Coherent Neutrino Nucleus Scattering at Reactors with Solid State Detector

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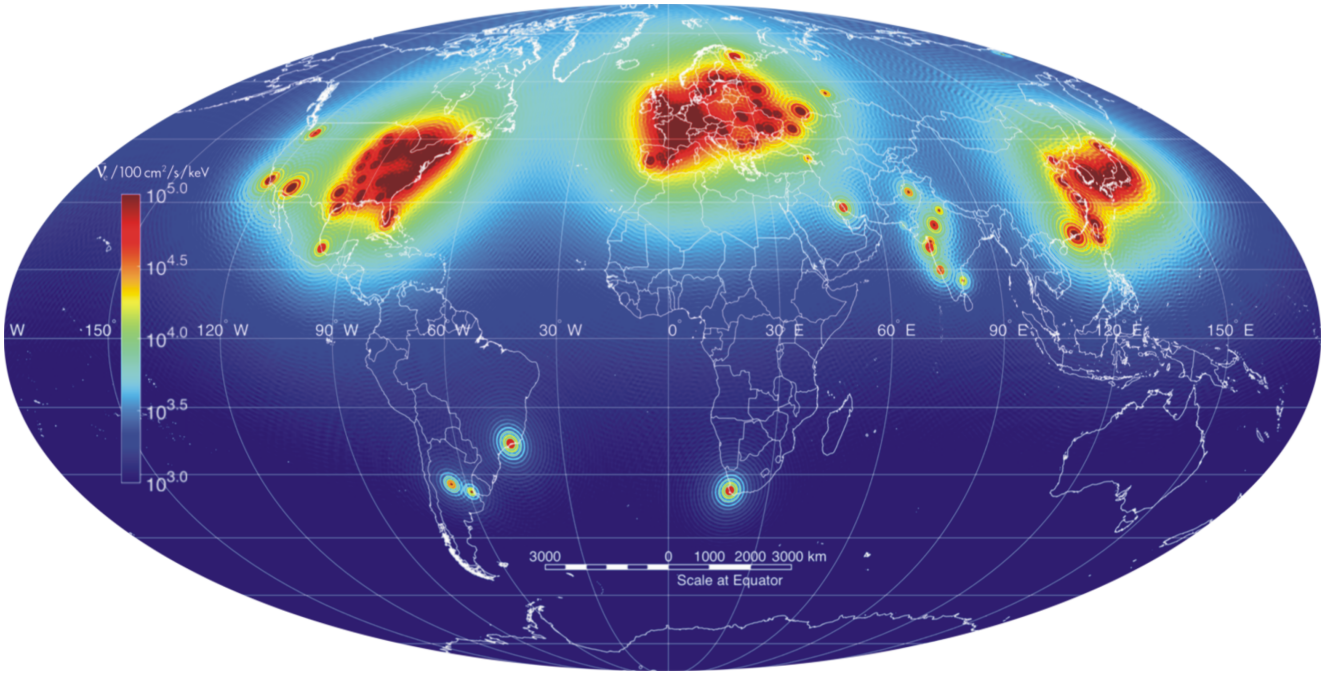
1. Motivation
2. Skipper CCD
3. Background studies in CCD at sea level
4. Future of Skipper CCD at nuclear reactors
5. BACK UP

Sources of neutrinos

Nuclear reactor as source of neutrinos (arXiv:2009.10741)

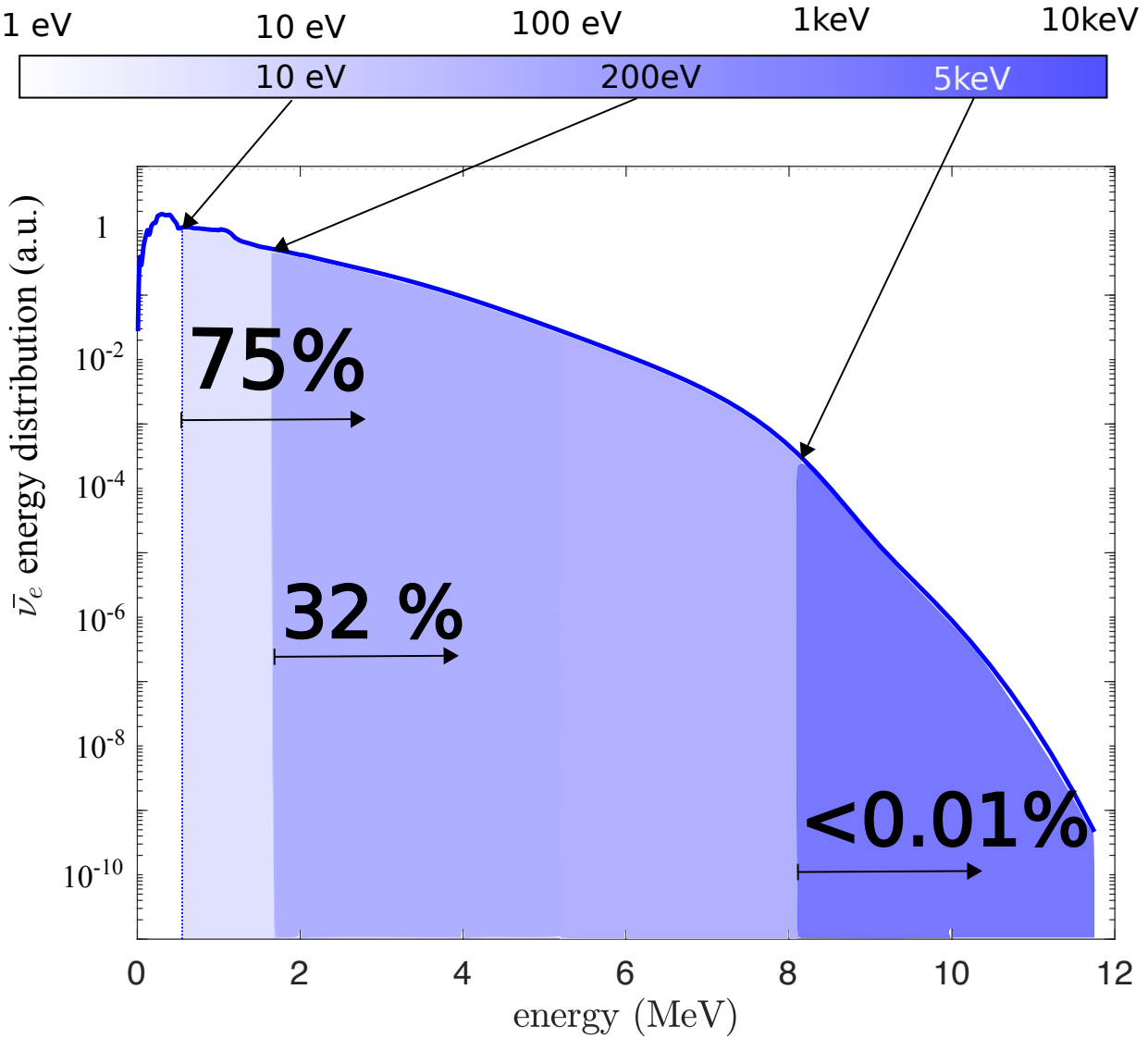
- Nuclear reactors 2×10^{20} ν/s in a 2GW$_{th}$.
- Spallation Neutron Source (SNS) 1.4×10^{15} ν/s.
- DUNE near detector 3.4×10^{6} ν/cm^2/s.
- Solar flux 7×10^{10} ν/cm^2/s.



It is difficult to access to these neutrinos (Si, A=28)

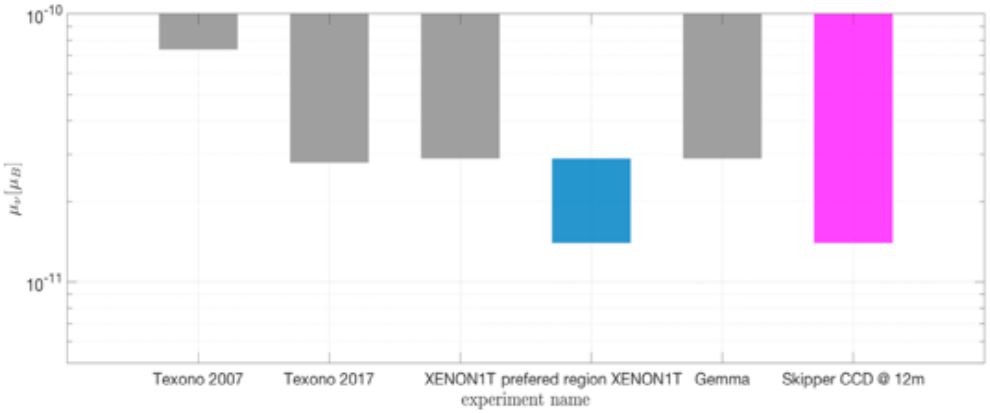
Minimum measurable nuclear-recoil energy

Observable neutrino flux

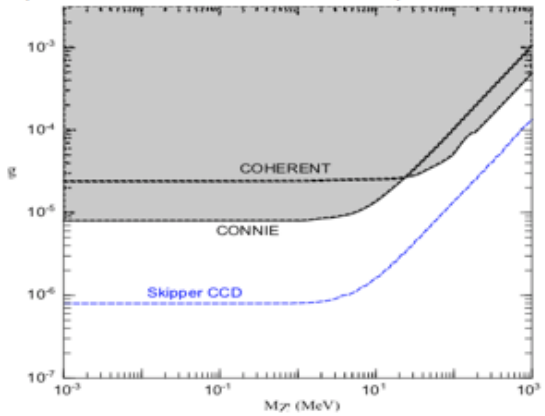


Opportunities for low threshold sensors

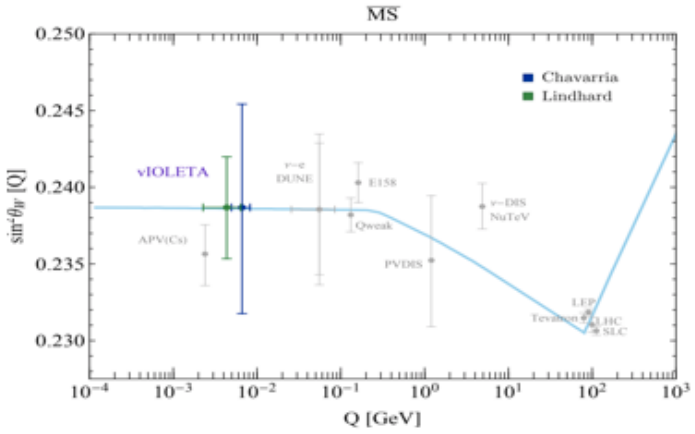
Neutrino properties: magnetic moment



New neutrino scalar interaction with nucleus (extension of arXiv:1910.04951)



High precision measurement of standard model (arXiv:2009.1074)



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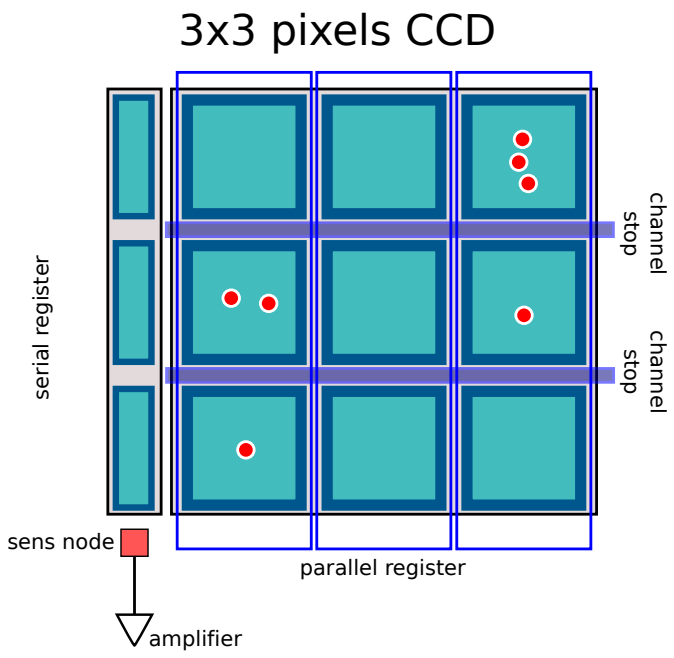
Skipper CCD readout designed at LBNL MSL

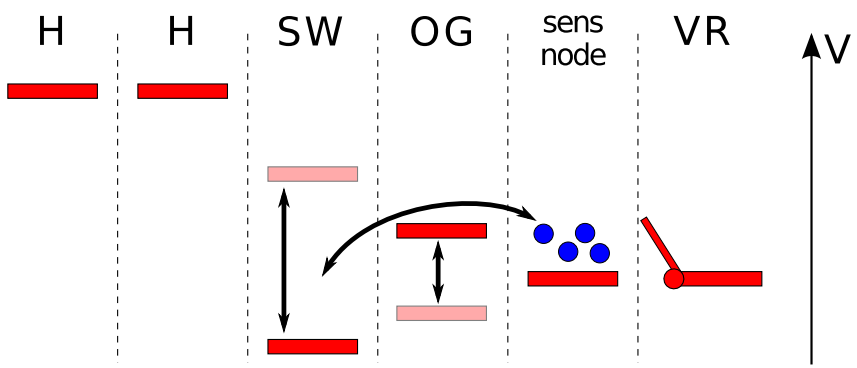
- 2003: Development of CCD on high resisitivity substrate at LBNL MSL (IEEE TRAns. Elec. Dev. Vol. 50, No. 1, 2003).
- 2011: Achieving sub-electron readout noise in Skipper CCDs (arXiv:1106.1839v2)
- 2017: Single-electron and single-photon sensitivity with a silicon Skipper CCD (arXiv:1706.00028)
- 2019: Low Threshold Acquisition controller for Skipper CCDs (arXiv:2004.07599)
- 2020: SENSEI: Direct-Detection Results on sub-GeV Dark Matter from a New Skipper-CCD (arXiv:2004.11378).

Packaged scientific sensor

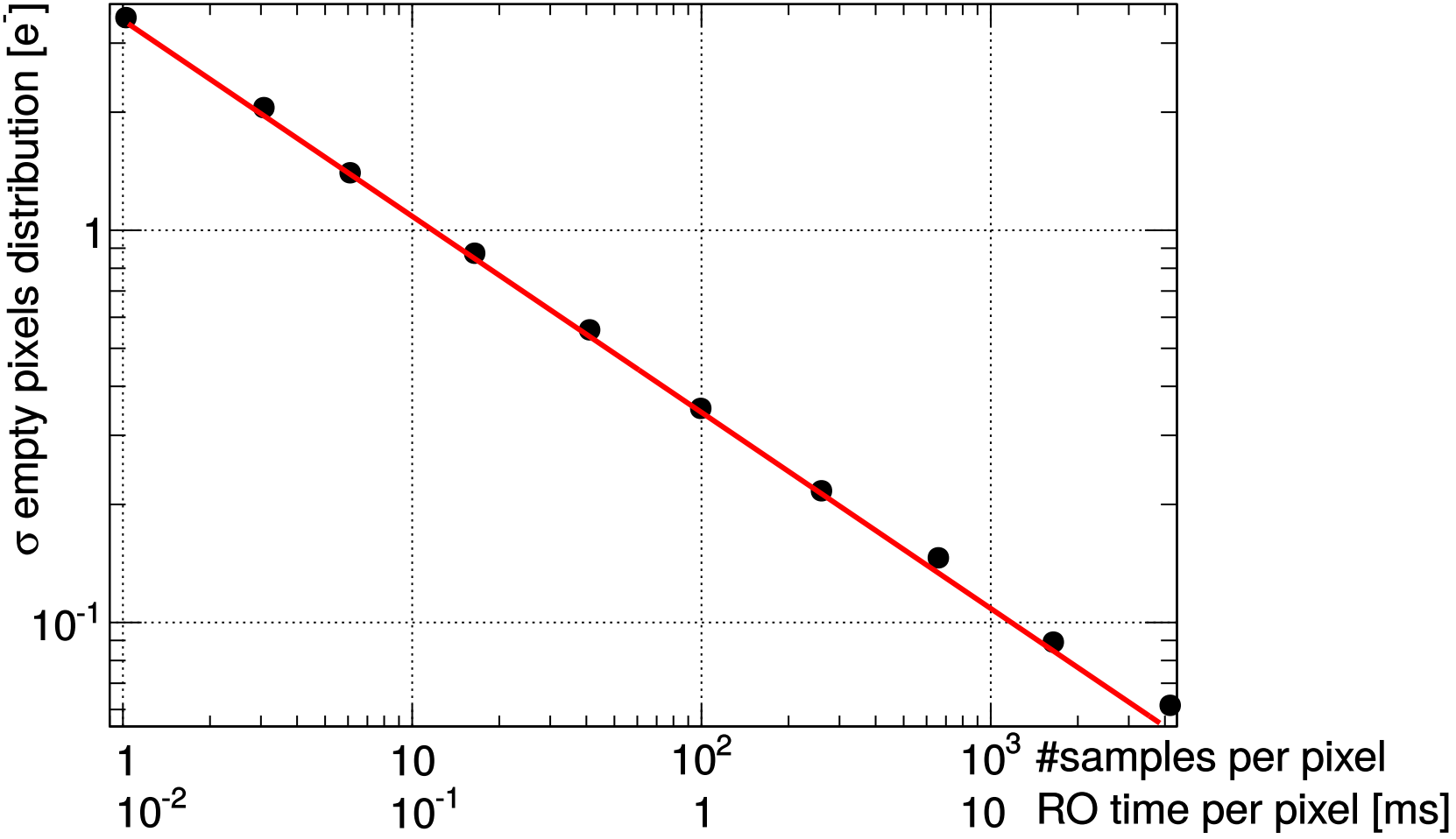
Lowering the noise: Skipper CCD

- **Main difference:** the Skipper CCD allows multiple sampling of the same pixel without corrupting the charge packet.
- The final pixel value is the average of the samples
  $\boldsymbol{Pixel\ value = \frac{1}{N}\Sigma_i^N\,(pixel\ sample)_i}$
- Idea proposed in 1990 by Janesick et al. (doi:10.1117/12.19452)

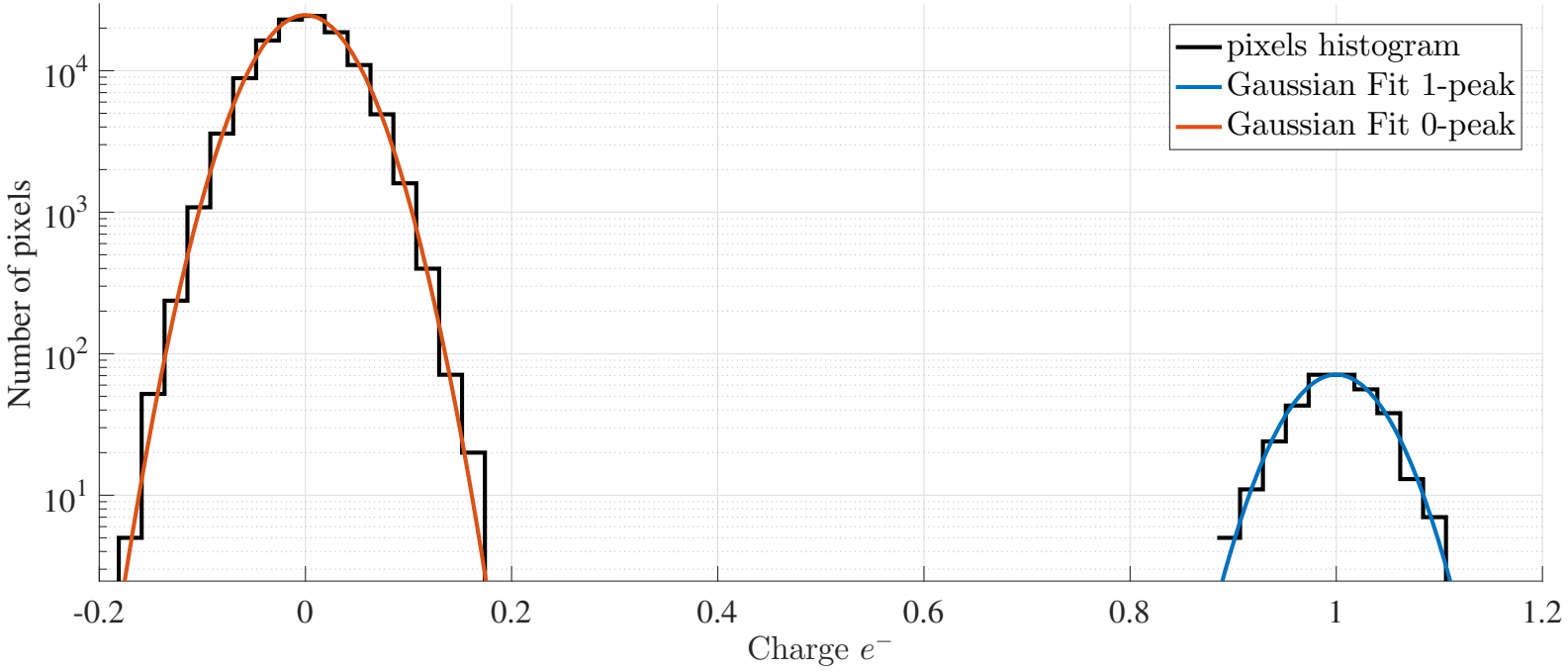




Noise vs. #samples - $1/\sqrt{N}$



Very good energy resolution



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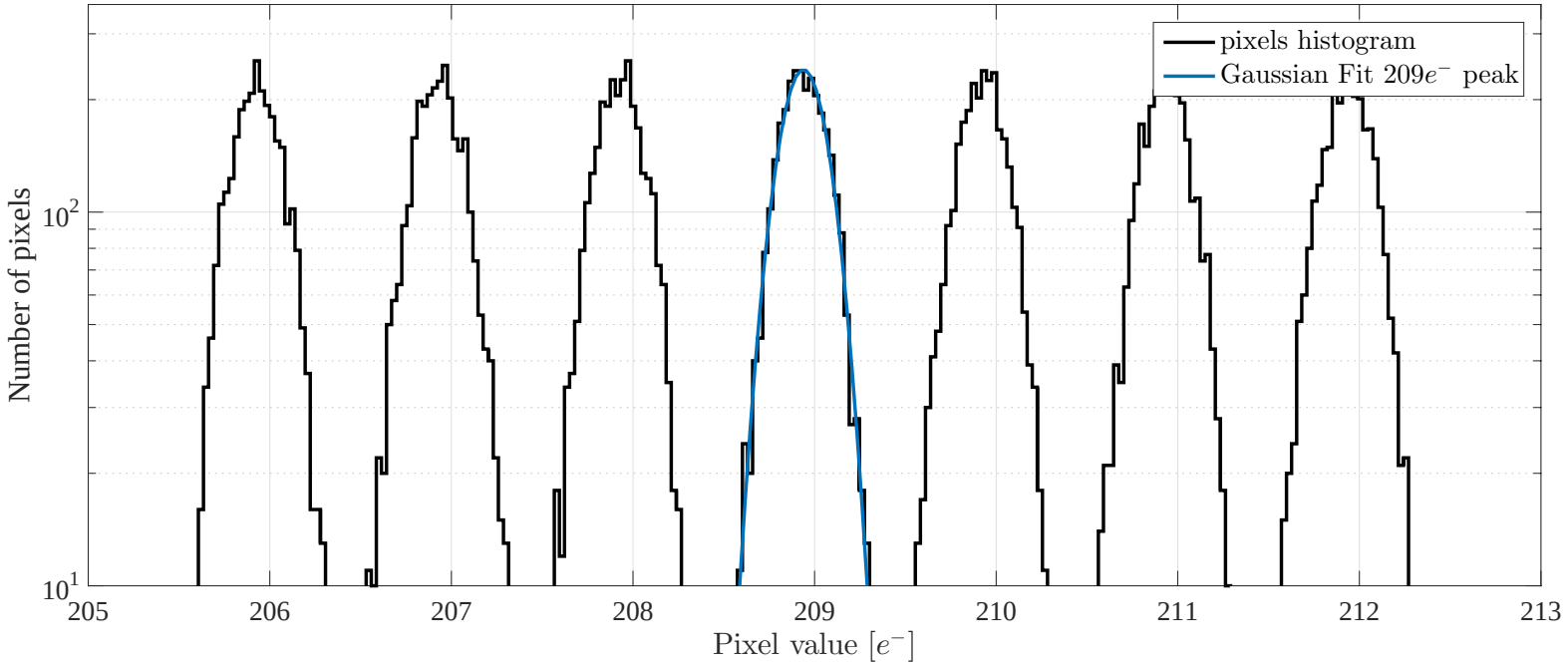
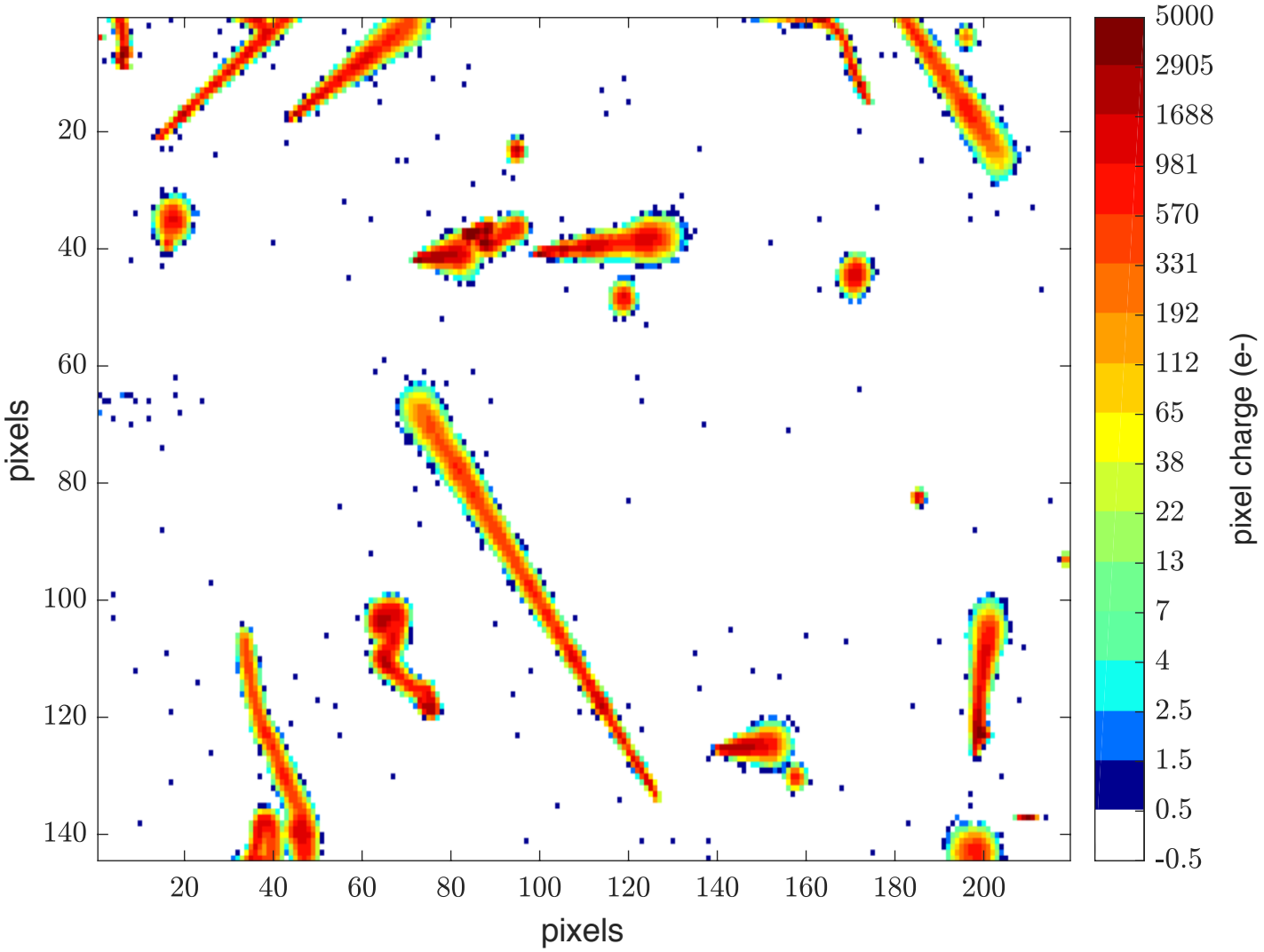


Image taken with Skipper CCD at sea level with no shield



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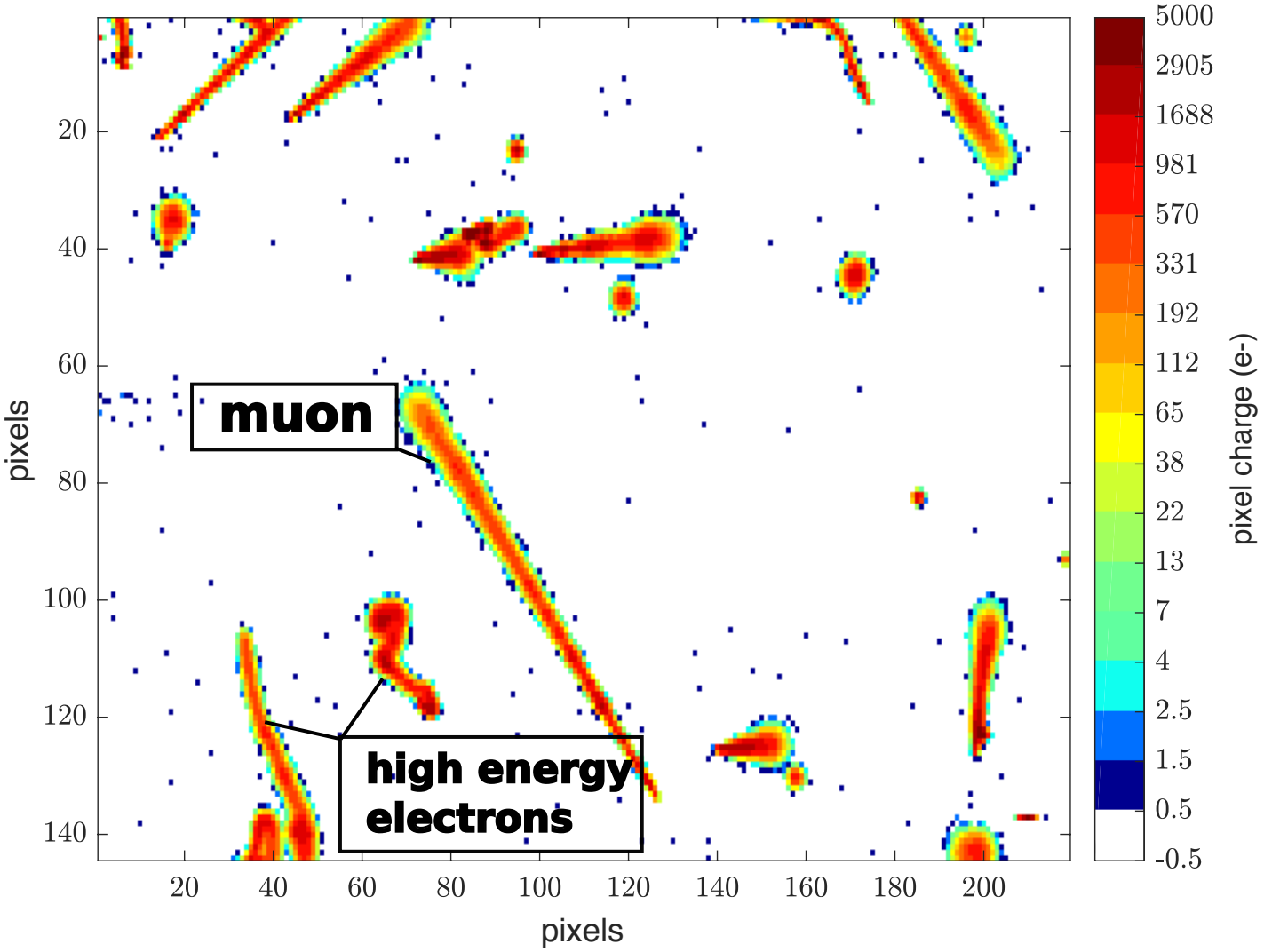


Image taken with Skipper CCD at sea level with no shield

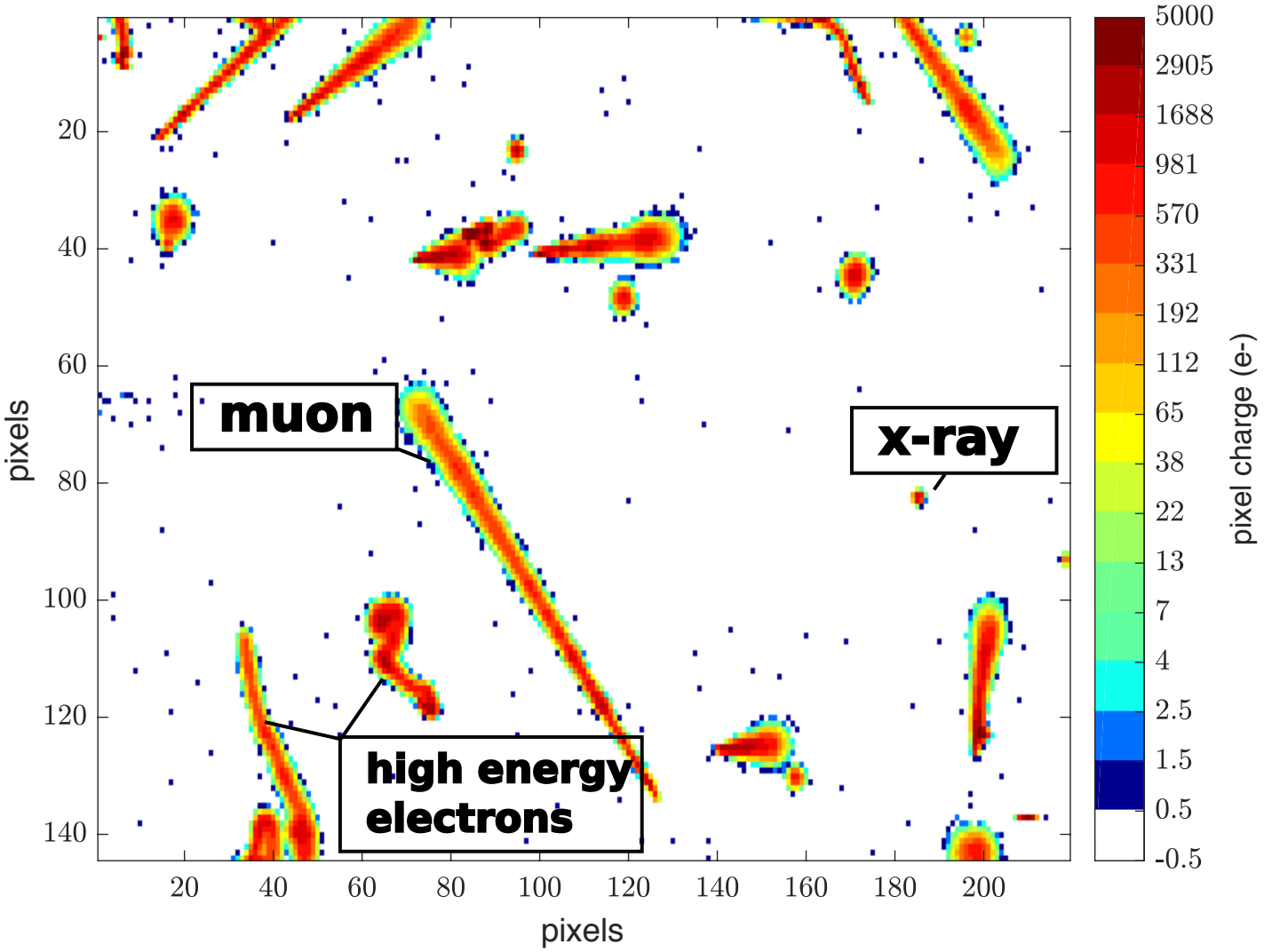
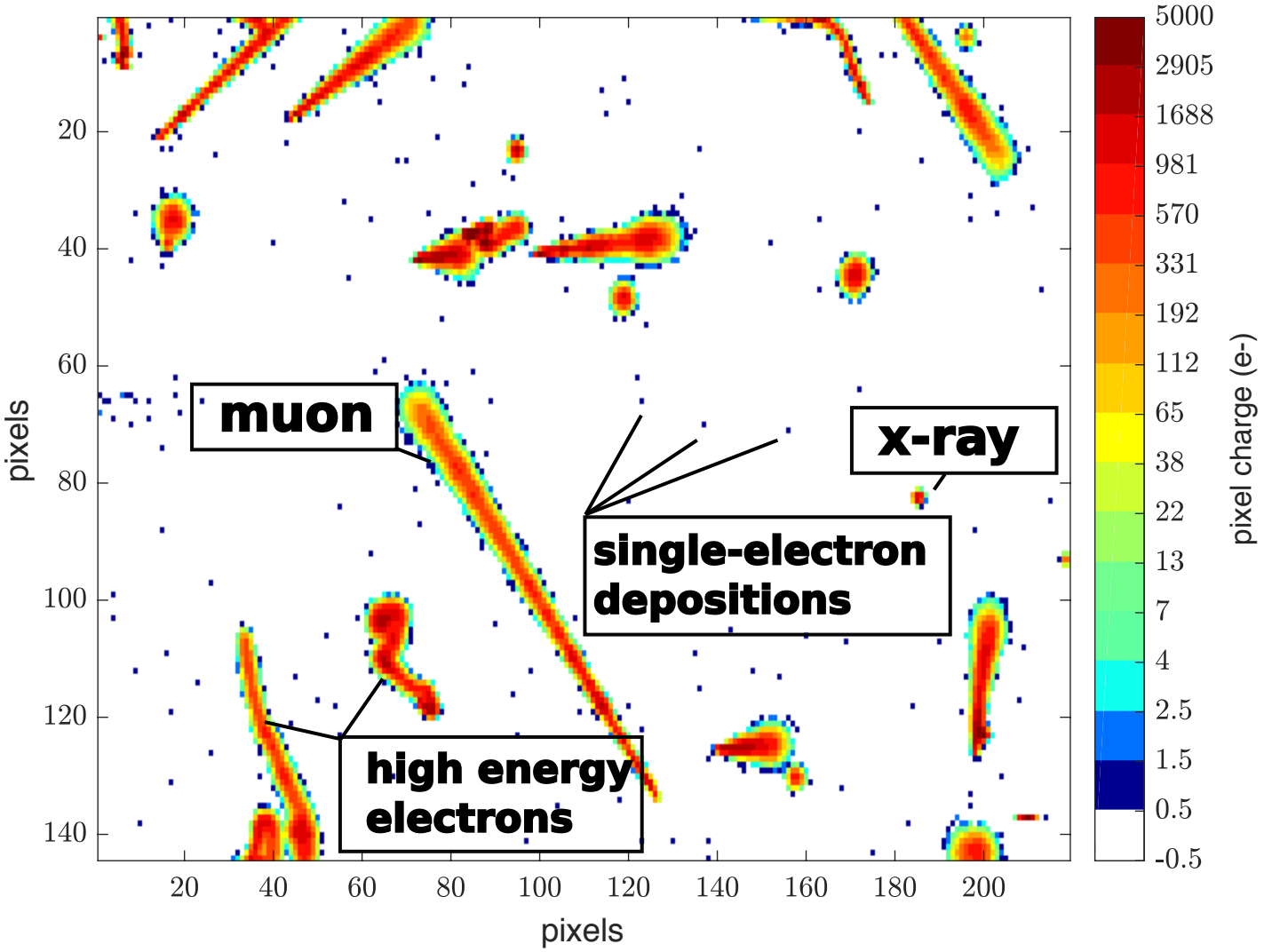
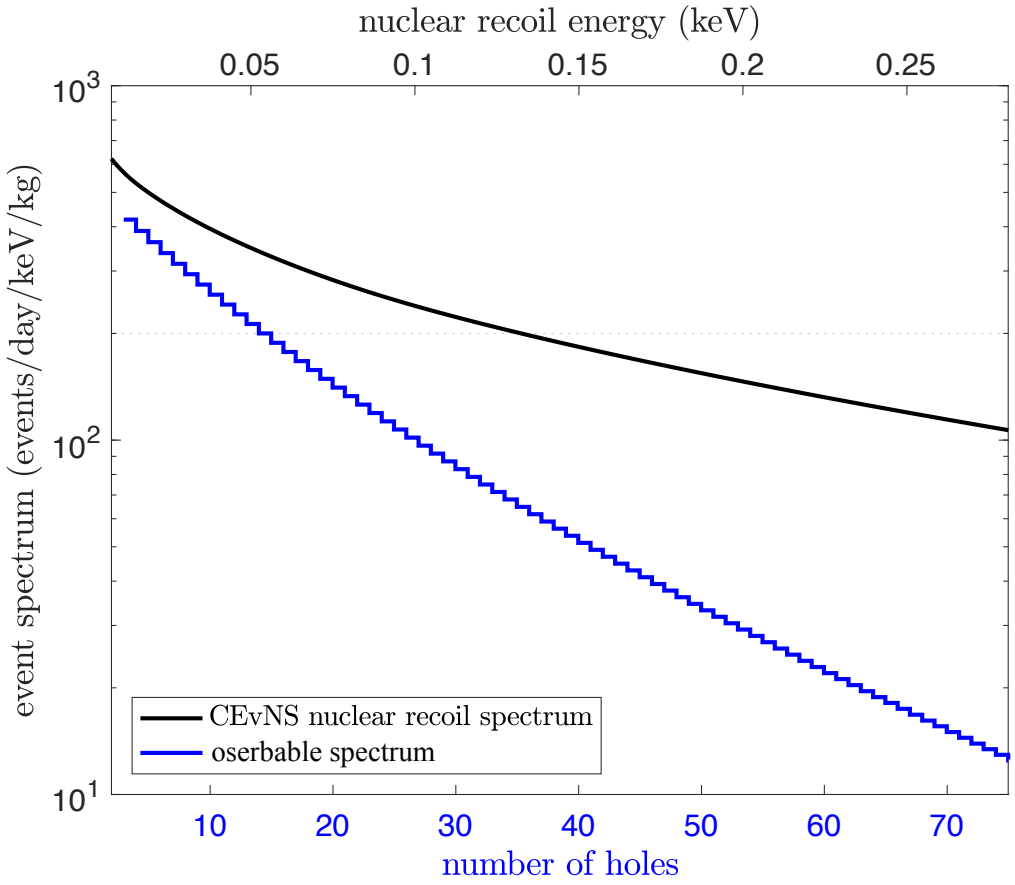


Image taken with Skipper CCD at sea level with no shield



CEνNS observation with Skipper



- **How low can we go in threshold? up to the Si band gap of 1.1eV?**
- Using very conservative quenching factor. Only using high energy measurements from Chavarria et al (arXiv:1608.00957).

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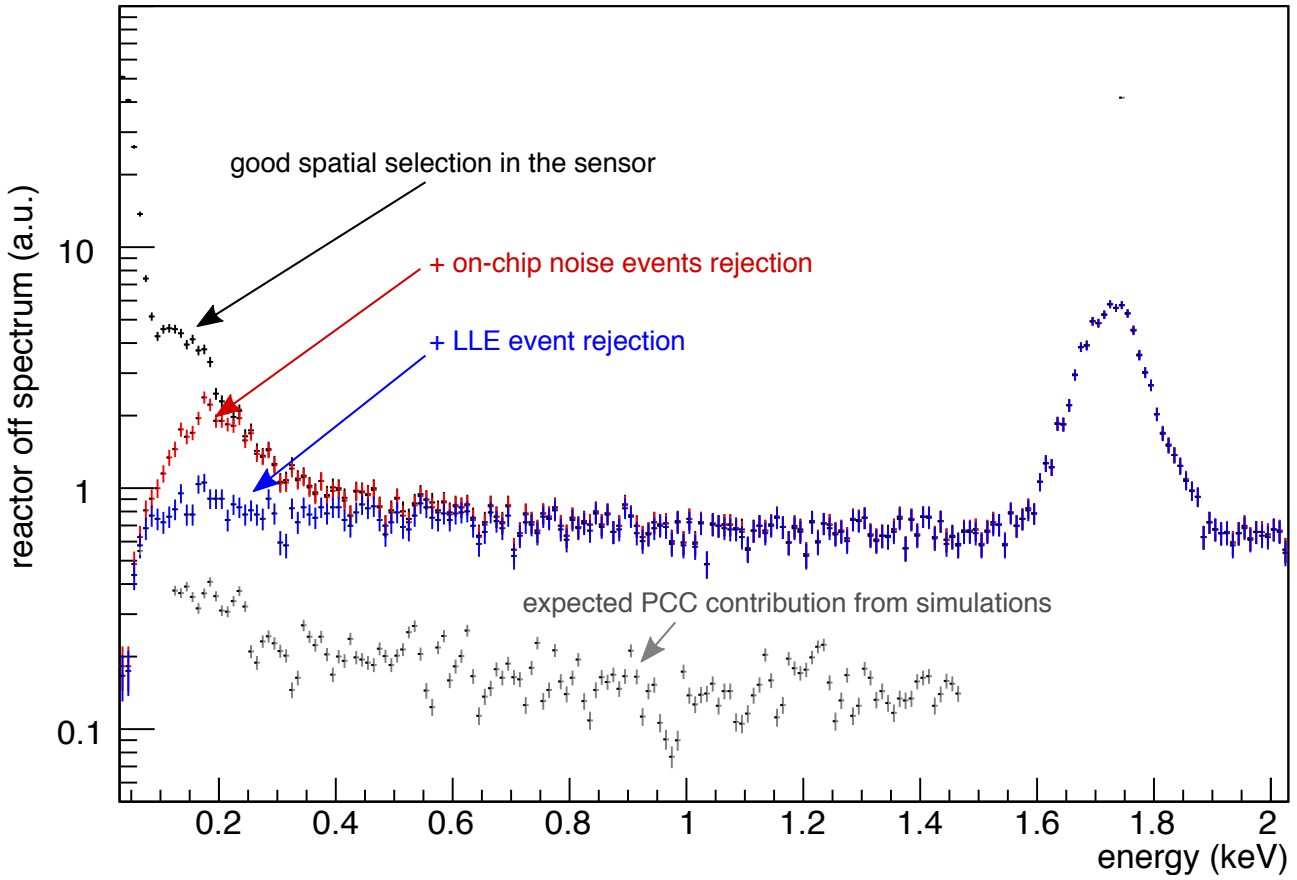
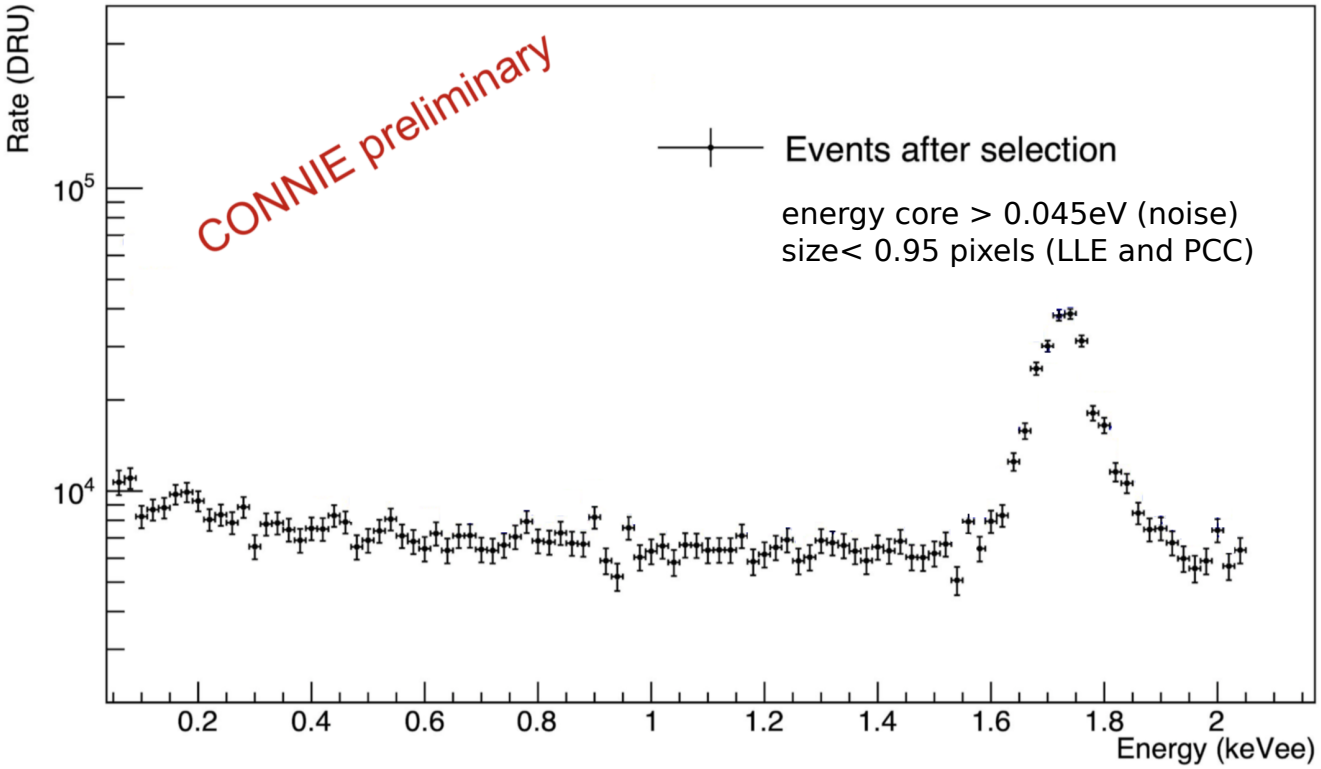
Summary of background studies and improvements in CONNIE (Preliminary)



- Huge improvement in background control from our last publication (from red to blue).
- Opportunity to keep reducing the background rate using back processing of our sensors.

Reactor OFF low energy spectrum after selection cuts



- Event selection criteria using the reactor OFF data:
  - Reject noise events: energy core > 0.045 eVee.
  - Reject LLE events and optimally size of events < 0.95 pixels.
- After this selection we can open.

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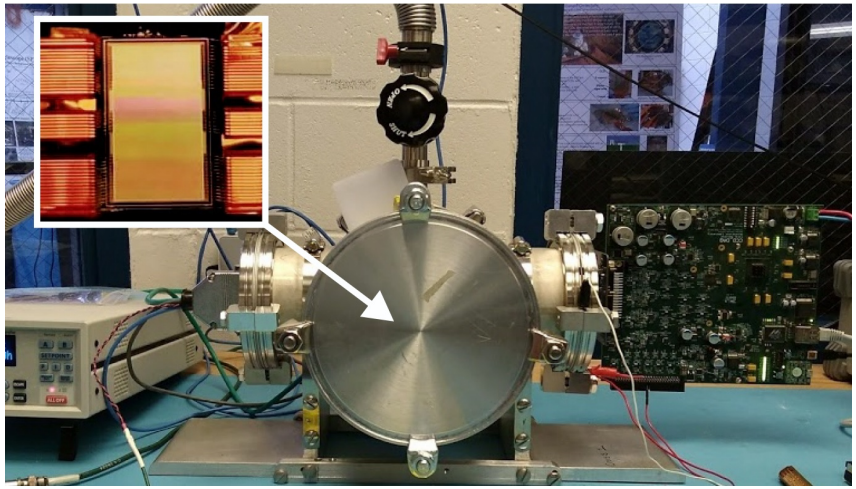
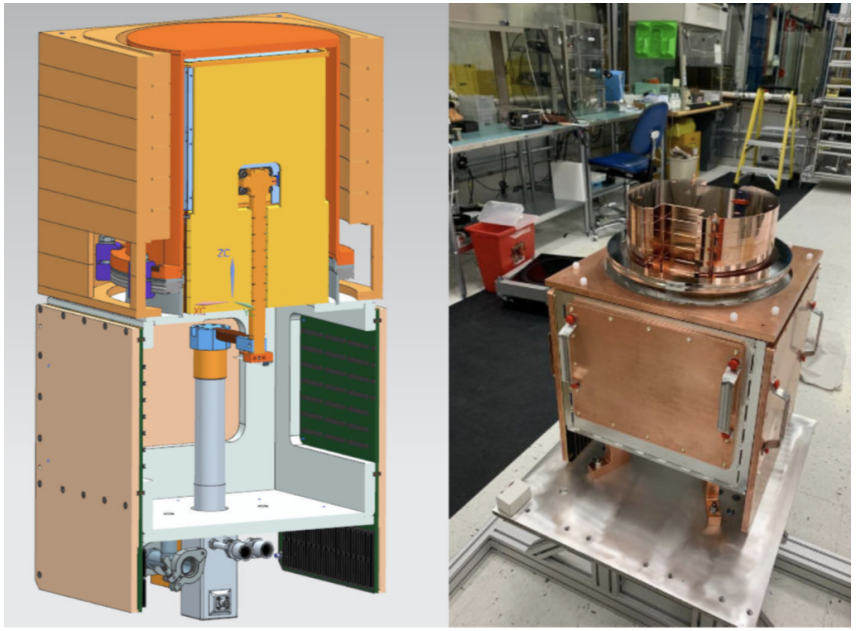
Developments @ FNAL

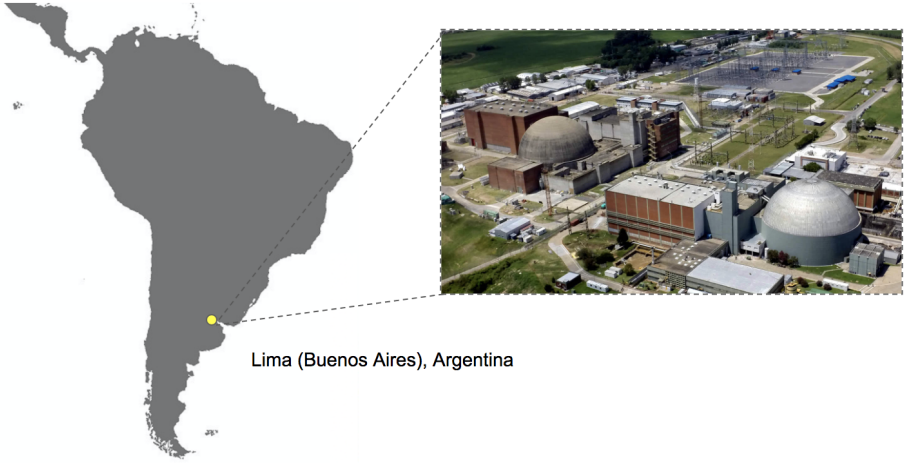


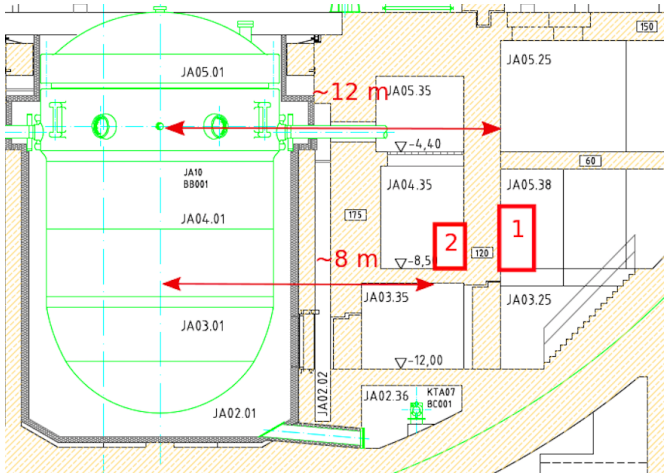


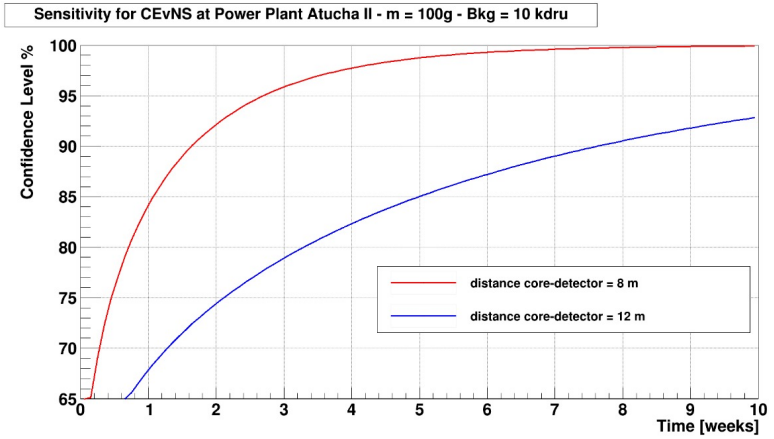
- 2-10 grams.
- Relatively cheap setups to study background below 100eV.
- Possible locations: Angra 2, Atucha 2, research reactors.

- Available design for 100-200 grams from the SENSEI experiment.

New possible location in Atucha 2 reactor







- Atucha 2 power plant.
- 8-12 m aways from a 2GW core.
- 3 times larger neutrino flux.
- Large nuclear physics community in Argentina.
- Background measurements being taken with HPGe detector.

νIOLETA

- Ambitious program: several kilograms Skipper CCD array for a short baseline program in a nuclear reactor.
- Neutrino Interaction Observation with a Low Energy Threshold Array (νIOLETA).
- νIOLETA webpage: violetaexperiment.com
- First workshop in Buenos Aires (December, 2019). Weekly meetings.

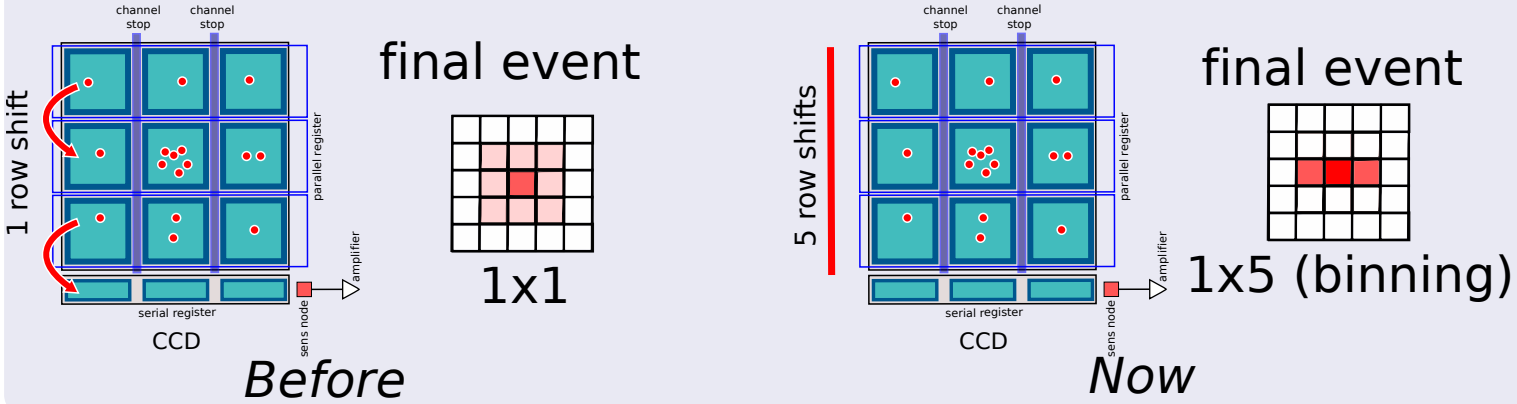
Conclusion

- There is a clear opportunity for physics searches at nuclear reactor with low threshold technologies.
- The CONNIE experiment is providing the lower threshold for neutrino observation at reactors.
- Skipper CCD technology is mature enough to allow the construction of experiments of several kilograms.
- Background studies below 50 eVee and quenching factor calibrations are important milestones for the near future.

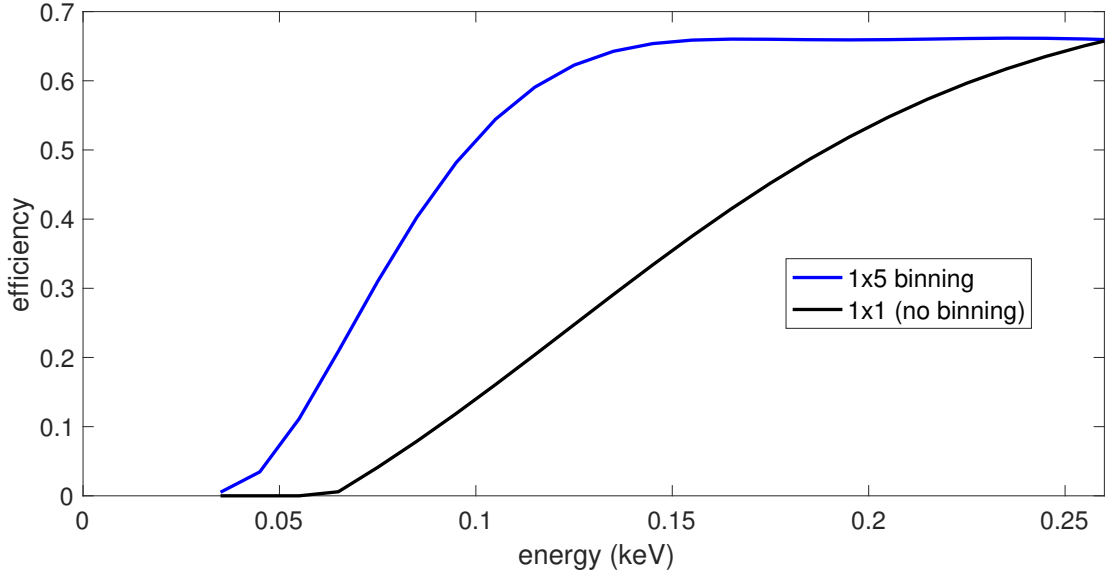
BACK UP SLIDES

Efficiency improvement at low energies with binning

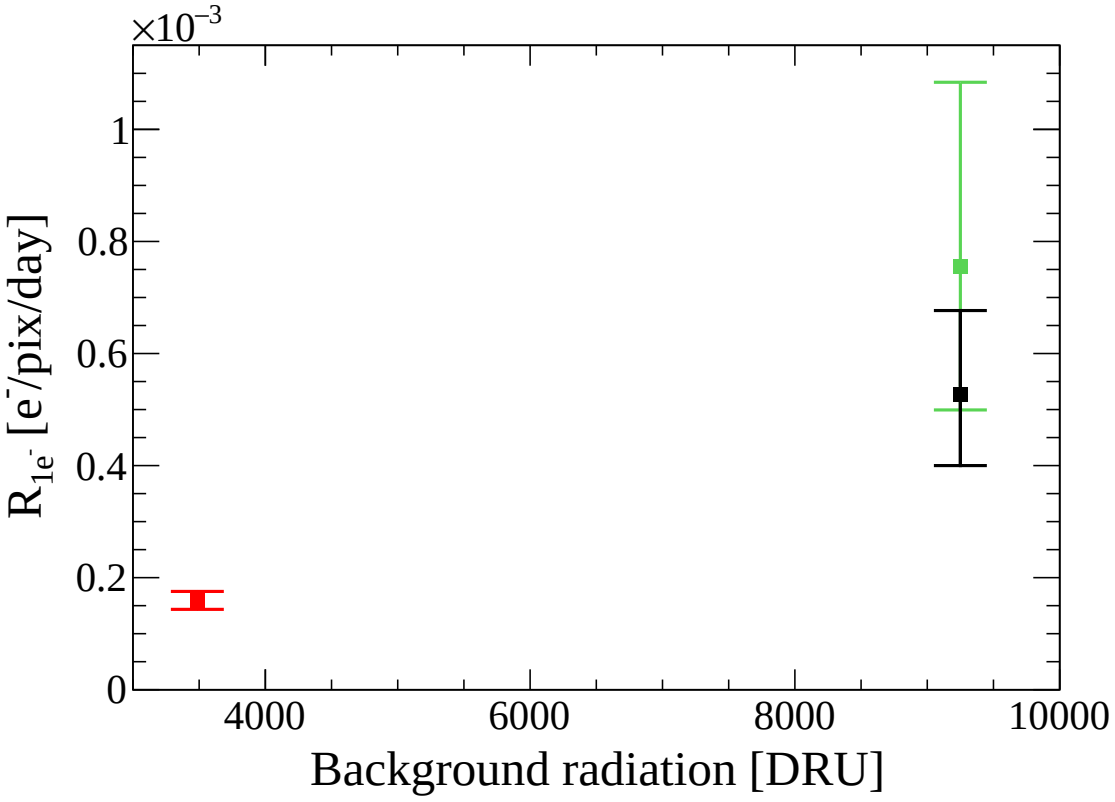
Readout modes



$$error = \sigma . \sqrt{N_{\text{pixels}}}$$



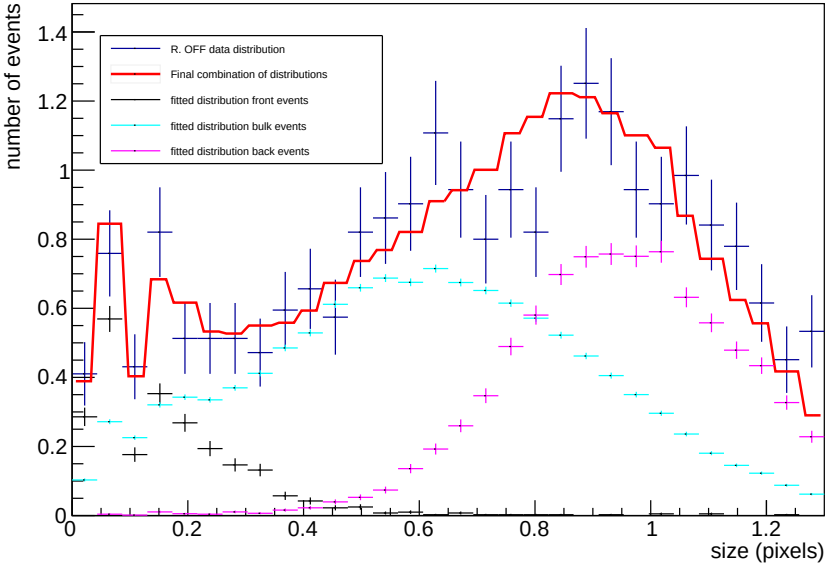
Single electron rate studies (arXiv:2004.11378)



- Single electron event rate (R_{1e-}) as a function of events with energies between 500eV and 10 keV.

PCC events: Size distribution of events for different energies

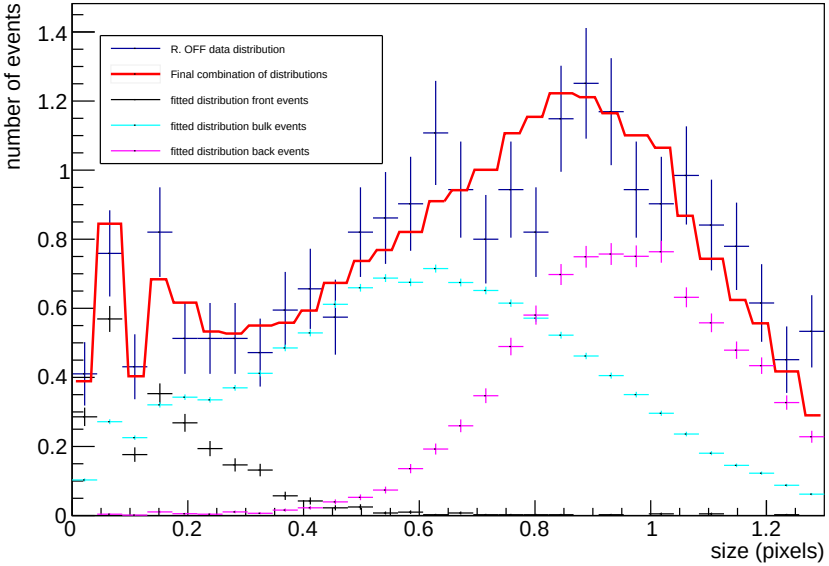
0.1-0.2keV



- **Front 10%**
- **Bulk 54%**
- **Back 36%**

PCC events: Size distribution of events for different energies

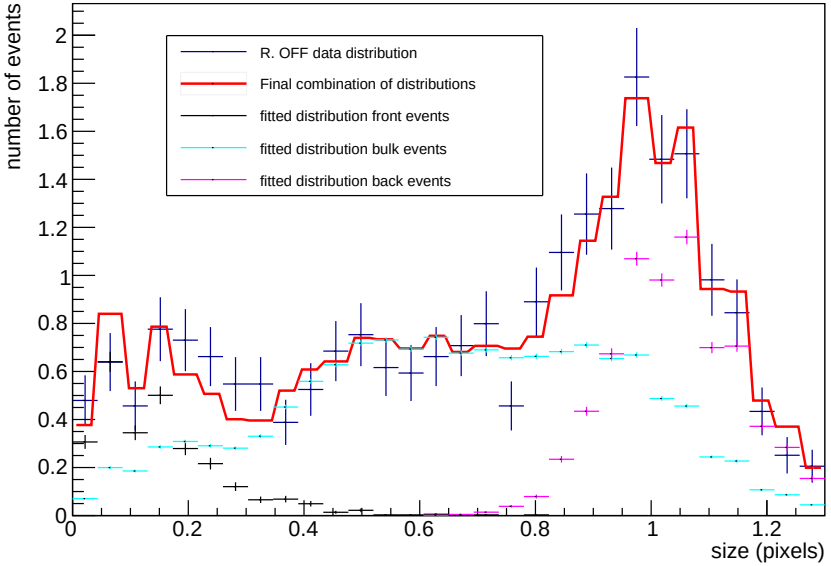
0.1-0.2keV



- **Front 10%**
- **Bulk 54%**
- **Back 36%**

0.4-0.5keV

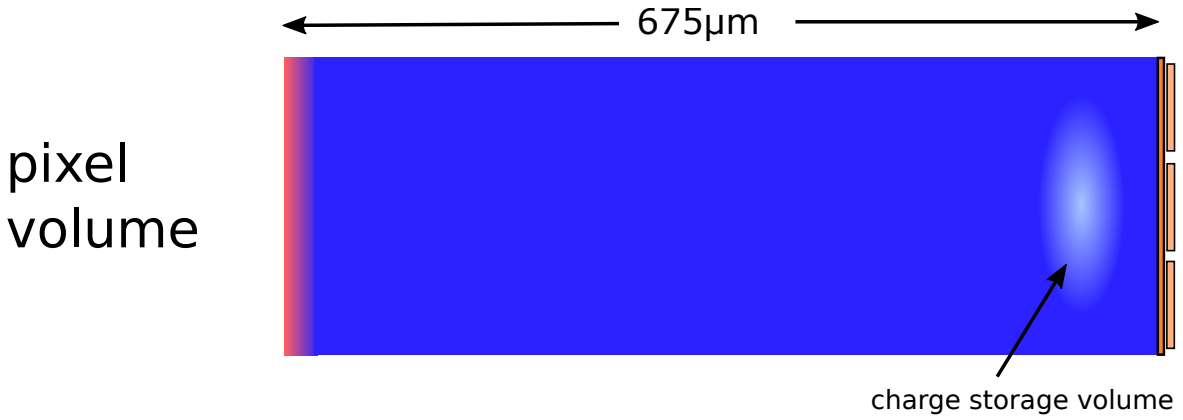
distribution of all data events during reactor off passing neutrino selection cuts



- **Front 11%**
- **Bulk 59%**
- **Back 30%**

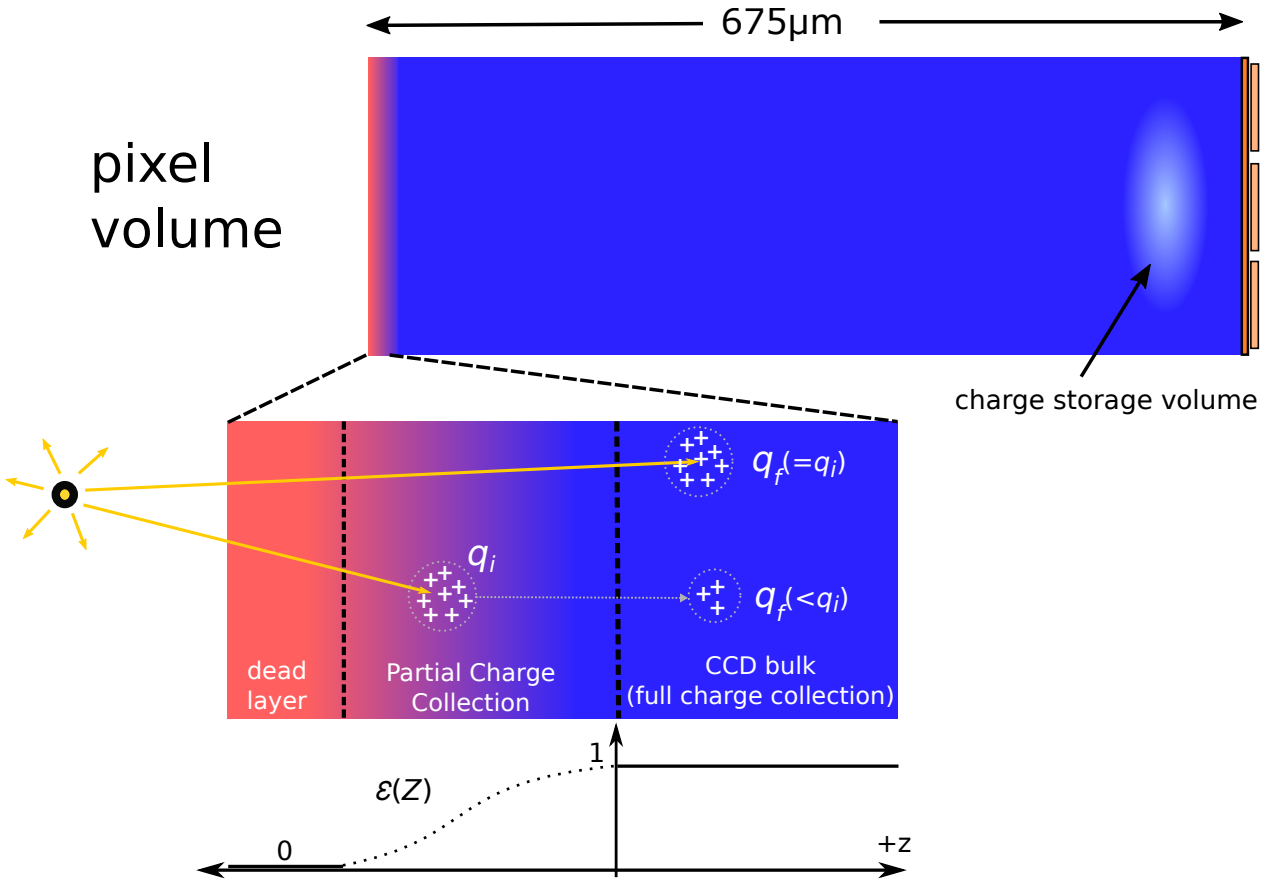
- Big contribution coming from the back of the sensor.
- The contribution seems to be larger for lower energies.

Studies on partial charge collection layer (arXiv:2007.04201)



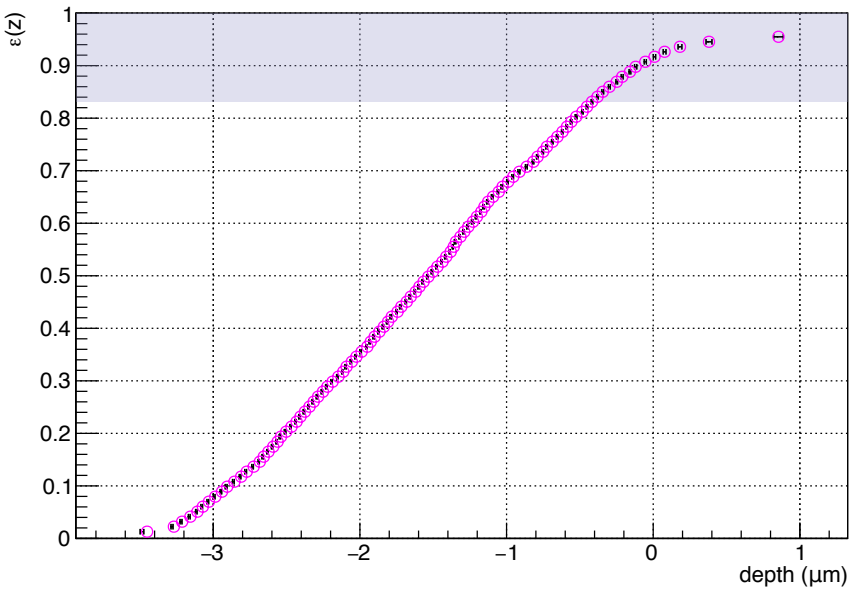
- This work allows a quantitative evaluation of the events coming from the back layer.

Studies on partial charge collection layer (arXiv:2007.04201)



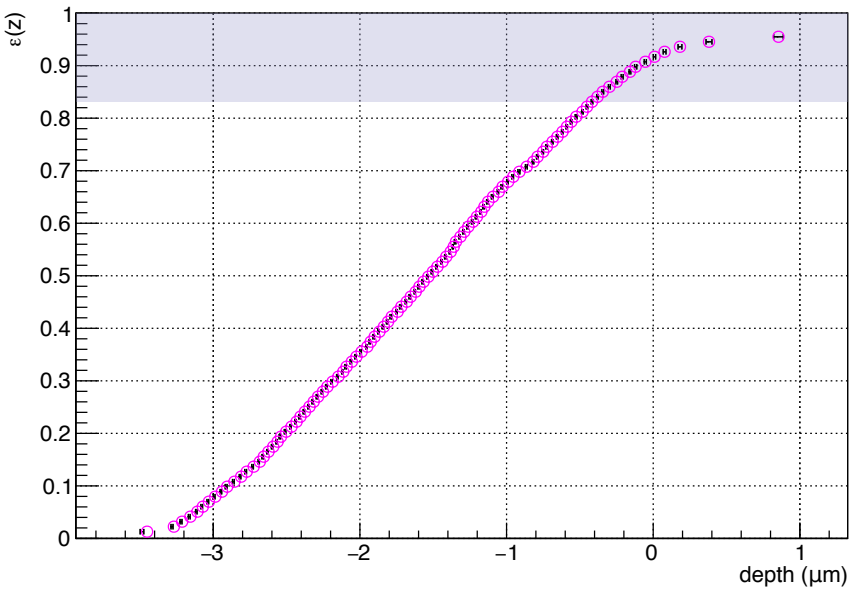
- This work allows a quantitative evaluation of the events coming from the back layer.

Measurement of efficiency collection (arXiv:2007.04201)



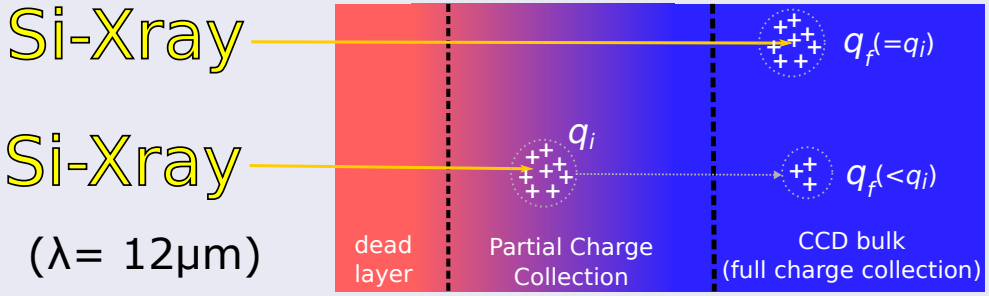
- $Q_{collected} = \varepsilon(z) \times Q_{original}$
- This work allows a quantitative evaluation of the events coming from the back layer.

Measurement of efficiency collection (arXiv:2007.04201)

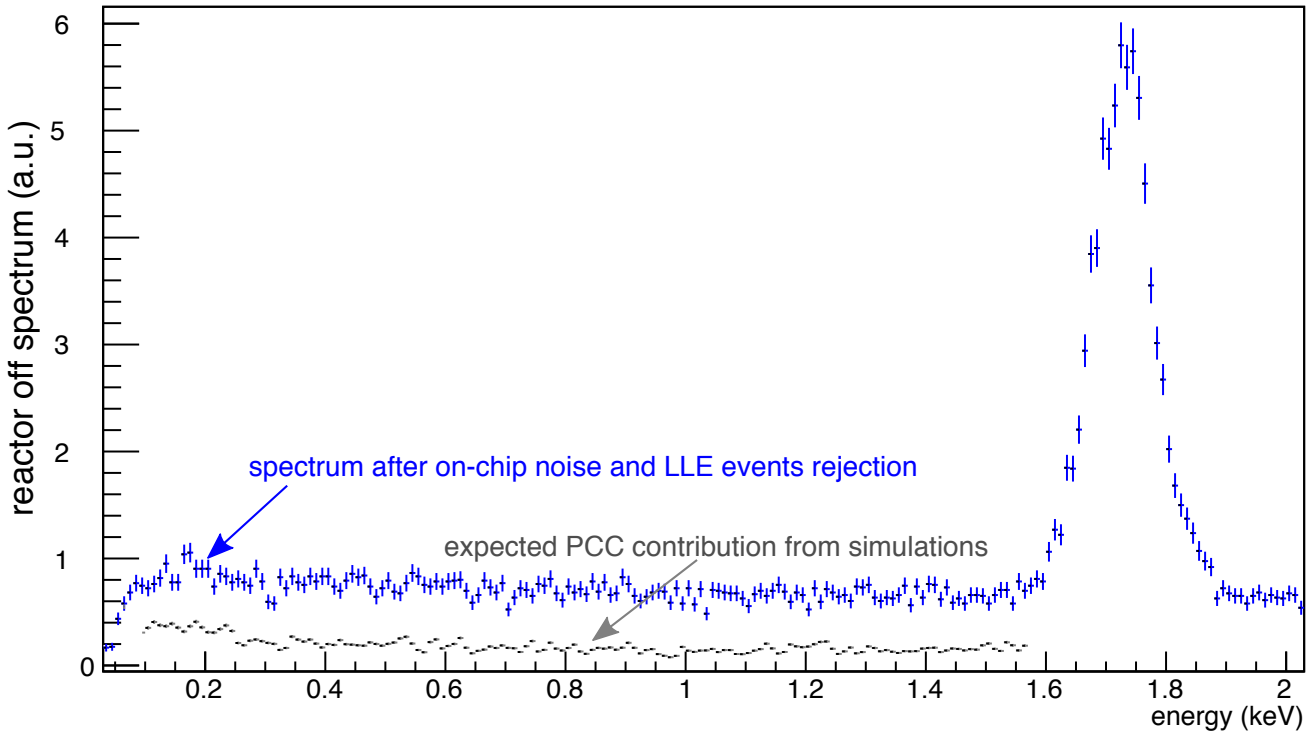


- $Q_{collected} = \varepsilon(z) \times Q_{original}$
- This work allows a quantitative evaluation of the events coming from the back layer.

Opportunity: use this measurement to evaluate impact in CONNIE



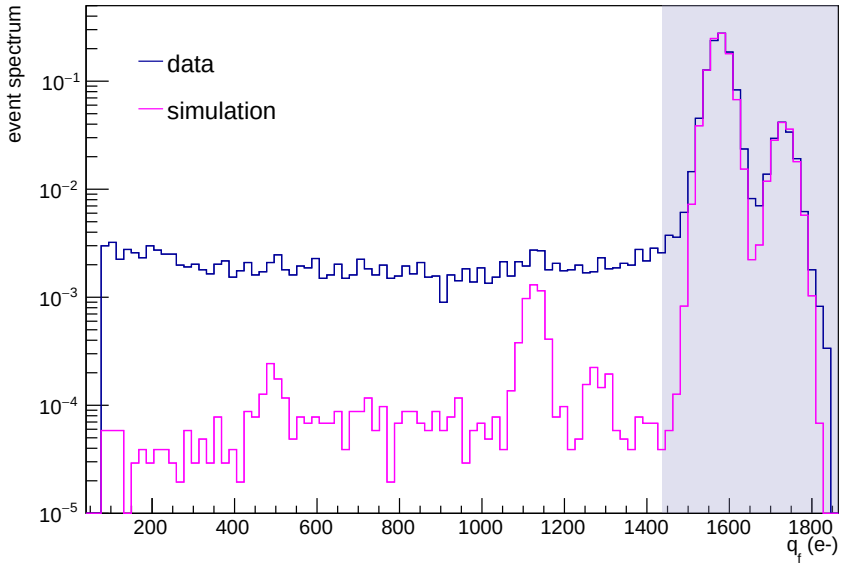
CONNIE: contribution of Si-Xrays to low energy events



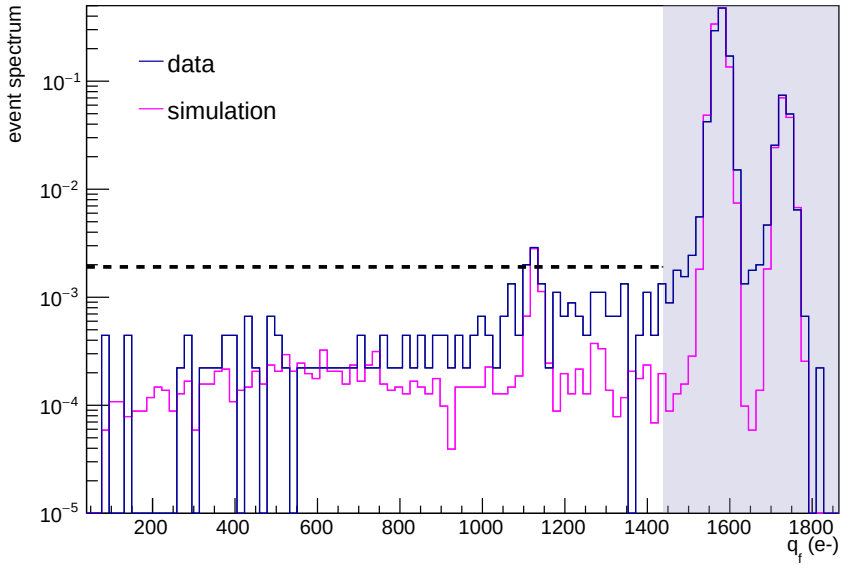
- Big opportunity to reduce the background rate in the future.
- Small slope towards lower energies as measured in the data.
- contribution close to 30% as measured in the data.

arXiv:2007.04201 also provides a solution for future sensors

No backside treatment



With backside treatment

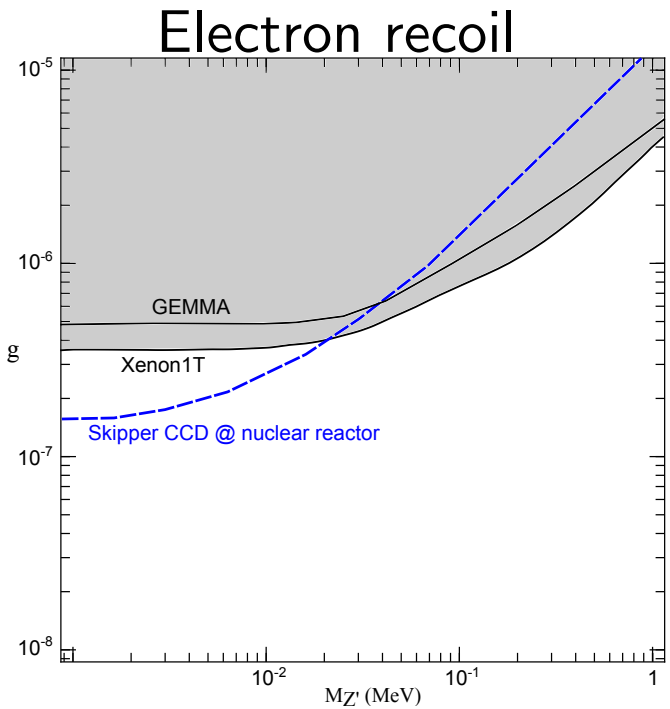


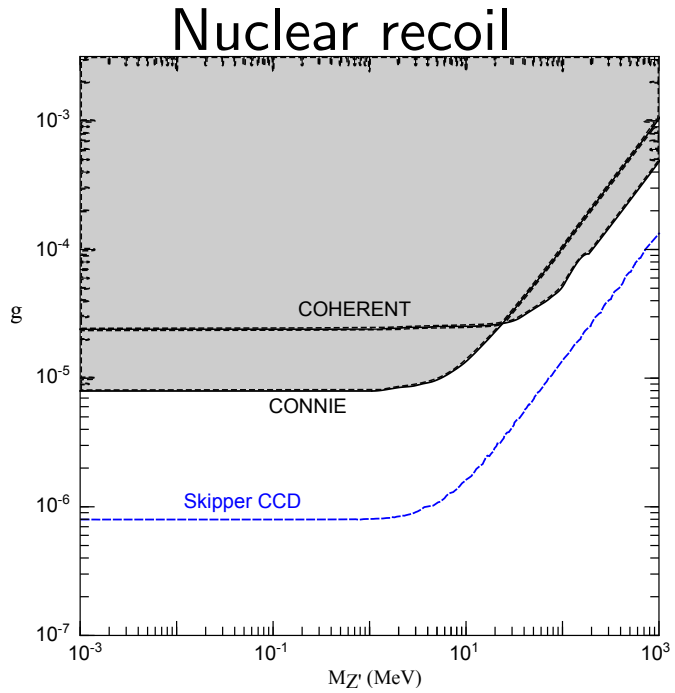
- Blue: measured spectrum; Pink: expected Compton contribution.
- Backside treatment proposed in JINST 12, C04018, drastically reduce the number of events at low energy.

Opportunities for low threshold sensors

Beyond standard model

- New light vector boson mediated interactions. Preliminary work: *S. R. Alcaraz, I. Martinez, G. F. Moroni, D. Rodrigues, I. Sidelnik, Y. Perez, et al.*
- 10kg detector running at 12 m from a 2GW$_{th}$ reactor for 3 years. Other constraints from arXiv:2006.11250 and arXiv:1910.04951.





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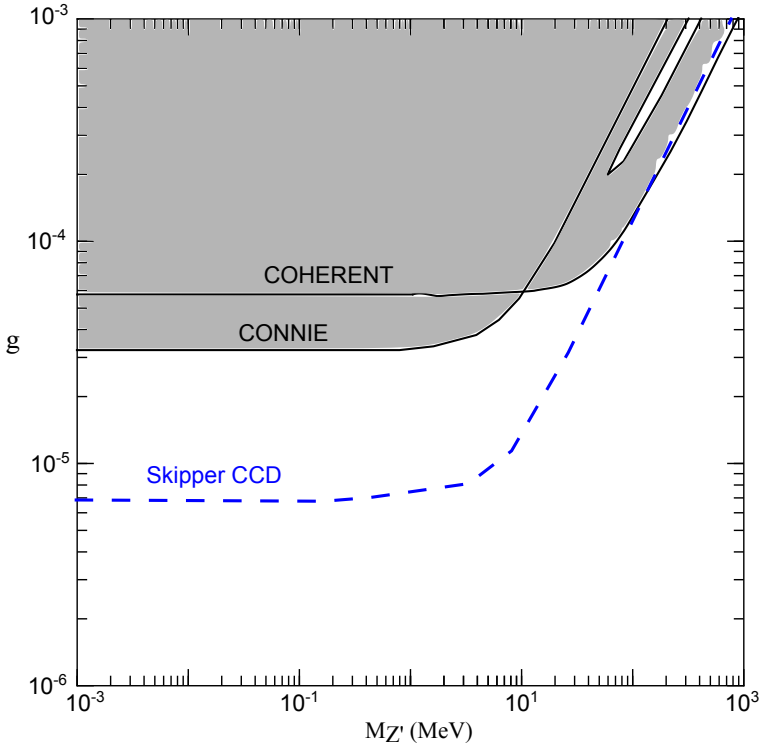
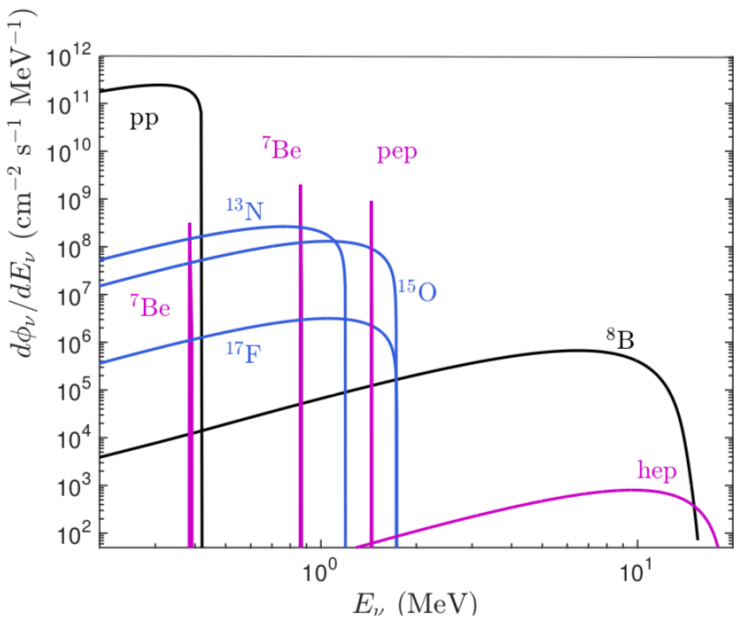
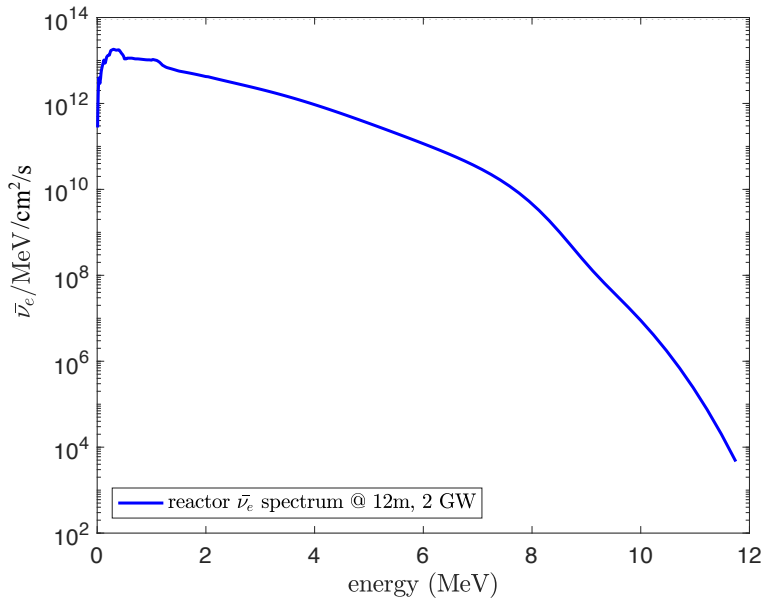


Opportunities for low threshold sensors

Exploring neutrino scattering floor for Dark Matter experiments.

- Neutrinos with similar energies. Different flavors.
- Solar neutrino spectrum from JHEP05(2016)118 and flux from PDG.
- Nuclear flux at 12 m from a 2GW$_{th}$ reactor.





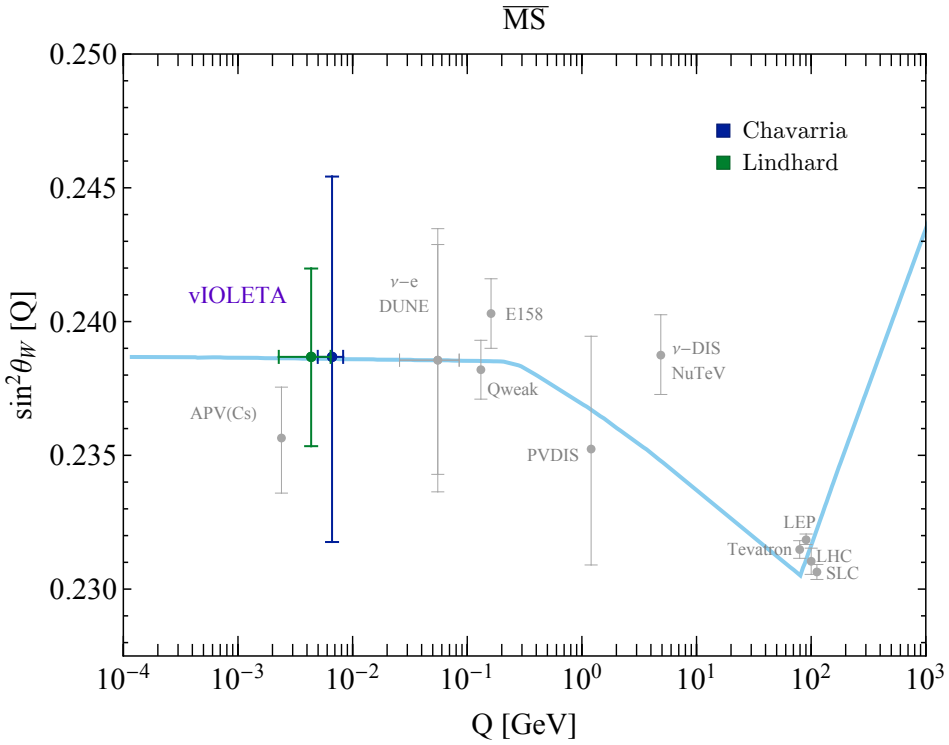
- Solar flux $\approx 7 \times 10^{10} \nu/\text{cm}^2/\text{s}$.
- reactor flux $\approx 1 \times 10^{13} \nu/\text{cm}^2/\text{s}$.

Opportunities for low threshold sensors

Reactor as a very intense gamma source

- Production-detection of Axion Like particles (arXiv:1912.0573)
- Production-detection of dark matter particles.

Opportunities for low threshold sensors

High precision measurements of the standard model

- arXiv:2009.10741: *The physics potential of a reactor neutrino experiment with Skipper CCDs: Measuring the weak mixing angle*
- 10kg detector running at 12 m from a 2GW$_{th}$ reactor for 3 years.