Status and perspectives of the CONNIE experiment

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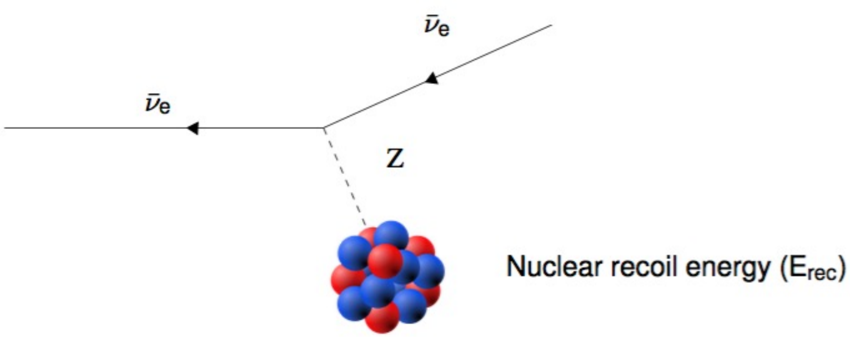
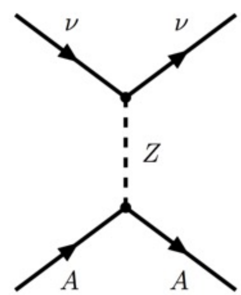
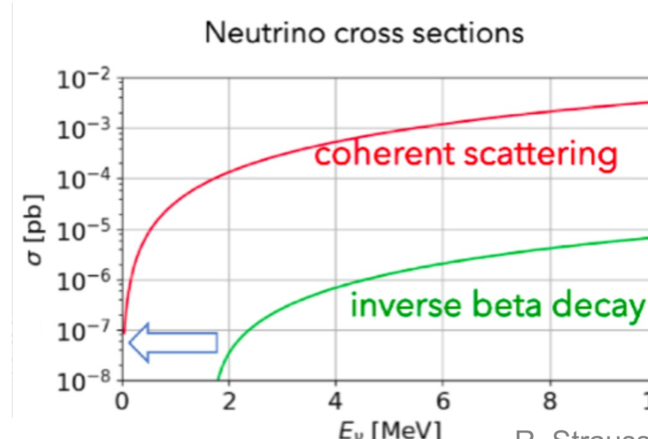
Coherent elastic νN scattering

- In the Coherent Elastic Neutrino-Nucleus Scattering (CEνNS) interaction, the neutrino scatters off the nucleus as a whole.
- Predicted in the Standard Model in 1974. D. Freedman, Phys.Rev. D 9 1389 (1974)
- Discovered by COHERENT in 2017 with neutrinos of E_ν ~20 MeV with a CsI detector and later with a Liquid Ar detector. Science 357, 1123, 2017; PRL 129 8, 081801, 2022; PRL, 126, 012002, 2021







R. Strauss, Magnificent CEvNS 2021

$$\frac{d\sigma}{dE_{rec}}(E_{\bar{\nu}_e}, E_{rec}) = \frac{G_F^2}{8\pi}[Z(4\sin^2\theta_W - 1) + N]^2 \times M(2 - \frac{E_{rec}M}{E_{\bar{\nu}_e}{}^2})|f(q)|^2$$

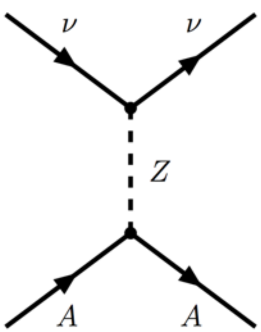
- Coherent enhancement, nuclear form-factor is f(q) ≈ 1 for low energies: E_ν < 50 MeV.
- The total cross-section is ≈ 4.22 x 10^{-45} N^2 E_ν^2 cm^2 (N = 14 for Si).
- Reactor neutrinos with E_ν ~1 MeV can probe new physics at low energies.

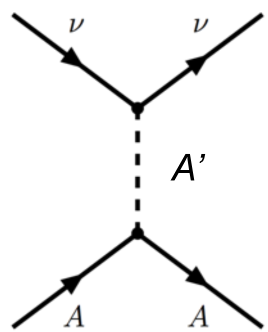
New Physics with neutrinos

- The coherent scattering rates are calculated with precision in the SM.
- Any discrepancy can be a sign of contributions from “New Physics” interactions:
  - Non-standard interactions of neutrinos.
  - Light sterile neutrinos.
  - Neutrino magnetic moment.
  - Neutrino millicharge.

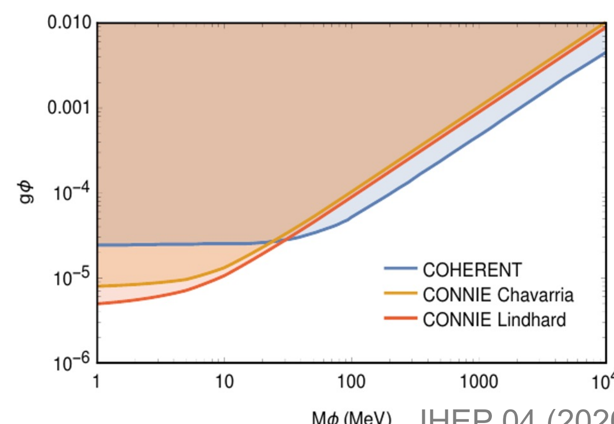
Y. Farzan et al, JHEP 05 (2018) 066
D.K. Papoulias et al, Front. Phys. 7 (2019) 191
J. Dent et al, PRD 96 (2017) 095007
T. Kosmas et al, PRD 96 (2017) 063013
O. Miranda et al, JHEP 07 (2019) 103
O. Parada, Adv. HEP 2020 (2020) 5908904

Standard Model





Model with New Physics



JHEP 04 (2020) 054

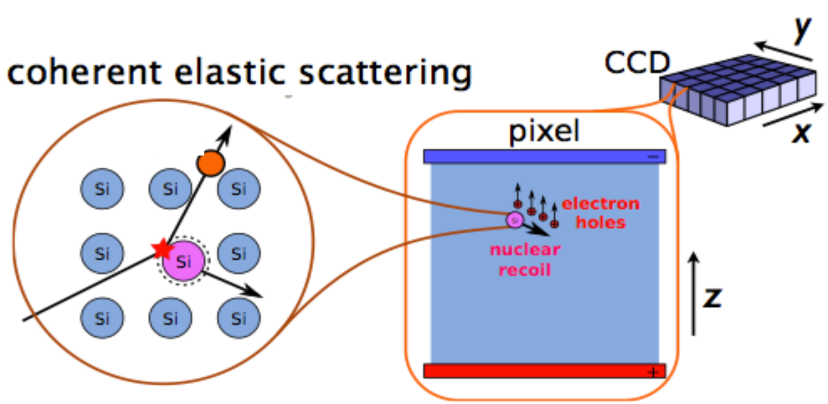
- Also important for direct DM searches and supernova physics.
- Weak angle measurement.
- Once the detection is established, it can be used to create compact detectors for reactor monitoring.

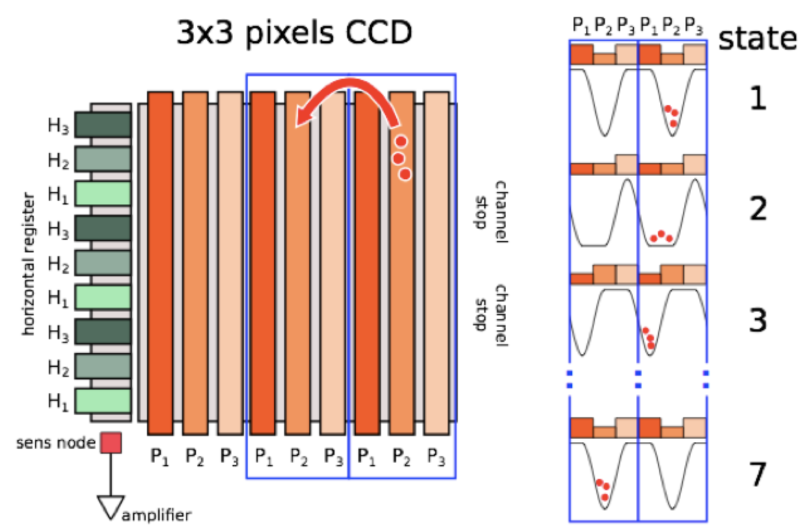
B. Cañas et al, PLB 784 (2018) 159
G. Fernandez-Moroni et al, JHEP 03 (2021) 186

B. Cogswell, P. Huber, Science and Global Security 24, 2 (2016) 114

The CONNIE experiment

- Coherent Neutrino-Nucleus Interaction Experiment (CONNIE).
- The main goal is to detect coherent elastic scattering of reactor antineutrinos off silicon nuclei and place limits on physics Beyond the Standard Model.
  - Nuclear recoil energies are small (E_{rec} ~keV).
  - Ionisation signals are a fraction of E_{rec} (quenching factor or ionisation efficiency).
- The detectors are thick (675 μm) scientific CCDs made from high resistivity silicon.
  - Charges are collected in potential wells and read out sequentially.
  - Low noise (~2 e-) and low dark current (~3 e-/pix/day).
  - Very low-energy detection threshold (~50 eV).





The CONNIE collaboration

COherent Neutrino-Nucleus Interaction Experiment

Argentina
Centro Atómico Bariloche
Universidad de Buenos Aires
Universidad del Sur / CONICET

Brazil
Centro Brasileiro de Pesquisas Físicas
Universidade Federal do Rio de Janeiro
CEFET – Angra
Universidade Federal do ABC
Instituto Tecnológico de Aeronáutica

Mexico
Universidad Nacional Autónoma de México

Paraguay
Universidad Nacional de Asunción

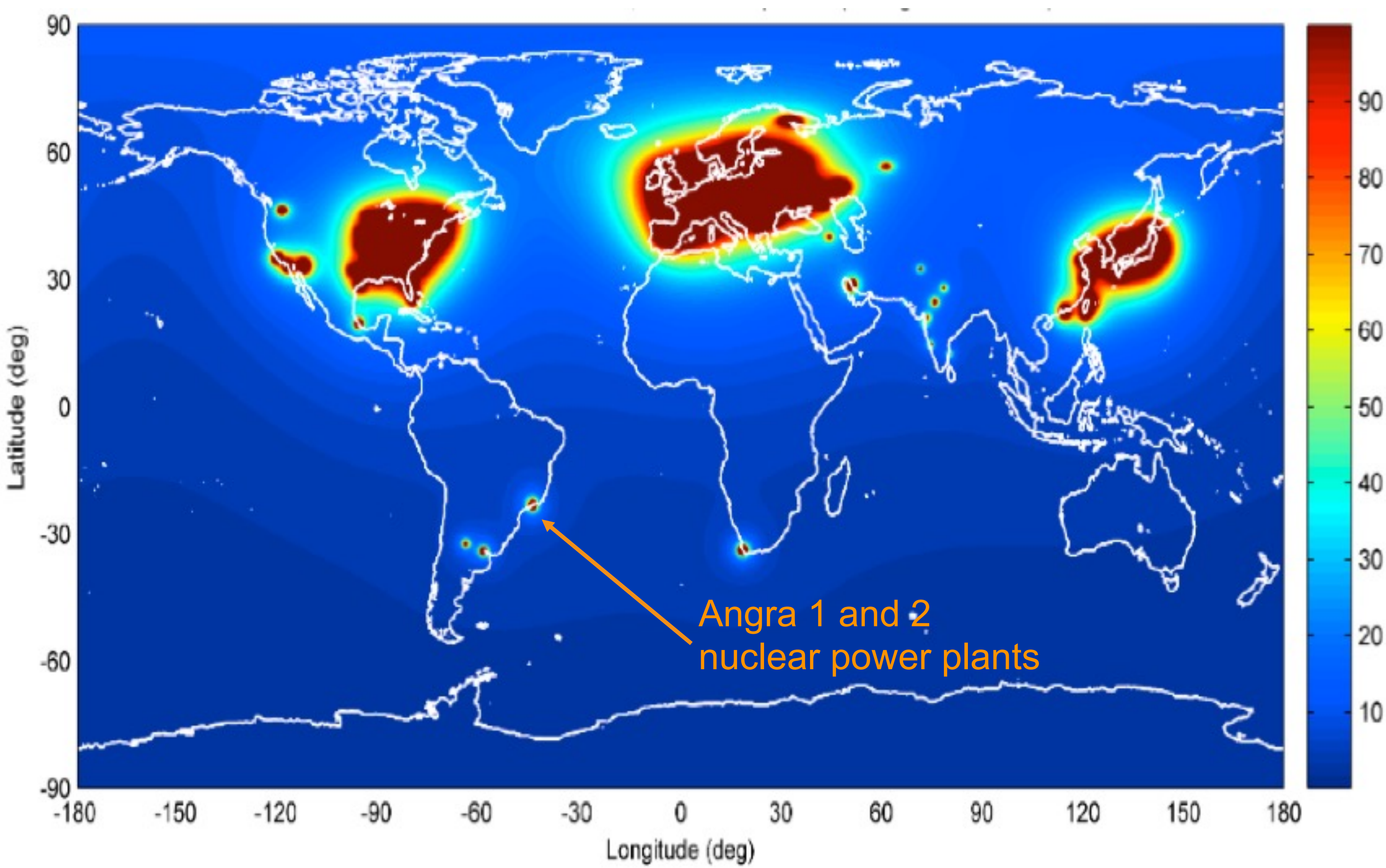
Switzerland
University of Zurich

USA
Fermilab National Laboratory

The CONNIE experiment

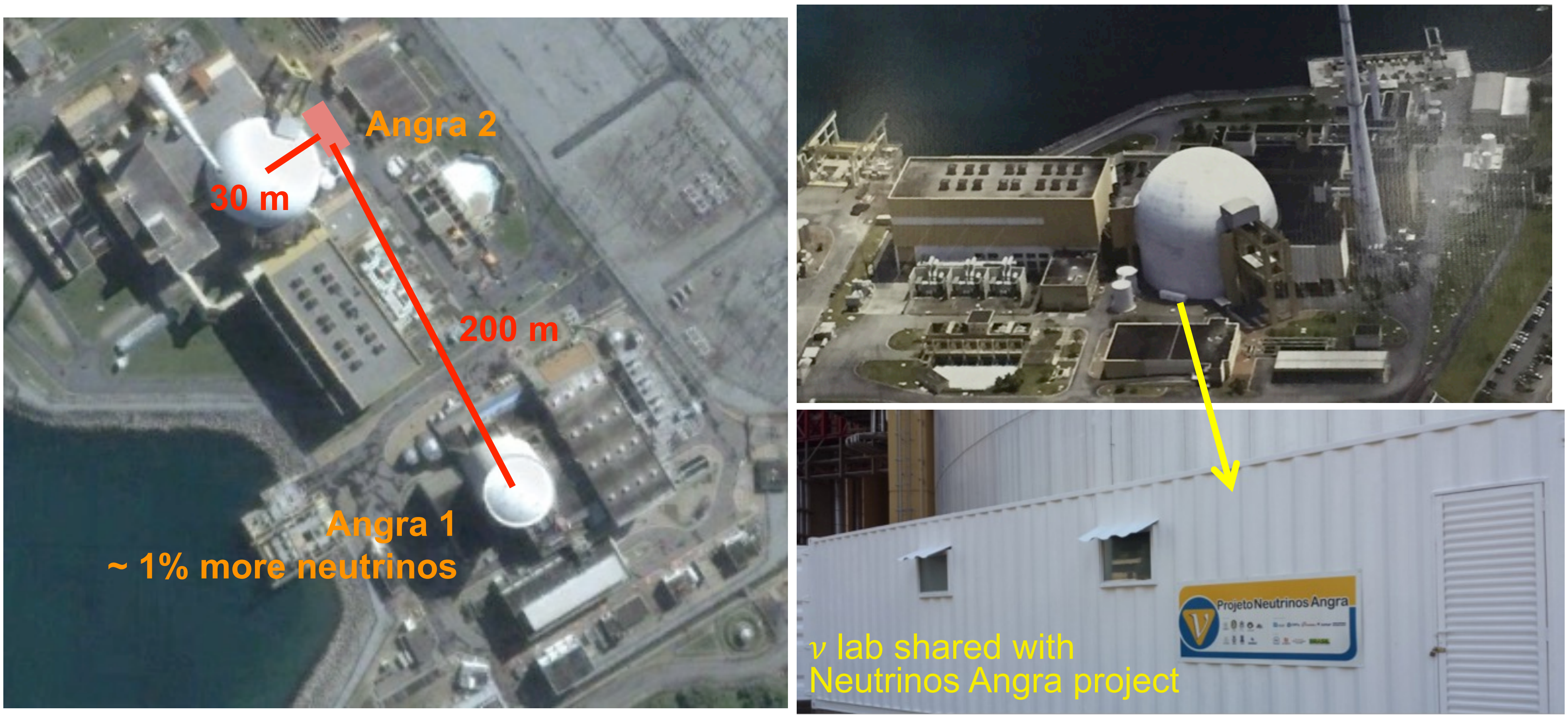
- CONNIE is located next to the Angra 2 reactor at the Almirante Álvaro Alberto nuclear power plant, near Rio de Janeiro, Brazil.

Reactor antineutrinos

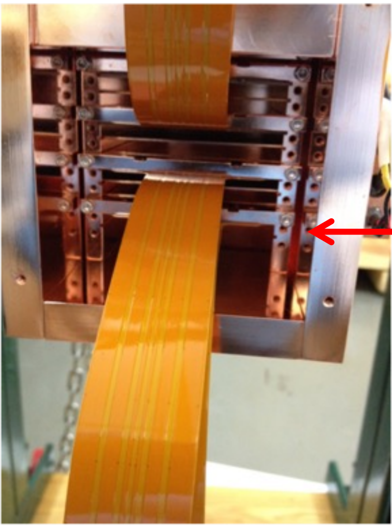


The CONNIE experiment

- At around 30 m from the nucleus of the 3.8 GW_{th} Angra 2 reactor.
- Shared lab with the Neutrinos Angra experiment.
- Antineutrino source with flux of 7.8 x 10^{12} $\bar{\nu}s^{-1}cm^{-2}$ at the detector position.



The CONNIE detector



Engineering run:
JINST 11 (2016) P07024

CCDs in
copper box

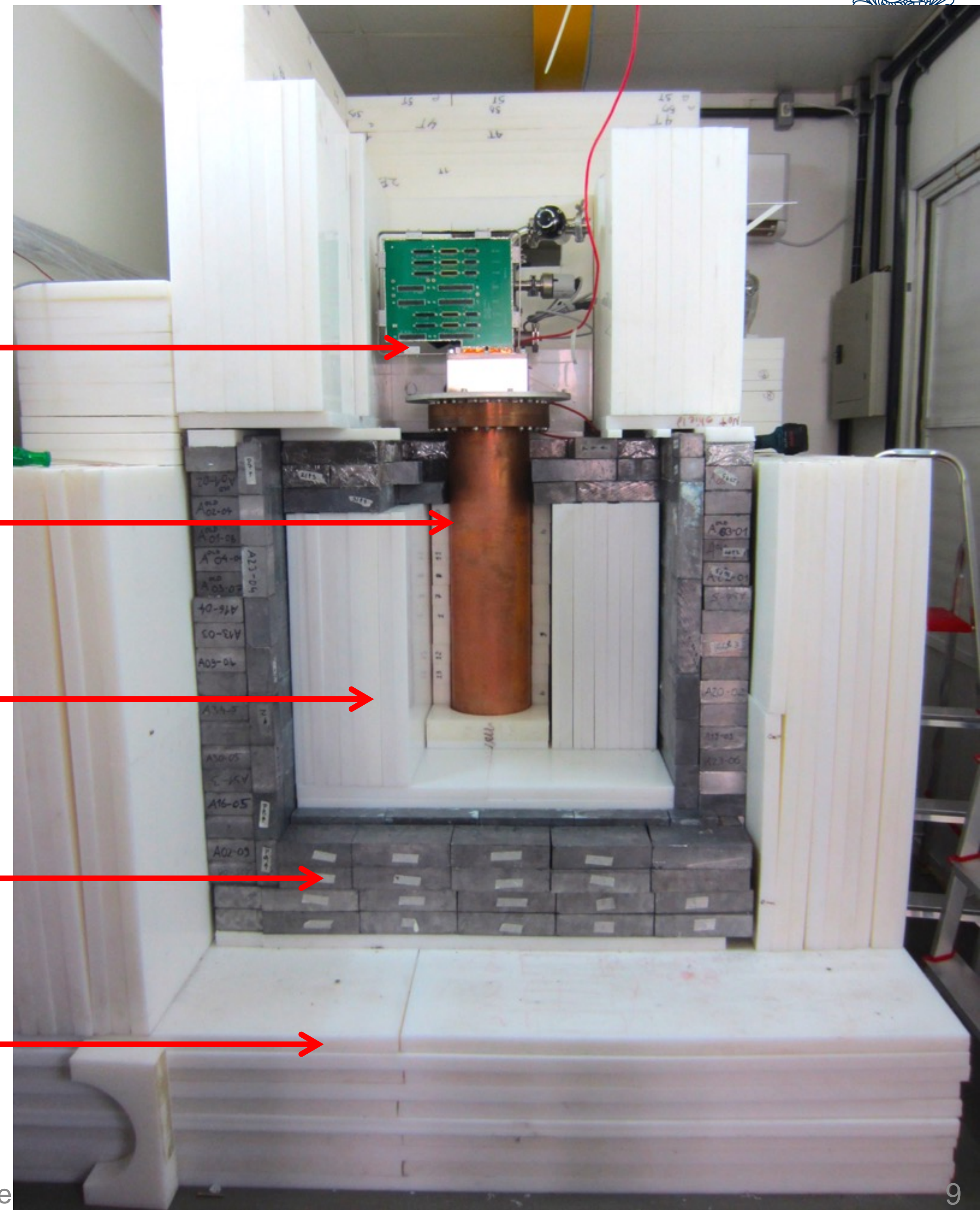
ViB readout board
(signal transport)

Dewar
(vacuum)

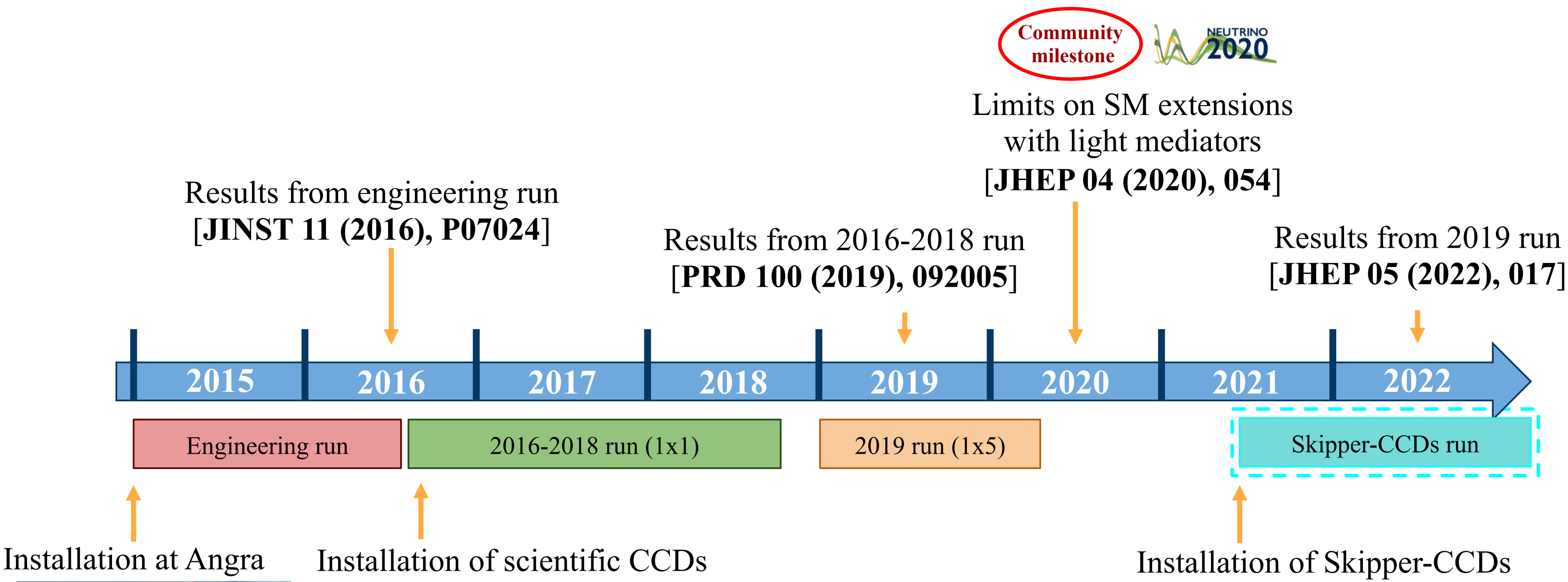
Inner Polyethylene – 30 cm
(neutrons)

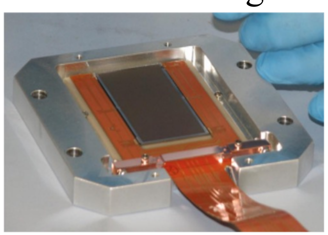
Lead – 15 cm
(gamma)

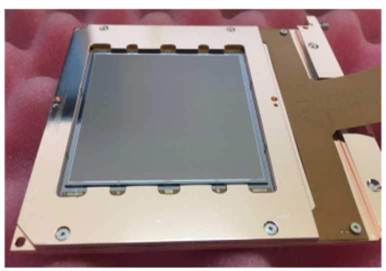
Outer Polyethylene – 30 cm
(neutrons)



CONNIE experiment timeline







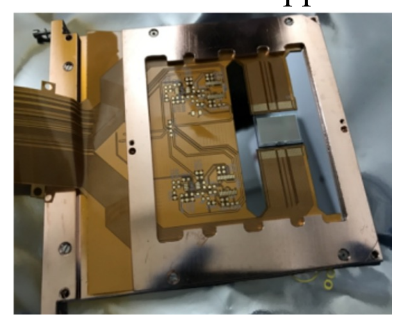


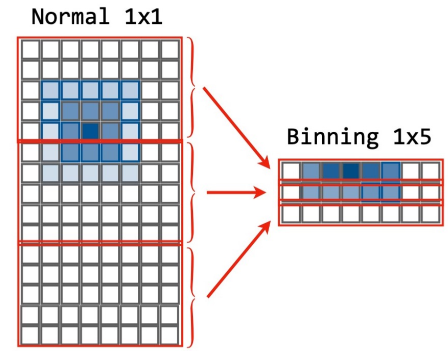
Image credit: Brenda Cervantes

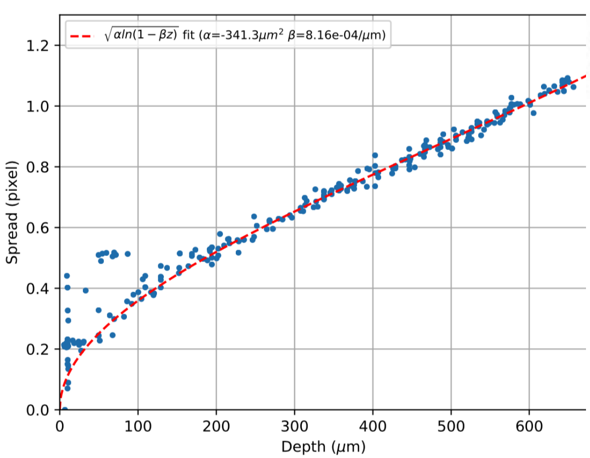
CONNIE 2019 run

JHEP 05:017, 2022

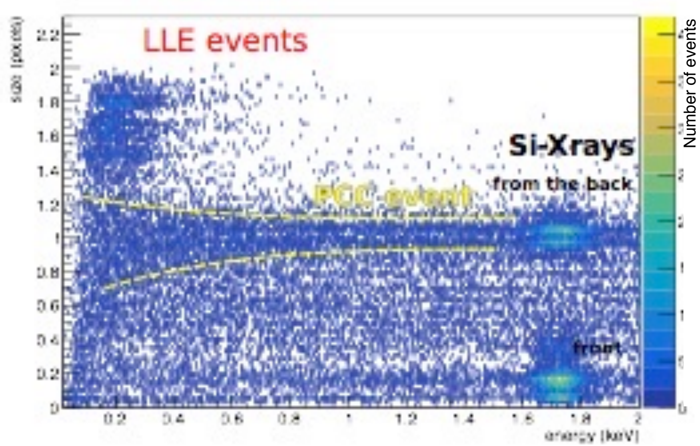
Improvements in data acquisition and analysis techniques in 2019:

- 1x5 pixel hardware rebinning reduces readout noise.
- Improved energy and size-depth calibrations.
- Low-energy background characterisation and reduction:
  - Large low-energy events;
  - Partial-charge-collection layer.
- Blind analysis and multiple cross-checks.

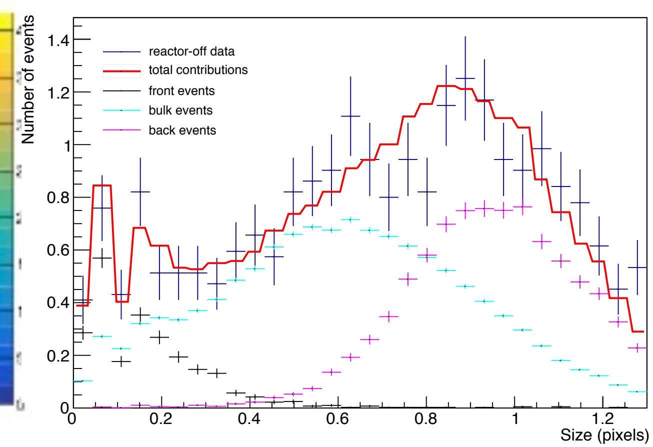




Size-depth calibration from muons



Large-size low energy events from high-energy tails and inactive volume are excluded.



Partial-charge-collection layer at the back of the sensor

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

CONNIE 2019 run

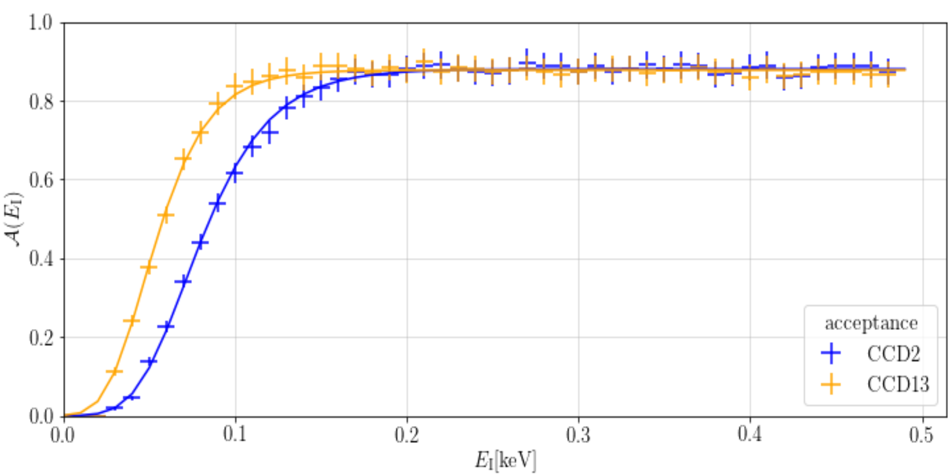
JHEP 05:017, 2022

Improvements in data acquisition and analysis techniques in 2019:

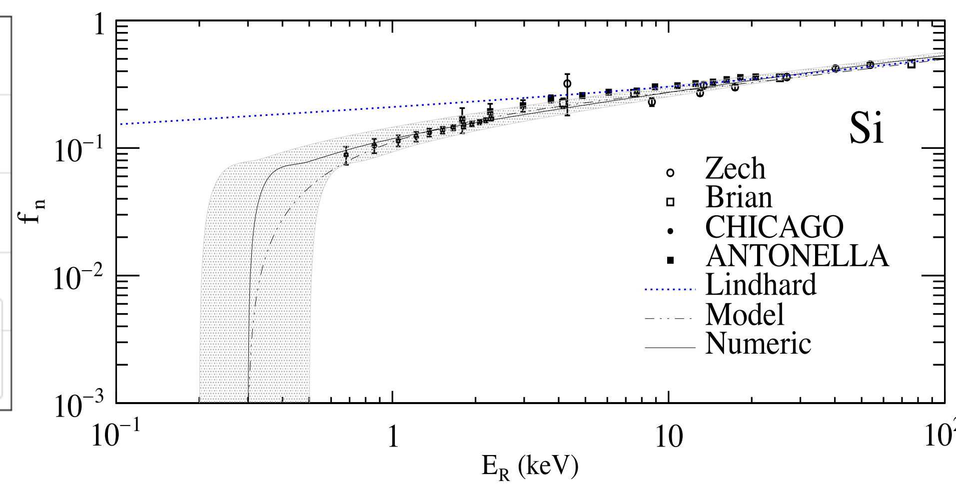
- Improved detector acceptance and selection efficiency at low E.
- Detection threshold is reduced to ~45 eV.
- Full efficiency reached at 100-150 eV.

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

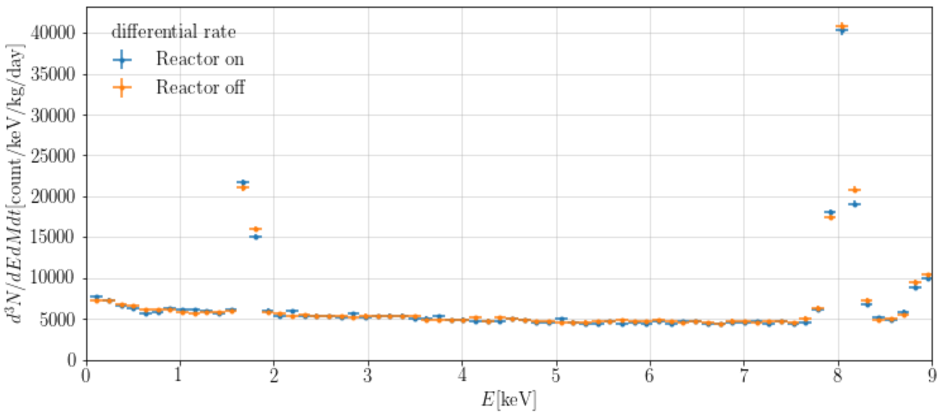


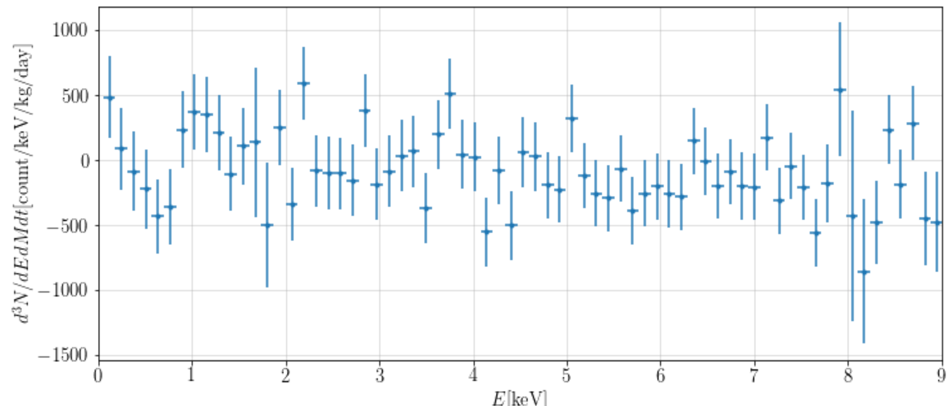
Sarkis quenching factor model for Si

CONNIE 2019 results

JHEP 05:017, 2022

- Energy spectrum from 8 CCDs with total active mass 44.48 g.
- Exposures of 31.85 days with reactor on and 28.25 days with reactor off.
- Total exposure of 2.7 kg-days.

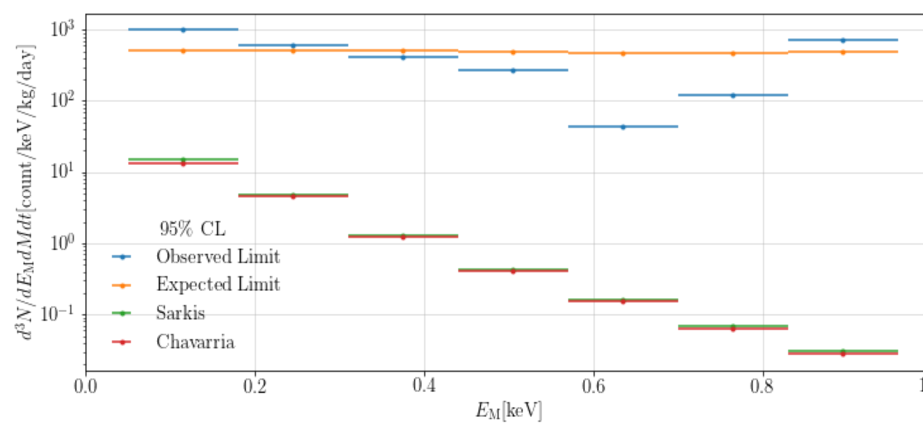




On – Off rates

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

- Expected limit in the lowest-energy bin is 34-39 times the prediction.
- Observed limit is 66-75 times the prediction.



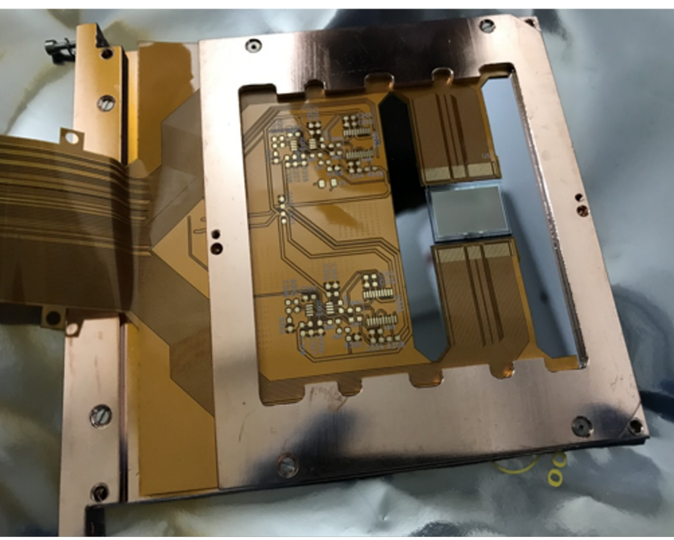
CONNIE with skipper CCDs

- Skipper CCD sensors offer a promising perspective to reach very low energies:
  - Repeated non-destructive charge measurement.
  - Reduction in electronic noise.
  - Individual electron detection.

J. Tiffenberg et al, PRL 119 (2017)

- Two skipper CCDs were installed at the CONNIE setup in July 2021.
  - 0.5k x 1k pixels each, 675 μm thickness, 0.4 g total mass.
  - New Low Threshold Acquisition readout electronics.
  - New dedicated Vacuum Interface Board.

G. Cancelo et al, JATIS 7 (2021), 1 015001

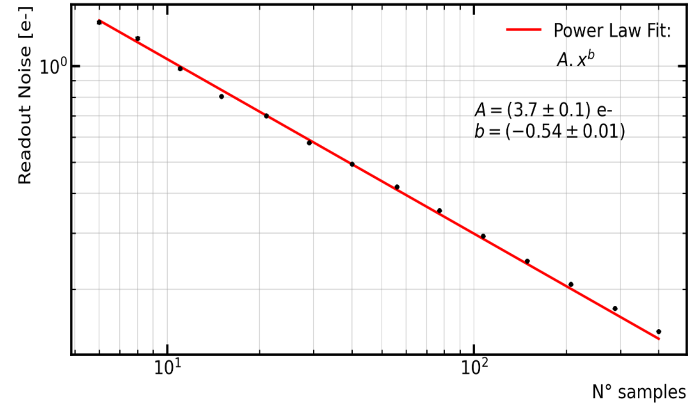


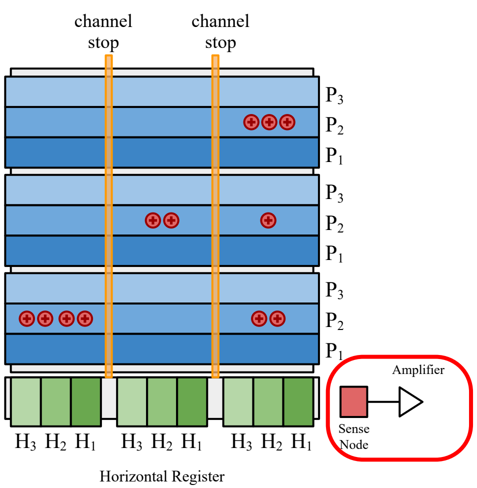
Skipper-CCD performance

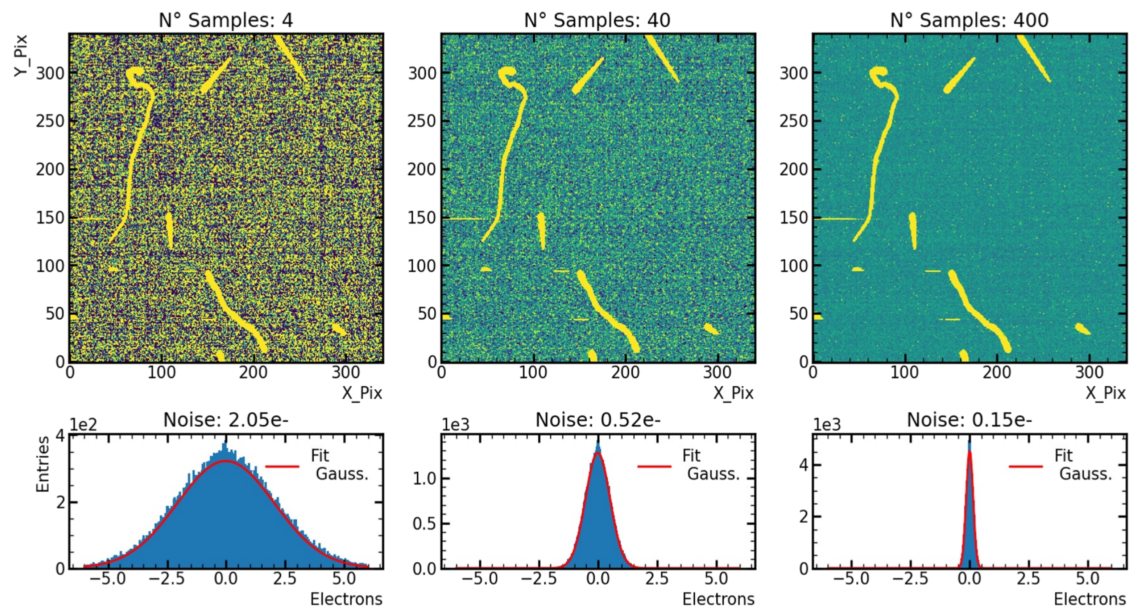
Preliminary

- Ongoing data taking to characterise skipper performance and background.
  - Tests of LTA acquisition and skipper readout mode.
  - Readout noise is reduced with N samples:

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





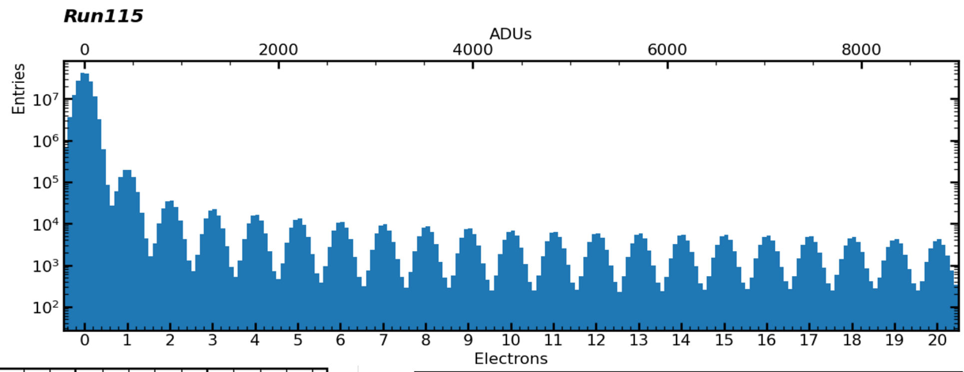


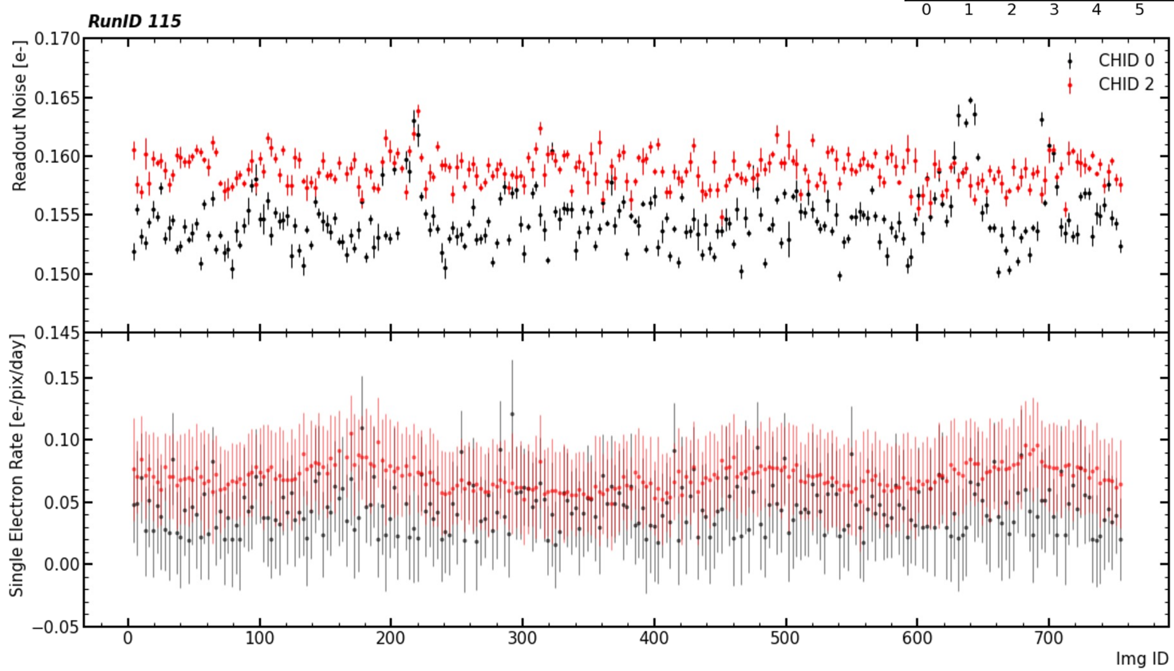
Multiple non-destructive independent measurements of each pixel charge

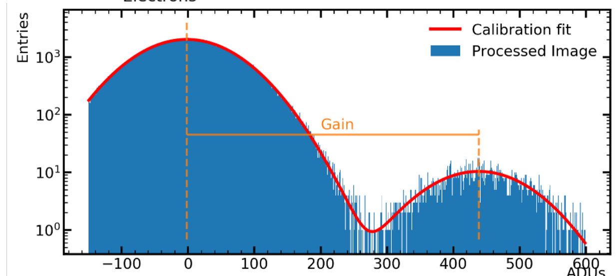
Skipper-CCD performance

Preliminary

- Ongoing data taking to characterise skipper performance and background.
  - Measurements of dark current and noise.
  - Energy calibration and linearity.
  - Event extraction algorithms.







Preliminary:

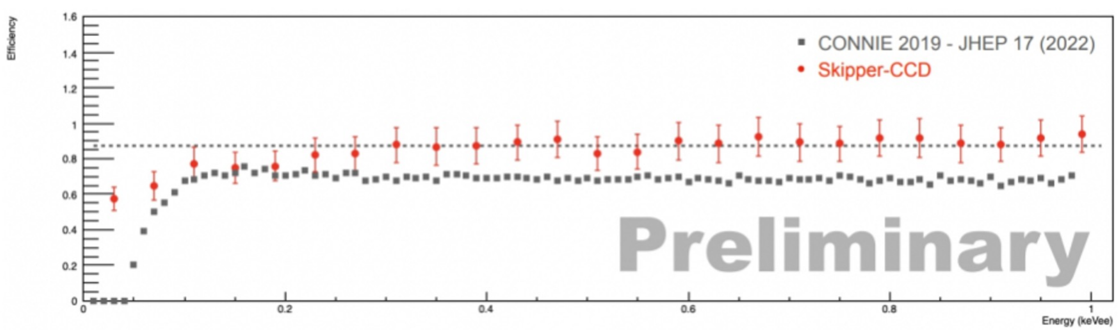
Noise = 0.16 e-

Single-electron rate = 0.05 e-/pix/day

Skipper-CCD performance

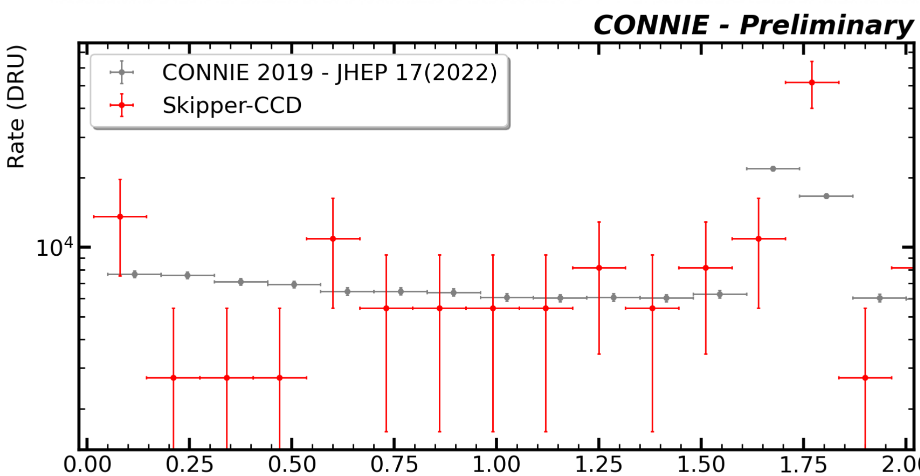
Preliminary

- Ongoing data taking to characterise skipper performance and background.
  - Efficiency determination.
  - Background energy spectrum at sea level with passive shielding.
  - Reactor-off data, a period of ~20 days. Total exposure 0.0028 kg-days for mass 0.5 g.

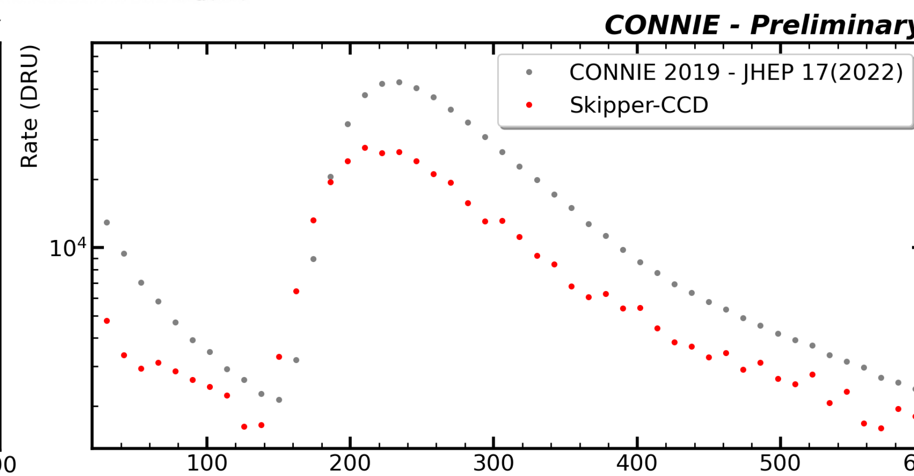


Efficiency

Threshold = 15 eV



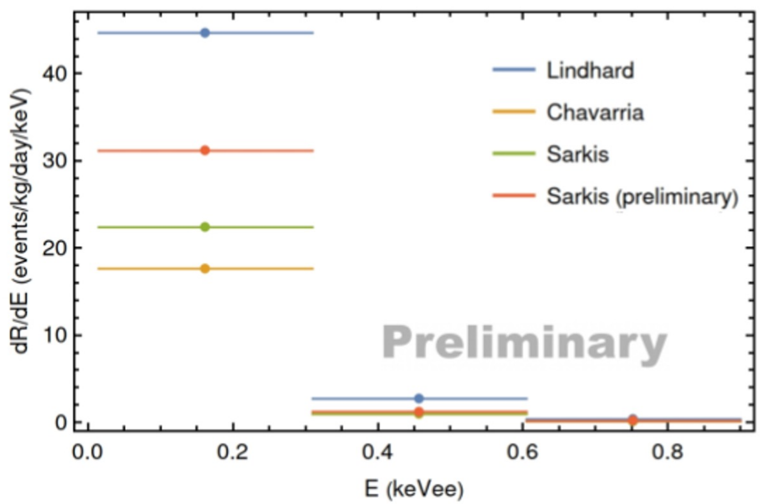
With preliminary cuts: bkg < 10 kdru

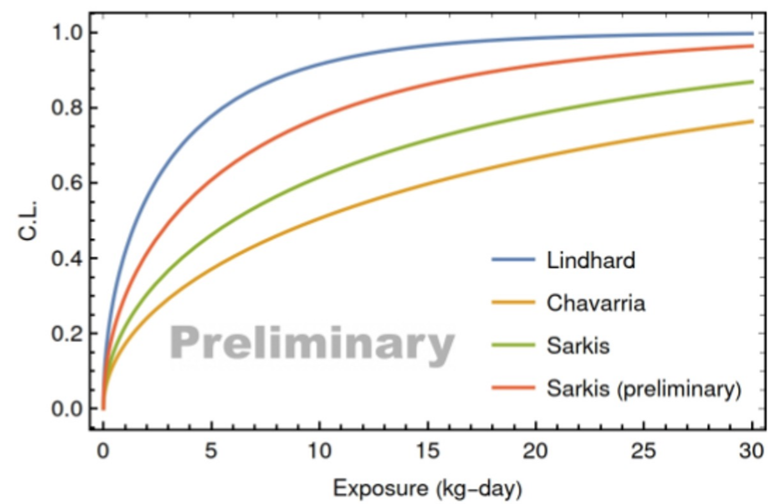


Spectrum at high energy, no cuts

CONNIE perspectives

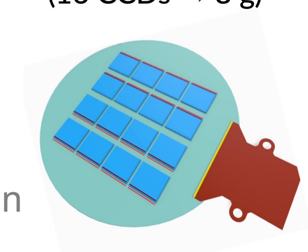
- Considering a threshold of 15 eV, we expect a CEνNS rate 2.2 times higher than in 2019.
- If we install a 1 kg detector at the CONNIE site, with a background rate of 4 kdru, it should run for 9 days (if Lindhard quenching factor) or 2 months (Chavarria) to observe CEνNS at a 90% C.L.



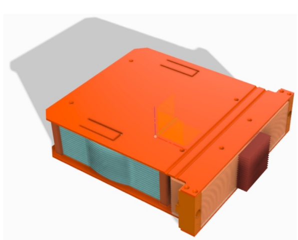


- Studying the possibility to increase sensor mass.
- And to go closer to the reactor, inside the dome.

Multi-Chip Module (16 CCDs → 8 g)



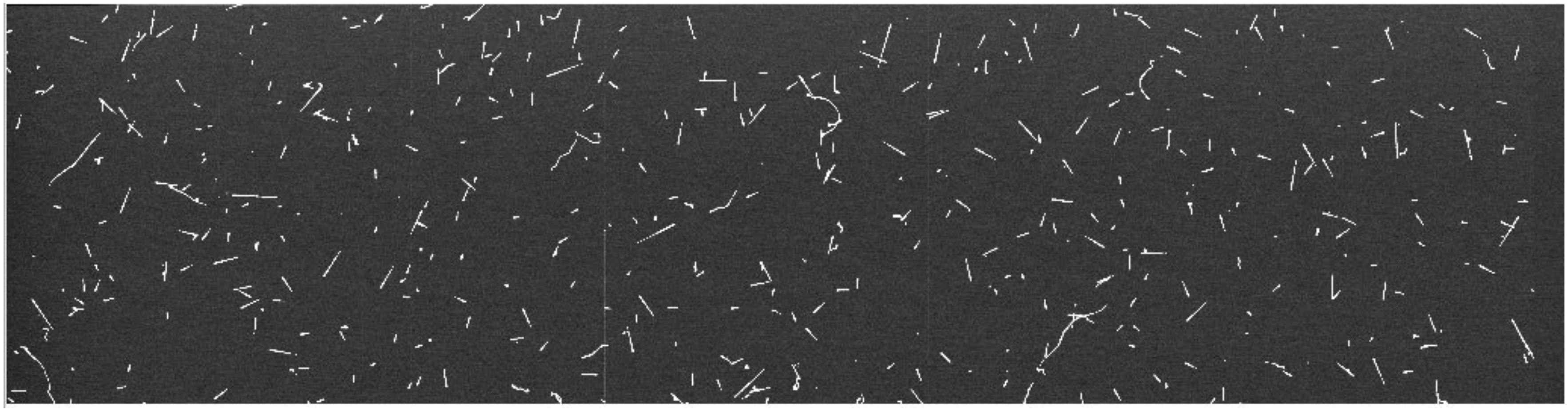
Super Module (16 MCMs → 100 g)



Oscura experiment design

Summary and outlook

- CCDs are a promising technology for detecting CEνNS at low energies.
- CONNIE was the first experiment to install skipper CCDs at a reactor, in 2021.
- Excelent skipper-CCD performance and stable operation.
- Preliminary analysis shows improved efficiency and background levels.
- Characterisation of skipper sensors and sea-level background will help prepare for a future larger-mass skipper-CCD experiment.

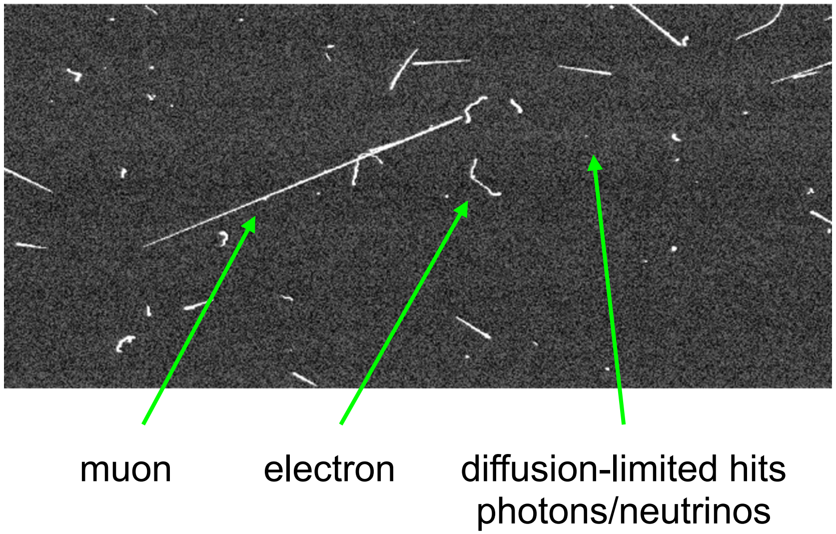


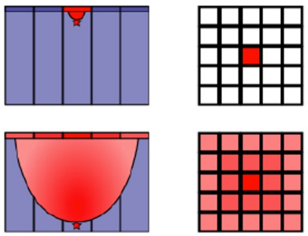
Back up

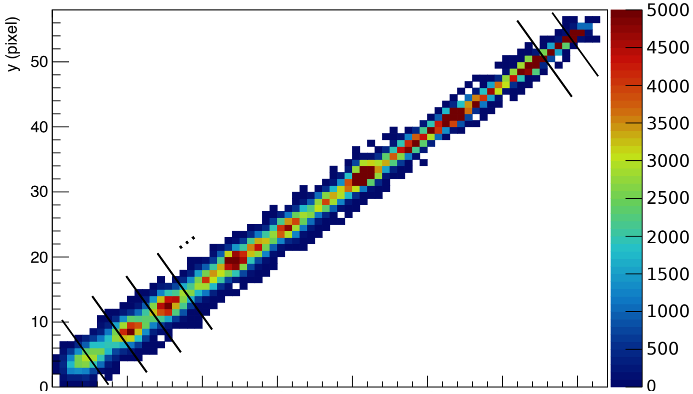
Event reconstruction

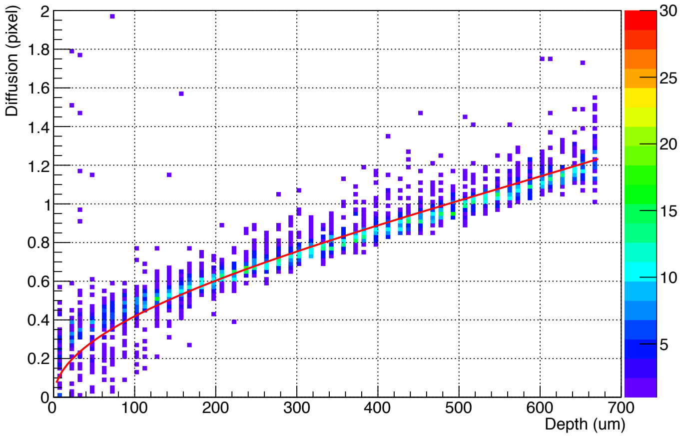
- Identify tracks based on geometry.
- Energy calibration in situ using Cu fluorescence x-rays.
- Depth versus diffusion width calibration using cosmic muons.
- Monitor the stability of natural backgrounds, noise and dark current.
- Low-energy neutrino selection based on likelihood test.

Phys. Rev. D 100 (2019) 092005

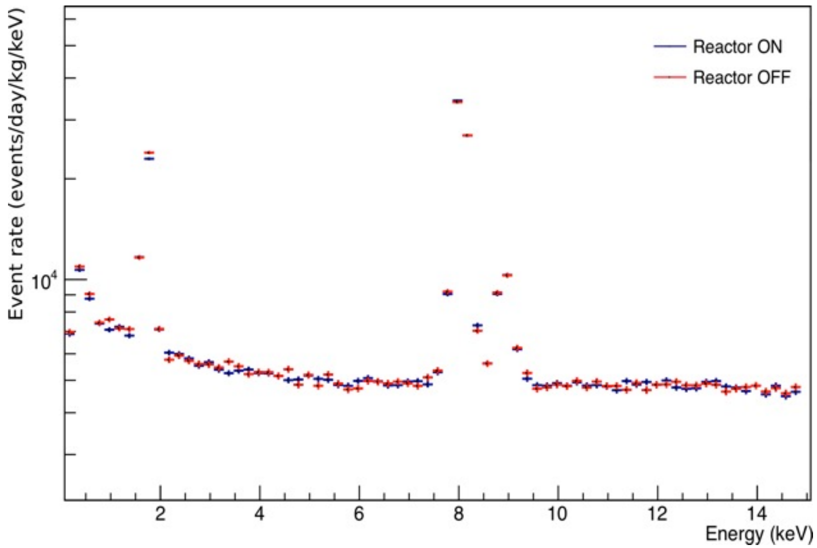






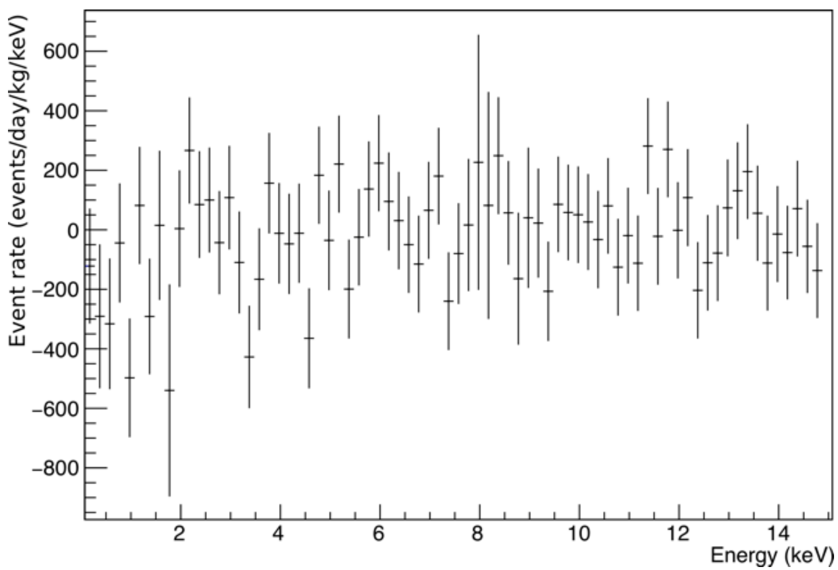


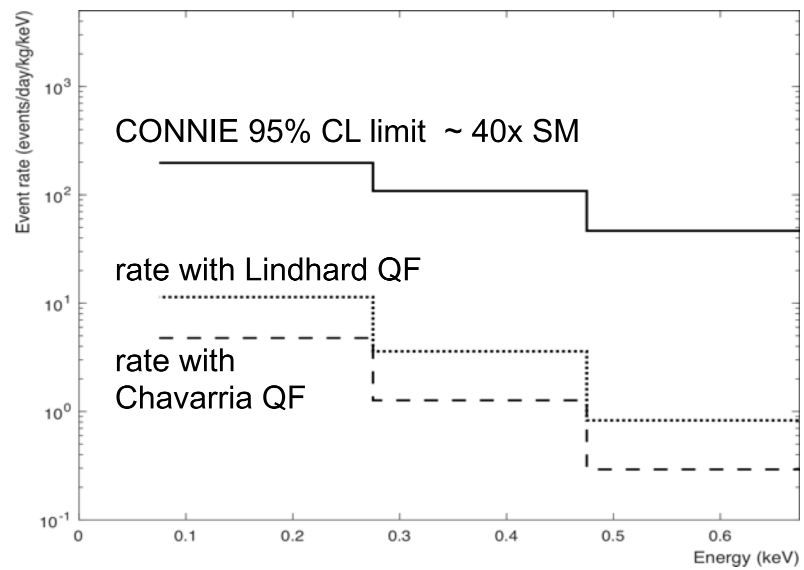
CONNIE Results 2016-18



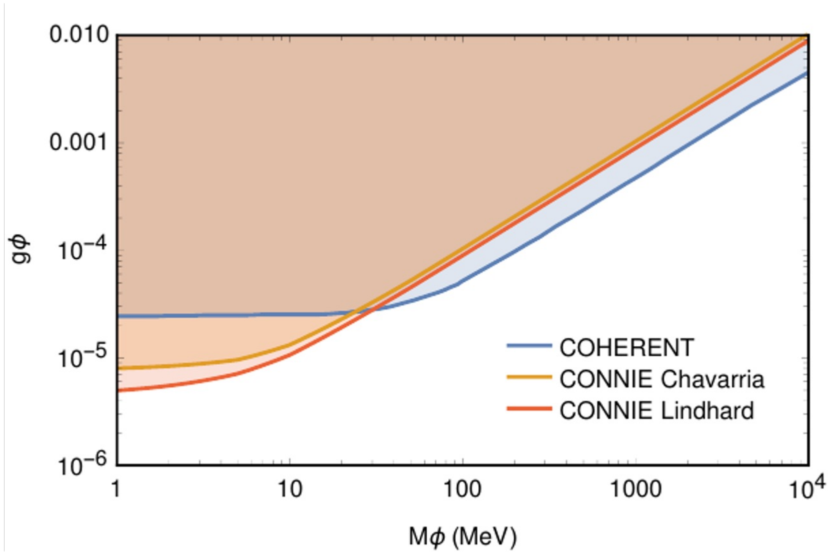
Phys. Rev. D 100 (2019) 092005

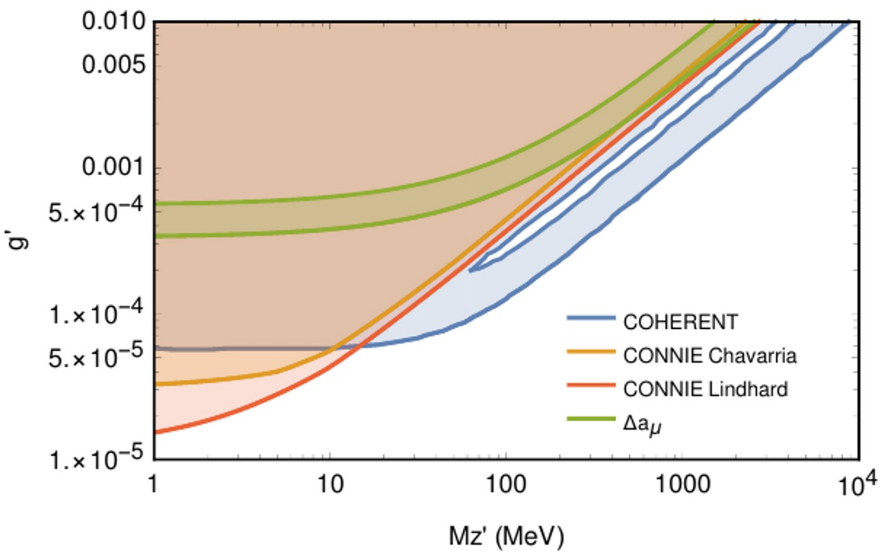
- 2016-18 run with an active mass 47.6 g.
- Energy spectrum with reactor on (2.1 kg-day) vs reactor off data (1.6 kg-day).
- An upper limit is placed on CEνNS event rate, compared to expected rate depending on quenching factor.





Non-standard interaction limits





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- 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.

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

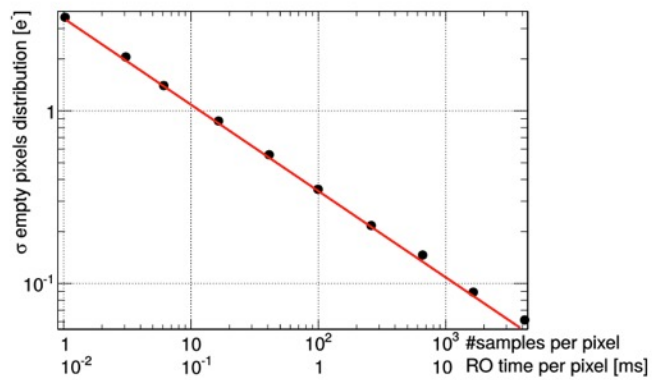
$$Q_\phi = \frac{(14N+15.1Z)g_\phi^2}{\sqrt{2}G_F\left(2ME_R + M_\phi^2\right)}$$

- We obtained 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.

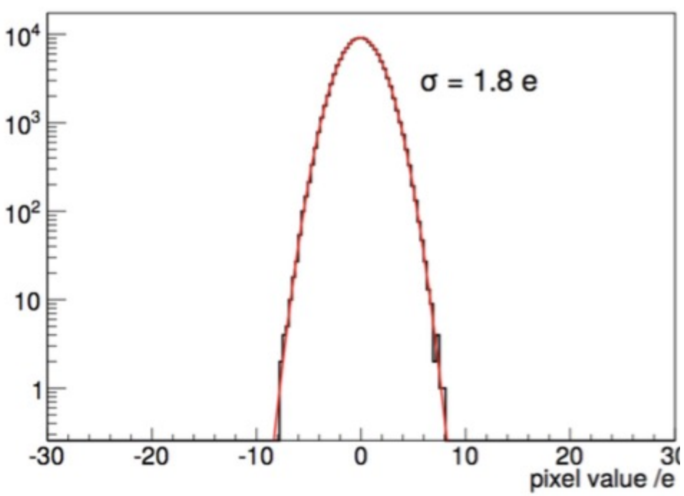
Perspectives: Skipper-CCDs

- Os sensores Skipper-CCD oferecem a perspectiva para alcançar energias muito baixas:
  - Medida repetida não destrutiva da carga.
  - Grande redução no ruído eletrônico de leitura.
  - Detecção de elétrons individuais.
- Tecnologia promissora para detecção de DM e neutrinos
  - Experimentos OSCURA, SENSEI, DAMIC-M...
  - Ótica quântica, astronomia, física nuclear.

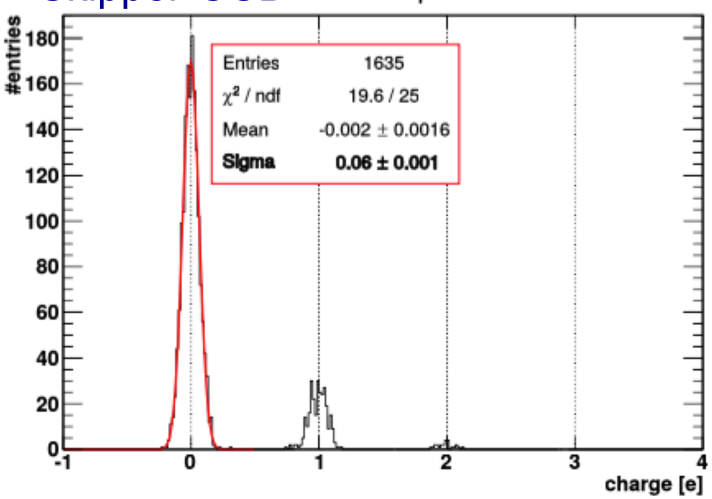
J. Tiffenberg et al, PRL 119 (2017)

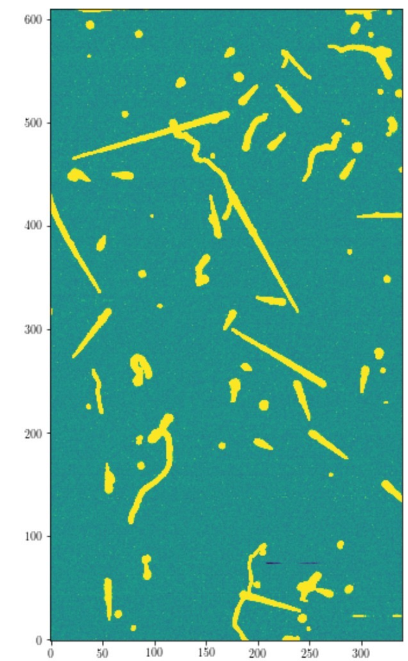


CONNIE atual



Skipper-CCD 4000 samples

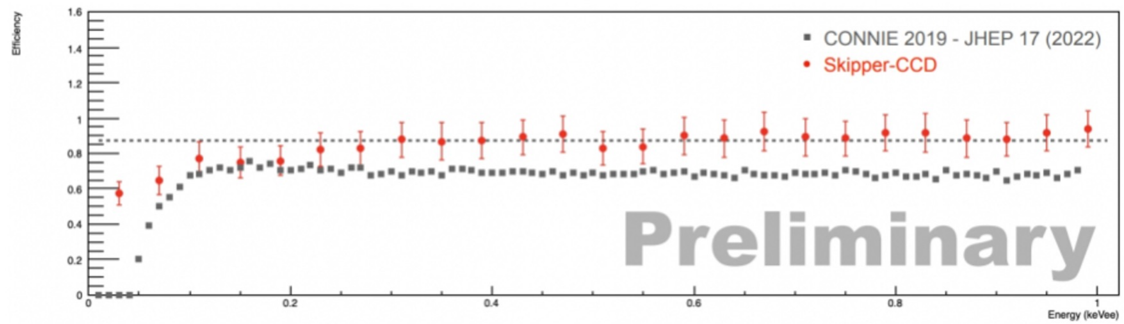


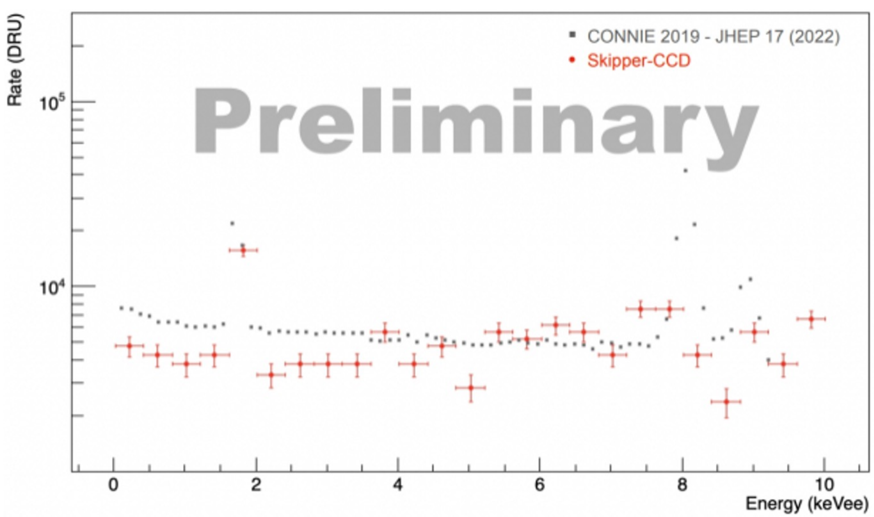


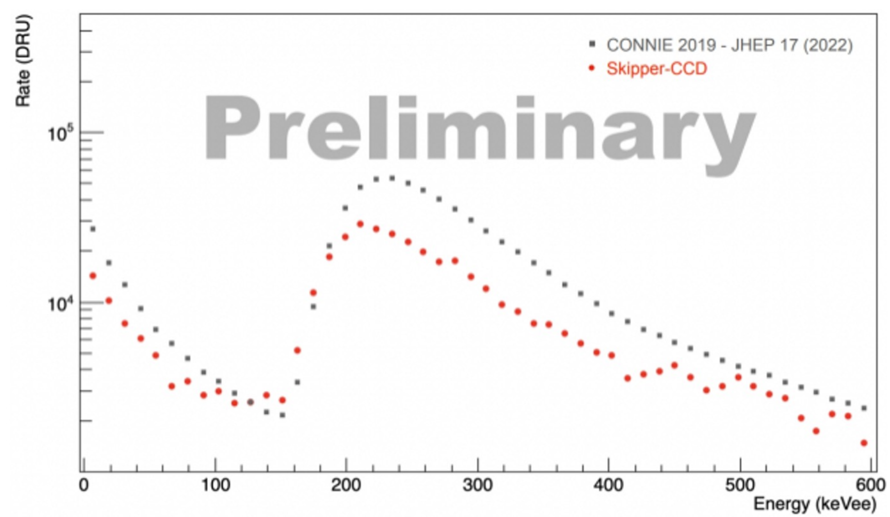
Skipper-CCD performance

Preliminary

- Ongoing data taking to characterise skipper performance and background.
  - Efficiency determination.
  - Background energy spectrum at sea level with passive shielding.
  - Reactor-off data, a period of ~20 days. Total exposure 0.0028 kg-days for mass 0.5 g.

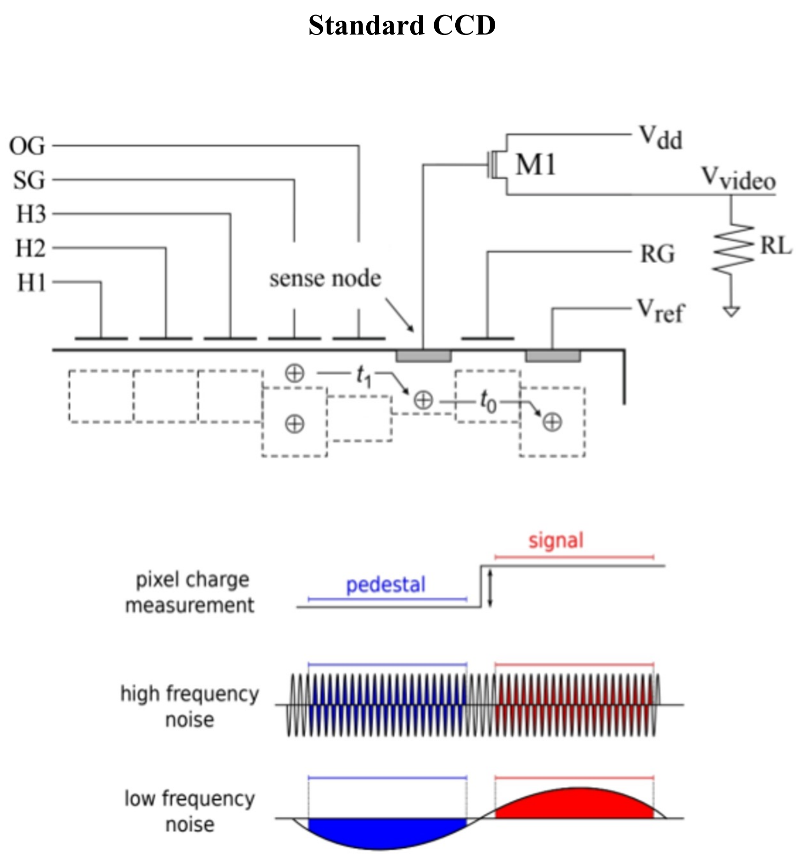


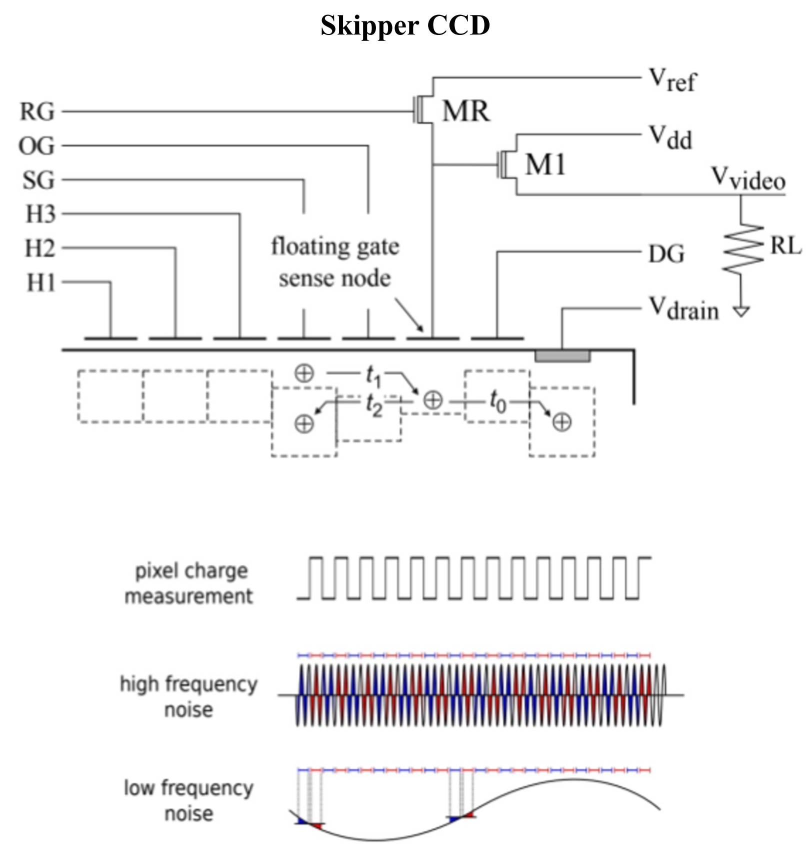




Skipper CCD readout

[PRL 119, 131802]

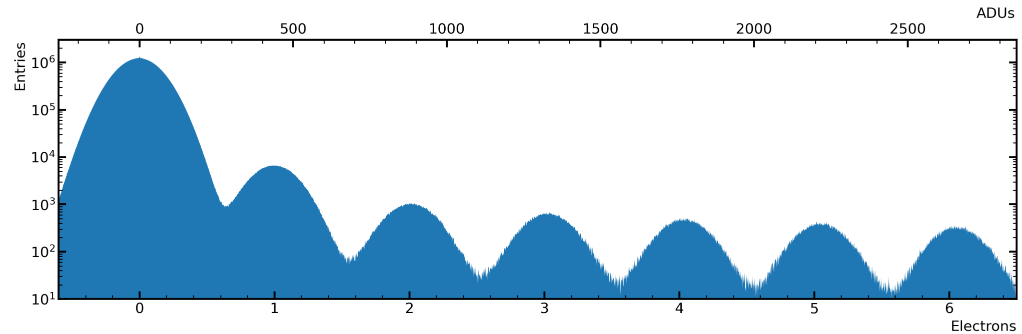


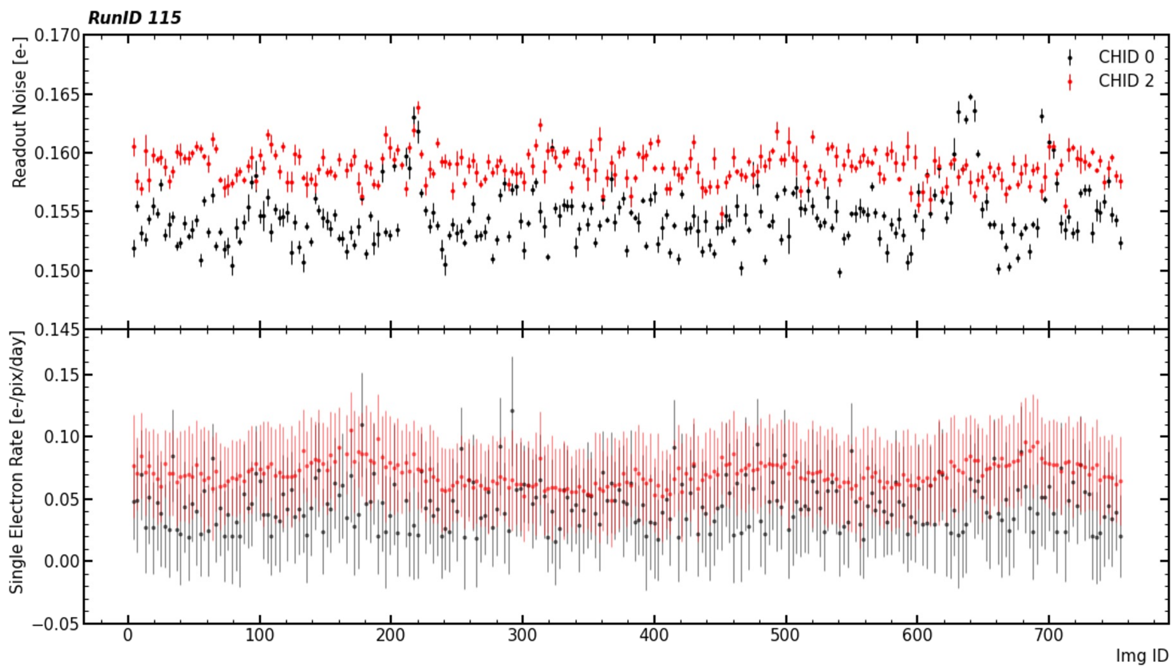


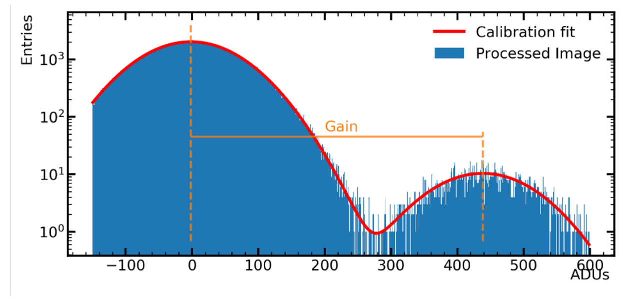
Skipper-CCD performance

Preliminary

- Ongoing data taking to characterise skipper performance and background.
  - Measurements of dark current and noise.
  - Energy calibration and linearity.
  - Event extraction algorithms.







Preliminary:

Noise = 0.16 e-

Single-electron rate = 0.05 e-/pix/day