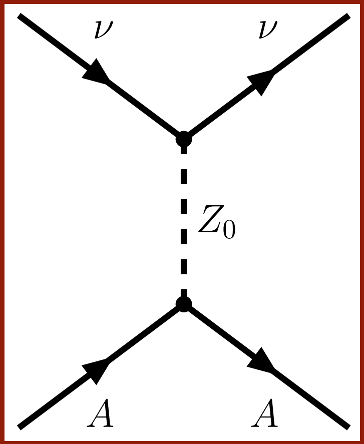
# Coherent Elastic Neutrino-Nucleus Scattering (CEνNS):

(Pronounced *seh-vens*)



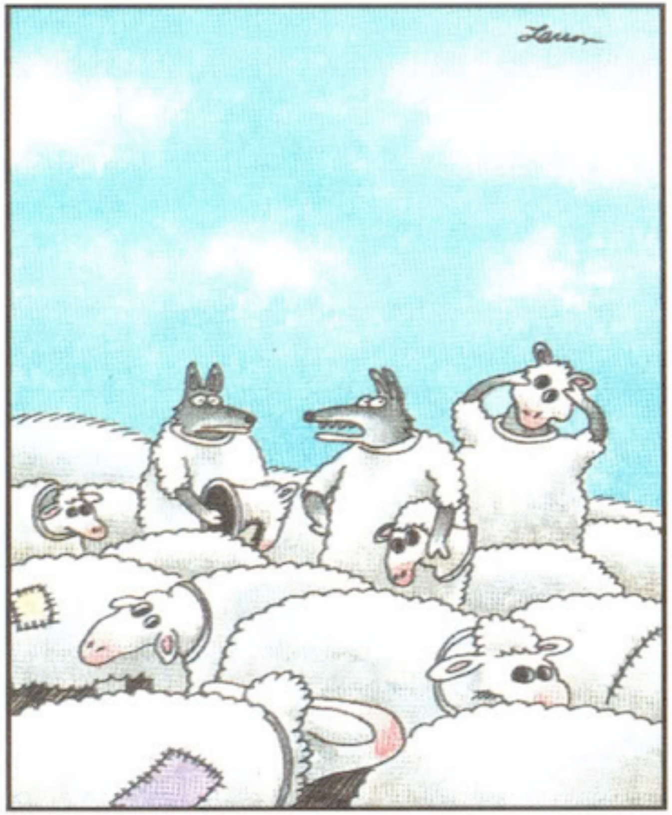

Robert Cooper

*http://neutrino.indiana.edu/rlcooper*

INDIANA UNIVERSITY

# Outline

- Physics Motivation for CEνNS
- How do we measure CEνNS?
  i.) Neutrino production
  ii.) Detection
  iii.) Background suppression
- Prominent accelerator efforts
  i.) CENNS at FNAL BNB
  ii.) COHERENT at ORNL SNS



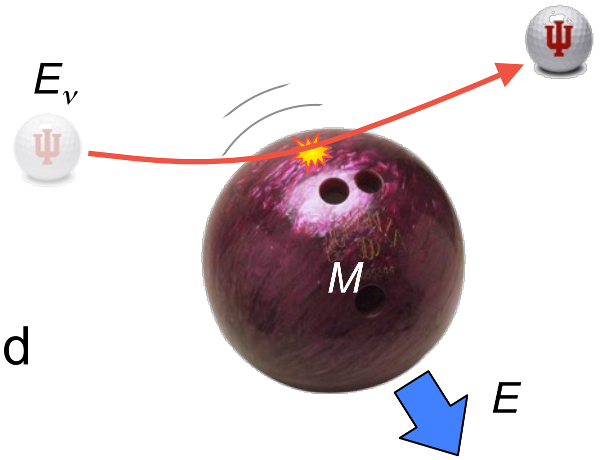
"Wait a minute! Isn't anyone here a real sheep?"

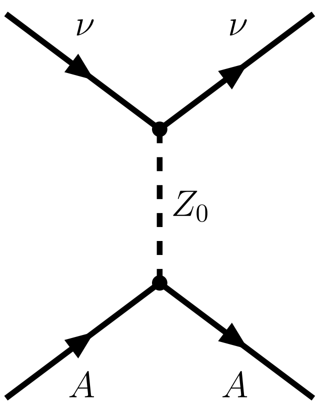
# Describing the CEνNS Signal

- To probe a "large" nucleus (few × $10^{-15}$ m)

$$E_\nu \lesssim \frac{hc}{R_N} \cong 50 \text{ MeV}$$

- Detector signature is the recoiling nucleus




- Recoil energy that is deposited

$$E_r^{\max} \simeq \frac{2E_\nu^2}{M} \simeq 50 \text{ keV}$$

- This is quite small for particle & nuclear physics → Dark Matter

# Structure of the CEνNS Signal

- Predicted scattering rate

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

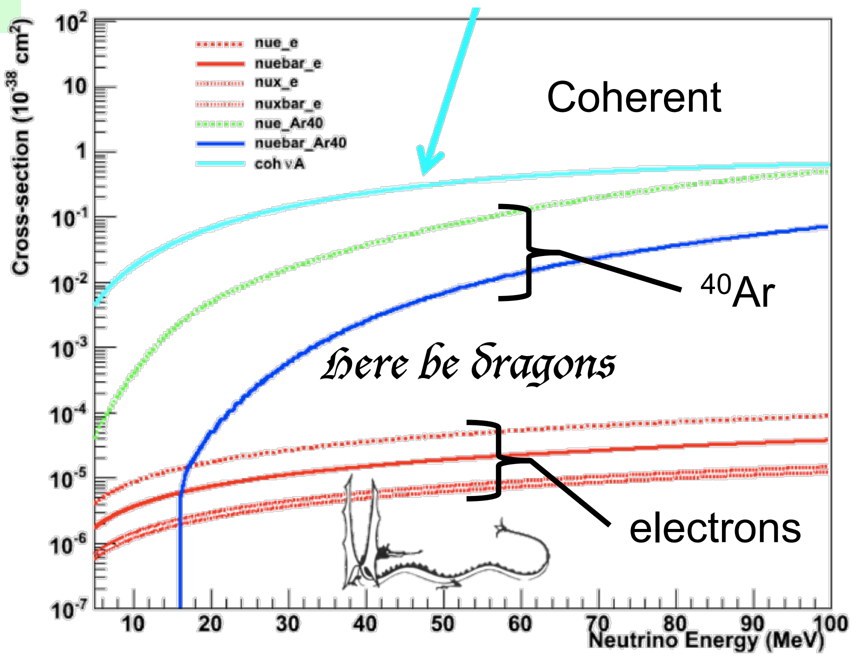
≈ 0 → protons have little influence

square of sum → part of coherence condition

nuclear form factor → distribution of neutrons

- Recoil energy ($M^{-1}$) and rate ($N^2$)

**ν Cross Sections vs. Energy (Ar)**

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[1]Image from K. Scholberg

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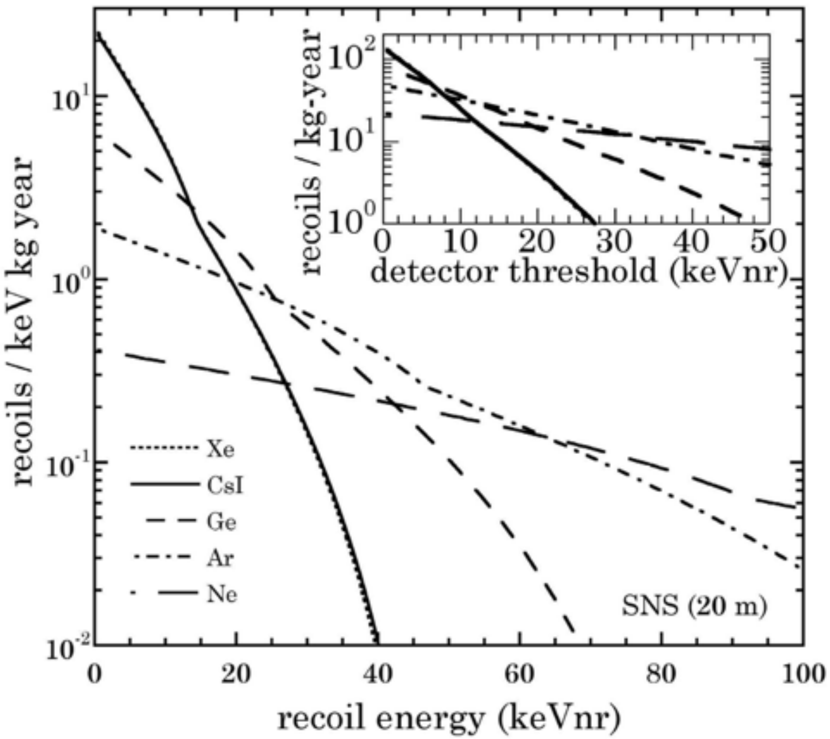
**Detection Rate vs. Target**




[1]J.I. Collar et al., Nucl. Instrum. Meth. **A773** (2014) 56. arXiv:/1407.7524 [physics.in-det]

# Physics Cases for CE$\nu$NS

- **Never been observed!**
- Oscillations (spatially)
- Form factors
- Supernova physics
- Non-standard interactions
- Irreducible dark matter background
- Low-mass dark matter searches (related)
- Neutrino-induced neutron production (related)

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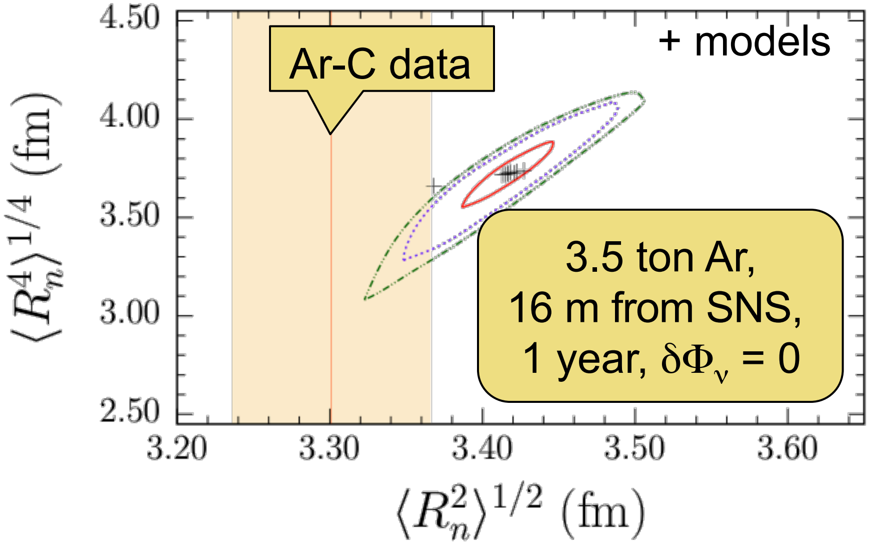
**$4^{th}$ vs $2^{nd}$ Form Factor Moments**

$$F(Q^2) = \frac{1}{Q_W}\left[F_n(Q^2) - (1 - 4\sin^2\theta_W)F_p(Q^2)\right]$$

$$F_n(Q^2) \approx \int \rho_n(r)\left(1 - \frac{Q^2}{3!}r^2 + \frac{Q^4}{5!}r^4 - \frac{Q^6}{7!}r^6 + \cdots\right) r^2 dr$$




[1]K. Patton et al., Phys. Rev. **C86** (2012) 024612. arXiv:/1207.0693 [nucl-th]

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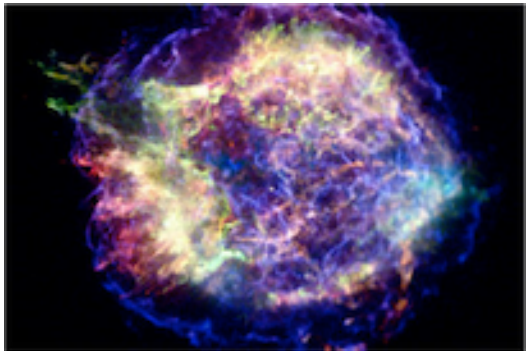
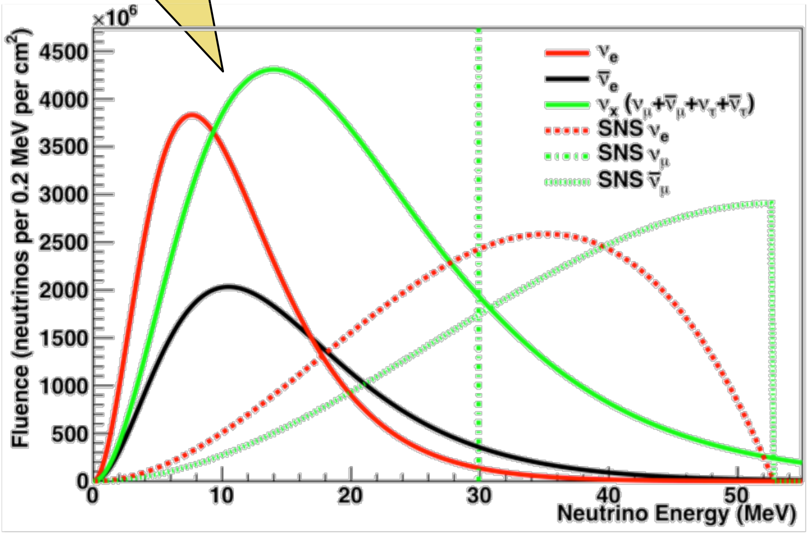
Supernova neutrino energy is similar to accelerator neutrinos



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[1]E.g., Horowitz et al., Phys. Rev. **D68** (2003) 023005. arXiv:astro-ph/0302071 [astro-ph]

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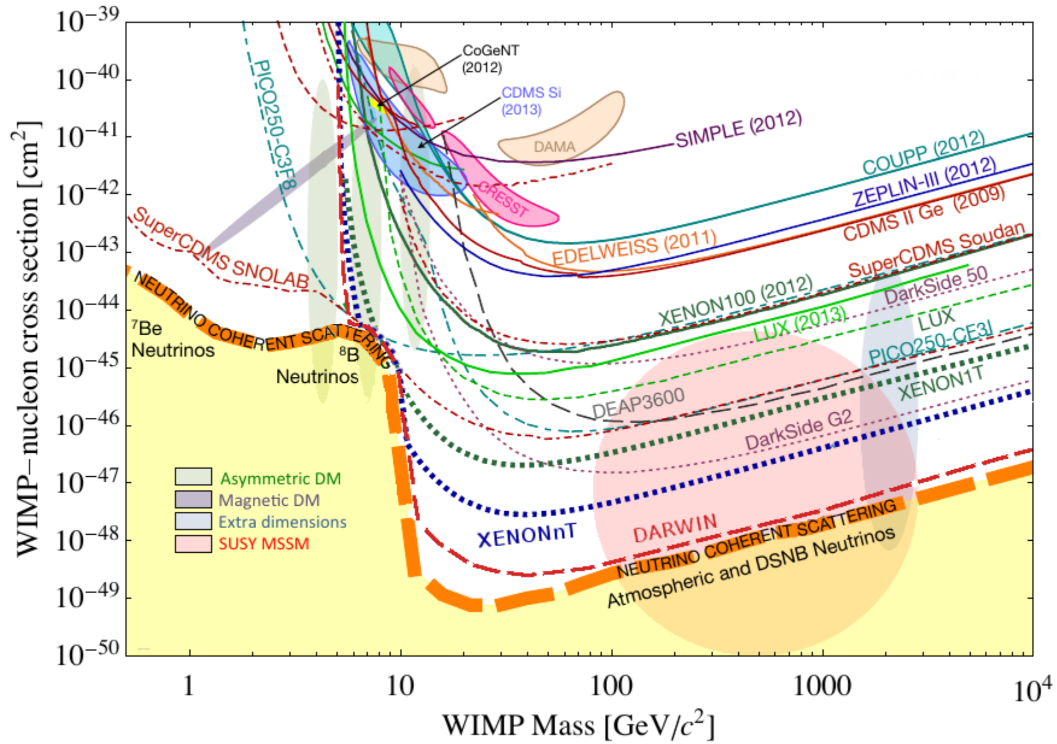
**Dark Matter Sensitivity**




[1]L. Baudis, Phys. Dark Univ. **4** (2014) 50-59. arXiv:/1408.4371 [astro-ph]

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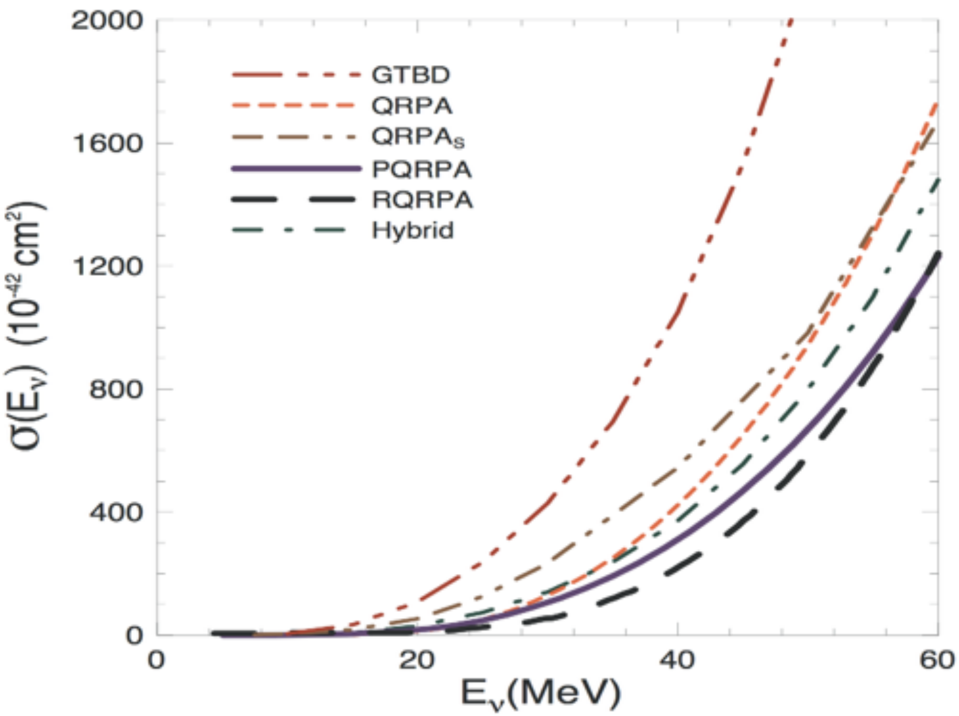
- **Neutrino-induced neutron production (related)**

**ν-induced neutron production on Fe**




[1]A.R. Samana & C.A. Bertulani, Phys.Rev. **C78** (2008) 024312. arXiv:/0802.1553 [nucl-th]

COHERENT SNS

## COHERENT at the Spallation Neutron Source

J. Adam,[1] P.S. Barbeau,[1,2] P. Barton,[3] A. Bolozdynya,[4] B. Cabrera-Palmer,[5] J.I. Collar,[6] R. Cooper,[3] R. Cooper,[7] D. Dean,[8] Y. Efremenko,[4,9] S. Elliott,[10] N. Fields,[11] M. Foxe,[12] A. Galindo-Uribarri,[8,9] M. Gerling,[5] M. Green,[8] G. Greene,[8,9] D. Hornback,[8] T. Hossbach,[12] E.B. Iverson,[8] S. Klein,[3] A. Khromov,[4] A. Kumpan,[4] W. Lu,[8] D. Markoff,[13,2] P. Mueller,[8] M. McIntyre,[14] J. Newby,[8] J. Orrell,[12] S. Penttila,[8] G. Perumpilly,[6] D. Radford,[8] H. Ray,[14] J. Raybern,[1,8] D. Reyna,[5] G. Rich,[2] D. Rimal,[14] K. Scholberg*,[1,†] B. Scholz,[6] S. Suchyta,[15] R. Tayloe,[7] K. Vetter,[15,3] and C.H. Yu[8]

[1] *Department of Physics, Duke University, Durham, NC 27708, USA*
[2] *Triangle Universities Nuclear Laboratory, Durham, North Carolina, 27708, USA*
[3] *Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[4] *National Research Nuclear University MEPhI, Moscow, 115409, Russia*
[5] *Sandia National Laboratories, Livermore, CA 94550, USA*
[6] *Enrico Fermi Institute, Kavli Institute for Cosmological Physics and Department of Physics, University of Chicago, Chicago, IL 60637*
[7] *Department of Physics, Indiana University, Bloomington, IN, 47405, USA*
[8] *Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*
[9] *Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996, USA*
[10] *Los Alamos National Laboratory, Los Alamos, NM, USA, 87545, USA*
[11] *Enrico Fermi Institute, Kavli Institute for Cosmological Physics and Department of Physics, University of Chicago, Chicago, IL 60637, USA*
[12] *Pacific Northwest Laboratory, Richland, WA 99352, USA*
[13] *Physics Department, North Carolina Central University, Durham, North Carolina 27707, USA*
[14] *Department of Physics, University of Florida, Gainesville, FL 32611, USA*
[15] *Department of Nuclear Engineering, University of California, Berkeley, CA, USA*

[1] https://fsnutown.phy.ornl.gov/fsnufiles/positionpapers/Coherent_PositionPaper.pdf

# SNS Neutron / Neutrino Source

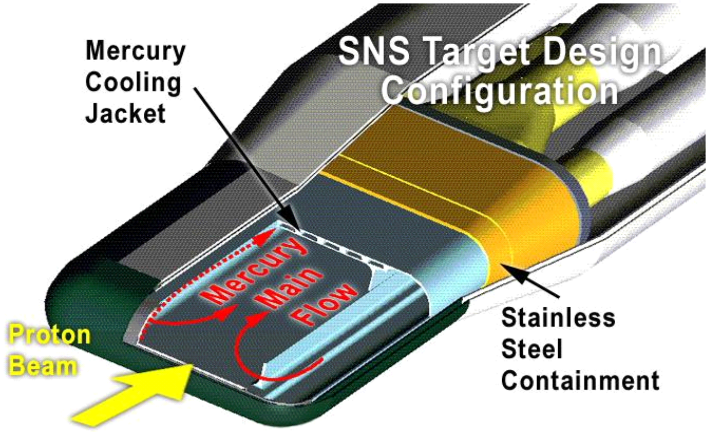
- Few GeV protons on target produces **stopped** $\pi^+$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

- Prototypical source is **S**pallation **N**eutron **S**ource
- SNS flux at 20 m

$\Phi^{SNS} = 3\times10^7\ s^{-1}\ cm^{-2}$

- 700 ns pulses at 60 Hz → ≈ $10^{-4}$ overall duty factor
- ≈ 1 GeV protons (few kaons) on liquid Hg target → ≈ 1 MW



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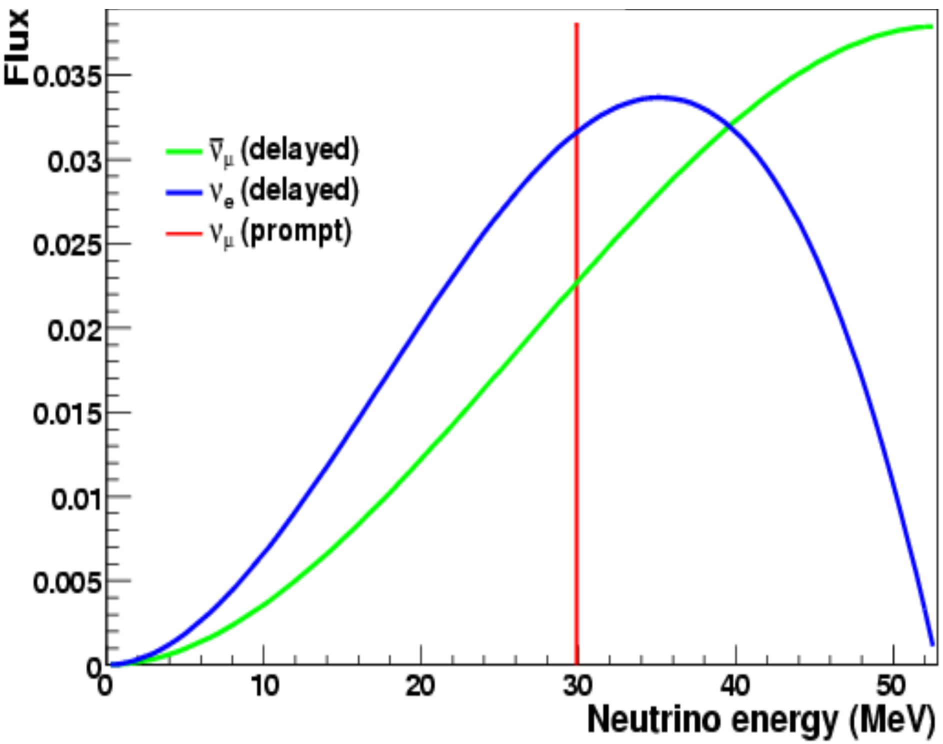
**SNS Stopped Pion Energy Spectrum**




[1] F.T. Avignone & Yu. Efremenko, J. Phys. **G29** (2003) 2615-2628.

# CEνNS Detectors for COHERENT

- Typically use dark matter detectors for CEνNS
  - ❑ Scalable (up to ton-scale)
  - ❑ Radiopure (duty factor helps)
  - ❑ Fast (correlate to beam pulse)
  - ❑ Low-detection threshold
  - ❑ *Nuclear- / electron-recoil ID

- Multiple targets:
  **CsI**, Ge, LXe for validation
  (optional: NaI and LAr)

- 14 kg, 7 keVnr threshold, at 20 m could discover CEνNS: 500 events year[-1]

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*CEνNS is typically a near threshold effect. Particle recoil ID tends to be difficult.
[1]J.I. Collar et al., Nucl. Instrum. Meth. **A773** (2014) 56. arXiv:/1407.7524 [physics.in-det]

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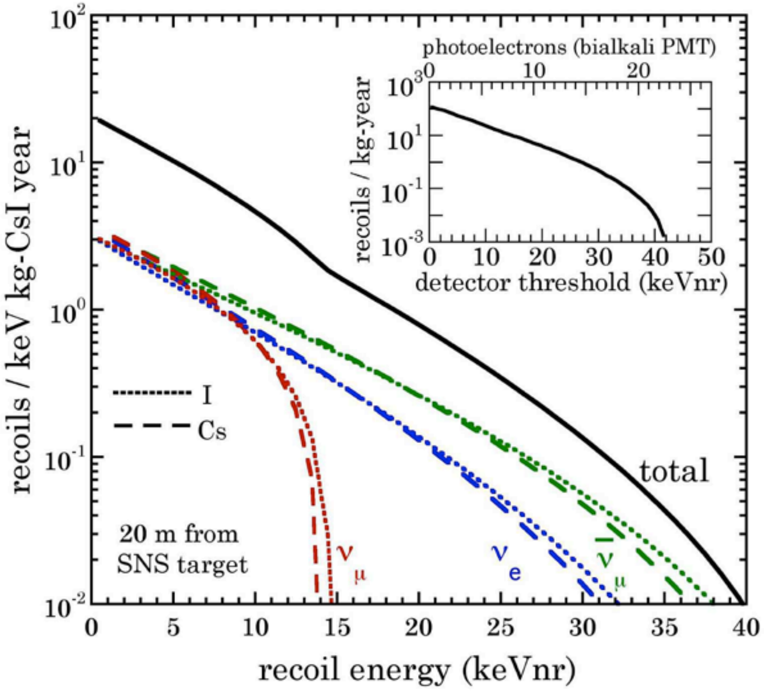
**Expected Rates for CsI at SNS**

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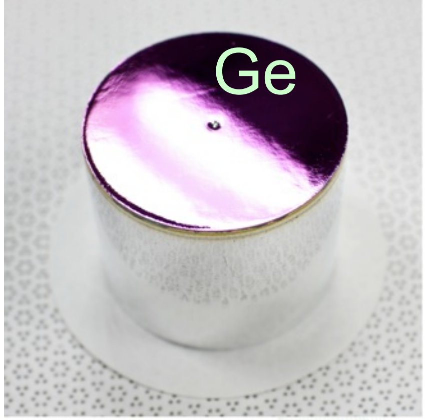
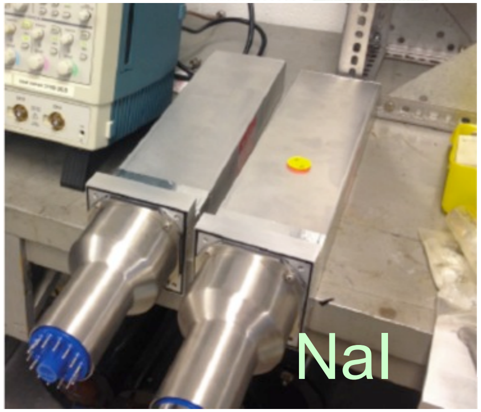



LBL PPC Detector

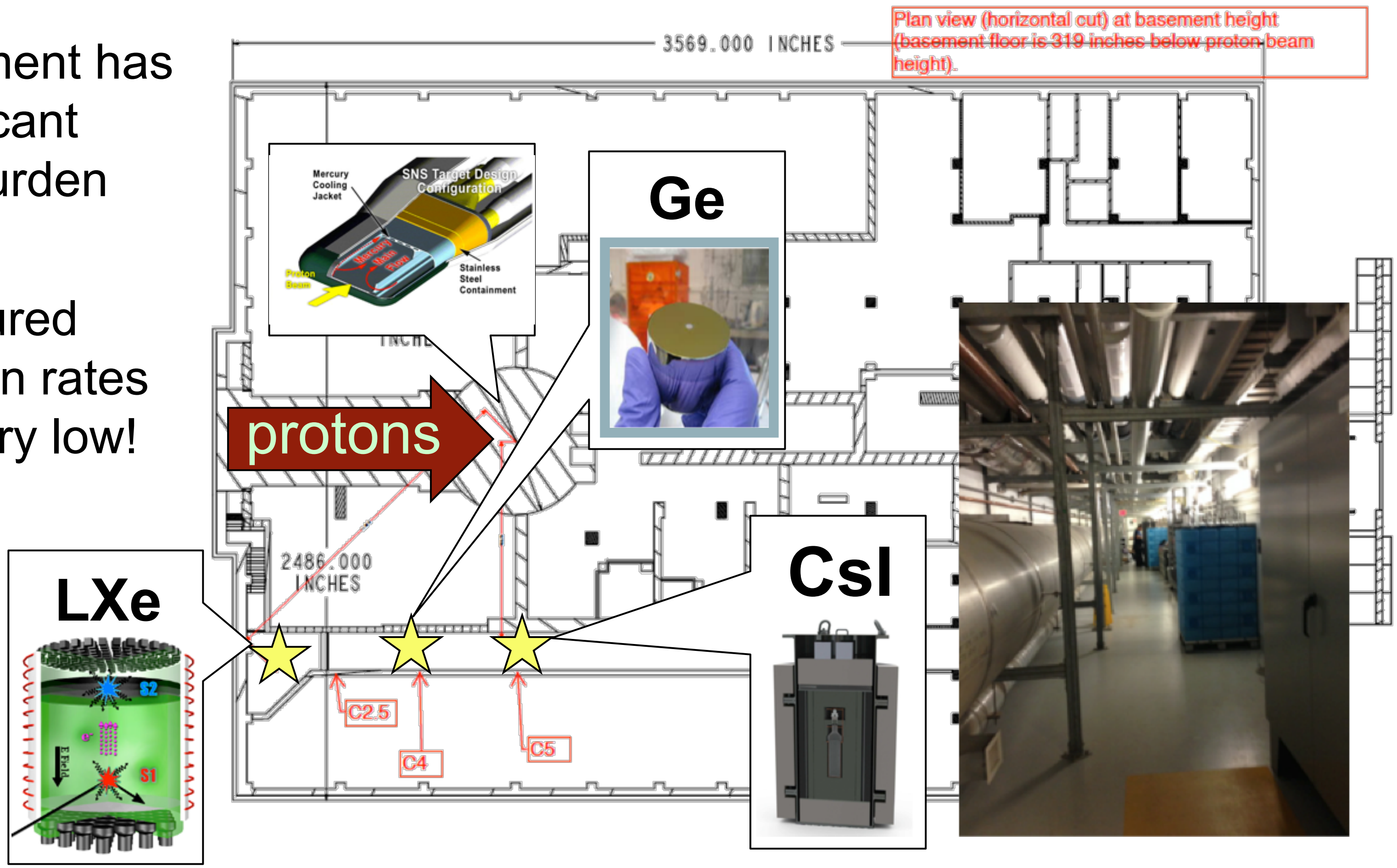




*CE$\nu$NS is typically a near threshold effect. Particle recoil ID tends to be difficult.
[1]J.I. Collar et al., Nucl. Instrum. Meth. **A773** (2014) 56. arXiv:/1407.7524 [physics.in-det]

# Siting and Backgrounds at SNS

- Basement has significant overburden
- Measured neutron rates are very low!



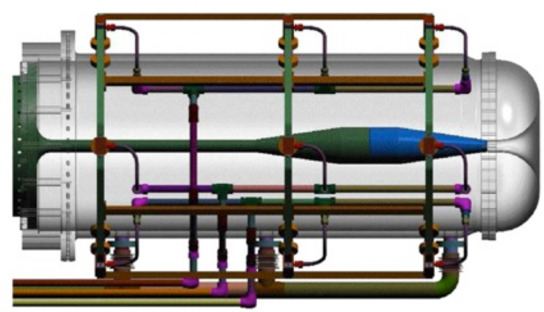
# CENNS at Fermilab BNB

PHYSICAL REVIEW D **89,** 072004 (2014)

**A method for measuring coherent elastic neutrino-nucleus scattering at a far off-axis high-energy neutrino beam target**

S. J. Brice,[1] R. L. Cooper,[2,*] F. DeJongh,[1] A. Empl,[3] L. M. Garrison,[2] A. Hime,[4] E. Hungerford,[3] T. Kobilarcik,[1] B. Loer,[1] C. Mariani,[5] M. Mocko,[4] G. Muhrer,[4] R. Pattie,[6] Z. Pavlovic,[4] E. Ramberg,[1] K. Scholberg,[7] R. Tayloe,[2] R. T. Thornton,[2] J. Yoo,[1] and A. Young[6]

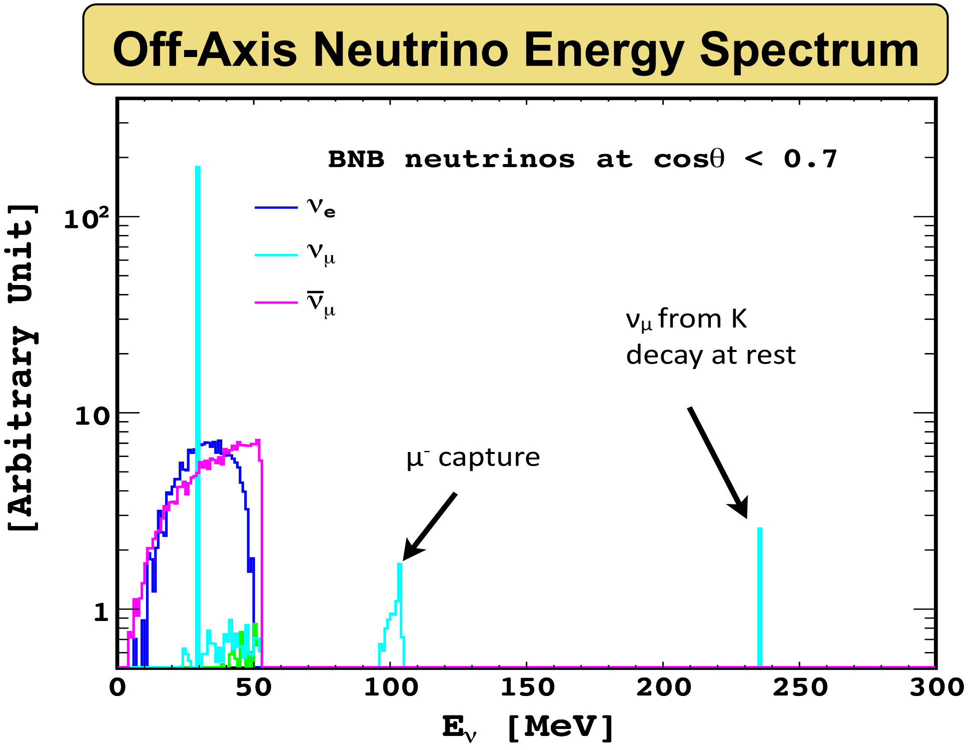
[1]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[2]*Indiana University, Bloomington, Indiana 47405, USA*
[3]*University of Houston, Houston, Texas 77204, USA*
[4]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[5]*Virginia Tech, Blacksburg, Virginia 24061, USA*
[6]*North Carolina State University, North Carolina 27695, USA*
[7]*Duke University, Durham, North Carolina 27708, USA*
(Received 25 November 2013; published 3 April 2014)



[1]S.J. Brice et al., Phys. Rev. **D29** (2014) 072004. arXiv:/1311.5958 [physics.in-det]

# Far-Off-Axis Approach for CENNS

- 8 GeV protons on thick Be target, horn focused mesons
- Far-off-axis predominantly decay-at-rest pions
- Siting at BNB can potentially be very close and/or easy
- $\Phi^{BNB} = 5\times10^5\ s^{-1}\ cm^{-2}$ (20 m, $\cos\theta < 0.5$)

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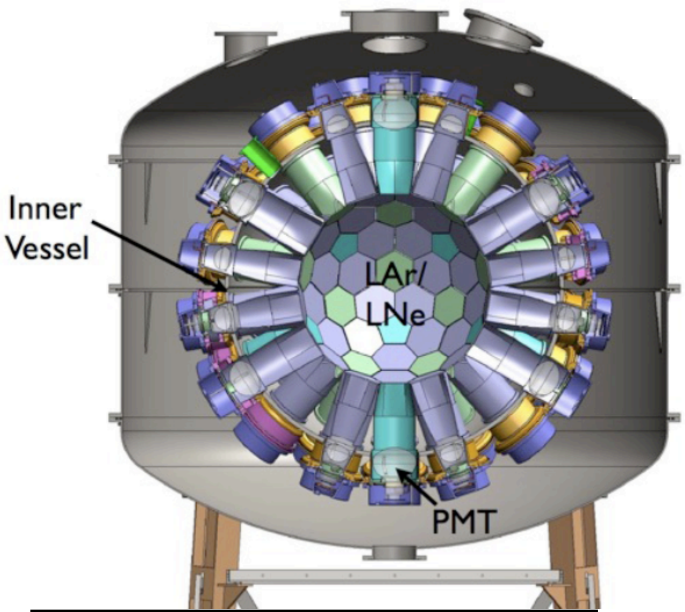
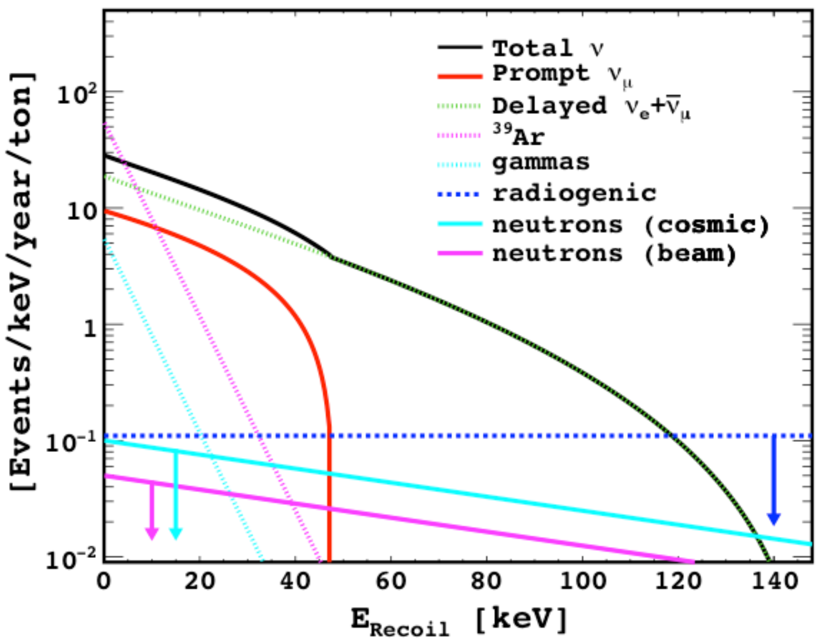
# MiniCLEAN: SNOLab → Fermilab

- Single-phase, LAr has copious VUV scintillation, 500 kg fiducial, radioactive purity

- ≈ 100 CENNS events / year, discovery and constrain non-standard interactions

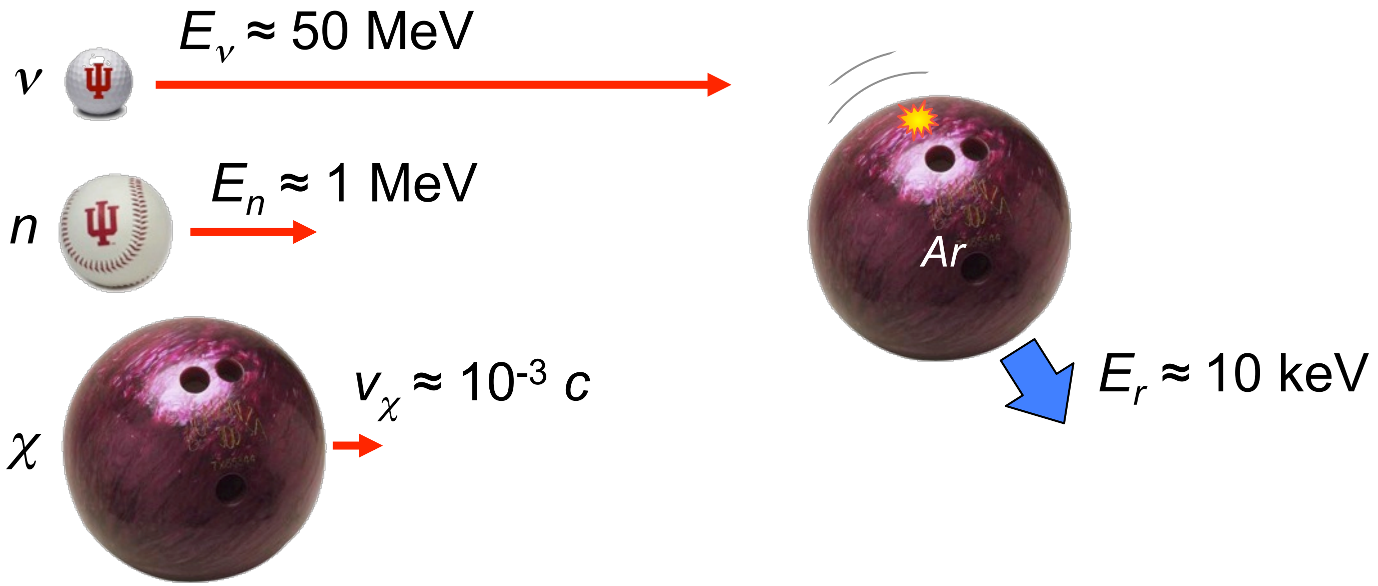



[1] S.J. Brice et al., Phys. Rev. **D29** (2014) 072004. arXiv:/1311.5958 [physics.in-det]

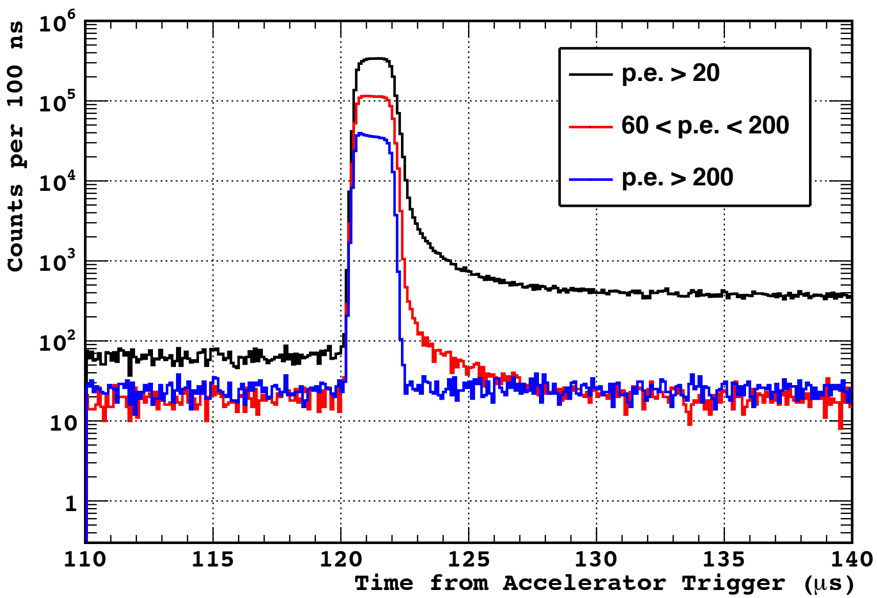
# Elastic Scattering Connection: ν, n, χ

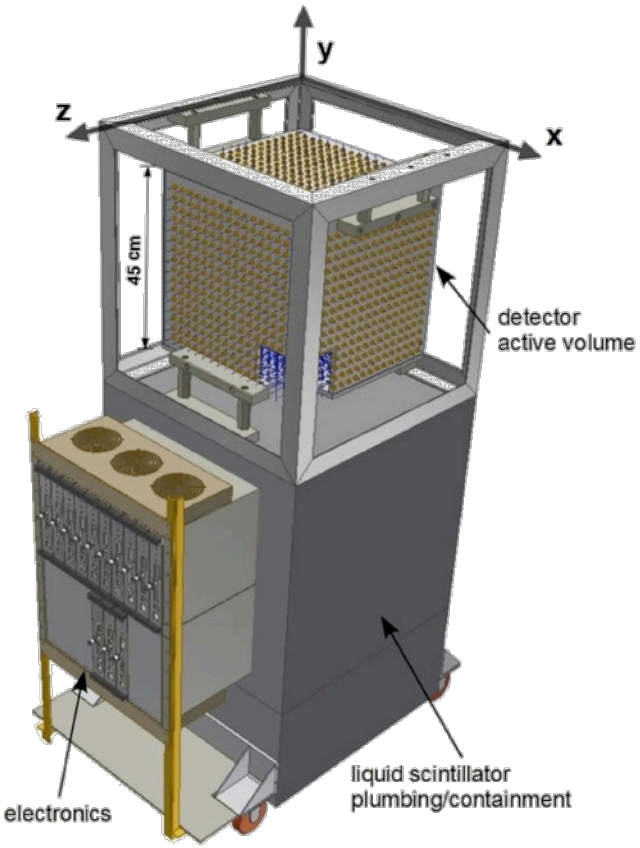
- Many indistinguishable sources of few × 10 keV nuclear recoils
- **Must measure neutron fluxes**



# SciBath Neutron Measurements at BNB

- SciBath is 80 L liquid scintillator tracking detector (768 optical fiber)




[1]R. Cooper et al. arXiv:/1110.4432 [hep-ex]
[2]S.J. Brice et al., Phys. Rev. **D29** (2014) 072004. arXiv:/1311.5958 [physics.in-det]

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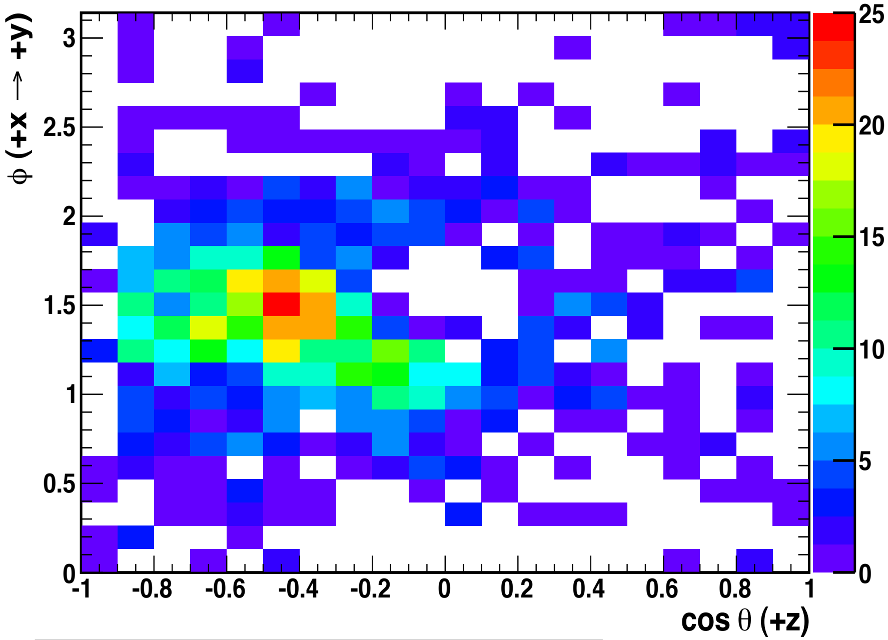
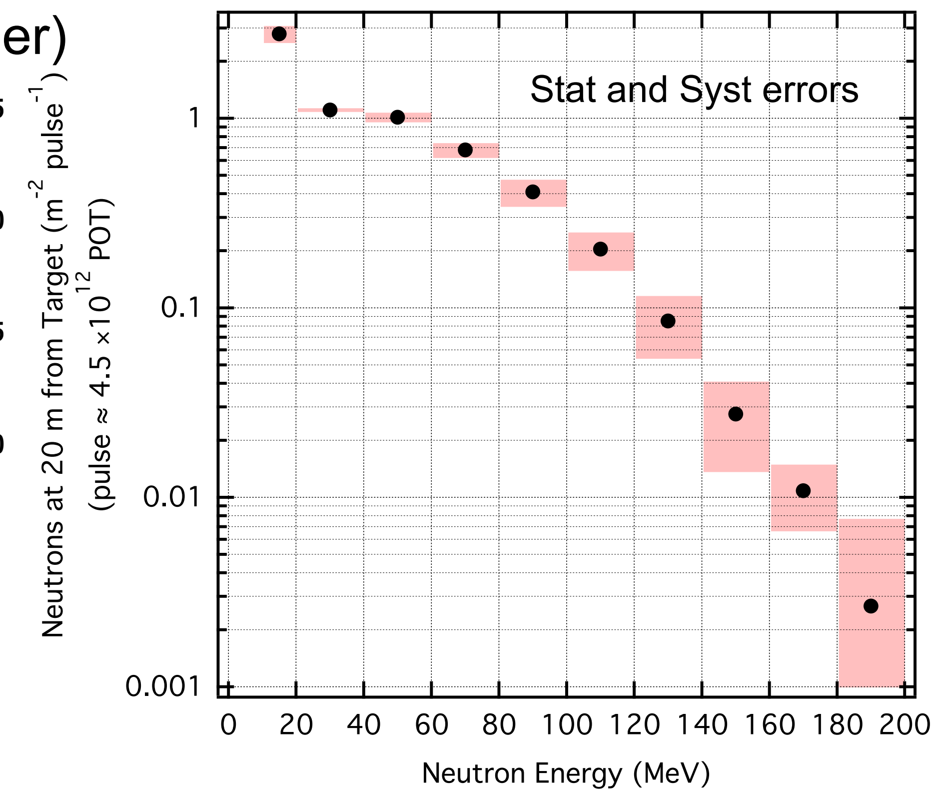




[1]R. Cooper et al. arXiv:/1110.4432 [hep-ex]

[2]S.J. Brice et al., Phys. Rev. **D29** (2014) 072004. arXiv:/1311.5958 [physics.in-det]

# CEνNS: A Phased Approach

| Phase | Detector Scale | Physics Goals | Comments |
|---|---|---|---|
| Phase 1 | 10-100 kg | First Detection | Precision flux not needed |
| Phase 2 | 100 kg – 1 ton | SM tests, NSI searches | Becoming systematically limited |
| Phase 3 | 1 ton – multi-ton | Neutron structure, neutrino magnetic moment | Systematics control a dominant issue; multiple targets useful |

- Much of the detectors, technology, and infrastructure in-place or will soon exist
- First results could be very soon!

[1]Table from K. Scholberg at Coherent NCvAs mini-workshop at FNAL

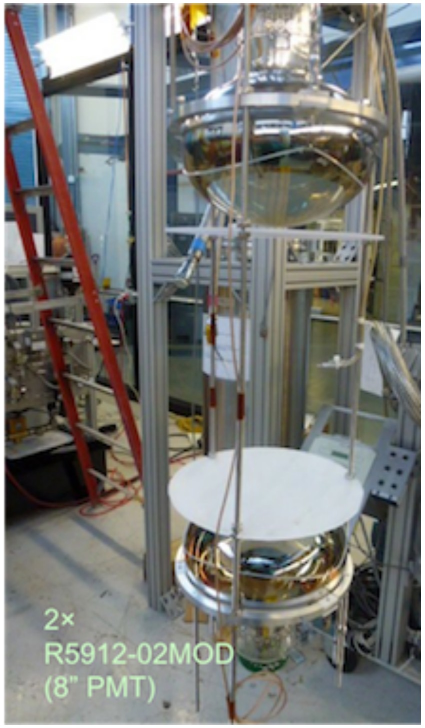
# Status of CEνNS Efforts

## COHERENT at SNS

- Some existing funding in place for current shielding and NIN tests
- Will pursue DOE funding later this summer
- Could see first light 2015-2016!

## CENNS at BNB

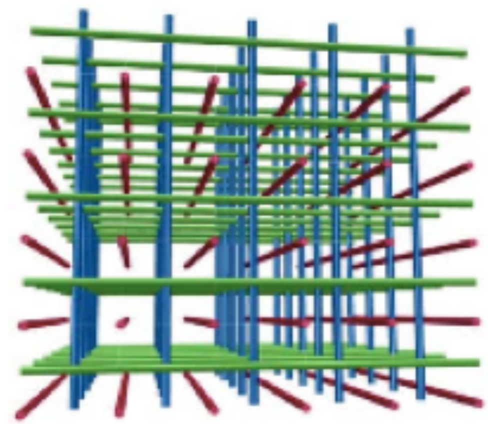
- MiniCLEAN could be moved by 2018
- Conclusive 7σ discovery in LAr in one year of running
- Developing 10-kg LAr prototype for neutron response and rates

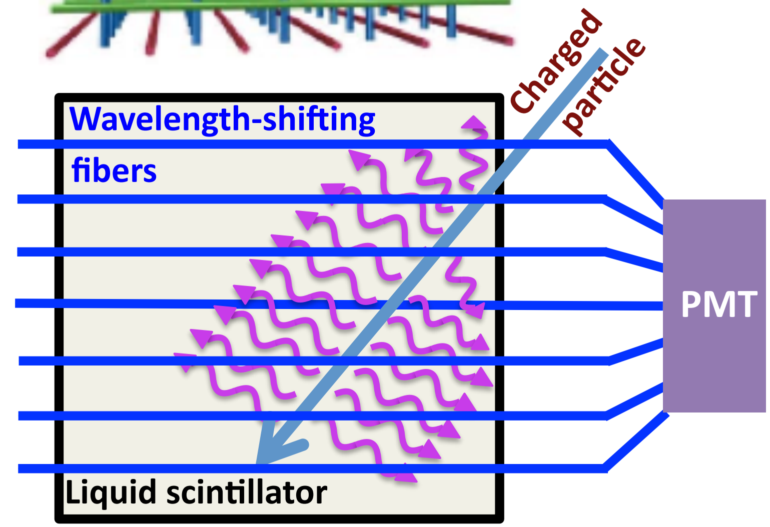


# BACKUPS

# SciBath Detector

- 80 L open volume of mineral oil based liquid scintillator
- Neutrons recoil off protons, create scintillation
- 768 wavelength shifting fibers readout
- IU built custom digitizer: 12 bit, 20 MS / s

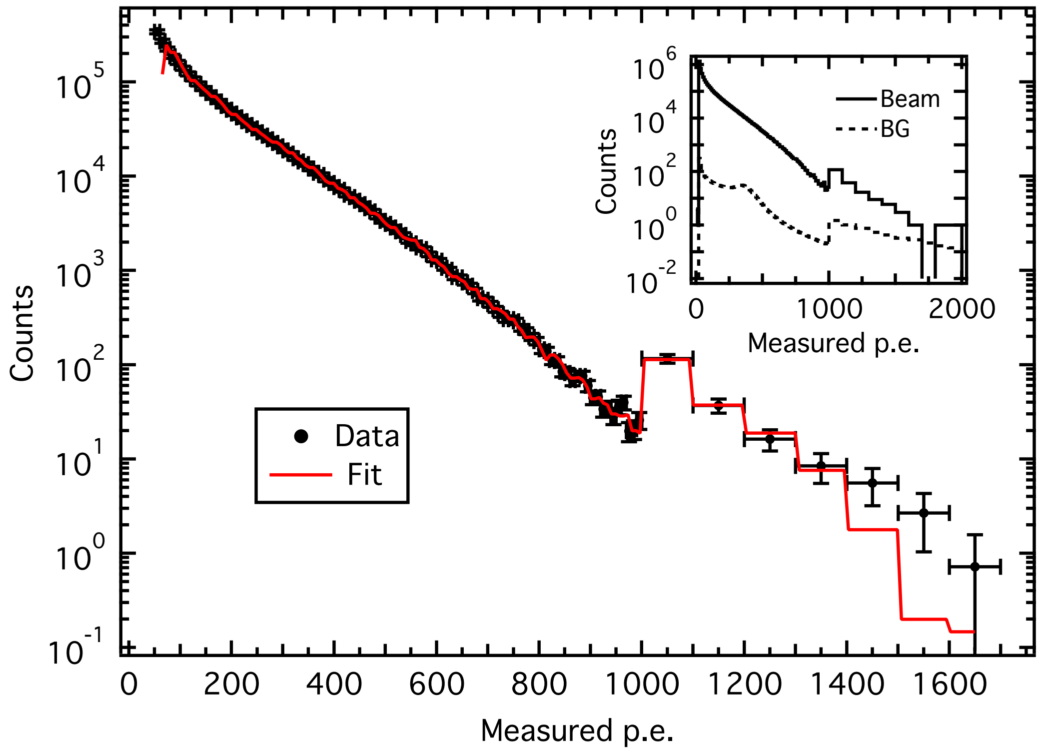




# BNB Neutron Energy Spectrum

- $E_n$ unfolded from PEs spectrum simulation of detector response
- 2.44 ± 0.34 pulse$^{-1}$ m$^{-2}$ ($E_n$ > 40 MeV)
- Lose sensitivity > 200 MeV;
- Neutron spectrum 20 m from BNB

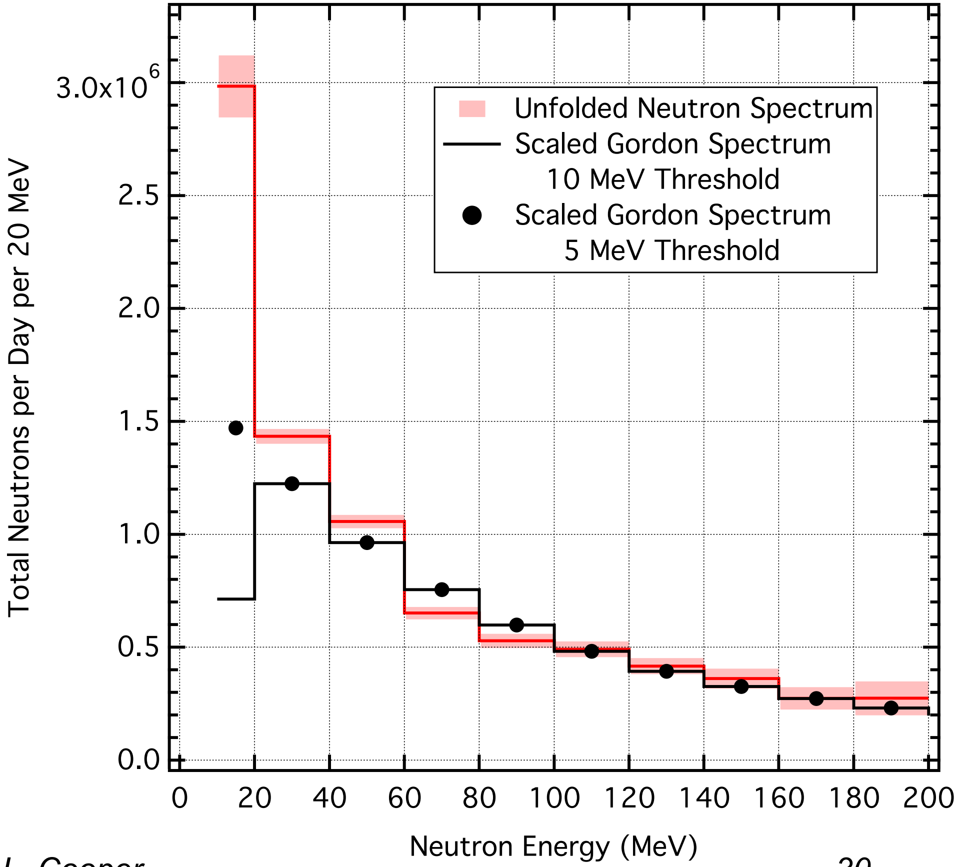
**Raw PE Spectrum In-Beam**



# Validation of Unfolding Techniques

- Cosmic ray neutron spectrum also unfolded
- Gordon et al., IEEE TNS **51**, (2004) 3427 parameterizes surface neutron flux from Bonner sphere data
- Energy shape matches, overall scale factor needed

**Unfolded Cosmic Neutron Spectrum**

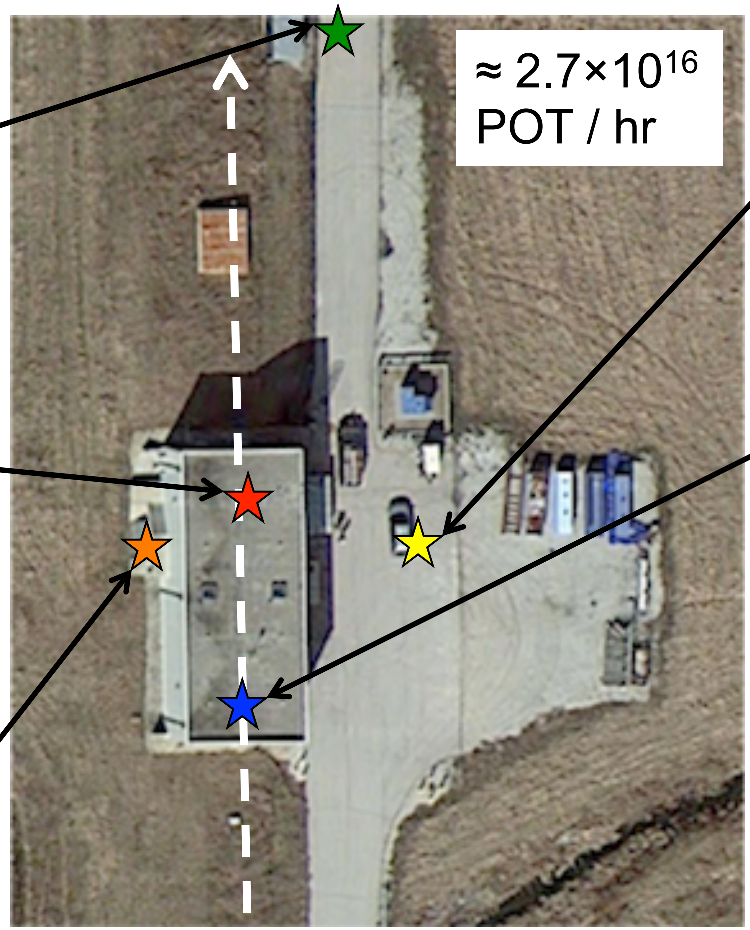


# Beam Off-Target Rates (> 0.5 MeV)

<u>50 m Absorber</u>
- 6 m from Fe beam stop
- 310 n / $10^{16}$ POT

<u>Collimator</u>
- 8 m from Be beam target
- 5608 n / $10^{16}$ POT

<u>Stairwell</u>
- 9 m from Be beam target
- 1384 n / $10^{16}$ POT



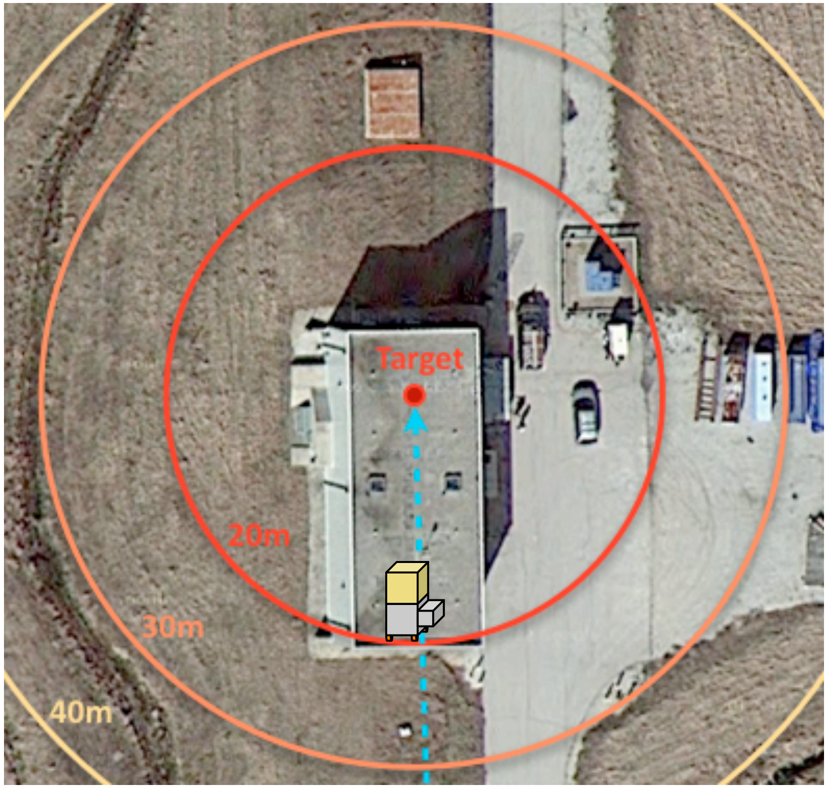

<u>Target 90° FOX</u>
- 20 m from Be beam target
- 390 n / $10^{16}$ POT

<u>2012 SciBath Loc</u>
- 20 m from Be beam target
- 211 n / $10^{16}$ POT

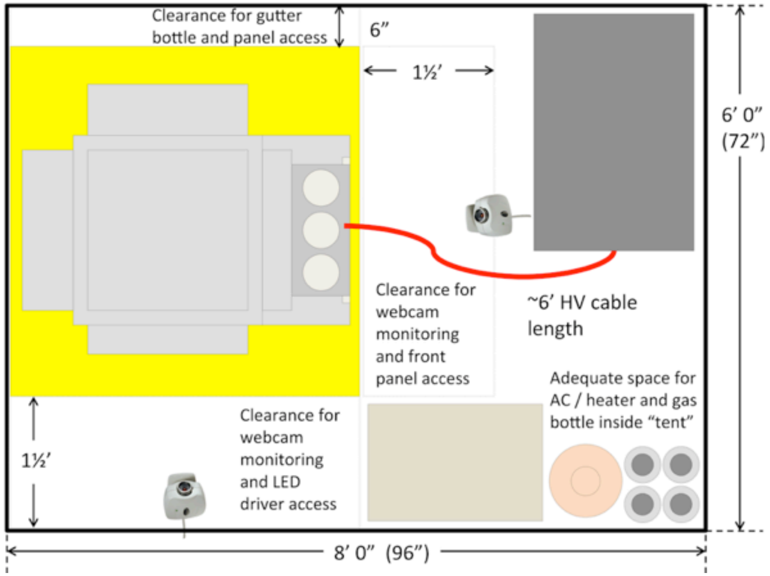
Neutron spectrum unfolding underway

# MI-12 Neutron Background Run

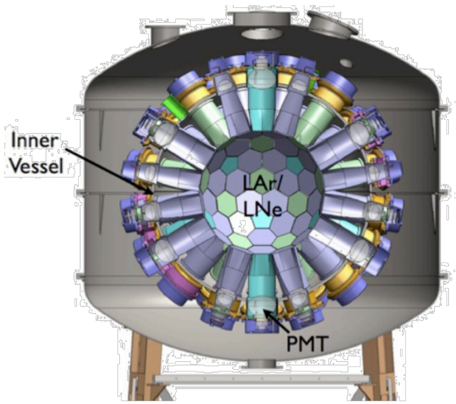
- Neutron flux ~20 m from target
- In-line behind beam target (ground)
- 29 Feb. – 23 Apr., 2012
- $4.9\times10^{19}$ total protons on target (POT) ($4.5\times10^{12}$ per pulse)



# Utility Trailer for BNB Measurement



# Summary of BNB Work for CENNS

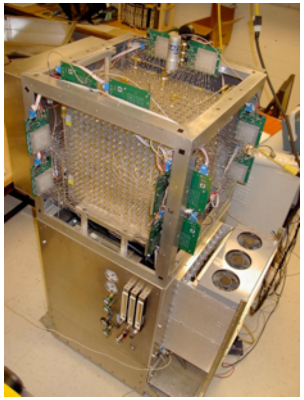



**MiniCLEAN**
First CENNS measurement

Neutrons backgrounds

LAr hardware testing

**SciBath**
Fast neutron measurements (10-200 MeV)



**EJ-301 Cells**
Portable array (0.5-20 MeV)

preparatory measurements

**CENNS-10**
10 kg LAr testing prototype

**CAPTAIN**
Low-E neutrino cross sections