Neganov-Luke light detectors for double-beta decay experiments

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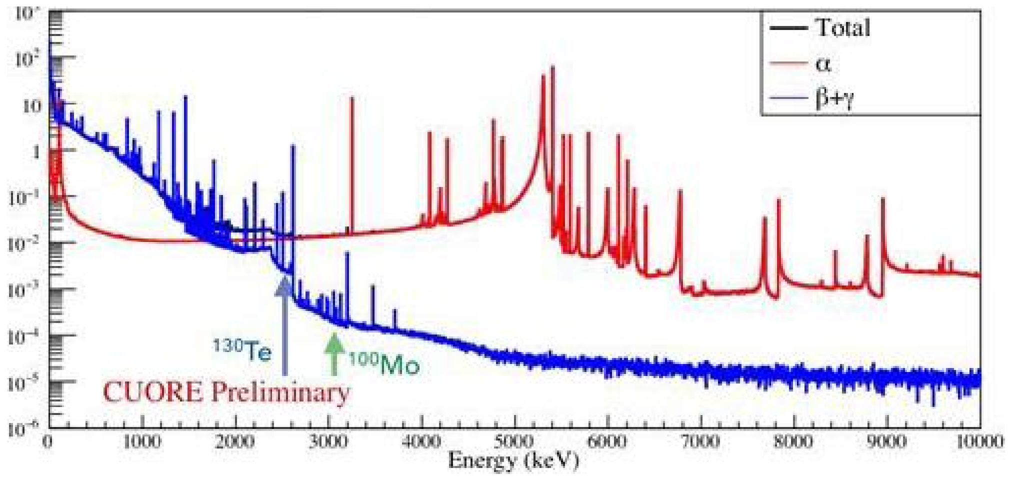
Why do we need new technologies for LDs?

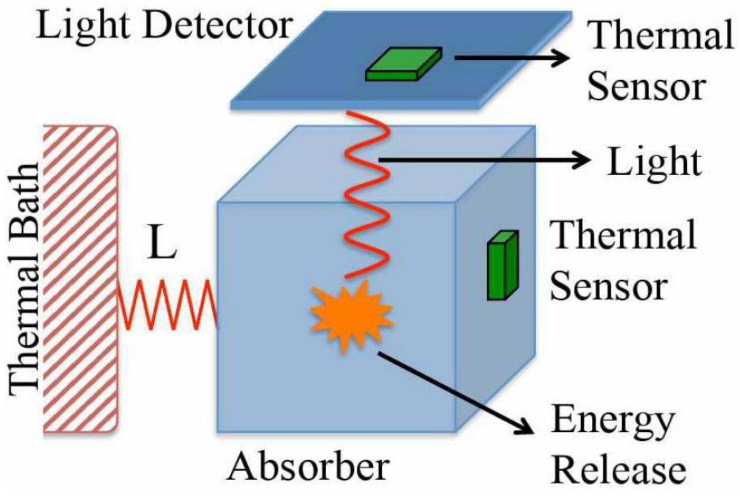
CUPID

CUPID - proposed next-generation 0v2b bolometric experiment that will use CUORE infrastructure with background level 100 times lower at the ROI

CUORE background



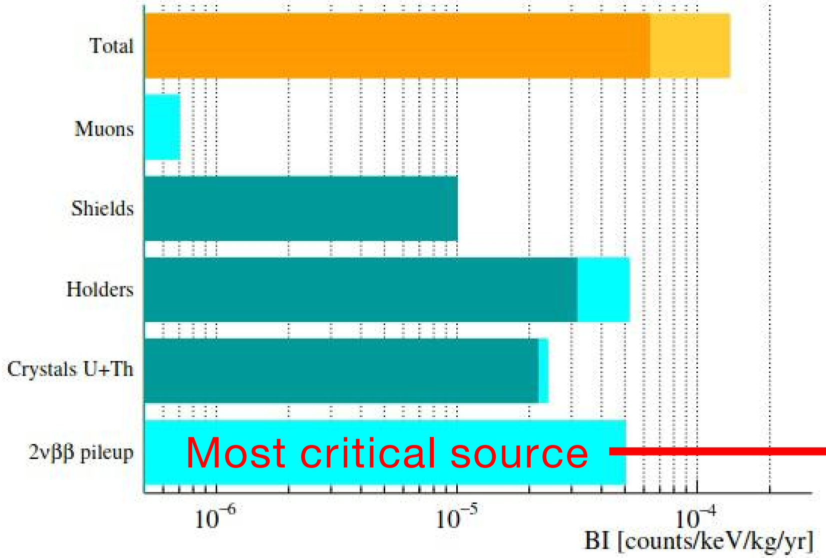
~50 counts/y in the ROI, dominated by surface alpha background



- Reject α background with **scintillating bolometers** (high-performing light detectors for effective rejection)
- Mitigate γ background by moving from ^{130}Te to **^{100}Mo** ($Q_{\beta\beta}$=3034keV)

CUPID

CUPID background model



Random coincidence of $2\nu2\beta$ events ($T_{1/2}^{2\nu2\beta}=7.1\times10^{18}$ y)

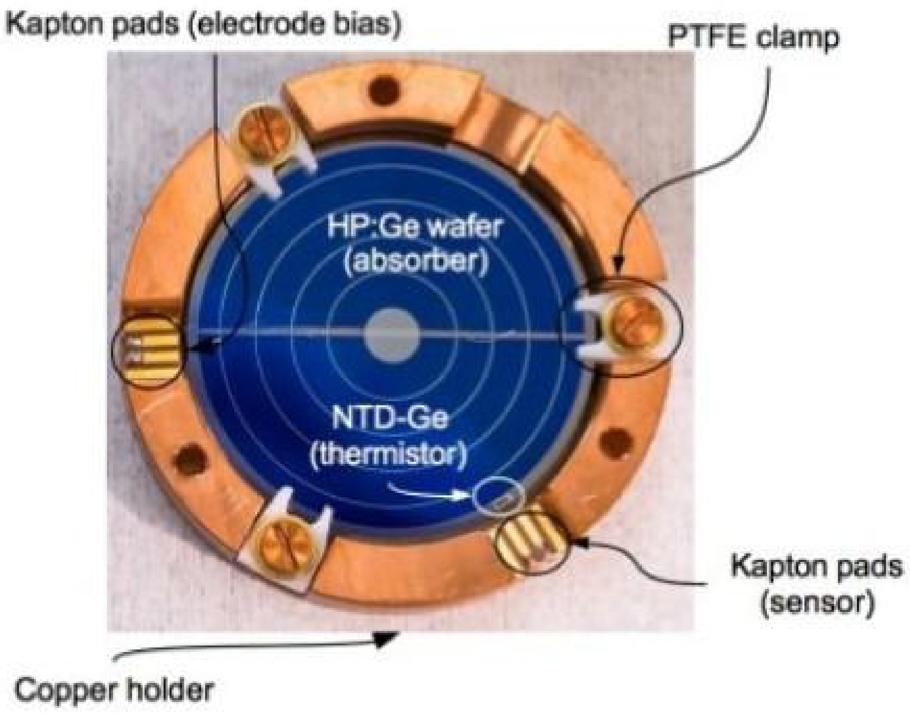
Pile-ups could be rejected by pulse shape but required:

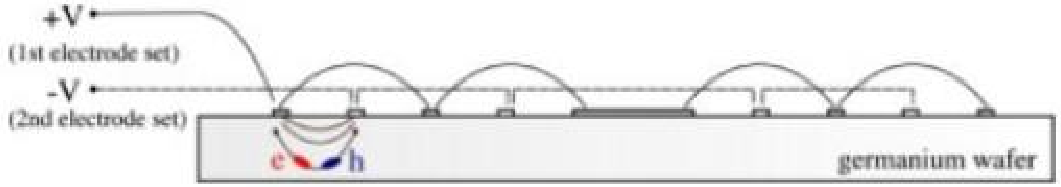
- Improve noise level in the heat and light channels
- Improve sensitivity and speed acting on sensor features
- Widen electronics bandwidth and increase sampling rate
- Investigate machine learning techniques
- Improve S/N and/or speed of light detectors by technological upgrades

- Minimization of the signal rise-time
- Improving of baseline RMS

→ The necessity of the light detectors technological upgrade

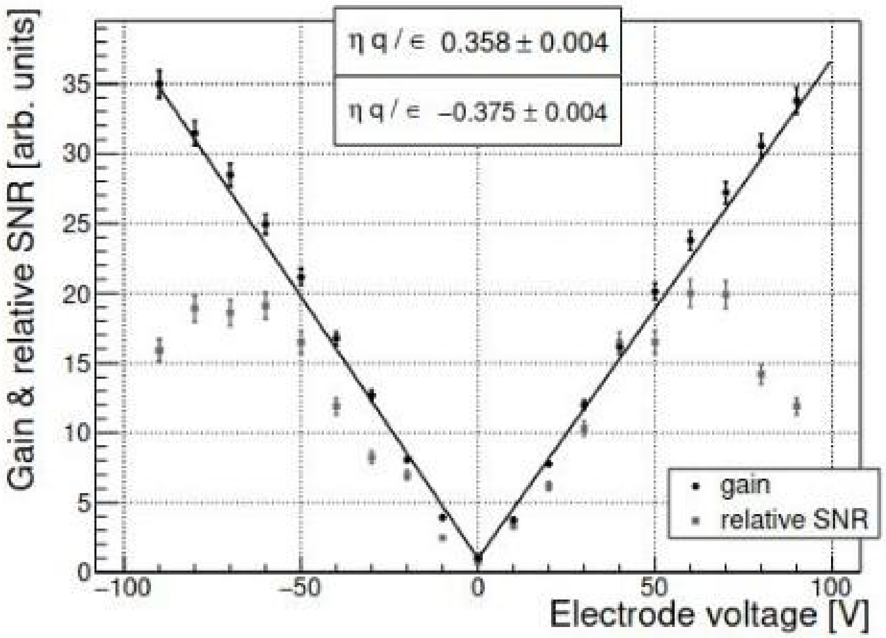
Neganov-Luke technology



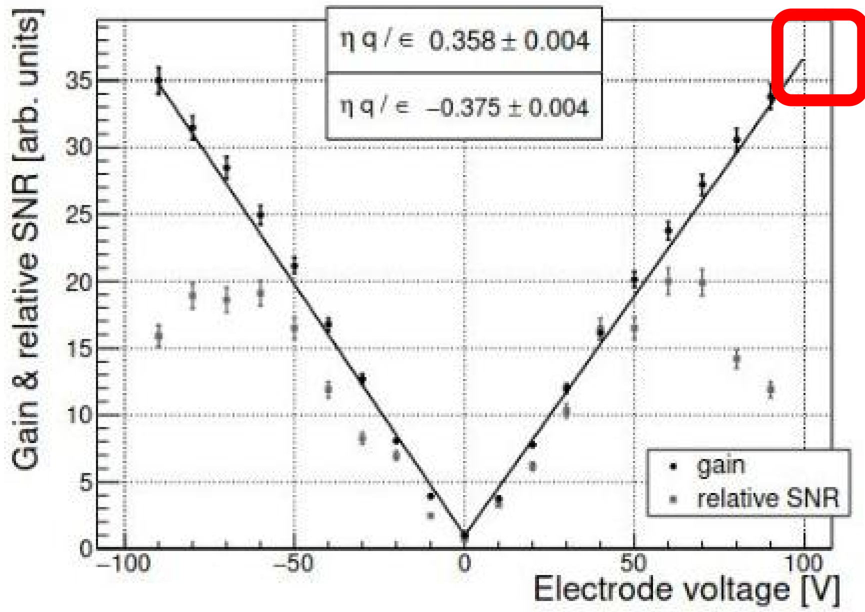


$$E_{tot} = E_0 \left(1 + \frac{q \cdot V_{el} \cdot \eta}{\epsilon}\right) = E_0 \cdot G_{NTL}$$

E_0: Energy of the ionizing particle
ε: Average energy required to generate an electron-hole pair
q: elementary charge
V_{el}: Potential between the electrodes
η: Amplification efficiency
G_{NTL}: Gain

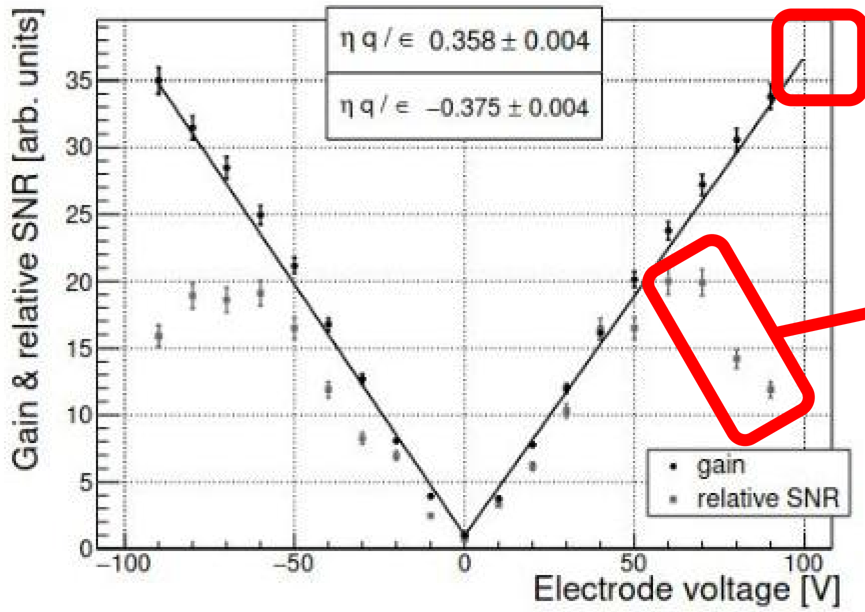


Possible difficulties



Limit in the voltage applied: after there is leakage current. Can heat up the cryostat !

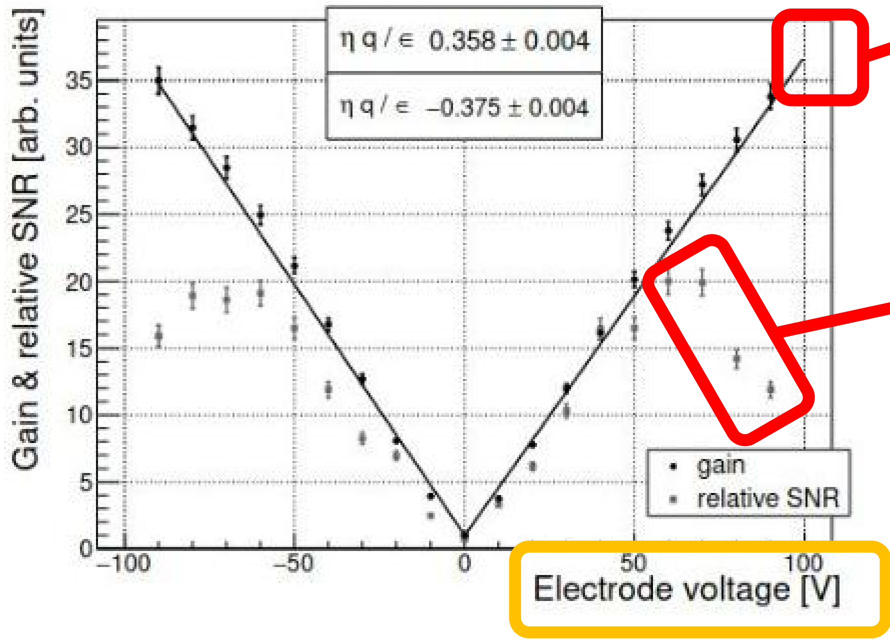
Possible difficulties



Limit in the voltage applied: after there is leakage current. Can heat up the cryostat !

Injection of extra noise after a threshold voltage value

Possible difficulties



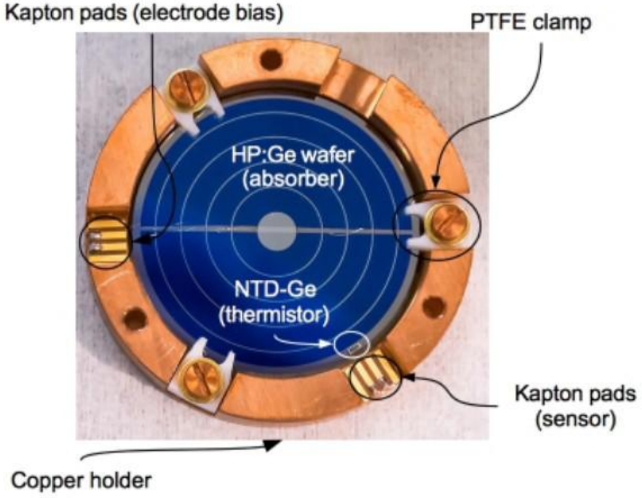
Limit in the voltage applied: after there is leakage current. Can heat up the cryostat !

Injection of extra noise after a threshold voltage value

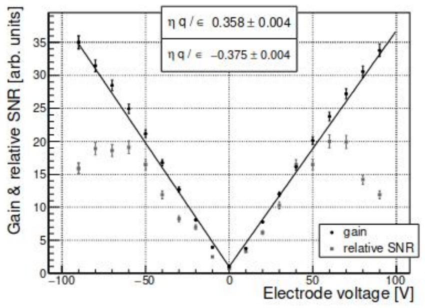
Requires more channels to inject the bias through the electrodes… But less critical, electronics is the same, channels can be parallelized…

First tests in IJCLab, Orsay

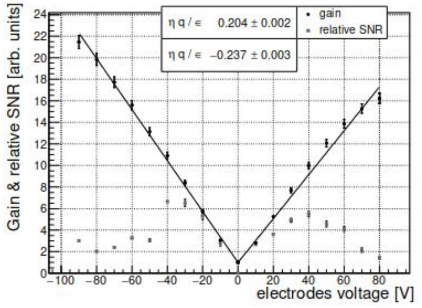
In the past, a lot of circular NTL LDs were produced in France for R&D, with good results obtained:



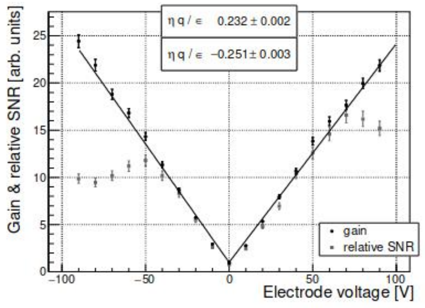
Circular wafer
Ø 44mm, 175µm thickness
200 nm Al electrodes
Circular geometry
Using shadow mask
for evaporation



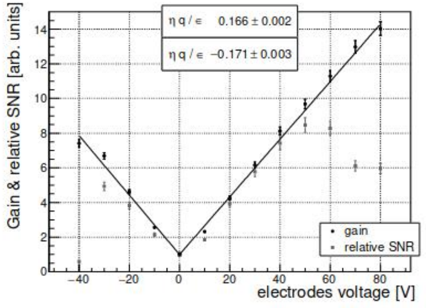
(a) NTLLD0 gain and signal-to-noise ratio.



(b) NTLLD1 gain and signal-to-noise ratio.



(c) NTLLD2 gain and signal-to-noise ratio.



(d) NTLLD3 gain and signal-to-noise ratio.

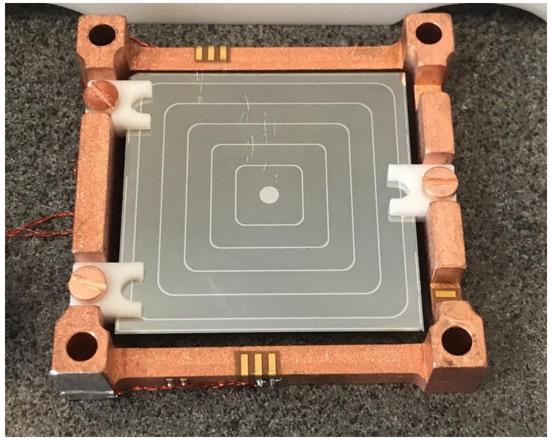
Operating voltage:
50-90V

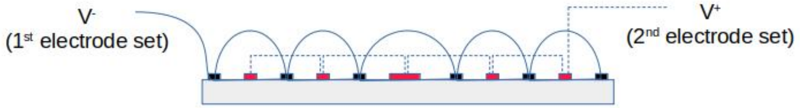
Noise RMS:
8-17eV

Gain:
~10

Tests of different electrodes geometries

"Concentric" geometry

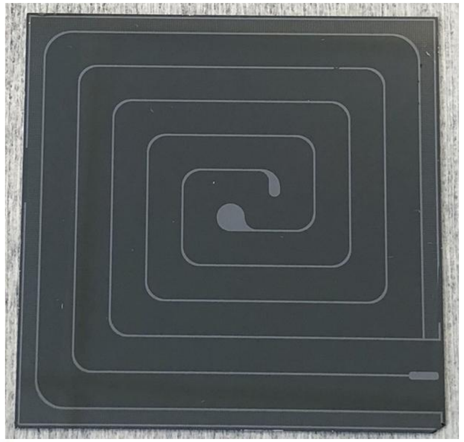




- 45x45x0.3 mm³ square HP Ge wafers
- 200 nm Al electrodes deposited on planar surface with photolithography by lift-off method
- 200 μm width electrodes with a 3.8 mm gap between them
- Maximum voltage 35V
- Effective gain ~7

- 45x45x0.3 mm³ square HP Ge wafers
- 200 nm Al electrodes deposited on planar surface with photolithography by lift-off method
- 2 x 200 μm width meandering electrodes with a 3.8 mm gap between them
- Maximum voltage 15V
- Effective gain ~4.6

"Meander" geometry



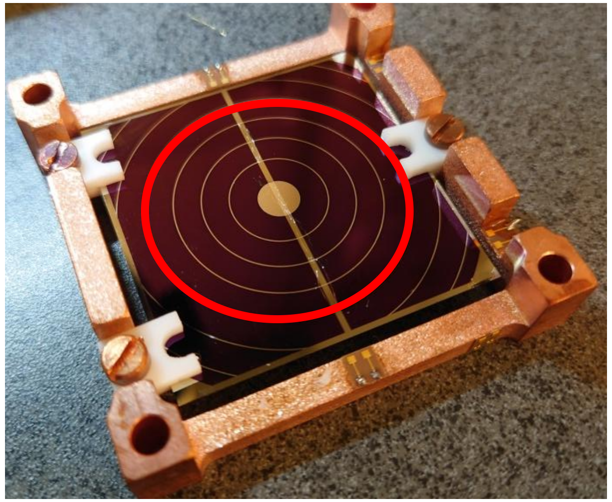
Tests of different electrodes geometries

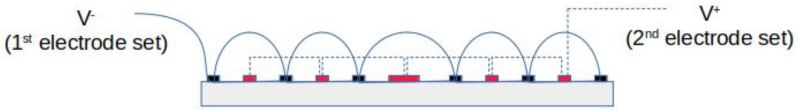
"Edge" geometry

- 45x45x0.3 mm^3 square HP Ge wafers
- 200 nm Al electrodes deposited on the edges
- Low electric field into the Ge → Allows higher NTL voltage
- Maximum voltage 190V
- Effective gain ~7

- 45x45x0.3 mm^3 square HP Ge wafers
- 200 nm concentric circular Al electrodes deposited on planar surface using evaporation
- Maximum voltage >170V
- Effective gain ~9

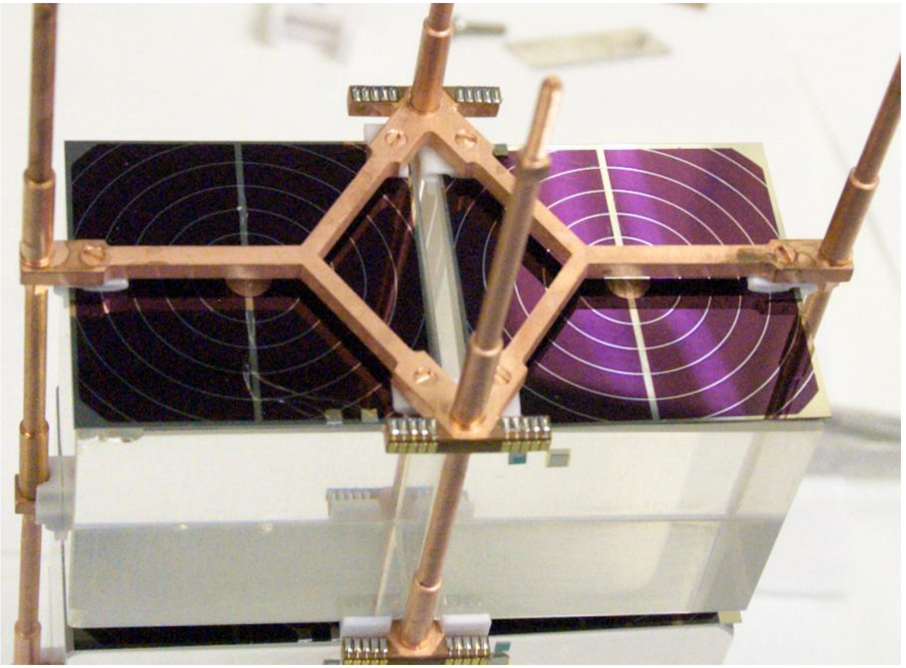
"Circular" geometry

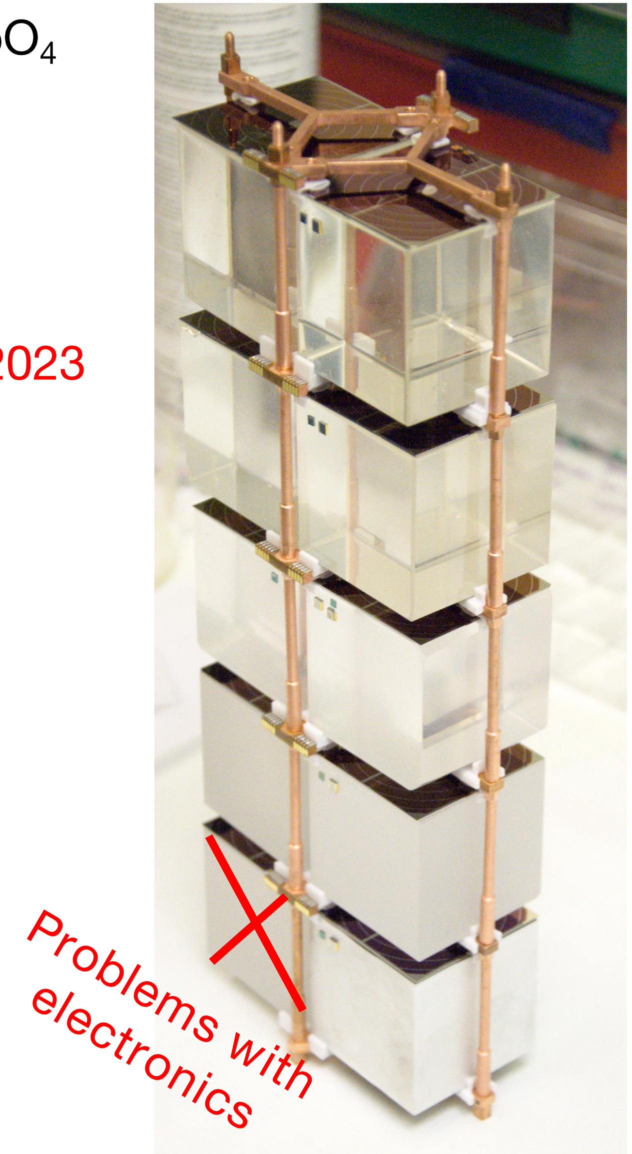




Underground measurement at LSC Canfranc

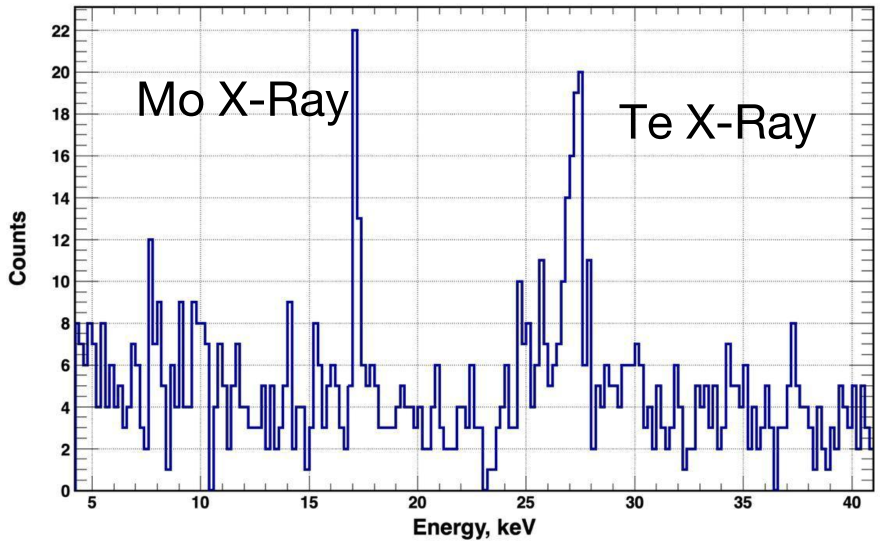
- The tower consists of 10 light detectors and 10 crystals (6 $Li_2{}^{100}MoO_4$ and 4 TeO_2
- 10 identical NL light detectors were produced using evaporation: circular concentric electrodes on square Ge wafers 0.3mm thickness
- Structure installed in Canfranc underground laboratory in February 2023

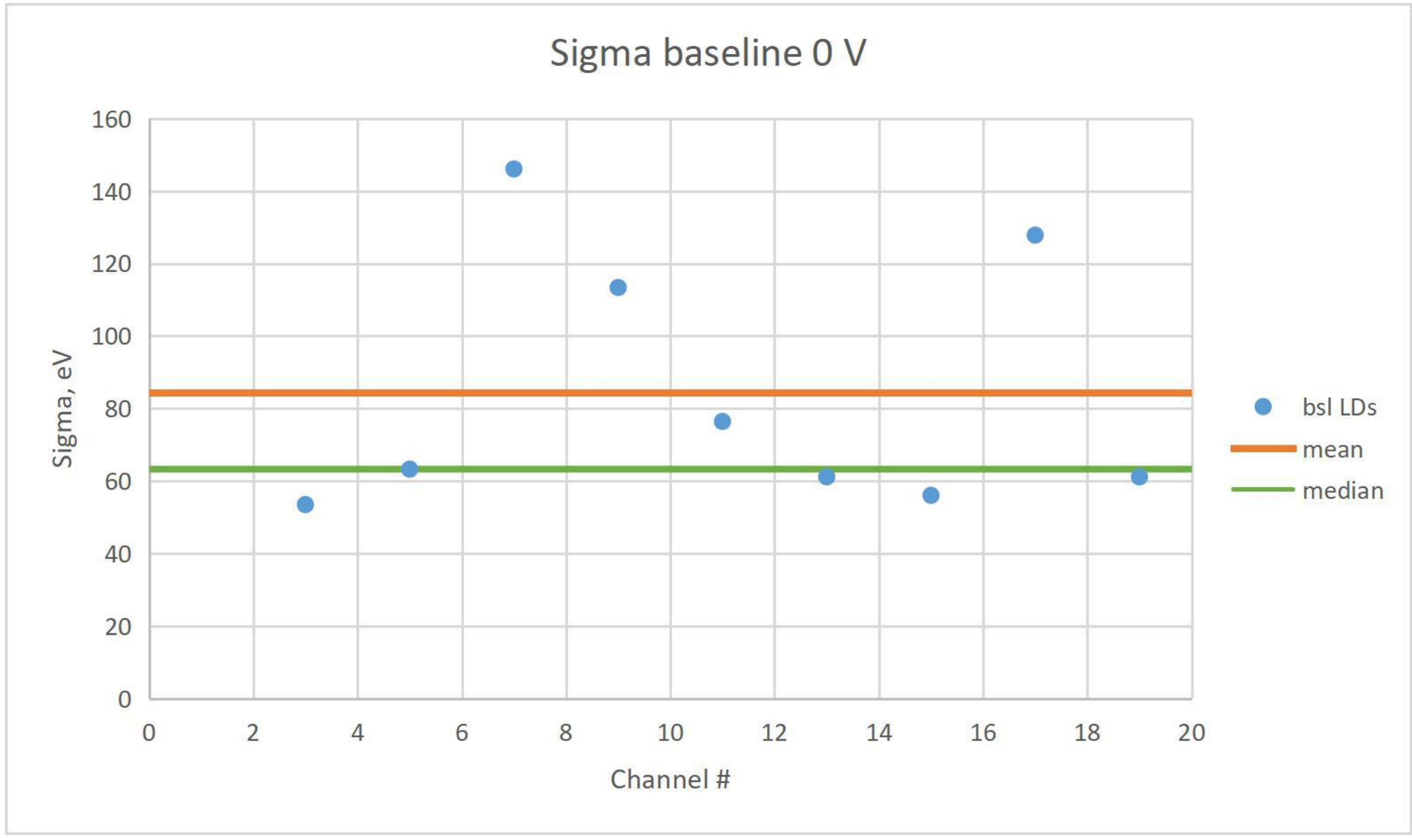




Underground measurement at LSC Canfranc

- First measurements with 0V NL bias to check the initial performance of light detectors:

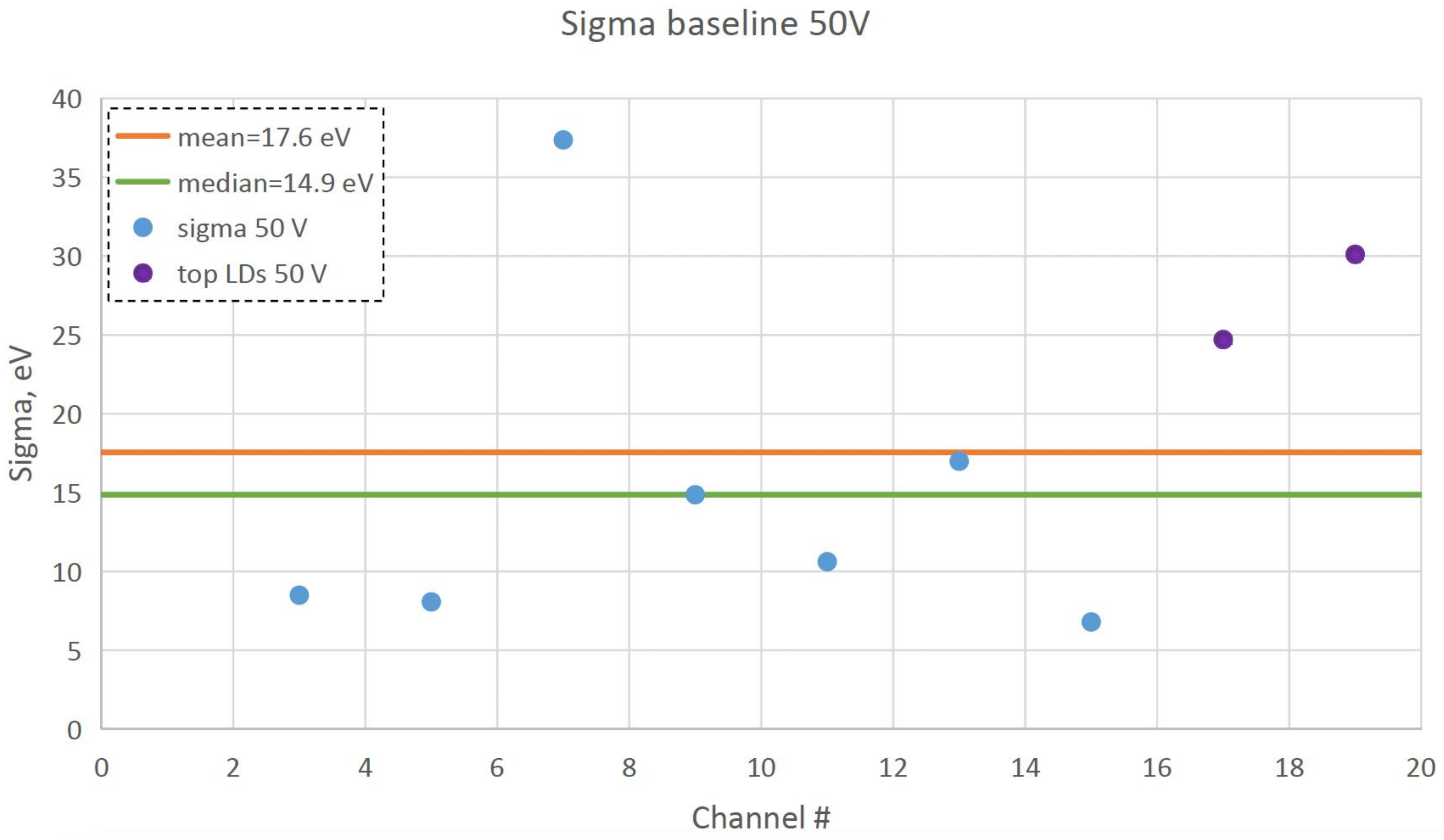




- Sigma baseline <85 eV is enough to have a more then 99% alpha rejection

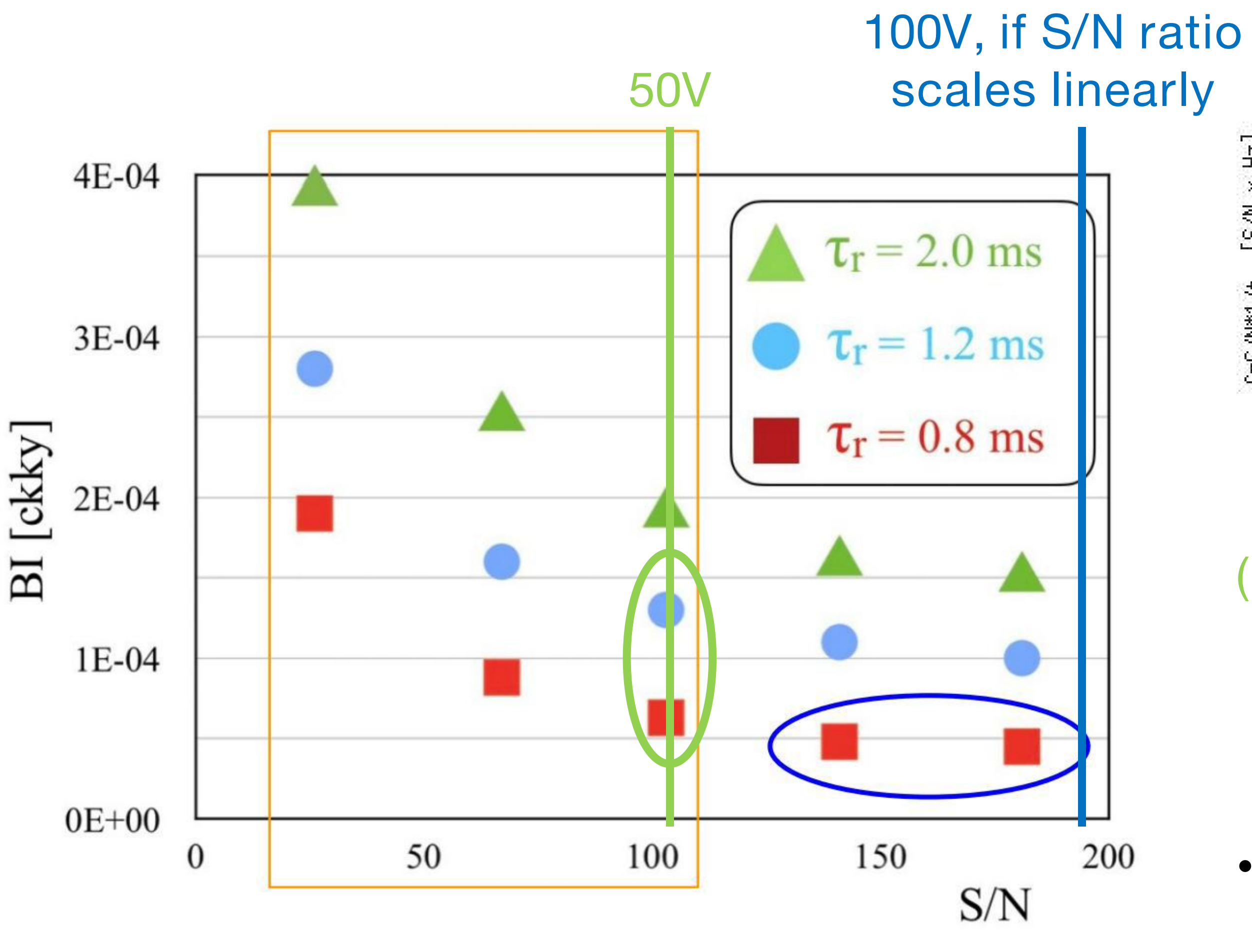
Underground measurement at LSC Canfranc

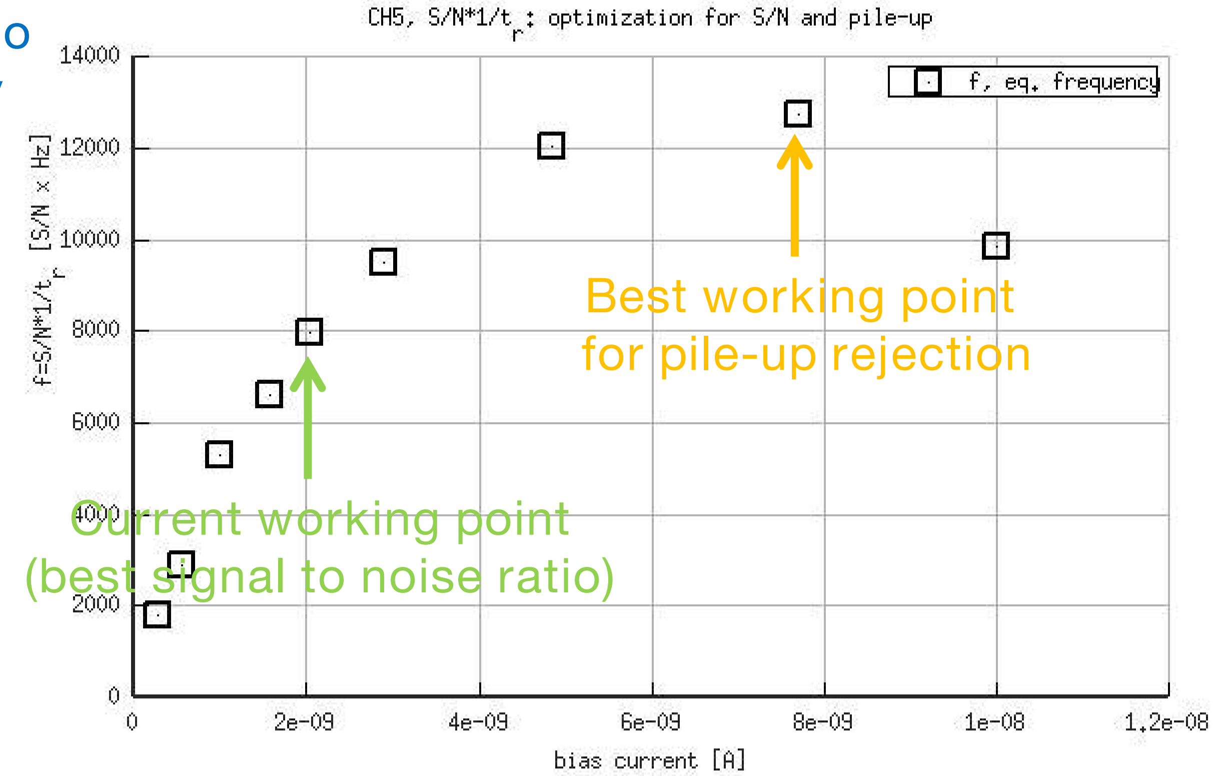
- 9/9 light detectors are working well at 50V NL bias: good noise, no leakage current



Underground measurement at LSC Canfranc

- Distribution for pile-ups rejection

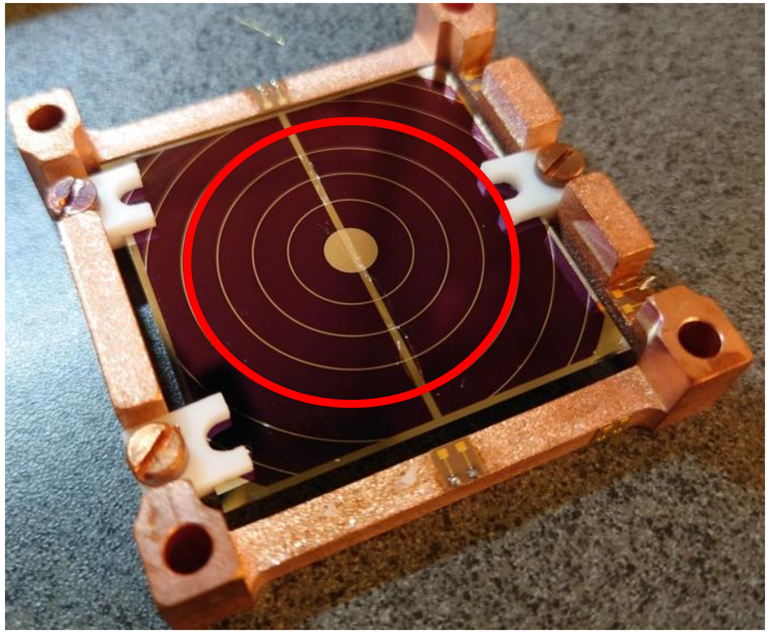




- Required additional optimisation for the best pile-up rejection using (S/N)/RiseTime parameter

Not optimal electrodes geometry

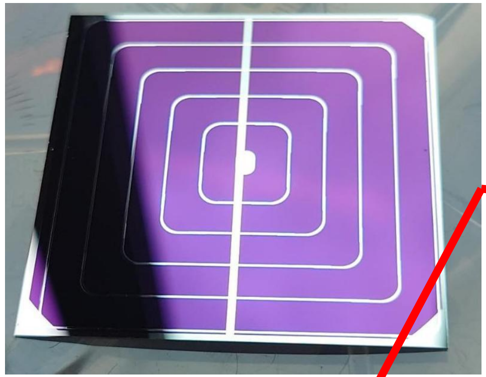
- Geometry of electrodes not optimized: for square light detectors with circular masks that were available at the moment
- Electrodes connected inside the circle, no field outside, 56% of the surface under bias

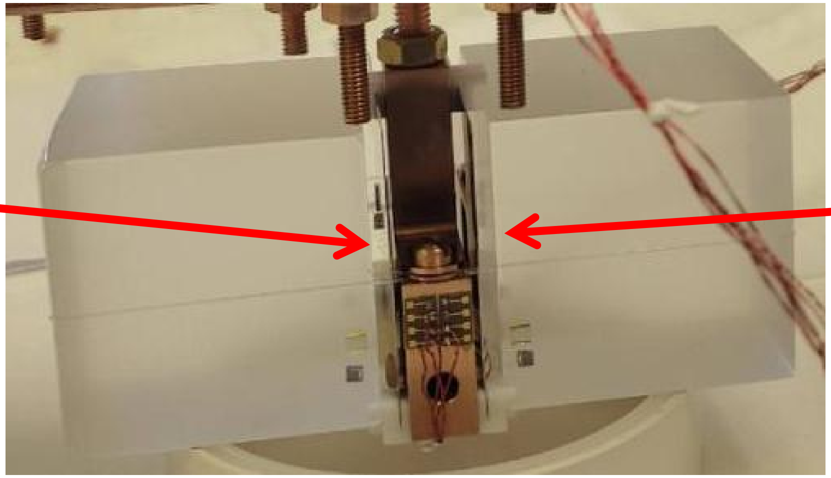


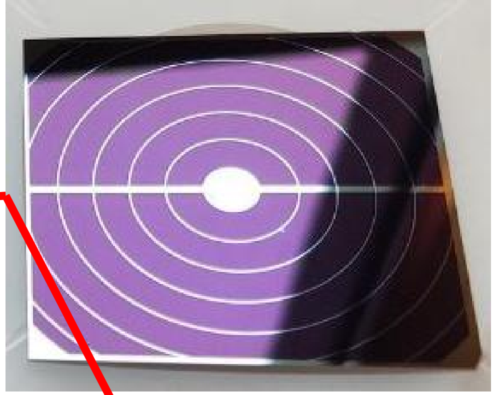
$$\sigma_{projected} = \frac{\sigma_{measured}}{AreaFactor}$$

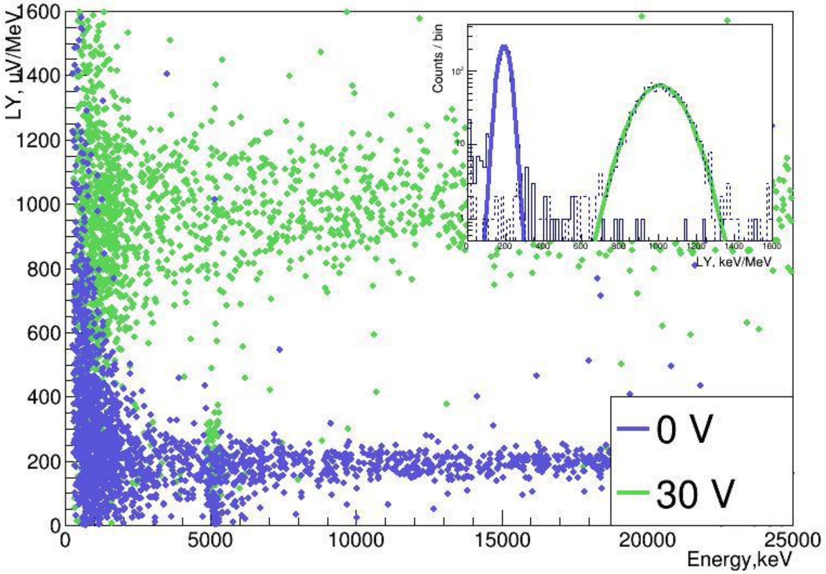
$$AreaFactor = \frac{Gain_{square}}{Gain_{circular}} = 1.79 - 0.79/Gain_{circular}$$

Aboveground measurement at IJCLab, Orsay



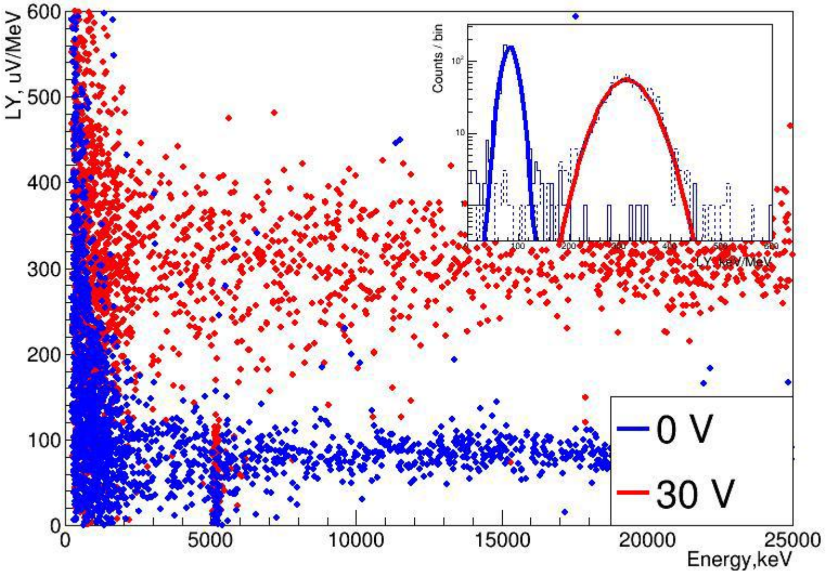






$$AreaFactor_{estim} = 1.5$$

$$\left(\frac{Gain_{square}}{Gain_{circular}}\right)_{meas} = 1.4$$



Summary

- Neganov-Luke light detectors are a promising technology to increase the signal to noise ratio and so to help to the pile-up rejection

- We are very reproducible in terms of production high performing NL light detectors. (9/9 detectors operating at 50V at Canfranc underground laboratory)

- With 50V NL bias we can reach mean value of sigma baseline of 17.6 eV

- Demonstrated that **BI<1×10^{-4} count/keV·kg·y is reachable** even in not optimal electrodes configuration at 50V NL voltage

- Aboveground measurements confirmed scalability of NL gain due to changing of electrodes geometry

- This technology has been recently selected to become the new baseline for CUPID light detectors

Thank you for attention!

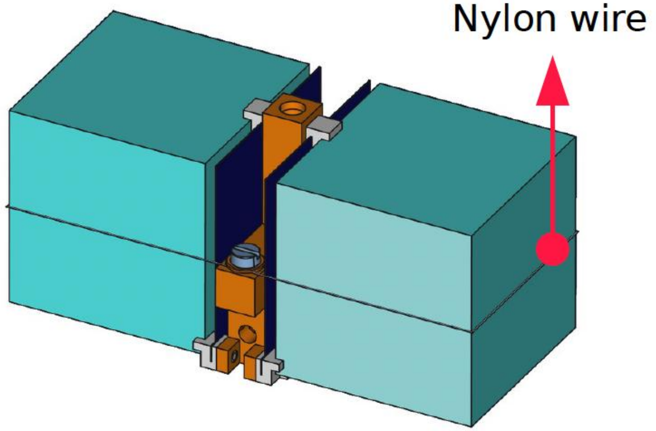
Backups

BINGO

An innovative detector assembly

- Minimize the amount of passive material
- Active shielding using the light detector position

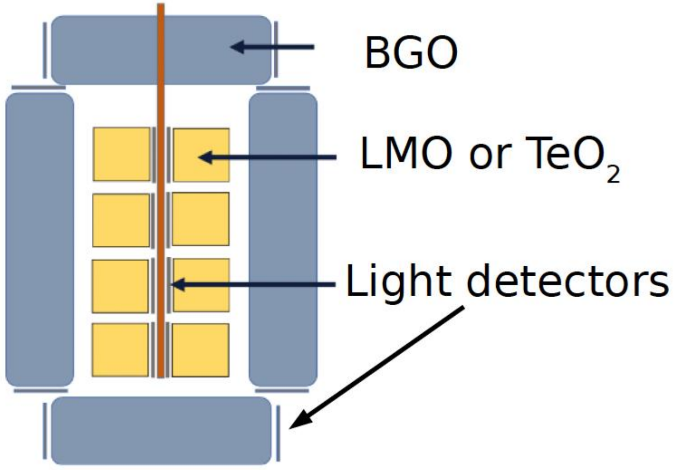
Geometrical reduction of the surface radioactivity + compact assembly for anticoincidence cuts



A cryogenic active veto

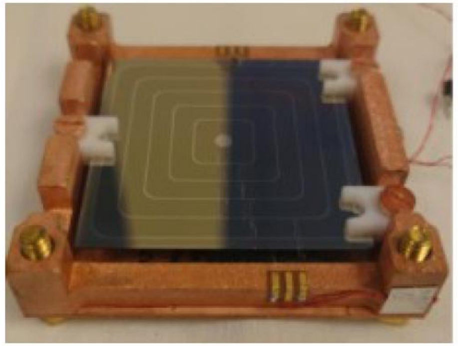
- Made of scintillators (BGO) with a 4π coverage operated at 20 mK Scintillation light read by its own light detectors

Suppress the external γ background and reject surface radioactivity from the crystals facing the active shield using anti-coincidence

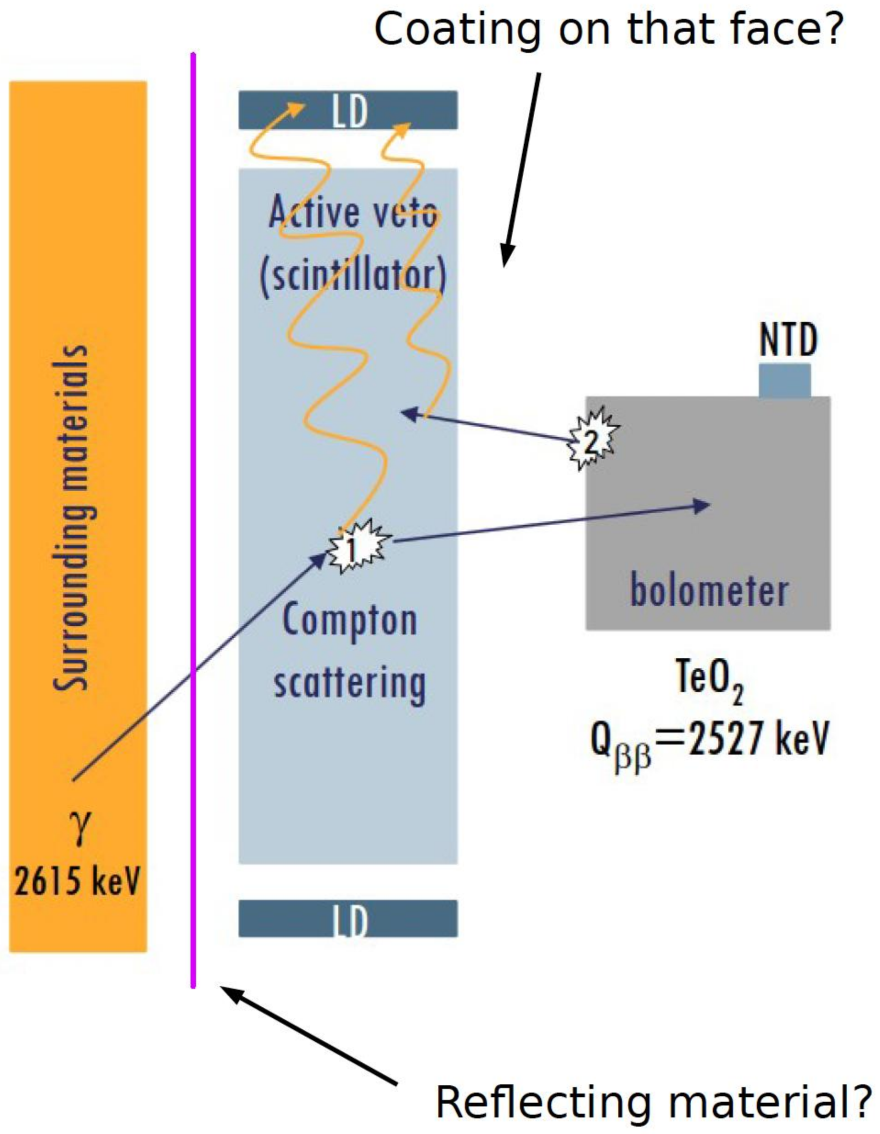


Neganov-Trofimov-Luke light detectors

- **Higher signal to noise ratio**
  → lower energy threshold= efficient suppression of external γ background with the veto
  → Reject the background induced by the 2νββ pileup events in LMO
- **Amplification of the tiny Cerenkov signal (TeO_2)**
  → α rejection



BINGO

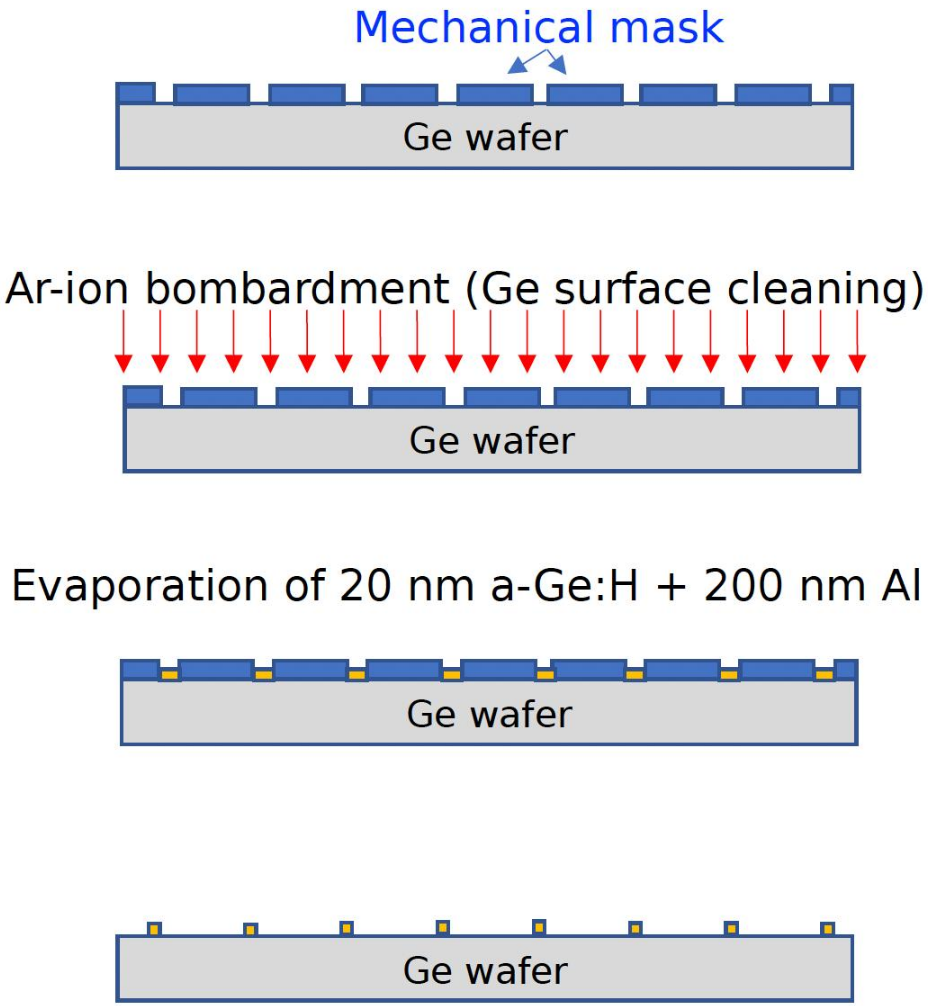


If the 2615 keV γ deposit a small amount of energy in the surrounding material (~80 keV) and the rest in TeO_2
→ **background in ROI**

With the veto, the γ interact within it before and emit scintillation light which is detected by the LD
→ **rejected by anticoincidence**

We estimated a conservative energy threshold to reach in the veto of about 50 keV (~hundreds of eV in the LD)
→ **NTL amplification on LD will help to reach it**

Evaporation



Lithography