$0\nu\beta\beta$ decay searches with the CUORE and CUPID experiments

End of Year Seminars

September 17-18, Pavia

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UNIVERSITÀ DI PAVIA

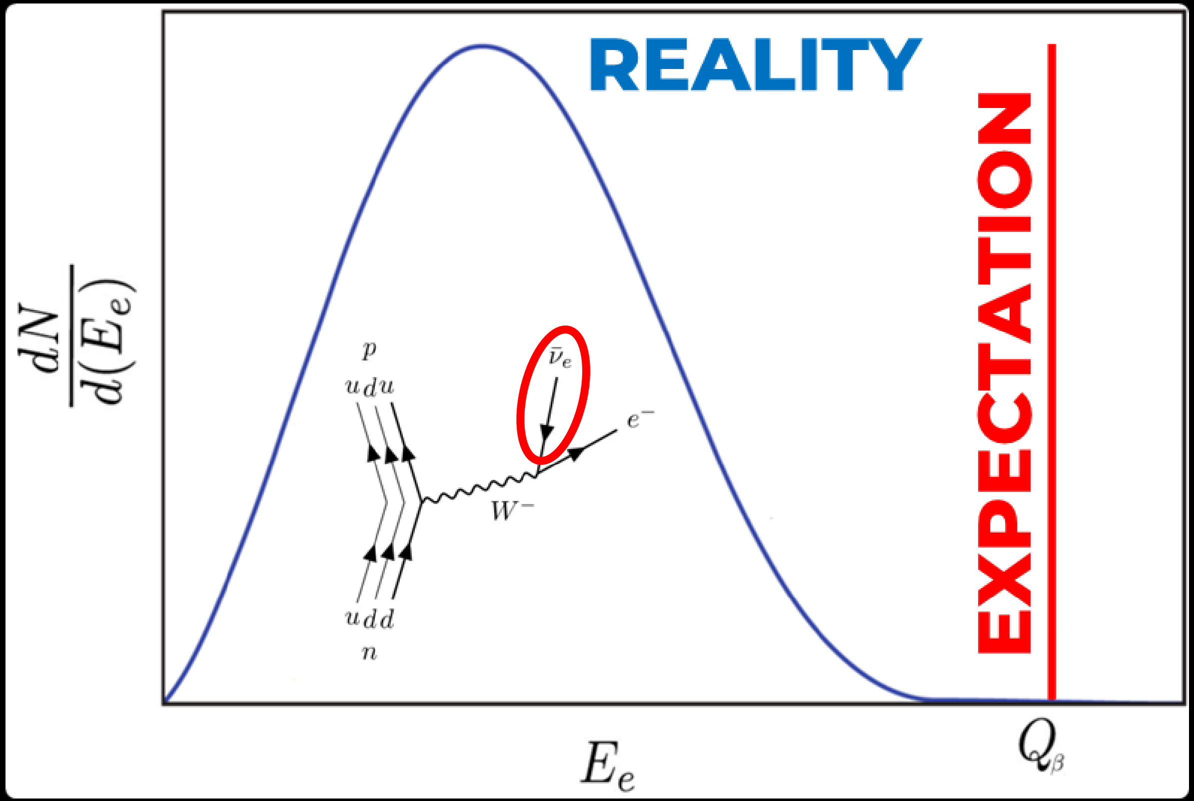
CUORE CUPID INFN Istituto Nazionale di Fisica Nucleare

Nino the Neutrino

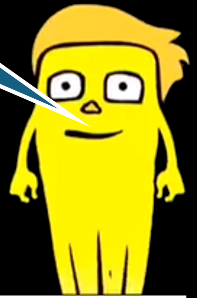
from “*Dal Sole alla Terra*”
a CERN & INFN Production

Do you want to know me ?

Toward the SM neutrino



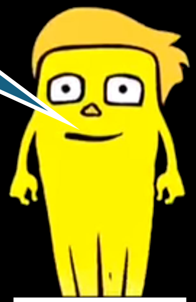
1930 W. Pauli
“invented” (anti)neutrinos to
explain the β-decay spectra



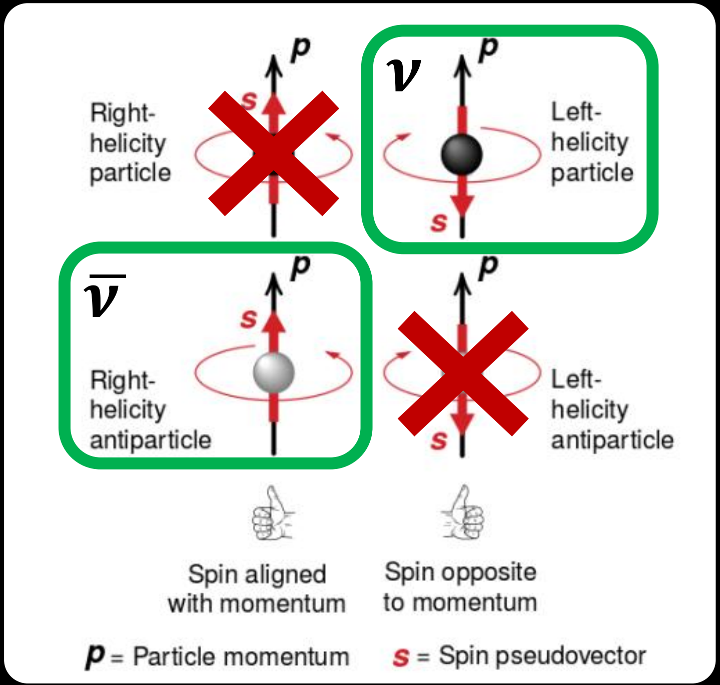

26 Years
LaTER

Toward the SM neutrino

1956 C. Cowan and F. Reines detected the first (anti-electron) neutrinos



Toward the SM neutrino



Neutrinos (ν) are fermions (spin = 1/2)

$$\begin{cases} i\gamma^\mu \partial_\mu \nu_L = m\nu_R \\ i\gamma^\mu \partial_\mu \nu_R = m\nu_L \end{cases}$$

No experimental proof of having mass

$$\begin{cases} i\gamma^\mu \partial_\mu \nu_L = 0 \\ i\gamma^\mu \partial_\mu \nu_R = 0 \end{cases}$$

In the SM, neutrinos …

… are fermions

… are massless

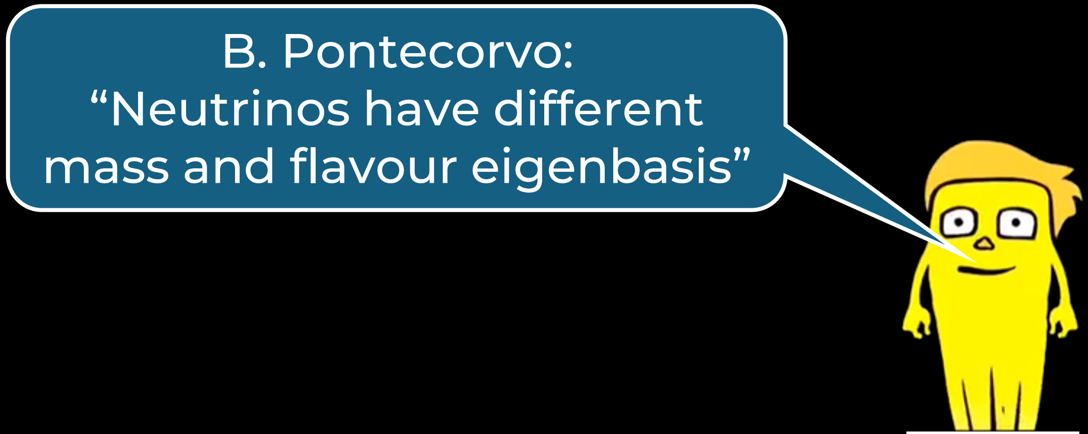
… have 3 flavours: ν_e ν_μ ν_τ

Are we missing something ?

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}\,|\nu_i\rangle$$

Pontecorvo-Maki-Nakagawa-Sakata mixing matrix

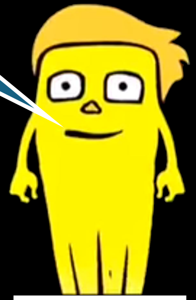
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$



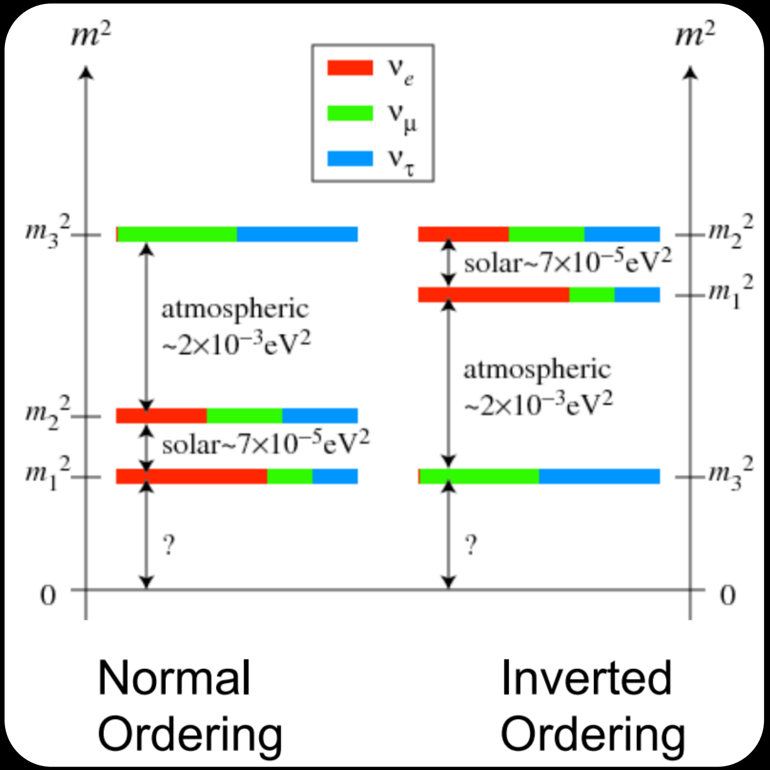
Are we missing something ?

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(1.27\,\frac{\Delta m^2 L}{E}\,\frac{[\mathrm{eV}^2]\,[\mathrm{km}]}{[\mathrm{GeV}]}\right)$$

1998 SuperKamiokande observed neutrino oscillations



Are we missing something ?



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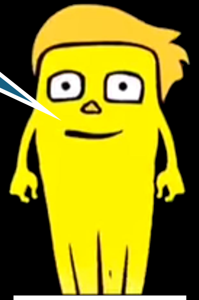
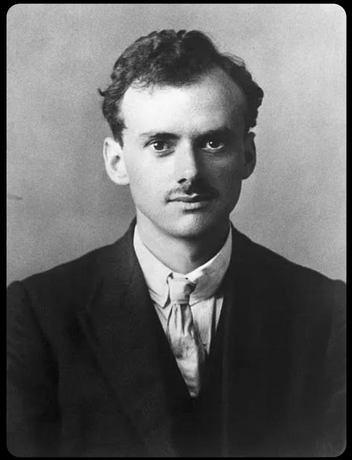
Ambiguity in the mass ordering for neutrinos



Beyond the Standard Model

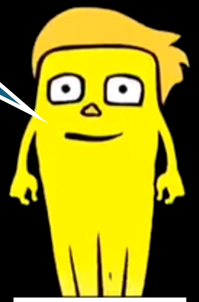
1. Can we add a mass term to the neutrinos in the Standard Model?
2. What about the smallness of their mass?



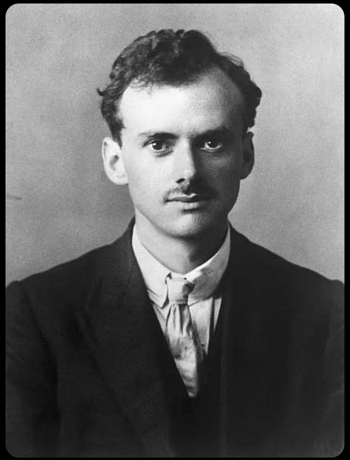
P. Dirac

E. Majorana

2 possible approaches: Dirac and Majorana neutrinos



Beyond the Standard Model

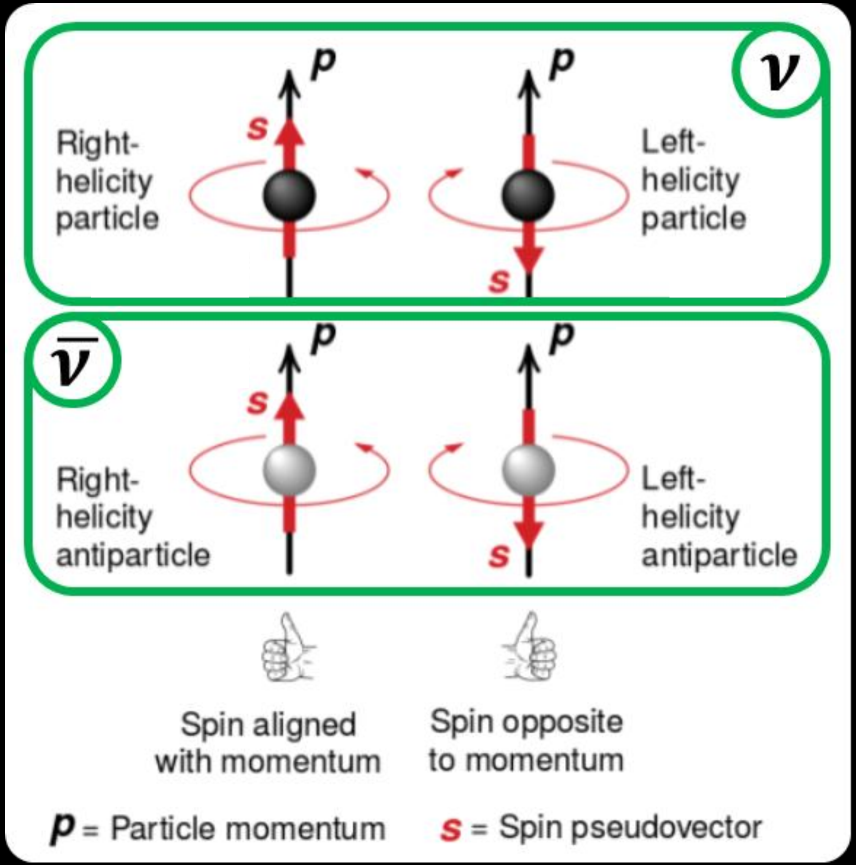


P. Dirac

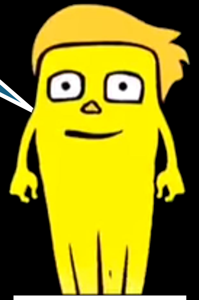
4 possible states:

$$\nu = \nu_L + \nu_R$$

$$\bar{\nu} = \bar{\nu}_L + \bar{\nu}_R$$



Neutrinos are massive: helicity ≠ chirality

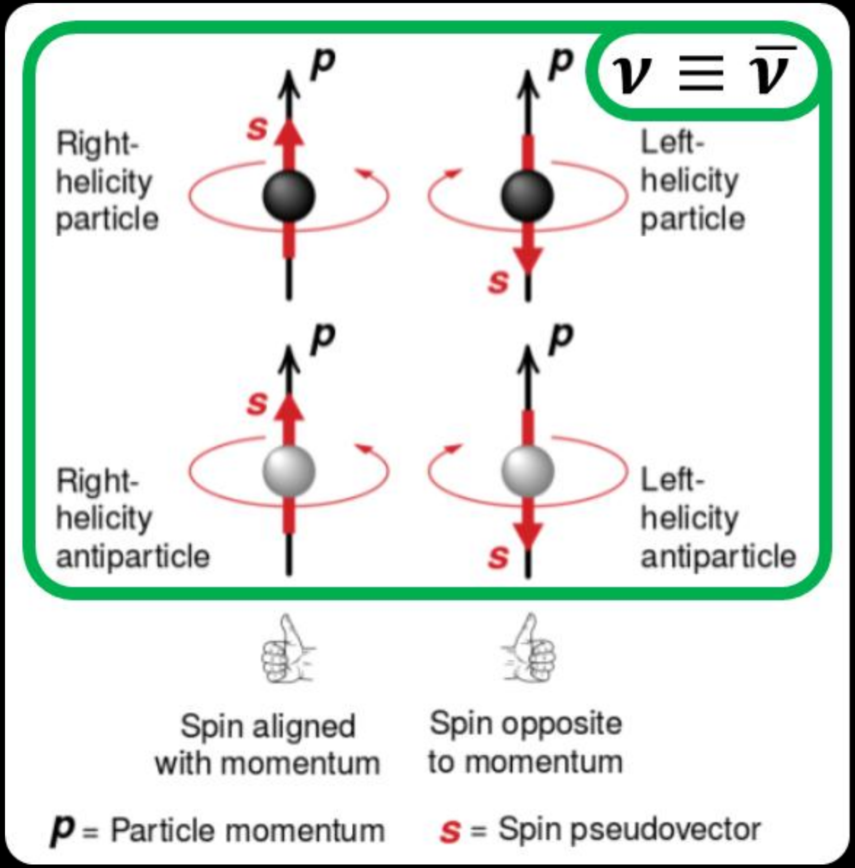


Beyond the Standard Model

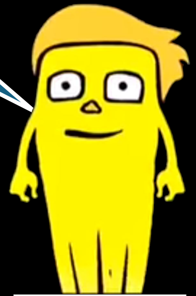
E. Majorana

2 possible states:

$\nu = (\nu_R)^C + \nu_R = (\nu)^C$



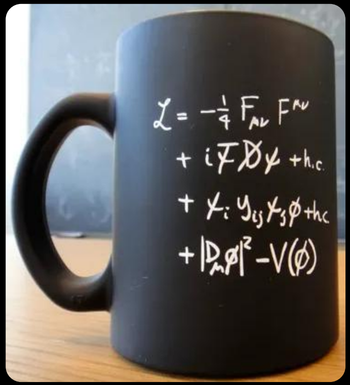
ν and $\bar{\nu}$ are different helicity states of the same particle



Beyond the Standard Model

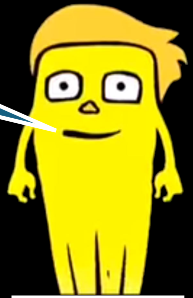
Standard Model

$m_\nu = 0$



$$\mathcal{L} = \begin{aligned} &+ i\bar{\nu}_L \partial_\mu \gamma^\mu \nu_L \\ &+ i\bar{\nu}_R \partial_\mu \gamma^\mu \nu_R \end{aligned}$$

All together now !



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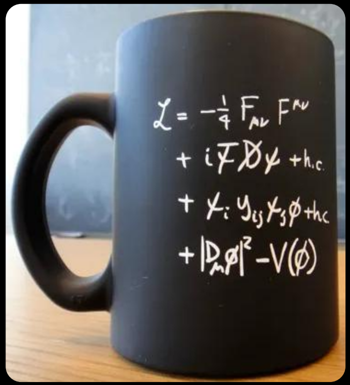
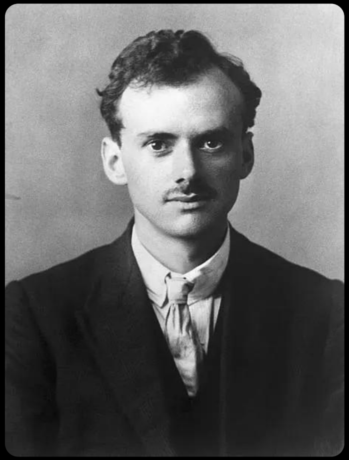


$$\mathcal{L} = \begin{array}{l} + i\bar{\nu}_L \partial_\mu \gamma^\mu \nu_L \\ + i\bar{\nu}_R \partial_\mu \gamma^\mu \nu_R \end{array}$$

Dirac Mass

$m_D \sim \mathrm{m}_{\text{quark/lepton}}$



$$-\left(m_D\, \bar{\nu}_R \nu_L + \mathrm{h.c.}\right)$$

Beyond the Standard Model

Standard Model

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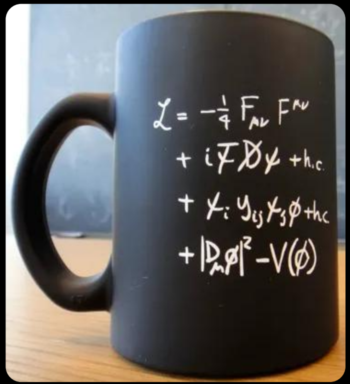

$$\mathcal{L} = \begin{array}{l} + i\bar{\nu}_L \partial_\mu \gamma^\mu \nu_L \\ + i\bar{\nu}_R \partial_\mu \gamma^\mu \nu_R \end{array}$$

+

Dirac Mass

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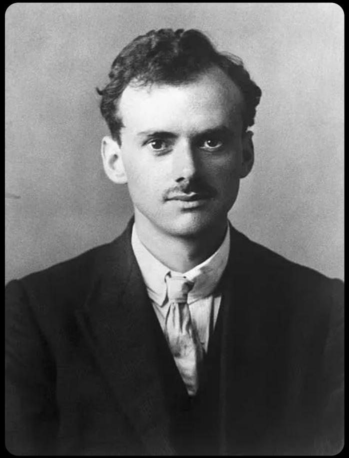


$$-\left(m_D\, \bar{\nu}_R \nu_L + \text{h.c.}\right)$$

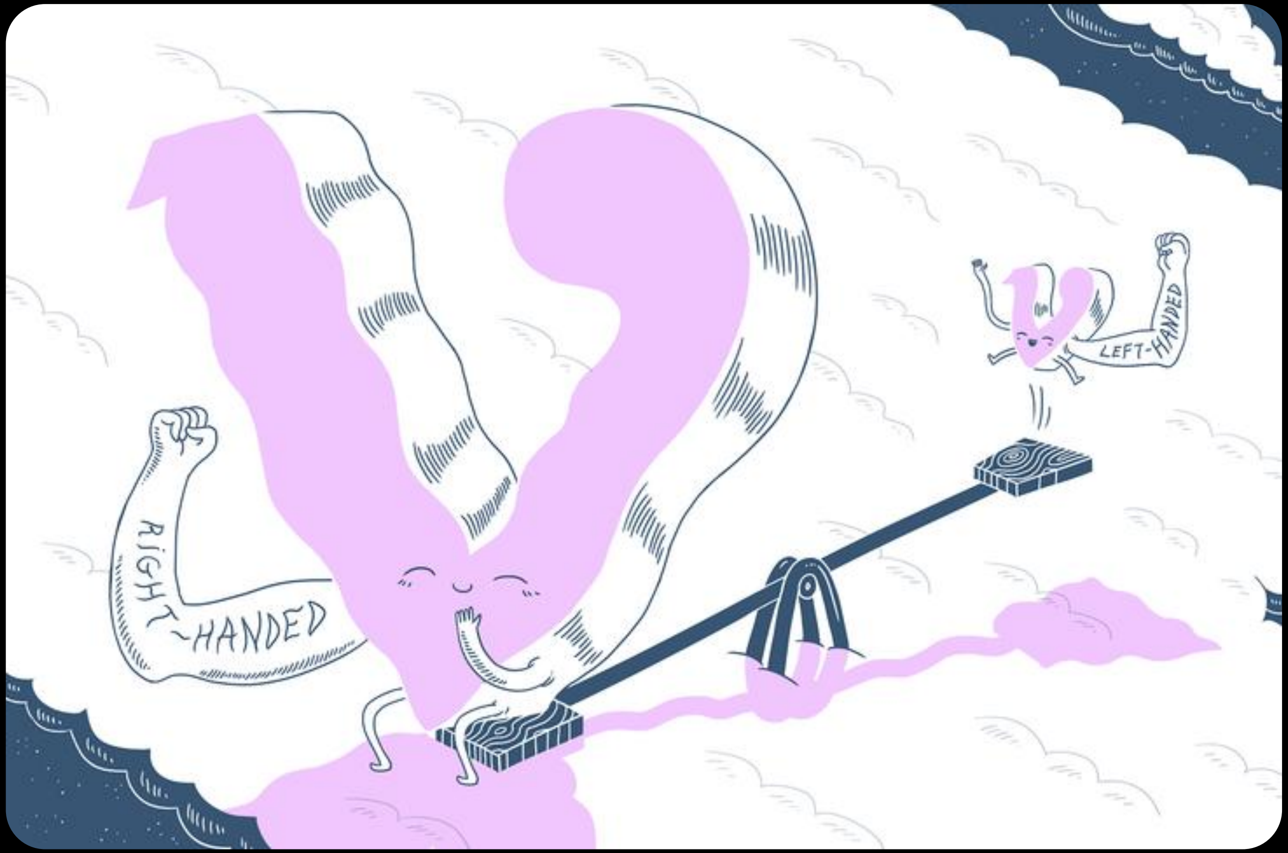
+

Majorana Mass

$m_R \gg m_D$

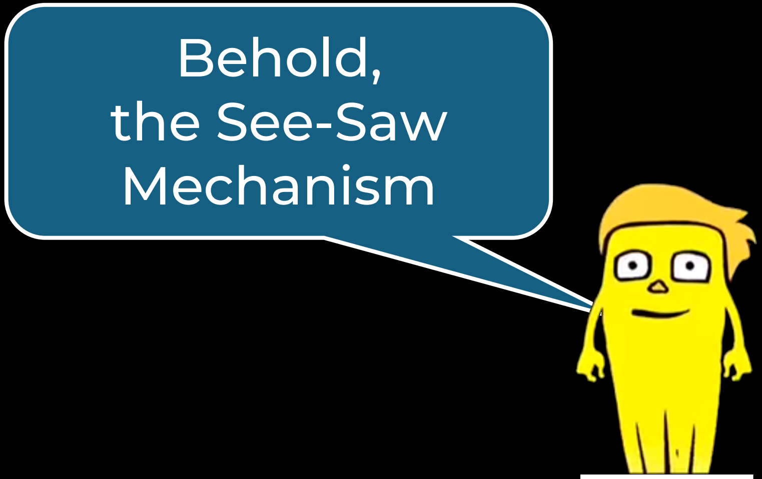
$$-\frac{1}{2}\left(m_R \overline{(\nu_R)^C} \nu_R + \text{h.c.}\right)$$

Beyond the Standard Model

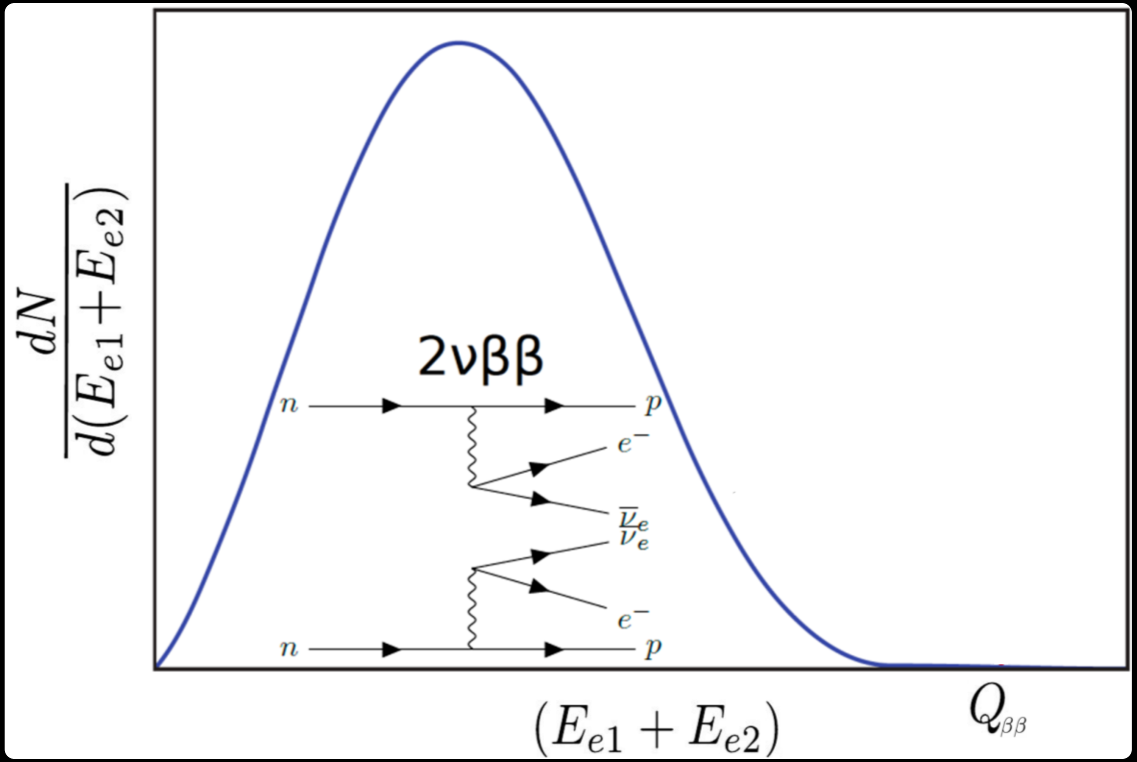


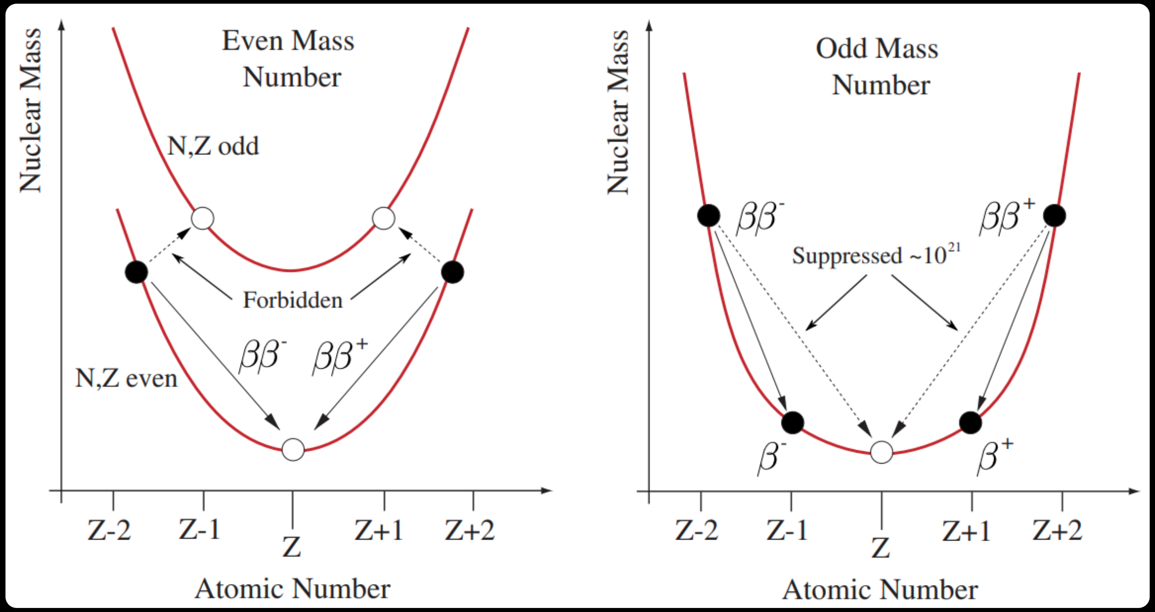
Light ν: $m_1 \simeq \frac{m_D^2}{m_R} \ll m_D$

Heavy ν: $m_2 \simeq m_R$

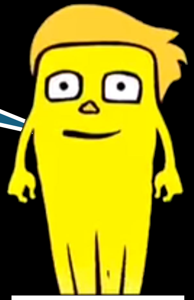


Double Beta Decay $(2\nu\beta\beta)$





$2\nu\beta\beta$ is a SM allowed and observed process



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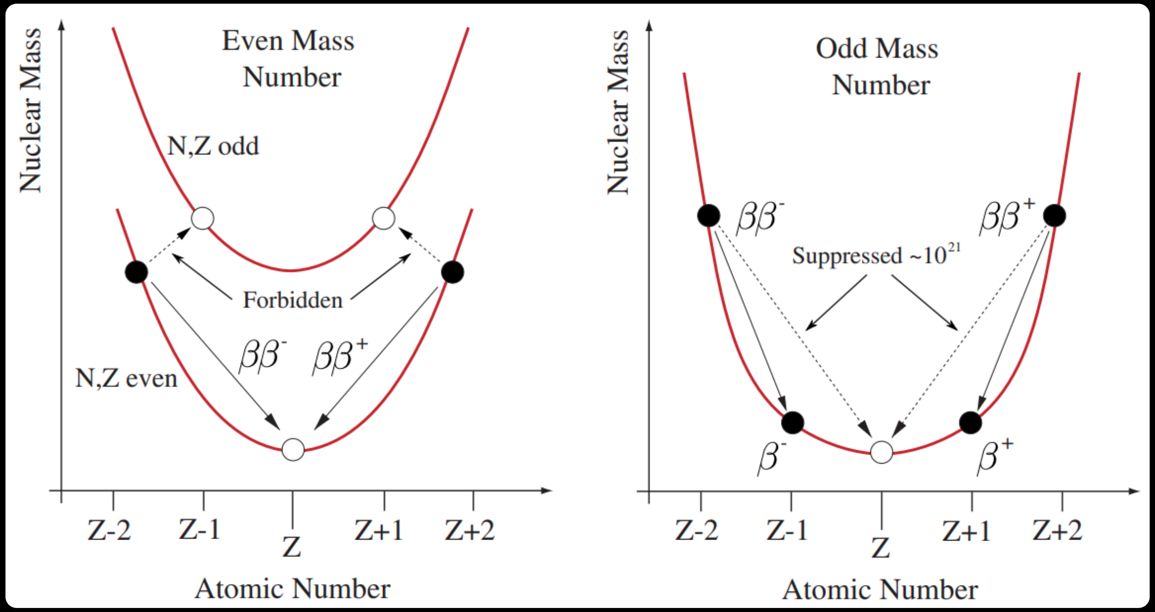
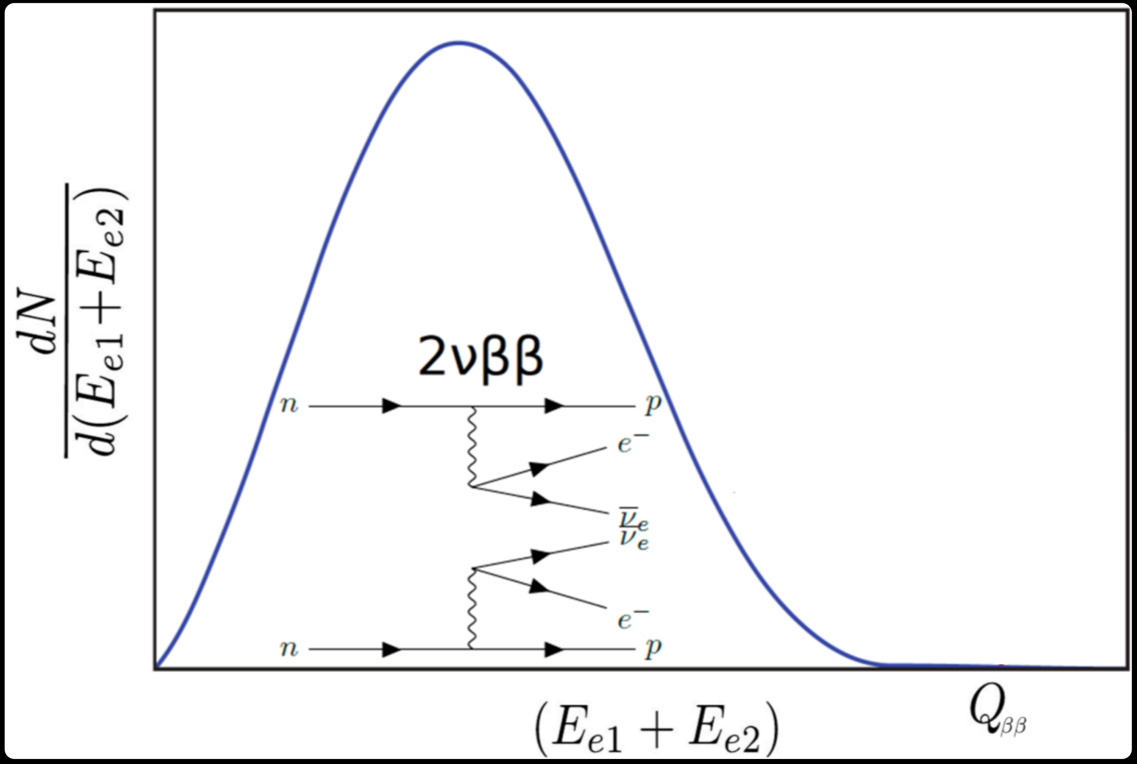
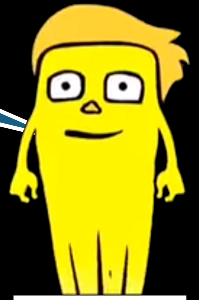
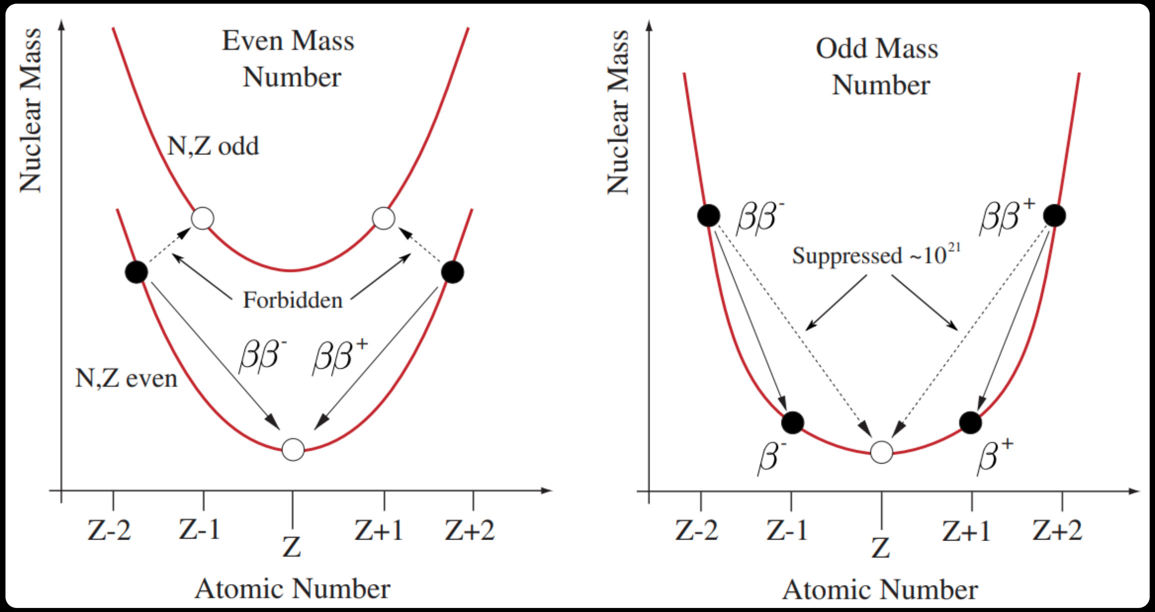


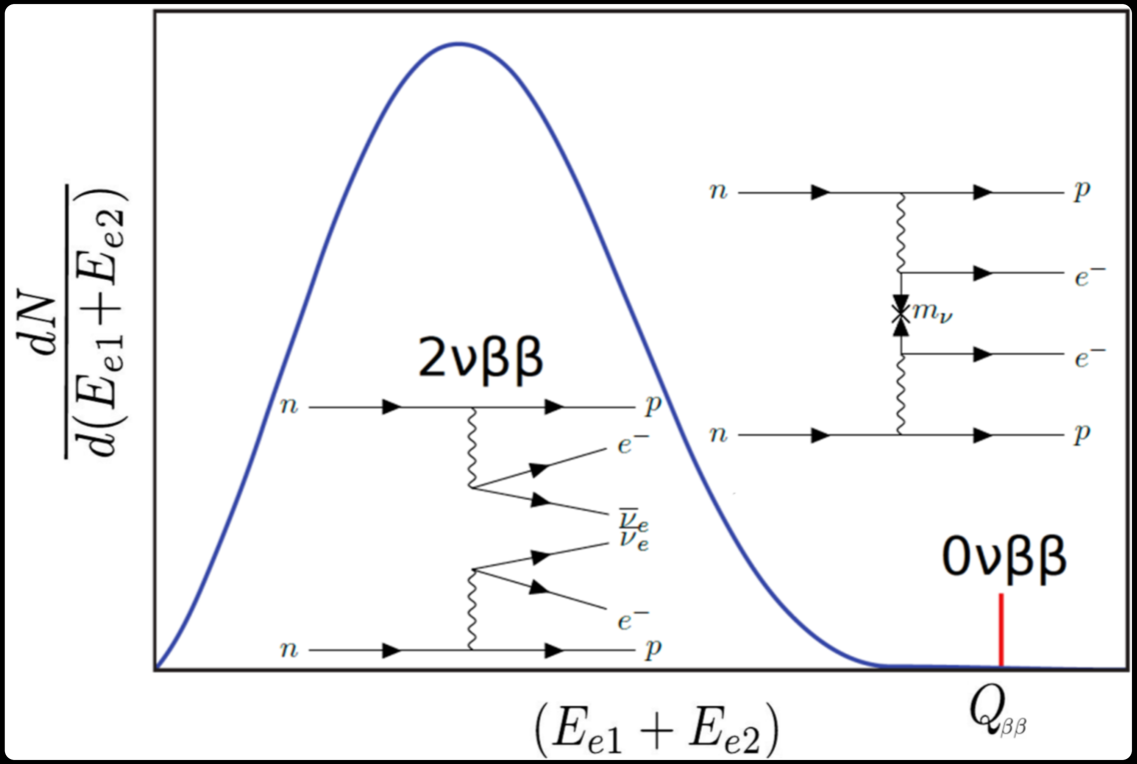


IF neutrinos are Majorana particles ...



Double Beta Decay $(2\nu\beta\beta)$





Neutrinoless Double Beta Decay $(0\nu\beta\beta)$

Sensitivity

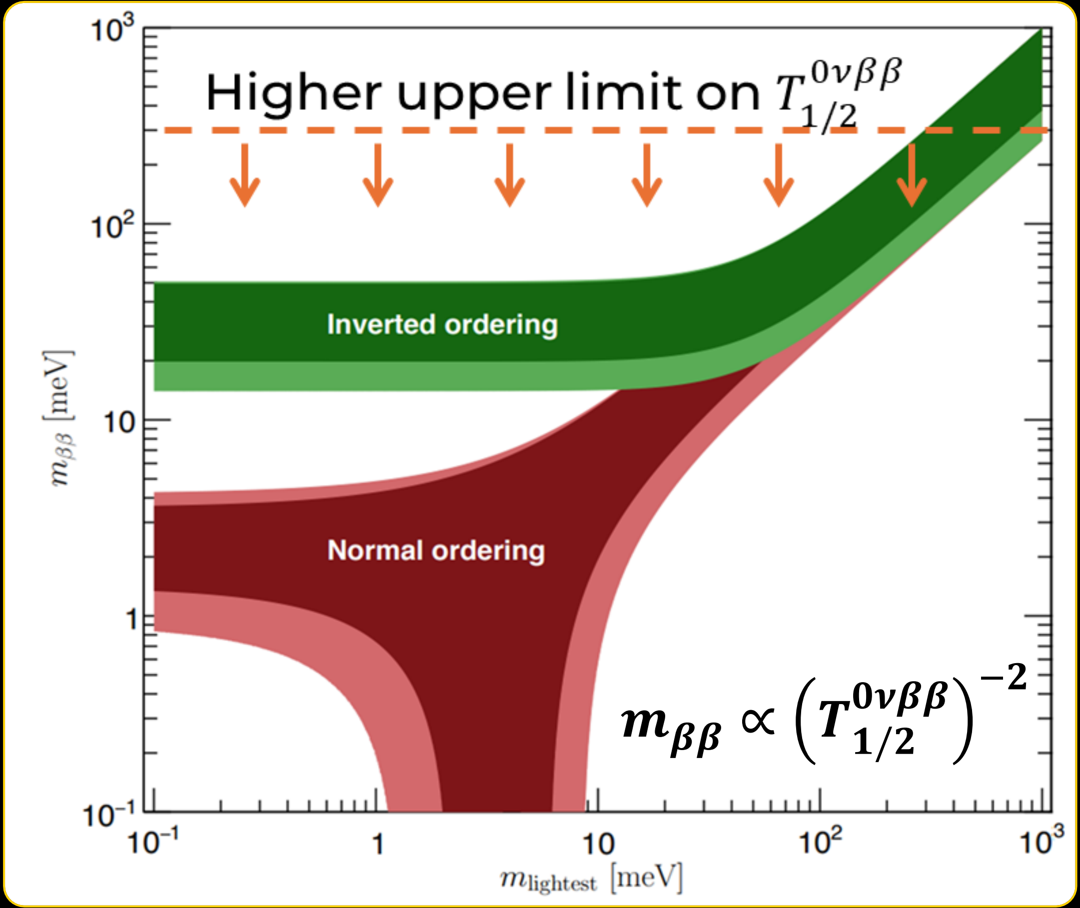
IF detected

- Matter-antimatter asymmetry ($\Delta L = 2$)
- Neutrino mass scale and hierarchy
- Majorana particles ($\nu \equiv \bar{\nu}$)

Observable

Effective Majorana Mass

$$(m_{\beta\beta})^2 = \left| \sum_{i=1,2,3} U_{e,i}^2 \, m_i \right|^2$$



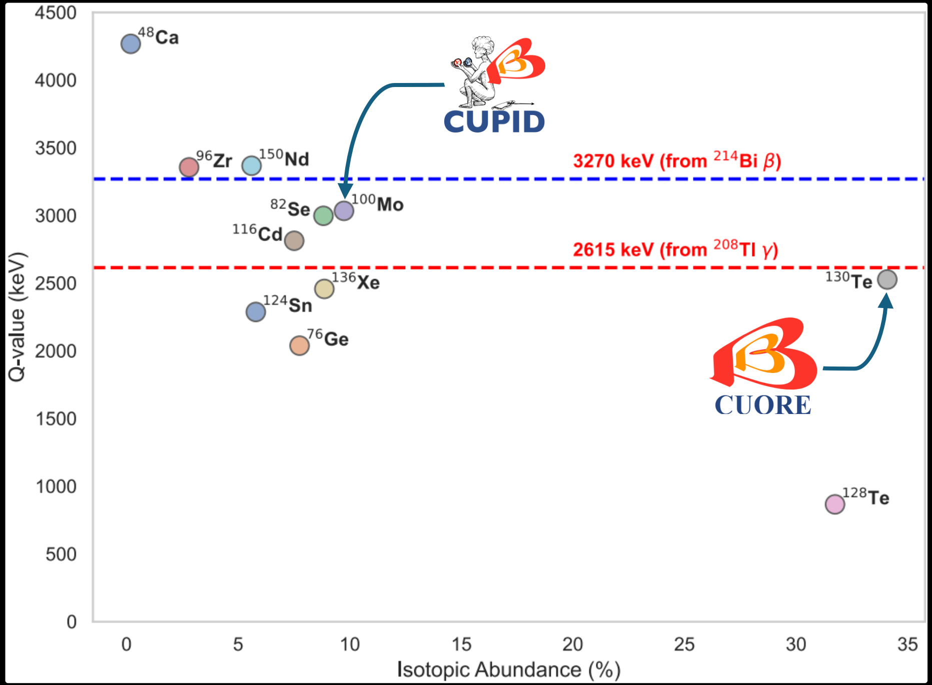
Detection Techniques

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

- $i.a.$ → Large isotopic abundance
- ϵ → High detection efficiency
- $M \cdot t$ → Large exposure (mass × livetime)
- b → Small background near the $Q_{\beta\beta}$
- ΔE → Good energy resolution

Detection Techniques

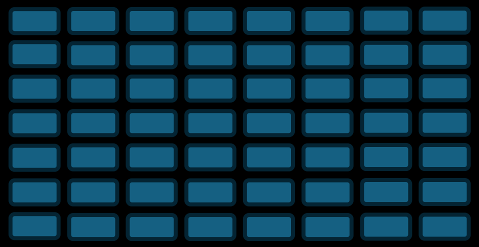
$$T_{1/2}^{0\nu\beta\beta} \propto i.a.\cdot\epsilon\cdot\sqrt{\frac{M\cdot t}{b\cdot\Delta E}}$$



MONOLITHIC DETECTOR

- ❖ Shelf-shielding
- ❖ Scalability

➔ Scintillators: KamLAND-Zen, SNO
➔ TPCs: nEXO, NEXT

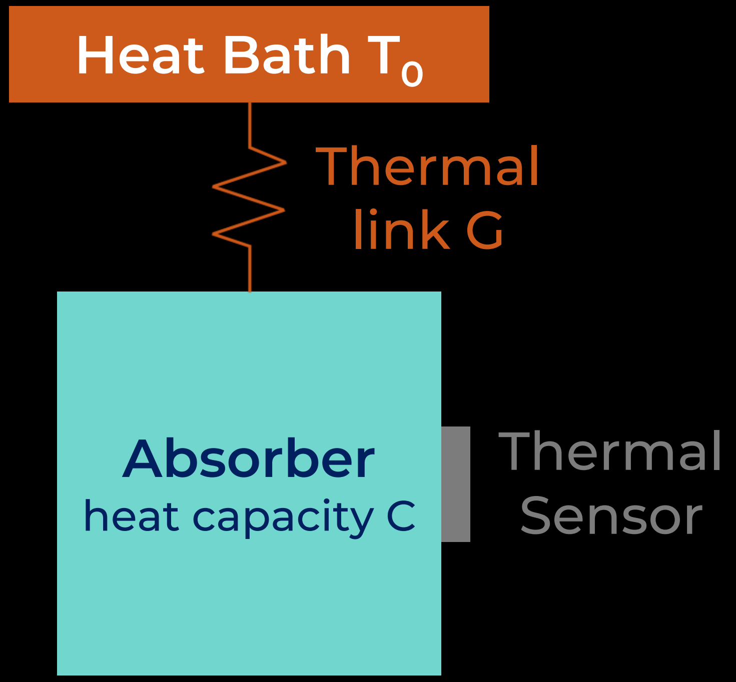


GRANULAR DETECTORS

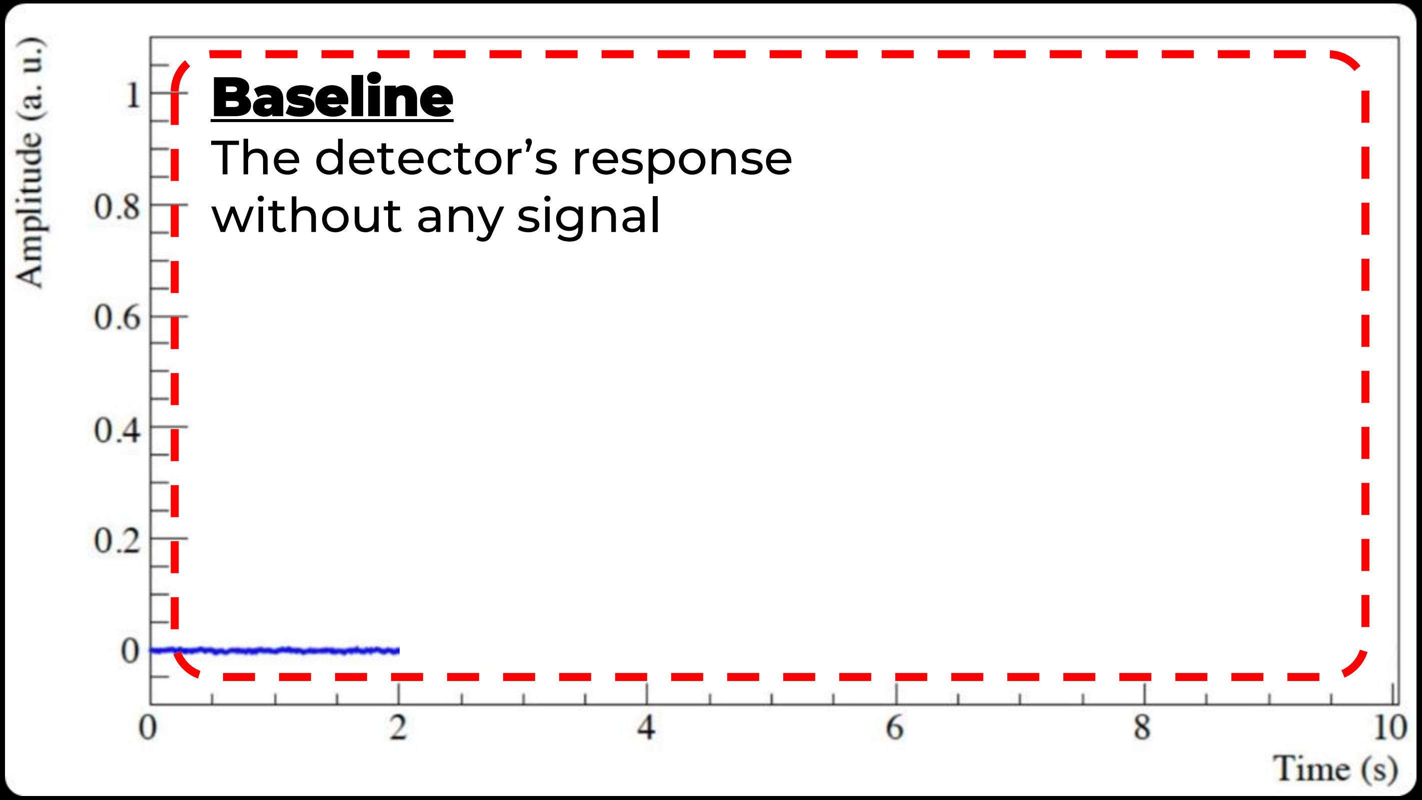
- ❖ Good Energy resolution
- ❖ Staging

➔ Bolometers: CUORE, CUPID
➔ Semiconductors: GERDA, LEGEND

Cryogenic Calorimeters



$T = T_0$



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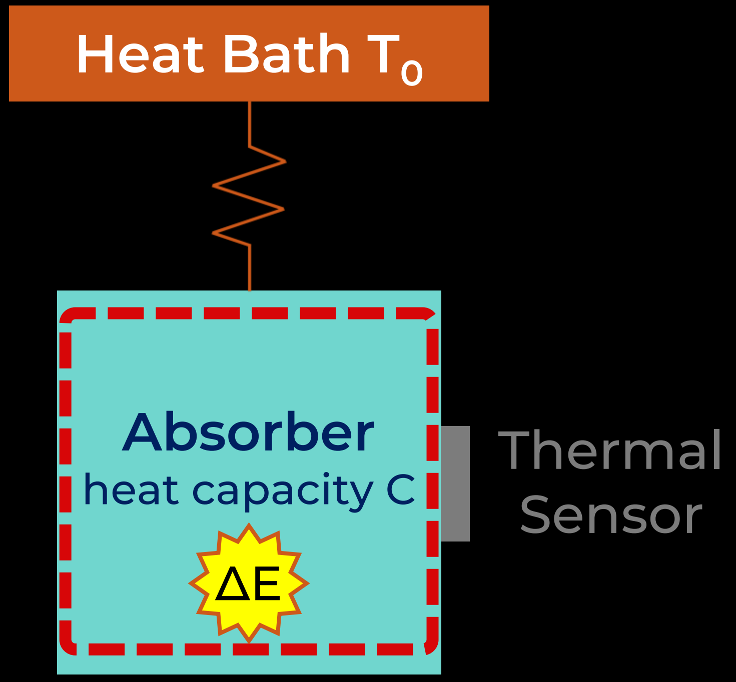

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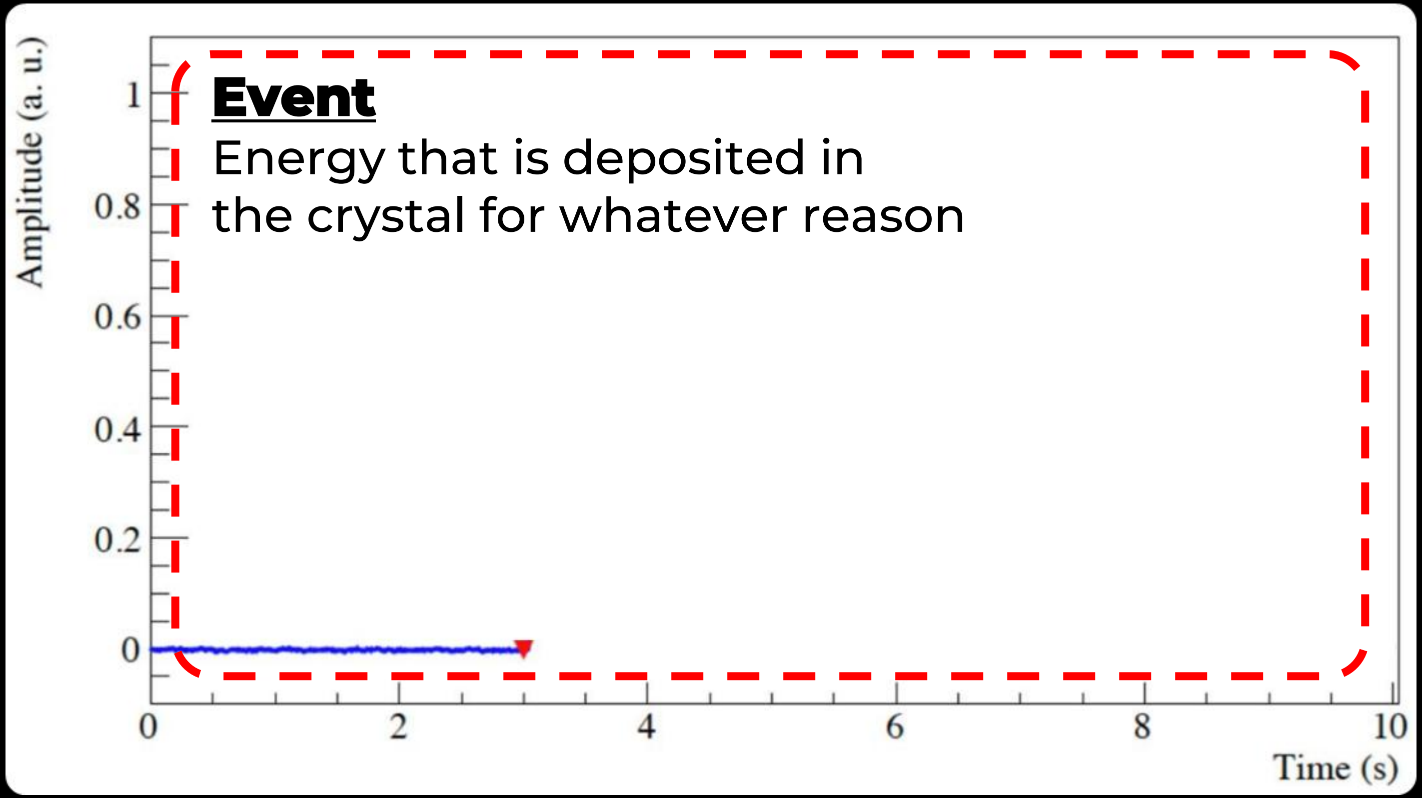

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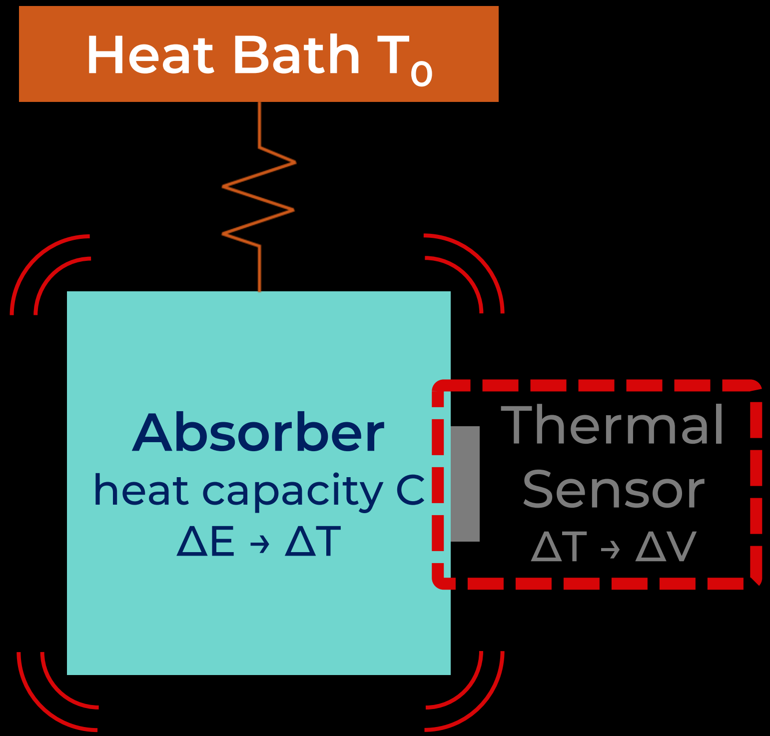
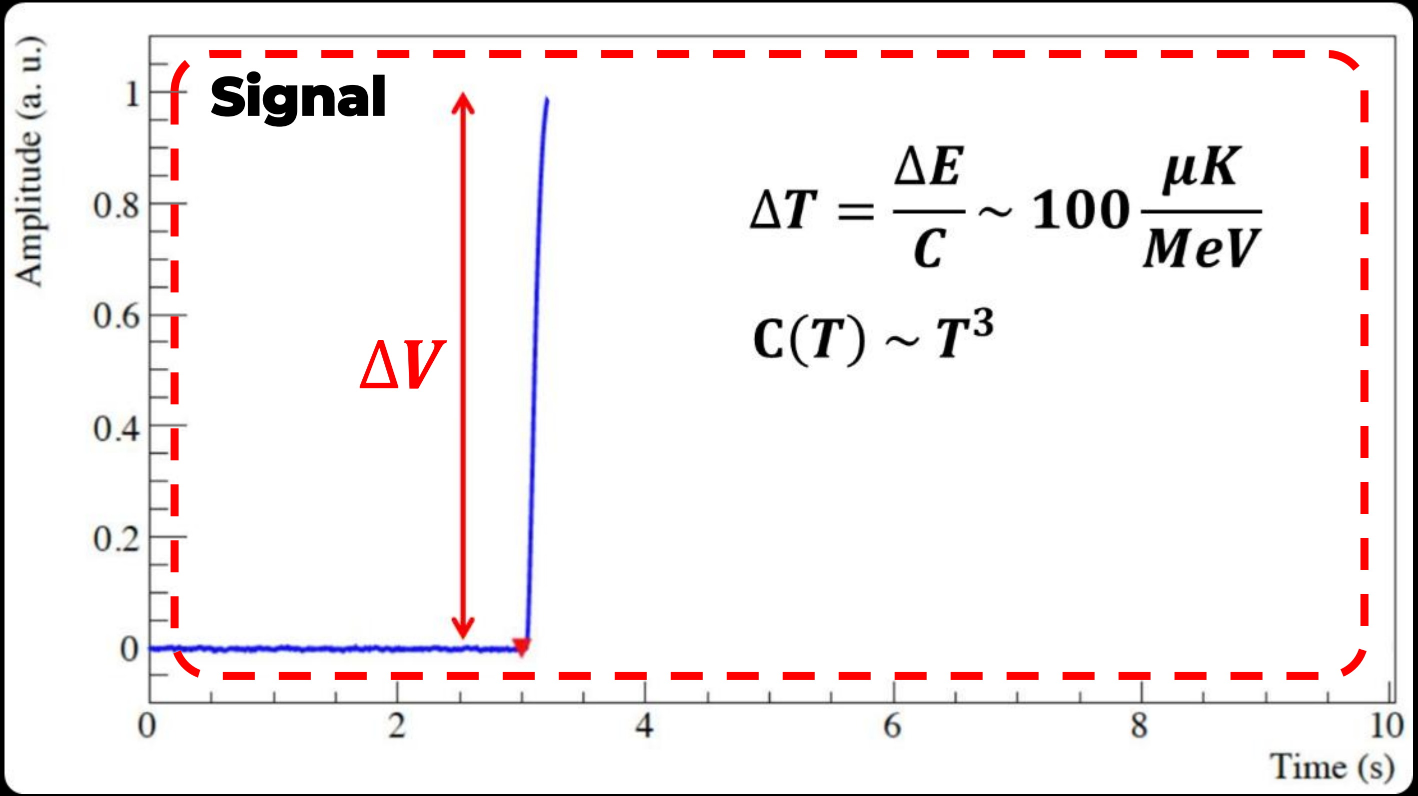


$$T = T_0 + \Delta T$$



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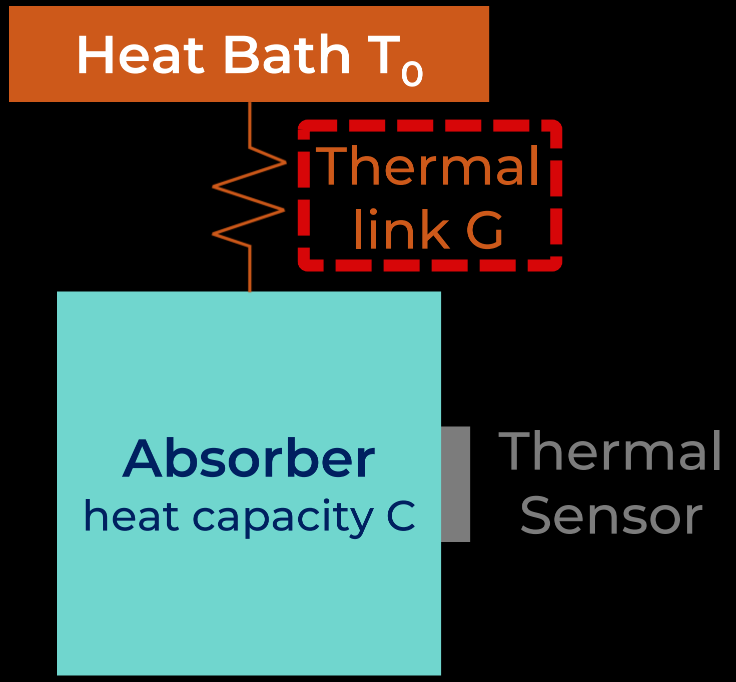

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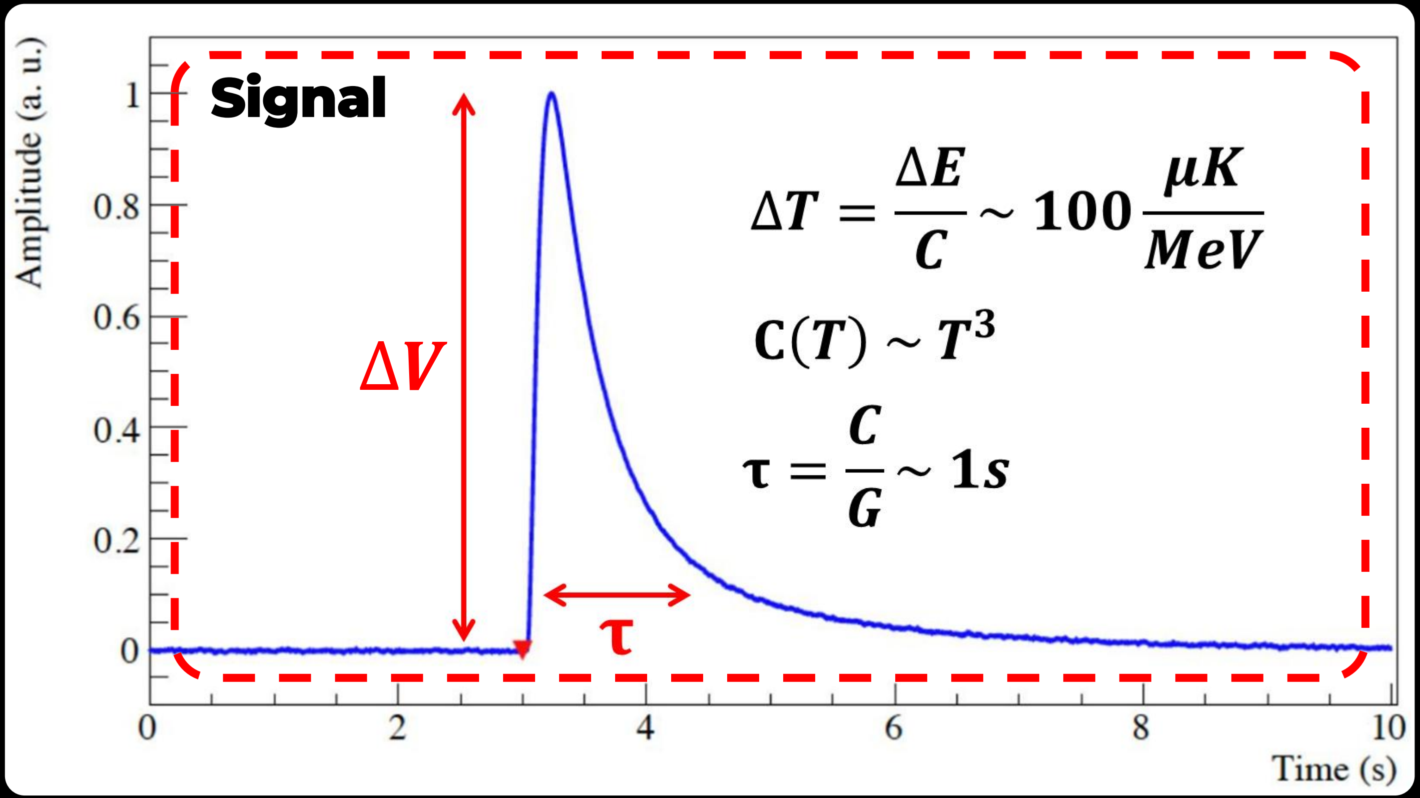


Slow pulses require a small rate of events

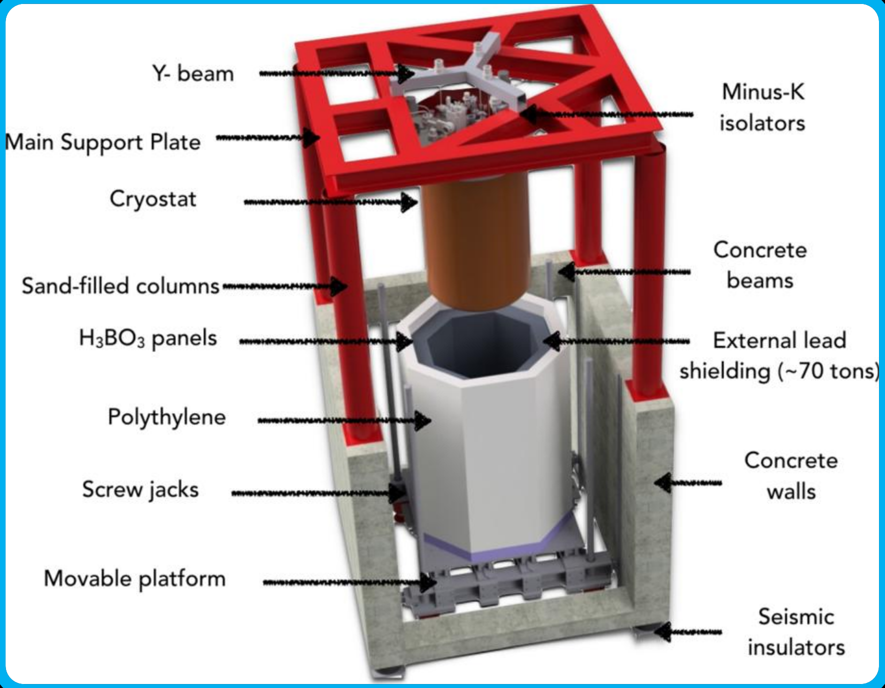
Challenges

Low Radioactivity

Challenges

Low Radioactivity

Low Vibrations



Challenges

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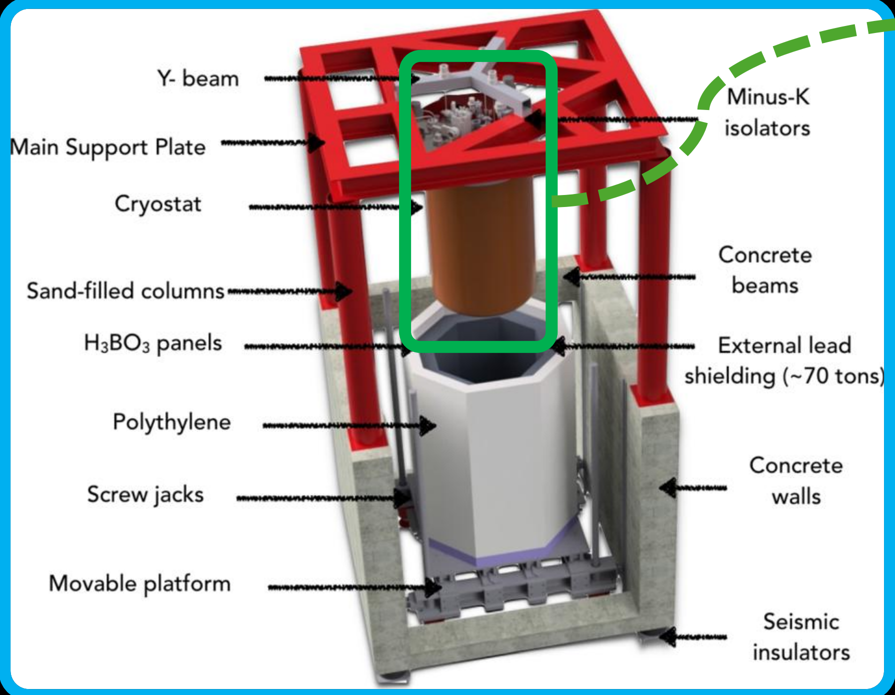
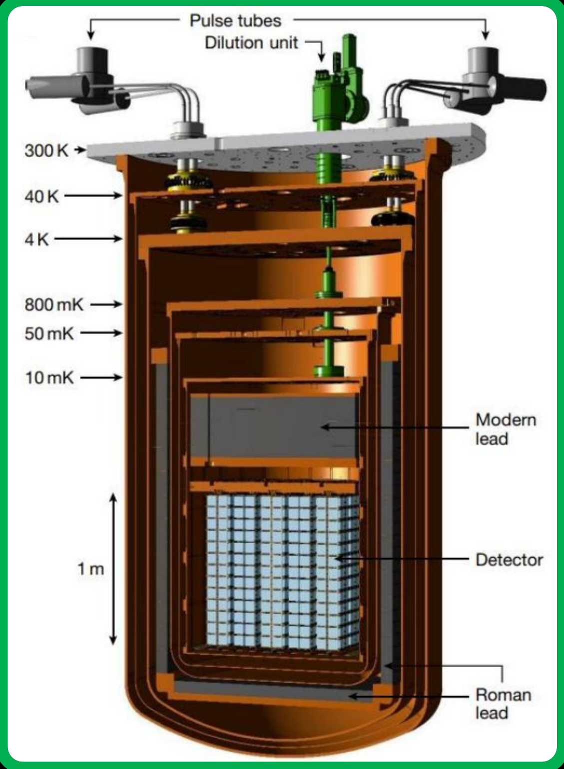




Low Temperatures

5x5x5 cm^3 crystals

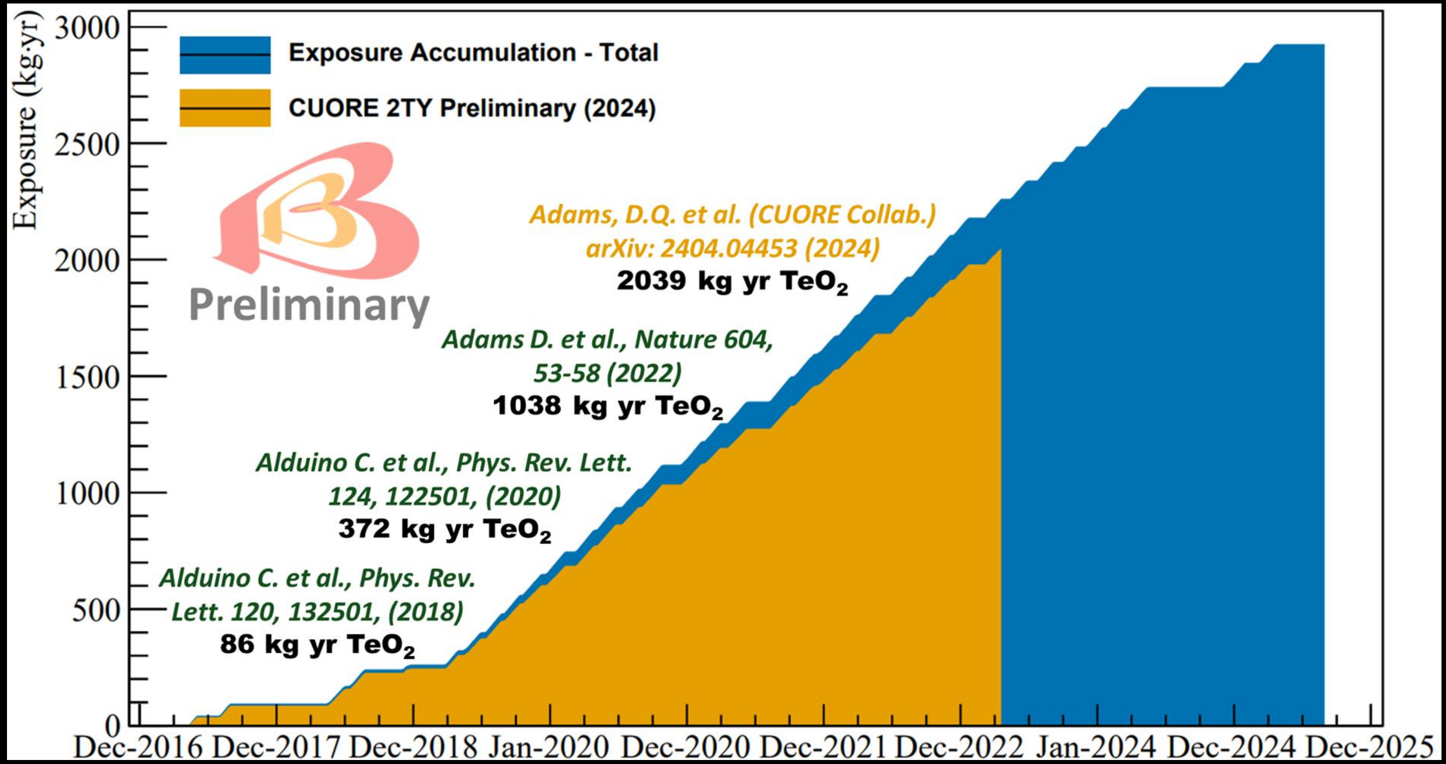
19 towers

13 floors

4 positions

CUORE with ^{130}Te

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



CUORE

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

5x5x5 cm^3 crystals
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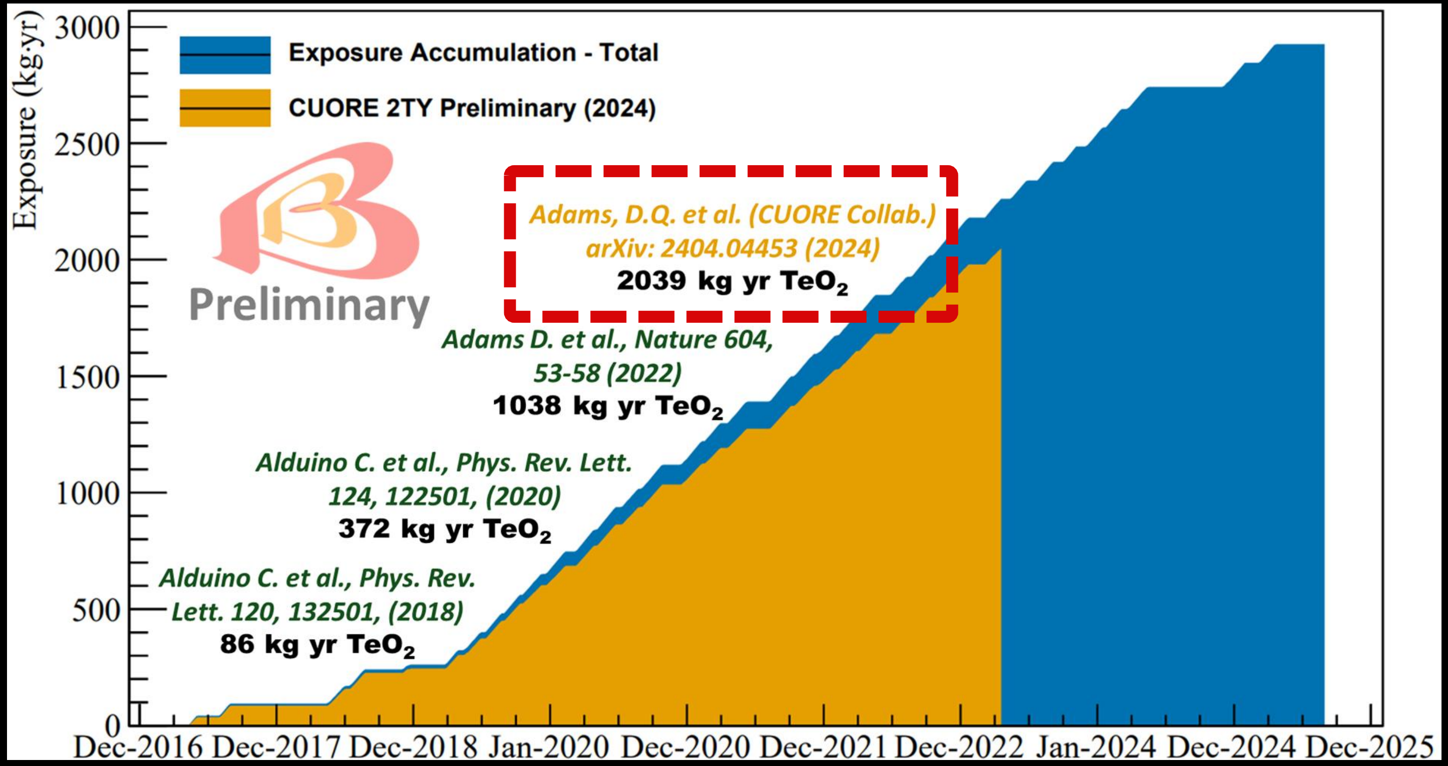
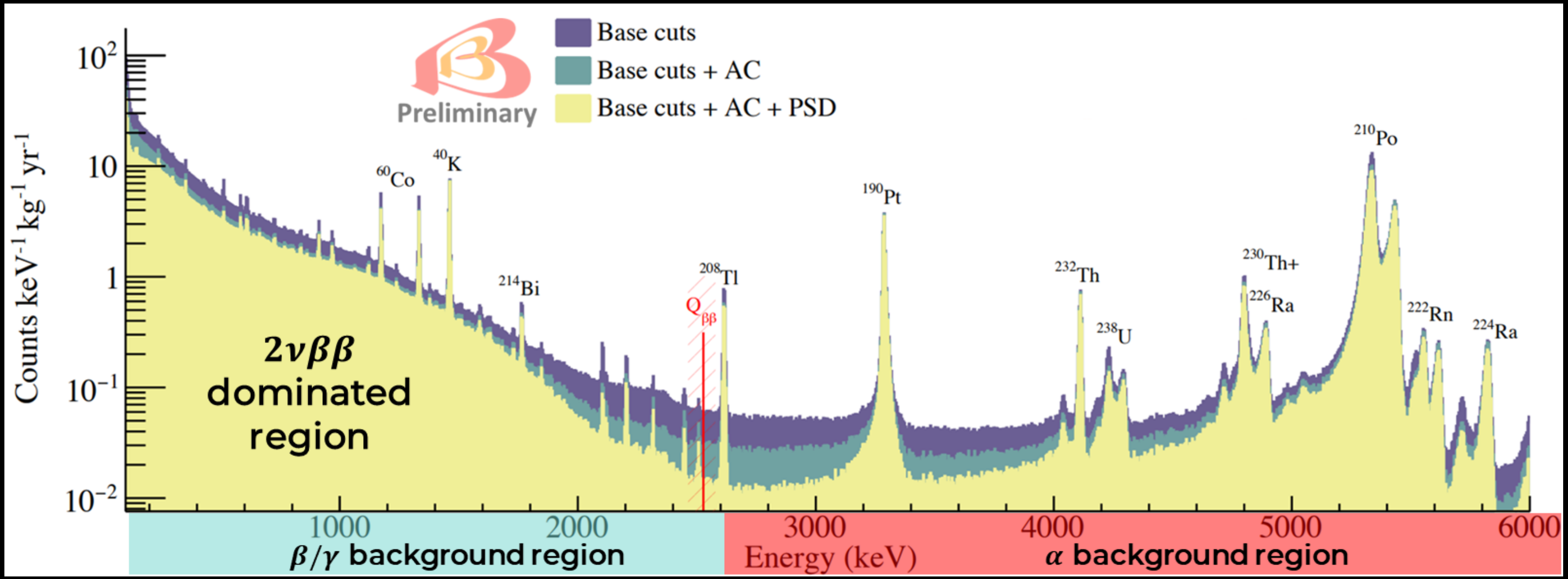


Cryogenic **U**nderground **O**bservatory for **R**are **E**vents

CUORE - Results

- ❖ Data-driven background model
  ➔ limits on other rare events
- ❖ Stable operation of a tonne-scale milli-kelvin cryogenic calorimeter



CUORE - Results

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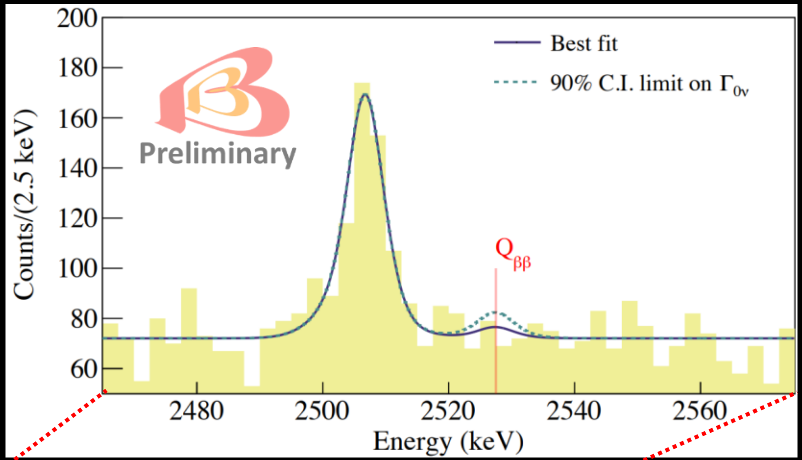
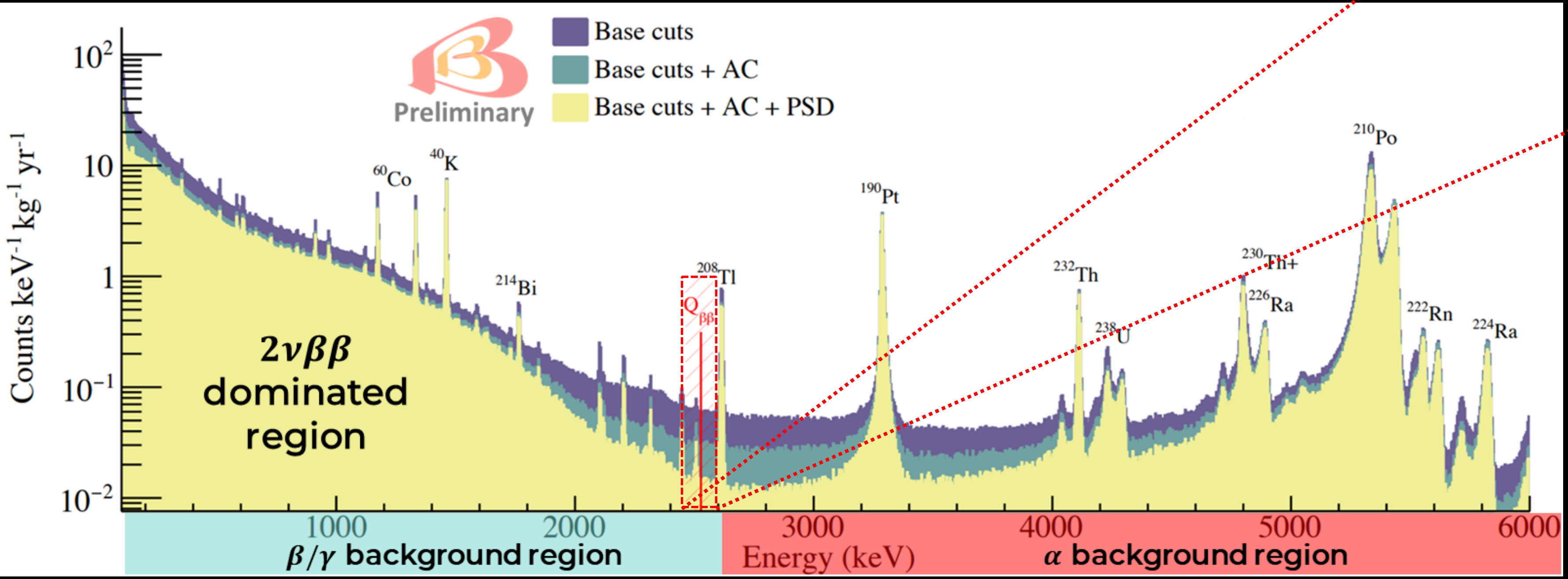
- ❖ Stable operation of a tonne-scale milli-kelvin cryogenic calorimeter

$T(^{130}\mathrm{Te})^{0\nu\beta\beta}_{1/2} > 3.8 \times 10^{25}$ yr (90% C.I.)





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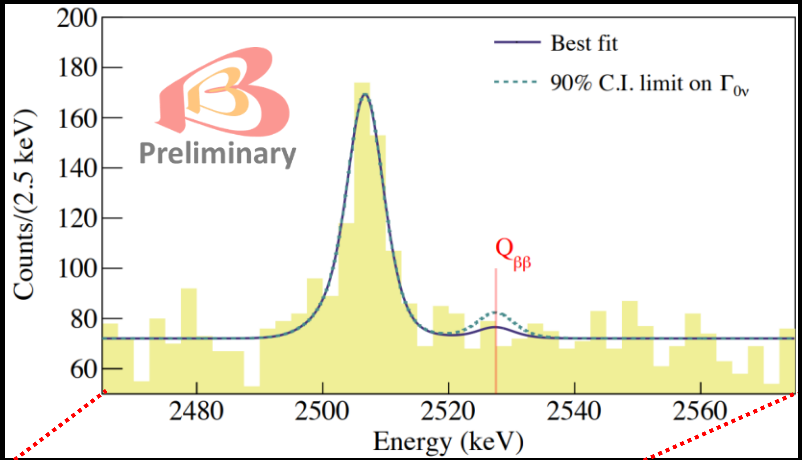
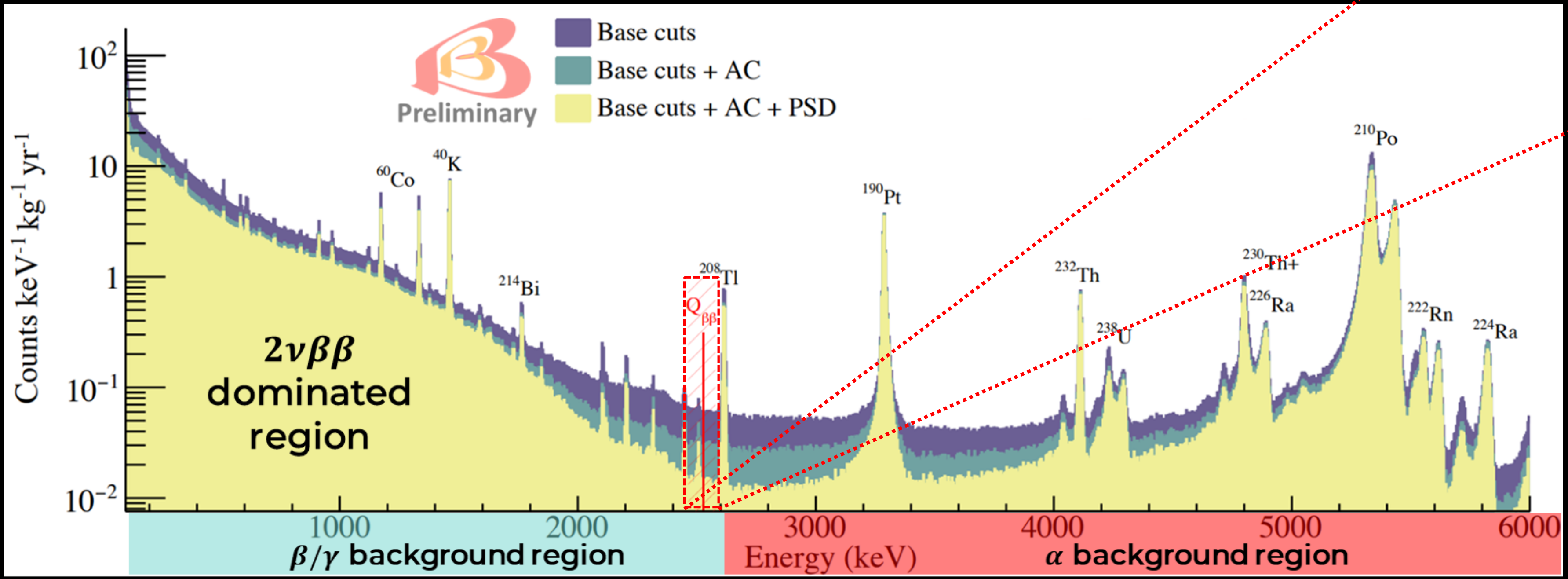


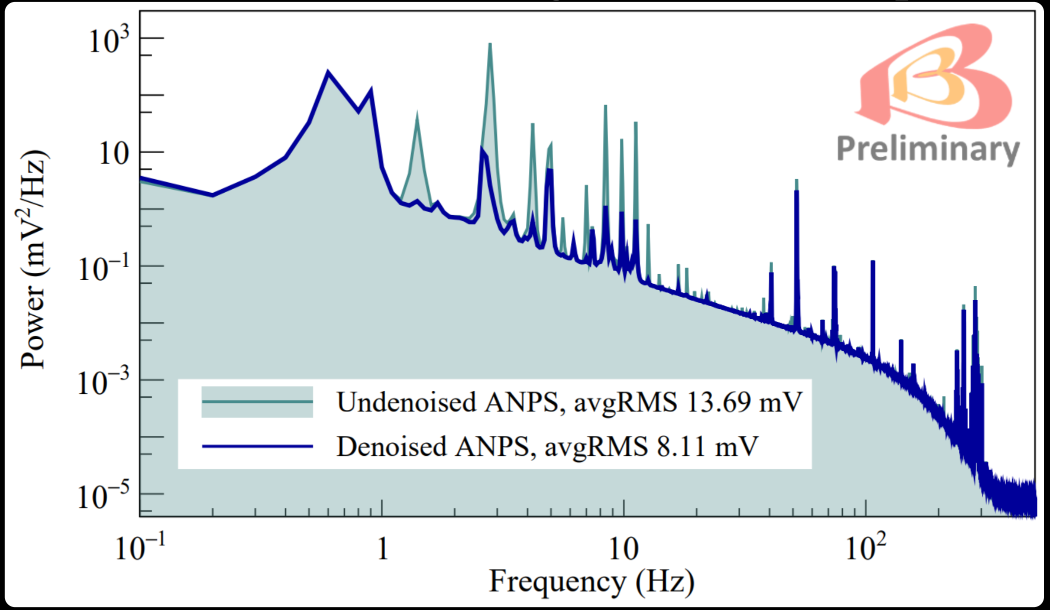


Goal: CUORE 3TY (effective)

... and limitations

Noise spoils the sensitivity

Average Noise Power Spectra



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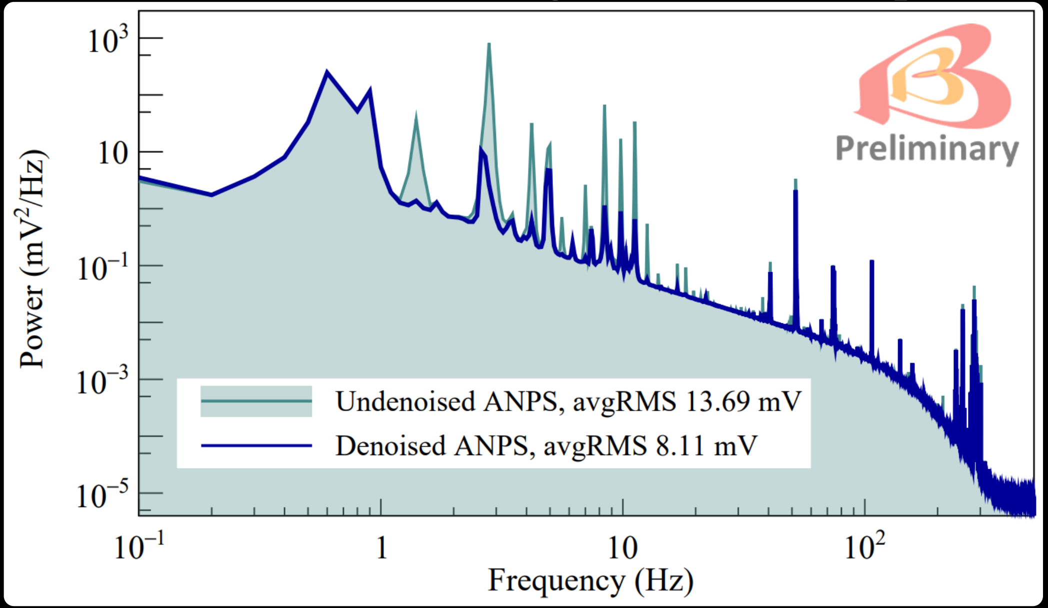
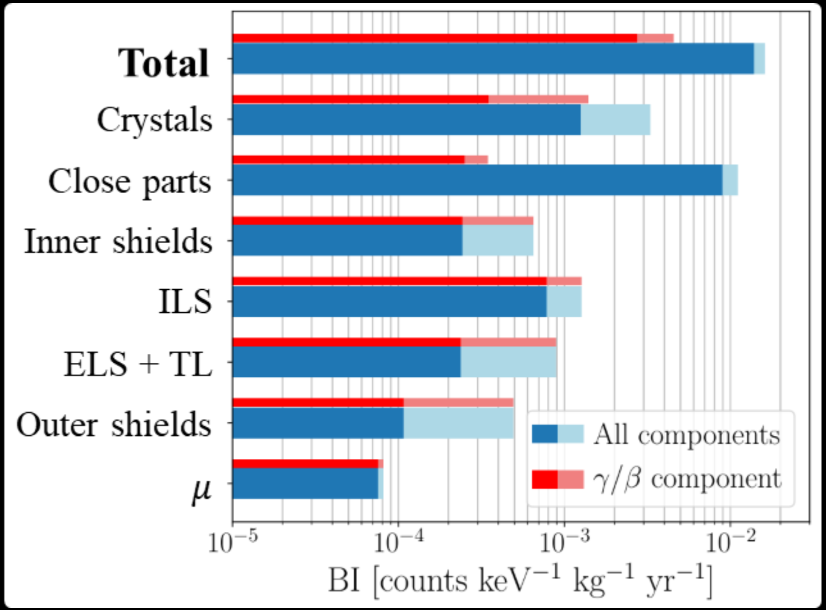
Average Noise Power Spectra





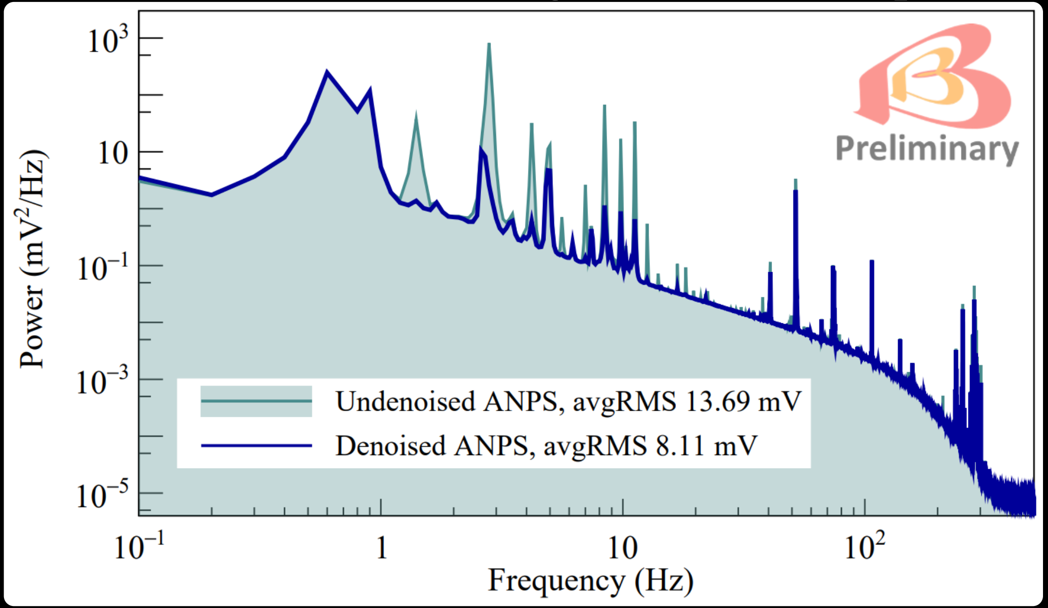
CUORE is background-limited

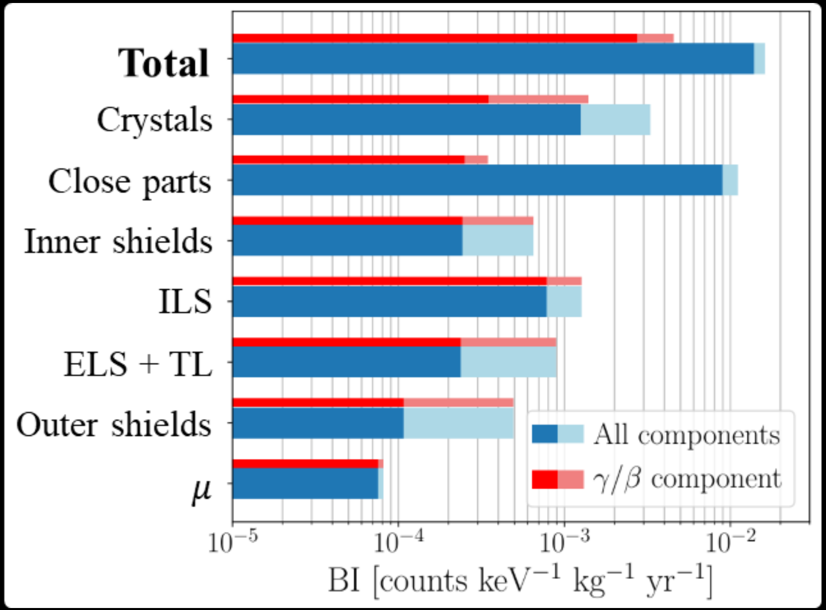
Background Index

... and limitations

Noise spoils the sensitivity
→ Denoising techniques

Average Noise Power Spectra





Background Index

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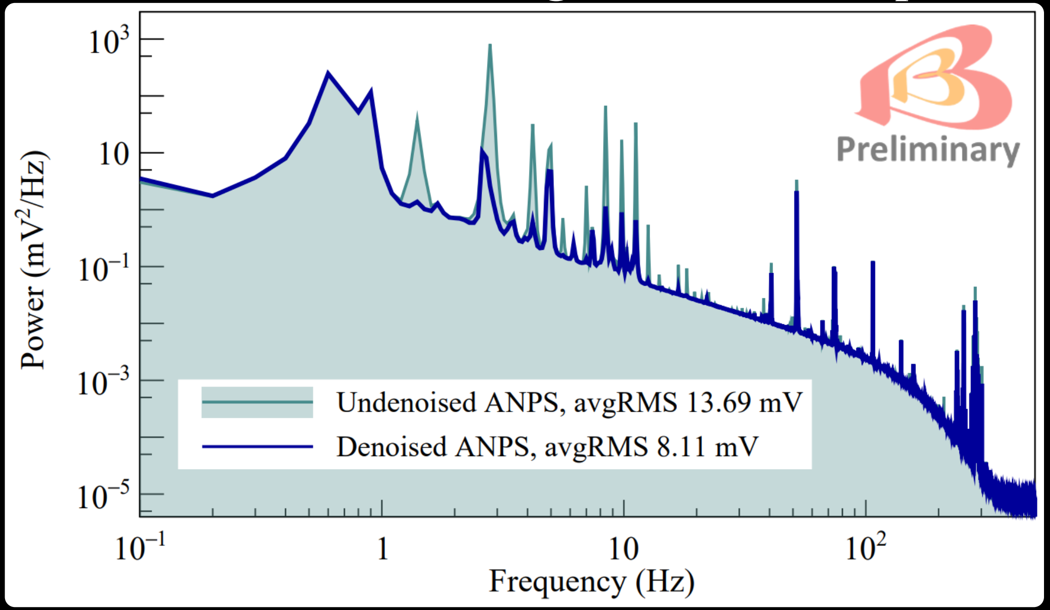
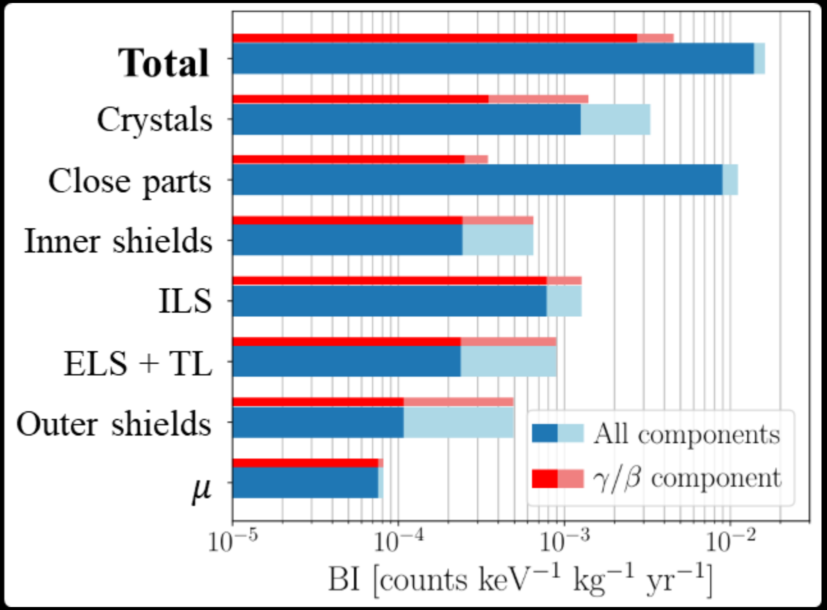




Background Index

CUORE is background-limited
→ Particle Identification

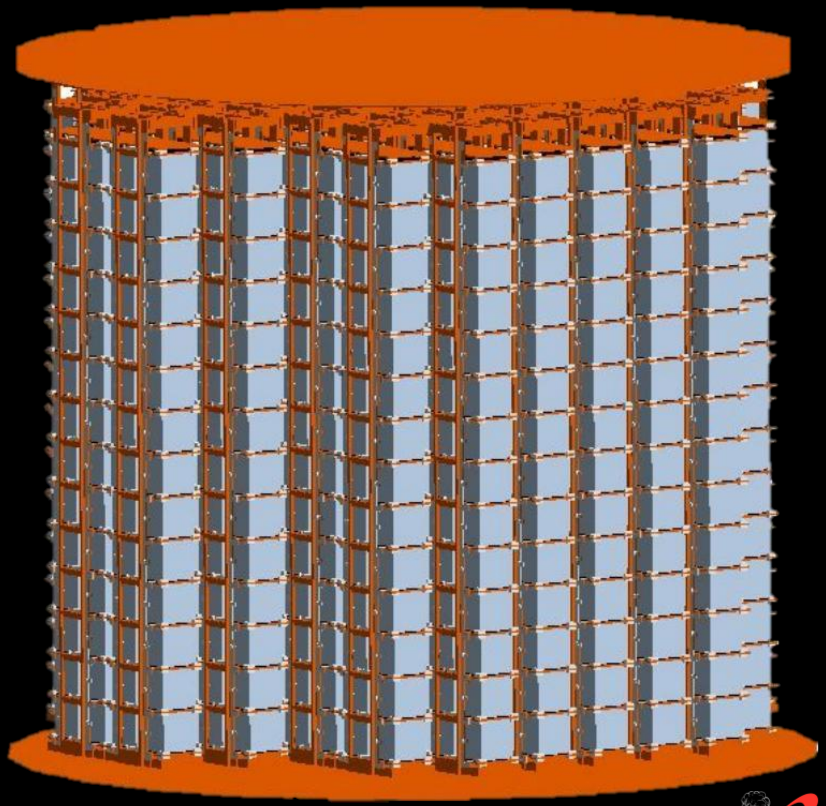
CUPID

CUORE's successor

^{130}Te

34% (i.a.)

2517.5keV ($Q_{\beta\beta}$)

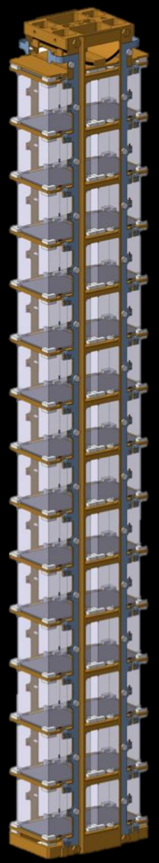


4.5x4.5x4.5 cm^3 crystals

57 towers

14 floors

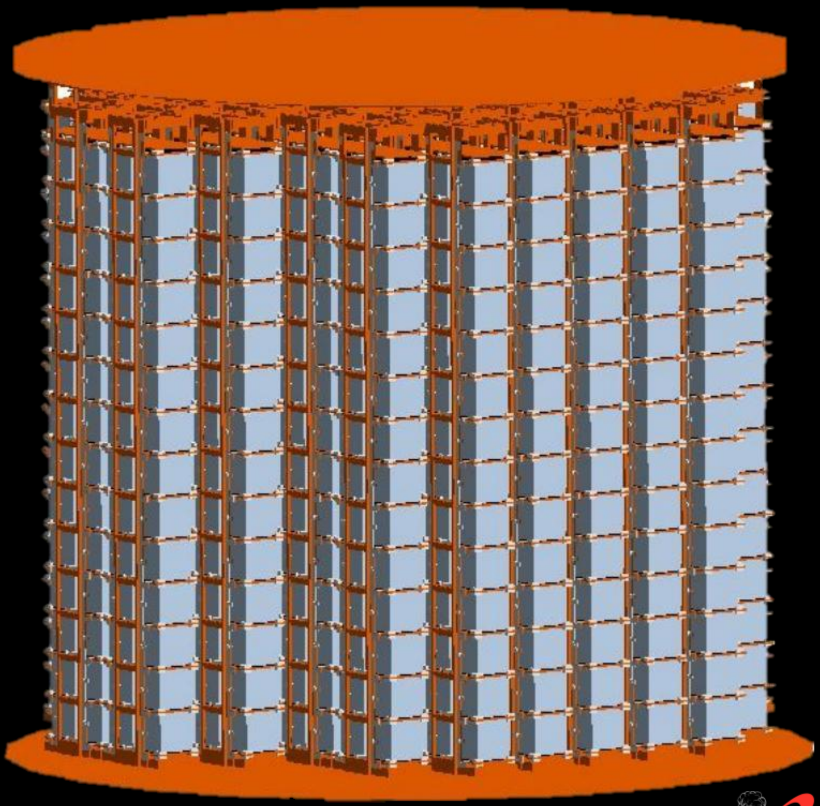
2 positions



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

CUPID

CUORE's successor



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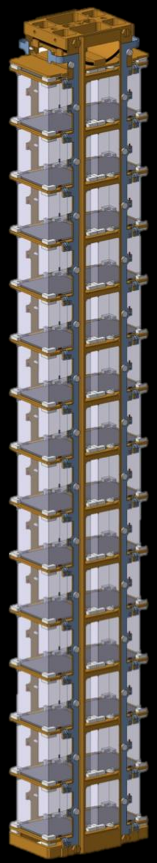


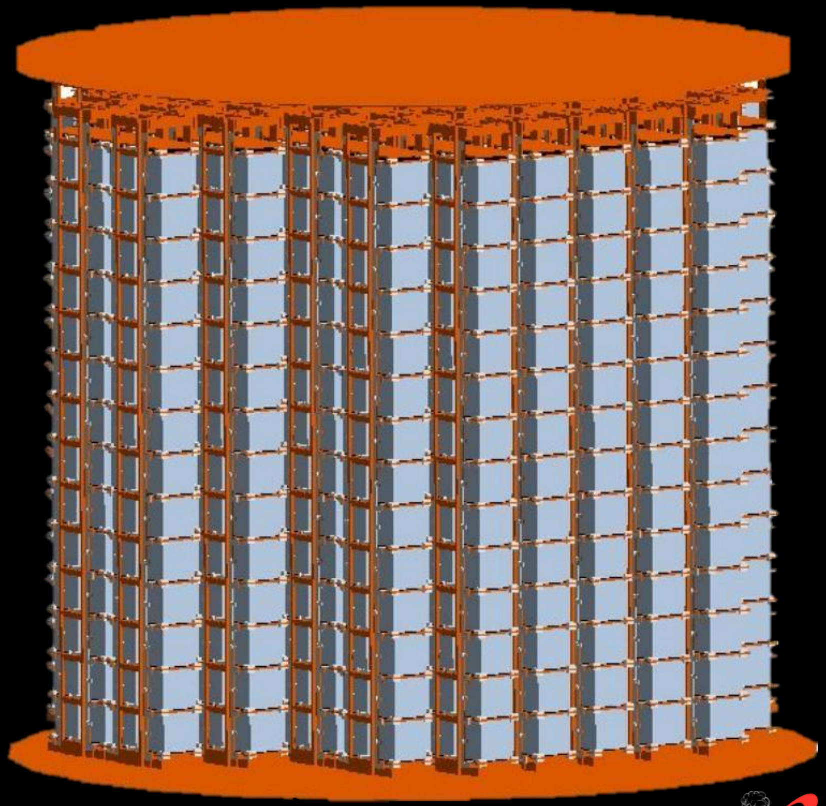
CUORE **U**pgraded with **P**article **ID**entification

CUPID

CUORE's successor

^{100}Mo

10% (i.a.)
3034keV ($Q_{\beta\beta}$)



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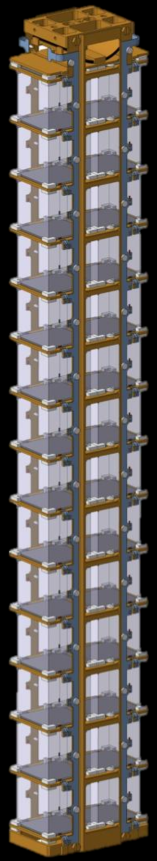


CUORE Upgraded with Particle IDentification

CUPID

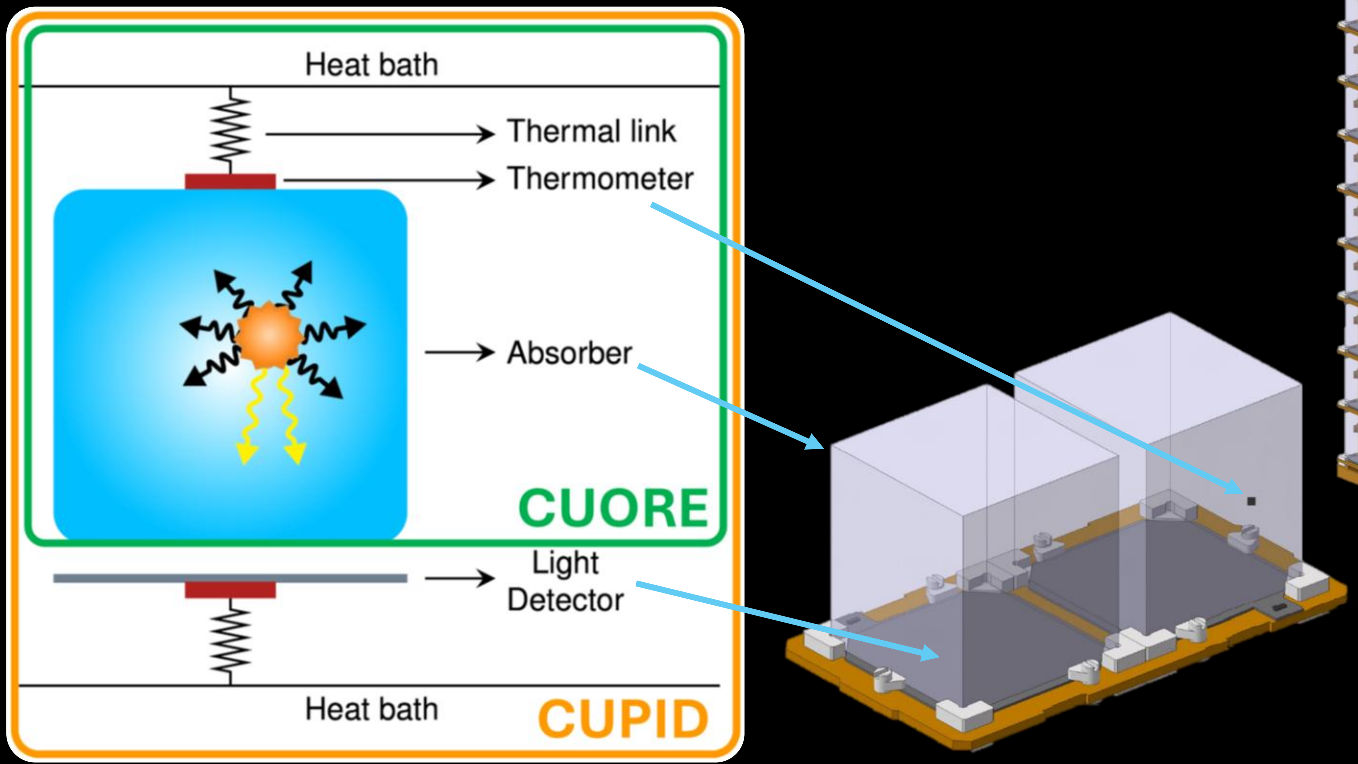
CUORE's successor

^{100}Mo

10% (i.a.)

3034keV ($Q_{\beta\beta}$)

Double readout strategy



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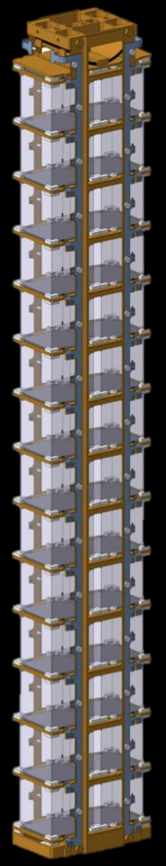


CUORE **U**pgraded with **P**article **ID**entification

CUPID

CUORE's successor

^{100}Mo

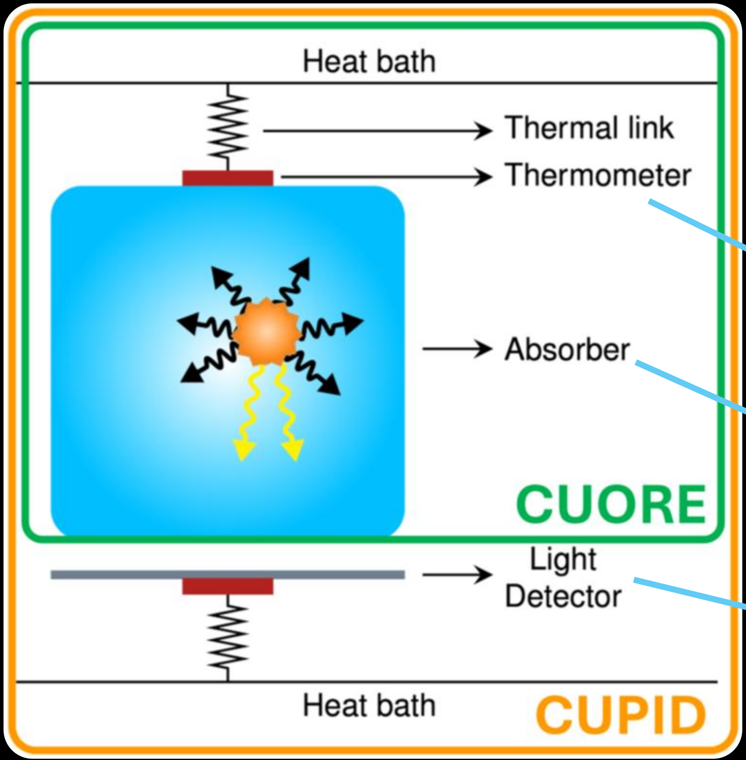
10% (i.a.)

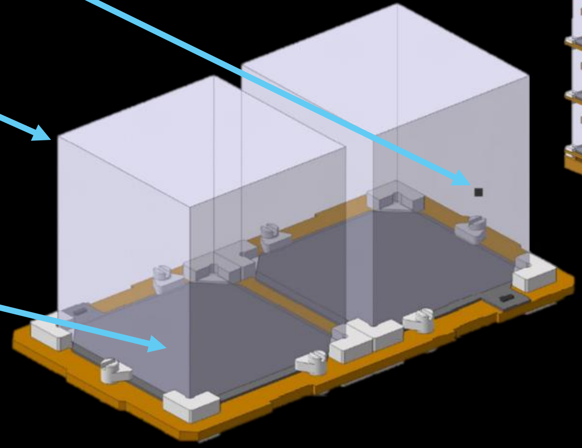
3034keV ($Q_{\beta\beta}$)

Double readout strategy

GOAL: $T_{1/2}^{0\nu\beta\beta} > 1.0 \times 10^{27}$ yr

(90% C.L. with 10 yr of livetime)





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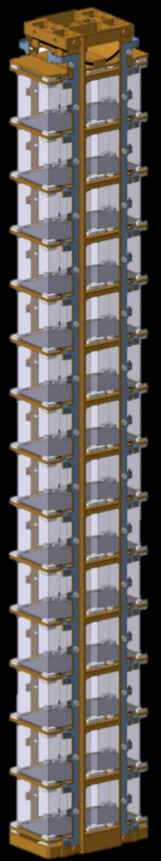
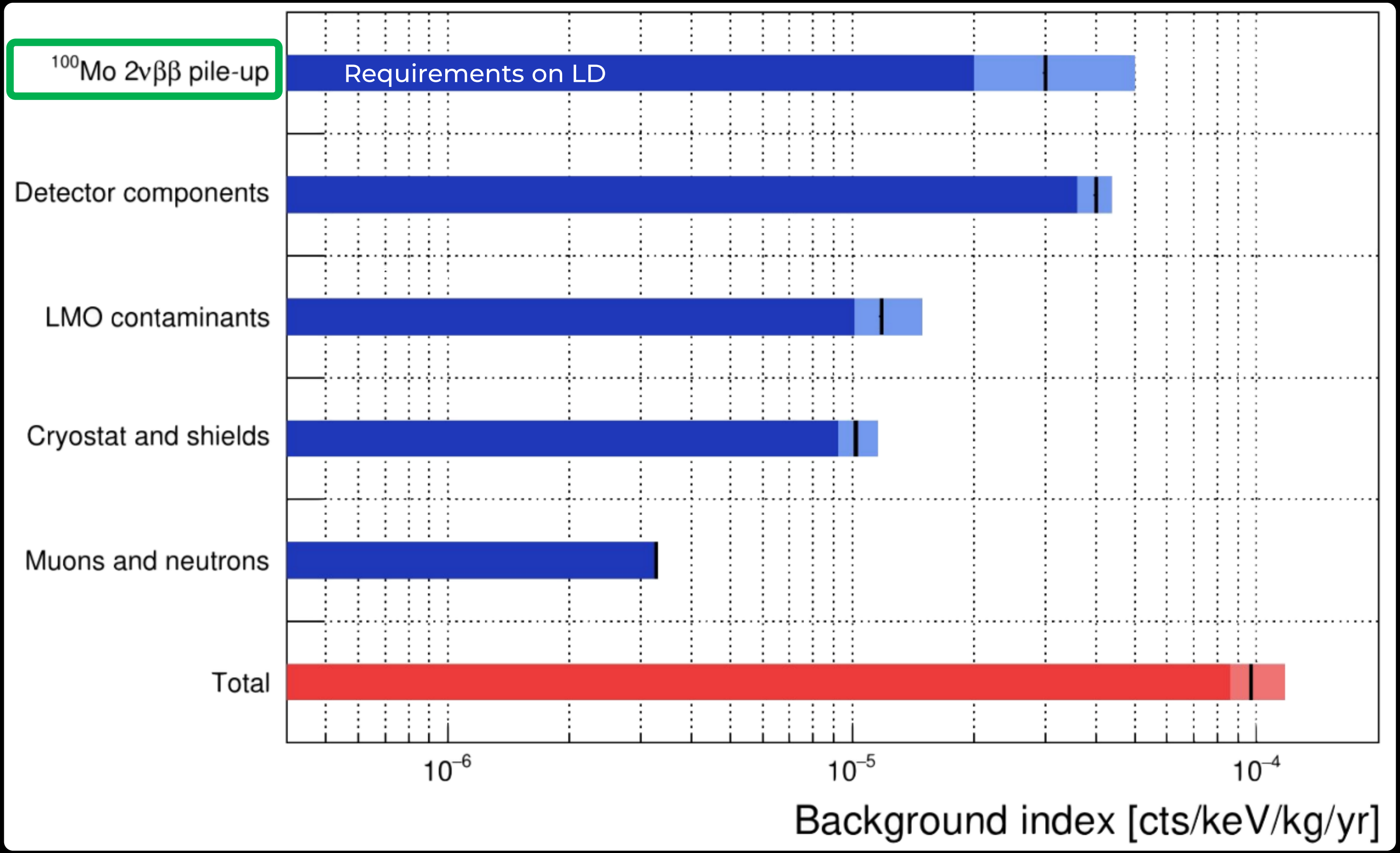


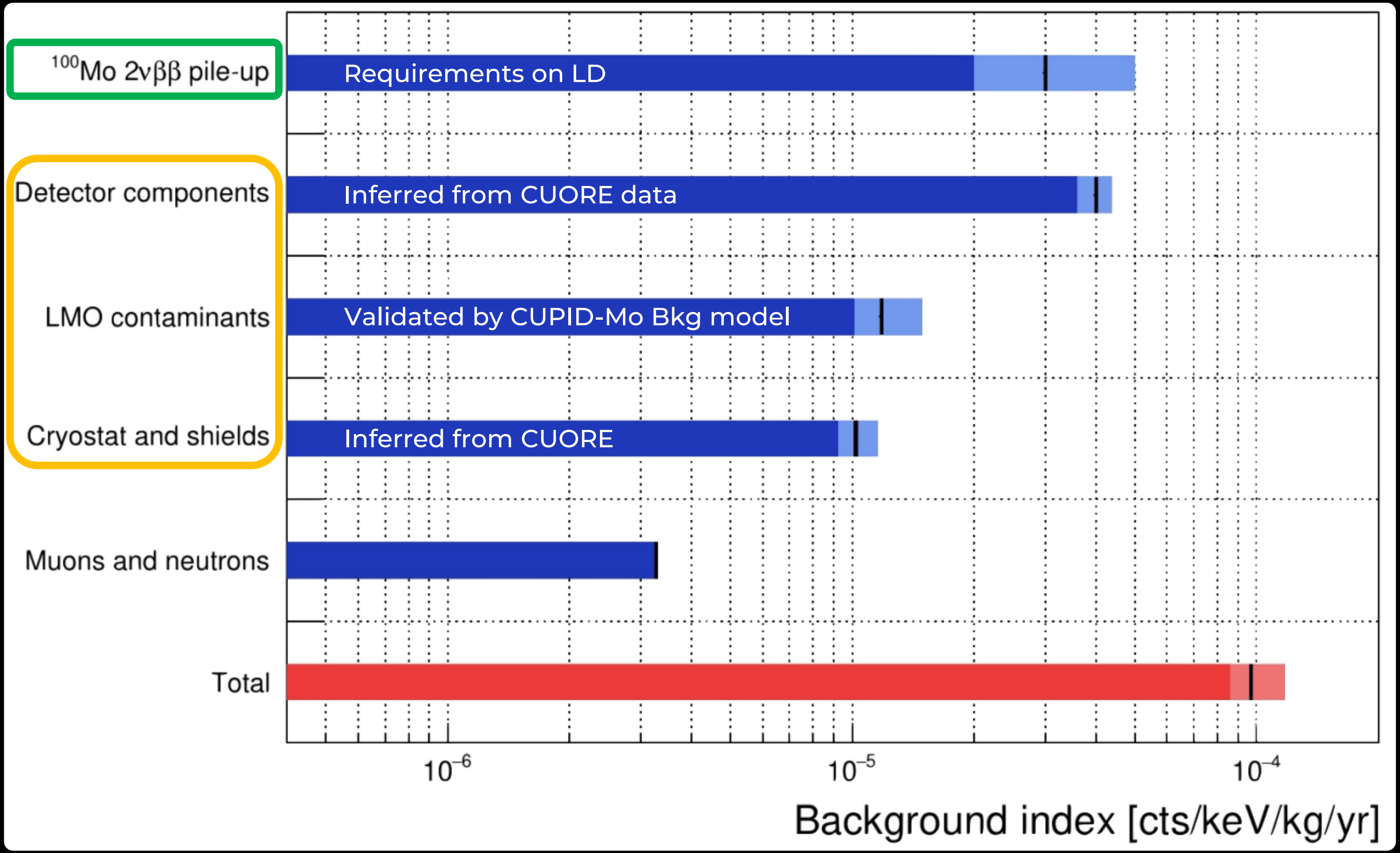
CUORE **U**pgraded with **P**article **ID**entification

CUPID – Background Budget



- ❖ Improve the time resolution
- ❖ Pile-up rejection

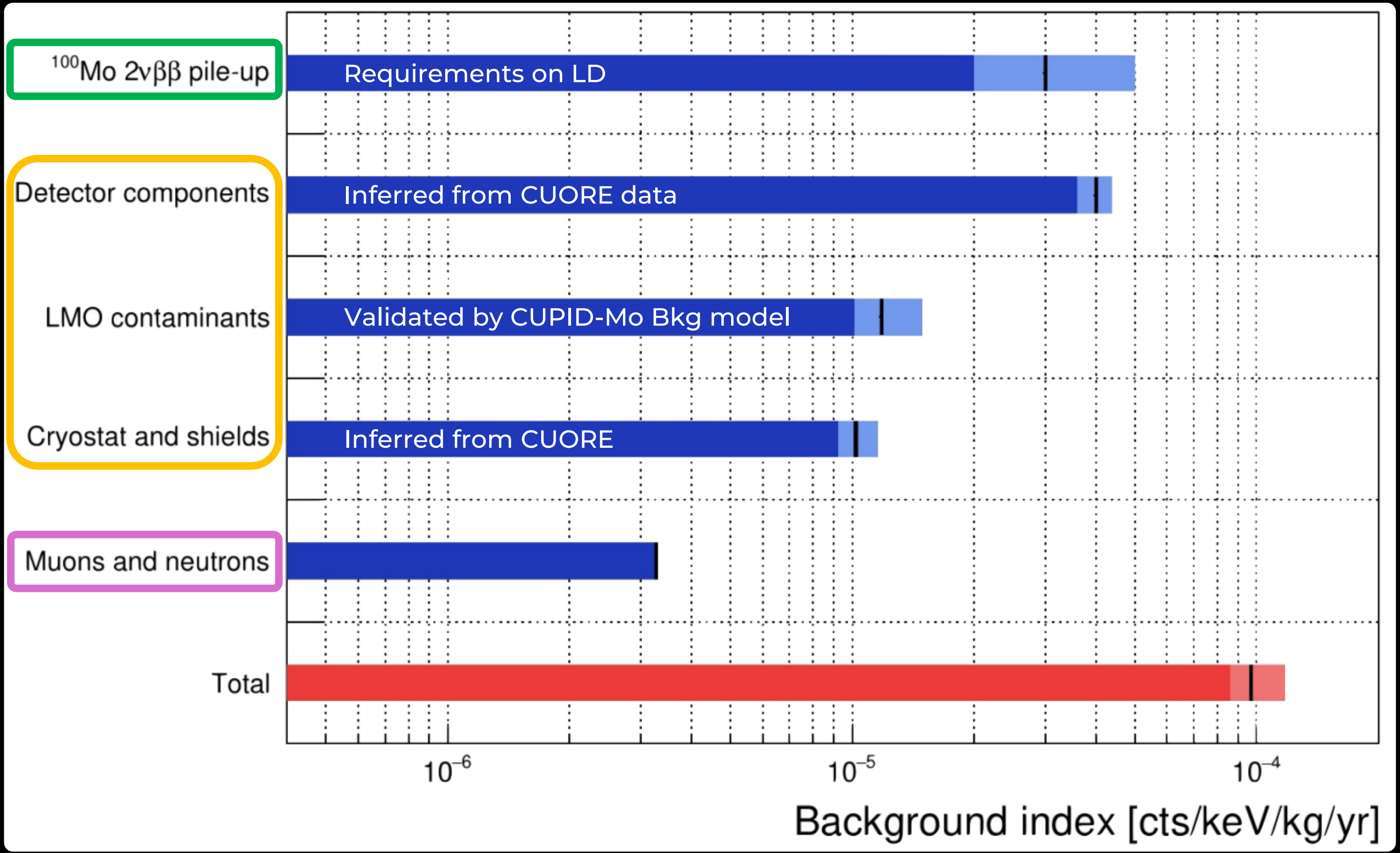
CUPID – Background Budget



- ❖ Improve the time resolution
- ❖ Pile-up rejection

- ❖ Noise reduction
- ❖ Radiopurity
- ❖ Delayed coincidence study

CUPID – Background Budget



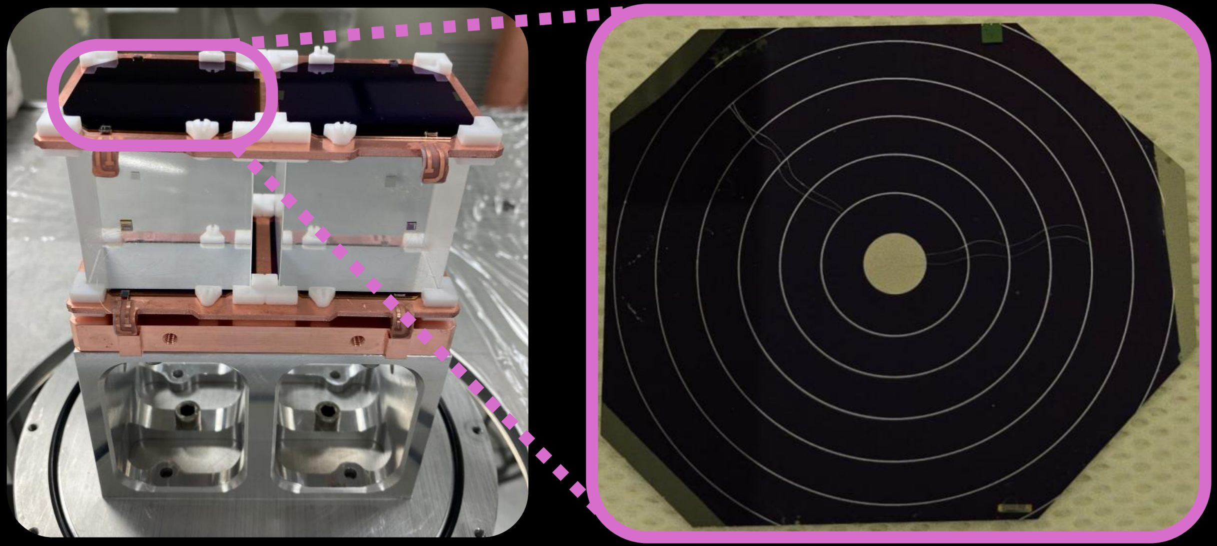
- Improve the time resolution
- Pile-up rejection

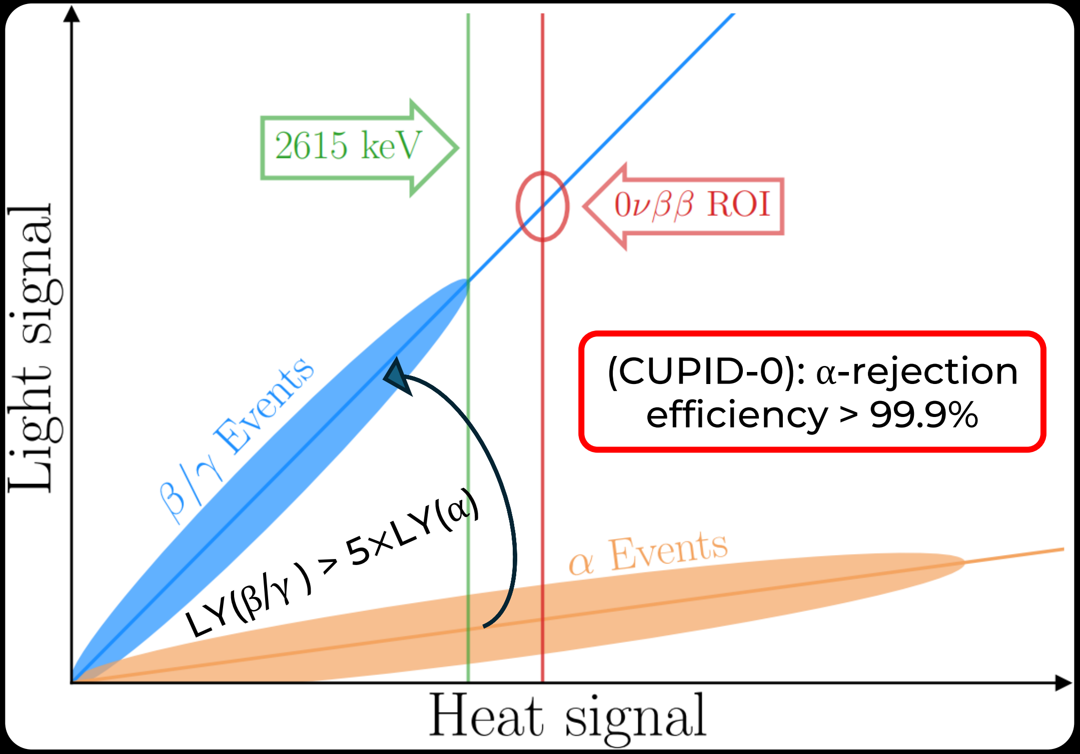
- Noise reduction
- Radiopurity
- Delayed coincidence study

- Muon tagger veto detectors
- Neutron absorbers

Light Detectors

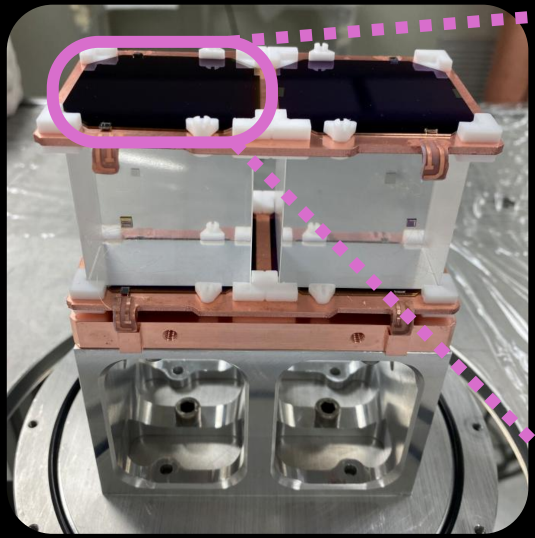
❖ Particle IDentification

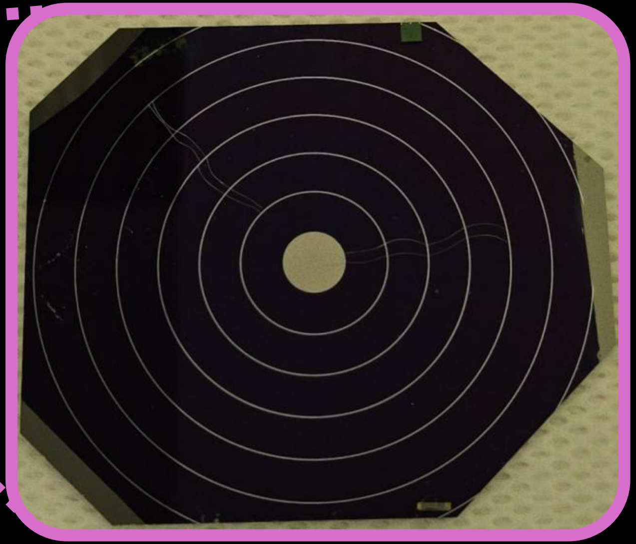


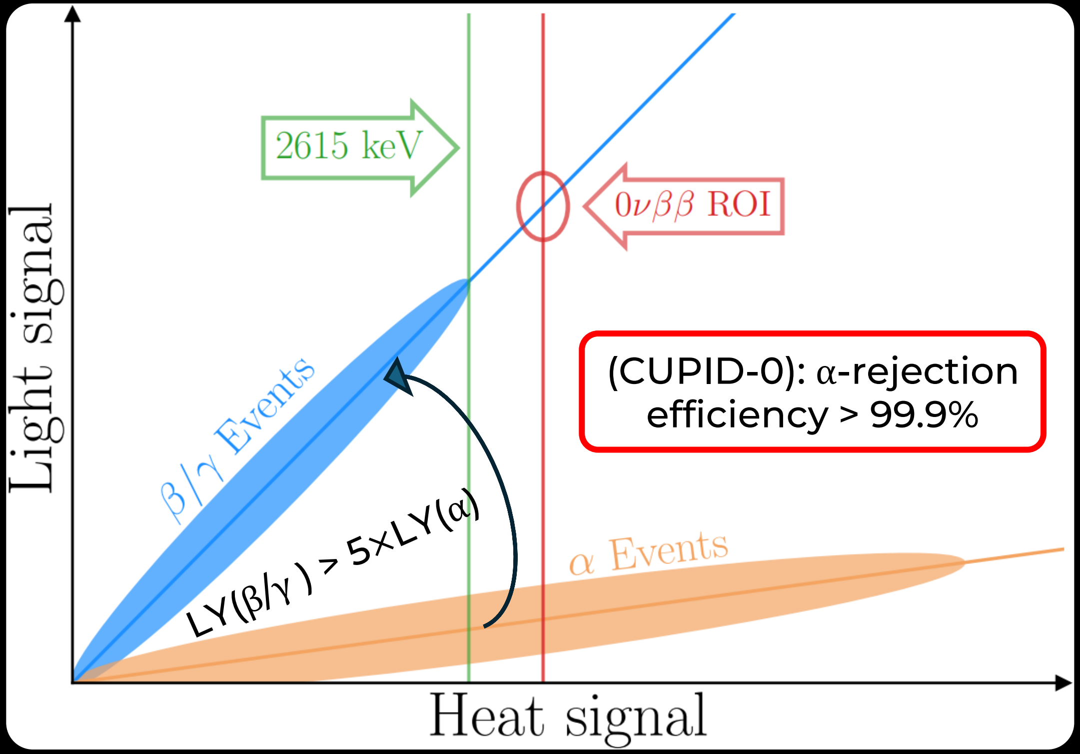


Light Detectors

- ❖ Particle IDentification
- ❖ Particle Shape Discrimination







Light Detectors

- ❖ Particle IDentification
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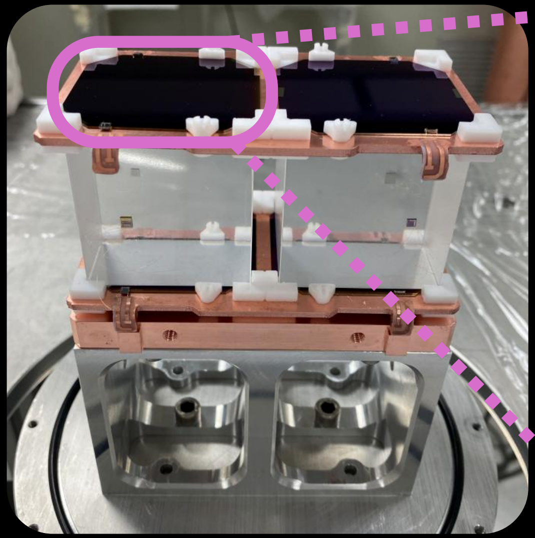
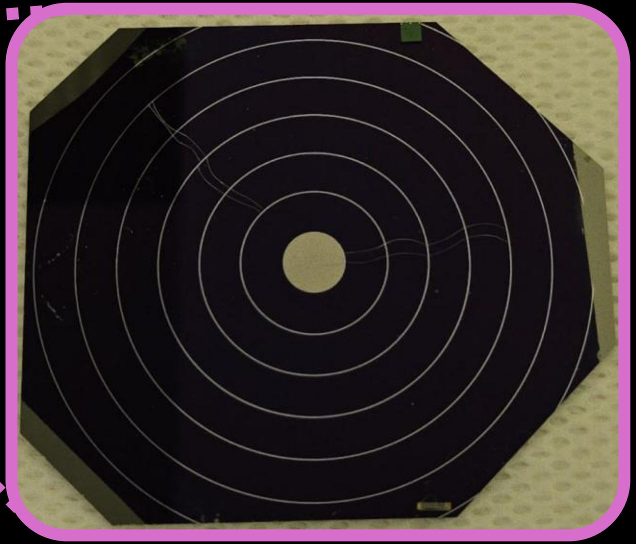
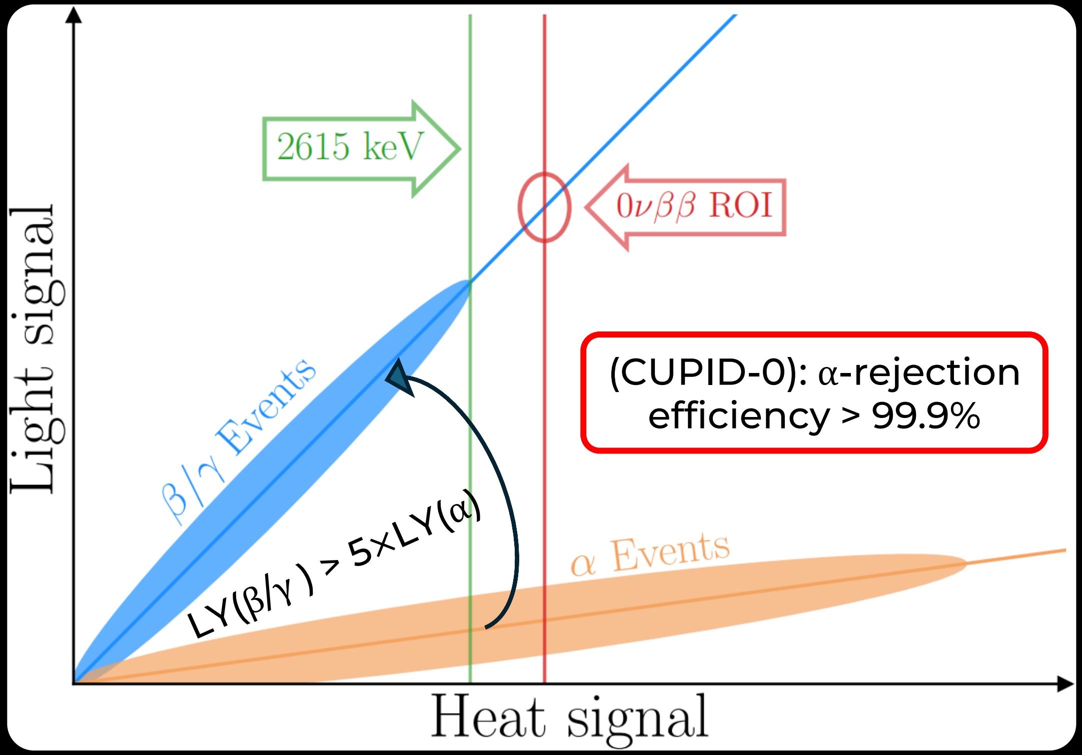




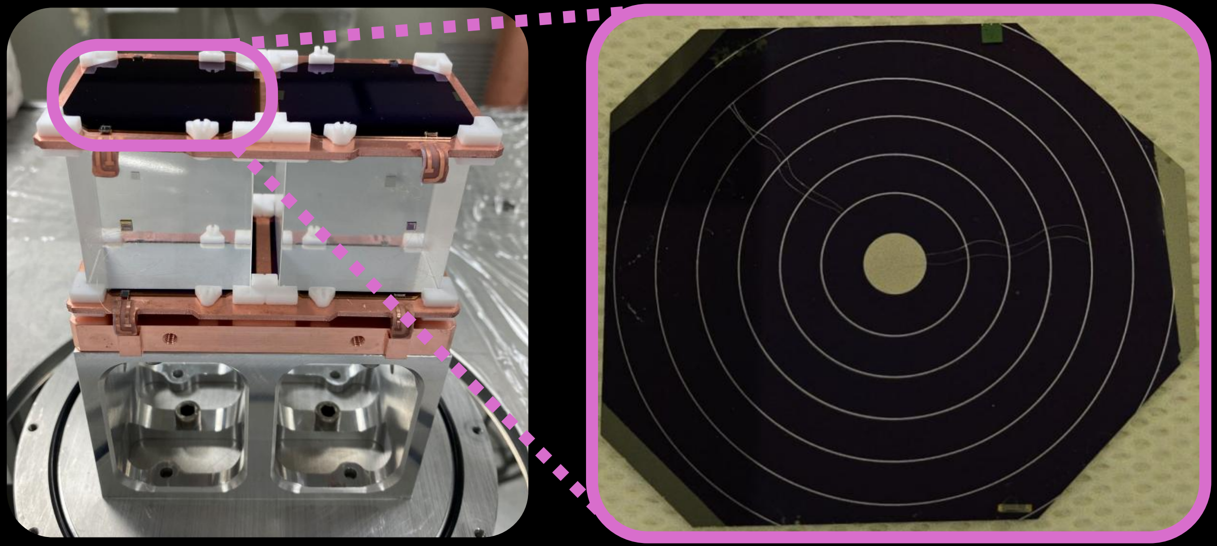


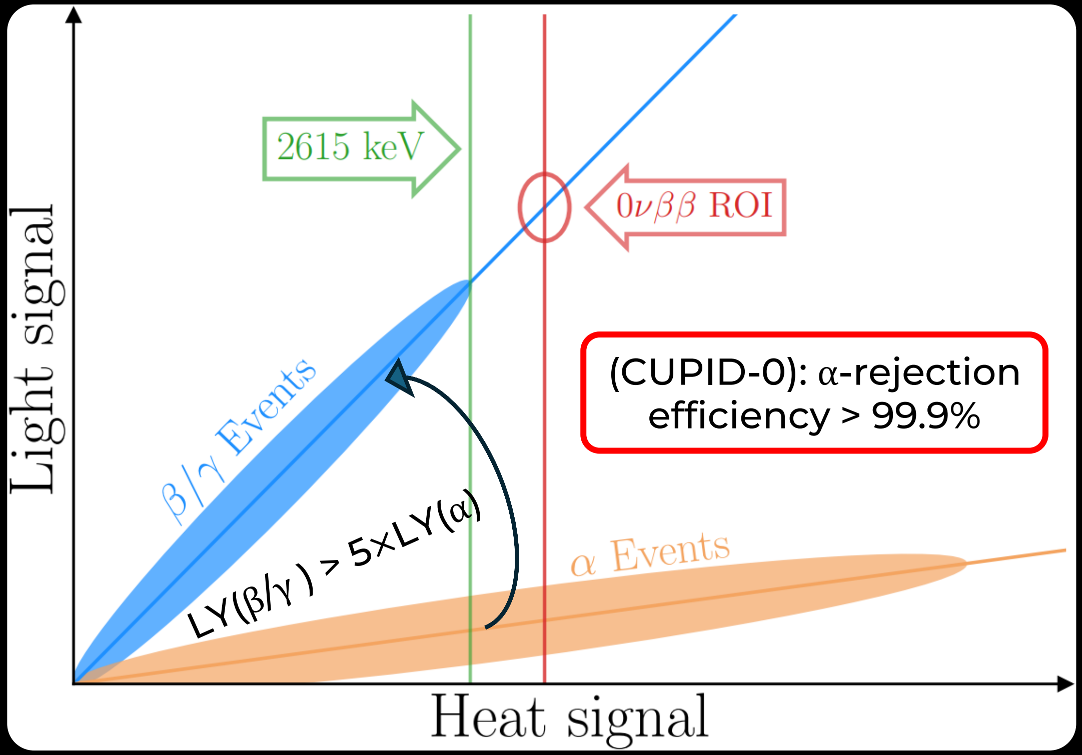
Neganov-Trofimov-Luke (NTL) Amplification

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

Light Detectors

- ❖ Particle IDentification
- ❖ Particle Shape Discrimination





➔ Charge accumulation is a problem !

Neganov-Trofimov-Luke (NTL) Amplification

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

Optical Injection System

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

Baseline: (Light Source + Optical Fibre) x 57 Towers

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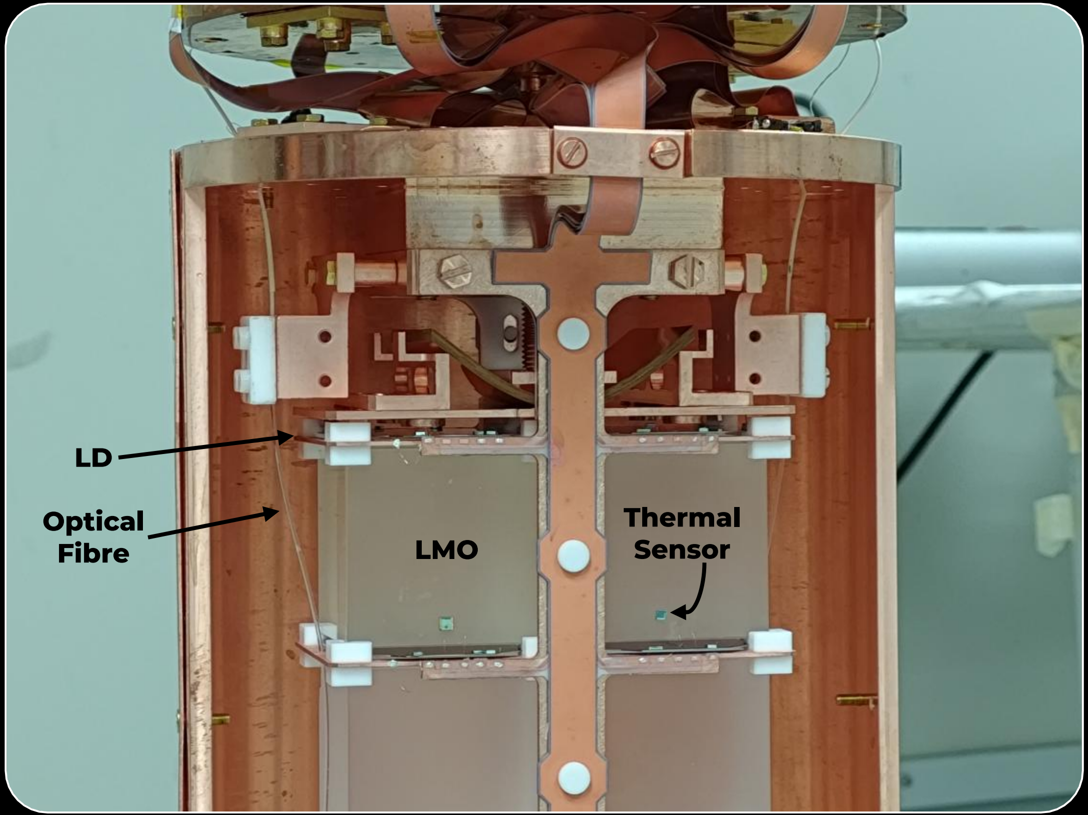
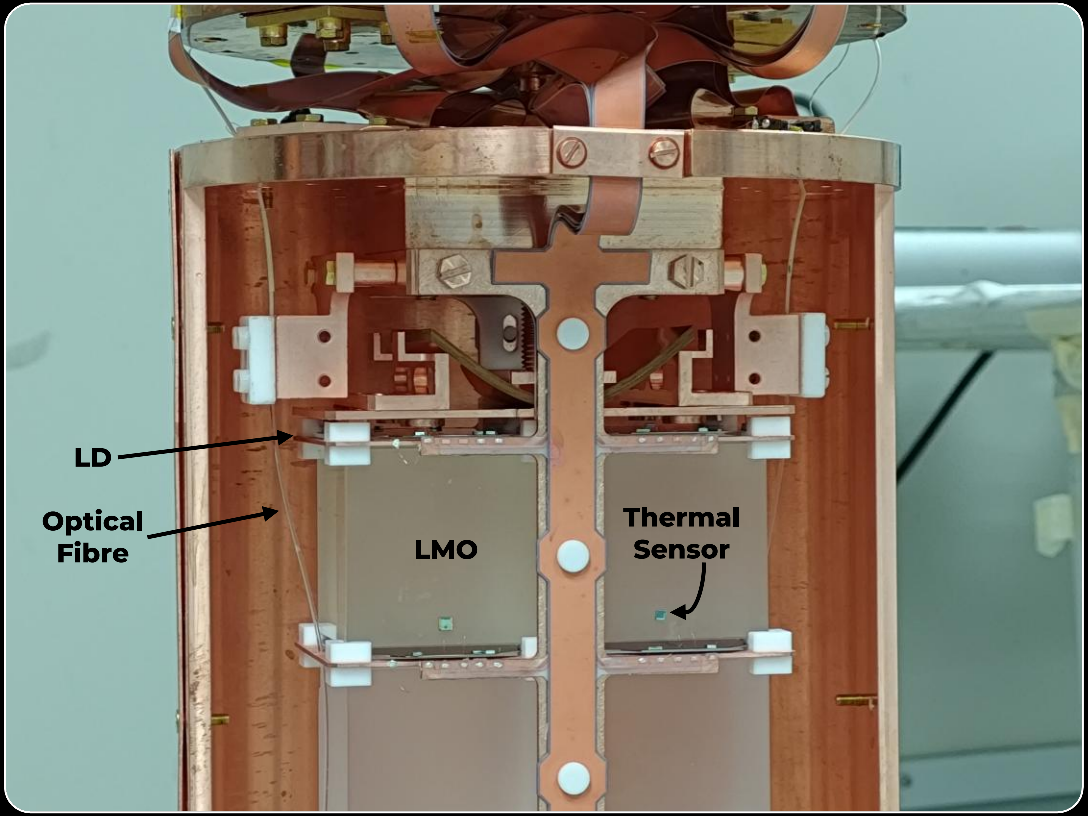


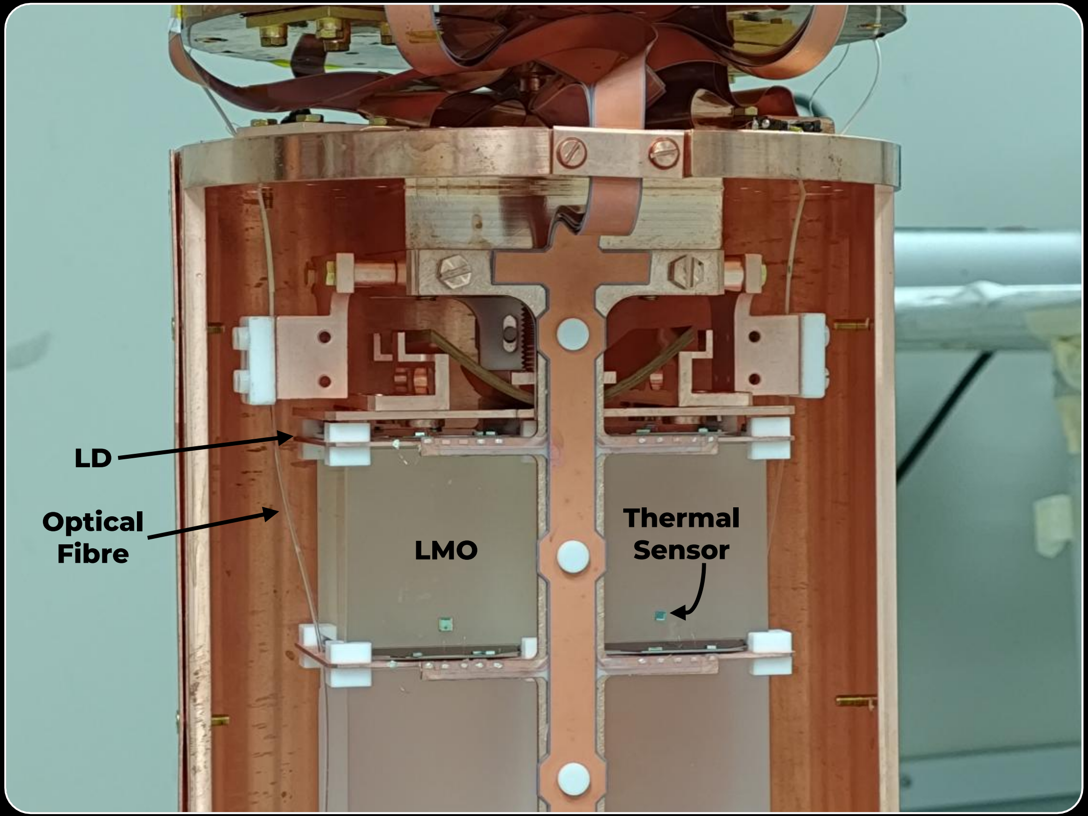
Optical Injection System



Applications

- ❖ LD periodic regeneration

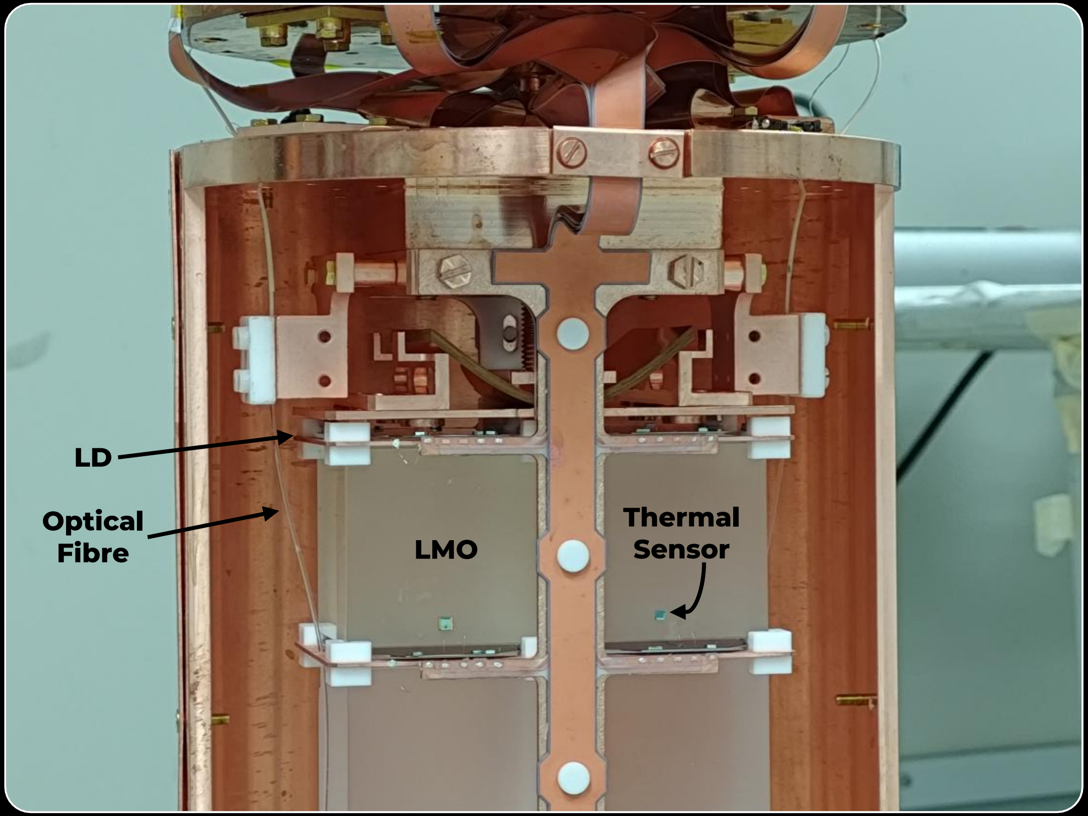
Optical Injection System



Applications

- ❖ LD periodic regeneration
- ❖ Pile-up ID efficiency monitoring

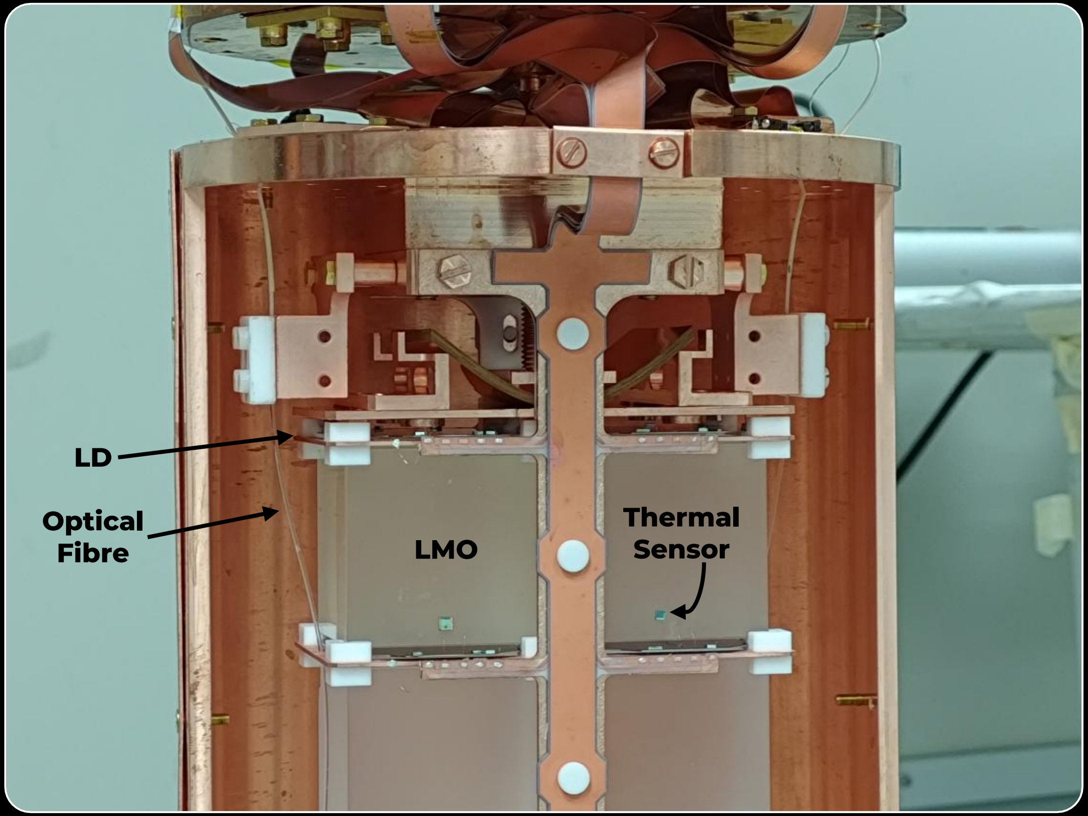
Optical Injection System



Applications

- ❖ LD periodic regeneration
- ❖ Pile-up ID efficiency monitoring
- ❖ LD stabilisation

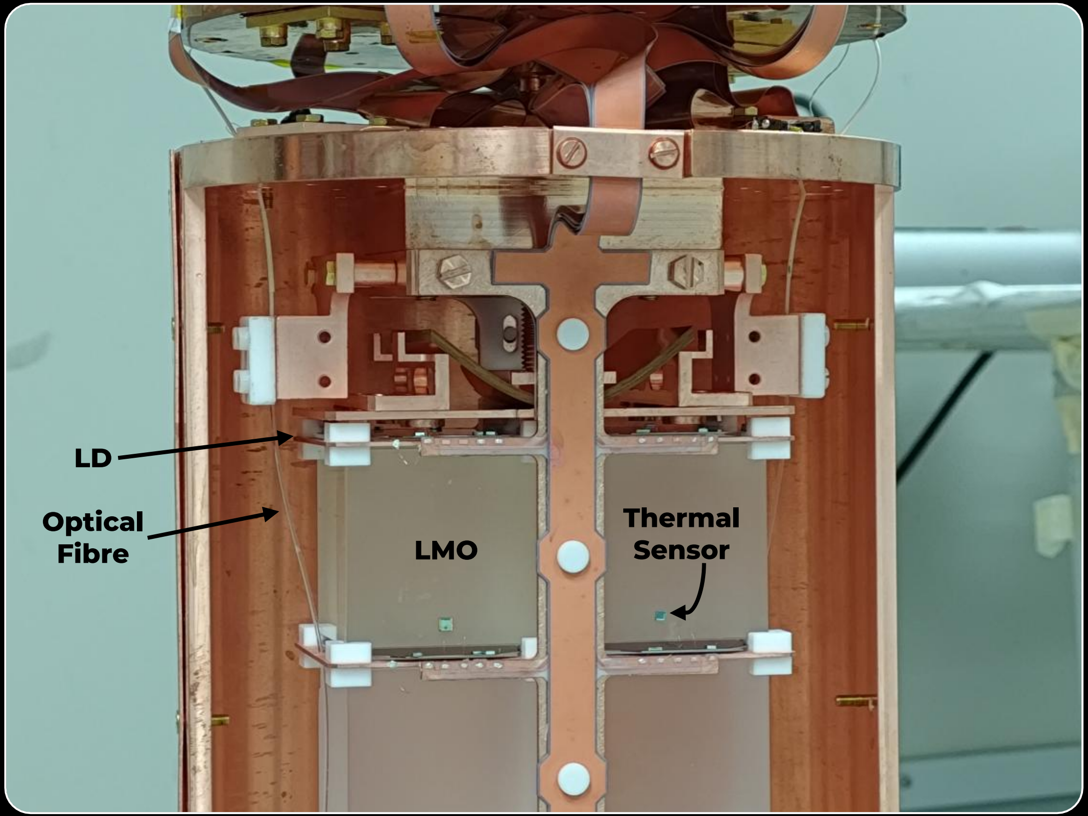
Optical Injection System



Applications

- ❖ LD periodic regeneration
- ❖ Pile-up ID efficiency monitoring
- ❖ LD stabilisation
- ❖ Energy calibration

Optical Injection System

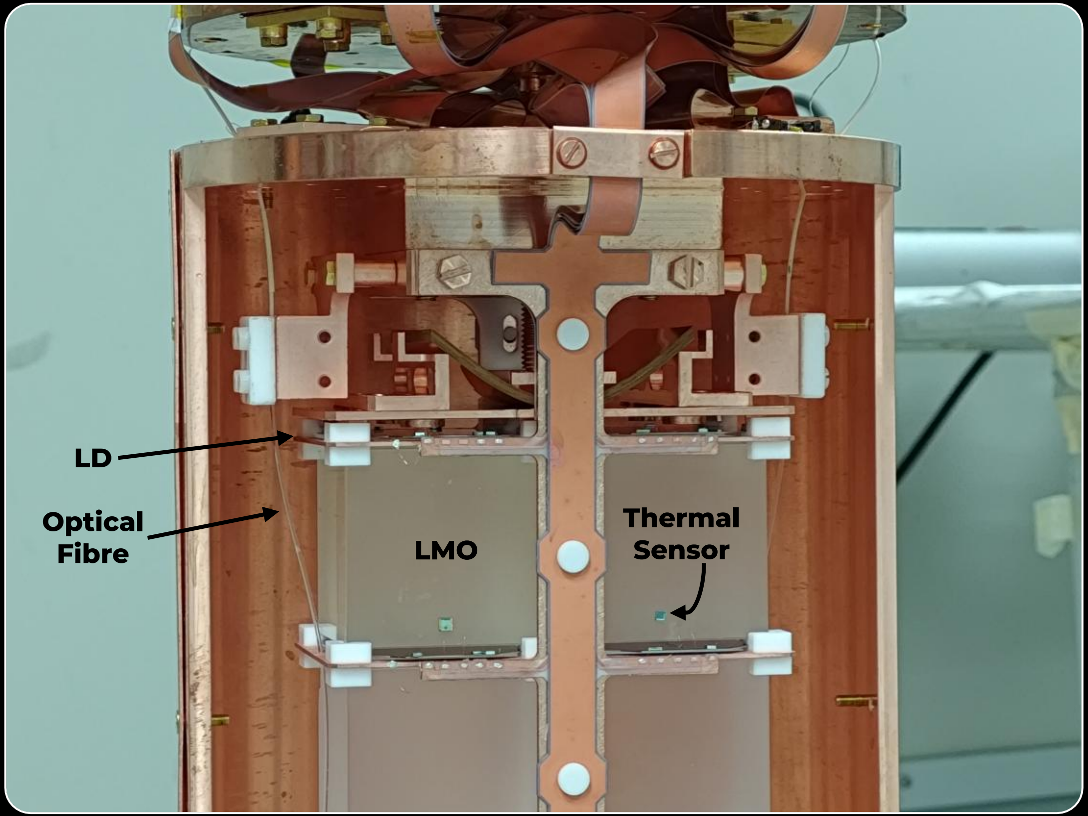


Requirements

- ❖ Multichannel
- ❖ Low radioactivity
- ❖ Low thermal load

Design

Optical Injection System



Requirements

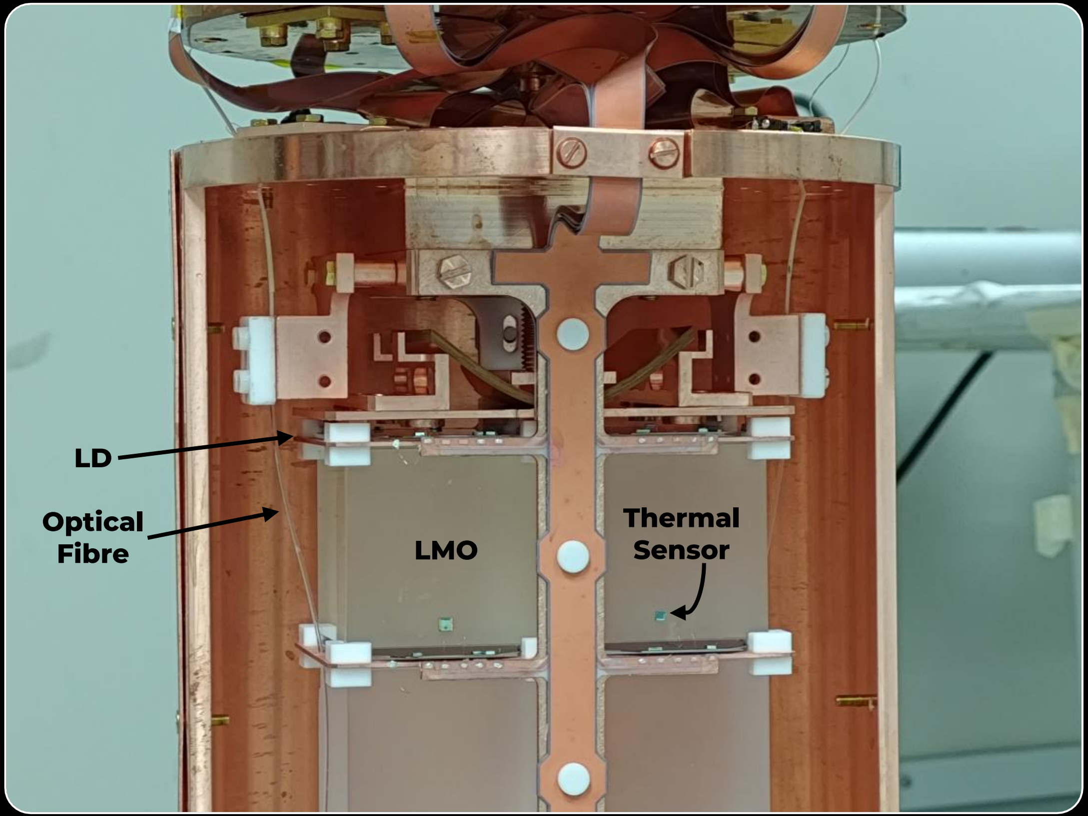
- ❖ Multichannel
- ❖ Low radioactivity
- ❖ Low thermal load

→ **Design**

- ❖ Stable pulses
- ❖ Wavelength

→ **Source**

Optical Injection System



Requirements

Design	Source	Electronics
❖ Multichannel ❖ Low radioactivity ❖ Low thermal load	❖ Stable pulses ❖ Wavelength	❖ Pulse width ❖ DAQ interface

Optical Injection System

Design

Electronics

Train of pulses approach **TESTED** @ Pavia

Software for the light source **TESTED** @ Pavia

Source

Optical Fibre **TESTED** @ Pavia

Light Source candidates **TESTED** @ Pavia

Optical Injection System

Design	Vertical Slice Test Tower (VSTT) **ONGOING**	@ LNGS
	➔ Test of a single CUPID tower	
Electronics	Train of pulses approach **TESTED**	@ Pavia
	Software for the light source **TESTED**	@ Pavia
	Integrate with the DAQ (VSTT) **ONGOING**	@ LNGS
	Test with bolometers (VSTT) **ONGOING**	@ LNGS
Source	Optical Fibre **TESTED**	@ Pavia
	Light Source candidates **TESTED**	@ Pavia
	Test with bolometers (VSTT) **ONGOING**	@ LNGS

Optical Injection System

Design

- Vertical Slice Test Tower (VSTT) ONGOING @ LNGS
  - ➔ Test of a single CUPID tower
- Design for multiple towers TO BE DEFINED

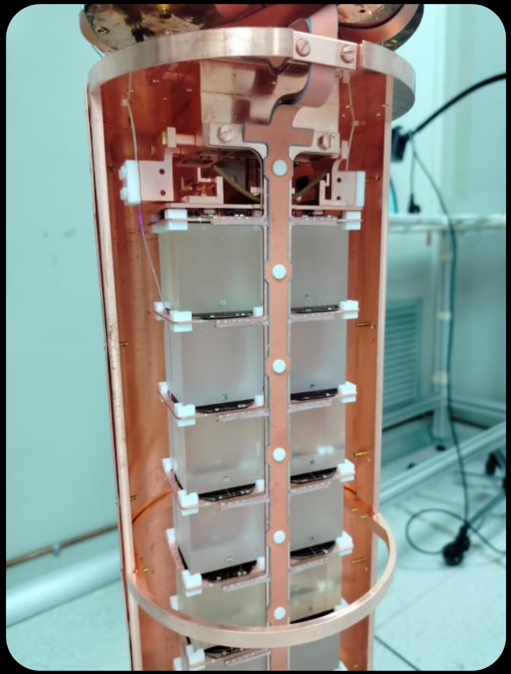
Electronics

- Train of pulses approach TESTED @ Pavia
- Software for the light source TESTED @ Pavia
- Integrate with the DAQ (VSTT) ONGOING @ LNGS
- Test with bolometers (VSTT) ONGOING @ LNGS

Source

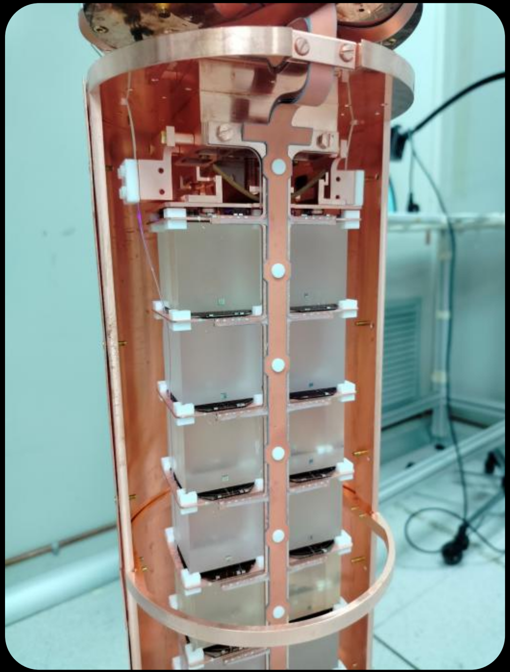
- Optical Fibre TESTED @ Pavia
- Light Source candidates TESTED @ Pavia
- Test with bolometers (VSTT) ONGOING @ LNGS

What's next !?



VSTT ONGOING

What's next !?

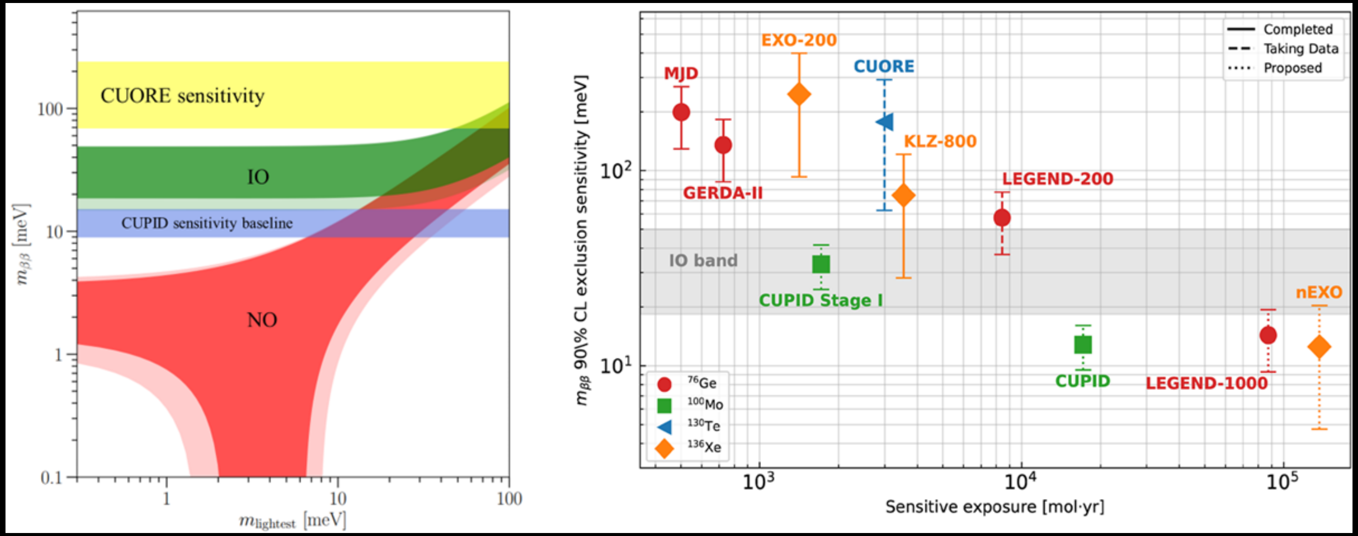


VSTT ONGOING

TIMELINE

2026 CUORE - 3 tonnes·yr limit
Cryogenic system upgrades
CUORE phase 2
➔ higher sensitivity for low energy signatures
➔ test of the upgrades

2030 CUPID Commissioning



THANK YOU FOR YOUR ATTENTION

The CUORE and CUPID collaborations,
Collaboration Meeting, LNGS May 2025

Where's
Nicola?

Main References

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

Search for Majorana neutrinos exploiting millikelvin cryogenics with CUORE
Nature 604 (2022) 7904, 53-58

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

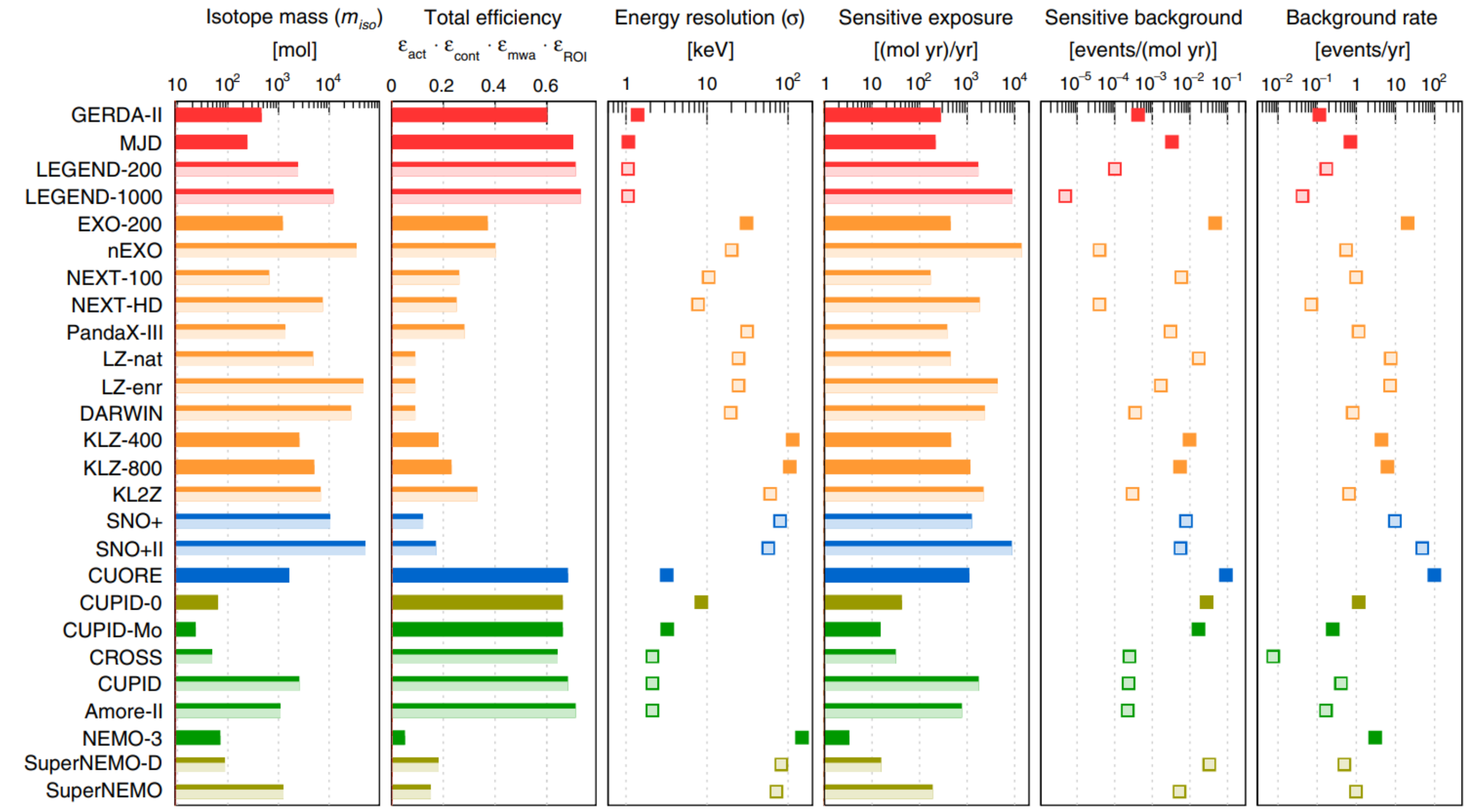
With or without ν? Hunting for the seed of the matter-antimatter asymmetry
arXiv: 2404.04453

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

CUPID, the Cuore upgrade with particle identification
Eur.Phys.J.C 85 (2025) 7, 737

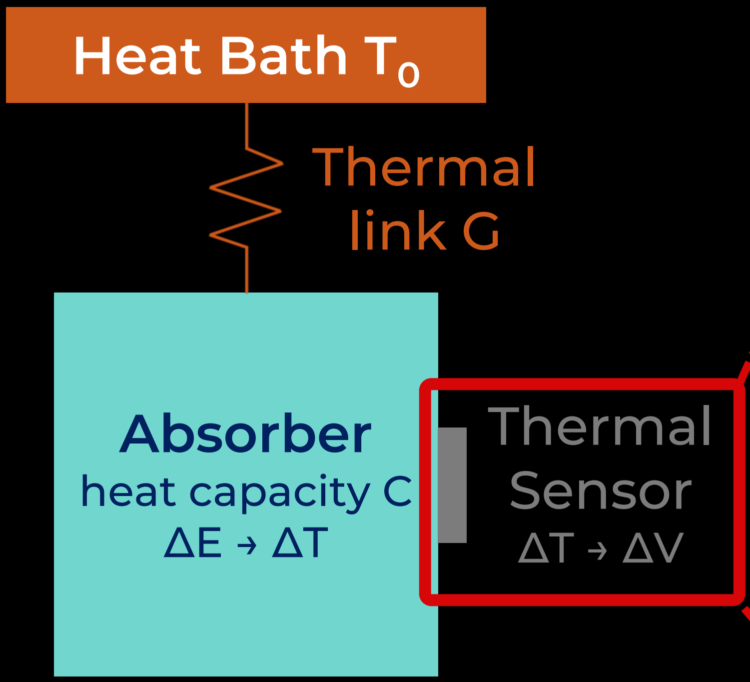
Backup

Detection Techniques and Performances



Experiment	Isotope	Status	Lab
High-purity Ge detectors			
GERDA-II	^{76}Ge	Completed	LNGS
MJD	^{76}Ge	Completed	SURF
LEGEND-200	^{76}Ge	Construction	LNGS
LEGEND-1000	^{76}Ge	Proposed	
Xe time-projection chambers			
EXO-200	^{136}Xe	Completed	WIPP
nEXO	^{136}Xe	Proposed	SNOLAB
NEXT-100	^{136}Xe	Construction	LSC
NEXT-HD	^{136}Xe	Proposed	
PandaX-III-200	^{136}Xe	Construction	CJPL
LZ-nat	^{136}Xe	Construction	SURF
LZ-enr	^{136}Xe	Proposed	SURF
Darwin	^{136}Xe	Proposed	
Large liquid scintillators			
KLZ-400	^{136}Xe	Completed	Kamioka
KLZ-800	^{136}Xe	Taking data	Kamioka
KL2Z	^{136}Xe	Proposed	Kamioka
SNO + I	^{130}Te	Construction	SNOLAB
SNO + II	^{130}Te	Proposed	SNOLAB
Cryogenic calorimeters			
CUORE	^{130}Te	Taking data	LNGS
CUPID-0	^{82}Se	Completed	LNGS
CUPID-Mo	^{100}Mo	Completed	LSM
CROSS	^{100}Mo	Construction	LSC
CUPID	^{100}Mo	Proposed	LNGS
AMoRE-II	^{100}Mo	Proposed	Yemilab
Tracking calorimeters			
NEMO-3	^{100}Mo	Completed	LSM
SuperNEMO-D	^{82}Se	Construction	LSM
SuperNEMO	^{82}Se	Proposed	LSM

Cryogenic Calorimeters - NTDs



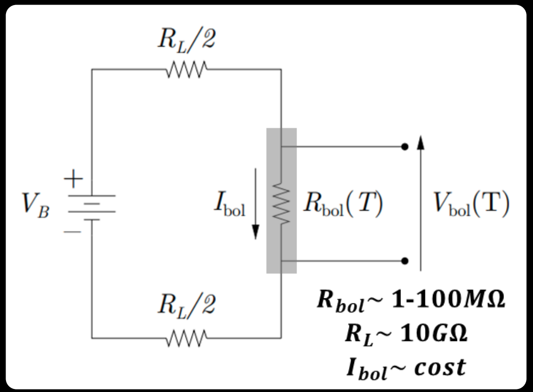
Neutron Transmutation Doped (Ge-NTD)

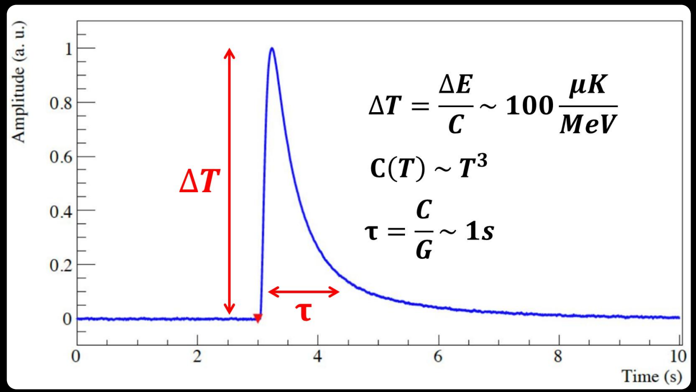
- Semiconductor Thermistor glued on the absorber
- Standard readout electronics
- Dynamic range from ~ 10keV up to ~ 10MeV
- At T << 10K , resistivity is temperature dependent

$$\rho = \rho_0 e^{\sqrt{T_0/T}}$$

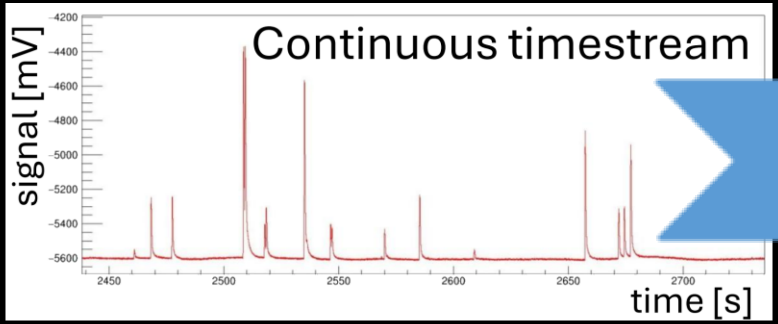
where (ρ_0 , T_0) depends on the doping level

- Sensible to mechanical vibrations and microphonism



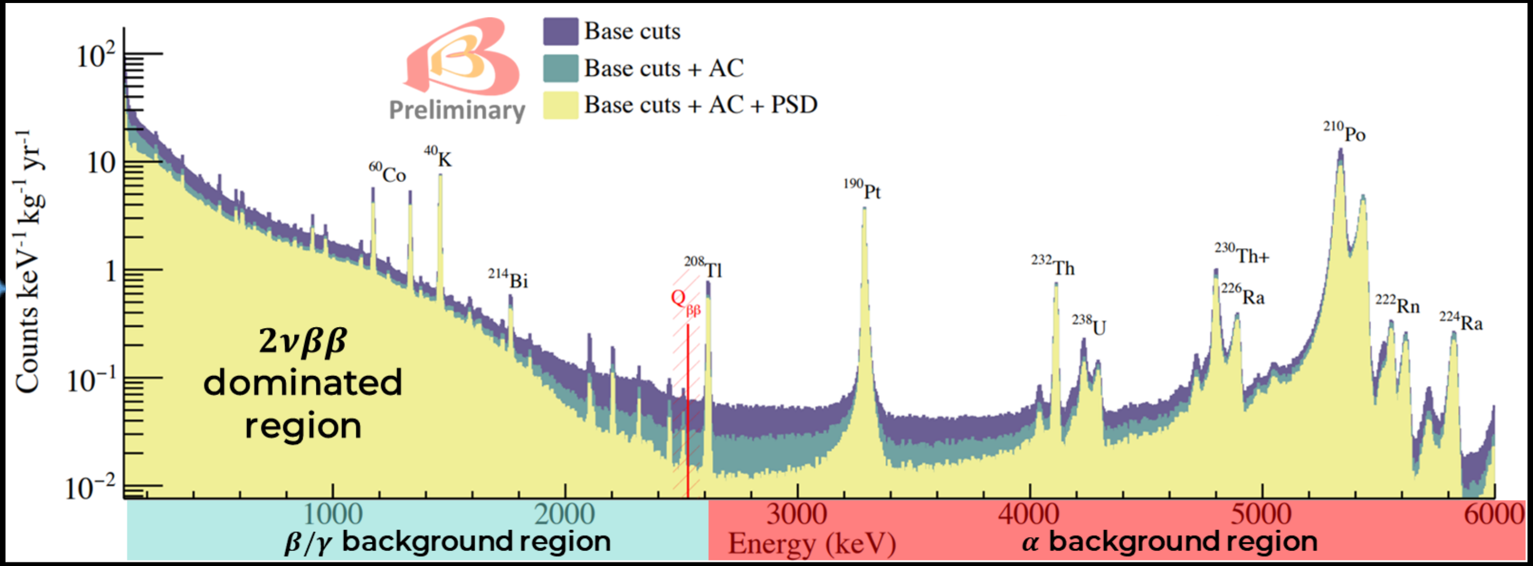


CUORE Analysis



Triggering → Signal denoising and filtering → Thermal gain stabilization → Energy calibration → Coincidence clustering

Pulse shape discrimination



Base cuts
trigger, pile-up,
energy reconstruction

Anti-coincidence (AC)
only single-crystal events

Pulse shape discrimination (PSD)
only signal-like events

Dilution Cryostat