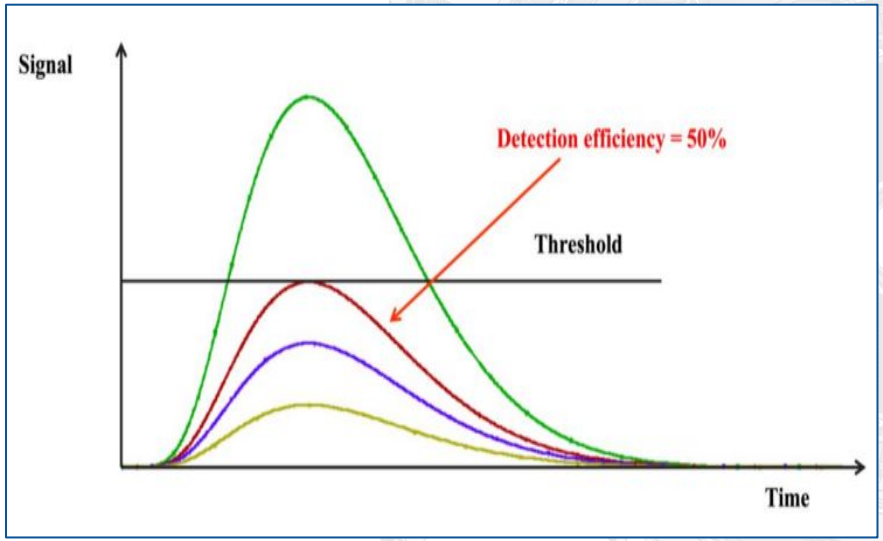
Light Calibration

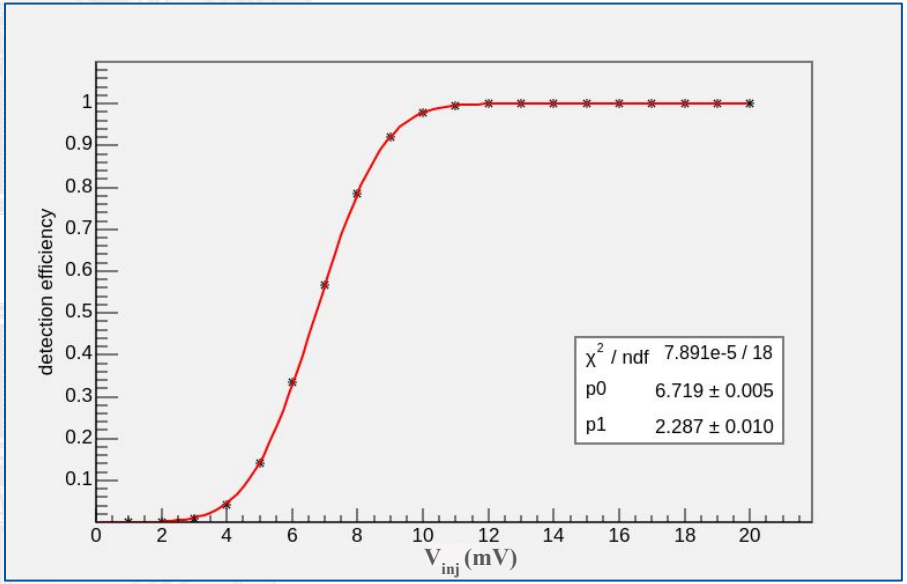
Experimental Setup :



Light Calibration

Measure Th->Q :





Light Calibration

Measure Th->Q :

channel	threshold (en mV)	std dev (mV)	channel	threshold (en mV)	std dev (mV)
0	6.72 ± 0.01	2.29 ± 0.01	16	6.64 ± 0.01	2.35 ± 0.01
1	6.43 ± 0.01	2.25 ± 0.01	17	6.23 ± 0.01	2.35 ± 0.02
2	6.21 ± 0.01	2.24 ± 0.01	18	6.40 ± 0.01	2.29 ± 0.02
3	6.23 ± 0.01	2.30 ± 0.02	19	6.27 ± 0.01	2.37 ± 0.01
4	6.45 ± 0.01	2.31 ± 0.01	20	6.15 ± 0.01	2.43 ± 0.01
5	6.29 ± 0.01	2.30 ± 0.02	21	6.08 ± 0.01	2.37 ± 0.02
6	6.74 ± 0.01	2.28 ± 0.02	22	6.28 ± 0.01	2.35 ± 0.02
7	6.66 ± 0.01	2.32 ± 0.01	23	6.45 ± 0.01	2.39 ± 0.01
8	6.48 ± 0.01	2.26 ± 0.02	24	6.59 ± 0.01	2.37 ± 0.02
9	6.55 ± 0.01	2.31 ± 0.02	25	6.64 ± 0.01	2.35 ± 0.02
10	6.24 ± 0.01	2.29 ± 0.01	26	6.68 ± 0.01	2.40 ± 0.02
11	6.38 ± 0.01	2.26 ± 0.01	27	6.29 ± 0.01	2.39 ± 0.02
12	6.25 ± 0.01	2.21 ± 0.03	28	6.08 ± 0.01	2.31 ± 0.02
13	6.37 ± 0.01	2.29 ± 0.02	29	6.14 ± 0.01	2.35 ± 0.02
14	6.09 ± 0.01	2.27 ± 0.02	30	6.33 ± 0.01	2.33 ± 0.01
15	6.17 ± 0.01	2.29 ± 0.01	31	6.20 ± 0.00	2.27 ± 0.01
moyenne c1	6.37	2.28	moyenne c2	6.33	2.35
channel	threshold (en mV)	std dev (mV)	channel	threshold (en mV)	std dev (mV)
32	5.94 ± 0.01	2.38 ± 0.01	48	5.61 ± 0.01	2.26 ± 0.01
33	5.97 ± 0.01	2.29 ± 0.01	49	6.10 ± 0.01	2.19 ± 0.02
34	6.20 ± 0.01	2.32 ± 0.01	50	5.41 ± 0.00	2.24 ± 0.01
35	6.29 ± 0.01	2.37 ± 0.02	51	5.78 ± 0.01	2.24 ± 0.01
36	5.86 ± 0.01	2.31 ± 0.01	52	6.15 ± 0.01	2.27 ± 0.02
37	5.71 ± 0.01	2.36 ± 0.02	53	5.49 ± 0.01	2.29 ± 0.02
38	5.56 ± 0.01	2.39 ± 0.01	54	5.56 ± 0.01	2.23 ± 0.02
39	6.13 ± 0.01	2.36 ± 0.01	55	5.79 ± 0.01	2.22 ± 0.02
40	6.28 ± 0.00	2.36 ± 0.01	56	6.08 ± 0.01	2.22 ± 0.02
41	6.02 ± 0.01	2.37 ± 0.02	57	5.36 ± 0.01	2.34 ± 0.02
42	6.30 ± 0.01	2.33 ± 0.02	58	5.64 ± 0.01	2.26 ± 0.01
43	5.81 ± 0.00	2.35 ± 0.01	59	5.27 ± 0.01	2.29 ± 0.02
44	6.21 ± 0.01	2.37 ± 0.02	60	5.75 ± 0.01	2.22 ± 0.02
45	5.65 ± 0.01	2.39 ± 0.02	61	5.35 ± 0.01	2.24 ± 0.01
46	5.74 ± 0.01	2.36 ± 0.01	62	5.81 ± 0.01	2.27 ± 0.02
47	6.04 ± 0.01	2.38 ± 0.01	63	5.55 ± 0.00	2.26 ± 0.01
moyenne c3	5.95	2.35	moyenne c4	5.64	2.25

Light Calibration

Measure Th->Q :

channel	threshold (en mV)	std dev (mV)	channel	threshold (en mV)	std dev (mV)
0	6.72 ± 0.01	2.29 ± 0.01	16	6.64 ± 0.01	2.35 ± 0.01
1	6.43 ± 0.01	2.25 ± 0.01	17	6.23 ± 0.01	2.35 ± 0.02
2	6.21 ± 0.01	2.24 ± 0.01	18	6.40 ± 0.01	2.29 ± 0.02
3	6.23 ± 0.01	2.30 ± 0.02	19	6.27 ± 0.01	2.37 ± 0.01
4	6.45 ± 0.01	2.31 ± 0.01	20	6.15 ± 0.01	2.43 ± 0.01
5	6.29 ± 0.01	2.30 ± 0.02	21	6.08 ± 0.01	2.37 ± 0.02
6	6.74 ± 0.01	2.28 ± 0.02	22	6.28 ± 0.01	2.35 ± 0.02
7	6.66 ± 0.01	2.32 ± 0.01	23	6.45 ± 0.01	2.39 ± 0.01
8	6.48 ± 0.01	2.26 ± 0.02	24	6.59 ± 0.01	2.37 ± 0.02
9	6.55 ± 0.01	2.31 ± 0.02	25	6.64 ± 0.01	2.35 ± 0.02
10	6.24 ± 0.01	2.29 ± 0.01	26	6.68 ± 0.01	2.40 ± 0.02
11	6.38 ± 0.01	2.26 ± 0.01	27	6.29 ± 0.01	2.39 ± 0.02
12	6.25 ± 0.01	2.21 ± 0.03	28	6.08 ± 0.01	2.31 ± 0.02
13	6.37 ± 0.01	2.29 ± 0.02	29	6.14 ± 0.01	2.35 ± 0.02
14	6.09 ± 0.01	2.27 ± 0.02	30	6.33 ± 0.01	2.33 ± 0.01
15	6.17 ± 0.01	2.29 ± 0.01	31	6.20 ± 0.00	2.27 ± 0.01
moyenne c1	6.37	2.28	moyenne c2	6.33	2.35
channel	threshold (en mV)	std dev (mV)	channel	threshold (en mV)	std dev (mV)
32	5.94 ± 0.01	2.38 ± 0.01	48	5.61 ± 0.01	2.26 ± 0.01
33	5.97 ± 0.01	2.29 ± 0.01	49	6.10 ± 0.01	2.19 ± 0.02
34	6.20 ± 0.01	2.32 ± 0.01	50	5.41 ± 0.00	2.24 ± 0.01
35	6.29 ± 0.01	2.37 ± 0.02	51	5.78 ± 0.01	2.24 ± 0.01
36	5.86 ± 0.01	2.31 ± 0.01	52	6.15 ± 0.01	2.27 ± 0.02
37	5.71 ± 0.01	2.36 ± 0.02	53	5.49 ± 0.01	2.29 ± 0.02
38	5.56 ± 0.01	2.39 ± 0.01	54	5.56 ± 0.01	2.23 ± 0.02
39	6.13 ± 0.01	2.36 ± 0.01	55	5.79 ± 0.01	2.22 ± 0.02
40	6.28 ± 0.00	2.36 ± 0.01	56	6.08 ± 0.01	2.22 ± 0.02
41	6.02 ± 0.01	2.37 ± 0.02	57	5.36 ± 0.01	2.34 ± 0.02
42	6.30 ± 0.01	2.33 ± 0.02	58	5.64 ± 0.01	2.26 ± 0.01
43	5.81 ± 0.00	2.35 ± 0.01	59	5.27 ± 0.01	2.29 ± 0.02
44	6.21 ± 0.01	2.37 ± 0.02	60	5.75 ± 0.01	2.22 ± 0.02
45	5.65 ± 0.01	2.39 ± 0.02	61	5.35 ± 0.01	2.24 ± 0.01
46	5.74 ± 0.01	2.36 ± 0.01	62	5.81 ± 0.01	2.27 ± 0.02
47	6.04 ± 0.01	2.38 ± 0.01	63	5.55 ± 0.00	2.26 ± 0.01
moyenne c3	5.95	2.35	moyenne c4	5.64	2.25

$$N_e = \frac{C * U}{e}$$

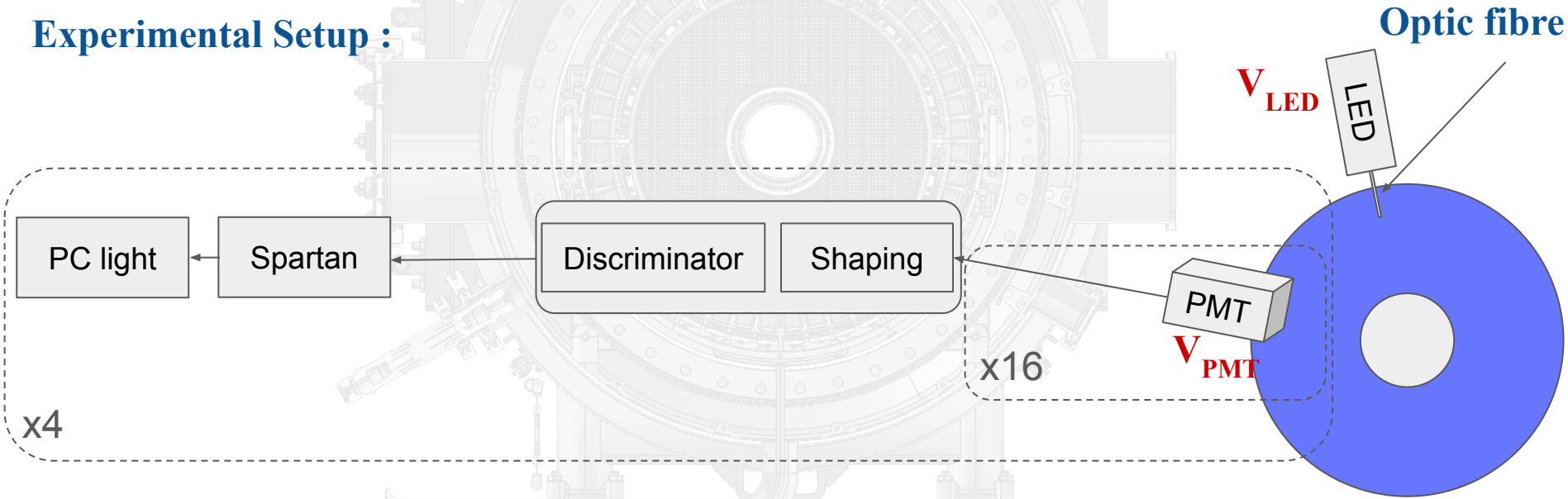
channel	gain (x 10^3)	noise (x 10^3)	channel	gain (x 10^3)	noise (x 10^3)
0	503.31 ± 0.38	171.30 ± 0.75	16	497.38 ± 0.56	176.12 ± 1.10
1	481.66 ± 0.55	168.90 ± 1.09	17	466.91 ± 0.64	176.34 ± 1.27
2	465.30 ± 0.42	167.98 ± 0.85	18	479.17 ± 0.63	171.43 ± 1.28
3	466.76 ± 0.87	172.08 ± 1.72	19	469.51 ± 0.51	177.69 ± 1.02
4	482.78 ± 0.54	173.18 ± 1.10	20	460.61 ± 0.53	181.69 ± 1.06
5	470.79 ± 0.61	172.16 ± 1.22	21	455.59 ± 0.83	177.46 ± 1.65
6	504.88 ± 0.67	170.55 ± 1.37	22	470.07 ± 0.82	176.06 ± 1.65
7	498.83 ± 0.54	173.69 ± 1.07	23	483.29 ± 0.46	178.74 ± 0.92
8	485.46 ± 0.86	169.51 ± 1.73	24	493.73 ± 0.71	177.39 ± 1.42
9	490.57 ± 0.59	173.20 ± 1.18	25	497.37 ± 0.60	175.67 ± 1.22
10	467.16 ± 0.48	171.33 ± 0.97	26	500.45 ± 0.65	179.74 ± 1.29
11	477.84 ± 0.48	169.26 ± 0.97	27	470.82 ± 0.69	179.39 ± 1.39
12	467.80 ± 1.06	165.19 ± 2.16	28	455.10 ± 0.76	173.01 ± 1.51
13	477.34 ± 0.72	171.67 ± 1.44	29	459.82 ± 0.66	175.92 ± 1.34
14	456.00 ± 0.81	170.19 ± 1.61	30	474.33 ± 0.40	174.81 ± 0.80
15	462.03 ± 0.55	171.41 ± 1.09	31	464.72 ± 0.28	170.24 ± 0.55
channel	gain (x 10^3)	noise (x 10^3)	channel	gain (x 10^3)	noise (x 10^3)
32	444.61 ± 0.55	177.91 ± 1.09	48	420.46 ± 0.49	168.99 ± 0.99
33	447.00 ± 0.45	171.77 ± 0.91	49	456.88 ± 0.80	163.92 ± 1.59
34	464.09 ± 0.47	174.05 ± 0.94	50	405.00 ± 0.22	167.75 ± 0.45
35	471.38 ± 0.82	177.24 ± 1.64	51	432.78 ± 0.38	167.81 ± 0.77
36	438.71 ± 0.43	173.09 ± 0.87	52	460.64 ± 0.57	169.84 ± 1.14
37	428.05 ± 0.70	176.58 ± 1.41	53	411.49 ± 0.91	171.61 ± 1.80
38	416.68 ± 0.40	179.09 ± 0.80	54	416.79 ± 0.60	167.18 ± 1.21
39	459.54 ± 0.39	176.71 ± 0.77	55	433.59 ± 0.64	166.66 ± 1.30
40	470.43 ± 0.23	176.68 ± 0.45	56	455.80 ± 0.64	166.06 ± 1.28
41	450.64 ± 0.68	177.20 ± 1.35	57	401.75 ± 0.77	175.59 ± 1.52
42	471.97 ± 0.71	174.71 ± 1.43	58	422.46 ± 0.38	169.03 ± 0.76
43	434.94 ± 0.37	176.05 ± 0.75	59	394.93 ± 0.60	171.39 ± 1.21
44	465.40 ± 0.62	177.90 ± 1.24	60	430.66 ± 0.59	166.38 ± 1.20
45	423.16 ± 0.76	178.90 ± 1.52	61	400.78 ± 0.50	167.76 ± 1.00
46	430.05 ± 0.53	176.45 ± 1.06	62	435.14 ± 0.66	169.93 ± 1.32
47	452.75 ± 0.45	178.11 ± 0.91	63	415.58 ± 0.33	169.06 ± 0.65

Light Calibration

Gain :

The gain is set to have a <u>one</u> photoelectron signal amplitude equal to the thresholds

Experimental Setup :

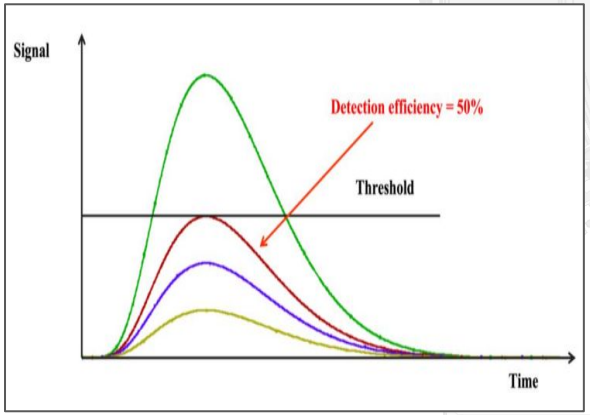


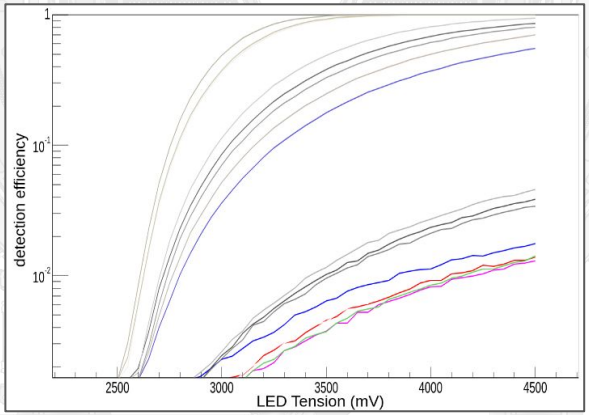
Light Calibration

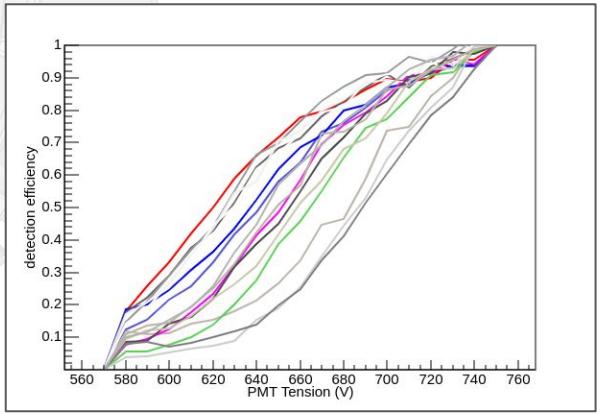
Gain :

The gain is set to have a <u>one</u> photoelectron signal amplitude equal to the thresholds
2 steps :

- **Generate LED signal to measure 1 PE on the PMT**
- **Find PMT power voltage to detecte 50 % of 1 PE signals**



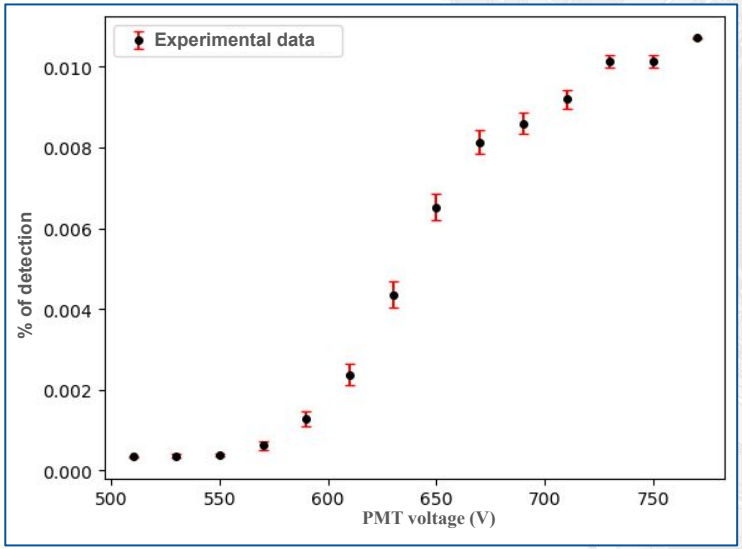




Light Calibration

Gain :

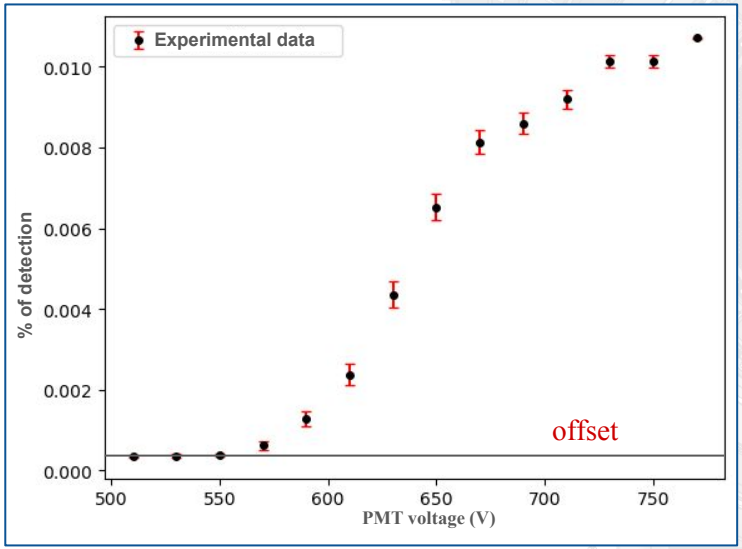
- With the LED voltage set, decrease the pmt voltage until you reach 50% of pulse detection



Light Calibration

Gain :

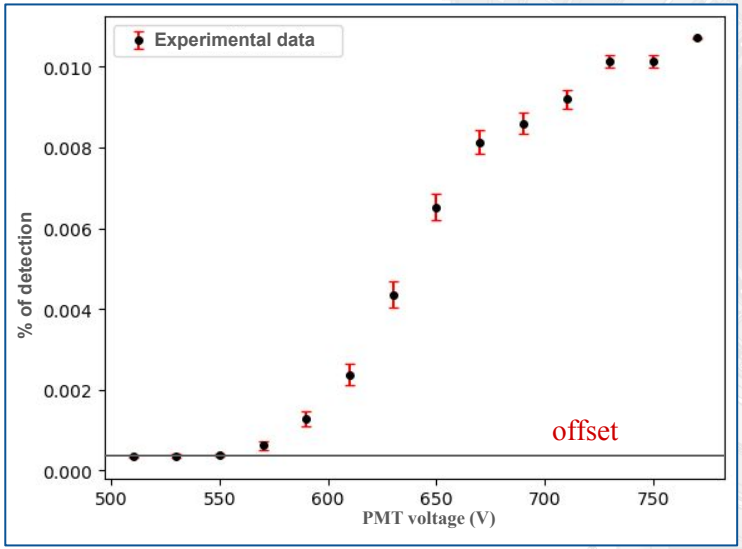
- With the LED voltage set, decrease the pmt voltage until you reach 50% of pulse detection

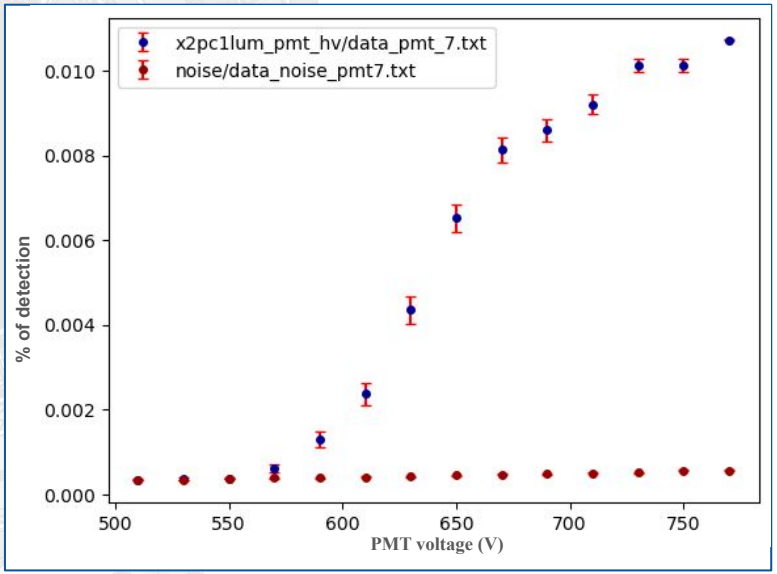


Light Calibration

Gain :

- With the LED voltage set, decrease the pmt voltage until you reach 50% of pulse detection

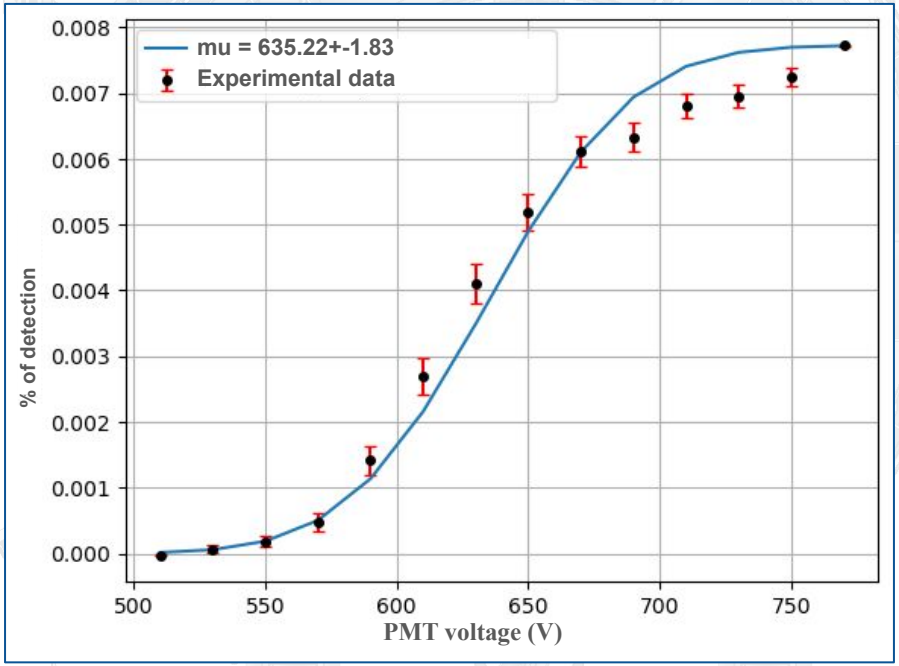




Light Calibration

Gain :

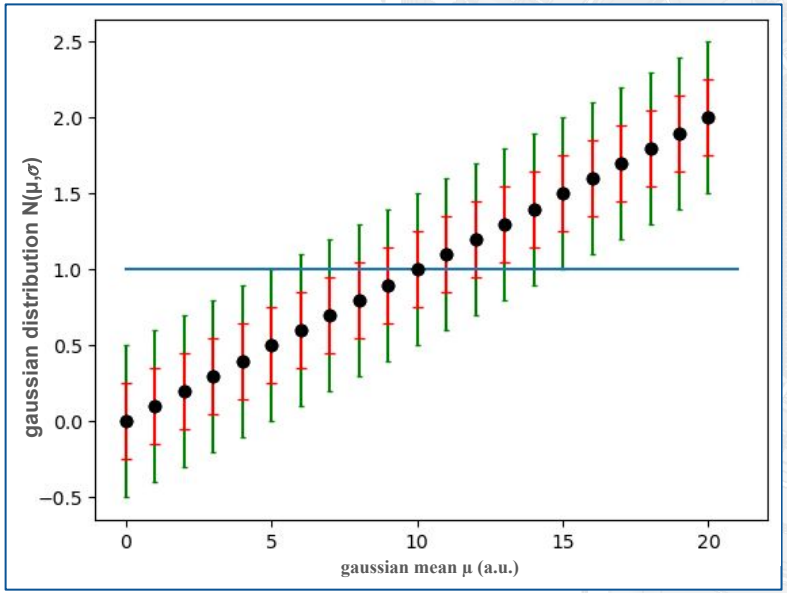
- With the LED voltage set, decrease the pmt voltage until you reach 50% of pulse detection



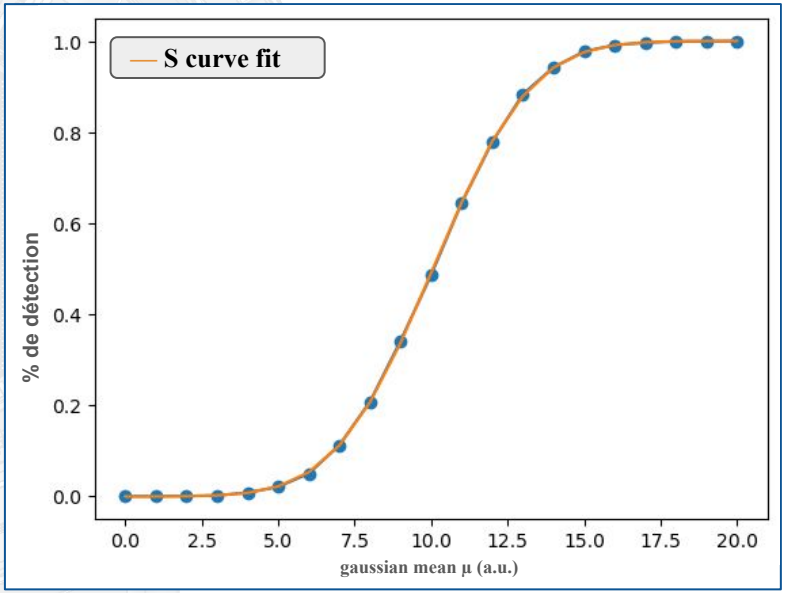
Light Calibration

Gain :

Constant fluctuation



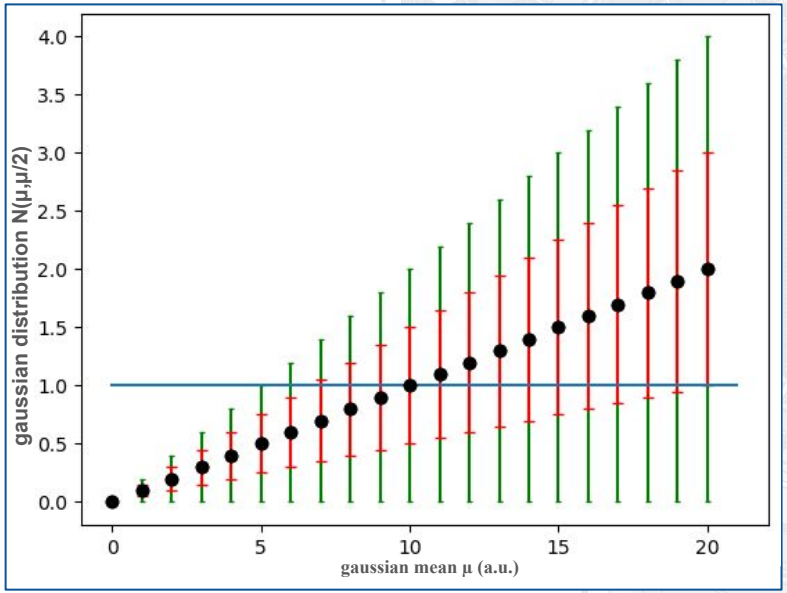
integration from 1 to infinity



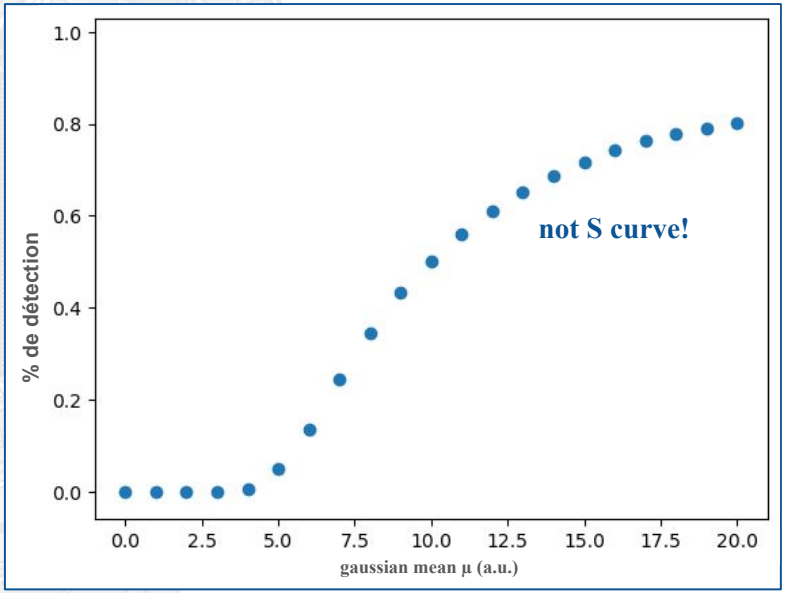
Light Calibration

Gain :

Proportional fluctuation



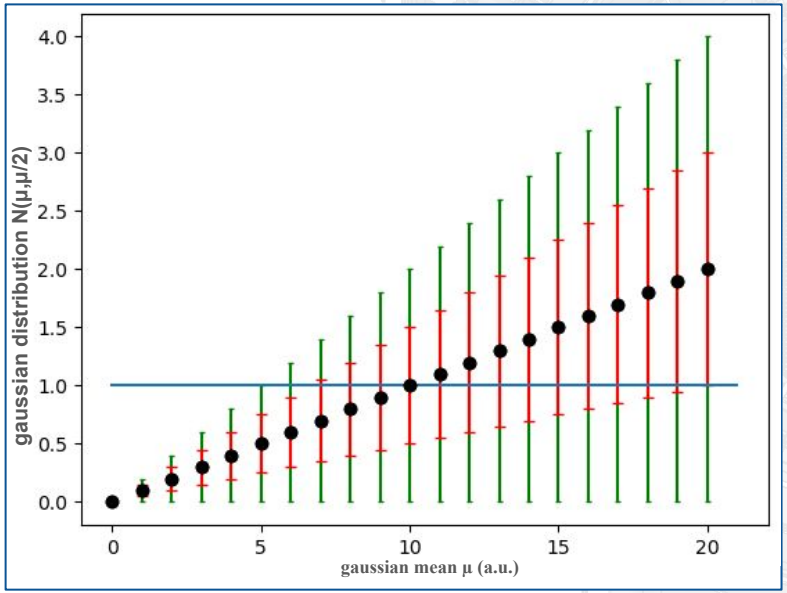
integration from 1 to infinity



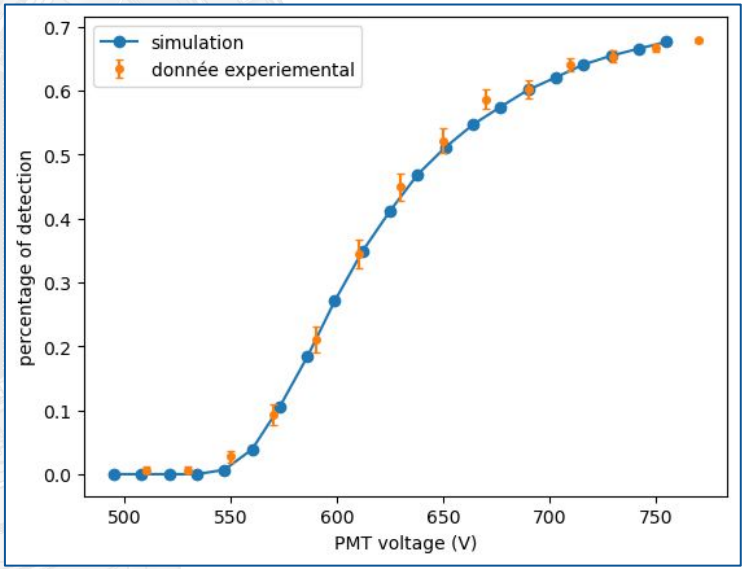
Light Calibration

Gain :

Proportional fluctuation

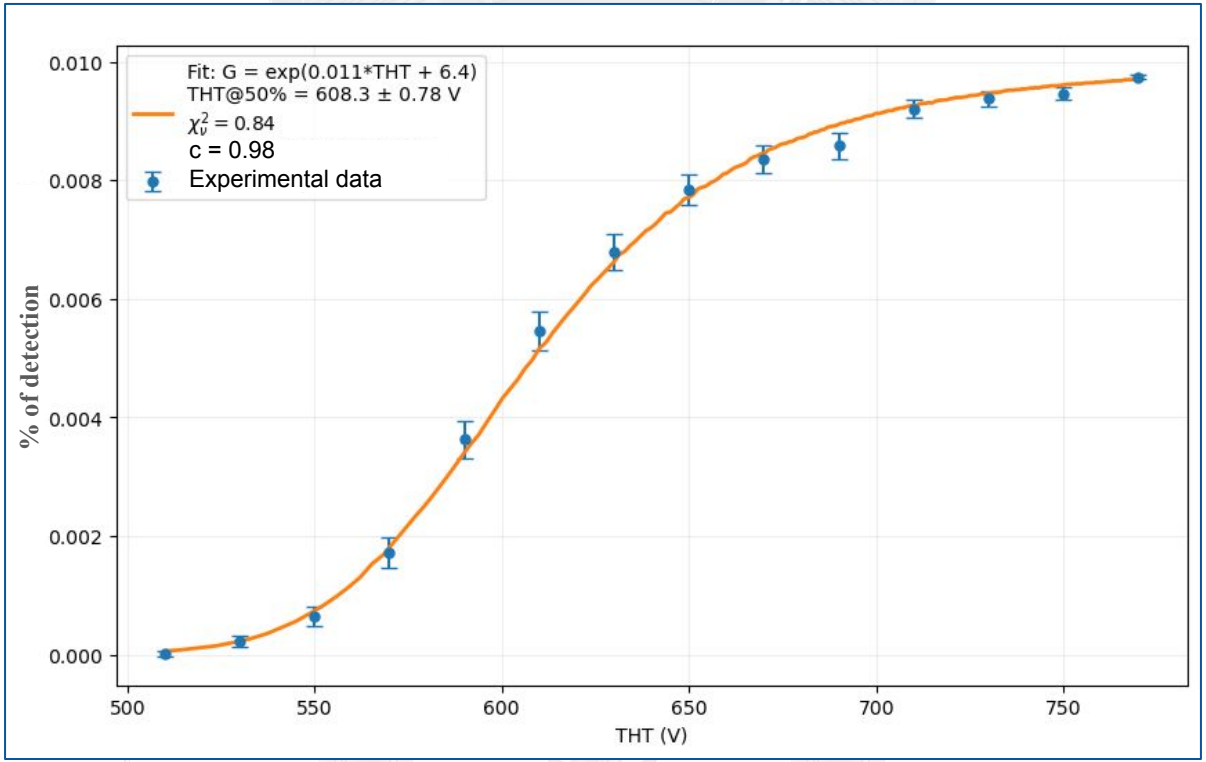


integration from 1 to infinity



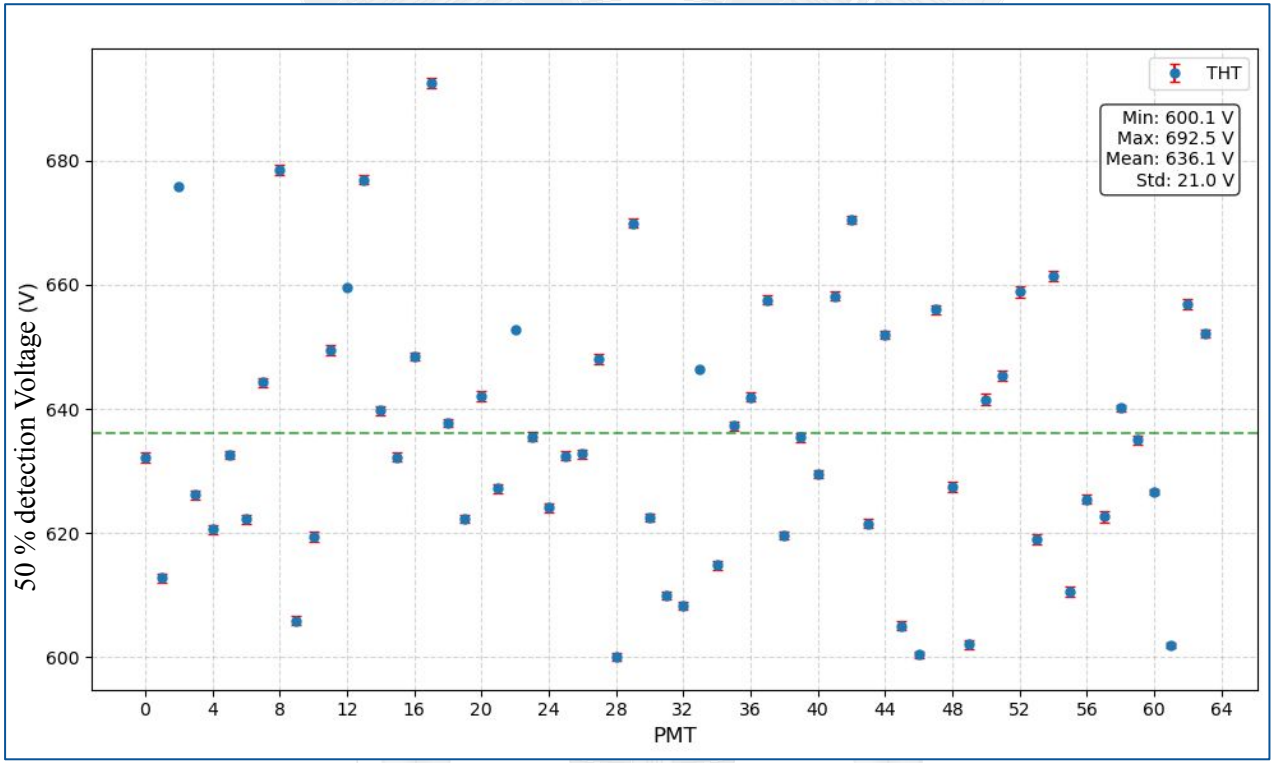
Light Calibration

Gain :



Light Calibration

Gain :



Conclusion :

- Thresholds are set and stable
- ToT-npe/ToT-walk curve are updated
- Gain method is developed, gain are set and the stability is under measurement

Perspective :

- Measure gain stability (in progress)
- Develop Charge/Light matching (in progress)
- Develop gamma tagging (in progress)
- Develop event configuration weighting
- Exploit the image reconstruction algo (Medhi Latif PhD)