III LASF4RI for HECAP Symposium:
Update of the Strategic Plan

Coherent Neutrino-Nucleus Scattering Experiment – CONNIE

Skipper-CCD technology in Latin America for neutrino detection

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ICIFI-ECYT_UNSAM-CONICET

CONNIE Collaboration

~ 35 members from 6 countries

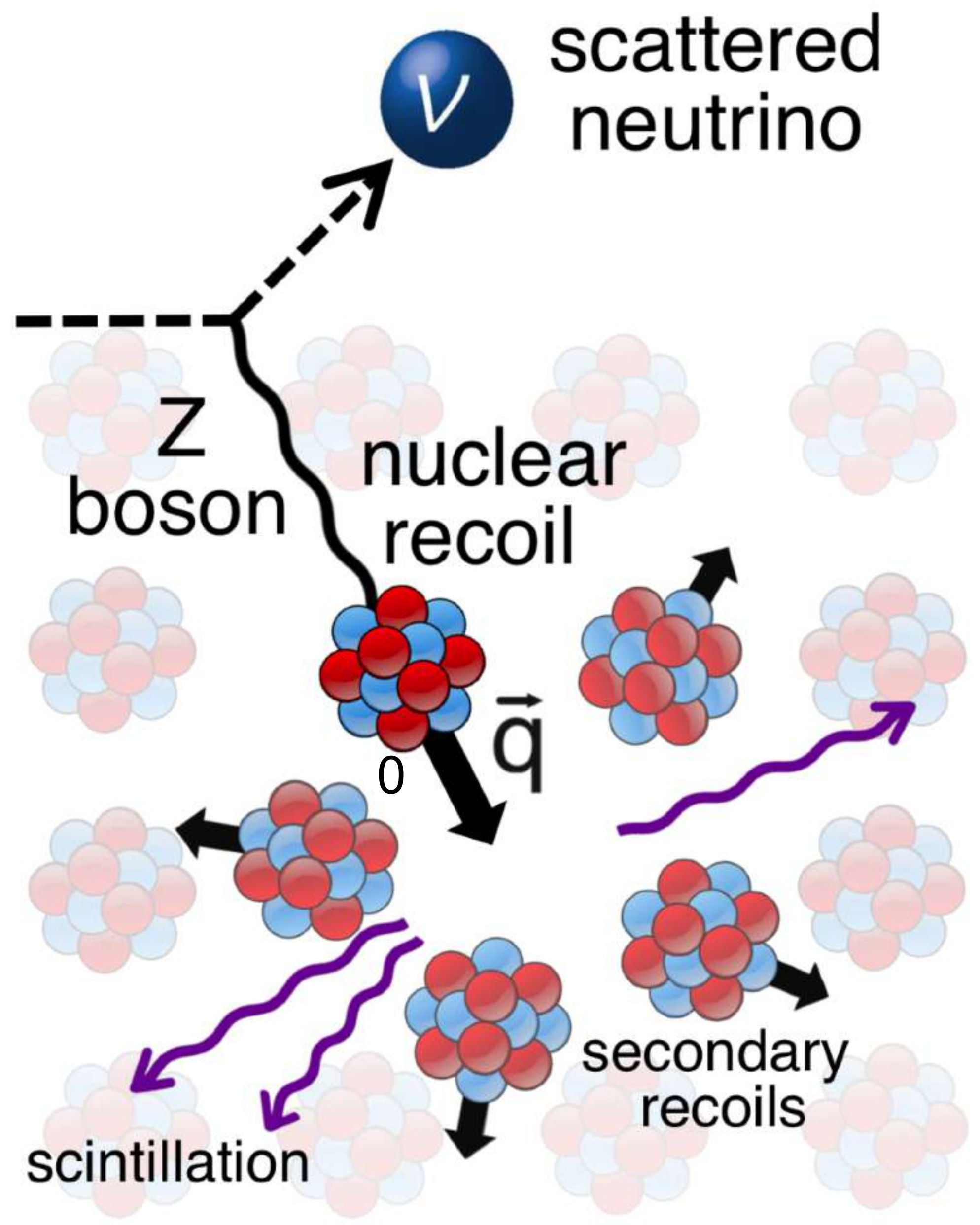
Centro Atómico Bariloche, CONICET, ICIFI – Universidad Nacional de San Martín, IFIBA – Universidad de Buenos Aires, Universidad de Córdoba, Universidad del Sur, Centro Brasileiro de Pesquisas Físicas, Universidade Federal do Rio de Janeiro, CEFET – Angra, Universidade Federal do ABC, Instituto Tecnológico de Aeronáutica, Universidad Nacional Autónoma de México, Universidad Nacional de Asunción, University of Zurich, Fermilab

Main goals

- Detect CEvNS in a nuclear power reactor for the first time using silicon-based Skipper-CCDs.
- Explore Beyond Standard Model (BSM) physics (LVM, neutrino electromagnetic properties, mCP, etc.)
- Develop an alternative method for monitoring power reactors for safeguard purposes.

CEvNS

Coherent Elastic Neutrino-Nucleus Scattering



- Process in which neutrinos scatter off a nucleus acting as a single particle
  - Predicted in the SM 1974 Phys.Rev. D 9 1389 (1974) & JETP Lett. 19 4 236 (1974)
  - Measured for the first time in 2017 by COHERENT Science 357 (2017)
  - Dominant process for Eν ≲ 50 MeV
  - Cross section increases as N^2

For:

$$q \cdot R << 1$$

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: $\sin^2\theta_W \sim \frac{1}{4}(\approx 0.22)$

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

Eν = neutrino energy
θ_W = weak mixing angle
Q_W = weak charge

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

CEvNS

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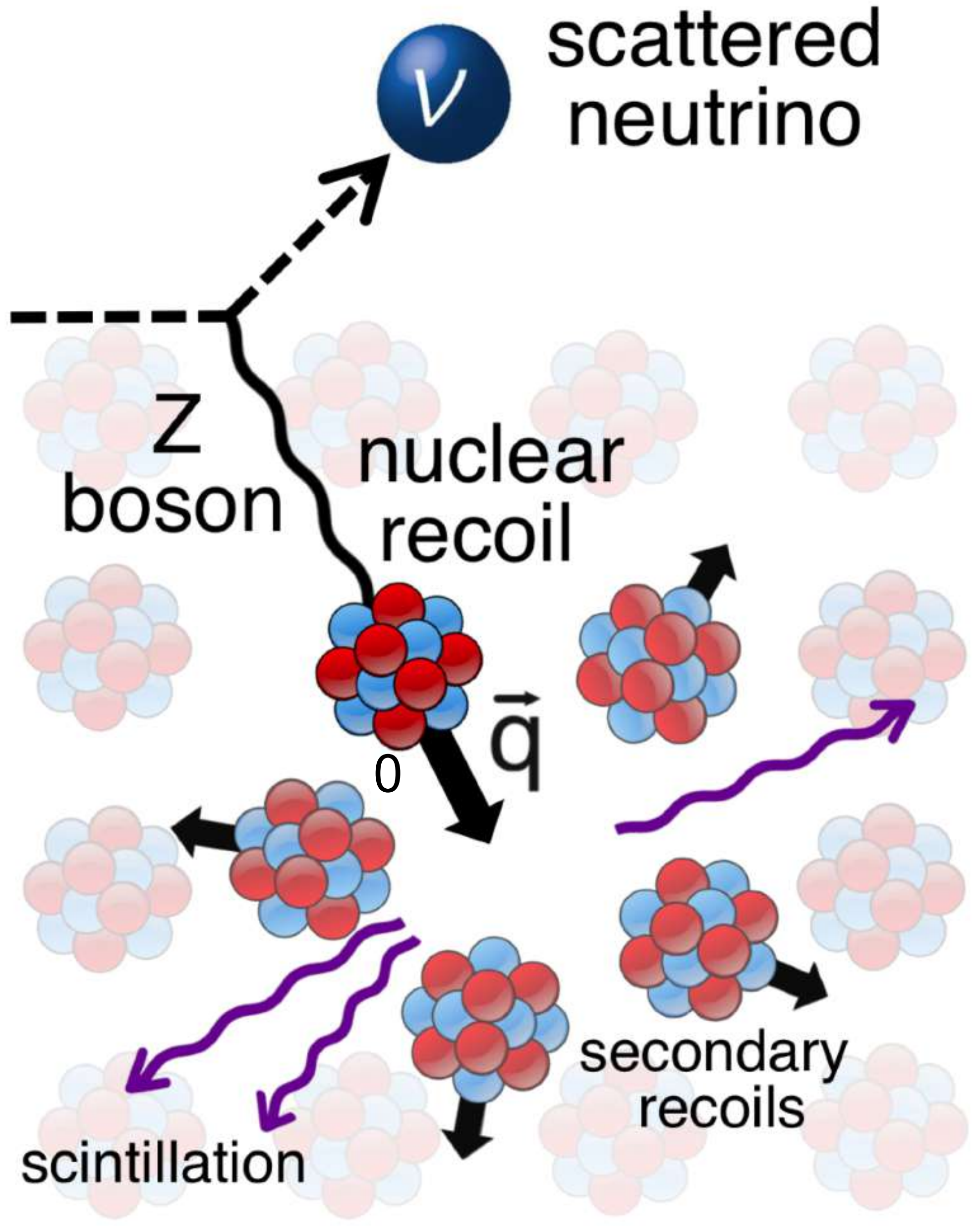
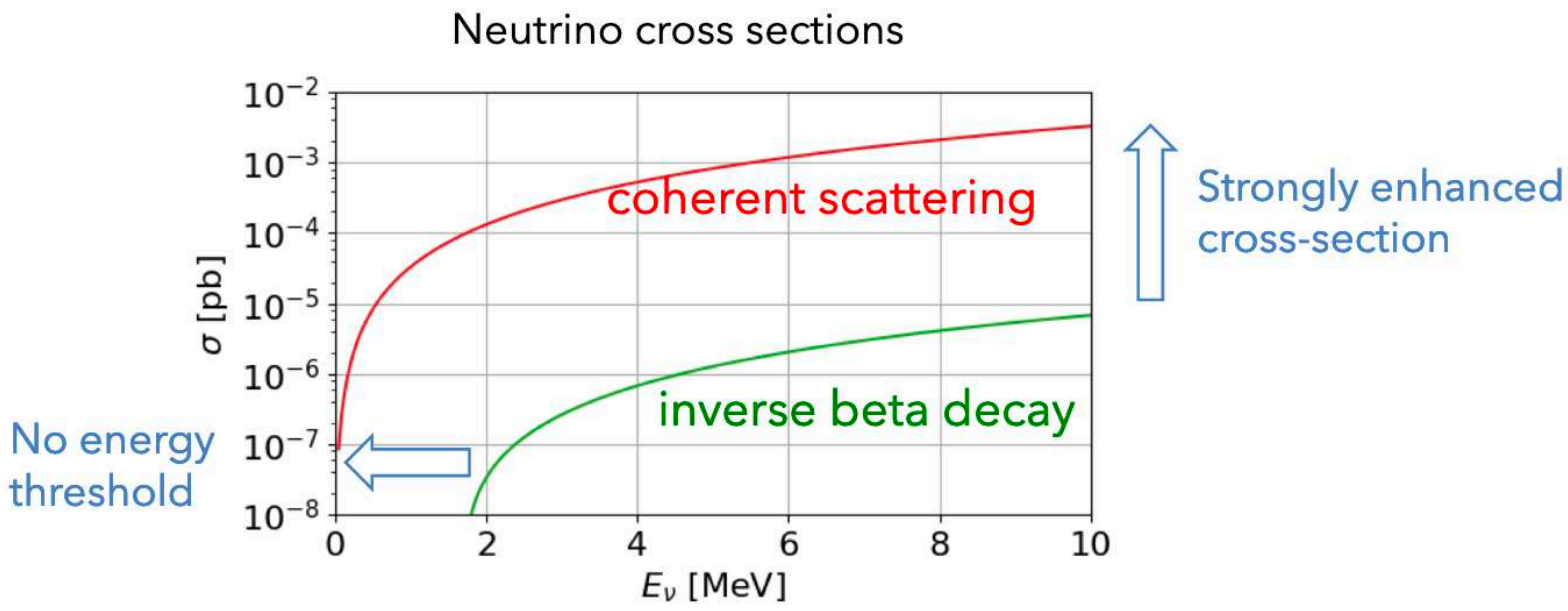
$$\sigma_{SM} \sim \frac{G_F^2}{4\pi} N^2 E_\nu^2$$





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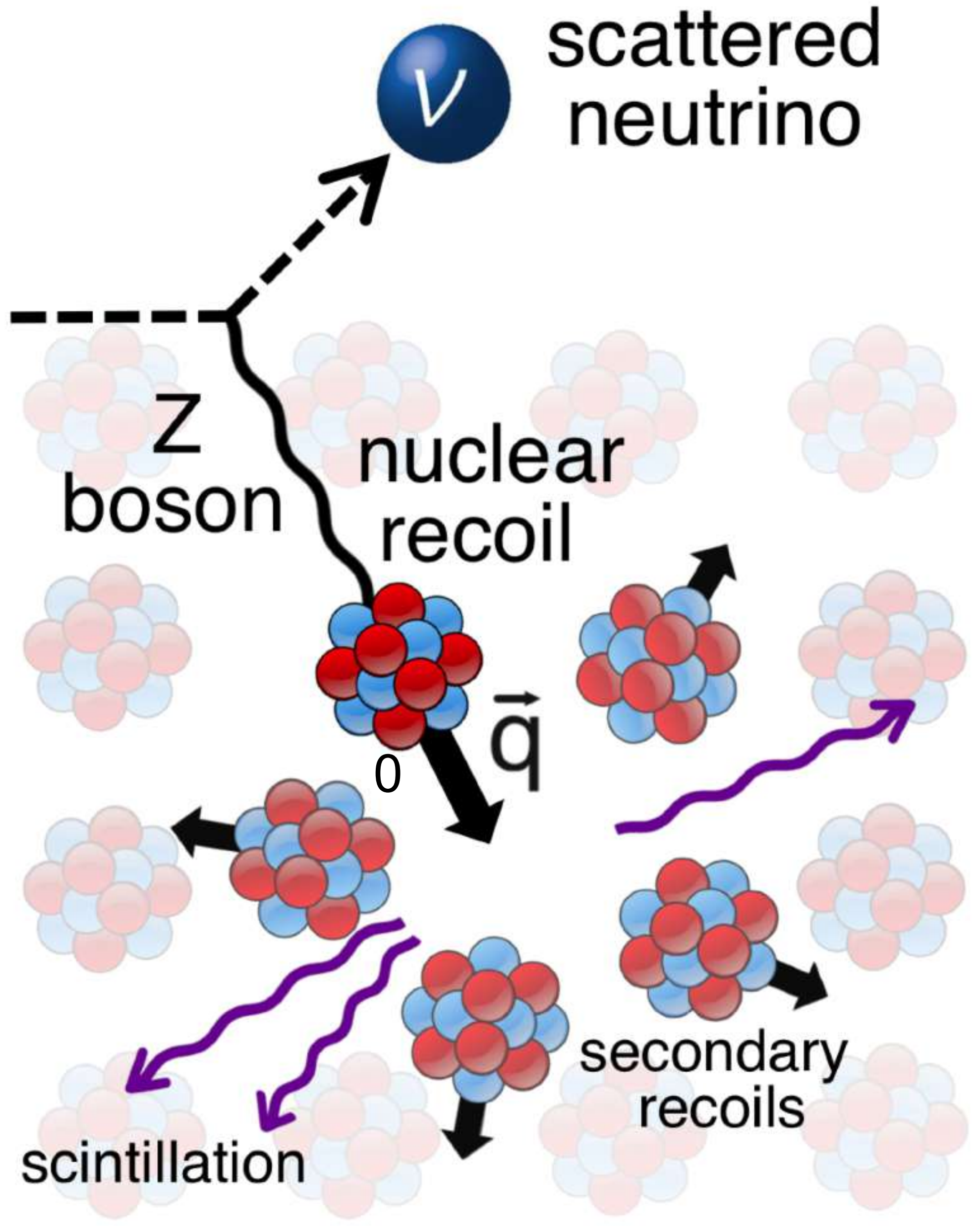

- Hard to observe due to tiny nucelar recoil energies

$$< E_r >= \frac{2}{3}\frac{(E_\nu/\mathrm{MeV})^2}{A}\mathrm{keV}$$

- Energies below the typical detection threshold of conventional neutrino experiments
- New low threshold and background technology developed together with the DM direct detection experiments

Why CEvNS?

- Fundamental neutrino interactions
  - Predicted by the SM (access to precision physics)
  - Beyond SM physics

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cross section measurements	arXiv: 1407.7524; arXiv: 2007.15688
Weinberg angle	arXiv:2102.06153; arXiv:2108.07310

neutrinos non-standard interactions (NSI)	arXiv:1708.02899; arXiv:1708.04255; arXiv:1812.02778; arXiv:1911.09831
neutrino electromagnetic properties	arXiv:1403.6344
light vector mediators	arXiv:1910.04951; arXiv:1804.03660; arXiv:2008.05022
axion-like particles (ALPs)	arXiv:1912.05733
light sterile neutrinos	arXiv:1201.3805; arXiv:151102834; arXiv:1708.09518
dark matter	arXiv:1711.04531; arXiv: 1710.10889

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- Nuclear physics (nuclear form factor, neutron distribution radius)

Cadeddu et al., PRD 101, 033004 (2020)

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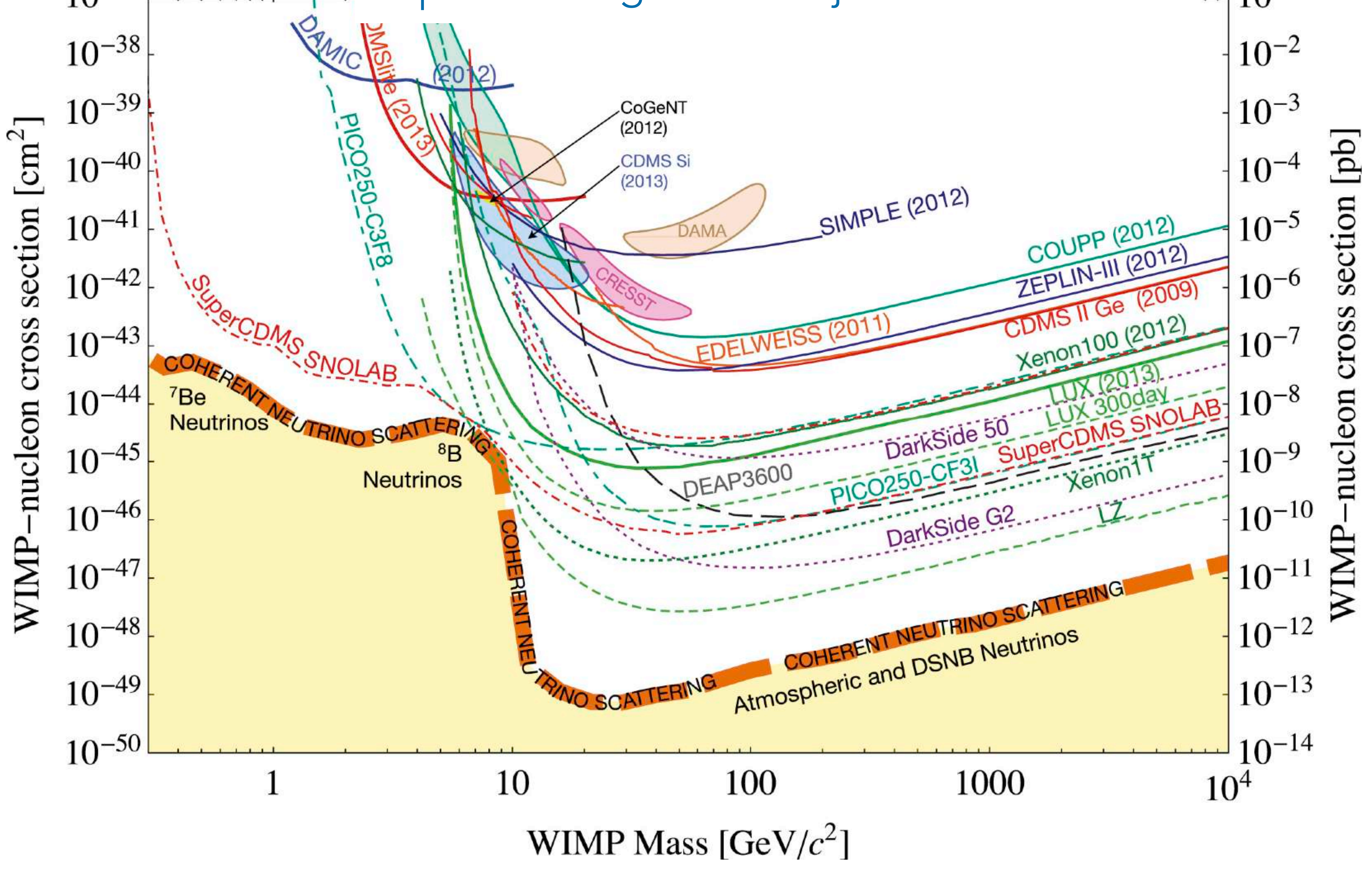
PRD 101, 033004 (2020)

- Background for DM experiments arXiv:2408.02877

https://doi.org/10.1016/j.dark.2014.10.005



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- Supernova neutrinos PRD 94, 10, 103009 (2016)
  - Energy transport: all neutrino flavors with E ~ 10 MeV
  - To detect SN neutrinos: tonne-scale DM detectors

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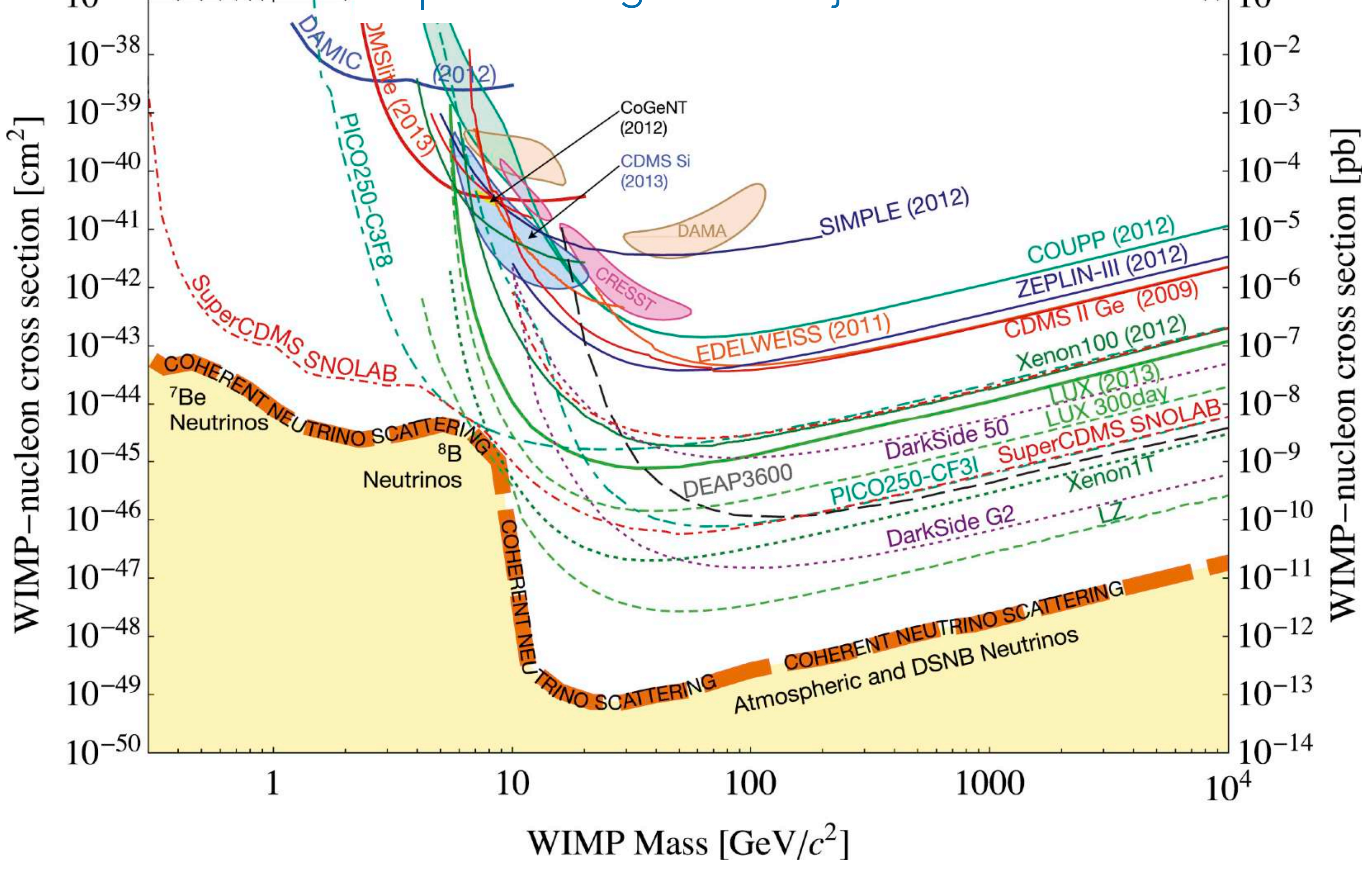

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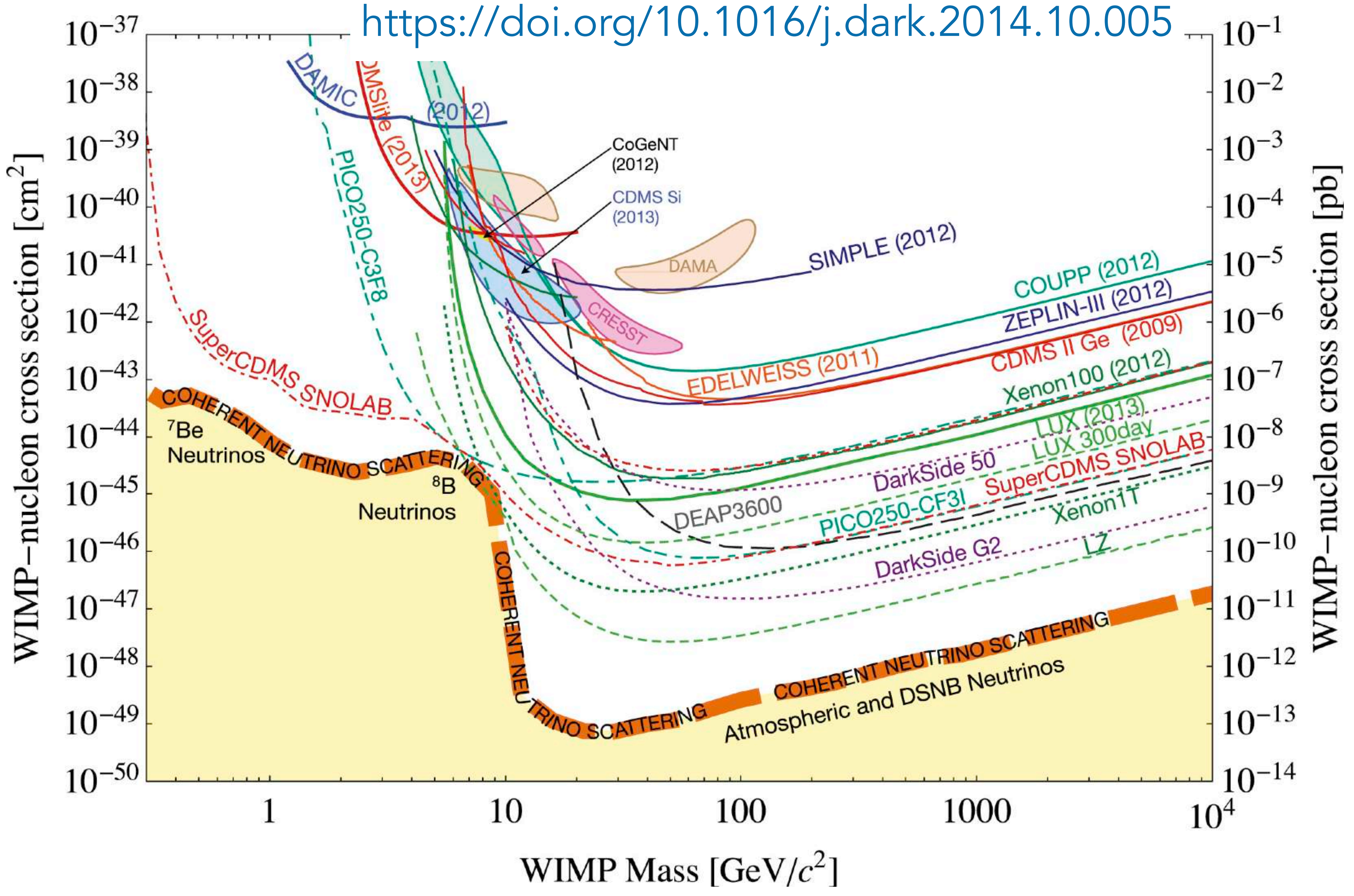
- Reactor physics
  - Reactor fluxes & monitoring (below IBD threshold)
  - Application for non-proliferation

Rev. Mod. Phys. 92, 1, 011003 (2020)
PRD 105, 056002 (2022)

https://doi.org/10.1016/j.dark.2014.10.005

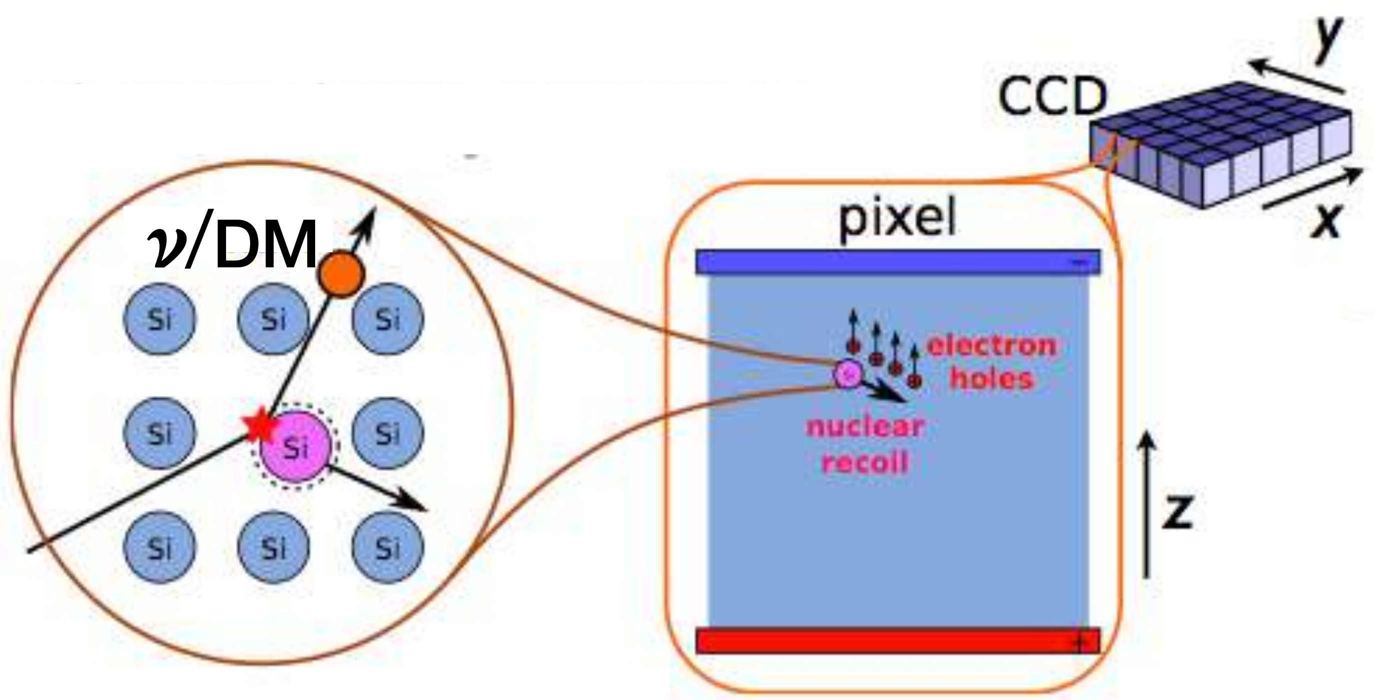


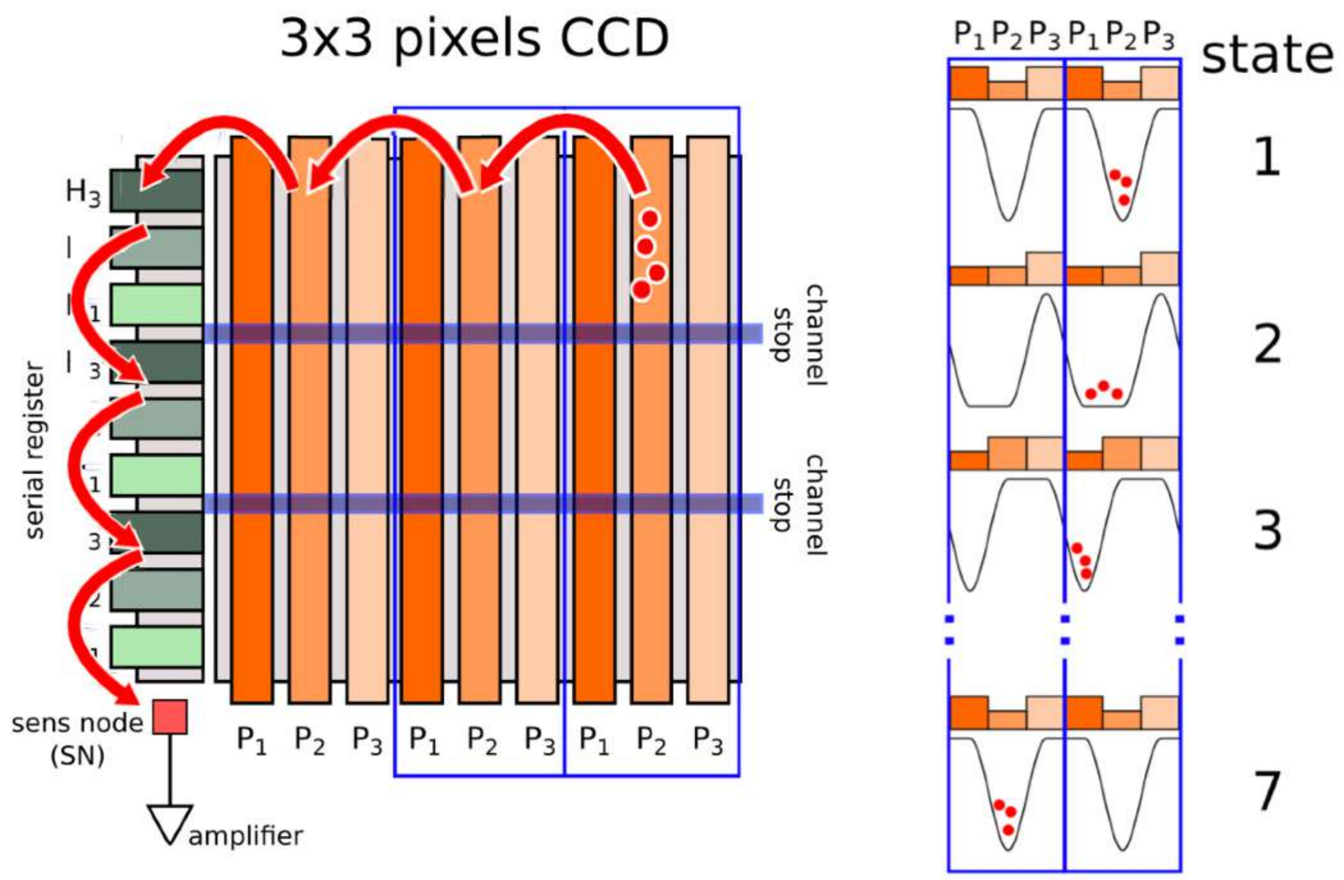
Word scenario

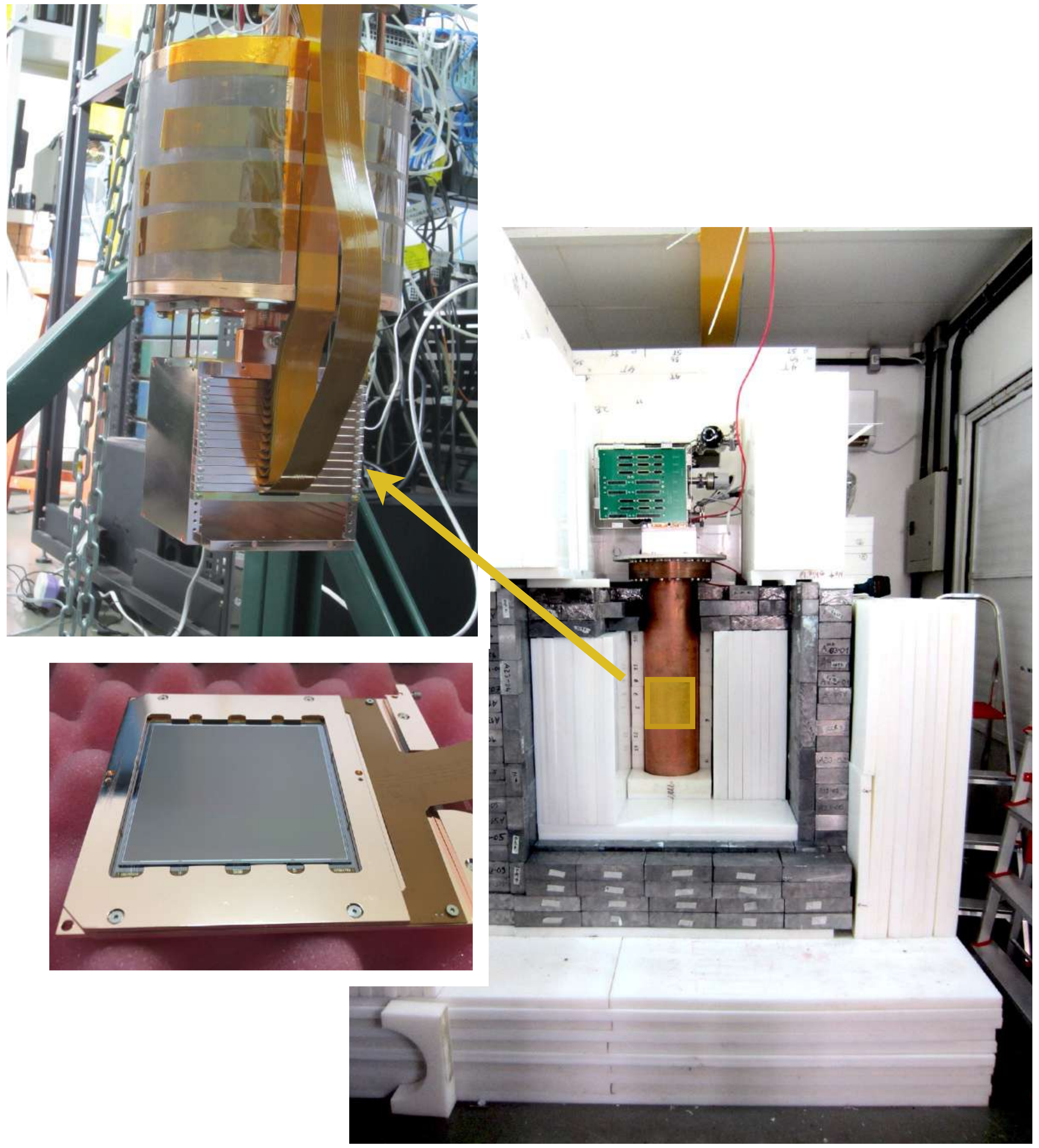
CONNIE

COherent Neutrino-Nucleus Interaction Experiment

- Experiment @ 30 m from the 3.9 GW reactor core
- Reactor-OFF periods (~1/14 months) for background measurements
- Flux: $\sim 10^{12}\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
- Passive shield (Lead + polyethylene)
- Energy threshold ~ 15 $\mathrm{eV_{ee}}$



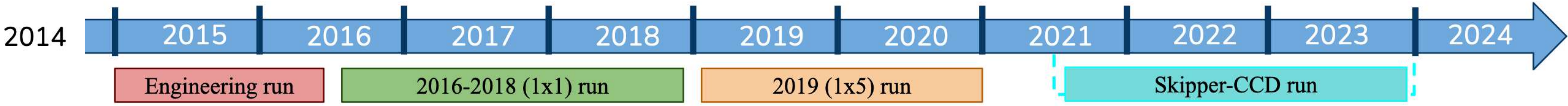




Timeline

10 years since it was installed @ Angra 2

04/2010 First idea: use CCDs for neutrino detection



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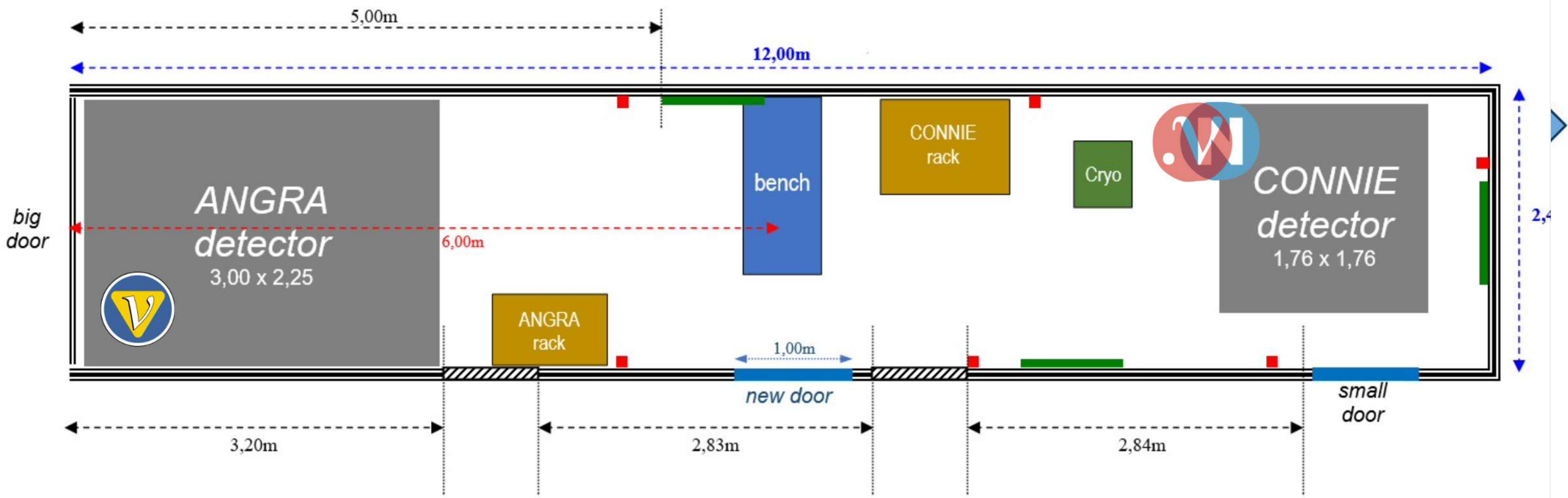
Start of a great partnership with Angra-Nu

see Ernesto's talk in this Session X
15:20-15:40 - From Safeguards Application to Fundamental Physics: Advancements in Reactor Neutrino Detection with the Brazilian ν-Angra Experiment

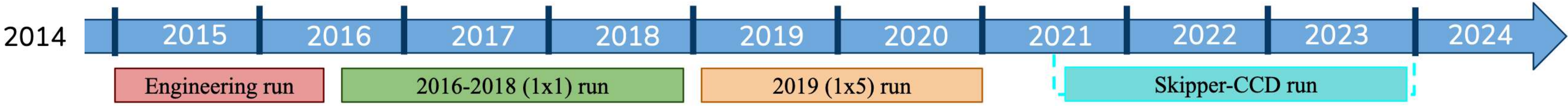
NuLAB
Laboratório de Neutrinos



Timeline

10 years since it was installed @ Angra 2

04/2010	First idea: use CCDs for neutrino detection
12/2010	Informal presentation at SILAFAE (Chile)
08/2011	New name (formerly nuCCD, Angra-CCD)
11/2011	Background measurement @ Angra 2 (Ge Detector)
04/2012	CONNIE – starting a collaboration (mailing list)
10/2012	Presentation at NuInt and visit to Angra 2
2013	Infraestructura preparation and shielding design (and testing) Detector tests and performance @ Fermilab
08/2014	Experiment shipped to Angra 2



Timeline

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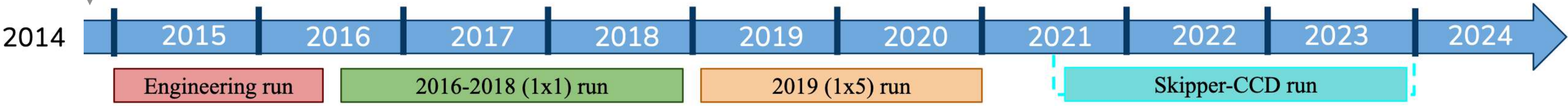
Installation at Angra

4 CCDs 2k x 4k pixels
250 μm thick (1 g each)



Results from engineering run
JINST 11 (2016), P07024

Timeline

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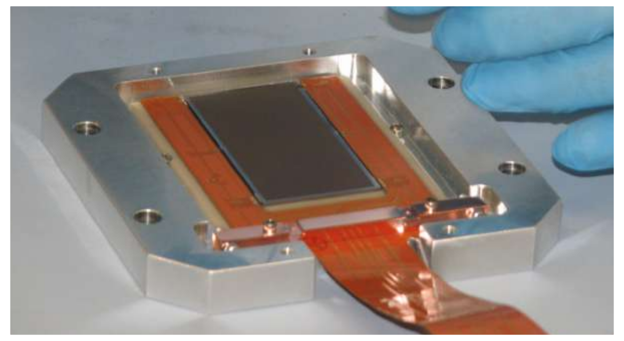
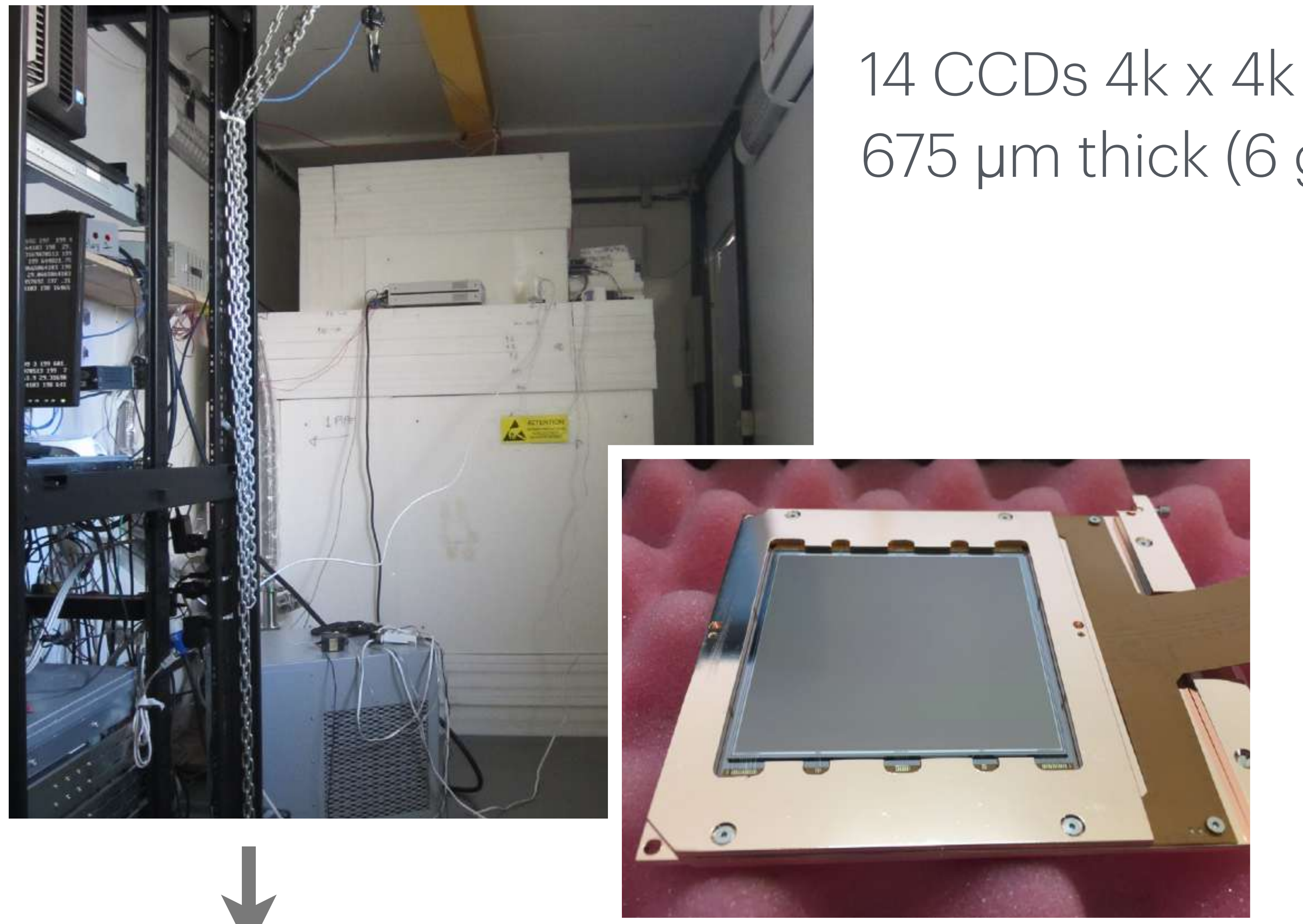
Installation at Angra

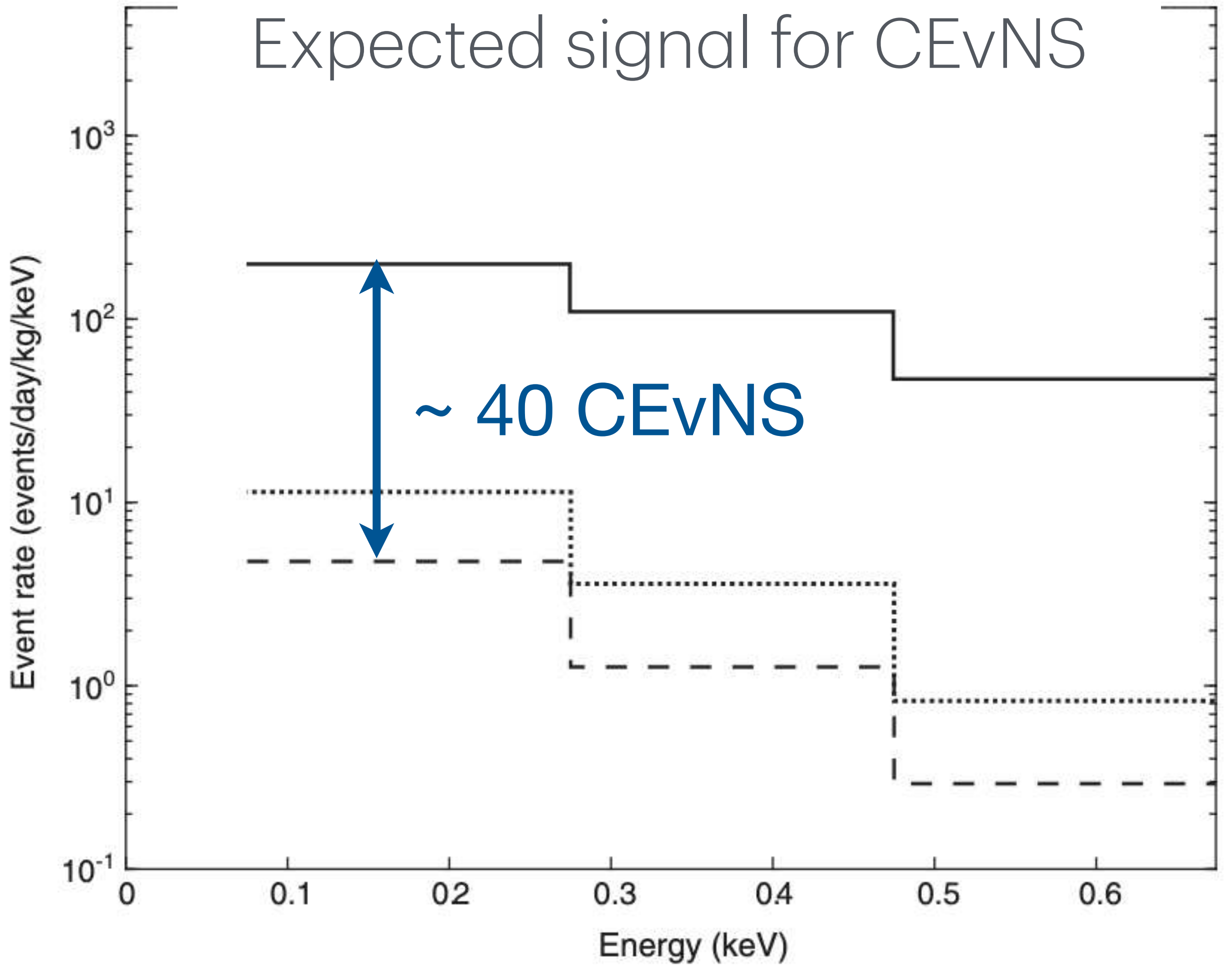


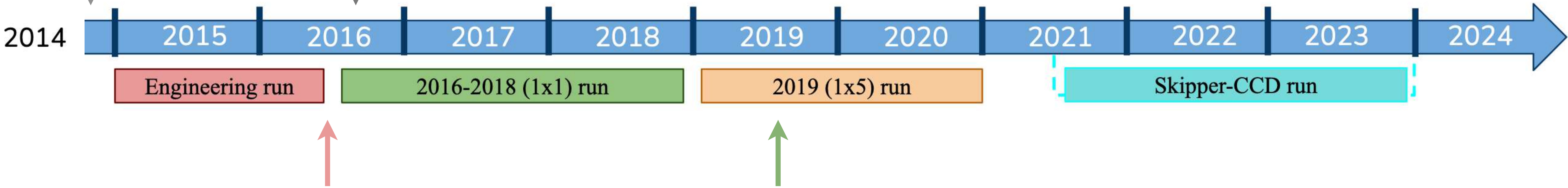
Installation of scientific CCDs



14 CCDs 4k x 4k pixels
675 μm thick (6 g each)

95% CL for the RON-ROFF rate
Expected signal for CEvNS





Results from engineering run
JINST 11 (2016), 07024

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

Timeline

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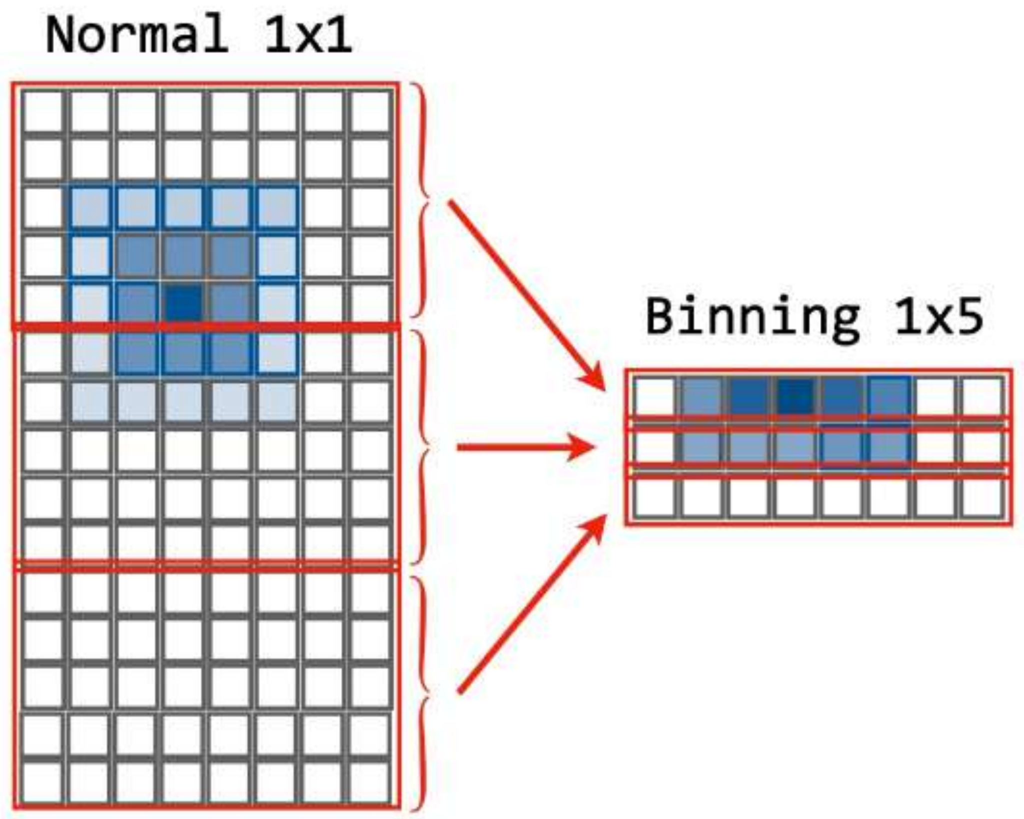
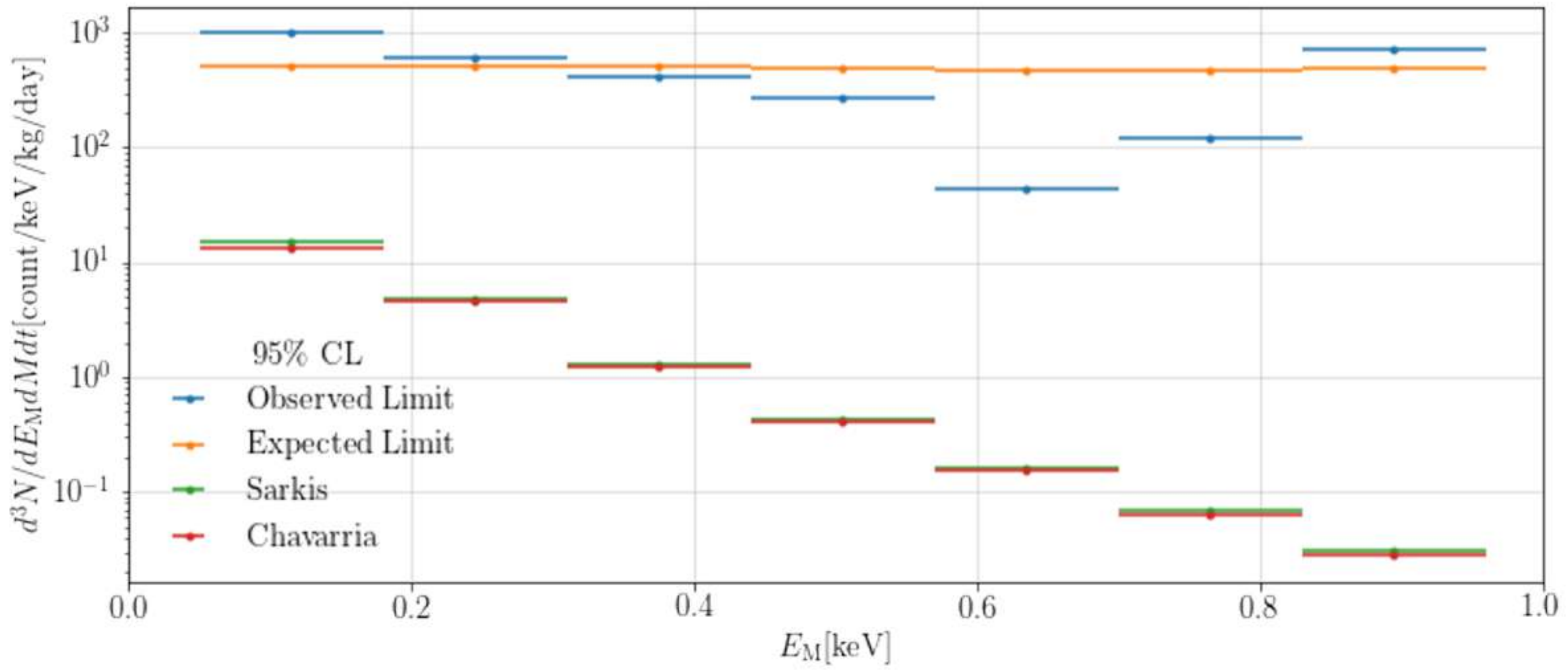
Improved sensitivity at low energies





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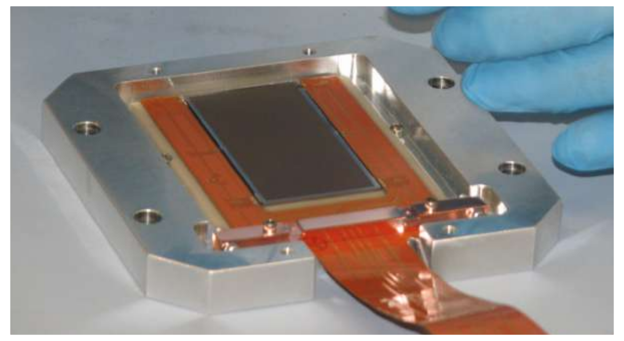

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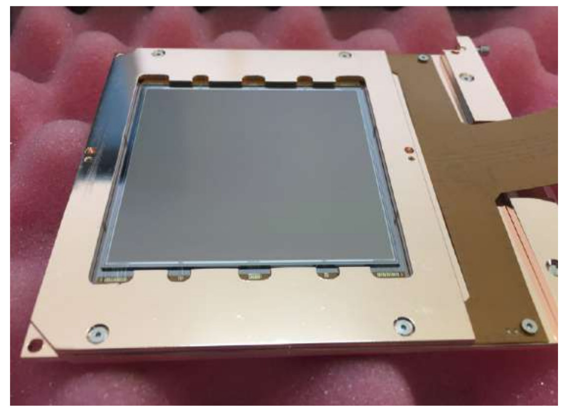
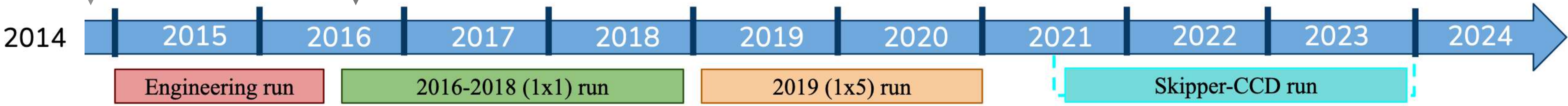




Results from engineering run
JINST 11 (2016), 07024

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

Results from 2019 run
JHEP 05 (2022), 017

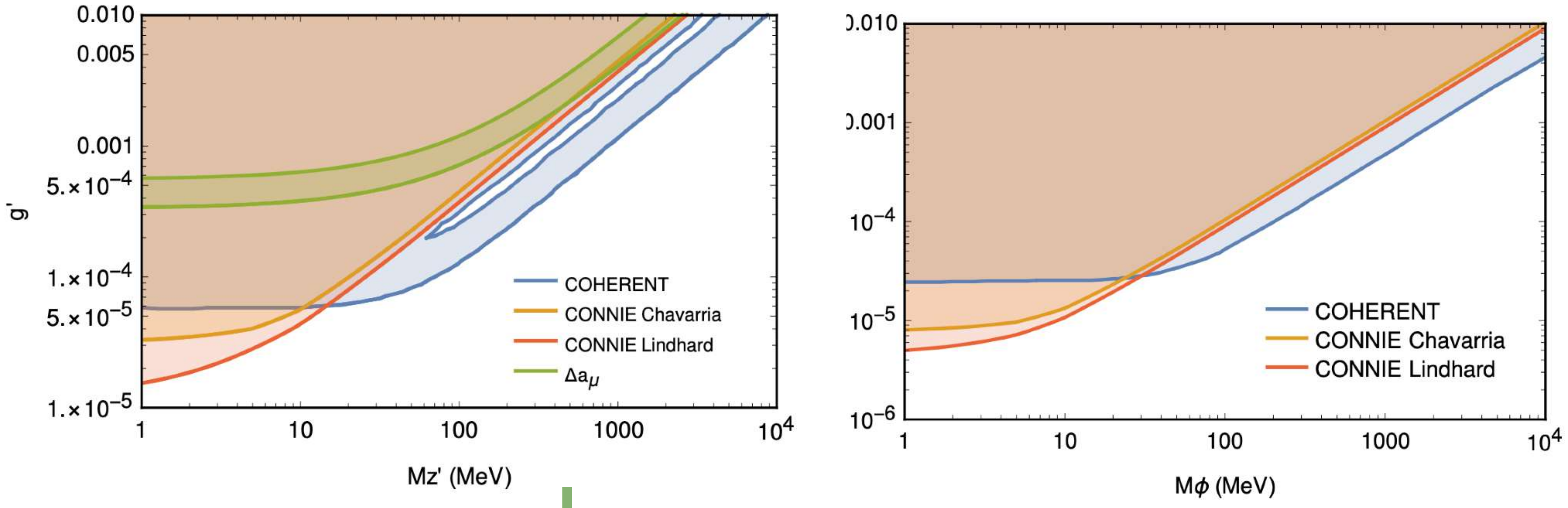
Timeline

10 years since it was installed @ Angra 2

Limits on SM extensions with light mediators

Community milestone

NEUTRINO 2020



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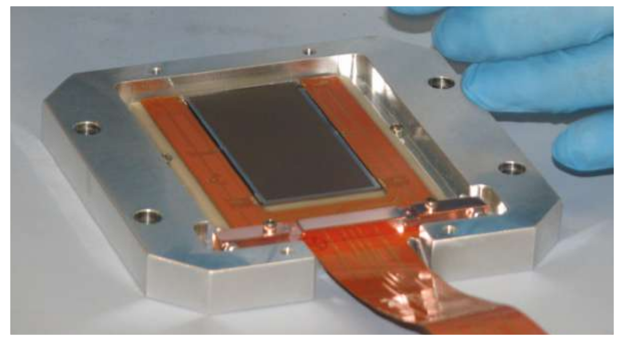

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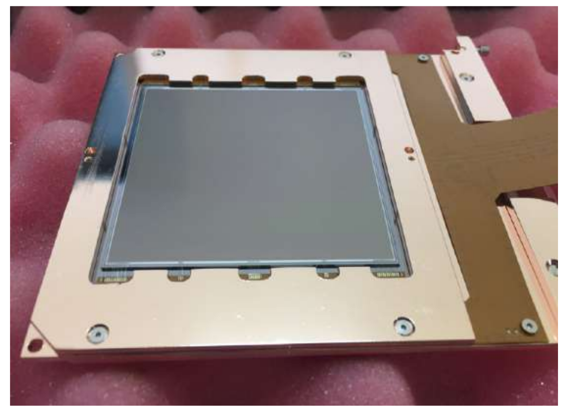
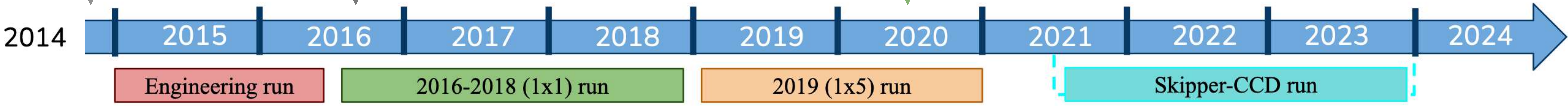


JHEP 04 (2020) 054



Results from engineering run
JINST 11 (2016), 07024

Results from 2016-2918 run
PRD 100 (2019), 092005

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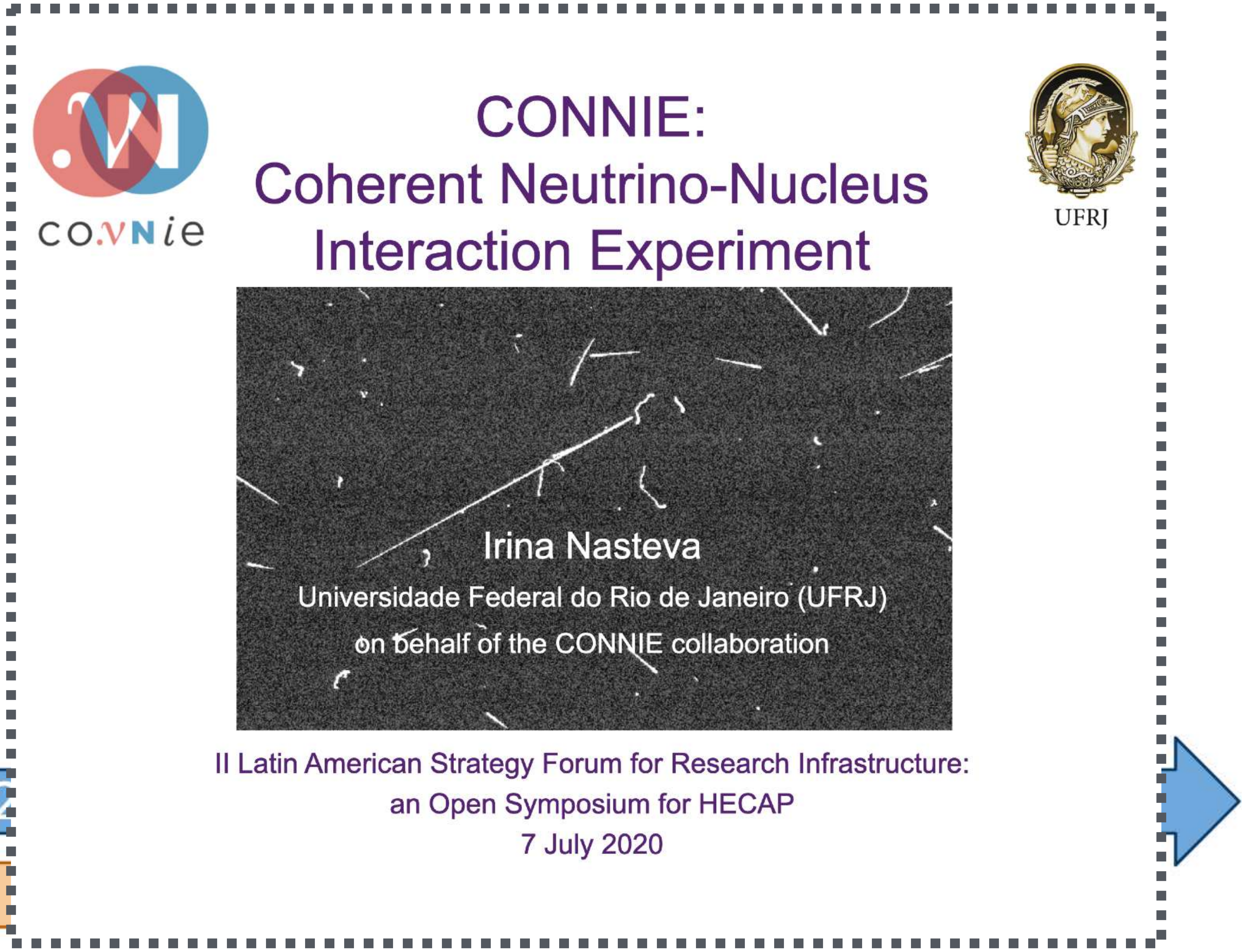
II Latin American Strategy Forum for Research Infrastructure: an Open Symposium for HECAP

July 6-10, 2020 (by videoconference)

ICTP-SAIFR, São Paulo, Brazil



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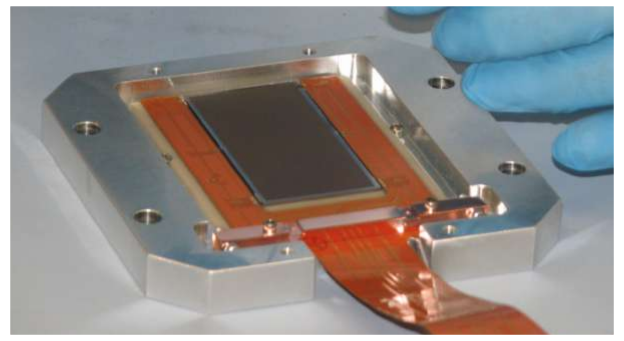

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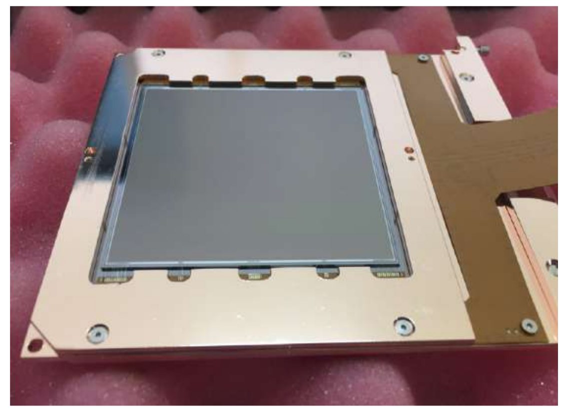
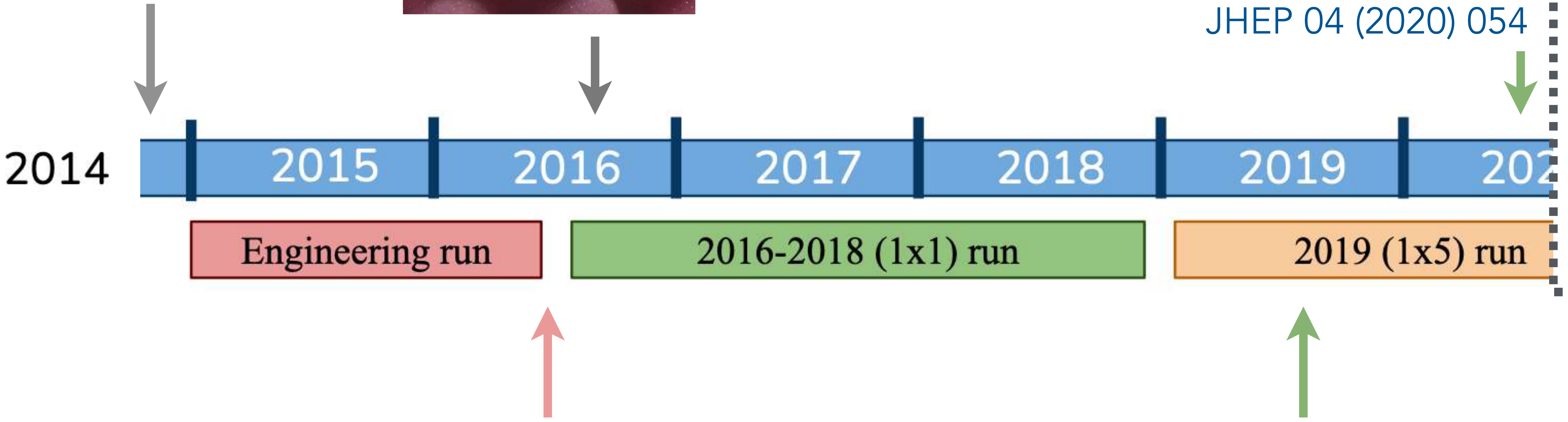


Limits on SM extensions with light mediators
JHEP 04 (2020) 054



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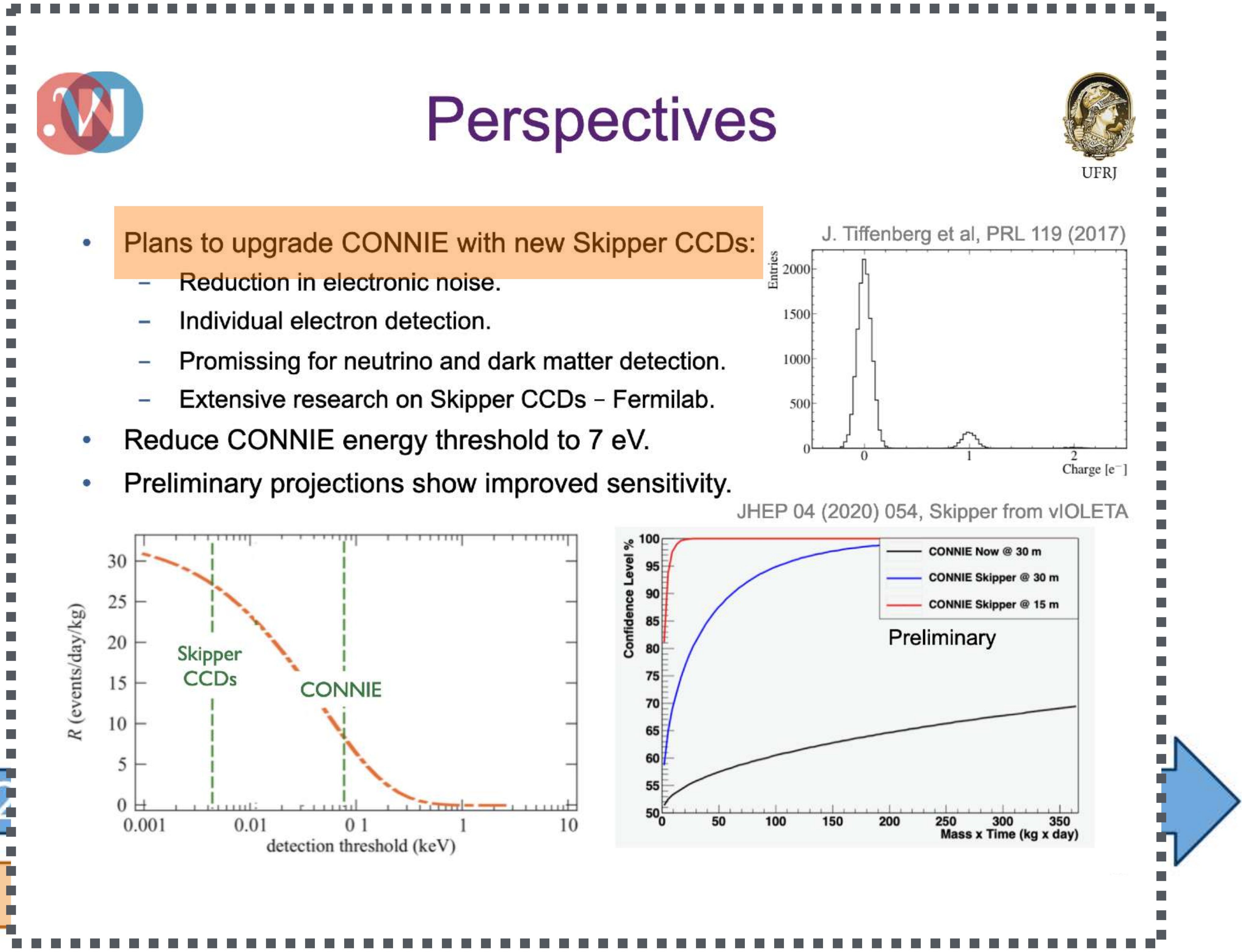

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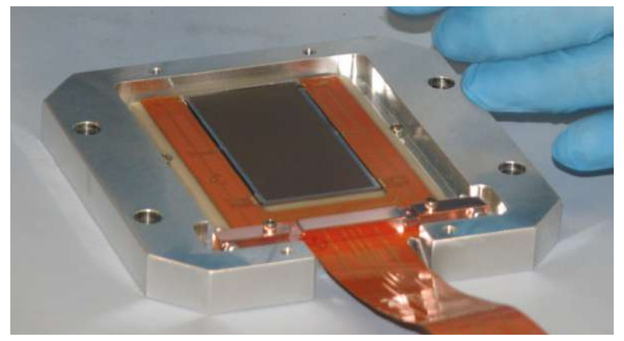

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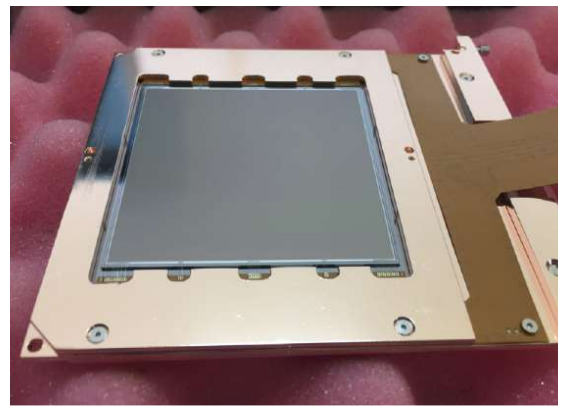

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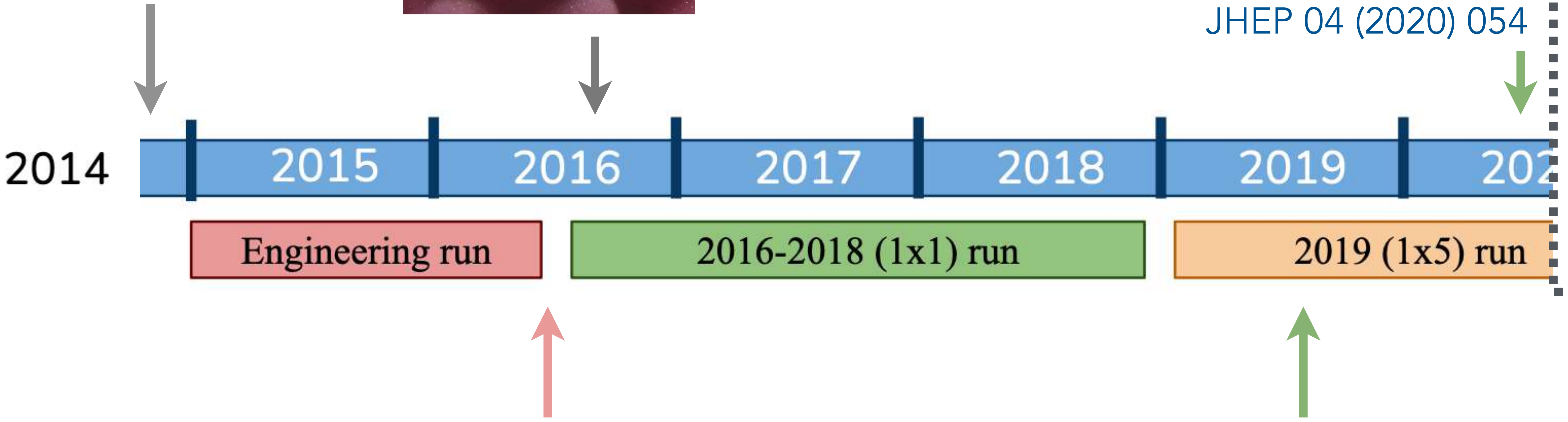

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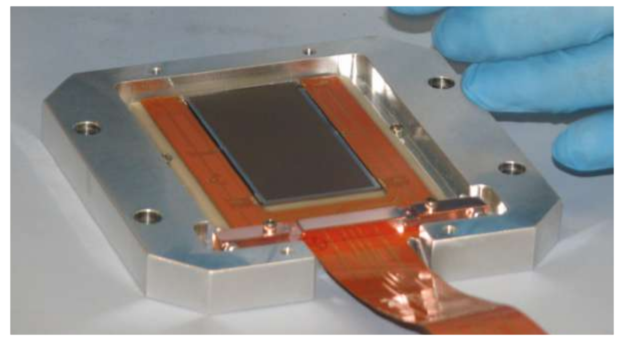

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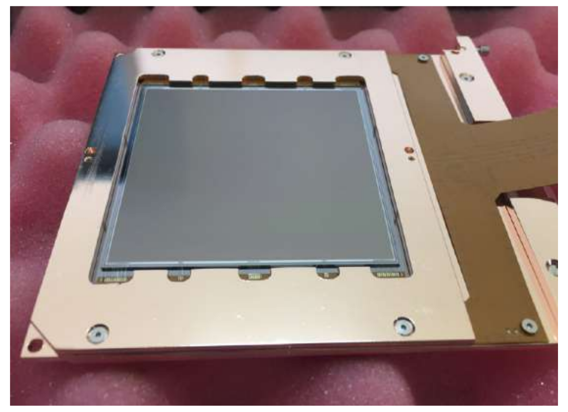

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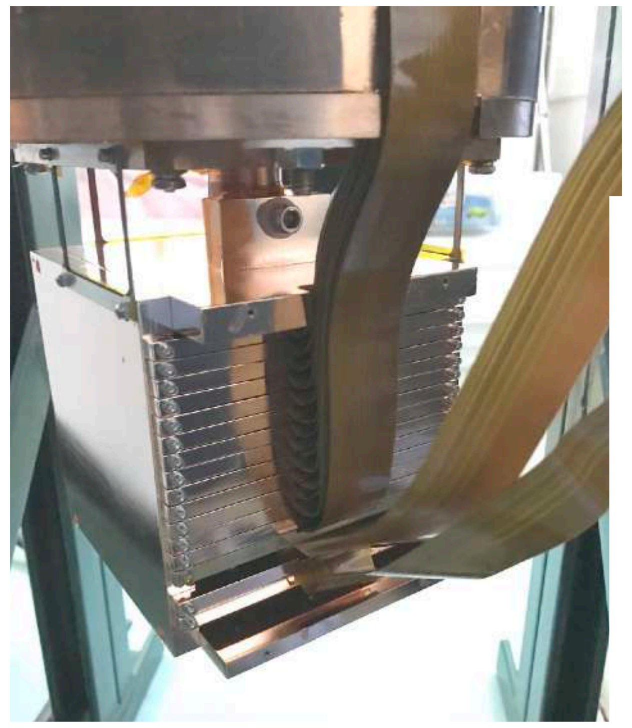
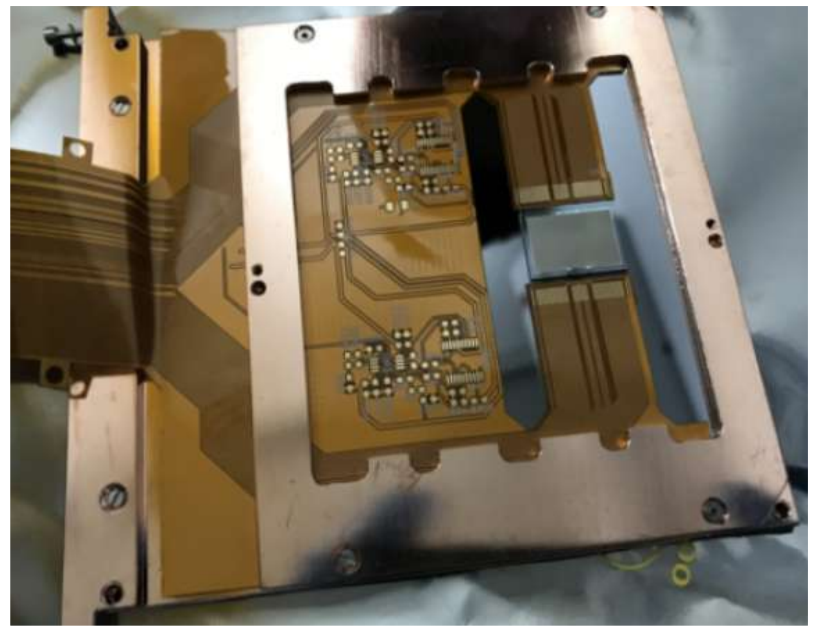
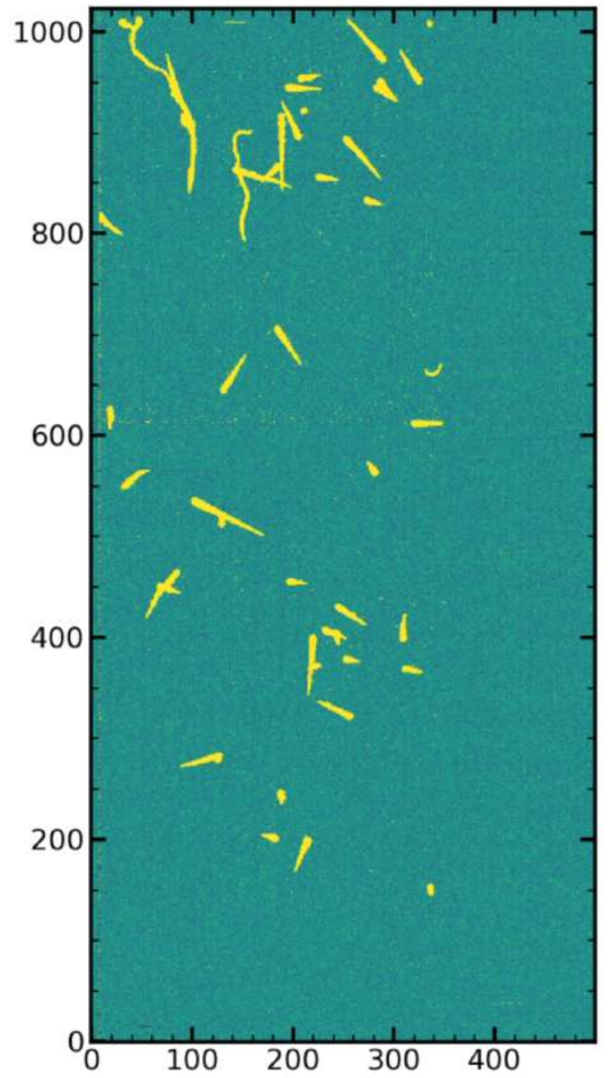
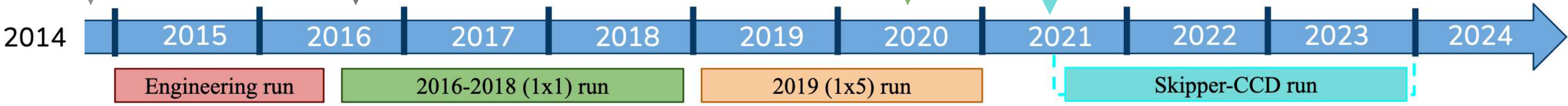
Installation of Skipper-CCDs



2 Skipper-CCDs 1022 x 682 pixels
675 μm thick (0.25 g each)







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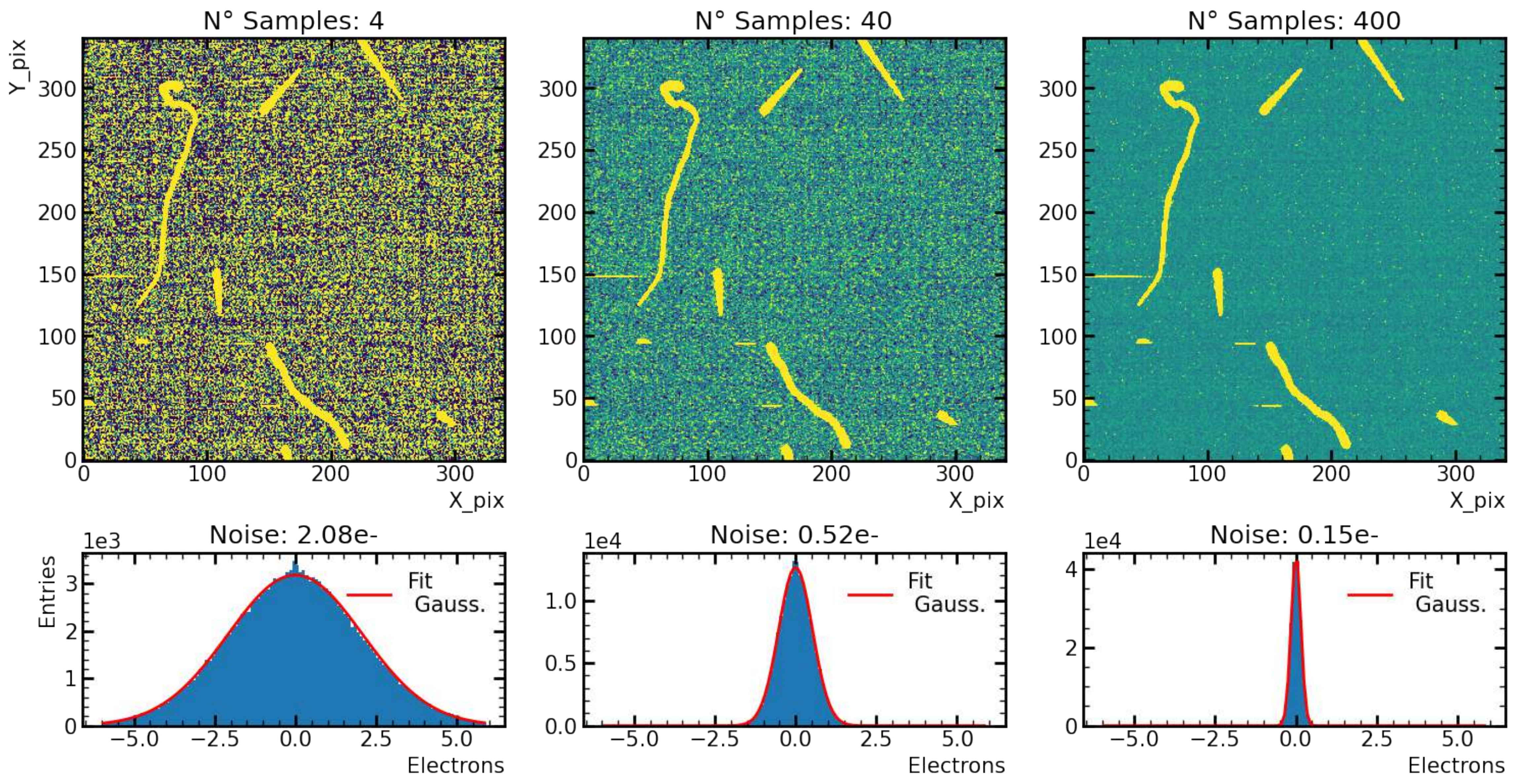
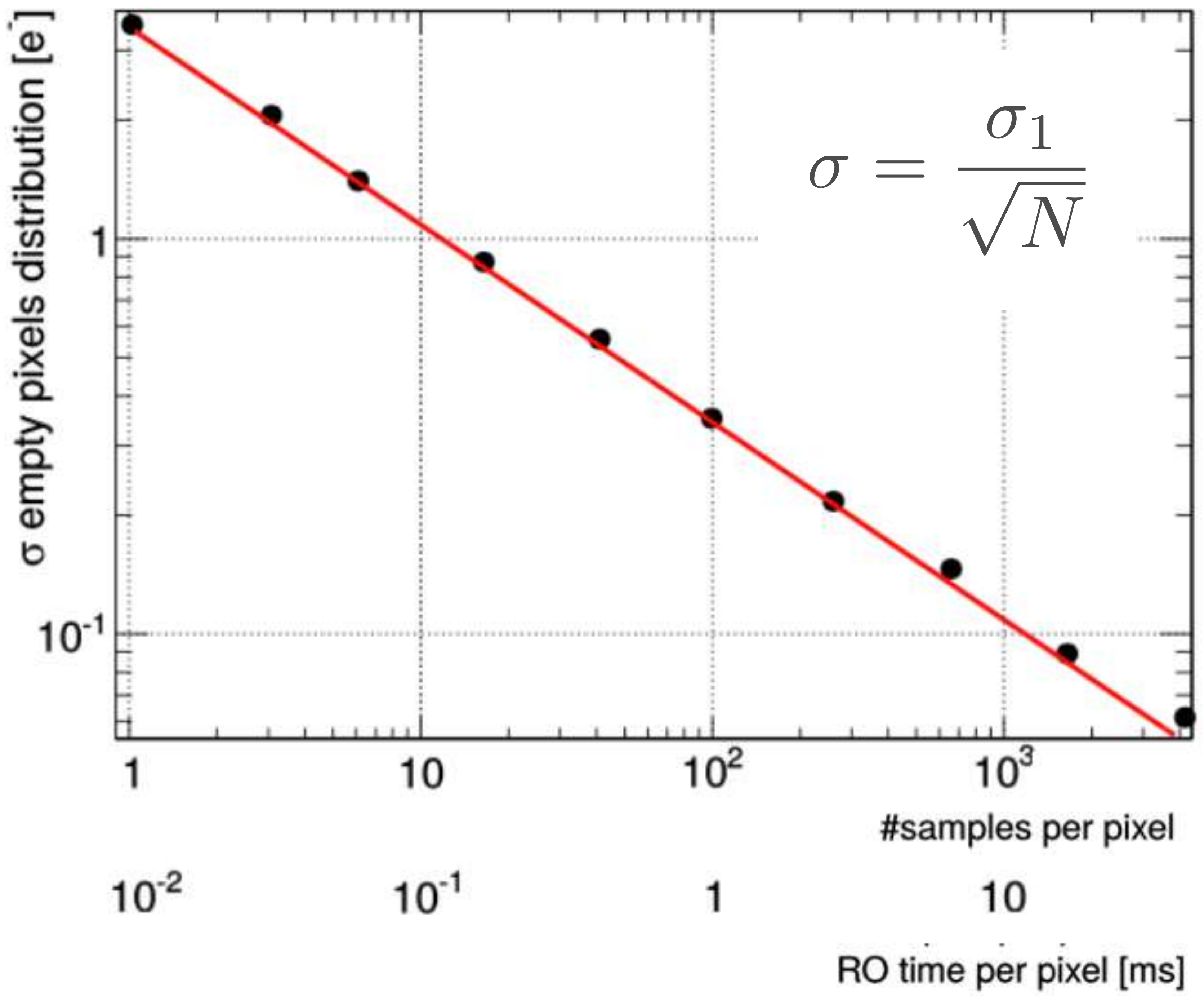
CONNIE-Skipper

New technology for individual electron detection

- Skipper-CCDs sensors allow one to reach very low energies
  - Allow multiple non-destructive charge measurements of each pixel
  - Sub-electron readout noise levels PRL 119, 131802 (2021)





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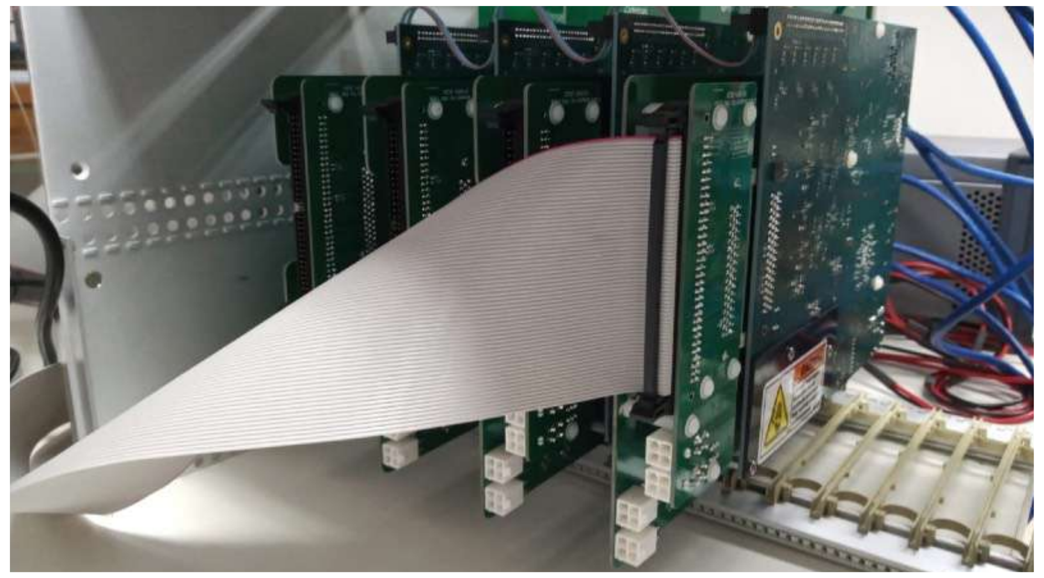
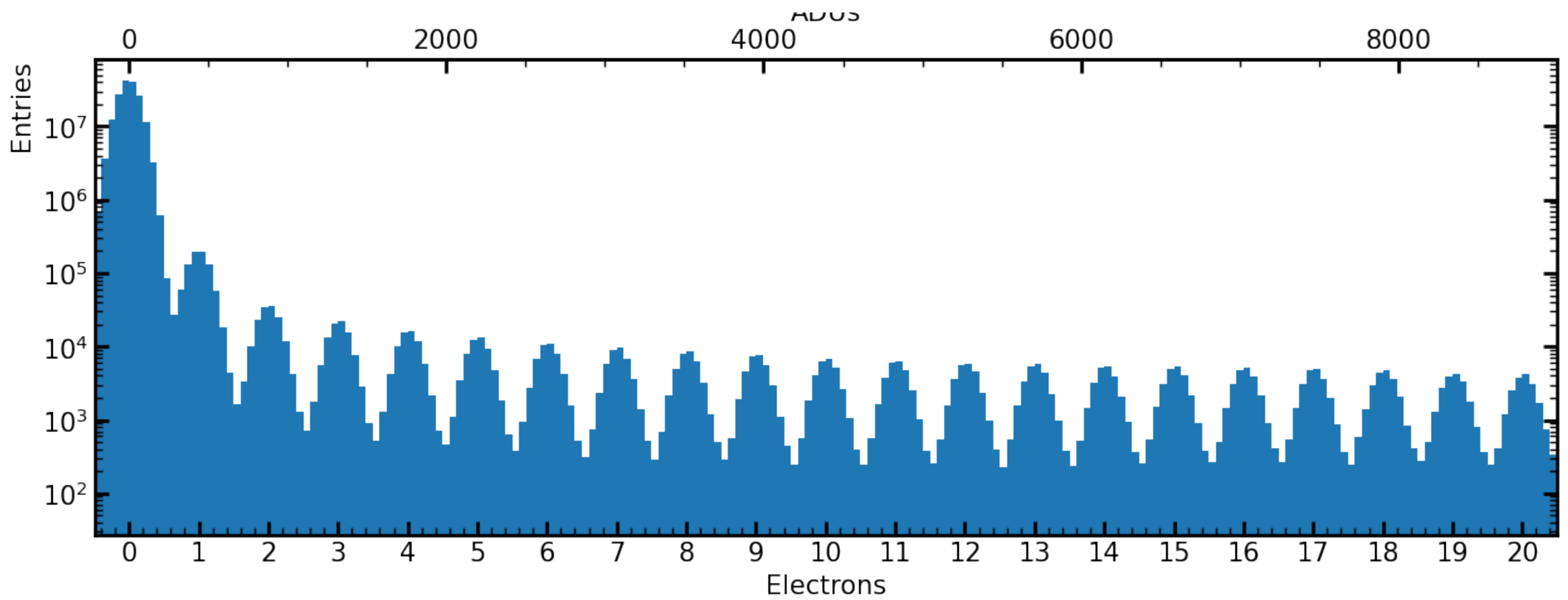
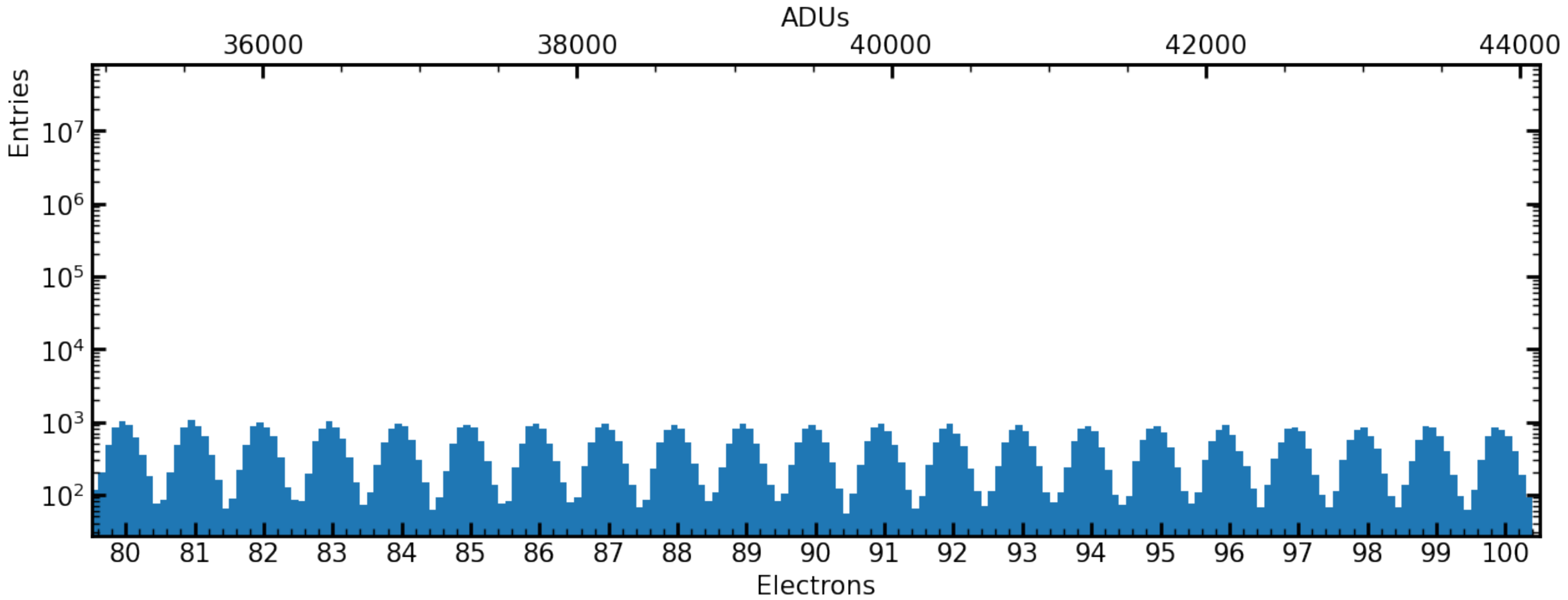
PRL 119, 131802 (2021)

- Skipper-CCDs @ CONNIE since July 2021
  - 2 skipper-CCDs (1022 x 682 pixel each)
  - new Low Threshold Acquisition (LTA) readout electronics
  - new VIB developed at CBPF
  - Readout noise: ~0.15e- RMS
  - Single electron rate: ~ 0.05 e-/pix/day

JATIS 7, 1, 015001 (2021)





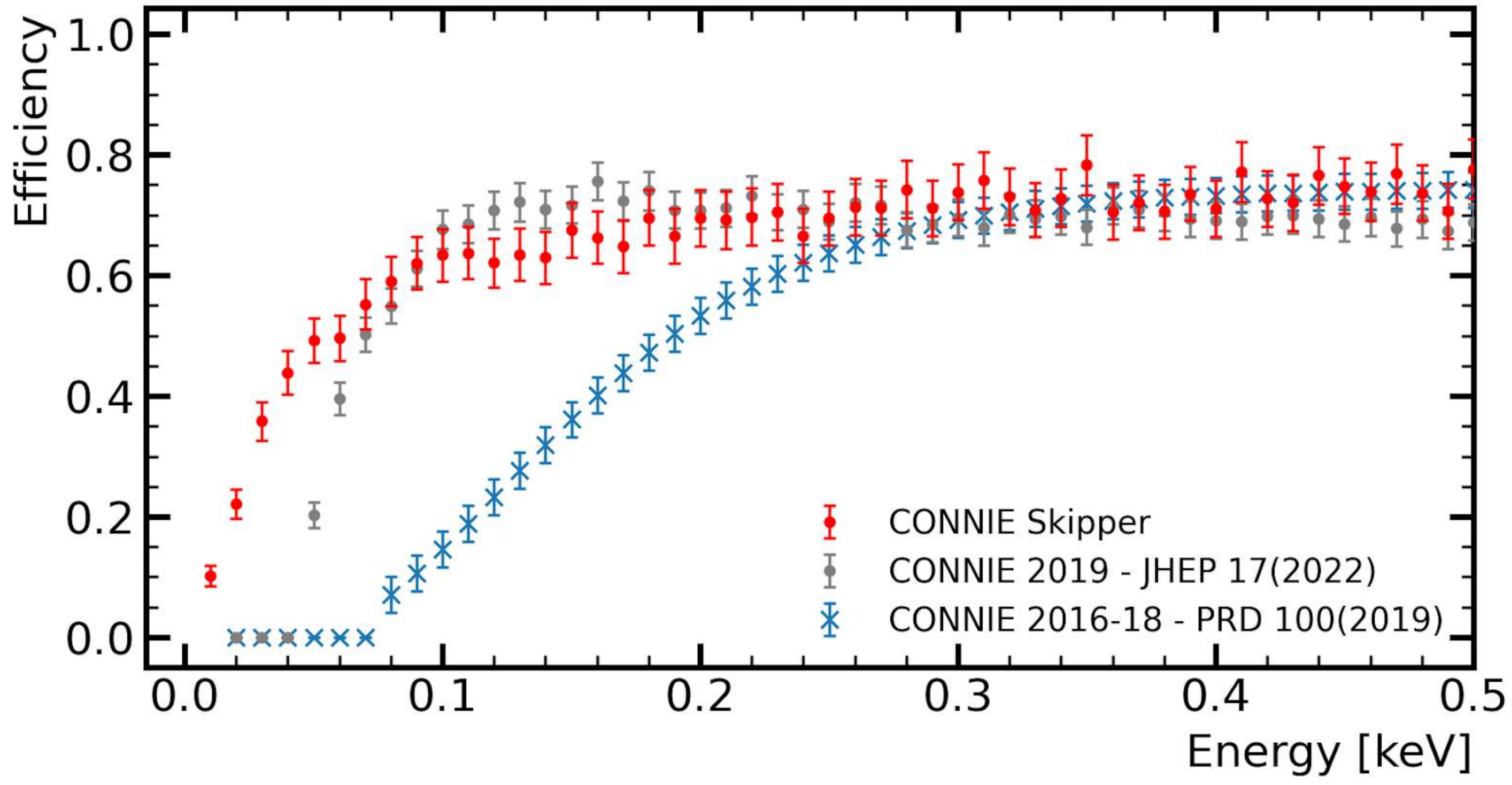


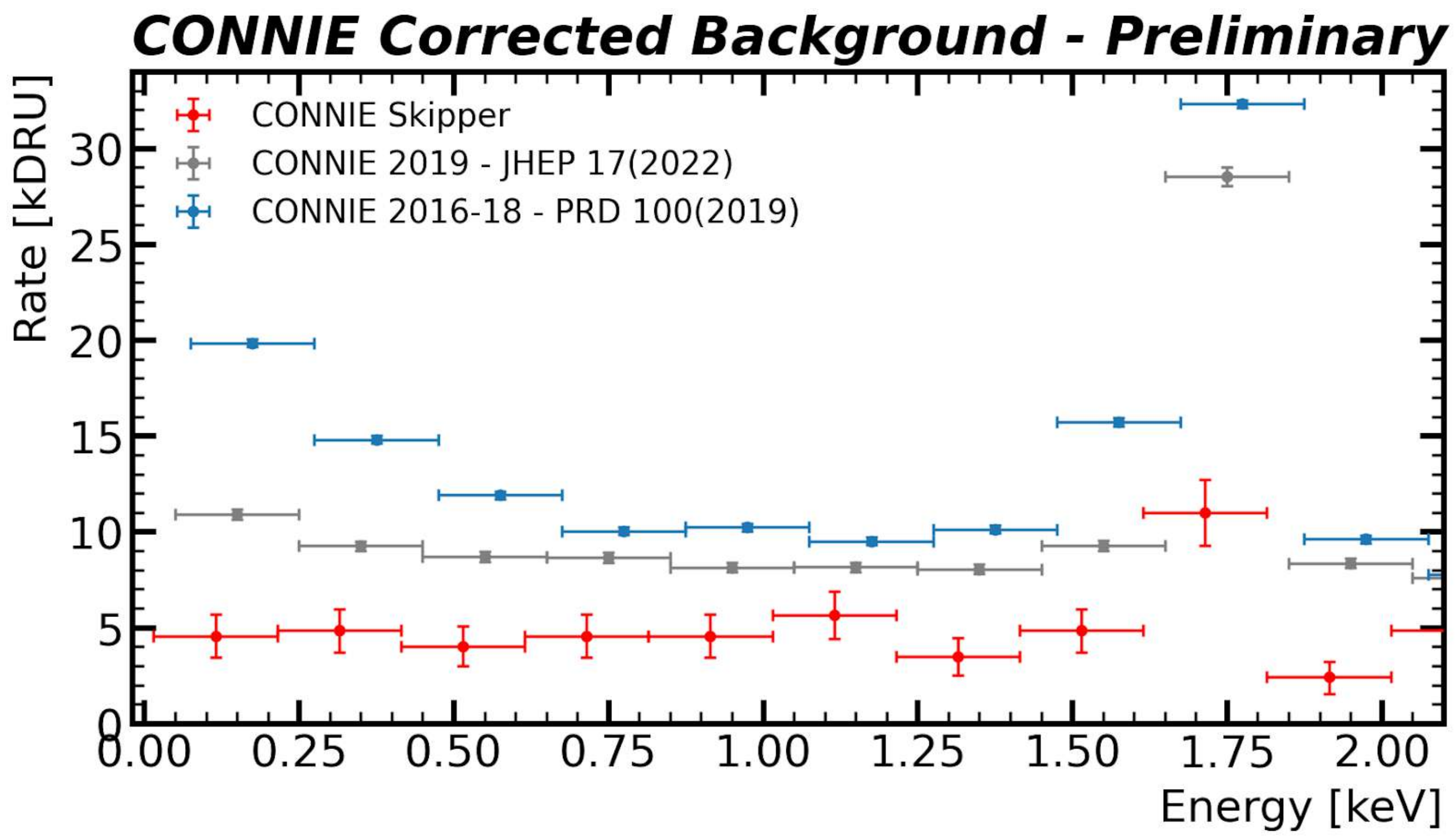
Background and efficiency selection

Improving the detector capabilities

arXiv:2403.15976

- Stable detector performance and background over the 2021-2022 period
- Efficiency determination using simulations
- Reaching a threshold of 15 eV
- Lower and flat background rate ~ 4 kdru (1 dru = 1 event kg^{-1} day^{-1} keV^{-1})

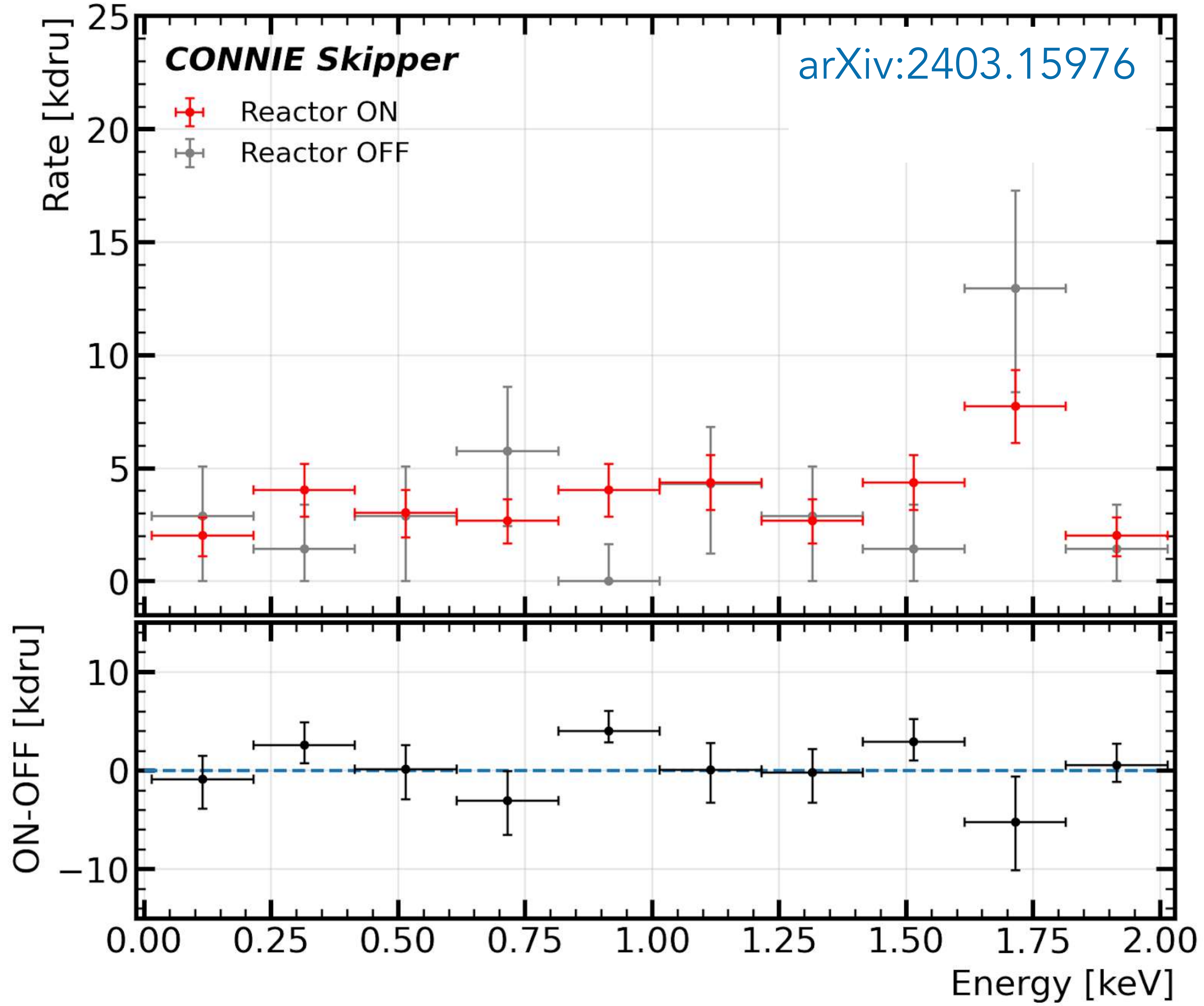




Energy spectrum

Improving the detector capabilities

- Comparison between RON and ROFF event rates



- Data taken: 243 days with RON and 57 days ROFF
- Exposure: 14.9 g-day RON and 3.5 g-day ROFF

- No excess rate observed
- A search for CEvNS in the lowest-energy bins
  - Updated reactor neutrino flux model
  - Updated Sarkis quenching factor model for Si

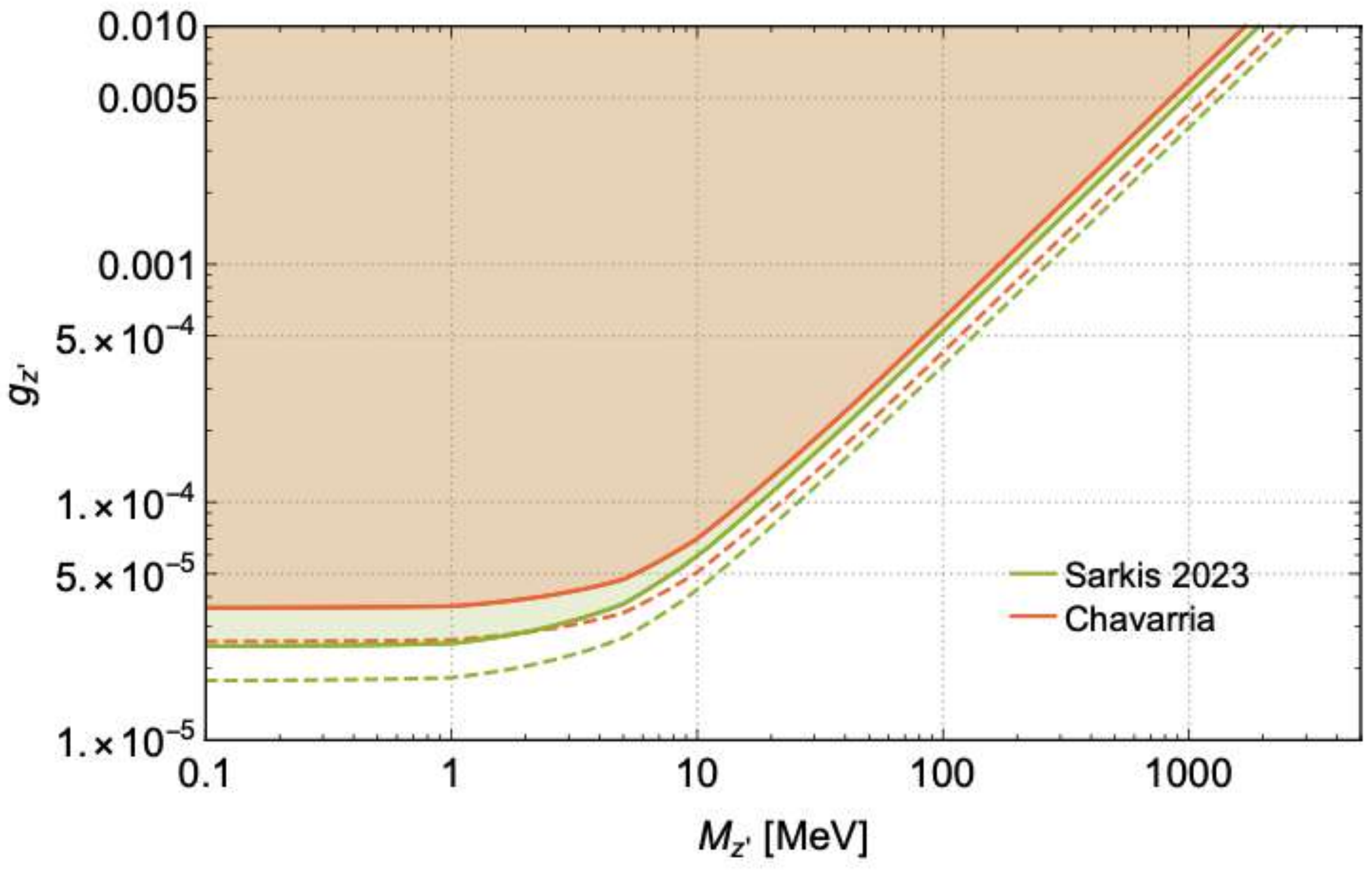
PRA 107, 062811 (2023)

  - Observed limit at 76x the SM predicted rate
  - Comparable to our previous limit with CCDs and 10^3 larger exposure

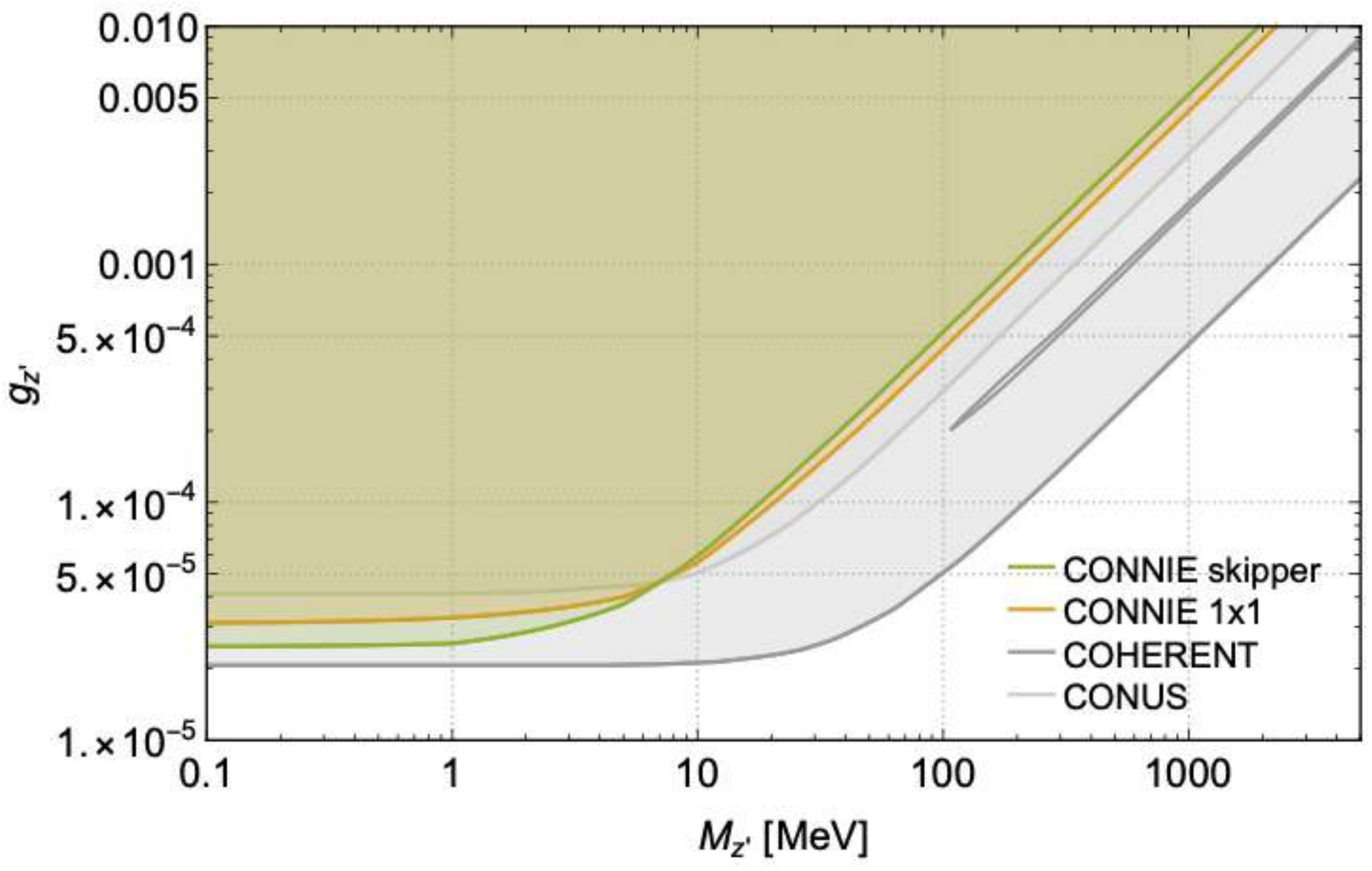
Light vector mediator search

BMS physics

- A new search for new light vector mediator Z′ in the CEvNS detection channel
  - In the framework of a universal simplified model JHEP 05, 118 (2016)
  - The rate for additional interactions, $R_{SM+Z'}$, is calculated and compared to the 90% CL
  - Based on the lowest-energy bin (15–215 eV)
  - Slight improvement at low $M_{Z'}$ over our previous limit in $g_{Z'}$



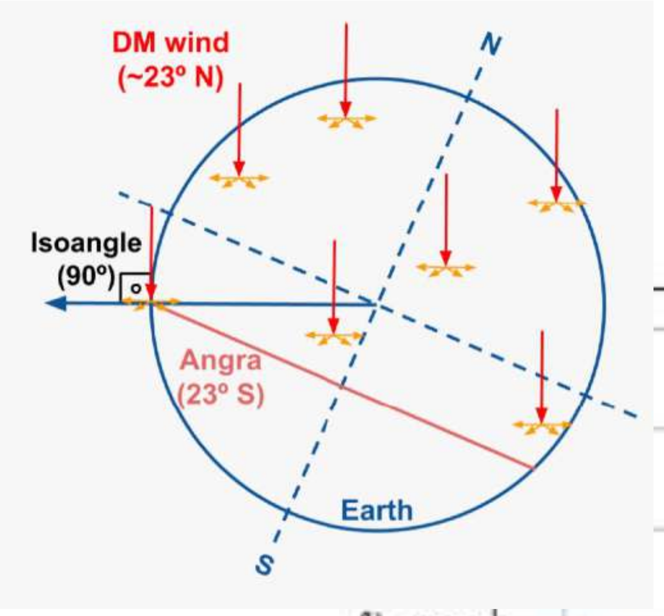
Comparison between QFs and projections for 5x smaller uncertainties and zero rate.



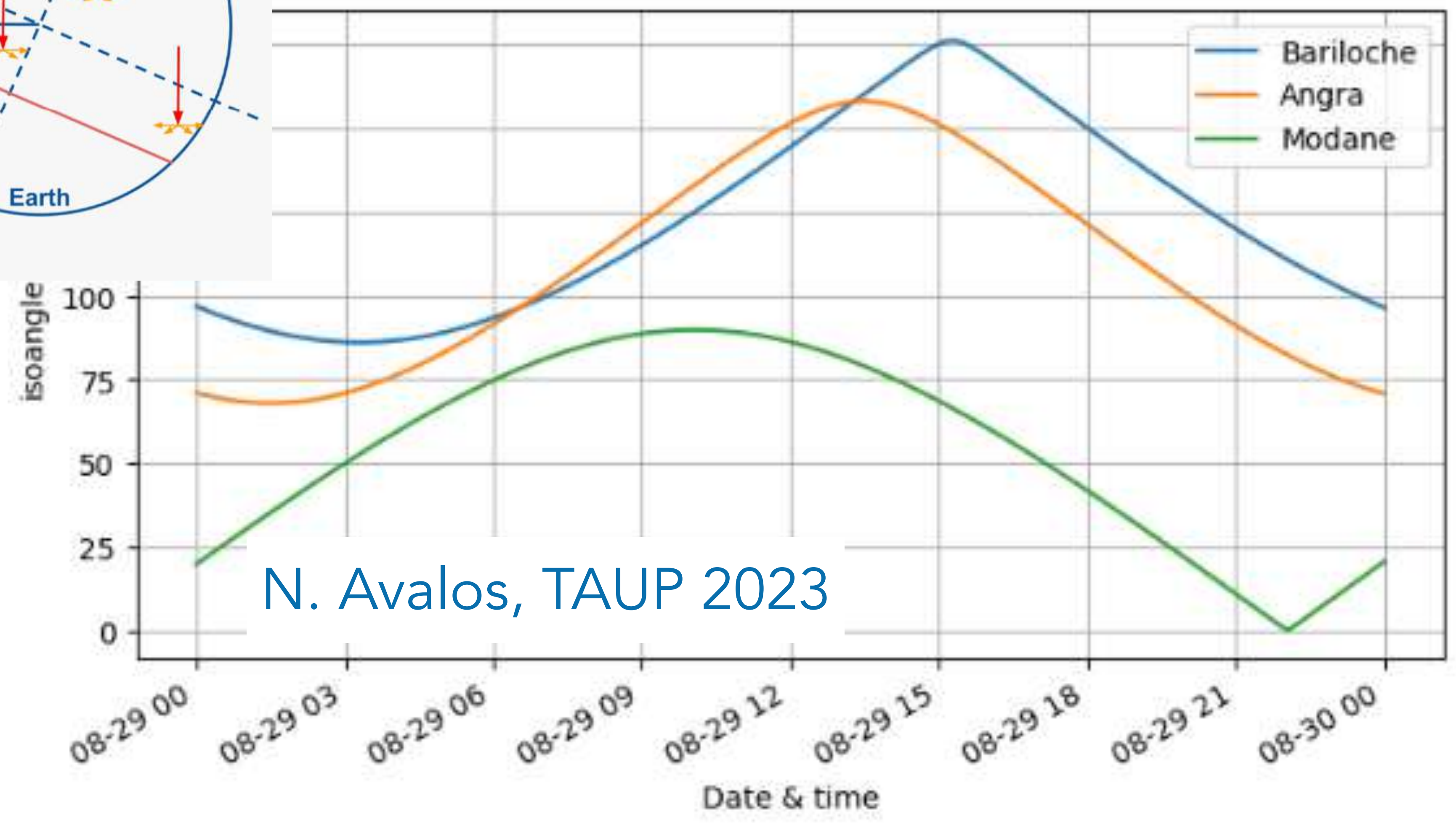
arXiv:2403.15976

Dark matter search

DM-electron interaction by diurnal modulation



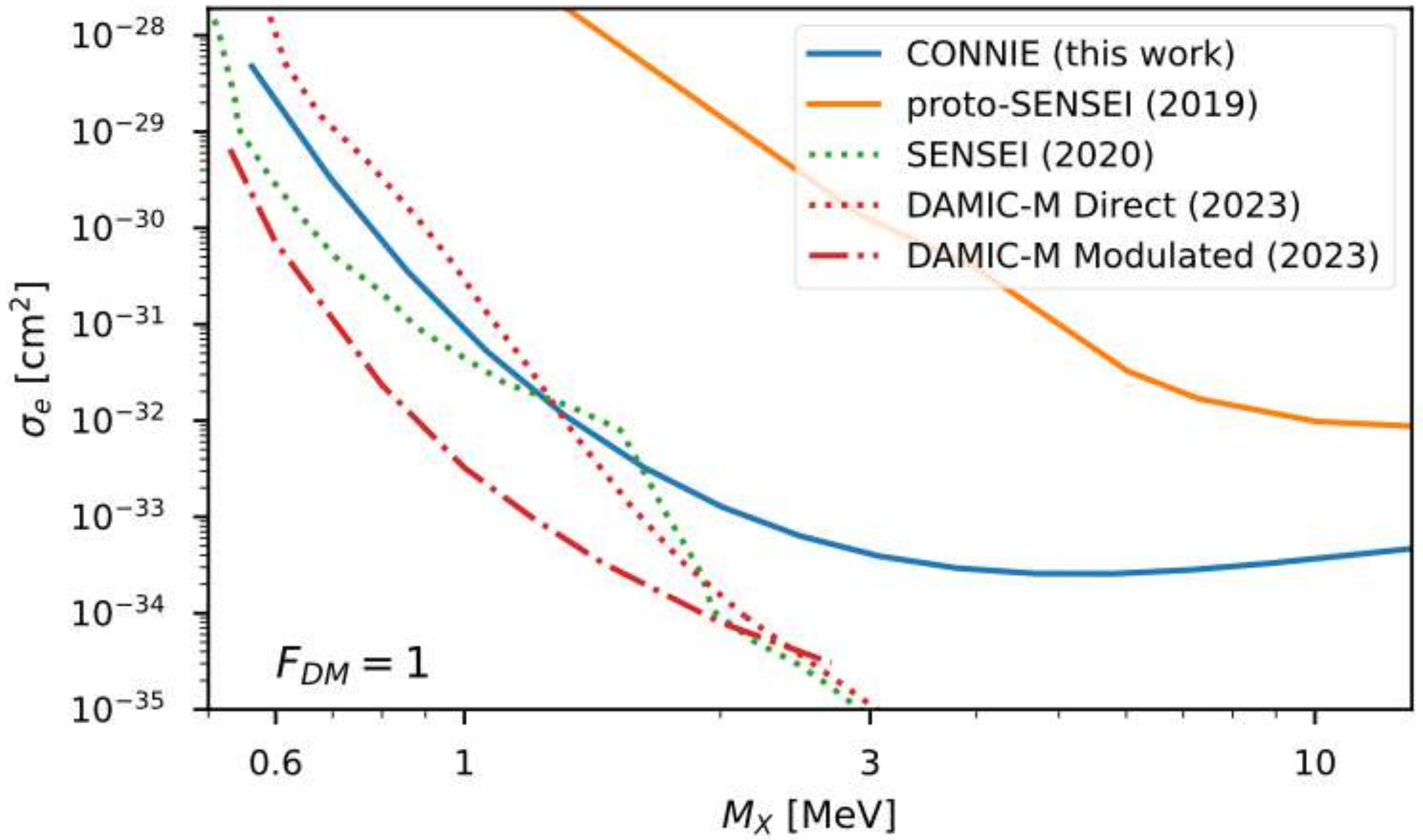
Galaxy DM winds comes from a preferred direction 40º N



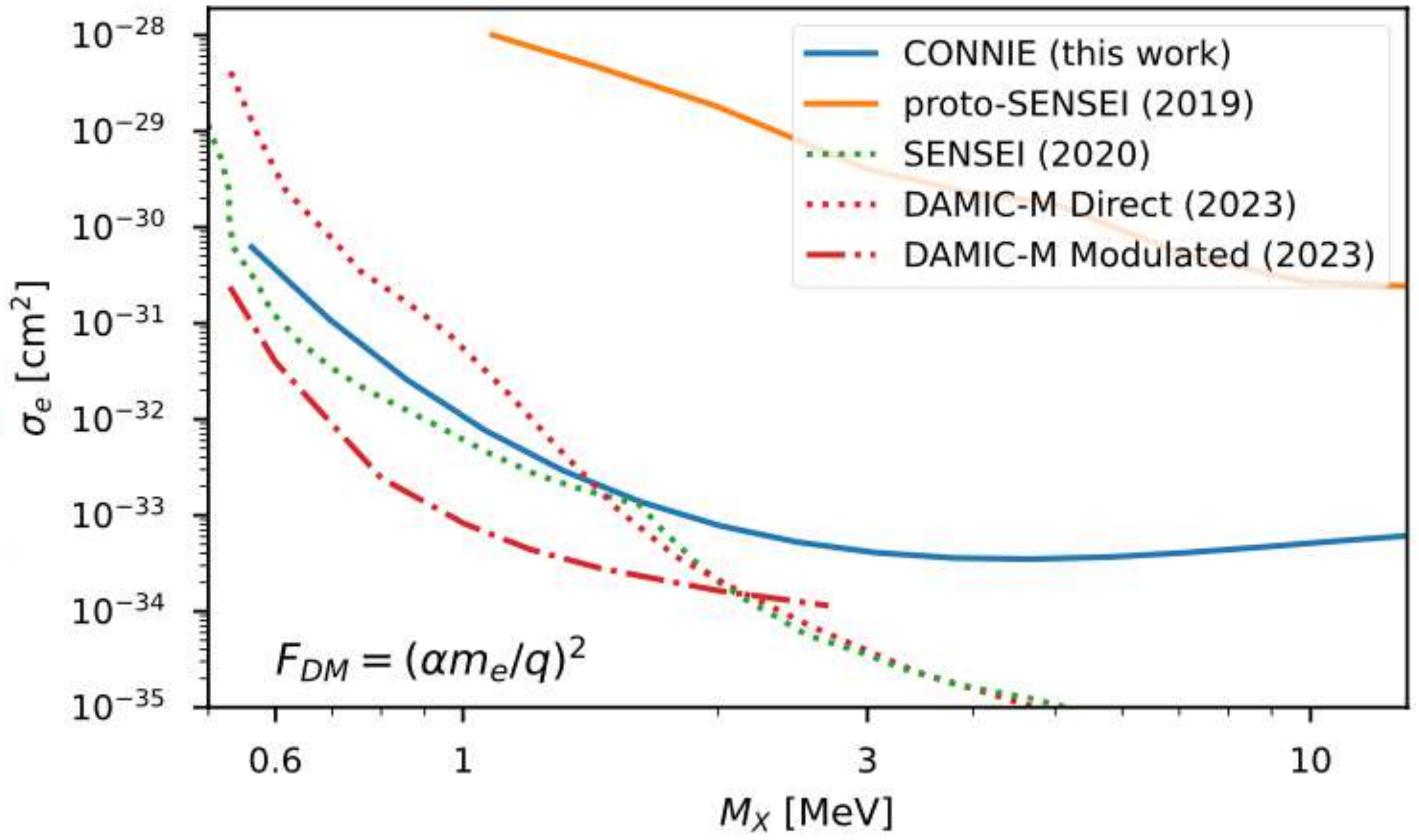
- Earth propagation induces a daily modulation
- Isodetection angle favors Southern hemisphere
- CONNIE at 23º S – isoangles [60-161]º

- Binned data compared to DaMaSCUS simulations
- Model with MeV-scale DM, which couples to SM particles via a kinetically-mixed dark photon (A')

- Best DM-electron limits by a surface experiment



Heavy mediator A'



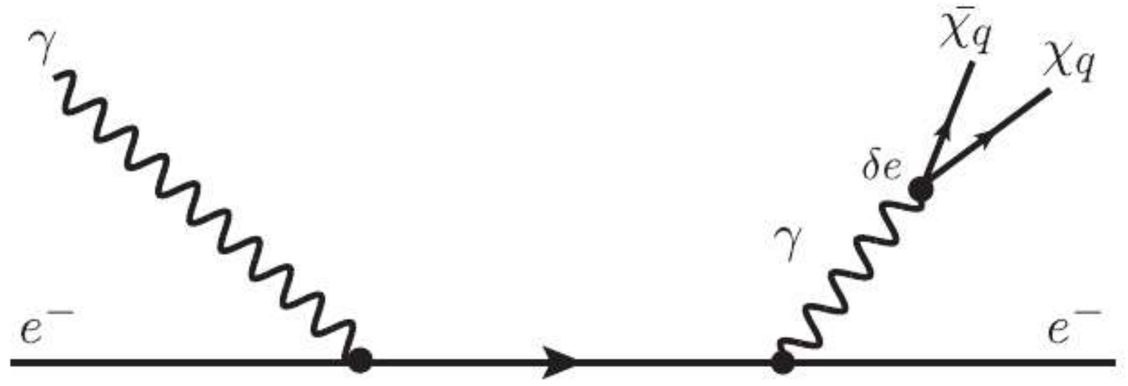
Ultralight mediator A'

arXiv:2403.15976

Search for millicharged particles (mCP)

CONNIE–Skipper + Atucha II

- Relativistic millicharged particles can be pair-produced from Compton-like scattering of HE γ-rays from nuclear reactors

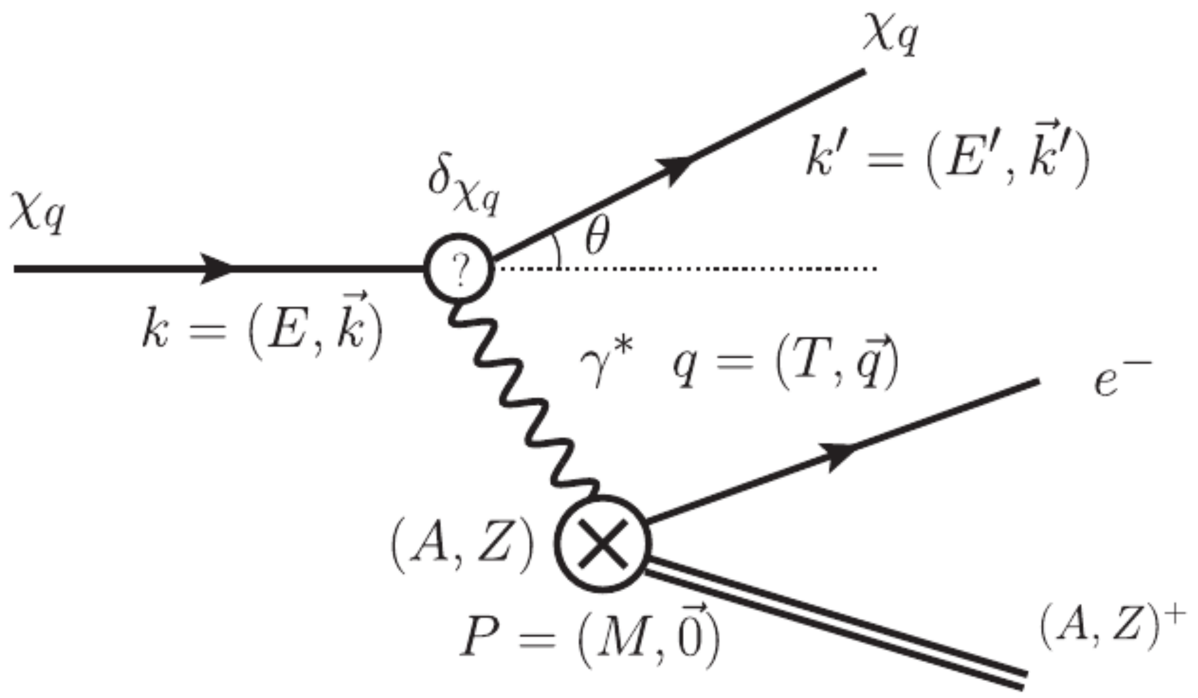


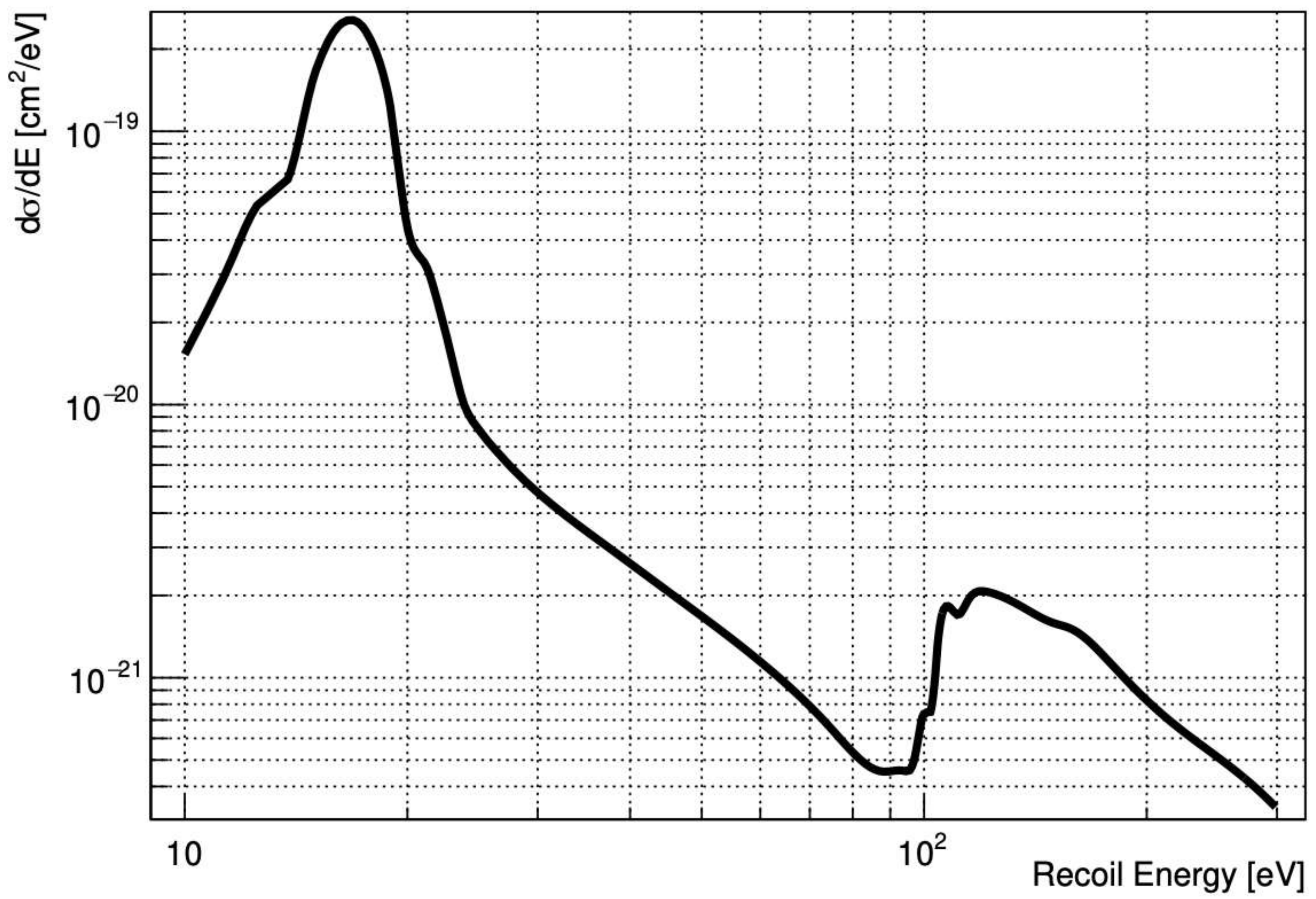
$$\frac{d\sigma}{dE_{\chi_q}}(\gamma e \to \chi_q \overline{\chi}_q e) = \frac{4}{3}\frac{\varepsilon^2 \alpha^3}{m_e^2 E_\gamma^3} \times [(3(E_{\chi_q}^2 + E_{\overline{\chi}_q}^2) + 2E_{\chi_q} E_{\overline{\chi}_q}^2] \log\left(\frac{2E_{\chi_q} E_{\overline{\chi}_q}}{E_\gamma m_{\chi_q}}\right)$$

- Interact electromagnetically with matter via ionization
  - cross-section includes collective excitations
  - plasmon peak at 10–25 eV

arXiv:2403.00123

$$\frac{d\sigma_{mCP}}{dE} \propto \epsilon^2$$



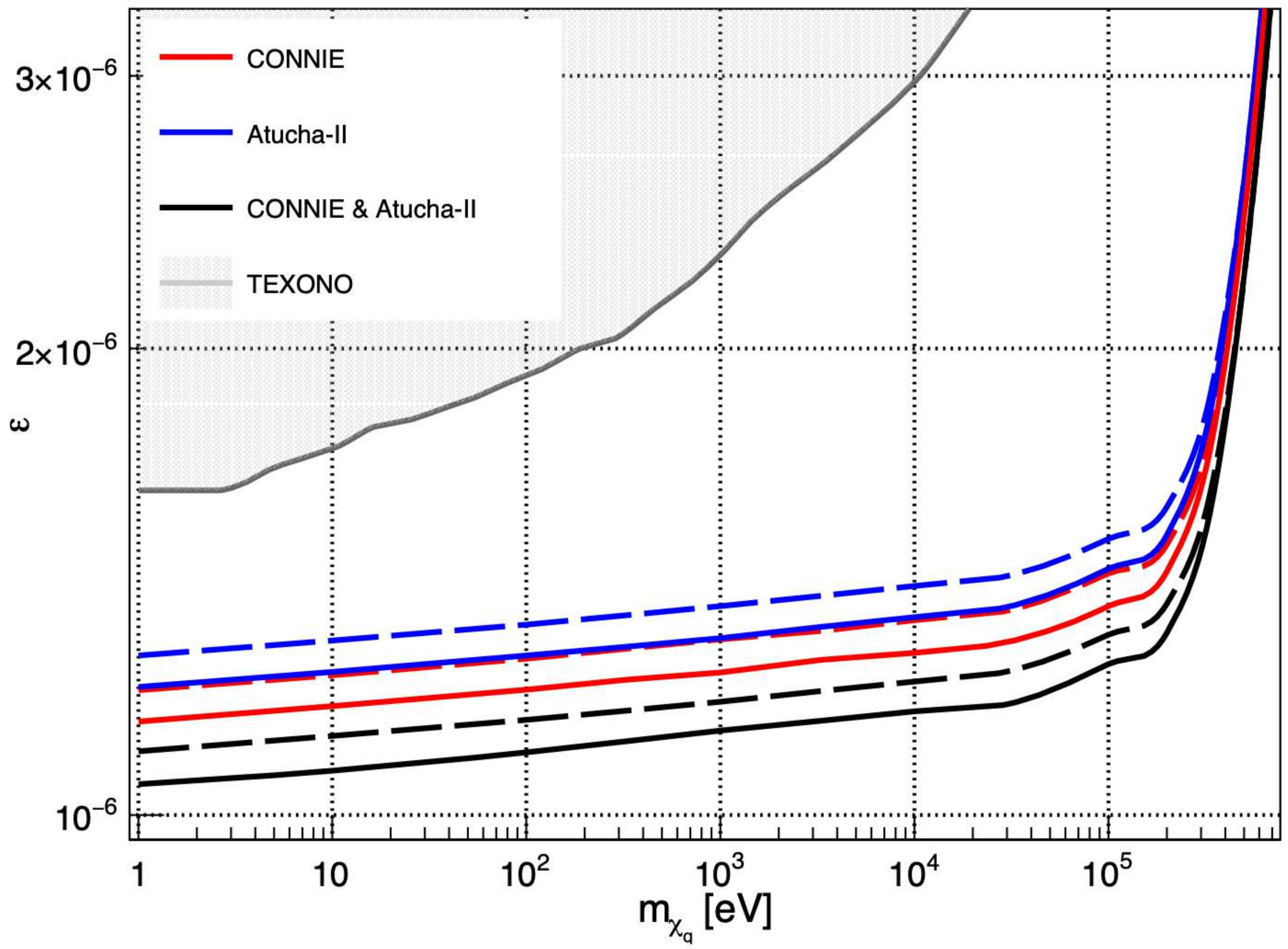


Search for millicharged particles (mCP)

CONNIE–Skipper + Atucha II

see Dario's talk in Session XIII

- Including secondary γ-rays from transport in the reactor core
- Based on 15-215 eV (CONNIE) and 40-240 eV (Atucha-II)
- Combined limit at 90% C.L. on the reactor mCP production



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

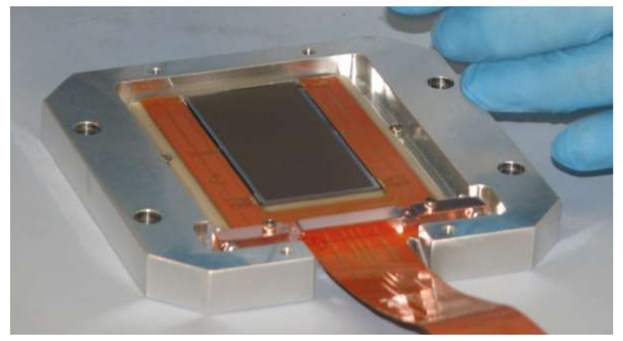
World-leading limits on mCP couplings over a large mass range for $m_{\chi q} < 1$ MeV

arXiv:2405.16316

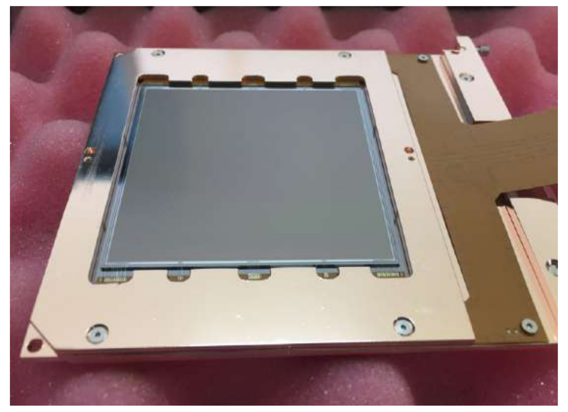
Multi-Chip-Module (MCM)

New compact module

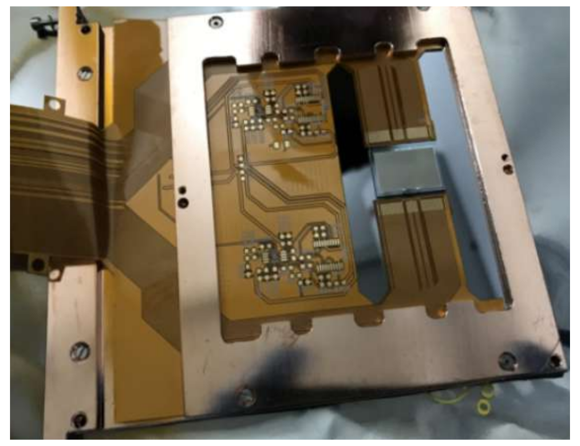
Installation at Angra

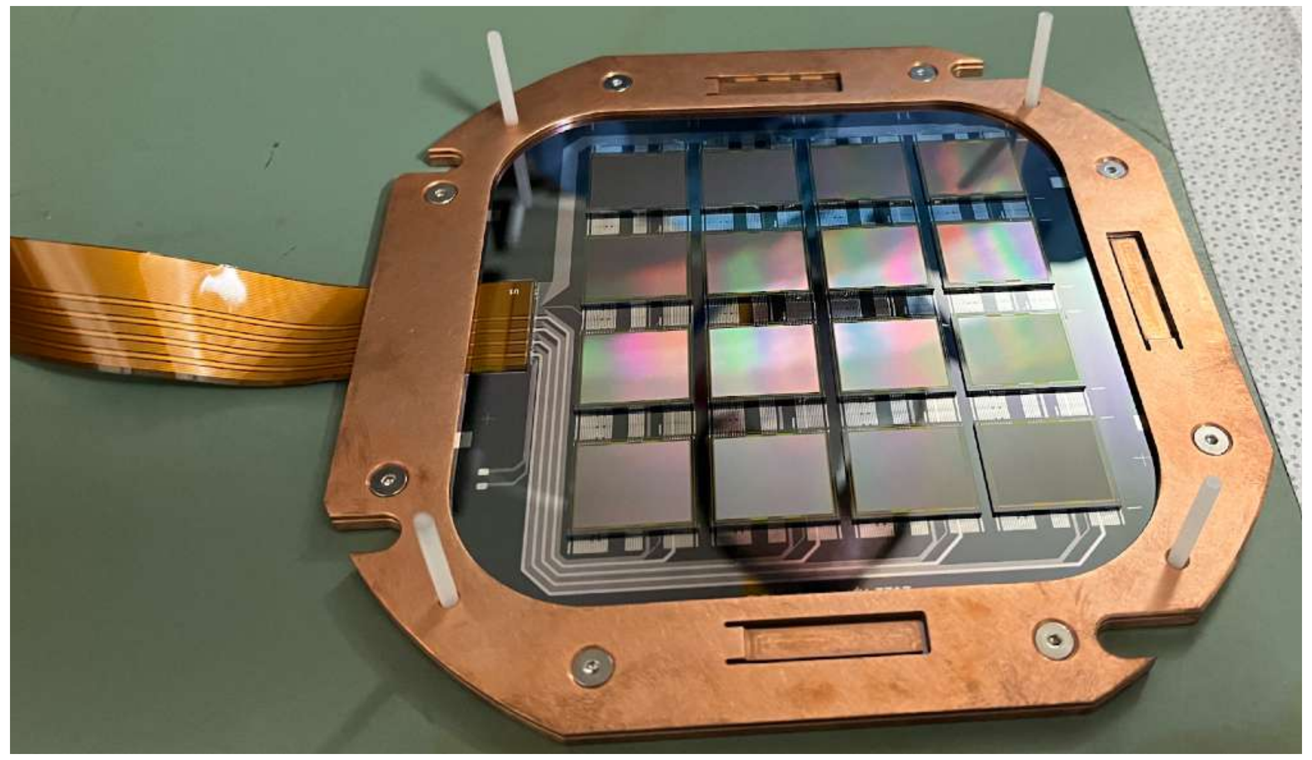


Installation of scientific CCDs



Installation of Skipper-CCD





16 Skipper-CCDs
1278 x 1058 pixels
725 μm thick (8 g)

MCM Installation

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

Engineering run

2016-2018 (1x1) run

2019 (1x5) run

Skipper-CCD run

Results from engineering run
JINST 11 (2016), 07024

Results from 2016-2918 run
PRD 100 (2019), 092005

Limits on SM extensions with light mediators
JHEP 04 (2020) 054

Results from 2019 run
JHEP 05 (2022), 017

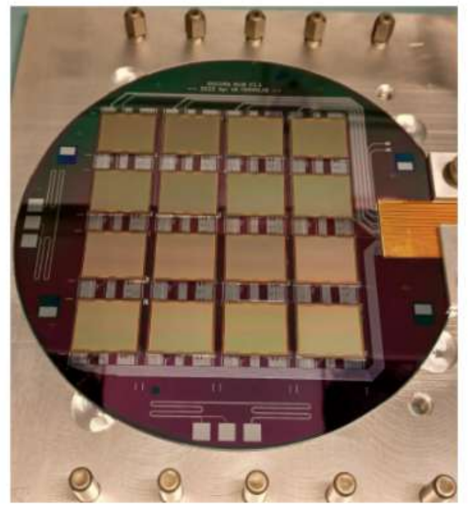
Results from CONNIE-Skypper run
arXiv:2403.15976

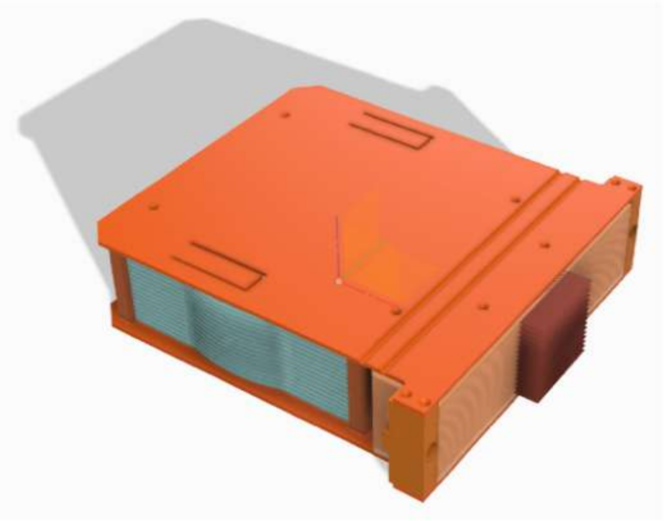
World-leading
limit to mCP
arXiv:2405.16316

CONNIE-MCM

Towards more massive experiments

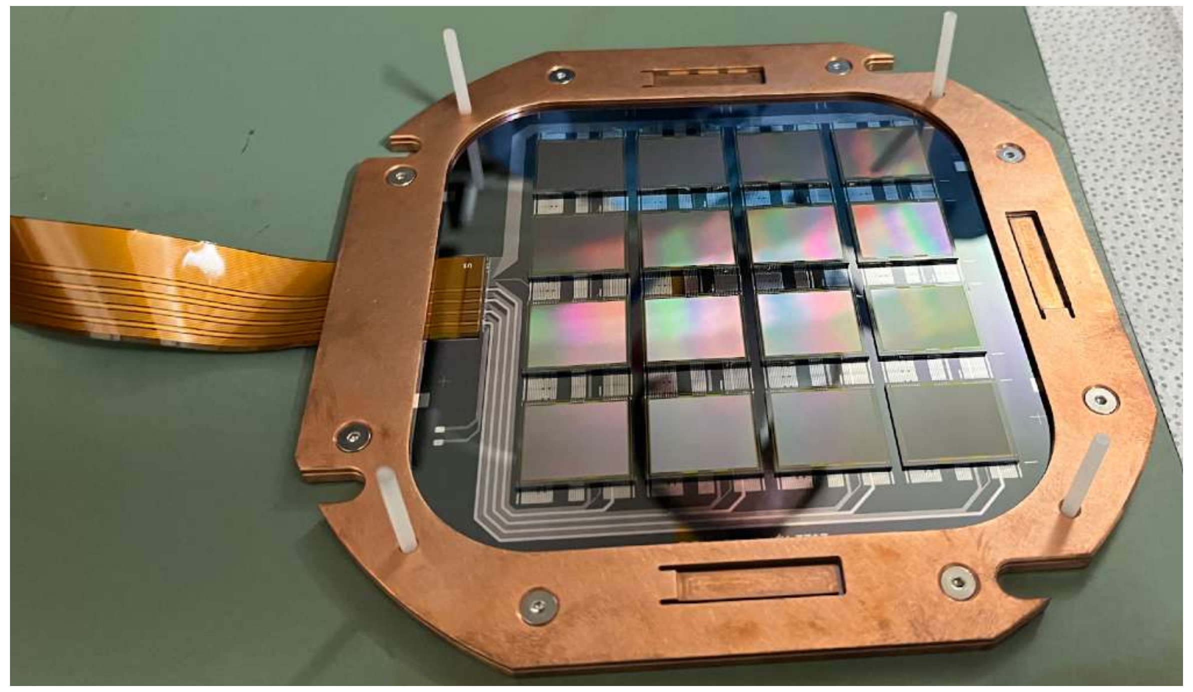
- A multi-Chip-Module (MCM) offers a new compact arrangement of sensors:
  - 16 Skipper-CCDs sensors on the same module
  - Designed for the Oscura experiment
  - Multiplexed readout

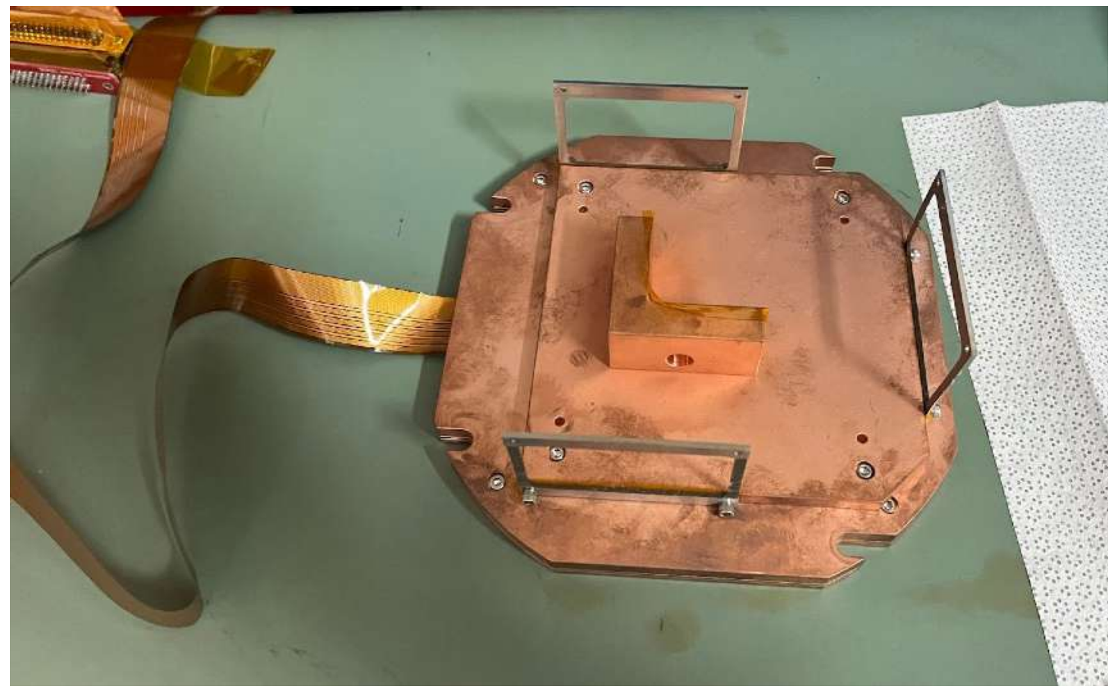


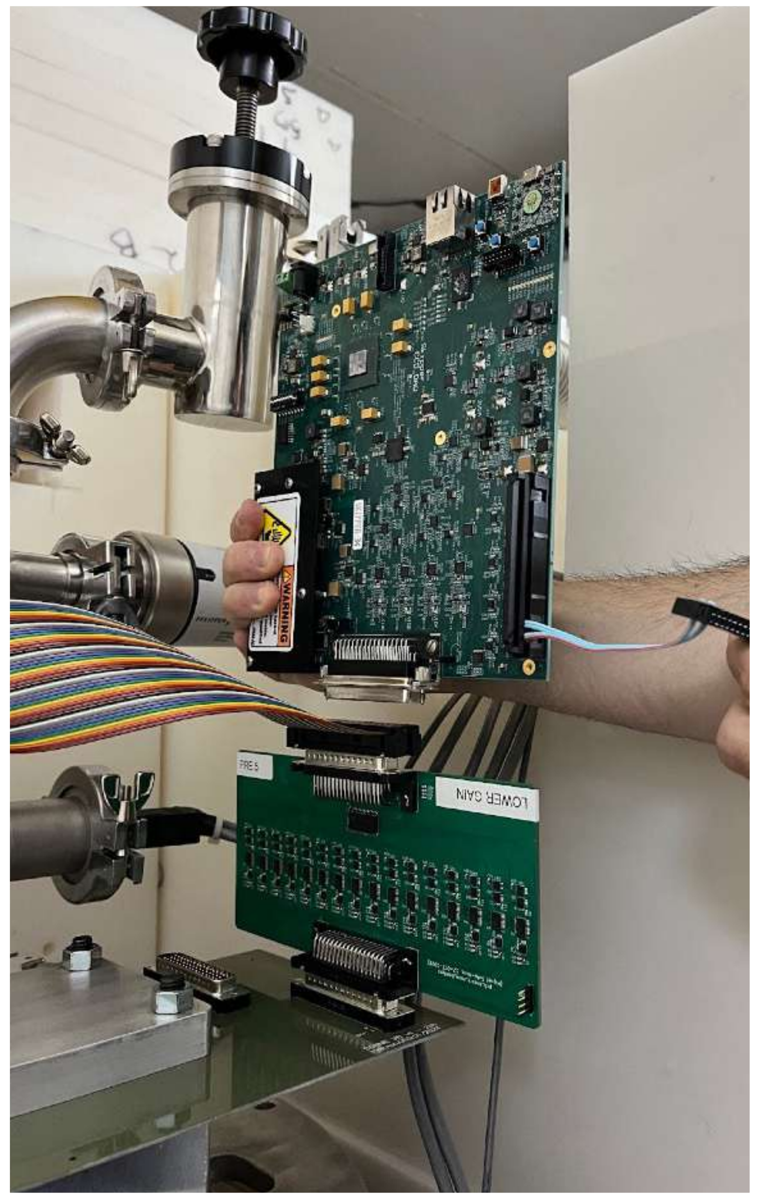


JINST 18, 08016 (2023); arXiv:2202.10518

- MCM was installed at CONNIE in May 2024
  - New VIB designed at CBPF
  - New multiplexer board
  - 32x increase in mass (8g) with respect to CONNIE-Skipper
  - Currently being commissioned and optimized



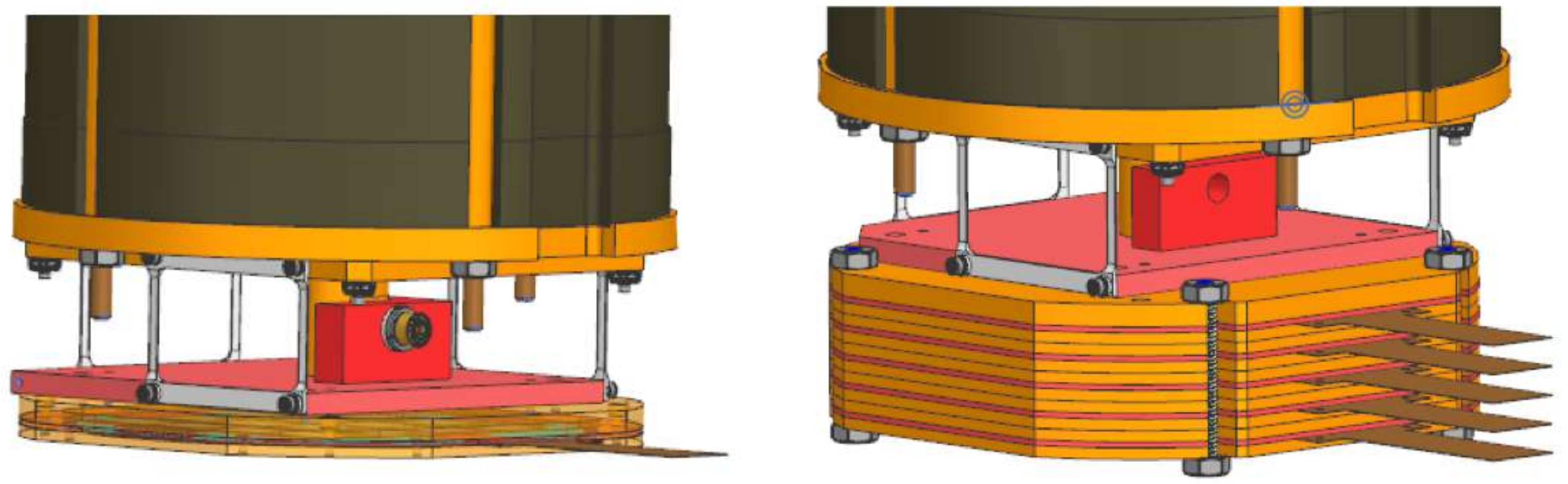




Next steps and expected challenges

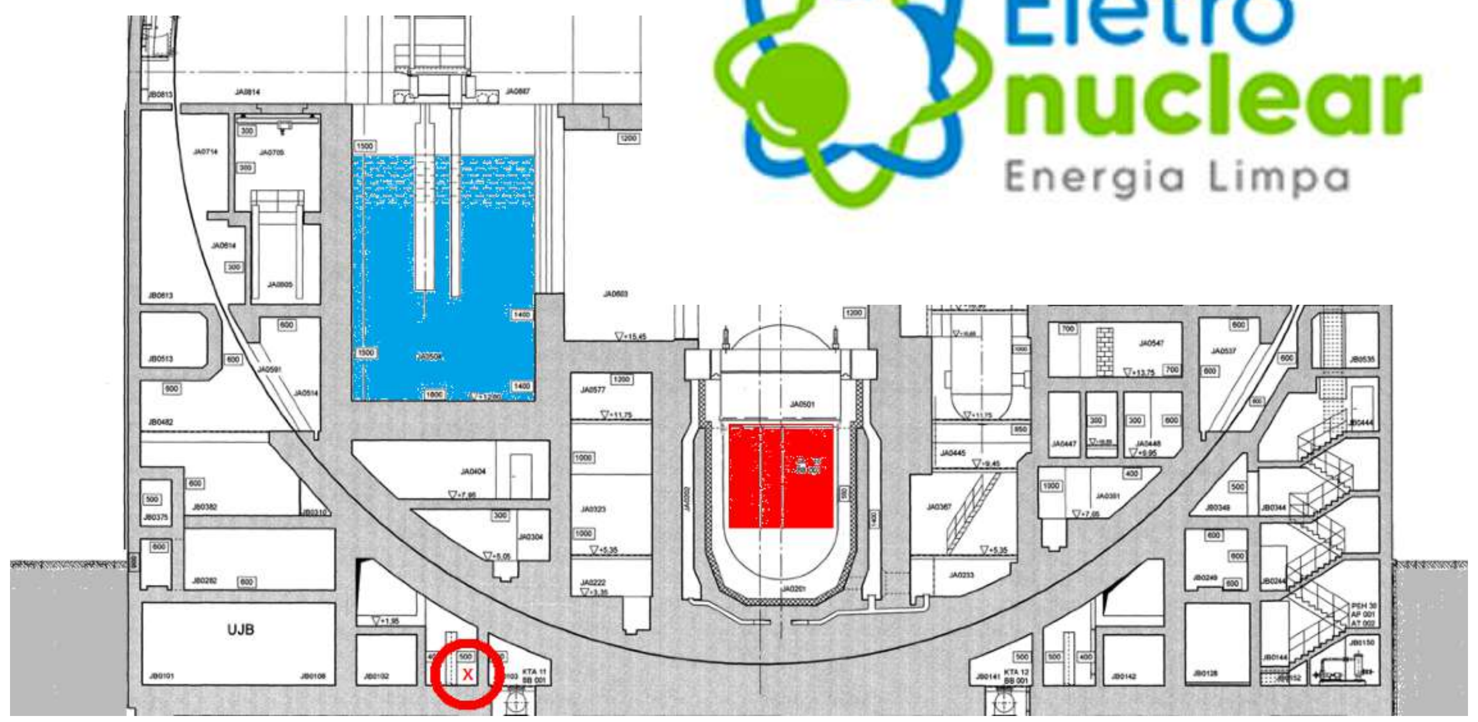
Towards CEvNS detection

- CONNIE-MCM
  - Optimizing performance for reactor OFF spectrum (Nov 2024) and reducing background.
  - Collecting data to improve current experimental limits.
  - Improvements in current BSM limits with 32 times more mass.
  - Proof of concept for a new technology to increase mass.
  - Synergy with Oscura: the first experiment to install an MCM.



- Increasing the neutrino flux
  - New position @ Angra 2 at 15 m to the reactor core identified
  - Increase in flux by a factor of ~4
  - Reduction in background by a factor of ~4 (rough estimation)
  - New compact detector design

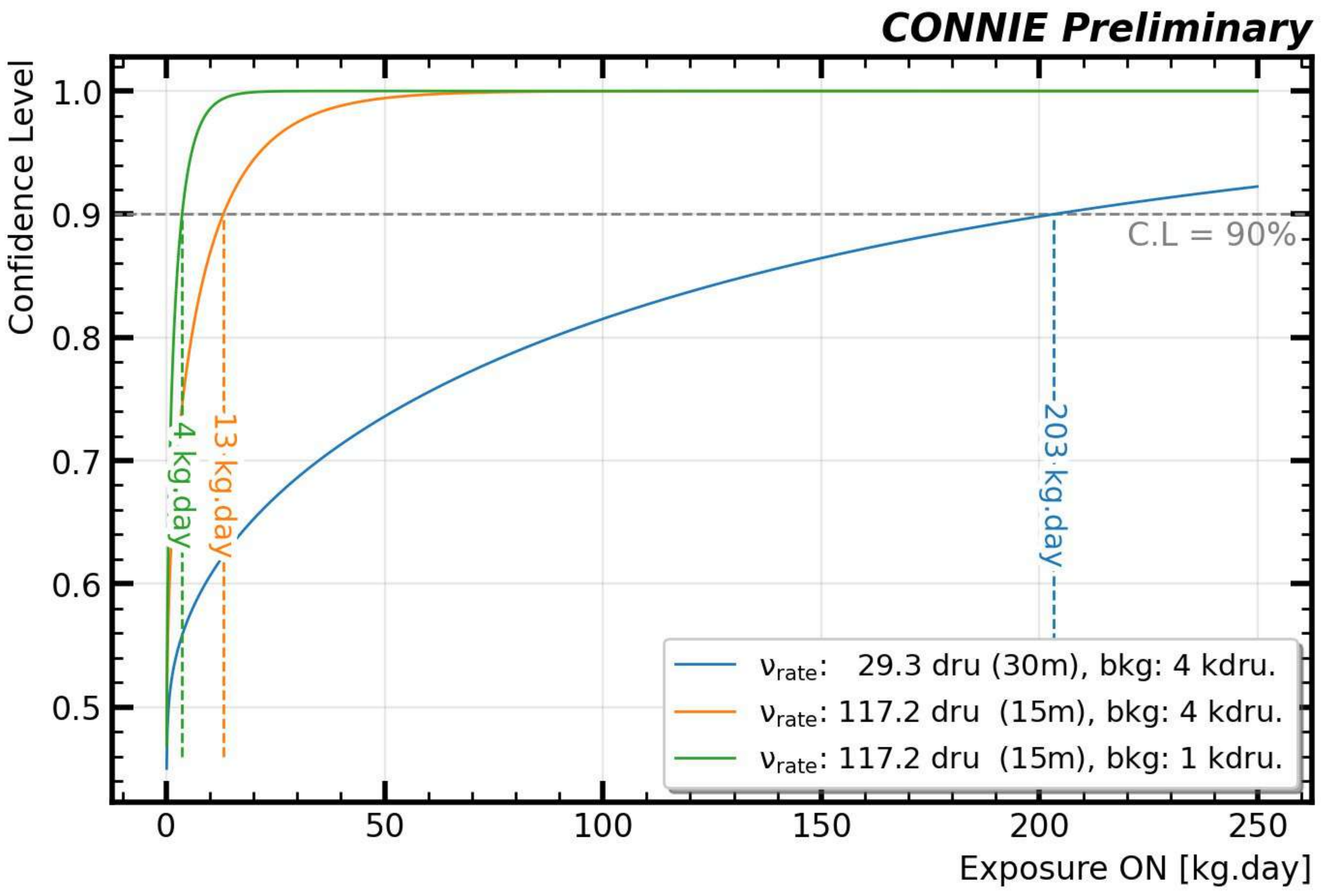
Currently negotiating a position in Angra 2

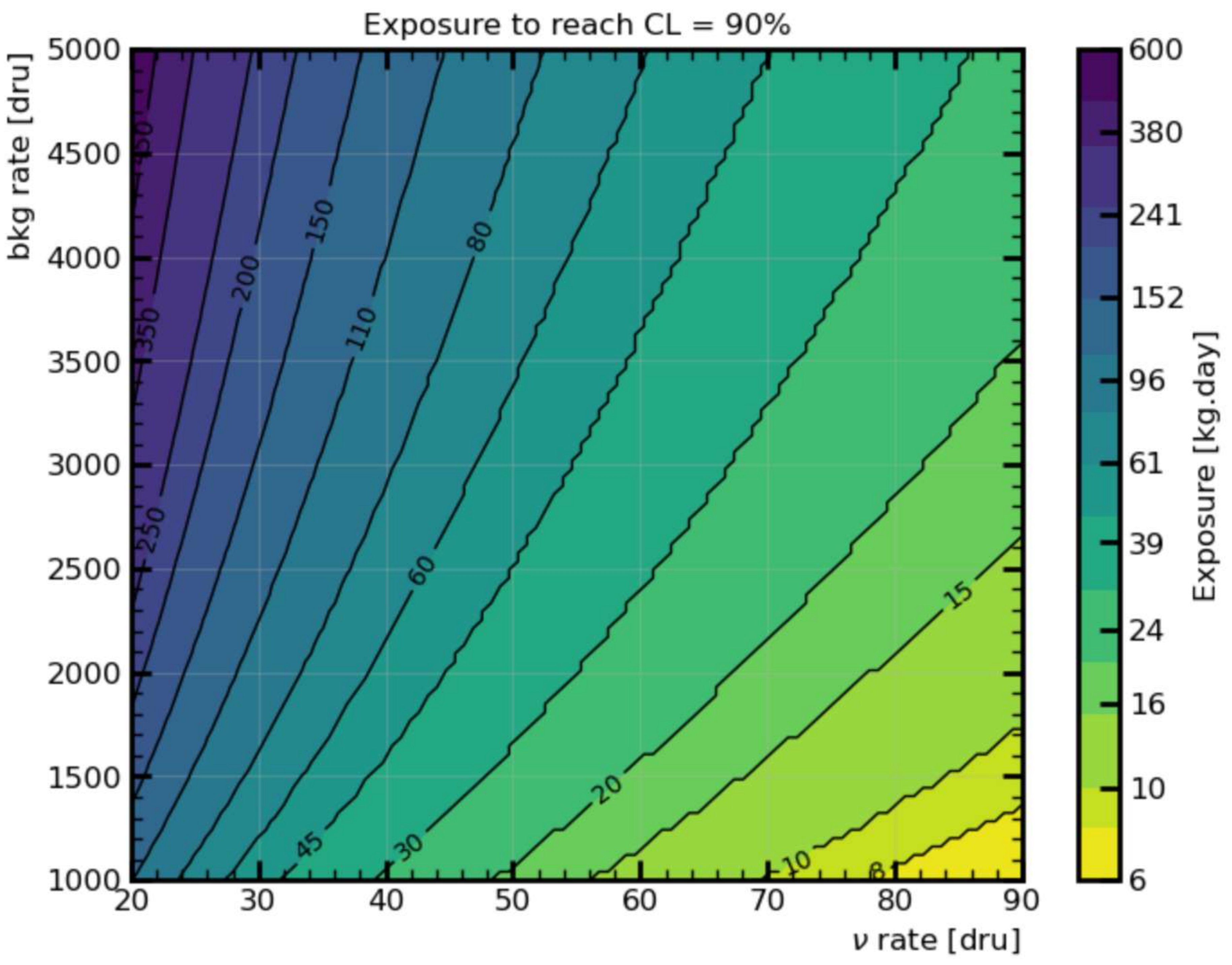


CONNIE perspectives

Towards CEvNS detection

- With a 15 eV threshold and a 1 kg detector at CONNIE (30 m from the reactor core), we need 200 days of operation to observe CEvNS with 90% CL, assuming the current background (4 kdru)

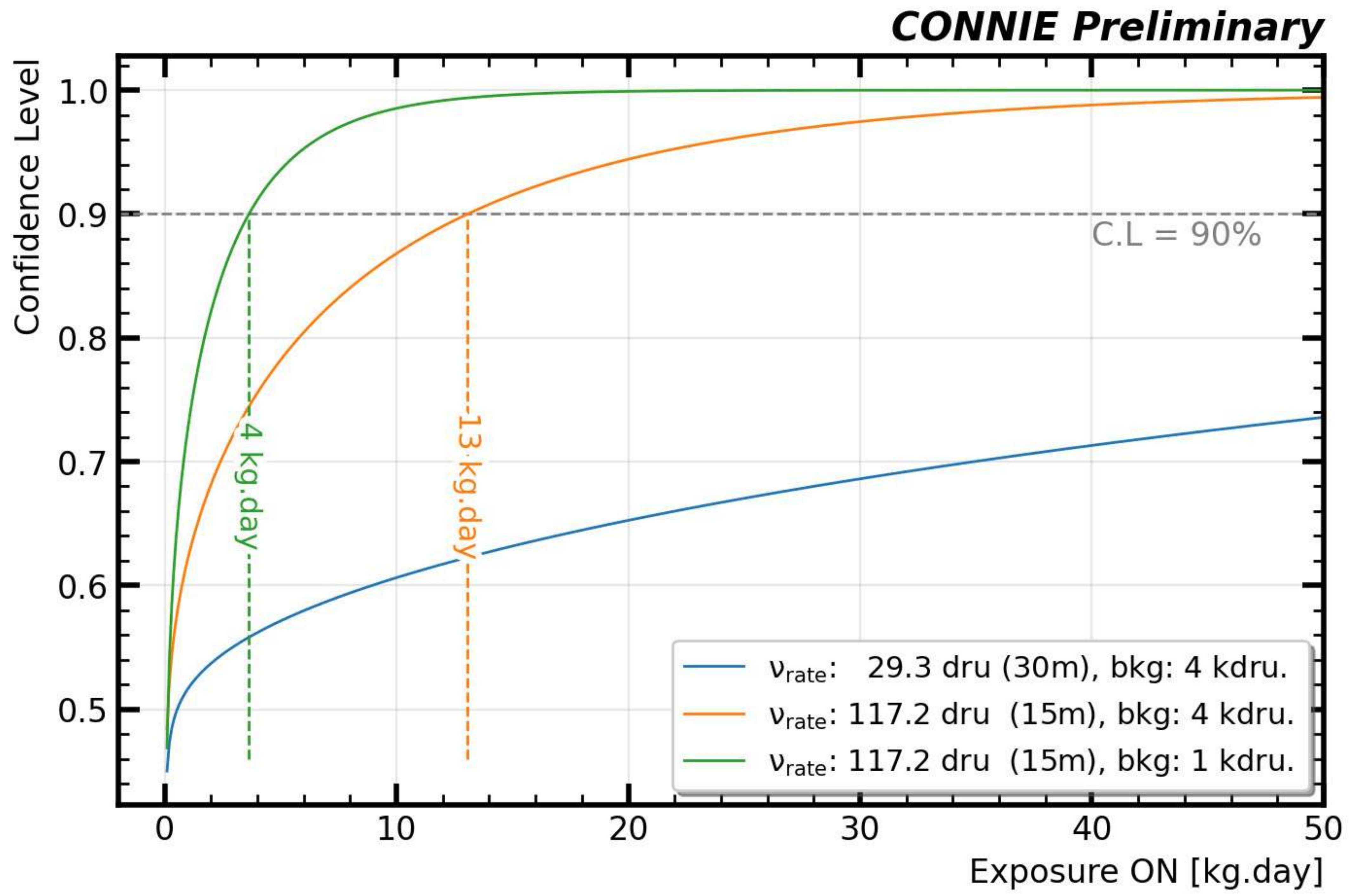


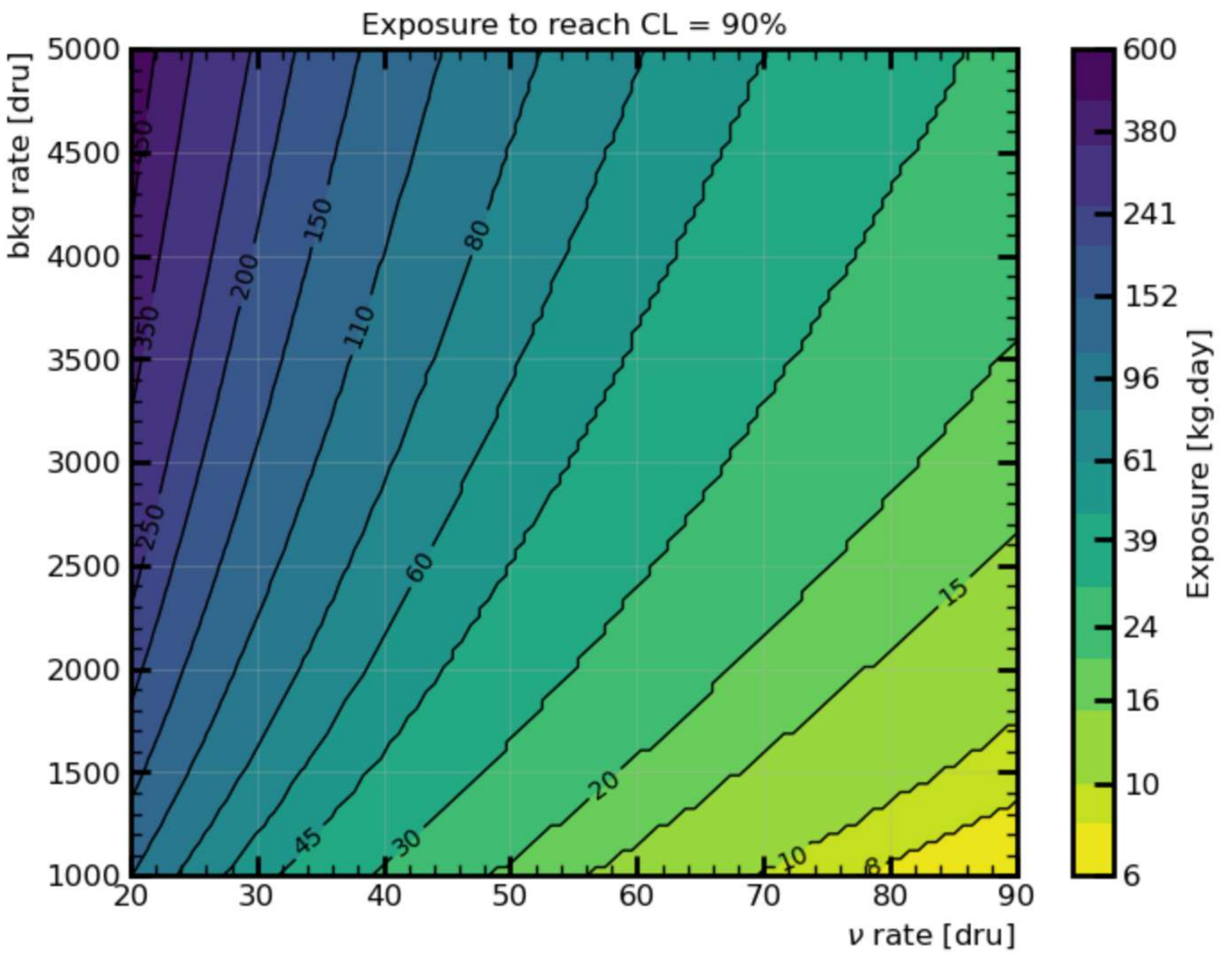


CONNIE perspectives

Towards CEvNS detection

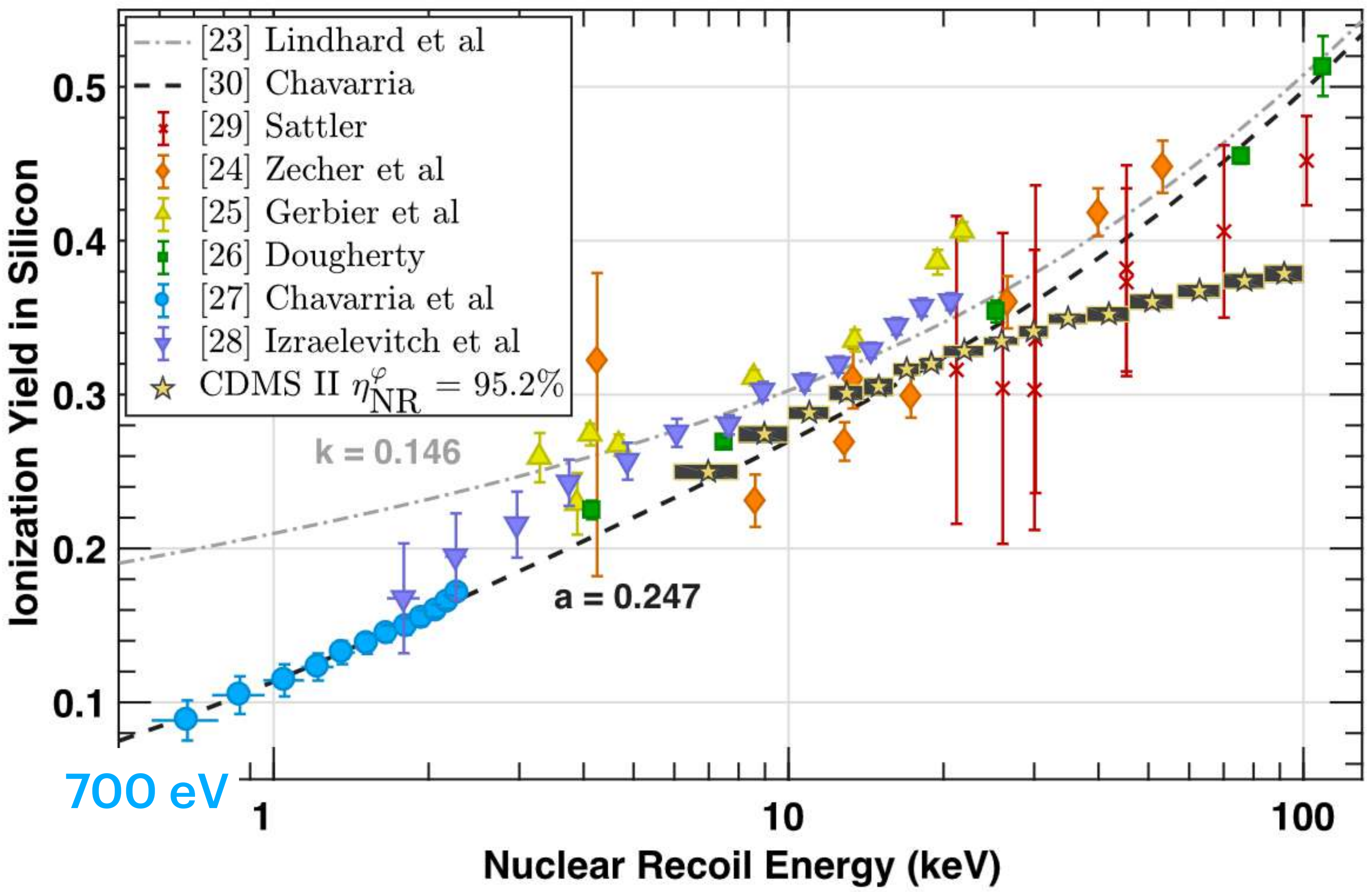
- With a 15 eV threshold and a 1 kg detector at CONNIE (30 m from the reactor core), we need 200 days of operation to observe CEvNS with 90% CL, assuming the current background (4 kdru)
- By moving to 15 m from the reactor core, we would need 13 days of operation to observe CEvNS with 90% CL under the same conditions and 4 days if the background can be reduced to 1 kdru





Other challenges

- Quenching factor measurement for low energies



$$\sigma_{SM} \sim \frac{G_F^2}{4\pi} N^2 E_\nu^2 \qquad < E_r >= \frac{2}{3}\frac{(E_\nu/\mathrm{MeV})^2}{A}\mathrm{keV}$$

$$E_I = Q \cdot E_r$$

Members of the CONNIE and Atucha-II led by LAMBDA (Argentina) are planning an experiment devoted to this measurement by using Skipper-CCDs in a research nuclear reactor

see Dario's talk in Session XIII
11:00-11:20 - LAMBDA: A World-Class Particle Physics Lab in South America

- Quenching theoretical model based on Lindhard theory led by a Mexican group (Sarkis)

Community synergy: fostering collaboration between different experiments and theoretical-experimental teams

Latin America synergy

CONNIE

- Collaborative Efforts Across Latin America
  - Establishing a world-class neutrino experiment in Latin America
  - Collaboration between different groups to advance Skipper-CCD technology
- Joint Efforts and Research Visits
  - Collaboration between Brazil (UFRJ & CBPF) and Argentina (LAMBDA & Universidad de Córdoba)
  - Focus on Skipper-CCD detector techniques, CONNIE data analysis, and new particle search
  - Resulted in the most stringent constraint on millicharged particles in nuclear reactors
- Building the Next Big Reactor Neutrino Experiment
  - Scaling Skipper-CCD technology to 100 g and beyond
  - Integration of thousands of Skipper-CCD sensors for future experiments
  - Ongoing engineering efforts for compact, low-noise electronics and stable packaging
- Impact and Future Prospects
  - Demonstrating the synergy between collaborations and groups in Latin America
  - The technology and collaborative framework set the stage for the next generation of neutrino detectors in the region

LAA-HECAP support

Summary and concluding remarks

- Skipper-CCDs showed to be very promising for detecting low-energy processes
- Excellent performance in 2021-2023 with flat background and 15 eV energy-threshold
- New CEvNS limit with 18.4 g-days is comparable to previous with larger exposure.
- New competitive limits on vector mediator, DM modulation and millicharged particles.
- The experiment started its next phase with a 16-sensor Multi-Chip-Module

- It is imperative to have a larger-mass (kg) reactor neutrino experiment with MCMs in the near future
- Efforts to increase the neutrino flux and decrease the background are on-going
- CONNIE is in a great position now as a very significant particle physics experiment in Latin America
  - Expertise in reactor neutrino experiments and training new specialists.

- Collaborative efforts across Latin America are advancing Skipper-CCD technology and setting the stage for world-class neutrino experiments by integrating thousands of sensors, demonstrating the region's synergy and leadership in next-generation neutrino detection.

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Thank you !!