First Observation of Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)

KAIST

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Observation of coherent elastic neutrino-nucleus scattering

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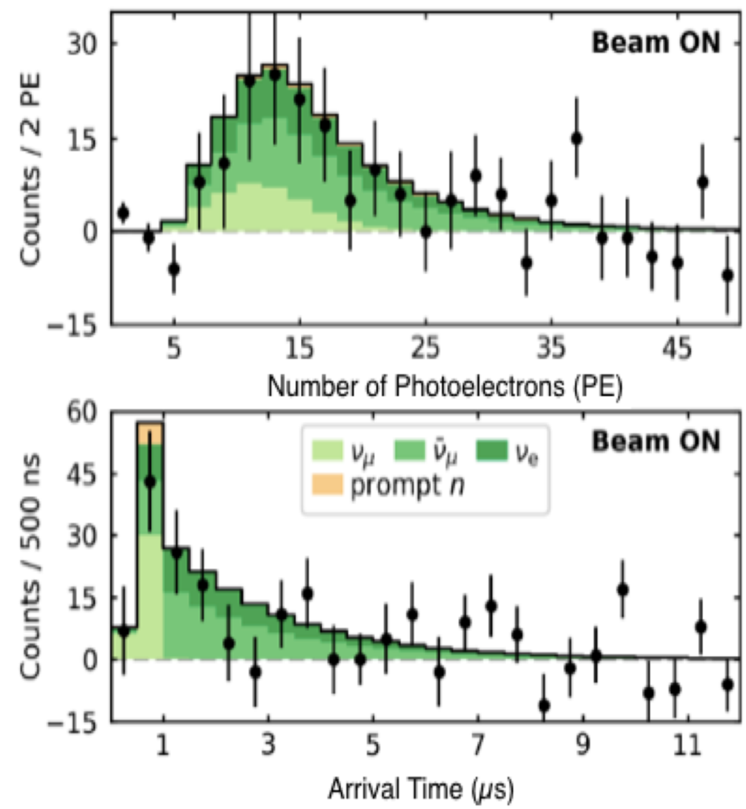

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

Straightforward calculation given the existence of weak neutral current

CEvNS has not been observed since its first prediction in 1974

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

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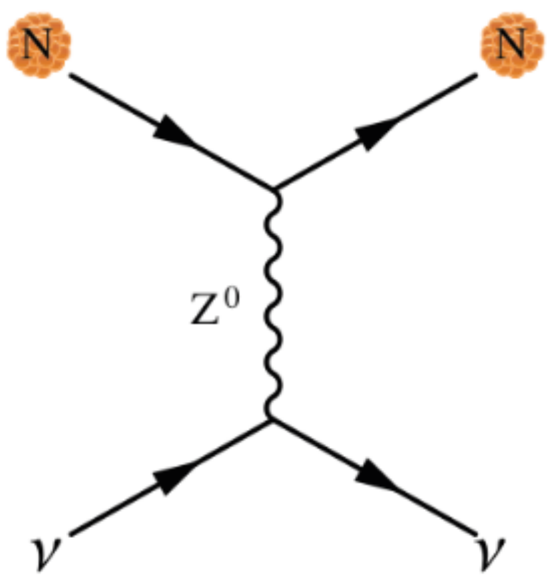
(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \rightarrow \nu + A$ should have a sharp coherent forward peak just as $e + A \rightarrow e + A$ 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 $\nu + A \rightarrow \nu + A^*$ 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.

$$\mathcal{L}_{eff} = \frac{G_F}{\sqrt{2}} l^\mu j_\mu$$



Cross section for zero-momentum transfer limit

$$\sigma_{\nu N} \simeq \frac{4}{\pi} E_\nu^2 \left[Z\omega_p + (A-Z)\omega_n\right]^2$$

$$g(Z_0 u) = \frac{1}{4} - \frac{2}{3}\sin^2\theta_W, \qquad g(Z_0 d) = -\frac{1}{4} + \frac{1}{3}\sin^2\theta_W$$

$$\omega_p = \frac{G_F}{4}(4\sin^2\theta_W - 1), \qquad \omega_n = \frac{G_F}{4}$$

Differential cross section for finite momentum transfer

$$\frac{d\sigma}{dE} = \frac{G_F^2}{4\pi}\left[(1-4\sin^2\theta_w)Z - (A-Z)\right]^2 M \left(1 - \frac{ME}{2E_\nu^2}\right) F(Q^2)^2$$

CEvNS Crossection

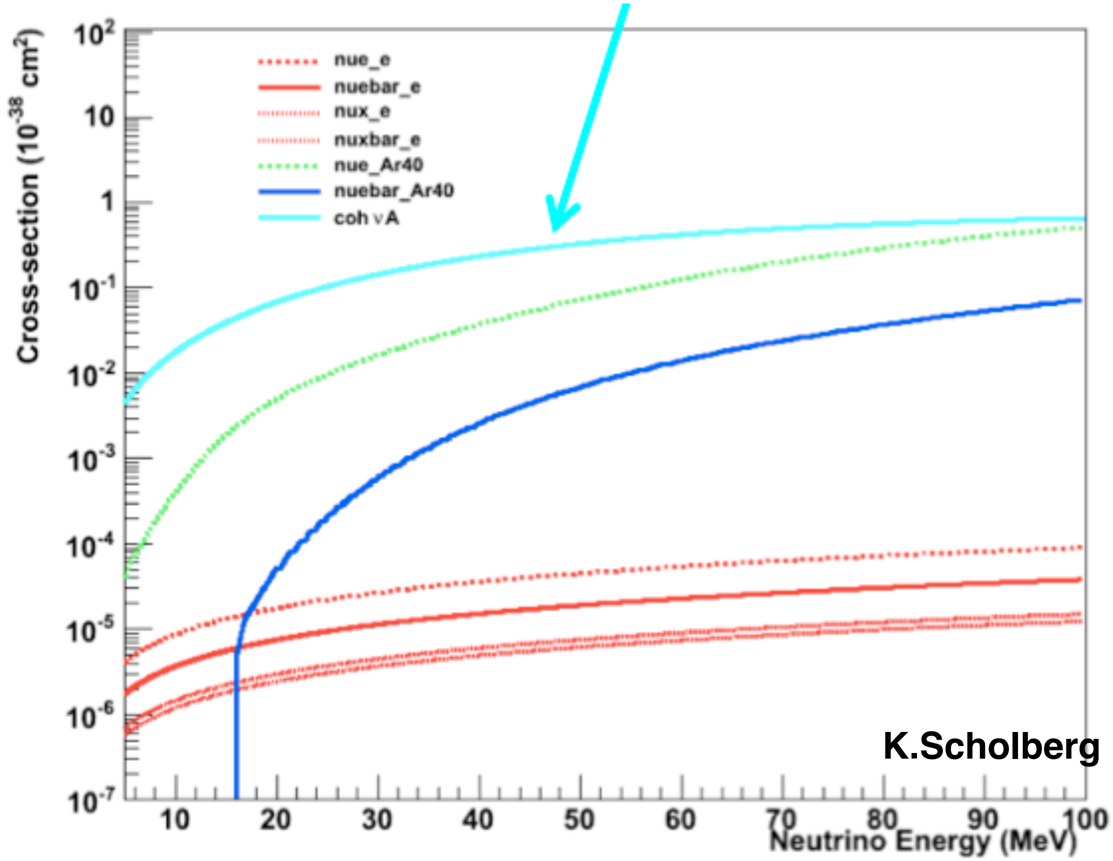
Largest cross section in the region of interest

For most of the detector target nucleus, the coherence condition is fulfilled by neutrino energy of

$$E_\nu < \frac{1}{R_N} \simeq 50 \text{ MeV}$$

$$E_{max} \simeq \frac{2E_\nu^2}{M} \simeq \mathcal{O}(100) \text{ keV}$$

Recoil energy is tiny



Requires a ton-scale detector with ~10 keV energy threshold

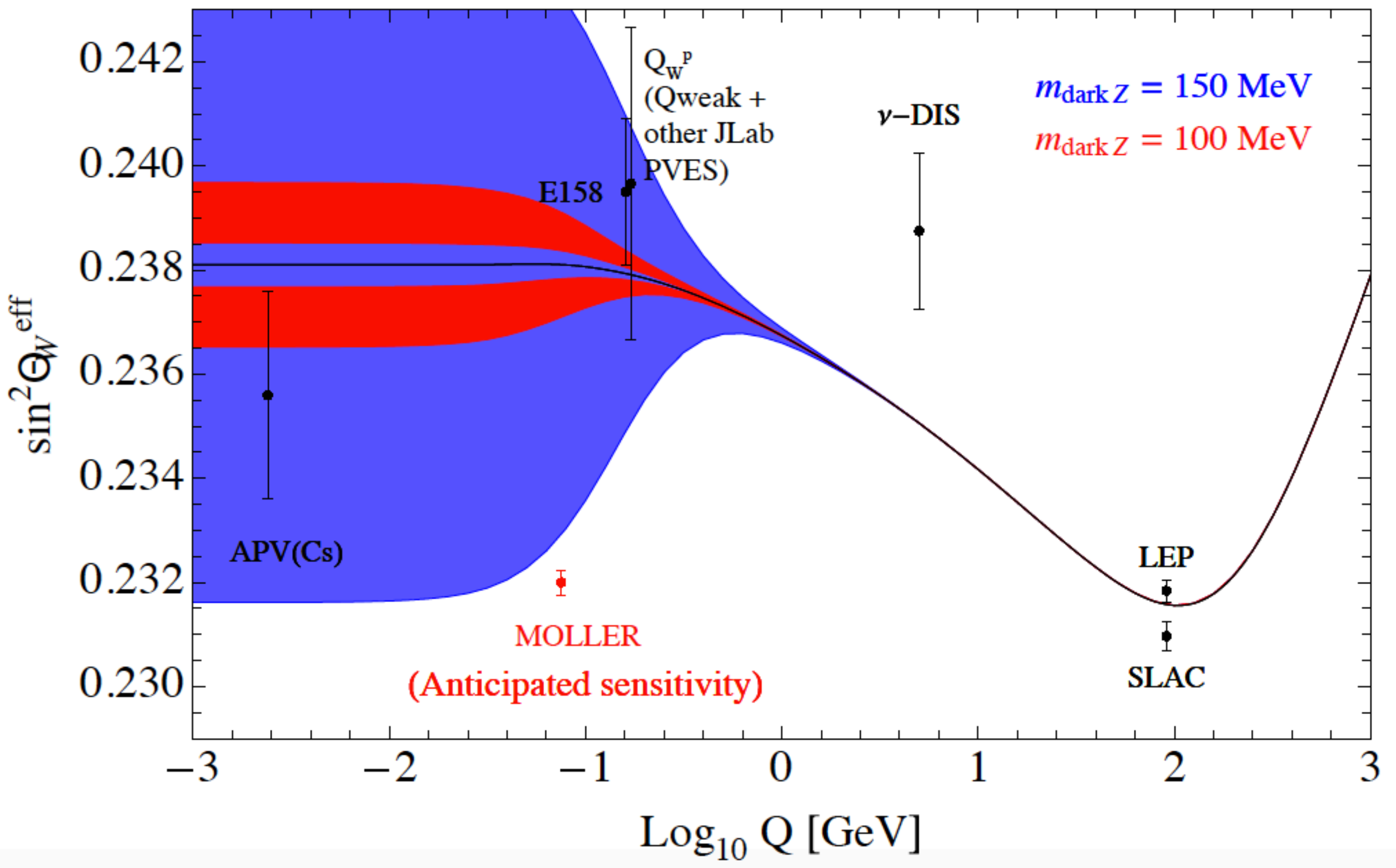
$$R \simeq \mathcal{O}(10^3) \left(\frac{\sigma}{10^{-39} cm^2}\right) \times \left(\frac{\Phi}{10^{13} \nu/year/cm^2}\right) \times \left(\frac{M}{ton}\right) events/year$$

Why CEvNS? — Weinberg Angle

θ_W is a free parameter in Standard Model.
There is no fundamental theory which explains its value.

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

$$\sigma_{tot} = \frac{G_F^2 E_\nu^2}{4\pi}\left[Z\left(1-4\sin^2\theta_W\right)-N\right]^2 F^2(Q^2)$$

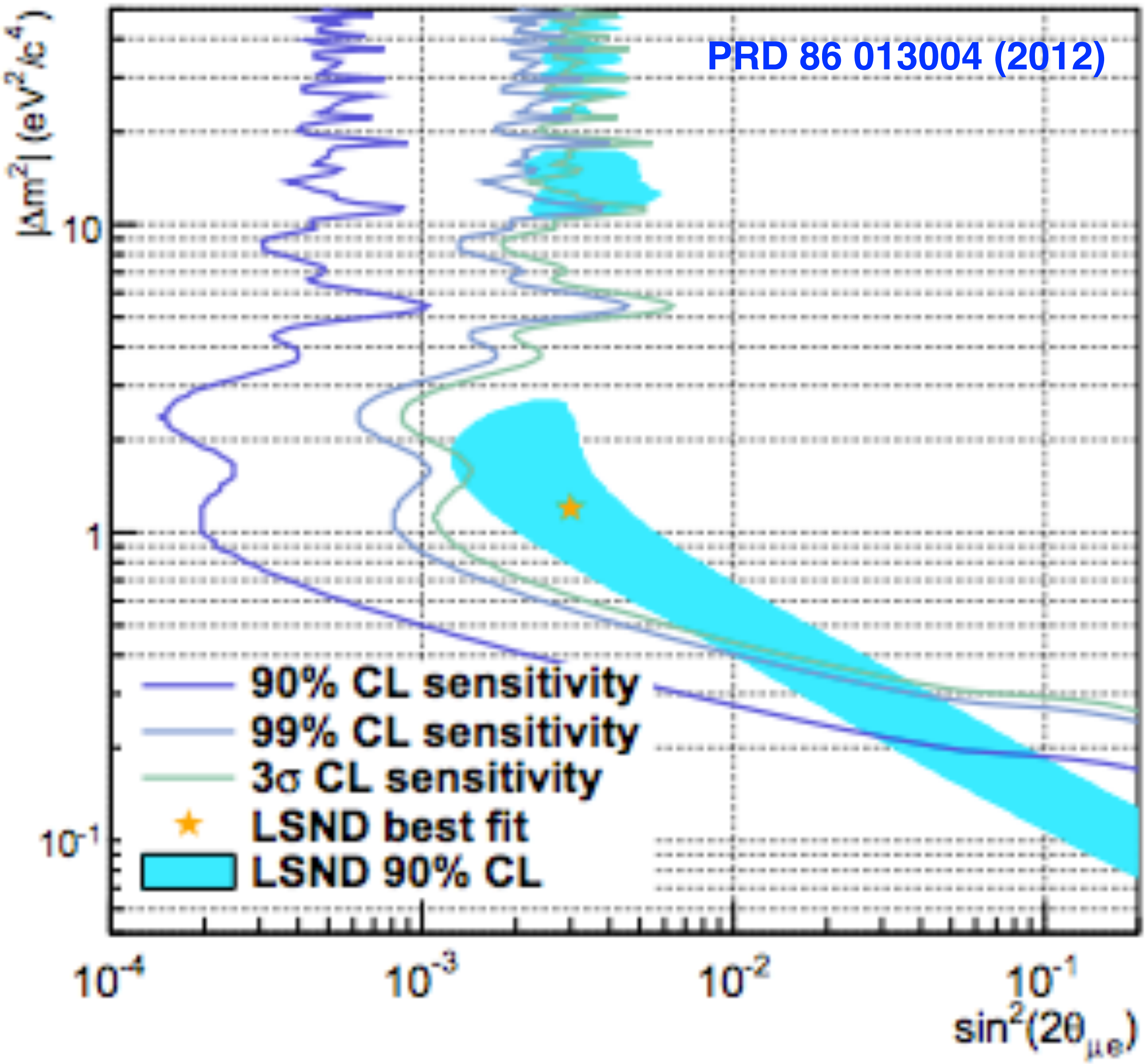


Why CEvNS? — Non Standard Interactions

$$\mathcal{L}_{\nu H}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta=e,\mu,\tau}} [\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5)\nu_\beta] \times (\varepsilon_{\alpha\beta}^{qL}[\bar{q}\gamma_\mu(1-\gamma^5)q] + \varepsilon_{\alpha\beta}^{qR}[\bar{q}\gamma_\mu(1+\gamma^5)q])$$

JHEP 03(2003) 011

NSI parameter limit	Source
$-1 < \varepsilon_{ee}^{uL} < 0.3$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$-0.4 < \varepsilon_{ee}^{uR} < 0.7$	
$-0.3 < \varepsilon_{ee}^{dL} < 0.3$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$-0.6 < \varepsilon_{ee}^{dR} < 0.5$	
$\lvert\varepsilon_{\mu\mu}^{uL}\rvert < 0.003$	NuTeV νN, $\bar{\nu} N$ scattering
$-0.008 < \varepsilon_{\mu\mu}^{uR} < 0.003$	
$\lvert\varepsilon_{\mu\mu}^{dL}\rvert < 0.003$	NuTeV νN, $\bar{\nu} N$ scattering
$-0.008 < \varepsilon_{\mu\mu}^{dR} < 0.015$	
$\lvert\varepsilon_{e\mu}^{uP}\rvert < 7.7 \times 10^{-4}$	$\mu \to e$ conversion on nuclei
$\lvert\varepsilon_{e\mu}^{dP}\rvert < 7.7 \times 10^{-4}$	$\mu \to e$ conversion on nuclei
$\lvert\varepsilon_{e\tau}^{uP}\rvert < 0.5$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$\lvert\varepsilon_{e\tau}^{dP}\rvert < 0.5$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$\lvert\varepsilon_{\mu\tau}^{uP}\rvert < 0.05$	NuTeV νN, $\bar{\nu} N$ scattering
$\lvert\varepsilon_{\mu\tau}^{dP}\rvert < 0.05$	NuTeV νN, $\bar{\nu} N$ scattering



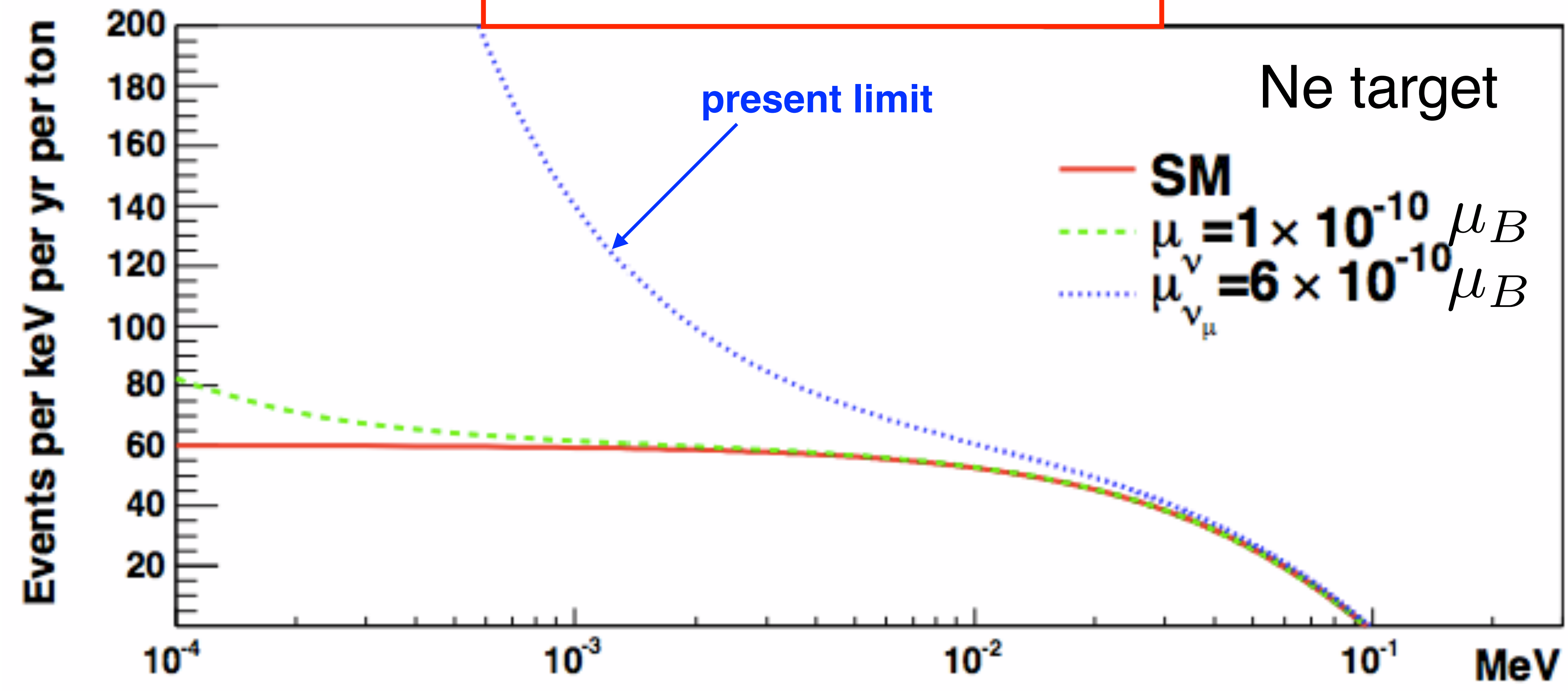
The development of a coherent neutrino scattering detection capability provides the most natural way to explore the sterile neutrino sector.

The neutral current interaction is the obvious way to probe non-active neutrino flavor stats, as the interaction sensitive to all active neutrinos.

Why CEvNS? — Neutrino Magnetic Moment

- Magnetic moment of neutrino enhances the recoil energy spectrum at low energy
  ➔ requires very low energy threshold detector

$$\frac{d\sigma}{dE} = \frac{\pi\alpha^2\mu_\nu^2 Z^2}{m_e^2}\left(\frac{1-E/k}{E} + \frac{E}{4k^2}\right)$$

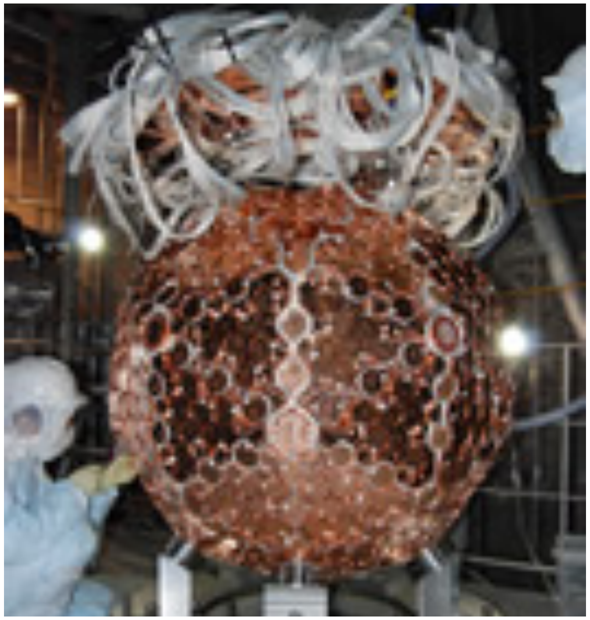


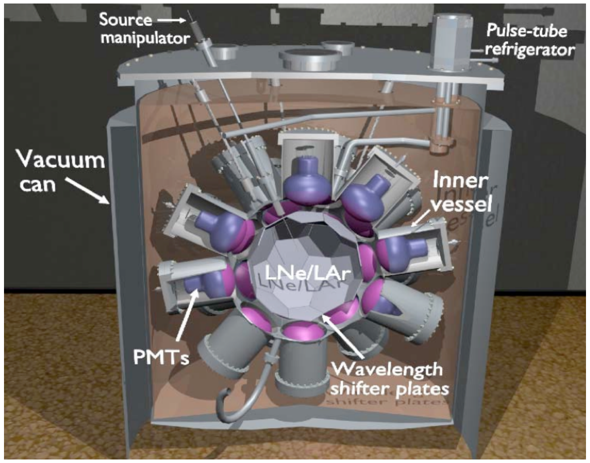
Why CEvNS? — Supernova

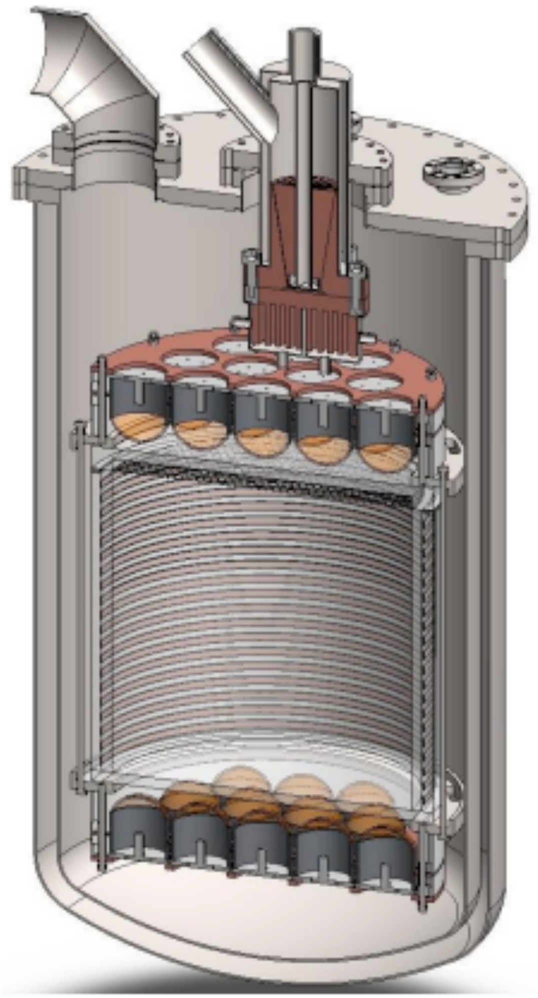
Large effect on Supernovae dynamics.
The measurement of CEvNS will validate the supernova explosion models

Low Background & Low Energy Threshold Detector

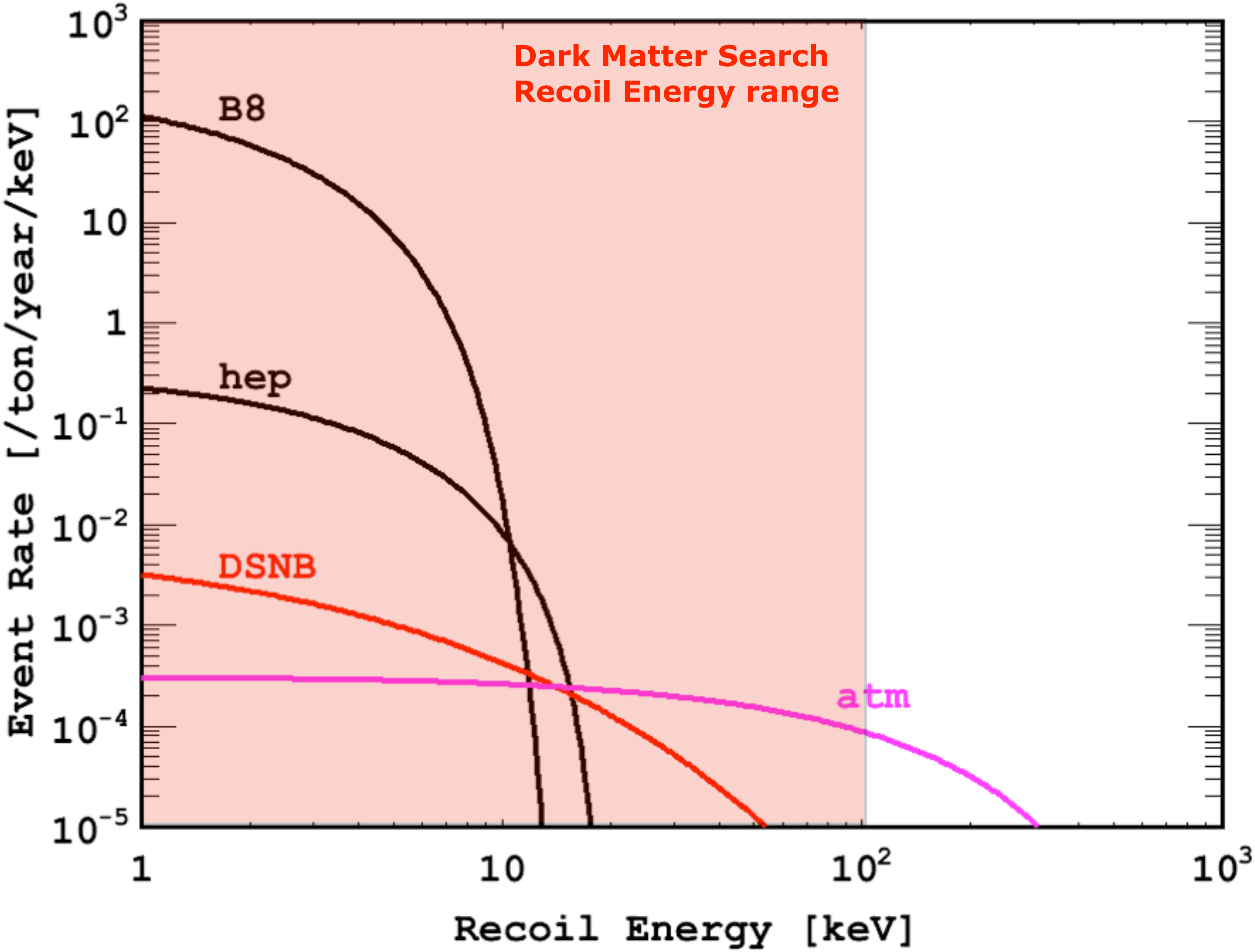
Recent innovation of Dark Matter detector technology makes it possible to access CENNS (<100 keV energy thresholds for nuclear recoil w/ low BG)



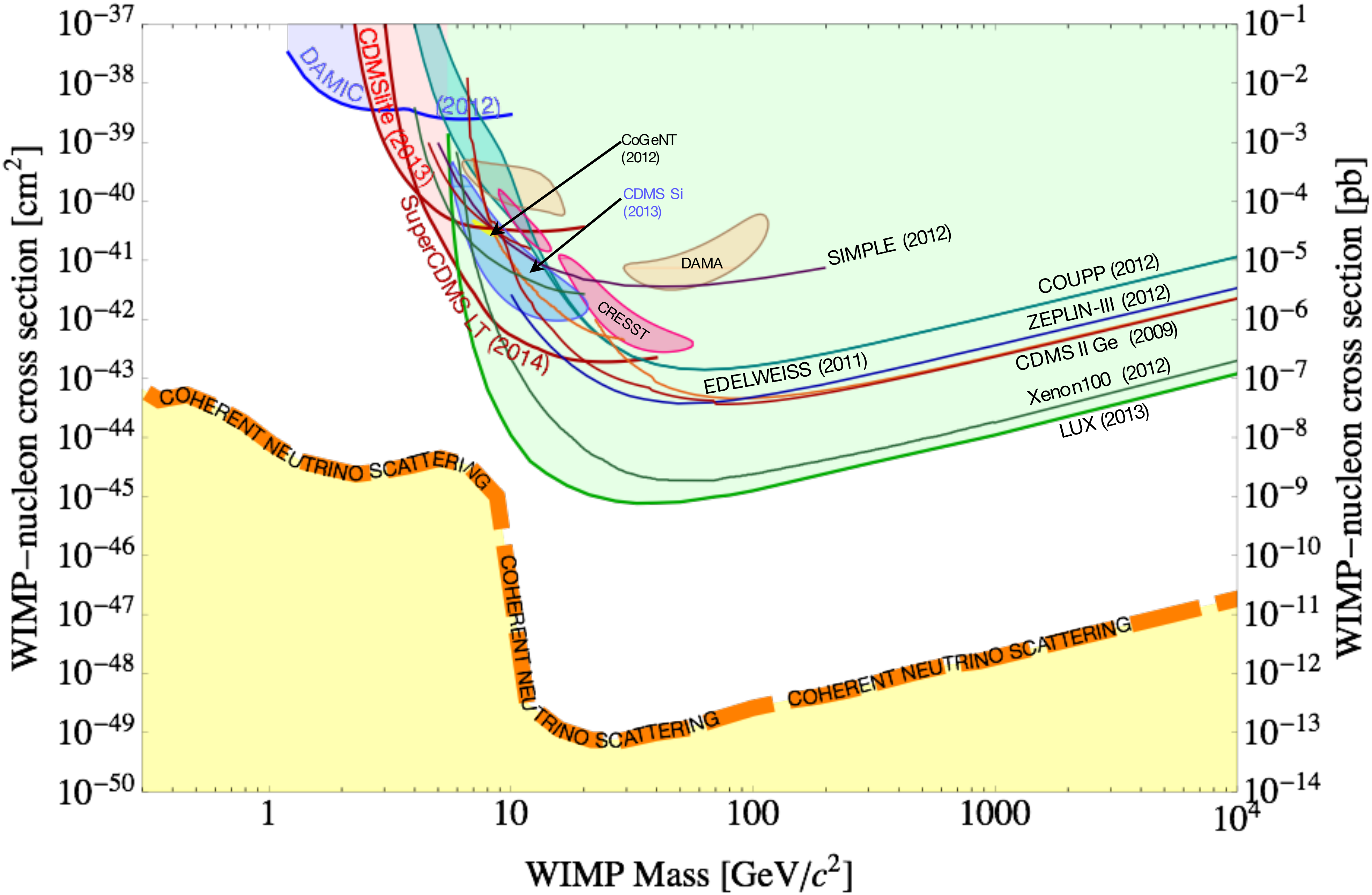


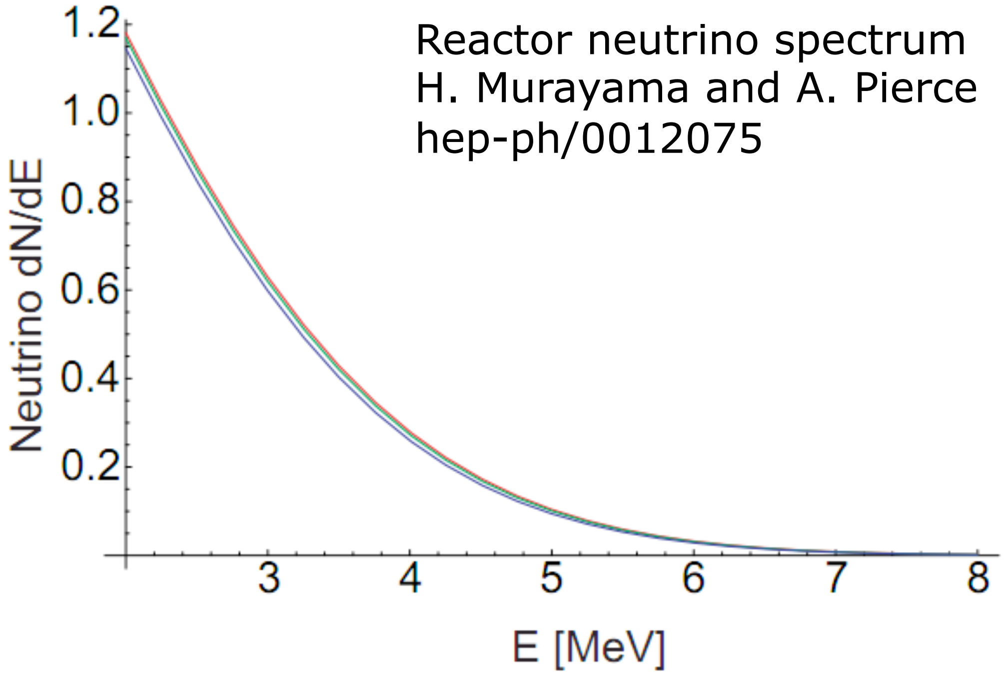


Neutrino Background



Neutrino Background



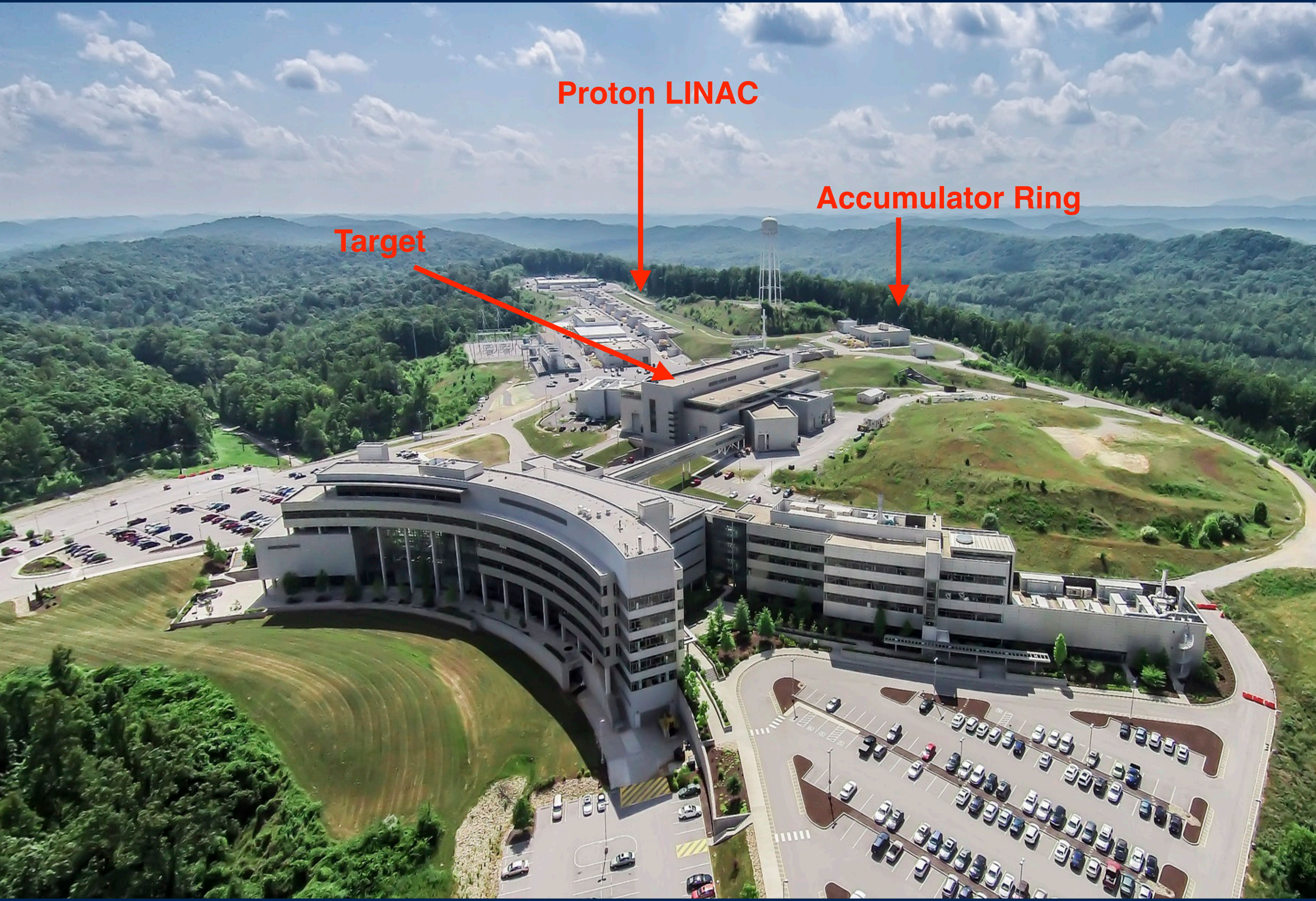


$$E_{max} \simeq \frac{2E_\nu^2}{M} < \mathrm{keV}$$

$$\Phi = 10^{20} \bar{\nu}_e / sec / 4\pi R^2 \qquad (\Phi = 10^{12} \bar{\nu}_e / sec / cm^2 @\ 20\ \mathrm{m})$$

- **Requires Ultra-clean, kg-size, ~100 eV threshold detector**
- Need to overcome steady state backgrounds and detector noise
- Reactor off-time can be used for background subtraction
- Detector development is very challenging for a realistic experiment

Oak Ridge National Laboratory (Spallation Neutron Source)

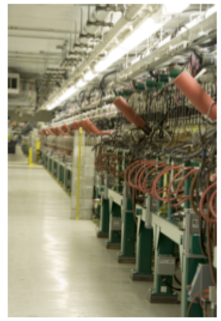


Oak Ridge National Laboratory

Neutrino Production at SNS

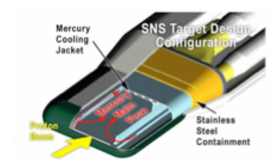
- Spallation Neutron Source (SNS) at Oak Ridge National Lab
  F. Avignone and Y. Efremenko, J. Phys. G, 29 (2003) 2615-2628

Proton linear accelerator, initial operation at 1.0 GeV; upgrade to 1.3 GeV planned



Accumulator ring, 400 ns pulse width

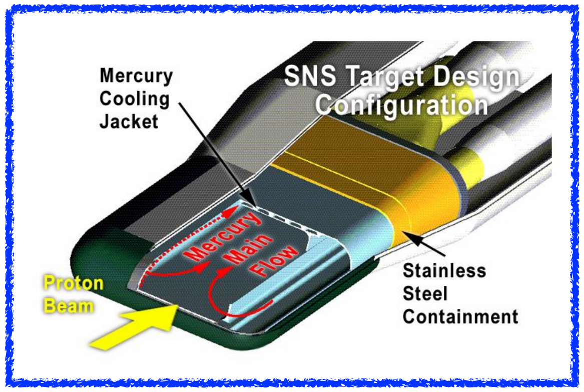
Proton beam bombards liquid Hg target

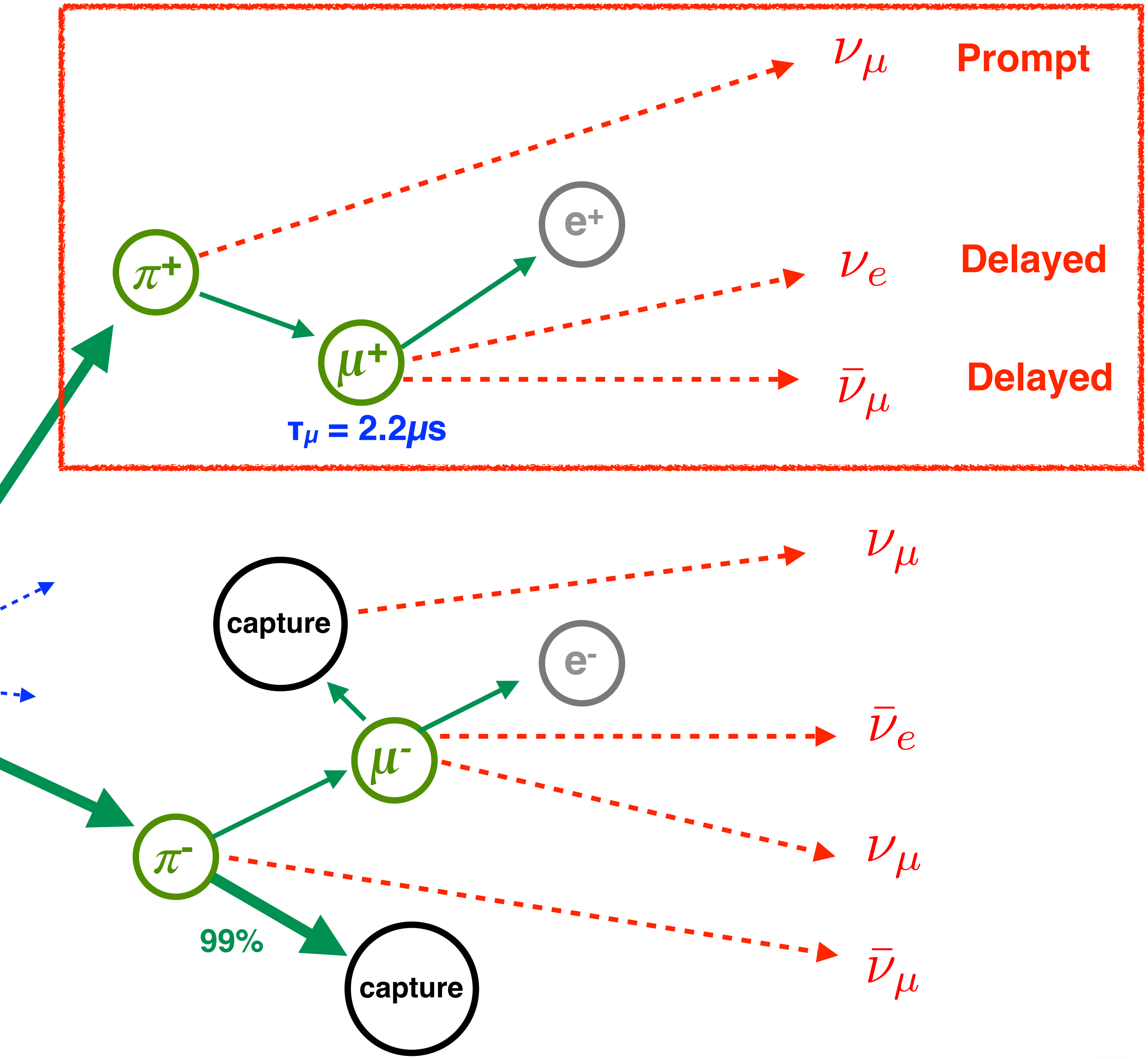


24 μC/pulse at 60 Hz ⇒ 1.4 MW power

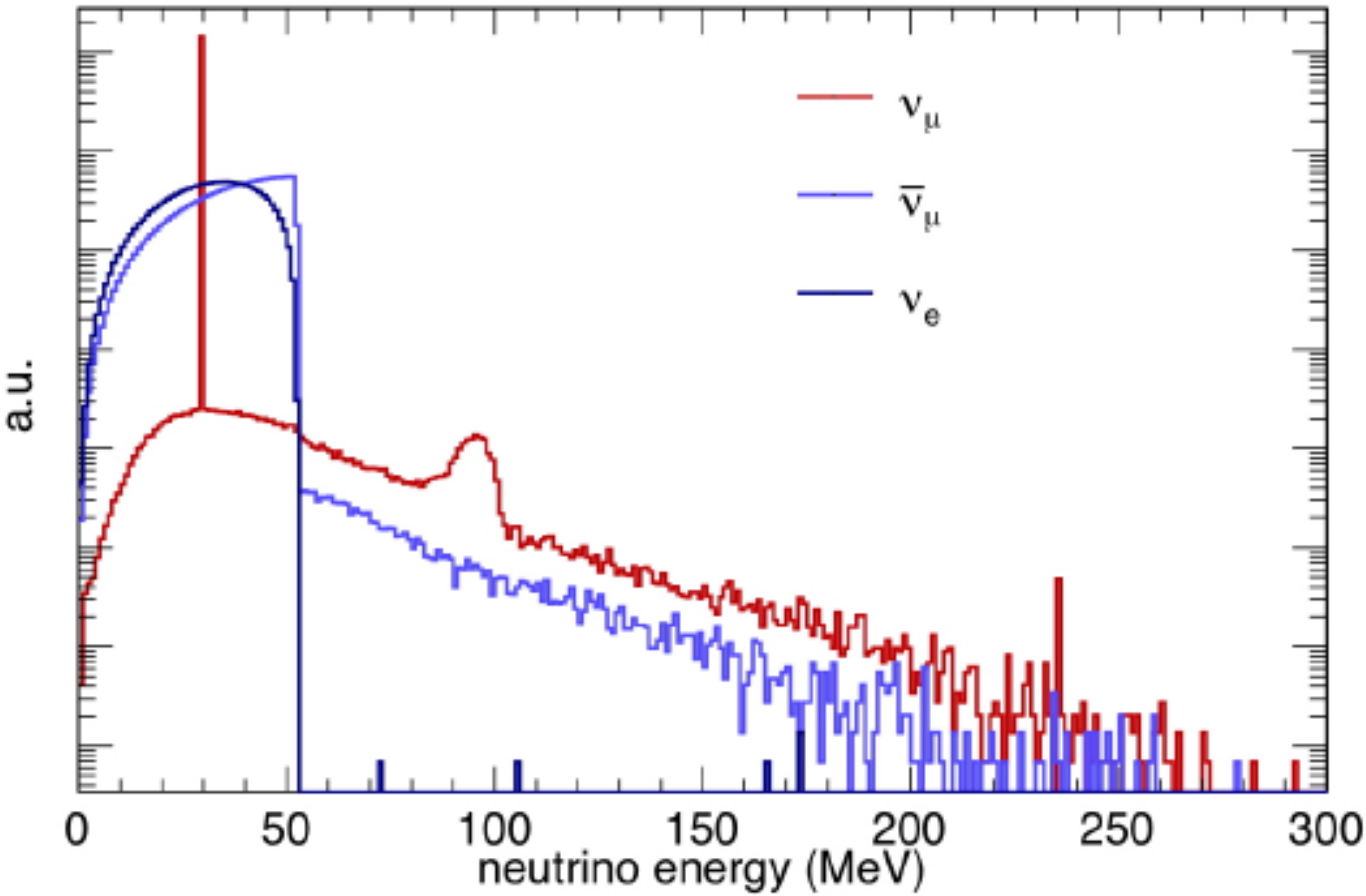
- Flux ~ 10^7/sec/cm^2 at 20m from the target
- 60 Hz pulsed source
- Steady-state background rejection factor ~10^{-4}
- Expected event rate in a single-phase 500kg LAr detector: ~890 events/year of detection (E_{th}>20 keV) at the proposed experiment site (46m from SNS target)

Neutrino Production at SNS

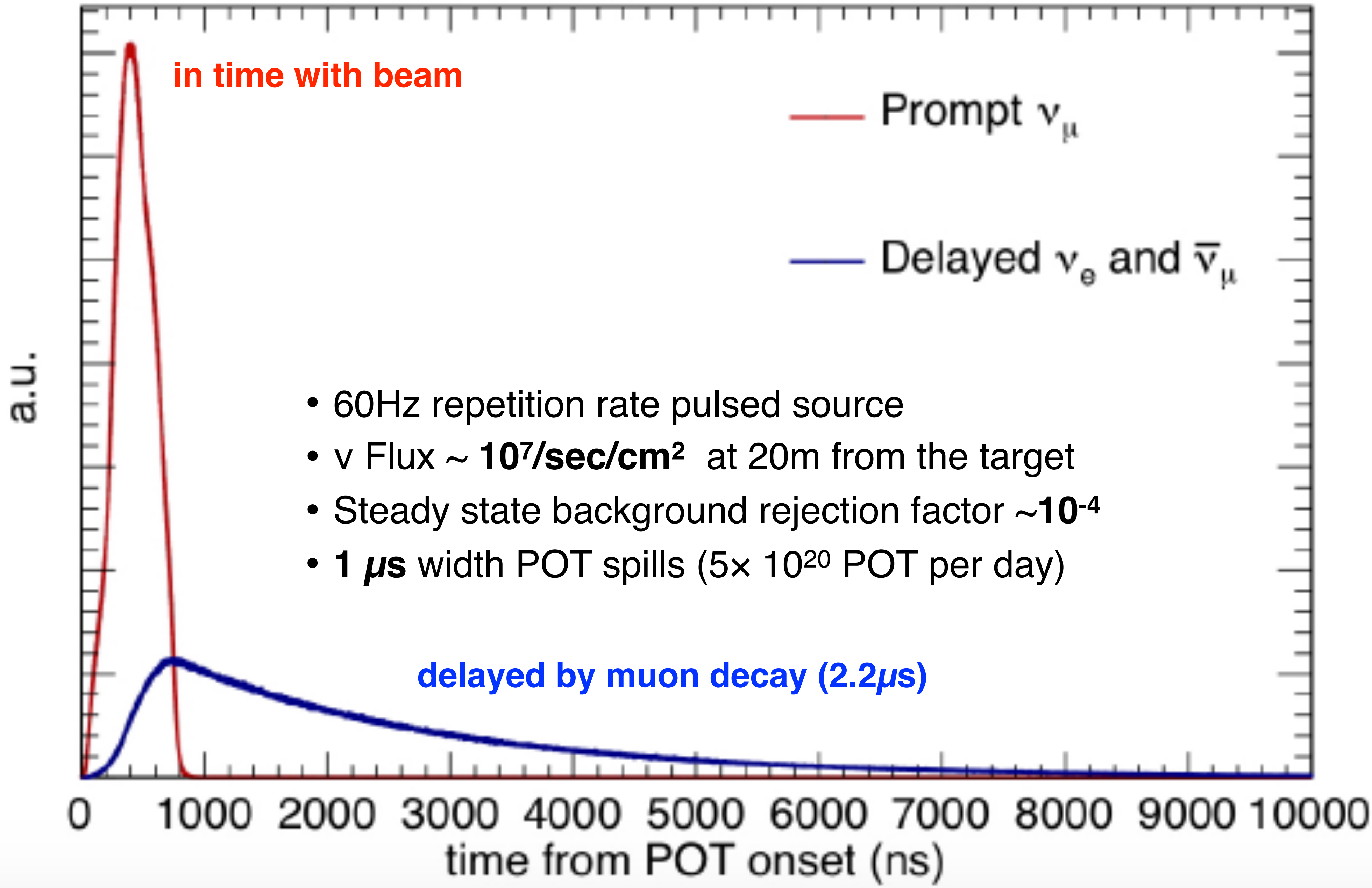




Neutrino Energy Spectrum from SNS

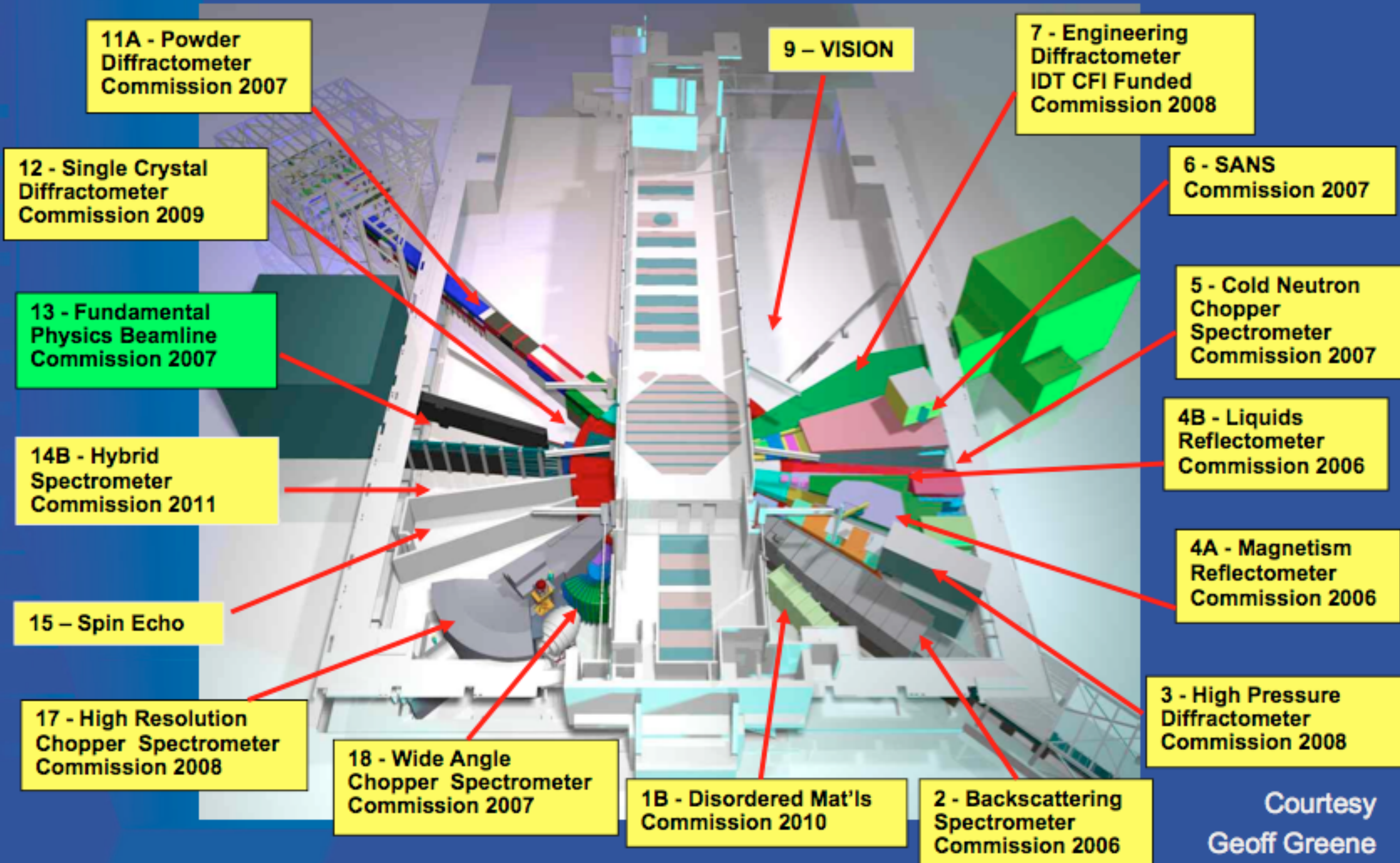


Neutrino Timing Profile at SNS



- 60Hz repetition rate pulsed source
- ν Flux ~ **10^7/sec/cm^2** at 20m from the target
- Steady state background rejection factor ~**10^{-4}**
- **1 μs** width POT spills (5× 10^{20} POT per day)

SNS Experiment Projects

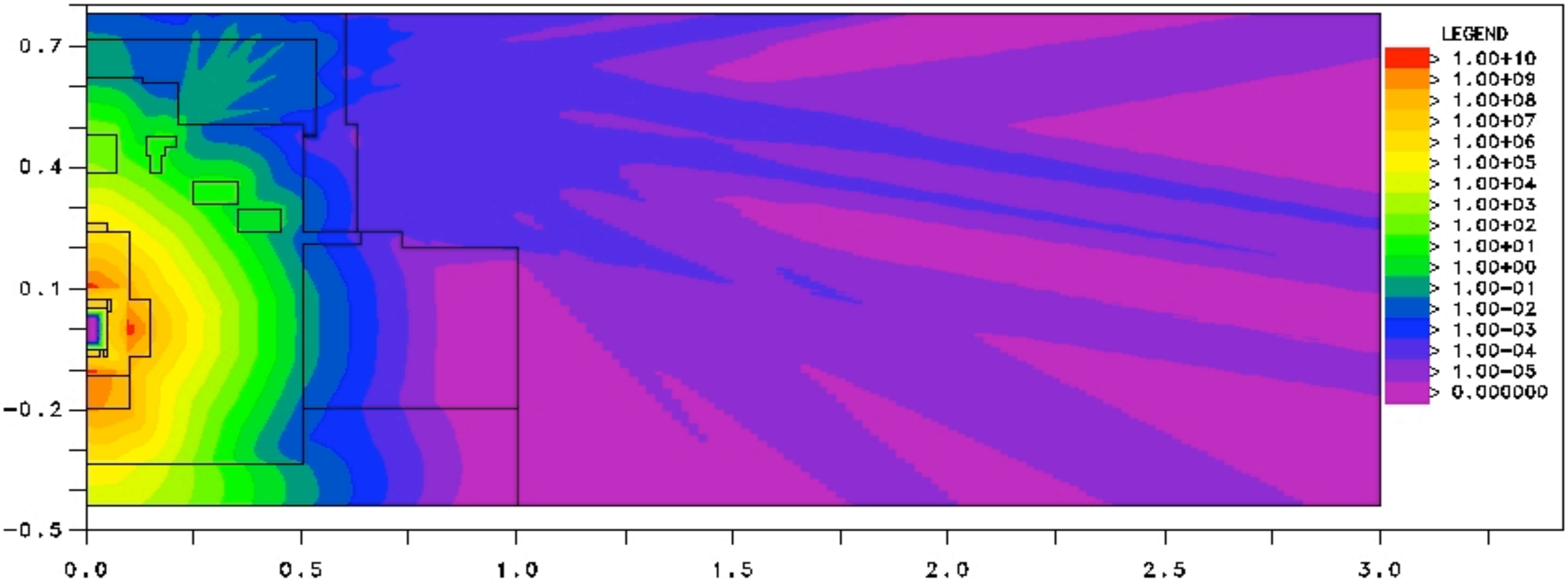


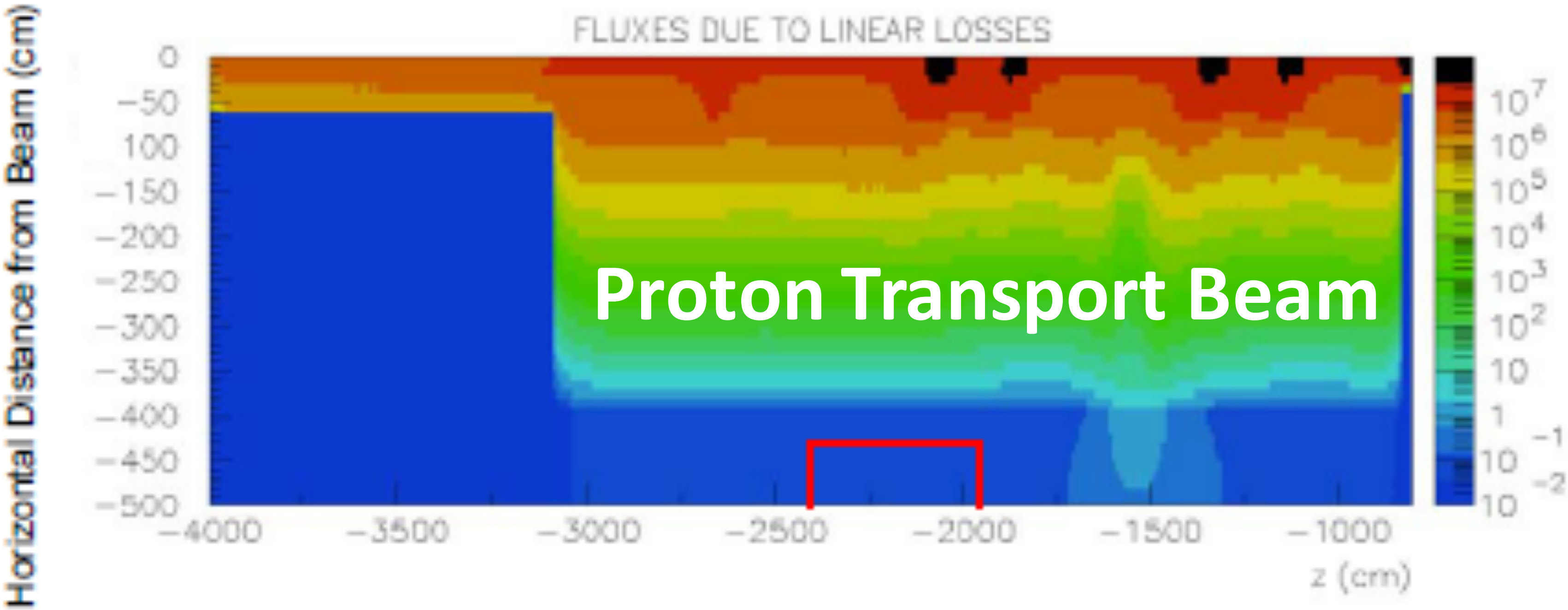
Courtesy Geoff Greene

R. Tschirhart, Fermilab Wine & Cheese June 2012

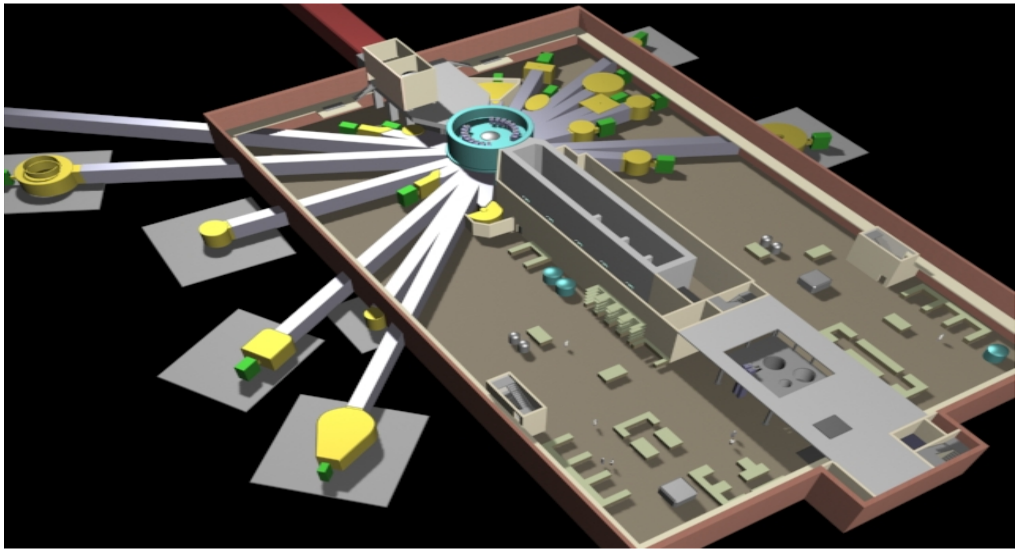
Fermilab

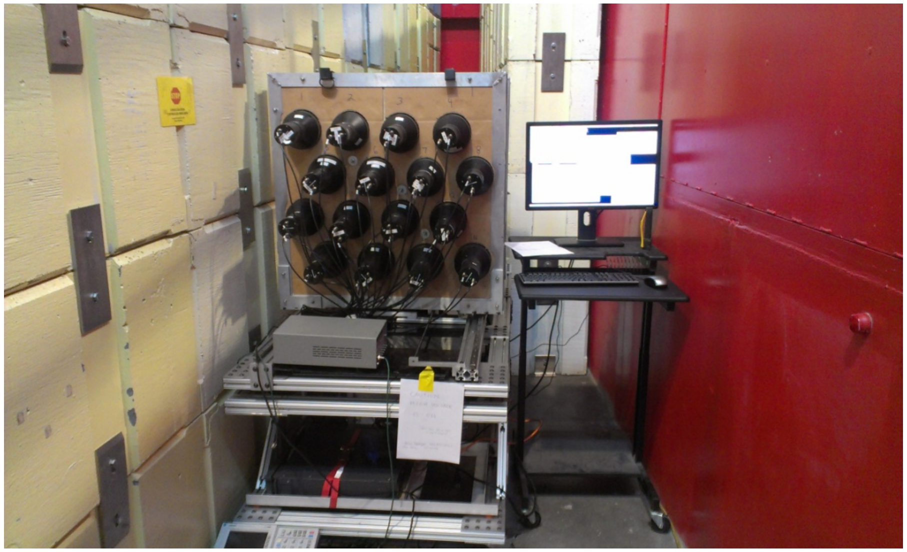
Neutrons in SNS (Simulations)

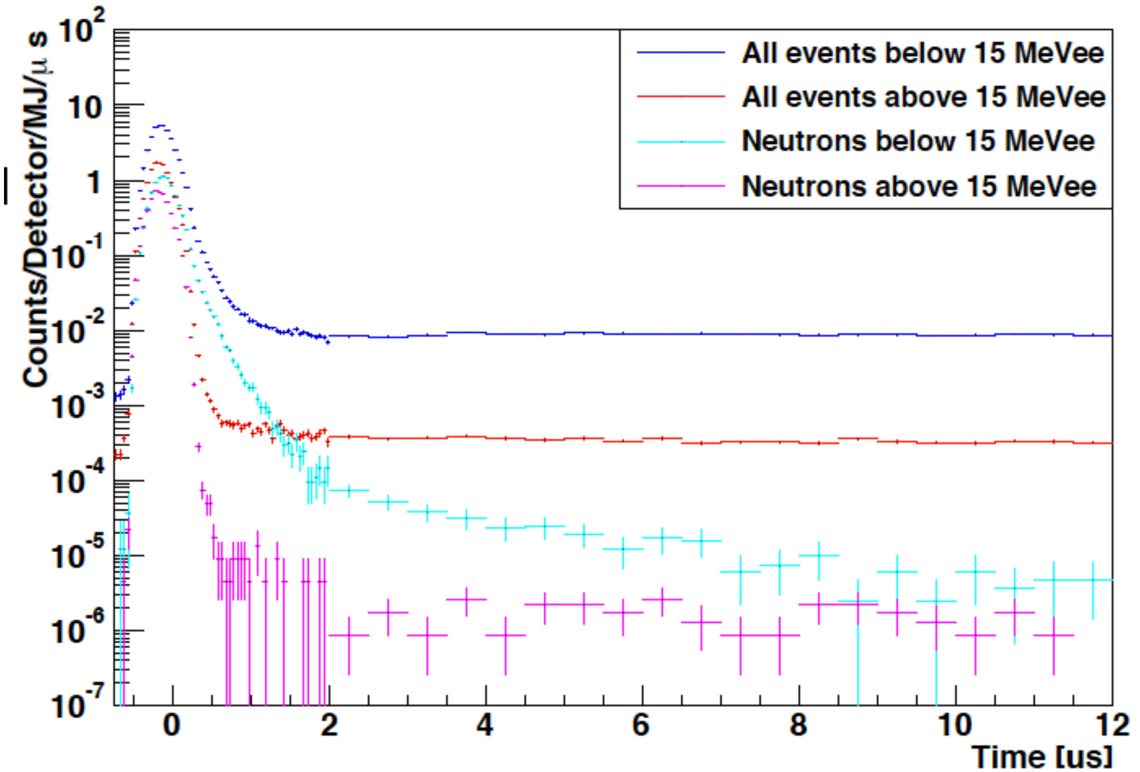




Neutron Background Measurement at SNS



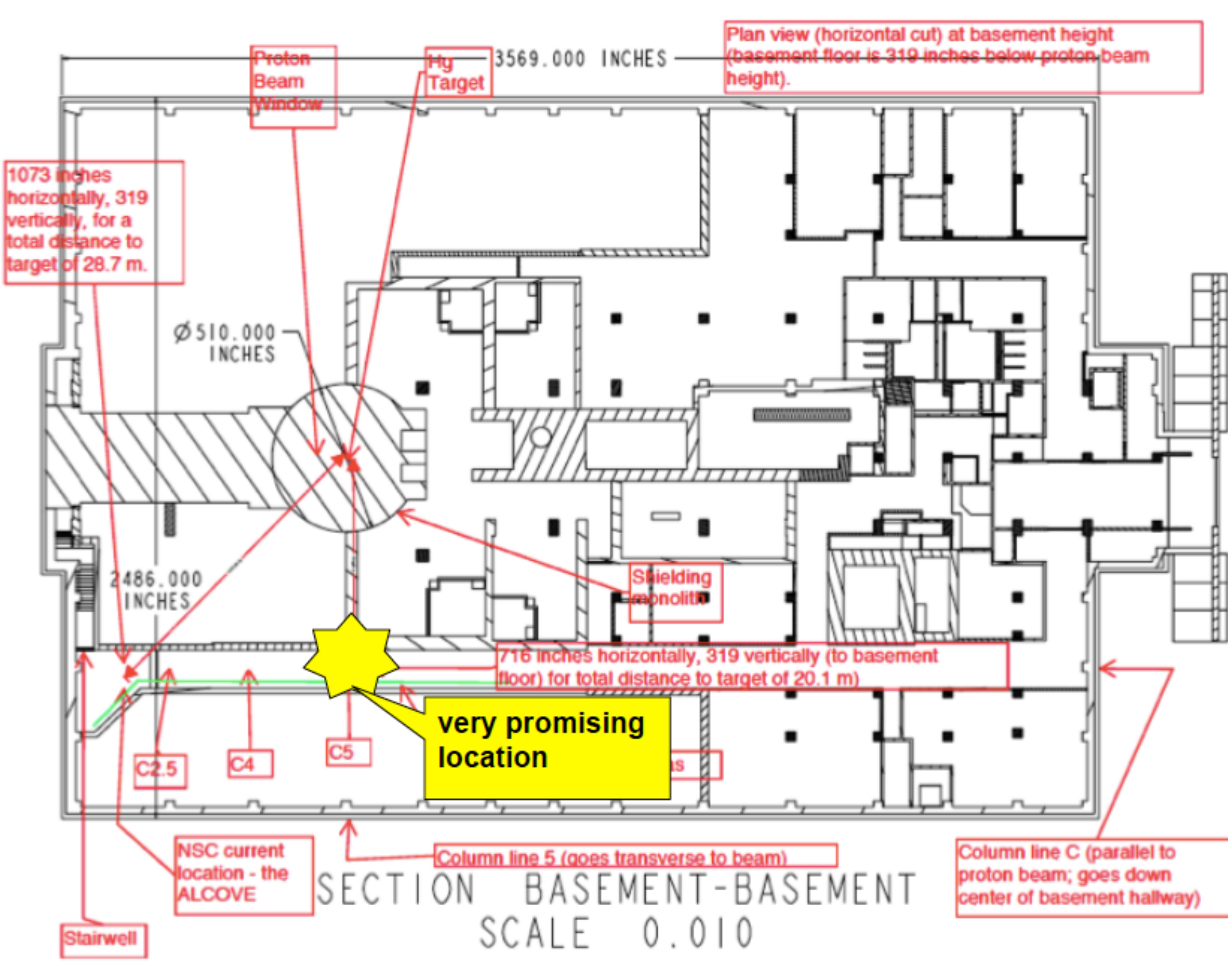


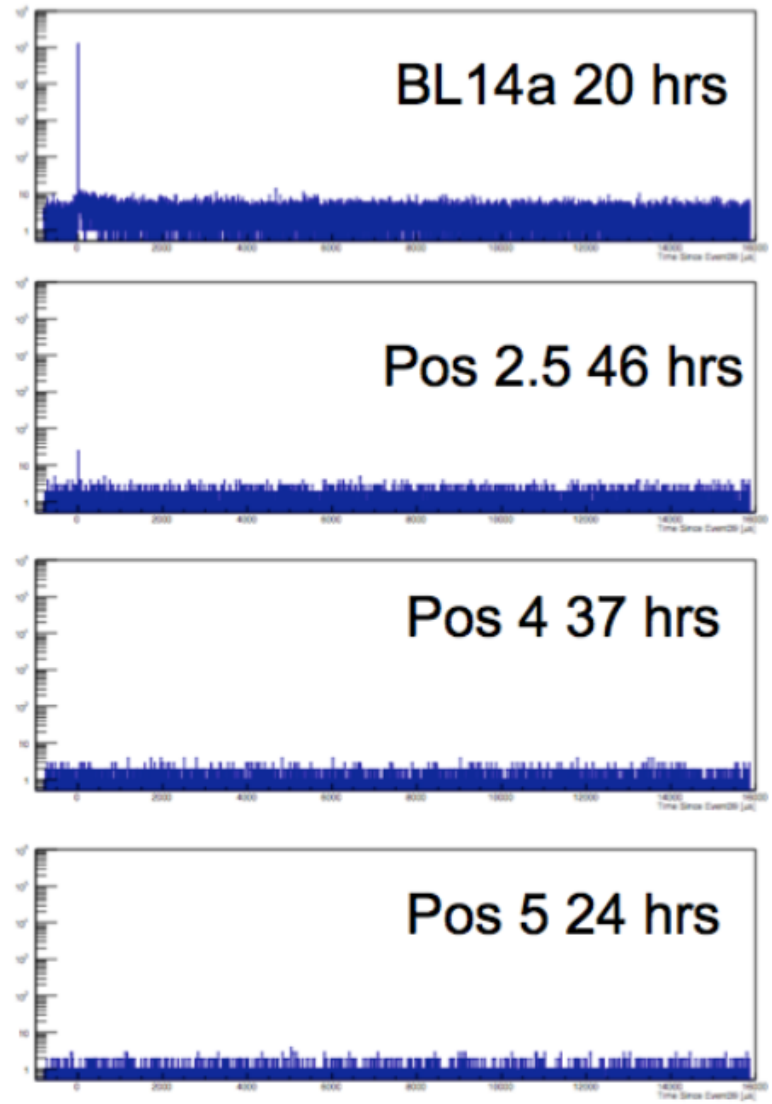


Neutron flux in the target building 10^4 times more than allowed level for the CEvNS measurement.

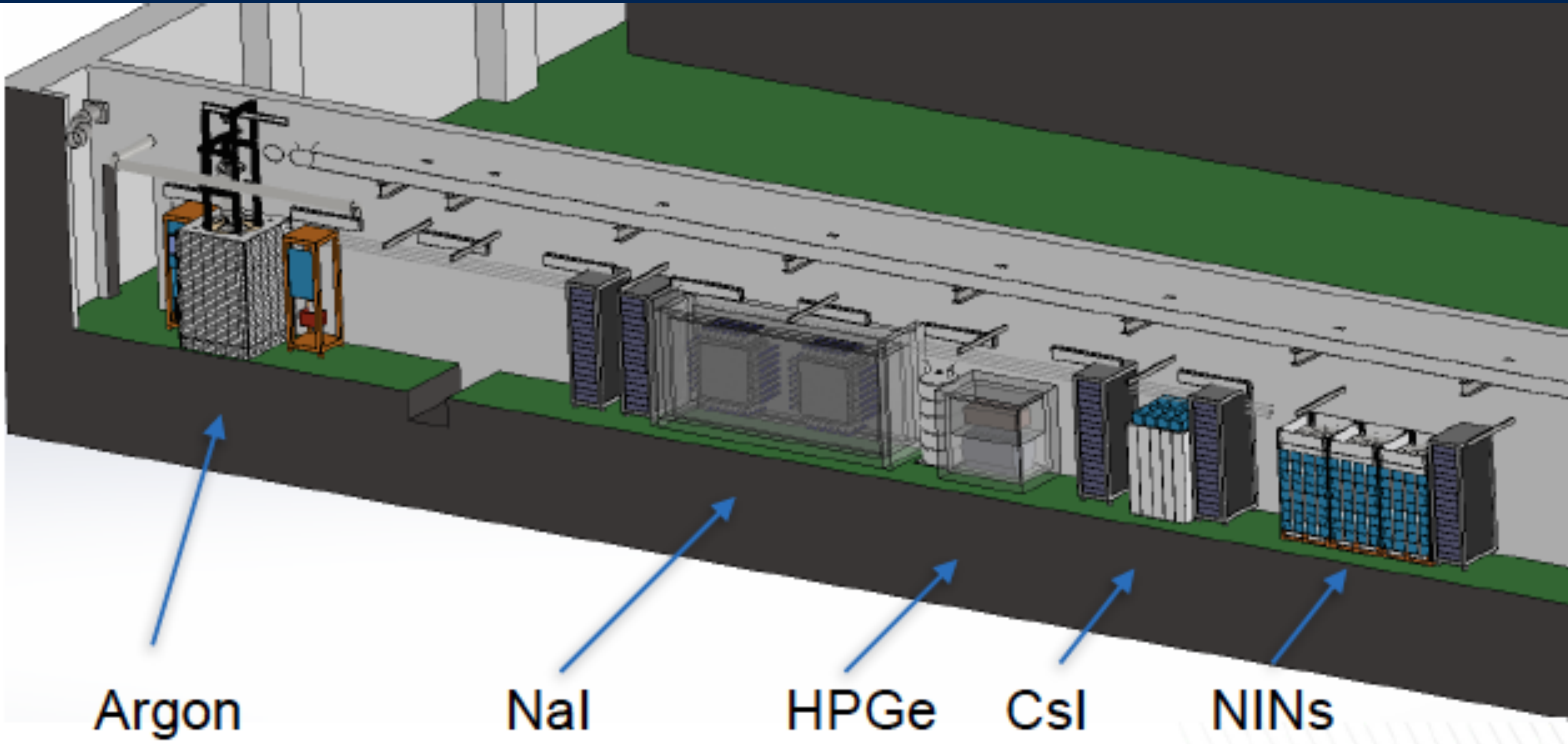
During the survey COHERENT collaboration found a very interesting location.
→ a very narrow hall way in the basement area of the target building

Neutron Background at SNS Target Building





Neutrino Alley



(29m from the target)

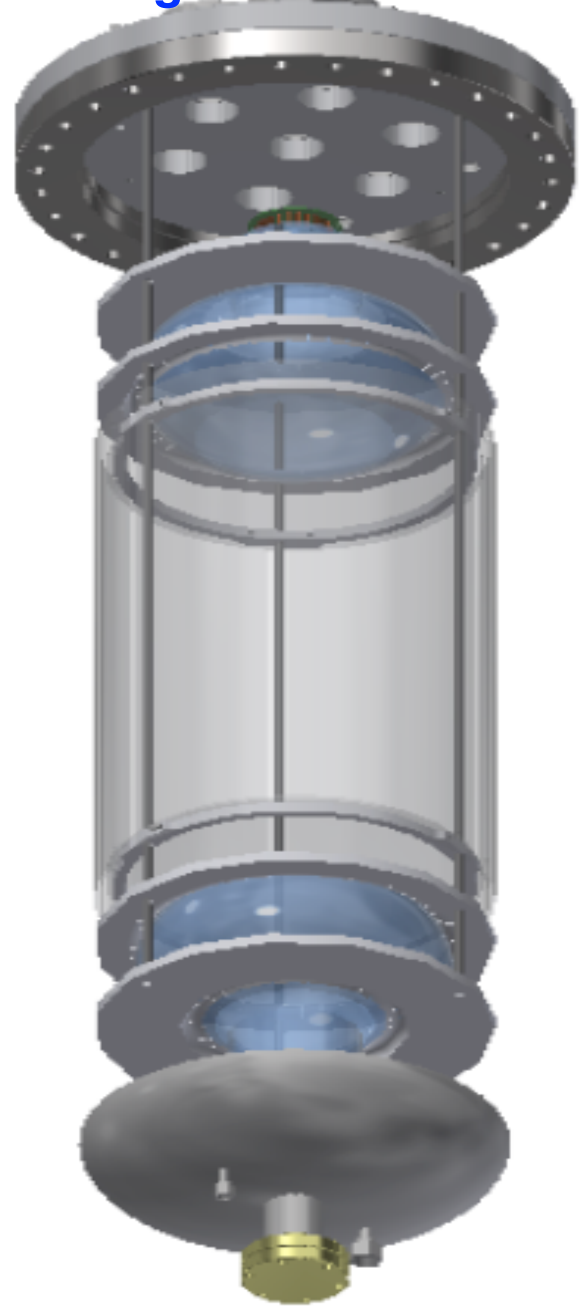
(20m from the target)

- The basement location (now called Neutrino Alley) is isolated from neutron beam lines
- SNS target to the Neutrino Alley is filled with concrete and gravel (12m of void free region)
- 8 m of water equivalent overburden (it’s in the basement — additional shielding)
- **Discovery of the location! (Flux = 1.7× 10^{11} ν_μ/cm^2/s @ CsI)**

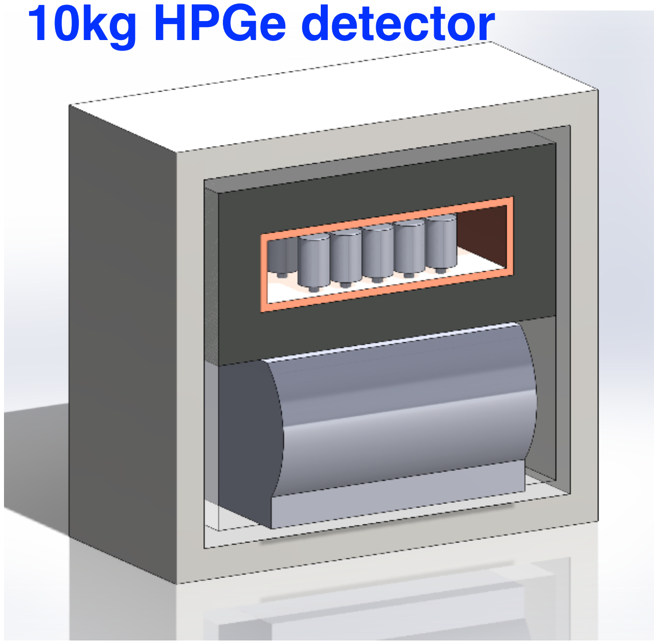
COHERENT Phase-1 Experiments

14kg CsI detector

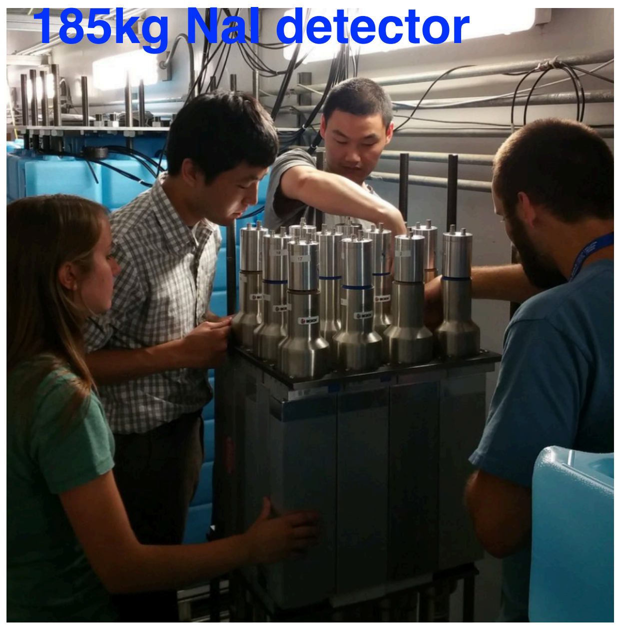
30kg LAr detector



10kg HPGe detector

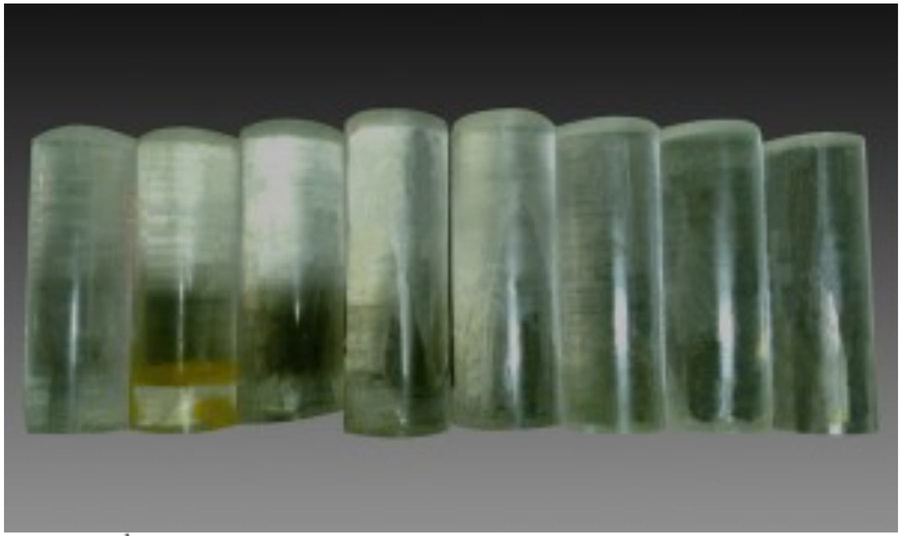


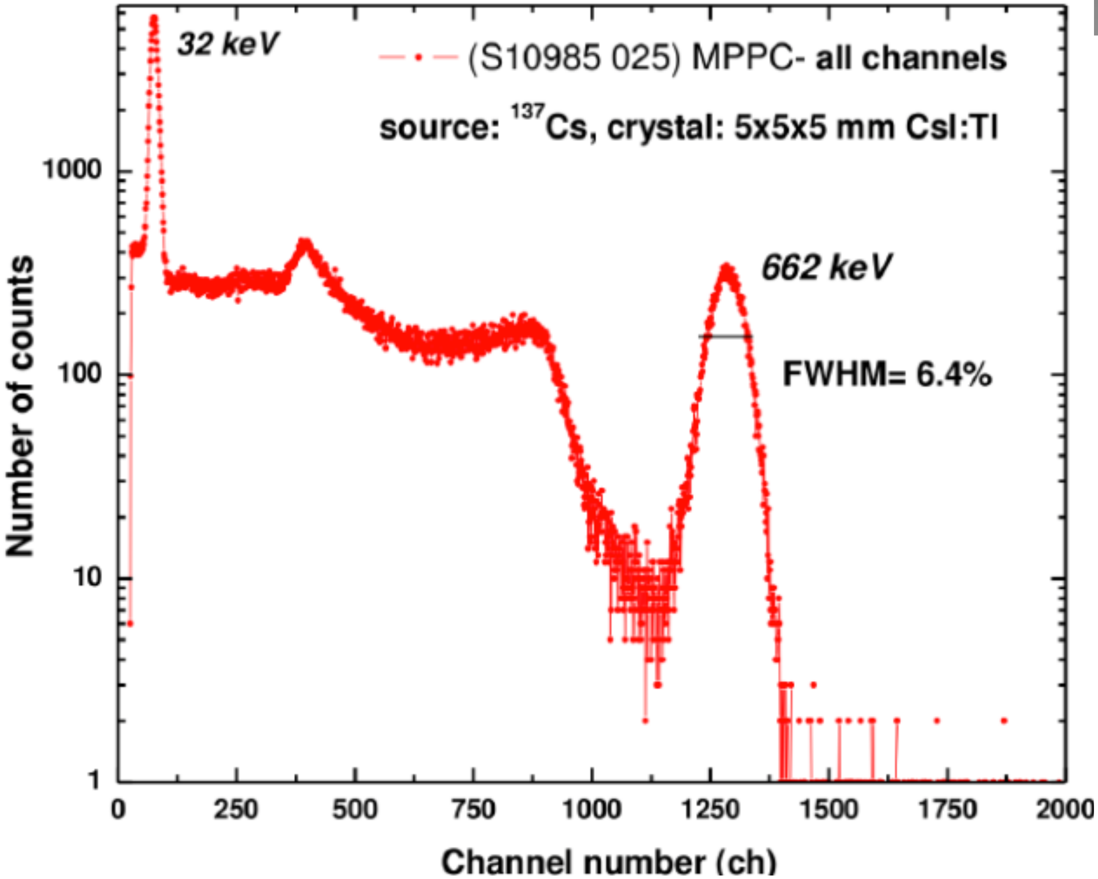
185kg NaI detector

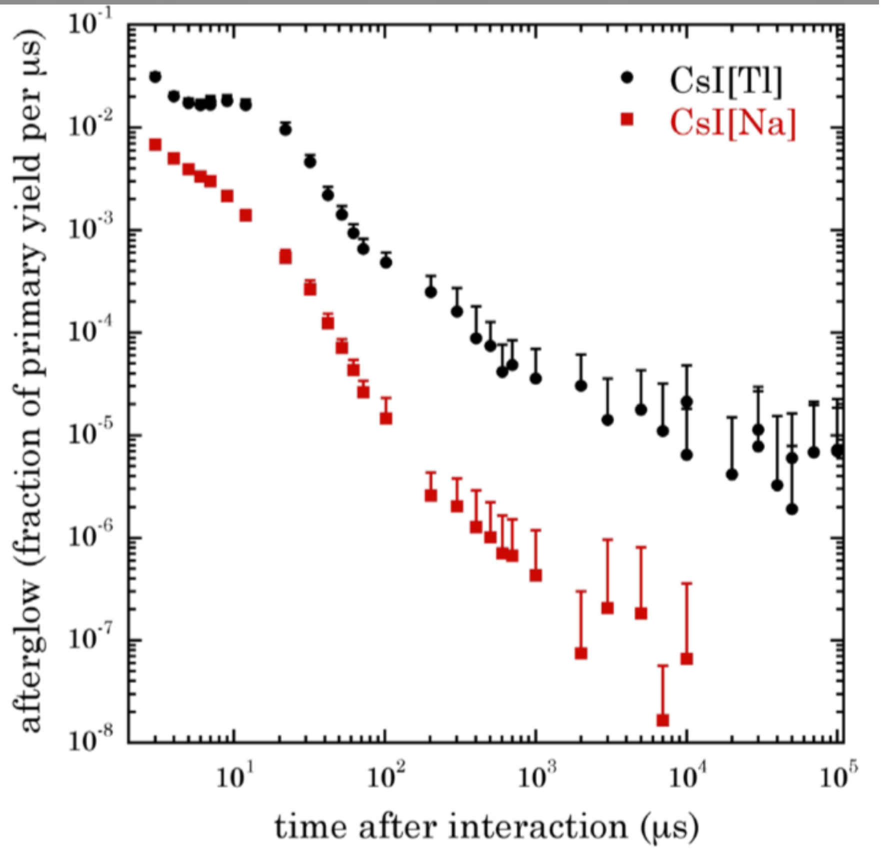


CsI Crystal Detector

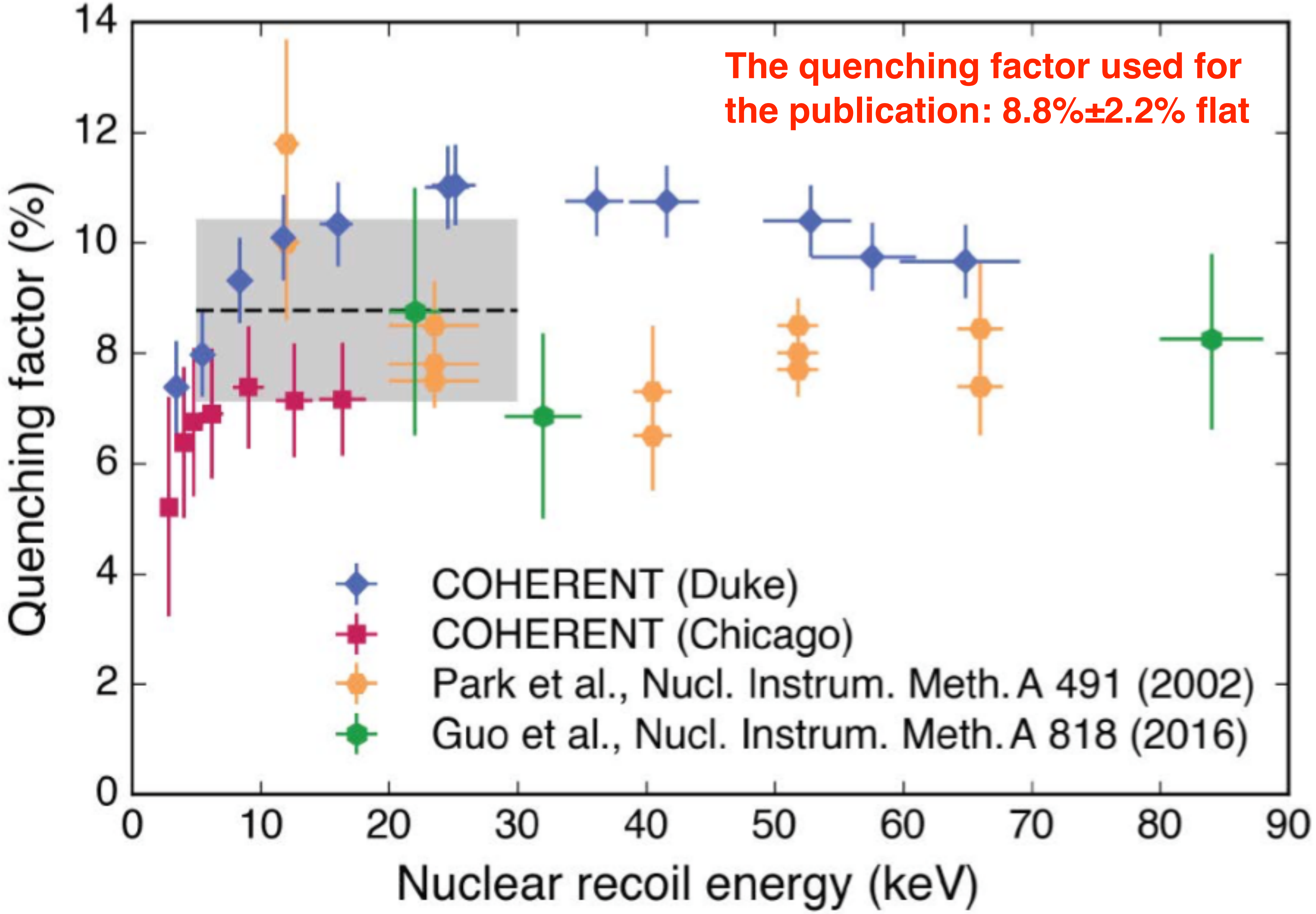
- **CsI detector characteristics**
  - High density 4.51g/cc
  - Can be built for low radioactivity
  - Very high light yield ~18pe/keVee but ~1.17pe/keVnr for nuclear recoil
  - Inexpensive ~1$/g



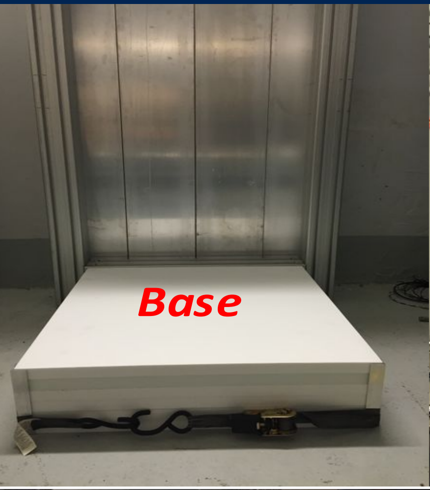


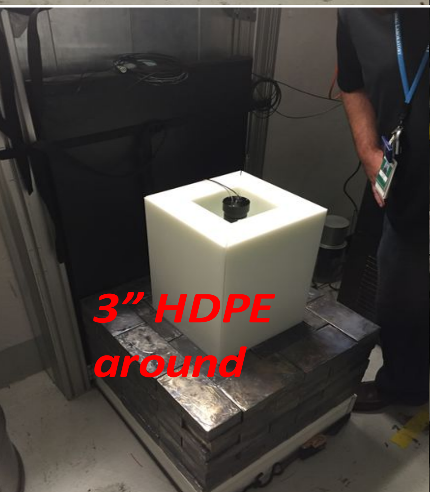


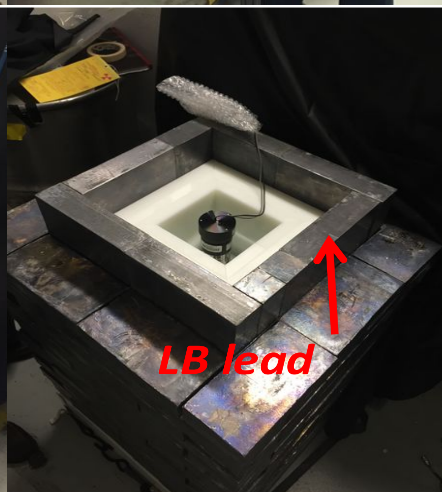
CsI Detector Quenching Factor

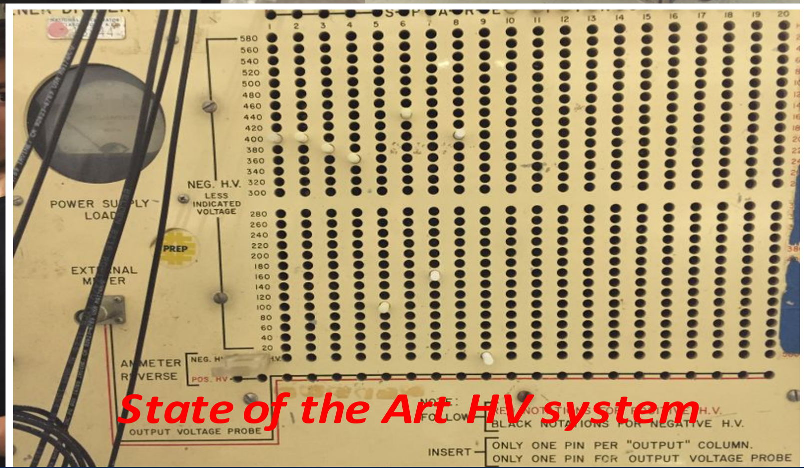


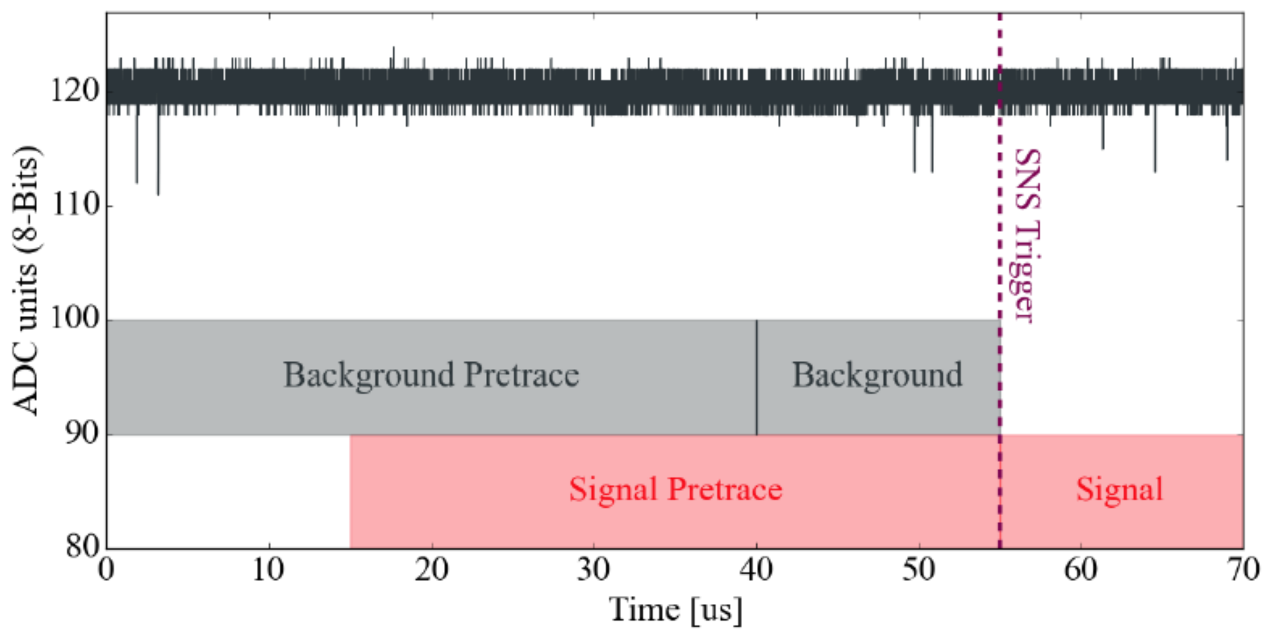
CsI Detector Installation

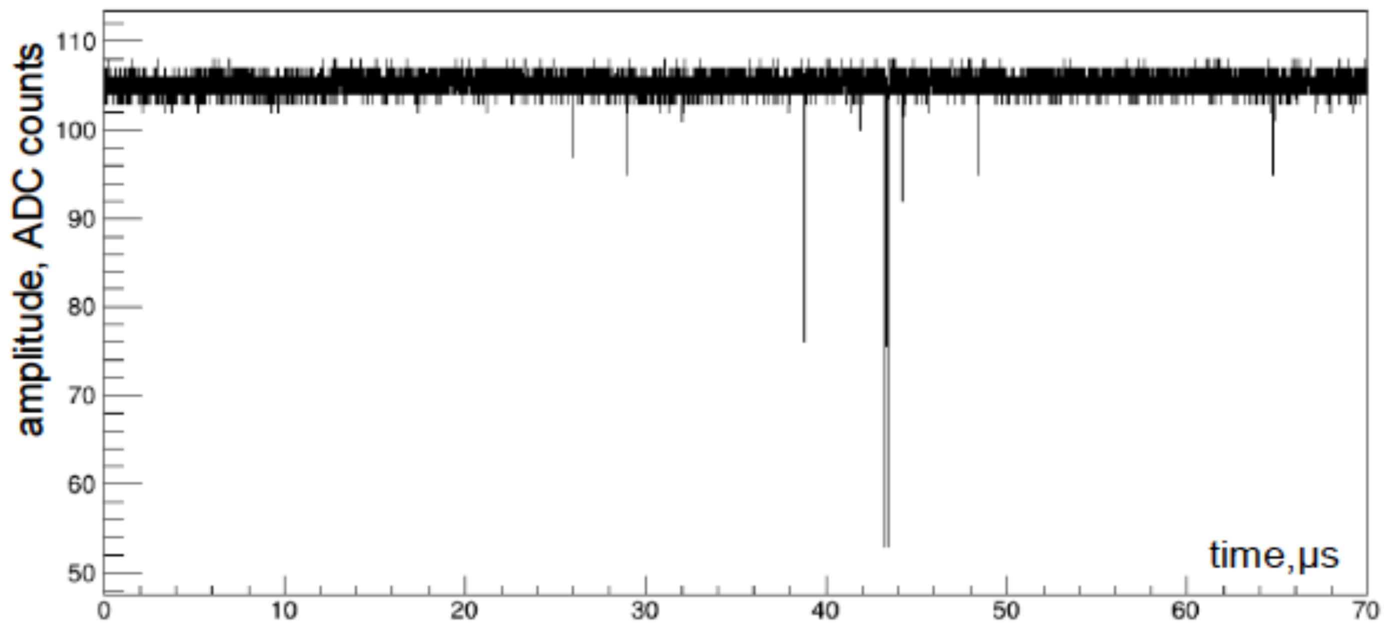









ADC units (8-Bits)
120
110
100
90
80
0
10
20
30
40
50
60
70
Time [us]
SNS Trigger
Background Pretrace
Background
Signal Pretrace
Signal


amplitude, ADC counts
110
100
90
80
70
60
50
0
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20
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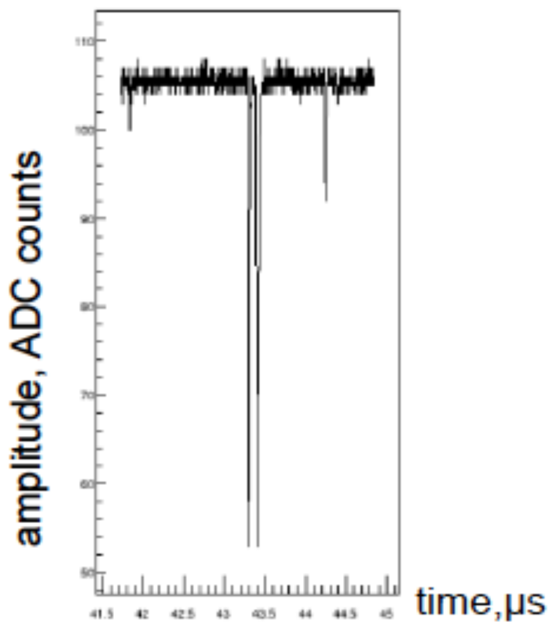
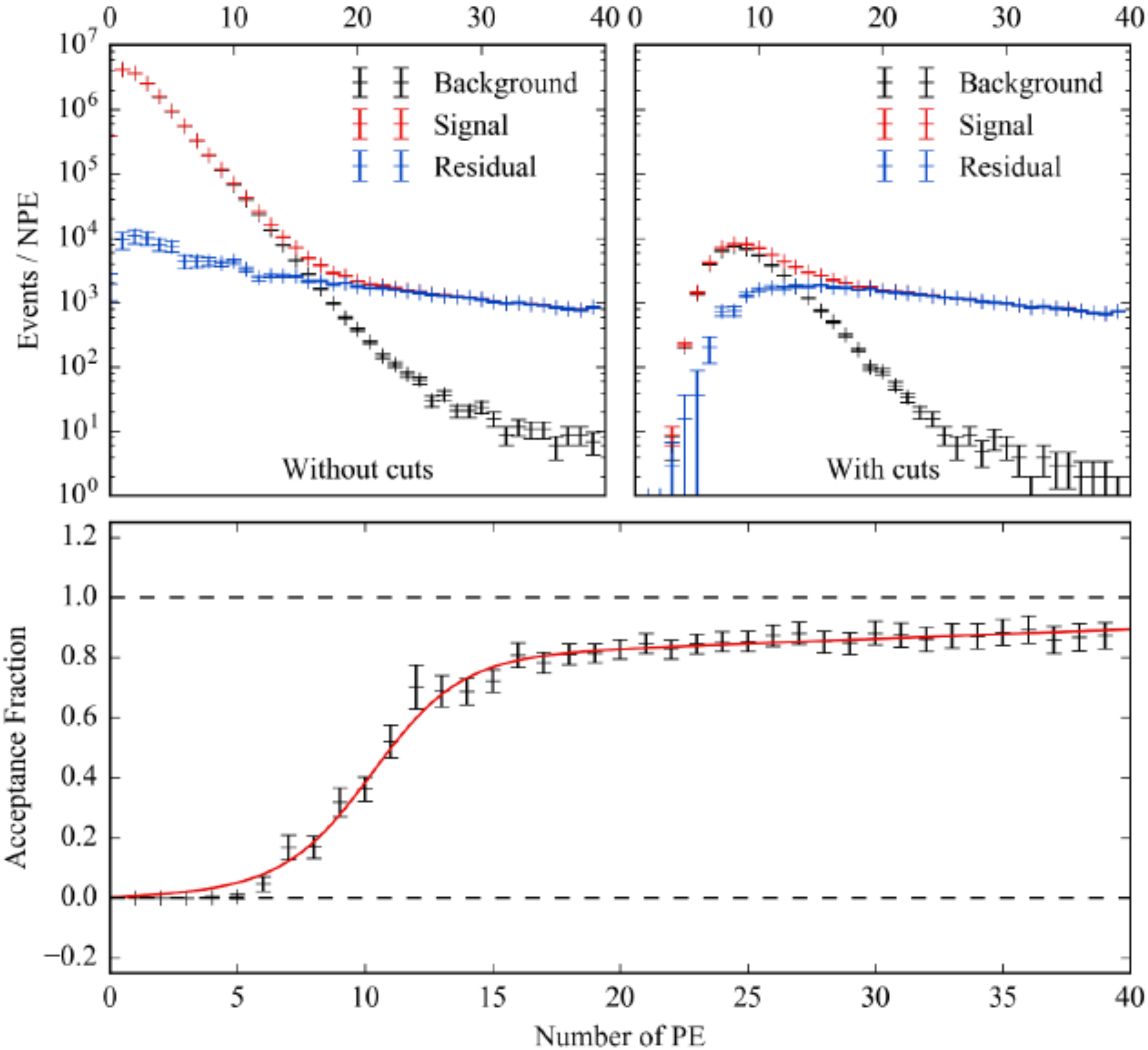
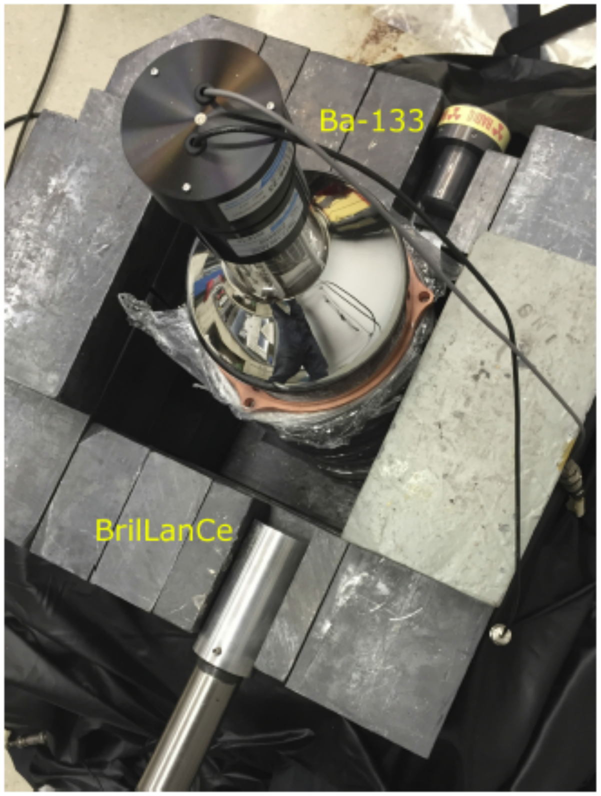
40
50
60
70
time,μs


amplitude, ADC counts
time,μs

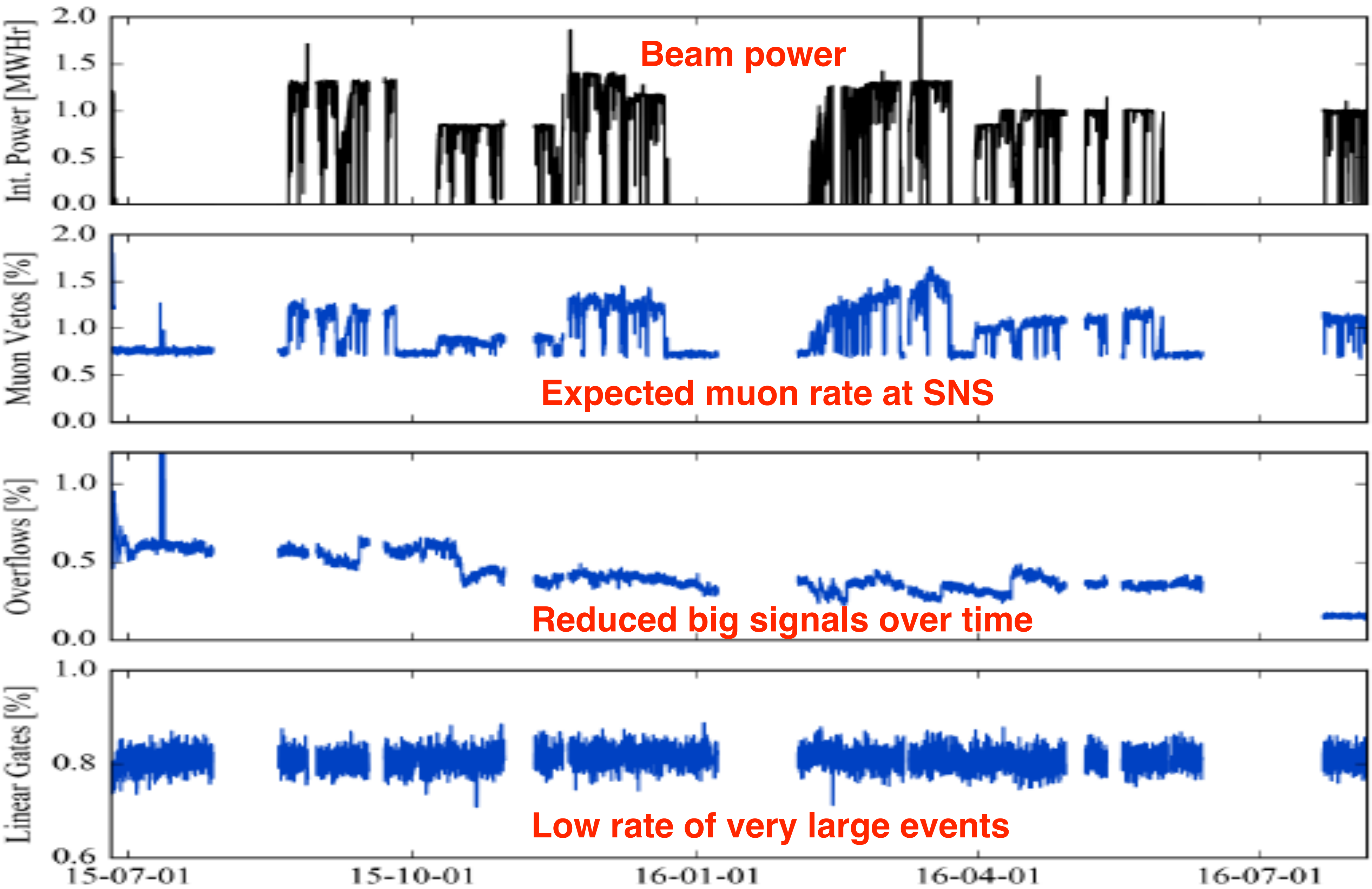
CsI Detection Efficiency



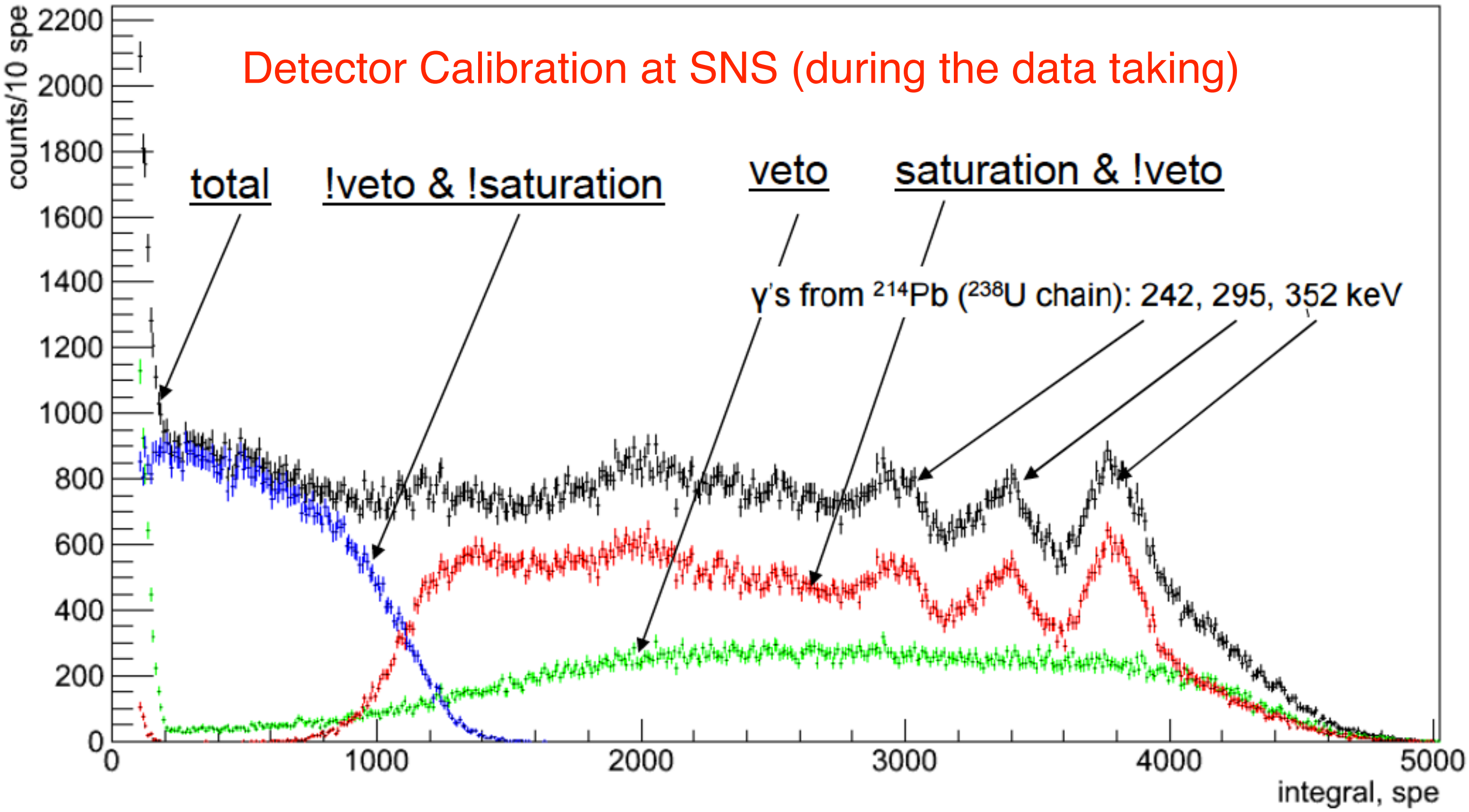


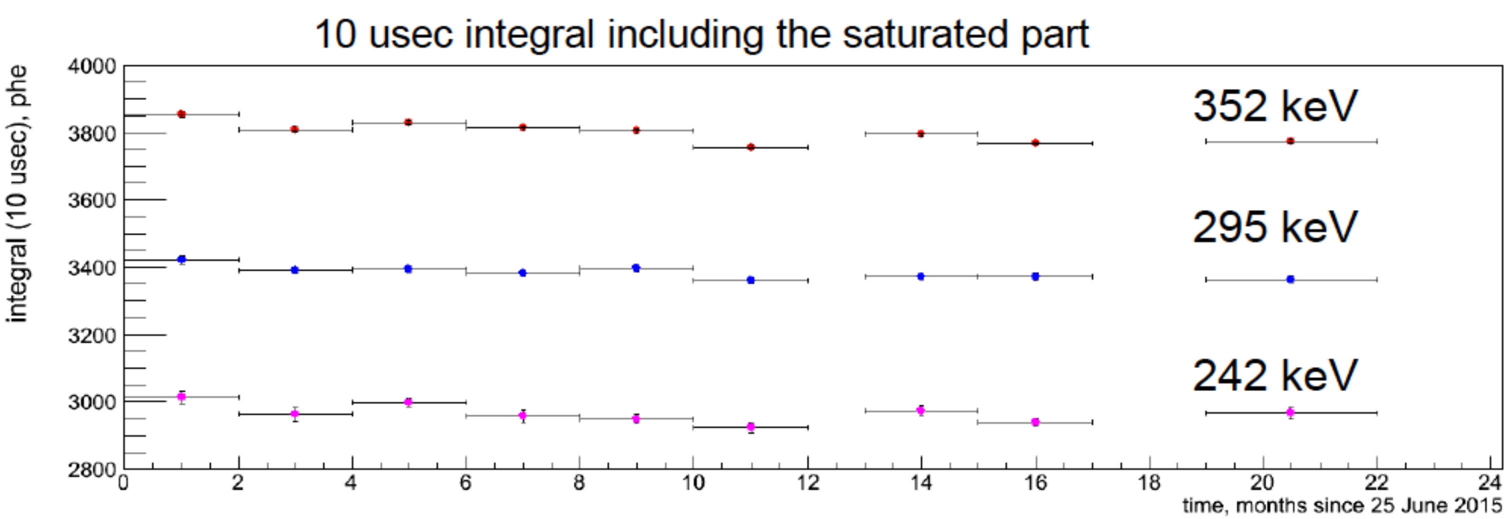
Detection efficiency calibration using Ba-133 source (@UChicago)

CsI Detector Stability Monitoring

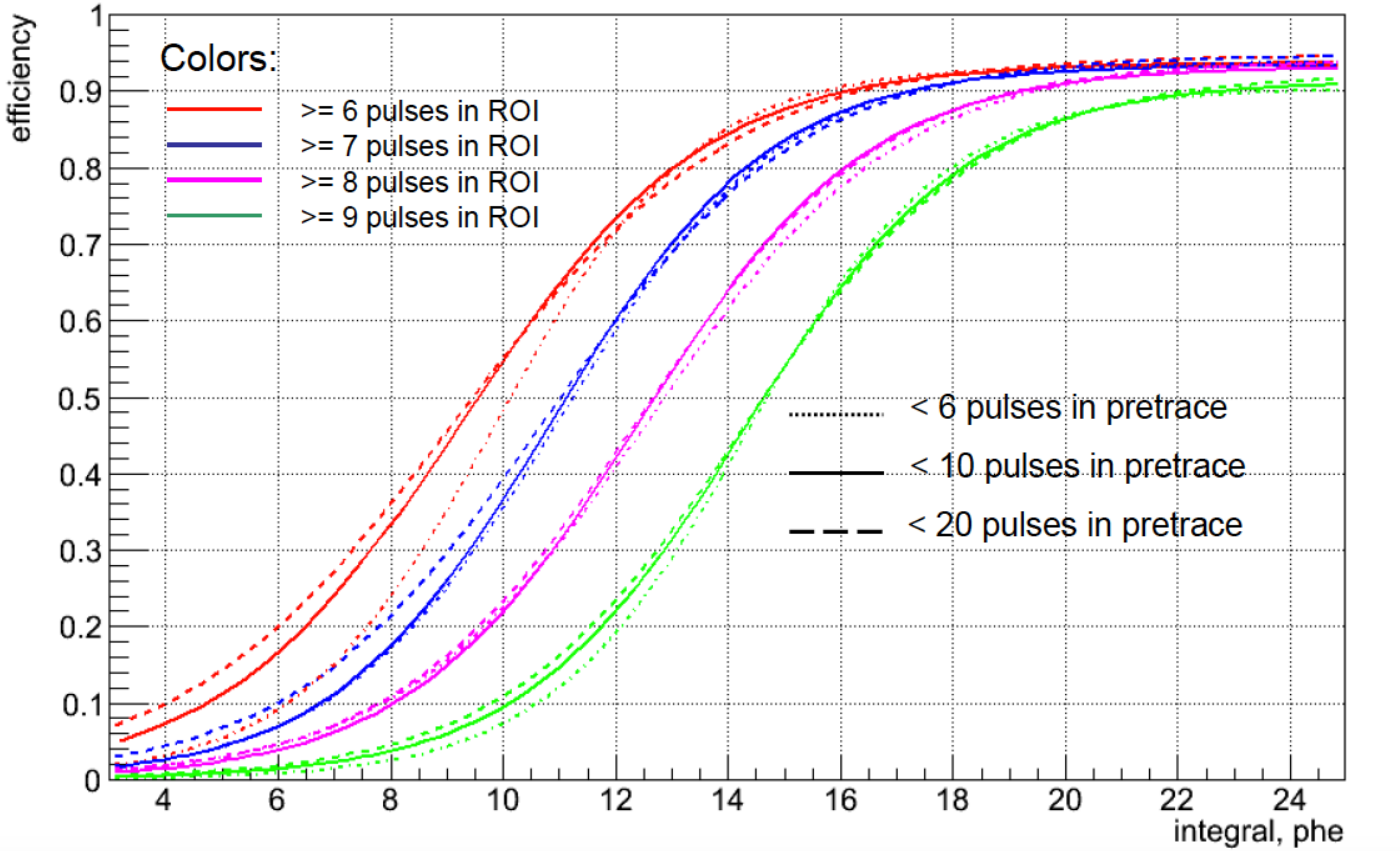


COHERENT Phase-1 Experiments

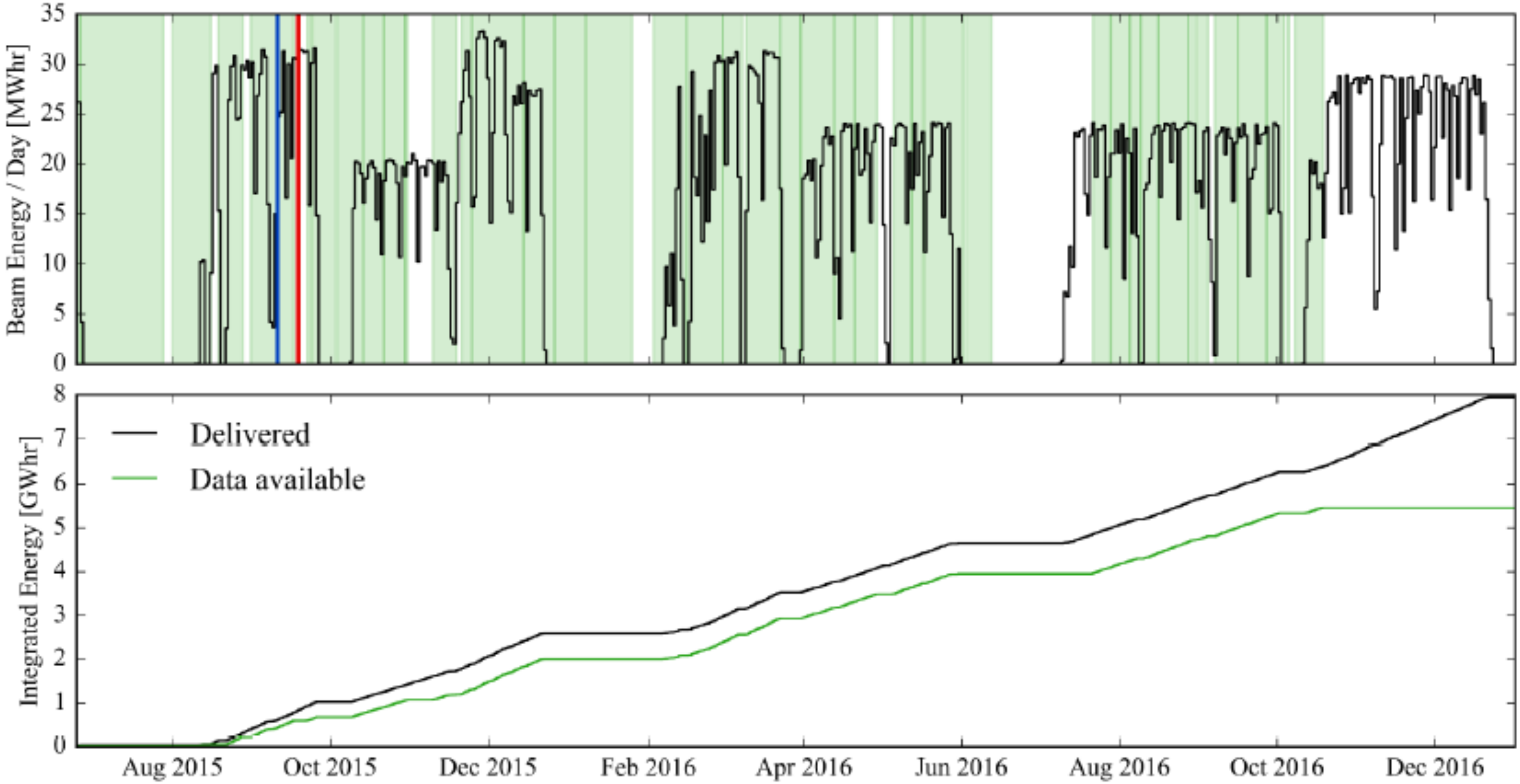




Signal Efficiency Based on Ba Calibration

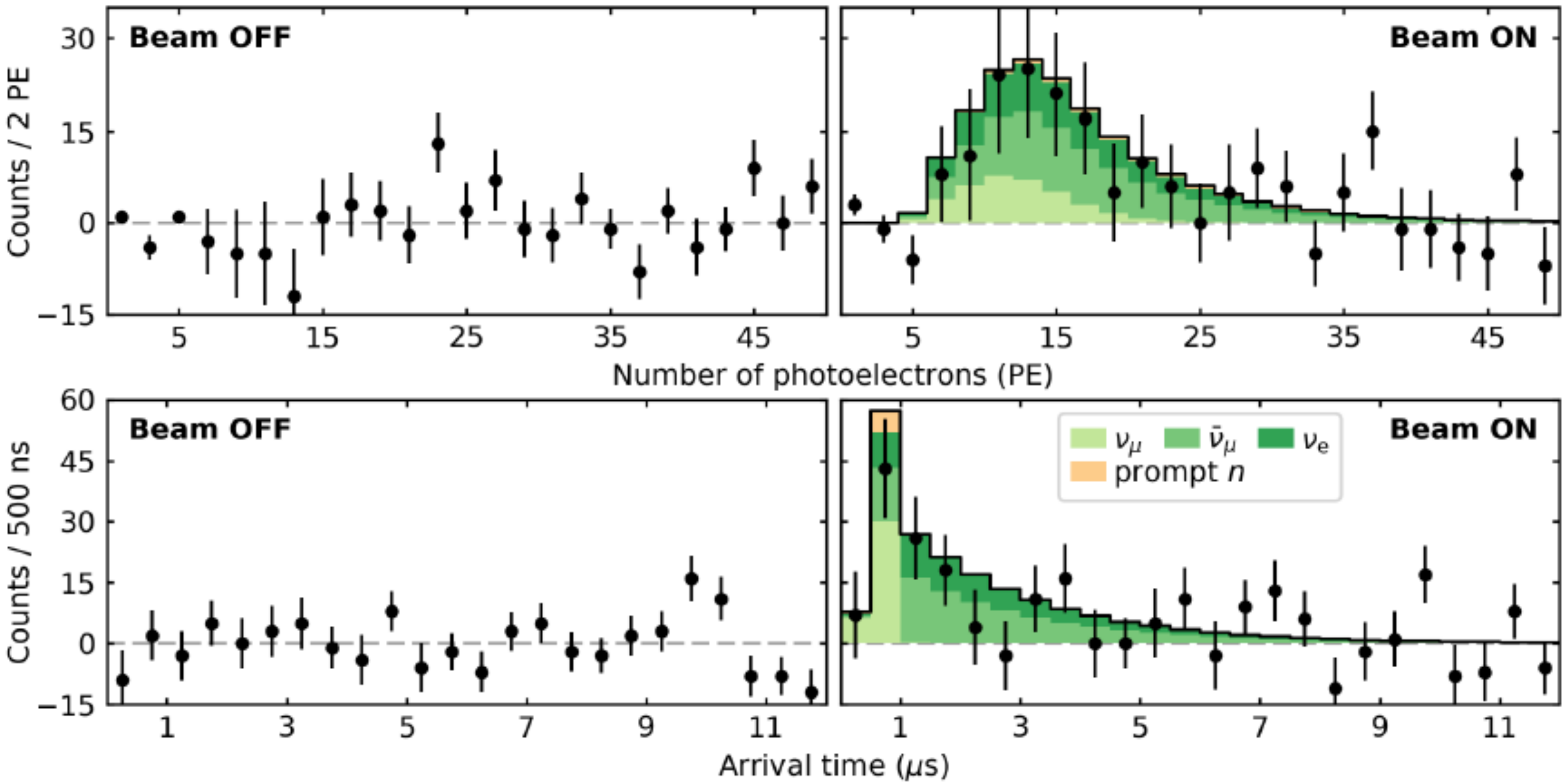


CsI Detector Data Accumulation



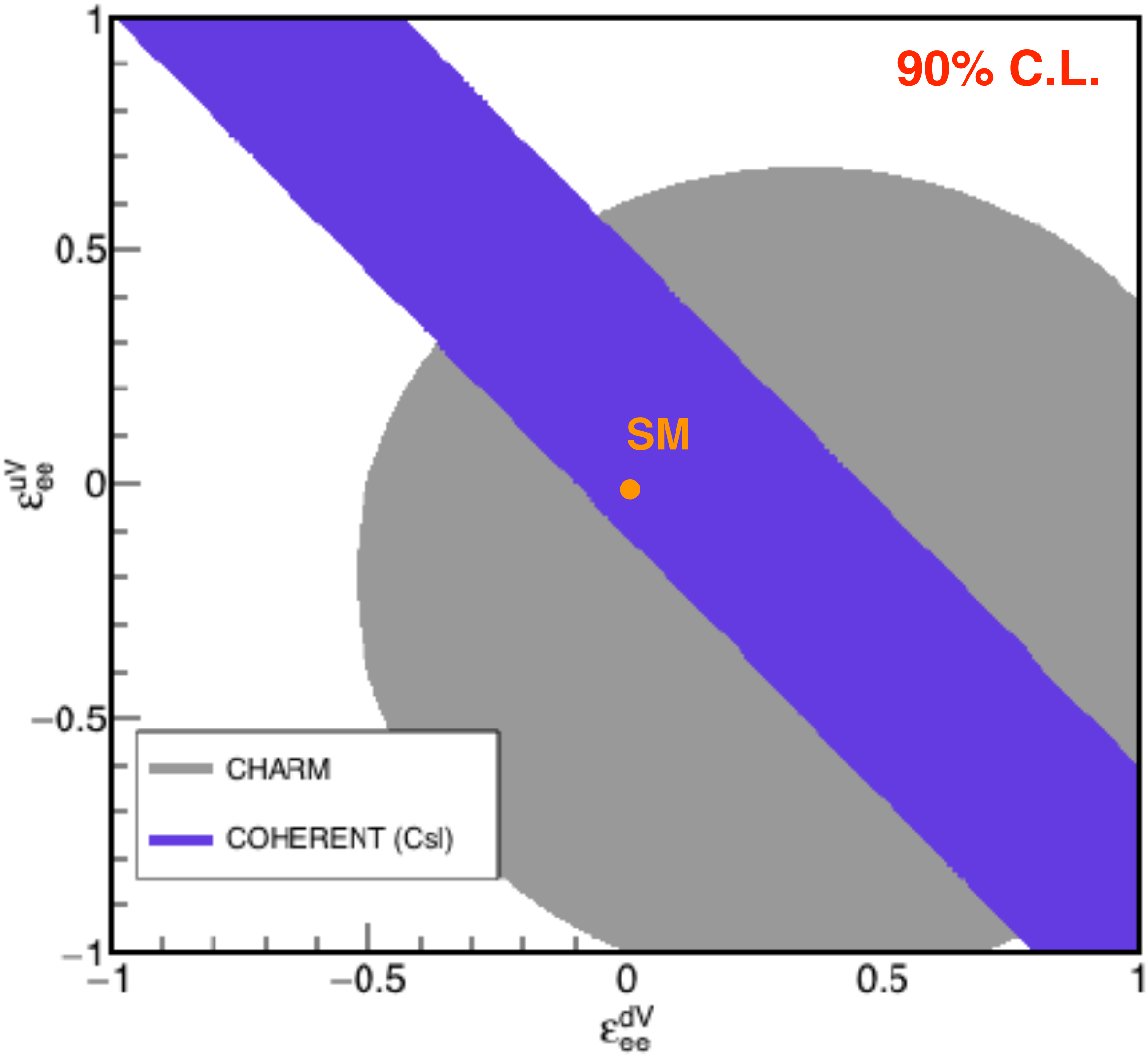
- Total 1.76×10^{23} Protons on Target were recorded (7.48GWh, 308 days)
- 0.22 grams of protons are delivered to the SNS target

- The first observation of CEvNS at a **6.7-sigma** confidence level
- Smallest neutrino detector ever (14.6kg)!



Constrain on Non-Standard Neutrino Interactions

$$\mathcal{L}_{\nu H}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta=e,\mu,\tau}} [\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5)\nu_\beta] \times (\varepsilon_{\alpha\beta}^{qL}[\bar{q}\gamma_\mu(1-\gamma^5)q] + \varepsilon_{\alpha\beta}^{qR}[\bar{q}\gamma_\mu(1+\gamma^5)q])$$



Citation

arXiv.org > hep-ph > arXiv:1708.02899

High Energy Physics – Phenomenology

A COHERENT enlightenment of the neutrino Dark Side

Pilar Coloma, M. C. Gonzalez-Garcia, Michele Maltoni, Thomas Schwetz

(Submitted on 9 Aug 2017)

In the presence of non-standard neutrino interactions (NS… are affected by a degeneracy which allows the solar mixing angle to be in the se… the dark side) and implies a sign flip of the atmospheric mass-squared difference… ambiguity in the determination of the ordering of neutrino masses, one of the ma… rrent and future experimental neutrino program. We show that the recent obser… neutrino–-nucleus scattering by the COHERENT experiment, in combination wit… data, excludes the NSI degeneracy at the 3.1σ (3.6σ) CL for NSI with up (down) …

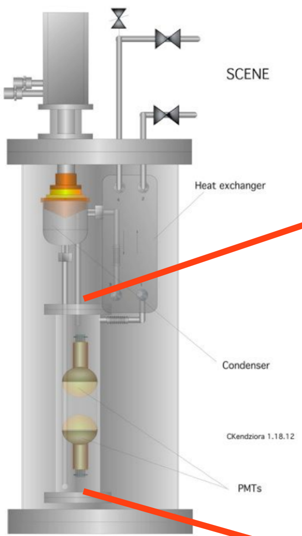
5-days after COHERENT results announcement

Comm… 5 pages, 3 figures
Subjects: **High Energy Physics – Phenomenology (hep-ph)**; High Energy Physics – Experiment (hep-ex)
Report number: FERMILAB-PUB-17-308-T, YITP-SB-17-28, IFT-UAM/CSIC-17-073
Cite as: arXiv:1708.02899 **[hep-ph]**
(or arXiv:1708.02899v1 **[hep-ph]** for this version)

Submission history

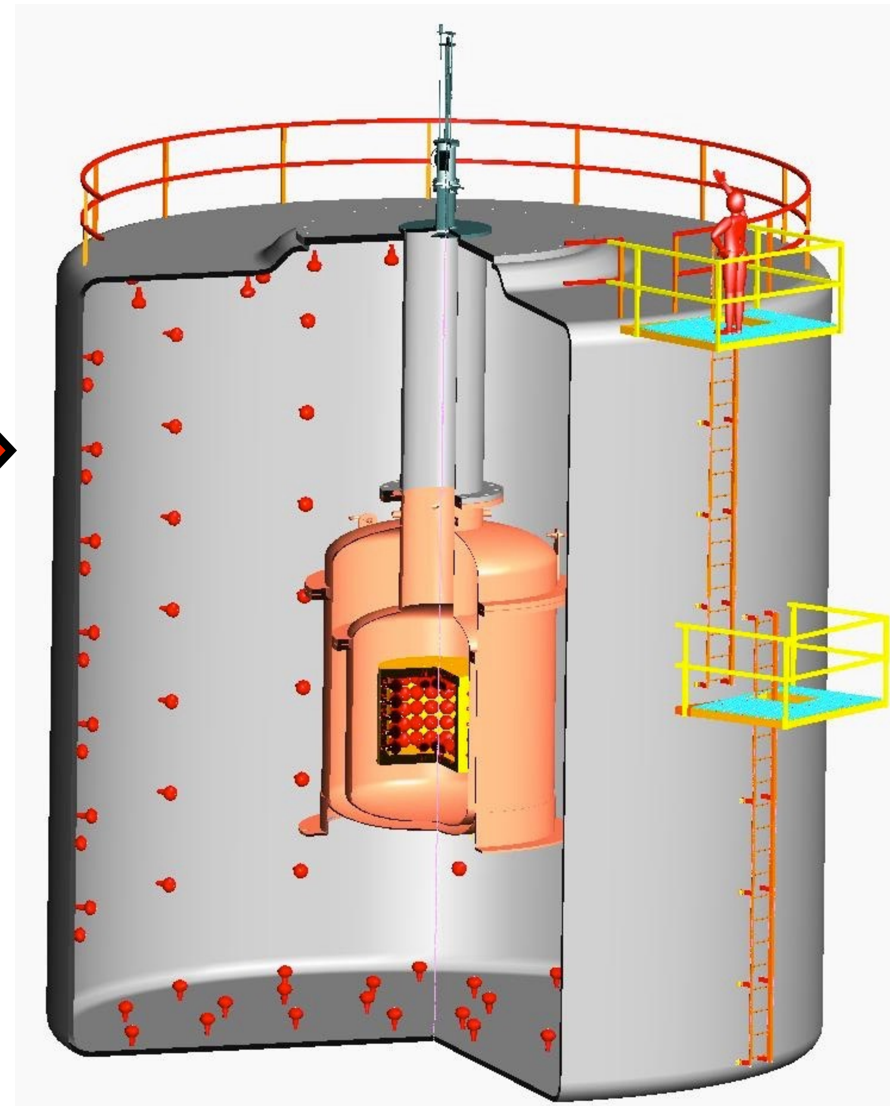
From: Pilar Coloma [view email]

Liquid Argon CEvNS Detector: CENNS

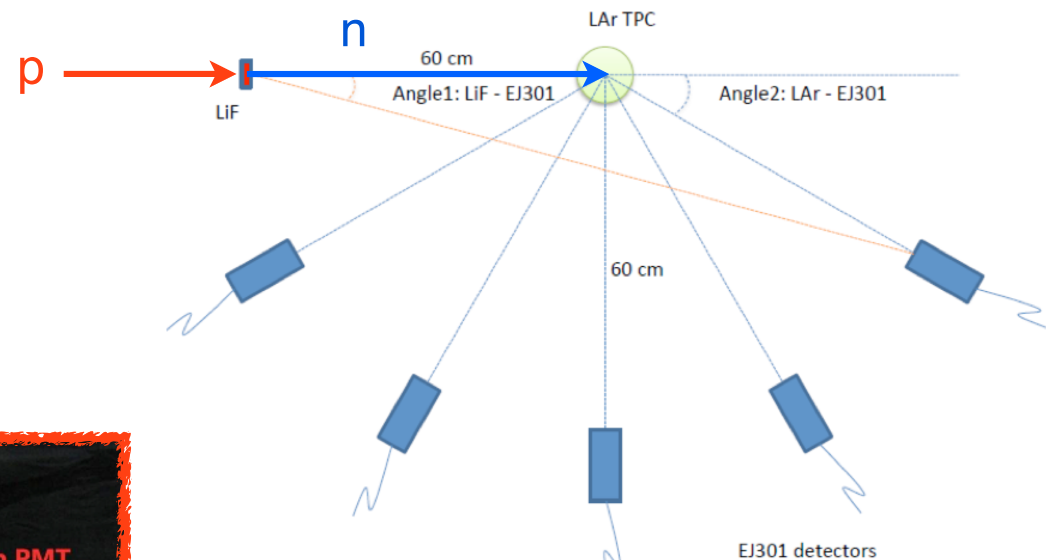


1-kg detector 2012
- Operational experience
- Measure scintillation light efficiency of nuclear recoils in LAr

10-kg detector 2013~2014
- Study beam induced neutron shielding near the beam target
- Characterize the BNB neutron backgrounds in LAr target
- Understand design issues of the ton-scale detector (LAr detector test stand)



Ton-scale detector for the CENNS experiment

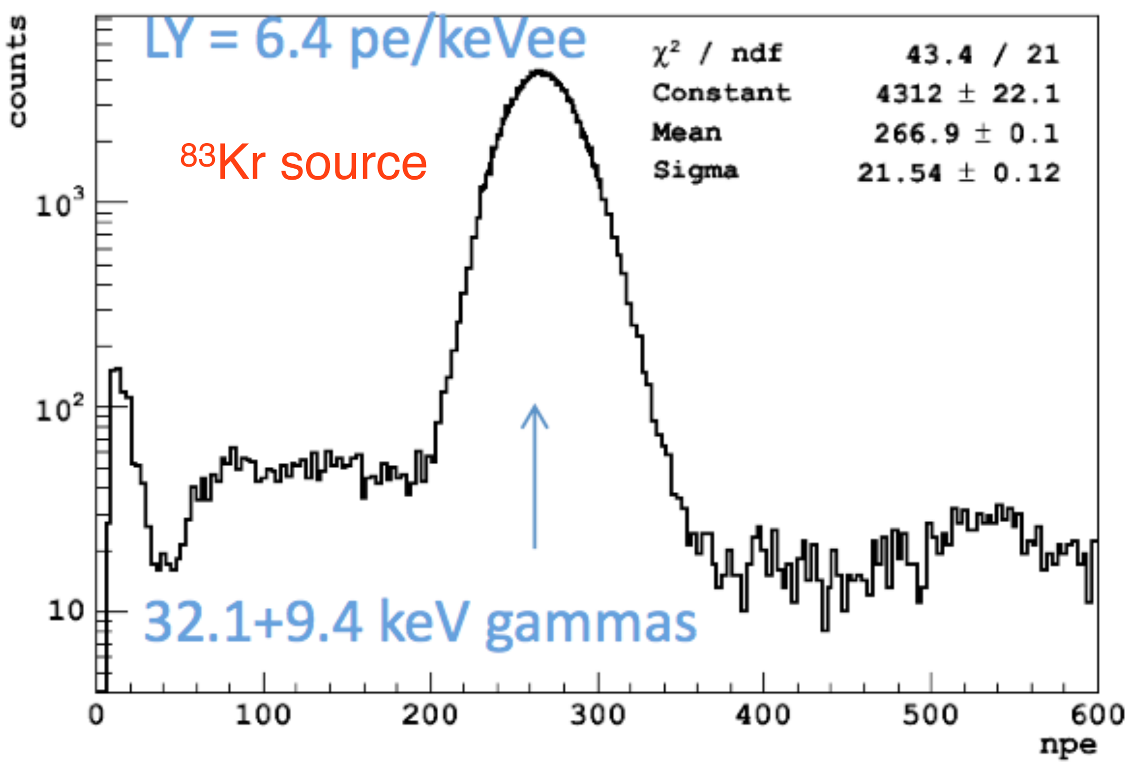


1-kg LAr prototype detector

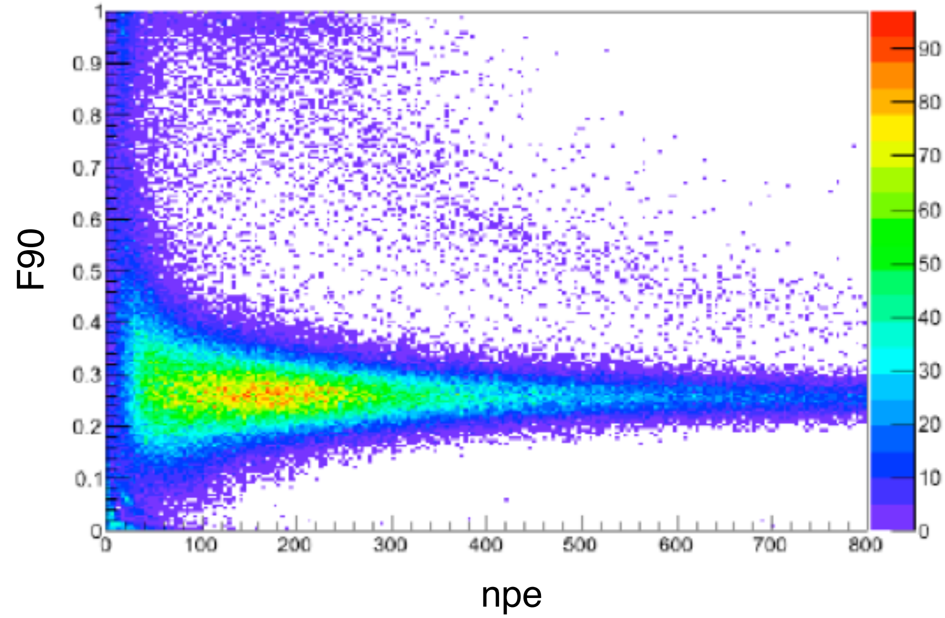
- **SCENE Collaboration: (CENNS +DarkSide)**
  SCintillation Efficiency of Noble Elements
- Goals:
  Measure scintillation light yield in low-energy (<50 keV) nuclear recoils
- Can run in single-phase mode or dual phase TPC mode
- Use pulsed neutron beam at University of Notre Dame

CENNS Detector R&D

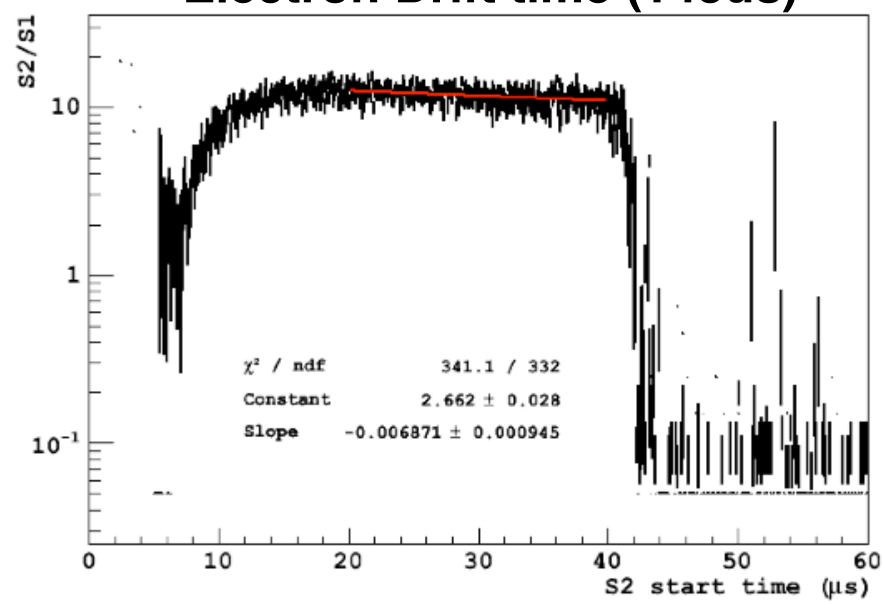
Gamma Light Yield (single phase)



Pulse Shape Discrimination

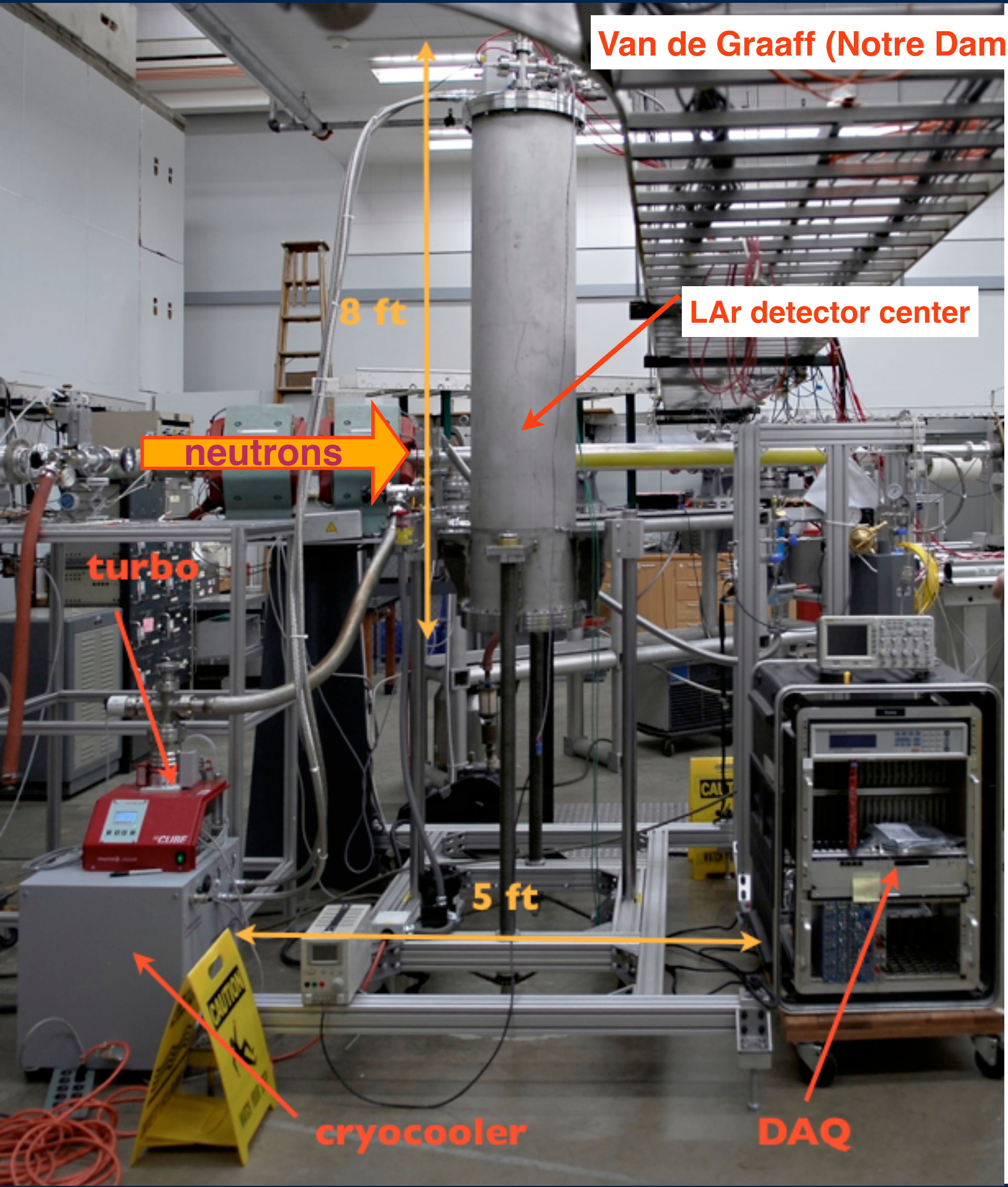


Electron Drift time (145us)

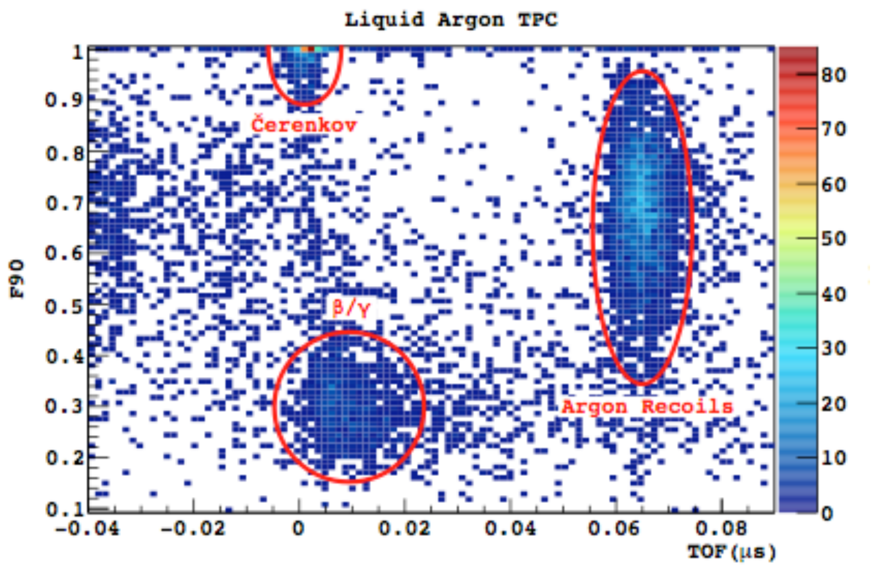


- Detector performance is good enough to carry out in-beam measurement
- Date taking at the end of 2012 and early 2013

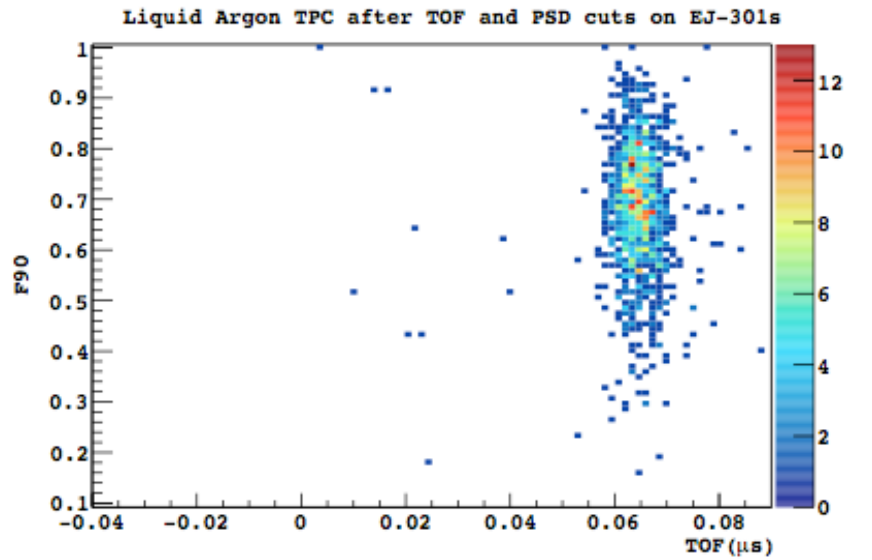
CENNS Detector R&D



Neutron Beam Data (before cut)

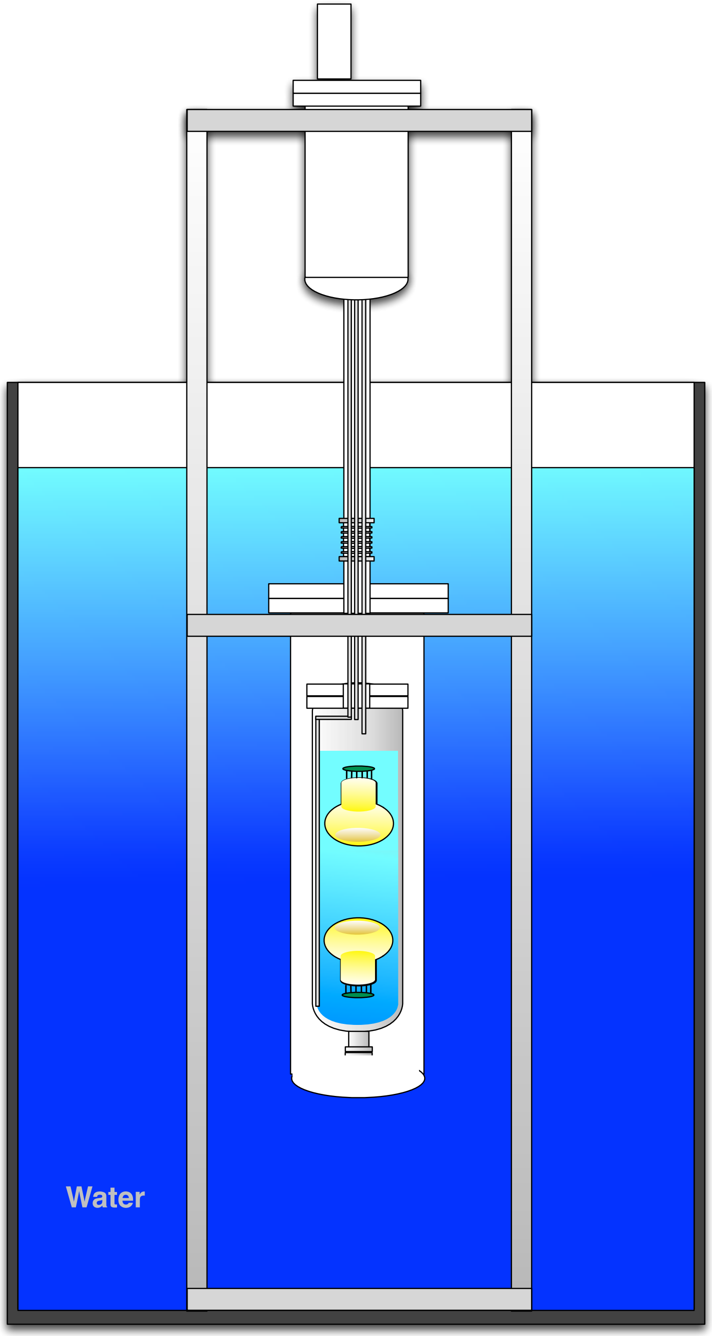


Neutron Beam Data (after cut)



10-kg prototype detector

- Goals:
  - Neutron background study at BNB area
  - Demonstrate detector capability
- Existing cryostat and gas handling system from 1-kg prototype
- Parts are ordered and/or purchased
- Initial phase will use two R5912-02MOD 8” PMTs (Hamamatsu)
- **Construction completed in October 2013**



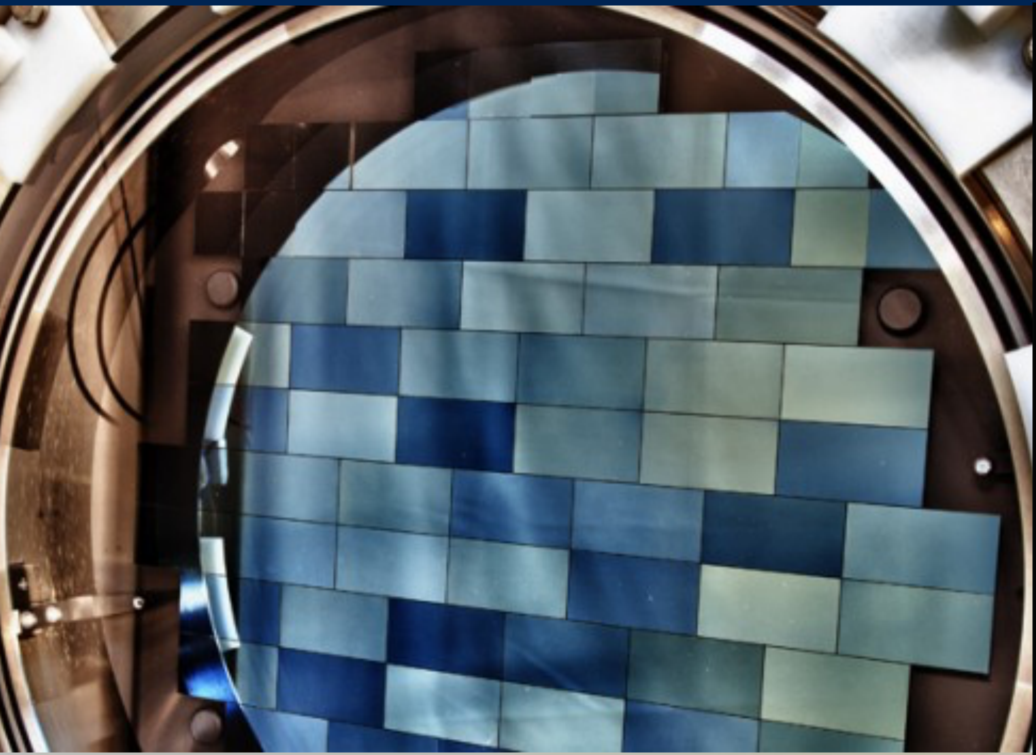
CENNS-10@Fermilab

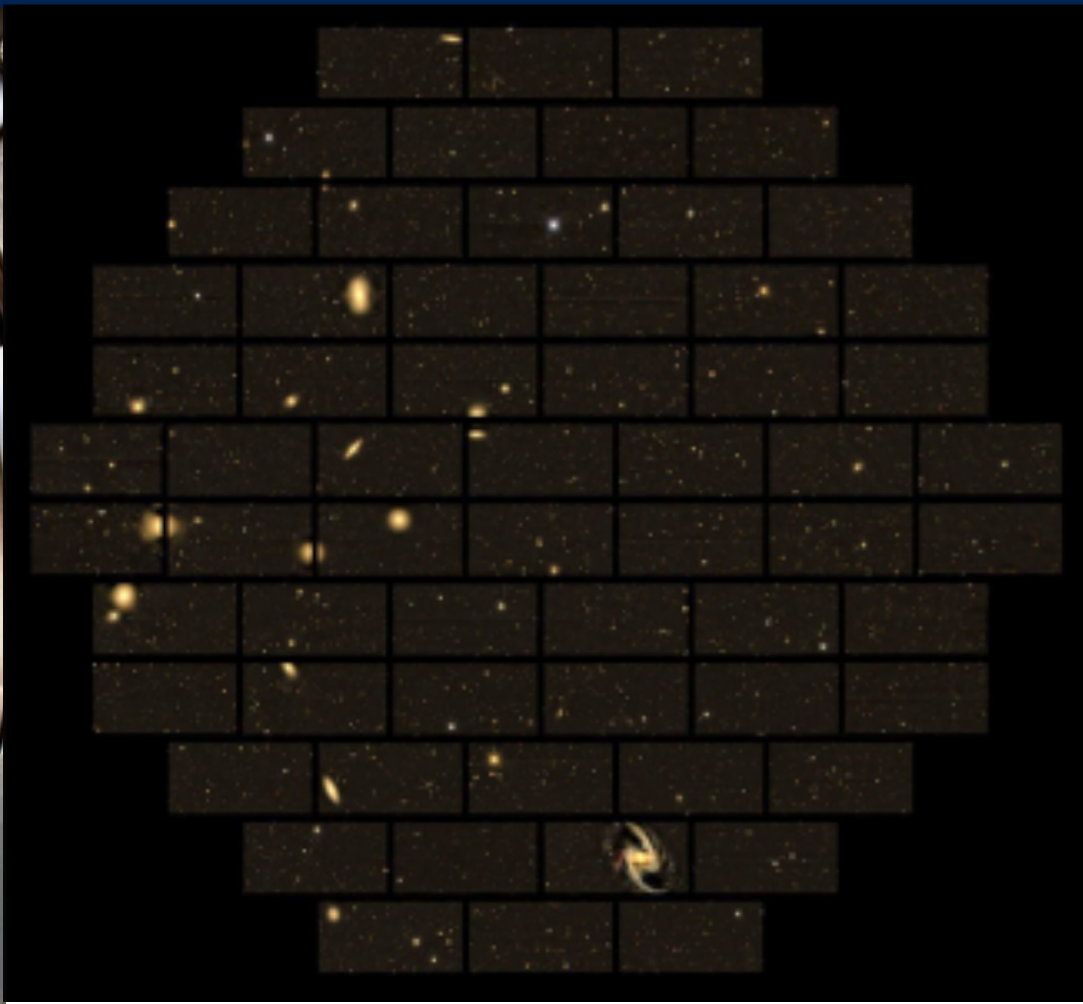
CENNS-10@Fermilab

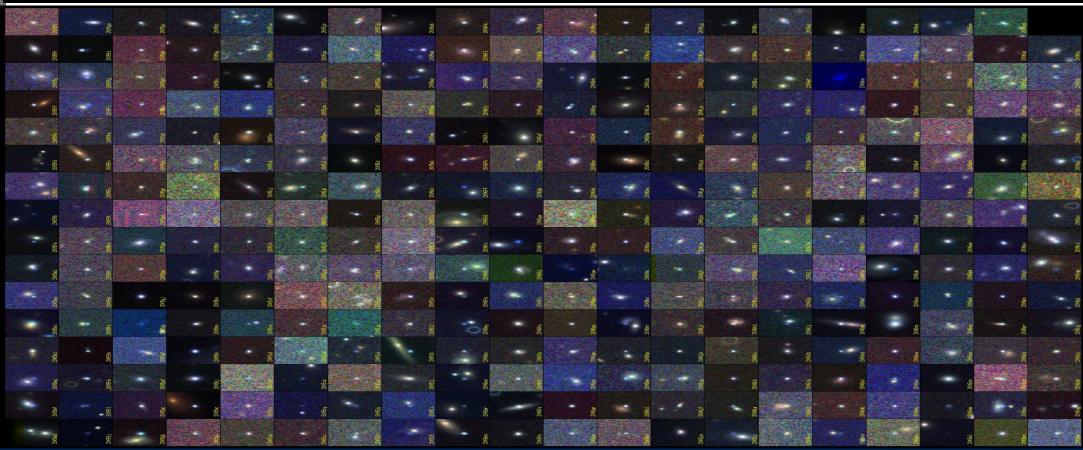
CENNS-10@ORNL

Data taking started in August 2017

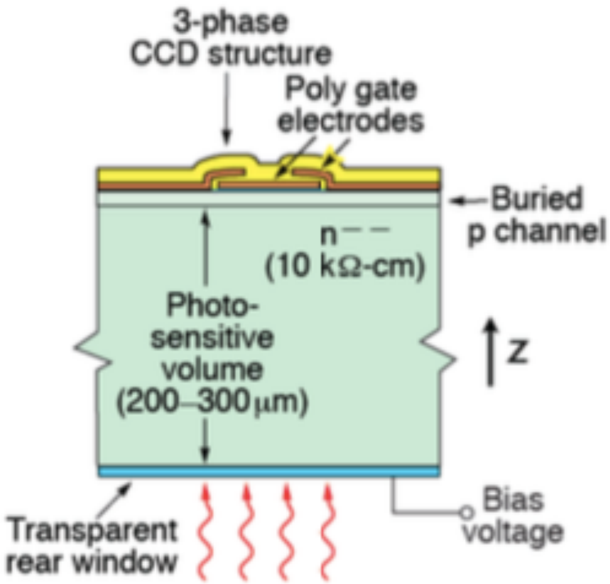
CCD Camera for Dark Energy Survey



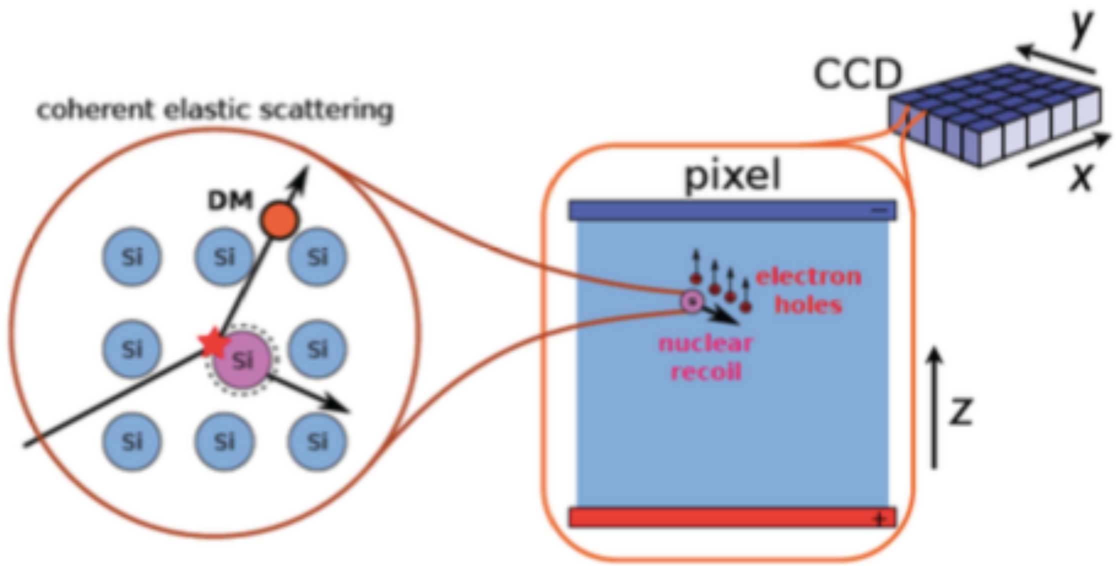




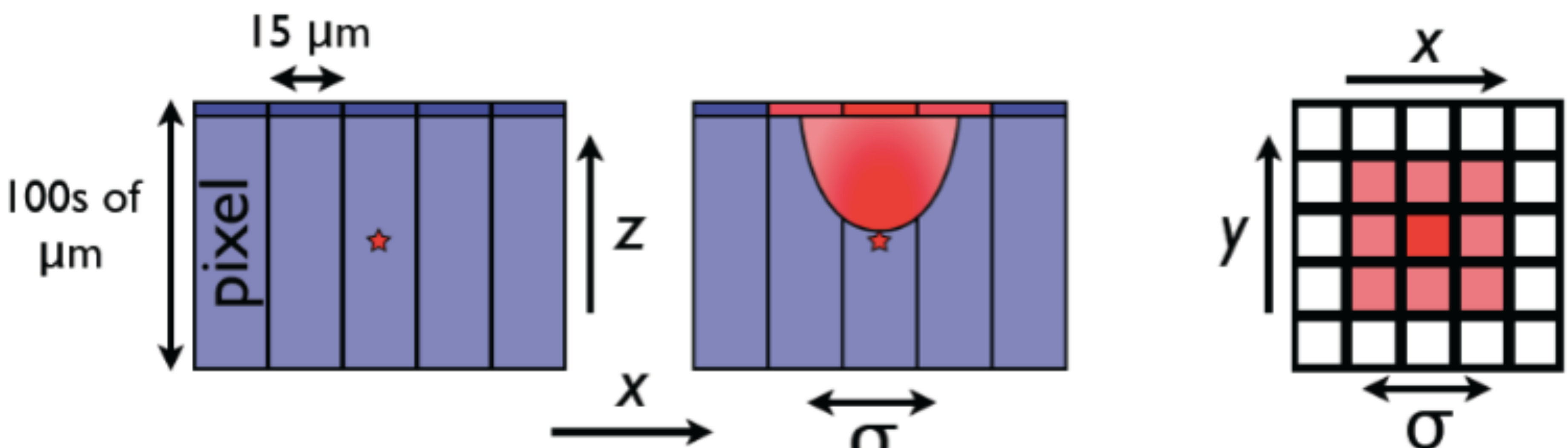
CCD Detector for CEvNS



(a) A CCD pixel

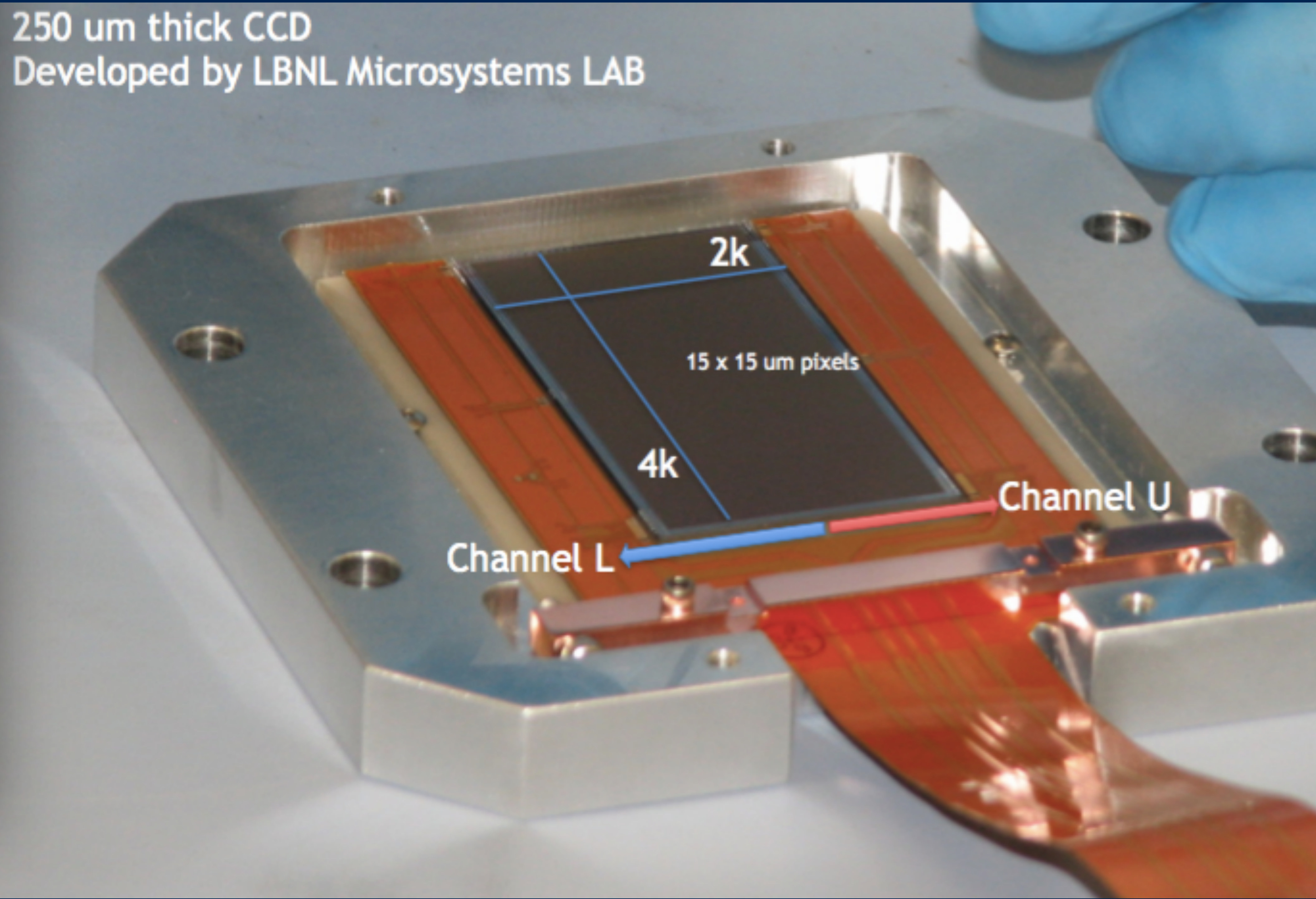


(b) WIMP detection principle

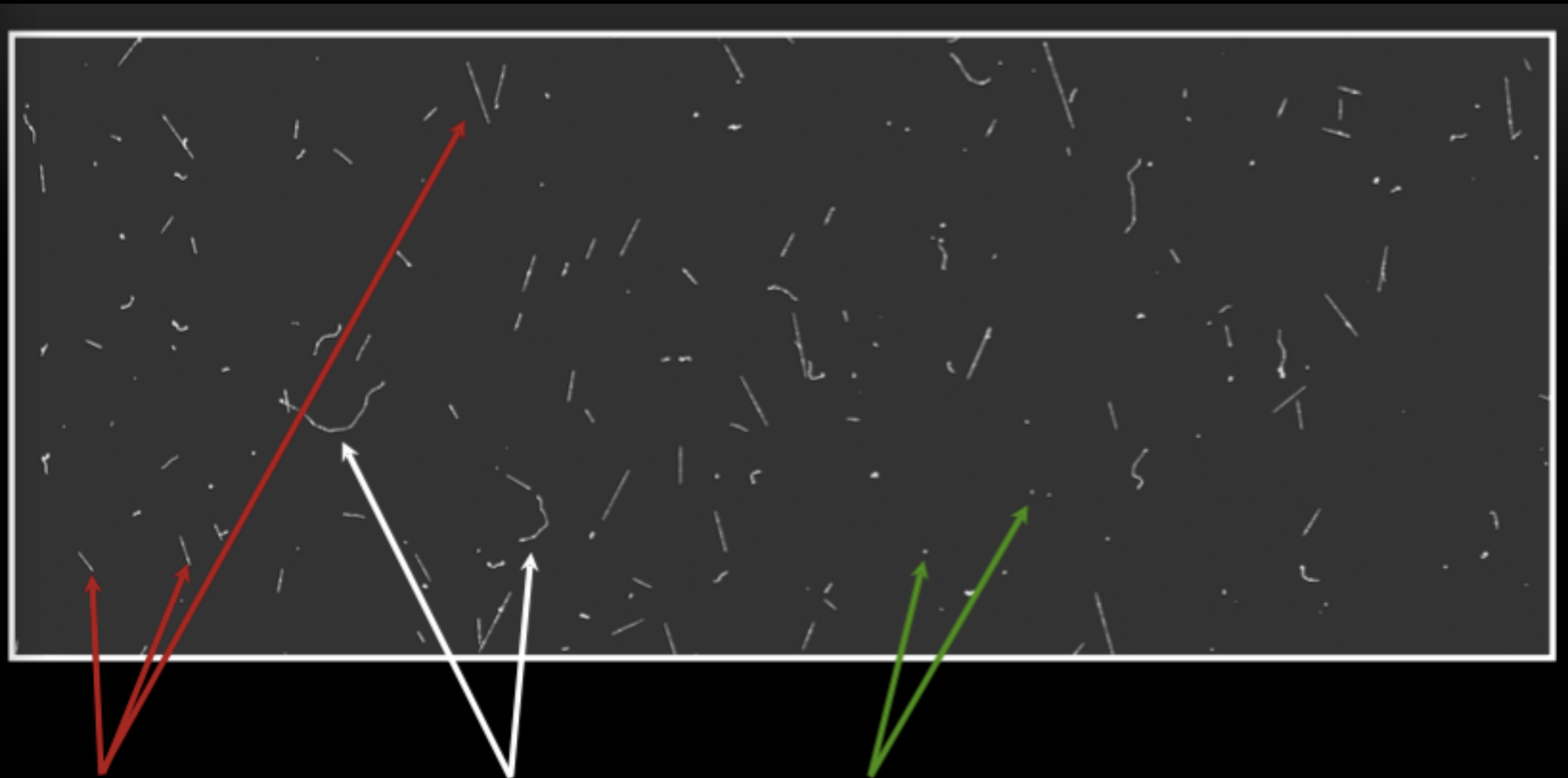


Recent developments by the MSL group at LBNL has allowed the fabrication for “massive” CCDs. 675 um is now possible.

CEvNS with CCD detector



CEvNS with CCD detector



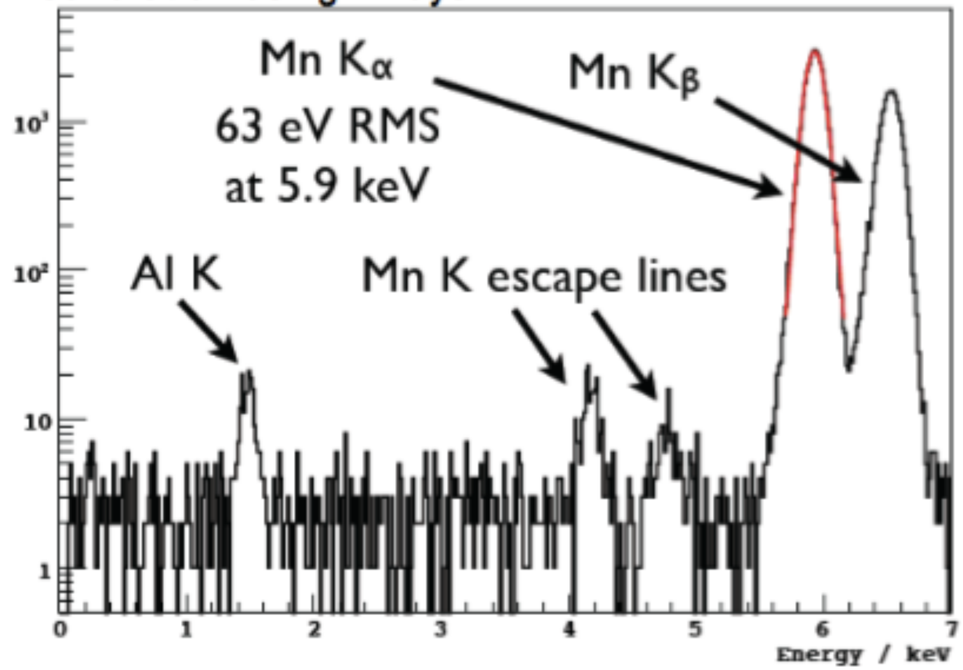
muons: long track

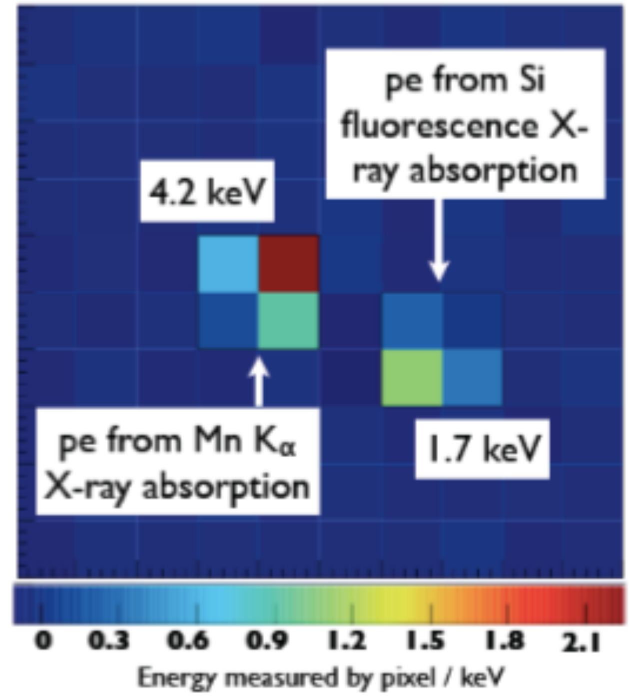
electrons:
scattered track (surface)

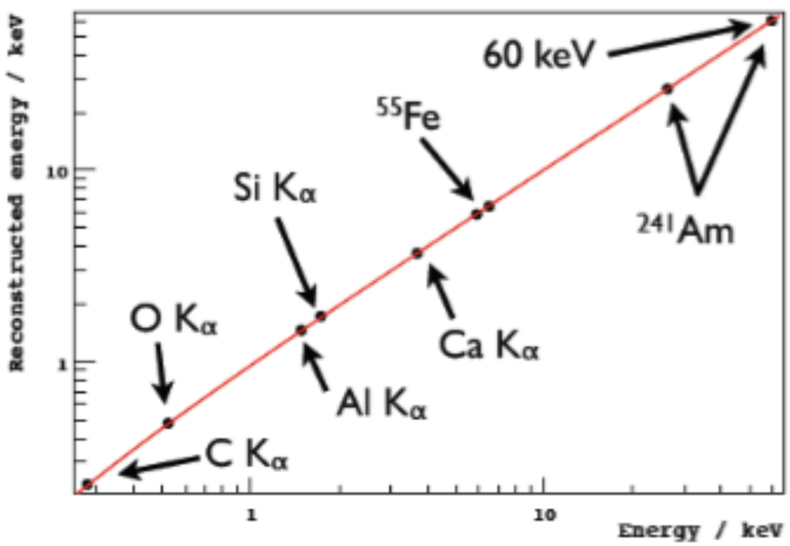
spot-like: potentially nuclear recoil interaction

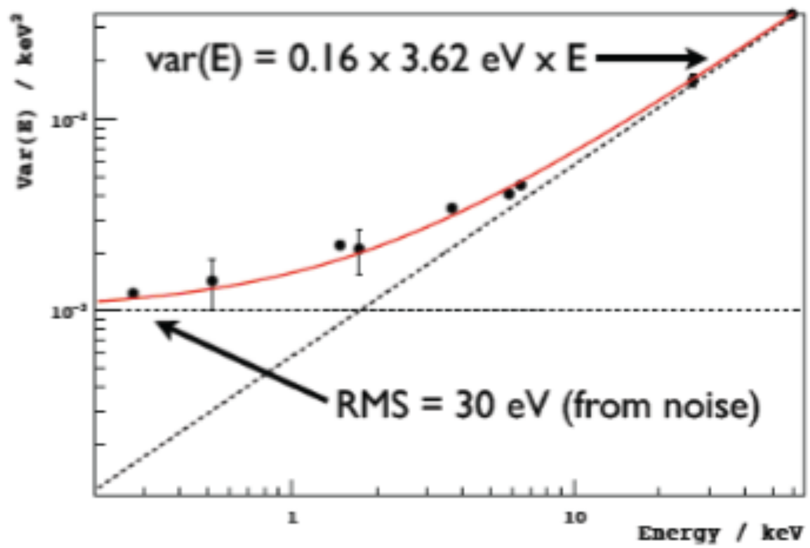
CEvNS with CCD detector

Calibration using X-rays



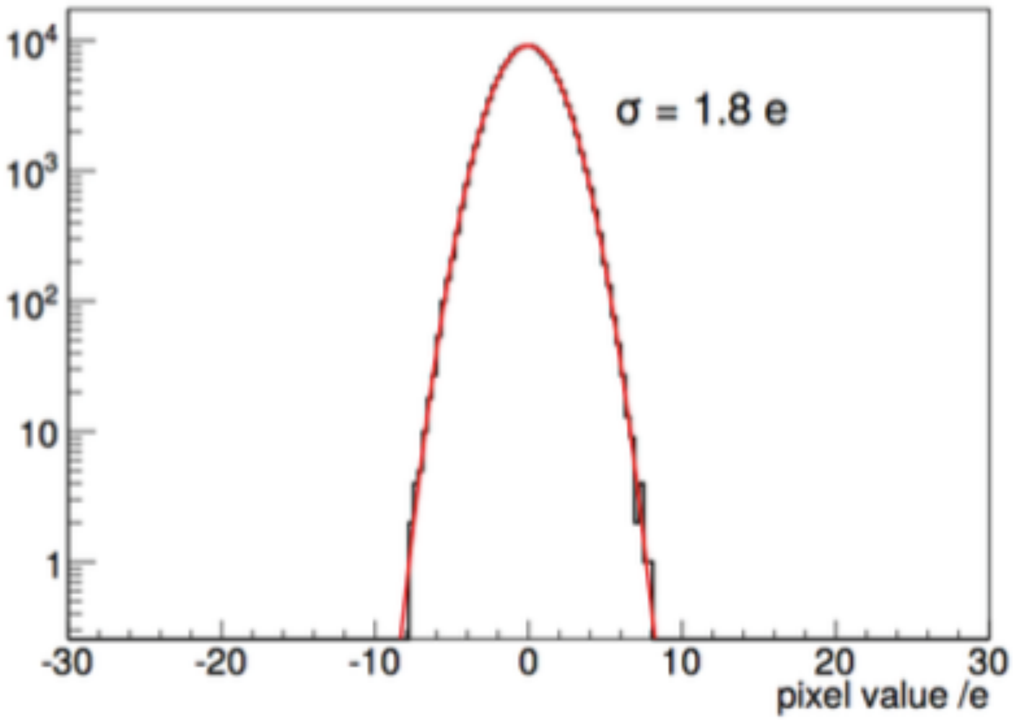




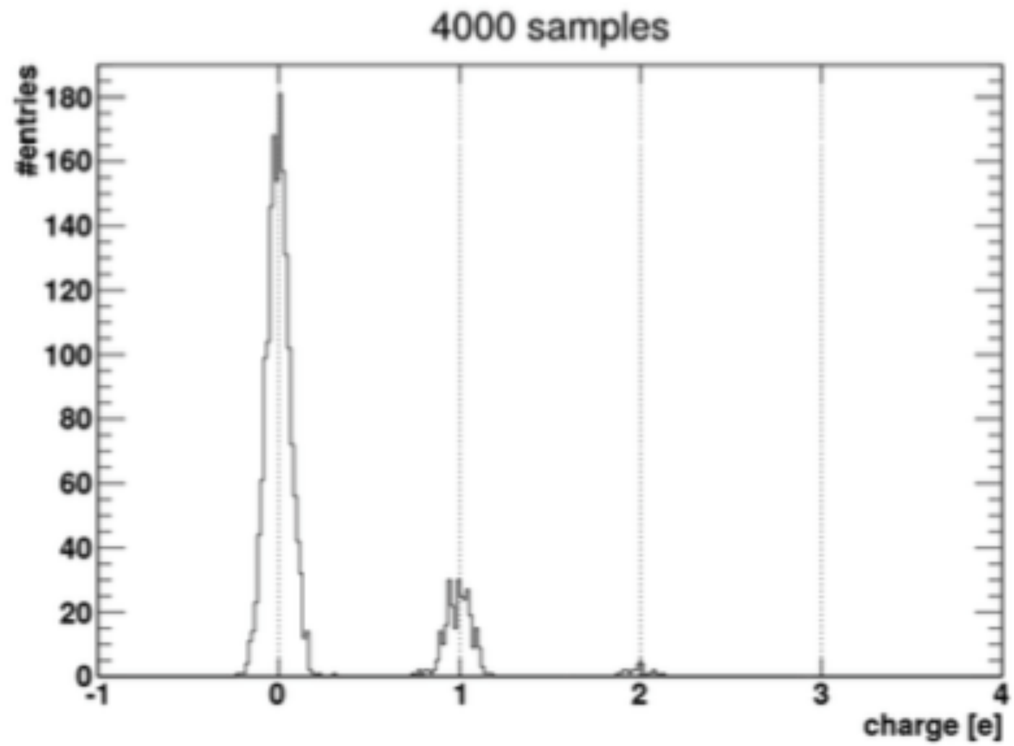


New CCD Development

CCD detector now



Skipper CCD (new development)



New CCD technology demonstrated (arXiv:1706.00028) allows reduction of the energy threshold by another factor of 2.

The goal of CCD based detector R&D is to lower the energy threshold down to order of 10s of eV

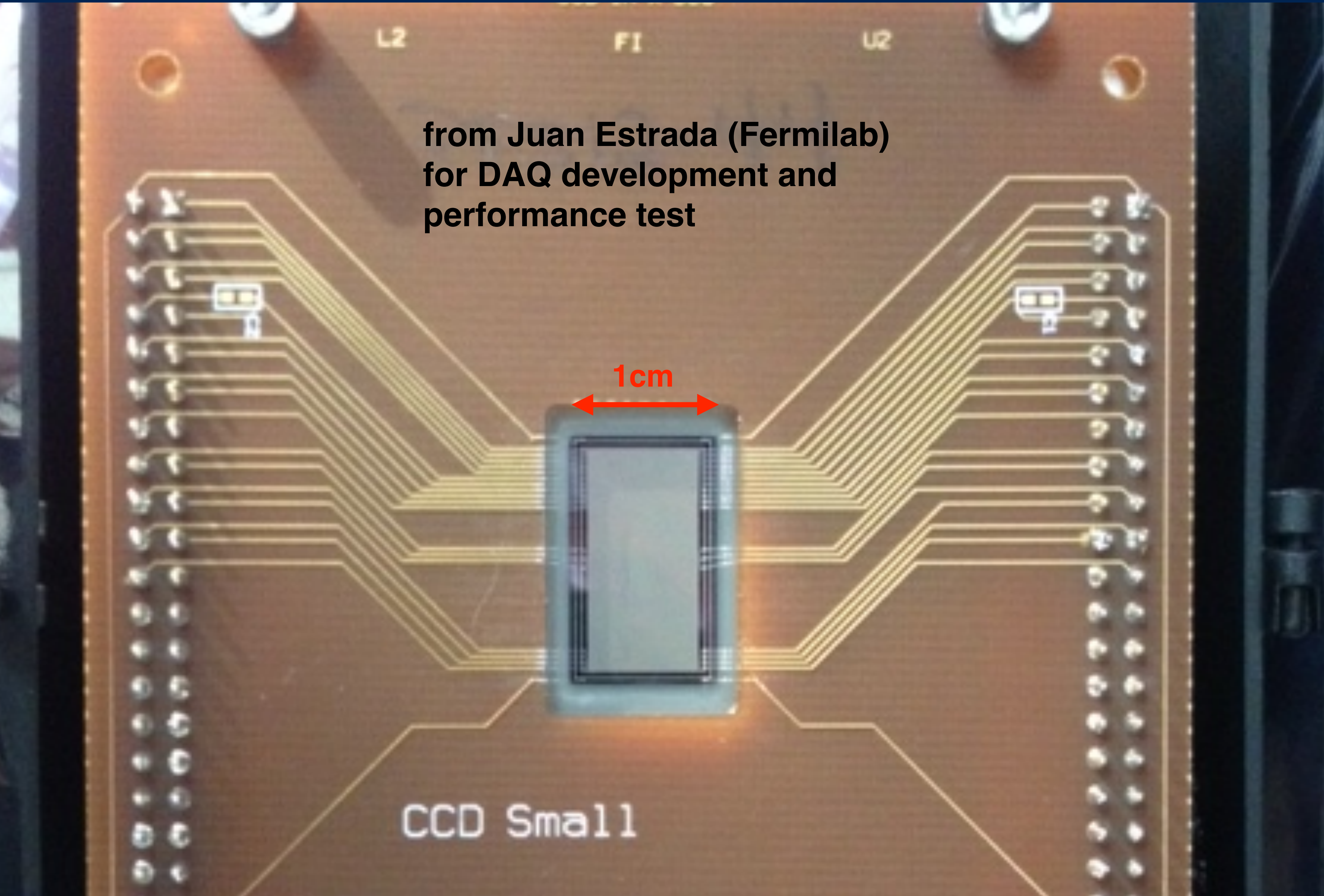
Remote Monitoring of Nuclear Reactions?

$$E_{max} \simeq \frac{2E_\nu^2}{M} < \mathrm{keV}$$

$$\Phi = 10^{20} \bar{\nu}_e / sec / 4\pi R^2 \qquad (\Phi = 10^{12} \bar{\nu}_e / sec / cm^2 @ \ 20 \ \mathrm{m})$$

A Test CCD at KAIST

from Juan Estrada (Fermilab)
for DAQ development and
performance test



CubeSat

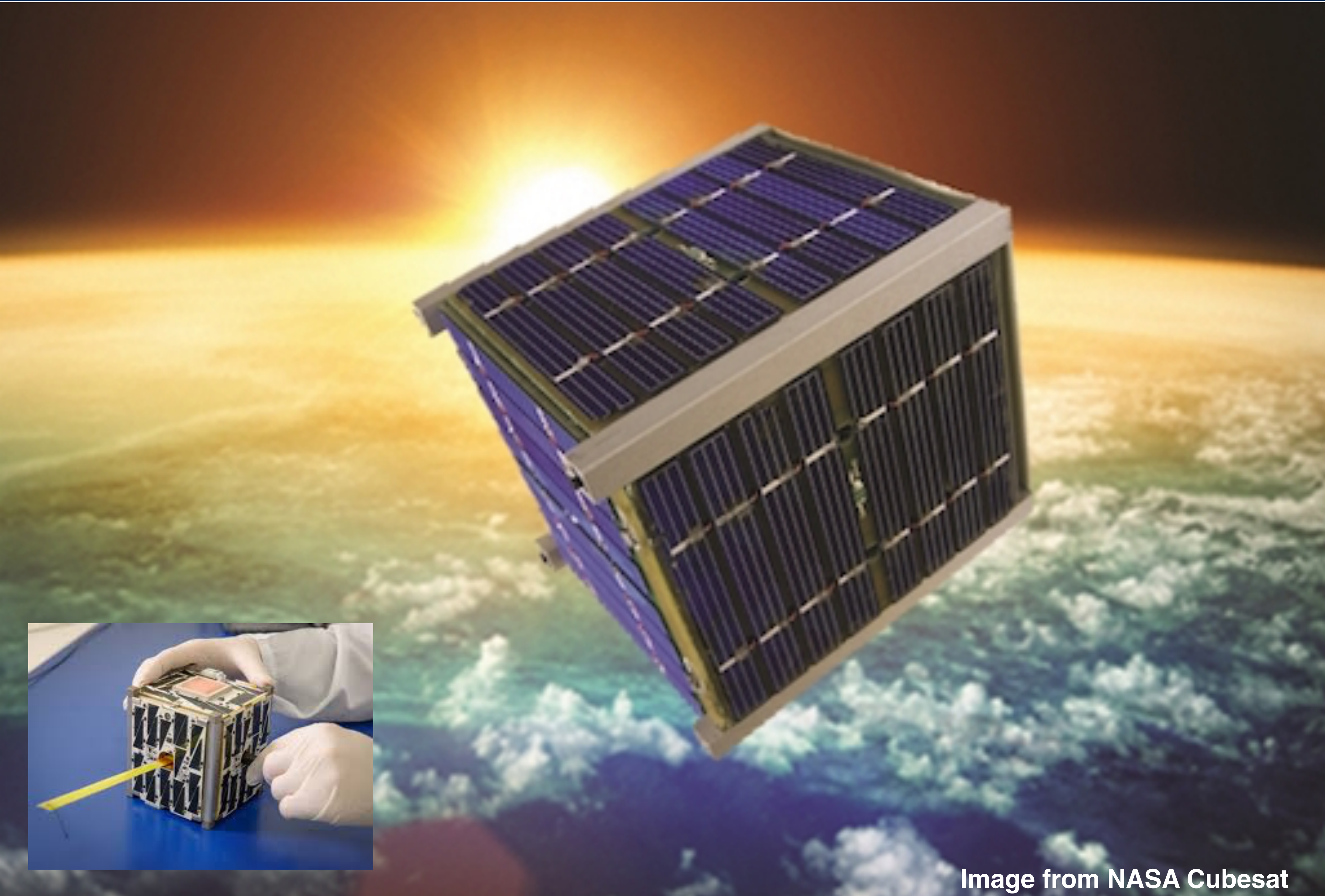


Image from NASA Cubesat

Summary

- COHERENT collaboration observed CEvNS process for the first time at Oak Ridge National Laboratory
- COHERENT collaboration will further establish the CEvNS process using different target material detectors
- There are vigorous R&D efforts to utilize the CEvNS process for various applications