Upgraded CONNIE experiment with Skipper CCDs

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for the CONNIE Collaboration

August 29, 2023

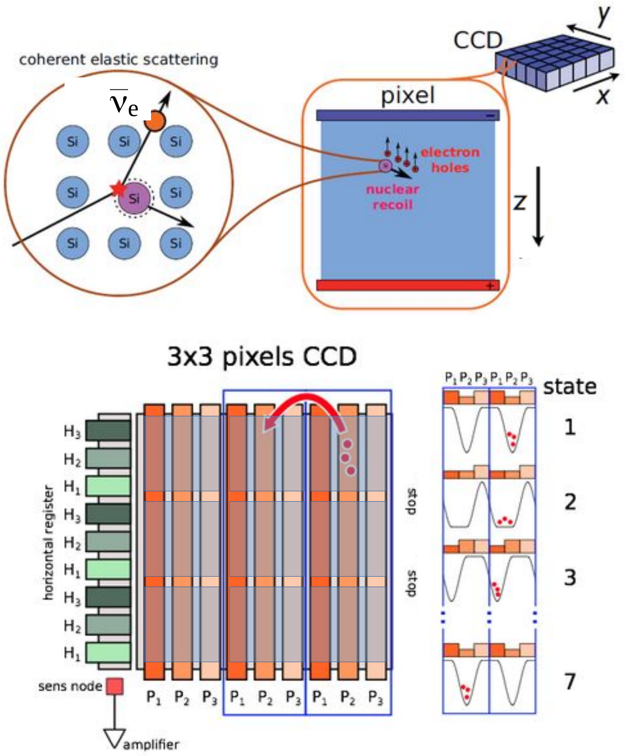
XVIII International Conference on Topics in Astroparticle and Underground Physics (TAUP2023), University of Vienna, Vienna, Austria

The CONNIE experiment

- Coherent Neutrino-Nucleus Interaction Experiment (CONNIE)
- 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).

  - Charge is collected in potential wells and read out sequentially
  - Charge diffusion allows for 3D reconstruction (depth-size rel.)
  - Low noise (~2 e-) and low dark current (~3 e-/pix/day) *
  - Low-energy detection threshold (~50 eV)*

  * with standard CCDs

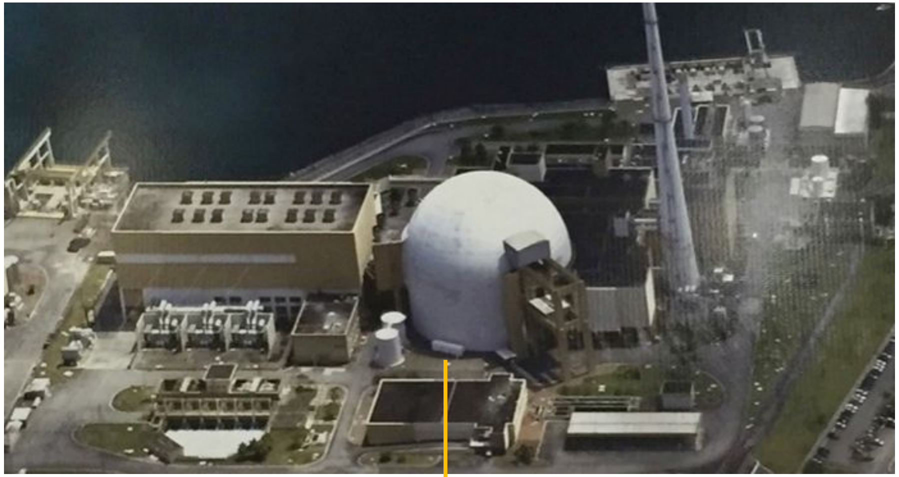


The CONNIE Collaboration

Centro Atómico Bariloche, Universidad de Buenos Aires, Universidad del Sur / CONICET, Universidad Nacional de San Martín, 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 [*15 inst, 6 count.*]

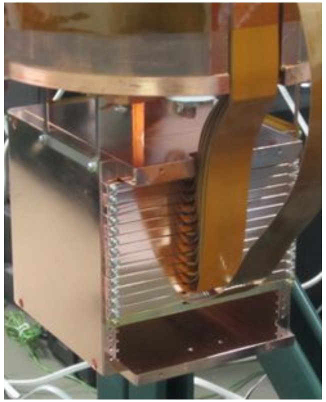
The CONNIE experiment

- 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 $\sim 7.8 \times 10^{12}\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$.
- Shares lab with the "Neutrinos Angra" experiment.

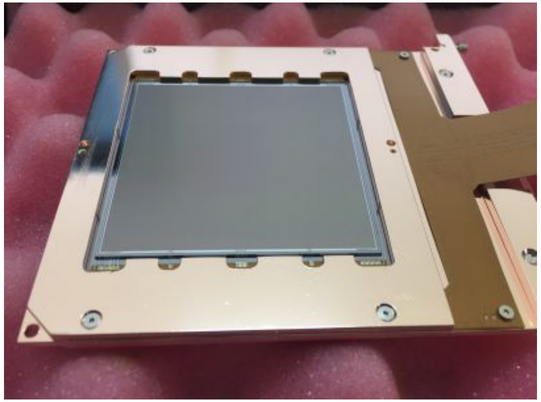


The CONNIE detector

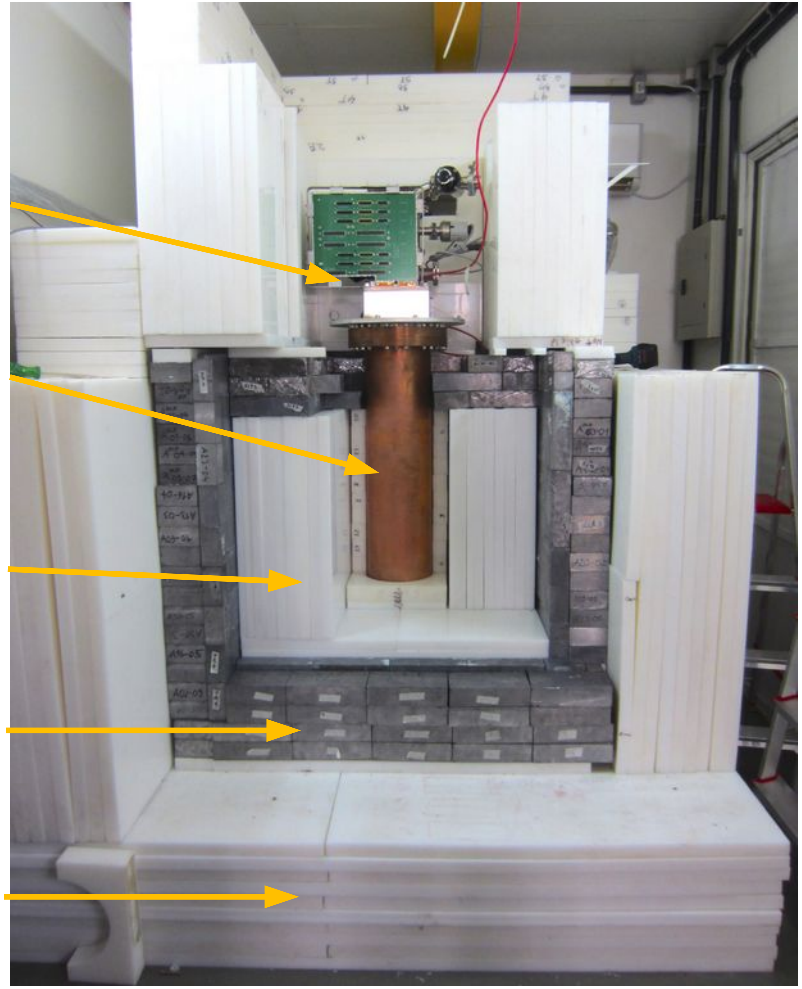
Installed in 2014. Upgraded in 2016



CCDs in copper box (2016 Upgrade)



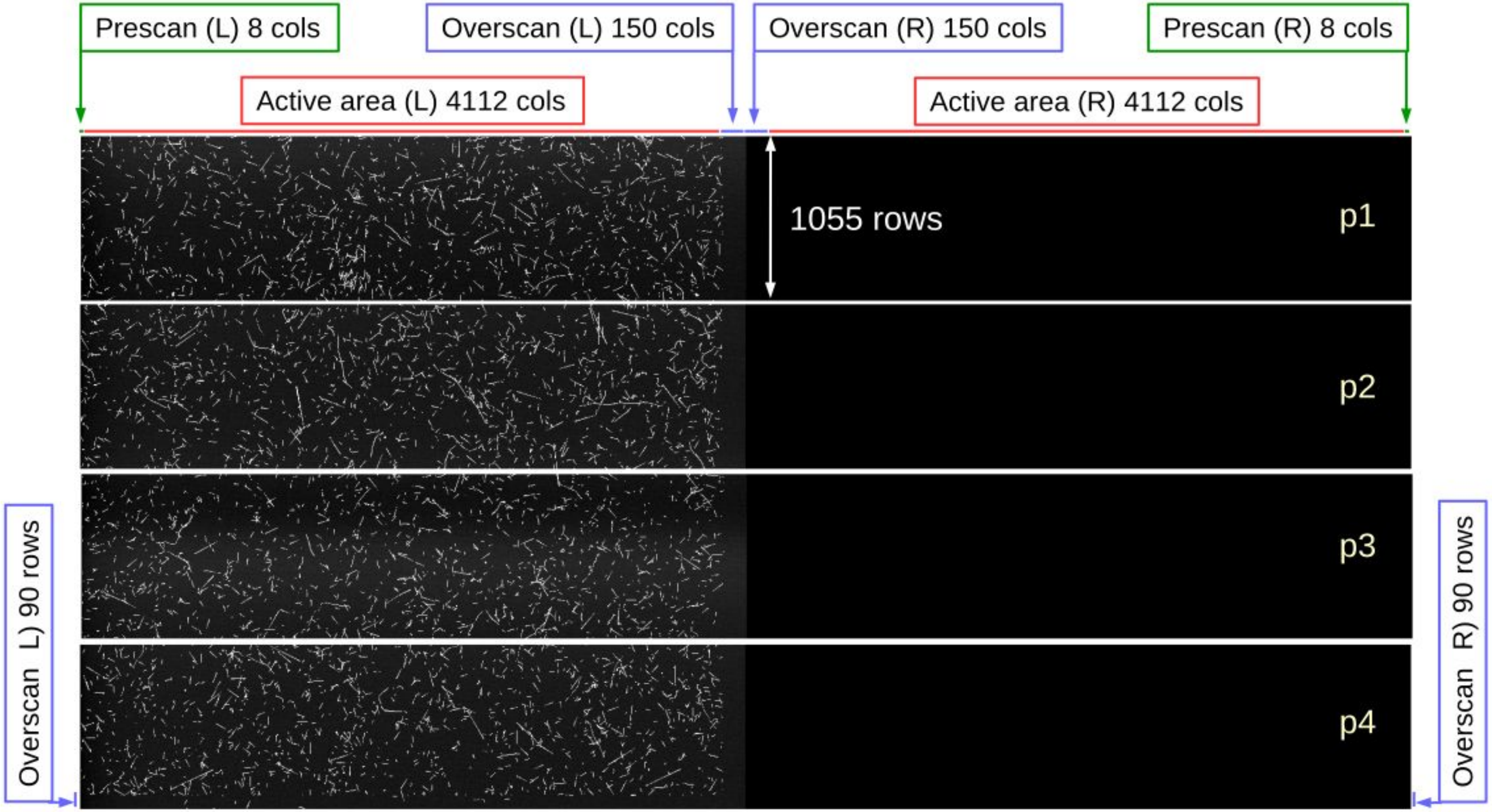
4k × 4k, 15 μm × 15 μm pix, 675 μm thick standard CCD



Engineering run:
JINST 11 (2016) P07024

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

Images (1x1 DAQ, 2016-2018)



Candidate event

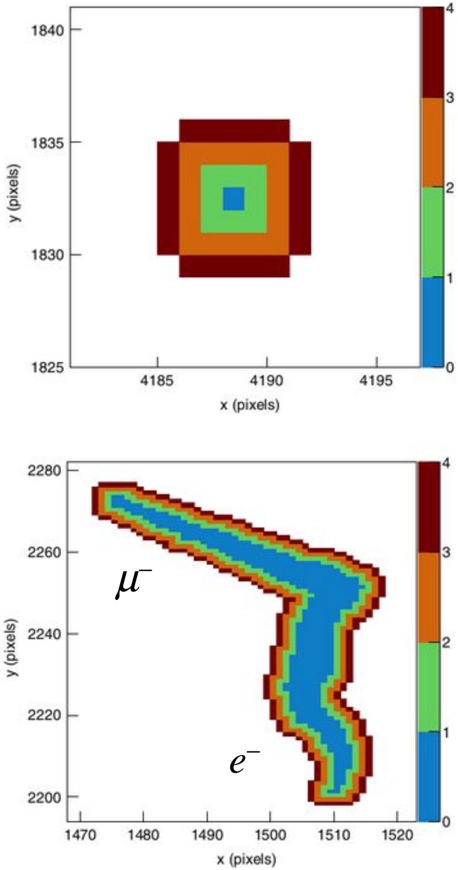


Image processing to reduce noise. Events extracted into catalogs.

CONNIE timeline

Community milestone — NEUTRINO 2020

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

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

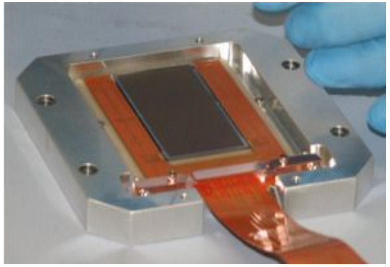
Results from 2016-2018 run **[PRD 100 (2019), 092005]**

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

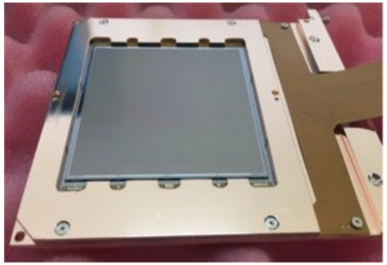
2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023

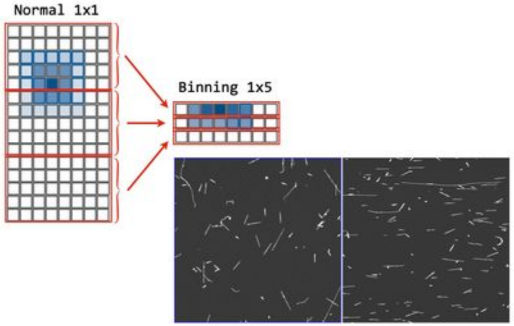
- Engineering Run
- 2016-2018 (1x1) Run
- 2019 (1x5) Run
- Skipper-CCD Run

Instalation at Angra

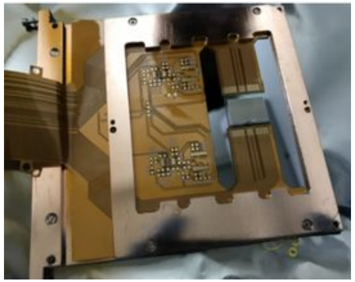


Upgrade to Scientific CCDs





Installation of Skipper-CCDs

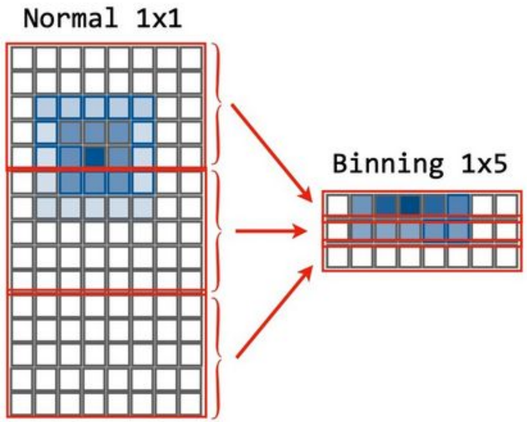


CONNIE 2019 run

JHEP 05:017, 2022

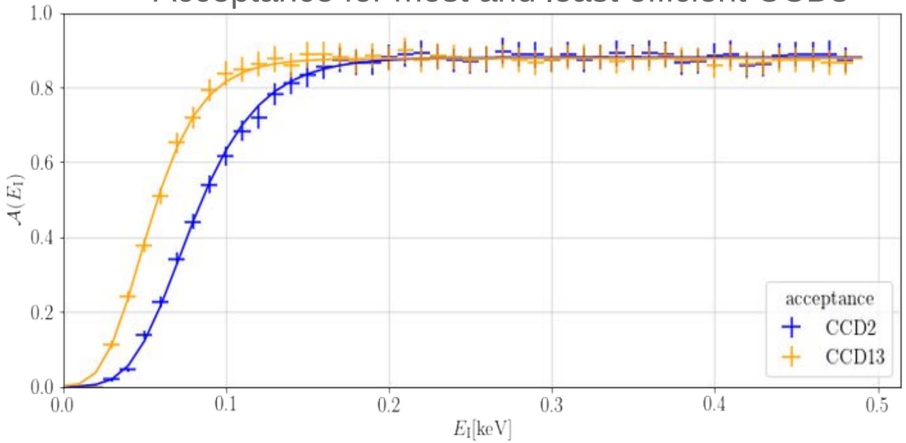
Improvements in data acquisition and analysis techniques:

- 1x5 pixel hardware rebinning reduces readout noise.
- Improved energy and size-depth calibrations
- Low-energy background characterization and reduction.
  - 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.

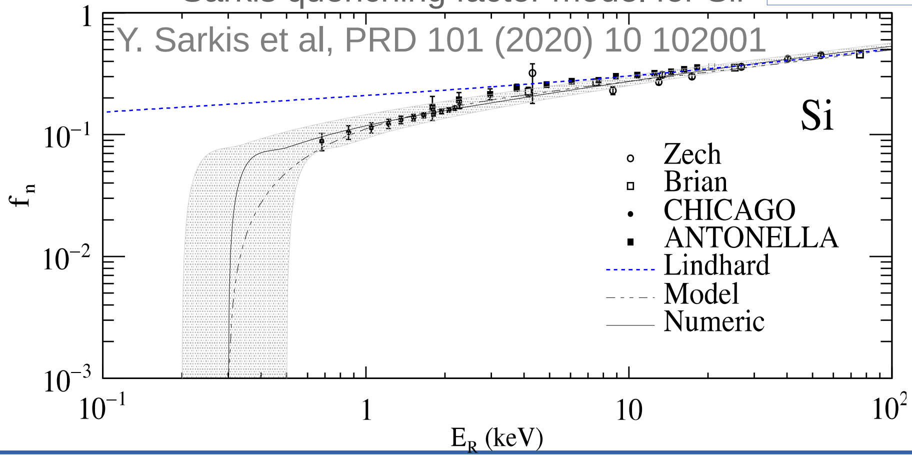


See Y. Sarkis.talk on Low-E Si QF.

Acceptance for most and least efficient CCDs



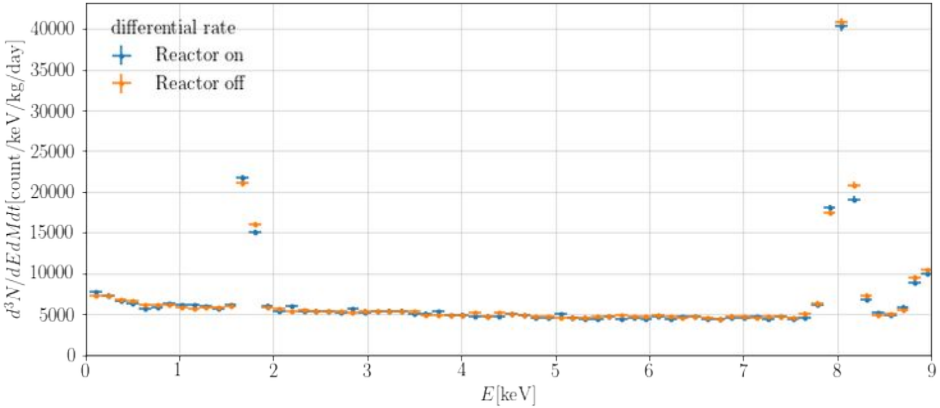
Sarkis quenching factor model for Sii

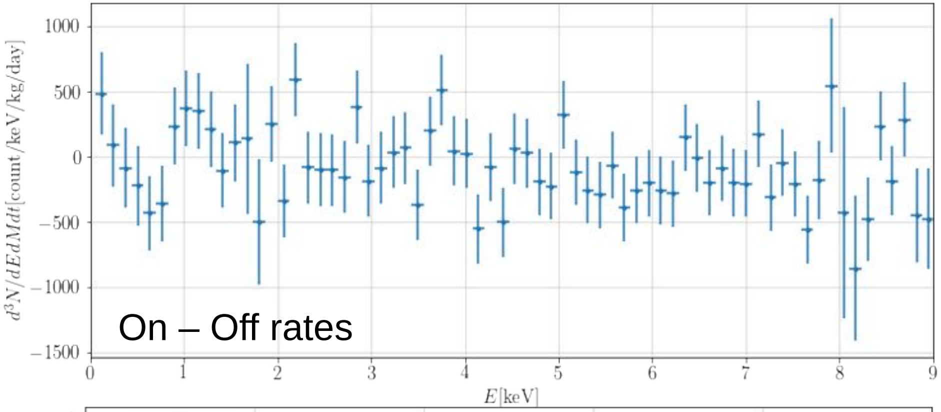


CONNIE 2019 results

JHEP 05:017, 2022

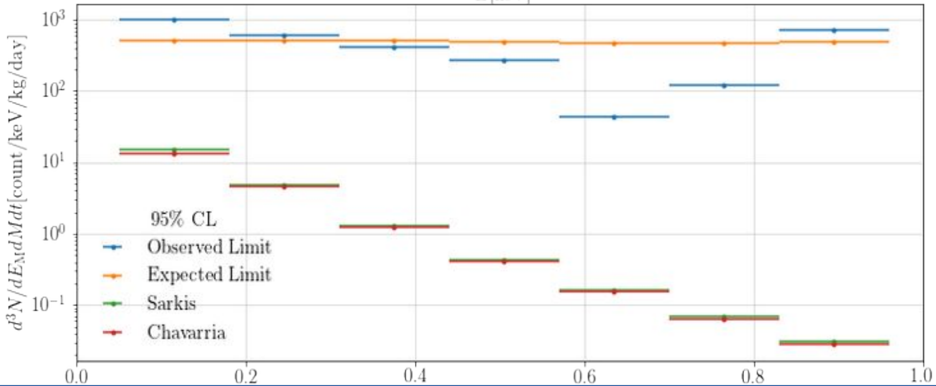
- Energy spectrum from 8 CCDs with total active fiducial mass of 36.2 g.
- Exposures of 31.85 days (reactor on) and 28.25 days (reactor off).
- Total exposure: 2.2 kg-days.





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.



Search for millicharged particles

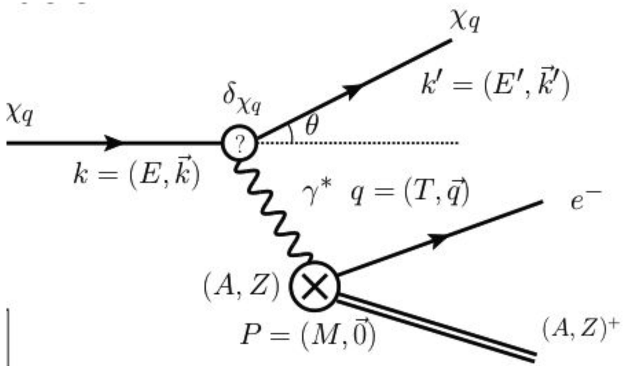
- Relativistic millicharged particles (χ_q), predicted in SM extensions with hidden sectors.

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

γ energy spectrum gives diff, flux. of χ_q :

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

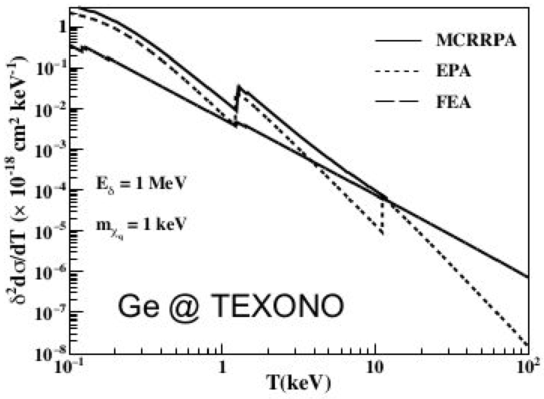
Detection: Atomic Ionization (t-channel).

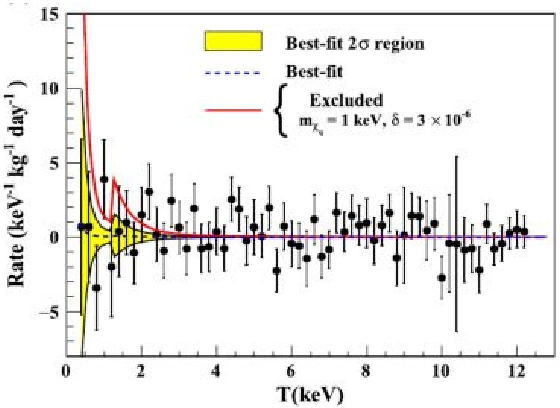


Diff. count-rate expected at detector:

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

Consider several models of the interaction cross-section





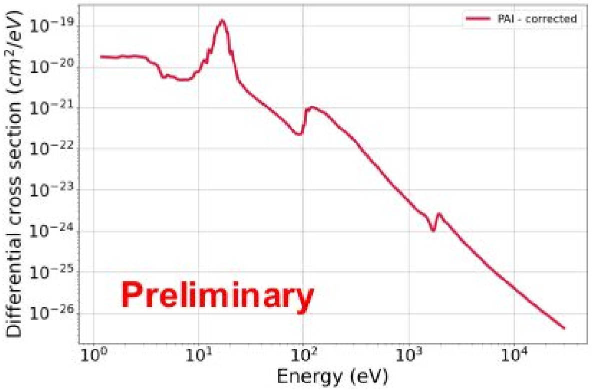
- On-Off spectrum can yield limits to χ_q production in reactors.
- **Preliminary** Search for χ_q in the CONNIE low-E data.

TEXONO collab., PRD 99, 032009 (2019)

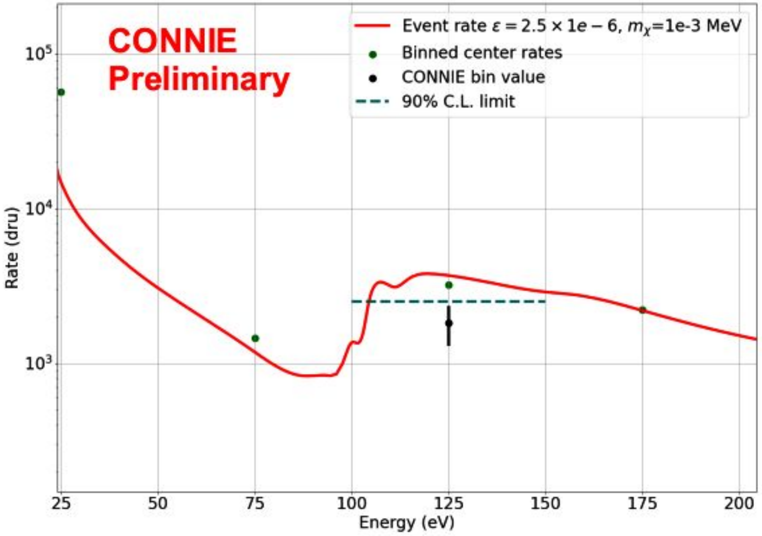
Search for millicharged particles

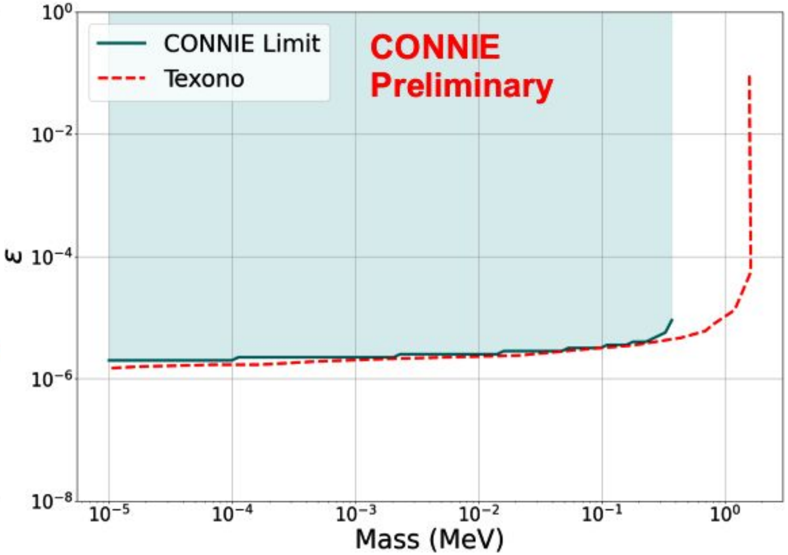
- Interacton with silicon from the Photo Absortion Ionization (PAI) model.

Differential PIA cross-section for Si



- 90% CL limit on χ_q production at reactors obtained for each mass, from the 100-150 eV bin in the 2019 data.
- Comparable to TEXONO. Will be updated with more data.





Plots by
Santiago Pérez &
Darío Rodrígues

CONNIE with Skipper-CCD's

See talk by M. Cababie
30 Aug,, 17:45, Hörsaal 21

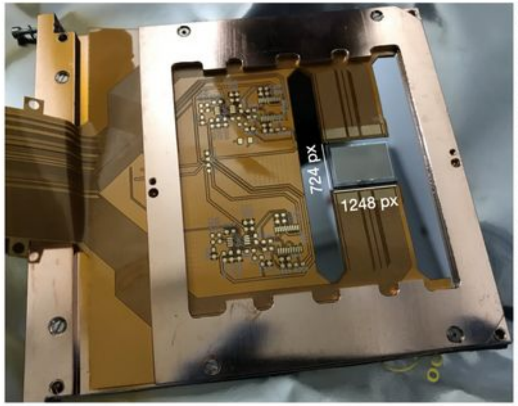
Skipper-CCDs

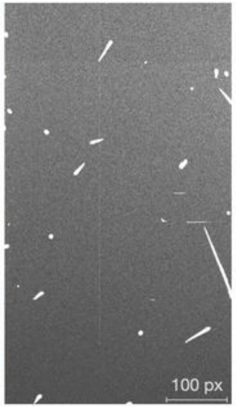
J. Tiffenberg et al, PRL 119 (2017)
G. Cancelo et al, JATIS 7, 1, 015001 (2021)

- Identical to standard CCDs regarding substrate, gate structure and channel stops. ***Different readout stage***.
- Allows repeated charge measurements → precise average.
- Capable of counting individual electrons.

Two Skipper-CCDs installed in the CONNIE cryostat, July 2021.

- 0.7k x 1.2k pixels ea, 675 µm thick, ~0.5 g total mass.
- New electronics LTA "*Low Threshold Acquisition*".
- New Vacuum Interface Board (VIB).





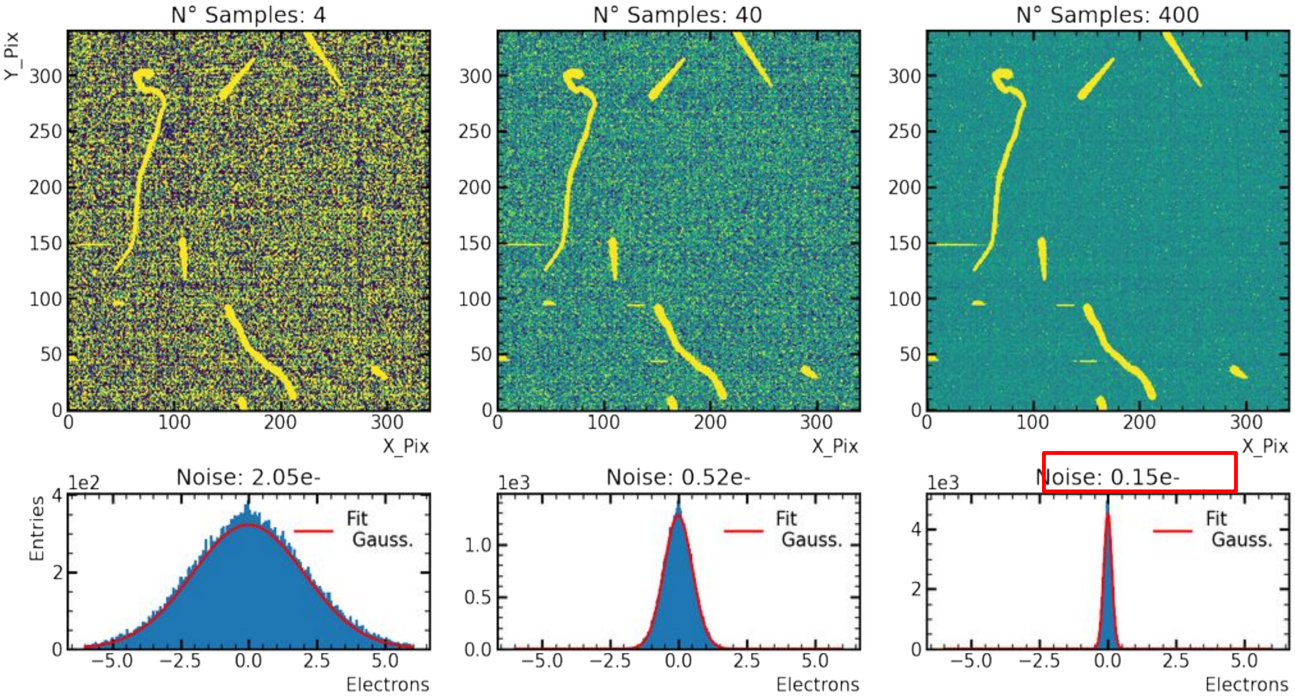
LTA electronics

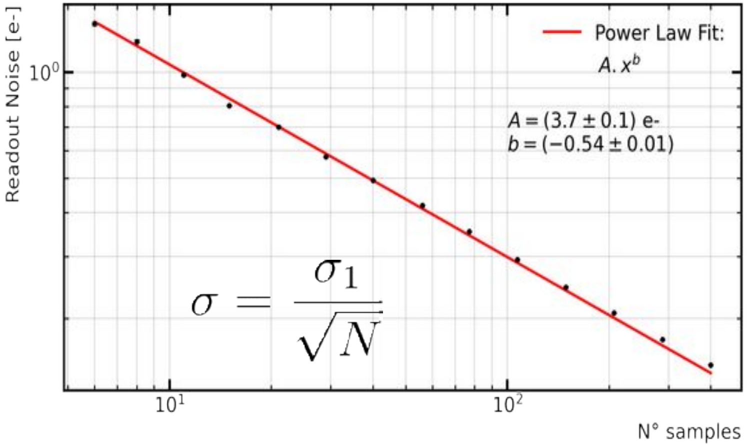
Skipper-CCD performance

Preliminary

- Characterized performance and noise level.
- Tested LTA electronics and readout mode for Skipper-CCDs.
- Readout noise reduced with N samples.

Plots by Pedro Ventura





$$\sigma = \frac{\sigma_1}{\sqrt{N}}$$

Continuous readout mode:

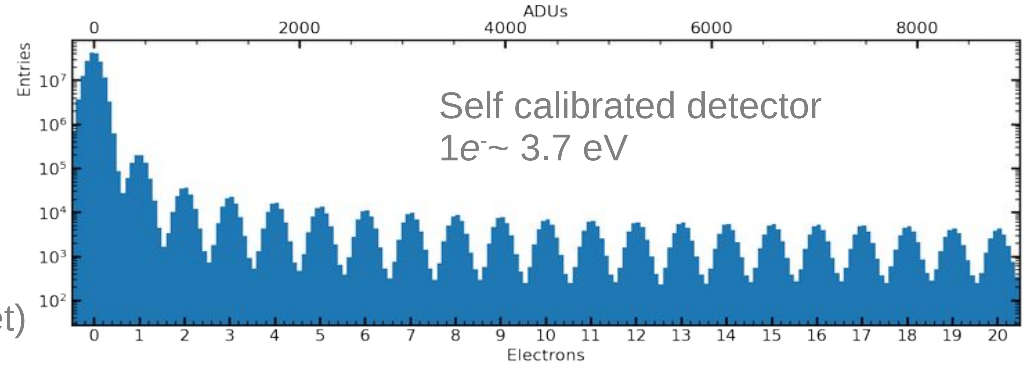
- Large # of samples → long readout time
- Exposure acquired during readout.
- Exposure time ~ ½ Readout time.

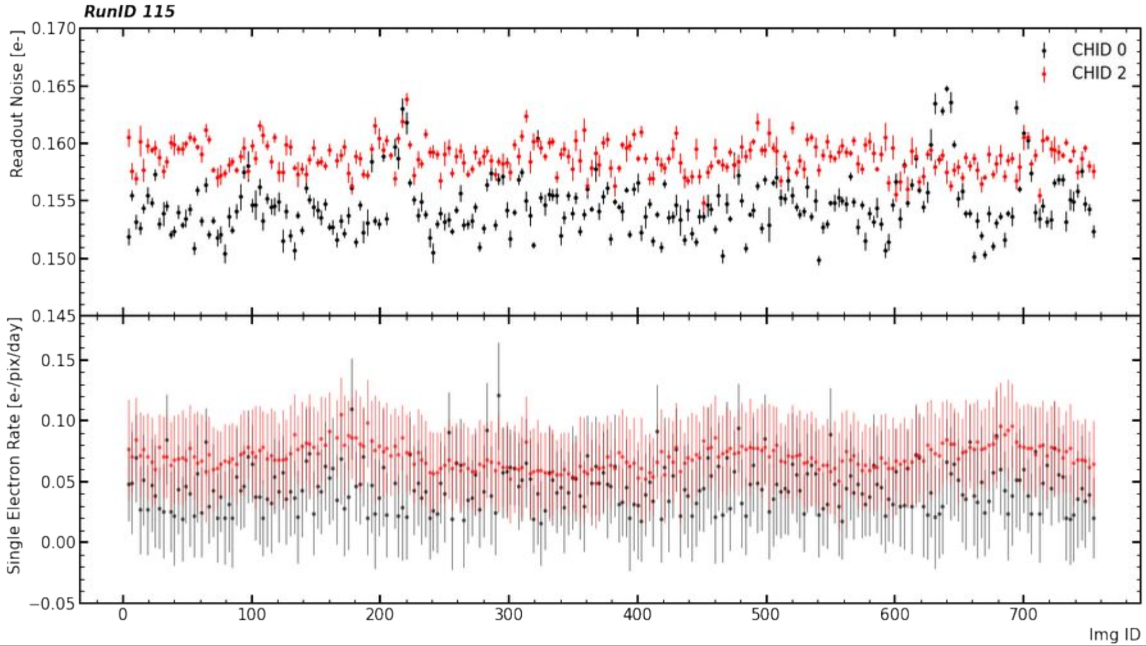
Skipper-CCD performance

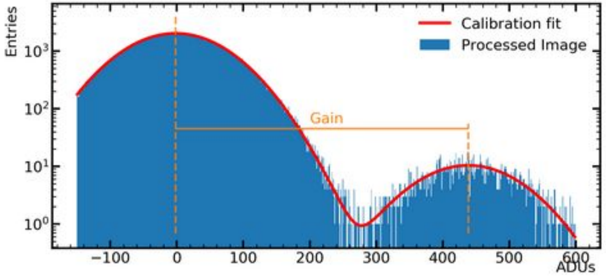
Preliminary

- Energy calibration and linearity
- Measurements of dark current and noise
- New event extraction algorithms.

Noise = 0.16 e-
Single-e^- rate = 0.05 e-/pix/day (good for a surface det)







Modulation of single-e^- rate can probe certain DM candidates

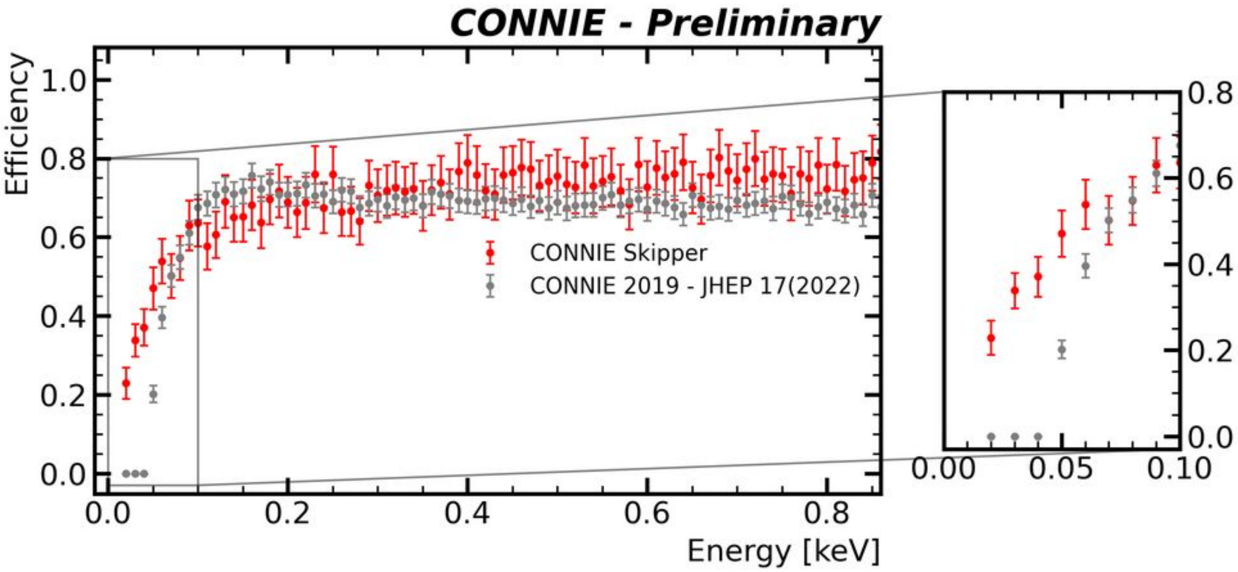
See talk by N. Avalos on DMSQUARE experiment, 29 Aug, 14:30, BIG-Hörsaal.

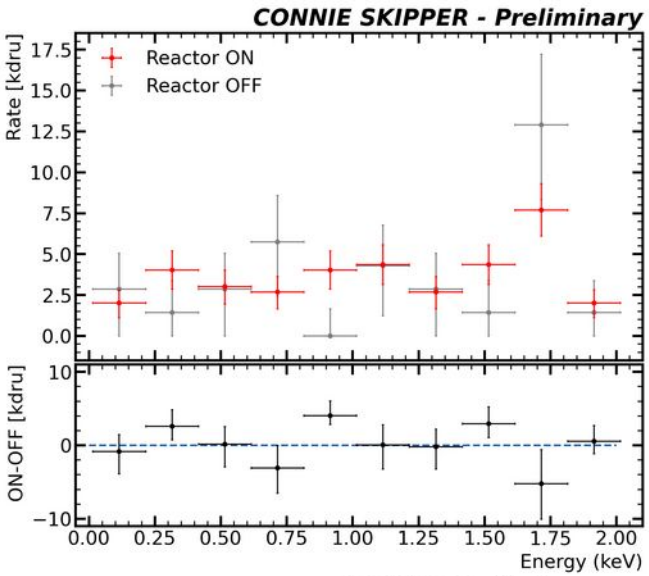
Plots by Pedro Ventura

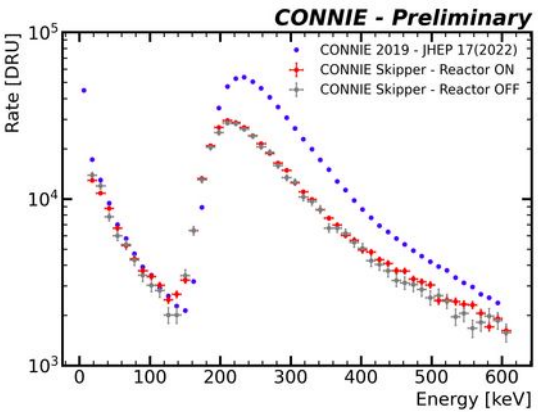
Skipper-CCD results

Preliminary

- Improved Low-E detection efficiency.
- Exposures (active mass ~0.1 g per CCD ×2):
  - Reactor-ON : ~15 g·day, exp time ~75 days, RO time: ~5 mo.
  - Reactor-OFF: ~3.5 g·day, exp time ~17 days, RO time: ~1.1 mo.
- Low-E bkgd (reactor off): ~3.2 kdru. Threshold ~15 eV.
- Flat background and Flat reactor ON-OFF spectra.





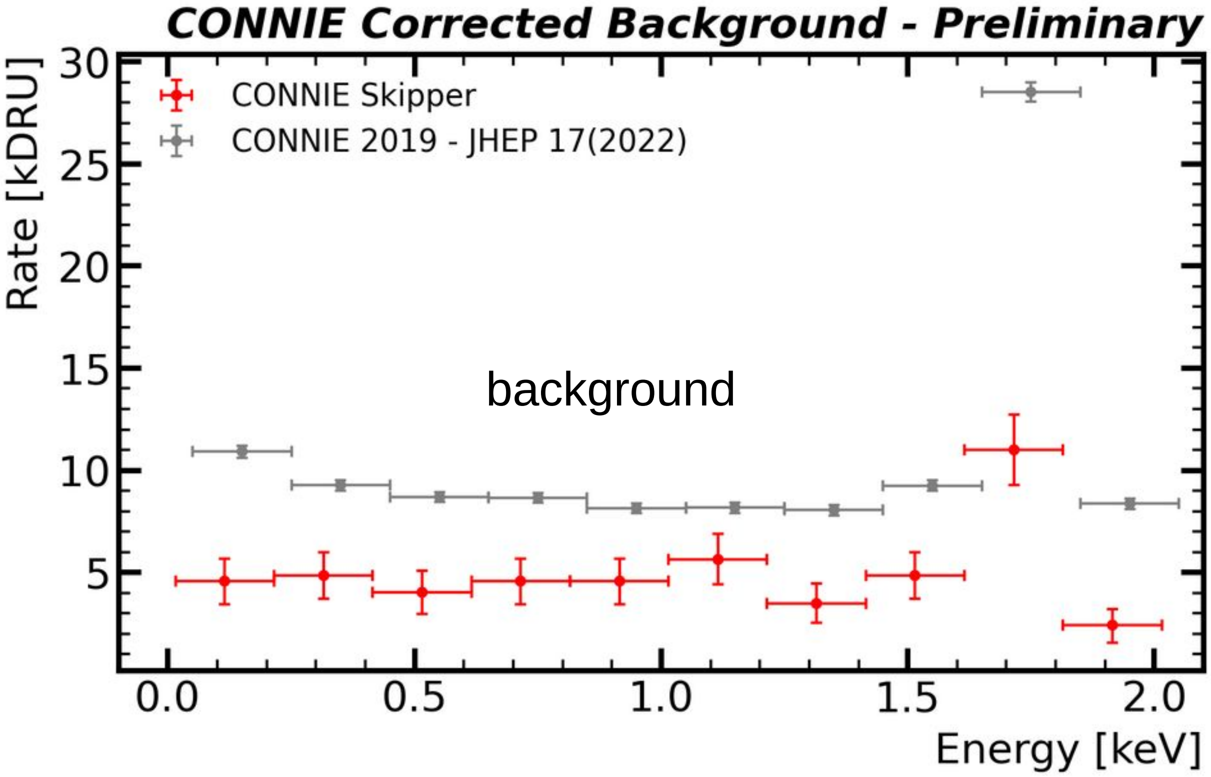


Plots by Pedro Ventura

Skipper-CCD improved background

Preliminary

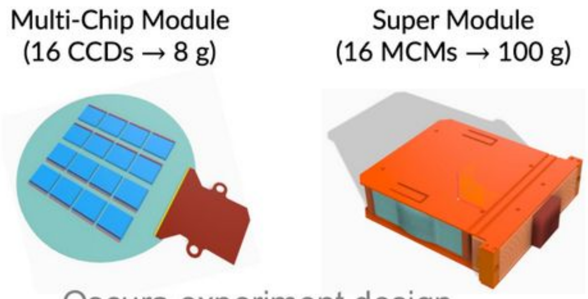
- Neglecting the CEvNS contribution **(Skipper CCD is small)**
- Reactor ON+OFF spectra gives better estimate of the background.
- Higher statistics sample shows a **flat spectrum** down to the threshold of 15 eV
- Background lower by a factor of 1.6 - 2



Plots by Pedro Ventura

CONNIE future perspectives

- Assuming a 20 eV threshold, we expect a CEνNS rate 2.2 times higher than in 2019.
- A 1 kg detector at the CONNIE site, with a bkgd rate of 4 kdru should observe CEνNS at 90% C.L. ~2 months (Chavarria QF).
- Current plan is to increase the sensor mass using the Oscura MCM design.
- Considering a larger increase in scale in the future.

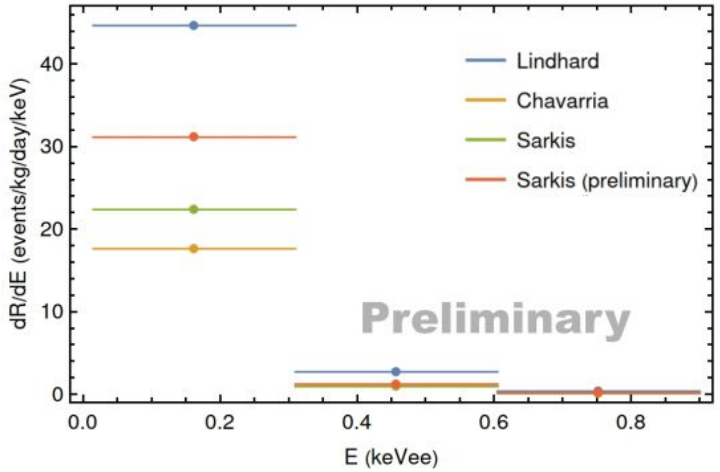


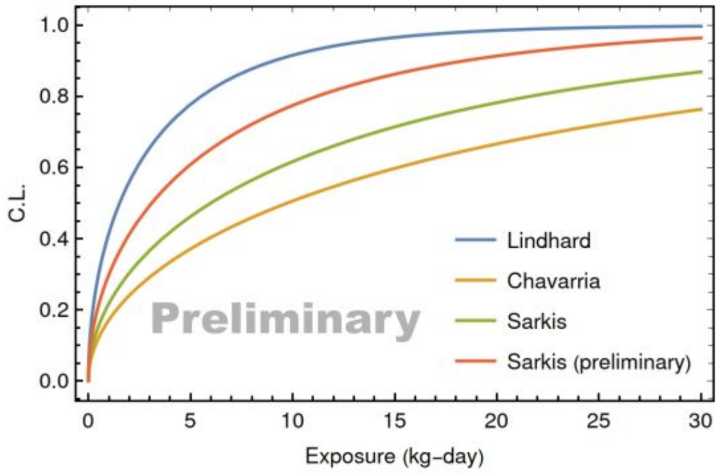
Oscura experiment design

See talk by N. Saffold on Oscura 28 Aug, 15:45, BIG-Hörsaal.

[arXiv:2304.04401]

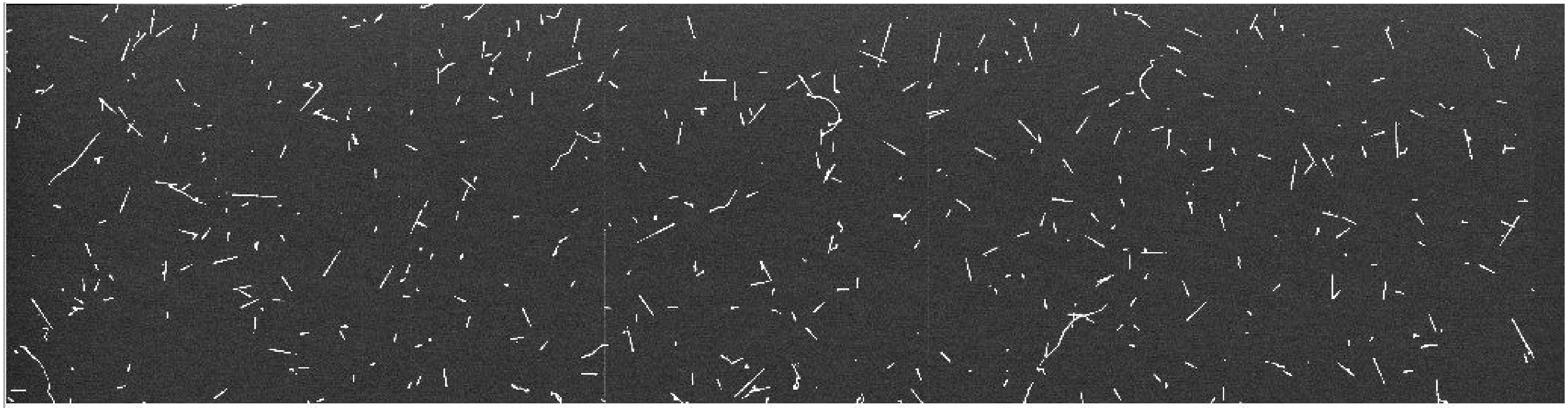
- Negotiations with Angra underway to move at 20 m from core (inside dome)





Summary and outlook

- CCDs are a promising technology for detecting CEvNS at low energies.
- Preliminary results using 2019 data show competitive limits on millicharged particles. Will be updated with full data set.
- CONNIE was the first experiment to install Skipper CCDs at a reactor, in 2021.
- Excellent skipper-CCD performance with improved efficiency and background levels.
- Prospects to increase the sensor mass and move inside the Angra 2 reactor dome.

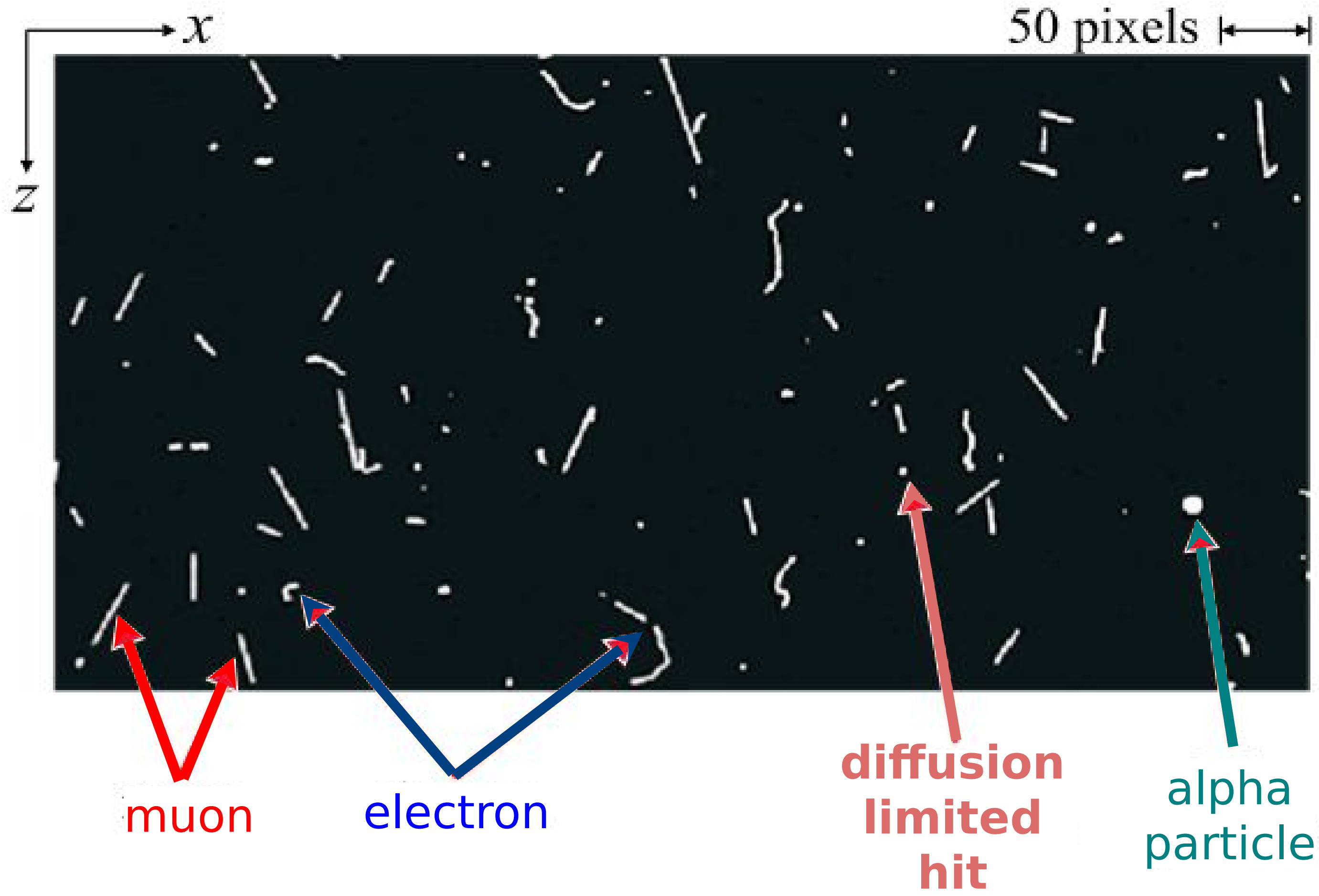


AAA acknowledges support from DGAPA-UNAM grants PAPIIT-IN106322 y PAPIIT-IN104723, and CONACYT grant CF-2023-I-1169

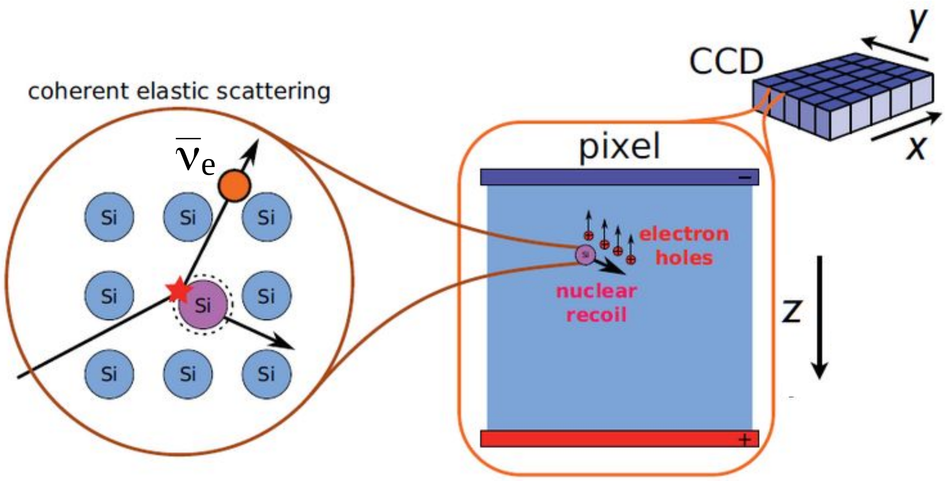
Thank you for your attention!

BACKUPS

CCD particle identification



CCD as a particle detector

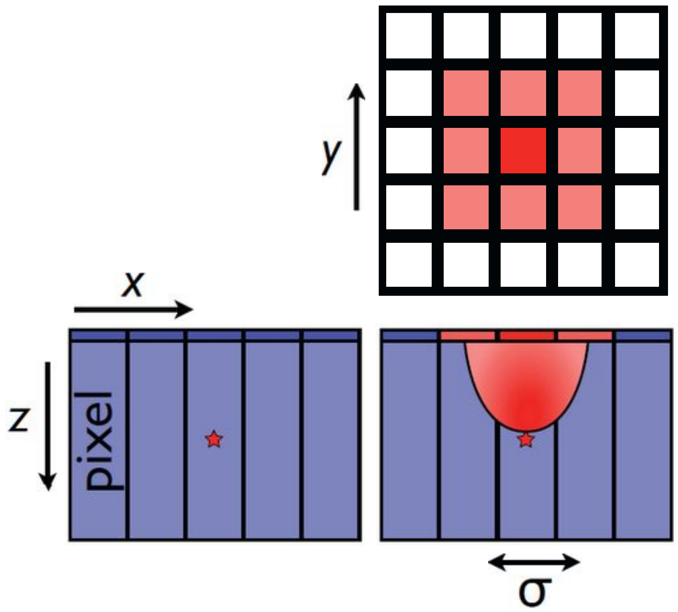


The scattering of the ν with a Si nucleus leads to ionization

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

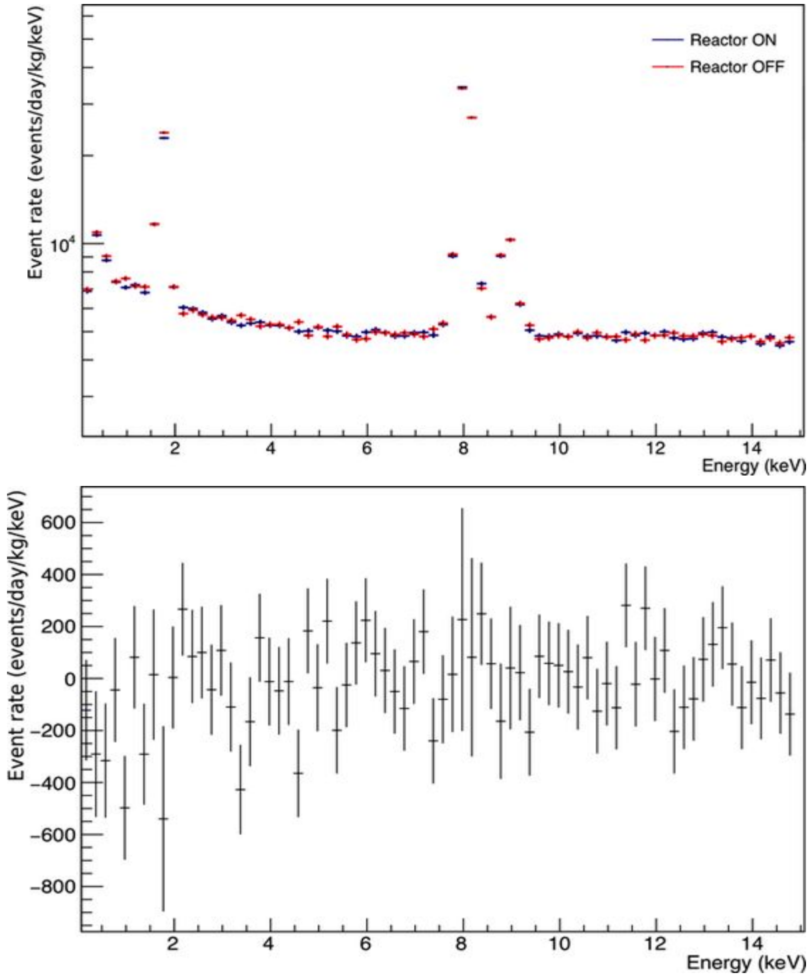
Charge diffuses in *x*-*y* plane as it drifts towards the gates

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

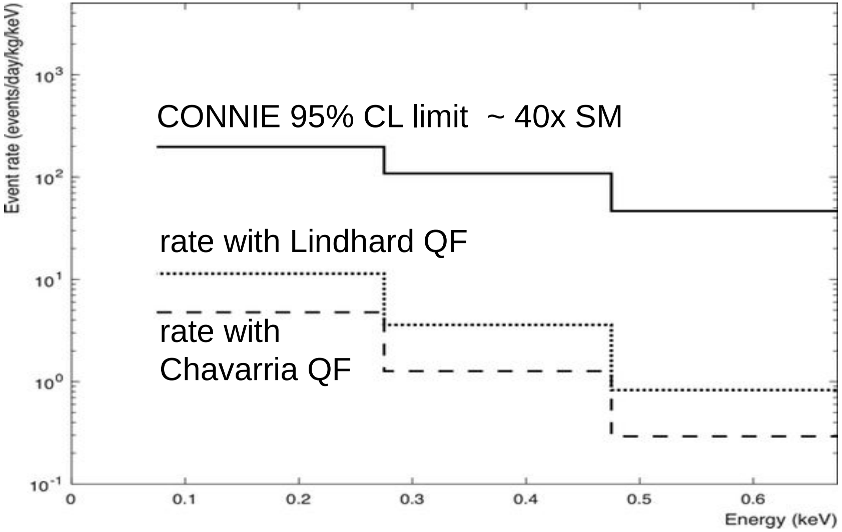


CONNIE results 2016–2018

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.



Constraints to physics BSM

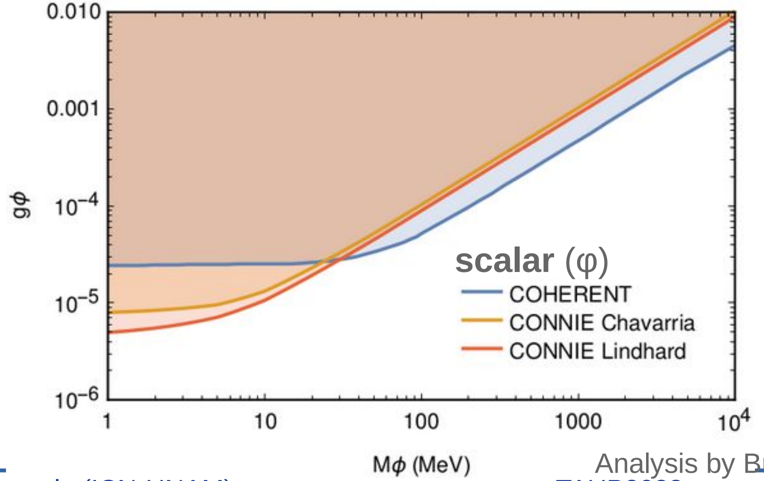
JHEP 04 (2020), 054

- 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_φ < 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

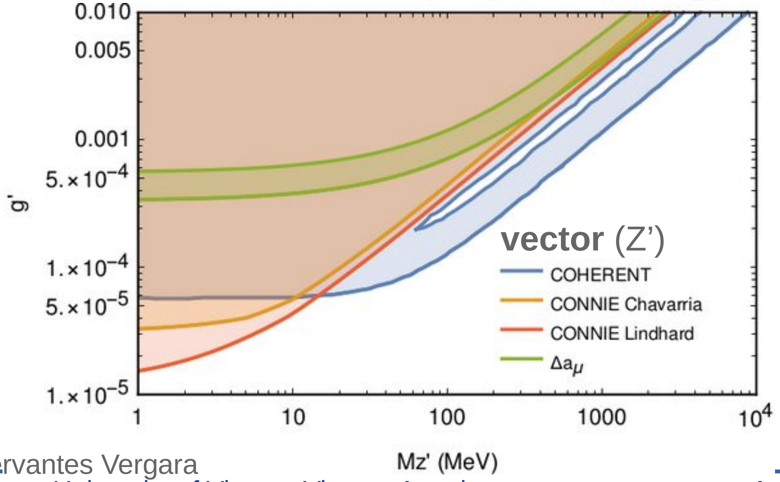
$$\frac{d\sigma_{SM+\phi}}{dE_R}(E_{\bar{\nu}_e}) = \frac{d\sigma_{SM}}{dE_R}(E_{\bar{\nu}_e}) + \frac{G_F^2}{4\pi} Q_\phi^2 \left(\frac{2ME_R}{E_{\bar{\nu}_e}^2}\right) MF^2(q)$$

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



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

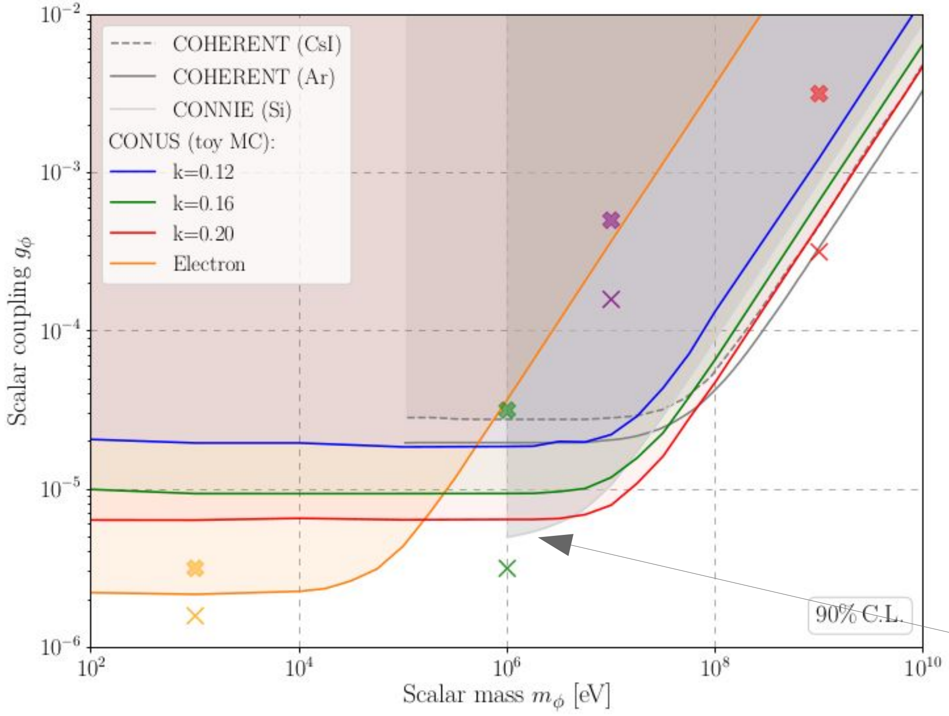
$$Q_{Z'} = \frac{3(N+Z)\, g'^2}{\sqrt{2} G_F (2ME_R + M_{Z'}^2)}$$



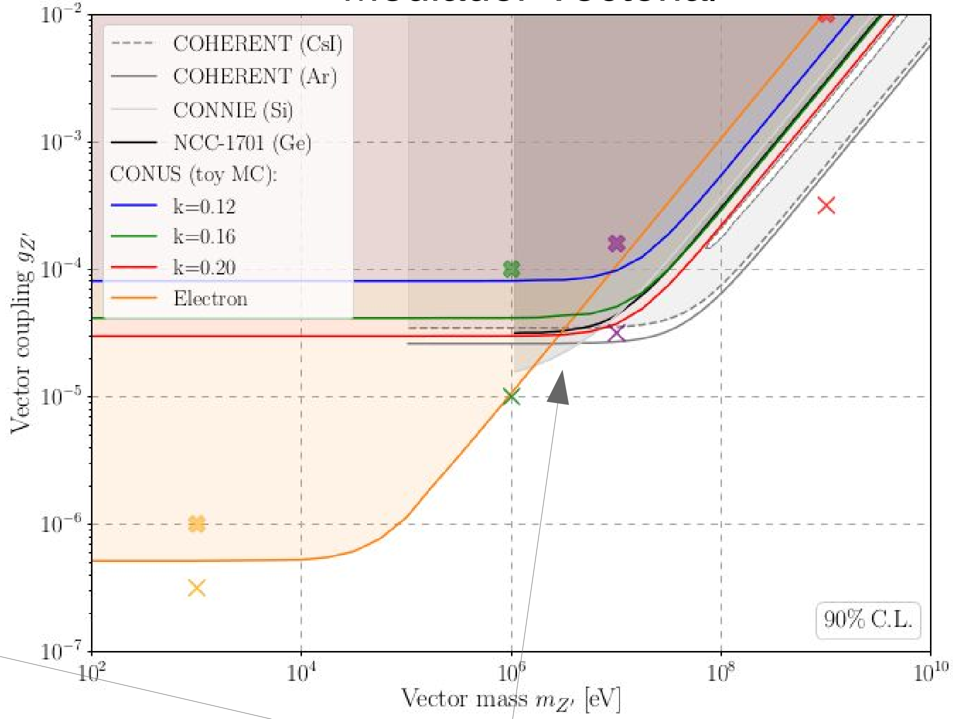
Analysis by Brenda Cervantes Vergara

Constricciones a física más allá del ME

Mediador Escalar



Mediador Vectorial



CONNIE aún mejor en esta región

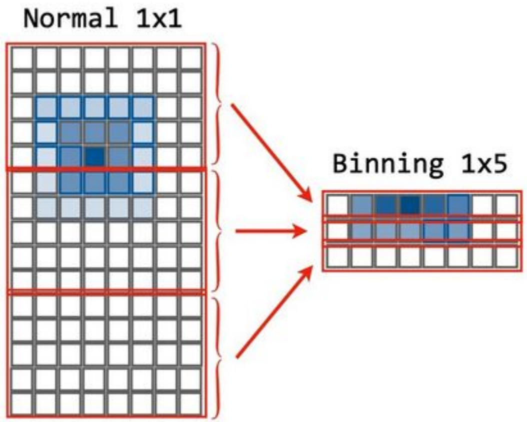
CONUS Collab. JHEP, 085, 05, 2022

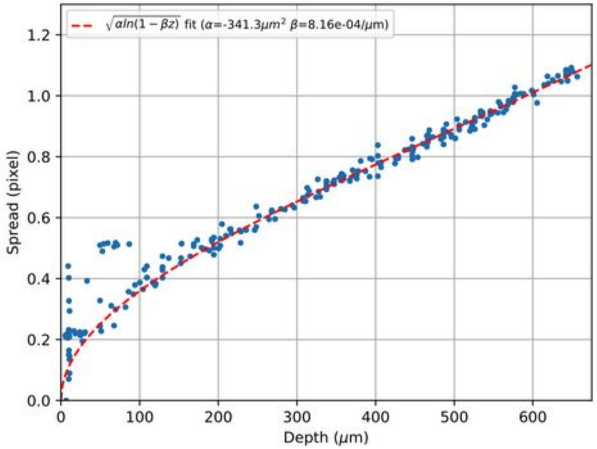
CONNIE 2019 run

JHEP 05:017, 2022

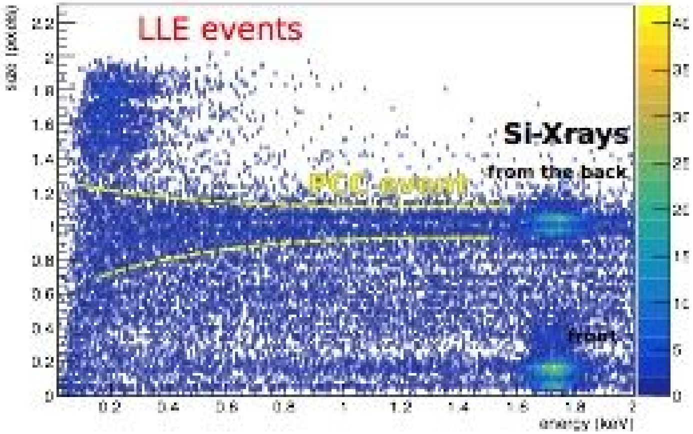
Improvements in data acquisition and analysis techniques:

- 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.



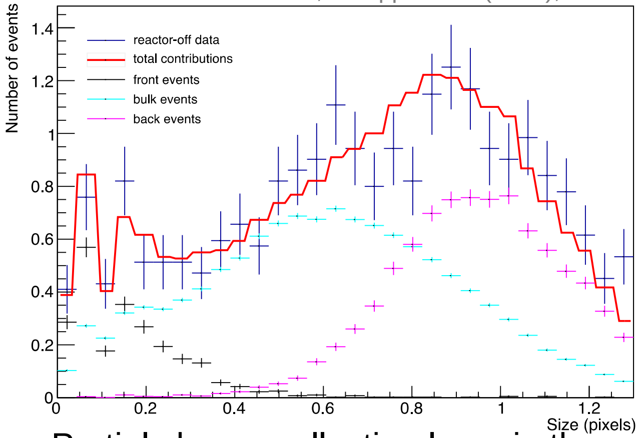


Depth-size muon calibration



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

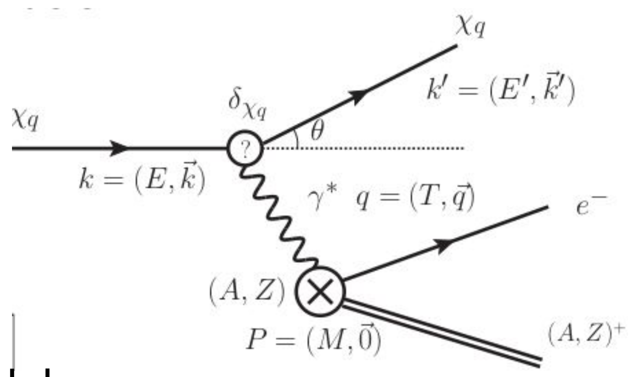
G. Fernandez-Moroni et al, PRApplied 15 (2021), 6 064026



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

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

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

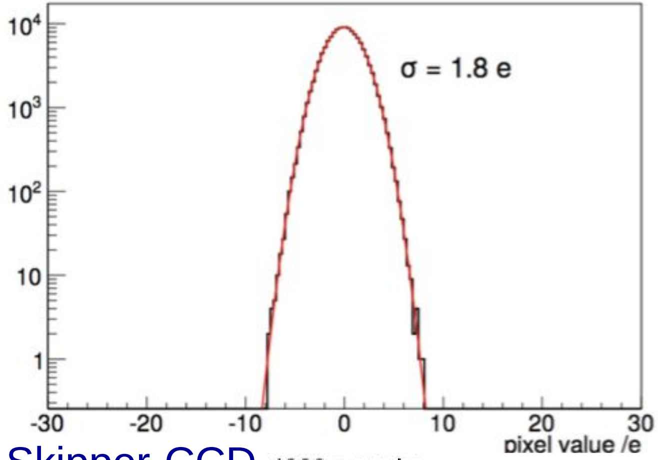
$$\frac{d\sigma_{mcp}}{dE} = \epsilon^2 \frac{d\sigma_{PAI}}{dE}$$

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

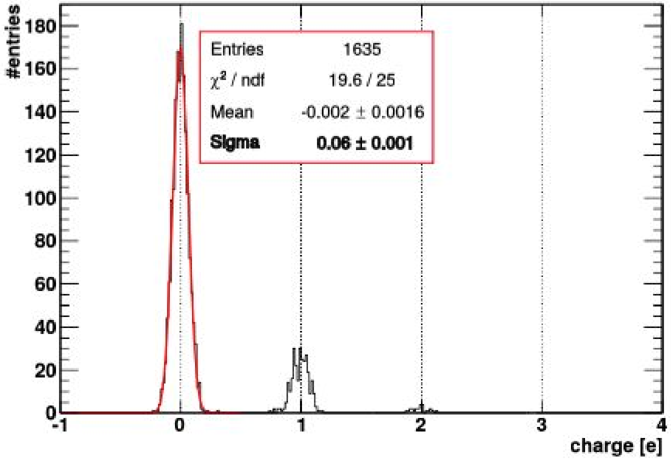
Skipper CCD

- 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



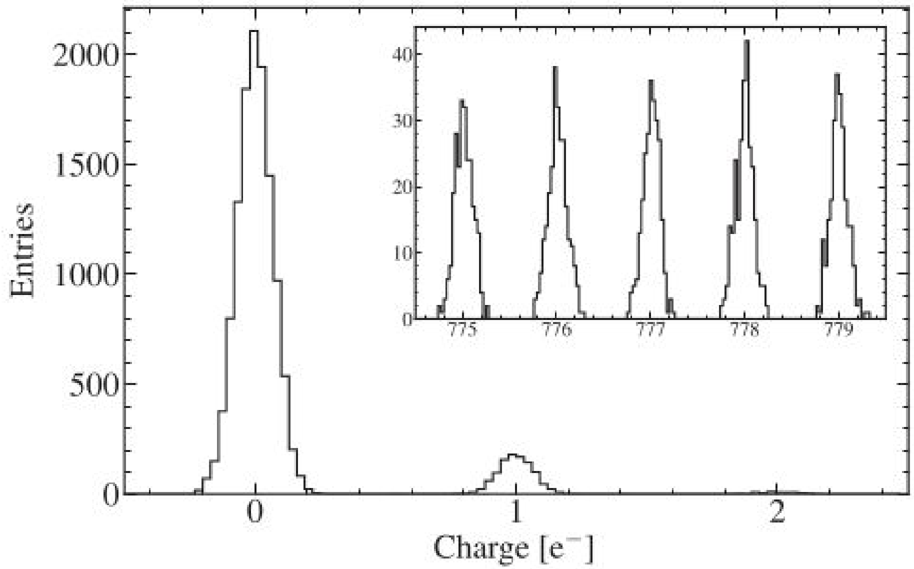
Skipper-CCD 4000 samples



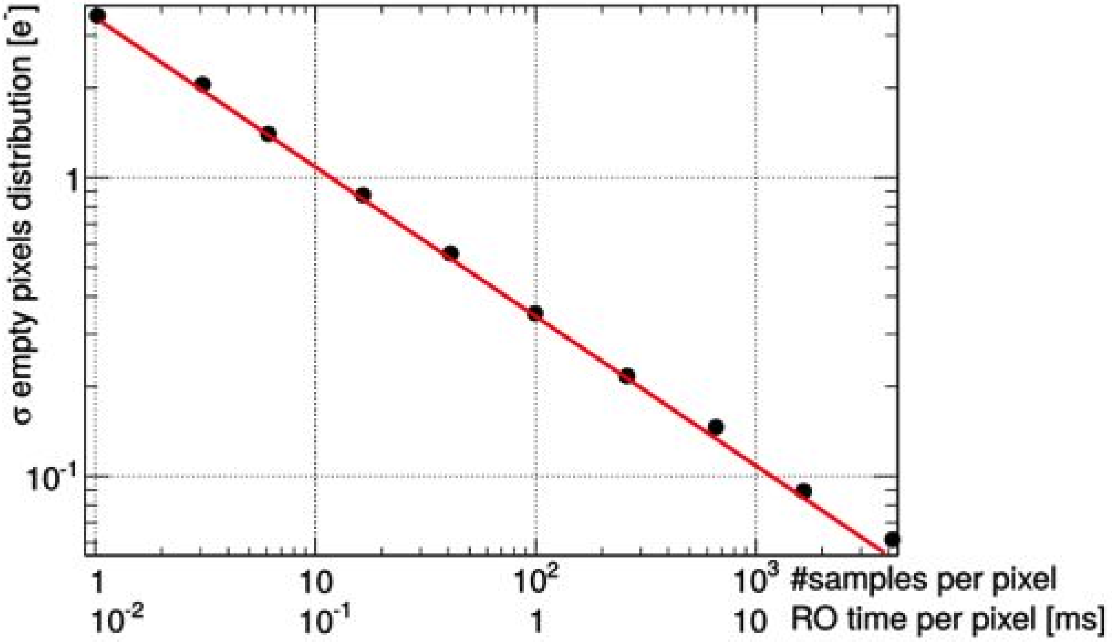
Sub-electronic readout noise

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

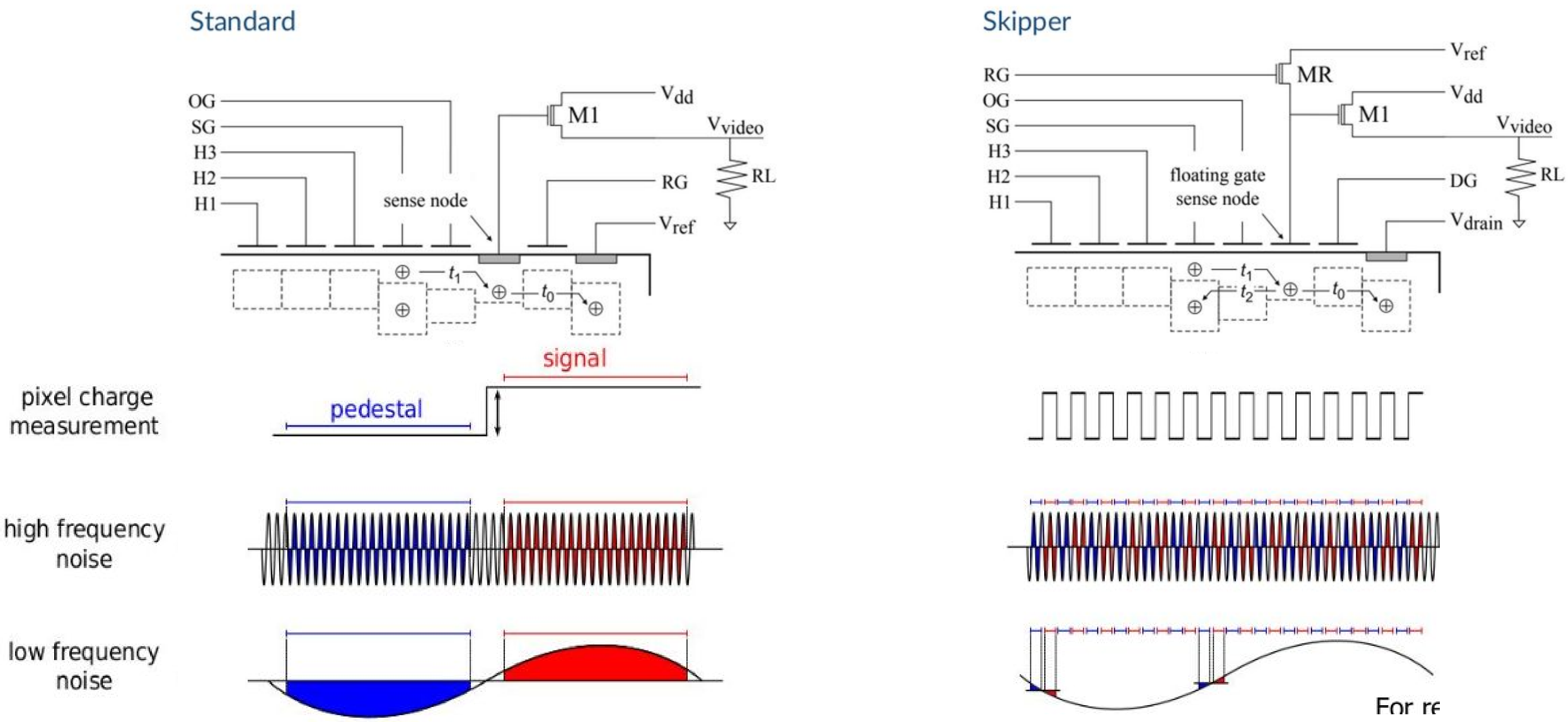
J. Tiffenberg et al, PRL 119 (2017)



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.

Skipper-CCD event selection

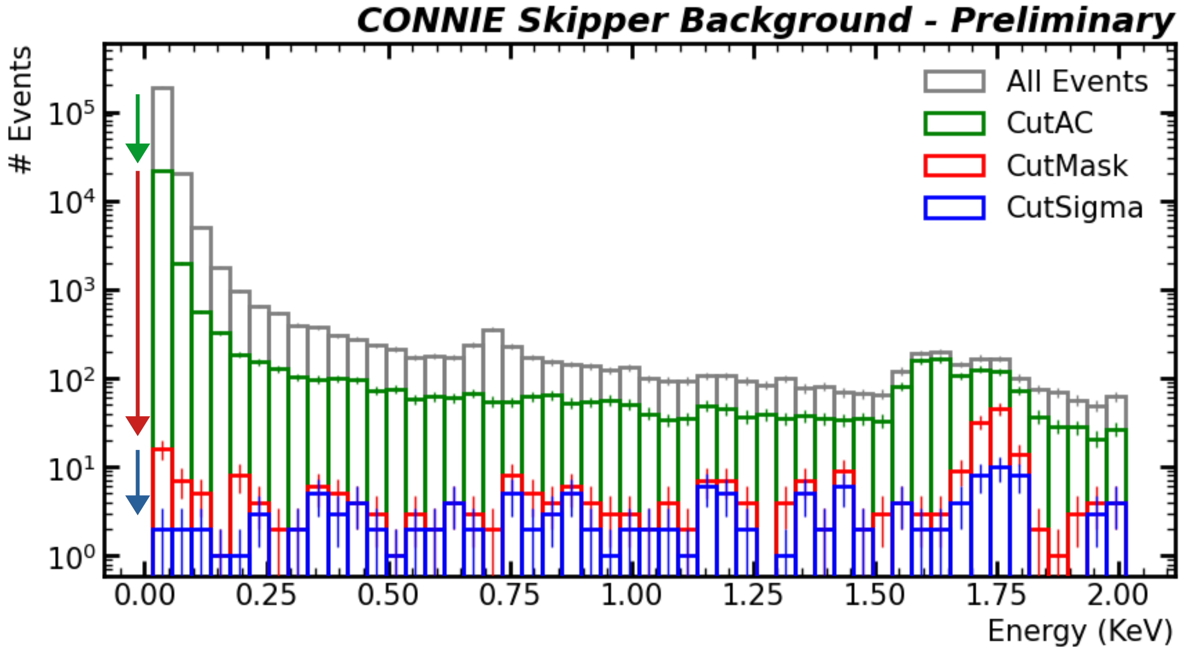
Preliminary

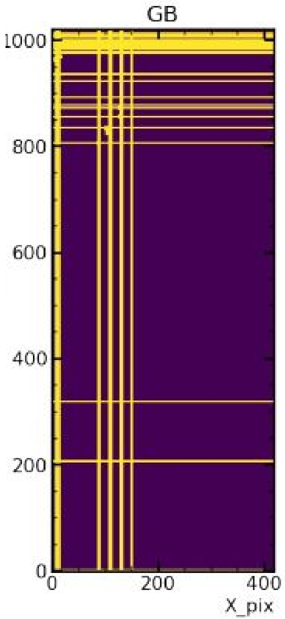
Selection cuts for Reactor-OFF data:

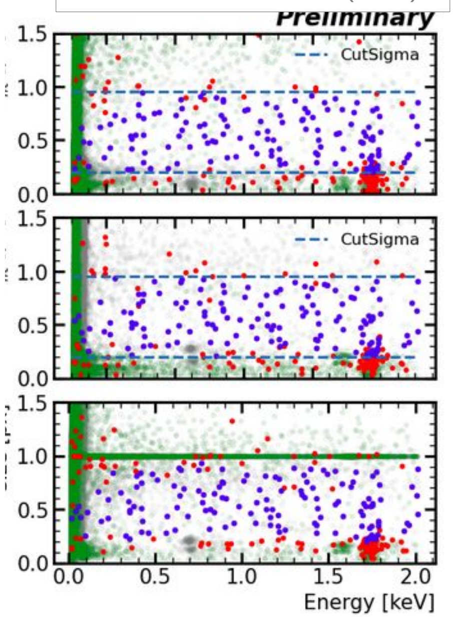
⌐ **S**ingle **E**lectron **R**ate

- **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)

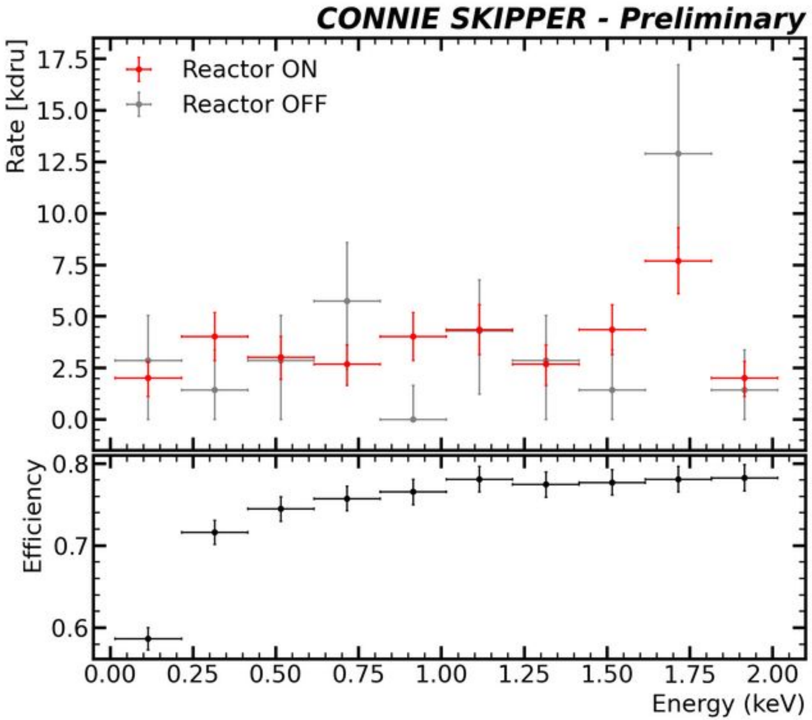


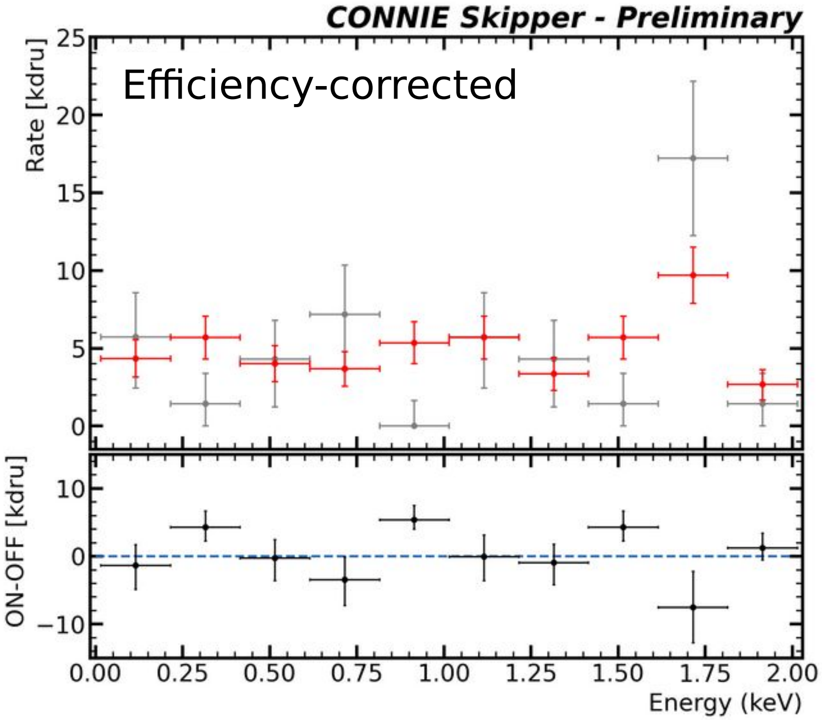




Skipper-CCD results

Preliminary





- Flat ON & OFF spectra down to 15 eV,
- Flat ON-OFF consistent witn zero.

Plots by Pedro Ventura