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Status and latest results from CONNIE with a skipper-CCD detector

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on behalf of the CONNIE Collaboration

~35 members from 6 countries



USA

Fermi National Accelerator Laboratory



Mexico

Universidad Nacional Autónoma de México



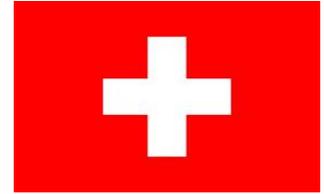
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ICIFI - Universidad de San Martín
IFIBA - Universidad de Buenos Aires
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Universidad del Sur
CONICET



CO.VNIE

**COHERENT NEUTRINO NUCLEUS
INTERACTION EXPERIMENT**



Switzerland

University of Zurich



Paraguay

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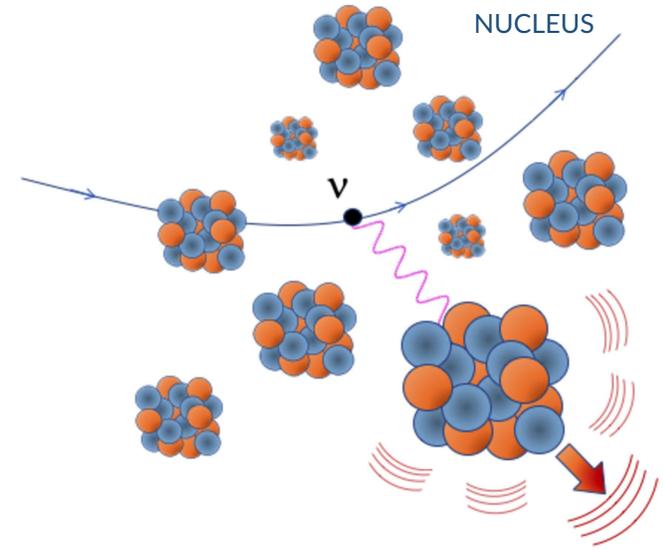
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CEFET - Angra

Coherent Elastic Neutrino-Nucleus Scattering (CE ν NS)

Process in which neutrinos scatter off a nucleus, and the nucleus recoils as a whole.

- SM weak neutral current interaction predicted in 1974. [PRD 9, 1389]
- Dominant process at low neutrino energies: $E_\nu < 60$ MeV.
- Enhanced cross section compared to other ν interactions: proportional to N^2 .



For:
 $q \cdot R \ll 1$

q = three-momentum transfer
 R = nuclear radius

$$q = \sqrt{2ME_r}$$

$$\frac{d\sigma_{SM}}{dE_R}(E_{\bar{\nu}_e}) = \frac{G_F^2}{8\pi} Q_W^2 \left[2 - \frac{2E_R}{E_{\bar{\nu}_e}} + \left(\frac{E_R}{E_{\bar{\nu}_e}} \right)^2 - \frac{ME_R}{E_{\bar{\nu}_e}^2} \right] M |F(q)|^2$$

$$Q_W = N - (1 - 4 \sin^2 \theta_W) Z$$

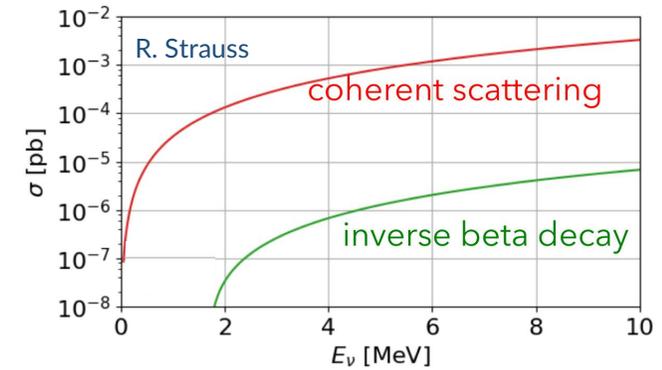
for: $\sin^2 \theta_W \sim \frac{1}{4}$

G_F = Fermi coupling constant
 Z = atomic number of the nucleus
 N = neutron number of the nucleus

E_ν = neutrino energy
 θ_w = weak mixing angle
 Q_w = weak charge

$F(q)$ = form factor
 M = mass of the nucleus

Neutrino cross sections



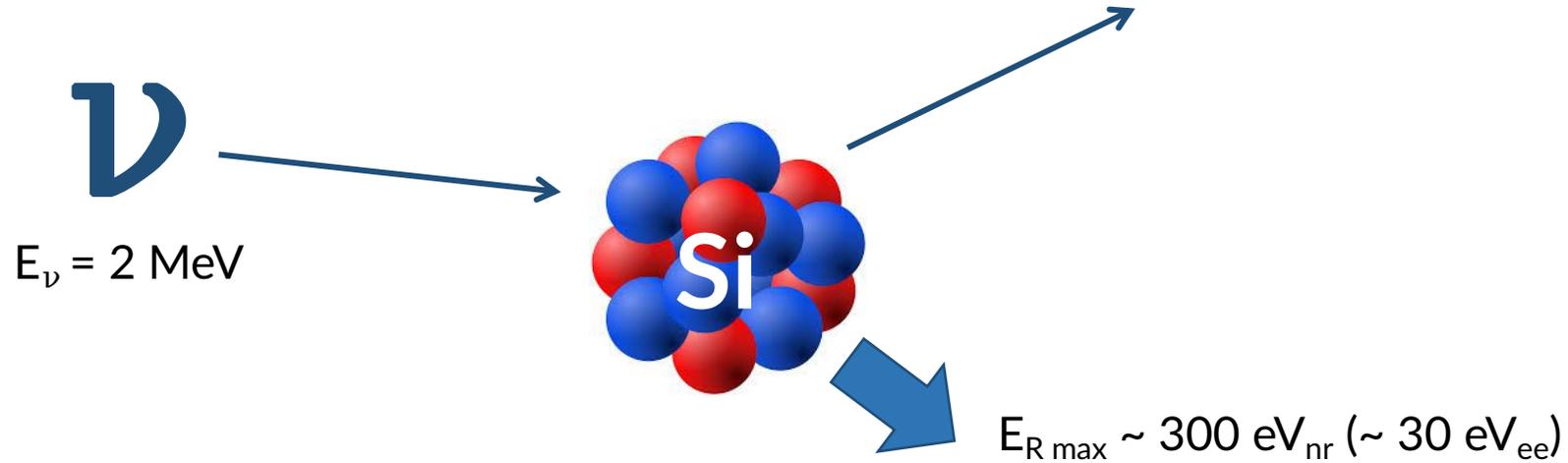
Relevance:

- SM electroweak physics (weak mixing angle, cross sections).
- BSM physics (ν EM properties, NSI, new mediators).
- Direct dark matter searches (neutrino fog).
- Nuclear physics (nuclear structure).
- Astrophysics (supernovae dynamics).
- Technological applications (reactor monitoring).

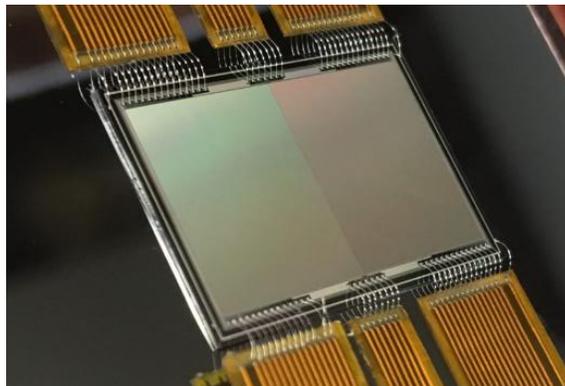
Coherent Elastic Neutrino-Nucleus Scattering (CE ν NS)

BUT hard to observe due to tiny nuclear recoil energies!

- First experimental observation by COHERENT in 2017. [Science 357, 6356]



A low-threshold detector and a high ν flux is desired!



The CONNIE experiment

Reactor neutrino experiment at ~30 m from the core of the 3.8 GW_{th} Angra 2 commercial reactor in Brazil.

- Flux of $7.8 \times 10^{12} \bar{\nu}_e/s \text{ cm}^2$ at CONNIE and $E_{\nu} < 4 \text{ MeV}$.
- Data taking with reactor ON and reactor OFF (1-month shutdown every ~13 months)

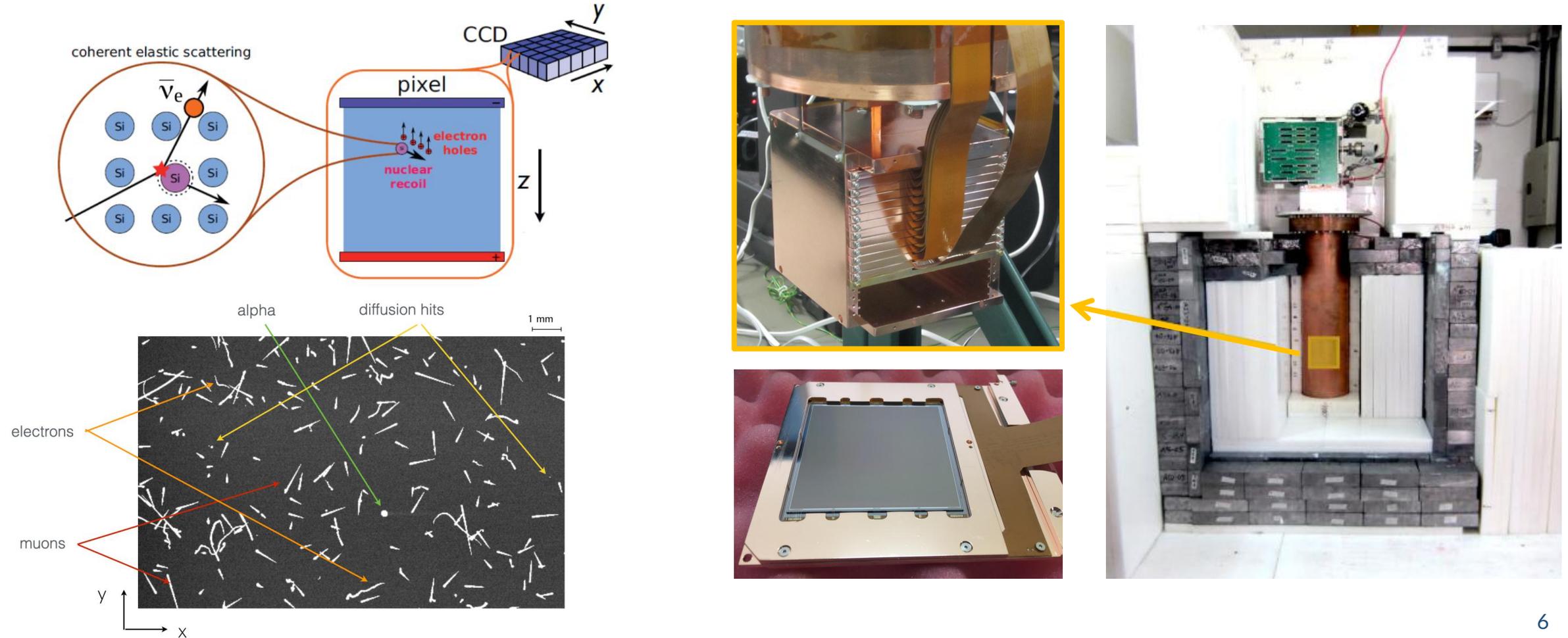


The CONNIE experiment

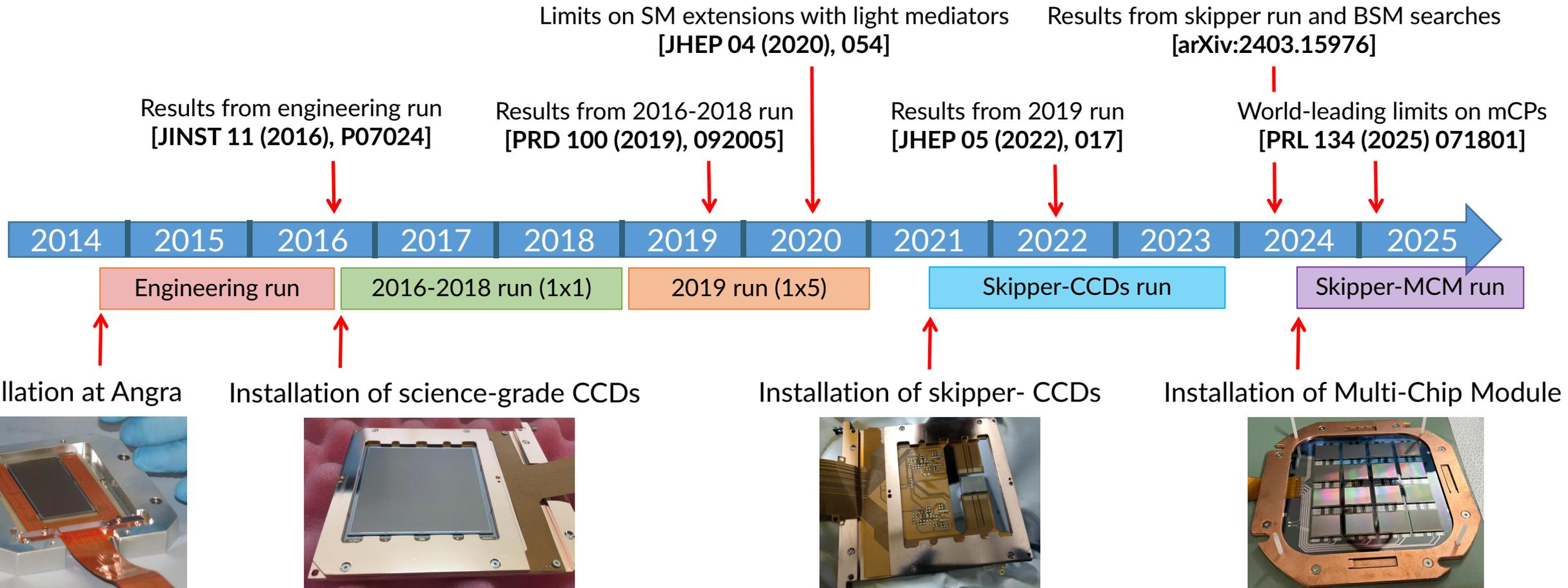
Sensors are scientific silicon charge-coupled devices (CCDs).

- Ionizing radiation creates electron-hole pairs. Created charge is measured and an image is generated.
- $\sim eV_{ee}$ detection threshold, $< 3e^-$ noise, μm -scale spatial resolution and low instrumental background.

Passive shield to reduce external backgrounds (lead + polyethylene).

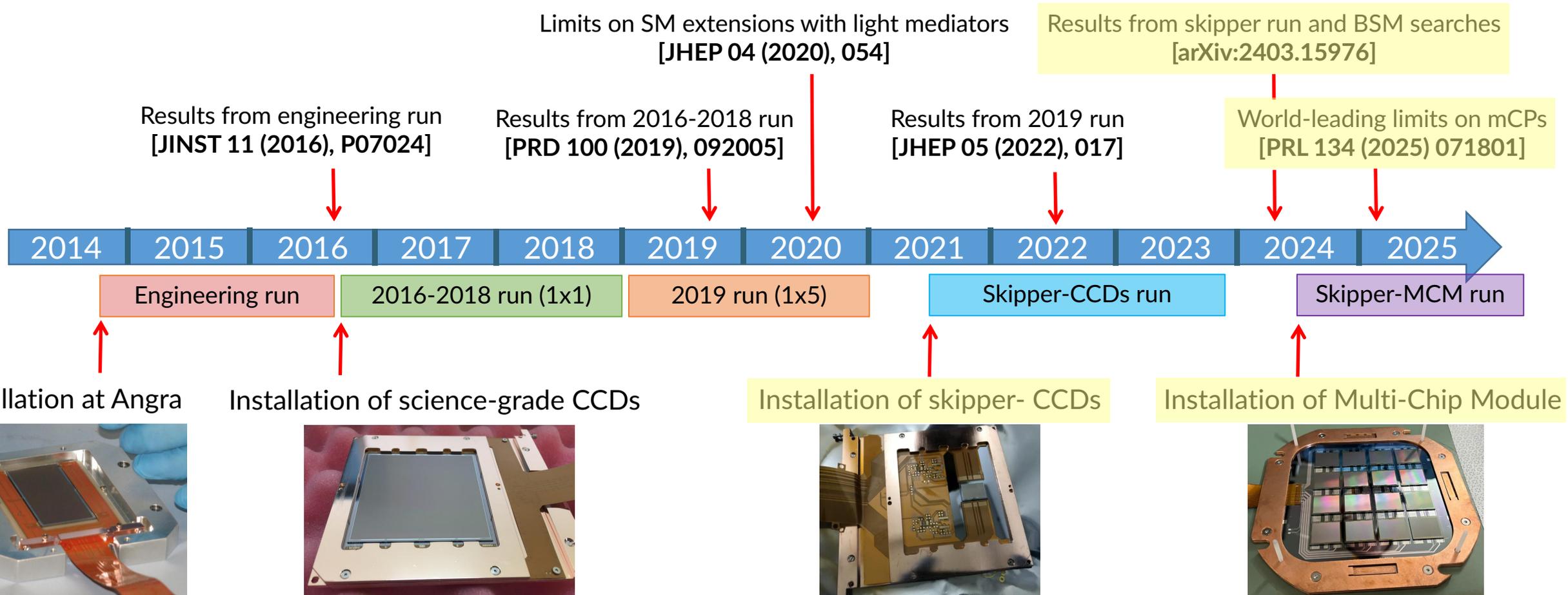


CONNIE timeline and milestones



CONNIE timeline and milestones

This talk!

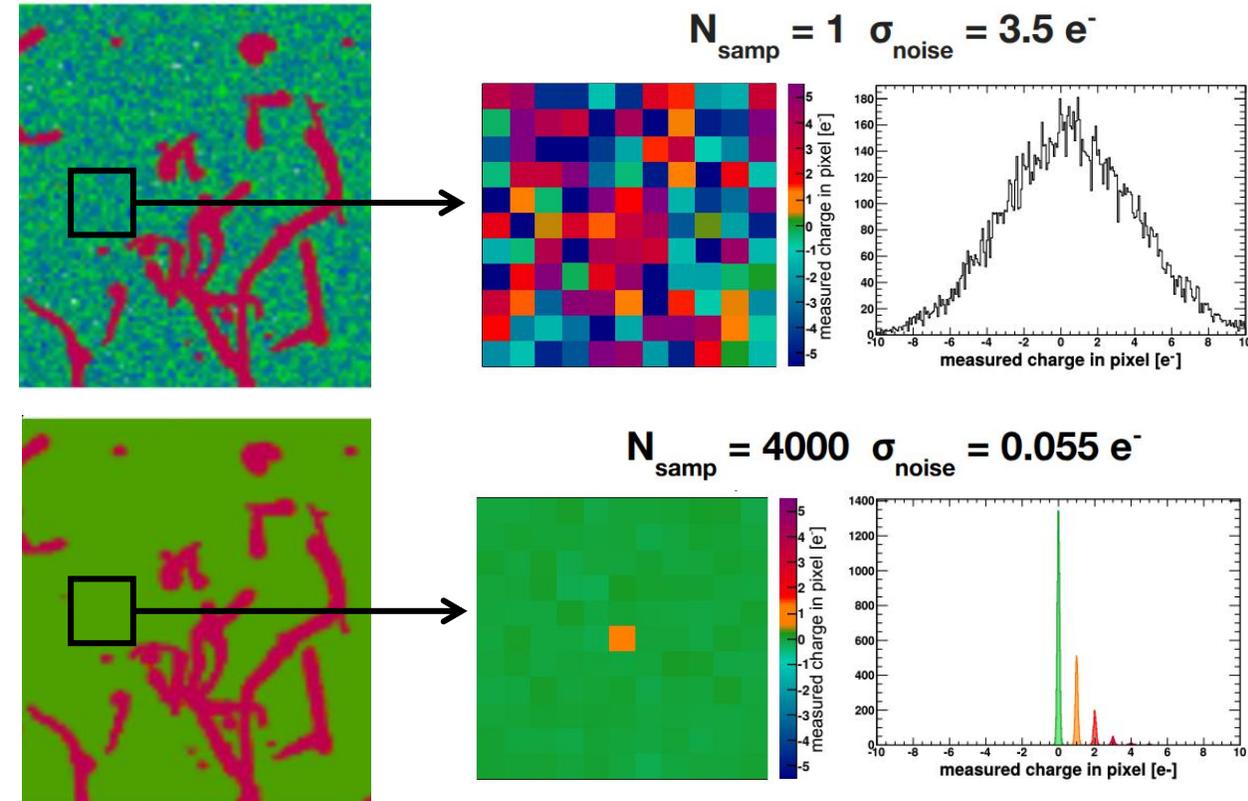
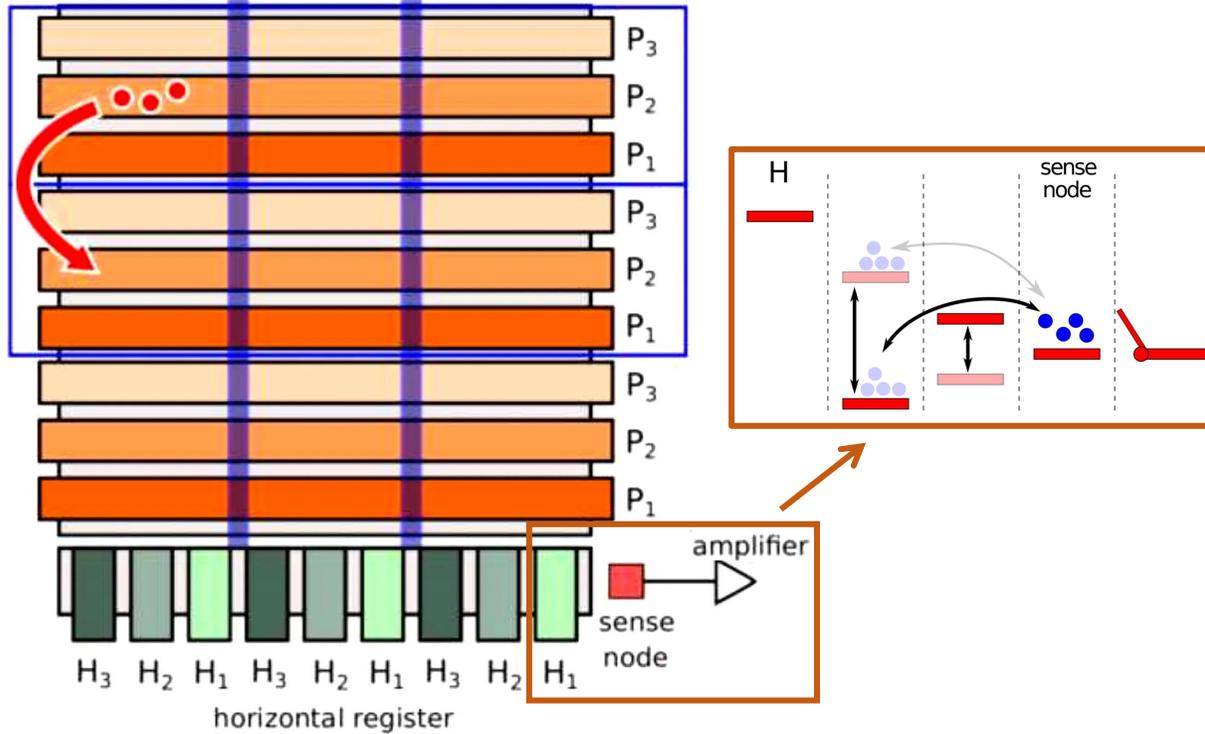


Skipper-CCDs: electron-counting sensors

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]

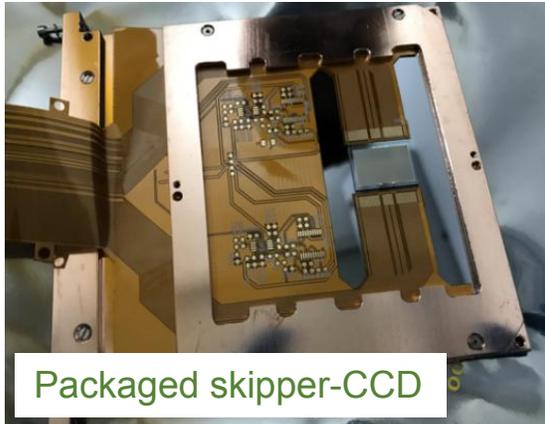
J. Tiffenberg et al.. Single-Electron and Single-Photon Sensitivity with a Silicon Skipper-CCD. [10.1103/PhysRevLett.119.131802]

CONNIE with skipper-CCDs: single modules

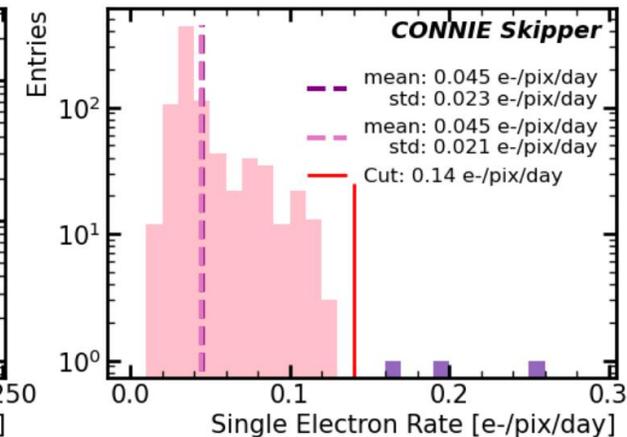
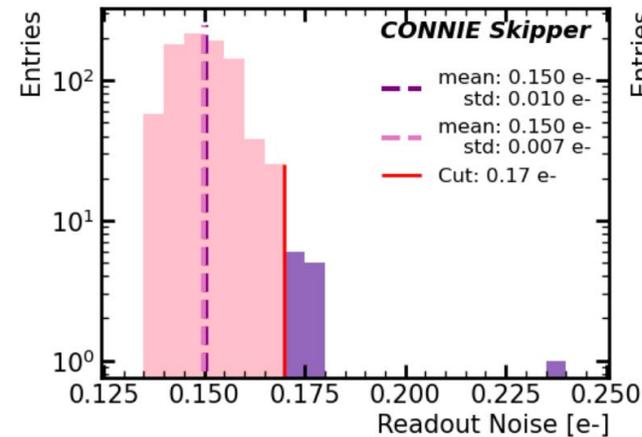
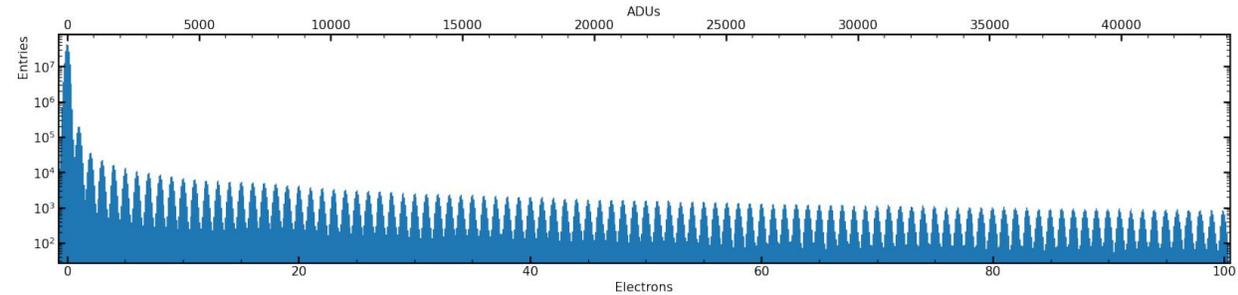
arXiv:2403.15976

First installation of skipper-CCDs at CONNIE in July 2021

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



Stable performance during 2021-2023 DAQ period.



CONNIE with skipper-CCDs: single modules

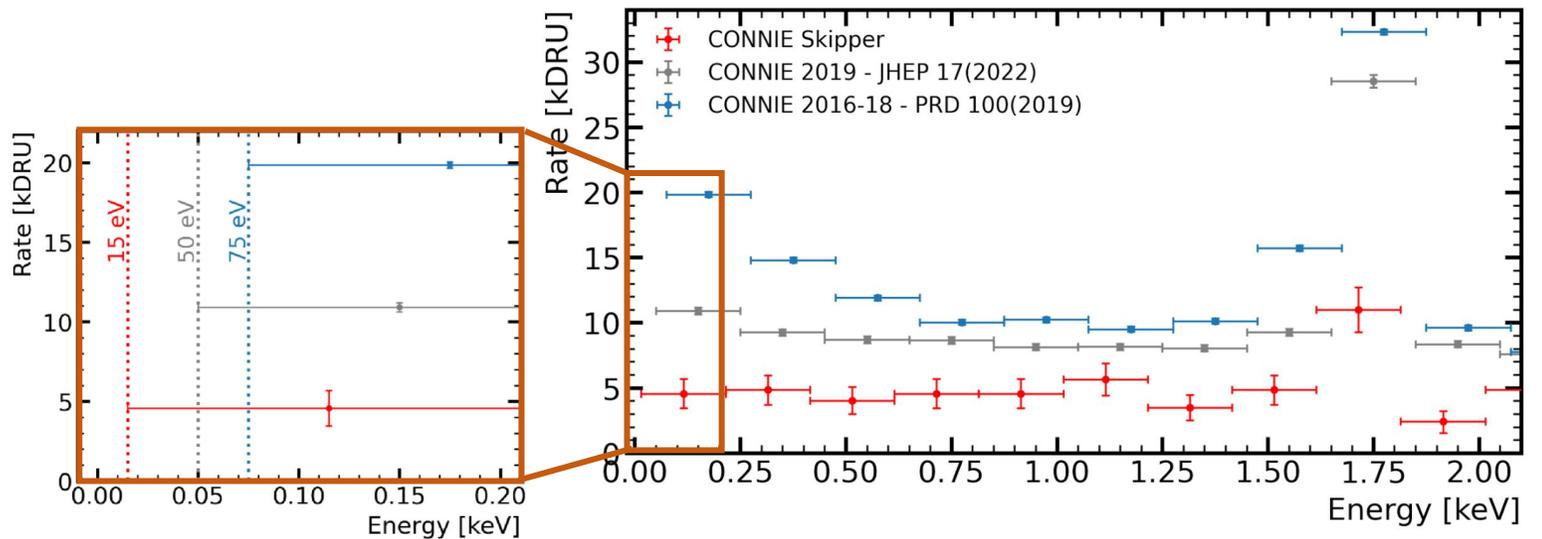
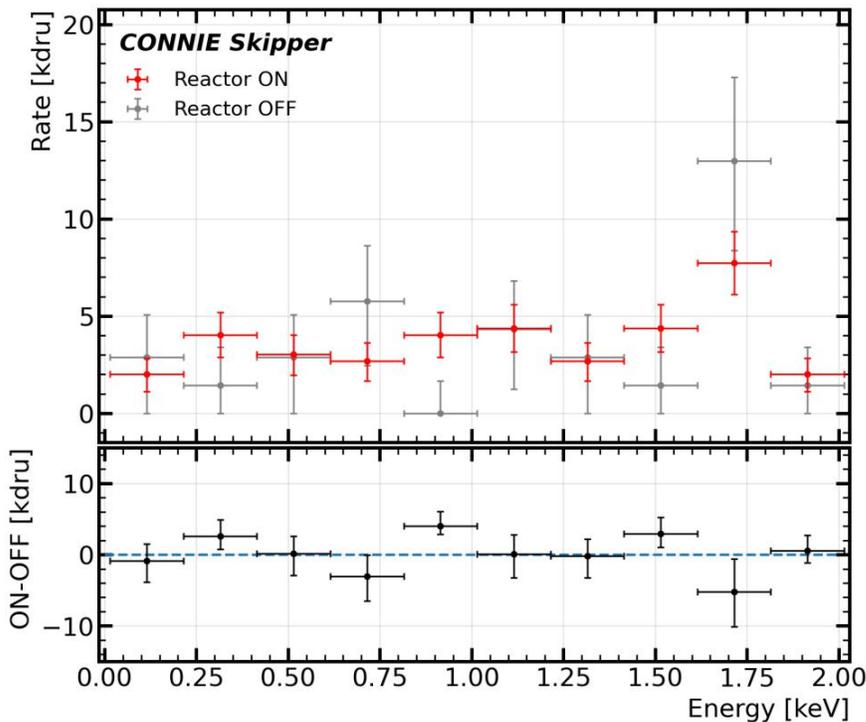
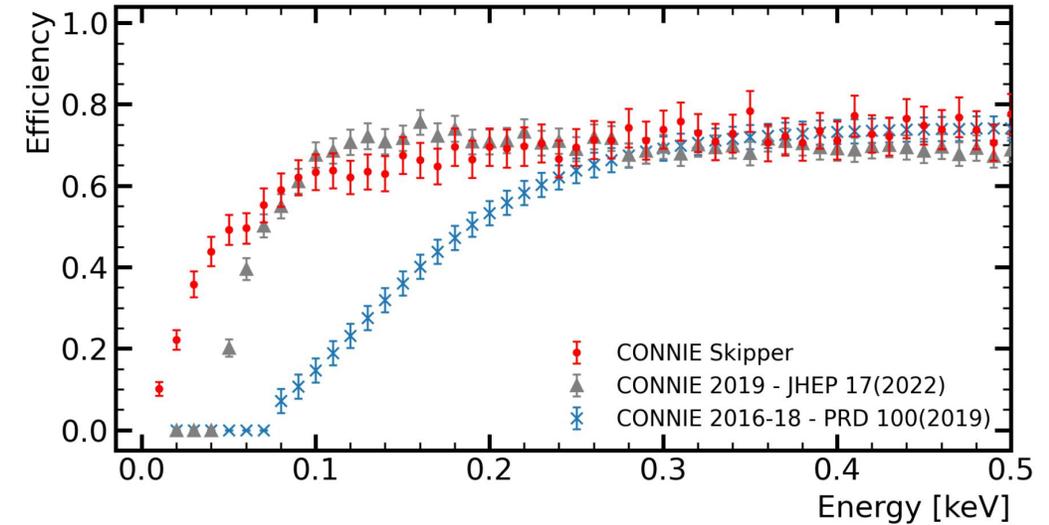
arXiv:2403.15976

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.

Effective exposure: 14.9 g-day reactor-on & 3.5 g-day reactor-off.

No excess observed.



Search for $CE\nu NS$ yield to a 95% limit of 76 times the predicted rate.

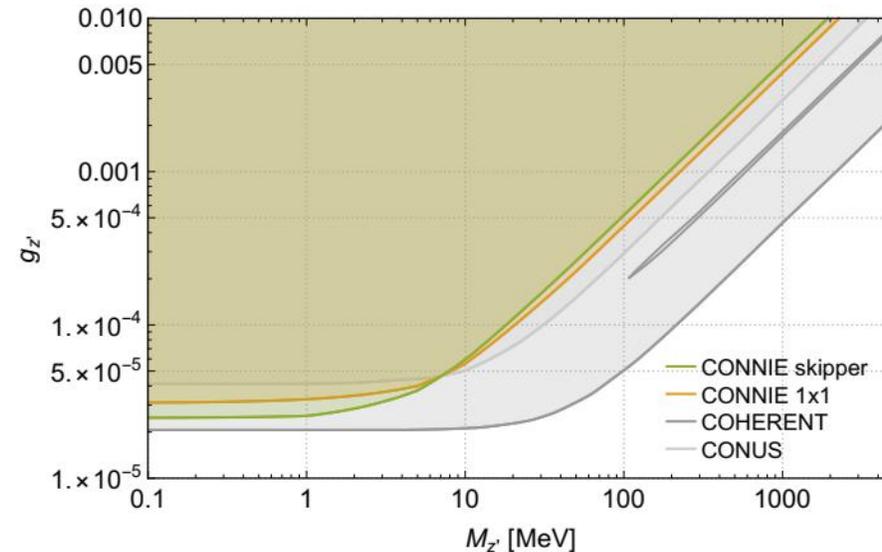
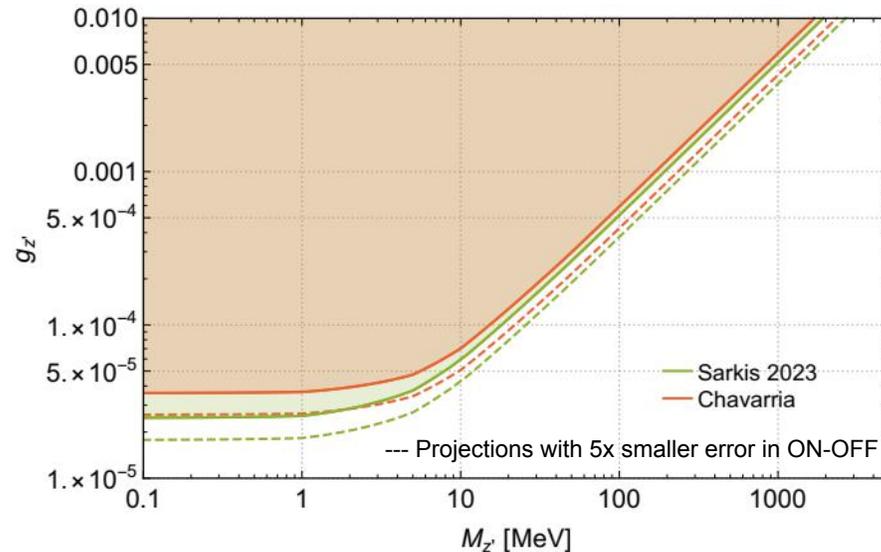
Comparable to previous limit with standard CCDs achieved with 10^3 more exposure.

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

Measured Energy [keV _{ee}]	Sarkis (2023) rate [kg ⁻¹ d ⁻¹ keV _{ee} ⁻¹]	Chavarria rate [kg ⁻¹ d ⁻¹ keV _{ee} ⁻¹]	Observed 95% C.L. [kg ⁻¹ d ⁻¹ keV _{ee} ⁻¹]	Expected 95% C.L. [kg ⁻¹ d ⁻¹ keV _{ee} ⁻¹]
0.015 – 0.215	29.3 ^{+4.6} _{-4.7}	17.7 ± 3.3	2.24 × 10 ³	3.18 × 10 ³
0.215 – 0.415	2.7 ^{+1.3} _{-1.2}	2.20 ± 0.21	7.36 × 10 ³	4.77 × 10 ³
0.415 – 0.615	0.43 ^{+0.41} _{-0.39}	0.36 ± 0.04	3.41 × 10 ³	3.31 × 10 ³

Search for light vector mediator yield to slight improvement at low $M_{Z'}$ over our previous limit.

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



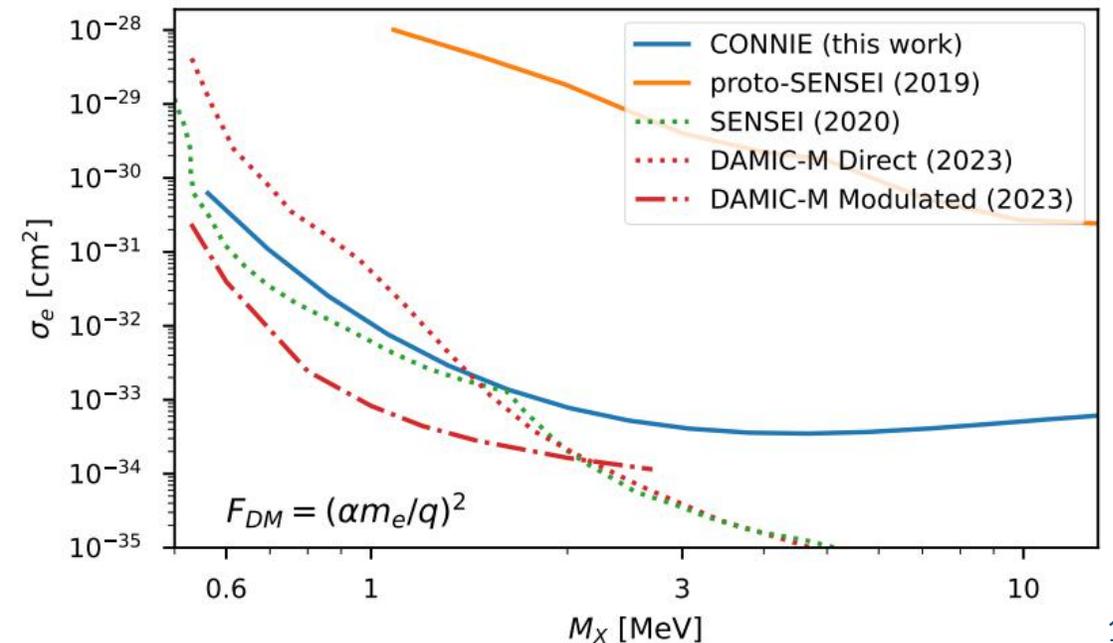
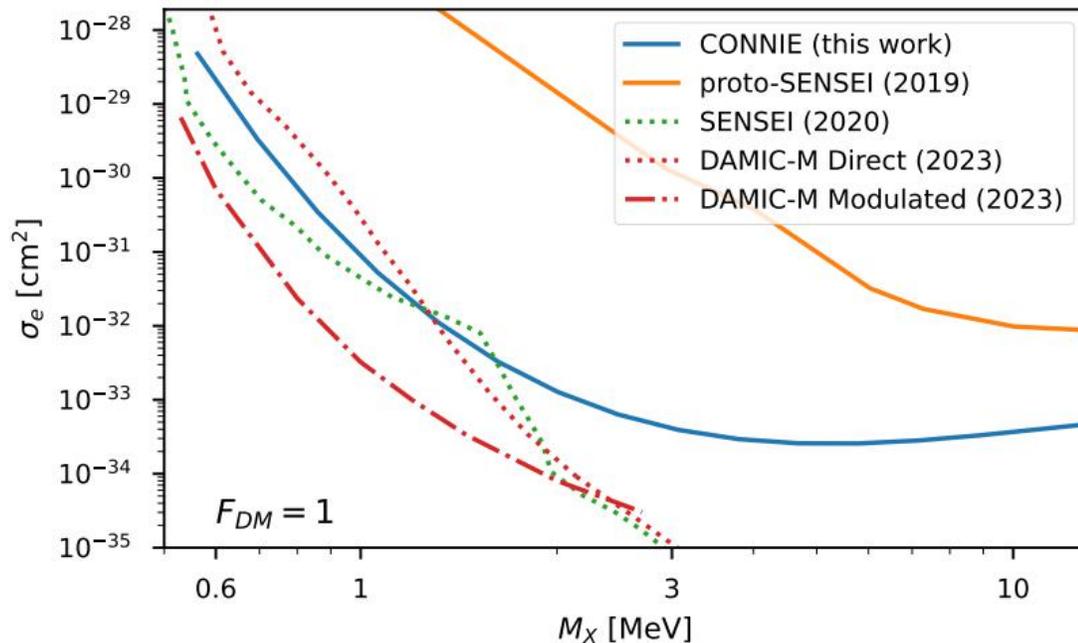
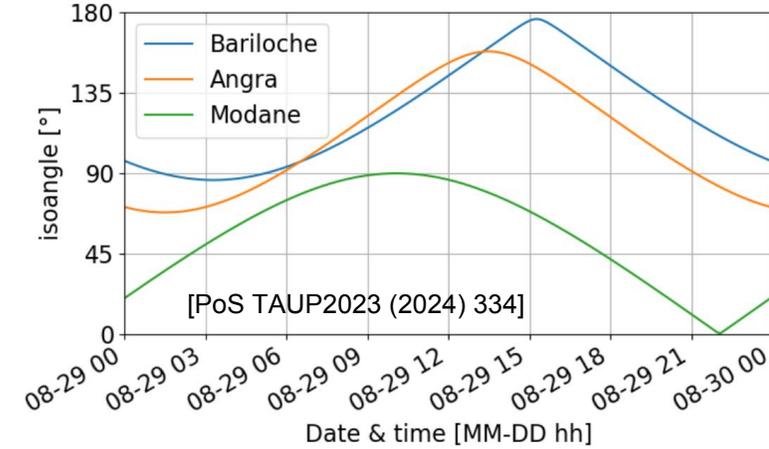
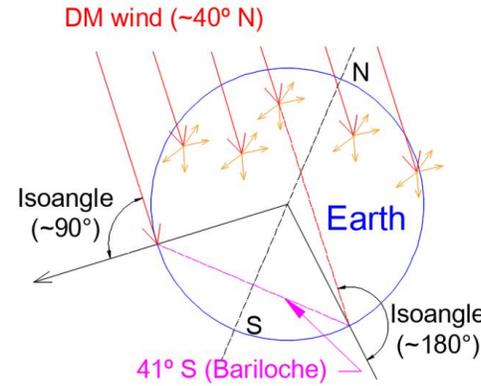
CONNIE with skipper-CCDs: single modules

arXiv:2403.15976

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

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

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



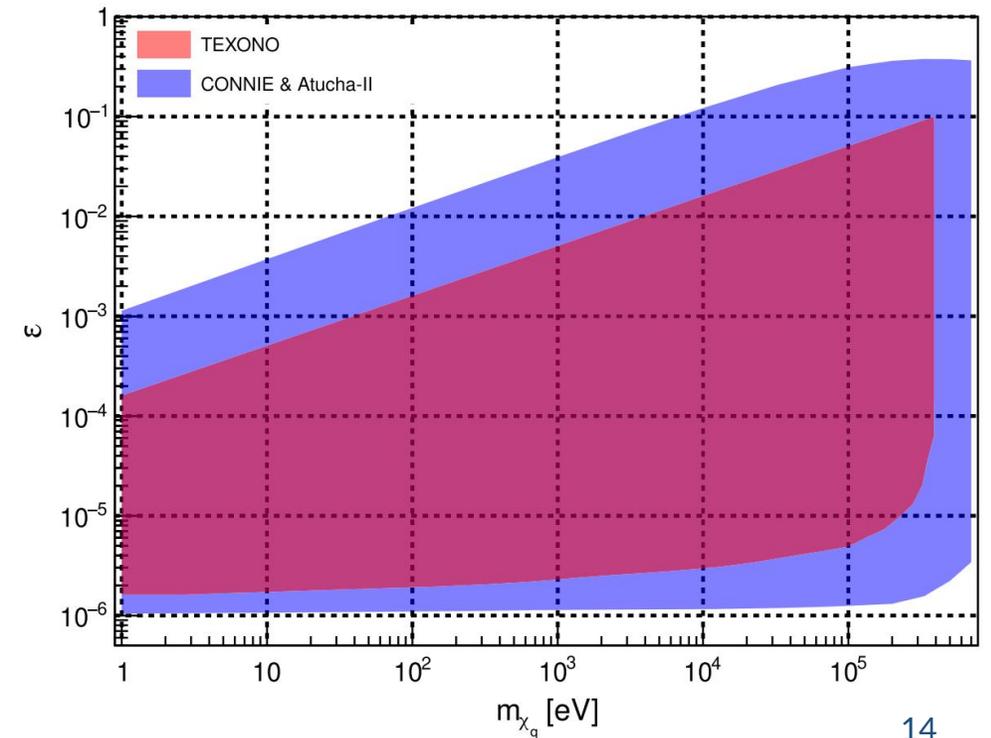
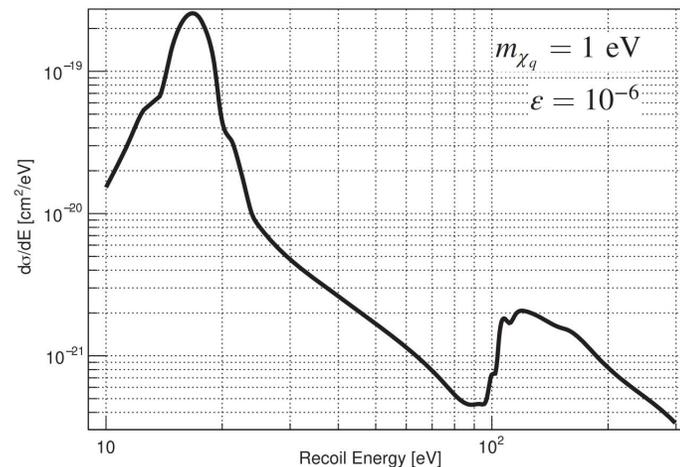
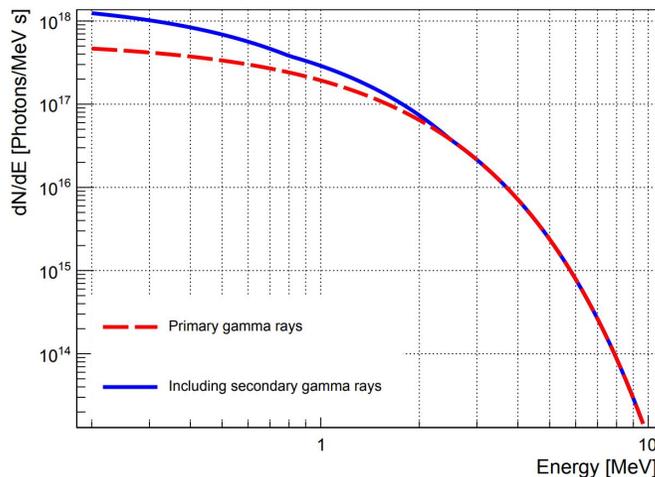
Search for reactor-produced mCPs, combining data with Atucha-II, yield to world-leading limits for masses <1 MeV

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



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

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



CONNIE with skipper-CCDs: multi-chip module

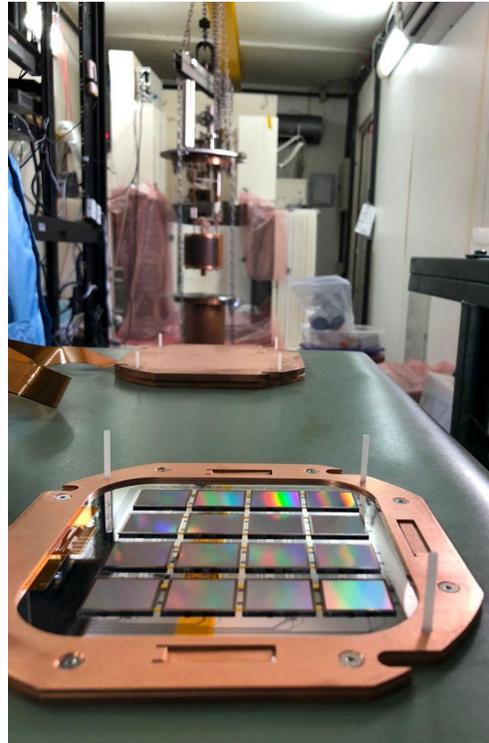
Exciting results from skipper-CCD single modules motivated the installation of a larger sensor array: the MCM!

Hardware developed for the 10-kg skipper-CCD detector of the Oscura dark matter experiment [[arXiv:2202.10518](#)].

- 16 skipper-CCDs (1278×1058 ($15 \mu\text{m}$)² pixels, 725- μm thick) in one MCM [[JINST 18 P08016](#); [IEEE JSen 25 \(5\) 8813](#)].
- Multiplexed readout electronics [[Sensors 22 \(11\), 4308](#); [JINST 18 P01040](#)].

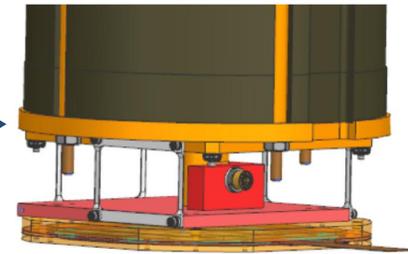
Installation of 1 MCM, new VIB and new multiplexer board in May 2024.

- 10x increase in mass (8 g) with respect to skipper-CCD single modules.

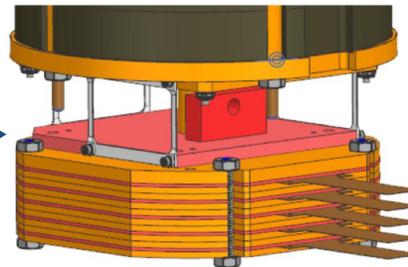


Scalable!

Now →



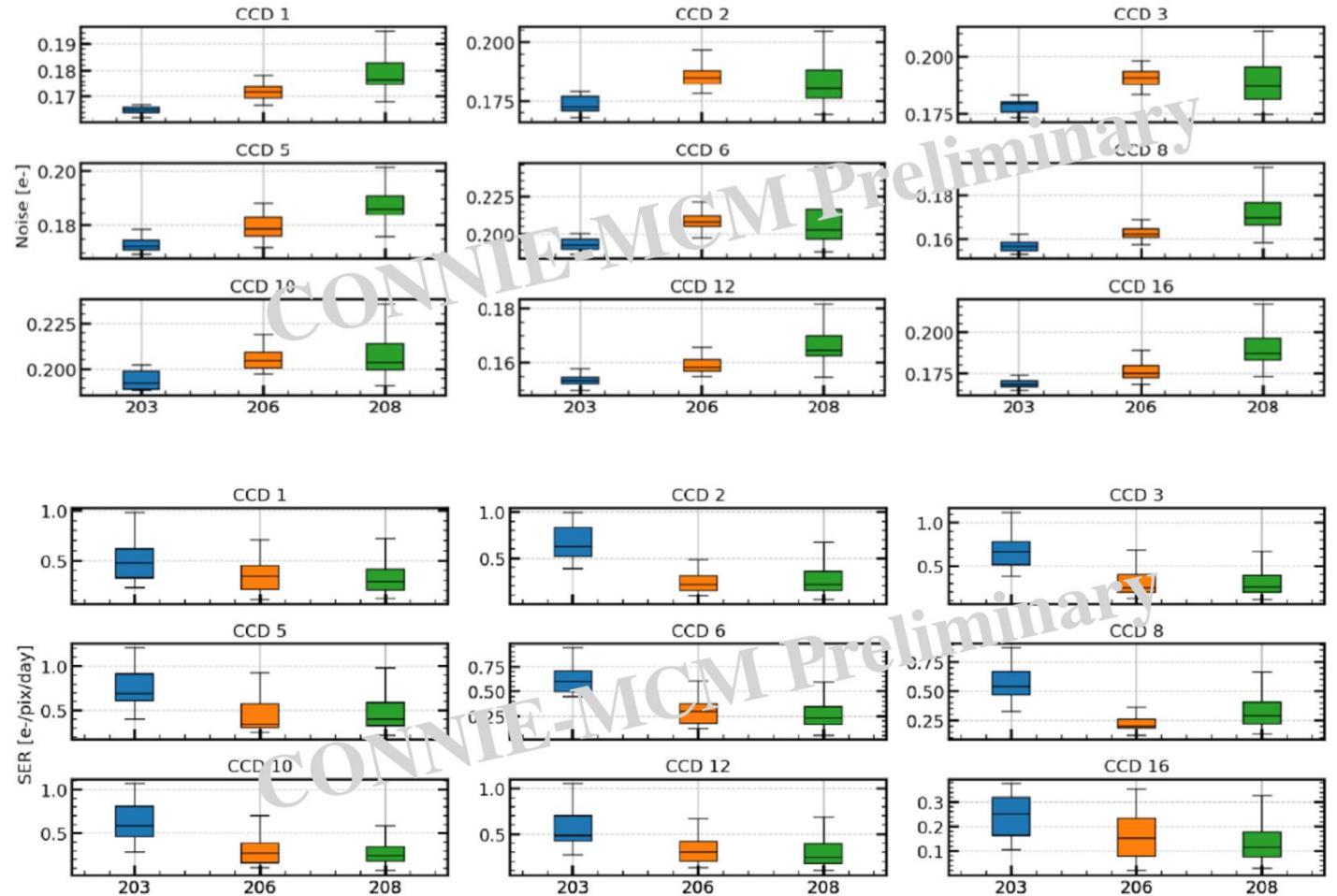
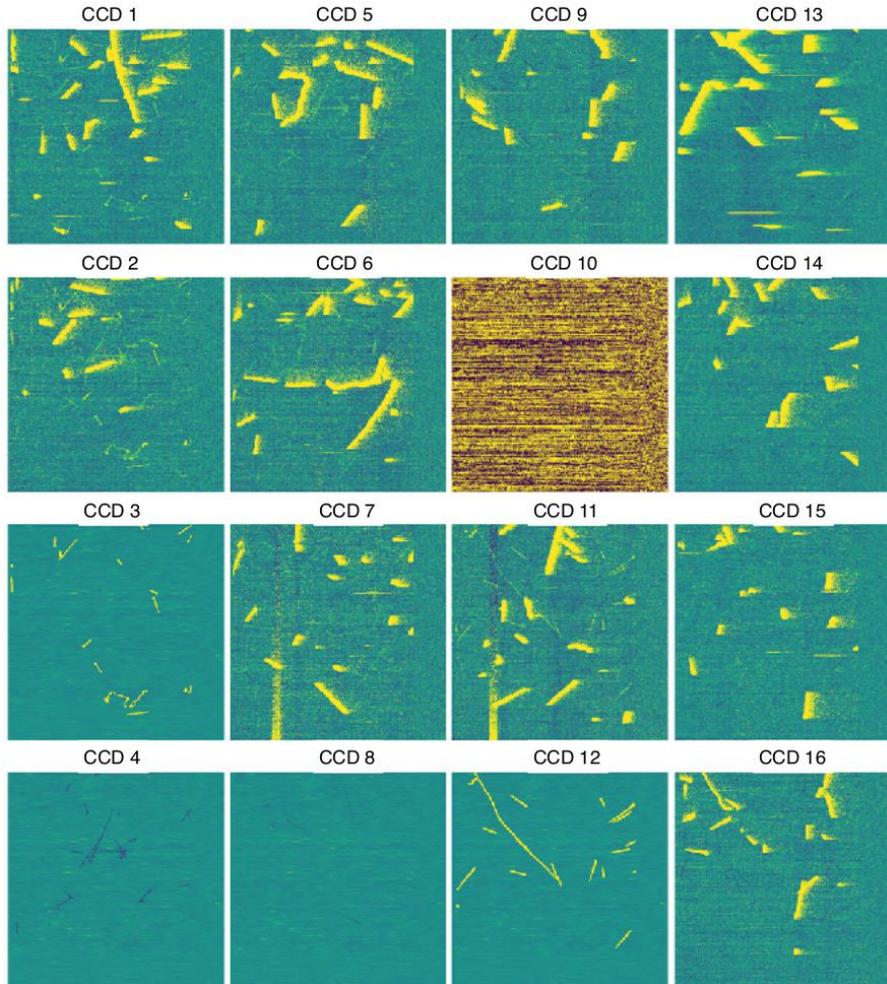
Future? →



CONNIE with skipper-CCDs: multi-chip module

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.



CONNIE future perspectives

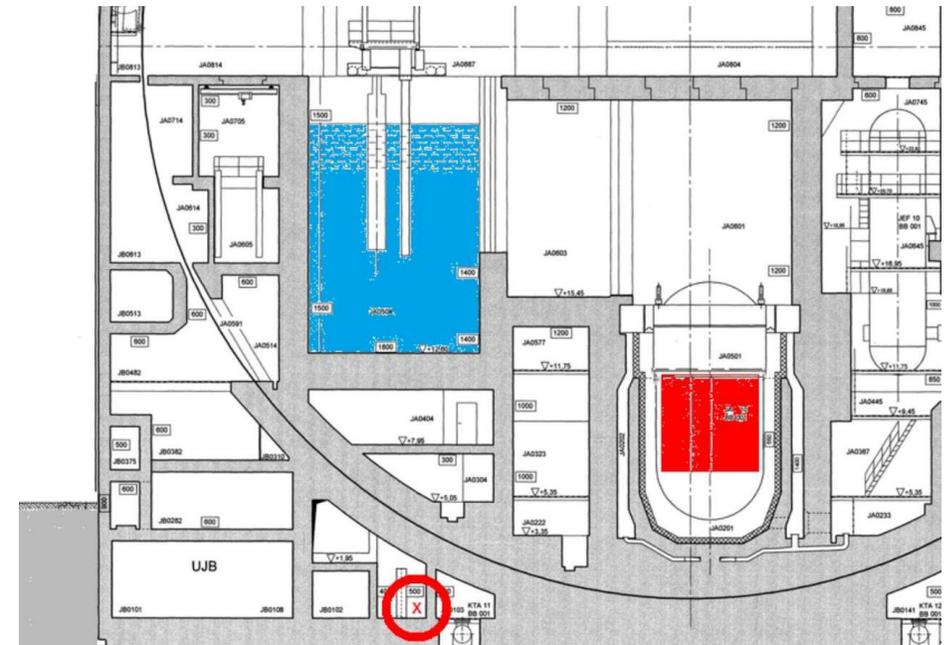
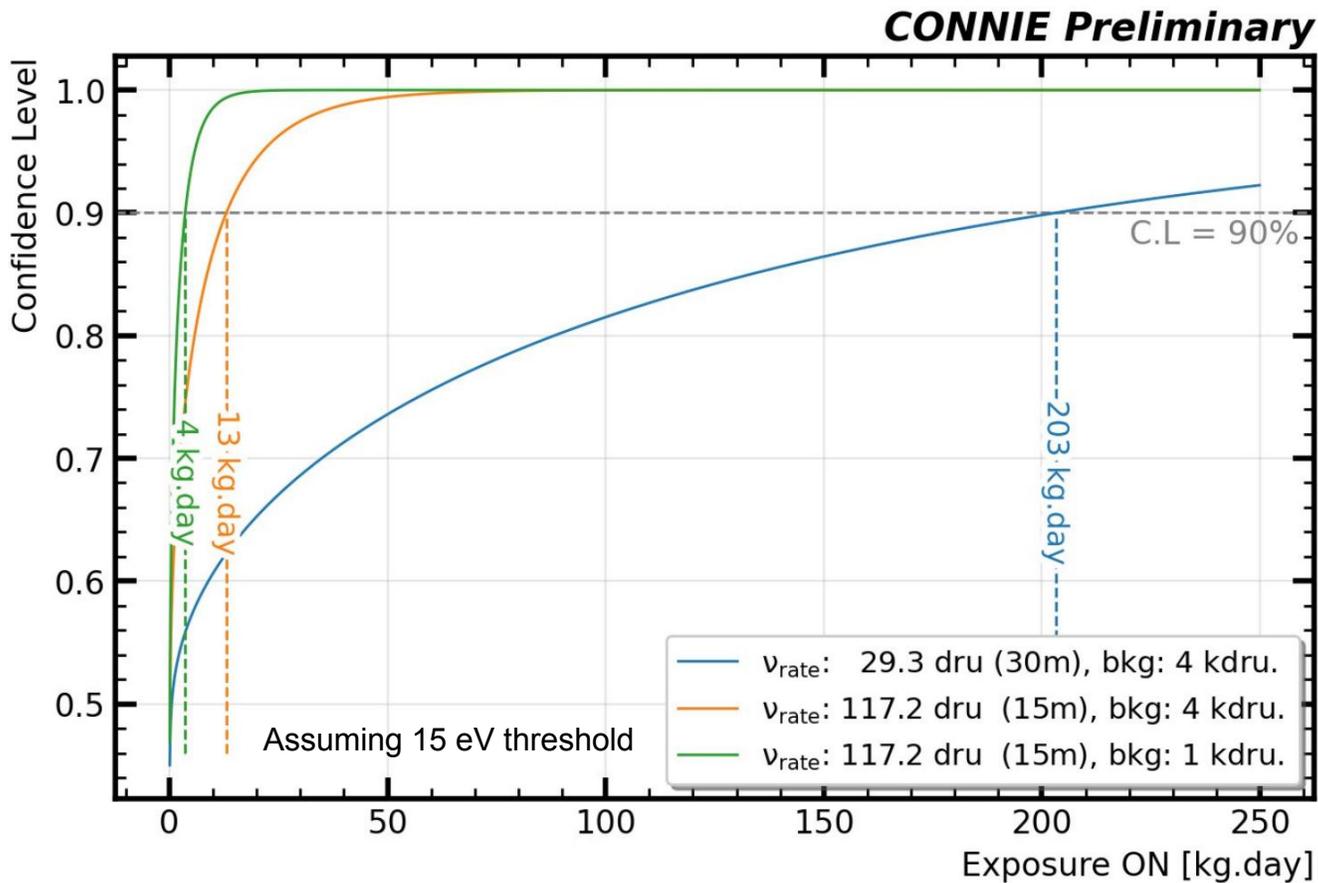
CONNIE-MCM run:

- Improve CE ν NS and BSM limits.
- Feasibility of increasing detector mass.

Possibility of increasing the ν flux by moving inside the dome (15m from core).

- Negotiations at Angra in place.

Towards CE ν NS detection:



Conclusions

- Skipper-CCDs showed very promising for detecting low-energy processes.
- Excellent performance in 2021-2023: flat background (~ 4 kdru) and $15 \text{ eV}_{\text{ee}}$ ($\sim 240 \text{ eV}_{\text{nr}}$) threshold.
- New $\text{CE}\nu\text{NS}$ 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.
- CONNIE started its next phase with a 16-sensor Multi-Chip-Module.
- Needed a larger-mass ($\sim 1 \text{ kg}$) skipper-CCD detector for $\text{CE}\nu\text{NS}$ detection.
- Efforts to increase the neutrino flux are also ongoing.

Stay tuned!

Thank you!

