CICENNS: a 300-kg CsI(Na) Detector for Coherent Elastic Neutrino-Nucleus Scattering

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on behalf of the CICENNS Collaboration

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Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)

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)

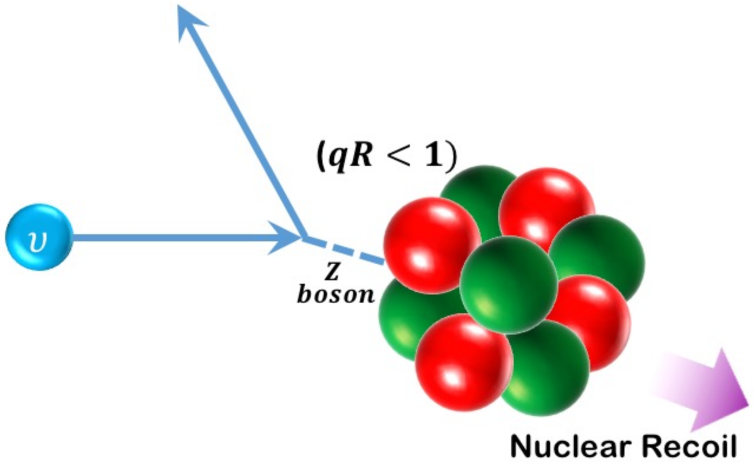
$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} Q_W^2 M \left(1 - \frac{MT}{2E_\nu^2}\right) F(Q^2)^2$$

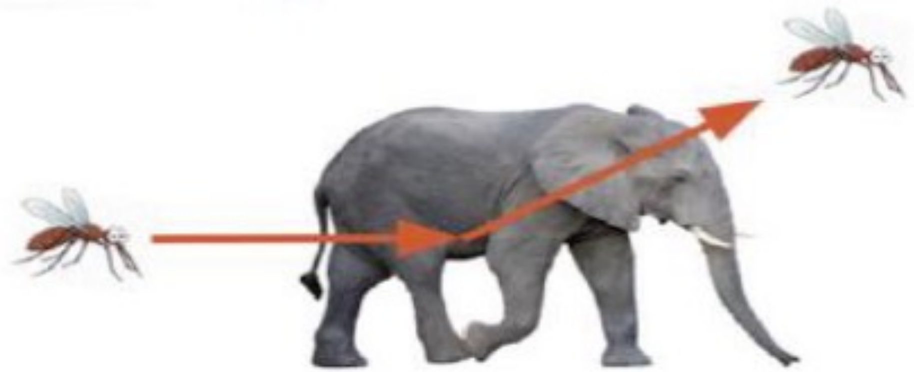
$$\sigma \propto Q_W^2 \propto (N - (1 - 4\sin^2\theta_W)Z)^2$$

$$\Longrightarrow \boxed{\sigma \propto N^2}$$

- qR < 1
- Z-exchange between neutrino and nucleus
- Nucleus recoils as a whole
- Coherent up to $E_\nu \sim 50$ MeV

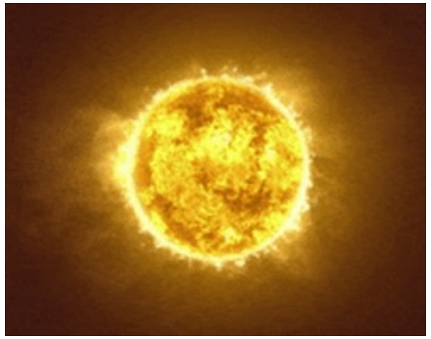
$$T_R \approx \frac{E_\nu^2(\mathrm{MeV})}{A} \ \mathrm{keV}$$

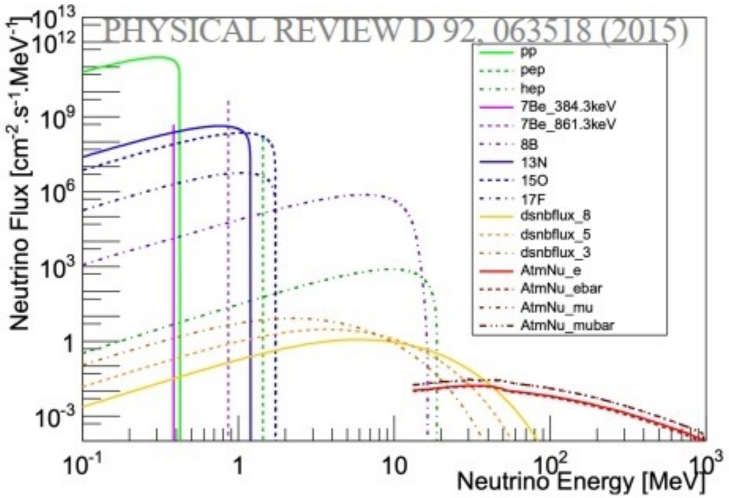




Neutrino sources for CEνNS detection

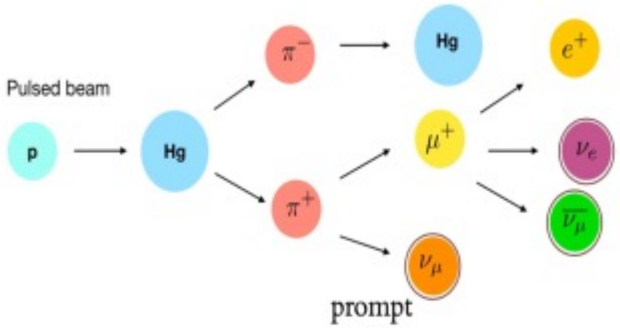
The Sun

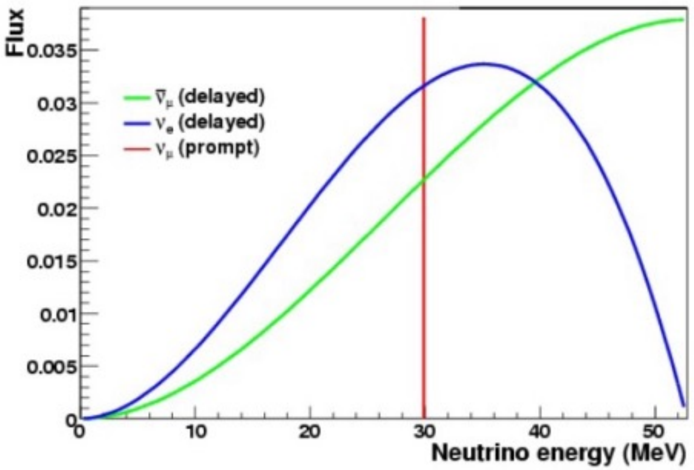




- ~5×10^6/s/cm^2 for ^{8}B neutrino
- Mostly $E_\nu < 10$ MeV
- Not observed yet

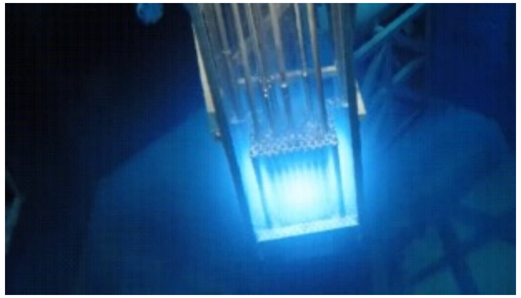
Spallation Neutron Source

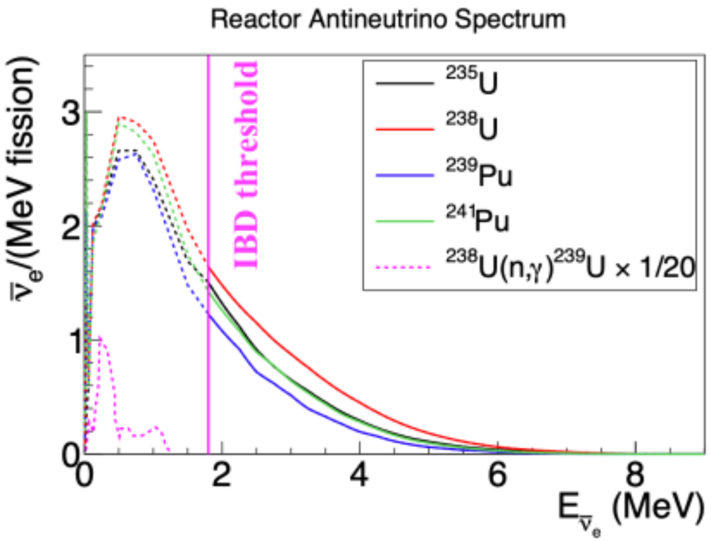




- ~1×10^7/s/cm^2 @ 20 m
- E_ν~ 50 MeV
- Observed in 2017

Nuclear Reactor

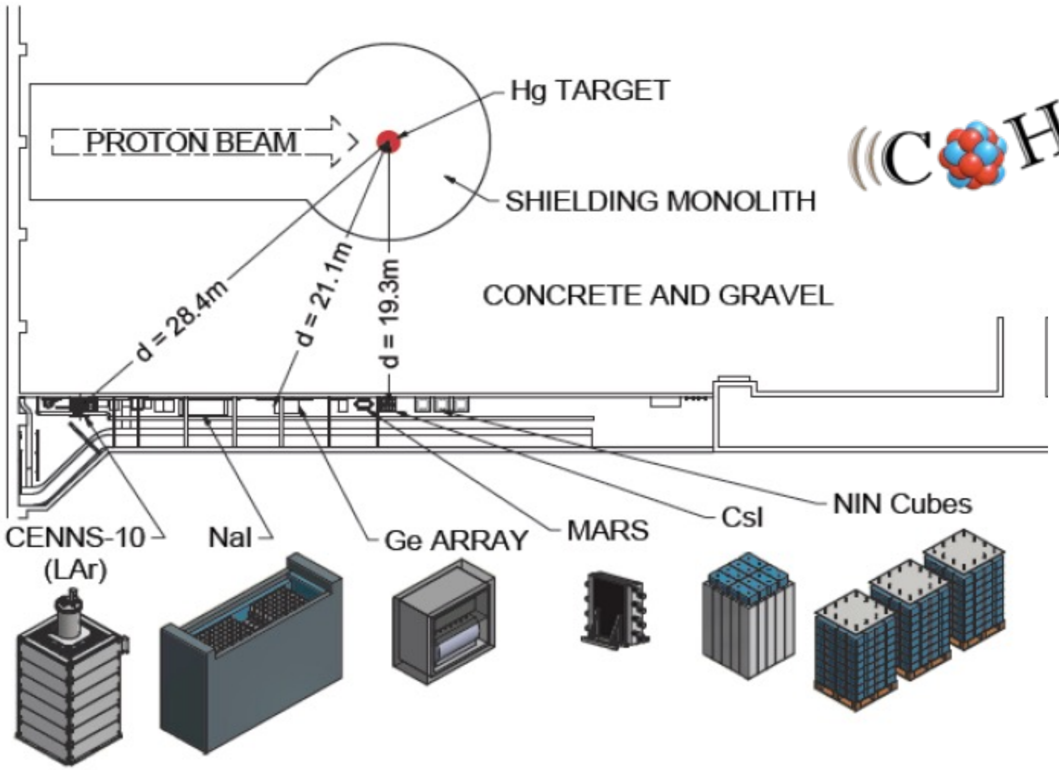




- ~1×10^{13}/s/cm^2 @ 25m with 3 GW power
- Mostly $E_\nu < 6$ MeV
- Not observed yet

First experimental observation by COHERENT

SCIENCE 357, no. 6356, 1123-1126 (2017)



- ➢ 14.6 kg CsI(Na) detector
- ➢ 308.1 day live-time (beam-on)
- ➢ 134 ± 22 events observed
- ➢ 6.7 σ observation

CICENNS experiment

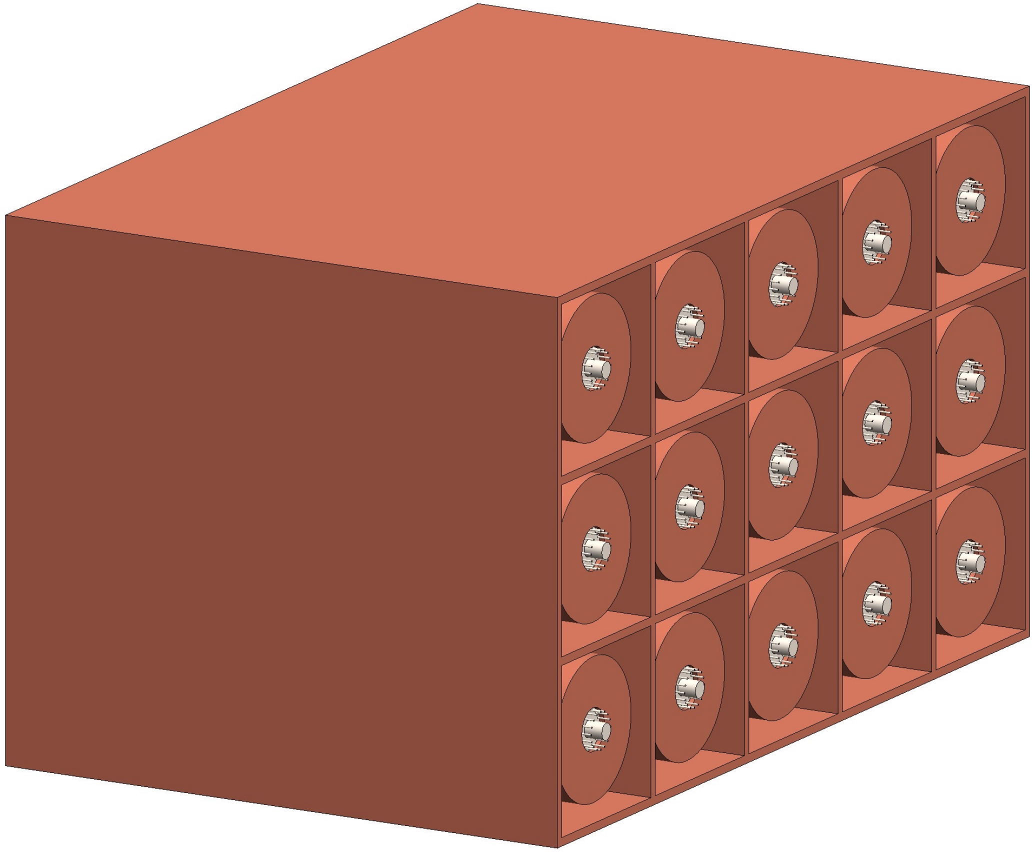
Development of 300-kg CsI(Na) detector for CEνNS

- Obtain sufficient CEνNS events with substantial target mass
- Establish a new field of studying unexplored physics using CEνNS

Detection of ~30 MeV neutrinos from pion/muon decays at rest
(at spallation neutron source)

- **Precise measurements**
  - CEνNS cross section → weak couplings at low momentum transfer
  - Mean radius of neutron distribution inside nucleus
- **New physics searches**
  - Non-standard neutrino interactions
  - A new region of neutrino magnetic moment
  - Efficient search for sterile neutrino oscillation by neutral current
  - New particle searches: dark photons or axion-like particles

Drawings of detector and shielding



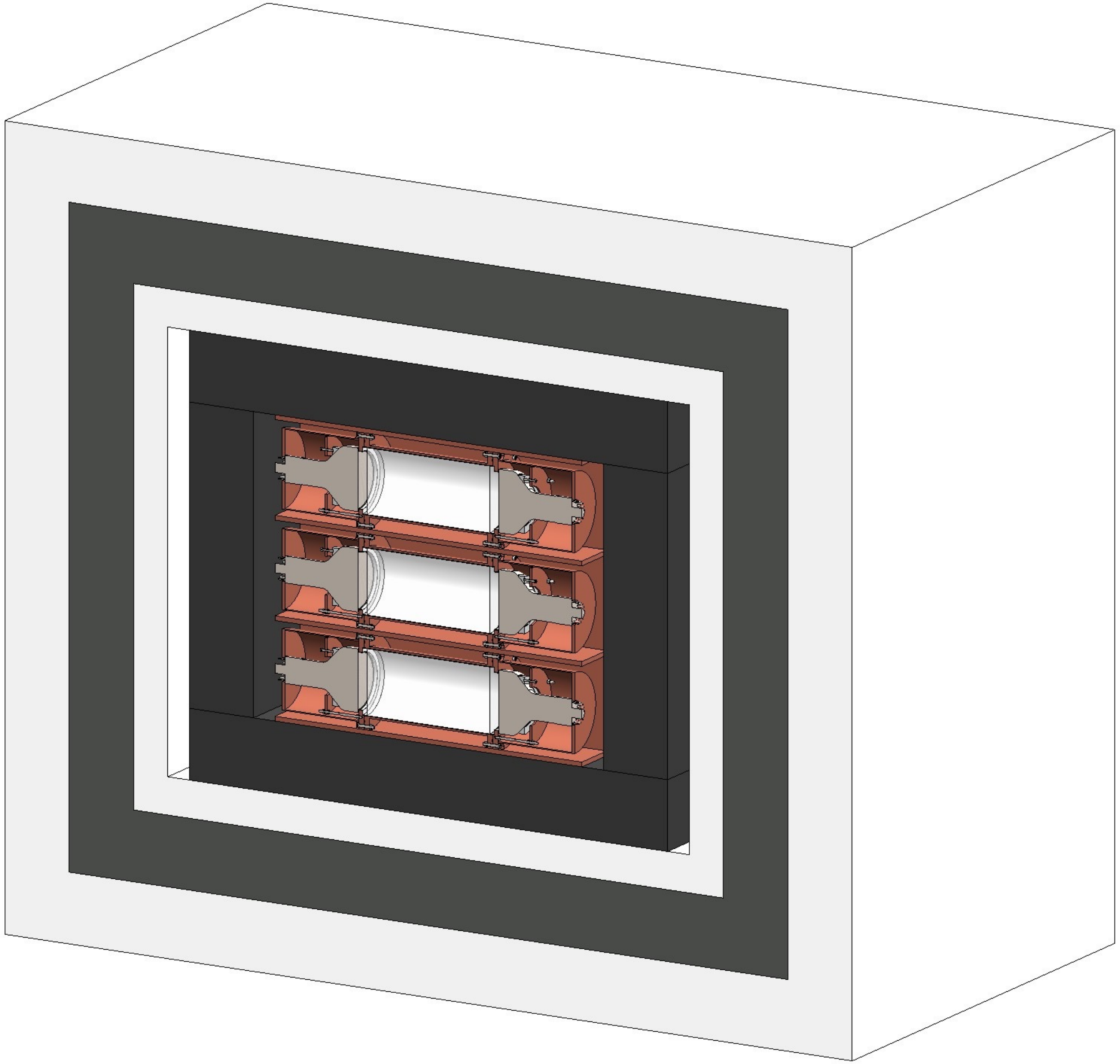
CsI(Na) crystal detector

- 20-kg CsI(Na) × 15
- 140 mm (Dia.) × 287 mm (L) each
- Two 5-inch R877-100 PMTs (super-bialkali)
- OFHC copper encapsulation

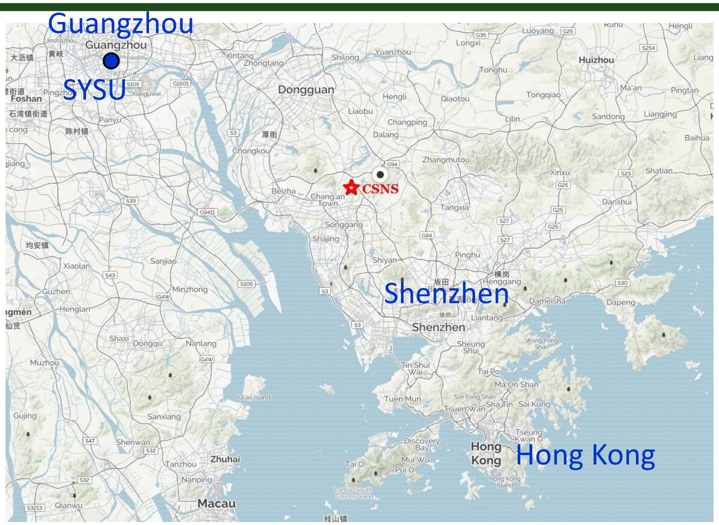
Drawings of shielding

Veto and shielding (from inside to outside)

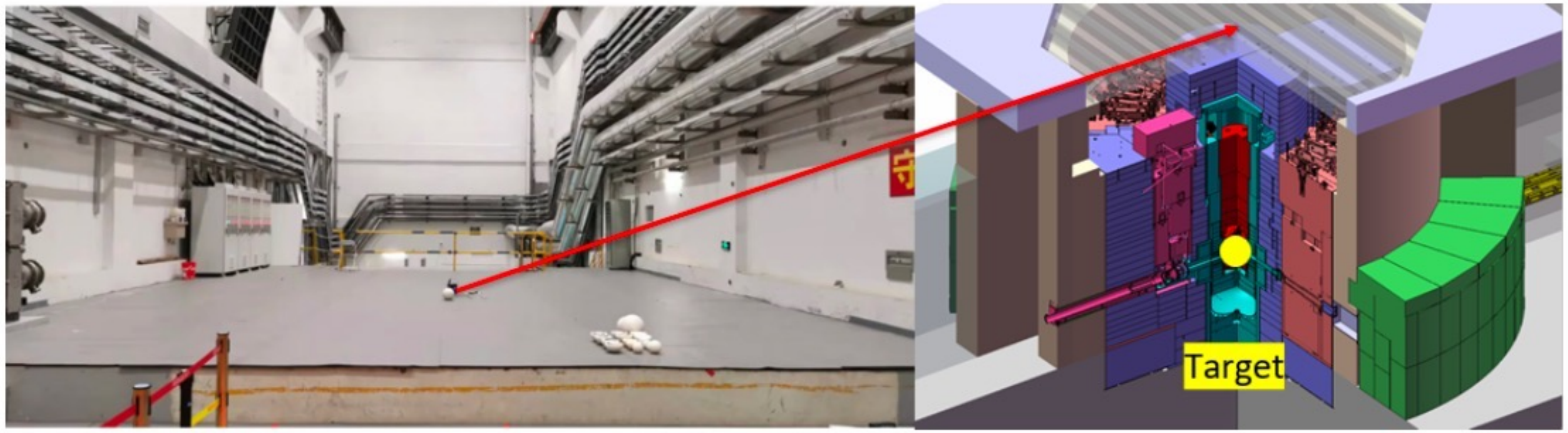
- 15-cm thick plastic scintillator as veto
- 8-cm thick inner HDPE
- 15-cm thick lead
- 15-cm thick outer HDPE



China Spallation Neutron Source (CSNS)



8.2 m above the beam target (7.2 m thick: steel, 1 m thick: concrete)



(Taken from C. Su, Q. Liu and T. Liang, arXiv:2303.13423 (2023))

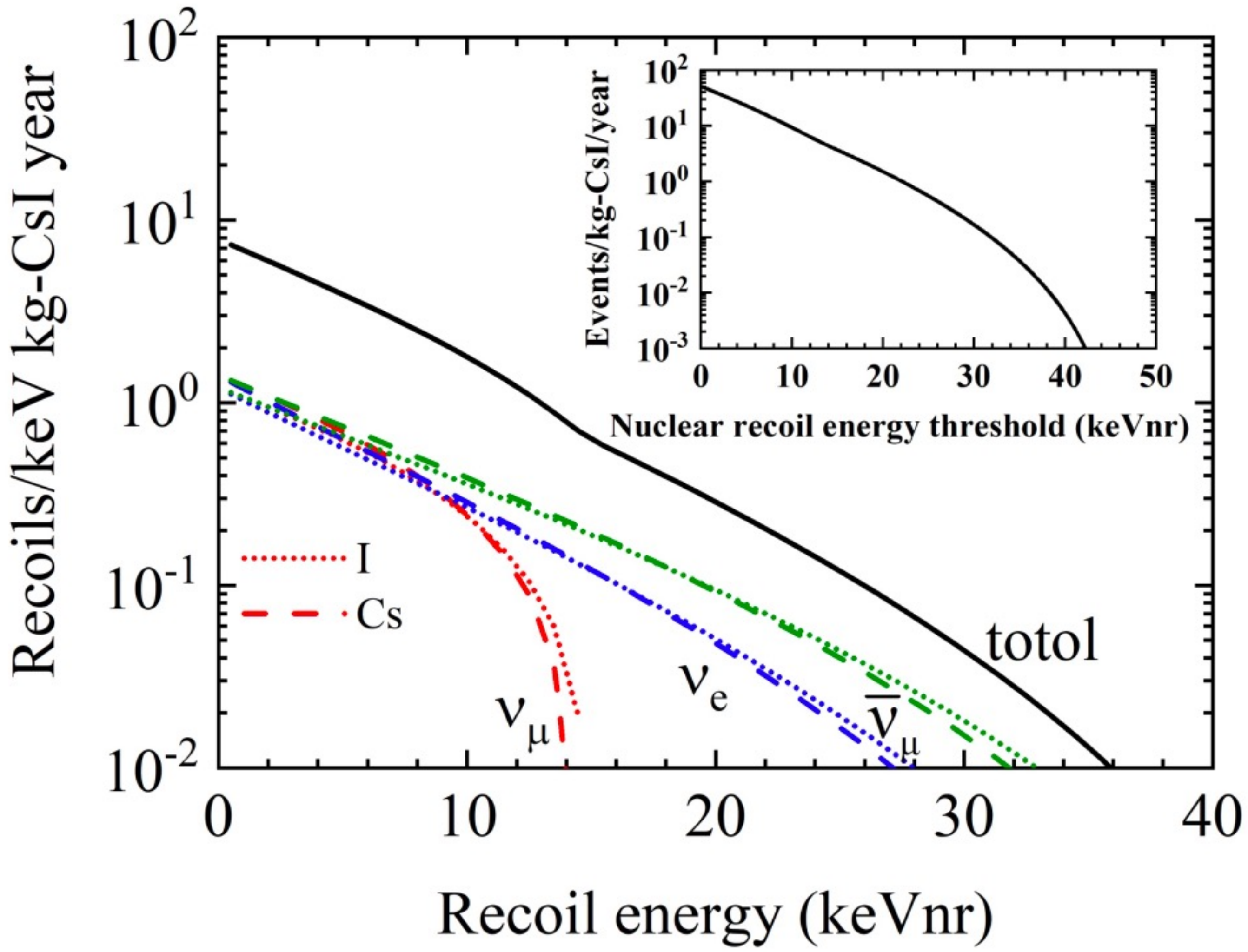
- 1.6 GeV proton beam
- 140 kW (→ 500 kW)
- 25 Hz repetition rate

Neutrino flux at 10.5 m: 2.0 x10^7 /cm^2/s (~40% of COHERENT)

→ ~2500 observed events with 300 kg (~300 events with 14.6 kg at COHERENT)

Expected CEνNS events of CICENNS at CSNS

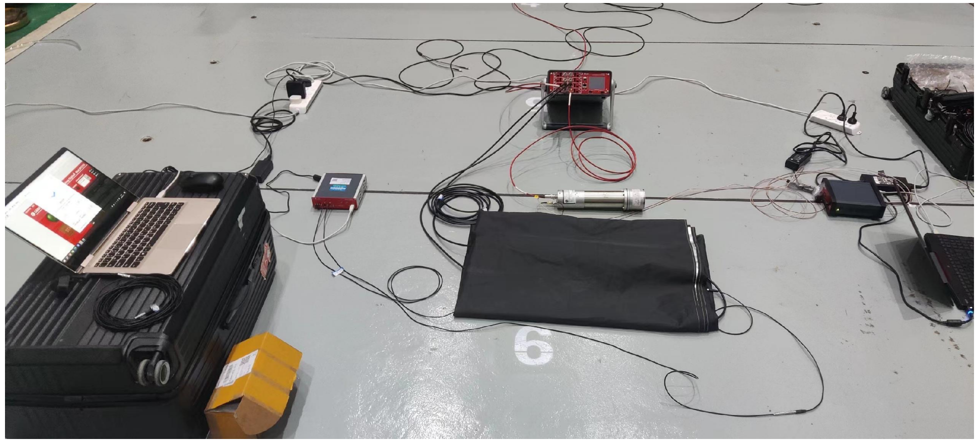
- 14.6 kg CsI(Na) crystal for ~300 CEνNS events (PRL 129, 081801, 2022)
- 300 kg CsI crystals for ~2,500 CEνNS events (neutrino flux at CSNS: ~40% of ONL) if the energy threshold is 5 keV_{nr}
- for ~4,000 CEνNS events if the energy threshold can be lowered to 2 keV_{nr}



Backgrounds

- Beam related fast neutron
  - The most significant background
  - On-site measurement on-going, joint effort from SYSU and UCAS
- PMT dark count pile-up
- Radioactivity in detector materials
  - Crystal internal background from ^{87}Rb, ^{137}Cs, ...
  - Background from PMTs and surrounding materials
- Environmental radioactivity
- Cosmic muon induced neutrons and gammas

Full Geant4-based MC on-going



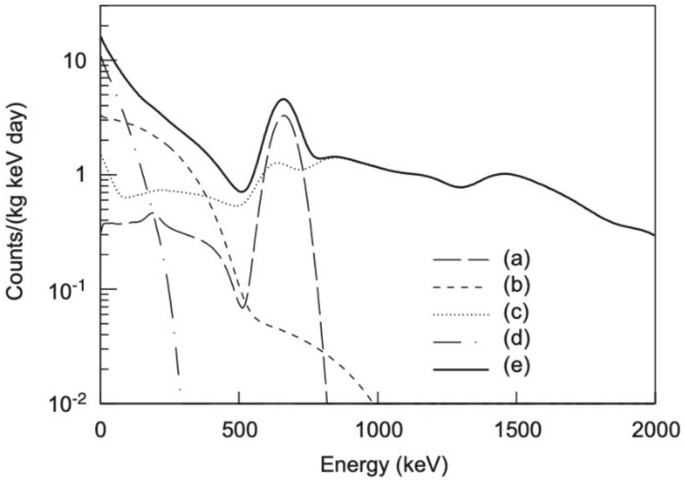


Figure 18: Background spectra obtained using GEANT4 simulation for a 20 kg CsI(Na) crystal with contaminations of 10 mBq/kg ^{137}Cs, 30 mBq/kg ^{134}Cs, and 10 ppb ^{87}Rb: (a) ^{137}Ba*; (b) ^{137}Cs; (c) ^{134}Cs; (d) ^{87}Rb; and (e) total summed spectrum.

(Ref: KIMS Collaboration, Nucl. Instr. Meth. A 571, 644 (2007))

Key features of CICENNS design

- Lower internal radioactivity background
  - 20 ppb ^{87}Rb in COHERENT → ~1 ppb ^{87}Rb achieved in CICENNS (collaboration with SICCAS)
- Lower dark count pile-up background
  - two PMTs on both ends of CsI(Na) crystal, ~3 orders of magnitude reduction (ref COSINE-100)
- Active veto
  - Plastic scintillator veto surrounding crystal detectors, mostly to veto beam related fast neutron, and also to identify cosmic muon track
- Better light collection of crystal encapsulation
- Multiple detector modules for further background rejection

Isotopes	^{238}U (ppt)	^{232}Th (ppt)	^{87}Rb (ppb)	^{137}Cs (mBq/kg).	^{134}Cs (mBq/kg).
CICENNS	10±10	30±10	∼0.5	??	??
KIMS	0.75±0.23	0.38±0.07	1.3±0.4	6.3±0.7	14.1±1.1
COHERENT	<1000	<1000	∼20	28±3.	26±2

Sensitivity: flavored CEvNS cross section and weak couplings

The CEvNS rate is a clean SM prediction

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

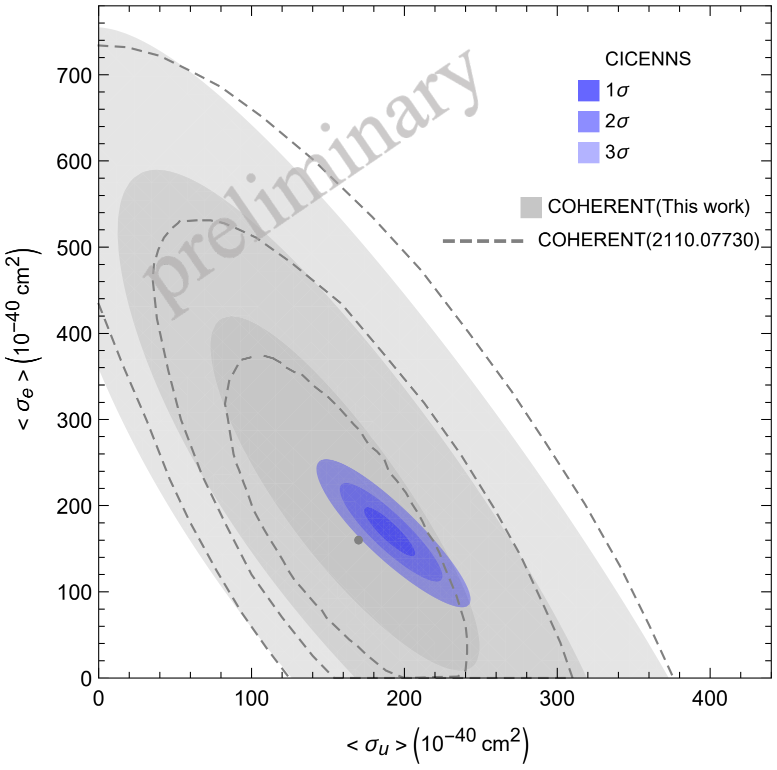
small nuclear uncertainties (±4.8%)

At momentum transfer Q=50 MeV/c

- COHERENT: $\sin^2\theta_W = 0.220^{+0.028}_{-0.026}$ (±10%)

→ CICENNS: ~1%

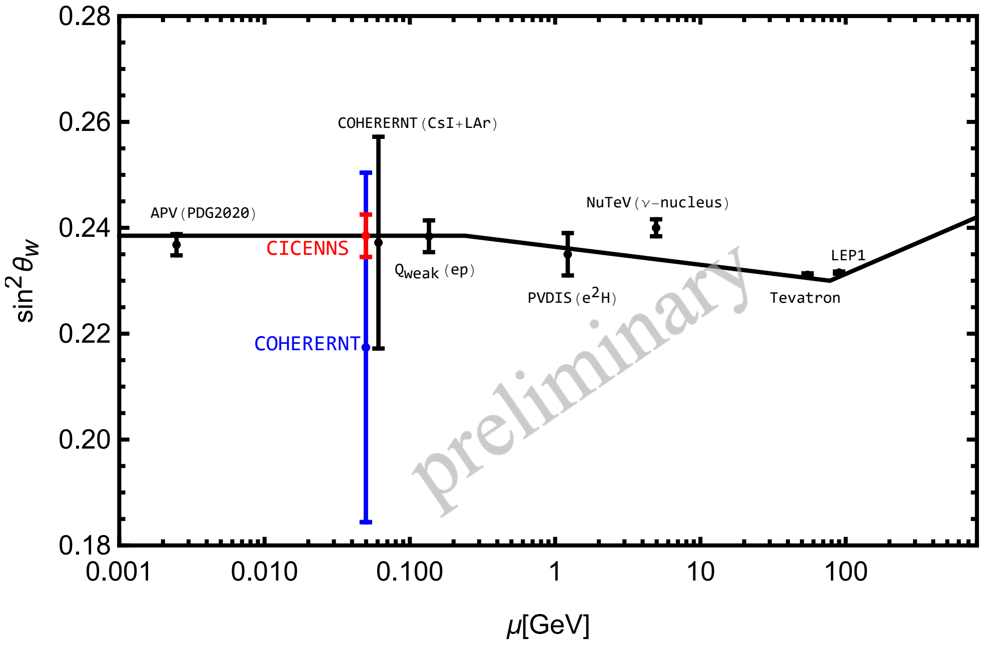
* SM prediction: 0.23857(5)



Uncertainty of CEvNS cross section:

- COHERENT: +18/-15%

→ CICENNS: 6.5%



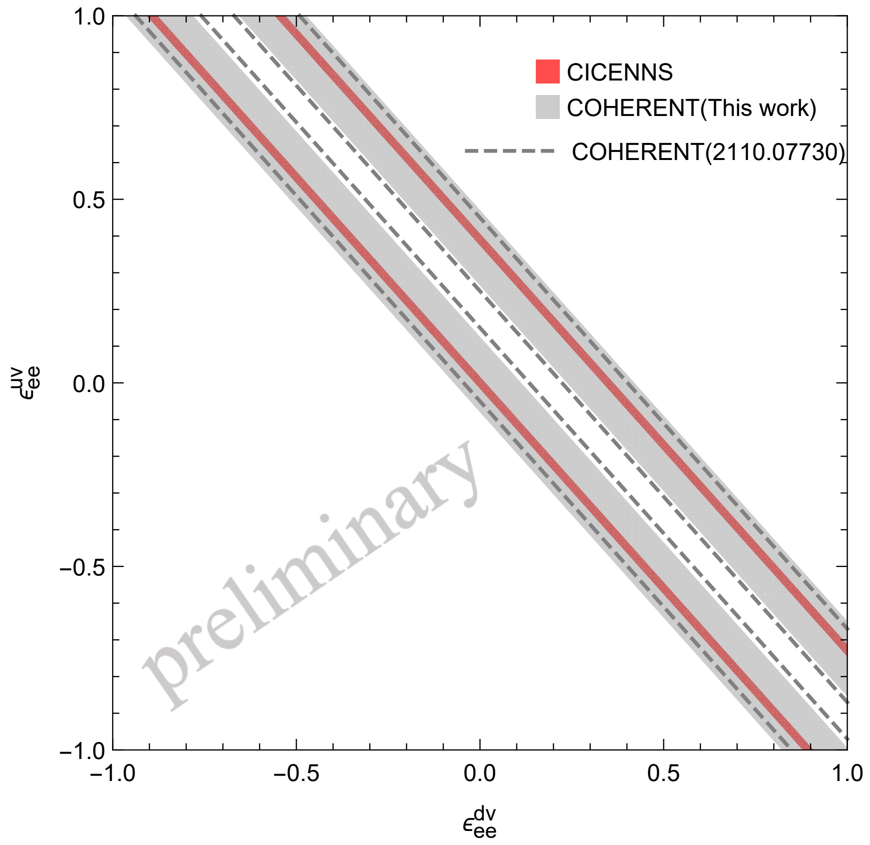
Sensitivity: Non-standard neutrino interaction

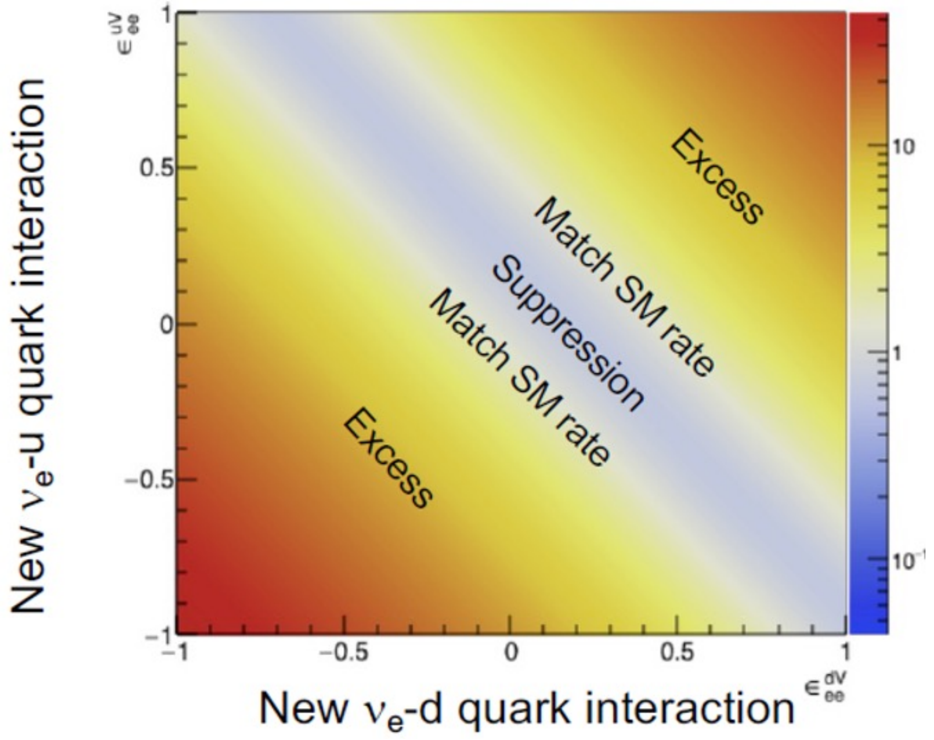
Look for a CEvNS **excess** or **deficit** wrt SM expectation

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

Ratio wrt SM

CsI



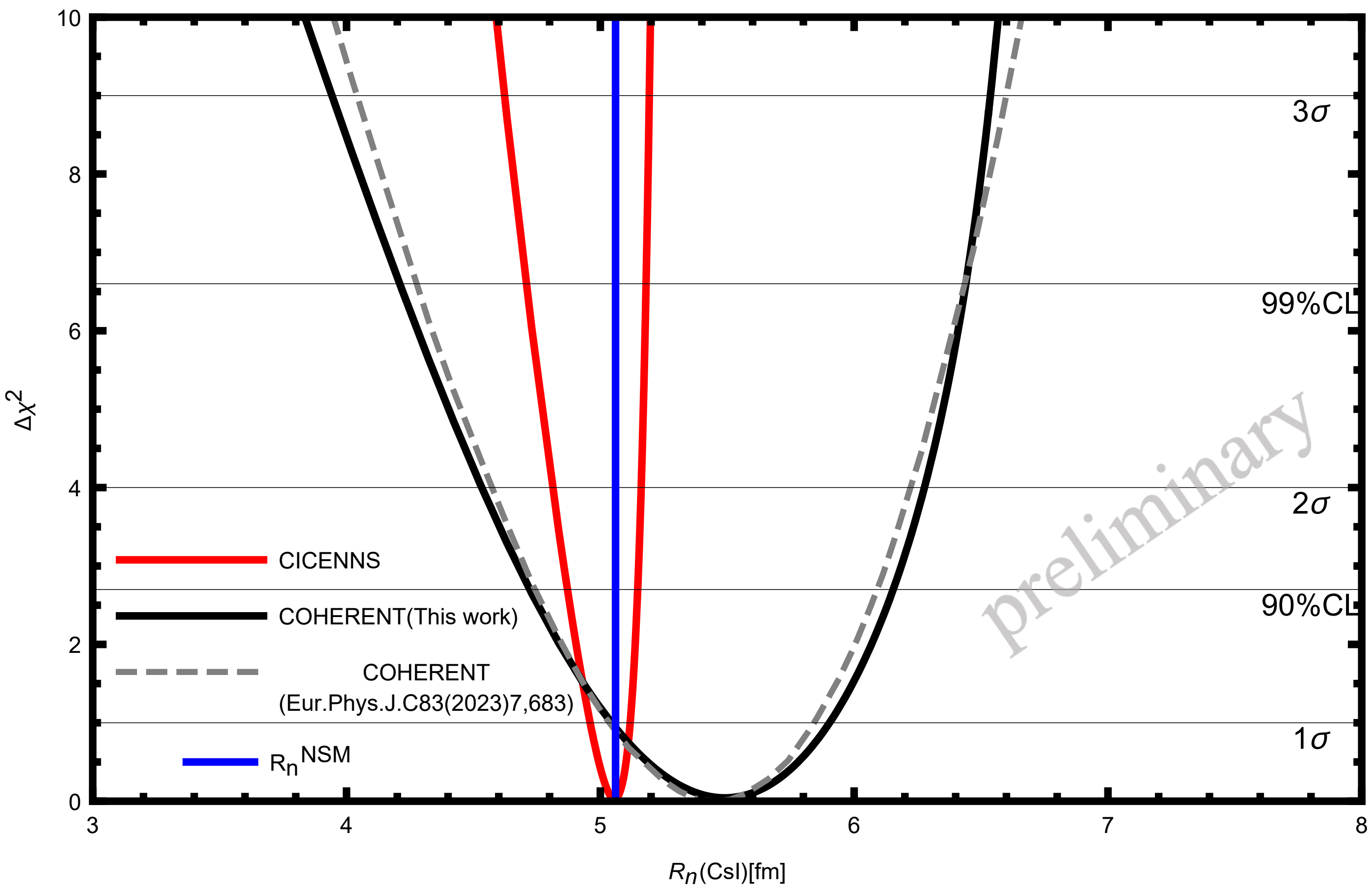


Sensitivity: mean radius of neutron distribution inside nucleus

Observed CEvNS recoil energy spectrum
→ mean radius of neutron distribution inside nucleus
(Cs or I: ~5 fm)

Uncertainty of neutron form factor
- COHERENT: ~8%

→ CICENNS: ~1%



Timeline

- Oct. 2022: CICENNS effort initiated at SYSU
- Dec. 2022: Procurement started
- Jan. 2023 – present
  - Physics design and engineer design
  - MOU signed between SYSU and SICCAS
  - R&D on CsI(Na) crystal purification
  - CsI(Na) mass production
  - PMT & electronics test
  - Full Geant4-based simulation of optical property and background
  - Technical Design Report in preparation
- End of 2024: Encapsulated CsI(Na) crystal detectors delivered to SYSU
- Mar. 2025: Completion of detector assembly
- Jun. 2025: Testing and commissioning at SYSU
- Jul. 2025: Start to deploy CICENNS at CSNS and taking data

Summary

- A 300-kg CsI(Na) crystal detector for CEνNS measurement at CSNS has been proposed, and is being built now.
- Precise test of SM at low momentum transfer and new physics search BSM are being pursued based on large statistics of CEνNS events.
- We wish to finalize the detector design and a TDR, and complete the detector construction in 2025.

We cordially invite your joining this effort!

Thank you!