Development of NTL light detectors for the CUPID 0νββ experiment

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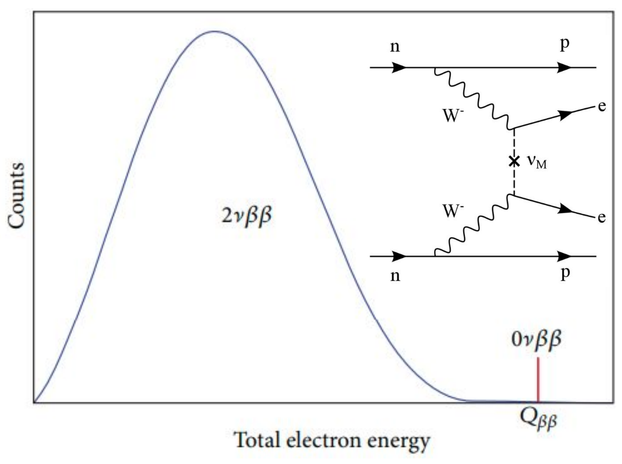
Neutrinoless Double-Beta Decay (0νββ)

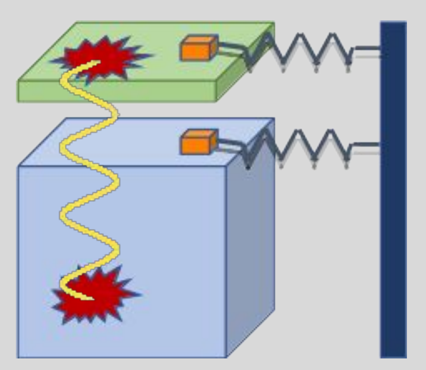
- Special case of the double-beta decay [1] (2^{nd} order process in weak interactions) possible only if neutrino is its own antiparticle and if lepton number conservation is violated
- **Signature:** mono-energetic peak in the two electrons spectrum

$$(T_{1/2}^{0\nu2\beta})^{-1} = G(Q,Z)g_A^4|M^{0\nu}|^2\frac{m_{\beta\beta}^2}{m_e^2}$$

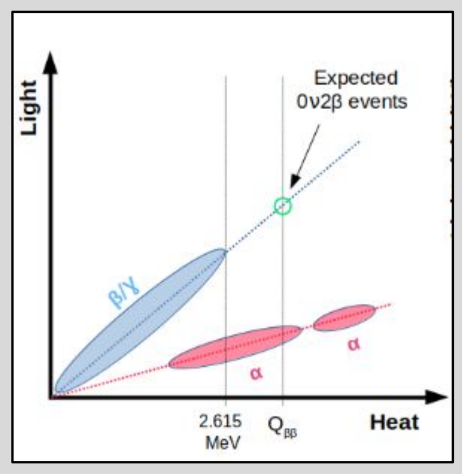
Current limits: $T_{1/2}^{0\nu2\beta} > 10^{24} - 10^{26}$ yr



Detection method: Scintillating bolometers



- Scintillating $Li_2{}^{100}MoO_4$ (LMO) crystal
- Ge **NTL** cryogenic light detector
- Thermistor (NTD Ge) - $R = R_0 e^{\sqrt{\frac{T_0}{T}}}$
- Thermal bath



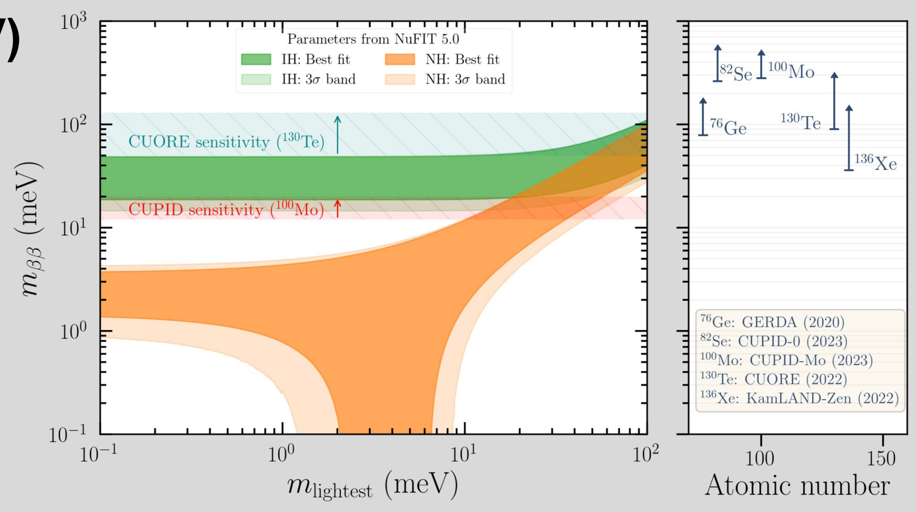
- **Detector=Source approach** → High efficiency (~ 80 – 90 %)
- Excellent energy resolution (< 0.2% in the ROI - Objective: 5 keV)
- Large masses achievable using arrays of crystals
- Large absorber material choice
- **α identification** and rejection demonstrated with CUPID-0 and CUPID-Mo

CUPID: CUORE Upgrade with Particle IDentification

CUPID [2] will be the successor of the CUORE experiment

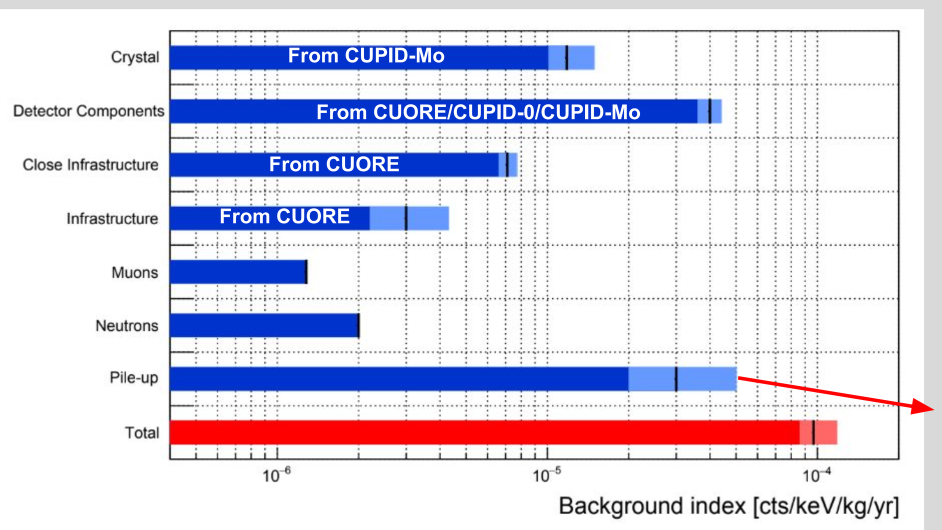
Primary goal: Search for 0νββ of ^{100}Mo ($Q_{\beta\beta}$=3034 keV)

- 1596 LMO crystals divided in 57 towers
  Total mass 450 kg (240 kg of ^{100}Mo)
- 1710 NTL Ge light detectors
- Will be installed inside CUORE cryostat at LNGS
- Half-life discovery sensitivity (3σ): 1×10^{27} yr
- $m_{\beta\beta}$ discovery sensitivity (3σ): 12-20 meV



CUPID expected background budget

A robust background model built using knowledge acquired with CUORE, CUPID-0 and CUPID-Mo experiments



Objective: b=$1\cdot10^{-4}$ ckky

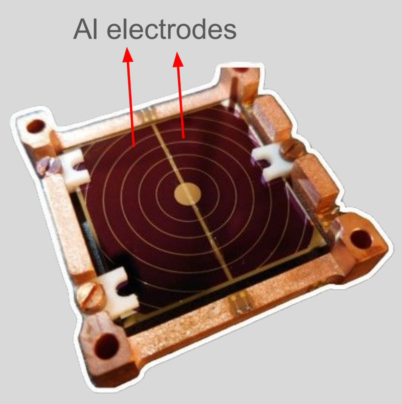
Pile-up events give a critical contribution due to fast ^{100}Mo 2νββ ($T_{1/2}^{2\nu2\beta}=7.1\times10^{18}$ yr) and slow detector response

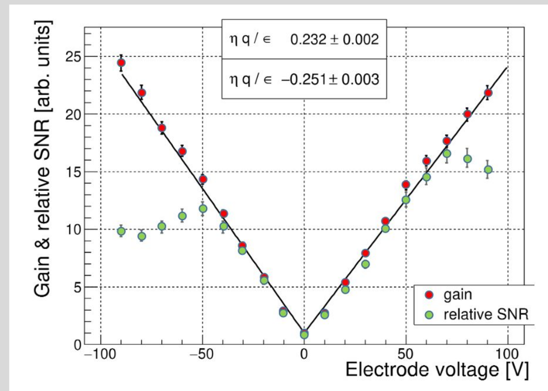
Goal: $0.5\cdot10^{-4}$ ckky

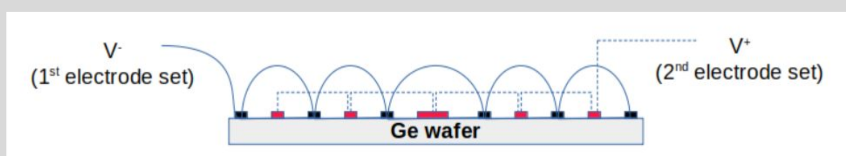
Light detectors are the key!

Neganov-Trofimov-Luke light detectors (NTL LDs)

Ge wafer with Al electrodes evaporated on the surface and operated with NTD Ge







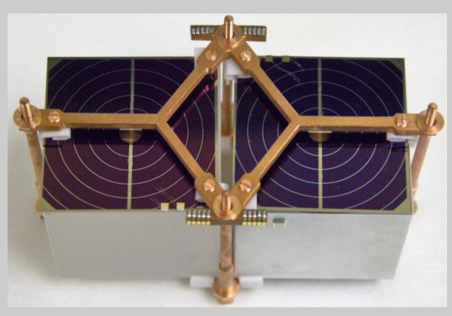
Neganov-Trofimov-Luke effect [3]:
Applying a voltage difference V through the electrodes causes the e-h pairs created by an event to drift, amplifying the heat signal.

$$E = E_0(1+\frac{q\cdot V_{el}\cdot\eta}{\epsilon}) = E_0\cdot G_{NTL}$$

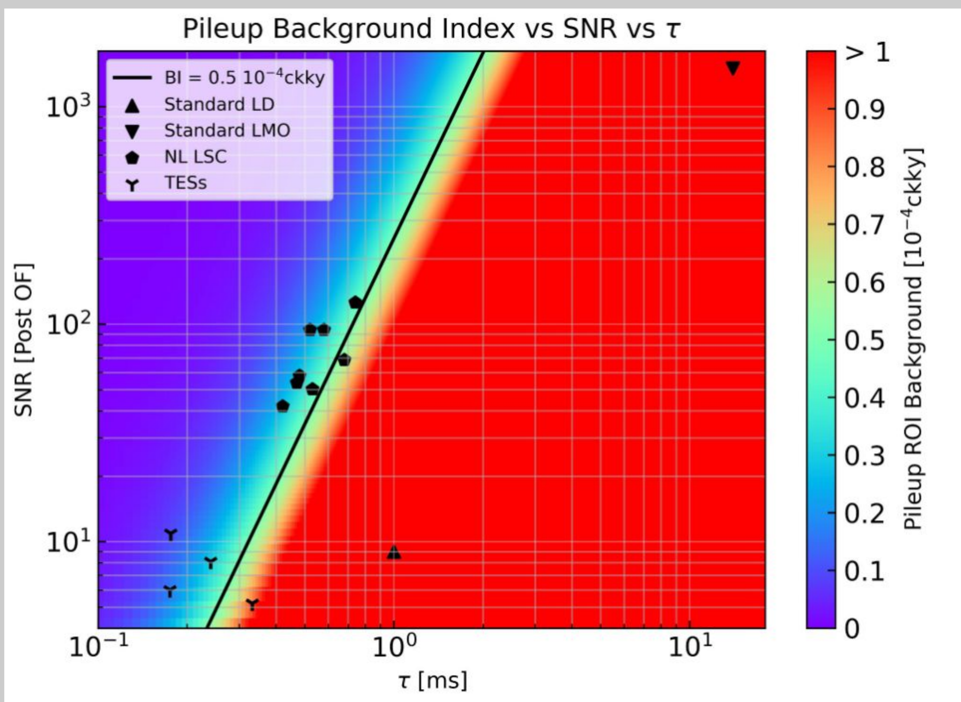
E_0: Particle energy	ε: energy required to create one e^-/h^+ pair
q: e^- charge	
V_{el}: Electrode bias	G_{NTL}: NTL gain

R&D on NTL LDs

1st underground measurement @ Laboratorio Subterraneo de Canfranc (LSC)

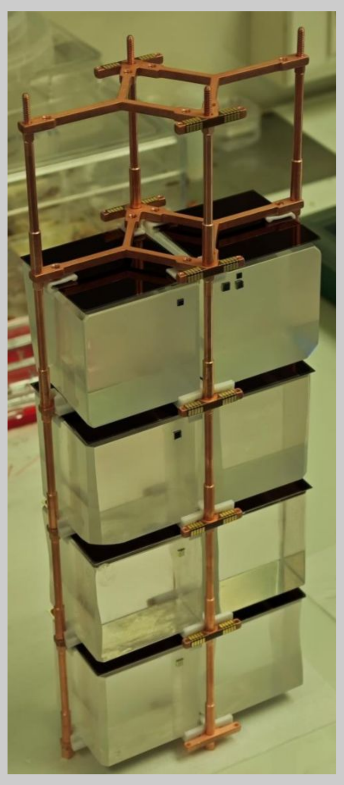


- 10 NTL LDs with concentric Al rings
- Ge-LD dimension: 45*45*0.3 mm
- Electrodes coverage is 56% → Geometric factor correction applied to extract the gain
- Assembled in a tower of five floors
- One discarded due to electronics problem

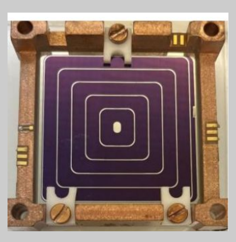


8/9 were biased with 80 V to study them →**7/8 LDs comply with the CUPID goal!**
A study of NTD response showed that rise times between 0.4 and 0.8 ms are achievable.

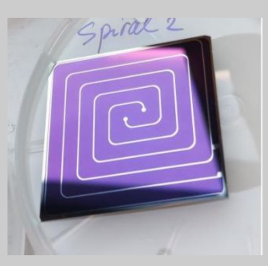
2nd underground measurement @ LSC: 14 NTL LDs and 3 different electrode geometries



Concentric electrodes:
- 10 LDs with concentric electrodes (previously tested)
- Showed consistent and similar results
- 9/10 can hold up to 140 V



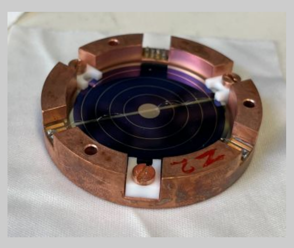
Square electrodes:
- 1 LD with square electrodes
- Advantages: full geometry coverage
- Similar result to the previous measurement (V_{max}=120 V)

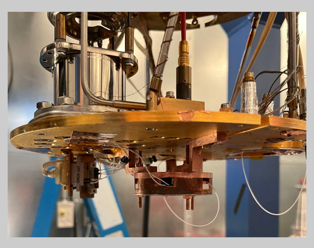


Spiral electrodes:
- 3 LDs with spiral electrodes
- Advantages: full geometry coverage + facilitate the evaporation & the bondings
- 2/3 can handle 60 V
- Gain on LED (610 nm) 2x higher than with concentric geometry

Validation of the Berkeley cryogenic setup for NTL LDs characterization

- Test of a device already characterized at IJCLab in France
- Comparison of the results and standardization of the test procedure underway



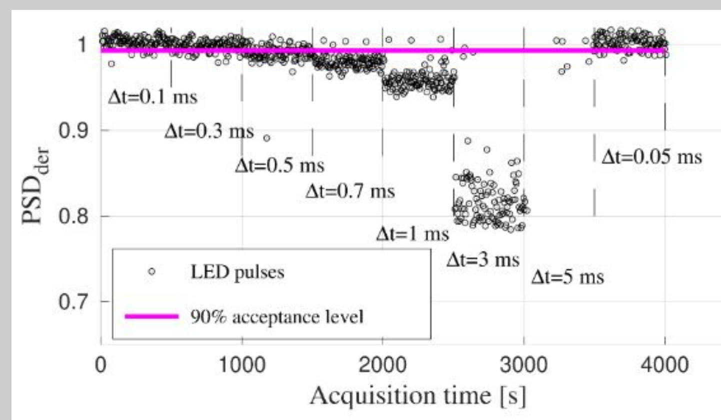


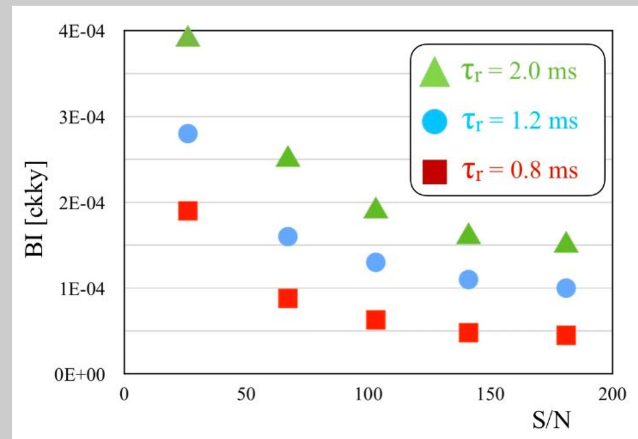
Other developments and future measurements

- Improvements of the fabrication procedure
- Leakage current investigation
- More electrode geometries explored
- Preparation of a CUPID-like tower composed of 30 NTL LDs (half produced in France and half in the USA)

NTL LDs for pile-up rejection

We can reject the pile-up events offline using parameters depending on the signal pulse-shape





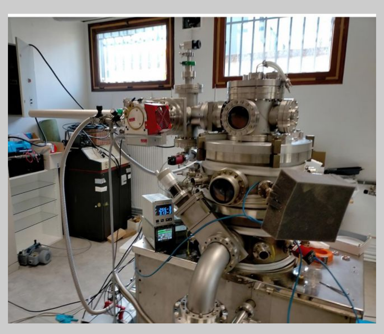
The efficiency of this method depends on the rise-time and the signal-to-noise ratio (SNR) of the signals [4].
The boost on the SNR provided by the NTL LDs is mandatory for CUPID to reach its objective. **Target number for the LDs:**

Rise-time	SNR	Baseline RMS σ @ 0 V
< 0.7 ms	> 130	100 eV

Detector production

Two production sites:

@ IJCLab, France
- Production of NTL LDs for over a decade
- Evaporation of the Al electrode with a shadow mask-based method
- Baseline for CUPID recipe



@ Argonne, USA
- Knowledge transfer with IJCLab ongoing
- 1^{st} batch of American NTL LDs will be soon produced
- Photo-lithography for electrode deposition will be also tried

For CUPID, the objective is to split the production of the 1710 NTL LDs between France and the USA

References

[1] *M. Agostini, et al., Rev. Mod. Phys. 95 (2023) 025002*
[2] *See "The CUPID 0νββ experiment" poster ID#376 by V. Berest at this conference*
[3] *V. Novati et al., Nucl. Instrum. Meth. A 940 (2019) 320*
[4] *A. Ahmine et al., The European Physical Journal C 83 (2023) 373*