COHERENT

Coherent Elastic Neutrino-Nucleus Scattering

KAIST

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on behalf of COHERENT collaboration

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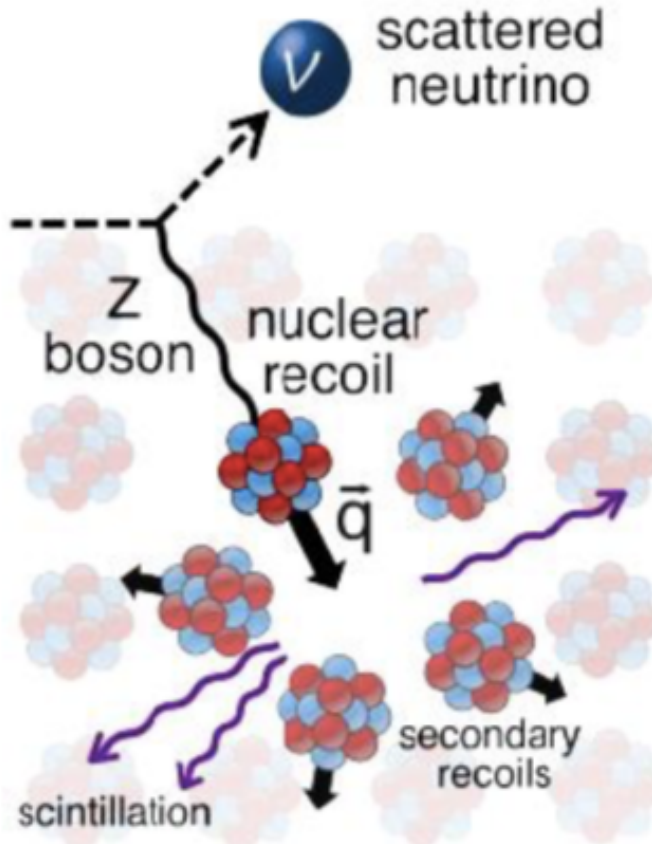
KIAS, Seoul, Korea

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

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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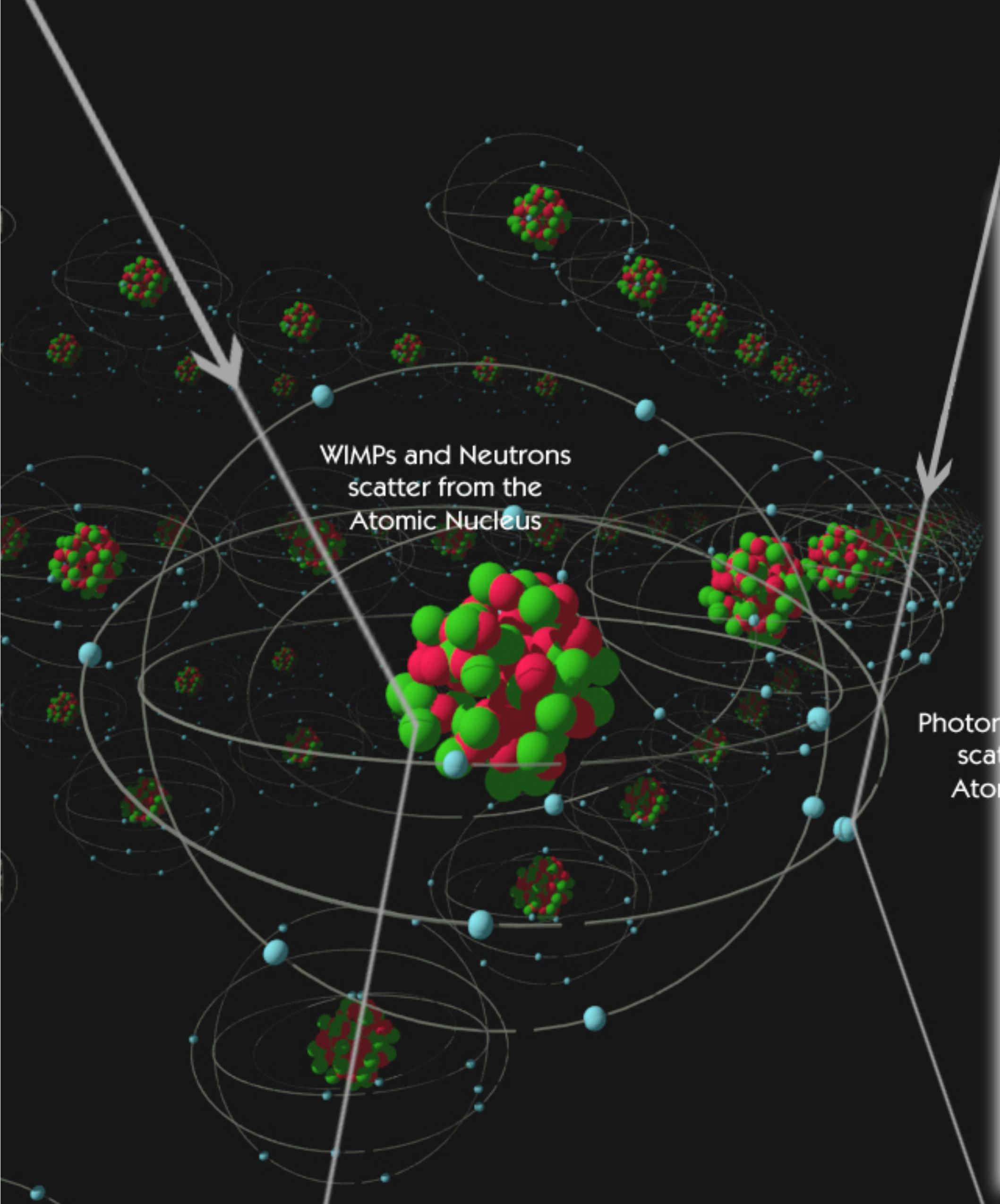
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790

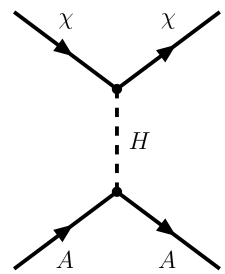
(Received 15 October 1973; revised manuscript received 19 November 1973)

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.

Why CEvNS? — Dark Matter Coherent Scattering

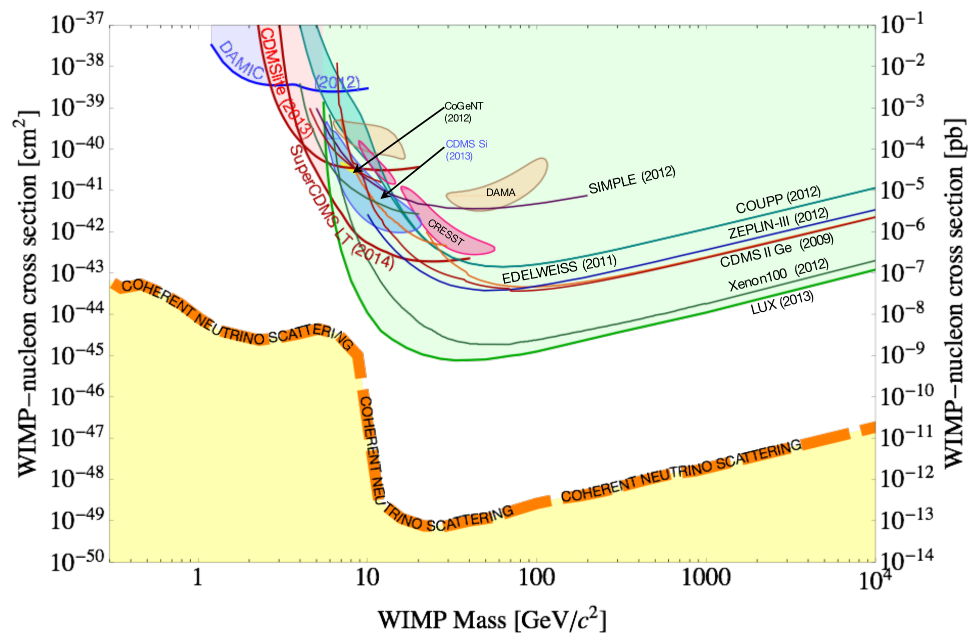
WIMPs (Weakly Interacting Massive Particles) coherent scatter from the entire nucleus





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

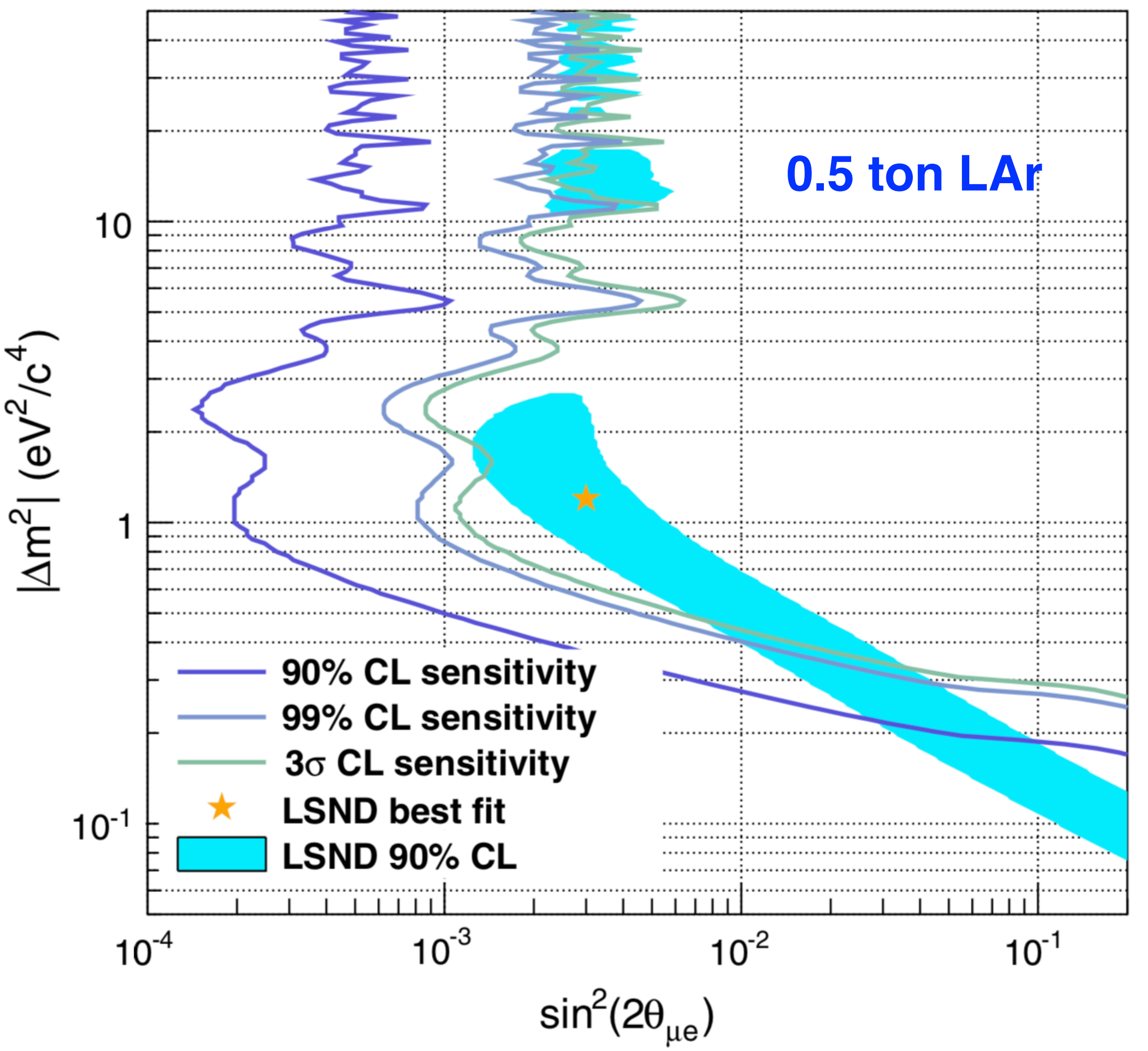
$$\frac{dR}{dE} = \frac{\sigma_0}{m_\chi}\frac{A^2}{2\mu_n^2}F_A^2(E) \times \rho_0 \int_{v_m} \frac{f(v)}{v}dv$$



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)



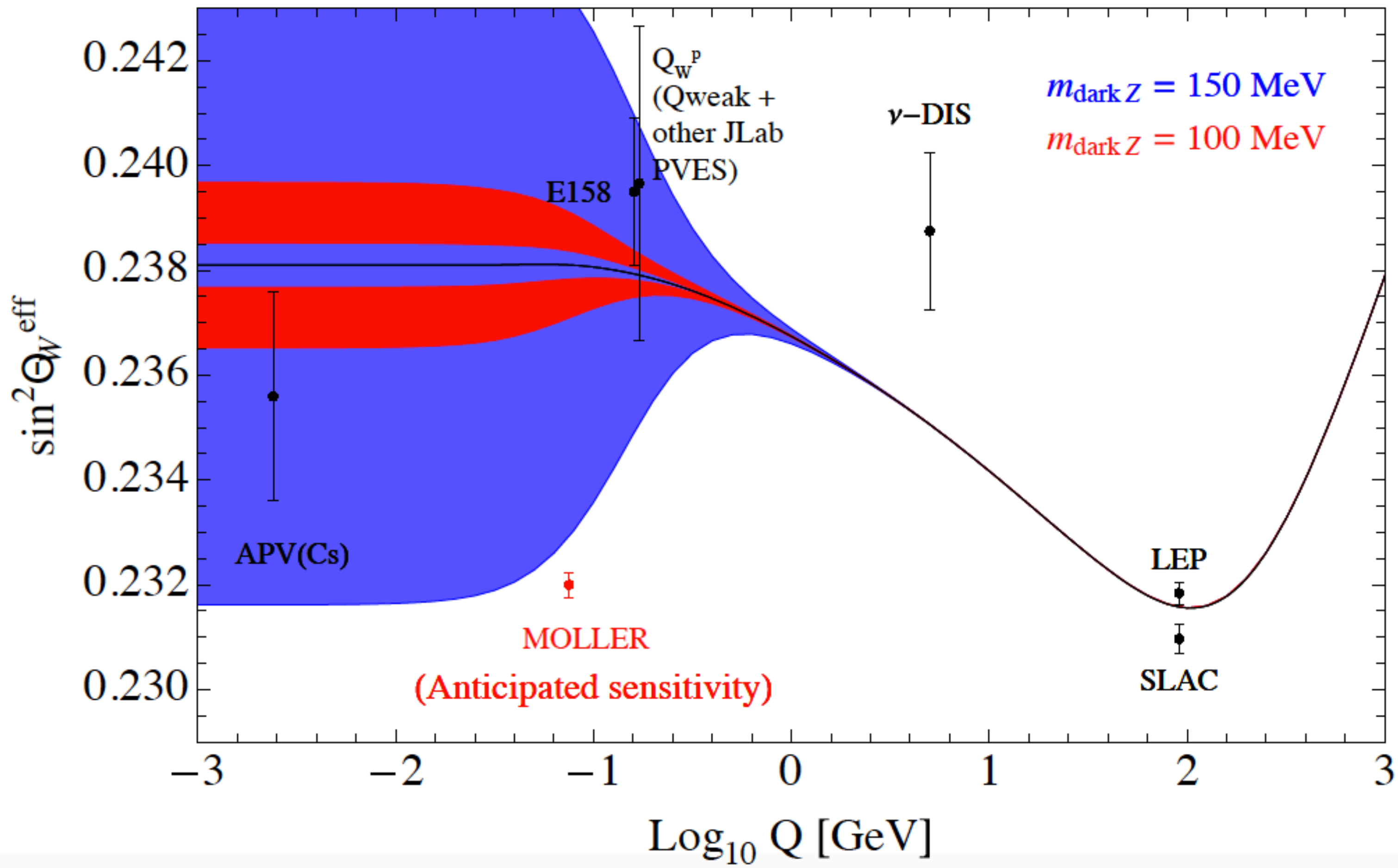
Why CEvNS? — Weinberg Angle

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

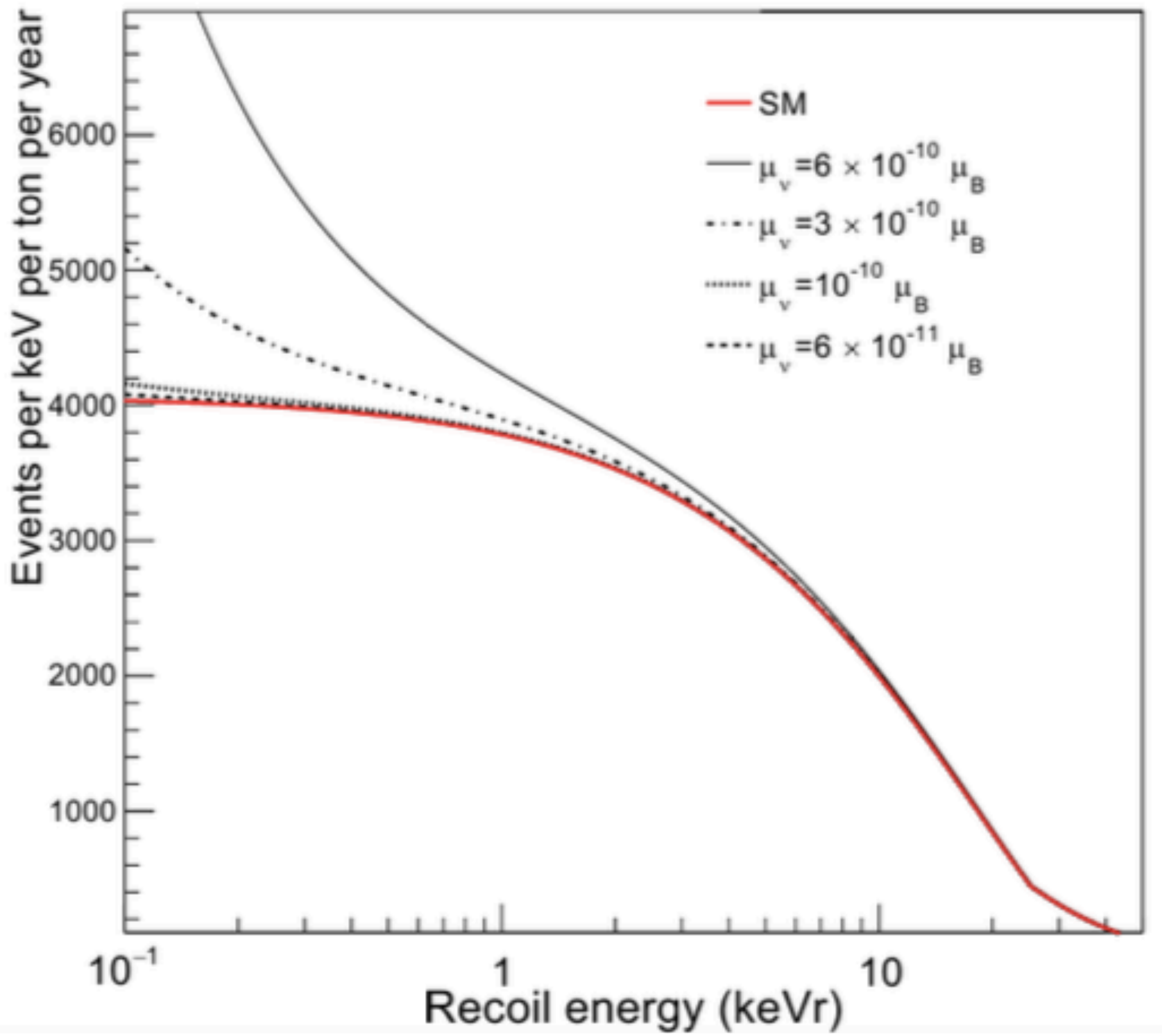
$$\mathcal{L}_{\nu H}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta=e,\mu,\tau}} [\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5)\nu_\beta] \times (\varepsilon_{\alpha\beta}^{qL}[\bar{q}\gamma_\mu(1-\gamma^5)q] + \varepsilon_{\alpha\beta}^{qR}[\bar{q}\gamma_\mu(1+\gamma^5)q])$$

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

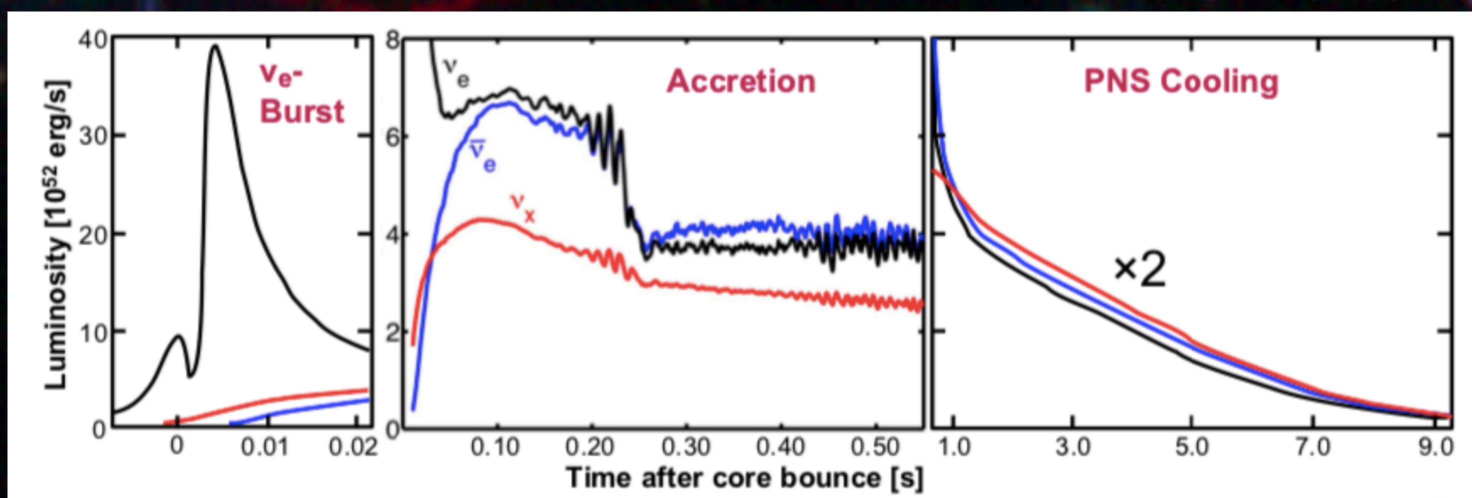
- Magnetic moment of neutrino enhance the recoil energy spectrum at low energy
  ➔ requires very low energy threshold detector



Why CEvNS? — Supernova Neutrinos

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

arXiv:1702.08713



CEvNS Event Rate

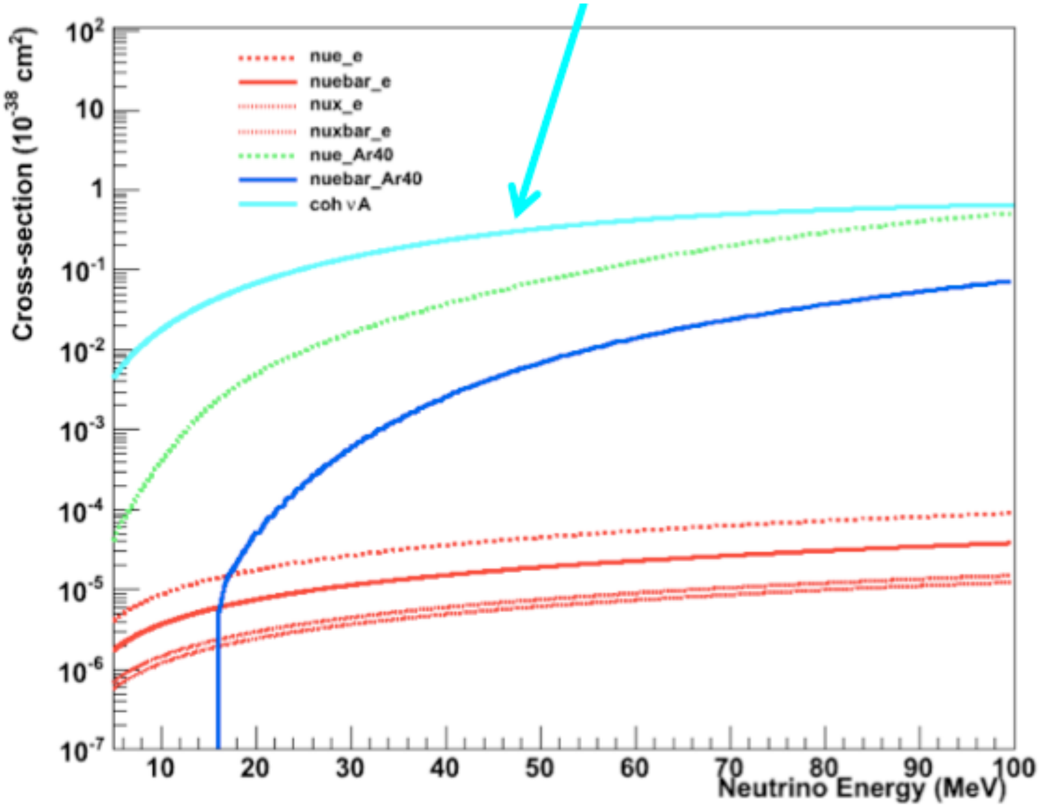
For most of the detector target nucleus, the coherence condition is fulfilled by neutrino energy of

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

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

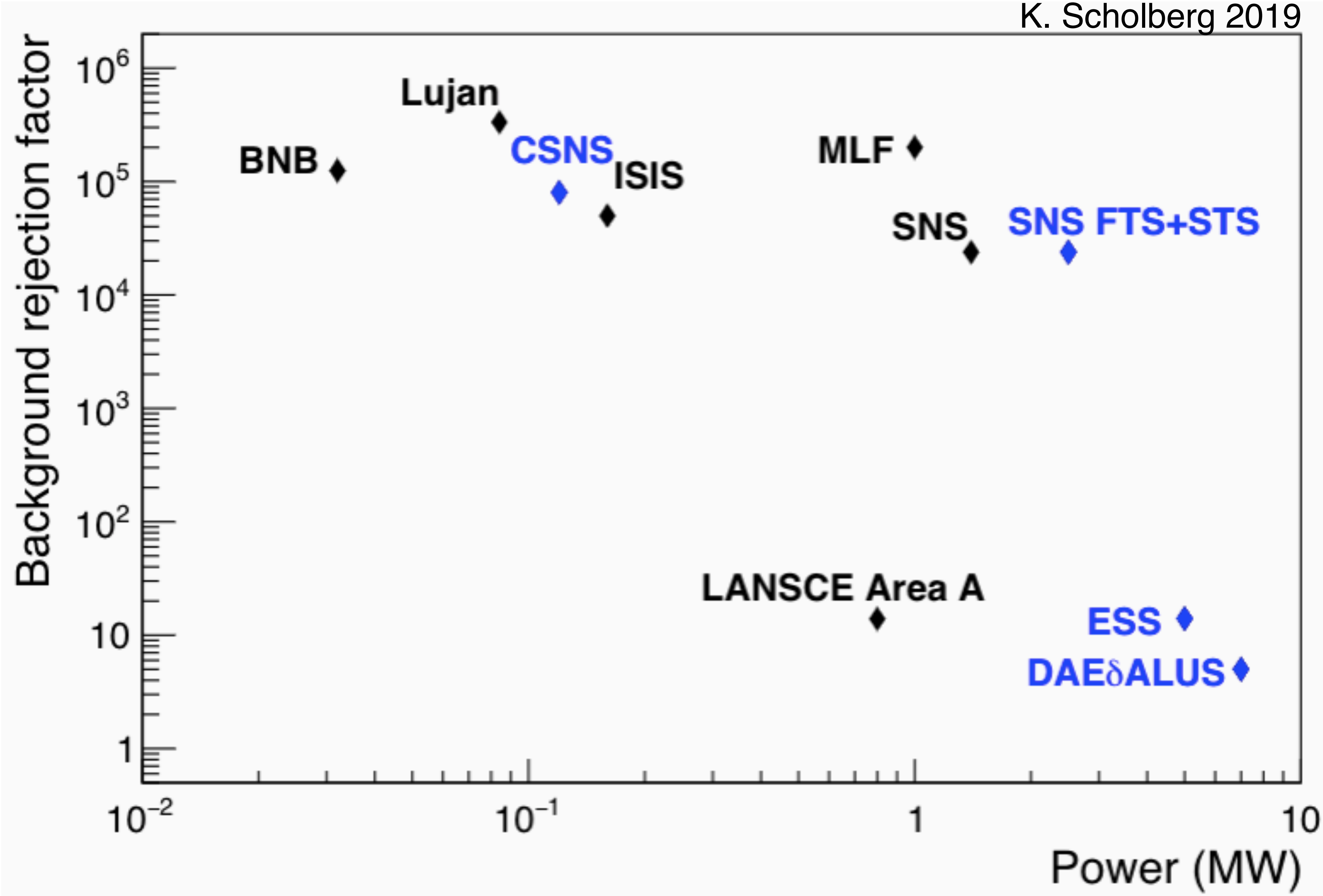
Recoil energy is tiny

Largest cross section in the region of interest

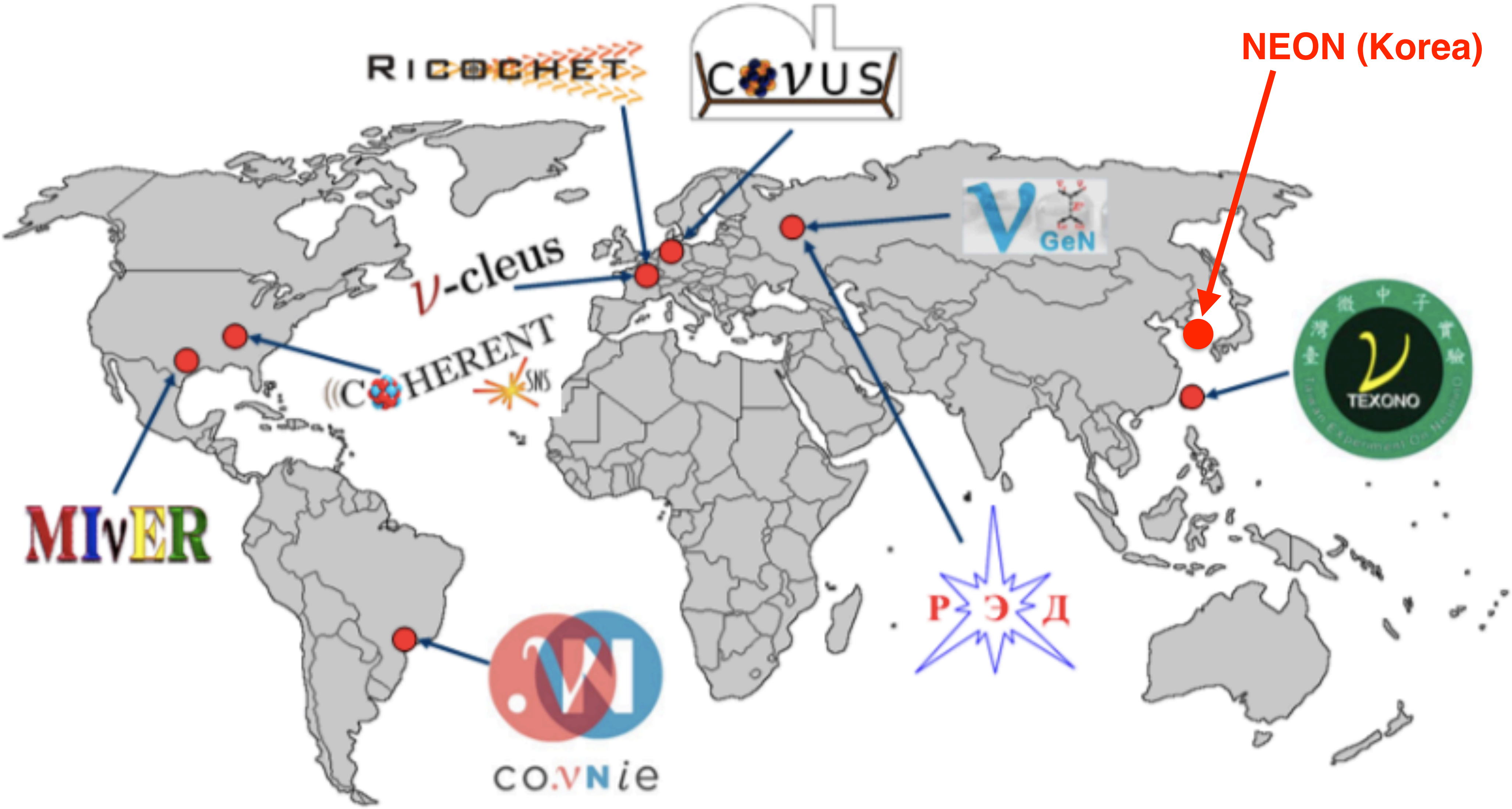


Requires a ton-scale detector with ~10 keV energy threshold
or very intensive neutrino source

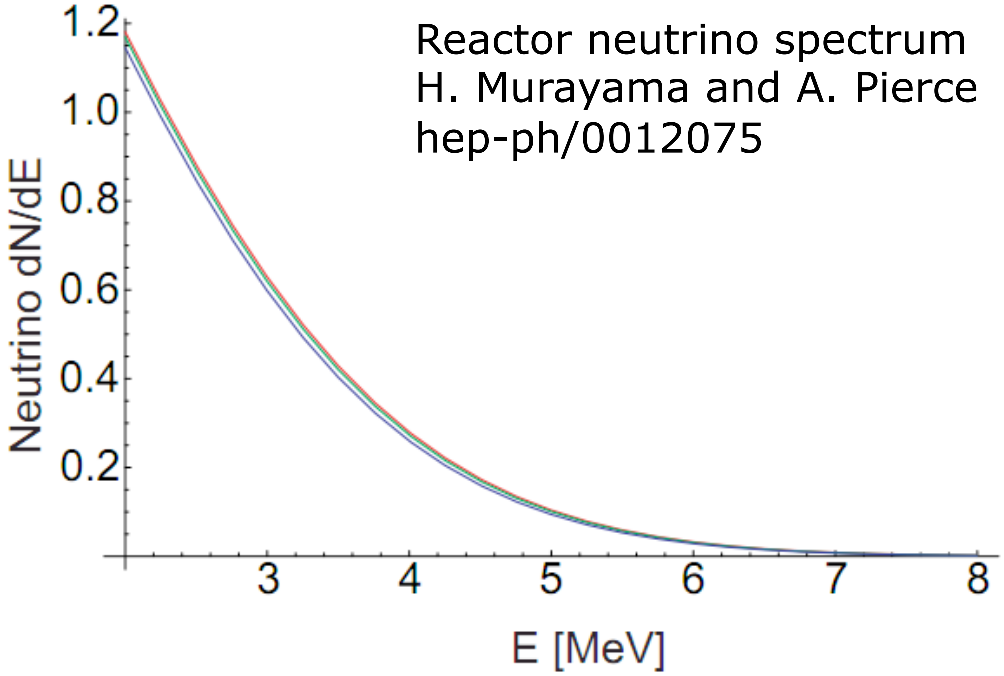
$$R \simeq \mathcal{O}(10^3)\left(\frac{\sigma}{10^{-39}cm^2}\right) \times \left(\frac{\Phi}{10^{13}\nu/year/cm^2}\right) \times \left(\frac{M}{ton}\right) events/year$$


K. Scholberg 2019
Background rejection factor
Power (MW)
BNB
Lujan
CSNS
ISIS
MLF
SNS
SNS FTS+STS
LANSCE Area A
ESS
DAEδALUS
10^6
10^5
10^4
10^3
10^2
10
1
10^{-2}
10^{-1}
1
10

CEvNS Searches



CEvNS at Reactors

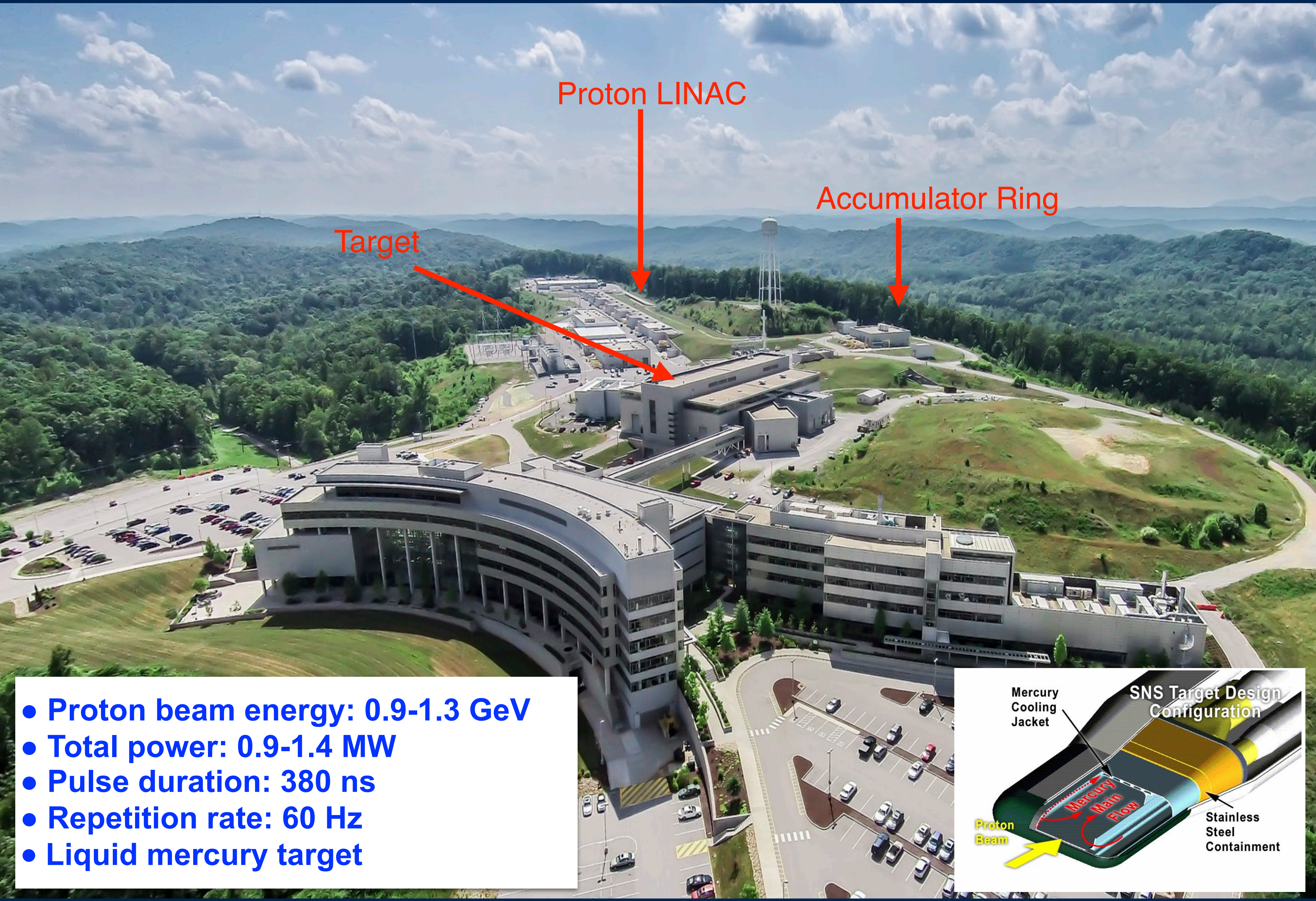


$$E_{max} \simeq \frac{2E_\nu^2}{M} < \text{keV}$$

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

- **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

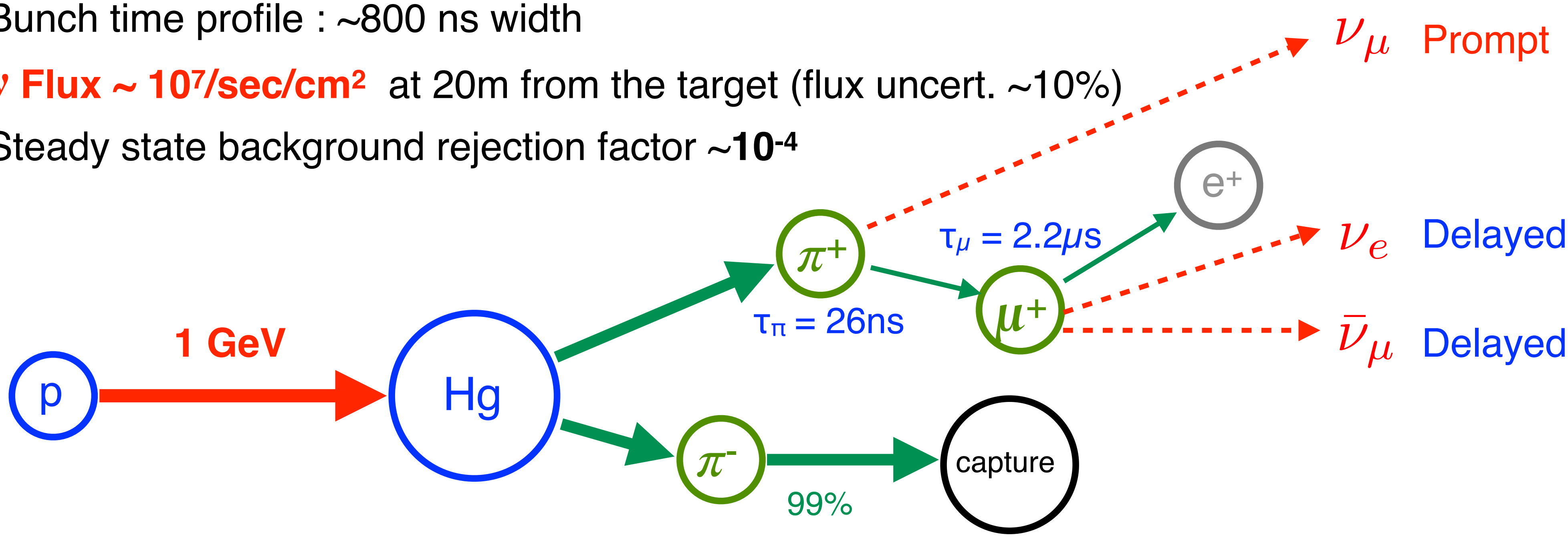
Spallation Neutron Source: Oak Ridge National Laboratory

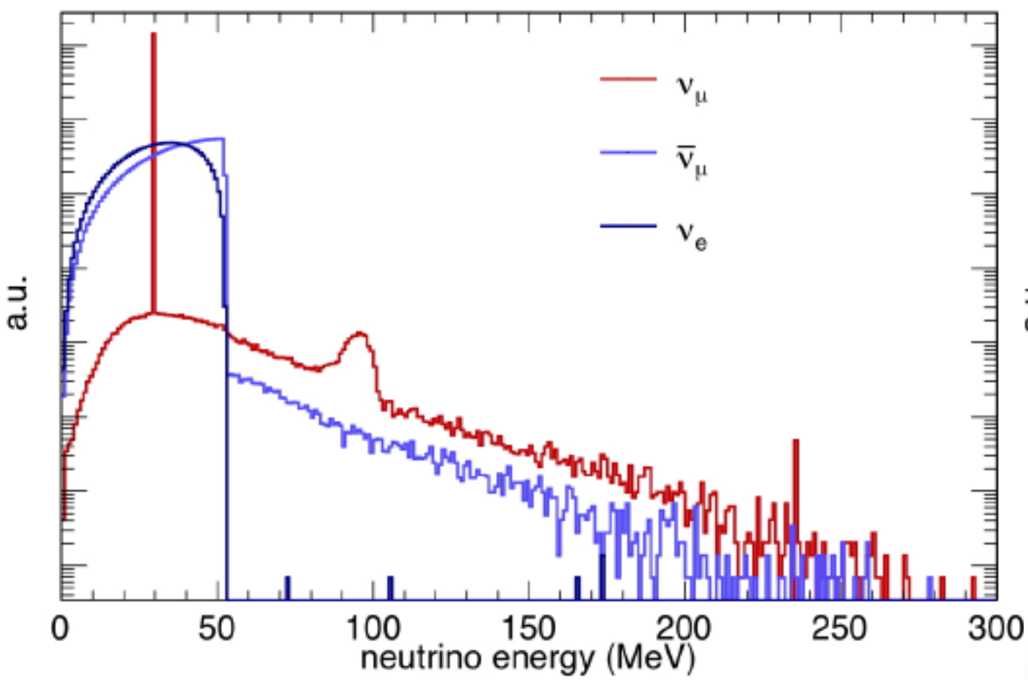


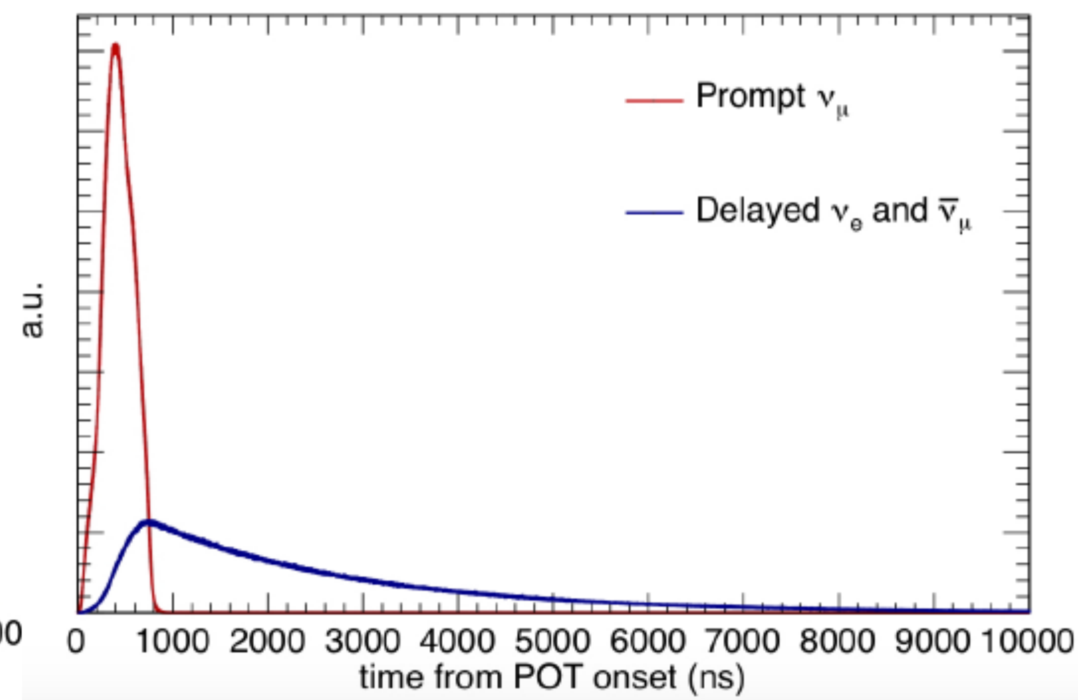
- **Proton beam energy: 0.9-1.3 GeV**
- **Total power: 0.9-1.4 MW**
- **Pulse duration: 380 ns**
- **Repetition rate: 60 Hz**
- **Liquid mercury target**

Neutrino Energy Spectrum from SNS

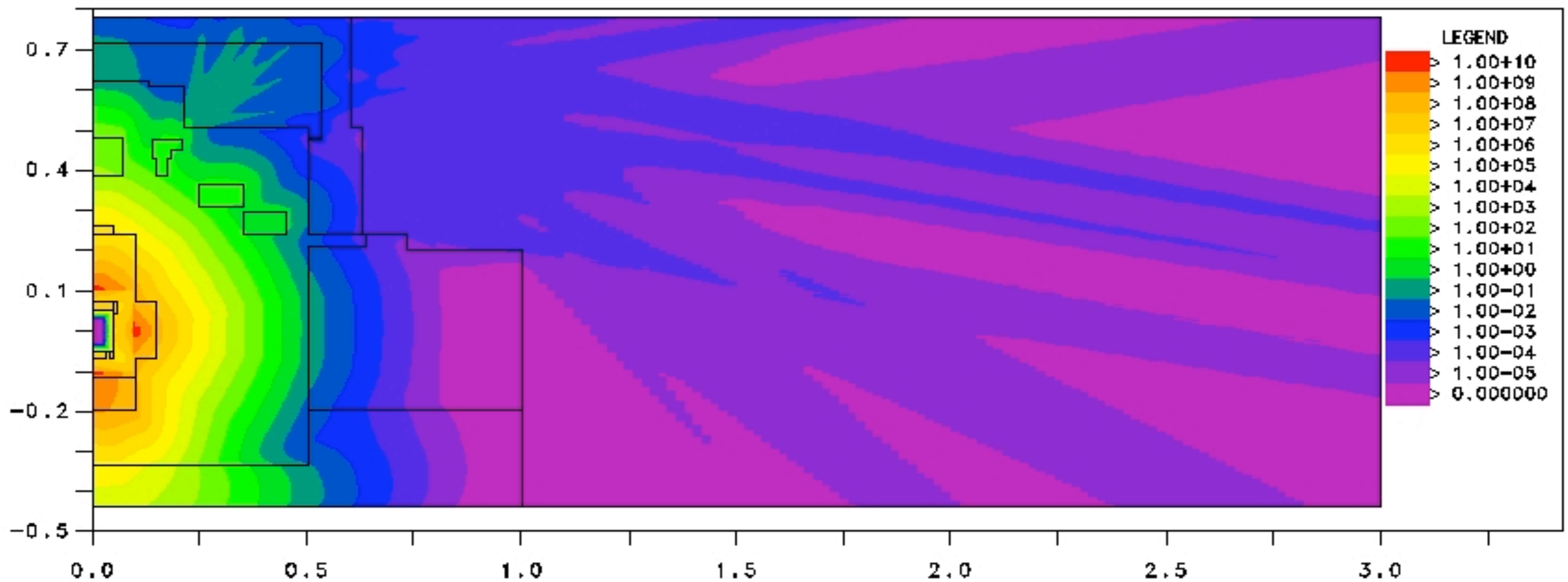
- Bunch time profile : ~800 ns width
- **ν Flux ~ 10^7/sec/cm^2** at 20m from the target (flux uncert. ~10%)
- Steady state background rejection factor ~**10^{-4}**

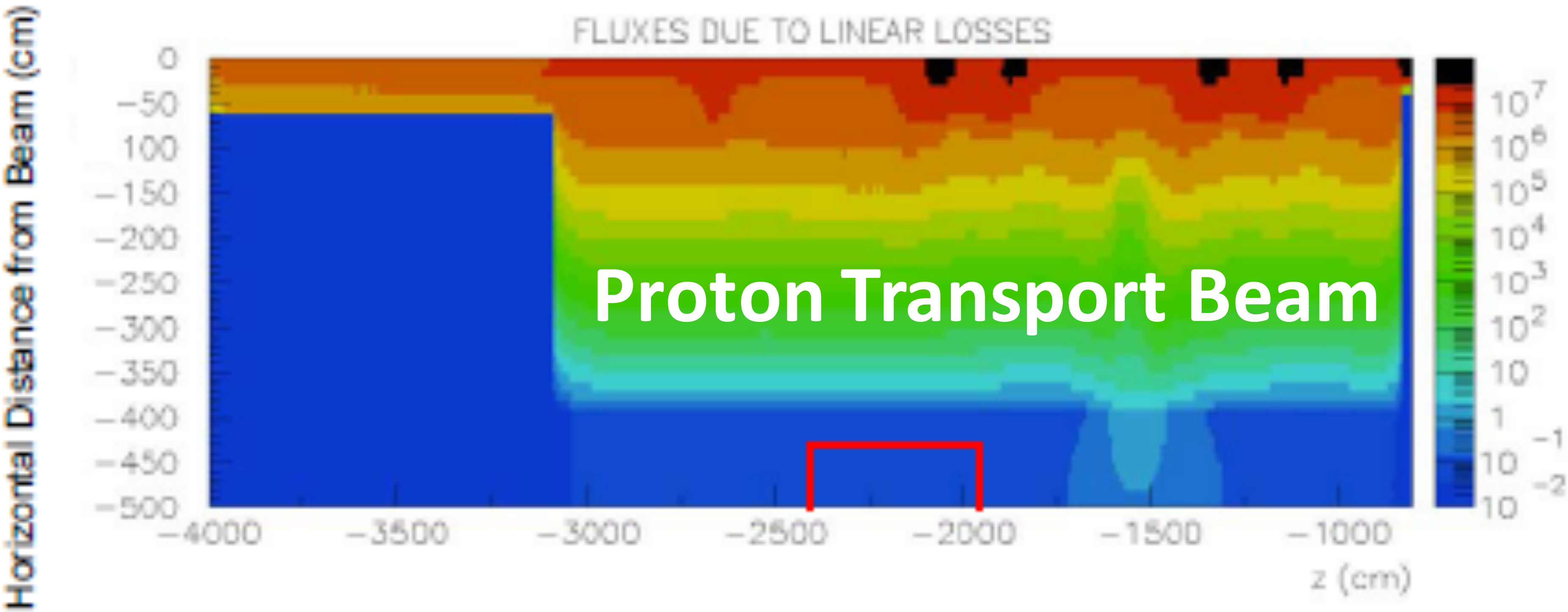




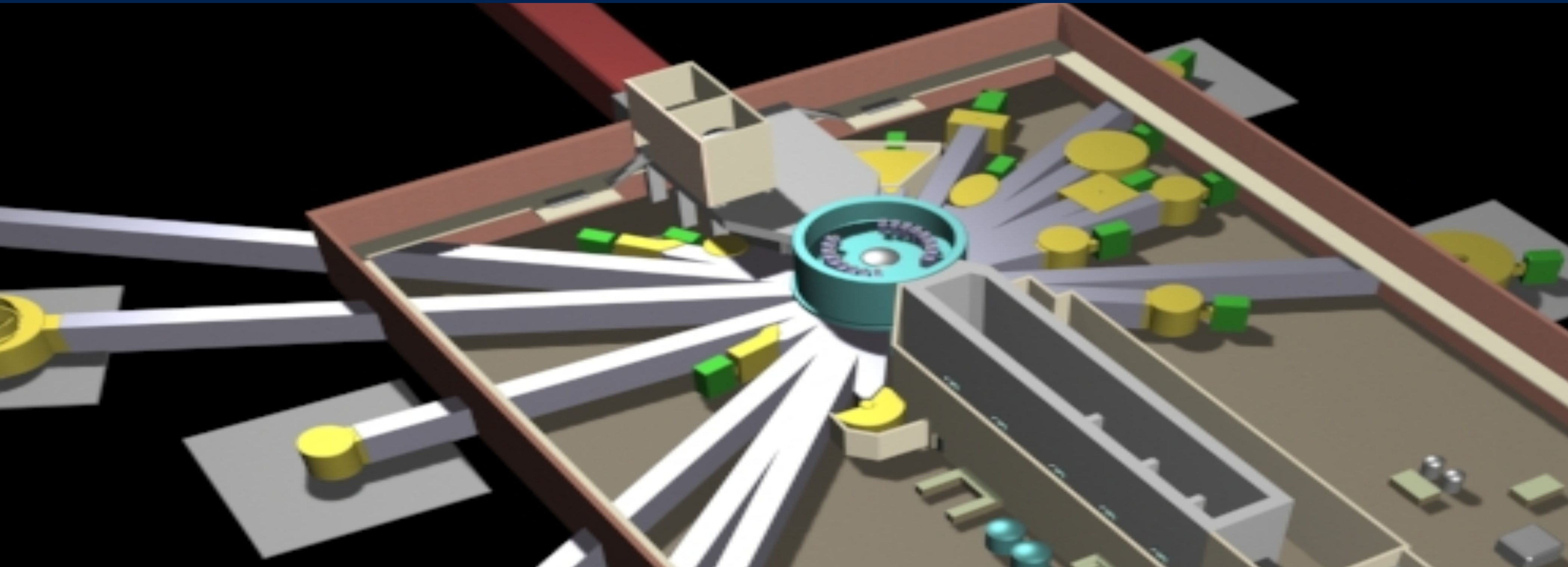


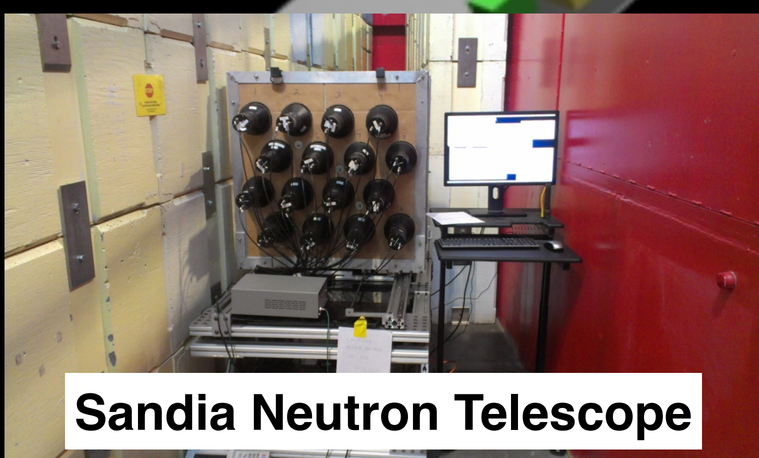
Neutrons at SNS (Simulations)

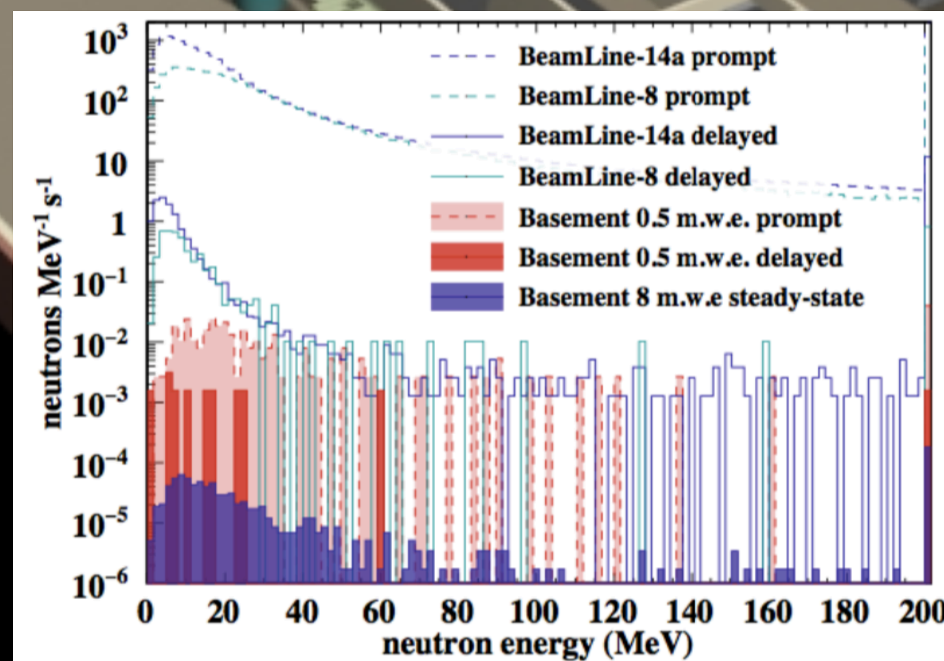




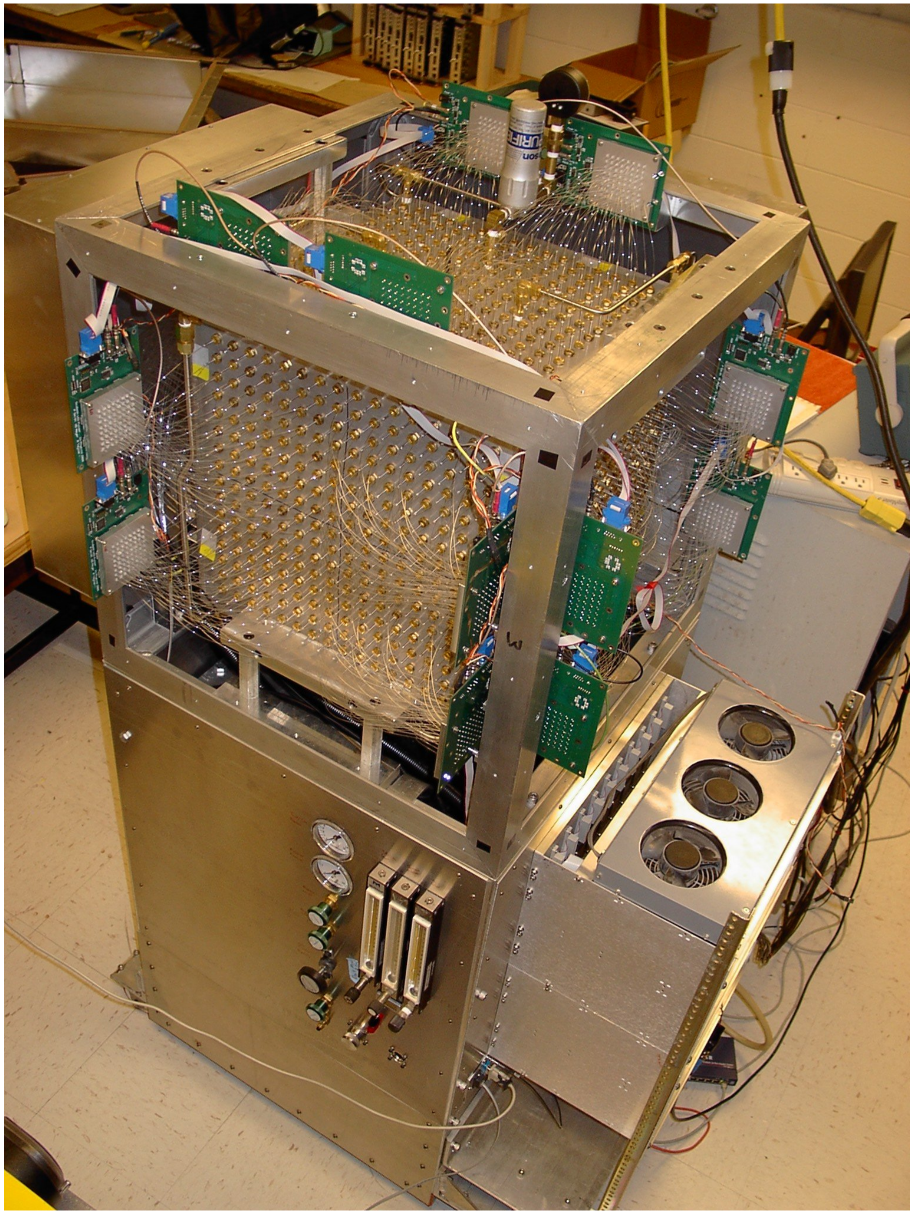
Neutrons at SNS

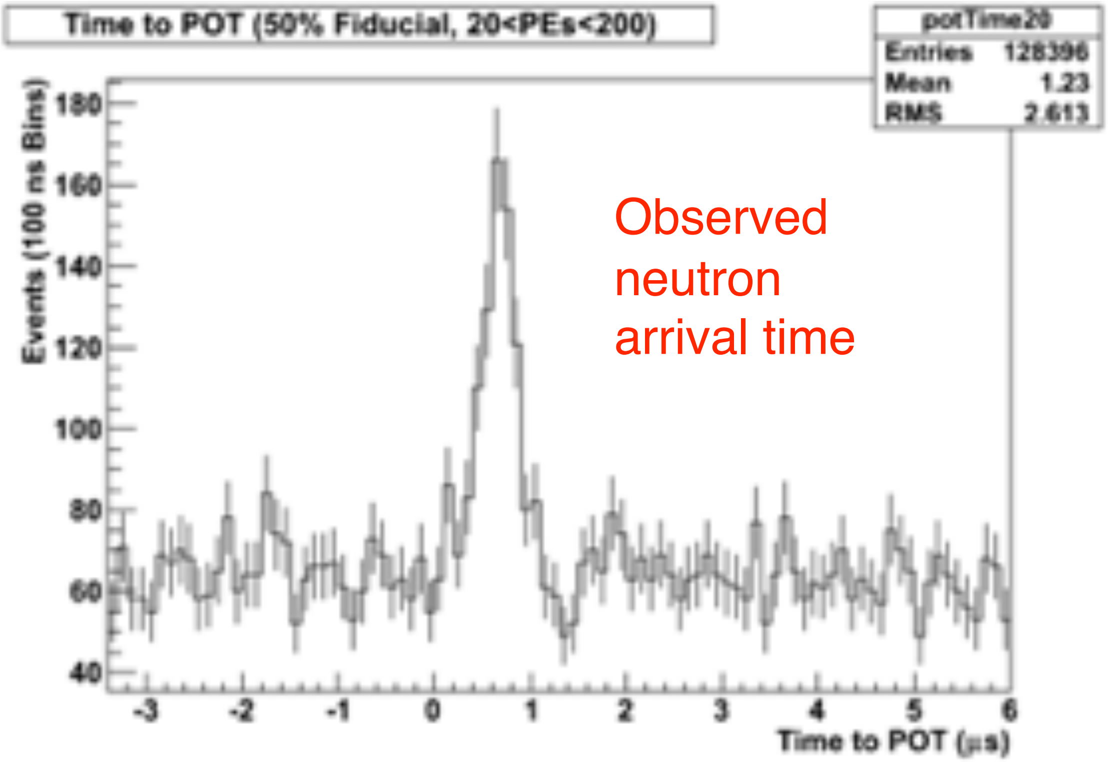


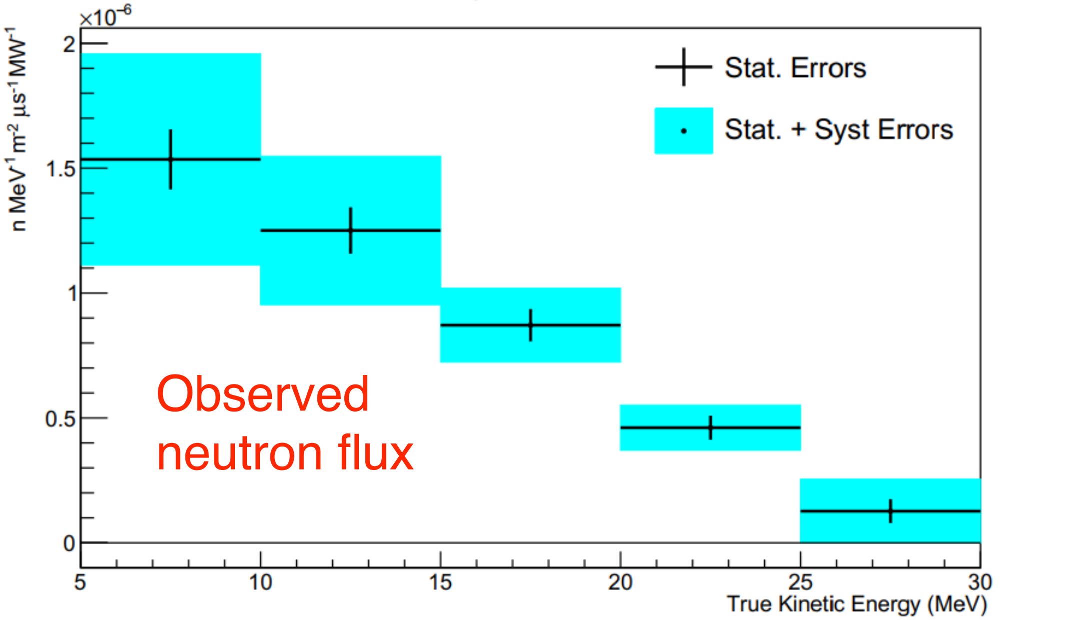




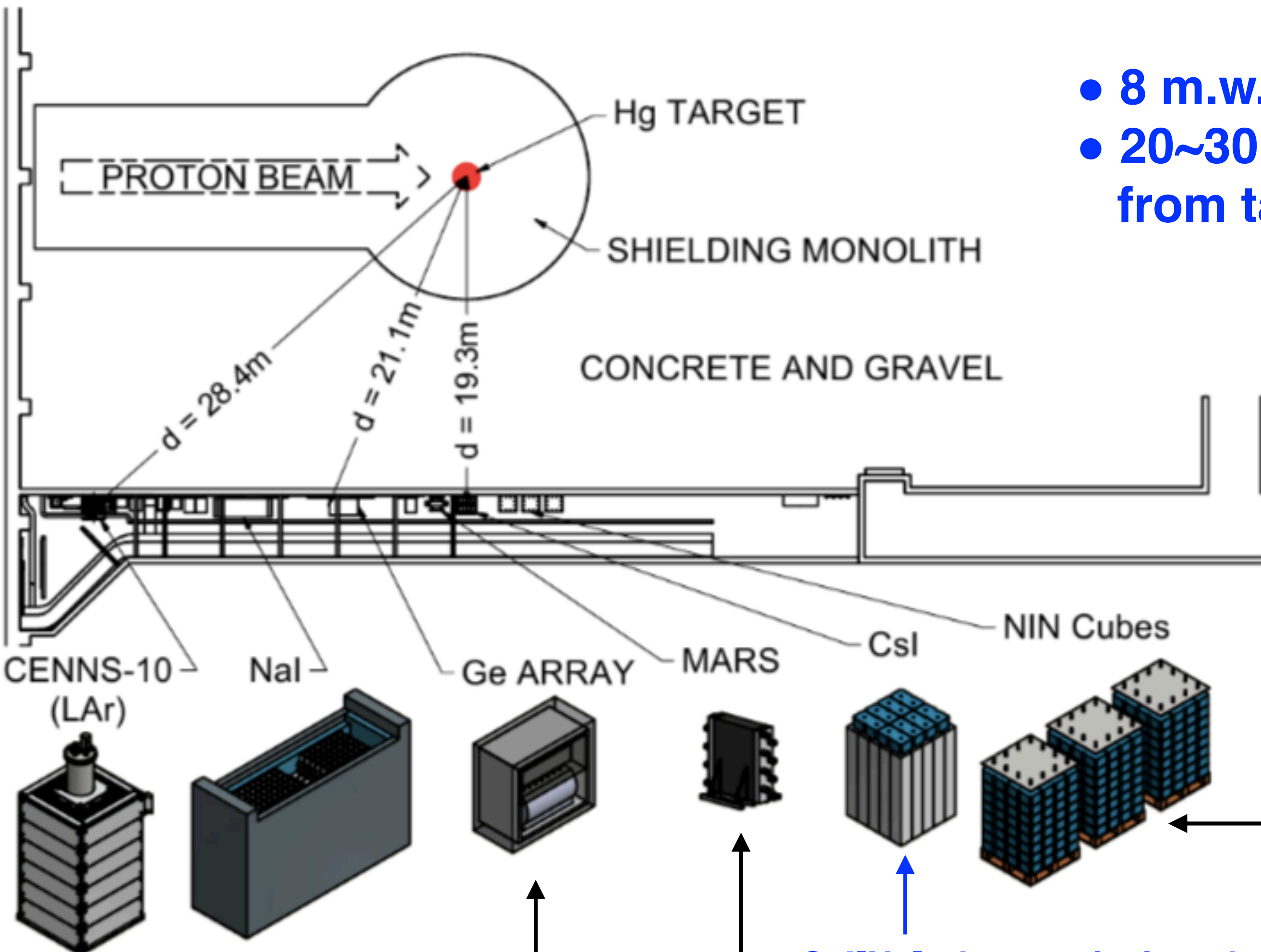
SciBath neutron detector from Indiana University







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

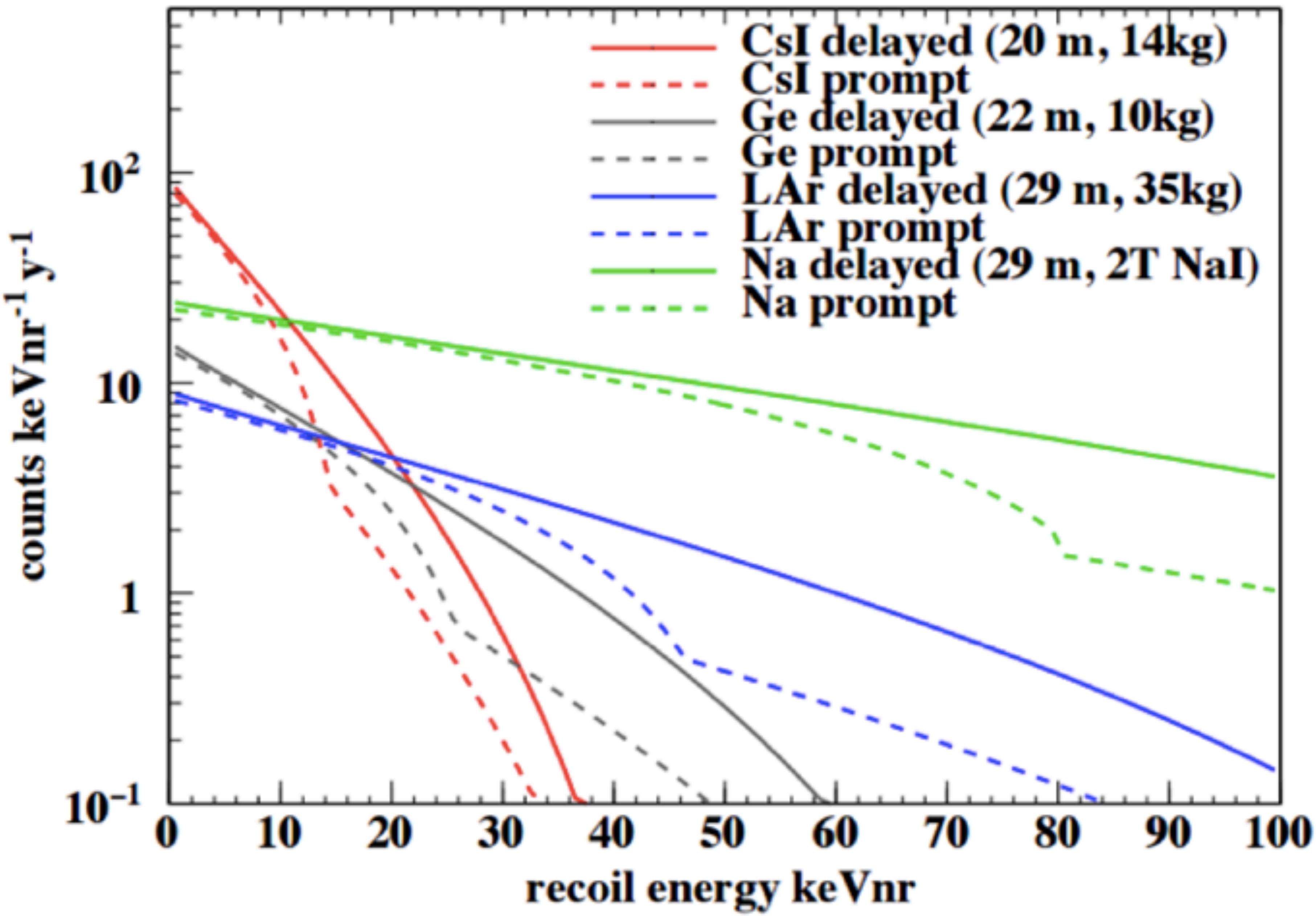
MARS, deployed: plastic scintillator interleaved with Gd coated Mylar sheets

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

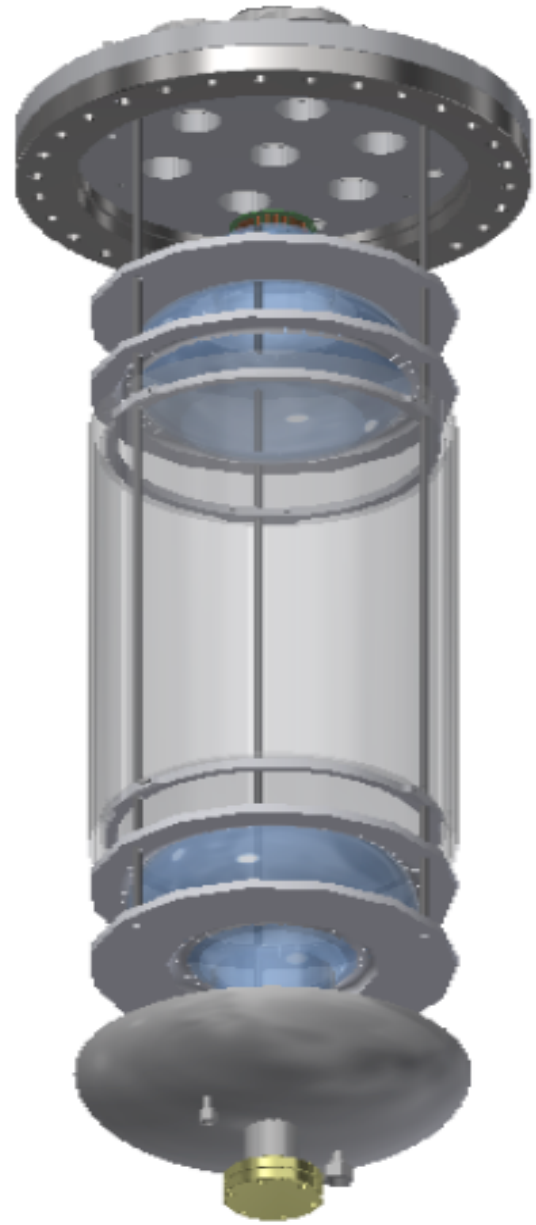
Expected CEvNS Events at SNS Neutrino Alley



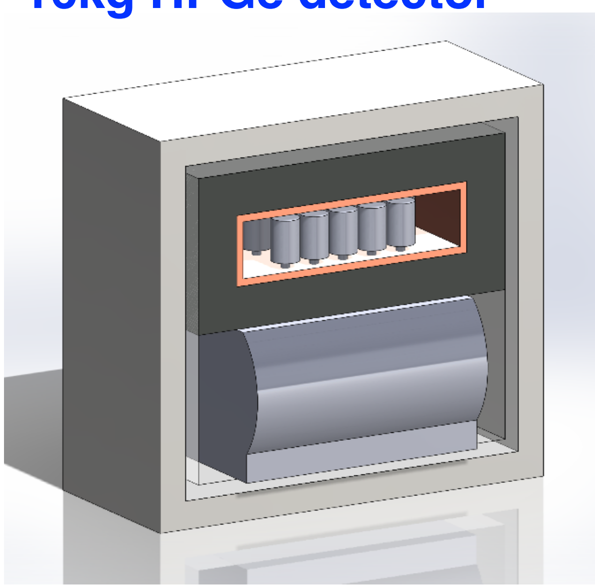
COHERENT Phase-1 Experiments

14kg CsI detector

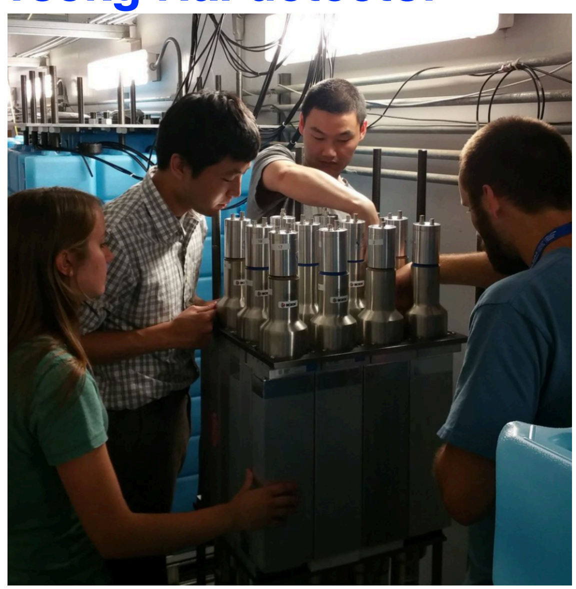
30kg LAr detector



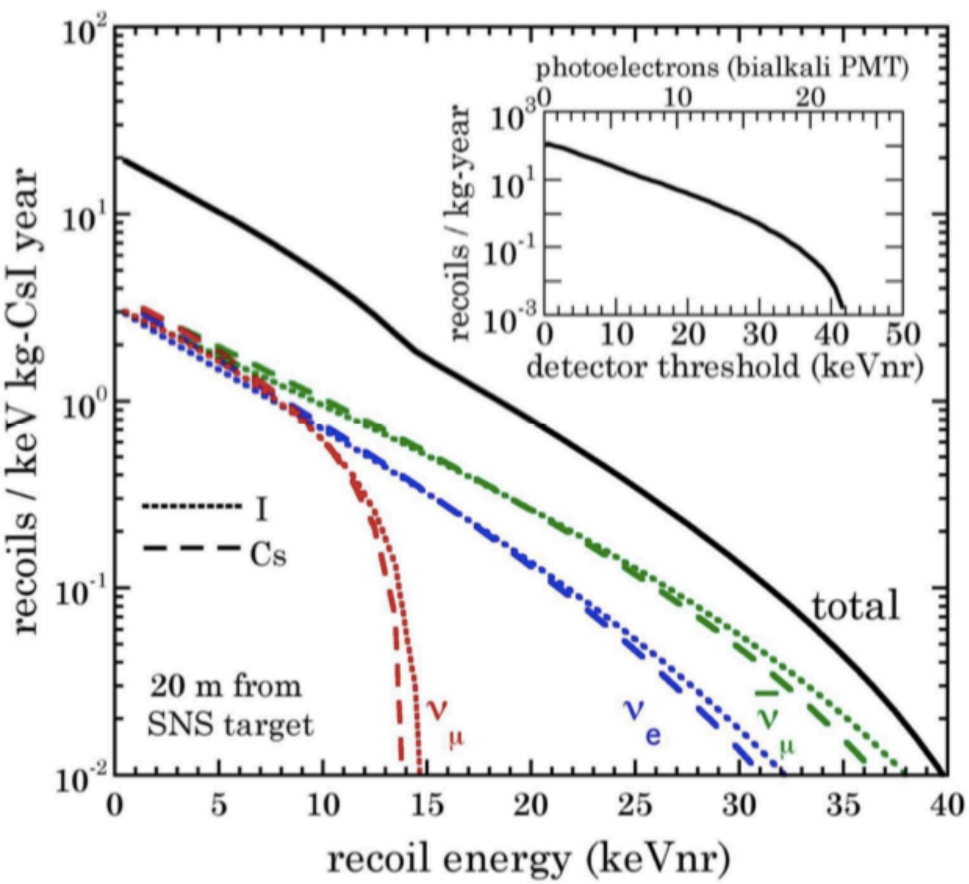
16kg HPGe detector

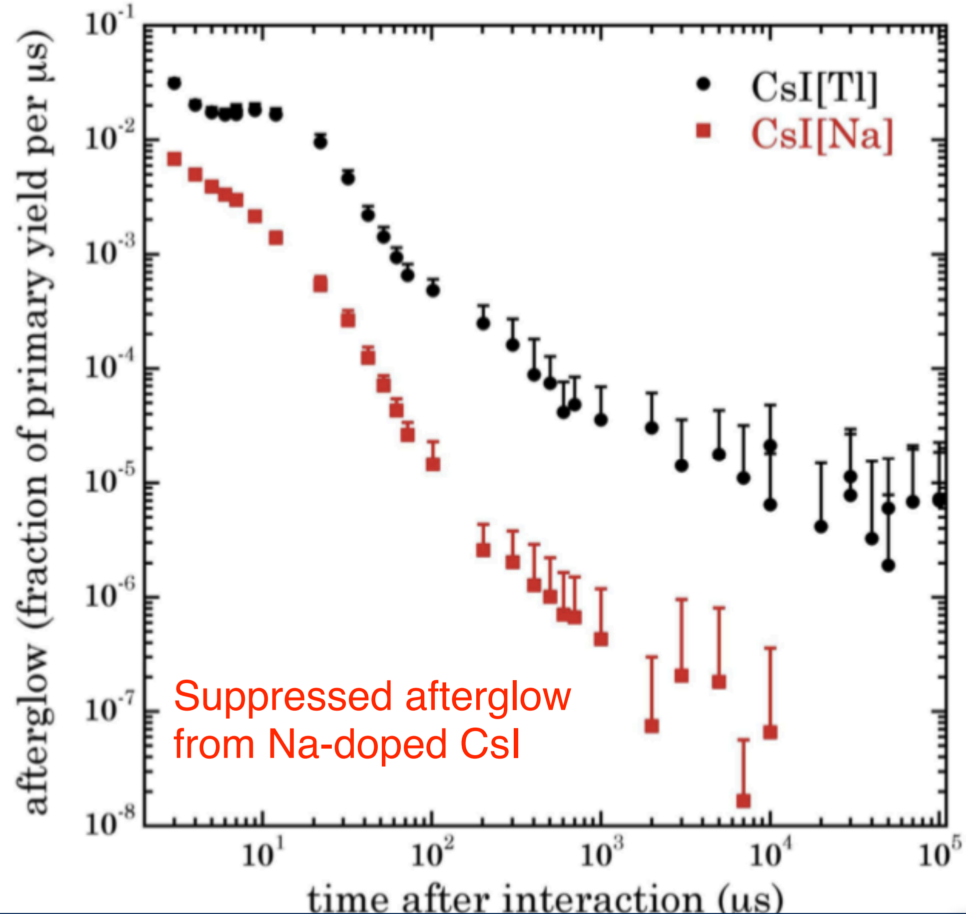


185kg NaI detector

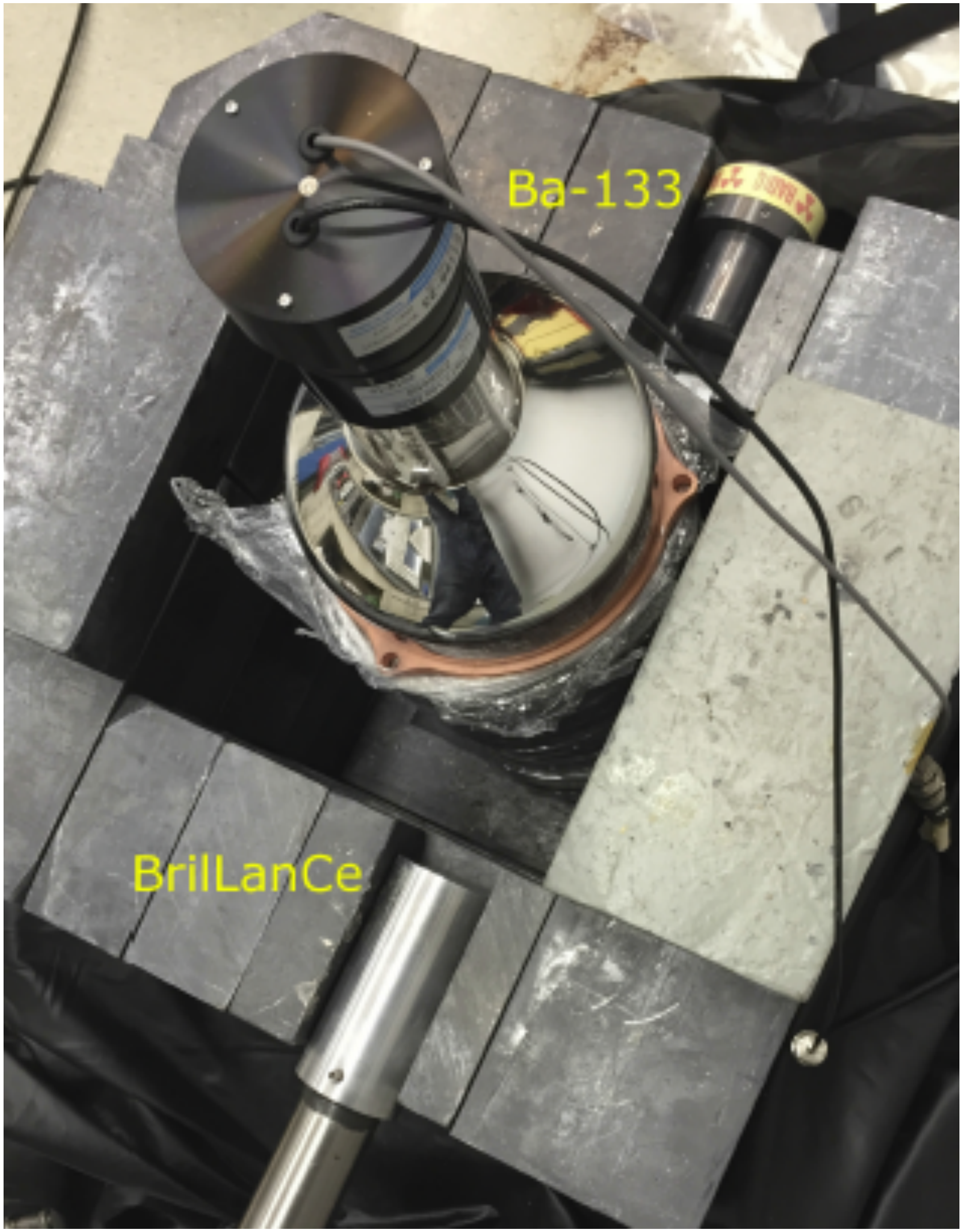


- **CsI detector characteristics**
  - High density 4.51g/cc
  - Can be built for low radioactivity
  - Very high light yield ~18pe/keVee (1.17pe/keVnr)
  - Inexpensive ~1$/g





CsI Detector in Neutrino Alley at SNS



CsI Detector in Neutrino Alley at SNS

Data Analysis:

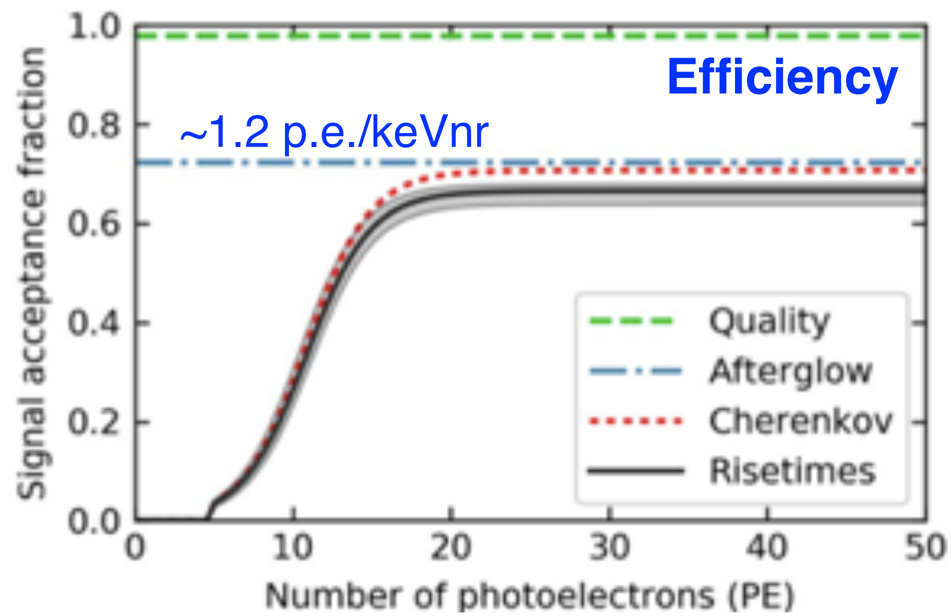
- count beam-on low-energy events (nuclear recoils)
- subtract steady state backgrounds from beam-off data
- measure/subtract beam-related backgrounds (neutrons):
- neutrino-induced neutrons ("NIN"s)

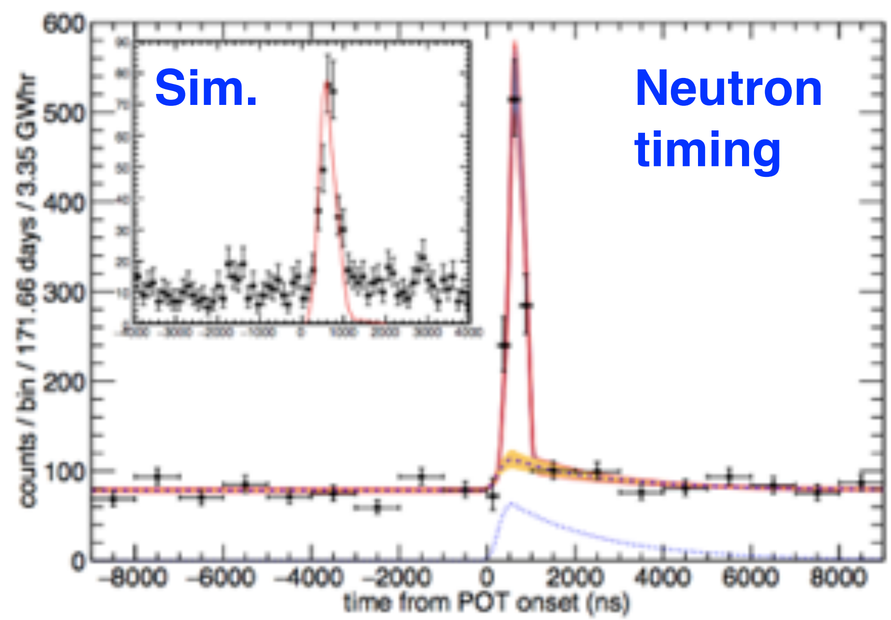
$\nu_e + {}^{208}\mathrm{Pb} \to {}^{208}\mathrm{Bi}^* + e^-$ CC

↘ 1n, 2n emission

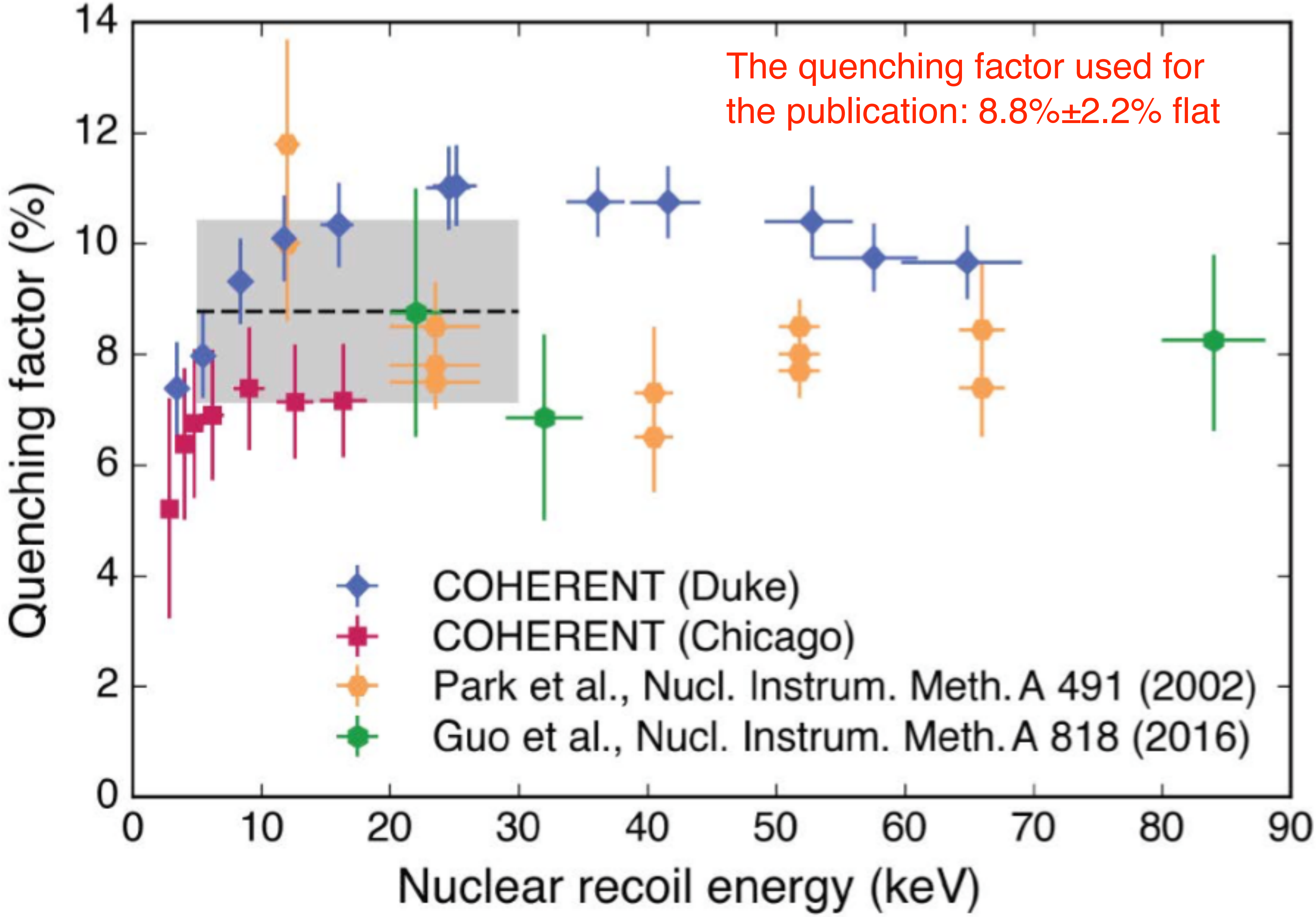
$\nu_x + {}^{208}\mathrm{Pb} \to {}^{208}\mathrm{Pb}^* + \nu_x$ NC

↘ 1n, 2n, γ emission

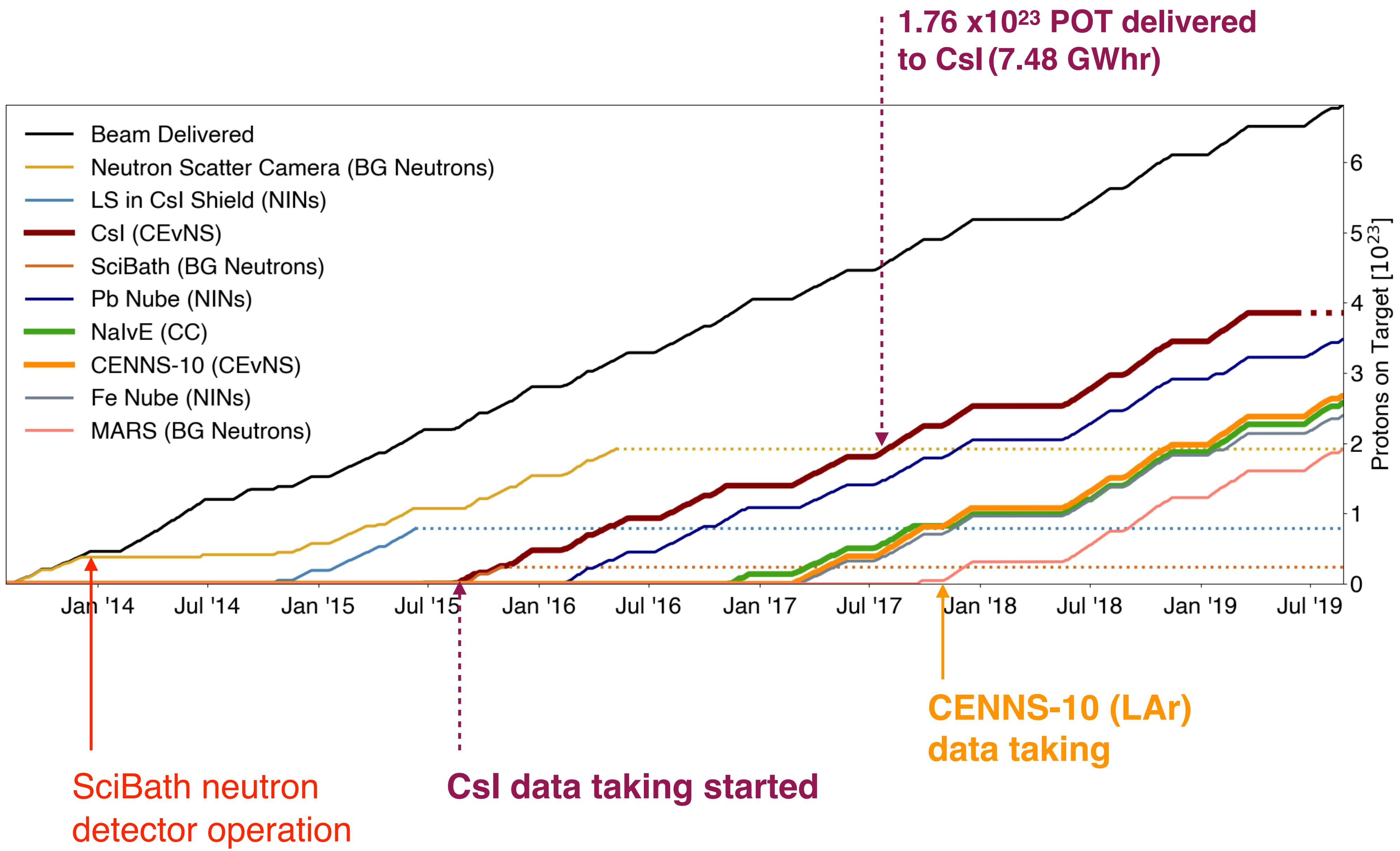




CsI Detector Quenching Factor

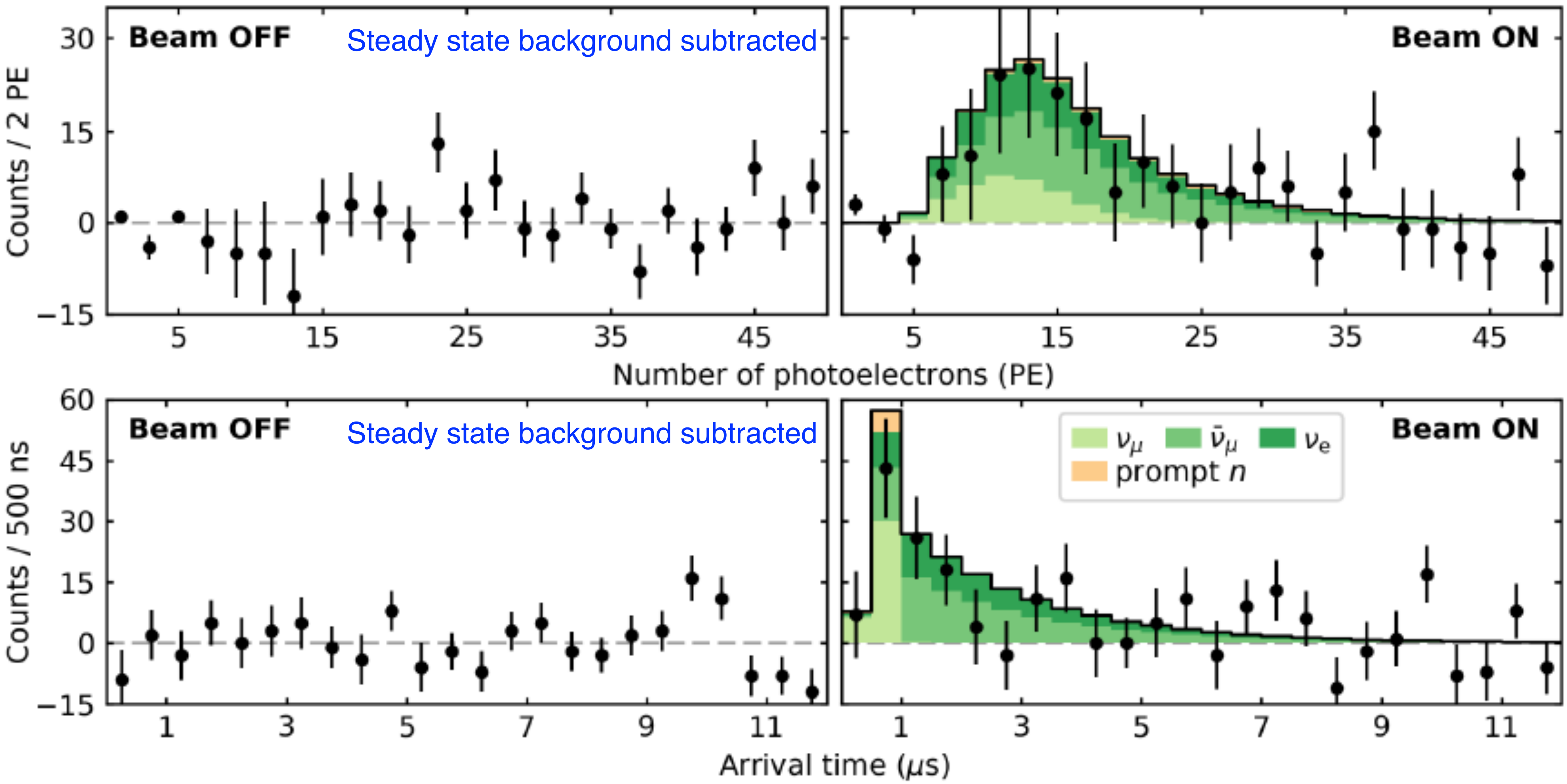


COHERENT Data Collection

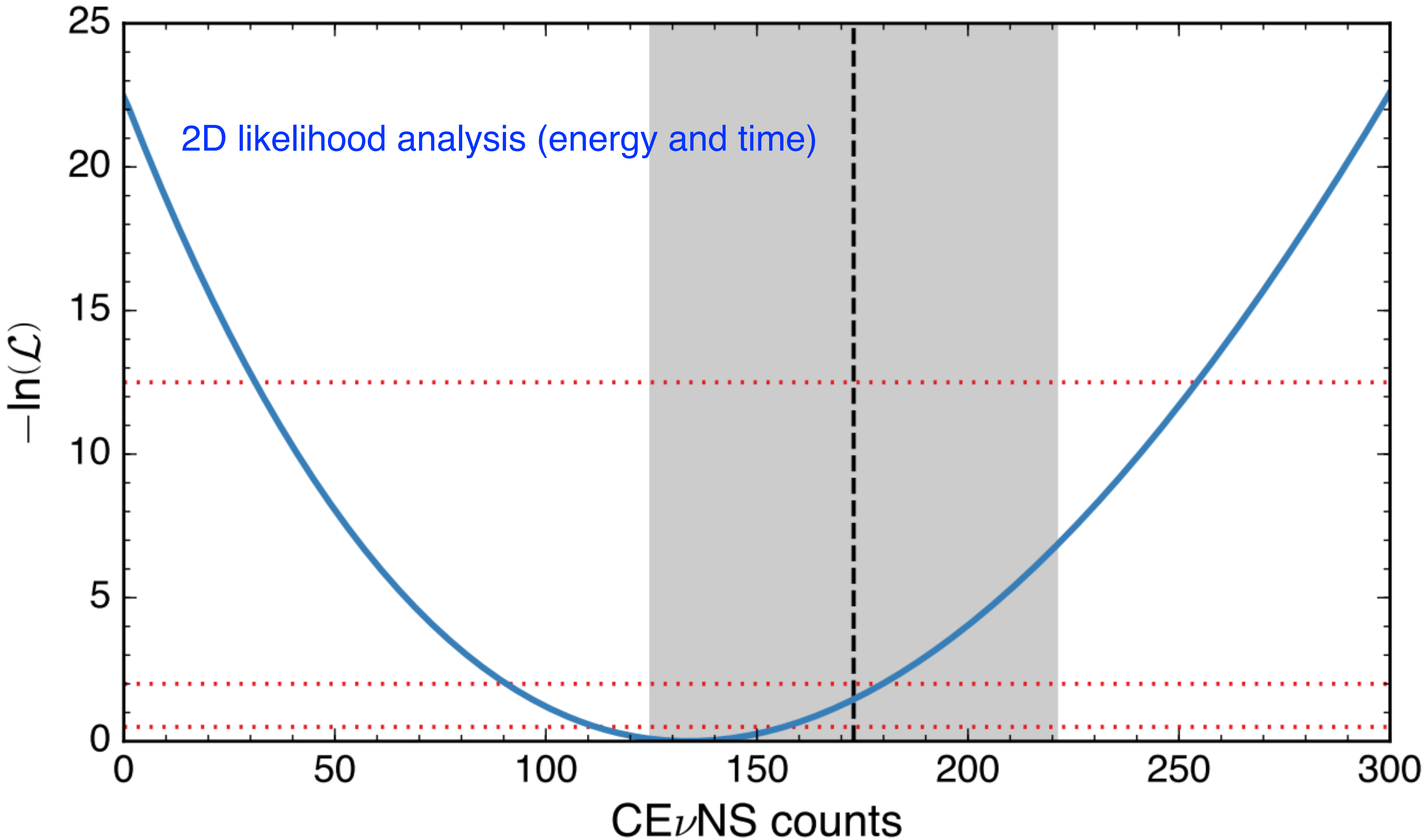


CEvNS Observation (CsI)

- 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 Cover 2017-09-15

Science REPORTS

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Observation of coherent elastic neutrino-nucleus scattering

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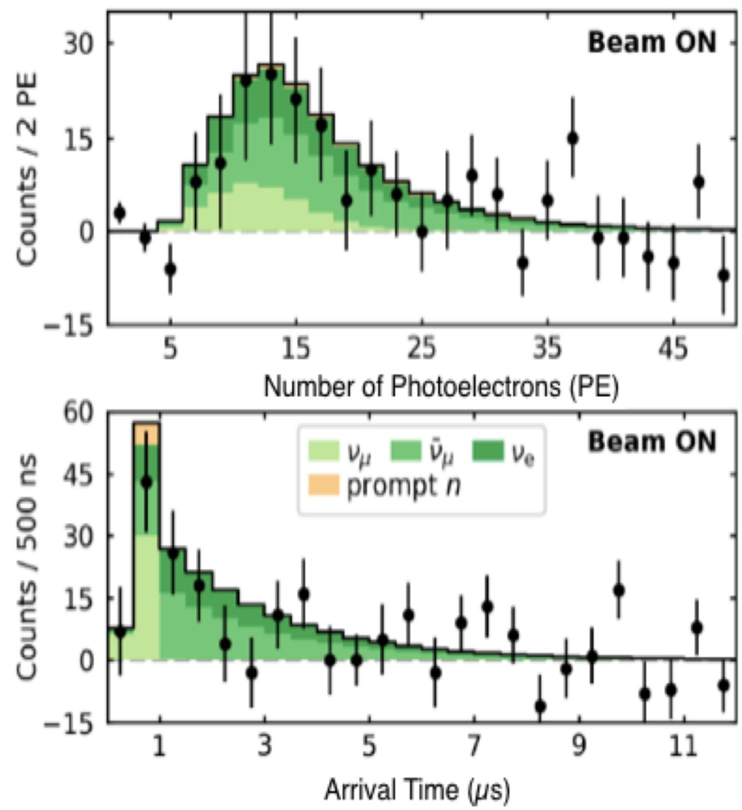
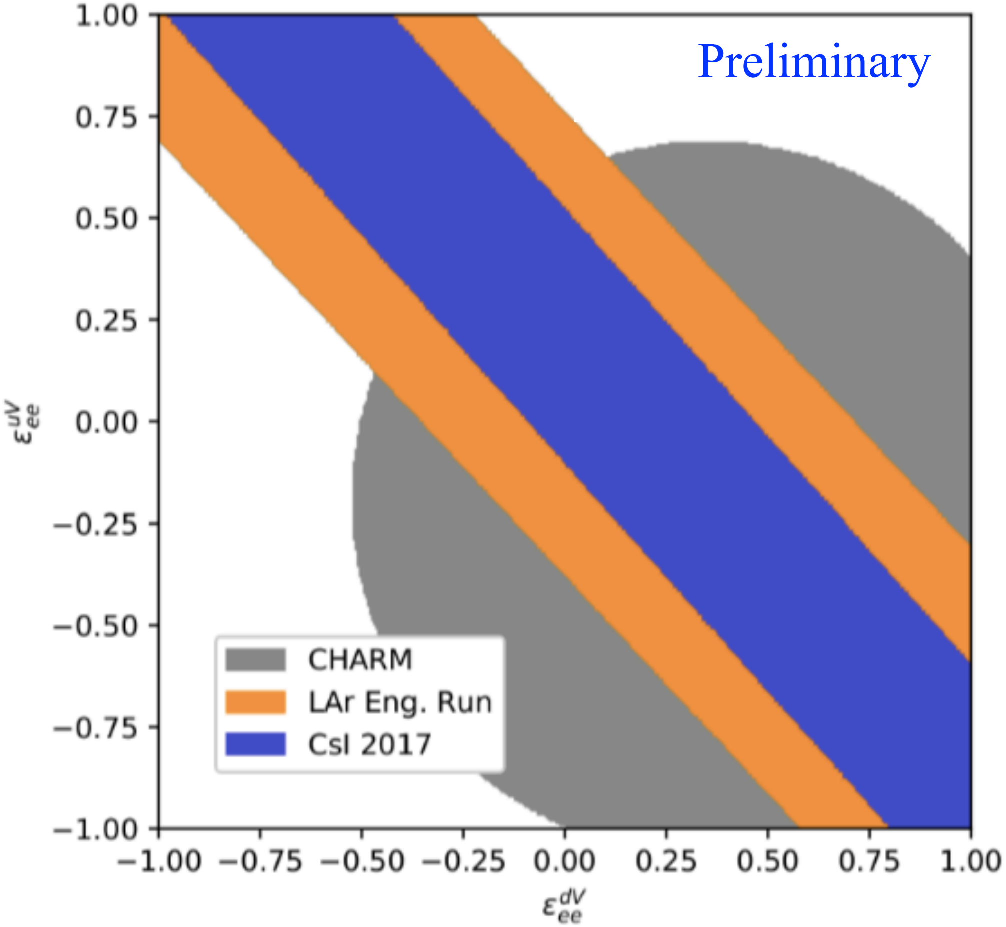


Constraint on Non-Standard Neutrino Interactions

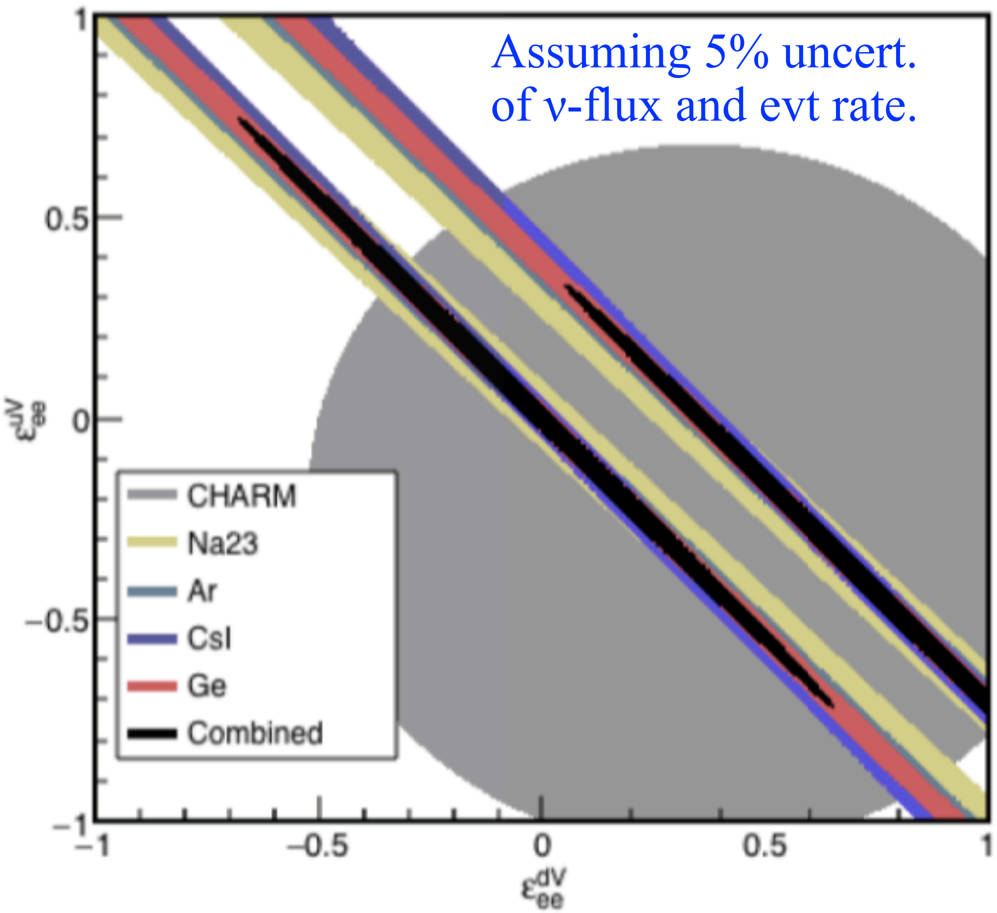
$$\mathcal{L}_{\nu H}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta=e,\mu,\tau}} [\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5)\nu_\beta] \times (\varepsilon_{\alpha\beta}^{qL}[\bar{q}\gamma_\mu(1-\gamma^5)q] + \varepsilon_{\alpha\beta}^{qR}[\bar{q}\gamma_\mu(1+\gamma^5)q])$$

for Non-Standard proton neutron coupling parameters

$$(g_V^p + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV})Z + (g_V^n + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV})N$$

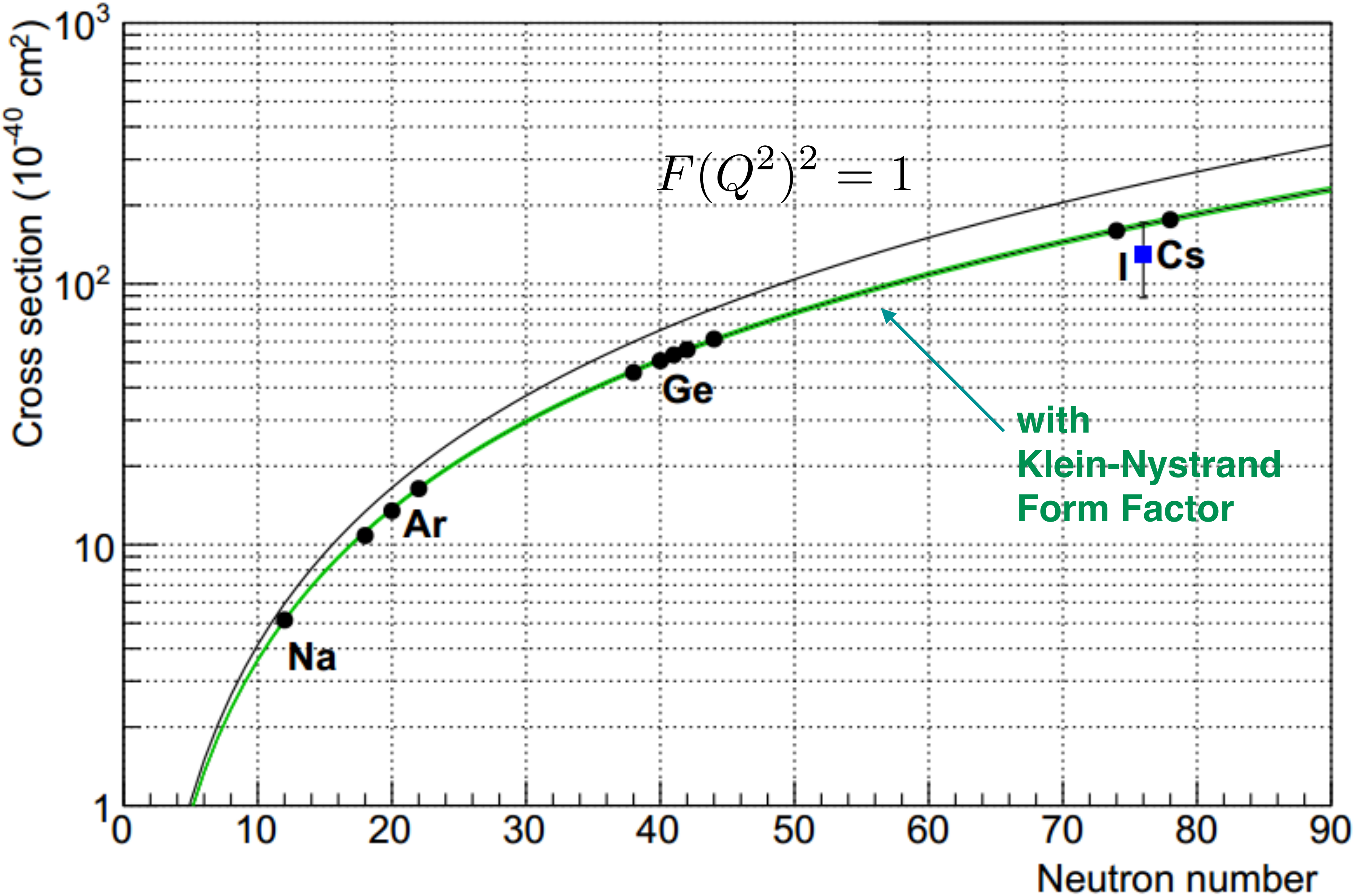


arXiv:1803.09183 by COHERENT



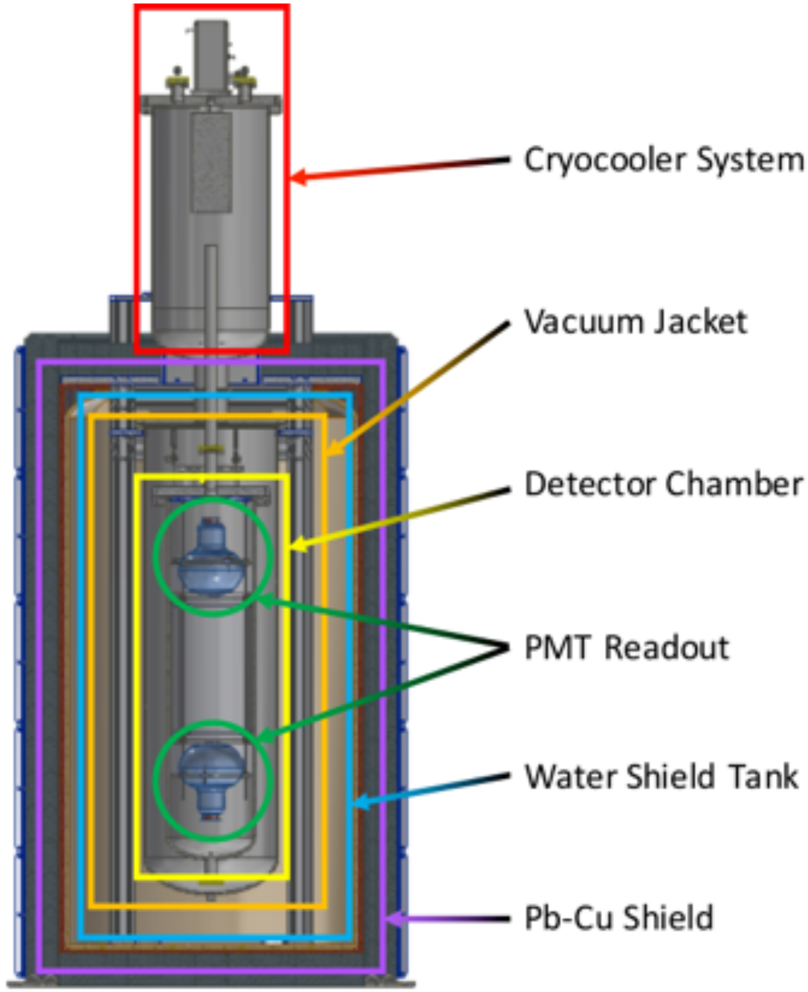
CEvNS Cross Section and Nuclear Form Factors

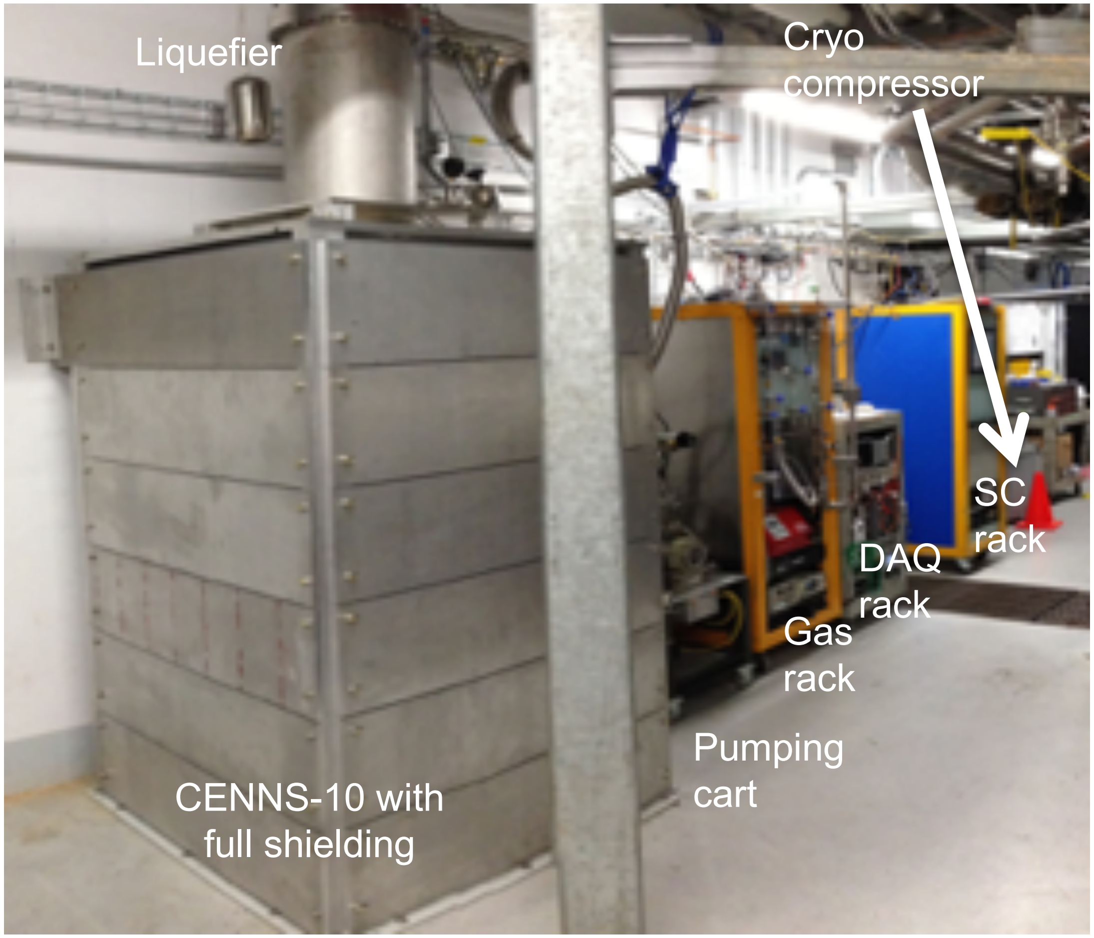
$$\frac{d\sigma}{dE} = \frac{G_F^2}{4\pi}[(1-4\sin^2\theta_w)Z - (A-Z)]^2 M \left(1 - \frac{ME}{2E_\nu^2}\right) F(Q^2)^2$$



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

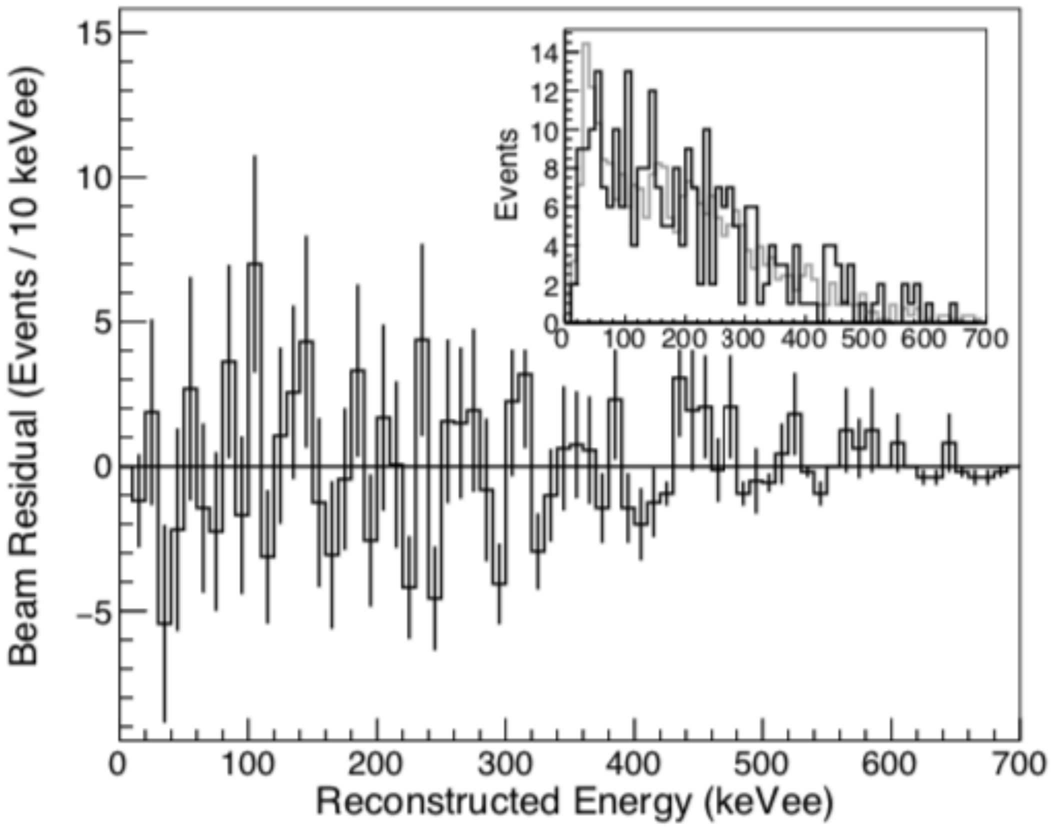


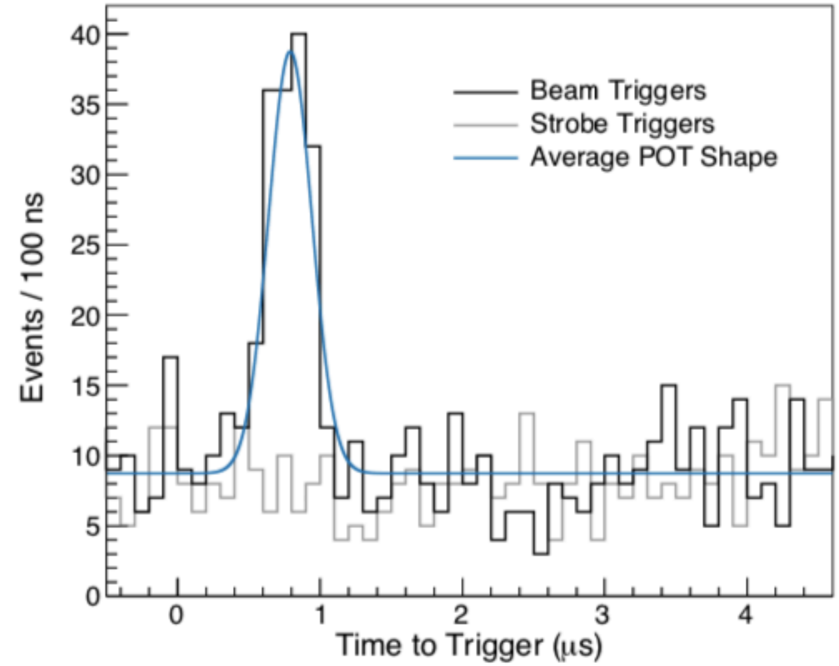


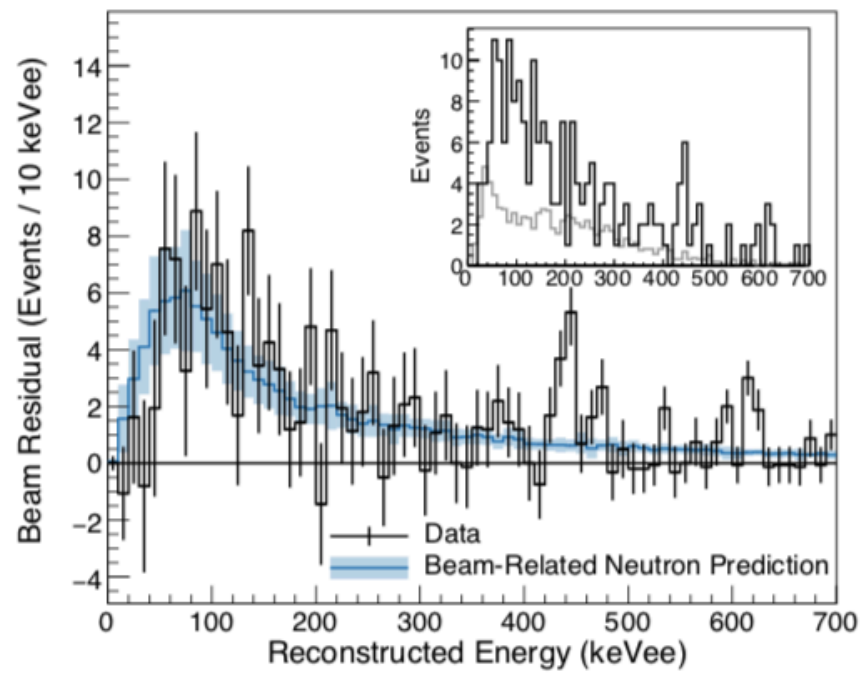
CENNS-10 (LAr): Engineering Run

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

arXiv:1909.05913



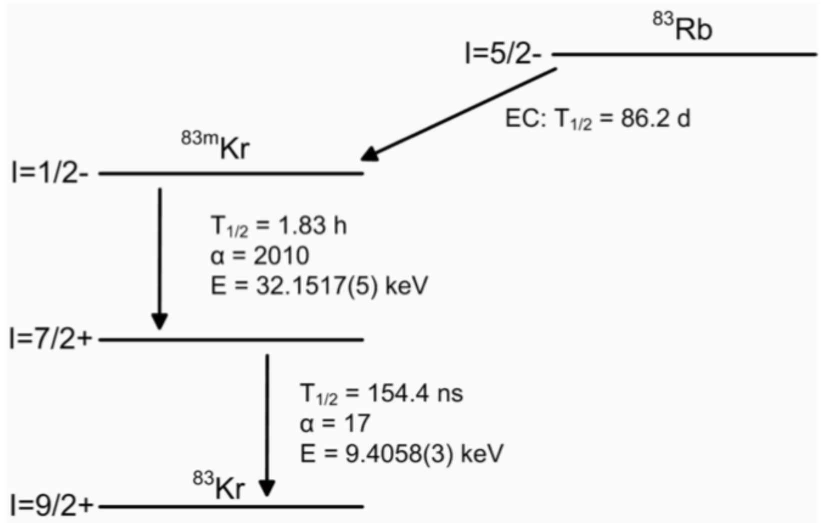


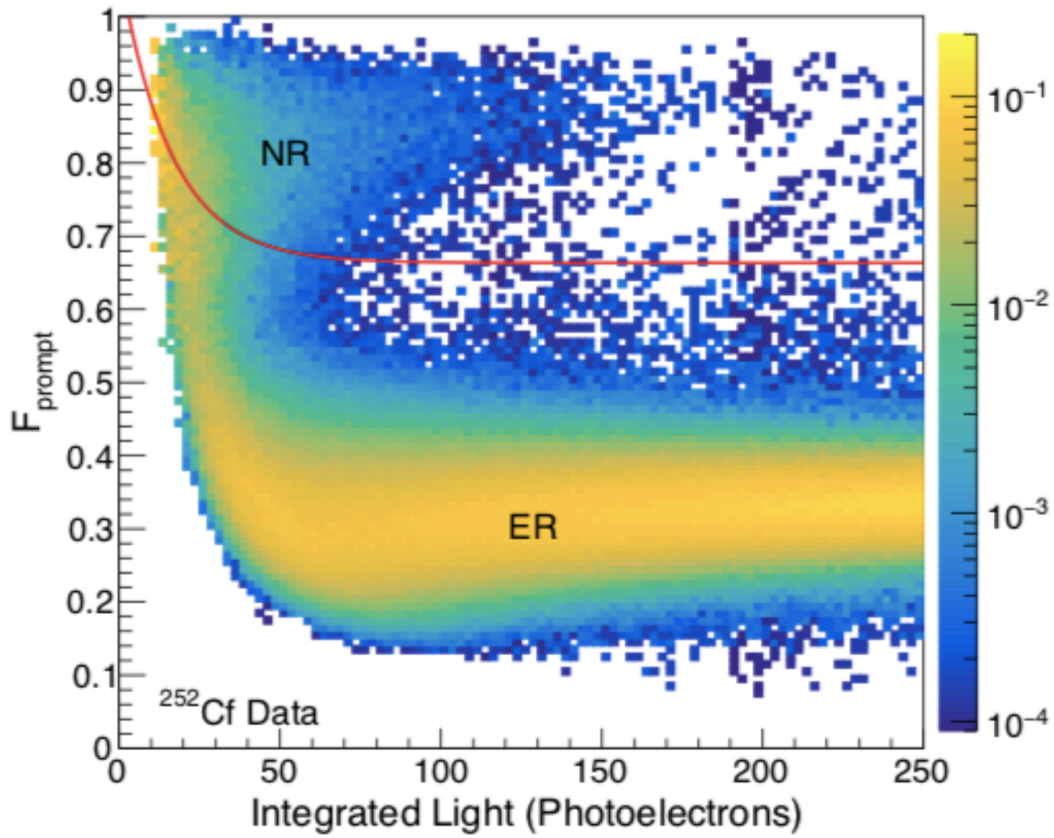


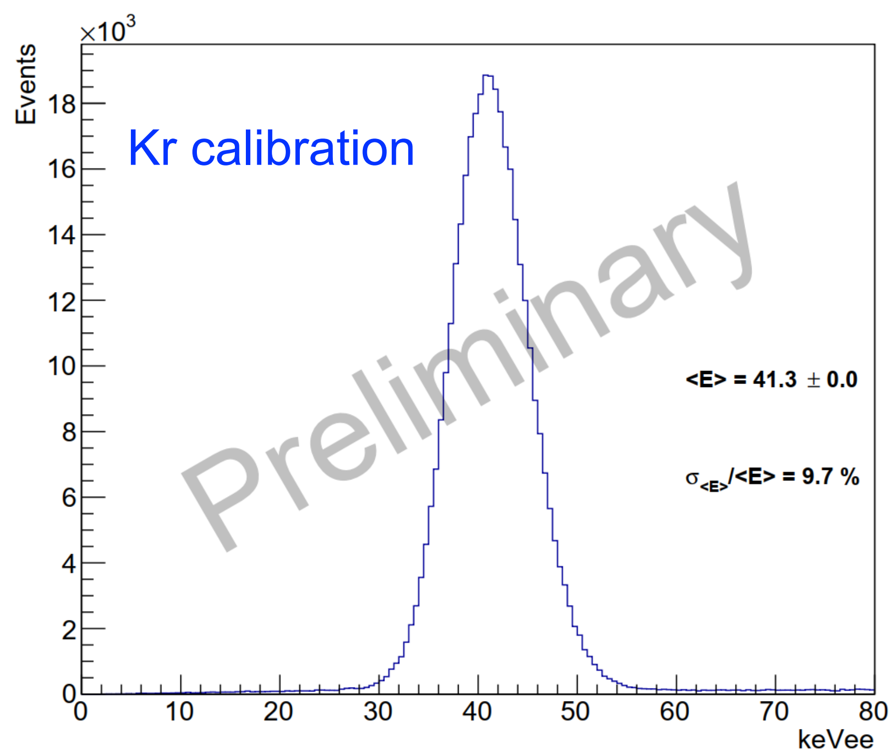
CENNS-10 (LAr): CEvNS Physics Run

July 2017 ~ : CEvNS physics run

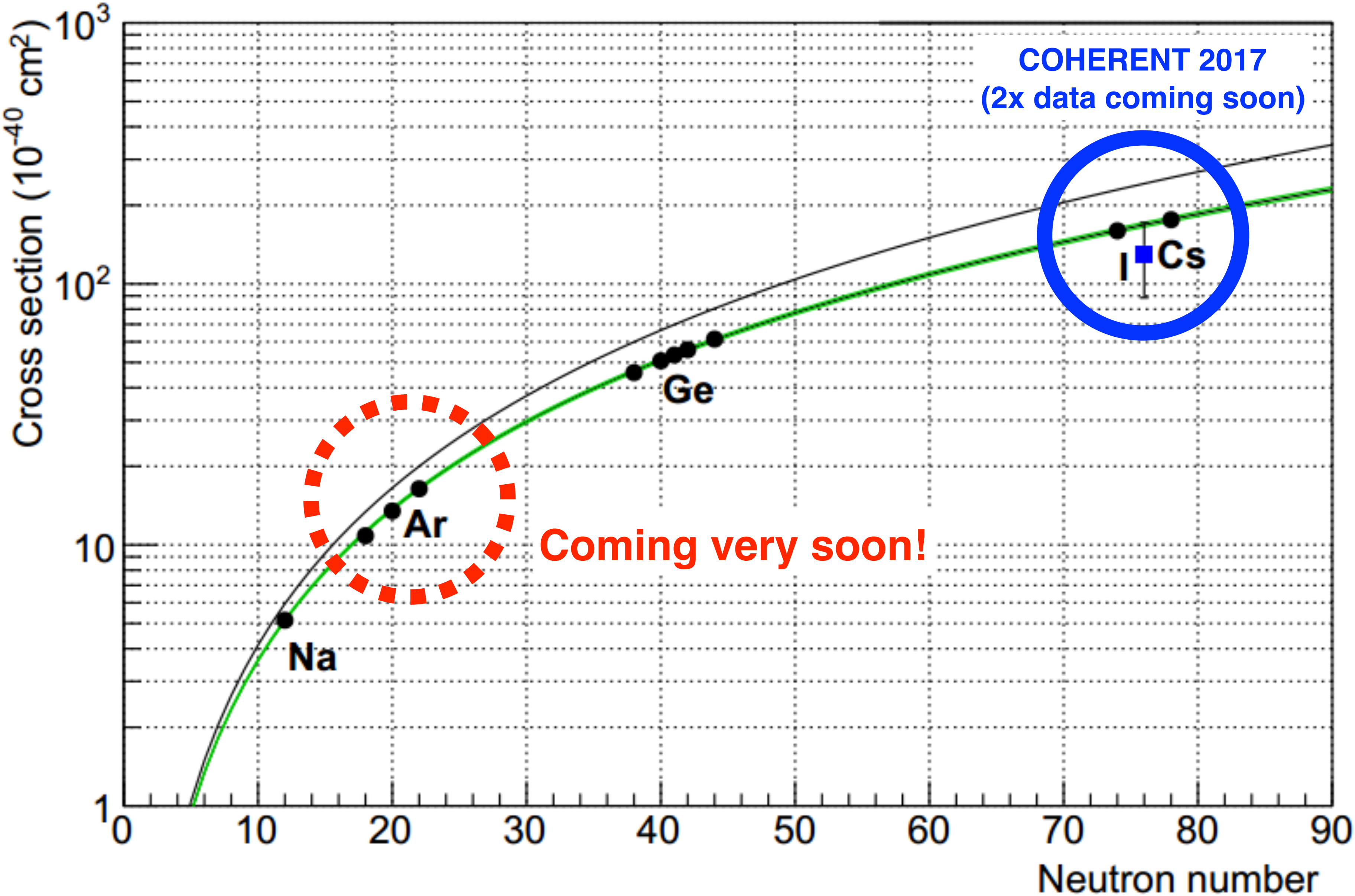
- Light yield: ~4 p.e./keV (^{83m}Kr calibration)
- Pulse shape discrimination, energy resolution and threshold appears good to test CEvNS in LAr
- **Unblinding the physics run data set now!**





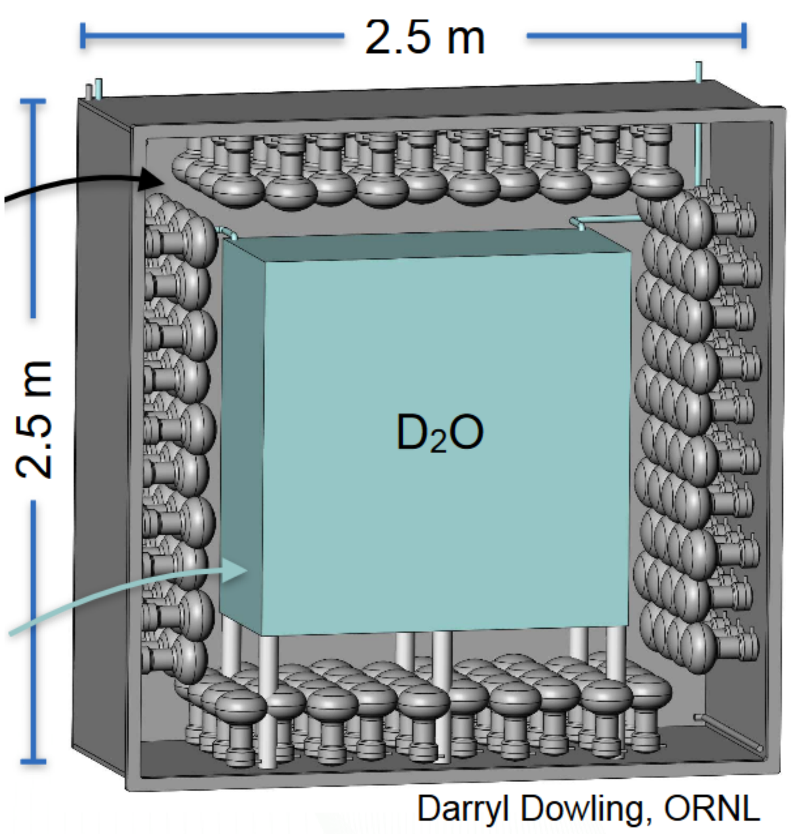


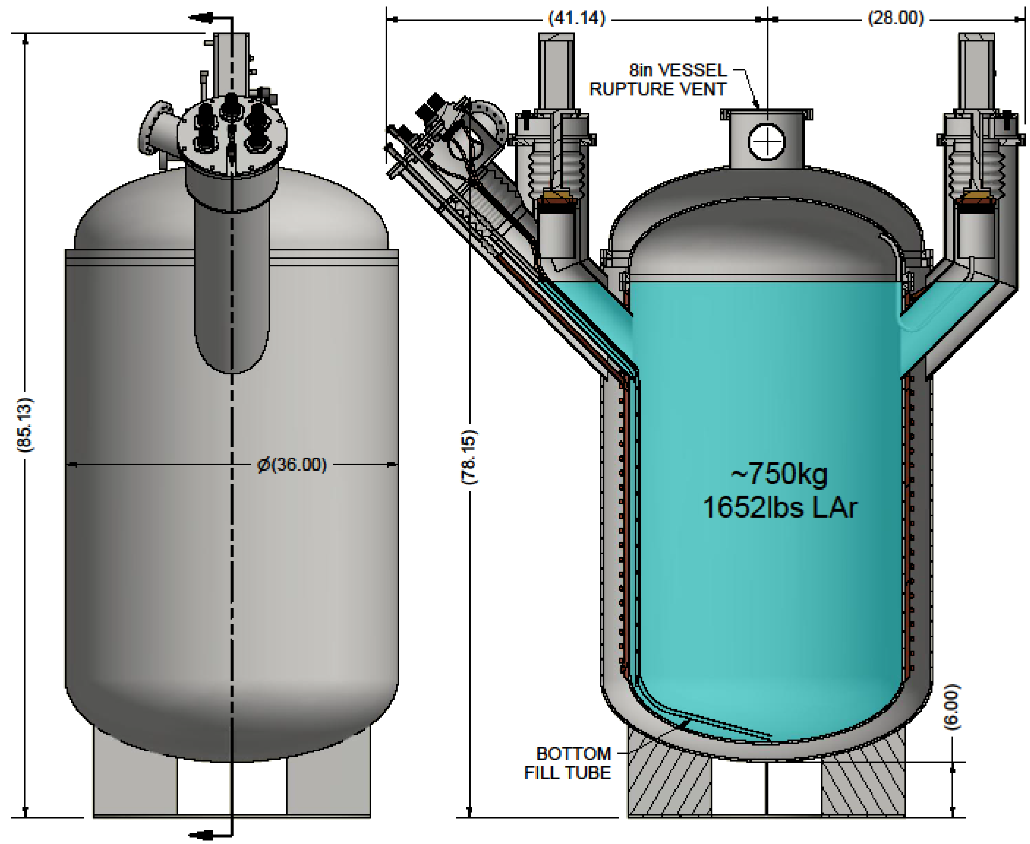
CENNS-10 (LAr): CEvNS Physics Run



COHERENT: What Next?

- **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





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 (addition to 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