Probing New Physics with Reactor Neutrinos and Skipper-CCDs at CONNIE

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NDM 2025 Topical School - Institut Henri Poincaré

Dark Matter Experiments

DAMIC
SENSEI
OSCURA*
~2 km Underground
(Canada)

DAMIC-M

~1.7 km Underground
Laboratoire Souterrain de Modane
(France)

Reactor Neutrinos and BSM Experiments

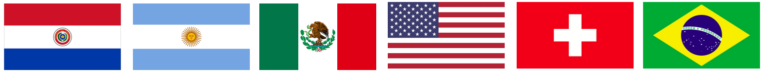
CONNIE
Angra 2
3.95 GW_{th}
Rio de Janeiro (Brazil)

ATUCHA -II

2.175 GW_{th}
Buenos Aires (Argentina)

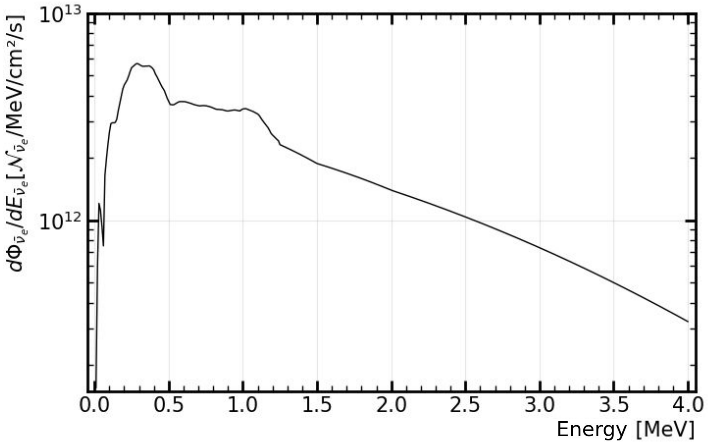
CONNIE: COherent Neutrino-Nucleus Interaction Experiment

- ➡ Collaboration: 34 members from 13 institutions:



- ➡ **Goal**: Measure Coherent Elastic neutrino-Nucleus Scattering (CEvNS) of reactor antineutrinos with silicon nuclei in scientific CCDs and probe BSM physics;

- ➡ Located 30 m from the **3.95 GW Angra2** reactor in Angra dos Reis - RJ, Brazil, CONNIE benefits from a high flux of approximately **7.8×10^{12}** $\bar{\nu}_e$/s cm².



CONNIE timeline and milestones

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

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

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

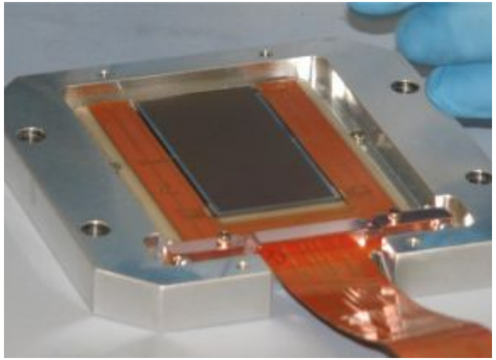
Results from 2019 run
[JHEP 05 (2022), 017]

Results from Skipper run
[arXiv:2403.15976]
[PRL 134 (2025), 071801]

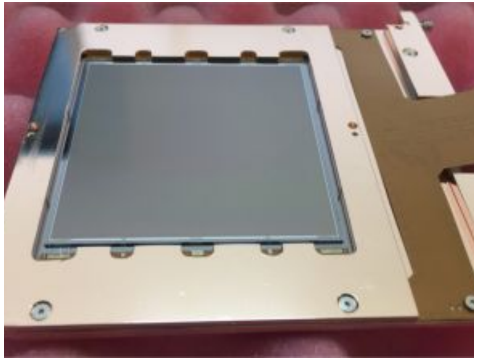
2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025

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

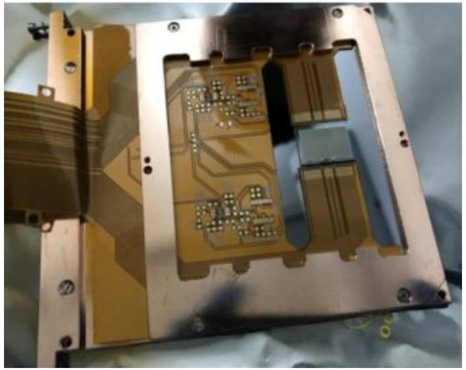
First detectors



Scientific CCDs

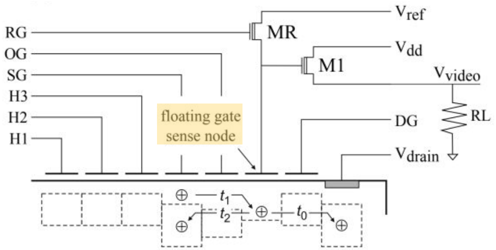


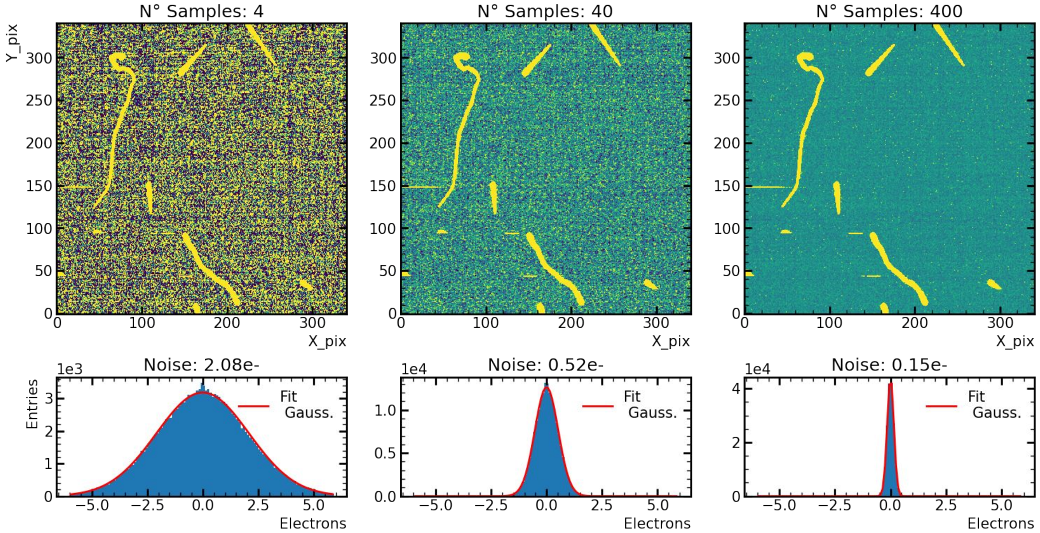
Skipper-CCDs

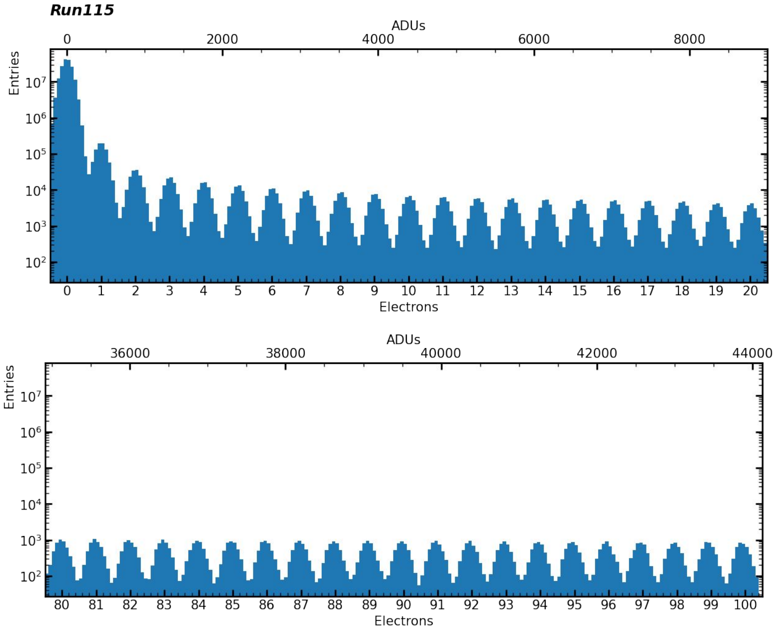


CONNIE Skipper-CCDs

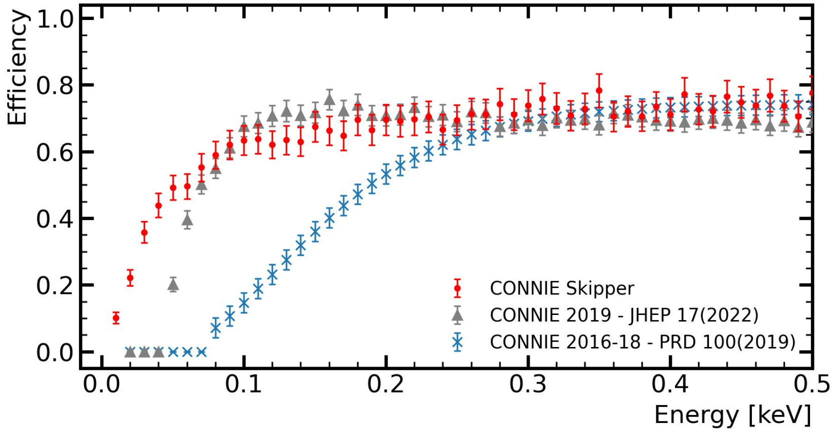
- ➡ Two Skipper-CCD were installed in July 2021 (1022×682 px, ~0.250 g);
- ➡ A floating gate amplifier allows multiple independent, uncorrelated samples of the pixel charge;
- ➡ Gaussian readout noise goes with $\sigma = \frac{\sigma_1}{\sqrt{N}}$;
- ➡ **Single-electron resolution**;



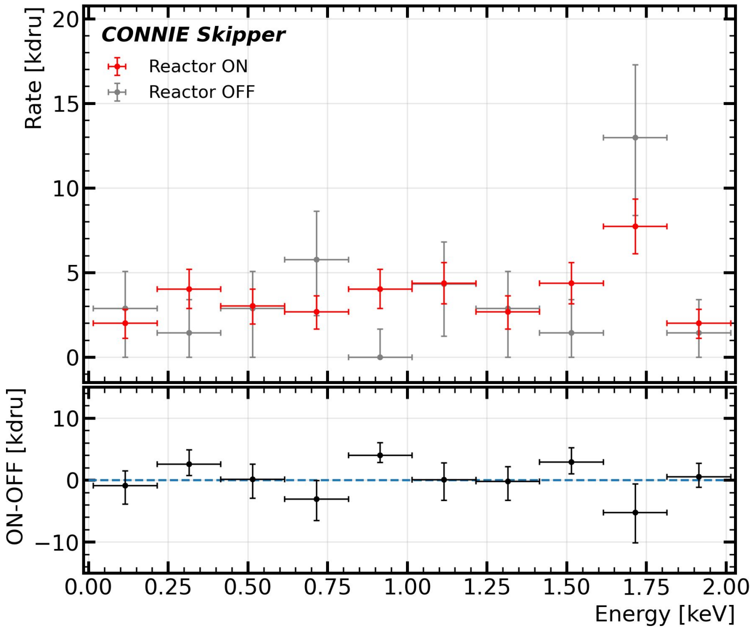




➡ Improved low-energy detection efficiency;



dru = events/kg/day/keV



➡ Overall efficiency reaches new thresholds of **15 eV**;

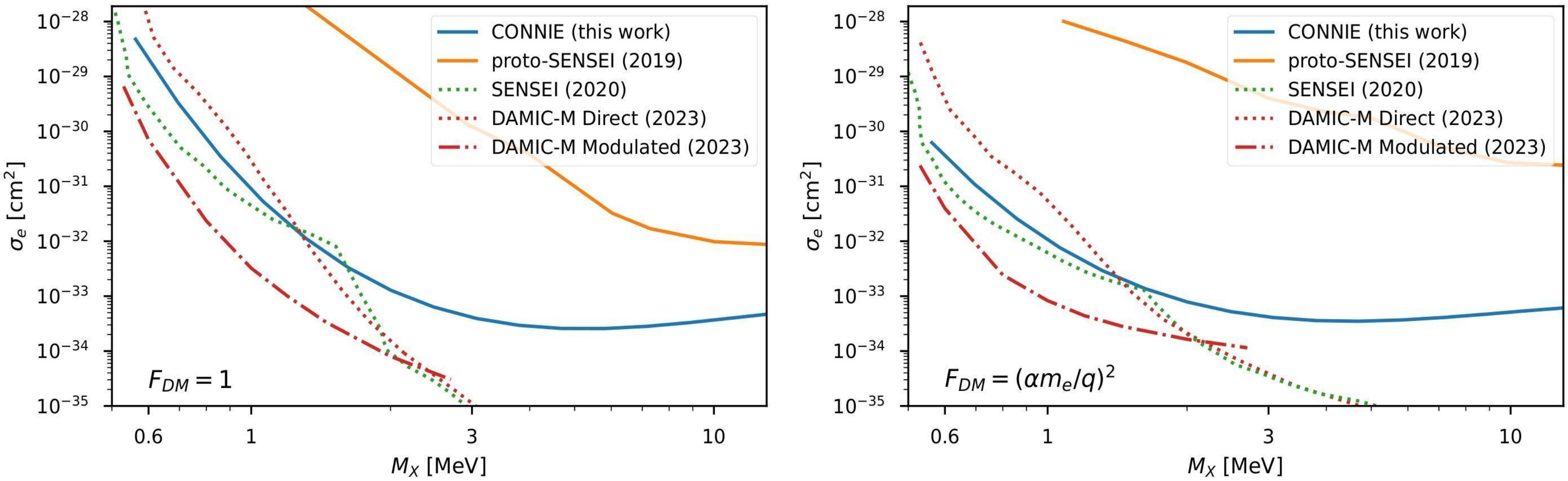
➡ **Lowest threshold** of any CEvNS experiment;

➡ No excess was seen in the difference between the rates, as expected due to the small mass of the detector.

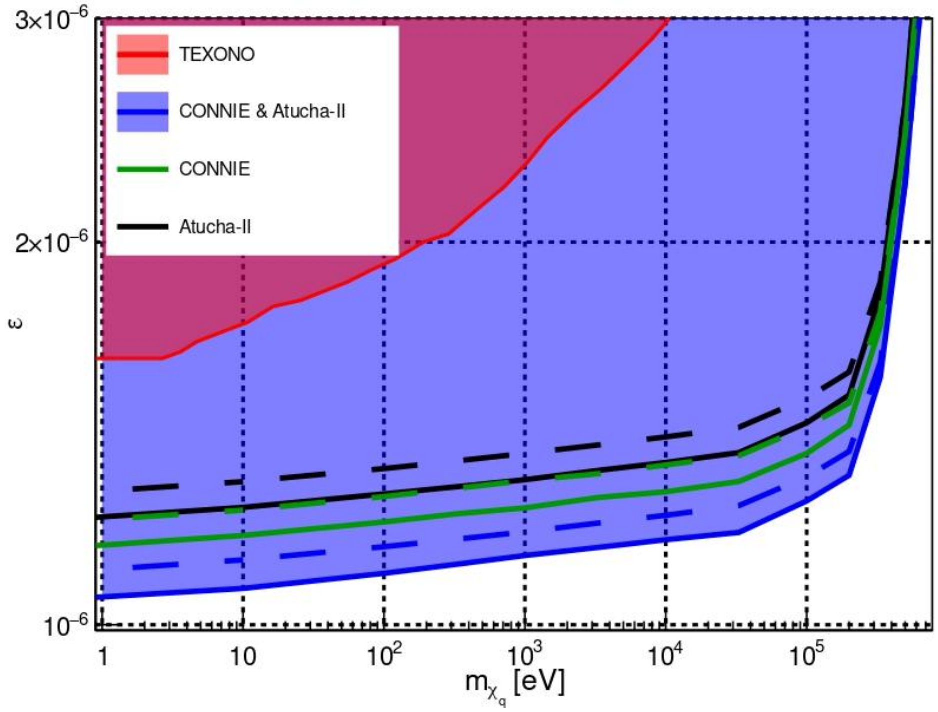
Measured Energy $[\mathrm{keV_{ee}}]$	Sarkis (2023) rate $[\mathrm{kg^{-1}d^{-1}keV_{ee}^{-1}}]$	Chavarria rate $[\mathrm{kg^{-1}d^{-1}keV_{ee}^{-1}}]$	Observed 95% C.L. $[\mathrm{kg^{-1}d^{-1}keV_{ee}^{-1}}]$	Expected 95% C.L. $[\mathrm{kg^{-1}d^{-1}keV_{ee}^{-1}}]$
0.015 – 0.215	$29.3^{+4.6}_{-4.7}$	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 Dark Matter search by diurnal modulation

- ➡ In the Southern Hemisphere, the isodetection angle spans over larger angles and the expected modulation becomes bigger;
- ➡ The computed rates are binned in the isodetection angle and compared with the observed single electron rate (~0.045 e-/pix/day);
- ➡ Simulations are carried out using DaMaSCUS to calculate the expected rate for each isodetection angle bin.

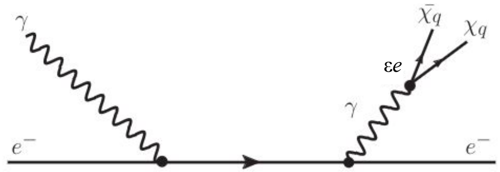


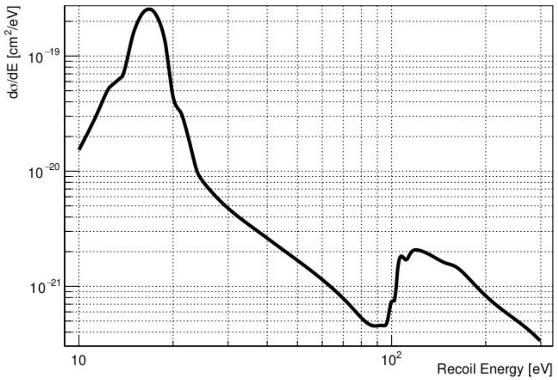
90% C.L. upper bounds on dark matter-electron interactions mediated by a heavy dark photon (left) and an ultralight dark photon (right).
Solid lines correspond to experiments running on the surface, dotted lines to direct limits obtained underground, and dashed to modulated limit obtained underground.



Exclusion limits at 90% C.L. as a function of the mass and charge fraction. Solid lines represent results considering production from both primary and secondary γ-rays, while dashed lines account for only primary γ-rays.

- ➡ A combined analysis of the collaborative effort between the two experiments;
- ➡ **World-leading limits** on the charge ε of particle within a mass range spanning six orders of magnitude;
- ➡ Produced in pairs by Compton-like interactions from primary γ-rays, as well as secondary γ-rays from transport and energy loss in the nuclear core.





Differential Interaction cross-section in silicon for particles with mass of 1 eV/c² and charge fraction $\varepsilon = 10^{-6}$

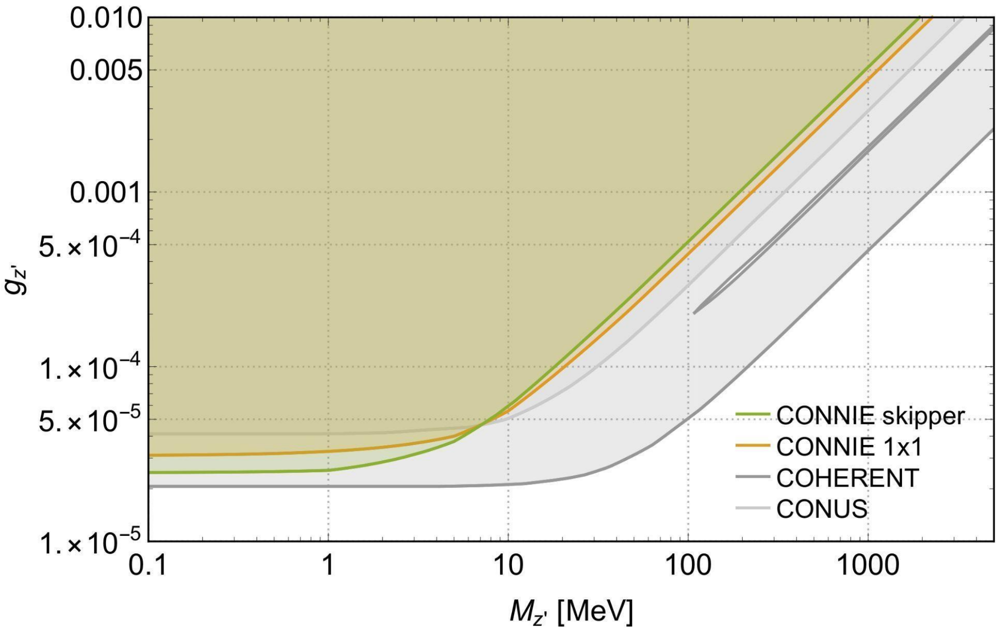
Search for New Light Mediators

- ➡ New mediators can be probed under the framework of simplified models;
- ➡ A new scalar or vector mediator could couple to neutrinos, charged leptons, and quarks;
- ➡ Using the CEνNS detection channel:

$$\frac{d\sigma_{SM+Z'}}{dE_R}(E_{\bar{\nu}_e}) = \left(1 - \frac{Q_{Z'}}{Q_W}\right)^2 \frac{d\sigma_{SM}}{dE_R}(E_{\bar{\nu}_e})$$

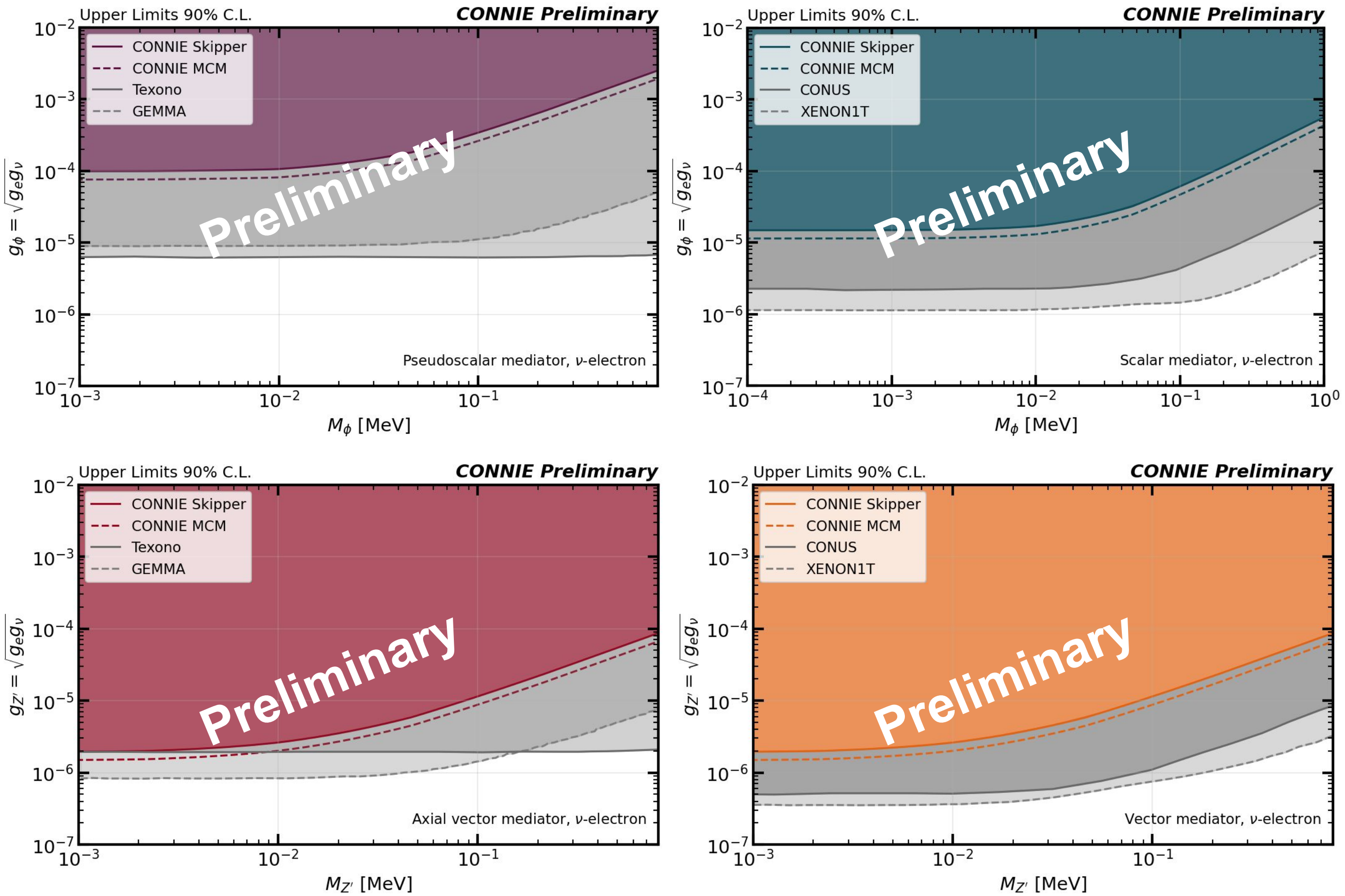
$$Q_{Z'} = \frac{3\,(N+Z)\,g'^2}{\sqrt{2}G_F\left(2ME_R + M_{Z'}^2\right)}$$

- ➡ Non-standard interactions in the neutrino-electron scattering channel can also be probed (Preliminary analysis):



CONNIE exclusion limits at the 95% C.L. from Skipper-CCDs considering the quenching factor from Sarkis (green) and the standard-CCD (yellow). For comparison, limits at the 90% C.L. from COHERENT (CsI+Ar) [JHEP05(2022)109] and CONUS (k = 0.16) [JHEP05(2022)085] data are also shown.

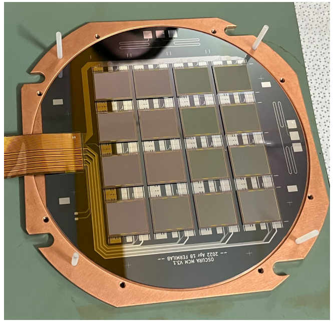
Non-Standard Interactions in Neutrino-electron Scattering

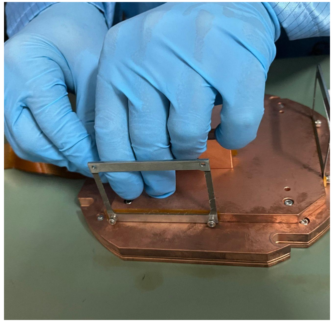


MCM and CONNIE future prospects

2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025

Engineering run | 2016-2018 run (1x1) | 2019 run (1x5) | Skipper-CCDs run | **MCM run**





Multi-Chip-Module (MCM)

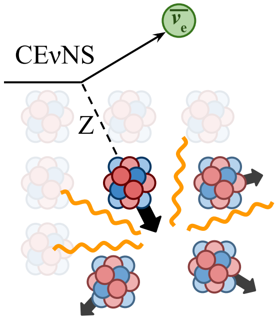
- ➡ Designed for the **OSCURA** experiment;
- ➡ **16 Skipper-CCDs** integrated into a **single module;**
- ➡ **~10x more mas**s compared to the CONNIE Skipper-CCDs;
- ➡ Features new multiplexed readout electronics and a dedicated vacuum interface board;
- ➡ Commissioning phase started October 2024;
- ➡ **Data acquisition already in progress.**

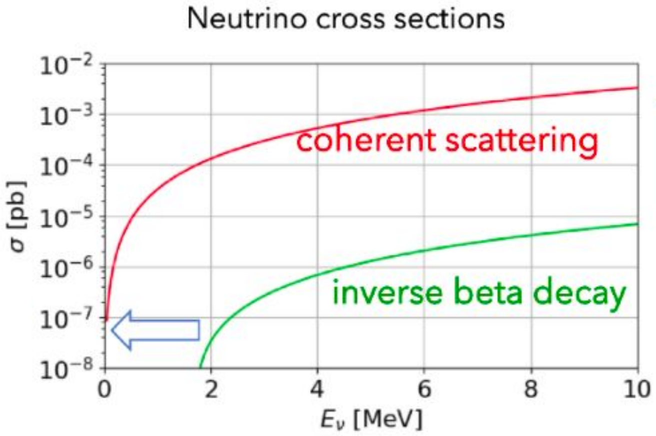
Thank you !

Acknowledgments:

Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)

- Predicted by the Standard Model in **1974** and first measured in **2017** by the COHERENT collaboration; [Science 357, 1123]
- **CEνNS**: A neutrino, of any flavor, interacts via neutral current with the nucleus, which recoils as a whole;
  - Nucleon wavefunctions are in phase in the low momentum transfer regime ($\lesssim$ 50 MeV, in Si)





Magnificent CEvNS, Raimund Strauss

- CEνNS cross section

$$\frac{d\sigma_{MP}}{dE_R}(E_{\bar{\nu}_e}) = \frac{G_F^2}{8\pi}Q_W^2\left[2 - \frac{2E_R}{E_{\bar{\nu}_e}} + \left(\frac{E_R}{E_{\bar{\nu}_e}}\right)^2 - \frac{ME_R}{E_{\bar{\nu}_e}^2}\right] M|F(q)|^2$$

$$Q_W = N - (1 - 4\sin^2\theta_W)Z$$

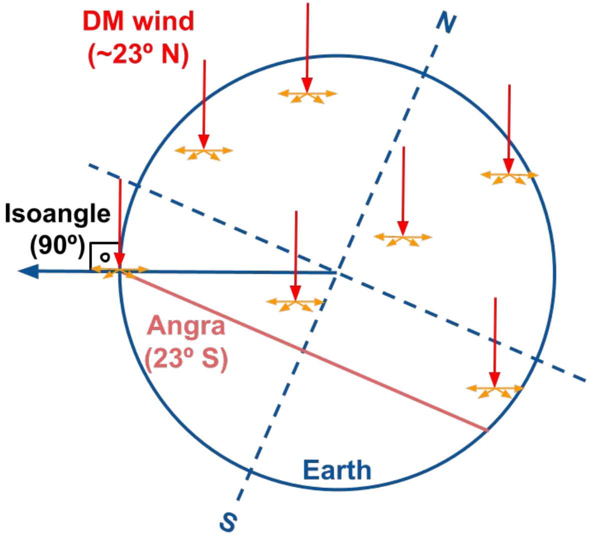
- Enhanced by being $\propto N^2$
- Difficult to observe due to the **small recoil energy**:

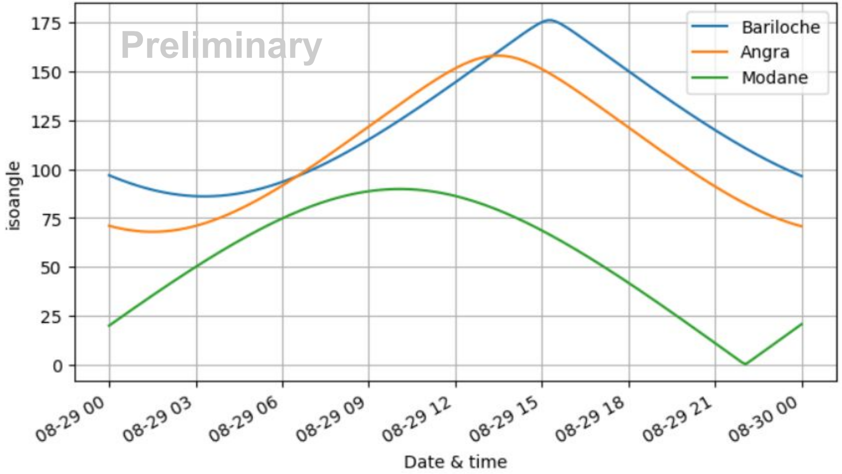
$E_R^{max} \approx 2E_\nu^2/M$, Si (M = 25.65 GeV) – E_ν = 2 MeV: E_R~ 300 eV

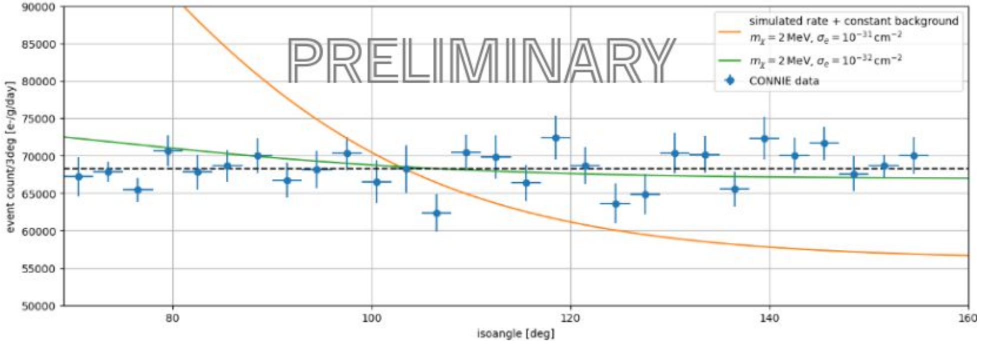
- A low-threshold detector and a high neutrino flux are required.

Light Dark Matter diurnal modulation

- ➡ DM particle wind arrives from a particular direction as the Solar system travels through the Galaxy;
- ➡ Isodetection angle: Angle between DM wind direction and the normal to the surface:







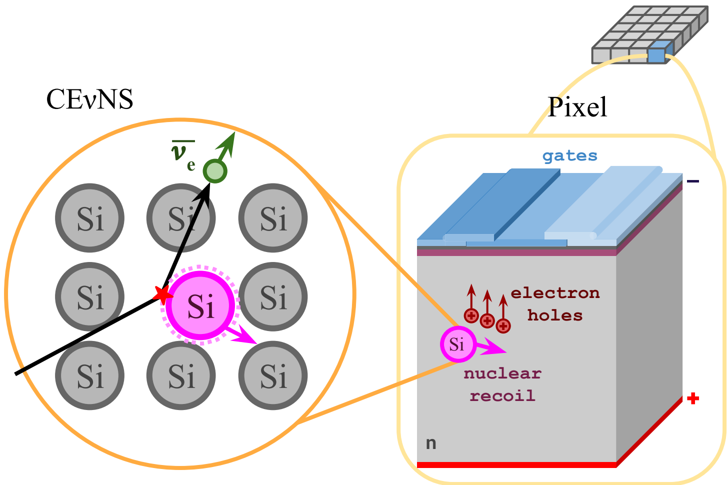
➡ CCDs are a mesh of **MOS** (metal-oxide-semiconductor) capacitors arranged in pixel format

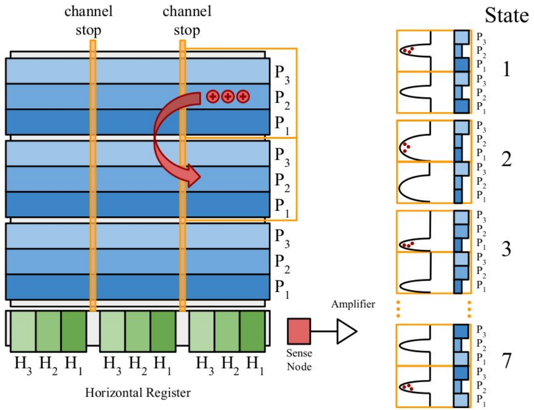
➡ Each pixel consists of a silicon **p-n junction**;

➡ A **depletion region** is established by applying an electric voltage to the substrate and the three-phase gate;

- **Electron-hole pairs** are produced when the substrate is ionized.
- For electrons, the energy required to produce a pair is **3.745 eV** in silicon at ~100 K.

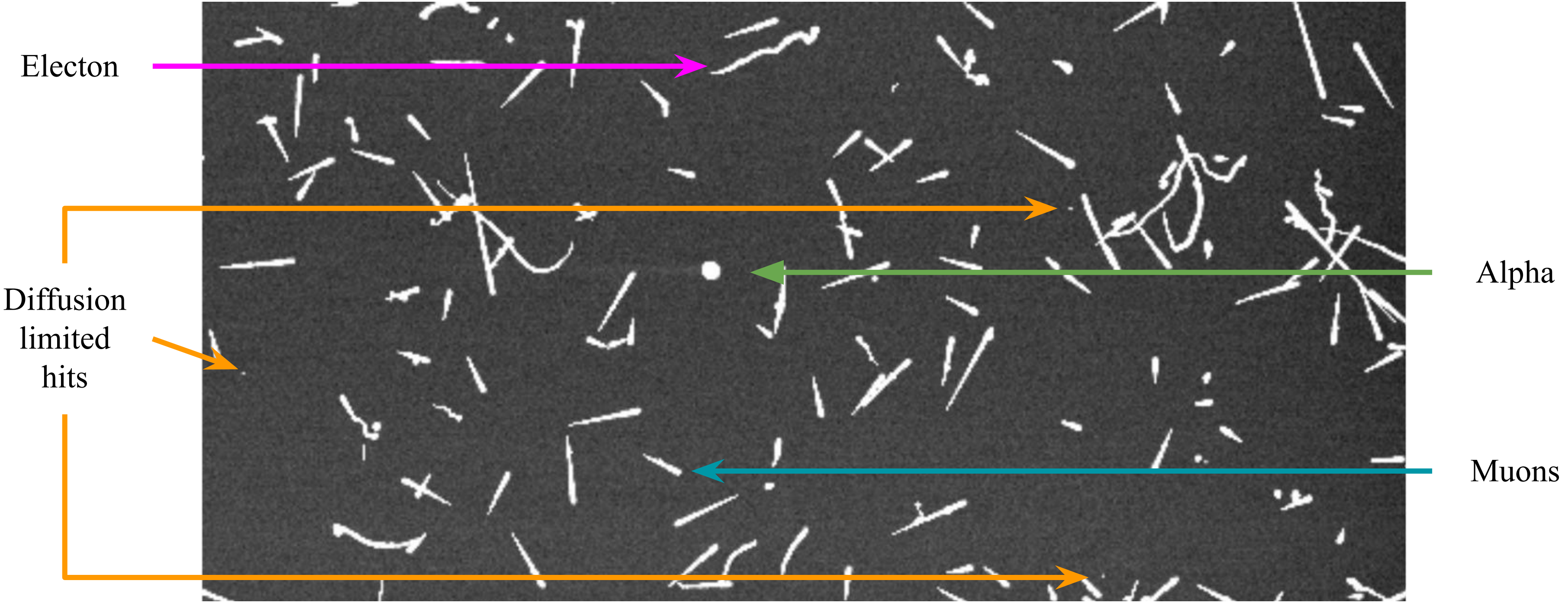
➡ Charges are collected in potential wells and **read out sequentially**.





Charged Coupled Devices (CCDs)

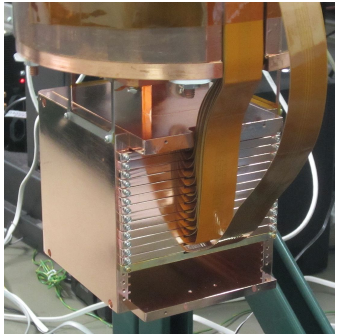
➡ Particles can be **identified** in a CCD image. The **CEνNS** signal is a **diffusion-limited event**.



Experimental Setup

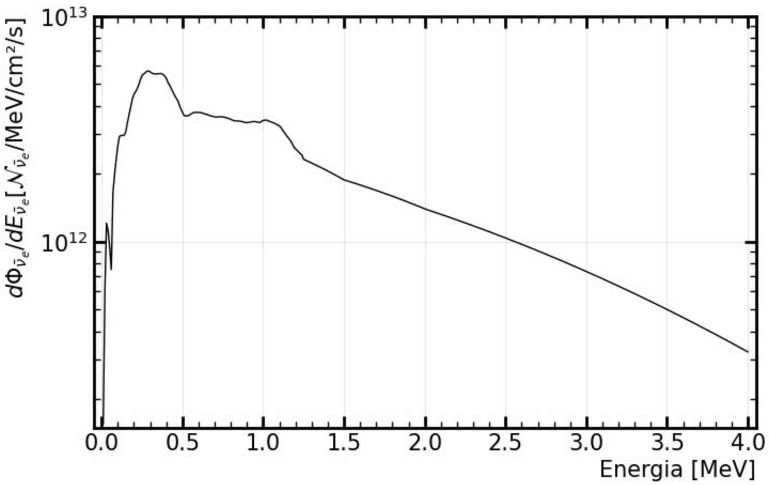
- The devices are kept in a cold box, inside an evacuated chamber (10^{-7} torr), and maintained at 100 K.
- Passively shielded.
- The experiment is operated remotely.

Standard CCDs layout



MCM layout

➡ Antineutrino flux at CONNIE



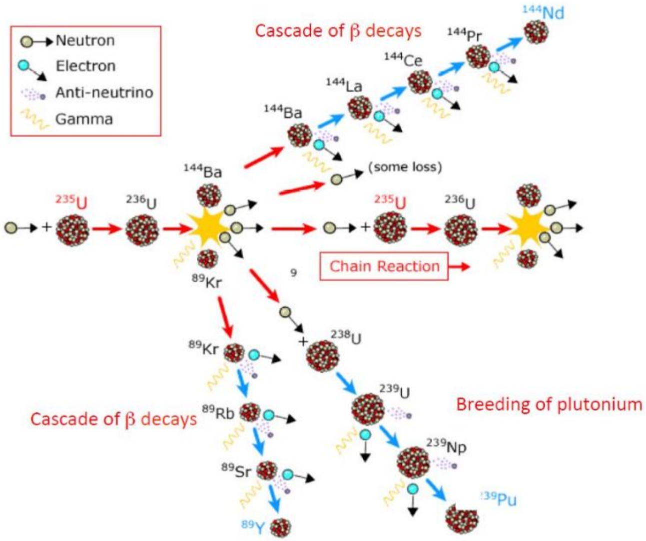
Dominant processes	(E release)	fis.frac.	$\bar{\nu}_e$/proc	$\bar{\nu}_e$/fis
^{235}U fission	202 MeV	0.56	6.14	3.43
^{238}U fission	205 MeV	0.08	7.08	0.56
^{239}Pu fission	210 MeV	0.30	5.58	1.67
^{241}Pu fission	212 MeV	0.06	6.42	0.38
n-capture on ^{238}U	202 MeV	0.60	2.00	1.20

<E rel> = 205.24 MeV/fis   Tot: 7.24

➡ Angra-2 and CONNIE:

- 3.95 GW_{th} Pressurized Water Reactor (PWR);
- Emits ~8.7×10^{20} ν_e/s (2.23×10^{20} ν_e/s/GW_{th});
- Flux ~7.8×10^{12} ν_e/s/cm² at 30m from core;

$$\text{Rate}_{\text{fis}} = \frac{3.95\ \text{GW}_{th}}{205.24\ \text{MeV/fis}} \approx 1.2\times10^{20}\text{fis/s}$$



[Reactor Neutrino Flux and Spectrum, Chao Zha. Neutrino Geoscience 2019]