School on DM & Nu 2018

Coherent Neutrinos

(with a bias towards the CONNIE experiment)

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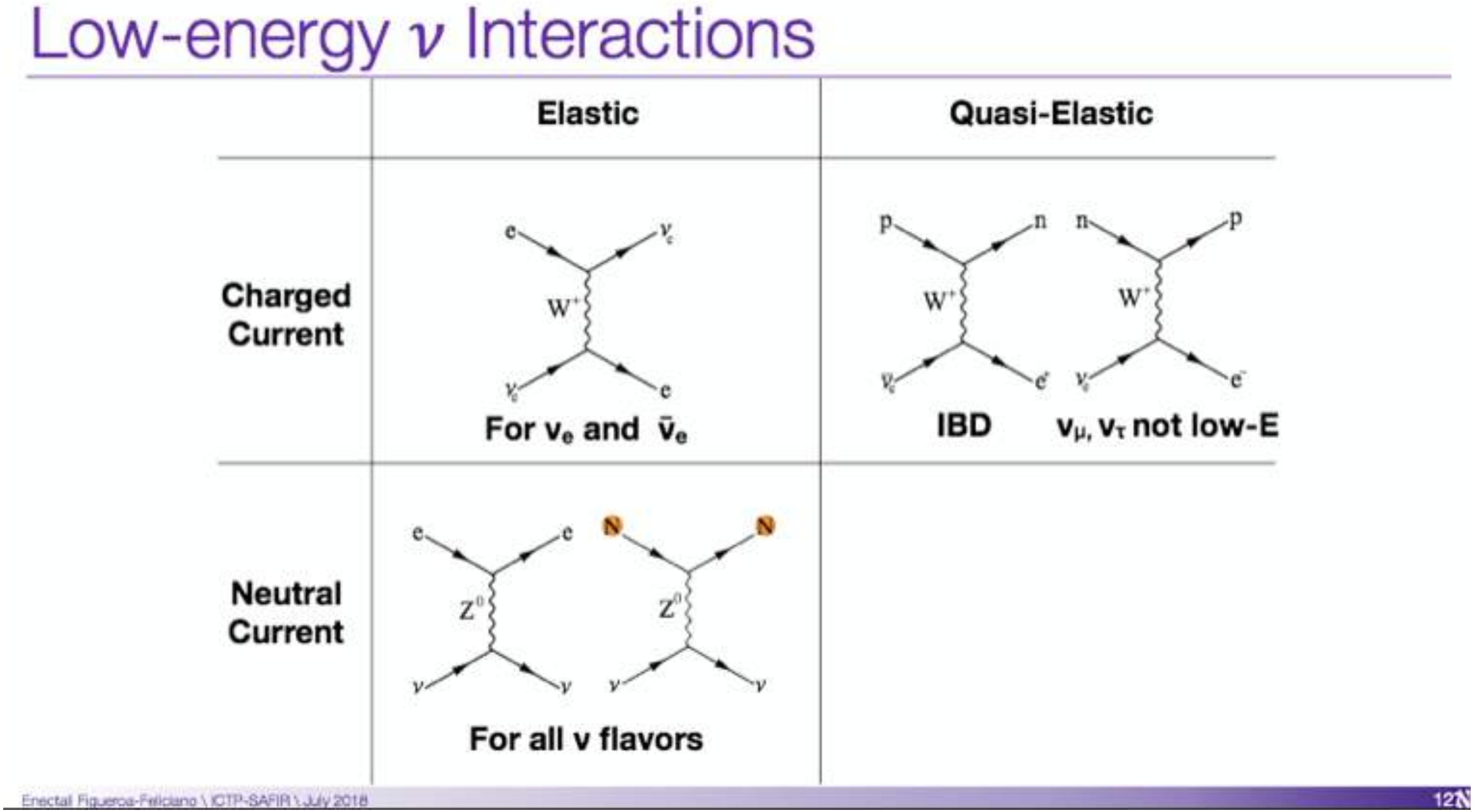
#VoltaMCTI

Neutrino interactions



Low-energy ν Interactions

	Elastic	Quasi-Elastic
Charged Current	For ν_e and $\bar{\nu}_e$	IBD ν_μ, ν_τ not low-E
Neutral Current	For all ν flavors	

Enectali Figueroa-Feliciano \ ICTP-SAFIR \ July 2018

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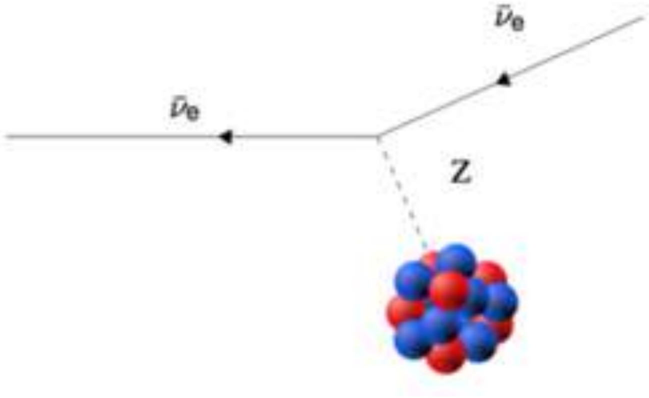
From Enectalí Figueroa-Feliciano

Coherent elastic neutrino-nucleus scattering (CEvNS)

- 1974 neutral curent neutrino interaction
- for neutrino energies below 50 MeV

In the coherent neutrino-nucleus neutral-current interaction, a neutrino of any flavor scatters off a nucleus transferring some energy in the form of a nuclear recoil.



- cross section

$$\frac{d\sigma}{d(\cos\theta)} = \frac{G^2}{8\pi}\left[Z(4\sin^2\theta_W - 1) + N\right]^2 E_\nu^2(1+\cos\theta)$$

G = Fermi constant

Z = atomic number of the nucleus

N = neutron number of the nucleus

Eν = neutrino energy

θ = scattering angle

θ_W = weak mixing angle

Coherent elastic neutrino-nucleus scattering (CEvNS)

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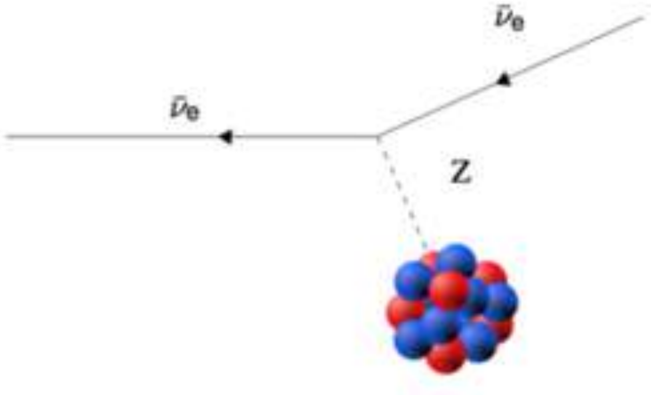


- cross section

$$\frac{d\sigma}{d(\cos\theta)} = \frac{G^2}{8\pi}\left[Z(4\sin^2\theta_W - 1) + N\right]^2 E_\nu^2(1+\cos\theta)$$

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

$Q^2 = 2E_\nu^2(1-\cos\theta)$

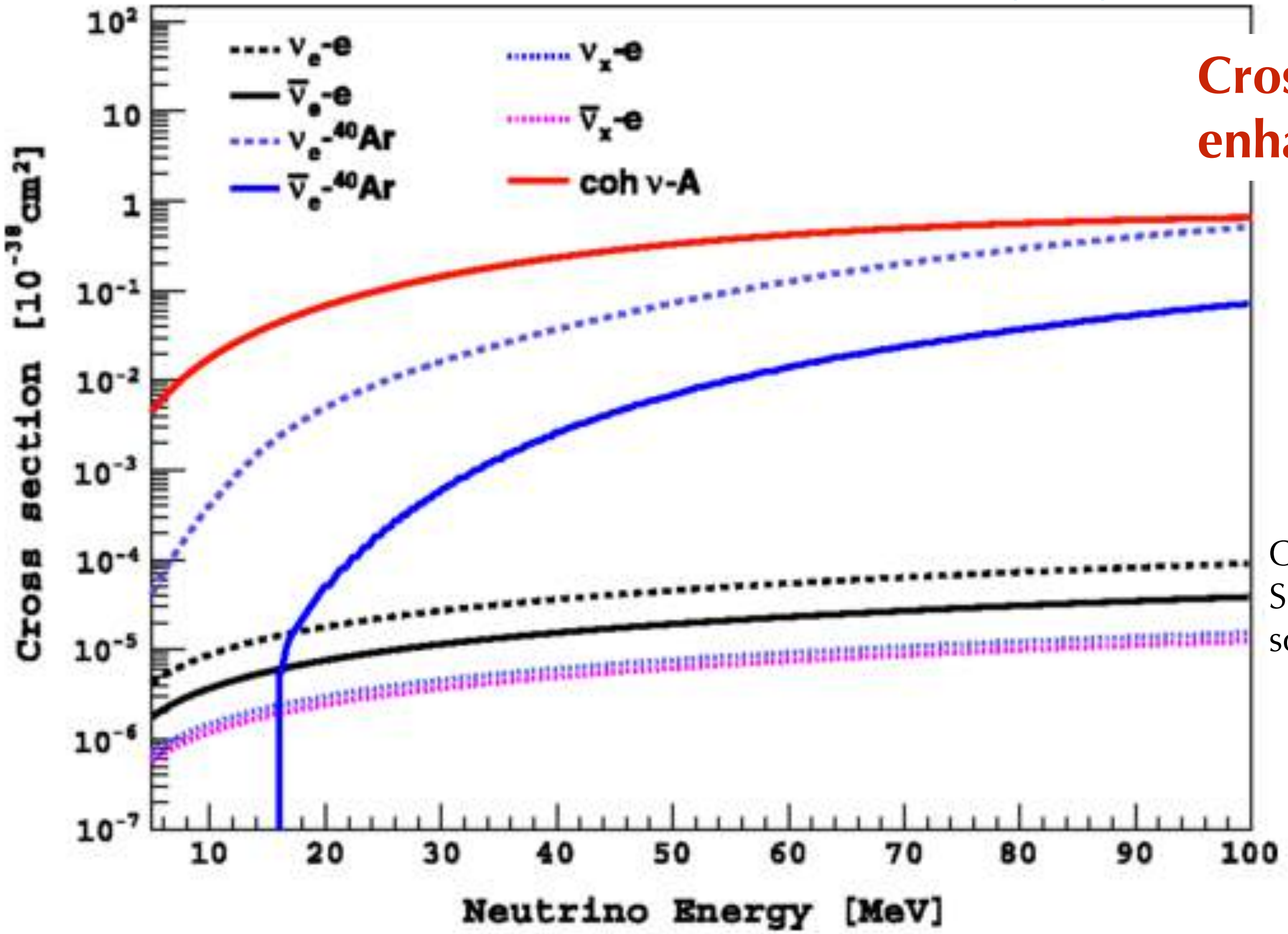
$$\sigma = \frac{G^2}{4\pi}\boxed{N^2}E_\nu^2$$

Cross section increases with N² !!

Q = three momentum transfer vector

Coherent elastic neutrino-nucleus scattering (CEvNS)

PRD 89 (2014) 072004



Cross section enhancement

Cross section used by Super-Kamiokande for solar neutrinos

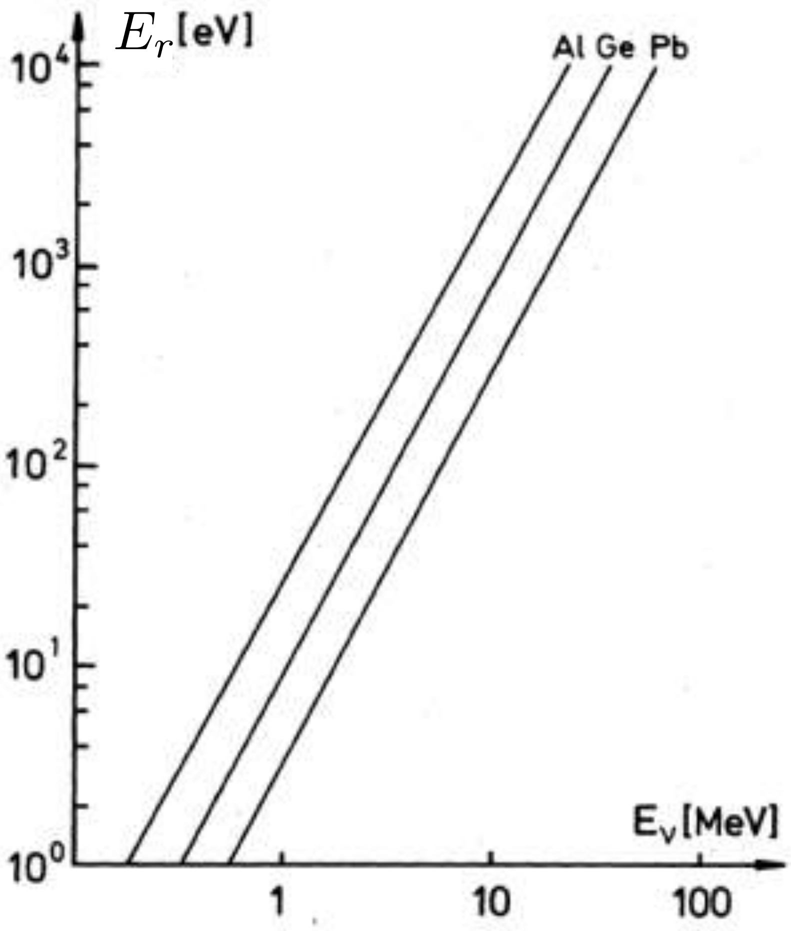
Coherent elastic neutrino-nucleus scattering (CEvNS)

- The high cross section for neutrino interactions is counter balanced by the tiny recoil energies ≲ keV

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

$$E_\nu \lesssim 50 \text{ MeV}$$

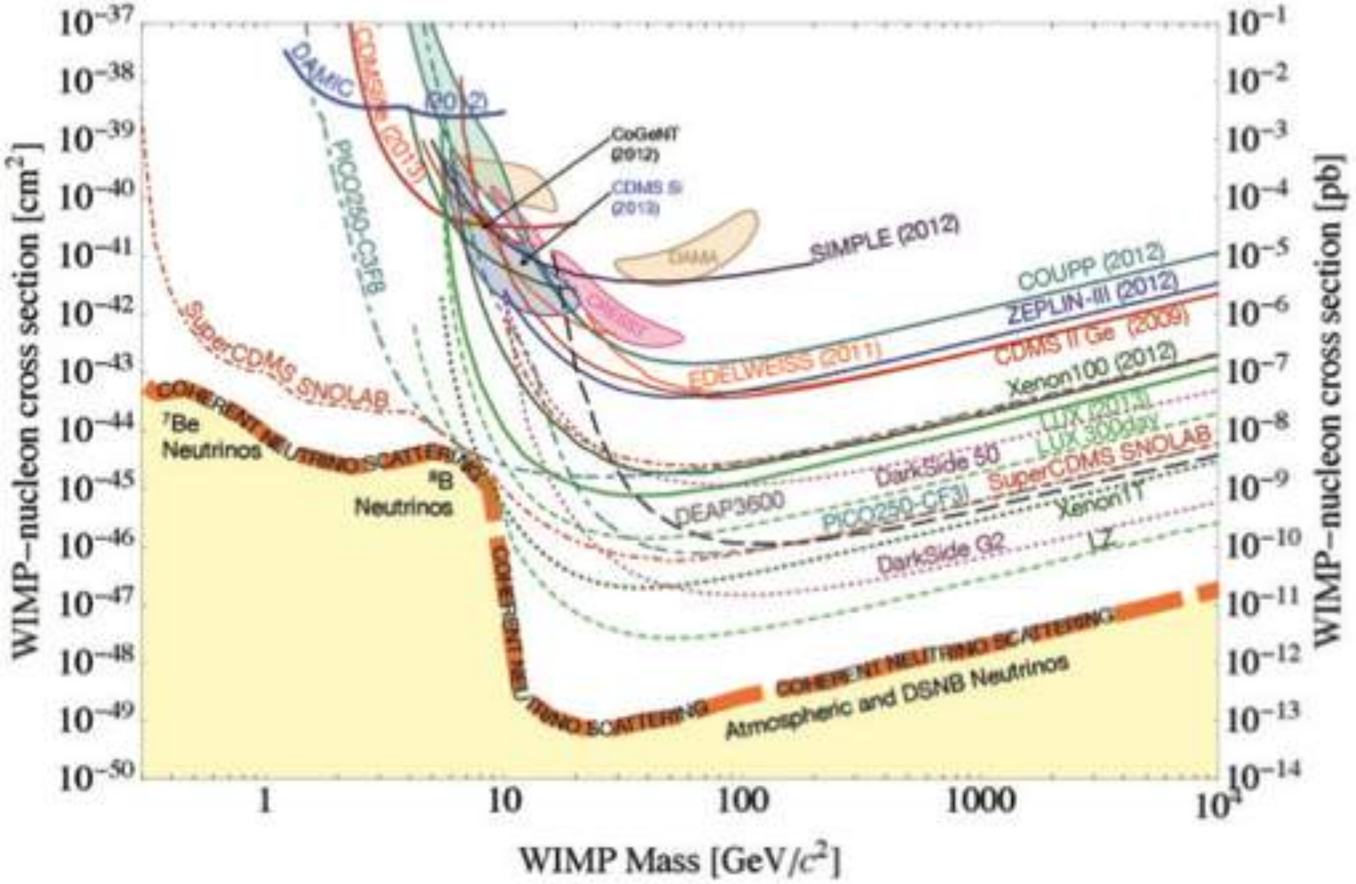
- Very difficult to measure in the past
- Now possible thanks to the development of low background detectors (DM)
- Recently measured by the COHERENT collaboration (Science 03 Aug 2017)



PRD 30 (1984) 2295

Why CEvNS is important?

- MeV-neutrino physics has great relevance for energy transport in supernovae
- Irreducible background for WIMP detection



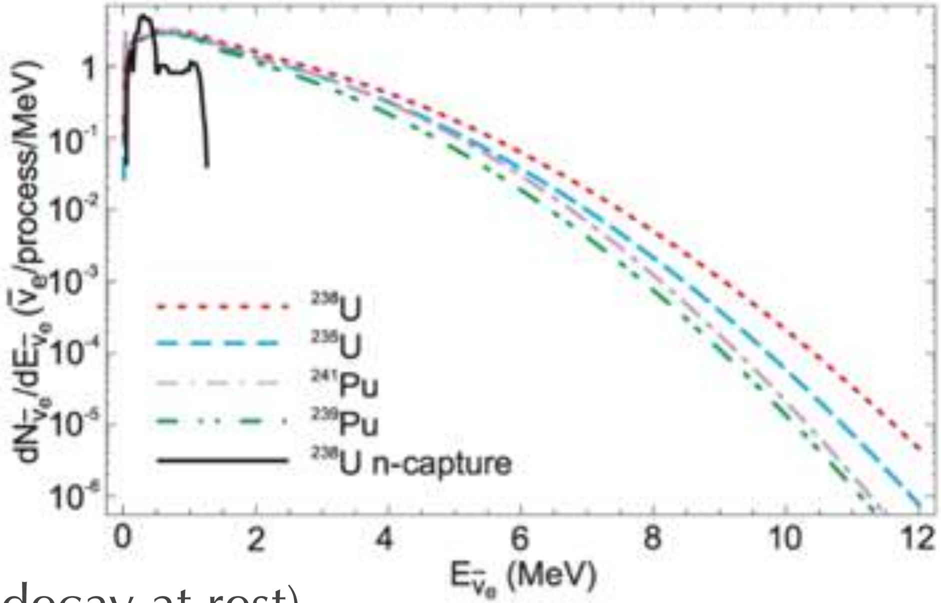
- New physics beyond Standard Model
- New tool for neutrino experiments (very short baseline oscillation experiments – low energy)
- Monitor nuclear reactors through their emitted neutrinos

Two ways to get high flux low energy neutrinos

- Neutrinos from a Nuclear Reactor
  - Very large flux, close to core
  - Low energy recoils, harder to see
  - Deal with background by shielding
  - A window to very low energy neutrino sector

Exp: MINER, CONNIE

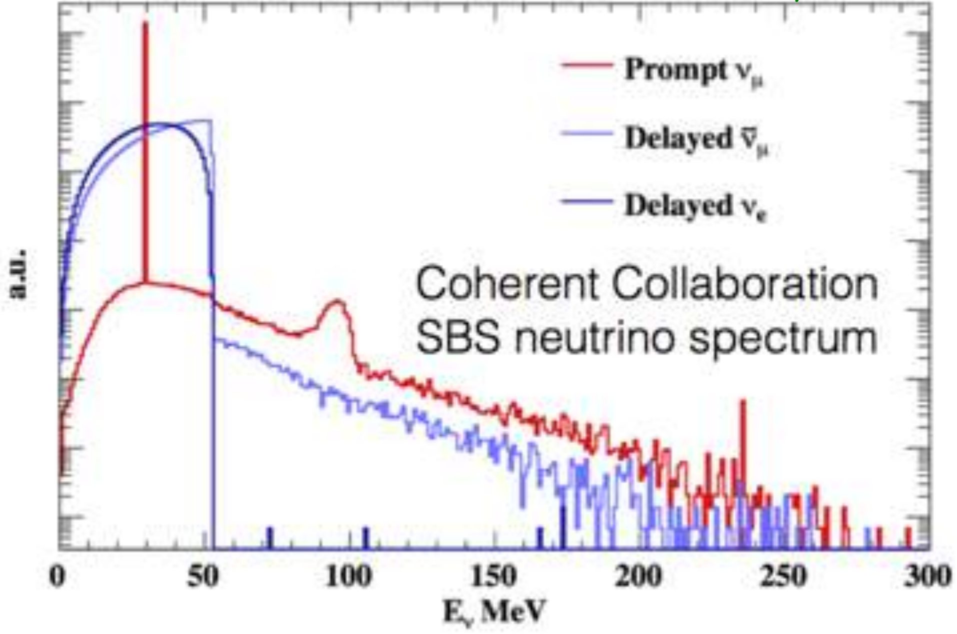
$\bar{\nu}_e$



- Neutrinos produced by stopped pions (decay at rest).
  - Higher energy recoils, easier to see
  - Pulsed to control background
  - Has to deal with beam associated background

Exp: **COHERENT**

ν_μ $\bar{\nu}_\mu$ ν_e

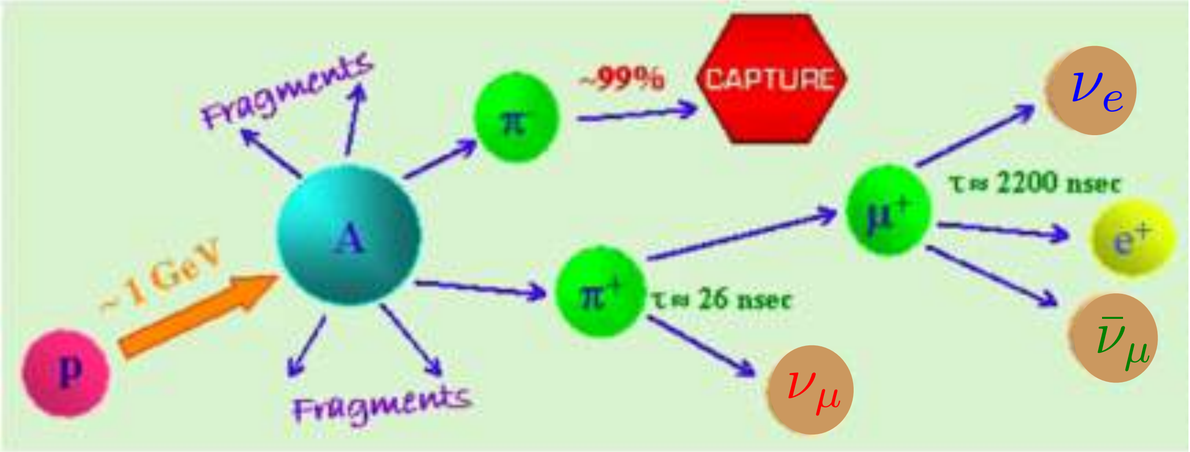


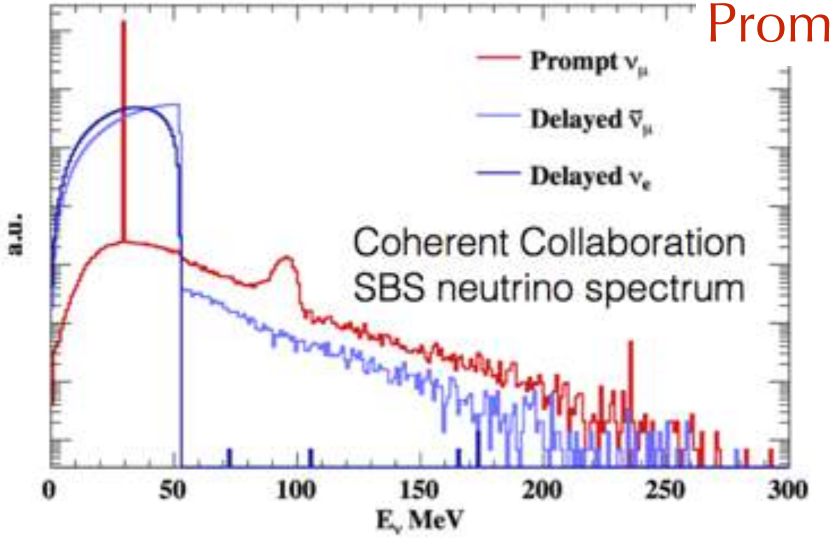
The COHERENT experiment

- Neutrino coming from a pulsed proton beam on a mercury target at the Oak Ridge National Laboratory (ORNL) Spallation Neutron Source

- Proton collisions with mercury create neutrons and neutrinos (4.3×10^{7} $cm^{-2}s^{-1}$ per flavor @ 20 m)

The COHERENT experiment





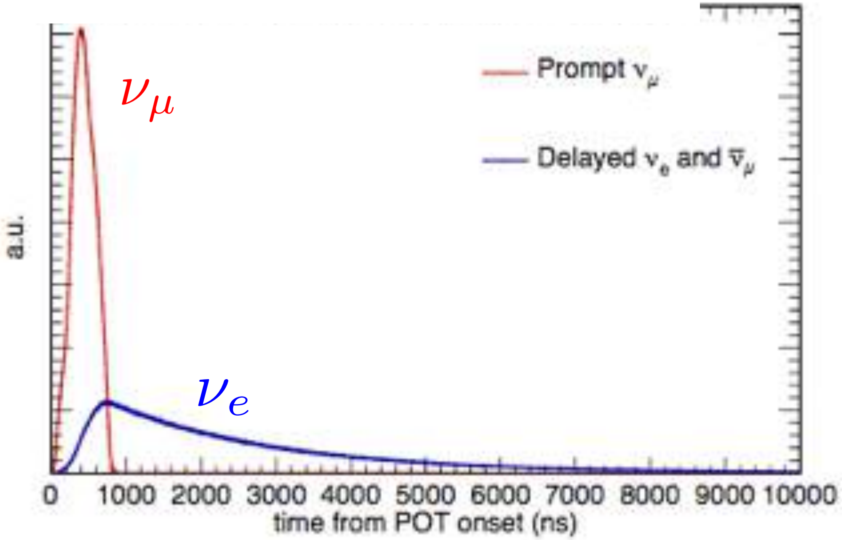
Prompt monochromatic 29.2 MeV

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\downarrow$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

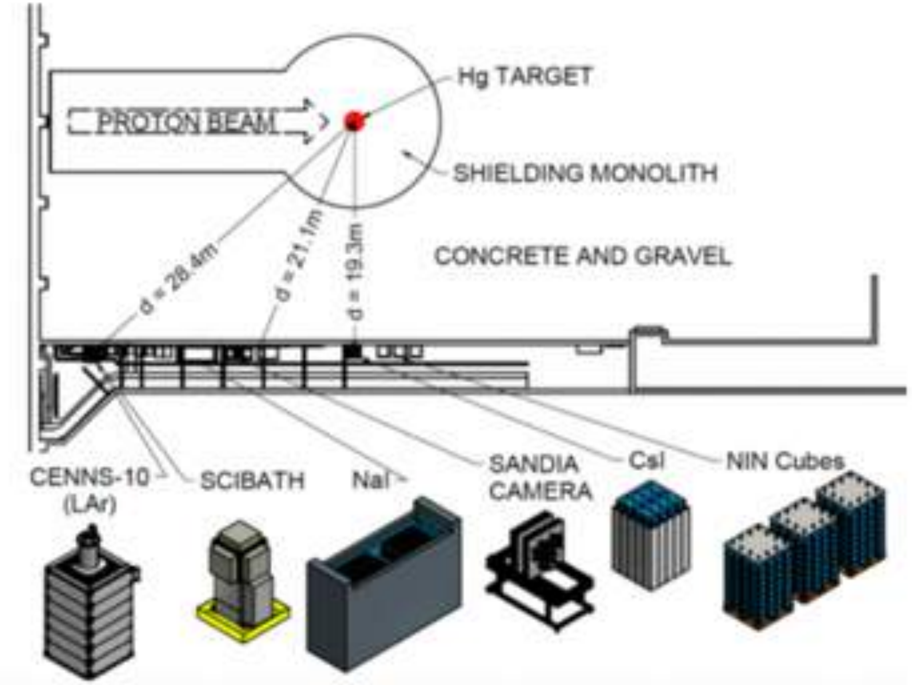
- Pulsing allows natural background rejection by a factor ~ 10^4
- Proton collisions with mercury create neutrons and neutrinos (4.3×10^7 cm^{-2}s^{-1} per flavor @ 20 m)



10.5281/zenodo.1228631

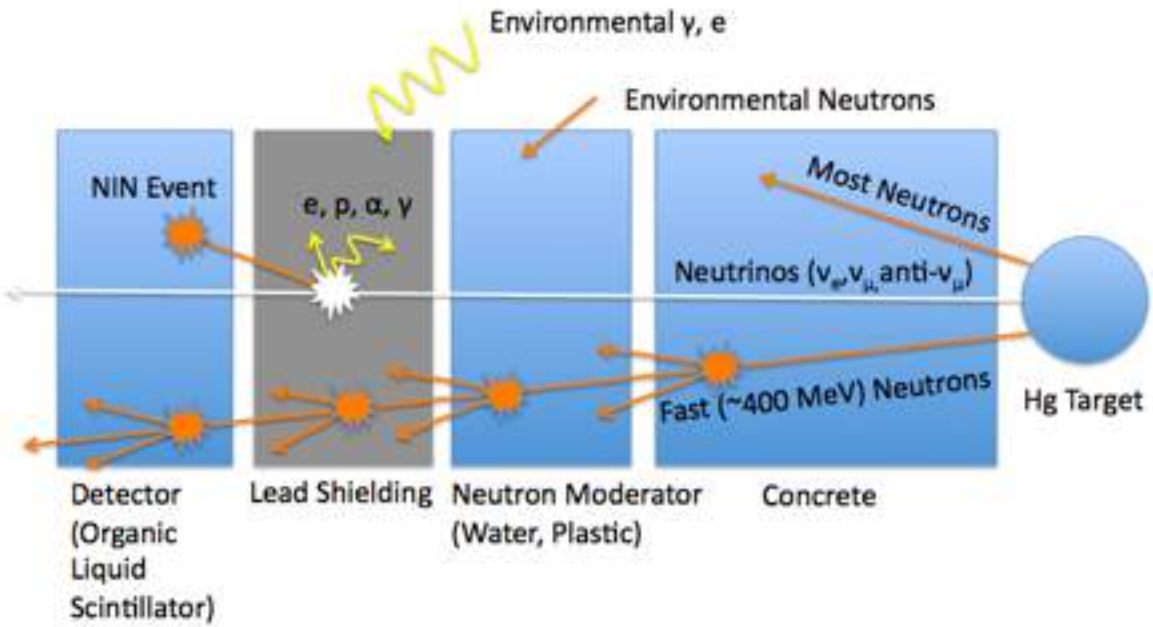
The COHERENT experiment

- Several low threshold detectors to explore the N^2 dependence in CEvNs



Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)	Start data-taking
CsI[Na]	Scintillating crystal	14.6	20	6.5	09/2015
NaI[Tl]	Scintillating crystal	185* /2000	28	13	*high-threshold deployment summer 2016
LAr	Single-phase	22	29	20	12/2016, Upgraded 07/2017
Ge	HPGe PPC	10	22	5	2018

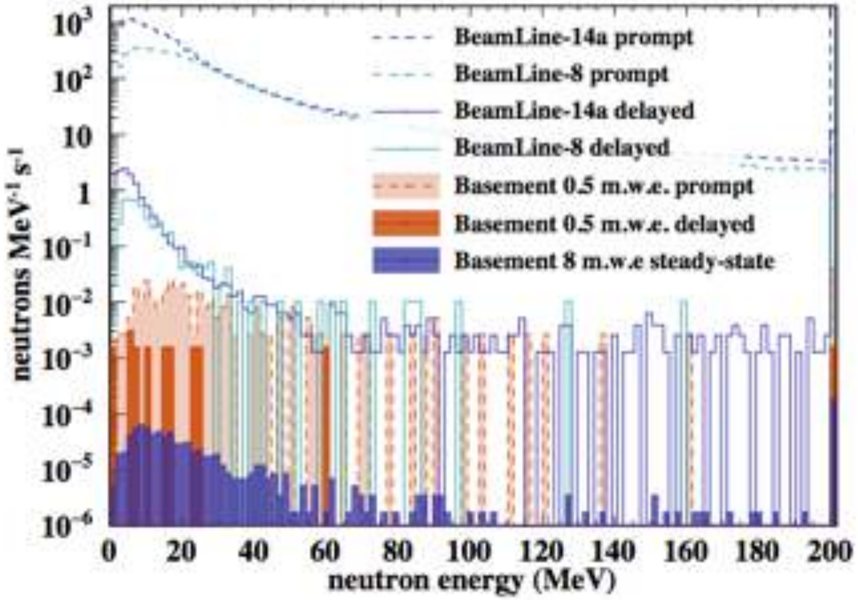
- Detectors (no CEvNs) to monitor:
  - Neutron background
  - Neutrino induced Neutron (NIN)

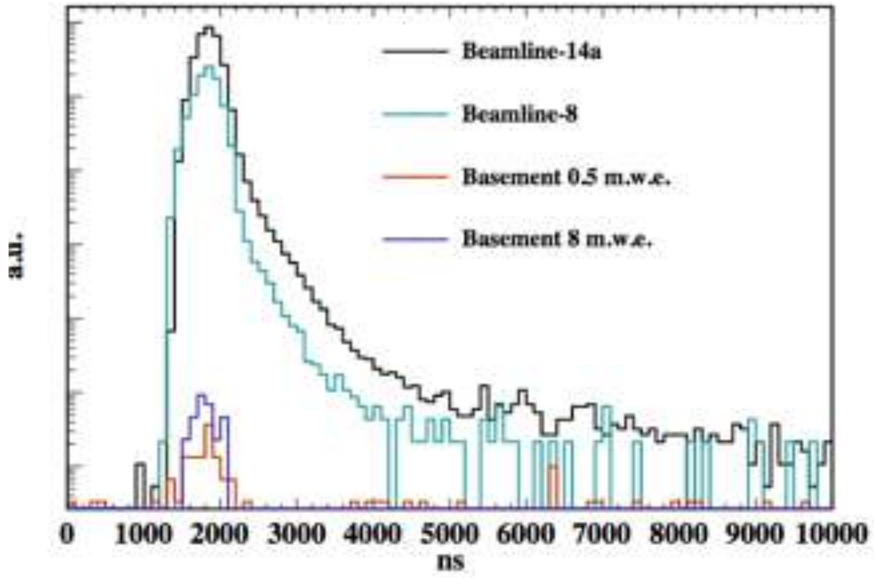


10.5281/zenodo.1228631

The COHERENT experiment

- Neutron background



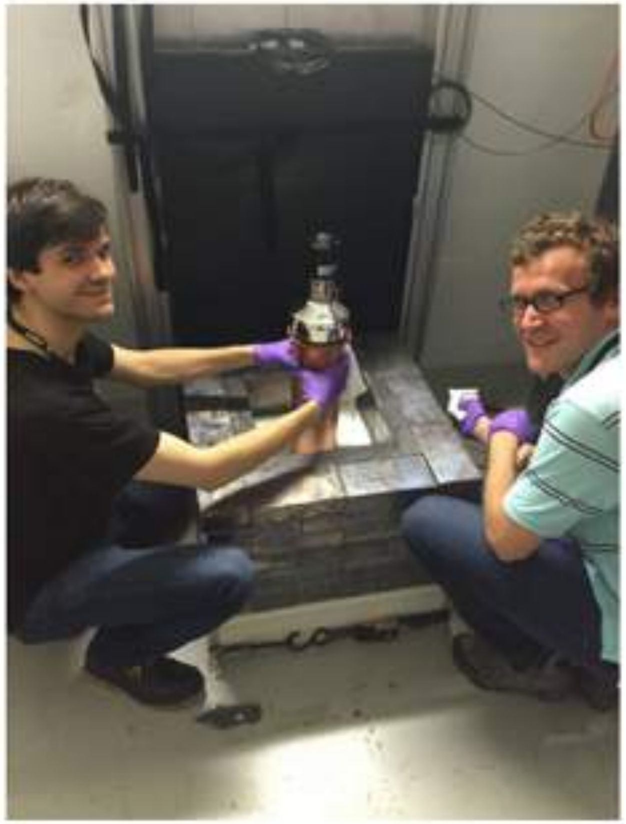


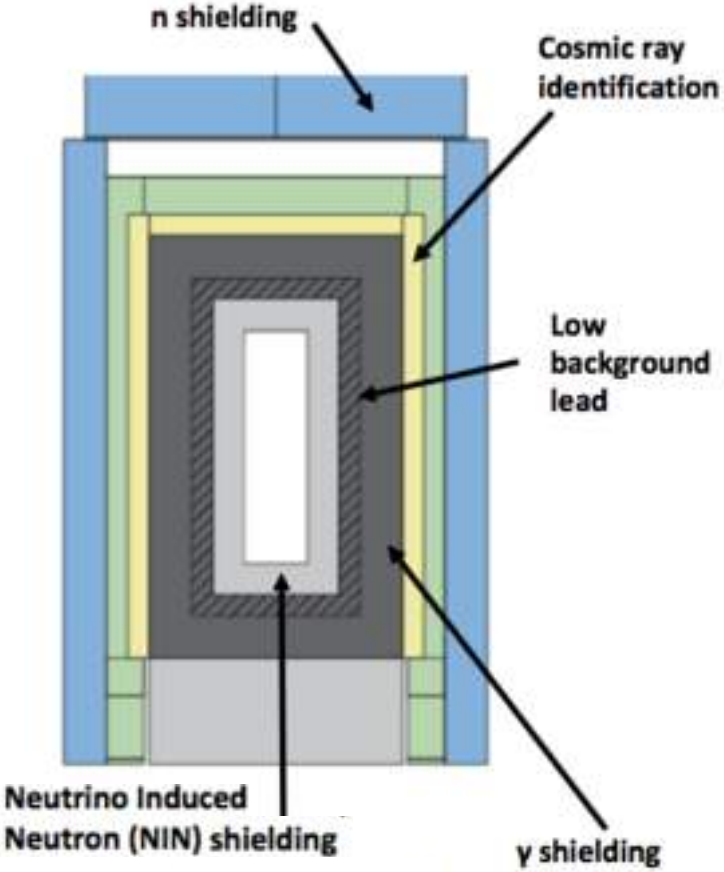
- Background in the basement is ~ 10^4 times lower than in the beam floor
- The SNS provides beam timing signals that allow precise selection of the arrival time of ν_μ protons on target.
- A small background contribution from beam-related neutrons is expected to add to the signal in the "prompt" window (coincident with protons)
- Neutron background is negligible in the "delayed" window, when the $\bar{\nu}_\mu$ and ν_e from muon decay arrive.

10.5281/zenodo.1228631

The COHERENT experiment

- First observation of CEvNS with the CsI[Na]
  - 14.6 kg sodium doped CsI inorganic crystal
  - Mature technology: low thresholds with large neutron numbers (N = 74, 78)
  - Room-temperature detector material
  - High light yield of 64 photons/keVee
  - Assembled at the University of Chicago and installed at the SNS in June 2015

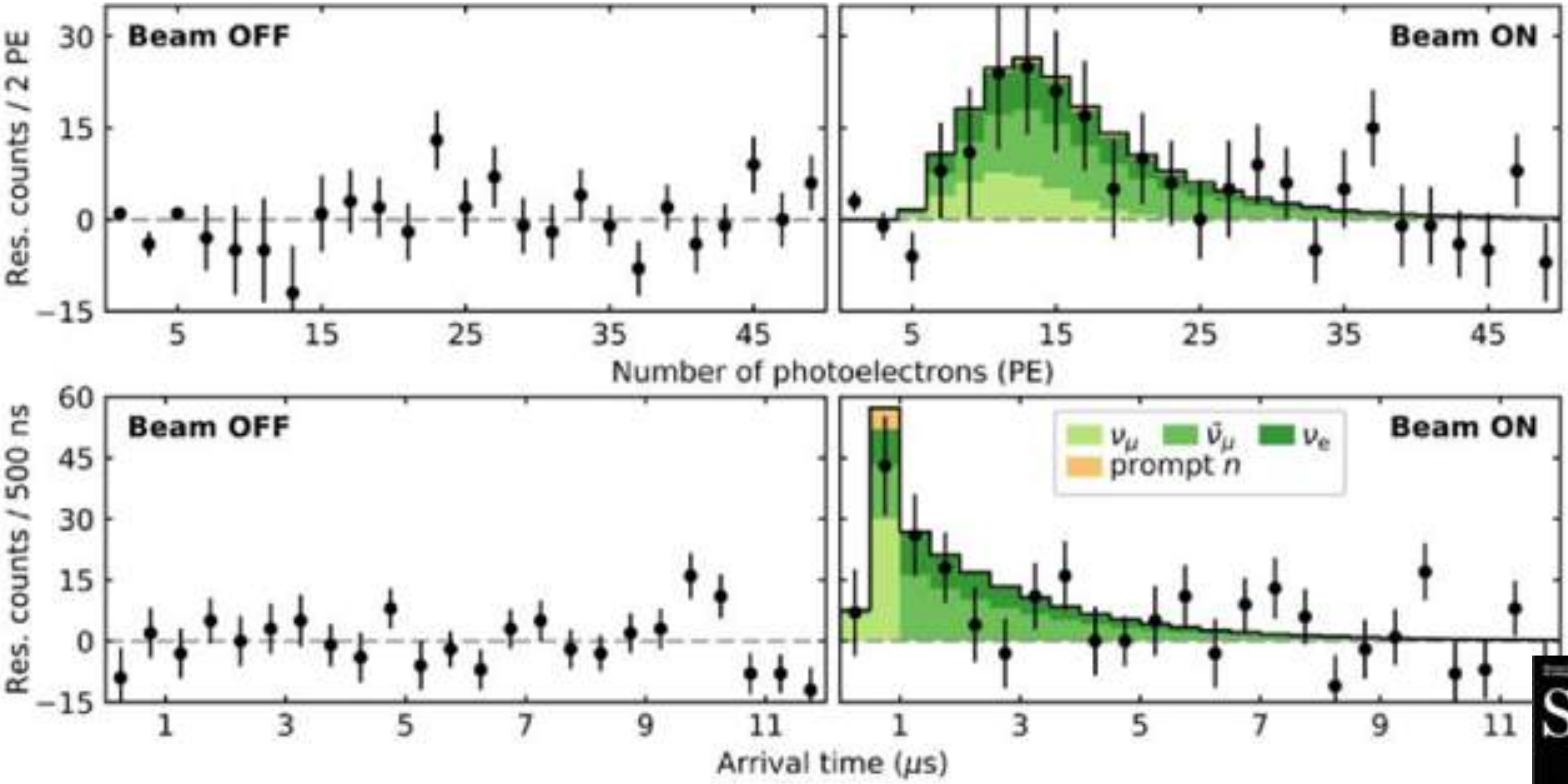




10.5281/zenodo.1228631

The COHERENT experiment

- First observation of CEvNS with the CsI[Na]
  - 153.5 live-days of SNS inactivity (“Beam OFF”)
  - 308.1 live-days of neutrino production (“Beam ON”)



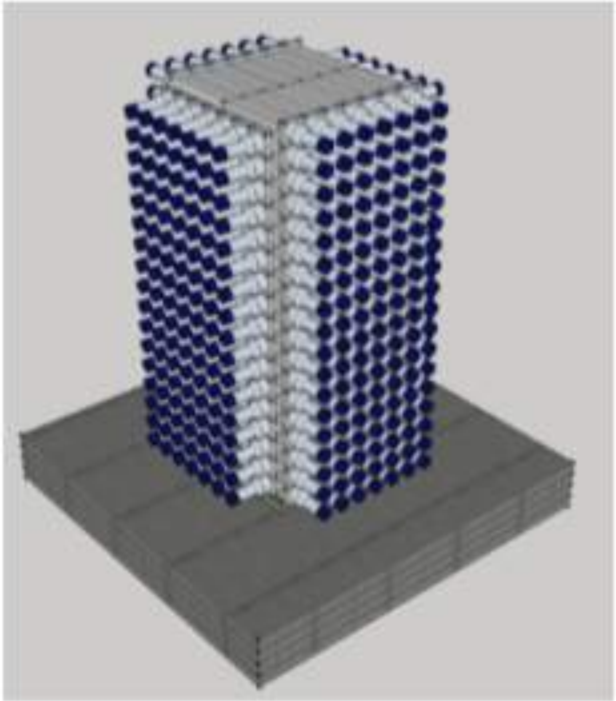
Consistency with the SM is observed at the 1-sigma level
(134 ± 22 events observed, 173 ± 48 predicted)

Presence of CEvNS at a 6.7-sigma level

Science, 3 Aug 2017

The COHERENT experiment

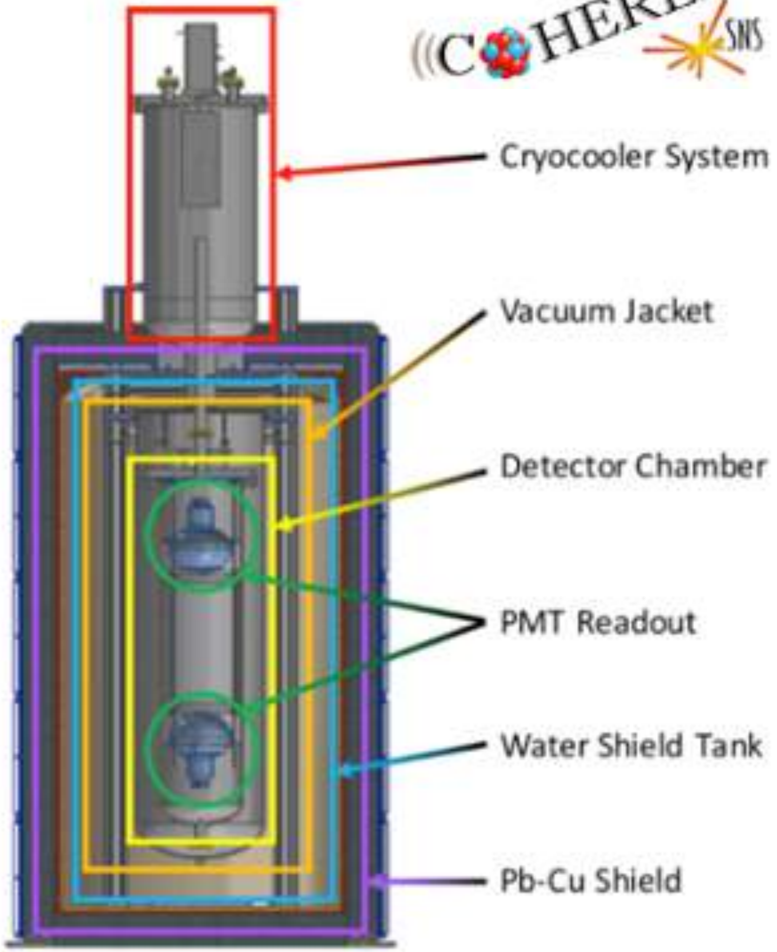
- NaI[Tl]
  - Thallium doped sodium iodide scintillating inorganic crystal (similar to CsI[Na]
  - 185 kg total (24 detectors of 7.7 kg each)
  - Currently not sensitive to CEvNS (Charged current interaction on ^{127}I)



Background characterization
for ton- scale upgrade

The COHERENT experiment

- LAr detector – CENNS-10 detector
  - Wavelength shifter tetraphenyl butadiene (TPB) coated Teflon side walls with 2 PMTs
  - ~ 22 kg fiducial volume
  - 20 keVnr energy threshold
  - Installed at SNS late 2016 and upgraded in June 2017 (better light collection capabilities)
  - Full shielding since August 2017 (Lead 4″, Copper 0.5″, and Water 9″)



Future upgrades:

1-ton detectors are planned

HPGe 10 kg detector (2018)

Two ways to get high flux low energy neutrinos

- Neutrinos from a Nuclear Reactor

  - Very large flux, close to core
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  - A window to very low energy neutrino sector

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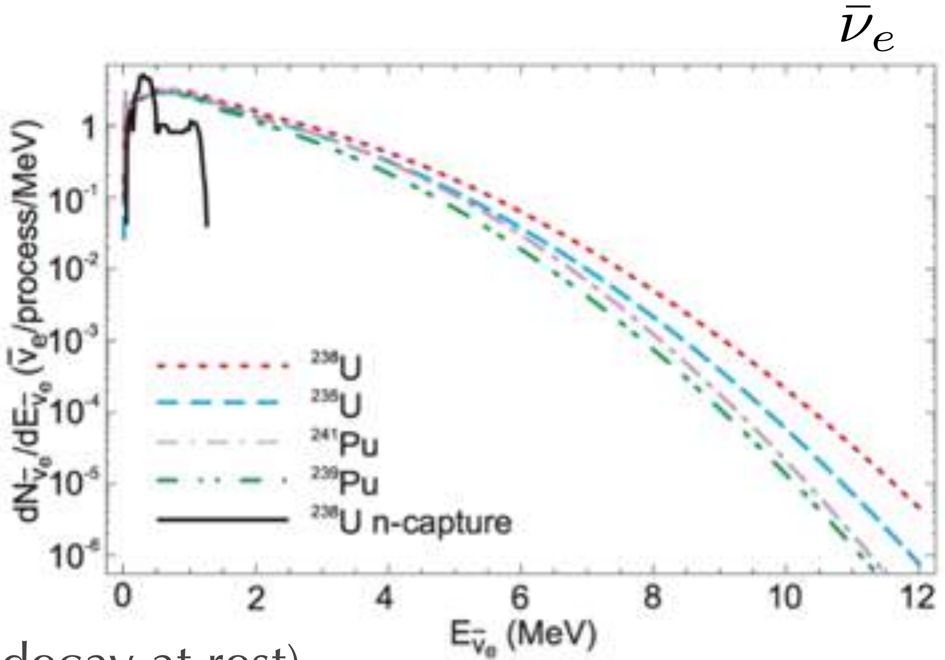

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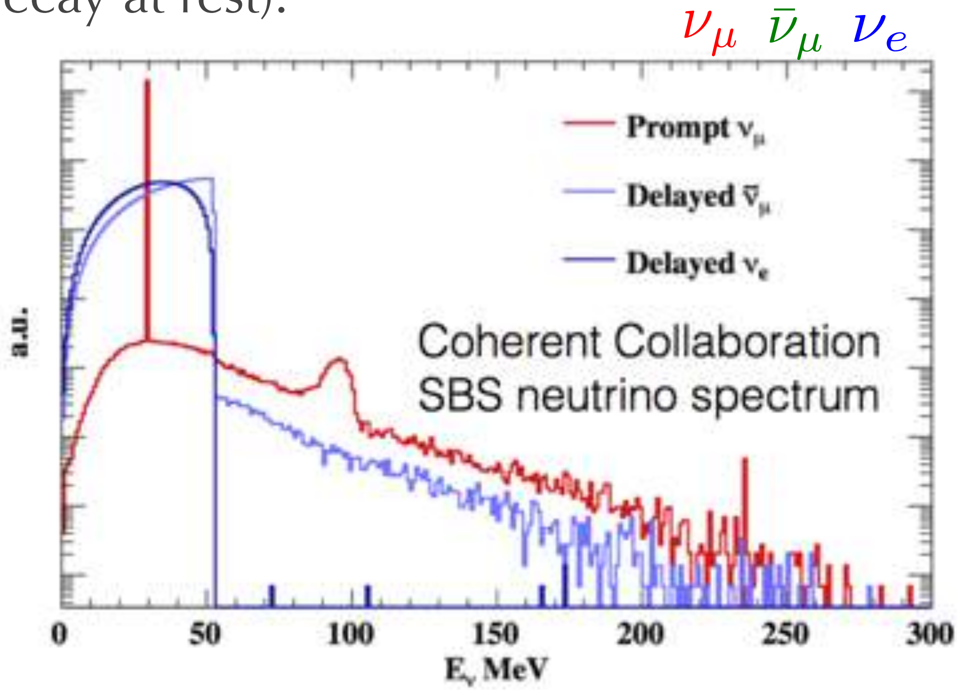
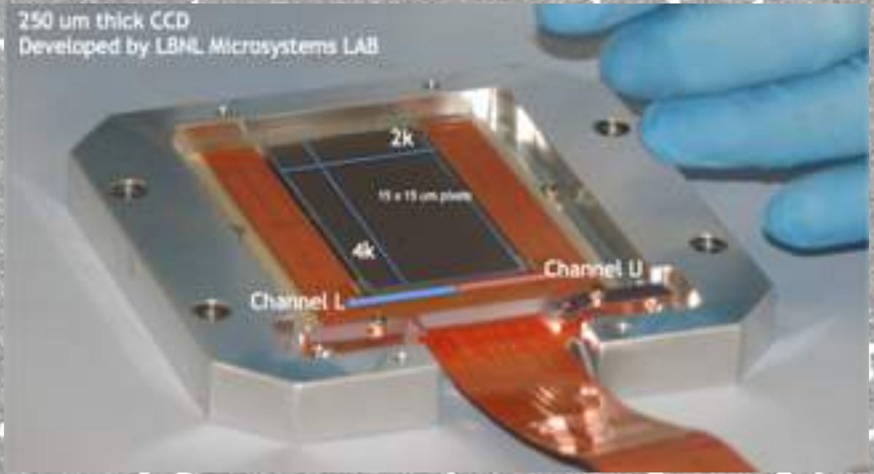
  Exp: COHERENT

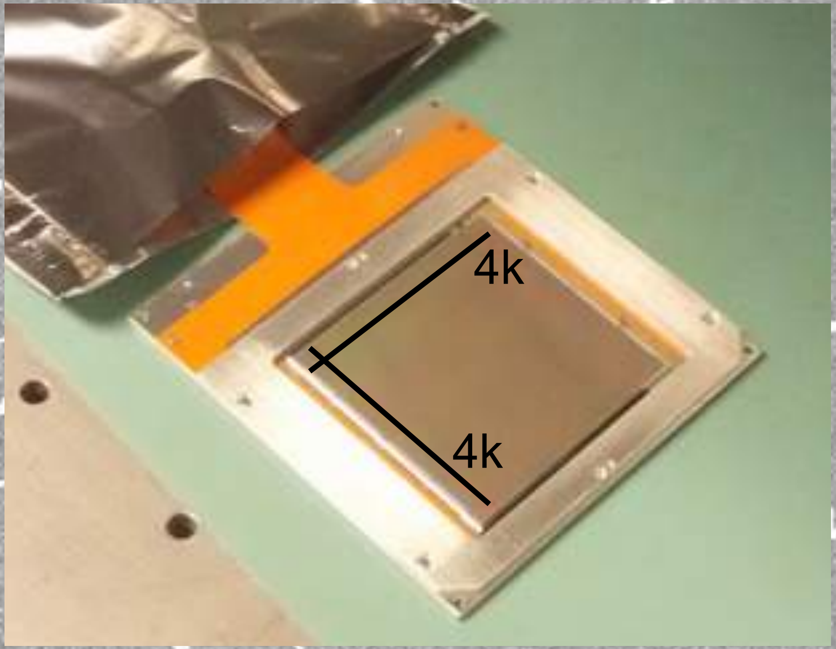


CONNIE Experiment

Coherent Neutrino-Nucleus Interaction Experiment



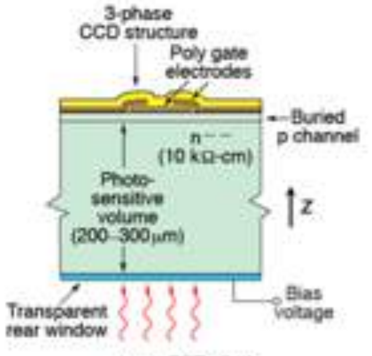
CONNIE15
250 μm CCDs
4 CCDs 1g each
To prove the concept



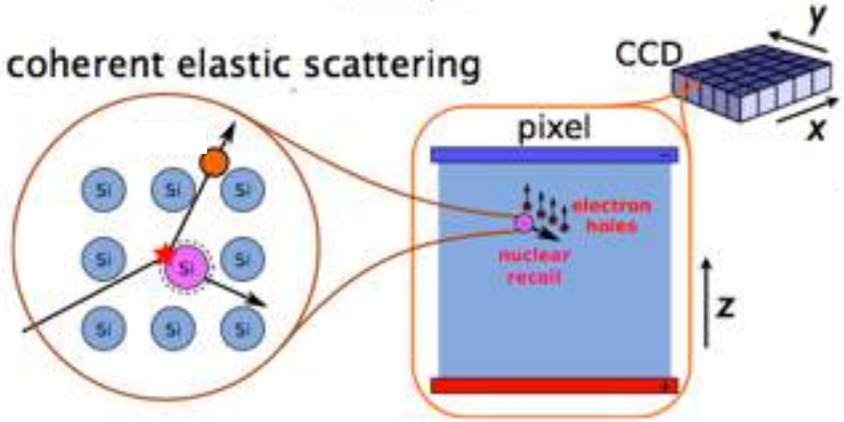
CONNIE
675 μm CCDs
14 CCDs 5.8 g each
Running since Aug 2016

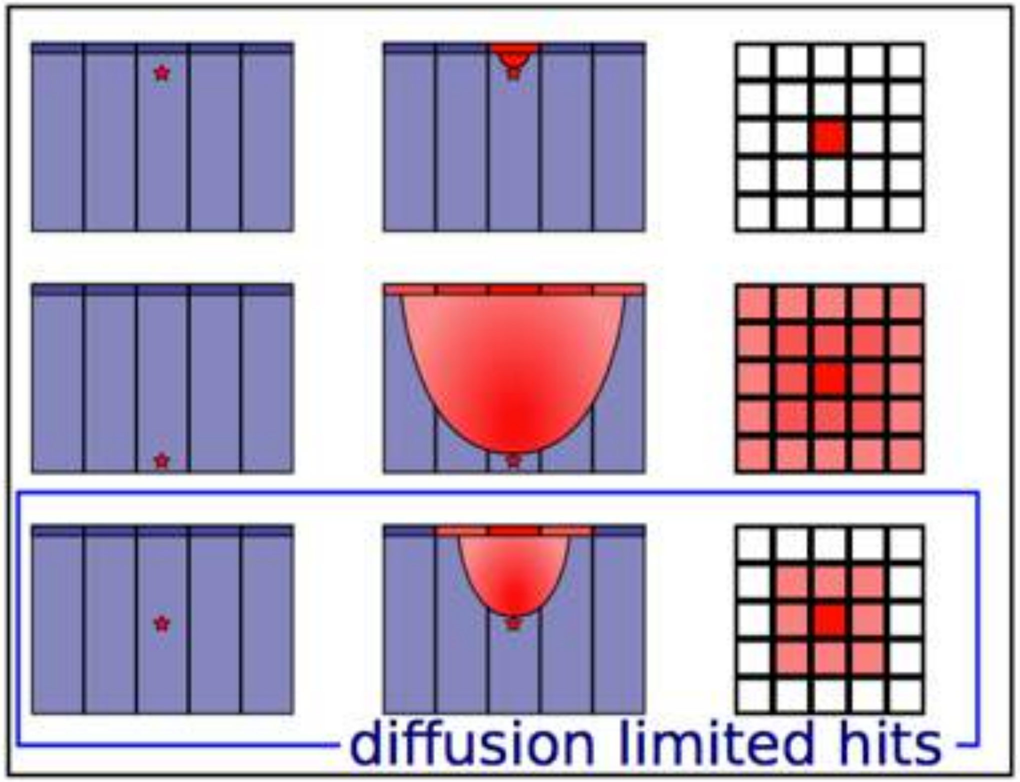
CCDs – Charge Coupled Device

- Characteristics
  - very low energy threshold detectors: 5.5 eV (RMS < 2 e^-)
  - pixels size of 15 μm x 15 μm
  - large mass compared to regular CCDs (now 675 μm, 4k x 4k)
  - "3D" information (diffusion): rejection of surface events

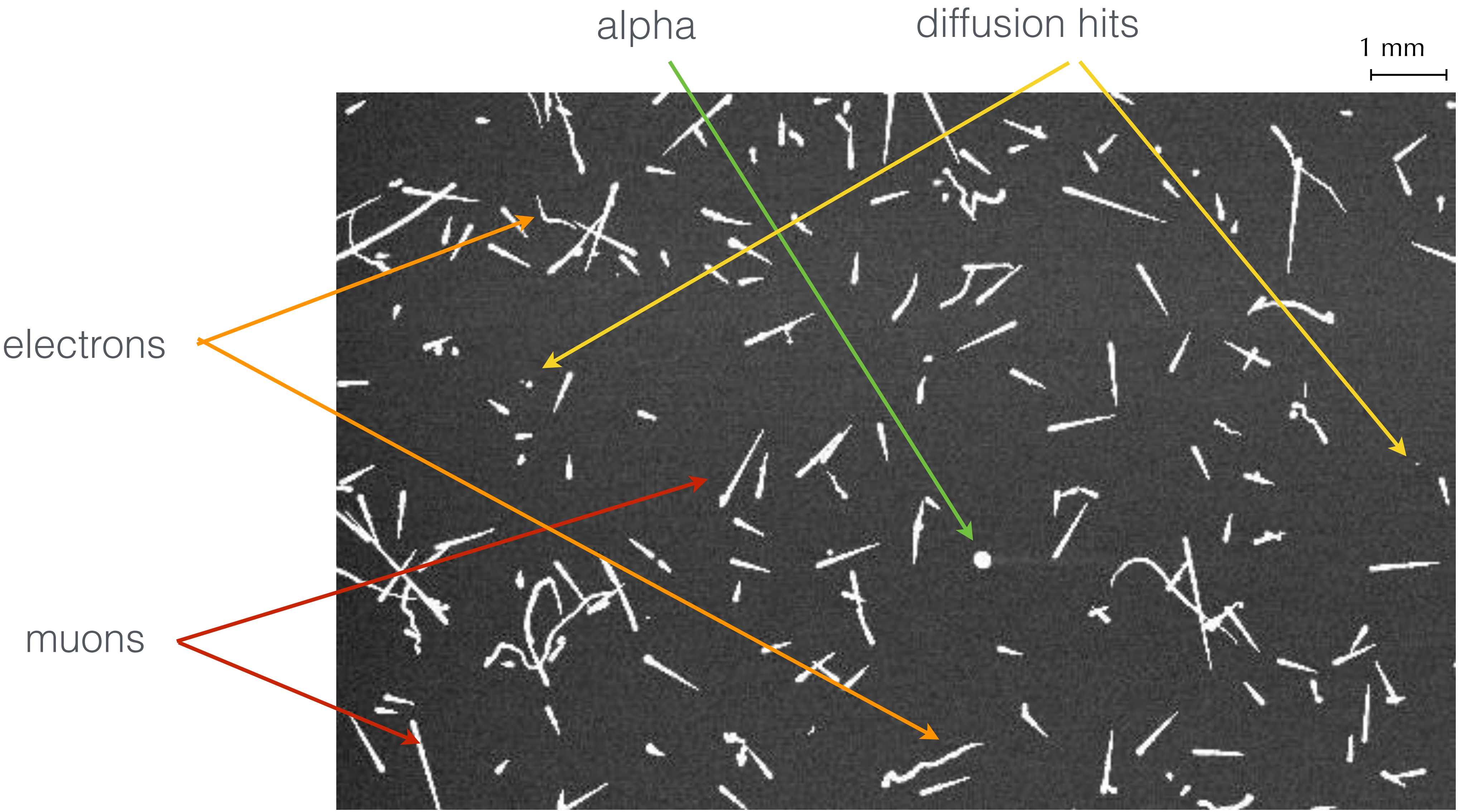


(a) A CCD pixel

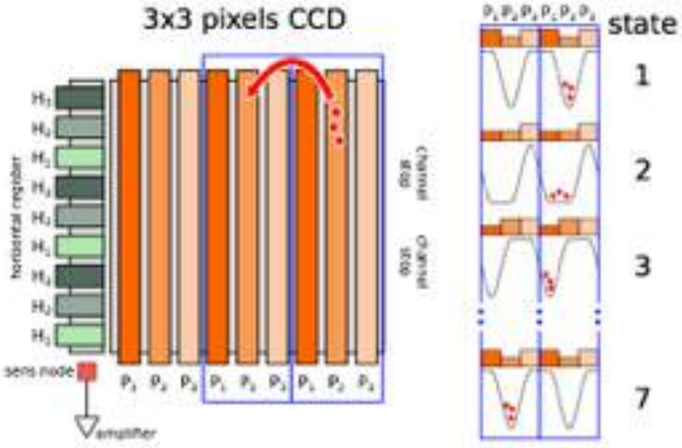




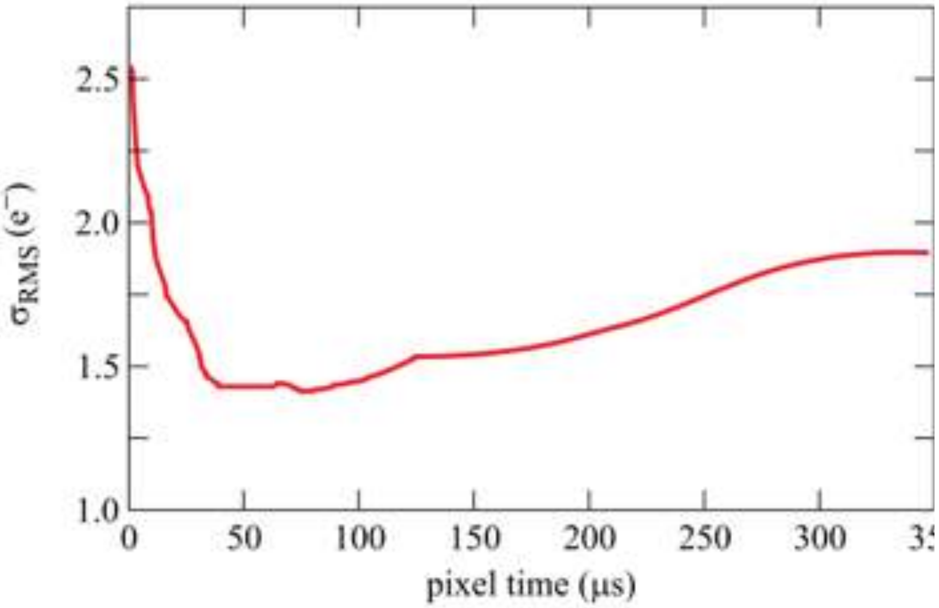
Particle identification CCD

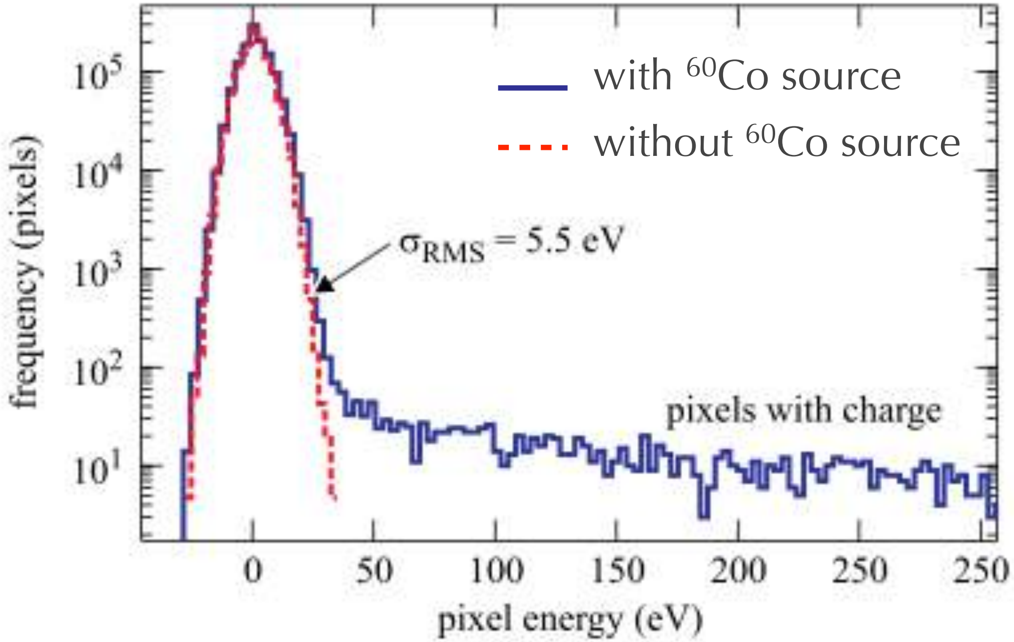


CCD readout - Noise



- Gaussian distribution with σ_{RMS} that depends on the readout time of the pixel
- Pixel time = 30 μs ⇒ $\sigma_{RMS} = 1.5e^-$ ≡ 5.5 eV of ionization energy





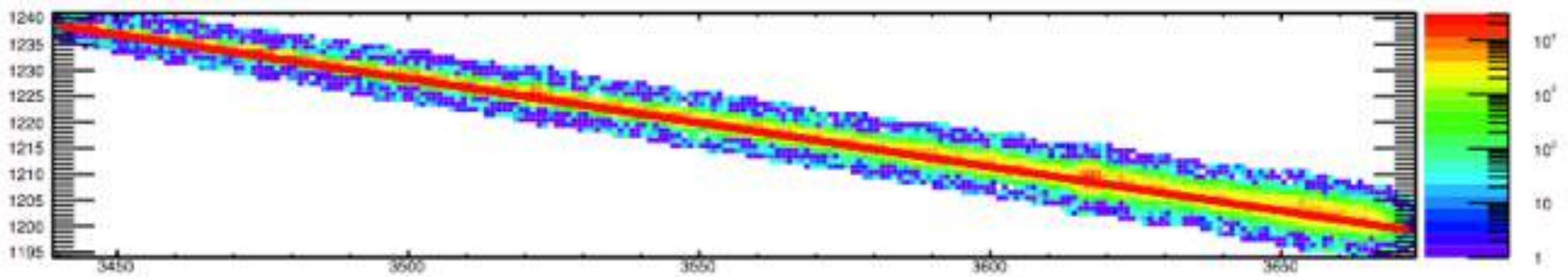
PRD91 (2015) 7, 072001

Diffusion from data

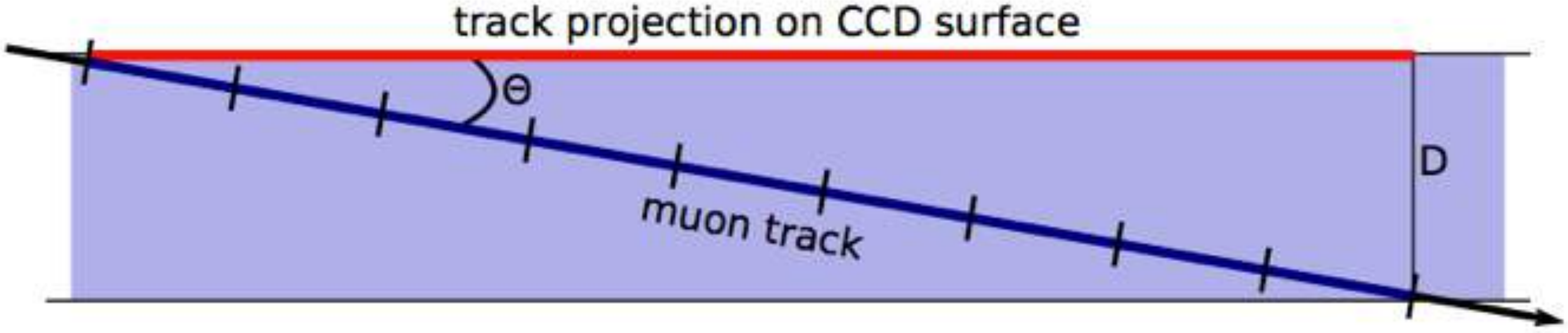
Tiffenberg

Using the muon track in the CCD

- Recorded track: CCD top view



- CCD side view

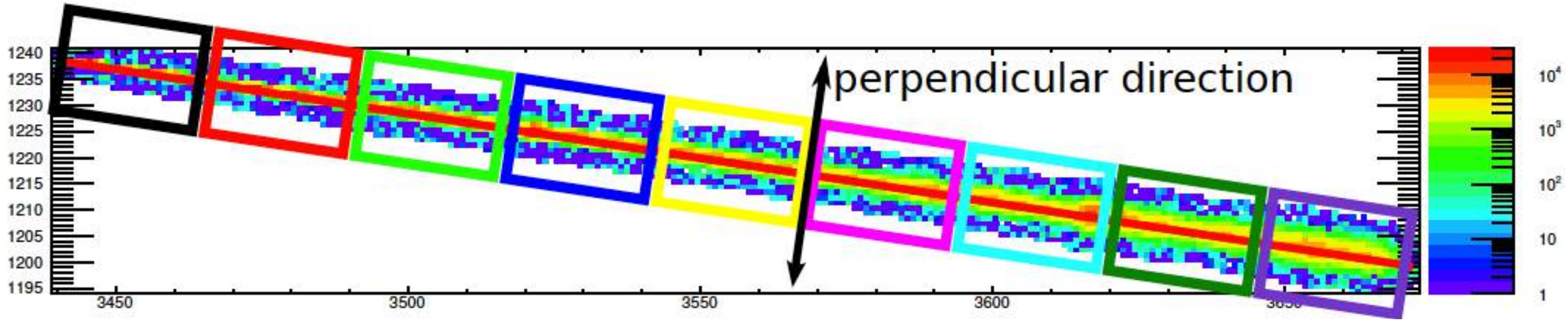


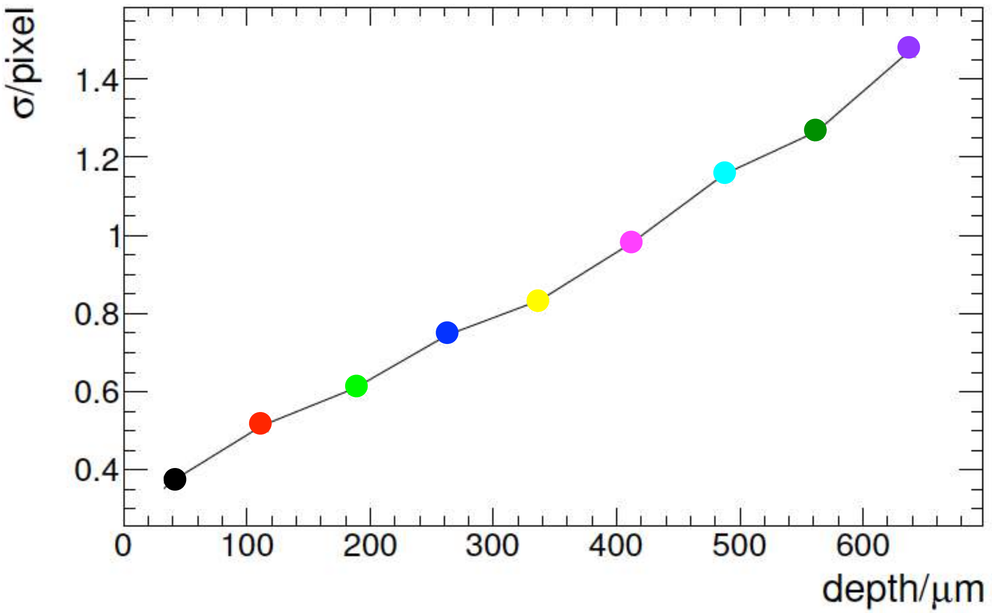
Diffusion from data

Tiffenberg

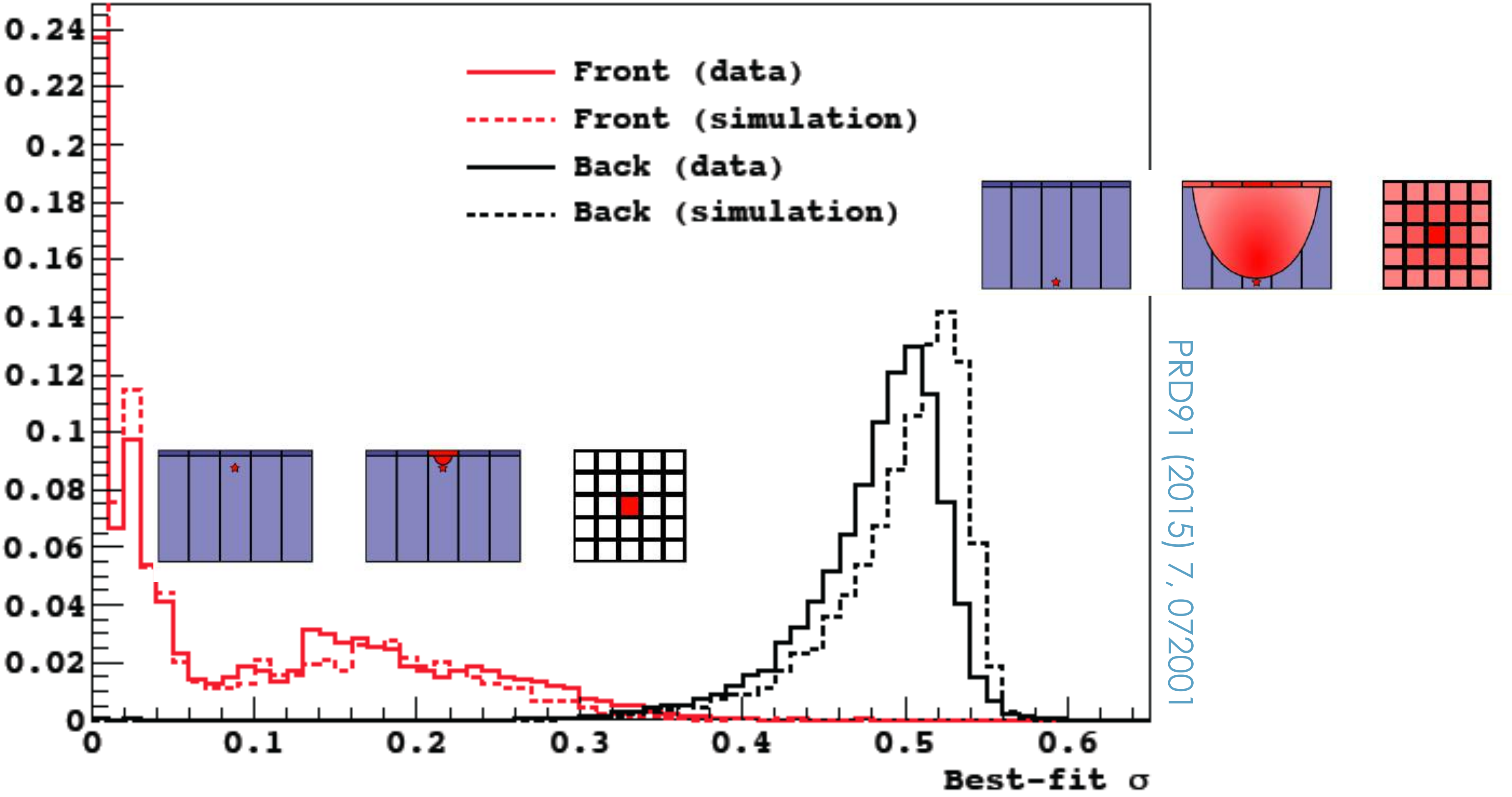
Diffusion can be measured as a function of the interaction depth

No need to rely on models.





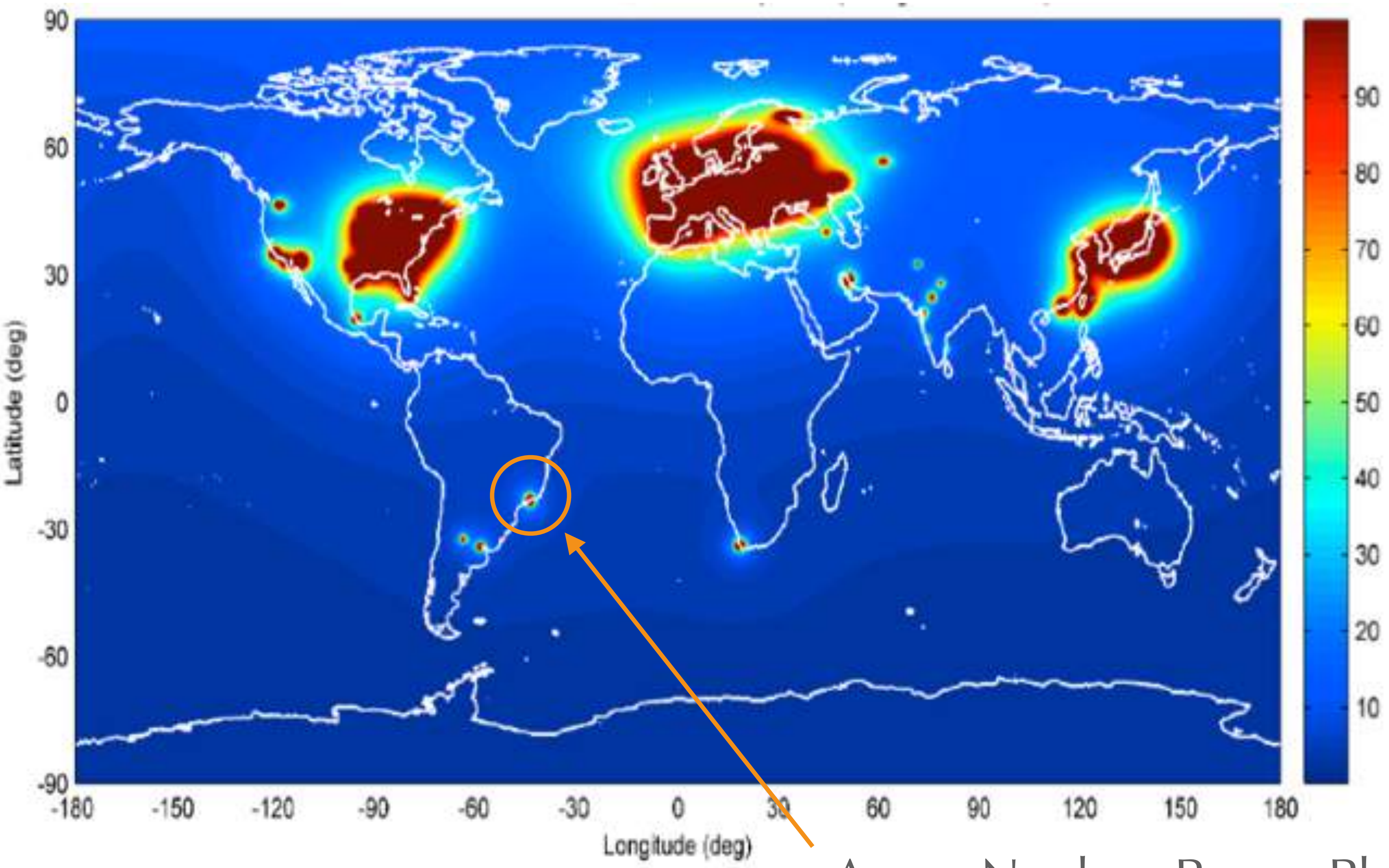
Diffusion from data



PRD91 (2015) 7, 072001

Diffusion can be modeled with a Gaussian distribution with lateral deviation from 0 to 0.55 pixels.

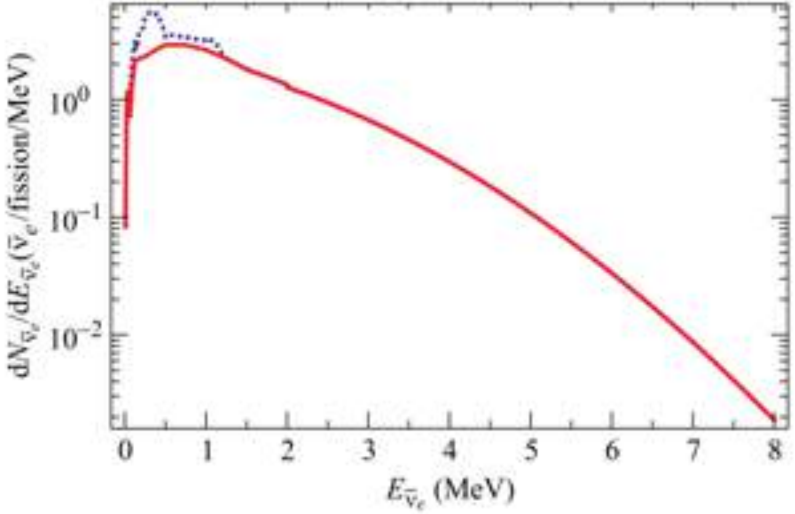
Anti-Neutrino sources



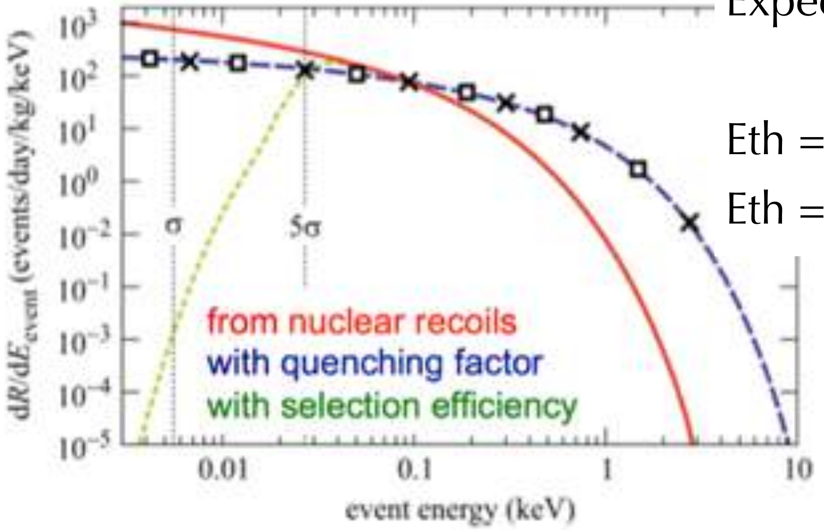
Angra Nuclear Power Plant

Angra Nuclear Power Plant

Total reactor antineutrino spectrum in the reactor per MeV



Energy spectra in silicon detectors



	Expected number events/kg/day
Eth = 5.5 eV (1σ)	28
Eth = 28 eV (5σ)	18

PRD91 (2015) 7, 072001

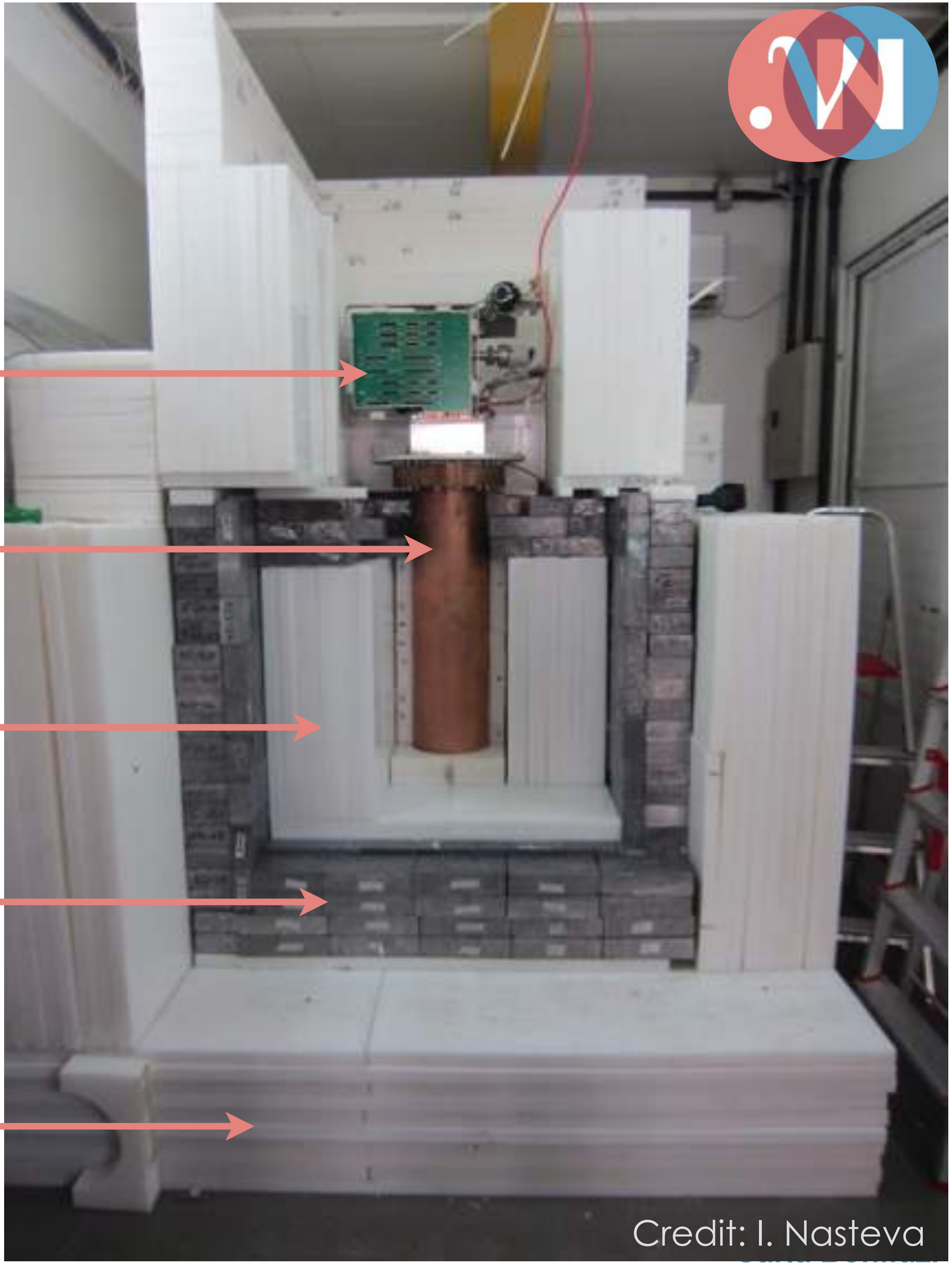
Angra Nuclear Power Plant

ν lab already installed by
Neutrinos Angra Project

Two experiments on the Neutrinos Lab

- Angra Neutrinos
- CONNIE

The detector



ViB board
(signals transport)

Dewar
(hold vacuum)

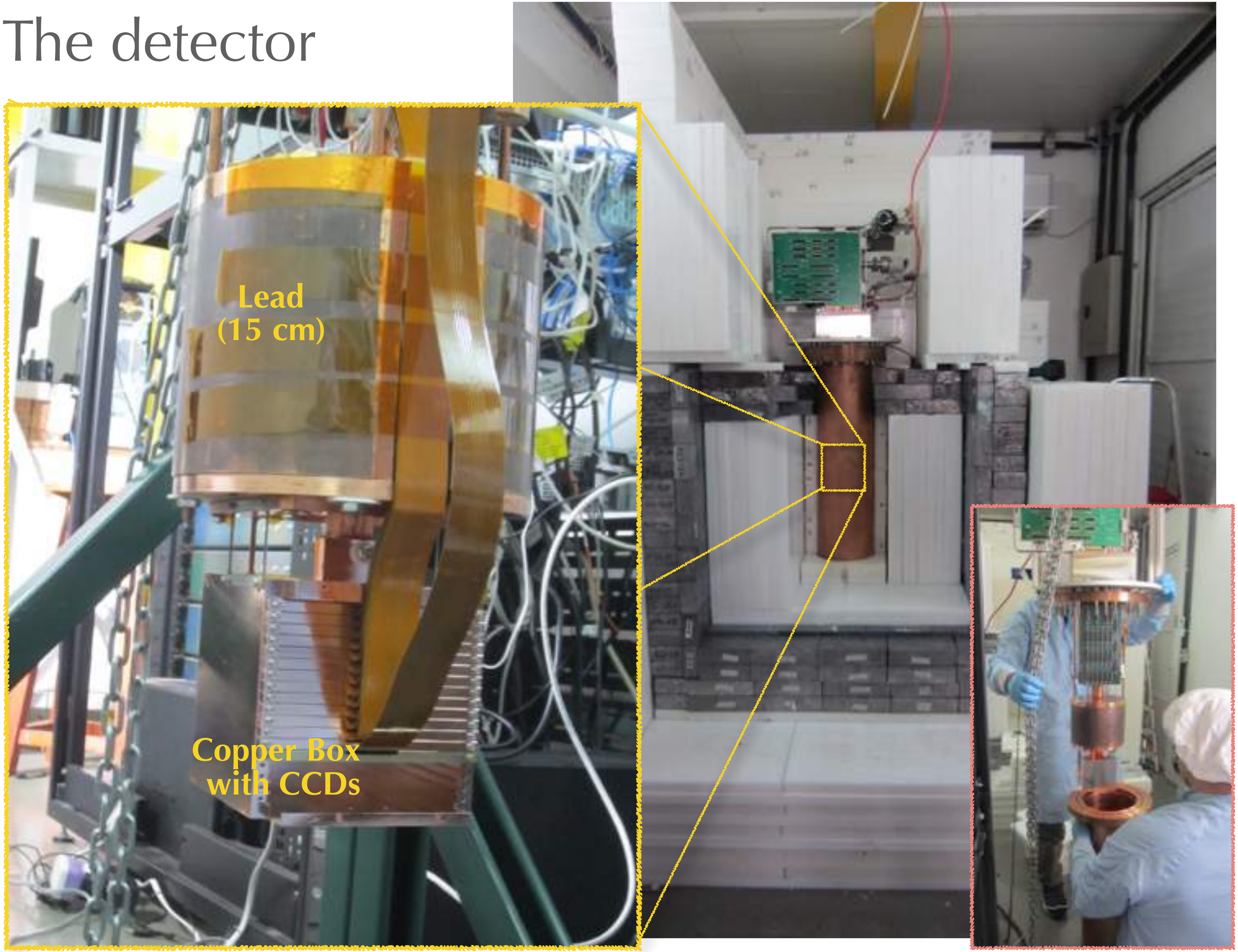
Inner
polyethylene (30 cm)

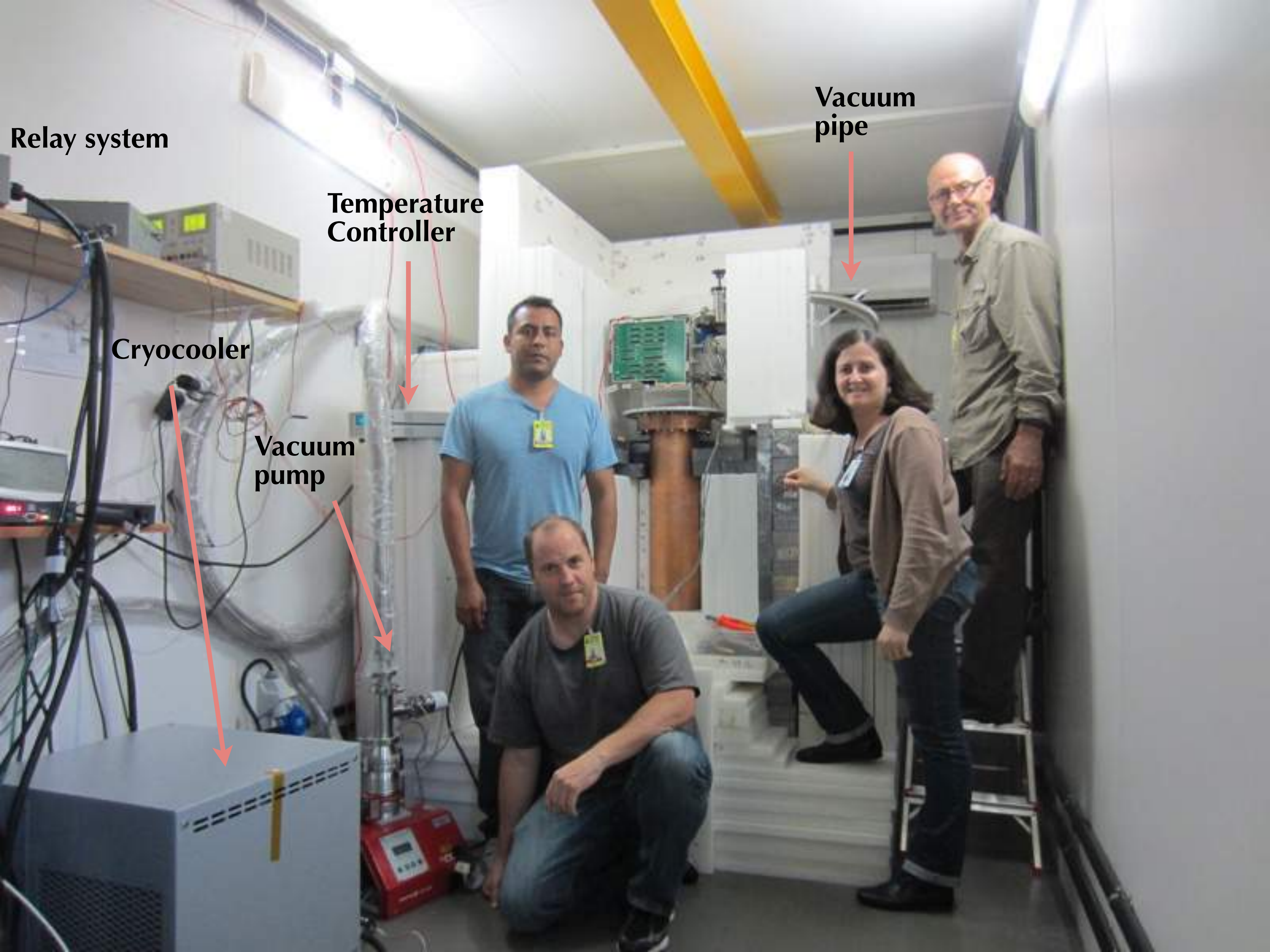
Lead (15 cm)
~ 800 bricks (Fermilab, USP, CBPF
and bought to Aurea)

Outer
polyethylene (30 cm)

Credit: I. Nasteva

The detector

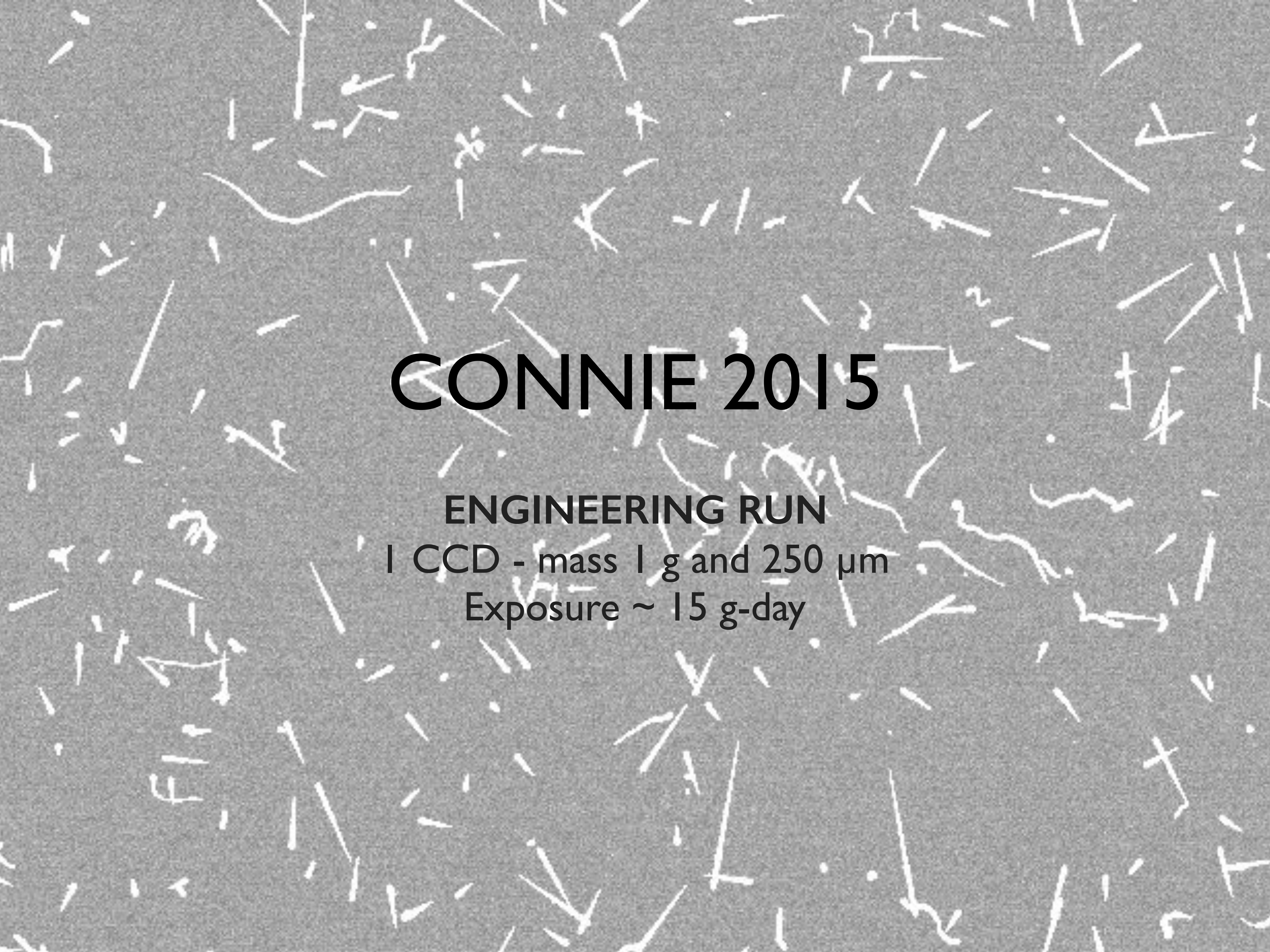



Relay system
Temperature Controller
Vacuum pipe
Cryocooler
Vacuum pump

Construction of the experiment @Angra

Timeline

- First visit in 2011
- Seriously making a plan in 2013
- **Installed a prototype December 2014**
  - **4 CCDs with 1 g and 250 μm each**
  - no-shield and partial shield measurements
- July-August 2015 – Full shield assembly completed
  - August - September 2015 – More than a full month with r**eactor ON**
  - September - October 2015 – Full month of r**eactor OFFs**
- July - August 2016 – Update
  - **14 CCDs with 5.8 g and 675 μm each**
  - **November - December 2016 – Reactor OFF**
  - Infrastructure problems (power line stability, power outage, etc)
- June 2017 – Maintenance of the experiment and improvement in the infrastructure
  - **February - March 2018 – Full month of reactor OFF**
  - **Now – Taking data with reactor ON**



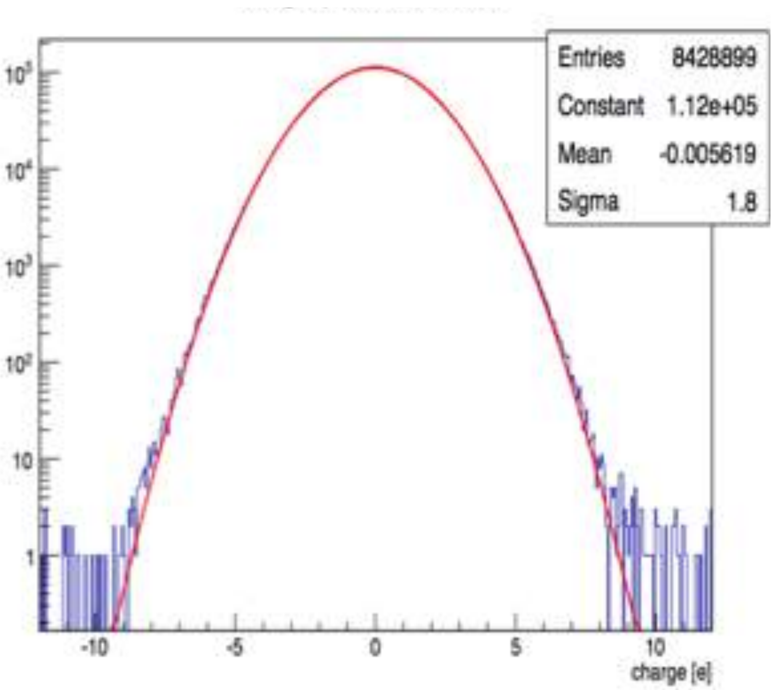
CONNIE 2015

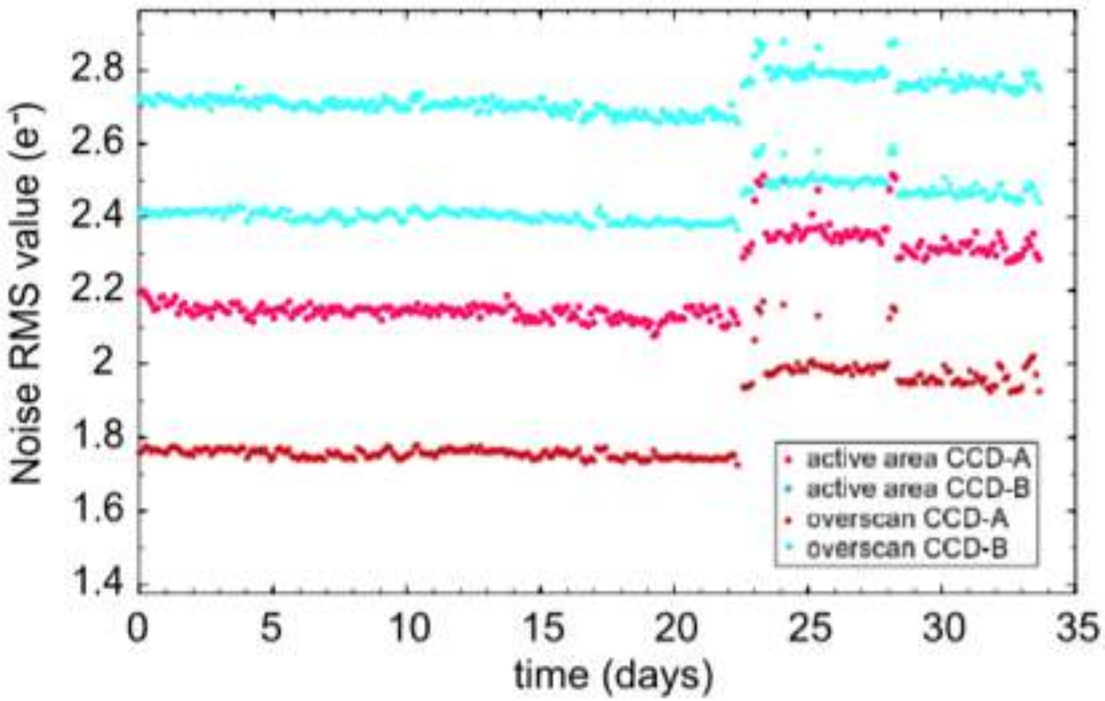
ENGINEERING RUN

1 CCD - mass 1 g and 250 μm

Exposure ~ 15 g-day

RMS noise

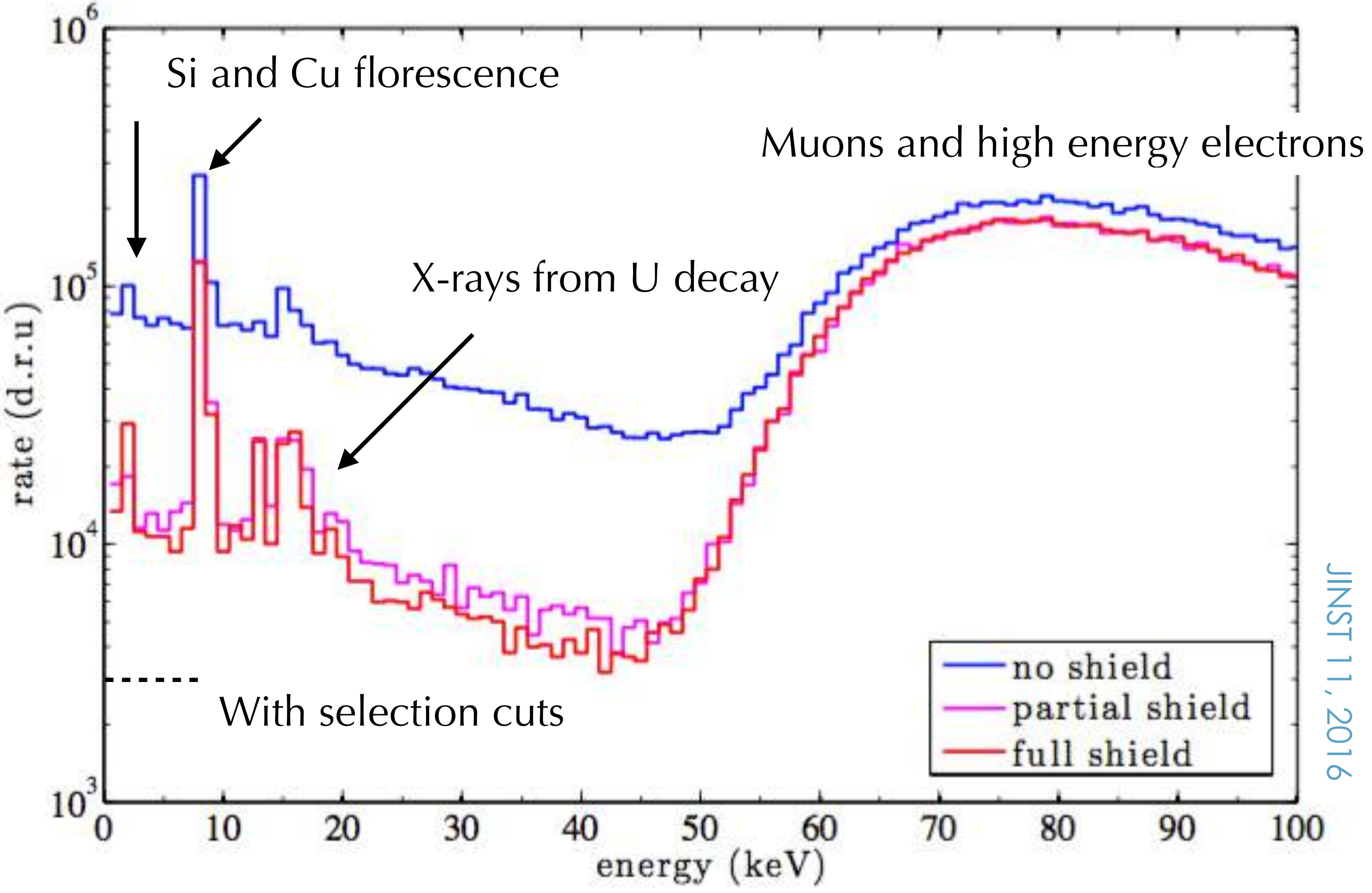




2015 we had a 2.2e- noise in the best CCD for the active area of the detector
This means that we had dark current, or IR photons hitting the detectors

This 10% decrease in the noise is a big deal. It corresponds to ~10 increase in the rate of noise hits at ~35 eV.

Energy spectrum



Si and Cu florescence

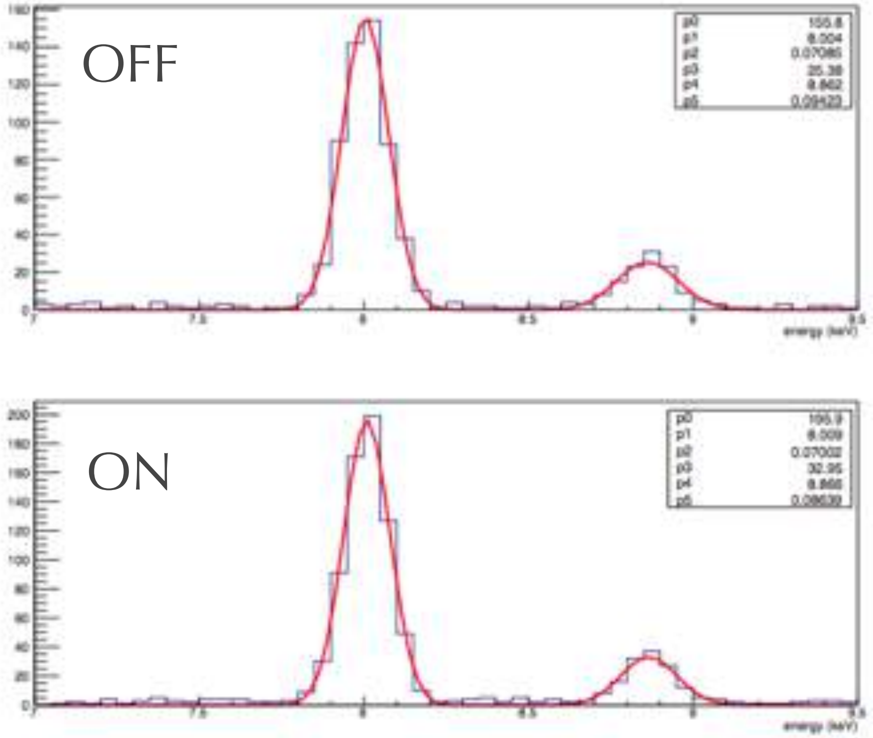
Muons and high energy electrons

X-rays from U decay

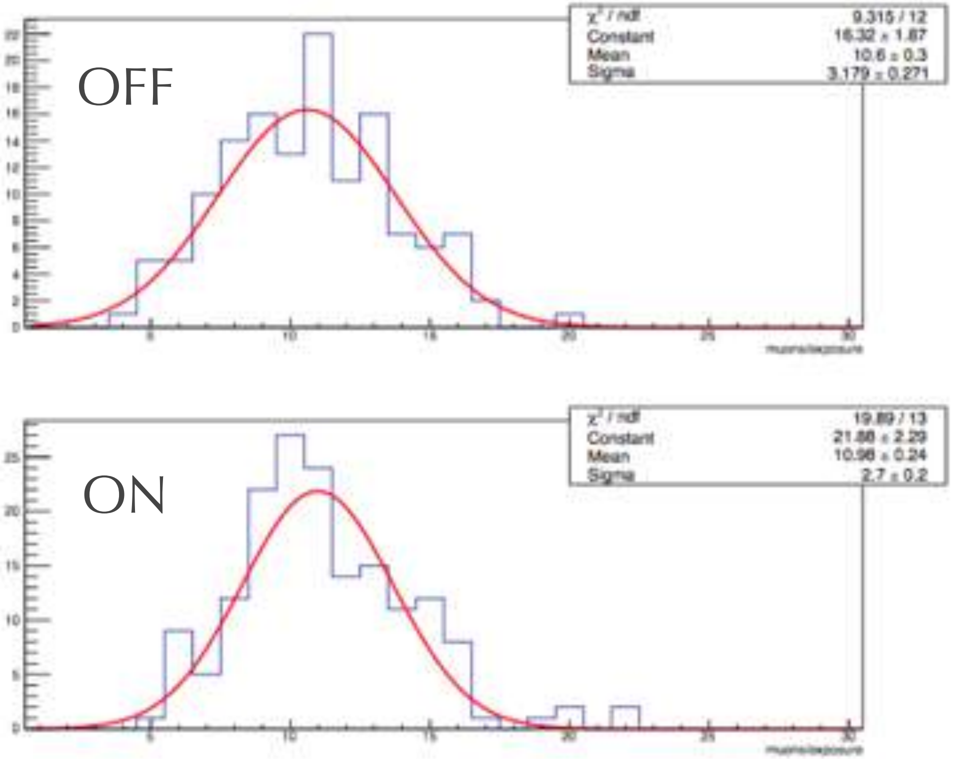
With selection cuts

JINST 11, 2016

Performance & Resolution

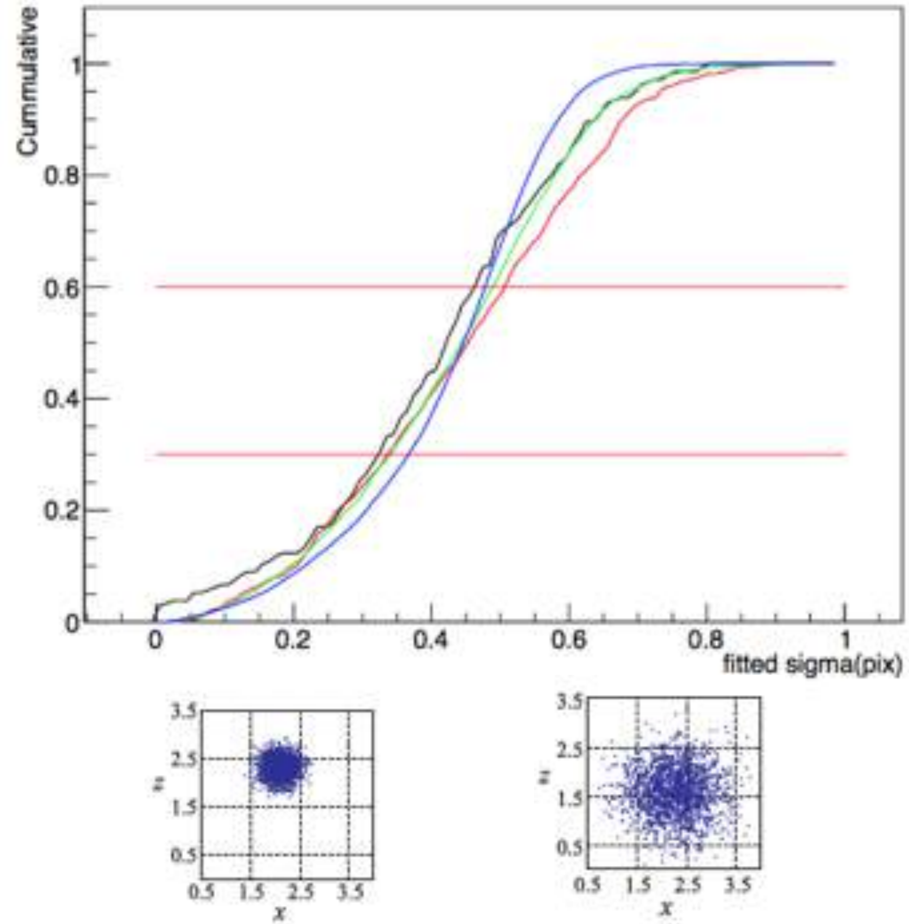


Cu fluorescence peaks for data collected with reactor OFF and ON



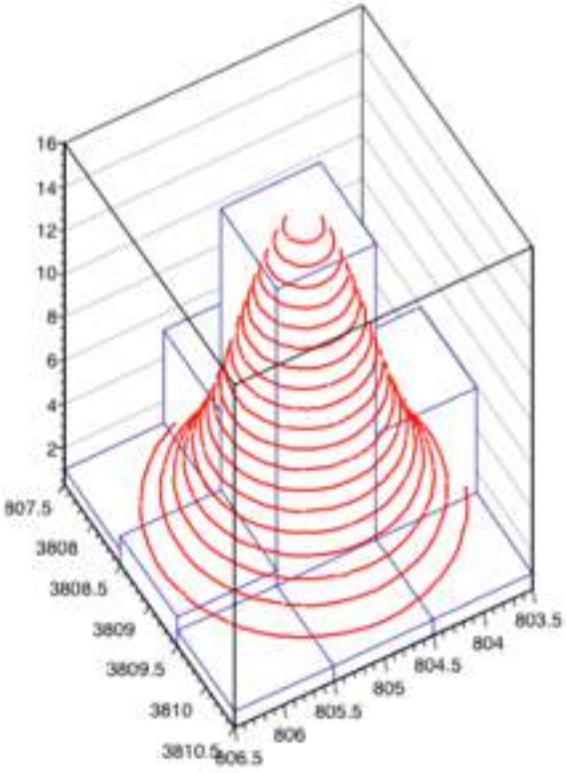
Muon events detected for each 8700 second exposure for reactor OFF and ON

Event selection & Efficiency



gates

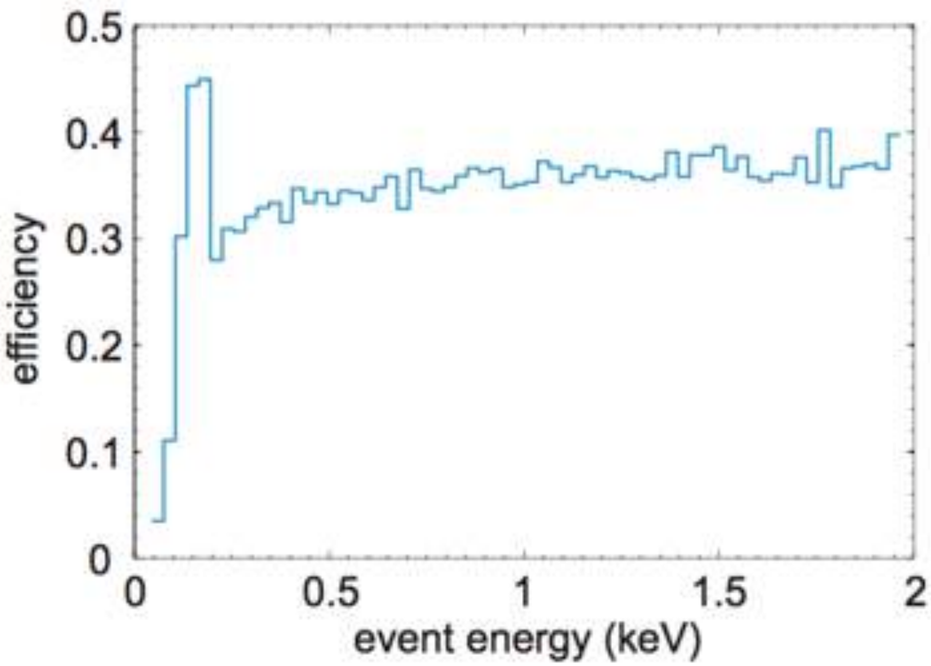
subastare contact



A 2-D Gaussian is adjusted to every hit found in the CCD image using a maximum likelihood technique.

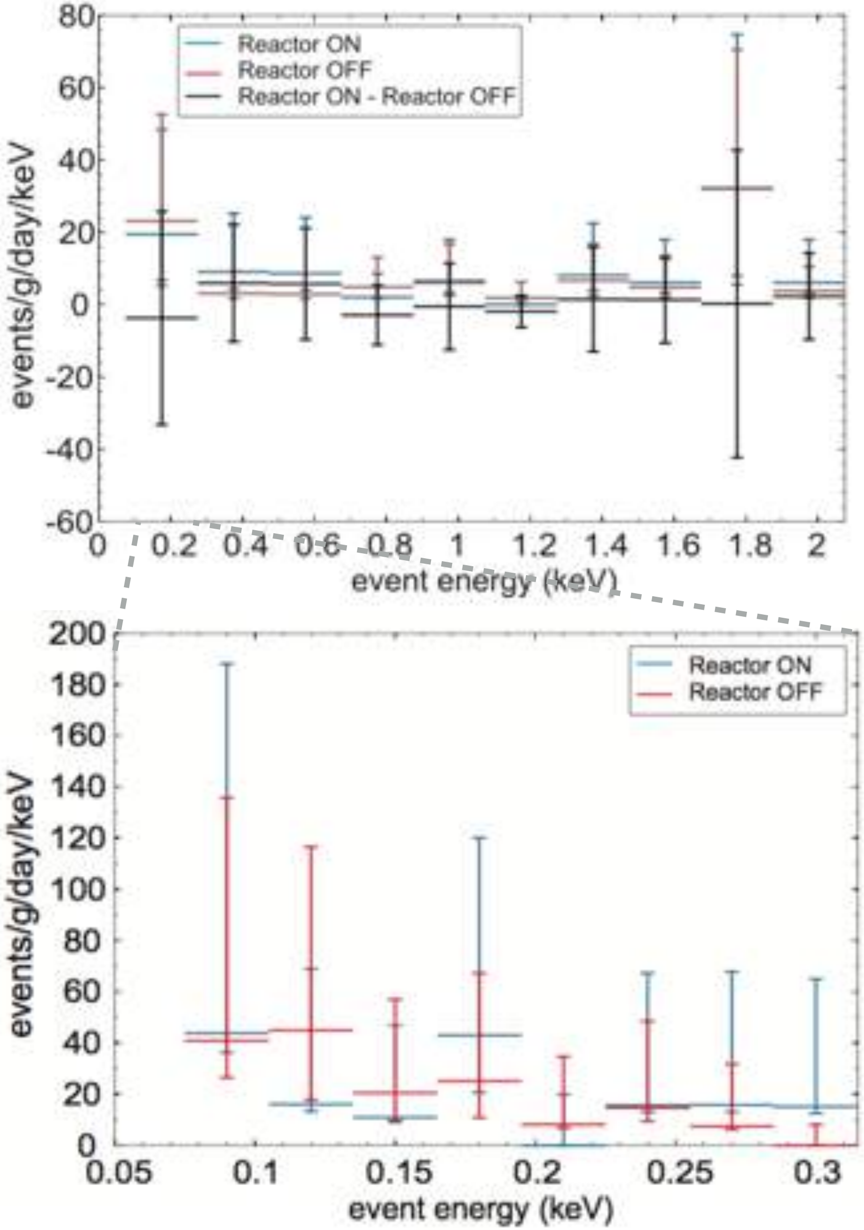
JINST 11, 2016

Event selection & Efficiency



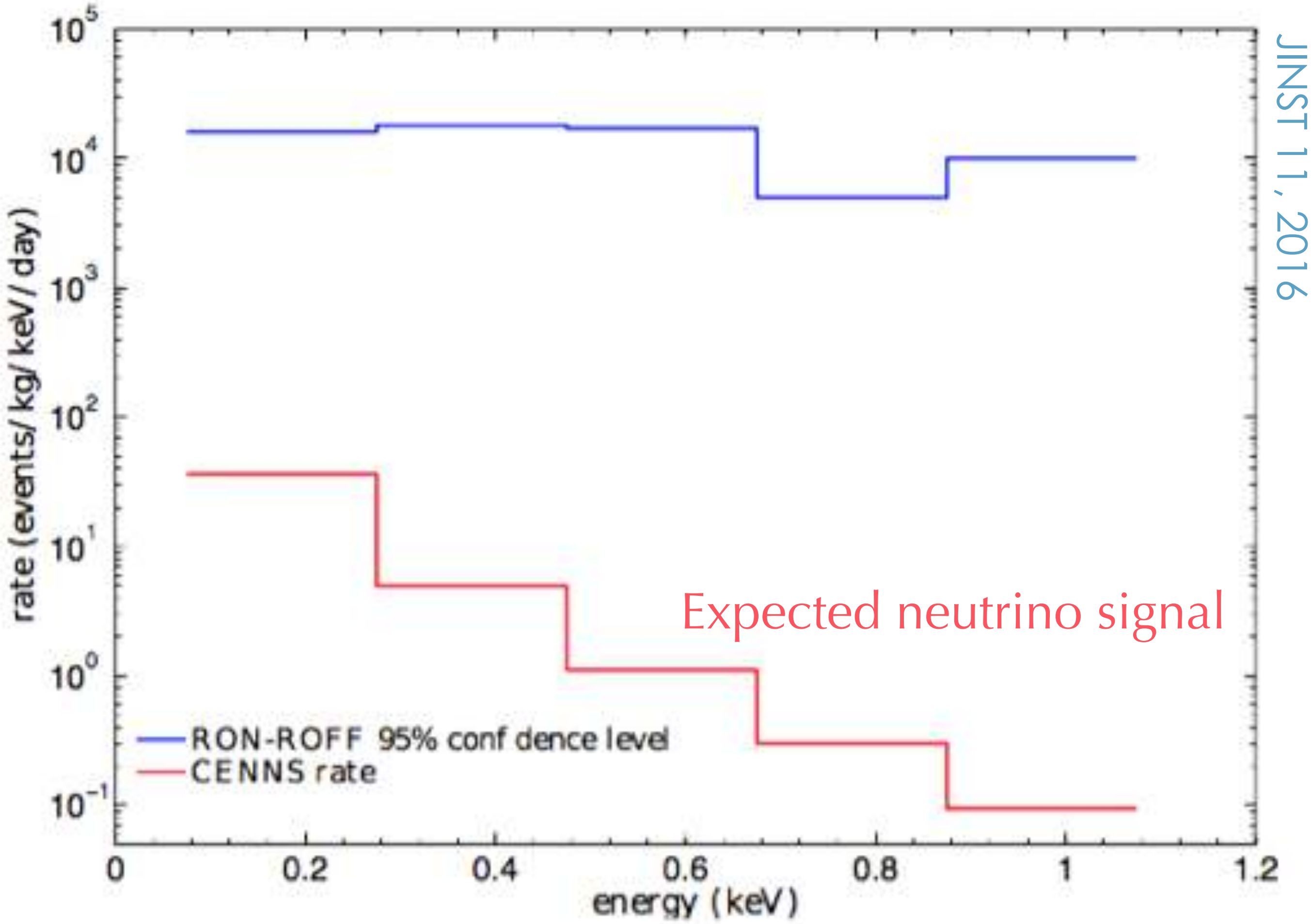
Rate of events with the reactor ON and OFF (corrected for the efficiency of the selection criteria)

The higher rate of events at 1.8 keV is produced by the silicon fluorescence X-ray.



JINST 11, 2016

Upper limit

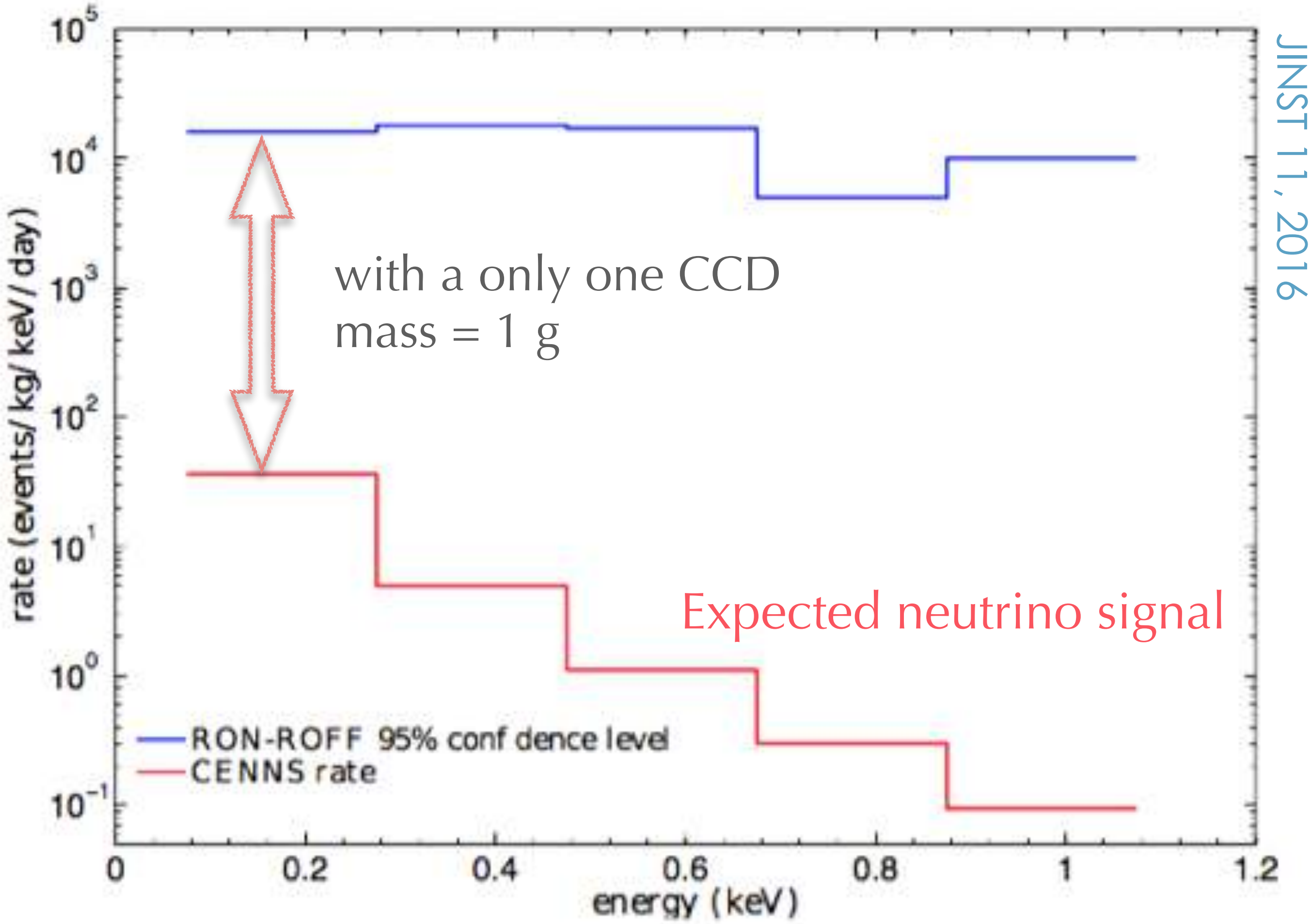


Expected neutrino signal

JINST 11, 2016

Upper limit of the coherent scattering interaction detection with the available data at 95 % confidence limit of the Reactor ON minus Reactor OFF signal rates

Upper limit



with a only one CCD
mass = 1 g

Expected neutrino signal

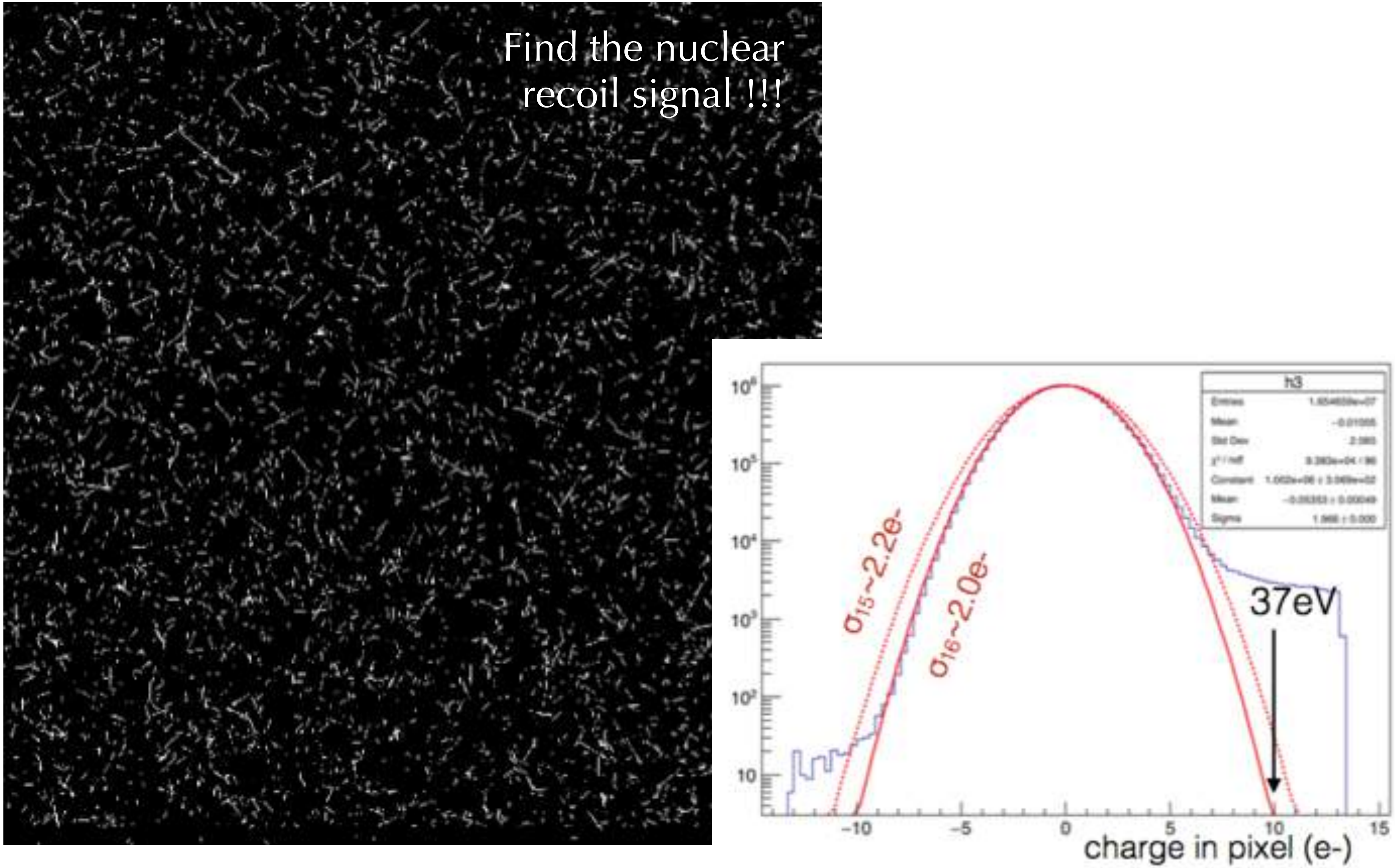
JINST 11, 2016

Upper limit of the coherent scattering interaction detection with the available data at 95 % confidence limit of the Reactor ON minus Reactor OFF signal rates

CONNIE 2016-17

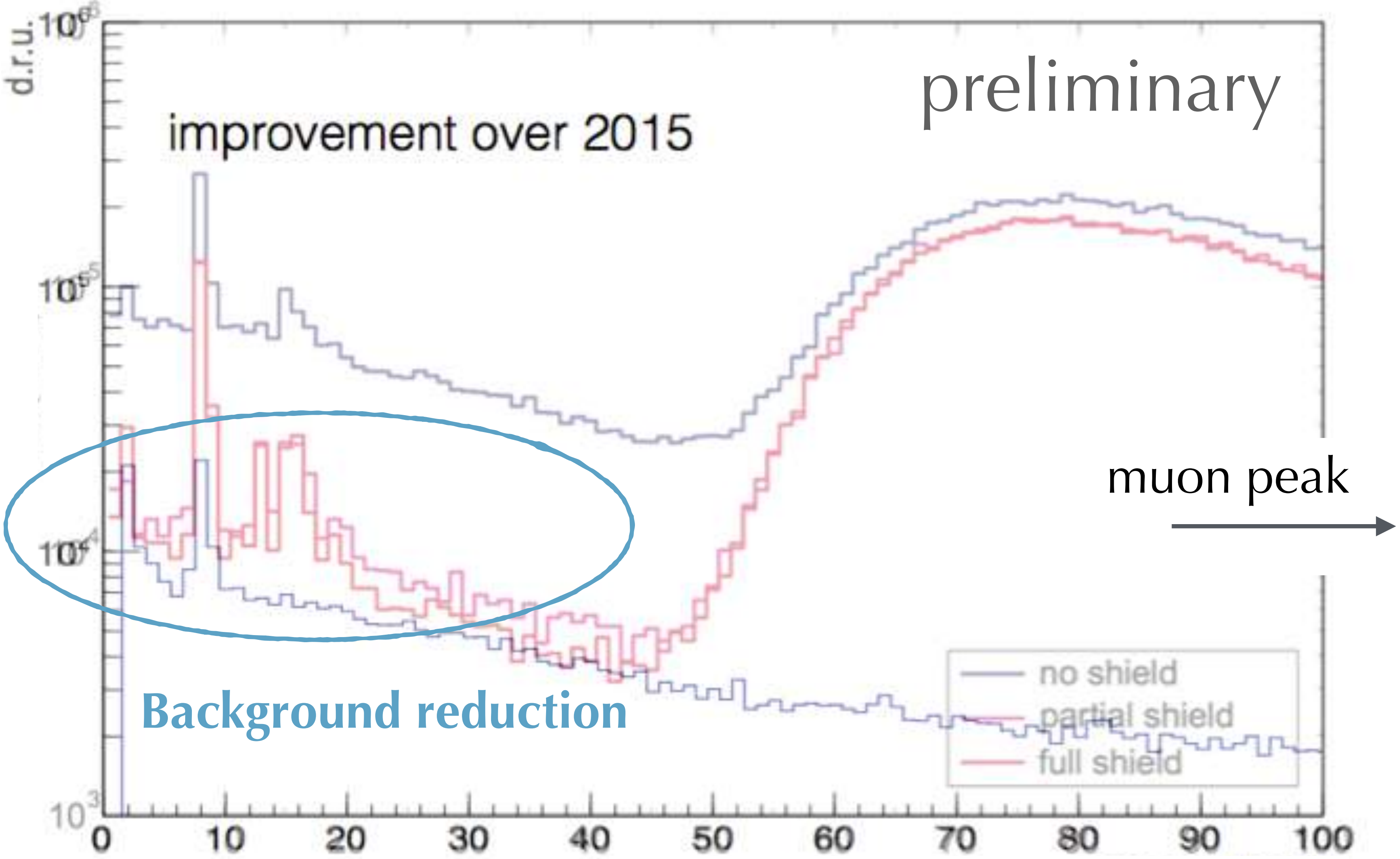
14 CCD installed – mass 5,8 g and 675 µm
Good CCDs selection for the analysis
Exposure ~ 340 g-day (23 times CONNIE 2015)

1 CCD @ 3 hours exposition



Find the nuclear recoil signal !!!

Improvement CONNIE 2016-17



improvement over 2015

preliminary

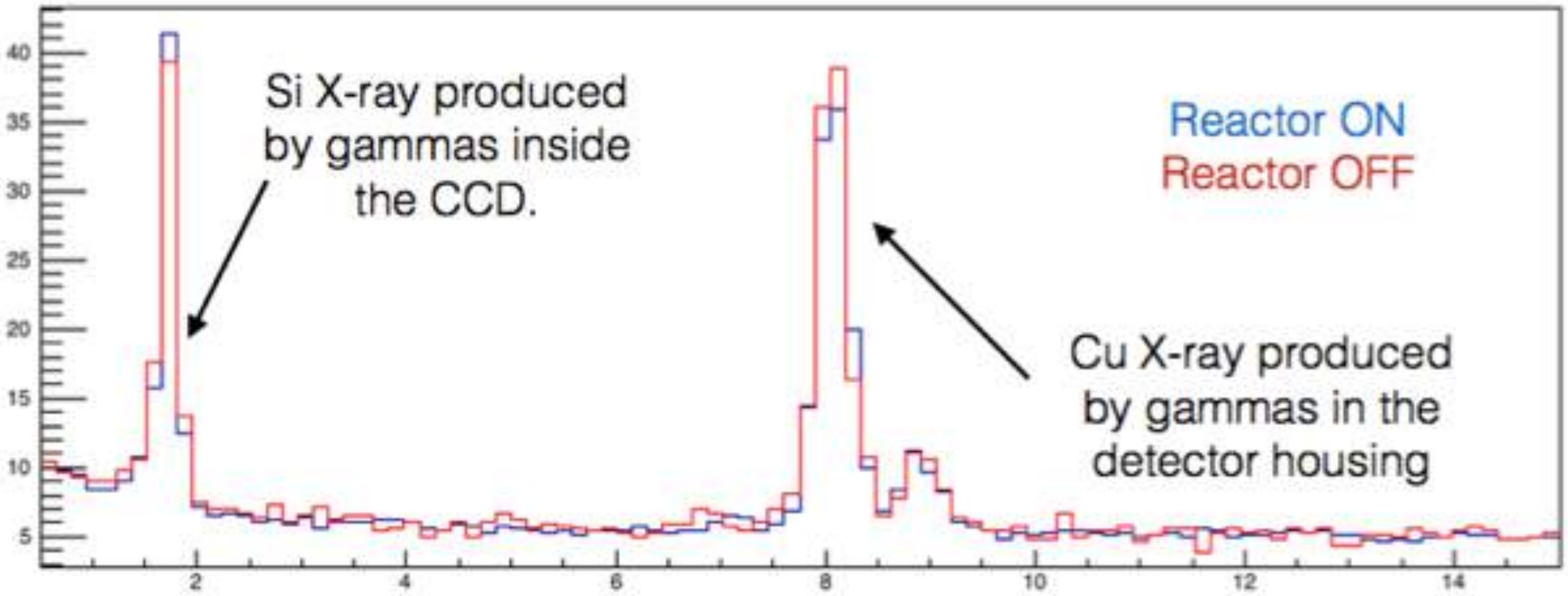
muon peak

Background reduction

Energy (keV)

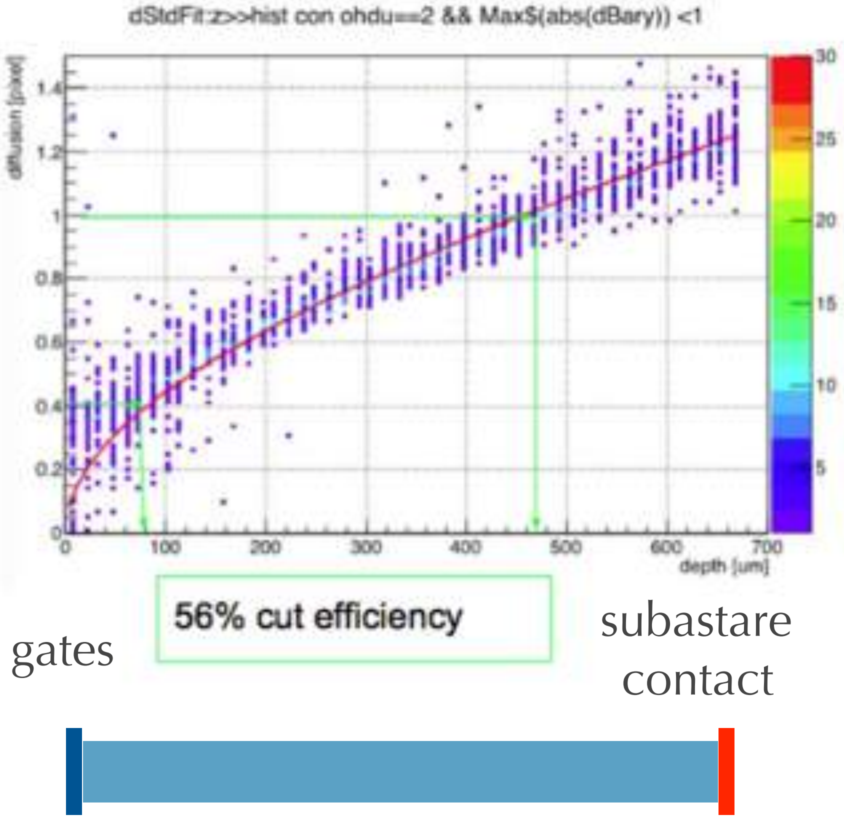
dru = events/kg/day/keV

Performance tests



Fluorescence X-rays are the same reactor ON/OFF.
This point to a stable gamma background.

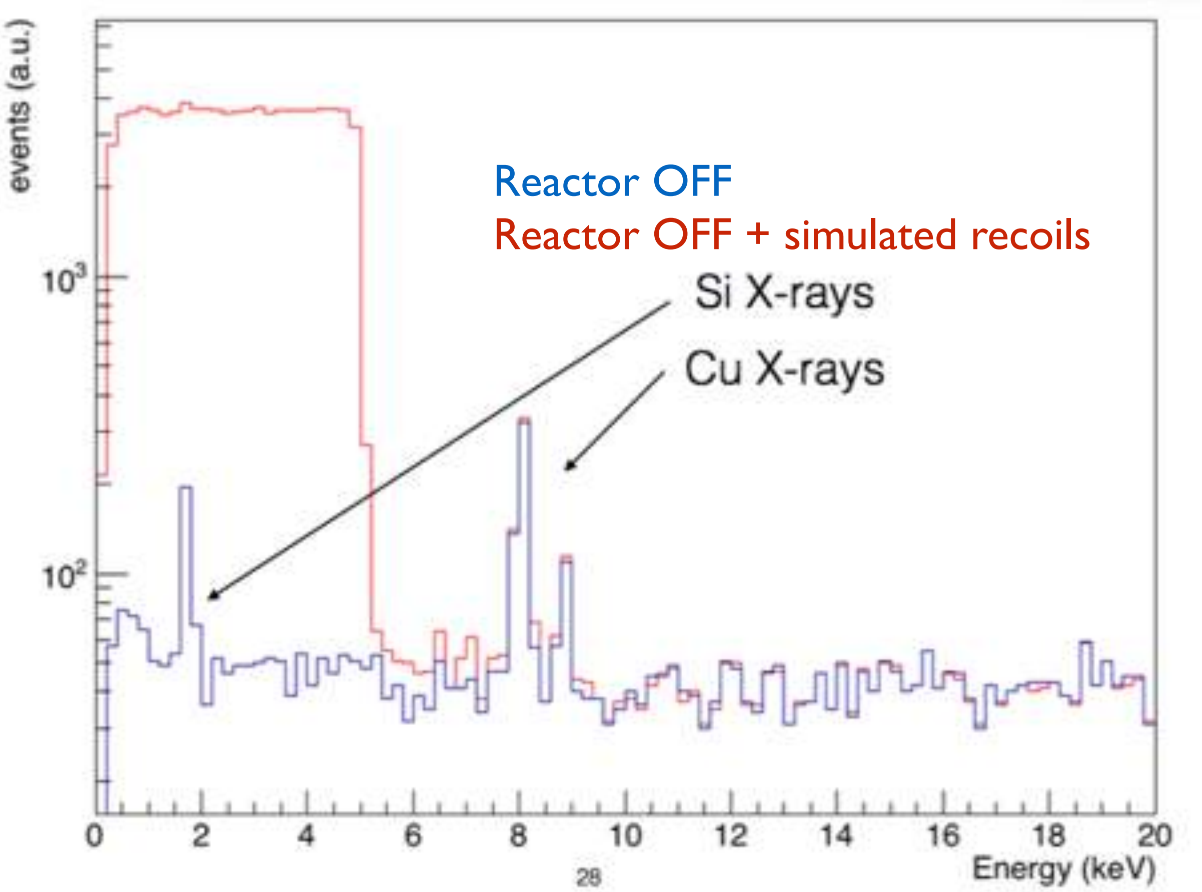
Efficiency CONNIE 2016-17



56% cut efficiency

gates

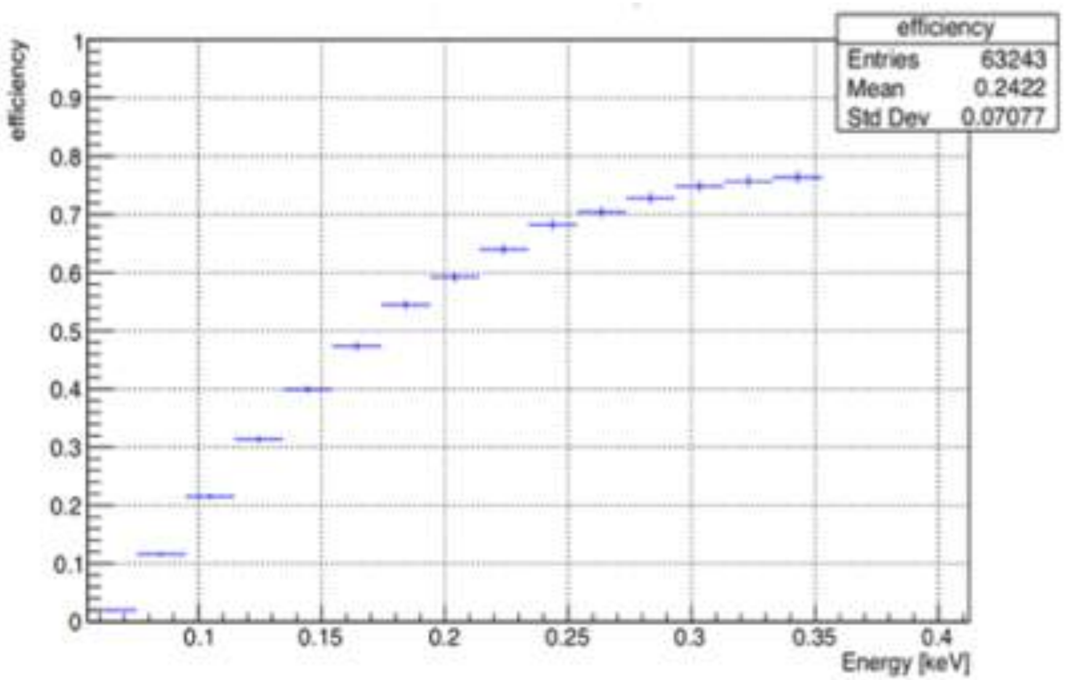
subastare contact

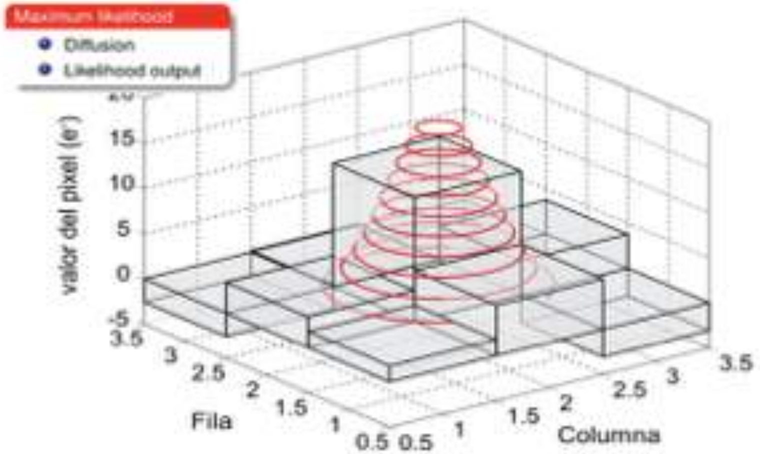


For the efficiency calculation we added simulated nuclear recoils (uniformly distributed inside the CCD) to the reactor OFF data

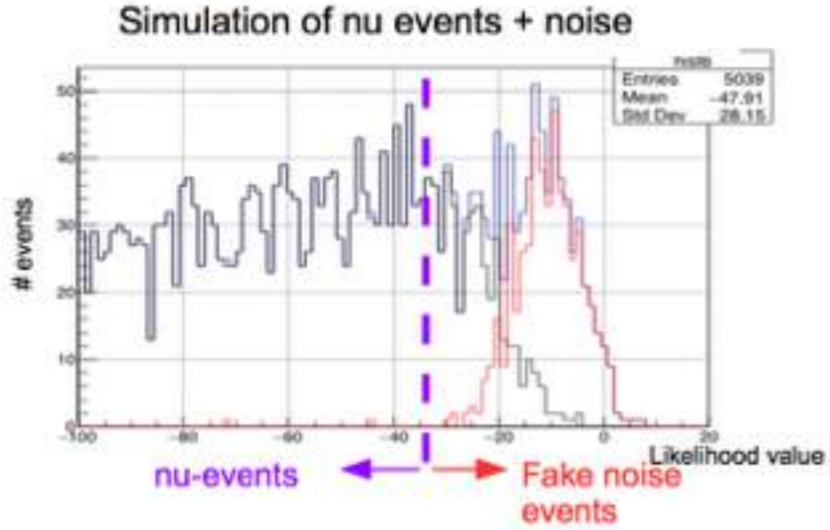
dru = events/kg/day/keV

Efficiency CONNIE 2016-17

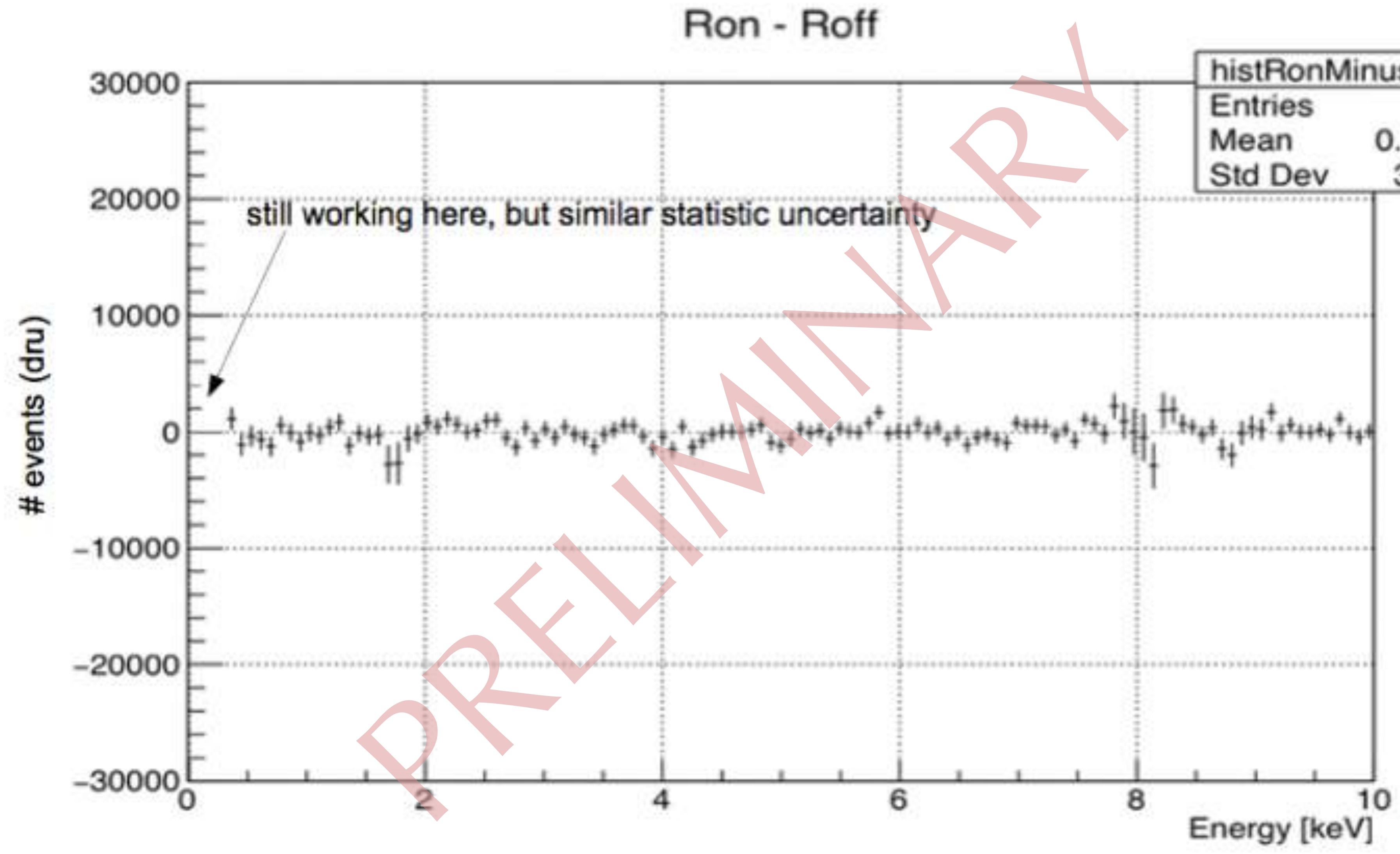




- Need to improve our low energy extraction
- At low energy we separate fake events from noise

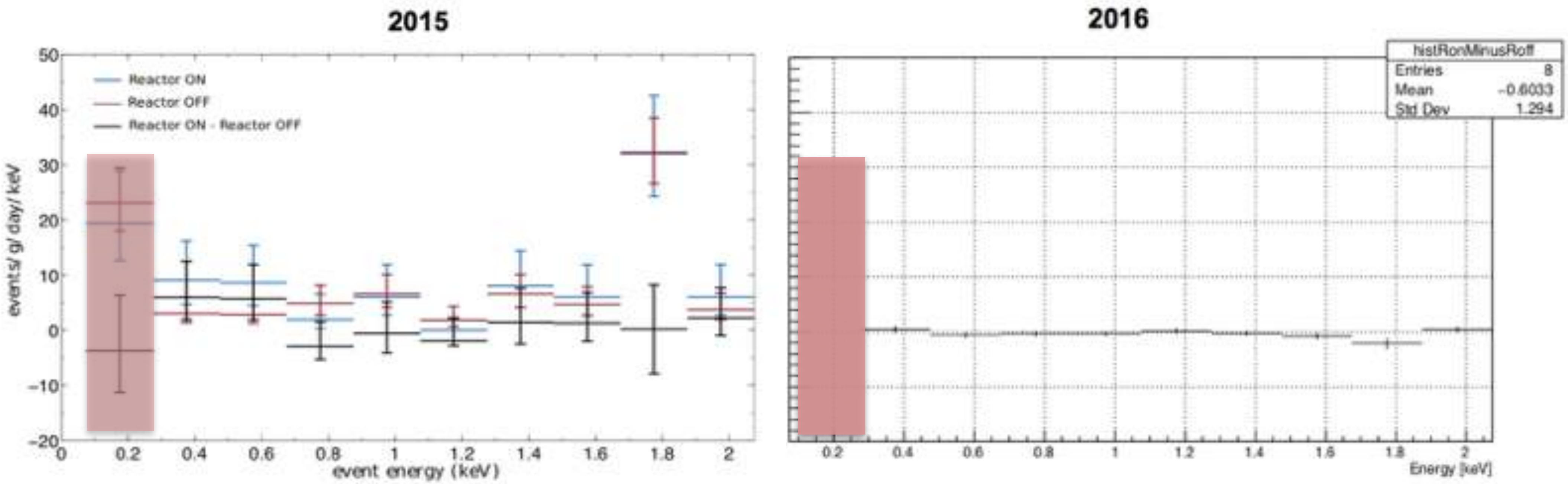


Reactor ON/OFF - CONNIE 2016-17



dru = events/kg/day/keV

Comparison 2015 and 2016-17

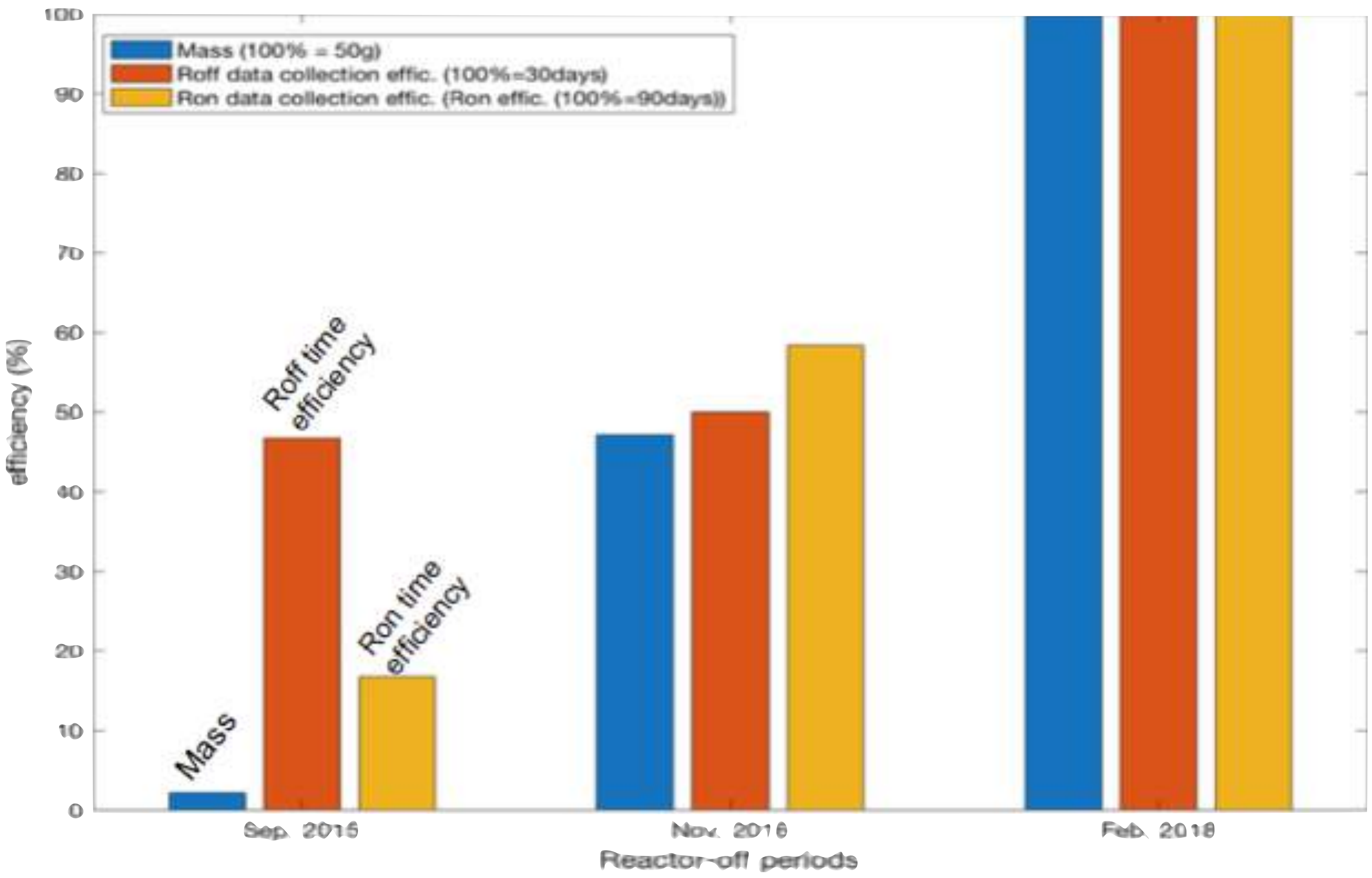


- Reduction of about **10 times**, expected by higher mass and higher data collection efficiency.
- Extra reduction of a factor of 2 is expected using Reactor OFF data from 2018.
- Extra reduction of a factor of up to 3 is expected using Montecarlo simulation.
- First bin is work in progress. It defines our sensitivity to the standard model. At least **ten times better** limit that in 2015.

CONNIE 2018

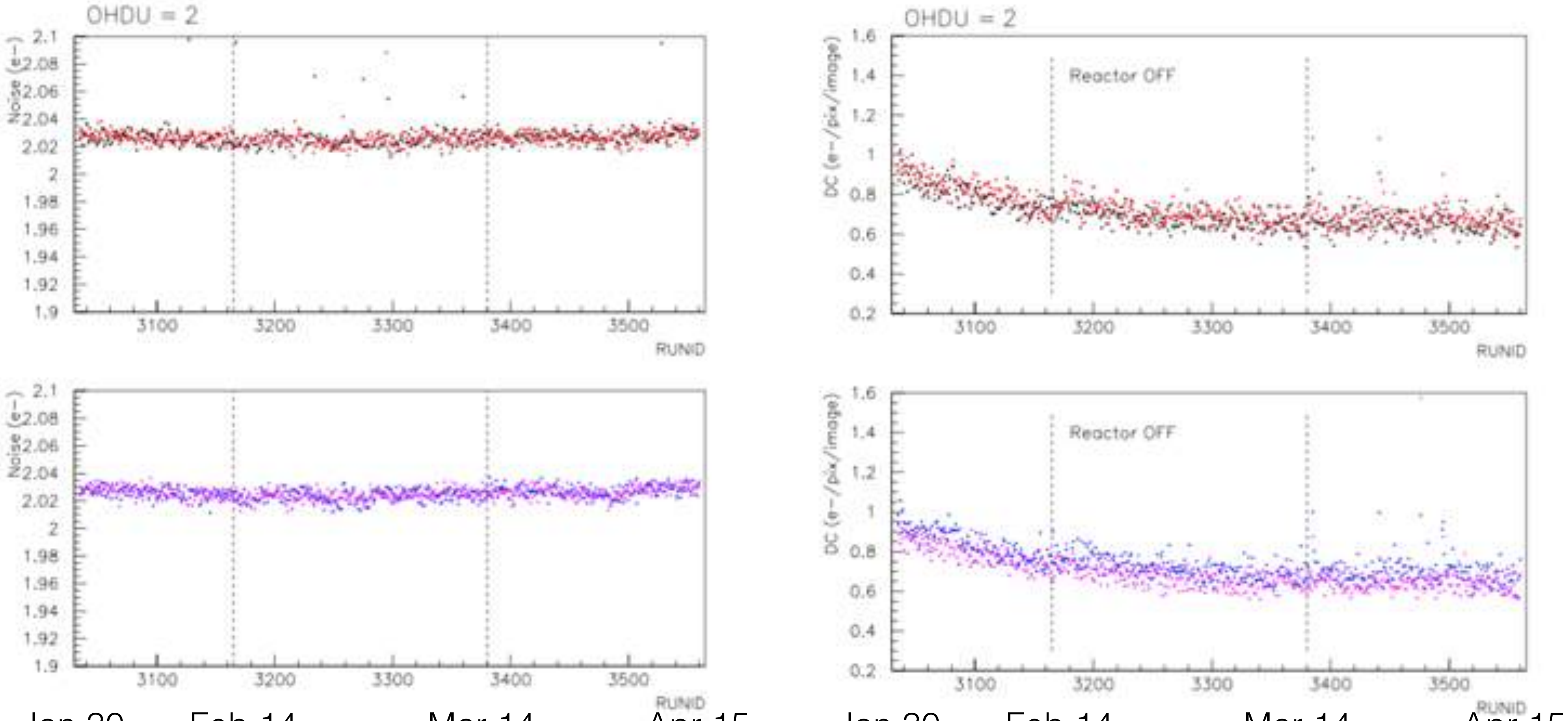
12 working CCDs – mass 5,8 g and 675 μm
In progress

Active mass and data collection efficiency



Performance: Noise and DC

Good performance in the last Reactor OFF/ON run



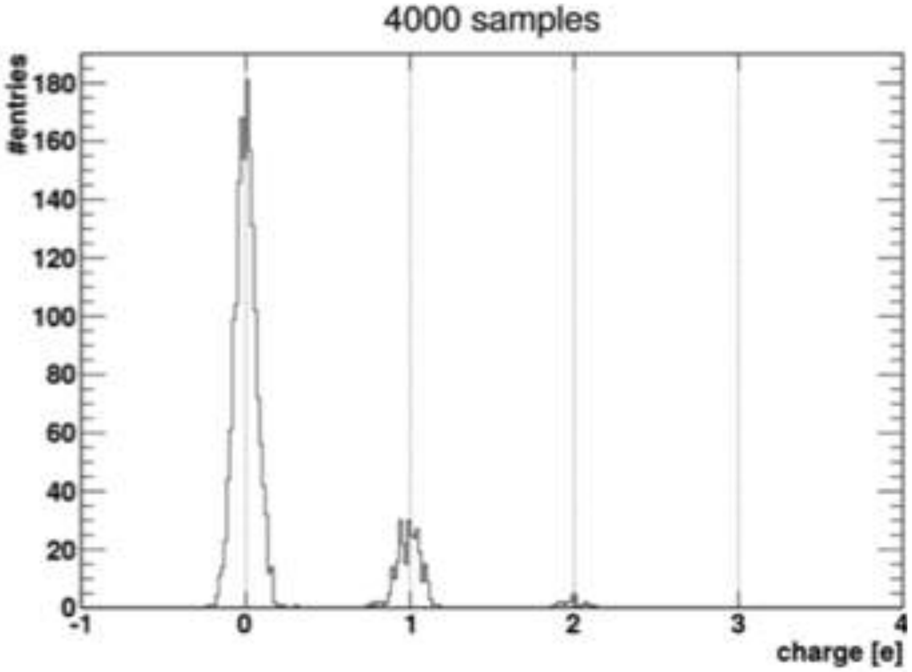
Jan 30 Feb 14 Mar 14 Apr 15

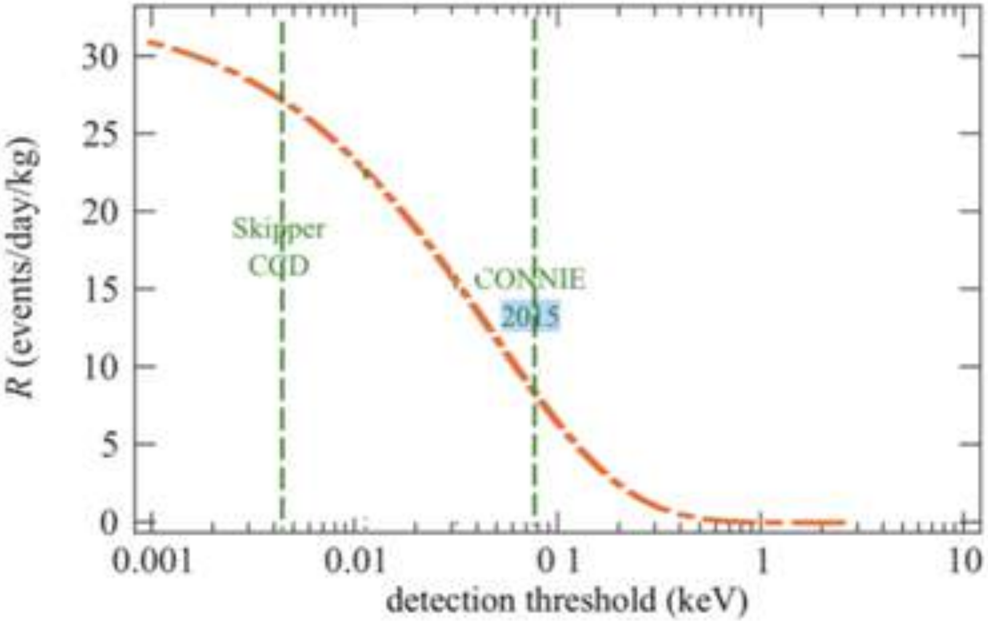
Jan 30 Feb 14 Mar 14 Apr 15

Analysis in progress

Next for CONNIE

- Finish the 2018 data analysis together with 2016/2017
- Continue taking more data
- Start to prepare the next detector generation – Skipper-CCD sensors.





We expect to get enough data in order to confirm the COHERENT result soon!

CEvNS was already measured (by COHERENT) and it is only the beginning…

CONNIE will soon able to confirm the detection and measure the CEvNS for very low energy neutrinos

- MeV-neutrino physics has great relevance for energy transport in supernovae
- Irreducible background for WIMP detection
- New physics beyond Standard Model
- New tool for neutrino experiments (very short baseline oscillation experiments – low energy)
- Monitor nuclear reactors through their emitted neutrinos

Other efforts in CEvNS detection by other experiments like MINER not covered here