COHERENT

Coherent Elastic Neutrino-Nucleus Scattering

KAIST

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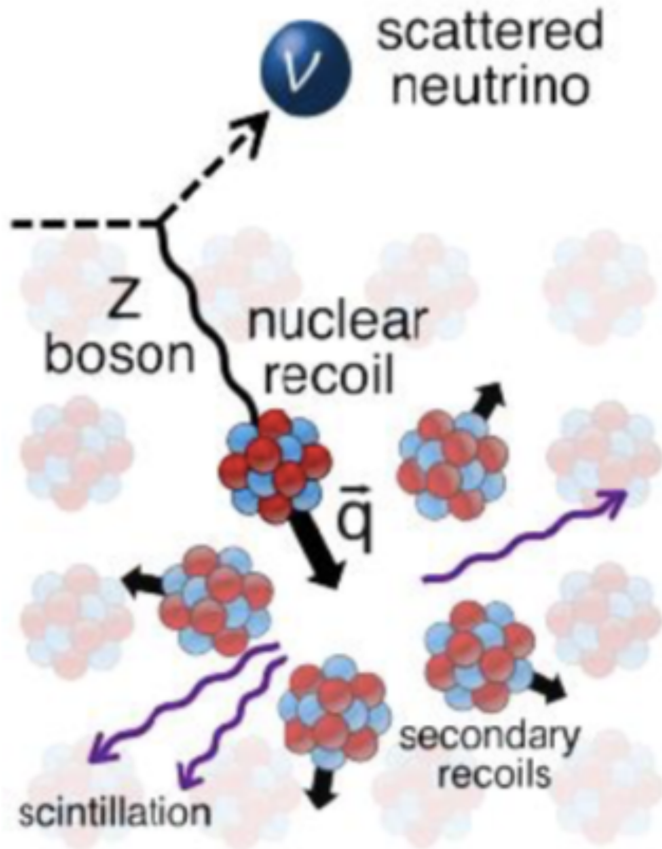
on behalf of COHERENT collaboration

2019-08-27
NuFact2019
Daegu, Korea

Neutral Current

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



Cross section for zero-momentum transfer limit

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

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

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

$\sin^2\theta_W = 0.231$ ➔ proton coupling is not significant

Differential cross section for finite momentum transfer

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

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

Straightforward calculation given the existence of **weak neutral current**

Coherent Elastic Neutrino-Nucleus Scattering predicted in 1974

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

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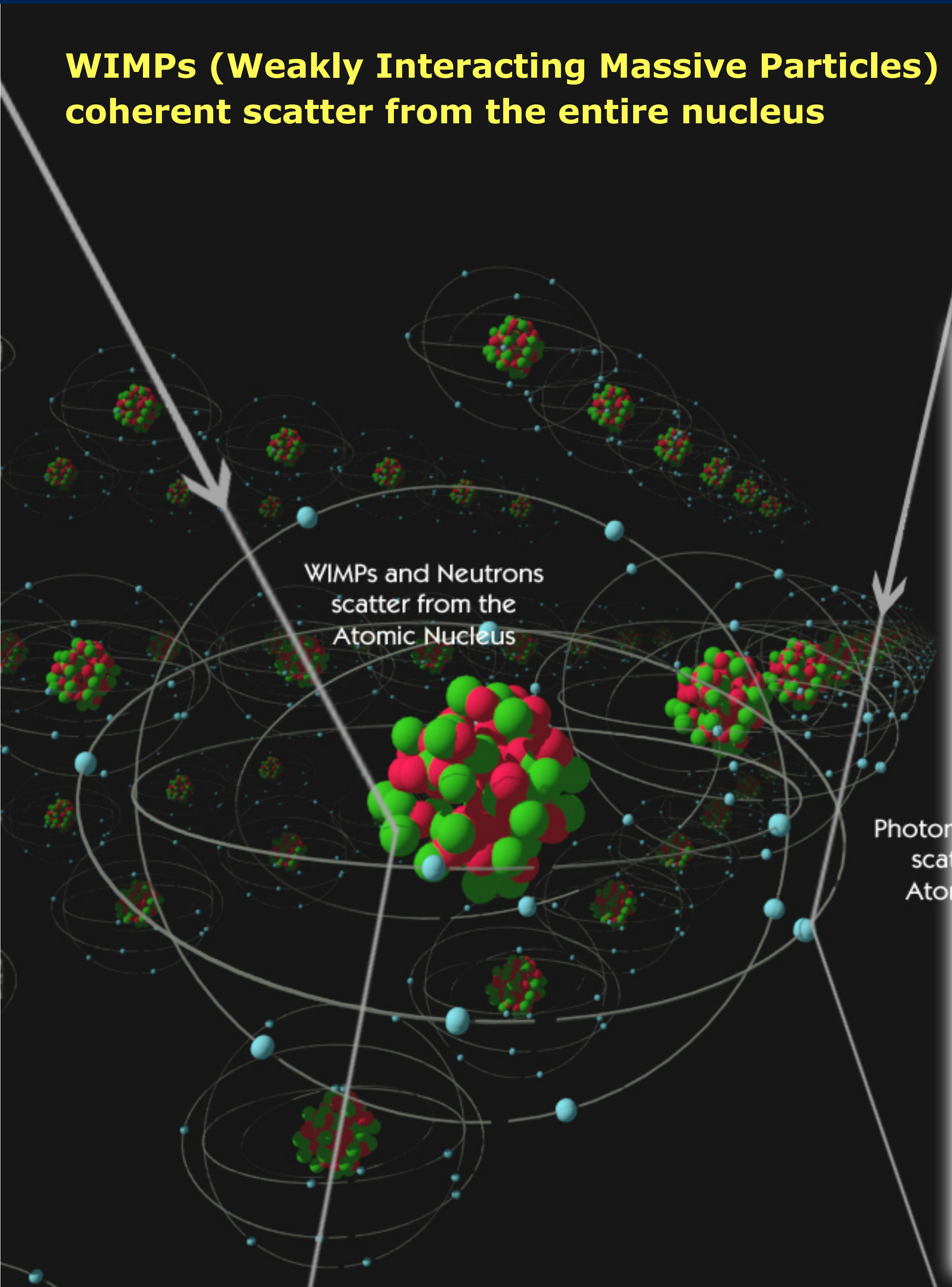
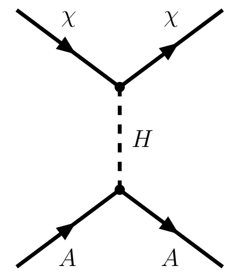
(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ 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.

Why CEvNS? — Dark Matter Coherent Scattering

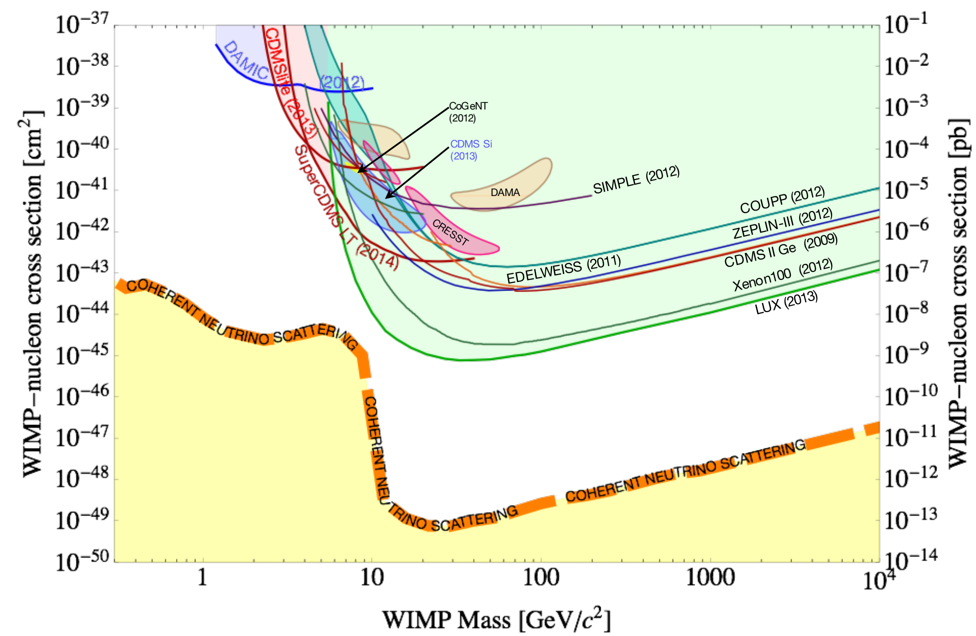
WIMPs (Weakly Interacting Massive Particles) coherent scatter from the entire nucleus





$$\sigma_{\chi N} \simeq \frac{4}{\pi}\mu^2[Zf_p + (A-Z)f_n]^2$$

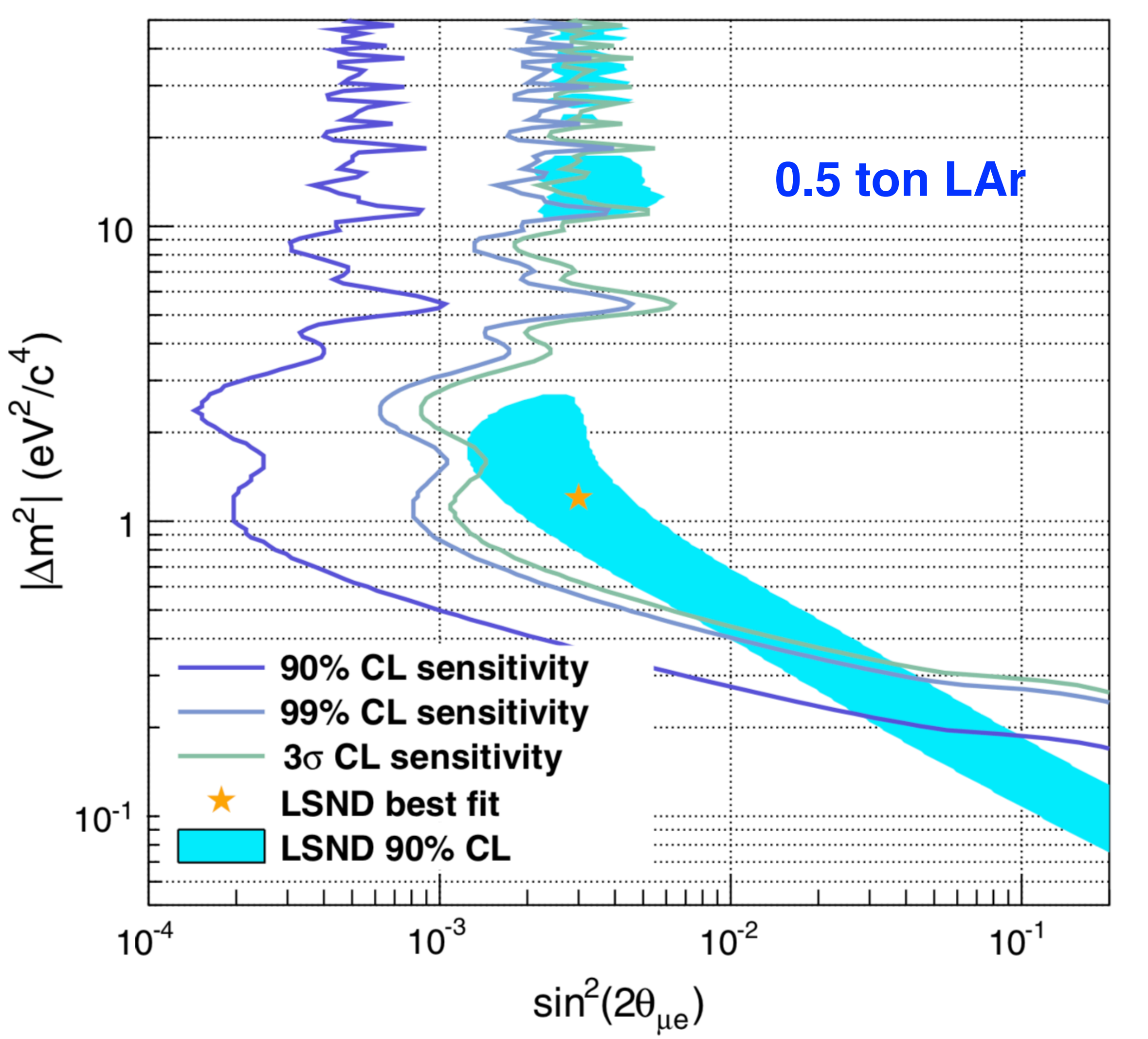
$$\frac{dR}{dE} = \frac{\sigma_0}{m_\chi}\frac{A^2}{2\mu_n^2}F_A^2(E) \times \rho_0 \int_{v_m} \frac{f(v)}{v}dv$$



Why CEvNS? — Sterile Neutrino Search

As Neutral-current is flavor blind and total neutrino flux preserved through active flavor neutrino oscillations, CEvNS is the most natural way to explore the sterile neutrinos. ➔ Look for deficit and spectral distortion

PHYSICAL REVIEW D **86,** 013004 (2012)



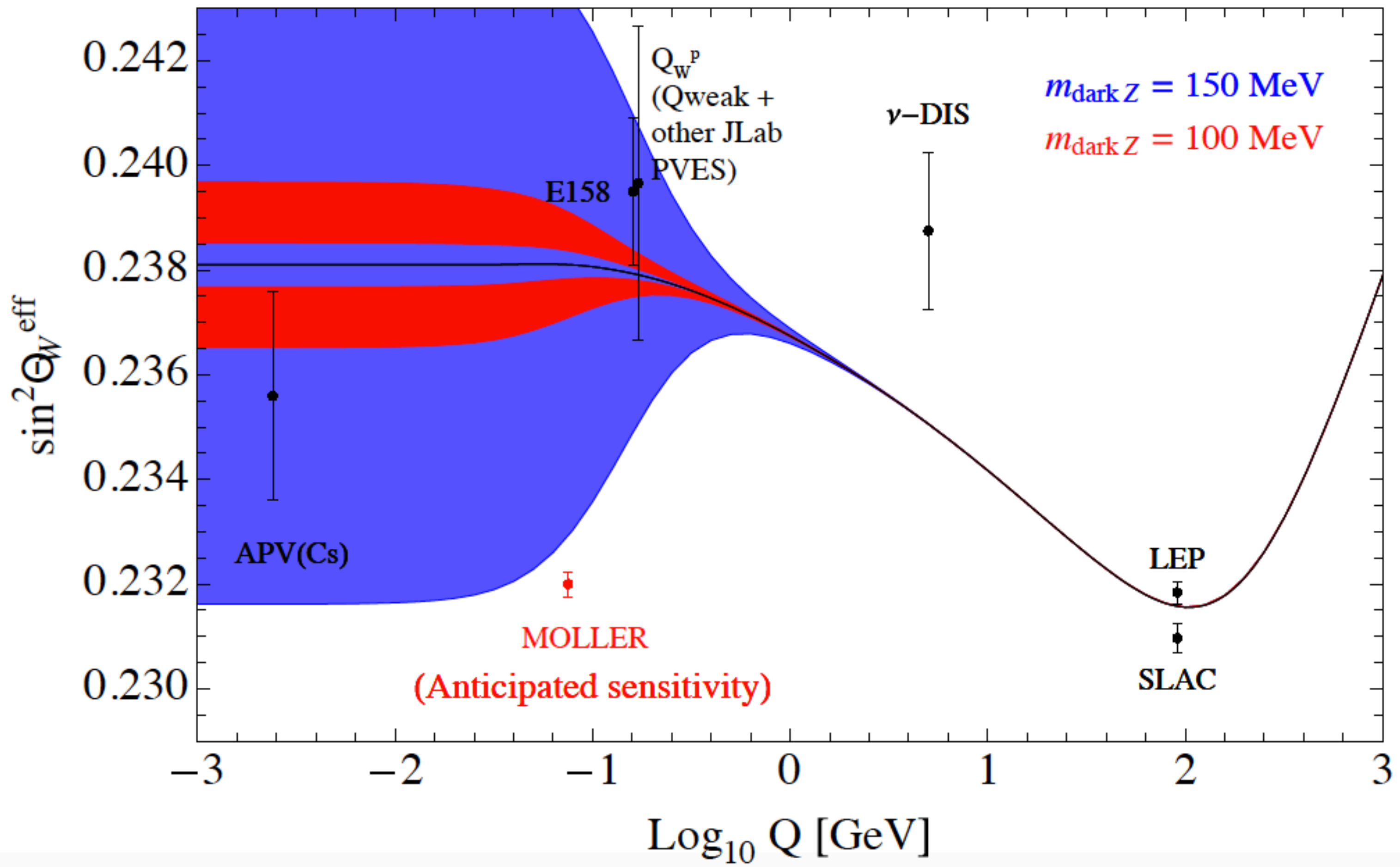
Why CEvNS? — Weinberg Angle

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

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

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

arXiv:1411.4088



Why CEvNS? — Non Standard Interactions

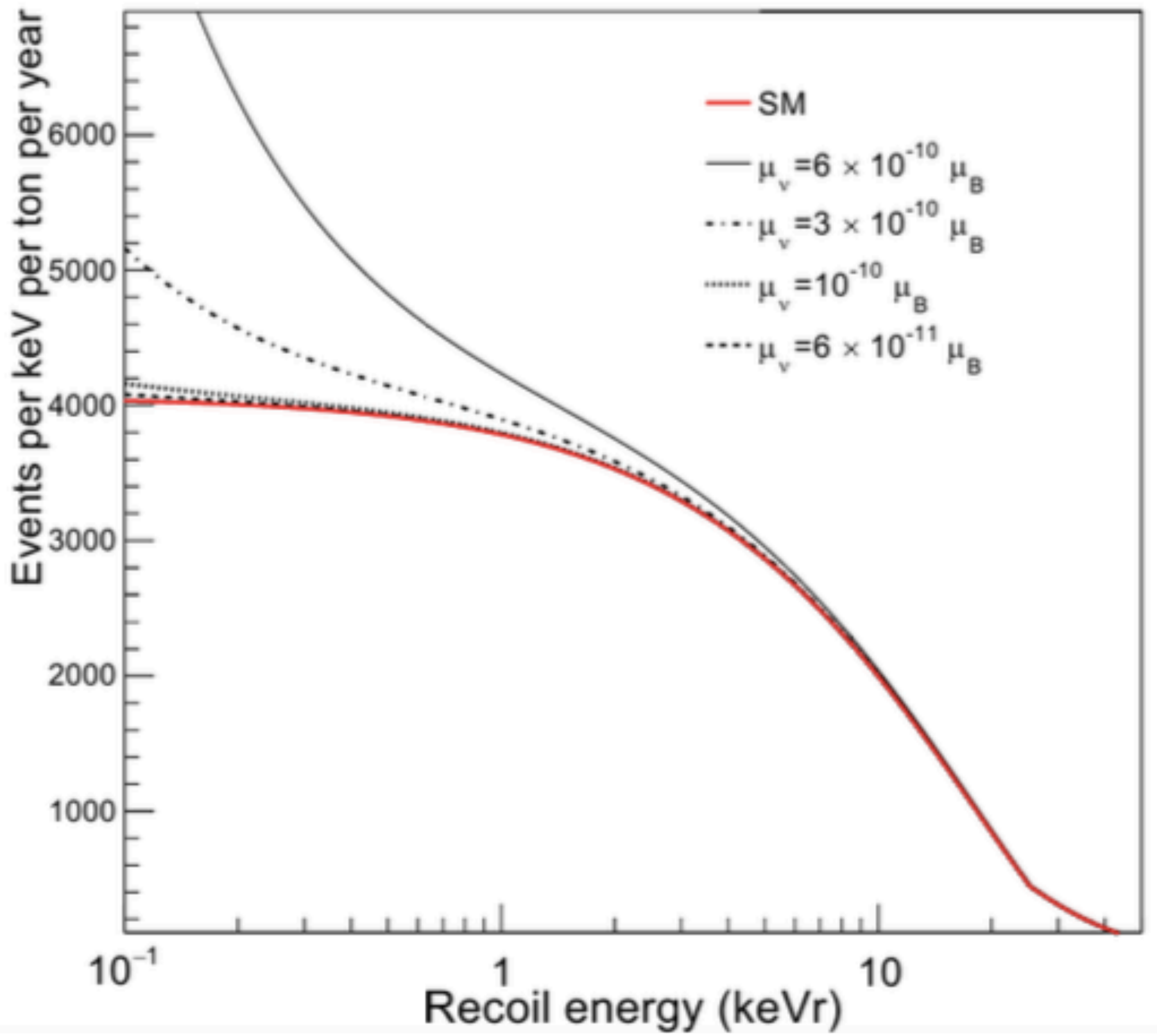
$$\mathcal{L}_{\nu H}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta=e,\mu,\tau}} [\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5) \nu_\beta] \times (\varepsilon_{\alpha\beta}^{qL} [\bar{q}\gamma_\mu (1-\gamma^5) q] + \varepsilon_{\alpha\beta}^{qR} [\bar{q}\gamma_\mu (1+\gamma^5) q])$$

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

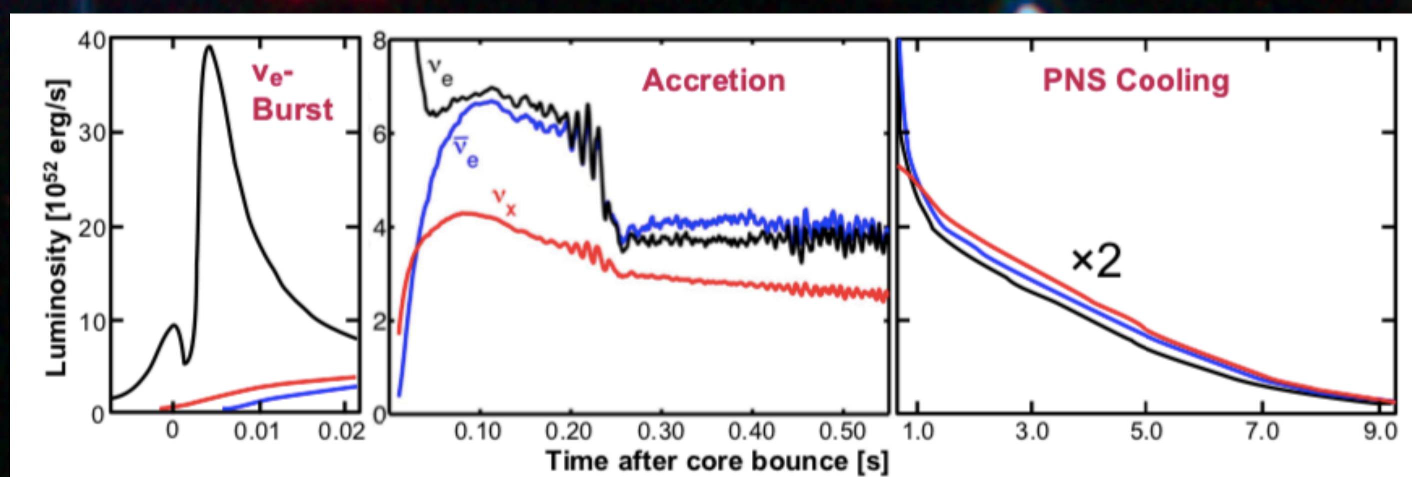
Why CEvNS? — Neutrino Magnetic Moment

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



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

arXiv:1702.08713



CEvNS Cross Section

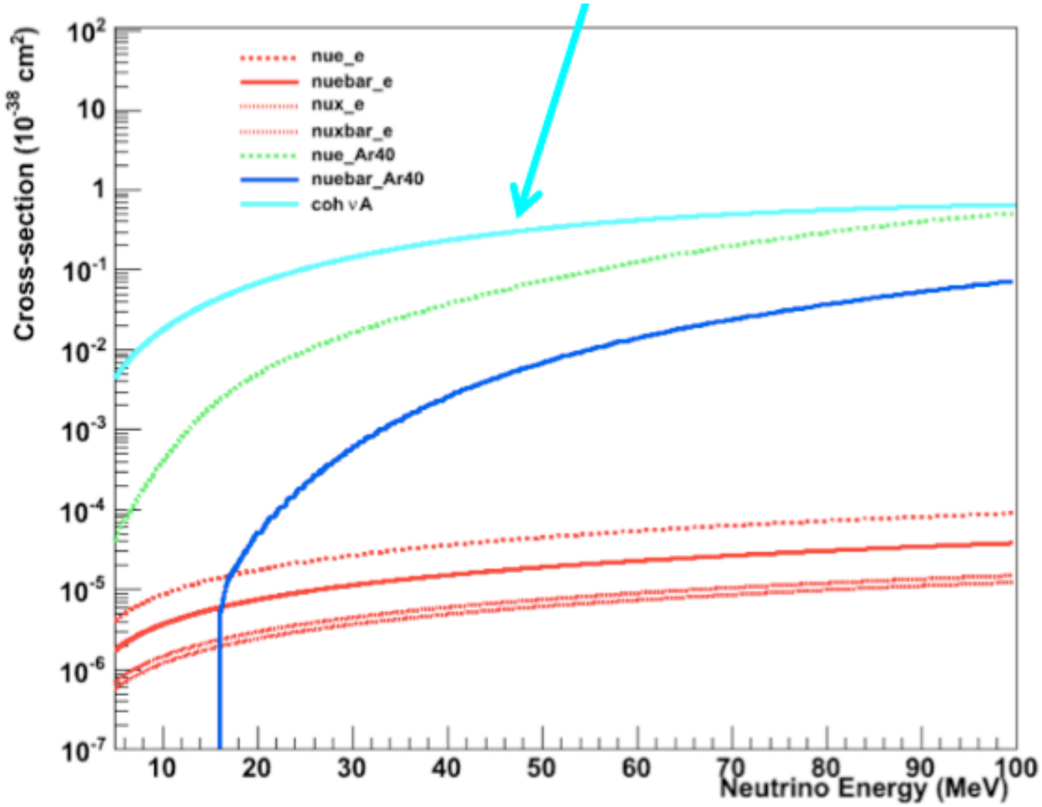
For most of the detector target nucleus, the coherence condition is fulfilled by neutrino energy of

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

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

Recoil energy is tiny

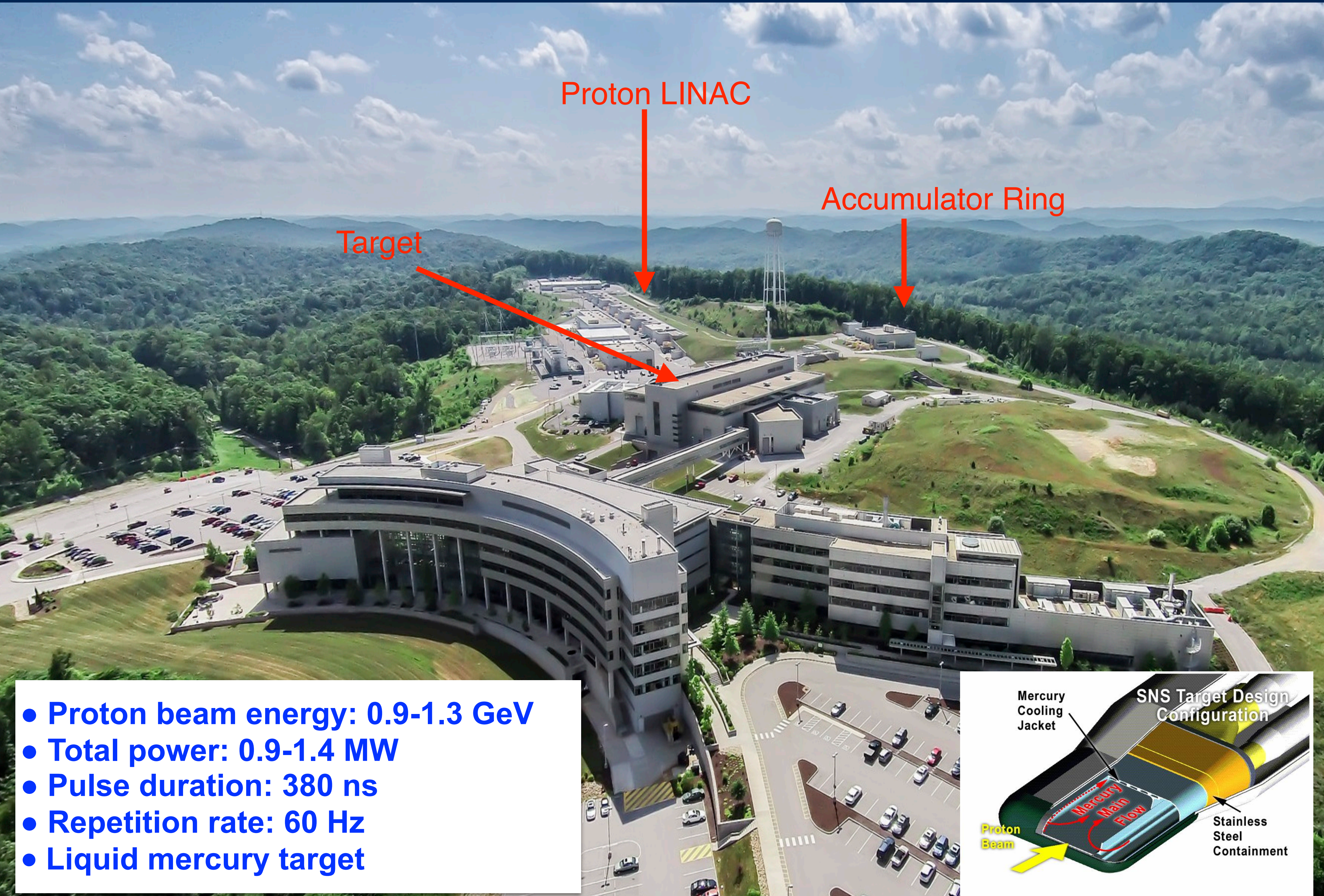
Largest cross section in the region of interest



Requires a ton-scale detector with ~10 keV energy threshold
or very intensive neutrino source

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

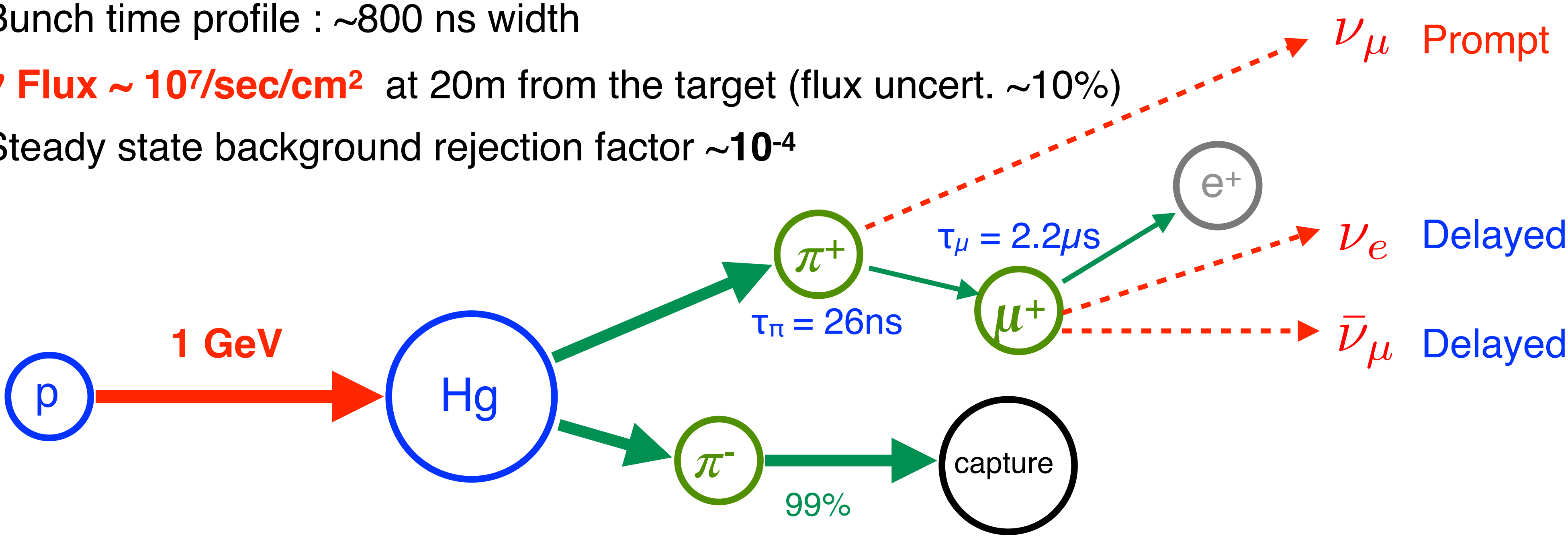
Spallation Neutron Source: Oak Ridge National Laboratory

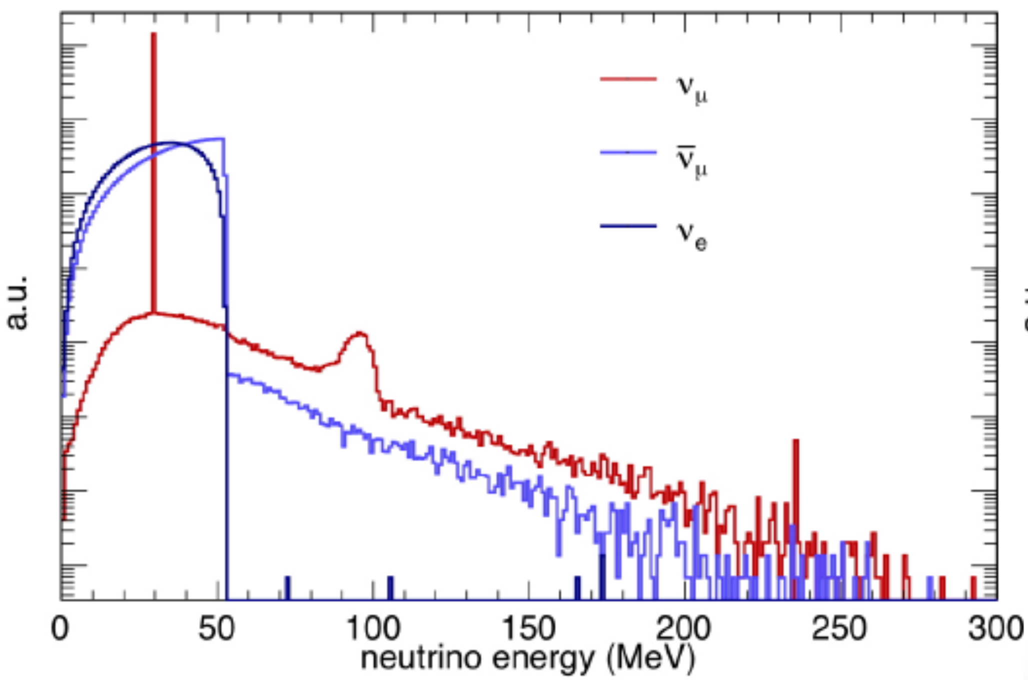


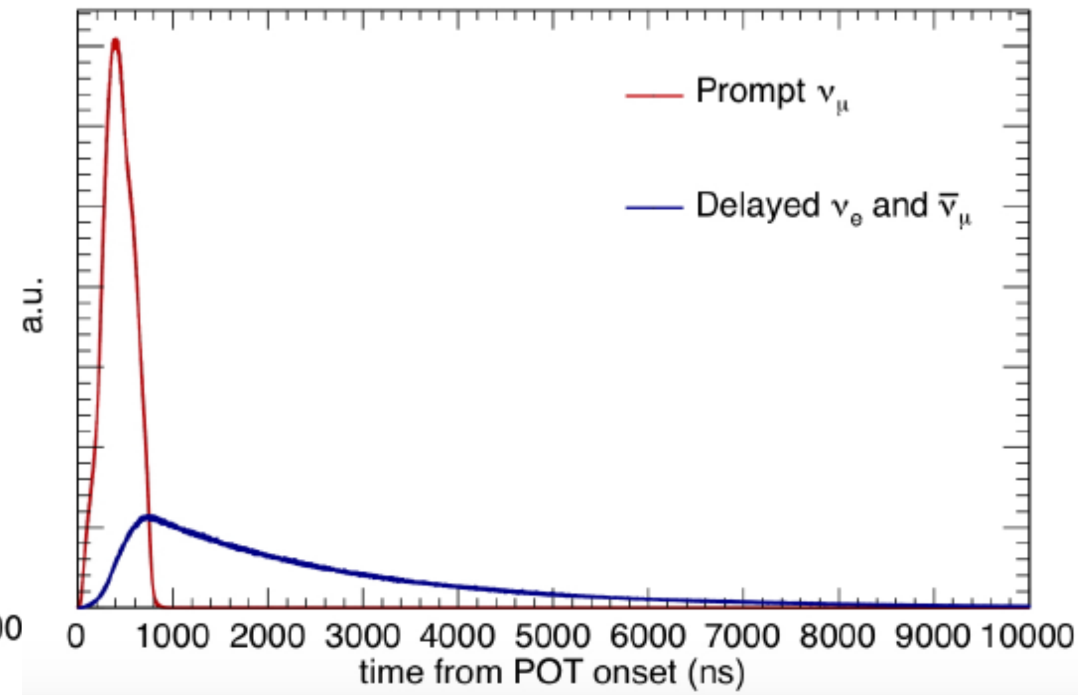
- Proton beam energy: 0.9-1.3 GeV
- Total power: 0.9-1.4 MW
- Pulse duration: 380 ns
- Repetition rate: 60 Hz
- Liquid mercury target

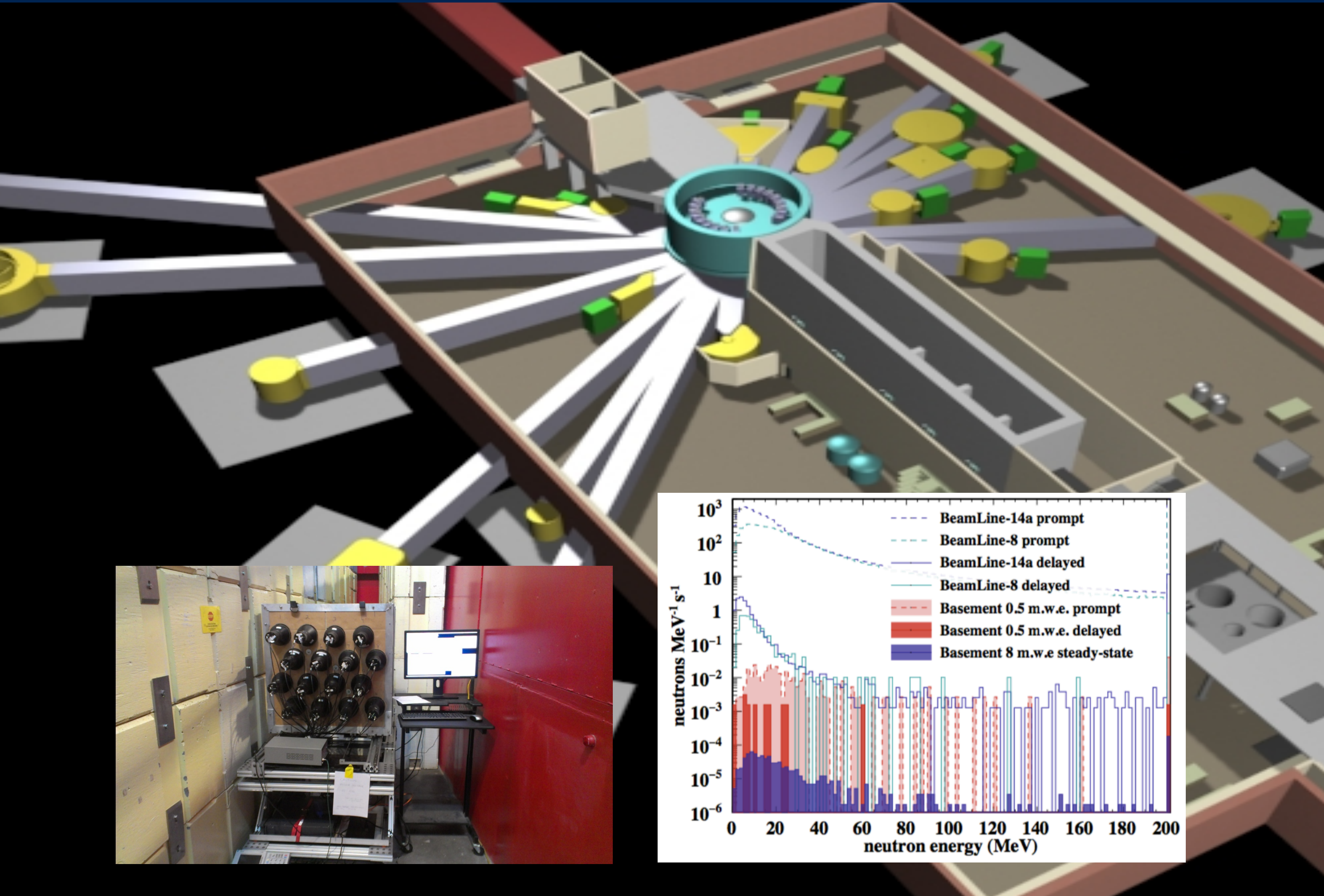
Neutrino Energy Spectrum from SNS

- Bunch time profile : ~800 ns width
- **ν Flux ~ 10^7/sec/cm^2** at 20m from the target (flux uncert. ~10%)
- Steady state background rejection factor ~$\mathbf{10^{-4}}$

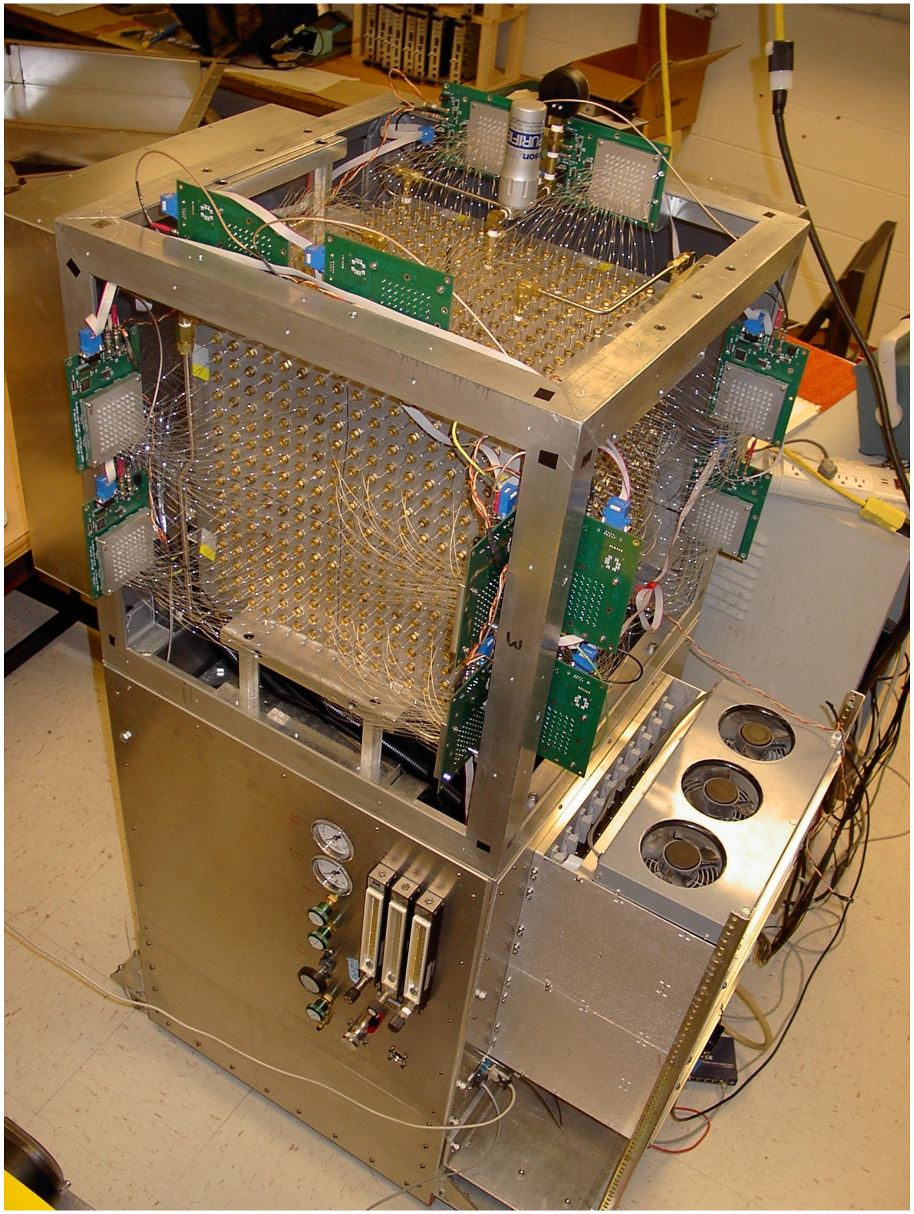


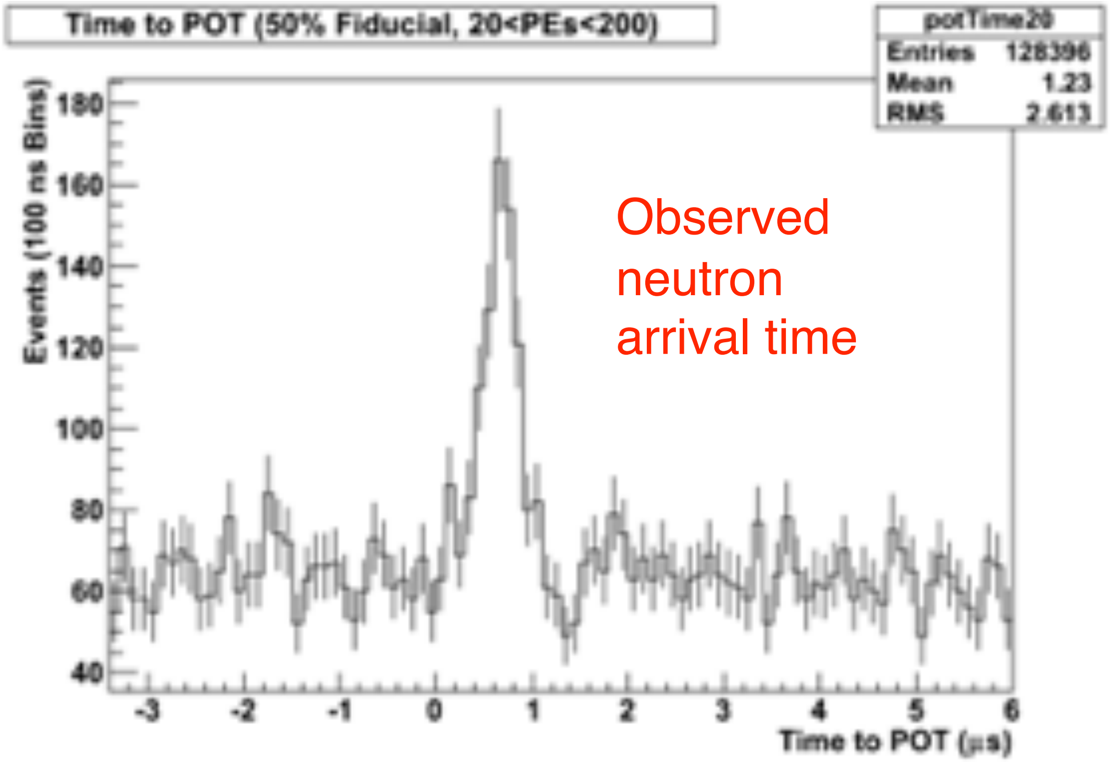


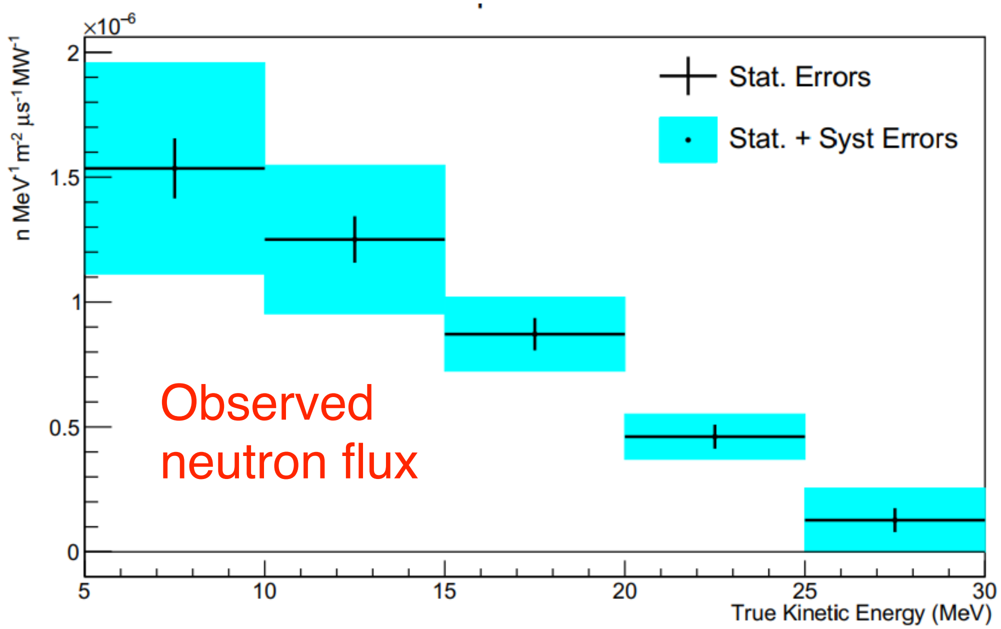



BeamLine-14a prompt
BeamLine-8 prompt
BeamLine-14a delayed
BeamLine-8 delayed
Basement 0.5 m.w.e. prompt
Basement 0.5 m.w.e. delayed
Basement 8 m.w.e steady-state
neutrons MeV^{-1} s^{-1}
10^{3}
10^{2}
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0 20 40 60 80 100 120 140 160 180 200
neutron energy (MeV)

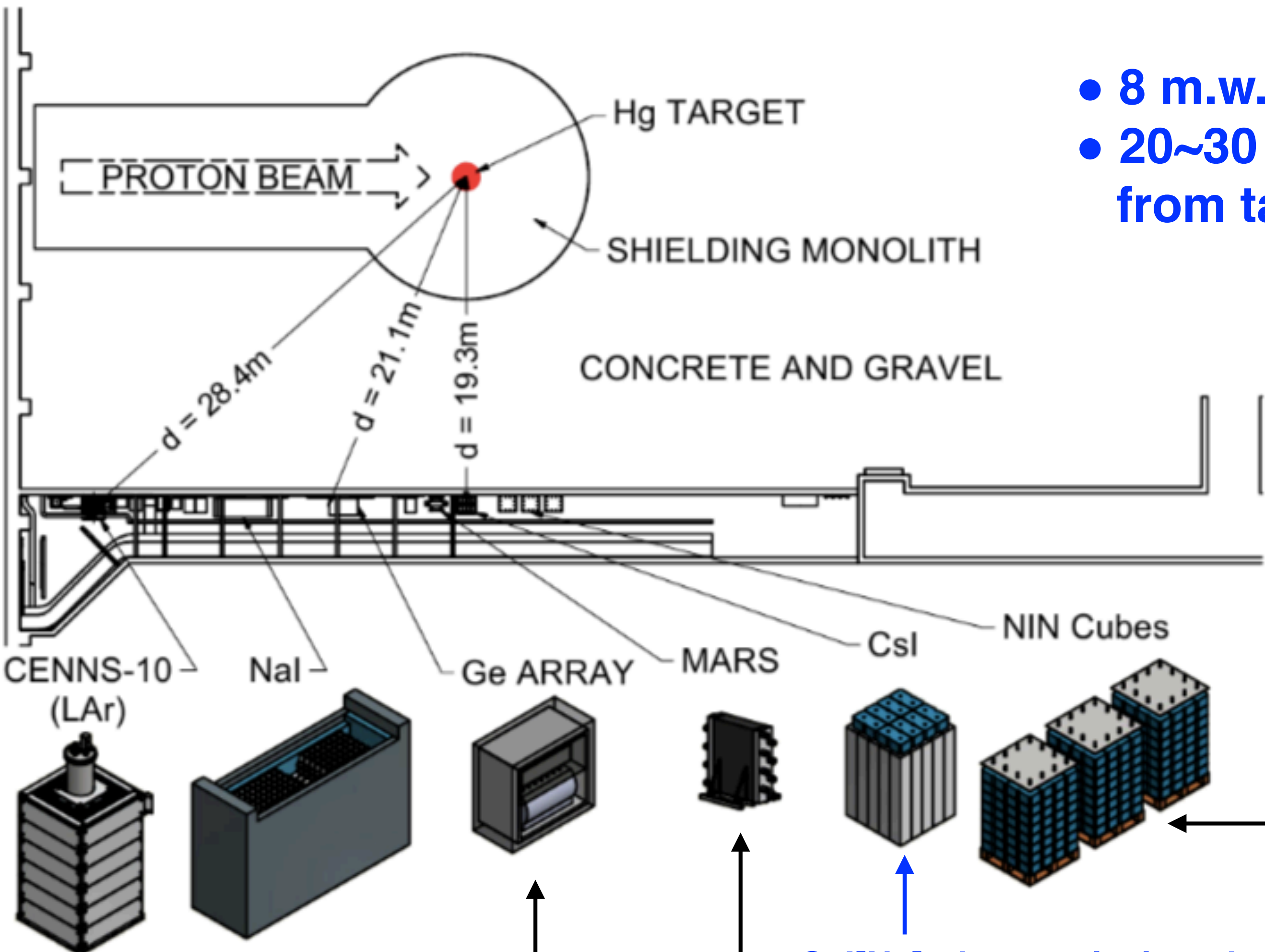
SciBath neutron detector
from Indiana University







Neutrino Alley at SNS



- **8 m.w.e vertical overburden**
- **20~30 m of gravel and concrete from target to alley**

Nubes: 4 LS cells/cube (2*2L+2*1.3L, EJ-301 –PSD capability) surrounded by lead / iron / copper

CsI[Na]: decommissioned: 14.5 kg crystal, single PMT, LY of 13.4 PE/keV, ~8 keVnr threshold

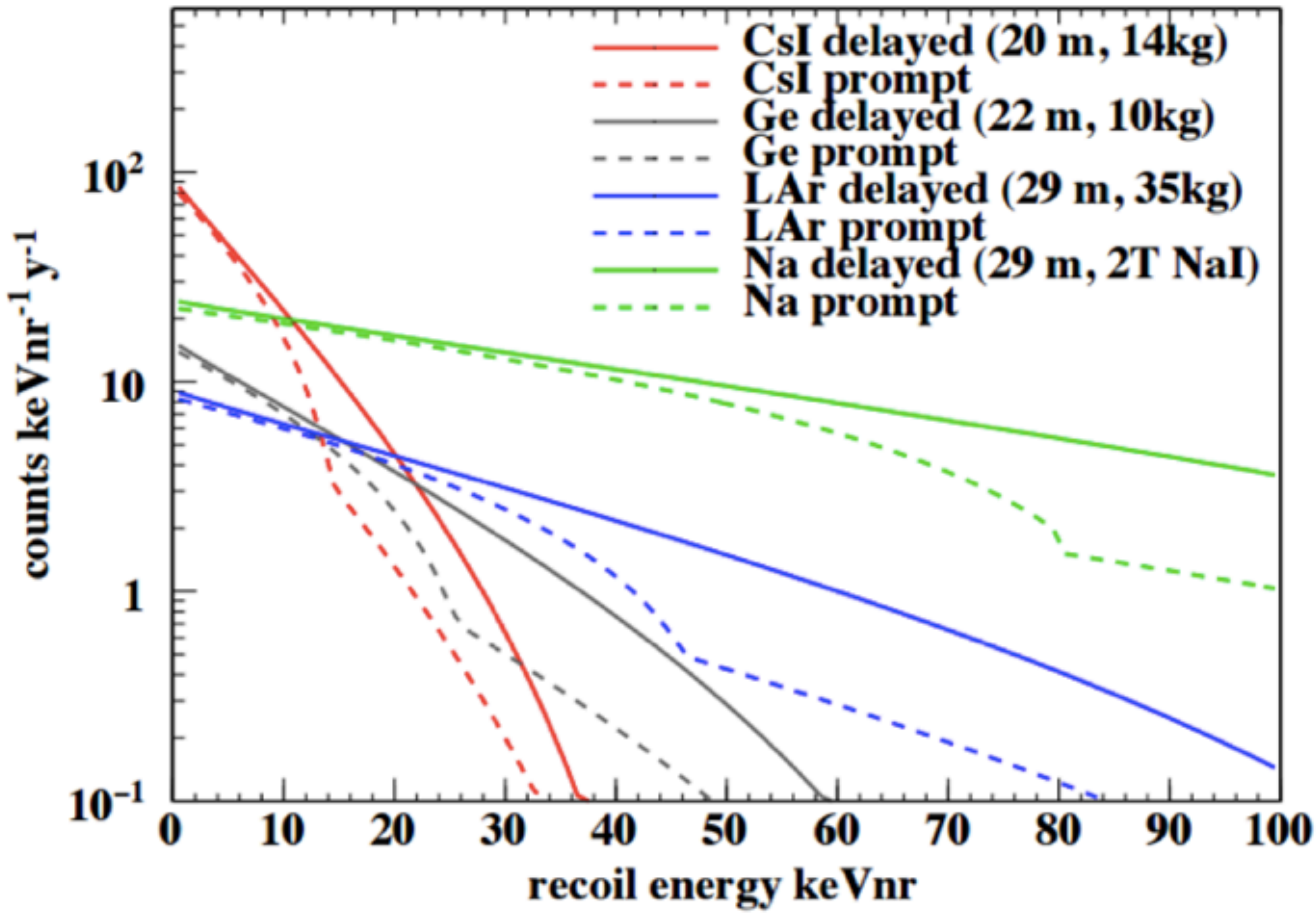
MARS, deployed: plastic scintillator interleaved with Gd coated Mylar sheets

HPGe PPC: 5 kg (cryostat ready) ➔ 16 kg, ~1keVnr threshold

NaI[Tl]: segmented 185 kg deployed, ~13 keVnr threshold

CENNS-10: 22 kg liquid argon detector, 2 PMTs readout, LY of 4.5 PE/keV, ~20 keVnr threshold

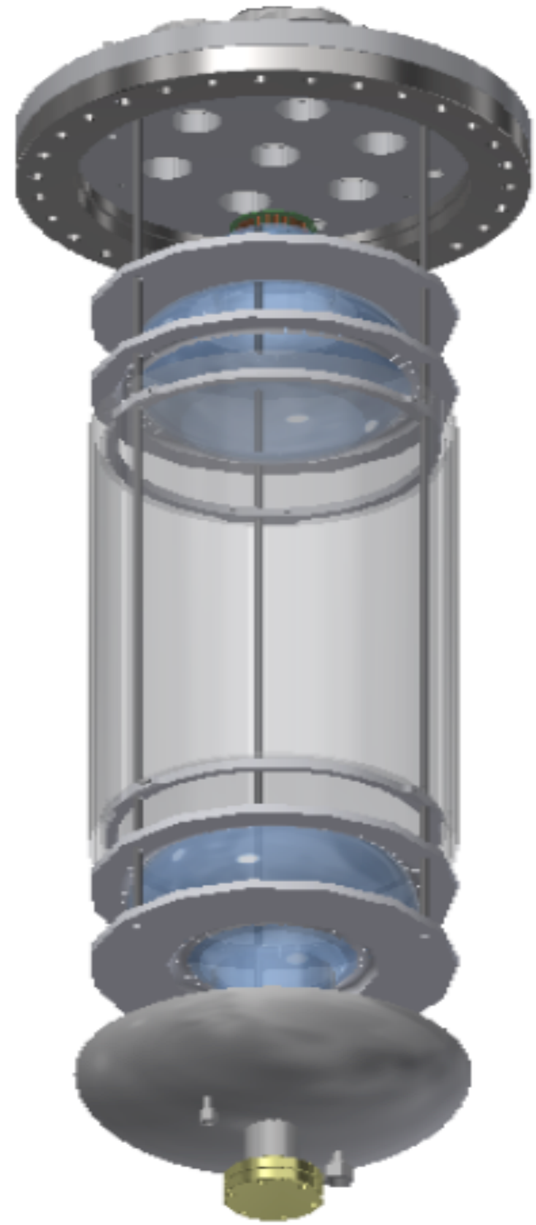
Expected CEvNS Events at SNS Neutrino Alley



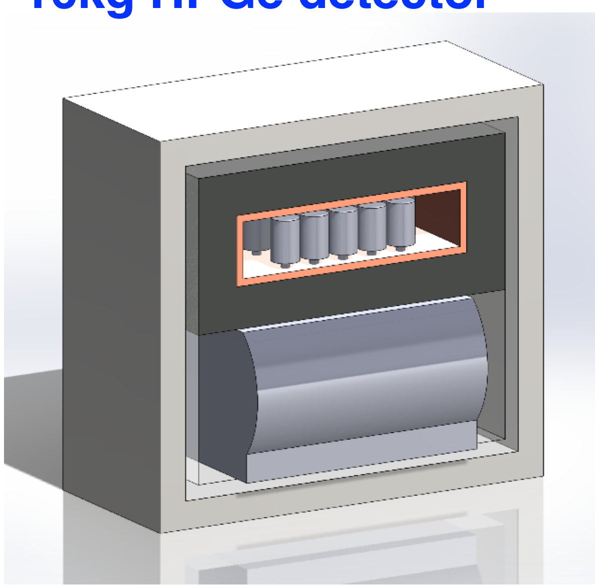
COHERENT Phase-1 Experiments

14kg CsI detector

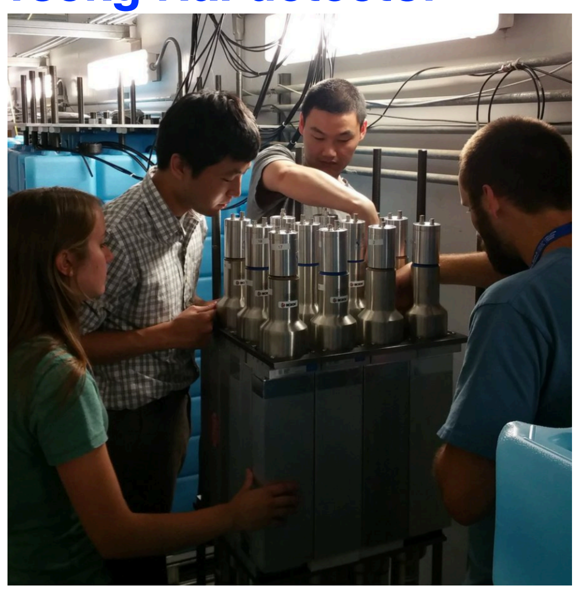
30kg LAr detector



16kg HPGe detector

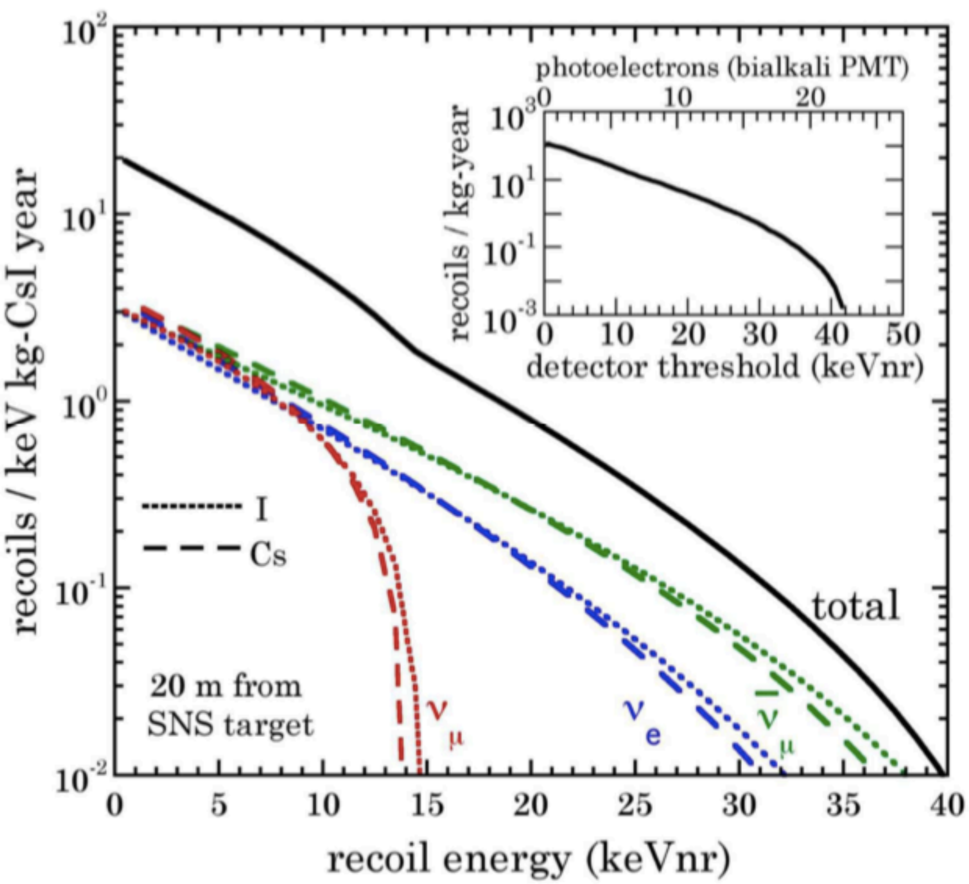


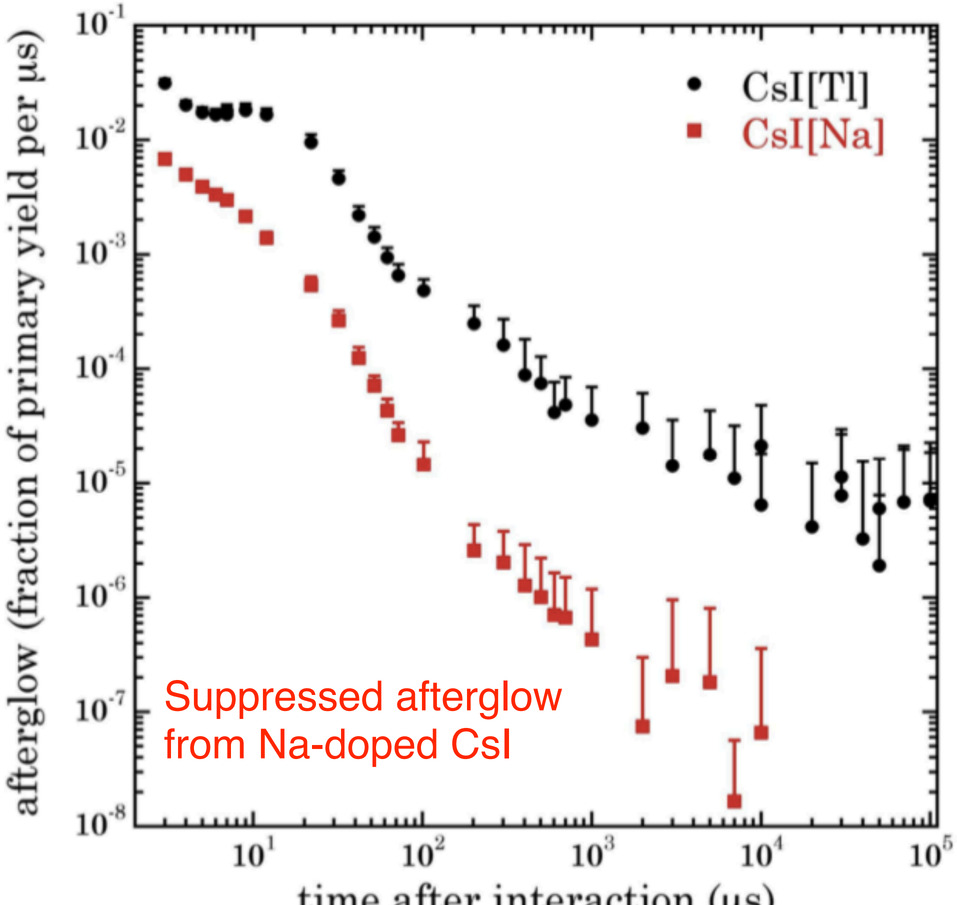
185kg NaI detector



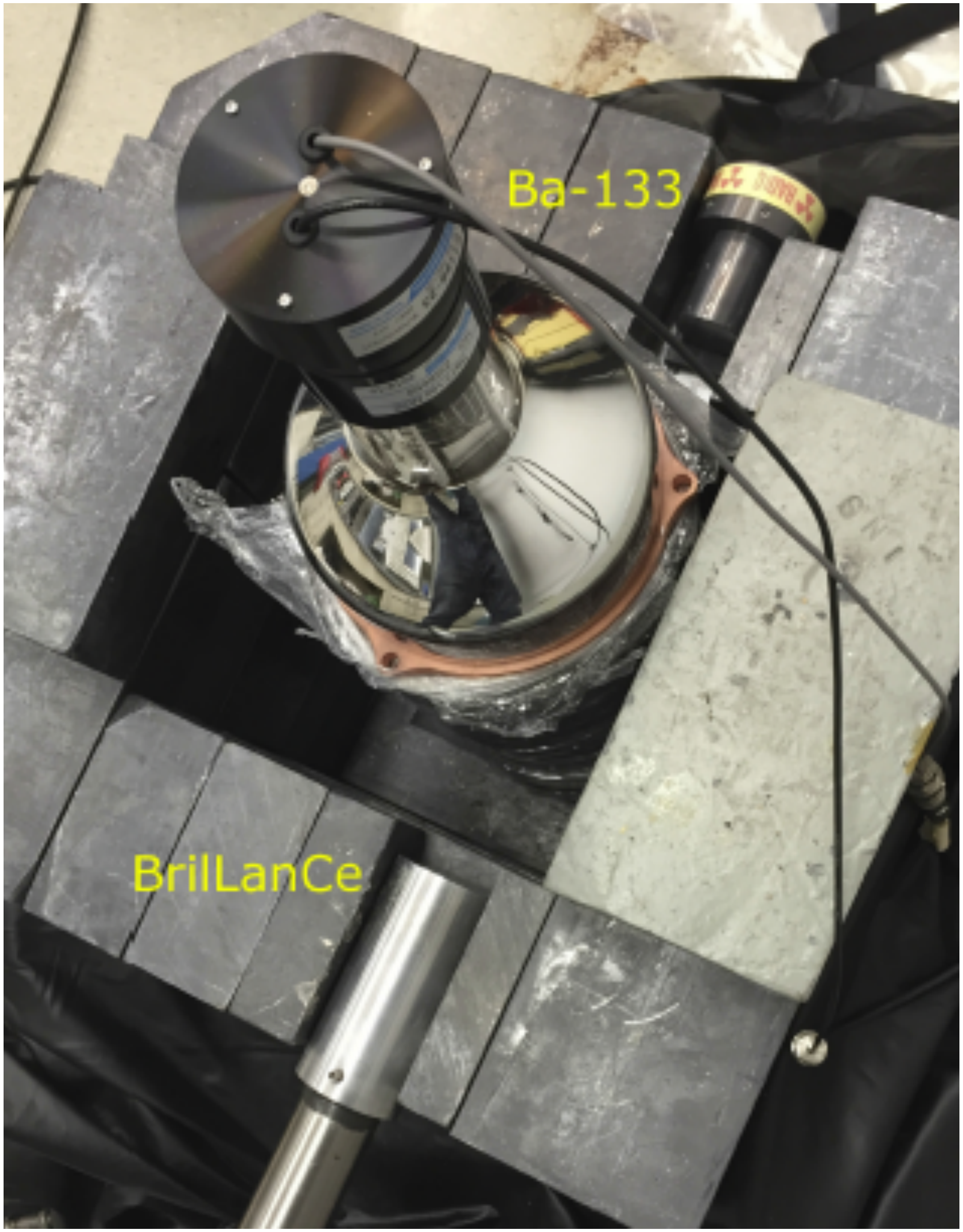
CsI Crystal Detector

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





CsI Detector in Neutrino Alley at SNS



CsI Detector in Neutrino Alley at SNS

Data Analysis:

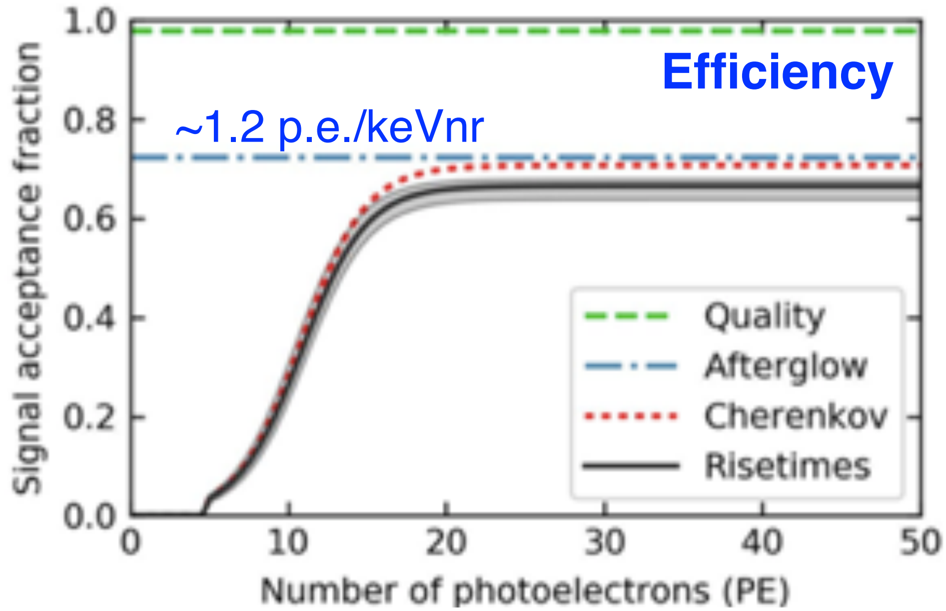
- count beam-on low-energy events (nuclear recoils)
- subtract steady state backgrounds from beam-off data
- measure/subtract beam-related backgrounds (neutrons):
- neutrino-induced neutrons ("NIN"s)

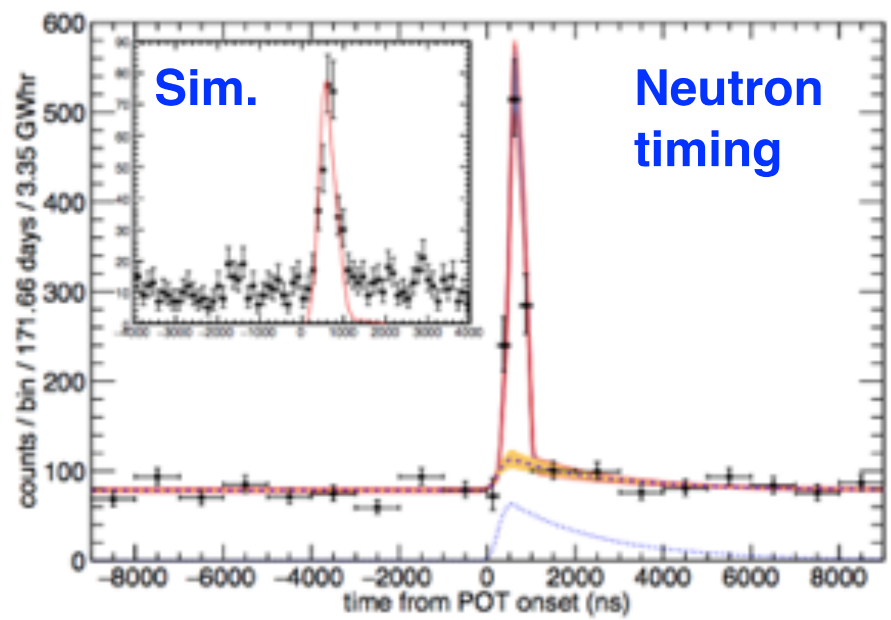
$\nu_e + {}^{208}Pb \rightarrow {}^{208}Bi^* + e^-$ CC

↘ 1n, 2n emission

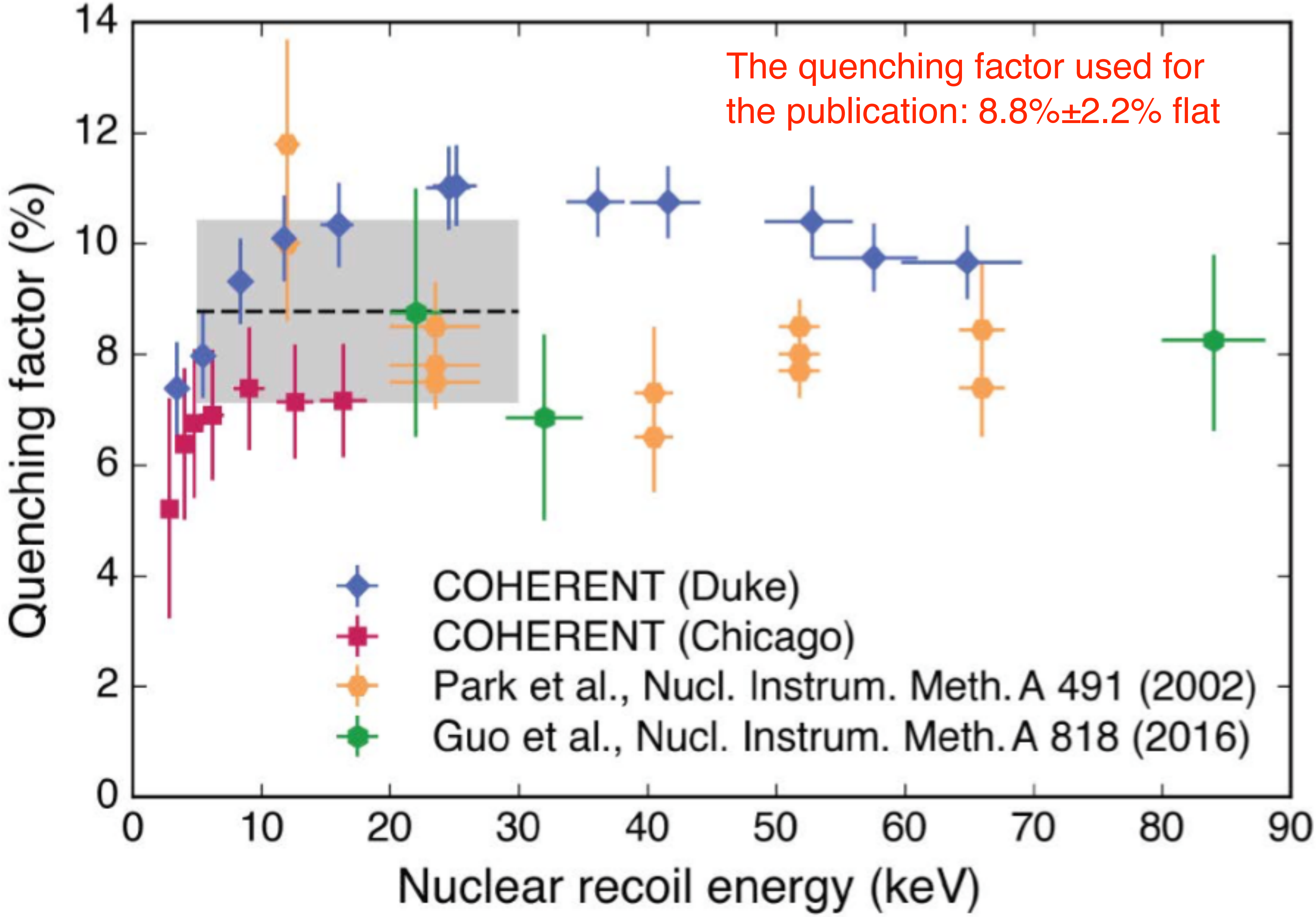
$\nu_x + {}^{208}Pb \rightarrow {}^{208}Pb^* + \nu_x$ NC

↘ 1n, 2n, γ emission



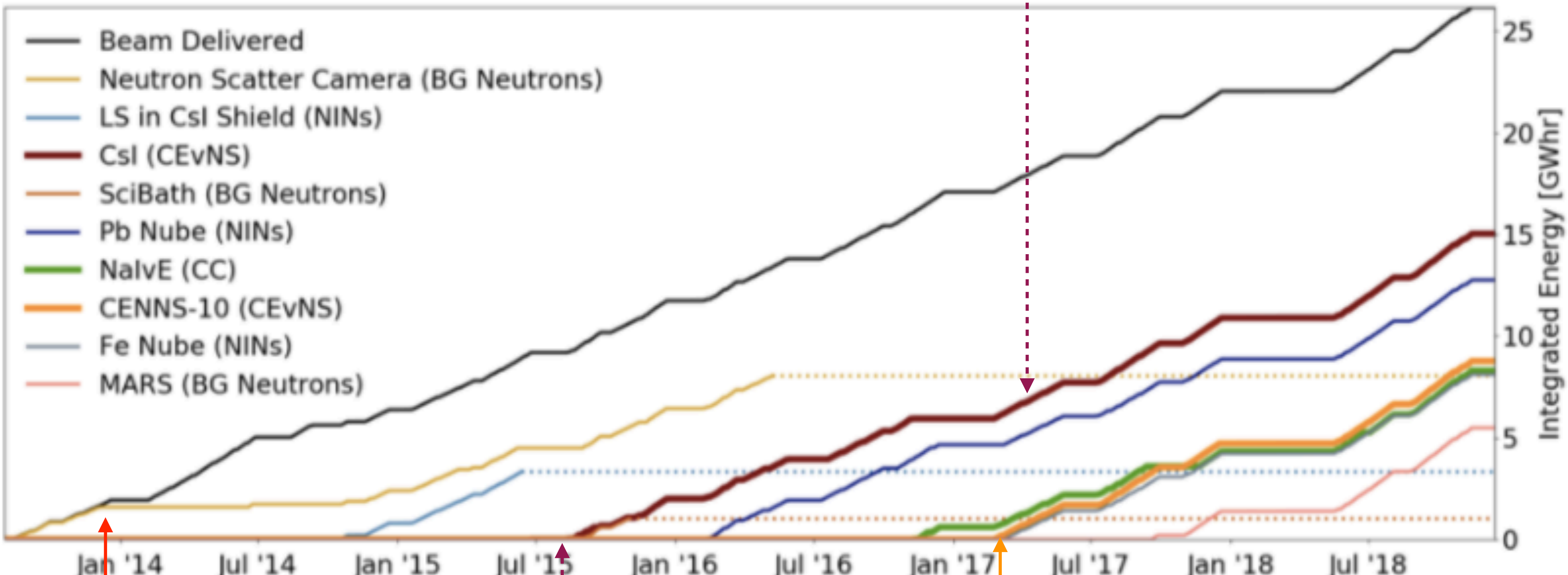


CsI Detector Quenching Factor



COHERENT Data Collection

1.76 x10^{23} POT delivered
to CsI (7.48 GWhr)

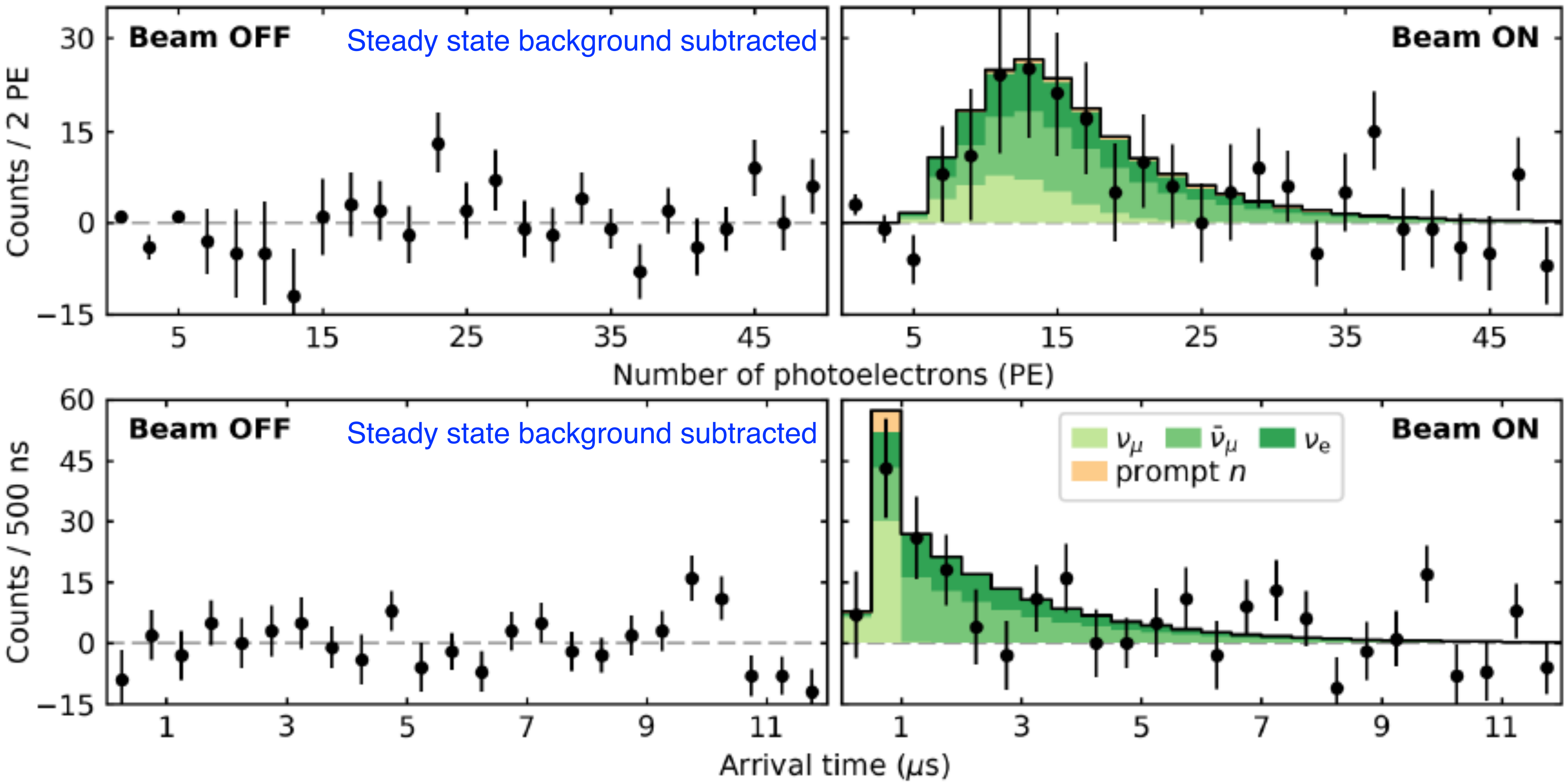


CENNS-10 (LAr) data taking

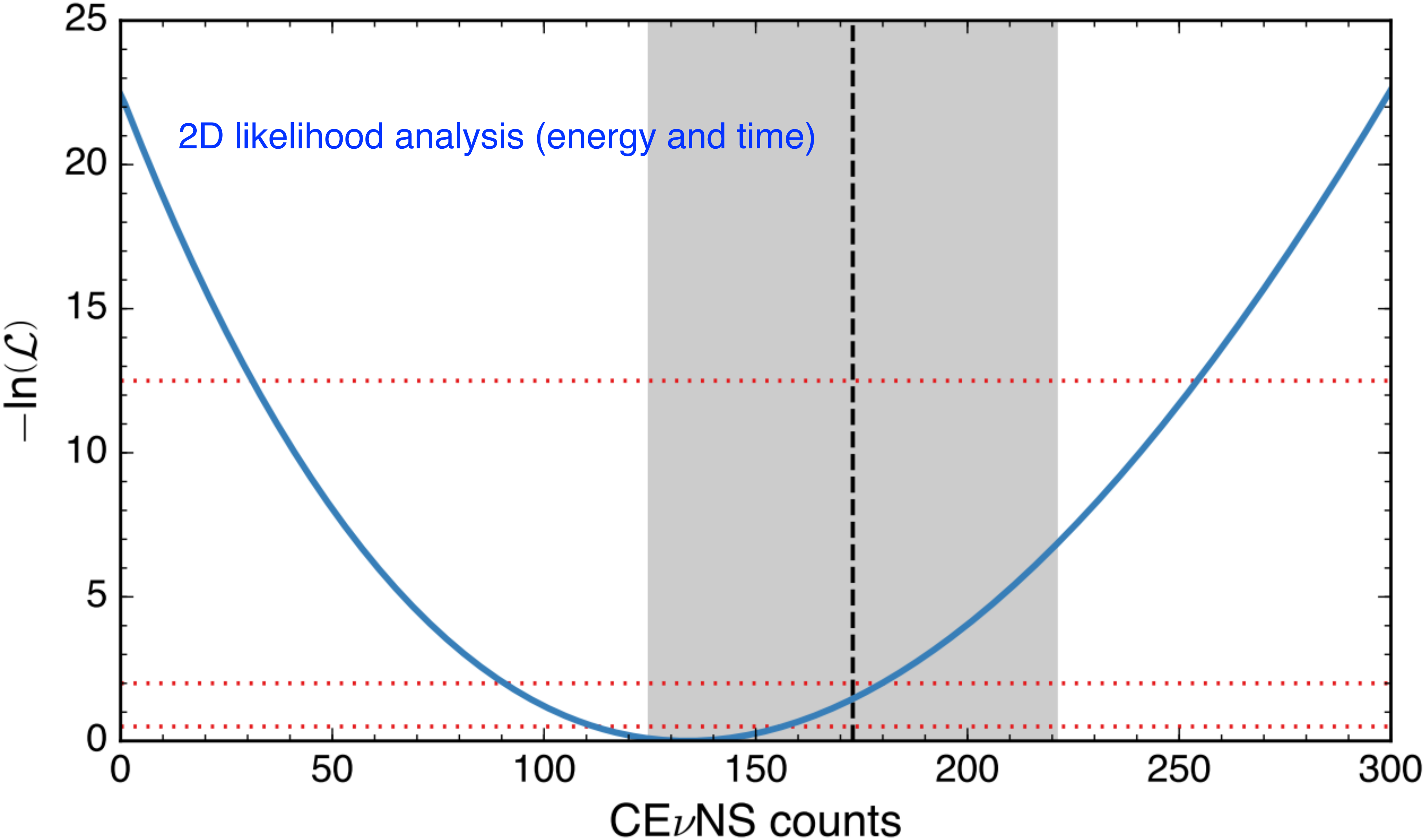
SciBath neutron
detector operation

CsI data taking started

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



- Best fit of data: 134 ± 22 CEvNS events (SM prediction: 173 ± 48 events)
- No CEvNS rejected at 6.7σ (consistent with SM within 1σ)



Science REPORTS

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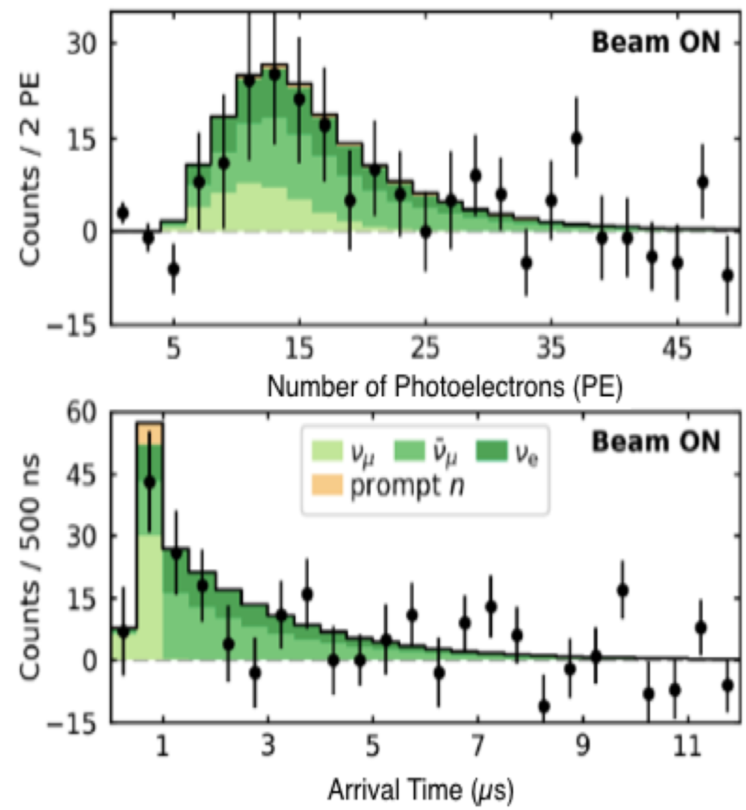
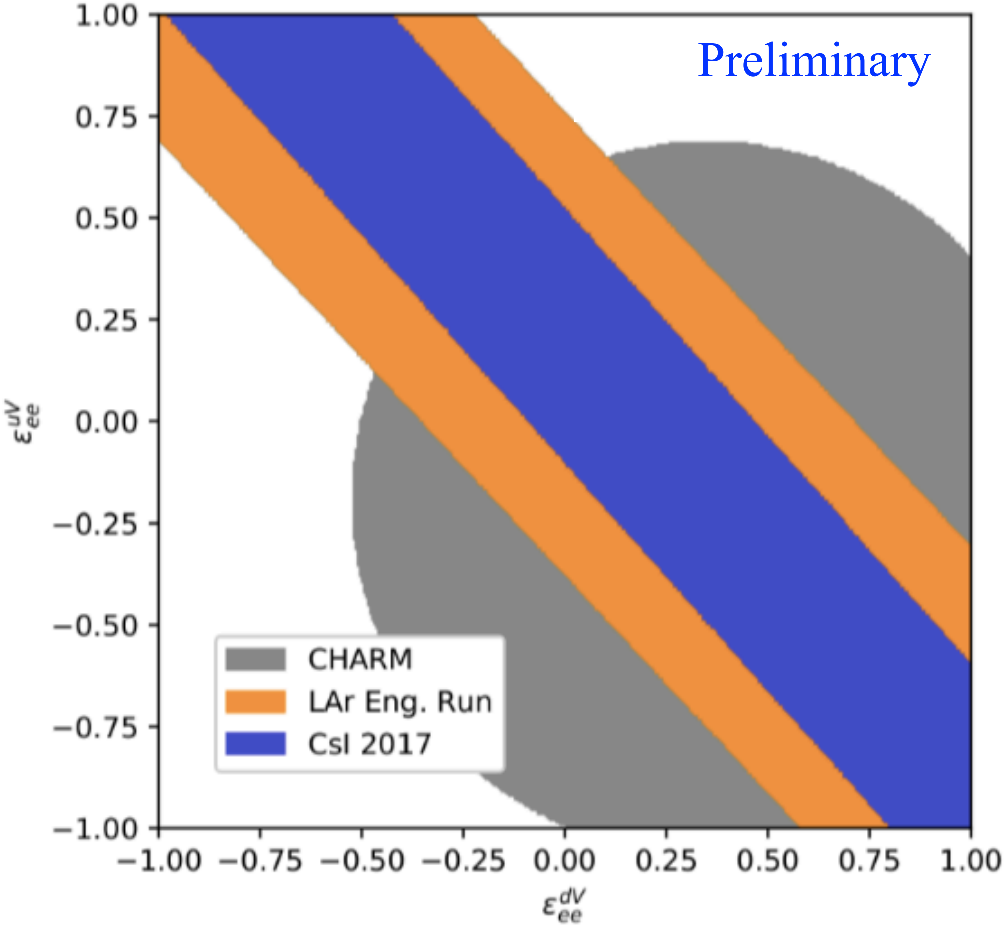
Observation of coherent elastic neutrino-nucleus scattering

D. Akimov,[1,2] J. B. Albert,[3] P. An,[4] C. Awe,[4,5] P. S. Barbeau,[4,5] B. Becker,[6] V. Belov,[1,2] A. Brown,[4,7] A. Bolozdynya,[2] B. Cabrera-Palmer,[8] M. Cervantes,[5] J. I. Collar,[9]* R. J. Cooper,[10] R. L. Cooper,[11,12] C. Cuesta,[13]† D. J. Dean,[14] J. A. Detwiler,[13] A. Eberhardt,[13] Y. Efremenko,[6,14] S. R. Elliott,[12] E. M. Erkela,[13] L. Fabris,[14] M. Febbraro,[14] N. E. Fields,[9]‡ W. Fox,[3] Z. Fu,[13] A. Galindo-Uribarri,[14] M. P. Green,[4,14,15] M. Hai,[9]§ M. R. Heath,[3] S. Hedges,[4,5] D. Hornback,[14] T. W. Hossbach,[16] E. B. Iverson,[14] L. J. Kaufman,[3]|| S. Ki,[4,5] S. R. Klein,[10] A. Khromov,[2] A. Konovalov,[1,2,17] M. Kremer,[4] A. Kumpan,[2] C. Leadbetter,[4] L. Li,[4,5] W. Lu,[14] K. Mann,[4,15] D. M. Markoff,[4,7] K. Miller,[4,5] H. Moreno,[11] P. E. Mueller,[14] J. Newby,[14] J. L. Orrell,[16] C. T. Overman,[16] D. S. Parno,[13]¶ S. Penttila,[14] G. Perumpilly,[9] H. Ray,[18] J. Raybern,[5] D. Reyna,[8] G. C. Rich,[4,14,19] D. Rimal,[18] D. Rudik,[1,2] K. Scholberg,[5] B. J. Scholz,[9] G. Sinev,[5] W. M. Snow,[3] V. Sosnovtsev,[2] A. Shakirov,[2] S. Suchyta,[10] B. Suh,[4,5,14] R. Tayloe,[3] R. T. Thornton,[3] I. Tolstukhin,[3] J. Vanderwerp,[3] R. L. Varner,[14] C. J. Virtue,[20] Z. Wan,[4] J. Yoo,[21] C.-H. Yu,[14] A. Zawada,[4] J. Zettlemoyer,[3] A. M. Zderic,[13] COHERENT Collaboration#

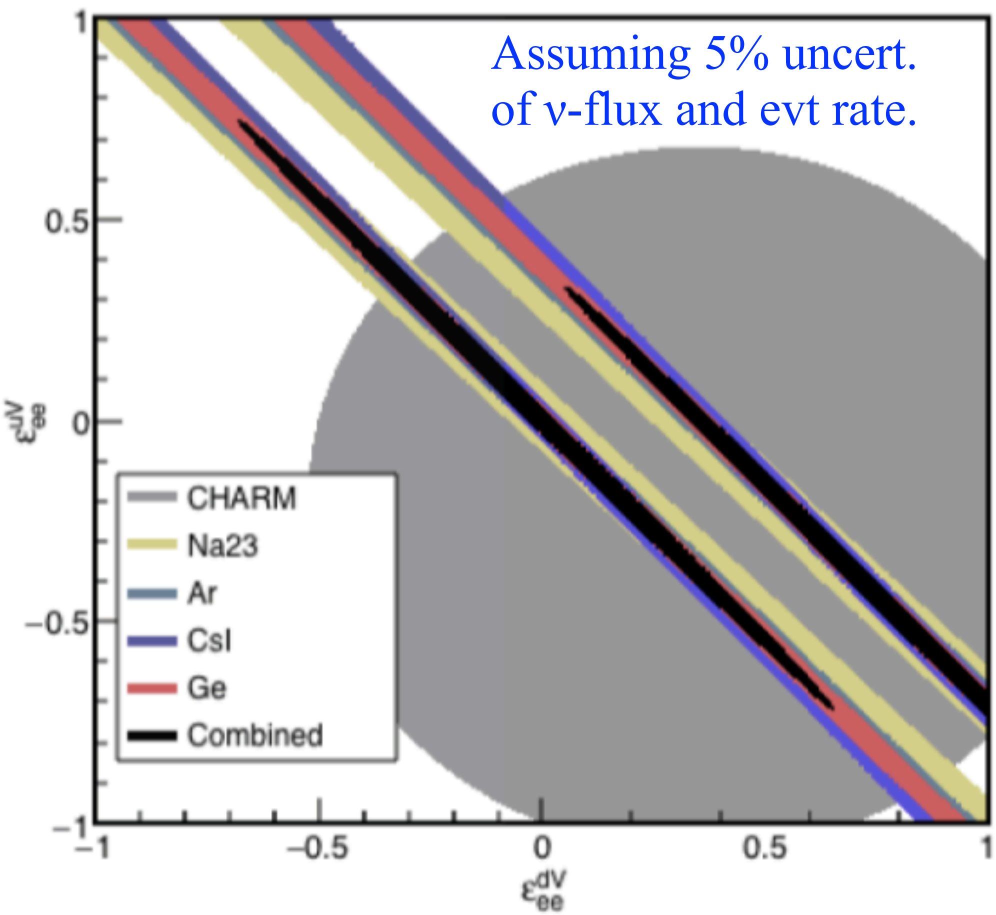


Constraint on Non-Standard Neutrino Interactions

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

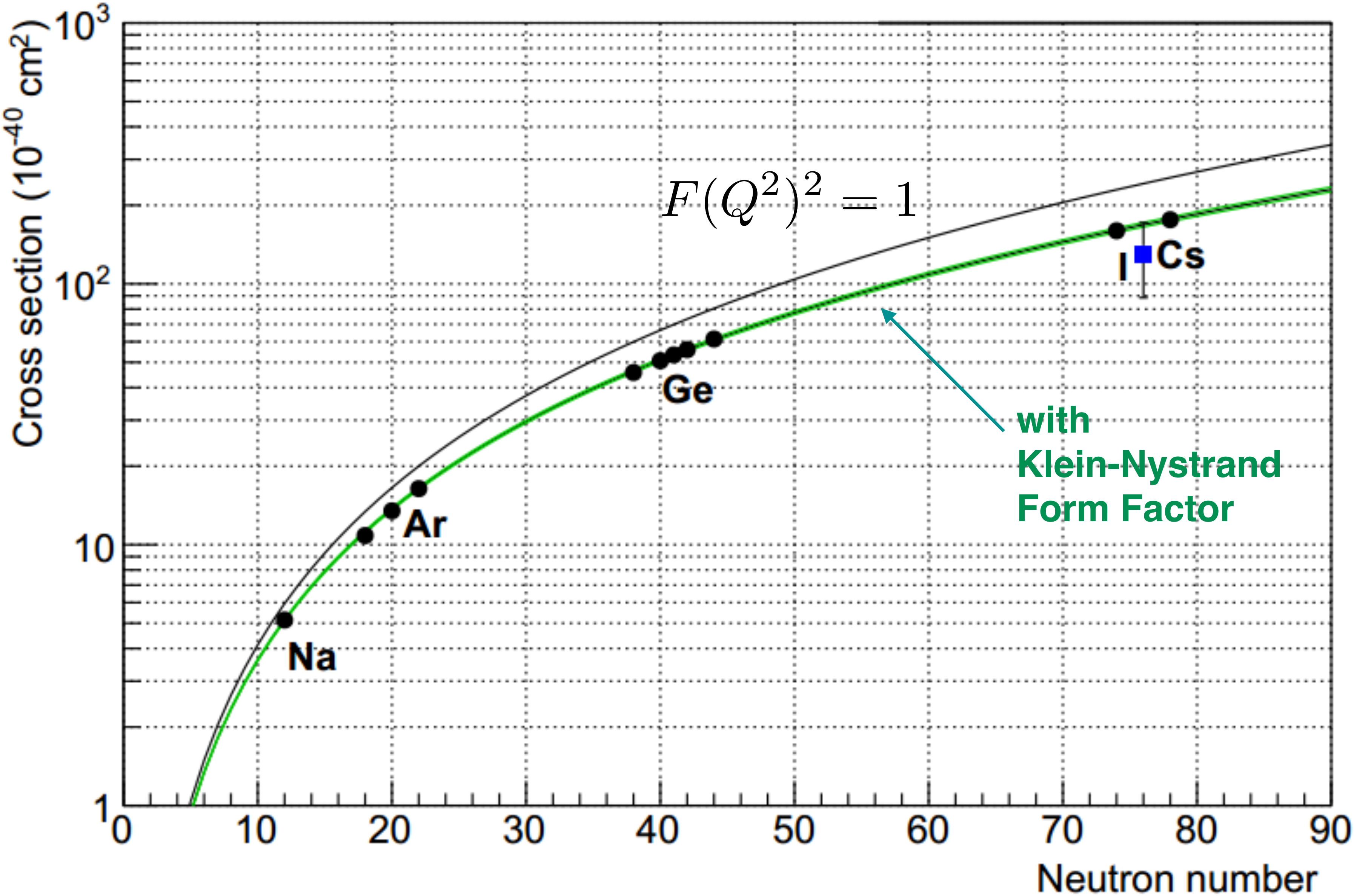


arXiv:1803.09183 by COHERENT



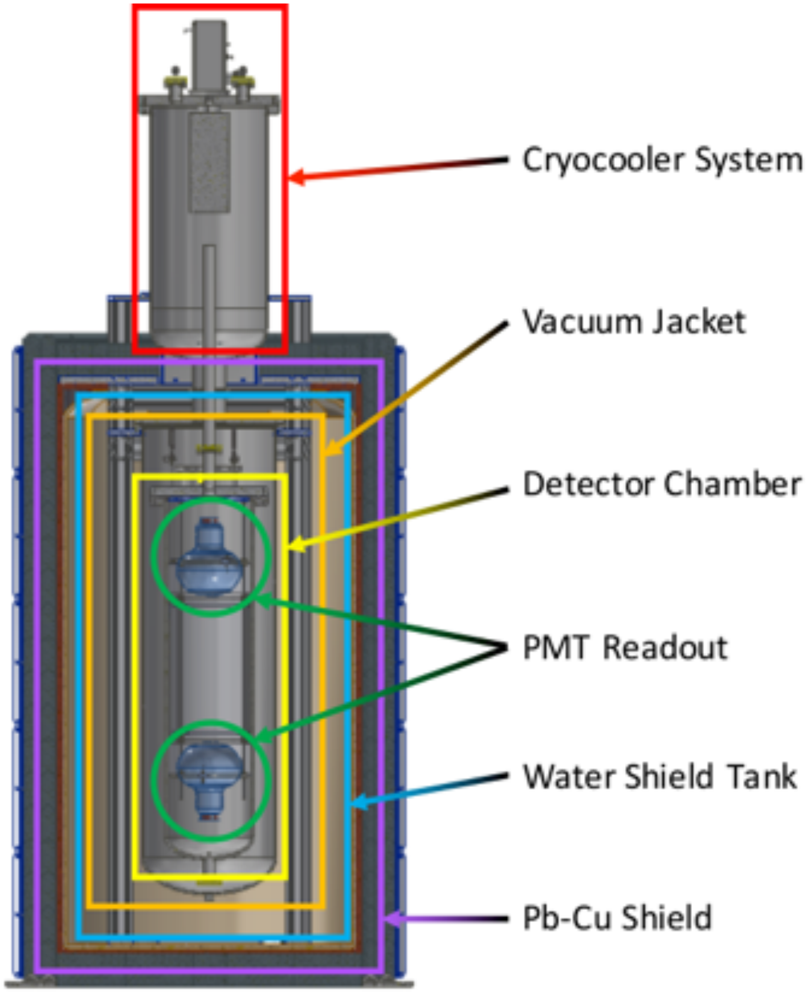
CEvNS Cross Section and Nuclear Form Factors

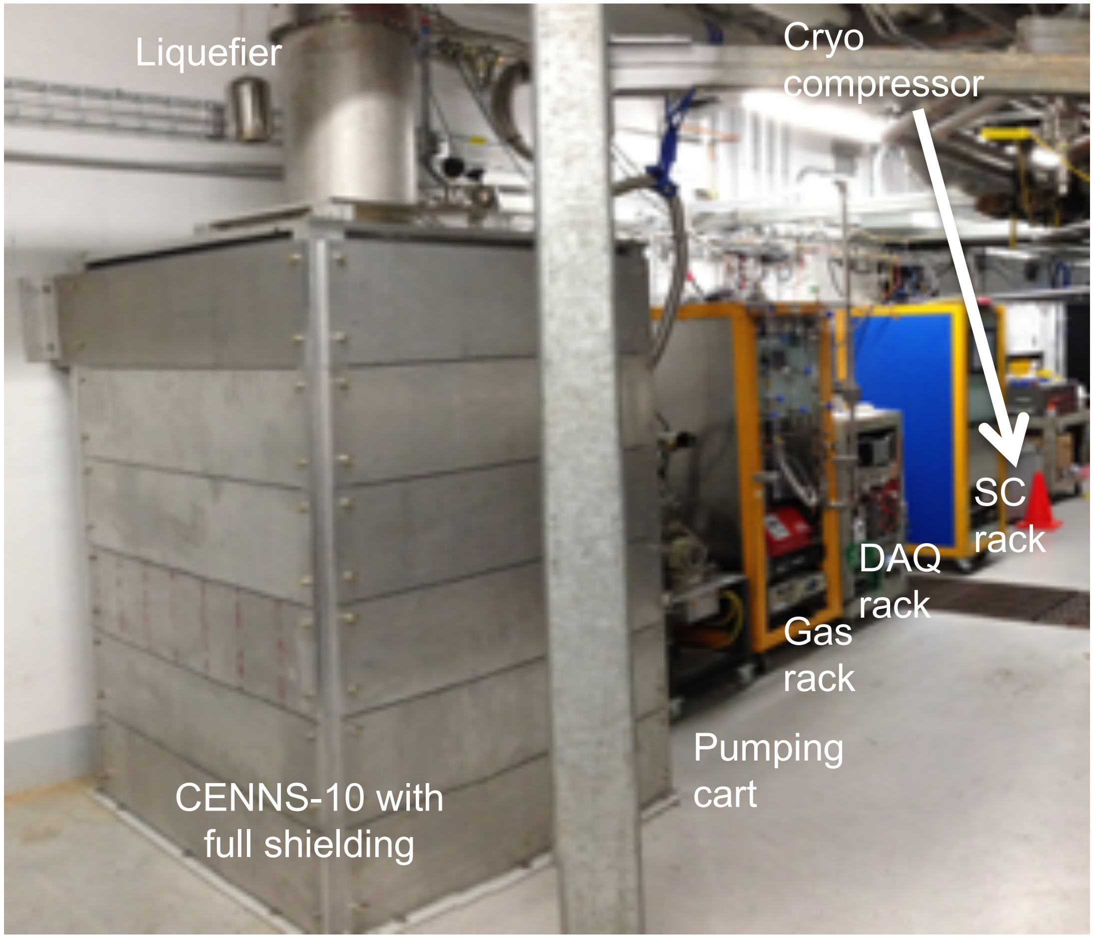
$$\frac{d\sigma}{dE} = \frac{G_F^2}{4\pi}[(1-4\sin^2\theta_w)Z - \boxed{(A-Z)}]^2 M\left(1-\frac{ME}{2E_\nu^2}\right)\boxed{F(Q^2)^2}$$



CENNS-10 (LAr)

- Built at Fermilab in 2013~2015 and moved to ORNL in fall 2016 (tested at Indiana Univ.)
- 22 kg LAr fiducial volume viewed by 8”PMTs (TPB-coated PMTs and teflon walls)
- Energy threshold: ~ 20keVnr
- Pb/Cu/H_2O shielding for passive background reduction
- Using beam trigger for active background shielding
- Expect ≈140 CEvNS events/SNS-year

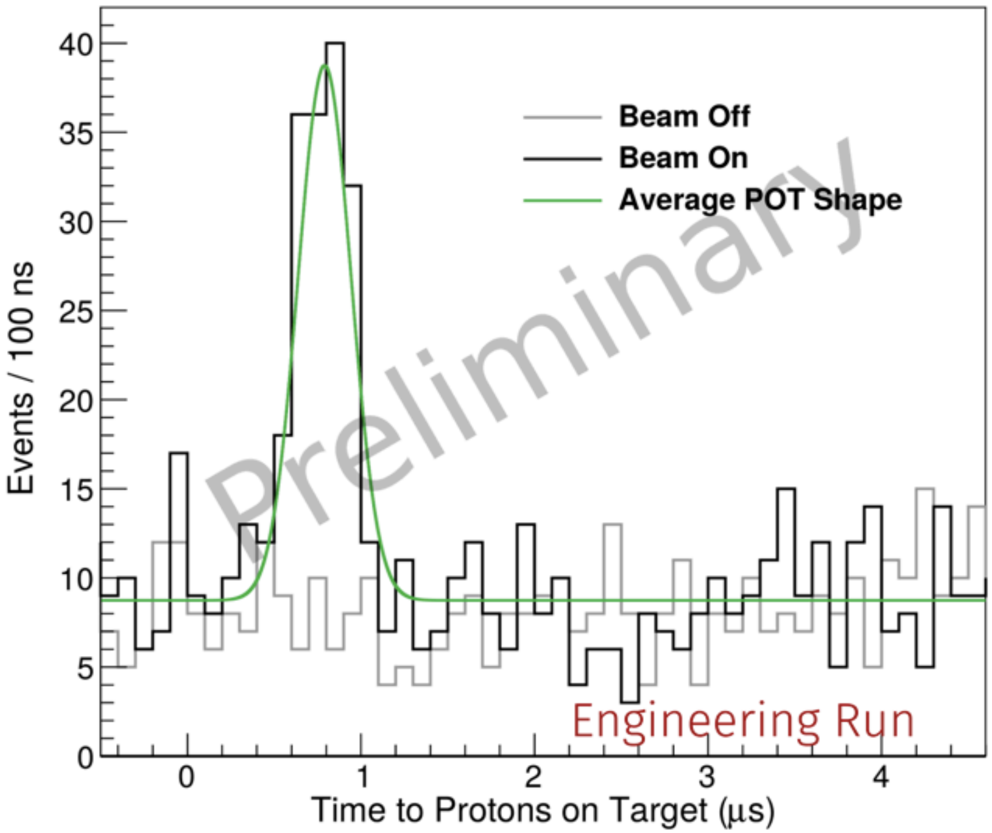


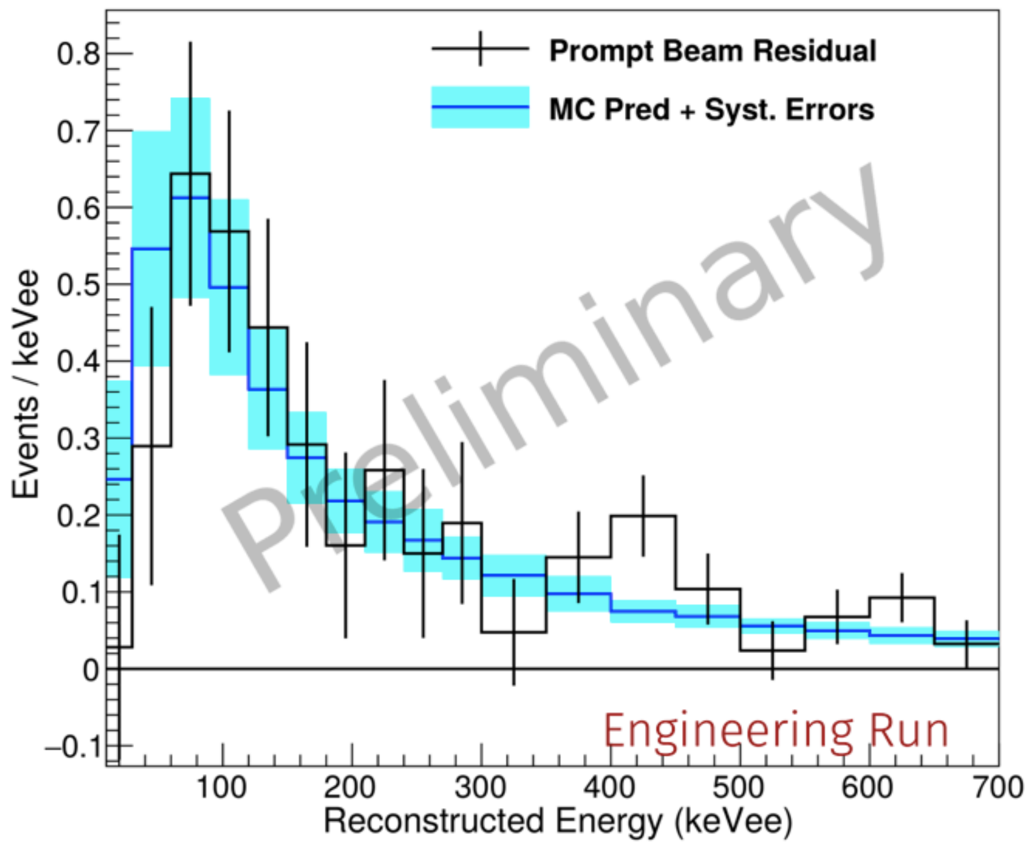


CENNS-10 (LAr): Engineering Run

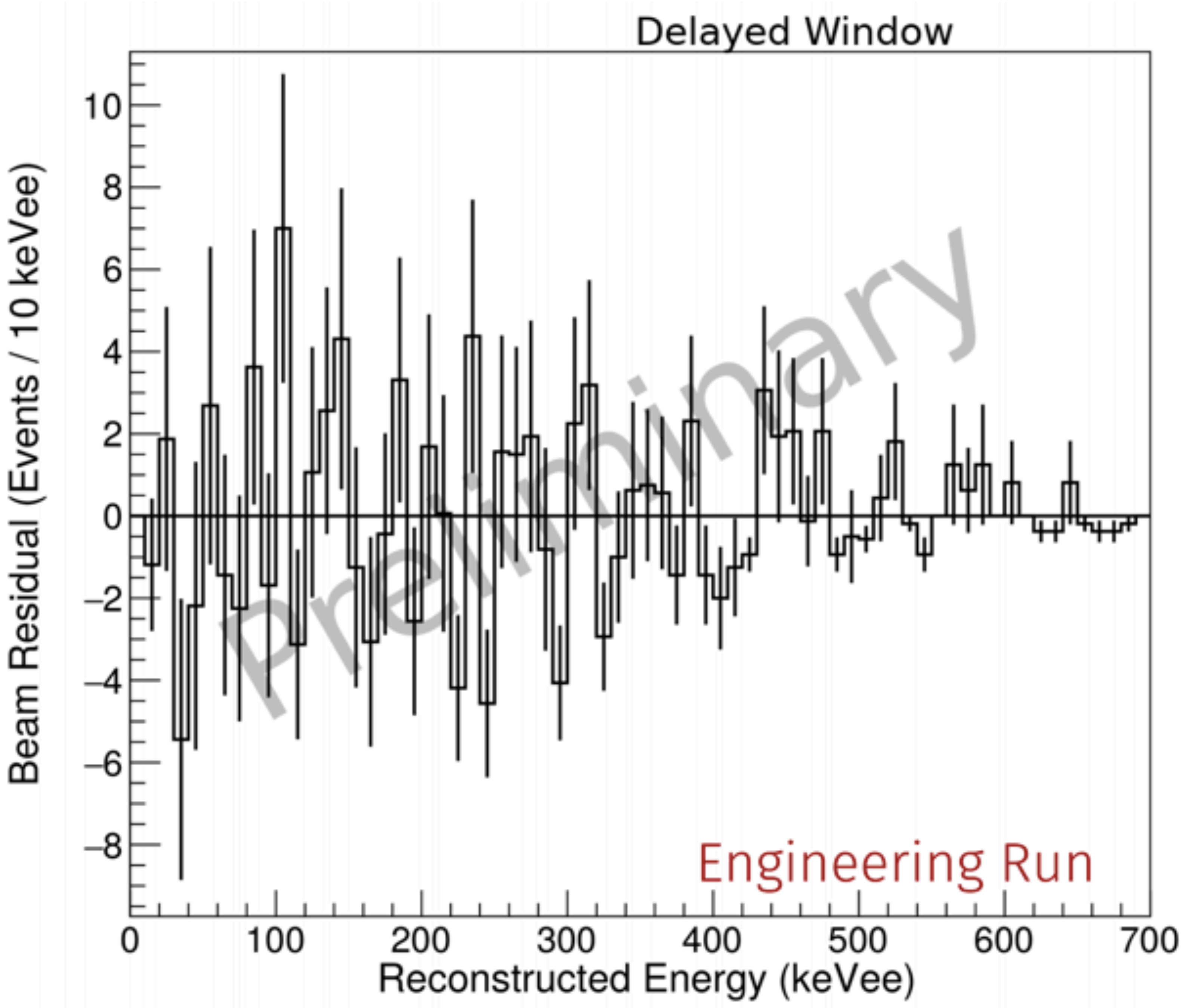
Results from CENNS-10 Engineering run (Preliminary):

- Event excess in time with beam
  ➔ Consistent with expected prompt beam-related neutron rate
- No event excess observed in delayed beam time window (0.5 events expected)
  ➔ Limit on delayed neutron backgrounds
  ➔ Limit on CEvNS cross section





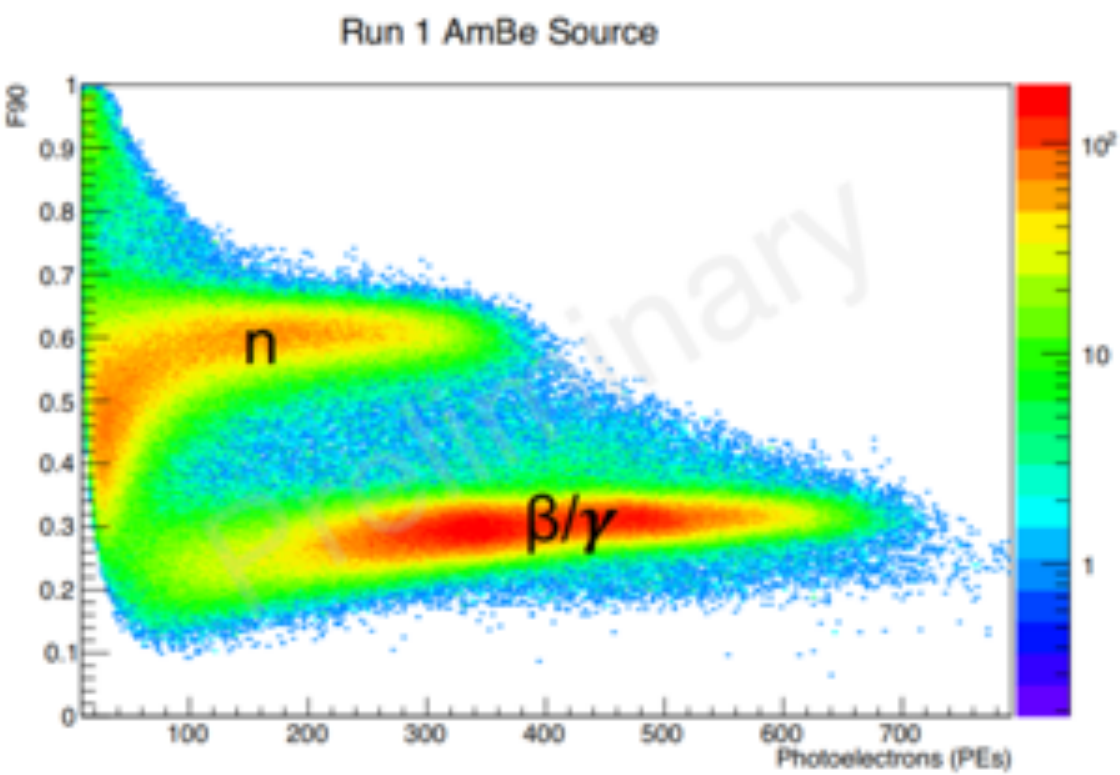
CENNS-10 (LAr): Engineering Run

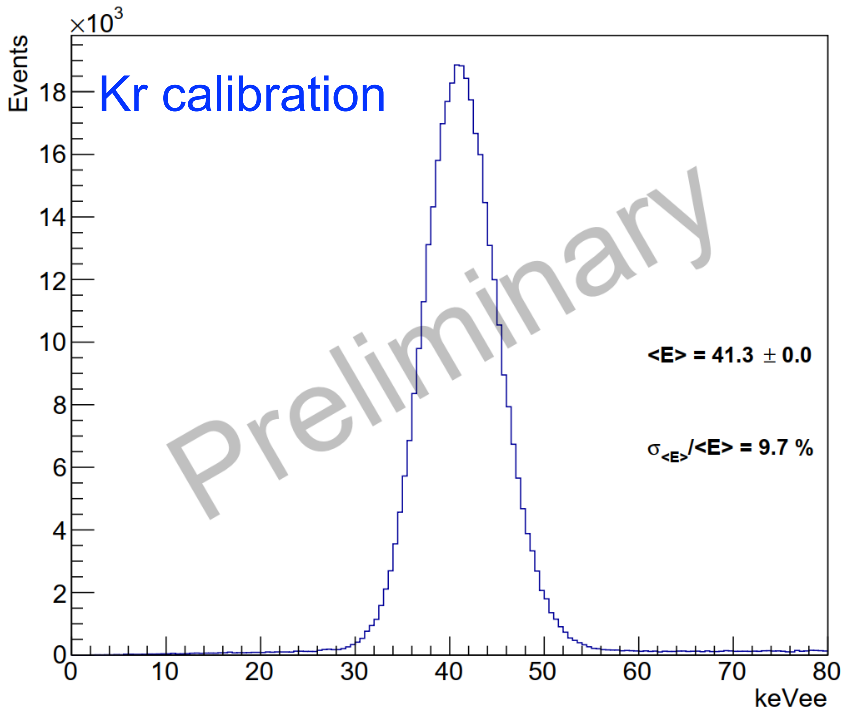


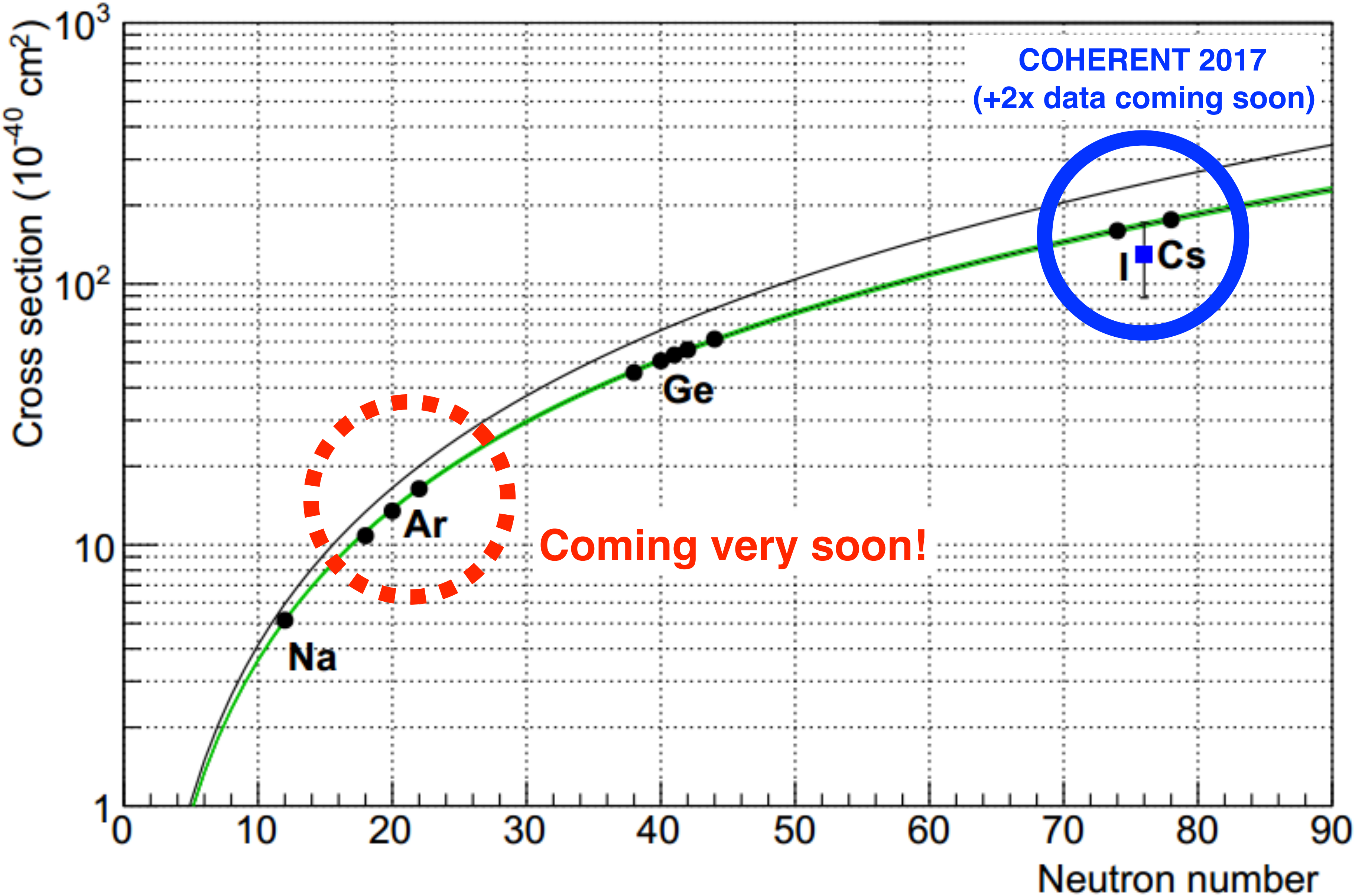
CENNS-10 (LAr): CEvNS Physics Run

July 2017 to 2019 (current) data: CEvNS physics run

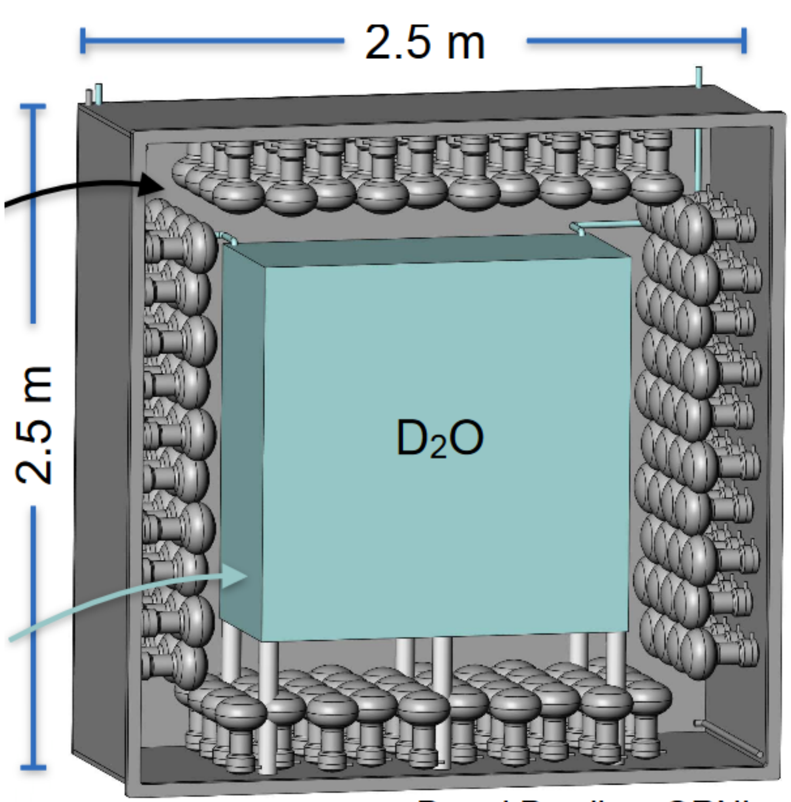
- Light yield: ~4 PE/keV (Kr calibration)
- PSD, energy resolution and threshold appears good to test CEvNS in LAr
- Unblinding the physics run data set very soon (Stay tuned!)



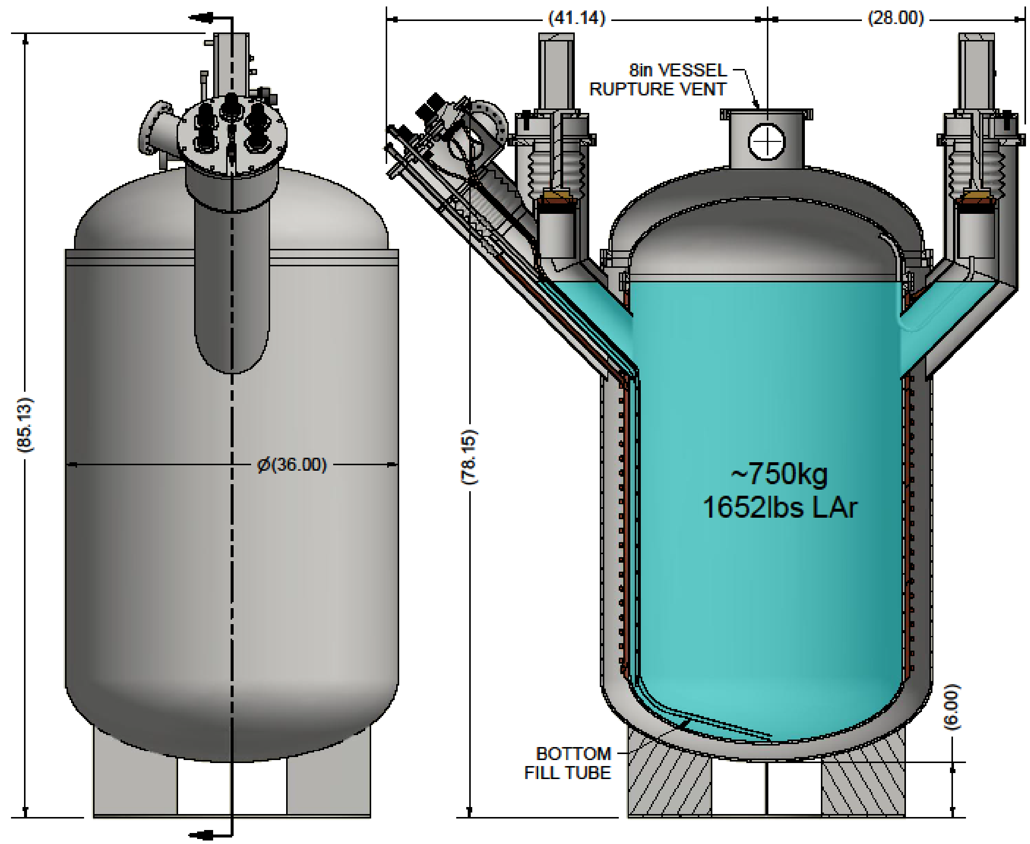



COHERENT 2017
(+2x data coming soon)
Coming very soon!
Cross section (10^{-40} cm^2)
10^3
10^2
10
1
0
10
20
30
40
50
60
70
80
90
Neutron number
Na
Ar
Ge
I
Cs

- **Data and results from Ge, NaI**
- **Proposals for larger detectors: beyond the observation of CEvNS**
  - 750 kg detector w/underground Ar (reduced ^{39}Ar): CENNS-750
  - D_2O detector for flux normalization



Darryl Dowling, ORNL



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

- CENNS-10 (LAr) is almost ready to report the first physics results ➔ test the N^2 dependence

- CsI (x2 of 2017) data analysis in progress

- There are vigorous R&D efforts to utilize the CEvNS process for various applications

COHERENT Collaboration

~80 members
~20 institutions