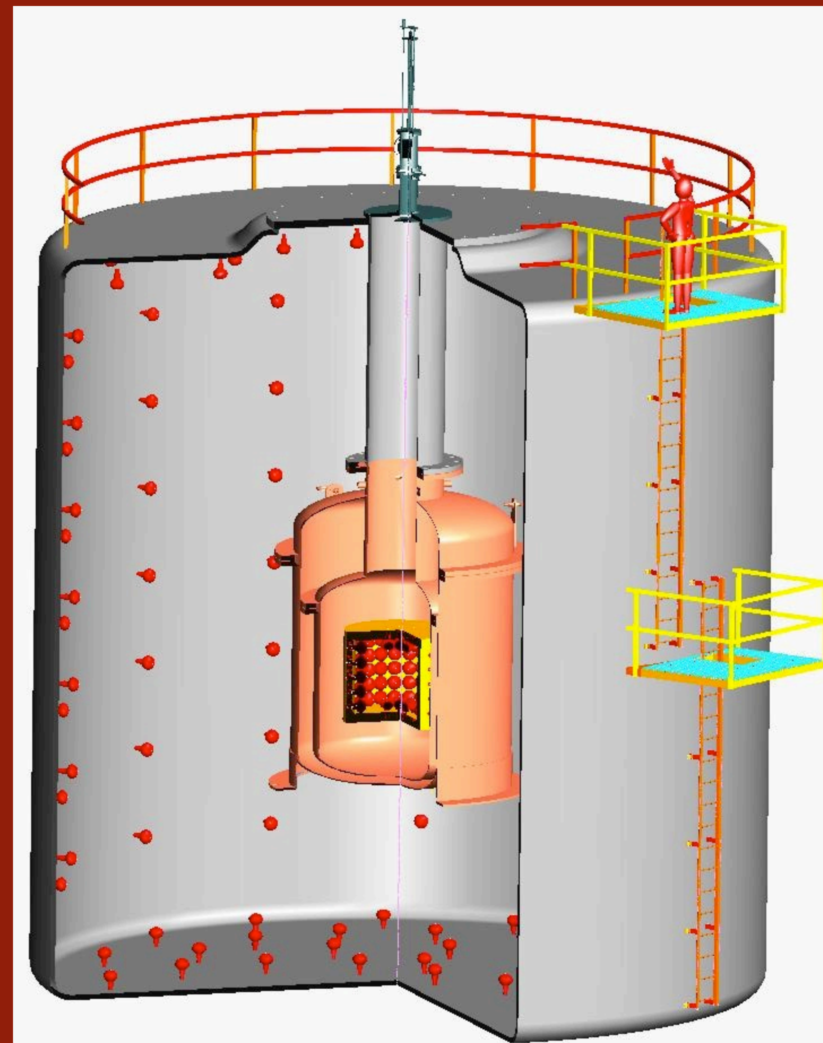
Standard Model Tests with Coherent Neutrino Scattering



Robert Cooper

INDIANA UNIVERSITY

What is CENNS?

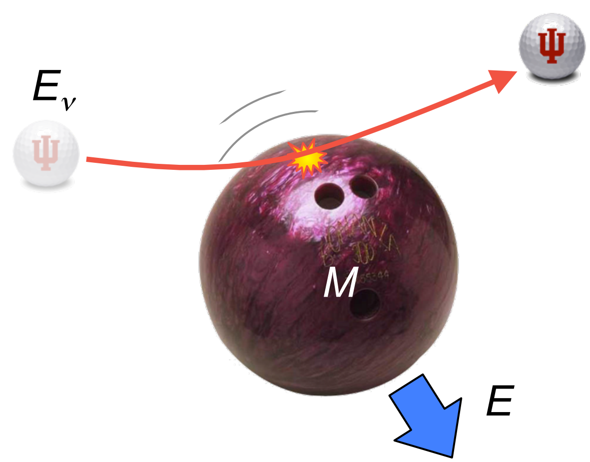
- **C**oherent **E**lastic **N**eutrino-**N**ucleus **S**cattering

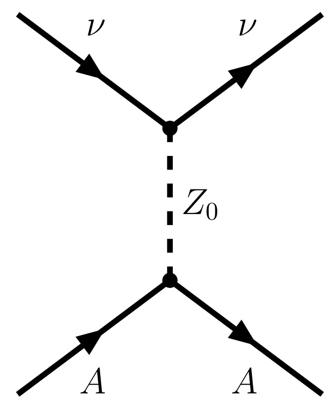
- To probe a “large” nucleus

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

- Recoil energy small

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





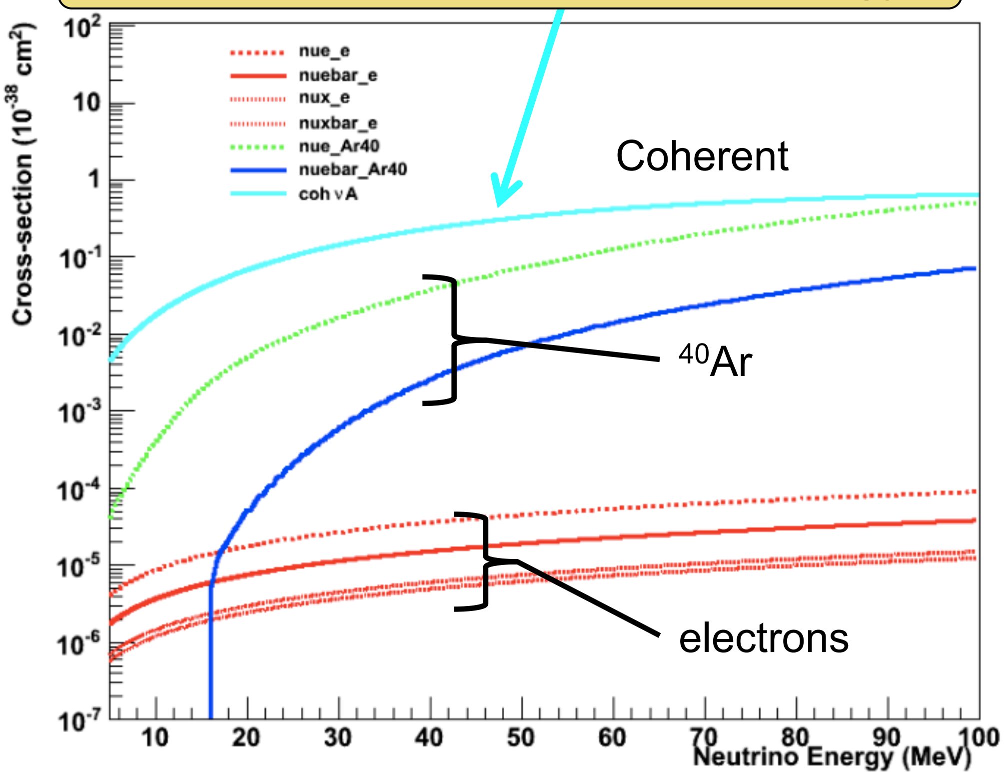
- Differential energy spectrum

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

Fundamental But Unobserved

- Low energy threshold is difficult
- Cross section actually **dominates** at low energy!
- Dark matter development is crucial
- Cross section goes as N^2
- Maximum recoil energy goes as M^{-1}
- Rate vs. threshold optimization problem

Neutrino Cross Sections vs Energy



K. Scholberg at Coherent NCvAs mini-workshop at FNAL

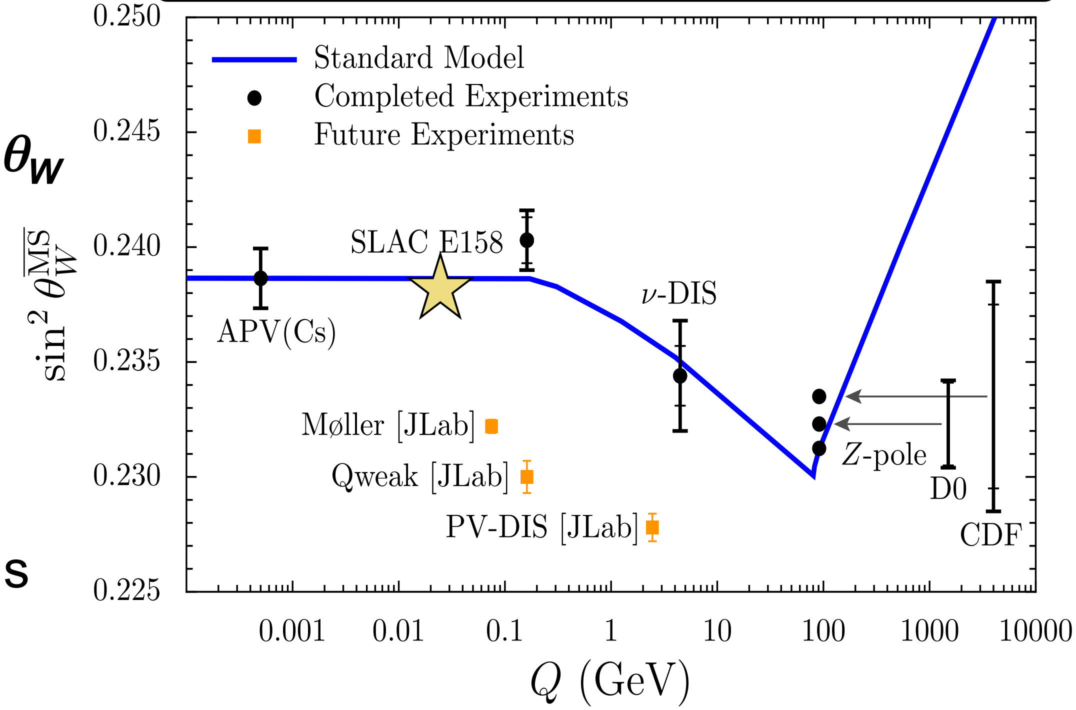
Physics Cases for CENNS

- **Never been observed!**
- SM tests: measure $\sin^2\theta_W$
- Form factors
- Supernova physics
- Non-standard Interactions
- Irreducible dark matter background

Physics Cases for CENNS

- Never been observed!
- **SM tests: measure $\sin^2\theta_W$**
- Form factors
- Supernova physics
- Non-standard Interactions
- Irreducible dark matter background

$\sin^2\theta_W$ vs. Q with possible CENNS



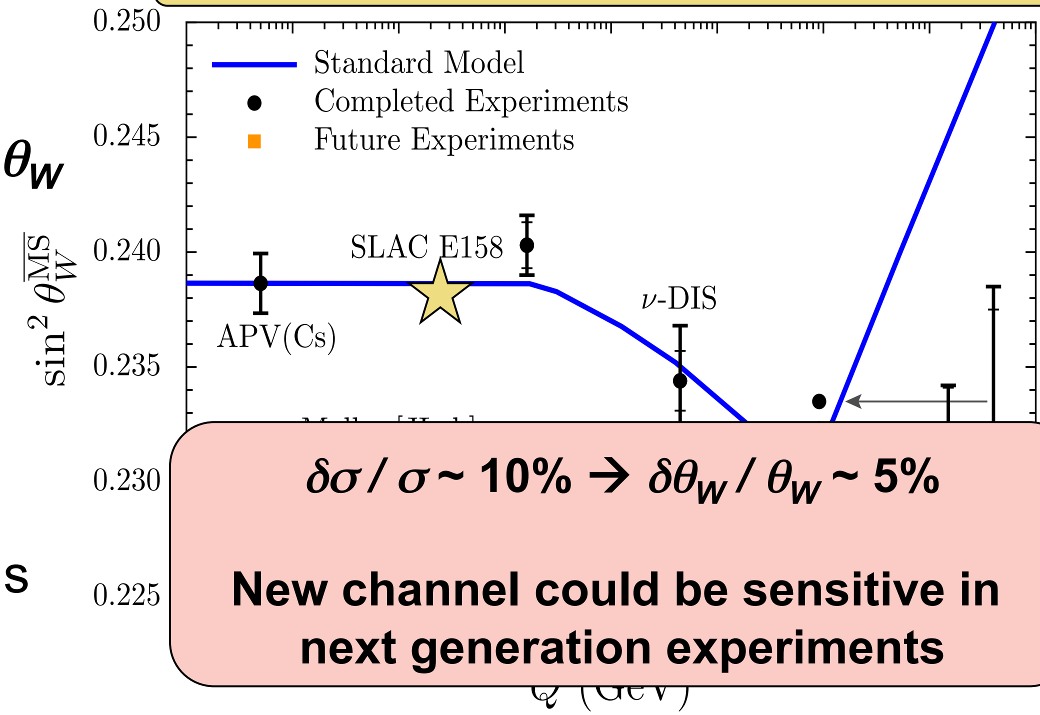
Bentz et al., Phys Lett B 693 (2010) 462-466
see also Scholberg, Phys Rev D 73 (2006) 033005

INDIANA UNIVERSITY

Physics Cases for CENNS

- Never been observed!
- **SM tests: measure $\sin^2\theta_W$**
- Form factors
- Supernova physics
- Non-standard Interactions
- Irreducible dark matter background

$\sin^2\theta_W$ vs. Q with possible CENNS



$\delta\sigma / \sigma$ ~ 10% → $\delta\theta_W / \theta_W$ ~ 5%

New channel could be sensitive in next generation experiments

Bentz et al., Phys Lett B 693 (2010) 462-466
see also Scholberg, Phys Rev D 73 (2006) 033005

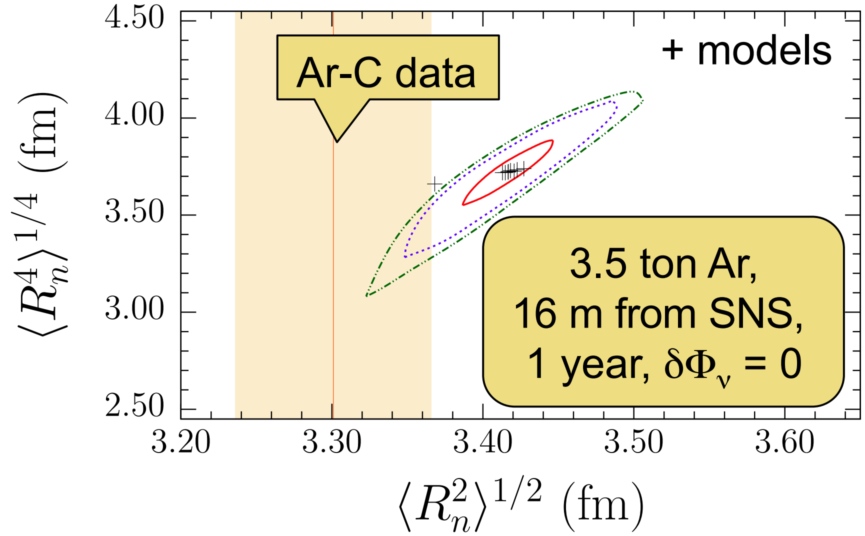
Physics Cases for CENNS

- Never been observed!
- SM tests: measure $\sin^2\theta_W$
- **Form factors**
- Supernova physics
- Non-standard Interactions
- Irreducible dark matter background

4th vs 2nd Form Factor Moments

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

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



Patton et al., arXiv/1207.0693

Physics Cases for CENNS

- Never been observed!
- SM tests: measure $\sin^2\theta_W$
- Form factors
- Supernova physics
- **Non-Standard Interactions**
- Irreducible dark matter background

$$\mathcal{L}_{\nu H}^{\mathrm{NSI}} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta=e,\mu,\tau}} [\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5)\nu_\beta](\varepsilon_{\alpha\beta}^{qL}[\bar{q}\gamma_\mu(1-\gamma^5)q] + \varepsilon_{\alpha\beta}^{qR}[\bar{q}\gamma_\mu(1+\gamma^5)q]). \quad (3)$$

TABLE I. Constraints on NSI parameters, from Ref. [35].

NSI parameter limit	Source
$-1 < \varepsilon_{ee}^{uL} < 0.3$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$-0.4 < \varepsilon_{ee}^{uR} < 0.7$	
$-0.3 < \varepsilon_{ee}^{dL} < 0.3$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$-0.6 < \varepsilon_{ee}^{dR} < 0.5$	
$\lvert\varepsilon_{\mu\mu}^{uL}\rvert < 0.003$	NuTeV νN, $\bar{\nu} N$ scattering
$-0.008 < \varepsilon_{\mu\mu}^{uR} < 0.003$	
$\lvert\varepsilon_{\mu\mu}^{dL}\rvert < 0.003$	NuTeV νN, $\bar{\nu} N$ scattering
$-0.008 < \varepsilon_{\mu\mu}^{dR} < 0.015$	
$\lvert\varepsilon_{e\mu}^{uP}\rvert < 7.7 \times 10^{-4}$	$\mu \to e$ conversion on nuclei
$\lvert\varepsilon_{e\mu}^{dP}\rvert < 7.7 \times 10^{-4}$	$\mu \to e$ conversion on nuclei
$\lvert\varepsilon_{e\tau}^{uP}\rvert < 0.5$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$\lvert\varepsilon_{e\tau}^{dP}\rvert < 0.5$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$\lvert\varepsilon_{\mu\tau}^{uP}\rvert < 0.05$	NuTeV νN, $\bar{\nu} N$ scattering
$\lvert\varepsilon_{\mu\tau}^{dP}\rvert < 0.05$	NuTeV νN, $\bar{\nu} N$ scattering

Physics Cases for CENNS

- Never been observed!
- SM tests: measure $\sin^2\theta_W$
- Form factors
- Supernova physics
- **Non-Standard Interactions**
- Irreducible dark matter background

$$\mathcal{L}_{\nu H}^{\mathrm{NSI}} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta=e,\mu,\tau}} [\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5)\nu_\beta](\varepsilon_{\alpha\beta}^{qL}[\bar{q}\gamma_\mu(1-\gamma^5)q] + \varepsilon_{\alpha\beta}^{qR}[\bar{q}\gamma_\mu(1+\gamma^5)q]). \quad (3)$$

TABLE I. Constraints on NSI parameters, from Ref. [35].

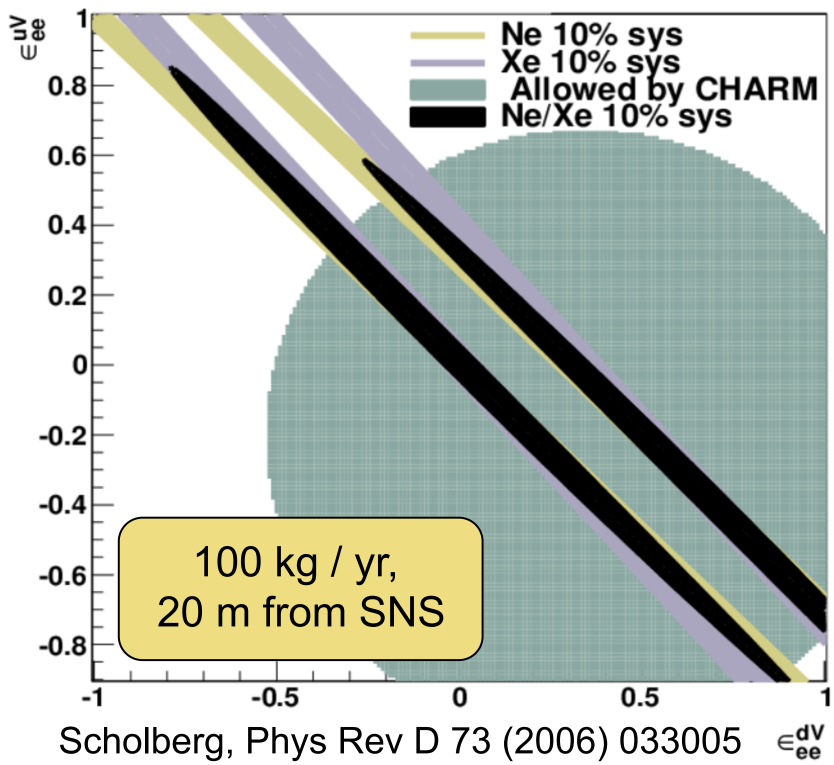
NSI parameter limit	Source
$-1 < \varepsilon_{ee}^{uL} < 0.3$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$-0.4 < \varepsilon_{ee}^{uR} < 0.7$	
$-0.3 < \varepsilon_{ee}^{dL} < 0.3$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$-0.6 < \varepsilon_{ee}^{dR} < 0.5$	
$\lvert\varepsilon_{\mu\mu}^{uL}\rvert < 0.003$	NuTeV νN, $\bar{\nu} N$ scattering
$-0.008 < \varepsilon_{\mu\mu}^{uR} < 0.0$	
$\lvert\varepsilon_{\mu\mu}^{dL}\rvert < 0.003$	
$-0.008 < \varepsilon_{\mu\mu}^{dR} < 0.0$	
$\lvert\varepsilon_{e\mu}^{uP}\rvert < 7.7 \times 10^{-4}$	
$\lvert\varepsilon_{e\mu}^{dP}\rvert < 7.7 \times 10^{-4}$	$\mu \to e$ conversion on nuclei
$\lvert\varepsilon_{e\tau}^{uP}\rvert < 0.5$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$\lvert\varepsilon_{e\tau}^{dP}\rvert < 0.5$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$\lvert\varepsilon_{\mu\tau}^{uP}\rvert < 0.05$	NuTeV νN, $\bar{\nu} N$ scattering
$\lvert\varepsilon_{\mu\tau}^{dP}\rvert < 0.05$	NuTeV νN, $\bar{\nu} N$ scattering

Very wide limits on ε_{ee} & $\varepsilon_{e\tau}$ terms

Physics Cases for CENNS

- Never been observed!
- SM tests: measure $\sin^2\theta_W$
- Form factors
- Supernova physics
- **Non-Standard Interactions**
- Irreducible dark matter background

ε_{ee} constraints in Ne & Xe



Scholberg, Phys Rev D 73 (2006) 033005

Accelerator Neutrino Sources

- Few GeV protons on target produces π^+

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

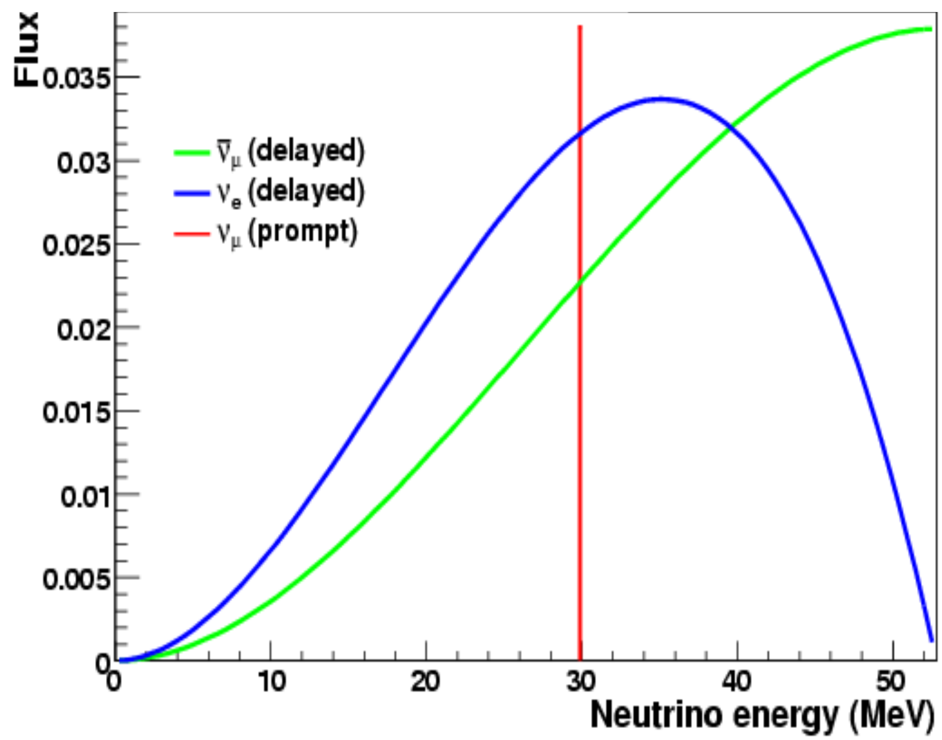
- Prototypical source is SNS

- SNS flux at 20 m

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

- Other alternatives?

SNS Stopped Pion Energy Spectrum



Avignone & Efremenko, J Phys G 29 (2003), 2615-2628

Accelerator Neutrino Sources

- Few GeV protons on target produces π^+

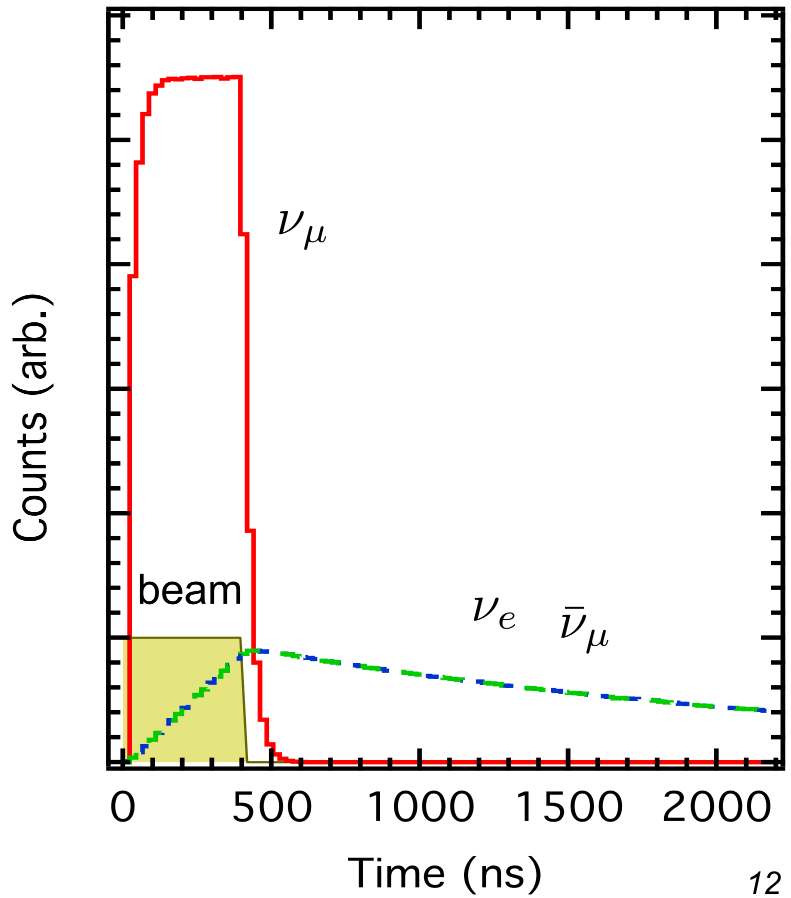
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

- Prototypical source is SNS
- SNS flux at 20 m

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

- Other alternatives?

SNS Neutrino Rates in Time

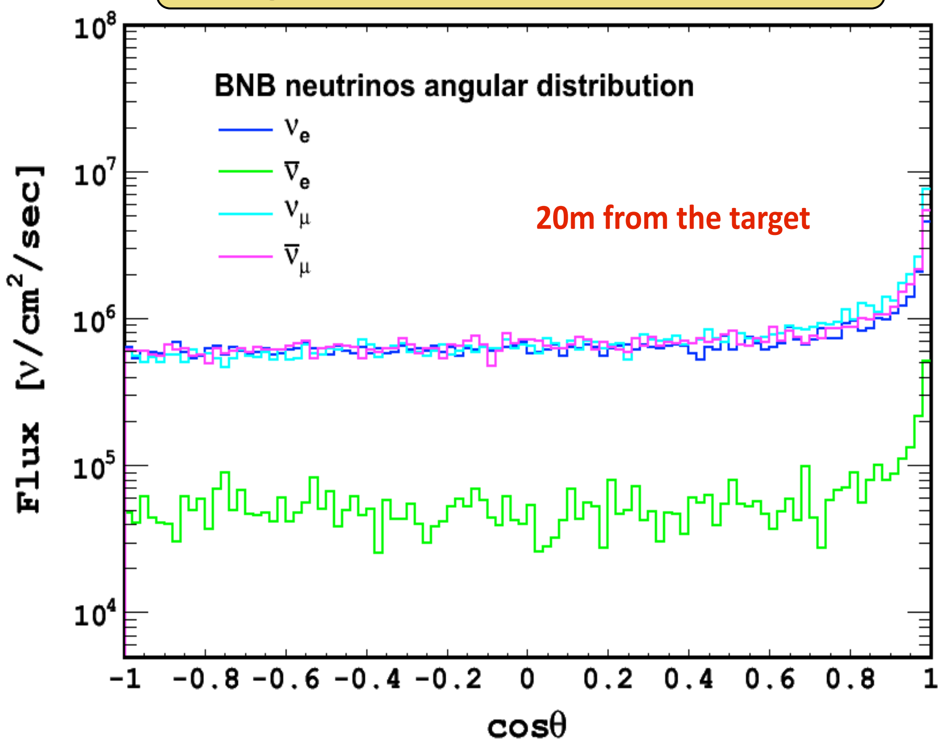


Pion Decay in Flight Source

- FNAL BNB is a pion decay in-flight source (8 GeV p^+)
- On-axis multi-GeV neutrinos
- Far off-axis spectrum is much softer and narrower
- BNB flux at 20 m, $\cos\theta < 0.5$

  $\Phi^{BNB} = 5\times10^5\ s^{-1}\ cm^{-2}$

Angle Off-Axis Neutrino Rate



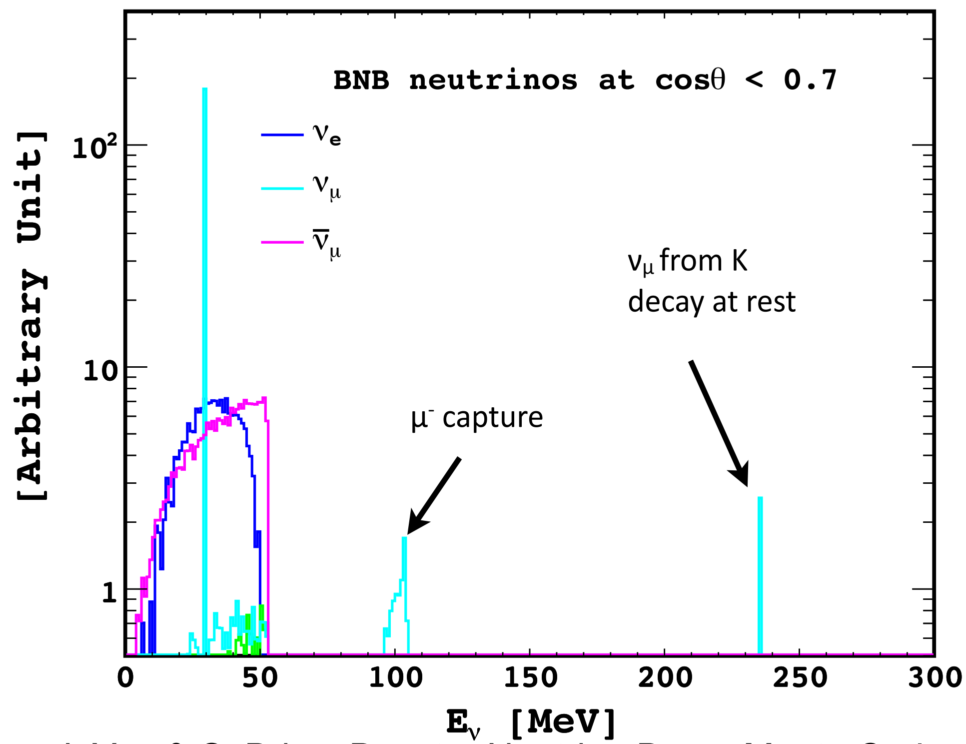
J. Yoo & S. Brice, Booster Neutrino Beam Monte Carlo

Pion Decay in Flight Source

- FNAL BNB is a pion decay in-flight source (8 GeV p^+)
- On-axis multi-GeV neutrinos
- Far off-axis spectrum is much softer and narrower
- BNB flux at 20 m, cos $\theta < 0.5$

$\Phi^{BNB} = 5\times10^5\ s^{-1}\ cm^{-2}$

Off-Axis Neutrino Energy Spectrum



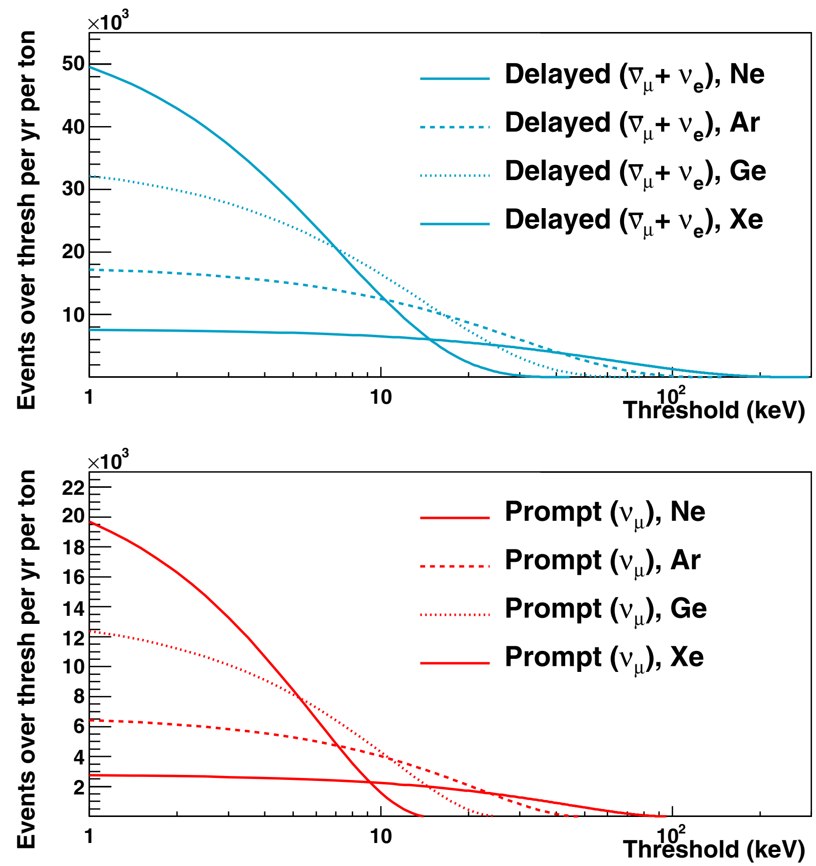
J. Yoo & S. Brice, Booster Neutrino Beam Monte Carlo

INDIANA UNIVERSITY

Detection of Coherent Scattering

- **Pick a dark matter technology**
- PPC high purity Ge
- CsI[Na] inorganic scintillators
- Dual phase LXe
- Single phase LAr & LNe

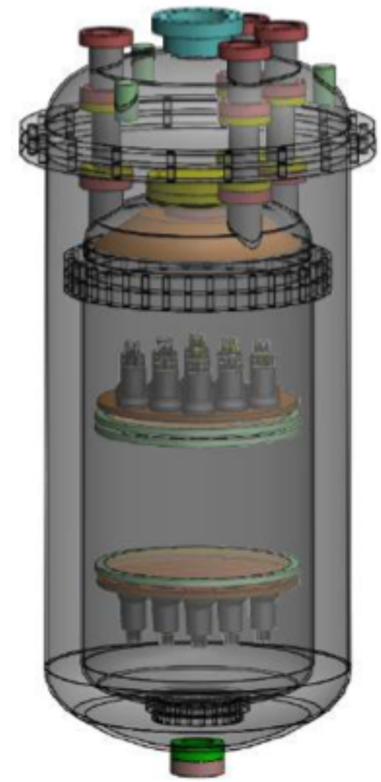
SNS Detection Rate [ton^{-1} $year^{-1}$]



Detection of Coherent Scattering

- Pick a dark matter technology
- PPC high purity Ge
- CsI[Na] inorganic scintillators
- **Dual phase LXe**
- Single phase LAr & LNe

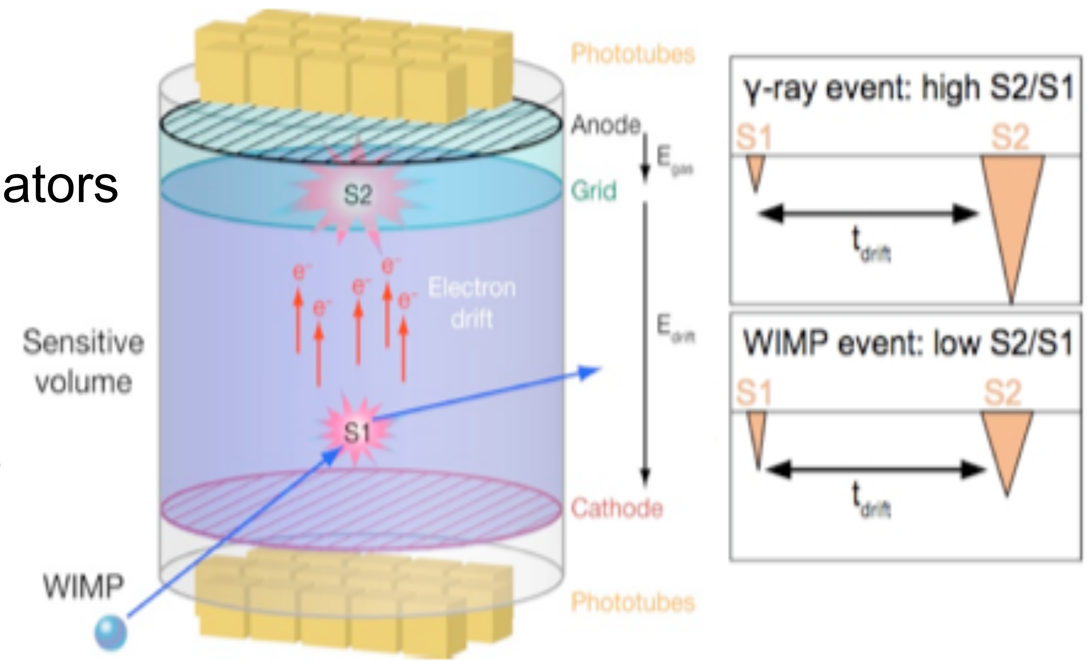
Red-1 and Red-100



Detection of Coherent Scattering

- Pick a dark matter technology
- PPC high purity Ge
- CsI[Na] inorganic scintillators
- **Dual phase LXe**
- Single phase LAr & LNe

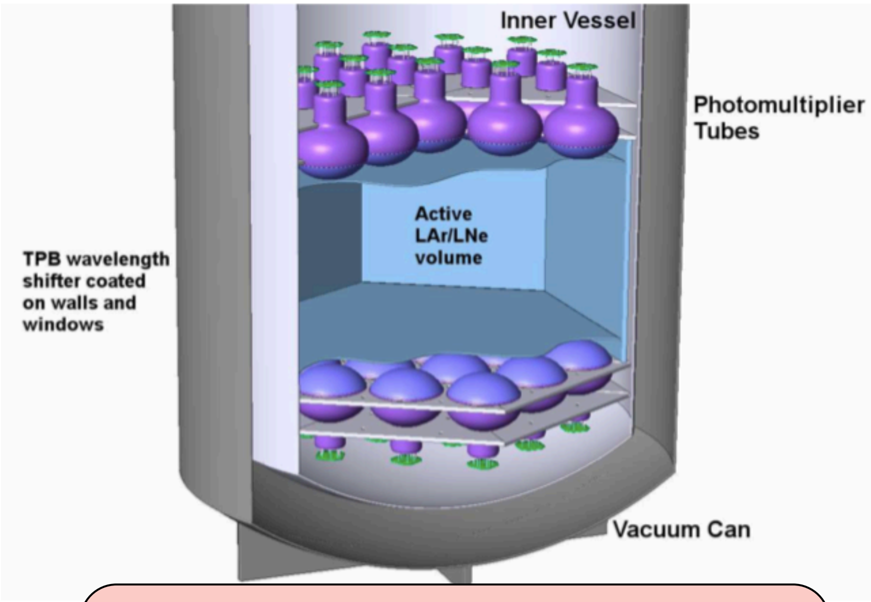
PSD from S1 & S2 Signals



Detection of Coherent Scattering

- Pick a dark matter technology
- PPC high purity Ge
- CsI[Na] inorganic scintillators
- Dual phase LXe
- **Single phase LAr & LNe**

CLEAR Proposal & FNAL Effort



Expect 200 events ton^{-1} year^{-1} 20 m from BNB at 32 kW and 30 keV threshold

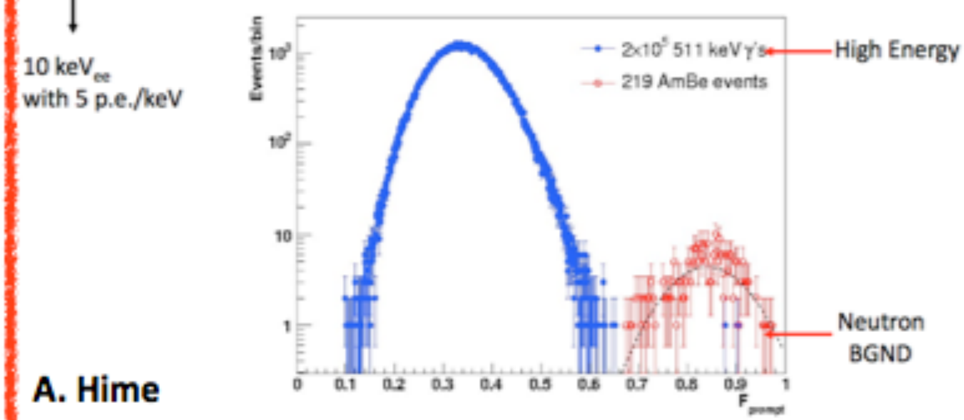
Detection of Coherent Scattering

- Pick a dark matter technology
- PPC high purity Ge
- CsI[Na] inorganic scintillators
- Dual phase LXe
- **Single phase LAr & LNe**

Scintillation PSD Possible

DEAP-0 Results & Projections for PSD in LAr

Avg. No. p.e.	Measured Leakage	Background Leakage	Projected PSD
50	$(2.4 \pm 0.6) \times 10^{-5}$	$(2.1 \pm 1.0) \times 10^{-5}$	1×10^{-10}
60	$(1.4 \pm 0.4) \times 10^{-5}$	$(1.5 \pm 0.9) \times 10^{-5}$	2×10^{-13}
70	$(1.0 \pm 0.4) \times 10^{-5}$	$(2.5 \pm 1.1) \times 10^{-5}$	1×10^{-17}



Detection of Coherent Scattering

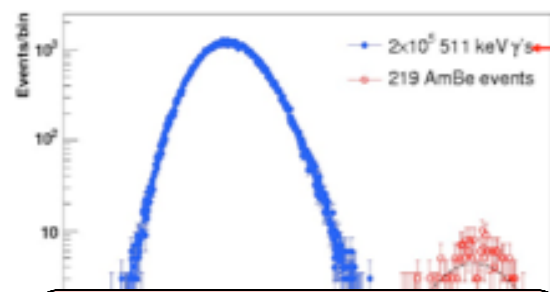
- Pick a dark matter technology
- PPC high purity Ge
- CsI[Na] inorganic scintillators
- Dual phase LXe
- **Single phase LAr & LNe**

Scintillation PSD Possible

DEAP-0 Results & Projections for PSD in LAr

Avg. No. p.e.	Measured Leakage	Background Leakage	Projected PSD
50	$(2.4 \pm 0.6) \times 10^{-5}$	$(2.1 \pm 1.0) \times 10^{-5}$	1×10^{-10}
60	$(1.4 \pm 0.4) \times 10^{-5}$	$(1.5 \pm 0.9) \times 10^{-5}$	2×10^{-13}
70	$(1.0 \pm 0.4) \times 10^{-5}$	$(2.5 \pm 1.1) \times 10^{-5}$	1×10^{-17}

10 keV_{ee} with 5 p.e./keV



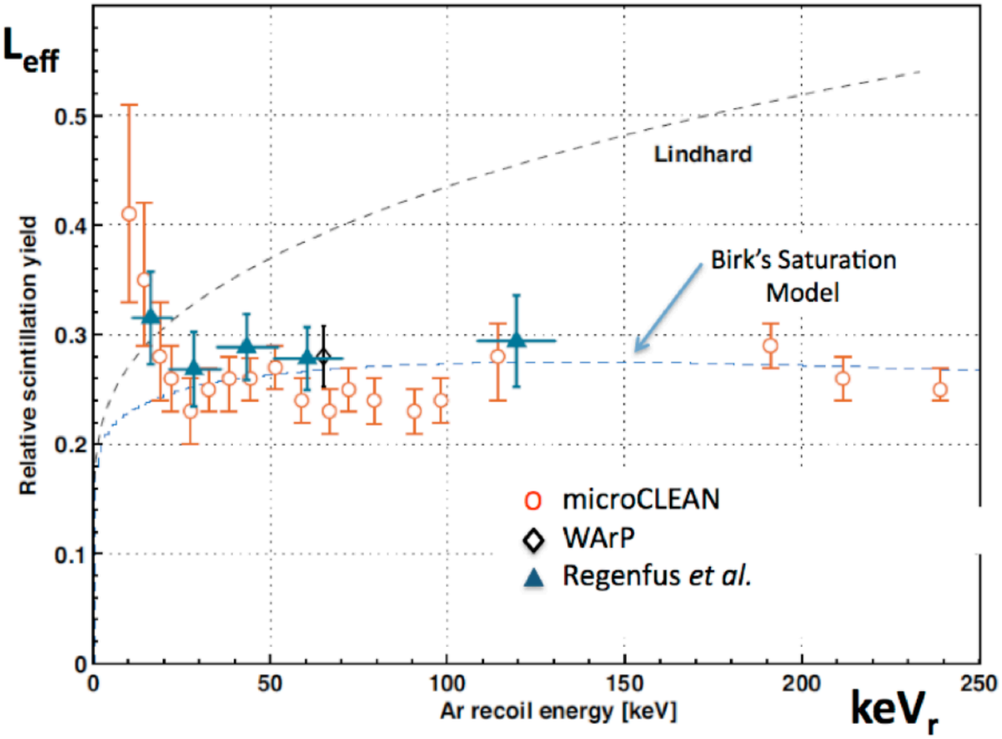
A. Hime

Beam duty factor & PSD mitigates ^{39}Ar contamination

Typical Sources of Uncertainty

- Duty factor (~ 10^{-5}) give total exposure ~ 300 s / year
  → cosmic background small
- Neutrino flux uncertainty
  ~ 5-10% → improvements?
- Quenching & scintillation efficiency L_{eff} uncertainties
- Beam correlated neutrons mimic neutrino signal

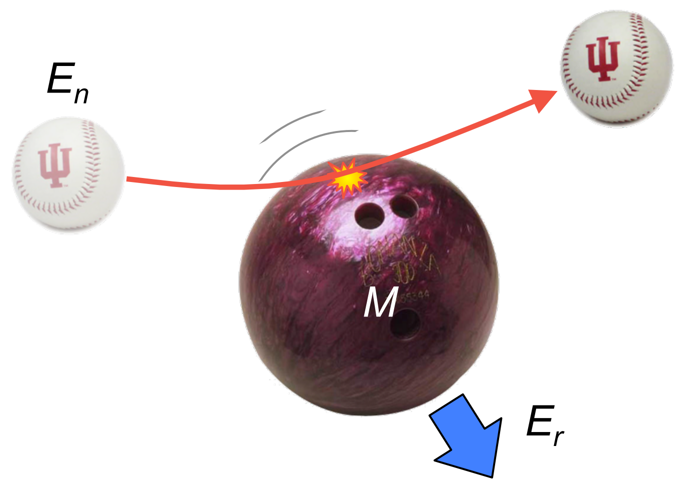
LAr Nuclear Recoil Scintillation Efficiency



Typical Sources of Uncertainty

- Duty factor (~ 10^{-5}) give total exposure ~ 300 s / year
  → cosmic background small
- Neutrino flux uncertainty
  ~ 5-10% → improvements?
- Quenching & scintillation efficiency L_{eff} uncertainties
- Beam correlated neutrons mimic neutrino signal

Neutron Scatter on ^{40}Ar

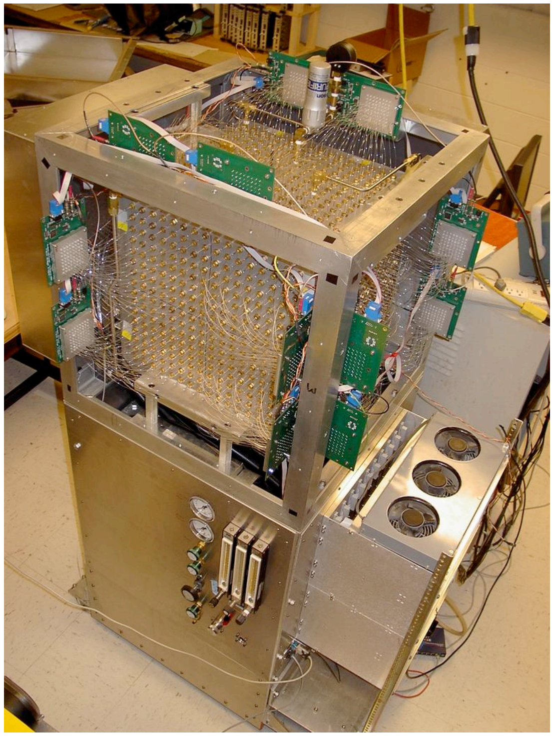


$$E_r^{\max} = \frac{4\mathcal{M}}{(\mathcal{M}+1)^2} E_n \simeq 0.1 E_n$$

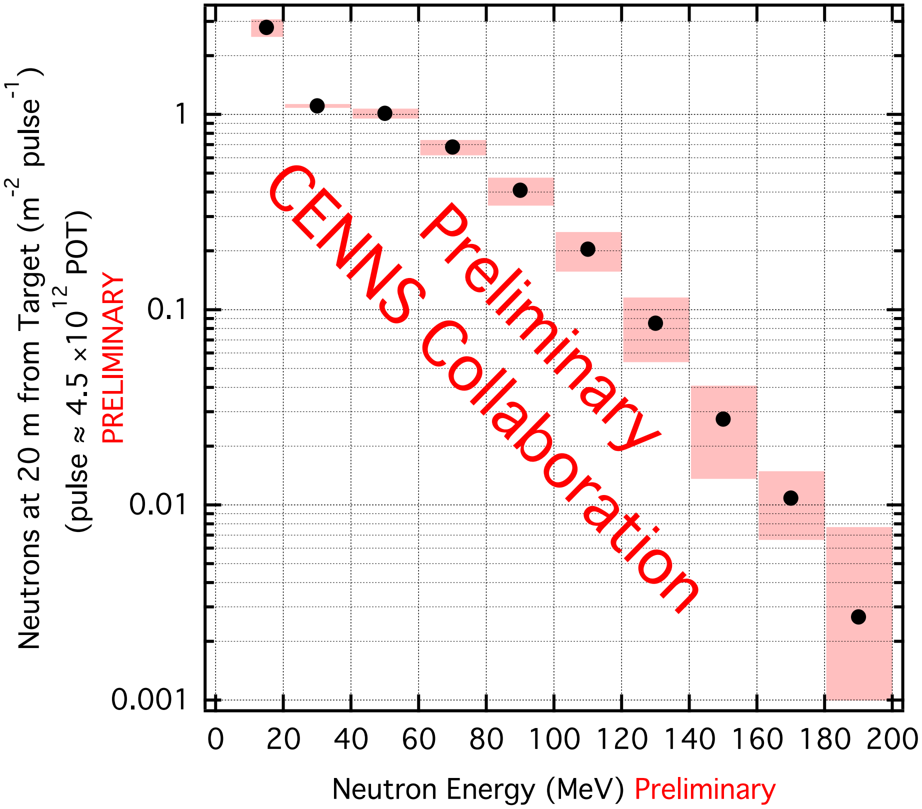
where $\mathcal{M} = M/m_n$

In-Beam Neutron Measurements

Indiana-Built SciBath Detector



BNB Neutron Spectrum at 20 m



Phases of Coherent ν-A Experiments

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	Systems control a dominant issue; multiple targets useful

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

- Detector technology exists, neutrinos sources exist, with neutron background mitigation experiments can operate near surface
- How can we engage your expertise?

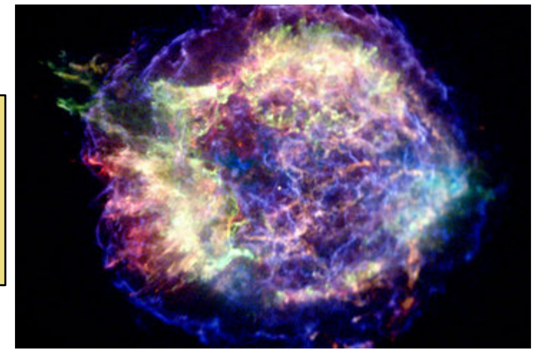
PINCH HITTERS (BACKUPS)

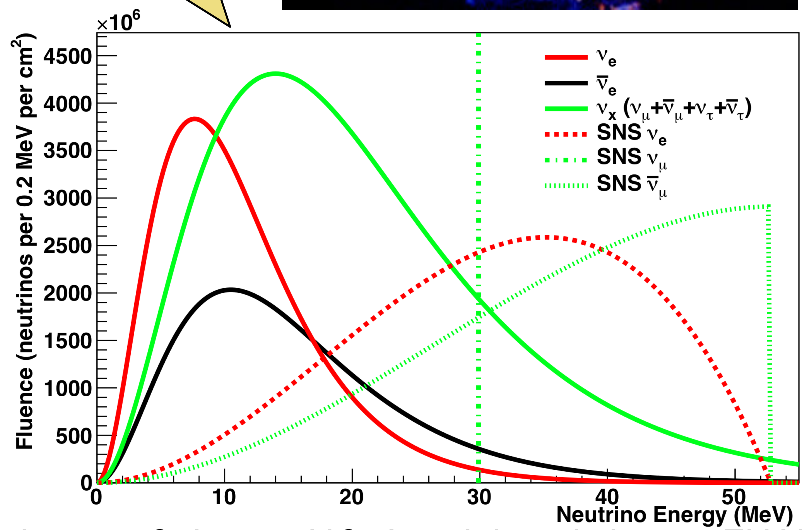
INDIANA UNIVERSITY

Physics Cases for CENNS

- Never been observed!
- SM tests: measure $\sin^2\theta_W$
- Form factors
- **Supernova physics**
- Non-standard Interactions
- Irreducible dark matter background

Supernova energy spectrum similar to stopped pions



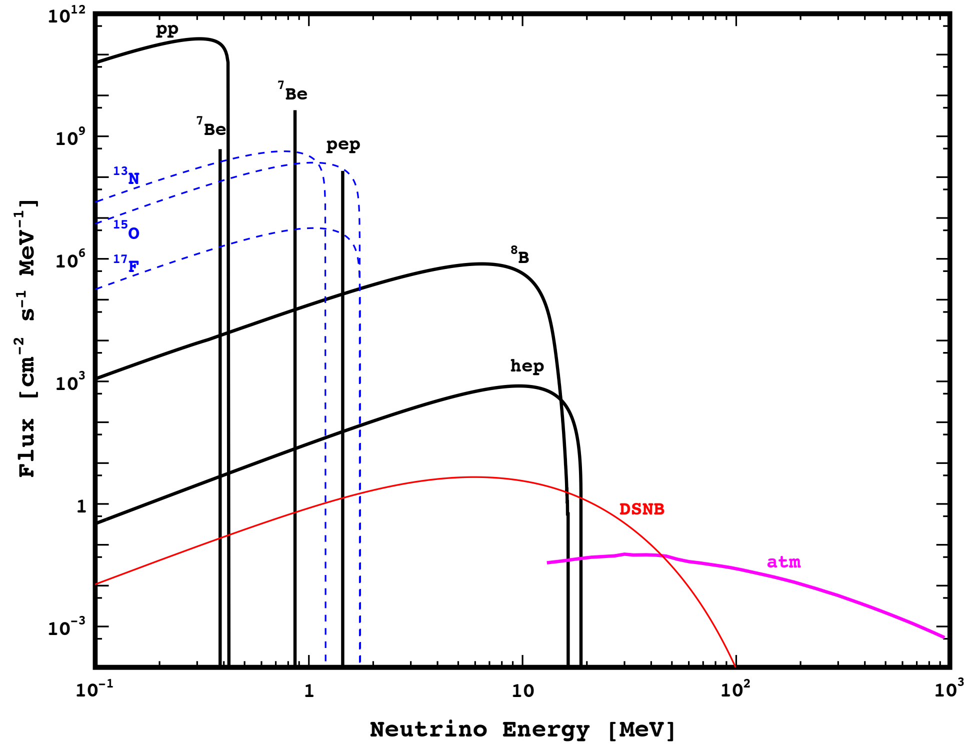


K. Scholberg at Coherent NCvAs mini-workshop at FNAL
See also Horowitz, Coakley, McKinsey Phys Rev D 68 (2003) 023005, astro-ph/0302071

Physics Cases for CENNS

- Never been observed!
- SM tests: measure $\sin^2\theta_W$
- Form factors
- Supernova physics
- Non-standard Interactions
- **Irreducible dark matter background**

Solar, Atmosphere, and SN Neutrinos



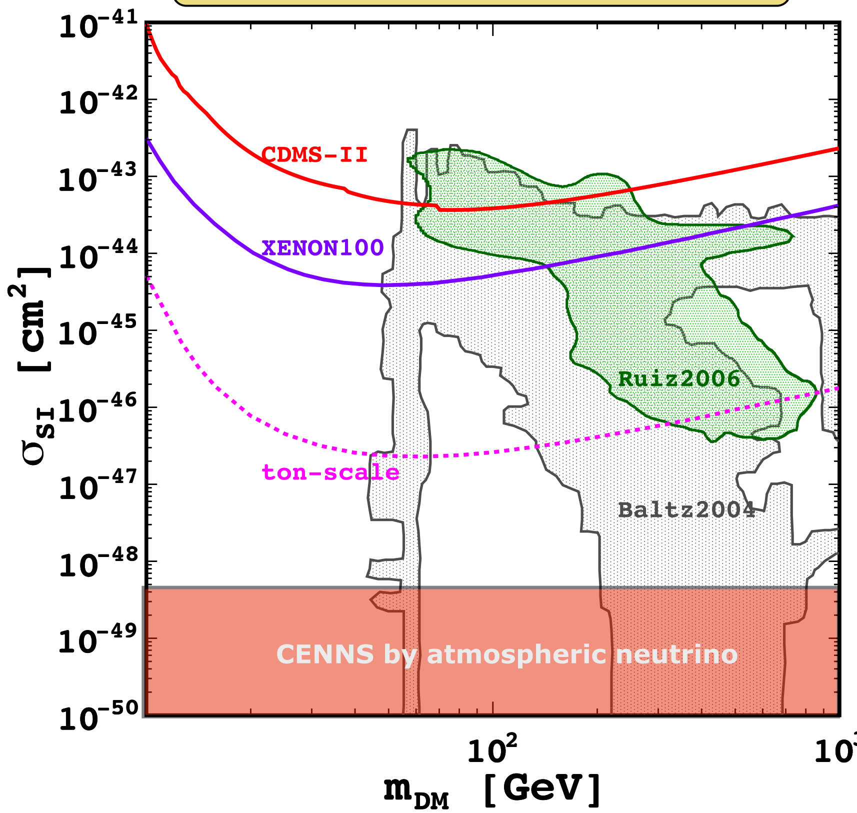
J. Yoo at Coherent NCvAS mini-workshop at FNAL

INDIANA UNIVERSITY

Physics Cases for CENNS

- Never been observed!
- SM tests: measure $\sin^2\theta_W$
- Form factors
- Supernova physics
- Non-standard Interactions
- **Irreducible dark matter background**

Dark Matter Sensitivity



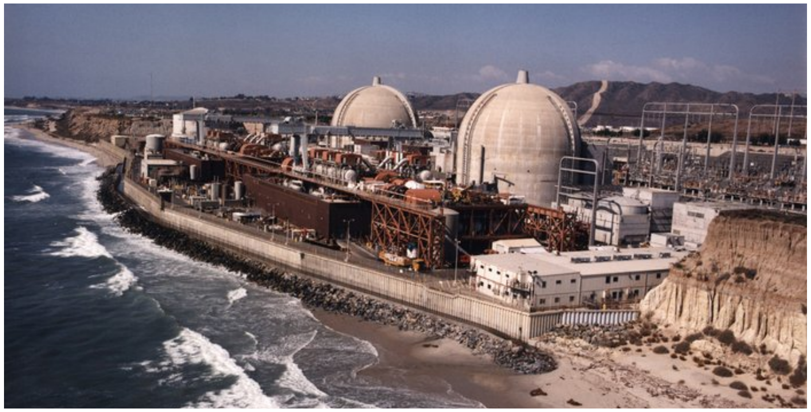
J. Yoo at Coherent NCvAS mini-workshop at FNAL

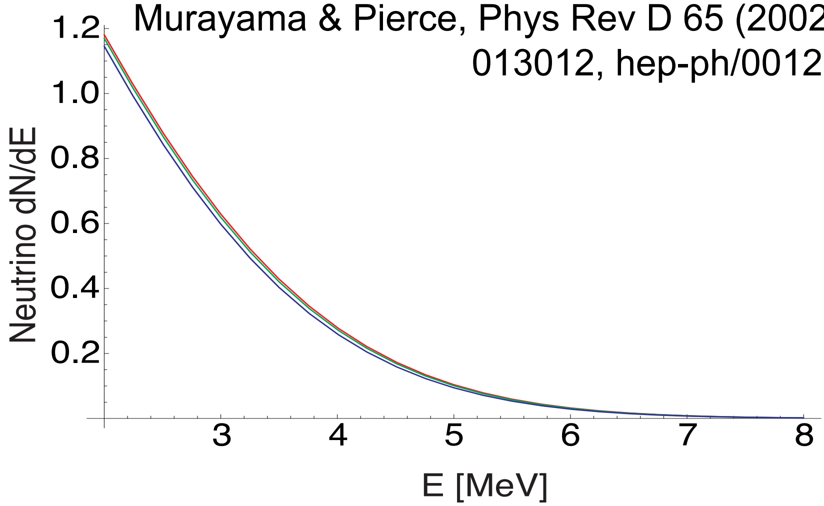
Reactor Neutrino Sources

- Reactors give very high flux

$$\Phi_{\bar{\nu}} \simeq 10^{20}\ \mathrm{s}^{-1}$$
$$\Rightarrow 10^{12}\ \mathrm{s}^{-1}\,\mathrm{cm}^{-2}$$ at 20 m

- Single $\bar{\nu}_e$ neutrino flavor
- Low energy forces detector thresholds < 10 keV
- Steady state running and backgrounds
- Reactor off for backgrounds
- Reactor monitoring applications



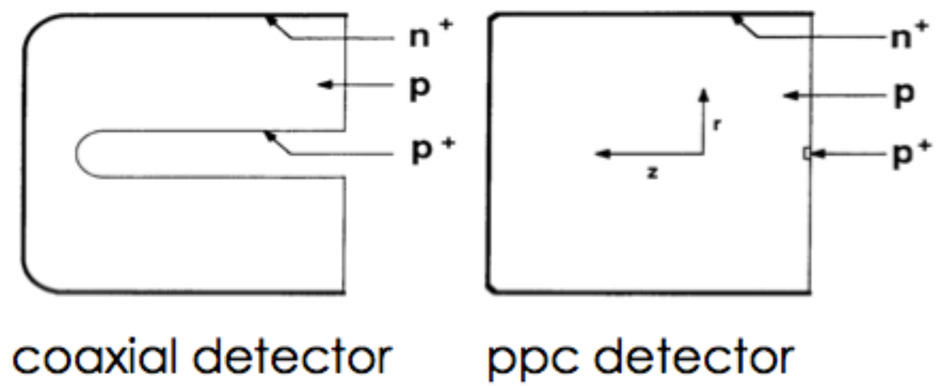


Murayama & Pierce, Phys Rev D 65 (2002), 013012, hep-ph/0012075

Detection of Coherent Scattering

- Pick a dark matter technology
- **PPC high purity Ge**
- CsI[Na] inorganic scintillators
- Dual phase LXe
- Single phase LAr & LNe

Majorana PPC Ge Detector

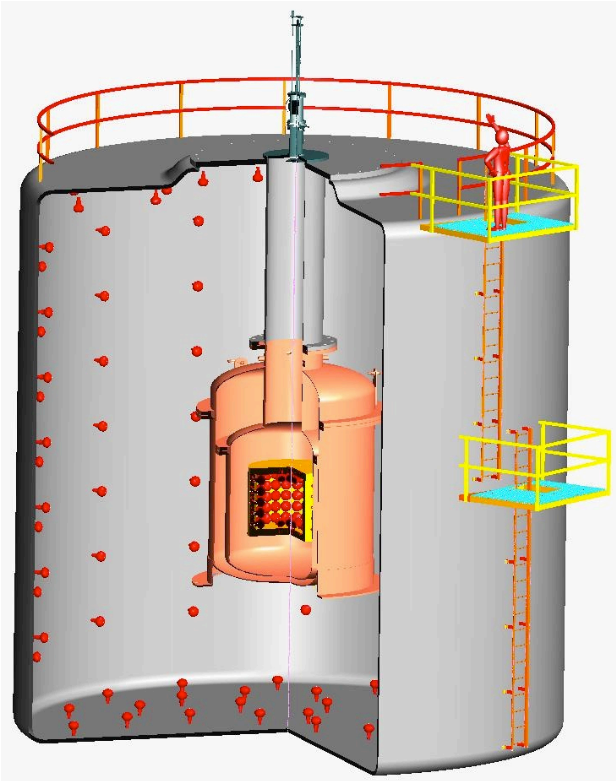


sub-keV thresholds
PPC allows multi-scattering site discrimination

Detection of Coherent Scattering

- Pick a dark matter technology
- PPC high purity Ge
- CsI[Na] inorganic scintillators
- Dual phase LXe
- **Single phase LAr & LNe**

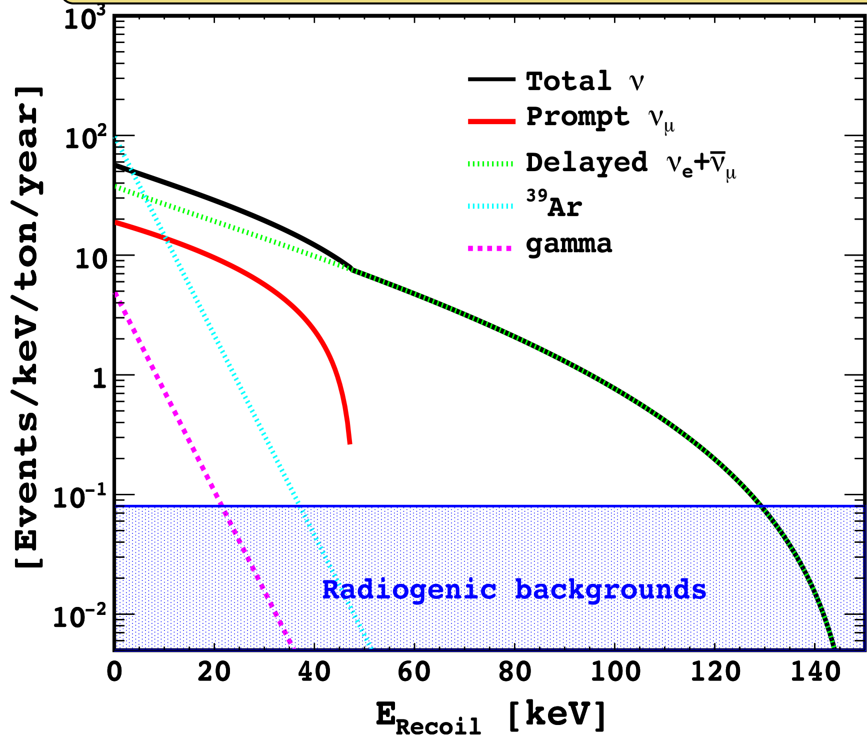
FNAL 1-ton LAr Detector



Background Rejection in Signal

- Beam duty factor ~ 10^{-5}
- Total exposure 300 s / year
- PSD can reject ^{39}Ar betas and gamma backgrounds
- Require beam-correlated neutrons < 10 year^{-1} ton^{-1}
- SciBath deployed to measure this rate

Detection Rate [kev^{-1} ton^{-1} year^{-1}]



J. Yoo at Coherent NCvAS mini-workshop at FNAL

BNB Experiment Layout