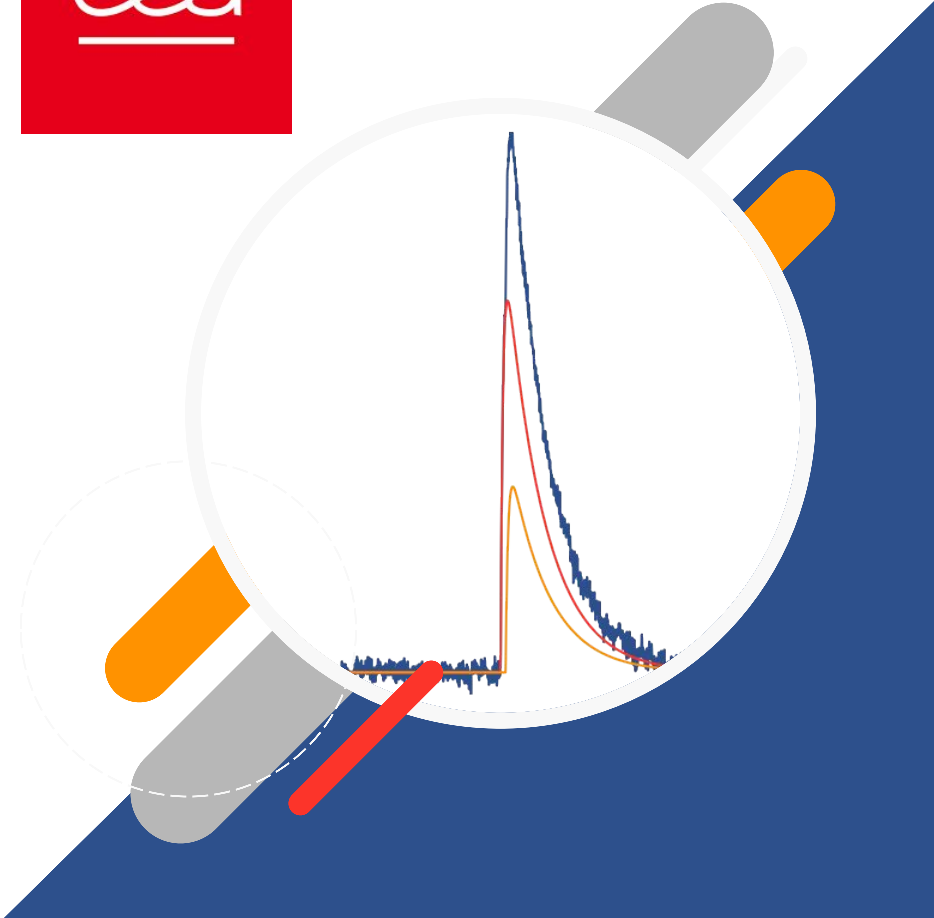
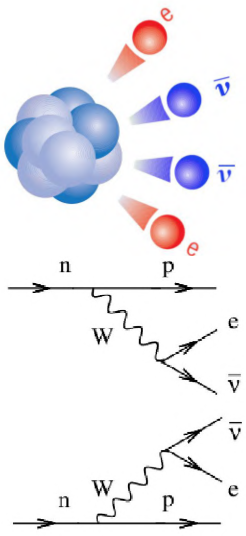
Improving the CUPID $0\nu\beta\beta$ science program with better pile up discrimination



Mathieu Pageot
on behalf of the CUPID collaboration

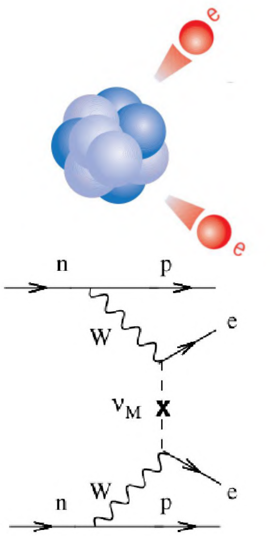
The $0\nu\beta\beta$ decay

$2\nu2\beta$



Allowed By Standard Model

$0\nu2\beta$



Needs Beyond Standard Model Physics !

$\Delta L = 2$

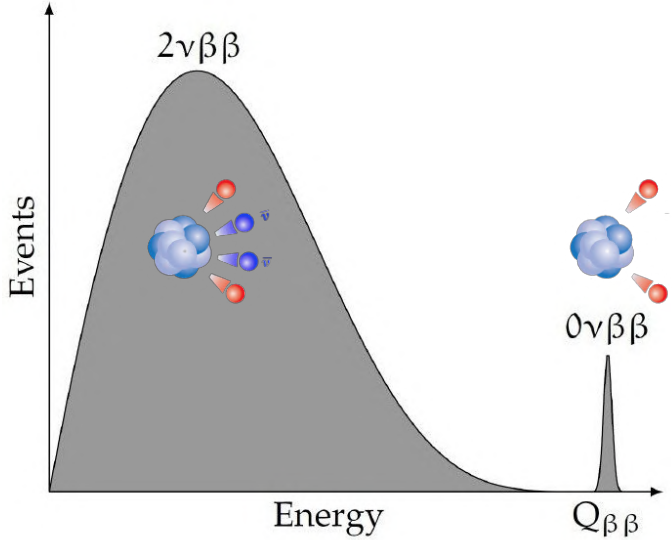
Lepton Number Violation

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

Majorana Particle

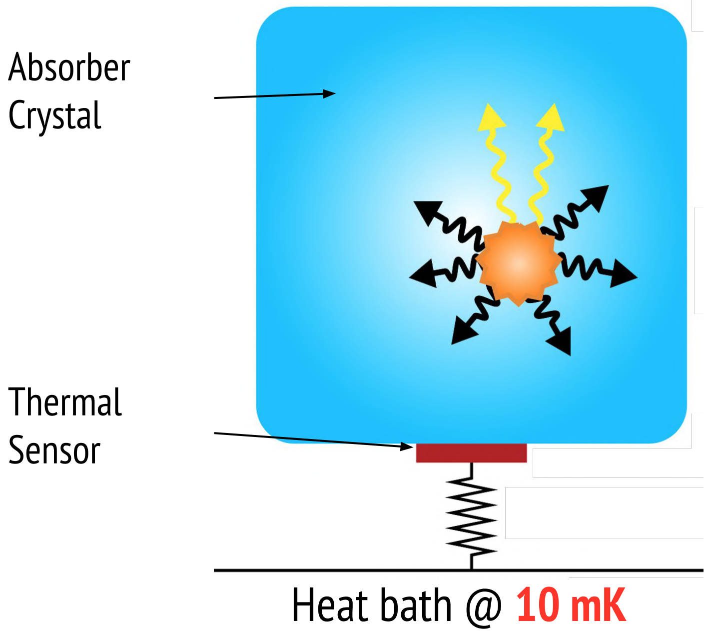
Detect $0\nu\beta\beta$

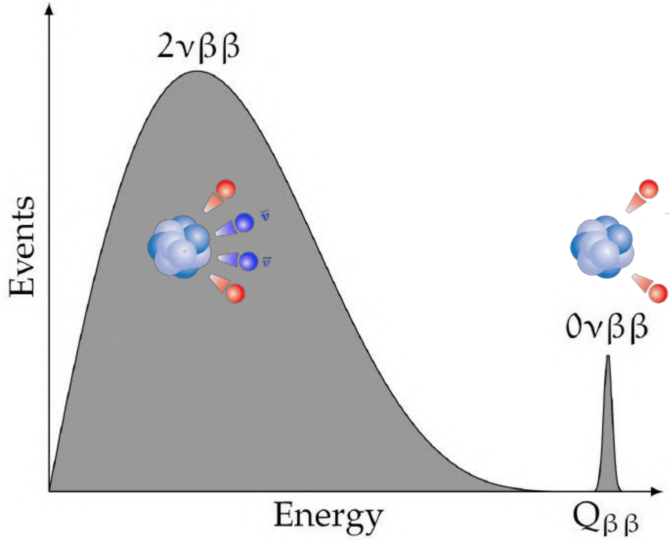
Main signature of the $0\nu\beta\beta$: peak at the Q-value of the reaction



Detect $0\nu\beta\beta$ with cryogenic calorimeters

Main signature of the $0\nu\beta\beta$: peak at the Q-value of the reaction





Cryogenic calorimeters

- High detection efficiency : $\beta\beta$ emitter embedded in the detector
- Flexible in isotope choice
- Excellent energy resolution ⟶ narrow $0\nu\beta\beta$ peak
- Scalable as array of O(1000) crystals (100g - 1kg each)

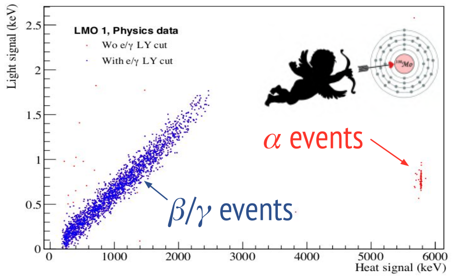
CUPID (CUORE Upgrade with Particle IDentification)

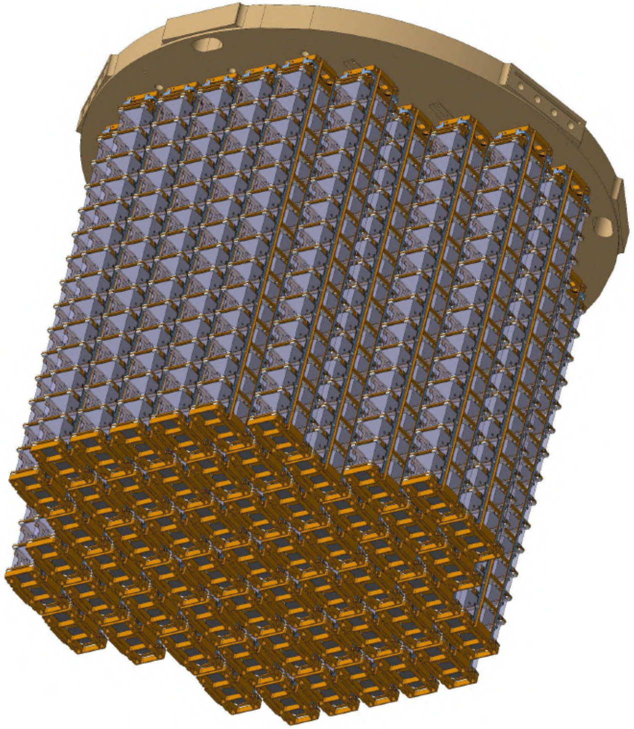
1596 Li_2MoO_4 crystals (240 kg of ^{100}Mo)

→ ^{100}Mo is one of the 2β isotope with the most advantageous phase space

1710 Ge light detectors

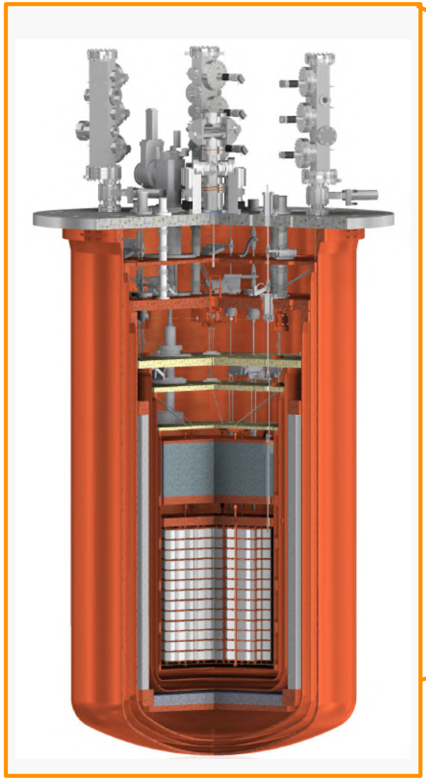
→ Main goal is to detect scintillation light from the crystal for α particle discrimination





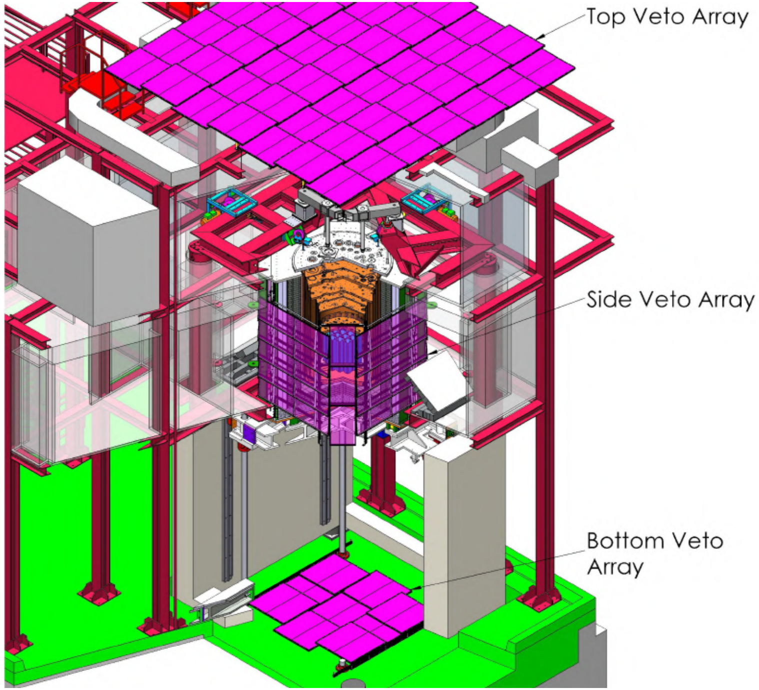
CUPID, the CUORE upgrade with particle identification. *European Physical Journal C, 85(7), 737.*

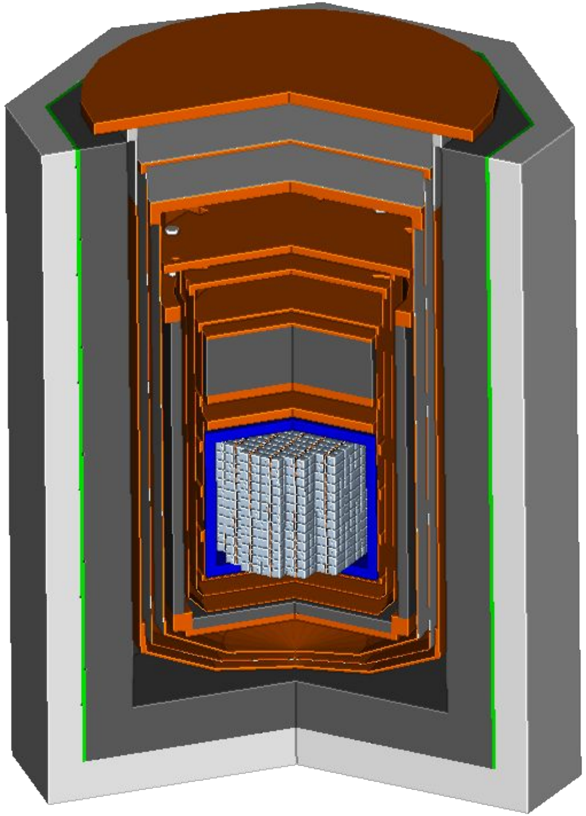
CUPID setup @ LNGS



Depth

CUPID setup @ LNGS

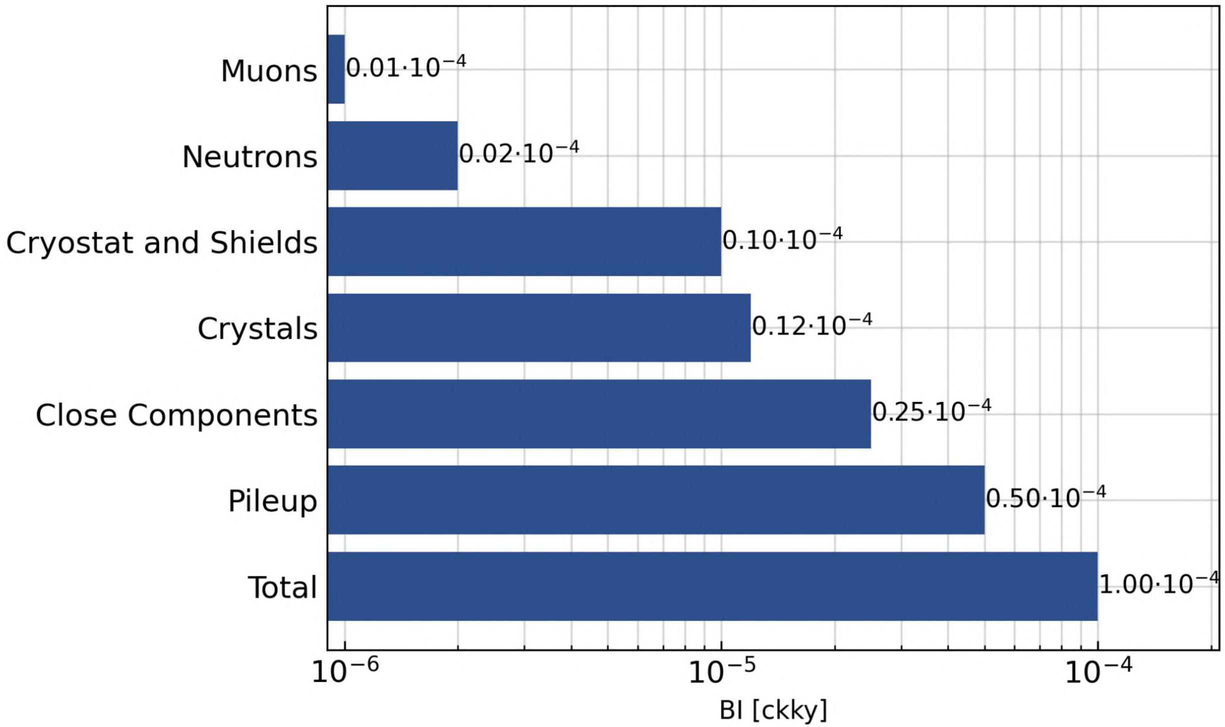




CUPID, a low background experiment

Coming from outside the detector structure :
mitigate by shielding and vetos

Mainly due to surface contamination:
mitigated by a clean assembly and coincidence between crystals



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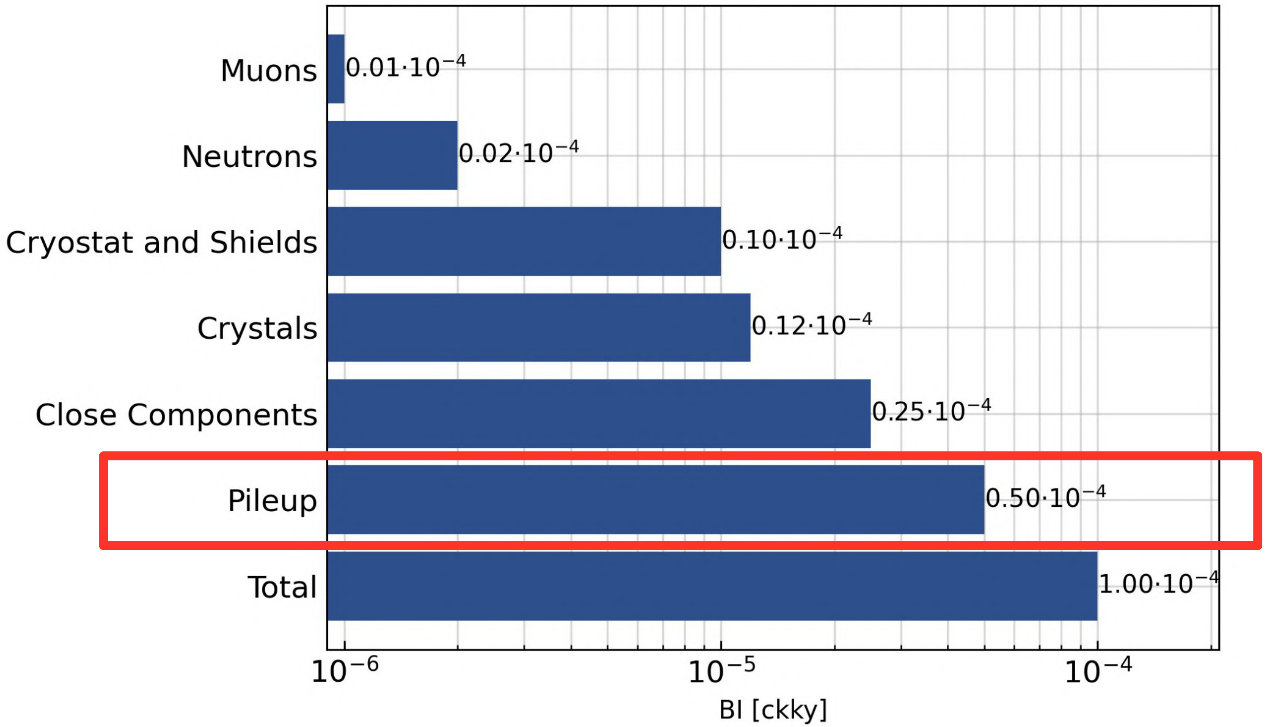
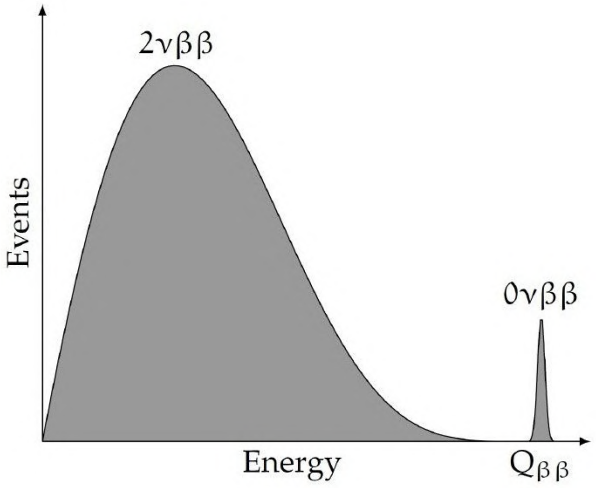


$2\nu\beta\beta$ pile-up

- ^{100}Mo has a high rate of $2\nu\beta\beta$

  $T_{½}$= 7.07×10^{18} yr [1] / ~0.6 mHz per crystal
- Bolometer are intrinsically slower than other detector



[1]https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.131.162501

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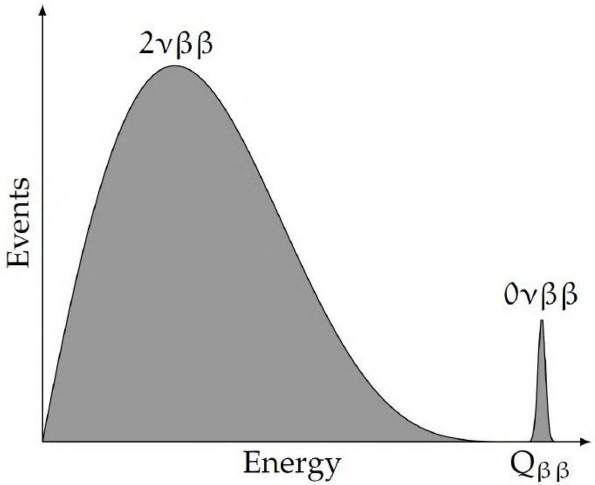
→ Two $2\nu\beta\beta$ events close enough in time that are not resolved.



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2νββ pile-up

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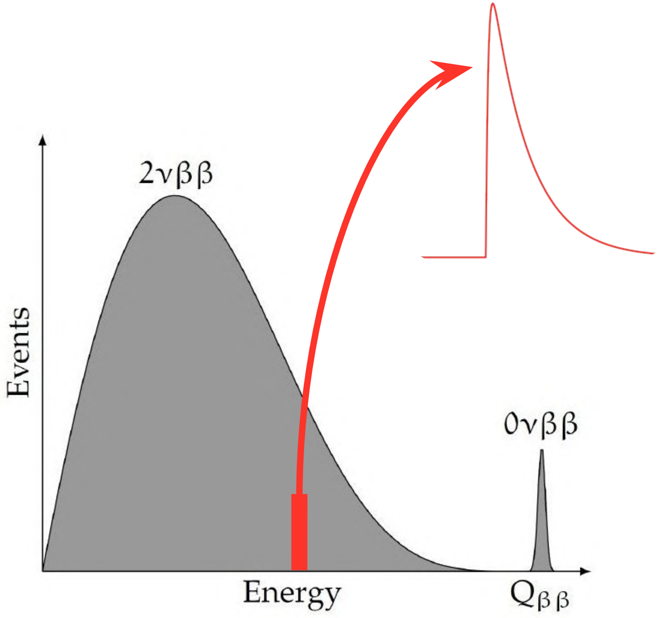

[1]https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.131.162501

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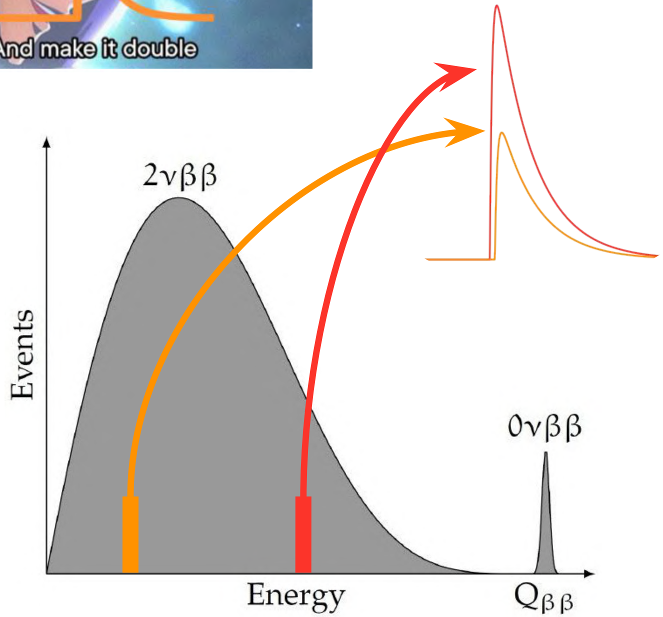

[1]https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.131.162501

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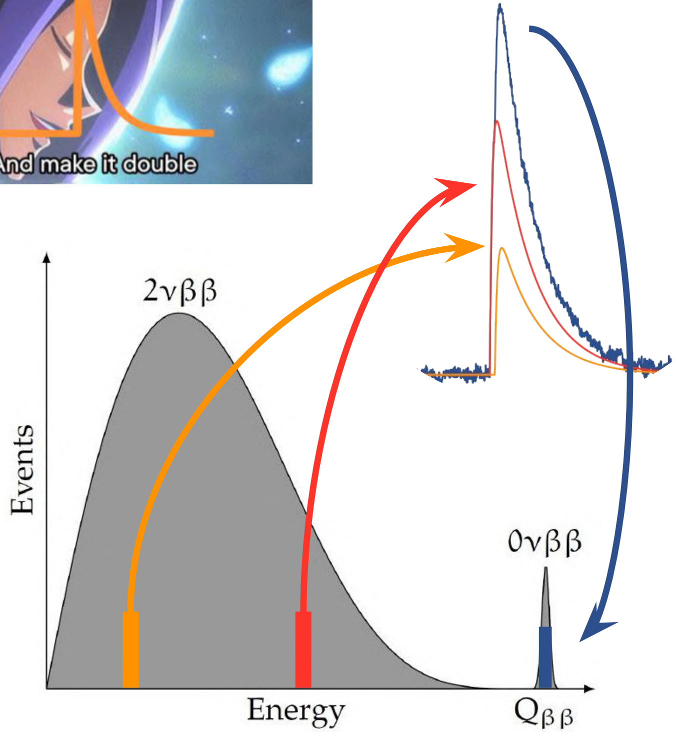
→ Two 2νββ events close enough in time that are not resolved. but **reconstructed** as a single event



[1]https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.131.162501

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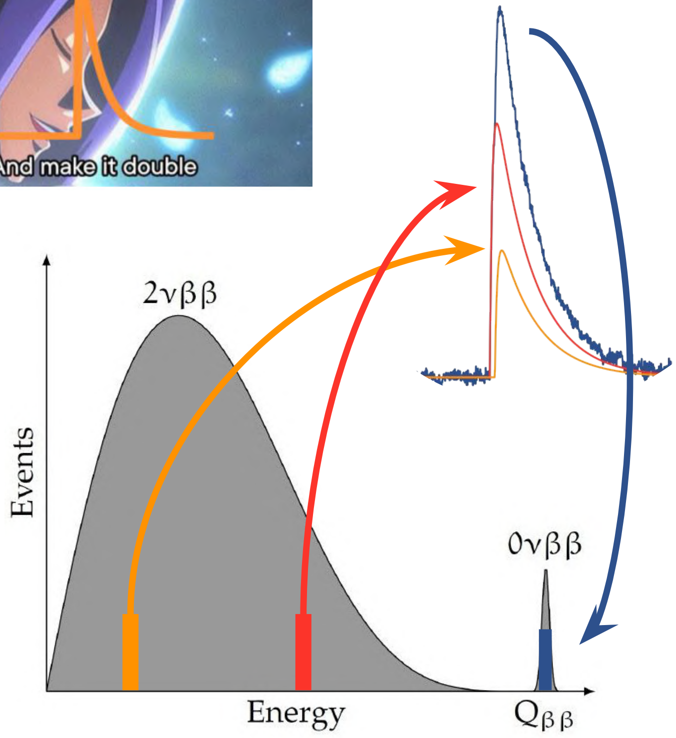
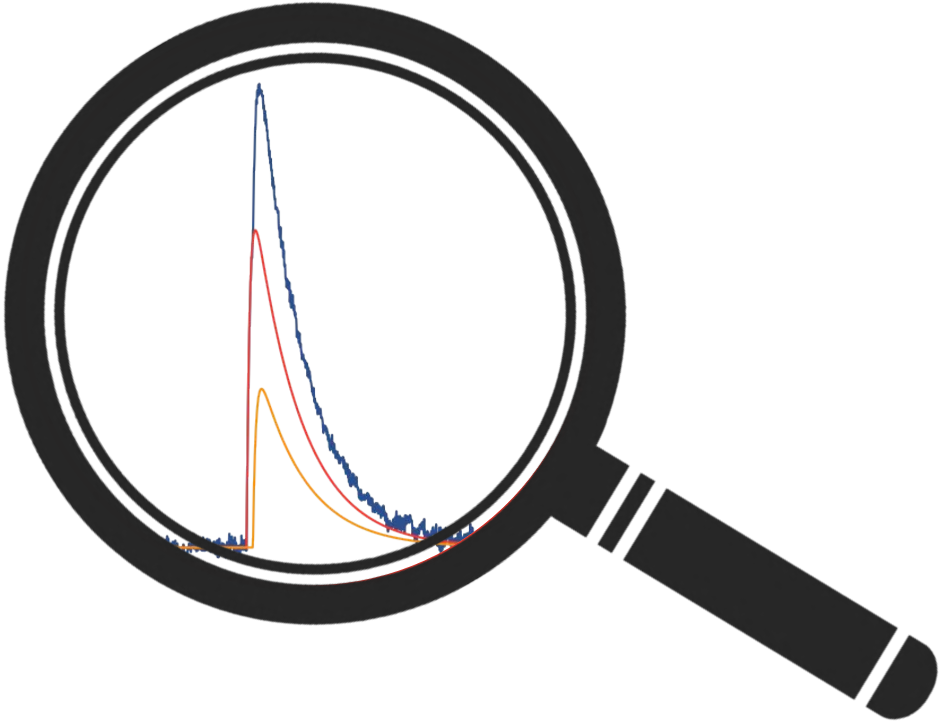


Extended background at high energy (Q-value and beyond)

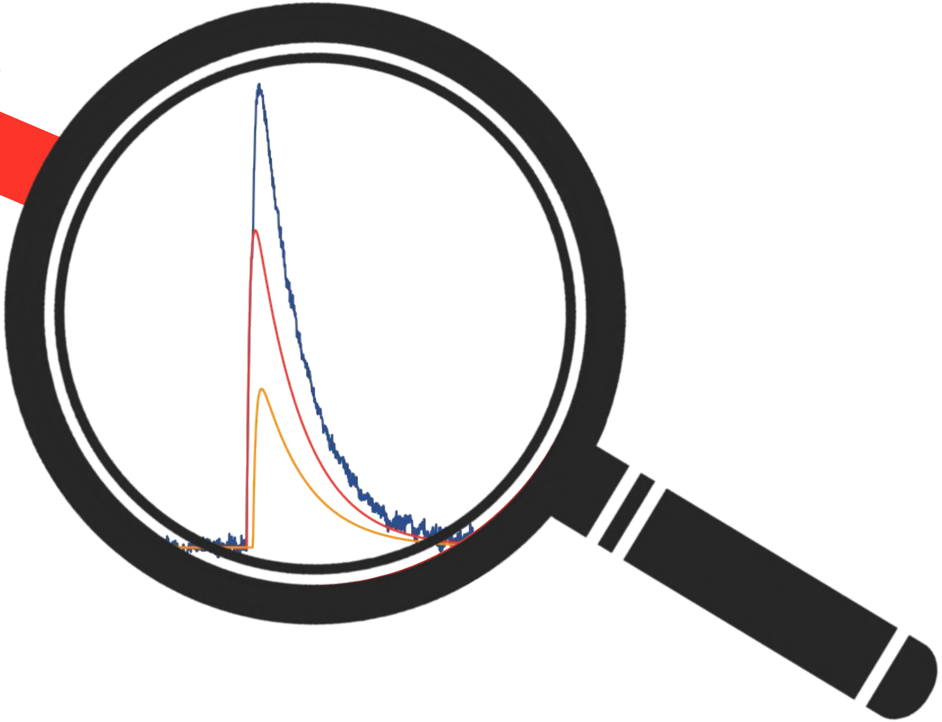
[1]https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.131.162501

Pile-up discrimination



Pile-up discrimination

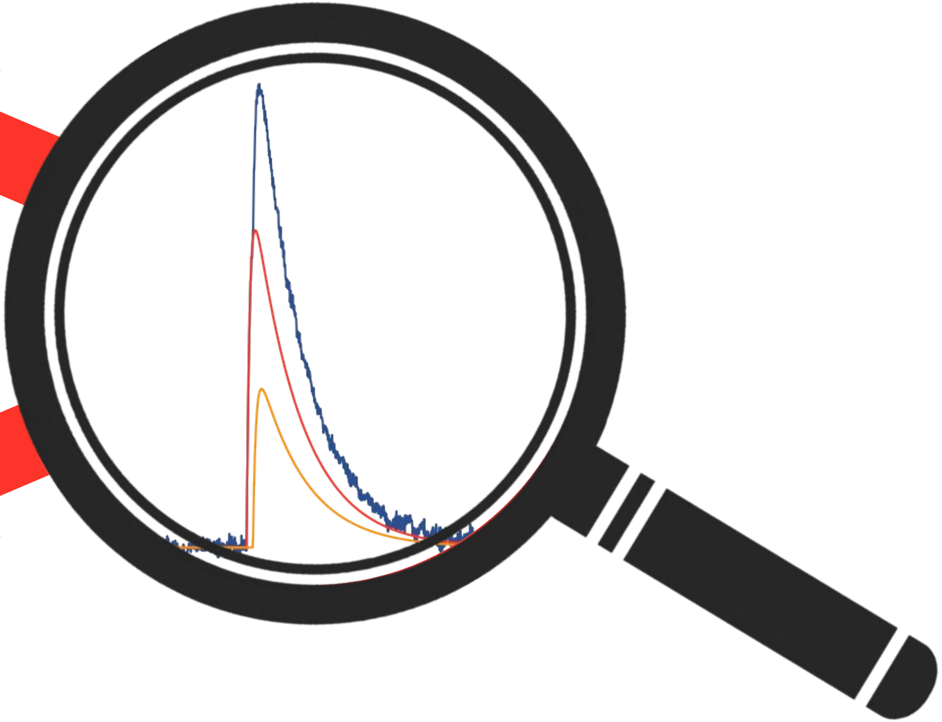
Use the light detector that are faster (~1 ms vs ~30 ms for crystals)



Pile-up discrimination

Use the light detector that are faster (~1 ms vs ~30 ms for crystals)

Improve the Signal to Noise ratio (SNR) with Neganov-Trofimov-Luke (NTL) amplification



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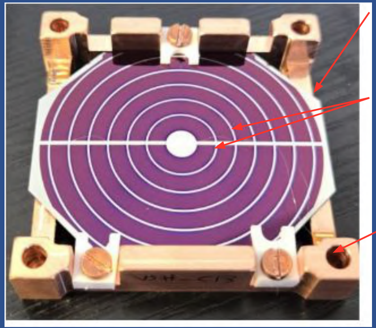
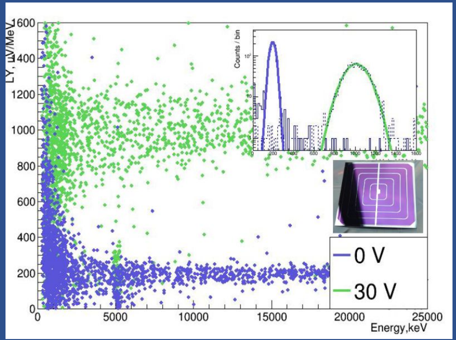
Improve the Signal to Noise ratio (SNR) with Neganov-Trofimov-Luke (NTL) amplification

Neganov-Trofimov-Luke (NTL) amplification

Drift electron/hole pair by applying a voltage on the Light detector to generate an additional heat signal and **gain in SNR.**





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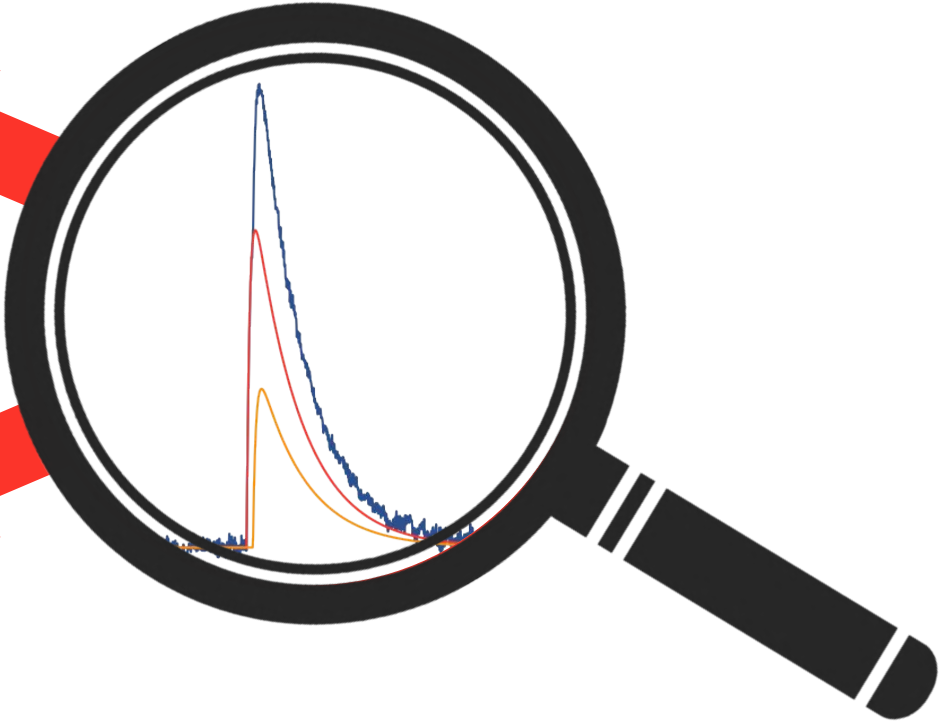

Pile-up discrimination

CUPID

Use the light detector that are faster (~1 ms vs ~30 ms for crystals)

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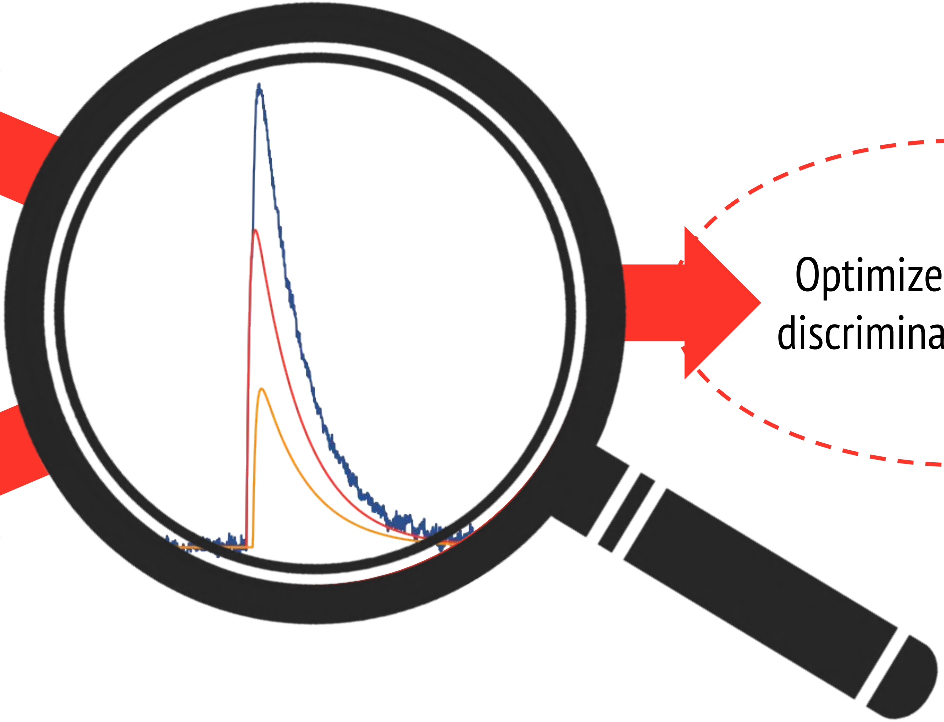


Optimize the pile-up discrimination analysis

Pile-up discrimination analysis

The technic uses a Pulse Shape Discrimination (PSD) parameter build upon the “optimal” filter :

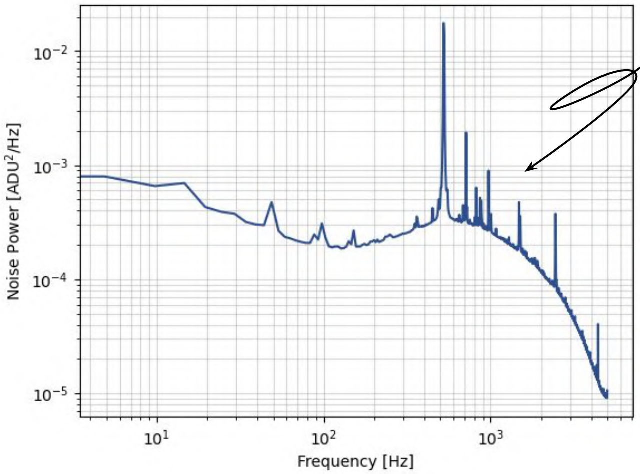
$$H(\omega) = \frac{\hat{s}^*(\omega)}{\mathcal{P}_N(\omega)}$$

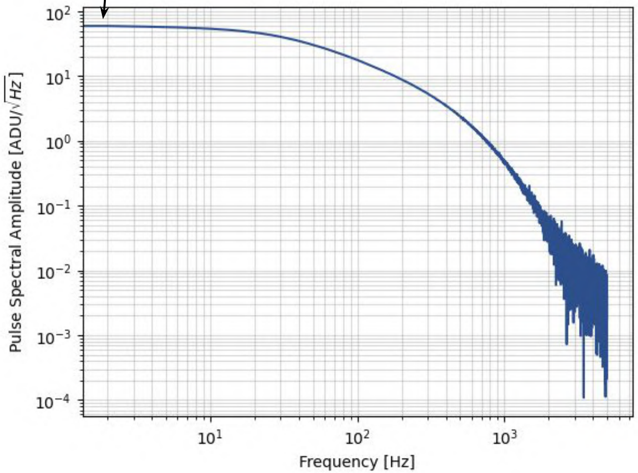
Pulse frequencies

Noise Power Spectrum

$$x_H(t) = Re(\mathcal{F}^{-1}(H(\omega)\hat{x}(\omega)))$$

Filtered pulse





Pile-up discrimination analysis

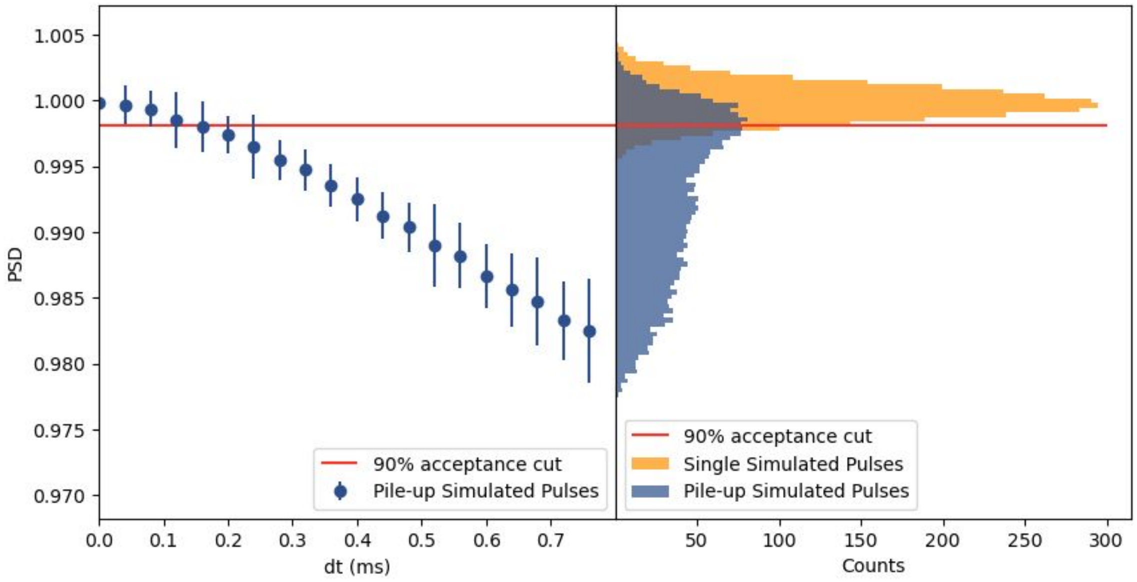
This PSD is currently set as the ratio of 2 energy estimator :

$$\tilde{A}_1 = max(x_H(t))$$

Sensitive to pileup

$$\tilde{A}_2 = \frac{\sum_t x_H(t) s_H(t)}{\sum_t s_H(t)^2}$$

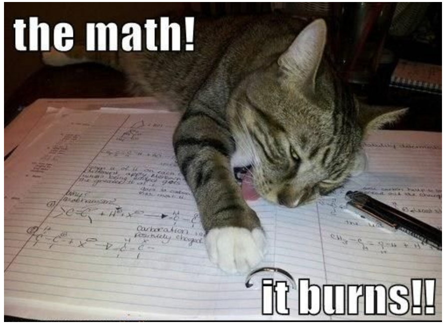
Less sensitive to pileup (for normalization)



- Optimal for maximizing **Signal / Noise Ratio**
- Not at all optimal for maximizing pile up discrimination

Need to refine frequency weighting to be more sensitive

Pile-up discrimination analysis Optimization



Calculation shows that :

$$\tilde{A}_1 = max(x_H(t))$$
$$\tilde{A}_2 \simeq max(x_{H'}(t))$$

with

$$H'(\omega) = H(\omega)\frac{|\hat{s}(\omega)|^2}{\mathcal{P}_N(\omega)}$$

Change to : $PSD = \dfrac{max(x_{H_1}(t))}{max(x_{H_2}(t))}$ with $H_i(\omega) = H(\omega) f_i(\omega)$ $f_i(\omega)$ to be optimized

Parameter to be minimized is the pileup acceptance defined as :

Defined by the cut efficiency

$$J[f_1, f_2] = \int_0^{t_{max}} (1 - \Phi(\frac{PSD[f_1, f_2](t)}{\sigma_{PSD}[f_1, f_2]} - N_\sigma)\, dt$$

cumulative distribution function (CDF) of the standard normal distribution

The minimization is done using Gradient descent technique

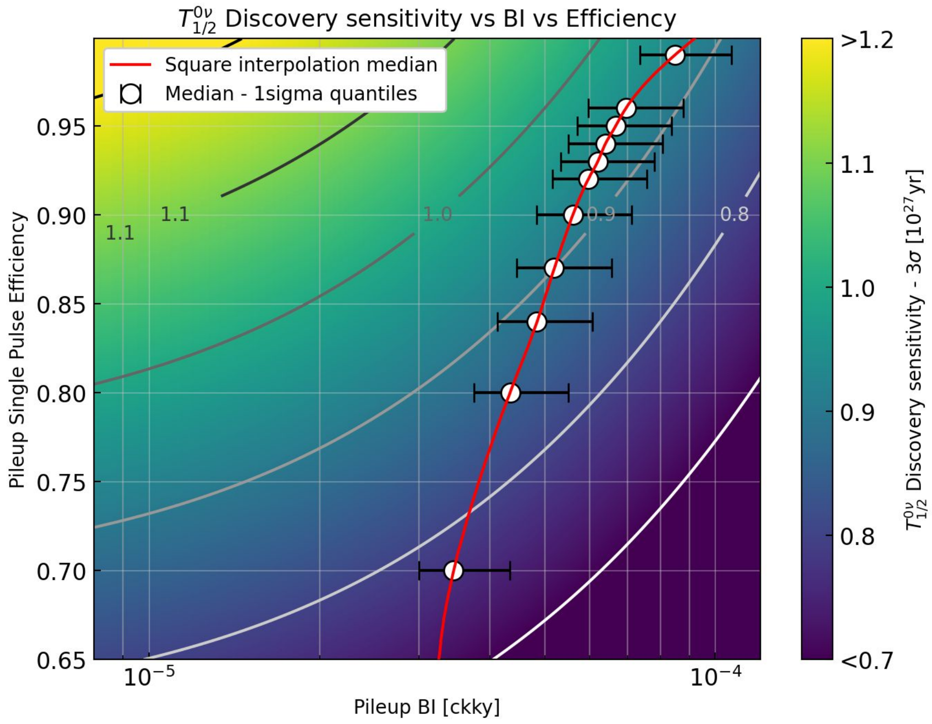
Pile-up discrimination analysis Performance assessment

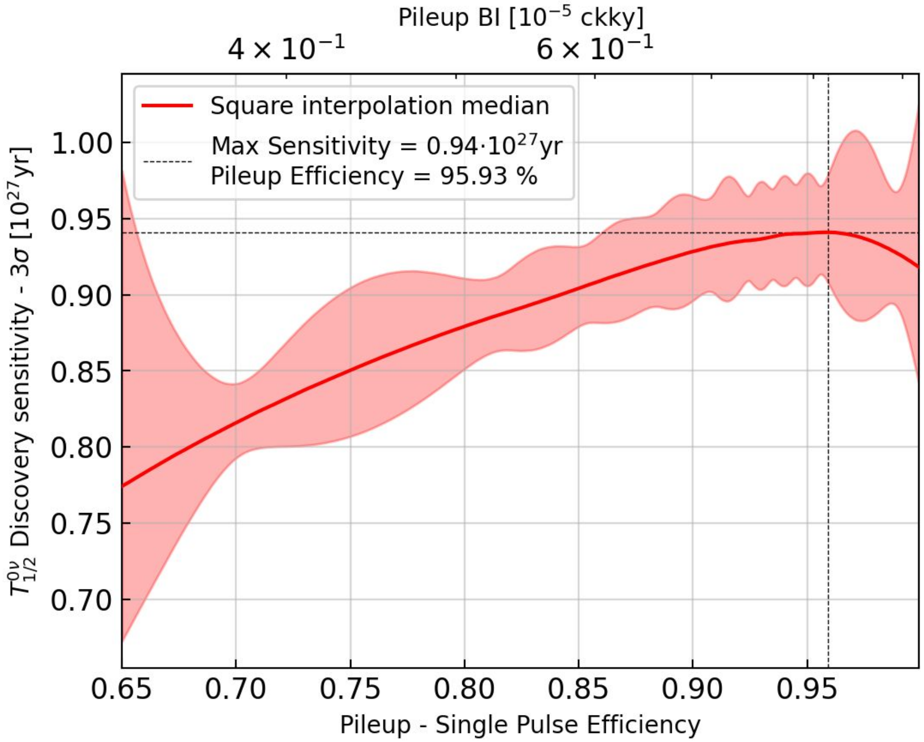
The algorithm is tested on a simulated dataset using pulses and noises from detectors of the CROSS experiment implementing NTL amplified light detectors

https://arxiv.org/abs/2507.15732

detector ID	risetime (ms)	SNR Optimum Filter	BI Optimum Filter 90% efficiency (1e-5 ckky)	BI pile-up Filter 90% efficiency (1e-5 ckky)	Improvement (%)
2	0.72	128	10.1	7.3	28
3	0.54	94	10.0	7.3	27
4	0.55	179	6.8	4.8	30
5	0.78	239	6.7	4.7	30
9	0.64	178	7.7	5.5	28
10	0.51	100	7.6	5.3	30
11	0.51	109	8.2	5.9	28
12	0.47	79	7.7	5.7	26
average			8.1	5.8	28

Optimizing the pile-up cut acceptance for $0\nu\beta\beta$ sensitivity

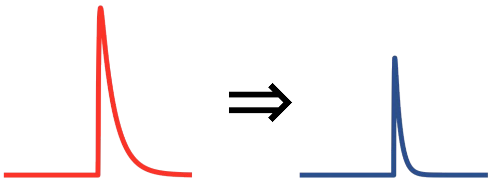




Improvement strategies

Optimize detector working point

Set detector working point for best SNR and time response combinaison



Improve further NTL amplification

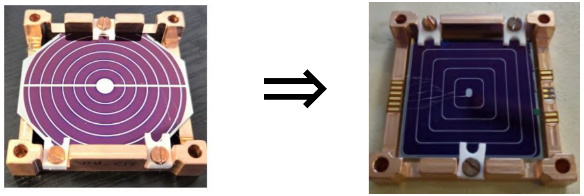
Work ongoing to improve NTL bias voltage and coverage

⇓

Better SNR

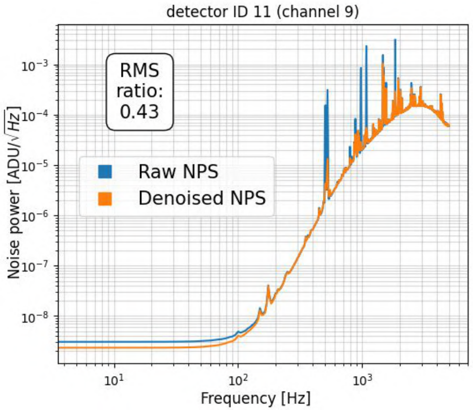
⇓

Better pile-up rejection



Denoising

Machine learning techniques for multichannel denoising are under developpement



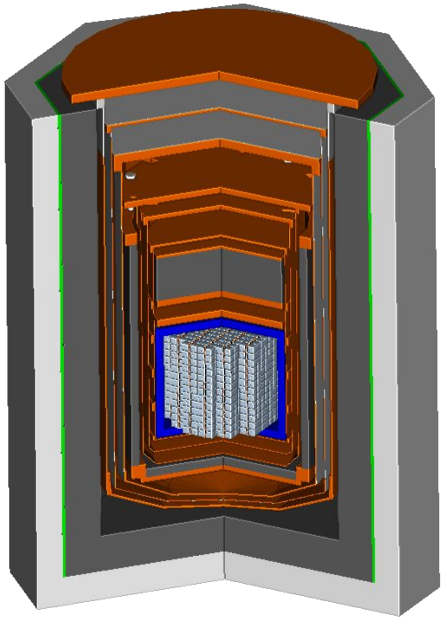
CUPID

IRN Neutrino

cea

Thank you!

CUPID BG projection

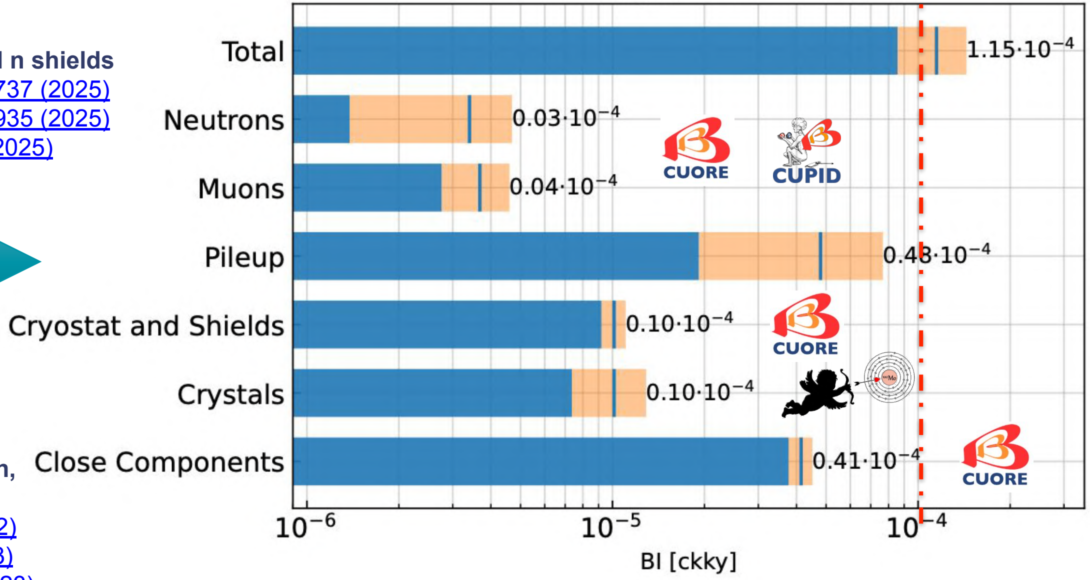


Cryostat and Background model
Phys. Rev. Lett. 126, 171801 (2021)
Phys. Rev. D 110, 052003 (2024)
arXiv:2509.05528

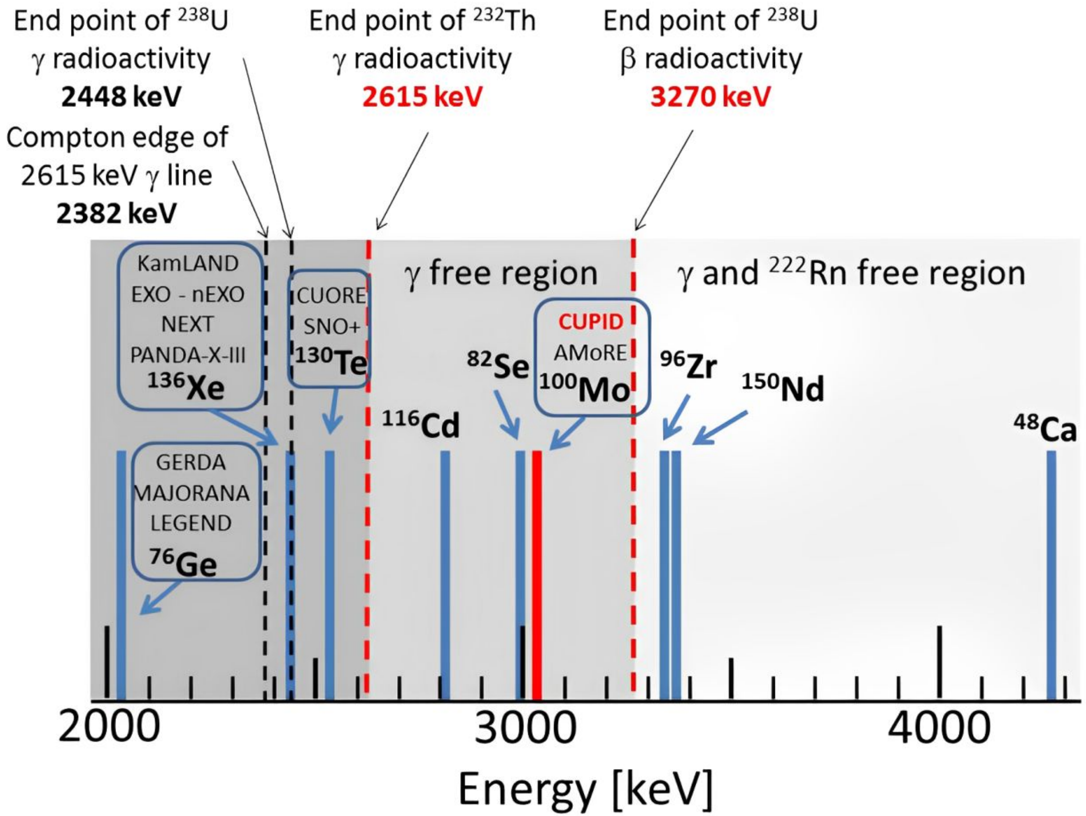
Tower design, and n shields
Eur. Phys. J. C 85, 737 (2025)
Eur. Phys. J. C 85, 935 (2025)
JINST 20 P08020 (2025)

Li_2MoO_4 crystals & rejection, pile-up
Eur. Phys. J. C 82, 1033 (2022)
Eur. Phys. J. C 83, 675 (2023)
Phys. Rev. Lett. 131, 16250 (2023)
arXiv:2507.15732v1 (2025)

CUPID BG simulation



Q-values of the different $\beta\beta$ isotopes



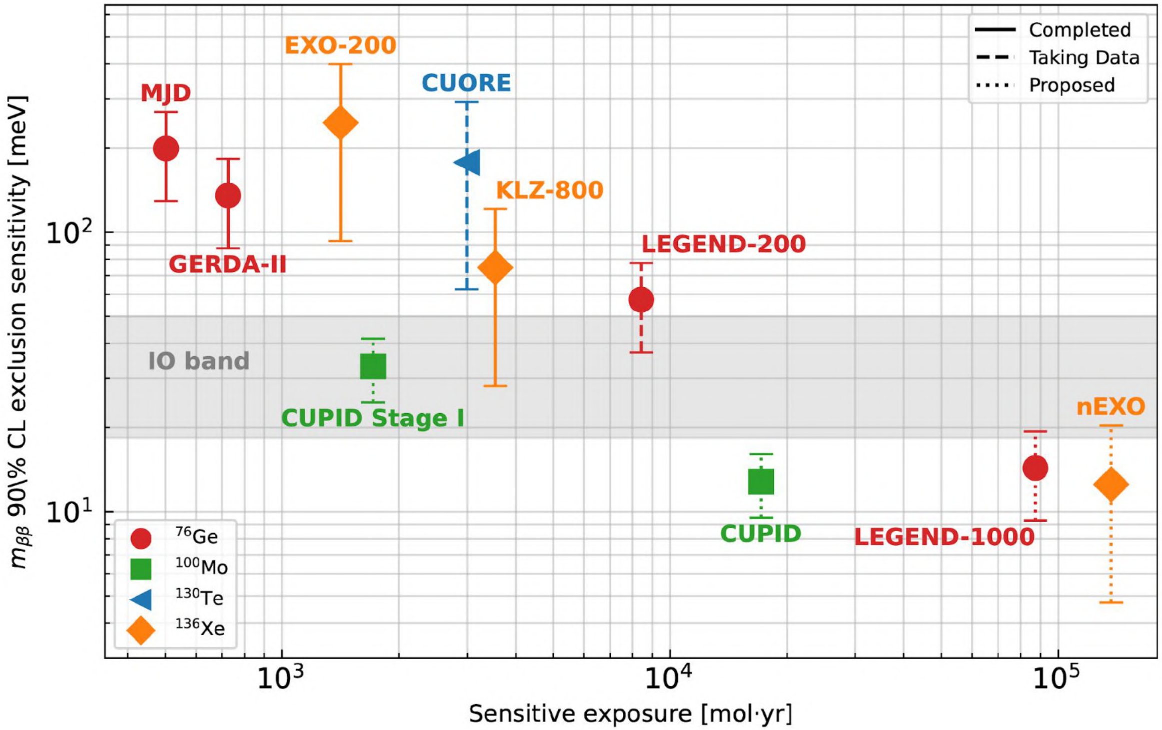
CUPID Sensitivity

$$T^{0\nu}_{1/2} = G^{0\nu}(Q,Z)|M^{0\nu}|^2(\frac{\langle m_{\beta\beta}\rangle}{m_e})^2$$

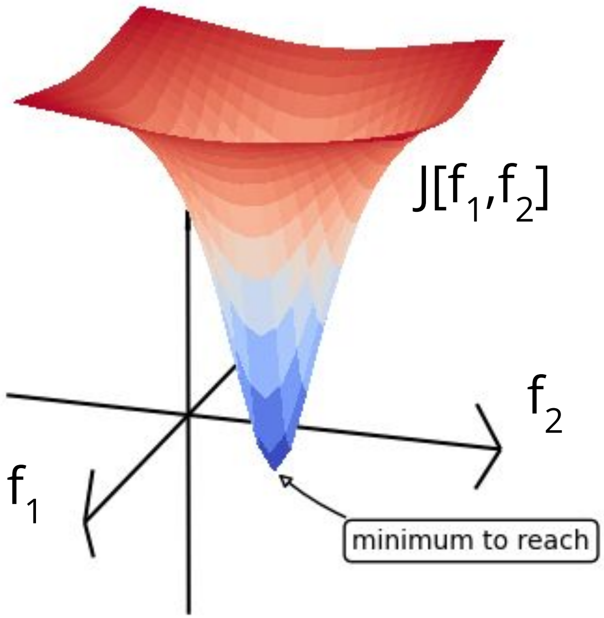
$$|m_{\beta\beta}| = |\sum_{i=0}^{3} U_{ei}^2 m_i|$$

CUPID goal:

- highly competitive sensitivity after **stage I**
- full coverage of the inverse order of the neutrino masses with the **stage II**



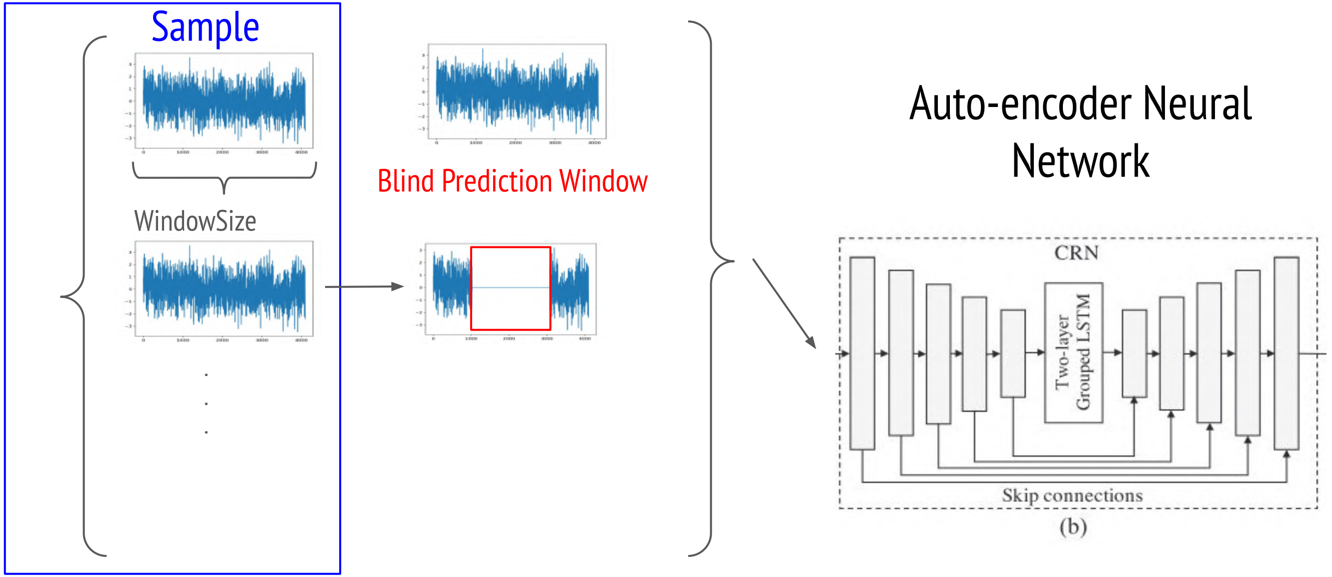
Gradient descent



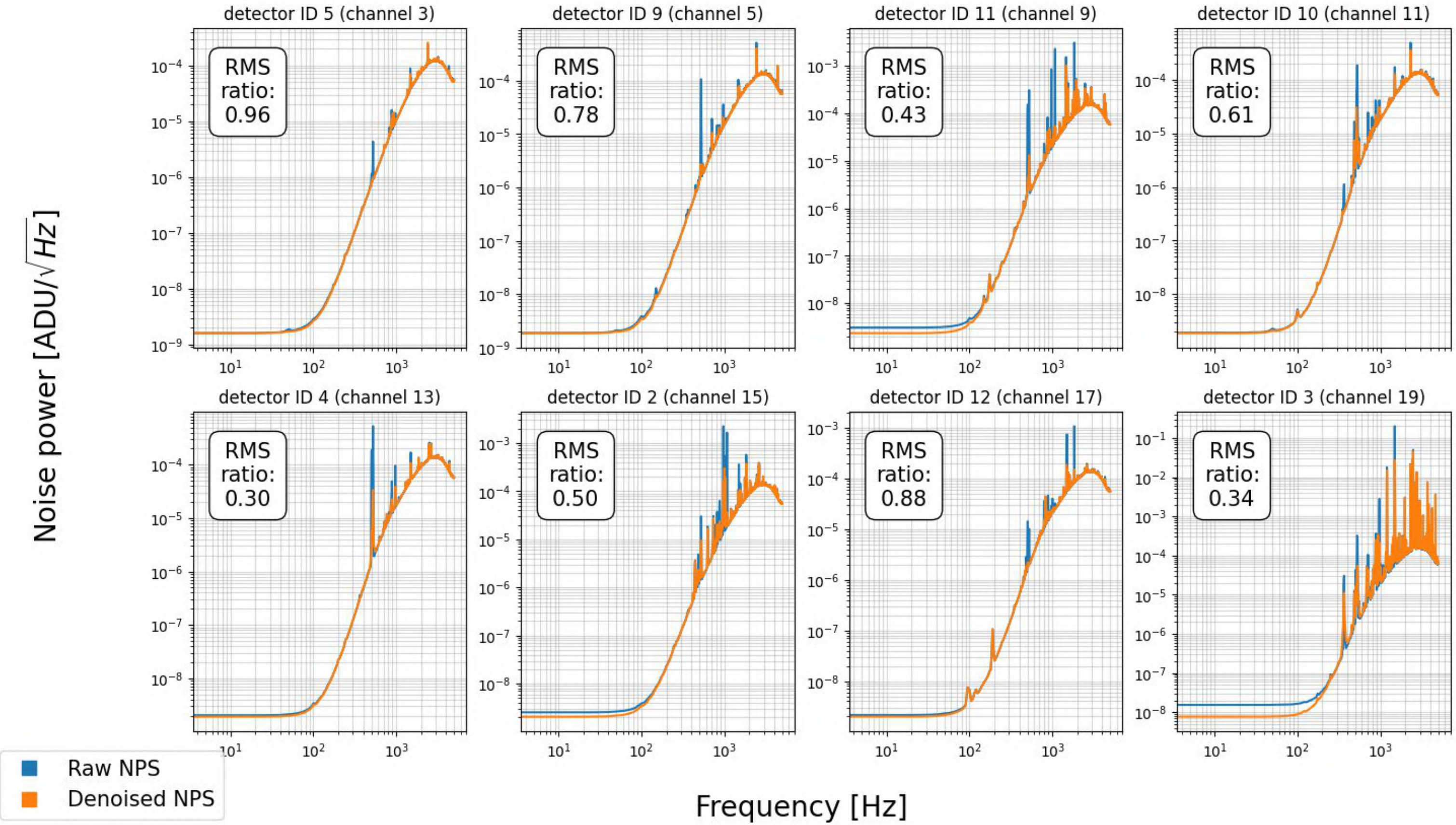
Not real data, just for visualization purpose

Denoising with Machine learning technics

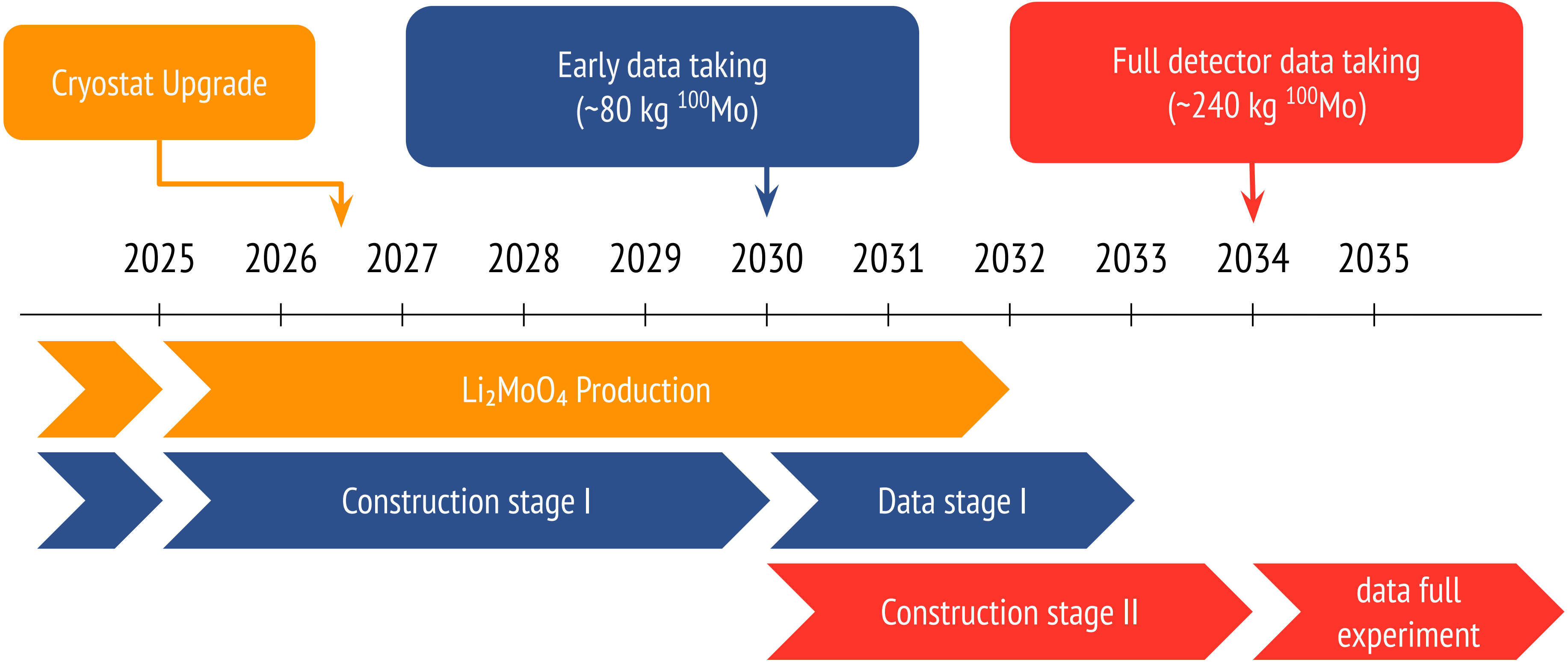
Idea : **“Predict” the noise** in a certain Window using the noise around as well as the Noise in surrounding channels and then **subtract the predicted noise from the pulse.**



Denoising with Machine learning technics



Timeline from CUORE upgrade to CUPID
Staged detector deployment



Test Towers GBPT and VSTT

GBPT(1) [arXiv:2503.04481]

First test tower for CUPID

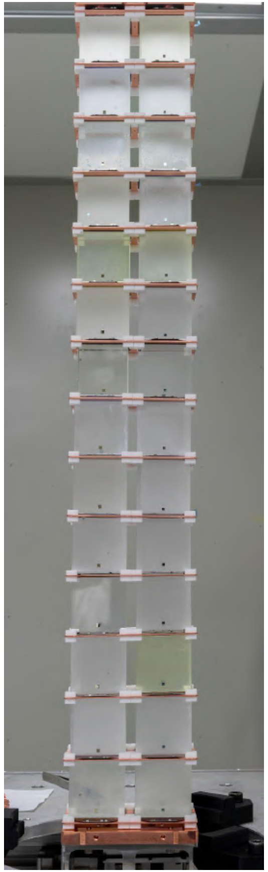
Revolutionary gravity based design

Detector close to CUPID requirements

To do : mitigate LD noise and demonstrate $2\nu\beta\beta$ pile-up rejection capability

(1): Gravity Based Prototype tower
(2): Vertical slice test tower

VSTT(2)

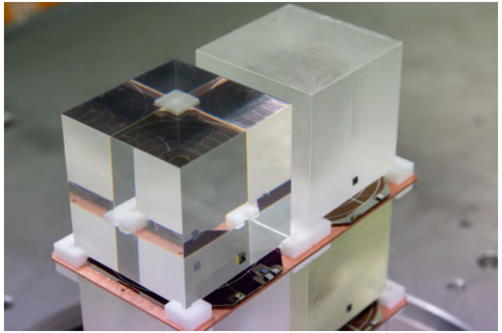


Build upon GBPT design, now with :

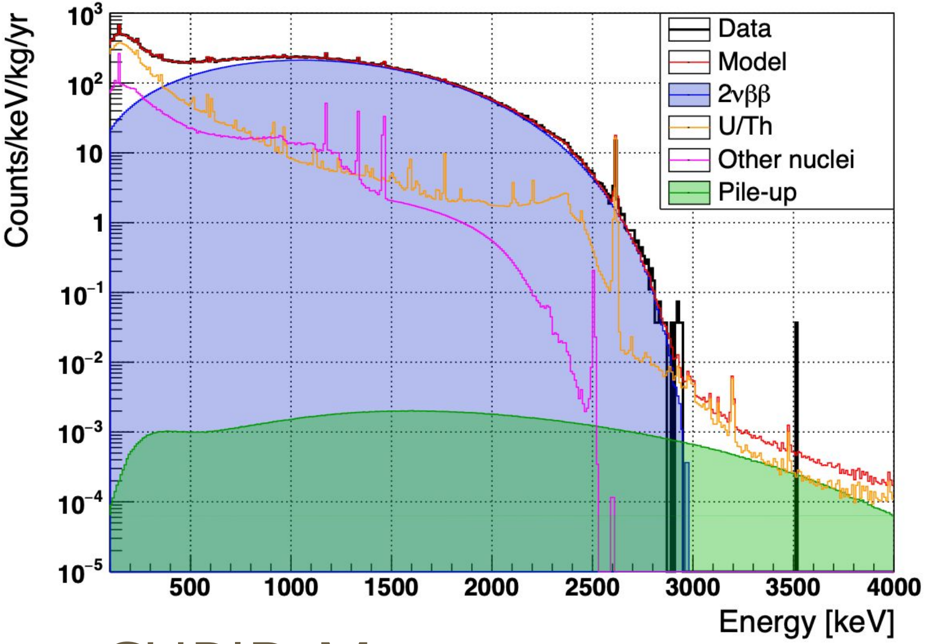
- NTL amplification light detectors
- Refined LD holders
- Gluing of the thermal sensor done with gluing robot

Assembly ongoing at LNGS

Cooldown and validation of performance by summer 2025



$2\nu\beta\beta$ pile-up ⇔ any event pileup



CUPID-Mo