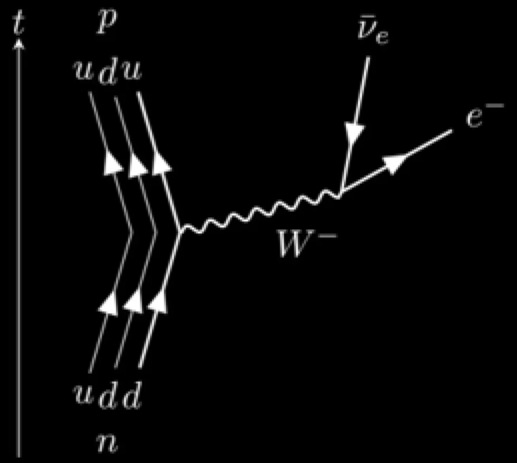
$0\nu\beta\beta$ decay searches with the CUORE and CUPID experiments

End of Year Seminars

September 17-18, Pavia

MANENTI Nicola

Massless Neutrinos: Standard Model



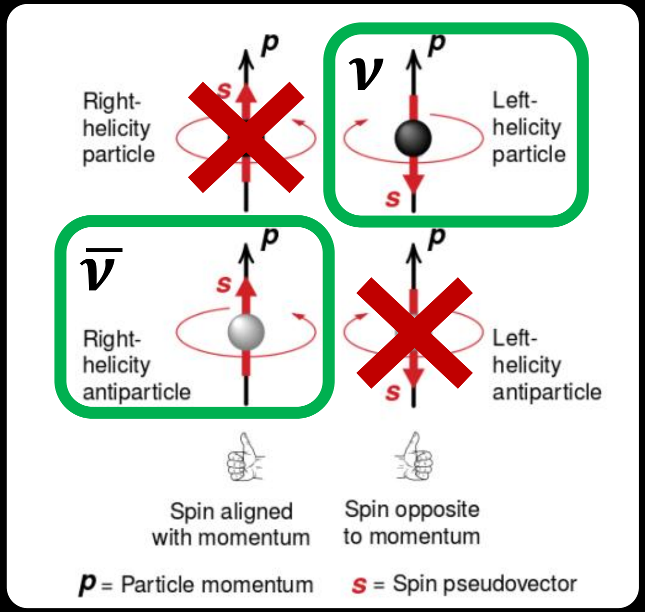
Neutrinos (ν) are fermions (spin = 1/2)
➔ Dirac equation:

$$(i\gamma^\mu\partial_\mu - m)\nu = 0 \qquad \begin{cases} i\gamma^\mu\partial_\mu\nu_L = m\nu_R \\ i\gamma^\mu\partial_\mu\nu_R = m\nu_L \end{cases}$$

No experimental proof of their mass
➔ theory can be simplified

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

Helicity measurements "prove" it



Nino the Neutrino
from "***Dal Sole alla Terra***"
a CERN & INFN Production

Neutrino Oscillations

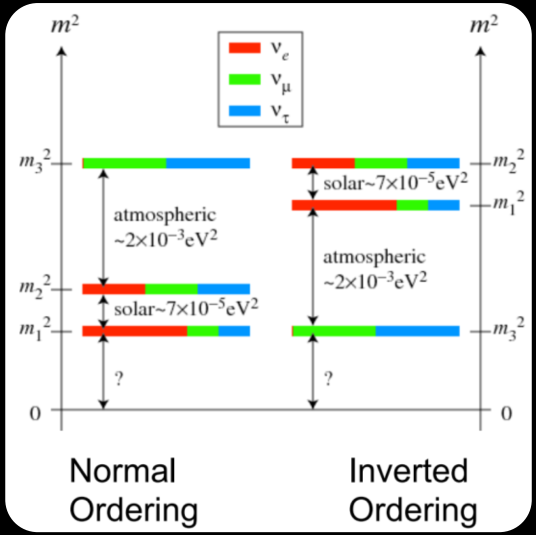
- ❖ neutrinos have different mass and flavor eigenbasis

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

- ❖ at least two neutrinos need to be massive

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

- ❖ oscillation experiments cannot probe the mass values, ambiguity in the mass ordering



Pontecorvo-Maki-Nakagawa-Sakata mixing matrix

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

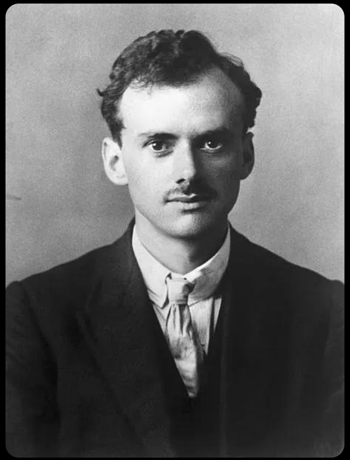
Observable

Majorana phases

Dirac ~~CP~~ phase

Massive Neutrinos and SM

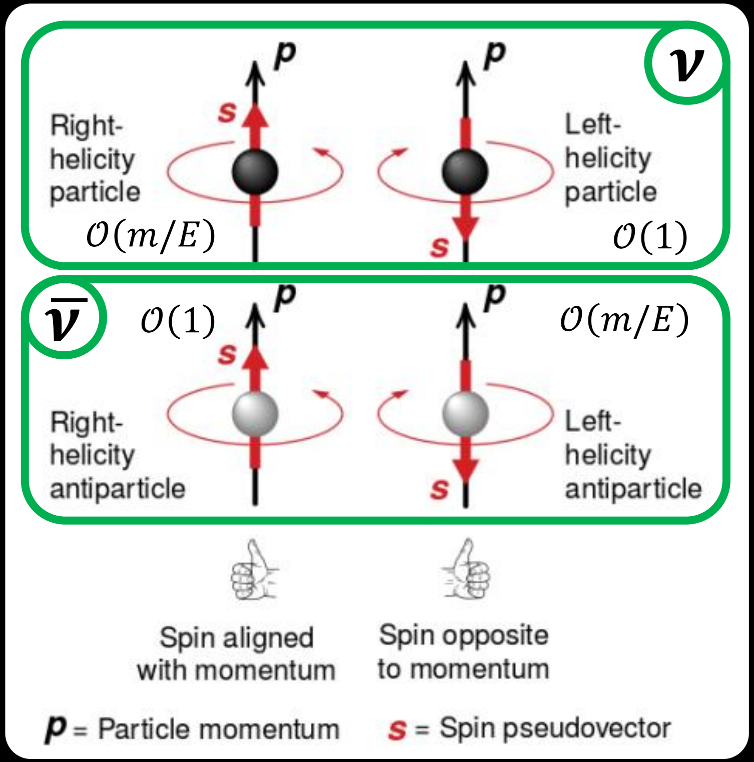
1. Can we add a mass term to the neutrinos in the Standard Model?
2. What about the smallness of their mass?



P. Dirac

νs are massive:

helicity ≠ chirality



4 possible states:

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

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

mass term:

$$m_D \bar{\nu}_L \nu_R + \text{ h.c.}$$

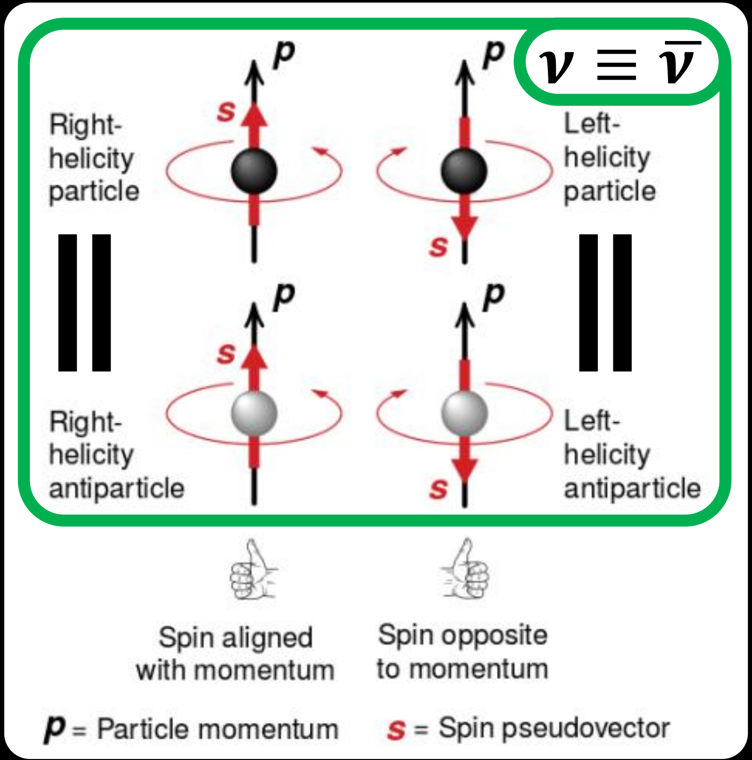
$$\nu_{L/R} = P_{L/R}\nu = \frac{1 \mp \gamma_5}{2}\nu$$

Massive Neutrinos and SM

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

E. Majorana

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



2 possible states:

$$\nu = \nu_L + \nu_L^C = \nu^C$$

mass terms:

$$(m_L \nu_L^T C \nu_L + \text{h.c.})$$

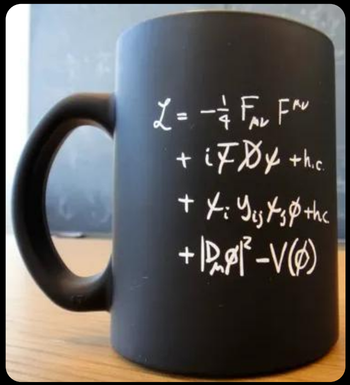
$$(m_R \nu_R^T C \nu_R + \text{h.c.})$$

$\nu^C = C\bar{\nu}^T \qquad C = i\gamma_2\gamma_0$

SM and Massive Neutrinos

Standard Model

$m_\nu = 0$

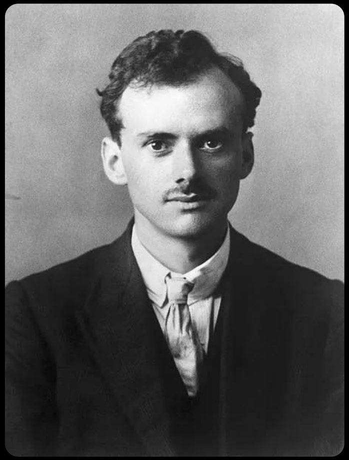


$$\mathcal{L} = \begin{array}{l} + i\bar{\nu}_L \partial_\mu \gamma^\mu \nu_L \\ + i\bar{\nu}_R \partial_\mu \gamma^\mu \nu_R \end{array}$$

+

Dirac Mass

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



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

+

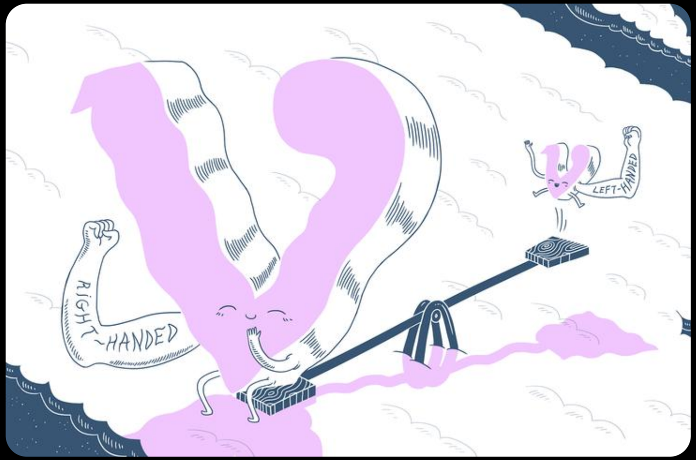
Majorana Mass

$m_L = 0 \quad m_R \gg m_D$

$$-\frac{1}{2}\left(m_L \bar{\nu}_L \mathrm{C} \bar{\nu}_L^{\mathrm{t}} + \mathrm{h.c.}\right)$$
$$-\frac{1}{2}\left(m_R \bar{\nu}_R \mathrm{C} \bar{\nu}_R^{\mathrm{t}} + \mathrm{h.c.}\right)$$

=

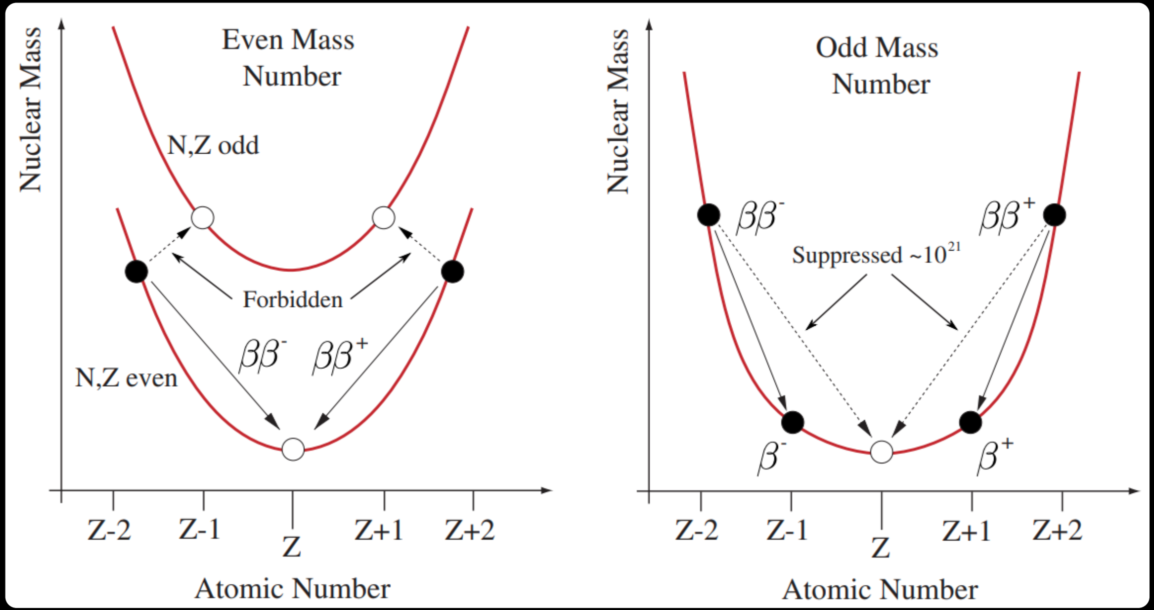
See-Saw Mechanism
(e.g. one flavor)



$m_1 \simeq \frac{m_D^2}{m_R} \ll m_D \qquad m_2 \simeq m_R$

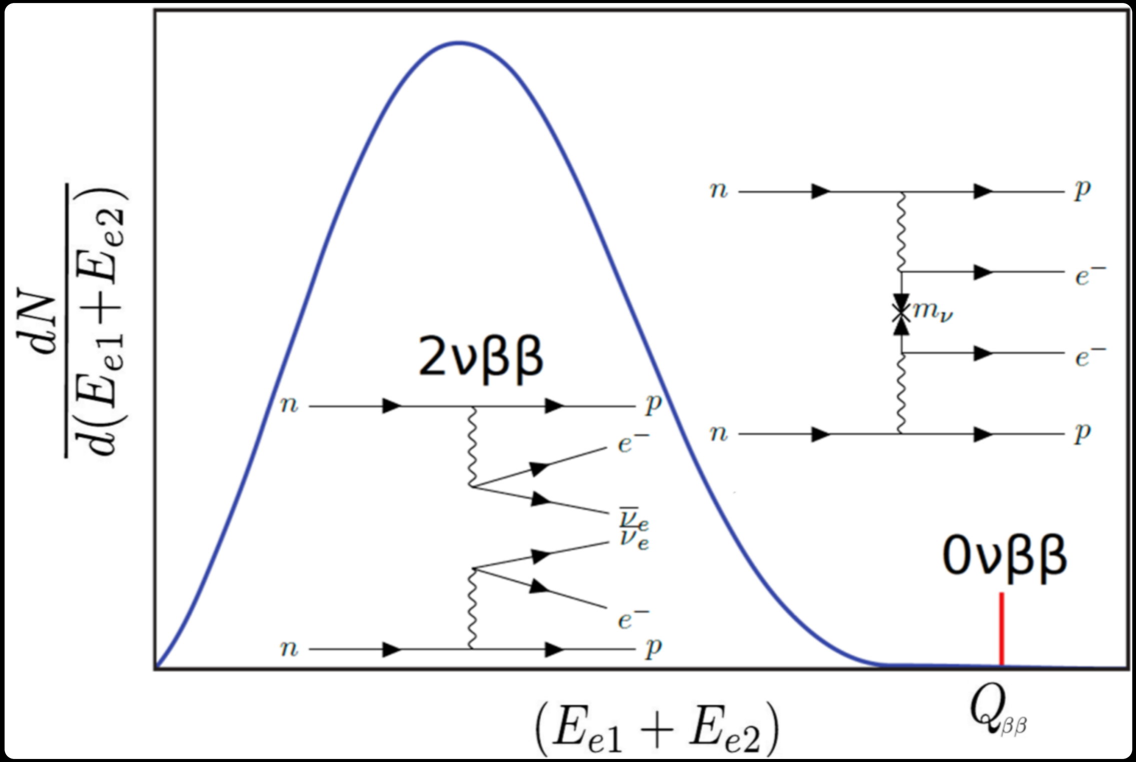
EW neutrino: $\nu_L = i\nu_{1L} + \frac{m_D}{m_R} \nu_{2L}$

Sterile neutrino: $(\nu_R)^C = -i\frac{m_D}{m_R} \nu_{1L} + \nu_{2L}$



Double Beta Decay

- 2nd order weak transition allowed by the SM
- Introduced by M. Goeppert-Mayer in 1935
- Rare process: $T_{1/2}^{2\nu\beta\beta} \sim 10^{18-21}$ yr
- 35 isotope candidates



Neutrinoless DBD

- Beyhond Standard Model counterpart of DBD
- Proposed by W.H. Furry in 1939
- Very rare process: $T_{1/2}^{0\nu\beta\beta} > 10^{24-26}$ yr

Sensitivity

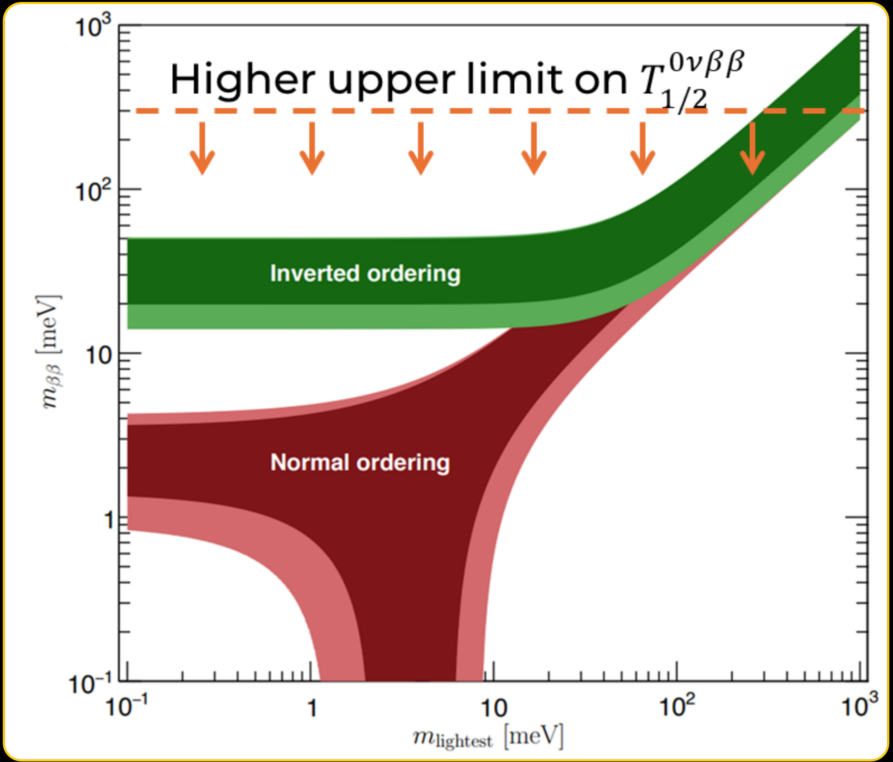
IF detected

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

Observable

Effective Majorana Mass

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



$$T_{1/2}^{0\nu\beta\beta} \propto \left[G^{0\nu} \times \left| M^{0\nu} \right|^2 \times m_{\beta\beta}^2 \right]^{-1}$$

- $T_{1/2}^{0\nu\beta\beta}$: $0\nu\beta\beta$ half-life
- $G^{0\nu}$: Phase Space Factor
- $M^{0\nu}$: Nuclear Matrix Element

Detection Techniques

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

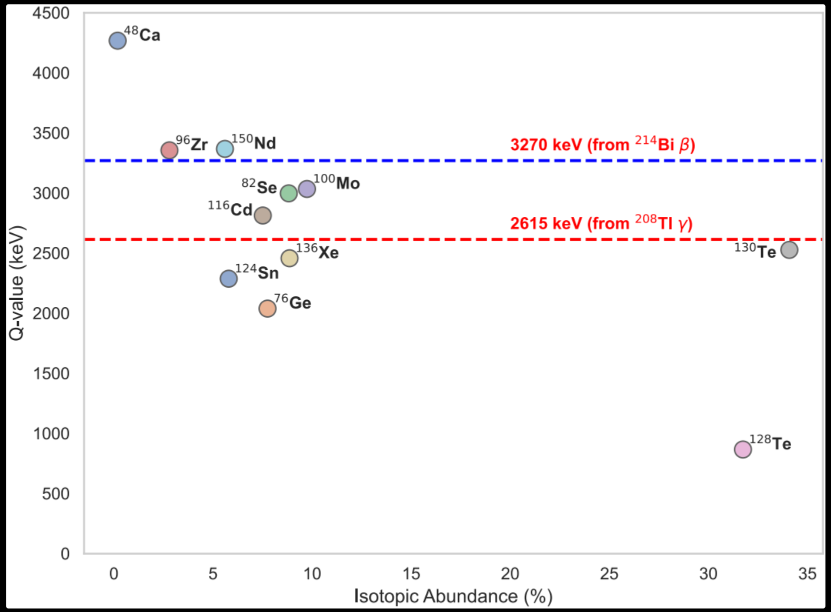
Large exposure (mass × livetime)

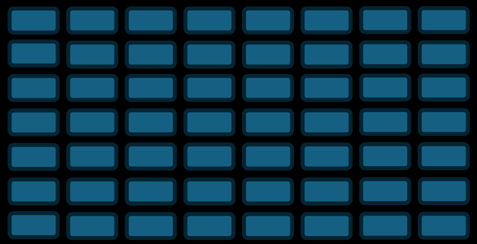
Large isotopic abundance

High detection efficiency

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

Good energy resolution





Granular Detectors

- ❖ Good Energy resolution
- ❖ Staging

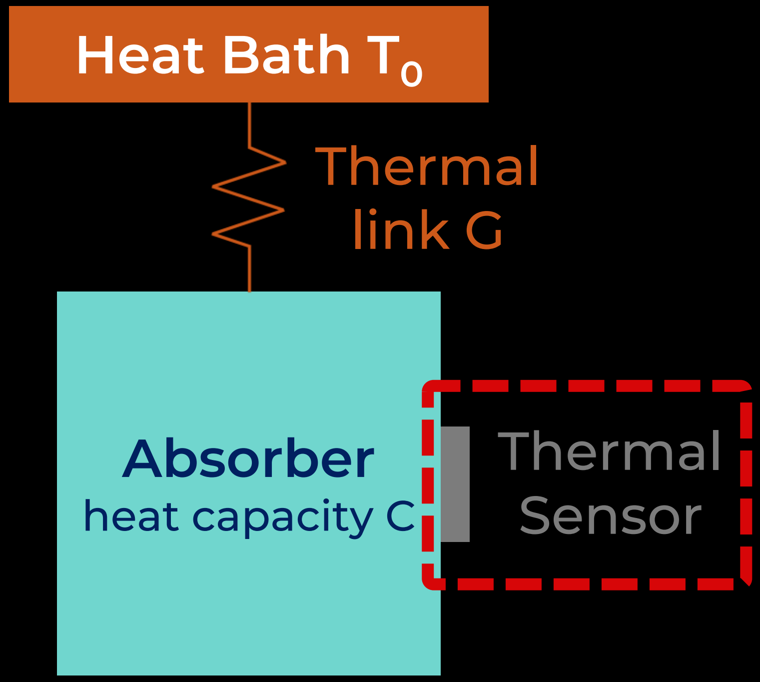
➔ Bolometers: CUORE, CUPID
➔ Semiconductors: GERDA, LEGEND

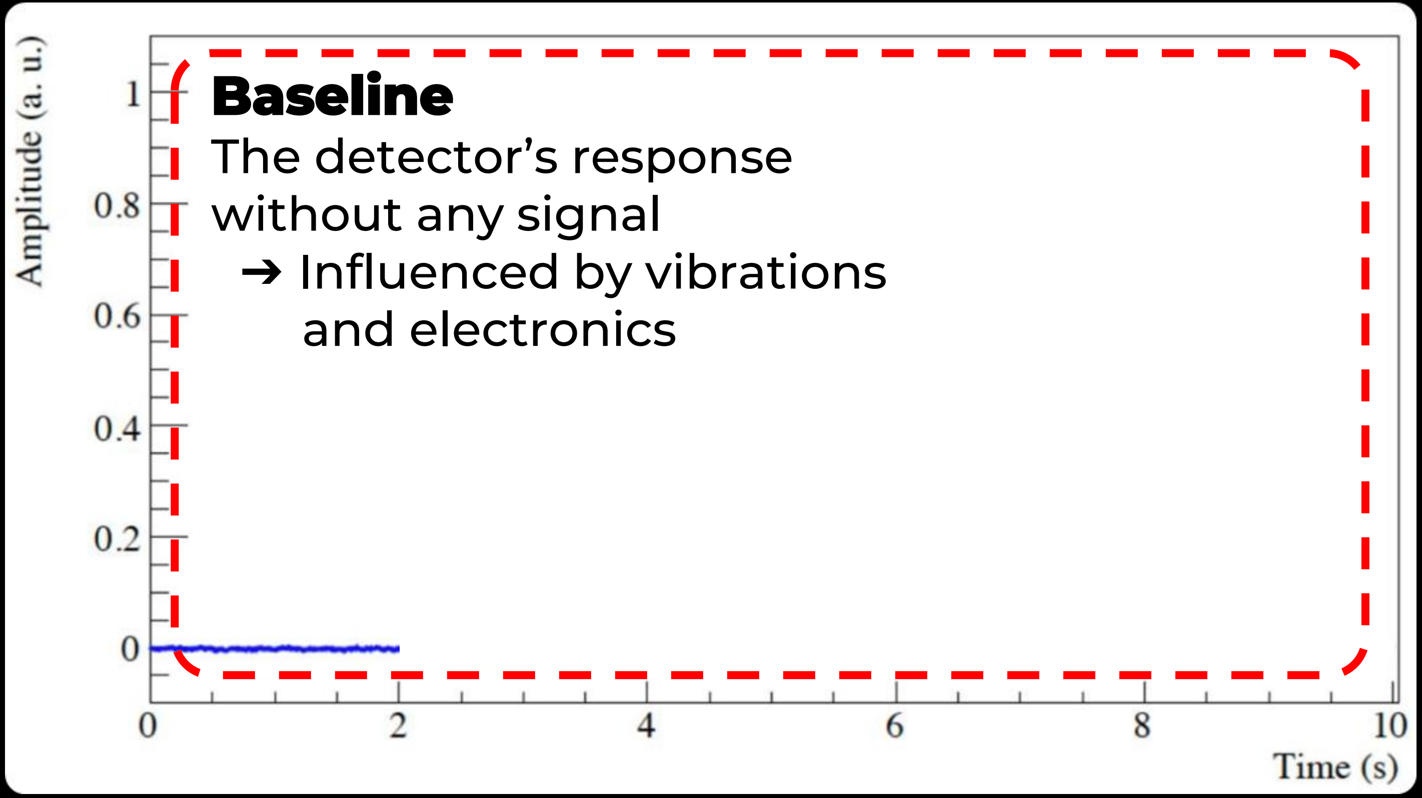
Monolithic Detector

- ❖ Shelf-shielding
- ❖ Scalability

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

Cryogenic Calorimeters





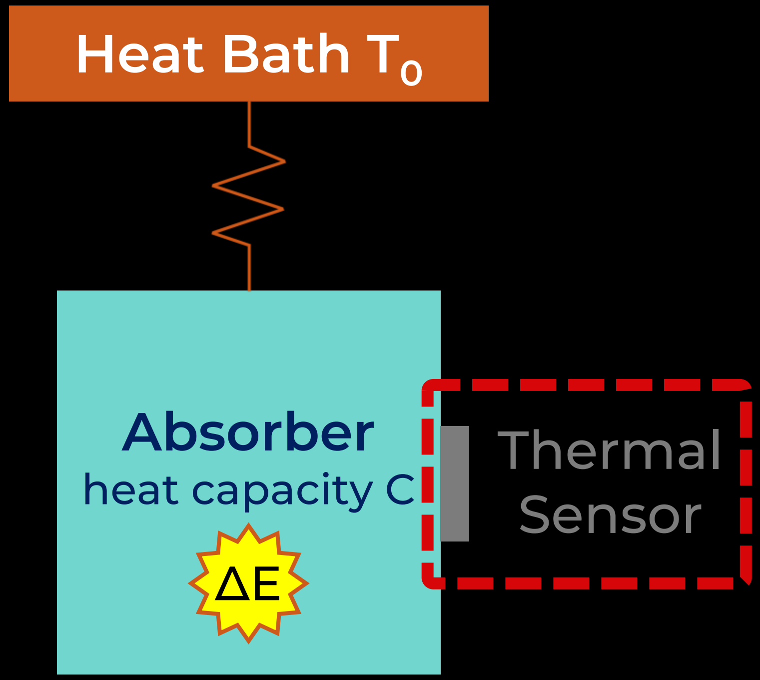
Baseline

The detector's response without any signal

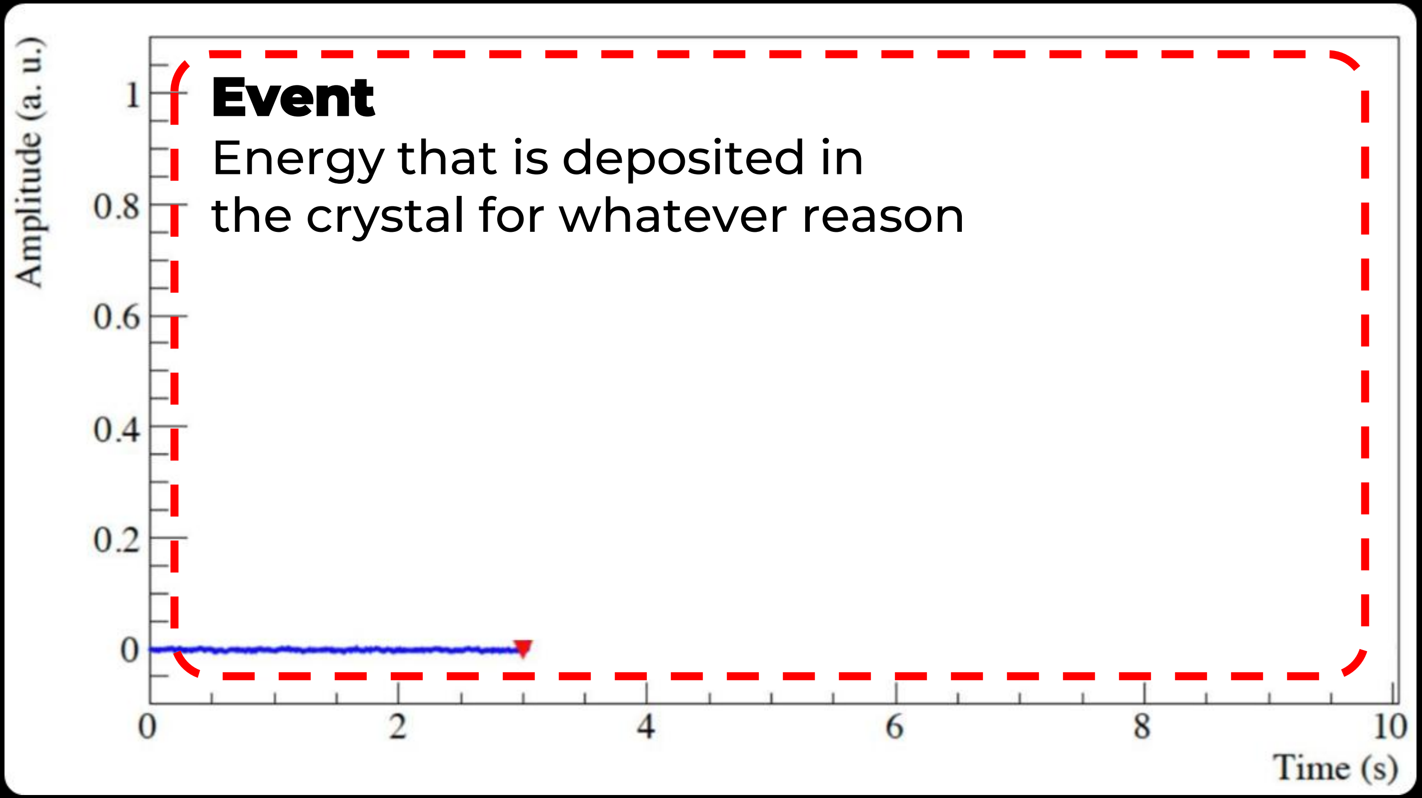
➔ Influenced by vibrations and electronics

$T = T_0$

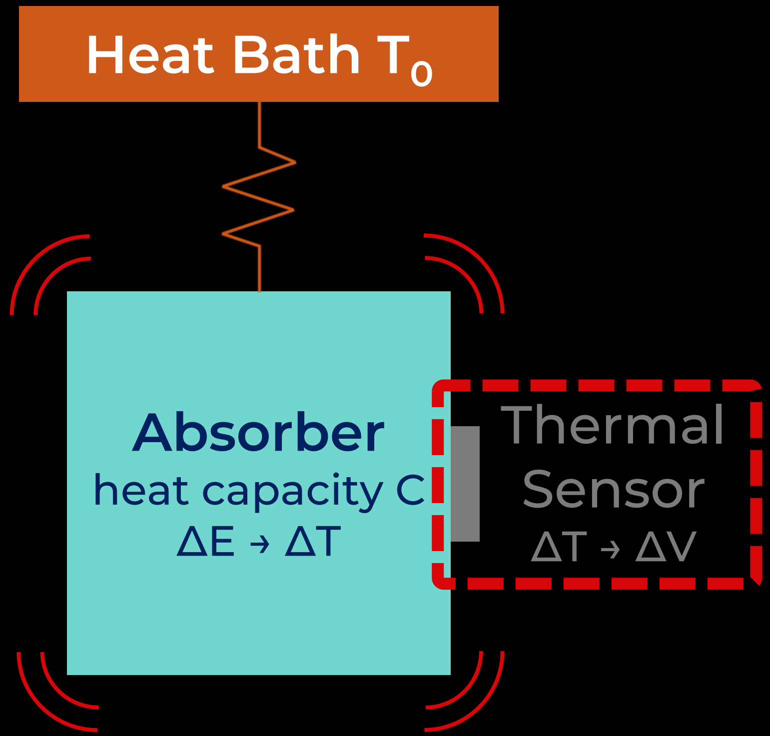
Cryogenic Calorimeters



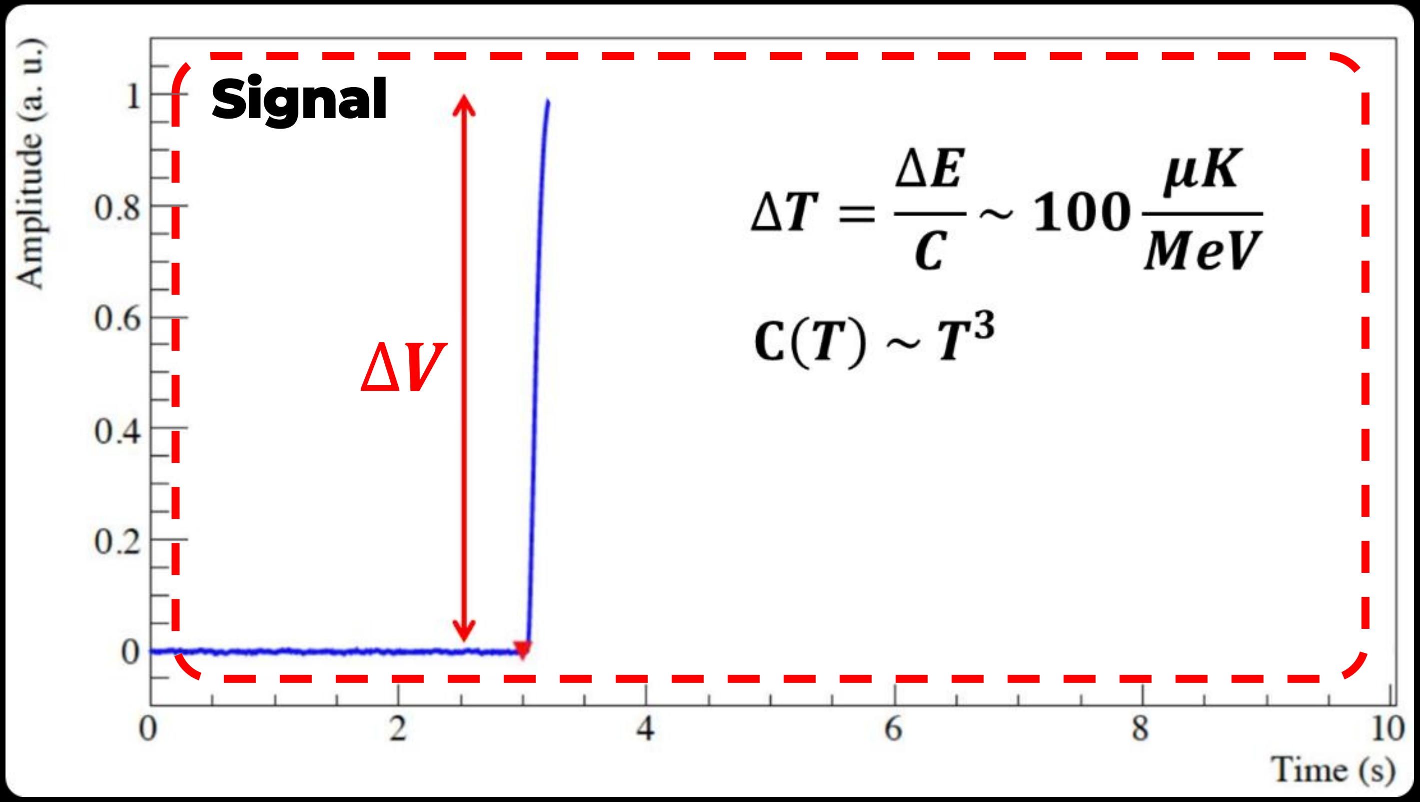
$T = T_0$



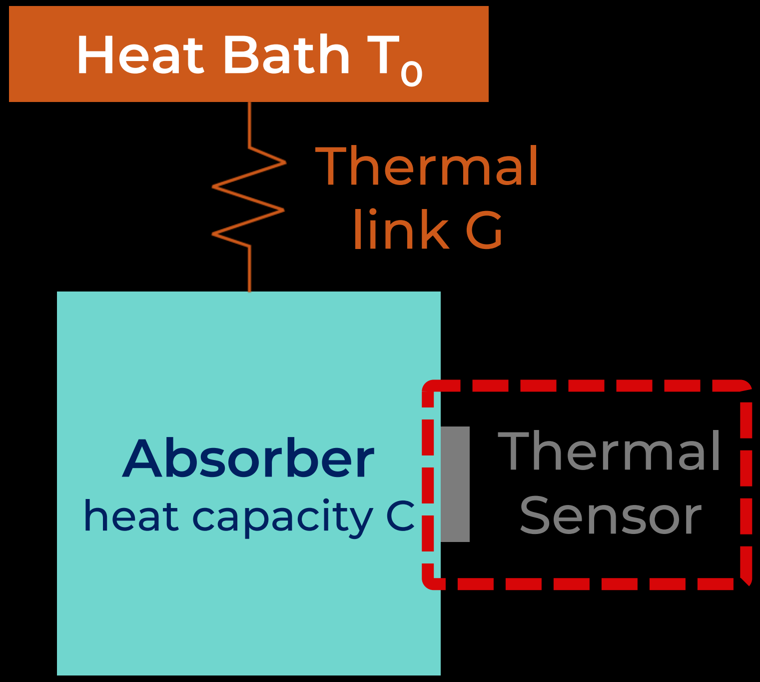
Cryogenic Calorimeters



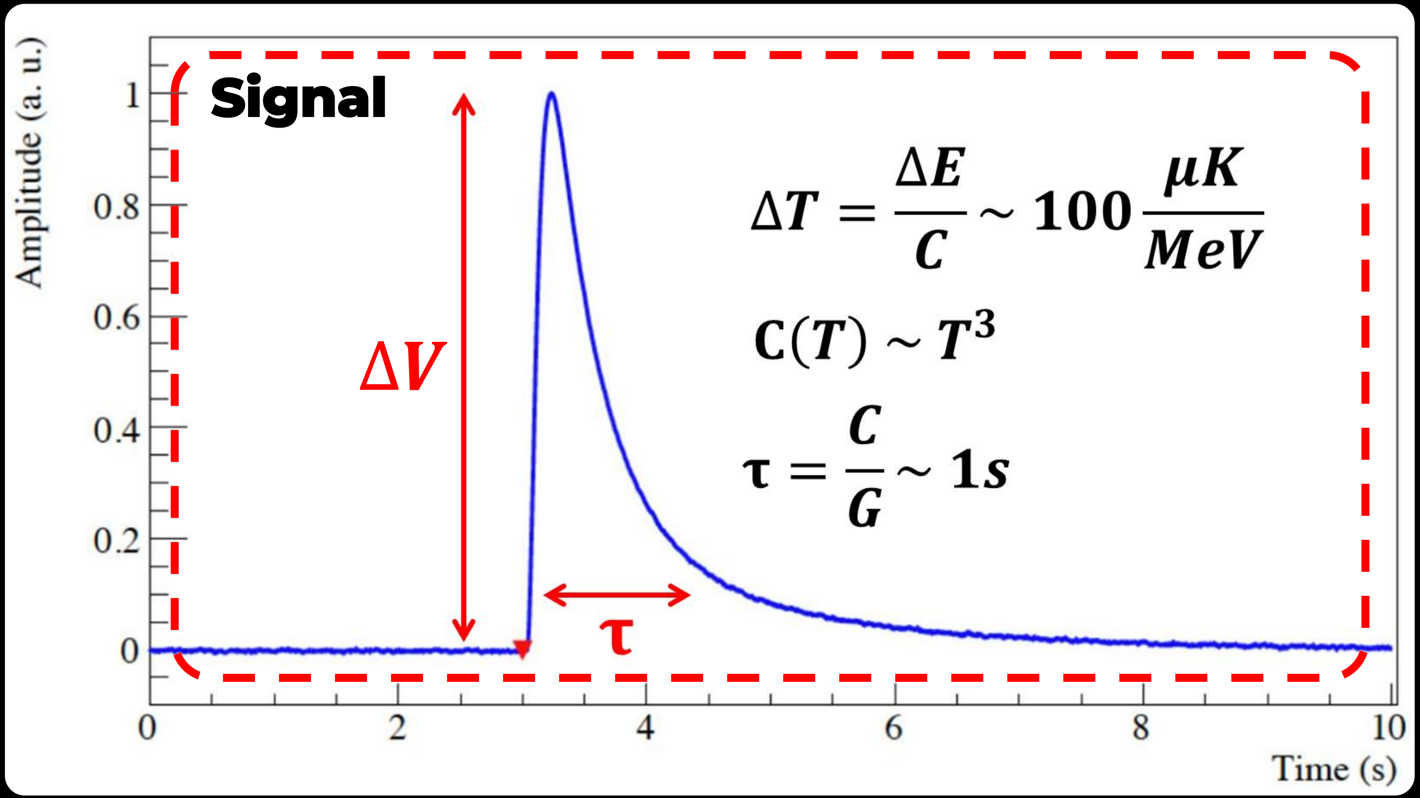
$$T = T_0 + \Delta T$$



Cryogenic Calorimeters



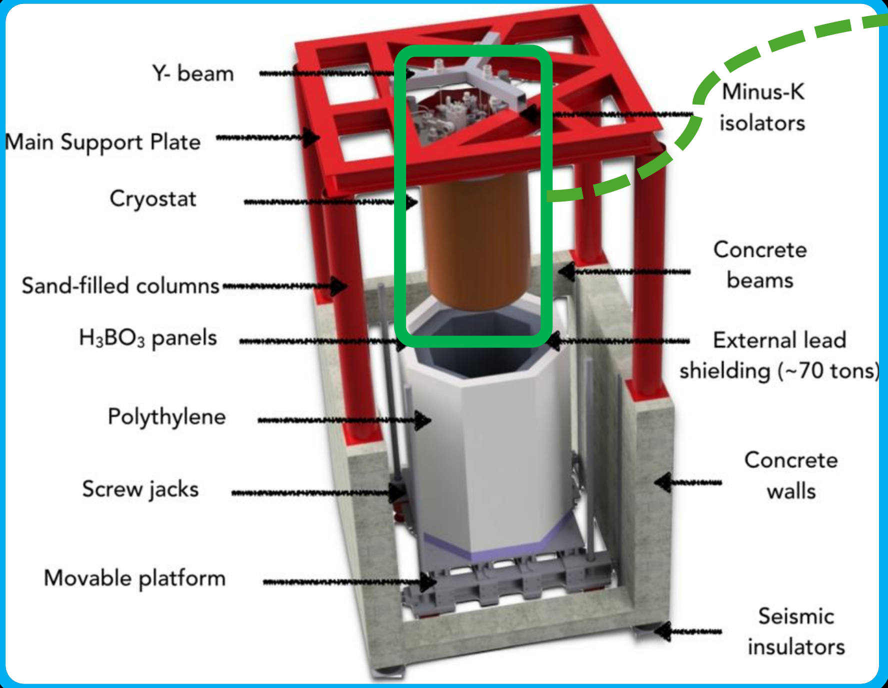
$T = T_0$

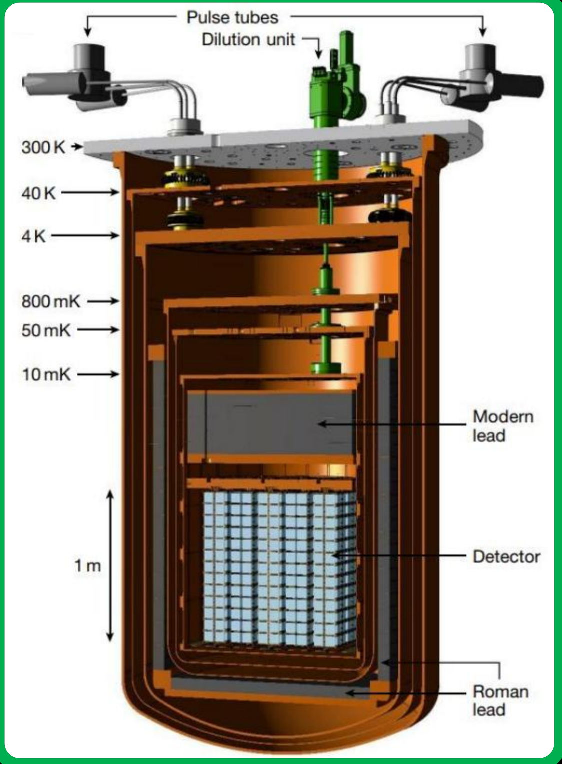


Challenges

Low Vibrations

- ❖ Noise diagnostic devices
- ❖ Decouple detectors and cryostat





Low Radioactivity

- ❖ Underground:

Average depth ~ 3600 m.w.e.
μ flux: 3×10^{-8} μ/s/cm^2
n flux: 4×10^{-6} n/s/cm^2 < 10 MeV
γ flux: ~0.73 γ/s/cm^2 < 3 MeV

- ❖ External shields

Low Temperatures

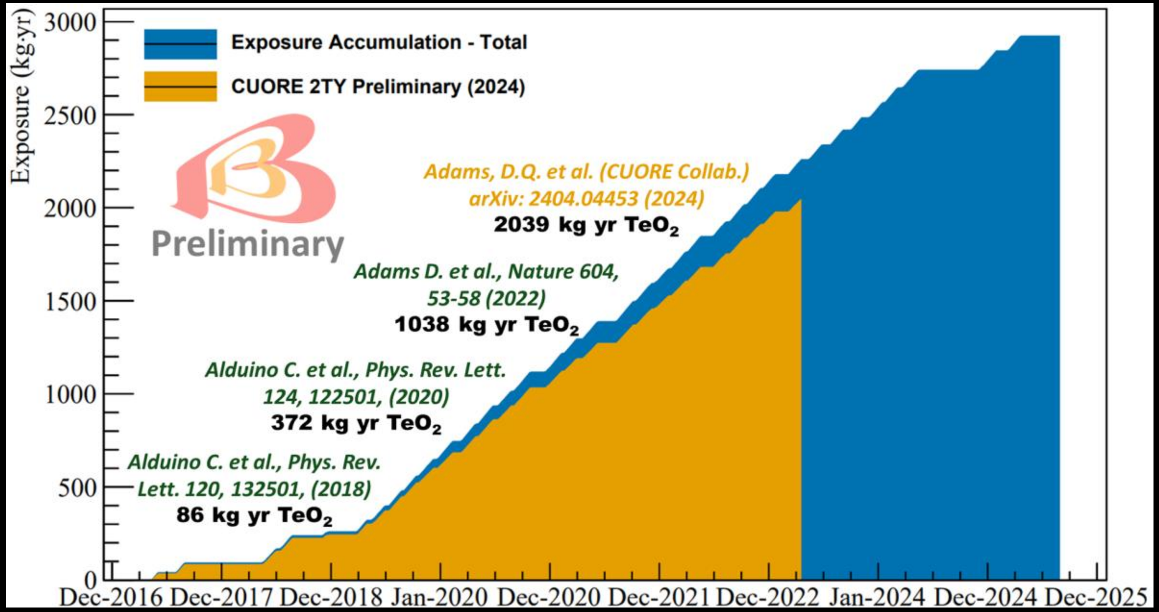
- ❖ Mass < 4K: 15 tons
  < 50mK: 3 tons
- ❖ Operating stably below 20mK for >> 1yr

5x5x5 cm^3 crystals
19 towers
13 floors
4 positions

CUORE with ^{130}Te

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

- ❖ 988 TeO_2 natural crystals ➔ total ^{130}Te mass of 206kg
- ❖ Dynamic range: ~ keV ➔ ~ MeV
- ❖ $\Delta E/E$ ~ 0.3% @ $Q_{\beta\beta}$

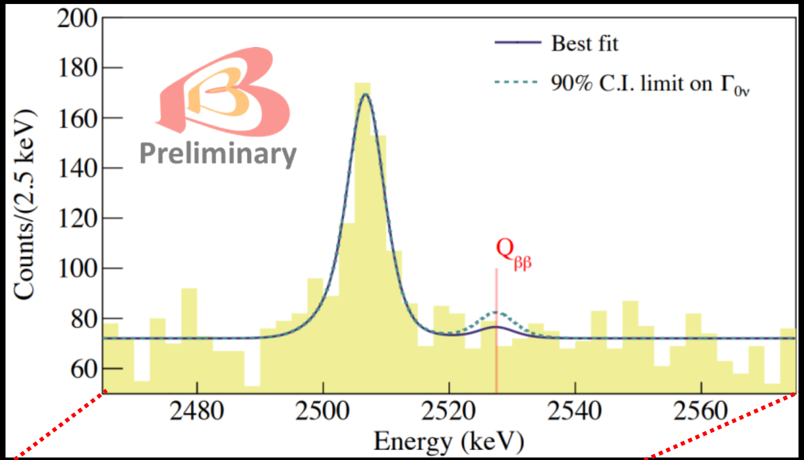


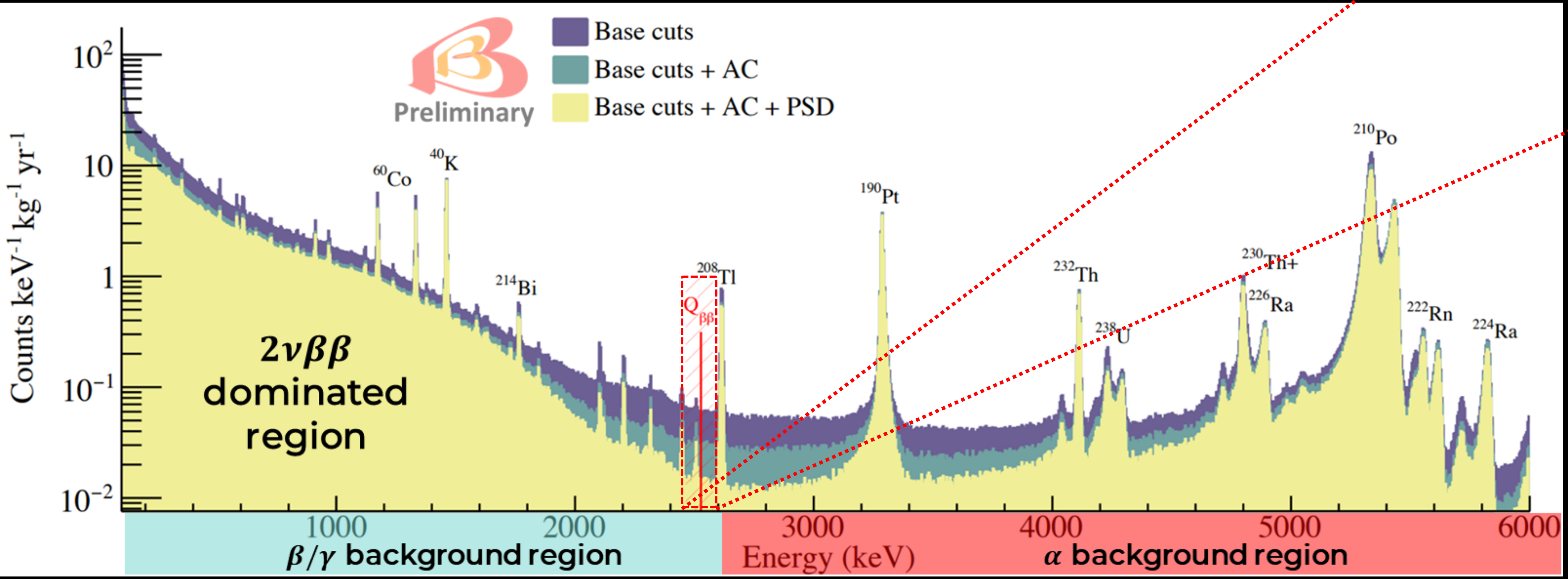
CUORE
Cryogenic **U**nderground **O**bservatory for **R**are **E**vents

Goal: 3 tonnes year of exposure

CUORE - Results

- ❖ Data-driven background model
  ➔ limits on other rare events
- ❖ Stable operation of a tonne-scale milli-kelvin cryogenic calorimeter
- ❖ $T(^{100}\mathrm{Te})^{0\nu\beta\beta}_{1/2} > 3.8 \times 10^{25}$ yr (90% C.I.)





Base cuts
trigger, pile-up, energy reconstruction

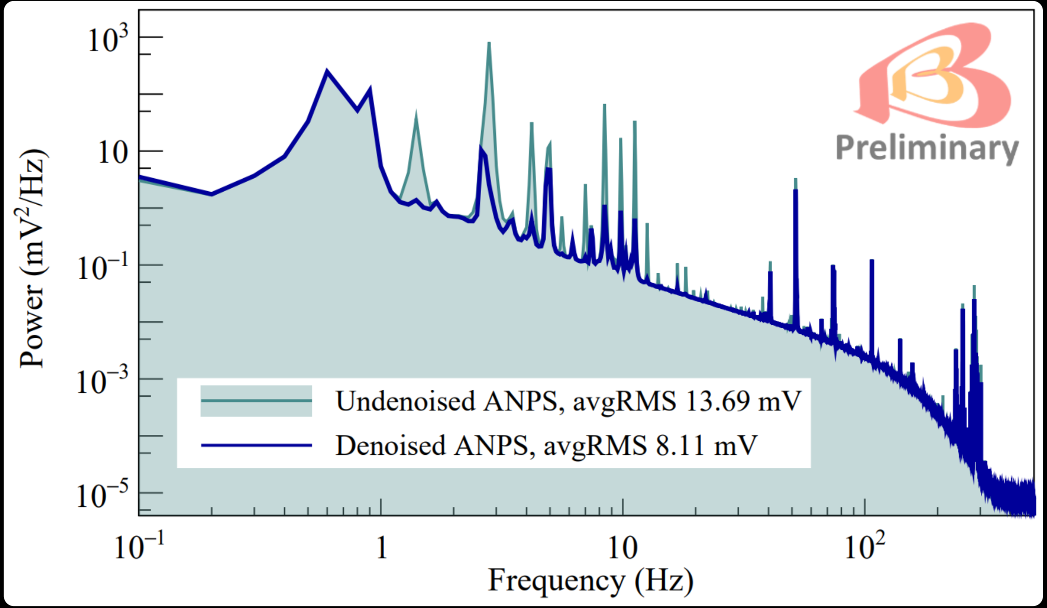
Anti-coincidence (AC)
only single-crystal events

Pulse shape discrimination (PSD)
only signal-like events

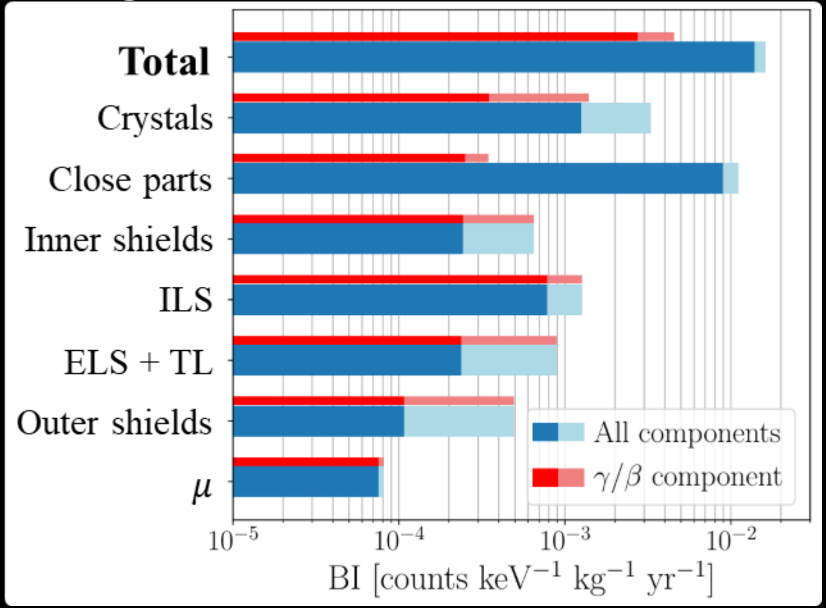
… and limitations

Vibrational noise and noise instabilities in the ~Hz range spoil the sensitivity
➔ Denoising techniques

Average Noise Power Spectra



Background Index

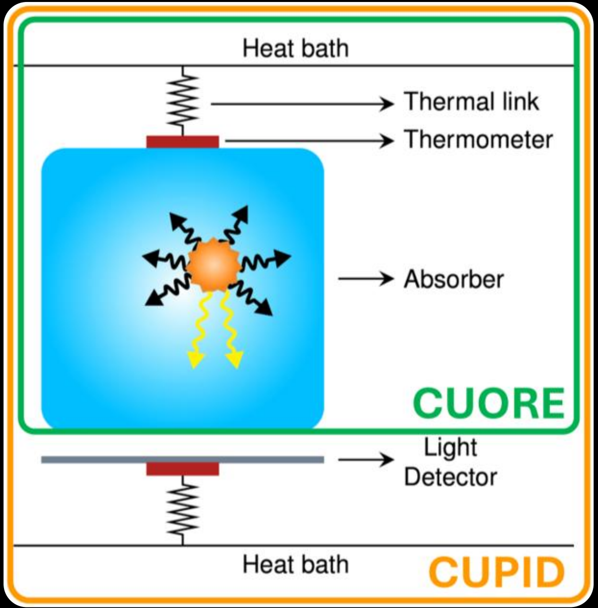


CUORE is background-limited by energy degraded α particles
➔ Particle Identification

CUPID with ^{100}Mo

^{100}Mo
10% (i.a.)
3034keV ($Q_{\beta\beta}$)

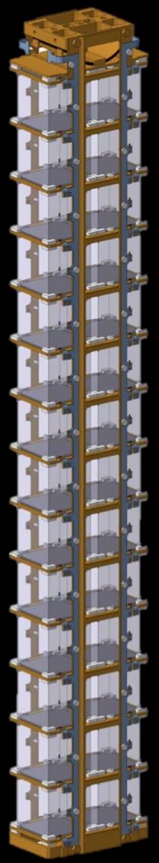
Favourable phase space and matrix element factors

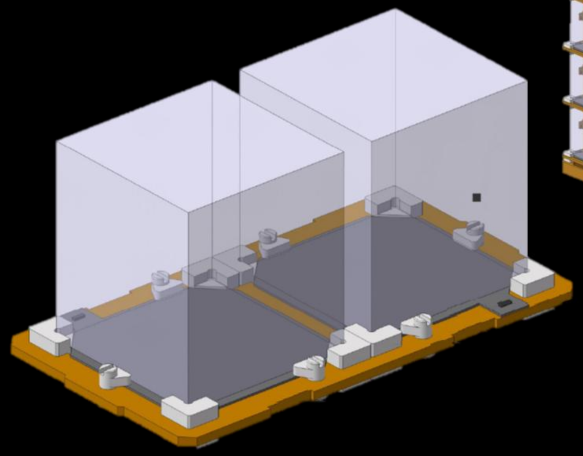


Baseline design

- Next-generation tonne scale experiment
- Will inherit CUORE’s infrastructure
- Double readout strategy (heat and light)
- 1596 $Li_2{}^{100}MoO_4$ enriched crystals
  ➔ 95% of ^{100}Mo, total mass of 240kg
- 1710 Ge-wafer Ligh Detectors
- ΔE < 5keV @ $Q_{\beta\beta}$

4.5x4.5x4.5 cm^3 crystals
57 towers
14 floors
2 positions

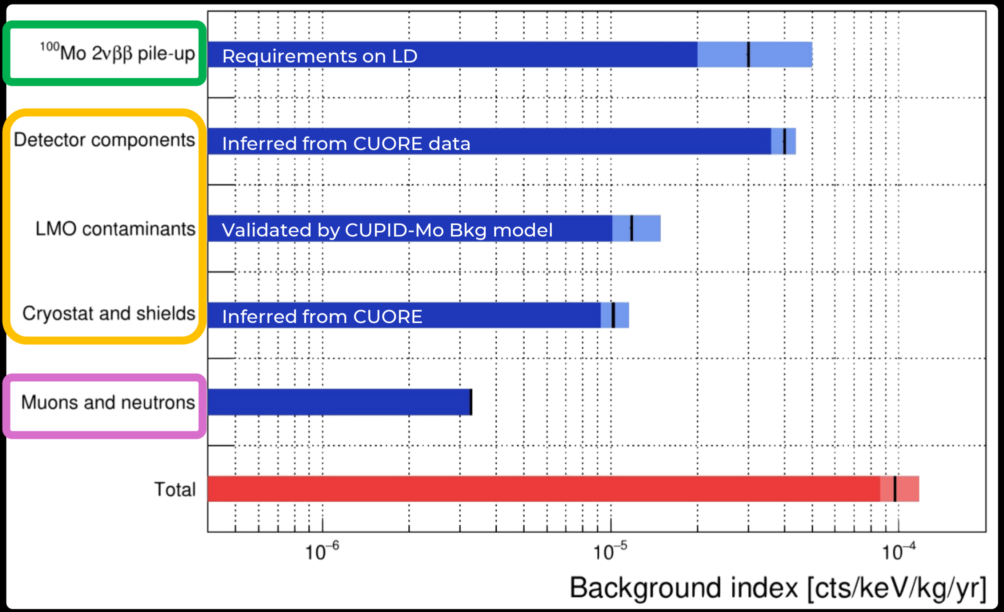




GOAL: $T_{1/2}^{0\nu\beta\beta} > 1.0 \times 10^{27}$ yr
(90% C.L. with 10 yr of livetime)

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

CUPID – Background Badget



- ❖ $Q_{\beta\beta}$ far from the γ-background
- ❖ Lower noise and higher bandwidth electronics
  - ➔ pulse tubes upgrade and thermalisation optimisation
  - ➔ auxiliary environmental sensors for denoising
- ❖ Material selection, cleaning, shielding
- ❖ Delayed coincidence cuts (U/Th chains).

Muon tagger veto detectors and neutron absorbers

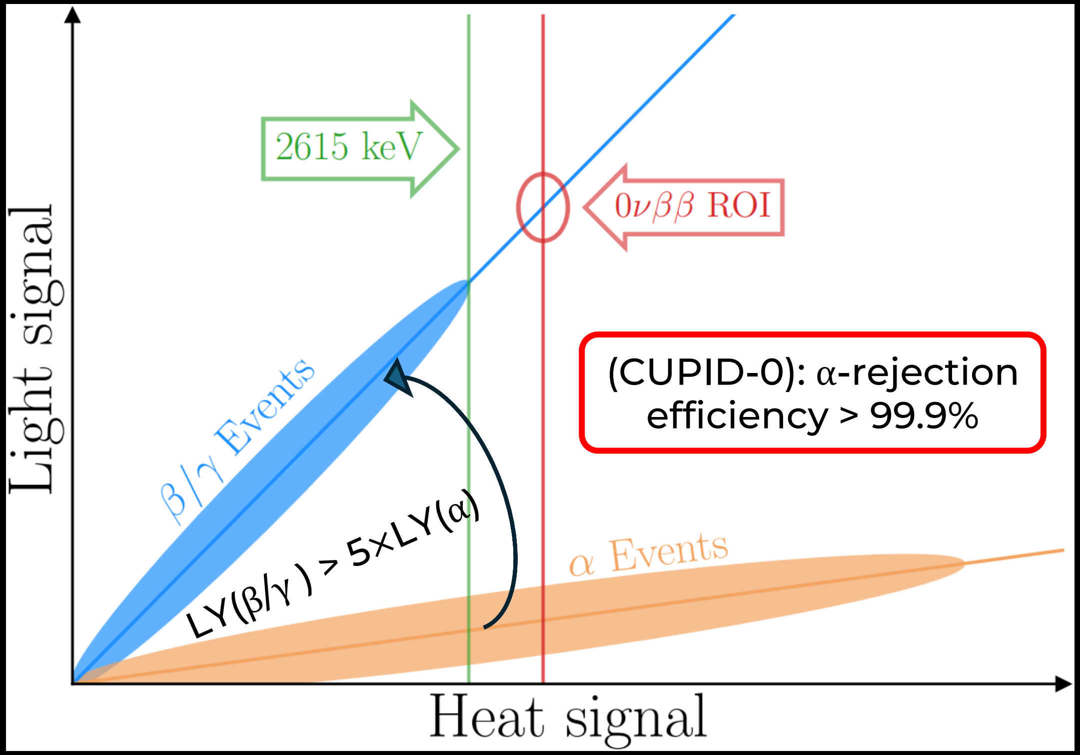
$$T(^{100}\text{Mo})^{2\nu\beta\beta}_{1/2} = 7.1 \times 10^{18}\ \text{yr}$$

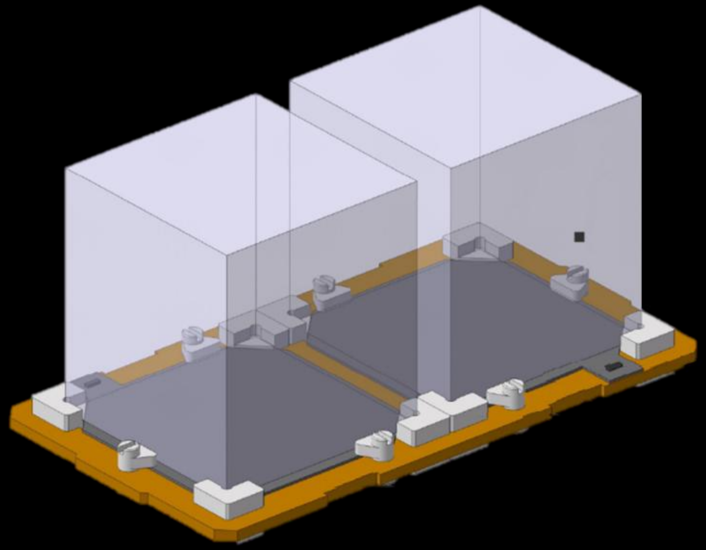
Random coincidences with $2\nu\beta\beta$ events not so negligible

➔ constraints on the LD timing resolution and SNR

LD - Requirements

- ❖ Particle IDentification
  - ➔ LY ~ 0.3 keV/MeV
  - ➔ Baseline resolution < 100eV RMS
- ❖ Particle Shape Discrimination
  - ➔ NTL amplification
  - ➔ Timing resolution < 170μs





Neganov-Trofimov-Luke amplification

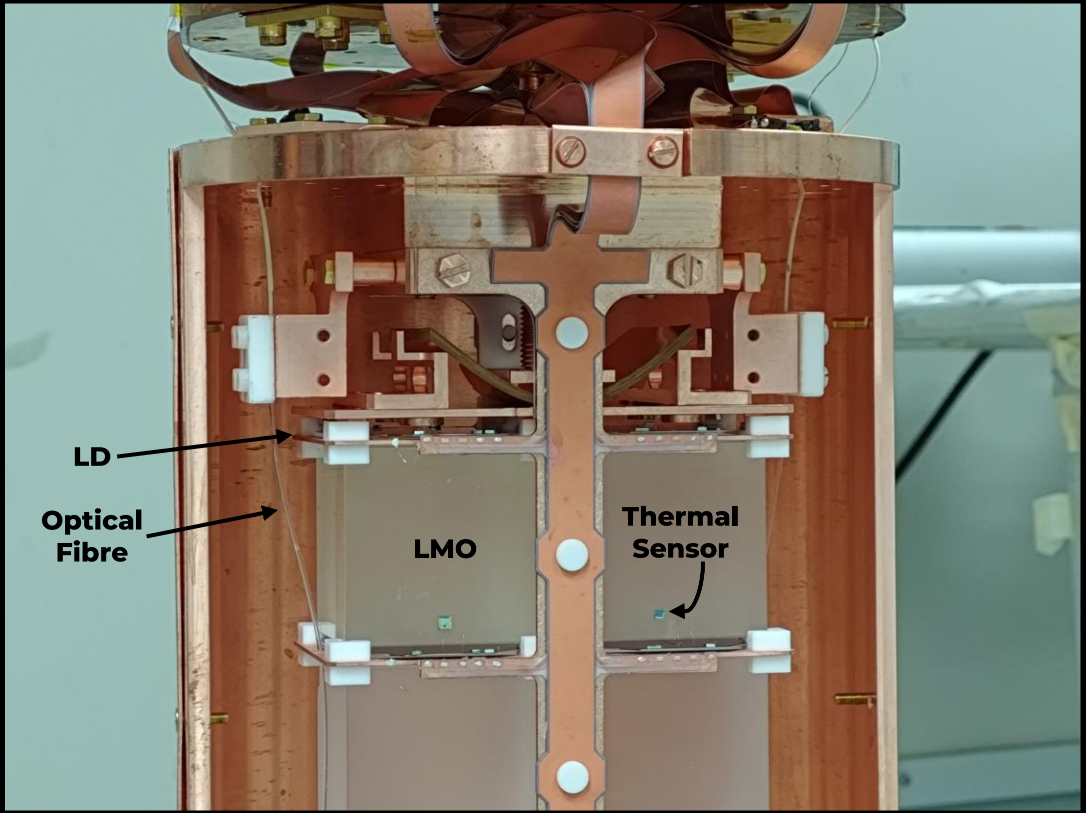
Electron-hole pairs created by light absorption are drifted by applying a voltage, thus producing additional heat

➔ Charge accumulation is a problem

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



Applications

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

Requirements

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

→ **Design**

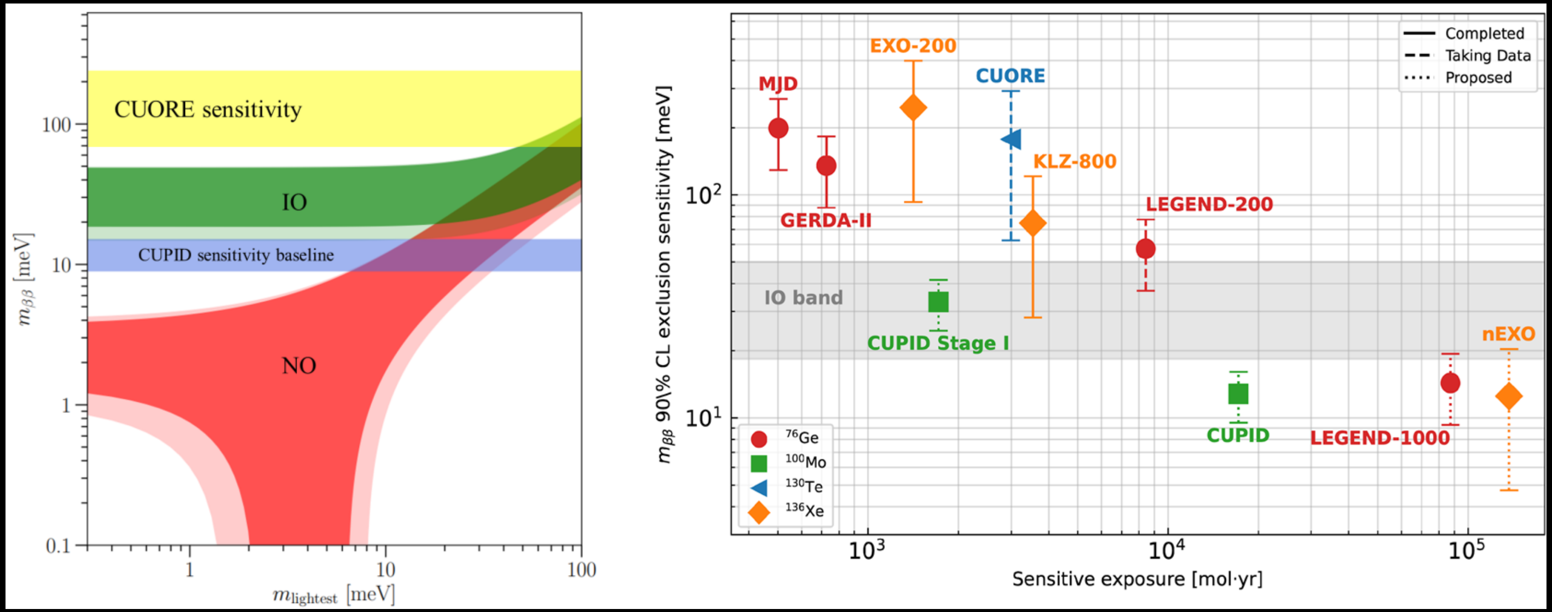
- ❖ Stable pulses
- ❖ Wavelength

→ **Source**

- ❖ Pulse width
- ❖ DAQ interface

→ **Electronics**

What's next !?



2026

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

2030

CUPID Commisioning

THANK YOU FOR YOUR ATTENTION

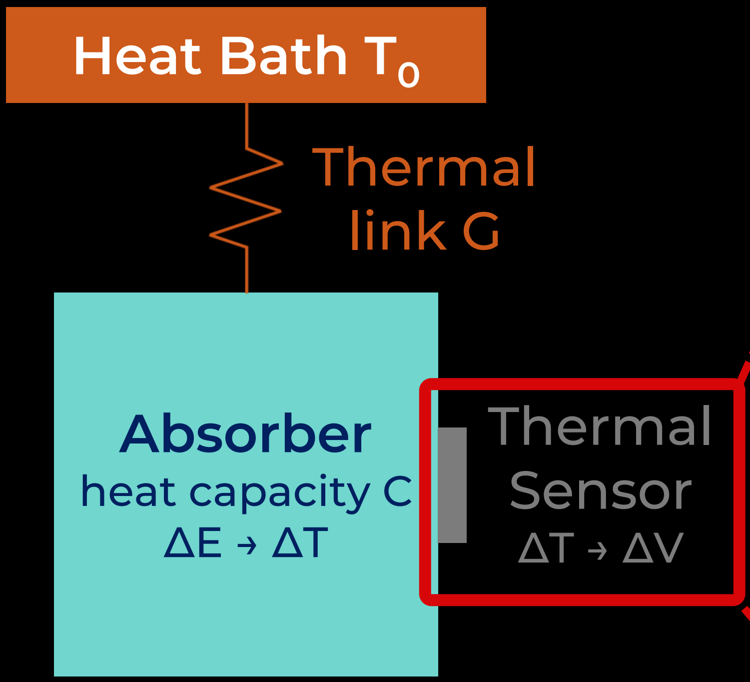
CUORE and CUPID collaborations, Collaboration Meeting, LNGS May 2025

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

Cryogenic Calorimeters - NTDs



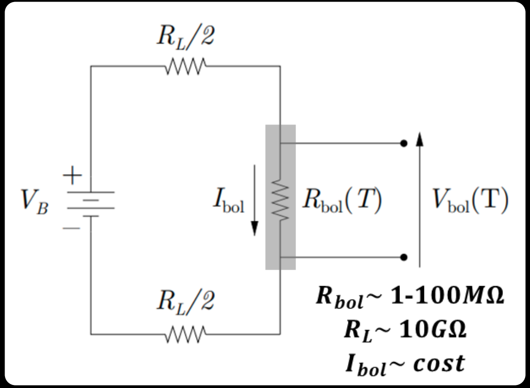
Neutron Transmutation Doped (Ge-NTD)

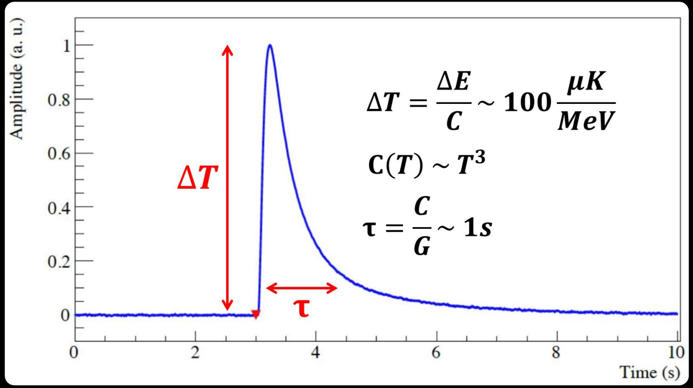
- Semiconductor Thermistor glued on the absorber
- Standard readout electronics
- Dynamic range from ~ 10keV up to ~ 10MeV
- At T << 10K , resistivity is temperature dependent

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

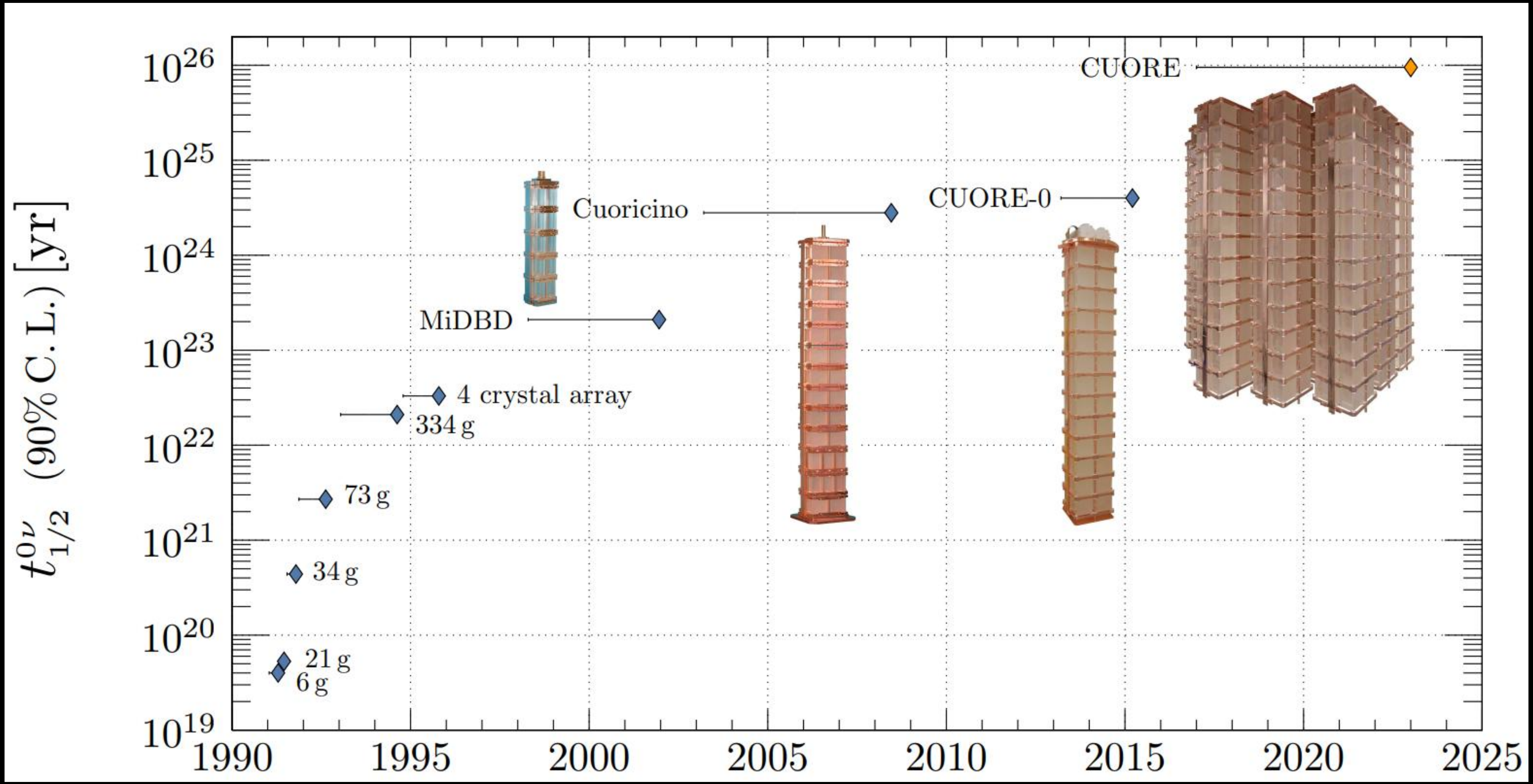
where (ρ_0 , T_0) depends on the doping level

- Sensible to mechanical vibrations and microphonism





Path toward CUORE



CUPID R&D Test

Dilution Cryostat