



**HAL**  
open science

## Charge-to-heat transducers exploiting the Neganov-Trofimov-Luke effect for light detection in rare-event searches

V. Novati, L. Bergé, L. Dumoulin, A. Giuliani, M. Mancuso, P. de Marcillac, S. Marnieros, E. Olivieri, D.V. Poda, M. Tenconi, et al.

► **To cite this version:**

V. Novati, L. Bergé, L. Dumoulin, A. Giuliani, M. Mancuso, et al.. Charge-to-heat transducers exploiting the Neganov-Trofimov-Luke effect for light detection in rare-event searches. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2019, 940, pp.320-327. 10.1016/j.nima.2019.06.044 . hal-02188838

**HAL Id: hal-02188838**

**<https://hal.science/hal-02188838>**

Submitted on 25 Oct 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

# Charge-to-heat transducers exploiting the Neganov-Trofimov-Luke effect for light detection in rare-event searches

V. Novati<sup>a</sup>, L. Bergé<sup>a</sup>, L. Dumoulin<sup>a</sup>, A. Giuliani<sup>a,b</sup>, M. Mancuso<sup>a</sup>,  
P. de Marcillac<sup>a</sup>, S. Marnieros<sup>a</sup>, E. Olivieri<sup>a,\*</sup>, D.V. Poda<sup>a,d</sup>, M. Tenconi<sup>a</sup>,  
A.S. Zolotarova<sup>c</sup>

<sup>a</sup>*CSNSM, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, 91405 Orsay, France*

<sup>b</sup>*DISAT, Università dell'Insubria, 22100 Como, Italy*

<sup>c</sup>*IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France*

<sup>d</sup>*Institute for Nuclear Research, 03028 Kyiv, Ukraine*

---

## Abstract

In this work we present how to fabricate large-area (15 cm<sup>2</sup>), ultra-low threshold germanium bolometric photo-detectors and how to operate them to detect few (optical) photons. These detectors work at temperatures as low as few tens of mK and exploit the Neganov-Trofimov-Luke (NTL) effect. They are operated as charge-to-heat transducers: the heat signal is linearly increased by simply changing a voltage bias applied to special metal electrodes, fabricated onto the germanium absorber, and read by a (NTD-Ge) thermal sensor. We fabricated a batch of five prototypes and ran them in different facilities with dilution refrigerators. We carefully studied how impinging spurious infrared radiation impacts the detector performances, by shining infrared photons via optical-fiber-guided LED signals, in a controlled manner, into the bolometers. We hence demonstrated how the radiation-tightness of the test environment tremendously enhances the detector performances, allowing to set electrode voltage bias up to 90 volts without any leakage current and signal-to-noise gain as large as a factor 12 (for visible photons). As consequence, for the first time we could operate large-area NTD-Ge-sensor-equipped NTL bolometric photo-detectors capable to reach sub 10-eV baseline noise (RMS). Such detectors open new frontiers for rare-event search

---

\*corresponding author

*Email address:* [emiliano.olivieri@csnsm.in2p3.fr](mailto:emiliano.olivieri@csnsm.in2p3.fr) (E. Olivieri)

experiments based on low light yield Ge-NTD equipped scintillating bolometers, such the CUPID neutrinoless double-beta decay experiment.

*Keywords:* Light detector, Ge bolometer, Neganov-Trofimov-Luke effect, Dark matter, Double-beta decay

---

## 1. Introduction

Bolometric light detectors are nowadays employed in several cryogenic experiments searching for rare events, as direct detection of dark matter (CRESST [1], COSINUS [2]) and searches for neutrinoless double-beta decay (AMoRE [3], LUCIFER/CUPID-0 [4], LUMINEU [5] and its follow-up CUPID-Mo [6]). They are coupled to the main scintillating crystals which contain the nuclear targets for the dark-matter particles or the nuclei that can undergo neutrinoless double-beta decay. The main crystal is operated as a bolometer and the simultaneous detection of heat and light signals associated to the same event can provide particle identification and consequently an active background rejection, as proposed in [7, 8, 9, 10] and successfully performed (see e.g. in [11, 12, 13]). In particular, composite heat-and-light detectors allow to control dominant background events such as nuclear recoils in dark-matter searches and alpha particles in double-beta-decay experiments.

In dark-matter searches, a high-performance light detector is required to lower the energy threshold [14] and to identify recoils of different-mass nuclei [15]. In double-beta decay searches, high-sensitivity light detectors are needed either to detect the feeble Cherenkov light emitted by poorly-scintillating crystals [16] (this is the case of the promising compound  $\text{TeO}_2$  [17, 18, 19, 20, 21]), or to help in pile-up rejection (as in  $^{100}\text{Mo}$ -enriched bolometers, [22, 23, 24]). The pile-up rejection capability is useful also to perform precision calorimetric measurements of rare- $\beta$ -decay spectral shapes (as those of  $^{113}\text{Cd}$  and  $^{115}\text{In}$ ) which can be used to scrutinize the value of the axial-vector coupling constant [25, 26, 27].

Neganov-Trofimov-Luke (NTL) effect [28, 29] can be exploited in high purity semiconductor-based bolometers for lowering the detection threshold and enhancing the signal-to-noise-ratio.

In case of an ionizing particle of primary energy  $E_0$  interacting in a semiconductor absorber, an extra heat energy is produced if charge carriers, created

32 by the particle interaction, are drifted by an electric field. The total heat  
 33 sensed by the bolometer is:

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

34 where  $\epsilon$  is the average energy required to generate an electron-hole pair,  $q$   
 35 is the elementary charge and  $V_{el}$  is the charge collecting potential between  
 36 electrodes (Fig. 1, bottom panel), deposited on the germanium absorber to  
 37 set a drifting electric field across this latter;  $\eta$  is an amplification efficiency  
 38 which accounts for an incomplete gain due to charge trapping or other losses  
 39 (in an ideal case  $\eta = 1$ ).

40 For  $V_{el} \gg \epsilon/q$  (NTL regime), the heat energy  $E_{tot}$  is mainly due to the  
 41 NTL effect; therefore, a bolometer operated under this condition behaves as  
 42 a voltage-controlled charge-to-heat amplifier. The NTL signal amplification  
 43 is observed in EDELWEISS [30] and CDMS [31] dark-matter search experi-  
 44 ments, which employ high purity germanium and silicon ionization-and-heat  
 45 composite bolometers.

46 To-date, several technologies of NTL bolometers for the detection of pho-  
 47 tons have been developed and used for the aforementioned applications. They  
 48 can be grouped according to the absorber material and the temperature sen-  
 49 sor as follows: silicon absorbers equipped with TES (Transition-Edge Sen-  
 50 sor) thermometers [14, 32, 33, 34, 35]; silicon absorber with NTD (Neutron-  
 51 Transmutation-Doped) germanium thermistors [36, 37]; and germanium ab-  
 52 sorbers read-out by NTD-Ge thermistors [38, 39, 40].

53  
 54 In this work we report on the fabrication method of NTL, NTD-Ge  
 55 equipped germanium bolometers and present the development, characteri-  
 56 zation and performance of five of them. Additional information and mea-  
 57 surements done with early NTL bolometric light detector prototypes can be  
 58 found in [41, 42, 43].

## 59 2. Detector fabrication

60 The development of NTL-effect-assisted cryogenic light detectors has been  
 61 carried out at CSNSM laboratory (Orsay, France). The detector absorbers  
 62 are done by electronic-grade germanium wafers (impurity level of the order  
 63 of  $10^{11}/\text{cm}^3$ ) of 44 mm diameter and 0.175 mm thickness, supplied by UMI-  
 64 CORE. Wafers are bombarded with argon ions to remove the germanium

65 oxide at the surfaces and improve the adherence of any subsequent structure  
 66 deposition onto the surfaces. A 50-nm-thick hydrogenated-amorphous ger-  
 67 manium layer is evaporated, as discussed in [44]. Five 100-nm-thick, 3.8-mm-  
 68 pitch annular concentric aluminium electrodes are then deposited. Finally  
 69 the wafers are coated by a 70-nm-thick SiO layer, to enhance the light ab-  
 sorbtion<sup>1</sup>. The germanium absorbers are mounted in copper holders and kept

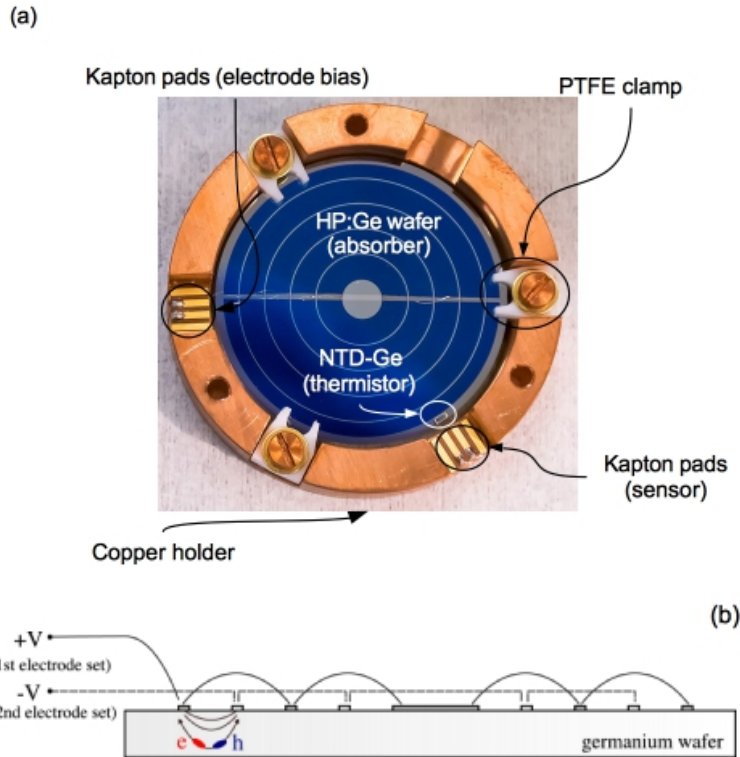


Figure 1: (a) A picture of a NTL-assisted light detector (NTLLD1). A thin region (grey strip crossing the annular electrodes) without any SiO coating is visible; it is used to connect via ultrasonic bonding the different annular electrodes (light circles) and create two sets of bias electrodes. (b) Sketch of the electrical connection between annular electrodes. An electrical potential  $\Delta V = V_+ - V_-$  can be applied to the two sets of bias electrodes, to drift electrons (e) and holes (h) as depicted in the scheme, along the electric field lines (black, solid).

<sup>1</sup>The enhancement of visible-wavelength photons absorption was initially found to be 35% [45].

70 by three PTFE clamps; absorbers are instrumented with a 5 mg NTD-Ge  
 71 thermistors. The electrical contacts between the detectors and the cryostat  
 72 cabling is ensured by Kapton-insulated Au-coated copper pads, glued on the  
 73 copper casing. The NTD-Ge thermistors are electrically connected to the  
 74 aforementioned pads through 25  $\mu\text{m}$  diameter,  $\sim 10$  mm long gold bonding  
 75 wires. These latter act also as thermal link between the absorbers and the  
 76 thermal bath. The aluminum electrodes are connected by 25  $\mu\text{m}$  diameter  
 77 aluminum bonding wires to form two separated sets of bias electrodes; a  
 78 voltage can be applied (Fig. 1(b)) to set a charge carrier drifting field within  
 79 the semiconductor absorber. Five NTL light detectors (from NTLLD0 to  
 80 NTLLD4) have been fabricated according to the above-presented scheme.  
 81 For two of them, the process was slightly changed: NTLLD0 did not have  
 82 any SiO coating and NTLLD4 was equipped with an NTD-Ge of smaller  
 83 mass ( $\sim 2$  mg) in order to enhance the sensitivity. Fig. 1(a) shows a picture  
 84 of NTLLD1 detector.

### 85 **3. Detector operation**

#### 86 *3.1. Equipment and conditions of low-temperature tests*

87 The NTL light detectors have been first operated aboveground, in dif-  
 88 ferent environments, i.e. two dry and one wet dilution refrigerators, at  
 89 the CSNSM laboratory [48, 42]. Some of them have been afterwards op-  
 90 erated underground at LNGS (Laboratory Nazionali del Grans Sasso, Italy)  
 91 and at LSM (Laboratoire Souterrain de Modane, France) where the CU-  
 92 PID R&D and EDELWEISS-III experiments are located, respectively (a de-  
 93 scription of both cryogenic facilities can be found e.g. in [42, 5]). In order  
 94 to reduce the noise due to vibrations generated by the pulse-tube of the  
 95 dry refrigerators [49], spring-loaded mechanical decoupling systems (see e.g.,  
 96 in [50, 51, 5, 52]) have been used.

97 Only in a few measurements the detectors under study were investigated  
 98 with visible light photons emitted by scintillating crystals; most of the tests  
 99 have been carried out with near-infrared photons, provided by an infrared  
 100 LED setup located at room temperature and guiding the photons via 0.2-  
 101 mm diameter, plastic optical fibers down to the light detectors. 0.85  $\mu\text{m}$   
 102 wavelength (Honeywell HFE4050) and 0.95  $\mu\text{m}$  wavelength (Osram LD271)  
 103 photon packages (bursts) were delivered, capable to provide total energies  
 104 ranging from a few eV up to few MeV in a single burst, by simply changing

105 the driving parameters (electrical pulse width and amplitude) of the LEDs.  
 106 The LEDs were also used to charge-reset the germanium absorbers [53].

107 Most of the measurements have been performed at temperatures as low  
 108 as 15 mK. A room-temperature, DC electronics with a 675 Hz lowpass cut-off  
 109 frequency [54] has been used to shape the thermistor signals, which have  
 110 been sampled at 5÷10 kHz to correctly reconstruct the signal shape.

### 111 3.2. Optimal working point settings

112 The NTD-Ge thermistor bias for the tested detectors has been chosen  
 113 by stabilizing the temperature of the mixing chamber and searching for the  
 114 maximal signal-to-noise ratio (SNR). To this end, we delivered constant LED  
 115 pulses (signal) and recorded the detector RMS baseline noise, for different  
 NTD-Ge sensor biases (Fig. 2).

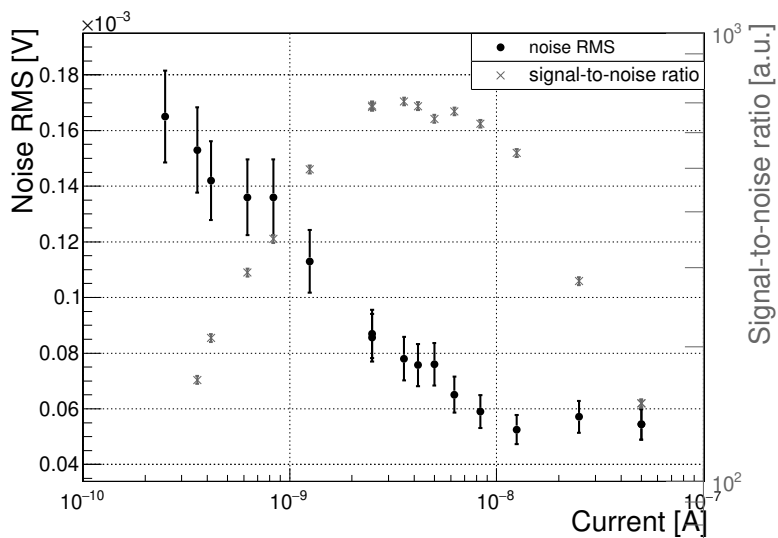
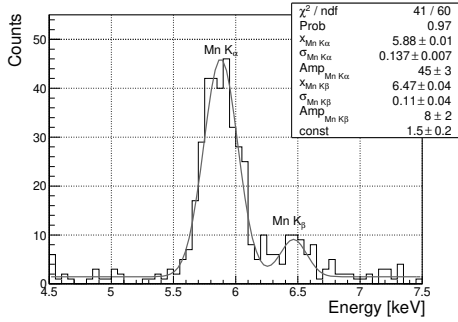


Figure 2: A signal-to-noise ratio (crosses) of the NTLLED2 detector as a function of the bias. The RMS noise (points) is also shown. For this detector and set-up, the maximal SNR is observed for a bias of 3 nA.

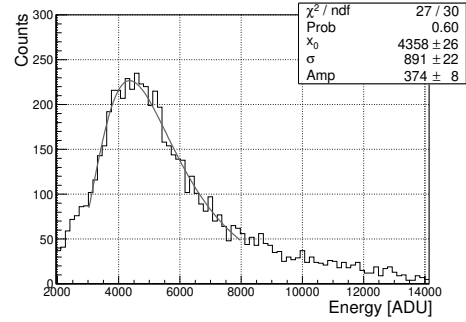
116

### 117 3.3. Calibration

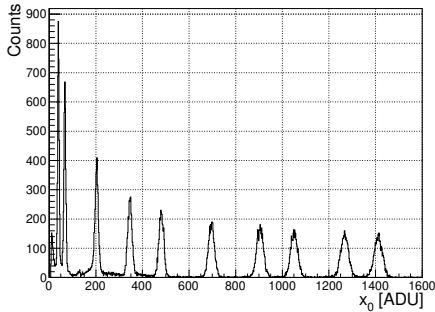
118 Several approaches have been used to calibrate the NTL bolometers, such  
 119 as: X-rays (e.g. a <sup>55</sup>Fe source, X-ray fluorescence induced by a high-intensity



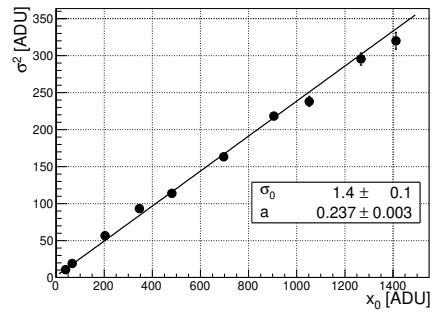
(a) Energy spectrum of an X-ray  $^{55}\text{Fe}$  source, irradiating the NTLLED1 detector.



(b) Muon signal distribution recorded with NTLLED4. The maximum of the distribution corresponds to about 100 keV (see text).



(c) LED pulses (bursts) of different intensities delivered to the detector (NTLLED2), which records signal of  $x_0$  amplitude (uncalibrated). Each peak has  $(x_0)_i$  mean and  $\sigma_i^2$  width.



(d) Squared peak width  $\sigma_i^2$  as a function of  $(x_0)_i$ . The number of photons impinging the detector is given by  $a \cdot x_0$ . The detector response (calibration) is derived by knowing the average wavelength of the LED photons.

Figure 3: Illustration of different detector calibration methods.



120  $\gamma$  source), scintillation, LED photon bursts and photon statistics, environ-  
121 mental muons.

122 A  $^{55}\text{Fe}$  source was often used to irradiate the detector absorber. A typical  
123 spectrum obtained is shown in Fig. 3(a).

124 As an alternative method, an external high-activity gamma source can be  
125 used to induce the X-ray fluorescence of the materials directly surrounding  
126 the detector [40]. One can also exploit the cosmic rays in an aboveground  
127 facility, by recording the bolometer signal distribution of muons crossing the  
128 germanium wafer. The muon energy loss probability is well-described by the  
129 Landau distribution [55] and is illustrated in Fig. 3(b). The most probable  
130 muon-induced energy release has been evaluated by Geant4-based Monte  
131 Carlo simulation<sup>2</sup> of the order of 100 keV (for a 0.175 mm thick germanium  
132 absorber).

133 The detector calibration can also be performed by using LED photon  
134 bursts and photon statistics, as successfully demonstrated in [33], and re-  
135 ported in Fig. 3(c),(d).

136 In NTL regime, we could not use the  $^{55}\text{Fe}$  X-ray lines (5.9 and 6.5 keV)  
137 to calibrate our detector energy response, since those lines were broad and  
138 washed-out. This behaviour is mainly due to: (1) e-h charge recombination  
139 in the primary plasma, created when the photon interacts within the germa-  
140 nium absorber. X-rays release all their energy in a well-defined point of the  
141 absorber, creating a dense plasma of electron-hole pairs. The electric field  
142 set in the germanium absorber via the bias electrodes separate and drift only  
143 the external charges (plasma erosion) whereas the internal e-h pairs eventu-  
144 ally recombine. This leads to an incomplete charge collection and hence a  
145 broadening of the detector signal; (2) e-h trapping due to defects, impurities  
146 and surface effects. Again, the e-h charges created by an ionising particle are  
147 trapped (while drifted toward the bias/collecting electrodes) and the detector  
148 experiences an incomplete charge collection.

149 For peak provided via LED photon bursts (where photons interact in the  
150 germanium simultaneously but over a large area) and for muon interactions  
151 this broadening is not observed. This is probably due to the fact that the  
152 e-h charge density is low and the charges are separated and drifted before

---

<sup>2</sup>The simulation has been performed in a very simplified approach, assuming a cosmic muon angular distribution proportional to  $\cos^2(\Theta_Z)$ , where  $\Theta_Z$  is the zenith angle. The generated particles are  $\mu^+$ 's with 3 GeV energy.

153 recombining. Therefore only these two latter techniques could be used for  
154 the calibration of the energy detector response in the NTL regime.

155 When a light detector is coupled to a source of scintillation and/or Cherenkov  
156 radiation, the registered light (initially calibrated e.g. by X-rays at 0 V elec-  
157 trode bias) can also be exploited [39]. It is worth noting that the calibration  
158 of a detector operated in the NTL mode strongly depends on the source  
159 used, since the quantum efficiency  $\epsilon$  depends on the particle and wavelength  
160 (we will see later in the text). In our application, the main purpose of NTL  
161 light bolometers is the detection of visible wavelength photons. Therefore  
162 the scintillation light is the most pertinent source of calibration.

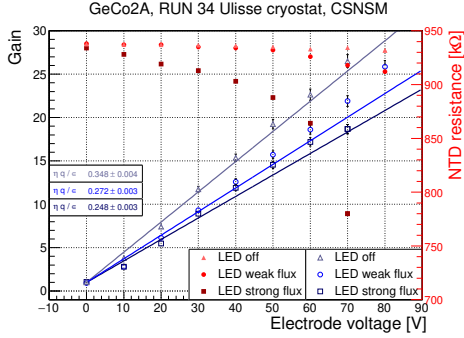
## 163 4. Detector performance

### 164 4.1. Photo-current noise

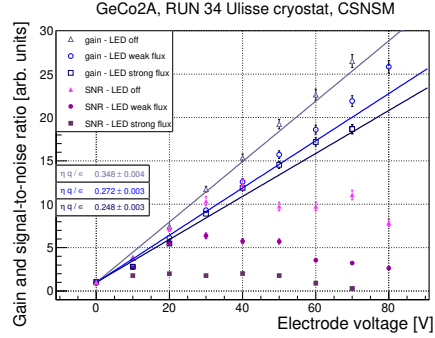
165 As observed in the very early investigations of NTL detectors [14, 32, 33],  
166 the performances (*i.e.* baseline noise and resolution) of these devices are  
167 strongly degraded if they receive a spurious photon flux (for example, coming  
168 from high temperature black-bodies). In particular, when a voltage bias is  
169 set on the bias electrodes, a power proportional to the photon flux times the  
170 voltage is dissipated; consequently the detector warms up and settles to a  
171 different working point. Before experiencing this heating, the detector shows  
172 a baseline excess noise.

173 To understand the aforementioned behaviour, we shined the detector with  
174 a constant photon flux in a controlled manner, by using an infrared LED. We  
175 monitored the NTL gain, the signal-to-noise ratio and the NTD-Ge resistance  
176 as a function of the electrodes bias, for different LED photon flux intensities.  
177 Fig. 4 gathers the results obtained with the NTLLD4 detector. The NTL gain  
178 still increases with respect to the electrode bias but the gain factor (slope)  
179 decreases, mainly due to a sensitivity degradation which is caused by the  
180 warming up of the working point (Fig. 4(a)). Moreover, the photo-current  
181 injection drastically affects the signal-to-noise ratio; at 40 V a reduction of  
182 this latter as high as 50% (80%) for the weak (strong) LED-driven photon  
183 flux is observed (Fig. 4 (c) and Fig. 4(d)).

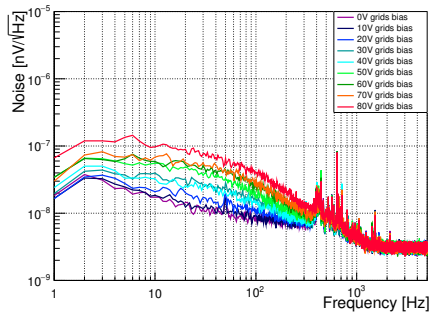
184 Therefore, the performance of NTL bolometers can be drastically im-  
185 proved by carefully shielding against spurious radiation, making the detector  
186 photon-tight with respect to environmental photons.



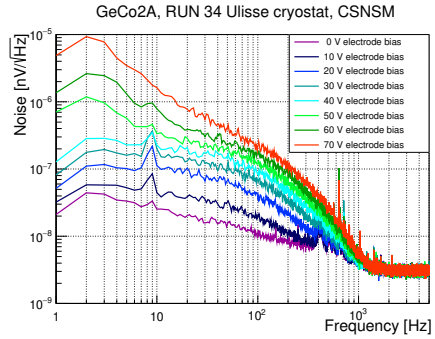
(a) Gain and NTD-Ge resistance, as a function of the electrode voltage bias and different LED photon flux intensity.



(b) Signal-to-noise ratio as a function of the electrode voltage bias, for different photon fluxes.



(c) Noise spectra of NTLLED4 detector signal acquired for different electrode voltage bias, without photon flux.



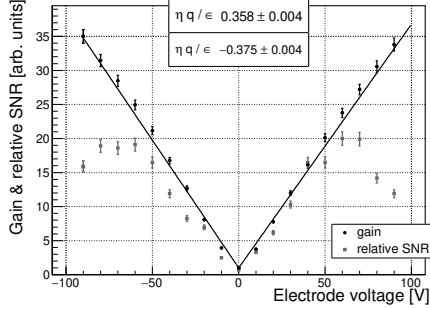
(d) Noise spectra of NTLLED4 detector signal, acquired for different electrode voltage bias and for different photon flux generated via the LED.

Figure 4: (*Color online*) NTL detector behaviour studies performed to inspect the impact of a spurious photon flux impinging the germanium (semiconductor) absorber.

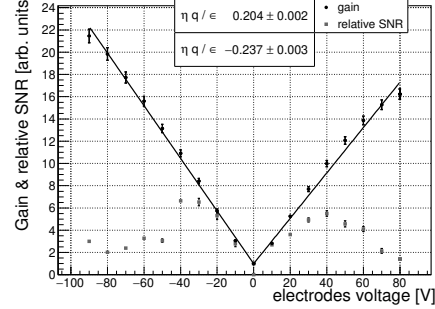
#### 187 4.2. Performance in NTL regime

188 The following detector parameters have been studied: the NTL signal  
189 amplification, the signal-to-noise ratio, the signal sensitivity and the noise  
190 conditions in different environments (*i.e.* different dilution refrigerators).

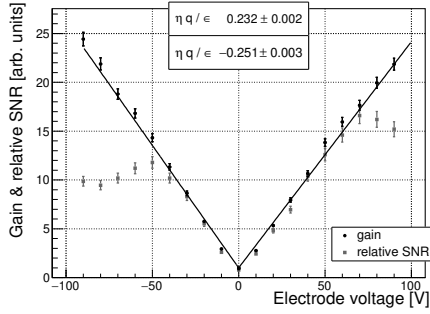
191 The evolution of the NTL gain was measured for a given photon wave-  
192 length by injecting constant intensity LED bursts at low repetition rate  
193 (about one every 3 s) and recording the signal (amplitude of the pulses) seen  
194 by the detector, while varying the electrode voltage bias. Simultaneously,  
195 the RMS baseline noise was monitored to estimate the signal-to-noise ratio,



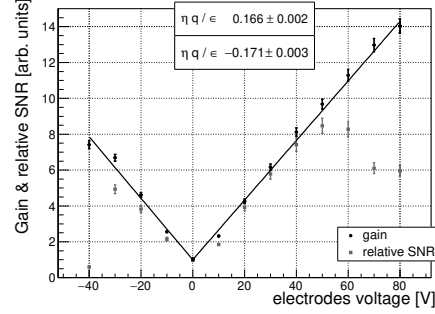
(a) NTLLD0 gain and signal-to-noise ratio.



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



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



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

Figure 5: Examples of gain and signal-to-noise ratio as a function of the electrode bias. A linear fit is used to derive the voltage NTL gain (*i.e.*,  $\eta \cdot q / \epsilon$ ) for LED photon bursts of  $0.85 \mu\text{m}$  wavelength photons.

196 for each bias value. The LED burst intensity was chosen to provide pulses on  
 197 the detector within the linear region of the detector response, for the highest  
 198 electrode bias. Fig. 5 shows some examples of the NTL gain  $G_{NTL}$  and the  
 199 corresponding SNR values, as a function of electrode voltage bias. Overall,  
 200 the NTL gain (slope) is almost similar with respect to the voltage polarity.  
 201 Nevertheless, the data show a difference in the gain (within 10%) when a  
 202 positive/negative bias is applied. A difference with respect to electrode bias  
 203 polarity is also observed, for the maximal SNR. This behaviour was already  
 204 observed in the early investigations [14, 32].

205 Data of Fig. 5 were fitted by a linear function to derive the value of the

206 amplification efficiency  $\eta$  (taking into account  $\epsilon$  for the used light source,  
207 Ref. [56]). The highest  $\eta$  value achieved with either the positive or the  
208 negative electrode bias is quoted in Table 1. The NTL amplification efficiency  
209 for  $0.52 \mu\text{m}$  wavelength photons (which is the average wavelength of photons  
210 of the Cherenkov radiation in  $\text{TeO}_2$  crystal [57]) is evaluated from the gain  
211 at the optimal (from the point of view of the signal-to-noise ratio) electrode  
212 voltage bias. Results are summarized in Table 1.

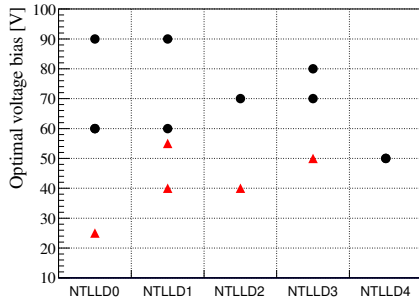
213 As previously stated, the gain of the NTL devices depends on the wave-  
214 length of the incident radiation [56]. The measurements described in this  
215 work have been performed with different light sources:  $0.85 \mu\text{m}$  and  $0.95 \mu\text{m}$   
216 wavelength photon bursts, scintillation light (peaked at  $\sim 0.6 \mu\text{m}$  wavelength)  
217 and Cherenkov light ( $\sim 0.52 \mu\text{m}$  wavelength, on the average). In order to  
218 consistently compare the performances, we rescaled the relative SNR and  
219 the baseline noise, for all of them, to  $0.52 \mu\text{m}$  wavelength photons.

Detector	Set-up	Run ID	$T_{holder}$ [mK]	Light $\lambda$ ( $\mu\text{m}$ )	Amplification efficiency $\eta$	Optimal bias $V_{el}$ (V)	Relative SNR		$S_A$ ( $\mu\text{V}/\text{keV}$ )	Noise RMS (eV)			Ref.
							[ $\lambda$ ]	[0.52 $\mu\text{m}$ ]	[ $V_{el}=0$ V]	[ $V_{el}=0$ V]	[ $V_{el}$ ]		
NTLLD0	A	II	18	0.85	0.62	60	20.0	11.4	0.49	170	17		
				0.62	0.53		12.5	10.2					
	D	–	n.a.	0.28	90	7.2	7.2	1.0	185	26	[38]		
		III	18	0.52	0.43	25	4.7	4.7	0.57	166	35		[39]
NTLLD1	A	I	18	0.85	0.39	40	6.6	3.7	0.74	153	41		
	B	–	20	0.62	0.48	90	11.5	11.0	0.53	91	8		
	D	III	18	0.52	0.40	55	3.5	3.5	1.3	87	25		[39]
	E	–	17		0.53	60	11.1	11.1	0.92	108	10		[40]
NTLLD2	A	I	18	0.85	0.29	40	6.8	3.9	0.58	109	28		
		II	19		0.41	70	16.6	9.9	0.83	98	10		
NTLLD3	A	I	17	0.85	0.28	50	8.5	4.8	0.61	230	47		
				0.95	0.33	80	19.8	9.8	1.1	99	10		
						70	17.2	8.6		60*	7*		
NTLLD4	A	–	15	0.85	0.63	50	12.6	7.9	1.5	123	11		
				0.60	0.52		11.4	10.7					

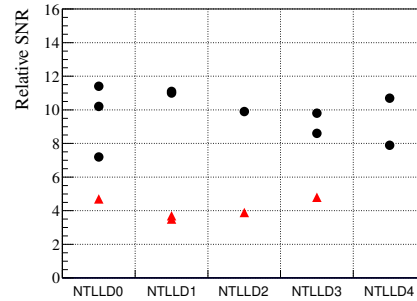
Table 1: Performance of NTL light detectors (see details in the text) characterized in different set-ups: A) Cryomech PT-405 equipped dry dilution unit (Air Liquide), B) wet dilution unit (CEA/SPEC developped), C) Cryomech PT-410 equipped dry dilution unit (Cryoconcept), D) CUPID R&D cryostat (wet, Oxford Instrument), and E) EDELWEISS-III cryostat (semi-dry, custom made by Néel Institute). The run identification number (ID) is indicated only for those measurements which are common for several light detectors. The temperature of the detector holder for each measurement is indicated by  $T_{holder}$ . The  $\epsilon$  for the typical wavelength  $\lambda$  of the used light sources is following [56]: 1.3–1.6 eV (0.95–0.85  $\mu\text{m}$ , LED), 2.2–2.3 eV (0.6–0.62  $\mu\text{m}$ , scintillation) and 2.5 eV (0.52  $\mu\text{m}$ , Cherenkov). The values of the amplification efficiency  $|\eta|$  correspond to the NTL gain measurements with the quoted light sources. The listed electrode bias  $V_{el}$  is optimal in term of the signal-to-noise ratio, relatively to the 0 V bias conditions. The best relative SNR is given for the used light sources with the quoted  $\lambda$  values and the Cherenkov radiation (0.52  $\mu\text{m}$ ). A signal sensitivity  $S_A$  is given for detectors operated without the NTL regime. The RMS baseline noise is specified for the electrode bias equal to 0 V and  $V_{el}$ . The NTLLD3 baseline noise level marked with \* was achieved with a pulse-tube switched off.

220

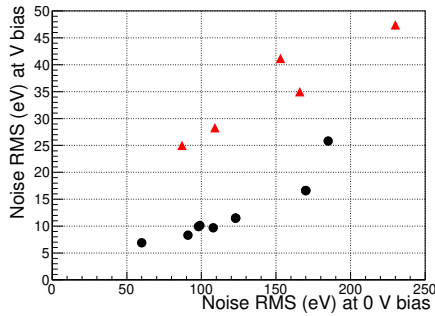
A graphical representation of the results given in Table 1, rescaled to  $0.52 \mu\text{m}$  wavelength photons, is given in Fig. 6. As shown in Sec. 4.1,



(a) Optimal voltage for each light detectors, measured in different runs.



(b) Relative SNR for each light detectors, measured in different runs.



(c) RMS noise at the optimal electrode bias as a function of the RMS noise with grounded electrodes (all detectors plotted).

Figure 6: (*Color online*) Graphical representation of some results given in Table 1, rescaled to  $0.52 \mu\text{m}$  photon wavelength. Point markers summarize the results of run-I and of those obtained in CUPID R&D cryostat (spurious infrared radiation impinging the detectors), whereas triangle markers summarize the results obtained in run-II and EDELWEISS cryostat (radiation-tight environment).

221

222 the NLT-assisted detectors are highly sensitive to the photo-current noise:  
 223 a special care must be taken to shield these devices from spurious (mainly  
 224 infra-red) radiation. The plots in Fig. 6 show how NTL bolometers differently  
 225 behave when tested in poor (triangle markers, CUPID R&D cryostat) and  
 226 good (points, *i.e.* EDELWEISS-III cryostat) radiation-tight environment.

227 We can look more into detail at the performances of the NTLLD2 detec-  
228 tor, obtained in run-I and run-II (Table 1). The performance improvement  
229 in run-II was achieved by simply strengthening the radiation-tightness of the  
230 cryostat experimental space: the inner 50 mK copper radiation shield sur-  
231 rounding the detector was coated with black-velvet infrared painting [58].  
232 The photo-current noise (Fig. 6.(a)) strongly conditions the optimal elec-  
233 trode bias, leading to variation of this latter as high as 100% and a difference  
234 in the relative SNR as large as a factor 2–3. No leakage (breakdown) cur-  
235 rents were observed for all the 5 bolometers up electrode bias values of 90 V,  
236 which hints that, likely, the signal-to-noise ratio can be improved by further  
237 enhancing the (infrared) photon-tightness of the test environment and/or  
238 bolometer holders.

239 Table 1 reports also the detector sensitivities and the typical noise level  
240 achieved with no NTL amplification. All detectors demonstrated sensitivi-  
241 ties as high as  $\sim 0.9 \mu\text{V}/\text{keV}$ , typical for NTD-Ge-instrumented germanium  
242 optical bolometers [5, 46]. The highest sensitivity with the NTLLD4 detector  
243 was obtained thanks to the reduced size of the NTD-Ge thermistor. A spread  
244 by a factor of 2–3 in the baseline noise levels is observed in different set-ups  
245 (*e.g.* compare the results for NTLLD1 and/or NTLLD3 reported in Table 1)  
246 and demonstrates how bolometers are fragile with respect to environmental  
247 vibrations [49, 52].

## 248 5. Discussion

249 In this work we have presented a process to upgrade/improve light semi-  
250 conductor bolometers, whatever the sensor technology, and enhance their  
251 performance. The process consists in the realisation of bias electrodes onto  
252 the semiconductor absorber to set an electric field within the semiconduc-  
253 tor and drift the charge carriers created by a (ionizing) particle interaction.  
254 This allow to benefit of the so-called NTL effect and lower the detection  
255 thresholds.

256 NTL-effect-based light detectors can be used to go beyond the current  
257 limit of many rare-event physics experiments.

258  
259 In neutrinoless double-beta searches based on heat-and-light composite  
260 bolometers, low threshold light detectors are used to suppress the back-  
261 ground. In the case of  $\text{TeO}_2$  based neutrinoless double-beta decay search, no



262 exploitable scintillation signal is to-date available to reject the alpha (dom-  
263 inant) background in the region of interest [17]. However, a particle iden-  
264 tification can be performed via Cherenkov radiation, emitted by electrons <sup>3</sup>  
265 [16]. The light signal available to discriminate between the alphas and the  
266 electron interaction is of about 100 eV for 2.5 MeV deposited heat, which is  
267 within the noise level of typical doped-semiconductor-sensor light detectors.  
268 Thanks to its low threshold capability, a NTL-effect-based light detector will  
269 be able to recover the light signal, hence to suppress the background.

270 The next-generation double-beta decay experiment CUPID (CUORE Up-  
271 grade with Particle IDentification), which is considering TeO<sub>2</sub> as a viable  
272 option to study the double-beta decay of the candidate <sup>130</sup>Te [21], could  
273 eventually benefit of the NTL effect light detector technology to suppress  
274 the background up to a factor of one hundred [12, 43].

275 In dark matter searches as CRESST [1], the NTL technology can improve  
276 the separation between the background generated by the electron recoils and  
277 the signal coming from nuclear recoils, expected for the interaction of WIMPs  
278 (weakly interactive massive particles, hypothetically constituting the dark-  
279 matter galactic halo) with the elemental composition of the target. This  
280 will lower the dark matter detection thresholds and open new possibility  
281 to explore wider WIMP mass region. Taking also into account that a spin-  
282 independent WIMP-nucleon elastic-scattering cross section is proportional to  
283 the square of the mass number of the target, NTL bolometers will improve  
284 the capability to distinguish nuclear recoils originated by WIMP scattering  
285 off light, middle or heavy nuclei in multi-target scintillation detector [15].

286 Low-threshold optical bolometers can also be exploited for the investi-  
287 gation of other rare processes as the study of a beta spectrum shape of  
288 4-fold-forbidden  $\beta$  decays of <sup>113</sup>Cd and <sup>115</sup>In [25] to scrutinize the value of  
289 the axial-vector coupling constant. Its value is expected to be similar to  
290 one involved in the neutrino-less double-beta decay process [26]. In spite of  
291  $10^{14}$ – $10^{16}$  yr half-live of these rare beta decays, the induced counting rate  
292 and subsequently the probability of pile-ups in macro-bolometers contain-  
293 ing these nuclides can be rather high, which strongly affects the precision of  
294 the spectrum reconstruction. Instead of using the macro-bolometer to trace

---

<sup>3</sup>No light is expected for the interaction of alpha particles from natural radioactivity because of four orders of magnitude higher energy threshold required for the associated light emission ( $\sim 50$  keV and  $\sim 400$  MeV respectively for TeO<sub>2</sub>.)

295 the beta spectrum, one can use this latter just as a scintillator and use the  
296 scintillation signal to reconstruct the beta spectrum itself. The advantage of  
297 this detection scheme is the reduction of the pile-up rate, since a light de-  
298 tector can have, typically, a time response 10–100 times faster than the one  
299 of a macro-bolometer. NTL-assisted bolometric light detectors will allow in  
300 this case to reconstruct beta spectra down to threshold comparable to those  
301 reached by macro-bolometers [27].

302 Moreover, they can be used in  $^{100}\text{Mo}$ -enriched neutrinoless double-beta  
303 decay experiments, to mitigate the irreducible background of scintillating  
304 bolometers coming from the pile-ups of the two-neutrino double-beta decay  
305 events [22, 23, 23].

## 306 6. Conclusions

307 Five NTL-effect-assisted germanium bolometers to detect photons of vis-  
308 ible and near infra-red wavelength have been fabricated at CSNSM labo-  
309 ratory (Orsay, France) by developing a specific fabrication process for the  
310 realization of bias electrodes on high purity germanium wafer. In this work  
311 we demonstrate how this fabrication process leads to reproducible detector  
312 performances in terms of gain, optimal electrode bias, signal-to-noise ratio,  
313 signal sensitivity and baseline noise. We also show how compulsory is the  
314 shielding against spurious (infrared) radiation of the experimental space to  
315 operate the detectors in the NTL-assisted regime and fully benefit of the  
316 NTL gain.

317 The detectors, when operated at 0 V electrodes bias, *i.e.* with idle NTL  
318 gain, show sensitivity of 0.5–1.5  $\mu\text{V}/\text{keV}$  and baseline noise of 90–230 eV  
319 (RMS), whereas they can reach a factor 10 better performances when op-  
320 erated in NTL regime at 50–90 V electrode bias, showing sub 10-eV base-  
321 line noise (RMS). The technology to fabricate NTL-assisted optical bolome-  
322 ters is currently mature to be integrated in large-scale cryogenic rare-event  
323 search experiments such CUPID [20], for which hundreds of reproducible,  
324 low-threshold, high signal-to-noise ratio light detectors are required, or in  
325 composite heat-and-light bolometers which exhibit tiny light yield.

## 326 7. Acknowledgments

327 This work was partially performed in the framework of the LUMINEU  
328 project funded by the Agence Nationale de la Recherche (ANR, France; ANR-  
329 12-BS05-004-04).

- 330 [1] G. Angloher, et al., Results on light dark matter particles with a low-  
331 threshold CRESST-II detector, *Eur. Phys. J. C* 76 (2016) 25.
- 332 [2] G. Angloher, et al., The COSINUS project: perspectives of a NaI scin-  
333 tillating calorimeter for dark matter search, *Eur. Phys. J. C* 76 (2016)  
334 441.
- 335 [3] V. Alenkov, et al., Technical Design Report for the AMoRE  $0\nu\beta\beta$  Decay  
336 Search Experiment, arXiv: 1512.05957v1.
- 337 [4] O. Azzolini, et al., CUPID-0: the first array of enriched scintillating  
338 bolometers for  $0\nu\beta\beta$  decay investigations, *Eur. Phys. J. C* 78 (2018)  
339 428.
- 340 [5] E. Armengaud, et al., Development of  $^{100}\text{Mo}$ -containing scintillating  
341 bolometers for a high-sensitivity neutrinoless double-beta decay search,  
342 *Eur. Phys. J. C* 77 (2017) 785.
- 343 [6] D. V. Poda,  $^{100}\text{Mo}$ -enriched  $\text{Li}_2\text{MoO}_4$  scintillating bolometers for  $0\nu 2\beta$   
344 decay search: from LUMINEU to CUPID-0/Mo projects, *AIP Conf.*  
345 *Proc.* 1894 (2017) 020017.
- 346 [7] C. Bobin, et al., Alpha/gamma discrimination with a  $\text{CaF}_2(\text{Eu})$  target  
347 bolometer optically coupled to a composite infrared bolometer, *Nucl.*  
348 *Instrum. Meth. A* 386 (1997) 453.
- 349 [8] A. Alessandrello, et al., A scintillating bolometer for experiments on  
350 double beta decay, *Phys. Lett. B* 420 (1998) 109.
- 351 [9] P. Meunier, et al., Discrimination between nuclear recoils and elec-  
352 tron recoils by simultaneous detection of phonons and scintillation light,  
353 *Appl. Phys. Lett.* 75 (1999) 1335.
- 354 [10] S. Pirro, et al., Scintillating double-beta-decay bolometers, *Phys. At.*  
355 *Nucl.* 69 (2006) 2109.
- 356 [11] S. Pirro, P. Mauskopf, Advances in bolometer technology for fundamen-  
357 tal physics, *Annu. Rev. Nucl. Part. Sci.* 67 (2017) 161.
- 358 [12] D. V. Poda, A. Giuliani, Low background techniques in bolometers for  
359 double-beta decay search, *Int. J. Mod. Phys. A* 32 (2017) 1743012.

- 360 [13] F. Bellini, Potentialities of the future technical improvements in the  
361 search of rare nuclear decays by bolometers, *Int. J. Mod. Phys. A* 33  
362 (2018) 1843003.
- 363 [14] M. Stark, et al., Application of the Neganov-Luke effect to low-threshold  
364 light detectors, *Nucl. Instrum. Meth. A* 545 (2005) 738.
- 365 [15] G. Angloher, et al., Results from 730 kg days of the CRESST-II Dark  
366 Matter search, *Eur. Phys. J. C* 72 (2012) 197.
- 367 [16] T. Tabarelli de Fatis, Cerenkov emission as a positive tag of double beta  
368 decays in bolometric experiments, *Eur. Phys. J. C* 65 (2010) 359.
- 369 [17] C. Brofferio, S. Dell’Oro, The saga of neutrinoless double beta decay  
370 search with  $\text{TeO}_2$  thermal detectors, arXiv: 1801.03580.
- 371 [18] V. I. Tretyak, Y. G. Zdesenko, Tables of double beta decay data — an  
372 update, *At. Data Nucl. Data Tables* 80 (2002) 83.
- 373 [19] C. Alduino, et al., First Results from CUORE: A Search for Lepton  
374 Number Violation via  $0\nu\beta\beta$  Decay of  $^{130}\text{Te}$ , *Phys. Rev. Lett.* 120 (2018)  
375 132501.
- 376 [20] G. Wang, et al., CUPID: CUORE (Cryogenic Underground Obser-  
377 vatory for Rare Events) Upgrade with Particle IDentification, arXiv:  
378 1504.03599.
- 379 [21] G. Wang, et al., R&D towards CUPID (CUORE Upgrade with Particle  
380 IDentification), arXiv: 1504.03612.
- 381 [22] D. M. Chernyak, et al., Random coincidence of  $2\nu 2\beta$  decay events as a  
382 background source in bolometric  $0\nu 2\beta$  decay experiments, *Eur. Phys. J.*  
383 *C* 72 (2012) 1989.
- 384 [23] D. M. Chernyak, et al., Rejection of randomly coinciding events in  
385  $\text{ZnMoO}_4$  scintillating bolometers, *Eur. Phys. J. C* 74 (2014) 2913.
- 386 [24] D. M. Chernyak, et al., Rejection of randomly coinciding events in  
387  $\text{Li}_2^{100}\text{MoO}_4$  scintillating bolometers using light detectors based on the  
388 Neganov-Luke effect, *Eur. Phys. J. C* 77 (2016) 3.

- 389 [25] V. I. Tretyak, Beta decays in investigations and searches for rare effects,  
390 talk given at Int. Workshop MEDEX 2017, Prague, Czech Republic, 29  
391 May – 02 July 2017.
- 392 [26] J. T. Suhonen, Value of the Axial-Vector Coupling Strength in  $\beta$  and  
393  $\beta\beta$  Decays: A Review, *Front. Phys.* 5 (2017) 55.
- 394 [27] A. Leder, et al., Measurement of Quenched Axial Vector Coupling Con-  
395 stant in In-115 Beta Decay and its Impact on Future  $0\nu\beta\beta$  Searches,  
396 poster presented at the XXVIII International Conference on Neutrino  
397 Physics and Astrophysics (Neutrino 2018), Heidelberg, Germany, 4–9  
398 June 2018.
- 399 [28] B. Neganov, V. Trofimov, USSR patent no 1037771, *Otkrytia i Izo-*  
400 *breteniya* 146 (1985) 215.
- 401 [29] P. N. Luke, Voltage-assisted calorimetric ionization detector, *J. Appl.*  
402 *Phys.* 64 (1988) 6858.
- 403 [30] L. Hehn, et al., Improved EDELWEISS-III sensitivity for low-mass  
404 WIMPs using a profile likelihood approach, *Eur. Phys. J. C* 76 (2016)  
405 548.
- 406 [31] R. Agnese, et al., New Results from the Search for Low-Mass Weakly  
407 Interacting Massive Particles with the Low Ionization Threshold Exper-  
408 iment, *Phys. Rev. Lett.* 116 (2016) 071301.
- 409 [32] C. Isaila, et al., Scintillation light detectors with Neganov-Luke ampli-  
410 fication, *Nucl. Instrum. Meth. A* 559 (2006) 399.
- 411 [33] C. Isaila, et al., Low-temperature light detectors: Neganov-Luke ampli-  
412 fication and calibration, *Phys. Lett. B* 716 (2012) 160.
- 413 [34] M. Willers, et al., Neganov-Luke amplified cryogenic light detectors for  
414 the background discrimination in neutrinoless double beta decay search  
415 with  $\text{TeO}_2$  bolometers, *JINST* 10 (2015) P03003.
- 416 [35] X. Defay, et al., Cryogenic Silicon Detectors with Implanted Contacts  
417 for the Detection of Visible Photons Using the Neganov-Trofimov-Luke  
418 Effect, *J. Low Temp. Phys.* 184 (2016) 274.

- 419 [36] M. Biassoni, et al., Large area Si low-temperature light detectors with  
420 Neganov-Luke effect, *Eur. Phys. J. C* 75 (2015) 480.
- 421 [37] L. Gironi, et al., Cherenkov light identification with Si low-temperature  
422 detectors with sensitivity enhanced by the Neganov-Luke effect, *Phys.*  
423 *Rev. C* 94 (2016) 054608.
- 424 [38] L. Pattavina, et al., Background suppression in massive TeO<sub>2</sub> bolometers  
425 with Neganov-Luke amplified light detectors, *J. Low Temp. Phys.* 184  
426 (2016) 286.
- 427 [39] D. R. Artusa, et al., Enriched TeO<sub>2</sub> bolometers with active particle dis-  
428 crimination: Towards the CUPID experiment, *Phys. Lett. B* 767 (2017)  
429 321.
- 430 [40] L. Bergé, et al., Complete event-by-event  $\alpha/\gamma(\beta)$  separation in a full-size  
431 TeO<sub>2</sub> CUORE bolometer by Neganov-Luke-magnified light detection,  
432 *Phys. Rev. C* 97 (2018) 032501(R).
- 433 [41] M. Tenconi, Development of luminescent bolometers and light detectors  
434 for neutrinoless double beta decay search, Ph.D. thesis, Université Paris-  
435 Sud (2015).
- 436 [42] M. Mancuso, Development and optimization of scintillating bolome-  
437 ters and innovative light detectors for a pilot underground experiment  
438 on neutrinoless double beta decay, Ph.D. thesis, Université Paris-Sud  
439 (2016).
- 440 [43] V. Novati, Sensitivity enhancement of the CUORE experiment via the  
441 development of Cherenkov hybrid TeO<sub>2</sub> bolometers, Ph.D. thesis, Uni-  
442 versité Paris-Saclay (2018).
- 443 [44] T. Shutt, et al., A solution to the dead-layer problem in ionization and  
444 phonon-based dark matter detectors, *Nucl. Instrum. Meth. A* 444 (2000)  
445 340.
- 446 [45] M. Mancuso, et al., An experimental study of antireflective coatings in  
447 Ge light detectors for scintillating bolometers, *EPJ Web Conf.* 65 (2014)  
448 04003.

- 449 [46] D. R. Artusa, et al., First array of enriched Zn<sup>82</sup>Se bolometers to search  
450 for double beta decay, *Eur. Phys. J. C* 76 (2016) 364.
- 451 [47] D. V. Poda, private communication.
- 452 [48] M. Mancuso, et al., An aboveground pulse-tube-based bolometric test  
453 facility for the validation of the LUMINEU ZnMoO<sub>4</sub> crystals, *J. Low*  
454 *Temp. Phys.* 176 (2014) 571.
- 455 [49] E. Olivieri, et al., Vibrations on pulse tube based Dry Dilution Refrig-  
456 erators for low noise measurements, *Nucl. Instrum. Meth. A* 858 (2017)  
457 73.
- 458 [50] S. Pirro, Further developments in mechanical decoupling of large ther-  
459 mal detectors, *Nucl. Instrum. Meth. A* 559 (2006) 672.
- 460 [51] C. Lee, et al., Vibration isolation system for cryogenic phonon-  
461 scintillation calorimeters, *JINST* 12 (2017) C02057.
- 462 [52] R. Maisonobe, et al., Vibration decoupling system for massive bolome-  
463 ters in dry cryostats, *JINST* 13 (2018) T08009.
- 464 [53] E. Olivieri, et al., Space-and-surface charge neutralization of cryogenic  
465 Ge detectors using infrared LEDs, *AIP Conf. Proc* 1185 (2009) 310.
- 466 [54] A. Alessandrello, et al., A programmable front-end system for arrays of  
467 bolometers, *Nucl. Instrum. Meth. A* 444 (2000) 111.
- 468 [55] L. D. Landau, On the energy loss of fast particles by ionization, *J. Phys.*  
469 (USSR) 8 (1944) 201.
- 470 [56] S. Koc, The quantum efficiency of the photo-electric effect in germanium  
471 for the 0.3–2  $\mu$  wavelength region, *Czechosl. J. Phys.* 7 (1957) 91.
- 472 [57] N. Casali, Model for the Cherenkov light emission of TeO<sub>2</sub> cryogenic  
473 calorimeters, *Astropart. Phys.* 91 (2017) 44.
- 474 [58] Mankiewicz NEXTEL<sup>®</sup> 3M, velvet-coating 811-21 and hardener 5524.