CENNS-1ton Experiment

Haemin Jeong

Overview

CENNS-1ton

ton-scale Liquid Argon detector

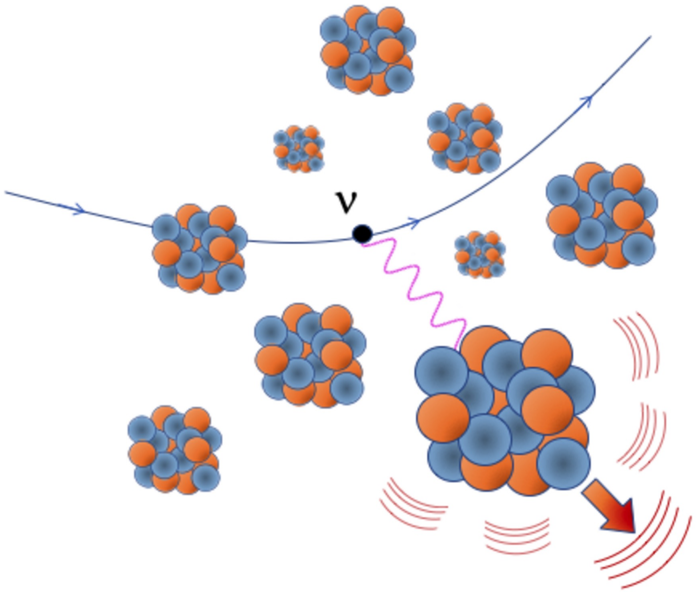
at Spallation Neutron Source

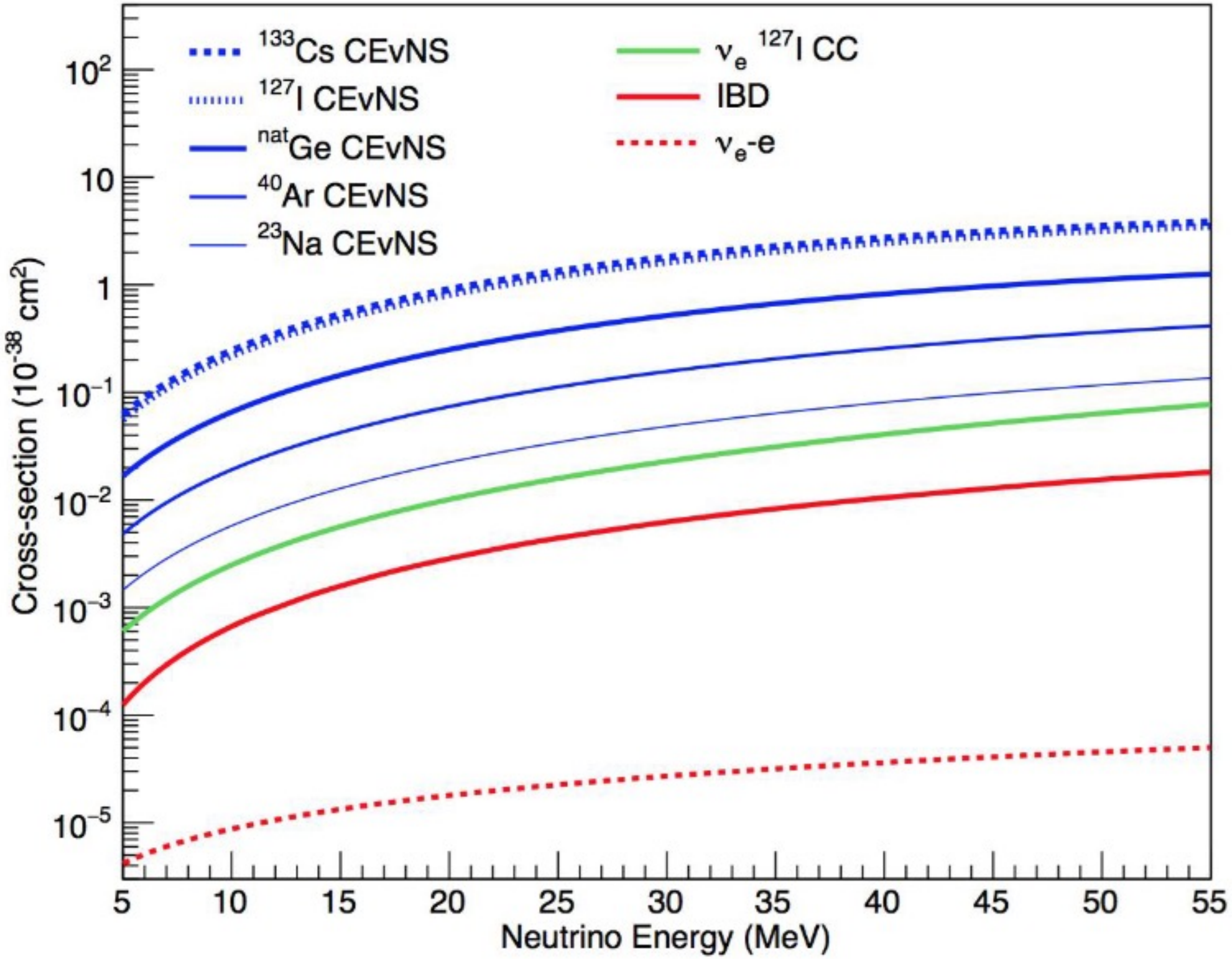
for precise CEvNS measurment

replacing CENNS-10

Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

- Neutrino interact with whole nucleus
  - Coherence condition: $E_\nu < 50\mathrm{MeV}$
  - Dominant process for $E_\nu < 100\mathrm{MeV}$
  - Small recoil energy $\boldsymbol{T < 50\mathrm{keV}}$





Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

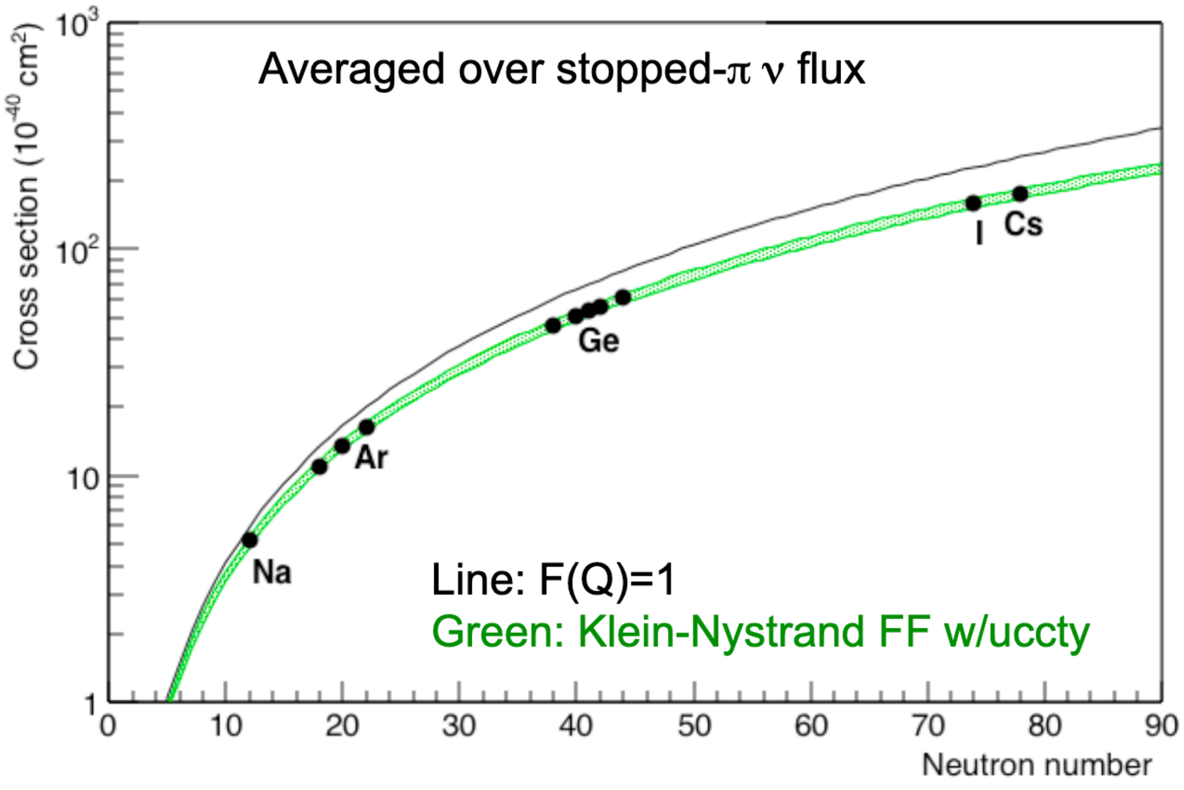
- Precisely predicted within the Standard Model

$$\frac{d\sigma}{dT} \cong \frac{G_F^2 M}{2\pi}\frac{Q_W^2}{4}F^2(Q)\left(2-\frac{MT}{E_\nu^2}\right)$$

E_ν: neutrino energy
T: nuclear recoil energy (~10 keV)
M: nuclear mass
Q: momentum transfer ($Q^2 = 2MT$)
$F(Q)$: nuclear form factor

$$Q_W = N - (1 - 4\sin^2\theta_W)Z$$
$$= N - 0.076\,Z$$

→ **N^2 dependence** in Standard Model



Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

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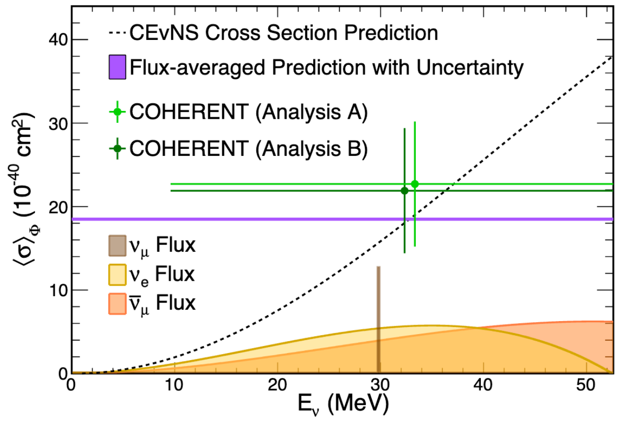
(Received 15 October 1973; revised manuscript received 19 November 1973)

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.

first theorized



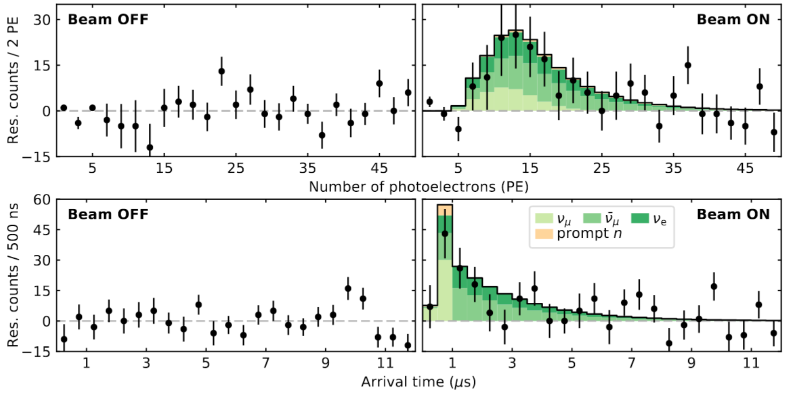
first observed at 3σ (CENNS-10, COHERENT)

1974

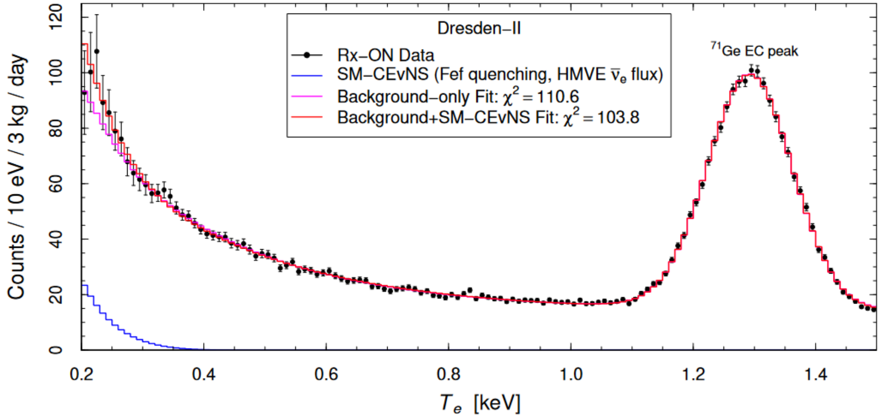
2017

2020

2022



first observed at 6.7σ (CsI, COHERENT)



first observed from reactor (Dresden-II)

Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

NOW… There are many CEvNS experiments

Experiment	Technology	Location	Source
COHERENT	CsI, Ar, Ge, NaI	USA	πDAR
CCM	Ar	USA	πDAR
ESS	CsI, Si, Ge, Xe	Sweden	πDAR
BULLKID	Si/Ge	Italy	Reactor
CONNIE	Si CCDs	Brazil	Reactor
CONUS	HPGe	Germany	Reactor
NEWS-G	Ar+2%CH4	Canada	Reactor
MINER	Ge/Si cryogenic	USA	Reactor
NEON	NaI(Tl)	Korea	Reactor
NUCLEUS	$CaWO_4$, Al_2O_3 cryogenic	Europe	Reactor
νGEN	Ge PPC	Russia	Reactor
RED-100	LXe dual phase	Russia	Reactor
Ricochet	Ge, Zn, Al, Sn cryogenic	France	Reactor
TEXONO	p-PCGe	Taiwan	Reactor
Dresden II	PCGe	USA	Reactor
SBC	Scintillating Bubble Chamber	Fermilab (R&D)	Reactor

Enectali Figueroa-Feliciano / Magnificent CEvNS / Mar 2023

CEvNS related physics

- Supernova Dynamics
- Nuclear Form Factor
- Non-Standard Interactions (NSI)
- Sterile Neutrino
- Dark Matter Background (Neutrino Floor)
- Beam Produced Dark Matter
- Weak Mixing Angle
- Neutrino EM property

CEvNS related physics

SM CEvNS cross section

$$\frac{d\sigma}{dT} \cong \frac{G_F^2 M}{2\pi} \frac{Q_W^2}{4} F^2(Q) \left(2 - \frac{MT}{E_\nu^2}\right)$$

$$Q_W = N - (1 - 4\,\mathbf{sin^2}\,\boldsymbol{\theta_W})Z$$

Weak mixing angle

Nuclear Form Factor

CEvNS related physics

SM CEvNS cross section

$$\frac{d\sigma}{dT} \cong \frac{G_F^2 M}{2\pi} \frac{Q_W^2}{4} F^2(Q) \left(2 - \frac{MT}{E_\nu^2}\right)$$

Considering vector mediated Non-Standard Interactions (NSI)

$$Q_W^2 \rightarrow Q_{NSI}^2 = \left[\left(g_V^P + 2\epsilon_{\alpha\alpha}^{uV} + \epsilon_{\alpha\alpha}^{dV}\right) Z F_Z(Q) + \left(g_V^n + \epsilon_{\alpha\alpha}^{uV} + 2\epsilon_{\alpha\alpha}^{dV}\right) N F_N(Q)\right]^2$$

$$+ \sum_{\beta \neq \alpha} \left|\left(2\epsilon_{\alpha\beta}^{uV} + \epsilon_{\alpha\beta}^{dV}\right) Z F_Z(Q) + \left(\epsilon_{\alpha\beta}^{uV} + 2\epsilon_{\alpha\beta}^{dV}\right) N F_N(Q)\right|^2$$

$$\frac{d\sigma}{dT} \cong \frac{G_F^2 M}{2\pi} \frac{Q_{NSI}^2}{4} F^2(Q) \left(2 - \frac{MT}{E_\nu^2}\right)$$

CEvNS related physics

SM CEvNS cross section

$$\frac{d\sigma}{dT} \cong \frac{G_F^2 M}{2\pi} \frac{Q_W^2}{4} F^2(Q)\left(2 - \frac{MT}{E_\nu^2}\right)$$

Considering neutrino EM moment

$$\frac{d\sigma_{\nu_\alpha - N}}{dT} = \frac{G_F^2 M}{\pi}\left(2 - \frac{MT}{E_\nu^2}\right)\left[-\frac{1}{2} N F_N(Q) + \left(\frac{1}{2} - 2\sin^2\theta_W\right) Z F_Z(Q)\right]^2$$

$$+ \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T} - \frac{1}{E_\nu}\right) Z^2 F_Z^2(Q) \frac{\mu_{\nu_\alpha}^2}{\mu_B^2}$$

CEvNS related physics

SM CEvNS cross section

$$\frac{d\sigma}{dT} \cong \frac{G_F^2 M}{2\pi}\frac{Q_W^2}{4}F^2(Q)\left(2-\frac{MT}{E_\nu^2}\right)$$

Considering radiative correction for neutrino charge radius

$$< r_{\nu_\alpha}^2 > = -\frac{G_F}{2\sqrt{2}\pi^2}\left[3-2\log\left(\frac{m_\alpha^2}{m_W^2}\right)\right]$$

It affects CEvNS cross section

$$\frac{d\sigma_{\nu_\alpha - N}}{dT} = \frac{G_F^2 M}{\pi}\left(2-\frac{MT}{E_\nu^2}\right)\left[-\frac{1}{2}NF_N(Q)+\left(\frac{1}{2}-2\sin^2\theta_W-\frac{2}{3}m_W^2\sin^2\theta_W < r_{\alpha\alpha}^2 >\right)ZF_Z(Q)\right]^2$$

$$+\frac{4}{9}m_W^4\sin^4\theta_W Z^2F_Z^2(Q)\sum_{\beta\neq\alpha}\left|< r_{\beta\alpha}^2 >\right|^2$$

CEvNS related physics

Precision measurement of CEvNS is important

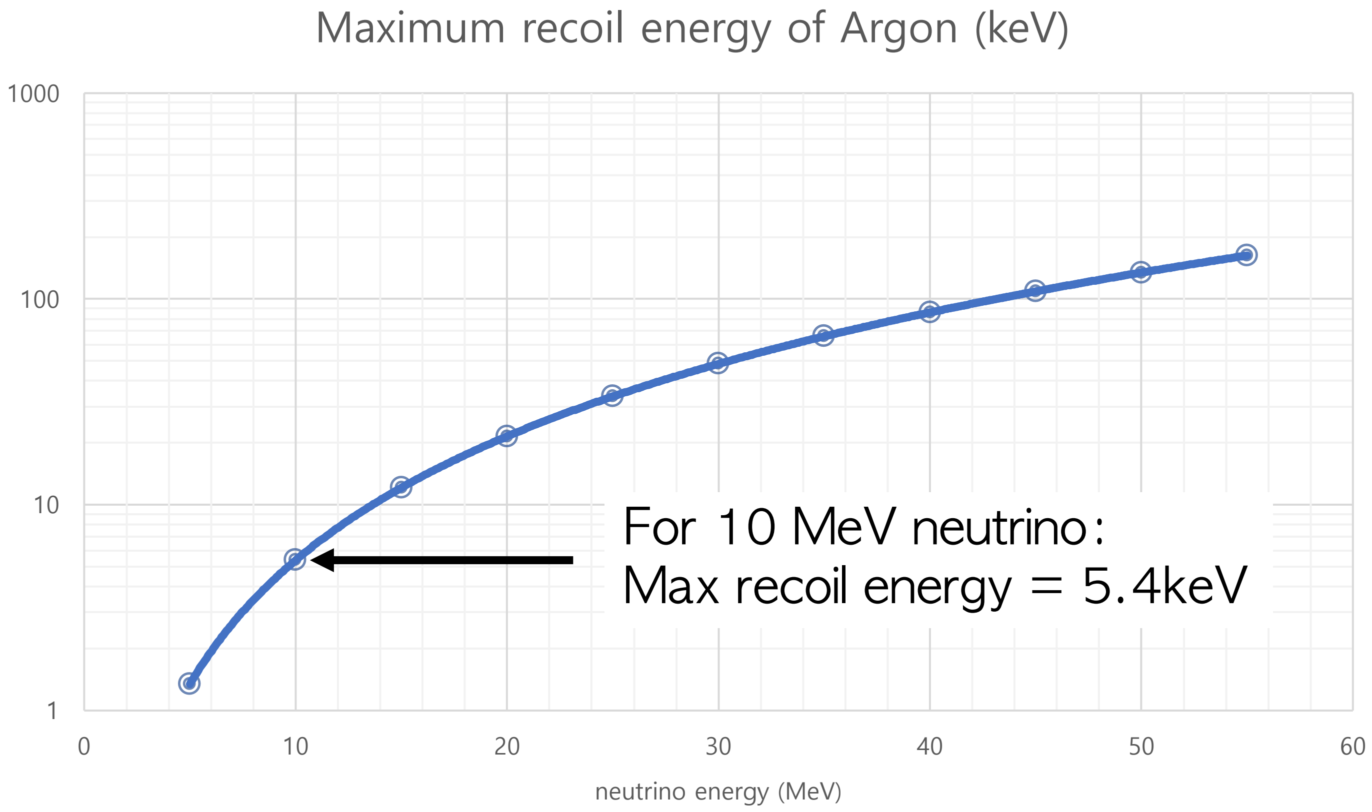
for many physics opportunities

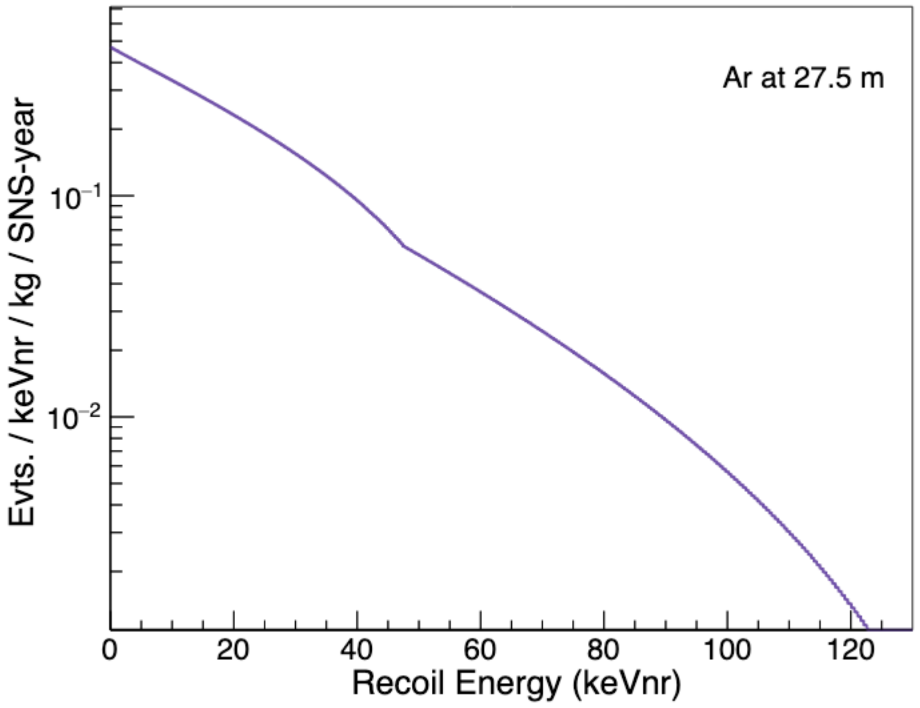
But hard to detect

How did CENNS-10 Measure CEvNS?

Measurable CEvNS Observable: O(10keV) nuclear recoil

Max recoil energy $\cong 2E_\nu^2/M$





How did CENNS-10 Measure CEvNS?

Spallation Neutron Source (SNS)

- High background rejection factor
- well-known neutrino energy & timing spectra

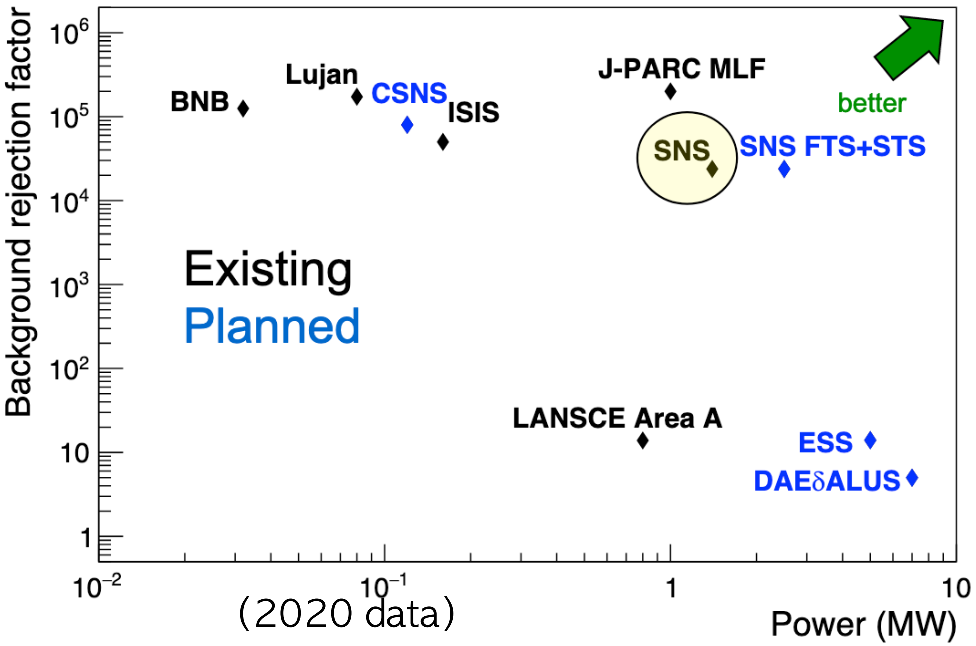
Liquid Argon

- high scintillation yield
- easily distinguish electron recoil by PSD

Low threshold & Low background

Spallation Neutron Source (SNS)

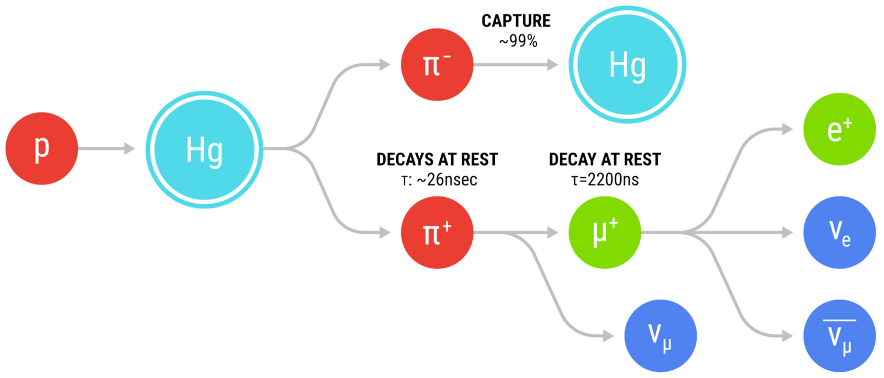
- Neutron Source in Oak Ridge National Laboratory (ORNL)
- Produce neutron by p-Hg collision (spallation)
- Neutrino is by-product from stopped pion decay

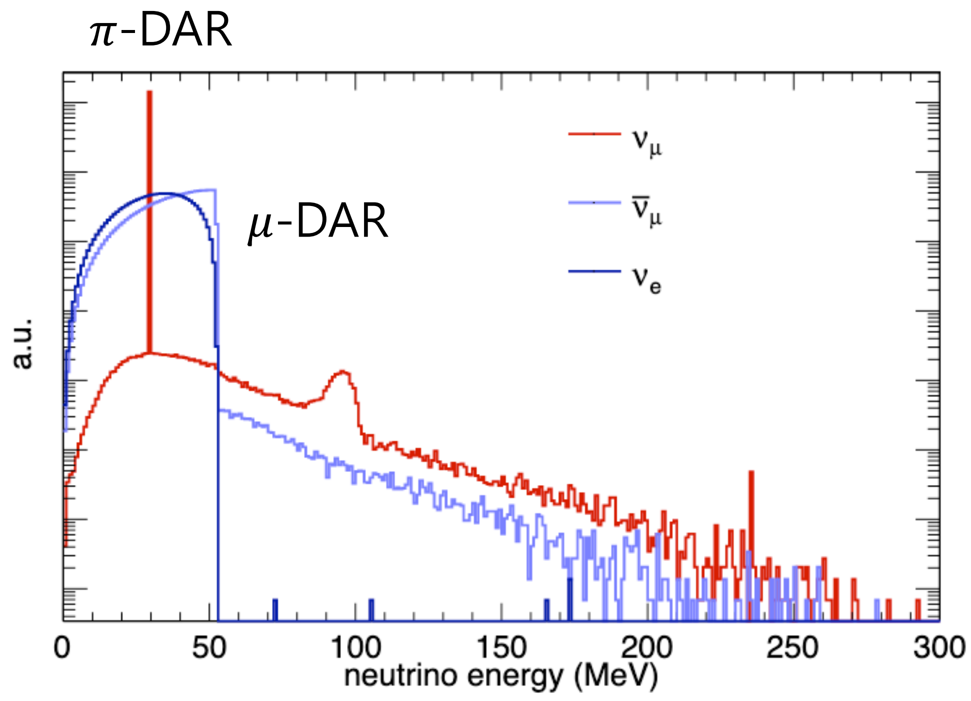


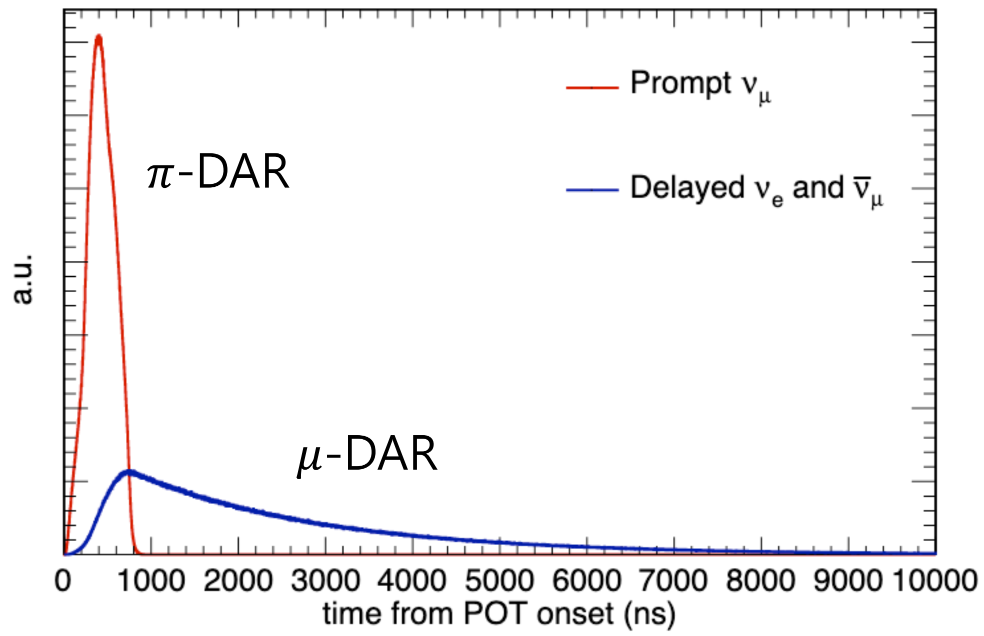
(2020 data)

Spallation Neutron Source (SNS)

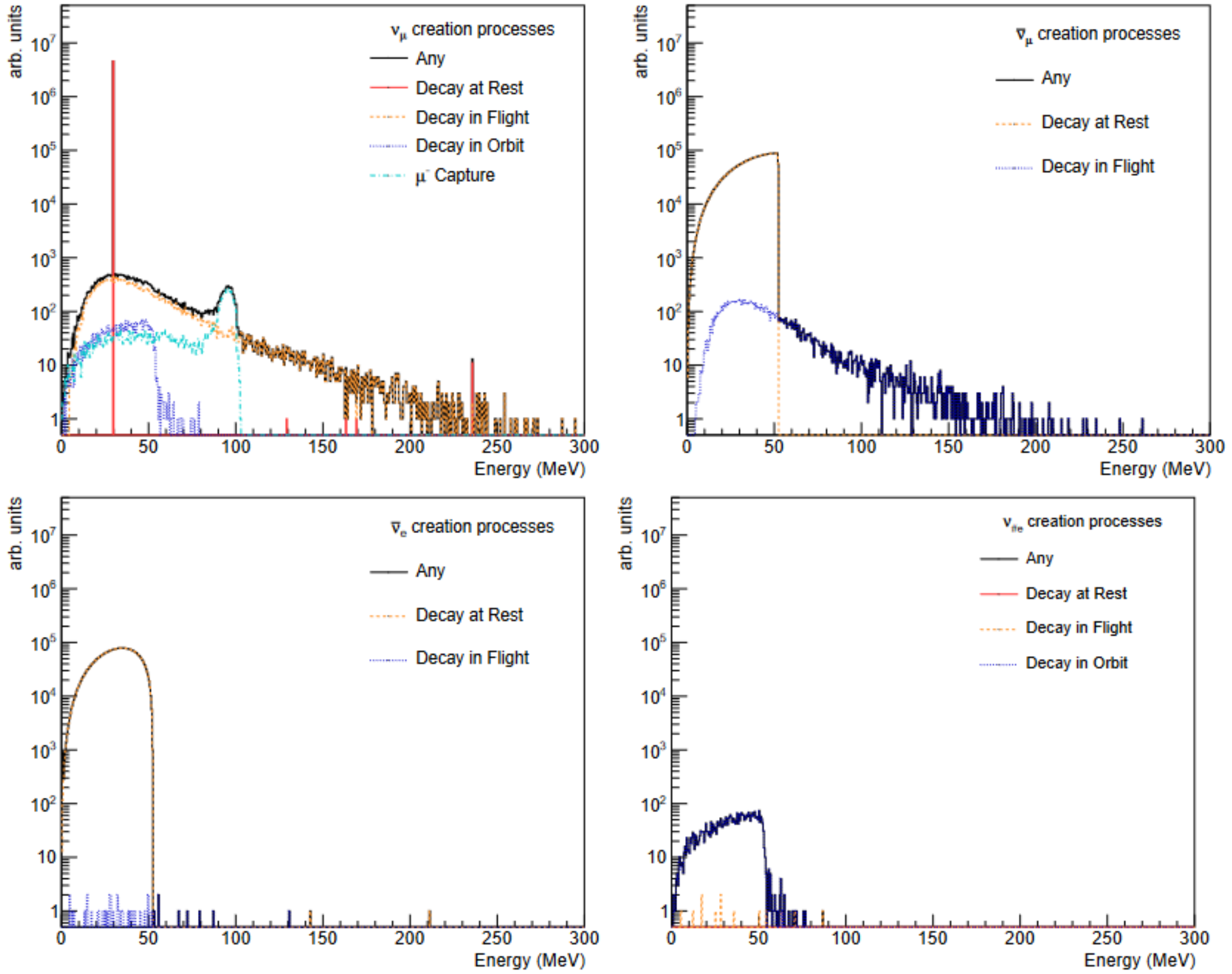
- Well known neutrino energy & timing spectrum from π-DAR
- 1GeV 60Hz proton beam with 1.4 MW
- ~7000 MWhr/year, ~4.25E22 neutrinos/year







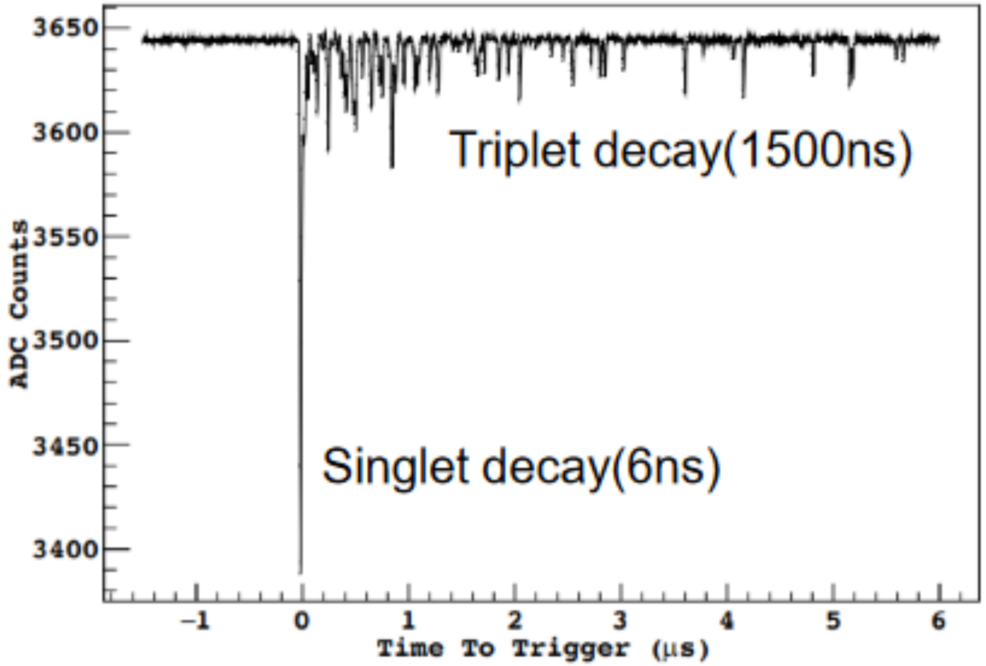
neutrino flux simulation at SNS using Geant4



	ν / POT	DAR	DIF	μ^- Cap	μ^- DIO	π^+ / μ^+	π^- / μ^-	K^+
ν_μ	0.0875	98.940%	0.779%	0.196%	0.084%	99.7185%	0.2812%	0.0003%
$\bar{\nu}_\mu$	0.0875	99.718%	0.282%	—	—	99.7187%	0.2813%	—
ν_e	0.0872	99.999%	0.001%	—	—	99.9999%	—	0.0001%
$\bar{\nu}_e$	0.0001	—	0.331%	—	99.669%	—	100%	—

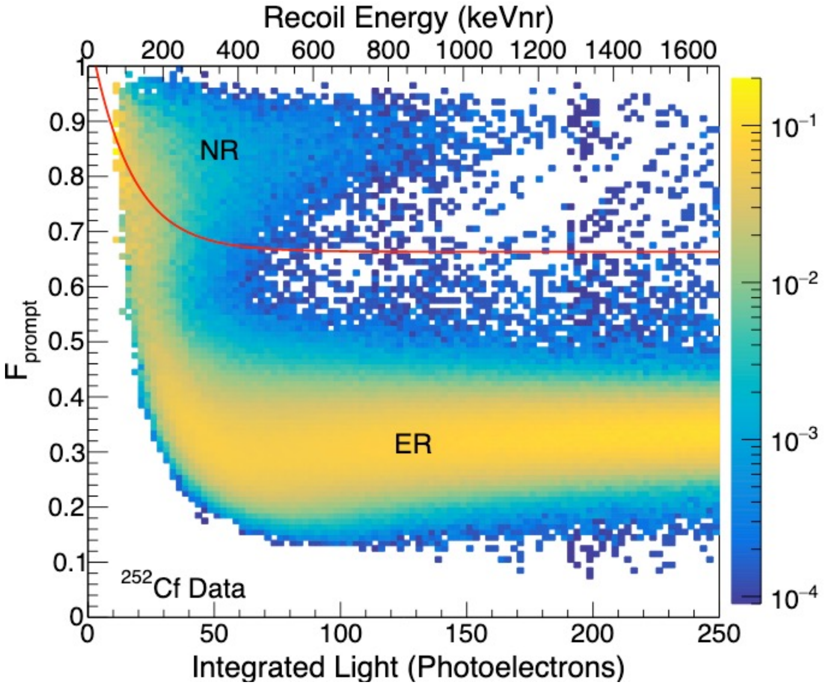
Liquid Argon

- very high scintillation yield (~40 photons/keVee)
- two excited states allow to distinguish nuclear recoil (NR) from electron recoil (ER)



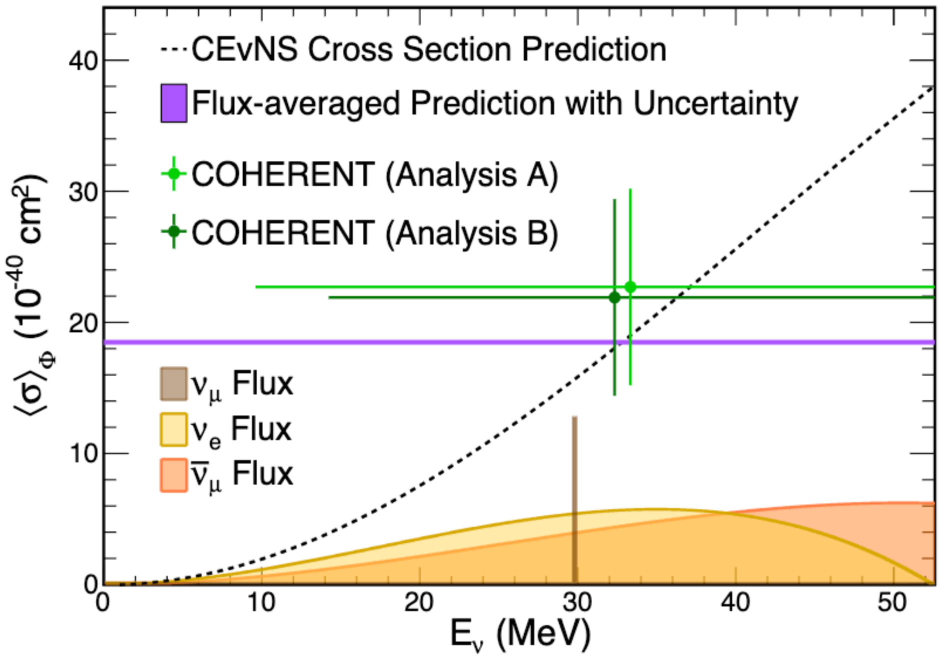
Use ratio

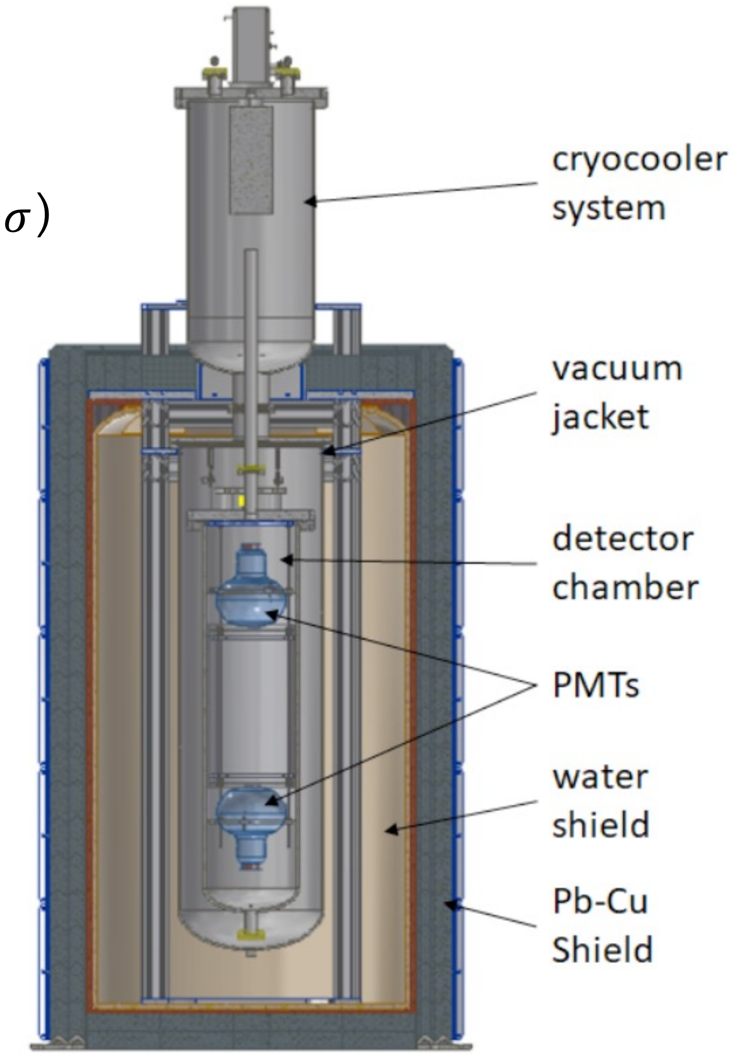
singlet decay to triplet decay



CENNS-10

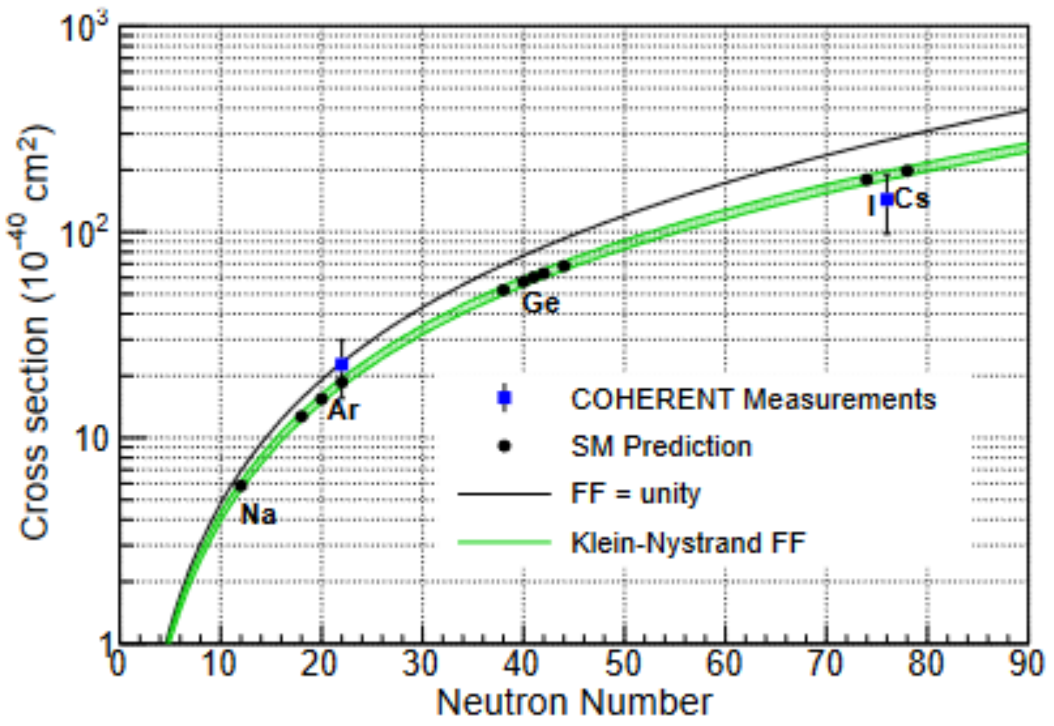
- 24-kg Liquid Argon detector at Spallation Neutron Source
- Low threshold: 20 keVnr / 4keVee
- Measured CEvNS cross section in 2020 (Reject null hypothesis at >3σ)
- Final analysis with x2 more data in progress

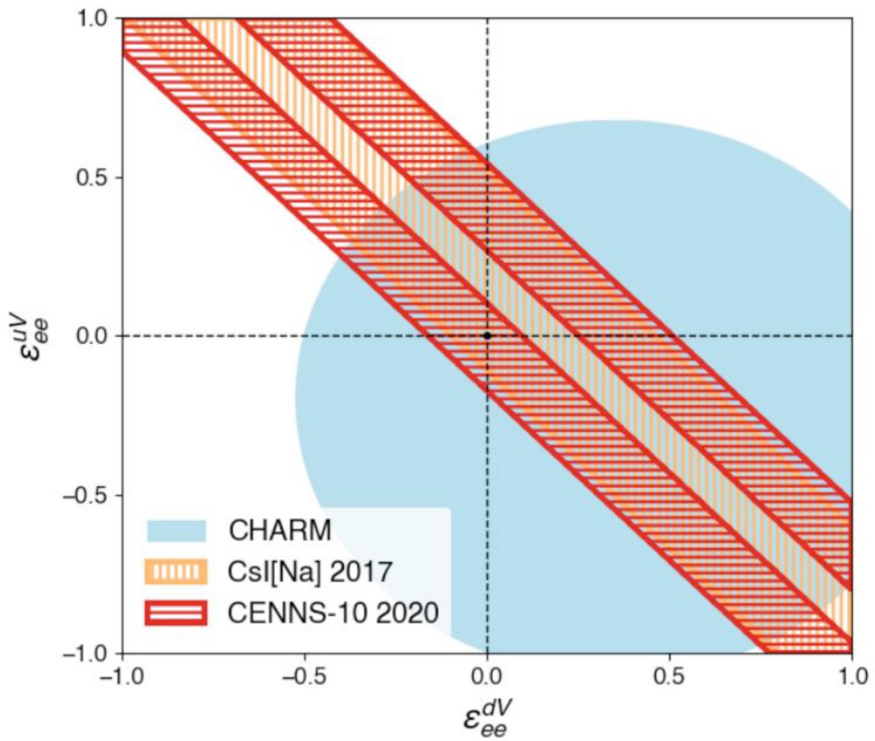




CENNS-10

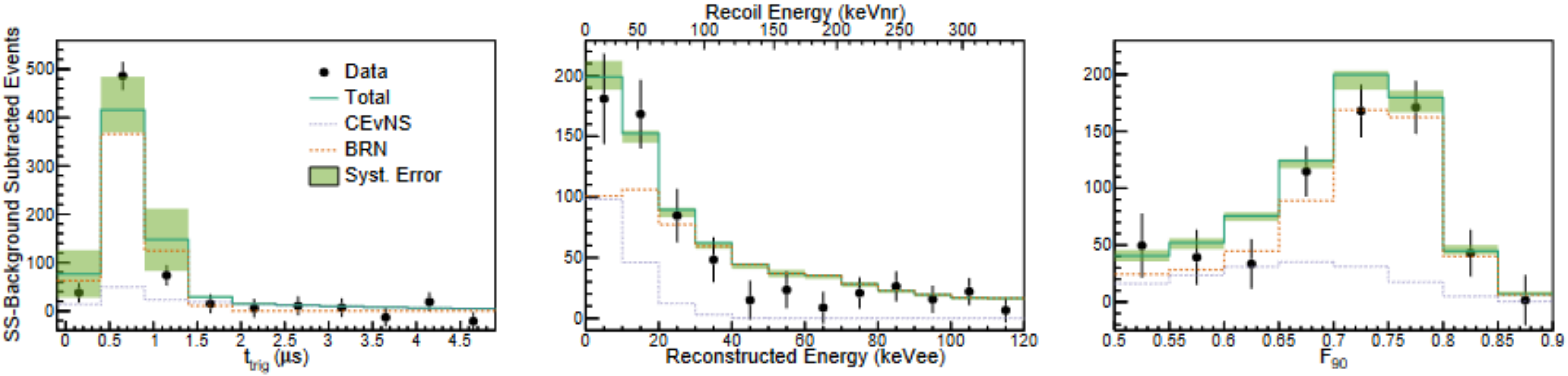
- Confirm N^2 dependence with the result of CsI detector
- Improved limits on non-standard interaction parameter





CENNS-10

- signals from three events: SSB, BRN, CEvNS
- Remove SSB (steady-state background) by subtracting beam-off from beam-on
- Calculate BRN (beam related neutron) by simulating with no water-shielding data
- Use time – energy – F90 3D distribution to extract CEvNS from background



CENNS-10

fit values (without systematic error)	US analysis	Moscow analysis
N_{CEvNS}	159 ± 43	121 ± 36
N_{BRN}, prompt	553 ± 34	222 ± 23
N_{BRN}, delayed	10 ± 11	
N_{SS}	3131 ± 23	1112 ± 41
total events fit	3853	1455

~30% statistical uncertainty

in CEvNS

CEvNS Rate Measurement Systematic Errors	
Error Source	Total Event Uncertainty
Quenching Factor	1.0%
Energy Calibration	0.8%
Detector Model	2.2%
F_{90}	7.8%
Active Volume	2.5%
Event Acceptance	1.0%
Nuclear Form Factor	2.0%
SNS Predicted Neutrino Flux	10%
Total Error	13.4%

- Statistical uncertainty : ~30%
- Systematic uncertainty : ~13%
  - Neutrino flux : ~10%

precision measurement strategy

Statistical uncertainty

- CENNS-1ton
- ~30% → ~4%

Neutrino Flux

- D2O detector
- ~10% → ~5% (theoretical limit = 3%)

Steady-State Background

- Use underground argon (UAr) instead of atmospheric argon (AAr)
- → reduce ^{39}Ar decay background

Beam Related Neutron (BRN)

- MARS detector
- → precision measurement of BRN

CENNS-1ton

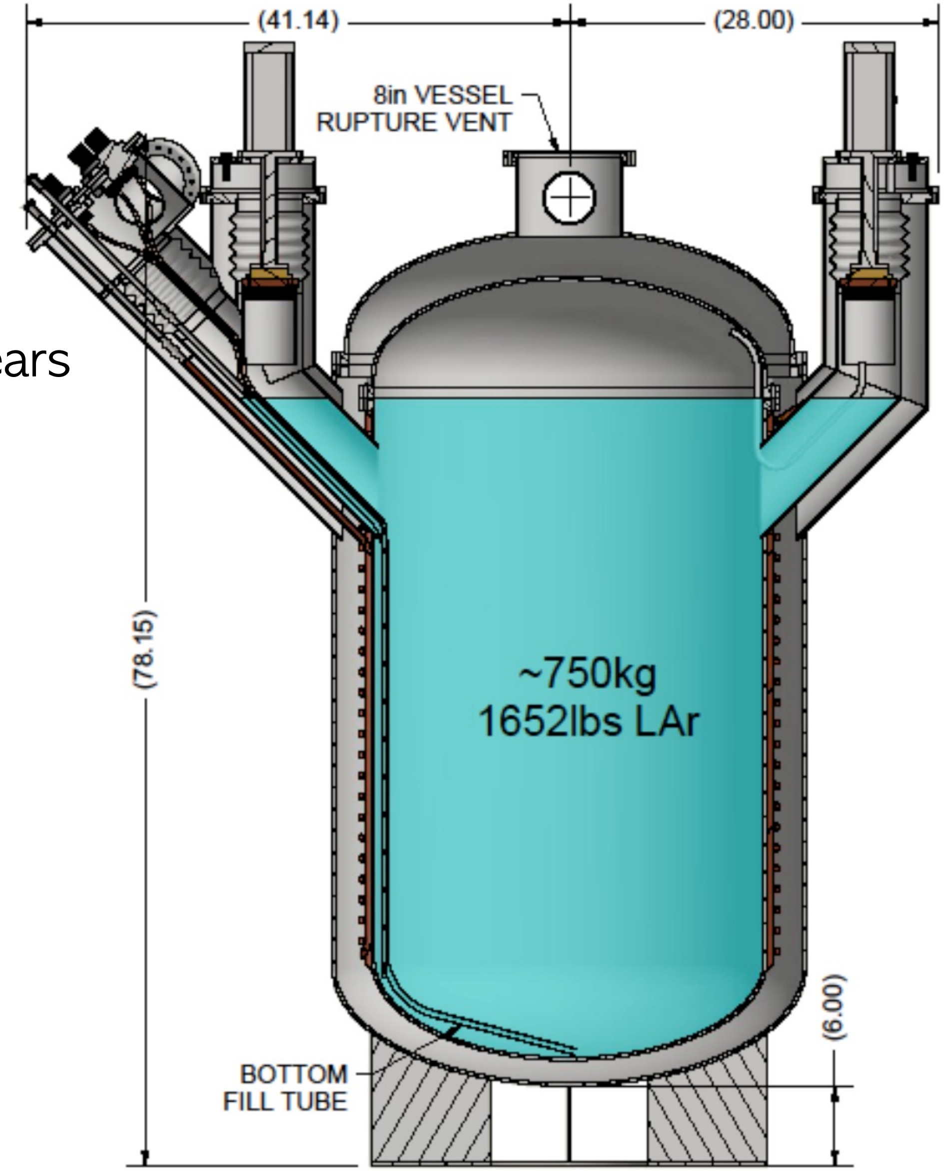
- 750-kg Liquid Argon detector replacing CENNS-10
- Observe ~3000 CEvNS/year
- Reduce statistical error from ~30% to ~4% within 3 years
- Construct in 2023~2024

$$N_{CEVNS} = 159\times\left(\frac{1yr}{1.5yr}\right)\times\left(\frac{610kg}{24kg}\right) \cong 3000$$

CENNS-10 data

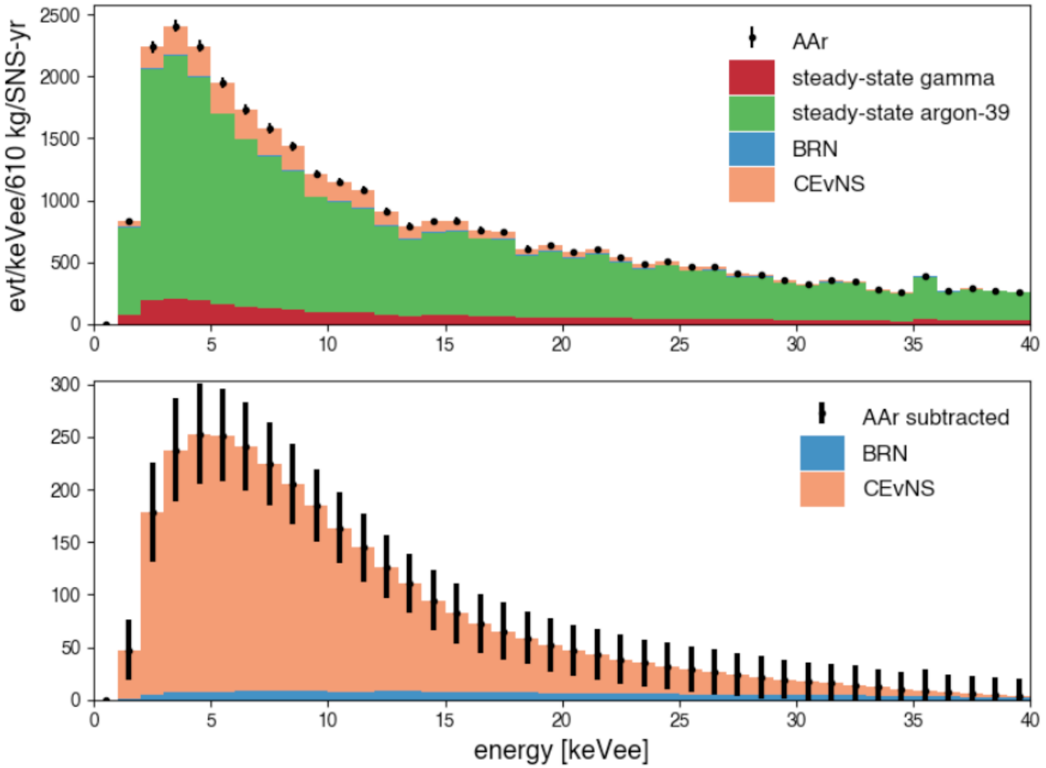
159 CEvNS for 1.5 yr

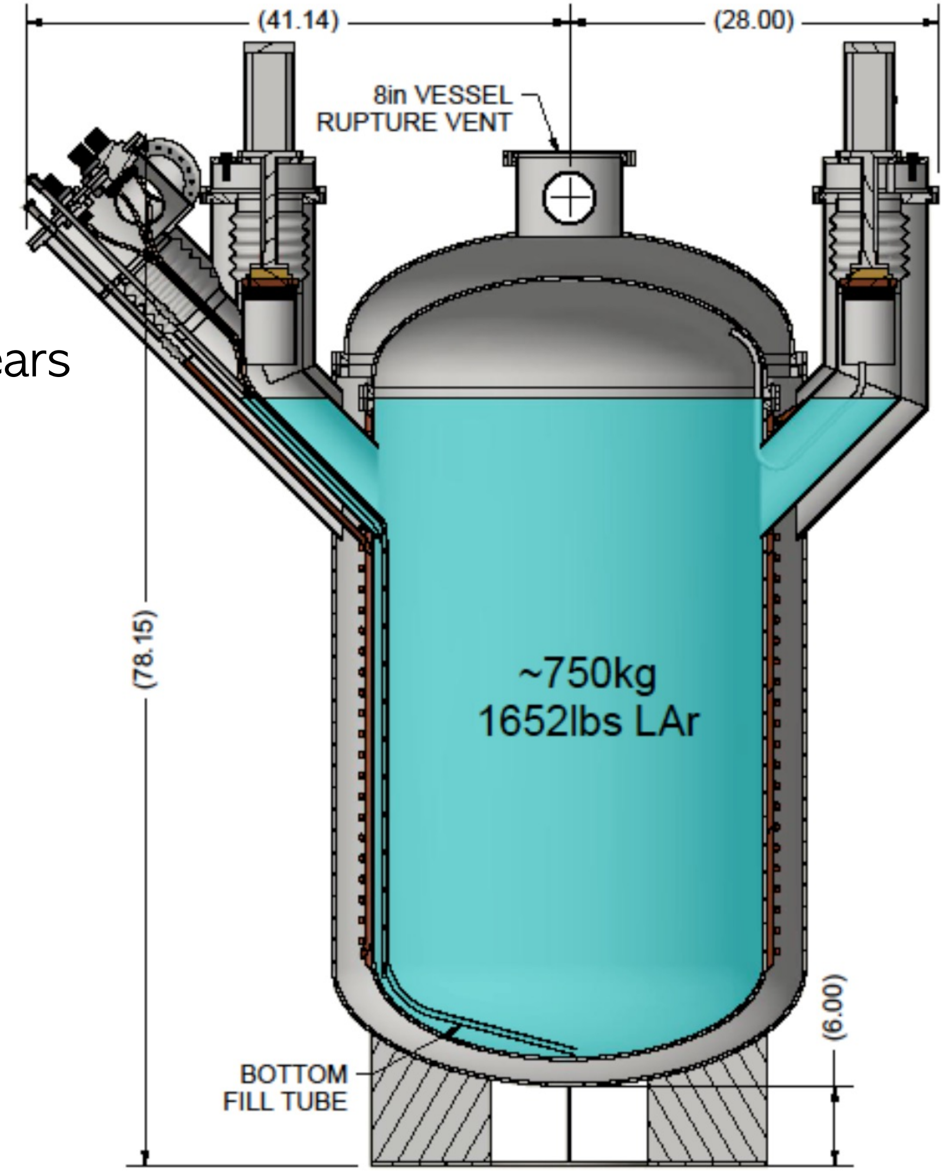
fiducial volume



CENNS-1ton

- 750-kg Liquid Argon detector replacing CENNS-10
- Observe ~3000 CEvNS/year
- Reduce statistical error from ~30% to ~4% within 3 years





Future Analysis with CENNS-1ton

- Non-Standard Interaction (NSI)
- Light Dark Matter search
- Inelastic neutrino-nucleus scattering cross section
- Weak mixing angle
- Nuclear Form Factor
- Supernova neutrino
- Sterile neutrino

Non-Standard Interaction (NSI)

- NSIs affect weak charge & $N_{CE\nu NS}$

$$N = \frac{\mathcal{E}}{M_T} \sum_{\alpha} \int_{E_r^a}^{E_r^b} dE_r \int_{E_\nu^{\min}}^{\infty} \frac{d\Phi_{\nu_\alpha}}{dE_\nu} \frac{d\sigma}{dE_r} \eta(E_r) dE_\nu$$

$$\frac{d\sigma}{dE_r} \cong \frac{G_F^2 M}{2\pi} \frac{Q_W^2}{4} F^2(Q) \left(2 - \frac{2T}{E_\nu} - \frac{MT}{E_\nu^2}\right)$$

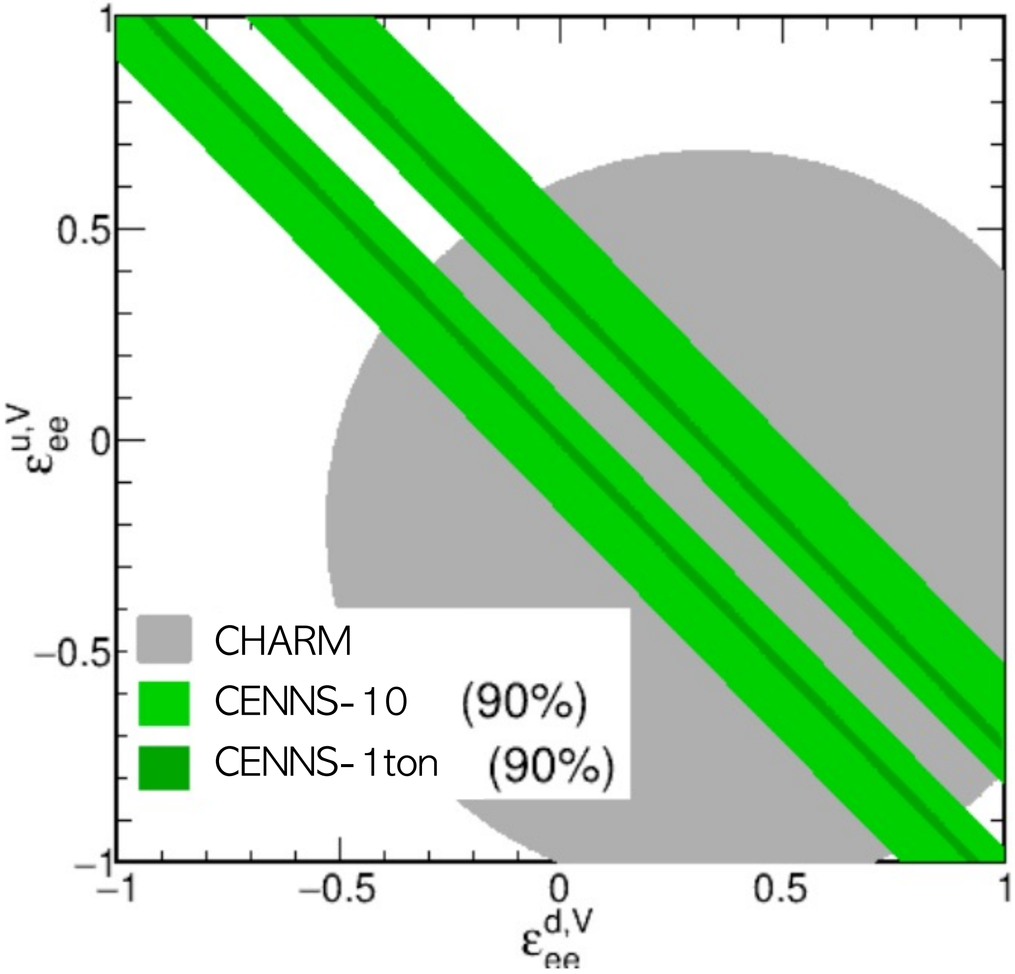
$$Q_{SM}^2 = [N - (1 - 4s_W^2)Z]^2$$

$$Q_V^2 = 4\left[Z\left(\frac{1}{2} - 2s_w^2 + 2\epsilon_{\alpha\alpha}^u + \epsilon_{\alpha\alpha}^d\right) + N\left(\epsilon_{\alpha\alpha}^u + 2\epsilon_{\alpha\alpha}^d - \frac{1}{2}\right)\right]^2 + 4\sum_{\beta\neq\alpha}\left|Z(2\epsilon_{\alpha\beta}^u + \epsilon_{\alpha\beta}^d) + N(\epsilon_{\alpha\beta}^u + 2\epsilon_{\alpha\beta}^d)\right|^2$$

$\epsilon_{\alpha\beta}$: NSI parameter

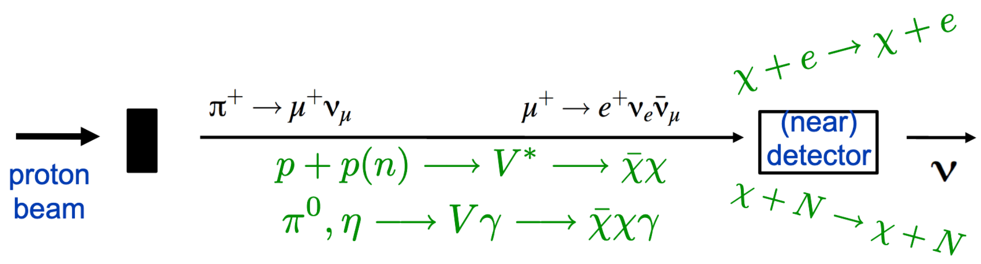
phenomenological NSI parameter: $\epsilon_{\alpha\beta}^N \equiv \epsilon_{\alpha\beta}^{u,V} + \frac{(2N+Z)}{(2Z+N)} \epsilon_{\alpha\beta}^{d,V}$

After 3 years of running CENNS-1ton



Beam produced Dark Matter search

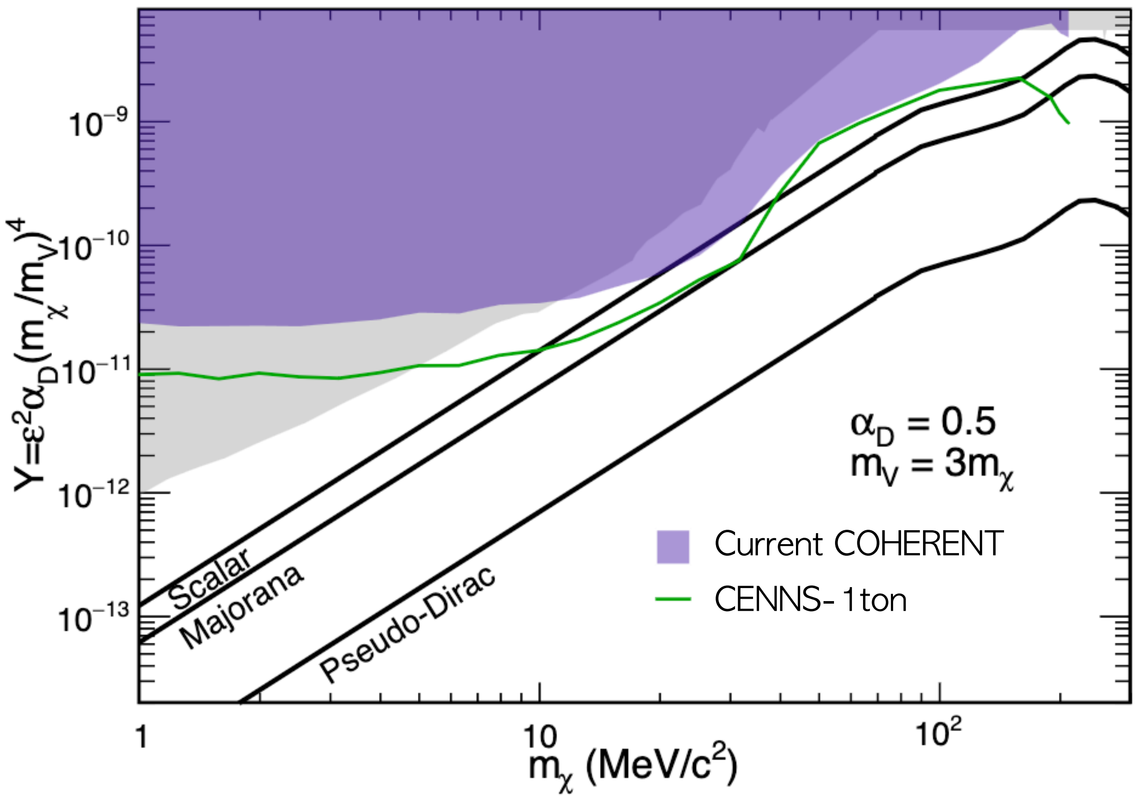
- 1 GeV proton beam can produce Light Dark Matter $(m_\chi < \text{GeV})$
- Benchmark model: 1 scalar dark matter with vector portal mediator



χ: scalar dark matter

V: vector portal mediator

After 3 years of running CENNS-1ton

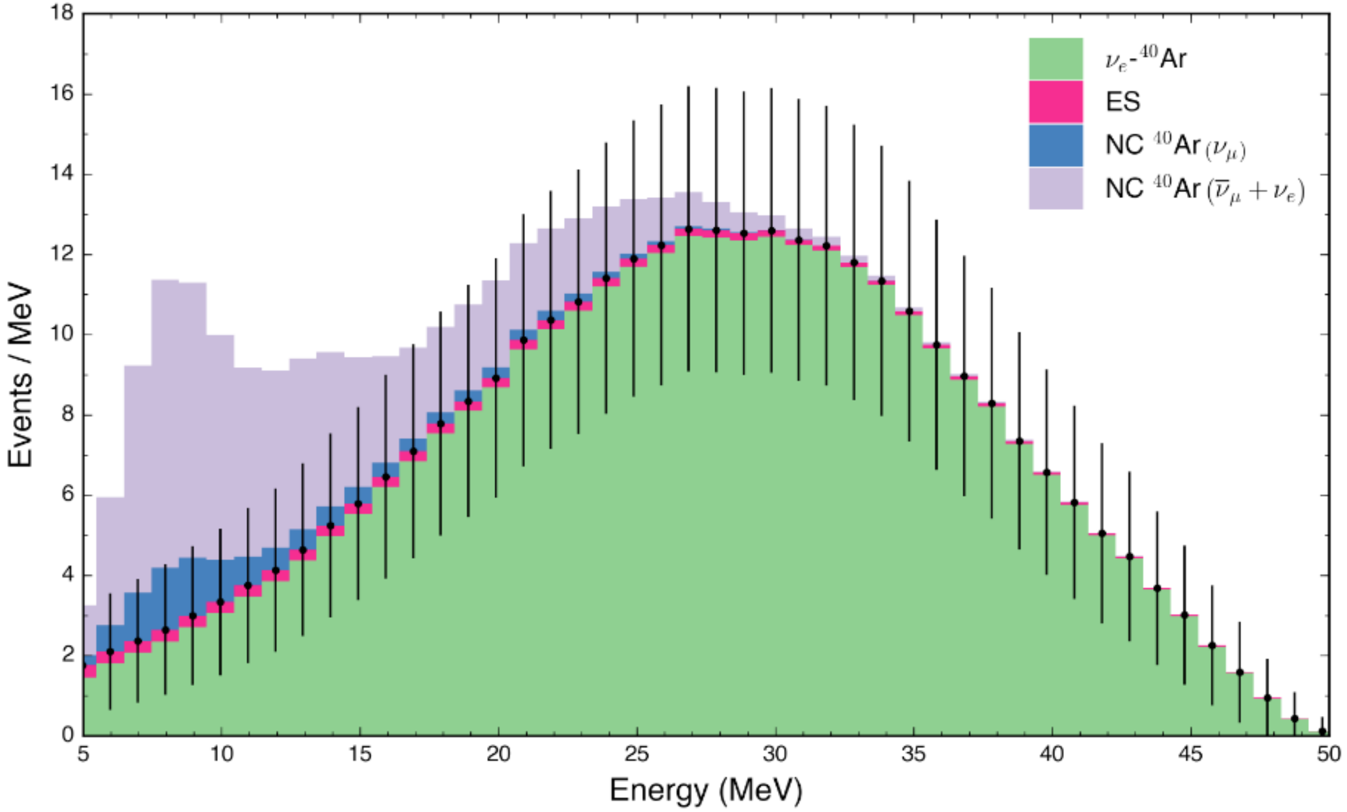


- Dark Matter is relativistic
- Can distinguish DM with CEvNS by timing cut

inelastic scattering

- Inelastic neutrino-argon scattering ($\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$)
- Record ~340 ν_e CC/year and ~100 NC/year of all flavors (calculated by MARLEY)

After 1 years of running CENNS-1ton



Summary

CENNS-10
24-kg LAr detector

- Observe CEvNS on Argon
- Check N^2 dependence to test Standard Model

↓

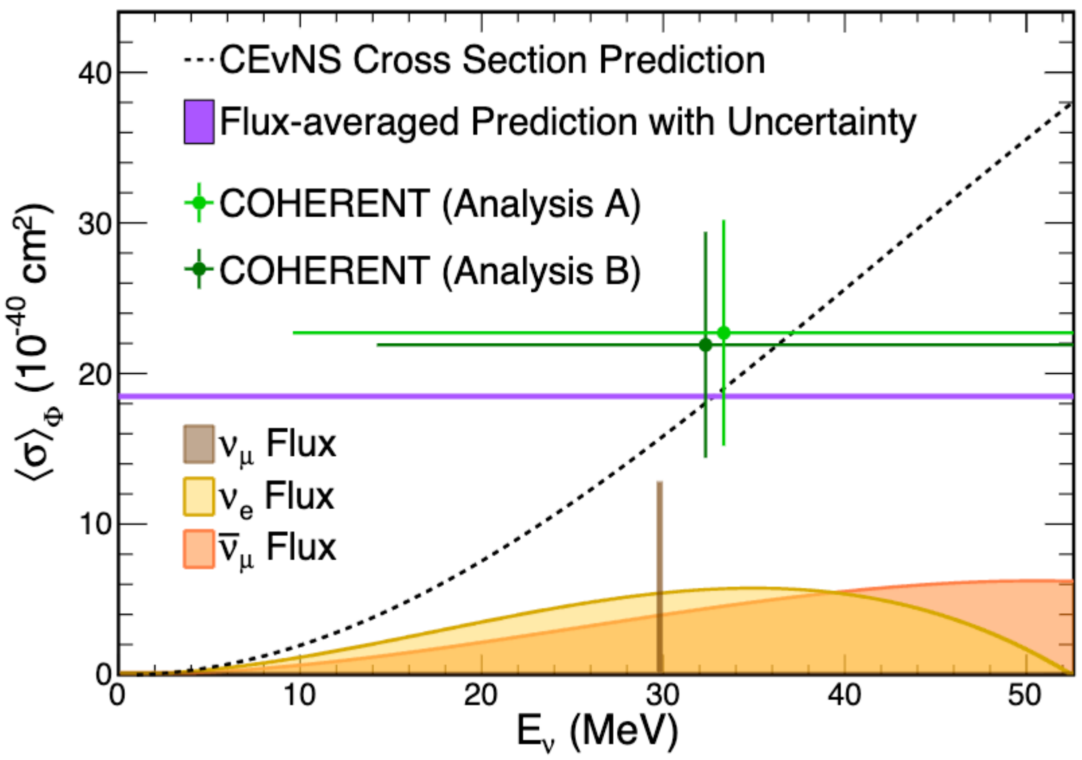
CENNS-1ton
750-kg LAr detector

- Precision measurement of CEvNS on Argon
- Study CEvNS related physics
- Construct in 2023~2024

Backup

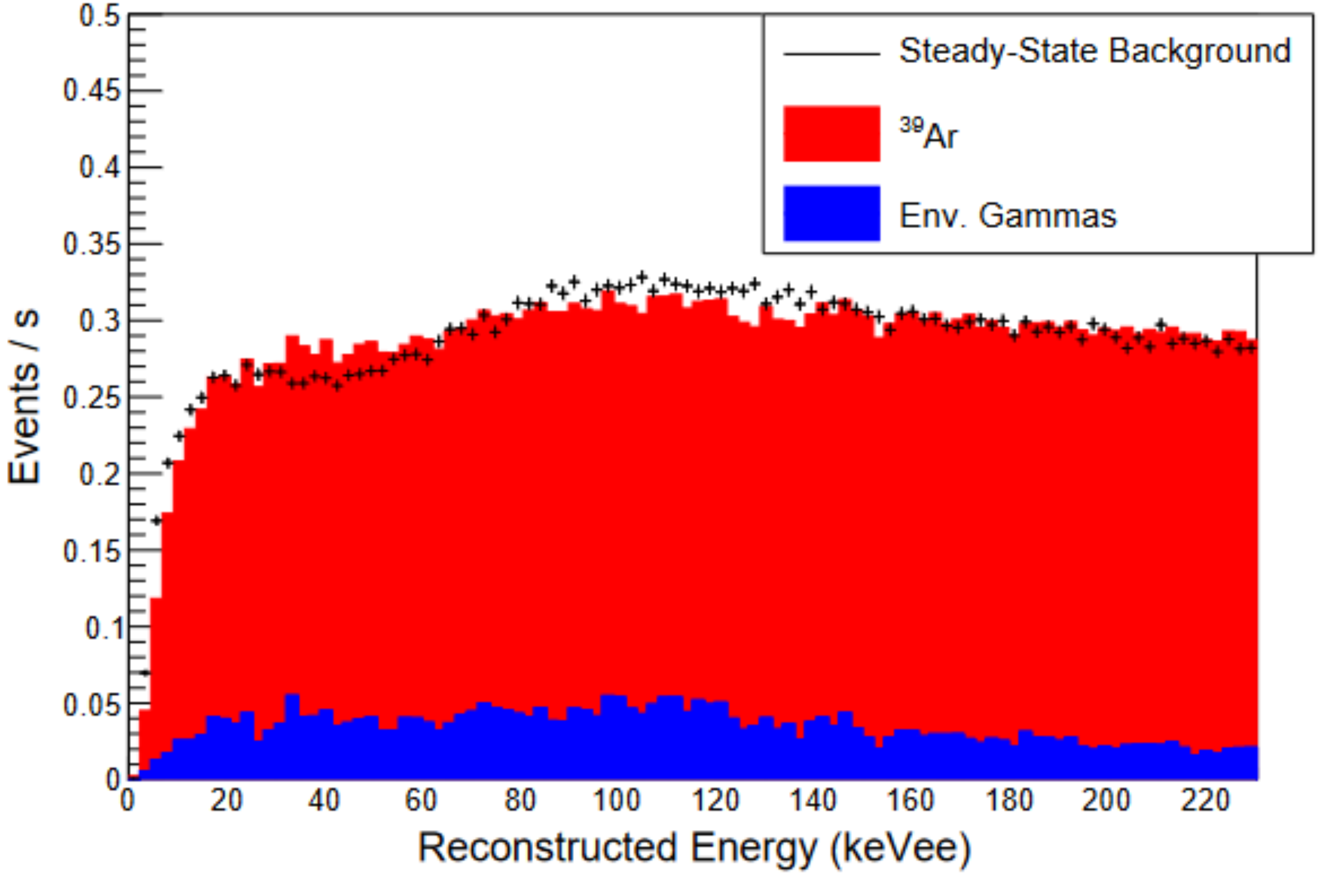
Result of CENNS-10

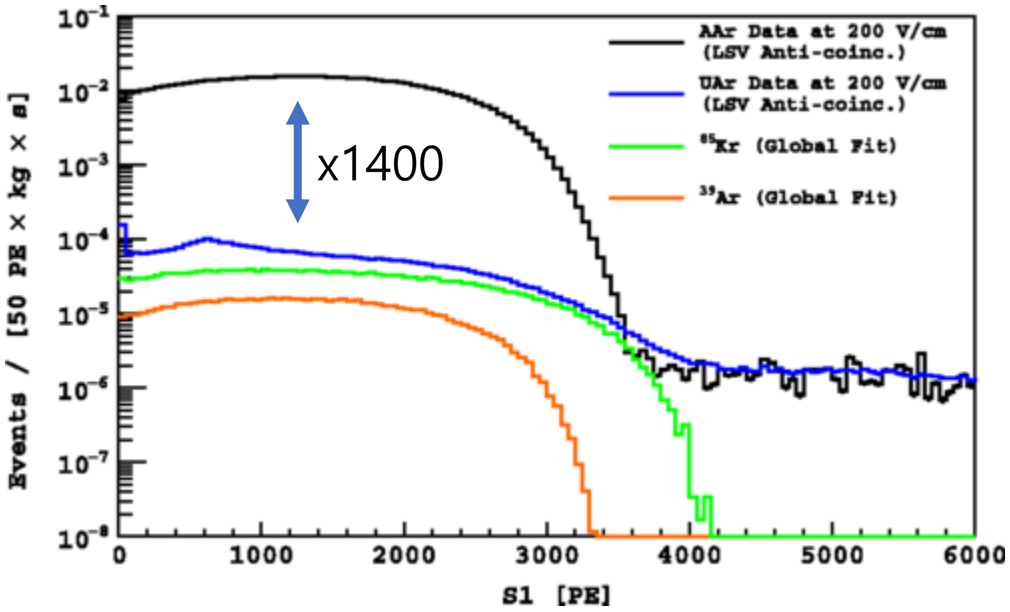
- SM prediction：128±17 events
- US analysis：159±43(stat.)±14(sys.)
- Moscow analysis：121±36(stat.)±15(sys.)



Steady-State background of CENNS-10

- Mainly came from 39Ar decay





CEvNS Detectors by COHERENT

	Argon	CsI	Other
1st Observe CEvNS Check N^2 dependence	**CENNS-10** 24kg LAr	**CsI-1** 14kg CsI	
2nd Precision measurement of CEvNS Study Beyond SM DM, NSI, neutron radius, …	**CENNS-1ton** 750kg LAr	**CryoCsI-1** 10kg cryogenic CsI	**Ge-1** 18kg HPGe PPC **NaI-2** 3.4t NaI[Tl] crystal
3rd Using CEvNS as experimental tool With STS (upgraded version of SNS) SN neutrino, Sterile neutrino, …	**CENNS-10ton** 10ton LAr	**CryoCsI-2** 700kg cryogenic CsI	

Near-Future Detectors by COHERENT

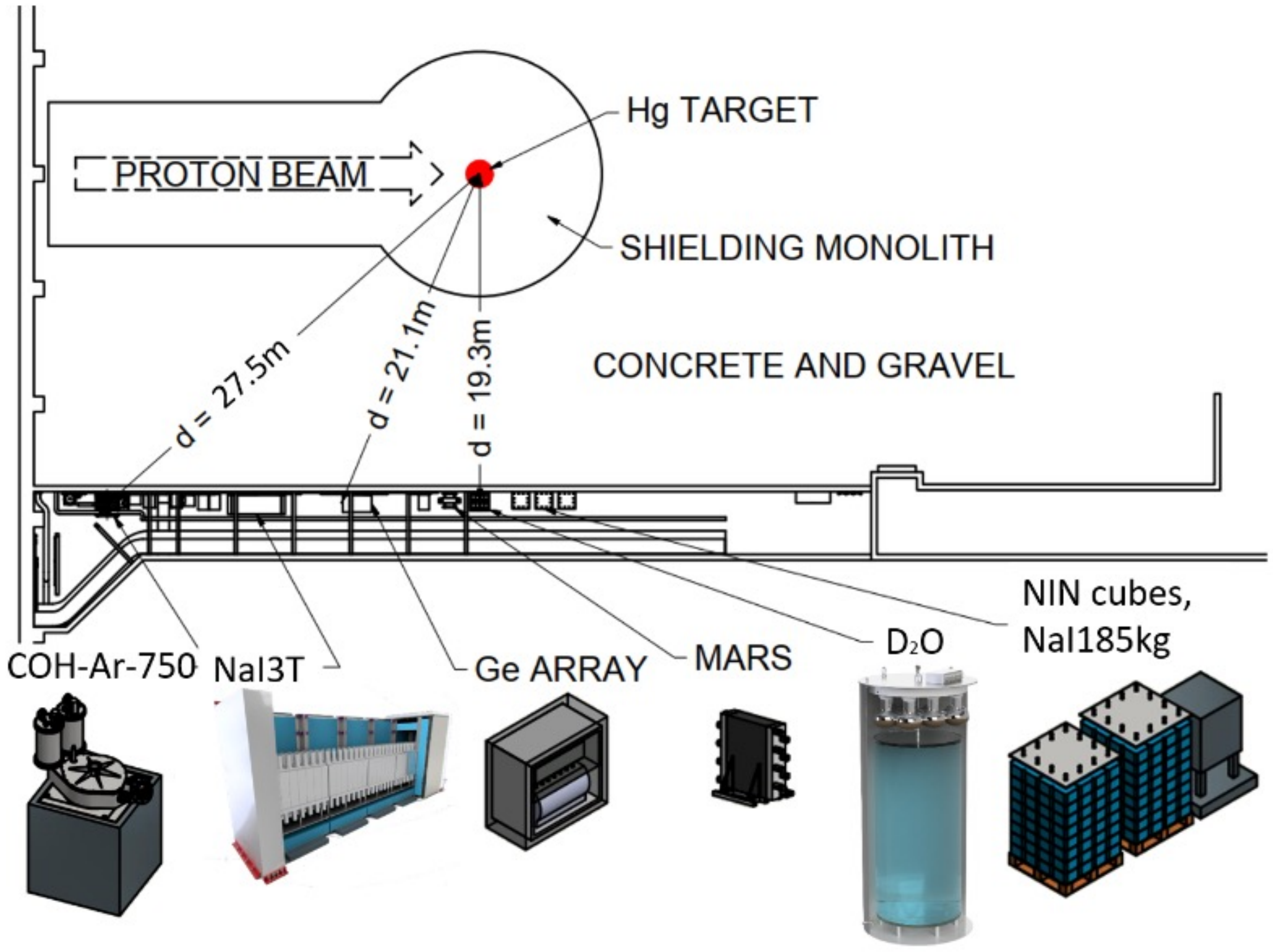
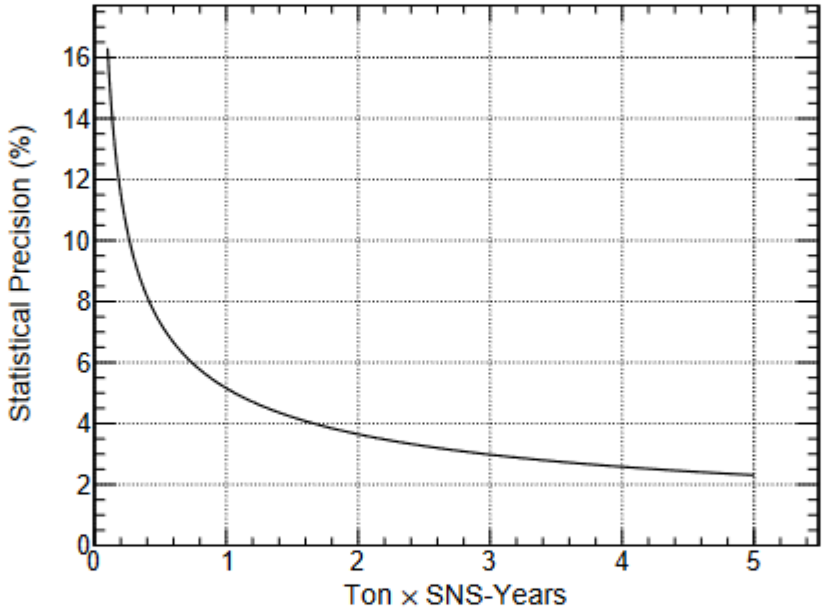


FIG. 8. Current and near-future detector subsystems in Neutrino Alley.

D2O detector

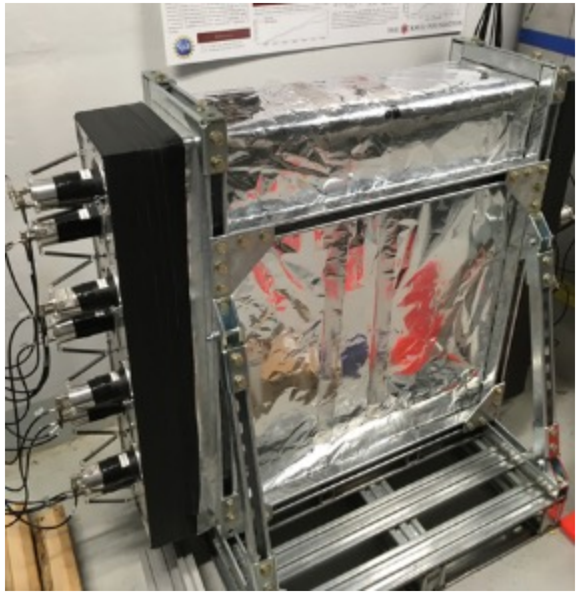
- Cross section of $\nu_e + \mathrm{d} \rightarrow p + \mathrm{p} + \mathrm{e}$ is well understood than others
- With 592kg D_2O, statistical uncertainty to 5% within 2 years
- Reduce neutrino flux uncertainty approaching theoretical uncertainty 2~3%
- Also, can study $\nu_e + \mathrm{O} \rightarrow \mathrm{e}^- + {}^{16}\mathrm{F}^*$, valuable for supernova detection

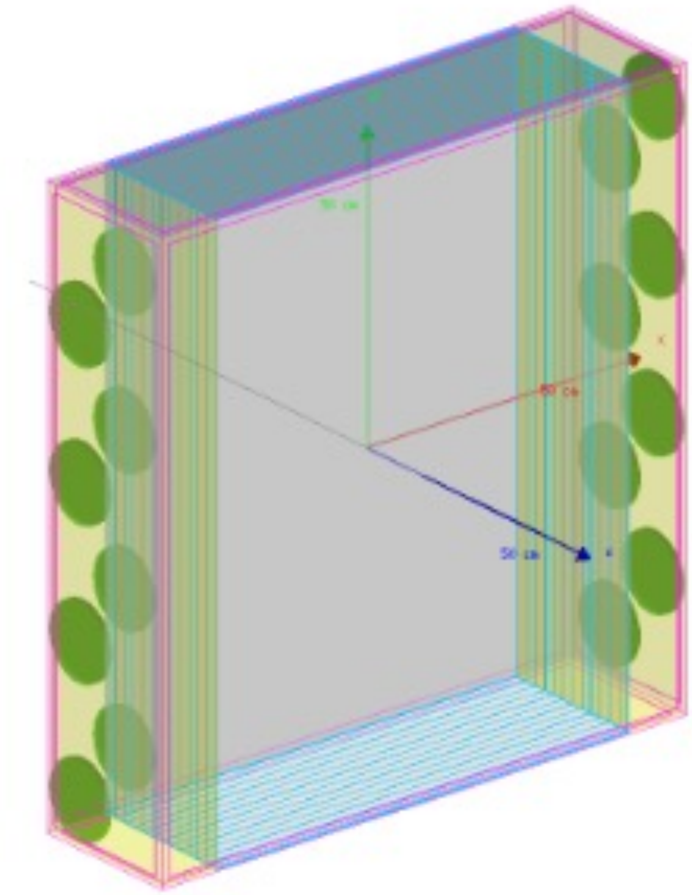
- Operating with H_2O since 2022
- for measuring $\nu_e + \mathrm{O}$ background



MARS detector

- Multiplicity and Recoil Spectrometer (MARS) monitor and characterize BRN background
- Fast neutron elastically interacts with hydrogen
- Lose energy in scintillator until Gd capture (~18.7 μ s)
- Appropriate for low energy neutron (〈50 MeV)





Upgrade Plan of SNS

Today First Target Station (FTS)	After 2024 Proton Power Upgrade (PPU)	After 2032 Second Target Station (STS)
1.4 MW 1 GeV 60Hz	2.0 MW 1.3 GeV 60Hz	2.8 MW 1.3 GeV 60Hz