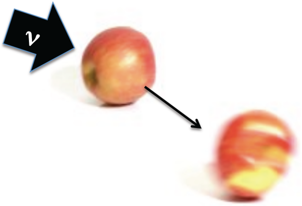
Coherent Elastic Neutrino-Nucleus Scattering

Katarzyna Grzelak

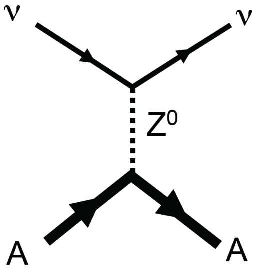
High Energy Physics Seminar
05.04.2019

Coherent elastic neutrino - nucleus scattering (CEvNS)

$\nu + A \rightarrow \nu + A$



A neutrino interacts with a nucleus.
The nucleus recoils as a whole.



For momentum transfer smaller than the inverse of nuclear size, $Q < 1/R$, a long-wavelength Z boson can probe the entire nucleus.

CEvNS

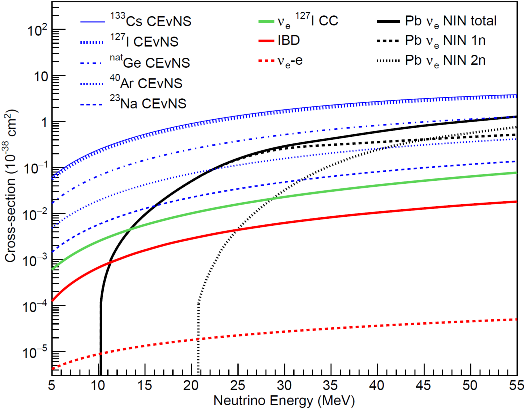
- CEvNS predicted in 1974 by Daniel Freedman
- First observation in 2017 by the COHERENT experiment at Oak Ridge National Laboratory
- The smallest neutrino detector: 14.6-kg sodium-doped CsI scintillator

D.Akimov et al. (COHERENT), Observation of Coherent Elastic Neutrino-Nucleus Scattering, Science(2017), arXiv:1708.01294
D.Akimov et al. (COHERENT), COHERENT 2018 at the Spallation Neutron Source, arXiv:1803.09183
Kate Scholberg, Fermilab Wine&Cheese, 2017

G.C.Rich, Neutrino 2018

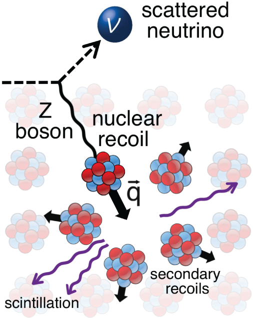
CEvNS – cross sections

Large cross section in comparison to other neutrino-matter interactions



- IBD – Inverse Beta Decay of $\overline{\nu}_e$
- ν_e-e – elastic scattering of ν_e on electrons
- NIN – Neutrino-Induced Neutron background

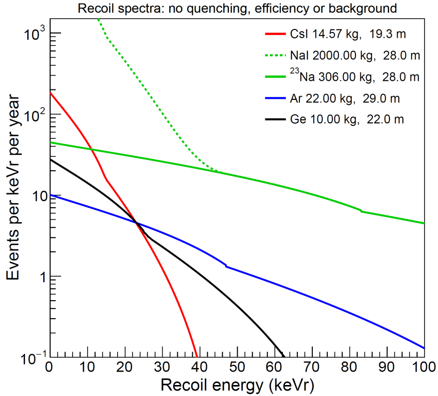
CEvNS - challenging process to observe



CEvNS process difficult to observe:

- low-energy nuclear recoil is the only observable
- detectors sensitive to low-energy recoils are also sensitive to backgrounds (neutron backgrounds !)
- need special source of low-energy neutrinos (energies satisfying $Q < 1/R$ ($<\sim$ 50 MeV for medium nucleus)

Large cross section but small nuclear recoil energies



- Maximum recoil energy $T_{max} = \frac{2E_\nu^2}{M+2E_\nu}$
- Heavier nuclei – higher cross section, but lower recoil energies
- WIMP DM detectors sensitive down to $\sim keV$ recoils

CEvNS cross section

Cross section predicted in the Standard Model.

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi}\left[(G_V + G_A)^2 + (G_V - G_A)^2\left(1 - \frac{T}{E_\nu}\right)^2 - (G_V^2 - G_A^2)\frac{MT}{E_\nu^2}\right]$$

E_ν – neutrino energy
T – nuclear recoil energy
M – nuclear mass
Q = $\sqrt{2MT}$ - momentum transfer
G_F – Fermi constant

G_V, G_A – SM weak parameters (V - vector, A - axial)

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi}\left[(G_V + G_A)^2 + (G_V - G_A)^2\left(1 - \frac{T}{E_\nu}\right)^2 - ({G_V}^2 - {G_A}^2)\frac{MT}{E_\nu^2}\right]$$

G_V – dominates
G_A – zero for spin-zero, negligible for heavy nuclei

$$G_V = (g_V^p Z + g_V^n N) F_{nucl}^V(Q^2)$$

$$G_A = (g_A^p (Z_+ - Z_-) + g_A^n (N_+ - N_-)) F_{nucl}^A(Q^2)$$

Z – proton number, N – neutron number
$Z_\pm, N_\pm$ – number of up and down nucleons
$F_{nucl}^{A,V}(Q^2)$ – nuclear form factor

CEvNS cross section

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi}\left[(G_V + G_A)^2 + (G_V - G_A)^2\left(1 - \frac{T}{E_\nu}\right)^2 - ({G_V}^2 - {G_A}^2)\frac{MT}{E_\nu^2}\right]$$

G_V – dominates

G_A – zero for spin-zero, negligible for heavy nuclei

$$G_V = (g_V^p Z + g_V^n N) F_{nucl}^V(Q^2)$$

$$G_A = (g_A^p (Z_+ - Z_-) + g_A^n (N_+ - N_-)) F_{nucl}^A(Q^2)$$

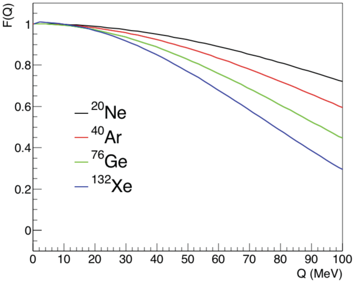
$g_V^{n,p}, g_A^{n,p}$ – vector and axial-vector weak couplings

CEvNS cross section

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi}\left[(G_V+G_A)^2 + (G_V-G_A)^2\left(1-\frac{T}{E_\nu}\right)^2 - (G_V^2-G_A^2)\frac{MT}{E_\nu^2}\right]$$

$$G_V = (g_V^p Z + g_V^n N) F_{nucl}^V(Q^2)$$

$$G_A = (g_A^p (Z_+ - Z_-) + g_A^n (N_+ - N_-)) F_{nucl}^A(Q^2)$$



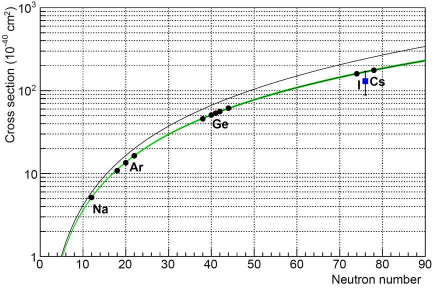
$F_{nucl}^{A,V}(Q^2)$ – nuclear form factors suppress cross section at large Q

For $T \ll E_\nu$, neglecting axial terms:

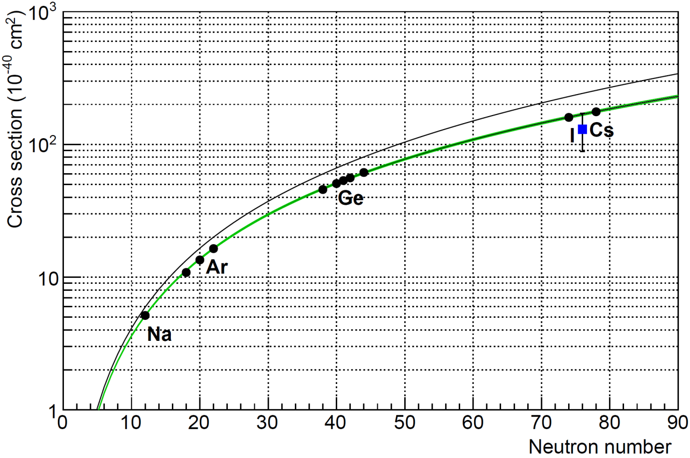
$$\frac{d\sigma}{dT} \simeq \frac{G_F^2 M}{2\pi} G_V^2 \left(2 - \frac{MT}{E_\nu^2}\right)$$

$G_V \propto N - (1 - 4\sin^2\theta_W)Z$, protons unimportant

$$\Rightarrow \frac{d\sigma}{dT} \propto N^2$$



CEvNS cross section



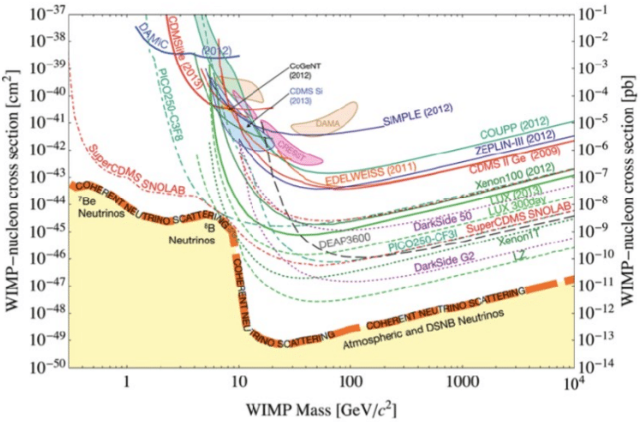
$$\frac{d\sigma}{dT} \propto N^2$$

Probability of neutrino interaction increases with the square of the number of neutrons in the target nucleus

CEvNS - physics motivations

- Various tests of SM predictions:
  - proportionality of the cross-section to neutron number squared
  - precision cross-section measurements
  - $\sin^2\theta_W$ at low Q
  - neutron distribution function (nuclear form factor)
  - ...
- Probe of physics beyond SM
  - Non-standard interactions of neutrinos
  - Search for sterile neutrinos
  - Neutrino magnetic moment
  - ...
- CEvNS is dark matter direct-detection background

CEvNS - background to WIMP searches



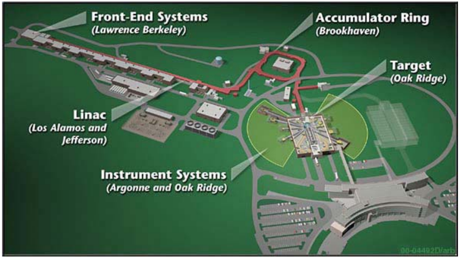
CEvNS of solar, atmospheric and diffuse supernovae neutrinos is an irreducible background for direct Dark Matter WIMP searches

First measurement of CEvNS

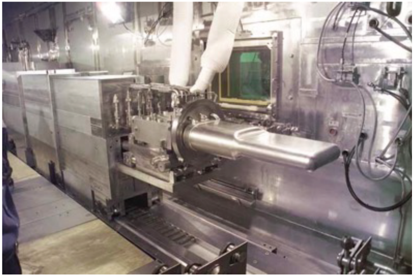
Spallation Neutron Source (SNS)

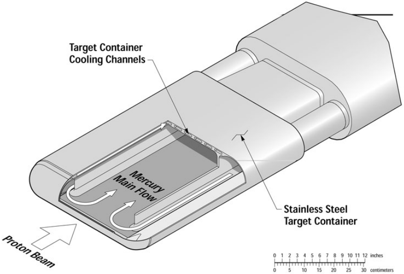
- The most intense pulsed source of neutrons
- Located at Oak Ridge National Laboratory in Tennessee
- Repetition rate 60 Hz
- Pulse duration $\sim 700 ns$
- Facility-wide 60Hz trigger, also during beam-off periods

Spallation Neutron Source

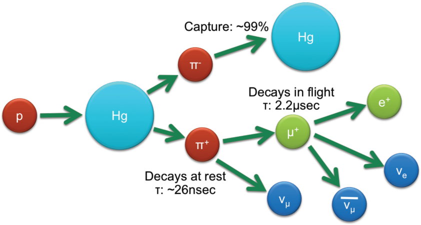


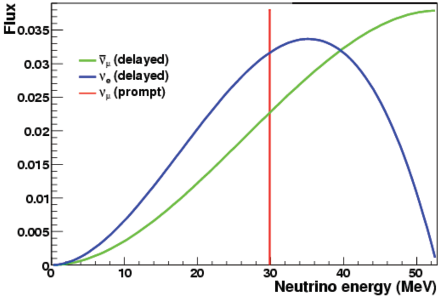
Protons of energy $\sim$ 1 GeV hit a liquid mercury target.





Spallation ~~Neutron~~ Neutrino Source





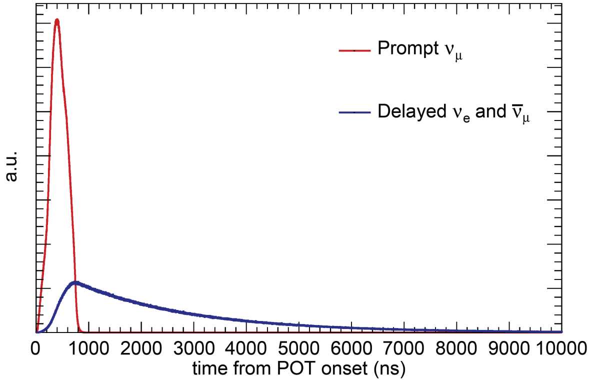
Isotropic flux of neutrons. Also isotropic flux of neutrinos:
PROMPT $\to$ 2-body decay, monochromatic, energy $\sim$ 30 MeV ν_μ

$$\pi^+ \to \mu^+ + \nu_\mu$$

DELAYED ($\tau_\mu = 2.2\mu s$) $\to$ 3-body decay, energies between 0 and $m_\mu/2$

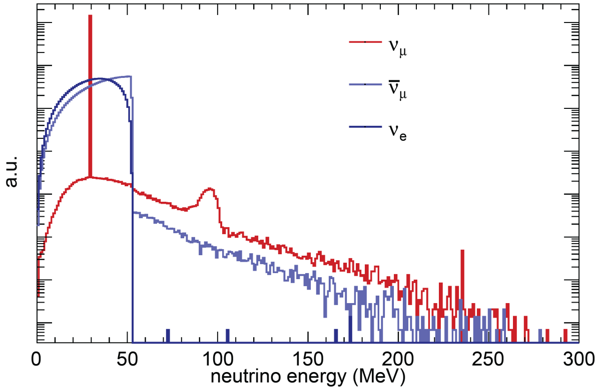
$$\mu^+ \to e^+ + \overline{\nu}_\mu + \nu_e$$

Time structure of the SNS source



- Prompt ν_μ in time with the proton pulse

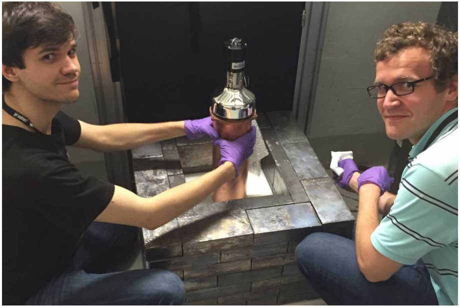
SNS: Clean DAR (decay-at-rest) neutrino flux



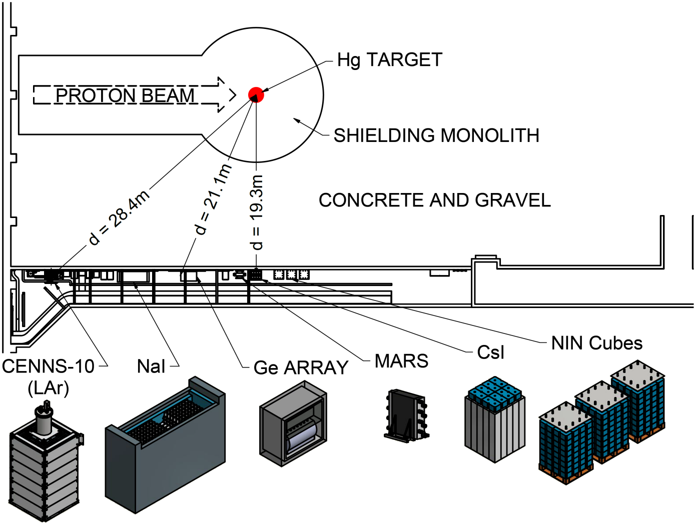
Contribution to the neutrino spectrum from decay-in-flight and μ-capture is small

COHERENT experiment - first detector

- The smallest neutrino detector, 14.6 kg sodium-doped CsI scintillator
- Operating at room temperature
- Located in the basement of SNS facility (Neutrino Alley)
- $\sim$ 20 m from the mercury target
- 8 m.w.e overburden



COHERENT experiment - location

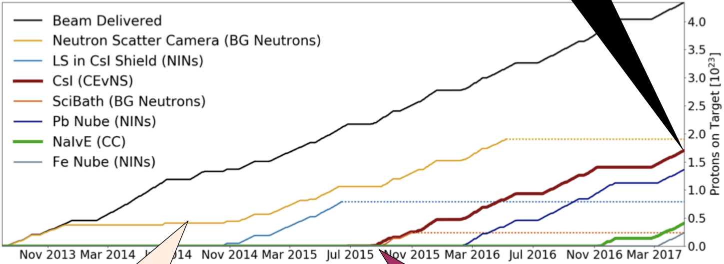


SNS neutrino flux @20m, (1.4 MW): $4.3 \times 10^{7} \nu cm^{-2} s^{-1}$

COHERENT data taking

COHERENT data taking

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



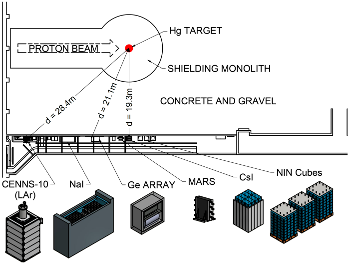
Neutron background data-taking for ~2 years before first CEvNS detectors

CsI data-taking starting summer 2015

46

K.Scholberg, Fermilab Wine&Cheese, 2017

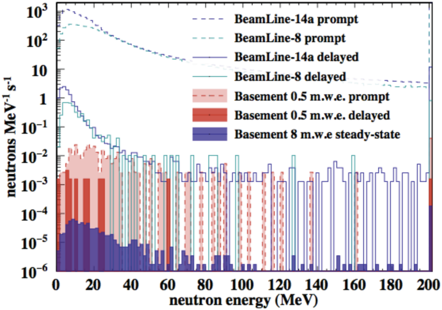
COHERENT experiment - backgrounds



- Steady-state backgrounds can be measured during off-beam periods.
- Primary backgrounds:
  - Prompt SNS neutrons
  - Neutrino-induced neutrons (NINs)
- Background measurement campaign before detector installation.

Neutron backgrounds

Fast neutron spectra measured in the SNS facility.
Neutron background in the basement (Neutrino Alley) is low.



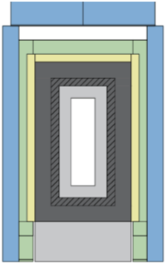
Neutrino Induced Neutrons (NINs)

CC interaction, 1n, 2n emission:

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

NC interaction, 1n,2n,γ emission:

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

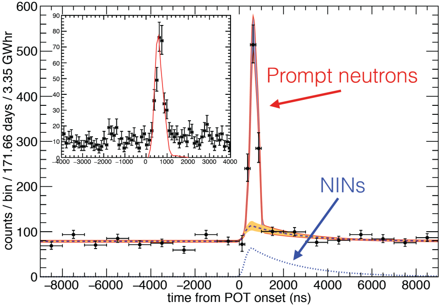


Layer	HDPE*	Low backg. lead	Lead	Muon veto	Water
Thickness	3"	2"	4"	2"	4"
Colour					

Innermost layer of high-density polyethylene (HDPE) reduces NIN background by more than an order of magnitude.

Neutron background measurements

Neutron detection system (EJ-301 liquid scintillator cell) inside the CsI shielding before CsI installation.



Predicted background from beam neutrons:

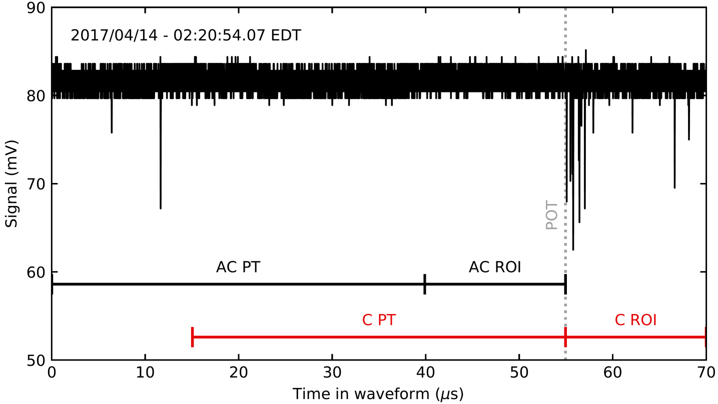
0.92 ± 0.23 events/GWhr

Predicted background from NIN neutrons:

0.54 ± 0.18 events/GWhr

$<\sim$ 11 neutron events in the 2017 CsI dataset

COHERENT – first results – example CsI waveform



PT – pretrace
ROI – region of interest
AC – anticoincidence
C – coincidence

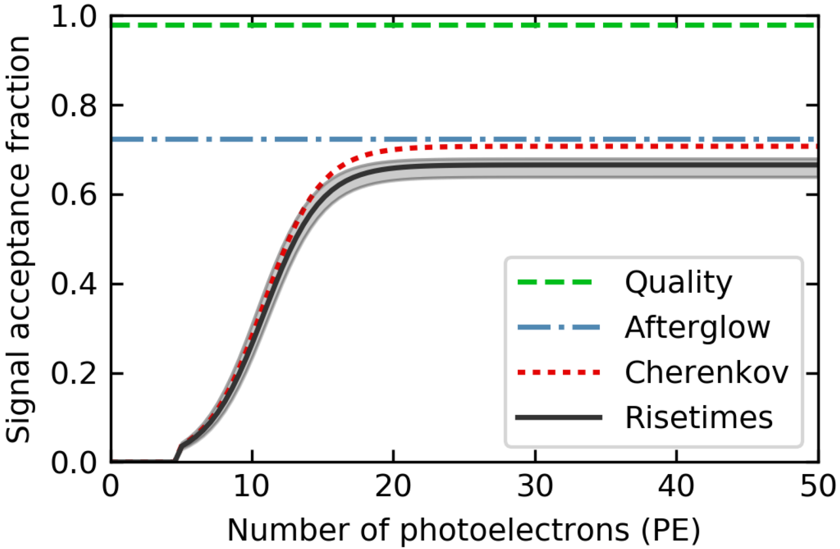
POT – time when the SNS timing signal triggered DAQ.
Pretraces used for afterglow background removal.

COHERENT – first results – selection

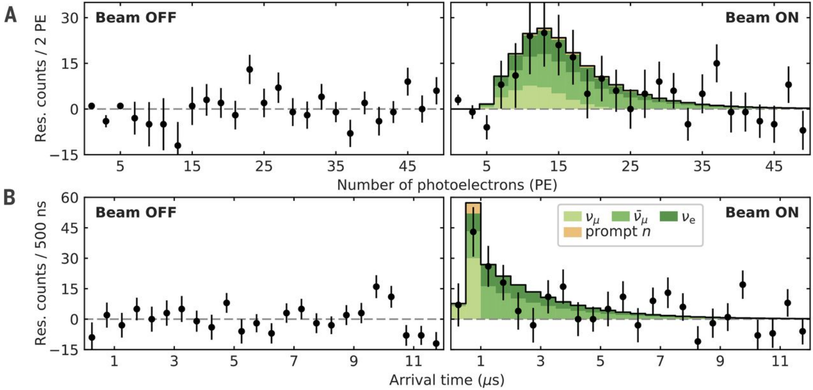
Quality	Remove coincidences in muon veto, deadtime from PMT saturation blocking, digitizer range overflow	Select recoil-like low-energy pulses, reject muons
Afterglow	Reject signals with >=4 peaks (~spe) in pretrace	Remove afterglow (phosphorescence) contamination
“Cherenkov”	Require minimum number of peaks in the scintillation signal	Remove accidental coincidences between Cherenkov emission in PMT window and dark counts/ afterglow
Risetime	Pulse-shape based	Remove misidentified scintillator onset, accidental groupings of dark counts, etc.

K.Scholberg, Fermilab Wine&Cheese, 2017

COHERENT - first results – signal acceptance

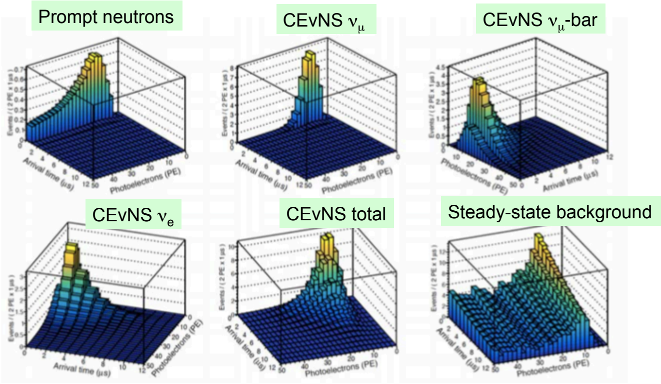


COHERENT experiment - first results, SM vs data



Residual differences between data in the 12 μs window following POT (proton-on-target) triggers, and those in a 12 μs window before.

Likelihood analysis: 2D in energy (pe) and time



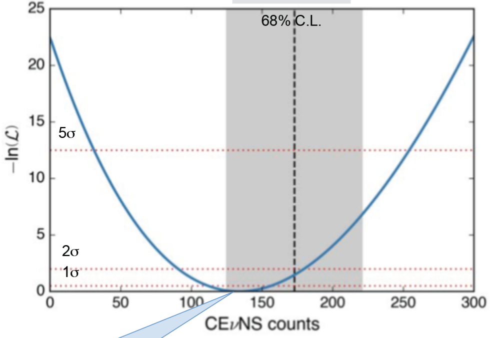
$6 \leq PE \leq 30$, $0 \leq t \leq 6000$ ns

Scholberg 53

K.Scholberg, Fermilab Wine&Cheese, 2017

Results of 2D energy, time fit

SM prediction, 173 events



Best fit: **134 ± 22** observed events

No CEvNS rejected at 6.7σ, consistent w/SM within 1σ

54

K.Scholberg, Fermilab Wine&Cheese, 2017

COHERENT - first results

Signal, background, and uncertainty summary numbers

$6 \leq PE \leq 30$, $0 \leq t \leq 6000$ ns

Beam ON coincidence window	547 counts
Anticoincidence window	405 counts
Beam-on bg: prompt beam neutrons	7.0 ± 1.7
Beam-on bg: NINs (neglected)	4.0 ± 1.3
Signal counts, single-bin counting	136 ± 31
Signal counts, 2D likelihood fit	**134 ± 22**
Predicted SM signal counts	**173 ± 48**

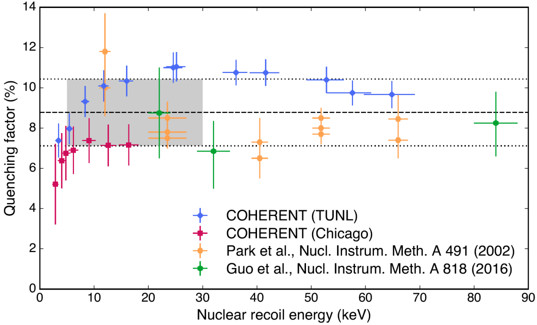
Uncertainties on signal and background predictions	
Event selection	5%
Flux	10%
Quenching factor	25%
Form factor	5%
Total uncertainty on signal	**28%**
Beam-on neutron background	25%

Dominant uncertainty (← Quenching factor)

55

K.Scholberg, Fermilab Wine&Cheese, 2017

Dominant uncertainty – quenching factor



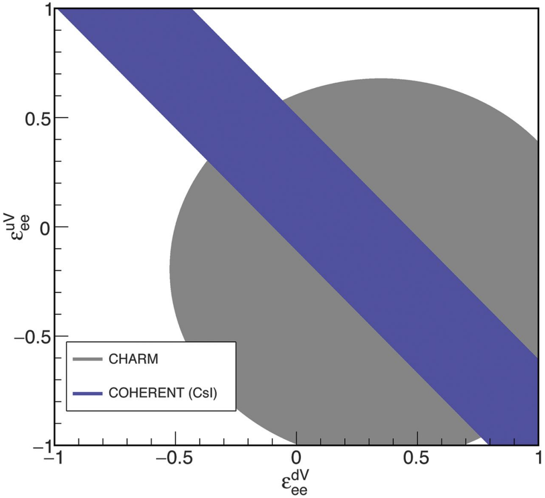
Nuclear recoils generate a fraction of light yield produced by an electron recoil of similar energy → Quenching Factor (keVr=QF*keVee), QF – fraction of observable energy.

$$13.348 pe/keVee \cdot 0.0878 keVee/keVr = 1.2 pe/keVr$$

(ee light yield) * QF = 1.2 pe/keVr

First constraint on physics beyond SM

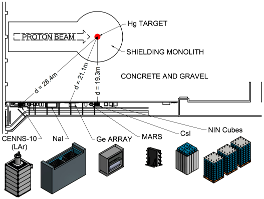
Constraints on non-standard neutrino-quark interactions



Future

All detectors of the COHERENT experiment

Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)	Data-taking start date
CsI[Na]	Scintillating Crystal	14.6	20	6.5	9/2015
Ge	HPGe PPC	10	22	5	2017
LAr	Single-phase	22	29	20	12/2016, upgraded summer 2017
NaI[Tl]	Scintillating crystal	185*/ 2000	28	13	*high-threshold deployment summer 2016



K.Scholberg, Fermilab Wine&Cheese, 2017

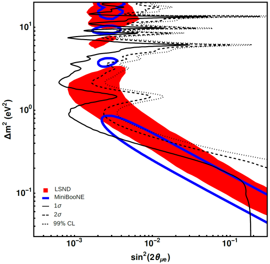
Four detectors to check N^2 dependence of the Standard Model CEvNS cross-section.

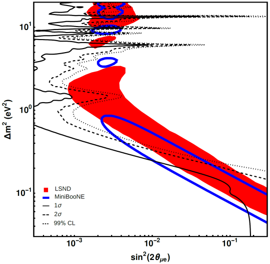
COHERENT physics goals

- Test of proportionality of the CEvNS cross-section to N^2
- Precision cross-section measurements, further tests of non-standard interactions
- CEvNS as background for dark matter WIMP searches
- ...
- Sensitivity to constrain sterile neutrino interpretation of LSND and MiniBooNE anomalies ?

Sterile interpretation of LSND & MiniBooNE results

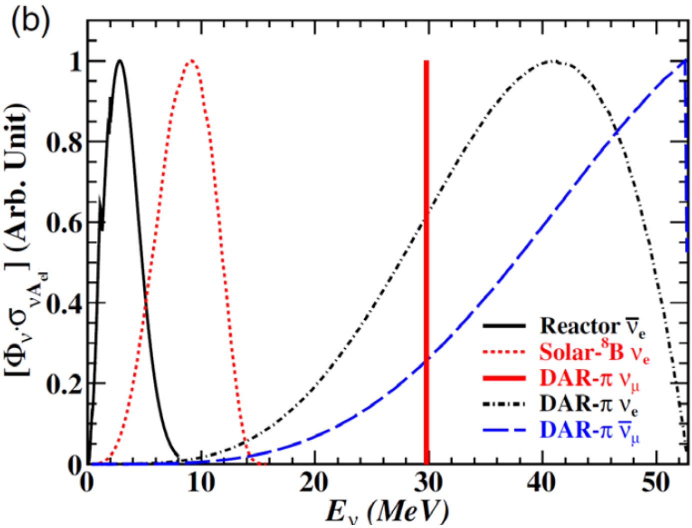
- In several papers the possibility to search for sterile neutrinos with CEvNS was already discussed
- Last (from 2019, arXiv:1901.08094) proposition: 100 kg CsI located at different baselines (20 m and 40m) at SNS-like facility to constrain sterile interpretation of LSND & MiniBooNE results



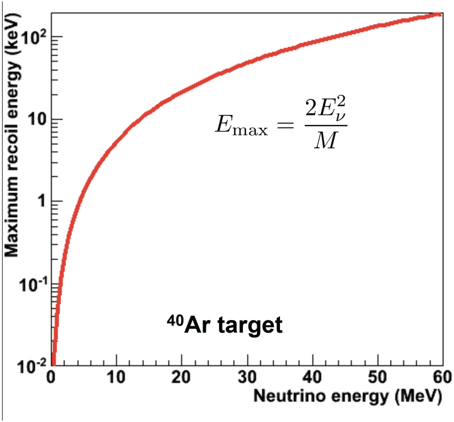


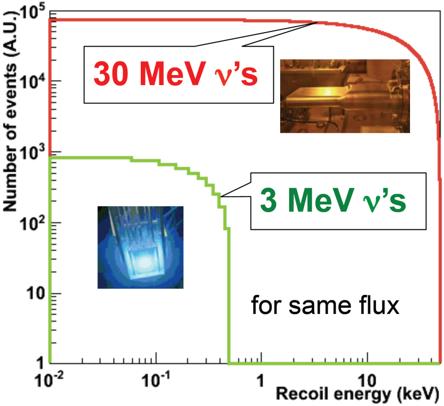
Left: 3 years of data taking, Right: 10 years of data taking

Other possibilities to study CEvNS



DAR vs reactor experiments





Both cross section and maximum recoil energy increase with neutrino energy.
(Energy cannot be too high to satisfy coherence condition.)

CONUS experiment

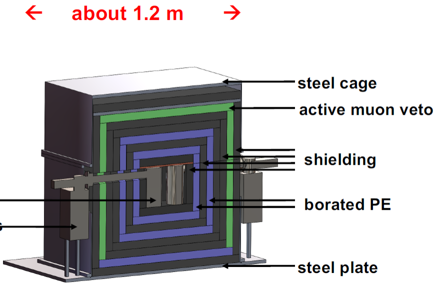
CONUS - one of the experiments to study coherent interactions of reactor $\overline{\nu}_e$, first results at Neutrino 2018.

Components:

- ``virtual depth" shielding
- 4 Germanium detectors
- PT cryocooling

➔ all ultra low background

- electronics & DAQ



M.Lindner, 2018

Summary

- CEvNS observed for the first time in 2017 by the COHERENT experiment at the SNS
- New opportunities to study neutrino physics
- Multiple physics motivations
- COHERENT continues to study CEvNS with various detectors
- Many different experiments search for or plan to study CEvNS using different detector techniques and reactor $\overline{\nu}_e$ (CONUS, CONNIE, MINER , Nu-CLEUS, Ricochet . . .)