Status and recent results from the CONNIE experiment with Skipper-CCDs

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for the CONNIE Collaboration

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CONNIE Collaboration

~ 35 members from 6 countries

Centro Atómico Bariloche, CONICET, ICIFI – Universidad Nacional de San Martín, IFIBA – Universidad de Buenos Aires, Universidad de Córdoba , Universidad del Sur, 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

Main goals

- Detect CEvNS with reactor neutrinos in silicon with Skipper-CCDs.
- Explore Beyond Standard Model (BSM) physics
- Develop monitoring of nuclear reactors with neutrino detection for safeguards.

CONNIE: Coherent Neutrino Nucleus Interaction Experiment

- Experiment @ 30 m from the 3.9 GW reactor core
- Reactor-OFF periods (~1/14 months) for background measurements
- Flux: ~7.8 × 10^{12} $\bar{\nu}_e$ cm^{-2} s^{-1}
- Passive shield (Lead + polyethylene)
- Energy threshold ~ 15 eV ee

CONNIE: experiment timeline

World-leading limit to millicharged particles
[PRL 134 (2025) 7, 071801]

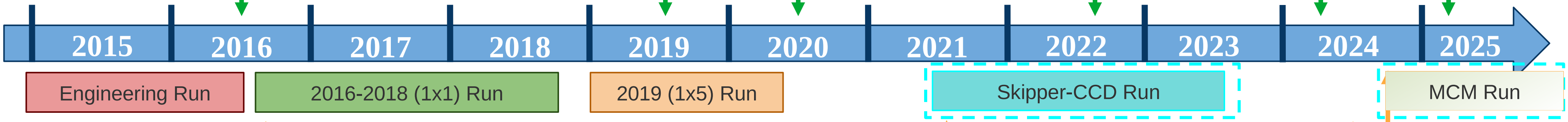
Limits on SM extensions with light mediators
[**JHEP 04 (2020), 054**]

Results from Skipper-CCD run
[**arXiv: 2403.15976**]

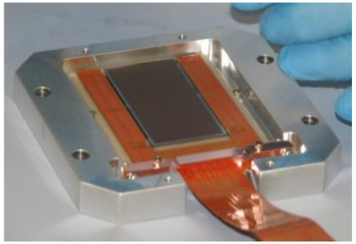
Resuls from Engineering run
[**JINST 11 (2016), P07024**]

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

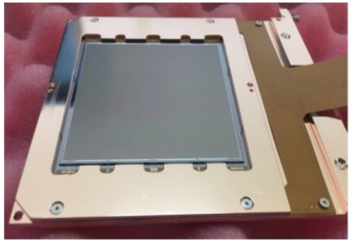
Results from 2019 run
[**JHEP 05 (2022), 017**]



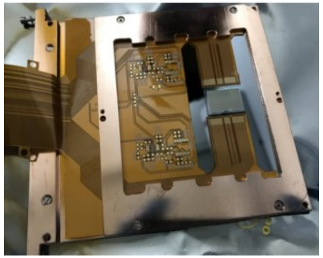
Instalation at Angra



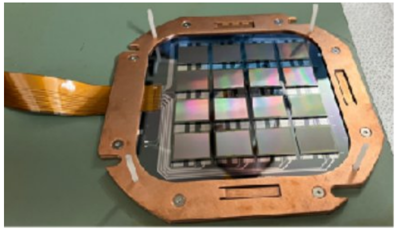
Upgrade to Scientific CCDs



Installation of Skipper-CCDs



Installation of Multi-Chip Module



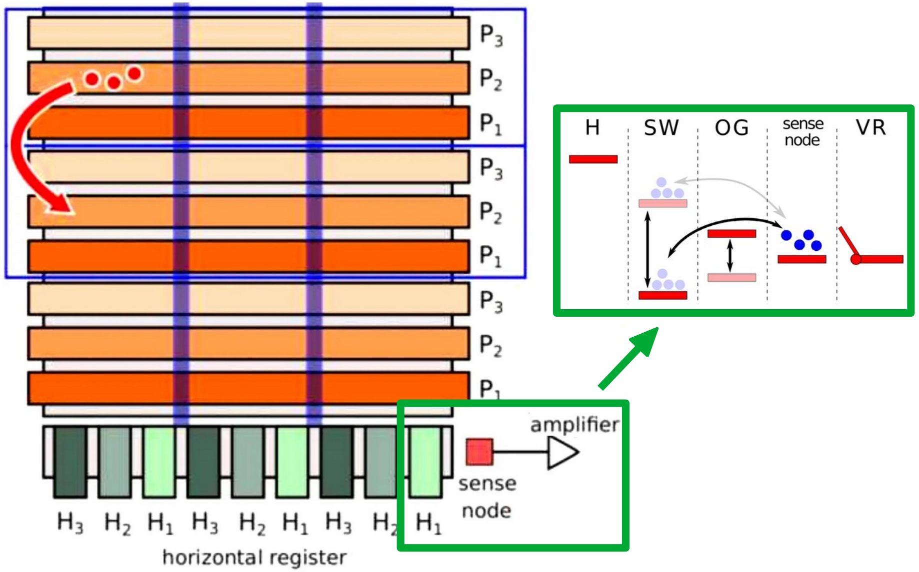
16 Skipper-CCDs, from Oscura

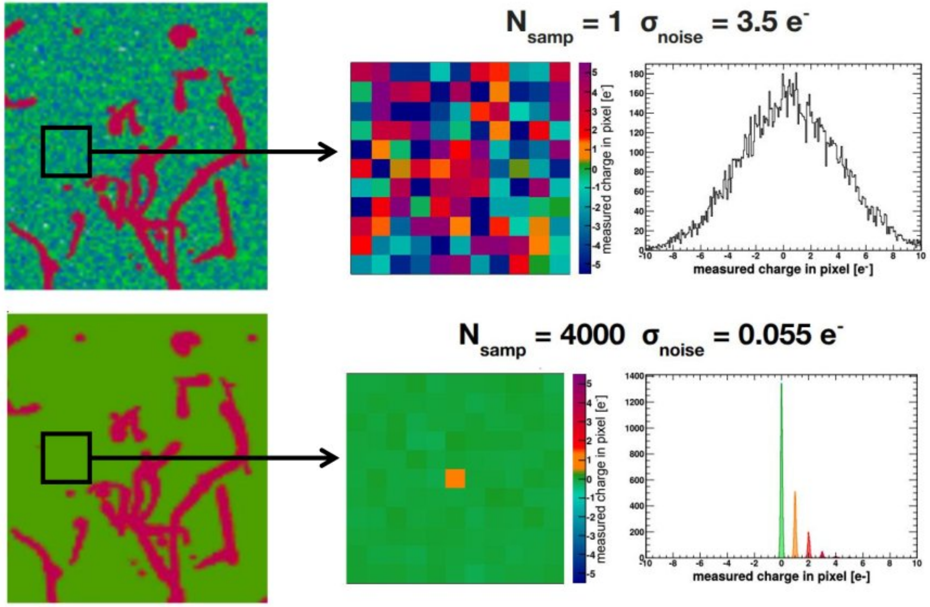
Skipper-CCDs: e⁻ counting sensors

New-generation CCDs with a readout stage that enables **multiple (N) measurements of the charge each pixel.**

- Readout noise is reduced as $\sigma = \frac{\sigma_1}{\sqrt{N}}$ reaching single-electron resolution!
- Promising technology for neutrino and dark matter direct detection (currently in use!) **Talk by M. Traina DM3A**

3x3 pixel CCD





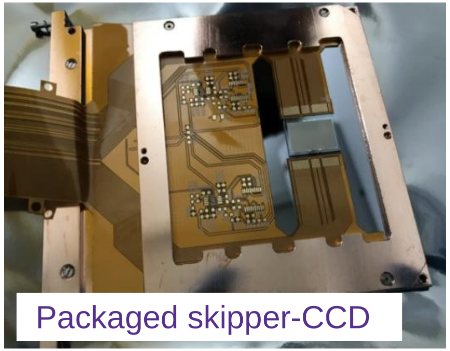
J. Janesick et al.. "New advancements in charge-coupled device technology: sub-electron noise and 4096×4096 pixel CCDs". [10.1117/12.19452]
G. Fernandez Moroni et al.. "Sub-electron readout noise in a Skipper CCD fabricated on high resistivity silicon". [10.1007/s10686-012-9298-x]
J. Tiffenberg et al.. "Single-Electron and Single-Photon Sensitivity with a Silicon Skipper-CCD". [10.1103/PhysRevLett.119.131802]

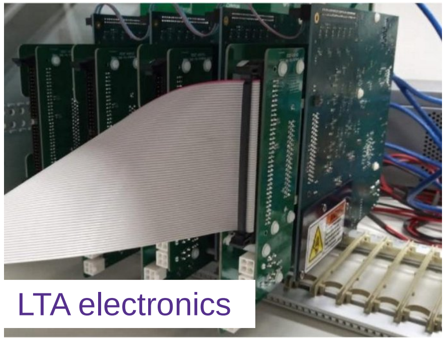
CONNIE with Skipper-CCDs: single sensors

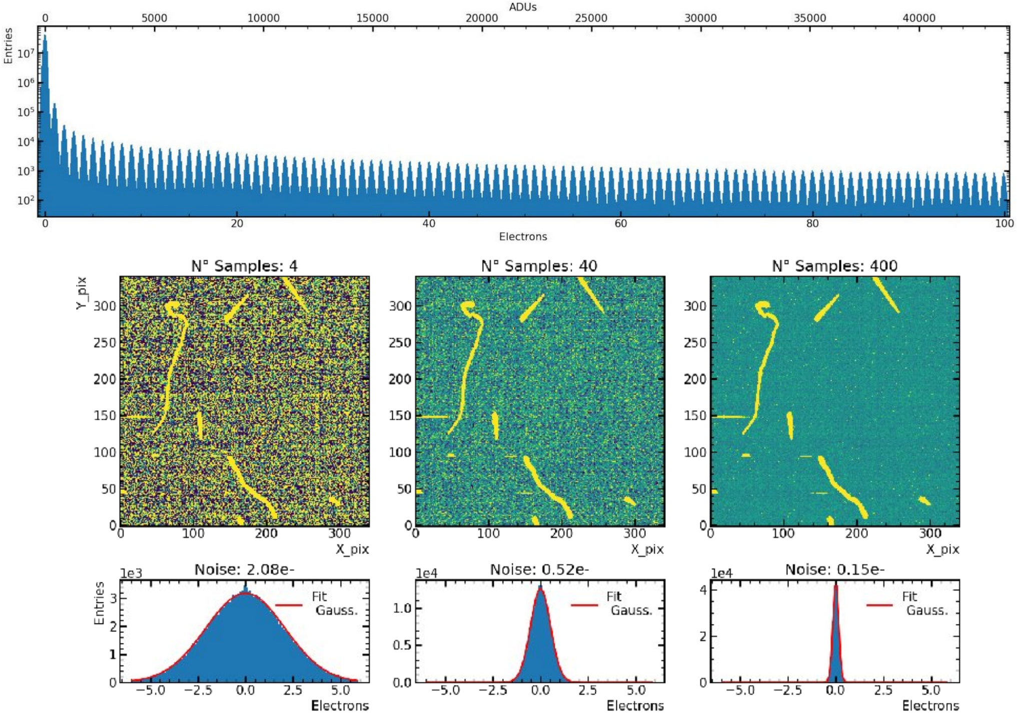
arXiv:2403.15976

First installation of skipper-CCDs at CONNIE in July 2021

- 2 LBNL-FNAL skipper CCDs (1022 x 682 (15 µm ^{2} pixels, 675-µm thick).
- New Low Threshold Acquisition (LTA) readout electronics. [JATIS 7 (2021), 1 015001]
- New dedicated Vacuum Interface Board.


Packaged skipper-CCD


LTA electronics



CONNIE with Skipper-CCDs: single sensors

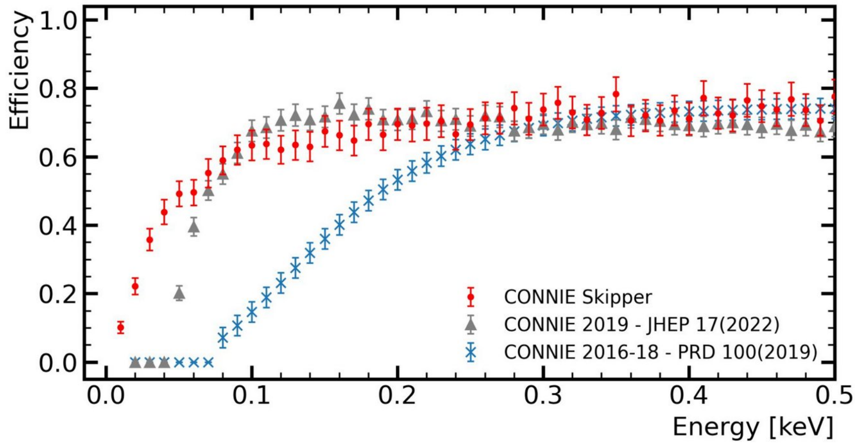
arXiv:2403.15976

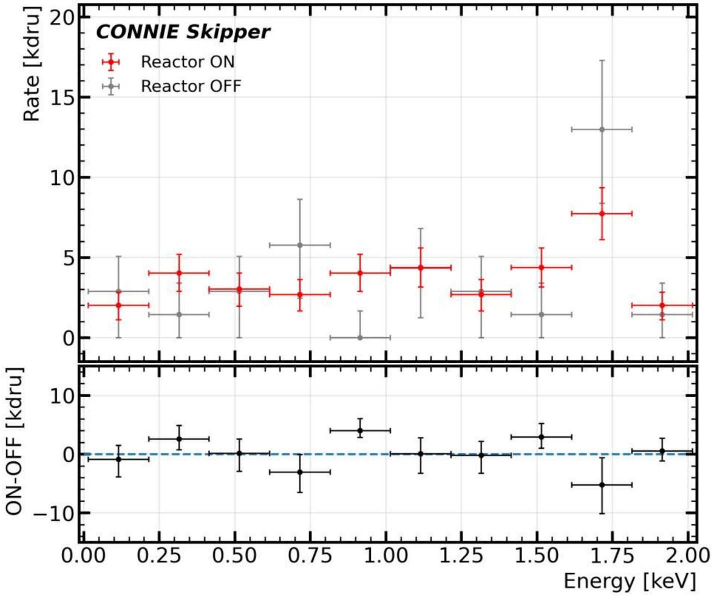
Improvements over standard-CCD runs:

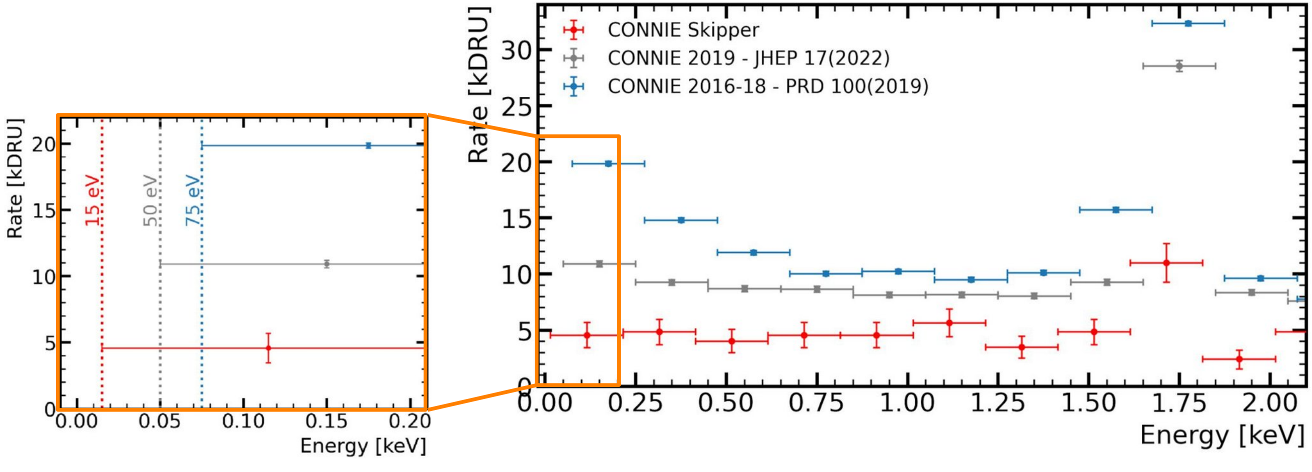
- Energy threshold reduced to 15 eV_{ee} (~240 eV_{nr}).
- Higher detection efficiency at lower energies.
- Lower and flat background rate: ~4 kdru.

Exposure: 14.9 g-day reactor-on & 3.5 g-day reactor-off.

No excess observed.







CONNIE with Skipper-CCDs: single sensors

arXiv:2403.15976

Search for CEνNS: 95% limit of 76 times the predicted rate.

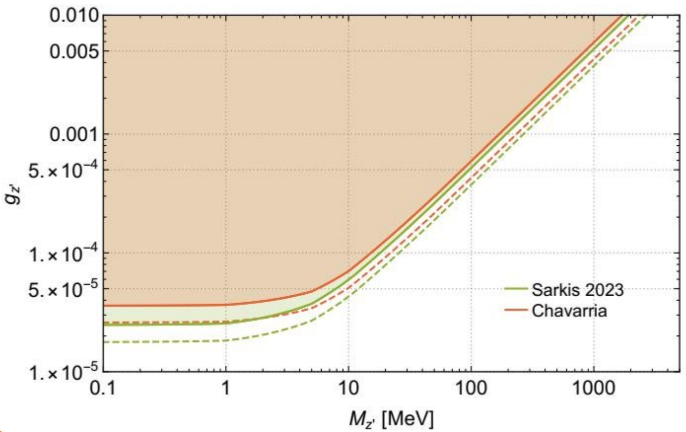
Comparable to previous limit with standard CCDs achieved with x10^3 larger exposure.

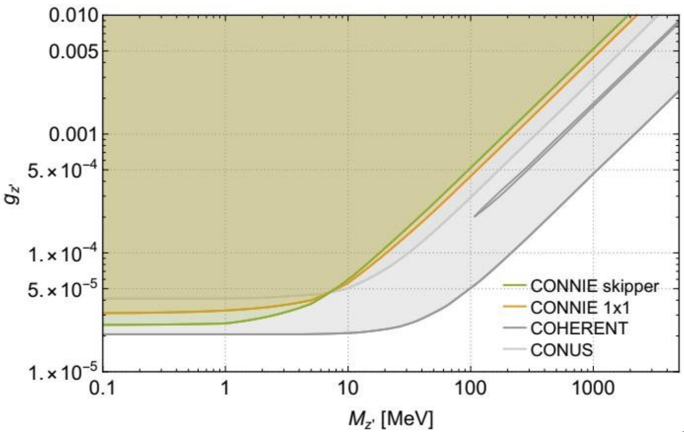
- Updated reactor neutrino flux & Sarkis model of nuclear recoils quenching factor [PRA 107, 062811] .

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

Search for light vector mediator: slight improvement at low M Z' over our previous limit.

- Considered simplified universal model [JHEP 05 (2016) 118] and lowest energy bin.





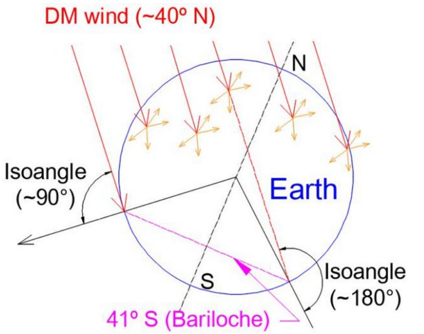
CONNIE with Skipper-CCDs: single sensors

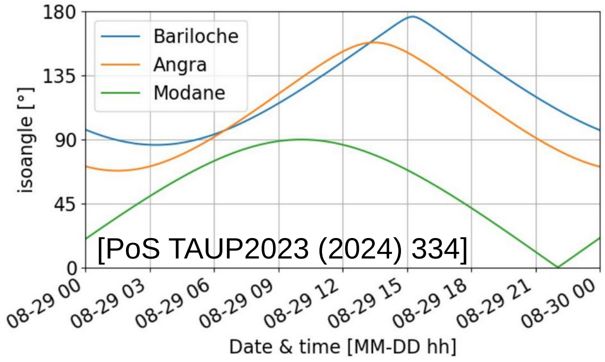
arXiv:2403.15976

Search for DM by diurnal modulation: best DM-electron limits by a surface experiment.

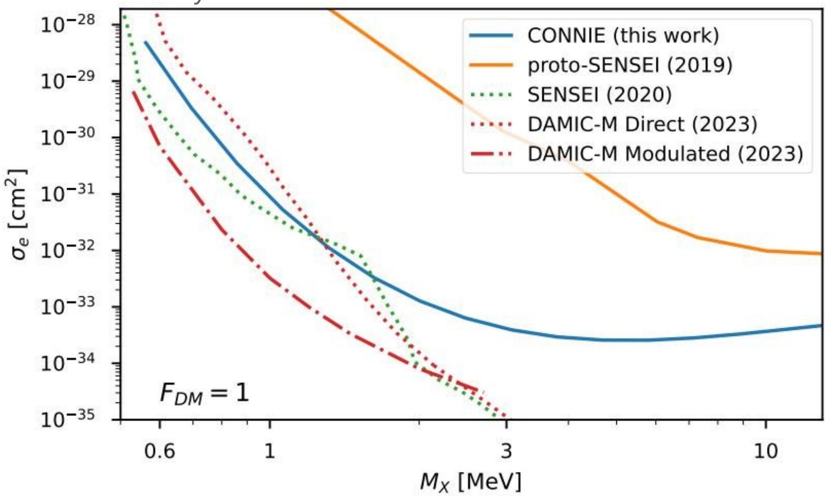
Galactic DM wind comes from a preferred direction.
Diurnal modulation by interactions in the Earth.
Enhanced in the southern hemisphere.

- Data compared to DAMASCUS simulations.
- Model with MeV-scale DM, coupling to the SM via a kinetically-mixed dark photon.

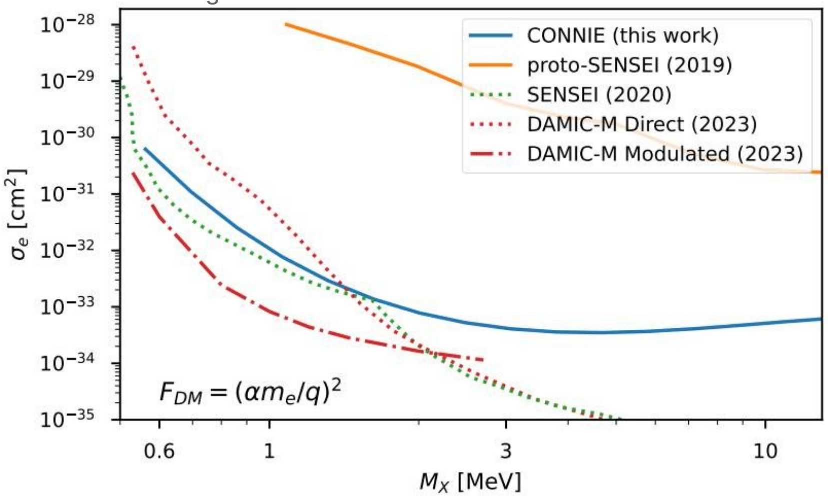




Heavy mediator



Ultra-light mediator

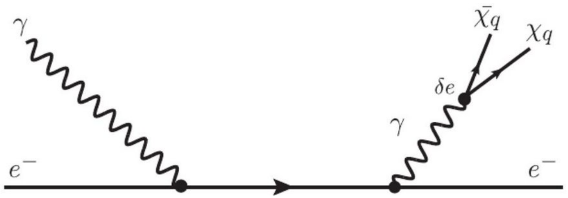


CONNIE with Skipper-CCDs: single sensors

PRL 134, 071801 (2025)

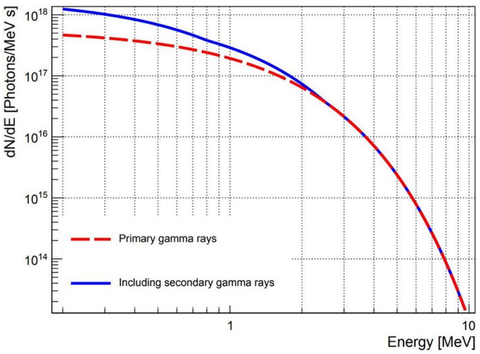
Joint search, with Atucha-II, for reactor-produced mCPs: → world-leading limits for masses <1 MeV

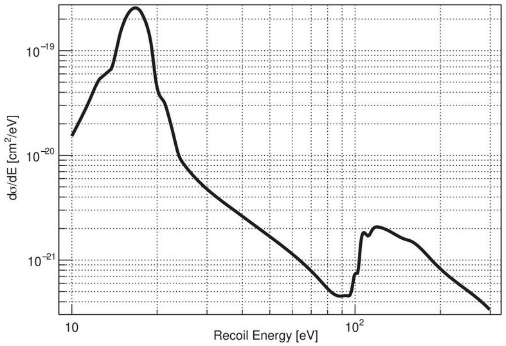
Relativistic mCPs could be produced from Compton-like scattering of HE ɣ-rays ion the reactor core.

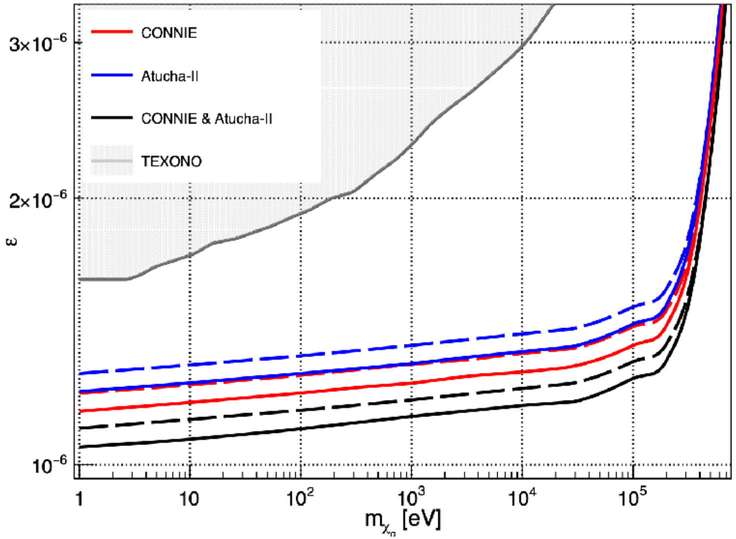


Observable	CONNIE	Atucha-II
Reactor ON exposure [g-day]	14.9	59.4
Reactor OFF exposure [g-day]	3.5	22.6
Energy bin [eV]	15–215	40–240
Reactor ON counts	6	168
Reactor OFF counts	2	71
90% C.L. upper limit on events	6.2	30.9

- Considered ɣ-ray spectrum from uranium fission and mCP production from primary and secondary γs.
- Included collective excitation effects [Comm Phys 7, 416 (2024)] in the detection cross-section.

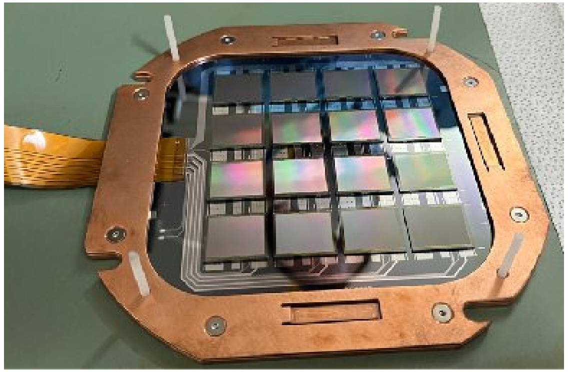






CONNIE-MCM (Multi-Chip Module)

Towards more massive experiments



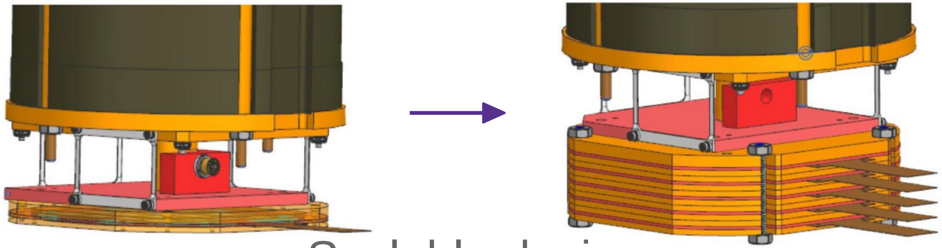
MCMs offer a new compact arrangement of sensors:

- 16 Skipper-CCDs sensors on the same module (8 g each)
- Each Skipper is 1278 x 1058 (15 μm)^2 pixels, 725-μm thick
- Designed for the Oscura DM experiment [JINST 18, 08016 (2023)]
- Multiplexed readout [Sensors 22 (11), 4308; JINST 18 P01040]

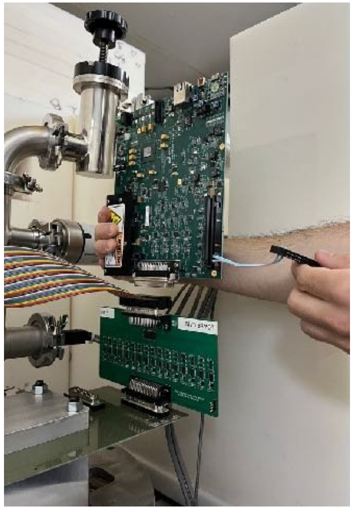
One MCM was commissioned at CONNIE in October 2024

- New VIB and multiplexer board
- 10x increase in mass with respect to single sensors
- Currently taking data -

Now Future



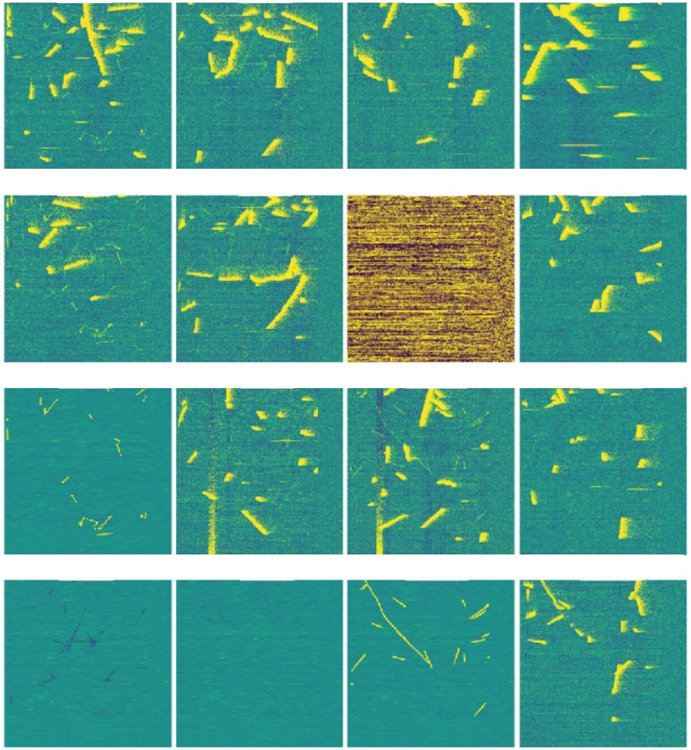
Scalable design

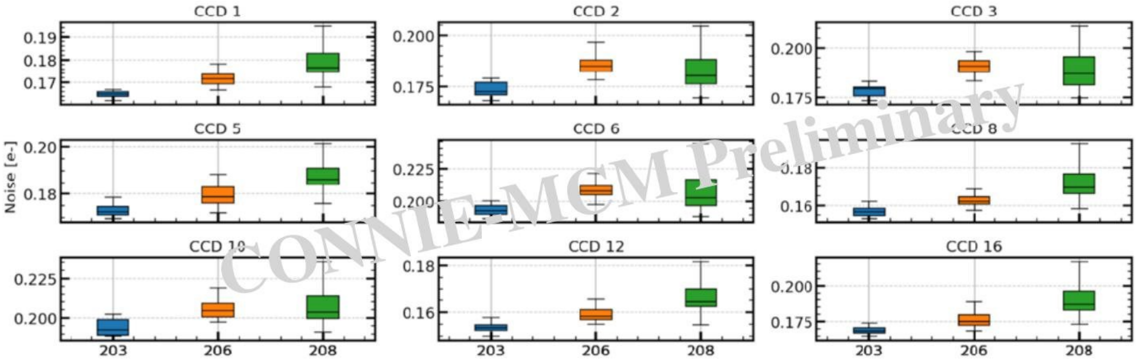


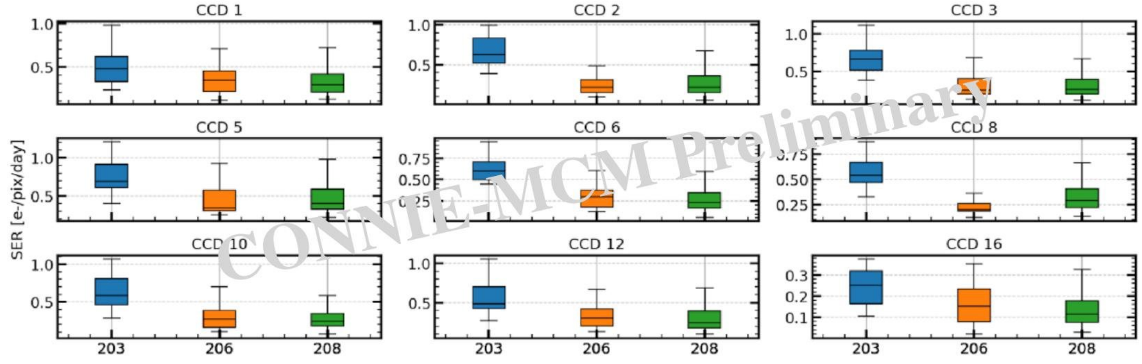
CONNIE-MCM Performance

Commissioning and optimization ongoing.

- 9/16 skipper-CCDs working in the current MCM.
- Performing stable: noise of 0.15-0.21 e - RMS and single-electron rate below 0.5 e - /pix/day.







Next steps and challenges

Towards CEvNS detection

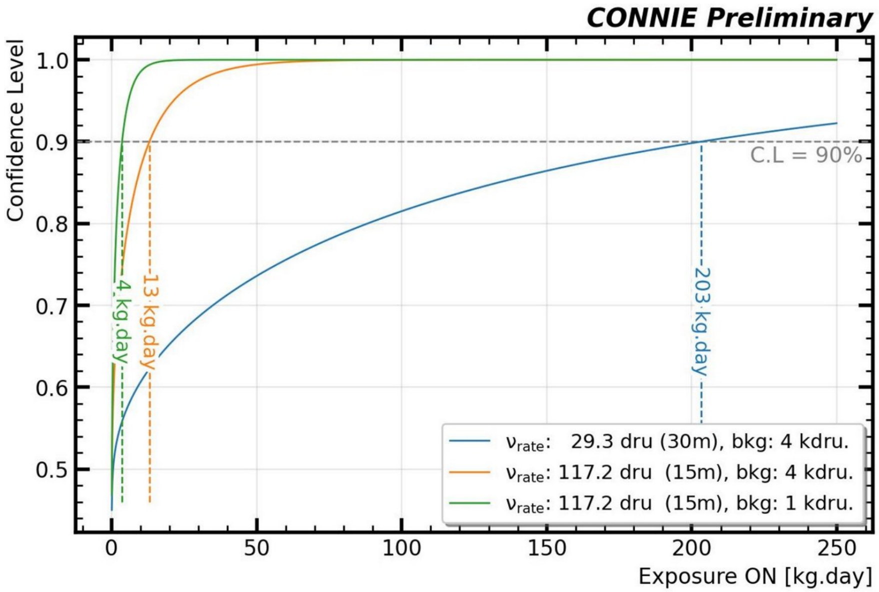
- CONNIE-MCM
  - Optimizing performance for reactor OFF spectrum (Nov 2024) and reducing background.
  - Collecting data to improve current experimental limits.
  - Improvements in current BSM limits with ~10 times more mass.
  - Proof of concept for new technology to increase mass.
  - Synergy with Oscura: first experiment to install an MCM at a nuclear reactor.

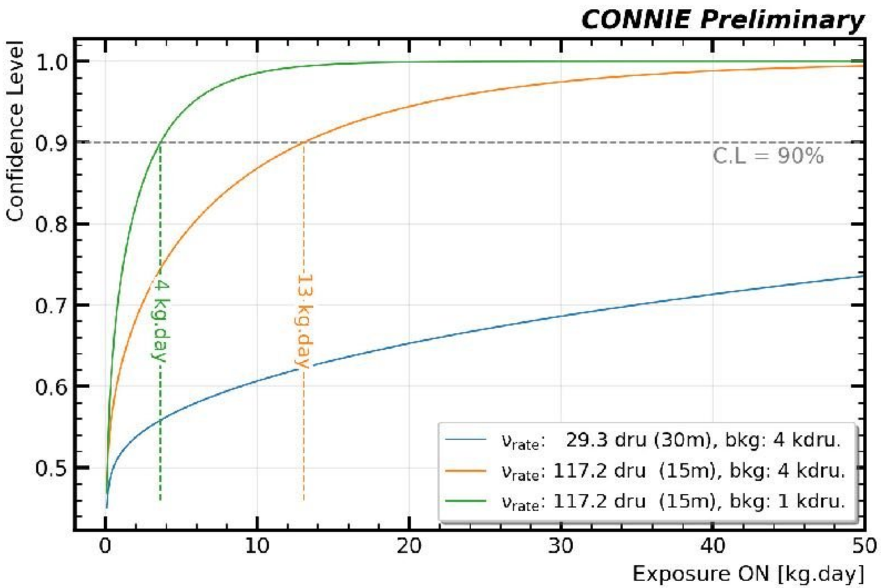
- Plans to increase the neutrino flux
  - New position @ Angra-2 (~17 m from reactor core, inside the dome) identified. Negotiations underway.
  - Would: - increase the flux by factor of ~3.
    - reduce background by factor of 3-4 (rough estimate).
  - Requires a new compact detector design.

CONNIE future perspectives

Towards CEvNS detection

- With 15 eV threshold and a 1 kg detector at CONNIE (30 m from the reactor core), we need **200 days** of operation to observe CEvNS with 90% CL, assuming the current background (4 kdru).
- Moving to 15 m from the reactor core, we would need **13 days** of operation to observe CEvNS with 90% CL under the same conditions and **4 days** if the background can be reduced to 1 kdru.

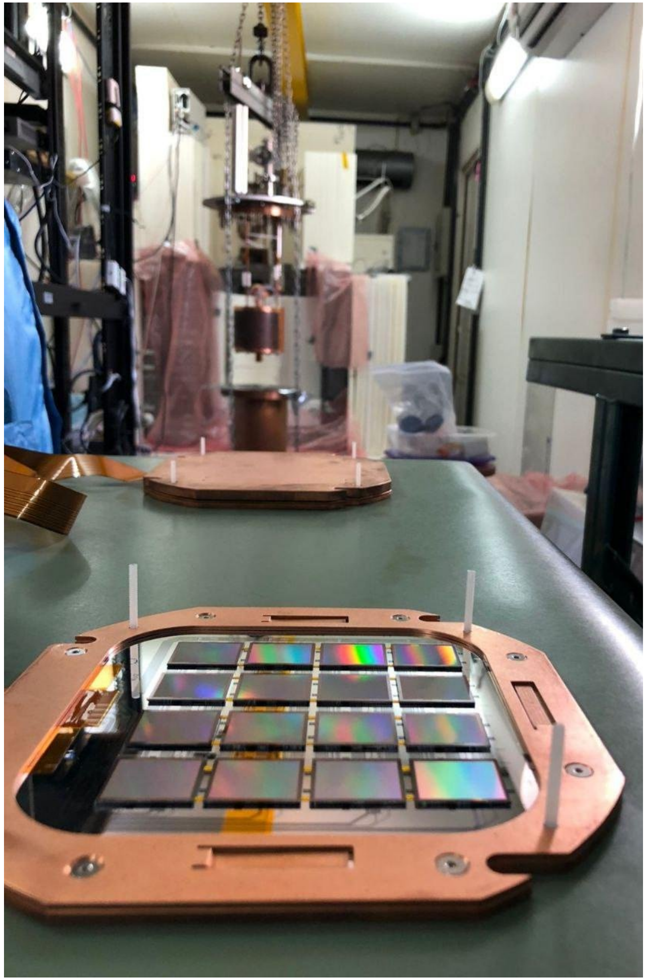




Conclusions

- Skipper-CCDs are a promising technology for detecting low-energy processes.
- Excellent performance in 2021-2023: flat background (~4 kdru) and 15 eV ee (~240 eV nr) threshold.
- New CEνNS limit with skipper-CCDs and 18.4 g-day comparable to limit with standard CCDs and 2.2 kg-day!
- Updated limits on: light vector-mediators, light DM by diurnal modulation, and millicharged particles (with Atucha-II).
- CONNIE started its next phase with a 16-sensor Multi-Chip-Module.
- Need a mass ~1 kg of skipper-CCDs for CEνNS detection.
- Efforts to increase the neutrino flux are on-going

Stay tuned!



co.vNie

Thank you for your attention!

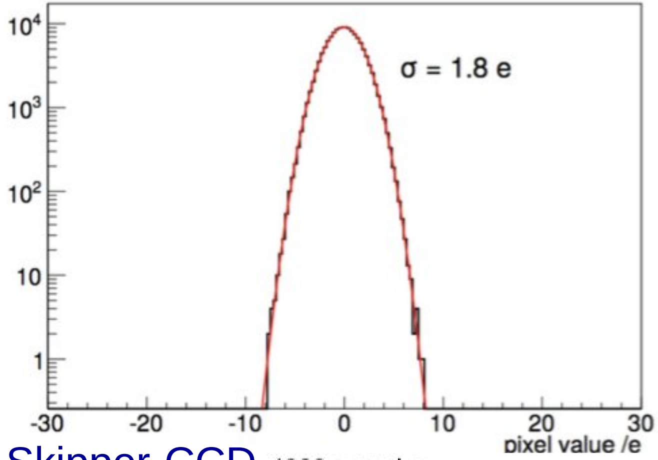
TAUP XICHANG

BACKUPS

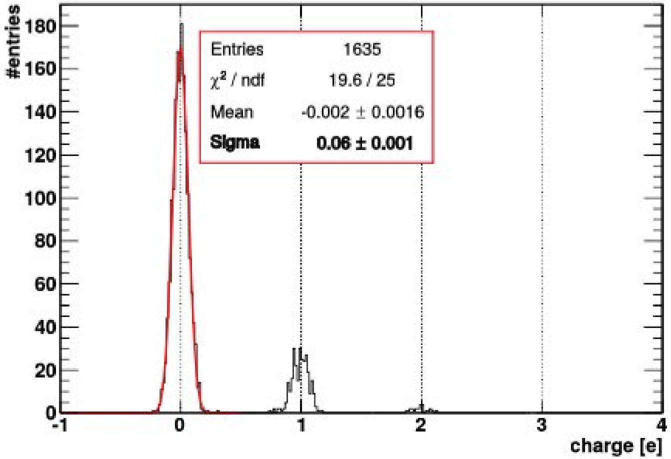
Skipper CCD

- Identical to standard CCDs regarding: substrate, gate structure, channel stops. ***Different readout stage***.
- Readout circuit modified to allow:
  - Non-destructive and repeated charge measurement.
  - Reduction of electronic noise.
  - Counting of individual ionization electrons.
- Promising technology for DM and ν experiments and other applications:
  - Experiments OSCURA, SENSEI, DAMIC-M …
  - Quantum optics, astronomy, nuclear physics.

Standar



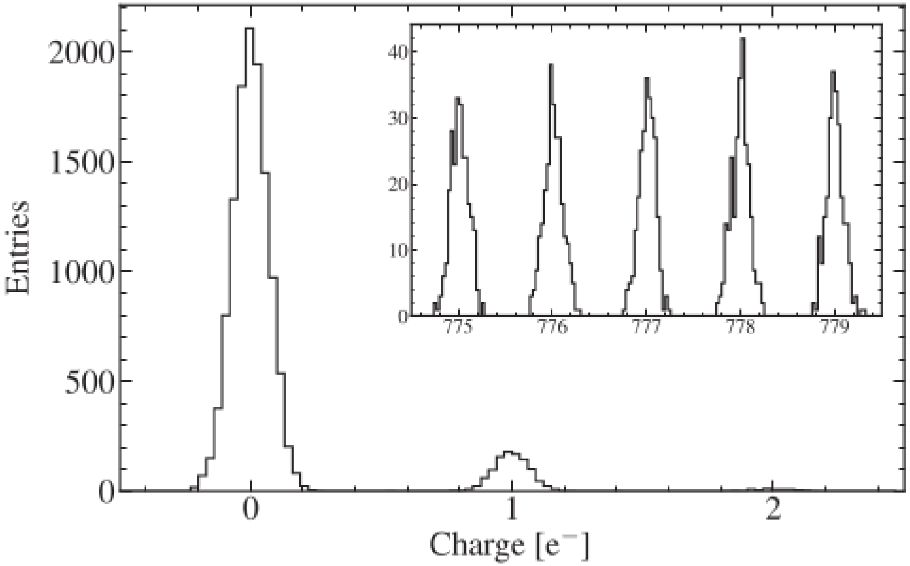
Skipper-CCD 4000 samples



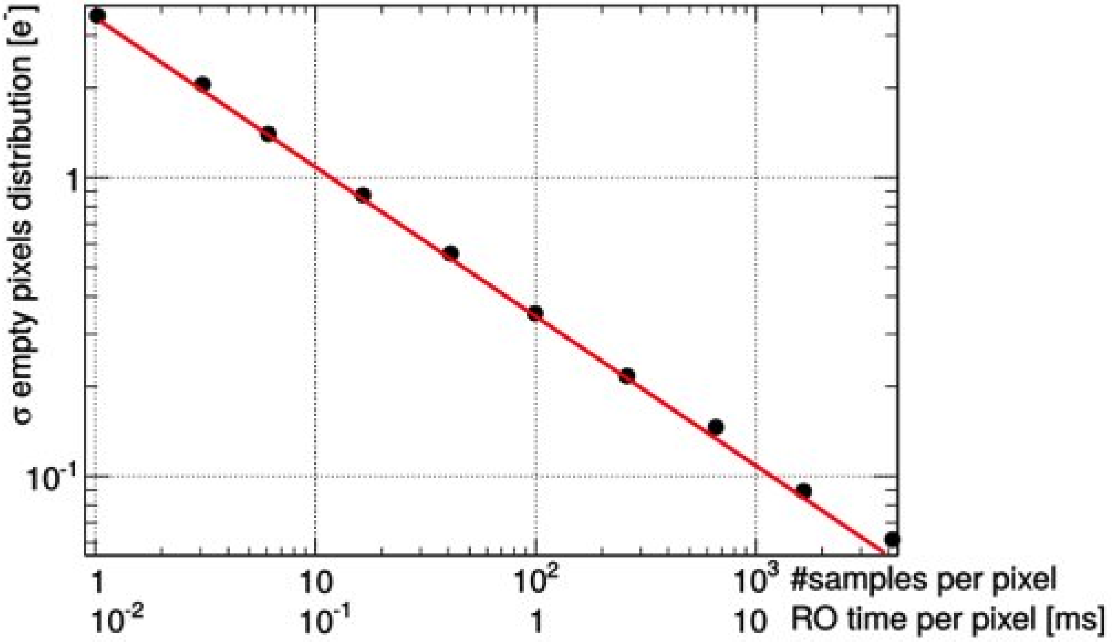
Sub-electronic readout noise

- Readout noise in Skipper-CCDs scales as 1/sqrt(N_{samp})
  Compromise between: **speed** *vs.* **resolution**.
- Can count individual electrons: *self calibrated* charge measurement.

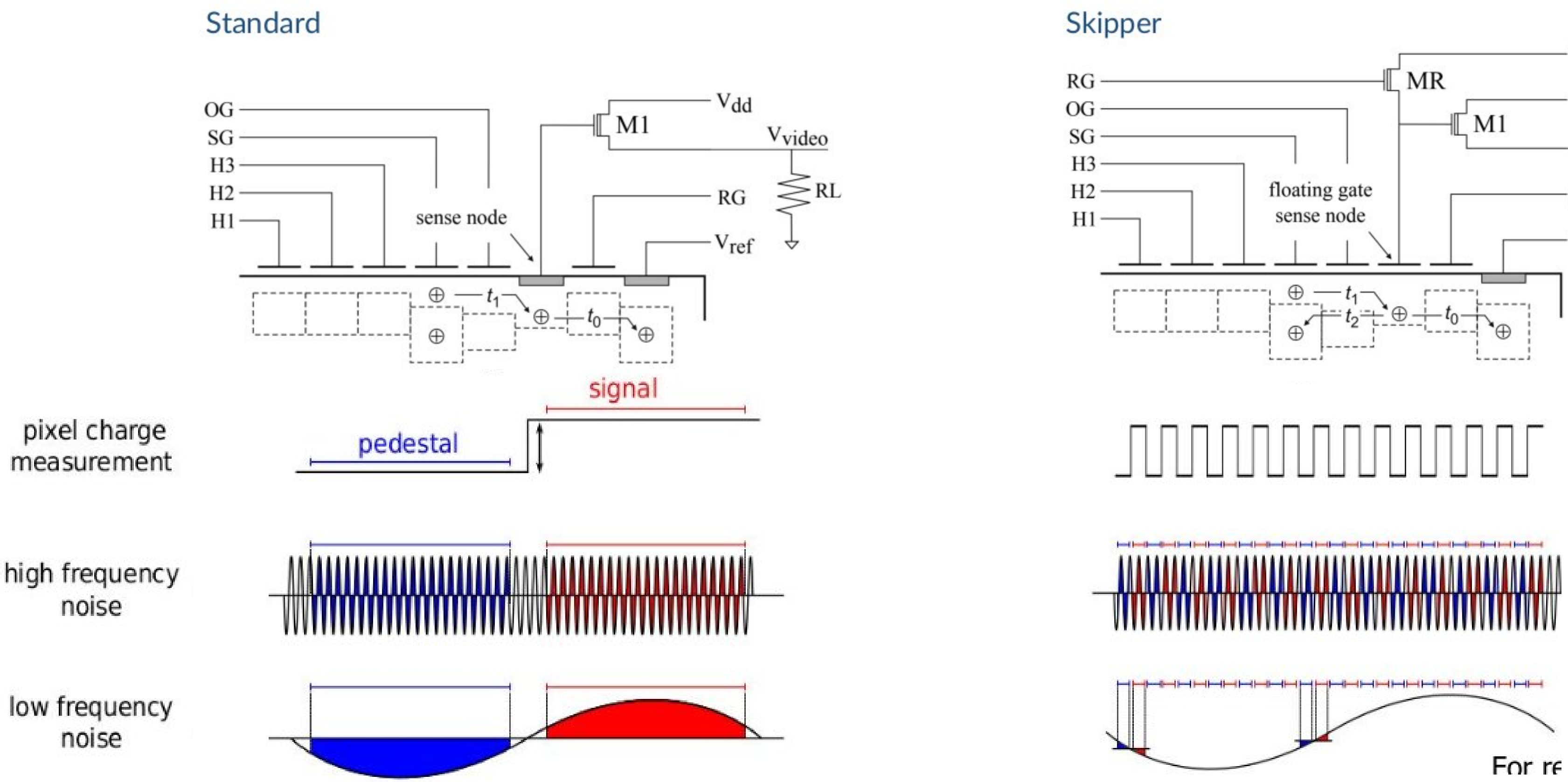
J. Tiffenberg et al, PRL 119 (2017)



J. Tiffenberg et al, PRL 119 (2017)



Standard vs skipper CCD readout



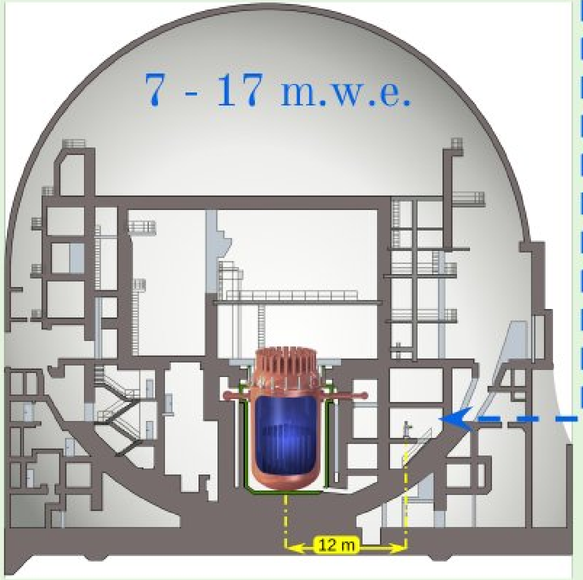
- Skipper: ruido de baja frecuencia se reduce significativamente en cada medición.
- Muchas mediciones → promedio preciso.

Atucha II Experiment

[Eliana Depaoli, Magnificent CEvNS 2025]

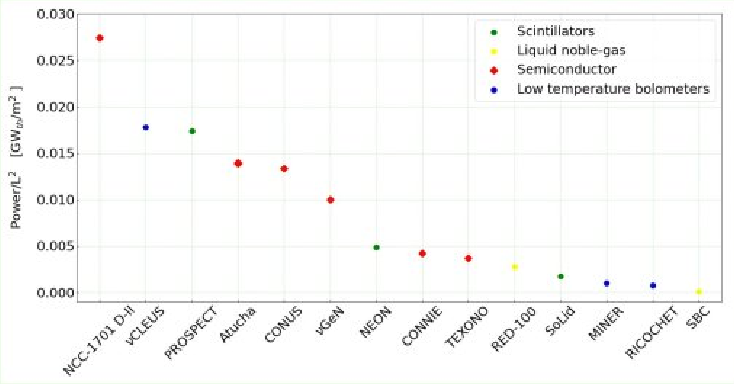
Short-baseline ν-experiment at Atucha II power plant

- Commercial facility, 2.2 GWth
- Fuel: Natural UO_2
- D_2O moderator & refrigerator



Dose 1 μSv/h @detector room

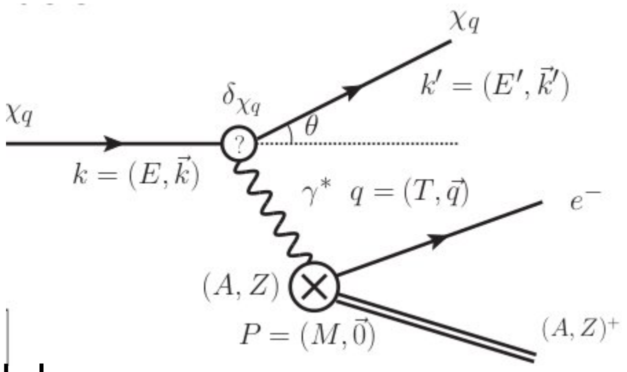
$$\Phi_\nu = 2.6 \times 10^{13}\, \bar{\nu}_e/\mathrm{cm}^2/\mathrm{s}$$



Magnificent CEvNS 2025. E. Depaoli

Search for Millicharged particles

- Detection: interaction with silicon via atomic ionization (t-channel)
- Semi-classical Photo Absorption Ionization (PAI) model.



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

Modeling the Form Factor with the Photo Absorption Ionization model:

Transverse — Longitudinal

$$\frac{d\sigma_{PAI}}{dE} = \frac{\alpha}{\beta^2\pi}\frac{\sigma_\gamma(E)}{EZ} ln[(1-\beta^2\epsilon_1)^2+\beta^4\epsilon_2^2]^{-1/2} + \frac{\alpha}{\beta^2\pi}\frac{1}{N_e\hbar c}\left(\beta^2-\frac{\epsilon_1}{|\epsilon|^2}\right)\Theta + \frac{\alpha}{\beta^2\pi}\frac{\sigma_\gamma(E)}{EZ} ln\left(\frac{2mc^2\beta^2}{E}\right) + \frac{\alpha}{\beta^2\pi}\frac{1}{E^2}\int_0^E\frac{\sigma_\gamma(E')}{Z}dE'$$

Relativistic rise in e. deposition — Cherenkov — Resonance absorption at atomic energy levels — Rutherford quasi free scatterings

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

Limit setting: search for the lowest coupling compatible with observed rate in the 100-150 eV bin.