Status of the CONNIE experiment using Skipper-CCDs

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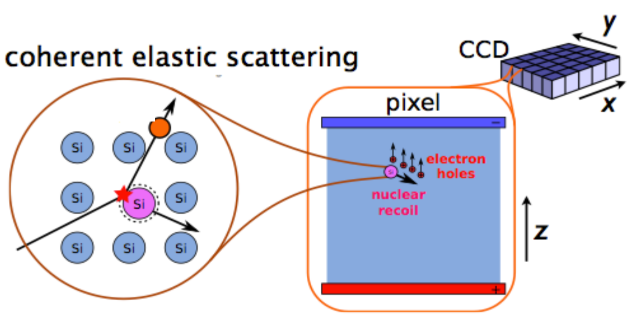
on behalf of the CONNIE collaboration

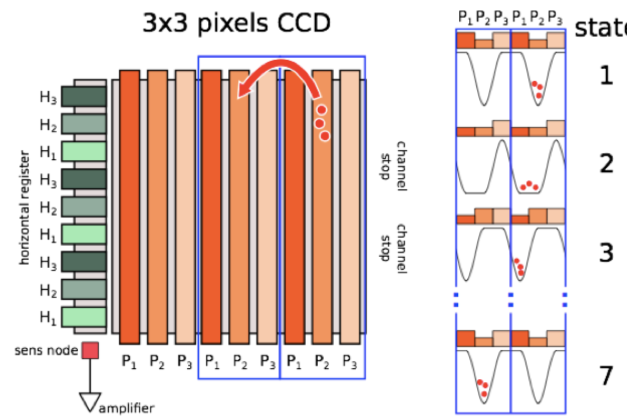
Magnificent CEνNS workshop
València, Spain, 13 June 2024

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 setup

(Skipper-)CCDs
in copper box

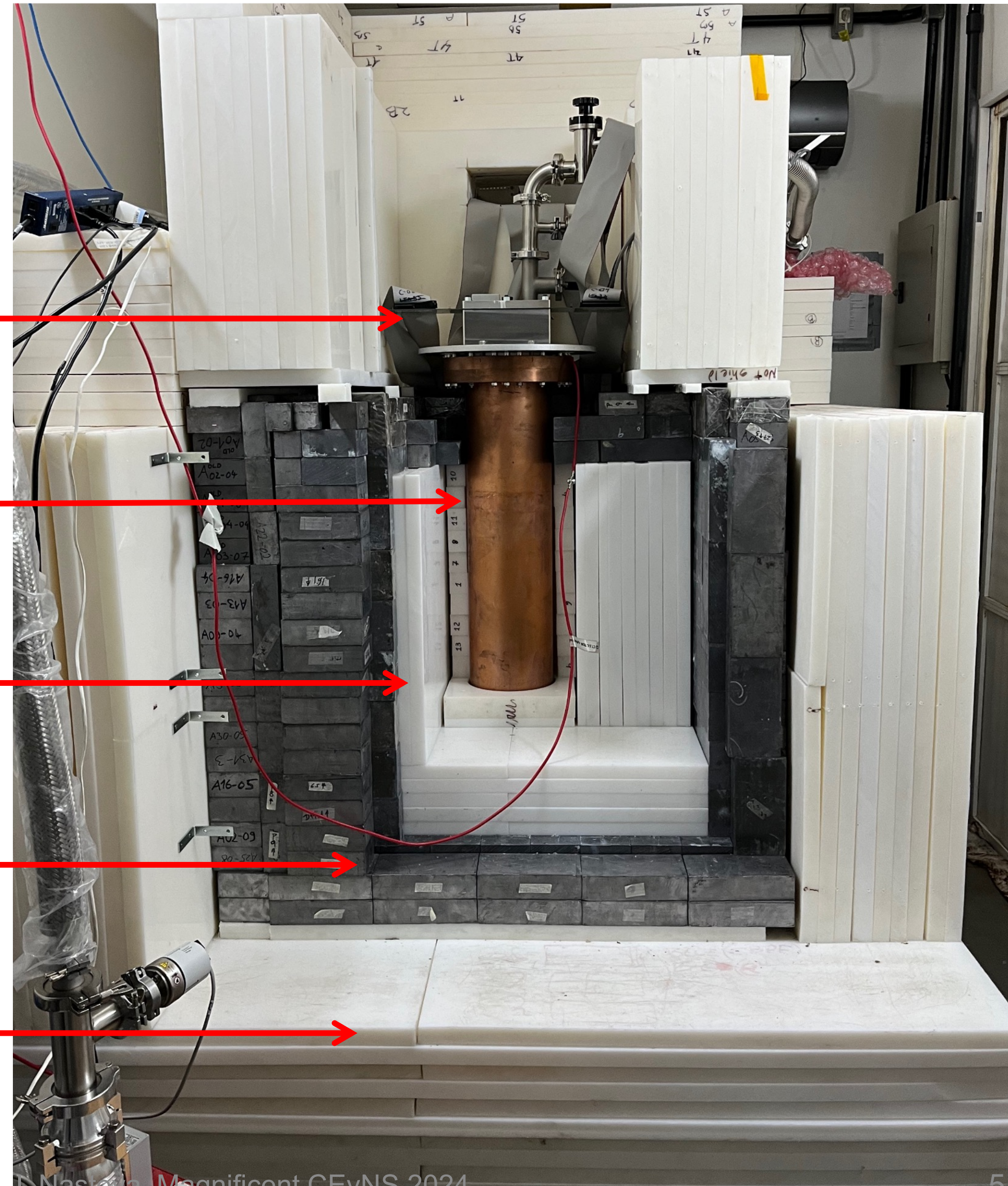
ViB readout board
(signal transport)

Dewar
(vacuum)

Inner Polyethylene – 30 cm
(neutrons)

Lead – 15 cm
(gamma)

Outer Polyethylene – 30 cm
(neutrons)



CONNIE experiment timeline

This time last year...

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

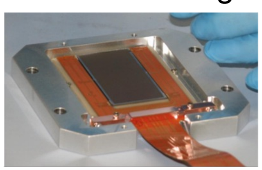
Results from 2016-2018 run
[PRD 100 (2019), 092005]

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

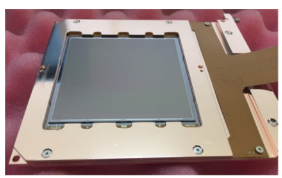
2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024

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

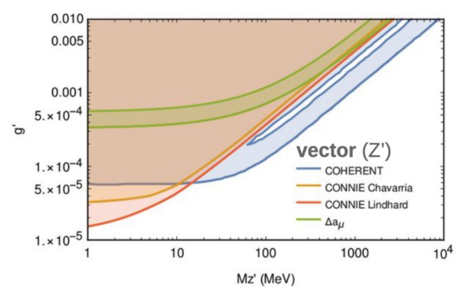
Installation at Angra



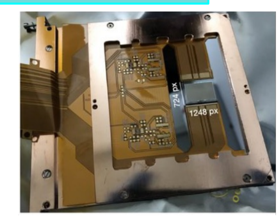
Installation of scientific CCDs

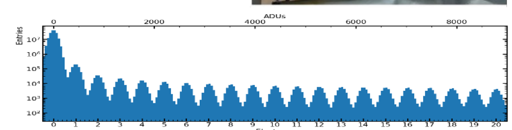


Limits on SM extensions with light mediators
[JHEP 04 (2020), 054]

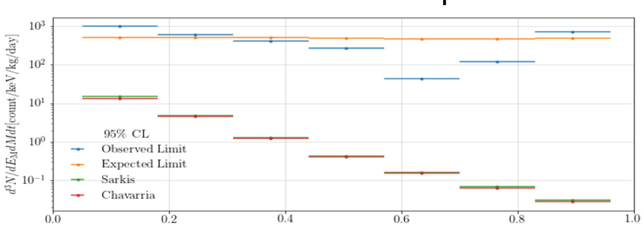


Installation of Skipper-CCDs





Upper limits at 90% C.L. on the measured neutrino rate vs predictions



CONNIE experiment timeline

New results in this talk:

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

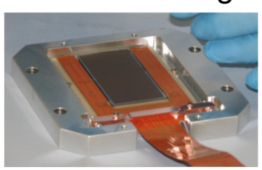
Engineering run

2016-2018 (1x1) run

2019 (1x5) run

Skipper-CCD run

Installation at Angra



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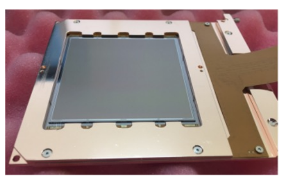
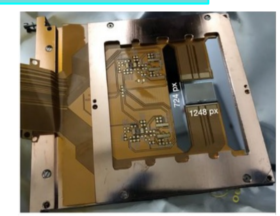
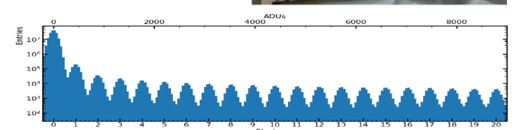


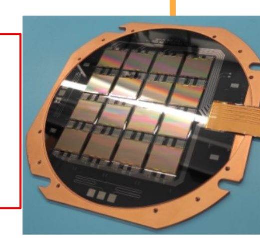
Limits on SM extensions with light mediators **[JHEP 04 (2020), 054]**

Installation of Skipper-CCDs



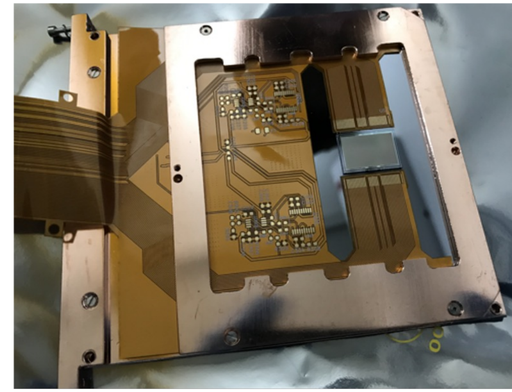


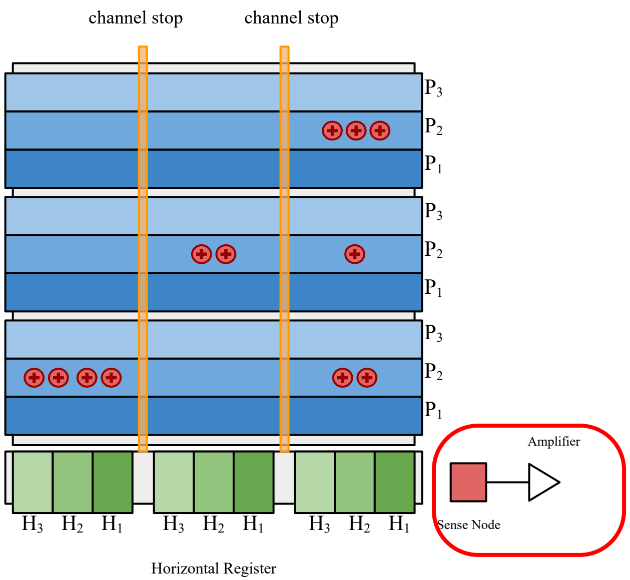
New: Installation of a Multi-Chip Module with Skipper-CCDs, May 2024
32x increase in mass

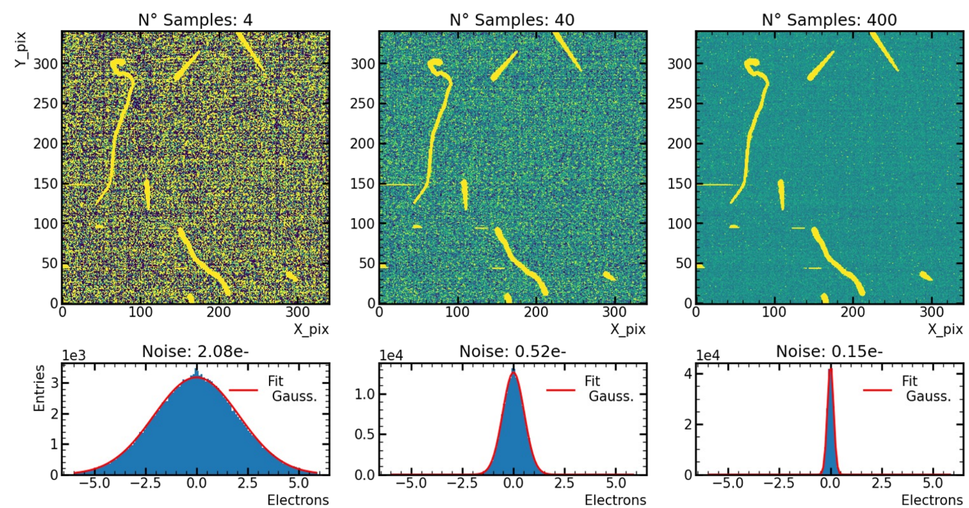


Skipper-CCD sensors

- 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.







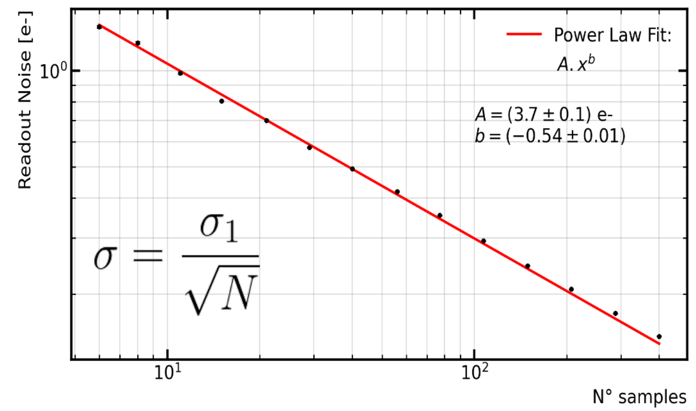
- Two Skipper-CCDs were installed at the CONNIE setup in July 2021.
  - 1022 x 682 pixels, 15 x 15 μm^2 each, 675 μm thickness, 0.5 g total mass.
  - Low Threshold Acquisition readout electronics. G. Cancelo et al, JATIS 7 (2021), 1 015001

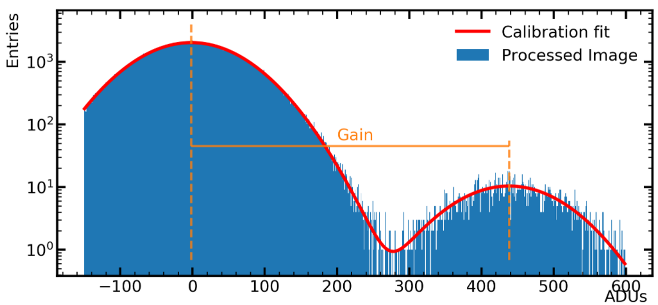
Skipper-CCD performance

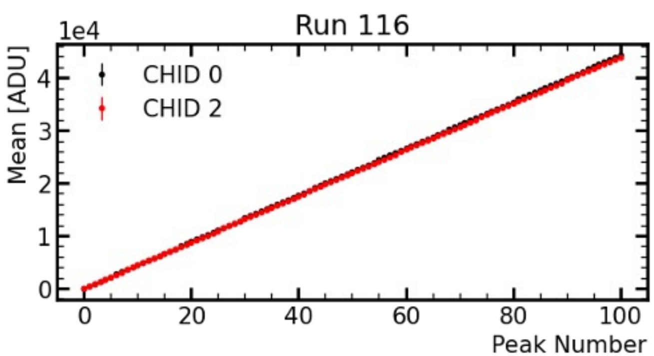
arXiv: 2403.15976

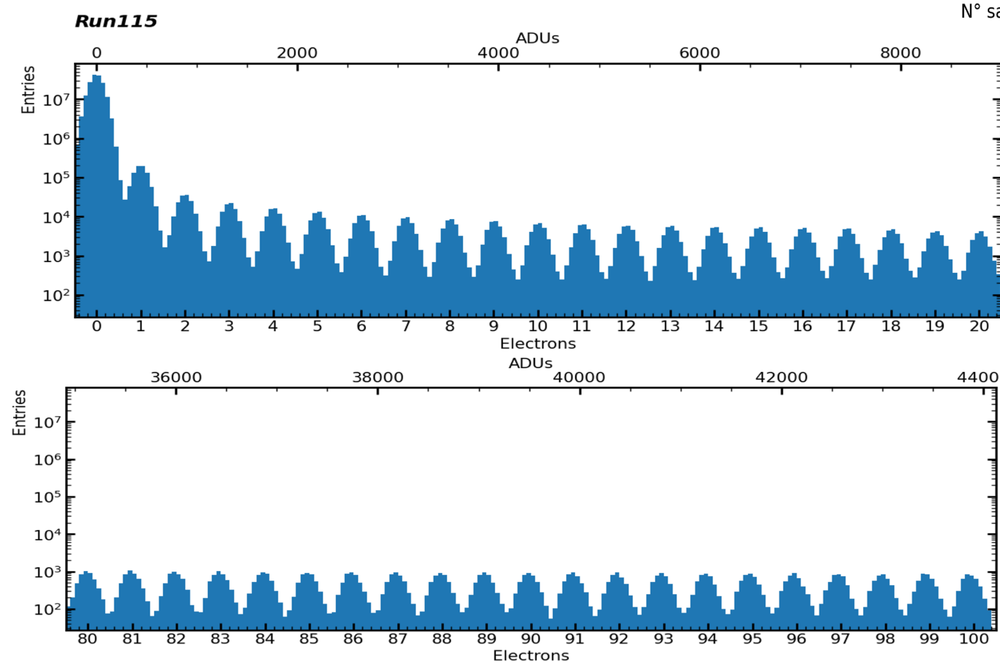
Stable detector performance and background over the 2021-2022 period.

- 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).







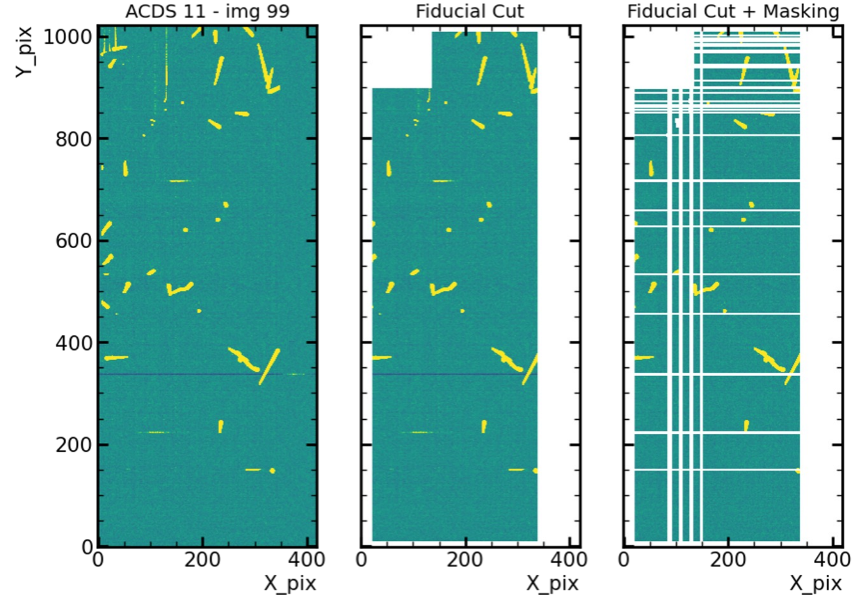


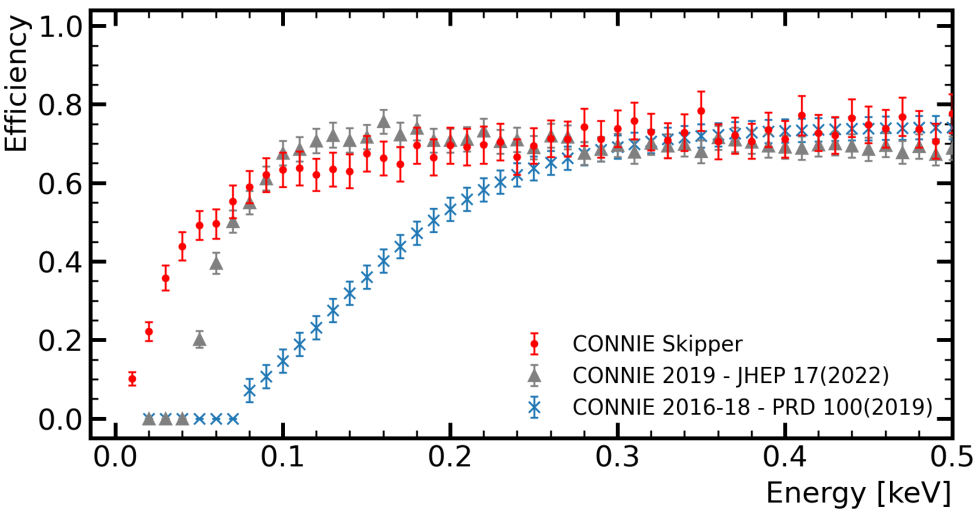
Selection and efficiency

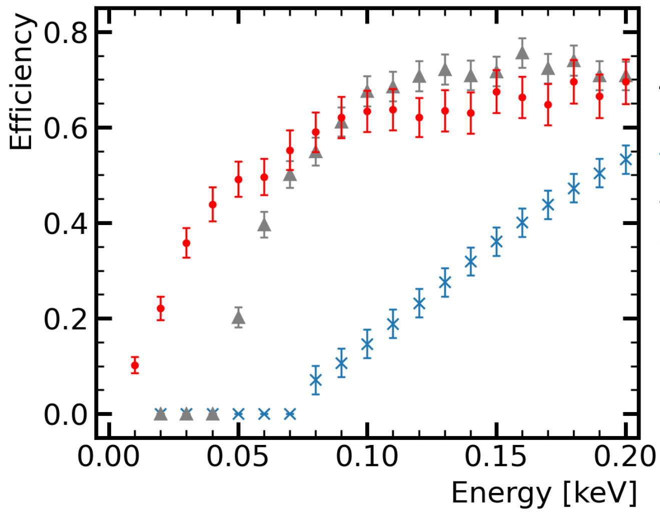
arXiv: 2403.15976

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-.
  - Data quality: 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.







Thresholds at
2018 – 75 eV
2019 – 50 eV
Skipper – 15 eV

Energy spectrum

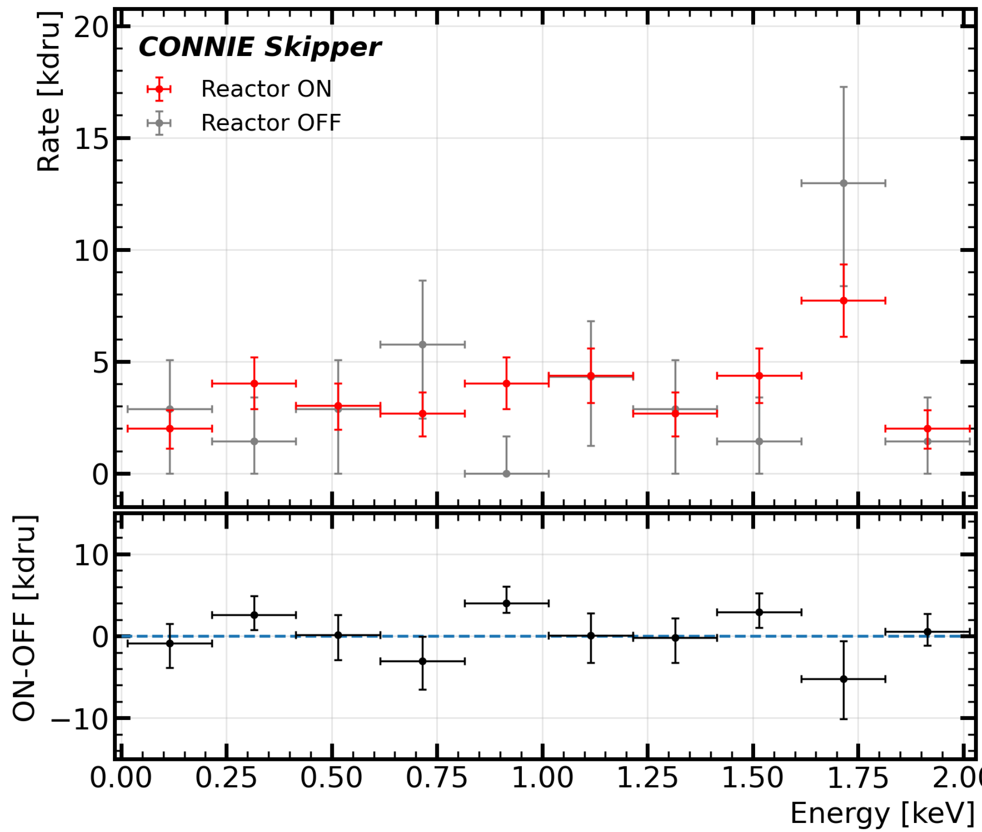
arXiv: 2403.15976

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

- Data taken during 243 days with reactor-on and 57 days off.
- Exposure of 14.9 g-days with reactor-on and 3.5 g-days off.

- No excess* observed.
- Flat background rate ≅ 4 kdru.
- Improved background and threshold.

* explained or unexplained



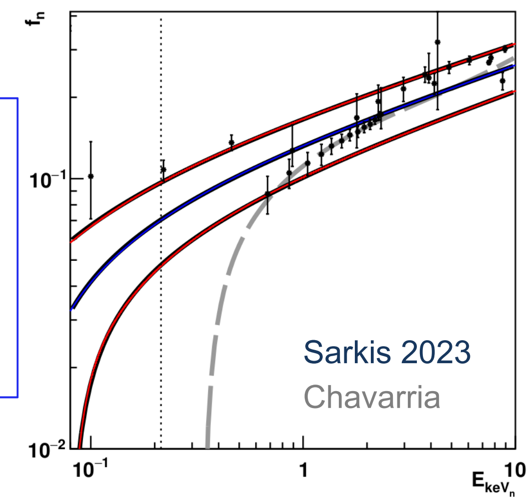
CEνNS search

arXiv: 2403.15976

A search for CEνNS in the lowest-energy bins of reactor on – off rates.

- Updated neutrino flux model with improved antineutrino spectra for ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu.
  - For E_ν > 0.44 MeV (15 eV_{ee}) the new and old model agree within 3%.
- Updated Sarkis quenching factor model for silicon. Phys. Rev. A 107, 062811 (2023)
  - Based on Lindhard, with improved descriptions of the electronic stopping, interatomic potential and electronic binding at sub-keV energies, E_{nr} > 0.24 keV_{nr} (15 eV_{ee}).

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	2.24×10^3	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



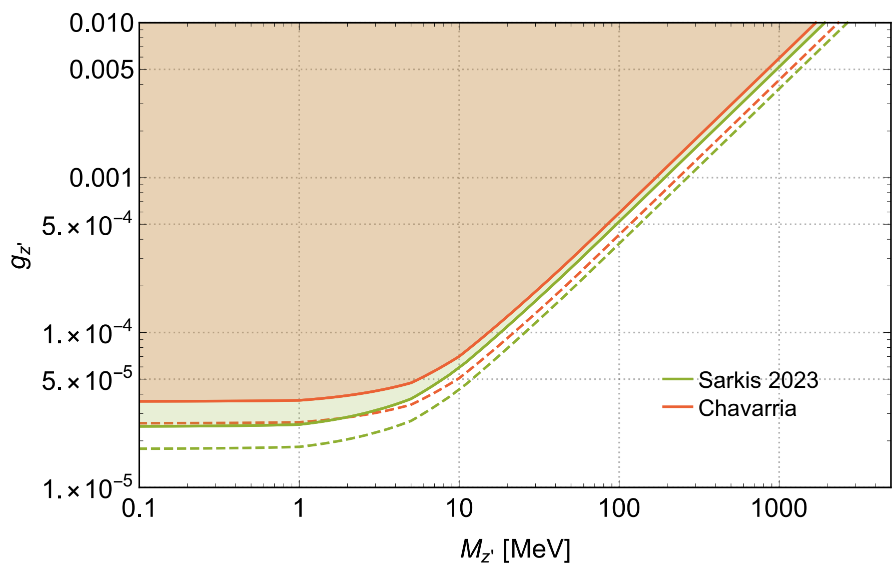
- Observed limit at 76x the SM predicted rate with Sarkis QF.
- Comparable to our previous limit with standard CCDs and 10^3 larger exposure.

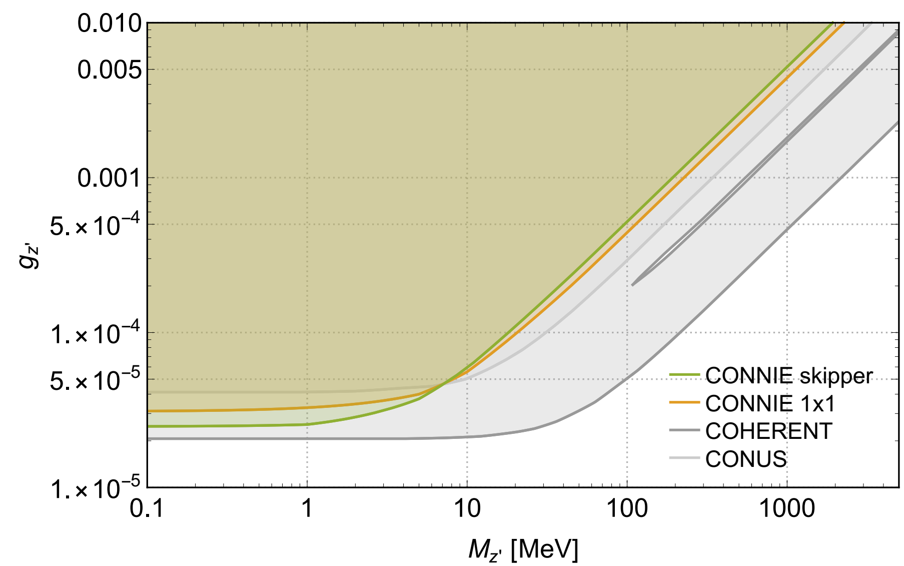
Light vector mediator search

arXiv: 2403.15976

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

- In the framework of a universal simplified model. JHEP 05, 118 (2016)
- 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 $g_{Z'}$.





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

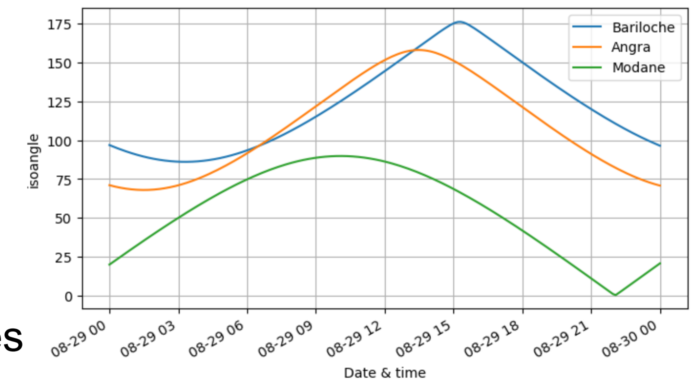
Dark matter search

arXiv: 2403.15976

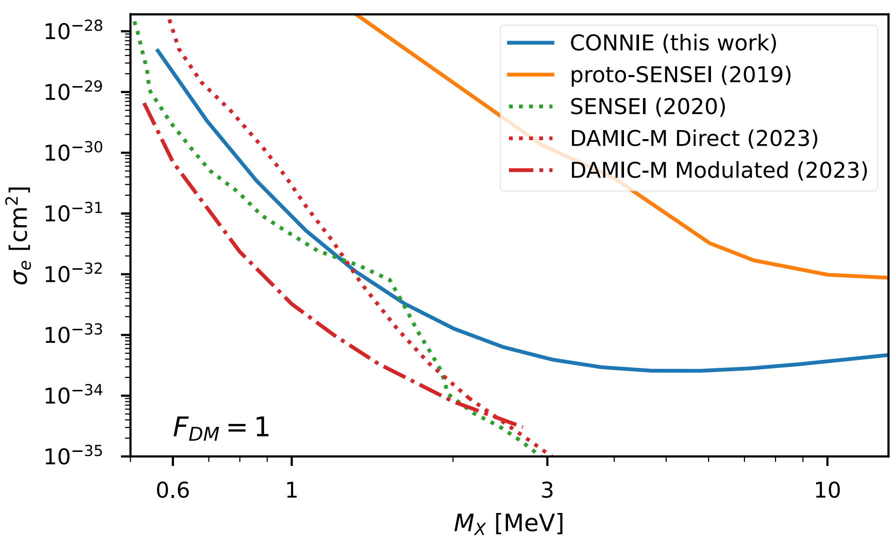
A search for DM-electron interactions by diurnal modulation.

- 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]°.

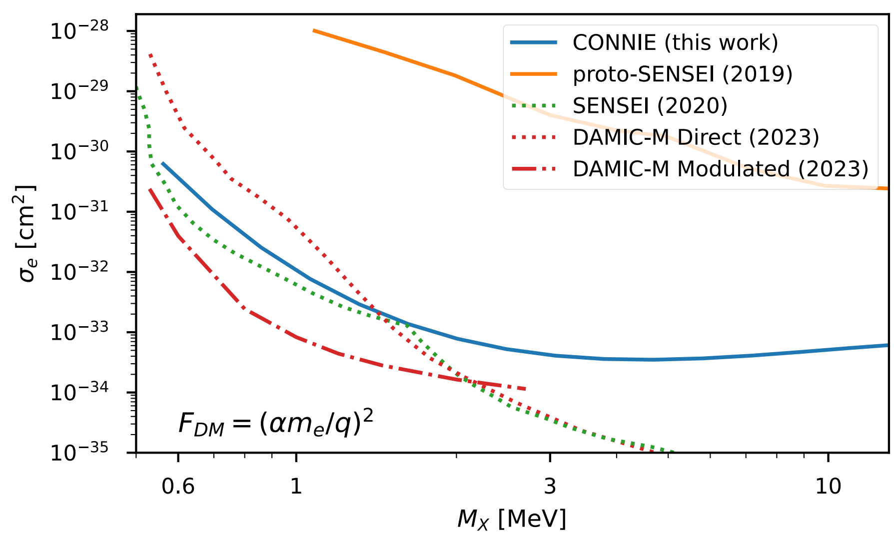
- Binned data are compared to DaMaSCUS simulations.
- Model with MeV-scale DM, which couples to SM particles via a kinetically-mixed dark photon (A').
- Best DM-electron limits by a surface experiment.



N. Avalos, TAUP 2023



Heavy mediator A′



Ultralight mediator A'

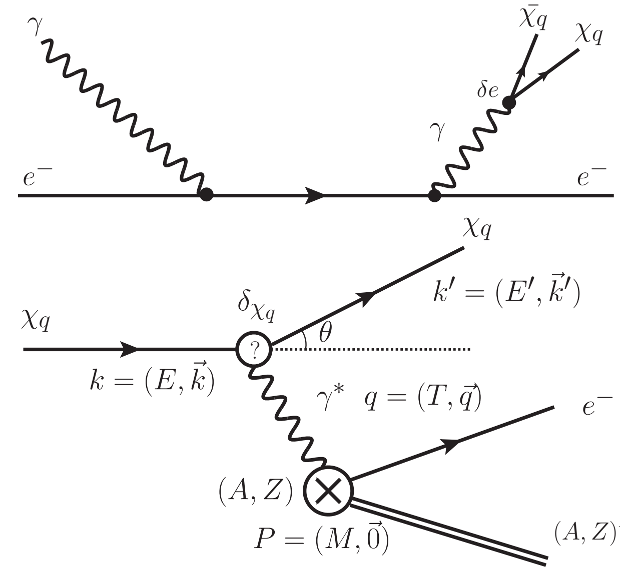
Search for millicharged particles

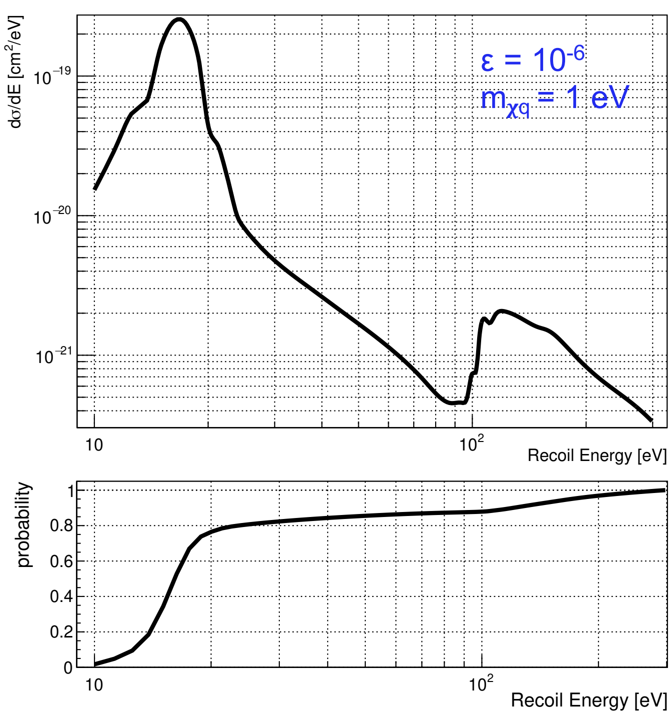
arXiv: 2405.16316

- Relativistic millicharged particles (χ_q) are predicted in hidden sector SM extensions.
- Can be pair-produced from Compton-like scattering of high-energy γ-rays from reactors.
- Differential χ_q flux from the γ spectrum:

$$\frac{d\phi_{\chi_q}}{dE_{\chi_q}} = \frac{2}{4\pi R^2} \int \frac{1}{\sigma_{\text{tot}}} \frac{d\sigma}{dE_{\chi_q}} \frac{dN_\gamma}{dE_\gamma} dE_\gamma$$

- Interact electromagnetically with matter via ionisation.





$q_{\chi q} = \varepsilon e$

- New interaction cross-section for low-energy ionisation by relativistic particles includes collective excitations.
  - Collective effects are encoded in the dielectric function calculated with the DarkELF(GPAW) code.
  - Plasmon peak at 10–25 eV.

R. Essig et al, arXiv: 2403.00123

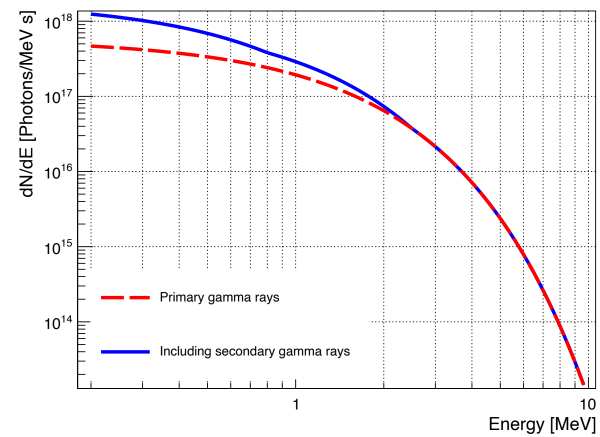
Search for millicharged particles

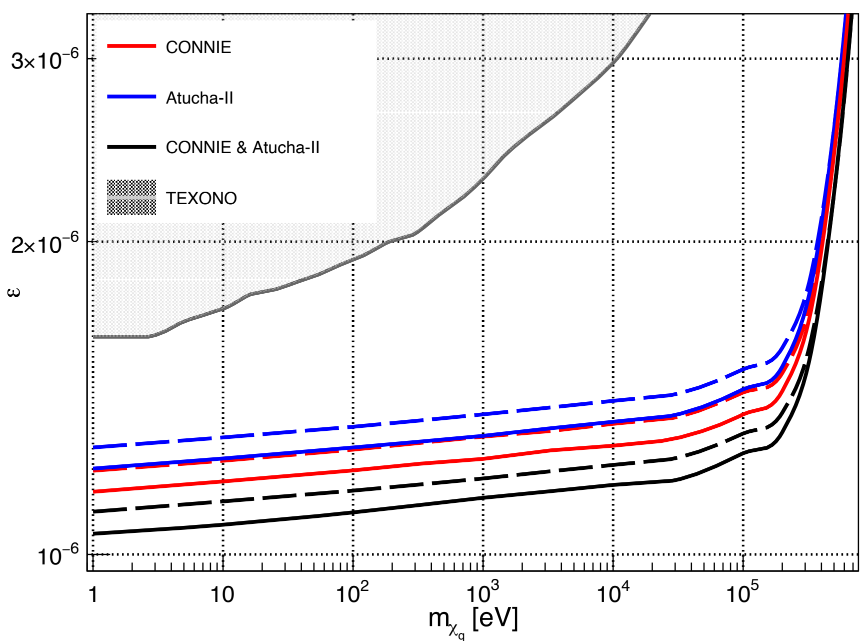
arXiv: 2405.16316

- Expected differential count rates at the detector:

$$\frac{dR}{dT} = \rho_A \int_{E_{\min}}^{E_{\max}} \left[\frac{d\sigma}{dT}\right] \left[\frac{d\phi_{\chi_q}}{dE_{\chi_q}}\right] dE_{\chi_q}$$

- Joint analysis between CONNIE and Atucha-II experiments.
  - Including secondary γ-rays from transport in the reactor core.
  - Based on 15–215 eV (CONNIE), 40–240 eV bin (Atucha-II).
  - Combined limit at 90% C.L. on reactor-χ_q production.



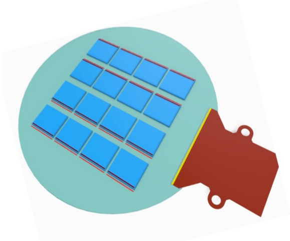


- World-leading limits on millicharged couplings over a large mass range for $m_{\chi q}$ < 1 MeV.

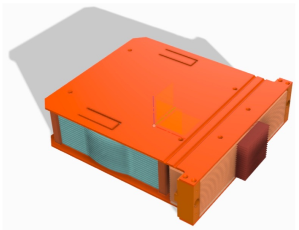
Next: a new compact module

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

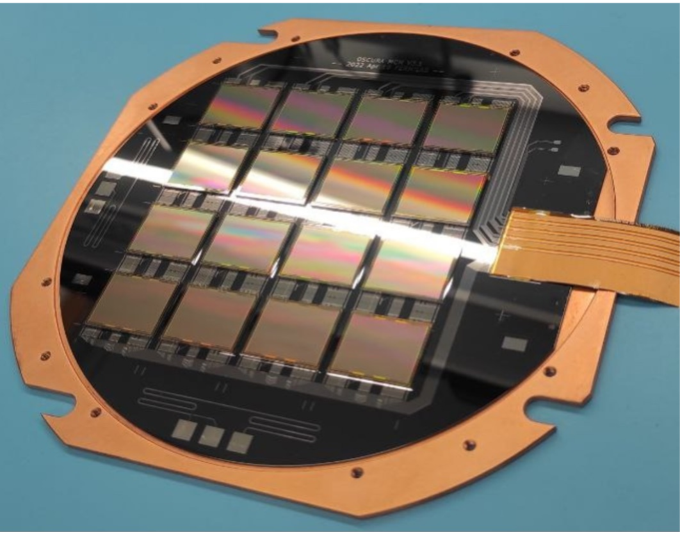
Multi-Chip Module (16 CCDs → 8 g)

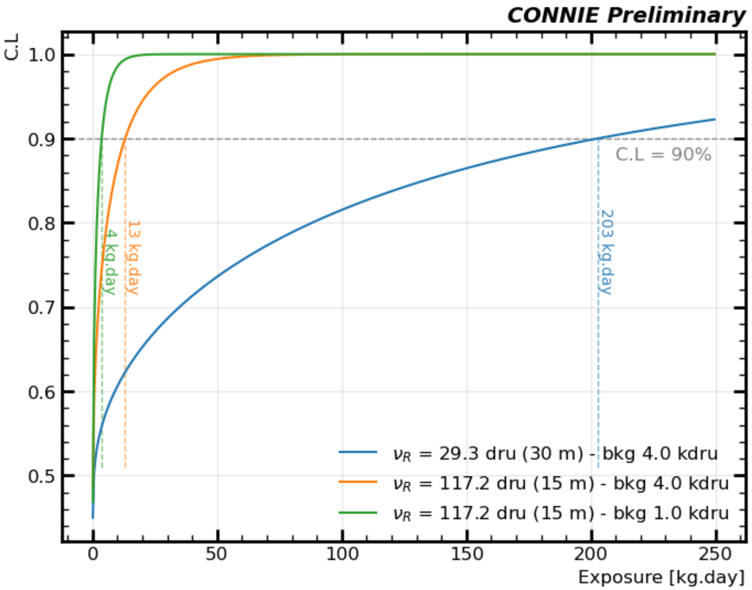


Super Module (16 MCMs → 100 g)



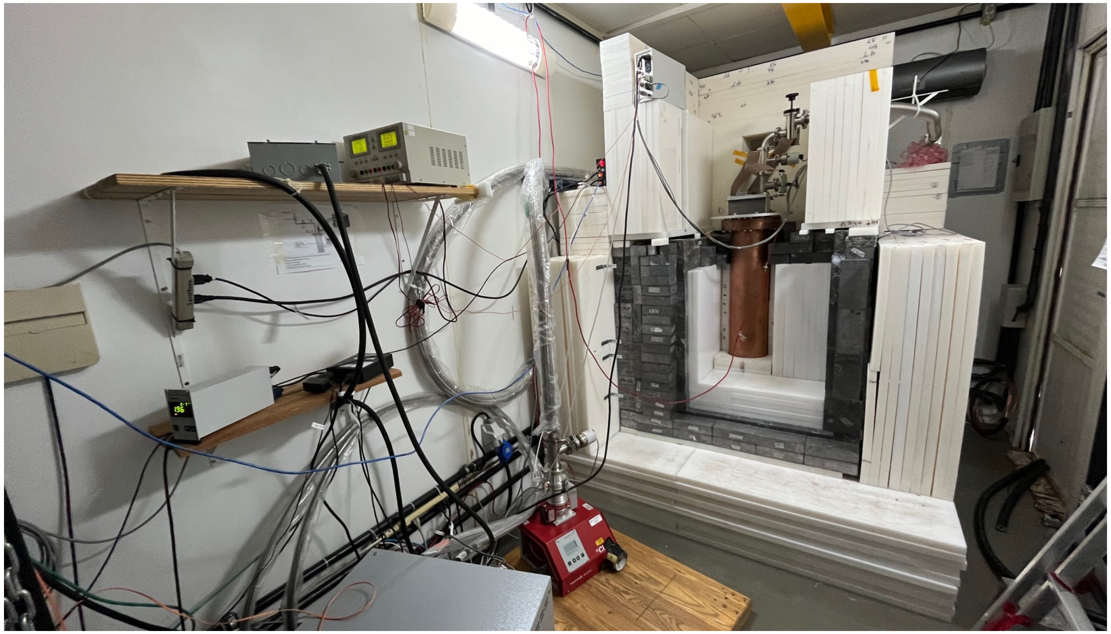
Oscura design [JINST 18 (08), P08016]





Summary and outlook

- Skipper-CCDs are very promising for detecting low-energy processes.
- 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.

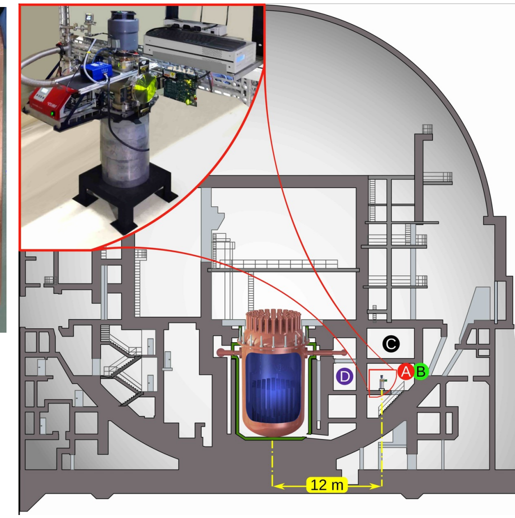


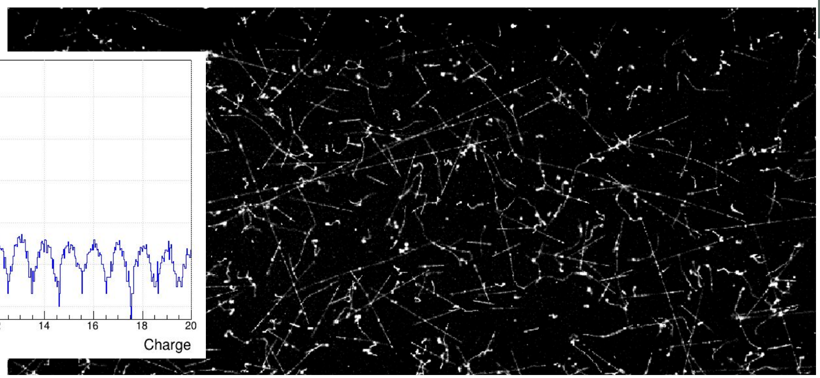
Lectureship job opening at the Federal University of Rio de Janeiro: https://inspirehep.net/jobs/2771627

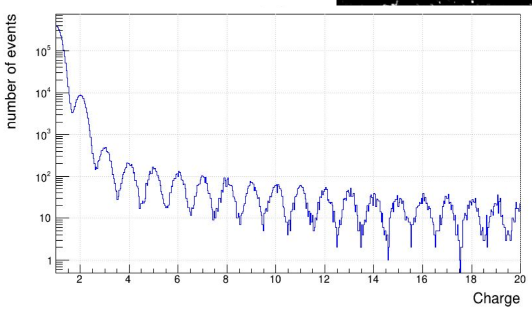
Back up

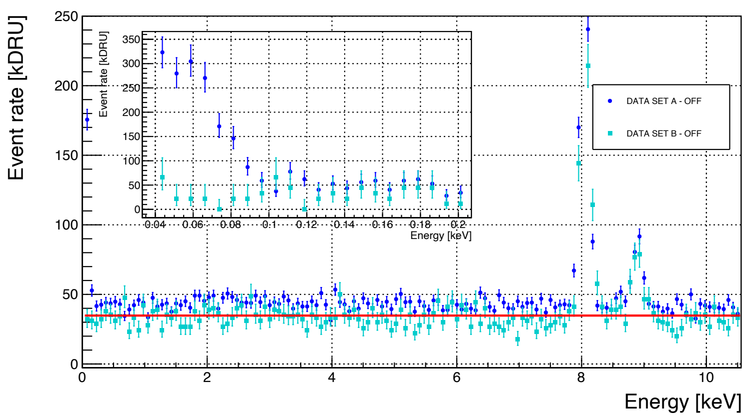
Atucha-II status

- Reactor neutrino experiment at 12 m from 2 GW_{th} the Atucha 2 reactor in Argentina.
  - Flux $2 \times 10^{13}\ \bar{\nu} s^{-1} cm^{-2}$.
- Taking data with Skipper-CCDs of 2.5 g.
  - Readout noise = 0.17e-.
  - Threshold = 40 eV.
  - Background ≅ 30 kdru.



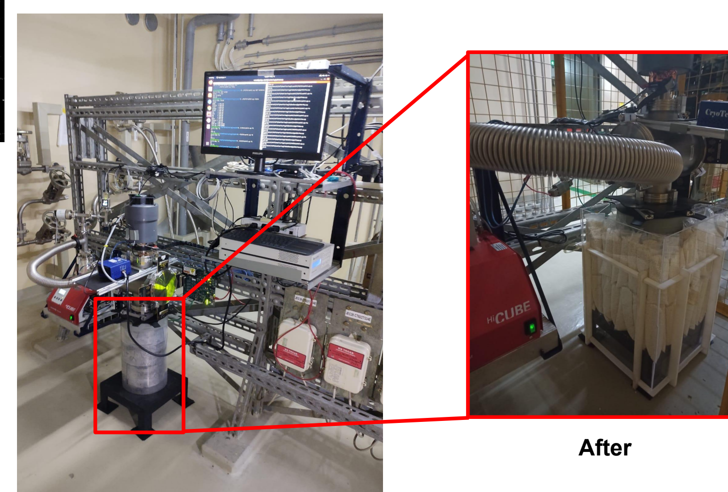






M. Cababie, TAUP2023

arXiv: 2401.0788



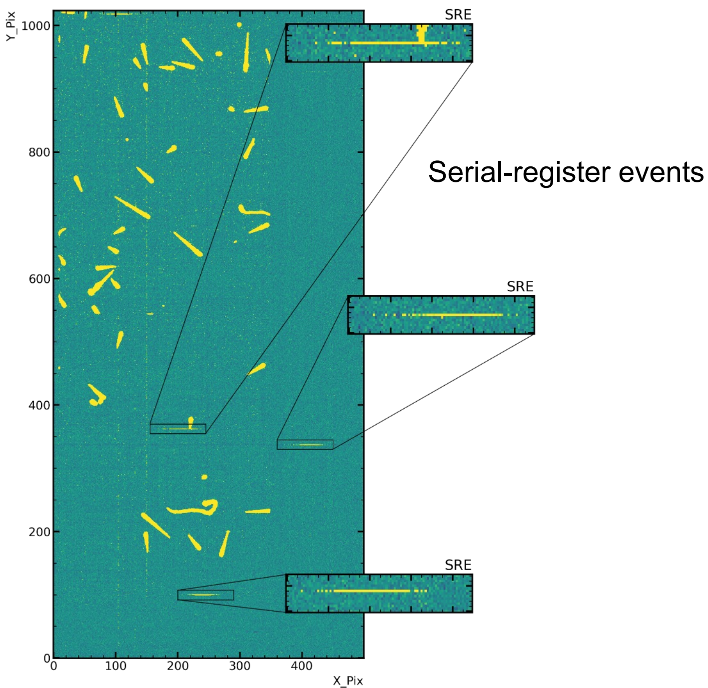
After

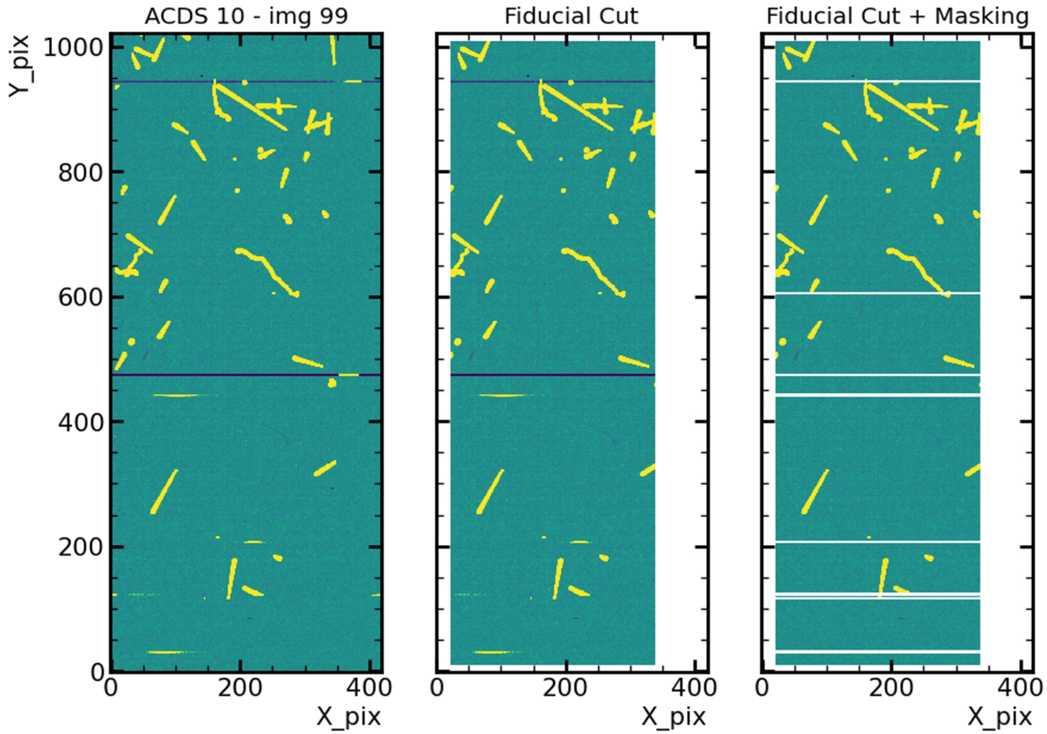
Skipper-CCD event selection

arXiv: 2403.15976

Selection cuts applied to reactor-off and on data:

- All Events: Energy threshold 15 eV.
- Fiducial cut: 10 pixel border in the Active Region.
- Masks: Global (Serial Register Event Mask + Hot Pixel Mask) + Master Hot Mask.
- Data quality: Noise < 0.17 e- and SER < 0.14 e-/pix/day.
- Extraction: clustering seed with 1.6 e- and adjacent pixels with 0.64 e-.
- Event size: diffusion 0.20 pix < $\sigma_{X,Yfit}$ < 0.95 pix.





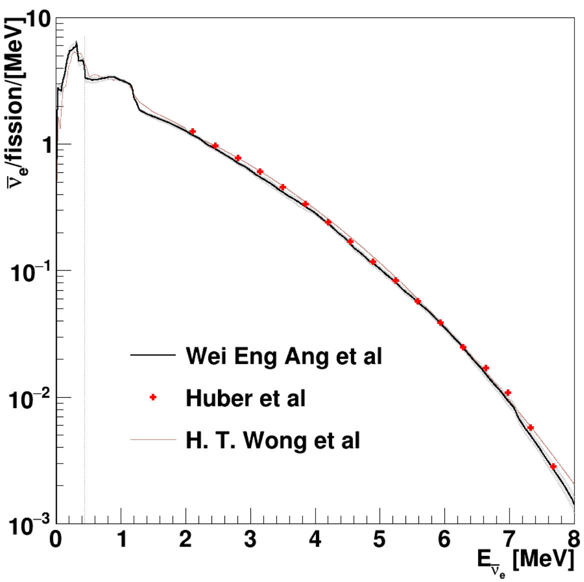
CEvNS search

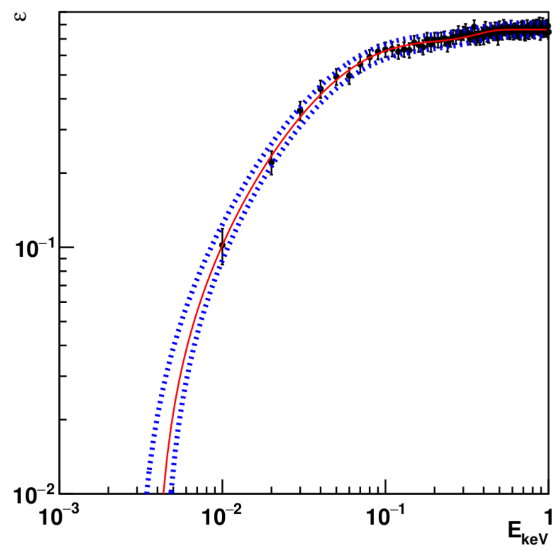
arXiv: 2403.15976

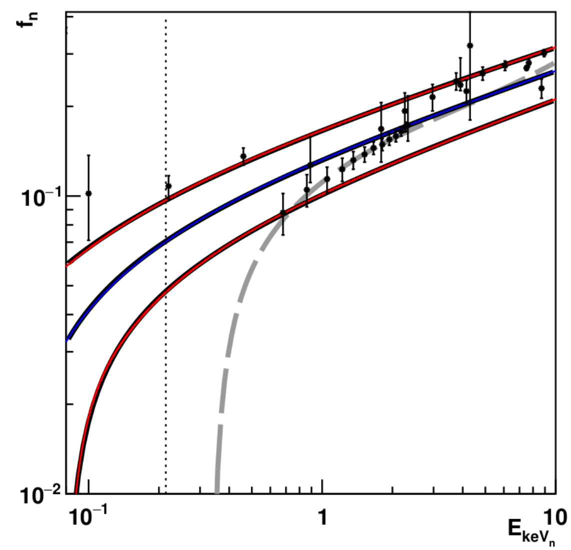
- Updated neutrino flux model with improved antineutrino spectra for ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu.
  - 15 eV_{ee} threshold corresponds to a minimum neutrino energy ~0.44 MeV,
  - Above that energy the new and old model agree within 3%.
- Updated Sarkis quenching factor model for silicon.

  Phys. Rev. A 107, 062811 (2023)

  - Based on Lindhard, with improved descriptions of the electronic stopping, interatomic potential and electronic binding at sub-keV energies, E_{nr} > 0.24 keV_{nr} (15 eV_{ee}).





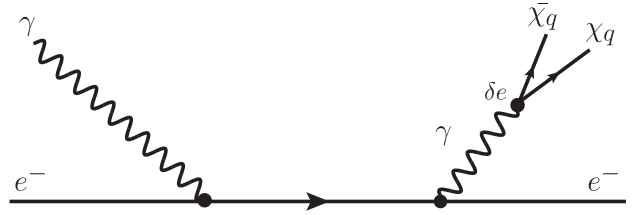


Search for millicharged particles

arXiv: 2405.16316

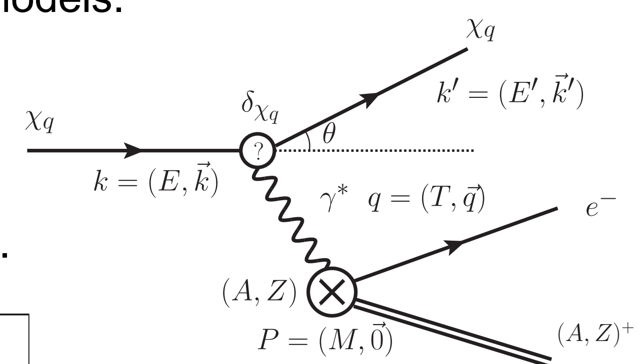
- The low-energy data can be used to search for relativistic millicharged particles (χ_q), predicted in hidden sector SM extensions.
- Can be pair-produced from Compton-like scattering of high-energy γ rays from reactors.
- Differential χ_q flux from the γ spectrum:

$$\frac{d\phi_{\chi_q}}{dE_{\chi_q}} = \frac{2}{4\pi R^2} \int \frac{1}{\sigma_{\text{tot}}} \frac{d\sigma}{dE_{\chi_q}} \frac{dN_\gamma}{dE_\gamma} dE_\gamma$$

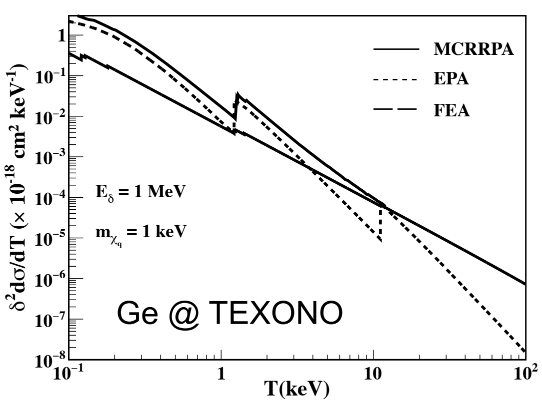


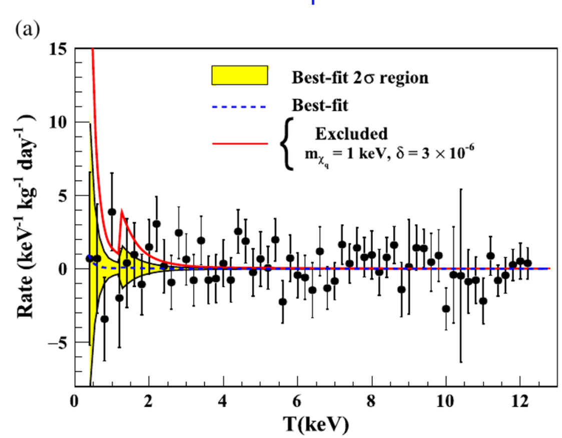
- Interact with matter via atomic ionisation in t-channel.
- The interaction cross-section is calculated with different models.
- Expected differential count rates at the detector:

$$\frac{dR}{dT} = \rho_A \int_{E_{\text{min}}}^{E_{\text{max}}} \left[\frac{d\sigma}{dT}\right] \left[\frac{d\phi_{\chi_q}}{dE_{\chi_q}}\right] dE_{\chi_q}$$



- On-off spectra can provide limits on reactor-χ_q production.





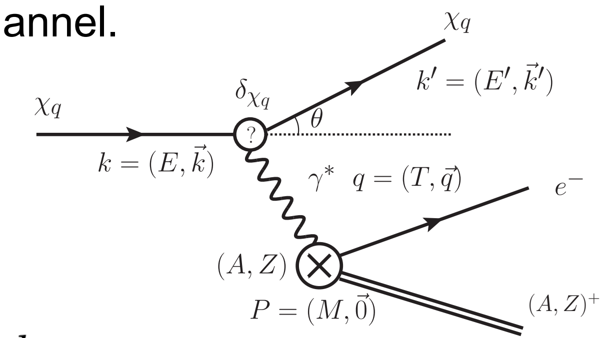
TEXONO collab., PRD 99, 032009 (2019)

Search for millicharged particles

arXiv: 2405.16316

- Detection: interaction with silicon via atomic ionisation in t-channel.
- Photo Absorption Ionisation (PAI) semiclassical model.

$$\frac{d\sigma_R}{dE} = \underbrace{z^2 \frac{2k_R}{\beta^2}\left(\frac{1-\beta^2 E/E_{max}}{E^2}\right)}_{ze \,\to\, \epsilon e}$$



$$\frac{d\sigma_{mcp}}{dE} = \epsilon^2 \frac{d\sigma_R}{dE} \longrightarrow \frac{d\sigma_{mcp}}{dE} = \epsilon^2 |F(E)|^2 \frac{d\sigma_R}{dE}$$

R. Essig et al, arXiv: 2403.00123

Modeling the Form Factor with the Photo Absorption Ionisation model:

$$\frac{d\sigma_{PAI}}{dE} = \overbrace{\underbrace{\frac{\alpha}{\beta^2\pi}\frac{\sigma_\gamma(E)}{EZ} ln\left[(1-\beta^2\epsilon_1)^2+\beta^4\epsilon_2^2\right]^{-1/2}}_{\text{Relativistic rise in e. deposition}} + \underbrace{\frac{\alpha}{\beta^2\pi}\frac{1}{N_e \hbar c}\left(\beta^2 - \frac{\epsilon_1}{|\epsilon|^2}\right)\Theta}_{\text{Cherenkov}}}^{\text{Transverse}} + \overbrace{\underbrace{\frac{\alpha}{\beta^2\pi}\frac{\sigma_\gamma(E)}{EZ} ln\left(\frac{2mc^2\beta^2}{E}\right)}_{\text{Resonance absorption at atomic energy levels}} + \underbrace{\frac{\alpha}{\beta^2\pi}\frac{1}{E^2}\int_0^E \frac{\sigma_\gamma(E')}{Z}dE'}_{\text{Rutherford quasi free scatterings}}}^{\text{Longitudinal}}$$

$$\frac{d\sigma_{mcp}}{dE} = \epsilon^2 \frac{d\sigma_{PAI}}{dE}$$

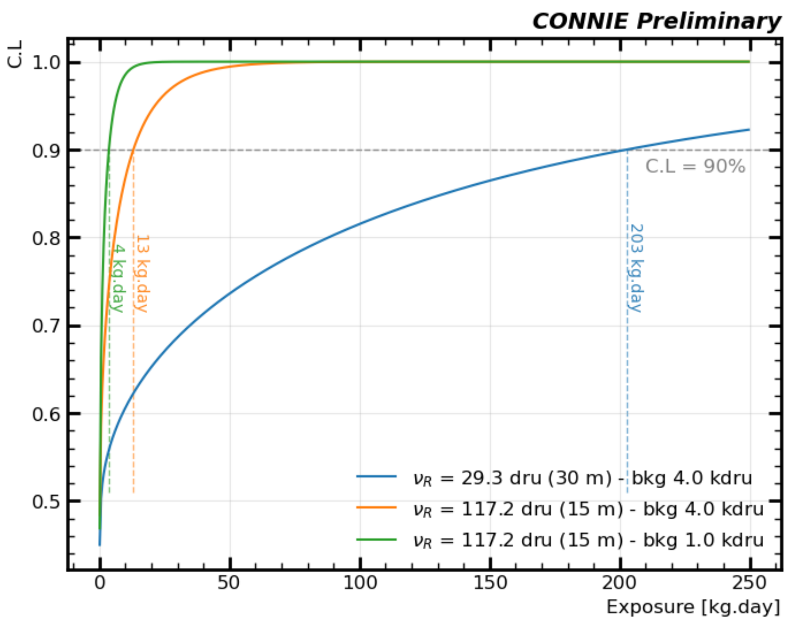
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\omega} = \frac{8\alpha\varepsilon^2}{n\beta^2}\int_{k_{\min}}^{k_{\max}} \frac{\mathrm{d}k}{k}\left\{\mathrm{Im}\left(-\frac{1}{\epsilon(\omega,k)}\right) + (\beta^2k^2-\omega^2)\,\mathrm{Im}\left(\frac{1}{-k^2+\epsilon(\omega,k)\omega^2}\right)\right\}$$

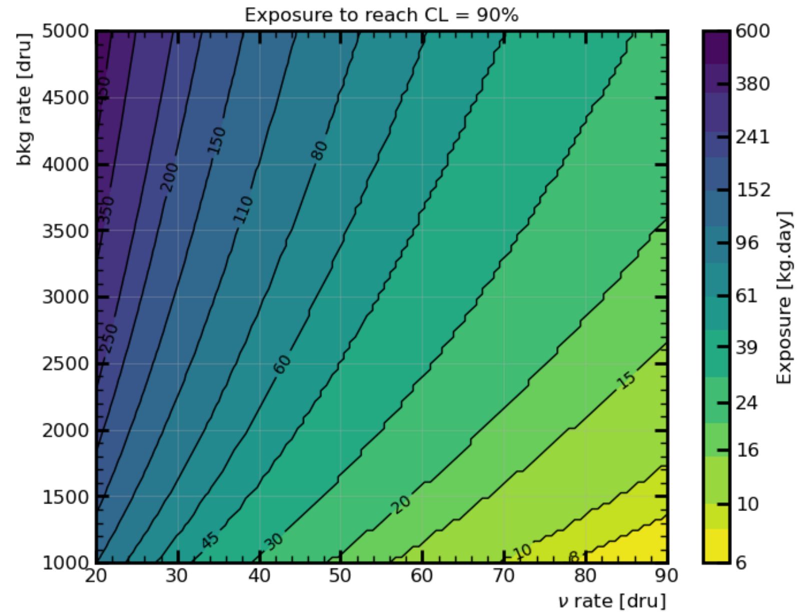
Collective effects are encoded in the dielectric function calculated with the DarkELF code

Limit setting: we search for the lowest coupling compatible with what we observed in the 15-215 eV bin.

CONNIE perspectives

- Considering a threshold of 15 eV, we expect a CEνNS rate 2.2 times higher than in 2019.
- If we install a 1 kg detector at the CONNIE site, with a background rate 4 kdru and threshold of 15 eV, it should run for 200 days if Sarkis QF to observe CEνNS at 90% CL.





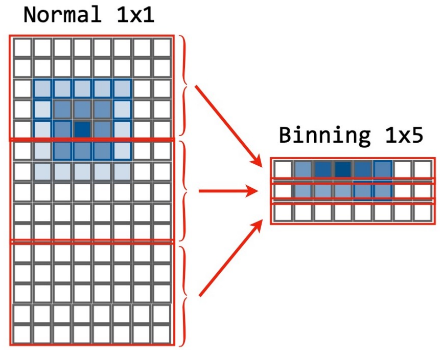
- Studying the possibility to increase sensor mass.
- Aim to go closer at 20 m to the reactor, below the dome.
  - Currently negotiating a position in Angra 2.

CONNIE 2019 run

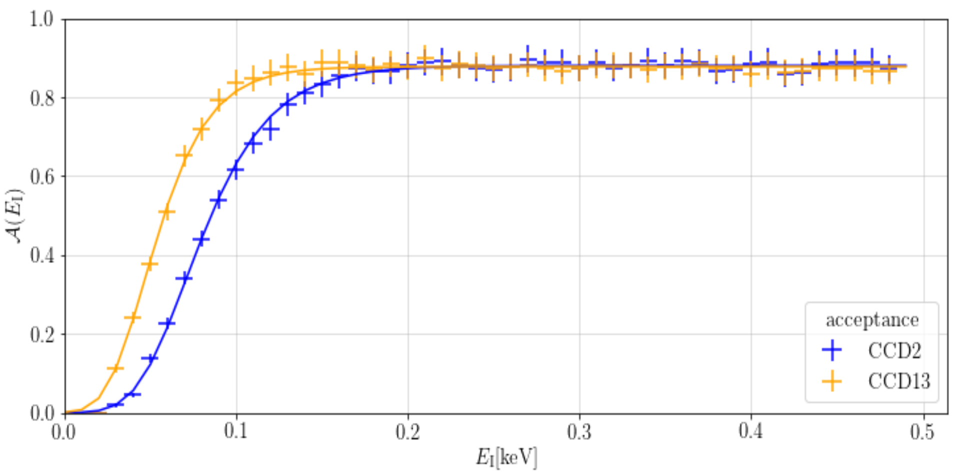
JHEP 05:017, 2022

Improvements in data acquisition and analysis techniques in 2019:

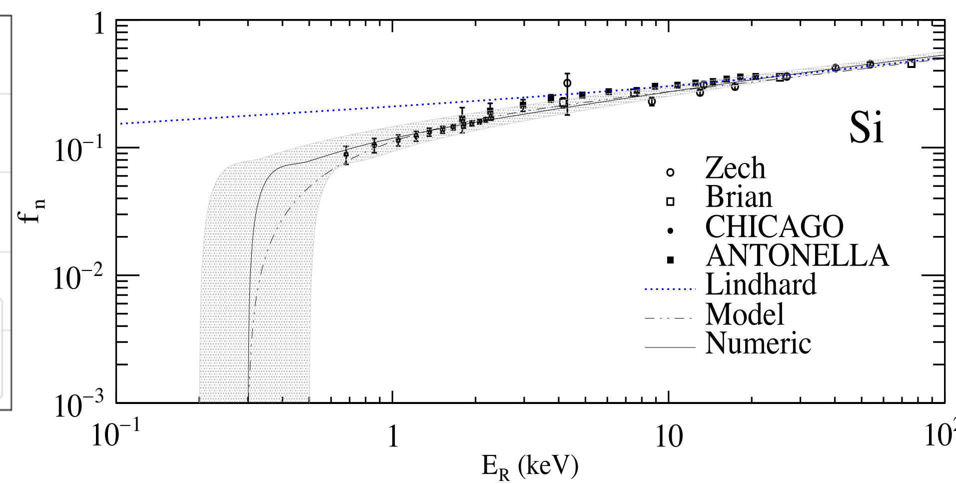
- 1x5 pixel hardware rebinning reduces readout noise.
- Improved energy and size-depth calibrations.
- Low-energy background characterisation and reduction.
  - Detection threshold is reduced to ~50 eV.
  - Full efficiency reached at 100-150 eV.
- Blind analysis and multiple cross-checks.
- New Sarkis quenching factor model for ionisation efficiency at low energies.



Y. Sarkis et al, PRD 101 (2020) 10 102001



Acceptance for most and least efficient CCDs

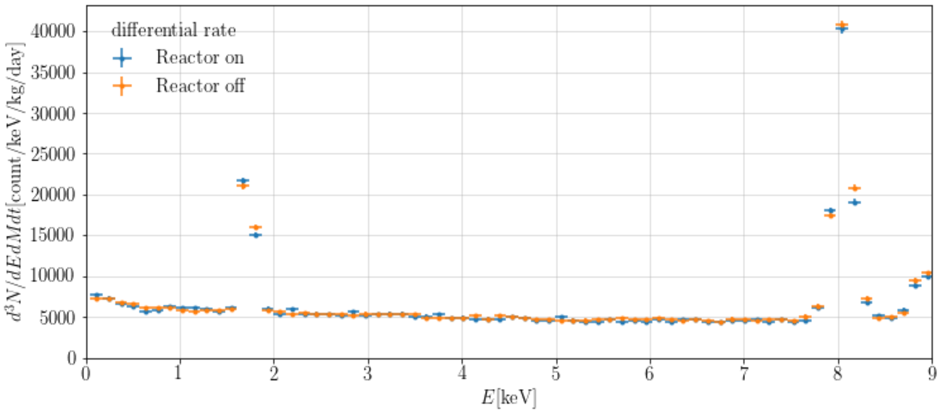


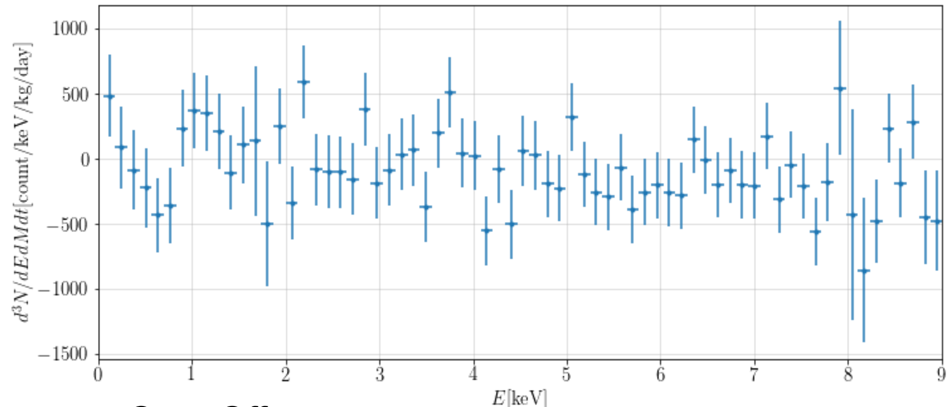
Sarkis quenching factor model for Si

CONNIE 2019 results

JHEP 05:017, 2022

- Energy spectrum from 8 CCDs with total active fiducial mass 36 g.
- Exposures of 31.85 days with reactor on and 28.25 days with reactor off.
- Total exposure of 2.2 kg-days.

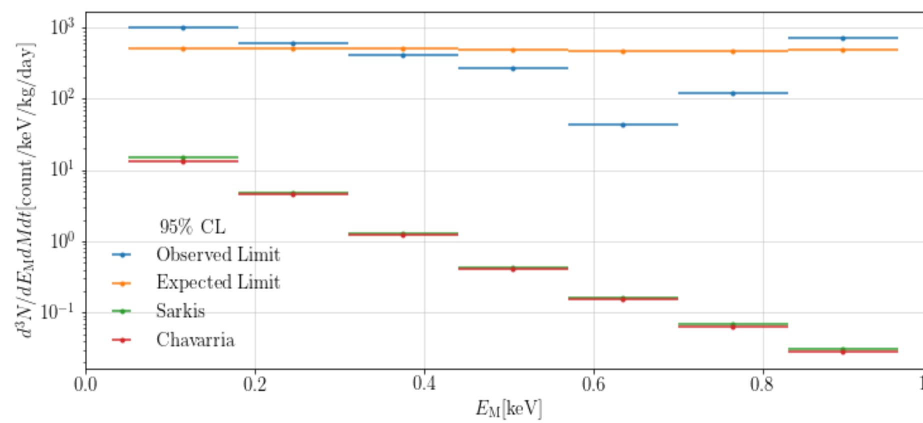




On – Off rates

Upper limits at 90% CL on the measured neutrino rate:

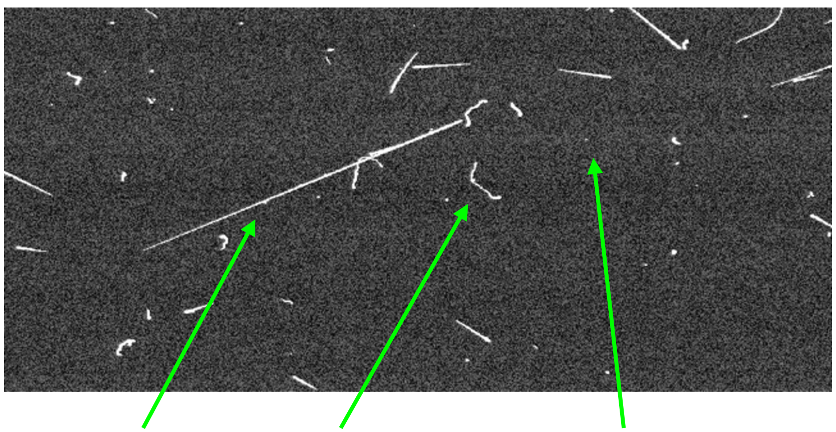
- Expected limit in the lowest-energy bin of (50-180) eV is 34-39 times the SM prediction.
- Observed limit is 66-75 times the prediction.



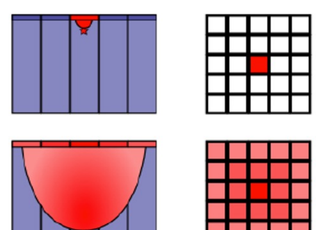
Event reconstruction

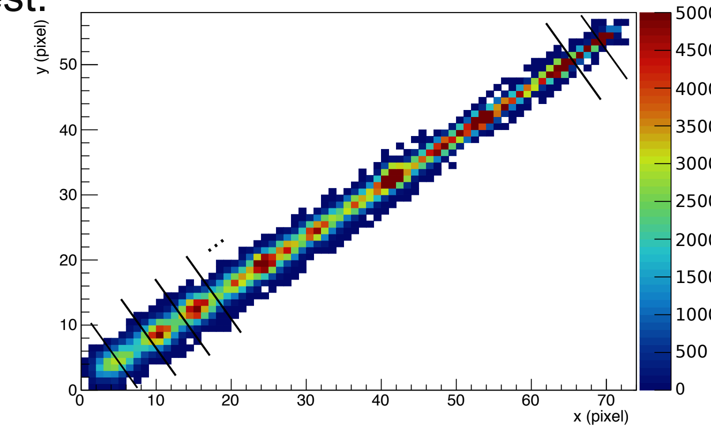
- Identify tracks based on geometry.
- Energy calibration in situ using Cu fluorescence x-rays.
- Depth versus diffusion width calibration using cosmic muons.
- Monitor the stability of natural backgrounds, noise and dark current.
- Low-energy neutrino selection based on likelihood test.

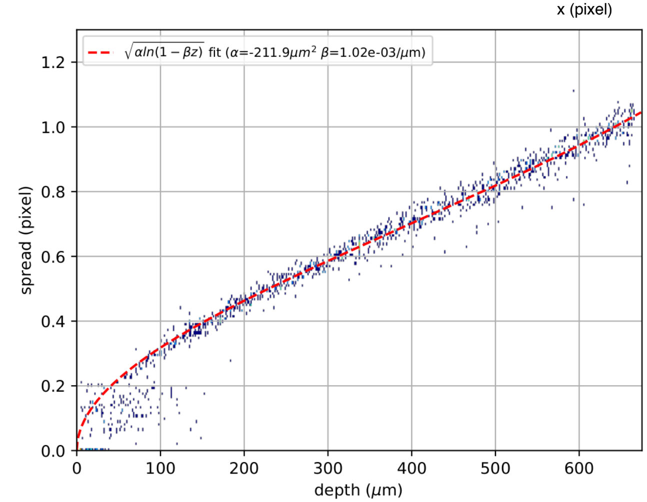
Phys. Rev. D 100 (2019) 092005



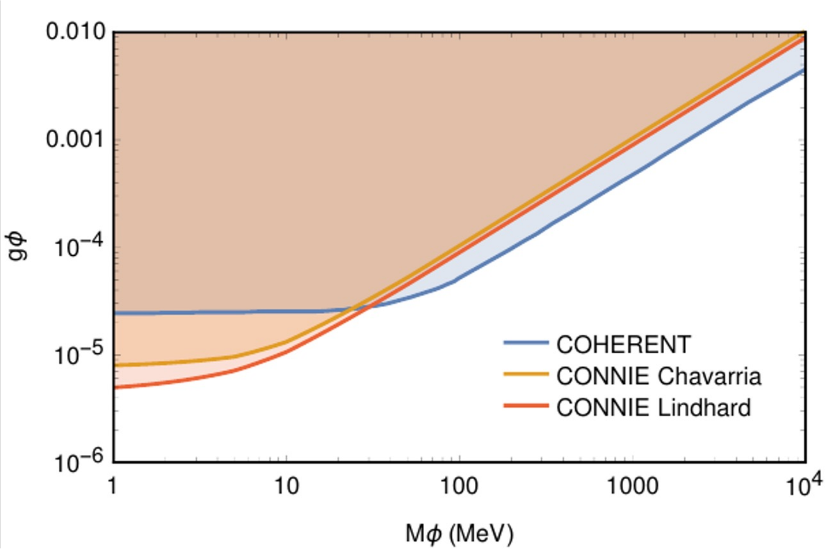
muon   electron   diffusion-limited hits photons/neutrinos

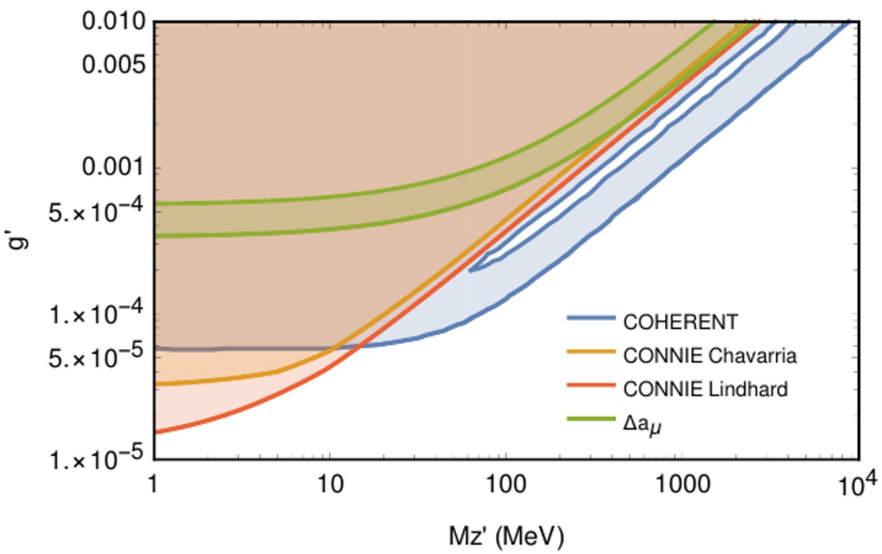






Non-standard interaction limits





JHEP 04 (2020) 054

- Event rates in the lowest-energy bin yield limits on non-standard neutrino interactions:
  - Light vector (Z') mediator.

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

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

  - Light scalar (ϕ) mediator.

$$\frac{d\sigma_{SM+\phi}}{dE_R}(E_{\bar{\nu}_e}) = \frac{d\sigma_{SM}}{dE_R}(E_{\bar{\nu}_e}) + \frac{G_F^2}{4\pi}Q_\phi^2\left(\frac{2ME_R}{E_{\bar{\nu}_e}^2}\right)MF^2(q)$$

$$Q_\phi = \frac{(14N+15.1Z)g_\phi^2}{\sqrt{2}G_F\left(2ME_R+M_\phi^2\right)}$$

- The most stringent limits for low mediator masses $M_{Z'}$ (M_ϕ) <10 MeV at the time.
- First competitive BSM constraints from CEνNS at reactors.

Skipper CCD readout

[PRL 119, 131802]