PROCEEDINGS OF SCIENCE

Searching for Dark Matter with the RES-NOVA detector

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The RES-NOVA project detects cosmic neutrinos (i.e., Supernovae) via coherent elastic neutrino-nucleus scattering (CENS) using archaeological Pb-based cryogenic detectors. The high CENS cross-section, due to the Pb's large atomic mass, and ultra-high radiopurity of archaeological Pb enable a highly sensitive, cm-scale observatory equally sensitive to all neutrino flavors. These features are also key for dark matter (DM) direct detection. RES-NOVA plans to conduct a direct detection campaign while waiting for neutrinos of astrophysical origin. Its sensitivity to low-energy nuclear recoils makes it excellent for detecting DM from our galactic halo. Under conventional WIMPs assumptions we project the expected sensitivity to DM particles with masses spanning over 4 orders of magnitude, revealing a complementary role to other existing ton-scale direct searches. Additionally, the relatively high natural abundance of Pb-207 enables RES-NOVA to detect spin-dependent interactions, making it suitable for a wide range of theoretical well-motivated dark matter candidates.

This dual capability allows for the search of dark matter particles directly scattering off nuclei in earth-based detectors and, at the same time, their possible imprint in astrophysical neutrinos, opening new intriguing possibilities for the search and characterization of dark matter particles.

39th International Cosmic Ray Conference (ICRC2025)
15–24 July 2025
Geneva, Switzerland

*Speaker

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1. Introduction

The nature of Dark Matter (DM), which constitutes about 85% of the universe's mass [14], remains one of the biggest open questions in modern physics [8]. The RES-NOVA project, originally designed to detect supernova neutrinos via coherent elastic neutrino-nucleus scattering (CEνNS) using cryogenic detectors made of archaeological Pb [17], exploits Pb's high radiopurity and large atomic mass for excellent sensitivity. Beyond neutrino detection, RES-NOVA offers a promising platform for direct DM searches through its sensitivity to low-energy nuclear recoils [7, 19].

The setup can probe DM interactions with ordinary matter, including spin-dependent couplings thanks to Pb's isotopic composition [2, 15]. This dual capability opens new experimental avenues for studying both astrophysical neutrinos and DM particles.

In this work, we explore RES-NOVA's potential for direct DM detection, presenting a preliminary background model and projected sensitivities across a range of DM masses and interaction types.

2. Dark Matter Signature in RES-NOVA

Direct detection of Dark Matter (DM) is a key goal in astroparticle physics [13]. RES-NOVA, originally designed for supernova neutrino detection via CEνNS, also offers unique opportunities for DM searches thanks to the ultra-low background and favorable nuclear properties of Pb.

DM detection in RES-NOVA relies on nuclear recoils from DM scattering off target nuclei, similar to neutrino interactions. Pb's large neutron and atomic numbers enhance sensitivity to both coherent neutrino scattering and DM interactions, while archaeological Pb's radiopurity reduces backgrounds critical for rare event searches.

A simplified estimate equating the DM-induced event rate with that from supernova neutrinos suggests RES-NOVA could reach sensitivities to spin-independent (SI) DM-nucleon cross sections around 10^{-45} cm^2. The DM signal would be continuous low-energy nuclear recoils, contrasting with the transient neutrino burst.

The DM-nucleus differential scattering cross section is approximated by:

$$\frac{d\sigma}{dE_R} \propto \frac{\sigma_{\text{DM-N}} A^2 |F(q)|^2}{v^2},$$

where $\sigma_{\text{DM-N}}$ is the DM-nucleon cross section, A the atomic number, $F(q)$ the nuclear form factor, and v the DM velocity.

RES-NOVA uses $PbWO_4$ crystals, where oxygen enhances momentum transfer, improving sensitivity across a broad DM mass range [4].

In addition to SI interactions, RES-NOVA can probe spin-dependent (SD) DM scattering via isotopes like ^{207}Pb (22.1% abundance, $J^\pi = 1/2^-$) and ^{17}O (0.037%, $J^\pi = 5/2^+$). The SD differential cross section depends on nuclear spin structure [10]:

$$\frac{d\sigma^{SD}}{dq^2} \propto \frac{\sigma^{SD}_{\text{DM-N}}}{v^2} \frac{S_n(q)}{2J+1},$$

where $S_n(q)$ is the spin structure function and J the nuclear spin.

^{207}Pb is an excellent SD target due to its simple nuclear structure and limited spin quenching, complementing lighter targets like ^{73}Ge and ^{29}Si [12]. ^{17}O is favorable for light DM, while ^{207}Pb covers heavier DM with accurate spin-dependent calculations.

These features make RES-NOVA a complementary and competitive platform to explore a wide range of DM masses and interaction types.

3. The RES-NOVA detector

The RES-NOVA detector employs advanced thermal detection techniques operating at cryogenic temperatures to enhance sensitivity and reduce noise. Its core component is an absorber made of $PbWO_4$ with very low heat capacity (C). The crystal absorber is thermally linked to a heat sink maintained at a stable mK temperature.

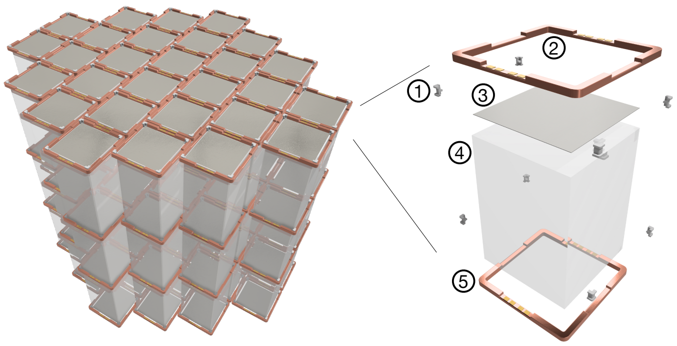

Figure 1: Schematic view of the RES-NOVA detector demonstrator. It consists of 3 layers of 28 crystals each, for a total $PbWO_4$ mass of 170 kg. On the right, details of a single detector module: 1) PTFE holding support for the crystal and light detector, 2) Cu top frame, 3) scintillation light detector absorber, 4) $PbWO_4$ crystal, and 5) Cu bottom frame.

The experiment is planned to be installed at the underground Gran Sasso Laboratory (Italy), benefiting from approximately 3800 m water equivalent of natural shielding provided by the Gran Sasso massif [6]. This site is ideal for operating detectors in low-background conditions.

When a particle (e.g., neutrino or DM) interacts with the absorber, it deposits energy (ΔE), causing a measurable temperature increase, ΔT, related to the absorber's heat capacity by $\Delta T \sim \Delta E/C$. At cryogenic temperatures, C is greatly reduced, following approximately a T^3 Debye law. This low heat capacity is critical for detecting small energy depositions. The design of sensitive temperature sensors is therefore vital to achieve the required detection thresholds for CEνNS and DM interactions.

RES-NOVA has successfully adopted Transition Edge Sensors (TESs) as thermal sensors, demonstrated with eV-scale cryogenic $PbWO_4$ detectors of about 15 g absorber mass [11]. The final detector demonstrator aims for a threshold around 1 keV with kg-scale absorbers. Following the methodology of [18] and the scaling laws in [20], this threshold is deemed achievable. Extensive R&D is ongoing to verify feasibility.

The demonstrator will consist of approximately 170 kg total mass, arranged in 84 $PbWO_4$ units, serving as a precursor to the larger RES-NOVA-1 (1.8 t) and future extensions [17].

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Each detector module comprises a $PbWO_4$ crystal coupled to a light detector (LD), typically a thin Ge absorber facing the crystal. This LD acts as a cryogenic calorimeter to detect scintillation light from the main absorber [5]. Simultaneous heat and light readout enables particle identification on an event-by-event basis [3]. Both absorbers are held by PTFE holders, which also provide a weak thermal link to the heat bath.

A preliminary detector layout is shown in Fig. 1: 84 modules arranged in three layers of 28 each, tightly packed. This design is preliminary, as the final crystal dimensions are under R&D to increase cross-sectional area from 17 cm^2 to 25 cm^2. The overall active volume is approximately $(30\ cm)^3$. While the number of modules may vary, preliminary Monte Carlo simulations indicate minimal impact on the background level in the Region of Interest (RoI). Details on expected background levels follow in the next section.

4. Background predictions

A preliminary background projection for the experiment was first outlined in [16], where the expected background level in the RoI and the physics potential of RES-NOVA phase 1 (with a total volume of $(60\ cm)^3$ corresponding to about 500 modules) were presented. Starting from a similar, but reduced active volume design, we extrapolated the achievable background level for the RES-NOVA demonstrator detector. To improve accuracy, we included not only the background sources considered previously but also extended the list of potential contributions, aiming at a comprehensive understanding of all backgrounds that could limit sensitivity to neutrinos or DM candidates.

Background sources are categorized by location: *External* (cosmic muons, environmental neutrons, and gammas in the underground lab), *Shields* (materials in detector shielding), *Detector* (bulk contamination in $PbWO_4$ crystals and structure), and *Surface* (contaminations on Cu/PTFE components facing crystals and on the crystals themselves). For *Shields*, we assumed layers of 15 cm polyethylene (PE), 15 cm modern Pb, and 7 cm high-purity Cu (including thermal radiation shielding with Cu tiles). Cosmogenic activation products in crystals and materials are neglected as secondary contributors [4]. Surface contaminations were modeled as double exponential layers with characteristic depths of 10 nm (superficial) and 10 μm (sub-superficial) [9].

We considered natural radioactive contamination from ^{232}Th and ^{238}U decay chains, including the ^{210}Pb sub-chain. Secondary radiation from these nuclides interacting with detector and infrastructure materials (e.g., electrons, Bremsstrahlung) was also included.

Simulations were performed with the Monte Carlo code *Arby*, based on the `GEANT4` toolkit [1].

Figure 2 shows the predicted total background spectrum for the RES-NOVA demonstrator, separated by background class. Detector parameters used are: energy resolution 200 eV, time resolution 0.1 ms, trigger and acquisition window 500 ms, and detector counting rate 0.1 mHz. Events are selected in anti-coincidence among detectors, requiring at least 500 ms separation.

Two operating configurations are considered: no particle discrimination ($PbWO_4$ read-out only) and 100% efficient rejection of e^- and γ events ($PbWO_4$ plus light detector read-out). This illustrates the conservative and optimistic extremes. Without discrimination, crystal intrinsic contamination dominates, despite those being upper limits rather than measured values. With full discrimination, background in the RoI improves by up to three orders of magnitude.

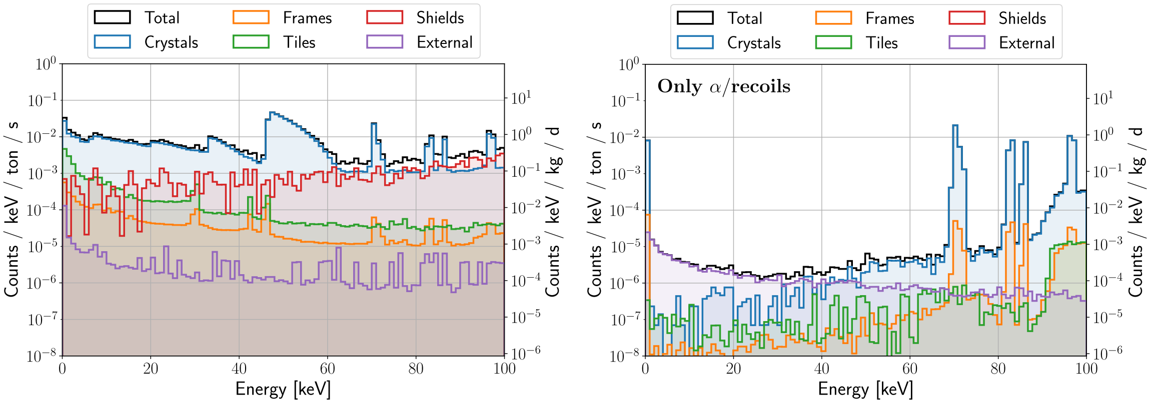

Figure 2: Background predictions in the region of interest for the RES-NOVA demonstrator (active volume $(30\text{ cm})^3$, mass 170 kg $PbWO_4$ crystals from archaeological Pb). Left: no particle discrimination ($PbWO_4$ read-out only). Right: 100% rejection of e^- and γ events using $PbWO_4$ + light detector read-out, leaving only nuclear recoils and alphas.

Results identify crystal bulk contaminations as the dominant background. The collaboration is actively working to benchmark the $PbWO_4$ crystal production. The experimental baseline aims at a background level of 10^{-3} counts/keV/ton/s[1] in coincidence mode, where more than one module triggers within about 1 s [16].

5. Sensitivity projections

We studied RES-NOVA's sensitivity to dark matter assuming 170 kg·year exposure and 200 eV energy resolution, targeting a 1 keV threshold. Sensitivities for spin-independent (SI) and spin-dependent (SD) interactions were calculated in two scenarios: conservative (no particle ID) and optimistic (100% background rejection).

This is the first projection with Pb as target. The nuclear spin of ^{207}Pb allows robust SD interaction studies beyond zero-momentum transfer approximations. Results in Fig. 3 show that background rejection significantly improves sensitivity, with more than an order of magnitude gain for a 30 GeV/c^2 WIMP at 2 ton·year exposure. RES-NOVA complements Xe-based experiments and approaches the neutrino background floor (neutrino fog) in optimistic conditions.

6. Summary

We present the dark matter detection potential of the RES-NOVA experiment, which uniquely uses radiopure archaeological Pb as an active target. After 1 year of data taking, RES-NOVA can probe DM-nucleon cross-sections down to 10^{-43} cm^2 for masses below 2 GeV/c^2, reaching 2×10^{-46} cm^2 at 20 GeV/c^2. The presence of ^{207}Pb also enables exploration of spin-dependent interactions.

An improved Monte Carlo background model supports these projections, showing that background rejection via simultaneous heat and light readout is effective. The demonstrator's sensitivity

[1]Equivalent to 0.086 counts/keV/kg/day

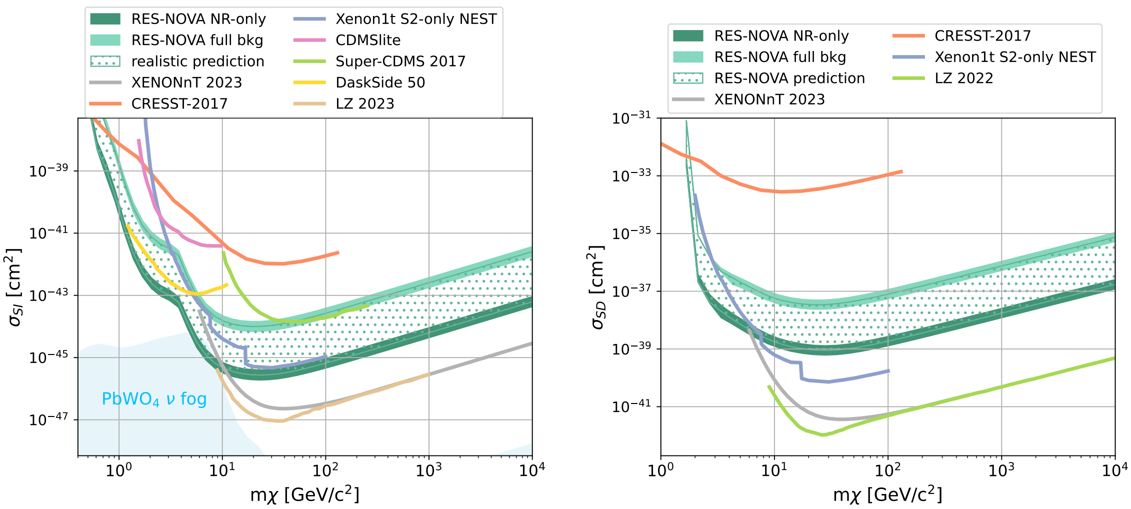

Figure 3: RES-NOVA sensitivity on dark matter cross-section for spin-independent (left) and spin-dependent (right) interactions after 1 year (170 kg·y). Light green and dark green bands show conservative and optimistic background scenarios. Limits from other experiments and the neutrino fog are also shown.

is not background limited after 1 year, and scaling up exposure promises further improvements, paving the way for larger-scale RES-NOVA detectors.

References

[1] S. Agostinelli et al. GEANT4–a simulation toolkit. *Nucl. Instrum. Meth. A*, 506:250–303, 2003. doi: 10.1016/S0168-9002(03)01368-8.

[2] A. Arbey and F. Mahmoudi. Dark matter and the early universe: A review. *Prog. Part. Nucl. Phys.*, 119:103865, 2021. ISSN 0146-6410. doi: 10.1016/j.ppnp.2021.103865.

[3] J. W. Beeman et al. New experimental limits on the alpha decays of lead isotopes. *Eur. Phys. J.*, A 49:50, 2013. doi: 10.1140/epja/i2013-13050-7.

[4] J. W. Beeman et al. Radiopurity of a kg-scale $PbWO_4$ cryogenic detector produced from archaeological Pb for the RES-NOVA experiment. *Eur. Phys. J. C*, 82(8):692, 2022. doi: 10.1140/epjc/s10052-022-10656-8.

[5] J.W. Beeman et al. Characterization of bolometric light detectors for rare event searches. *J. Instrum.*, 8(7), 2013. doi: 10.1088/1748-0221/8/07/P07021.

[6] G. Bellini et al. Cosmic-muon flux and annual modulation in borexino at 3800 m water-equivalent depth. *J. Cosmol. Astropart. Phys.*, 2012(05):015, may 2012. doi: 10.1088/1475-7516/2012/05/015.

[7] J. Billard, E. Figueroa-Feliciano, and L. Strigari. Implication of neutrino backgrounds on the reach of next generation dark matter direct detection experiments. *Phys. Rev. D*, 89:023524, Jan 2014. doi: 10.1103/PhysRevD.89.023524.

[8] J. Billard et al. Direct detection of dark matter APPEC committee report. *Rep. Prog. Phys.*, 85(5):056201, apr 2022. doi: 10.1088/1361-6633/ac5754.

[9] M. Clemenza, C. Maiano, L. Pattavina, and E. Previtali. Radon-induced surface contaminations in low background experiments. *Eur. Phys. J. C*, 71:1805, 2011. doi: 10.1140/epjc/s10052-011-1805-0.

[10] J. Engel, S. Pittel, and P. Vogel. Nuclear physics of dark matter detection. *Int. J. Mod. Phys. E*, 1:1–37, 1992. doi: 10.1142/S0218301392000023.

[11] N. Ferreiro Iachellini et al. Operation of an Archaeological Lead $PbWO_4$ Crystal to Search for Neutrinos from Astrophysical Sources with a Transition Edge Sensor. *J. Low Temp. Phys.*, 209(5-6):872–878, 2022. doi: 10.1007/s10909-022-02823-8.

[12] T. S. Kosmas and J. D. Vergados. Cold dark matter in SUSY theories. The Role of nuclear form-factors and the folding with the LSP velocity. *Phys. Rev. D*, 55:1752–1764, 1997. doi: 10.1103/PhysRevD.55.1752.

[13] Marcin Misiaszek and Nicola Rossi. Direct detection of dark matter: A critical review. *Symmetry*, 16(2):201, 2024. ISSN 2073-8994. doi: 10.3390/sym16020201.

[14] S. Navas et al. Review of particle physics. *Phys. Rev. D*, 110:030001, Aug 2024. doi: 10.1103/PhysRevD.110.030001.

[15] S. Nussinov. Technocosmology — could a technibaryon excess provide a "natural" missing mass candidate? *Phys. Lett. B*, 165(1):55–58, 1985. ISSN 0370-2693. doi: 10.1016/0370-2693(85)90689-6.

[16] L. Pattavina et al. RES-NOVA sensitivity to core-collapse and failed core-collapse supernova neutrinos. *J. Cosmol. Astropart. Phys.*, 2021(10):064, oct 2021. doi: 10.1088/1475-7516/2021/10/064.

[17] Luca Pattavina, Nahuel Ferreiro Iachellini, and Irene Tamborra. Neutrino observatory based on archaeological lead. *Phys. Rev. D*, 102(6):063001, 2020. doi: 10.1103/PhysRevD.102.063001.

[18] F. Pröbst, M. Frank, S. Cooper, P. Colling, D. Dummer, P. Ferger, G. Forster, A. Nucciotti, W. Seidel, and L. Stodolsky. Model for cryogenic particle detectors with superconducting phase transition thermometers. *J. Low Temp. Phys.*, 100(1):69–104, 1995. doi: 10.1007/BF00753837.

[19] Bernard Sadoulet. Forty years of dark matter searches. *Nucl. Phys. B*, 1003:116509, 2024. ISSN 0550-3213. doi: 10.1016/j.nuclphysb.2024.116509.

[20] R. Strauss et al. Gram-scale cryogenic calorimeters for rare-event searches. *Phys. Rev. D*, 96 (2):022009, 2017. doi: 10.1103/PhysRevD.96.022009.