The main goal is to look for new physics using coherent elastic $\nu$–nucleus scattering.
Coherent elastic neutrino-nucleus scattering (CEvNS)

CEvNS cross section in the SM:

\[
\frac{d\sigma}{dT} = \frac{G_F^2 M}{4\pi} \left( [1 - 4 \sin^2 \theta_W] Z - N \right)^2 \left[ 1 - \frac{T}{T_{max}} \right] F_{nucl}^2(q^2)
\]

Dominating type of interaction for heavy nuclei and \(E_\nu < 50 \text{ MeV}\)!
Coherent elastic neutrino-nucleus scattering (CEvNS)

Predicted in 1974...

“Coherent effect of a weak neutral current”,
D. Freedman, PRD v.9, n.5 (1974)

“Isotopic and chiral structure of neutral current”,

...with first observation
43 years after

Low energy recoil nucleus in a final state: \[ T_{\text{max}} = \frac{2E_{\nu}^2}{(M + 2E_{\nu})} \]

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>( T_{\text{max}}, \text{keV} ) ( (E_{\nu} = 5 \text{ MeV}) )</th>
<th>( T_{\text{max}}, \text{keV} ) ( (E_{\nu} = 30 \text{ MeV}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{12}\text{C})</td>
<td>4.44</td>
<td>159.0</td>
</tr>
<tr>
<td>(^{23}\text{Na})</td>
<td>2.32</td>
<td>83.2</td>
</tr>
<tr>
<td>(^{40}\text{Ar})</td>
<td>1.33</td>
<td>47.9</td>
</tr>
<tr>
<td>(^{74}\text{Ge})</td>
<td>0.72</td>
<td>25.9</td>
</tr>
<tr>
<td>(^{133}\text{Cs})</td>
<td>0.40</td>
<td>14.4</td>
</tr>
</tbody>
</table>

Observation requires combination of a large flux of neutrino with proper \( E_{\nu} \) and a low-threshold detector
Bunches of ~1 GeV protons on the Hg target with 60 Hz frequency

Proton bunch time profile with FWHM of ~350 ns

Capture

νμ

τ≈26 ns

τ≈2200 ns

π^-

99%

π^+

μ^+

e^+

ν_e

ν_μ

Total neutrino flux

4.3 \cdot 10^7 \text{ cm}^{-2} \text{s}^{-1} \text{ at 20m}

\begin{align*}
\pi^+ &\rightarrow \text{Capture}\\
\nu_\mu &\rightarrow \tau\approx 26 \text{ ns}\\
\mu^+ &\rightarrow \tau\approx 2200 \text{ ns}\\
\nu_e &\rightarrow
\end{align*}
"Neutrino alley"

**COHERENT detectors are hosted by the target building basement**

- **8 MWE vertical overburden**
- **20 m of steel, concrete and gravel with no voids in the direction of the target**
Detector subsystems

- CsI[Na], deployed → decommissioned: 14.5 kg crystal, single PMT readout, LY of 13.4 PE/keV, ~8 keV_{nr} threshold

- CENNS-10, deployed: 22 kg liquid argon detector, 2 PMTs readout, LY of 4.5 PE/keV, ~20 keV_{nr} threshold

- NaI[Tl]: segmented 185 kg, deployed → 2T, ~13 keV_{nr} threshold (Na recoils)

- HPGe PPC: 5 kg (cryostat ready, funding secured) → 16 kg, ~150 eVee threshold expected (~1 keV_{nr})

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

- MARS, deployed: BC-408 plastic scintillator interleaved with Gd coated Mylar sheets
## Physics Sensitivity

<table>
<thead>
<tr>
<th>Topic</th>
<th>CsI</th>
<th>Ar</th>
<th>NaI</th>
<th>Ge</th>
<th>Nubes</th>
<th>D₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-standard neutrino interactions</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
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<tr>
<td>Weak mixing angle</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
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<tr>
<td>Neutrino magnetic moment</td>
<td></td>
<td>✔️</td>
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<td>✔️</td>
<td>✔️</td>
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<tr>
<td>Inelastic CC/NC cross-section for supernova</td>
<td>✔️</td>
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<tr>
<td>Nuclear form factors</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
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<tr>
<td>Accelerator-produced dark matter</td>
<td>✔️</td>
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<td>✔️</td>
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<tr>
<td>Sterile oscillations</td>
<td></td>
<td>✔️</td>
<td></td>
<td>✔️</td>
<td>✔️</td>
<td></td>
</tr>
</tbody>
</table>

**Recoil spectra: no quenching, efficiency or background**

\[
\frac{d\sigma}{dT} = \frac{G_F^2 M}{4\pi} \left( [1 - 4\sin^2 \theta_W] Z - N \right)^2 \left[ 1 - \frac{T}{T_{\text{max}}} \right] F_{\text{nuc}}^2 (q^2)
\]

**Study of some of these benefits from the multi-detector approach!**
Nuclear form-factors

Vector current neutron form-factor studies with CEvNS suggested in

K. Patton et al., PRC 86 (2012)

May be less precise than e-nucleus PV experiments but will be available for larger set of nuclei + not model dependent as hadron-nucleus scattering

See talks by X. Huang and M. Cadeddu

COHERENT results utilized in:

M. Caddedu et al., arXiv: 1710.02730
Xu-Run Huang, Lie-Wen Chen, arXiv: 1902.07625
D. Papoulias et al., arXiv:1903.03722
Various $\nu$-quark NSI contributions may indicate themselves in a CEvNS rate

E.g. vector current-like:

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

Impact of COHERENT data on $\nu$-quark NSI discussion

**Tensor current contributions**


**Light vector and scalar mediators**

J. Liao, D. Marfatia., PLB 775 (2017)


Y. Farzan et al., JHEP 66 (2018)

**Effect of NSI on interpretation of oscillation data (LMA-D solution)**

P. Coloma et al., PRD 96 (2017)

**Majorana $\nu$ TMM**

Neutrino magnetic moment

Possible with 15 kg of low threshold HPGe PPC, however can hardly be competitive with $\nu$-$e$ scattering results for $\nu_e$ (current limit $\sim 3 \cdot 10^{-11} \mu_B$)

Can compete for $\nu_\mu$!

(best limit of $6 \cdot 10^{-10} \mu_B$ from LSND)
New channel, but need sub-percent precision to compete with PV ES

From the talk by X. Huang, based on COHERENT data:

$$\sin^2 \theta_W^* = 0.21^{+0.13}_{-0.10}$$
COHERENT future

LAr-750 (R&D, proposals pending): 750/610 kg (tot./fiducial), underground (low $^{39}$Ar) argon

D20 (R&D, $d_2O$ secured): 670 kg
Cherenkov detector to reduce flux unc-ty

See talks by D. Rudik and A. Kumpan

unsubtracted data, atmospheric Ar

Unsubtracted data, underground argon

Subtracted data

$\sim$3000 CEvNS events/year

now: 10% $\nu$ flux uncertainty

4 years run time to get few % statistical precision
CC and NC inelastic $\nu$ interactions

**Nubes:**

\[ \nu_e + {}^{208}\text{Pb} \rightarrow e^- + {}^{208}\text{Bi}, \]
\[ \nu + {}^{208}\text{Pb} \rightarrow \nu + {}^{208*}\text{Pb} \]

\[ + \text{decay of a nucleus with neutrons in the final state} \]

...and reactions of the same kind for Fe, Cu

Interesting for HALO and as backg. for CEvNS

**LAr-750:** $\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}$

\[ \sim 440 \text{ CC/NC inelastic events/year expected} \]

Interesting for Duve (supernova signature)

**NaI[Tl]:** $\nu_e + {}^{127}\text{I} \rightarrow e^- + {}^{127}\text{Xe}$  - compare to LAMPF result

<table>
<thead>
<tr>
<th>$^{127}\text{I}$</th>
<th>$^{127}\text{I}(\nu_e, e^-)^{127}\text{Xe}$</th>
<th>Stopped $\pi/\mu$</th>
<th>LSND</th>
<th>210-310 [Quasi-particle] (Engel et al., 1994)</th>
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<tr>
<td>$^{127}\text{I}$</td>
<td>$^{127}\text{I}(\nu_e, e^-)^{127}\text{Xe}$</td>
<td>Stopped $\pi/\mu$</td>
<td>$284 \pm 91\text{(stat)} \pm 25\text{(sys)}$</td>
<td>210-310 [Quasi-particle] (Engel et al., 1994)</td>
</tr>
</tbody>
</table>
**Accelerator produced Dark Matter at SNS**

**Vector portal:** mixing of the vector mediator with photons in $\pi^0/\eta^0$ decays

- P. deNiverville et al., PRD 95 (2017)
- B. Batell et al., PRD 90 (2014)

**Leptophobic portal:** mediator coupling only to baryons

$\chi$ arrives to the detector with prompt $\nu$ and beam-related neutrons

- may be constrained by "delayed" $\nu$ CEvNS
- constrained from the dedicated measurements

A "DM" particle interact with the target [detector nuclei] coherently $\rightarrow \sigma$ enhancement!
LAr-750 could put better limits on the parameter space of these models [1-100 MeV $m_\chi$].

Plots by D. Pershey, pub. in draft.
Near-term future

- **CsI[Na] has 2x statistics more than by the time of the first observation**
  Ongoing analysis and discussions regarding quenching factor values, please use older values till the new QF publication by collaboration

- **LAr “box” is about to be opened, SM predicts ~130 events for this data set**
Summary

**Studying CEvNS:**
- the first result has impact on nuclear physics and $\nu$-quark NSI
- multiple detectors continue data taking $\rightarrow$ new isotopes, stricter limits

**Working on systematics:**
- ongoing analysis of quenching factor data for the target elements
- R&D of $D_2O$ to reduce $\nu$ flux uncertainty

**Making the most of opportunities**
- looking for CC/NC interactions
- testing the sensitivity to accelerator produced DM
CEvNS search activities around the world

Thank you for your attention!
Backup-1: Sterile neutrinos

with D$_2$O to reduce flux uncertainty

at 19.5 m

at 19.3 m and 27.5 m
Ongoing analysis and discussions regarding QF, please use older values [D. Akimov et al., Science v.357, 2017] till the new QF publication by collaboration.
Backup-3: prompt neutron backgrounds

Measurement of total flux and energy distribution of neutrons:

- Scibath
- Sandia Camera

The spectrum is power-law in 1-100 MeV energy region + estimate on the flux: $1.5 \cdot 10^{-7} \text{ cm}^{-2}\text{s}^{-1}$

Neutron flux measurement within the shielding:

- LS EJ-301 with PSD capability
  - 3 liters of LS
  - taking data for half a year

Fit procedure:
1. Power-law spectrum on the input
2. Propagation through the shielding
3. Fit of the $E_{\text{dep}}$ distribution

Result: $1.09 \cdot 10^{-7} \text{ cm}^{-2}\text{s}^{-1}$, power law exponent $\alpha = -1.6$