Shedding light on CUORE & CUPID: Characterisation of Bolometers

End of Year Seminars

September 17th, Pavia

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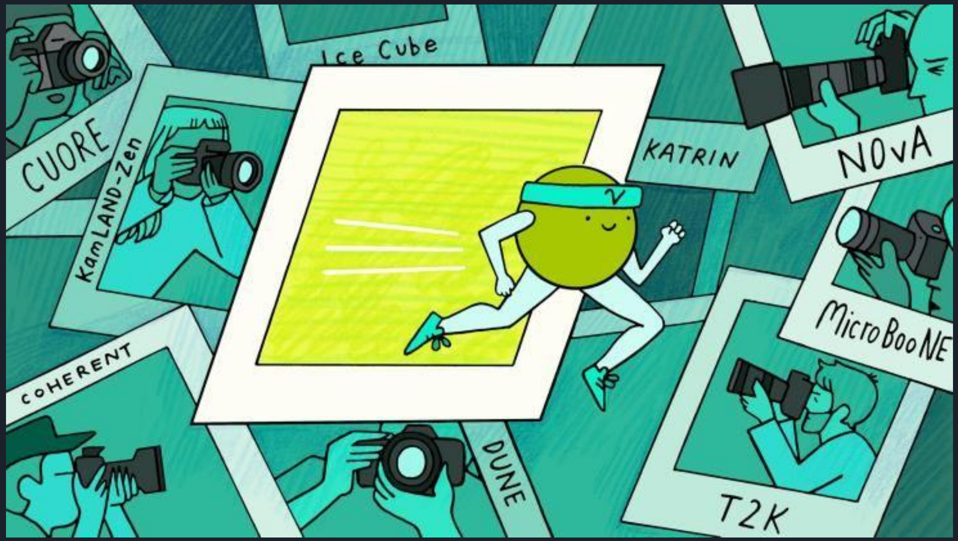
Dr. COPELLO Simone

Neutrinos

NEUTRINOs are Standard Model elemental particles, more specifically massive neutral-charged leptons.



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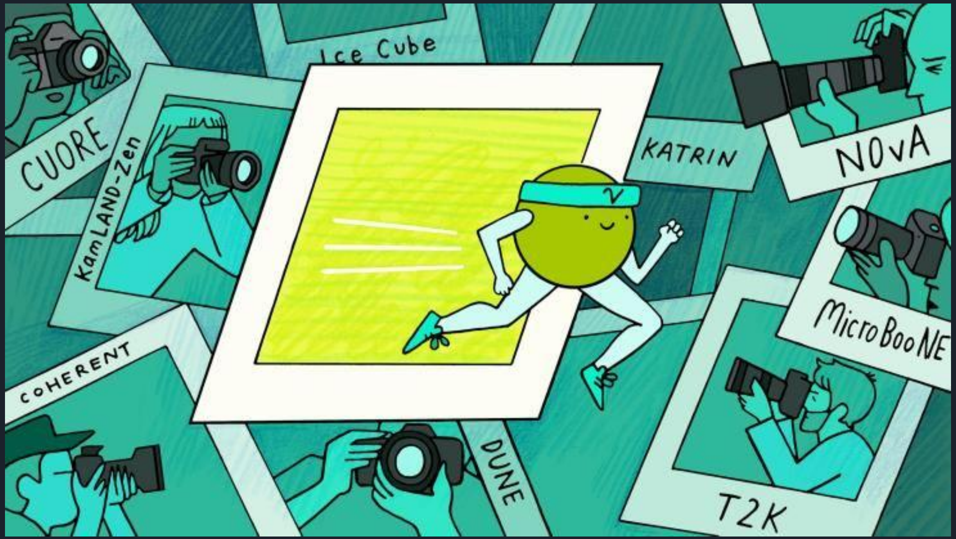


Flavor states (produced and detected): ν_e, ν_μ, ν_τ

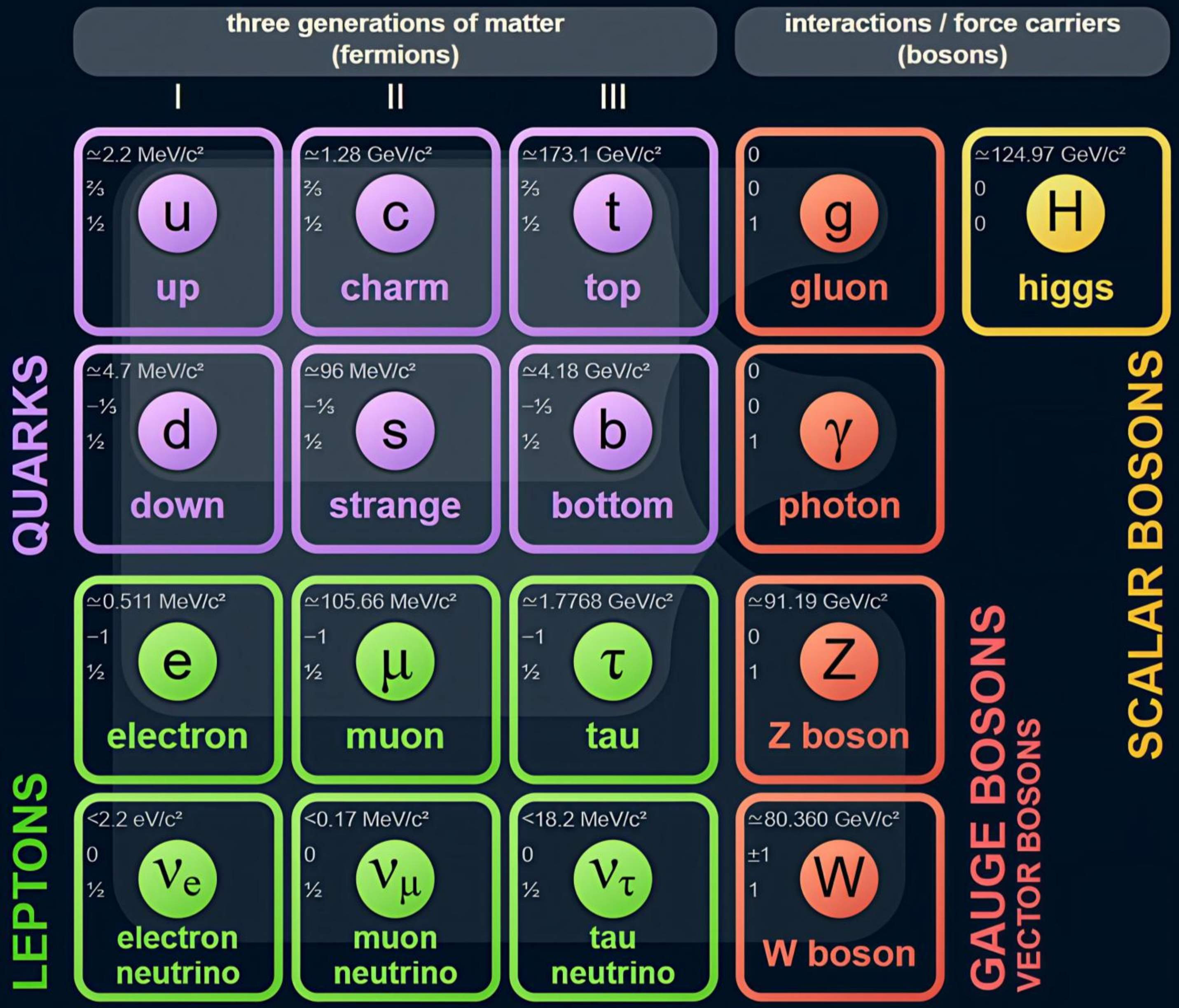
unitary mixing ⟷

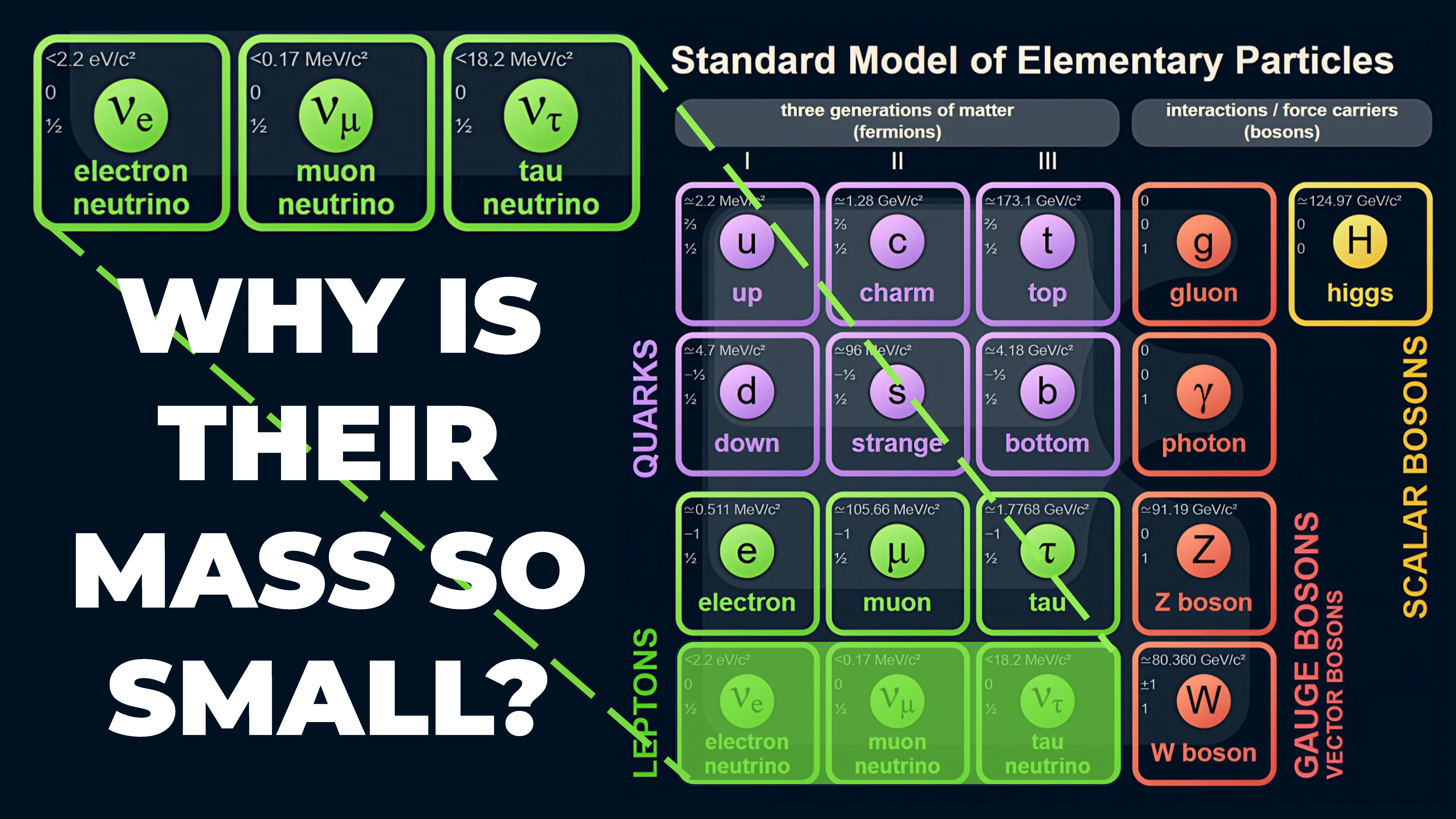
$|U|^2$ Δm_{ij}^2

3 mixing angles
1 CP phase
absolute masses
(to be measured)

Mass states (propagate with definite mass): ν_1, ν_2, ν_3

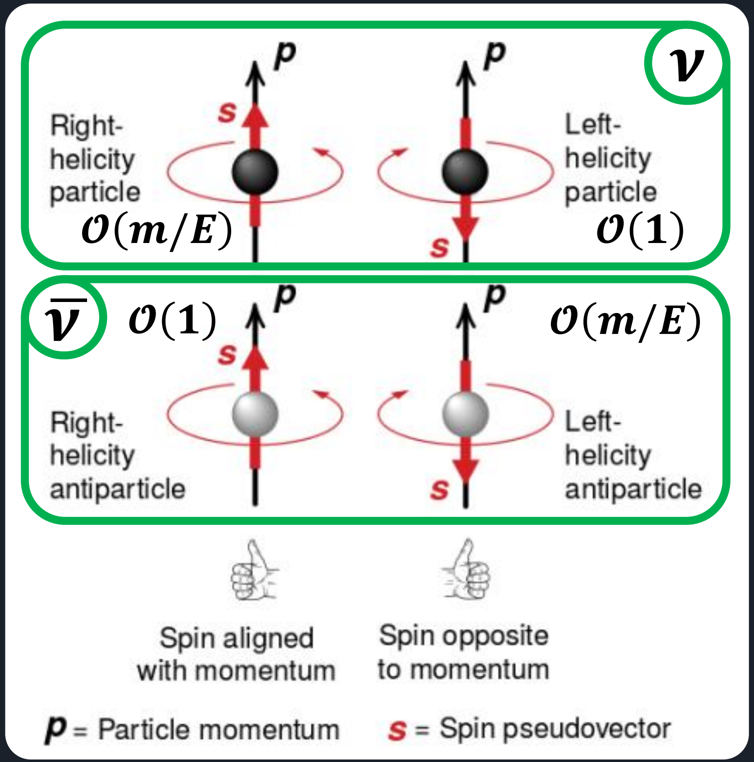
Standard Model of Elementary Particles





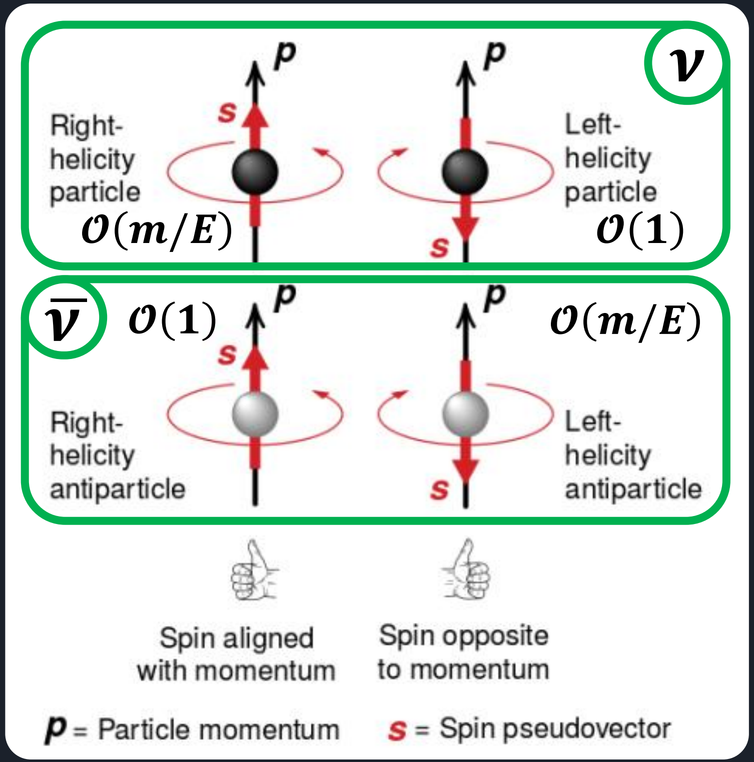
<2.2 eV/c²
0
½
νe
electron neutrino
<0.17 MeV/c²
0
½
νμ
muon neutrino
<18.2 MeV/c²
0
½
ντ
tau neutrino
WHY IS THEIR MASS SO SMALL?
Standard Model of Elementary Particles
three generations of matter (fermions)
interactions / force carriers (bosons)
I
II
III
≃2.2 MeV/c²
⅔
½
u
up
≃1.28 GeV/c²
⅔
½
c
charm
≃173.1 GeV/c²
⅔
½
t
top
0
0
1
g
gluon
≃124.97 GeV/c²
0
0
H
higgs
≃4.7 MeV/c²
−⅓
½
d
down
≃96 MeV/c²
−⅓
½
s
strange
≃4.18 GeV/c²
−⅓
½
b
bottom
0
0
1
γ
photon
≃0.511 MeV/c²
−1
½
e
electron
≃105.66 MeV/c²
−1
½
μ
muon
≃1.7768 GeV/c²
−1
½
τ
tau
≃91.19 GeV/c²
0
1
Z
Z boson
<2.2 eV/c²
0
½
νe
electron neutrino
<0.17 MeV/c²
0
½
νμ
muon neutrino
<18.2 MeV/c²
0
½
ντ
tau neutrino
≃80.360 GeV/c²
±1
1
W
W boson
QUARKS
LEPTONS
GAUGE BOSONS
VECTOR BOSONS
SCALAR BOSONS

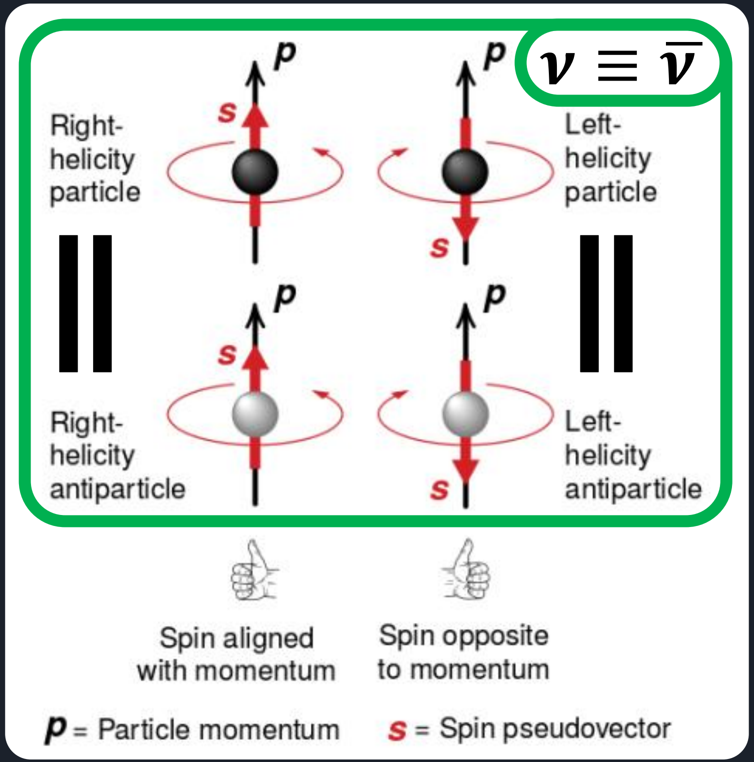
Majorana Particles ?



Dirac: ν are massive
helicity $\neq$ chirality
4 possible states

Majorana Particles ?





Dirac: ν are massive
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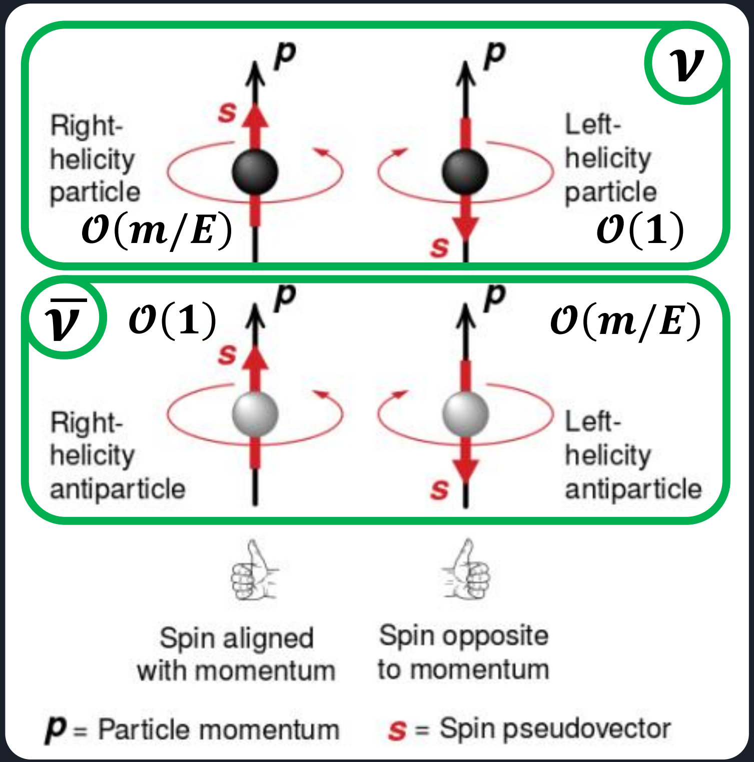
Majorana: $\nu = \nu_L + \nu_L^C = \nu^C$
ν and $\bar{\nu}$ are different helicity states of the same particle

Majorana Particles ?



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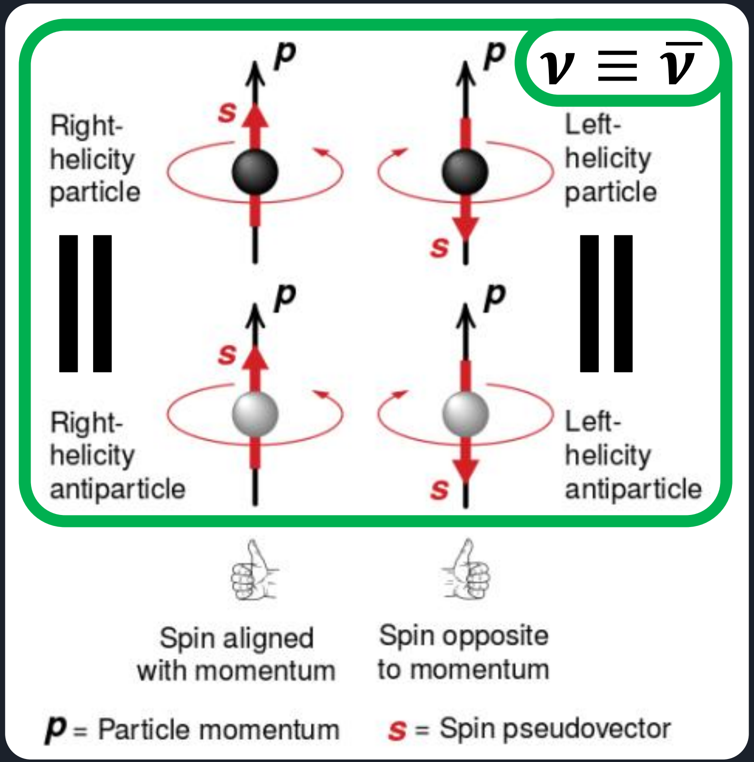
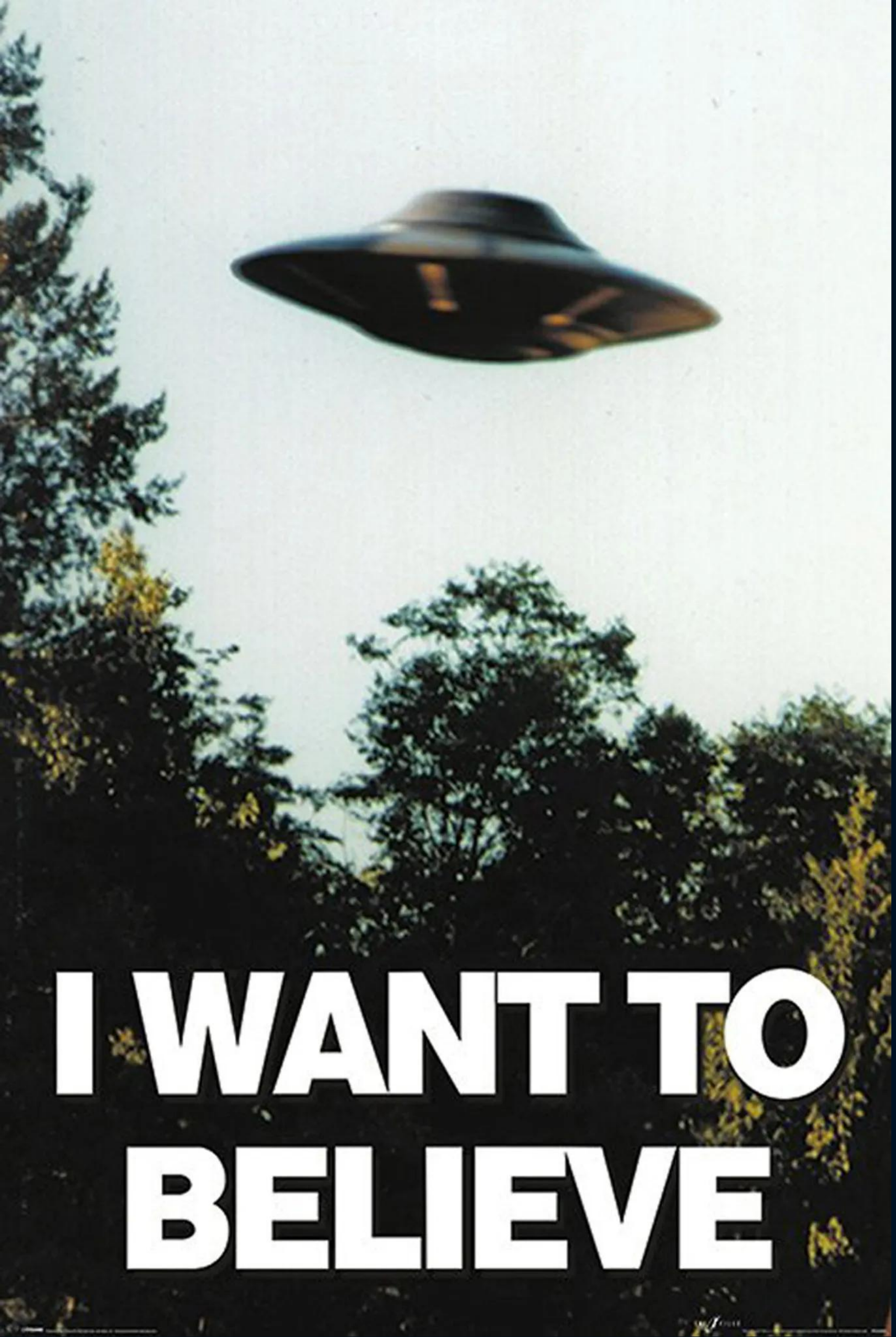


Majorana: $\nu = \nu_L + \nu_L^C = \nu^C$
ν and $\bar{\nu}$ are different helicity states of the same particle

IF TRUE, IT IS THEN POSSIBLE TO EXPLAIN THEIR SMALL MASS VALUE



BUT HOW TO PROVE IT ?

Double Beta Decay

You can imagine it as two beta decays happening simultaneously

$$(A, Z) \rightarrow (A, Z+1) + e^- + \bar{\nu}$$
$$(A, Z+1) \rightarrow (A, Z+2) + e^- + \bar{\nu}$$

… with neutrinos (Standard Model allowed)

2nd order weak transition

$T_{1/2}^{2\nu\beta\beta} \sim 10^{18-21}$ yr

Double Beta Decay

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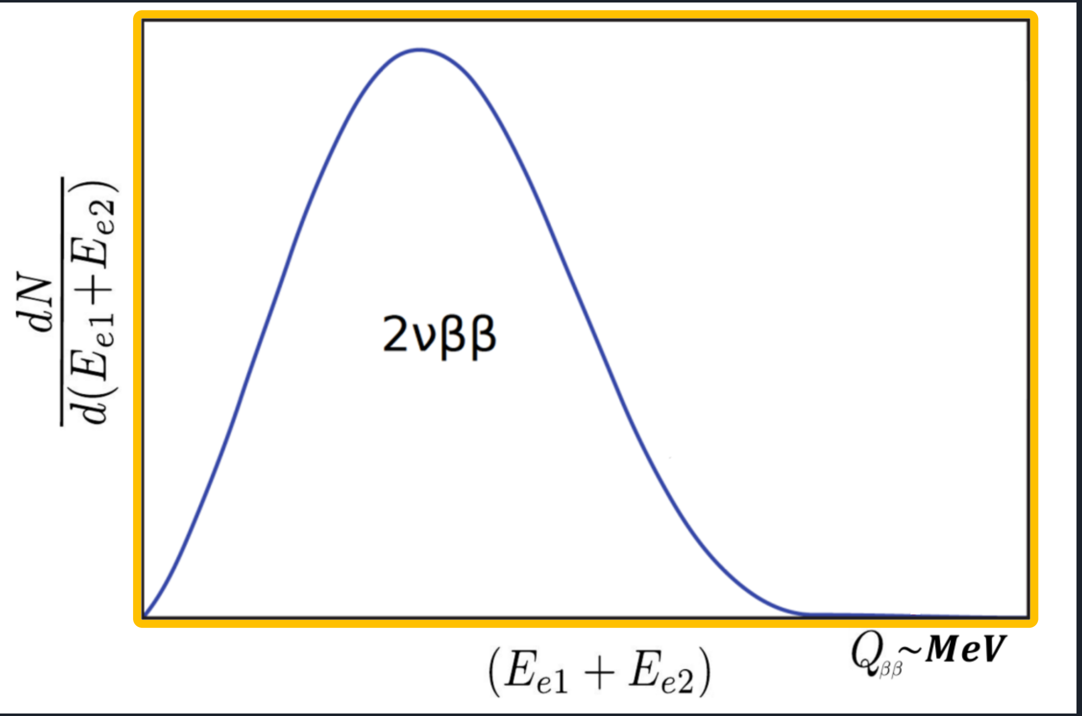

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2nd order weak transition

$T_{1/2}^{2\nu\beta\beta} \sim 10^{18-21}$ yr

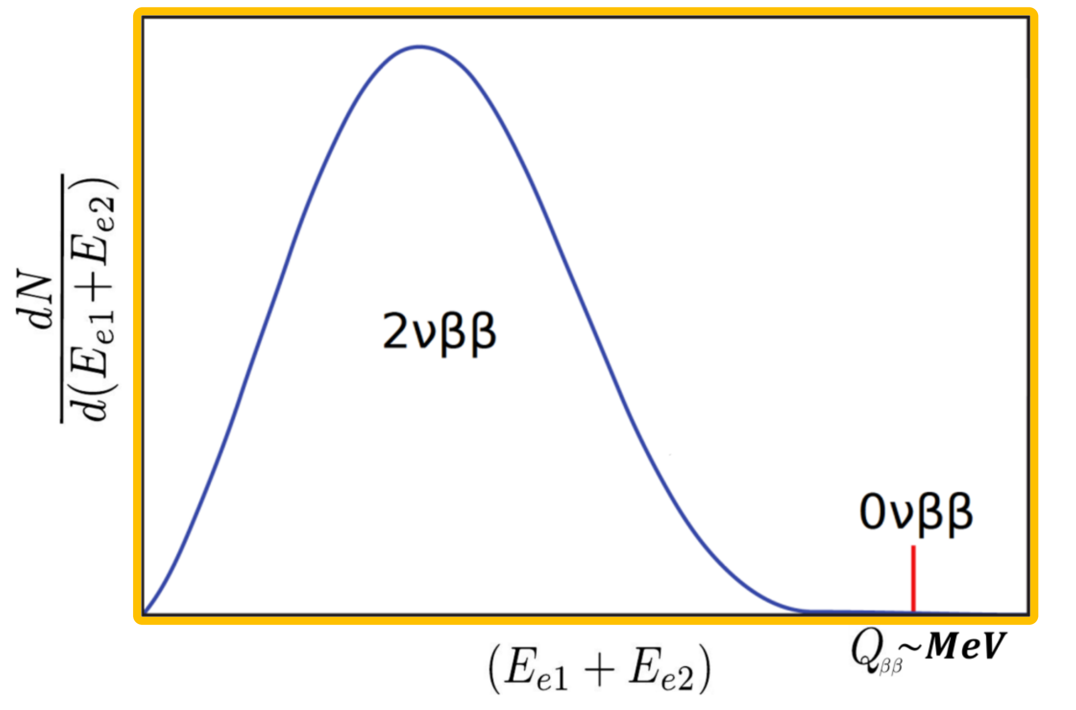
Double Beta Decay

You can imagine it as two beta decays happening simultaneously

WHY THIS PROCESS?

- Nuclear decay
- Easy to Scale
- Signature

$$(A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}$$
$$(A,Z+1) \rightarrow (A,Z+2) + e^- + \bar{\nu}$$



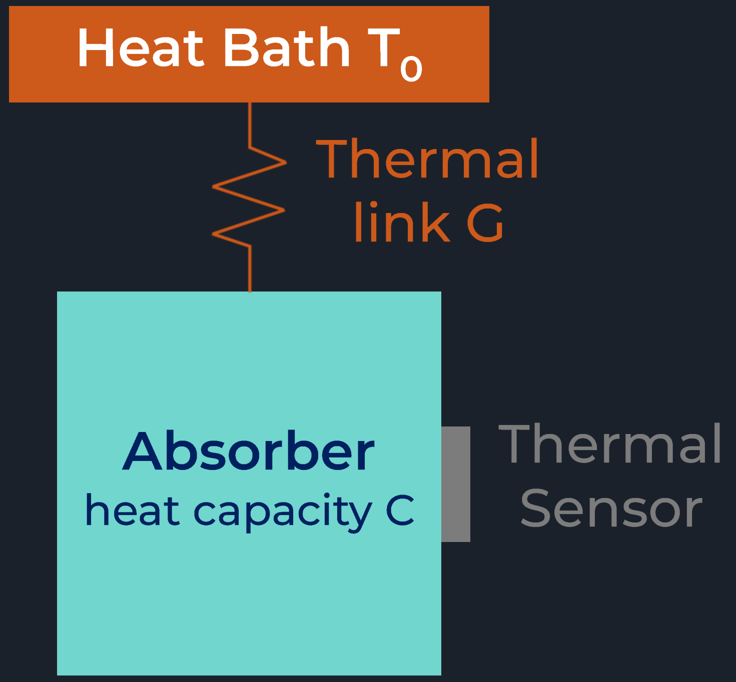
… with neutrinos (Standard Model allowed)
2nd order weak transition
$T_{1/2}^{2\nu\beta\beta} \sim 10^{18-21}$ yr

… without neutrinos (Hypothetical process)
will prove their Majorana Nature
$T_{1/2}^{0\nu\beta\beta} > 10^{24-27}$ yr

HOW CAN WE IMPROVE OUR CHANCES ?

$$T_{1/2}^{0\nu\beta\beta} \propto \sqrt{\frac{M}{\Delta E}}$$

Bolometers

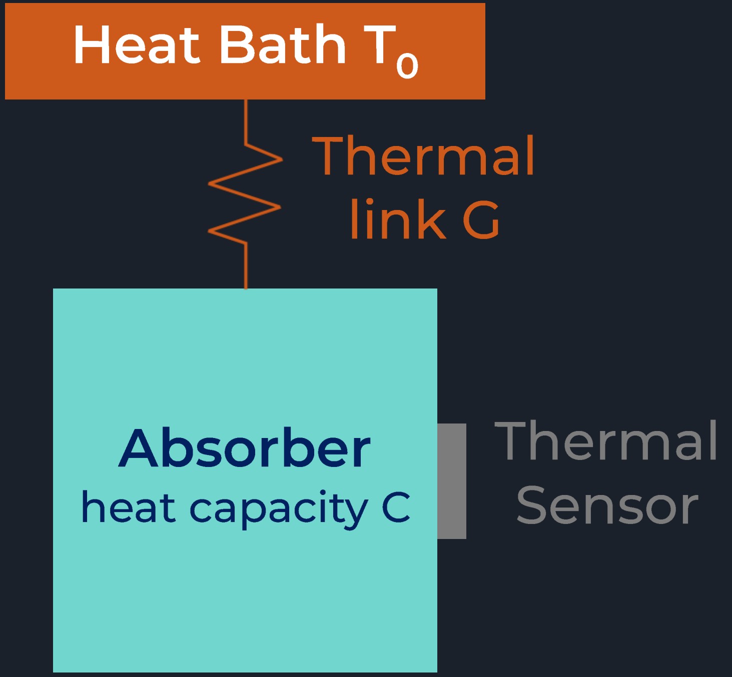


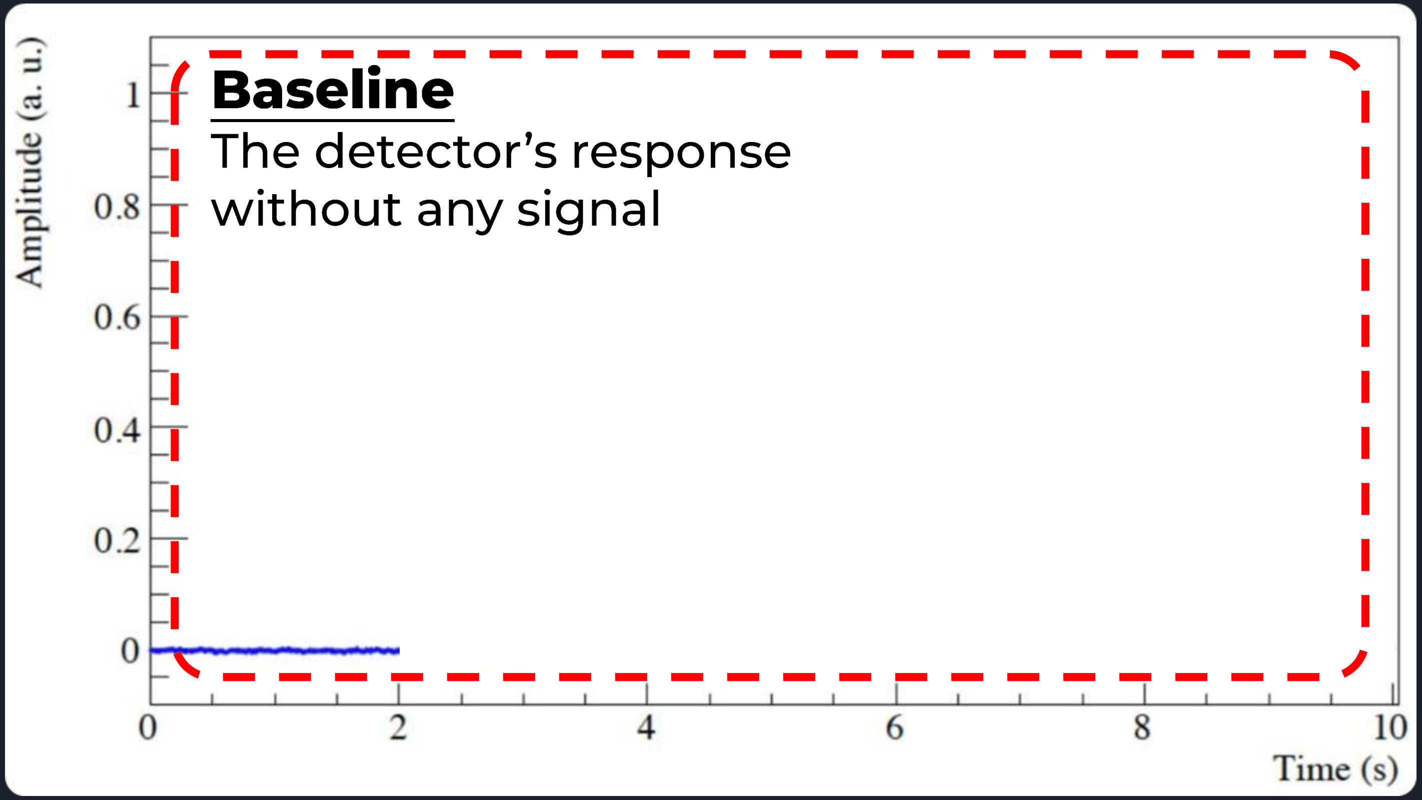
An extremely sensitive thermometer that measures relative variations of temperature

DETECTOR = SOURCE

- Dynamic range from ~ 10keV up to ~ 10MeV
- At T << 10K, the response is temperature-dependent

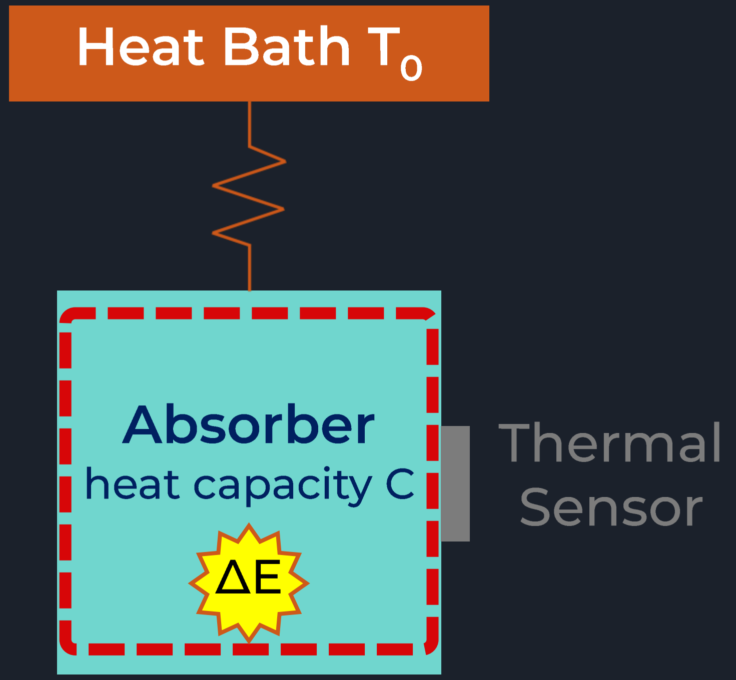
Signal Formation

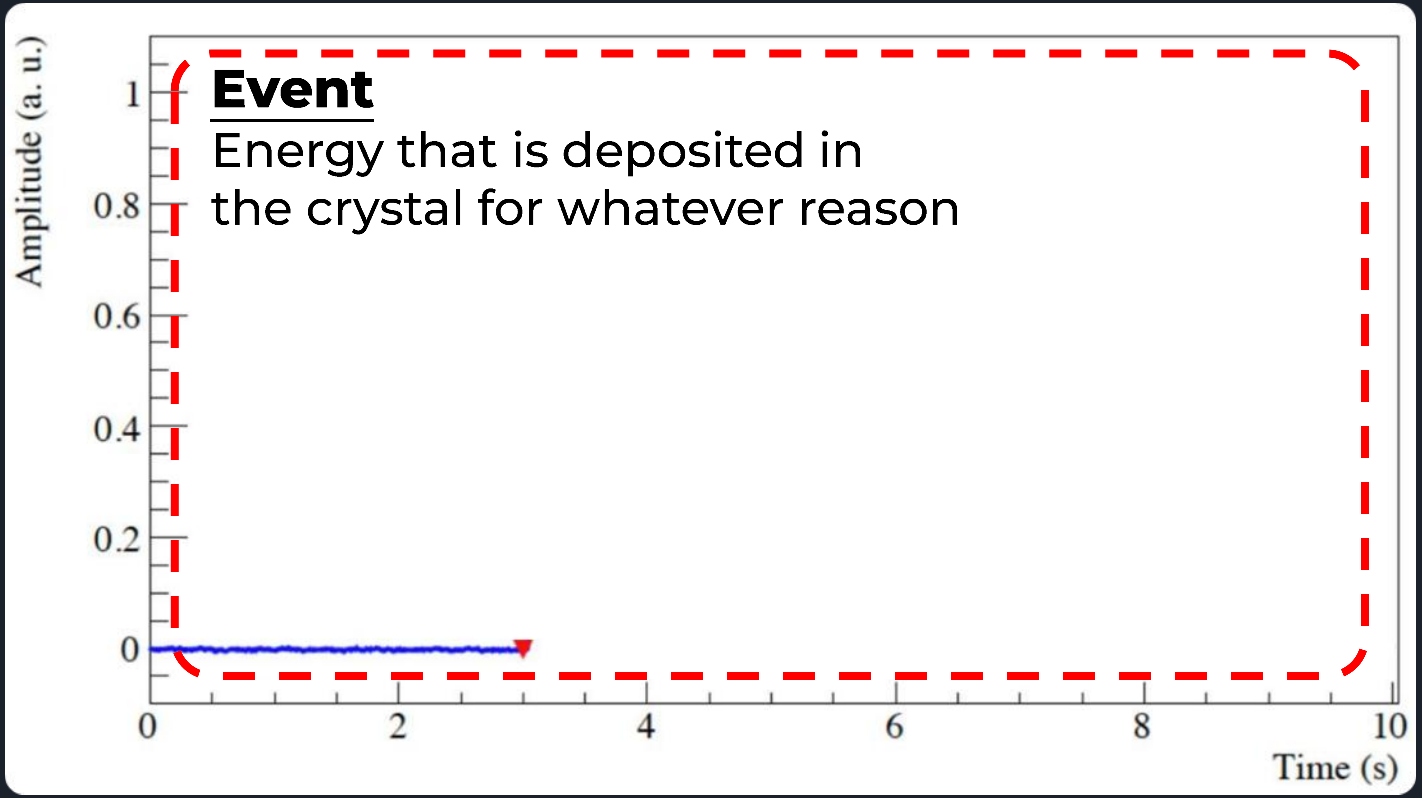




$$T = T_0$$

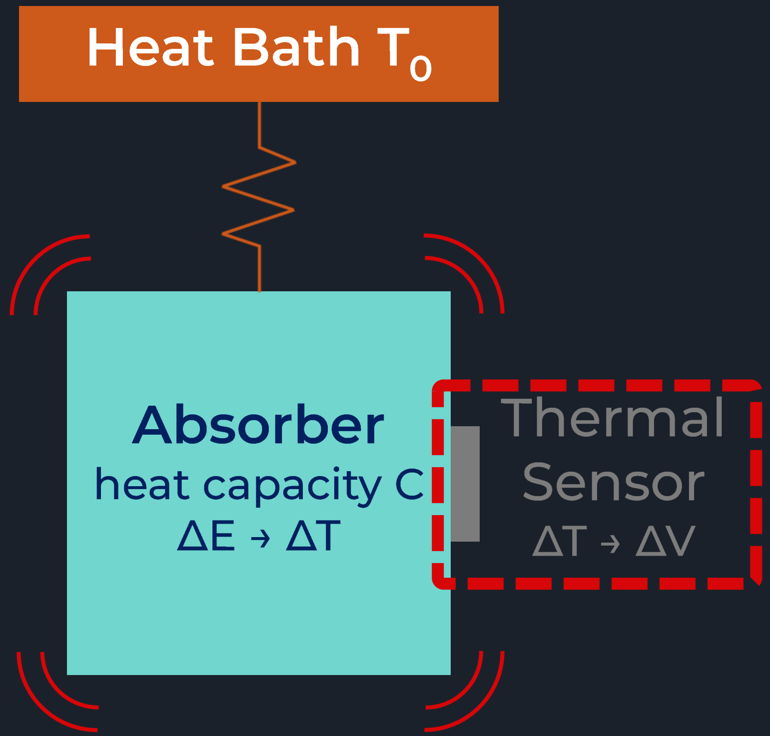
Signal Formation



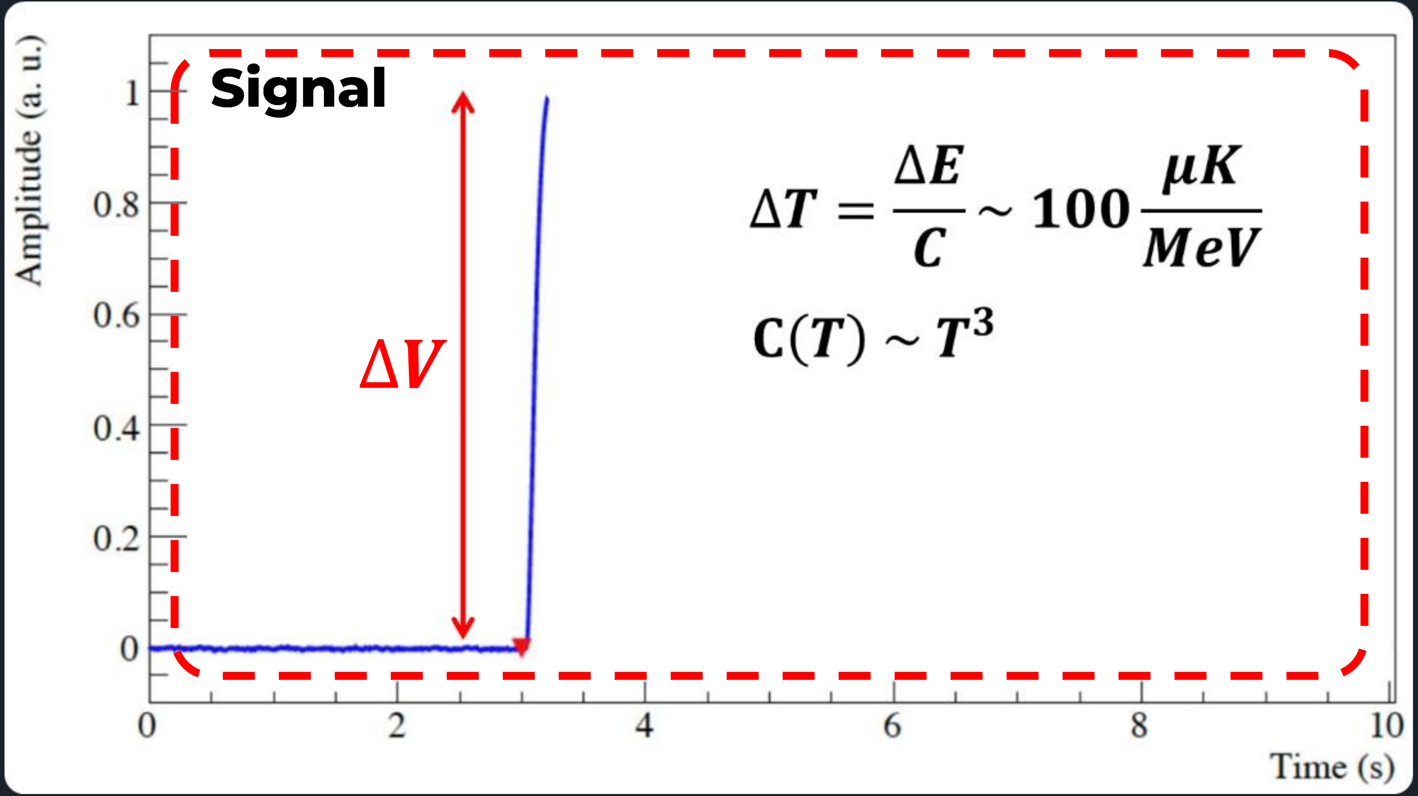


$T = T_0$

Signal Formation



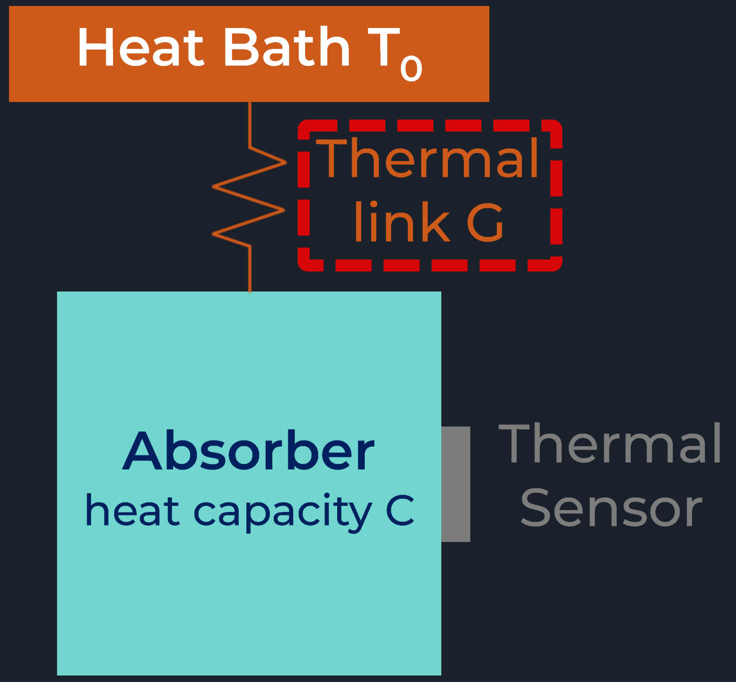
$T = T_0 + \Delta T$



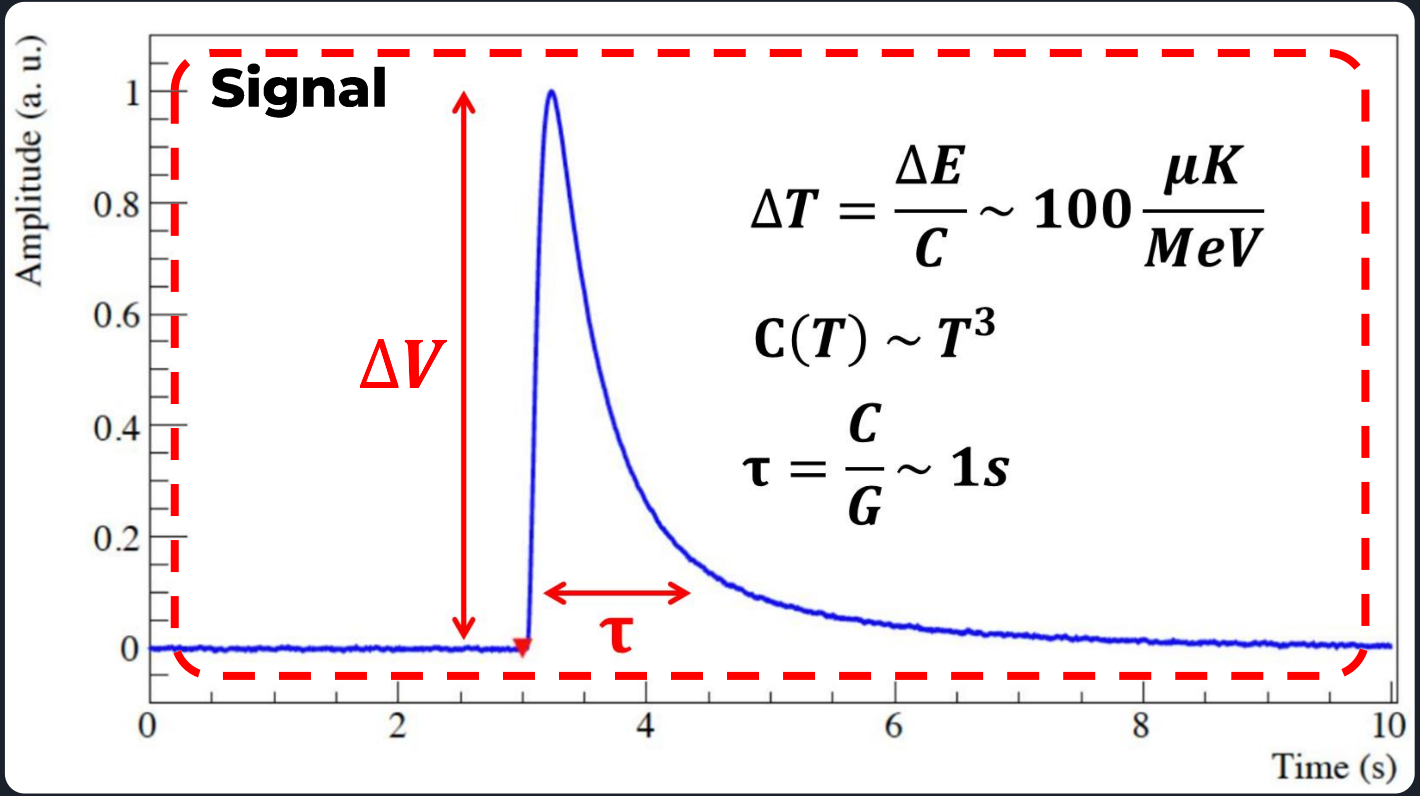
$$\Delta T = \frac{\Delta E}{C} \sim 100 \frac{\mu K}{MeV}$$

$$C(T) \sim T^3$$

Signal Formation



$T = T_0$



Slow pulses require a small rate of events

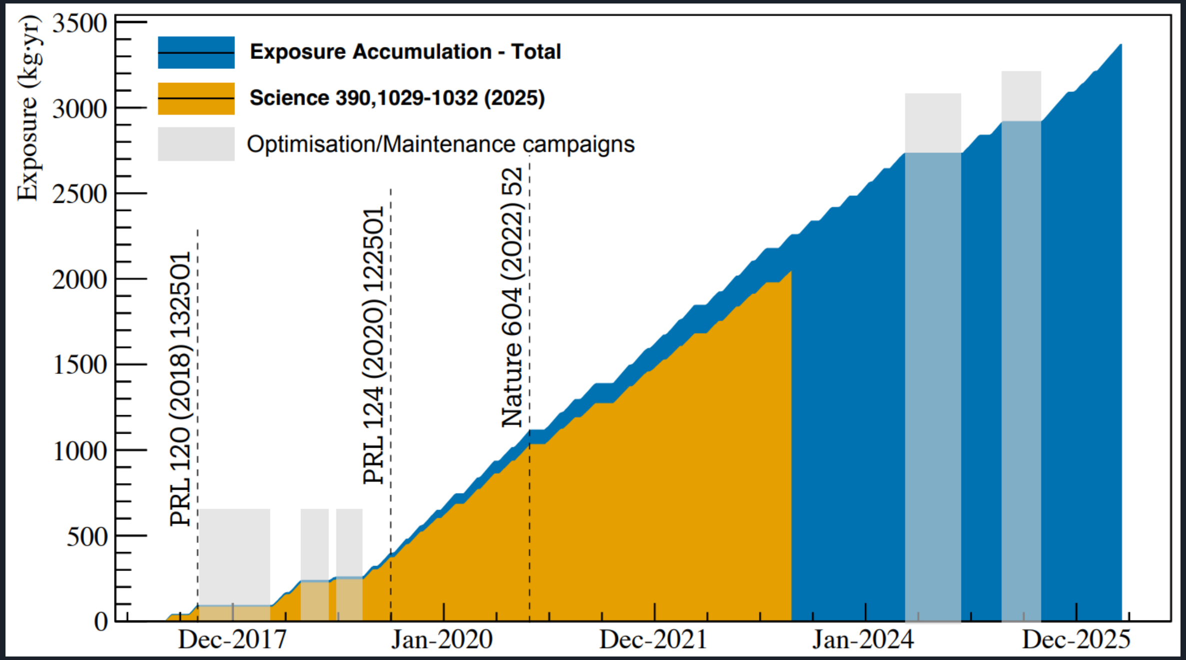
$0\nu\beta\beta$ with

CUORE CUPID

CUORE

^{130}Te
34% (i.a.)
2517.5keV ($Q_{\beta\beta}$)

$0\nu\beta\beta$ campaign concluded on June 9, 2026



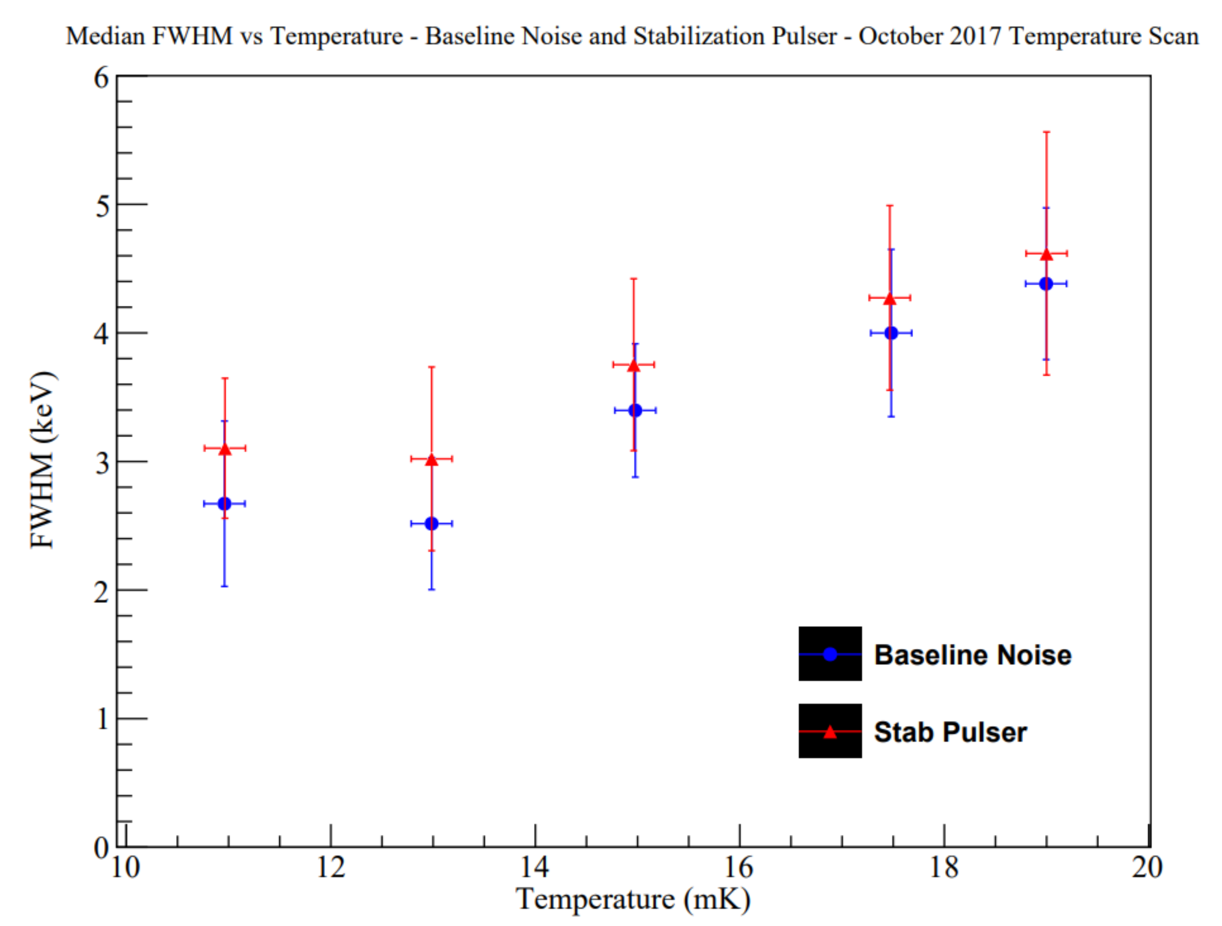
~1000 TeO_2
5x5x5 cm^3
crystals
750g each
(208g ^{130}Te)

CURRENTLY ONGOING:
- Technical measurements are currently ongoing
- $0\nu\beta\beta$ data processing and analysis

Cryogenic **U**nderground **O**bservatory for **R**are **E**vents

Sensor’s response

A set of measurements to investigate the achievable energy resolutions at different temperatures.
Comparison with data taken at the start of CUORE (9 years ago)

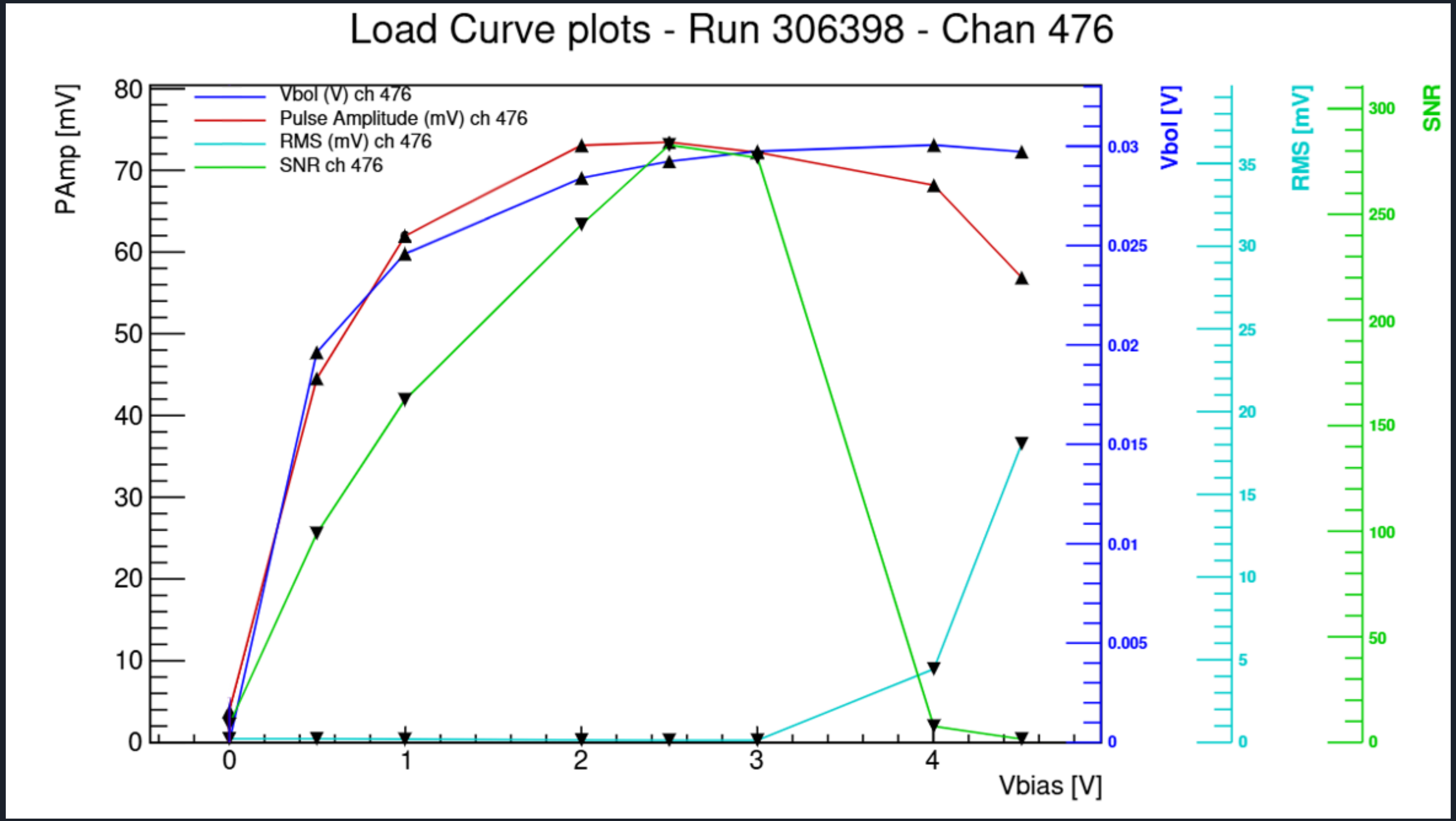


Sensor's response

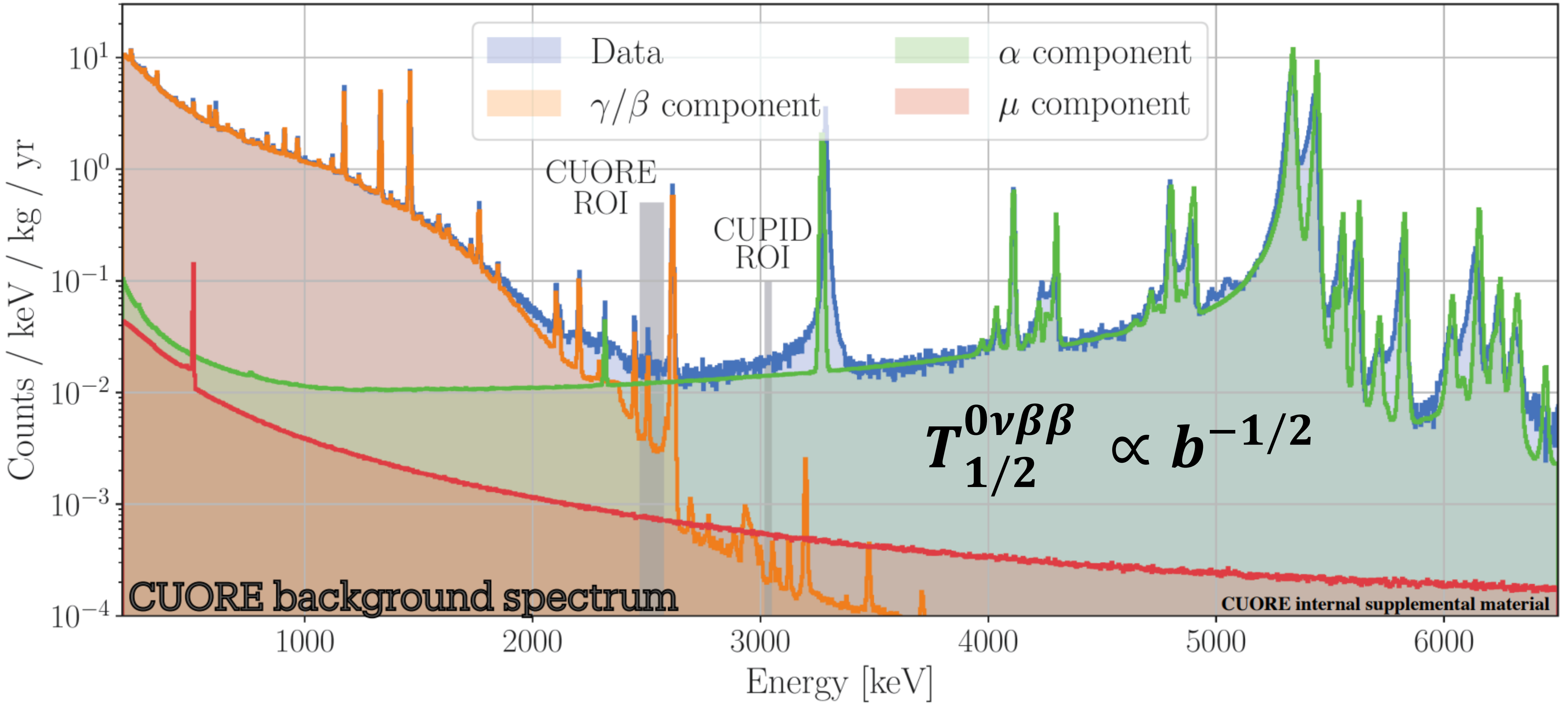
Procedure

1. Set the working temperature
2. Optimise the working points: (Maximise Signal/Noise + Minimise the RMS)
3. Calibrate the detectors

ONGOING



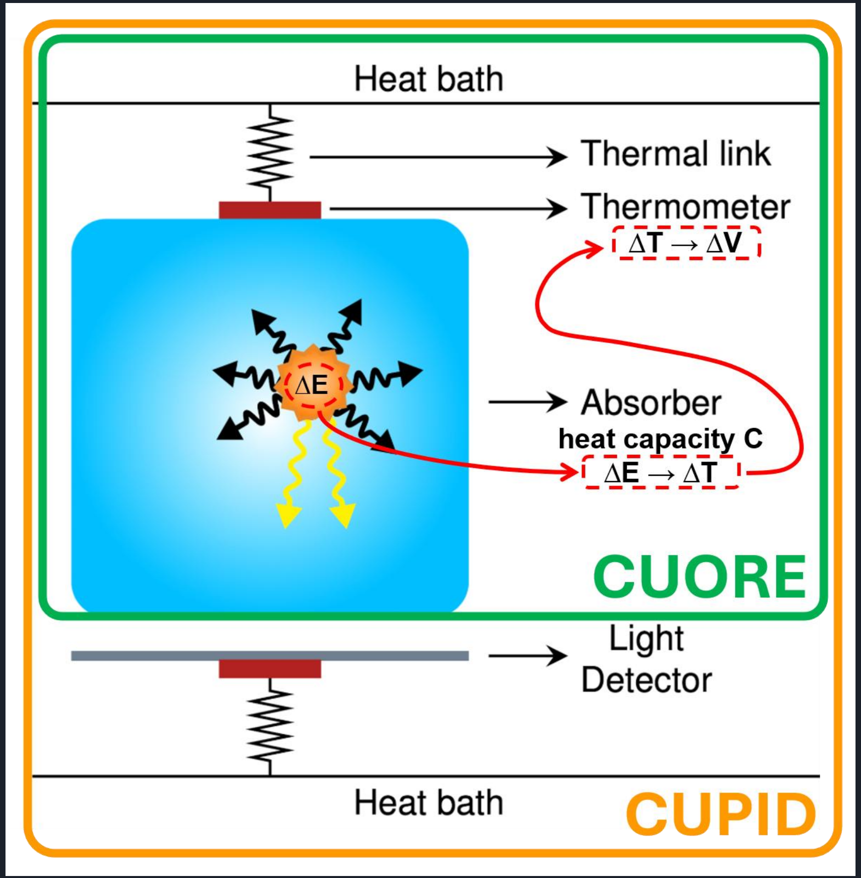
Background Limited

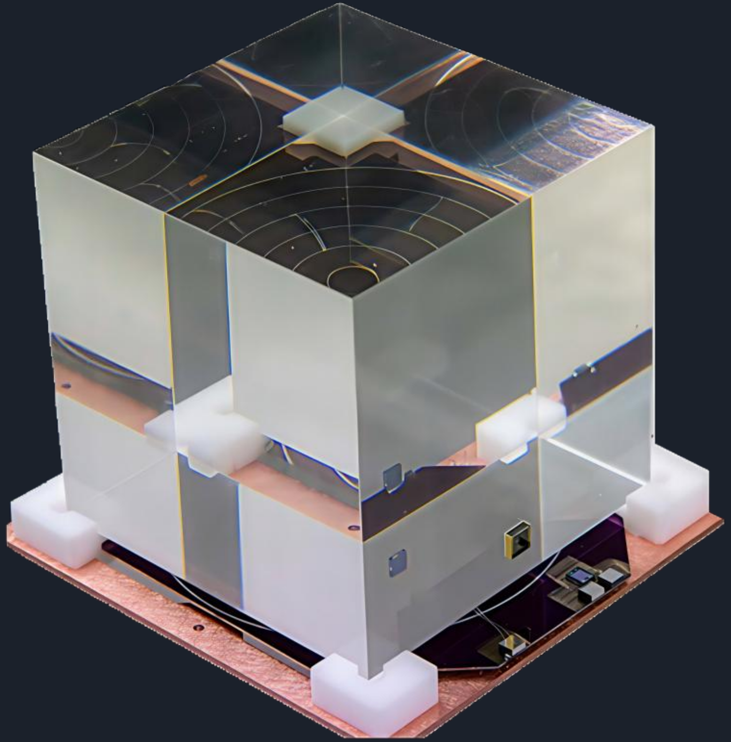


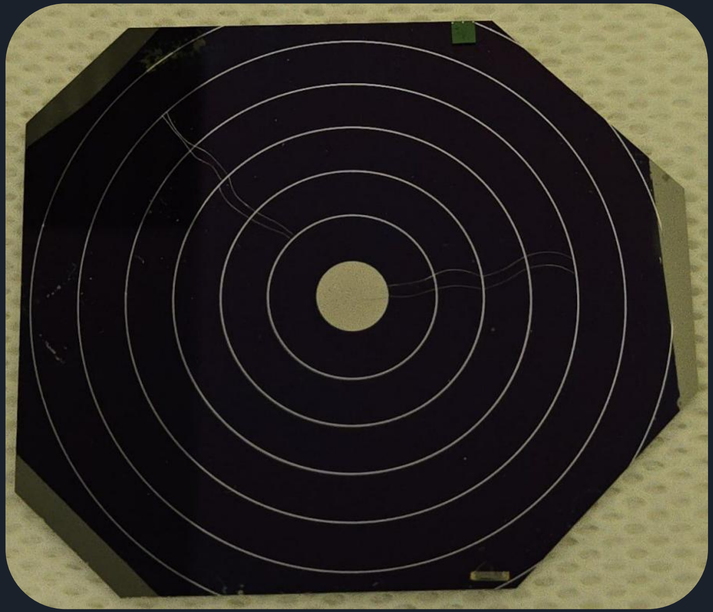
$$T_{1/2}^{0\nu\beta\beta} \propto b^{-1/2}$$

CUPID

DOUBLE READOUT TECHNIQUE





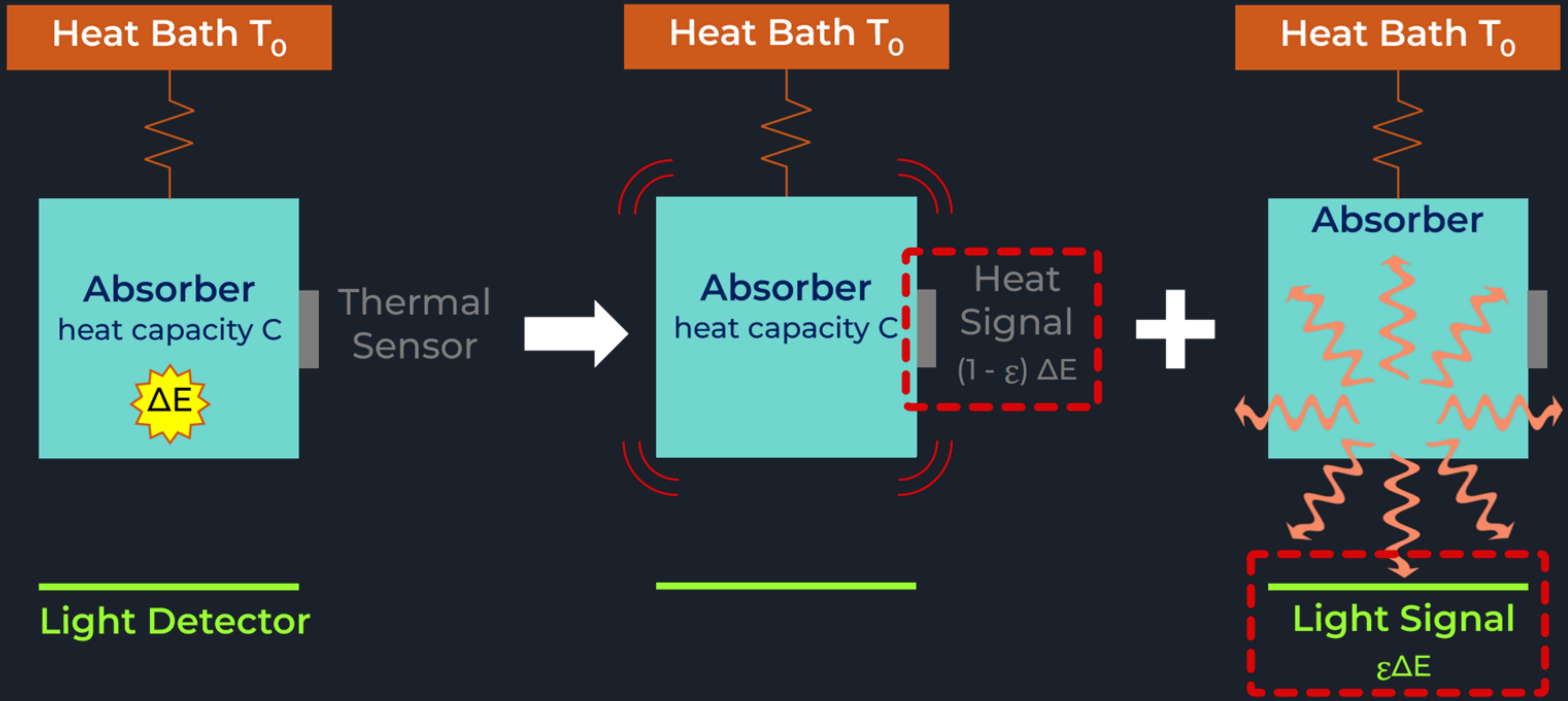


HEAT (LMO) ~1600 Li_2MoO_4 45x45x45 mm^3 crystals
280g each (149g ^{100}Mo)

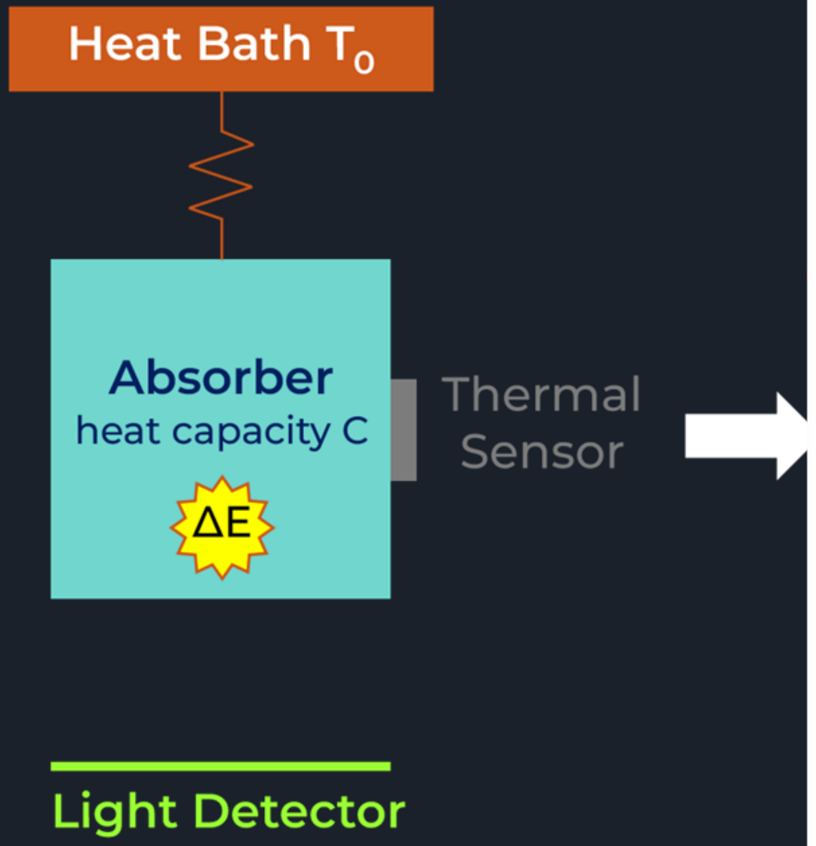
LIGHT (LD) ~1700 Ge-wafers 0.5mm-thick

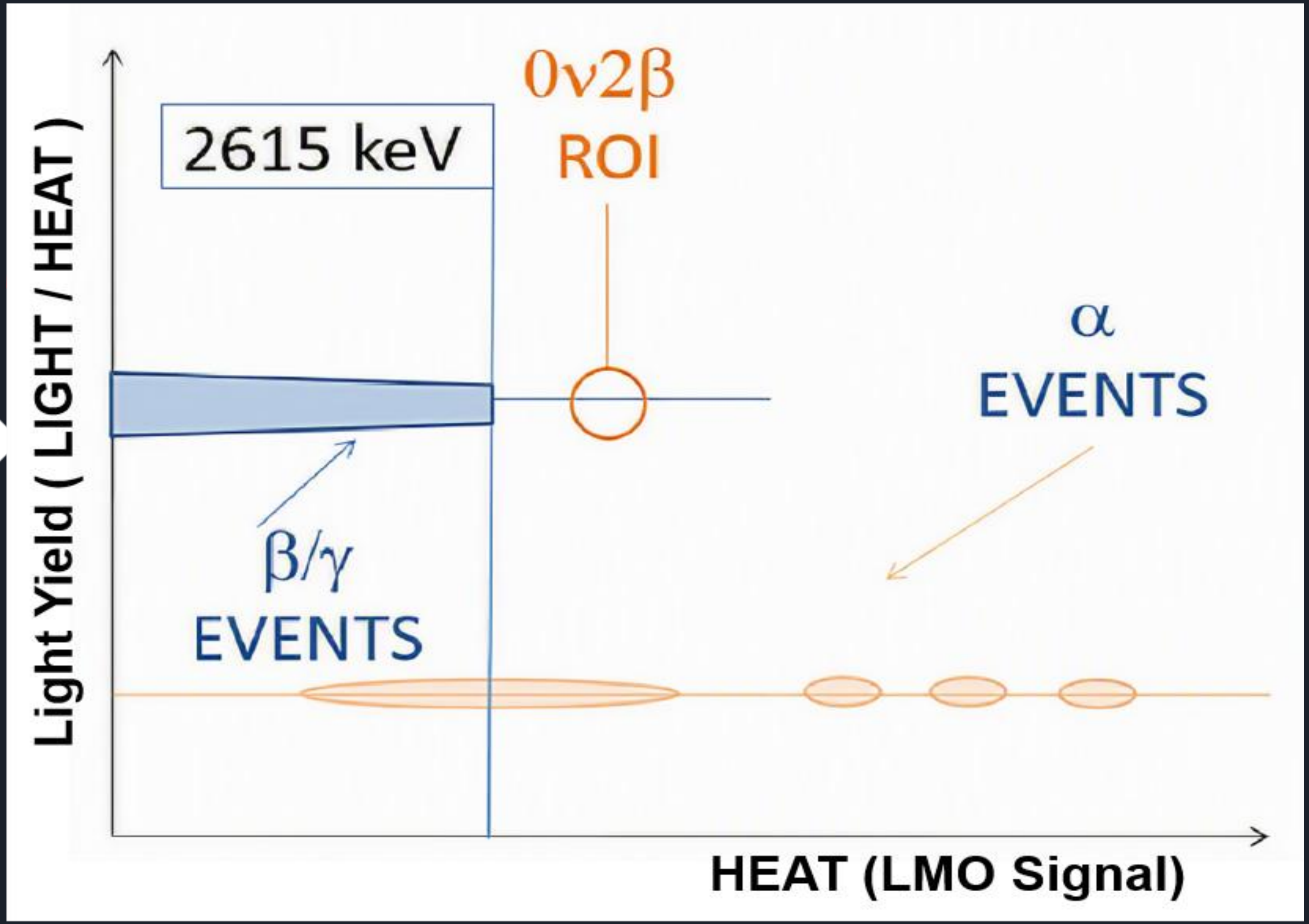
CUORE **U**pgraded with **P**article **ID**entification

CUPID-like event



CUPID-like event





Background Constraints

CUORE
Infrastructure
Background Model

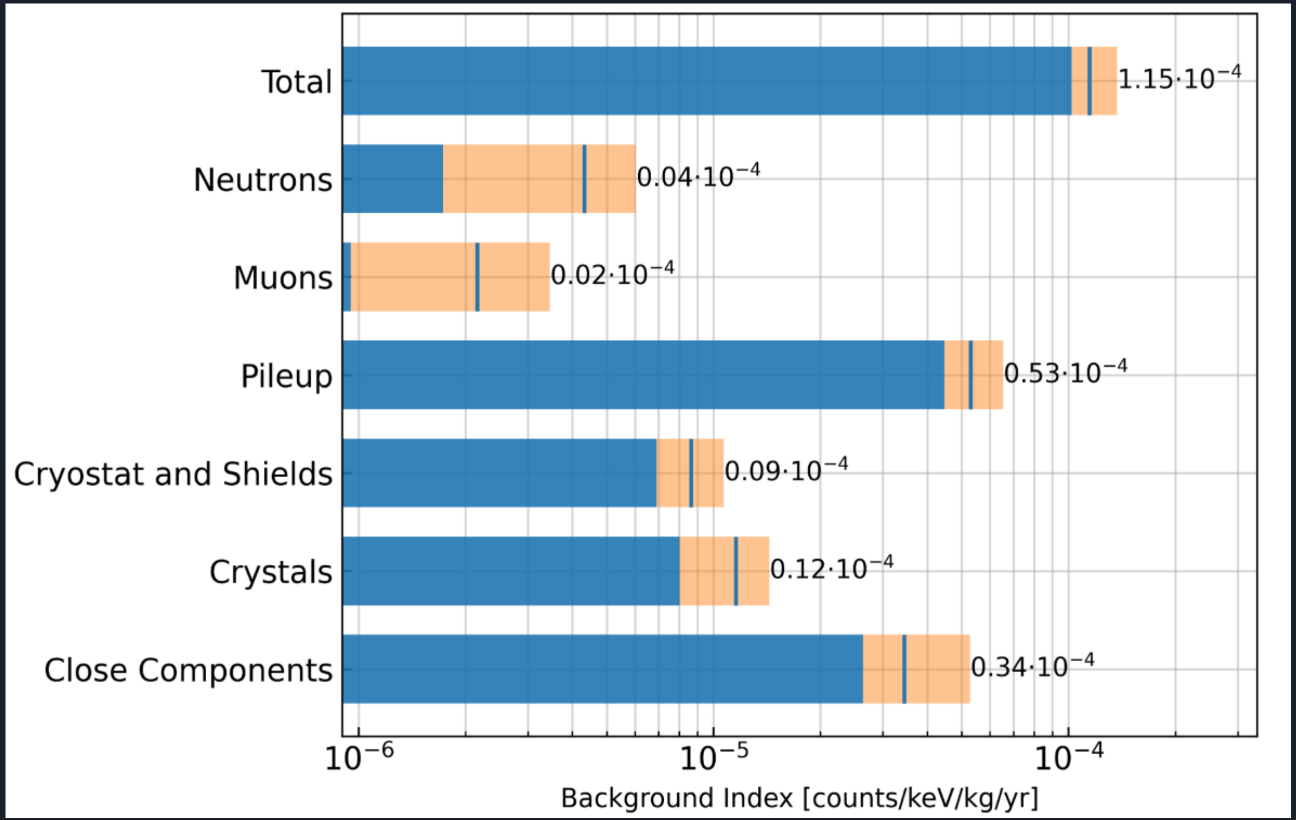
+

CUPID-0
Scintillation Bolometers

+

CUPID-Mo
LMO Crystals
Background Model

CUPID MC-Simulation



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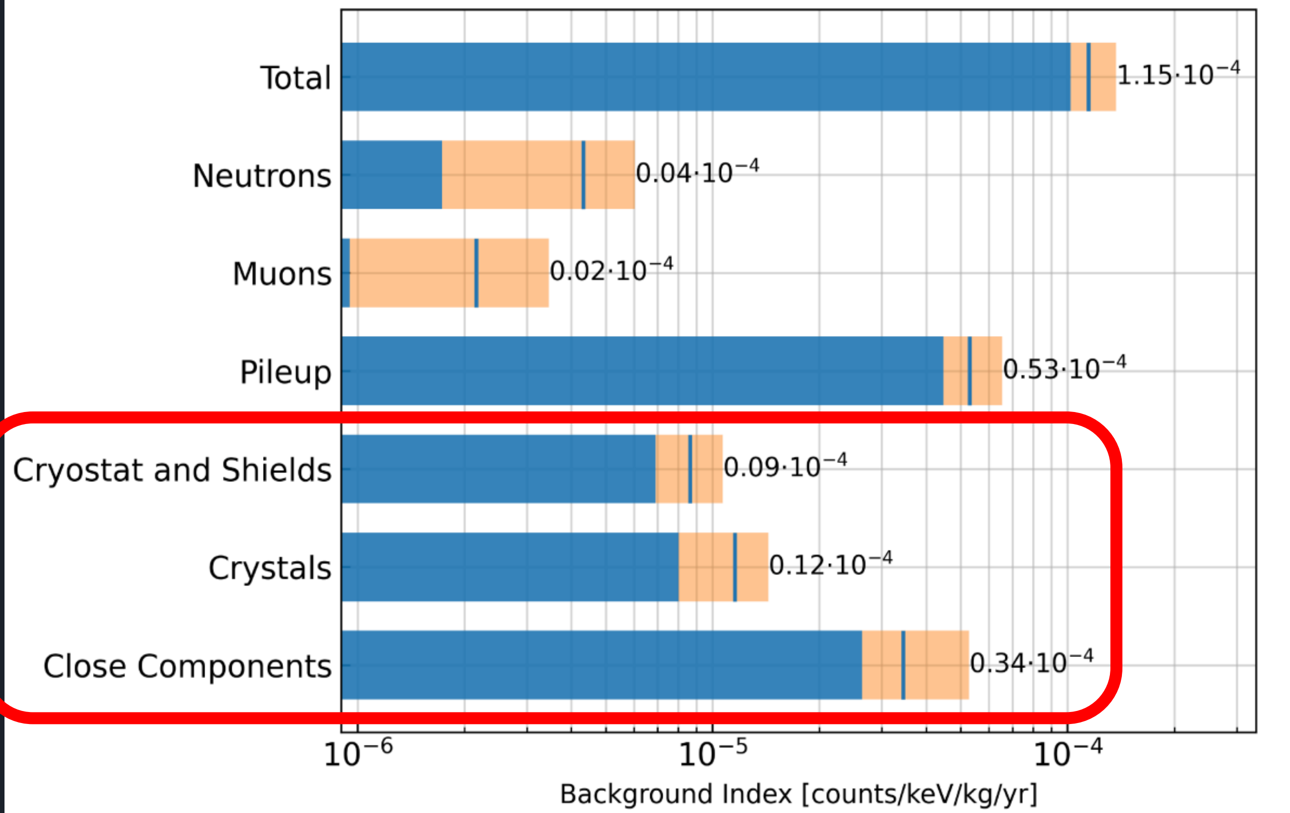

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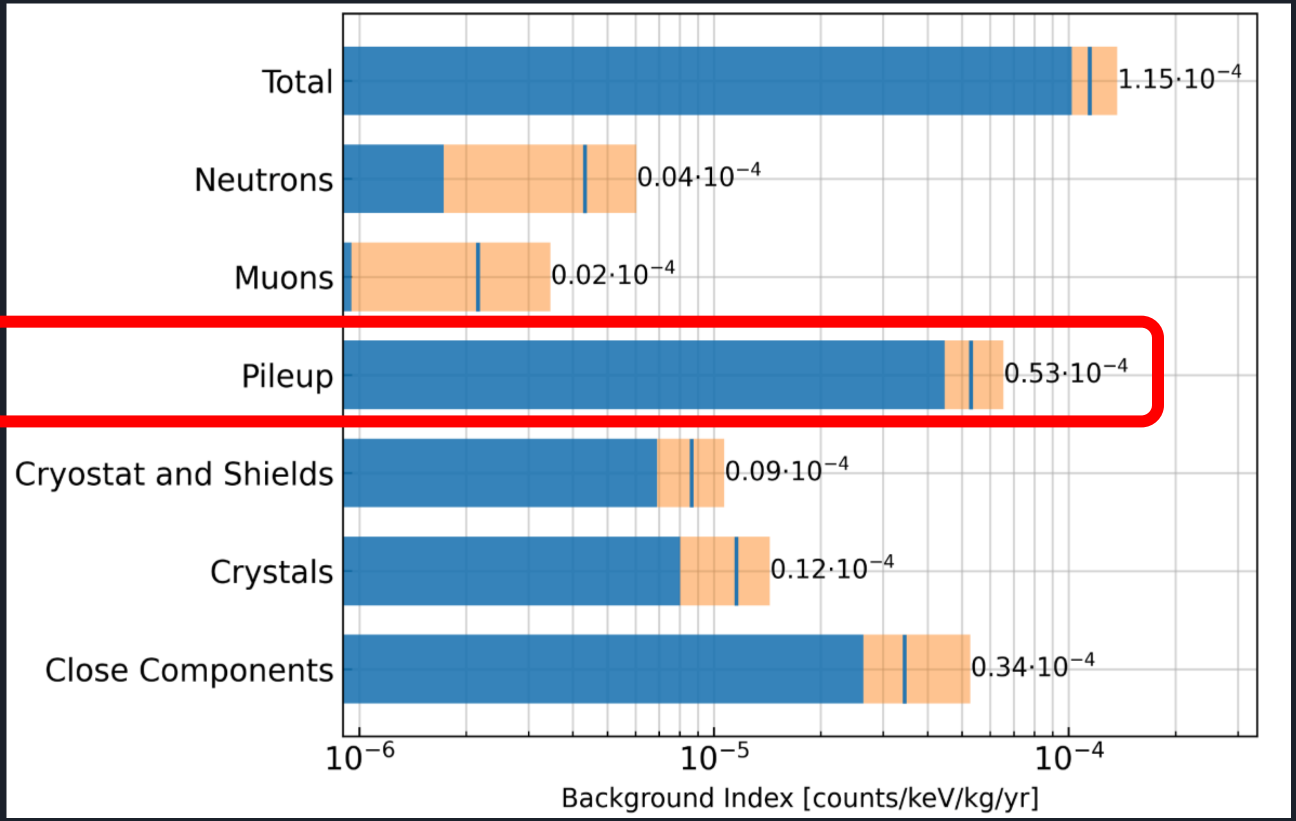
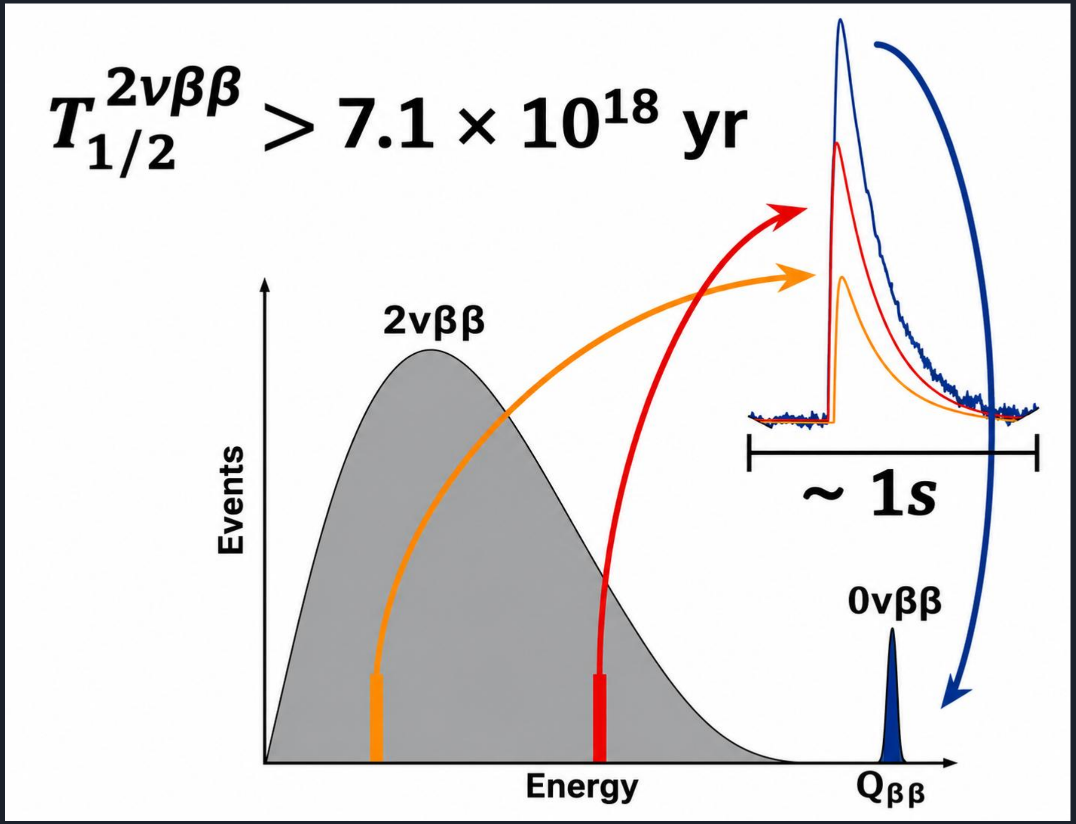
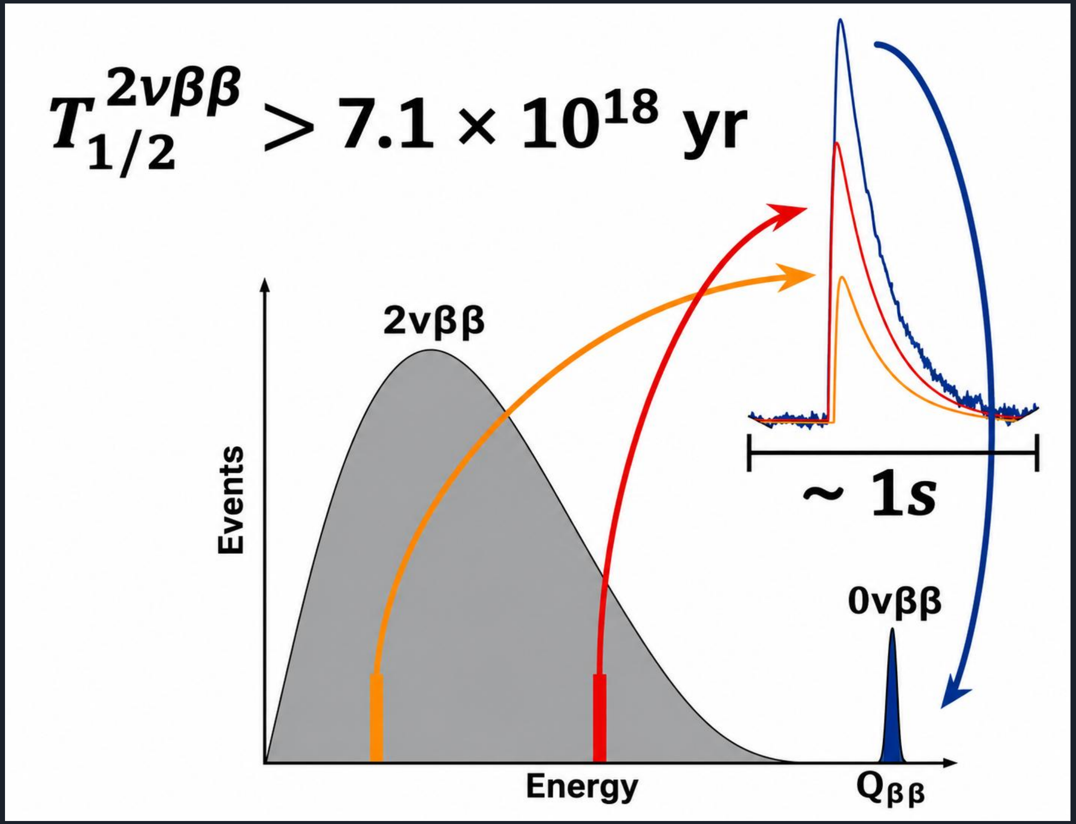


Pile-up Background



From two unresolved $2\nu\beta\beta$ events (4 electrons)

Pile-up Background

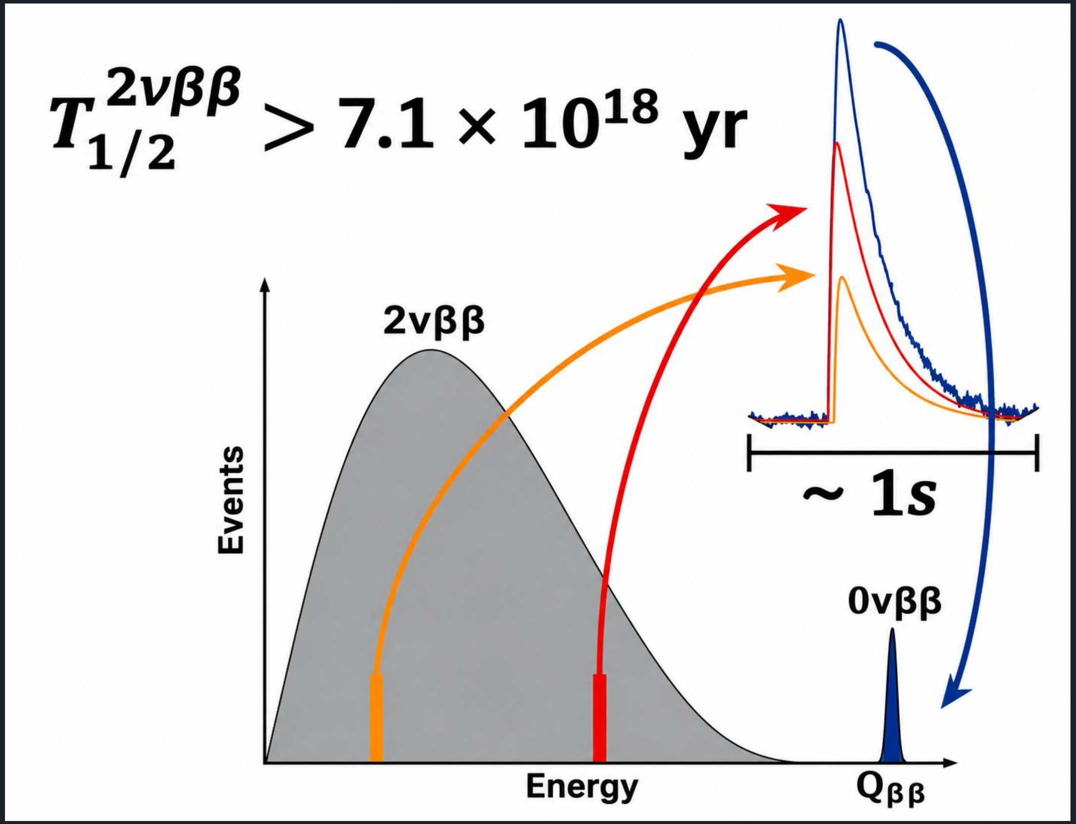


From two unresolved $2\nu\beta\beta$ events (4 electrons)

LD CONSTRAINTS

Rise Time < 500us
Signal-to-Noise Ratio > 140
Baseline Resolution < 100eV
Timing Resolution < 170us

Pile-up Background



From two unresolved $2\nu\beta\beta$ events (4 electrons)

LD CONSTRAINTS

Rise Time < 500us
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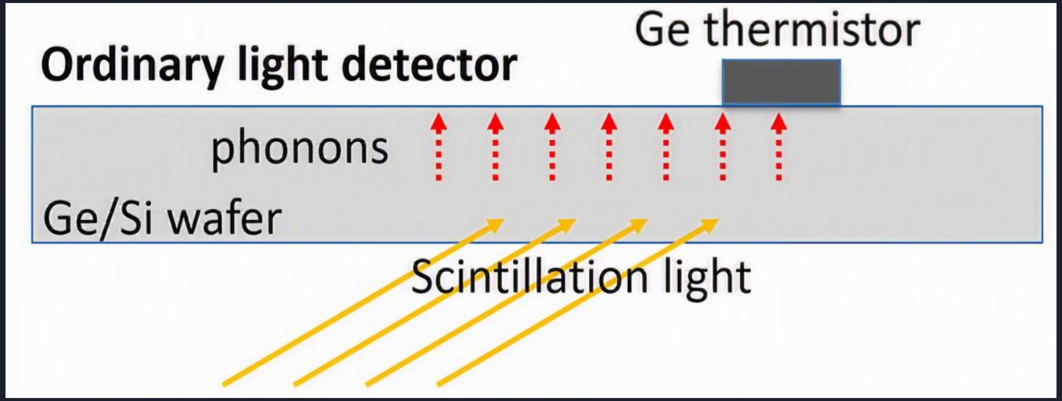
REJECTION ALGORITHM

Offline pulse-shape filtering,
BUT it requires detectors with known signal response and stationary noise

LD



LD Signal

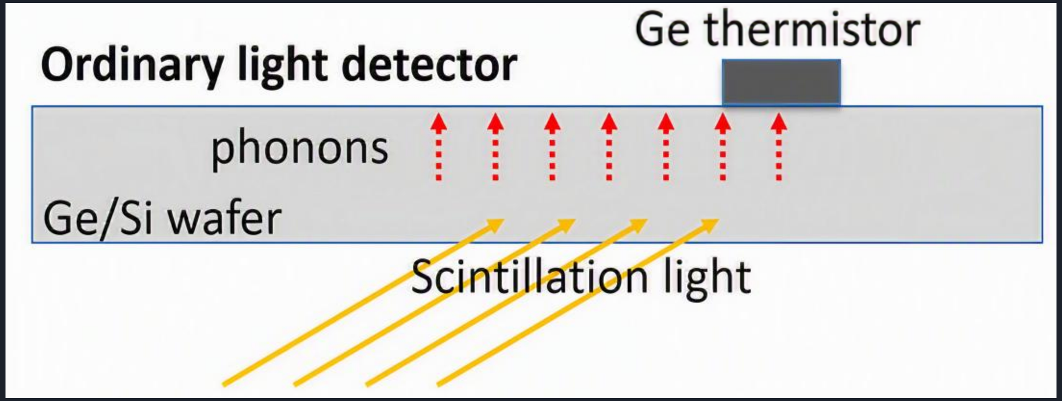
$$\boxed{E_{tot}} = E_0$$

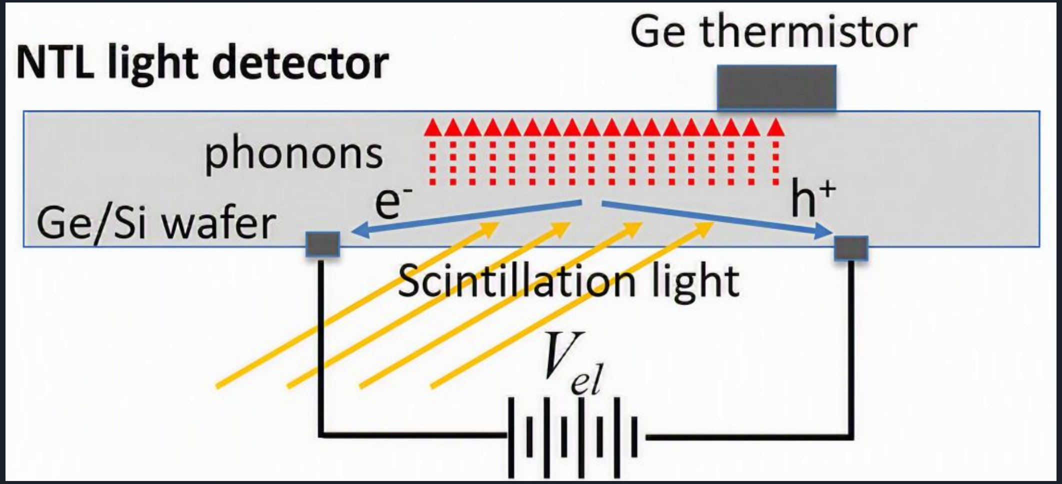
Luke-assisted LD

Electron-hole pairs created by light absorption are drifted by applying a voltage, thus producing additional heat.

$$E_{tot} = E_0 \left(1 + \eta \frac{e \cdot V_{el}}{\varepsilon}\right)$$

LD Signal
Efficiency
NTL Gain





Luke-assisted LD

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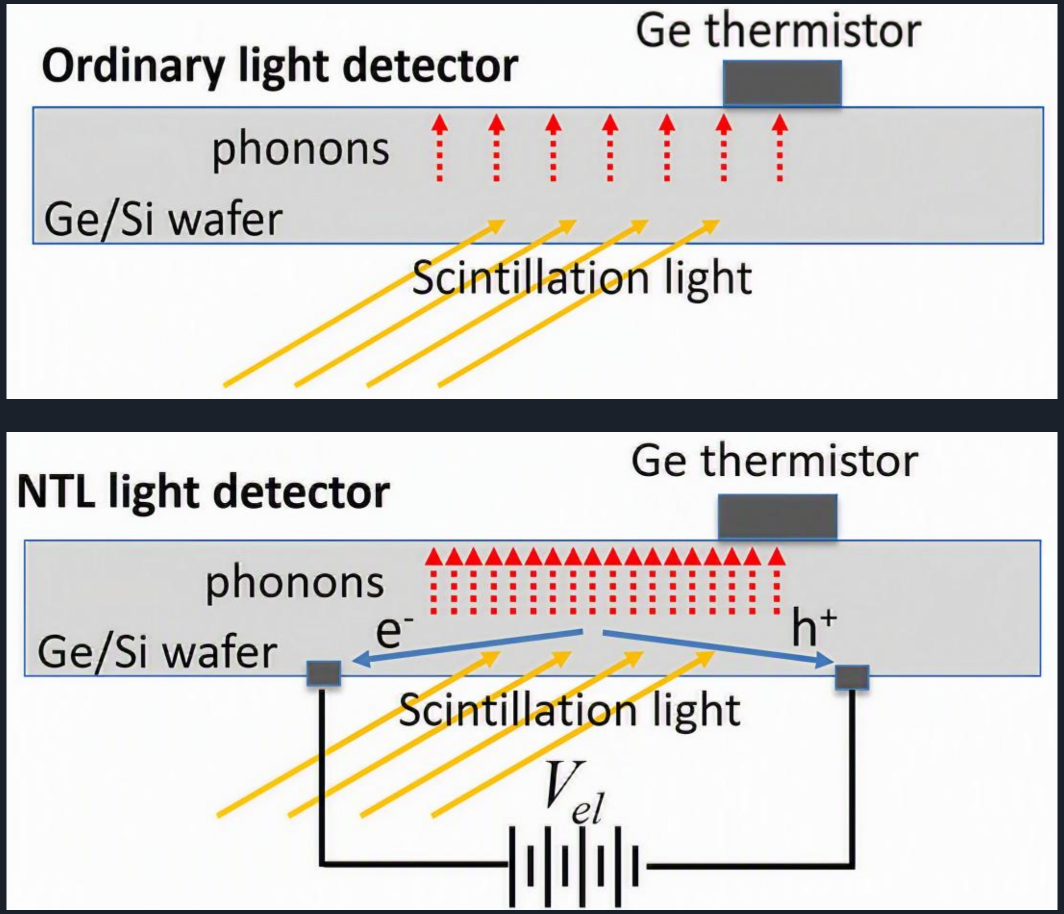
$$E_{tot} = E_0 \left(1 + \eta \frac{e \cdot V_{el}}{\varepsilon}\right)$$

LD Signal
Efficiency
NTL Gain

GAIN LOSS OVER TIME

Charge accumulation over time worsens the effective gain, requiring then the regeneration of the wafers.



VSTT (Jul ‘25 – Aug ‘26)

CUPID single-tower setup deployed at *Gran Sasso National Laboratory:*

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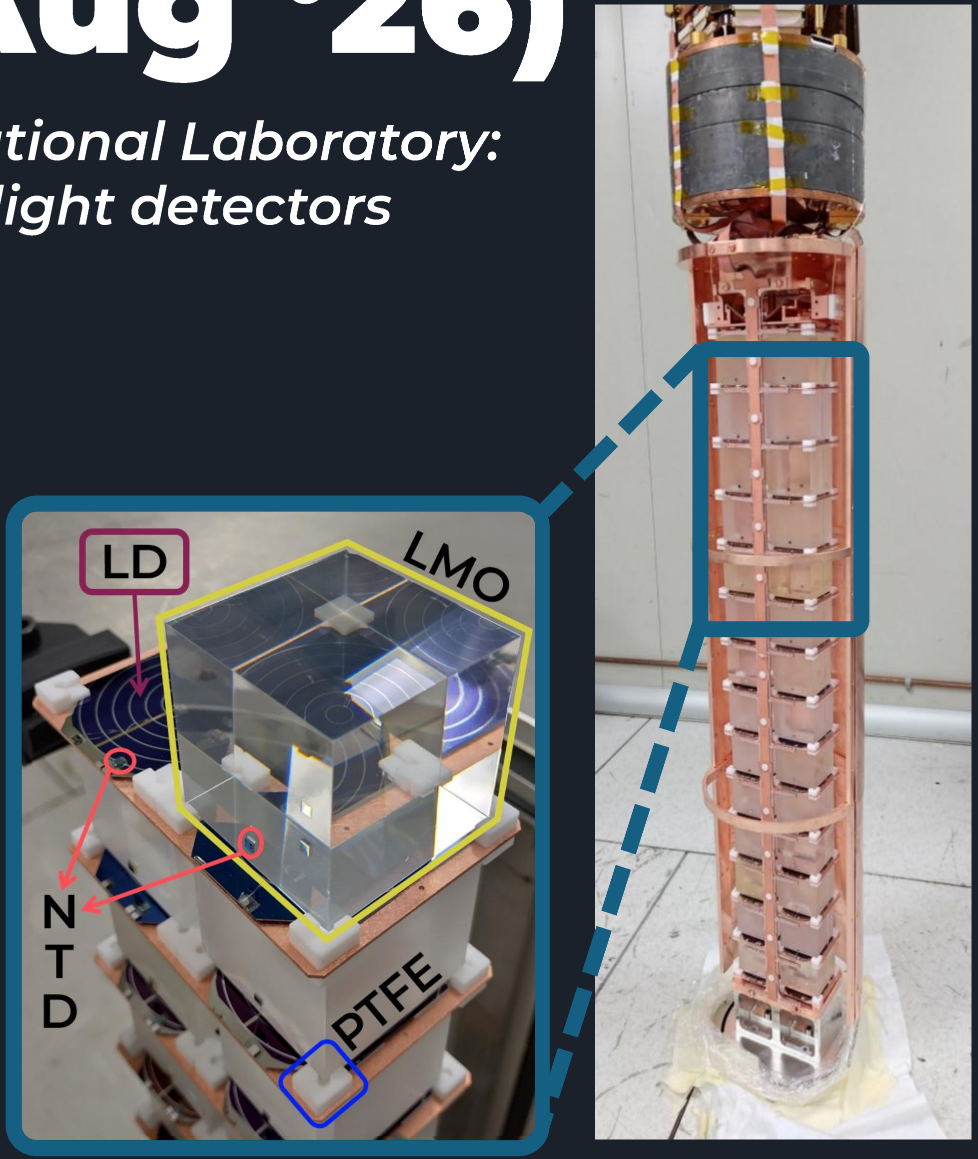
CUPID single-tower setup deployed at *Gran Sasso National Laboratory:*

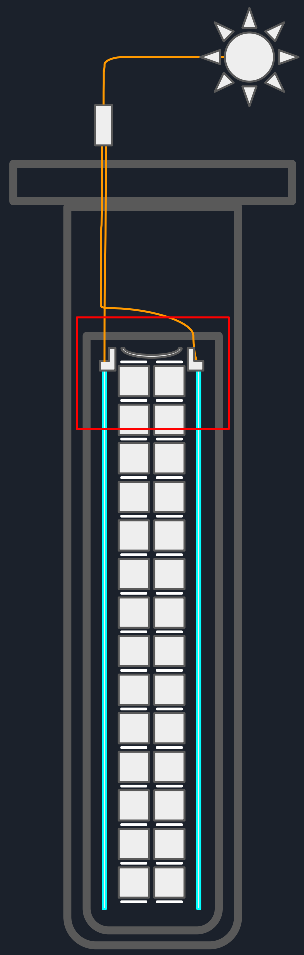
- *Focused on the study of Luke-assisted light detectors and their performance*

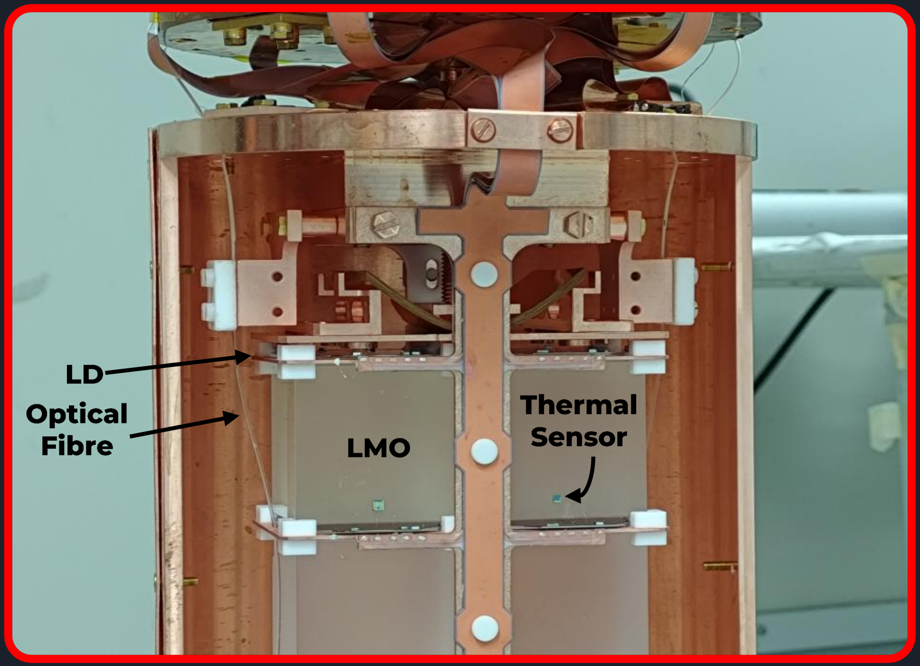


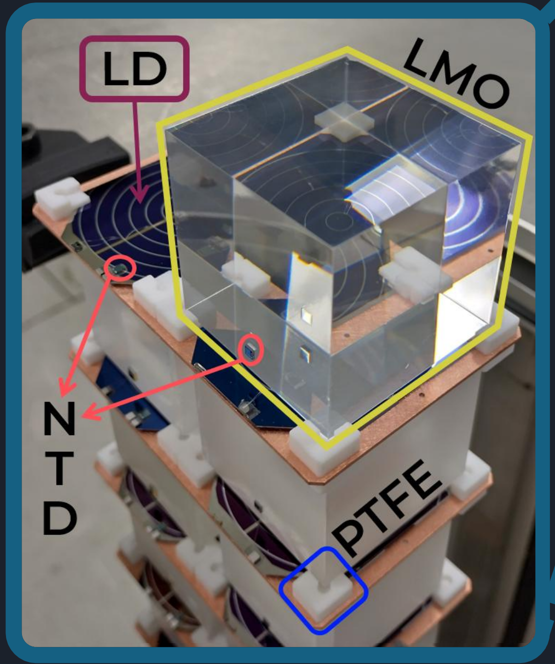
VSTT (Jul '25 – Aug '26)

CUPID single-tower setup deployed at *Gran Sasso National Laboratory:*

- *Focused on the study of Luke-assisted light detectors and their performance*
- *First test of a support apparatus (Optical Injection System) for the injection of light into the light detectors.*





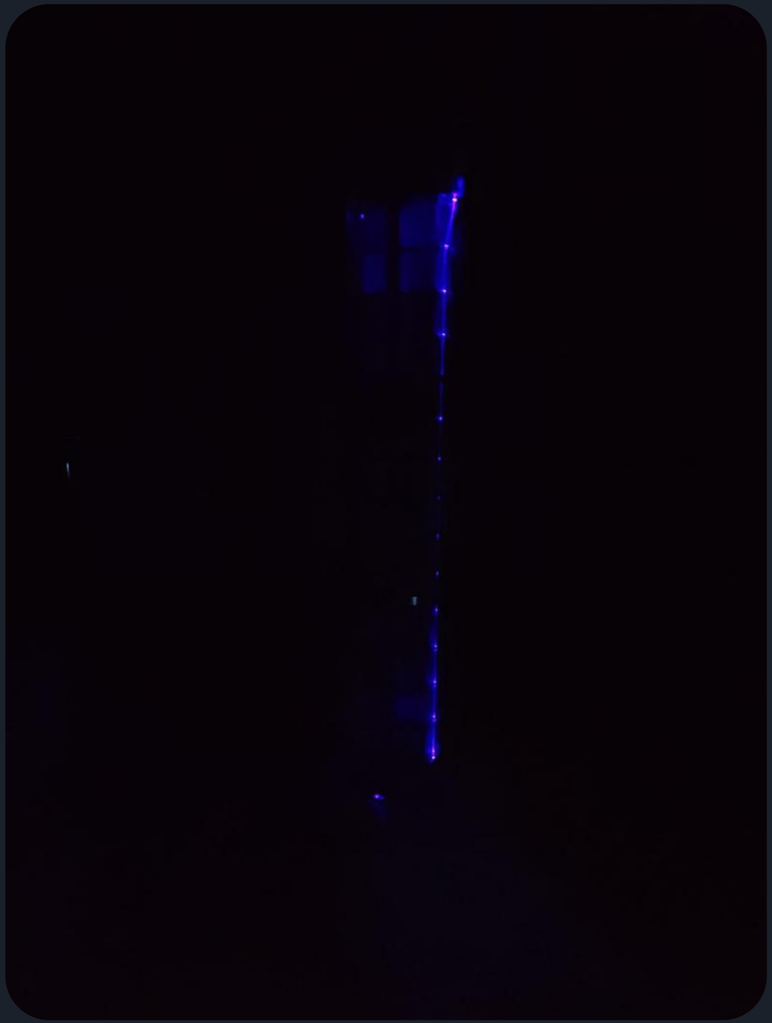


VSTT (Jul ‘25 – Aug ‘26)

CUPID single-tower setup deployed at *Gran Sasso National Laboratory*:

On-site shifter and member of the data-taking team

Optical Injection System



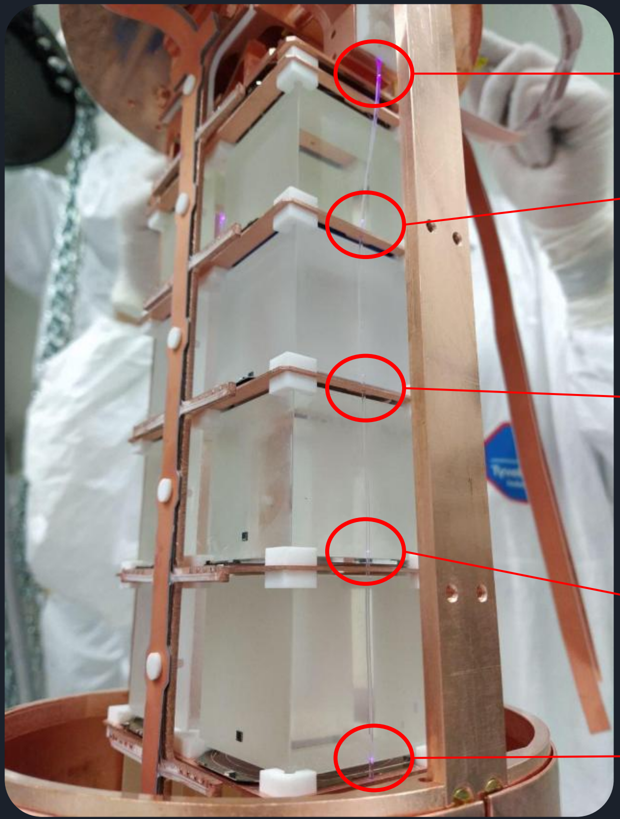
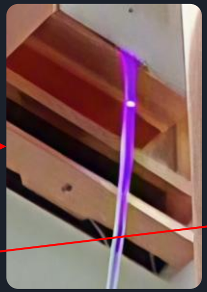
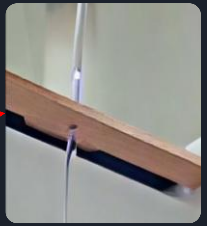
OIS - DEFINITION

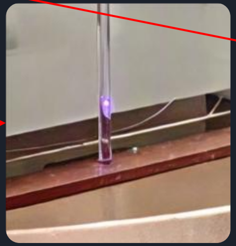
A system capable of injecting light pulses of a given wavelength to be absorbed by a group of LDs.

It should be capable of:

1. Regeneration
2. Simulate pile-up
3. Calibration

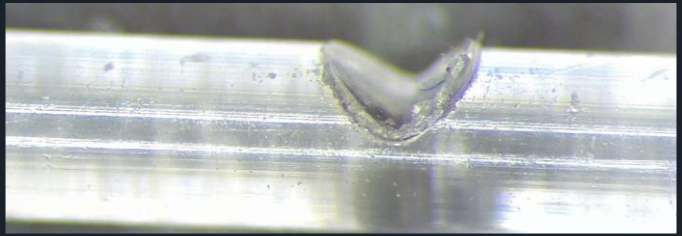
Optical Injection System



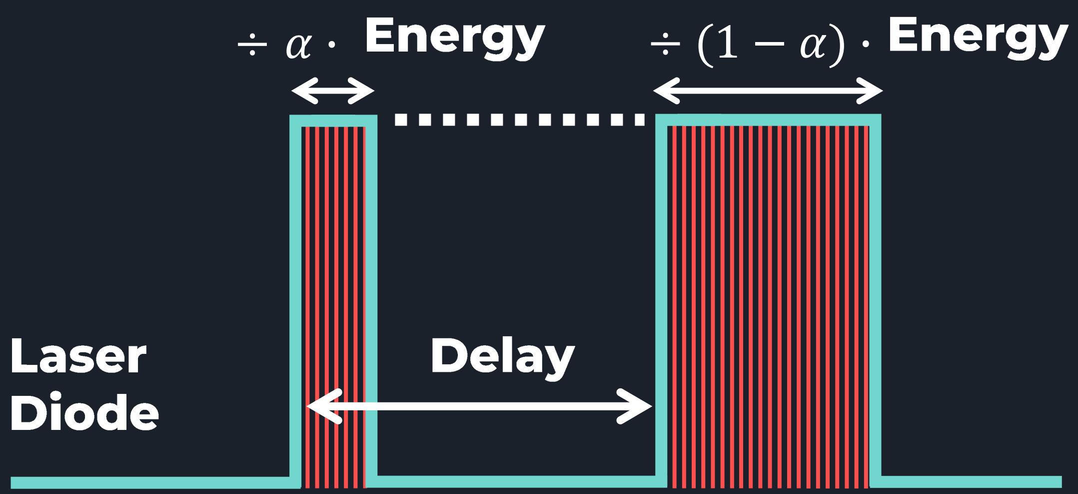

Fast check with a laser light source (not the actual one in VSTT)

Improve the system efficiency to decrease the interference with the cryogenics

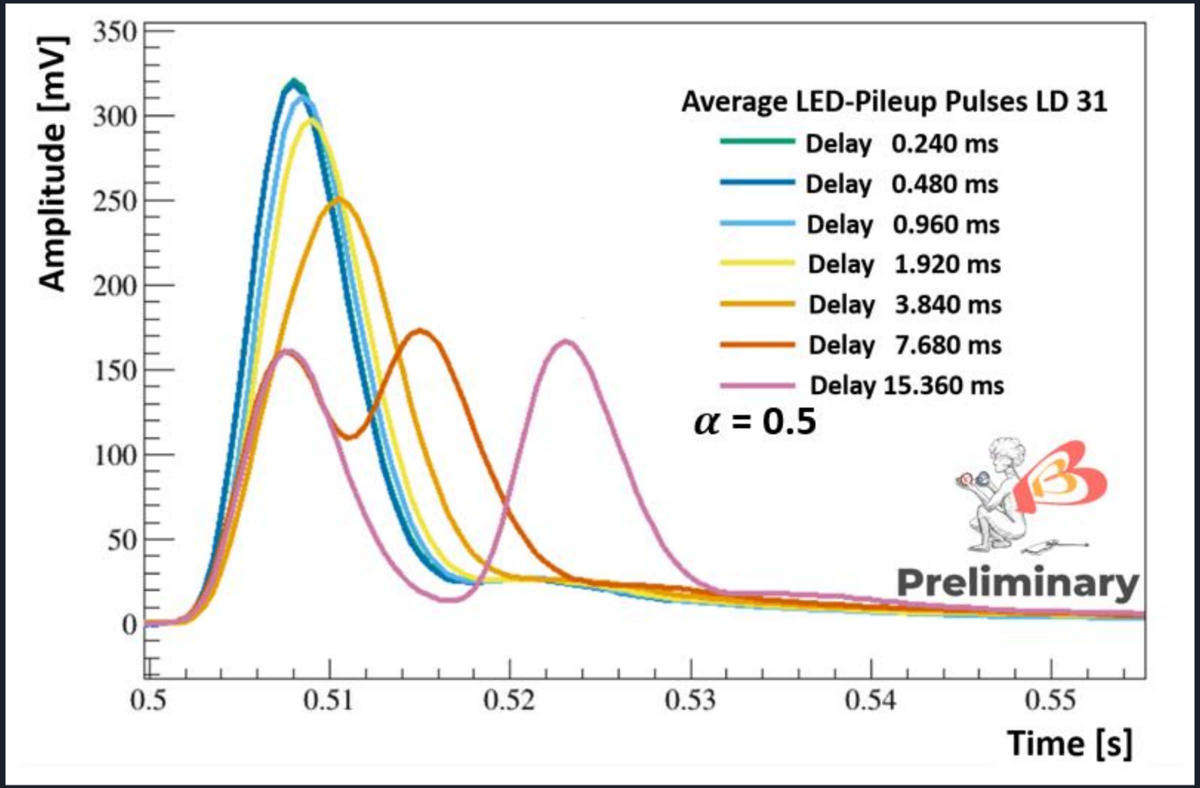


→ fix the diffusion angle
→ specific light spot at LD level

OIS: Pileup Rejection

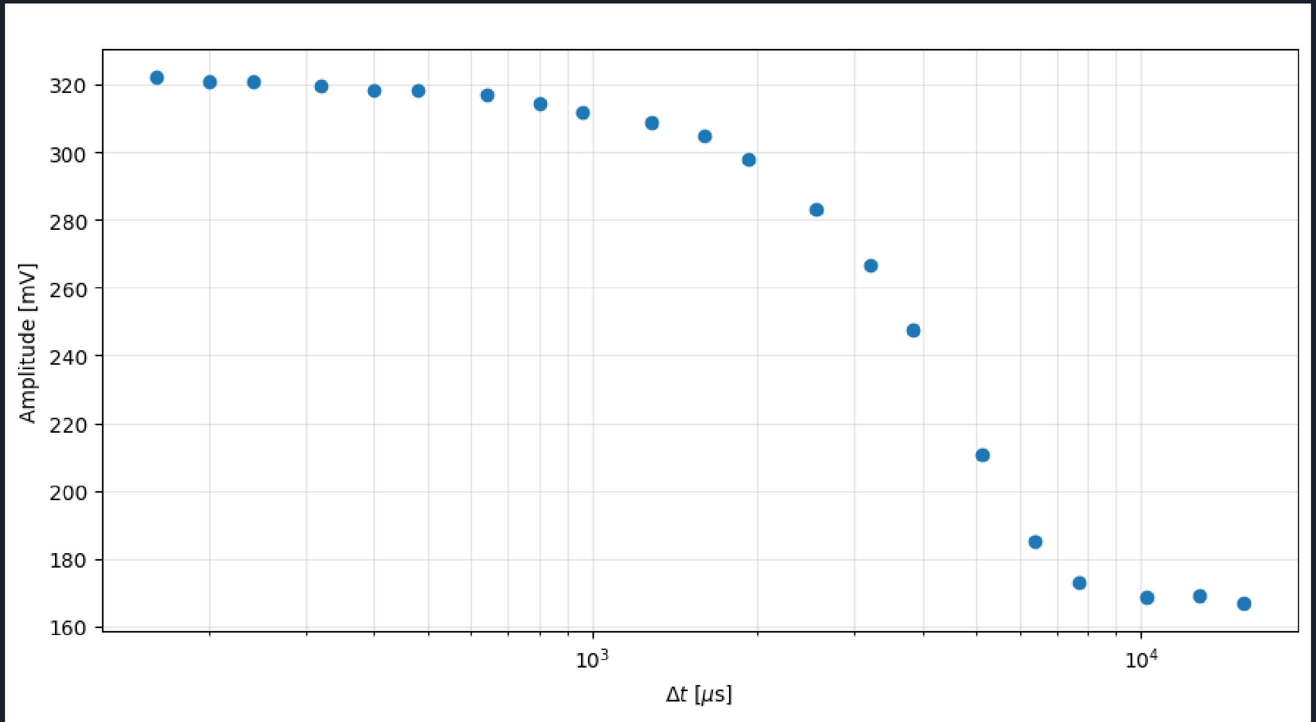


Simulate an event of given Energy, as the pile-up of two events with smaller energy and a variable time delay between them.



OIS: Pileup Rejection

My proposal is a simple ML-based linear discrimination to probe the rejection power of more unstable configurations, like optimisation stages.



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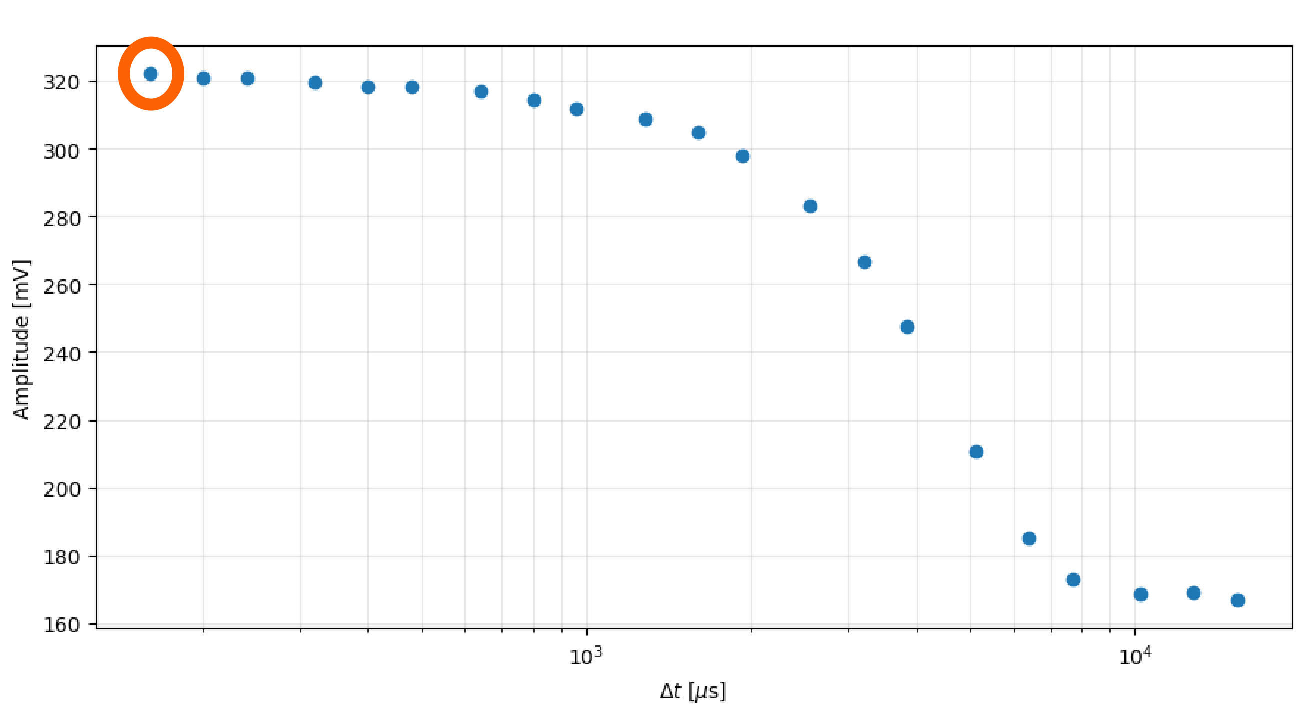

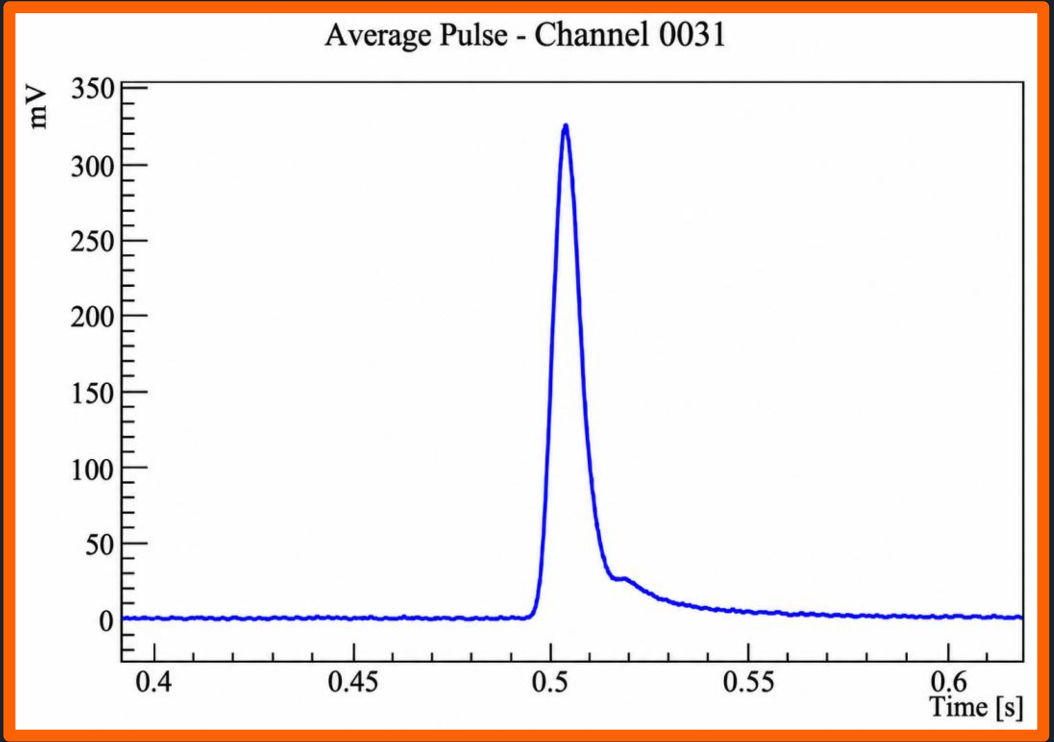

OIS: Pileup Rejection

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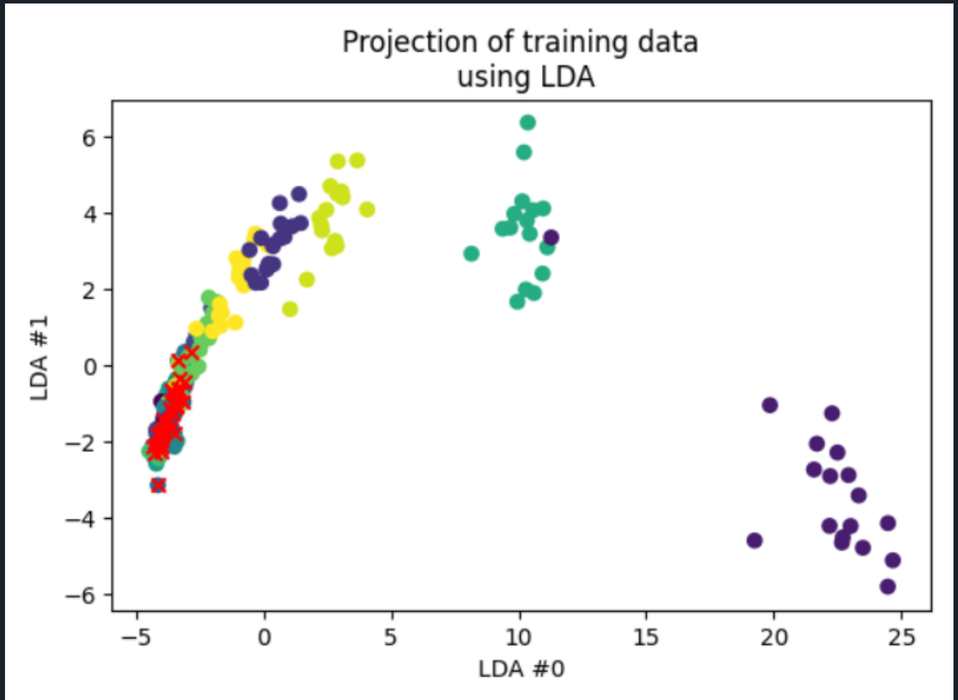
PULSE SHAPE PARAMENTERS



OIS: Pileup Rejection

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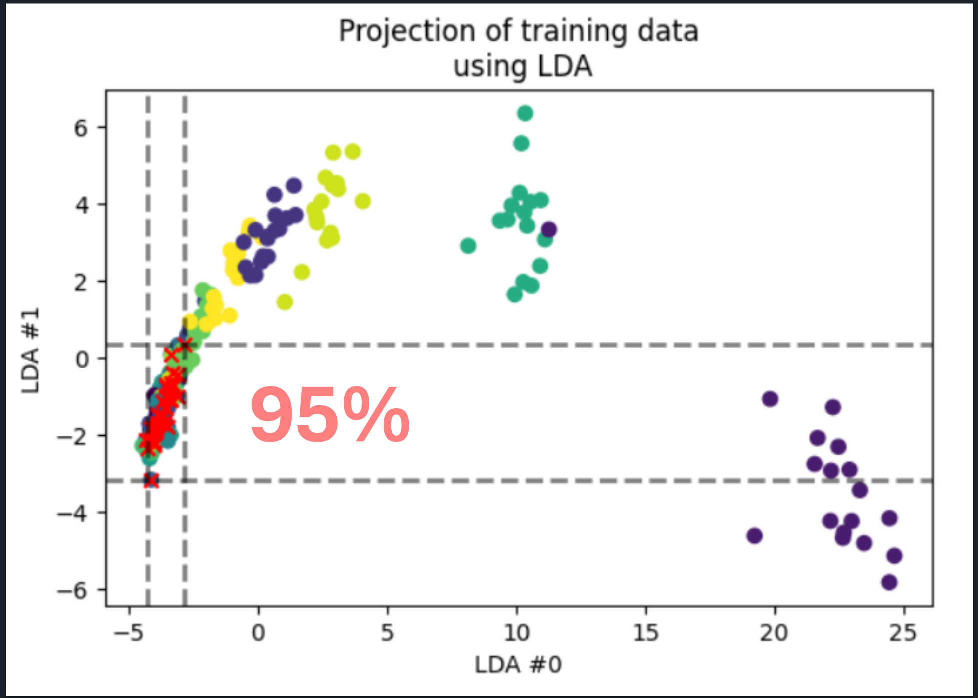
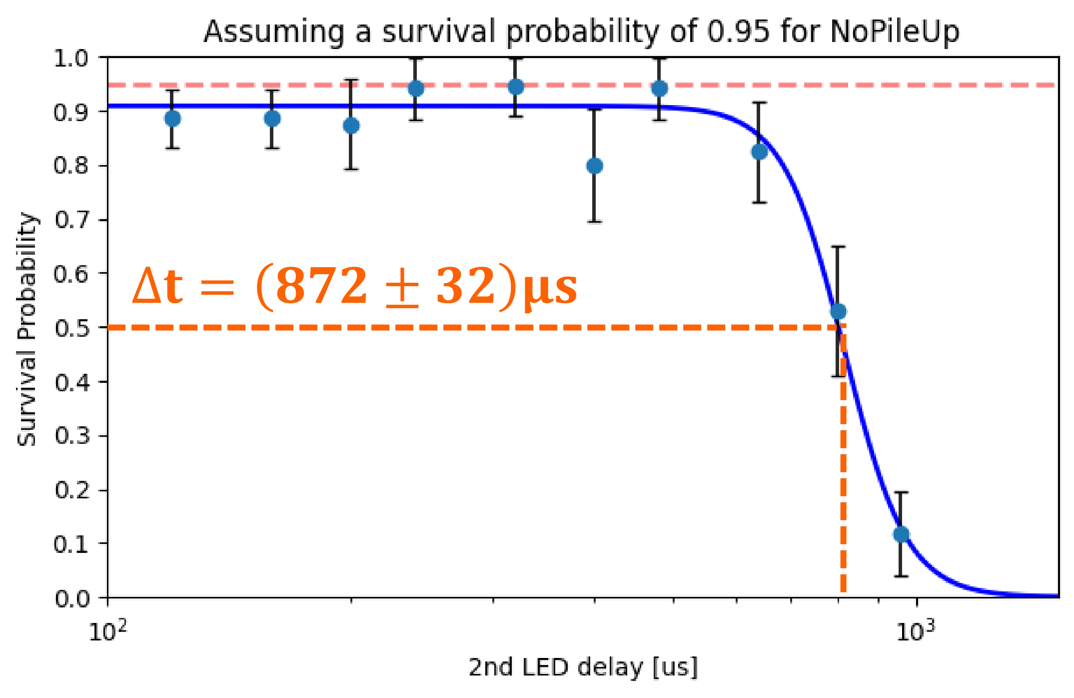
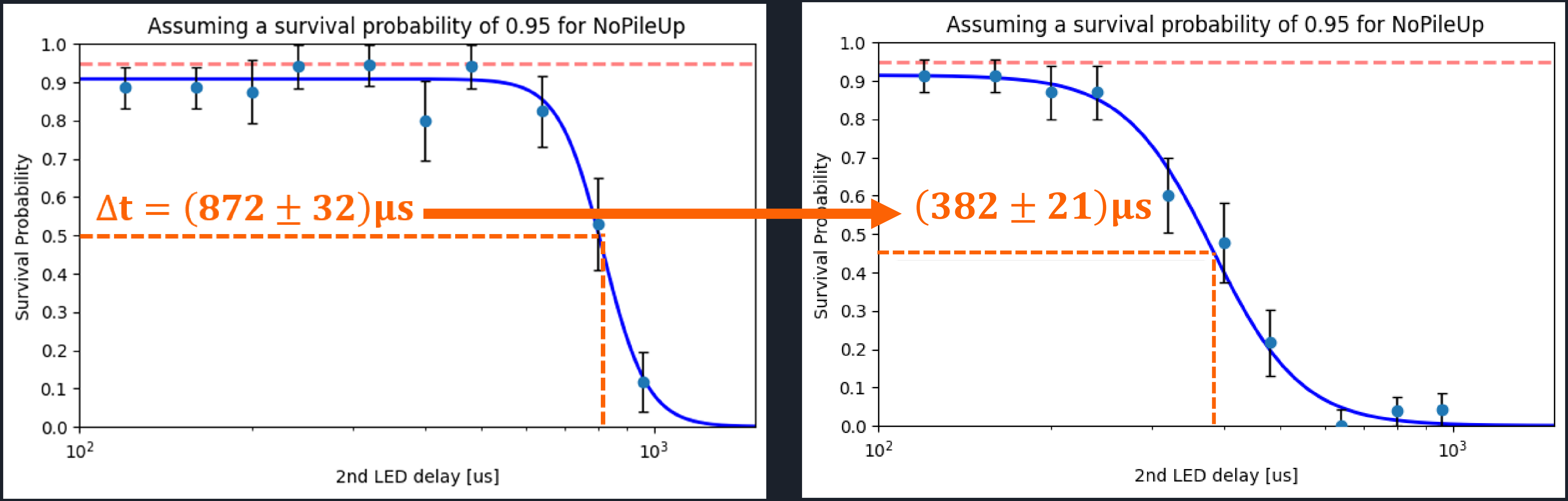




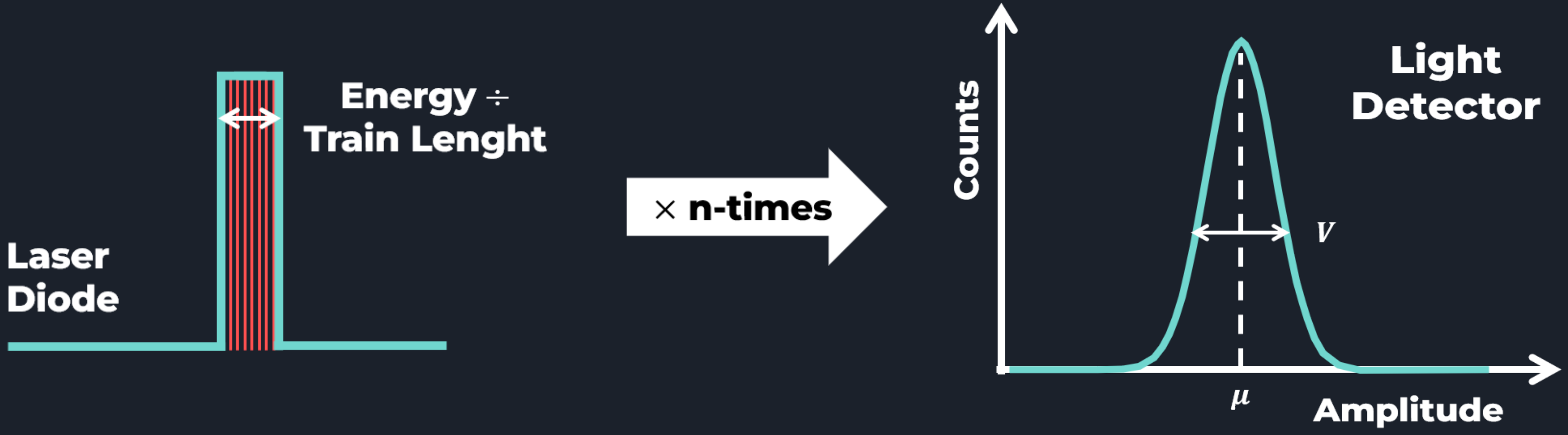
OIS: Pileup Rejection

NTL - Off

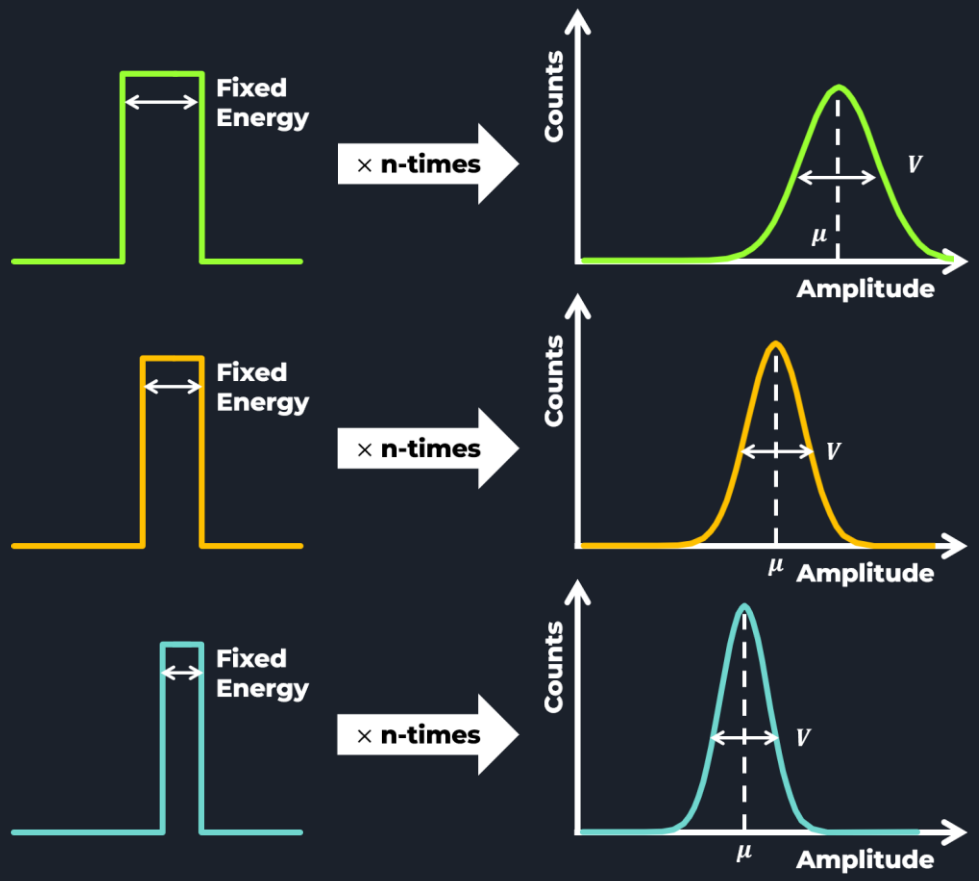
NTL – 60V (Gain~7.4)



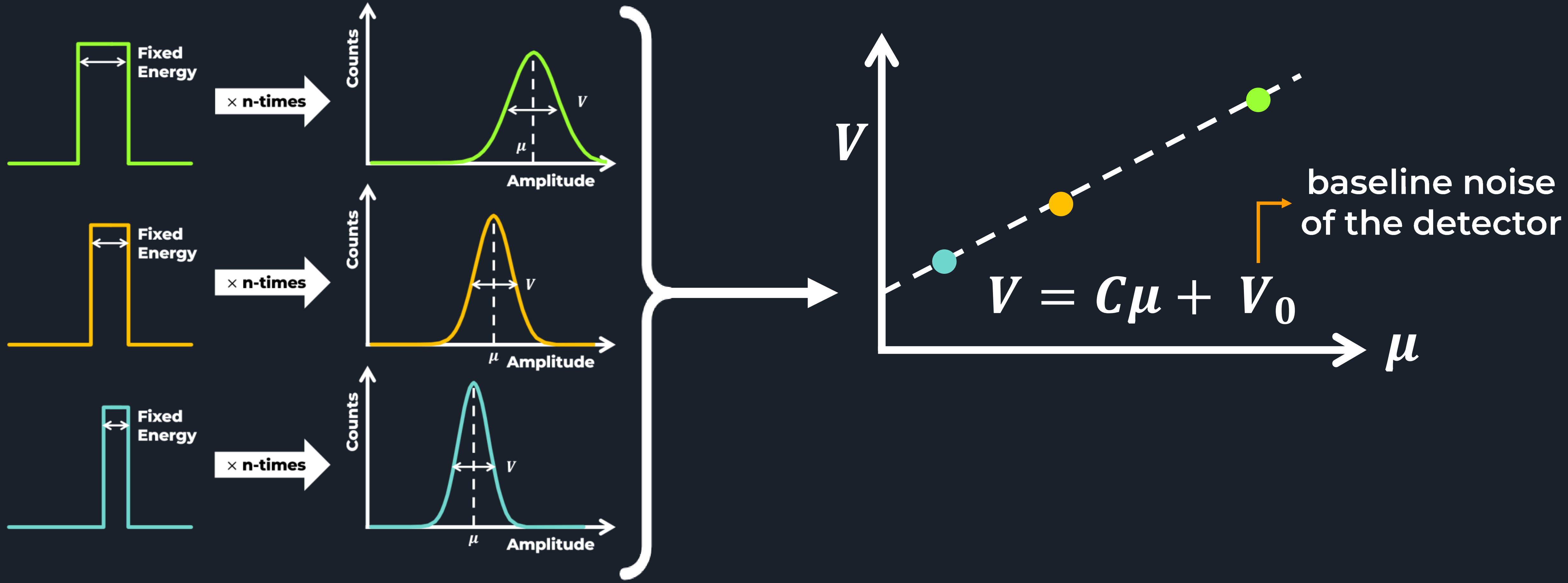
OIS: LD Calibration



OIS: LD Calibration

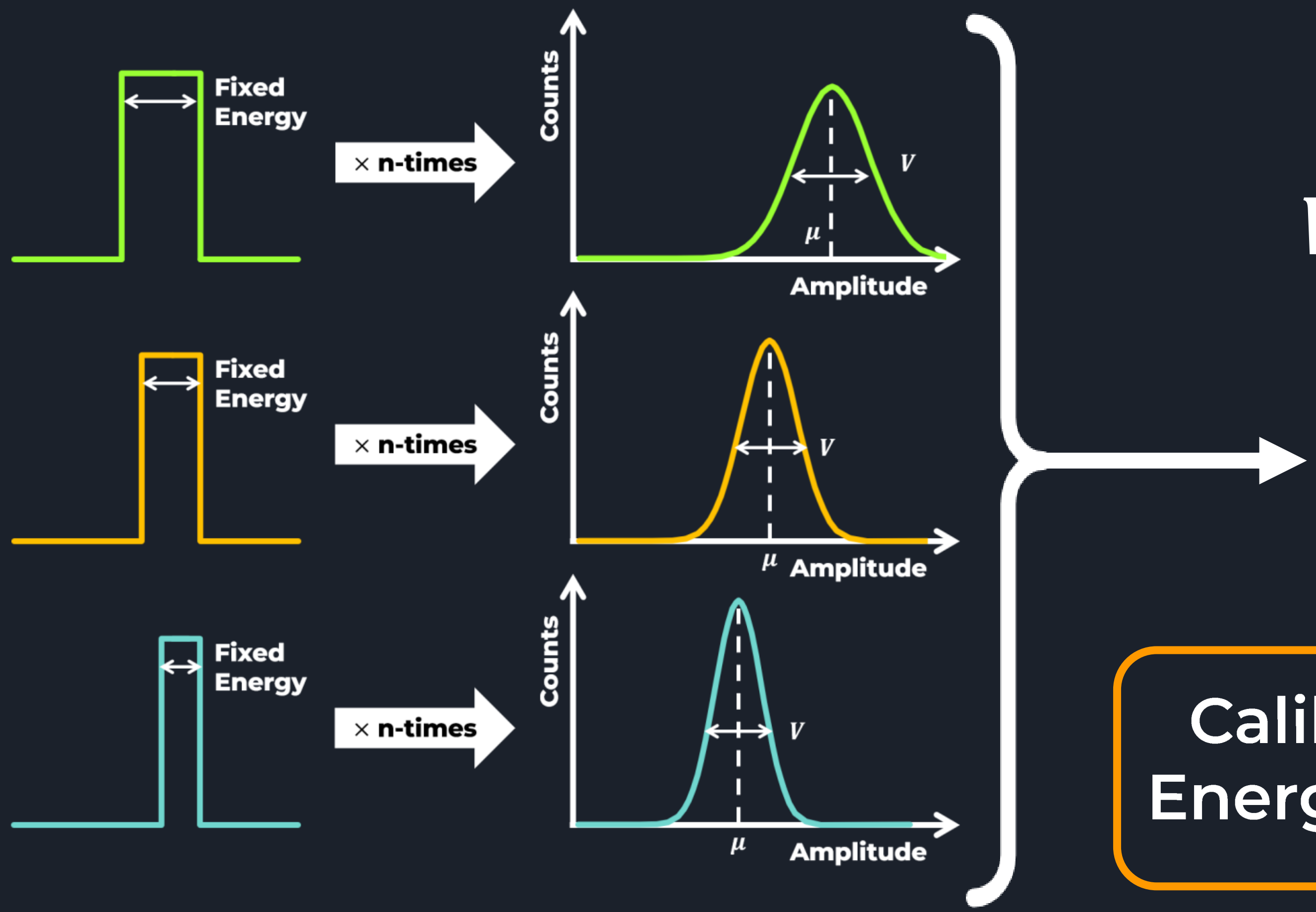


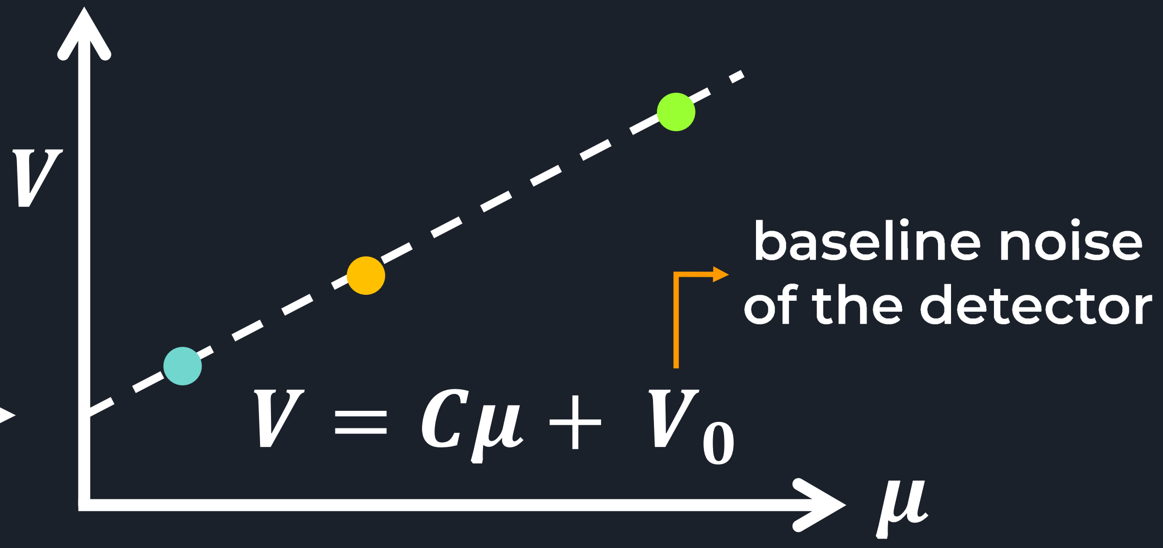
OIS: LD Calibration



$$V = C\mu + V_0$$

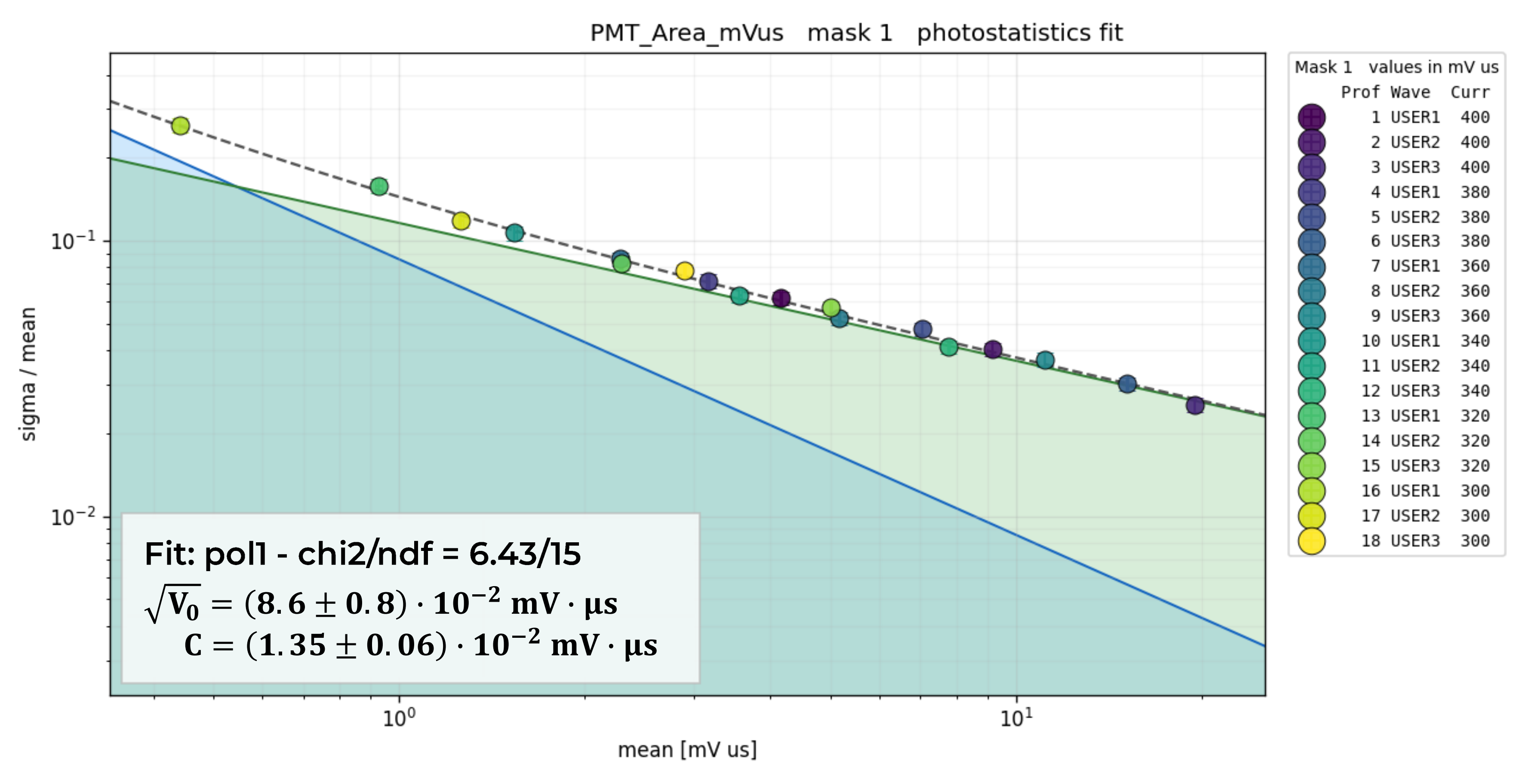
OIS: LD Calibration





$$\text{Calibrated Energy [keV]} \approx \frac{1.24}{\lambda[\mathrm{nm}] \cdot C}\ \text{Amplitude}$$

OIS: LD Calibration



Contribution

— Noise

— Poisson

Calibration Factor: (0.156 ± 0.007) [keV/(mV · µs)]

Optical Calibration Pavia

CUPID will require the deployment of 57 independent towers, i.e. injection systems.
The baseline is to equip each OIS with its own light source.

Optical Injection System

- Light Source (LED / Laser Diode)
- Thermometer
- Climatic Chamber
- Light Detector (PMT / Photodiode)

Optical Calibration Pavia

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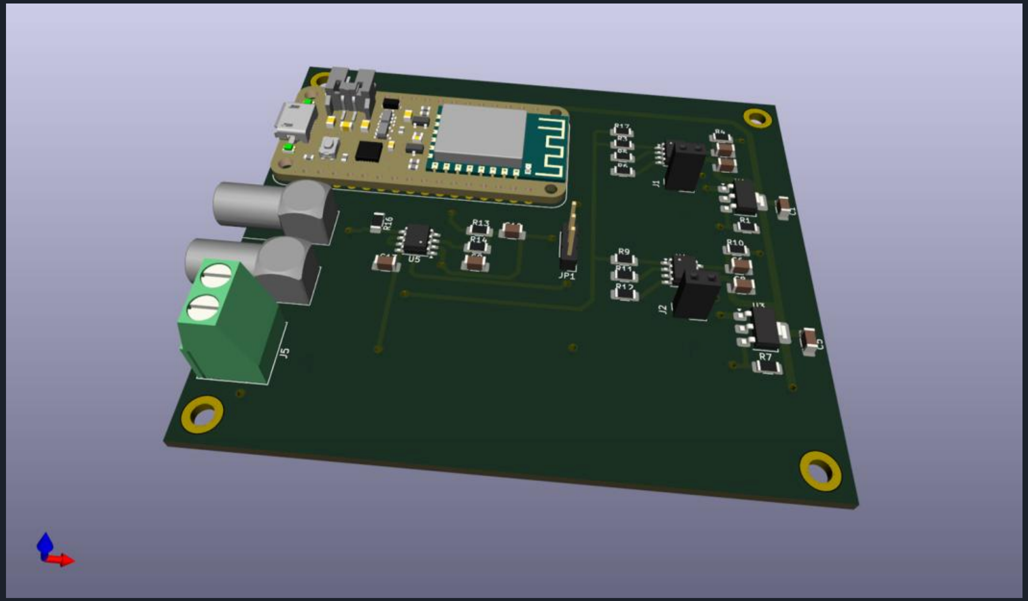

Induce instabilities that can spoil the optical calibration.

Characterise potential light sources

Development of a multi-source driver

Optical Calibration Pavia

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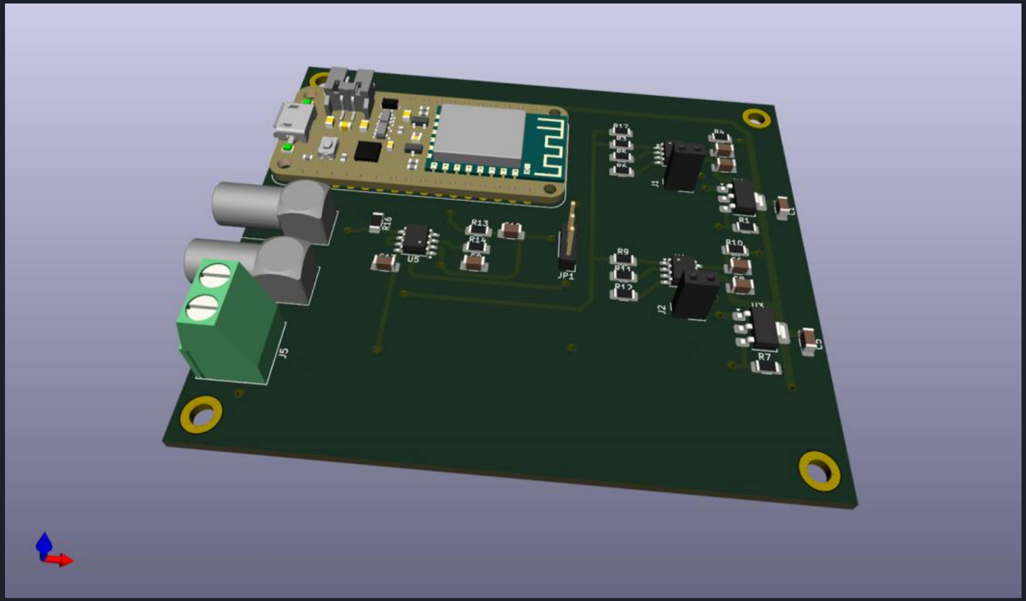

Induce instabilities that can spoil the optical calibration.

Characterise potential light sources

Development of a multi-source driver

ALMOST FINAL SETUP READY BY THE END OF THE YEAR

My contributions

CUORE

- $\longrightarrow$ Data Processing for the $0\nu\beta\beta$ ONGOING
- $\longrightarrow$ How temperature affects the energy resolution STARTED

CUPID

- $\longrightarrow$ Development of the Optical Injection System ONGOING
- $\longrightarrow$ Optical calibration of the CUPID Light Detectors ONGOING
- $\longrightarrow$ ML-based pile-up rejection algorithm TO BE VALIDATED

THANK YOU FOR YOUR ATTENTION !

References 1/3

Half-life and Precision Shape Measurement of the $2\nu\beta\beta$ Decay of ^{130}Te
CUORE Collaboration, Phys. Rev.Lett. 135 (2025) 8, 082501

Toward the discovery of matter creation with neutrinoless $\beta\beta$ decay
Rev.Mod.Phys. 95 (2023) 2, 025002

Optimization of the CUORE detector during the commissioning phase
Stefano Dell'Oro PhD Thesis

With or without ν? Hunting for the seed of the matter-antimatter asymmetry
arXiv: 2404.04453

Sensitivity of the CUPID experiment to $0\nu\beta\beta$ decay of ^{100}Mo
arXiv:2504.14369

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CUPID, the Cuore upgrade with particle identification

CUPID Collaboration, Eur. Phys. J. C 85 (2025), 7, 737

Search for Majorana neutrinos exploiting millikelvin cryogenics with CUORE

CUORE Collaboration, Nature 604, 53-58 (2022)

The CUORE Cryostat

D'Addabbo A. et al., J Low Temp Phys 193, 867-875 (2018)

A gravity-based mounting approach for large-scale cryogenic calorimeter arrays

The CUPID Collaboration, Eur. Phys. J. C 85, 935 (2025)

Data-driven background model for the CUORE experiment

CUORE Collaboration, Phys. Rev. D 110 (2024), 052003

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CUPID, pre-CDR

CUPID Collaboration, arXiv:1907.09376

Measurement of the $2\nu\beta\beta$ Decay Rate and Spectral Shape of 100 Mo from the CUPID-Mo Experiment,

C. Augier, et al. Phys. Rev. Lett. 131, 162501 (2023)

Credits to https://www.symmetrymagazine.org/ for the images

The experimental recipe

$$T_{1/2}^{0\nu\beta\beta} \propto i.a. \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{b \cdot \Delta E}}$$

Large exposure (mass × livetime)

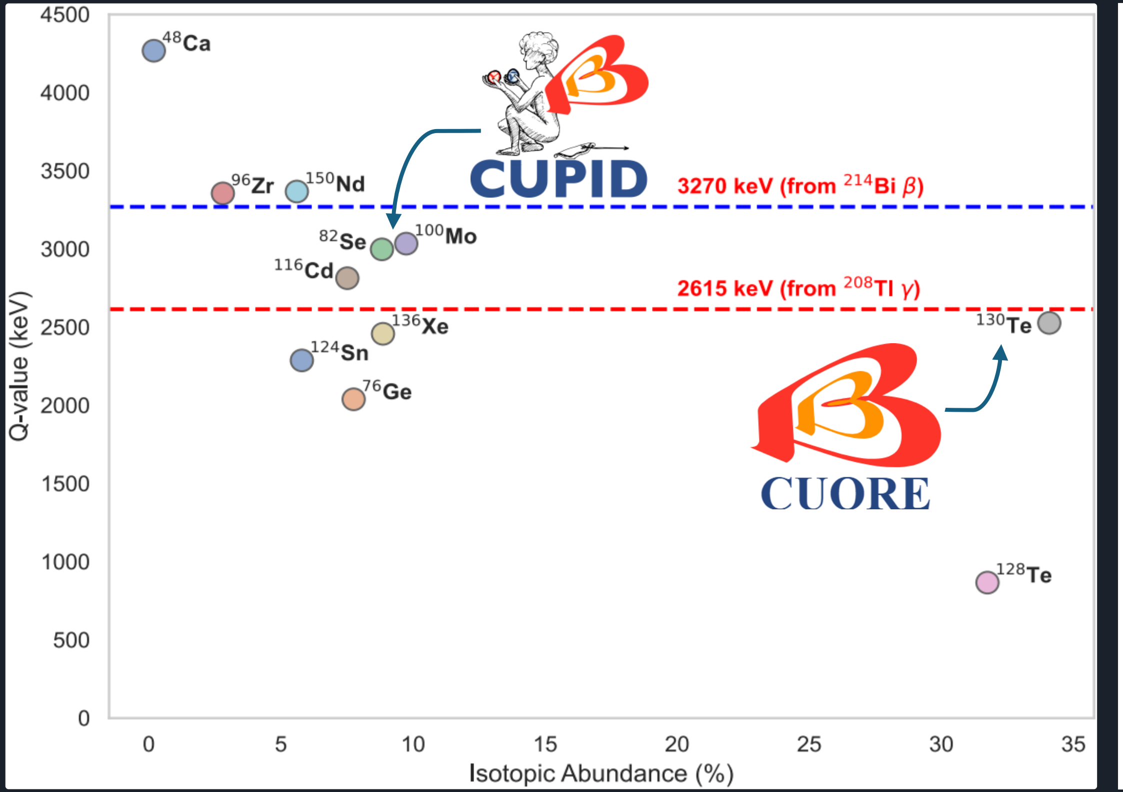
Large isotopic abundance

High detection efficiency

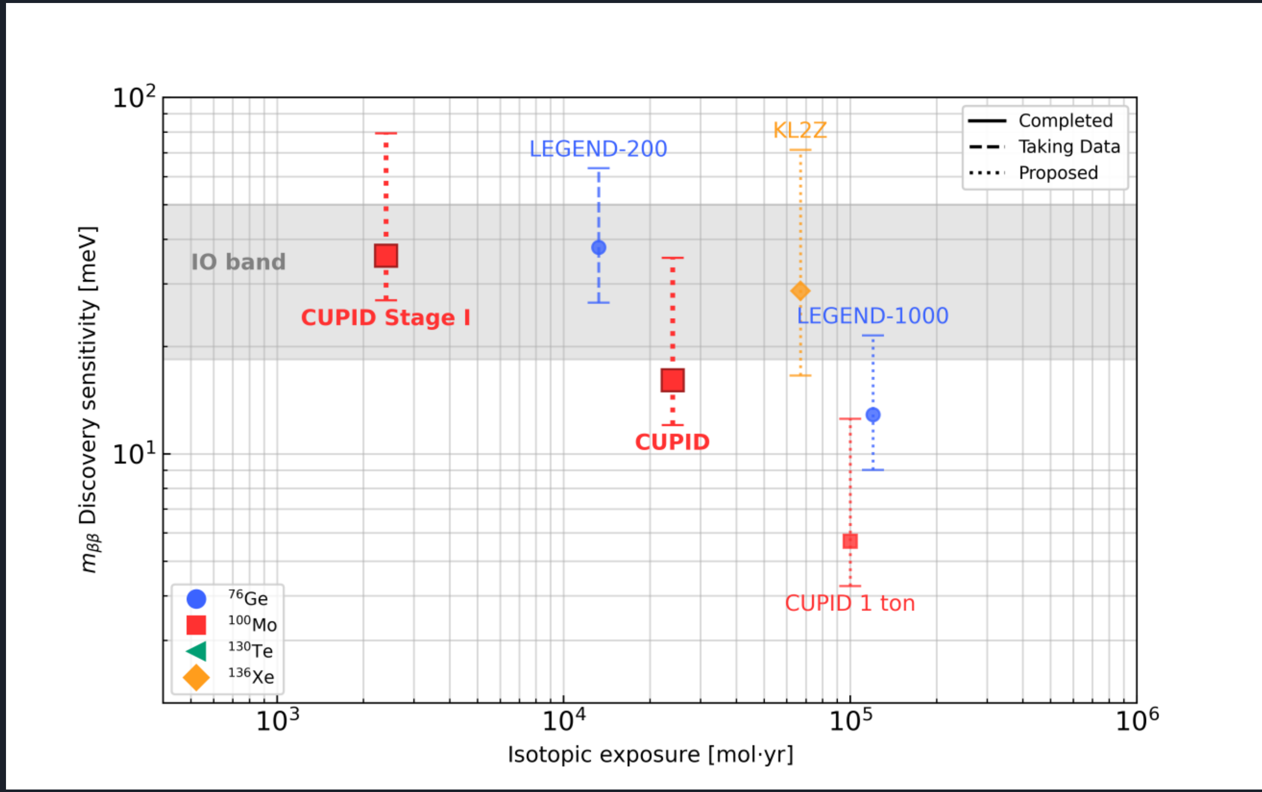
Small background near the $Q_{\beta\beta}$

Good energy resolution

0nbb

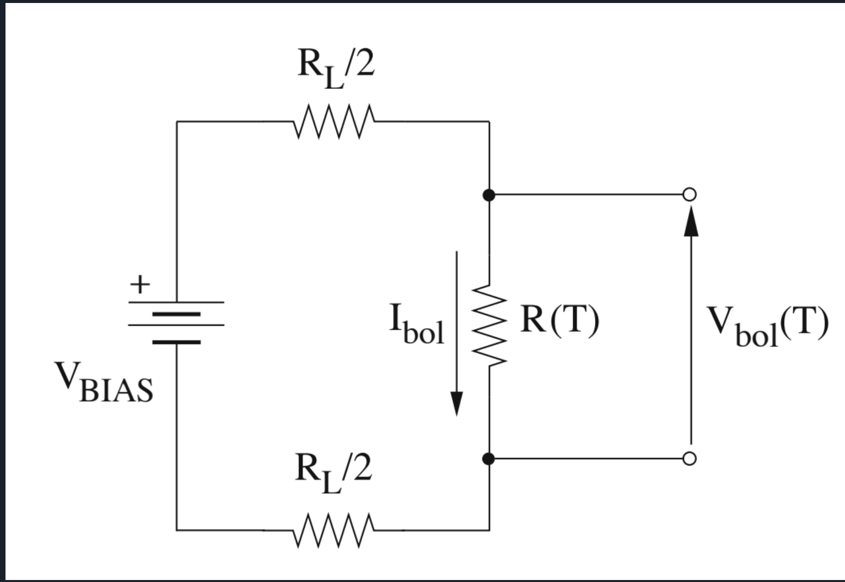


48Ca
96Zr
150Nd
82Se
100Mo
116Cd
136Xe
130Te
124Sn
76Ge
128Te
CUPID
CUORE
3270 keV (from 214Bi β)
2615 keV (from 208Tl γ)
Q-value (keV)
Isotopic Abundance (%)

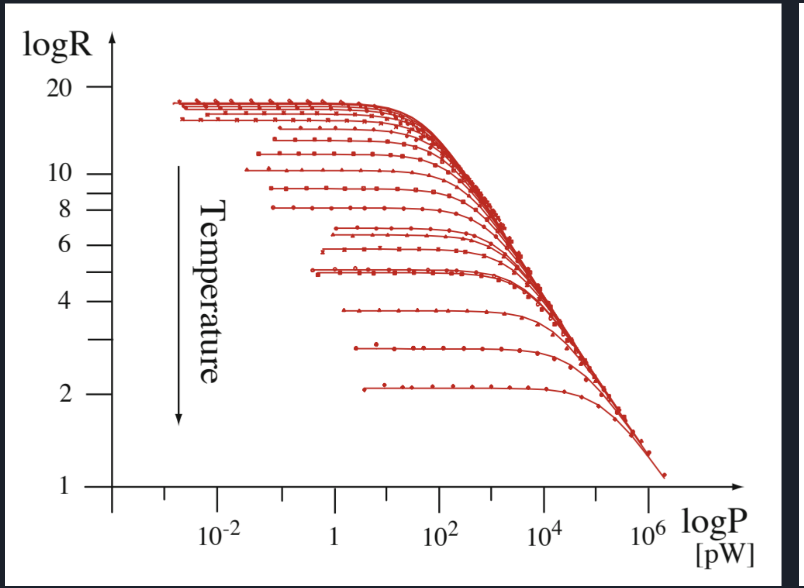


Completed
Taking Data
Proposed
LEGEND-200
KL2Z
IO band
CUPID Stage I
LEGEND-1000
CUPID
CUPID 1 ton
76Ge
100Mo
130Te
136Xe
$m_{\beta\beta}$ Discovery sensitivity [meV]
Isotopic exposure [mol·yr]

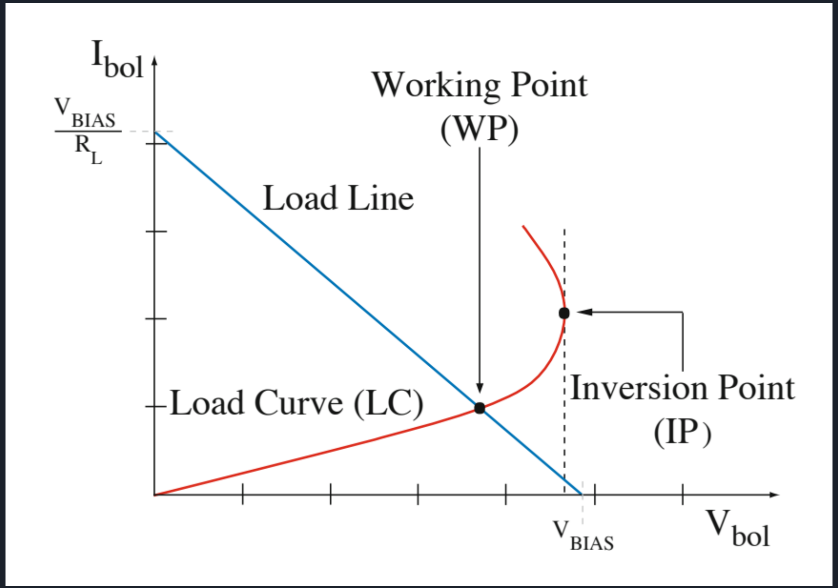
NTD Sensors



$R_L/2$
+
V_{BIAS}
I_{bol}
R(T)
$V_{bol}(T)$
$R_L/2$



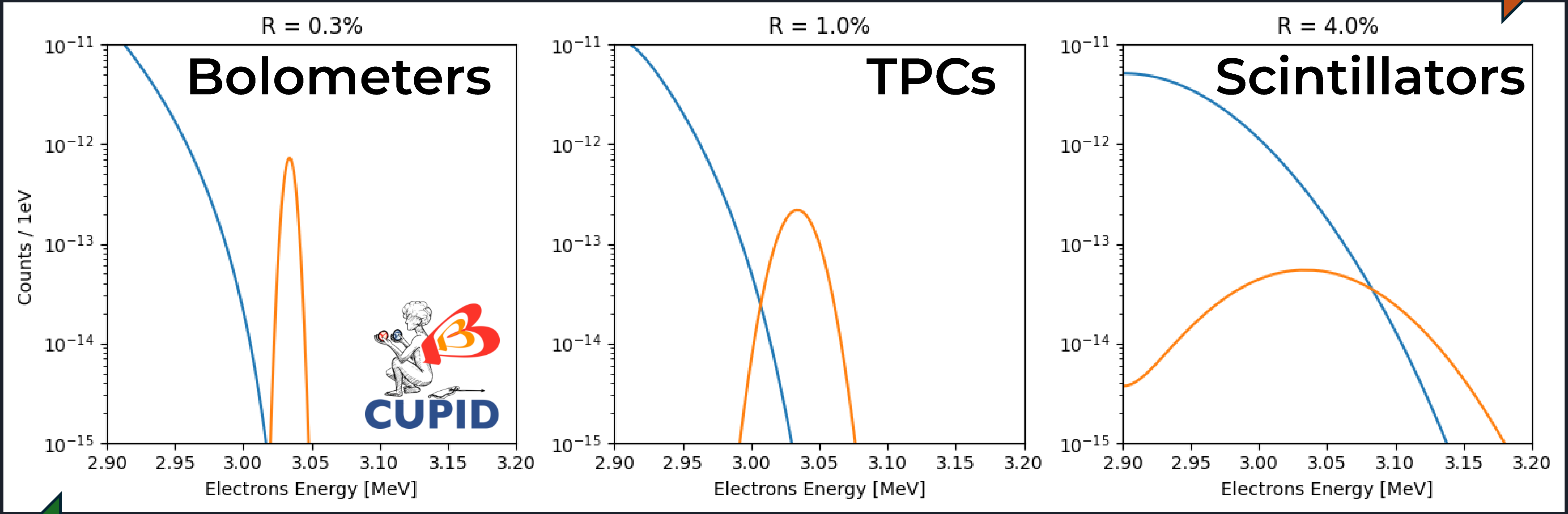
logR
20
10
8
6
4
2
1
Temperature
10^{-2}
1
10^{2}
10^{4}
10^{6}
logP
[pW]



I_{bol}
$\frac{V_{BIAS}}{R_L}$
Working Point
(WP)
Load Line
Load Curve (LC)
Inversion Point
(IP)
V_{BIAS}
V_{bol}

Detection Technique

KG MASS SCALING FRIENDLY TONNE



1keV BEST ENERGY RESOLUTION 100keV

CUPID Official Timeline