Estudio de interacciones de neutrinos y nueva física con dispositivos CCD de nueva generación

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[CONNIE Collaboration]

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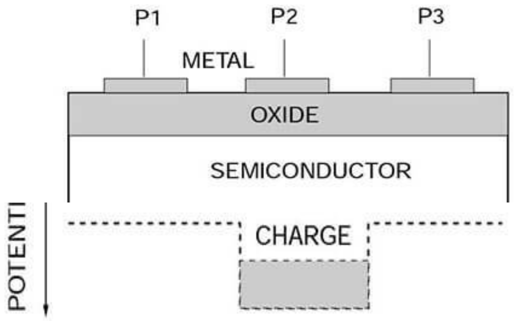
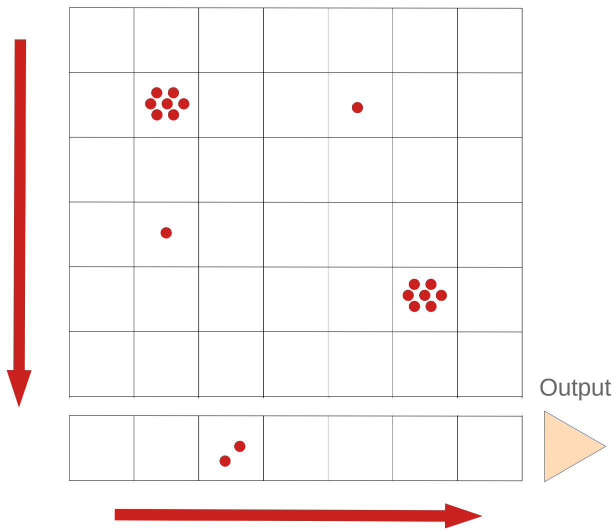
Outline

- Charge Coupled Devices (CCDs)
- The CONNIE experiment
    - Results with standard CCDs
- Results with Skipper CCDs
- Summary

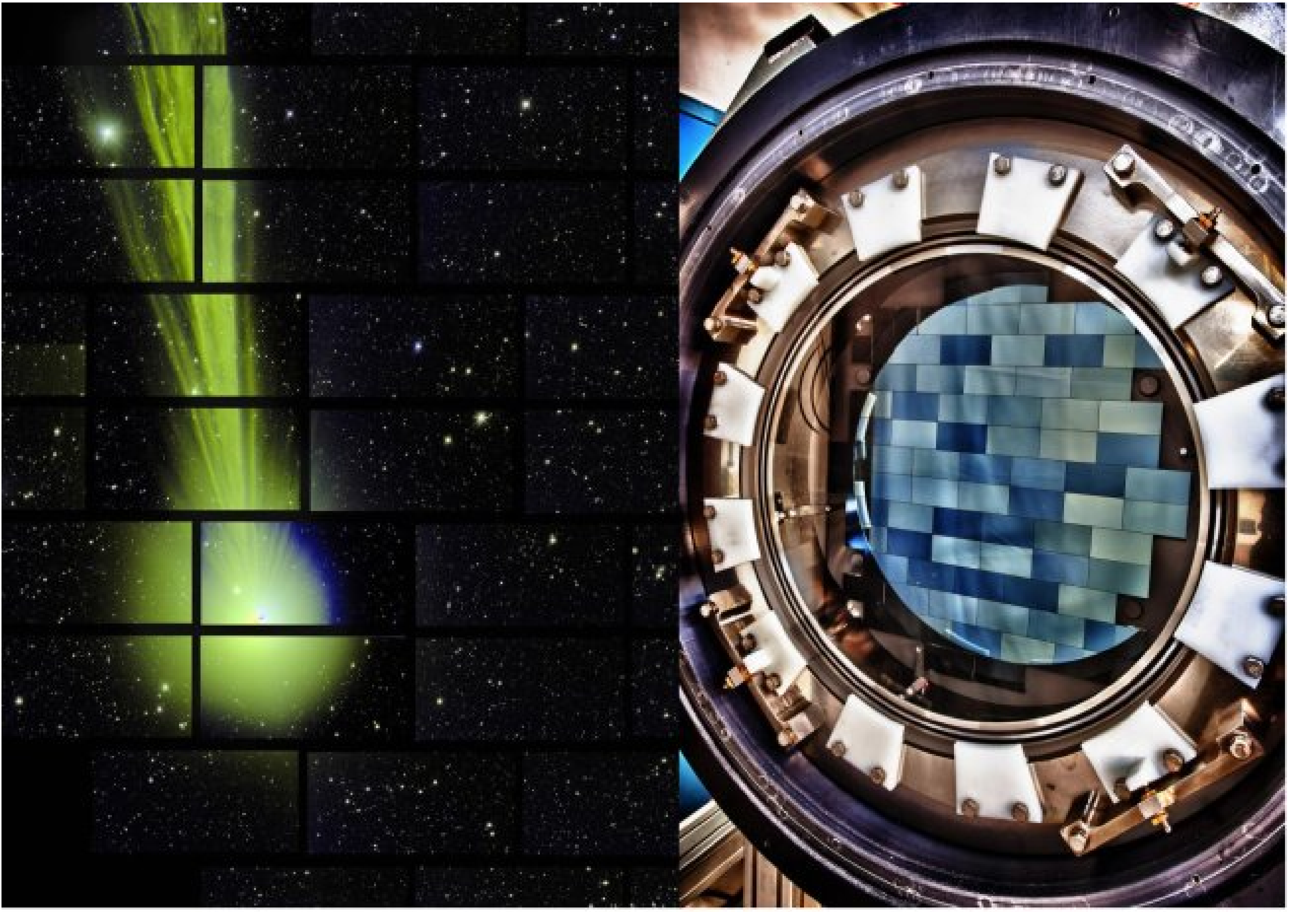
Charge-Coupled Devices (CCD)

- Array of MOS capacitors on a Si substrate. Can store images of energy depositions, producing e-h pairs, in pixels across the substrate area.
- An electric field drifts the carriers (holes) across the substrate to be collected near the surface in gate electrodes.
- Charge is moved between neighboring capacitors with an external control circuit.
- After an exposure, the pixel charges are moved to an amplifier to be read out.
- Widely used in astronomical cameras.





CCDs in astronomical cameras



www.darkenergysurvey.org

Used in astronomy since their invention in 1970.

LBNL Microsystems Lab developed thick (~100s μm) CCDs for DECam.

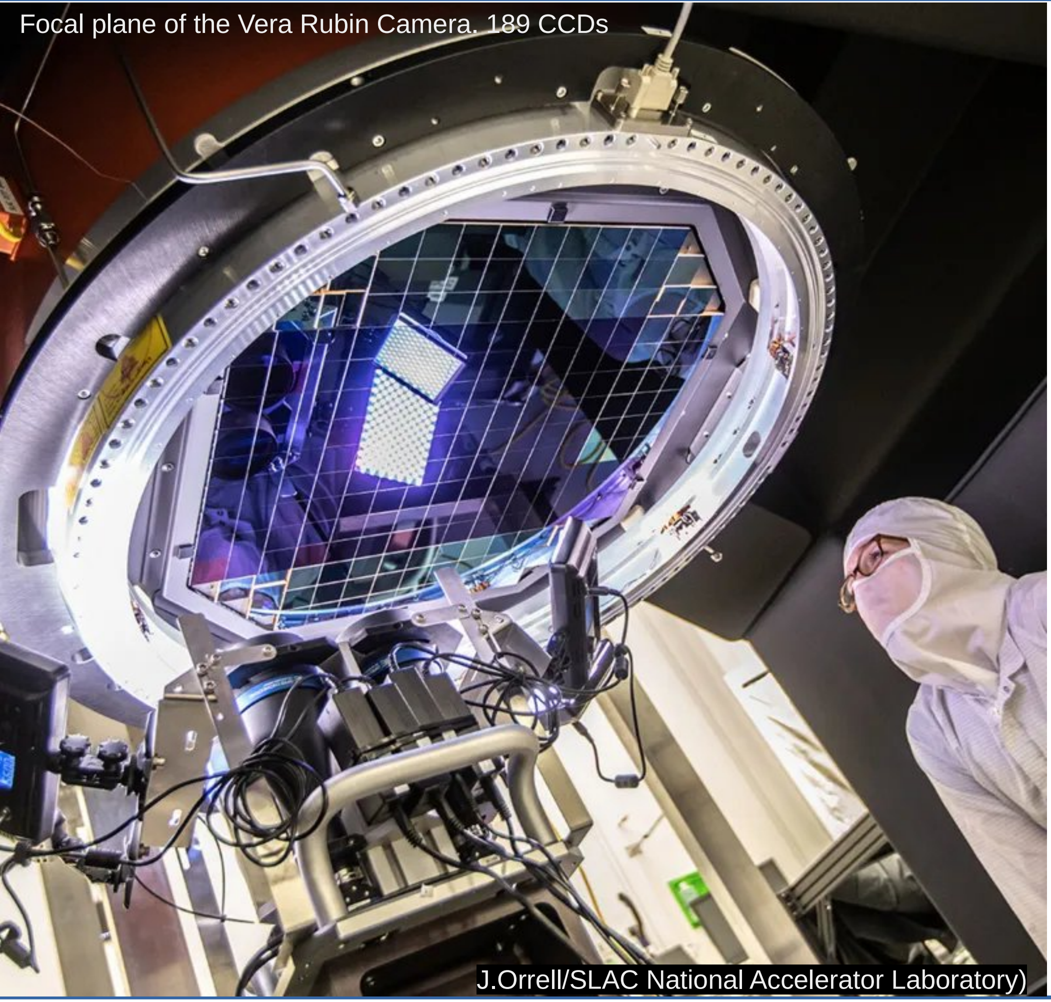
[10.1109/TED.2002.806476]

- Great spacial resolution (pixel 15 μm)
- High charge transfer efficiency
- **Low energy threshold (~40 eV)**
- **Low readout noise (~2 e^-)**
- **DC of only a few e^- /pix/day**

Now used in particle physics

CCDs in astronomical cameras

Focal plane of the Vera Rubin Camera. 189 CCDs



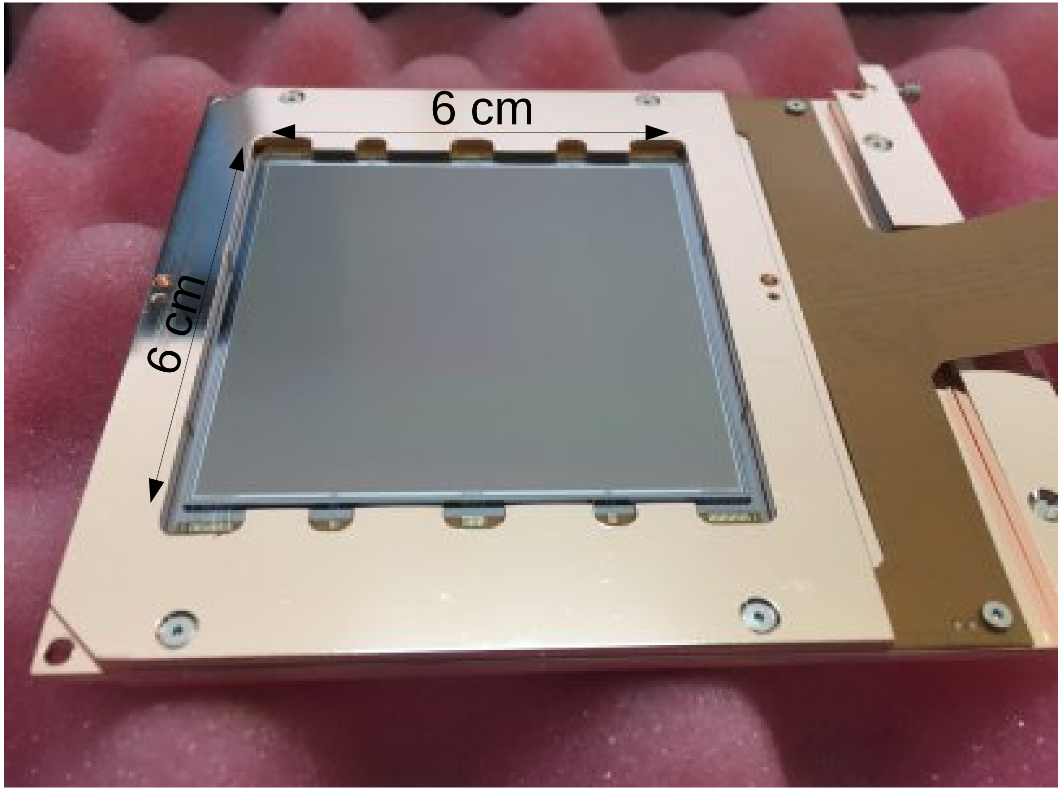
J.Orrell/SLAC National Accelerator Laboratory)

The Vera Rubin LSST camera

- 189 CCDs
- 32,000 pixels

Coordinated by SLAC, developed by University of Arizona, BNL and Teledyne-E2V (UK).

Scientific CCDs (standard)



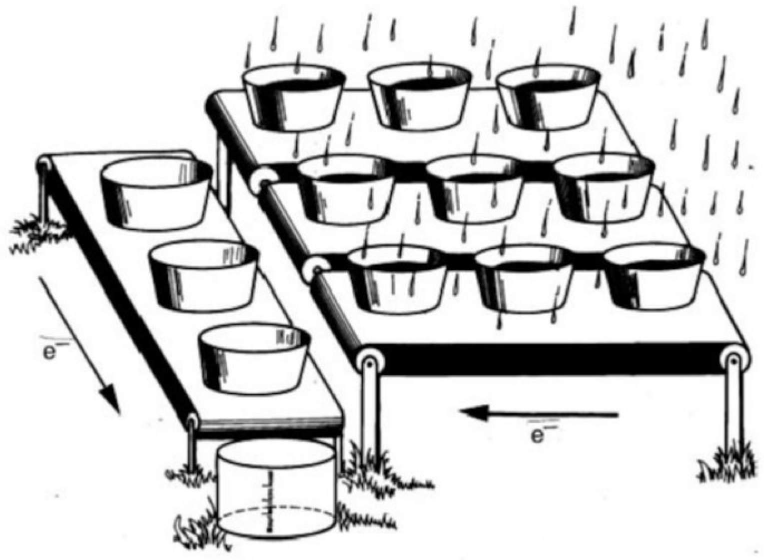
Pixel size:	15 μm x 15 μm
# of pixels:	4000 x 4000
CCD thickness:	675 μm
CCD mass:	5.95 g
Operation Temp:	< 100 K

Readout noise ~ 2.0 electrons RMS
Energy threshold < 50 eV_{ee}

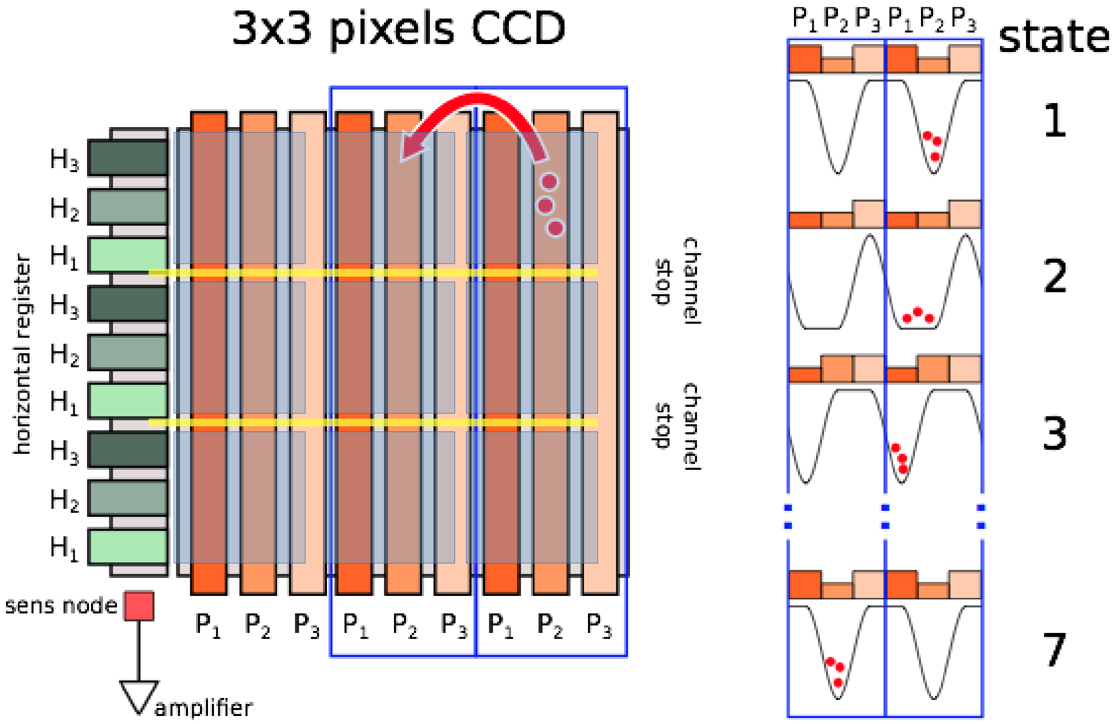
Manufactured with very high resistivity Si:

→ low radioactive level
→ low dark current (~ 0.1 e- / pix / day)
→ negligible number of lattice defects.

CCD readout

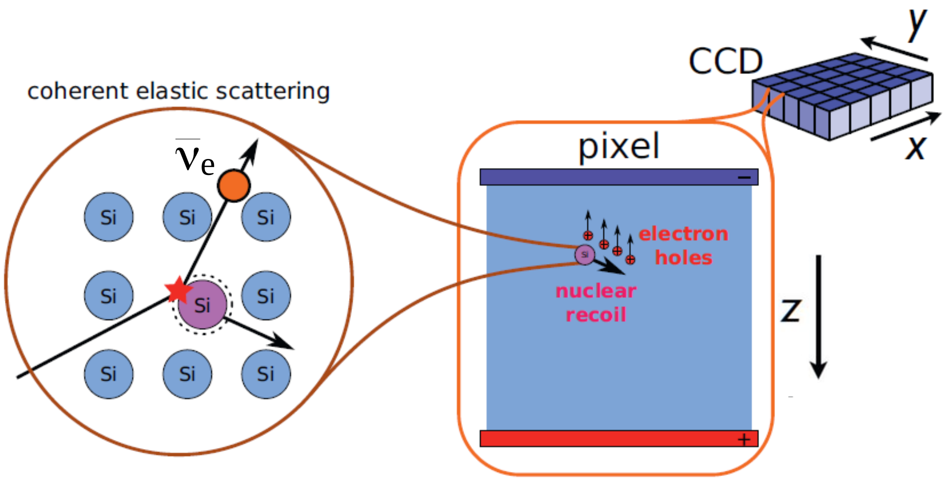


J.R. Janesick, 2001



Capacitance of the system fixed by the *sensing node*: C = 0.05 pF ⇒ 3μV/e

CCD as a particle detector

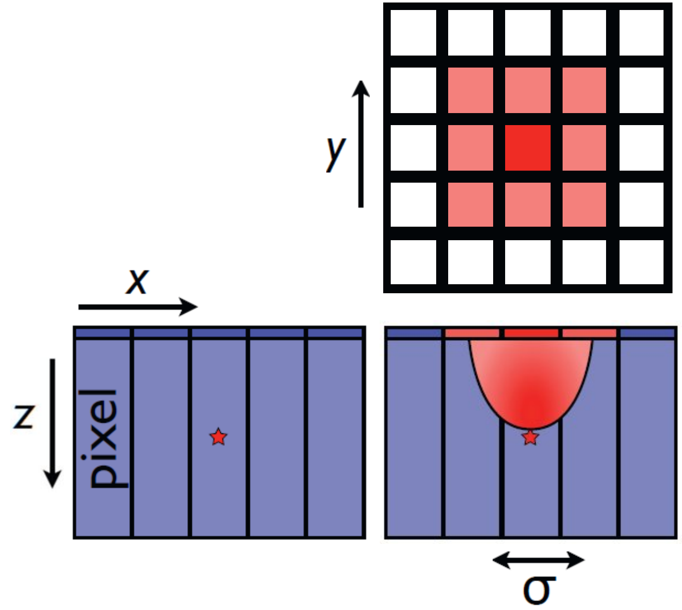


The scattering of the ν with a Si nucleus leads to ionization

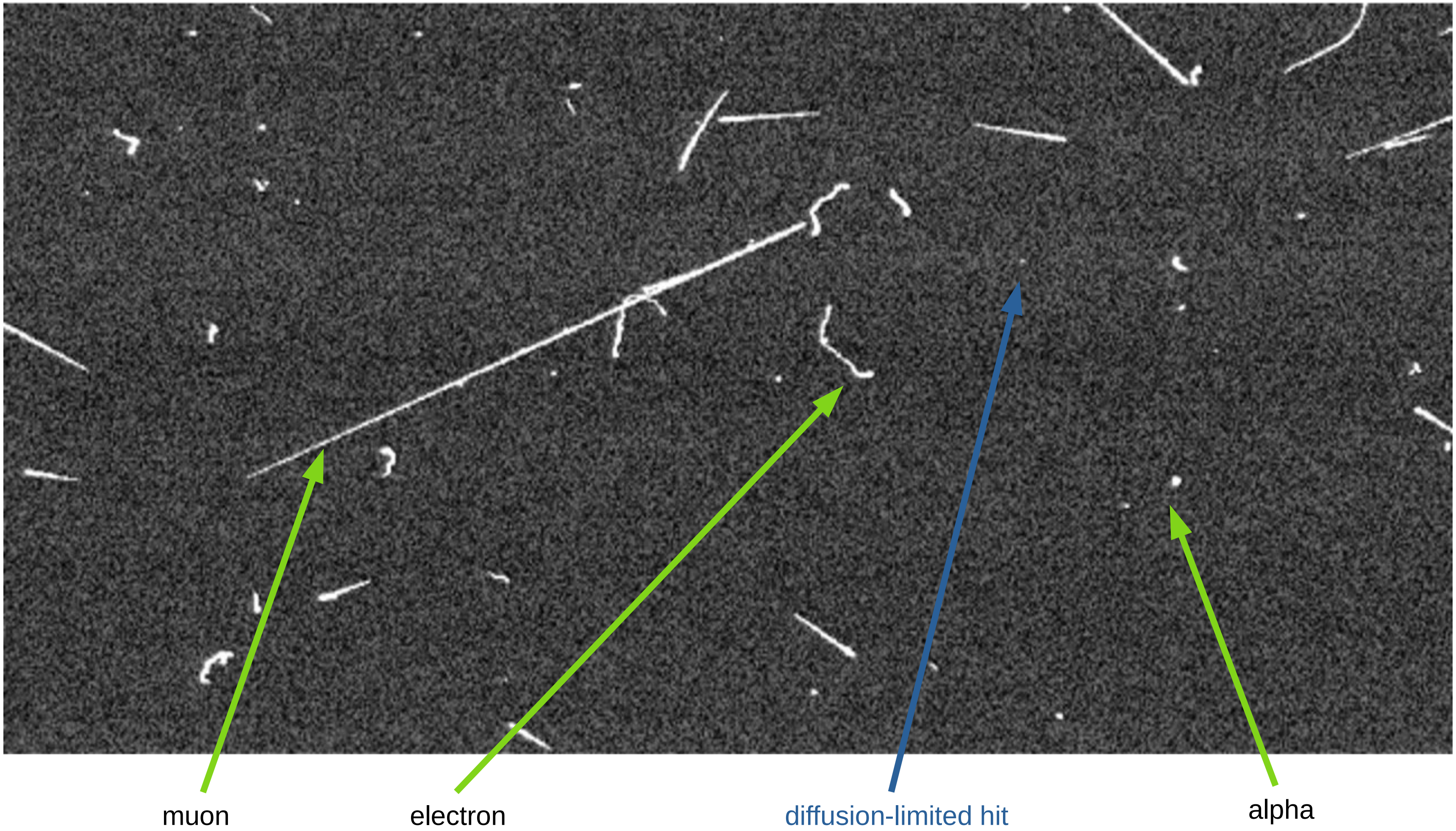
Charge carriers are drifted along z direction and collected at CCD gates

Charge diffuses in *x-y* plane as it drifts towards the gates

The radial spread of the cluster is used to estimate its position in z within the CCD bulk.

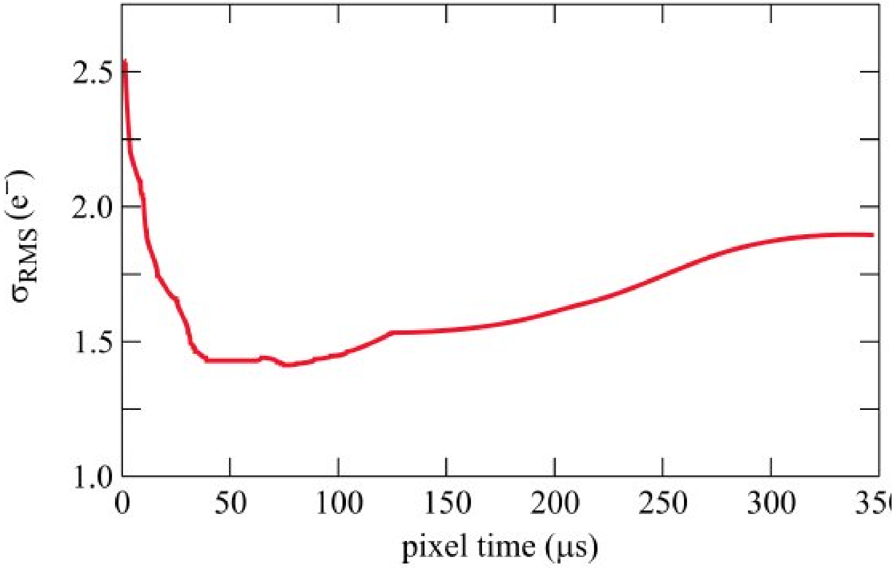


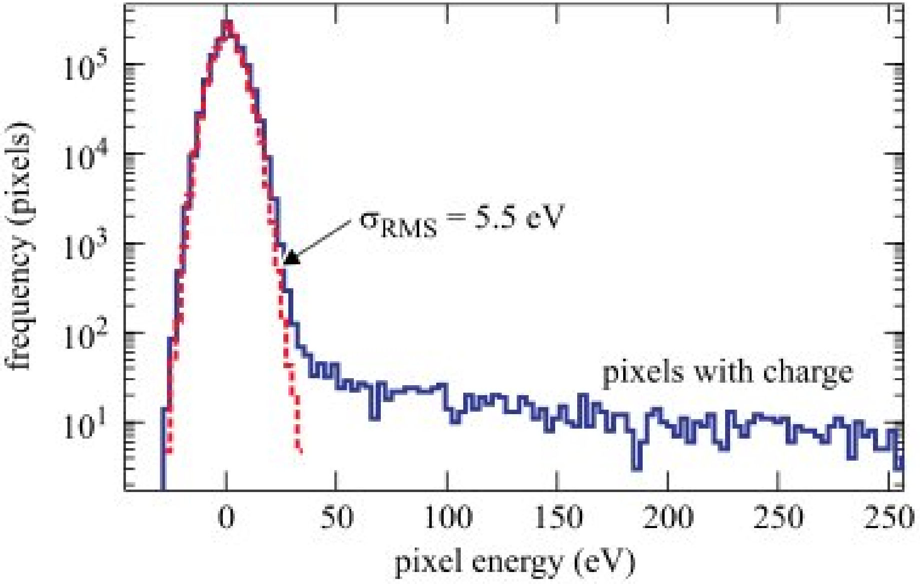
CCD as a particle detector



Readout noise in standard CCD

- Added to each pixel pixel by the amplifier when the charge is readout.
- Gaussian distribution with σ_{RMS} which depends on the pixel readout (integration) time.
- Pixel time = 30 μs $\Rightarrow$ σ_{RMS} = 1.5 e- ≡ 5.5 eV of ionization energy.



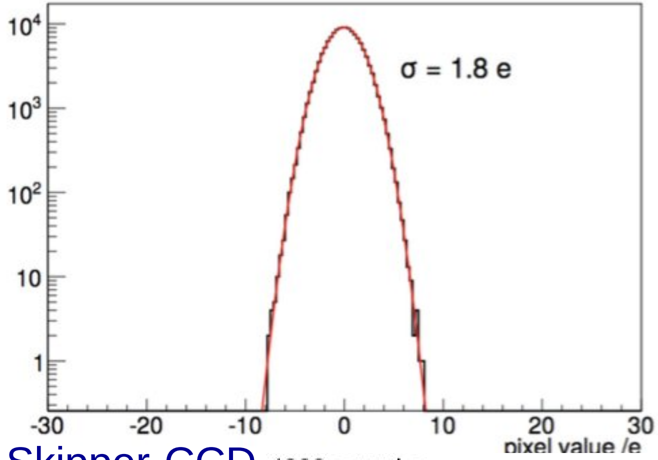


PRD91 (2015) 7, 072001

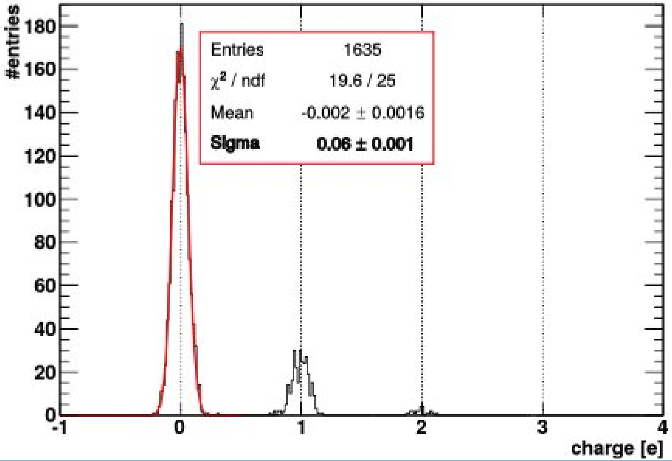
Skipper CCD

- 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.

Standard



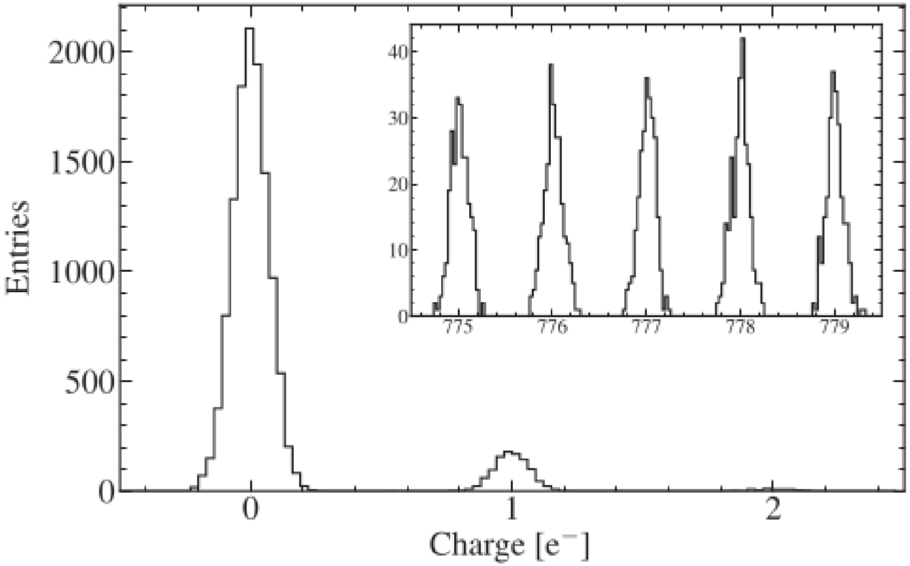
Skipper-CCD 4000 samples

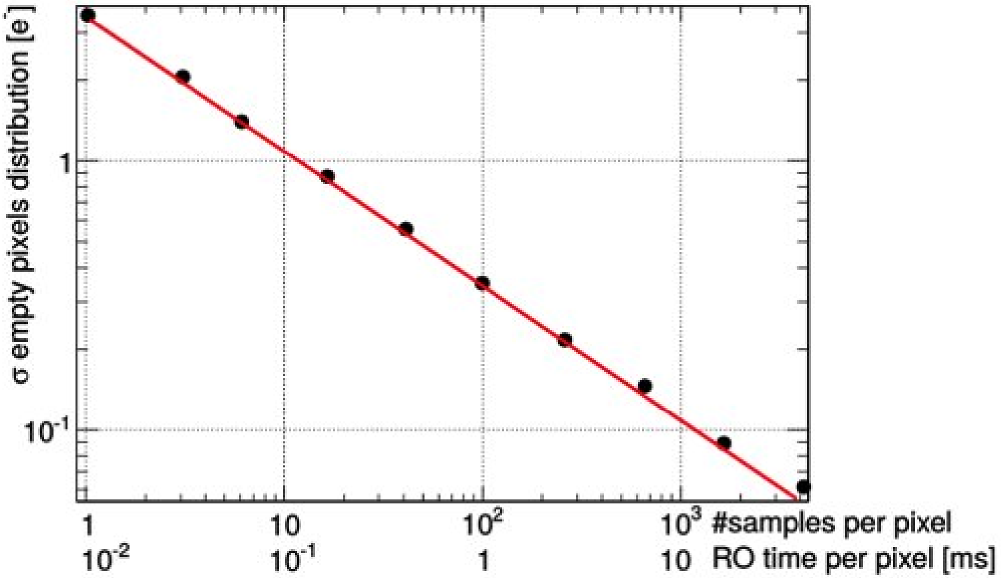


Sub-electronic readout noise

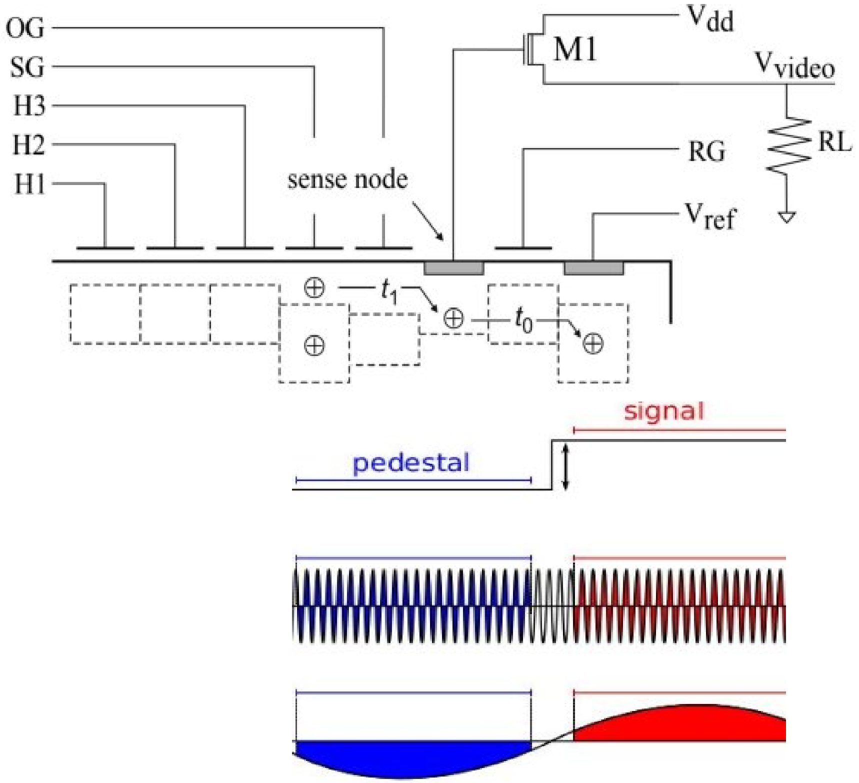
- Readout noise in Skipper-CCDs scales as 1/sqrt(N_{samp})
- Compromise between: **speed** *vs.* **resolution**.
- Can count individual electrons: *self calibrated* charge measurement.

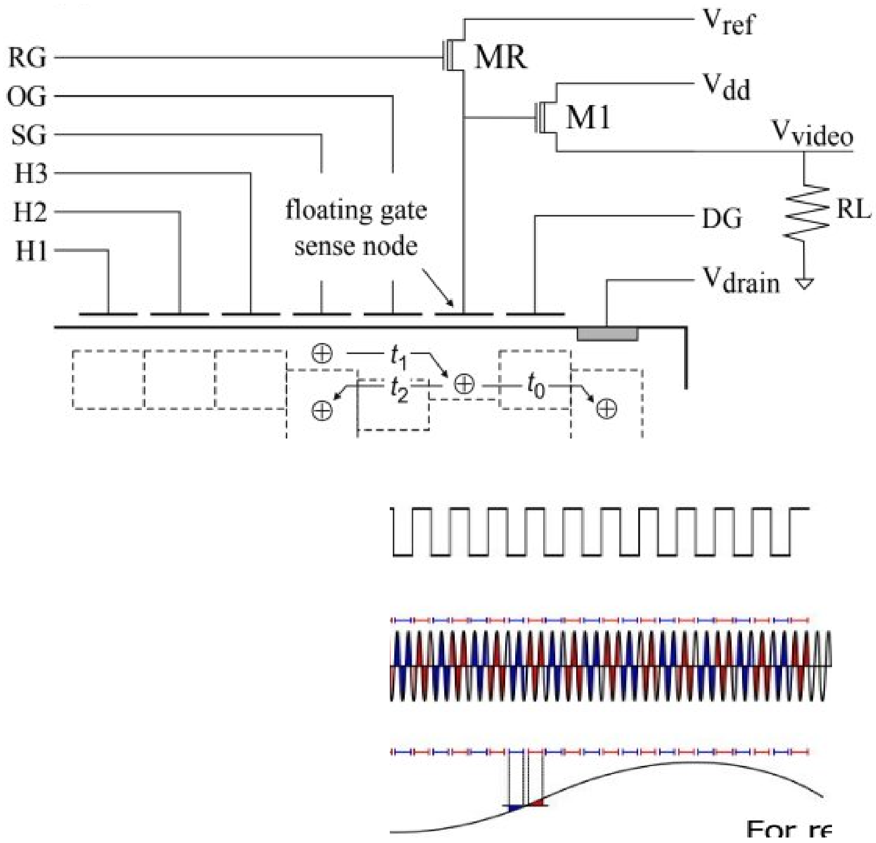
J. Tiffenberg et al, PRL 119 (2017)





Standard vs skipper CCD readout





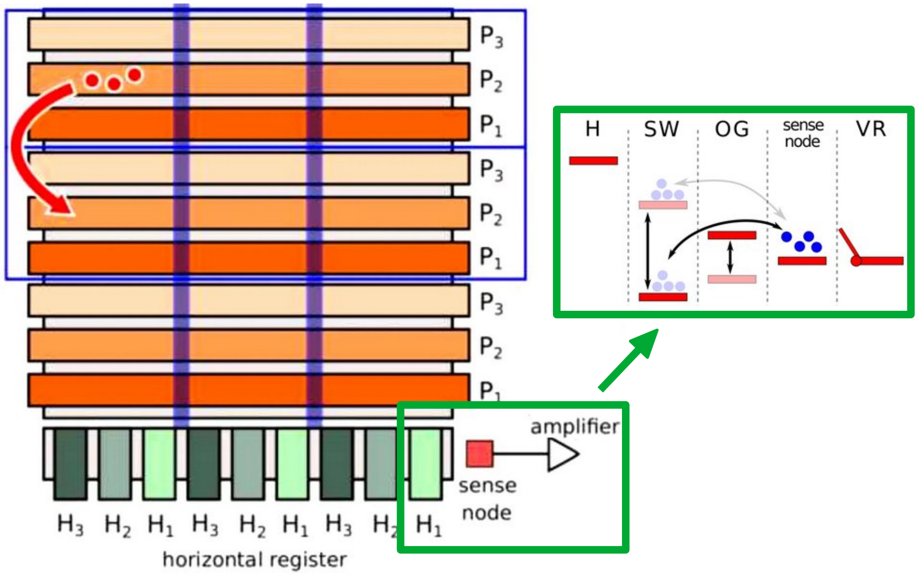
- Skipper: reduce significativamente el ruido de baja frecuencia en cada medición.
- Muchas mediciones → promedio preciso.

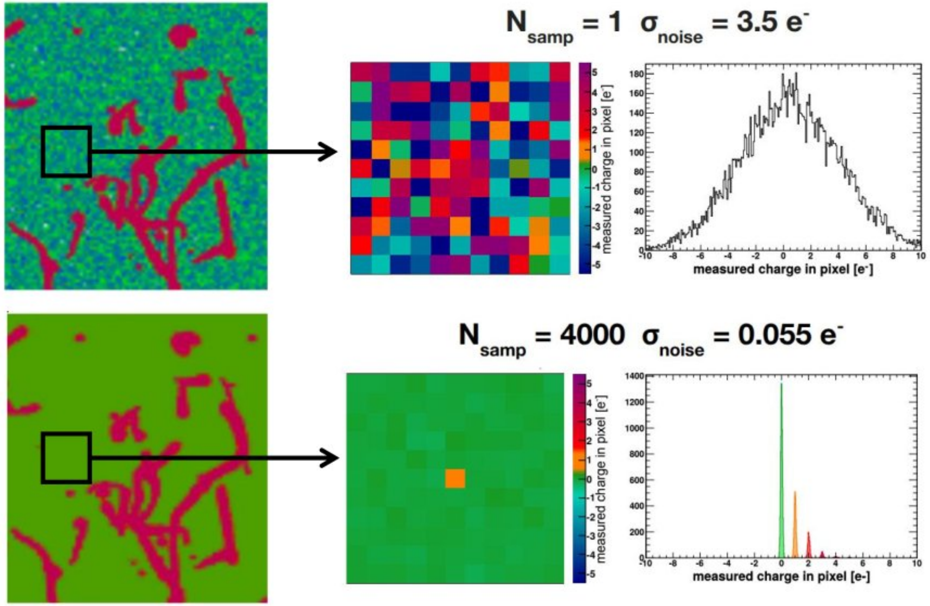
Skipper-CCDs: e^- counting sensors

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!)

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

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, Instituto Tecnológico de Aeronáutica , Universidad Nacional Autónoma de México, Universidad Nacional de Asunción, University of Zurich, Fermilab

Main goals

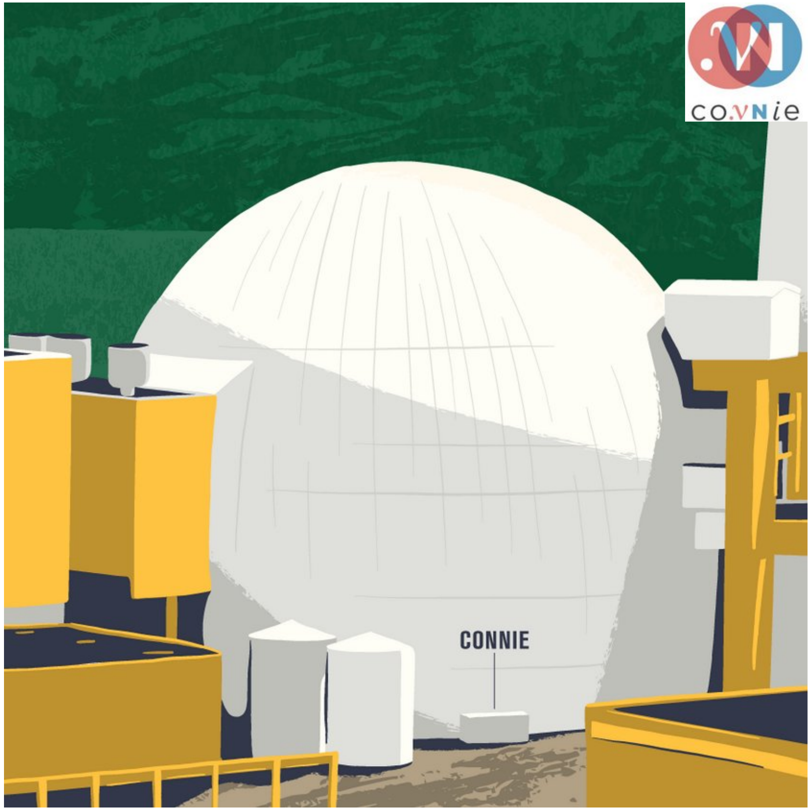
- Detect CEvNS with reactor neutrinos in silicon with Skipper-CCDs.
- Explore Beyond Standard Model (BSM) physics
- Develop monitoring of nuclear reactors with neutrino detection for safeguards.

The CONNIE experiment

- Coherent Neutrino-Nucleus Interaction Experiment
- Its main goal is to detect coherent elastic scattering of reactor antineutrinos off silicon nuclei and place limits in BSM physics.
- The detectors are thick (675 μm) scientific CCDs made from high resistivity silicon operated at cryogenic temperatures (<100 K).

  - Low noise (> 1 e-) and low dark current (~0.2 e-/pix/day) *

  - Low-energy threshold (~15 eV)*

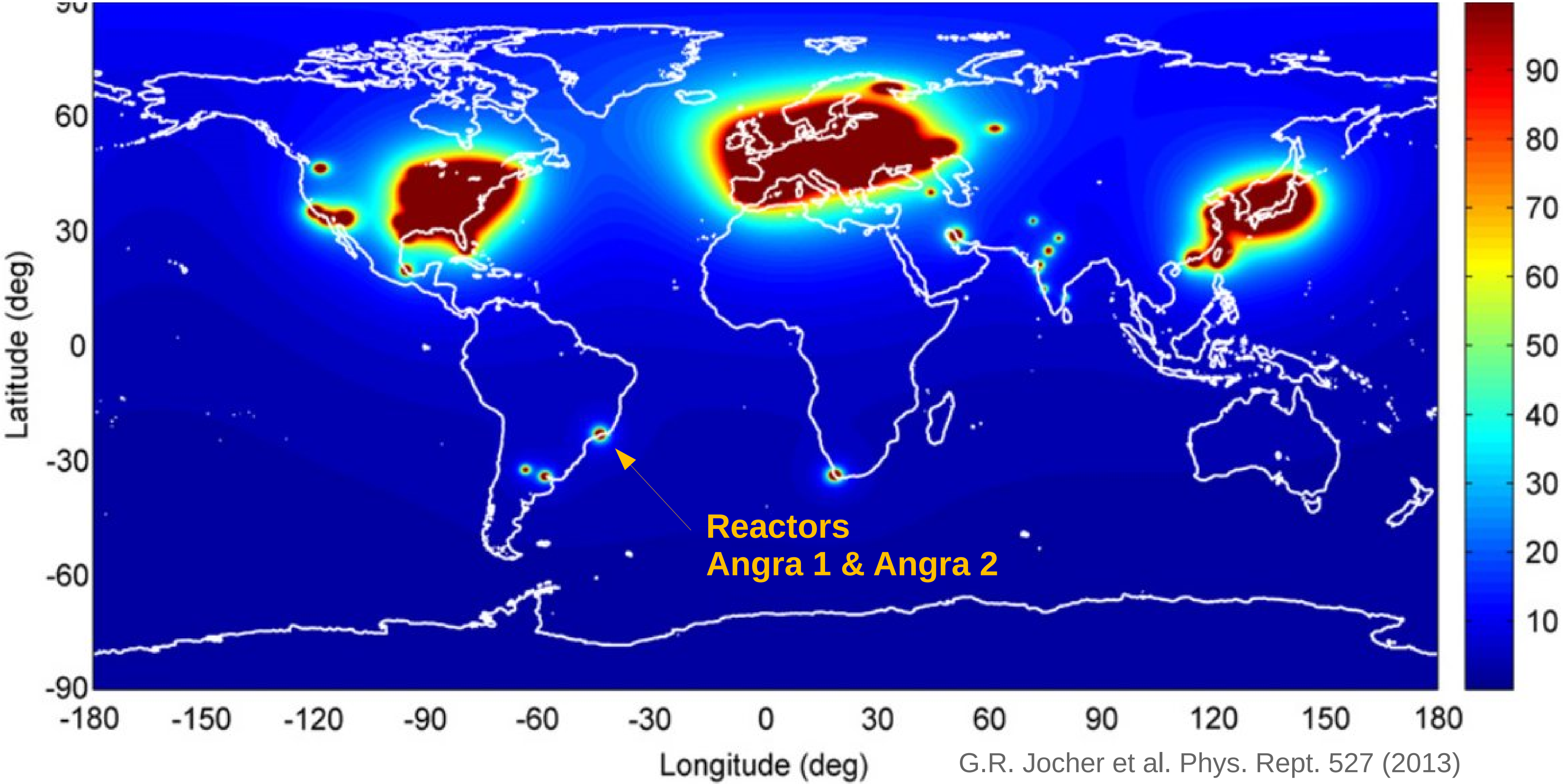


* Skipper-CCDs

The CONNIE experiment

- Located in the Almirante Alvaro Alberto nuclear plant near Rio de Janeiro, Brazil.
- At 30 m from the core of the 3.95 GW_{th} Angra 2 reactor. Flux of ~7.8×10^{12} $\bar{\nu}_e$ cm^{-2} s^{-1}.
- Shares lab with the “Neutrinos Angra” experiment.

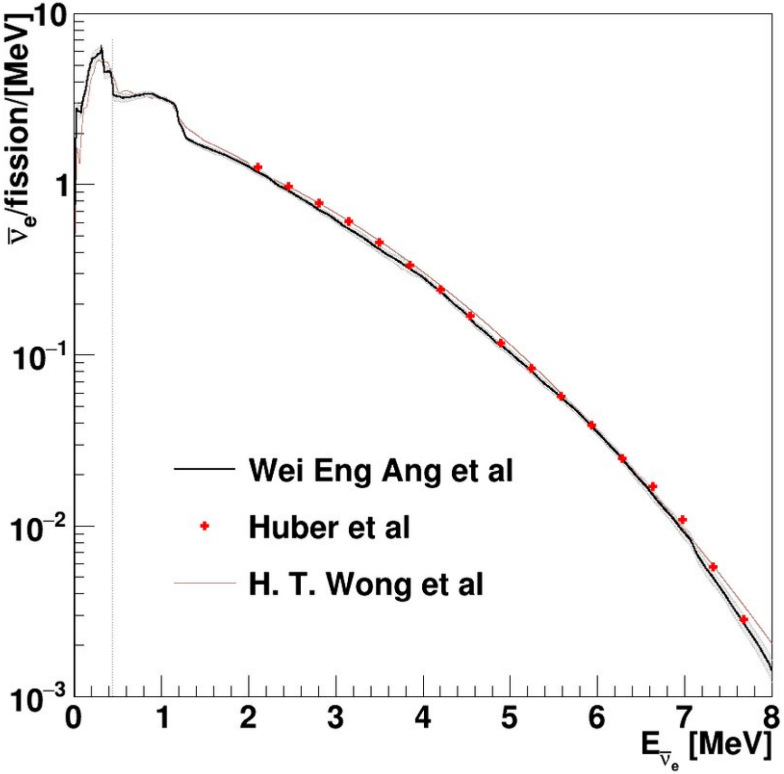
Reactor antineutrinos



G.R. Jocher et al. Phys. Rept. 527 (2013)

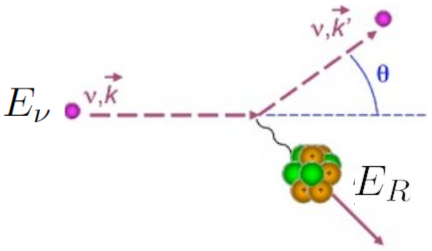
Reactor $\bar{\nu}_e$'s from Angra-2

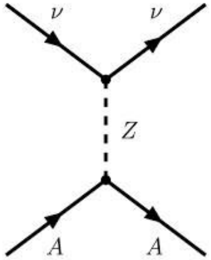
- Updated neutrino flux model with improved antineutrino spectra for 235 U, 238 U, 239 Pu, 241 Pu.
- 15 eV ee threshold corresponds to a minimum neutrino energy ~0.44 MeV,
- Above that energy the new and old model agree within 3%.

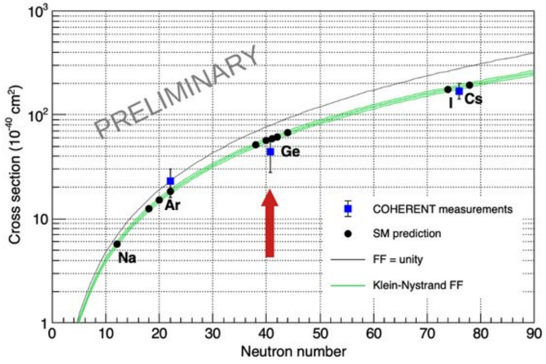


CEνNS: "Coherent Elastic ν-N Scattering"

Neutral current interaction where a neutrino of any flavor scatters off a nucleus as a whole.







Weak nuclear charge Q_W^2 ~ N^2

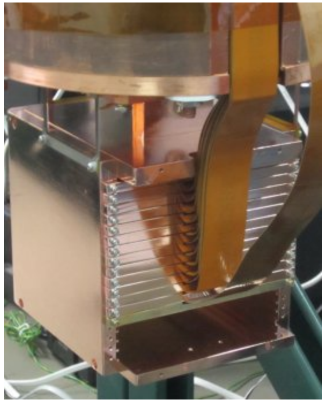
$$\frac{d\sigma_{SM}}{dE_R}(E_{\bar{\nu}_e}) = \frac{G_F^2}{4\pi}\left[N - (1 - 4\sin^2\theta_W)Z\right]^2\left(1 - \frac{ME_R}{2E_{\bar{\nu}_e}^2} - \frac{E_R}{E_{\bar{\nu}_e}} + \frac{E_R^2}{2E_{\bar{\nu}_e}^2}\right) MF^2(q)$$

- First observed by the COHERENT Collaboration with ν's with E~16-53 MeV in CsI (Science 357, 1123, 2017), liquid Argon (PRL, 126, 012002, 2021) and Germanium (arXiv:2406.13806, 2024) detectors.
- **Recently *"detected"* by CONUS+ (3.7σ) with reactor antineutrinos with a Germanium detector (Nature, 643, 1229-1233, 2025)**.

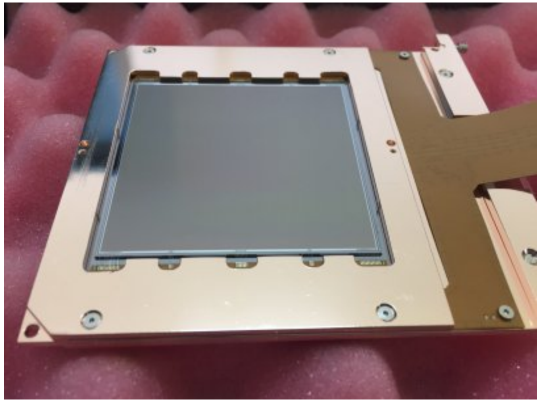
Studies at lower energies (Reactors) have complimentary sensitivity to BSM physics.

The CONNIE detector

Installed in 2014. Upgraded in 2016, 2021, and 2024



CCDs in copper box
(2016 Upgrade)

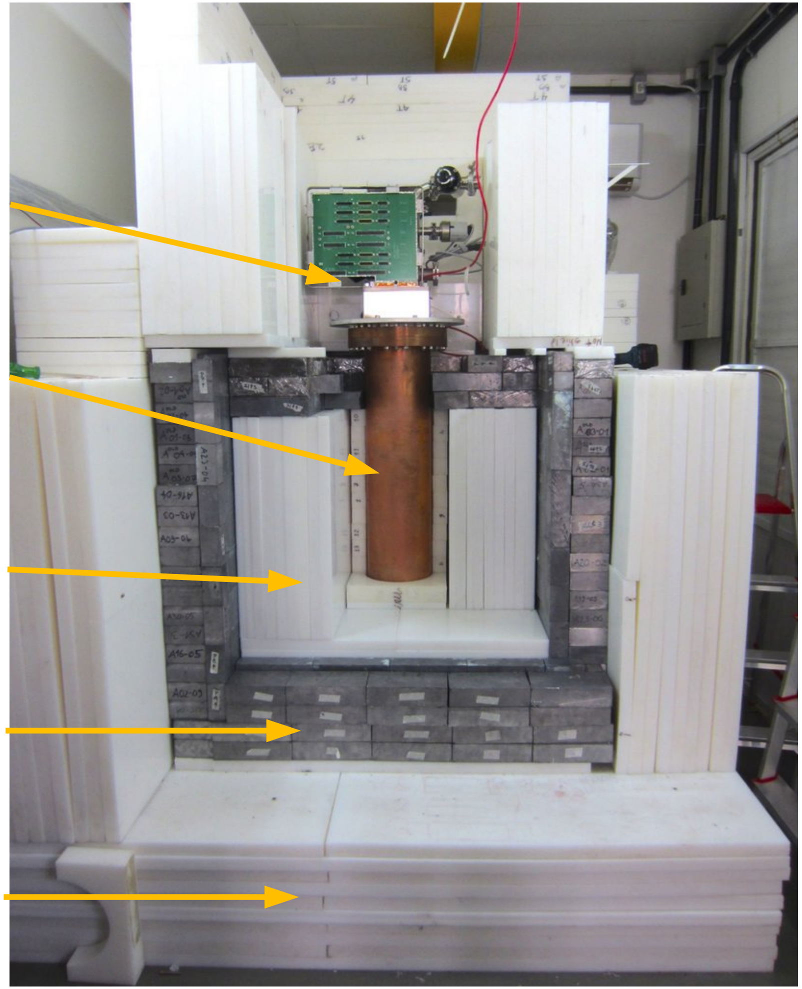


4k × 4k, 15 μm × 15 μm pix,
675 μm thick standard CCD

Engineering run:
JINST 11 (2016) P07024

2016 Upgrade:
Phys. Rev. D 100, 092005 (2019)

2021 Upgrade:
Phys. Rev. D 100, 092005 (2019)



CONNIE experiment timeline

NEUTRINO 2020 **Community milestone**

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

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

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

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

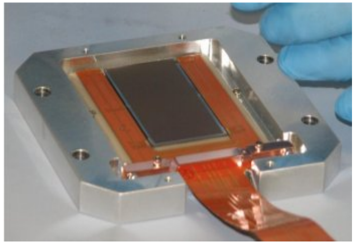
Results from 2016-2018 run [**PRD 100 (2019), 092005**]

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

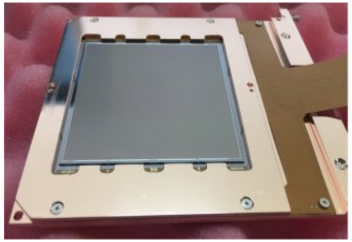
2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025

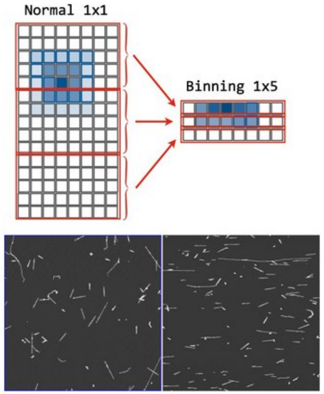
Engineering Run | 2016-2018 (1x1) Run | 2019 (1x5) Run | Skipper-CCD Run | MCM Run

Instalation at Angra

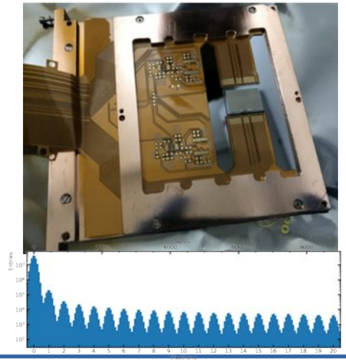


Upgrade to Scientific CCDs

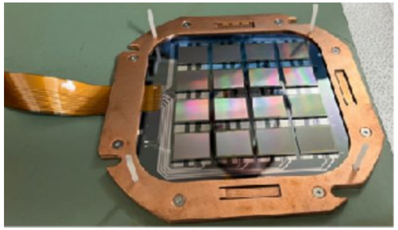




Installation of Skipper-CCDs

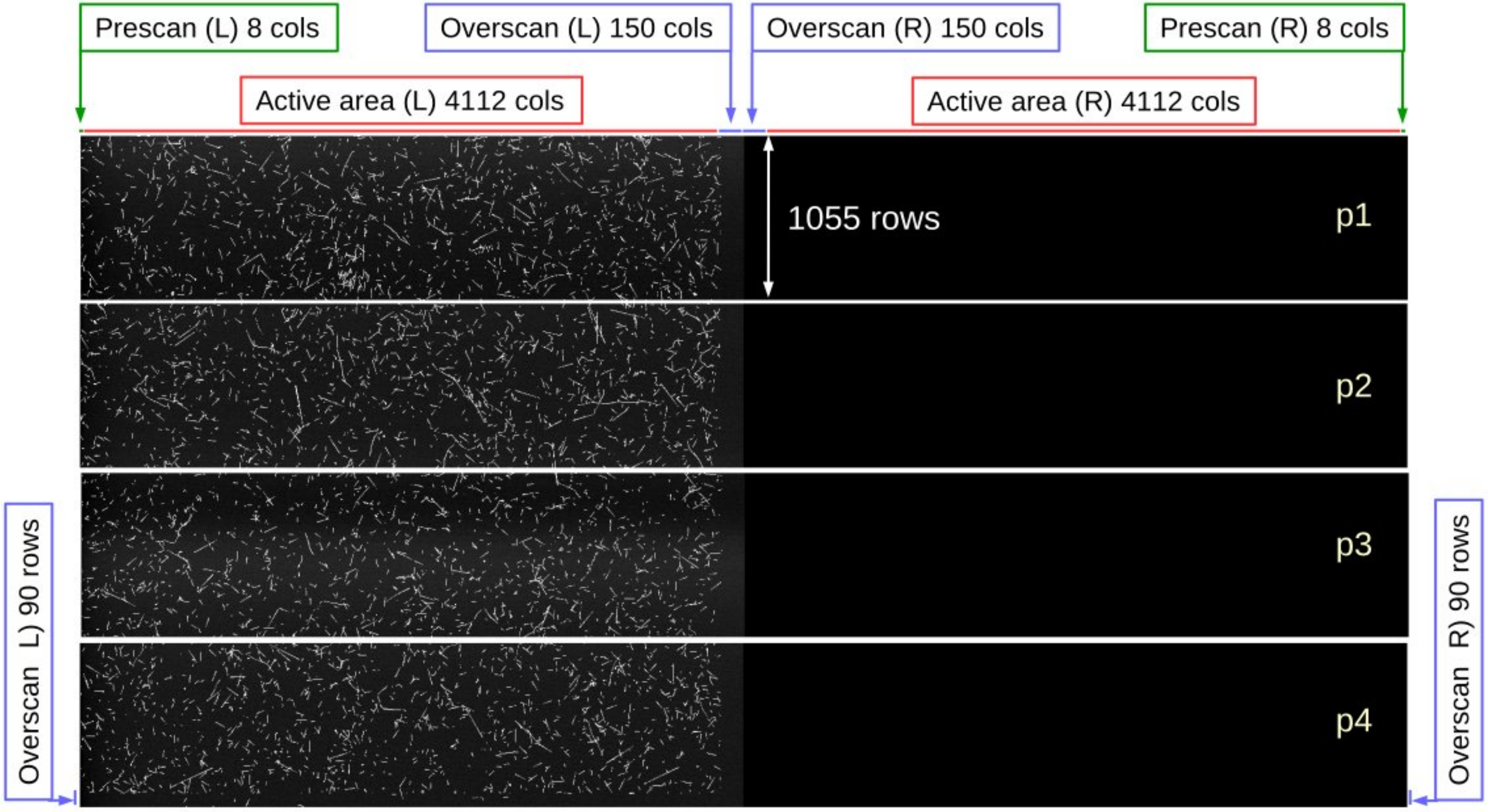


Installation of Multi-Chip Module

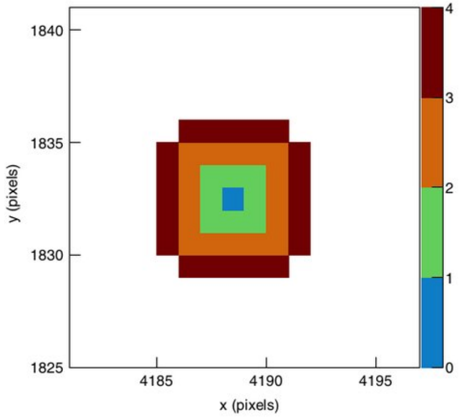


16 Skipper-CCDs, from Oscura

Images (1x1 DAQ, 2016-2018)



Candidate event



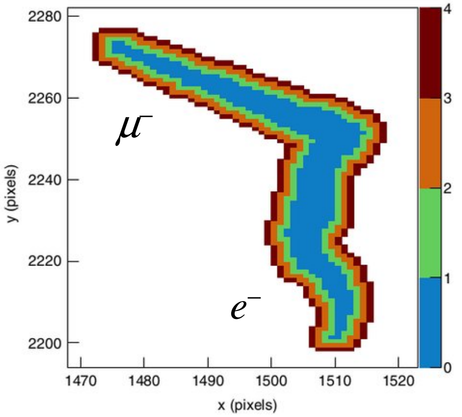
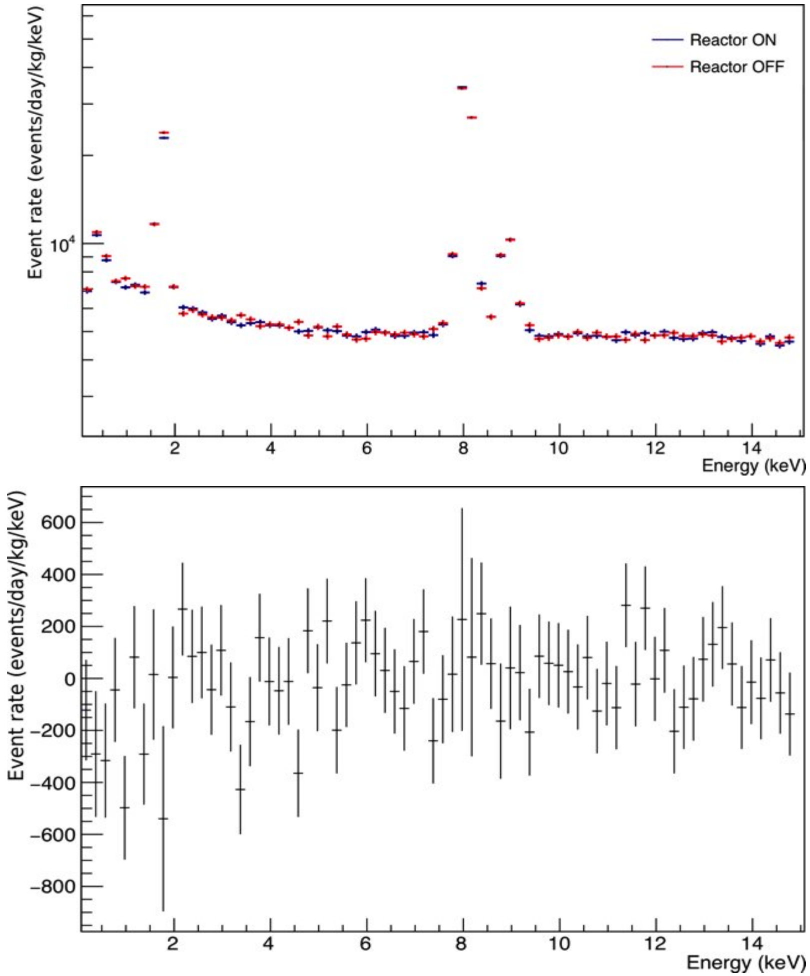


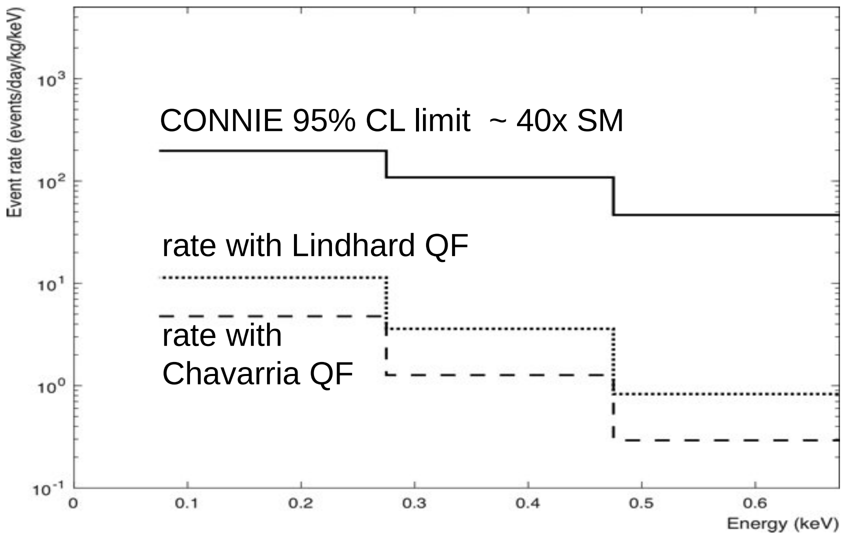
Image processing to reduce noise. Events extracted into catalogs.

CONNIE results 2016–2018

Phys. Rev. D 100 (2019) 092005



- 2016-18 Run with a ctive mass of 47.6 g.
- Readout noise ranging from 1.7-2.2 e-
- Energy spectrum with reactor on (2.1 kg-day) vs data with reactor off (1.6 kg-day).
- Extract upper limit for the CEνNS event rate.
- Comparison with expected rate depends on QF.

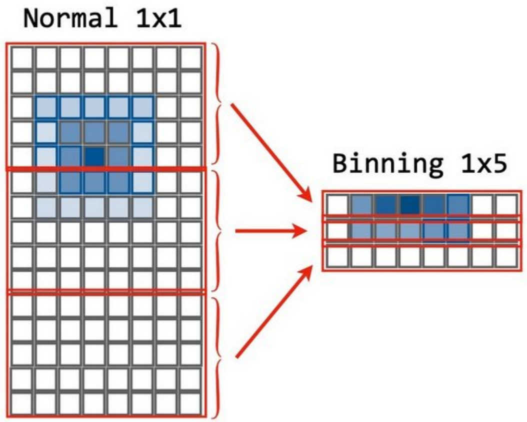


CONNIE 2019 run

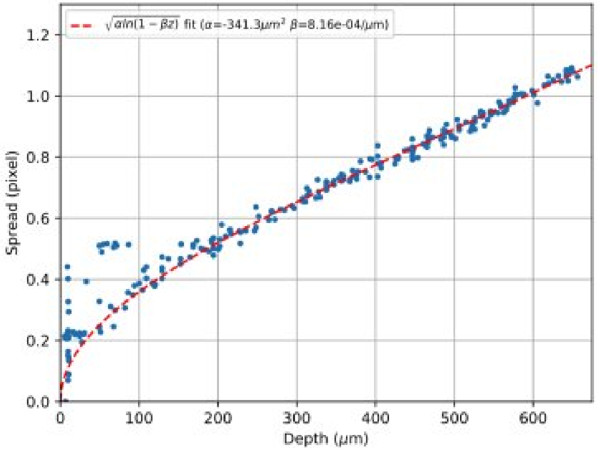
JHEP 05:017, 2022

Improvements in data acquisition and analysis techniques:

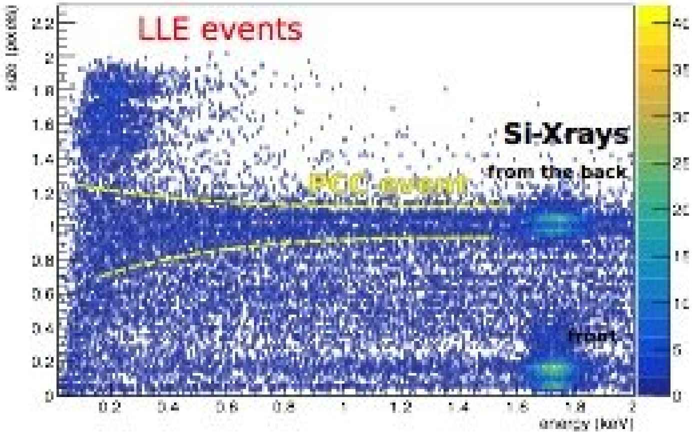
- 1x5 pixel hardware rebinning reduces readout noise (still ~ 1.5 - 2 e^-).
- Improved energy and depth-size calibrations
- Low-energy background characterization and reduction.
  - Cuts to remove anomalous large low energy (LLE) events
  - Simulation of Partial Charge Collection (PCC) layer in the back side of the CCD improves predicted energy spectrum.



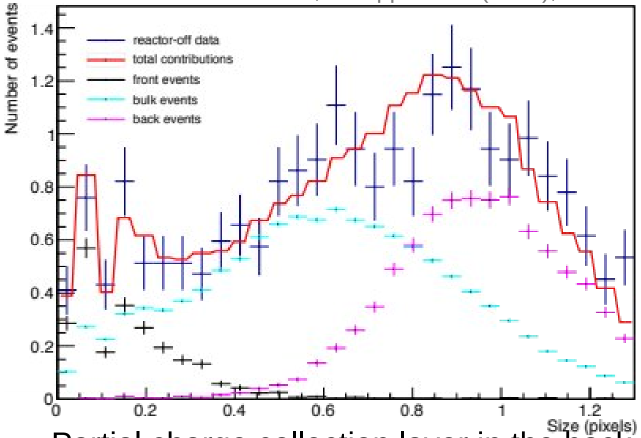
G. Fernandez-Moroni et al, PRApplied 15 (2021), 6 064026



Depth-size muon calibration



LLE from high-E tails and inactive volume are excluded.



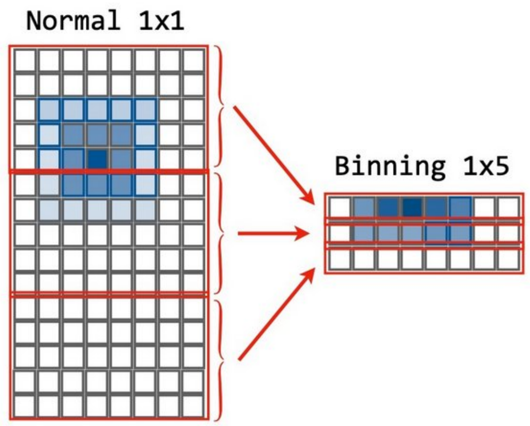
Partial charge collection layer in the back side of the sensor.

CONNIE 2019 run

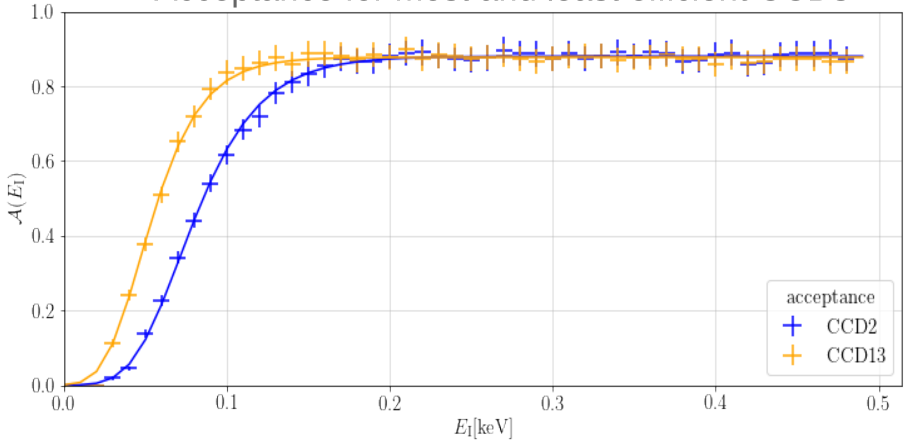
JHEP 05:017, 2022

Other improvements:

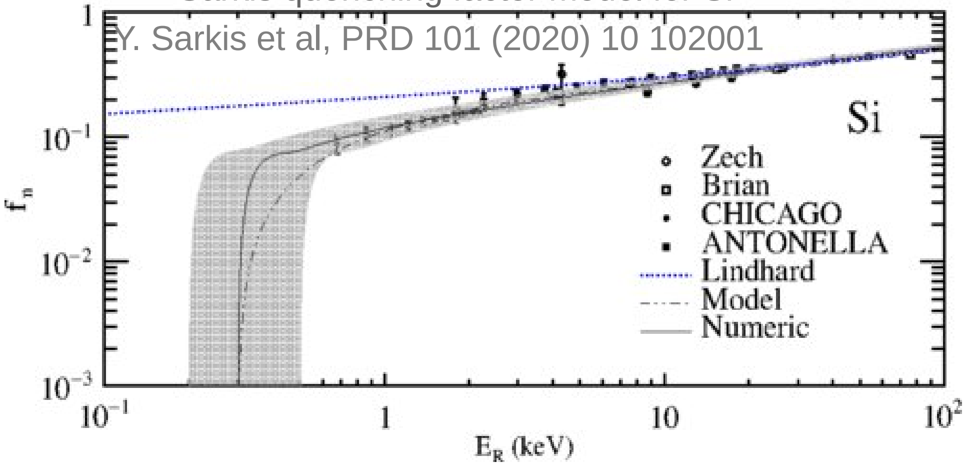
- Detection threshold reduced to ~50 eV
- Full efficiency reached at 100-150 eV
- Blind analysis and multiple crosschecks.
- Used Sarkis quenching factor model for ionisation efficiency at low energies.



Acceptance for most and least efficient CCDs



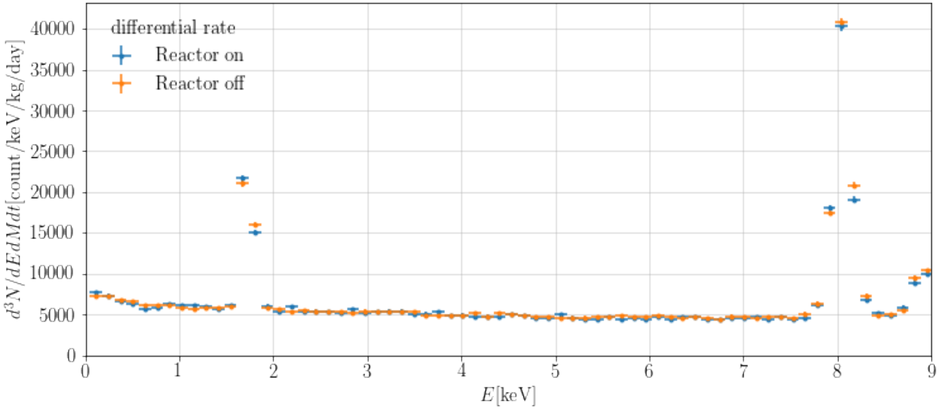
Sarkis quenching factor model for Si

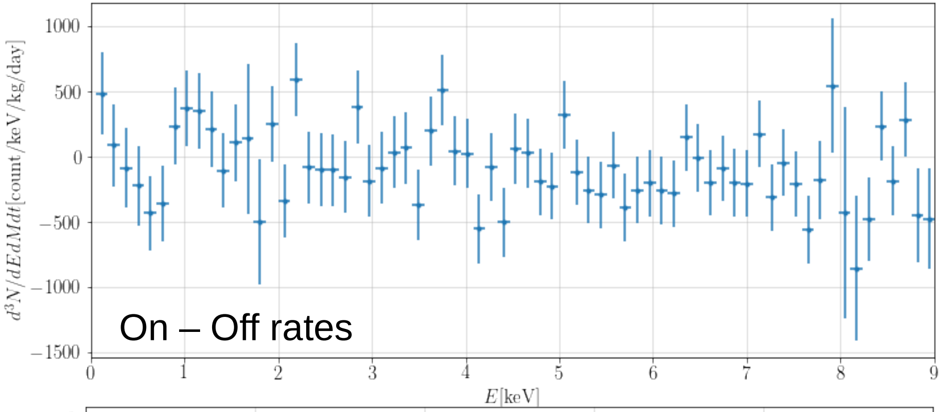


CONNIE 2019 results

JHEP 05:017, 2022

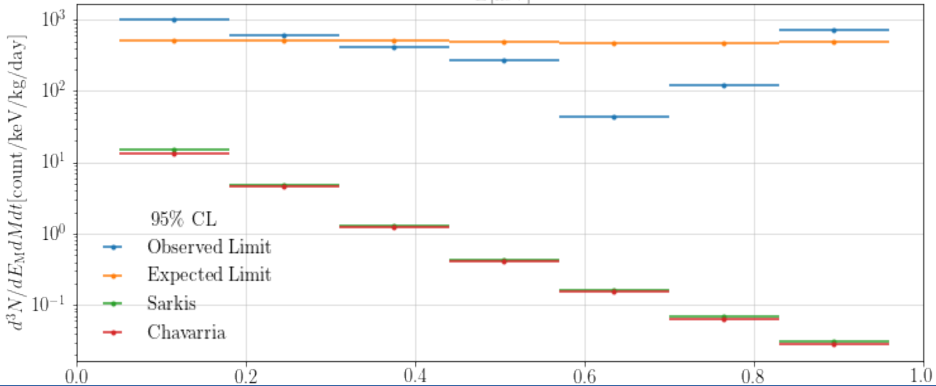
- Energy spectrum from 8 CCDs with total active fiducial mass of 36.2 g.
- Exposures of 31.85 days (reactor on) and 28.25 days (reactor off).
- Total exposure: 2.2 kg-days.





Upper limits at 95% CL on the measured CEvNS rate. Lowest energy bin:

- Expected limit is 34-39 times the prediction.
- Observed limit is 66-75 times the prediction.

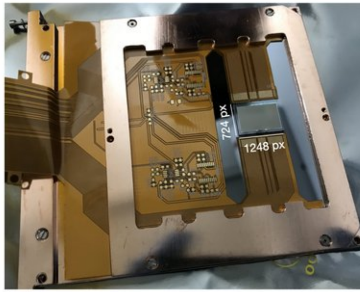


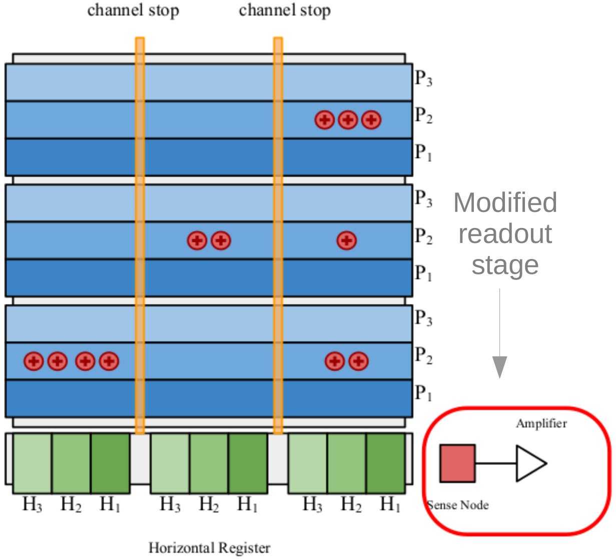
Results with Skipper CCDs

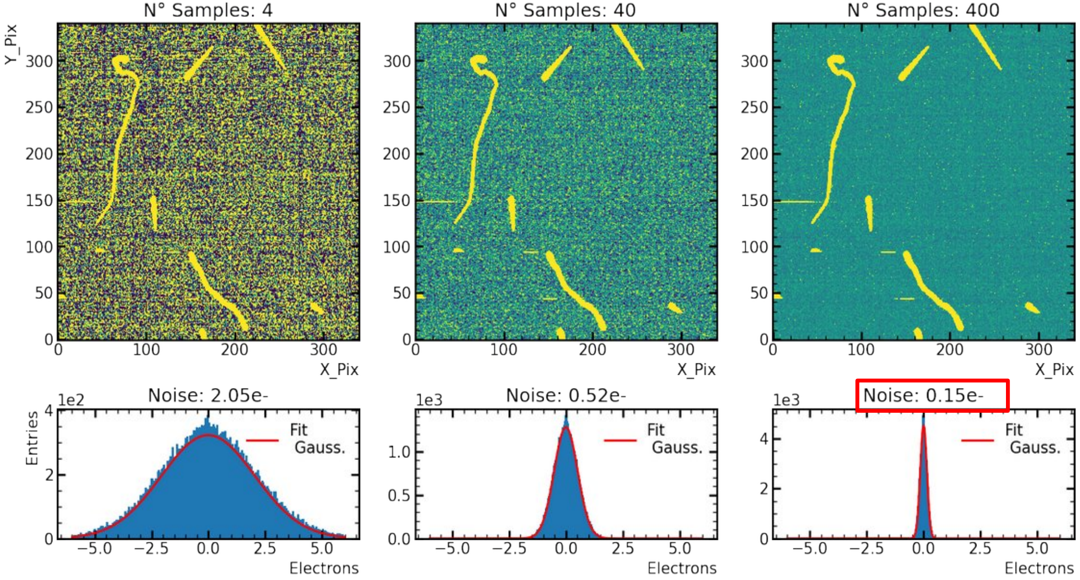
CONNIE with Skipper-CCD’s

Two Skipper-CCDs installed in the CONNIE setup in July 2021.

- 1022 x 682 pixels, 15 x 15 μm^2, 675 μm thick each ⇒ 0.5 g total mass.
- Low Threshold Acquisition readout lectronics G. Cancelo et al, JATIS 7, 015001 (2021)





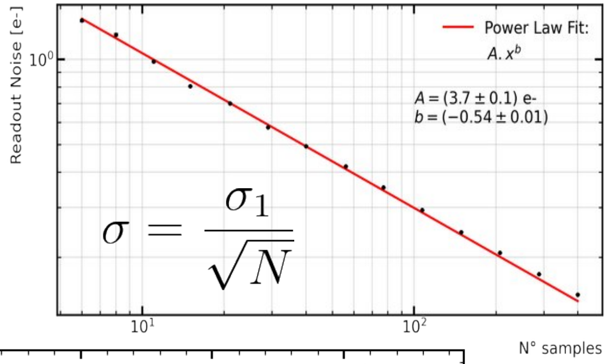


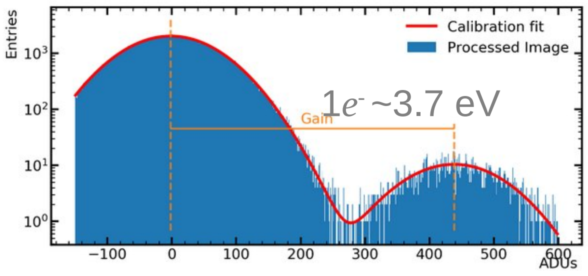
Skipper-CCD performance

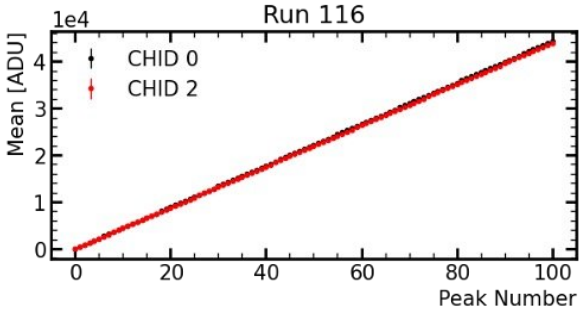
arXiv: 2403.15976

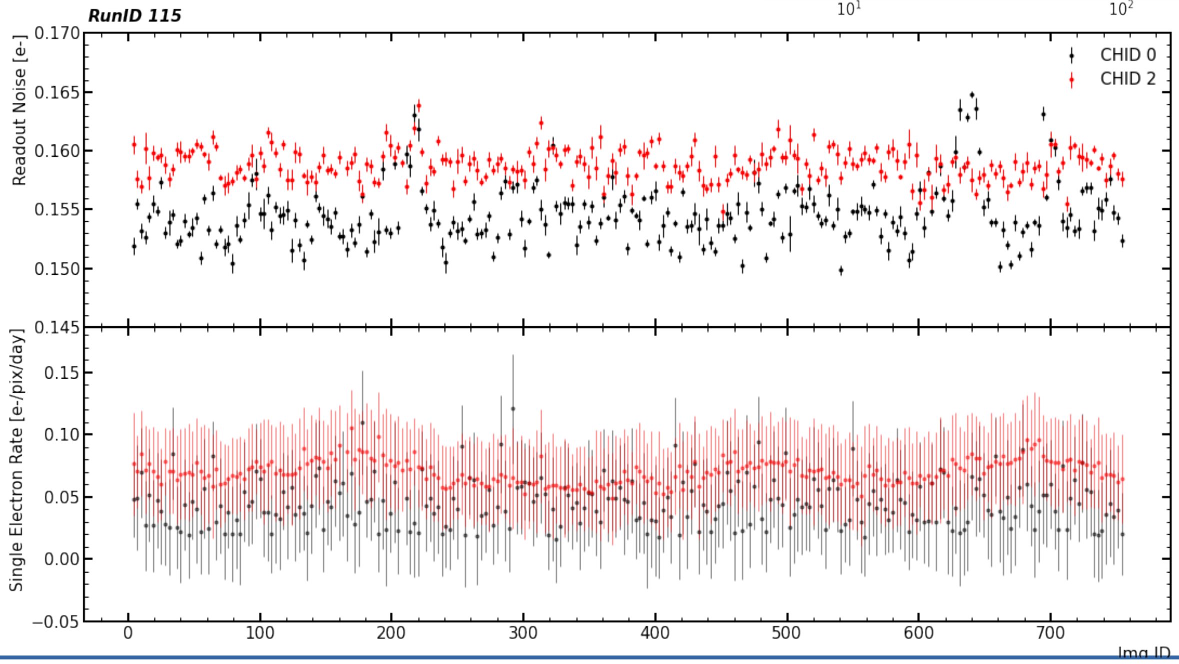
Stable detector performance and background over the 2021-2022 period.

- Each pixel charge is read out with N = 400 samples.
- Ultra-low noise = 0.15 e-.
- Self-calibrated detector, $1e^{-}$ ~3.7 eV.
- Single-electron rate = 0.045 e-/pix/day (low for surface).









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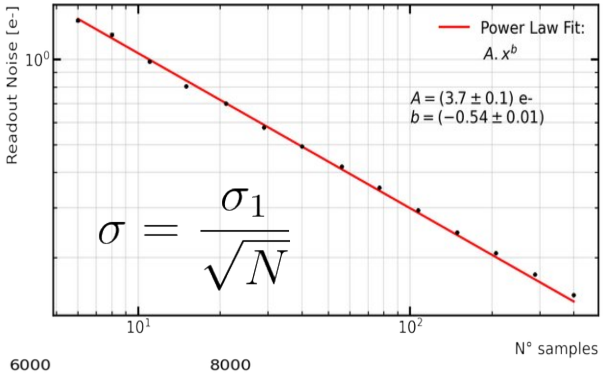
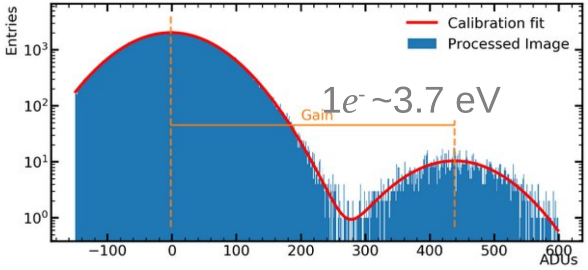
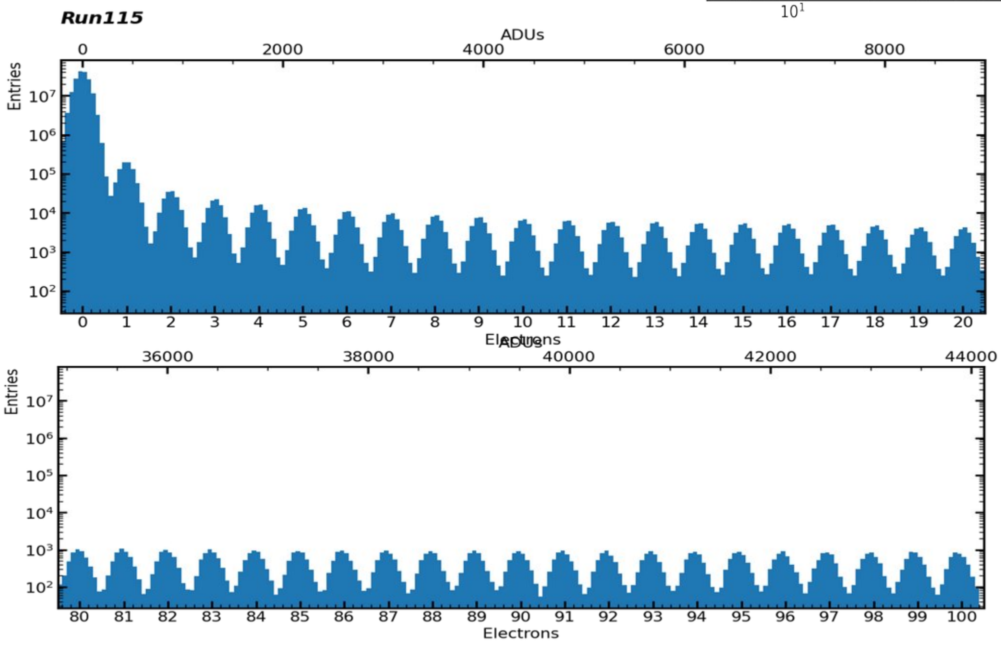
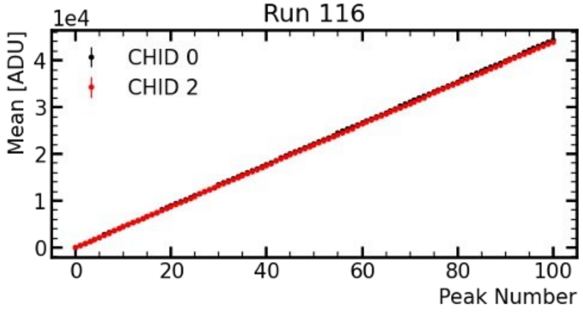


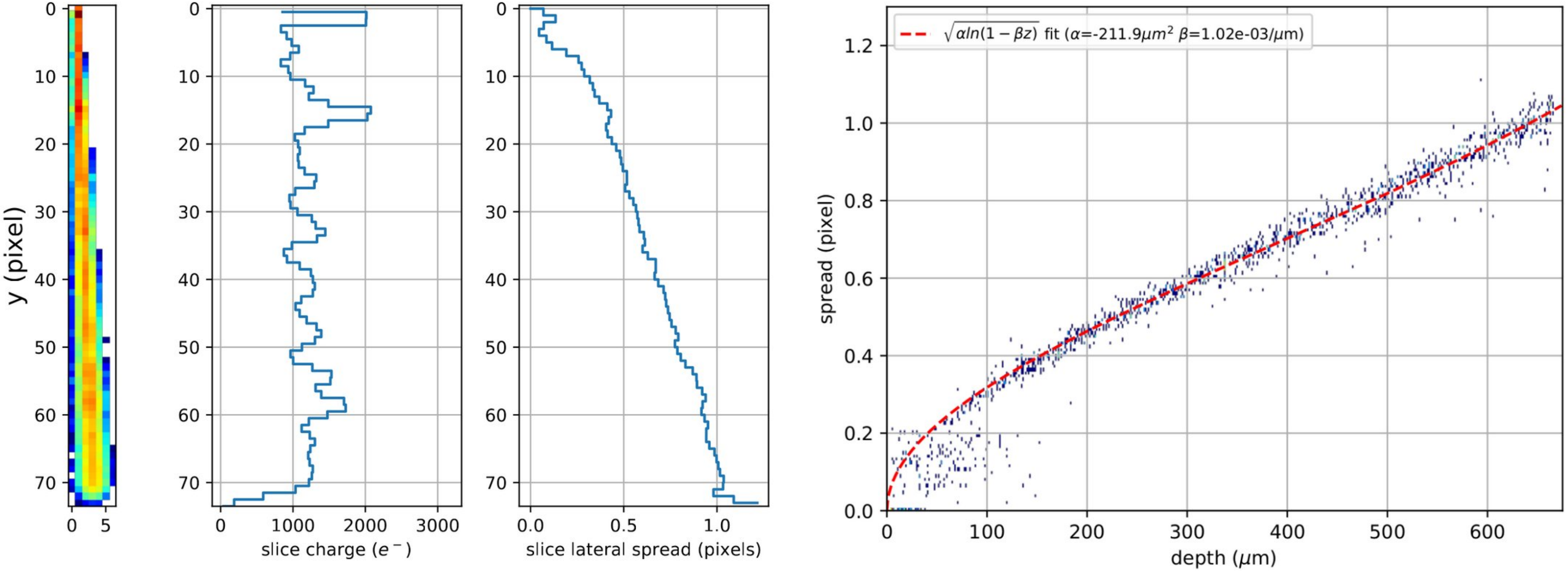






Skipper-CCD depth vs size calibration

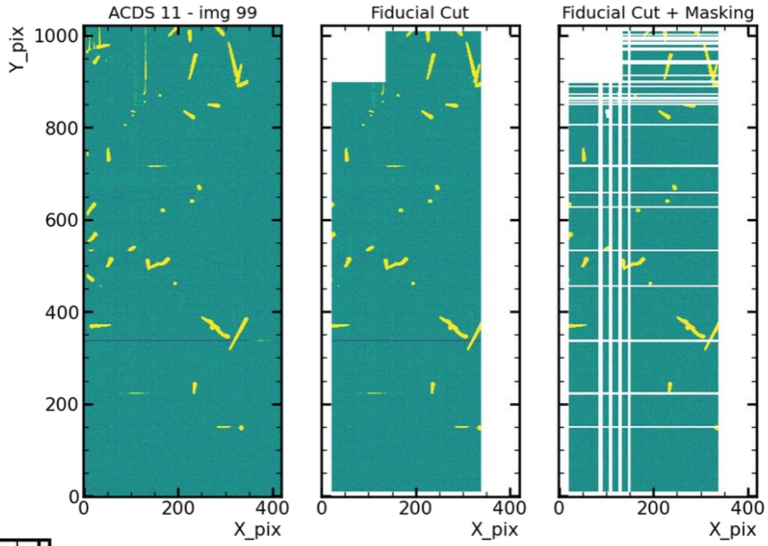
Calibration using “*y*-parallel” muons

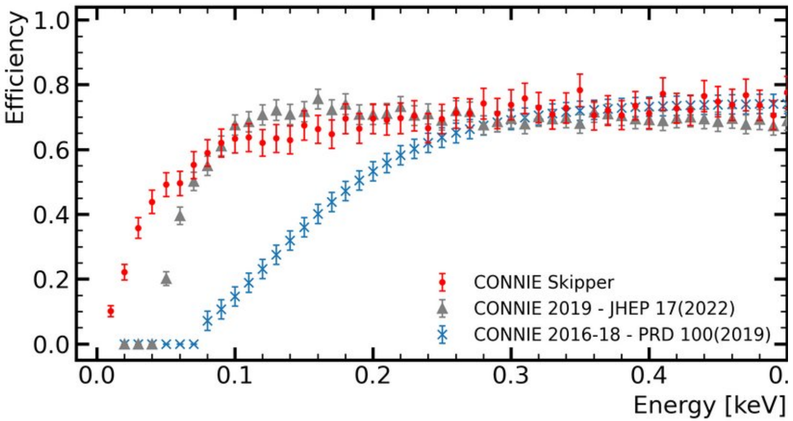


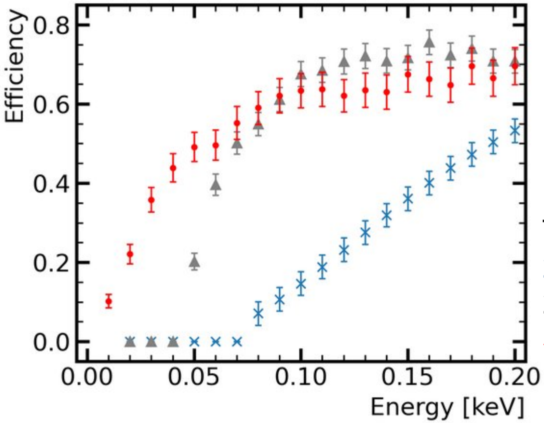
Selection and efficiency

arXiv: 2403.15976

- 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 < σ X,Yfit < 0.95 pix.
- Efficiency determined from simulations.
- Allows to lower the threshold to 15 eV.







Threshold:
2018: 75 eV
2019: 50 eV
Skipper: 15 eV

CONNIE with Skipper-CCDs: single sensors

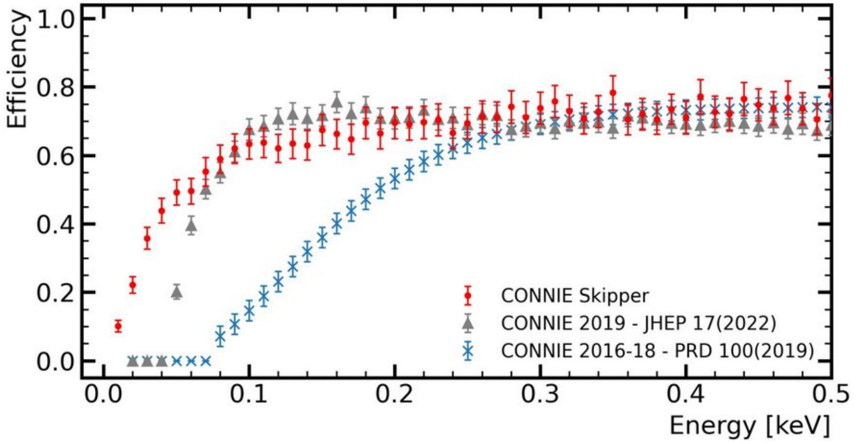
arXiv:2403.15976

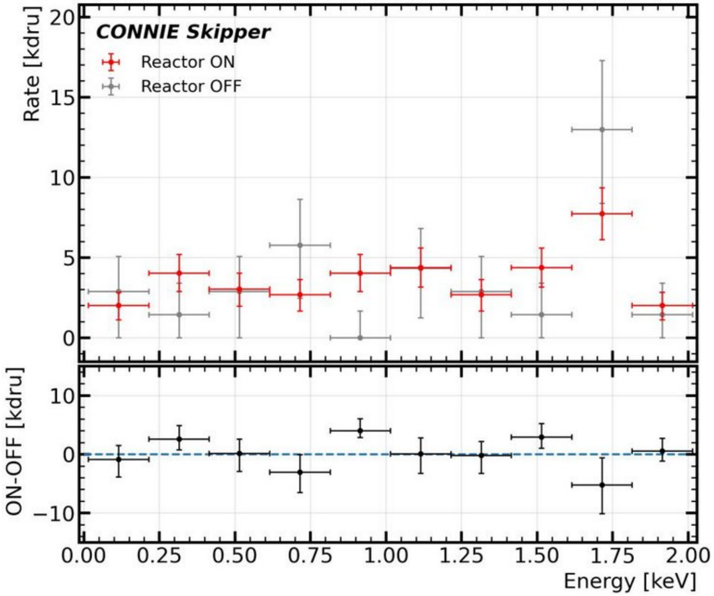
Improvements over standard-CCD runs:

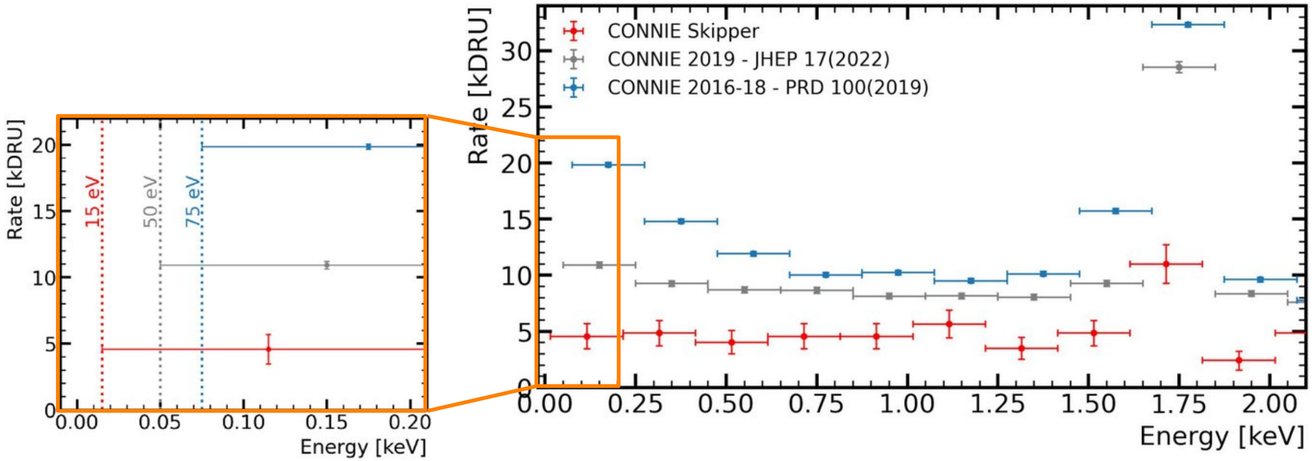
- Energy threshold reduced to 15 eV_{ee} (~240 eV_{nr}).
- Higher detection efficiency at lower energies.
- Lower and flat background rate: ~4 kdru.

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

No excess observed.





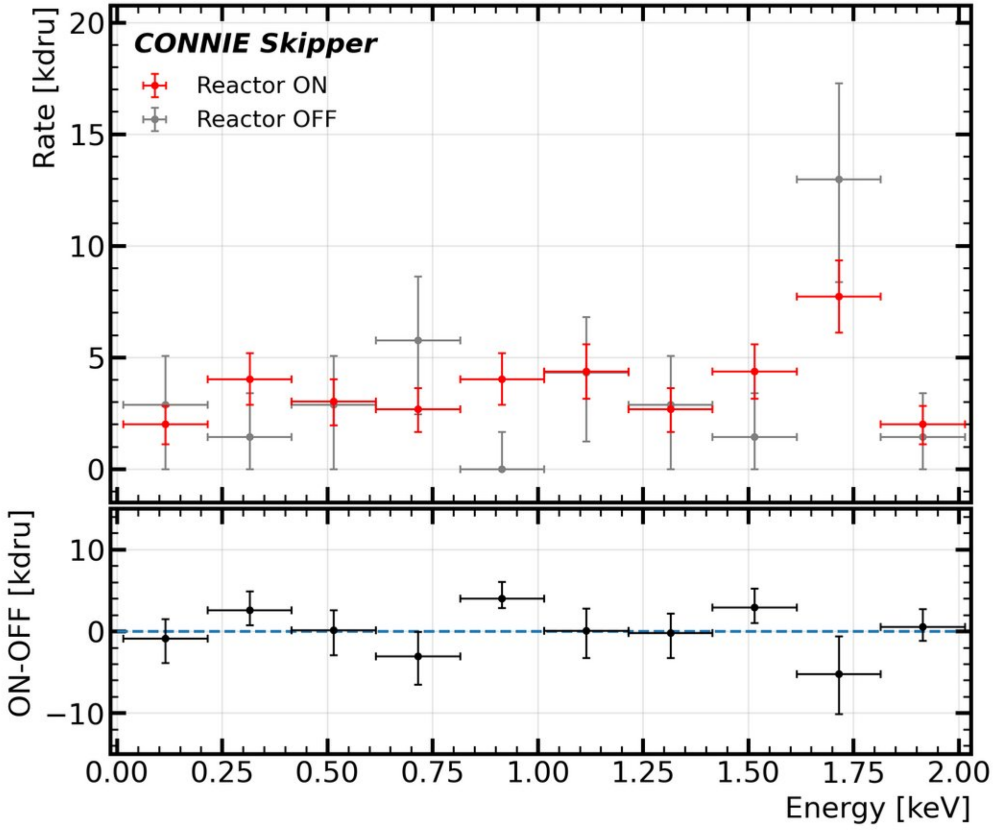


Energy spectrum

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 with Reactor-OFF.
- No excess (CEvNS or otherwise) observed.
- Flat background rate ≅ 4 kdru.
- Improved background and threshold.



Plots by Pedro Ventura

CEνNS search

arXiv: 2403.15976

A search for CEνNS in the lowest-energy bins of reactor ON – OFF rates.

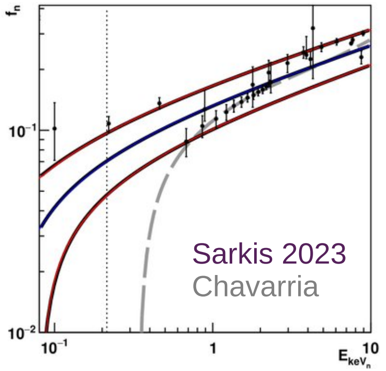
- Updated neutrino flux model with improved antineutrino spectra for ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu.

  For E_ν > 0.44 MeV (15 eV ee) the new and old model agree within 3%.

- Updated Sarkis quenching factor model for silicon. Y. Sarkis et al, PRA 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 $[\mathrm{keV_{ee}}]$	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



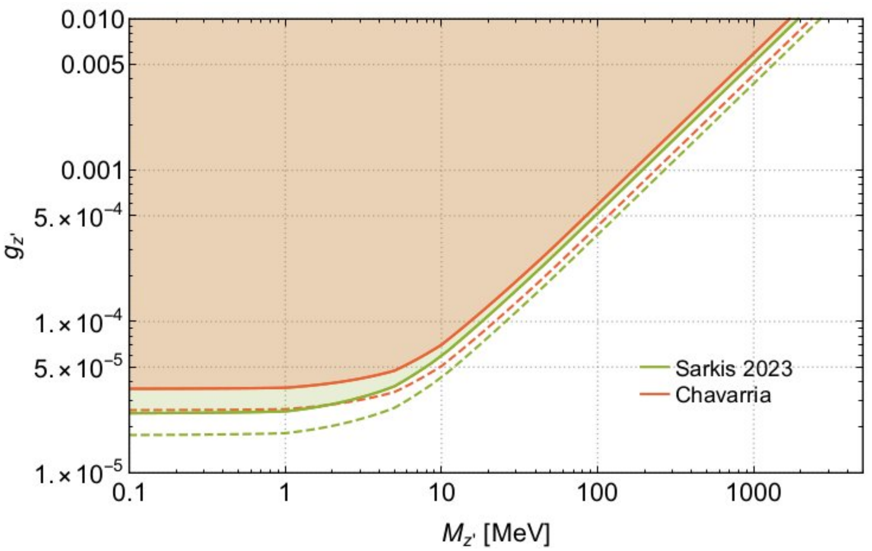
- Observed limit at 76x the expected SM predicted Rate (with Sarkis QF).
- Comparable to our previous limit with standard CCDs and 10^3 larger exposure.

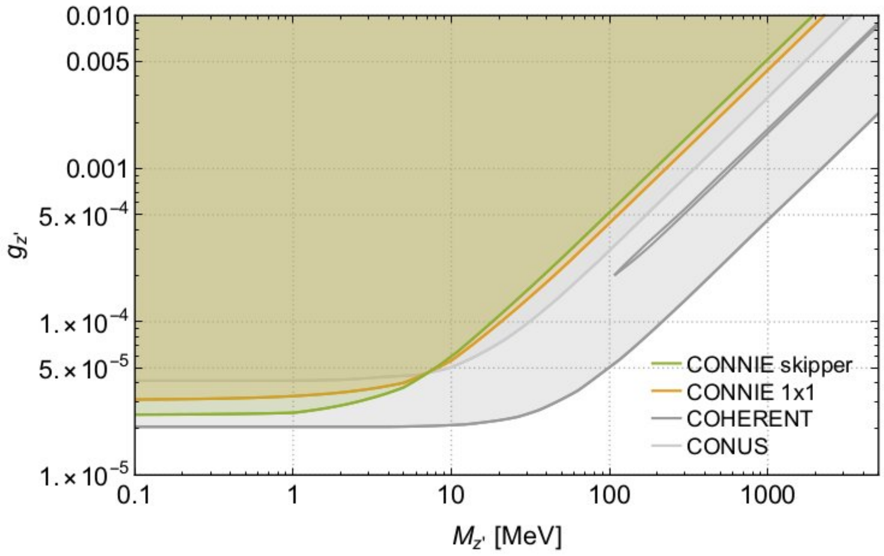
Light vector mediator search

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 $g_{Z'}$.





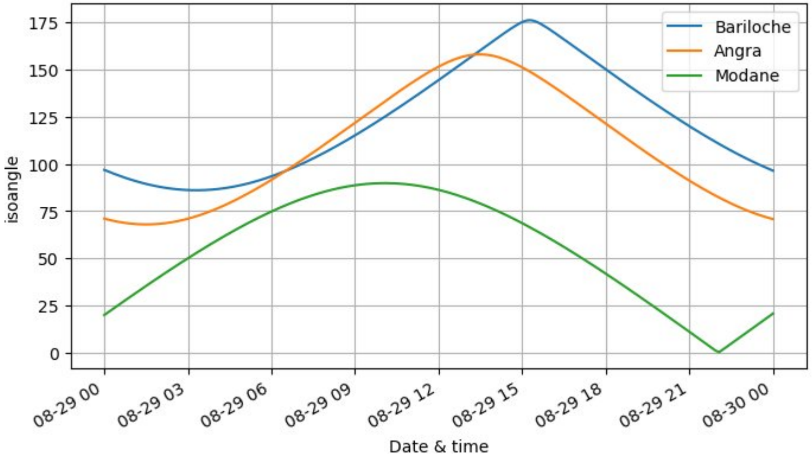
Comparison between QFs and projections for 5x smaller uncertainties and zero rate

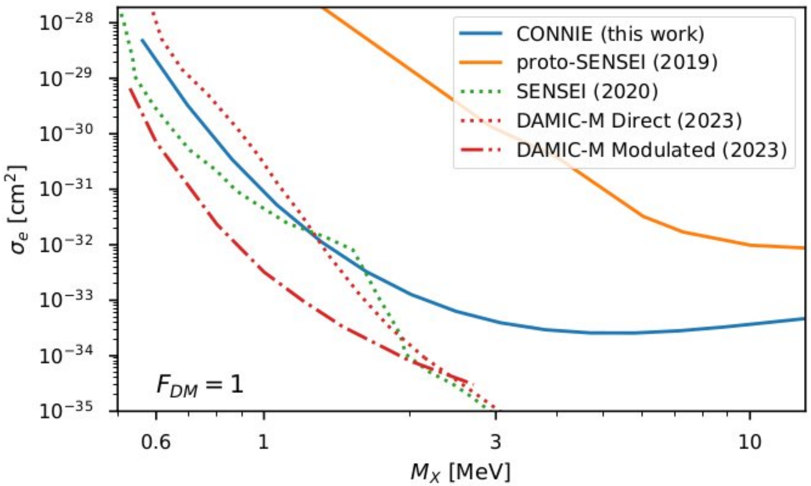
Dark matter search

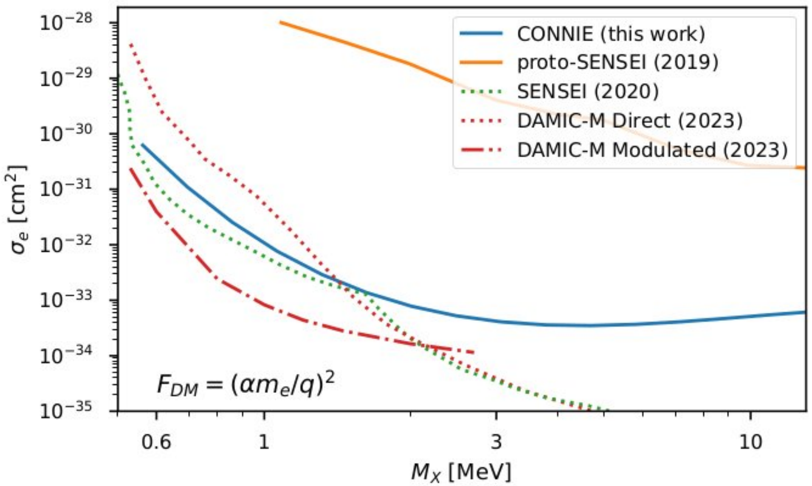
arXiv: 2403.15976

- A search for DM-electron interactions by ***diurnal modulation***.
  - Galaxy DM wind comes from a preferred direction 40° N.
  - Earth motion induces daily modulation (isodetection angle favours Southern Hemisphere)
  - CONNIE at 23° S can scan angles between 65°-161°
- Binned data are compared to DaMaSCUS simulations
- Model with MeV-scale DM coupling to SM particles via a kinetically mixed dark photon (A')
- Best DM-electron limits by a surface experiment.

N. Avalos, TAUP 2023





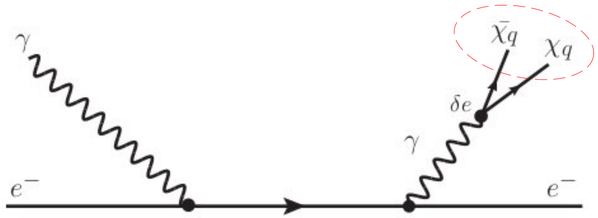


Search for millicharged particles

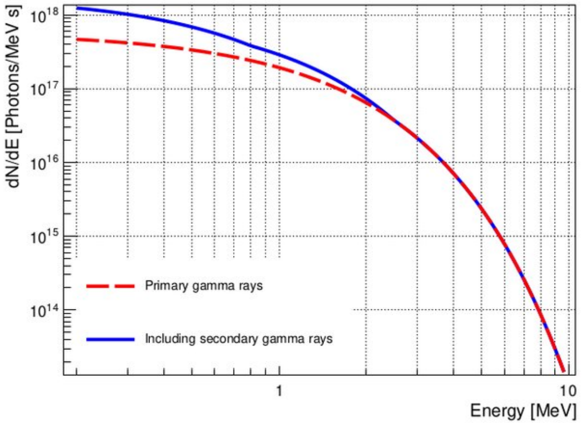
PRL, 134,071801 (2025)

Relativistic millicharged particles (χ_q), predicted in SM extensions with hidden sectors.

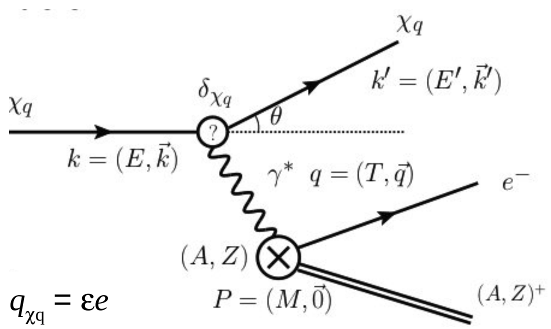
Production: Compton-like scattering of high-energy γ's from the reactor



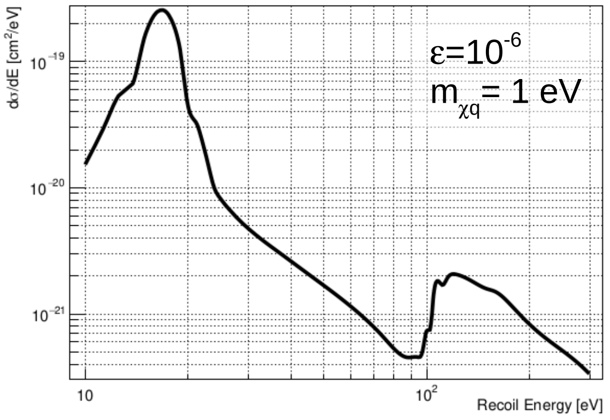
Including secondary γ's from transport in the reactor core.



Detection: Atomic Ionization



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



Reactor γ spectrum gives diff. flux. of χ_q

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

Diff. count-rate expected at detector:

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

Cross-section for low-energy ionisation by relativistic particles includes collective excitations

- Collective effects encoded in the dielectric function calculated with the DarkELF (GPAW) code.
- Plasmon peak at 10–25 eV .

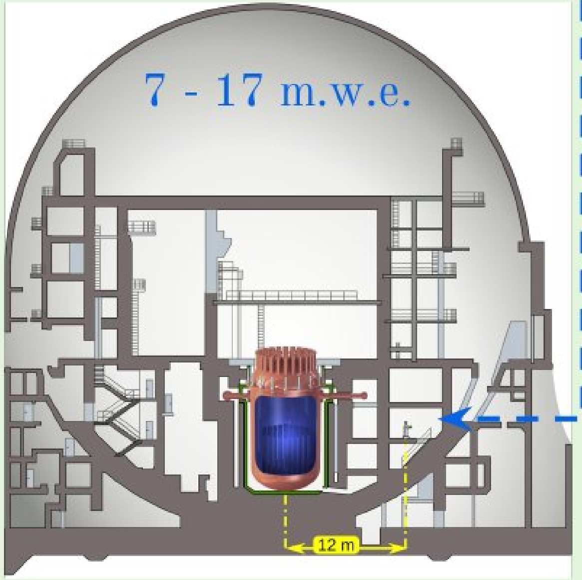
R. Essig et al, arXiv: 2403.00123

Atucha II Experiment

[Eliana Depaoli, Magnificent CEvNS 2025]

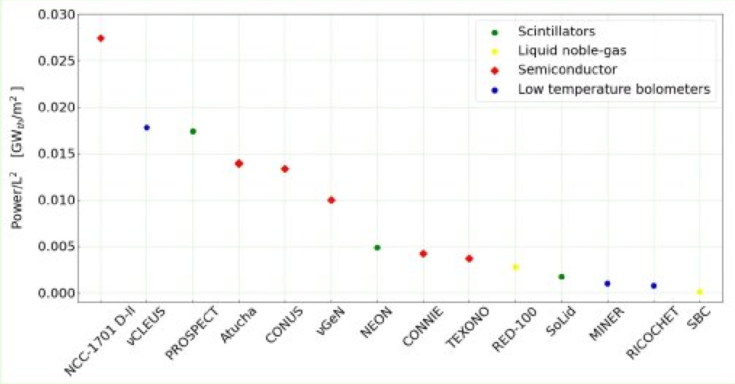
Short-baseline ν-experiment at Atucha II power plant

- 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

PRL, 134,071801 (2025)

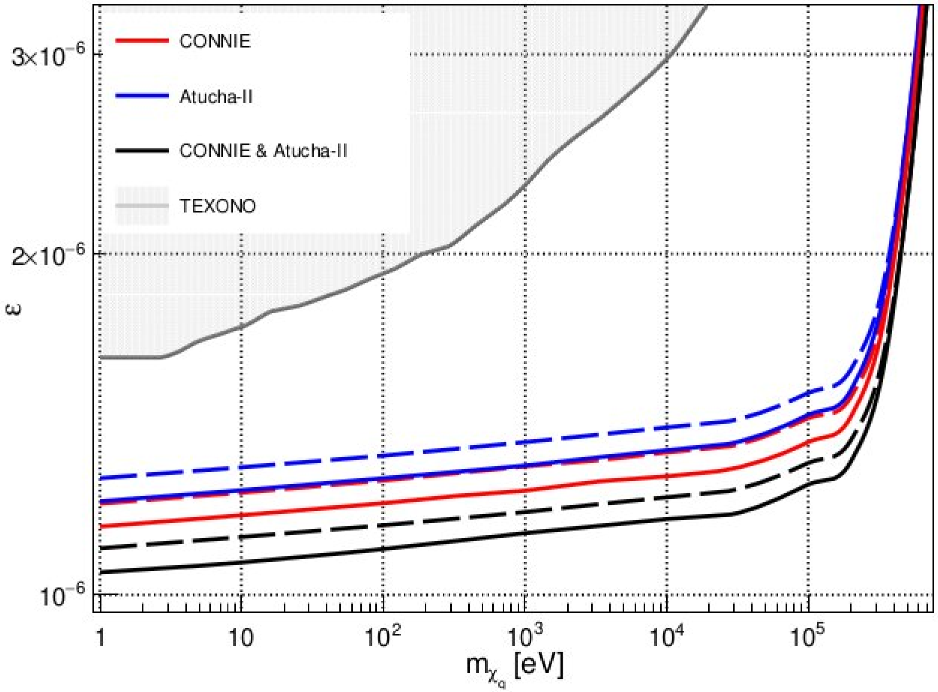
Joint analysis between CONNIE and Atucha-II experiments.

- Based on the lowest energy bins:

  - 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 wide mass range for $m_{\chi q}$< 1 MeV.

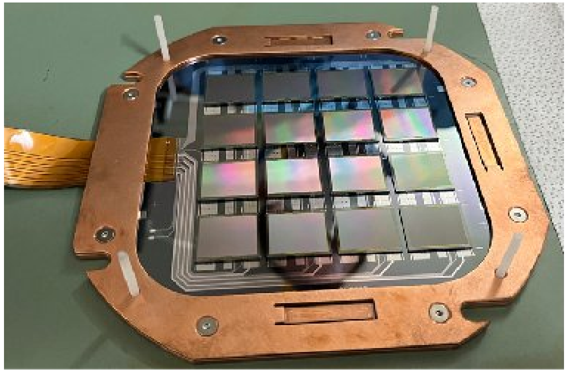


CONNIE with Skipper-MCM's

Towards more massive experiments

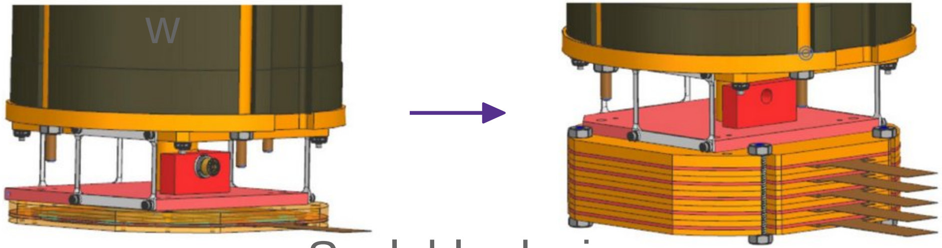
Multi-Chip Modules offer a new compact arrangement of sensors:

- 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]

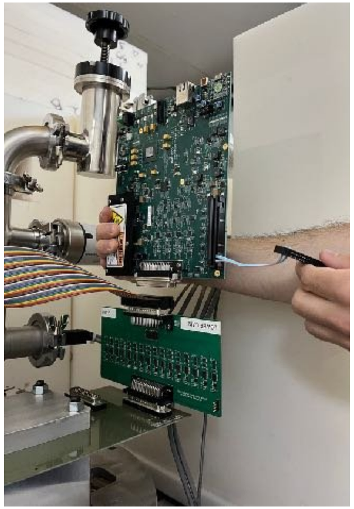


One MCM was commissioned at CONNIE in October 2024

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



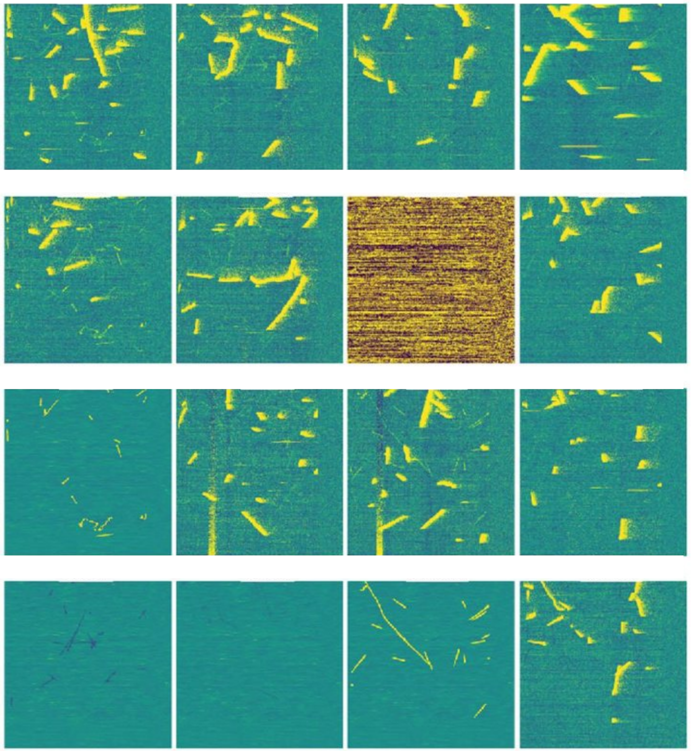
Scalable design

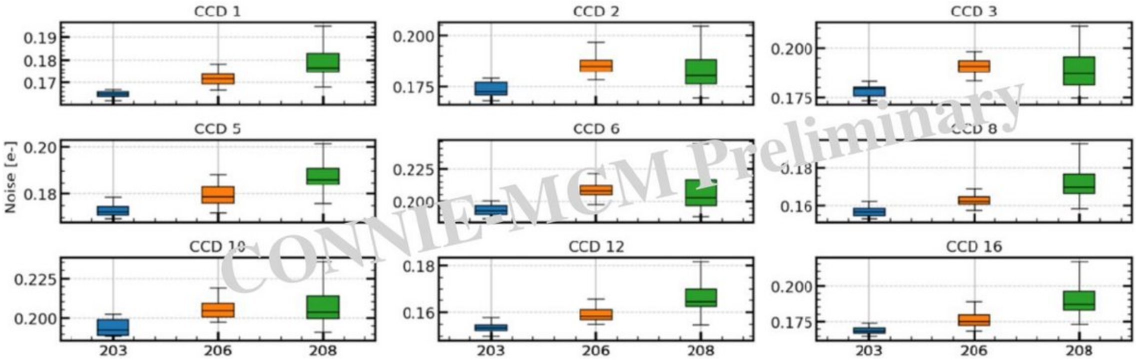


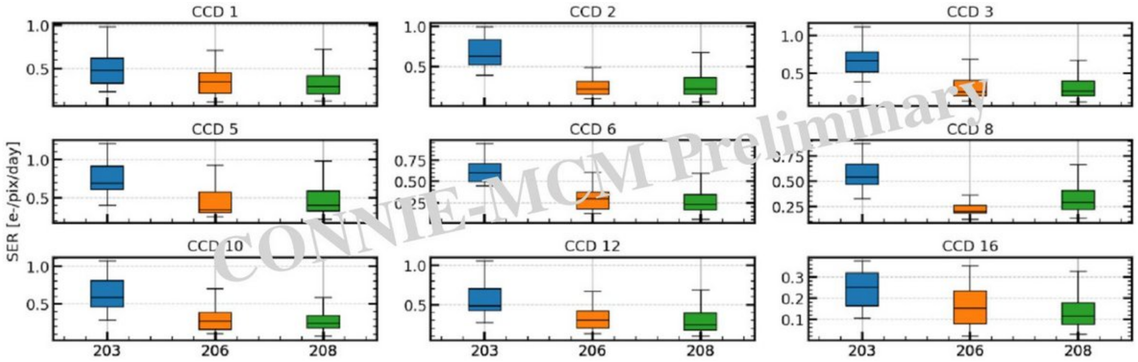
CONNIE-MCM Performance

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

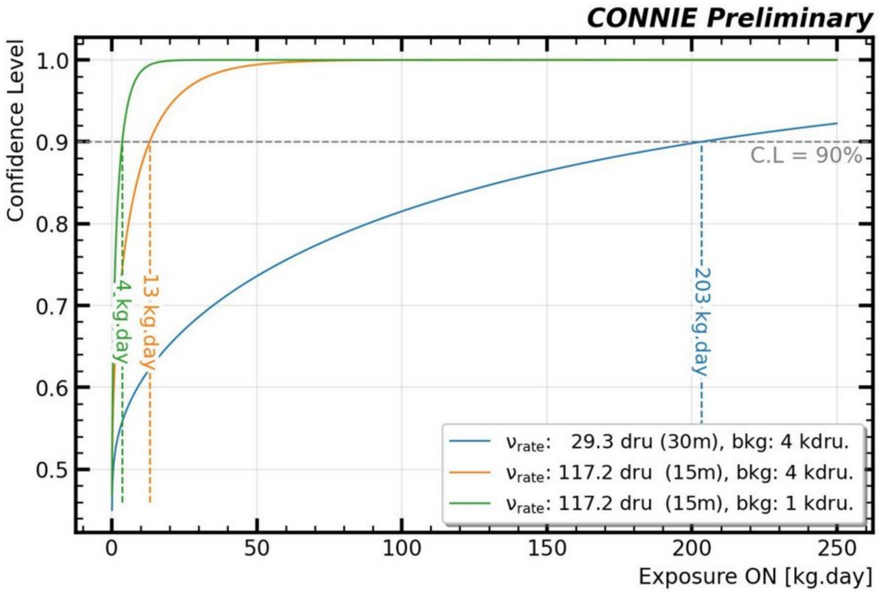
- CONNIE-MCM
  - Optimizing performance for reactor OFF spectrum (Nov 2024) and reducing background.
  - Collecting data to improve current experimental limits.
  - Improvements in current BSM limits with ~10 times more mass.
  - Proof of concept for new technology to increase mass.
  - Synergy with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

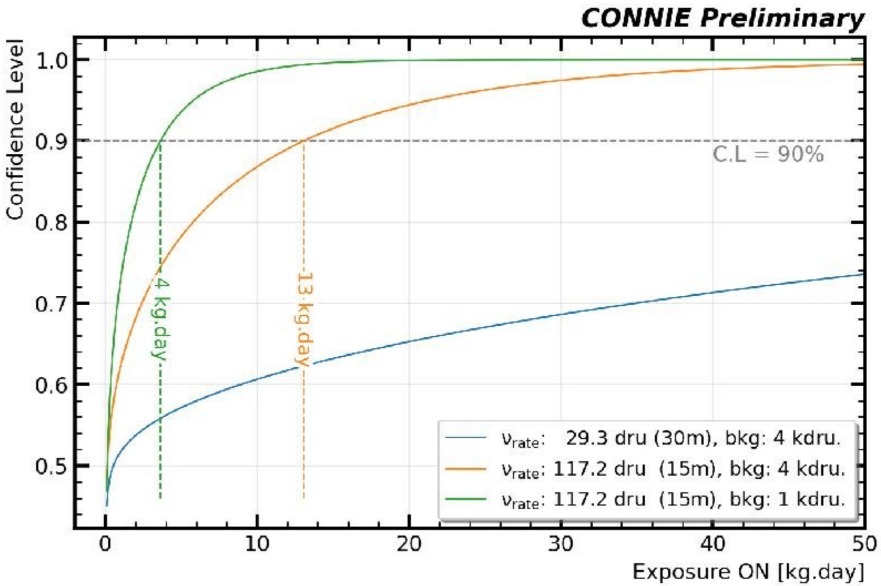
- Plans to increase the neutrino flux
  - New position @ Angra-2 (~17 m from reactor core) identified. Negotiations underway.
  - Would: - increase the flux by factor of ~3.
    - reduce background by factor of 3-4 (rough estimate).
  - Requires a new compact detector design.

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.





Grupo de Neutrinos y MO del ICN

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Cristian Macías Acevedo (Maestría)
Stephane Magaña Cailly (Lic)
Mauricio Sánchez Ramírez (Lic).

Area de Criogenia,
Laboratorio de Detectores

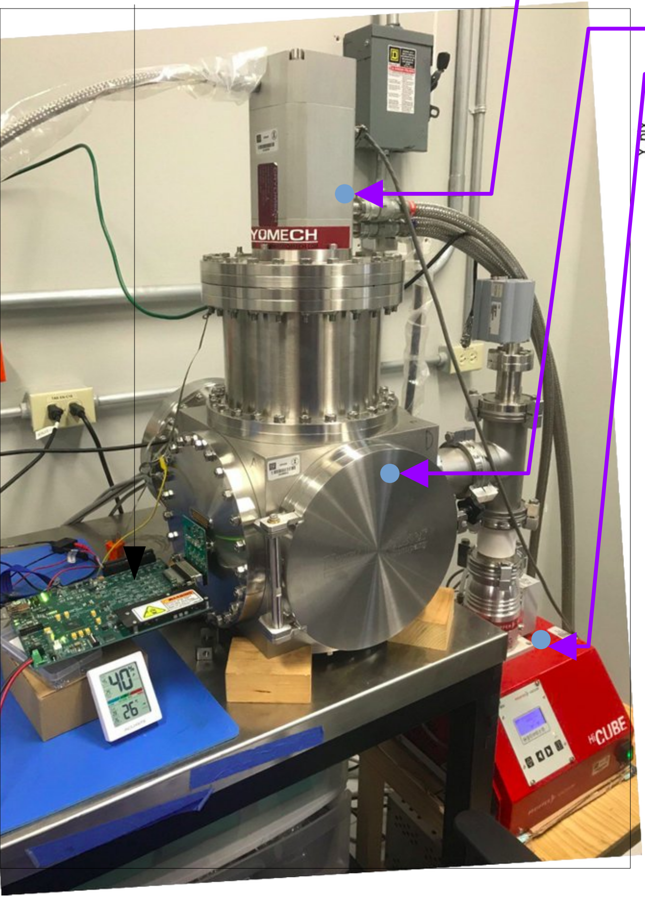
CCD test-Bench @ ICN

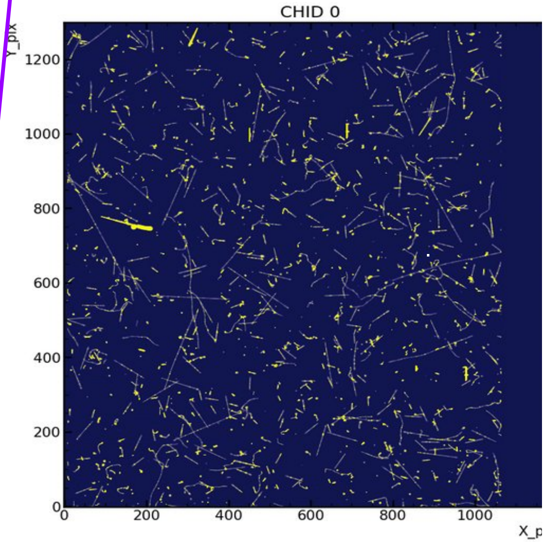
LTA electronics

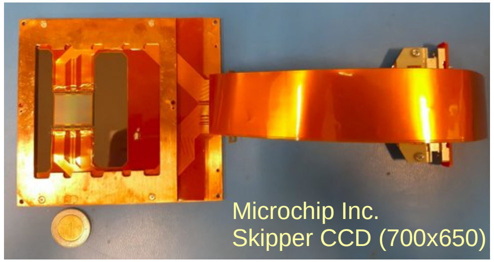
Cryocooler (cool to ~140 K)

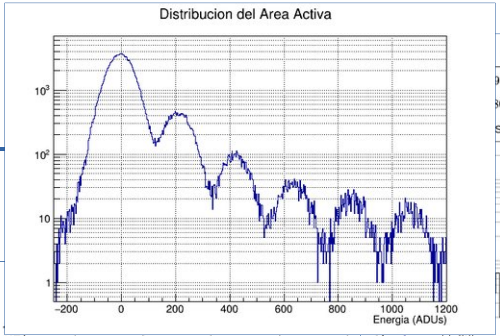
Vacuum chamber (2e-7 Torr)

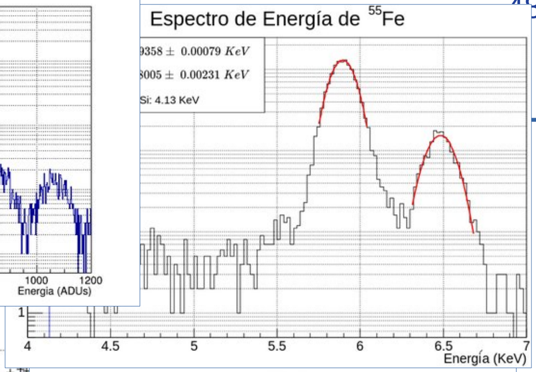
Dry vacuum pump

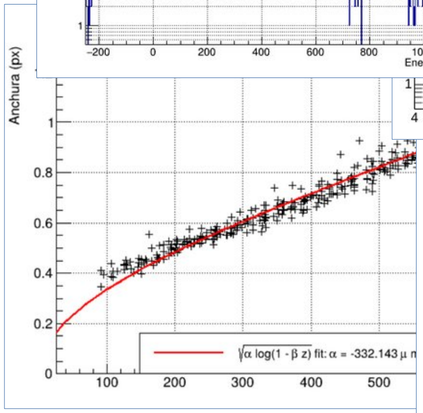


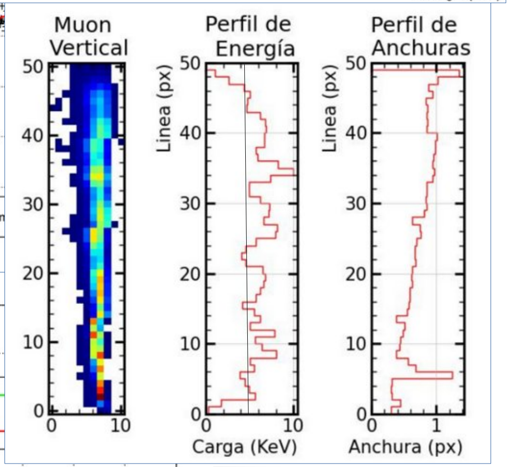


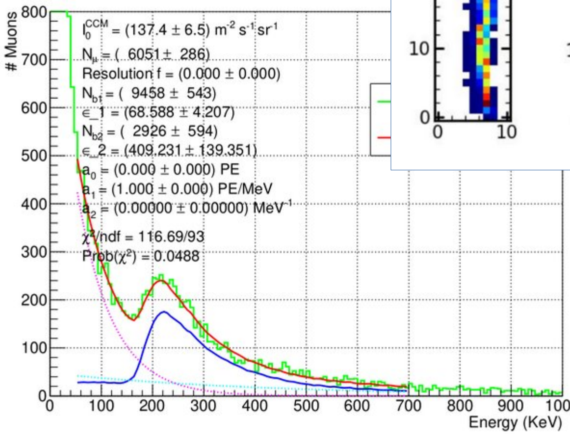








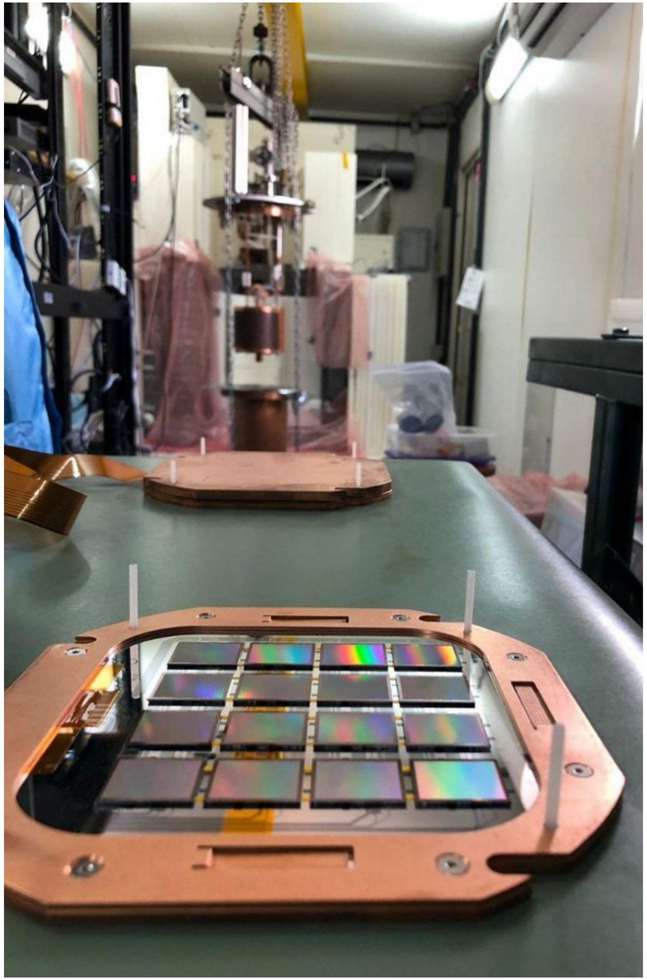




Final remarks

- 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!
- Data yield competitive limits on vector mediator, light DM by diurnal modulation and millicharged particles (with Atucha-II).
- CONNIE started its next phase with a 16-sensor Multi-Chip-Module.
- Needed a mass ~1 kg of skipper-CCDs for CevNS detection.
- Efforts to increase the neutrino flux are on-going.

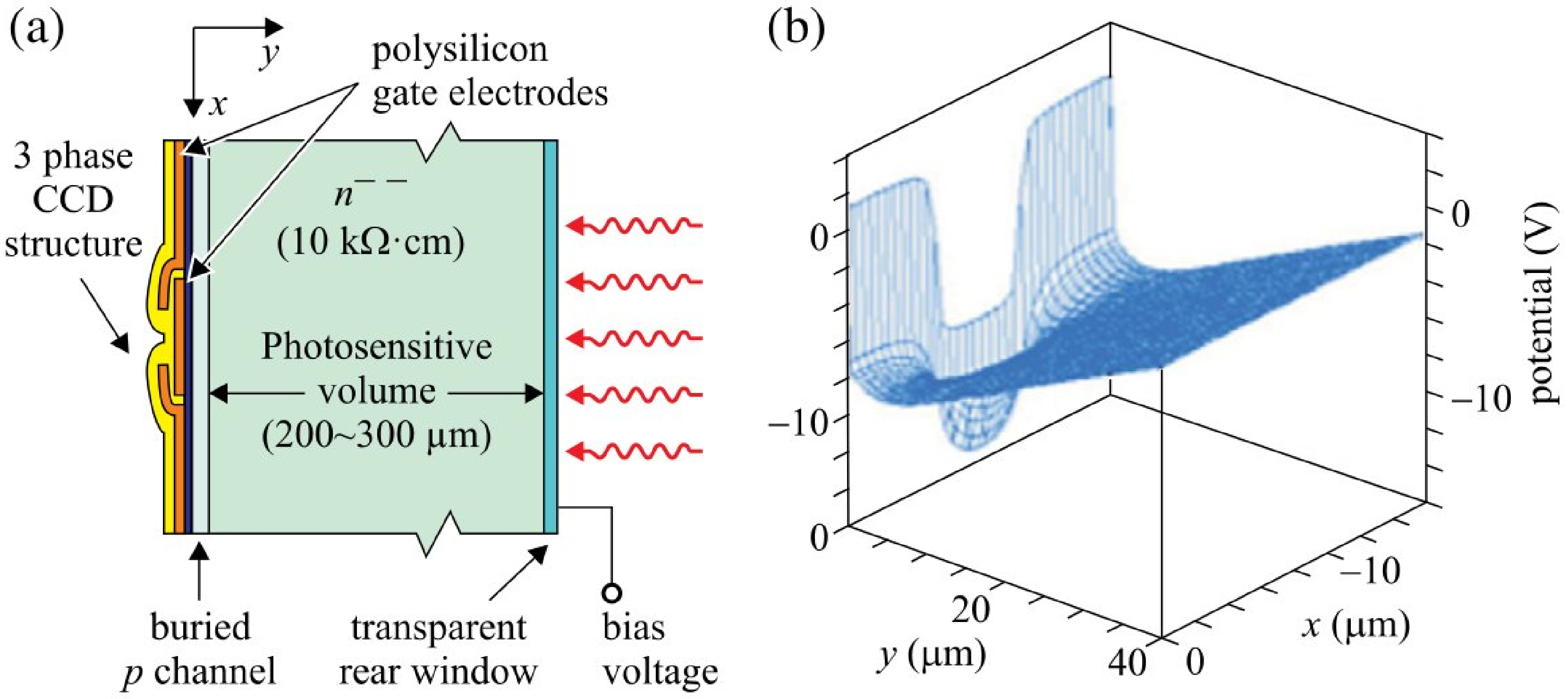
Thank you for your attention!



Thank you for your attention!

BACKUPS

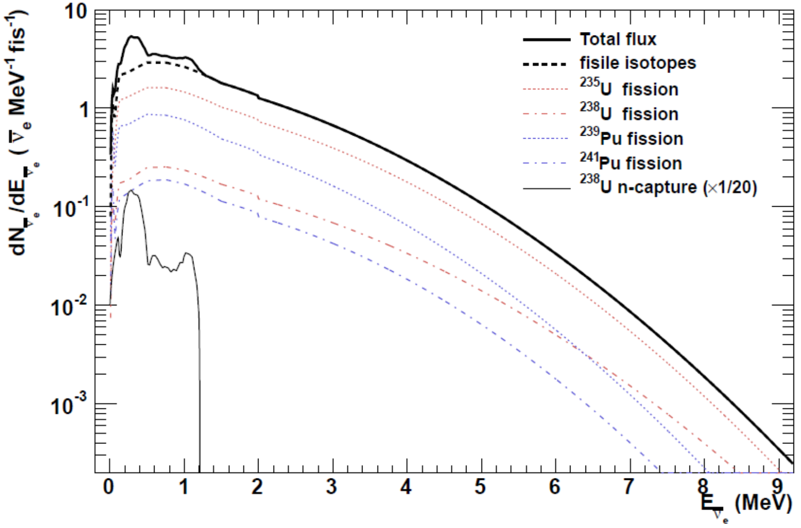
CCD Pixel

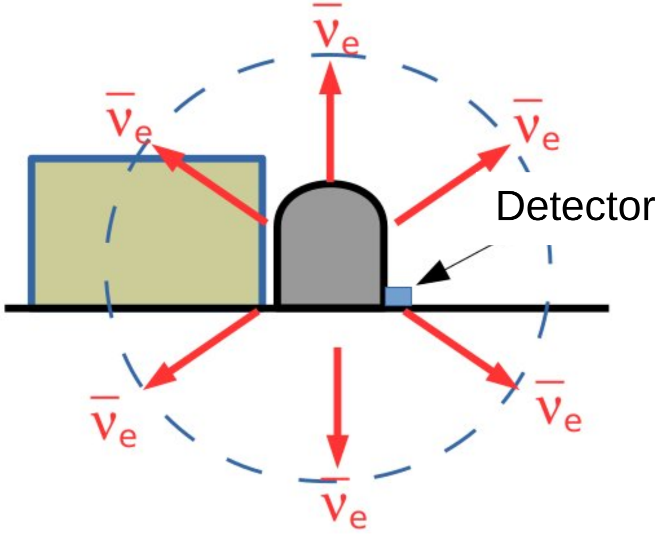

(a)
y
x
polysilicon
gate electrodes
3 phase
CCD
structure
n^{--}
(10 kΩ·cm)
Photosensitive
volume
(200~300 μm)
buried
p channel
transparent
rear window
bias
voltage
(b)
0
−10
0
0
−10
potential (V)
20
40
y (μm)
0
−10
x (μm)

Reactor $\bar{\nu}_e$'s from Angra-2

- Angra-2: 3.95 GW_{th} pressurized water reactor (PWR).
- Emits ~8.7×10^{20} $\bar{\nu}_e s^{-1}$ (2.23×10^{20} $\bar{\nu}_e s^{-1} GW_{th}^{-1}$).
- Flux ~7.8×10^{12} $\bar{\nu}_e\, cm^{-2}\, s^{-1}$ at 30 m from the core.

$$fisRate = \frac{3.95\ GW_{th}}{205.24\ \mathrm{MeV/fis}} \approx 1.2 \times 10^{20}\ \mathrm{fis/s}$$





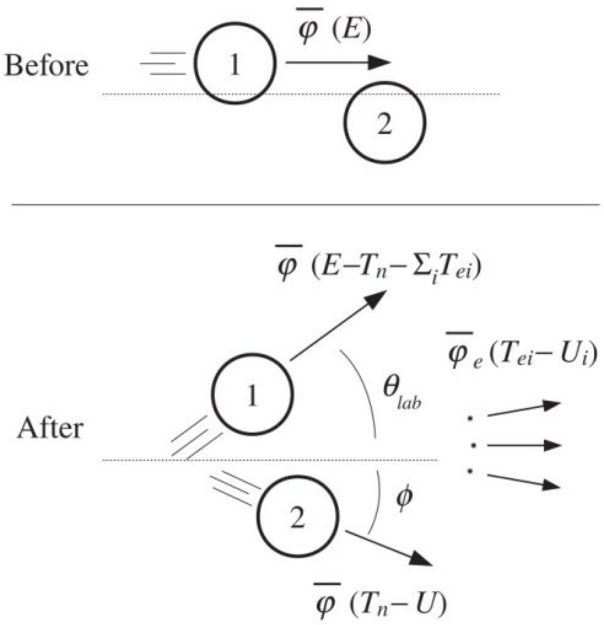
Needs update!

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

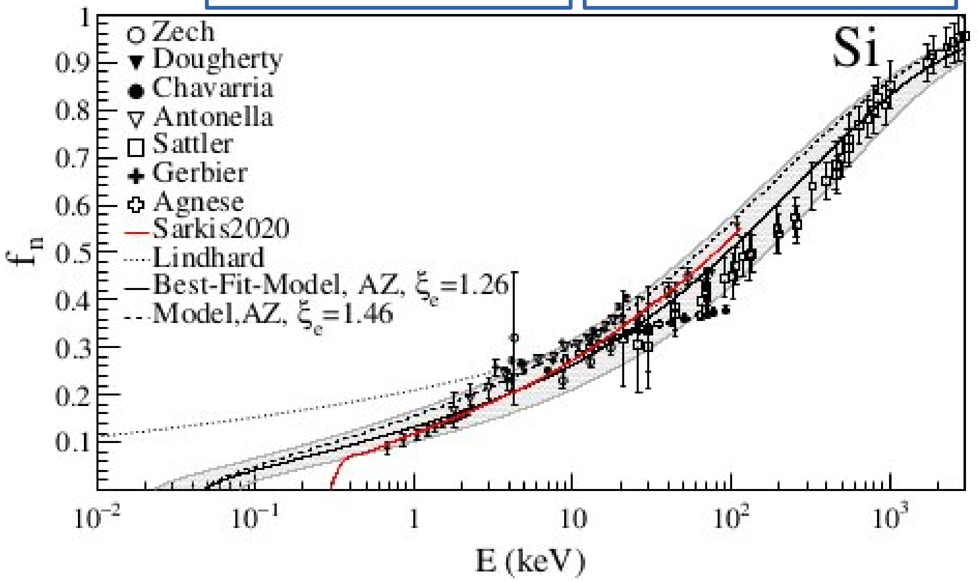
Quenching Factor (nuclear recoils)

- Y. Sarkis developed a model for the ionization efficiency of nuclear recoils in pure cristals (Si & Ge). Extension of the Lindhard model to incluide binding energy.
- Crucial to calculate limits in experiments.
- Model can be also used for noble liquid detectors (LAr, LXe).



PRD101(2020)102001

PRA107(2023)062811



Constraints to physics BSM

JHEP 04 (2020), 054

- Event rate in lowest E bin gives limits to non-standard neutrino interactions: Simplified models with light **scalar** (φ) and **vector** (Z') mediators.
- Restrictive limits for low mediator masses $M_{\varphi} < 30$ MeV, $M_{Z'} < 10$ MeV.
- First competitive constriction to BSM physics from CEvNS in reactors!
- Best current limit from the CONUS experiment [JHEP, 085, 05, 2022]

NEUTRINO 2020

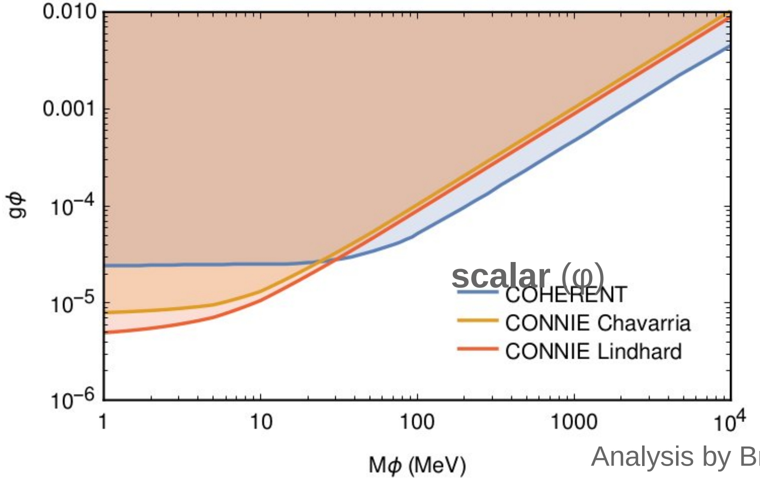
Community milestone

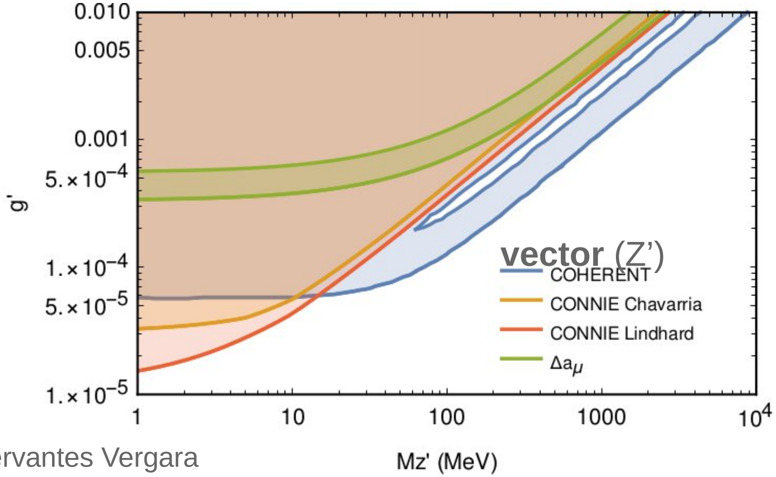
$$\frac{d\sigma_{SM+\phi}}{dE_R}(E_{\bar{\nu}_e}) = \frac{d\sigma_{SM}}{dE_R}(E_{\bar{\nu}_e}) + \frac{G_F^2}{4\pi}Q_\phi^2\left(\frac{2ME_R}{E_{\bar{\nu}_e}^2}\right)MF^2(q)$$

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

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

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





Analysis by Brenda Cervantes Vergara

Skipper-CCD event selection

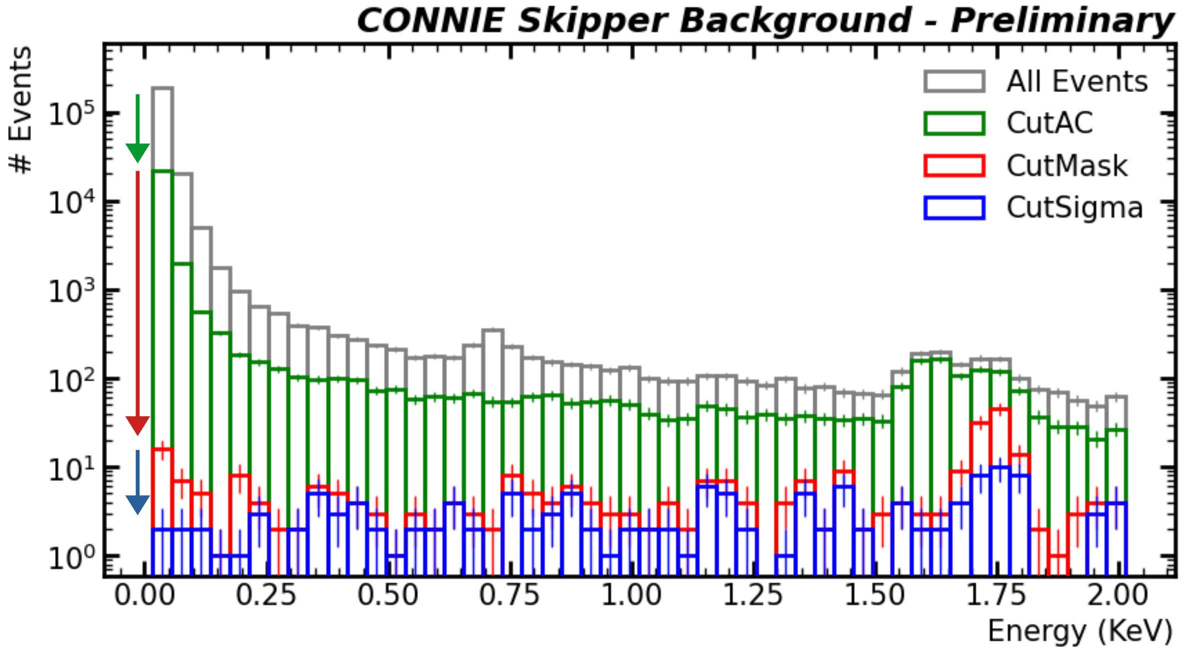
Preliminary

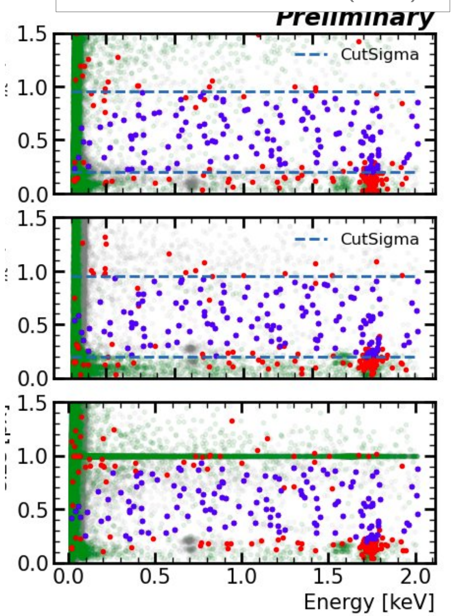
Selection cuts for Reactor-OFF data:

⌐ **S**ingle **E**lectron **R**ate

- **All Events:** E threshold 15 eV & Noise < 0.164 e- & SER < 0.1 e-/pix/day (performance cut);
- **CutAC:** Edge of 10 pixels in the active region;
- **CutMask:** Global (SRE Mask + HotPix Mask + MasterHot_RC + MasterHot_Pix);
- **CutSigma:** $\sigma^{X}_{FIT}|\sigma^{Y}_{FIT}$ = 0.2 - 0.95 pixel.

0.2- limited by our reco-algo
0.95- same as in 2019 (PCC)





The CONNIE experiment

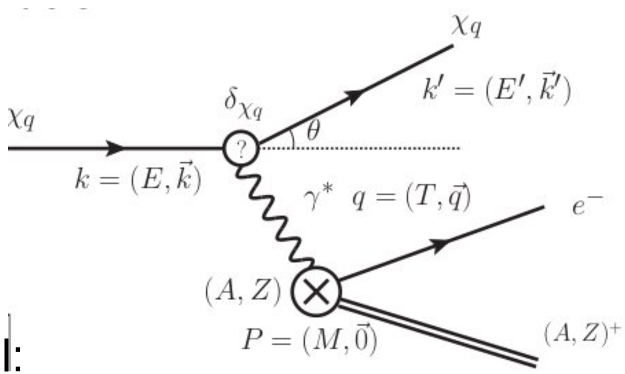
Located in the Almirante Alvaro Alberto nuclear plant near Rio de Janeiro, Brazil.

Outdated

Search for Millicharged particles

arXiv: 2405.16316

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



$$\frac{d\sigma_R}{dE} = z^2 \frac{2k_R}{\beta^2}\left(\frac{1-\beta^2 E/E_{max}}{E^2}\right)$$

$ze \rightarrow \epsilon e$

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

Modeling the Form Factor with the Photo Absorption Ionization model:

Transverse | Longitudinal

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

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

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

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

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

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

Search for millicharged particles

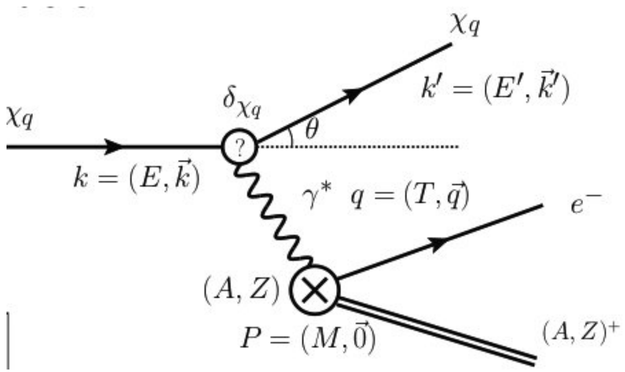
- Relativistic millicharged particles (χ_q), predicted in SM extensions with hidden sectors.

Production: Compton-like scattering of high energy γ's from reactors.

γ energy spectrum gives diff, flux. of χ_q :

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

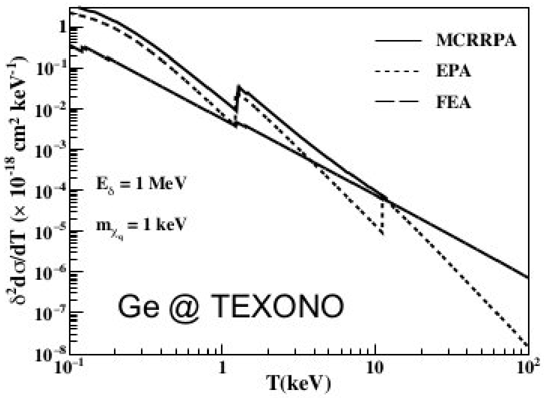
Detection: Atomic Ionization (t-channel).

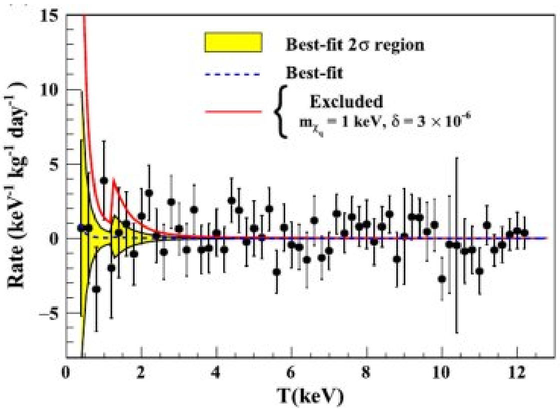


Diff. count-rate expected at detector:

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

Consider several models of the interaction cross-section





- On-Off spectrum can yield limits to χ_q production in reactors.
- **Preliminary** Search for χ_q in the CONNIE low-E data.

TEXONO collab., PRD 99, 032009 (2019)