New results on searches for CEνNS and Physics Beyond the Standard Model using Skipper-CCDs at CONNIE

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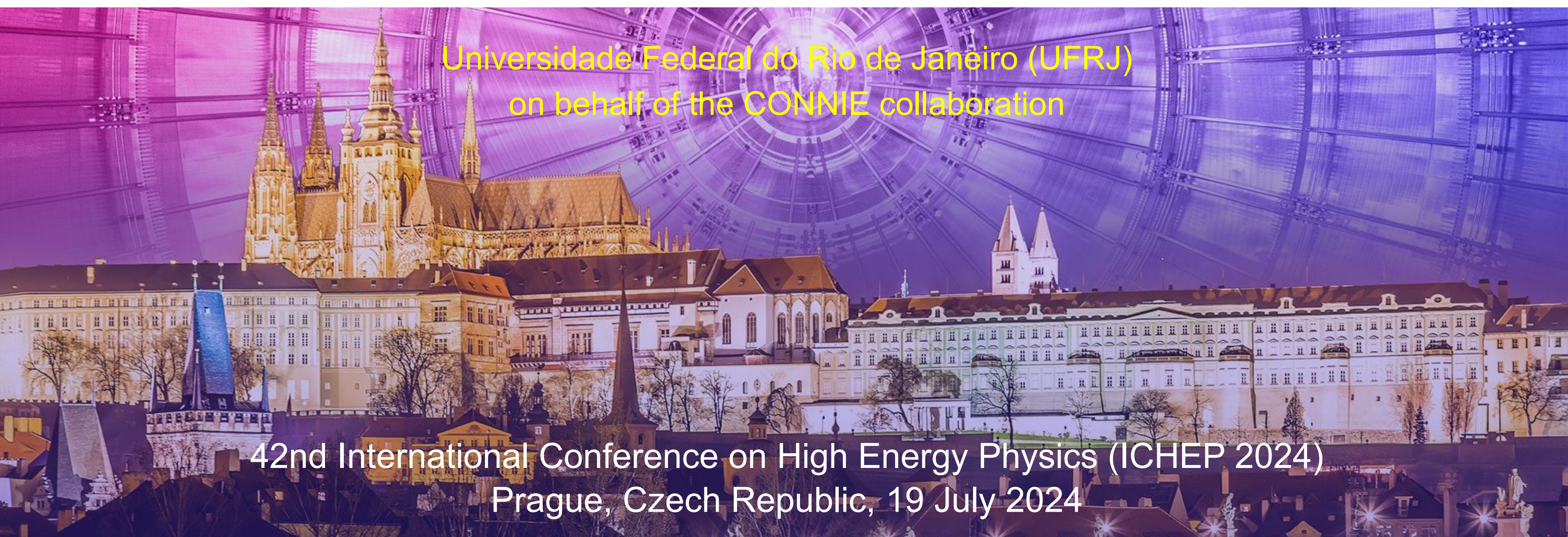
on behalf of the CONNIE collaboration



42nd International Conference on High Energy Physics (ICHEP 2024)
Prague, Czech Republic, 19 July 2024

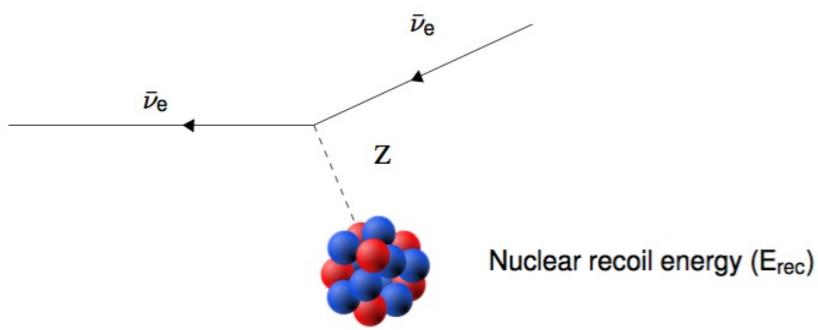
Coherent elastic νN scattering

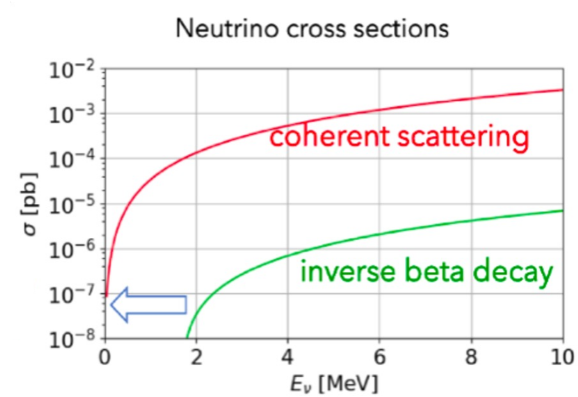
- In the Coherent Elastic Neutrino-Nucleus Scattering (CEνNS) interaction, the neutrino scatters off the nucleus as a whole.
- Predicted in the Standard Model in 1974.

D. Freedman, Phys.Rev. D 9 1389 (1974)
V.B. Kopeliovich and L.L. Frankfurt, JETP Lett. 19 4 236 (1974)

- Discovered by COHERENT in 2017 with a pulsed neutrino beam (SNS, E_ν ~30 MeV) and CsI, and later LAr and Ge detectors.

Science 357 1123, 2017; PRL 129 8, 081801, 2022; PRL, 126, 012002, 2021, arXiv: 2406.13806





R. Strauss, M7s2021

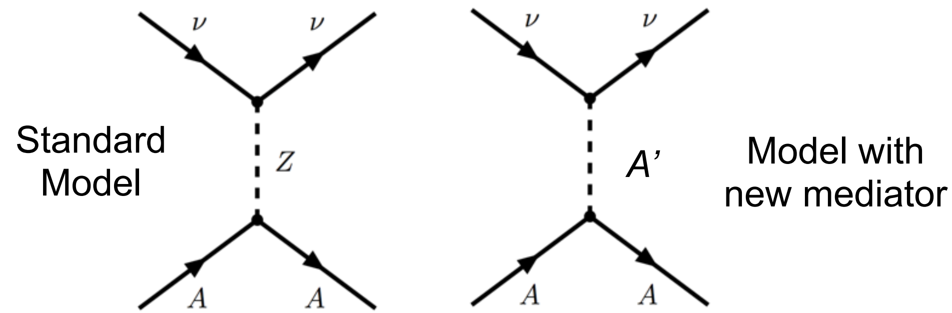
$$\frac{d\sigma(E_\nu, E_{nr})}{dE_{nr}} = \frac{G_F^2 M_n}{\pi}\left(1 - \frac{M_n E_{nr}}{2E_\nu^2}\right)\left[g_V^p(\sin^2\theta_w) Z F_Z(|q^2|) + g_V^n N F_N(|q^2|)\right]^2$$

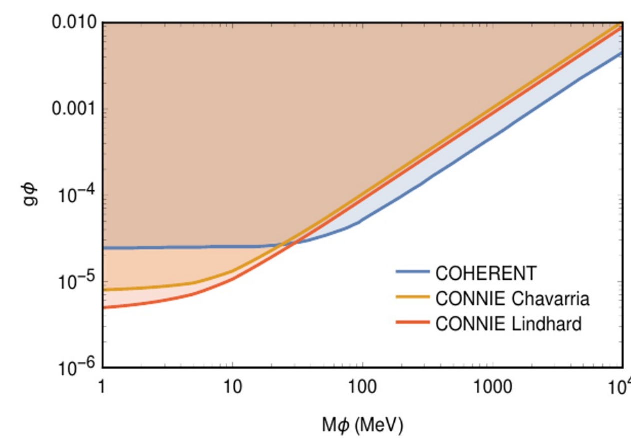
$$g_V^p = \frac{1}{2} - 2\sin^2\theta_w \cong 0.0227 \qquad g_V^n = -\frac{1}{2}$$

- Coherent enhancement for E_ν < 50 MeV.
- Nuclear form-factor is f(q) ≈ 1 for low energies.
- Reactor neutrinos with E_ν ~1 MeV can probe new physics at low energies.

Physics with CEνNS

- EW precision tests
  - Weak mixing angle
- New neutrino interactions
  - Nonstandard interactions
  - Generalised interactions
  - New mediators
- Neutrino properties
  - Neutrino charge radius
  - Neutrino magnetic moments
- Nuclear physics
  - Nuclear form factors
  - Neutron radius and skin
- Supernovae
- Solar neutrinos
- Sterile neutrinos
- Dark matter
- Nuclear nonproliferation and safeguarding



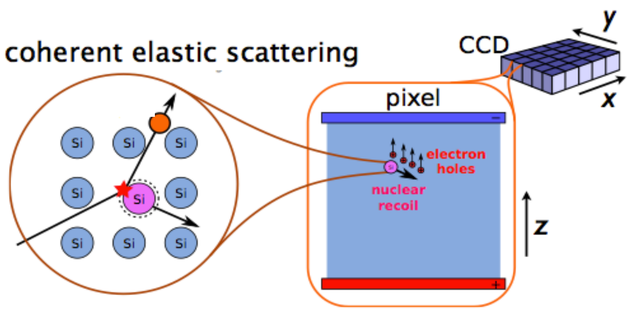


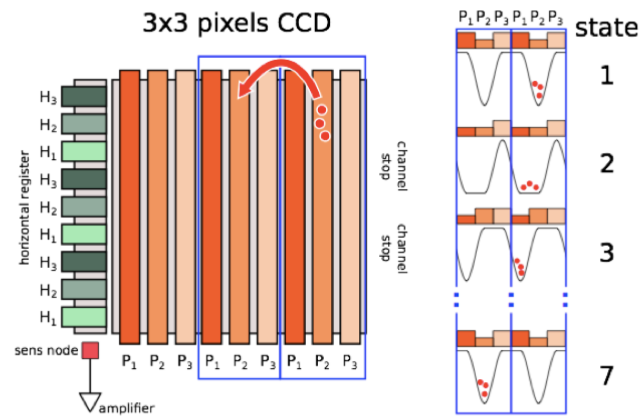
CONNIE, JHEP 04 (2020) 054

The CONNIE experiment

PRD 100 (2019) 092005

- Coherent Neutrino-Nucleus Interaction Experiment.
- Thick fully depleted scientific CCD detectors made from high-resistivity silicon.
  - Charges are collected in the pixel potential wells and read out sequentially.
  - Low noise and low single-electron rate.
  - Low-energy detection threshold.





~35 members

CONNIE collaboration:

Centro Atómico Bariloche, Universidad de Buenos Aires, Universidad del Sur / CONICET, Centro Brasileiro de Pesquisas Físicas, Universidade Federal do Rio de Janeiro, CEFET – Angra, Universidade Federal do ABC, Instituto Tecnológico de Aeronáutica, Universidad Nacional Autónoma de México, Universidad Nacional de Asunción, University of Zurich, Fermilab

The CONNIE experiment

- CONNIE is located next to the Angra 2 reactor at the Almirante Álvaro Alberto nuclear power plant, near Rio de Janeiro, Brazil.

The CONNIE experiment

- At around 30 m from the nucleus of the 3.95 GW_{th} Angra 2 reactor.
- Shared lab with the Neutrinos Angra experiment.
- Antineutrino source with flux of $7.8 \times 10^{12}\ \bar{\nu} s^{-1} cm^{-2}$ at the detector position.

CONNIE detector

CCDs
in copper box

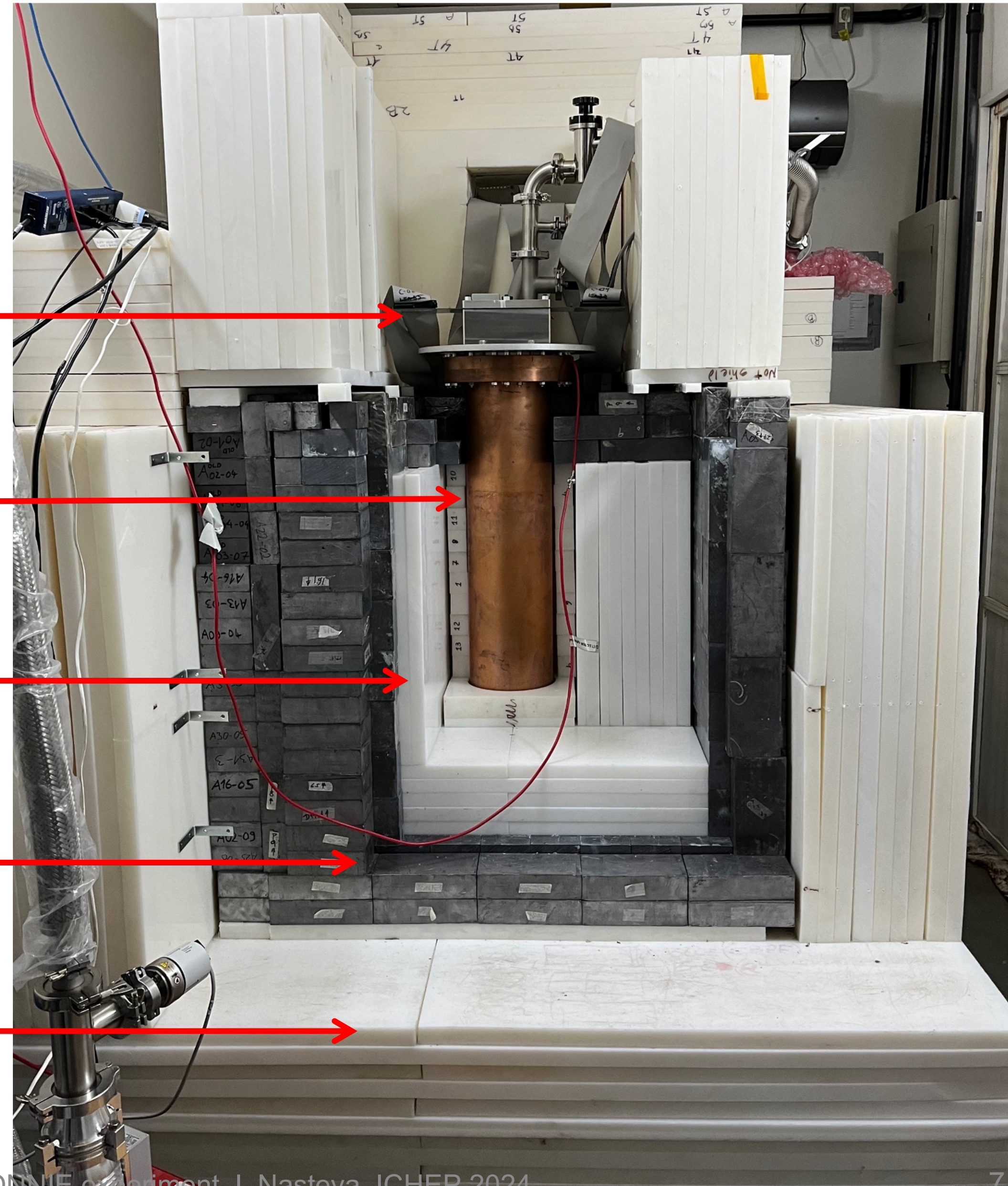
ViB readout board
(signal transport)

Dewar
(vacuum)

Inner Polyethylene – 30 cm
(neutrons)

Lead – 15 cm
(gamma)

Outer Polyethylene – 30 cm
(neutrons)



CONNIE experiment timeline

NEW Search for reactor-produced millicharged particles with Skipper-CCDs [arXiv: 2405.16316]

NEW Searches for CEvNS and Physics beyond the Standard Model using Skipper-CCDs [arXiv: 2403.15976]

Results from engineering run [JINST 11 (2016), P07024]

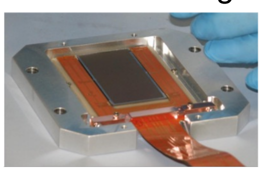
Results from 2016-2018 run **[PRD 100 (2019), 092005]**

Results from 2019 run **[JHEP 05 (2022), 017]**

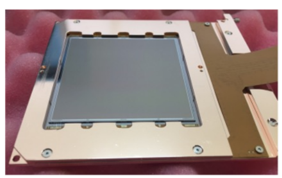
2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024

Engineering run | 2016-2018 (1x1) run | 2019 (1x5) run | Skipper-CCD run

Installation at Angra

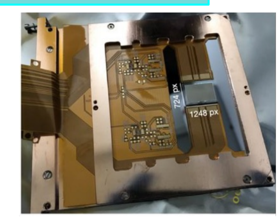


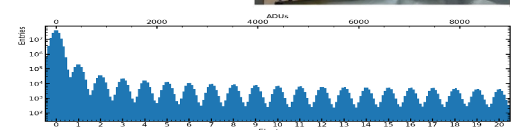
Installation of scientific CCDs



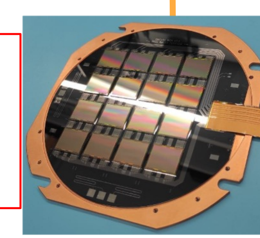
Limits on SM extensions with light mediators **[JHEP 04 (2020), 054]**

Installation of Skipper-CCDs



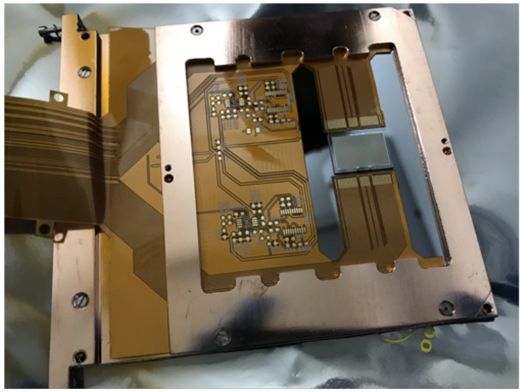


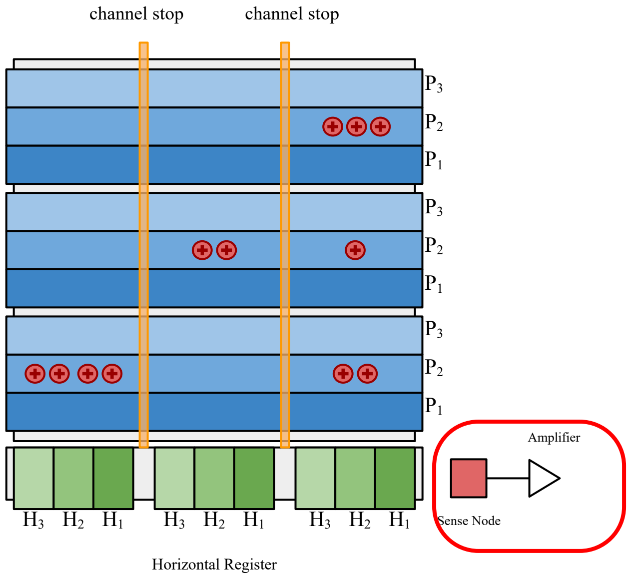
New: Installation of a Multi-Chip Module with Skipper-CCDs, May 2024
32x increase in mass

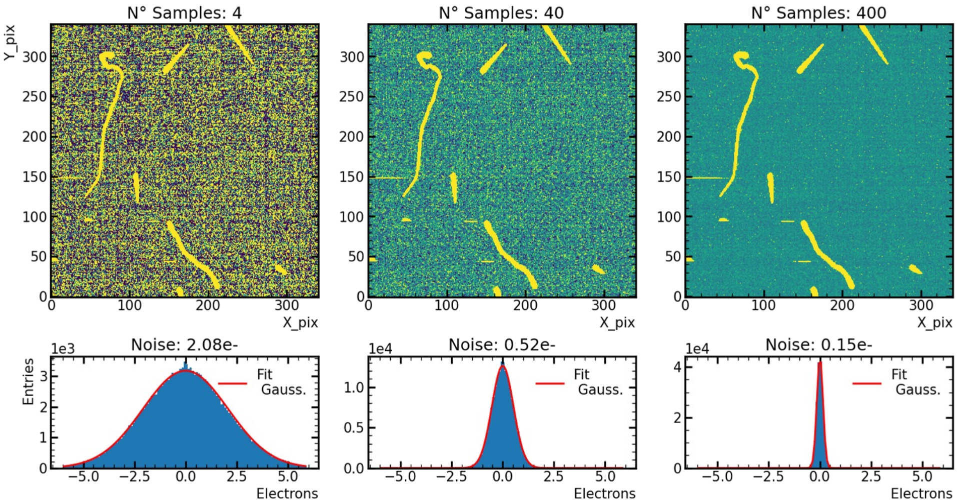


Skipper-CCD sensors

- Skipper-CCD sensors allow to reach very low energies:
  - Repeated non-destructive charge measurement.
  - Sub-electron noise levels. J. Tiffenberg et al, PRL 119 (2017)
  - Individual electron detection.







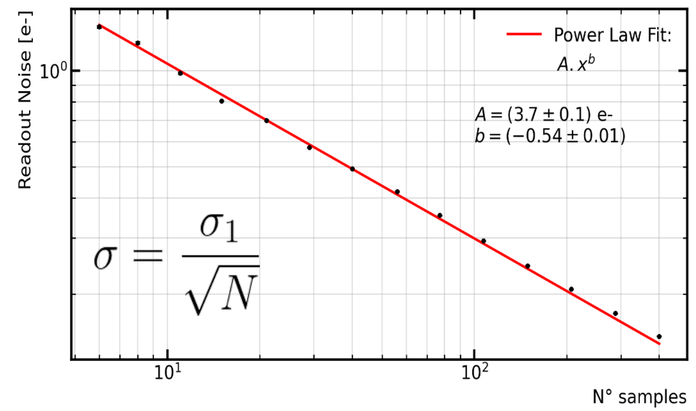
- Two Skipper-CCDs were installed at the CONNIE setup in July 2021.
  - 1022 x 682 pixels, 15 x 15 μm^2 each, 675 μm thickness, 0.5 g total mass.
  - Low Threshold Acquisition readout electronics. G. Cancelo et al, JATIS 7 (2021), 1 015001

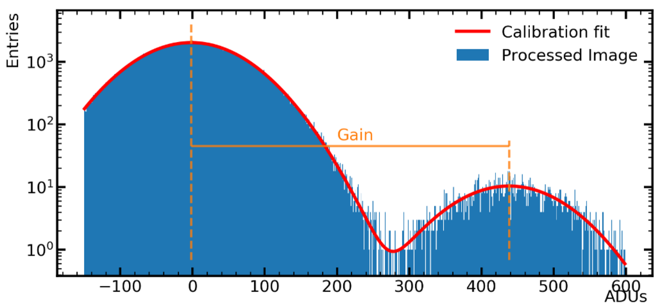
Skipper-CCD performance

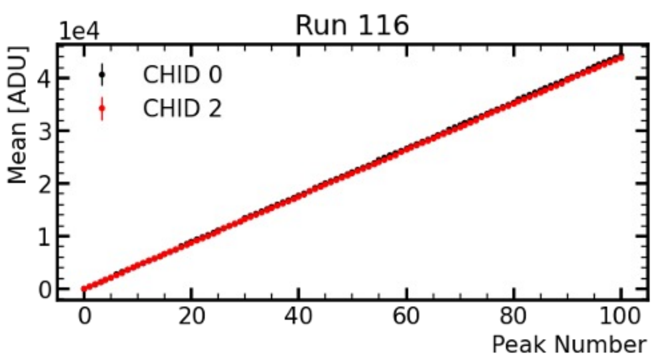
arXiv: 2403.15976

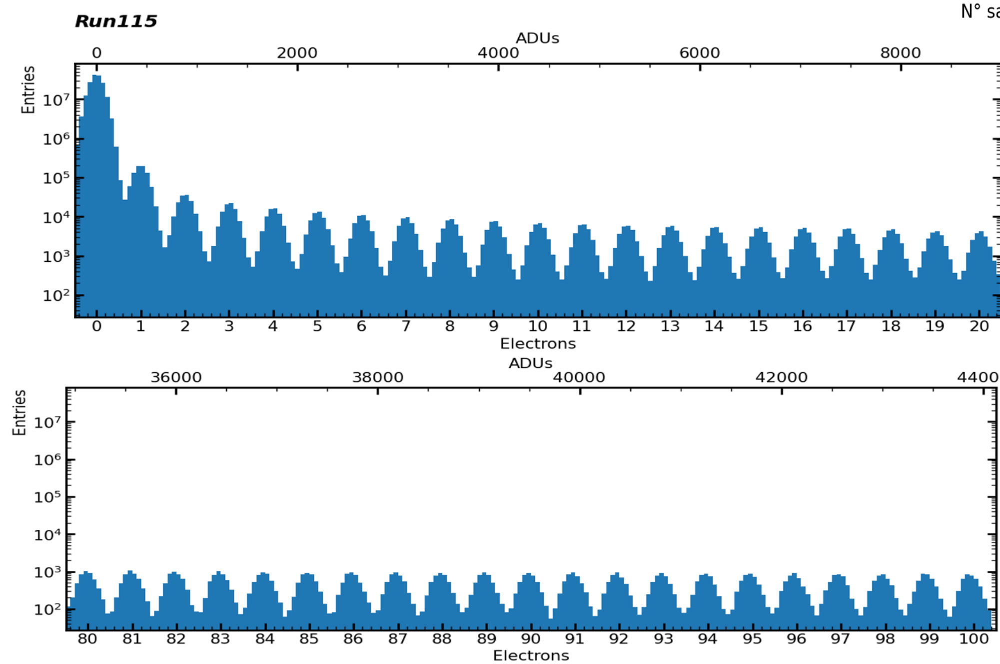
Stable detector performance and background over the 2021-2022 period.

- Each pixel charge is read out with N = 400 samples.
- Ultra-low noise = 0.15 e-.
- Self-calibrated detector.
- Single-electron rate = 0.045 e-/pix/day (low for surface).







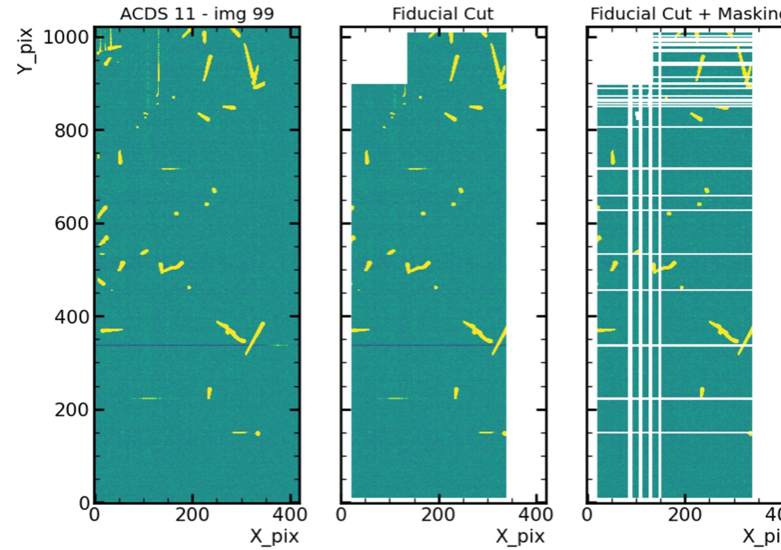


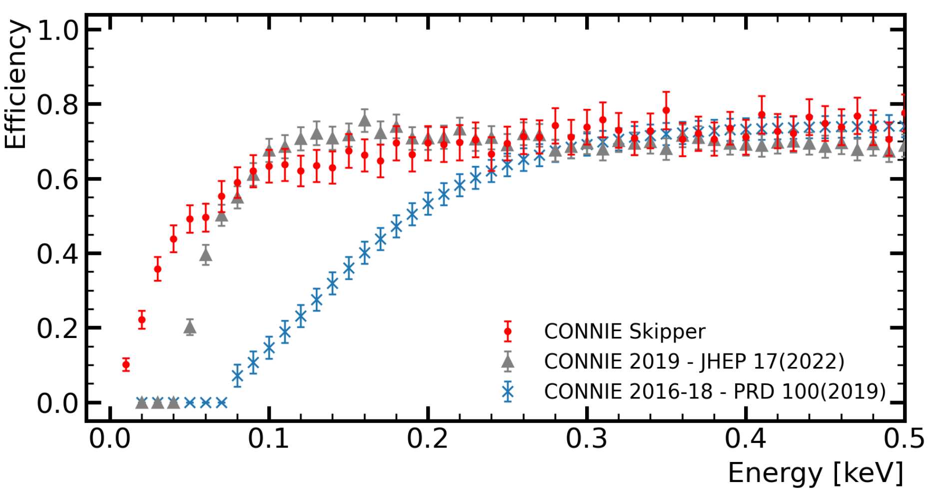
Selection and efficiency

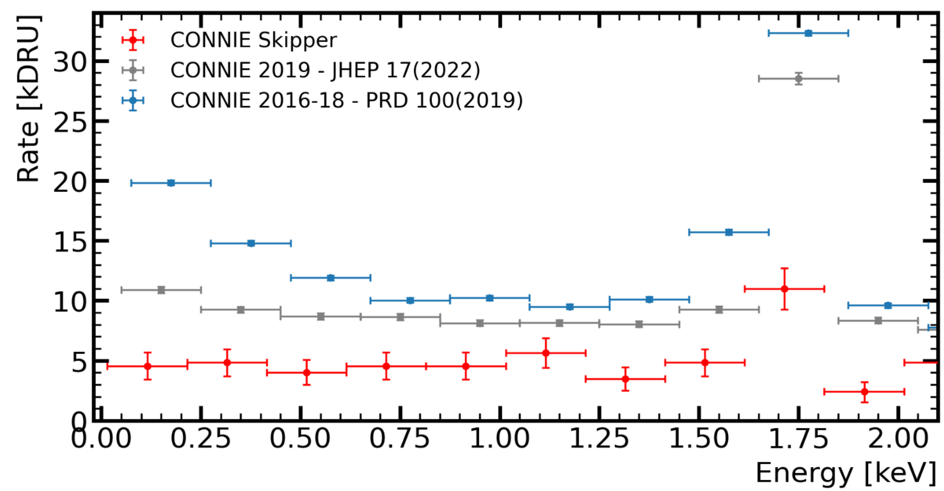
arXiv: 2403.15976

Stable detector performance and background over the 2021-2022 period.

- Event extraction and selection:
  - Excluding sensor edges,
  - Masking hot columns/rows/serial register,
  - Data quality: Noise < 0.17 e-, SER < 0.14 e-/pix/day,
  - Event size: diffusion 0.20 < $\sigma_{X,Yfit}$ < 0.95 pix.
- Efficiency determination using simulations.
- Allows to lower the threshold to 15 eV.
- Lower and flat background rate ≅ 5 kdru.







CEνNS search

arXiv: 2403.15976

Comparison between the reactor-on and reactor-off event rates.

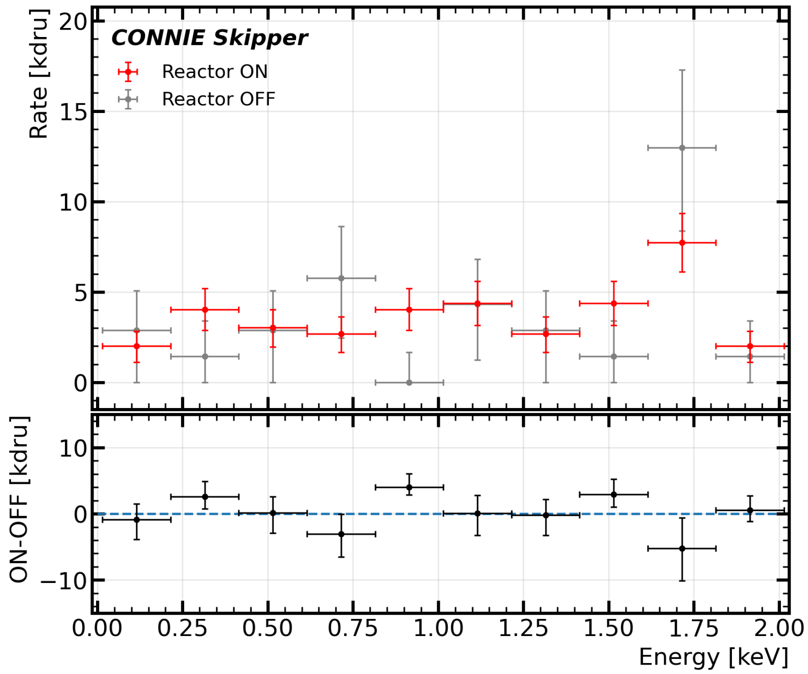
- Data taken during 300 days in 2021-2022.
- Exposure: 14.9 (3.5) g-days reactor-on(off).

A search for CEνNS in the lowest-energy bins.

- Updated reactor neutrino flux model.
- Updated Sarkis quenching factor model for Si.

Phys. Rev. A 107, 062811 (2023)

- Observed limit at 76x the SM predicted rate.
- Comparable to our previous limit with standard CCDs and 10^3 larger exposure.



Measured Energy $[\mathrm{keV_{ee}}]$	Sarkis (2023) rate $[\mathrm{kg^{-1}d^{-1}keV_{ee}^{-1}}]$	Chavarria rate $[\mathrm{kg^{-1}d^{-1}keV_{ee}^{-1}}]$	Observed 95% C.L. $[\mathrm{kg^{-1}d^{-1}keV_{ee}^{-1}}]$	Expected 95% C.L. $[\mathrm{kg^{-1}d^{-1}keV_{ee}^{-1}}]$
$0.015 - 0.215$	$29.3^{+4.6}_{-4.7}$	17.7 ± 3.3	2.24×10^3	3.18×10^3
$0.215 - 0.415$	$2.7^{+1.3}_{-1.2}$	2.20 ± 0.21	7.36×10^3	4.77×10^3
$0.415 - 0.615$	$0.43^{+0.41}_{-0.39}$	0.36 ± 0.04	3.41×10^3	3.31×10^3

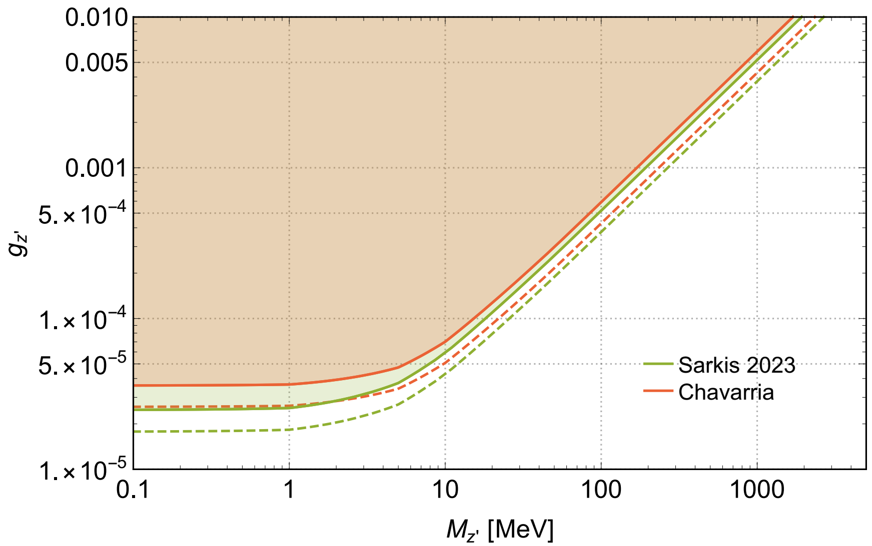
Light vector mediator search

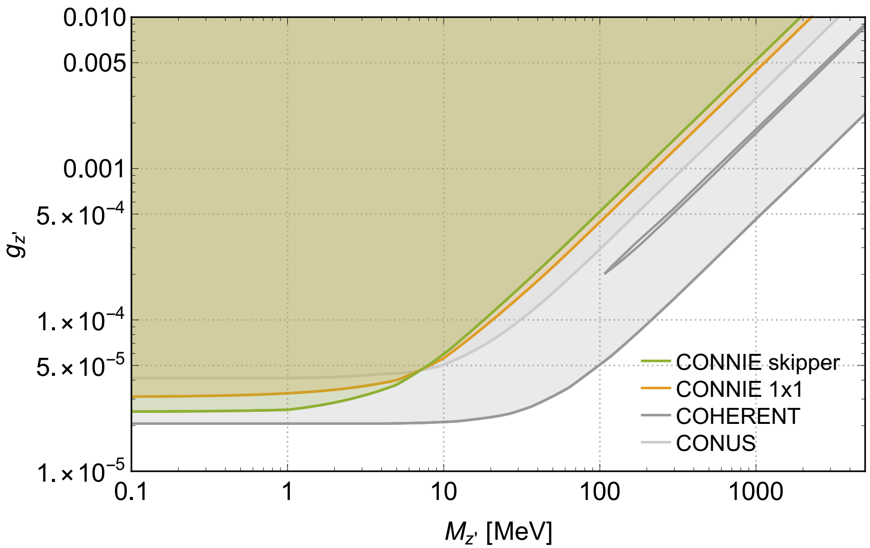
arXiv: 2403.15976

A search for new light vector mediator *Z'* in the CEνNS detection channel.

- In the framework of a universal simplified model.
- The rate for additional interactions, $R_{SM+Z'}$, is calculated and compared to limit at 90% C.L.
- Based on the lowest-energy bin (15–215 eV).
- Slight improvement at low $M_{Z'}$ on our previous limit in $g_{Z'}$.

JHEP 05, 118 (2016)





Comparison between QFs and projections for 5x smaller uncertainties and zero rate.

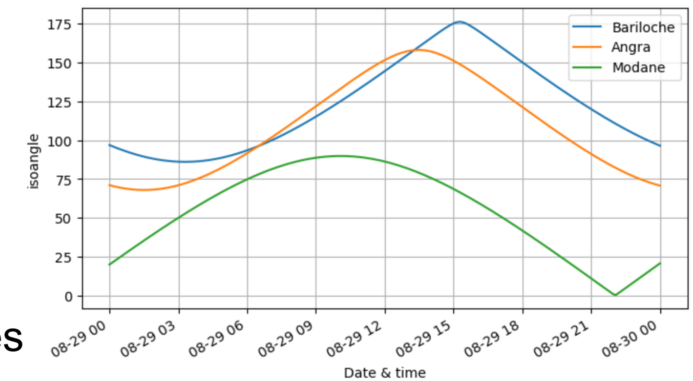
Dark matter search

arXiv: 2403.15976

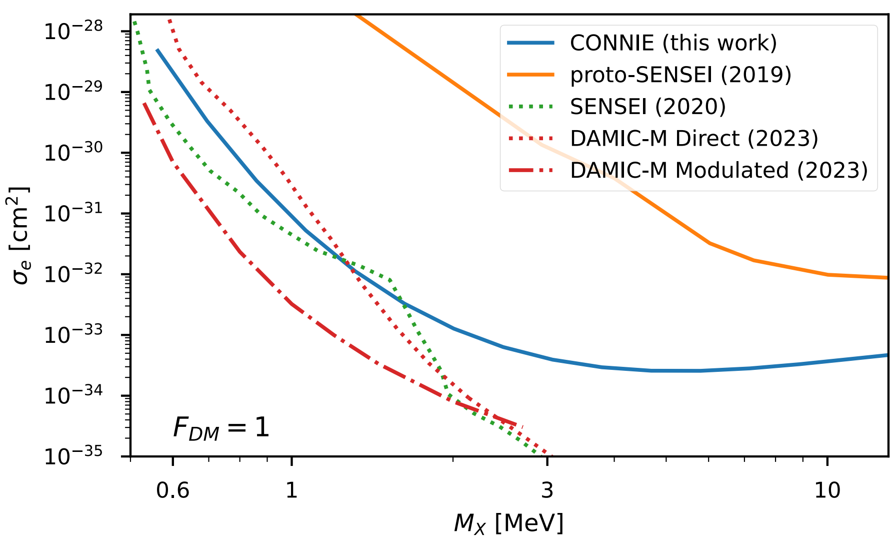
A search for DM-electron interactions by diurnal modulation.

- Galaxy DM wind comes from a preferred direction 40° N.
- Earth propagation induces a daily modulation – isodetection angle favours Southern hemisphere.
- CONNIE at 23° S, allowing to scan isoangles [65–161]°.

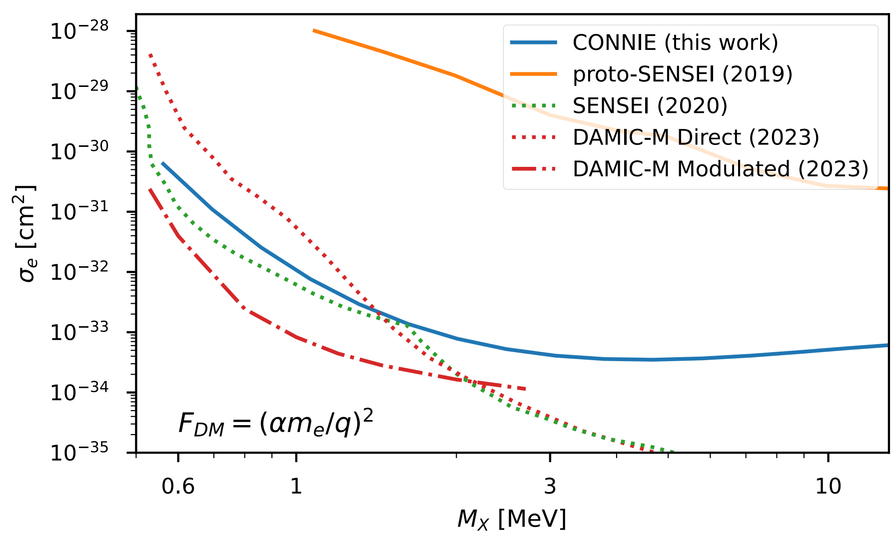
- Binned data are compared to DaMaSCUS simulations.
- Model with MeV-scale DM, which couples to SM particles via a kinetically-mixed dark photon (A').
- Best DM-electron limits by a surface experiment.



N. Avalos, TAUP 2023



Heavy mediator A′

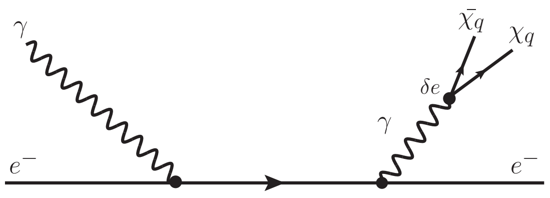


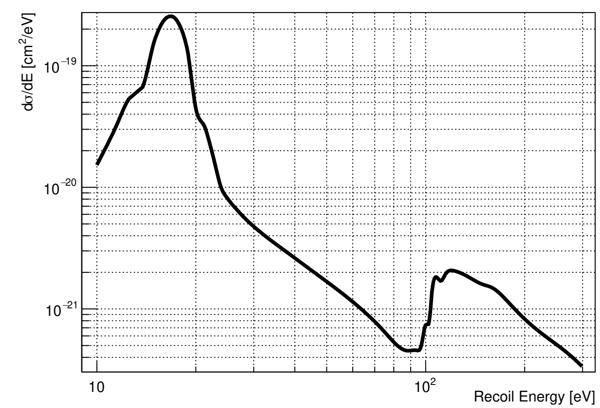
Ultralight mediator A'

Search for millicharged particles

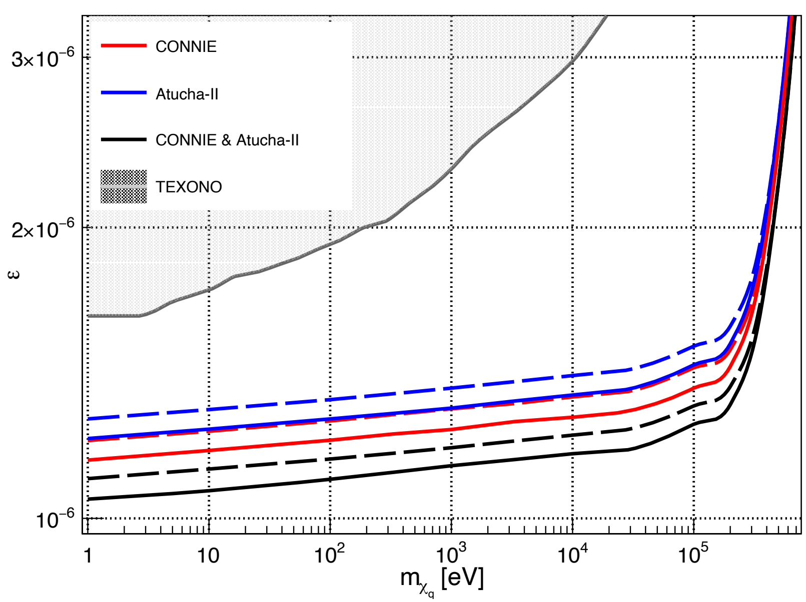
arXiv: 2405.16316

- Relativistic millicharged particles (χ_q) can be pair-produced from Compton-like scattering of high-energy γ-rays from reactors.
- Interact electromagnetically with matter via ionisation.
  - Cross-section includes collective excitations.
  - Plasmon peak at 10–25 eV. R. Essig et al, arXiv: 2403.00123





- Joint analysis between CONNIE and Atucha-II experiments.
  - Including secondary γ-rays from transport in the reactor core.
  - Combined limit at 90% C.L. on reactor-χ_q production.

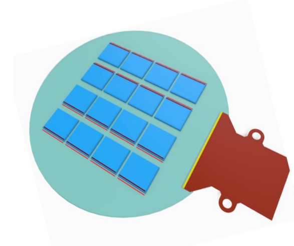


- World-leading limits on millicharged couplings over a large mass range for $m_{\chi q}$ < 1 MeV.

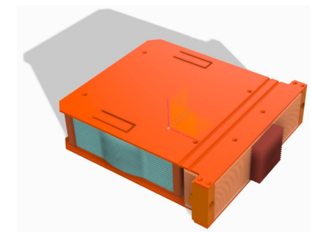
Next: a new compact module

- A Multi-Chip-Module (MCM) offers a new compact arrangement of sensors:
  - 16 Skipper-CCD sensors on the same module.
  - Designed for the Oscura experiment.
  - Multiplexed readout.

Multi-Chip Module
(16 CCDs → 8 g)

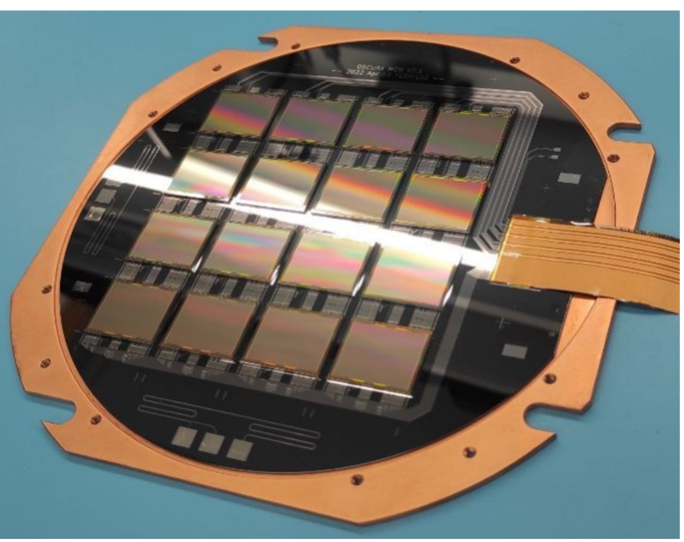


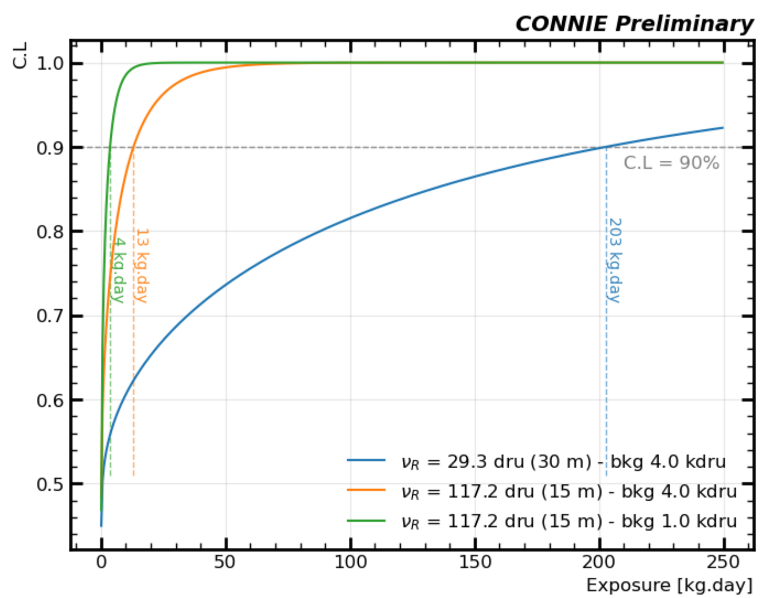
Super Module
(16 MCMs → 100 g)



Oscura design [JINST 18 (08), P08016]

- An MCM was installed at CONNIE in May 2024:
  - New vacuum interface and multiplexer boards.
  - 32x increase in mass (8 g).
  - Currently being commissioned.





Summary and outlook

- Skipper-CCDs are very promising for detecting low-energy processes.
- CONNIE achieved an excellent performance in 2021-2023 with flat background and 15 eV threshold.
- New CEνNS limit with 18.4 g-days is comparable to previous with higher exposure.
- New competitive limits on vector mediator, DM modulation and millicharged particles.
- The experiment started its next phase with a 16-sensor Multi-Chip-Module.