CONNIE first results with Skipper CCDs

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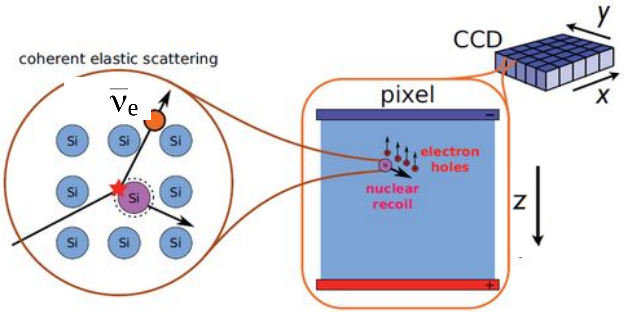
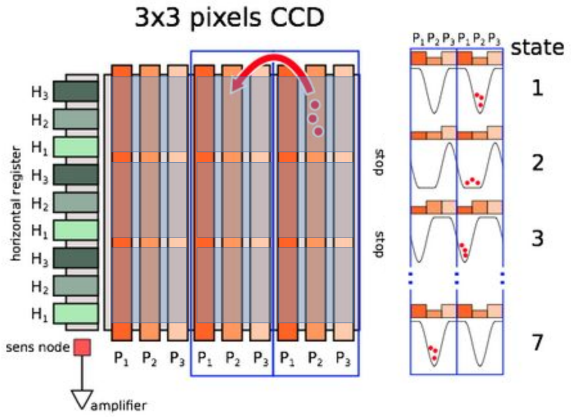
EXCESS23@TAUP Workshop, University of Vienna, Vienna, Austria

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

* with standard CCDs



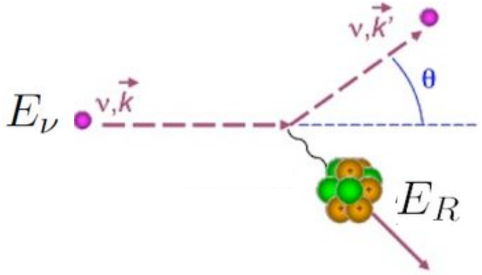


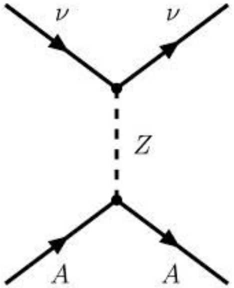
The CONNIE Collaboration

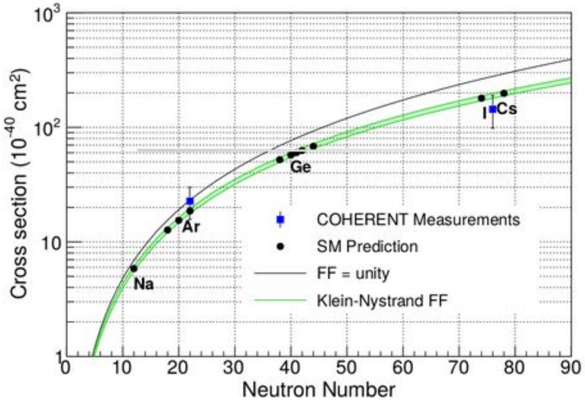
Centro Atómico Bariloche, Universidad de Buenos Aires, Universidad del Sur / CONICET, Universidad Nacional de San Martín, Centro Brasileiro de Pesquisas Físicas, Universidade Federal do Rio de Janeiro, CEFET-Angra, Universidade Federal do ABC, Instituto Tecnológico de Aeronáutica, Universidad Nacional Autónoma de México, Universidad Nacional de Asunción, University of Zurich, Fermilab [*15 inst, 6 count.*]

CEνNS: “Coherent Elastic ν-N Scattering”

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







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

First observed by the COHERENT Collaboration with neutrinos of *E*~16-53 MeV in CsI (Science 357, 1123, 2017), and liquid Argon (PRL, 126, 012002, 2021) detectors.

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

The CONNIE experiment

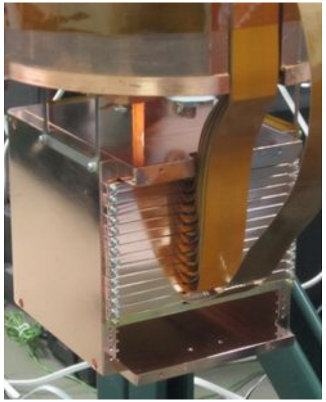
CONNIE is located next to the Angra 2 reactor at the Almirante Álvaro Alberto nuclear power plant, near Rio de Janeiro, Brazil.

The CONNIE experiment

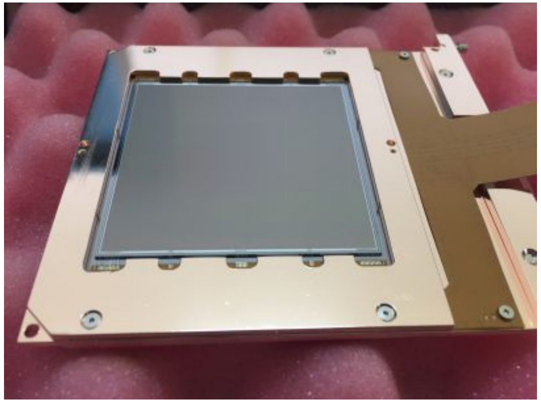
- At 30 m from the core of the 3.95 GW_{th} Angra 2 reactor. Flux of ~7.8 × 10^{12} $\bar{\nu}_e\,cm^{-2}\,s^{-1}$.
- Shares lab with the “Neutrinos Angra” experiment.

The CONNIE detector

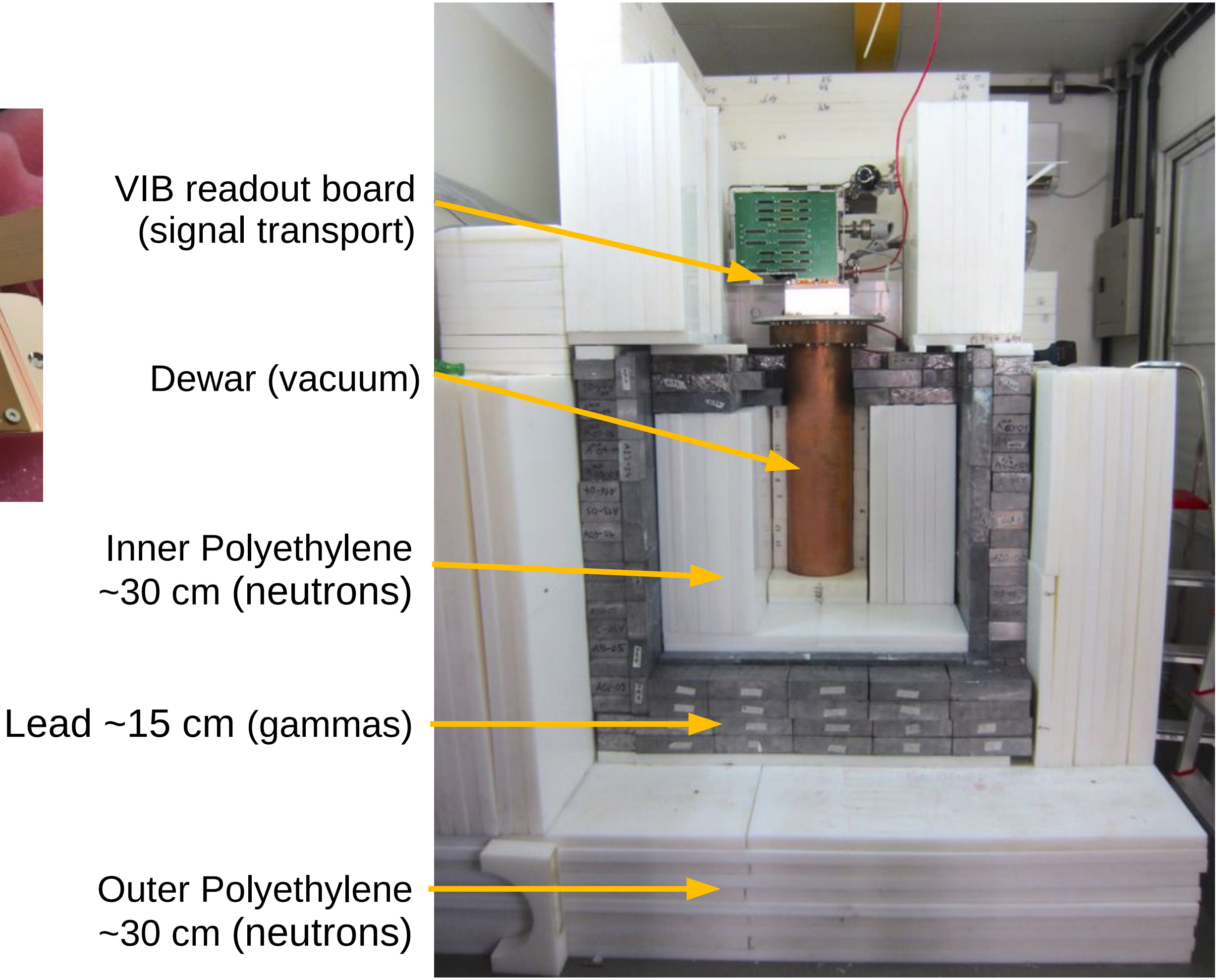
Installed in 2014. Upgraded in 2016



CCDs in copper box
(2016 Upgrade)



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



VIB readout board
(signal transport)

Dewar (vacuum)

Inner Polyethylene
~30 cm (neutrons)

Lead ~15 cm (gammas)

Outer Polyethylene
~30 cm (neutrons)

Engineering run:
JINST 11 (2016) P07024

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

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**

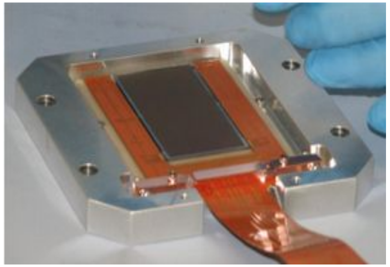
Engineering Run

2016-2018 (1x1) Run

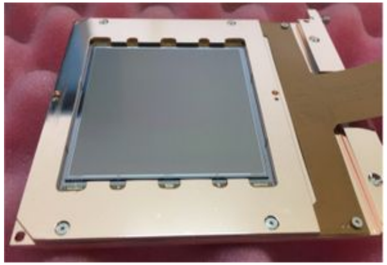
2019 (1x5) Run

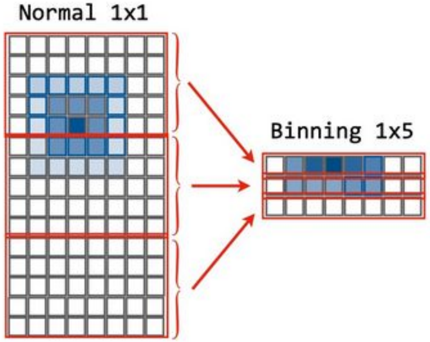
Skipper-CCD Run

Instalation at Angra

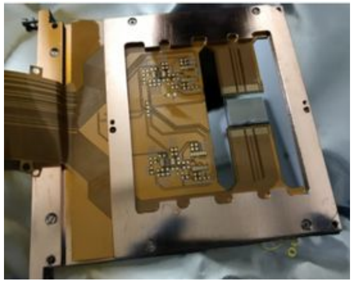


Upgrade to Scientific CCDs

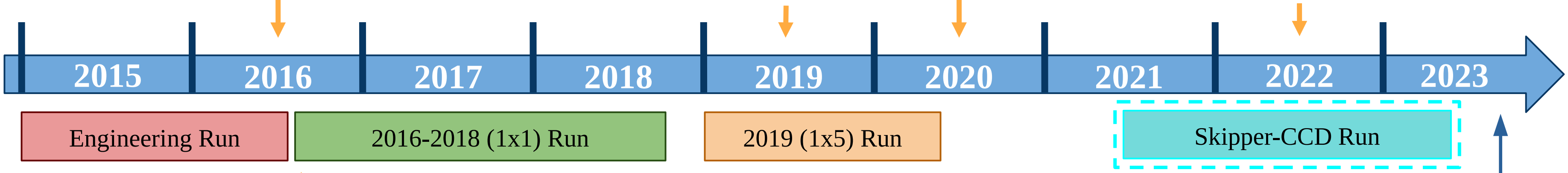




Installation of Skipper-CCDs



CONNIE timeline



Community milestone

Limits on SM extensions with light mediators
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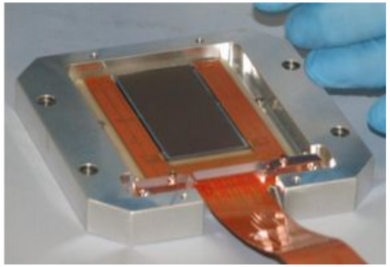
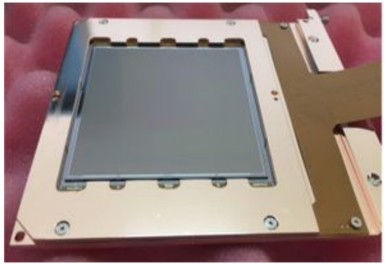
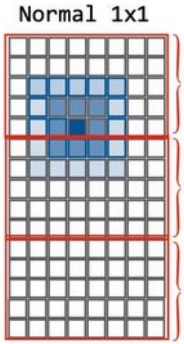
Instalation at Angra



Upgrade to Scientific CCDs



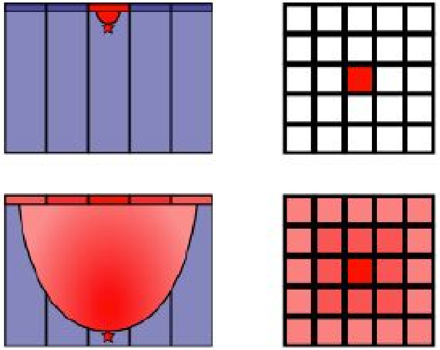


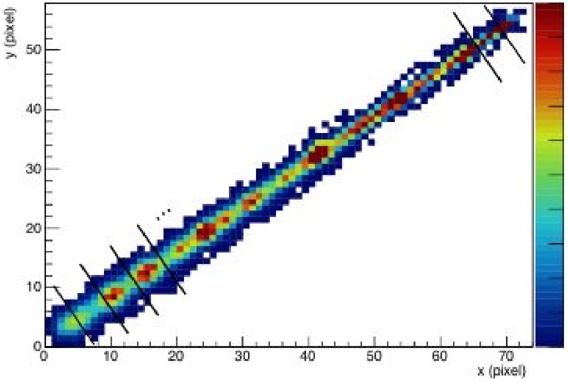
Ongoing physics analyses:

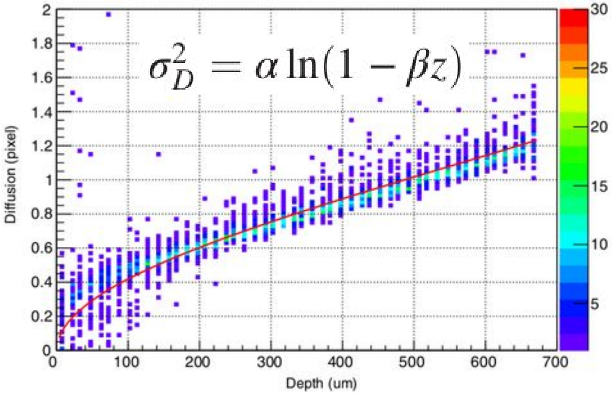
- Millicharged particle search
  [See talk by AA-A @TAUP23]
- DM search through diurnal modulation
  [See talk by Nicolás Avalos @TAUP23]

CONNIE 2016-2018 run (1x1 DAQ)

- Characterize depth-size relation with muon tracks



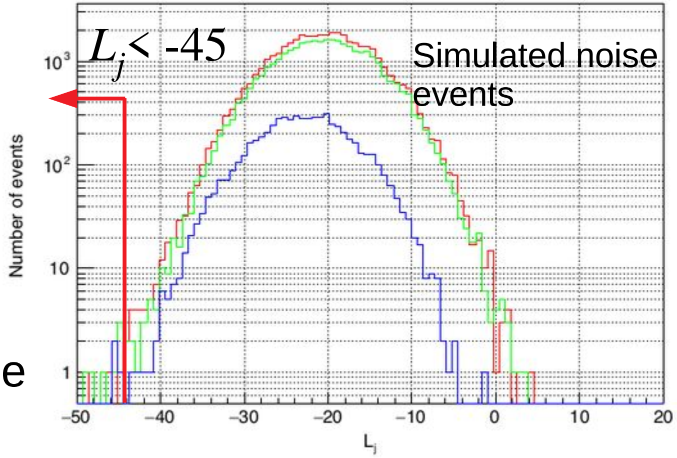




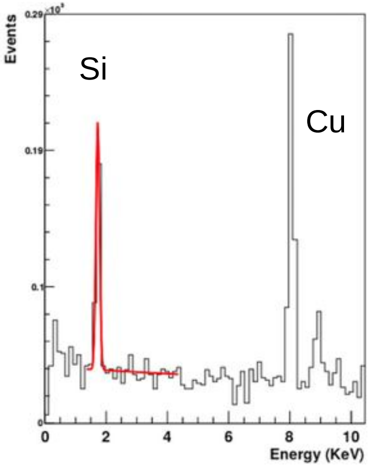
- Low-E event selection based on likelihood test over the *N* pixels in each event "*j*":

$$L_j(P_1,\ldots,P_N|\sigma)=\sum_{i=1}^{N}(-1)^{n_i}\left(\frac{P_i^2}{2\sigma^2}+\log(\sqrt{2\pi}\sigma)\right)$$

Neutrino-like events: $L_j < -45$.

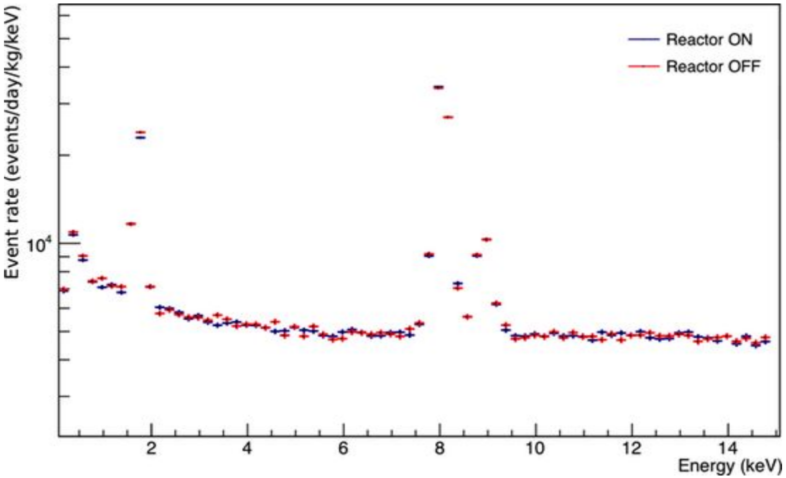


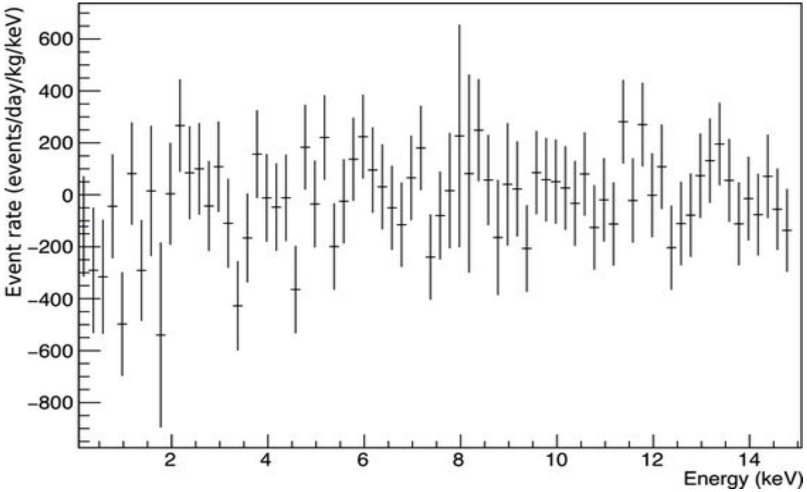
- Energy calibration with Si and Cu fluorescence peaks.



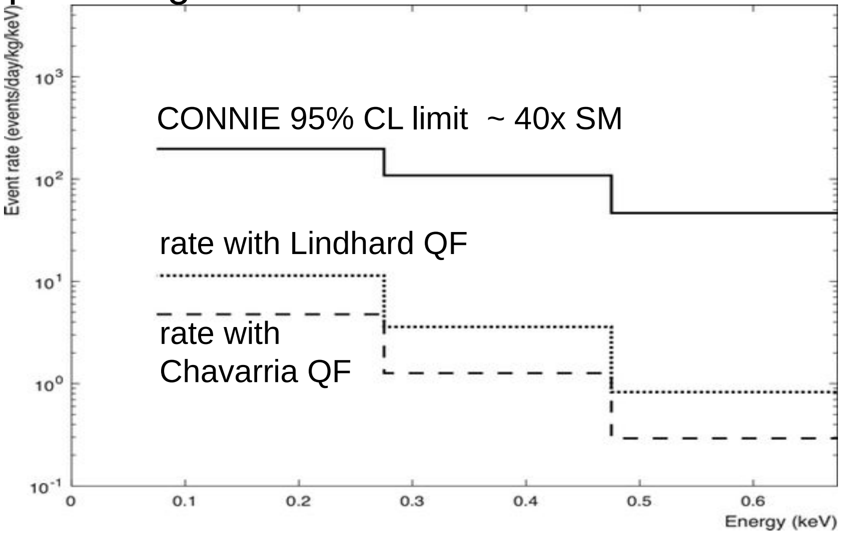
CONNIE results 2016–2018

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 the quenching factor.

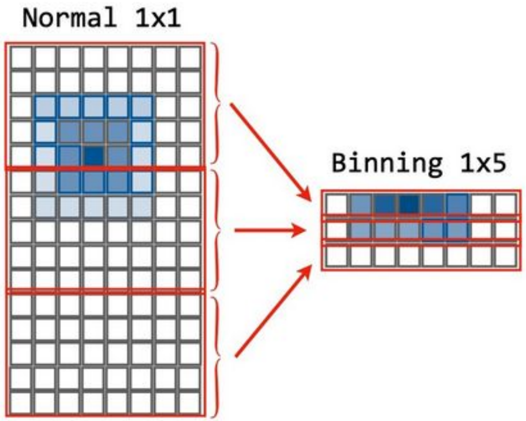


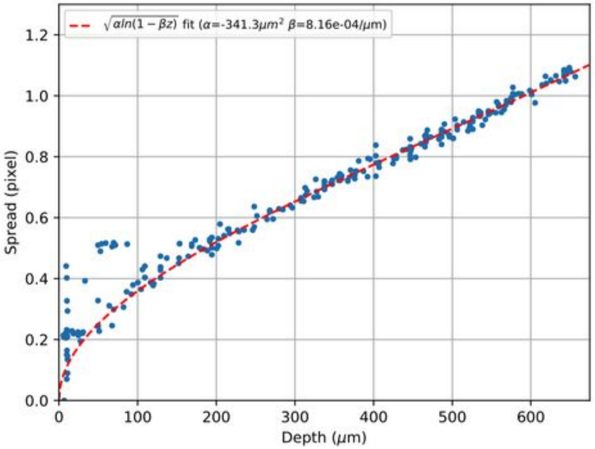
CONNIE 2019 run

JHEP 05:017, 2022

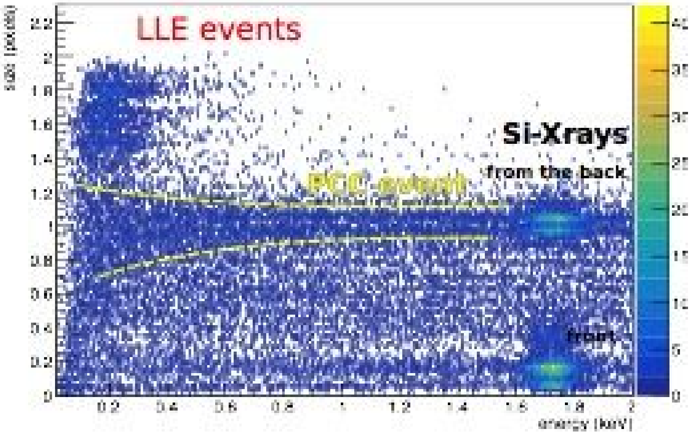
Improvements in data acquisition and analysis techniques:

- 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.



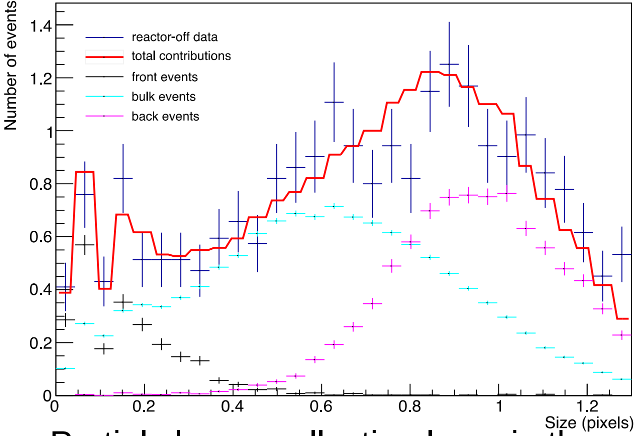


Depth-size muon calibration



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

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



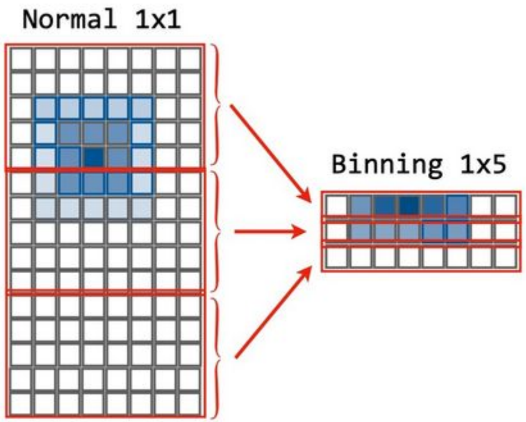
Partial charge collection layer in the back side of the sensor.

CONNIE 2019 run

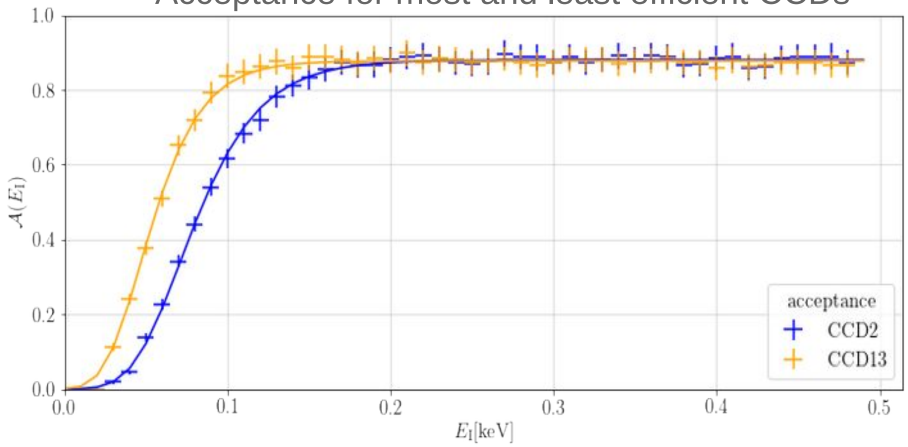
JHEP 05:017, 2022

Improvements in data acquisition and analysis techniques:

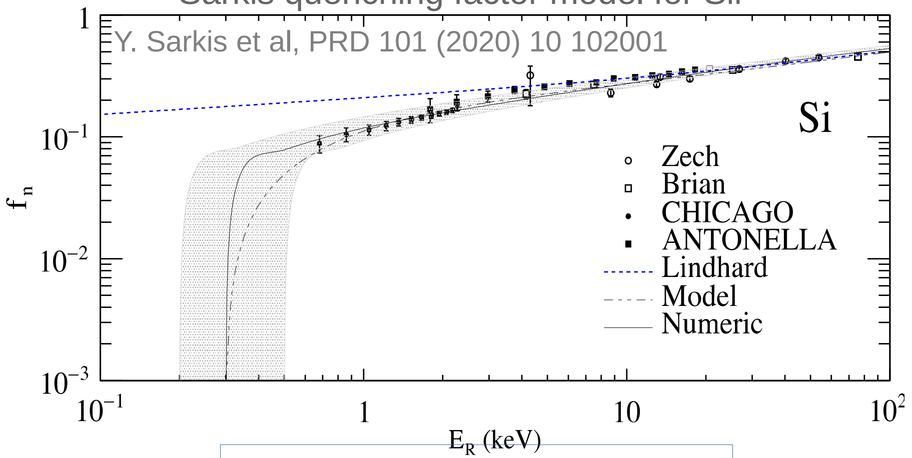
- Improved determination of the efficiency.
  - Detection threshold reduced to ~50 eV.
  - Full efficiency reached at 100-150 eV.
- Blind analysis and multiple crosschecks.
- Used Sarkis quenching factor model for ionisation efficiency at low E.



Acceptance for most and least efficient CCDs



Sarkis quenching factor model for Sii



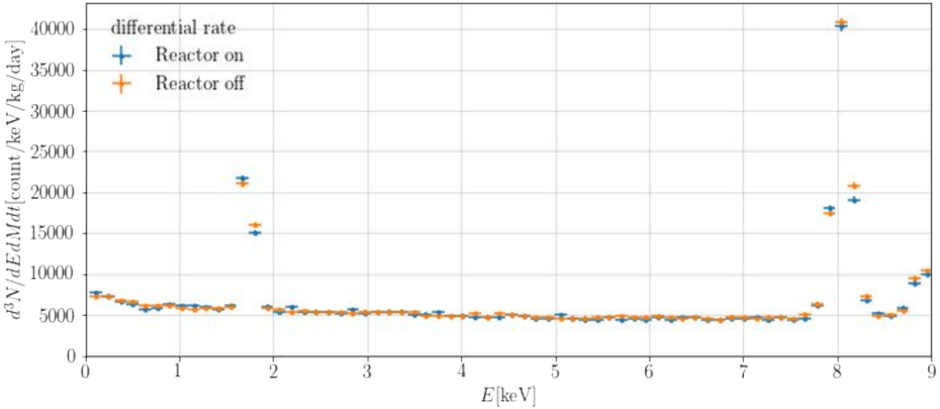
Y. Sarkis et al, PRD 101 (2020) 10 102001

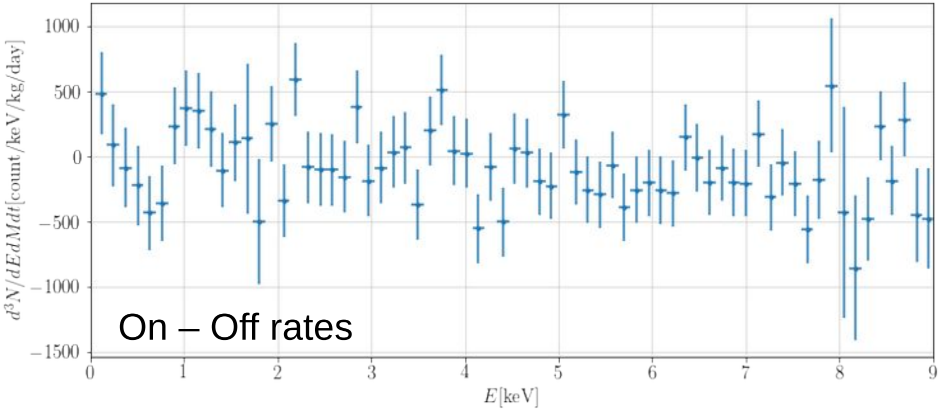
See Y. Sarkis.talk on Low-E Si QF.

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.

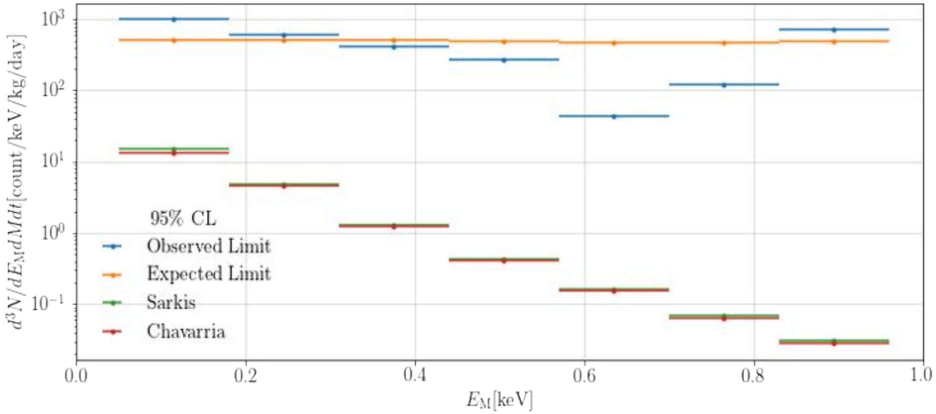




On – Off rates

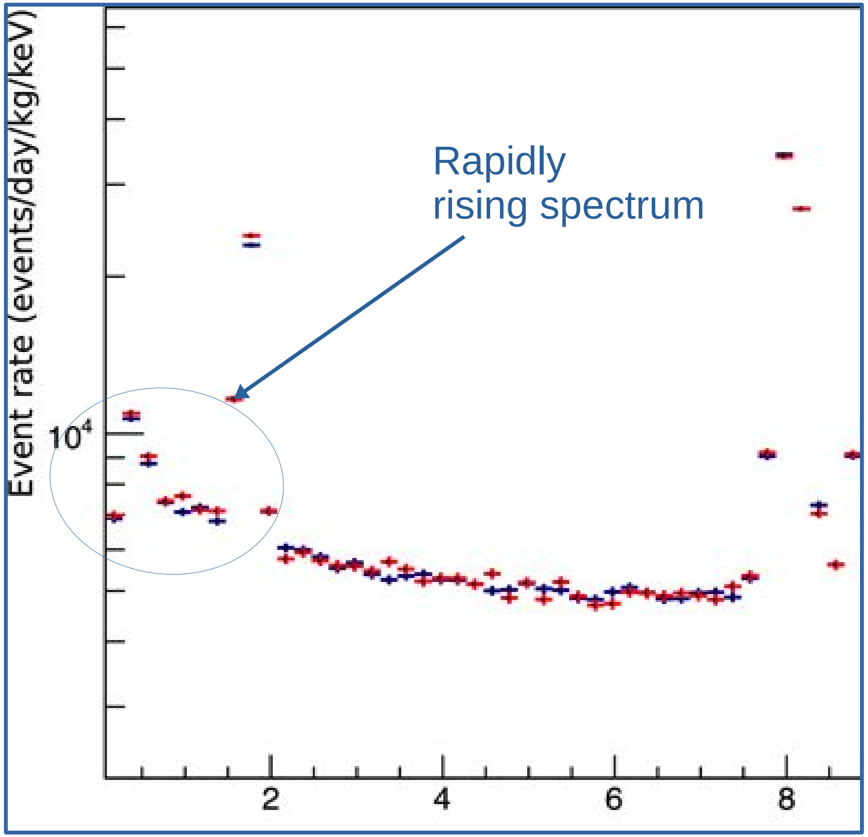
Upper limits at 95% CL on the measured CEvNS rate. Lowest energy bin:

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



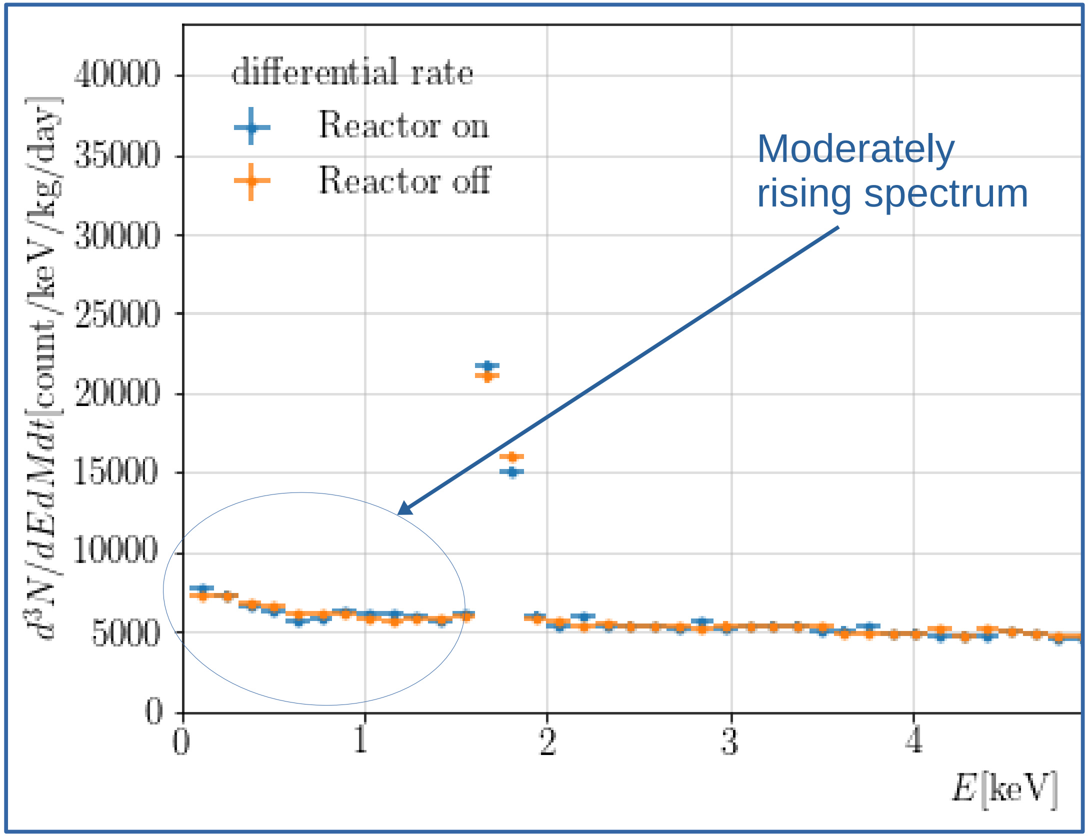
CONNIE pre-Skipper Low-E spectra

2016-2018 data: PRD 100 (2019) 092005



Rapidly rising spectrum

2019 data: JHEP 05:017, 2022



Moderately rising spectrum

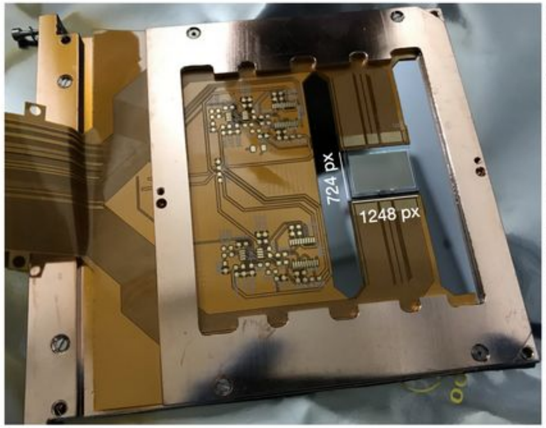
- Improvements due to binning and better SNR

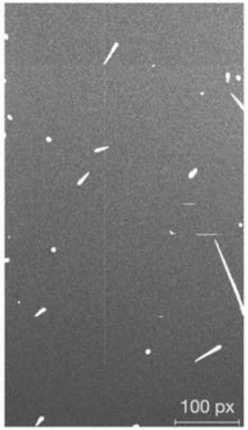
CONNIE with Skipper-CCD’s

See talks by M. Cababie, R. Smida and M. Trania on Skipper CCDs

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

- 0.5k x 1k pixels ea, 675 µm thick, ~0.5 g total mass.
- New electronics LTA “*Low Threshold Acquisition*”.
- New Vacuum Interface Board (VIB).



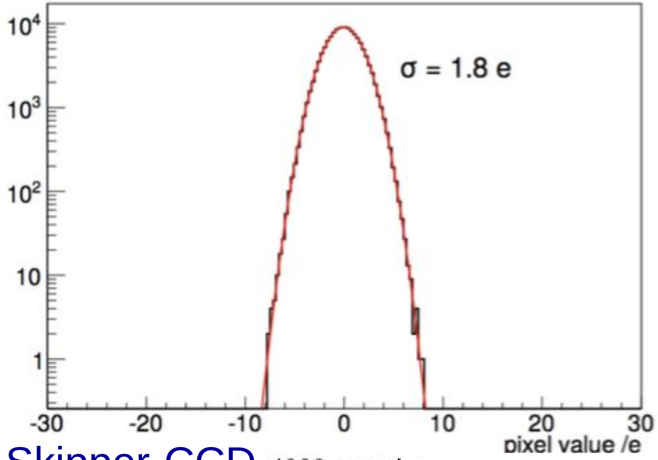


LTA electronics

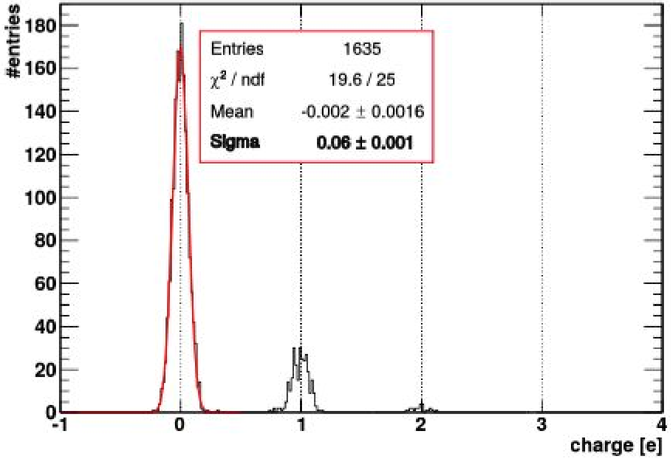
Skipper CCD

- 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.
- **Continuous readout mode:**
  - Large number of samples → long readout time
  - Exposure acquired during readout.
  - Exposure time ~ ½ Readout time.

Standard



Skipper-CCD 4000 samples

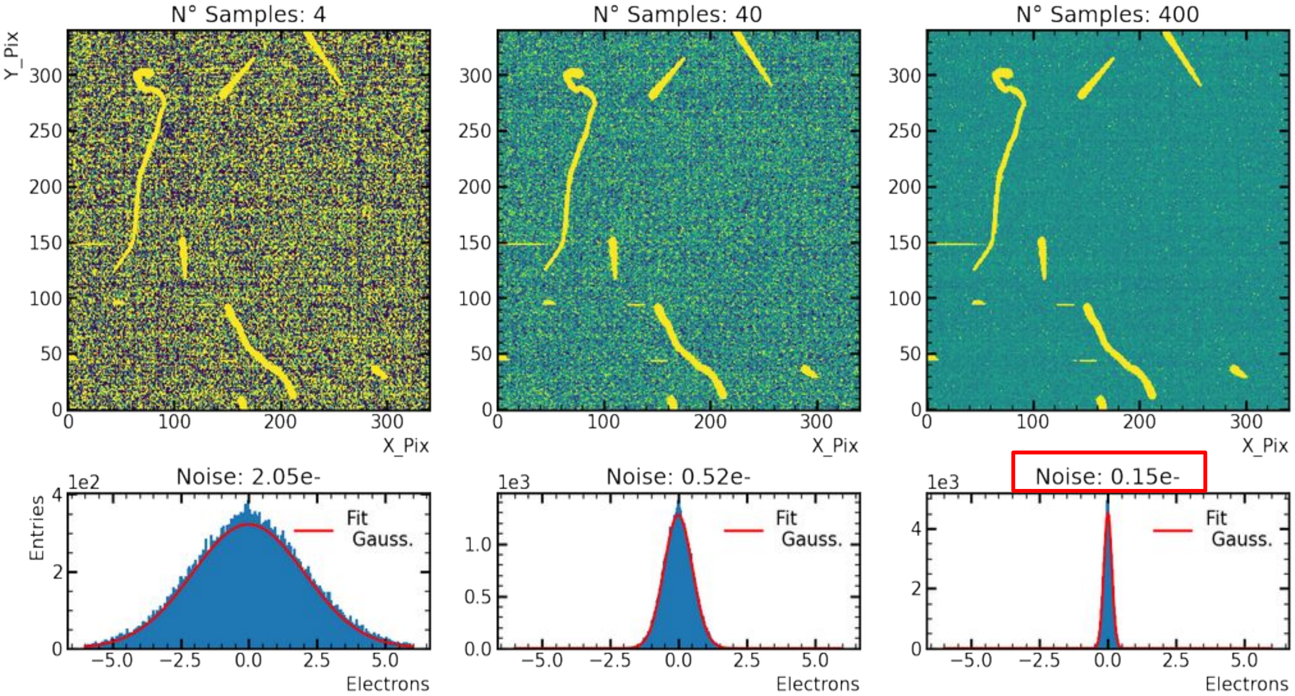


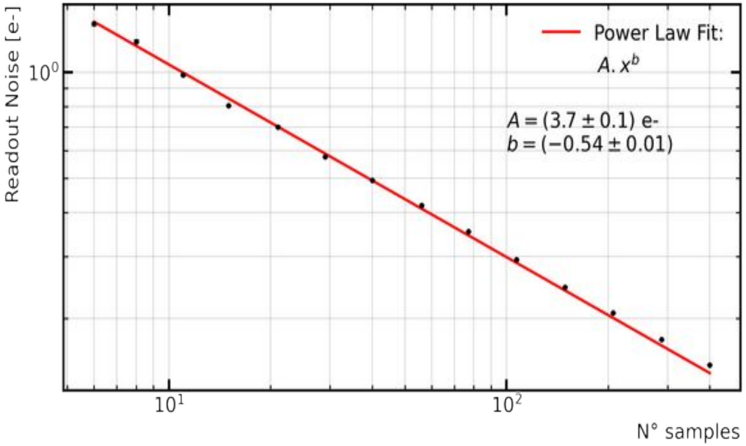
Skipper-CCD performance

Preliminary

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

Plots by Pedro Ventura





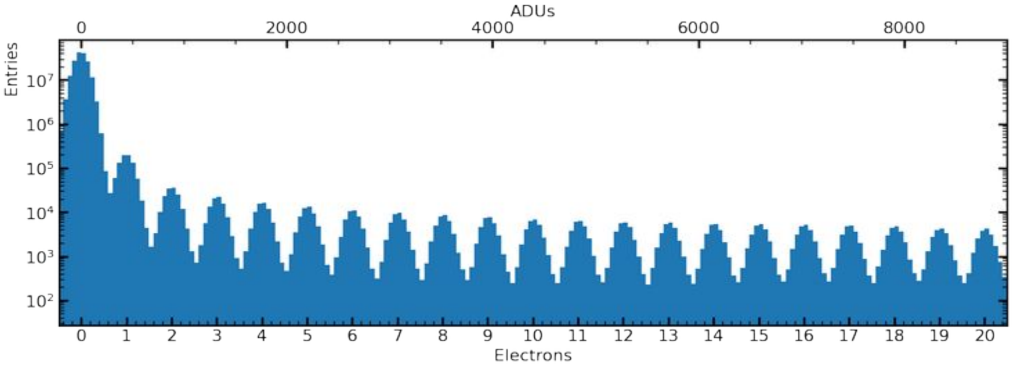
$$\sigma = \frac{\sigma_1}{\sqrt{N}}$$

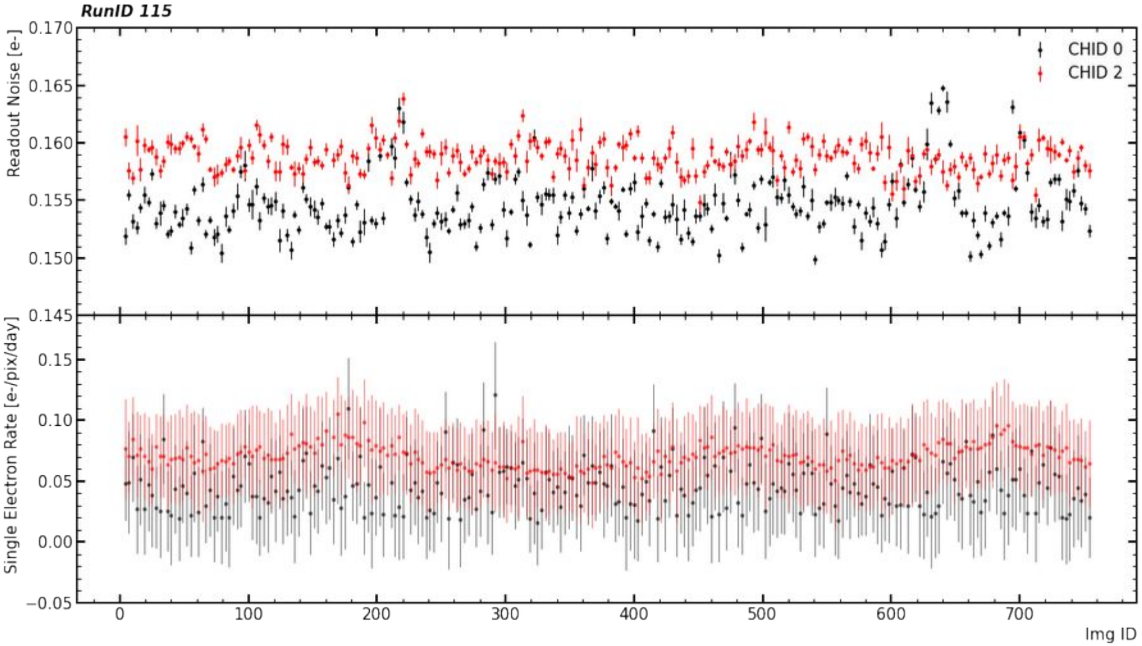
Skipper-CCD performance

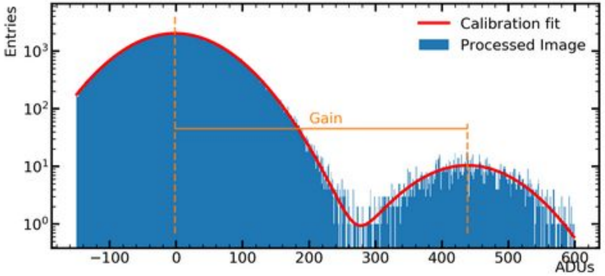
Preliminary

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

  Seed pix uses 1.6 e-. Add pix with 0.6 e (single e- rate at surface is high). Limits our threshold.







Preliminary:

Noise = 0.16 e-

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

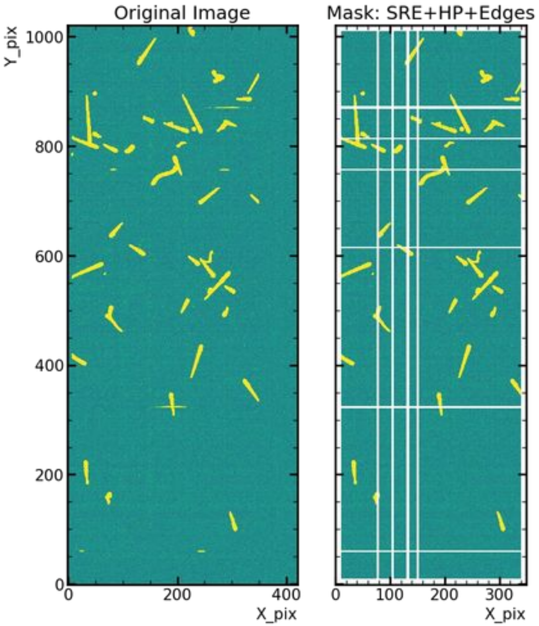
(very good for surface level)

Plots by Pedro Ventura

Skipper-CCD Serial Register Events

→ Serial Register Events - SRE:

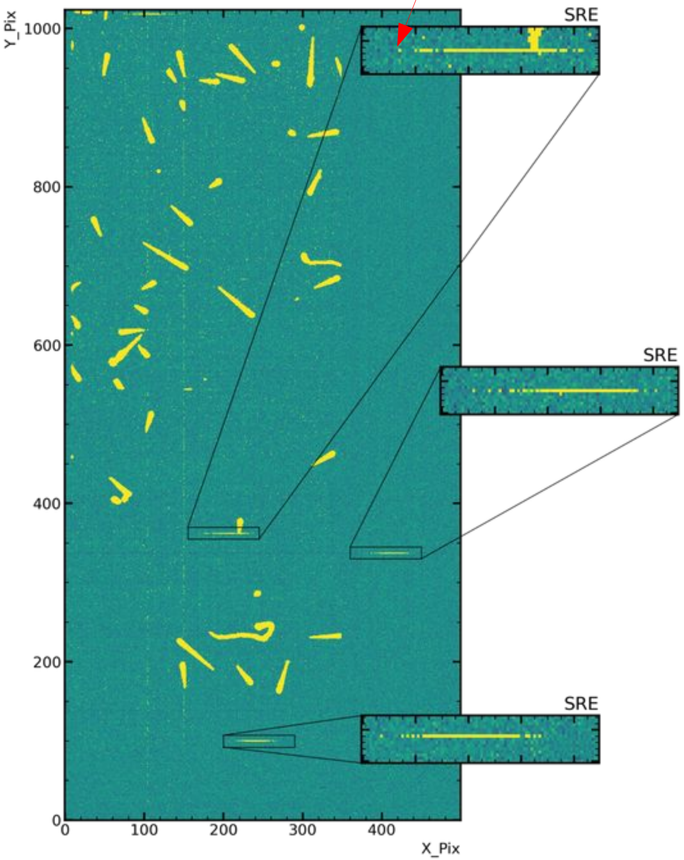
- Horizontal events due to particles that interact with a region of inactive silicon and charges reach the pixels in the Serial Register.
- Isolated charges can be misidentified as diffusion-limited hits → Background events to avoid.



analysis and plots by Pedro Ventura & Carla Bonifazi

→ Masking Routine:

- Rows with SRE are masked;
- Rows/column with too many charged pixels and hot pixels are masked;
- 10 Pixels masked around the border of the active region;
- Events with their barycenter over a masked area are flagged and excluded from analysis.



Isolated charge in SRE row

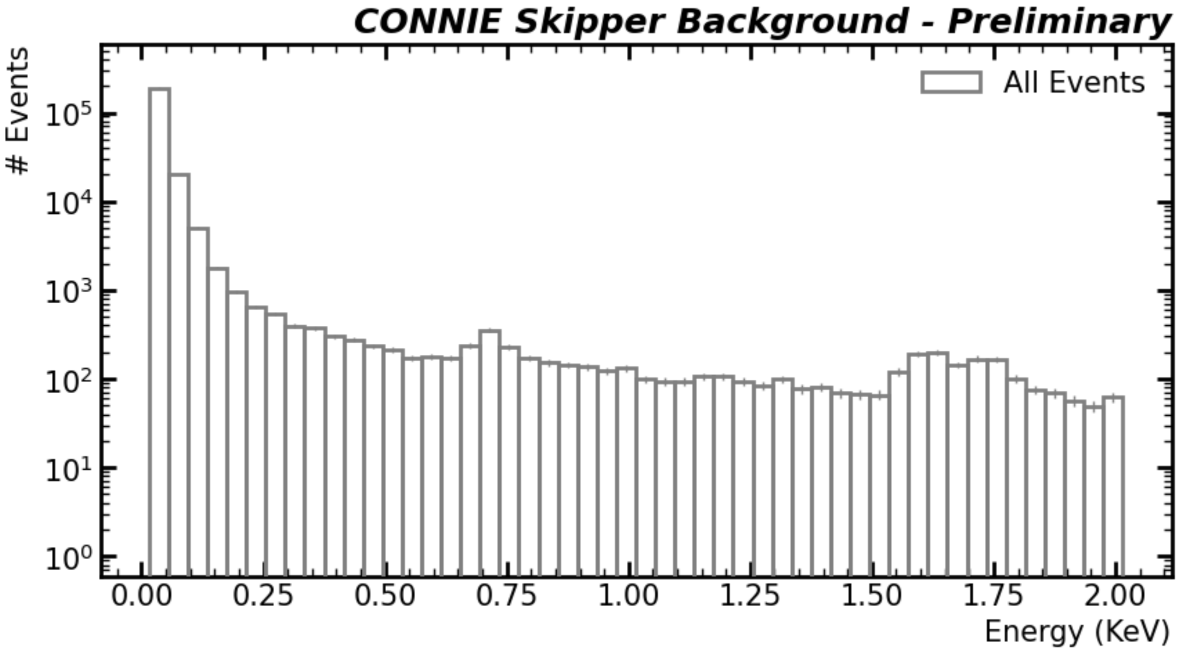
Skipper-CCD event selection

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.



Skipper-CCD event selection

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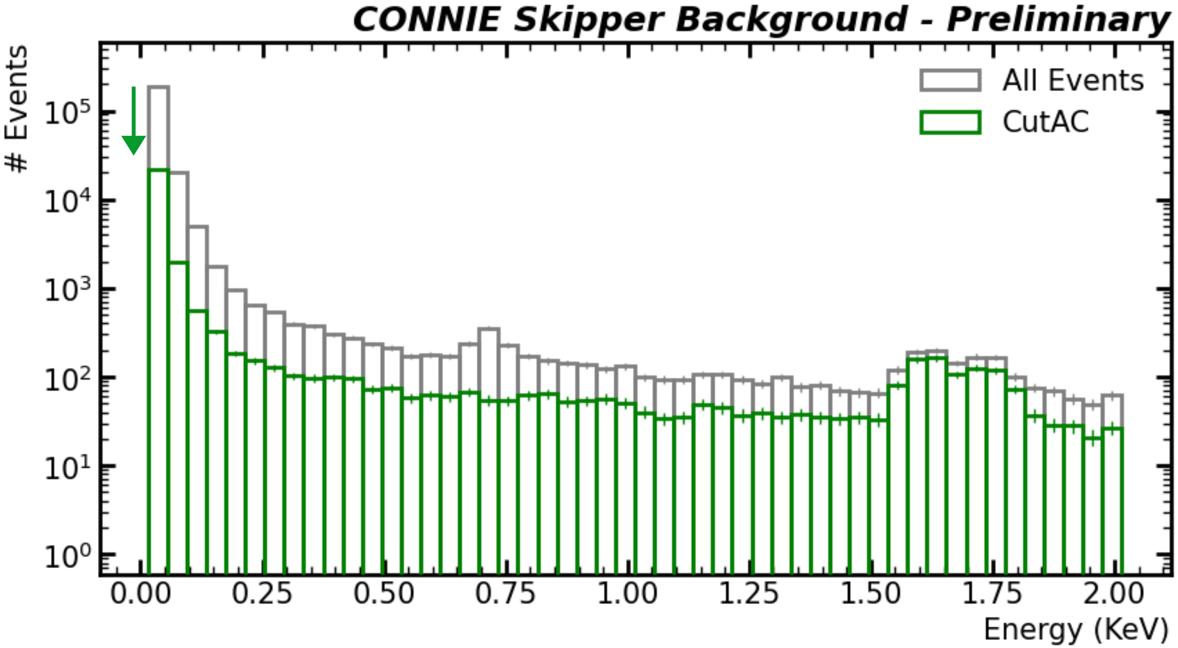
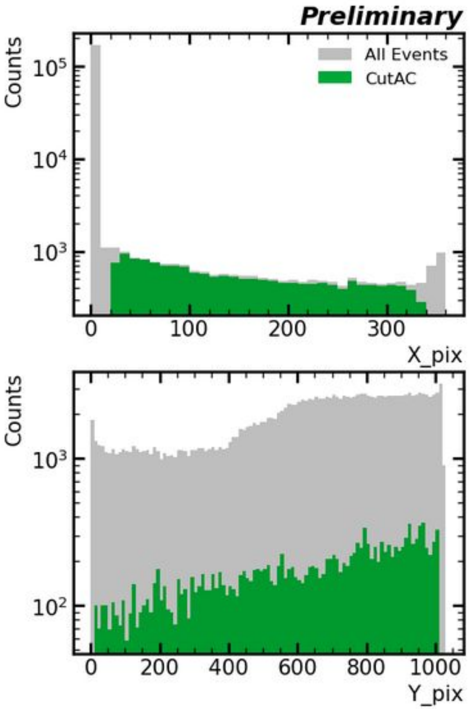




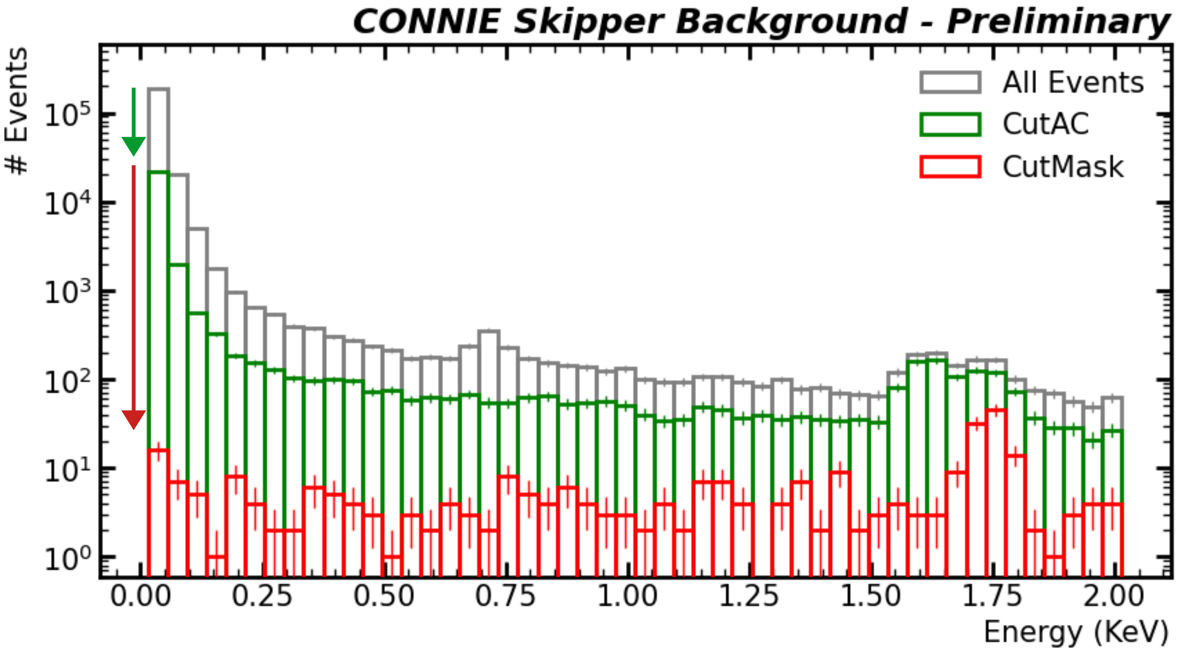
Skipper-CCD event selection

Preliminary

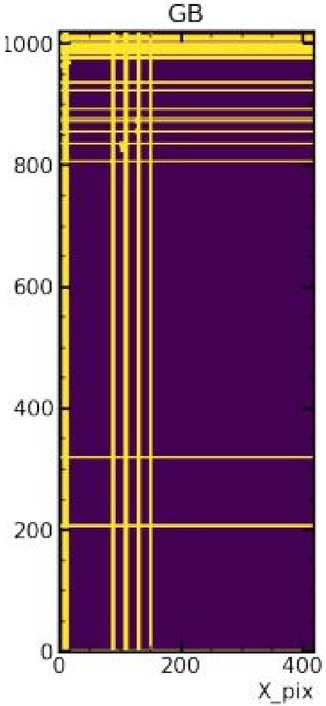
Selection cuts for Reactor-OFF data:

⌐ **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.



Most aggressive cut down by × few 1000 in first bin!



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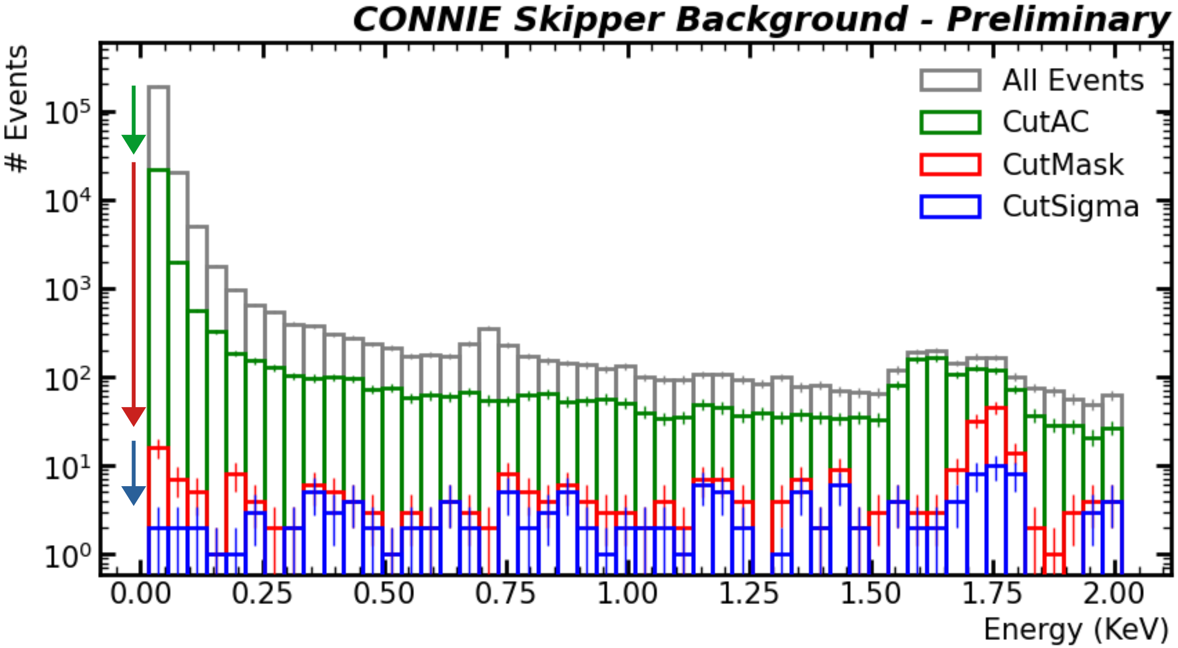
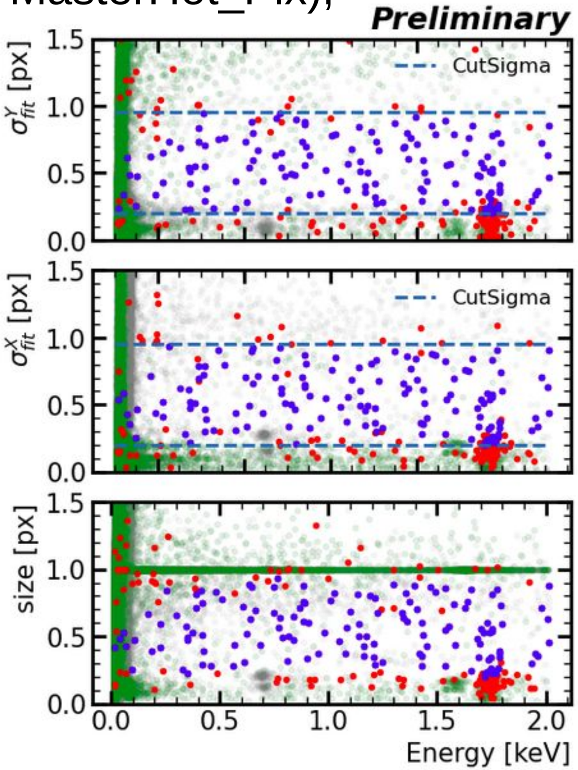
0.2- limited by our reco-algo
0.95- same as in 2019 (PCC)

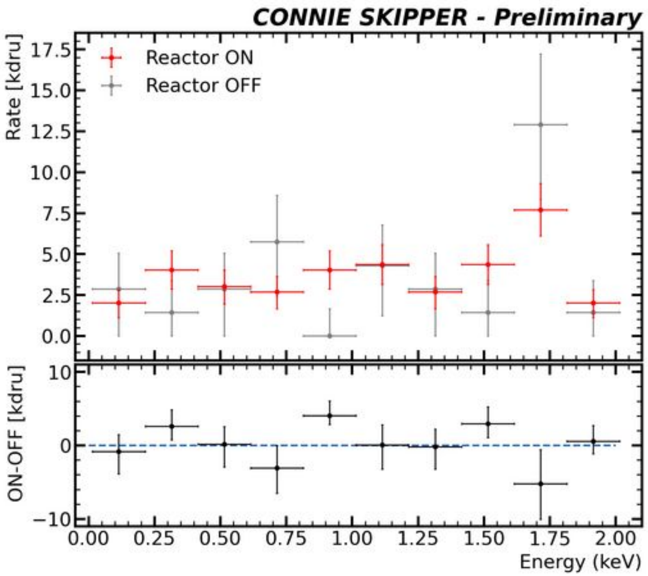


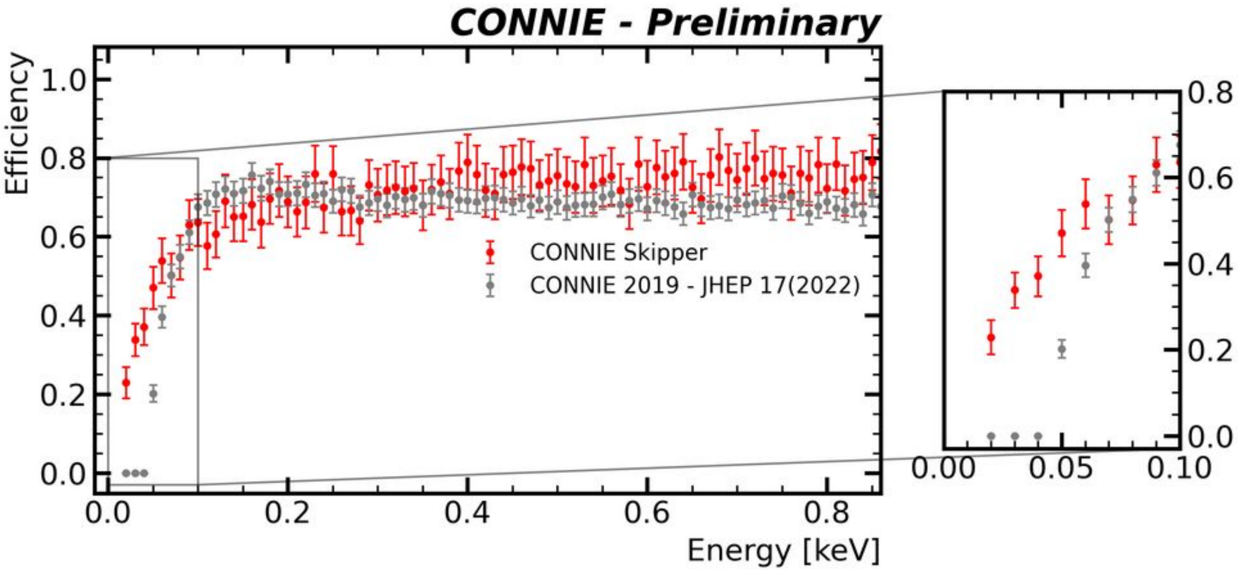


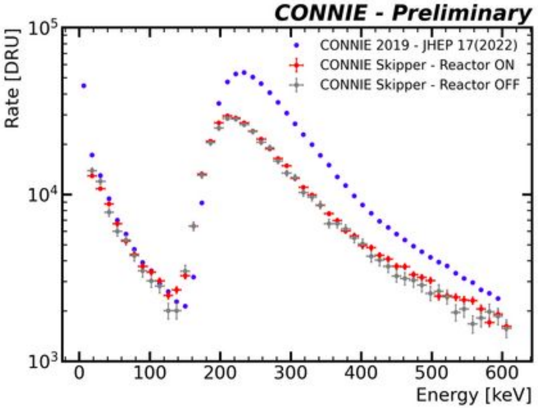
Skipper-CCD results

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 reactor ON-OFF spectrum.





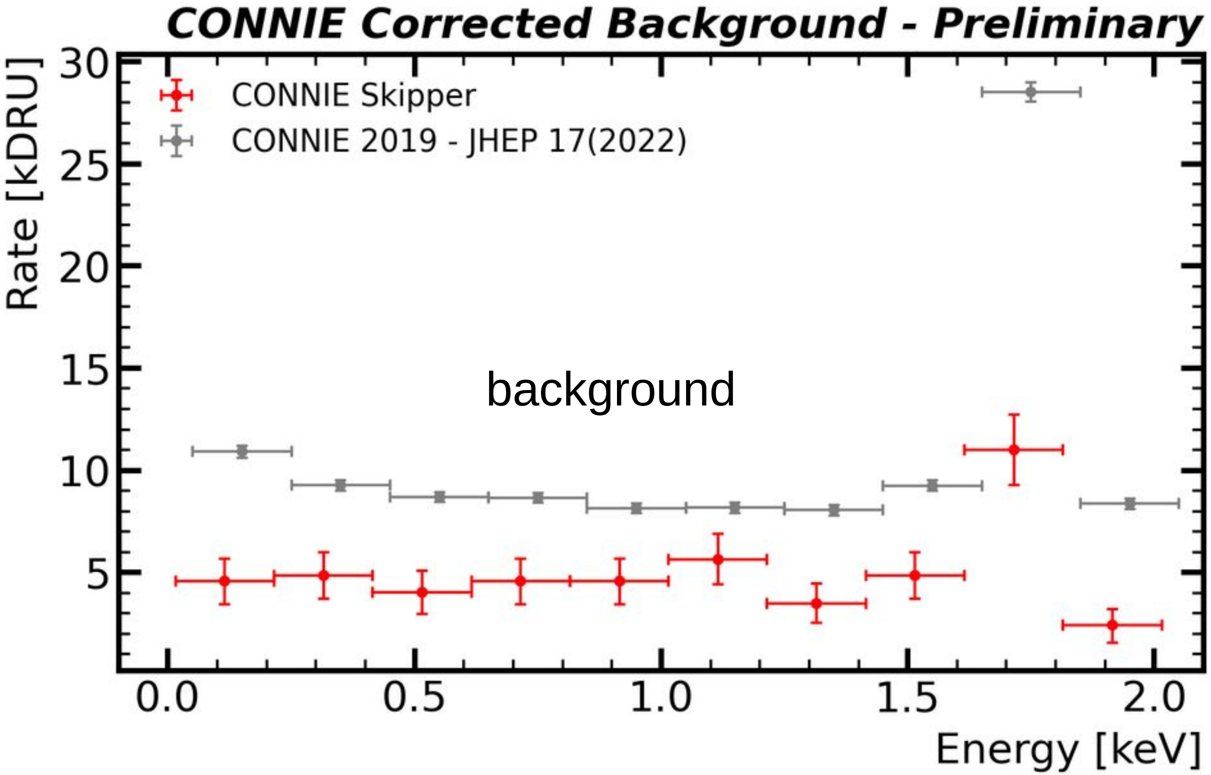


Plots by Pedro Ventura

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

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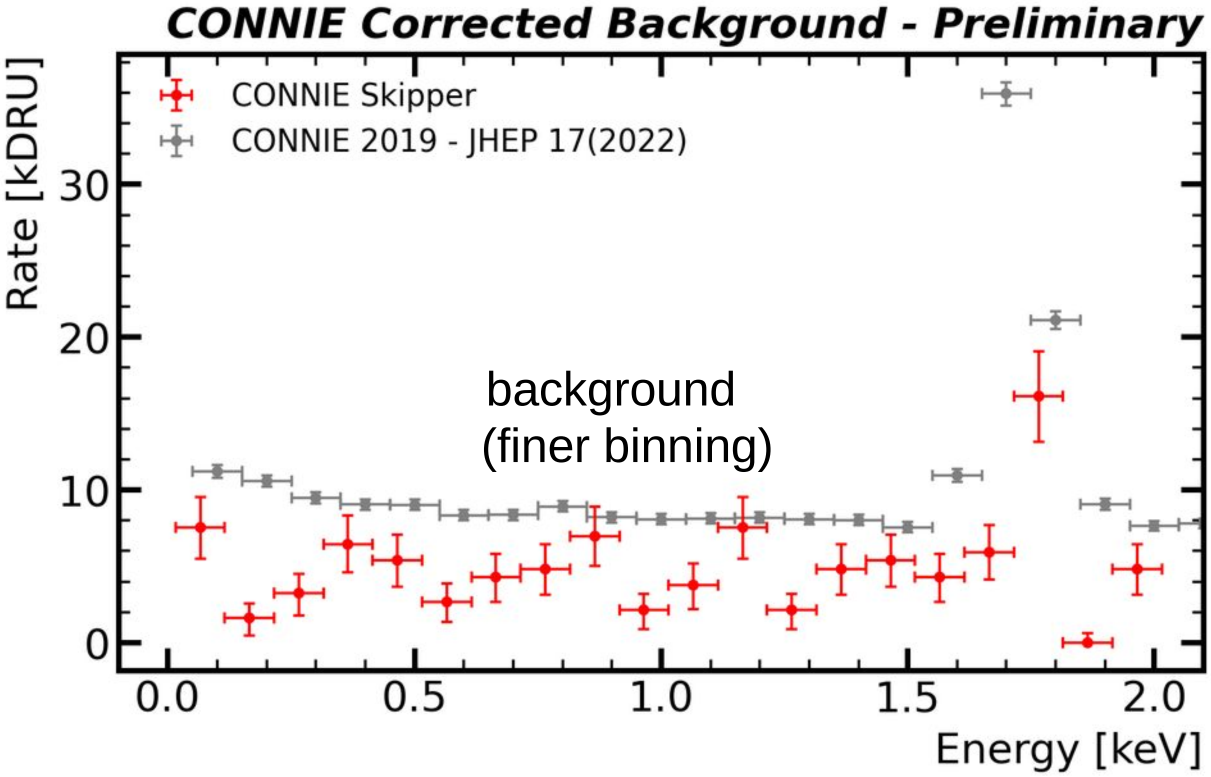


background
(finer binning)

Plots by Pedro Ventura

CONNIE future perspectives

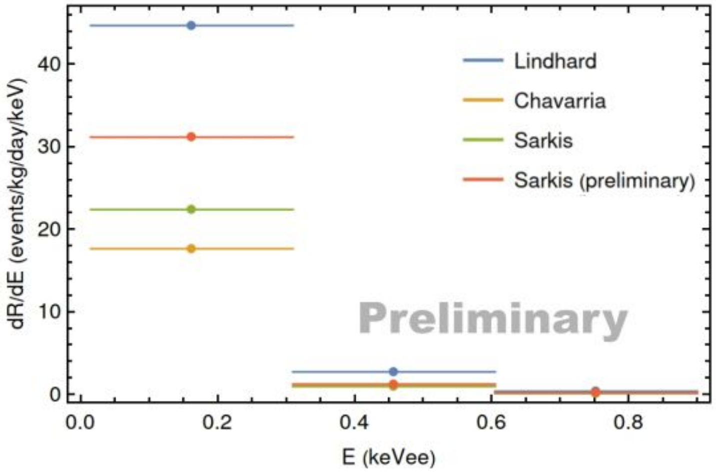
- Assuming a 20 eV threshold , we expect a CEνNS rate 2.2 times higher than in 2019.
- A 1 kg detector at the CONNIE site, with a bkgd rate of 4 kdru should observe CEνNS at 90% C.L. in 11 days (Lindhard QF) or ~2 months (Chavarria QF).
- Current plan is to increase the sensor mass using the Oscura MCM design.
- Considering a larger increase in scale in the future.

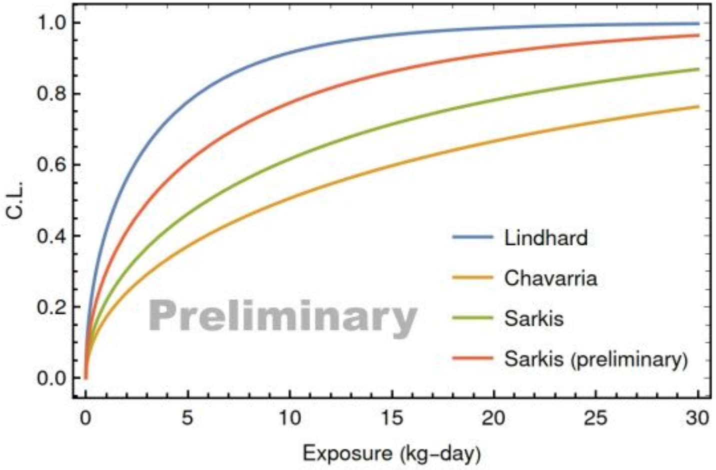

Multi-Chip Module (16 CCDs → 8 g)
Super Module (16 MCMs → 100 g)

Oscura experiment design

[arXiv:2304.04401]

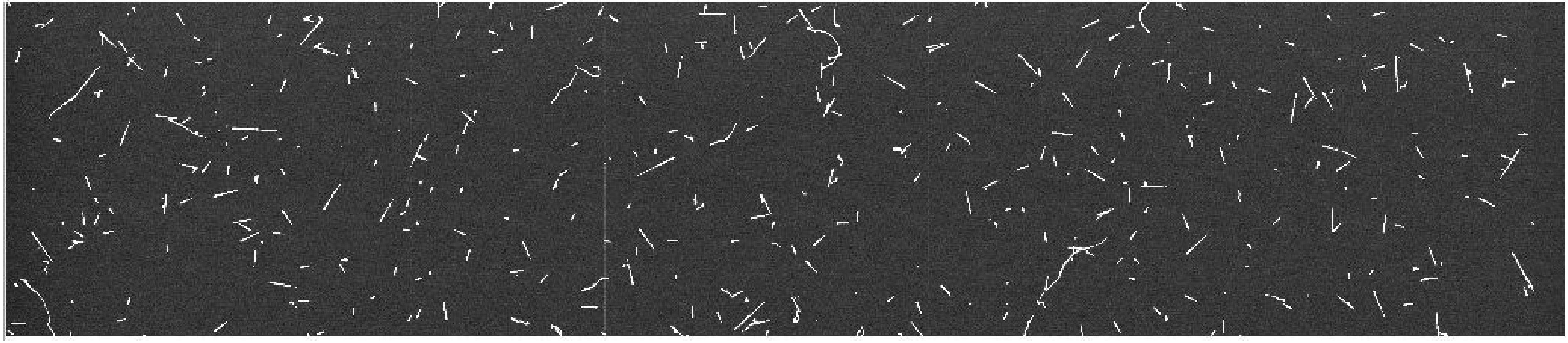
- Negotiations with Angra underway to move at 20 m from core (inside dome)





Summary and outlook

- CONNIE was the first experiment to install Skipper-CCDs at a reactor in 2021.
- Excellent Skipper-CCD performance: improved efficiency and background levels.
- Aggressive event selection cuts yield **flat background spectrum**, reduced by a factor of ~2 compared to 2019 data (standard CCDs).
- Very promising results. Need to install **larger sensors** to **verify flatness** of Low-E spectrum **with increased statistics**.
- Plans to increase the sensor mass and move inside the reactor dome underway.
- New physics analyses with Skipper data ongoing.

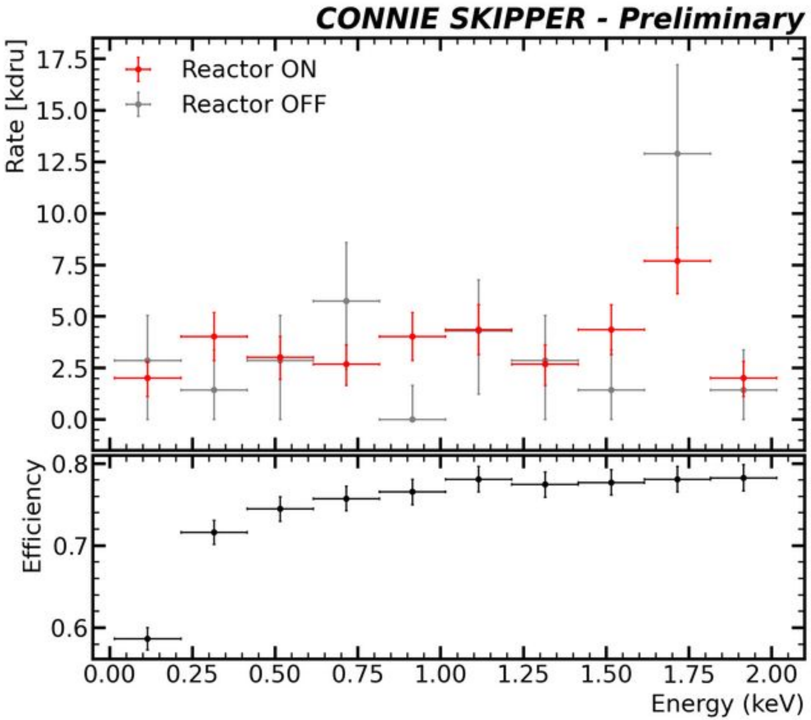


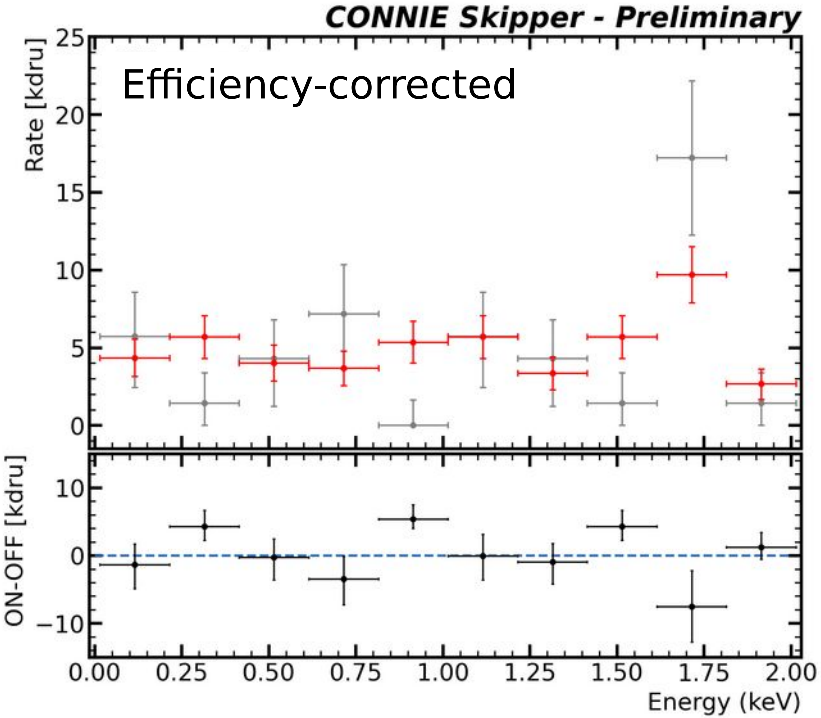
AAA acknowledges support from DGAPA-UNAM grants PAPIIT-IN106322 y PAPIIT-IN104723, and CONACYT grant CF-2023-I-1169

BACKUPS

Skipper-CCD results

Preliminary

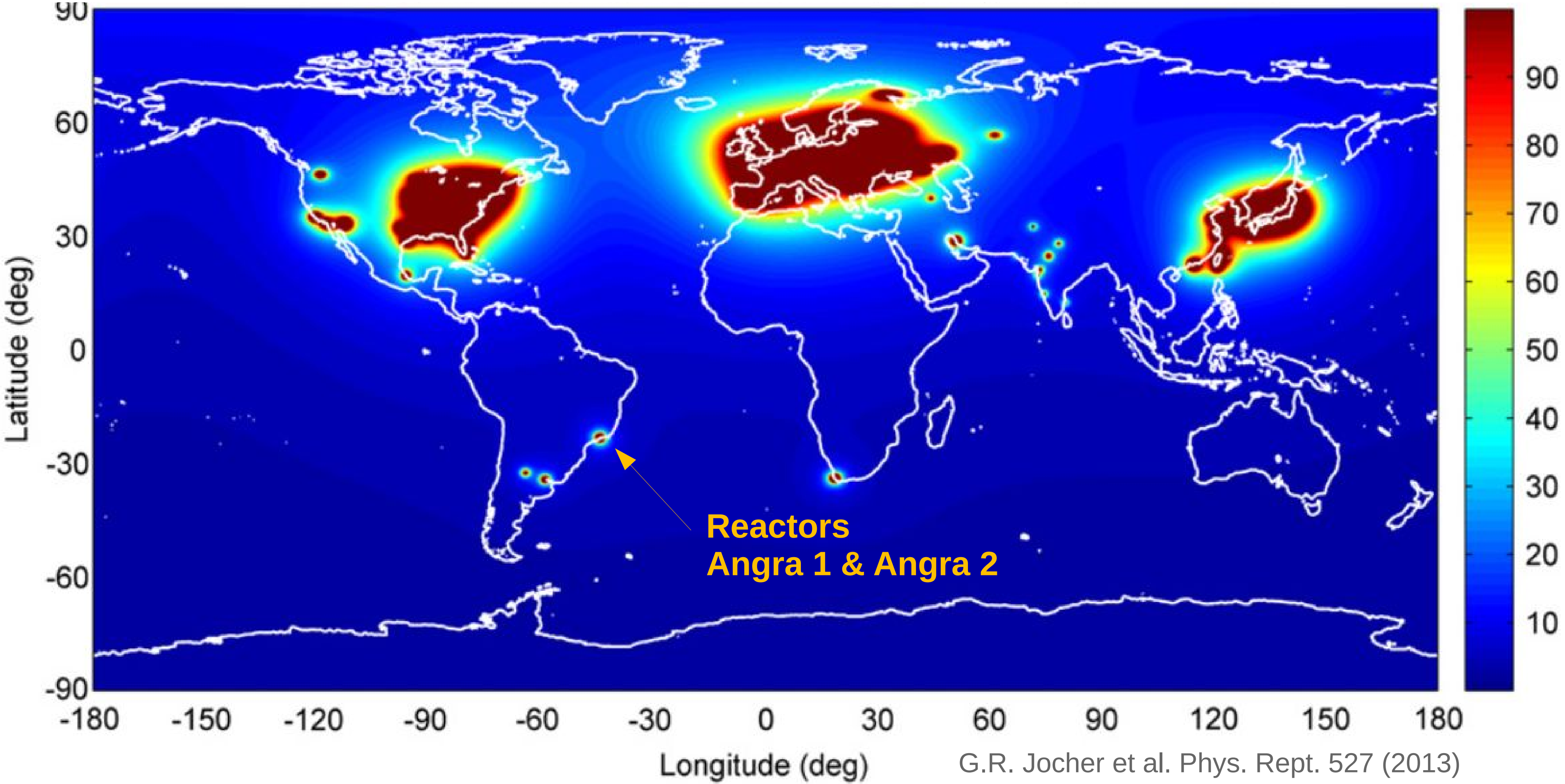




- Flat ON & OFF spectra down to 15 eV,
- Flat ON-OFF consistent witn zero.

Plots by Pedro Ventura

Reactor antineutrinos



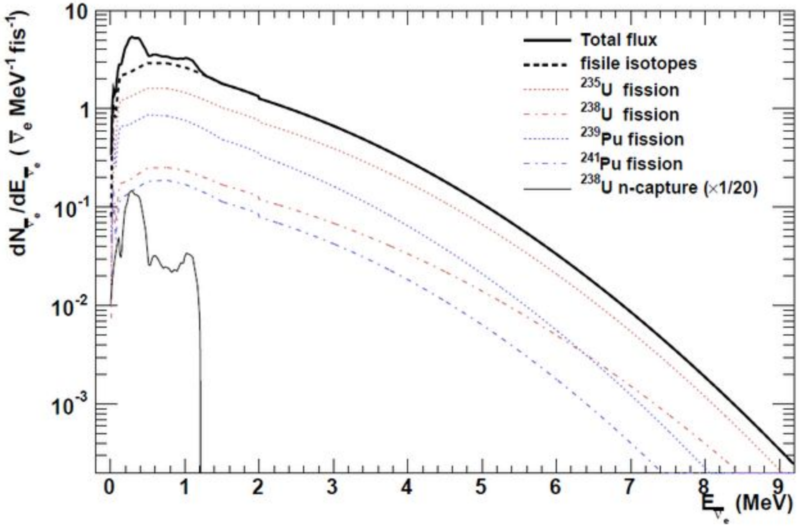
Reactors
Angra 1 & Angra 2

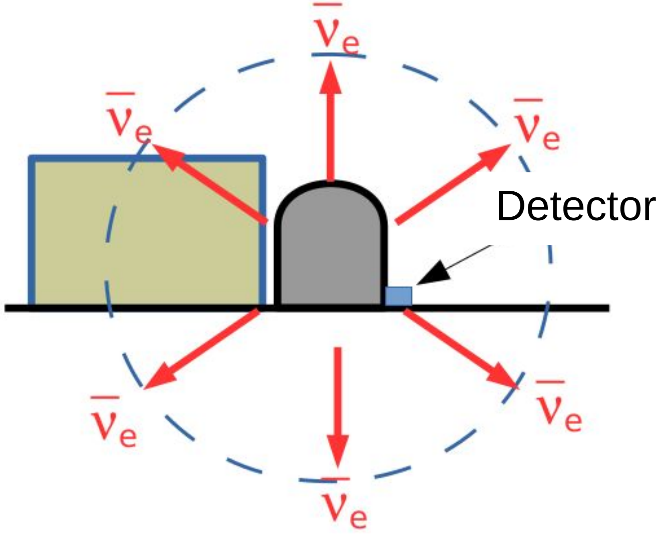
G.R. Jocher et al. Phys. Rept. 527 (2013)

Angra-2 Antineutrino flux

- 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.

$$fisRate = \frac{3.95\ \mathrm{GW}_{th}}{205.24\ \mathrm{MeV/fis}} \approx 1.2\times10^{20}\ \mathrm{fis/s}$$

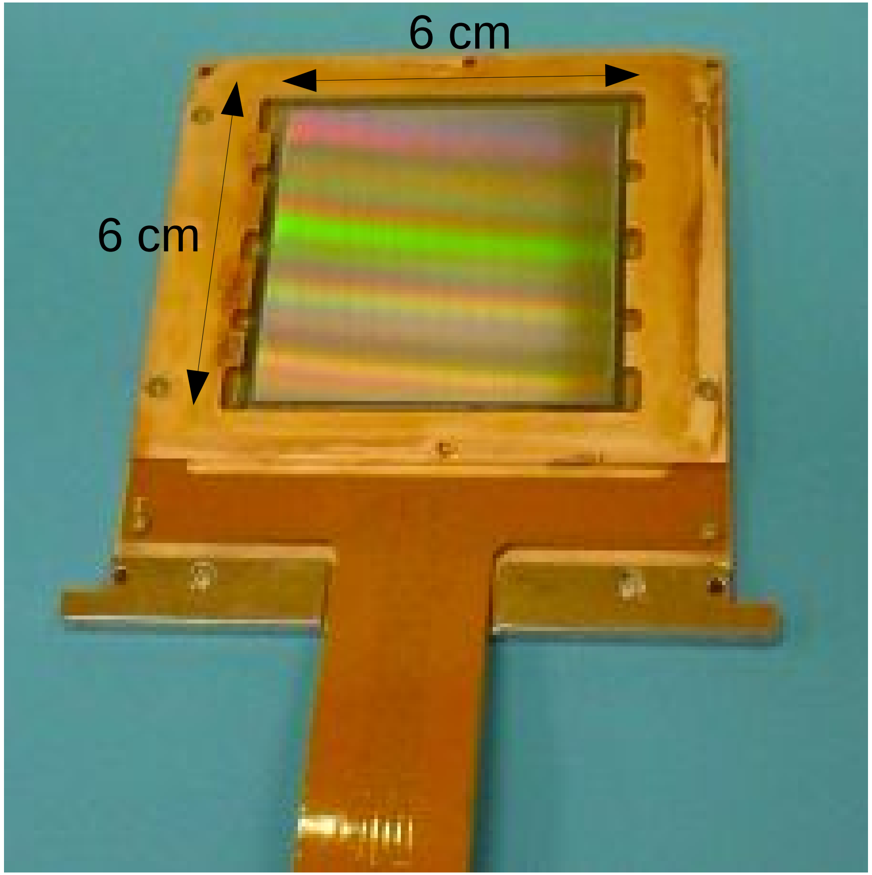




Dominant processes	(E release)	fis.frac.	$\bar{\nu}_e$/proc	$\bar{\nu}_e$/fis
^{235}U fission	202 MeV	0.56	6.14	3.43
^{238}U fission	205 MeV	0.08	7.08	0.56
^{239}Pu fission	210 MeV	0.30	5.58	1.67
^{241}Pu fission	212 MeV	0.06	6.42	0.38
n-capture on ^{238}U	202 MeV	0.60	2.00	1.20

<E rel> = 205.24 MeV/fis Tot: 7.24

CONNIE CCD (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.

Constraints to physics BSM

JHEP 04 (2020), 054

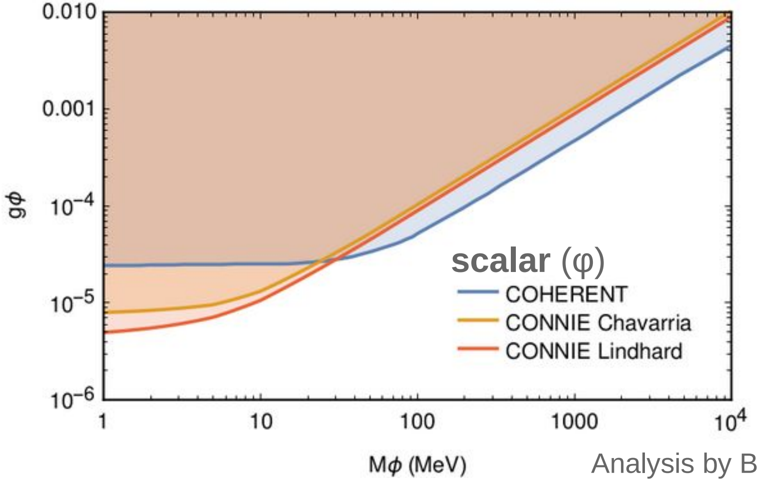
- Event rate in lowest E bin gives limits to non-standard neutrino interactions: Simplified models with light **scalar** (φ) and **vector** (Z’) mediators.
- Restrictive limits for low mediator masses $M_\varphi < 30$ MeV, $M_{Z'} < 10$ MeV.
- First competitive constriction to BSM physics from CEvNS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

NEUTRINO 2020

Community milestone

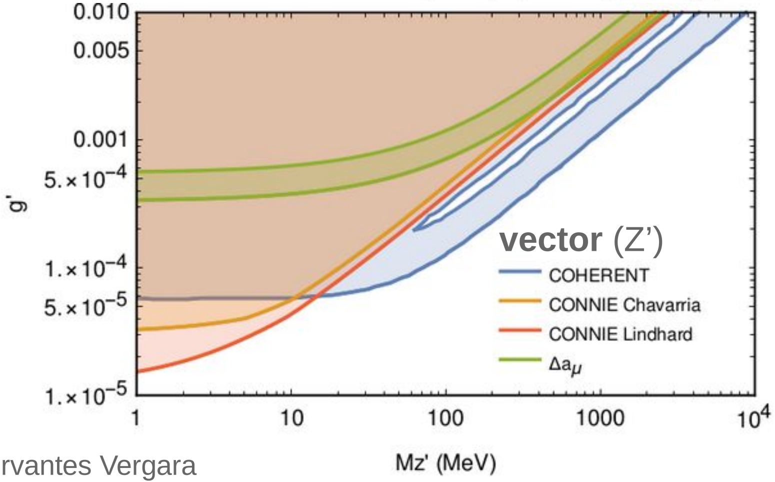
$$\frac{d\sigma_{SM+\phi}}{dE_R}(E_{\bar{\nu}_e}) = \frac{d\sigma_{SM}}{dE_R}(E_{\bar{\nu}_e}) + \frac{G_F^2}{4\pi}Q_\phi^2\left(\frac{2ME_R}{E_{\bar{\nu}_e}^2}\right)MF^2(q)$$

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



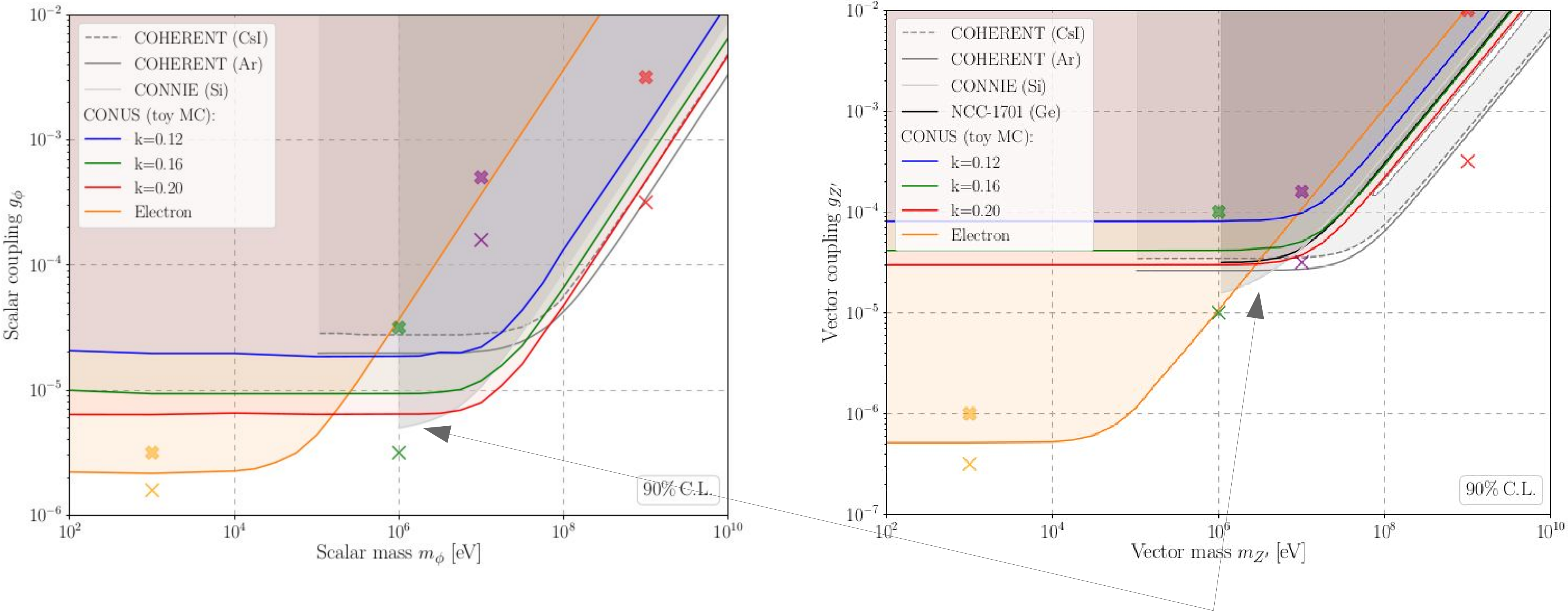
$$\frac{d\sigma_{SM+Z'}}{dE_R}(E_{\bar{\nu}_e}) = \left(1-\frac{Q_{Z'}}{Q_W}\right)^2\frac{d\sigma_{SM}}{dE_R}(E_{\bar{\nu}_e})$$

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



Analysis by Brenda Cervantes Vergara

Constraints to physics BSM



Scalar mediator

Vector mediator

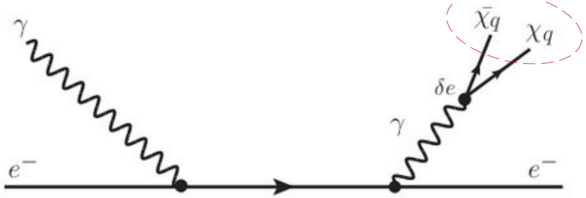
CONNIE

CONUS Collab. JHEP, 085, 05, 2022

Search for millicharged particles

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

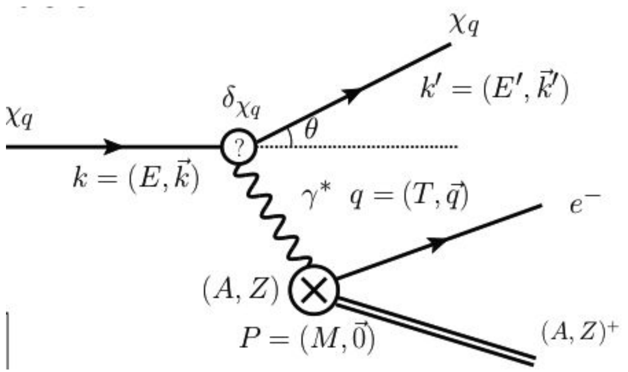
Production: Compton-like scattering of high energy γ's from reactors.



γ energy spectrum gives diff, flux. of χ_q :

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

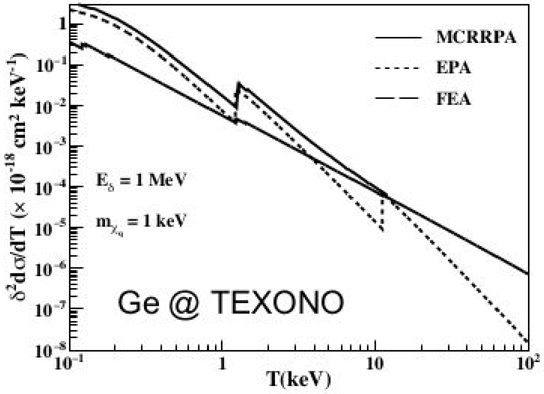
Detection: Atomic Ionization(t-channel).

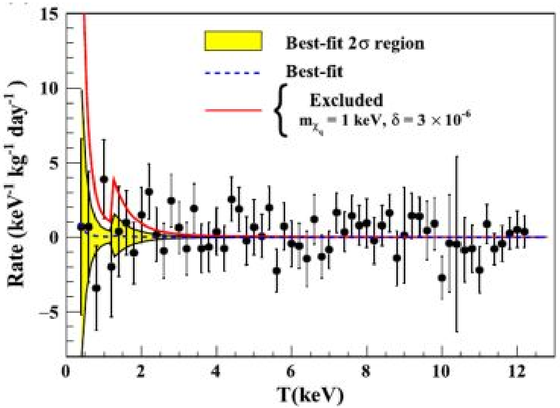


Diff. count-rate expected at detector:

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

Consider several models of the interaction cross-section





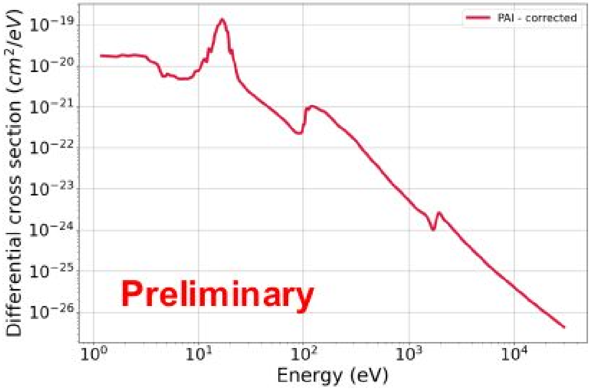
- On-Off spectrum can yield limits to χ_q production in reactors.
- **New (preliminar)** Search for χ_q in the CONNIEl ow-E data.

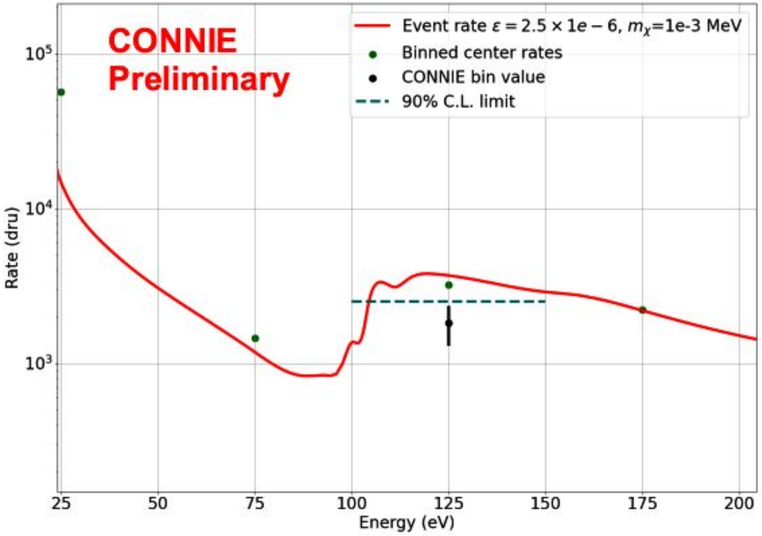
TEXONO collab., PRD 99, 032009 (2019)

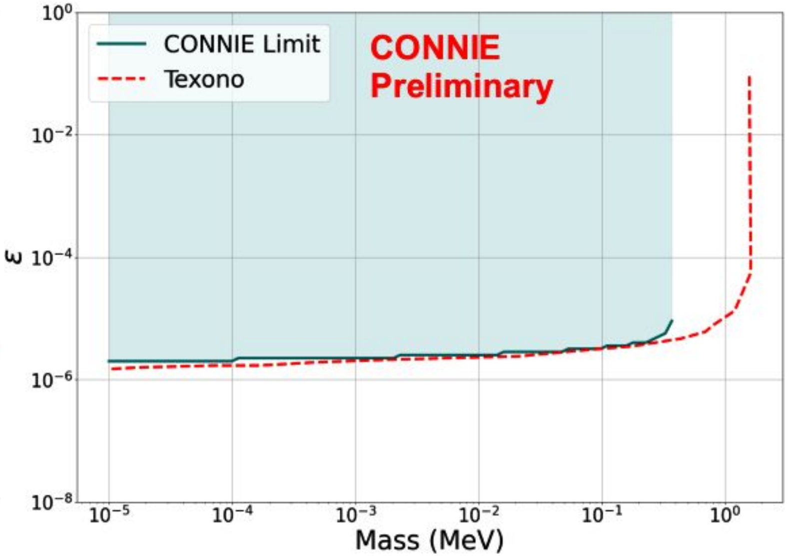
Search for millicharged particles

- Interaction with silicon from the Photo Ionization Absorption (PIA) model.
- 90% CL limit on χ_q producción 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.

Differential PIA cross-section for Si

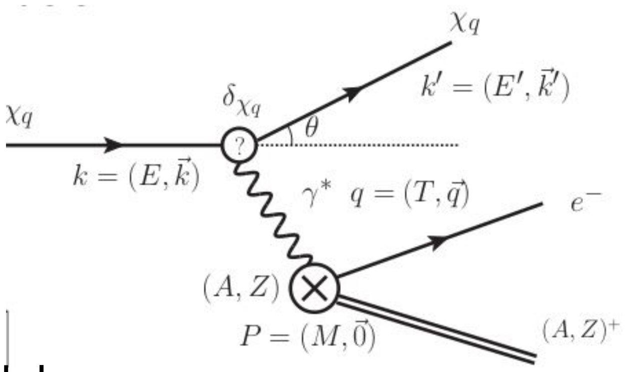






Plots by
Santiago Pérez &
Darío Rodrígues

Search for Millicharged particles



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

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

Modeling the Form Factor with the Photo Absorption Ionisation model:

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

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

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

Quenching Factor (nuclear recoils)

- Y. Sarkis developed a model for the nuclear recoil ionization efficiency in pure crystals (Si & Ge), extending Lindhard’s model to include the binding energy.
- Crucial to calculate predicted rate in direct DM and neutrino experiments.
- Model also appears to work well for noble liquids.

See talk by Y, Sarkis @ TAUP23

PRD101(2020)102001 **PRA107(2023)062811**