Light detectors for $0\nu2\beta$ experiments

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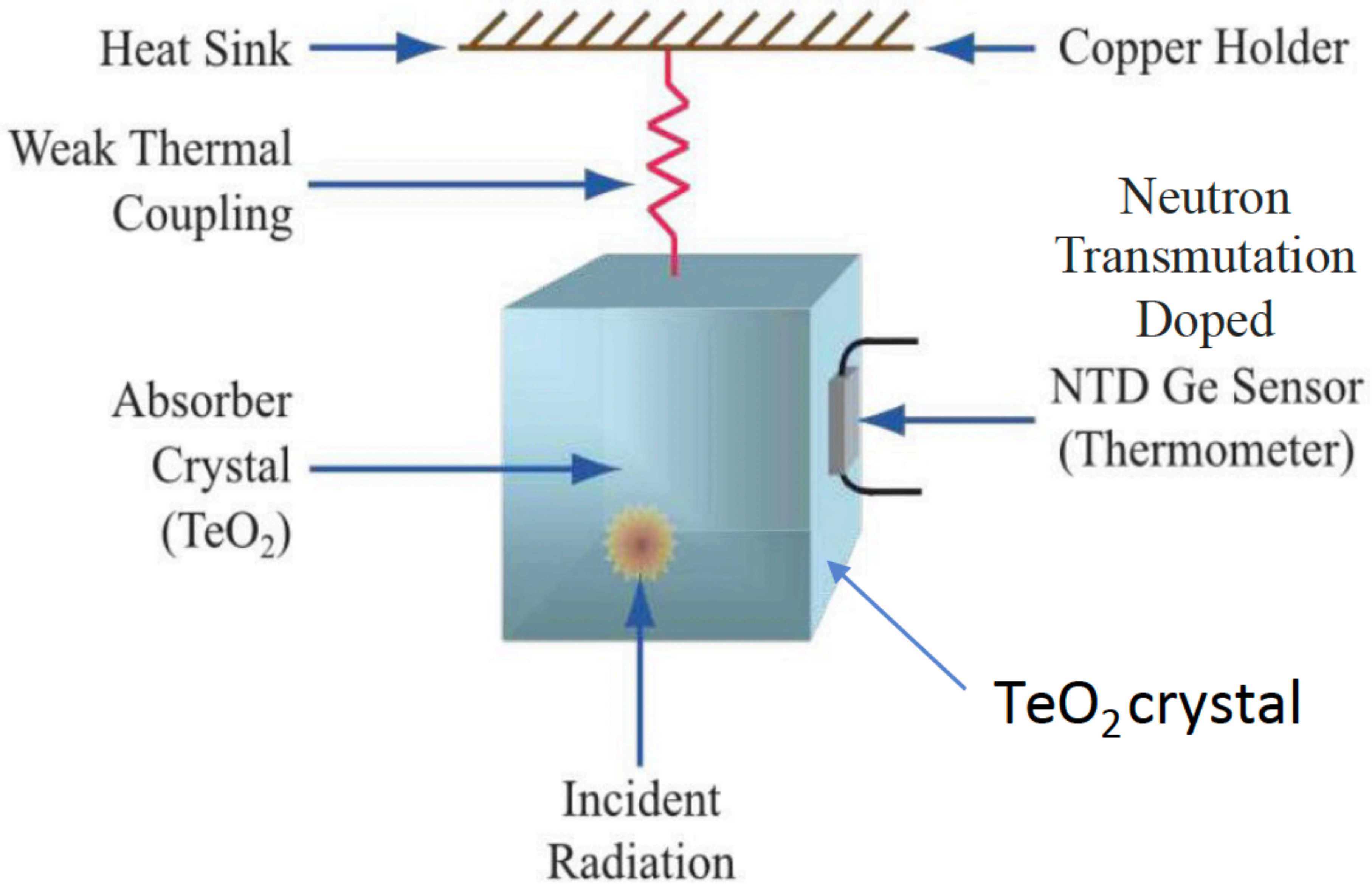
Exploring the Dark Side of the Universe Tools 2024, 2-7 June 2024

CUORE

CUORE ^{130}Te
pure thermal detector
(**bolometer**)
T ~ 10 mK



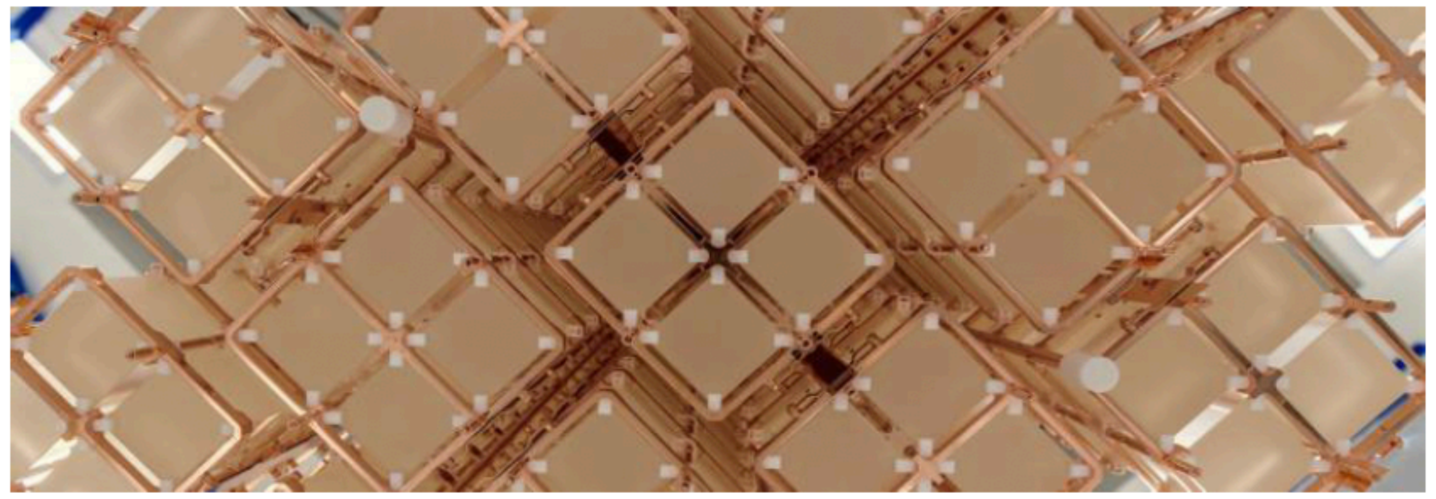
No PID → α background → b~10^{-2} c/(keV kg y)

Q = 2527 keV < 2615 keV → γ background → b~10^{-3} c/(keV kg y)

No enrichment: ^{130}Te I.A. ~34%

CUORE - Cryogenic Underground Observatory for Rare Events

- Located in Gran Sasso, Italy
- Main objective: $0\nu\beta\beta$ in ^{130}Te
- 988 TeO_2 crystals, 5x5x5 cm^3 each
- Total mass: 742 kg TeO_2 (natural Te)
- ^{130}Te mass: 206 kg
- Current analysed exposure: 2023 kg y
- **$T_{1/2}^{0\nu}$ > 3.33 x 10^{25} yr at 90% C.I.**
- **$m_{\beta\beta}$ < 75 - 260 meV at 90% C.I.**



From CUORE to CUPID

CUORE ^{130}Te
pure thermal detector
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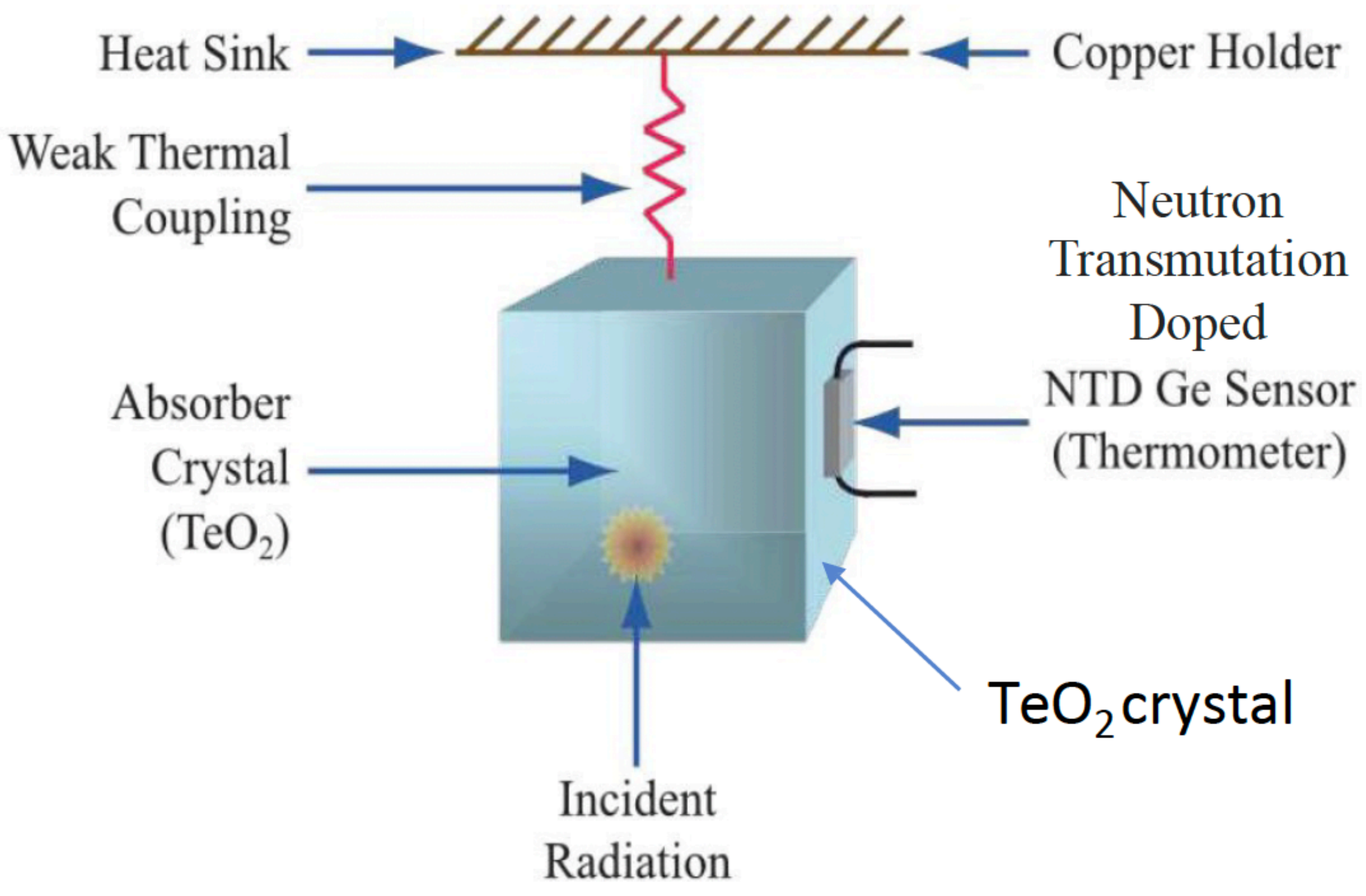
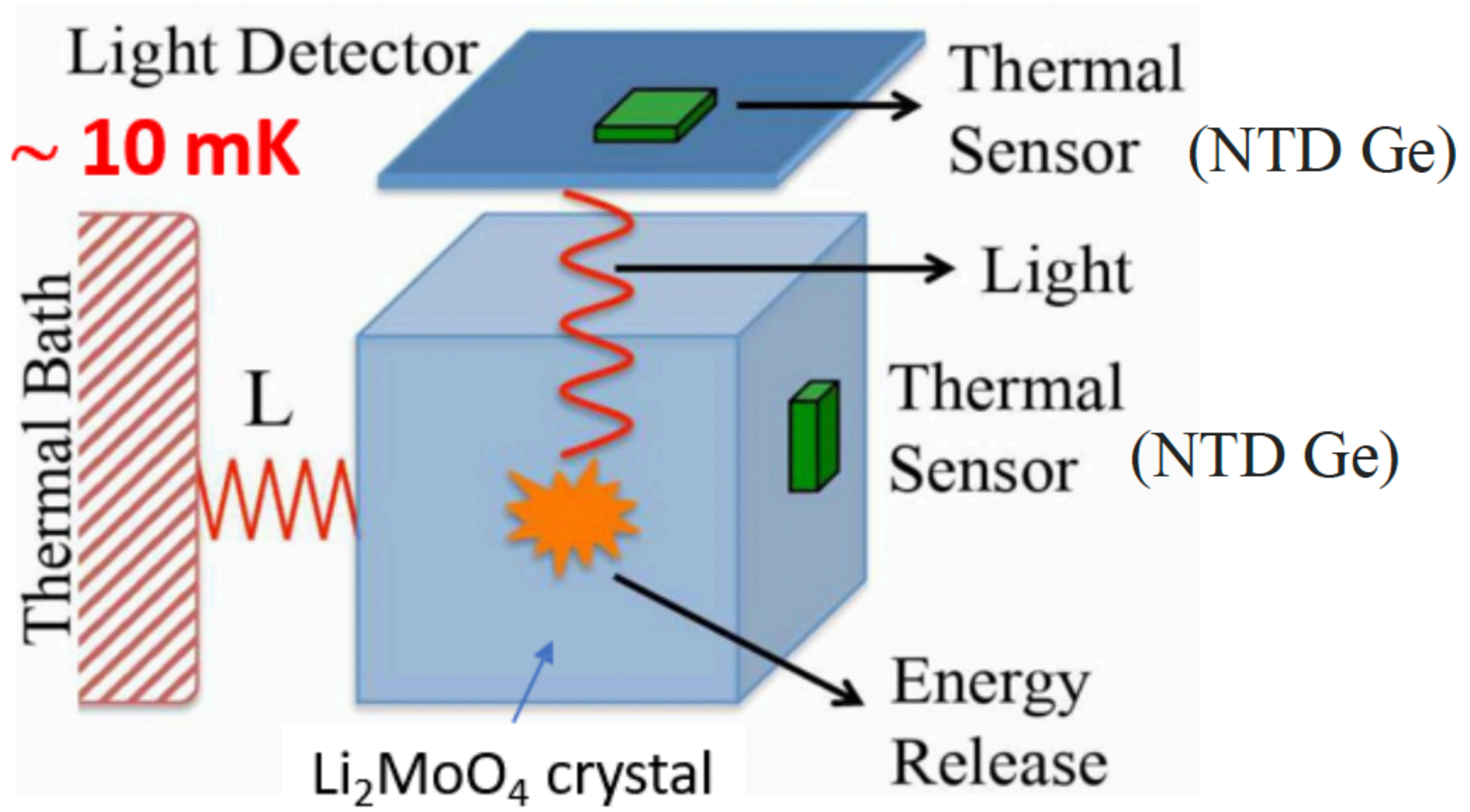


No PID

Q = 2527 keV < 2615 keV

No enrichment: ^{130}Te I.A. ~34%

CUPID ^{100}Mo
heat + light
(**scintillating bolometer**)



~~α background~~ ← **PID**

~~γ background~~ ←

Q = 3034 keV

> 2615 keV

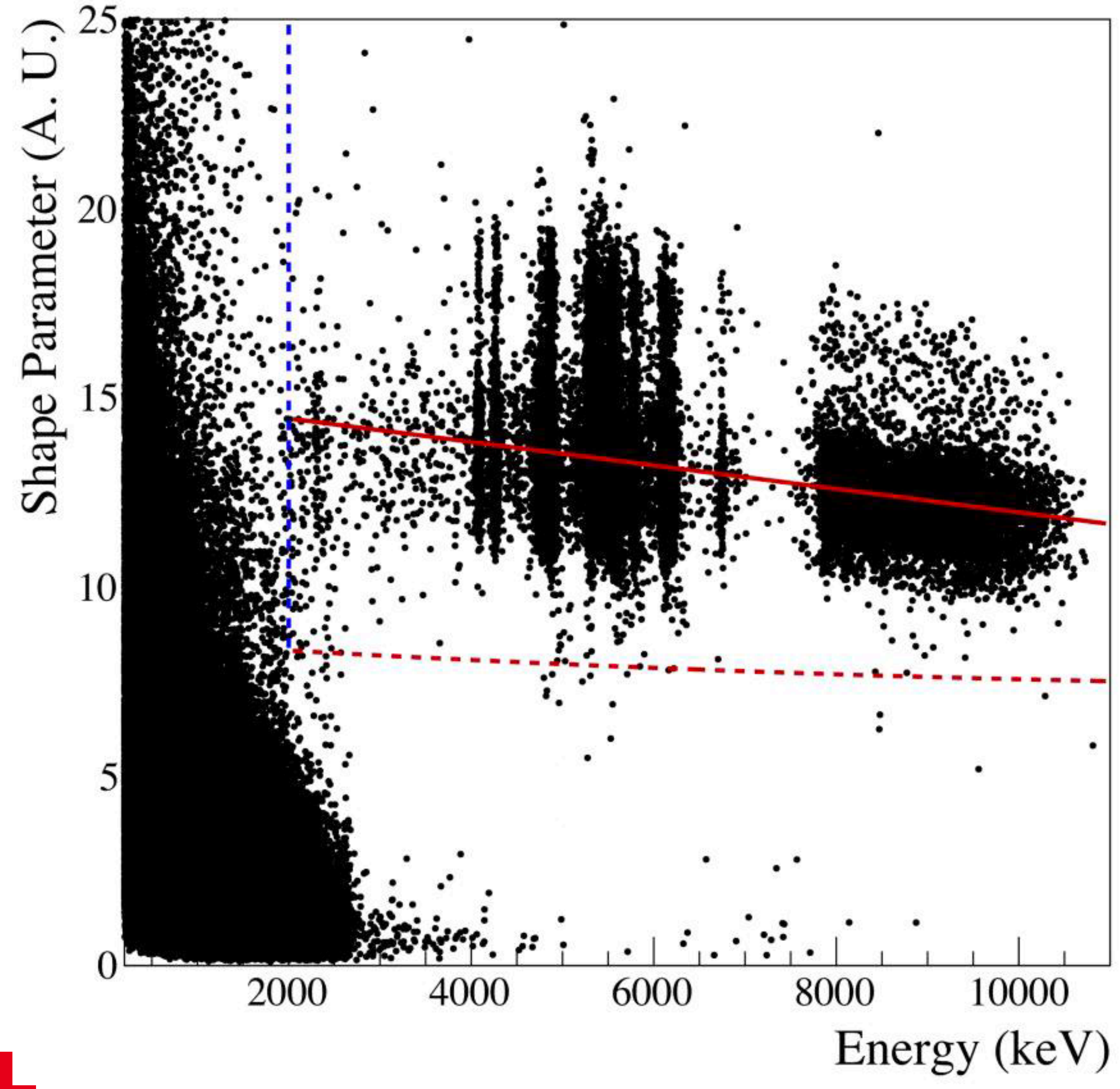
Goal: b~10^{-4} c/(keV kg y)

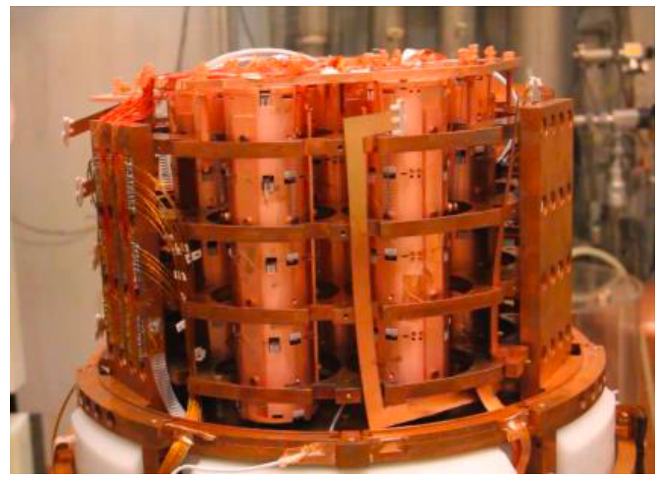
Enrichment in ^{100}Mo is possible on large scale

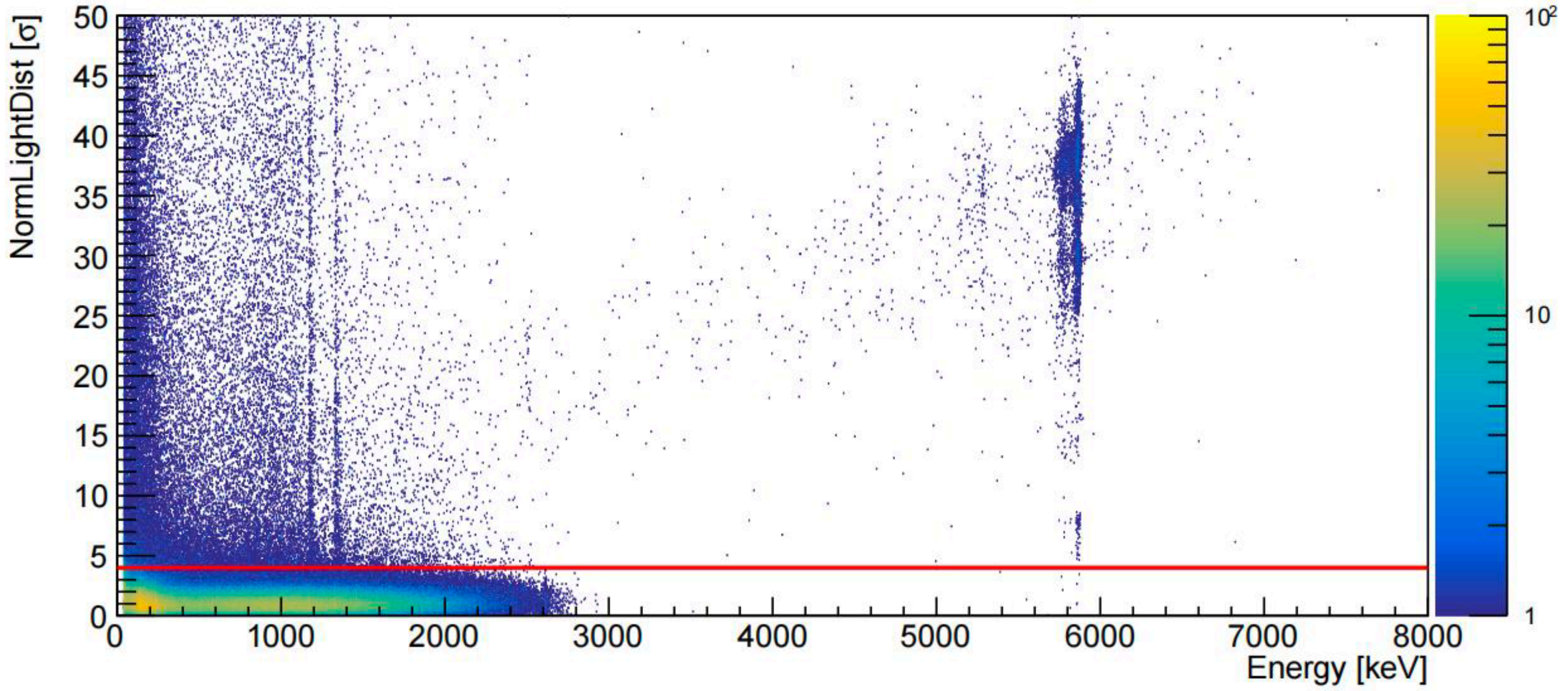
CUPID-0 and CUPID-Mo demonstrators

- CUPID-0: first pilot experiment for CUPID with scintillating bolometers ($Zn^{82}Se$) in LNGS
- >99.9% α rejection
- ΔE = 21.8 keV @ $Q_{\beta\beta}$ (2998 keV)
- Reached background:

$$b = 3.5 \times 10^{-3} \text{ counts/keV/kg/yr}$$





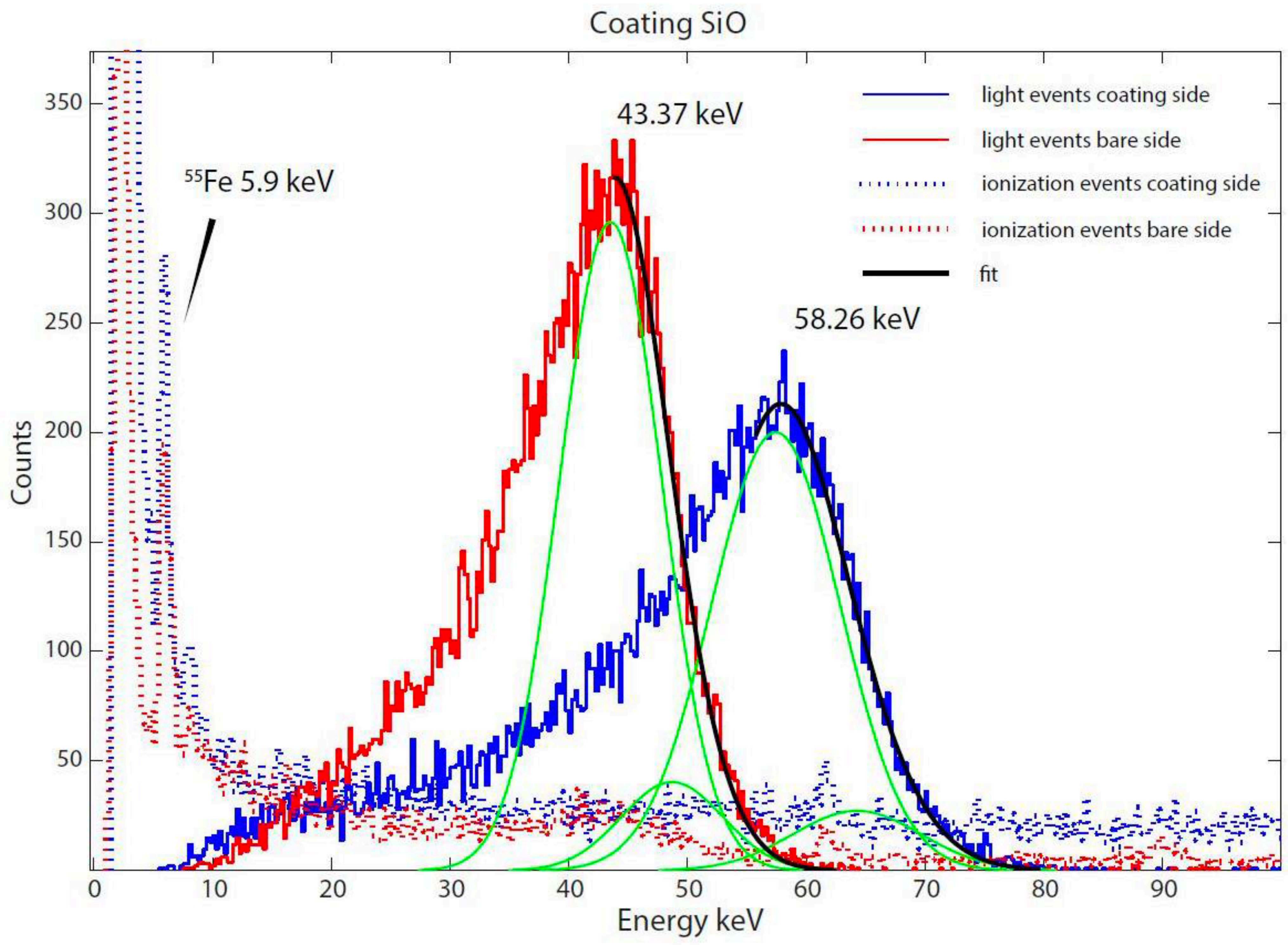


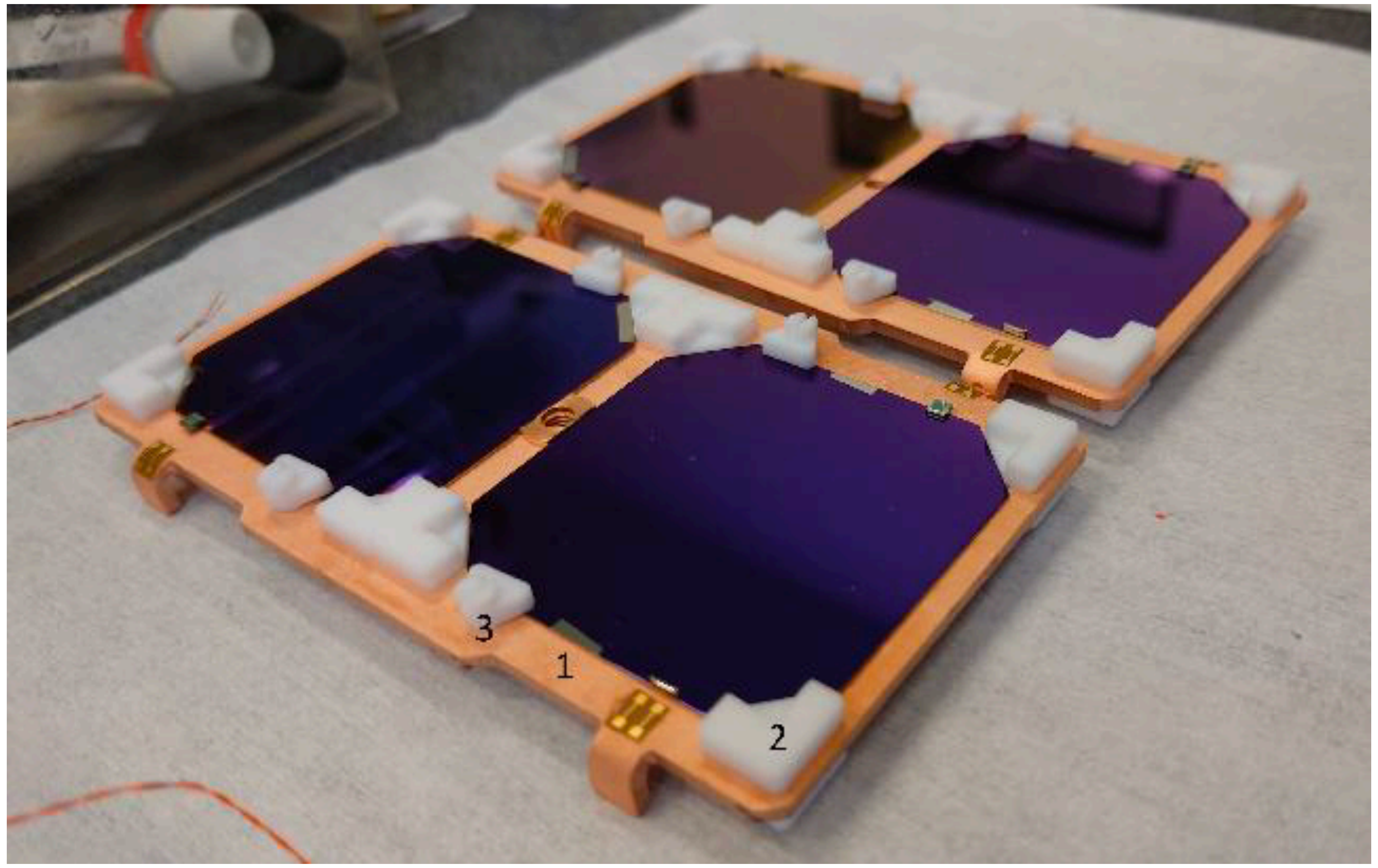
- CUPID-Mo: $Li_2{}^{100}MoO_4$ dual read-out detectors
- >99.9% α rejection
- ΔE = 7.4 keV @ $Q_{\beta\beta}$ (3034 keV)
- Demonstrated best background index reached in bolometric experiments:

$$b = 2.7^{+0.7}_{-0.6} \times 10^{-3} \text{ counts/keV/kg/year}$$

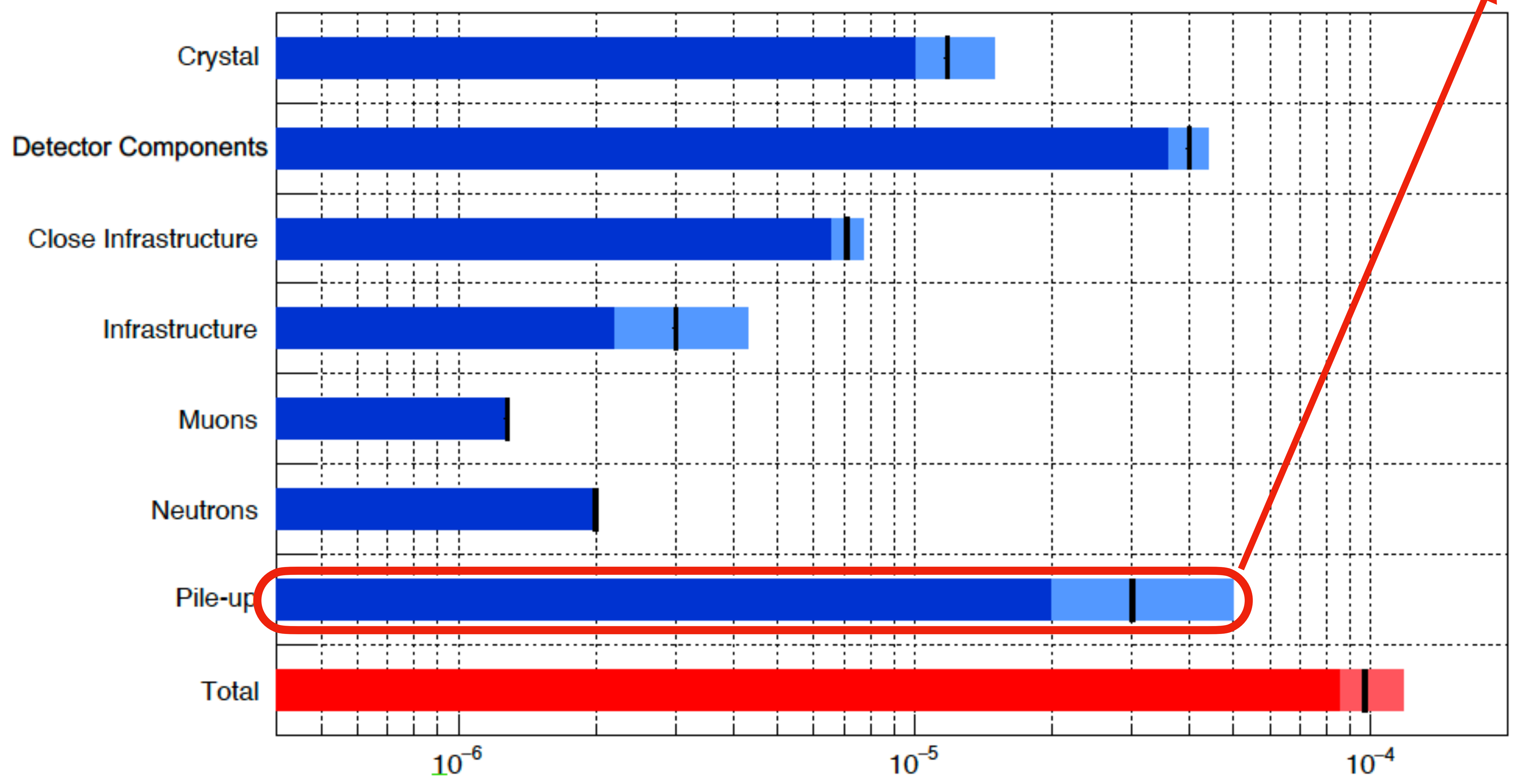
SiO coating

- To improve the light collection of our LDs we use 70nm SiO coating
- Well-tested with hundreds of LDs, confirmed improvement of ~ 30% with respect to bare Ge
- SiO coating can be done by evaporation





Pile-ups as the main background contributor



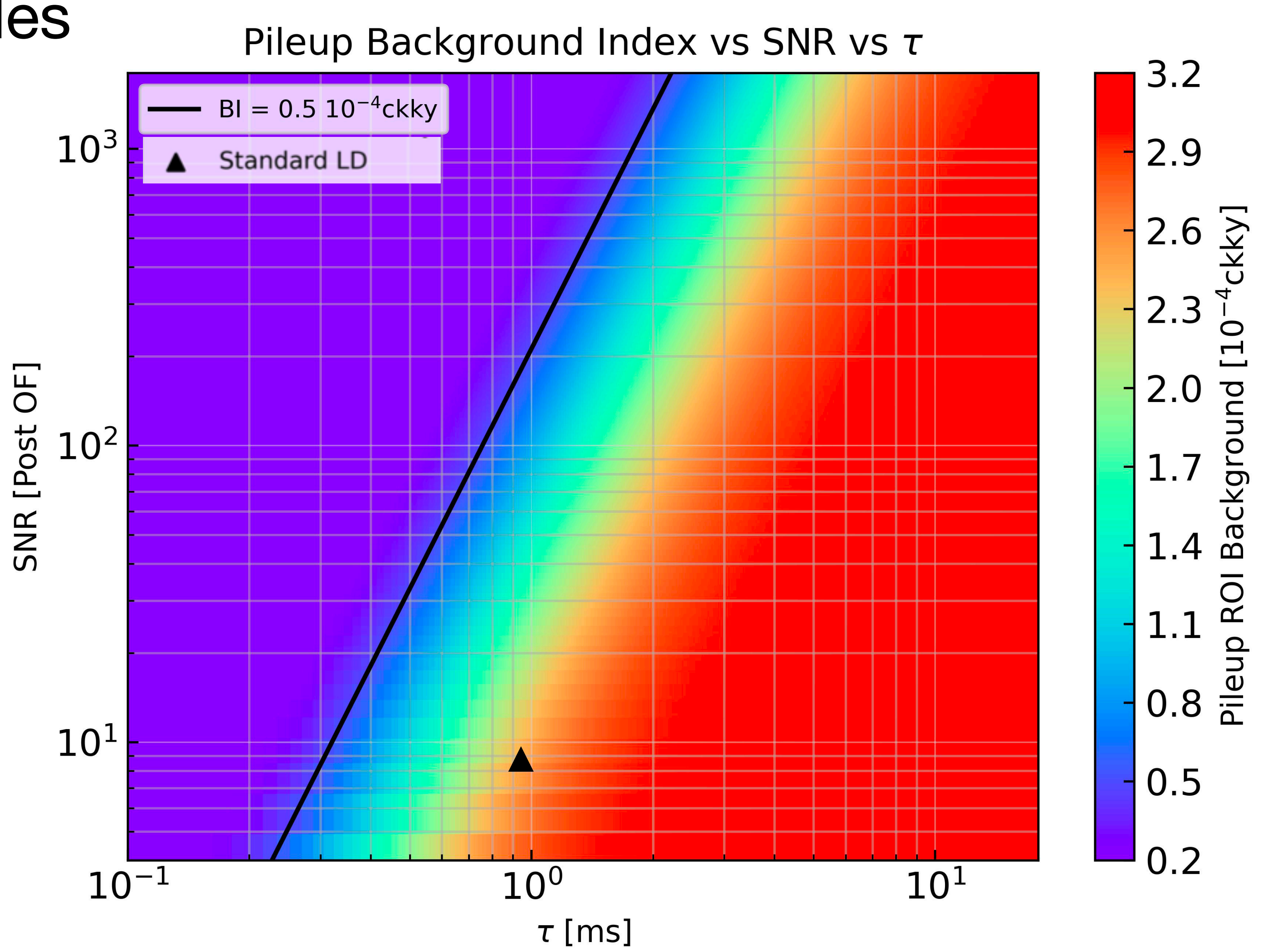
The goal for pile-up background for CUPID:

$< 5 \times 10^{-5}$ counts/keV/kg/yr

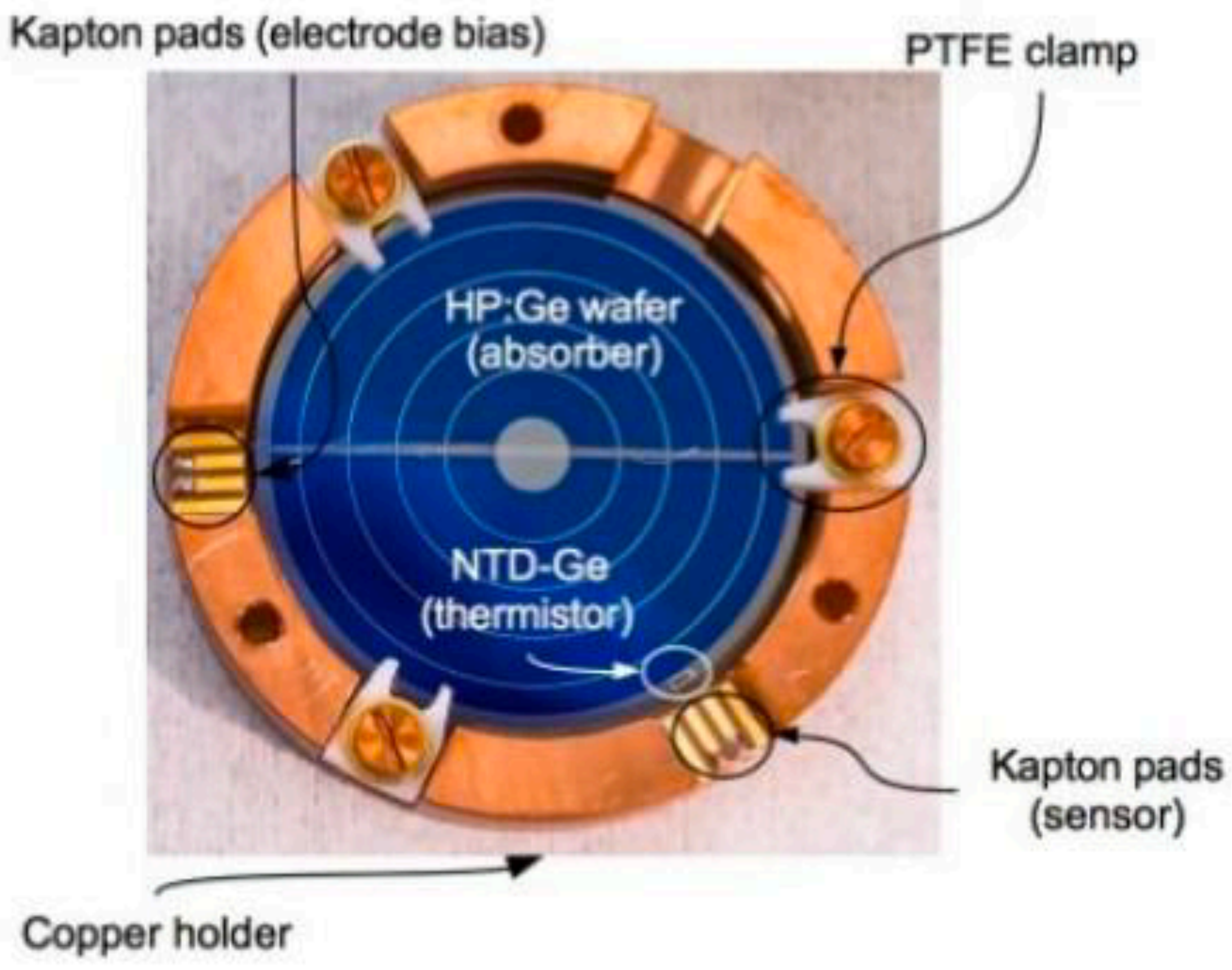
Random coincidence with $2\nu\beta\beta$ events ($T_{1/2}^{2\nu\beta\beta} = 7.1 \times 10^{18} y$)

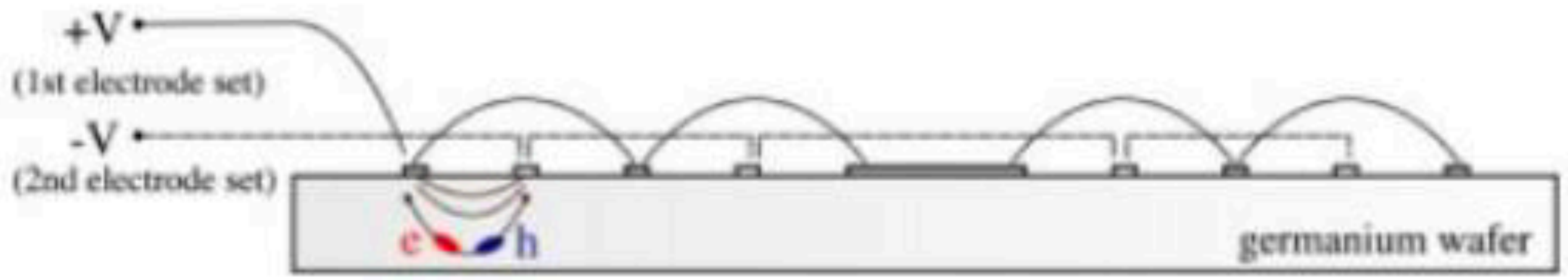
Pile-ups could be rejected by pulse shape but required:

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



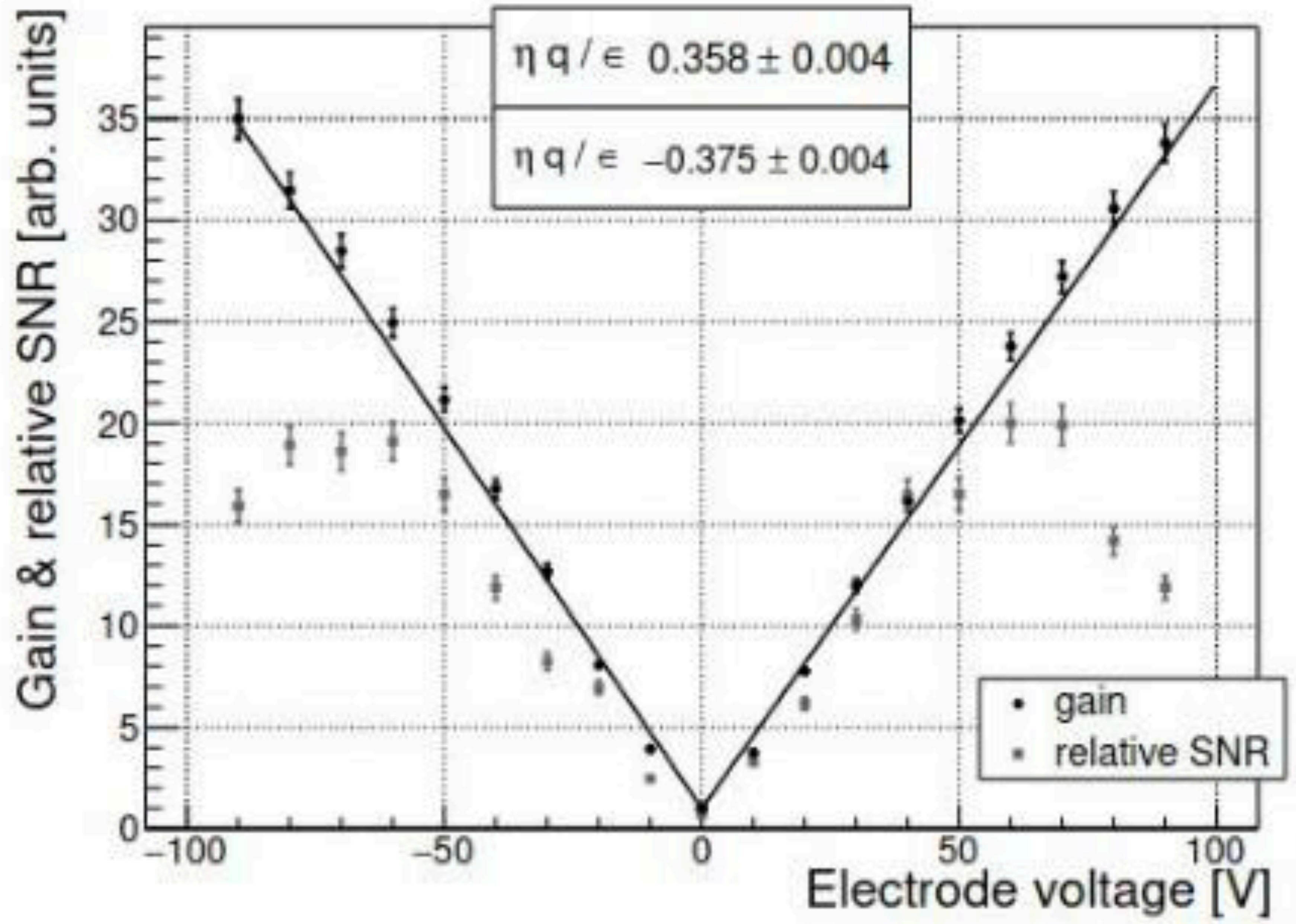
Neganov-Luke effect



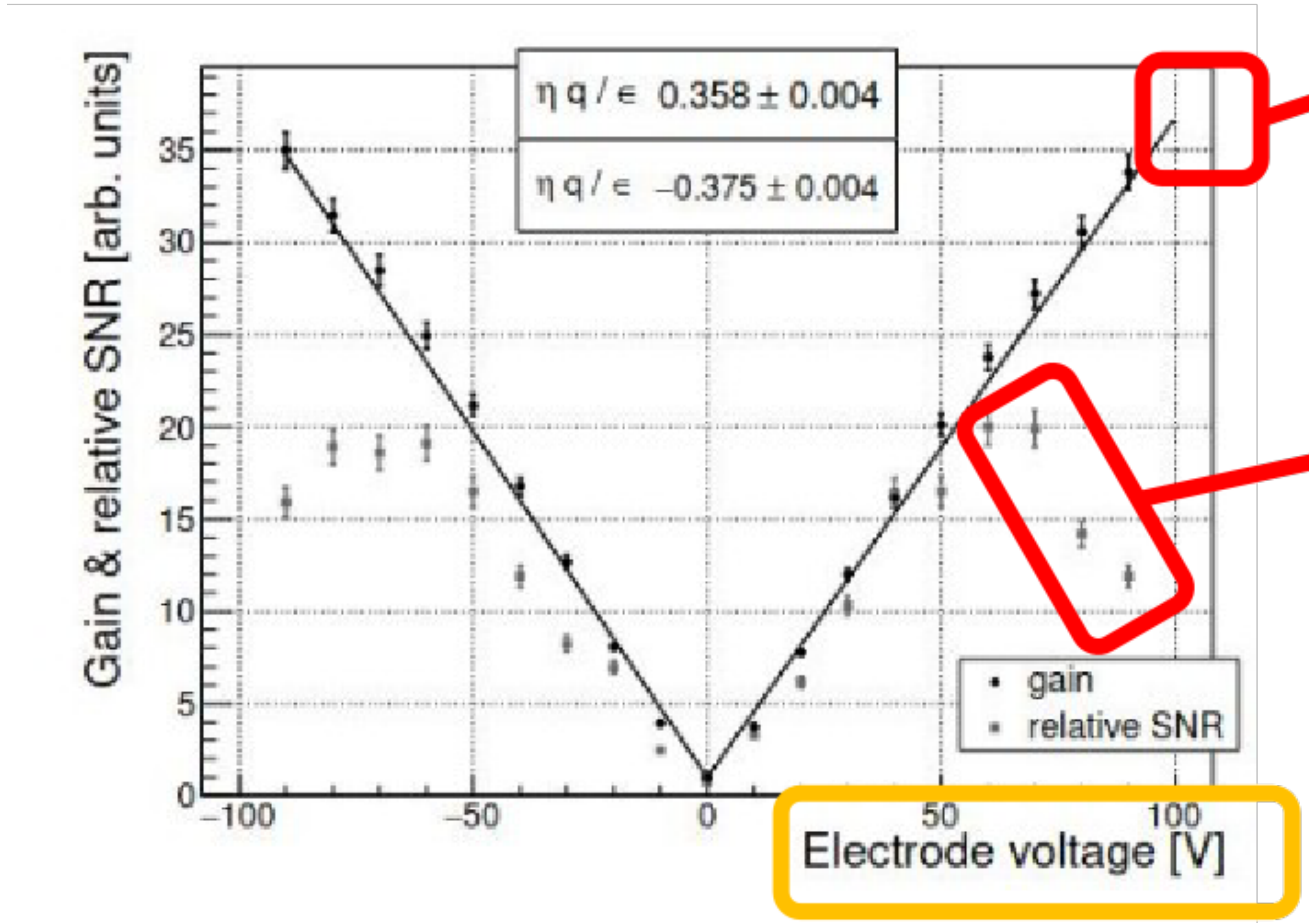


$$E_{tot} = E_0 \left(1 + \frac{q \cdot V_{el} \cdot \eta}{\epsilon}\right) = E_0 \cdot G_{NTL}$$

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



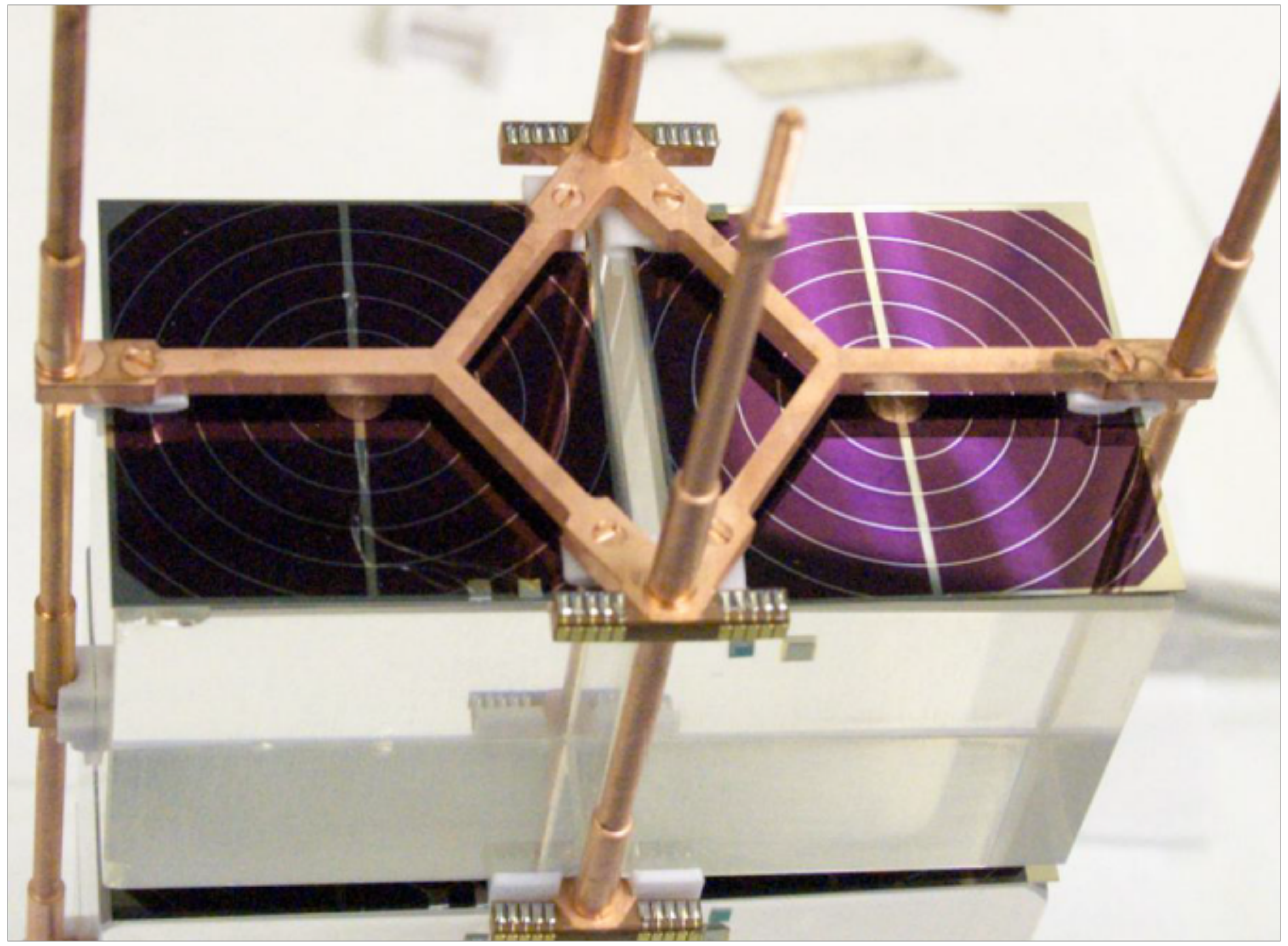
Limitation of the applied voltage: after a certain voltage we have a **leakage current** —> we heat up the cryostat

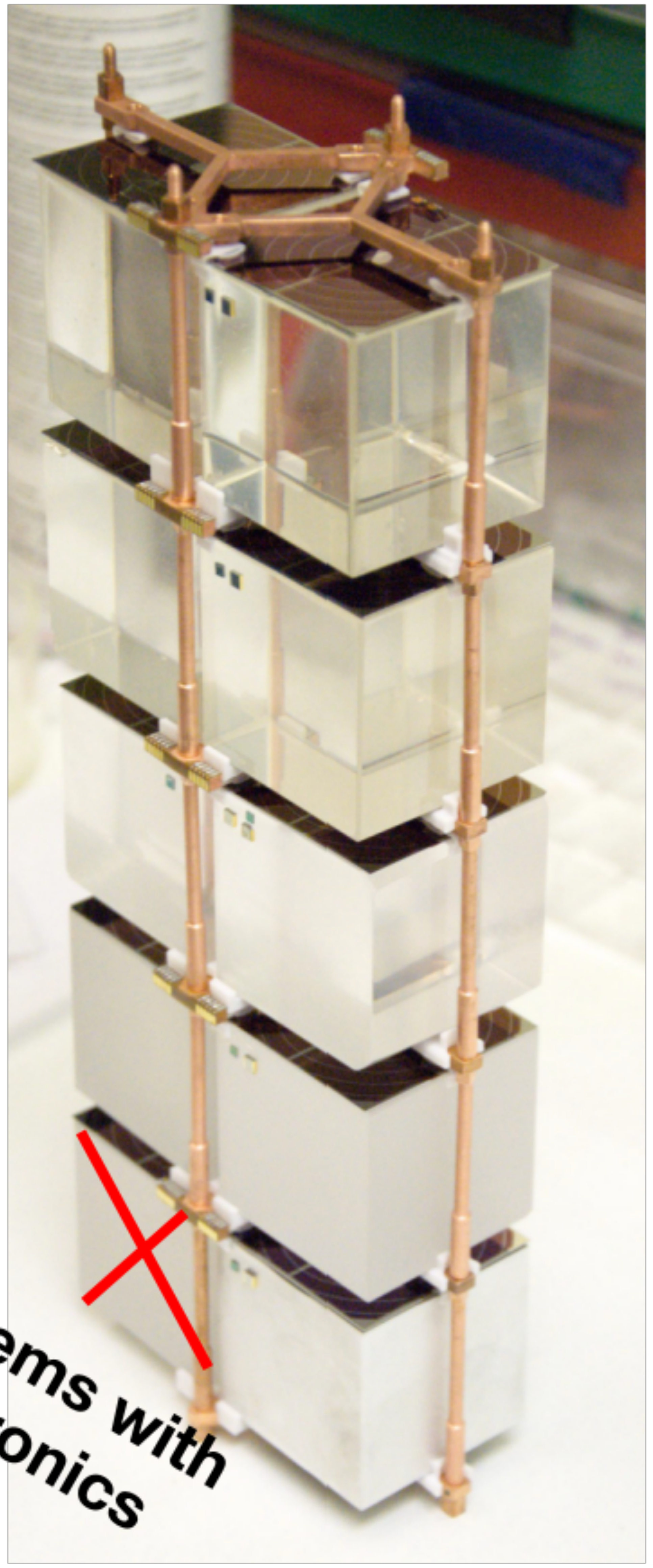
Injection of **extra noise** after a threshold voltage value

Requires more channels to inject the bias through the electrodes. This can be easily solved by parallelising of channels

10 NTL LDs underground measurement

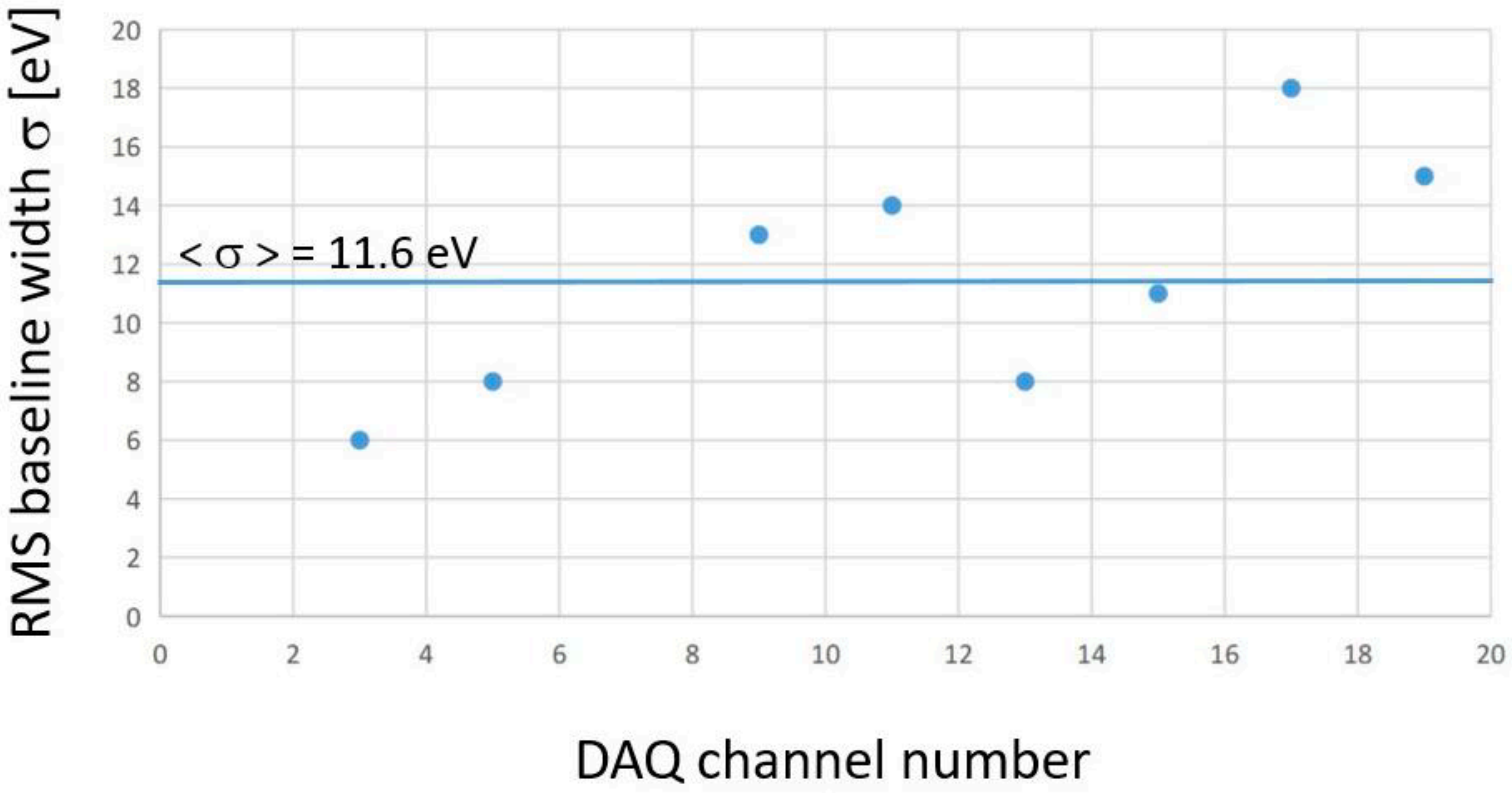
- The tower consists of **10 light detectors and 10 crystals** (6 $Li_2{}^{100}MoO_4$ and 4 TeO_2
- **10 identical NL light detectors** were produced using evaporation: circular concentric electrodes on square Ge wafers 0.3mm thickness
- Structure installed in Canfranc underground laboratory in **February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

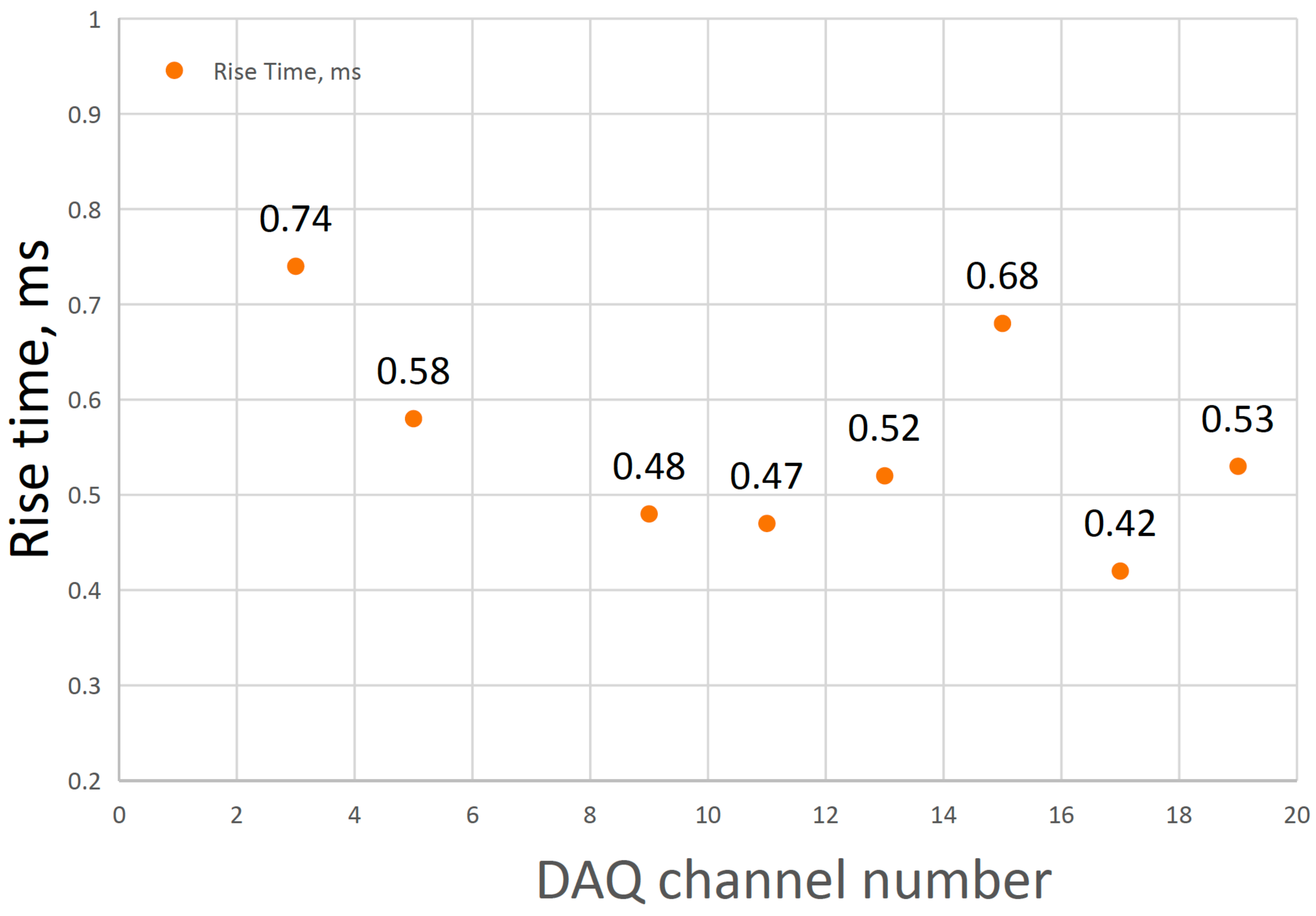




10 NTL LDs underground measurement

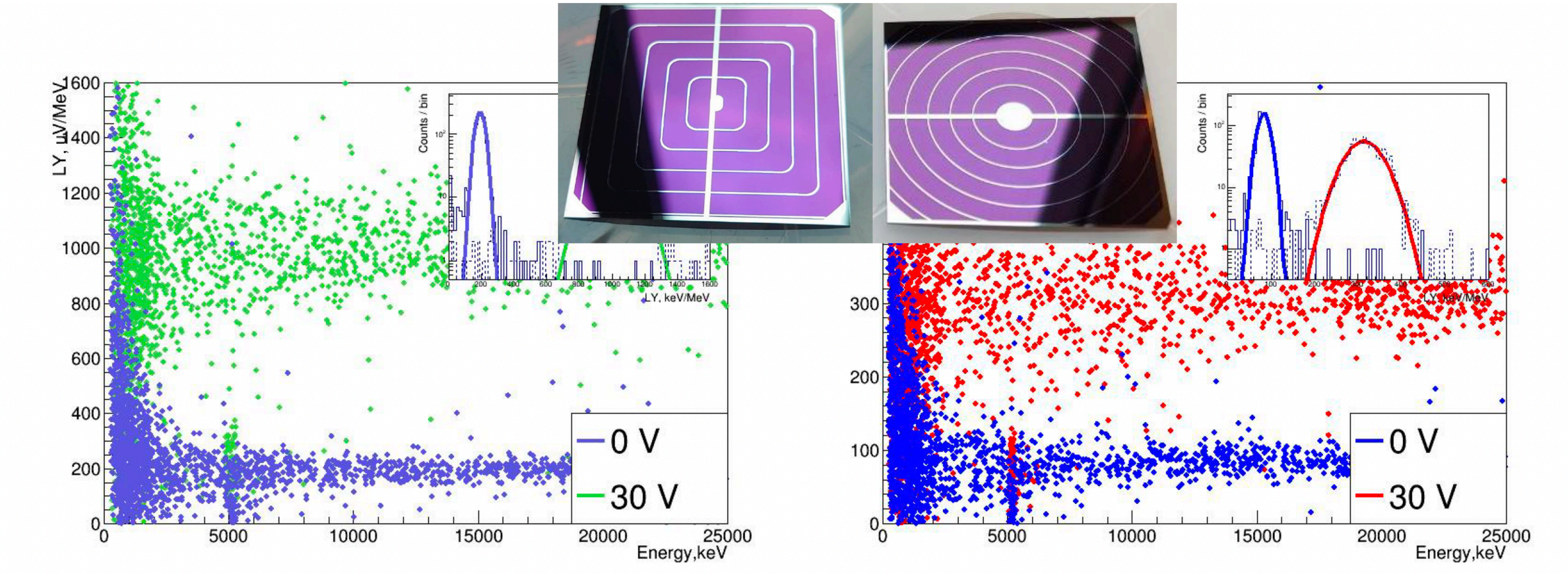
- Good initial performance of light detectors at 0V. Mean **baseline resolution <85 eV** (99% alpha rejection)
- 8/9 detectors were biased in parallel to 80V. Reached average **baseline resolution 11.6 eV and rise-time ~0.5ms**





Optimisation of the area under NTL boost

- Electrodes geometry is not optimised for square wafers
- A direct comparison of two electrode geometries has been done
- Measured gain improvement with square geometry corresponds to our expectations



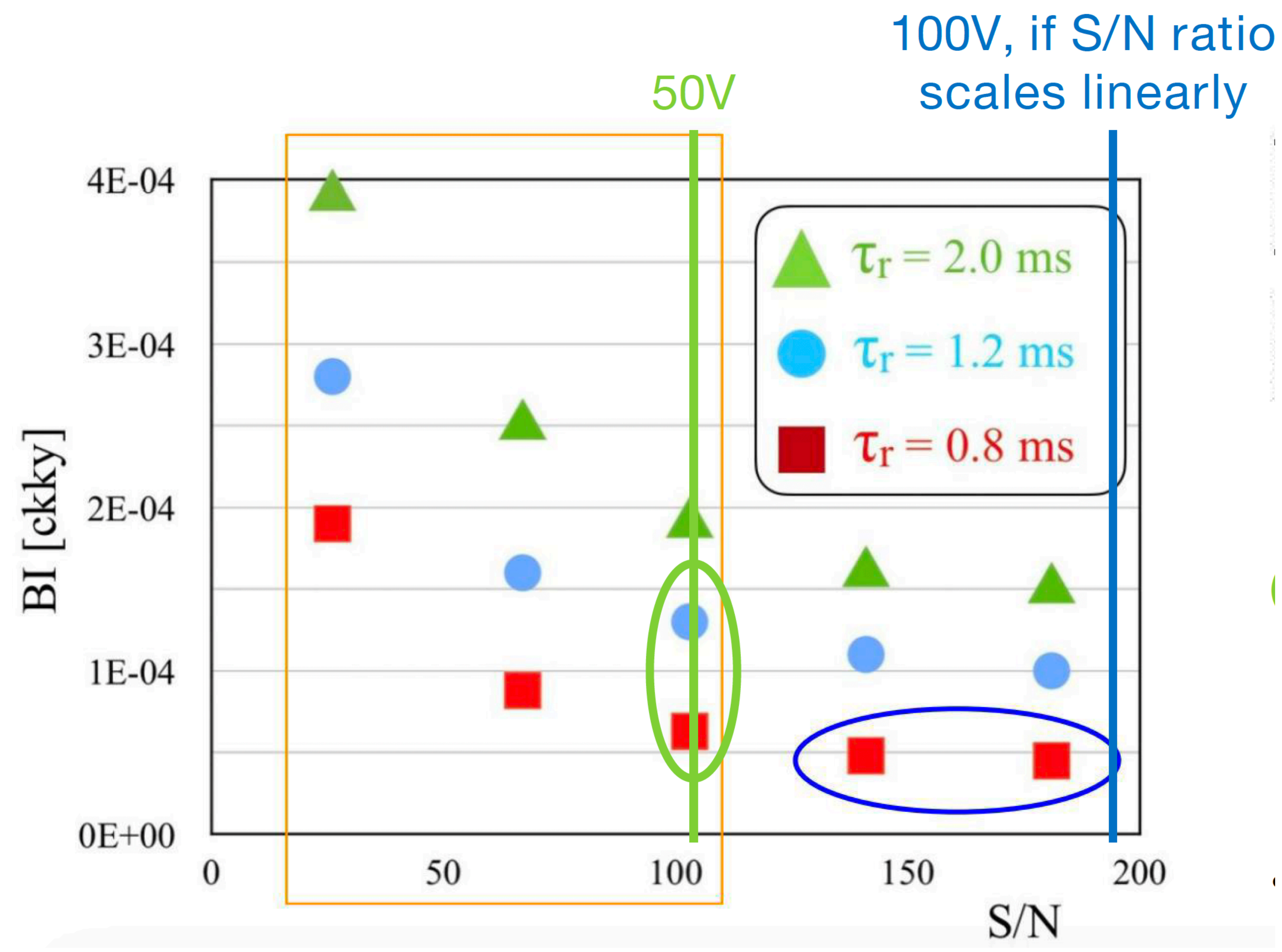
Gain(square grids)=5.4

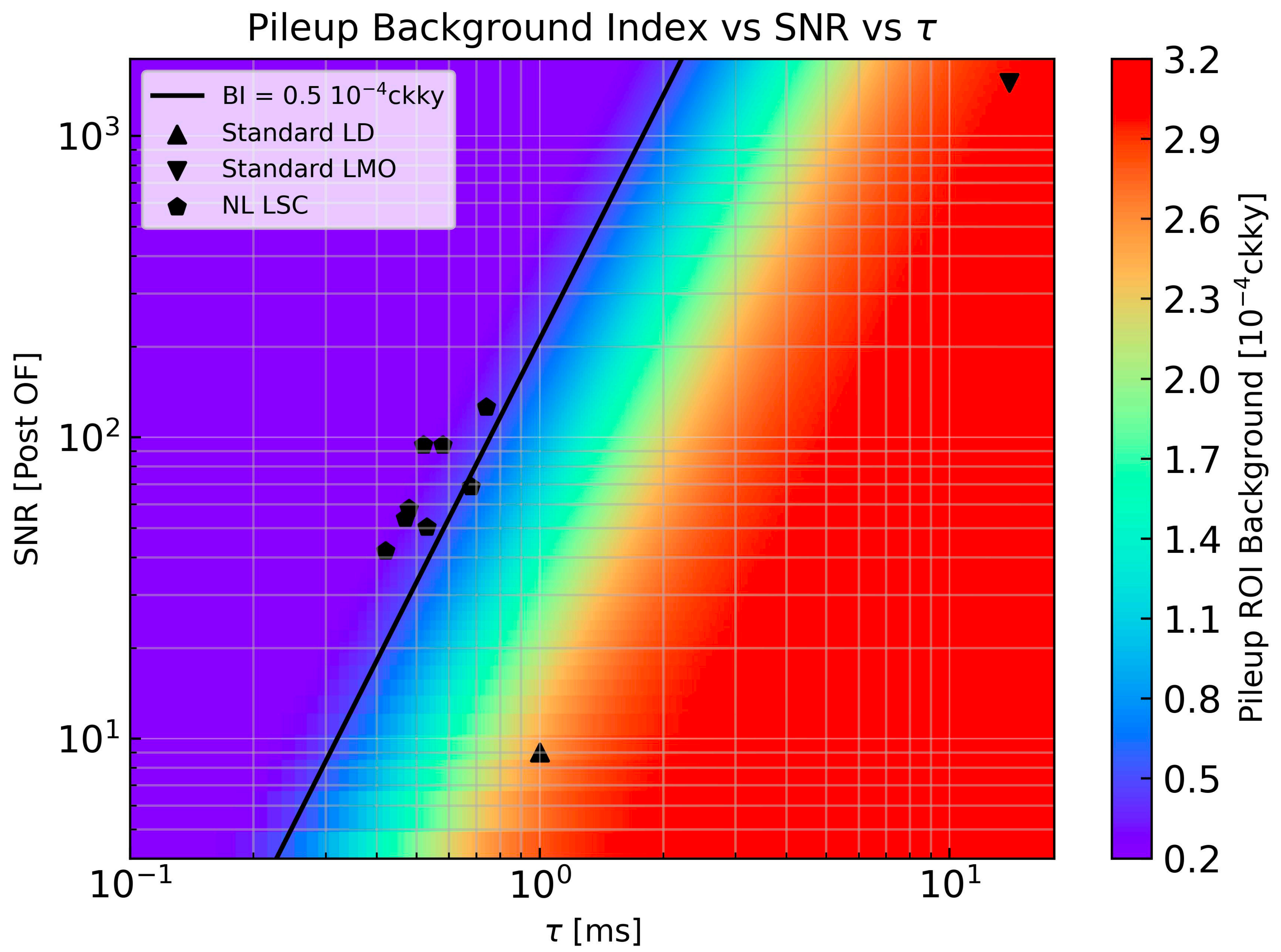
Gain(circle grids)=3.4

Ratio measured ≈ 1.6 -> corresponds to expectations: $Gain_{(xV)meas} = 0.44(Gain_{0V} = 1) + 0.56Gain_{full\_surf}$

Pile-ups rejection

- To maximise the pile-up rejection efficiency light detectors were optimised in such a way to have the shortest possible rise time (NTDs were over-biased) with a high enough signal-to-noise ratio



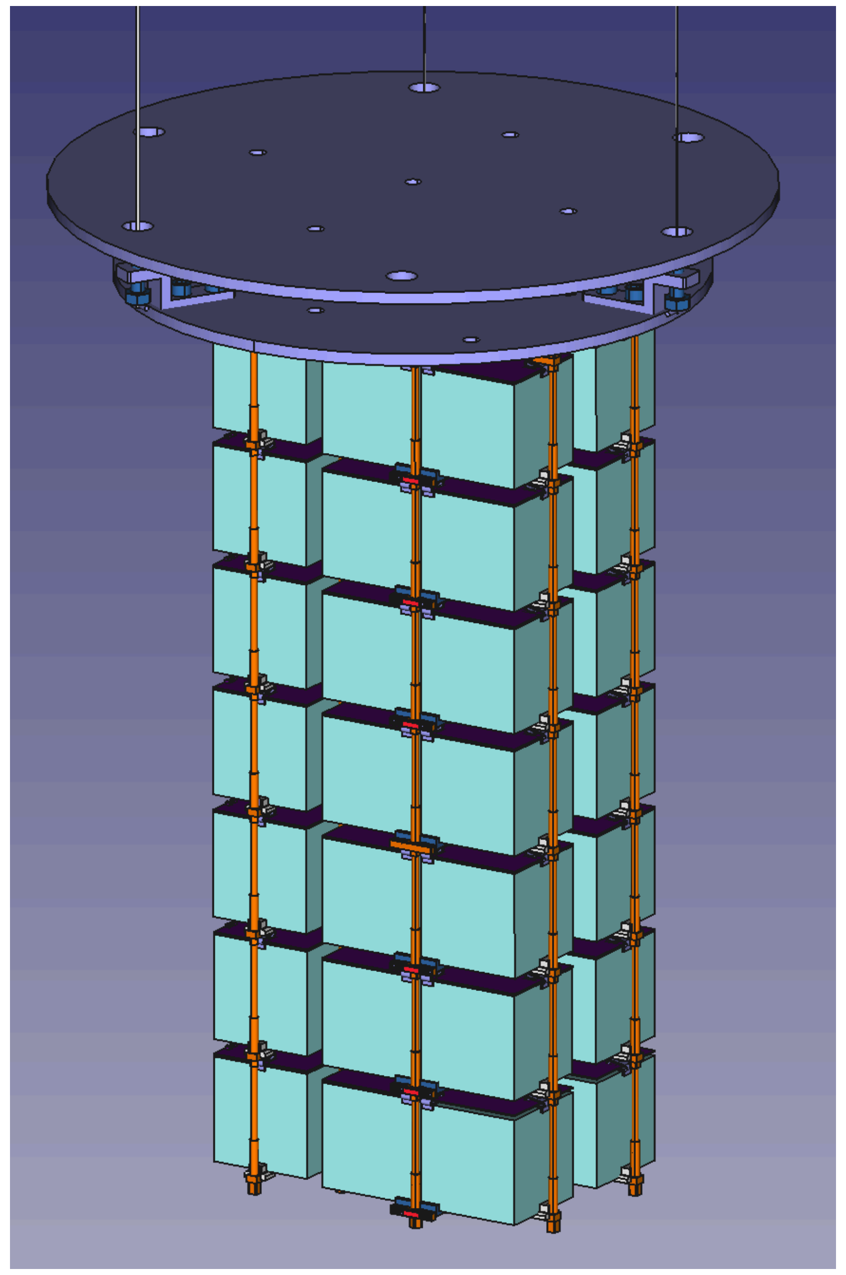


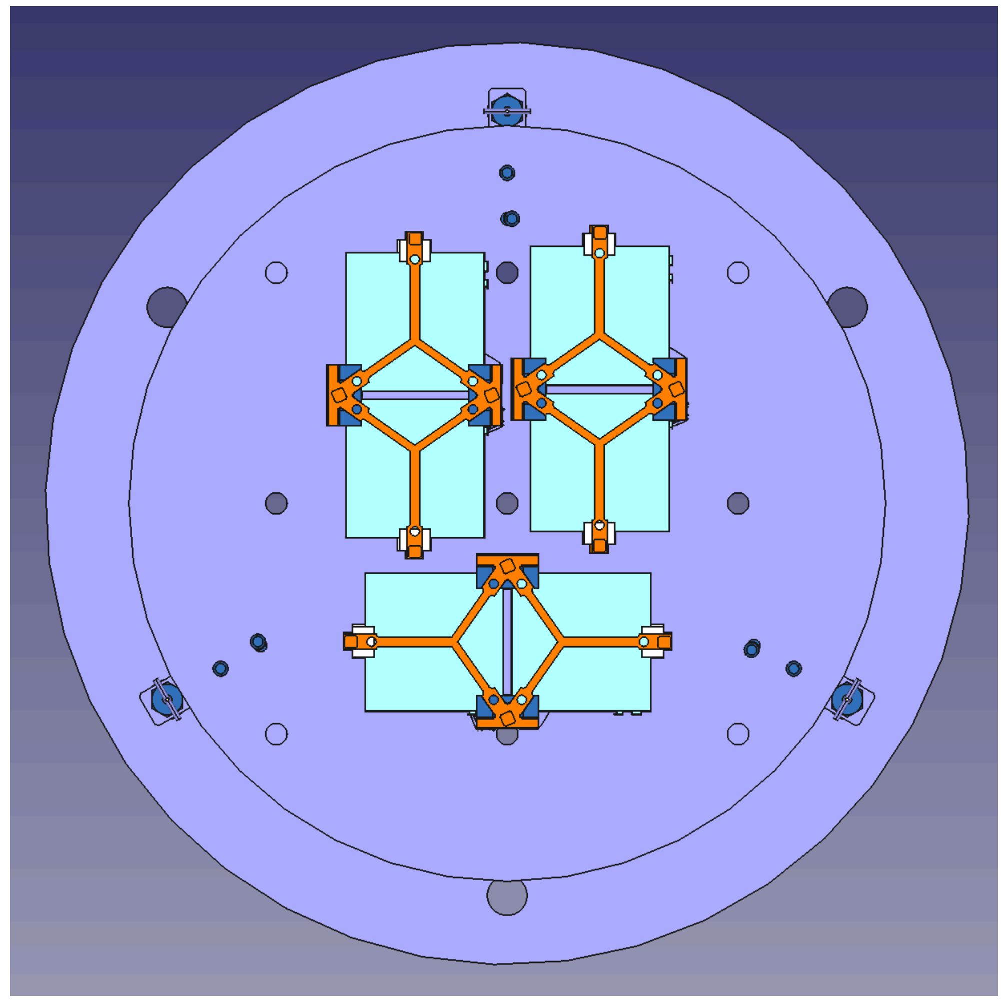
- We showed that with NTD sensors we can achieve a rise-time <0.5 ms

- 7/8 tested light detectors were able to reach pile-up background index $<0.5 \times 10^{-5}$ counts/keV/kg/yr

Future demonstrators with NTL technology

CROSS





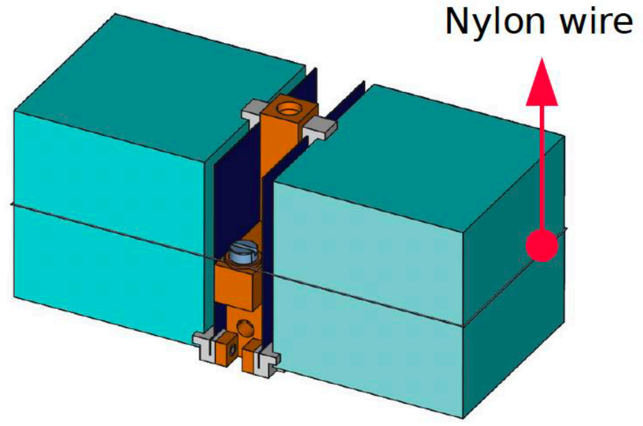
- 42 square Neganov-Luke light detectors with different electrode designs will be used in final demonstrator

BINGO

An innovative detector assembly

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

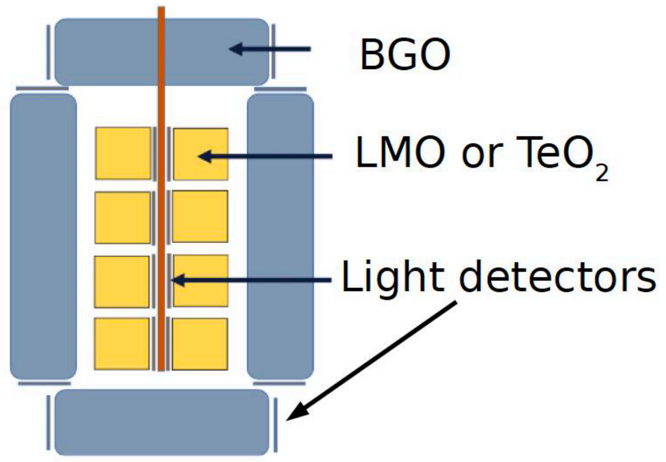
Geometrical reduction of the surface radioactivity + compact assembly for anticoincidence cuts



A cryogenic active veto

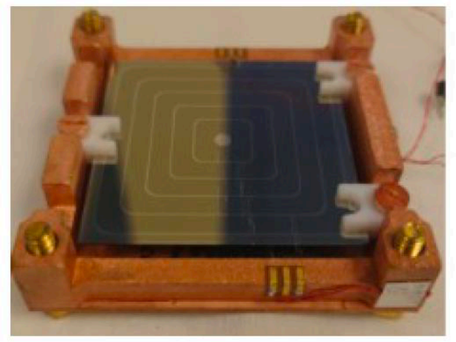
- Made of scintillators (BGO) with a 4π coverage operated at 20 mK Scintillation light read by its own light detectors

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



- 56 Neganov-Luke light detectors of different shapes will be used in the MINI-BINGO demonstrator
- R&D on the selection of the best detector design is ongoing

Summary

- Bolometric light detectors are a powerful tool for highly **efficient background reduction**
- Scintillating bolometer technology allows us to **reject up to 99.9% of α background** in the ROI due to the different light emissions for α and β/γ events
- Neganov-Luke effect helps us to **increase the signal-to-noise ratio** significantly
- Aboveground measurements **confirmed the scalability of NL gain** due to changes in electrodes geometry
- Demonstrated **high pile-up rejection efficiency** with optimised detector design and working parameters. Work on the improvement is still ongoing
- Neganov-Luke technology will be tested with high statistics in CROSS and BINGO demonstrators and at the end **will be used for the CUPID experiment**