New results from CONNIE with Skipper-CCDs at the Angra-2 reactor

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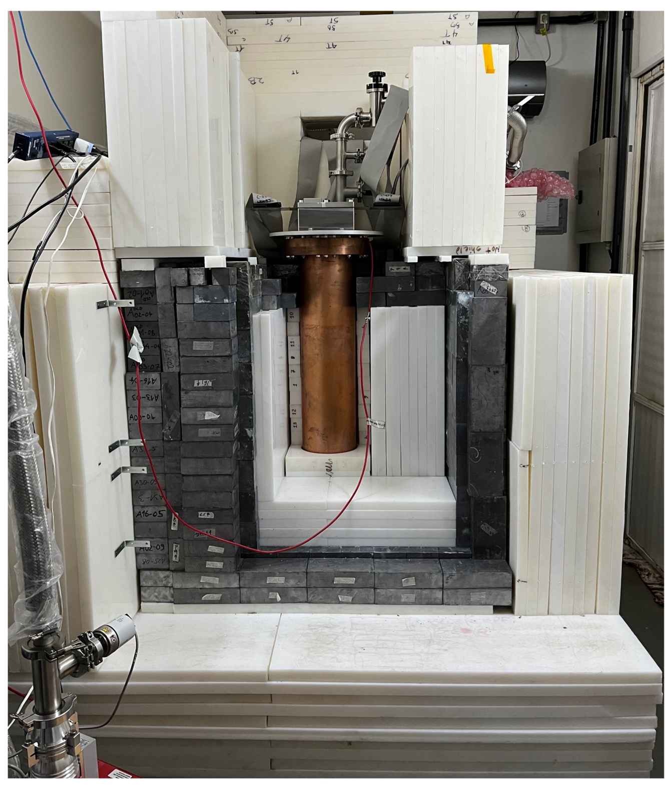
The CONNIE detector

The Coherent Neutrino-Nucleus Interaction Experiment (CONNIE) aims to measure the coherent elastic scattering (CEνNS) of reactor anti-neutrinos off silicon nuclei in CCDs and probe physics beyond the standard model [1,2]. Located at 30 m from the core of the 3.8 GW Angra-2 reactor in Angra dos Reis, Brazil, it receives a flux of 7.8×10^{12} $\bar{\nu}_e$/s cm².

CONNIE site at the Almirante Álvaro Alberto nuclear power plant in Angra dos Reis, Brazil



View of the CONNIE detector setup

The silicon CCD sensors are kept in a vacuum vessel at ~100 K. A Low Threshold Acquisition board [3] is used for control and data acquisition. The CCDs collect data by getting continuously read out without prior exposure.

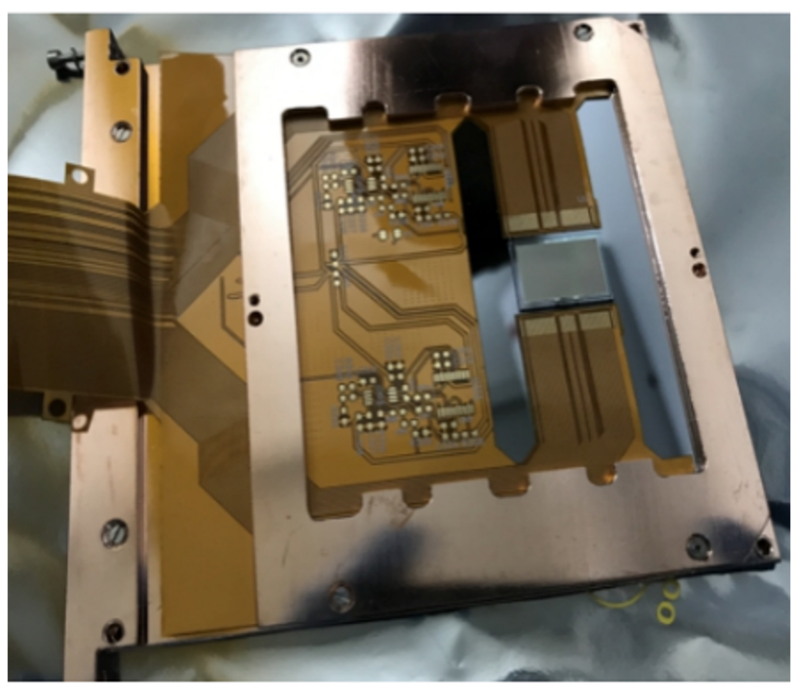
The detector is surrounded by passive shielding: outer and inner 30 cm polyethylene layers to block neutrons and a 15 cm layer of lead to block photons.

In July 2021 two Skipper-CCDs were installed in CONNIE and the results [4] are presented here.

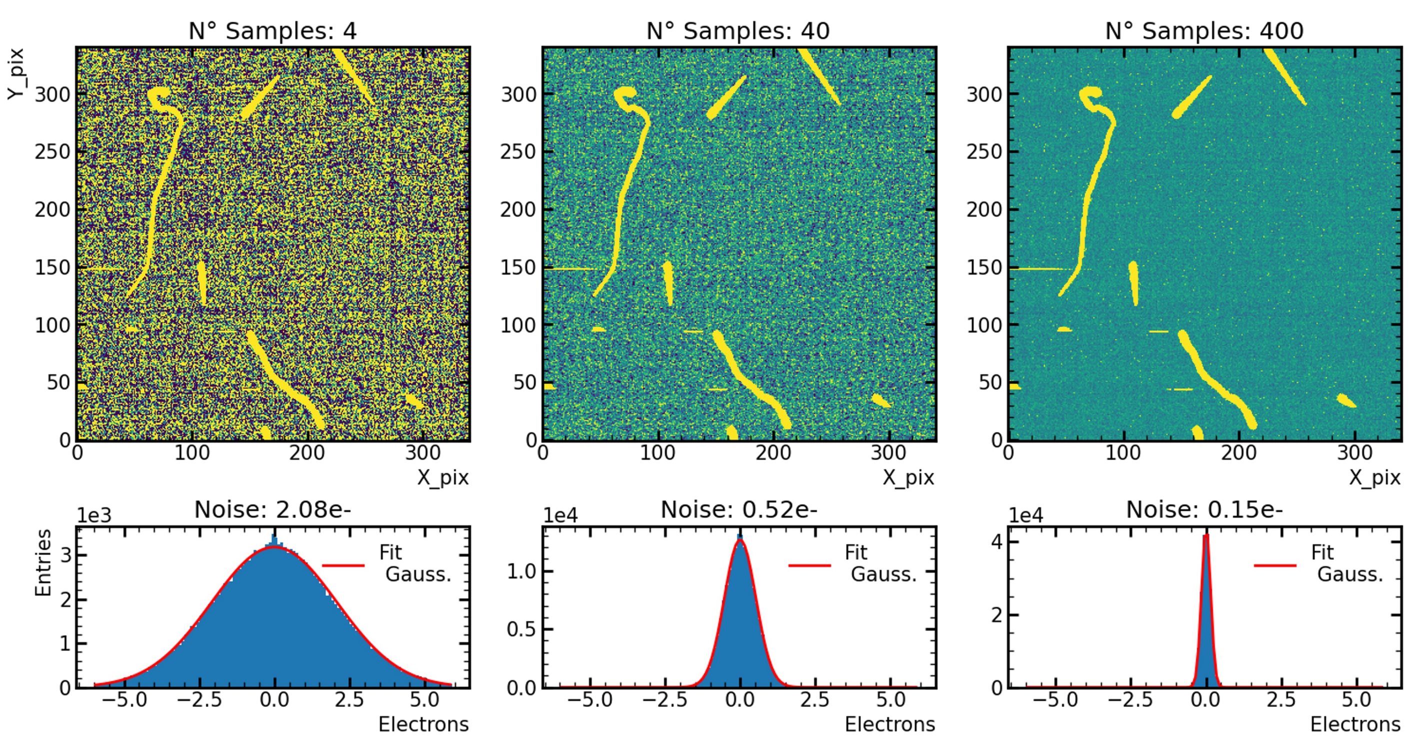
Skipper-CCDs

Skipper-CCDs are pixelated arrays of MOS devices. A non-destructive sequential readout stage enables multiple charge samplings in each pixel, reducing the readout noise to sub-electron levels [5]. This allows to lower the detection energy threshold and optimise their sensitivity to low energies for detecting CEνNS.

The two Skipper-CCDs at CONNIE have 1022×682 pixels of 15×15 μm² each, and a thickness of 675 μm. They are read out with 400 samples per pixel.

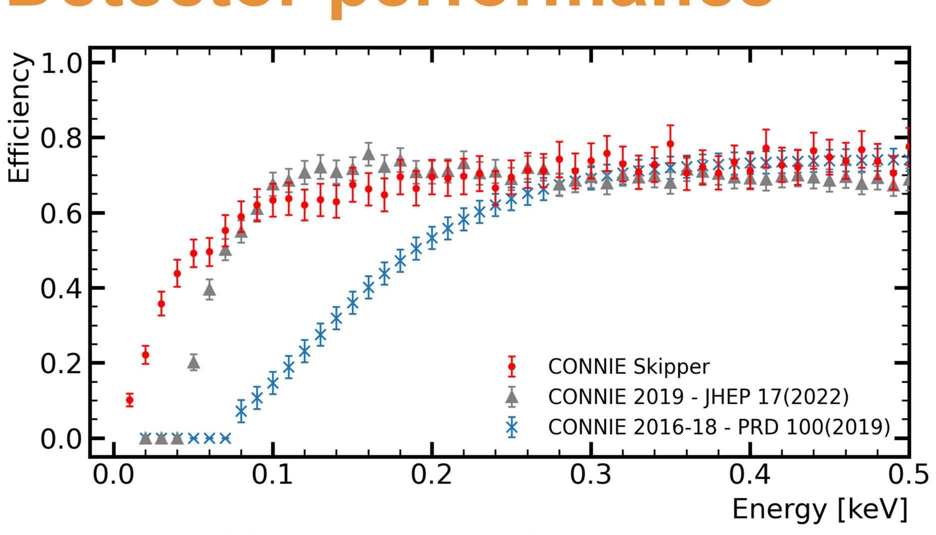


One of the CONNIE Skipper-CCDs



Impact of the number of samples on the sharpness of the image and the readout noise

Detector performance



CONNIE detection efficiency [4]

CONNIE took data with two Skipper-CCDs of 0.25 g total active mass in 2021–2023. The detectors showed stable operation and low noise.

The overall detection efficiency accounts for the event extraction acceptance and the selection cuts. Based on the efficient operation and selection performance at low energies, the threshold was reduced to 15 eV.

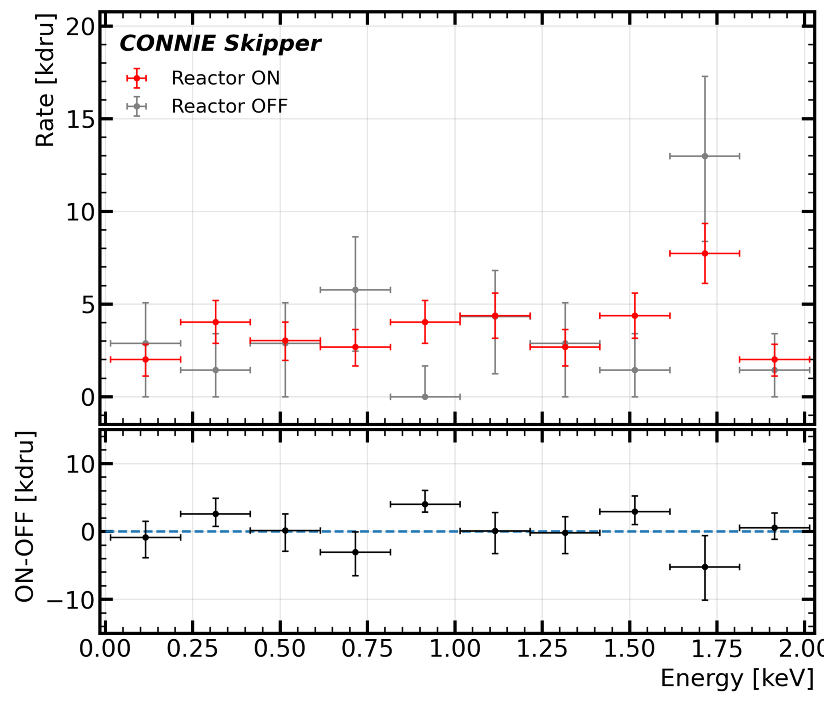
The sensors achieved an ultra-low noise of 0.15 e-, and a good single-electron rate of 0.045 e-/pix/day, considering the surface location.

The background is measured in reactor-OFF periods, resulting in a flat rate of ~5 kdru at the lowest energies.

Reactor Periods	Readout Time	Exposure Time	Total Exposure
OFF	1.1 months	17 days	3.5 g-day
ON	5 months	75 days	14.9 g-day

Dataset used in the analysis [4]

Search for CEνNS



Reactor-ON and OFF spectra and their difference [4]

Reactor-ON and OFF spectra are measured after applying the data selection and quality criteria. The spectra are consistent between the two periods, and their rate difference is compatible with zero.

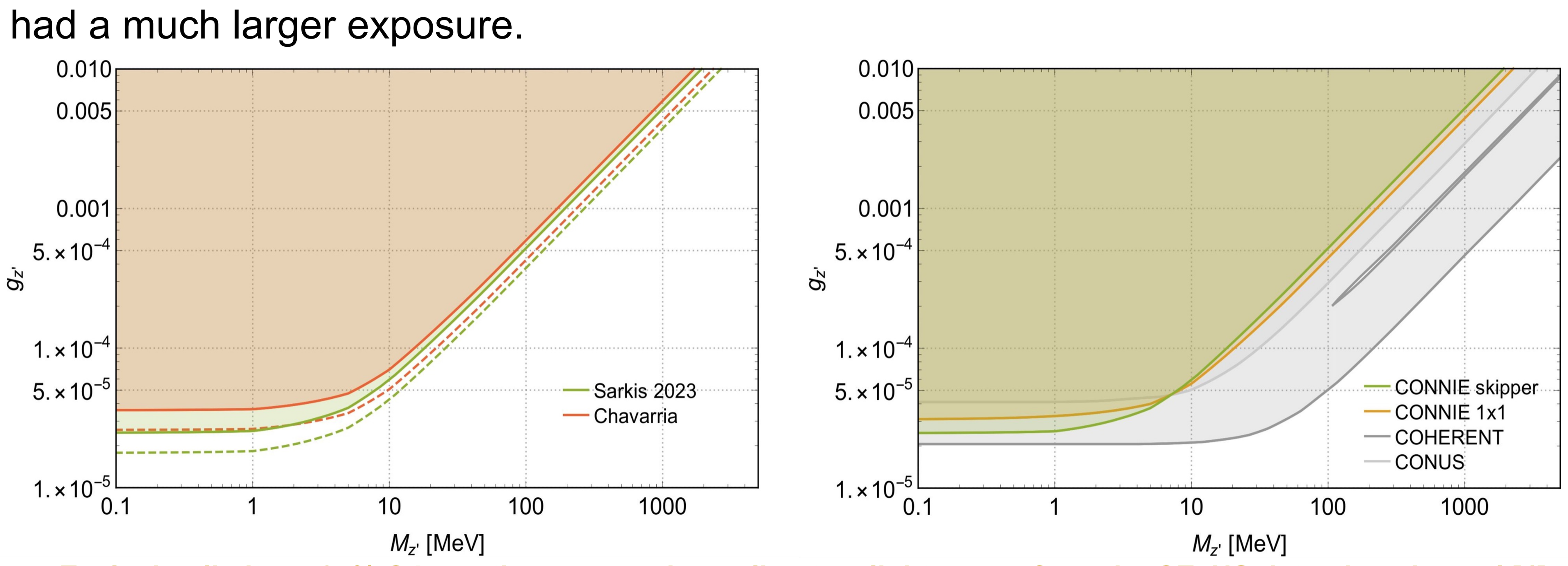
A 95% C.L. upper limit is established on the observed event rates [4]. It is compared to the predicted SM rates, calculated using a new Sarkis quenching factor model [6]. The limits are comparable to the previous [7], based on a much larger exposure, and extend the sensitivity to a record low energy of 15 eV.

Measured Energy [keV$_{ee}$]	Sarkis (2023) rate [kg^{-1}d^{-1}keV$_{ee}$$^{-1}$]	Chavarria rate [kg^{-1}d^{-1}keV$_{ee}$$^{-1}$]	Observed 95% C.L. [kg^{-1}d^{-1}keV$_{ee}$$^{-1}$]	Expected 95% C.L. [kg^{-1}d^{-1}keV$_{ee}$$^{-1}$]
0.015 − 0.215	$29.3^{+4.6}_{-4.7}$	17.7 ± 3.3	2.24 × 10³	3.18 × 10³
0.215 − 0.415	$2.70^{+1.3}_{-1.2}$	2.20 ± 0.21	7.36 × 10³	4.77 × 10³
0.415 − 0.615	$0.43^{+0.41}_{-0.39}$	0.36 ± 0.04	3.41 × 10³	3.31 × 10³

CEvNS expected event rates and resulting limits [4]

Light vector mediator search

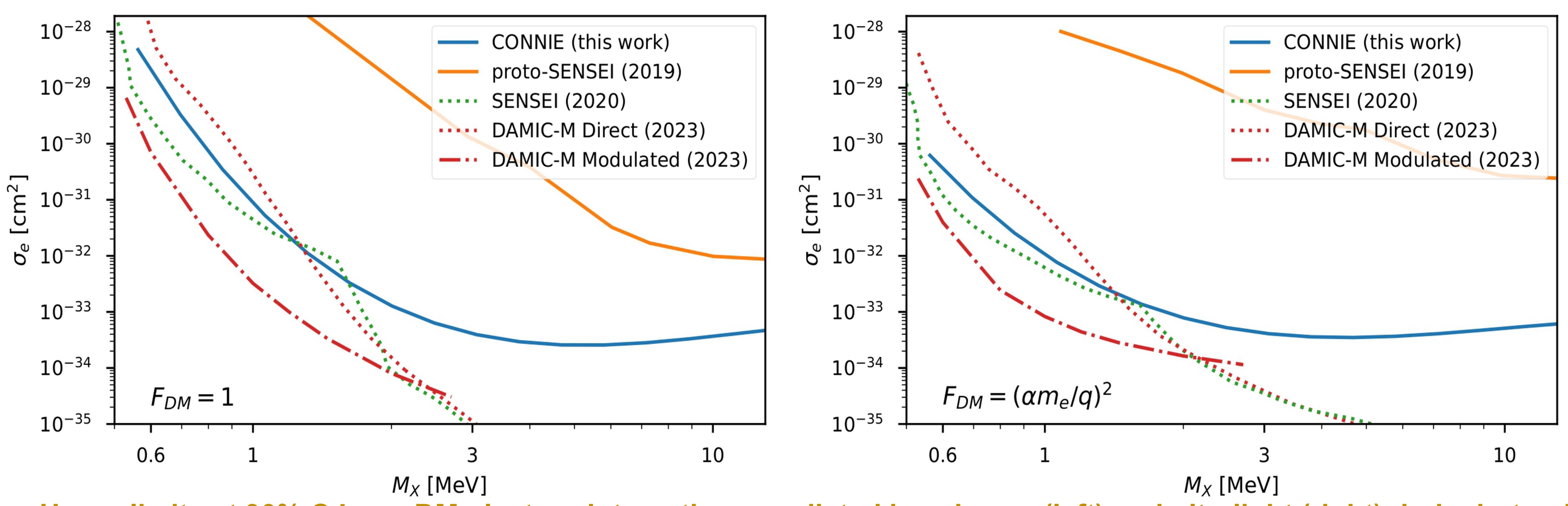
The event rate in the lowest-energy bin is used to constrain the parameter space of a simplified model with a new light vector mediator *Z’*, using the CEνNS detection channel. The exclusion limit represents an improvement to our previous result [2] which had a much larger exposure.



Exclusion limits at 95% C.L. on the mass and coupling to a light vector from the CEνNS detection channel [4]

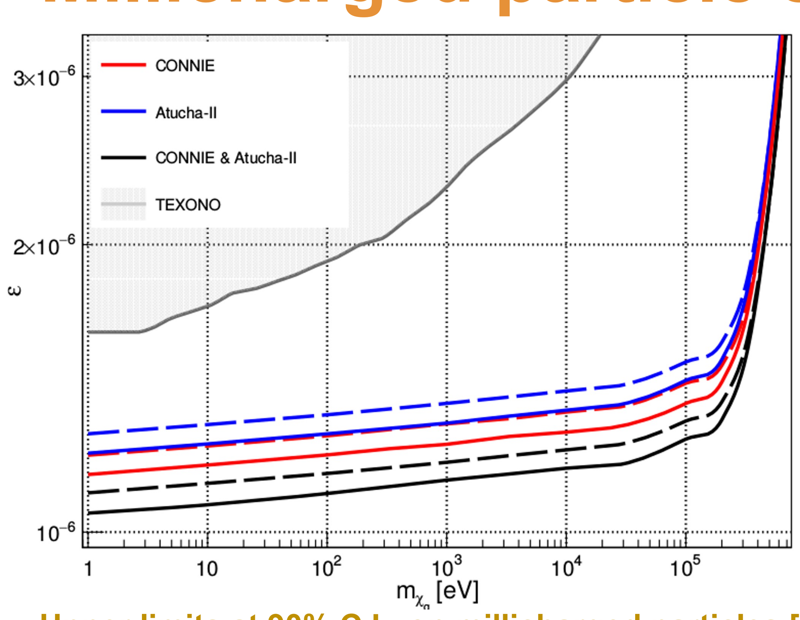
Dark matter search by diurnal modulation

A first search for dark matter (DM) by diurnal modulation by CONNIE is performed by comparing the event rates as a function of the isodetection angle, in order to constrain models with MeV-scale DM, which couple to SM particles via a kinetically-mixed dark photon (*A′*). The study [4] imposes the best limits on the DM-electron scattering cross-section, obtained by a surface-level experiment, for heavy and ultralight *A′*.



Upper limits at 90% C.L. on DM-electron interactions mediated by a heavy (left) and ultralight (right) dark photon [4]

Millicharged particle search

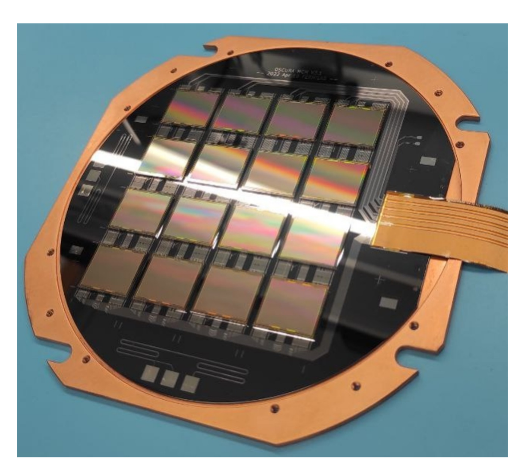


Upper limits at 90% C.L. on millicharged particles [8]

Relativistic millicharged particles (χ_q) can be pair-produced by high-energy photons in the reactor core. Their interaction with the sensor via atomic ionisation can be strongly enhanced at low energies thanks to a plasmon peak. A search for millicharged particles is performed in collaboration with the Atucha-II experiment which also uses Skipper-CCDs. It yields the most restrictive limit on the χ_q charge within a mass range spanning six orders of magnitude [8].

Perspectives

In May 2024, a Multi-Chip-Module (MCM) of Skipper-CCDs was successfully installed at the CONNIE experiment. The MCM, designed for the Oscura experiment [9], contains 16 sensors in a compact arrangement, resulting in a 32-fold increase in sensor mass. We estimate that a future 1-kg detector with the current detection parameters could detect CEνNS at 90% C.L. in two months.



MCM for CONNIE, design by Oscura [9]

Acknowledgments

Eletronuclear, FAPERJ, CNPq

References

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[3] G. Cancelo et al., JATIS 7, 1 015001 (2021).
[4] CONNIE Collaboration, **arXiv:2403.15976** (2024).
[5] J. Tiffenberg et al., Phys. Rev.Lett. 119, 131802 (2017).
[6] Y. Sarkis et al., Phys. Rev. A 107, 062811 (2023).
[7] CONNIE Collaboration, J. High. Energ. Phys. 05, 17 (2021).
[8] CONNIE and Atucha-II Collaborations, **arXiv.2405.16316** (2024).
[9] OSCURA Collaboration, JINST 18 P08016 (2023).

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