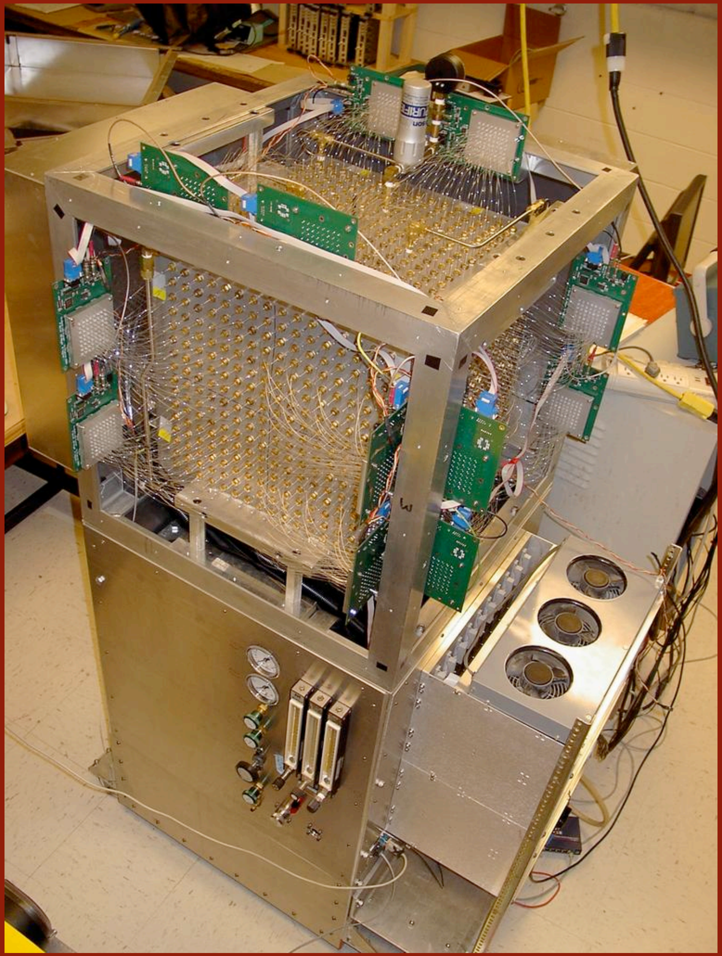
A Future Coherent Elastic Neutrino-Nucleus Scattering Experiment at Fermilab

Robert Cooper



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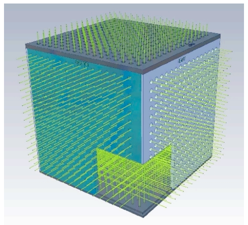


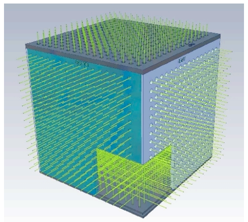
Outline

1. What is coherent ν scattering and its physics opportunities?

2. How do we measure coherent ν scattering?
   i.) Detector ii.) **Neutrino Source** iii) **Background Rejection**

3. Deployment of the SciBath detector
   i.) What is a SciBath ii.) What did we measure?

4. Future plans



What is CENNS?

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

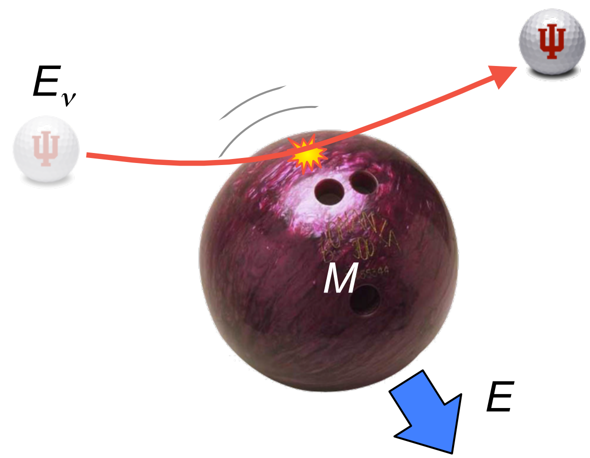
- To probe a “large” nucleus

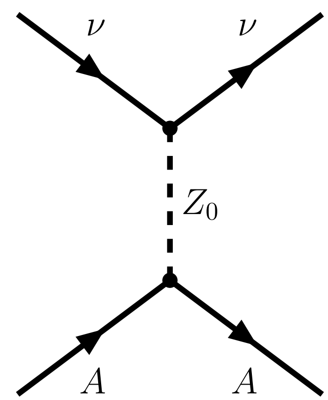
$$E_\nu \lesssim \frac{hc}{R_N} \cong 50 \text{ MeV}$$

- Recoil energy small

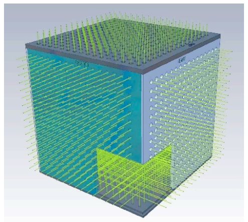
$$E_r^{\max} \simeq \frac{2E_\nu^2}{M} \simeq 50 \text{ keV}$$

- Differential energy spectrum



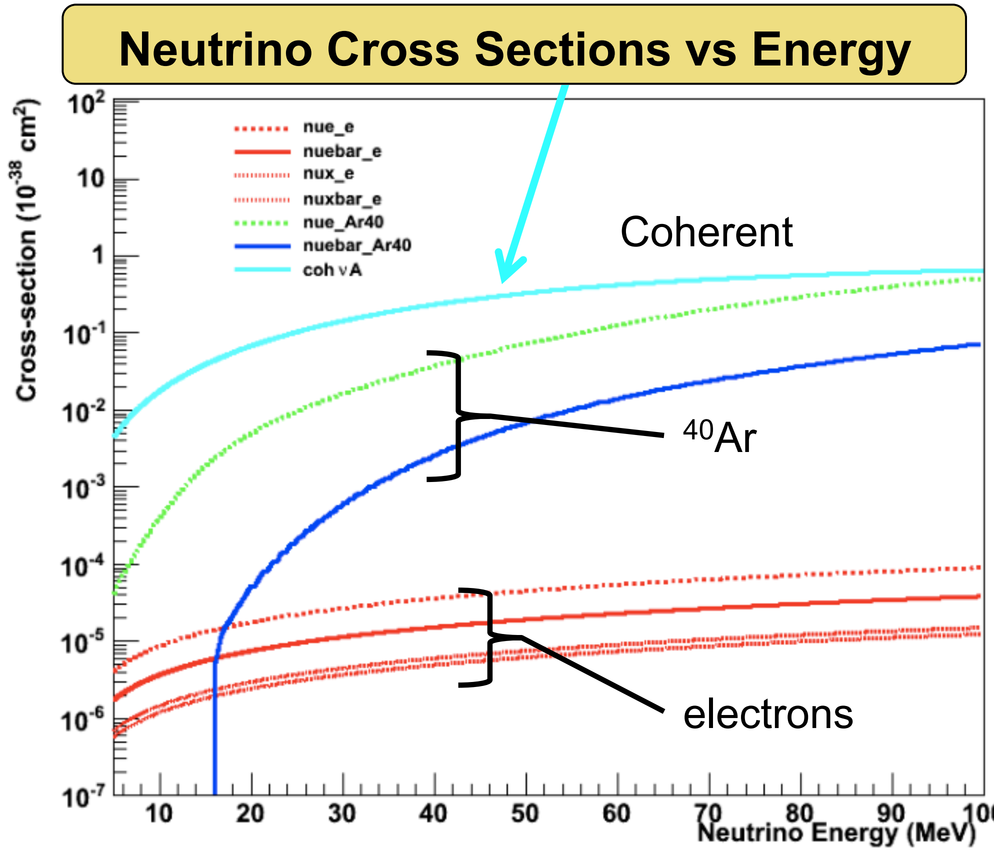


$$\frac{d\sigma}{dE} = \frac{G_F^2}{4\pi}\left[(1-4\sin^2\theta_w)Z - N\right]^2 M\left(1-\frac{ME}{2E_\nu^2}\right)F(Q^2)^2$$

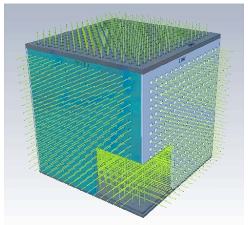


Fundamental But Unobserved

- 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

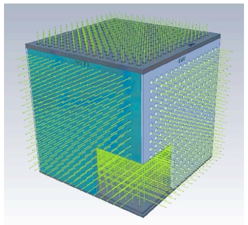


K. Scholberg at Coherent NCvAs mini-workshop at FNAL



Physics Cases for CENNS

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

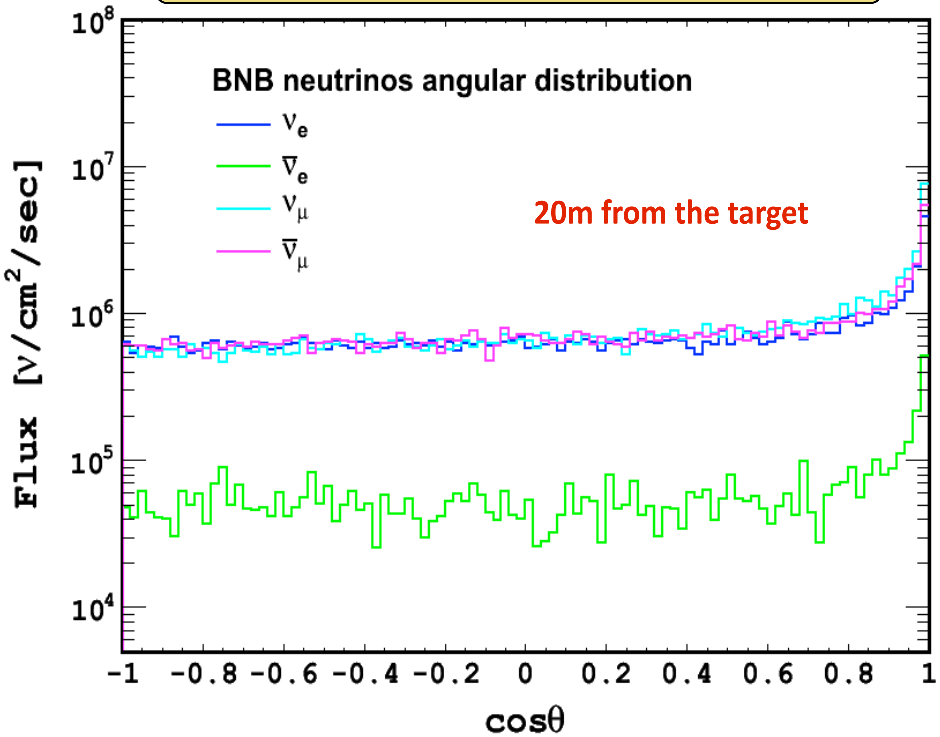


Pion Decay in Flight Source

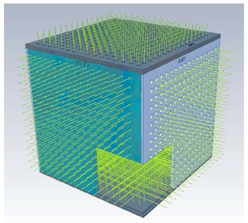
- FNAL BNB is a pion decay in-flight source
- On-axis multi-GeV neutrinos
- Far off-axis spectrum is much softer and narrower
- BNB flux at 20 m, cos θ < 0.5

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

Angle Off-Axis Neutrino Rate



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



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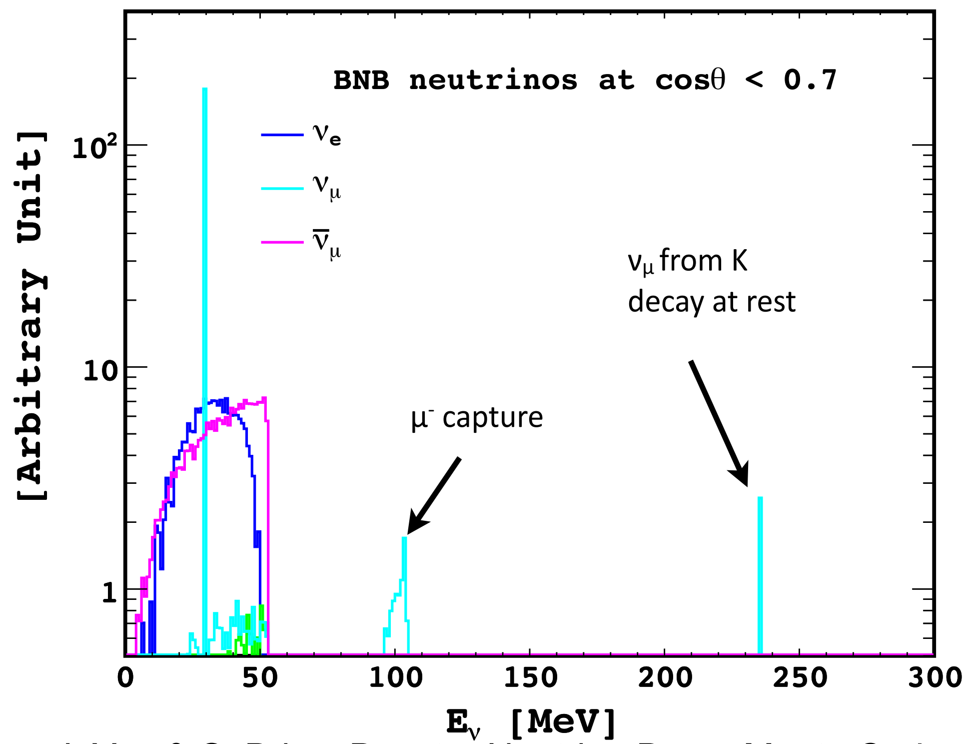
Off-Axis Neutrino Energy Spectrum



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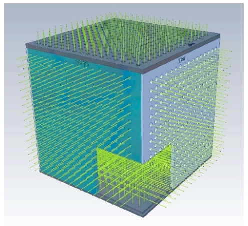
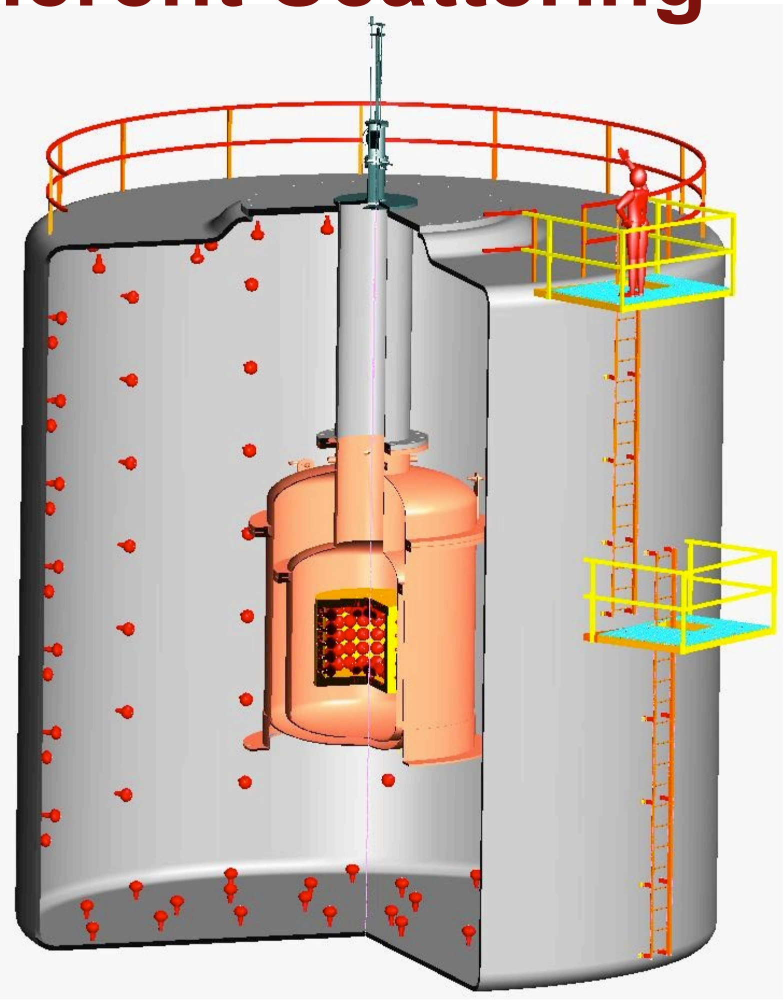
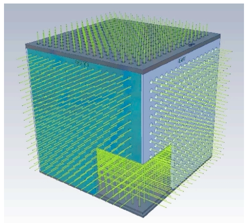


Detection of Coherent Scattering

- Detection in general: pick a dark matter technology
- Our proposal: 1-ton, single-phase liquid Argon (LAr)
- DEAP / CLEAN technology
- SCENE 1 kg prototype has shown viability
- 200 events ton^{-1} $year^{-1}$ (30 keV threshold, 32 kW)





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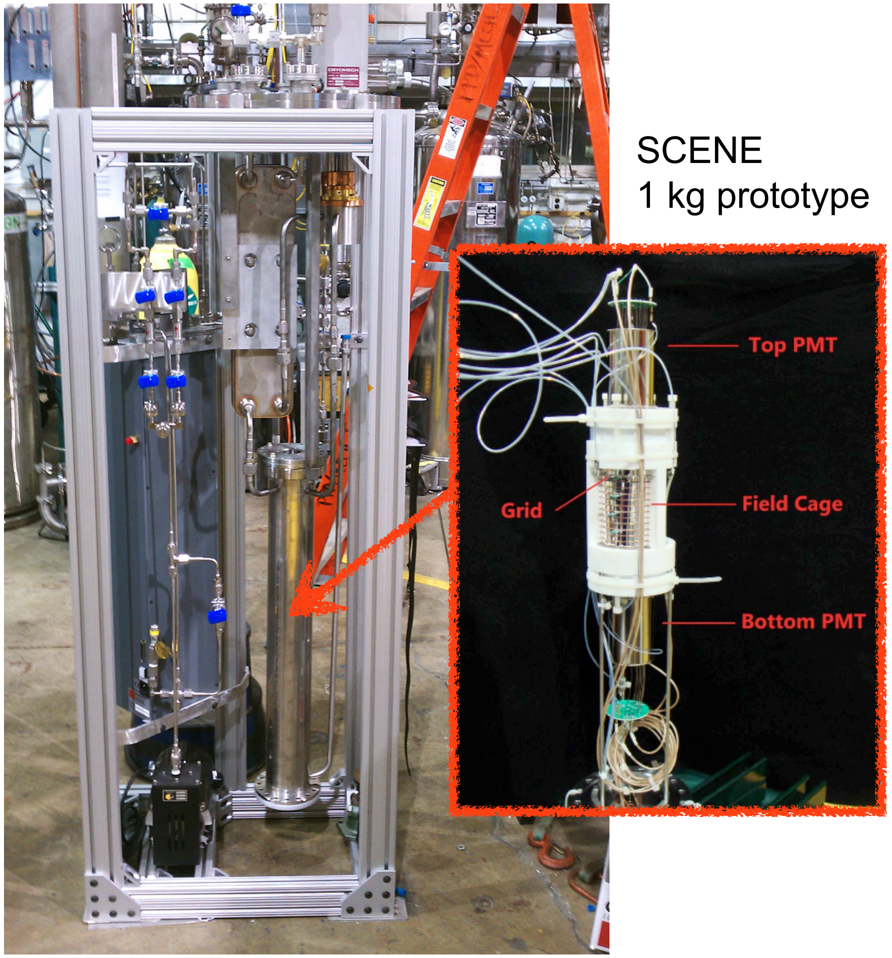
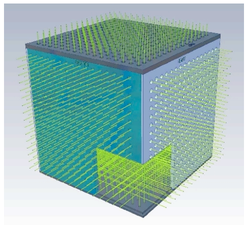


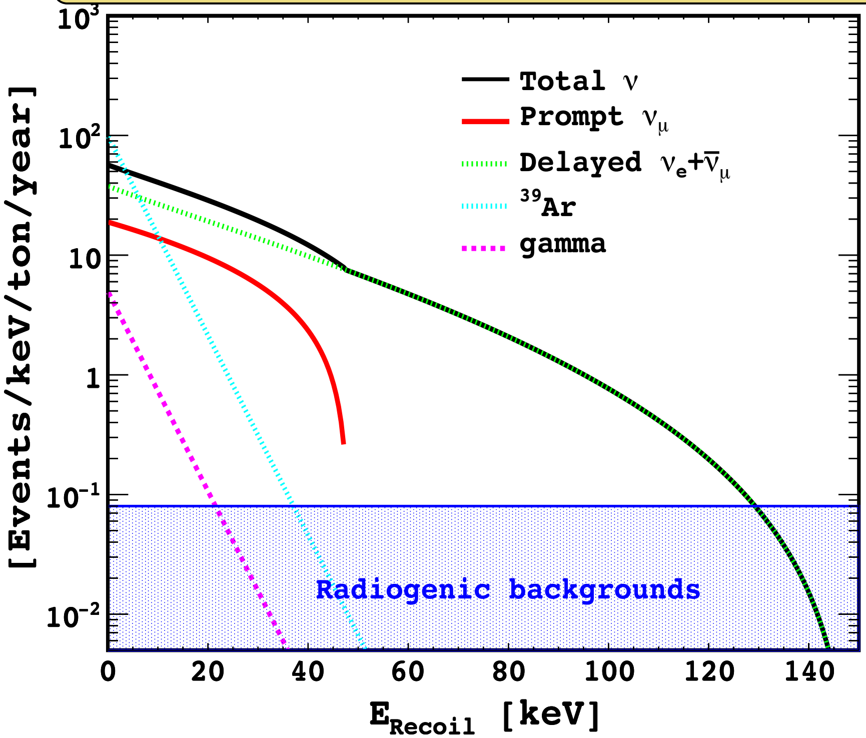
SCENE
1 kg prototype



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

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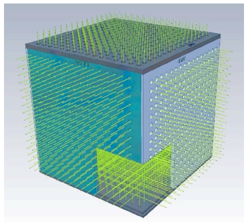

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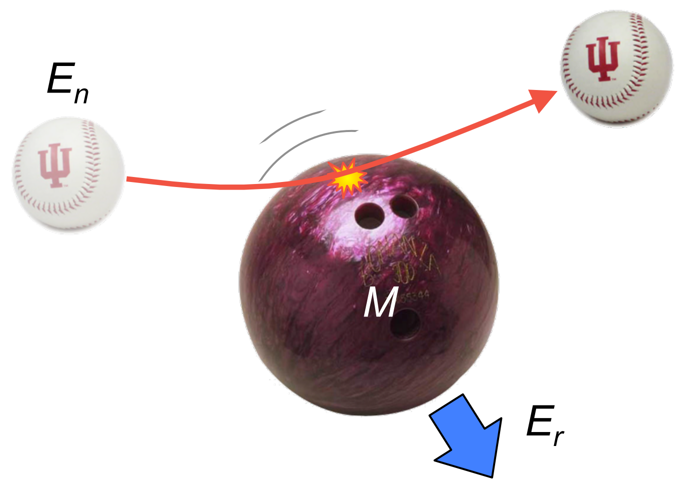
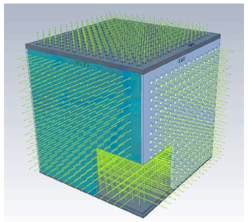
Neutron Scatter on ^{40}Ar



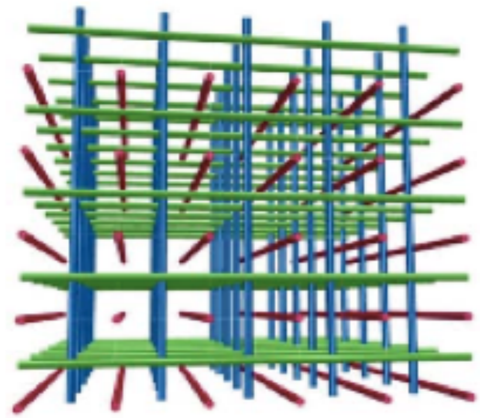
$$E_r^{\max} = \frac{4\mathcal{M}}{(\mathcal{M}+1)^2} E_n \simeq 0.1 E_n$$

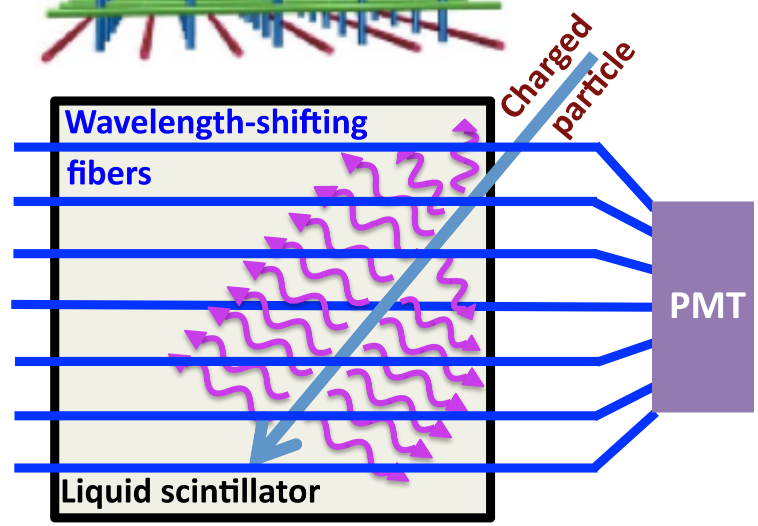
where $\mathcal{M} = M/m_n$

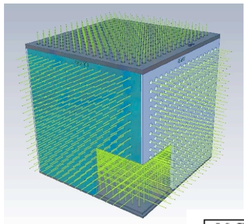


SciBath Detector

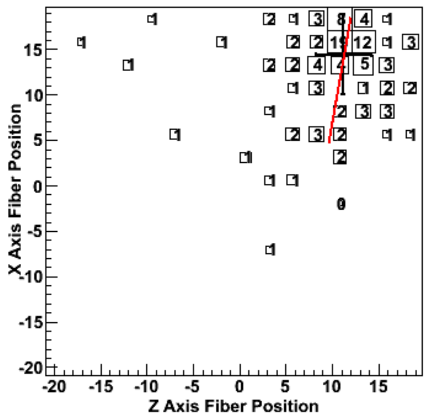
- 80 L open volume of mineral oil based liquid scintillator
- Neutrons recoil off protons, create scintillation
- 768 wavelength shifting fibers readout
- IU built custom digitizer: 12 bit, 20 MS / s

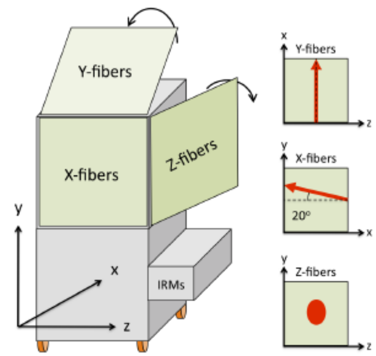




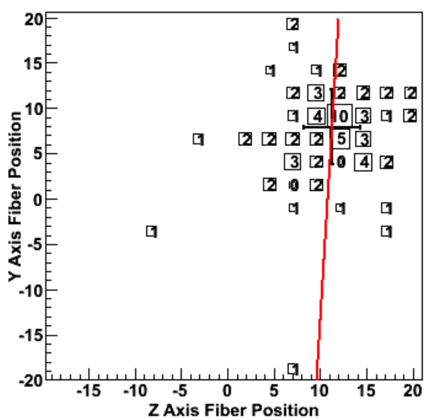


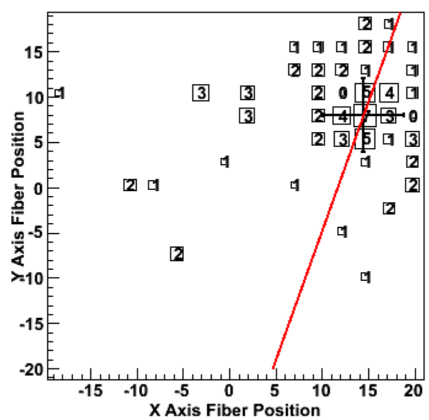
Sample Neutron Candidate Event

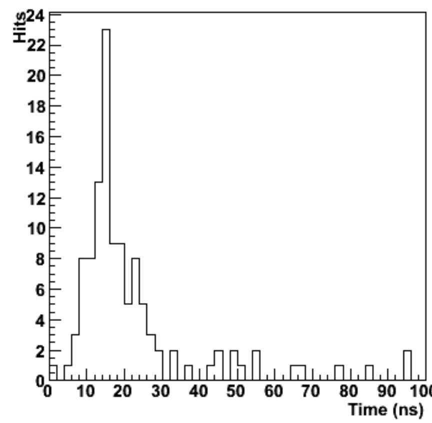


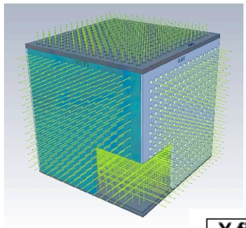


Event Num: 10642 (95796)
Multiplicity: 124
Total PEs: 283.0
PEs -- X: 80.8 Y: 115.8 Z: 86.4
PEs^2 -- X: 282.5 Y: 784.6 Z: 252.9
T0: 92.284587701 s
Time to last BIB: 0.0001213 s
$\bar{x}$ = 14.4 ± 4.4 cm -- skew = -2.92 -- kurt = 13.34
$\bar{y}$ = 7.9 ± 4.1 cm -- skew = -1.55 -- kurt = 10.71
$\bar{z}$ = 11.3 ± 3.0 cm -- skew = -2.21 -- kurt = 17.16
$\bar{t}$ = 30.6 ± 43.4 s -- skew = 5.84 -- kurt = 45.41
EigenVals: 71.20, 30.03, 14.64
EigenVect 1: $-0.03\hat{x} + -0.05\hat{y} + 1.00\hat{z}$
EigenVect 2: $-0.94\hat{x} + 0.33\hat{y} + -0.01\hat{z}$
EigenVect 3: $0.33\hat{x} + 0.94\hat{y} + 0.06\hat{z}$
Point χ^2: 683.47 Track χ^2: 1541.23
$\bar{d}$ = 12.9 ± 3.2 cm -- skew = -5.15 -- kurt = 63.69
Track length, ellipsoid: 29.43 , rod: 24.65
Spherical radius: 9.83 Eigenvector length: 42.42

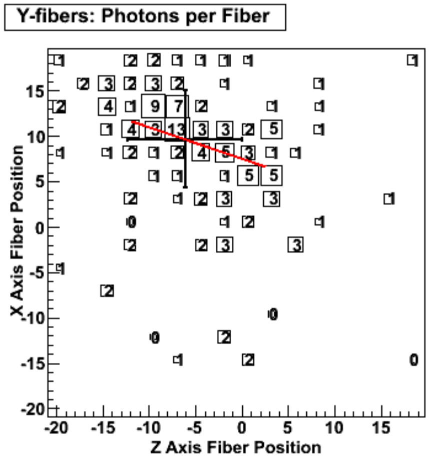


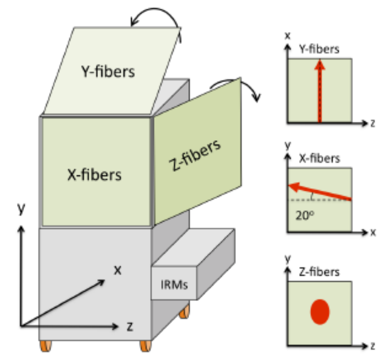




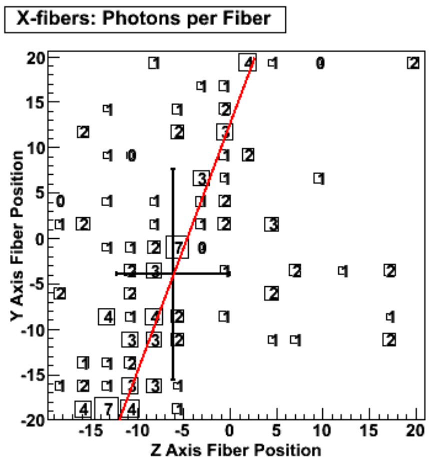


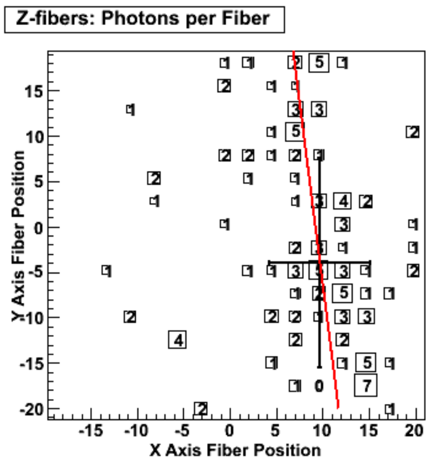
Sample Muon Candidate Event

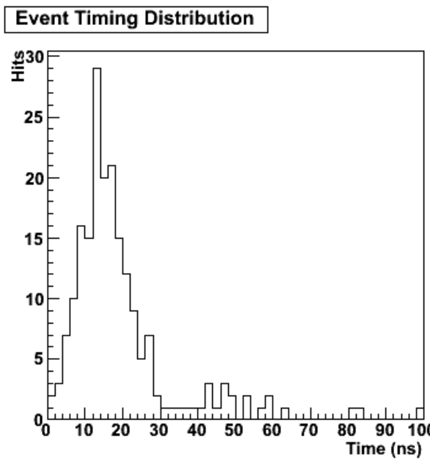


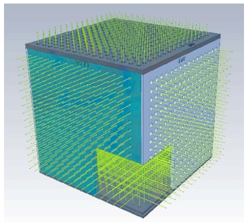


Event Num: 109 (1206)
Multiplicity: 204
Total PEs: 412.6
PEs -- X: 126.0 Y: 158.1 Z: 128.5
PEs^2 -- X: 337.9 Y: 668.8 Z: 360.9
T0: 3.272227153 s
Time to last BIB: 0.0009486 s
$\bar{x}$ = 9.7 ± 5.4 cm -- skew = -1.64 -- kurt = 6.62
$\bar{y}$ = -4.0 ± 11.6 cm -- skew = 0.47 -- kurt = 2.14
$\bar{z}$ = -6.1 ± 6.1 cm -- skew = 0.90 -- kurt = 4.70
$\bar{t}$ = 24.7 ± 36.9 s -- skew = 6.92 -- kurt = 60.43
EigenVals: 196.01, 183.20, 34.72
EigenVect 1: $0.65\hat{x} + -0.19\hat{y} + 0.74\hat{z}$
EigenVect 2: $-0.75\hat{x} + -0.31\hat{y} + 0.58\hat{z}$
EigenVect 3: $0.12\hat{x} + -0.93\hat{y} + -0.34\hat{z}$
Point χ^2: 1502.27 Track χ^2: 1496.78
$\bar{d}$ = 6.9 ± 12.7 cm -- skew = -0.41 -- kurt = 2.00
Track length, ellipsoid: 58.69 , rod: 47.70
Spherical radius: 18.57 Eigenvector length: 42.86

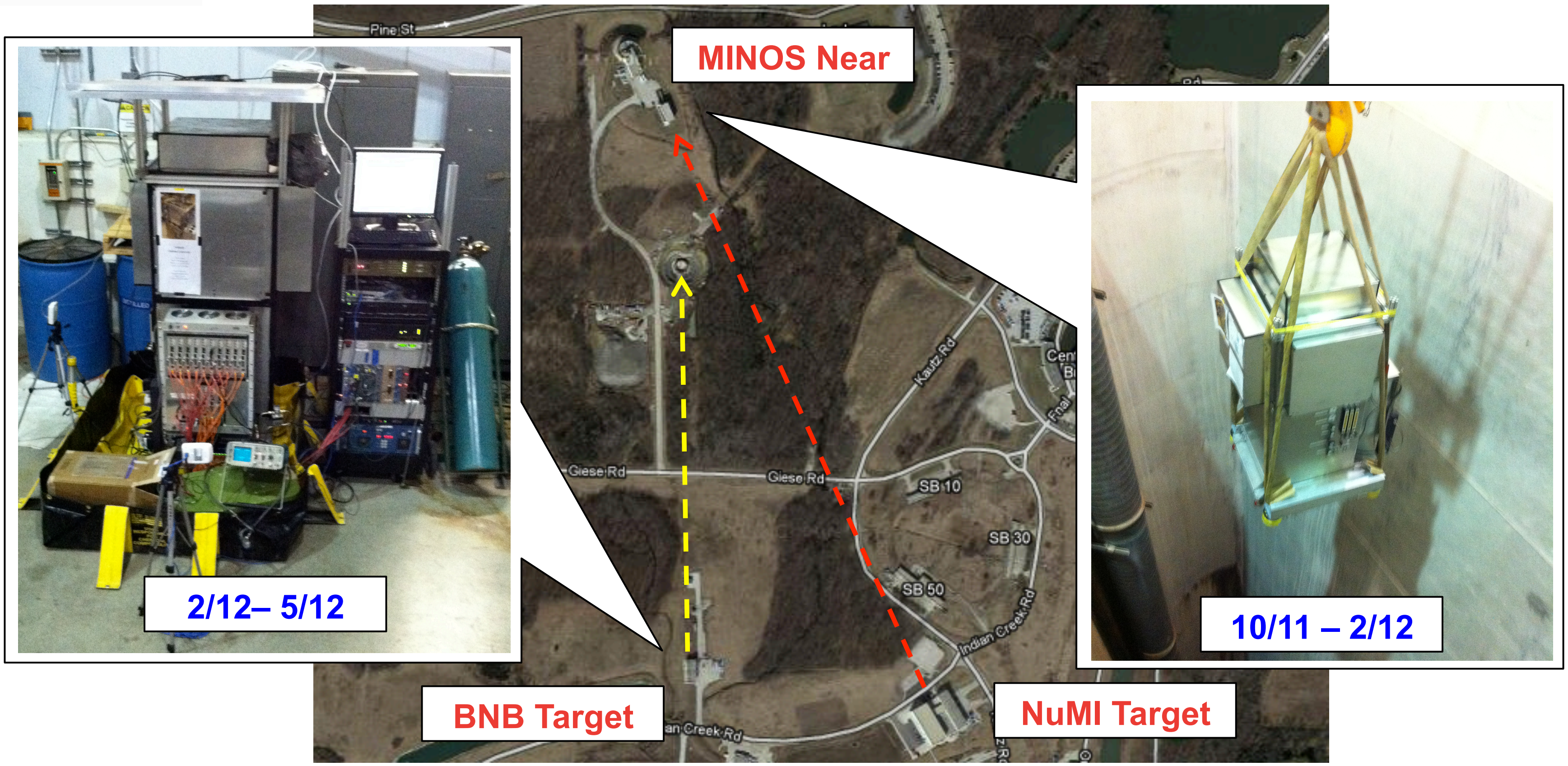


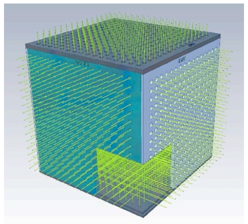






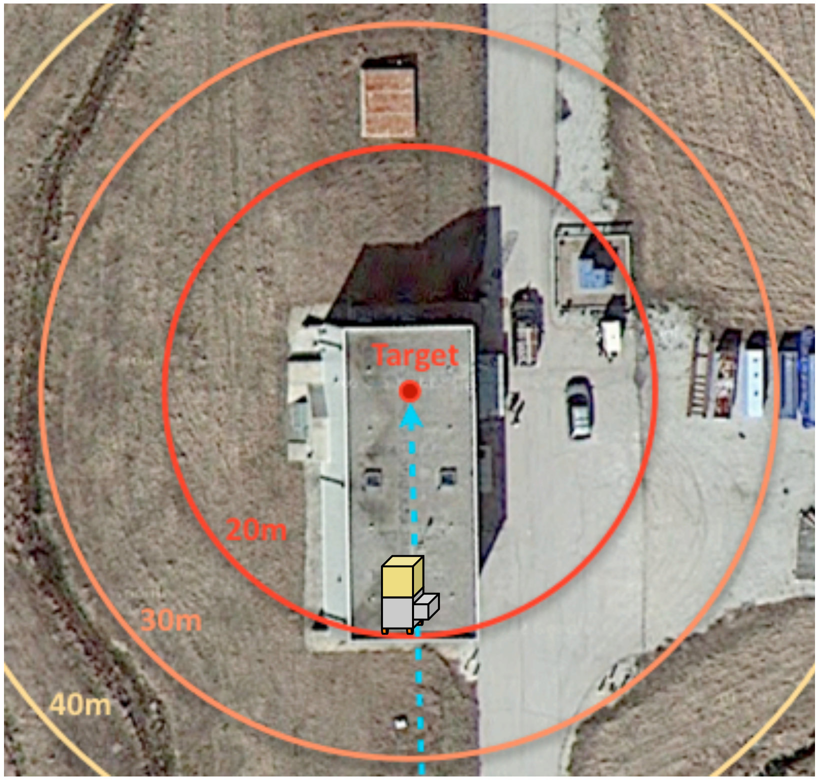
Fermilab Measurement Sites

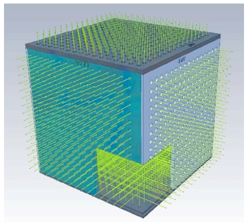




MI-12 Neutron Background Run

- Neutron flux ~20 m from target
- In-line behind beam target (ground)
- 29 Feb. – 23 Apr.
- 4.9×10^{19} total POT (4.5×10^{12} per pulse)





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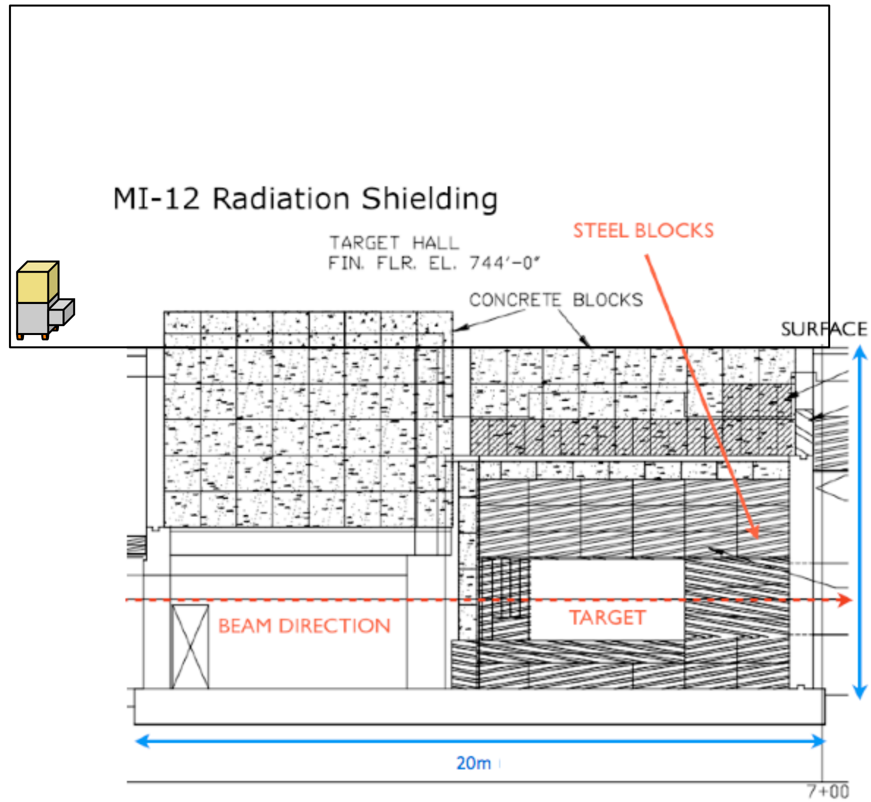
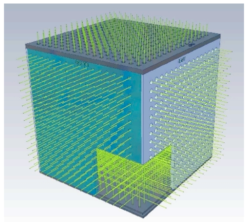
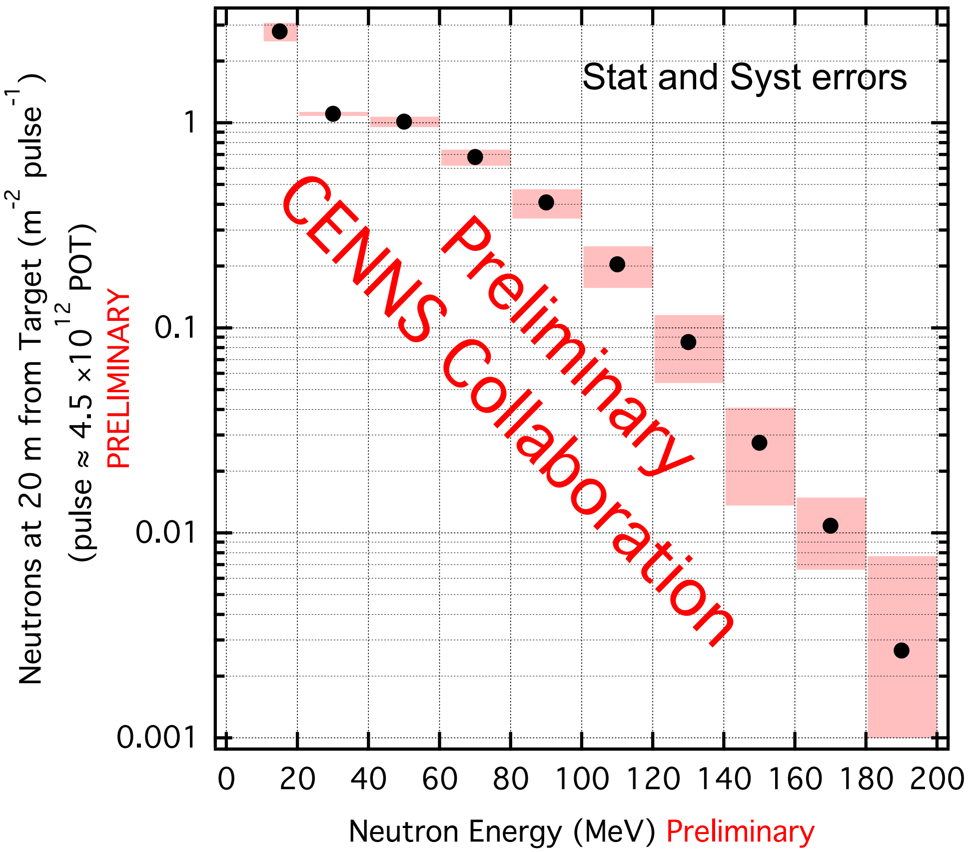


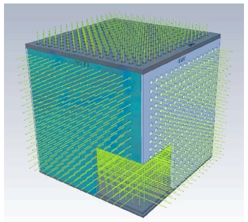


BNB Neutron Energy Spectrum

- E_n unfolded from PEs using fit and MC response function
- Soft threshold at 10 MeV
- 2.44 ± 0.34 pulse^{-1} m^{-2} (E_n > 40 MeV)
- Fit loses sensitivity above 200 MeV; fit truncated
- Neutron spectrum 20 m from BNB

Unfolded Neutron Energy Spectrum

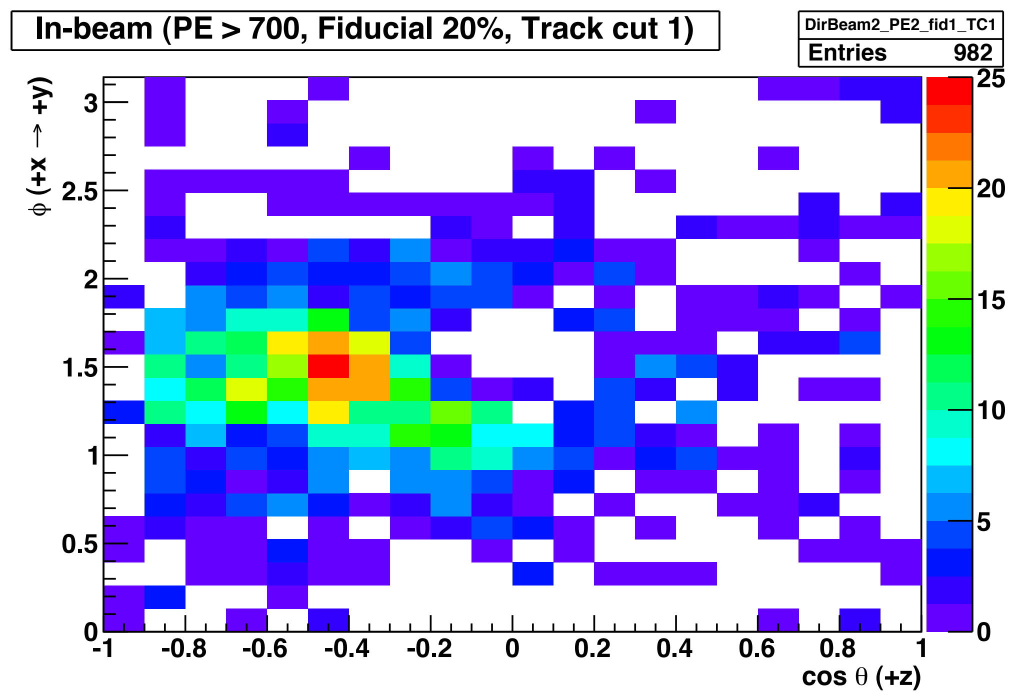


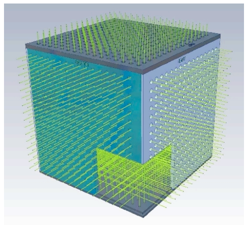


Direction Spectrum

- High PE protons will be track-like; can be imaged
- Principle component analysis yields eigenvector
- Back-projecting direction spectrum tends to point upstream of target ?!
- Tracking validated with cosmic rays and NuMI beam

High-PE, Proton Direction Spectrum





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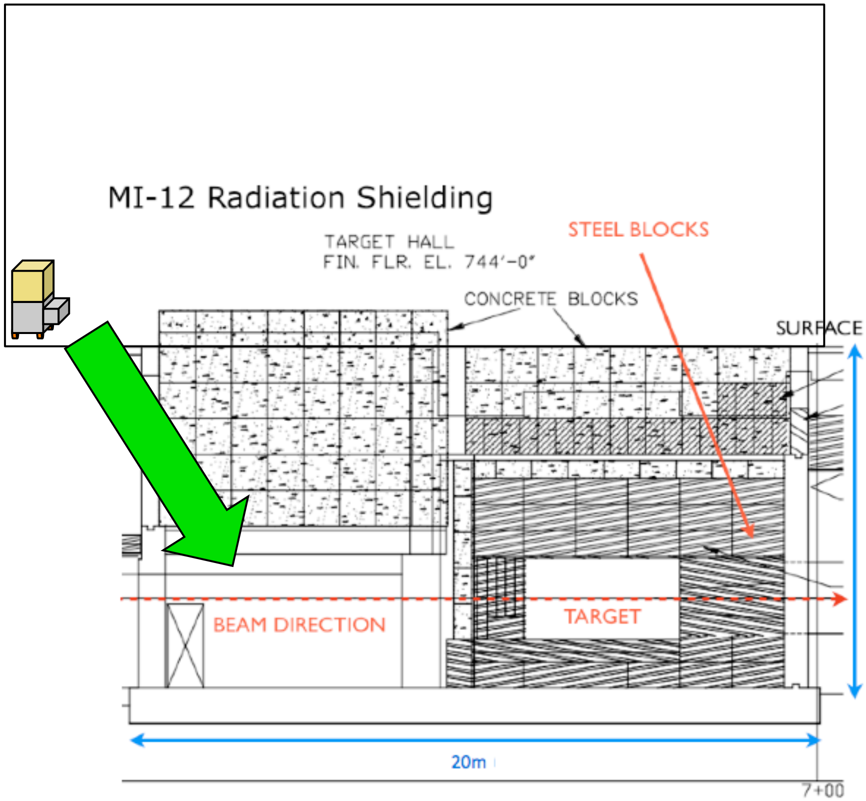
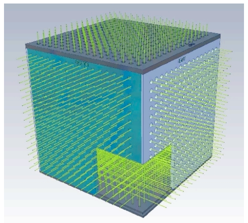
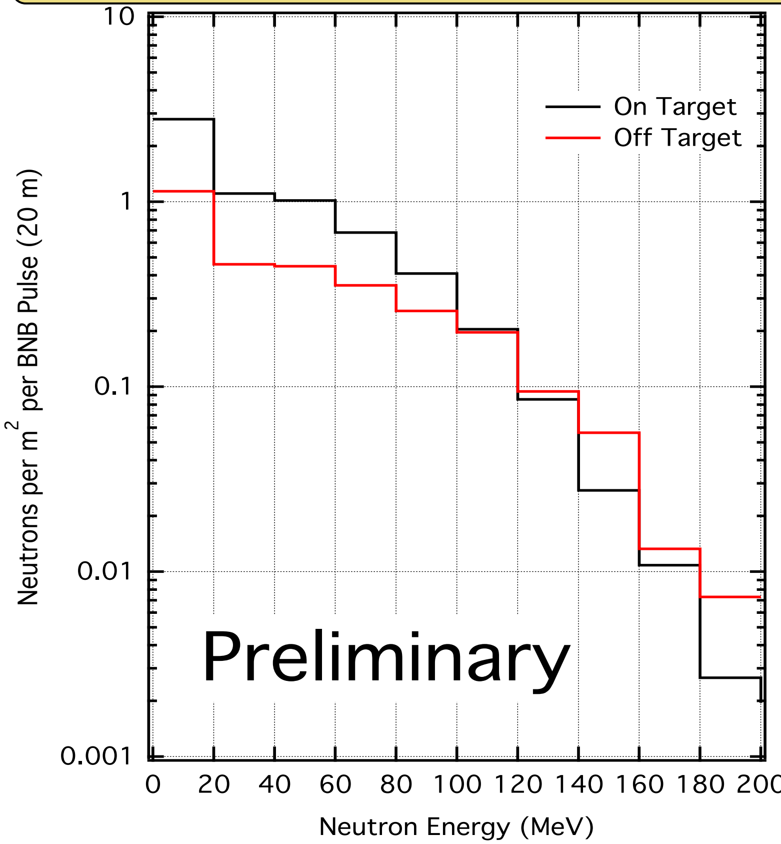


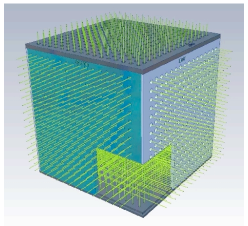


Beam Off-Target Runs

- Beam deviated Fe beamstop 50 m downstream for 1 week
- 1.43 ± 0.15 pulse^{-1} m^{-2} ($E_n > 40$ MeV)
- Off-target direction spectrum similar to on-target data ?!
- Off-target energy spectrum appears to be "harder" ?!
- Scraping beam upstream ?

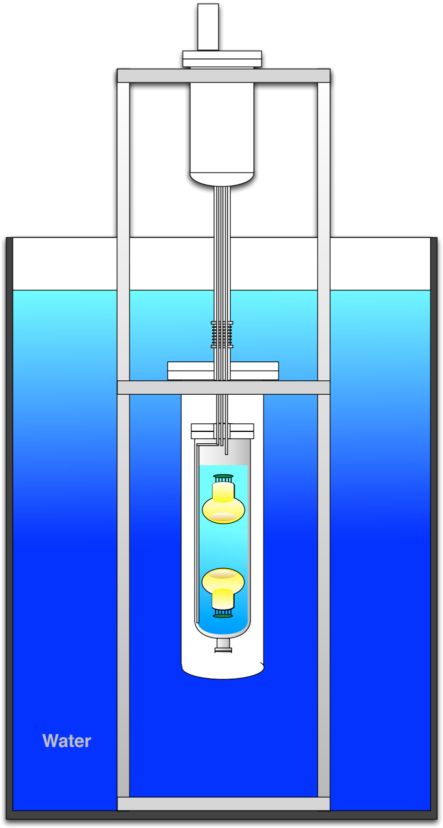
On- and Off-Target Energy Spectra

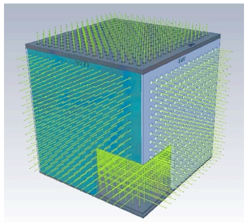




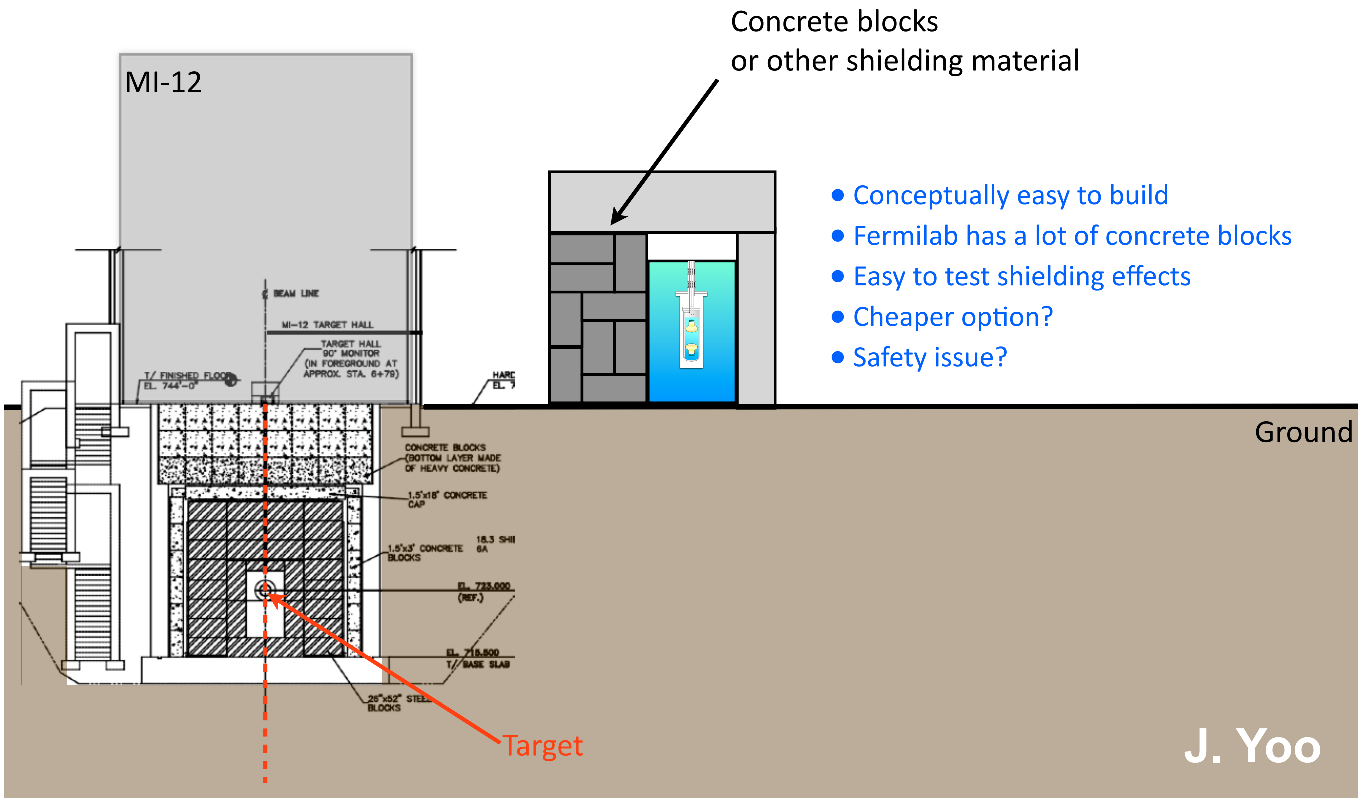
10 kg Prototype Detector

- Currently under construction
- Neutron studies with new shield (with SciBath)
- Utilize cryostat and PMTs from 1 kg detector
- Ready for calibration this summer

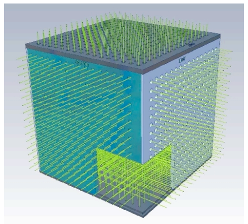




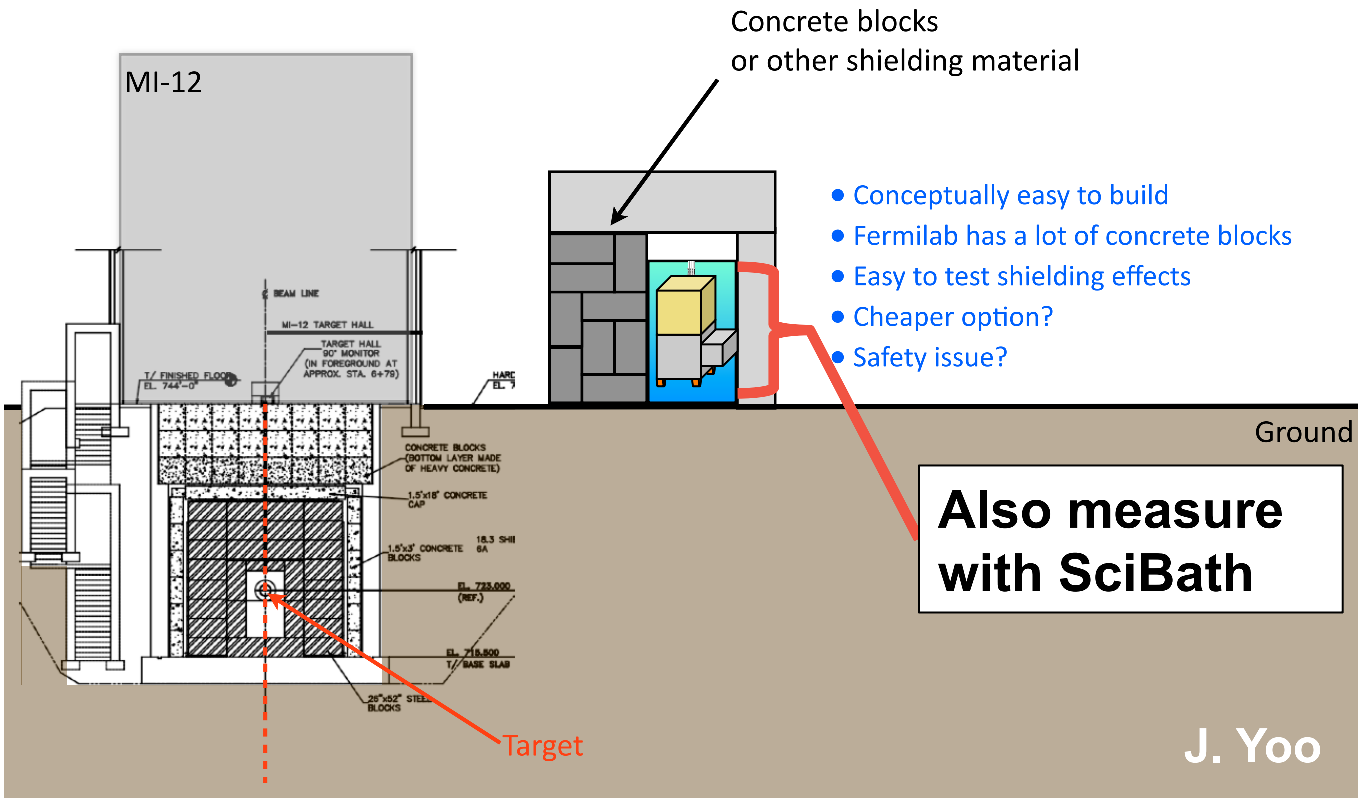
Shielding Studies



- Conceptually easy to build
- Fermilab has a lot of concrete blocks
- Easy to test shielding effects
- Cheaper option?
- Safety issue?

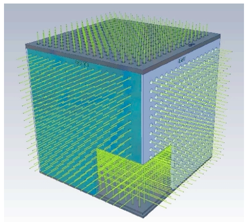


Shielding Studies

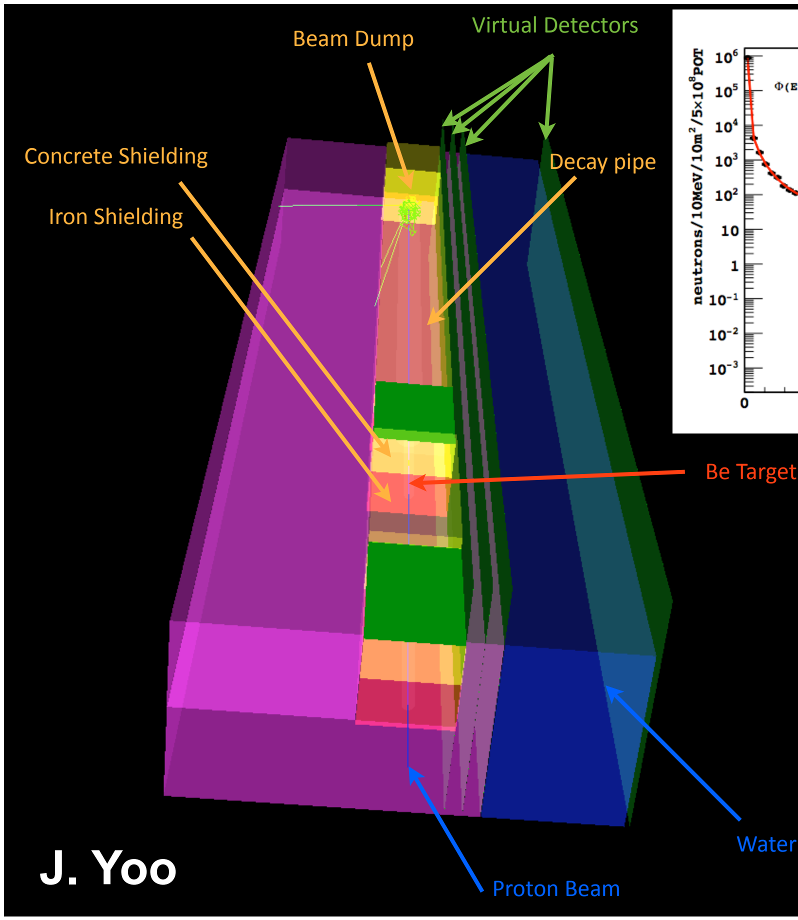


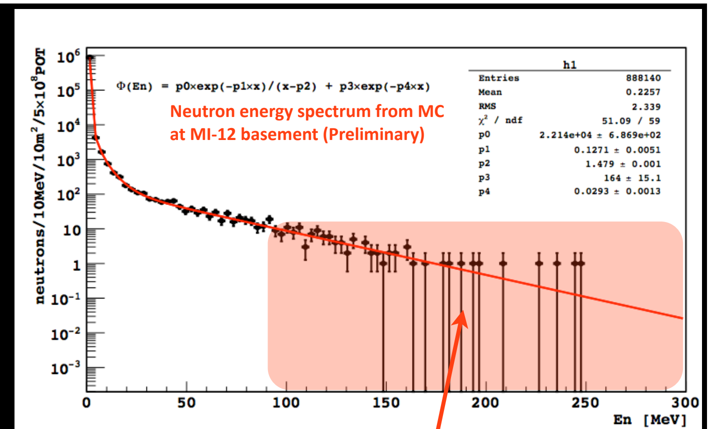
- Conceptually easy to build
- Fermilab has a lot of concrete blocks
- Easy to test shielding effects
- Cheaper option?
- Safety issue?

Also measure with SciBath



Beam Neutron MC Efforts



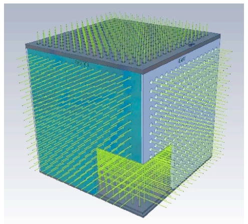


Fast Neutrons

- at least ~10m of shielding needed
- often counterintuitive
- need for different layers (steel, concrete, water, poly …)

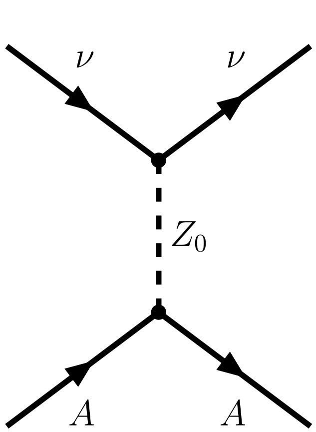
Experiment doesn't have to be zero BG

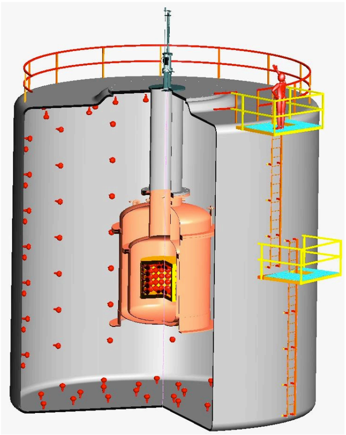
- trade offs between neutrino flux, background rate and live time

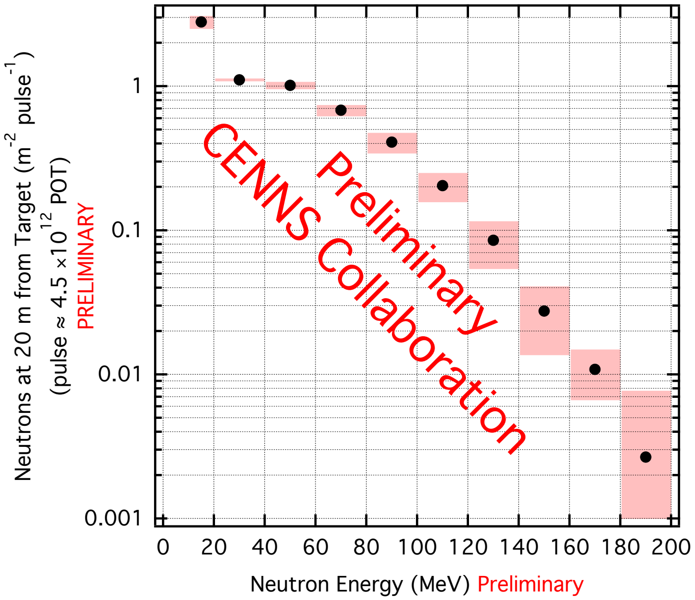


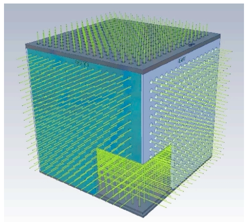
Summary

- CENNS is well motivated
- Proposed 1-ton, single phase LAr (DEAP/CLEAN)
- Characterized BNB neutrons for off-axis neutrino source
- Off-target data is interesting
- More calibrations and background runs ahead?

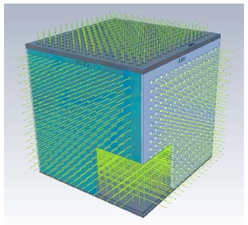




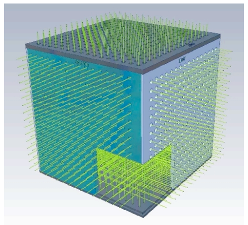




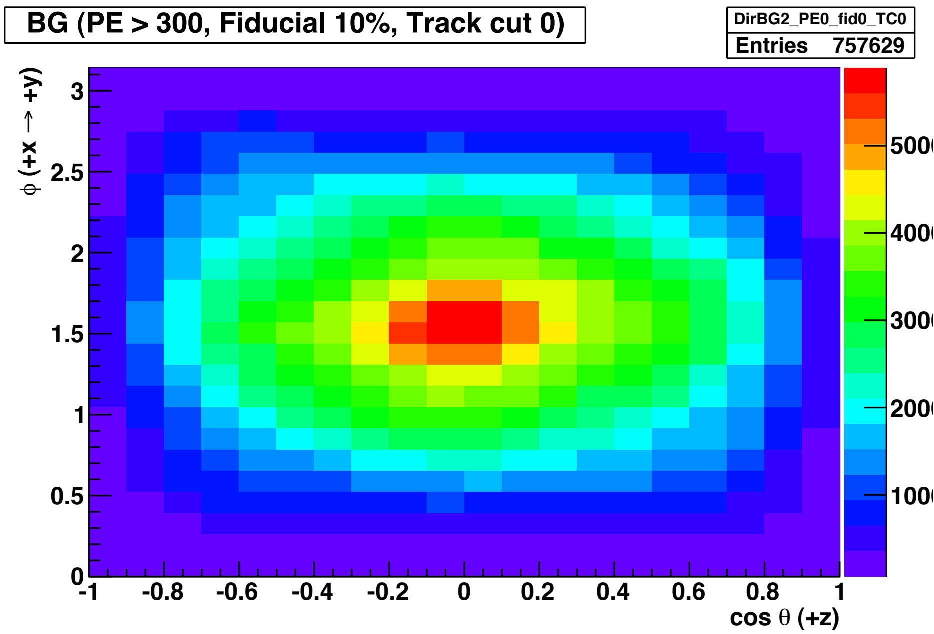
Thank You!

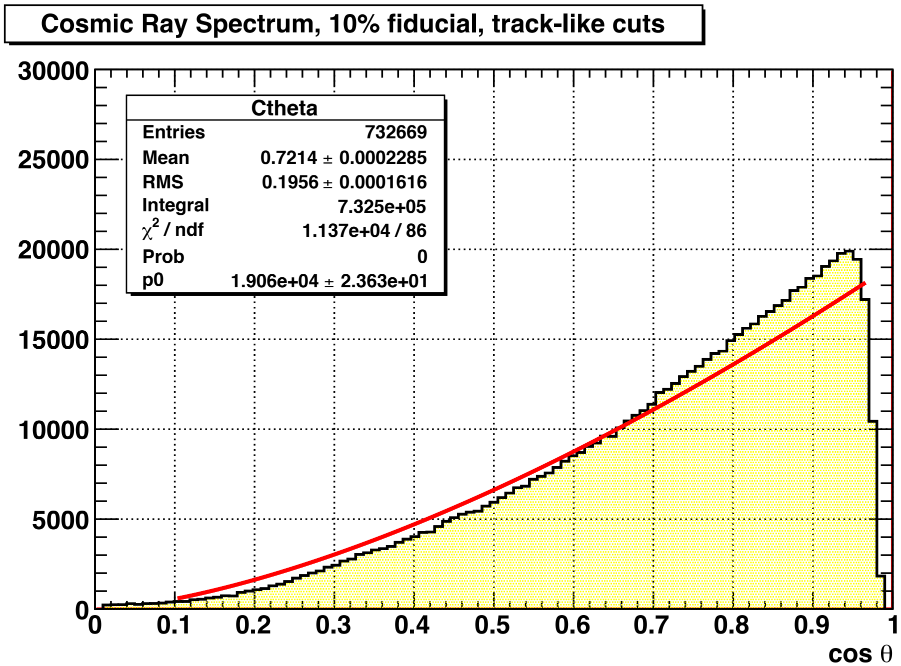


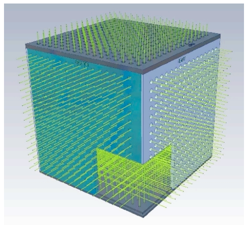
PINCH HITTERS (BACKUPS)



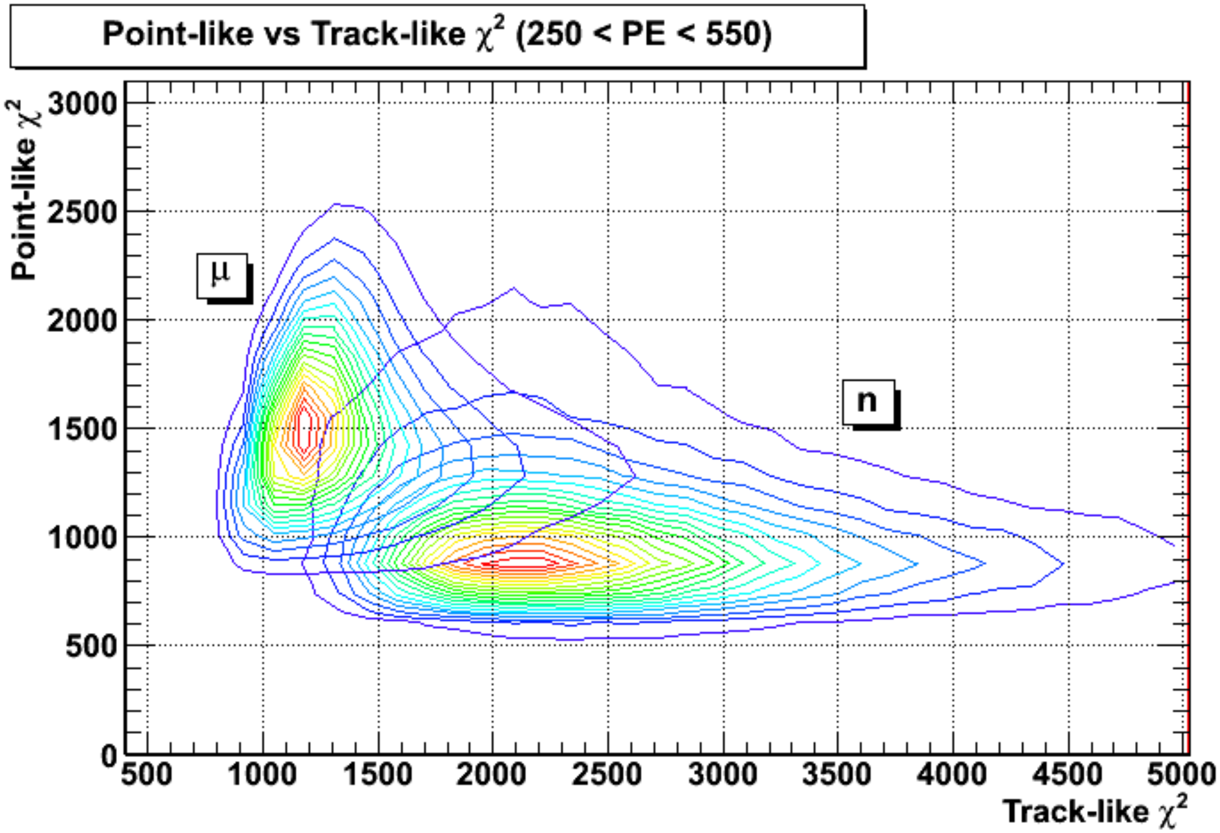
Cosmic Ray Direction Spectrum

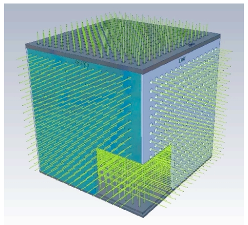




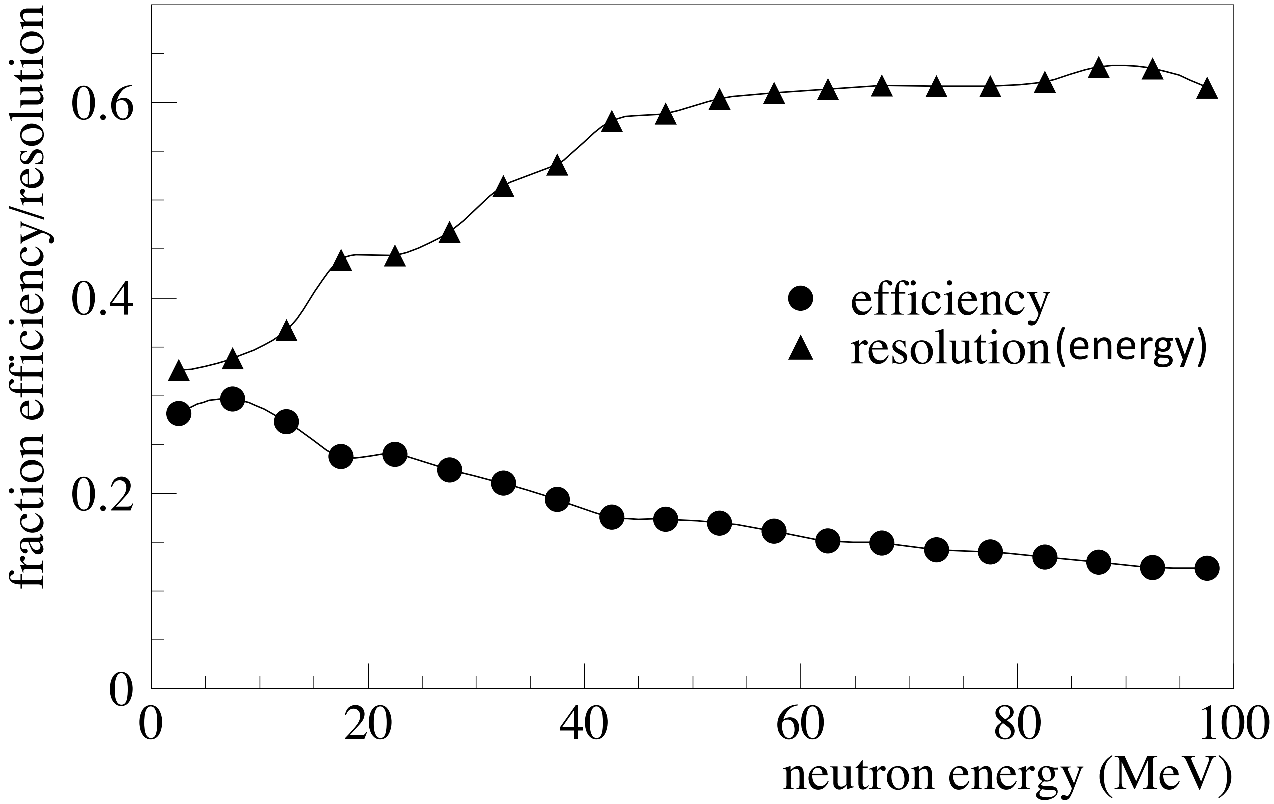


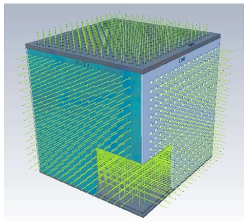
n / μ Particle Discrimination





Neutron Sensitivity (w. *n*-capture)

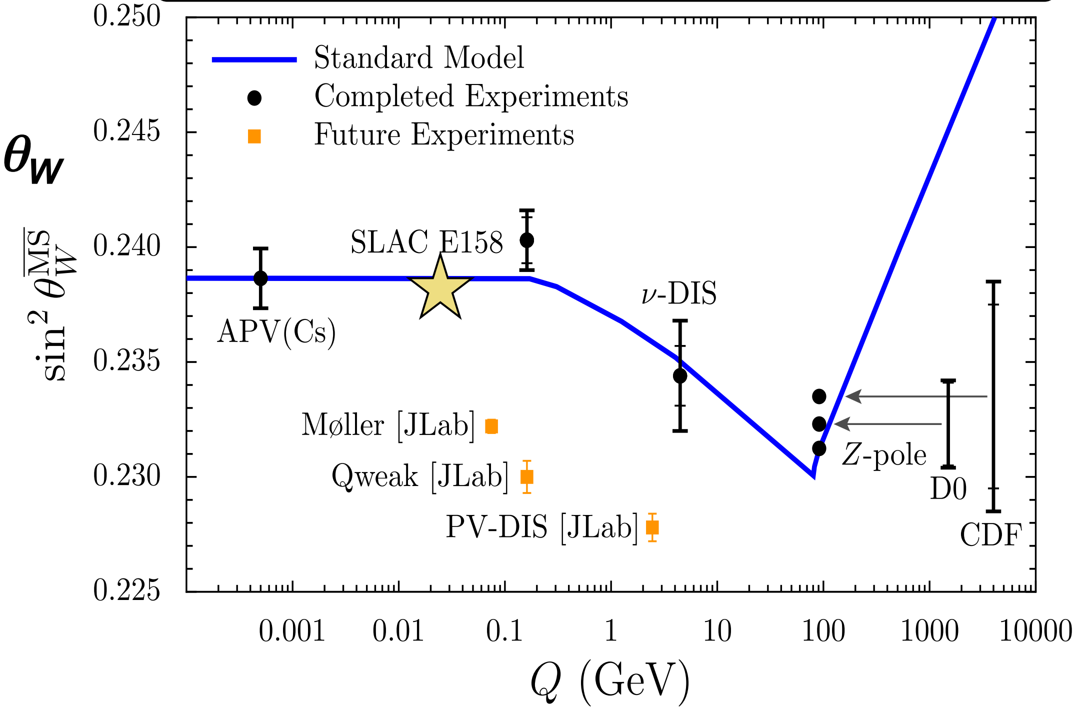




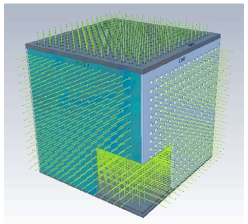
Physics Cases for CENNS

- Never been observed!
- **SM tests: measure $\sin^2\theta_W$**
- Form factors
- Supernova physics
- Reactor monitoring
- 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



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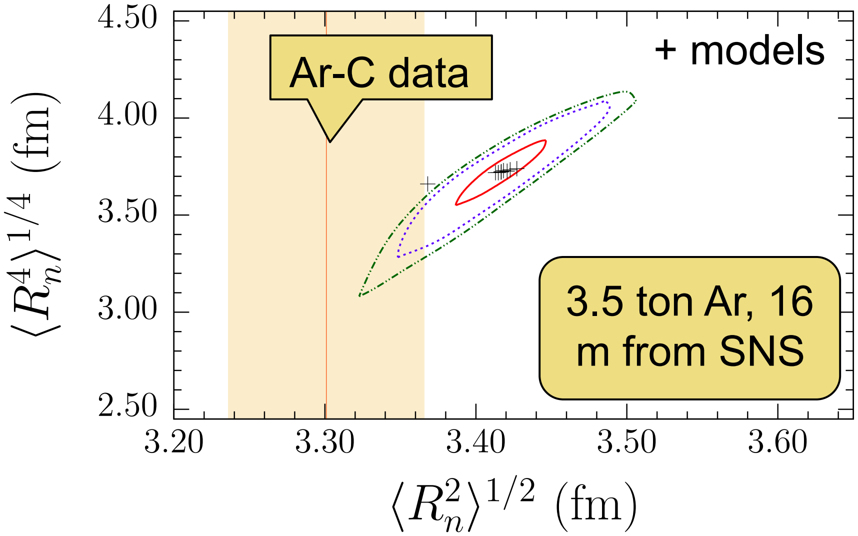
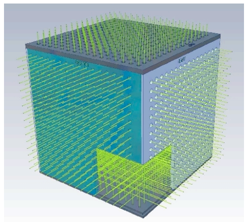
4th vs 2nd Form Factor Moments

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

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



Patton et al., arXiv/1207.0693



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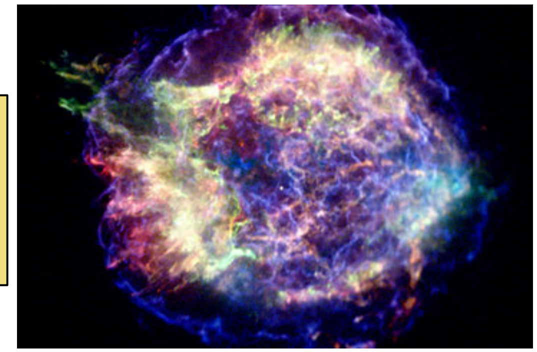
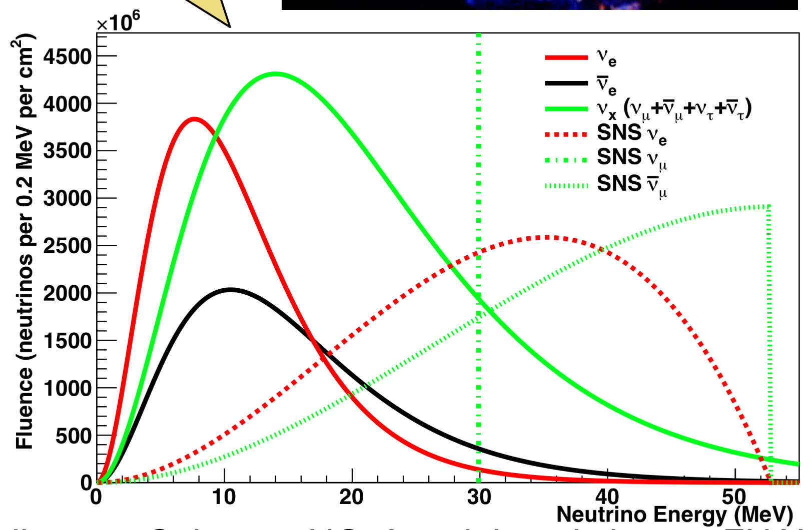
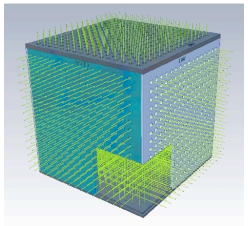
Supernova energy spectrum similar to stopped pions





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



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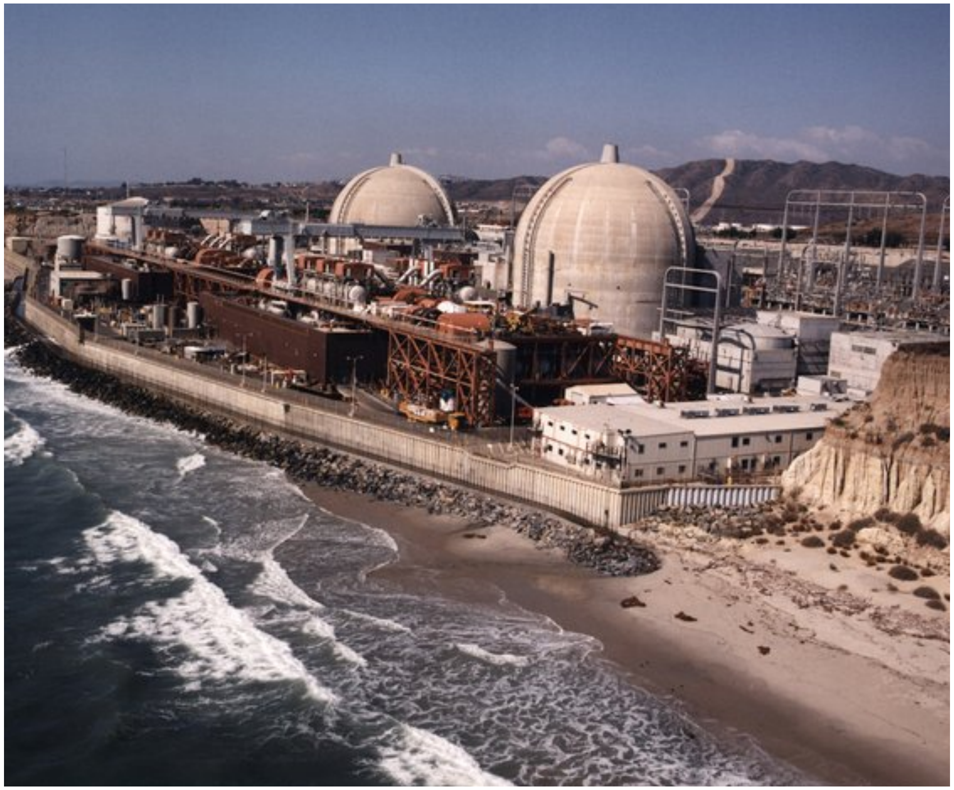
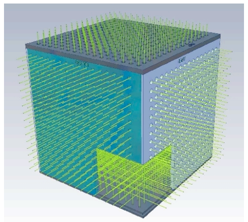


Especially see work from LLNL, SNL, A. Bernstein, etc.



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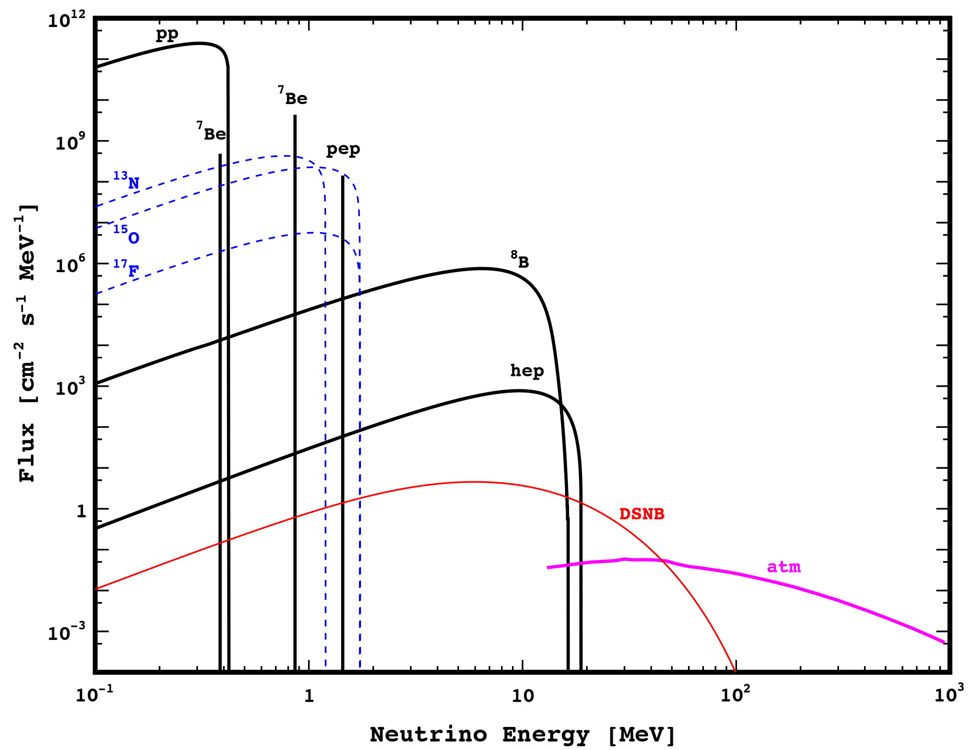
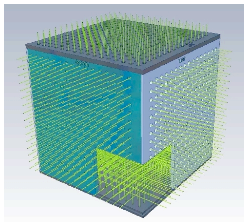
Solar, Atmosphere, and SN Neutrinos



J. Yoo at Coherent NCvAS mini-workshop at FNAL



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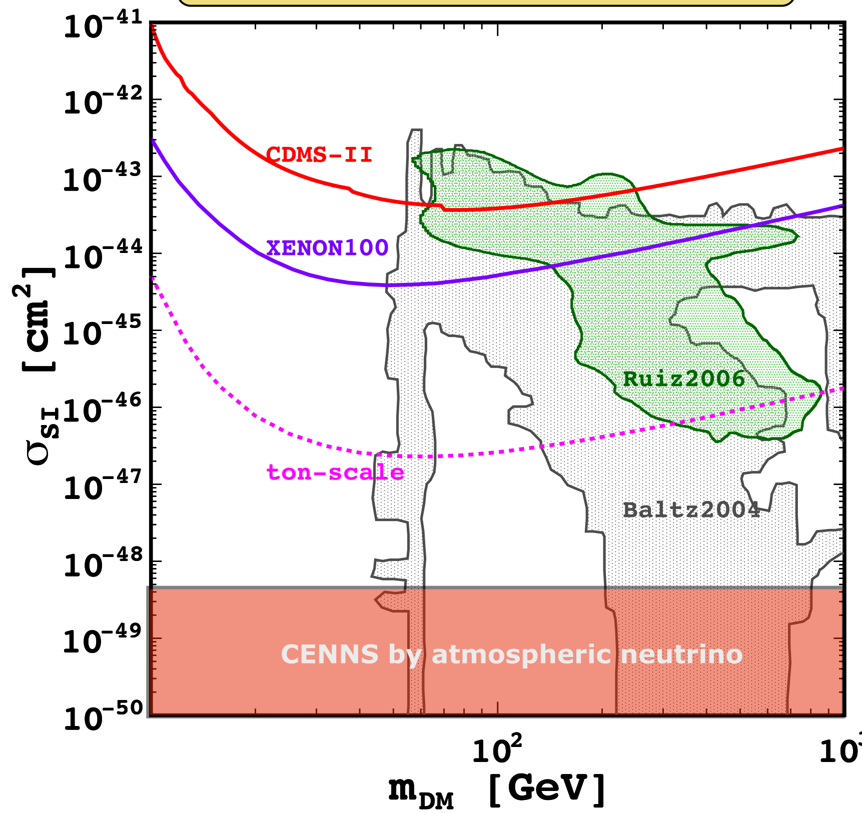
Dark Matter Sensitivity



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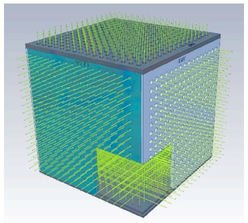
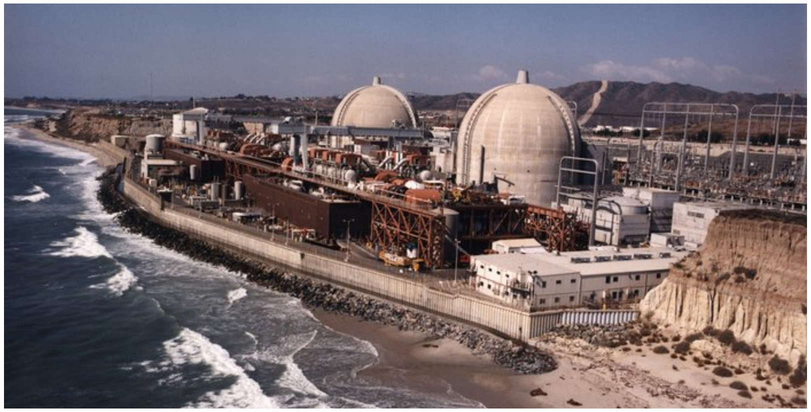


Reactor Neutrino Sources

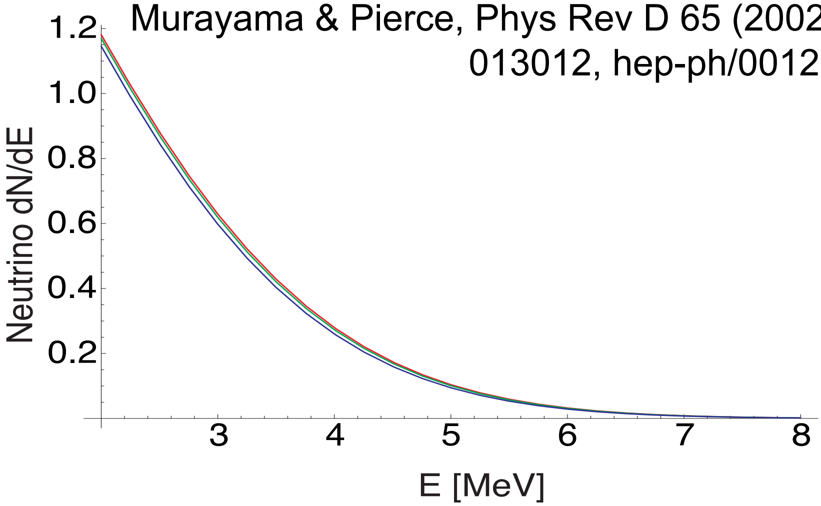
- Reactors give very high flux

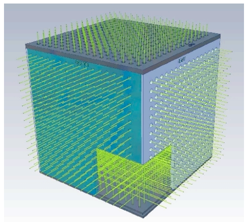
$$\Phi_{\bar{\nu}} \simeq 10^{20}\ \mathrm{s}^{-1}$$
$$\Rightarrow 10^{12}\ \mathrm{s}^{-1}\,\mathrm{cm}^{-2} \text{ at 20 m}$$

- 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





Accelerator Neutrino Sources

- Few GeV protons on target produces π^+

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

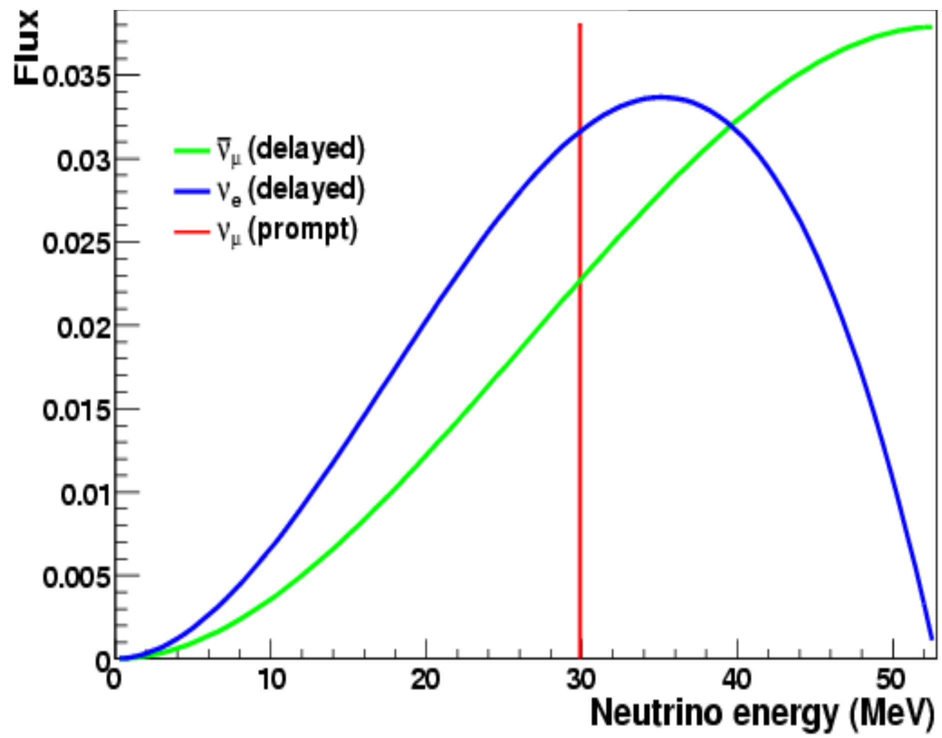
- Prototypical source is SNS

- SNS flux at 20 m

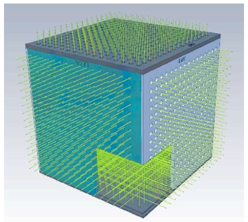
$\Phi^{SNS} = 1\times10^7\ s^{-1}\ cm^{-2}$

- Other alternatives?

SNS Stopped Pion Energy Spectrum



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



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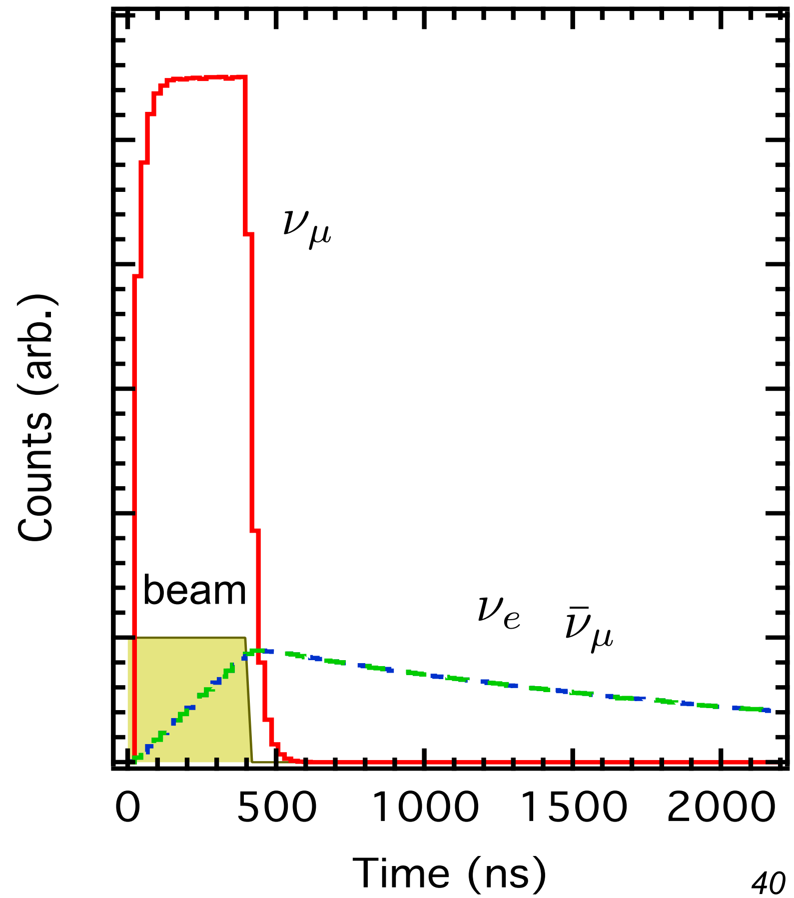
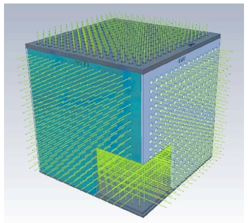
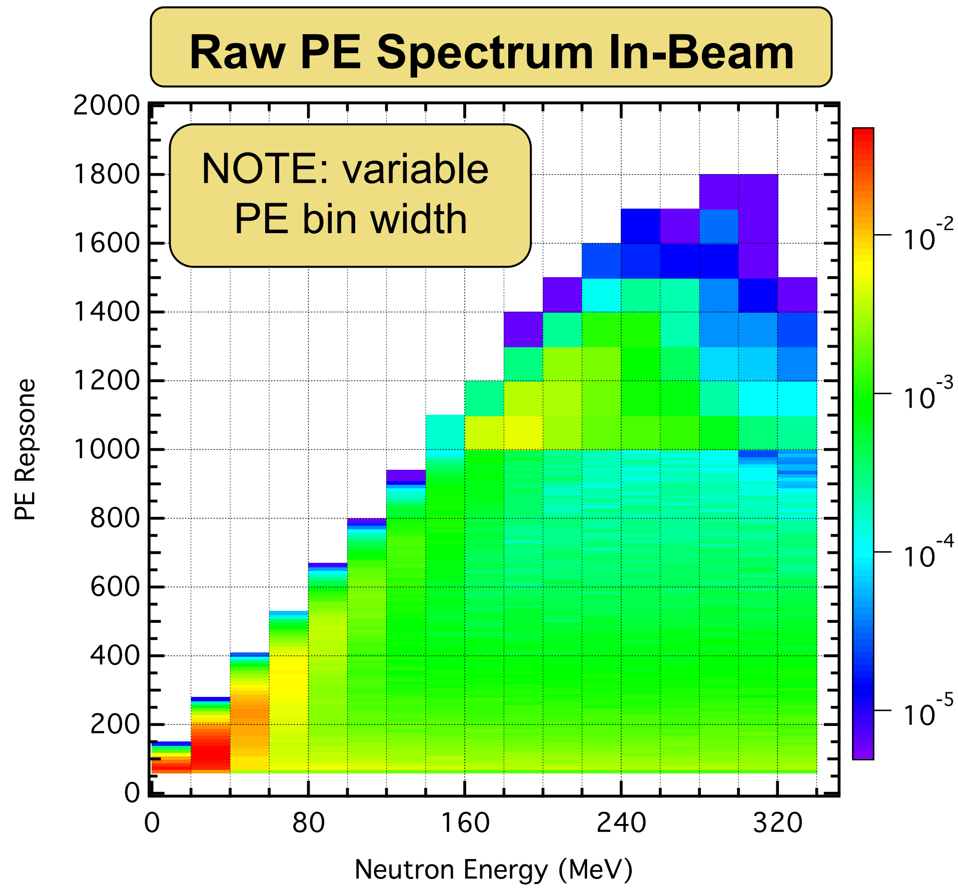
SNS Neutrino Rates in Time

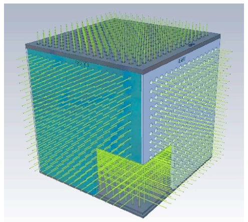




BNB Neutron Energy Spectrum

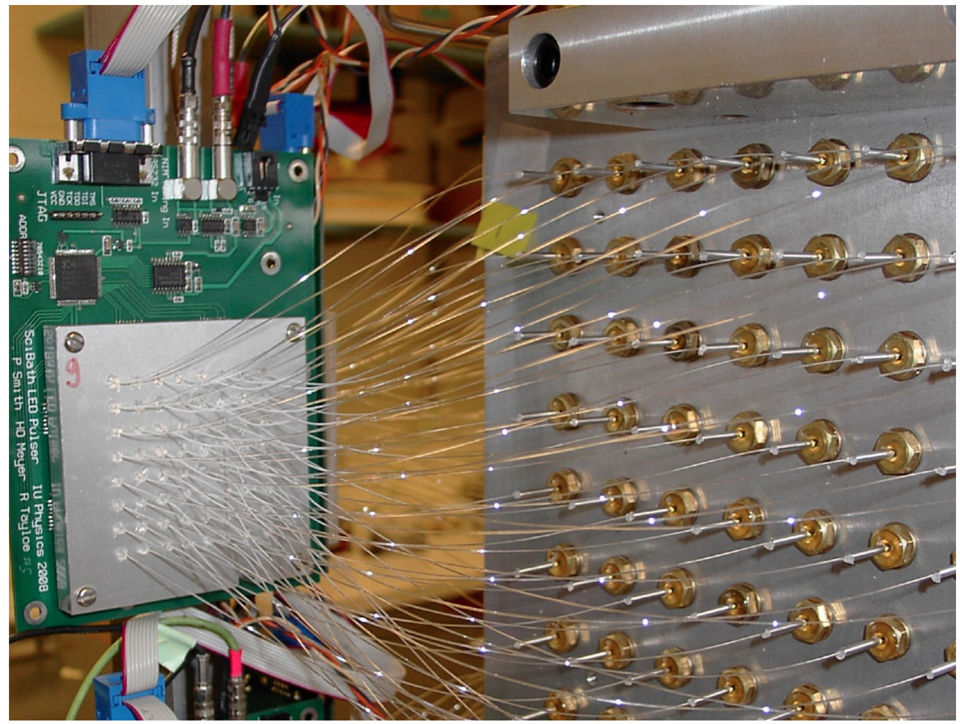
- E_n unfolded from PEs using fit and MC response function
- Soft threshold at 10 MeV
- 2.44 ± 0.34 pulse^{-1} m^{-2} (E_n > 40 MeV)
- Fit loses sensitivity above 200 MeV; fit truncated
- Neutron spectrum 20 m from BNB

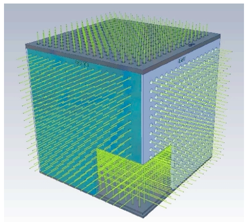




Photoelectron to ADC Calibration

- **Photoelectron (PE)**: an optical photon ejects an electron from PMT surface via the photoelectric effect
- Low-light LED calibrates ADC to single photons
- Approximately 30 ADC channels per PE
- PMTs balanced with HV





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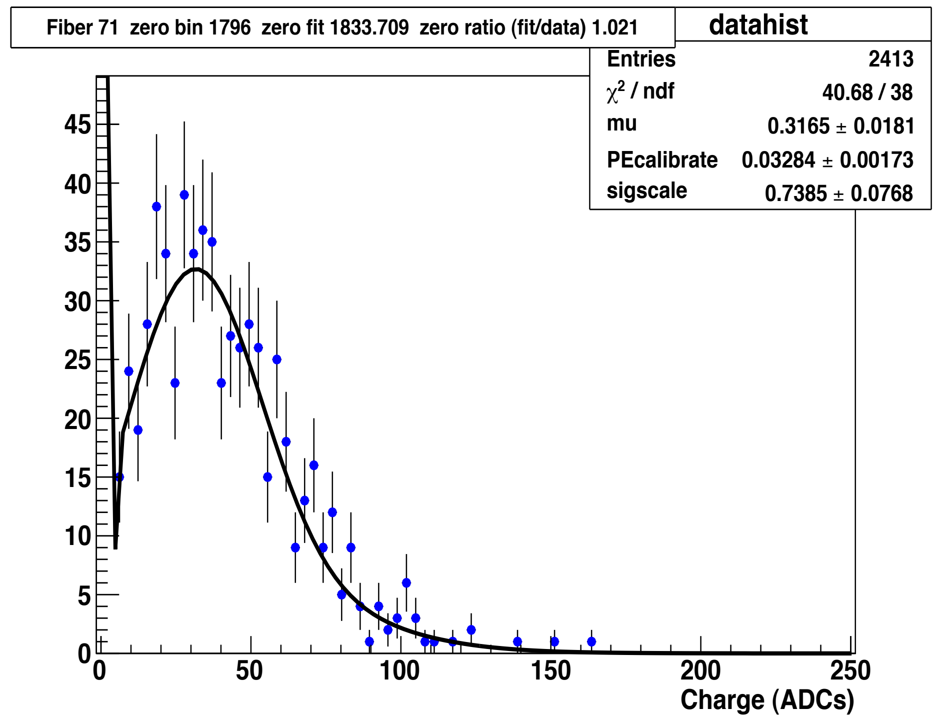
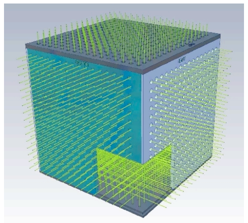
Single-PE LED Calibration

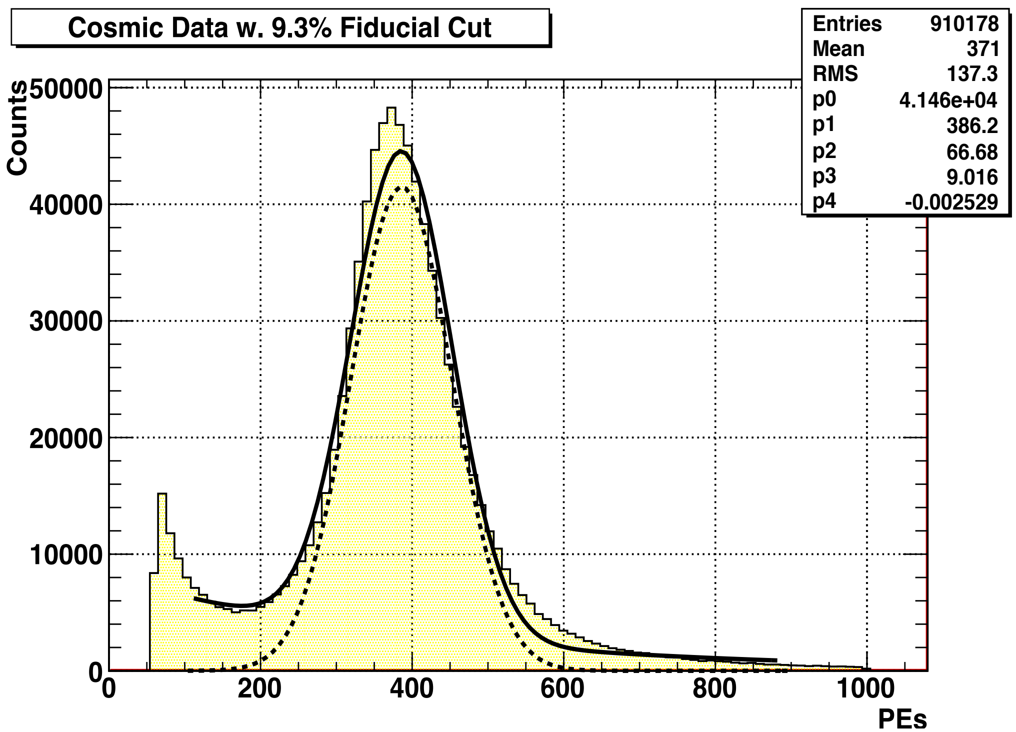


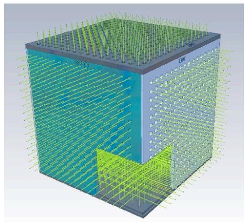


Cosmic Ray Calibrations

- Cosmic ray muons are minimum ionizing
- Deposits approximately 65 MeV at 390 PE peak
- 6 detected PE / MeV
- $n(p, d)\gamma$ 2.2 MeV gamma rays validate calibration
- Expanded calibration program soon …

MIP Cosmic Ray Calibration Peak

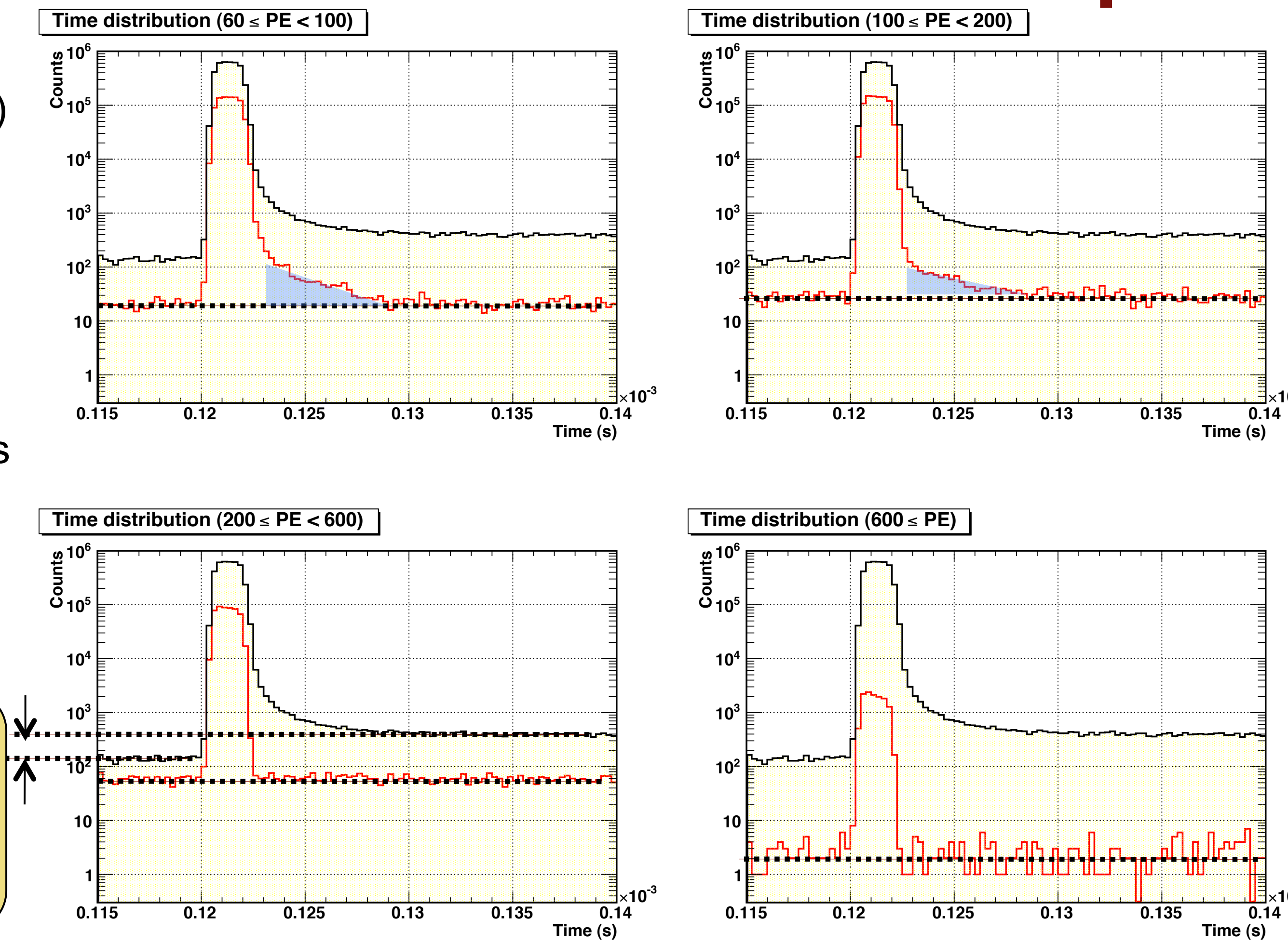


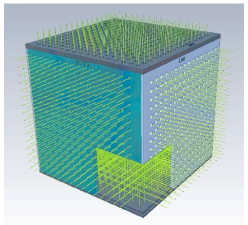


MI-12 Beam Time Per PE "Group"

- **BLACK** Traces (PE > 30)
- **RED** traces all return to pre-beam background levels within few μs
- 60 < PE < 200 (top plots) shows **EXCESS** to few μs
  PE > 200 (bottom plots) shows no excess
- Moderation in shielding?

Lifetime ≈ 200 μs.
From 2.2 MeV γ from
n(*p*, *d*)γ from neutron
captures in scintillator.





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Raw PE Spectrum In-Beam