Detecting Coherent elastic neutrino-nucleus scattering

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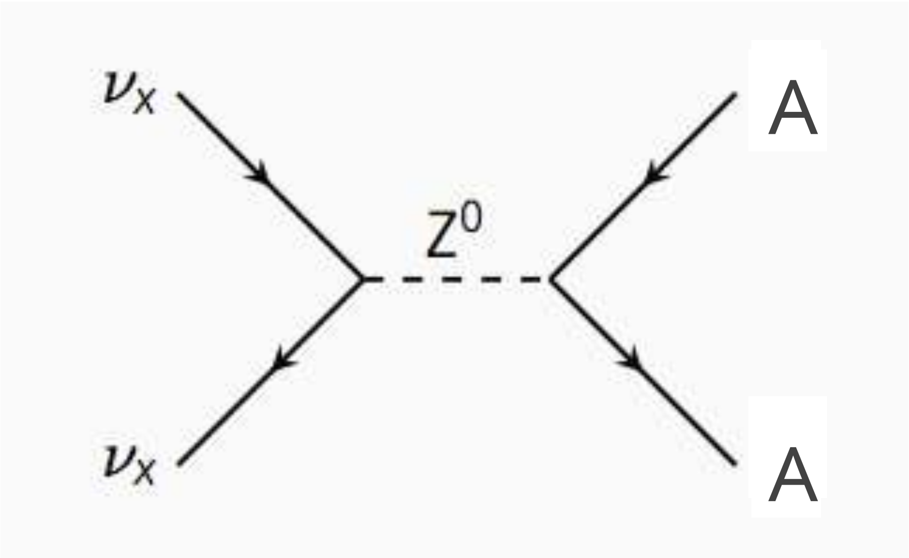
NOVEMBER 8-12, 2021

What is CEνNS?



Coherent Elastic
Neutrino-Nucleus Scattering

is a process in which neutrinos scatter off a nucleus acting as a single particle

- Predicted in 1974 by Freedman
  D. Freedman, Phys.Rev. D 9 1389 (1974)

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

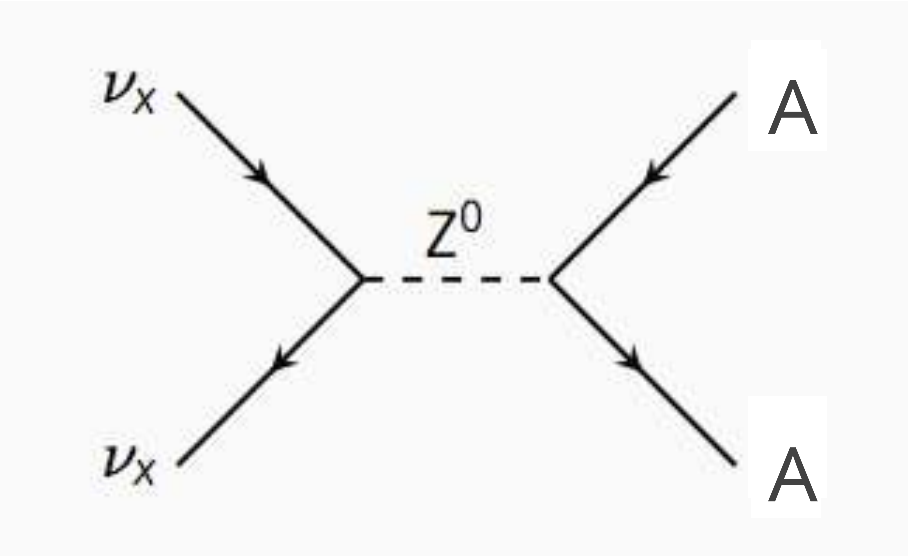
Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm^2 on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \to \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

There is recent experimental evidence[1] from CERN and NAL which suggests the presence of a neutral current in neutrino-induced interactions. A primary goal of future neutrino experiments is important to interpret experimental results in a very broad theoretical framework.[4] We assume a general current-current effective Lagrangian

What is CEνNS?



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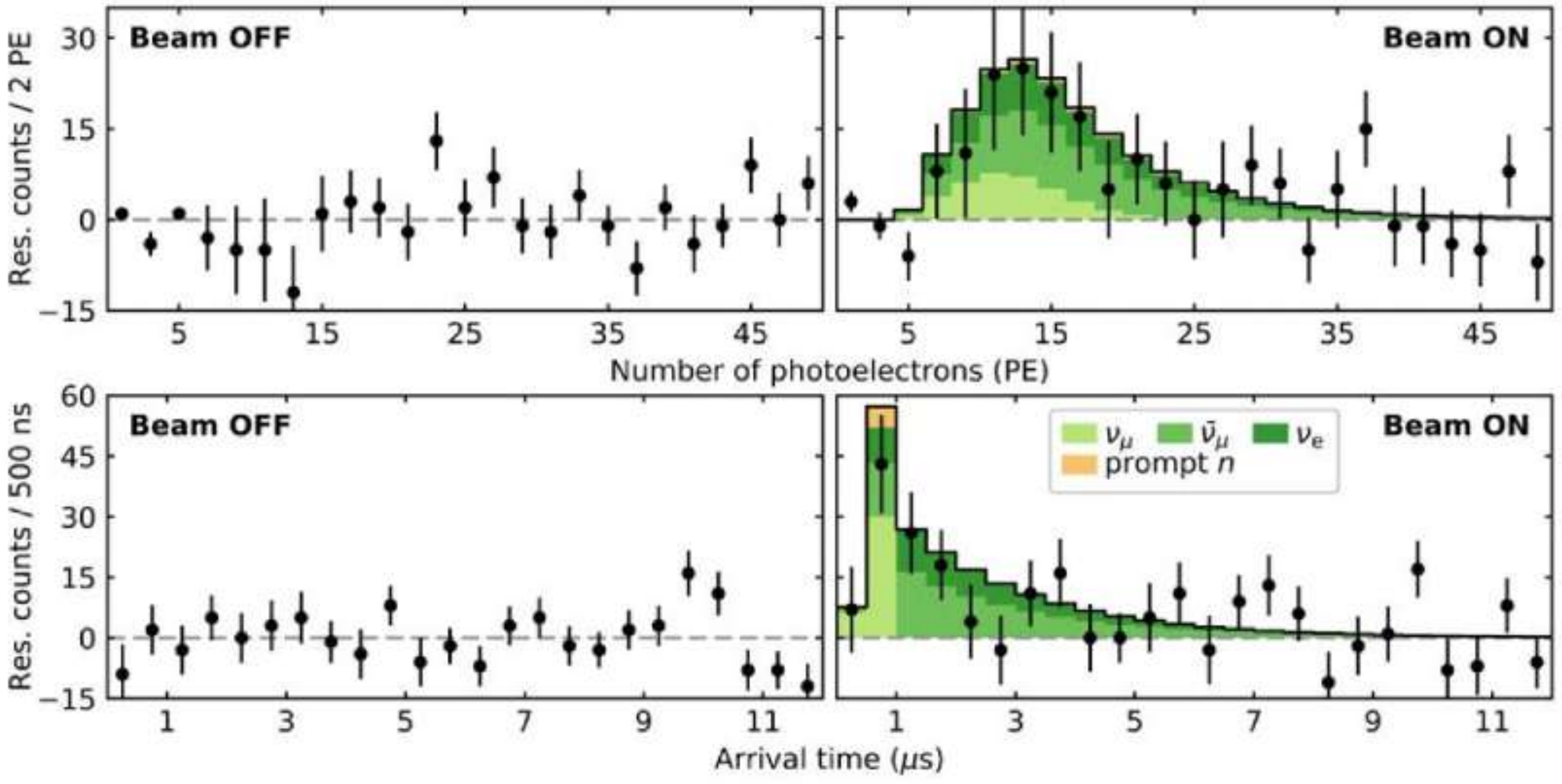

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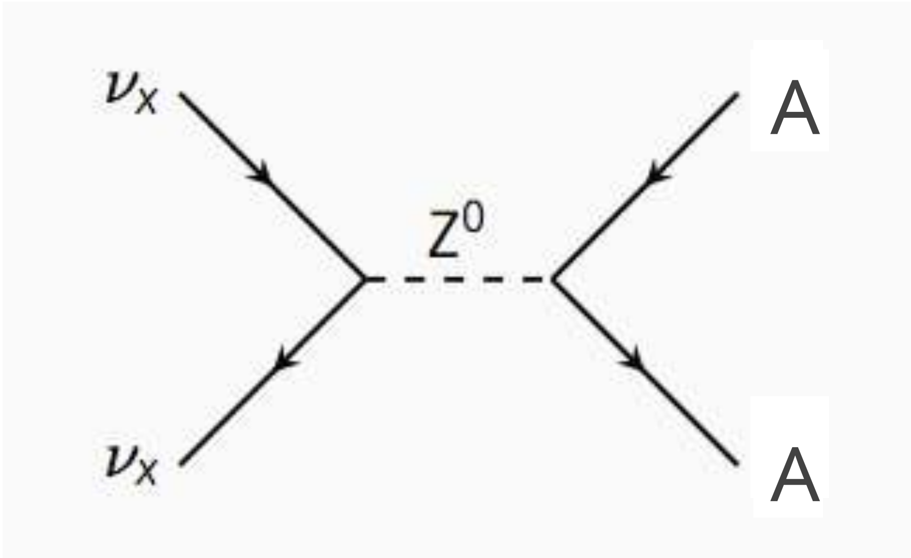

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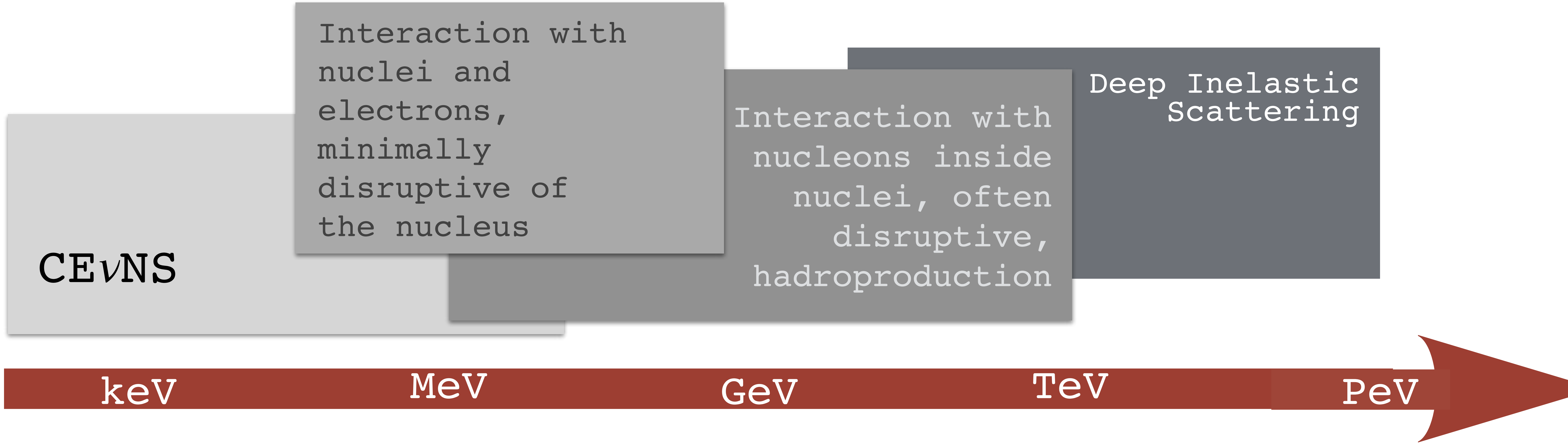

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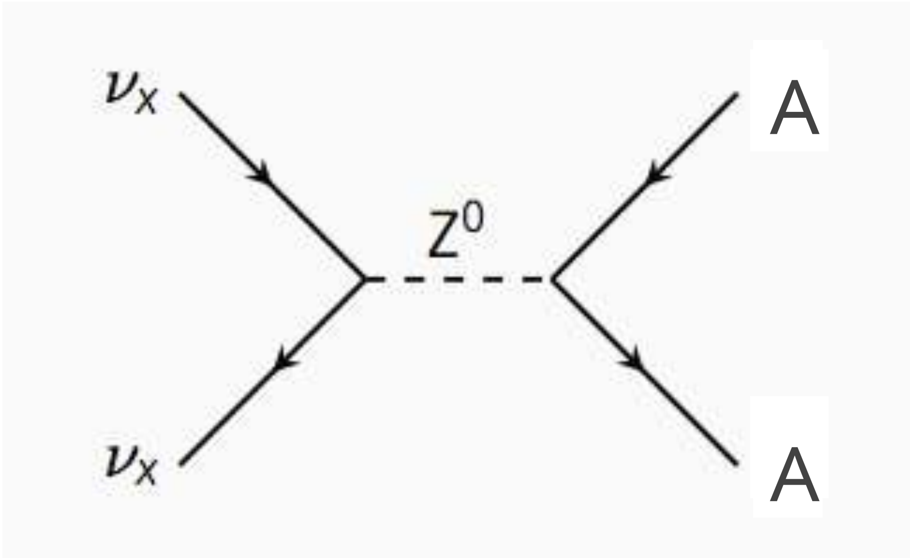

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- Dominant process for $E_\nu \lesssim 50$ MeV
- Cross section increases with N^2

For:
$$q \cdot R << 1$$

q = three-momentum transfer
R = nuclear radius

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

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

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

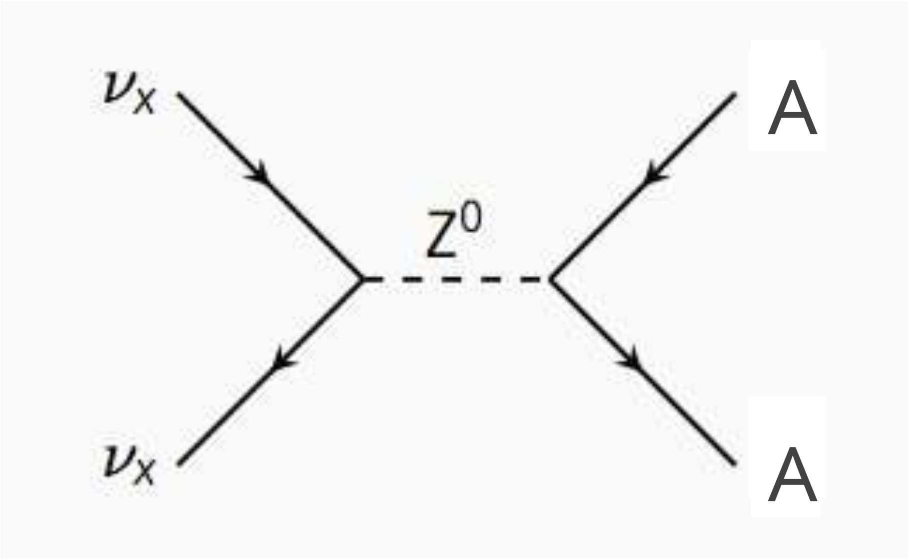
for: $\sin^2\theta_W \sim \frac{1}{4}(\approx 0.22)$

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

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

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

What is CEνNS?



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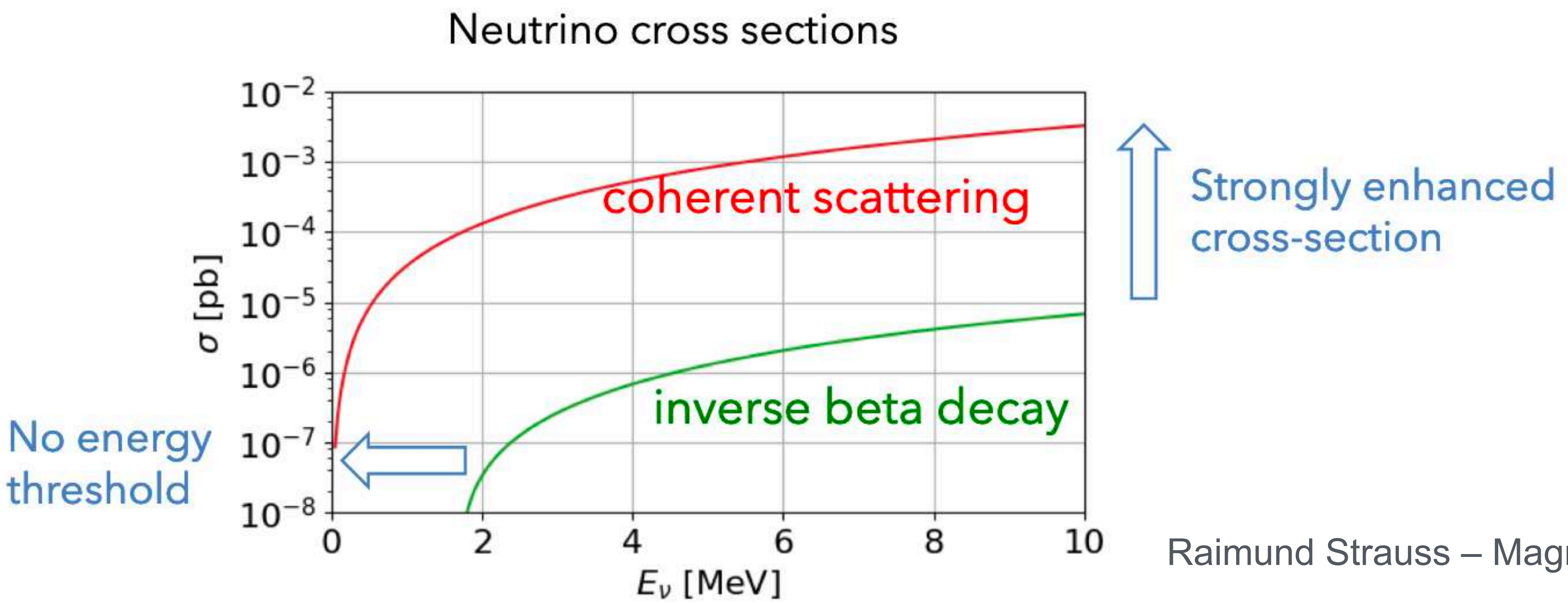
- Cross section increases with N^2 $\sigma_{SM} \sim \frac{G_F^2}{4\pi} N^2 E_\nu^2$



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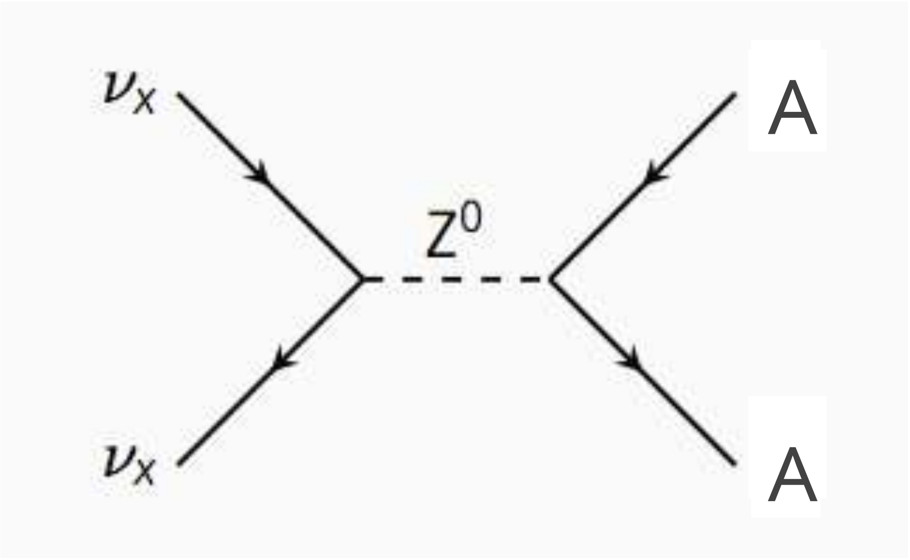
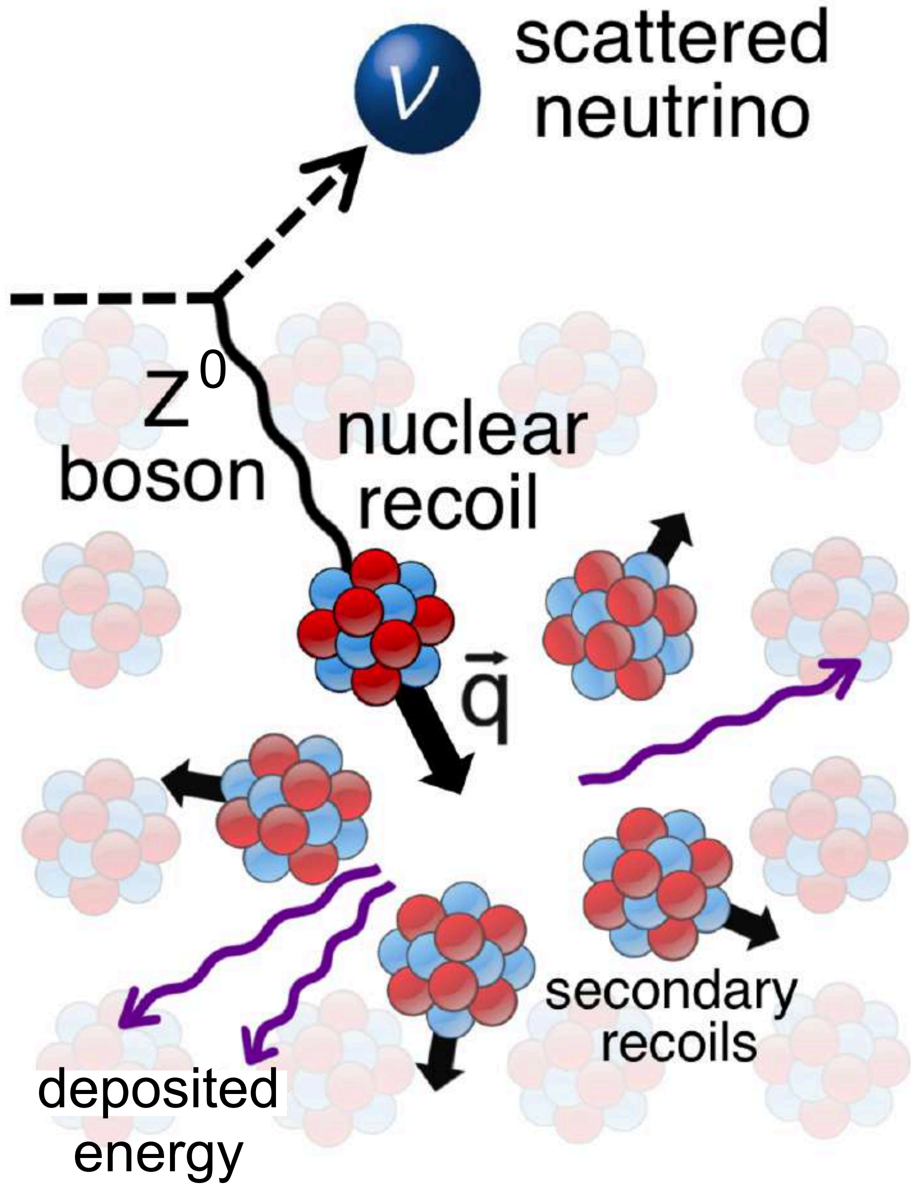


Large cross section...

...but hard to observe due to tiny nuclear recoil energies:

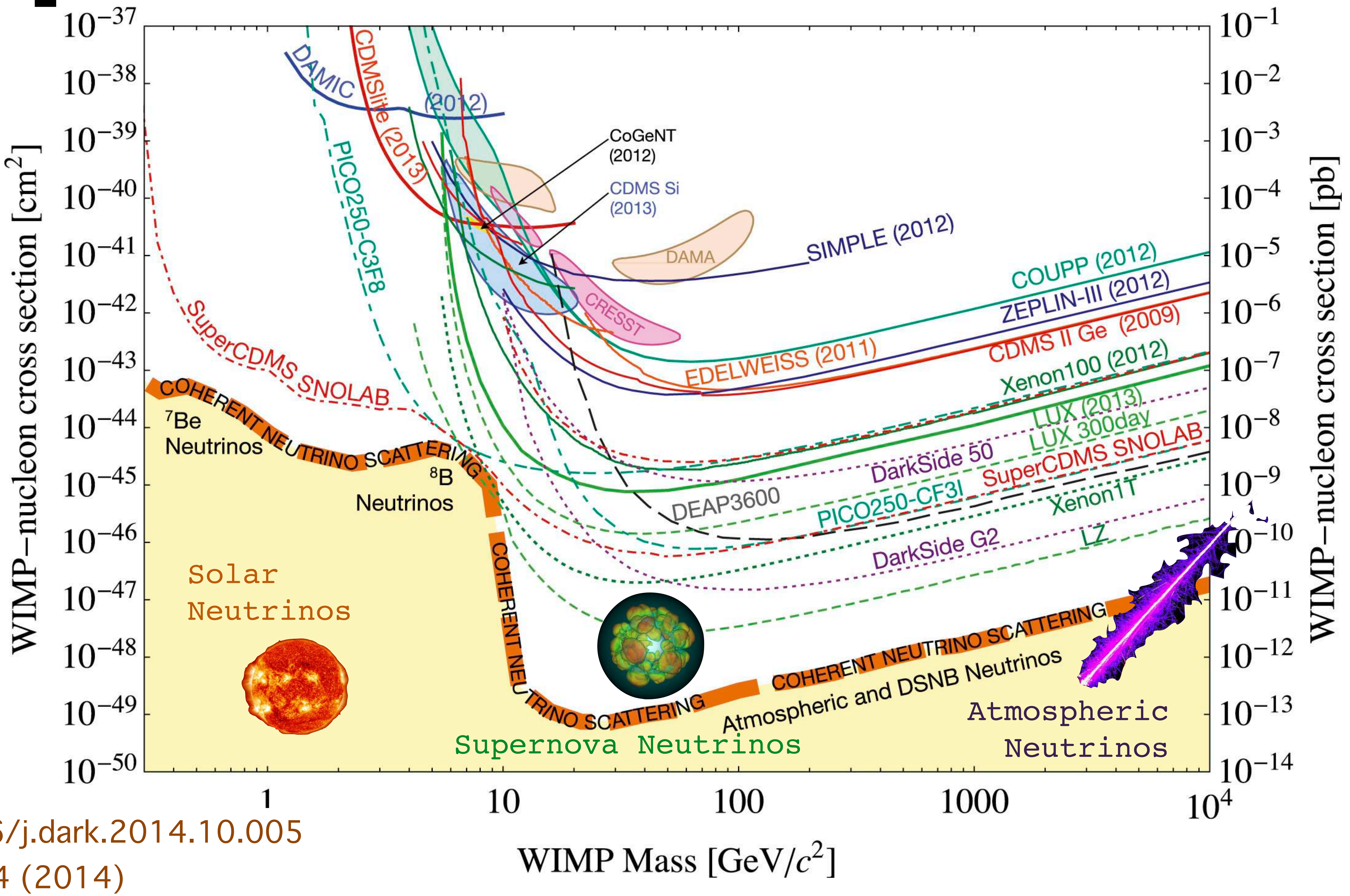
$$< E_r >= \frac{2}{3}\frac{(E_\nu/\text{MeV})^2}{A}\text{keV}$$



- Energies below the typical detection threshold of conventional neutrino experiments
- Now low threshold and background detectors available thanks to the efforts done for dark matter experiments.

Why CEνNS?

Background for DM experiments



https://doi.org/10.1016/j.dark.2014.10.005
Phys. Rev. D 89, 023524 (2014)

What is CEνNS good for?

Fundamental neutrino interactions

- Precision test of SM
  - cross section measurements
    arXiv: 1407.7524; arXiv: 2007.15688
  - Weinberg angle
    arXiv:2102.06153; arXiv:2108.07310
- Beyond SM physics
  - neutrino non-standard interactions (NSI)
    arXiv:1708.02899; arXiv:1708.04255; arXiv:1812.02778; arXiv:1911.09831
  - neutrino electromagnetic properties
    arXiv:1403.6344
  - light mediators
    arXiv:1910.04951; arXiv:1804.03660; arXiv:2008.05022
  - axion-like particles
    arXiv:1912.05733
  - light sterile neutrinos
    arXiv:1201.3805; arXiv:151102834; arXiv:1708.09518
  - dark matter
    arXiv:1711.04531; arXiv: 1710.10889

What is CEνNS good for?

Fundamental neutrino interactions

- Precision test of SM
- Beyond SM physics

Nuclear physics

- Nuclear form factor
  - form factor suppresses cross section at large three momentum transfer
  - very well known, < ~5% uncertainty on event rate
- Neutron distribution radius (Rn)

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

What is CEνNS good for?

Fundamental neutrino interactions

- Precision test of SM
- Beyond SM physics

Nuclear physics

- Nuclear form factor
- Neutron distribution radius (Rn)

Supernova neutrino

- Energy transport in supernovae: all neutrinos flavors with E ~ tens-of-MeV
- To detect SN neutrinos (tonne-scale DM detectors)

Lang et al PRD 94, 10 (2016) 103009

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Reactor physics

- Reactor monitoring
- Application for non-proliferation

A. Bernstein, et al Rev. Mod. Phys. 92 (2020) no.1, 011003

Neutrino Sources

for CEνNS

Requirements:

- High flux
- Neutrino production well understood
- Low background rates
- Multiple flavors
- etc

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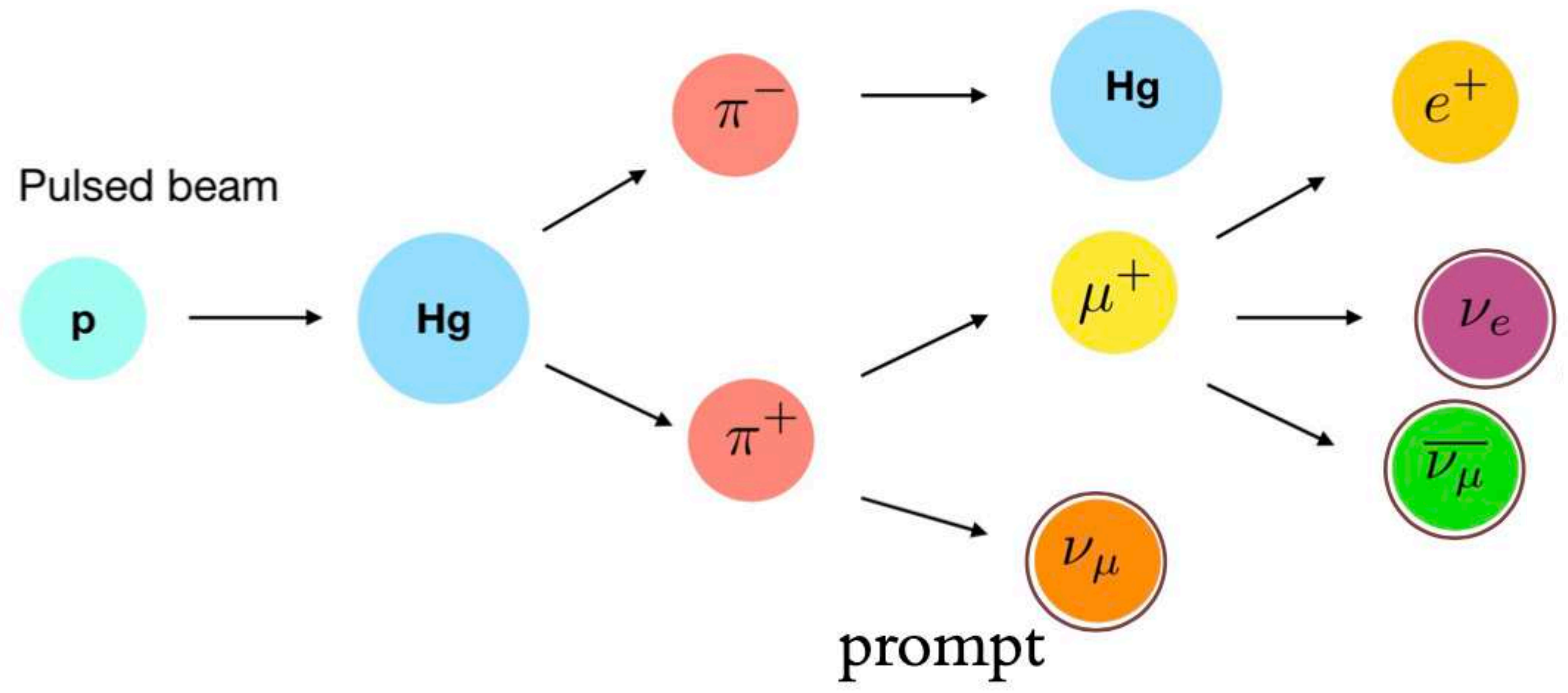


‣ Stopped-pion beams

Pion-decay-at-rest neutrino source:
neutrinos are produced from the decay of pions and muons

- intermediate neutrino energies (~ 30 MeV)
- slightly incoherent
- pulsed beam for background rejection

Neutrino Sources

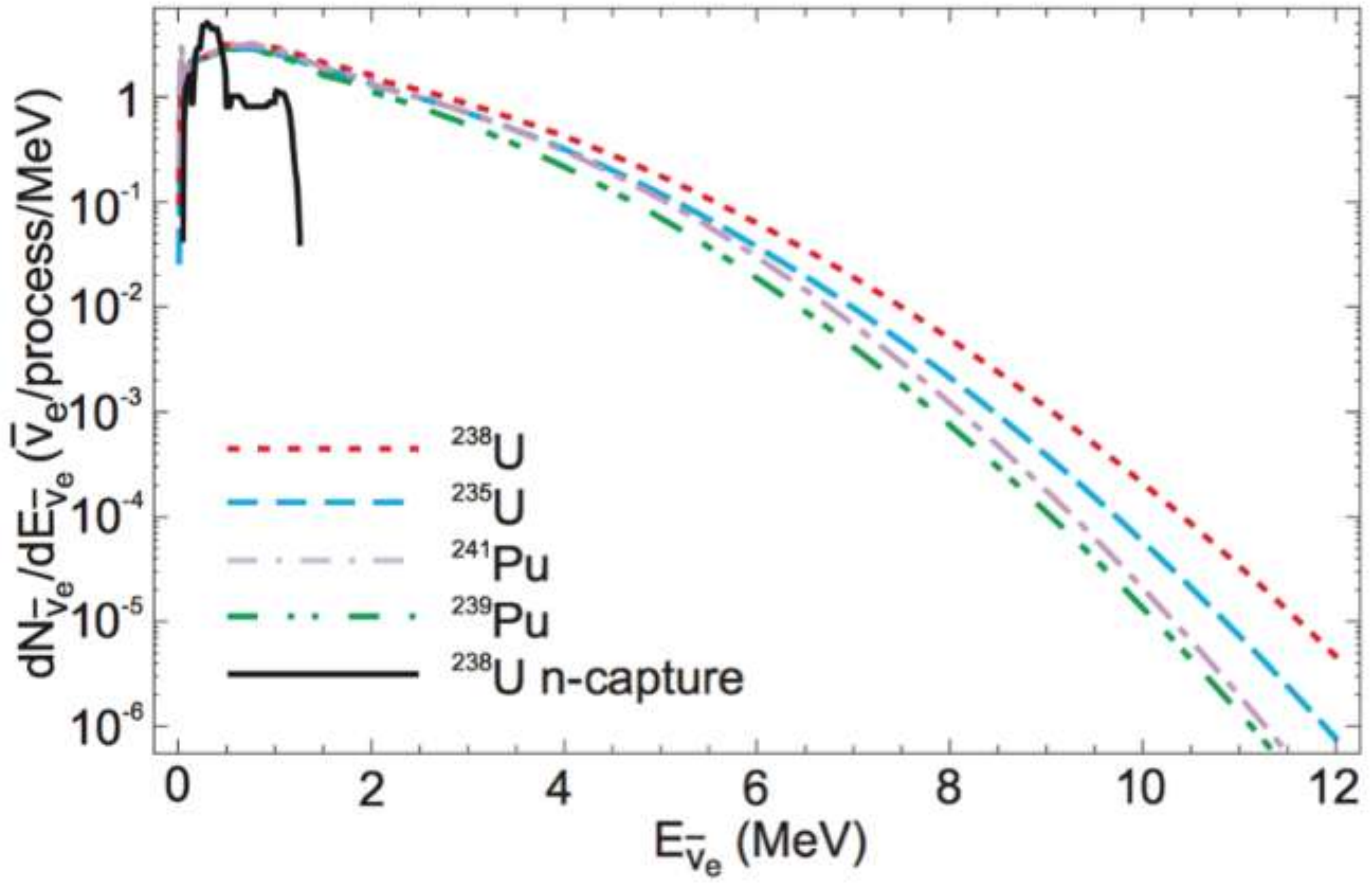
for CEνNS

Requirements:
- High flux
- Neutrino production well understood
- Low background rates
- Multiple flavors
- etc

Nuclear reactors

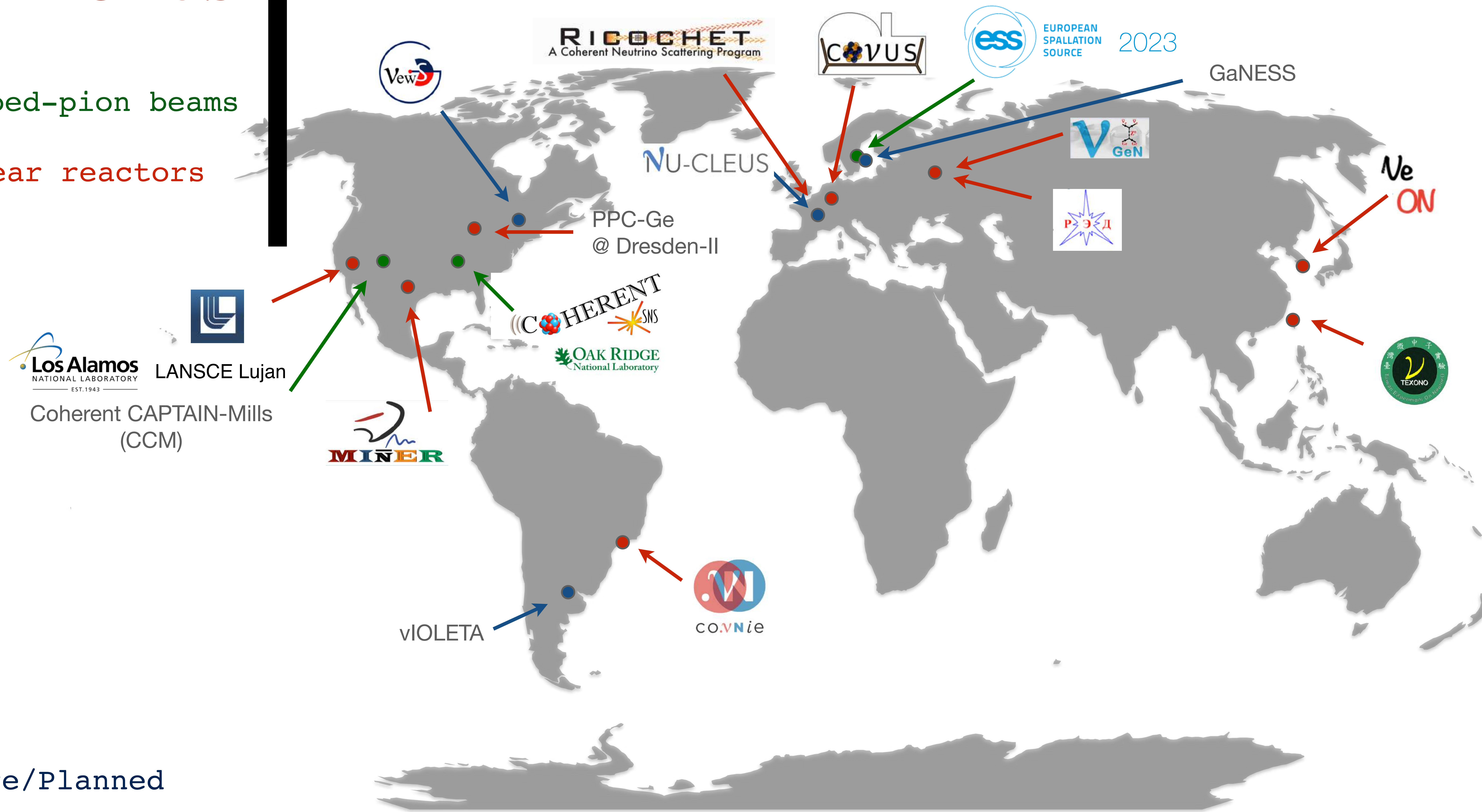
Neutrinos are produced in beta decays of fission fragments

- high flux ~ 10^{20} ν/s (power reactors)
- Intense @ MeV energies (up to 10 MeV)
- Clean in background, active and passive shielding



Experiments

- Stopped-pion beams
- Nuclear reactors

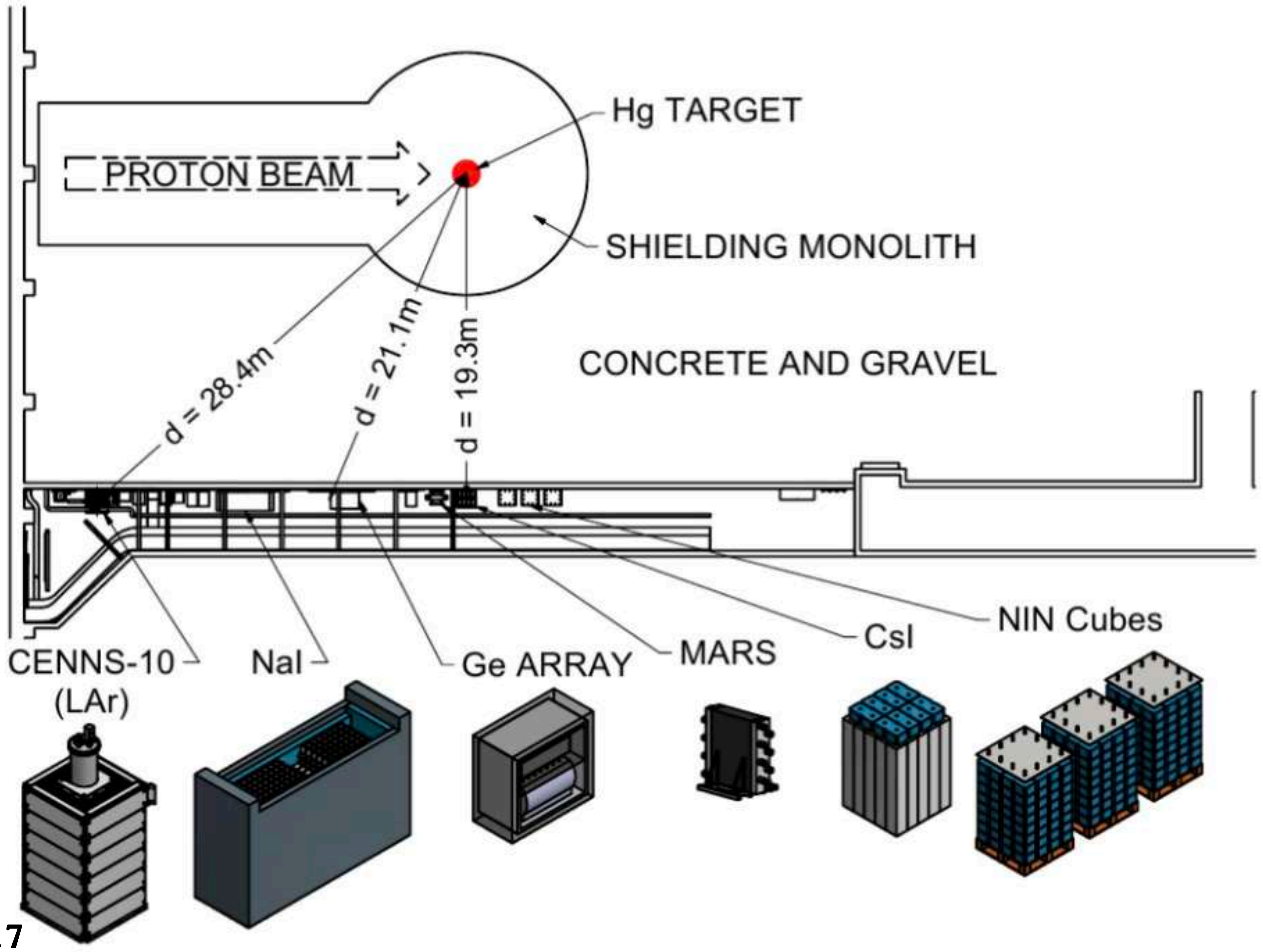


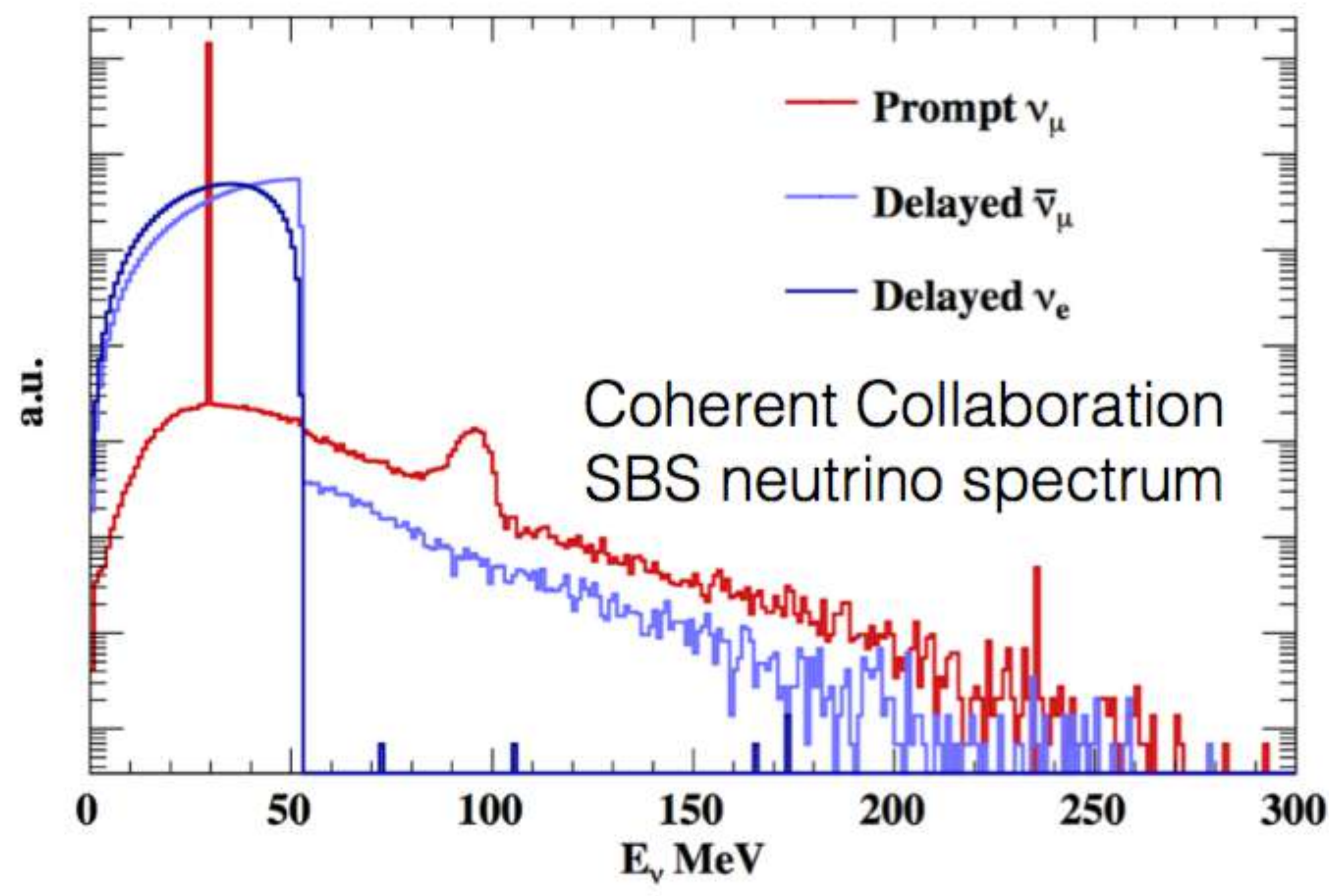
- Future/Planned

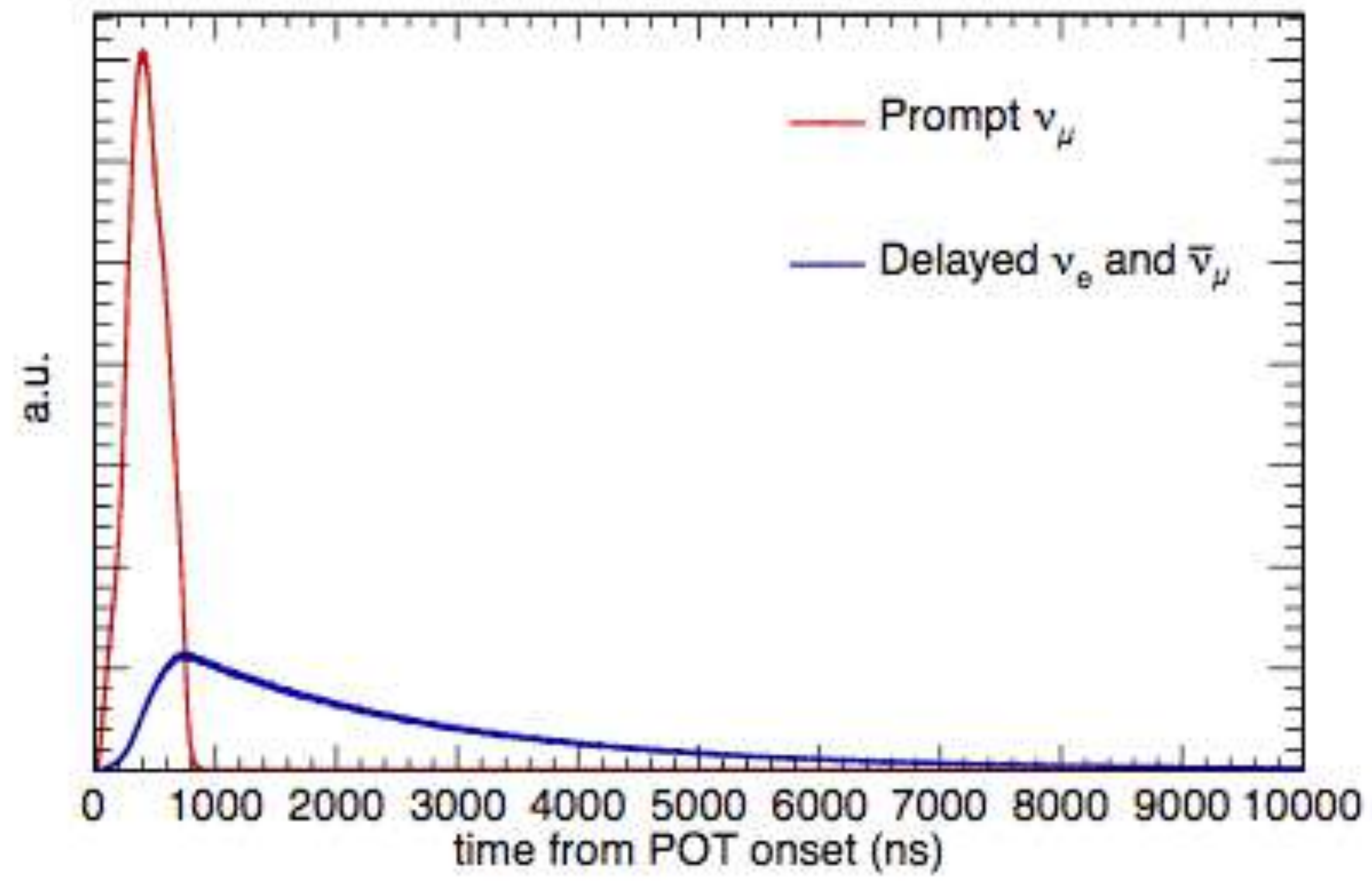
Stopped-pion beam experiments

COHERENT Experiment — SNS

- Spallation Neutron Source – 1 GeV proton beam
- Pion-decay-at-rest neutrino source
  - prompt monochromatic ~ 30 MeV
- Pulsed beam @ 60Hz for background rejection (factor ~ 10^4)
- Multi-target program to measure N^2 dependence



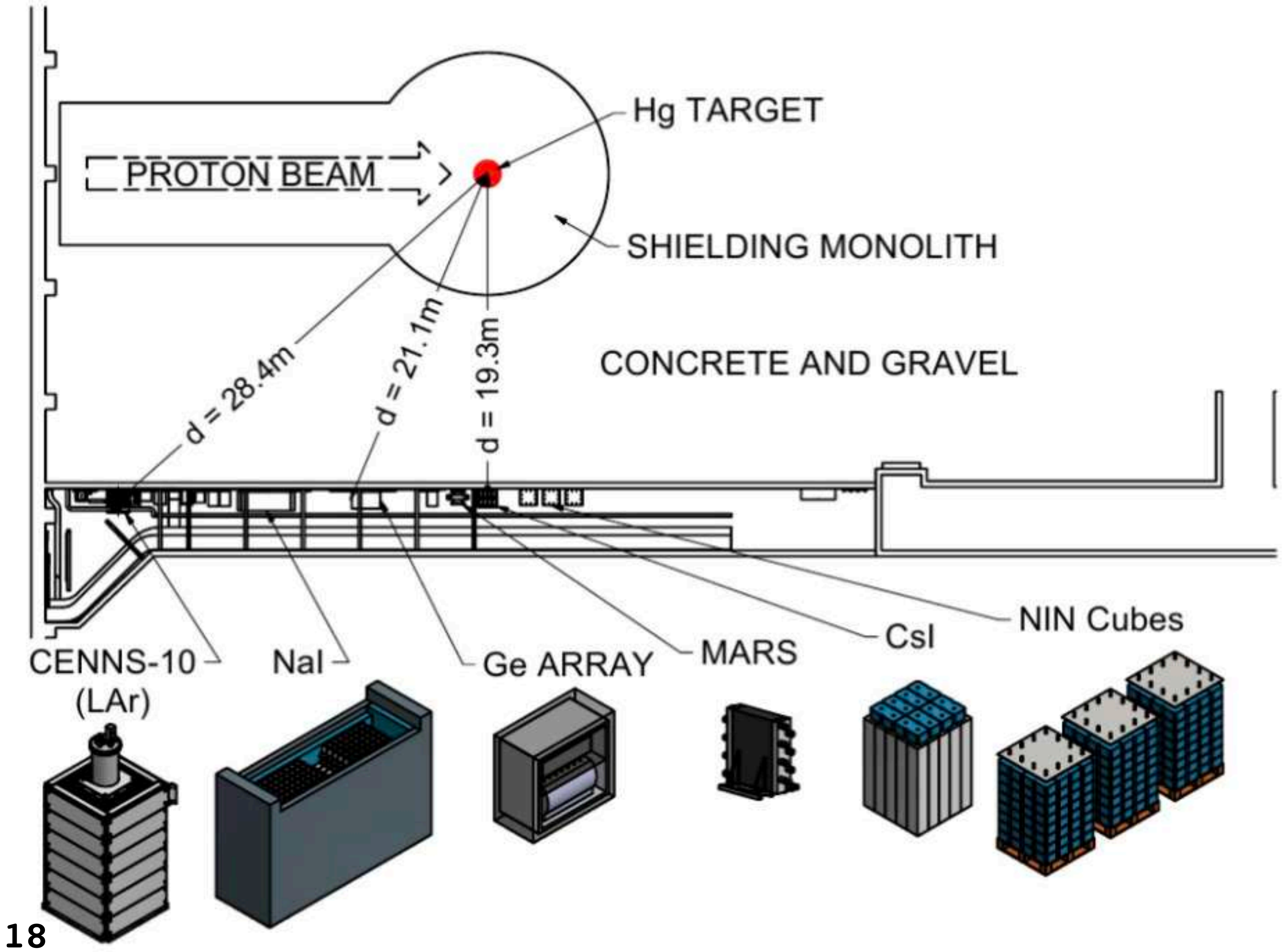


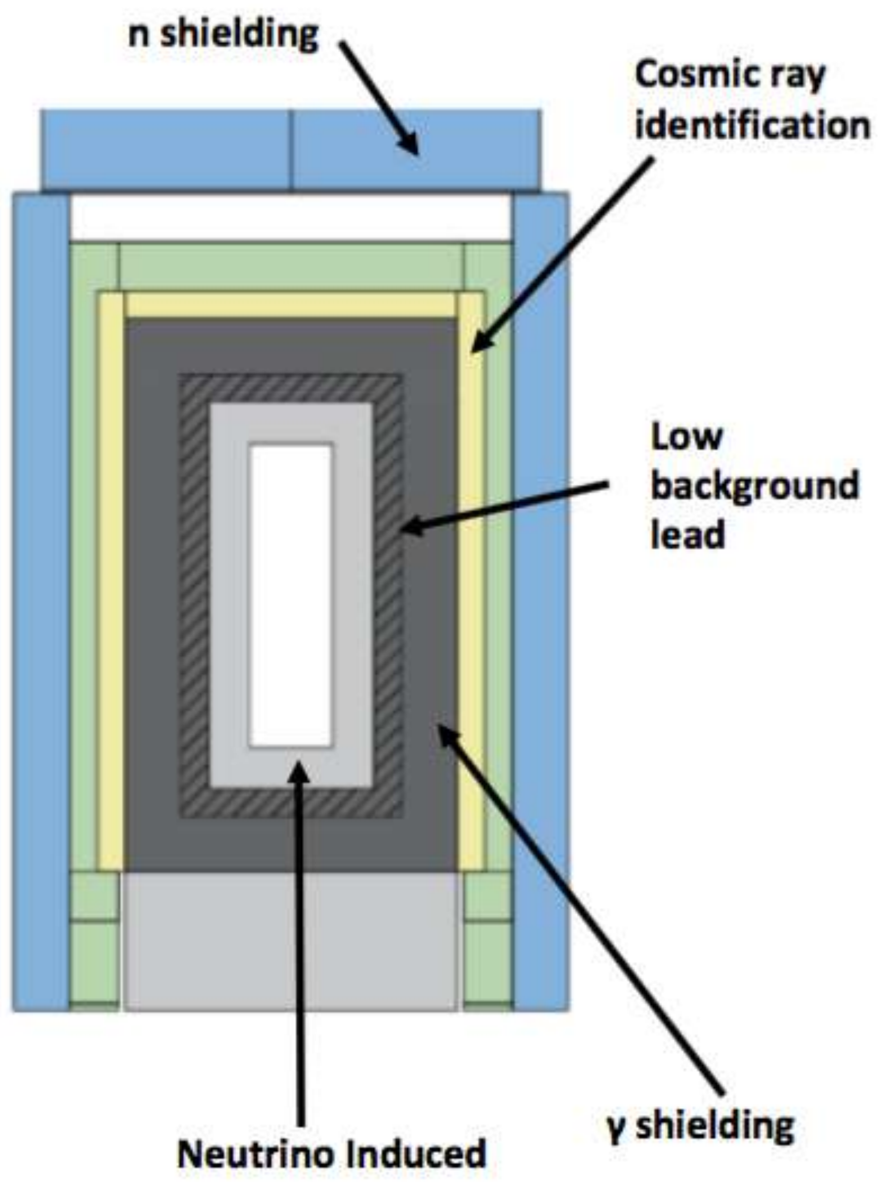


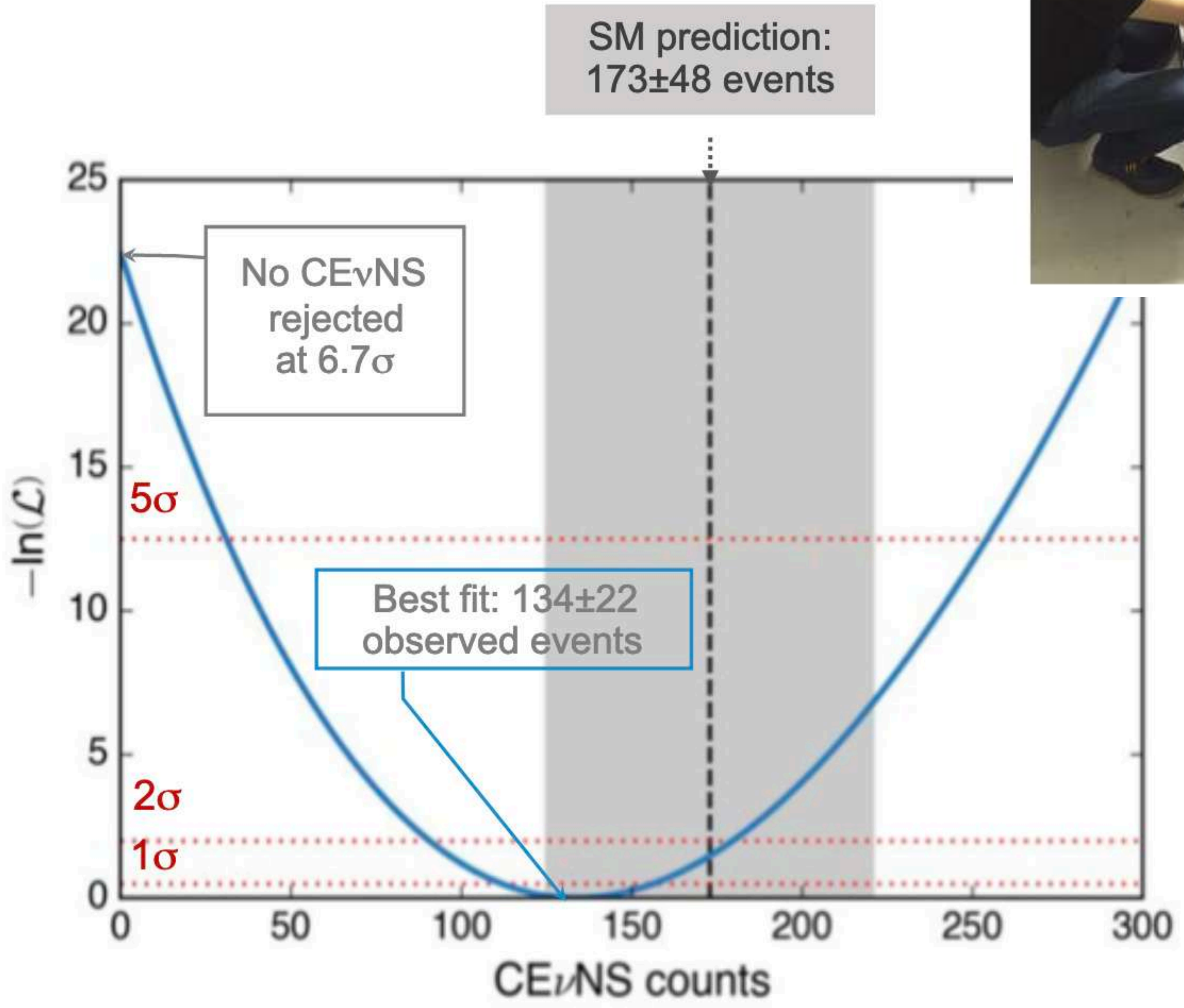
Stopped-pion beam experiments

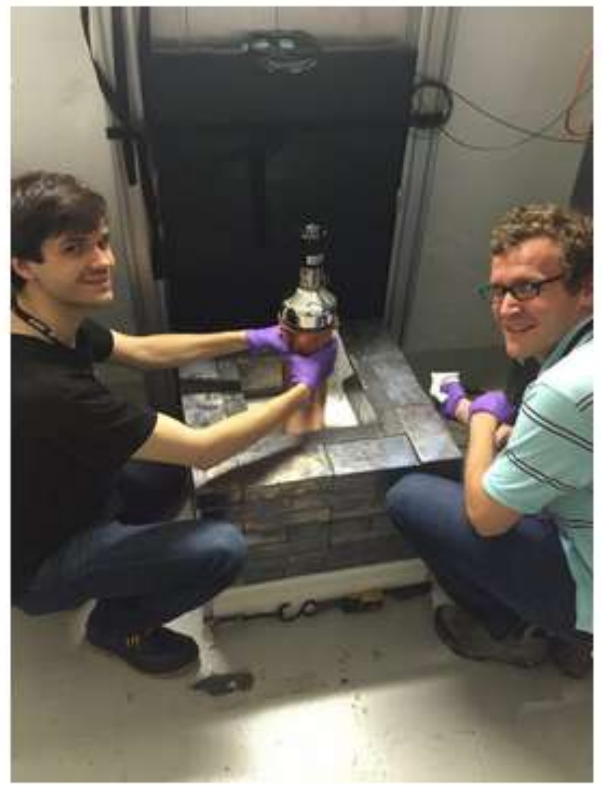
COHERENT CsI

- 2017 First CEνNS detection
- 14.6 kg CsI scintillating cristal
- 19.3 m from the source
- 134 ± 22 events observed (173 ± 48 predicted)
- 6.7σ significance







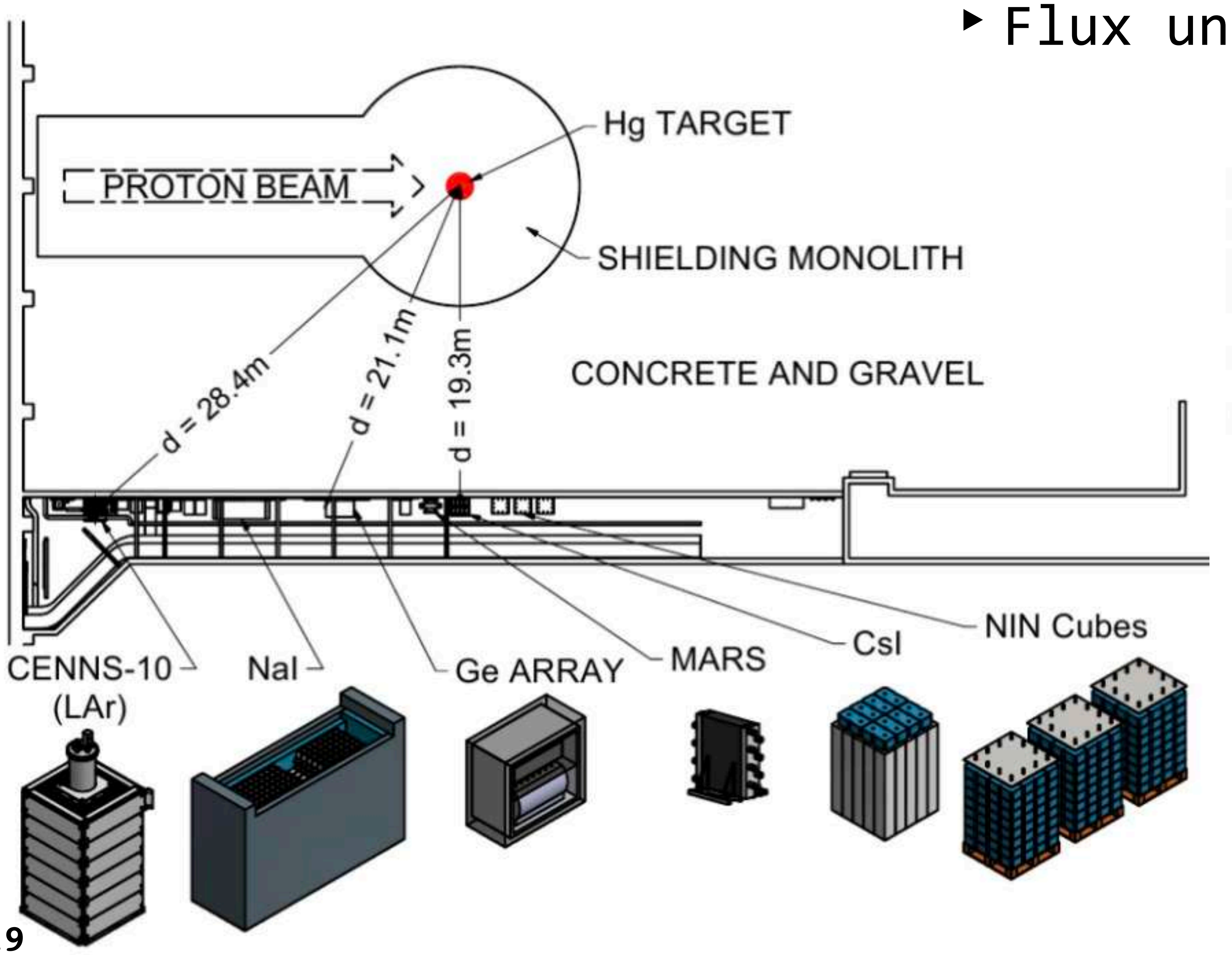


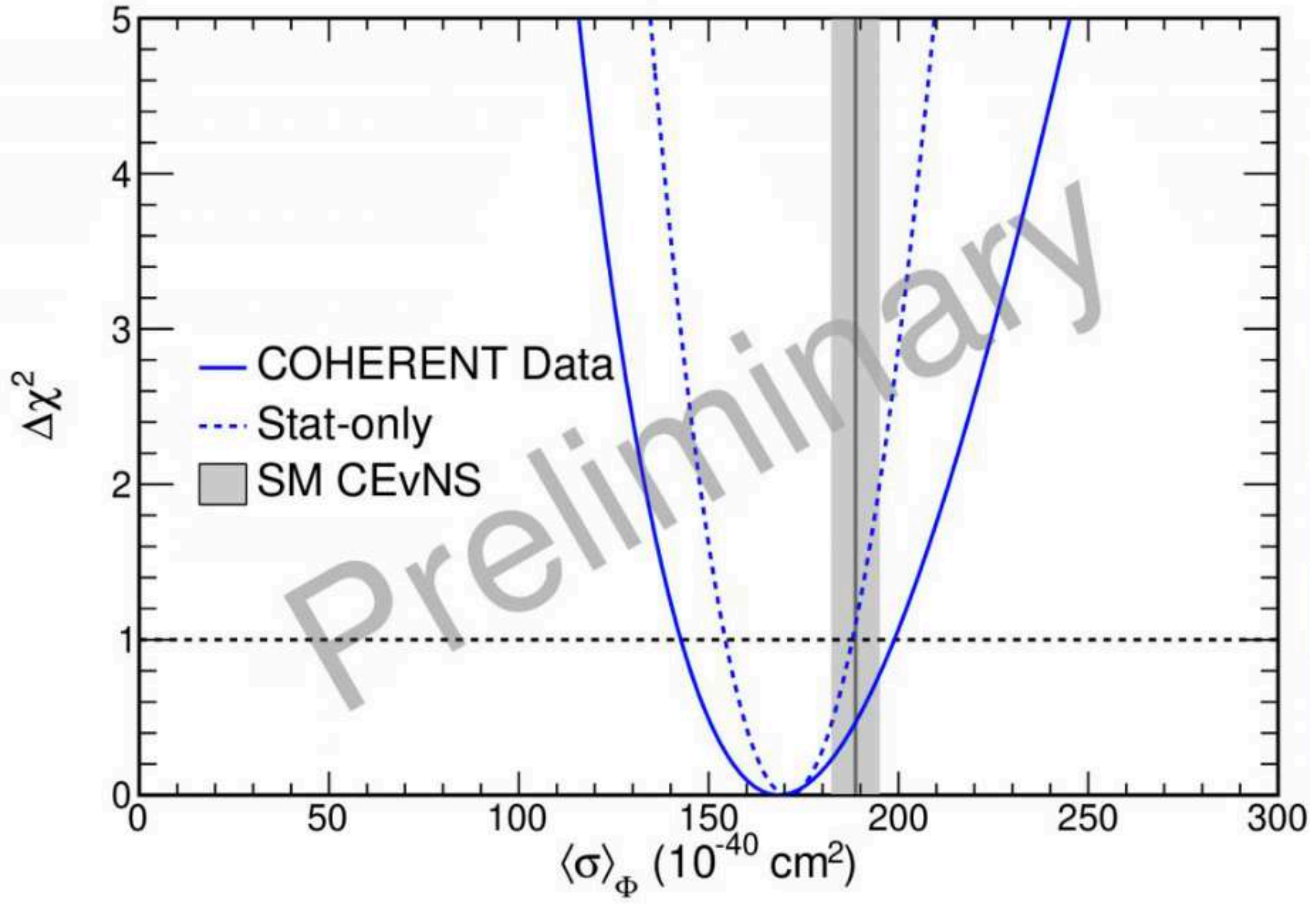
M. Green @ Magnificent CEvNS 2019

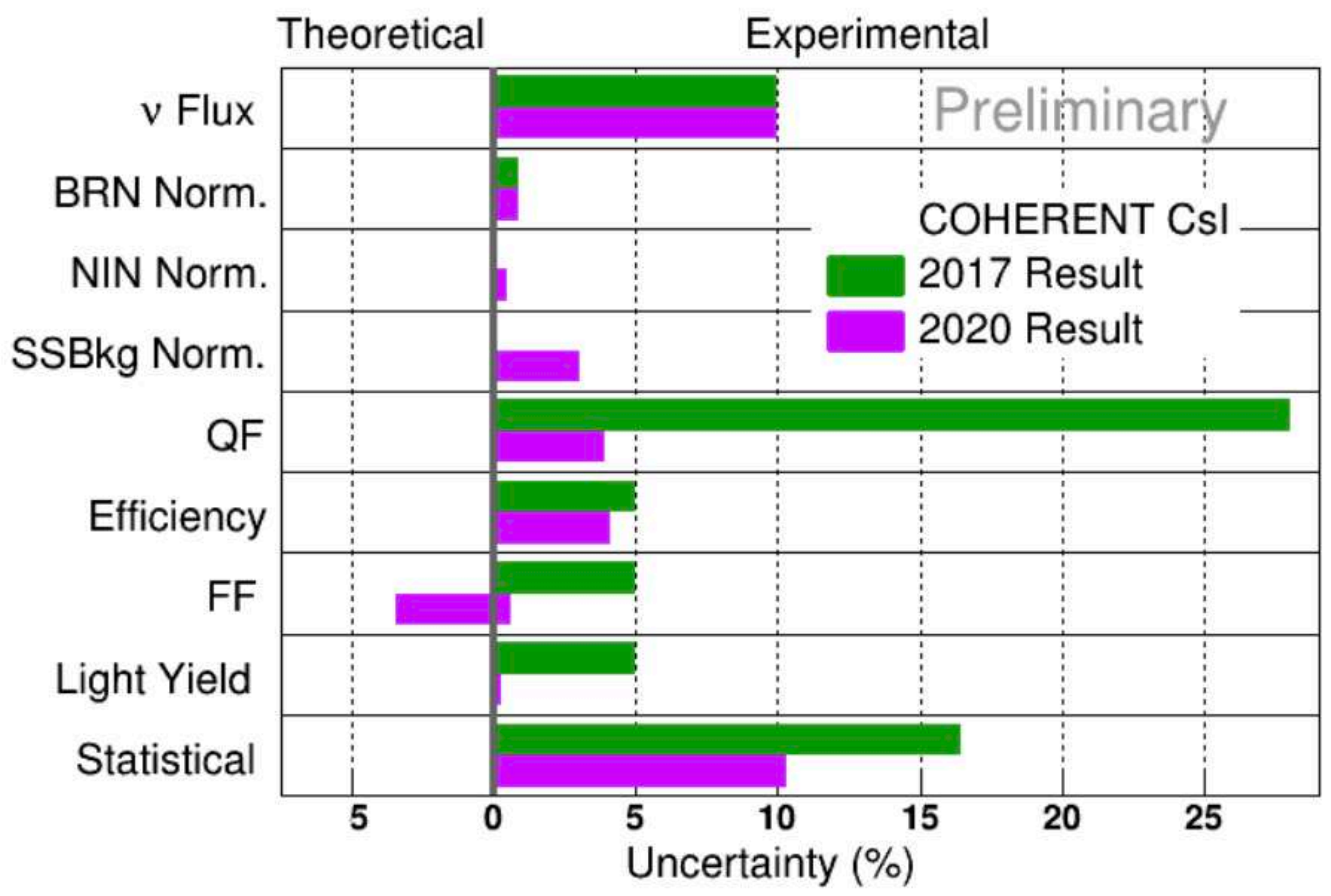
Stopped-pion beam experiments

COHERENT CsI 2020

- 2020 More statistics! +2x
- Better signal reconstruction
- 306 ± 20 events observed (333 ± 11 (th) ± 42 (ex) predicted)
- No CEνNS rejection: 11.6σ
- Result consistent with SM prediction at 1σ
- Flux uncertainty dominates the systematic uncertainties (13%)





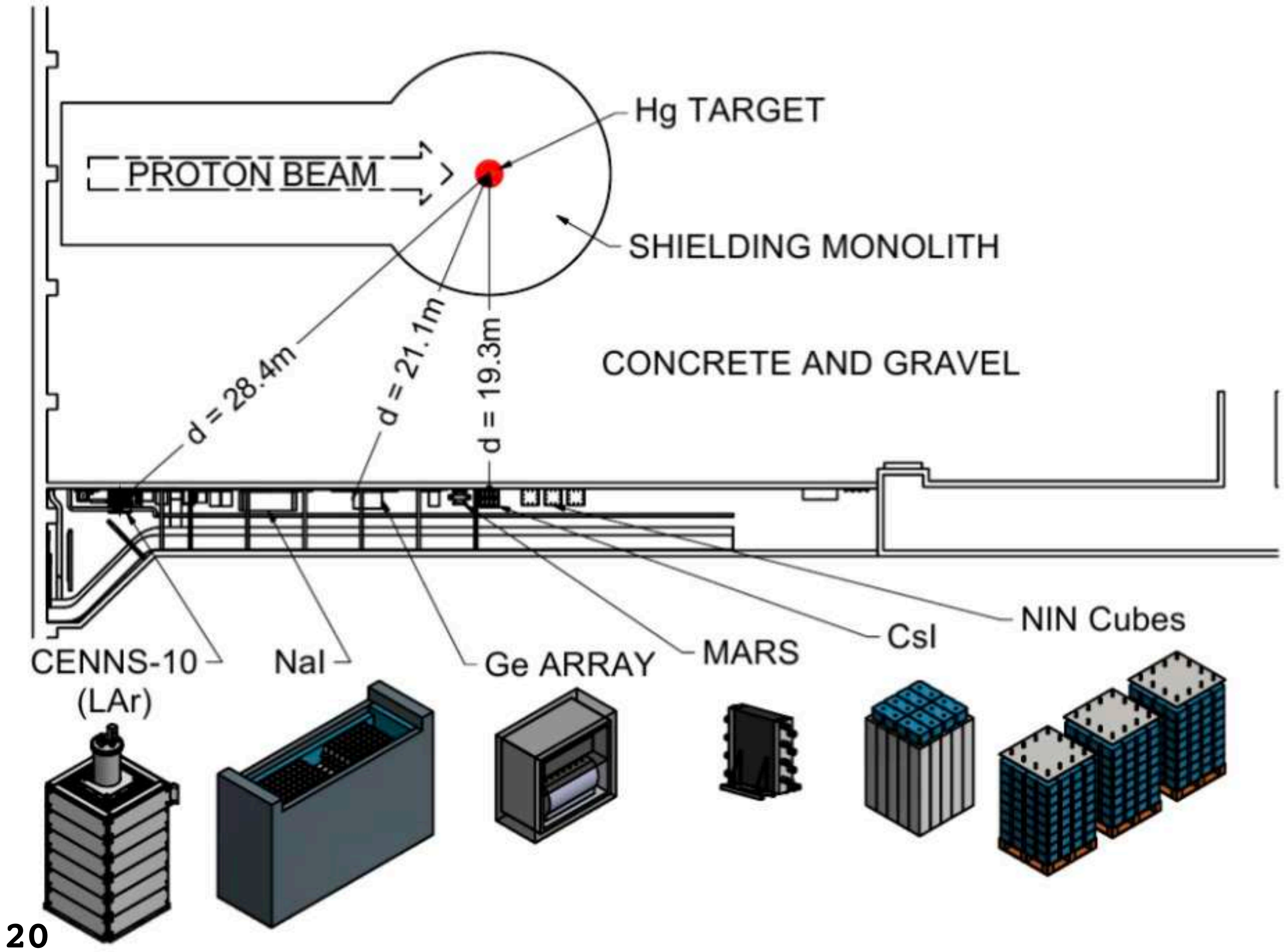


D. Pershey @ Magnificent CEvNS 2020

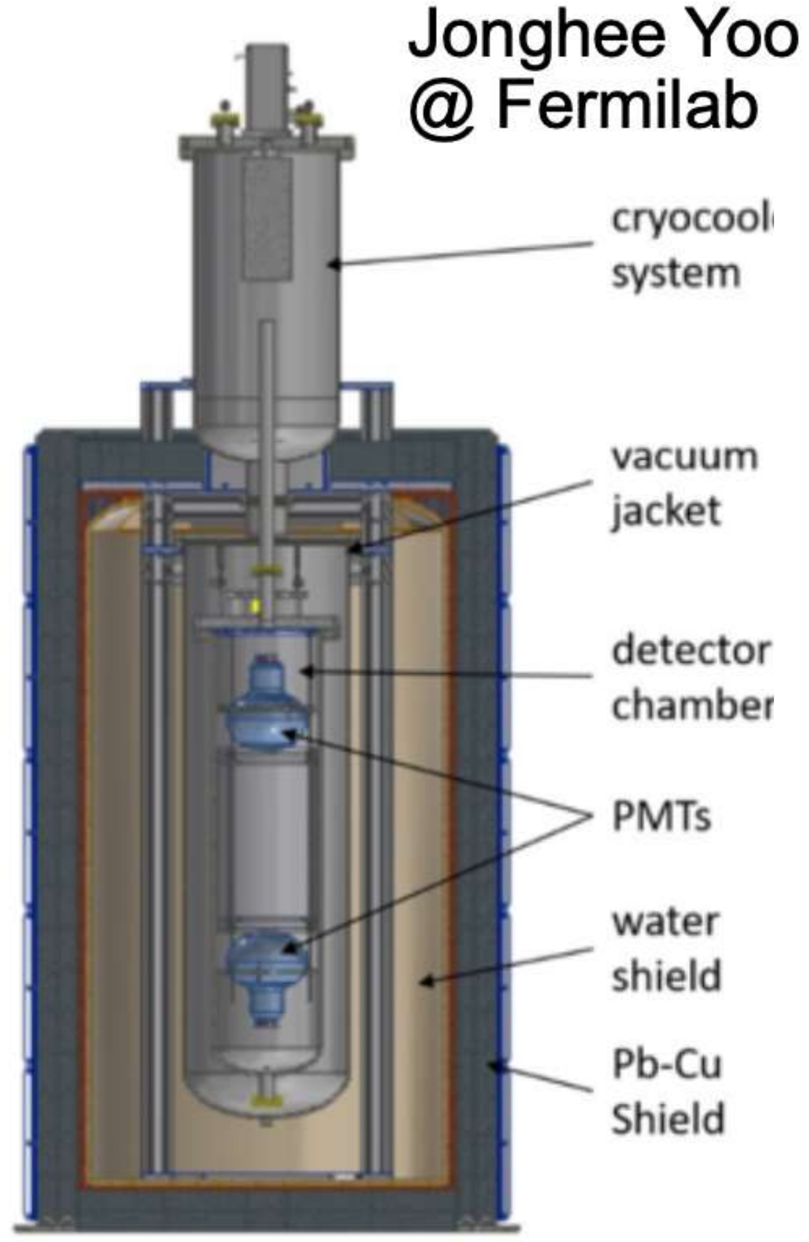
Stopped-pion beam experiments

COHERENT in Argon

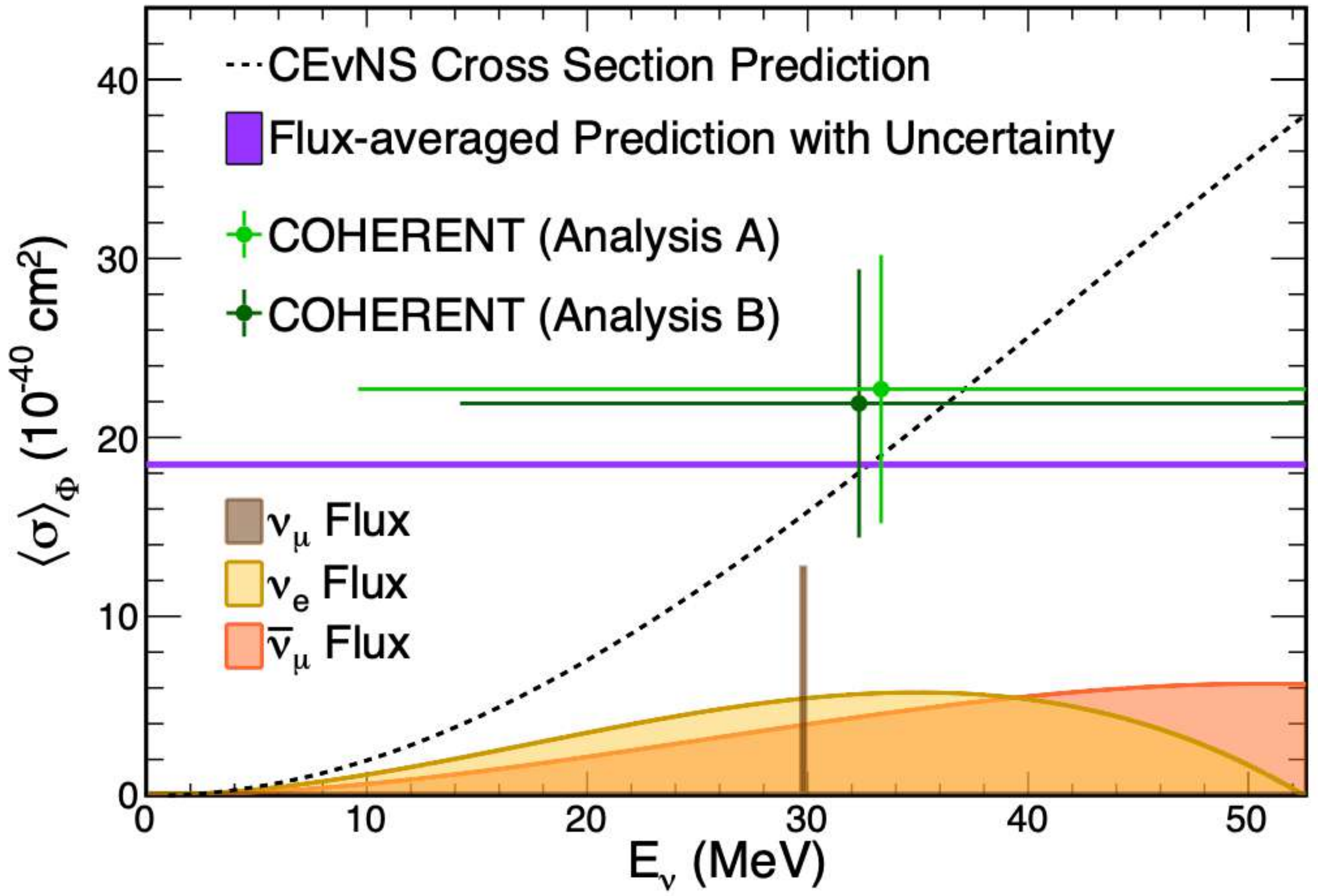
- 2020 first results with he CENNS-10 detector
- Active mass 24 kg at 27.5 m from the source
- Single phase only (scintillation) with a threshold at 20 keV_{nr}
- 2 independent blind analyses
- 3σ CEνNS detection significance



Jonghee Yoo @ Fermilab



Cross section = $(2.3 \pm 0.7)10^{-39}$ cm^2



COHERENT, Phys. Rev. Lett. 126, 012002 (2021)

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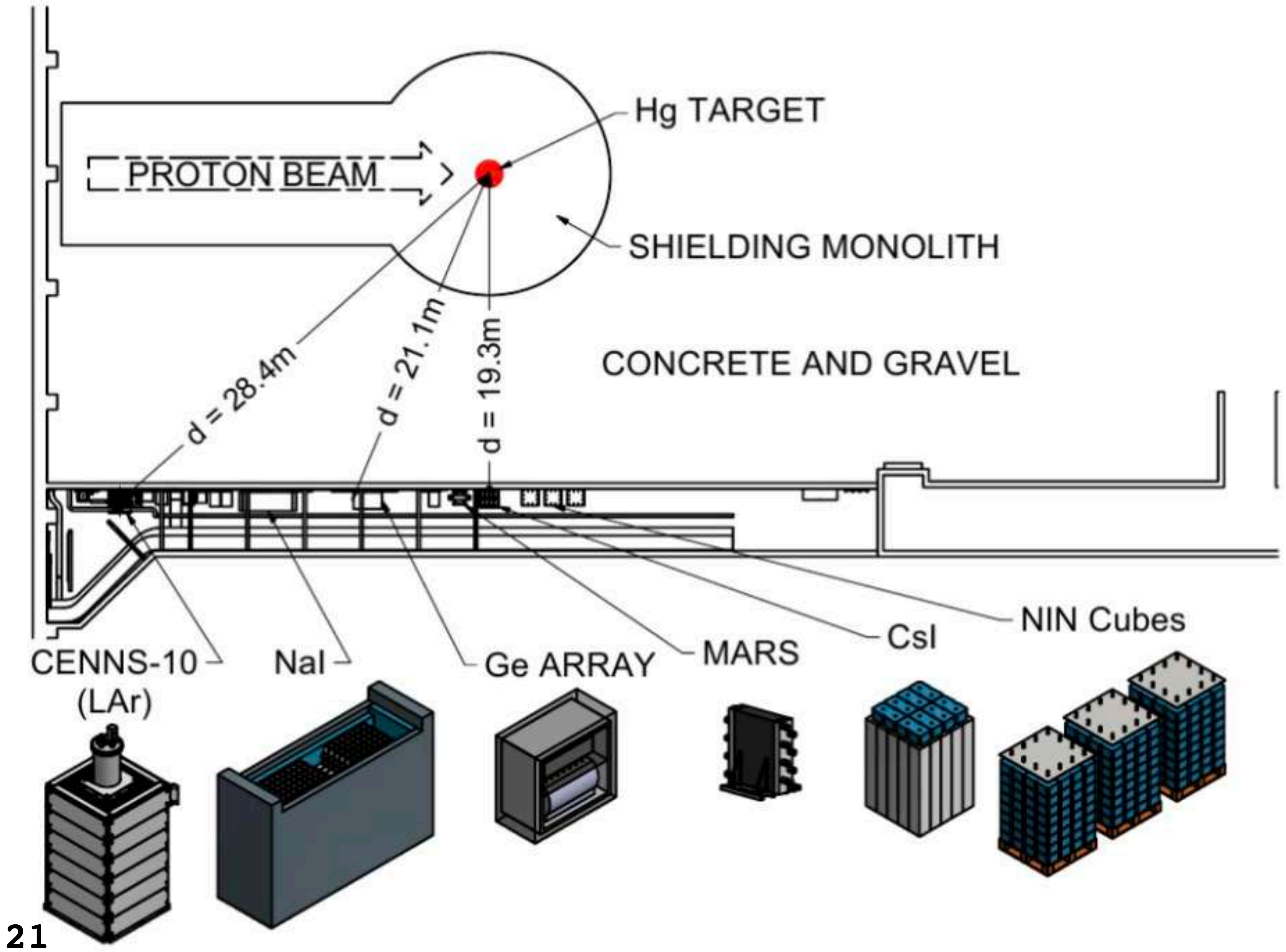
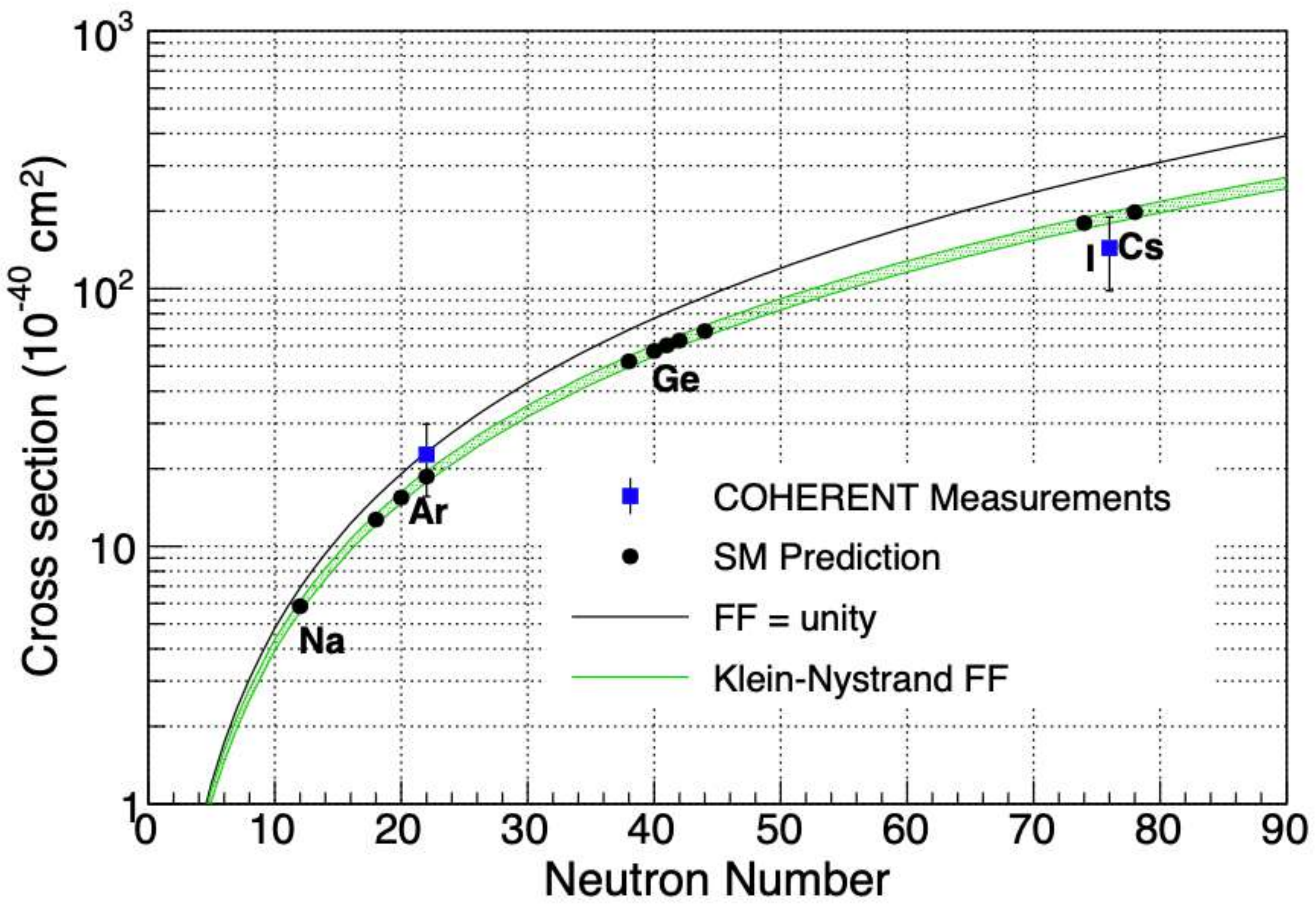


First confirmation of SM prediction of N^2 dependence !

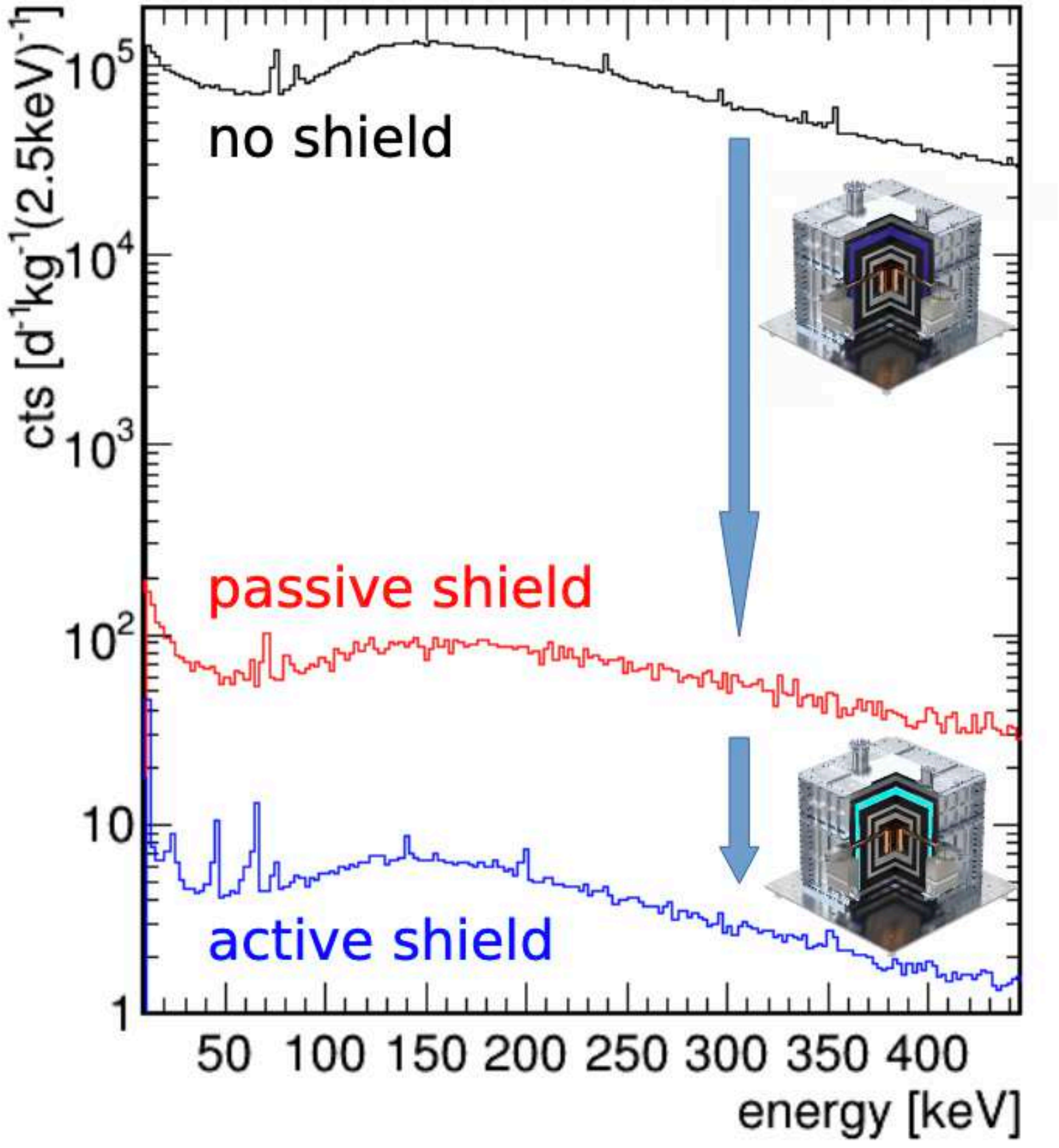


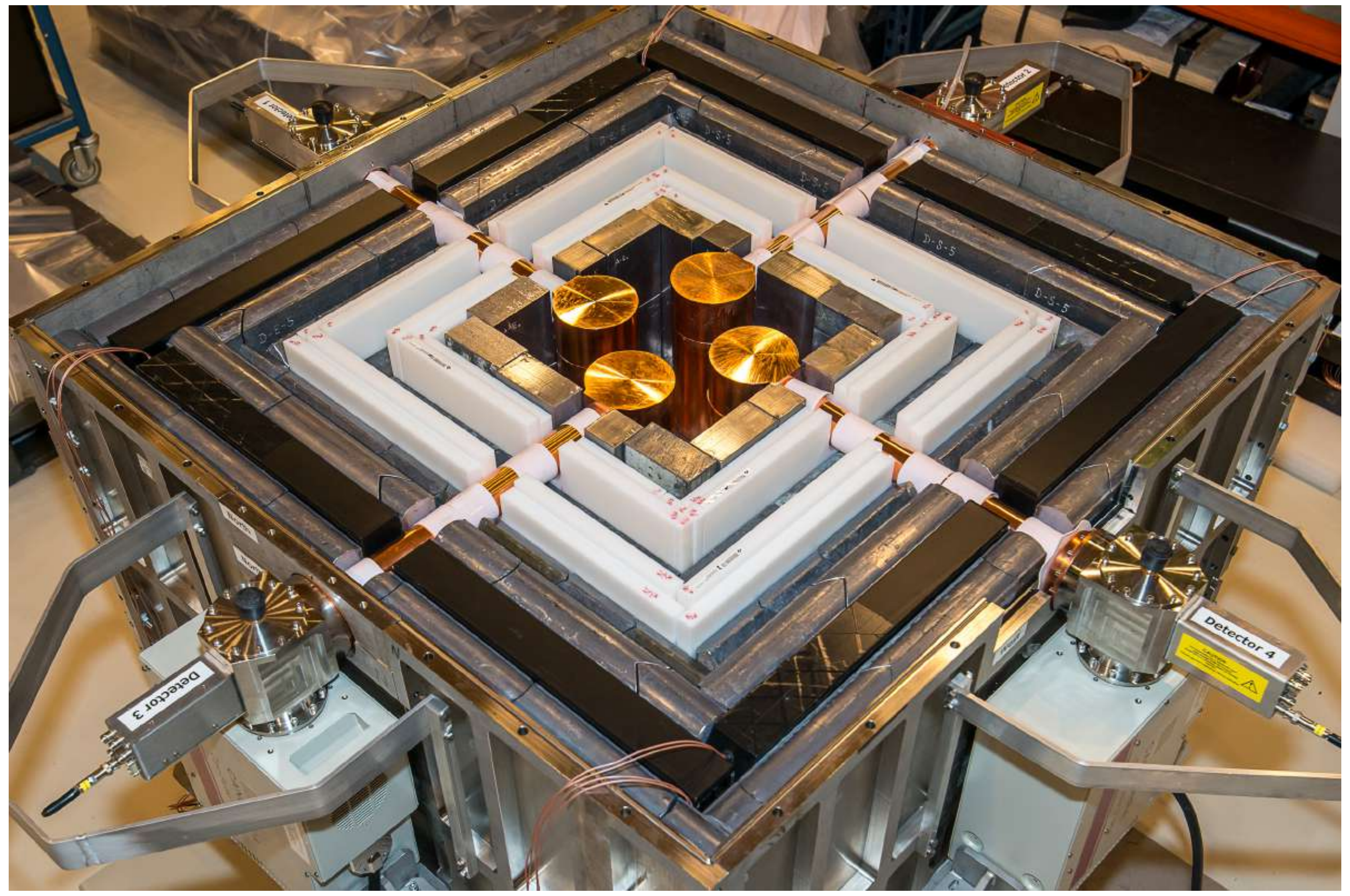
J. Newby @ Neutrino2020

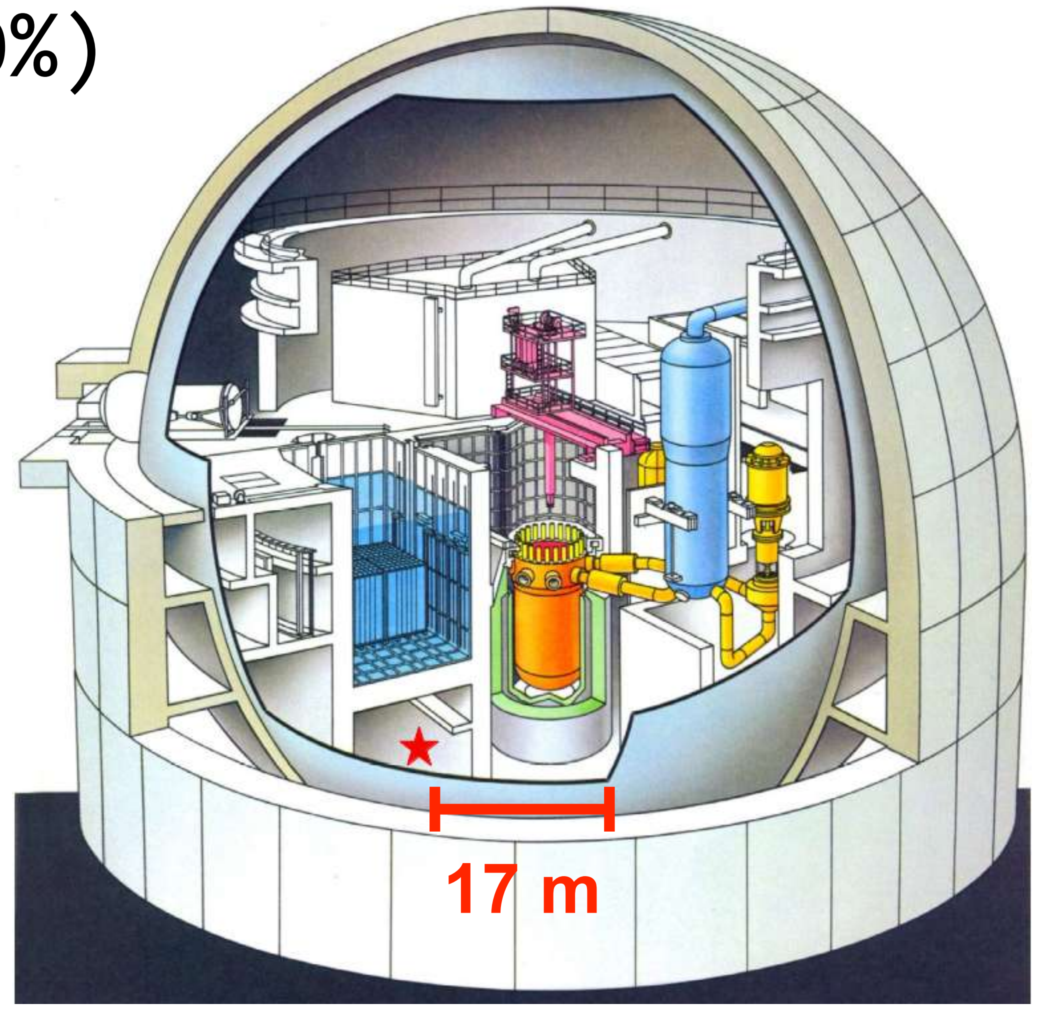
Nuclear reactors

CONUS

- Experiment @ 17 m from the 3.9 GW reactor core
- Flux: $2 \cdot 10^{13}\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
- Reactor-OFF periods (~1 month/year) allows to study the surrounding background
- Four 1kg-HPGe detectors (low-background crystals)
- Passive and active shield (10^4 fold suppression)
    - Lead + polyethylene
    - Active muon-veto (plastic scintillators)
- Energy threshold ~ 300 eV_{ee} (efficiency ~ 100%)





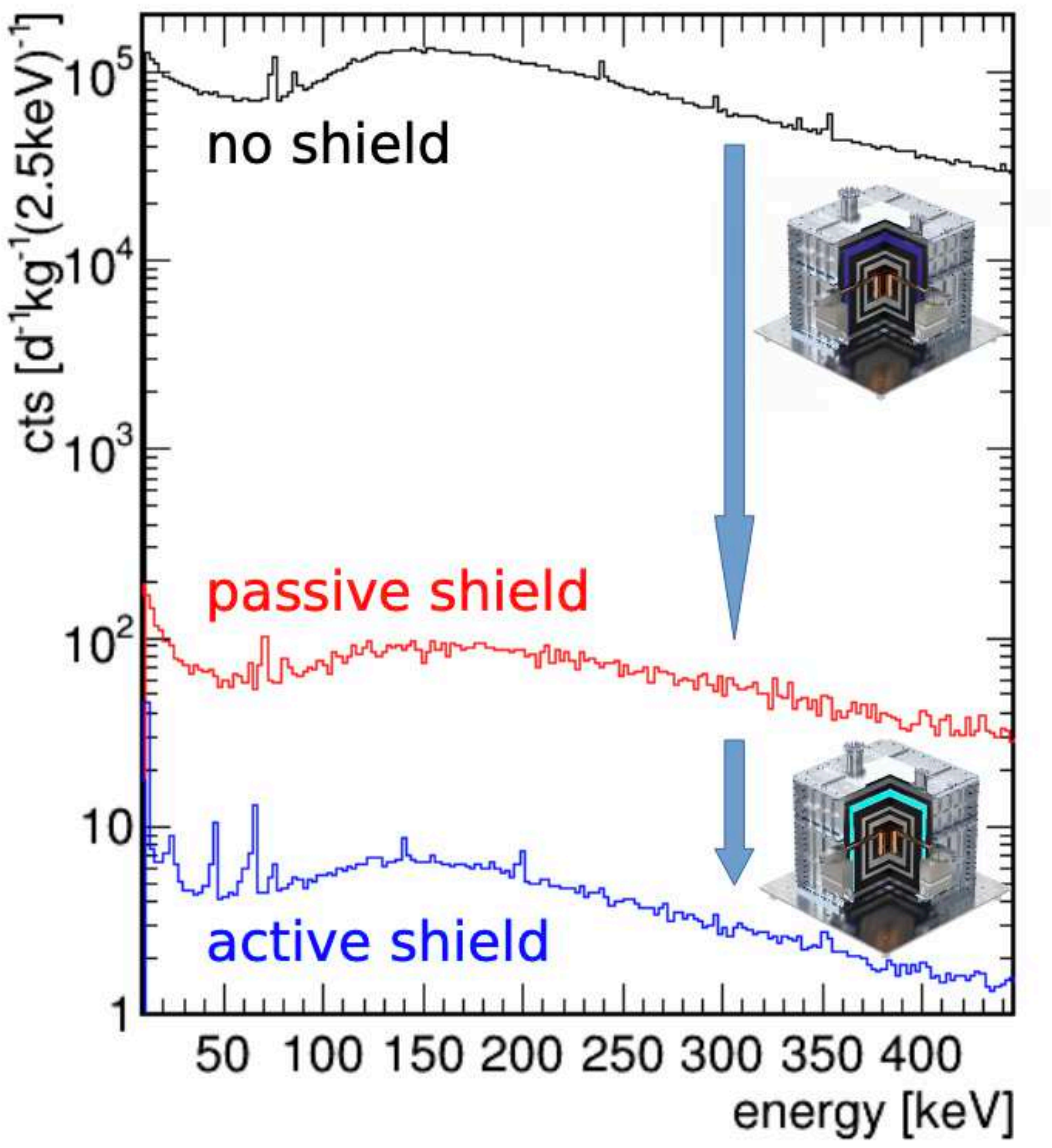


Brokdorf nuclear power plant in Germany

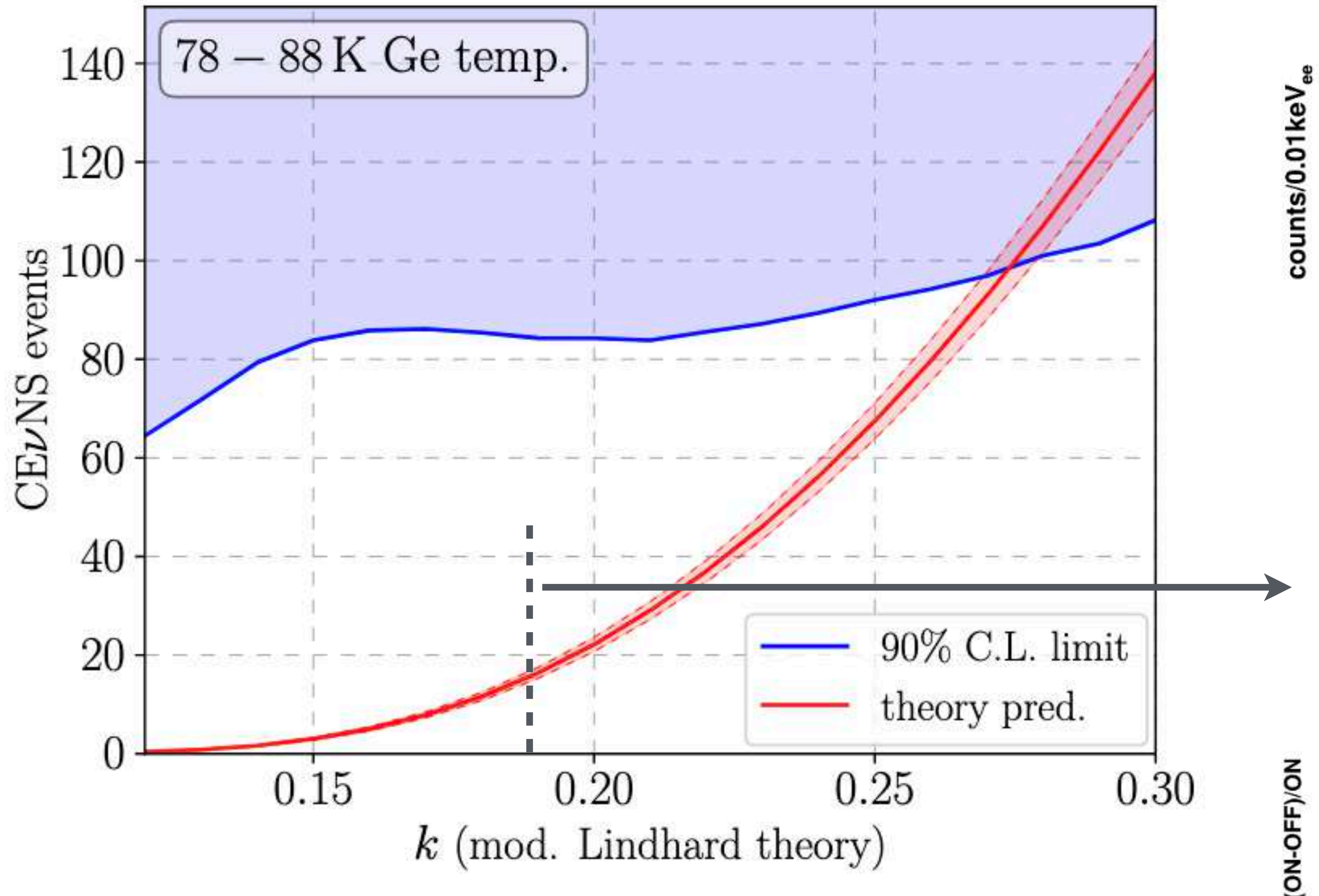
Nuclear reactors

CONUS

- Best limit on CEνNS in the fully coherent regime as a function of the quenching factor parameter k

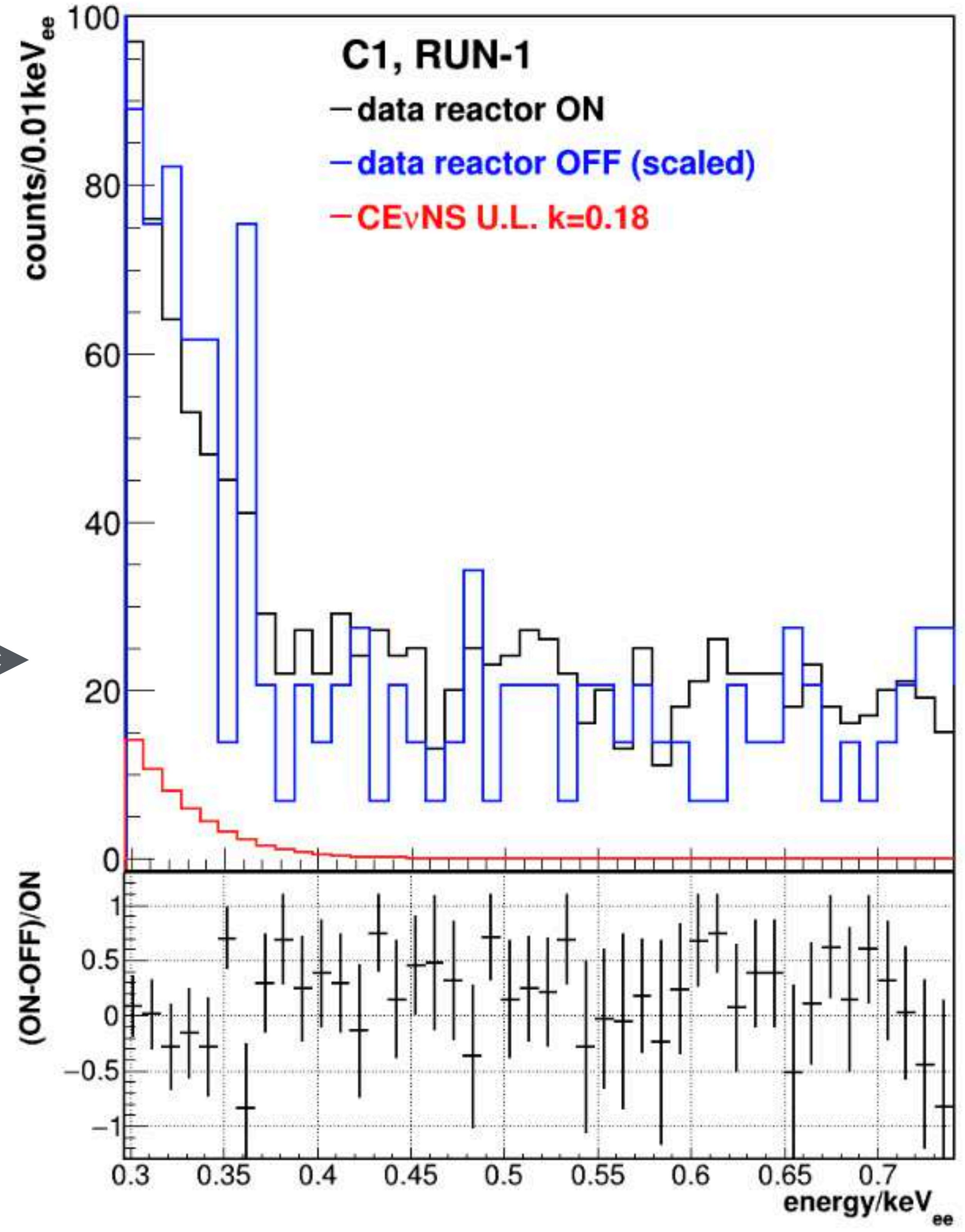


k < 0.27 desfavorece by data



CONUS, PRL 126, 041804 (2021)

Measurement spectra



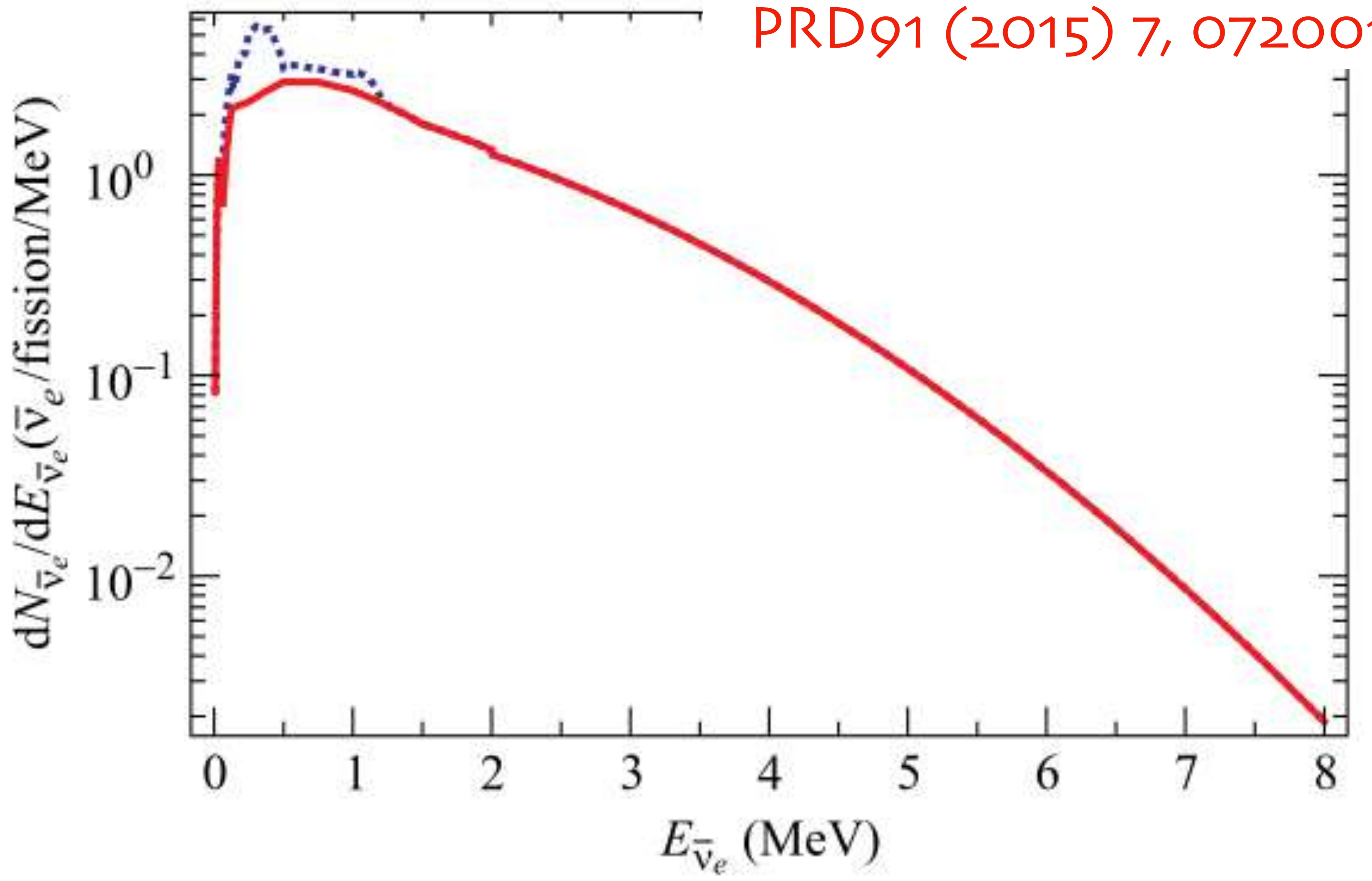
J. Hakenmüller @ Magnificent CEvNS 2020

Nuclear reactors

CONNIE

Coherent Neutrino-Nucleus Interaction Experiment

- Experiment @ 30 m from the 3.9 GW reactor core
- Flux: $\sim 10^{12}\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
- 14 CCDs of 6 g each
- Passive shield (Lead + polyethylene)
- Reactor-OFF periods (~1/14 months) for maintenance



PRD91 (2015) 7, 072001

Colaboración Internacional

~ 30 miembros

CONNIE

Coherent Neutrino-Nucleus
Interaction Experiment

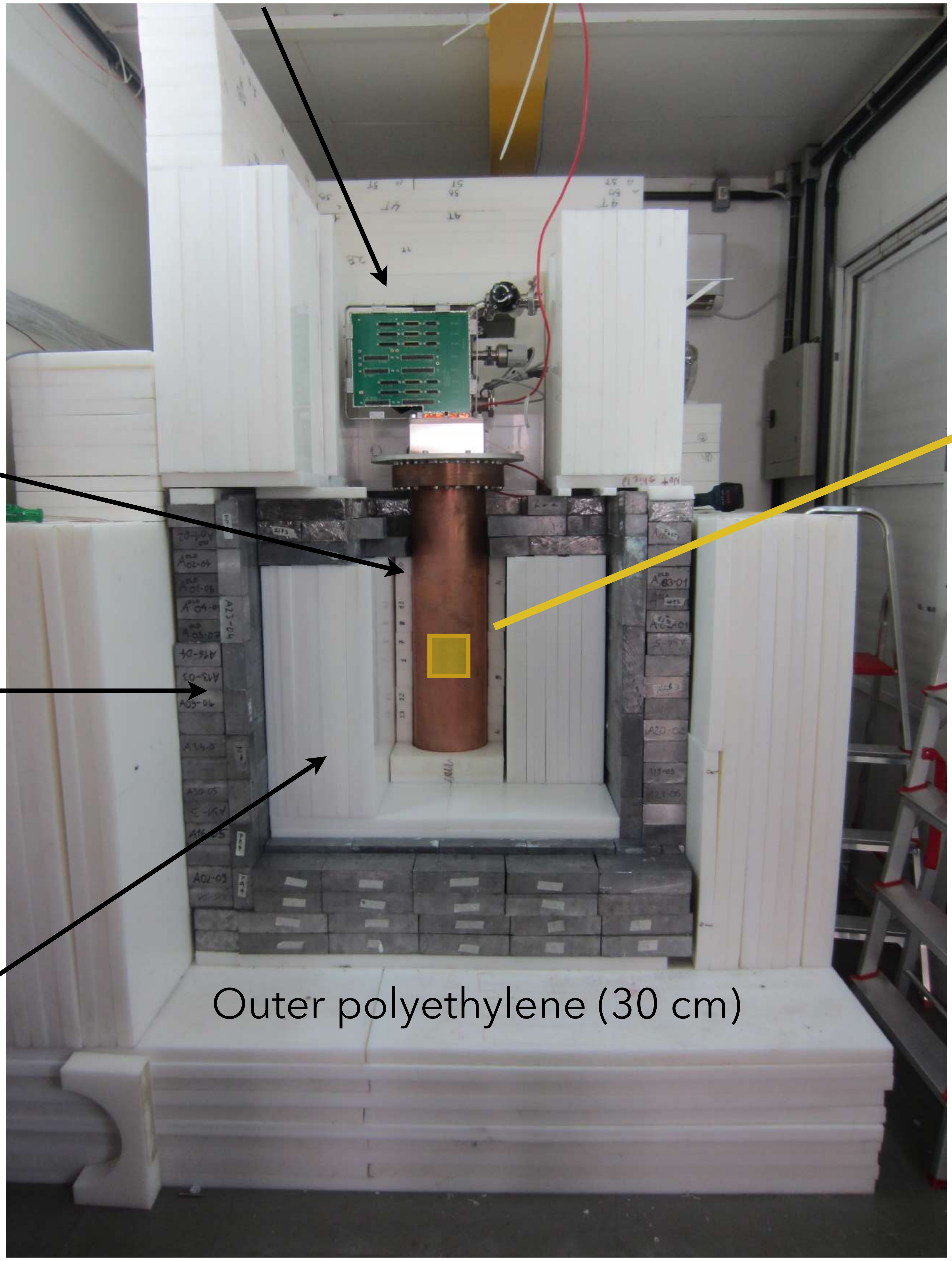
The detector

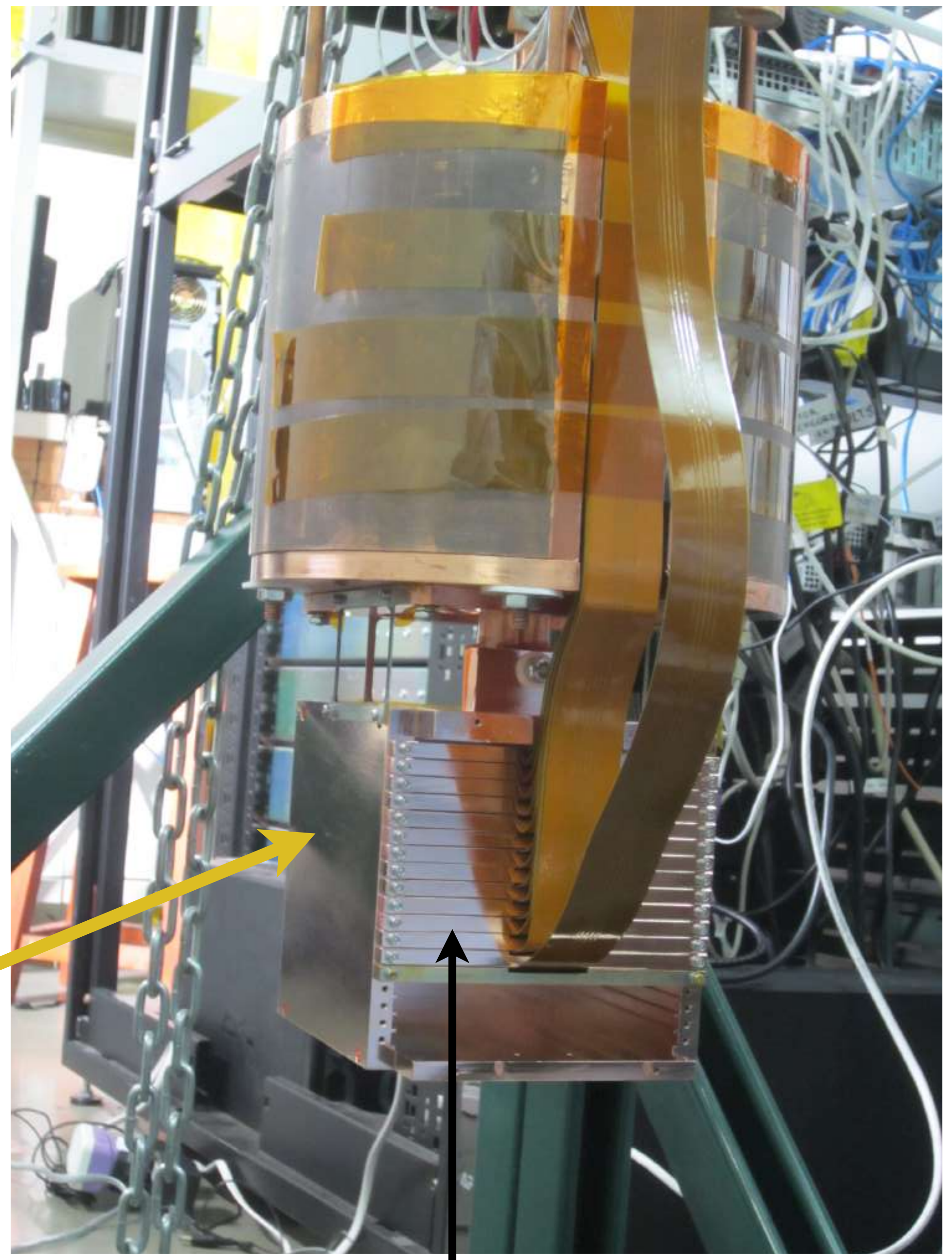
Vacuum interface board (VIB)

Dewar
(hold vacuum)

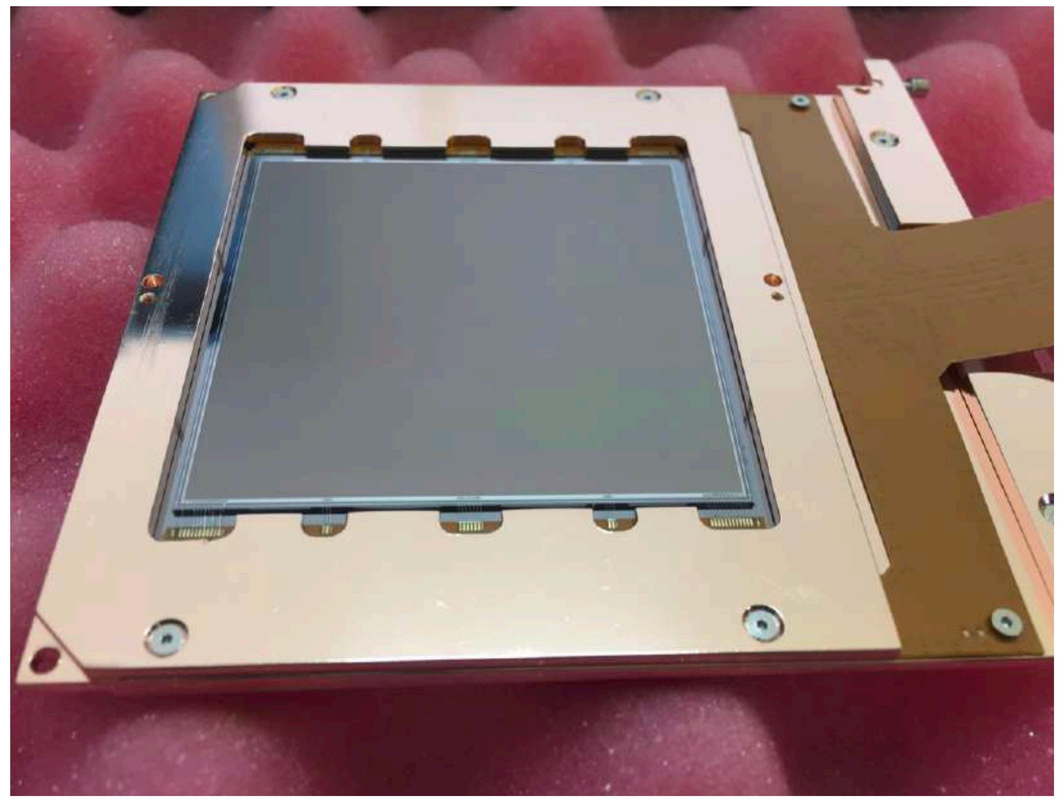
Lead (15 cm)
~ 800 bricks

Inner
polyethylene
(30 cm)





14 Coupled Charge Devices (CCDs)



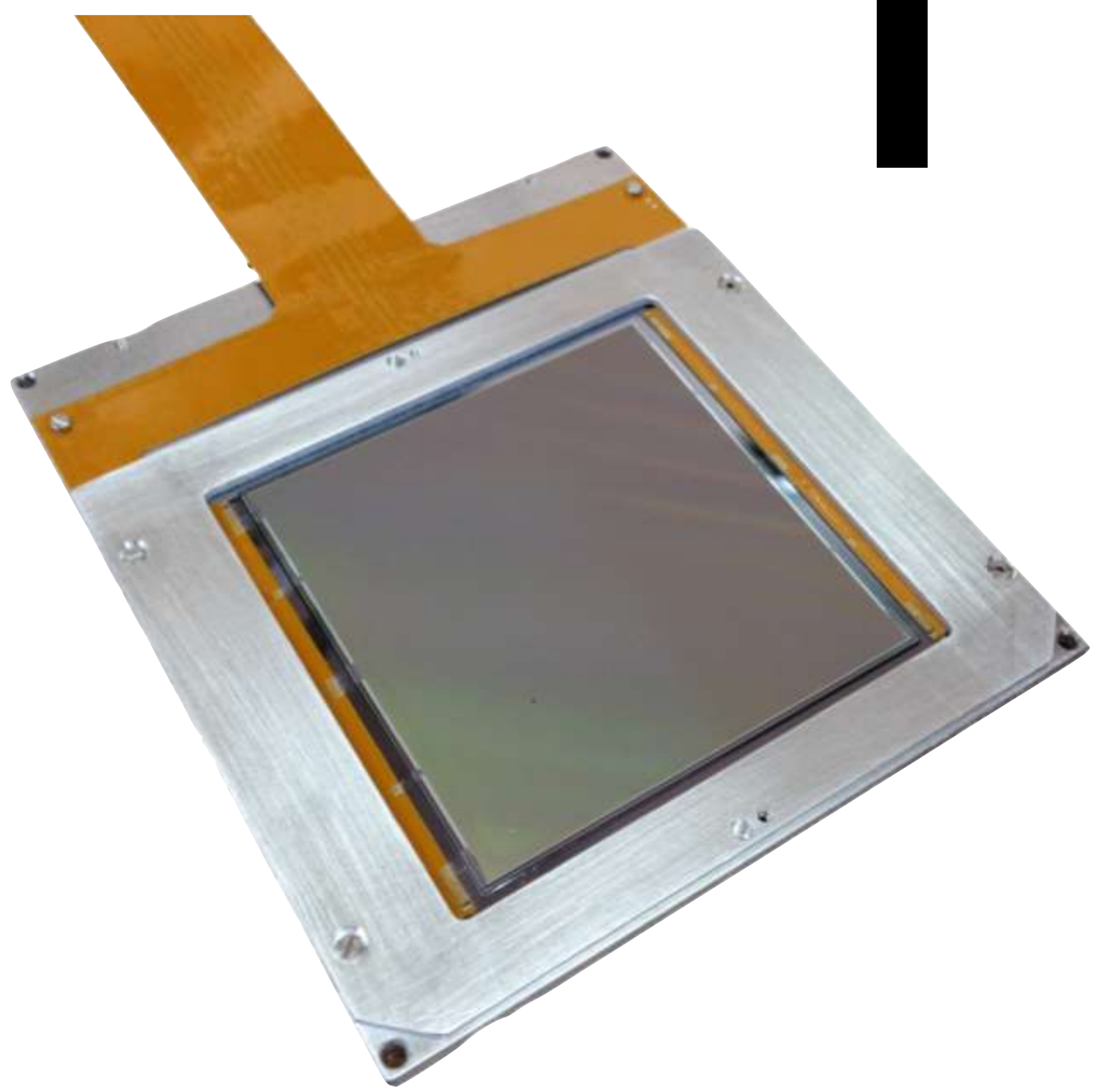
4k x 4k pixels

CONNIE

Coherent Neutrino-Nucleus
Interaction Experiment

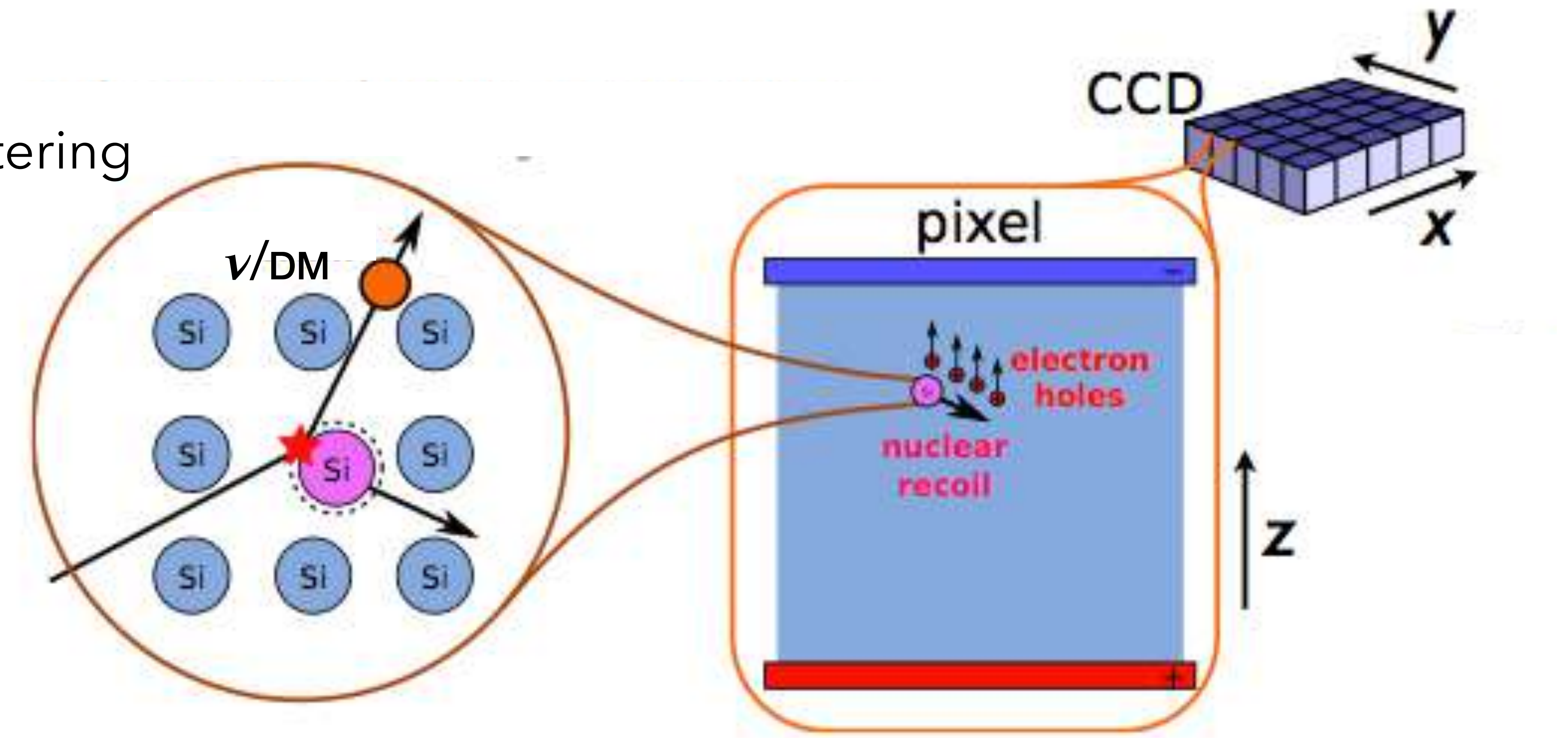
The detector

Detect the neutrino coherent interaction with Si nuclei
by measuring the ionization produced by nuclear recoil



16 Mpix CCDs with 15 μm x 15 μm per pixel
675 μm thick with a total mass of 6 g each
developed by Lawrence Berkeley National
Laboratory MicroSystems Lab

Elastic coherent scattering



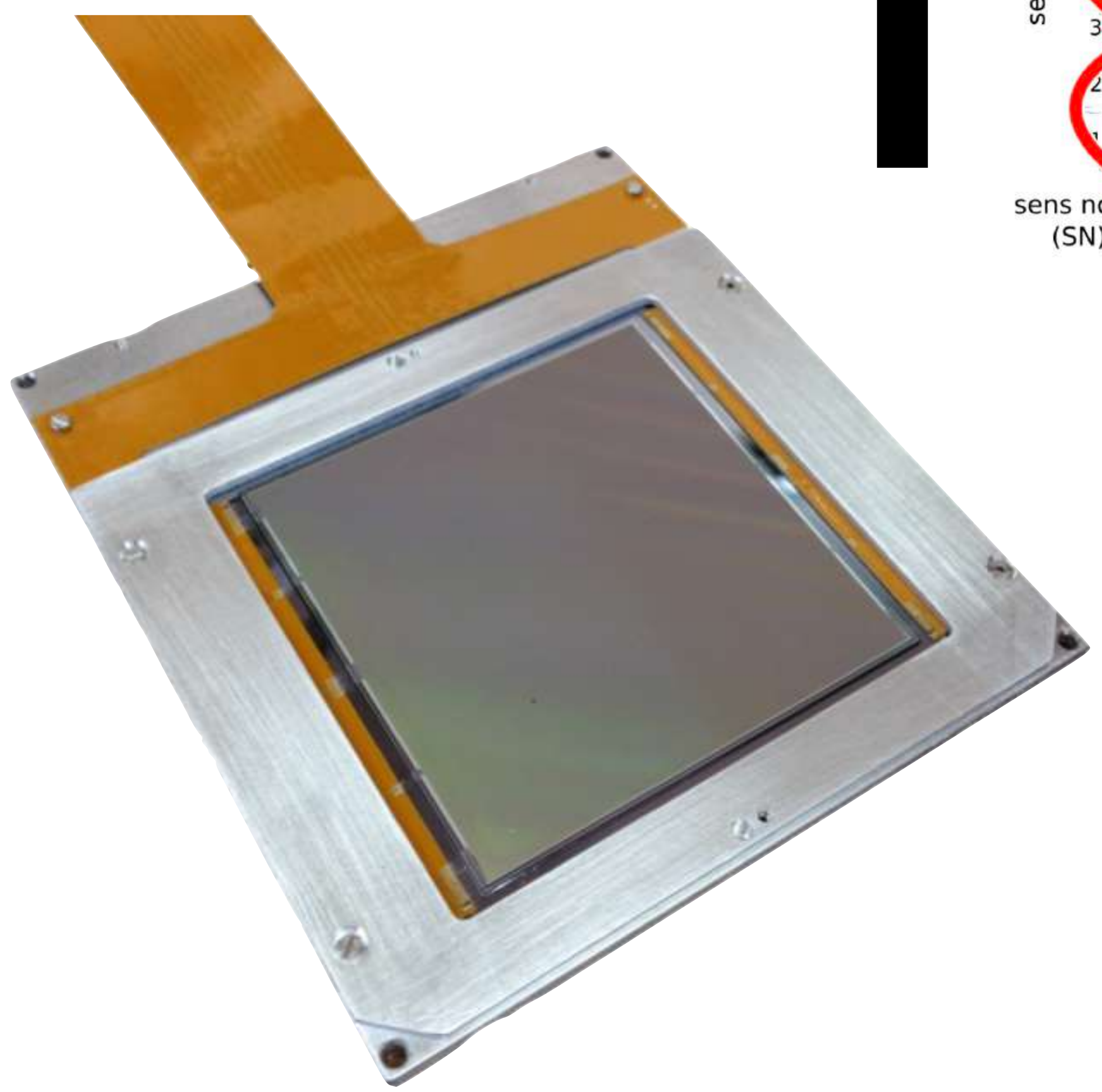
Advantage:
- Target is the detector itself
- Low detection threshold
- Very good spatial resolution

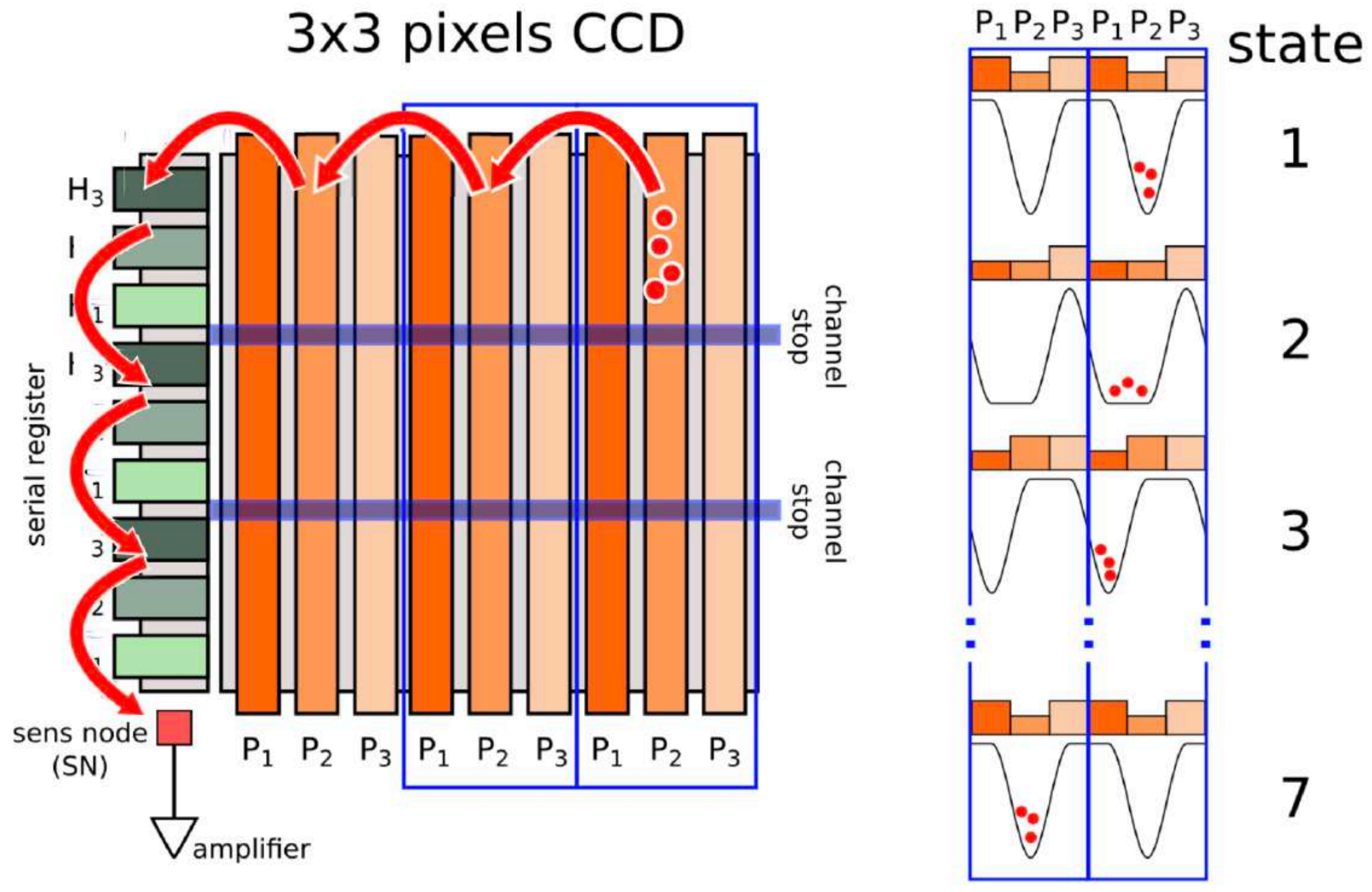
Challenges:
- Small ionization energies
- Never measured ionization efficiency (quenching factor)

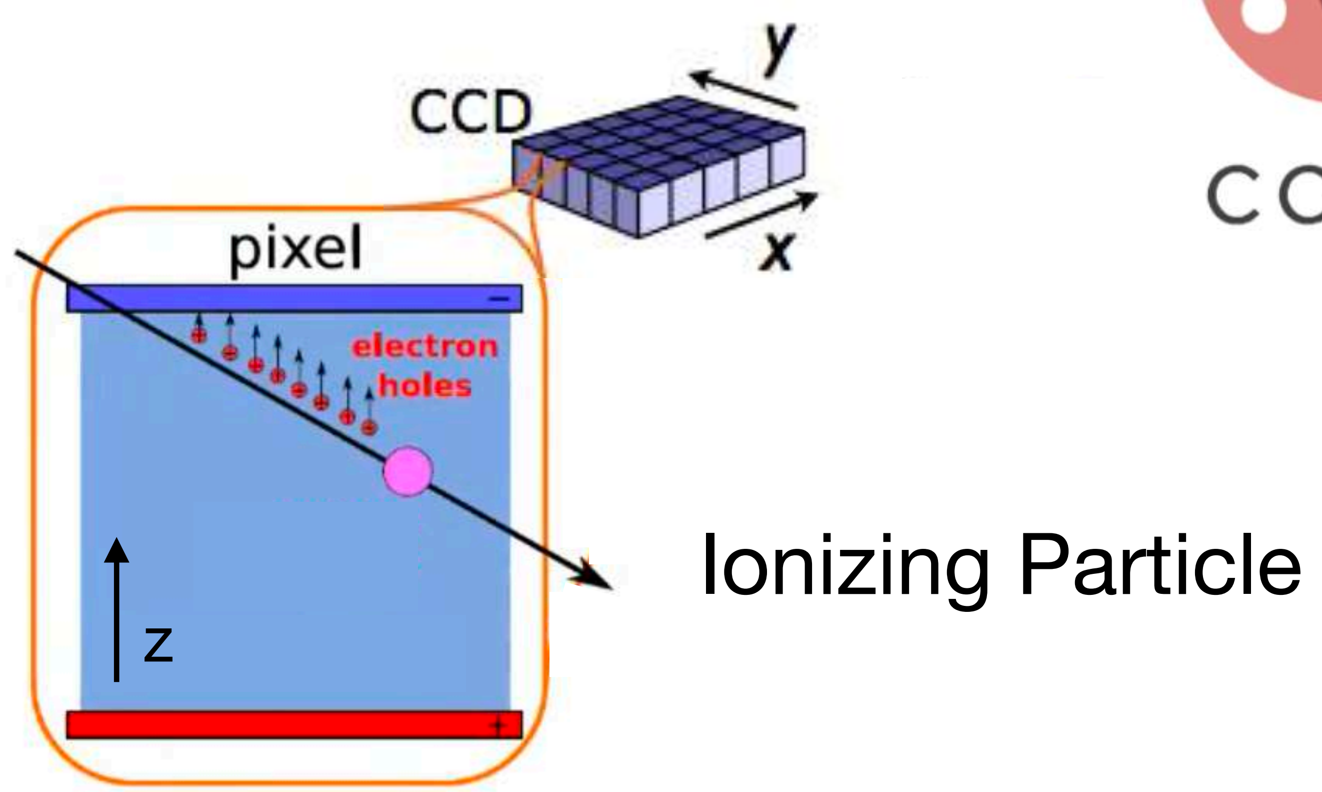
CONNIE

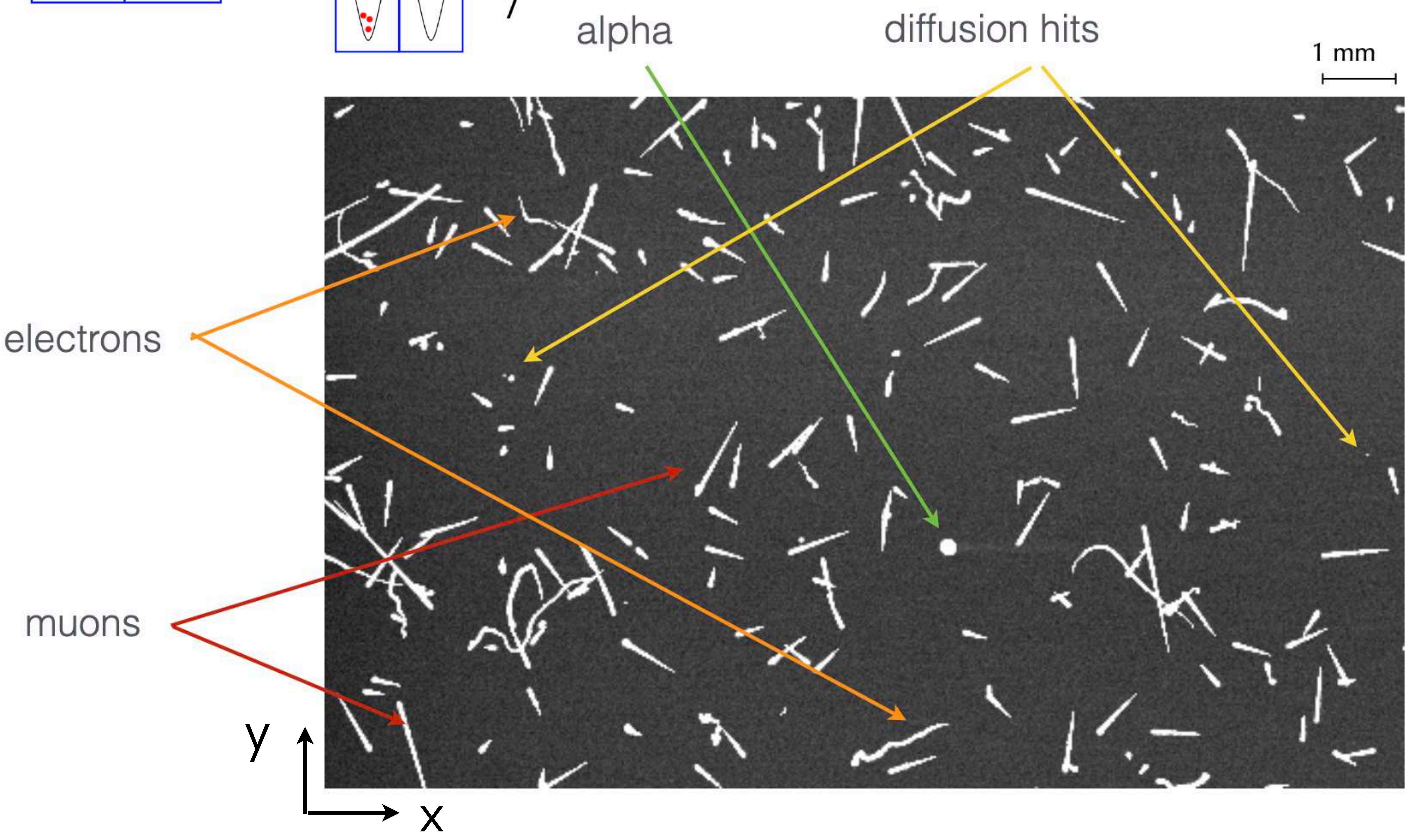
Coherent Neutrino-Nucleus Interaction Experiment

The detector









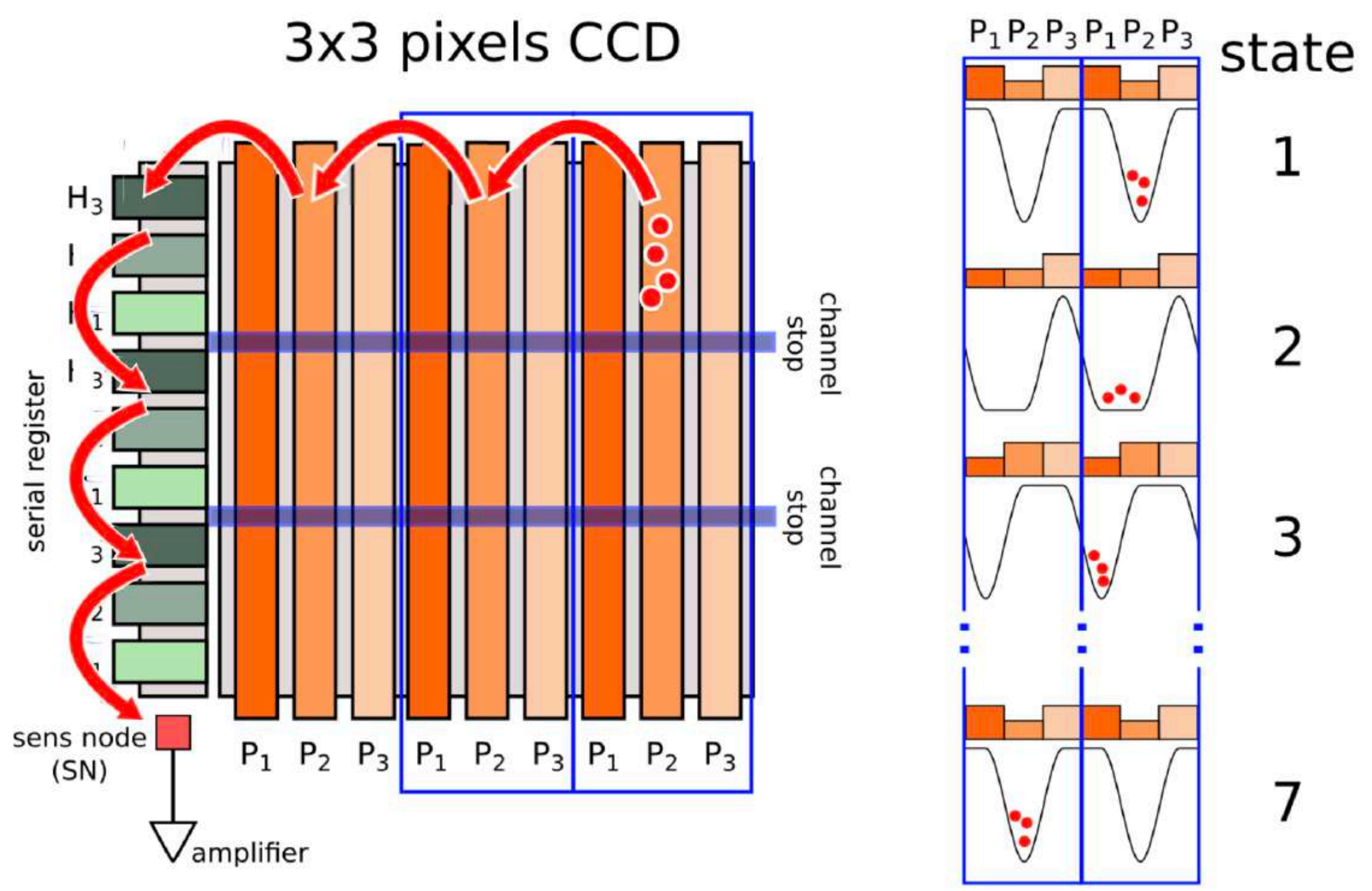
16 Mpix CCDs with 15 μm x 15 μm per pixel
675 μm thick with a total mass of 6 g each
developed by Lawrence Berkeley National Laboratory MicroSystems Lab

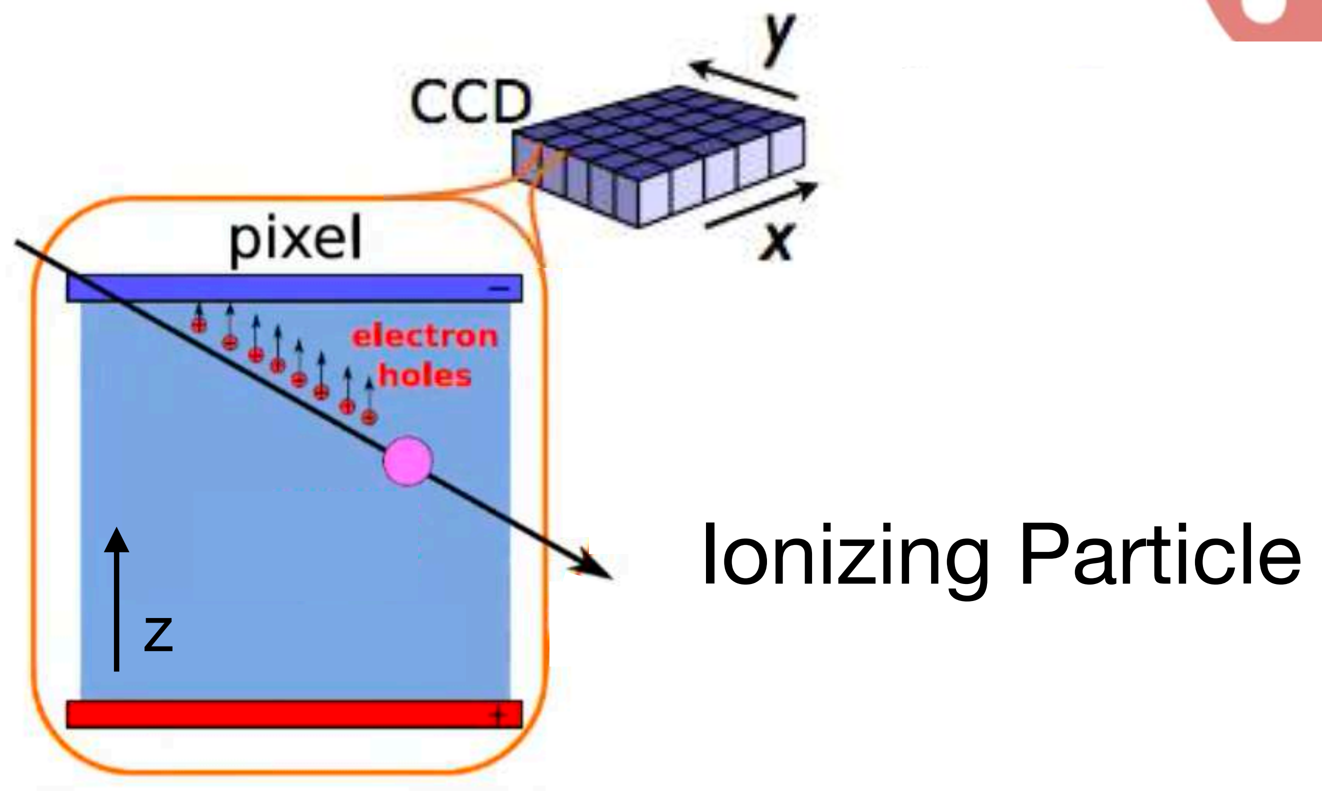
CONNIE

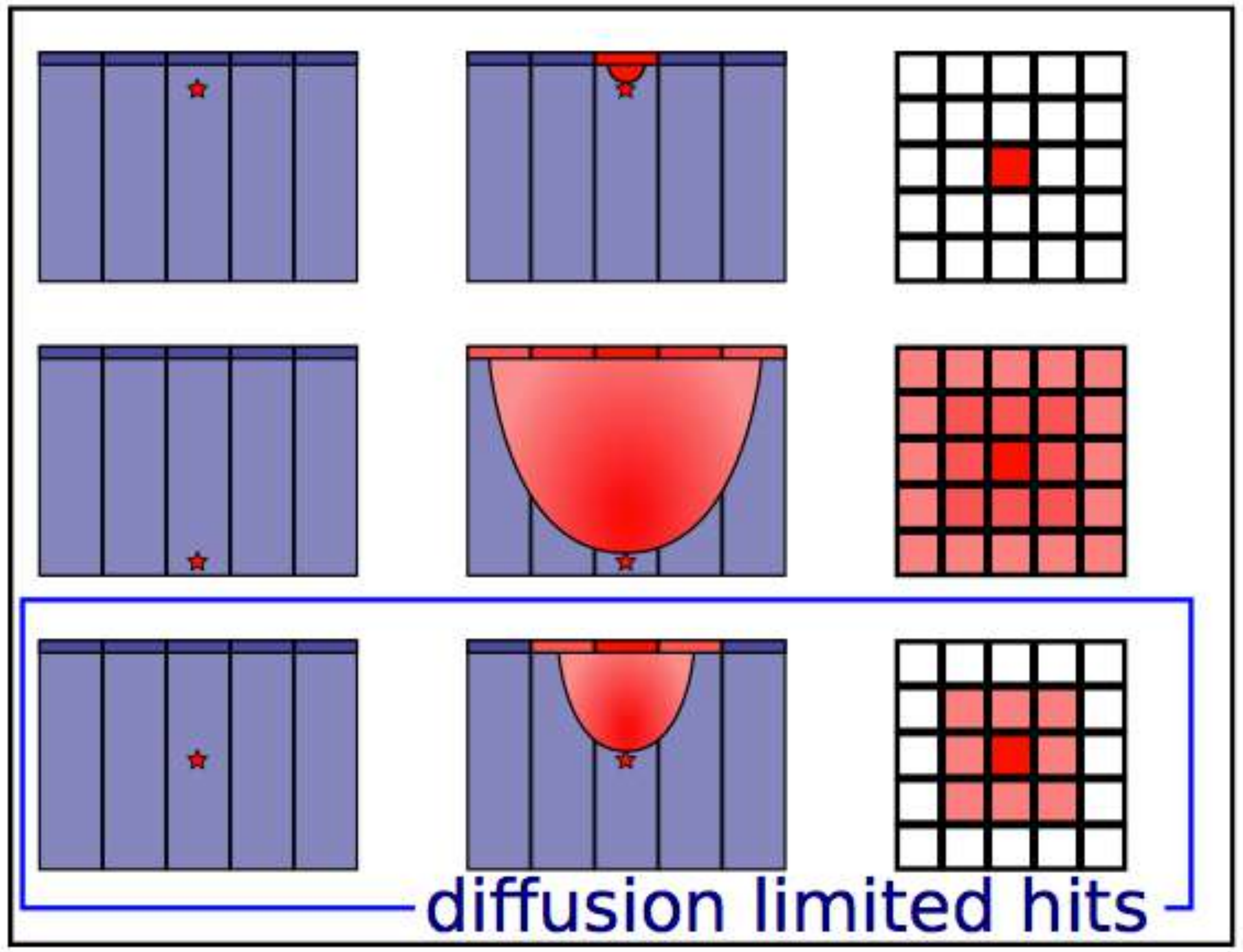
Coherent Neutrino-Nucleus Interaction Experiment

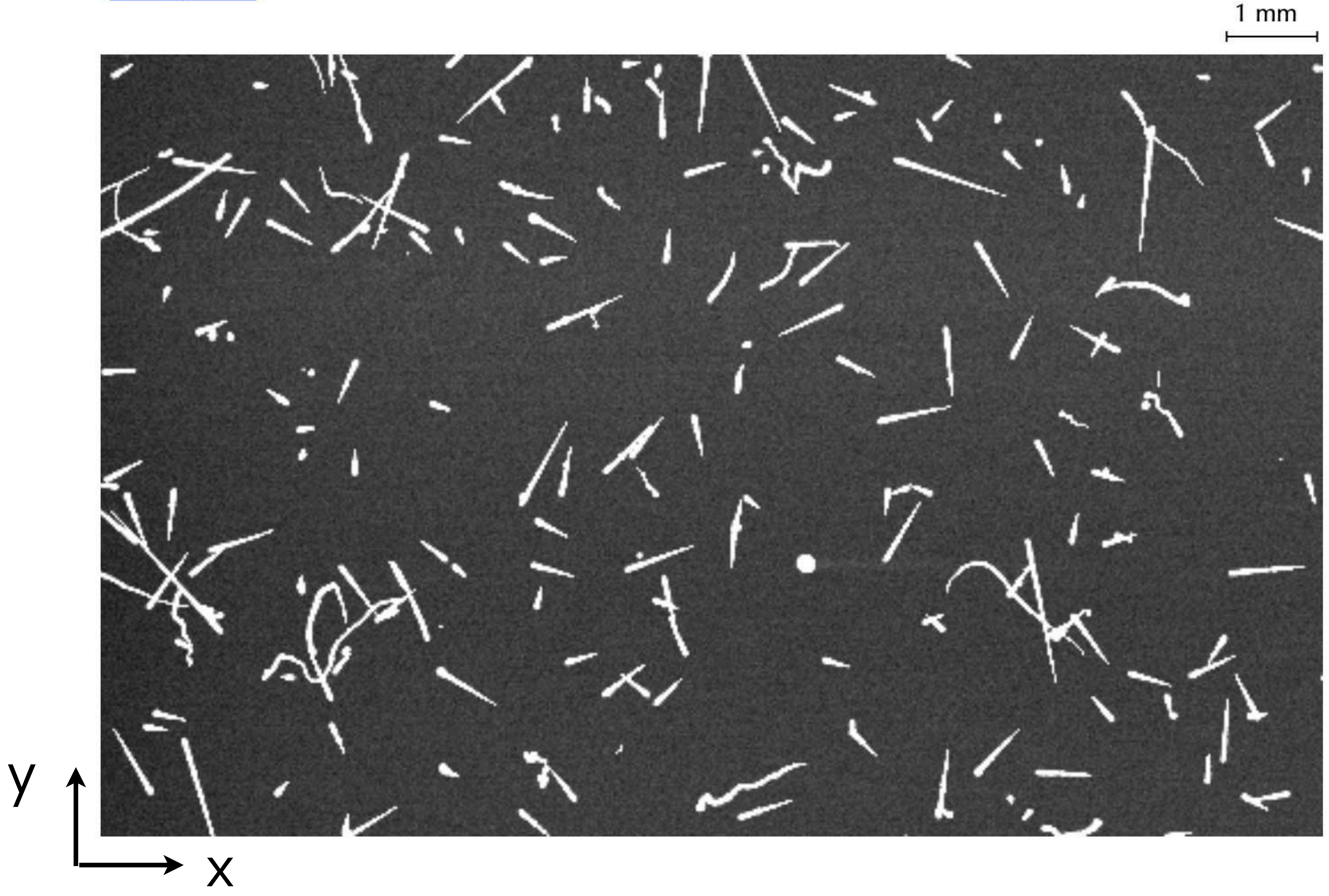
Diffusion gives the possibility of 3D reconstruction

The detector





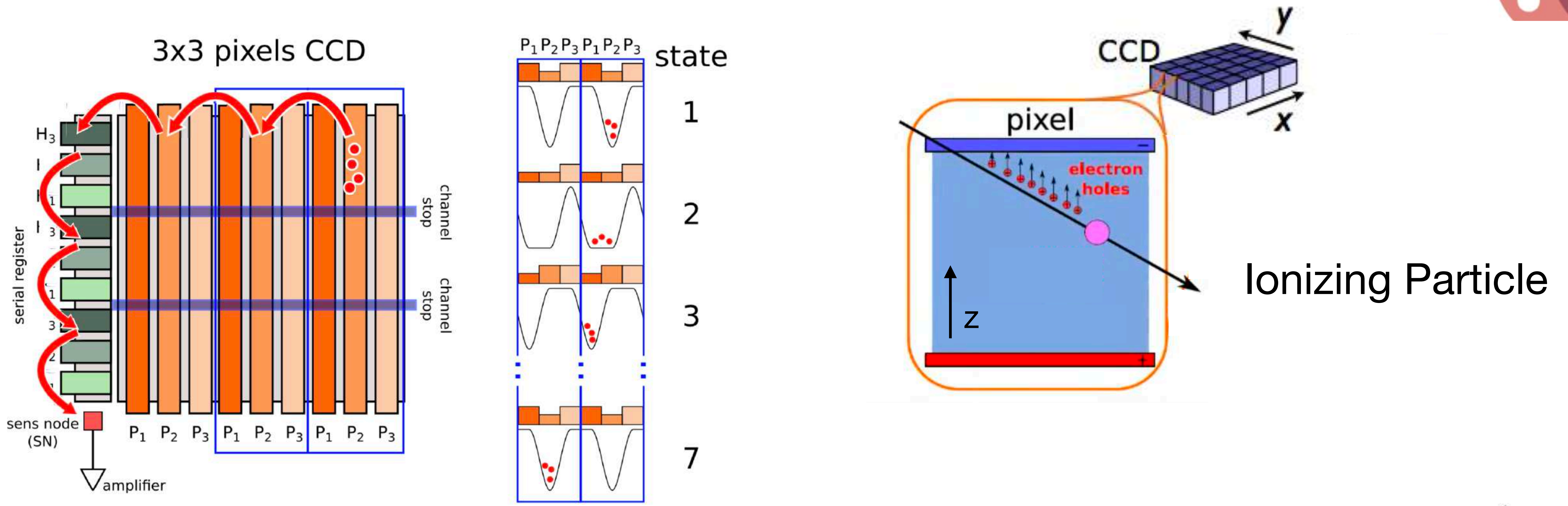


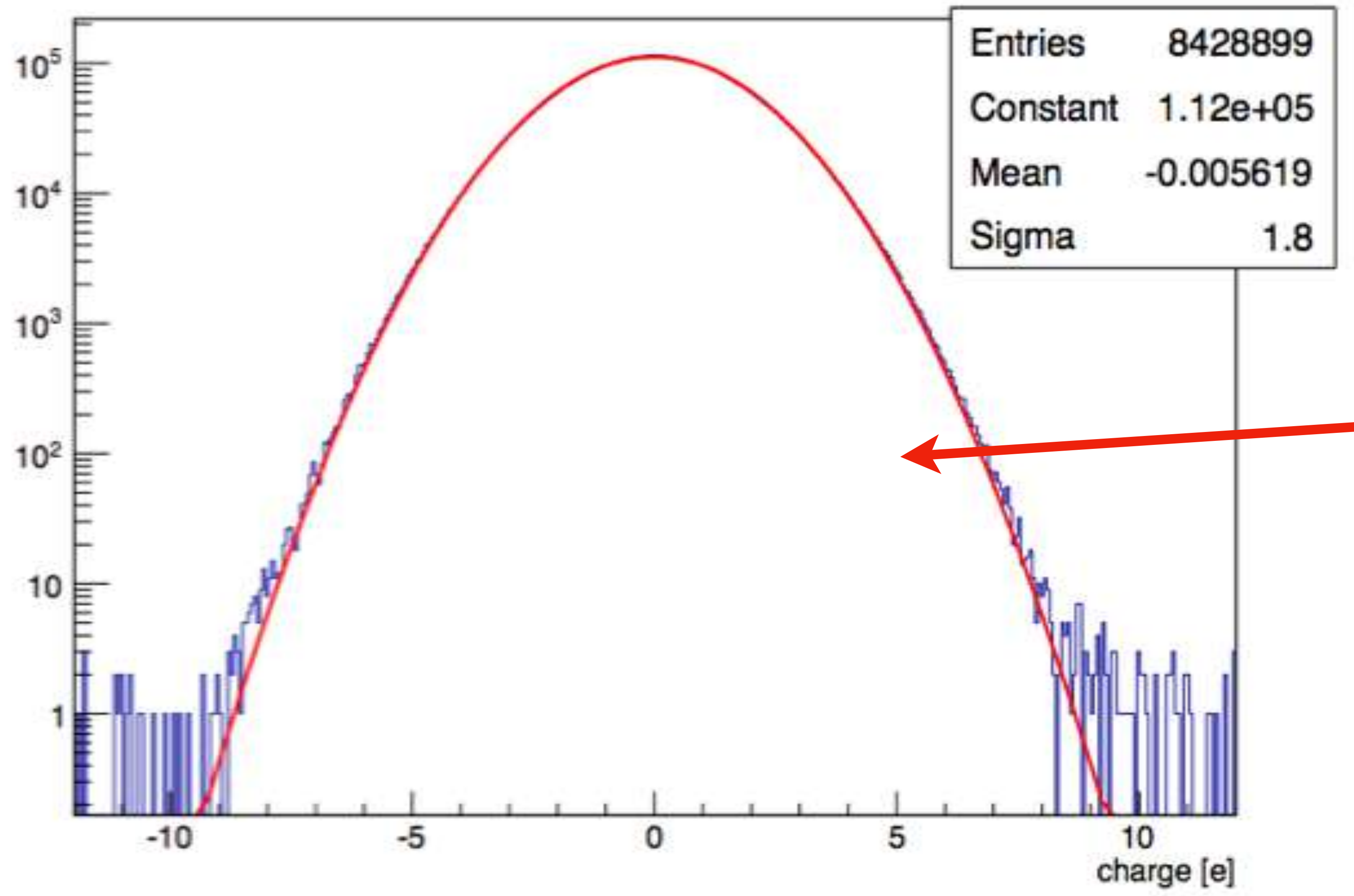


CONNIE

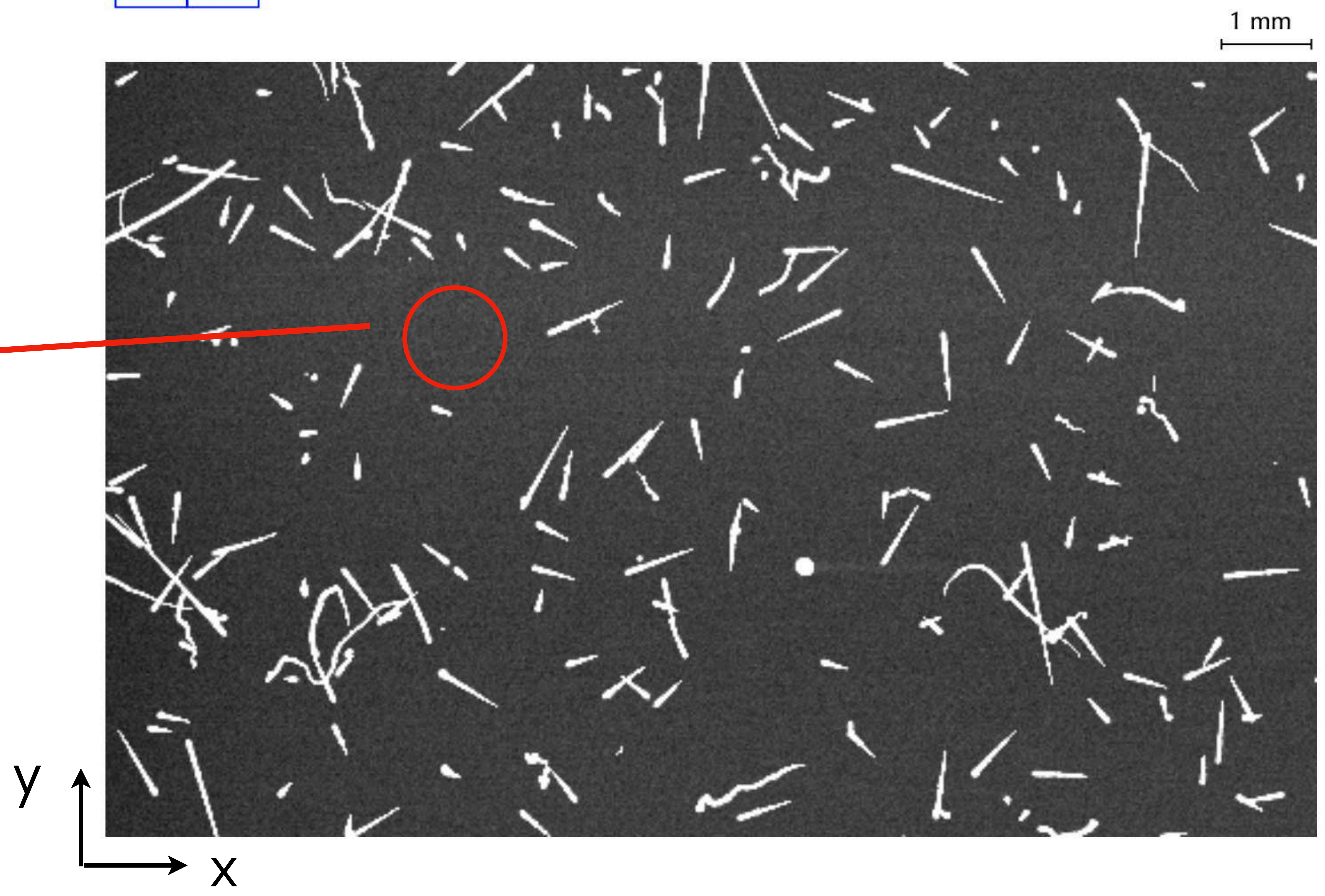
Coherent Neutrino-Nucleus Interaction Experiment

The detector





Low readout noise ~ 2e-



CONNIE Results

First results from 2016-2018 run.
Active mass 47.6 g.

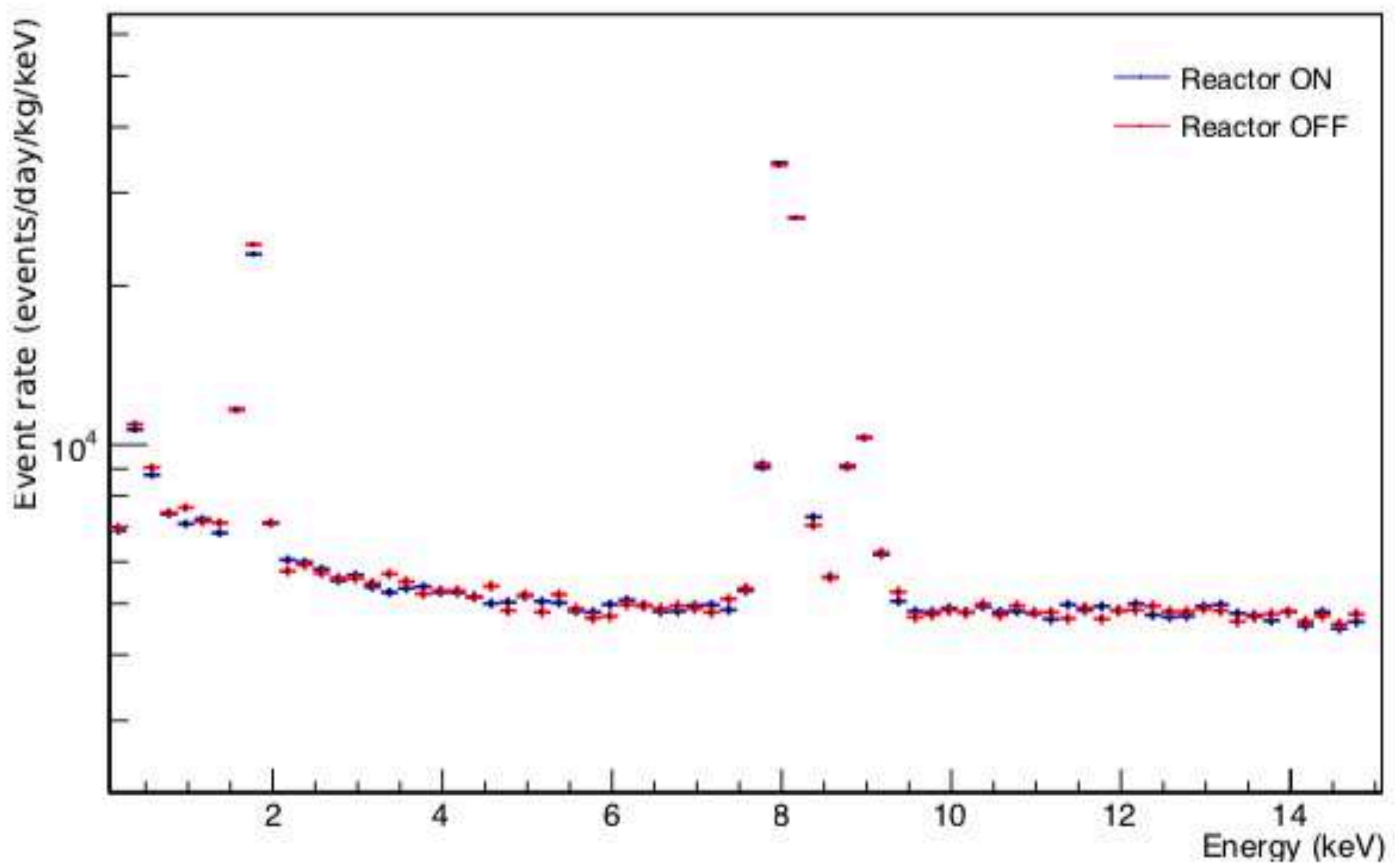
Exposure:

Reactor ON: 2.1 kg-day
Reactor OFF: 1.6 kg-day

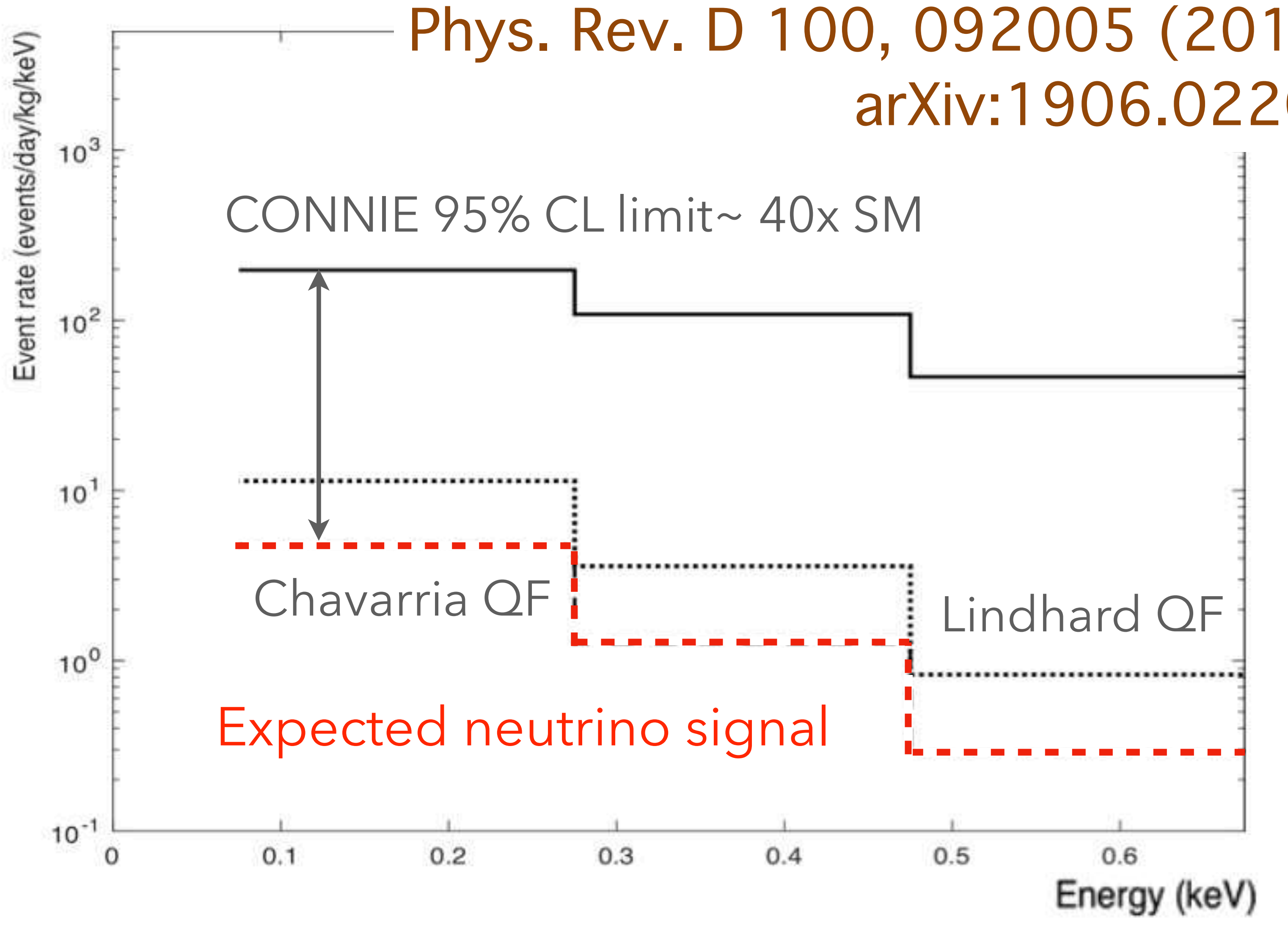
Limit on CEvNS event rate, depending on quenching factor.

First competitive BSM constraints from CEvNS at reactors

- Energy spectrum

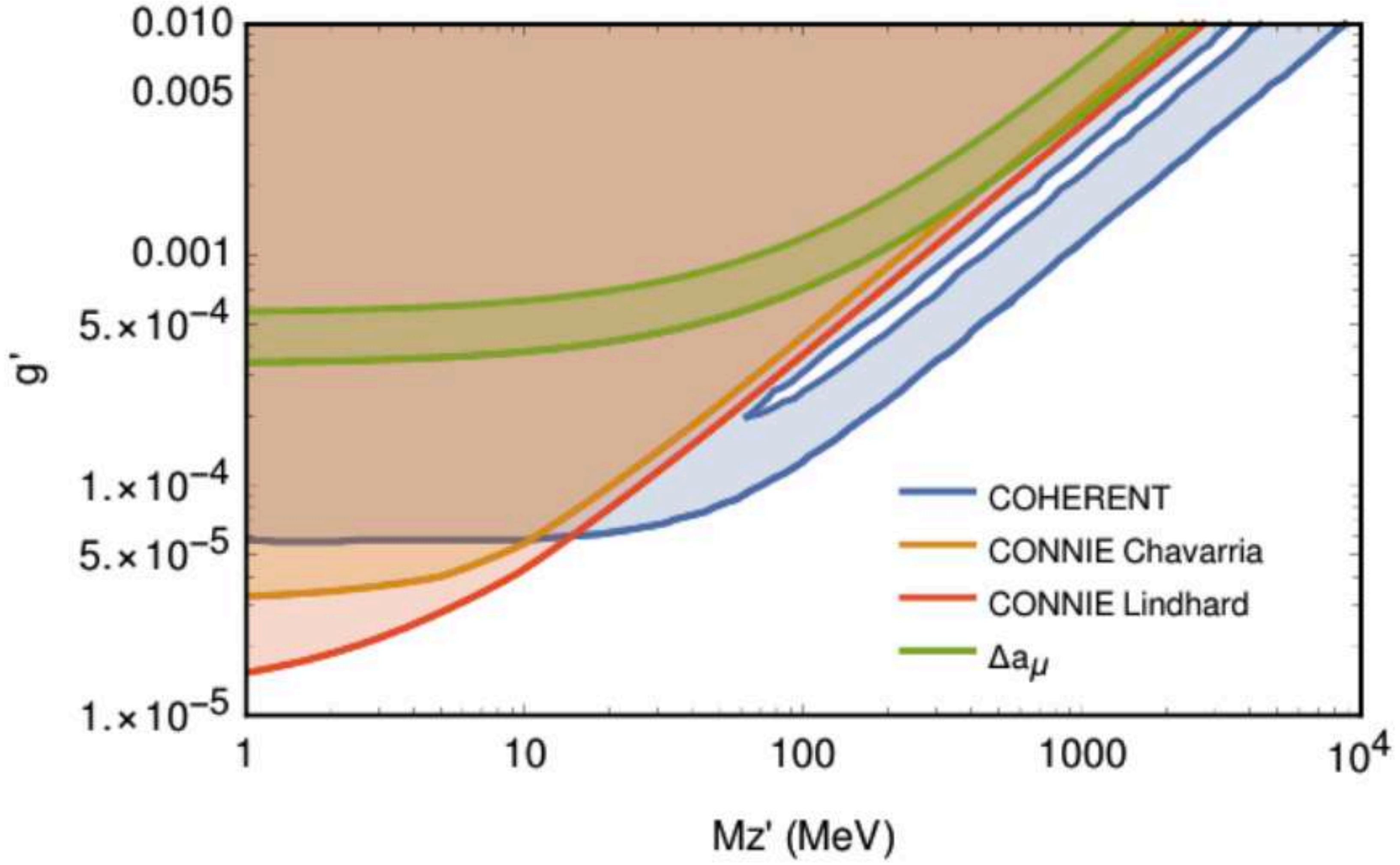


Phys. Rev. D 100, 092005 (2019)
arXiv:1906.02200

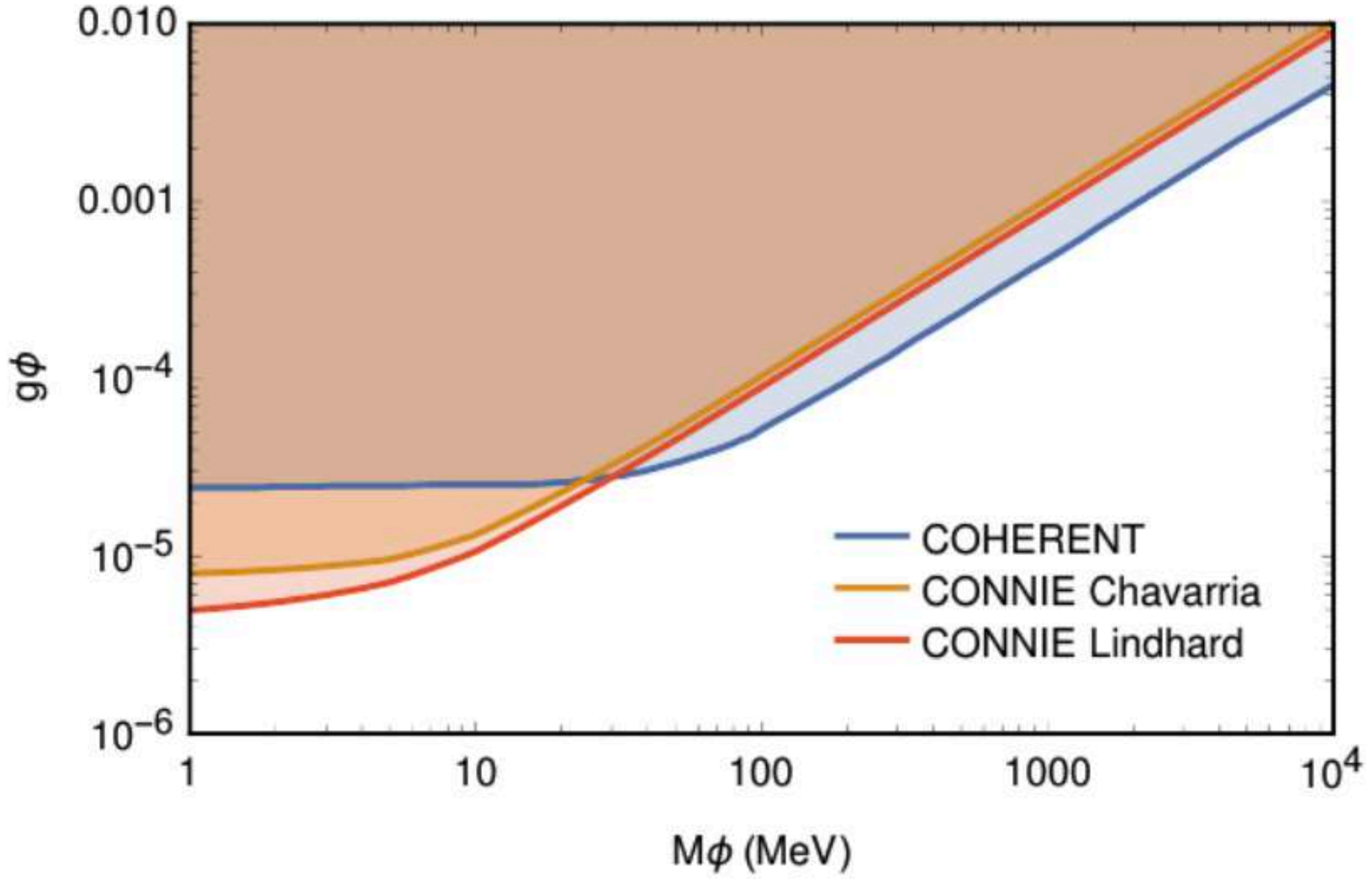


- Limits on simplified SM extensions with light mediators

Light vector (Z') mediator



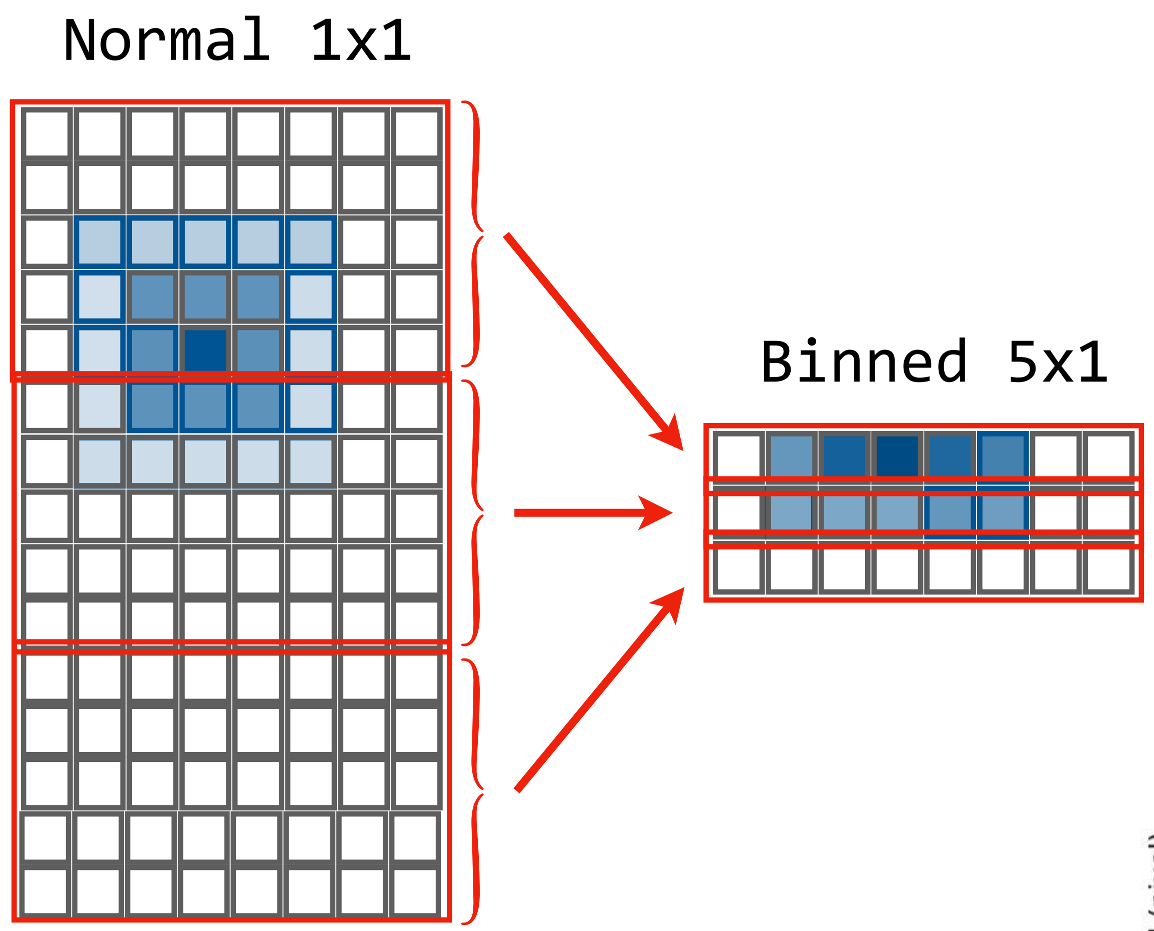
Light scalar (ϕ) mediator



JHEP 2020, 54 (2020); arXiv:1910.04951

CONNIE Results

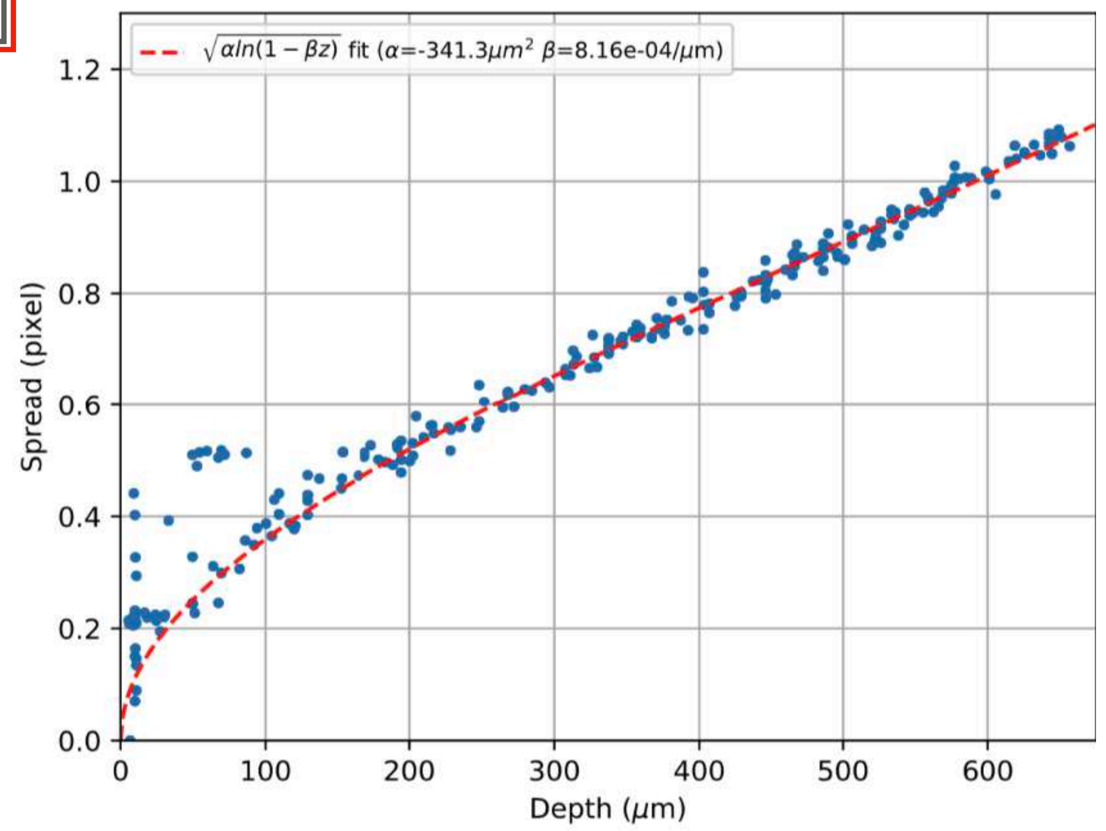
◆ New data taking setup (5x1 binning – better signal-noise ratio)



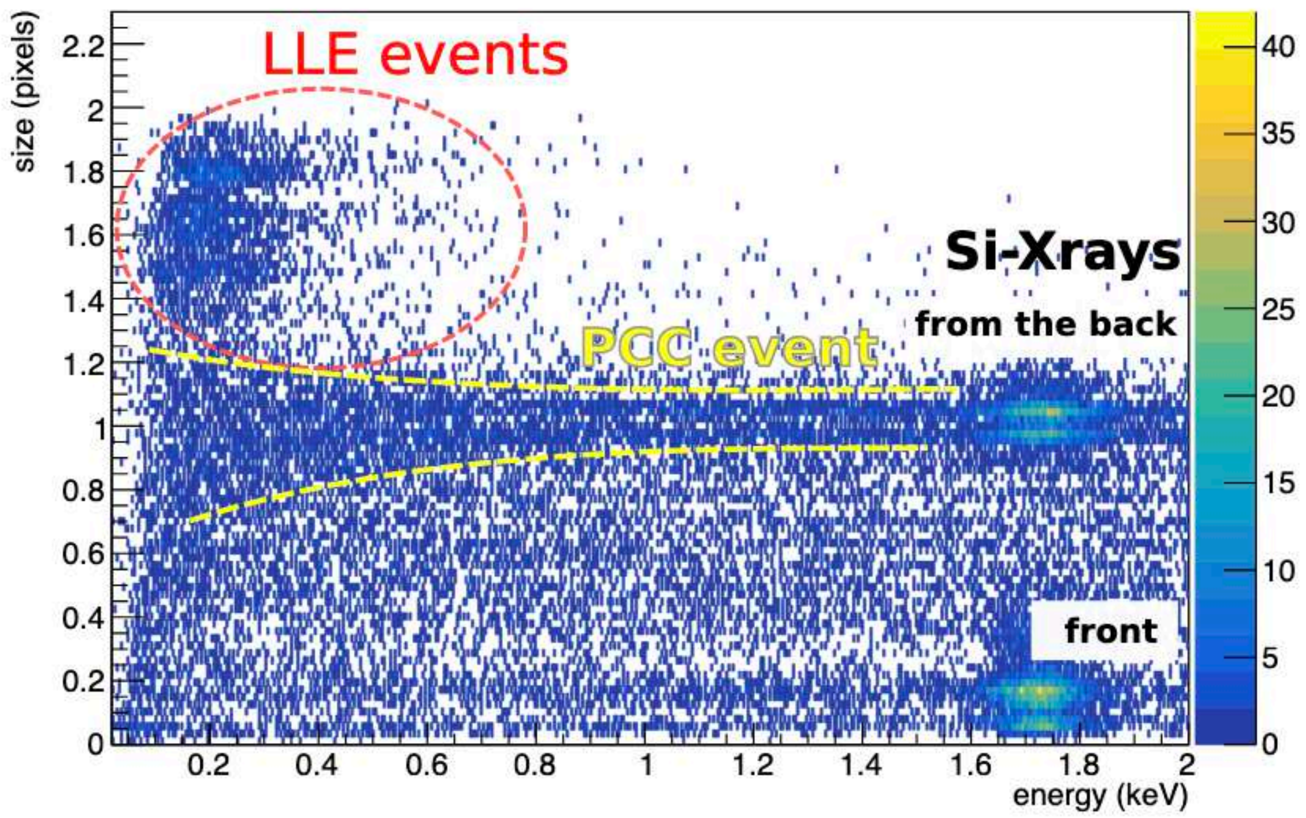
Analysis:

- Improved energy and size-depth calibrations
  Better low-energy background characterization and rejection
- Large low-energy (LLE) events
- Partial-charge-collection (PCC) layer events
- Spatial uniformity check
- Perform multiple cross-checks

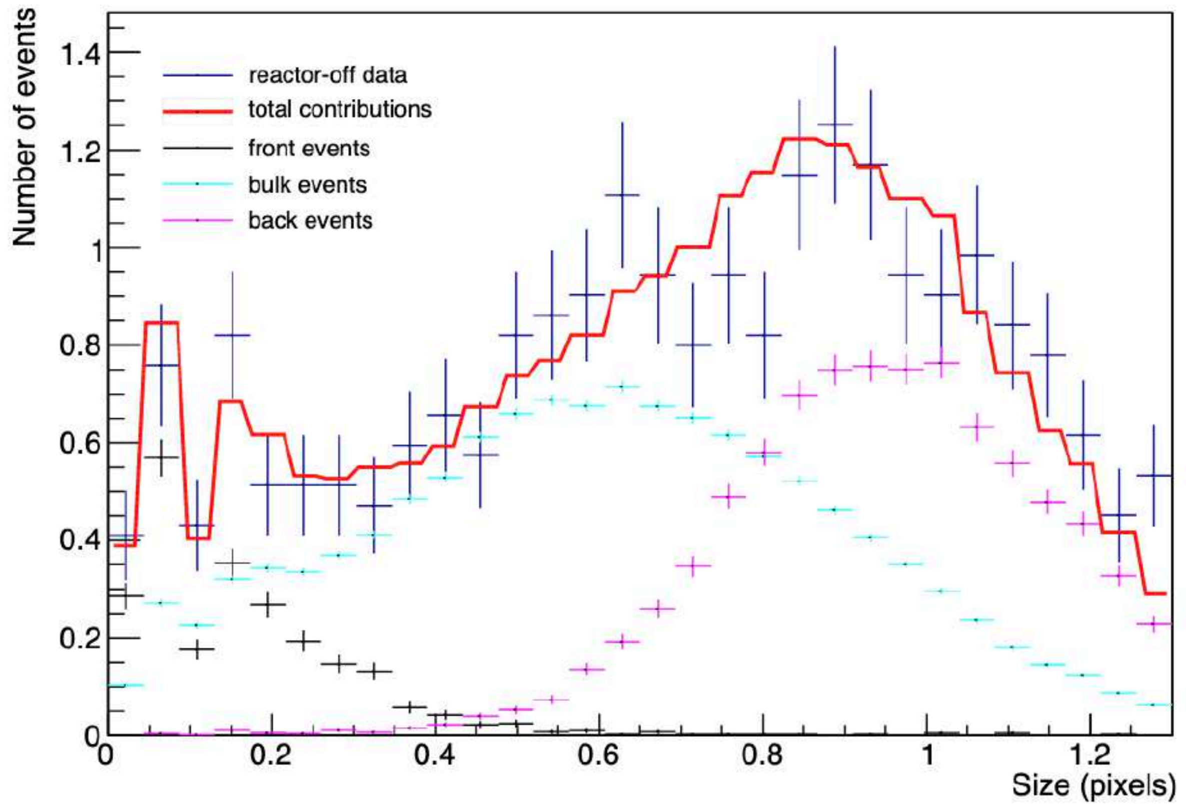
Size-depth calibration



Large low-energy events



Partial-charge-collection



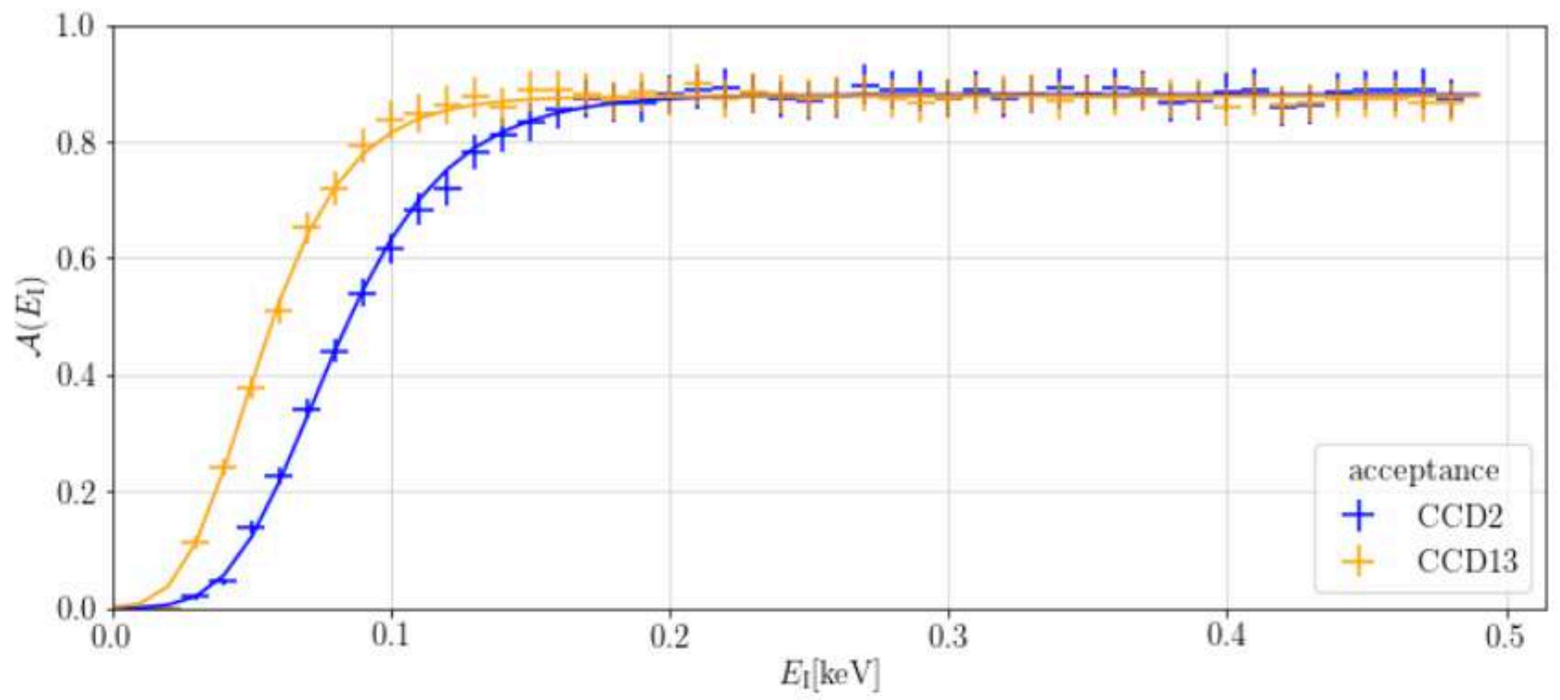
New paper!
arXiv:2110.13033

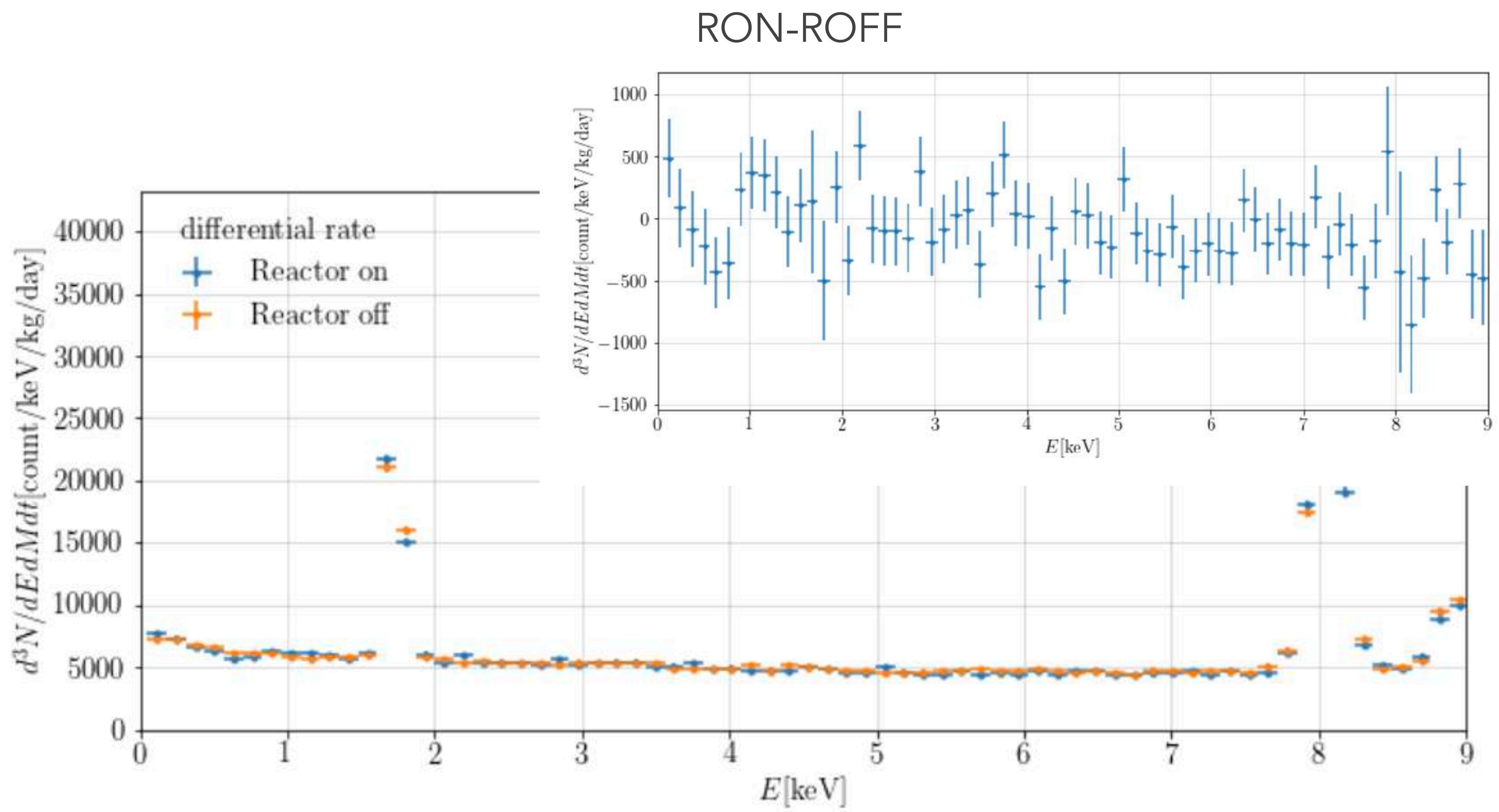
Blind analysis

- Freeze analysis parameters with ROFF data
- Stability checks with mid to high energy RON data
- Unblind low energy RON data

CONNIE Results

- 2019 data
  - Improved detector extraction acceptance and selection efficiency at low energies:
    - Threshold reduced to ~50 eV
    - Full acceptance reached at 100-150 eV
  - Total exposure:
    2.7 kg-day (31.85 days with RON & 28.25 days with ROFF)
  - RON-ROFF consistent with zero
    95% C.L. limit on observed (expected) CEνNS rate





New paper!
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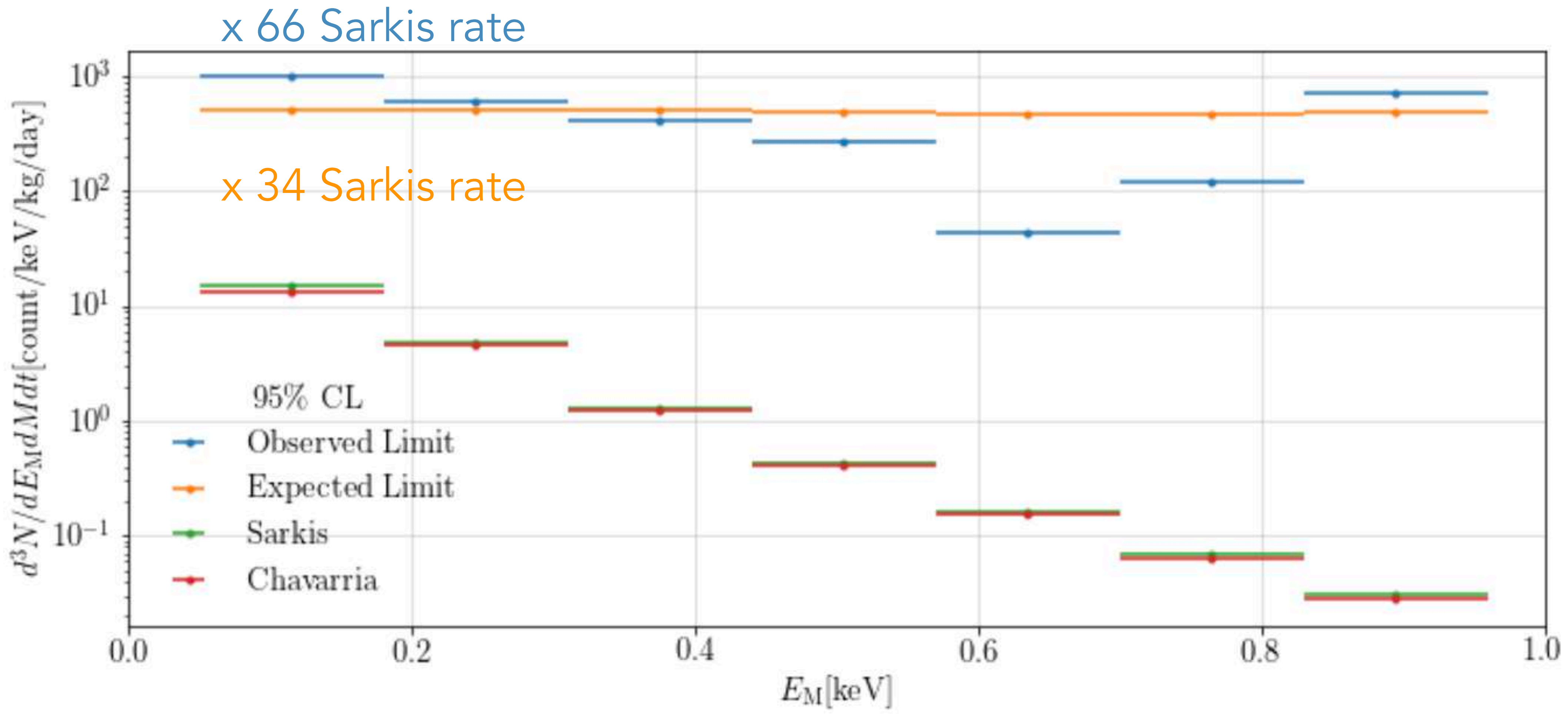


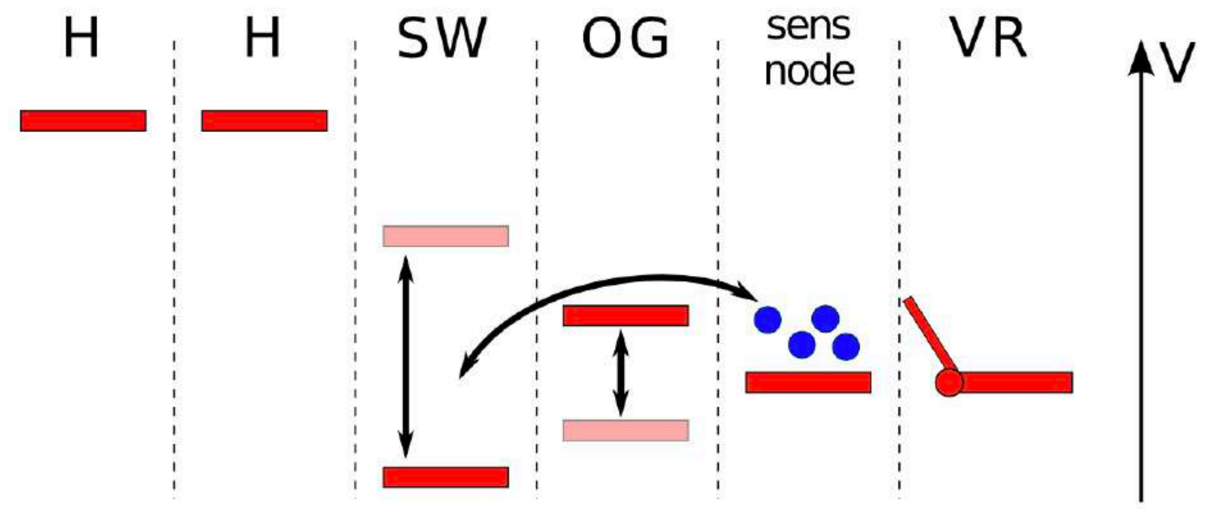
CEvNS detection: larger mass / lower threshold / lower background / larger flux

Skipper CCDs

New technology

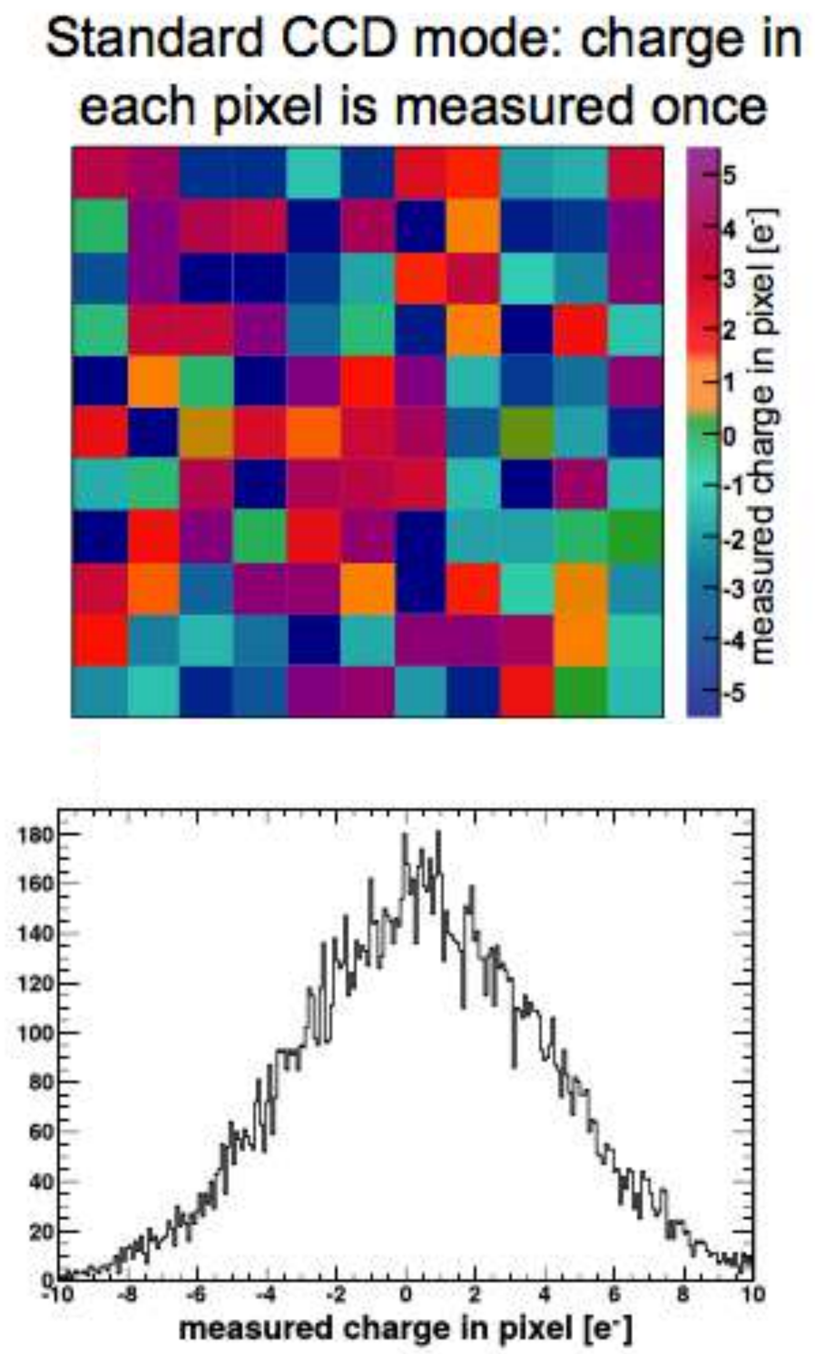
- Skipper-CCDs allows one to decrease the detection threshold to ~15 eV

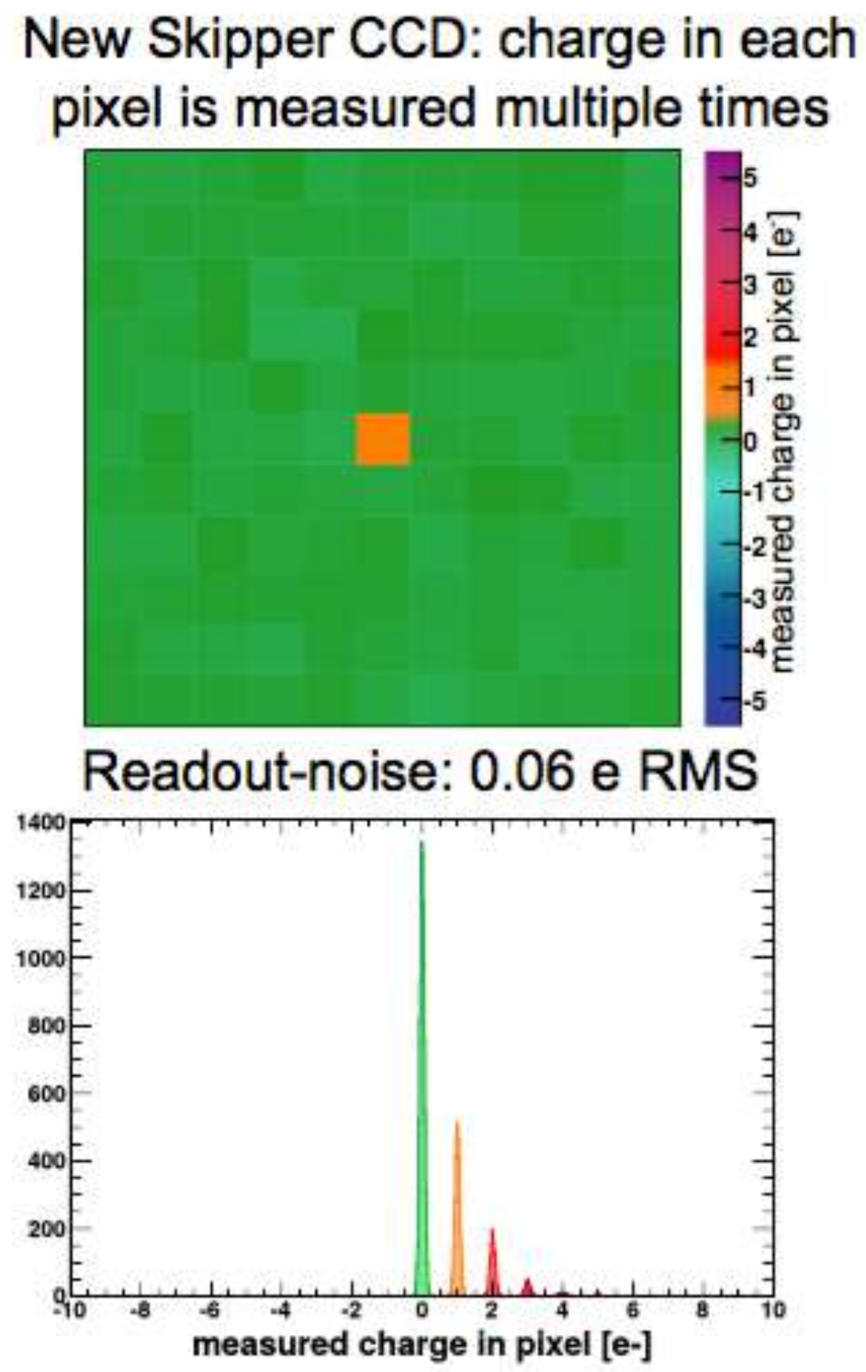
Proposed in 1990 by Janesick et al. (doi:10.1117/12.19452)



multiple readings of the charge of the same pixel

◆ Counting electrons (0, 1, 2, …)





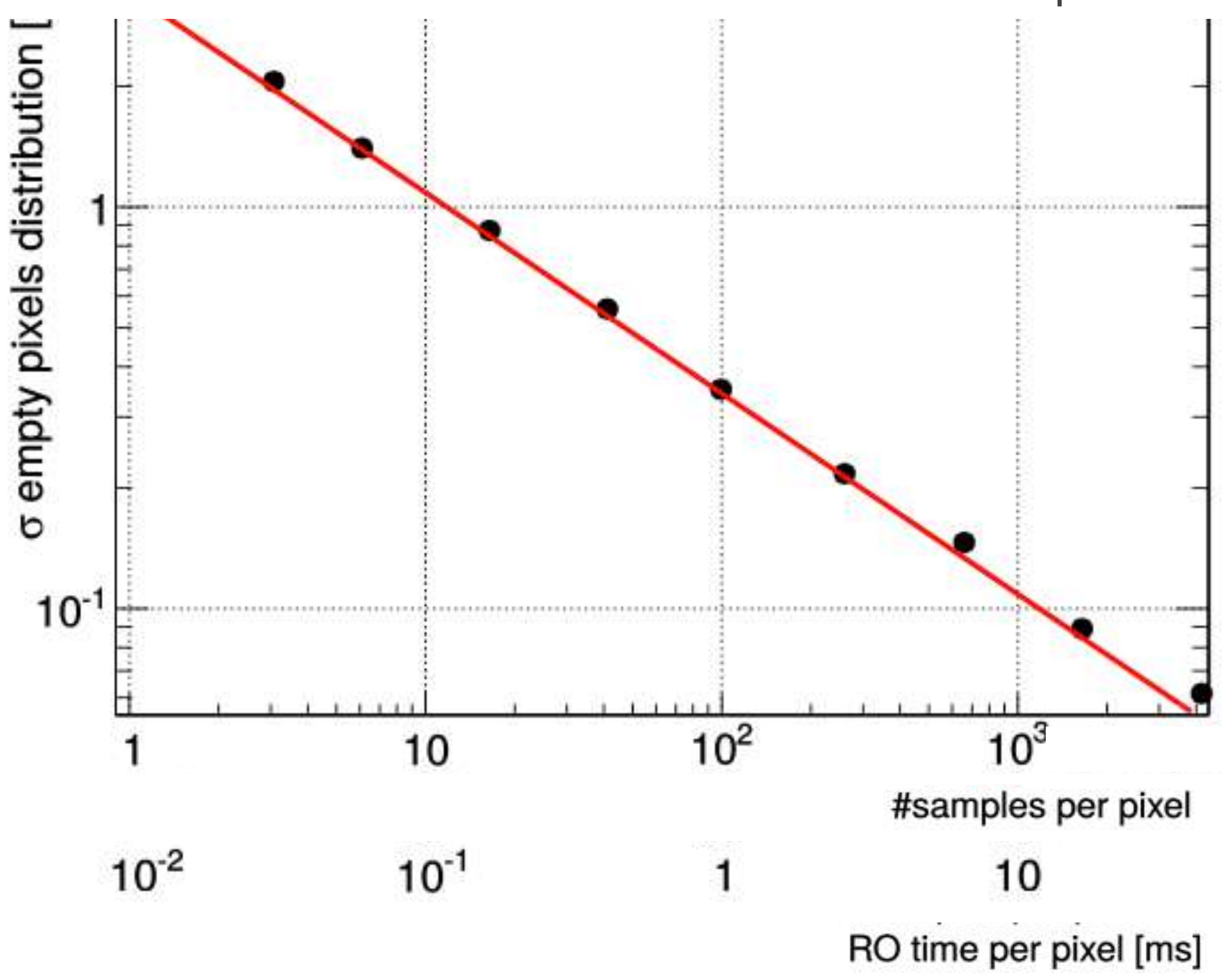
$N_{\text{readouts}} = 1$

$\sigma = 3.5e^{-}$

$N_{\text{readouts}} = 4000$

$\sigma = \frac{3.5e^{-}}{\sqrt{4000}} = 0.06e^{-}$

Readout noive vs number of samples



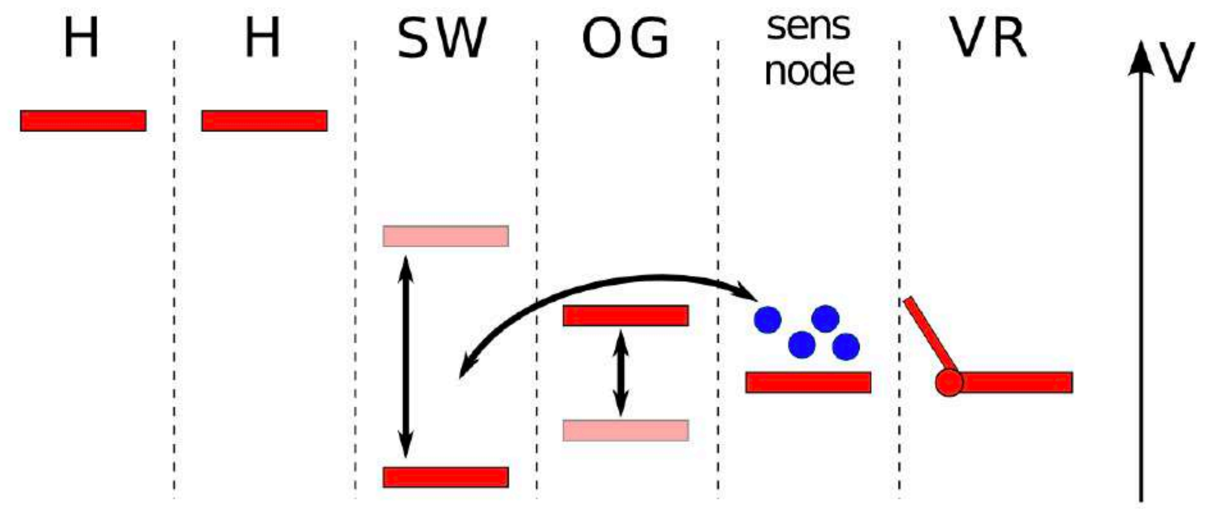
J. Tiffenberg et al, PRL 119 (2017)
using a detector designed by Stephen Holland (LBNL)
PRL 125, 171802 (2020)
SENSEI DM experiment currently using skipper CCDs

Skipper CCDs

New technology

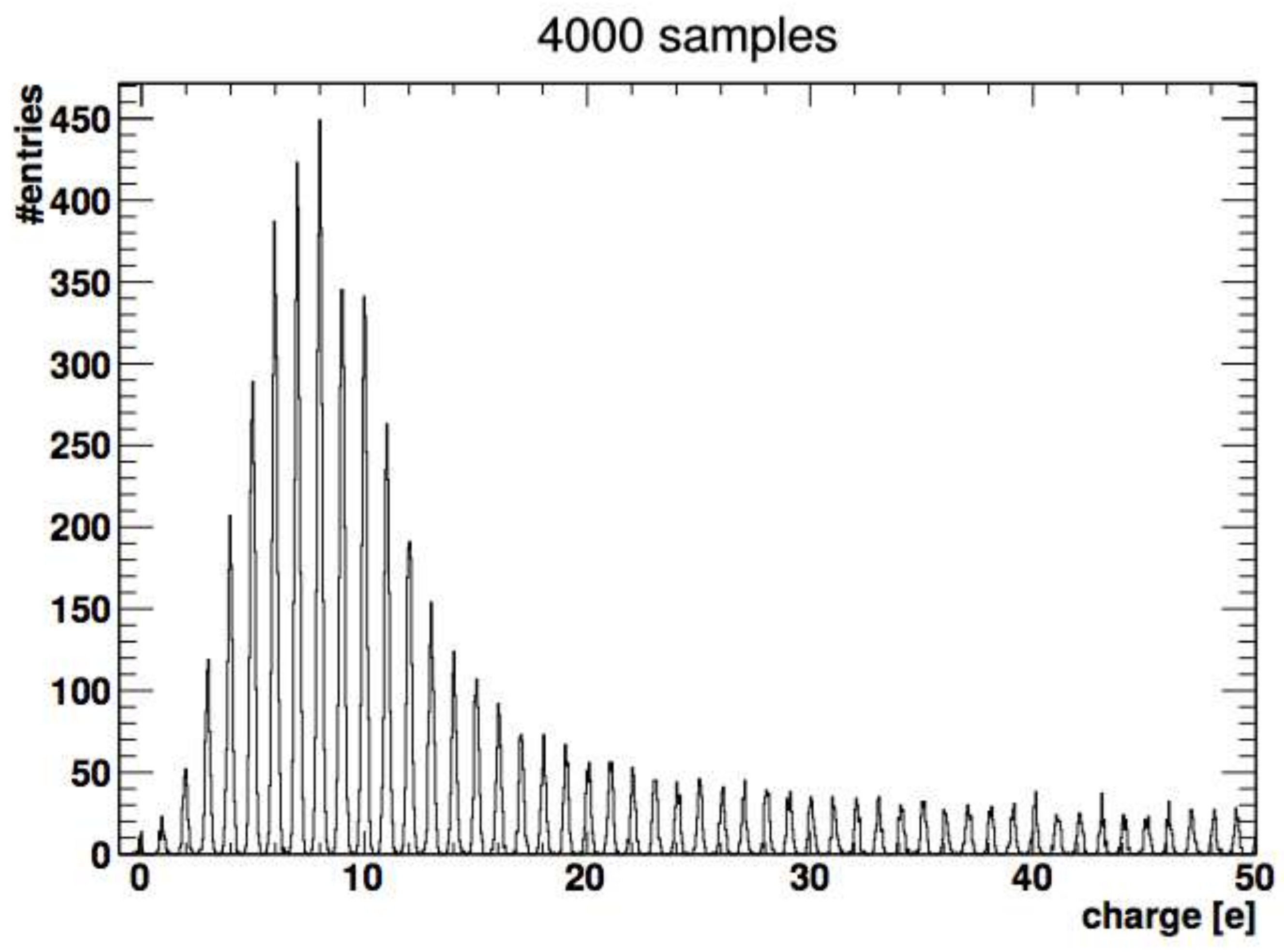
- Skipper-CCDs allows one to decrease the detection threshold to ~15 eV

Proposed in 1990 by Janesick et al. (doi:10.1117/12.19452)

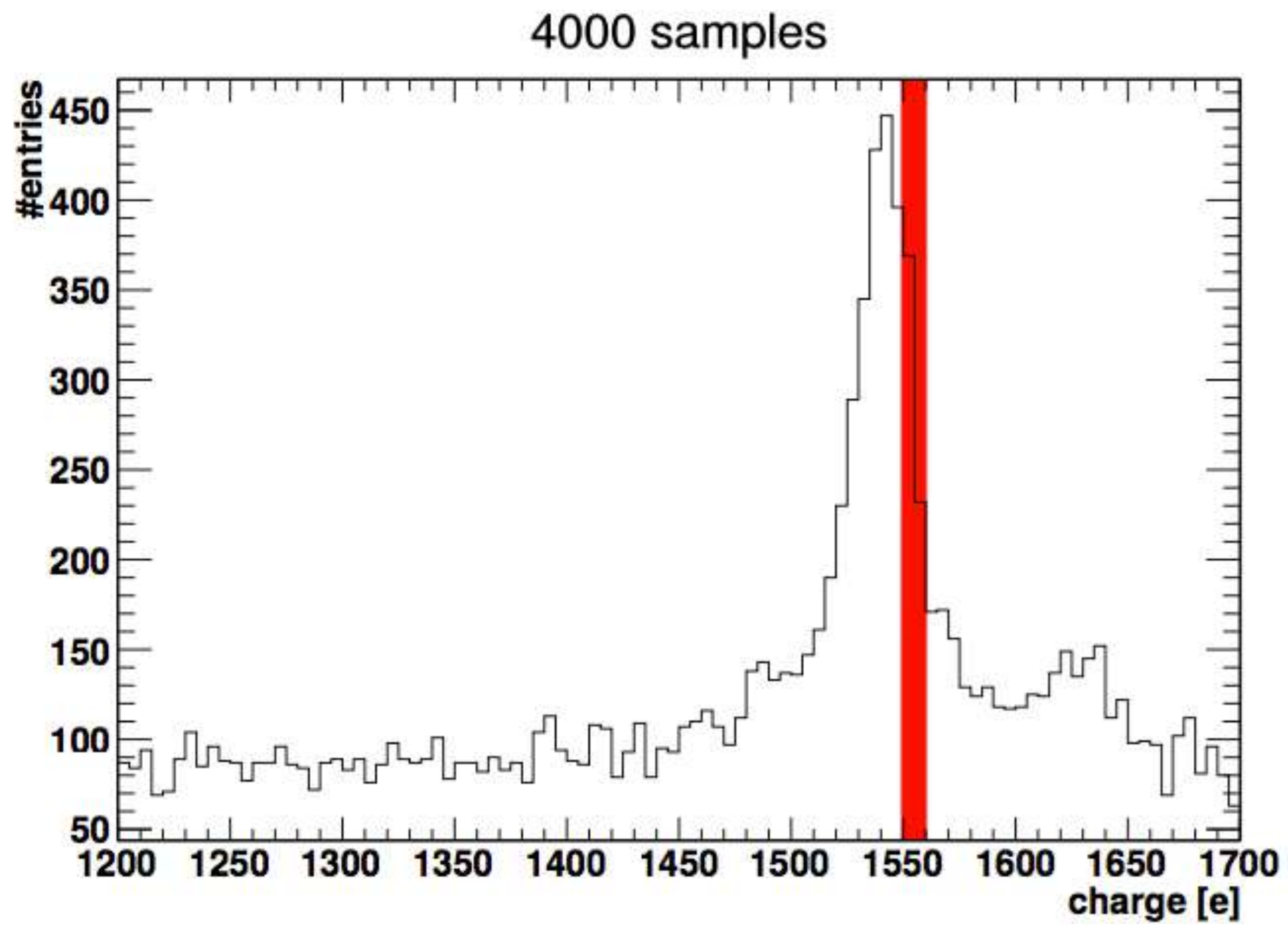


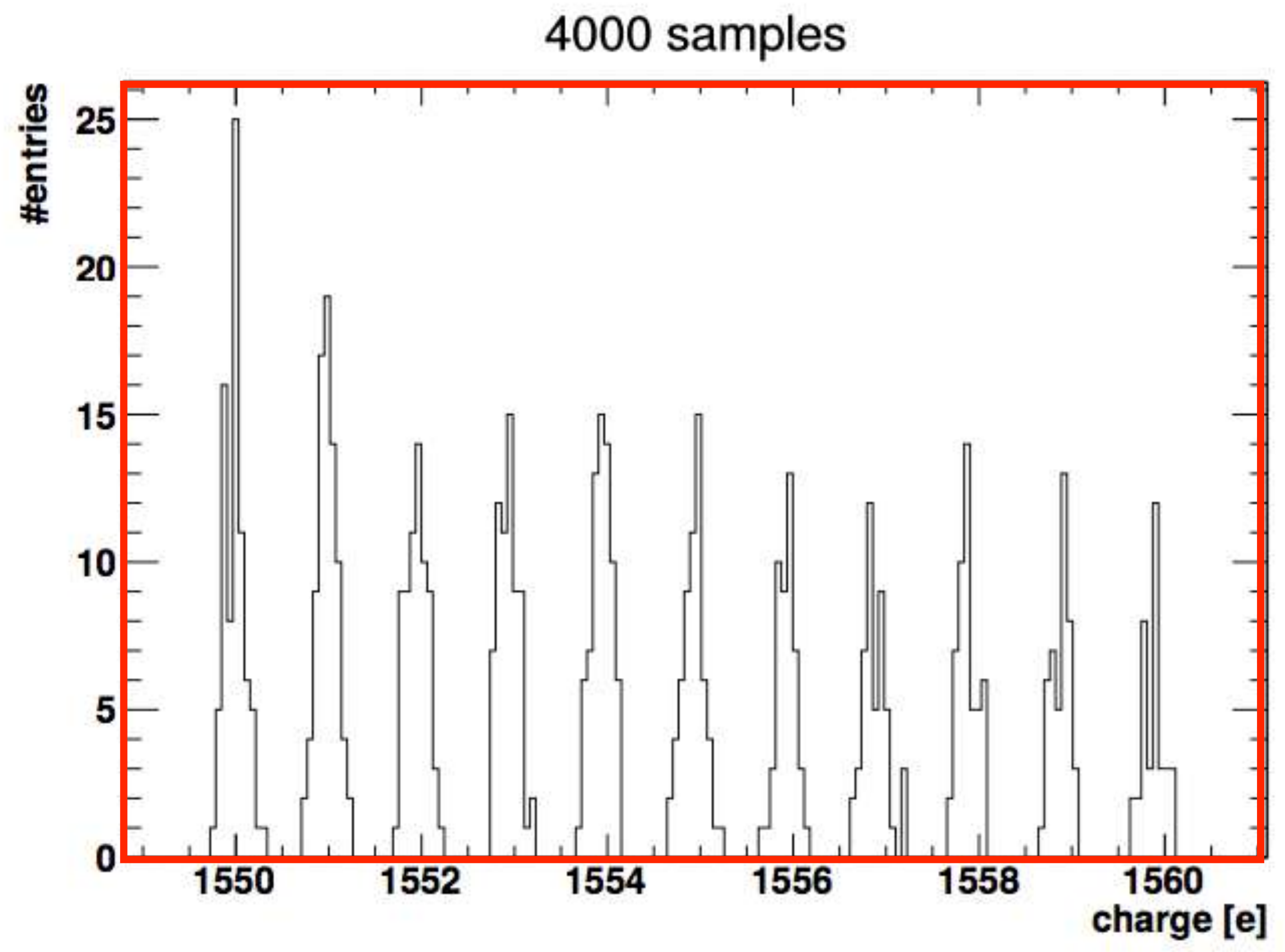
multiple readings of the charge of the same pixel

- Counting electrons (… 48, 49, 50, …)



… 1550, 1551, 1552 …



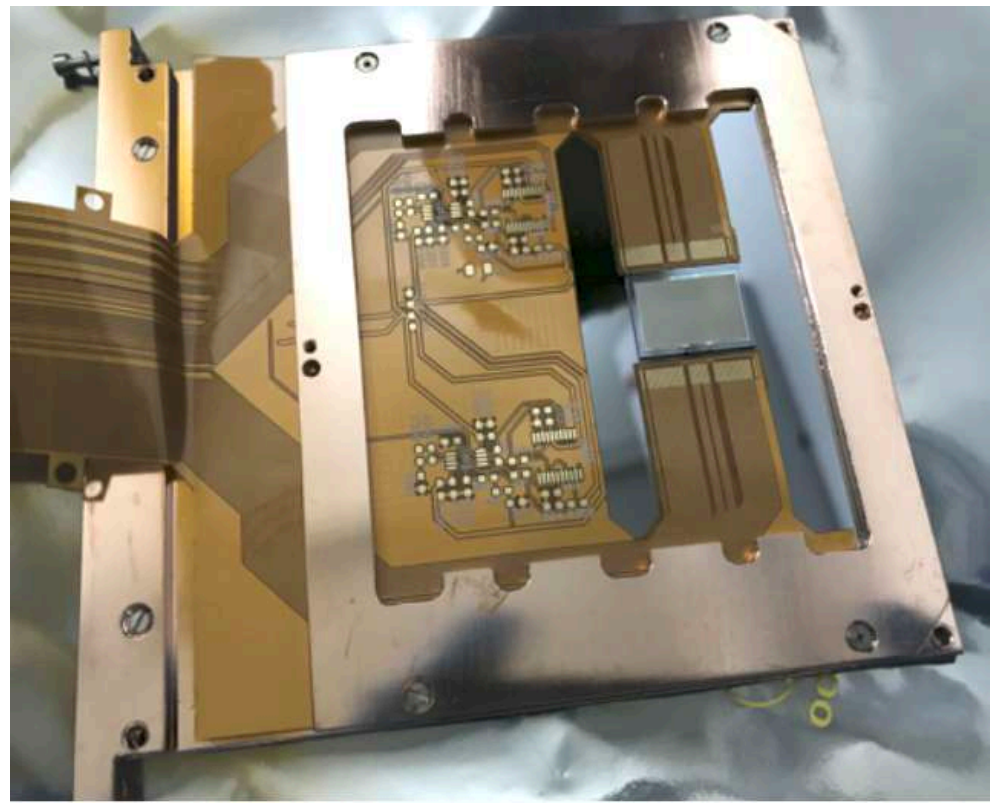


Used in the SENSEI experiment

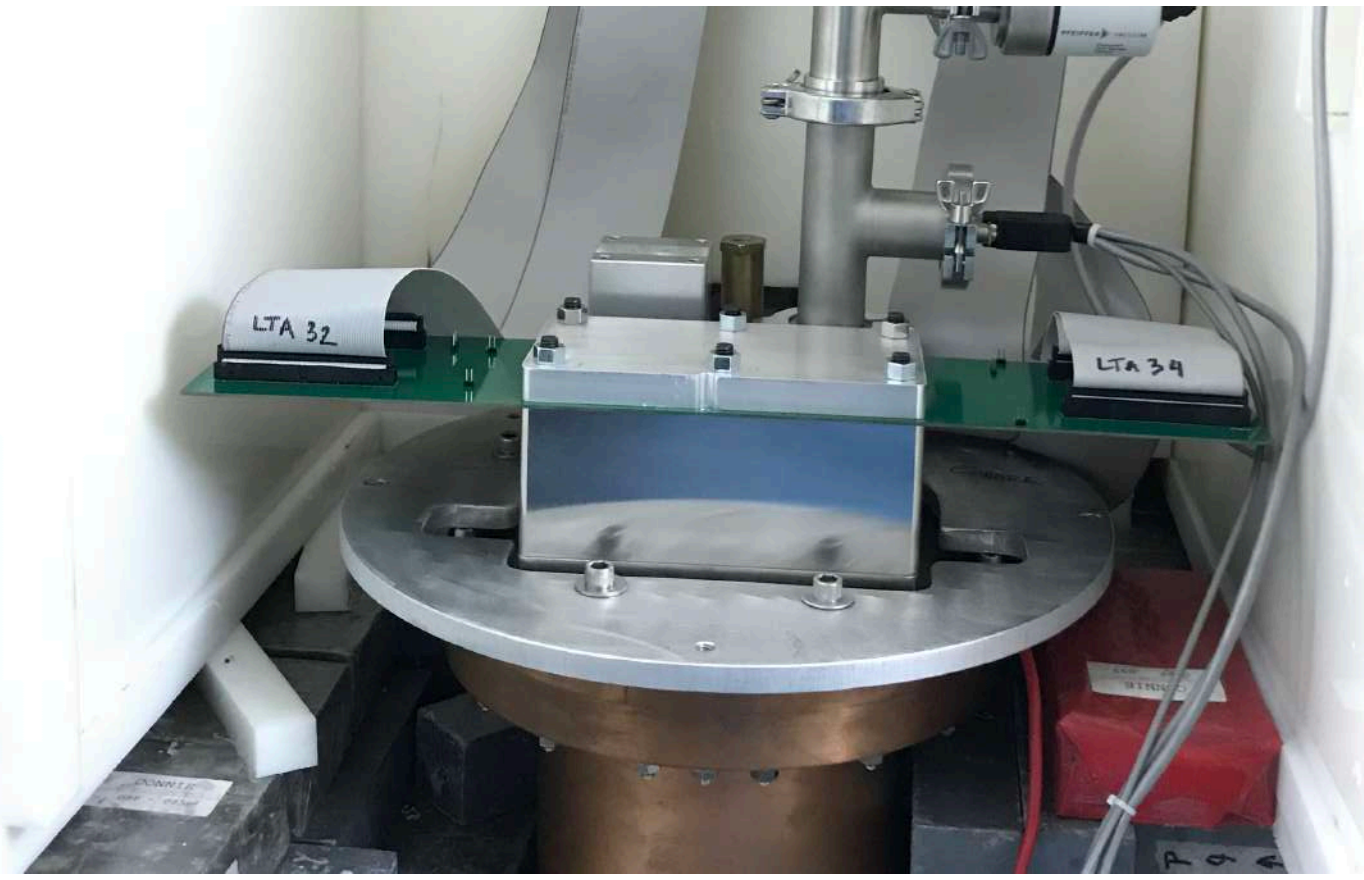
- Objective: detect DM-e interactions by measuring ionization produced by electron recoil
- Best world limits for sub-GeV DM

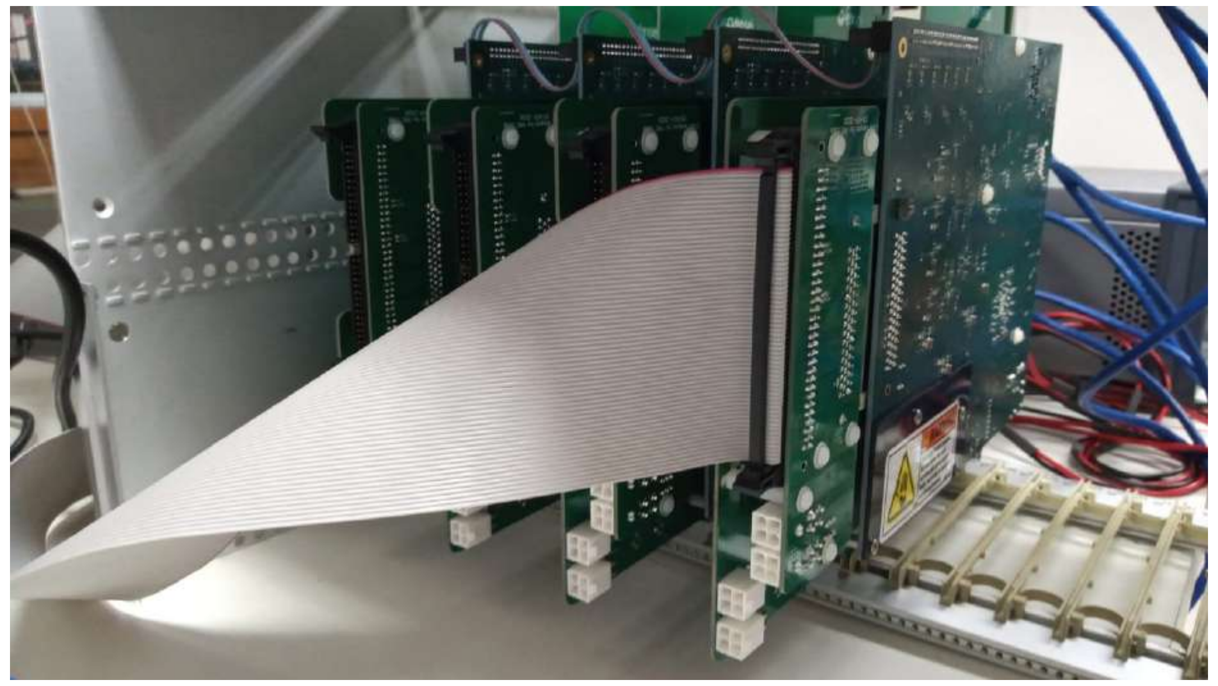
Phys.Rev.Lett. 122 (2019) 16, 161801
Phys.Rev.Lett. 125 (2020) 17, 171802

Installation of 2 Skipper-CCDs in CONNIE



2 Skipper CCDs of
1022 x 682 pixels each





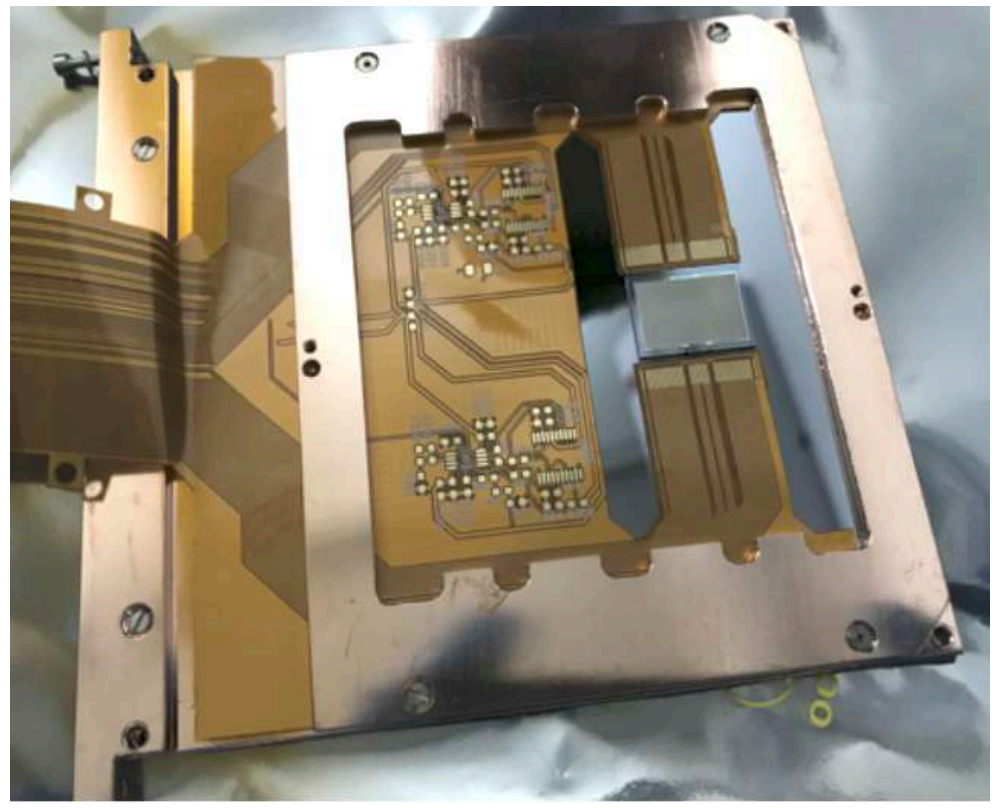
Low Threshold Acquisition (LTA)
readout electronics

JATIS 7, 1 015001 (2021)

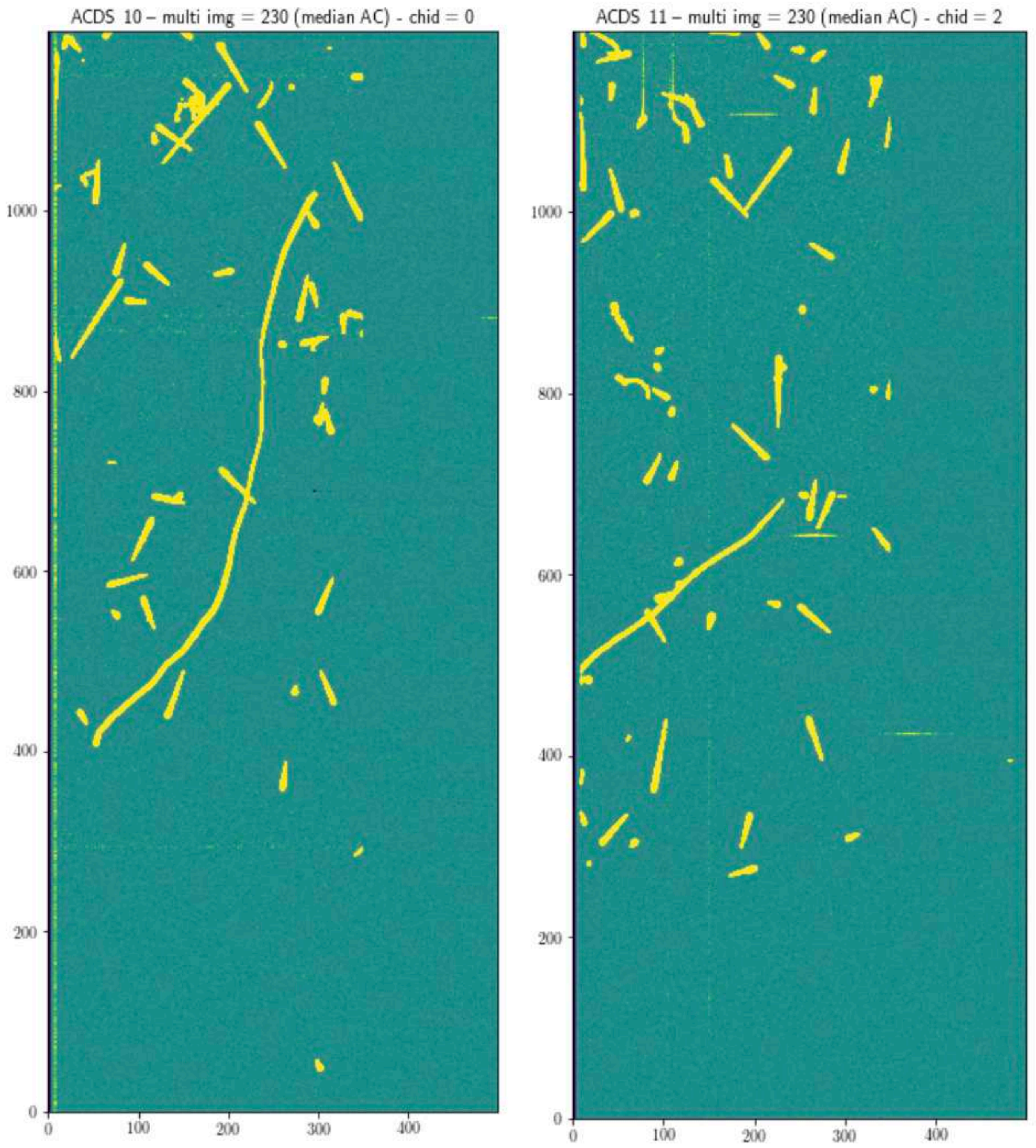
New vacuum interface board installed

Installation of 2 Skipper-CCDs in CONNIE

Towards the new generation of experiments for CEvNS detection @ reactors

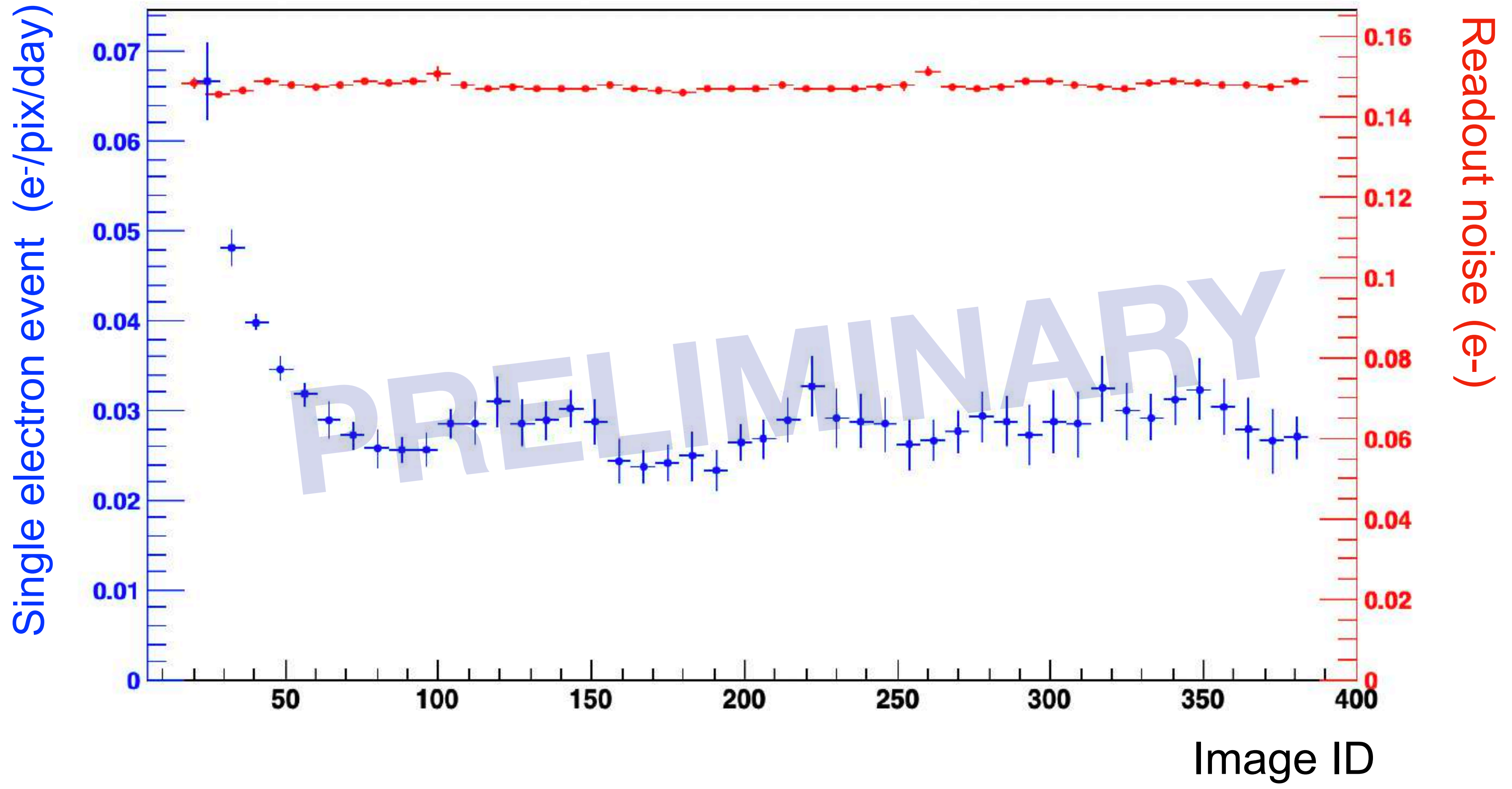


2 Skipper CCDs of 1022 x 682 pixels each

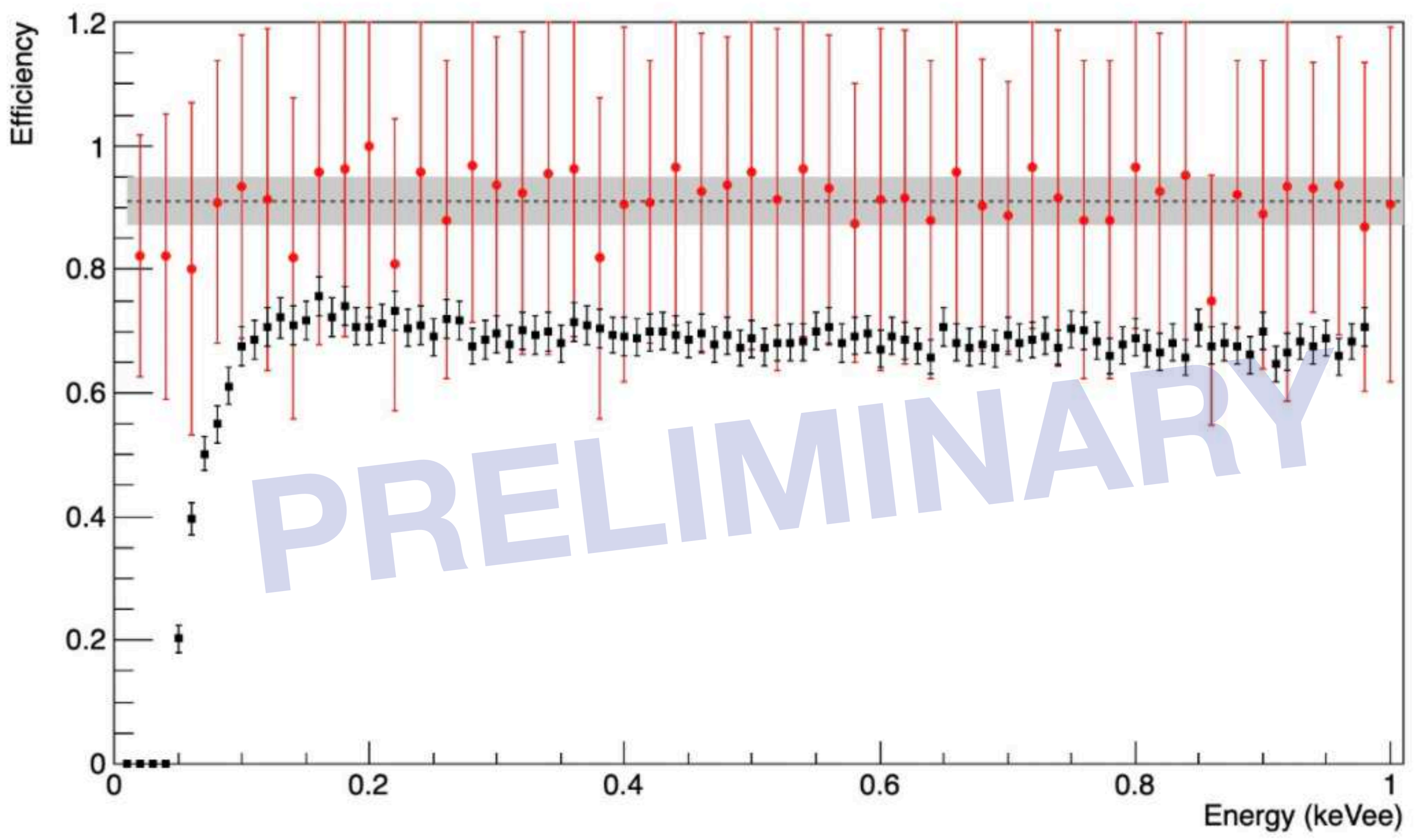


Images with 400 samples per pixel

◆ Performance



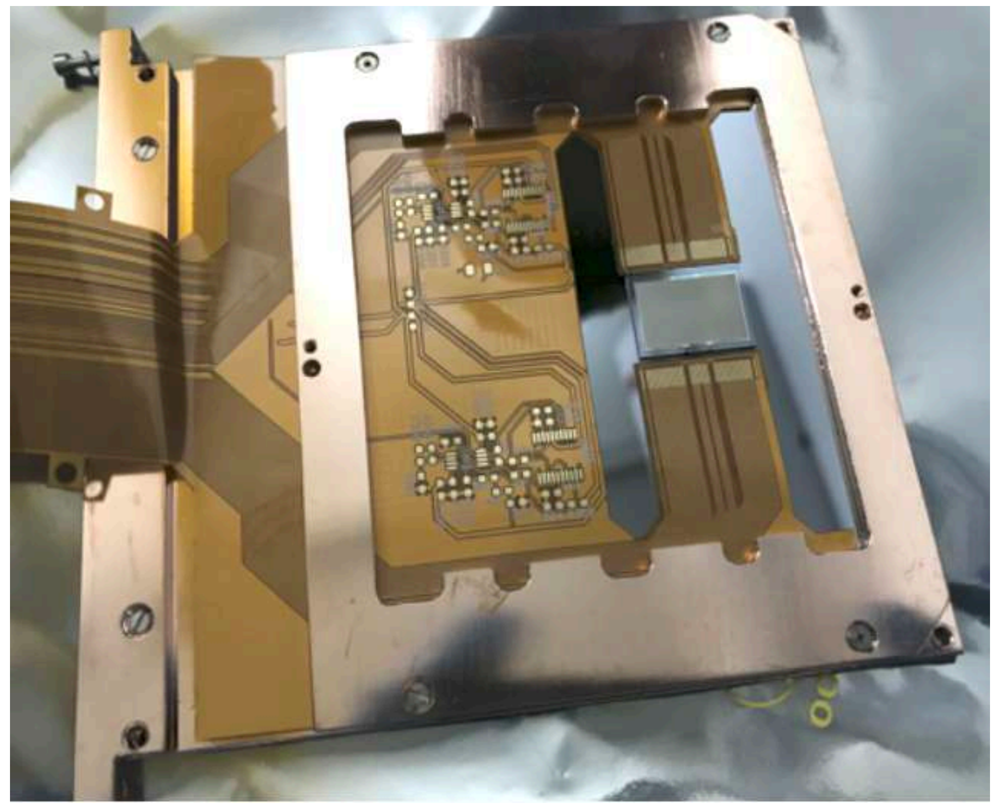
◆ Event selection efficiency



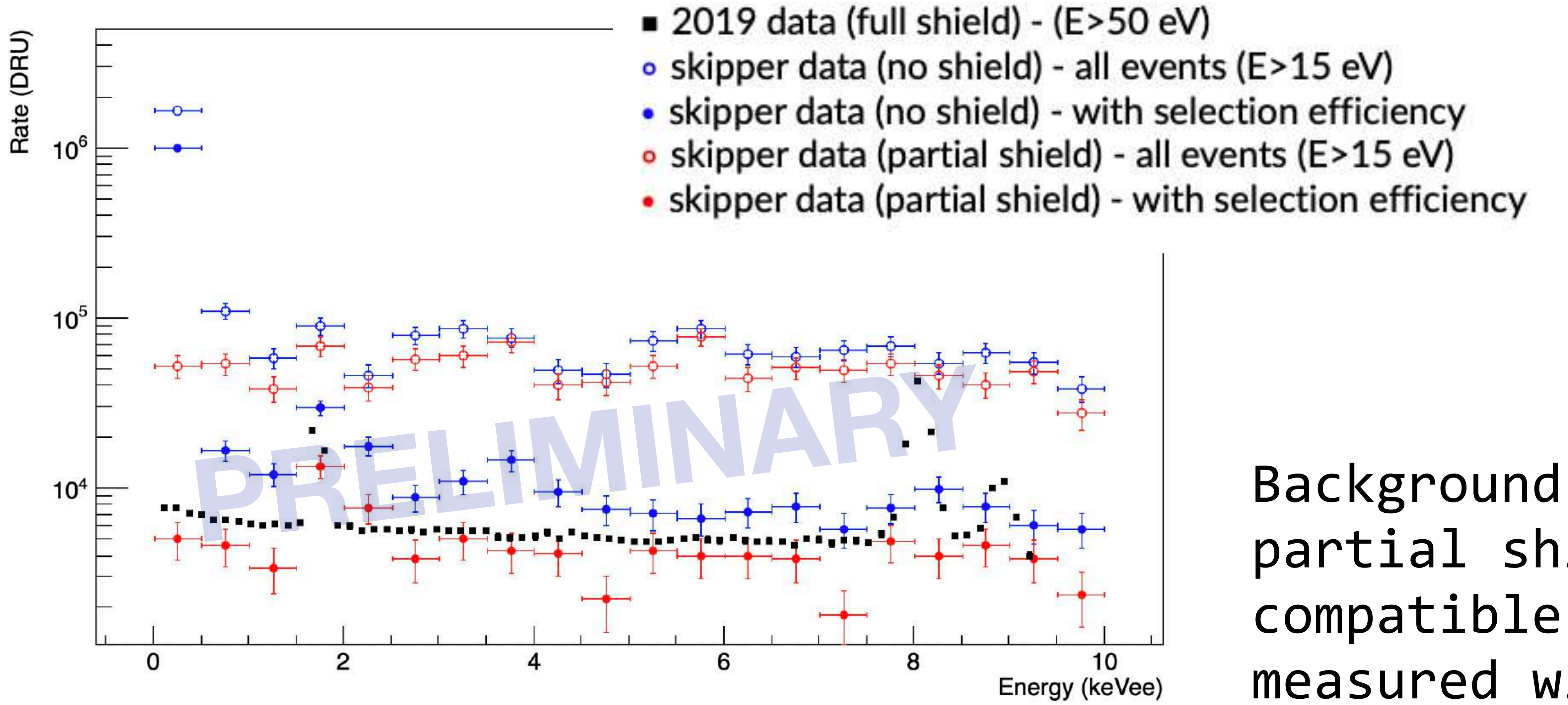
- ◆ Study the response of these sensors and the reading electronics in Angra 2
- ◆ Determine the background at sea level
- ◆ Taking data in a stable way since July 2021

Installation of 2 Skipper-CCDs in CONNIE

Towards the new generation of experiments for CEvNS detection @ reactors



2 Skipper CCDs of
1022 x 682 pixels each

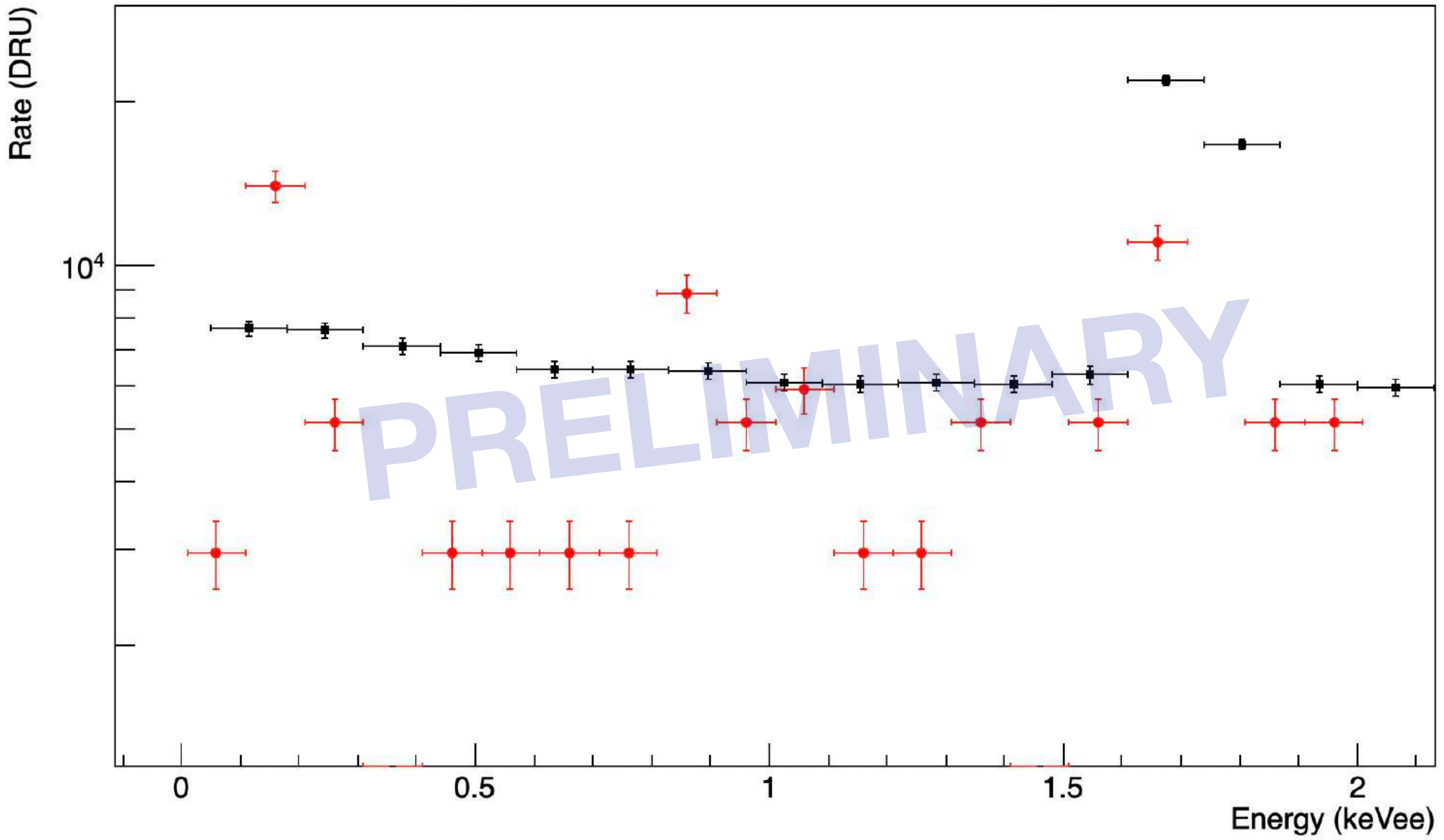


Background measured with partial shielding is now compatible with the background measured with 2019 data

2 data sets:

- Without shield: exposure 0.43 g-day
- With partial shield (30 cm polyethylene and 5 cm lead): exposure 1.7 g-day

NOW: closing completely the shielding!



Summary

- CEνNS: very active field
- Exciting moment: new results from different experiments (and techniques) expected soon.
- New facilities and next generation experiments being designed
- Synergy between experiments and theory

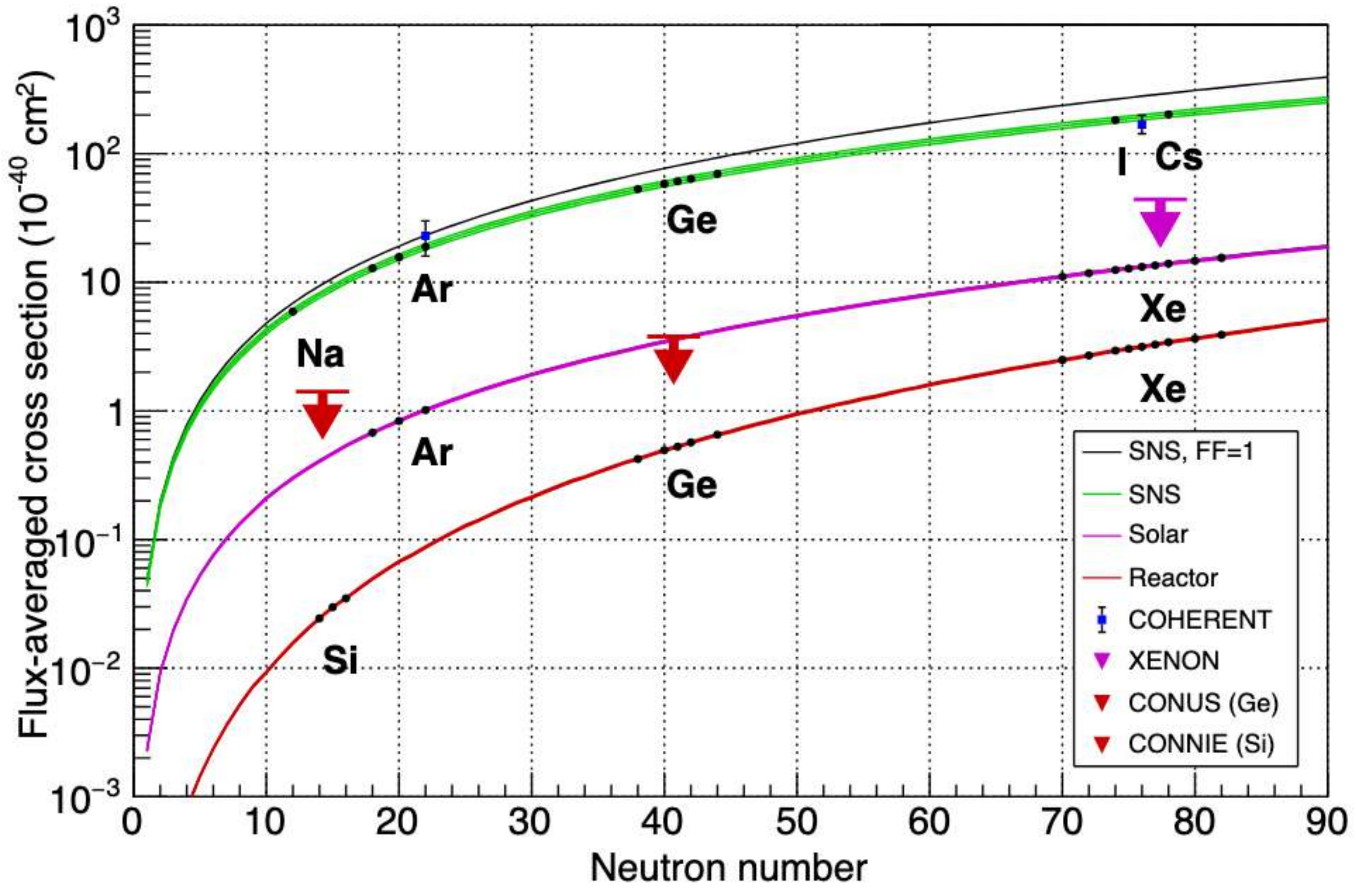


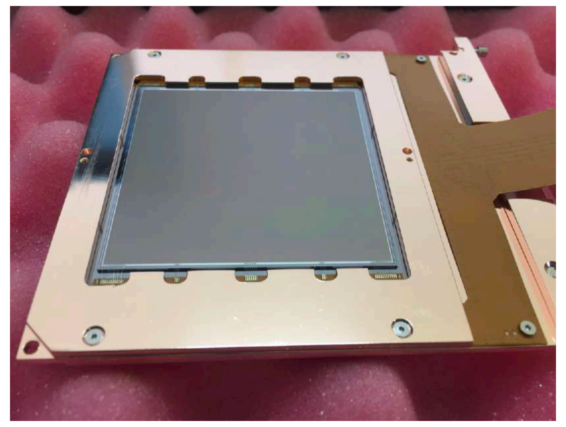
Figure: Kate Scholberg

- CCDs are a promising technology for detecting CEvNS at low energies
- CONNIE has demonstrated to be competitive constraining BSM physics
- In 2019 run data analysis we achieved better sensitivity due to binning and improved analysis

Summary

- Skipper CCDs allow to improve greatly the low-energy sensitivity
- The first skipper data at a reactor are encouraging → stable, low noise and DC, rate with partial shield competitive with CONNIE 2019 rate
- Characterization of skipper CCDs at sea-level background will help prepare for a future larger-mass skipper CCD experiment

CCD 4k x 4k



Skipper - CCD 1k x 6k

Started discussions for installing skipper CCDs inside the dome of the reactor at Angra (~17 m away from the core)

Recently, the vIOLETA collaboration(*) installed a CCD Skipper 12 m from the core of the Atucha 2 reactor (2.2 GW)

(*) https://www.violetaexperiment.com/

Thank you !!

NOVEMBER 8-12, 2021