EDELWEISS/RICOCHET

Joint project for Direct Dark Matter search and precision study of CEνNS with new cryogenic detectors

JINR group

V. Belov, V. Brudanin, Yu. Gurov, A. Inoyatov, B. Kalinova, D. Karaivanov, S. Kazarcev, J. Khushvaktov, A. Lubashevskiy, S. Evseev, V. Evsenkin, D. Filosofov, N. Mirzaev, L. Perevoshikov, D. Ponomarev, A. Rakhimov, I. Rozova, S. Rozov, A. Salamatin, K. Shakhov, N. Temerbulatovs, V. Trofimov, Yu. Vaganov, V. Volnykh and E. Yakushev

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Form No. 24

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EDELWEISS/Ricochet

CODE OF THEME 03-2-1100-2010/2021

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NAME OF PROJECT DEPUTY LEADERS: S. Rozov (rozovs@jinr.ru)

DATE OF SUBMISSION OF PROPOSAL OF PROJECT TO SOD _________

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Форма № 24

Объединенный проект прямого поиска темной материи и прецизионного исследования CEvNS с новыми криогенными детекторами

Проект EDELWEISS/Ricochet

ШИФР ТЕМЫ 03-2-1100-2010/2021

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ДАТА ПРЕДСТАВЛЕНИЯ ПРОЕКТА В НОО _________

ДАТА НТС ЛАБОРАТОРИИ 5 ноября 2020 НОМЕР ДОКУМЕНТА 2020-11

ДАТА НАЧАЛА ПРОЕКТА EDELWEISS/RICOCHET: __январь 2022________________

(ДАТА ПЕРВОГО УТВЕРЖДЕНИЯ ПРОЕКТА (EDELWEISS-II) на НТС ЛЯП): 4 декабря 2005

Форма № 25

ЛИСТ СОГЛАСОВАНИЙ ПРОЕКТА

ПОЛНОЕ НАЗВАНИЕ ПРОЕКТА: Объединенный проект прямого поиска темной материи и прецизионного исследования CEvNS с новыми криогенными детекторами

УСЛОВНОЕ ОБОЗНАЧЕНИЕ ПРОЕКТА ИЛИ КОЛЛАБОРАЦИИ: EDELWEISS/ Ricochet

ШИФР ТЕМЫ 03-2-1100-2010/2021

ФИО РУКОВОДИТЕЛЯ ПРОЕКТА: Якушев Евгений Александрович

УТВЕРЖДЕН ДИРЕКТОРОМ ОИЯИ

СОГЛАСОВАНО	ПОДПИСЬ	ДАТА
ВИЦЕ-ДИРЕКТОР ОИЯИ		
ГЛАВНЫЙ УЧЕНЫЙ СЕКРЕТАРЬ		
ГЛАВНЫЙ ИНЖЕНЕР		
НАЧАЛЬНИК НОО		
ДИРЕКТОР ЛАБОРАТОРИИ		20.11.2020
ГЛАВНЫЙ ИНЖЕНЕР ЛАБОРАТОРИИ		20.11.2020
РУКОВОДИТЕЛЬ ПРОЕКТА		18-11.2020
ЗАМ. РУКОВОДИТЕЛЯ ПРОЕКТА		18.11.2020

ОДОБРЕН

ПКК ПО НАПРАВЛЕНИЮ

Form No. 25

PROJECT ENDORSEMENT LIST

Joint project for Direct Dark Matter search and precision study of CEvNS with new cryogenic detectors

EDELWEISS/Ricochet

CODE OF THEME 03-2-1100-2010/2021

NAME OF PROJECT LEADER: Evgeny Yakushev

APPROVED BY JINR DIRECTOR

ENDORSED BY	SIGNATURE	DATE
JINR VICE-DIRECTOR		
CHIEF SCIENTIFIC SECRETARY		
CHIEF ENGINEER		
HEAD OF SCIENCE ORGANIZATION DEPARTMENT		
LABORATORY DIRECTOR	[signature]	20.11.2020
LABORATORY CHIEF ENGINEER	[signature]	20.11.2020
PROJECT LEADER	[signature]	18.11.2020
PROJECT DEPUTY LEADERS	[signature]	18.11.2020

ENDORSED

RESPECTIVE PAC

Form No. 26

Schedule proposal and resources required for the implementation of the Project

EDELWEISS/Ricochet

<table>
<tr><th colspan="3" rowspan="2">List of parts and devices; Resources; Financial sources</th><th rowspan="2">Cost of parts (K US$), resources needs</th><th colspan="3">Allocation of resources and money</th></tr>
<tr><th>1st year</th><th>2nd year</th><th>3rd year</th></tr>
<tr><td rowspan="7">Main parts and equipment</td><td colspan="2">1. Materials required for tests of low threshold detectors (shielding, veto system, etc). Equipments for the clean room.</td><td>45</td><td>15</td><td>15</td><td>15</td></tr>
<tr><td colspan="2">2. Spectroscopic electronics. Low background iodine containing neutron detectors.</td><td>45</td><td>15</td><td>15</td><td>15</td></tr>
<tr><td colspan="2">3. Materials and equipments for the Ricochet cryosystem.</td><td>65</td><td>50</td><td>10</td><td>5</td></tr>
<tr><td colspan="2">4. Materials and equipment for maintenance of JINR EDELWEISS detectors (three neutron detectors, two radon detectors, alpha spectrometer, HPGe spectrometers).</td><td>30</td><td>10</td><td>10</td><td>10</td></tr>
<tr><td colspan="2">5. Materials and equipment for calibration purposes. It includes making of new radioactive source. Radiochemistry equipment.</td><td>15</td><td>5</td><td>5</td><td>5</td></tr>
<tr><td colspan="2">6. Materials and equipments for R&D at JINR (electronics, clean room materials, laboratory equipments)</td><td>70</td><td>20</td><td>20</td><td>30</td></tr>
<tr><td colspan="2">Total</td><td>270</td><td>115</td><td>75</td><td>80</td></tr>
<tr><td rowspan="2">Resources</td><td rowspan="2">Norm-hours</td><td>JINR workshop</td><td>3300</td><td>1100</td><td>1100</td><td>1100</td></tr>
<tr><td>DLNP workshop</td><td>1500</td><td>500</td><td>500</td><td>500</td></tr>
<tr><td rowspan="2">Financial sources</td><td>JINR budget</td><td>Budget spending</td><td>270</td><td>115</td><td>75</td><td>80</td></tr>
<tr><td>Off-budget sources</td><td>Grants;
Other sources
(these funds are not currently guaranteed)</td><td>30</td><td>10</td><td>10</td><td>10</td></tr>
</table>

PROJECT LEADER E. Yakushev

Форма № 26

Предлагаемый план-график и необходимые ресурсы для осуществления проекта EDELWEISS/Ricochet

Наименование узлов и систем установки, ресурсов, источников финансирования			Стоимость узлов (тыс.$) установки. Потребности в ресурсах	Предложения Лабораторий по распределению финансирования и ресурсов		
				1 год	2 год	3 год
Основные узлы и оборудование	1. Материалы для тестирования низкопороговых детекторов (защита, вето система и т.д.). Оборудование чистой комнаты.		45	15	15	15
	2. Спектрометрическая электроника. Низкофоновые нейтронные спектрометры на основе йодсодержащих детекторов.		45	15	15	15
	3. Материалы и оборудование для криогенной системы Ricochet		65	50	10	5
	4. Материалы и оборудование для поддержания работоспособности детекторов, находящихся под нашим управлением в EDELWEISS и Ricochet (3 нейтронных детектора, 2 радоновых детектора, альфа-спектрометр, HPGe спектрометры)		30	10	10	10
	5. Материалы и оборудование для проведения калибровок, включая создание калибровочных источников. Радиохимическое оборудование.		15	5	5	5
	6. Материалы и оборудование для проведения R&D в ЛЯП (электроника, материалы для чистой комнаты, оборудование лабораторий).		70	20	20	30
	Итого		**270**	**115**	**75**	**80**
Необходимые ресурсы	Нормо-часы	ОП ОИЯИ	3300	1100	1100	1100
		ООЭП ЛЯП	1500	500	500	500
Источники финансирования	Бюджет	Затраты из бюджета	**270**	**115**	**75**	**80**
	Внебюджетные средства	*Средства по грантам. Другие источники финансирования (получение данных средства в настоящее время не гарантировано)*	*30*	*10*	*10*	*10*

РУКОВОДИТЕЛЬ ПРОЕКТА Е.А. Якушев

Form No. 29

Estimated expenditures for the Project EDELWEISS/Ricochet, Joint project for Direct Dark Matter search and precision study of CEvNS with new cryogenic detectors

#	Designation for outlays	Total cost	1 year	2 year	3 year
	Direct expenses for the project				
1.	Networking	6.0K US$	2.0	2.0	2.0
2.	DLNP workshop	1500 norm-hours	500	500	500
3.	JINR workshop	3300 norm-hours.	1100	1100	1100
4.	Materials	75.0K US$	25.0	25.0	25.0
5.	Equipment	195.0K US$	90.0	50.0	55.0
6.	Collaboration fee	60.0K US$	20.0	20.0	20.0
7.	Travel expenses	75.0K US$	25.0	25.0	25.0
	Total	**411.0K US$**	**162.0K US$**	**122.0K US$**	**127.0K US$**

PROJECT LEADER

LABORATORY DIRECTOR

LABORATORY CHIEF ENGINEER-ECONOMIST

Форма № 29

Смета затрат по проекту EDELWEISS/Ricochet, Объединенный проект прямого поиска темной материи и прецизионного исследования CEvNS с новыми криогенными детекторами

№№ пп	Наименование статей затрат	Полная стоимость	1 год	2 год	3 год
	Прямые затраты на Проект				
1.	Компьютерная связь	6.0K US$	2.0	2.0	2.0
2.	ООЭП ЛЯП	1500 норм ч.	500	500	500
3.	ОП ОИЯИ	3300 норма ч.	1100	1100	1100
4.	Материалы	75.0K US$	25.0	25.0	25.0
5.	Оборудование	195.0K US$	90.0	50.0	55.0
6.	Взнос в коллаборацию	60.0K US$	20.0	20.0	20.0
7.	Командировочные расходы	75.0K US$	25.0	25.0	25.0

Итого по прямым расходам 411.0K US$ 162.0K US$ 122.0K US$ 127.0K US$

РУКОВОДИТЕЛЬ ПРОЕКТА

ДИРЕКТОР ЛАБОРАТОРИИ

ВЕДУЩИЙ ИНЖЕНЕР-ЭКОНОМИСТ ЛАБОРАТОРИИ

1. Abstract

In direct searches for Dark Matter (DM) a technology developing by **EDELWEISS** experiment is arrays of Ge mono-crystal detectors operated at a temperature of few mK and equipped with electrodes and thermal sensors. Applying a small (few V/cm) external field, a simultaneous measurement of ionization and heat signals allows efficient identification of nuclear and electron recoils. New results demonstrated the high relevance of cryogenic Ge detectors for the search of DM interactions producing eV-scale signals. The region of "light WIMPs" will be further investigated in the EDELWEISS experiment thanks to advantage of energy resolution below 20 eV reachable with new array of HPGe bolometers. This stage is in the R&D phase, building of improved detectors, their holders and supports, improvement of the background and acquisition. The unlimited target of current R&D and measurements in the EDELWEISS experiment is achievement of sensitivity allowing detection of B-8 solar neutrinos through coherent elastic neutrino-nucleus scattering (CEvNS). The same technology and detectors will be applied for precision measurements of CEvNS in the region of full coherency in the **Ricochet** experiment (reactor neutrinos). Due to direct energy reconstruction (heat signal) the main uncertainty arising due to not well known quenching in germanium will be avoided. 1 kg of new cryogenic detectors (developing thanks to joint R&D of EDELWEISS and Ricochet teams) will be integrated in the Ricochet cryostat. The Ricochet is going to be deployed at ILL (Grenoble, France) site, on a distance at about 8 m from the 58 MW nuclear reactor, with first results expected to 2025. In addition to the main goal: precise (1% level) study of CEvNS the experiment will target NMM and other New physics phenomena. Possibility of further phases of the experiment at a Nuclear power plant (a 3.2 GW reactor) at Russia is under investigation.

2. Introduction

The project is continuation of the EDELWEISS scientific program conducting by JINR in the international collaboration. In the same time, during the new phase use of the unique detectors developed originally for direct dark matter search will be extended to precise investigation of the Coherent Elastic Neutrino(ν)-Nucleus Scattering (CEνNS) process to search for new physics in the electroweak sector. This project is named Ricochet. Both projects will be conducted with huge overlap in conducted R&Ds (detectors), man power, infrastructure (the main one is the EDELWEISS setup and other equipment at the LSM underground laboratory).

Both projects have aims to search for new physics:

- Since there are no Dark Matter particles in the Standard Model, their search in a wide mass region is simultaneously an important test for new physics (EDELWEISS).
- Percentage-level precision to CEνNS planning in Ricochet, leading to unprecedented sensitivity to various exotic physics scenarios (see appendix 1).

Recently achieved in the EDELWEISS an unprecedented energy resolution below 20 eV together with excellent background discrimination revealed that cryogenic HPGe detector based experiments are uniquely well suited to probe the CEνNS process at the lowest energies, i.e. in the near zero (10) eV energy-range, where new physics signatures are expected to arise. Indeed, the overwhelming advantage of bolometers, compared to any other detection techniques, is that the deposited energy from a neutrino-nucleus interaction is fully sensed, therefore they act as true calorimeters with almost no quenching effects. In the present time this is the only way for measurement of CEνNS with 1% precision or better.

The EDELWEISS experiment will continue its searches for evidence of direct WIMPs from Milky Way galaxy scattering of Ge nuclei within cryogenic Ge crystals. The main objective of the experiment is now shifted to the low-mass WIMPs region (1 GeV/c^2 and below). This region could be investigated in the experiment thanks to advantage of few tens eV energy resolution reachable with HPGe bolometers via the Neganov-Trofimov-Luke effect of internal amplification of the heat signal. Search of "light WIMPs" become especially motivated due to controversial results of some other experiments. Some theoretical models are also favorable to the "light WIMP" scenario. EDELWEISS detectors have an excellent background rejection performance and the energy resolution, thus can explore parameters of WIMPs and other possible candidates for dark matter in the region inaccessible with large Ar/Xe detectors.

JINR team is expected to contribute to the projects in the following: 1) Development of new low threshold Ge detectors; Assembly and commissioning; 2) New cryosystem development and running; 3) Development of methods for low background measurements; 4) Data taking (this includes daily routine procedures, as well as regular and special calibration runs); 5) Low background study and development of methods of neutron and radon detection; 6) Detector simulations and data analysis; Publication of results. 7) Preparation of a NPP site for possible further phases of the Ricochet project.

Participation in the project provides to JINR an important access to low background infrastructure needed for R&D of JINR neutrino experiments at the Kalinin NPP.

3. State-of-the-art of the science case proposed

Neutrinos and dark matter are two fundamental subjects of the modern physics. EDELWEISS/Ricochet joint project aims to yield results on the edge of the both problems applying newest bolometric detectors working in eV energy region. The base for the projects is detectors developed for current EDELWEISS-LT phase of the experiment directed to DM search.

There are strong evidences of the existence of non-baryonic dark matter (DM) at almost every cosmic scale [1,2]. Theories and simulations regarding hierarchical structure formation indicate that this non-luminous component may manifest itself in the form of a gas of Weakly Interacting Massive Particles (WIMPs) [3]. There is no viable candidate in the Standard Model for the composition of this cold DM. It is very intriguing that the most favored solution to the problem of hierarchy in particle physics, SUSY, predicts that the Universe is filled with WIMPs. Natural candidates, like the neutralino, have a predicted mass in the range of a few GeV/c^2 to TeV/c^2 and an elastic scattering cross section on nucleons at the weak scale [4]. Furthermore, they are characterized by a dominant interaction with atomic nuclei, inducing low-energy nuclear recoils in the target material, and could be thus detected in the so-called direct detection experiments [5]. There is an intense experimental activity on the direct detection since many years, for which the most promising results have been obtained with liquid noble and cryogenic detectors (see e.g. [6–14] and references therein).

Direct search for DM is the fundamental scientific problem addressed by the EDELWEISS. It searches for DM using an array of cryogenic germanium bolometers with phonon and ionization channels, it thus able to identify events induced by nuclear recoils. In the present time there is an increasing gain of interest for the search of low-mass WIMPs and other DM particles (axions, etc) arising on the one hand from no observation yet of SUSY at the LHC and on the other hand from new theoretical approaches favouring lighter candidates [15-17]. As an example, asymmetric DM models linking the relic density to the baryon asymmetry predict DM particles with masses of a few GeV/c^2 [18-20]. The EDELWEISS experiment originally designed for the search of WIMPs of O(100 GeV/c^2) has undergone a redirection of its strategy to optimization of used detectors for low-mass (light) WIMP searches. During the current phase un unprecedented charge resolution of 0.53 electron-hole pairs (RMS) has been achieved using the Neganov-Trofimov-Luke internal amplification [39, 40]. With this the experiment set the first Ge-based constraints on sub-MeV/c^2 DM particles interacting with electrons, as well as on dark photons down to 1 eV/c^2 [14]. These results demonstrate the high relevance of cryogenic Ge detectors for the search of DM interactions producing eV-scale electron signals. The region of "light WIMPs" could be further investigated in the EDELWEISS experiment thanks to advantage of energy resolution below 20 eV reachable with new HPGe bolometers. This stage is in the R&D phase, it is devoted to building of improved detectors, their holders and supports, improvement of the background and acquisition. The EDELWEISS experiment is installed in the deep underground laboratory, the Laboratoire Souterrain de Modane (LSM). Its detectors cooled down to cryogenic temperatures (~20 mK) in order to perform a simultaneous measurement of ionization and heat signals. Charge collection is carried out by concentric electrodes interleaved on all the absorber surfaces. The readout of the four types of electrodes allows fiducial selection of events and results in a crucial background rejection for surface α- and β-events. The unlimited target of current R&D and measurements in the EDELWEISS experiment is achievement of sensitivity to light WIMPs, that will also allow detection of B-8 solar neutrinos through coherent neutrino-nucleus scattering (CEvNS). The same technology will be applied for precision measurements of CEvNS in the region of full coherency (reactor neutrinos – Ricochet experiment). Thanks to direct energy reconstruction (heat signal) the main uncertainty due to quenching will be avoided.

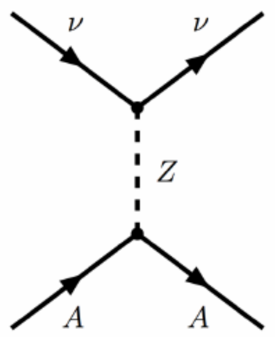


Fig. 3.1: *Feynman diagram of the CENNS process as predicted by the SM [21].*

The measurement of CEvNS has been a holy grail in neutrino physics since its prediction almost 40 years ago [21] see Fig. 3.1. This elastic scattering process, inducing sub-keV nuclear recoils, proceeds via the neutral weak current and benefits from a coherent enhancement proportional to the square of the number of nucleons A^2, suggesting that even a kg-scale experiment will observe a sizable neutrino signal. This opens the possibility to probe the neutrino sector with orders of magnitude smaller experiments than current and planned kiloton-scale ones with a new approach. The full coherence condition, when the wavelength of the scattering is longer than the size of the nucleus, is guaranteed for nearly all nuclear targets when neutrino energies are below ~10 MeV. Such neutrinos are produced in copious amounts in the Sun, and at nuclear power and research reactors.

The search for physics beyond the Standard Model with CEvNS requires to measure with the highest level of precision the lowest energy range of the induced nuclear recoils, as most new physics signatures induce energy spectral distortions in the sub-100 eV region. By providing the first percentage-level precision CEvNS measurement down to $O(10)$ eV, thanks to next generation cryogenic bolometers with unprecedented low-energy threshold and background rejection capabilities, the Ricochet collaboration proposes to go far beyond simply completing the Standard Model picture by testing various exotic physics scenarios (see Appendix 1). These include for instance the existence of sterile neutrinos and of new mediators, which could be related to the long lasting Dark Matter (DM) problem, and the possibility of Non-Standard Interactions (NSI) that would dramatically affect our understanding of the electroweak sector.

Thanks to its exceptionally rich science program, CEvNS has led to significant worldwide experimental efforts, over the last decades, with several ongoing and planned dedicated experiments based on a host of techniques. Most of these experiments are, or will be, located at nuclear reactor sites producing low-energy neutrinos (~3 MeV): CONNIE using Si-based CCDs [22]; TEXONO [23], νGeN [24] and CONUS [25] using ionization-based Ge semiconductors; and MINER [26], NuCLEUS [27] using cryogenic detectors. Only the COHERENT experiment [28] is looking at higher neutrino energies (~30 MeV) as produced by the Spallation Neutron Source (SNS) at Oak Ridge. In August 2017, the COHERENT experiment has reported the first CEvNS detection at the 6.7-sigma level. Even though this first detection has only limited sensitivity to new physics, as most new physics signatures will arise in the sub-100 eV region, COHERENT has proven the existence of this new neutrino detection channel that opens the door to a myriad of new scientific opportunities that we wish to explore with Ricochet.

Ongoing and planned cryogenic CEvNS experiments

We hereafter focus only on cryogenic detector based experiments as they are uniquely well suited to probe the CEvNS process at the lowest energies, where new physics signatures are expected to arise (see Appendix 1: New Physics with CEvNS). Indeed, the overwhelming advantage of bolometers, compared to any other detection techniques, is that the deposited energy from a neutrino-nucleus interaction is fully sensed, therefore they act as true calorimeters with almost no quenching effects. Based on this unique characteristic, MINER, NuCLEUS and Ricochet are new CEvNS bolometer-based experiments being developed in the wake of the long experience of cryogenic direct dark matter detection experiments CDMS, CRESST and EDELWEISS respectively. We give hereafter a brief description of MINER and NuCLEUS, as Ricochet will be further detailed in the next section.

MINER is a cryogenic bolometer-based experiment that is located at the 1 MW thermal power research reactor from the Mitchell Institute in Texas [26]. The experiment will use Si and Ge bolometers with a total target mass of 10 kg combined with a projected energy threshold of about 100 eV with no background discrimination. The great originality of this project is that the core is movable such that the distance between the core and the detectors can vary from 2 to 10 meters.

NuCLEUS is a gram to kg scale planned cryogenic bolometer-based experiment that will be deployed at the Chooz power plant, 80 meters away from the two 4.25 GWth reactor cores [29]. It will use a combination of $CaWO_4$ and Al_2O_3 detectors with an assembly of vetoing detectors to provide fiducialization and therefore reject both internal and external. The NuCLEUS strategy is to focus primarily on lowering the energy threshold, at the cost of drastically reducing the size of the individual bolometers. They are therefore planning to go with two phases of 10 g and 1 kg, that should start in 2022 and 2024 respectively, to reach a high precision measurement.

4. Main results for the previous implementation period

Identification of a WIMP or neutrino induced interactions in a detector is a challenging task, owing to the rate of expected interactions being very small compared to the event rates expected from background radioactivity of present detectors with highest purity and from cosmic radiation. In addition, the recoil energies are very small, in the range of eV to a few tens of keV.

In the early 1980s, a number of groups began researching cryogenic detectors, operating in the millikelvin temperature range, for applications in neutrino physics and DM searches. After over two decades of development, the technique has matured and there are numerous science results that have been obtained with cryogenic detectors. These results cover a wide range of topics: contributions to x-ray astronomy, the spectrometry of heavy biomolecules, the detection of extremely rare events (*e.g.*, neutrino-less double beta decay), several DM results, and finally neutrino investigation with CEvNS. The main reason for beginning an intense technology development program more than twenty years ago was the clearly identified need for lower energy threshold and better energy resolution in massive detectors for rare event searches. Cryogenic detectors were, and are, considered to be a most promising technique, requiring only milli-eV for producing a countable information carrier, compared with ~3 eV for semiconductor detectors and in the region of ~100 eV for scintillators. Consequently, at an energy of 5.89 keV (^{55}Fe source), the energy resolutions obtained are 3.2 eV (Si-thermistors) and 3.9 eV (Ti/Au TES) for small cryodetectors. This can be compared to resolutions of ~2000 eV for NaI-Tl scintillators. The good energy resolution is a top priority for low mass WIMP (and other light DM particles) search and for precision measurement of CEvNS.

The EDELWEISS scientific programs started as experiment directed to search for WIMP DM using natural HPGe detectors. The EDELWEISS detectors are cryogenic (work temperature is about 20 mK) Ge bolometers with simultaneous measurement of phonon and ionization signals. The comparison of the two signals provides a highly efficient event-by-event discrimination between nuclear recoils (induced by WIMP and also by neutron scattering) and electrons. For the past 25 years EDELWEISS is the leading experiment for direct Dark Matter search with Germanium detectors.

In the present time there is an increasing gain of interest for the search of low-mass WIMPs (with mass below 10 GeV/c^2) arising on the one hand from non evidence yet for SUSY at the LHC and on the other hand from new theoretical approaches favoring lighter candidates [16-18]. Thermal relics in this mass range are somewhat disfavored both from constraints set by Fermi-LAT searches for annihilation signals in dwarf galaxies [30], and from the impact that WIMP annihilation would leave on the cosmic microwave background anisotropies [31]. However, many scenarios have been proposed where the evolution of the "dark" and "visible" sectors in the early Universe are such that the relic DM number density is naturally close to the baryon density [32-34]. The current measurements of the corresponding mass densities then imply that m_W ~ 5 GeV/c^2, which is thus definitely become the desired subject of experimental search. EDELWEISS cryogenic bolometers with excellent energy resolutions is then a natural choice for investigation of low mass WIMP region.

Reducing detection thresholds is a common objective shared by all DM experiments as the theoretical recoil energy spectrum falls typically with an exponential behavior. It is compulsory for low-mass WIMP searches as the spectrum is increasingly softer as the WIMP mass gets lower. The Neganov-Trofimov-Luke [39,40] boost is used in the current EDELWEIS detectors to lower thresholds by amplifying the signal through the application of high voltage biases on collecting electrodes.

In 2019-2020, new experimental results were mainly associated with the development of unique low-threshold detector bolometers that allow detecting nuclear recoils from extremely low energies of ~20 eV. Such parameters were achieved thanks to: 1) internal signal amplification with using the Trofimov-Neganov-Luke effect; 2) the use high electron mobility transistors (HEMT); 3) a special suspension system for detectors in the holders, which reduces the influence of cryostat vibrations associated with operating cryocoolers.

At the first stage a number of tests were performed at "on ground" laboratory with new dry dilution cryostat that become a prototype to now developing cryosystem of the Ricochet setup. The cryostat is a Hexadry-200 commercially available from Cryoconcept [35], which has been upgraded to reduce the vibration levels of the mixing chamber by mechanically decoupling the cold head of the pulse tube cryocooler from the dilution unit [36]. The vibrations at the detector level were further mitigated with the use of a dedicated suspended tower [37]. The latter consists in a 25-cm-long elastic pendulum, attached to the 1 K stage by a Kevlar string and a stainless steel spring, holding the detector tower situated below the mixing chamber at 10 mK. The detector tower is thermally anchored to an intermediate holding structure, via supple copper braids, which also hosts the connectors for the detector readout. This suspended tower design significantly reduces detector vibrations, with displacements in the order of a few nanometers (rms) in all three axes, leading to substantial gains in energy resolutions. This was verified with the energy calibration by the use of a low-energy X-ray ^{55}Fe source irradiating the bottom side of the Ge crystal, opposite to the Ge-NTD heat sensor, inducing an interaction rate of ∼0.3 Hz. The ^{55}Fe source produces two lines corresponding to the K_α and K_β lines of Mn at 5.90 and 6.49 keV, respectively. They are clearly visible on the left panel of Fig. 4.1, showing the calibrated energy as a function of time over the 137-hour acquisition period. The energy resolution of these peaks is 34 eV (rms).

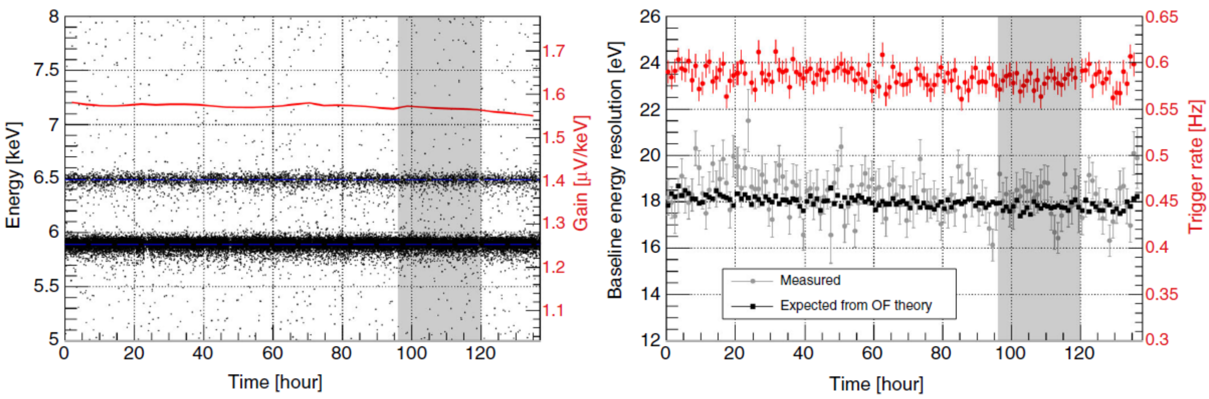


Fig. 4.1: *Left: Event energy distribution between 5 and 8 keV as a function of time. The horizontal bands at 5.90 and 6.49 keV correspond to the Kα and Kβ x-ray lines, respectively, of Mn emitted by the* ^{55}Fe *source. The data have been corrected for the measured time evolution of the detector gain as a function of time, shown as the red line, and corresponding to the right-hand axis. Right: Baseline heat energy resolution (RMS) in eV as a function of time. The gray dots are the values derived from a fit to the energy distributions of the noise event selection, and the black squares are those derived from the ratio of the signal and noise PSDs. The corresponding trigger rates in hertz are shown as red dots. Each data point corresponds to one hour. The gray shaded region in both panels corresponds to the interval of the blinded dataset used for DM search.*

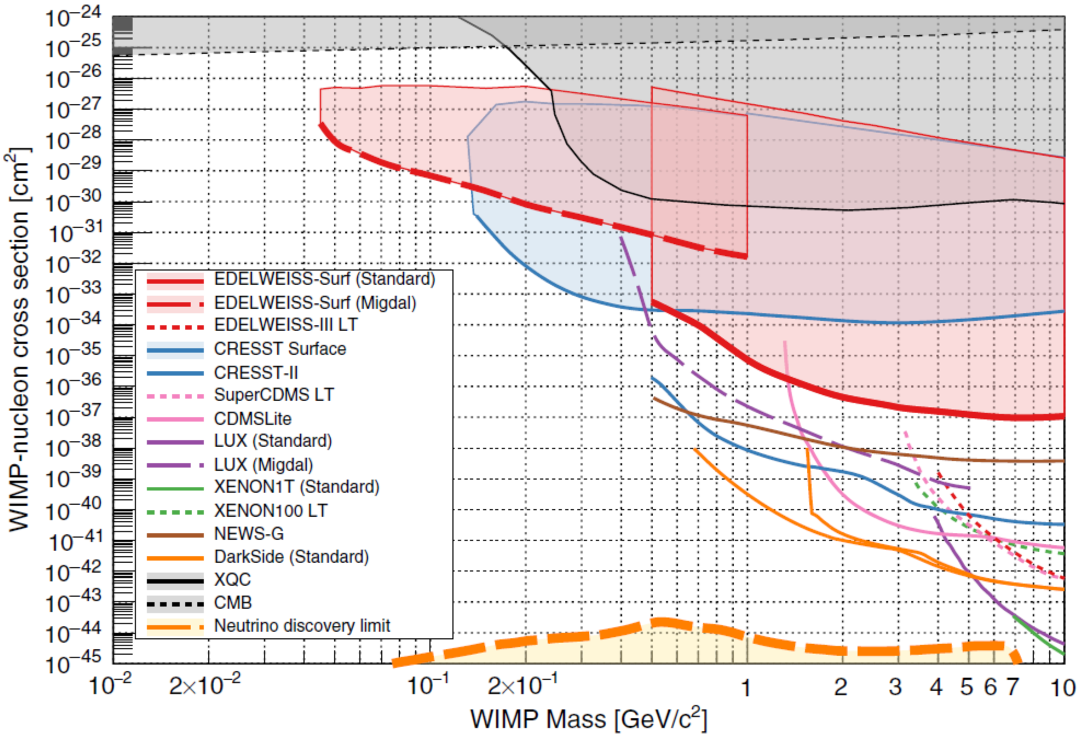


Fig. 4.2: *The 90% C.L. limits on the cross section for spin-independent interaction between a DM particle and a nucleon as a function of the particle mass. The thick solid red line corresponds to the result from the standard WIMP analysis. The associated red contour is obtained from the SIMP analysis, taking into account the slowing of the DM particle flux through the material above the detector. The thick dashed line and its accompanying red contour are obtained in the Migdal analysis. These results arecompared to those of other experiments (see text). Other results using the Migdal effect are shown as dashed lines. For more information and references see [38].*

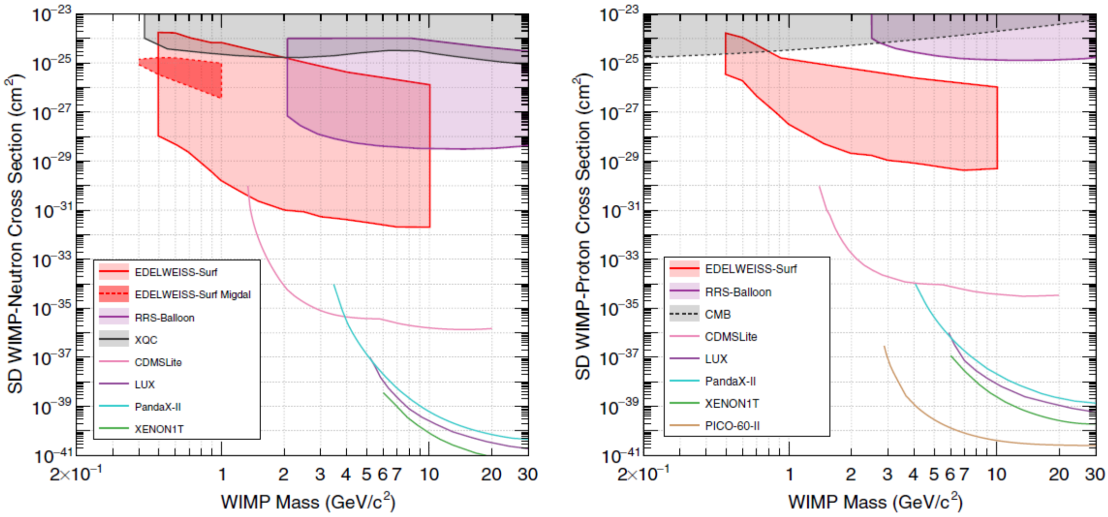


Fig. 4.3: *The 90% C.L. limits on the cross section for spin-dependent interactions assuming a dark matter coupling only to neutrons (left panel) and to protons (right panel) as a function of the particle mass obtained in the present work. The thick red lines and contours correspond to the presented surface dark matter search taking into account Earth-shielding effects and the so-called Migdal effect (dashed line) which is only relevant for the neutron SD coupling. These results are compared to those of other direct detection experiments available to the date of the result publication shown as solid lines: LUX (purple), XENON1T (green), PICO-60-II (brown), CDMSLite (pink), and PANDAX-II (blue). For more information and references see [38].*

From measurements with new detectors "on ground", new DM search results were obtained and published in 2019 [38] (Figs. 4.2 and 4.3). We searched for DM with masses between 45 MeV/c^2 and 10 GeV/c^2. The energy deposits were measured using a Ge-NTD thermal sensor with a 60 eV analysis threshold. This performance, combined with the nearly completely stationary behavior of the detector, led to the achievement of the first limit for the spin-independent interaction of sub-GeV WIMPs based on a germanium target. The experiment provides the most stringent, nuclear-recoil-based, above-ground limit on spin-independent interactions above 600 MeV/c^2. The search results were also interpreted in the context of SIMPs, taking into account the screening effect of the atmosphere and material surrounding the detector. The lower part of the excluded region for SIMPs represents the most stringent constraint for masses above 600 MeV/c^2. The upper part of the excluded region is limited by Earth shielding effects: it probes the largest SIMP-nucleon cross sections of any direct detection experiment, excluding a value of 10^{-27} cm^2 for a 1 GeV/c^2 WIMP. There are a number of complementary constraints on SIMP DM, including searches for DM annihilation to neutrinos; anomalous heating of Earth; heating of Galactic gas clouds; and DM-cosmic ray interactions. These typically require additional assumptions about the properties of the DM particle, while the EDELWEISS constraints depend only on its large scattering cross section with nuclei and its interactions near Earth. The dark matter search has also been extended to interactions via the Migdal effect, resulting in the exclusion for the first time of particles with masses between 45 and 150 MeV/c^2 with cross sections ranging from 10^{-29} to 10^{-26} cm^2. These limits also take fully into account the modeling of Earth-shielding effects essential for obtaining accurate constraints for such large cross section values. Finally, interpreted in terms of spin-dependent interactions with protons or neutrons, our results exclude new regions of the parameter space below masses of 1.3 GeV/c^2. In this case, atmospheric stopping is significant and has a strong effect on the derived exclusion limits, in particular for WIMP-proton interactions and the Migdal effect. The level of performance achieved during these test measurements also opens the possibility of a first experimental measurement of the Migdal effect using a neutron calibration source. Eventually, this level of detector performance, achieved in an above-ground laboratory with a 30 g-scale massive bolometer, become also very promising in the context of start the Ricochet scientific program for low energy and high-precision measurement of the coherent elastic neutrino-nucleus scattering process.

At the second stage, 11 different Ge new detectors with different designs were used at the LSM underground laboratory. Run at <21 mK continued since January 2019 to June 2020. In the same time rest of the EDELWEISS cryostat was used for joint physics run with CUPID-Mo $0\nu2\beta$ search (discussion of which is out of the subject of this document). Data analysis is continued. We compare detector physics in 32g, 200 g and 800g detectors. Compare performance of NTD and NbSi-TES heat sensors (Fig. 4.4). We were able to obtain near single-electron sensitivity on 33 and 200 g detectors. An unprecedented charge resolution of 0.53 electron-hole pairs (RMS) has been achieved using the Neganov-Trofimov-Luke internal amplification [14]. With preliminary data we set the first Ge-based constraints on sub-MeV/c^2 DM particles (Fig. 4.5 and 4.6) interacting with electrons, as well as on dark photons down to 1 eV/c^2. These are competitive with other searches and demonstrate the high relevance of cryogenic Ge detectors for the search of DM interactions producing eV-scale electron signals. Future context for the 2020-2021: EDELWEISS and Ricochet common R&D for detectors with even lower energy thresholds. The aim is to have 1 kg HPGe array with: 10 eV phonon resolution and 20 eVee ionization resolution.

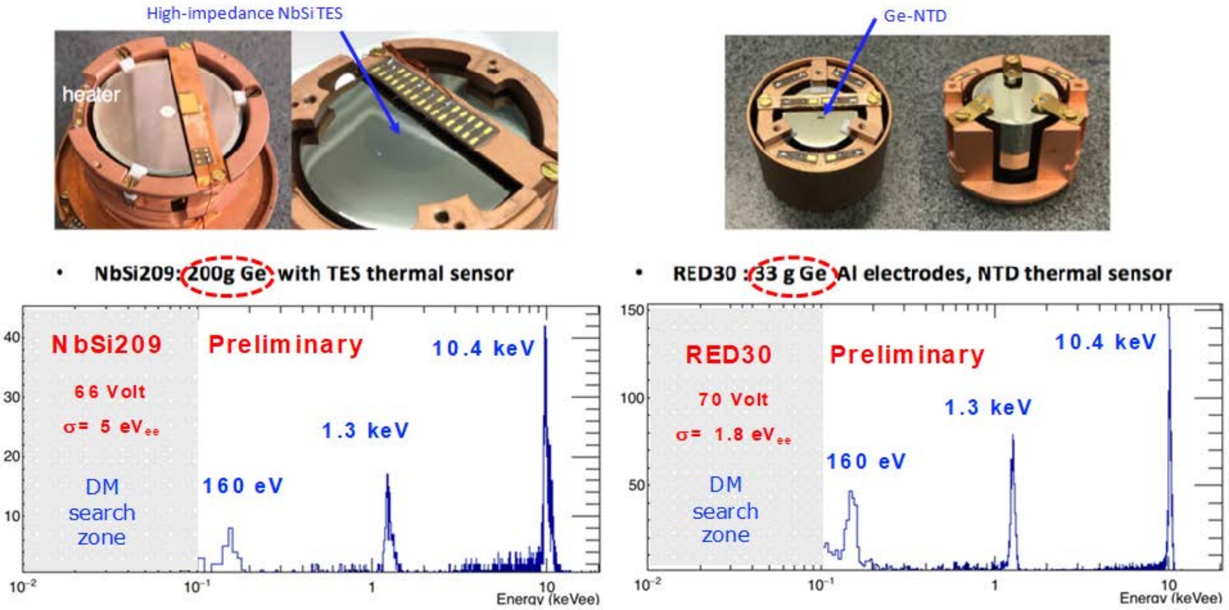


Fig. 4.4: *View of two significantly different EDELWEISS detectors and their energy calibration spectra. Near zero energy thresholds were achieved for both cases.*

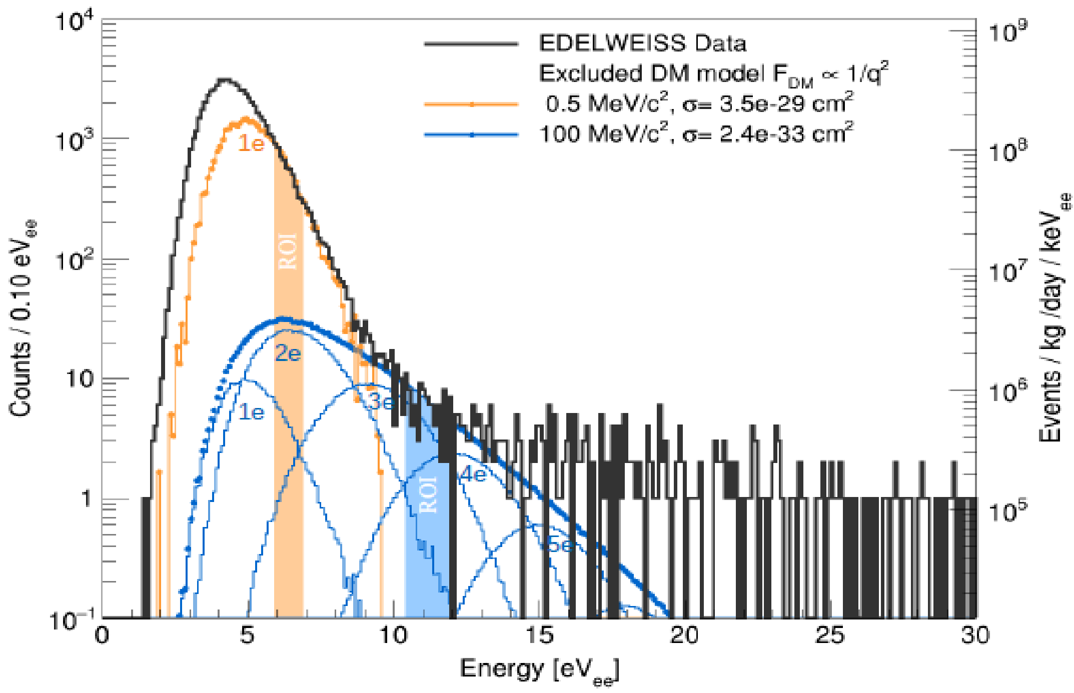


Fig. 4.5: *Energy spectrum of the events selected for the DM search (black) [14]. The thick blue (orange) histogram is the simulation of the signal excluded at 90% C.L. for a DM particle with a mass of 10 (0.5) MeV/c^2, and F_{DM} = 1/q^2. The thin-line histograms of the same color represent the individual contributions of 1 to 5 electron-hole pairs. The corresponding ROIs used to set the upper limits are shown as shaded intervals using the same color code.*

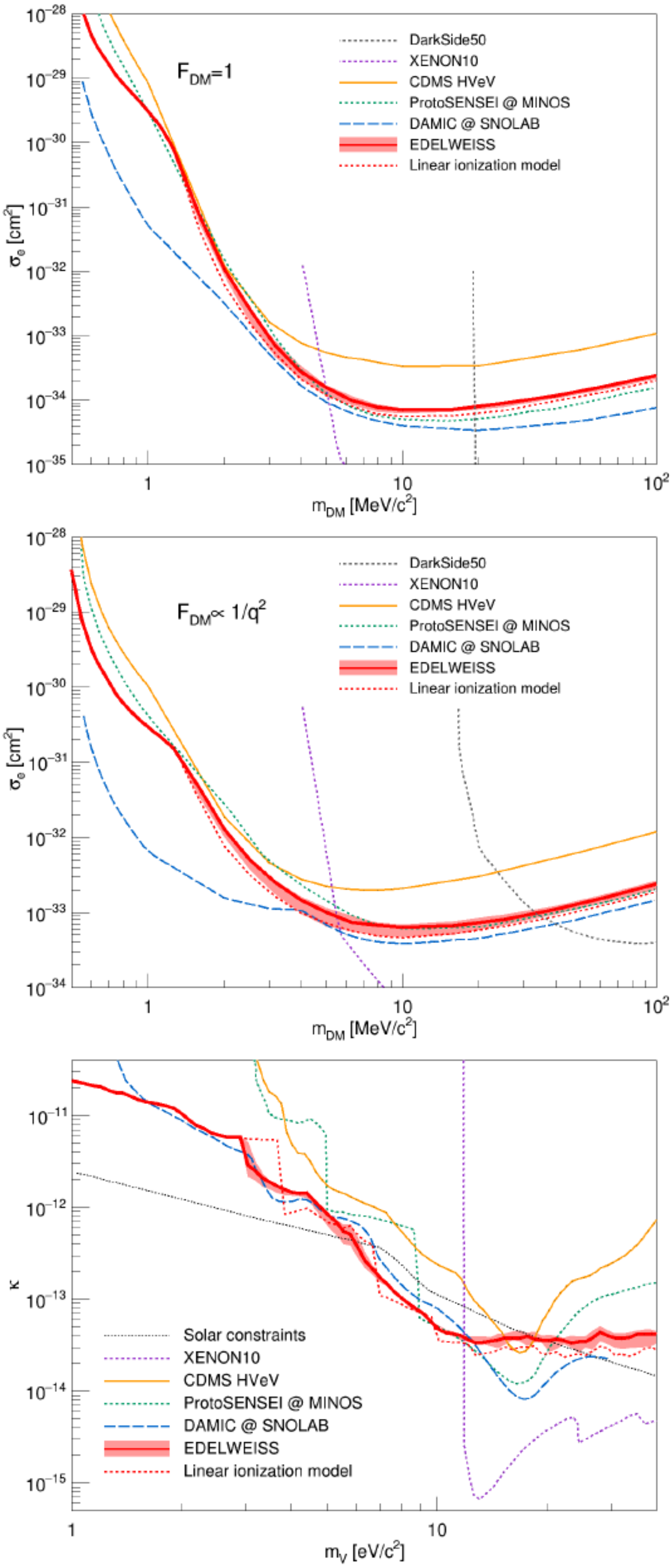


Fig. 4.6: *90% C.L. upper limit on the cross section for the scattering of DM particles on electrons, assuming a heavy (top panel) or light (middle panel) mediator. Bottom: 90% C.L. upper limit on the kinetic mixing of a dark photon. The EDELWEISS 2020 results are shown as the red line. The shaded red band and dotted red line represent alternative charge distribution models (see [14]). Also shown are constraints from other direct detection experiments and solar constraints (see [14] for references).*

The main result achieved during the current stage is connected to a number of intermediate "small" results that are not subject of this report. More details can be found in the EDELWEISS publications for last 5 years (2015-2020) listed below in the chronological order:

- NA Mirzayev et al, Low radioactive NH_4Cl flux, Journal of Instrumentation 15 (05), T05004, 2020
- Q Arnaud et al (EDELWEISS collaboration), First germanium-based constraints on sub-MeV Dark Matter with the EDELWEISS experiment, arXiv:2003.01046, 2020
- DV Ponomarev et al, Measuring Low Neutron Fluxes at the Modane Underground Laboratory Using Iodine-Containing Scintillators, Instruments and Experimental Techniques 62 (3), 309-311, 2019
- E Armengaud, et al (EDELWEISS collaboration), Searching for low-mass dark matter particles with a massive Ge bolometer operated above ground, Physical Review D 99 (8), 082003, 2019
- PS Fedotov, NN Fedyunina, DV Filosofov, EA Yakushev, G Warot, A novel combined countercurrent chromatography–inductively coupled plasma mass spectrometry method for the determination of ultra trace uranium and thorium in Roman lead, Talanta 192, 395-399, 2019
- E Armengaud, et al (EDELWEISS collaboration), Searches for electron interactions induced by new physics in the EDELWEISS-III germanium bolometers, Physical Review D 98 (8), 082004, 2018
- Q Arnaud, et al (EDELWEISS collaboration) Optimizing EDELWEISS detectors for low-mass WIMP searches, Physical Review D 97 (2), 022003, 2018
- E Armengaud, et al (EDELWEISS collaboration), Measurement of the cosmogenic activation of germanium detectors in EDELWEISS-III, Astroparticle Physics, 91, 2017, 51-64
- E Armengaud, et al (EDELWEISS collaboration) Performance of the EDELWEISS-III experiment for direct dark matter searches, Journal of Instrumentation, 12, 08, P08010, 2017, arXiv preprint arXiv:1706.01070
- L Hehn, et al (EDELWEISS collaboration) Improved EDELWEISS-III sensitivity for low-mass WIMPs using a profile likelihood approach, 2016, The European Physical Journal C 76 (10), 548
- E Armengaud, et al (EDELWEISS collaboration) Constraints on low-mass WIMPs from the EDELWEISS-III dark matter search, 2016, Journal of Cosmology and Astroparticle Physics 2016 (05), 019
- AV Rakhimov, et al, Neutron activation analysis of polyethylene from neutron shield of EDELWEISS experiment, Radiochimica Acta 103 (9), 673-678, 2015

During participation of JINR in the EDELWEISS program the most cited (more than 300 times) article is: E Armengaud et al. “Final results of the EDELWEISS-II WIMP search using a 4-kg array of cryogenic germanium detectors with interleaved electrodes”. Phys.Lett. B702 (2011), pp. 329–335. arXiv: 1103.4070 [astro-ph.CO]

5. Description of the proposed research

The EDELWEISS/Ricochet are going to use jointly developed cryogenic detectors in two setups: in the LSM underground laboratory, and near the ILL nuclear research reactor. Measurements at LSM are going to provide data about an ideal background and DM search. It has to be mentioned that in own turn the Ricochet data are going to clarify the CEνNS' background for DM searches. The Ricochet will use new cryogenic setup, so-called dry ^3He-^4He dilution cryostat, that is not required any helium and nitrogen refills for many years. Such a test cryostat has been already used for the current R&D phase and demonstrated its applicability for planned research [38]. There are plans to eventually replace current LSM underground setup with such new technology cryosystem, with an aim to reduce low level noises and radioactive backgrounds.

The cryogenic detectors

The EDELWEISS/Ricochet detectors are designed to provide the first percentage precision CEνNS measurement in the sub-100 eV energy region to search for new physics in the electroweak sector and to be competitive with low-mass DM searches in eV mass range. Therefore, they have to fulfill the following specifications:

- Energy thresholds in the $O(10)$ eV range, as the discovery potential scales exponentially with lowering the energy threshold;
- Significant background rejection combined with a low-radioactivity environment, as the experiment's sensitivity scales linearly with the signal-to-noise ratio;
- Total target mass of about one kilogram to have significant sensitivity to new physics signatures in both cases (DM and CEνNS).
- Accommodation of several monolithic target materials, as most new physics signatures, such as Non-Standard Interactions, depend on the target's nuclear properties.

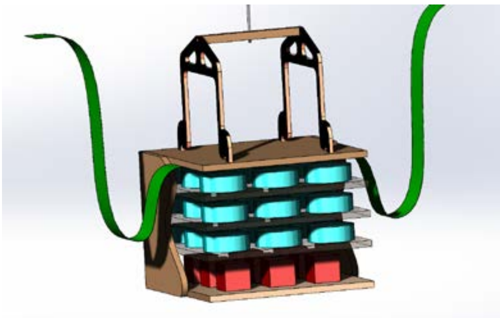


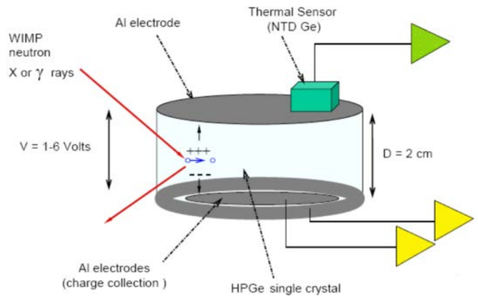
Fig. 5.1: *Cryogenic detector assembly suspended below the inner shielding – CryoCube with its 27 Ge crystals (blue) and the Q-Array with its 9 Zn crystals (red) – suspended below the inner shielding.*

Two detector technologies will be used: cryogenic Ge-semiconductors and Zn-superconducting metals, which are both well suited to provide electromagnetic background discrimination at the lowest energies. Figure 5.1 shows a simplified design of the Ricochet cryogenic detector assembly. It consists of a total array of 36 bolometers of about 30 g each, leading to a total payload of 1.3 kg, and divided among two sub-arrays: the CryoCube (27 Ge-crystals) and the Q-Array (9 Zn). The crystals from the two detector arrays will be packed together and encapsulated in radio-pure infrared-tight copper box suspended below the inner shielding with its dedicated cryogenic suspension system and cold front end electronics.

Ge semi-conductor

In semiconductor bolometers, the rejection between backgrounds and WIMP or CEνNS-signal events will be achieved thanks to the double measurement of the heat and ionization energies, which ratio depends on the nature of the interacting particle: γ- or β-induced electronic recoils (electromagnetic interactions), DM induced electronic recoils; CEνNS- , WIMPs-, or neutron-induced nuclear recoils (lattice interactions).

Scheme of detection principle of a heat and ionization detector



The goal is to reach ~10 eV (RMS) energy resolution in heat and ~20 eV (RMS) resolution in ionization to provide a rejection power of about 10^3 down to the energy threshold. To reach such background rejection to all sorts of electromagnetic backgrounds, two key features have to be met: i) Fully Inter-Digited (FID) electrodes, as first introduced by the EDELWEISS collaboration [44], thanks to which events happening near the surface can be tagged as such and be rejected while providing excellent charge collection for bulk events; ii) ~10 eV ionization energy resolution (RMS), which is few times better than the best resolution achieved so far in such massive cryogenic bolometers. This will be achieved thanks to dedicated low-noise HEMT-based preamplifiers combined with low-capacitance cabling and detectors.

The fabrication of the Ge detectors will be accomplished by the collaboration. High purity Ge crystals are available commercially. Charge collection electrodes are based on evaporated thin films of Aluminum that can be patterned to an optimized design using lithography and shadow mask techniques. The available fabrication facilities allow to cover both flat and lateral surfaces of the Ge crystal. An amorphous Ge:H layer is deposited prior to the Al film to improve the charge collection efficiency, especially for near surface events. In a second step, a heat sensor is implemented using NTD-Ge thermistors that are glued directly onto the Ge crystal. The detector is finally mounted into its copper holder.

EDELWEISS/Ricochet groups have successfully demonstrated a 55 eV energy threshold on a 33-g Ge bolometer operated from a surface lab early 2019 [38] and with several detectors in underground laboratory in 2020 [14], suggesting that the very low-energy threshold of 50 eV is secured. Nowadays, the main R&D focus is dedicated to demonstrating the rejection capabilities of the electromagnetic backgrounds down to the energy threshold. To that end, a first bolometer combining a heat sensor and four ionization electrodes (see Fig. 5.2 left panel) has been tested above ground test facility and exposed to an AmBe neutron source. Fig. 5.2 (right) shows the resulting event distribution on the ionization yield where two populations of events can clearly be identified: electronic recoils and nuclear recoils. An improvement by a factor of 10 on the ionization resolution, hence on the particle identification threshold, is expected due to transition from the FET-based to our upcoming HEMT-based preamplifiers [41]. To that end, a first version of a HEMT-based preamplifer developed by EDELWEISS/Ricochet is being designed and tested.

The collaboration is expects to have by mid-2022 the Ge-based CryoCube detector array, including its cold front-end electronics (HEMT-based preamplifiers) and cabling, which is fully funded by French side. During R&D phase the same detectors will be used underground to DM search.

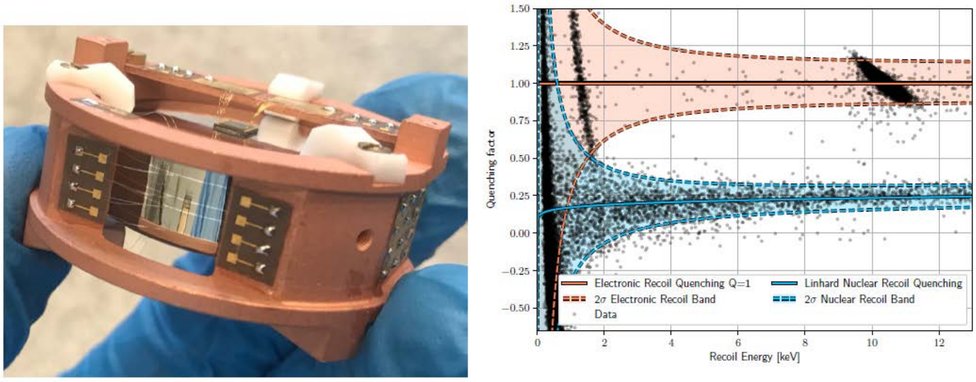


Fig 5.2: *Photograph of a 10 mm height and 30 mm diameter Ge detector prototype with 4 electrodes, one NTD-Ge heat sensor mounted in its copper holder. Right: Neutron calibration of the detector represented on the quenching versus recoil energy. Two populations of events are: electronic recoils with Q ~ 1 (red band) and nuclear recoils with Q ~ 0.3 (blue band). Electronic captures from the K and L shells of the ^{73}Ge at 10.37 keV and 1.3 keV respectively are also visible and are used for calibration. Those two lines have been activated by an exposition of the detectors to a high activity neutron source.*

Zinc Superconductors

The Ricochet experiment will also use metallic superconductor (Zn) absorbers for its bolometric array. These detectors are developing by the US Ricochet group which are not member of the EDELWEISS, thus in beginning this technology will be used exclusively for Ricochet. The motivation for using new detectors is twofold: i) zinc detectors may offer the unique advantage of providing strong discrimination between events arising from most residual backgrounds and CEvNS-induced recoils, and ii) it opens the door to a completely new detection technique that could theoretically reach down to the Cooper pair binding energy [42]. Recently, new 40-g zinc cubes have been produced by RMD, Inc (see Fig. 5.3 – left panel). Each detector is instrumented with two gold pads, one in direct contact with the zinc absorber, the other having a 50-100 nm ZnO layer in between the two metals. Such a configuration will allow one to simultaneously measure the phonon and the phonon+quasi-particle population from a given particle energy deposition. This will enable a better understanding of the potential background discrimination capabilities of metallic superconductors. We plan to use transition edge sensors (TES) for the readout of the phonon and quasi-particle signals from these superconducting bolometers. Initial prototype TES chips (with a transition temperature of 80 mK) have been developed by Argonne National Laboratory for this use (see Fig. 5.3 – right panel).

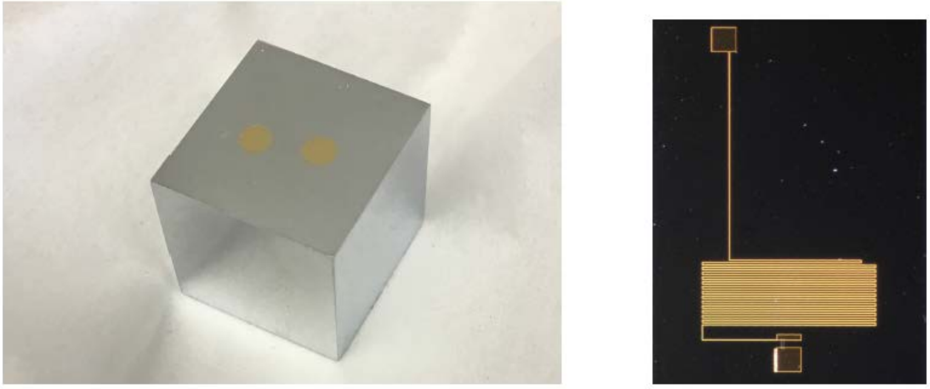


Fig 5.3: *Left: Zinc cubic crystal developed by RMD, Inc. Two gold readout pads (left: direct Au-Zn contact, right: Au-ZnO-Zn contact) are present for phonon and quasi-particle readout. Right: Transition edge sensor "chip" with 80 mK T_c developed at Argonne National Laboratory.*

The experimental setup

In this section design of **new Ricochet setup** will be addressed as the EDELWEISS one is well known and properly documented in the technical review of the experiment published in Journal of Instrumentation, 12, 08, P08010, 2017 (see Appendix 2). Some improvements in detectors' holders, preamplifiers, data acquisition will be implemented as result of the joint EDELWEISS/Ricochet R&Ds. It corresponds to a general philosophy of the experiment: continuous improvement of the energy resolution and energy threshold, increasing of the detector mass, with simultaneous reduction of the background. Thanks to this approach during each of the previous stages of the EDELWEISS experimental program world leading results of DM search have been obtained.

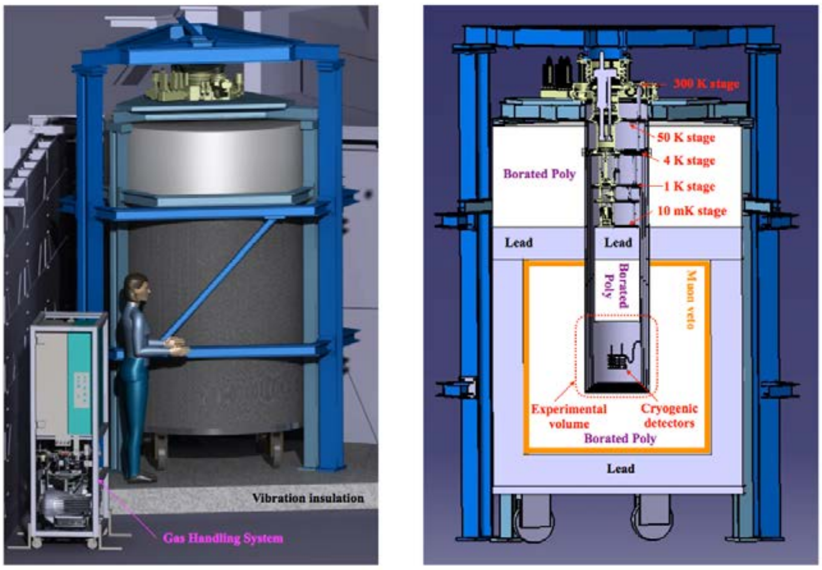


Fig 5.4: *Left panel: Future Ricochet experimental setup, illustrating the cryostat held by a double-frame, its movable lead and polyethylene(PE) shields and its gas handling system (GHS). For clarity, the tubing from the GHS and the cryostat is not shown. Right panel: Open view of the Ricochet setup where the dilution refrigerator, the internal shields, the muon-veto, and the experimental volume hosting the detectors and the cold electronics are shown. The double frame has a mass of 1.5 tons, the lead 22 tons and the PE 3 tons, all previous masses are subject to changes depending of the final design.*

Thanks to the high CEνNS cross section, Ricochet will be a compact neutrino experiment with a total detector payload of about one kilogram. Due to its use of cryogenic detectors running at ~10 mK and its need to mitigate the environmental backgrounds, the future Ricochet experiment will need the operation of a dry dilution refrigerator surrounded by both lead and polyethylene shields. Fig. 5.4 shows a preliminary drawing of the future Ricochet experiment with the following specifications and infrastructure requirements:

- The cryostat: is composed of a dilution unit with several stages (50K, 4K, 1K, 100mK, and 10mK) as shown on the right panel of Fig. 5.4. The detector will be suspended below the mixing chamber. To minimize the stray capacitance from the cabling, the cold front-end electronics will be thermally anchored at 1K but mounted in the near proximity of the detectors, within the experimental volume, thanks to a cold finger. Eventually, the warm electronics, containing the bias DACs, signal preamplifiers and digitizers will be mounted directly on the 300K flange. Based on the excellent noise performance achieved in the EDELWEISS-III experime, the digitized signals will be sent to the data acquisition system using optical fibers.
- The double frame: the cryostat will be held by two mechanically isolated frames. One for the dilution unit hosting the cryogenic detectors, and the other one for mechanical isolation of the pulse tube cold head, that generates high vibration levels, from the dilution fridge. This vibration mitigation strategy has been shown to reduce by about two orders of magnitude the vibration induced by the pulse tube cryocooler at the detector [36]. The total height of the setup, including the additional floor is 3.4 m with a ground footprint corresponding to a 2.2 m diameter circle. These dimensions are however still subject to changes depending on the final design of the experiment.
- The gas handling system (GHS): it contains all the pumps, the ^{3}He/^{4}He tank, the Pulse Tube (PT) compressor, and the tubing required to operate the cryostat. The cooling of the two first stages of the cryostat is based on a PT cryocooler. The cooling of the two first stages (50K and 4K) is ensured by a Stirling thermal cycle oscillating from 9 to 18 bars at a frequency of ~1 Hz. A 10 mK base temperature is further obtained with an ^{3}He/^{4}He dilution circuit in closed loop that is using a 2 bar compressor, a dry primary pump and a turbo pump. Vacuum in the cryostat is created thanks to an additional primary and a turbo pump. The GHS is 2 meters tall (total) with a ground footprint of 2 m^2.
- The shields: the cryostat will be encapsulated by different layers of passive materials to reduce the environmental backgrounds. Our preliminary shielding design counts a first layer of borated polyethylene (40 cm thick), a muon-veto (except inside the cryostat), then a lead layer (20 cm thick), and an additional 40 cm thick layer of polyethylene on top to further reduce the reactogenic neutrons. In total, including the frames, we anticipate a load of about 25 tons.
- A small (few-meters squares) semi-clean space should also be in close proximity of the Ricochet experiment in order to store the detectors in a dust-free environment prior to their integration in the cryostat.

The Ricochet experimental site

On the current phase the Ricochet collaboration has decided to focus its efforts on the ILL (Grenoble, France) the H7 experimental site, where the STEREO neutrino experiment is currently running and will be decommissioned in 2021. The H7 site starts at about 8 m from the ILL reactor core that provides a nominal nuclear power of ~57.8 MW, leading to a neutrino flux at the Ricochet detectors of 1.4×10^{12} cm^{-2}s^{-1}. The reactor is operated in cycles of typically 50 days duration with reactor-off periods sufficiently long to measure reactor-independent backgrounds, such as internal radioactivity or cosmogenically induced backgrounds, with good statistics. The available space is about 3 m wide, 6 m long and 3.5 m high. It is located below a water channel providing about 15 m water equivalent (m.w.e) against cosmic radiation. It is not fed by a neutron beam and is well-shielded against irradiation from the reactor and neighbouring instruments. The site is well-characterized in terms of backgrounds, and the operation of the STEREO neutrino experiment has been successfully demonstrated [45].

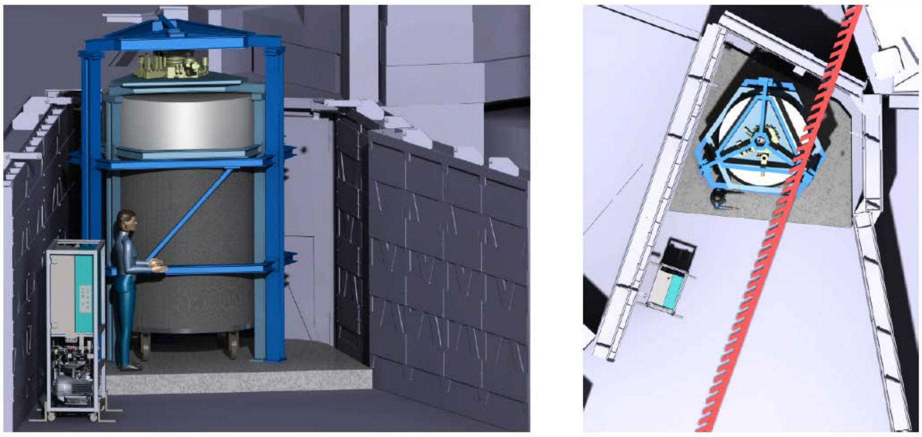


Fig 5.5: *Side (left) and top (right) view of the proposed Ricochet experiment deployed in the H7 site at the ILL, about 8 meters away from the 57.8 MW reactor core. Shown are the cryostat, hosting the ultra sensitive cryogenic detectors, its holding structure made of two frames, its integrated shielding and the Gas Handling System (GHS). The red thick line (right panel) shows the footprint of the water channel.*

Figure 5.5 presents a preliminary design of the future Ricochet experiment deployed at the ILL-H7 experimental site. After completing the proposed stage of the Ricochet, for further investigations it is considered to use a site at a commercial 3.2 GW reactor with much better signal to background ratio. One of such sites is Novovoronezh NPP (NVNPP). Proper characterization of the site will be one of the tasks for JINR group during the next 3 years.

Expected Ricochet signal

Fig. 5.6 presents the expected signal and targeted background event rates as a function of the recoil (kinetic) energy expected for the Ricochet experiment installed at 8 meters from the ILL reactor core. The blue solid line is the CEνNS event rate as predicted by the Standard Model. Also shown are the total background expected before (solid line) and after (long dashed line) the electromagnetic background rejection. We then expect to observe ~15.5 CEνNS events/kg/day between 50 eV and 1 keV and a total background rate of ~100 events/kg/day and ~5 events/kg/day before and after background discrimination. With a signal-to-noise ratio of S/B ~3, we expect to reach a 5-σ CEνNS detection after only a couple of days and a percentage-level precision measurement after one year of reactor ON data, i.e. two years on site.

Sensitivity to New Physics is detailed in Appendix 1.

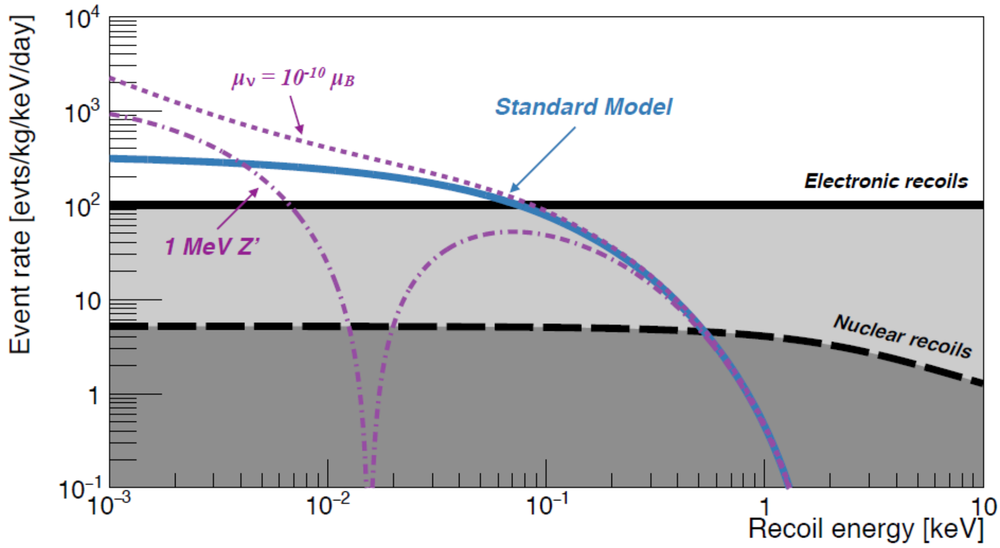


Fig 5.6: *Expected event rate and targeted background levels as a function of the recoil energy for the Ricochet experiment deployed at 8 meters from the ILL reactor core. The blue solid line is the standard model predicted CEνNS event rate while the dot-dashed and dashed blue lines are respectively from adding a 1 MeV Z' boson and a NMM (see appendix 1). The black solid and long-dashed lines represent the electronic and nuclear recoil background populations respectively.*

CEνNS physics potential

The following projected discovery reach and exclusion limits are computed using a profile likelihood analysis where we assumed 5% systematic uncertainties on all backgrounds, and a 70% detection efficiency mostly due to the deadtime loss from the muon-veto. Figure 5.7 presents the CEνNS discovery significance (left panel) and the CEνNS precision measurement (right panel) as a function of time assuming Ricochet science data taking starting on the 1st of July 2022. As one can see, a 5-σ significance detection is reachable in only a couple of days with both detector technologies. After the first reactor cycle (of about ~50 days) we should reach a ~30-σ significance and a corresponding 5% CEνNS precision measurement, where we should start being sensitive to possible exotic physics scenario. After 9 reactor cycles, i.e. two years and a half onsite, we will reach the targeted ~1% precision measurement (not including signal systematics), that will lead to orders of magnitude improved sensitivities to various new physics scenarios compared to existing experiments.

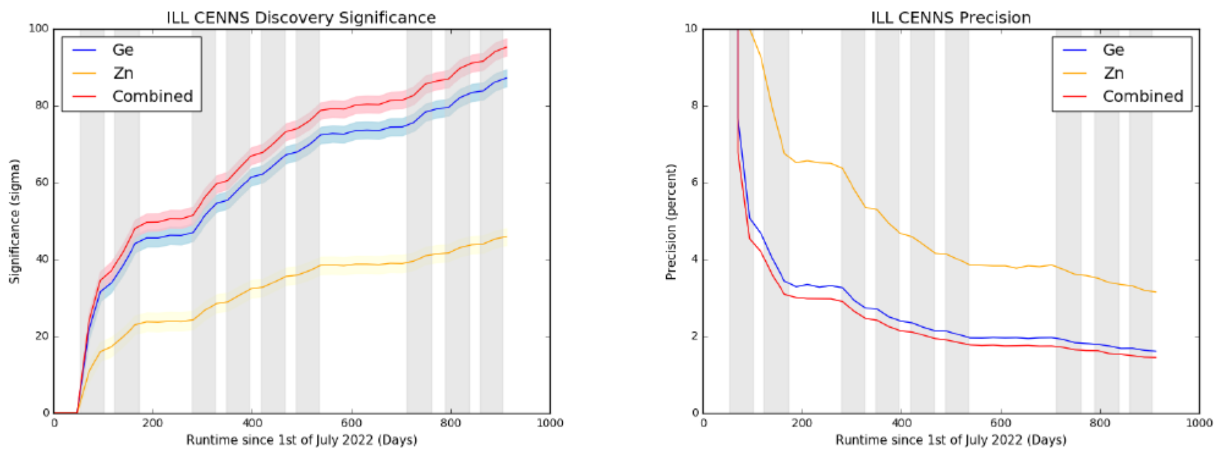


Fig 5.7: *CEνNS discovery significance and precision as a function of exposure. Median significance and precision (and 95% confidence level bands) for the discovery of CEνNS using Ge (blue), Zn (yellow), and the combination of the two (red). Grey regions indicate time periods*

DM physics potential

Further ahead the requirements to the EDELWEISS will to approach the neutrino floor, which corresponds to the coherent scattering of neutrinos from several astrophysical sources as solar ^{8}B neutrinos. Fig. 5.8 shows sensitivity projections derived from the likelihood analysis for a large exposure of 50000 kg d and resolutions of both heat and ionization channels at 100 eV. Limits are computed for both 8 V and 100 V bias voltages and plotted in purple and black, respectively. Solid lines of Fig. 5.8 correspond to the expected limits achievable considering the current EDELWEISS background budget, with the exception of heat-only events, which are supposed to be completely suppressed. Thick dashed lines (dot dashed lines) are obtained assuming not only no more heat-only events (a reduction of heat-only events by a factor 100), but also no more neutrons and a reduction of the Compton background by a factor 10 (R&D for new materials, shields, the cryosystem). The background-free sensitivity is shown in thin dashed lines.

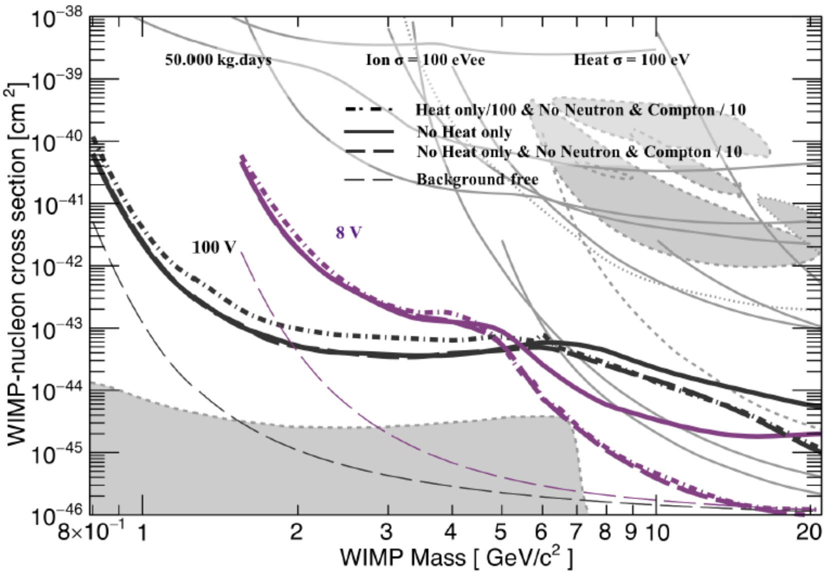


Fig. 5.8: *Projected sensitivities for a large exposure of 50 000 kg d with strongly improved background levels and R&D upgrade performance achieved, with baseline resolutions of heat and ionization channels at 100 eV. Limits are computed using a likelihood analysis at 8 V (purple) and 100 V (black) assuming a suppression of the heat-only background (solid line), and no more neutron background associated with a reduction of the Compton background by a factor 10 (thick dashed line). The background-free sensitivity is shown in thin dashed lines.*

6. Time schedule

It has to be mentioned that timely realization of the Ricochet scientific program is only possible to 1) detectors already developed in joint R&D EDELWEISS/Ricochet, 2) detectors characterization in EDELWEISS, 3) available electronics and data acquisition system, 4) available infrastructure for low background measurements and for material selection, 5) available supplementary detectors for background measurements/monitoring, 6) the ILL site is well known thanks to the STEREO experiment, 7) calibration procedures for low energy region are well established. In general, the Ricochet will be impossible without the EDELWEISS. In the same time financial resources available for development of Ricochet detectors are the base for ultra-low mass DM search in EDELWEISS.

Time	**Task**
First year	Ricochet: complete building of all Ge detectors (1 kg), their tests, building and commissioning of the cryo-system, shields, supplementary systems. Start the Ricochet implementation at ILL site. EDELWEISS: using of new detectors in a special detection modes for reduction of heat-only events. Building and testing of new HPGe crystals with different termistors, holders, crystal treatments, delivery of the detectors to LSM, measurements.
Second year	Ricochet: Start of data taking. Background measurements, calibrations. Improved MC model based on real data. Implementation of Zn detectors. First results. EDELWEISS: results with accumulated data. Decision about further EDELWEISS detectors design. Selection of materials for improved EDELWEISS setup at LSM.
Third year	Ricochet: data taking, results. Finalizing characterization of NVNPP site for possible further Ricochet implementation. EDELWEISS: Upgrade of EDELWEISS setup at LSM with new cryo-system/shields.

7. Estimation of human resources

Institutes forming the collaborations are:

Centre de Spectroscopie Nucleaire et de Spectroscopie de Masse, IN2P3-CNRS, Universite Paris XI, Orsay, France	EDELWEISS and Ricochet
Univ Lyon, Universite Lyon 1, CNRS/IN2P3, IP2I-Lyon, F-69622, Villeurbanne, France	EDELWEISS and Ricochet
Institut Neel, CNRS/UJF, Grenoble, France	EDELWEISS and Ricochet
CEA, Universite Paris-Saclay, Gif-sur-Yvette, France	EDELWEISS only
Karlsruhe Institute of Technology, Institut fur Kernphysik, Karlsruhe, Germany	EDELWEISS only (not yet approved for next stage)
Univ. Grenoble Alpes, CNRS, Grenoble INP, LPSC-IN2P3, 38000 Grenoble, France	Ricochet only
Laboratory of Nuclear Problems, JINR, Dubna, Russia	EDELWEISS and Ricochet
Institut Laue-Langevin, CS 20156, 38042 Grenoble Cedex 9, France	Ricochet only
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA, USA	Ricochet only
Department of Physics \& Astronomy, Northwestern University, Evanston, IL 60208-3112, USA	Ricochet only
University of Massachusetts, Amherst, MA 01003, USA	Ricochet only
University of Wisconsin-Madison, Department of Physics, Madison, WI 53706-1390, USA	Ricochet only

By performing of previous stages of EDELWEISS the collaboration demonstrated that has experts required to build and produce new innovative HPGe detectors, building of mK cryostat and its running, performing of low background measurements in the surface and underground laboratories.

JINR group human resources are:

Name	Category	Responsibilities	Time that each participant will give to the work under the Project in relation to its Full Time Equivalent(FTE)
V. Belov	Physicist	NVNPP site measurements, new detectors, commissioning and running.	0.1
V. Brudanin	Physicist	Administrative work	0.1
Yu. Gurov	Physicist	Detectors' development and production	0.2
A. Inoyatov	Physicist	Spectrometry, calibrations	0.2
B. Kalinova	Engineer	Project support, low background technique	0.1
D. Karaivanov	Physicist	Low background technique	0.2
Z. Kazarcev	Physicist	NVNPP site measurements, new detectors, commissioning and running.	0.1
J. Khushvaktov	Physicist	MC, data analysis	0.3
A. Lubashevskiy	Physicist	MC, data analysis, cryosystem.	0.2
S. Evseev	Engineer	Detector building, testing, calibration, running, cryosystem.	0.5
V. Evsenkin	Engineer	Test of supplementary detectors, MC, calibration	0.5
D. Filosofov	Radiochemist	Radiochemistry, low background technique	0.3
N. Mirzaev	Radiochemist	Radiochemistry, low background technique	0.3
L. Perevoshikov	Physicist	Computer and calculation support, MC, data analysis, spectrometry	0.2
D. Ponomarev	Engineer	Neutron background measurements, detectors building, testing. Experiment running. Cryosystem.	0.3
A. Rakhimov	Radiochemist	Radiochemistry, neutron activation analysis, nuclear spectrometry	0.2
I. Rozova	Engineer	Data analysis	0.1
S. Rozov	Physicist	Background study and improvement, detector building, testing, calibration, running,	0.5

		cryosystem.	
A. Salamatin	Physicist	Acquisition system	0.1
K. Shakhov	Engineer	Radon gas, radon emanation detection / development and measurements	0.9
N. Temerbulatova	Radiochemist	Radiochemistry, low background technique	0.2
V. Trofimov	Physicist	Cryosystems	0.3
Yu. Vaganov	Physicist	Calibration sources, spectrometry	0.2
V. Volnykh	Engineer	Computer support	0.1
E. Yakushev	Physicist	Administrative work, radon and neutron measurements, detectors building, commissioning, running, cryosystem.	0.7
Total FTE (Engineers): 2.5, Total FTE (Scientific staff): 4.2, Total FTE: 6.7			

8. SWOT (Strengths, Weaknesses, Opportunities, Threat) analysis

First, let us point out major risks for the experiments.

The schedule of the project can be significantly affected due to factors connected to stability of running of all components of the experiment including cryosystem with dilution cryostat and its stability, electronics, acquisition system, subsystems. Though failure of different components of the setups is difficult to predict, the collaboration already accumulated more than 20 years of running of the cryogenic setups, with accumulated experience in fixing of arising problems including problems with the cryosystem in short time.

One of critical part of any low background experiment is avoiding of its contamination from outside. The trace activities on unacceptable level can be accumulated due to calibrations with not properly tested (on radioactive leak and integrity) radioactive sources, due to radon and other radioactive gases in atmosphere, due to dust and dirt. To avoid these problems a set of special procedures is in place during all stages of experiment starting from the detector production to calibration measurements. Only specially certified materials can be entered into the clean room surrounding the setup. All works performed in the clean room are under continuous control of dust and radon level. Only double encapsulated and properly tested radioactive sources are used for calibrations. Minimal quantity of such sources is allowed. Special clean environment will be build for the Ricochet setup at ILL site.

Now, let us consider some of the scientific challenges: the main challenge for EDELWEISS and Ricochet rare-event search experiments is to distinguish a DM and CEνNS signals from recoils induced by natural radioactivity, cosmic rays and other sources. In other words, the most important problem in both experiments is the background. Thus, the key to the success of the experiments is the possibility to identify with high efficiency the background events, which can mimic the signal. The EDELWEISS/Ricochet experiments together with traditional methods of background reduction uses several special methods for discrimination of backgrounds (heat/ionization measurements, FID detectors for discrimination of surface events, PSD for reduction of the noise).

For the Ricochet experiment proper interpretation of results will be strongly depended on stability of the neutron background, especially for comparison of reactor ON/OFF runs. Analysis of this question is addressed in Appendix 4.

Another important point to worry about for the Ricochet is vibrations that could generate unwelcome low energy noises in the region of interest. Analysis of this question is addressed in Appendix 5.

As the Ricochet experiment aim is 1% level precision measurements, the questions about possible systematic become extremely important. Analysis of the Ricochet systematic is performed in Appendix 3.

9. Contribution of JINR group

Dubna team of the EDELWEISS/Ricochet project is formed on the base of Department of Nuclear Spectroscopy, DLNP. This department has a huge almost 50-years experience in high-precision nuclear spectrometry using semiconductor and scintillator detectors in general and 30-years experience of rare processes studies in underground environment.

Dubna team participates and will make commitments to the following parts of the EDELWEISS/ricochet project:

- Development of new low threshold Ge detectors; Assembly and commissioning;
- New cryosystem for the Ricochet: development and running;
- Development of methods for low background measurements;
- Data taking (this includes daily routine procedures, as well as regular and special calibration runs);
- Low background study and development of methods of neutron and radon detection;
- Selection and production of less radioactive materials;
- Detector simulations and data analysis; Publication of results.
- Characterization of a NPP site for possible further phases of the Ricochet project. (see Appendix 6 for first measurements already performed at Novovoronezn NPP site.)

Below some of above topics described in details:

9.1 Assembly and commissioning of EDELWEISS setup, data taking

From start of the second phase of EDELWEISS experiment in 2005, Dubna team did a sufficient commitment in setup assembly. Our responsibilities include commissioning of EDELWEISS environment (clean room operation and procedures, developing procedures of operation with radioactive sources on the site, etc); participation in cryostat assembly and detector installation and wiring; sources on site certifications before its using for EDELWEISS. We participate in commissioning and debugging of electronics and data taking. The data taking process includes need for everyday procedures as detectors regenerations, calibrations, etc. That requires participation in shift duties shared between experts on data taking in few EDELWEISS institutions. Significant part of this work is done from Dubna.

The accumulated experience will be used for the Ricochet deployment at ILL site, it commissioning and running.

9.2 Low background study and development of methods of neutron and radon detection

For unbiased interpretation of results of rear-event search experiments, it is critically important to have a wide knowledge and understanding of all background sources. Both the value of the background and its changes with time are important. Main activities of Dubna team are connected to experimental and MC studies of backgrounds. Experimental studies include:

- participation in material selection process (measurements on designated for these measurements and located at LSM HPGe low background spectrometers);
- continuous monitoring of fast neutrons with build at JINR detection system;
- measurement of fast neutrons produced by muons in coincidence with muon veto system;

- measurement of thermal neutrons with build in JINR low background neutron detection system;
- monitoring of radon level at proximity to the cryostat and at output of anti-radon factory as well at detector storage with build in JINR high sensitive (1 mBq/m^3) and low background radon detection systems.

Main results of above studies are:

1) We measured fast and thermal neutron levels and its changes with time at LSM underground laboratory. Continuous measurements of neutron flux are already continued for about 15 years.
2) We achieved ^{222}Rn level below of 20 mBq/m^3 at EDELWEISS cryostat proximity. Gamma background at EDELWEISS has been reduced by several times with help of continuous control of the radon level at time of WIMPs data taking.
3) We implemented fundamentally new neutron detection method with using delayed γγ coincidences in iodine containing scintillators.
4) We started characterization of the ILL Ricochet site (see Appendix 4).

Some of detectors owning by JINR group are shown on figures 9.1-9.3.

Fig. 9.1: *Detectors developed at JINR for study of neutron background at EDELWEISS environment. Left picture is detector of fast neutrons; right one is detector of thermal neutrons (on the wall).*

Fig. 9.2: *Photo of the ^{3}He filled proportional counter installed at close proximity to the EDELWEISS cryostat (left) and at ILL Ricochet site (right).*

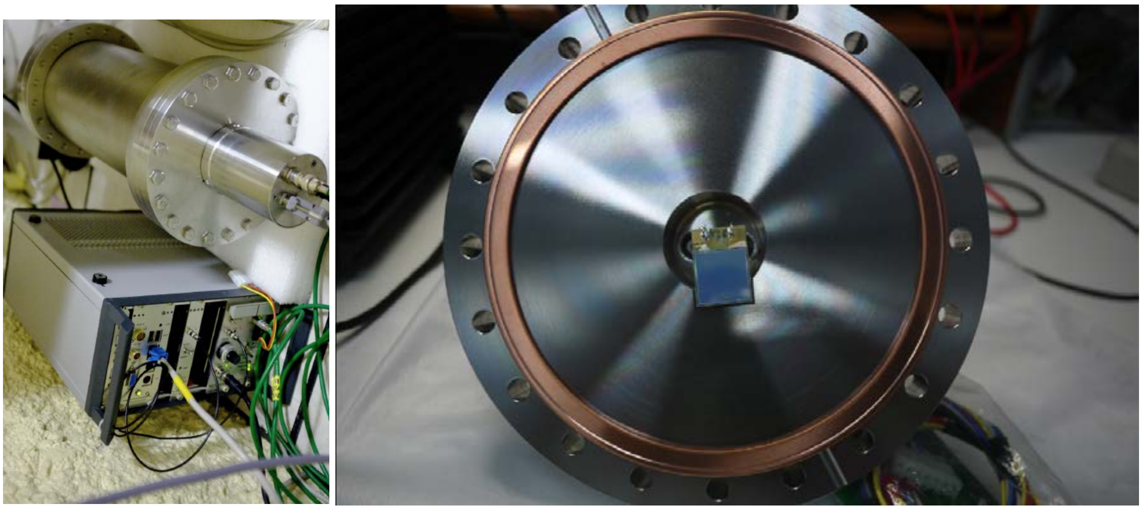


Fig. 9.3: *Mobile high sensitive radon detection system.*

9.3 Ricochet cryosystem

The JINR group will be responsible for new cryosystem of the Ricochet setup. There are several main parameters to which the cryosystem has to be build:

- Low radioactivity (will be provided by material selection with our facilities at LSM);
- Low noise (will be provided by double frame suspension, special suspension system for detectors);
- The cryostat has to hold temperature of ~1.5 kg detectors below 20 mK (dilution cryostat);
- First amplification electronics will be located inside of the cryostat (Fig 9.4 shows the preliminary scheme of the cryostat).

The cryosystem will be built in cooperation with the Cryoconcept company [35], that already supplied the test cryostat used for last 3 years for EDELWEISS/Ricochet R&D (fig 9.4, left).

Fig. 9.4: *Left: Test EDELWEISS/Ricochet dry cryostat. Right: Scheme of the Ricochet cryostat.*

9.4 MC simulations of background at EDELWEISS

Performed in our group MC studies were mainly dedicated to the interpretation of background caused by ^{210}Pb trace contamination of detectors' surfaces. To study this background, a source of ^{210}Pb has been prepared and installed into EDELWEISS in front of one of the detector. As first step, we created detailed particle generator, which simulates particles from $^{210}\text{Pb} \rightarrow {}^{210}\text{Bi} \rightarrow {}^{210}\text{Po} \rightarrow {}^{206}\text{Pb}$ decay chain, including low energy atomic process. Low energy physic packages of Geant4 and Penelope toolkits have been used for particle's transport. Using experimental information about number of detected α from ^{210}Po decay, we were able to explain nature of background events in low-energy region including nuclear recoil band. This provided key information on interpretation of detected background at WIMPs runs. From comparison of experimental and MC data, we were also able to obtain function of the efficiency of charge collection on the detector's surface. This parameter is important for applying of physics based cuts on fiducial volume.

As result of our MC work 2 main aims were achieved:

1) We clearly demonstrated that surface background events are connected with lead contamination (we were able to reproduce experimental spectrum in low energy region based only on known intensity of alpha particles with high energy).
2) Parameters for fiducial volume cuts for ID/FID detectors were estimated.

9.5 Low radioactivity, study in LSM

In LSM our group is (partly) responsible for selection of materials with low radioactive level. Two HPGe detectors available for screening of material radioactivities in LSM (Fig 9.6). Additionally for detailed and deep study of background conditions at LSM and at EDELWEISS at particular, we build and delivered to EDELWEISS site alpha spectrometer with an alpha detector of high area (Fig 9.5).

Fig. 9.5: *Photo of the vacuum chamber of the alpha spectrometer containing electronic module (preamplifier, shaping amplifier, power supply, vacuum control module).*

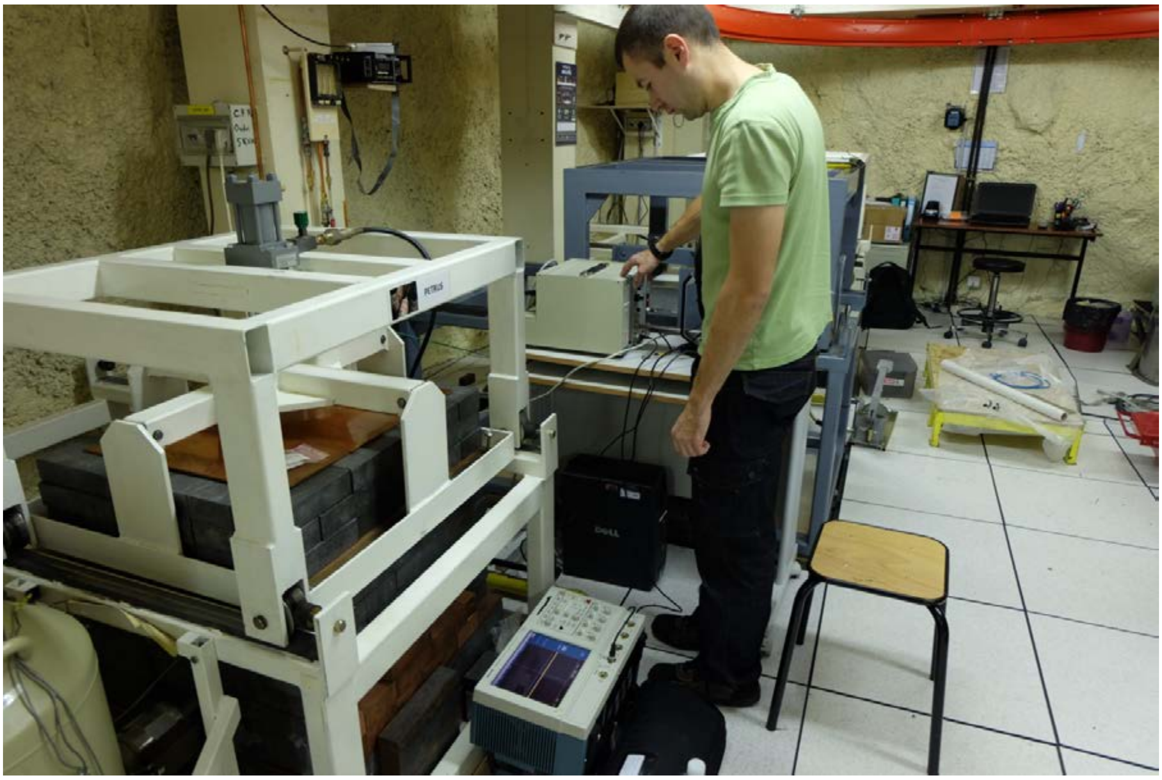


Fig. 9.6: Adjustment of EDELWEISS HPGe detector GENTIANE by S.Rozov (member of the JINR group).

With radiochemistry group, we are also working on new clean materials for new phases of EDELWEISS/Ricochet. This includes production of ultra radioactive clean solder and flux. Part of this work was published in [43].

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Appendix 1, New Physics with CEνNS

With such a low-energy and high-precision measurement of the CEνNS process, Ricochet will be uniquely positioned to probe new physics in the electroweak sector. We hereafter discuss projected sensitivities to some exotic scenarios which are further detailed in [J.Billard, J.Johnston and B.J.Kavanagh, JCAP **1811**, no. 11, 016 (2018)]:

The Neutrino-Magnetic Moment (NMM): as neutrinos oscillate, they must have a non-vanishing mass and sufficiently large mixing with each other. In the case of a Dirac neutrino, the minimal extension of the standard model leads to a small but nonzero neutrino magnetic moment of about 10^{-19} μ_B. This theoretical limit is orders of magnitude below the most stringent ground-based limit from GEMMA < 2.9×10^{-11} μ_B (90% C.L.) [A. G. Beda, et al. GEMMA collaboration, Phys. Part. Nucl. Lett. **10**, 139 (2013)]. However, in some more general extensions, including new physics at the TeV-scale, the NMM can be as high as 10^{-15} μ_B and 10^{-12} μ_B for Dirac and Majorana neutrinos respectively [M. Lindner, B. Radovcic, and J. Welter, JHEP **1707**, 139 (2017)]. Therefore, the observation of an anomalously large NMM, inducing sub-100 eV CEνNS spectral distortions, would unambiguously lead to two major conclusions: 1) there is new physics, and 2) neutrinos are Majorana fermions; which will have tremendous implications on the global neutrino physics program. Our goal is to provide the first CEνNS-based NMM limit down to ~10^{-11} μ_B (90% C.L.) by 2024.

Searching for new massive mediators: the Coherent Elastic Neutrino-Nucleus Scattering is done through the exchange of the Standard Model **Z** boson. Plausible extensions of the SM suggest the presence of an additional vector mediator boson [E. Bertuzzo et al., JHEP **1704**, 073 (2017)], that couples both to the neutrinos and the quarks, called *Z'*. The latter could therefore interfere with the standard CEνNS process and modify the observed effective weak nuclear hyper-charge. Fig. A1.1 (left panel) presents the anticipated 90% C.L. upper limit on the Z' coupling that we aim to achieve with the Ricochet experiment. Unlike fixed target (APEX[S. Abrahamyan, et al., Phys. Rev. Lett. **107**, 191804 (2011)]) or collider-style (LHC di-electron searches [M. Aboud, et al., ATLAS Collaboration, Phys. Lett. B **761**, 372-392 (2016); V. Khachatryan, et al., CMS Collaboration, Phys. Lett. B **768**, 57-80 (2017)]) experiments, CEνNS-based experiments have the unique possibility to scan any Z' masses. As the constraint on the Z' coupling evolves as $(\text{exposure})^{1/4}$ if not background limited, the Ricochet's key feature is its sub-100 eV energy threshold combined with its significant background rejection. Eventually, we see that within a year, the proposed Ricochet experiment will improve by about two orders of magnitude over the current COHERENT result.

Searching for Non-Standard Interactions (NSI): new physics that is specific to neutrino-nucleon interaction is currently quite poorly constrained, and is motivated in some beyond-SM scenarios [J. Barranco, O. G. Miranda, and T. I. Rashba, Phys. Rev. D **76**, 073008 (2007)]. In the context of a model-independent effective field theory, the Lagrangian describing the neutrino-nucleon interaction leads to NSI operators, which can either enhance or suppress the CEνNS event rate. Fig. A1.1 (right panel) shows the 90% C.L. allowed regions derived from several particle physics experiments including CHARM [J. Dorenbosch, et al. [CHARM Collaboration], Phys. Lett. B **180**, 303-307 (1986)], LHC mono-jet searches [J. A. Friedland, M. L. Graesser, I. M. Shoemaker, and L. Vecchi, Phys. Lett. B **714**, 267-275 (2012)], the recent COHERENT result, and Ricochet's anticipated sensitivity. The Ricochet result is shown as: Ge only (blue), Zn only (orange), and Ge + Zn combined (red). Due to the interference between the couplings, CEνNS constraints lead to two allowed regions (not visible for COHERENT as they overlap). We can therefore appreciate the complementarity between these two targets which breaks the degeneracy along the up- and down-quark neutrino-electron couplings. Such neutral current NSI constraints, as expected from Ricochet, will be mandatory to future long-baseline experiments exploring the neutrino mass hierarchy, such as DUNE [P. Coloma and T. Schwetz, Phys. Rev. D **95**, 079903 (2017)]. After only one year of data taking, our goal is to either discover or exclude NSI in the low-energy electroweak sector.

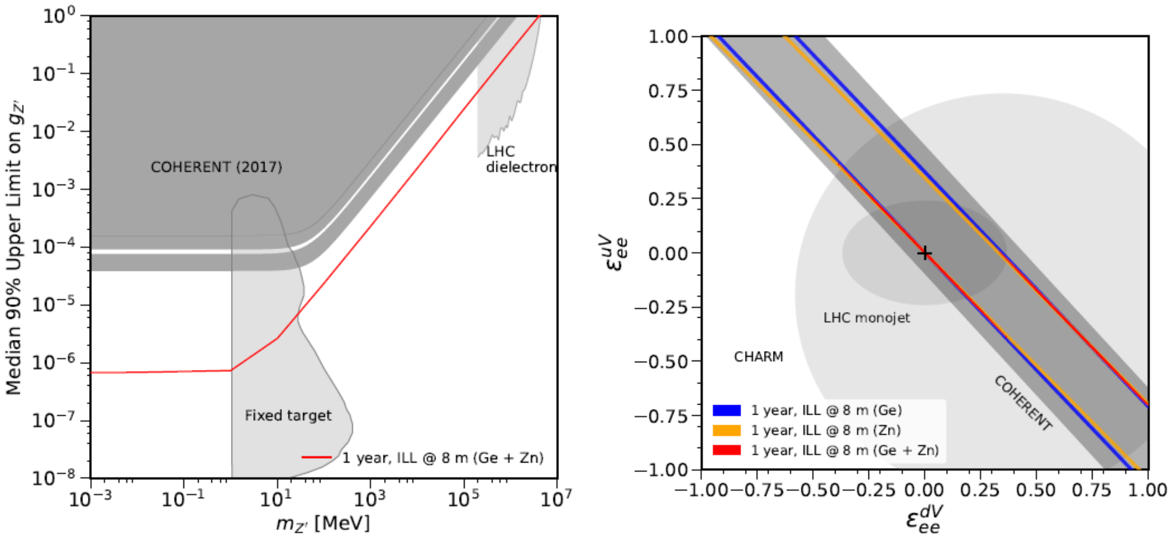

Fig. A1.1: *Projected sensitivities of the Ricochet experiment, located at 8 m from the ILL reactor core, to new physics searches in the low-energy CENNS sector where a 50 eV energy threshold and an electromagnetic background rejection power of 10^3 was assumed. Left: constraints on Z' searches where we have assumed unified coupling to the quarks. The results are shown as 90% C.L. upper limits on the Z' coupling. Also presented are current leading constraints from the APEX fixed target experiment, LHC di-electron searches, and COHERENT. Right: constraints on Non-Standard neutrino-quark Interactions in the neutrino-electron sector. Results are shown as 90% C.L. allowed regions. Also shown are current experimental constraints from LHC mono-jet searches, CHARM, and COHERENT. The cross represents the Standard Model.*

A precise CENNS measurement will also allow test the existence of sterile neutrinos. For the typical sterile neutrino masses required to explain the LSND anomaly [Aguilar-Arevalo et al., LSND collaboration, Phys. Rev. D **64**, 112007 (2001)] ($\Delta m_{41}^2 \sim 1$ eV^2), and for typical neutrino energies from nuclear reactors of ~3 MeV, the wavelength of active-to-sterile oscillations is of a few meters. Therefore, to be competitive, such a search has to be done few meters away from a compact nuclear reactor in order to observe the spectral distortions and change in normalizations induced by the existence of a sterile neutrino with a sufficient significance. Thanks to its compact reactor core, assuming Ricochet to be deployed at ILL should also lead to competitive sensitivities to eV-scale sterile neutrinos with a new and complementary approach from ongoing experiments. To that end, combined analyses between STEREO and Ricochet, both operated at the ILL-H7 site but using two different neutrino detection mechanism, could provide valuable information to the reactor neutrino community.

Appendix 2, EDELWEISS experiment, technical paper

E Armengaud, et al (EDELWEISS collaboration) Performance of the EDELWEISS-III experiment for direct dark matter searches, Journal of Instrumentation, 12, 08, P08010, 2017, arXiv preprint arXiv:1706.01070

Appendix 3, Ricochet systematics

As we are aiming for a percentage-level precision measurement of the CEνNS process, it is pivotal to properly anticipate and mitigate possible sources of signal systematics. We hereafter list three different sources of systematics that could potentially limit the ultimately achievable precision of the low-energy CEνNS measurement from the Ricochet experiment at ILL.

Anti-neutrino reactor flux predictions

Accurate prediction of the reactor anti-neutrino flux and the resulting CEνNS rate is important for precision measurements of new physics. Table A3.1 shows the predicted uncertainties on parameters that affect the CEνNS rate prediction. The thermal power P_{th}}[C. E. Fillon. [Stage] CEA Paris Saclay. 2017. <cea-01668555>] and distance to the core [N.Allemandou et al., STEREO Collaboration, JINST **13**, no. 07, P07009 (2018)] have previously been measured for the ILL reactor site. The energy released per fission has been calculated with an uncertainty of 0.2% to 0.5% for fission isotopes in a commercial PWR reactor, with an uncertainty of 0.2% for ^{235}U [V. I. Kopeikin, L. A. Mikaelyan and V. V. Sinev, Phys. Atom. Nucl. **67**, 11 (2004)]. This uncertainty may vary for the ILL reactor, but a value around 0.3% can be expected. Uncertainties on the fission fractions α_i will be of order 1% on ^{235}U and 5-10% on other fission isotopes, since ^{235}U will be the dominant fission isotope. Uncertainties of 10% on α_i will lead to small uncertainties around 1% on the total rate, due to similarites in rate and shape of the four fission isotope spectra.

Table A3.1: *Expected systematics on the CEνNS rate.*

	Uncertainty on Parameter	Approximate uncertainty on CEνNS Rate
P_{th}	1.4%	1.4%
Distance	0.3%	0.6%
E/fission	~0.3%	~0.3%
α_i	≤1% for ^{235}U 5-10% ^{239}Pu, ^{241}Pu	<< 0.5%
S_i	Conversion: 2-3%	2-3 %
	Summation: 5-10%	
σ_k	0.5% (θ_w)	

Prediction of the fission spectra S_i must be performed differently for the portions of the spectra above and below the inverse beta decay threshold of 1.8 MeV. Above 1.8 MeV the neutrino flux can be constrained by converting IBD measurements from other experiments to constraints on the flux. In particular, Ricochet would be able to use data from the STEREO experiment to constrain the ILL reactor flux in this region. Typical uncertainties from such conversion are 2-3%. Below 1.8 MeV there are currently no measurements of the neutrino flux from reactors, meaning that the flux must be predicted by using summation calculations of the spectra from the decay products of fission isotopes in the reactor. Summation calculations can be performed by coupling the output of the spectrum calculation tool BESTIOLE with evaluated cumulative fission yields [T. A. Mueller et al., Phys. Rev. C **83**, 054615 (2011)]. The uncertainties on such summation calculations have not previously been calculated, but are expected to have larger values around 5-10%.

The uncertainty on the fission spectra S_i will be energy dependent, meaning that they must be combined together with the CEνNS cross section σ_k of the target isotope. The total uncertainty on the CEνNS rate will come from convolving the covariance matrix of the fission spectra with the CEνNS cross section. In IBD experiments, a 2-3% uncertainty on S_i has resulted in a 2-3% uncertainty on the total rate. A similar result can be expected for a CEνNS experiment for neutrinos with energies above 1.8 MeV. This spectral uncertainty and the uncertainty on the thermal reactor power will be the two dominant uncertainties on the CEνNS rate at energies above 1.8 MeV. The expected uncertainty on the rate of lower energy neutrinos would be larger, due to the larger 5-10% uncertainties on summation calculations. However, despite 69% of the neutrino flux having energies below 1.8 MeV, the small CEνNS cross section at low energies means that a small portion of the total CEνNS rate will come from low energy neutrinos. Indeed, even if a CEνNS measurement could be performed with no threshold, only 17% of the total rate would come from neutrinos below 1.8 MeV, and a 10% uncertainty on the summation calculation would only contribute 1.7% uncertainty to the total rate. In the case of a 50 eV threshold, a 10% uncertainty on the summation calculation would only contribute 0.2% uncertainty to the total rate. This indicates that even though the uncertainty on the low energy flux is large, it will not be the dominant contributor to the total rate uncertainty.

Low-energy nuclear recoil energy calibration

Understanding the response of our detectors to both electron and nuclear recoils is paramount for the Ricochet experiment as we both need to 1) discriminate between backgrounds and signal, and 2) accurately recover the true kinetic energy of the CEνNS induced nuclear recoil at extremely low energies. The response of Ge detectors to electron recoils is different than to nuclear recoils, due to the so-called quenching factor, also referred to as the ionization yield. This is the number of electron-hole pairs created when a recoil event occurs in the detector. The ratio of electron-hole pairs created per input recoil energy is dependent on both the recoil energy and the type of recoil (electron or nuclear recoil). This difference in response is exploited in the Ricochet detectors to discriminate gamma backgrounds (which produce electron recoils) from neutrino and neutron recoil (which produce nuclear recoils). In order to do this discrimination, accurate measurements of this ionization yield difference is needed at the low energies of the CEνNS signal we are measuring. These measurements do not currently exist. In addition, we need to calibrate the response of the actual Ricochet detectors, ideally *in situ*, so that we minimize systematic errors and are able to calibrate any day-to-day variations in response. Thus, we have a two-pronged approach to measure the nuclear response *in situ* for both Ge and Zn detectors and to measure the ionization yield of Ge *ex situ* through the IMPACT calibration program.

In situ calibration using 24 keV neutrons

The *in situ* calibration plan centers on a pulsed and effectively-monoenergetic source of 24.4 keV neutrons. The most informative event topology is a neutron double-scatter spread between two detector elements (see Figure A3.1), allowing the scattering angle and therefore scattering energy to be known. 24.4 keV is a convenient energy for probing the CEνNS energy range: on a Ge or Zn target nucleus, the 10-45 degree scattering angle range corresponds to a recoil energy range of 10-200 eV. Fe has been used by many groups in the past to filter neutrons to this quasi-monoenergetic state, taking advantage of a narrow anti-resonant feature in the ^{56}Fe neutron scattering cross section. It is novel to pair that Fe-based filter with the moderated flux of a DT neutron generator, but this pairing is appropriate in the Ricochet case given that a low calibration flux is in fact desired, and given that a pulsed calibration source is advantageous in reducing backgrounds to the calibration. The University of Massachusetts Amherst will provide the experimental apparatus.

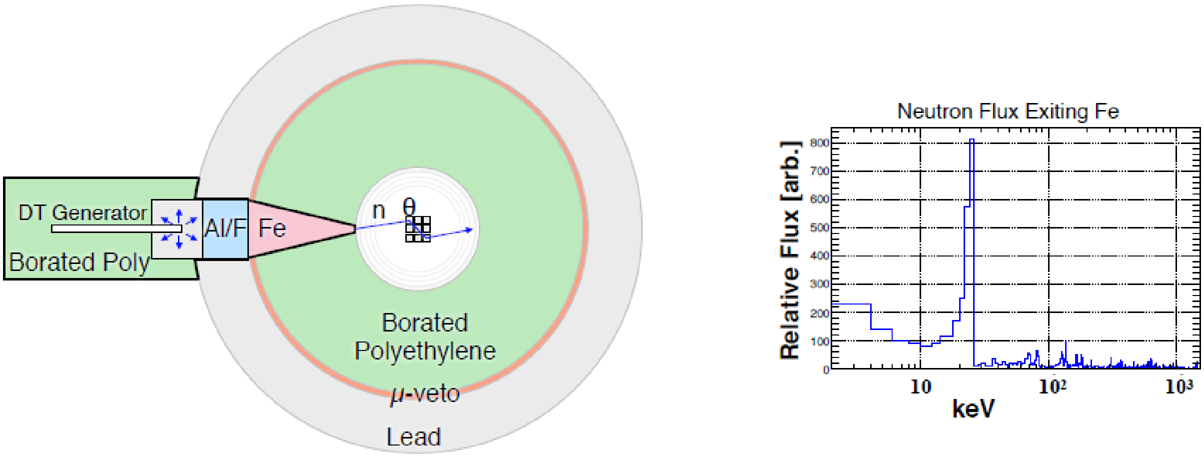

Fig. A3.1: *The in situ neutron calibration source consists of a DT neutron generator (14.2 MeV), followed by several stages of moderating and filtering materials: ~10 cm of Pb, ~20 cm of an Al/F mixture, and finally ~40 cm Fe for the final filtering to 24.4 keV. These moderating/filtering materials are inserted in a special port formed by removing a portion of the polyethylene and Pb shielding. The DT generator is surrounded by B-doped polyethylene to reduce human exposure. The most interesting event topology is a double scatter spread between two detectors, with the angle defining the energy of the first scatter. Right: A Geant4 simulation of the neutron flux leaving the end of the Pb/Al/F/Fe assembly shows the high purity of the monoenergetic 24.4 keV flux.*

Ex situ calibration of Ge response

The Ionization Measurement with Phonons At Low Temperatures (IMPACT) program is a precision measurement of the ionization yield in the energy range between 50 eV and a few keV with small 1 cm^2 × 4 mm thick devices at the Triangle Universities Nuclear Laboratory (TUNL) neutron beam facility. This measurement will provide not only the ionization yield at each neutron recoil energy, but also a direct measurement of the statistics of ionization production – allowing a direct measurement of the Fano factor down to the lowest recoil energies. The same detectors operated at 0 V (i.e. no Trofimov-Neganov-Luke amplification) will enable a direct measurement of the percentage of energy that goes into crystal (Frenkel) defects as a function of recoil energy [R. Agnese et al., App. Phys. Lett. **113**, 092101 (2018)]. The first measurement at TUNL, using a Si device, was done in the summer of 2019, with data analysis ongoing. A second measurement using a Ge device is under preparation. The experimental apparatus will be provided by Northwestern University.

In-situ neutron background monitoring

One last important source of systematics arises from the neutron induced nuclear recoils in the energy range of interest for CEvNS studies, which cannot be discriminated based on the Ge/Zn particle identification capabilities. We therefore need to properly evaluate and statistically subtract this low-energy neutron background component from the observed energy distribution to obtain the neutrino signal. To do so, one needs to be able to precisely evaluate the expected number of neutron events, and their low-energy distribution, in the Ge and Zn detectors, thanks to an *in-situ* and independent fast neutron spectroscopy measurement.

Lithiated bolometers are the most promising detectors for this concern, since the Q value of the neutron capture reaction on ^{6}Li (4.78 MeV) is well above the natural gamma background ending at 2.6 MeV ^{208}Tl line), and that the simultaneous heat and scintillation measurements can ensure a background free fast neutron monitoring. Two main bolometric targets incorporating lithium nuclei have been studied up to now: LiF and LMO by the ROSEBUD and LUMINEU collaborations respectively. Based on their previous studies, it has been demonstrated that such bolometers can achieve energy resolution of a few keV at the capture peak of 4.78 MeV, suggesting that fast neutron spectroscopy is feasible for neutron energies relevant to the region of interest for CEνNS. Indeed, the minimum neutron energies required to produce Ge or Zn nuclear recoils of 50 eV and 1 keV are 1 and 20 keV respectively. An array of a few scintillating lithiated bolometers is under consideration for an in-situ monitoring of the fast neutron background of Ricochet at ILL. Calibration measurements, combined with Geant4 simulations, are currently under investigation to 1) demonstrate the performance and the interest of such an *in-situ* neutron monitoring technique, and 2) optimize its integration with the Ge and Zn detector array. If such *in-situ* neutron monitoring approach is proven to be suitable for Ricochet, the experimental apparatus will be provided by the IJCLab.

Appendix 4, ILL site neutrons

As Ricochet plans on being at only ~8 meters from the reactor core, the reactogenic neutron background will play a crucial role in the experiment. Fast neutron scatterings are able mimic the expected CEνNS signals, in producing low-energy nuclear recoils that cannot be discriminated thanks to particle identification. Moreover, even thermal neutrons could be a problem through secondary reactions. Indeed some γ, after (n,γ) reactions, are highly energetic and have therefore large enough penetration power to be the source of further (γ,n) reactions, or even produce elastic scatterings on Ge nuclei. Though coherent photon-nucleus scattering cross sections are negligible for nuclear recoils above 50 eV, it is worth noticing that kinetically a 5 MeV gammas can produce nuclear recoils up to ~200 eV.

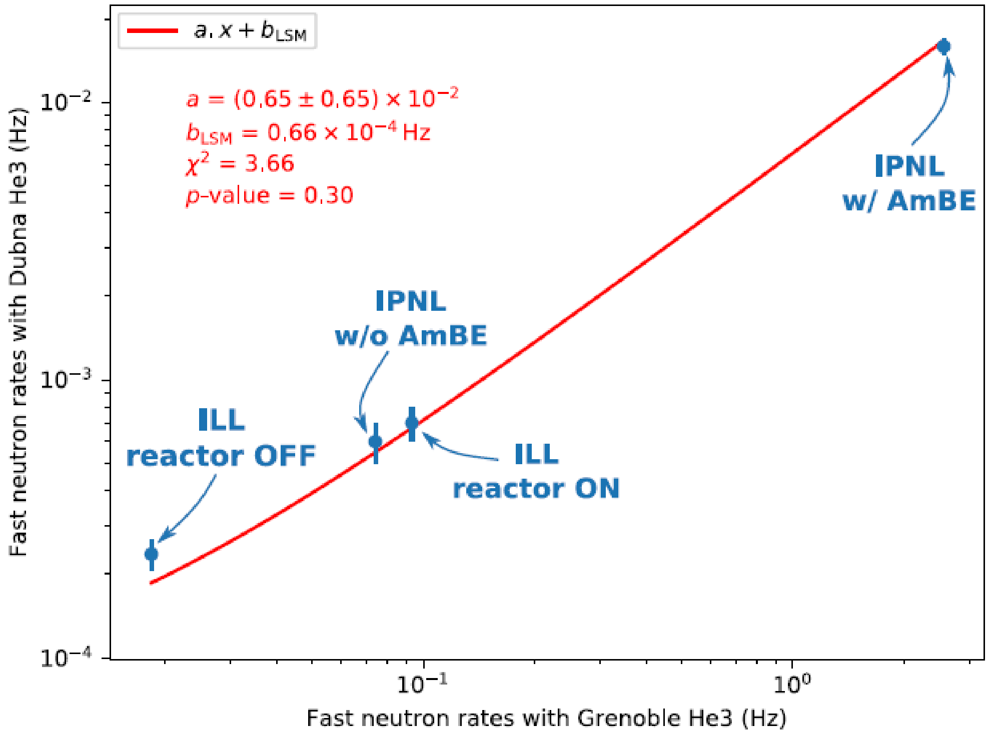

Fig. A4.1: *Correlation between the fast neutron measurements from the ILL (x-axis) and JINR (y-axis) ^{3}He TPC, realised at the ILL-H7 site (reactor ON and OFF) and at IP2I – Lyon (with and without an AmBe neutron source). The quality of the correlation (p-value of 30%) is shown by the red curve that takes into account the ultra-low α- contamination of the JINR detector that was previously characterized at the EDELWEISS (LSM).*

In Ricochet the neutron problem will be properly addressed by: 1) Preliminary on-site measurements, thus realistic Geant4 calculations of the shield can be performed; 2) On-site neutron monitoring during the Ricochet experiment will be done thanks to adjacent He-3 detectors; 3) Monitoring of fast neutrons via high energy reactions on Ge (inelastic scatterings with excitation of energy levels that are easily detectable with the combination of heat and ionization measurements); 4) *in-situ*, i.e. within the Ricochet cryostat, monitoring of fast neutrons will be achieved thanks to lithiated bolometers. Lastly, it is worth emphasizing that neutrons reaching the cryogenic detectors can be further rejected from event multiplicity in several detectors. This has been proven to be very efficient in large arrays of Ge detectors such as the EDELWEISS experiment.

During 2019-2020, fast neutron measurements have been performed within the STEREO casemate, more precisely between the the STEREO detector and its front wall (closest to the reactor). To that end, two ^{3}He Time Projection Chamber (TPC) were used simultaneously though operated in different mode:

- Fast neutron moderation: the ILL TPC was inserted inside a thick (20 cm) polyethylene shield further surrounded by a few cm thick B_4C layer acting as thermal neutron catcher. In such a configuration, this TPC was maximally sensitive to few MeV ambient neutrons. The fast neutron flux is then assessed by computing the capture rate between 400 keV to 800 keV.
- Fast neutron spectroscopy: The JINR TPC is an ultra-low background proportional counter (low α- background), with large dynamic range, and excellent intrinsic energy resolution. It was therefore used in a “capture on flight” mode with no moderator, but was only surrounded by B_4C neutron catcher to avoid pile-ups of thermal neutron captures. This way, for events with energies beyond the capture line at 764 keV, the neutron energy can be derived thanks to $E_{neutron} = E_{measured}$ - 764 keV. However, it should be noted, that contributions from fast neutron elastic scattering are also expected beyond the capture line. The fast neutron flux, and information about its energy spectrum, is then assessed by counting the rate of events between 1 MeV and 6 MeV.

Figure A4.1 shows the fast neutron rates as measured by the two ^{3}He TPC described above, with the ILL (moderation) and JINR (spectroscopy) setups on the x- and y-axes respectively. We observe an excellent correlation between these two fast neutron monitoring approach which gives us great confidence in the validity of our measurements, done both at ILL (reactor ON/OFF) and IP2I - Lyon (with/without an AmBe neutron source). It should be noted that the ultra-low α- background (producing events around 5 MeV at a rate of 6.6×10^{-5} Hz in the JINR detector has been characterized at the EDELWEISS site and was properly taken into account in the interpretation of our results which conclusions are the following:

- The fast neutron flux between reactor ON and OFF is about 5 times larger
- The fast neutron flux between reactor ON and the IP2I lab, with no calibration sources, is about 20% higher

Interestingly, the low-energy neutron background at IP2I has been previously measured with our RED80 prototype Ge bolometer and shown to be about 10^4 events/keV/kg/day (DRU) at 2 keV. This suggests that a similar low-energy neutron background should be observed with our Ge bolometers at the ILL reactor ON assuming no shielding surrounding the Ricochet cryostat. This is indeed confirmed by the Geant4 simulations. Moreover, this suggests that the Ricochet shielding has to be designed to reach attenuation levels of 10^3 to 10^4 to reach our physics goals. According to our Geant4 simulations, including both cosmogenic and reactogenic contributions to the neutron background, reaching such attenuation factor seems feasible. As a matter of fact, it is worth noticing that as reactogenic neutrons have energies lower than 10 MeV, they are easier to shield against compared to cosmogenic ones which can have energies up to few GeV. This further highlight the great advantage of the ILL-H7 site, where the STEREO experiment is currently running, thanks to its artificial overburden of about 15 m.w.e from the water channel.

Appendix 5, ILL site vibrations

Due to the high sensitivity of cryogenic detectors to environmental vibrations, it is of paramount importance to make sure that the vibration levels at ILL are either low enough or can be efficiently mitigated to ensure a proper operation of the Ricochet experiment. We therefore performed vibration measurements at different places, within the STEREO experiment perimeter, in the H7 site at ILL. Following the procedure described in [E. Olivieri, J. Billard, M. De Jesus et al., NIM-A **858** 73-79, (2017)], we used a PCB39B04 high sensitivity, low intrinsic noise, one-axis accelerometer. The latter was mounted within a cylindrical vacuum chamber of a total mass of about 1 kg. A compilation of the vibration measurements, expressed as acceleration power spectral densities is shown in Figure A5.1. We then compare measurements performed with the accelerometer disposed directly onto the concrete floor (red) to the ones obtained with two different thicknesses of visco-elastic vibration insulator (green and cyan). For the sake of completeness, we also compare these ILL results to the ones obtained at IP2I (Lyon) with no insulation (black), and to the theoretical ultimate vibration level predicted by seismic models (dark blue). We can conclude that without insulation, the vibration level at ILL is similar to the one observed at IP2I up to ~50 Hz and then becomes two orders of magnitude larger with a maximum at about 300 Hz. Such vibration levels, though beyond the detector bandwidth, can produce dramatic microphonic noises or even produce parasitic heat loads on the detectors due to internal frictions. Thanks to the use of visco-elastic materials used as insulators, we were able to show that vibration levels comparable to the ones observed in Lyon are reachable. Furthermore, the GRANIT and GAMS experiments, also requiring low vibration levels, are operating successfully at ILL. We are therefore confident that a suitable vibration mitigation system, such as floating deck or passive/active dampers, could be specifically designed to achieve the Ricochet requirements.

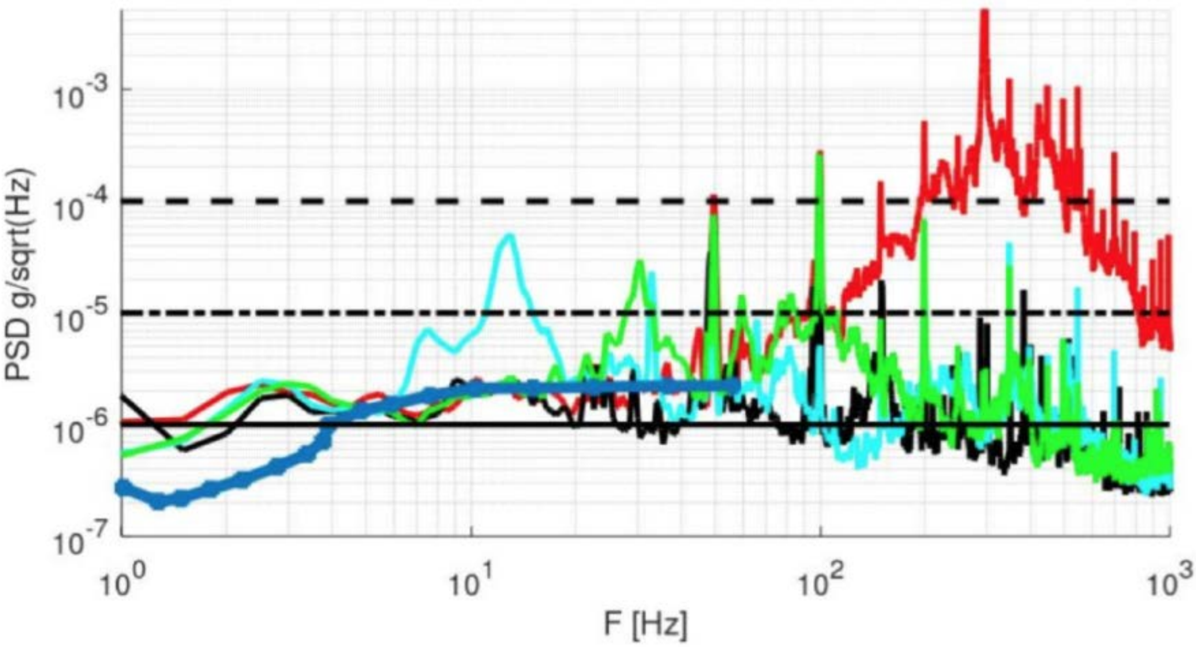

Fig. A5.1: *Compilation of vibration measurements realised at ILL in the STEREO casemate (red – with no insulation, green and cyan – with two different thicknesses of vibration insulation), at the IP2I (Lyon) with no insulation (black), and compared to a seismic model (blue).*

Appendix 6, NVNPP site preliminary investigation

To conduct the further phases of the Ricochet experiment (after ILL stage), a study was begun of the potential location of the setup near WWER-1200 reactor of the Novovoronezh NPP. The first place of investigation was located at unit #6 of Novovoronezh NPP under new 3+ generation WWER-1200 reactor with maximal thermal power 3212 MW. The place is located at -5.4 m (underground) level, has a strong basement, and has no significant noises or vibrations (subject for further detailed investigations). The distance from the reactor core is about 25 m.

Up to now, two most crucial measurements were conducted: muon study and neutron's measurements.

Maximal registered muon flux was found to be 16.2 μ m^{-2} sr^{-1} sec^{-1}, that is about 7 times less with respect to the maximal flux at the sea level. This corresponds to ~50 meters of water equivalent. There is expected anisotropy of the muon flux connected with better shielding from side where the reactor is located.

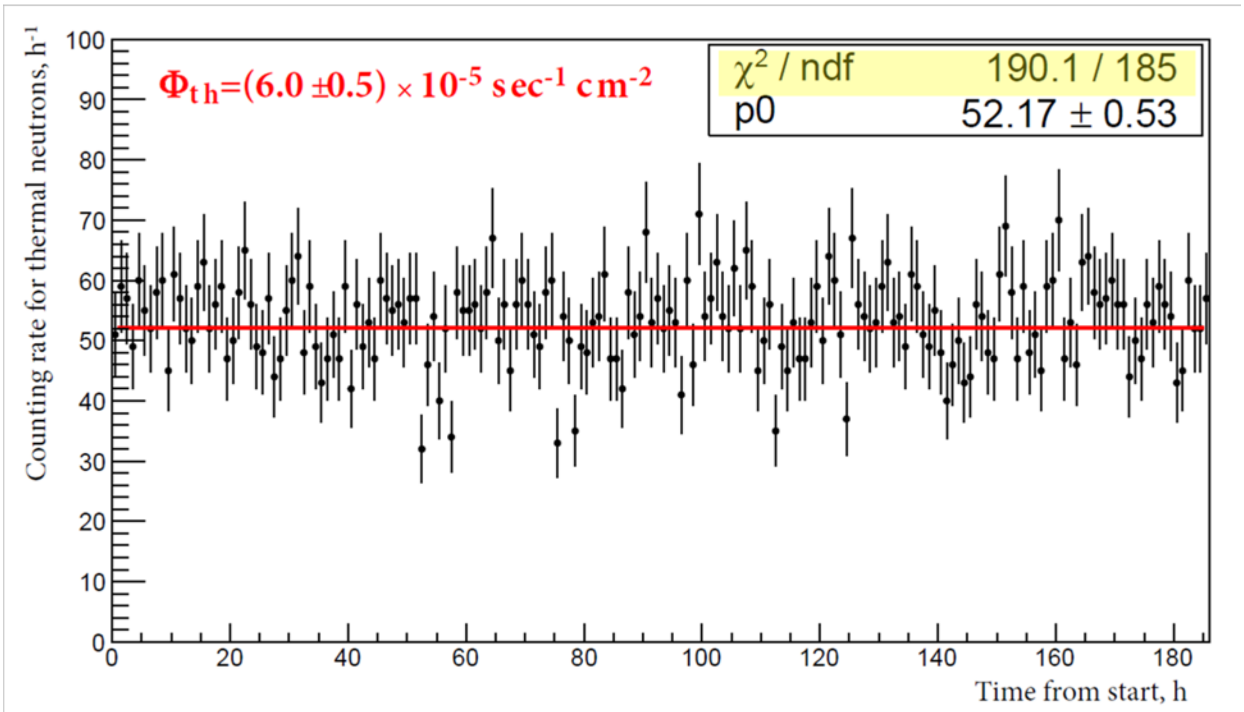

Fig. A6.1: *Stability of the counting rate for detector of thermal neutrons set at NVNPP.*

For neutron background: thermal neutron flux during reactor ON was found to be 6.0(5) $\times$ 10^{-5} n cm^{-2} sec^{-1} with reduction factor 33 to the sea level. During about several days of measurements no significant fluctuations of the flux were detected (Fig A6.1). Factor for reduction for fast neutrons is ~25. Thus, in agreement with low muon flux we found significant reduction factors for both fast and thermal neutrons.

The measurements will be continued in this and another places for their proper characterization for further Ricochet measurements.