PROCEEDINGS OF SCIENCE

Detecting supernova neutrinos with RES-NOVA archaeological Pb cryogenic detectors

S. Quitadamo[a,b,*] **for the RES-NOVA group of interest**

[a] *Gran Sasso Science Institute, Viale F. Crespi 7, L'Aquila, Italy*

[b] *Laboratori Nazionali del Gran Sasso, Via G. Acitelli 22, Assergi, Italy*

E-mail: simone.quitadamo@gssi.it

Core-collapse supernovae (SN) mark the end of the life of massive stars life (>8 $M_\odot$). Such a process leads to the emission of a high-intensity flux of all-flavor (anti-)neutrinos, with $\sim 10^{58}$ ν ejected within a time window of $\simeq 10$ s. SN-neutrinos carry away a large fraction of the binding energy of the progenitor star, and they are a direct probe of the stellar core. Therefore their detection would provide insights about the many processes happening during the core collapse of the star and the SN explosion.

RES-NOVA aims to deploy the first SN-ν observatory consisting in an array of cryogenic detectors made from archaeological Pb. The detection channel will be the Coherent Elastic neutrino-Nucleus Scattering (CEνNS), which provides higher cross section of interactions with respect to other detection mechanisms and also allows to be equally sensitive to all the neutrino flavours emitted during a SN. These features will allow RES-NOVA to deploy a small-scale SN-ν observatory with high sensitivity to all the (anti-)neutrinos components of a SN exploding within our galaxy.

XVIII International Conference on Topics in Astroparticle and Underground Physics (TAUP2023)
28.08-01.09.2023
University of Vienna

*Speaker

PoS(TAUP2023)219

1. Detection of SN-ν through CEνNS

Currently running SN-ν observatories are mostly sensitive to $\nu_e/\overline{\nu}_e$ interactions through inverse-β decay and elastic scattering on electrons. However during a SN explosion all (anti-)neutrinos flavors are produced (figure 1 left). In a conventional scenario [1], $\simeq\frac{2}{3}$ of the star binding energy is carried away by not-electronic (anti-)neutrinos. Therefore the developing of a detection technique highly and equally sensitive to all the neutrino flavor components would be a breakthrough in the field. Such technique can rely on the coherent elastic neutrino-nucleus scattering (CEνNS) [2]. Being a neutral-current weak process, it is equally sensitive to all $\nu/\overline{\nu}$ flavors. The cross section of CEνNS scales (for spin-0 interactions) as the square of the neutron number of the target nucleus [3]. For a Pb nucleus the CEνNS cross-section is $\sim 10^2 - 10^3$ times higher than inverse-β decay (figure 1 right), opening the possibility of a high-statistics SN-ν observation with a small-scale detector, equally sensitive to all flavors.

Since the experimental signature of CEνNS is a nuclear recoil, detectors with a low-energy threshold of $\simeq$1 keV are required. The requirement of Pb-based detectors with such a low-energy threshold can be addressed by low-temperature calorimeters operating at the mK scale [4].

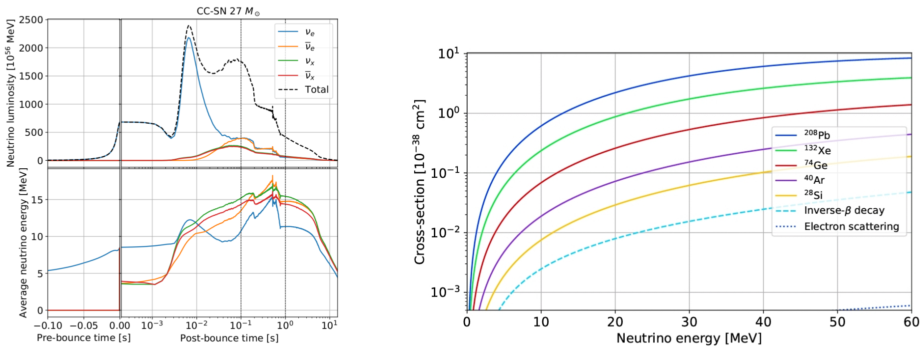

Figure 1: Left: Time evolution of ν luminosity and average ν energy for a 27 $M_\odot$ core-collapse SN occurring at 10 kpc. Right: CEνNS cross sections as a function of the incoming ν energy for different target nuclei. The cross sections for inverse-β decay and neutrino elastic scattering on electrons are also shown for comparison.

2. RES-NOVA demonstrator

The RES-NOVA project aims to deploy a SN-ν detector exploiting the CEνNS with archaeological Pb-based cryogenic detectors. The demonstrator will consist of an array of 54 $^{arch}PbWO_4$ crystals operated as low temperature calorimeters (figure 2 left) read out by Transition Edge Sensors (TESs) [4]. The RES-NOVA demonstrator will be a highly-compact detector, with a total volume equivalent to 30·30·30 cm^3, corresponding to about 150 kg of $PbWO_4$. The implementation of TESs as thermal sensors allows RES-NOVA to reach its requirements in terms of low-energy threshold ($\simeq$1 keV) and of time resolution ($\sim$100 μs). A fast time resolution brings several advantages: it reduces the pile-up of multiple signals in case of a near-by SN detection, it allows performing coincidence analysis between different crystals for background reduction [5], and it provides a prompt alert to the community in case a SN event takes place [6].

RES-NOVA is proposed to be installed underground at the Gran Sasso National Laboratory (LNGS, Italy) to suppress the cosmic rays-induced background. In order to increase the sensitivity to farther SN, the intrinsic background of the crystals must also be suppressed. Ultra-low background level in the region of interest ($\lesssim$30 keV of nuclear recoil energy) can be achieved by using ^{arch}Pb for the crystals production. The advanced lead purification techniques implemented by ancient Romans and Greeks [7] led to the reduction of the amount of long-living isotopes belonging to the natural decay chains in the lead samples. Moreover, during the long cool-down time passed from the lead purification to nowadays ($\simeq$2000 years), the concentration of many short-living isotopes underwent multiple halvings, accordingly to their half-life. The main background source in $PbWO_4$ crystals made from modern lead comes from ^{210}Pb, produced by the ^{238}U decay chain. The separation of ^{210}Pb in lead samples is difficult due to their chemical affinity. ^{210}Pb contamination in lead can effectively be reduced only through a cool-down time on the time scale of its half-life (22 years). Therefore ^{arch}Pb features radiopurity levels which can not be reached by modern low-background lead, in particular regarding ^{210}Pb [8] [9]. The implementation of ^{arch}Pb-based detectors allows RES-NOVA to aim for a target background index of $\sim 10^{-3}\ \frac{\text{counts}}{\text{keV}\cdot\text{ton}\cdot\text{s}}$, which could not be achieved with detectors made from modern lead (figure 2 right).

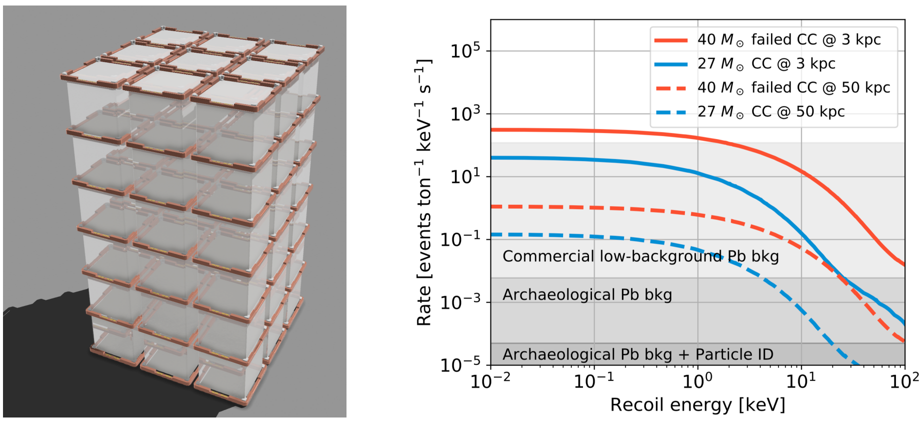

Figure 2: Left: Model of the RES-NOVA demonstrator. Right: Comparison between the expected signal rate from different SN events and the expected background rate in different types of lead samples (represented by the different shades of gray).

3. RES-NOVA sensitivity

Thanks to the high cross section of CEνNS on lead and to the high radiopurity of ^{arch}Pb, even a small scale detector as the RES-NOVA demonstrator can scan 90% of galactic SN candidates, namely up to a distance of $\simeq$20 kpc (figure 3) [10]. The highly modularity of the detector and its fast time resolution granted by TES read-out make RES-NOVA suitable also for the detection of nearby SN by reducing the impact of pile-up.

In order to increase the sensitivity to farther SN candidates, the future upgrades of RES-NOVA will focus on scaling up the active volume of the detector (figure 3). Nevertheless these upgrades will be very compact detectors if compared with currently running SN-ν observatories, and they will allow to reconstruct the main SN parameters with comparable precision [10].

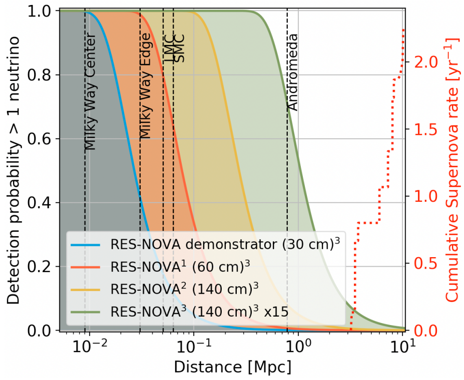

Figure 3: Neutrino detection probability as a function of the SN distance for a benchmark SN model (27 $M_\odot$). The colors refers to the three different RES-NOVA phases. The red dashed line shows the cumulative SN rate.

4. Conclusions

RES-NOVA is a newly proposed observatory for SN-ν, which will exploit the CEνNS with ^{arch}Pb-based low-temperature calorimeters for intrinsic background suppression. The CEνNS will allow to deploy highly-compact detectors which will be sensitive to the total ν flux emitted by most of the galactic SN candidates. RES-NOVA can therefore contribute in achieving the first simultaneous detection of gravitational waves, electromagnetic counterpart and neutrino signals coming from a SN, leading to major breakthroughs in multi-messenger astronomy. At the present time, RES-NOVA is the only European planned neutrino observatory solely dedicated for SN neutrino studies.

References

[1] A. Mirizzi, I. Tamborra, H.-Th. Janka, N. Saviano, K. Scholberg, R. Bollig, L. Hüdepohl, S. Chakraborty, Supernova neutrinos: Production, oscillations and detection. La Rivista del Nuovo Cimento 39 (2016). DOI:10.1393/ncr/i2016-10120-8.

[2] D. Akimov et al., Observation of coherent elastic neutrino-nucleus scattering. Science 357, 1123-1126 (2017). DOI:10.1126/science.aao0990.

[3] K. Scholberg, Prospects for measuring coherent neutrino-nucleus elastic scattering at a stopped-pion neutrino source. Phys. Rev. D 73, 033005 (2006). DOI:10.1103/PhysRevD.73.033005.

[4] S. Pirro, P. Mauskopf, Advances in Bolometer Technology for Fundamental Physics. Annu. Rev. Nucl. Part. Sci. 67, 161-181 (2017). COI:10.1146/annurev-nucl-101916-123130.

[5] L. Pattavina et al. (RES-NOVA), RES-NOVA sensitivity to core-collapse and failed core-collapse supernova neutrinos, JCAP 10, 064. DOI:10.1088/1475-7516/2021/10/064.

[6] P. Eller et al., Online triggers for supernova and pre-supernova neutrino detection with cryogenic detectors. JCAP 10 (2022) 024. DOI: 10.1088/1475-7516/2022/10/024.

[7] G. Jones, The Roman Mines at Riotinto. The Journal of Roman Studies, 70, 146-165 (1980). DOI:10.2307/299560.

[8] J. W. Beeman et al. (RES-NOVA Group of Interest), Radiopurity of a kg-scale PbWO4 cryogenic detector produced from archaeological Pb for the RES-NOVA experiment, Eur. Phys. J. C 82, 692 (2022). DOI:10.1140/epjc/s10052-022-10656-8.

[9] L. Pattavina, J. W. Beeman, M. Clemenza, et al., Radiopurity of an archaeological Roman lead cryogenic detector. Eur. Phys. J. A 55, 127 (2019). DOI:10.1140/epja/i2019-12809-0.

[10] L. Pattavina, N. F. Iachellini, I. Tamborra, Neutrino observatory based on archaeological lead. Phys. Rev. D 102, 063001 (2020). DOI: 10.1103/PhysRevD.102.063001.