Neutrino physics at a reactor with the CONNIE experiment

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for the CONNIE Collaboration

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The CONNIE Collaboration

COherent Elastic Neutrino Nucleus Interaction Experiment

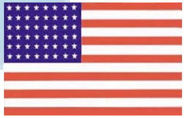
Argentina
Centro Atómico Bariloche
Universidad de Buenos Aires
Universidad del Sur / CONICET
ICAS / ICIFI / UNSAM

Brazil
Centro Brasileiro de Pesquisas Físicas
Universidade Federal do Rio de Janeiro
CEFET-Angra

Mexico
Universidad Nacional Autónoma de México

Paraguay
Universidad Nacional de Asunción

Switzerland
University of Zurich



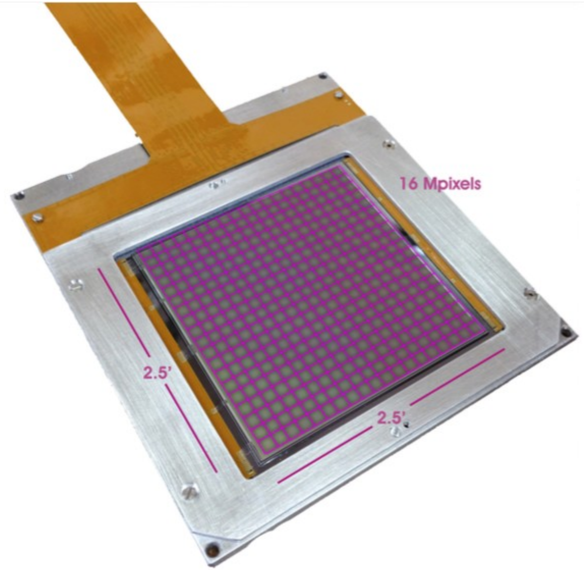
USA
Fermi National Accelerator Laboratory

14 institutions, 6 countries ~30 people

CONNIE Experiment Motivation

- CONNIE's goal is to detect the Coherent Elastic Neutrino-Nucleus Scattering (CEνNS) in Silicon nuclei at reactor neutrino energies (< 10 MeV).
- The experiment will use this channel to probe the existence of new physics BSM.
- Will use scientific CCDs developed at LBNL Microsystems Lab (originally for DECam and DESI). Also used in the DAMIC (Dark Matter In CCDs) experiment

Pixels:	15 μm x 15 μm (4000 x 4000 pixels)
CCD thickness (mass):	675 μm (5.95 grams)
Operation Temp:	< 100 K
Readout noise	~2.0 electrons RMS
Energy Threshold	< 50 eV_{ee}

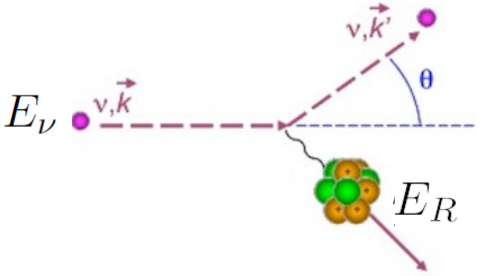


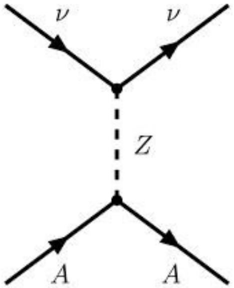
- Manufactured with very high resistivity silicon:

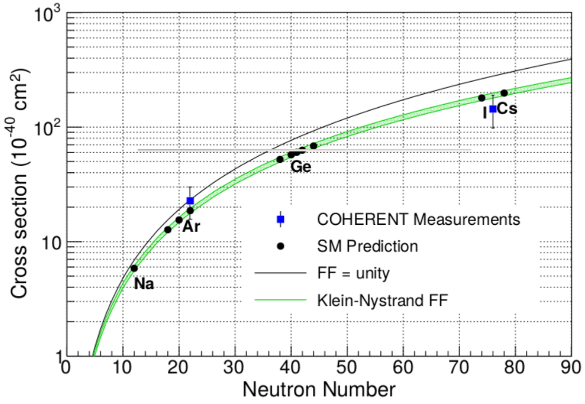
  → low radioactive backgrounds
  → low dark current (~ 0.1 e- / pix / day)

Coherent Elastic ν-N Scattering (CEνNS)

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







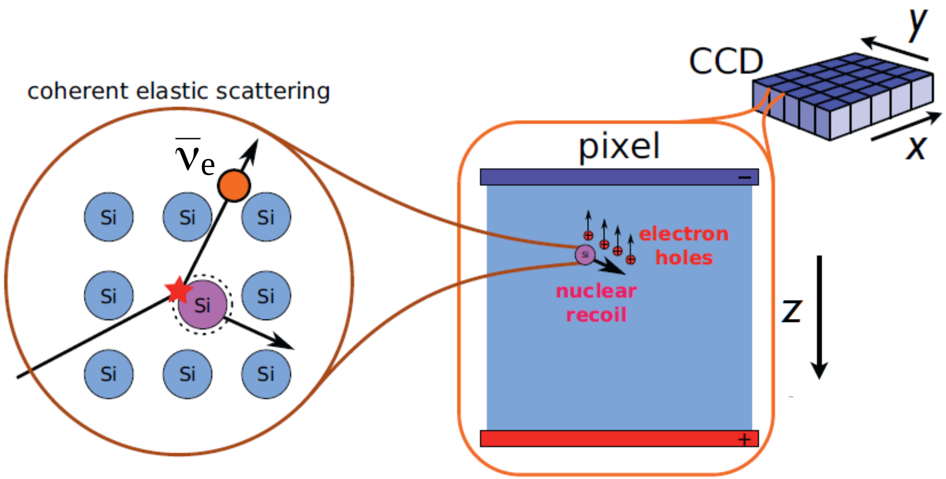
Weak nuclear charge $Q_W^2 \sim N^2$

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

First observed by the COHERENT Collaboration with neutrinos of E~16-53 MeV with a CsI detector (Science 357, 1123, 2017), and a Liquid Ar detector (PRL, 126, 012002, 2021).

Observation at lower energies (Reactors) may hint at Physics BSM.

CCD as a particle detector

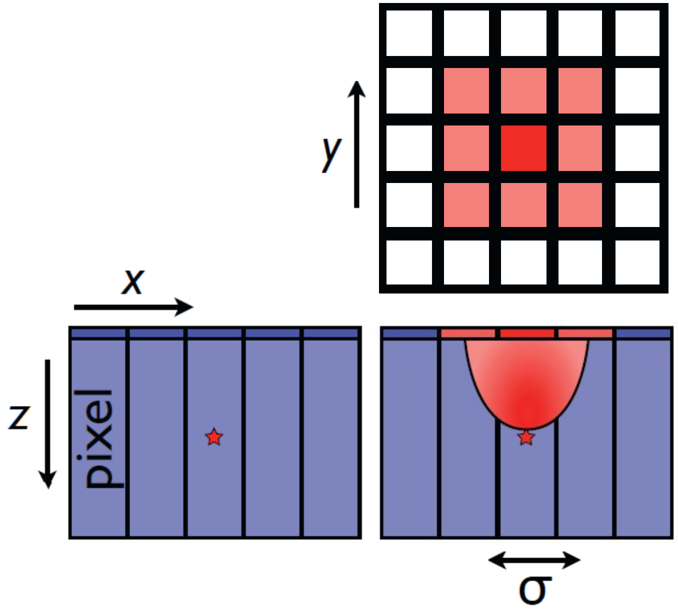


The scattering of the ν with a Si nucleus leads to ionization

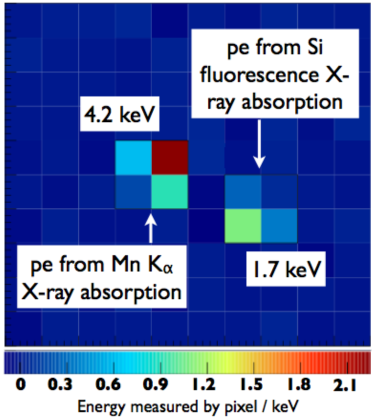
Charge carriers are drifted along z direction and collected at CCD gates

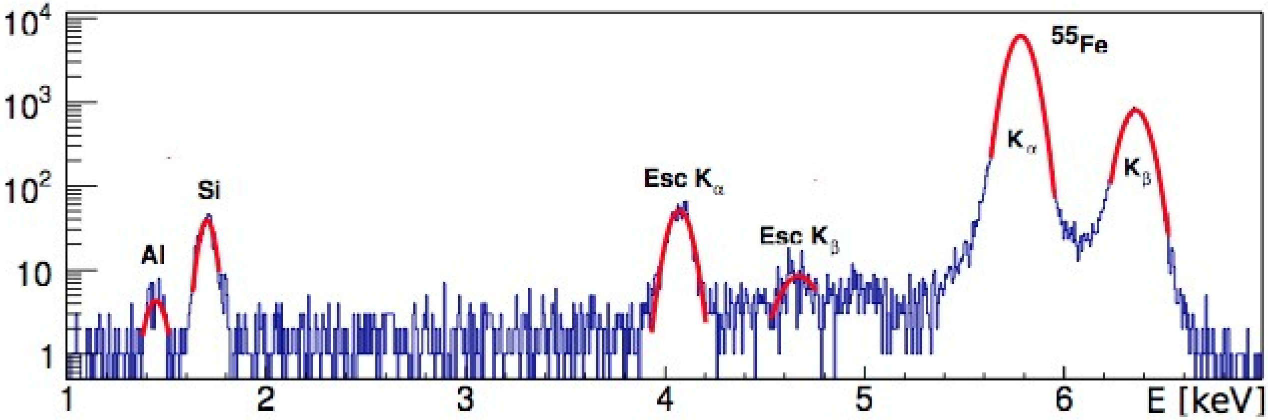
Charge diffuses in *x*-*y* plane as it drifts towards the gates

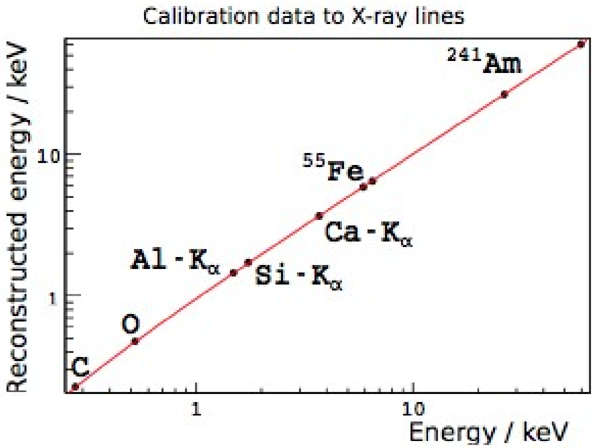
The radial spread of the cluster is used to estimate its position in z within the CCD bulk.

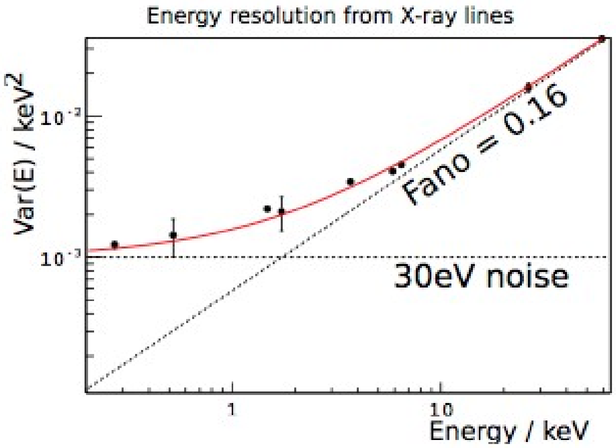


CCD energy response (X-rays)

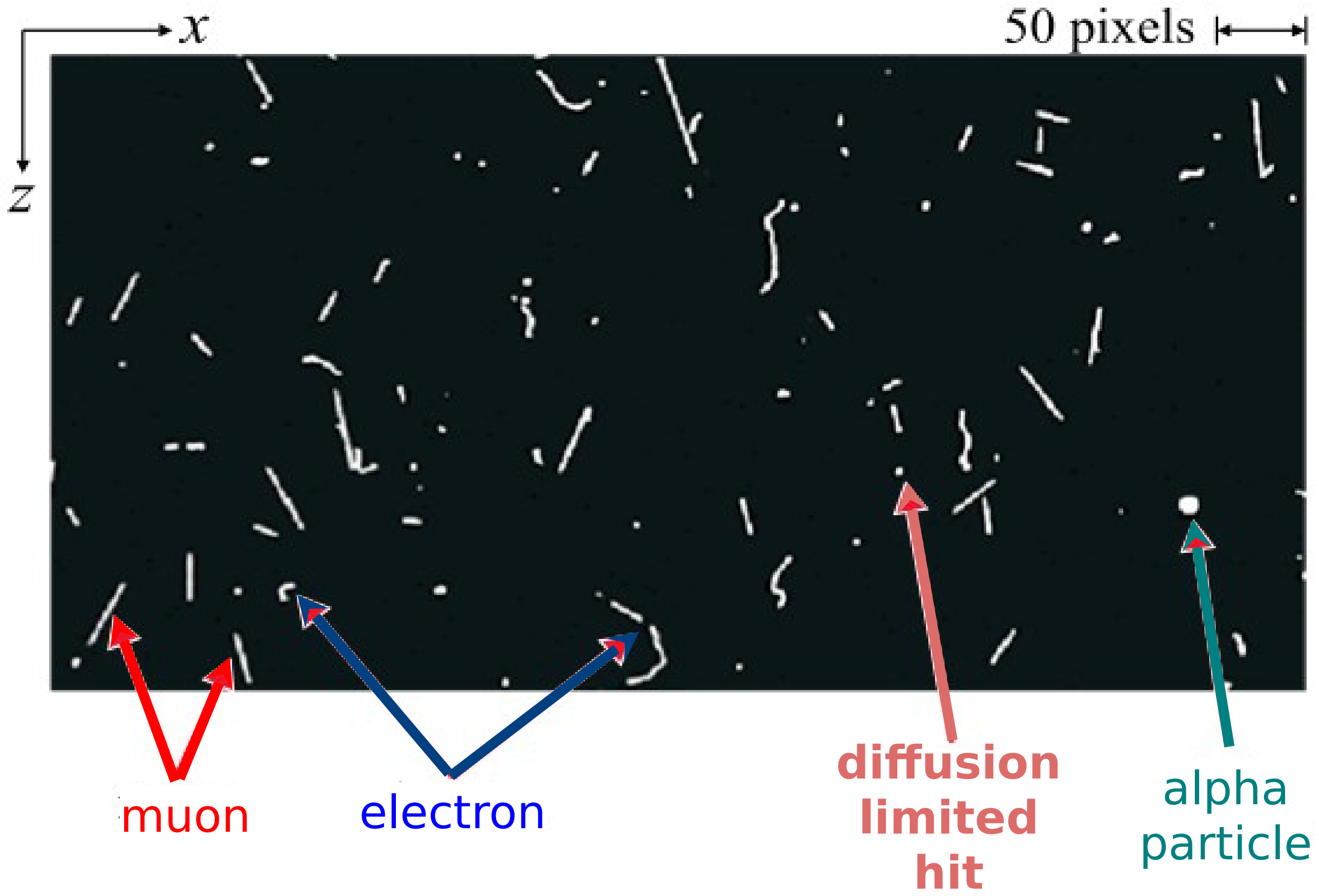








CCD particle identification

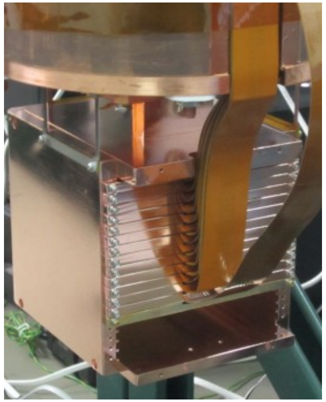


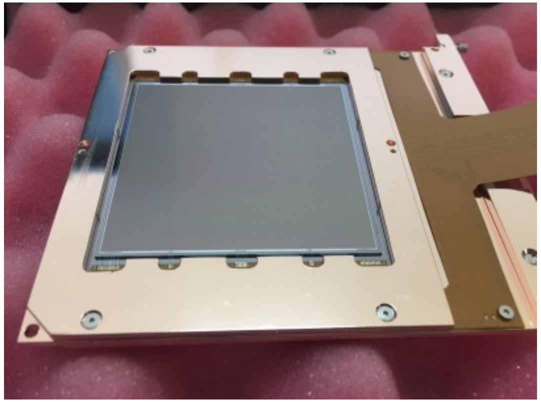
The CONNIE Detector

Installed in 2014 and upgraded in 2016

- 14 CCDs installed (5.95 g each)
- 2 disconnected due to issues early in run
- 8 good CCDs selected for physics analysis (good noise, charge transfer efficiency & stability)

4k × 4k pixel, 15 μm × 15 μm, 675 μm thick





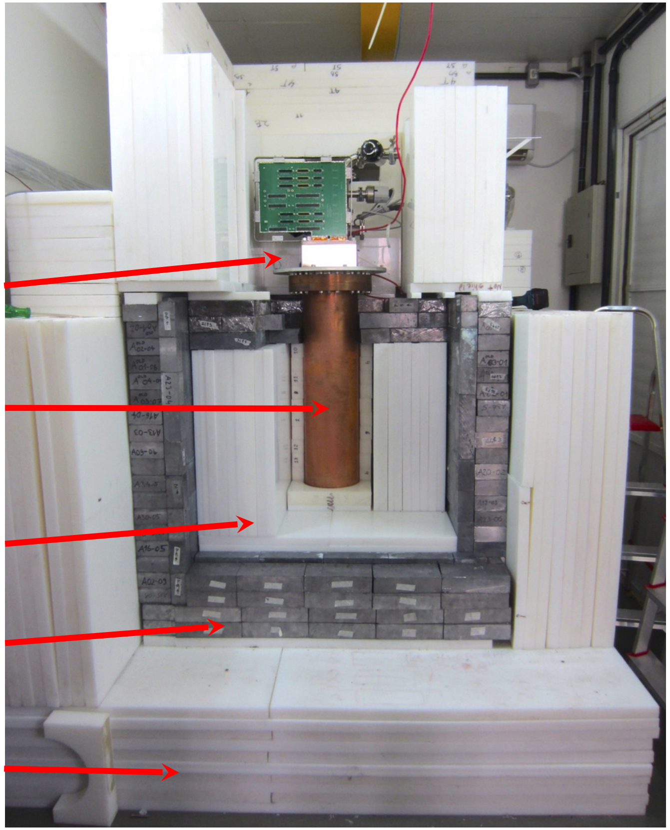
ViB readout board (signal transport)

Dewar in vacuum

Inner Polyethylene (neutrons) 30 cm

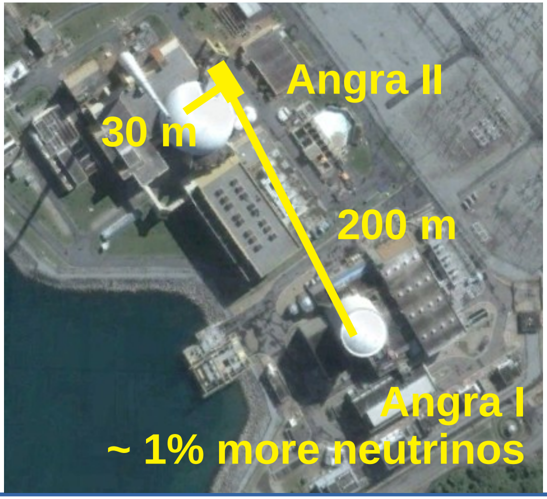
Lead (gamma) 15 cm

Outer Polyethylene (neutrons) 30 cm



JINST 11 (2016) P07024

Angra Nuclear Power Plant



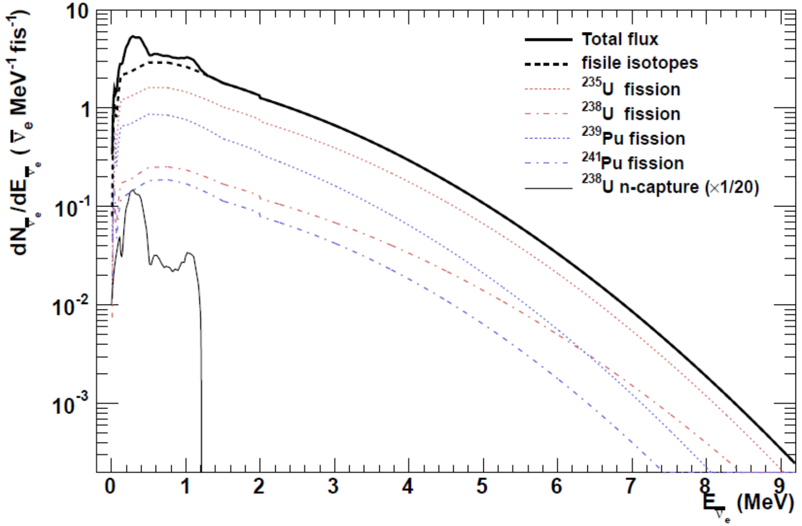
CONNIE at the Angra-2 reactor

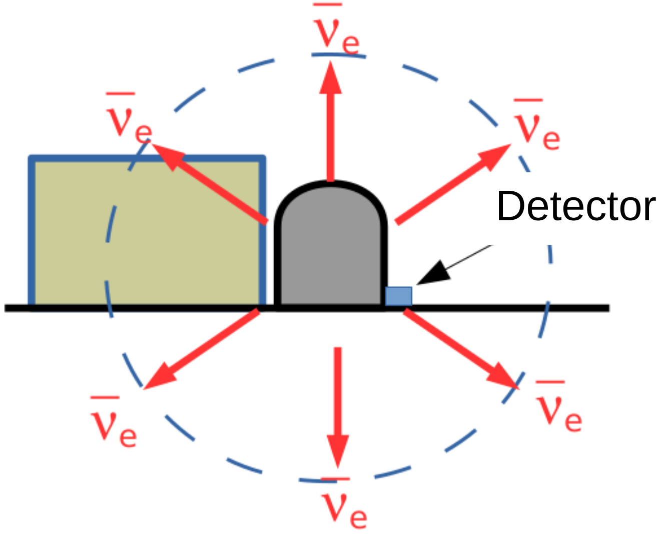
Angra-2 is a 3.95 GW_{th} Pressurized Water Reactor (PWR).

Emits ~8.7×10^{20} $\bar{\nu}_e$ s^{-1} (2.23×10^{20} $\bar{\nu}_e$ s^{-1} GW_{th}^{-1}).

At 30 m the flux is ~7.8×10^{12} $\bar{\nu}_e$ cm^{-2} s^{-1}.

$$fisRate = \frac{3.95\ \mathrm{GW}_{th}}{205.24\ \mathrm{MeV/fis}} \approx 1.2 \times 10^{20}\ \mathrm{fis/s}$$





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 Timeline and Milestones

Engineering run

- Dec 2014 Four 1 gram CCDs installed at Angra
- Aug 2015 Full shield installed

  1 month data ReactorON (Sep) + 1 month data ReactorOFF (Oct)
- Apr 2016 Published run data results [JINST 11 (2016), P07024], Demonstrated remote operations, low noise (<2 e^-) stable bkgd rates

1st Detector Upgrade

- Aug 2016 14 x 5.9 g CCDs installed at Angra

  Data season I: Aug 2016 - Mar 2017 (incl. ROFF)

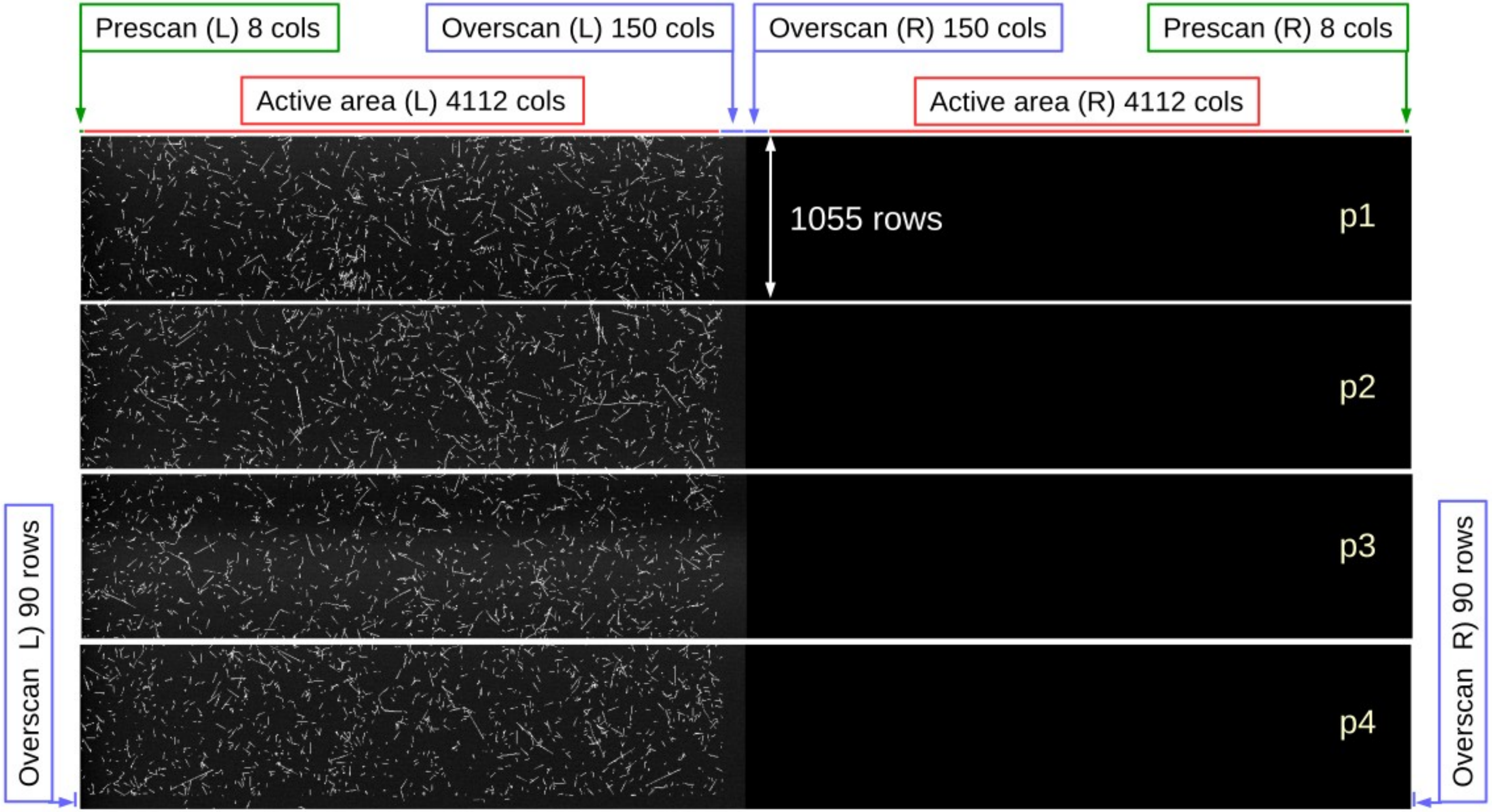
  Data season II: Mar – Dec 2017 (no ROFF)

  Data season III: Jan – Aug 2018 (incl. ROFF)
- Jan 2019 New readout configuration (1x5 running) with reduced noise
- Nov 2019 Published 2016-2018 run data results [Phys. Rev. D. 100 (2019), 092005] Model independent limit on New Physics
- Apr 2020 Published BSM Physics limits [JHEP 04 (2020), 054]
- July 2021 Ongoing analysis of 2019 data with improved noise

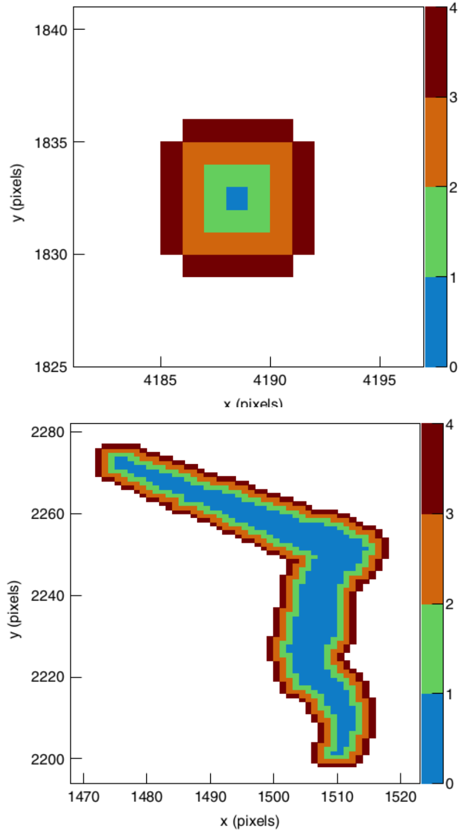
Skipper CCD Installation (pre-Upgrade)

- July 2021 2 x Skipper CCDs (1248×724 pix^2) installed at Angra

CONNIE Images (1x1 DAQ, 2016-2018)

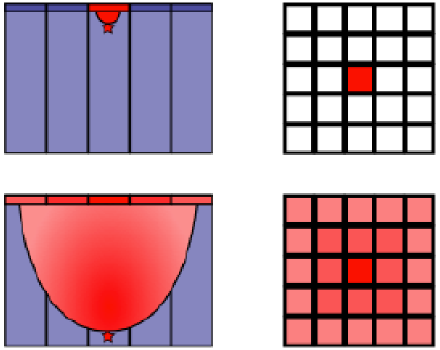


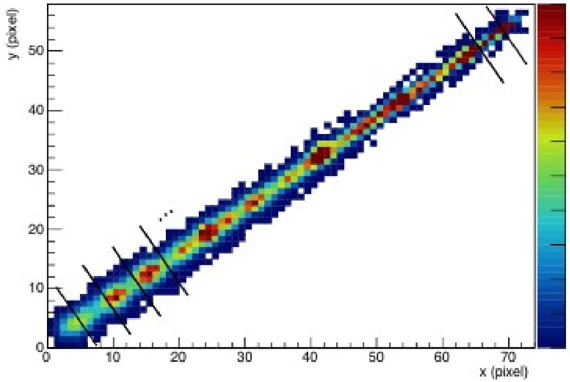
Event catalog extraction

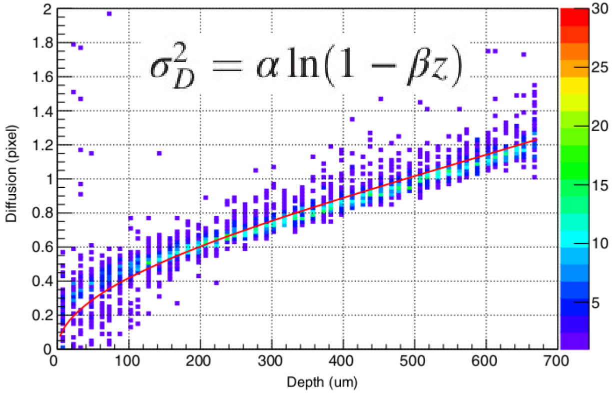


Depth calibration and Low E event selection

- Muon tracks used to characterize depth/size relation



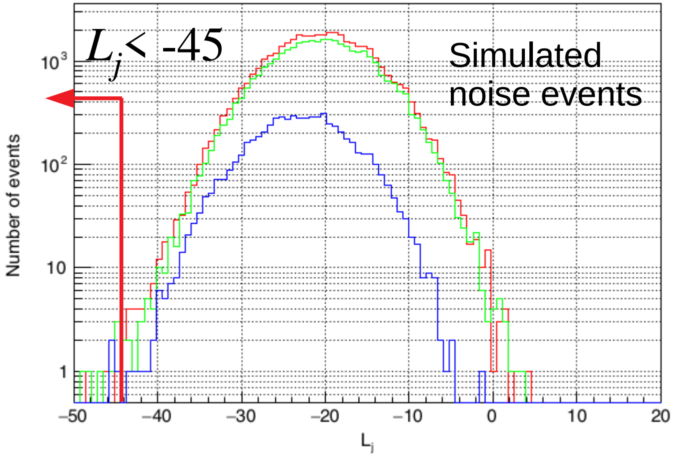




- Low *E* event selection based on Likelihood test over *N* pixels of *j*th event:

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

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



Results 2016–2018

Monitor data stability

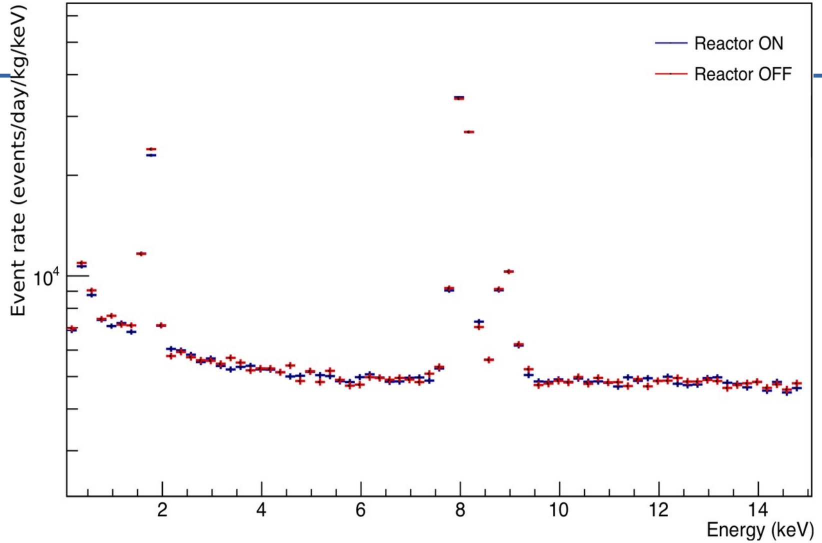
- read-out noise and dark current
- calibration of Cu and Si fluorescence peaks
- Low and high energy event rates

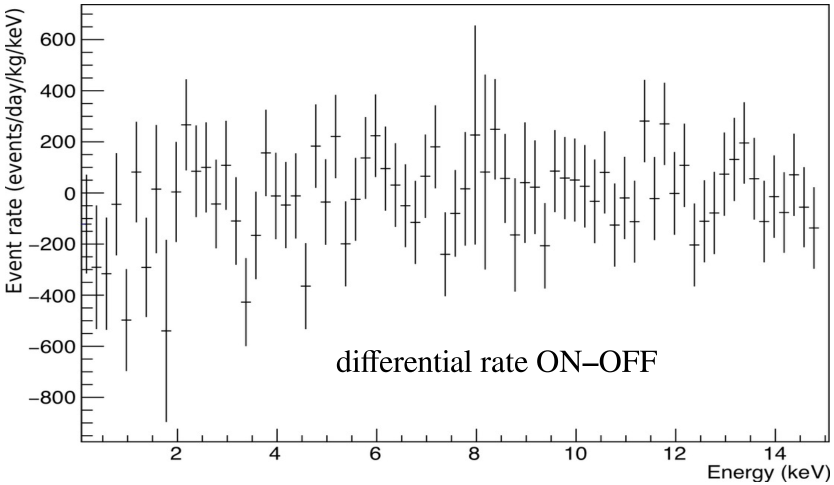
Data quality cuts

- discard images with high read-out noise and dark current
- remove CCD edge effect and dead pixels

Total exposure:

Reactor **ON** (2.1 kg·day) and **OFF** (1.6 kg·day)



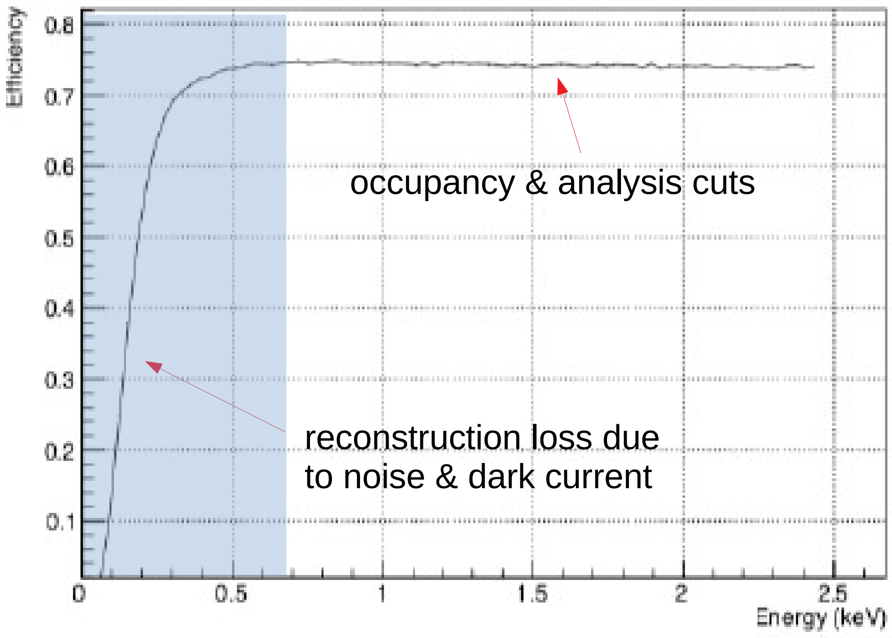


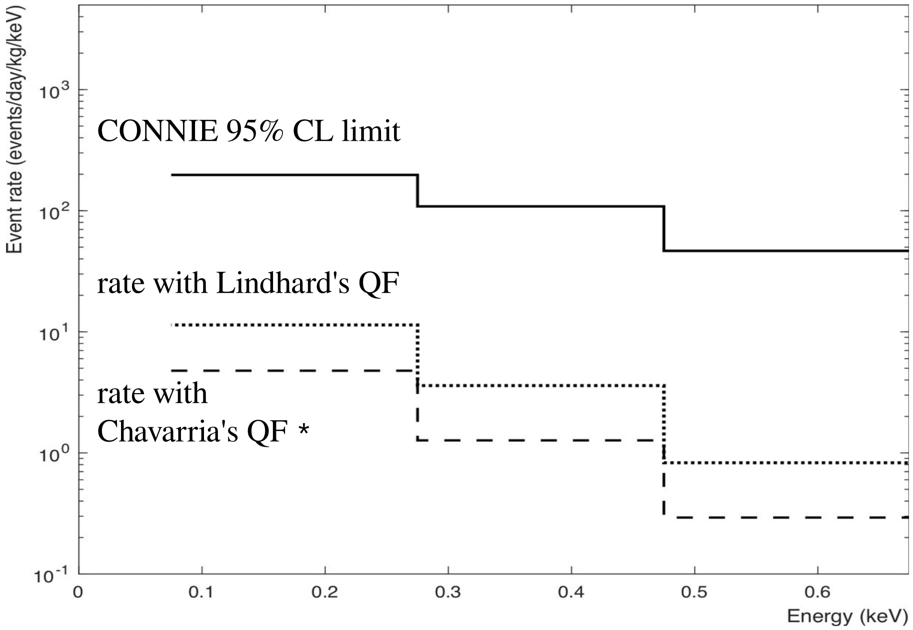
Results 2016–2018

acceptance & efficiency calculation

- simulate low-energy neutrino events in each Reactor OFF image and process the full event reconstruction analysis

- uncertain quenching factor (QF)
- place limit at ×41 the SM expected rate





Phys. Rev. D 100 (2019) 092005

* A. Chavarría et al. PRD 94 (2016) 082007

Constraints on BSM physics

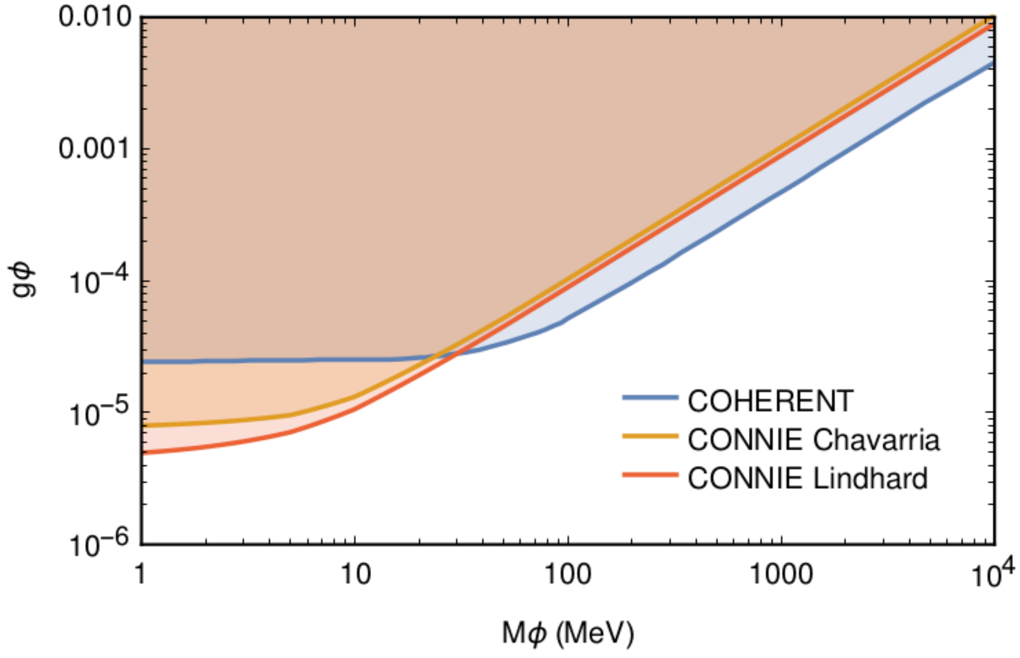
- Event rates in the lowest-energy bin yield limits on non-standard neutrino interactions:

simplified light **scalar** (φ) mediator model

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

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

- we obtain the most stringent limits for low mediator masses M_φ < 30 MeV
- first competitive BSM constraint from CEνNS in reactors!



JHEP 04 (2020), 054

Constraints on BSM physics

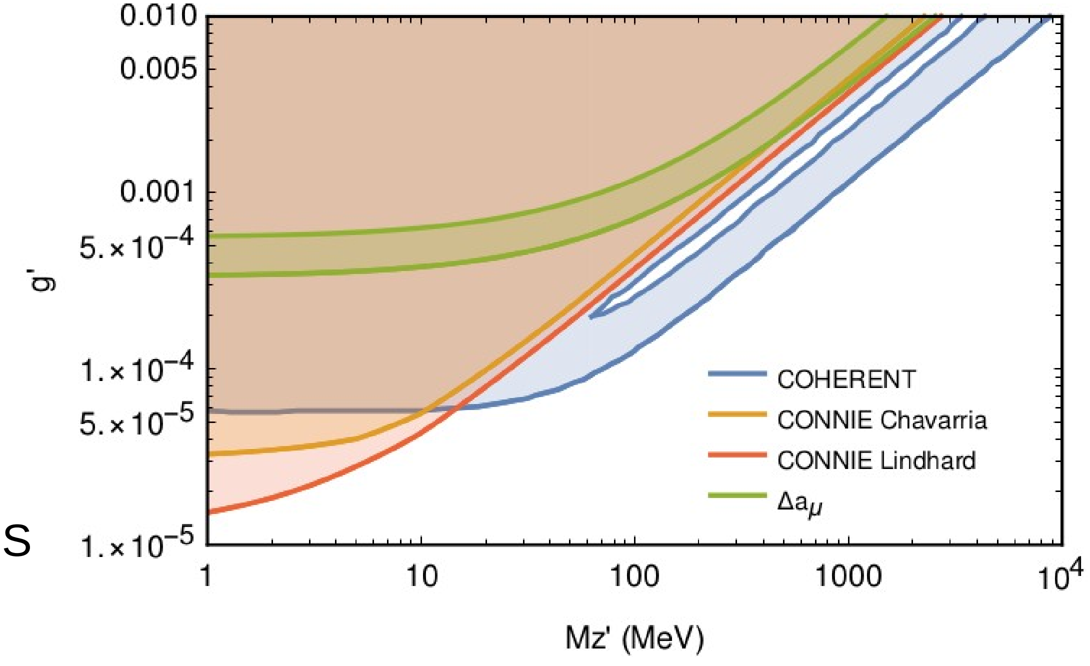
- Event rates in the lowest-energy bin yield limits on non-standard neutrino interactions:

simplified light **vector** (Z') mediator model

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

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

- we obtain the most stringent limits for low mediator masses $M_{Z'}$ < 10 MeV
- first competitive BSM constraint from CEvNS in reactors!



JHEP 04 (2020), 054

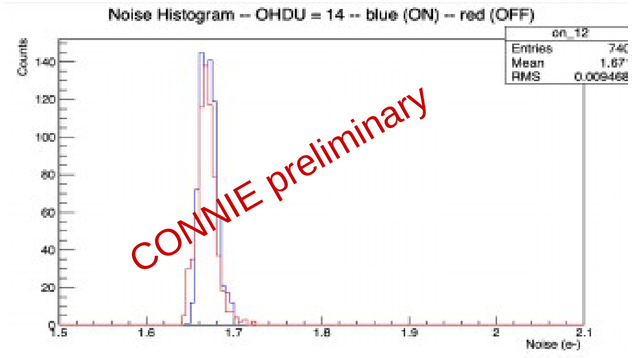
CONNIE 2019 data

1x5 rebinning of the data acquisition (higher acceptance for E > 100 eV)

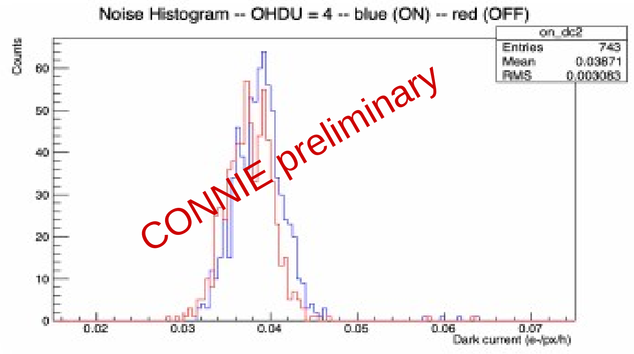
- decrease exposure time (from 3h to 1h)
- recalibration of the depth diffusion
- multiple cross-checks

blind analysis

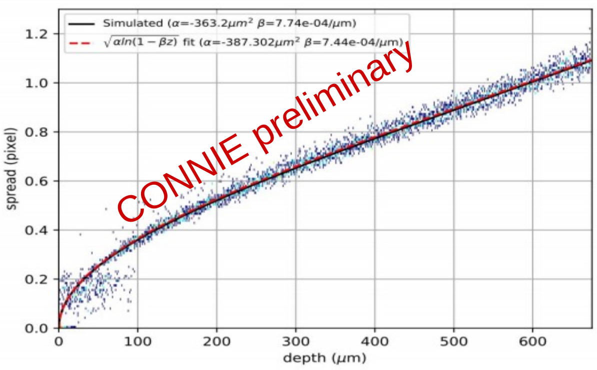
- freeze analysis parameters with reactor OFF data
- stability check-ups with mid to high energy reactor ON data
- unblind the reactor ON 2019 data



- stability of readout noise per each image



- stability of dark current per each image



- depth calibration stability using muons

CONNIE 2019 data

Analysis improvements

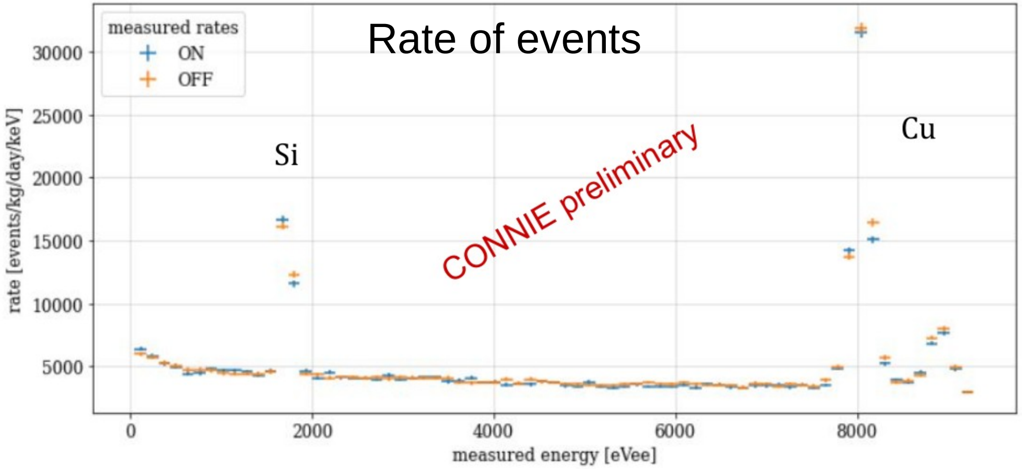
- rebinning 1x5
- Exposures:

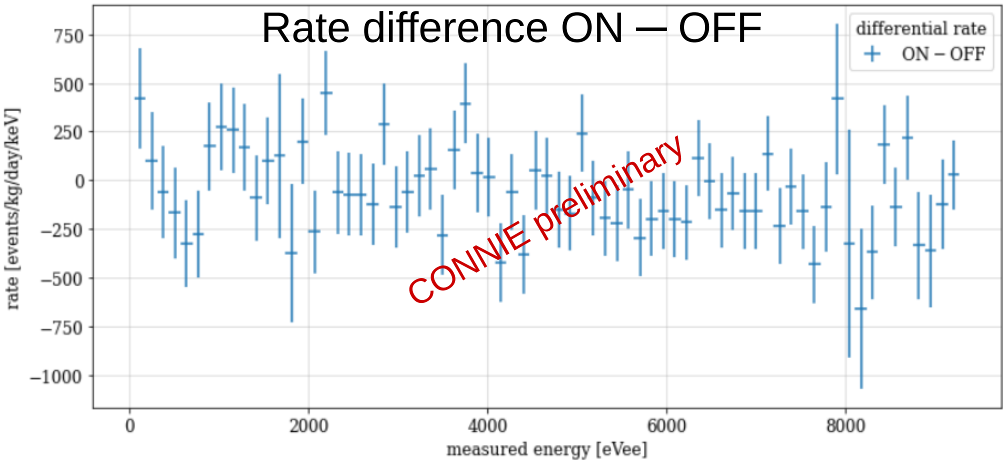
  reactor OFF 1.35 kg·day

  reactor ON 1.52 kg·day

Reactor OFF

- understand and control the low-E background
- improvement of event selection

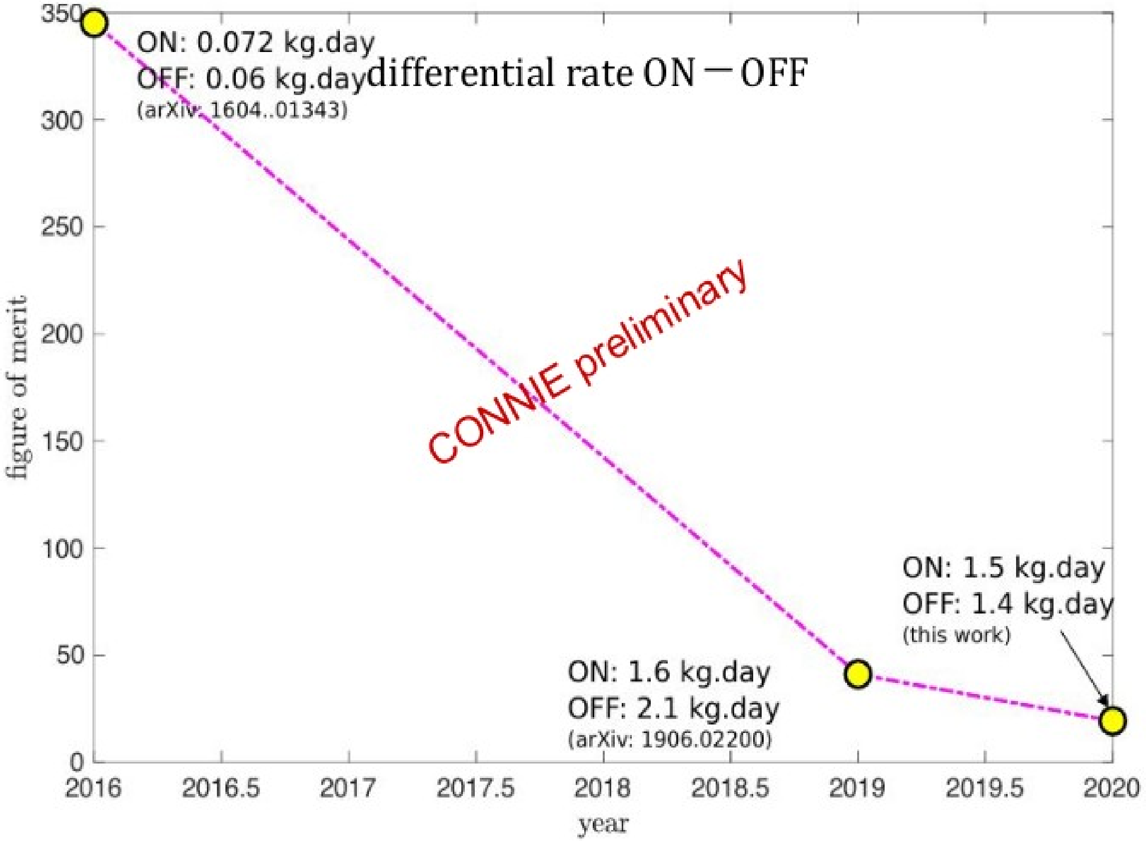




CONNIE 2019 data

rebinning 1x5

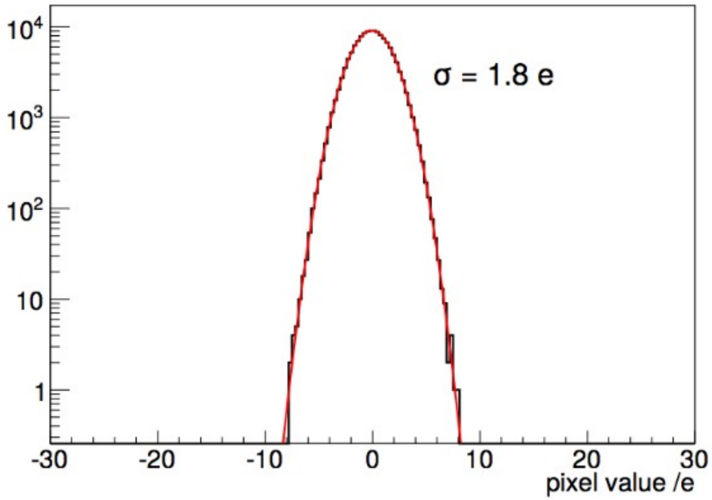
- increased acceptance for E>100 eV
- 2x increase in the neutrino rate
- improved sensitivity



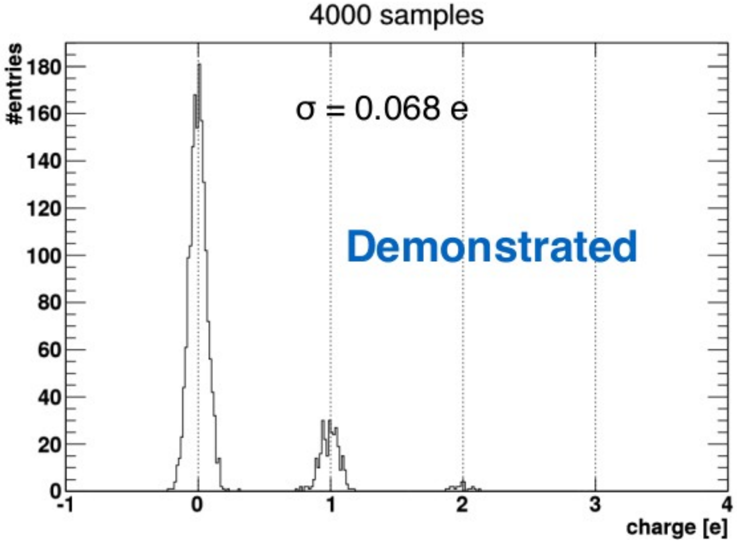
Perspectives: Skipper CCDs

- allows multiple sampling of each pixel during data acquisition
- reduces readout noise with number of samplings $\sigma \propto \sigma_{1\ sample} / \sqrt{N}$
- 100% acceptance – **detect single electrons**
- promising for neutrino and dark matter detection

standard CCD readout noise



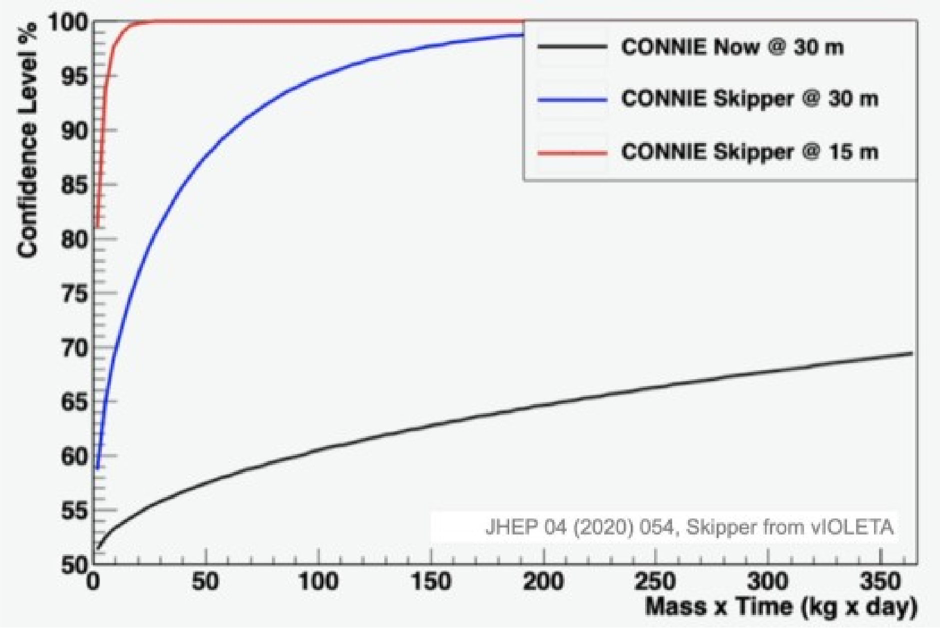
skipper CCD readout noise



J. Tiffenberg et al. Phys.Rev.Lett. 119 (2017)

Perspectives: Skipper CCDs

- CONNIE-like detector with Skipper CCDs
  - expected increase of up to 6x in neutrino rate
  - threshold of ~ 7 eV
  - better control the background
- Understand skipper performance at sea-level within CONNIE environment will be crucial.



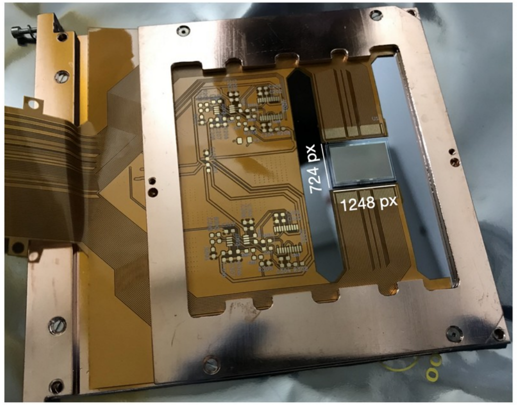
2021 pre-Upgrade: Skipper CCDs @ Reactor

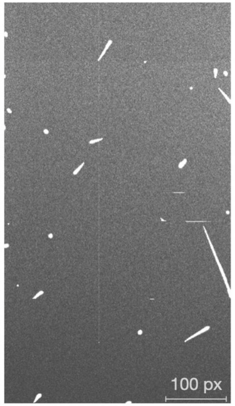
pre-Upgrade

- 28 June – 1 July, 2021
- New Electronics (**L**ow **T**hreshold **A**cquisition replaces *Monsoon* system)
- New Vacuum Interface Board (ViB)
- Installed 2 Skipper (1248×724 pix^2) + 2 Std CCDs

Goals (towards next generation experiment):

- Study Skipper-CCD performance and bkgd's
- Test LTA electronics





LTA electronics

2021 pre-Upgrade: Skipper CCDs @ Reactor

Image with 1 sample

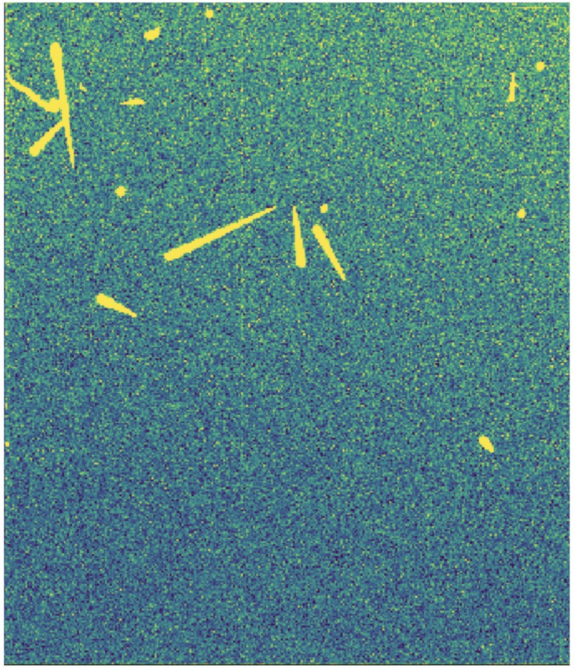
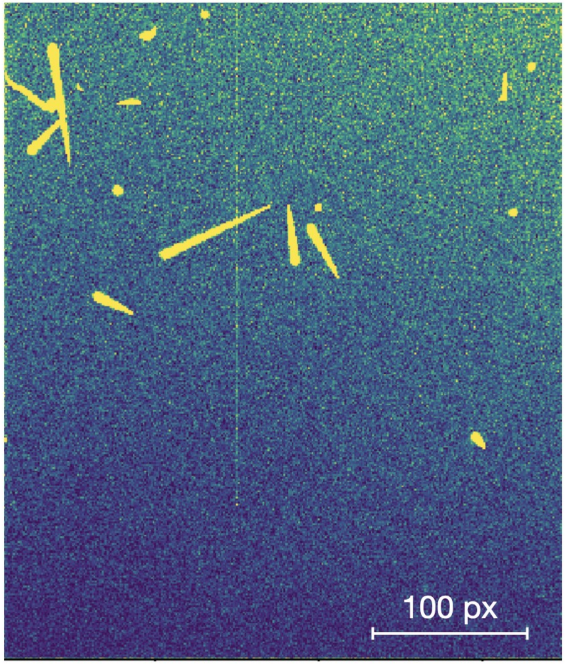
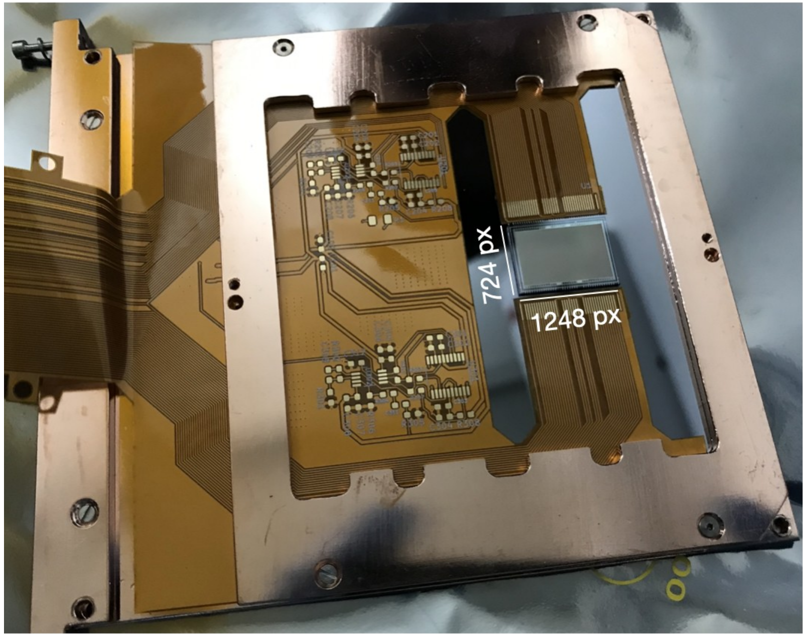


Image with 400 samples





First images from CONNIE Skipper CCDs

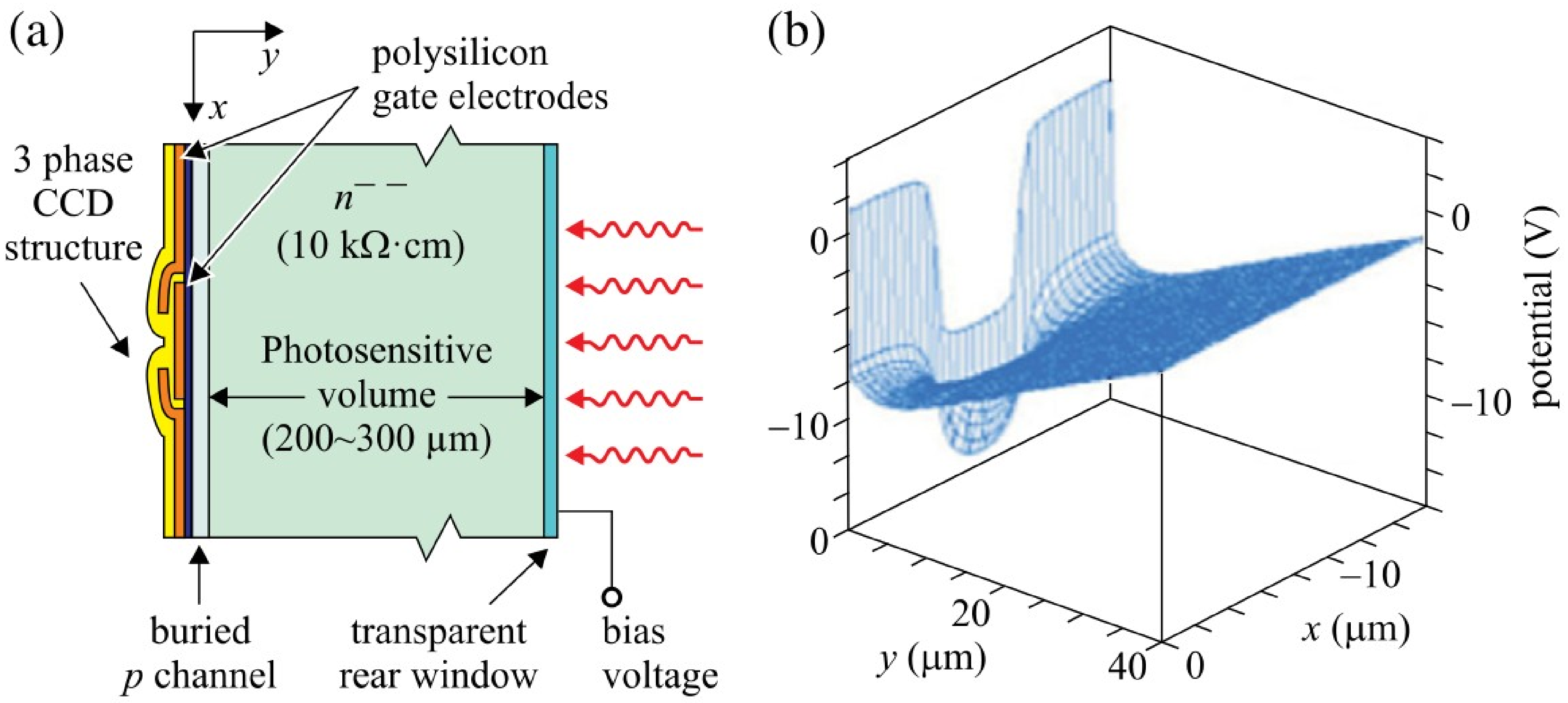
Summary

- CCDs are a promising technology to observe CEνNS at low energies
- The 2016–2018 data allowed us to place the most stringent limits on BSM low mediator masses (M < 10 MeV)
- Achieved improved sensitivity with 2019 data
- **Paper in preparation**
- **New 2020 data analysis in progress**
- Skipper CCDs greatly reduce the noise and allow better controlling of the background rate.
- June 2021 Upgrade: installed 2 Skipper CCDs at CONNIE container. Will pave the way for next generation CCD neutrino experiment.

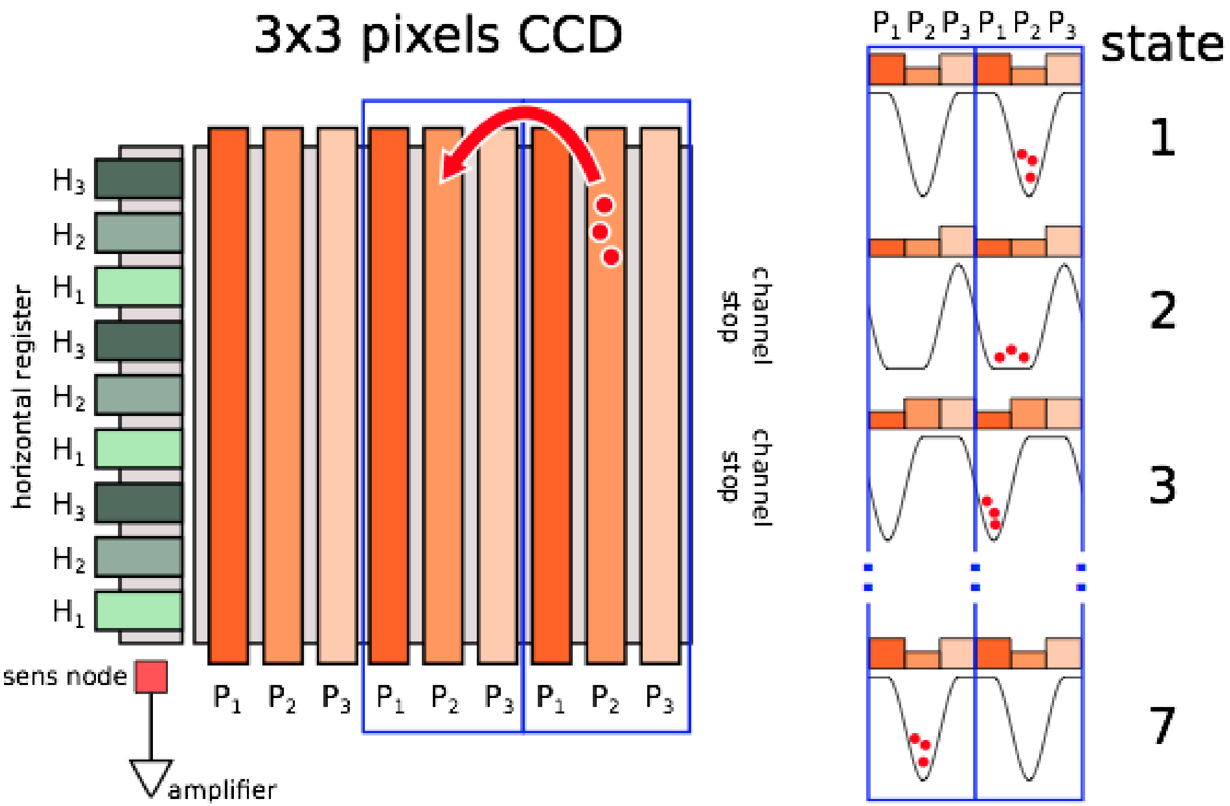
Thank you for your attention!

BACKUPS

CCD pixel


(a)
y
x
polysilicon
gate electrodes
3 phase
CCD
structure
n⁻ ⁻
(10 kΩ·cm)
Photosensitive
volume
(200~300 μm)
buried
p channel
transparent
rear window
bias
voltage
(b)
0
−10
0
20
40
y (μm)
0
−10
x (μm)
0
−10
potential (V)

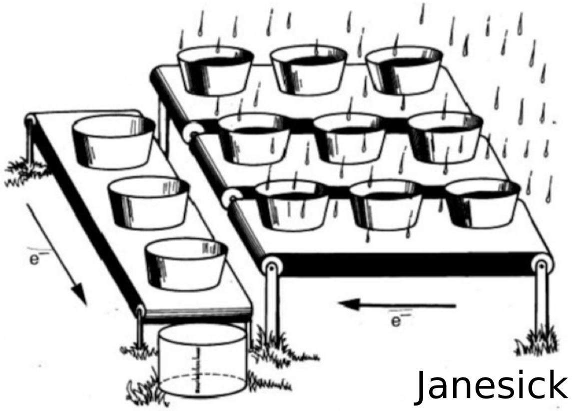
CCD readout



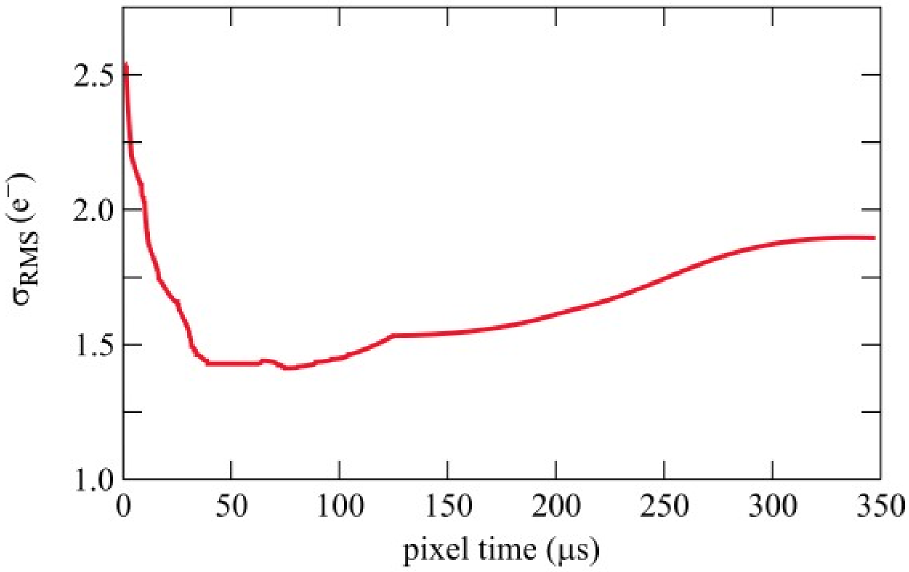
Capacitance of the system is set by the sens node: C = 0.05 pF ⇒ 3μV/e

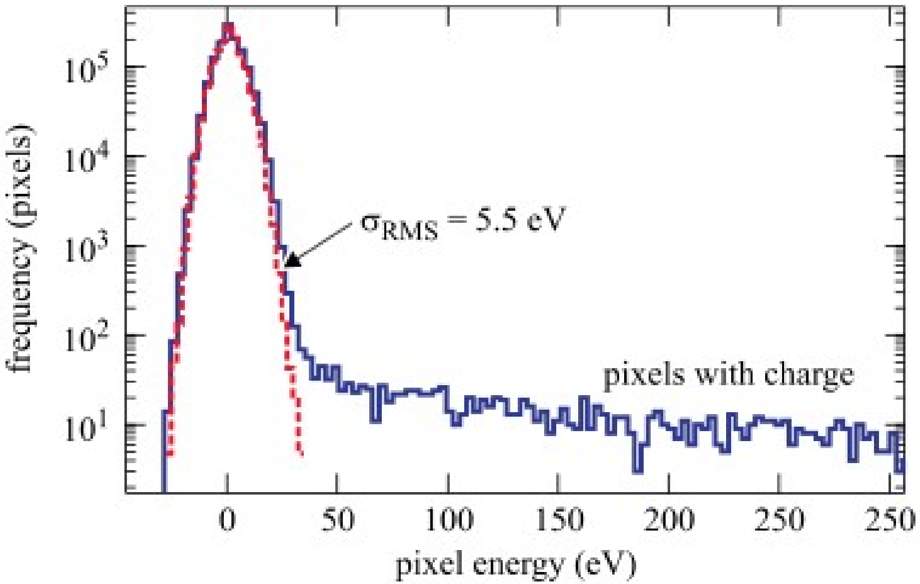
CCD readout noise

- Added to each pixel by the output amplifier during the charge readout.
- Gaussian distribution with σ_{RMS} that depends on the pixel readout time.
- Pixel time = 30 μs ⇒ σ_{RMS} = 1.5 e- ≡ 5.5 eV of ionization energy



Janesick





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Engineering run, 2015

CCD Detector

CCD Detectors in copper box