# Far-off-axis neutrino source at Fermilab

**Jonghee Yoo**
**Fermilab**

**10 October 2012**
**Mini-workshop on Coherent-NCvAs**

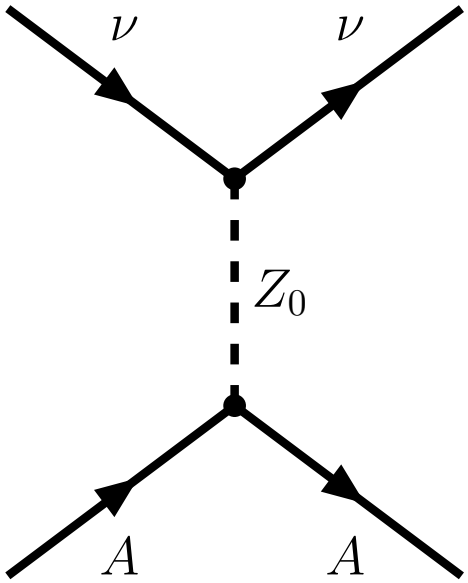
## Coherent-NCvAS has never been observed!

- Test Standard Model weak mixing angle ($\sin\theta_W$): K.Scholberg, PRD73 (2006)
- Non-standard interaction of neutrinos: J.Barranco et al, hep-ph/0702175
- Neutrino magnetic moment:
  - Conclusive measurement requires intensive neutrino flux (Project-X era)
- Neutron form factor from coherent-NCvAS: P.S.Amanik et al, hep-ph/0707.4191
- Important input to understand supernova explosion
- Oscillations to sterile neutrinos, Z', ….

→ **Neutrinos always provided us with the physics beyond the *then-Standard Model* !**

# Coherent-NCvAS

$$\mathcal{L}_{eff} = \frac{G_F}{\sqrt{2}} l^\mu j_\mu$$




**Cross section for zero-momentum transfer limit**

$$\sigma_{\nu N} \simeq \frac{4}{\pi} E_\nu^2 \left[ Z\omega_p + (A - Z)\omega_n \right]^2$$

$$g(Z_0 u) = \frac{1}{4} - \frac{2}{3}\sin^2\theta_W, \qquad g(Z_0 d) = -\frac{1}{4} + \frac{1}{3}\sin^2\theta_W$$

$$\omega_p = \frac{G_F}{4}(4\sin^2\theta_W - 1), \qquad \omega_n = \frac{G_F}{4}$$

**Differential cross section for finite momentum transfer**

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

# Requirements of the coherent-NCvAS

**For most of the detector target nucleus, the coherence condition is fulfilled by neutrino energy of**

$$E_\nu < \frac{1}{R_N} \simeq 50 \text{ MeV}$$

$$E_{max} \simeq \frac{2E_\nu^2}{M} \simeq \mathcal{O}(100) \text{ keV}$$

**Coherent-NCvAS cross section at these energy (~50MeV)**

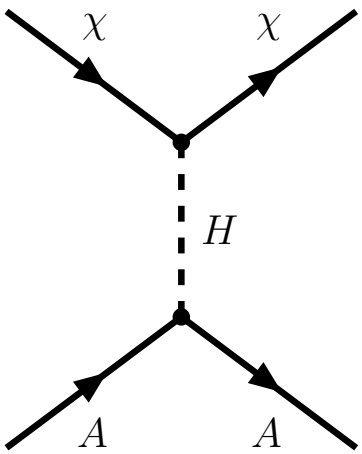
$$\sigma_{\nu N} \simeq 10^{-39} cm^2$$

cf) v-N charged current : $10^{-40}$cm$^2$
v-e elastic scattering : $10^{-43}$cm$^2$

**Requires a ton-scale detector with ~10 keV energy threshold**

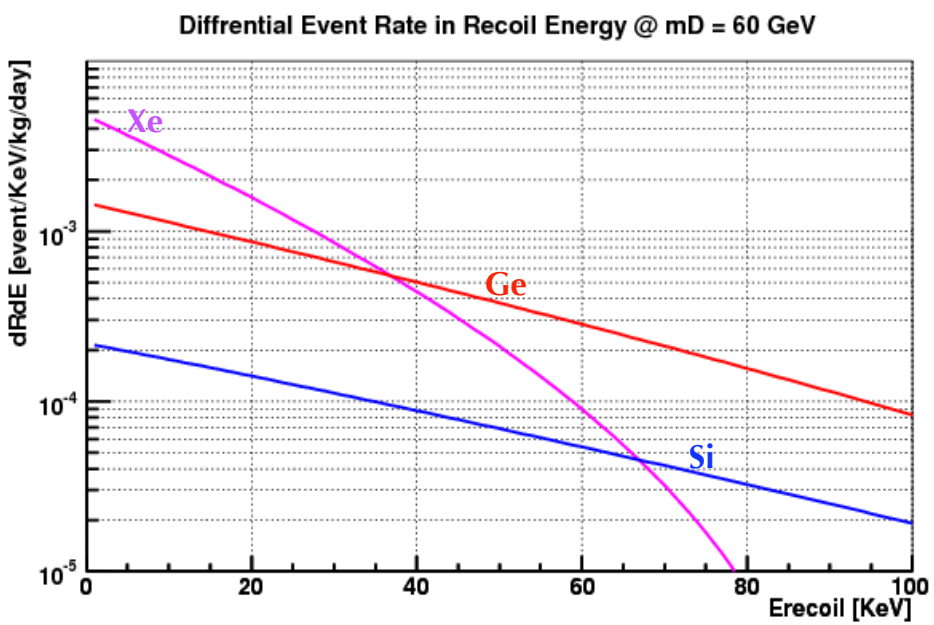
$$R \simeq \mathcal{O}(10^3) \left(\frac{\sigma}{10^{-39} cm^2}\right) \times \left(\frac{\Phi}{10^{13} \nu/year/cm^2}\right) \times \left(\frac{M}{ton}\right) events/year$$

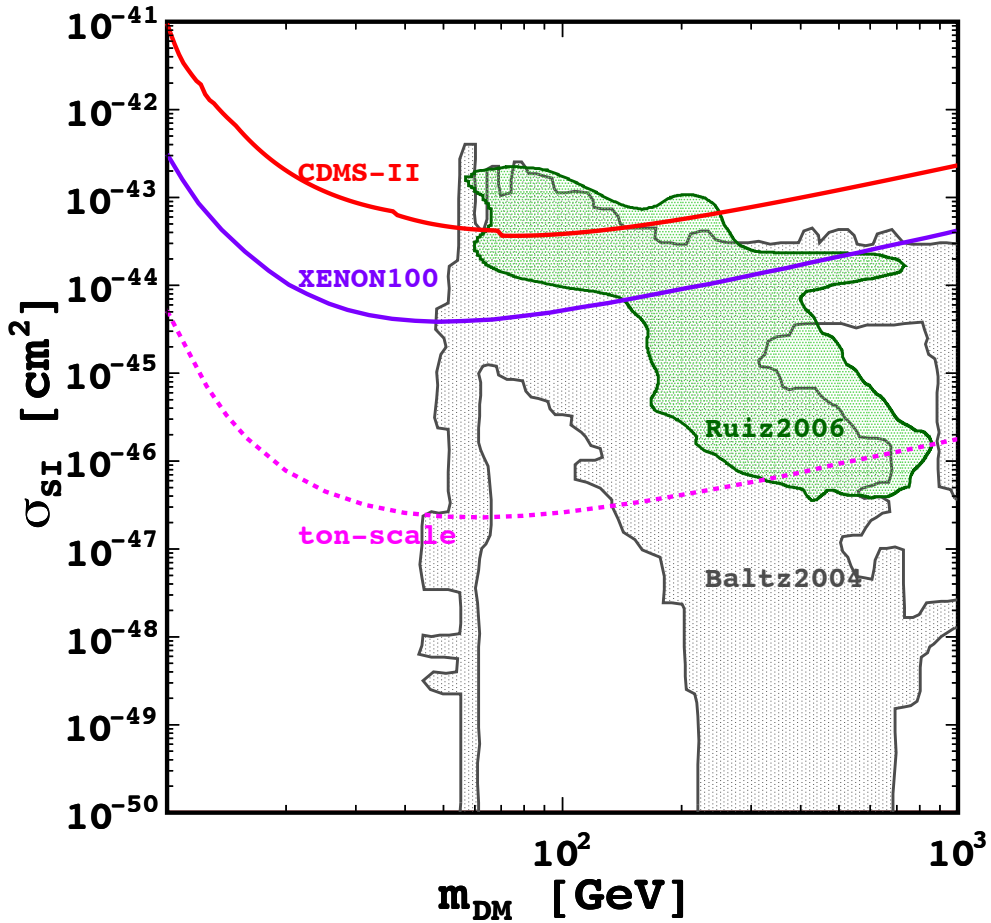
# Dark Matter Search




$$\sigma_{\chi N} \simeq \frac{4}{\pi}\mu^2[Zf_p + (A-Z)f_n]^2$$

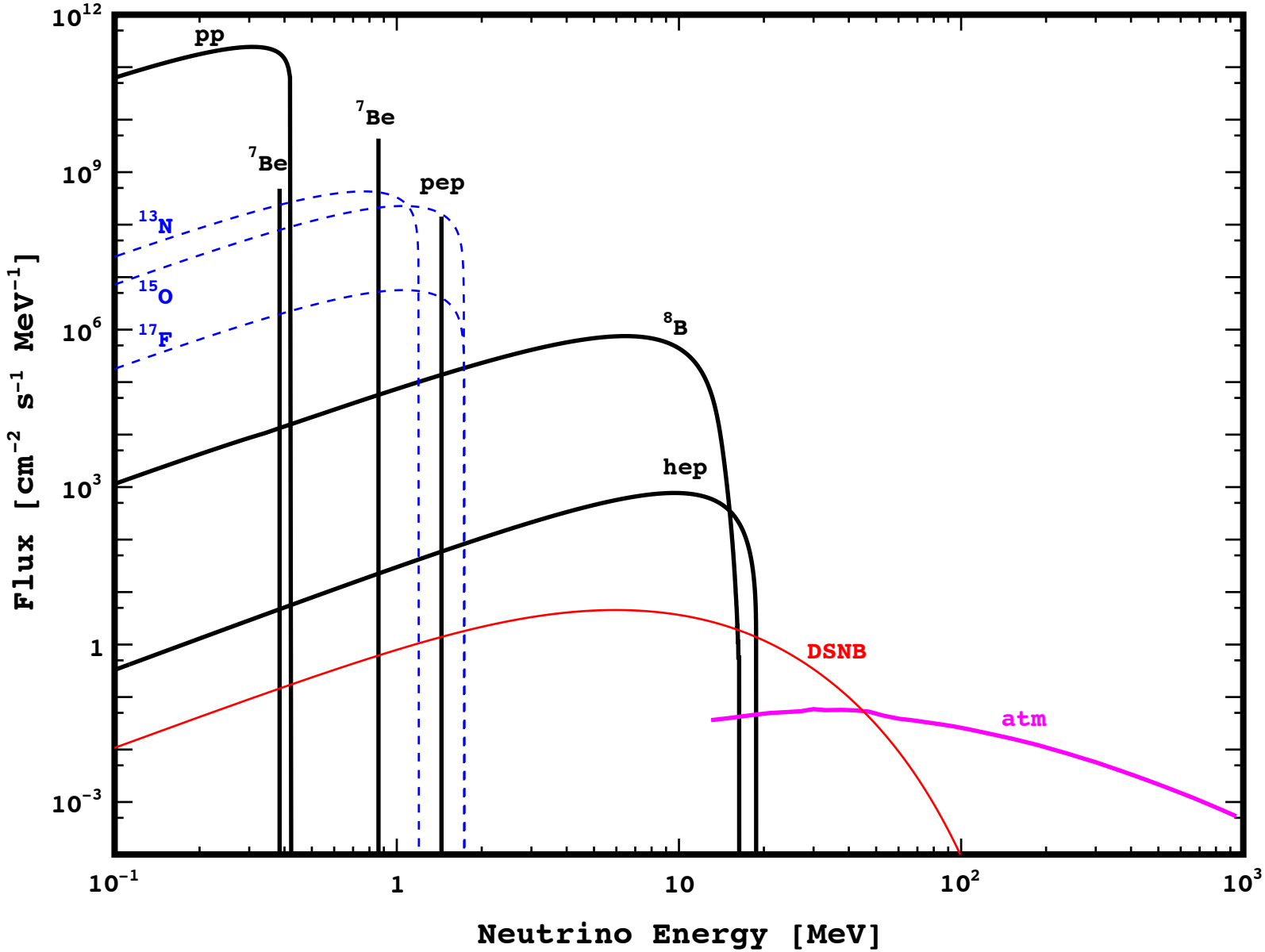
$$\frac{dR}{dE} = \frac{\sigma_0}{m_\chi}\frac{A^2}{2\mu_n^2}F_A^2(E) \times \rho_0 \int_{v_m} \frac{f(v)}{v}dv$$



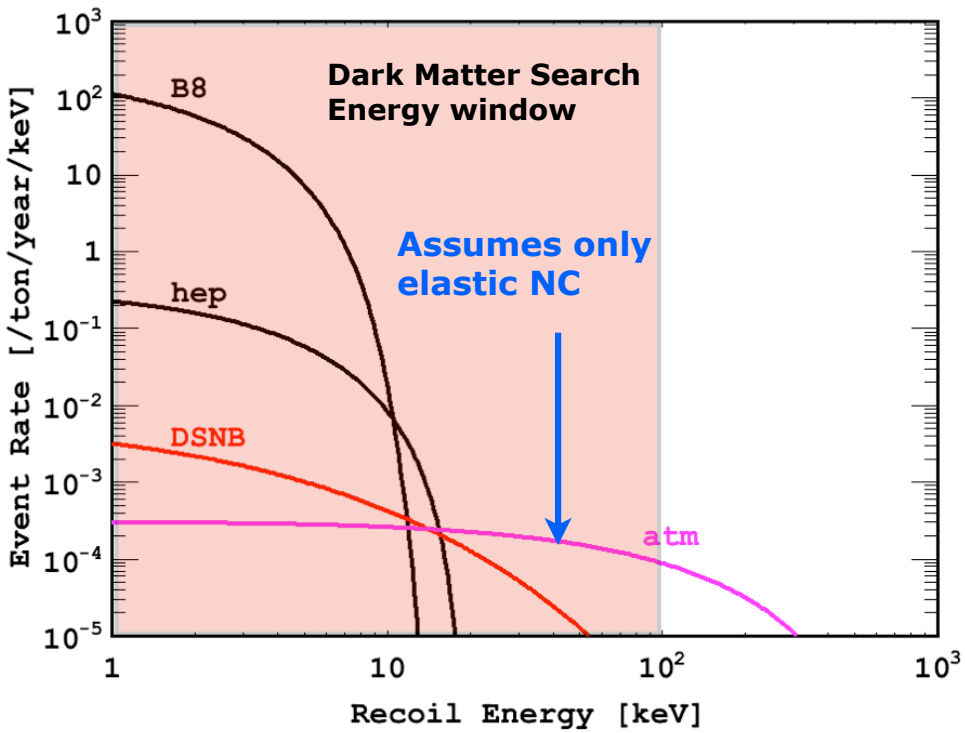



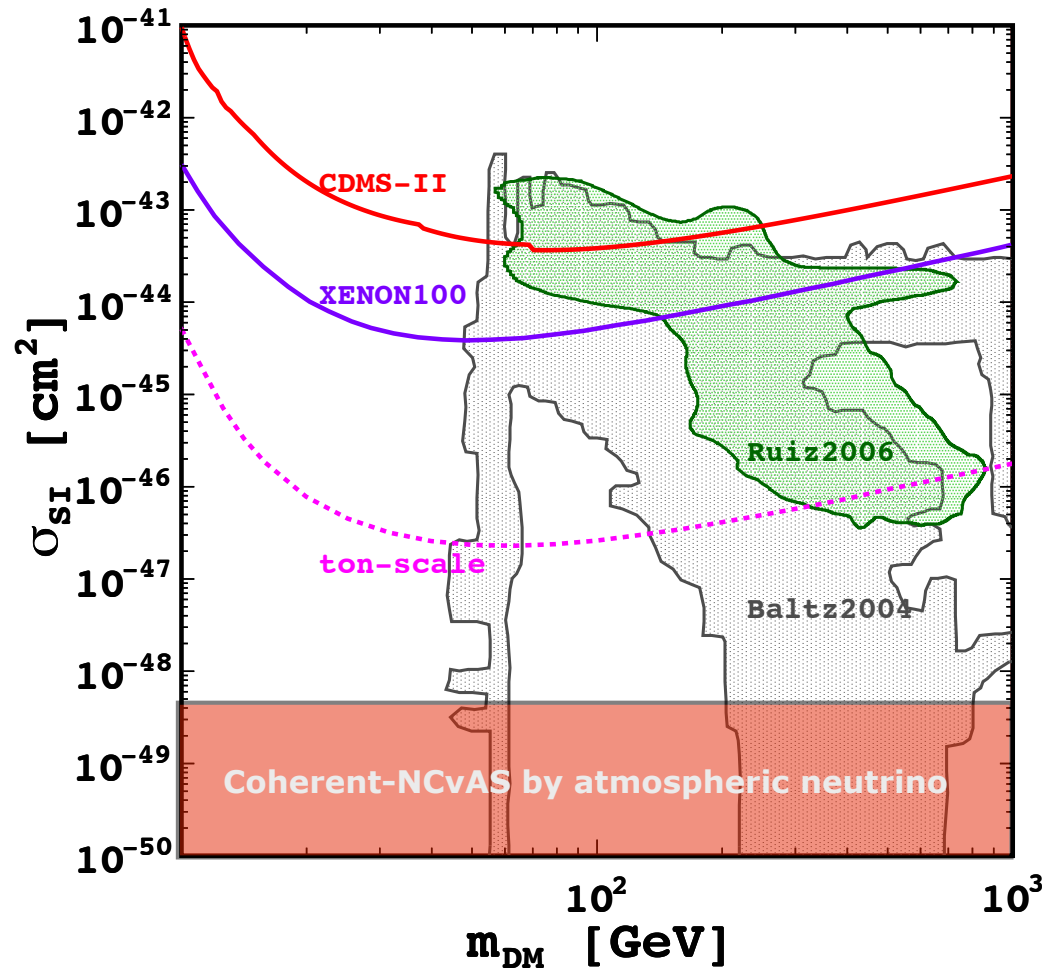
# Irreducible Backgrounds

## Neutrinos from astrophysical origin



# Irreducible Backgrounds



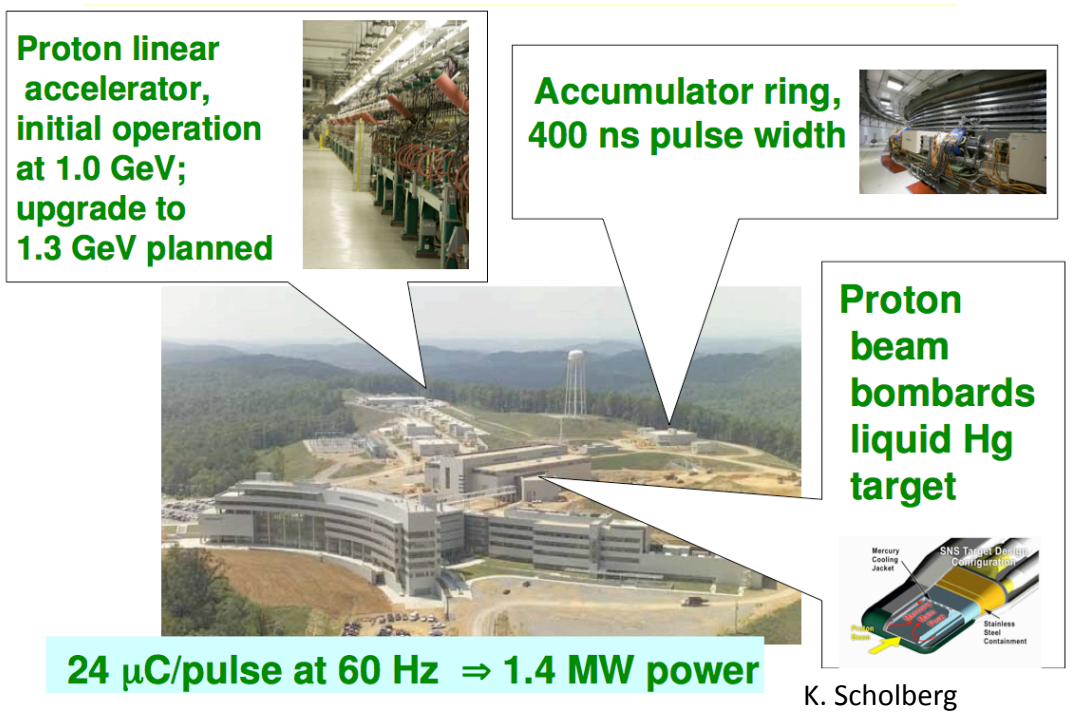

- Coherent scattering of atmospheric neutrino is an irreducible background in future *O*(10 ton) scale dark matter experiments (see Strigari, arXiv:0903.3630)

- What about the inelastic interaction tail by high energy neutrinos?

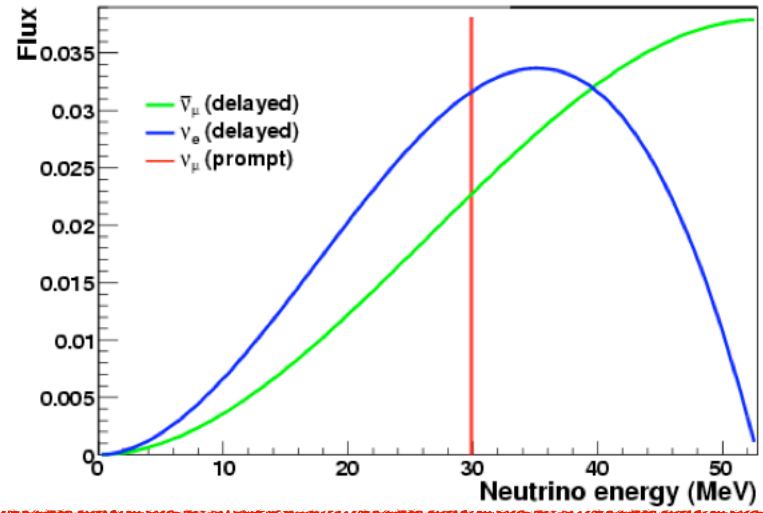
Sensitivity of dark matter detectors will be saturated out by irreducible neutrino backgrounds

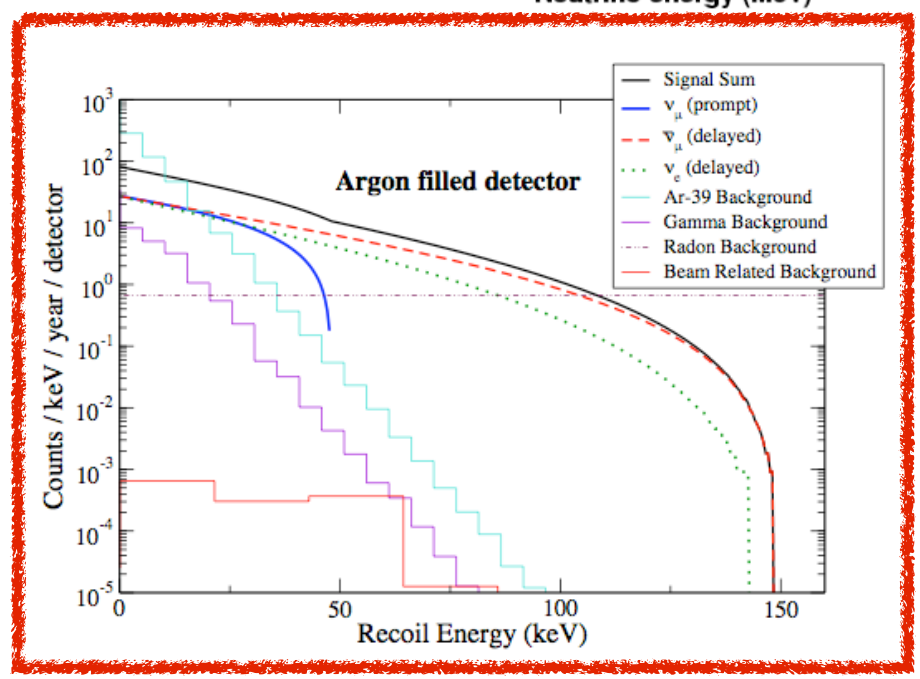
# Neutrino Source from Stopping Pions

- See **CLEAR** proposal : K. Scholberg *et al.*, hep-ex:0910.1989
- Spallation Neutron Source (SNS) at Oak Ridge National Lab
  F. Avignone and Y. Efremenko, J. Phys. G, 29 (2003) 2615-2628



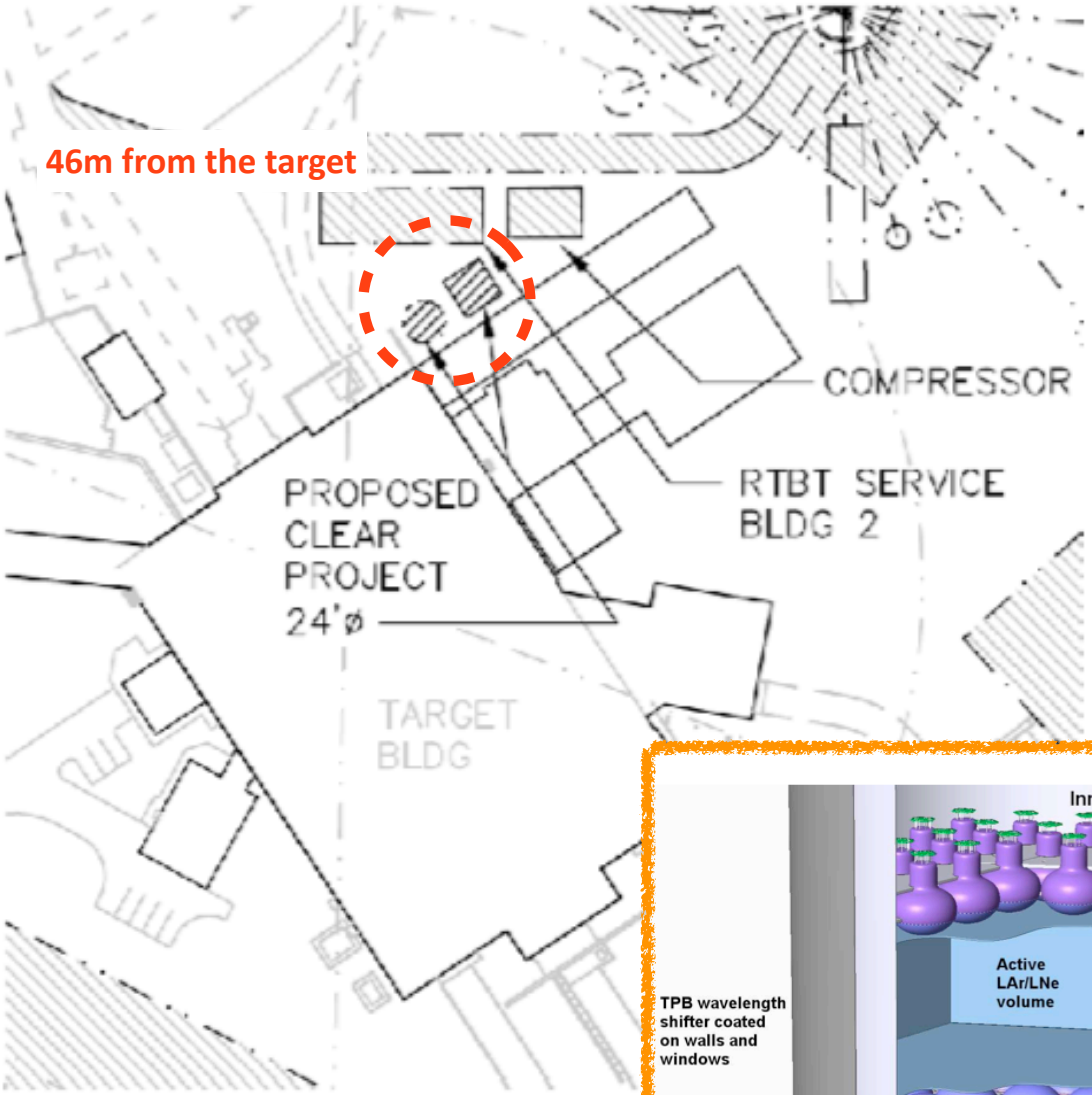

K. Scholberg

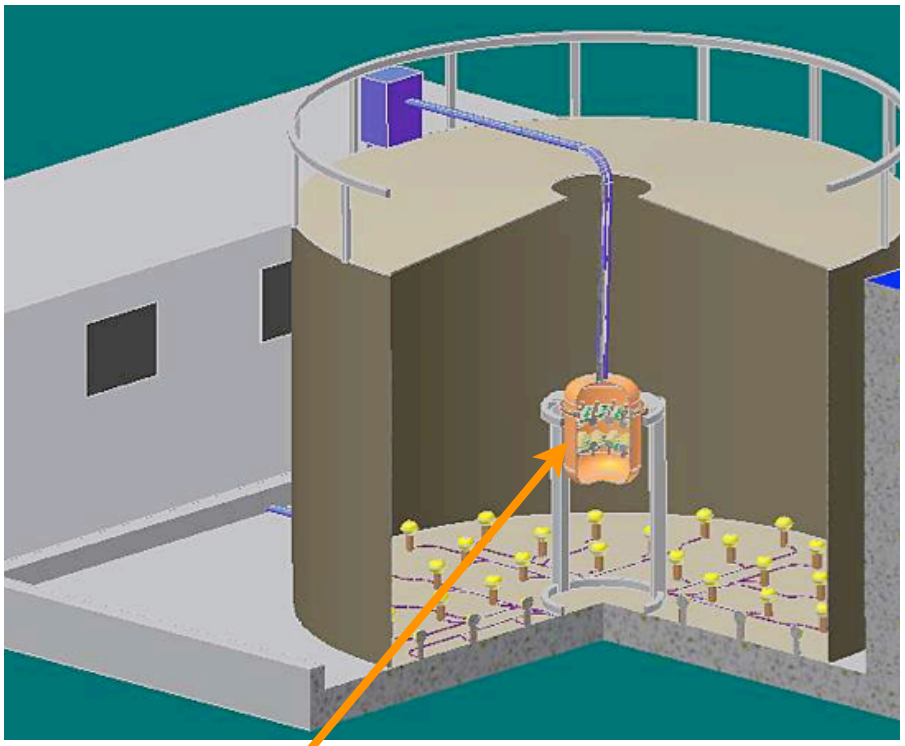


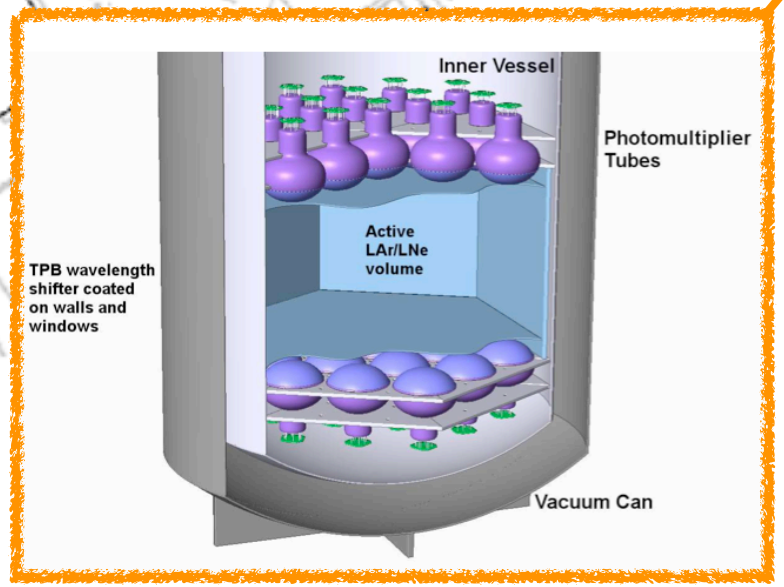




- Flux ~ $10^7$/sec/cm$^2$ at 20m from the target
- 60 Hz pulsed source
- Steady state background rejection factor ~$10^{-4}$
- Expected event rate in a single-phase 500kg LAr detector: ~890 events/year of detection ($E_{th}$>20 keV) at the proposed experiment site (46m from SNS target)

# CLEAR proposal



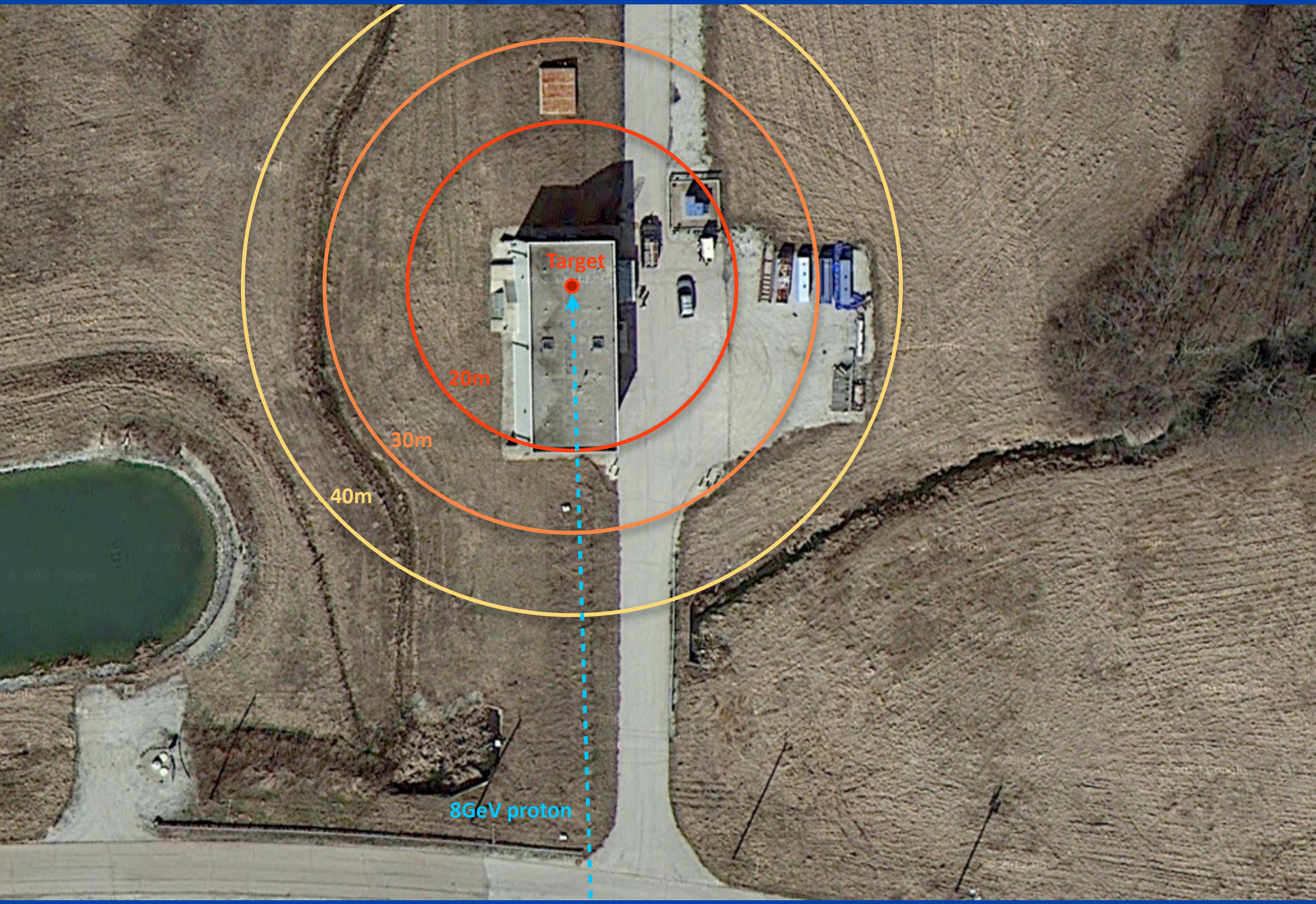






~0.5 ton of single phase ultra-sensitive LAr/LNe detector

# Neutrinos at Fermilab

# MI-12 Target Building Area

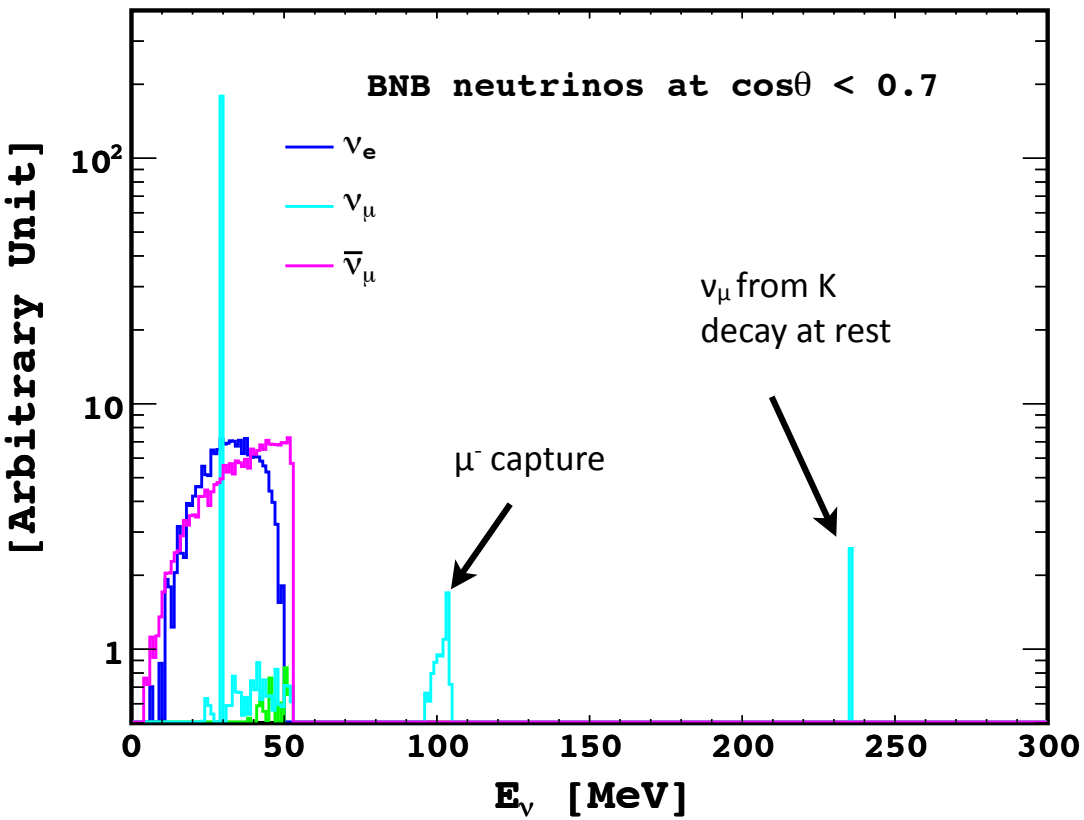


# Far-Off-aXis (FOX) Neutrinos at BNB

**Beam MC Configuration**

- Use standard Booster Beam MC
  - release stopping pion cuts in the original MC
- 8 GeV, 5Hz $5\times10^{12}$ Protons on Beryllium target
  - 32 kW max power
- 173 kA horn current neutrino mode

From Booster Beam MC (S.Brice)

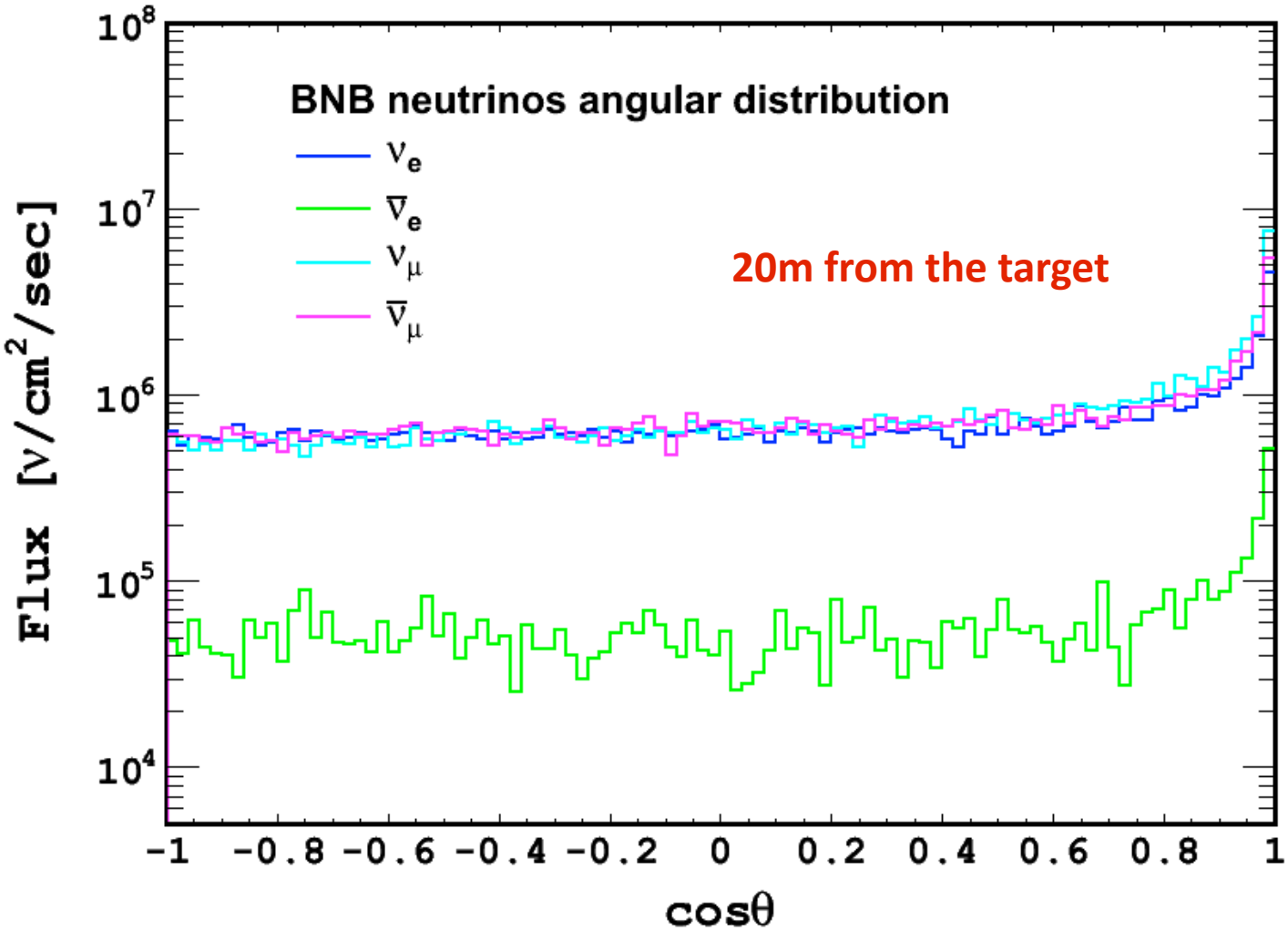



arXiv:0806.1449

| Particle | Lifetime (ns) | Decay mode | Branching ratio (%) |
|---|---|---|---|
| $\pi^+$ | 26.03 | $\mu^+ + \nu_\mu$ | 99.9877 |
| | | $e^+ + \nu_e$ | 0.0123 |
| $K^+$ | 12.385 | $\mu^+ + \nu_\mu$ | 63.44 |
| | | $\pi^0 + e^+ + \nu_e$ | 4.98 |
| | | $\pi^0 + \mu^+ + \nu_\mu$ | 3.32 |
| $K_L^0$ | 51.6 | $\pi^- + e^+ + \nu_e$ | 20.333 |
| | | $\pi^+ + e^- + \bar{\nu}_e$ | 20.197 |
| | | $\pi^- + \mu^+ + \nu_\mu$ | 13.551 |
| | | $\pi^+ + \mu^- + \bar{\nu}_\mu$ | 13.469 |
| $\mu^+$ | 2197.03 | $e^+ + \nu_e + \bar{\nu}_\mu$ | 100.0 |

Dominant neutrino production process at the Far-Off-aXis is pion decay at rest

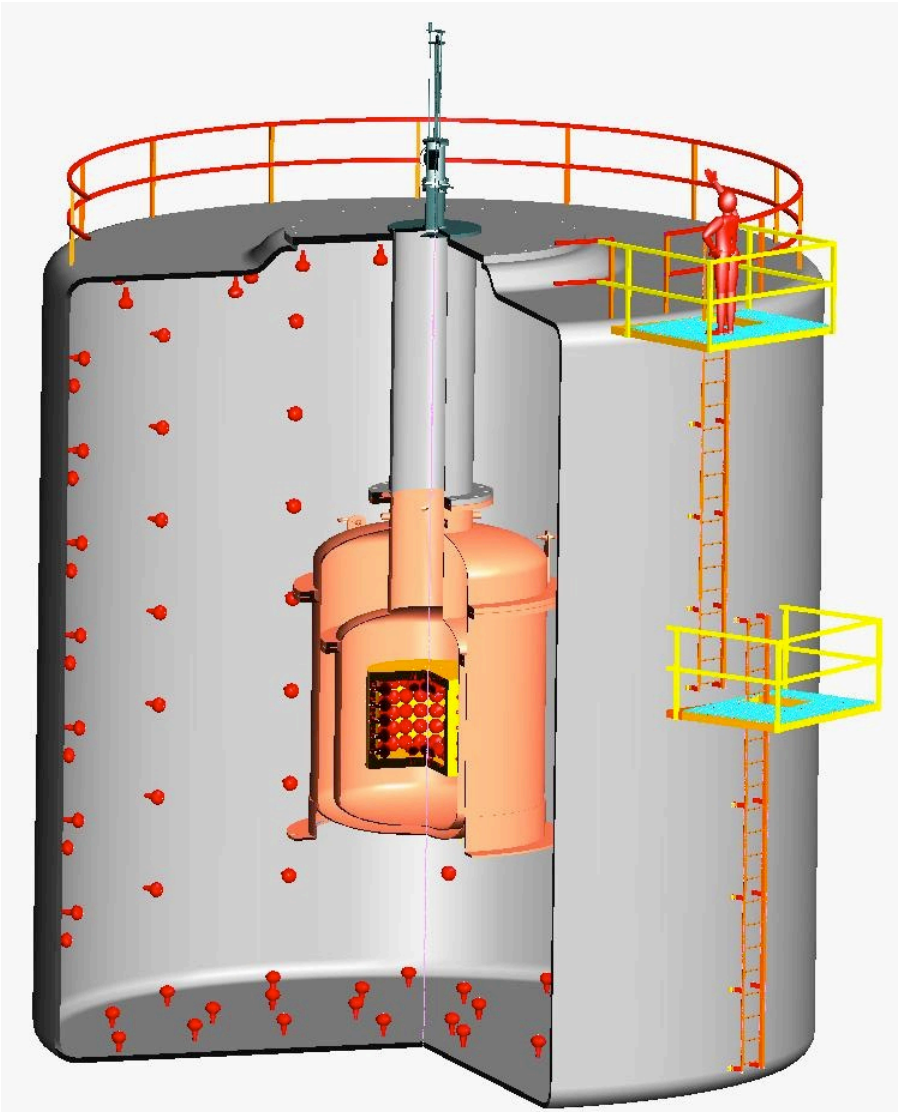
# Far-Off-aXis (FOX) Neutrinos at BNB




- **$\phi \cong$ 5x10$^5$ ν/cm$^2$/s @20m (cosθ<0.5)** (cf. $\phi$(SNS)$\cong 10^7$ν/cm$^2$/s@20m, **1x10$^6$ν/cm$^2$/s @60m**)
- Systematic uncertainties of the neutrino flux estimation should be checked in detail

# Low Energy Threshold LAr Neutrino Detector

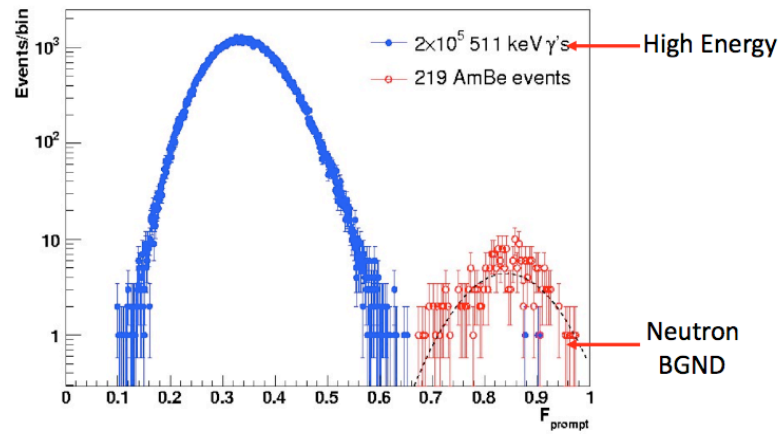
A ton-scale single phase LAr detector may perform the first ever observation of the coherent-NCvAS at Fermilab



DEAP-0 Results & Projections for PSD in LAr

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

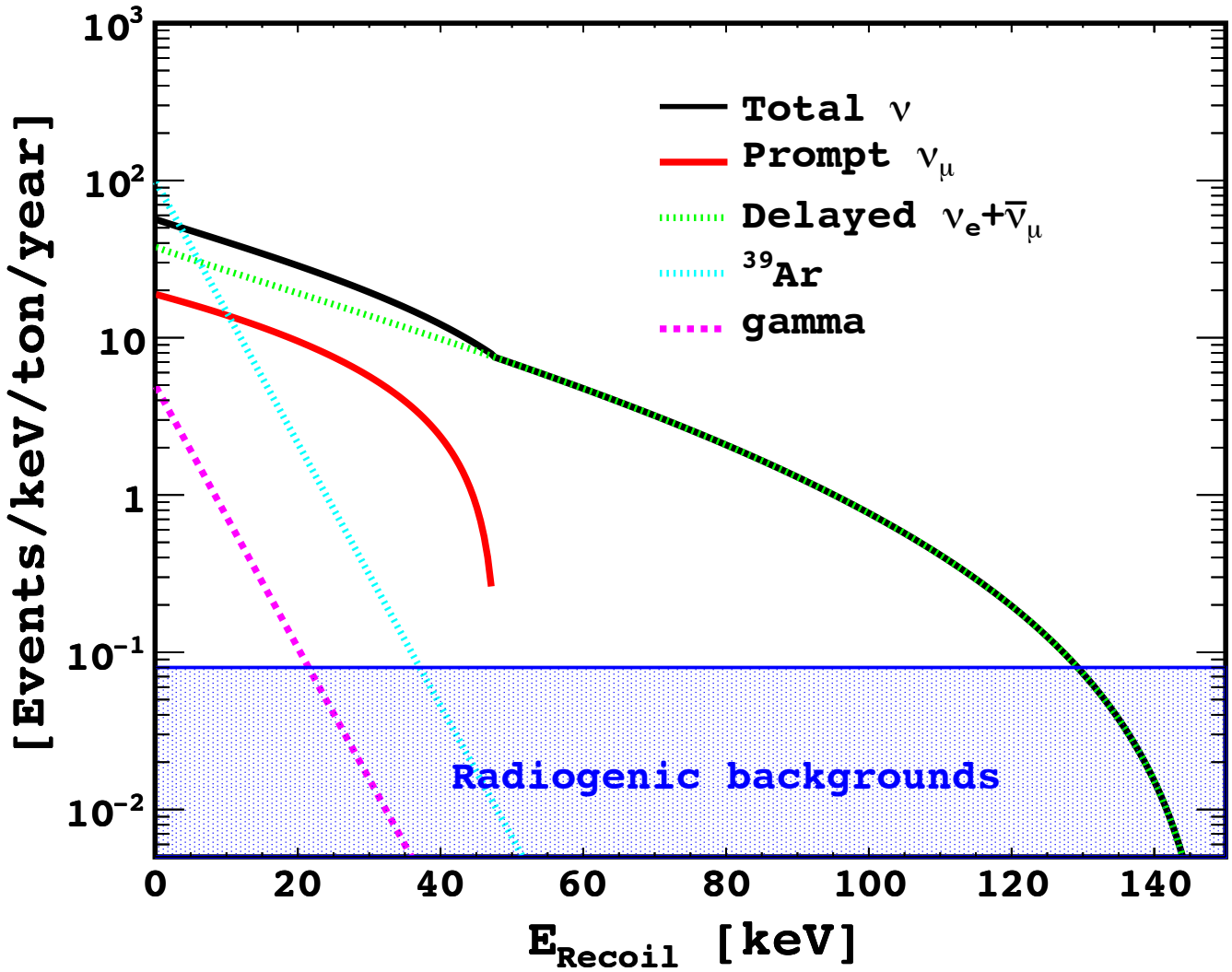
10 $keV_{ee}$ with 5 p.e./keV




**A. Hime**

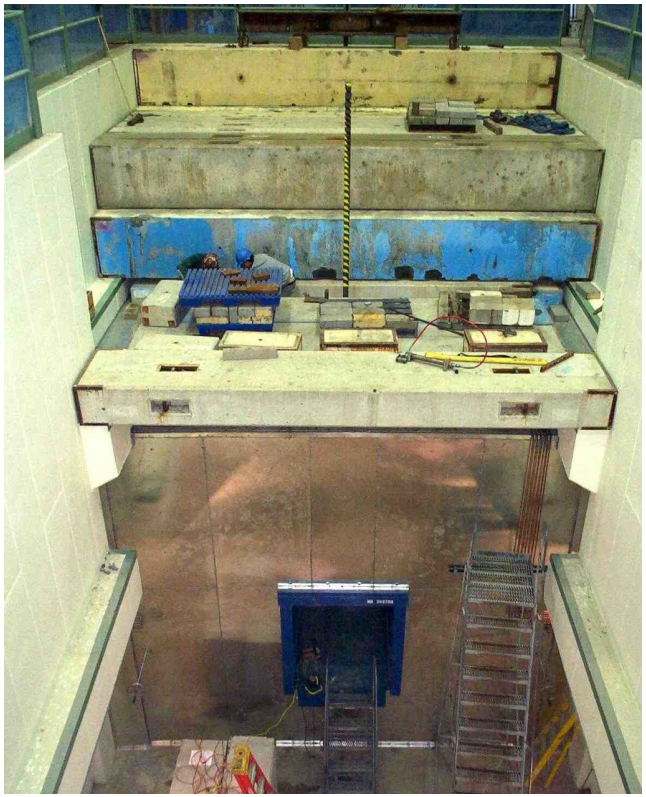
- Well known detector technology (DEAP/CLEAN)
- Use pulse shape discrimination of nuclear recoil (fast) and electron recoil (slow) signal in LAr (see Boulay and Hime: astro-ph/0411358)
- Long live ($\tau$ = 269yr) $^{39}$Ar beta decay (1kBq/ton) wouldn't be a serious issue due to duty factor of pulsed beam & Pulse Shape Discrimination (PSD)

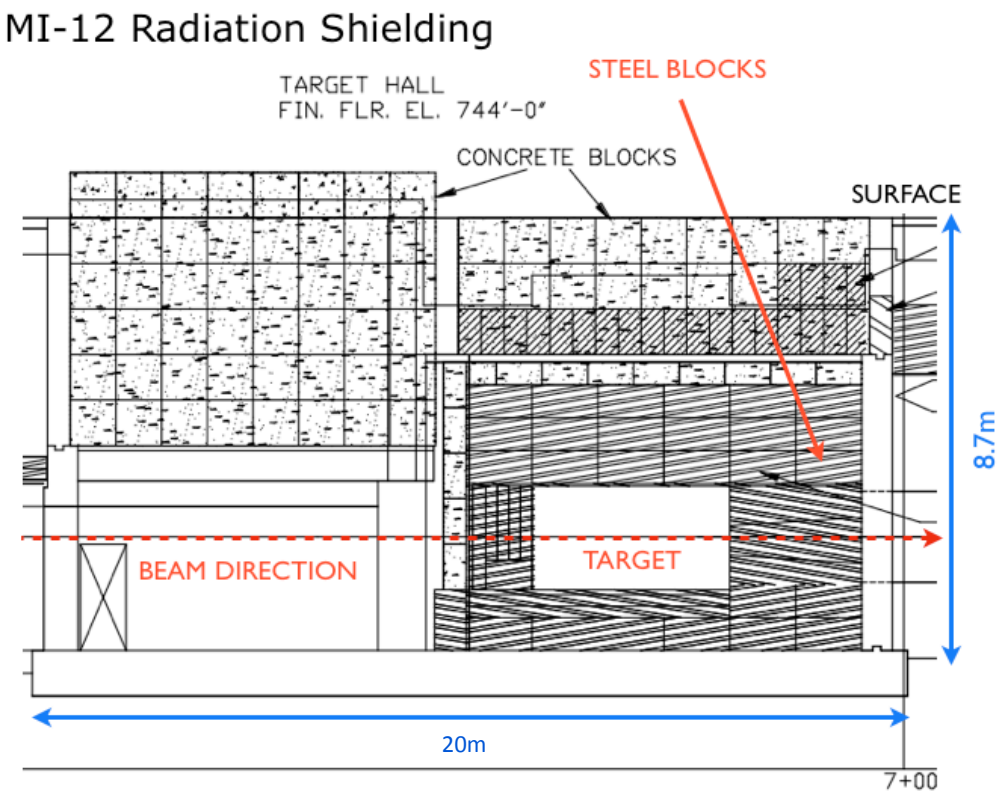
# Expected Coherent-NCvAS Event Rates at FOX




- 20m from the target ($\phi \cong 5\times10^5$ v/cm$^2$/s)
- Steady state background rejection factor ~$10^{-5}$ (Total exposure: ~300 sec/year)
- Expected event rate in a single-phase 1-ton LAr detector: ~200evt/year ($E_{th}$> 30 keV @32kW)
- **Beam-induced neutron backgrounds ?**

# BNB Target Radiation Shielding

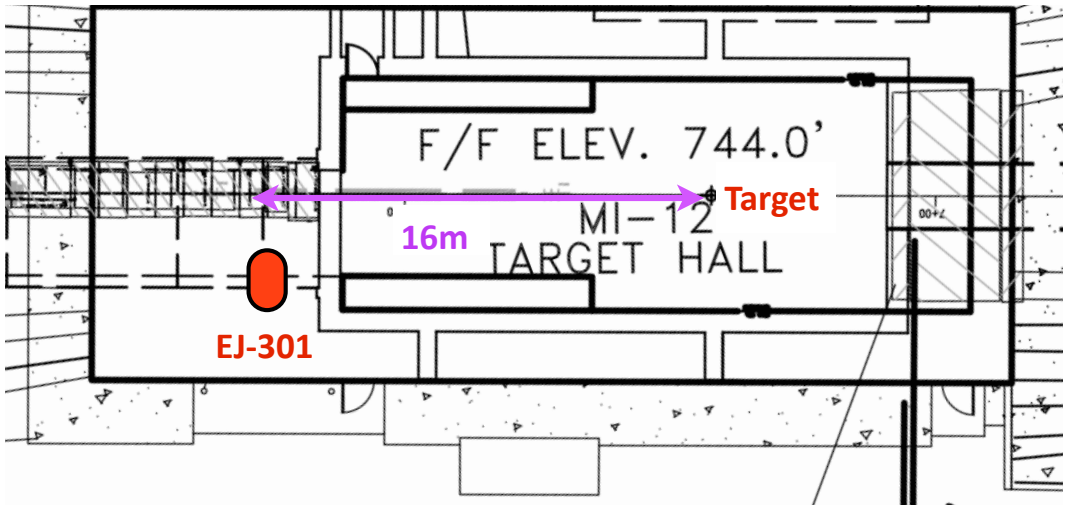


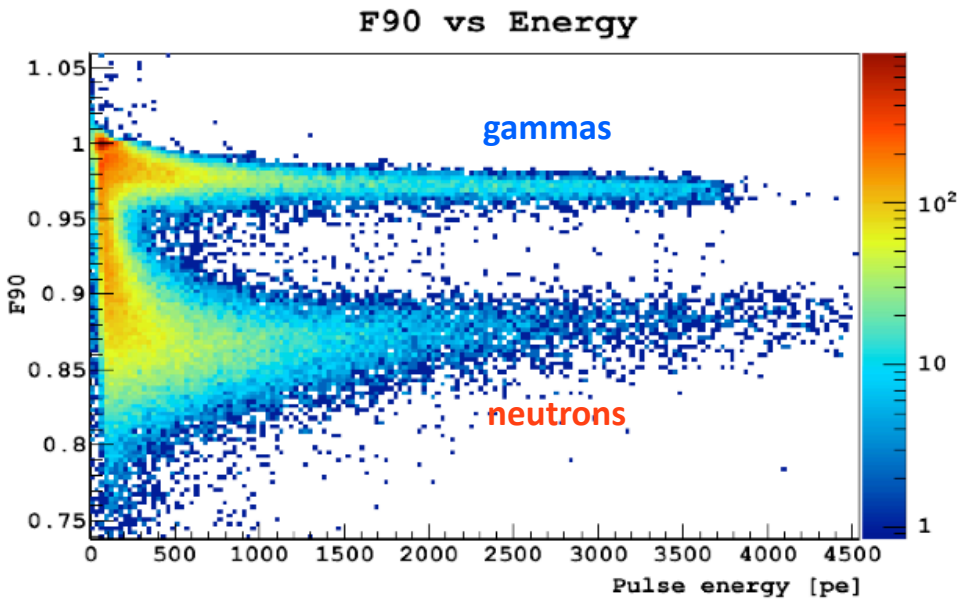



- Target is located 6.4m underground from the building surface
  - 2.6m-thick iron shielding blocks
  - 2.5m-thick concrete shielding blocks
- Neutron yield/pulse: $N_n$=($5\times10^{12}$ pot/pulse) × (30 neutrons/proton)=$1.5\times10^{14}$ neutrons/pulse
  - $\phi_n$(@surface;R=640cm w/ iron & concrete shielding) = ~102 neutrons/pulse/$m^2$
  - For 5"D×5"H neutron detector : Rate = 1.3 neutron pass/pulse
  - → **This is far from the accurate estimation**
- **Best way to figure out the backgrounds at the target building is to measure them**

# Beam-induced Background Survey (March~April 2012)

## MI-12 (TOP VIEW)




## EJ-301 Commercial Liquid Scintillator at MI-12 surface

- No (or rare, if any) beam-induced muons
- Gammas are easy to shield (lead blocks)
- Neutron shielding wasn't easy

→ **see B.Loer's talk in this workshop**

# SciBath-768 Neutral Particle Detector

**Initial Survey : Feb 2012**

- Commercial 5"D EJ-301 neutron detector
- Establish logistics of data taking procedure at the target building
- Measure beam induced event rate

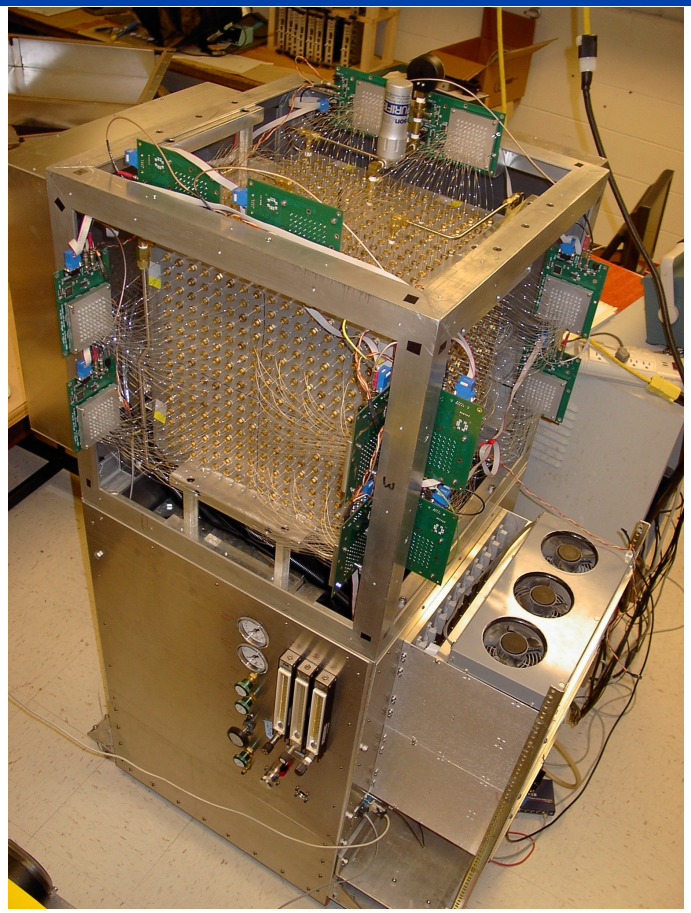
**SciBath (Indiana University)**

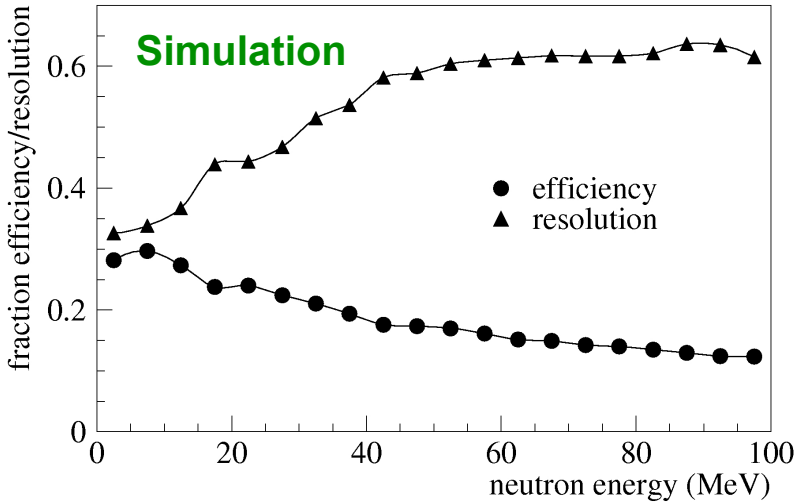
- $(45cm)^3$ volume containing
- 82 liters (70kg) of liquid scintillator: mineral oil, 11% pseudocumene, + PPO
- 3 16x16 grids, in x,y,z (768 total), 2.5cm spacing, 1.5mm wavelength-shifting (WLS) fibers (UV->blue)
- coupled to clear plastic fibers, routed to readout:
- 12 Hamamatsu 64-anode PMTs
- custom-built readout system

**Goal**

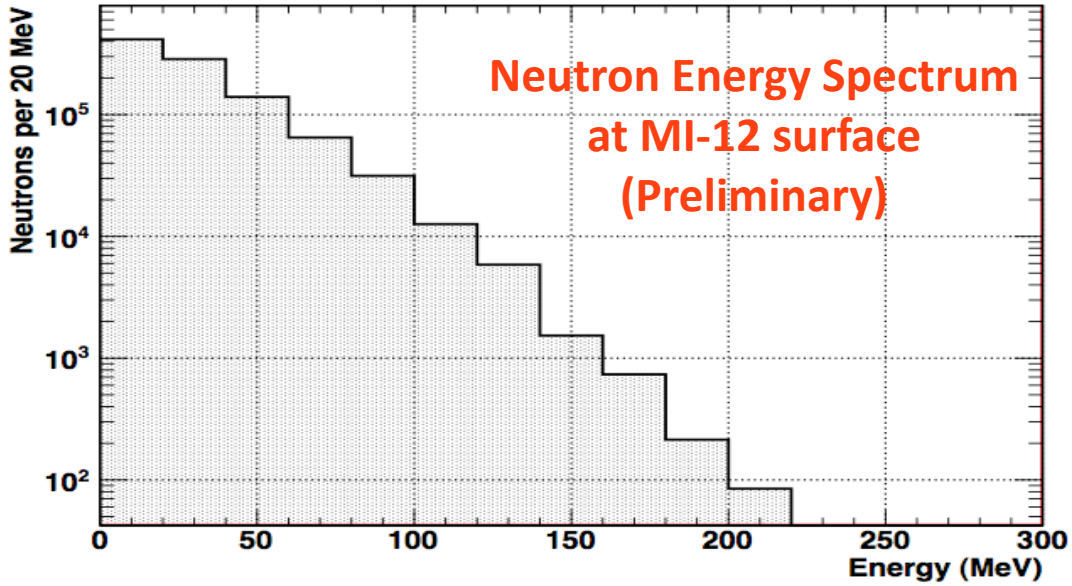
- Beam induced neutron background measurement
- Measure energy spectrum of the neutrons
- cosmic-induced fast neutron flux measurement

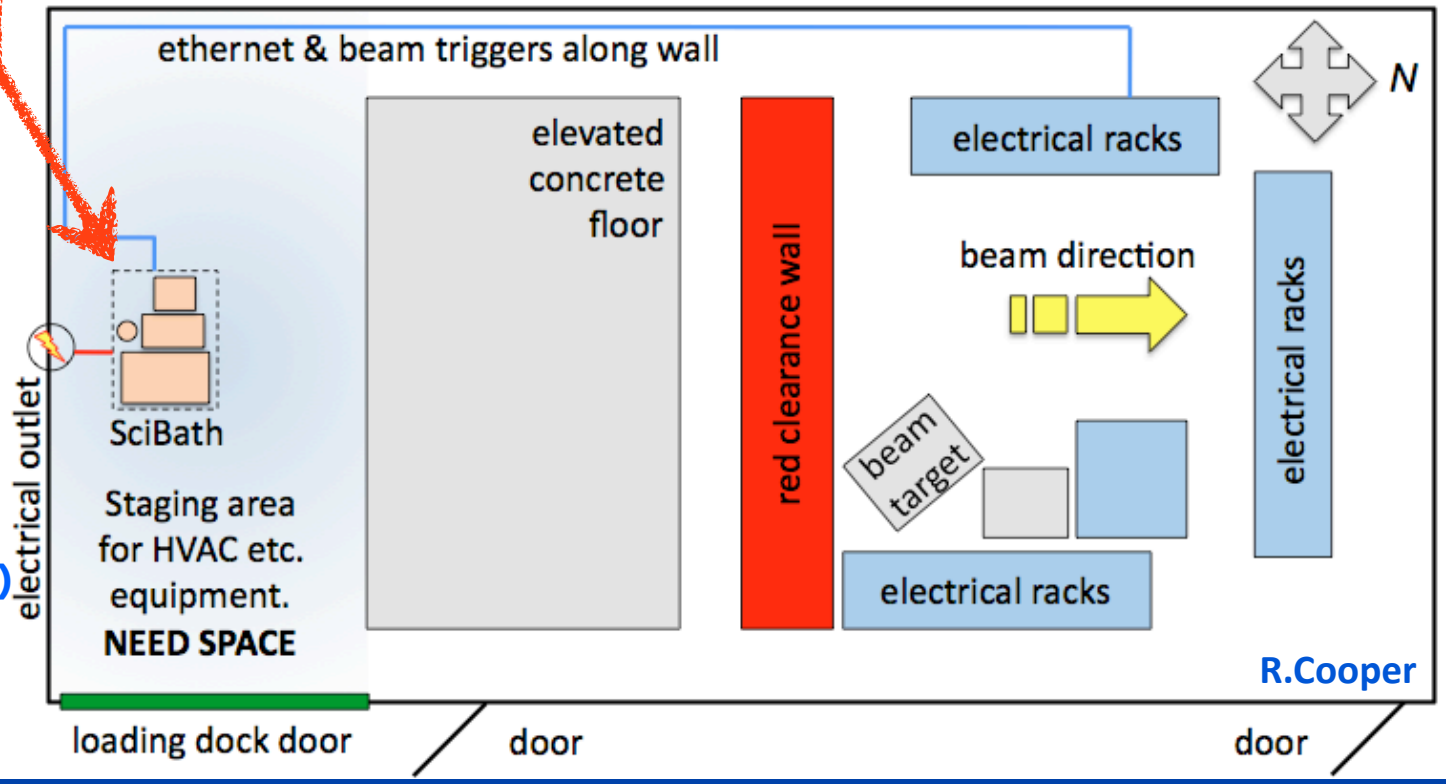
→ See R. Cooper's talk in this workshop





# SciBath at BNB Target Building (March~April 2012)

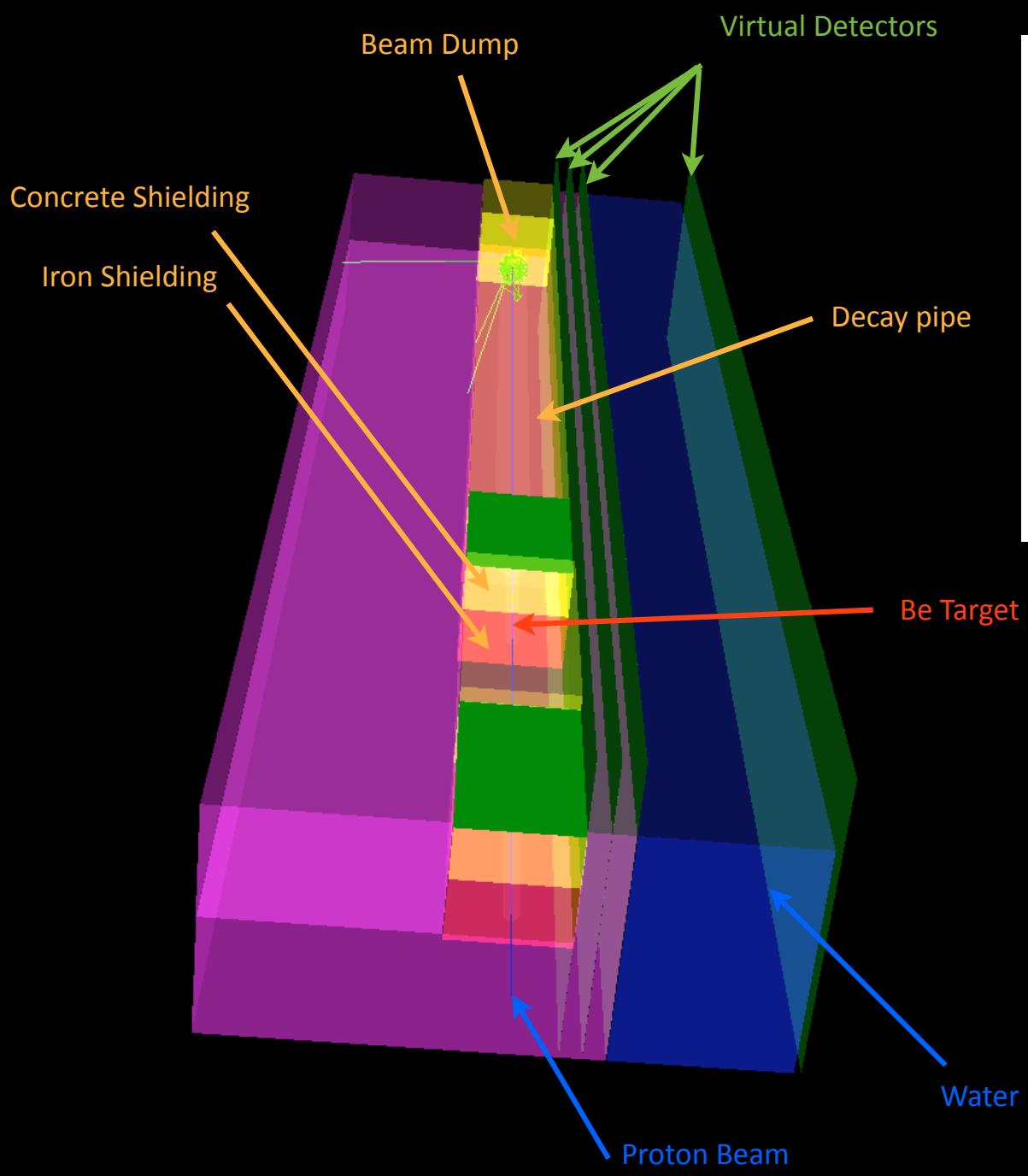


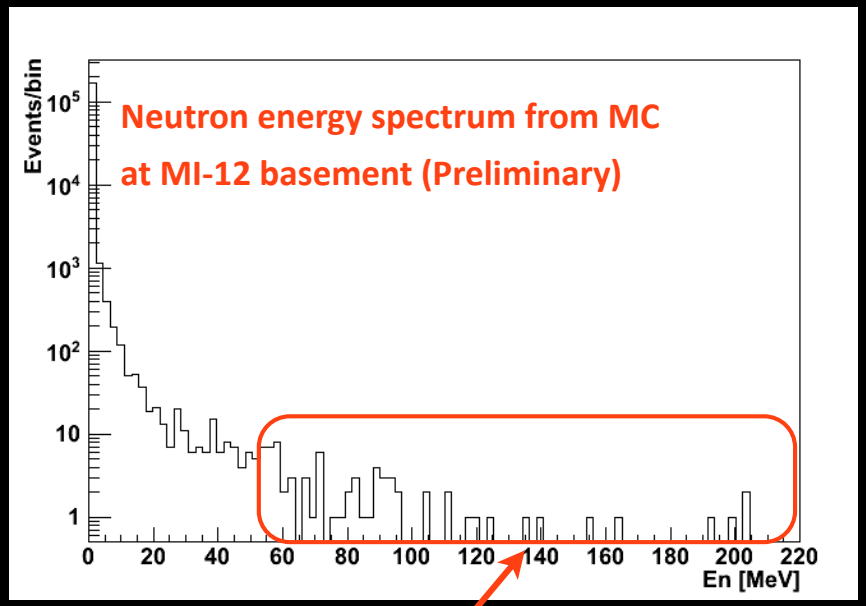




- **Pre-beam, in-beam, off-beam backgrounds measurements**
- **Data taking completed**
  29 Feb ~ 23 Apr 2012
  Scheduled beam shutdown
- **Neutron spectrum measurement (preliminary)**

→ **See R. Cooper's talk in this workshop**

# Beam Background Simulation (in progress)




These fast neutrons are notorious ones

**Experiment doesn't have to be zero BG**
- **trade offs between neutrino flux, background rate and live time**

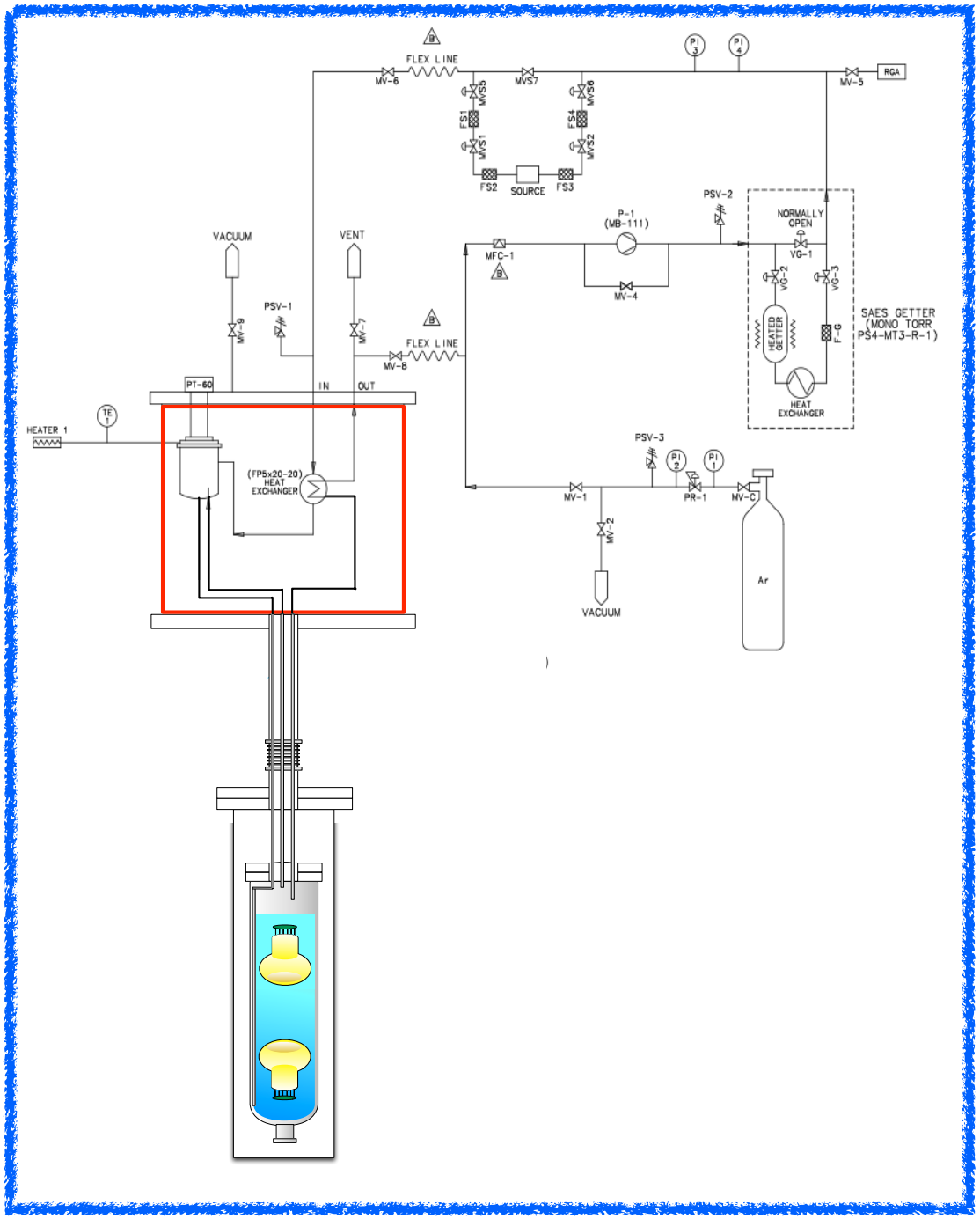
**Advice from U.Tennessee colleagues**
- **at least ~10m of shielding needed**
- **often counterintuitive**
- **need for different layers (steel, concrete, water, poly …)**
- **GEANT gives OK first approximation**

# Neutron Background and Shielding Study Plan

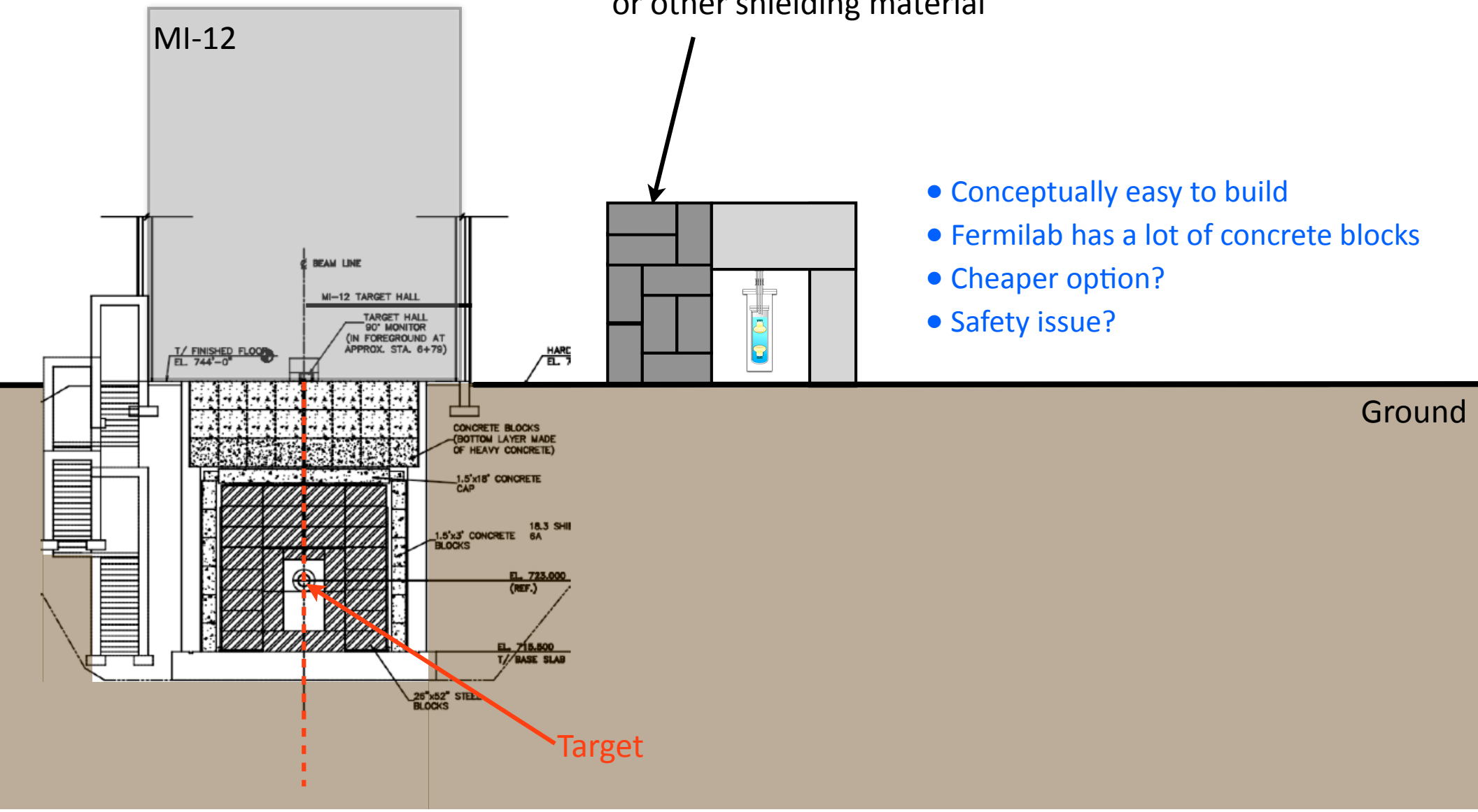
## 10-kg prototype detector

- Goals:
  - Neutron background study
  - Demonstrate detector capability
- Existing cryostat and gas handling system from 1-kg prototype
- Parts are ordered and/or purchased
- Initial phase will use two R5912-02MOD 8” PMTs (Hamamatsu)
- To be ready in early 2013

→ See Ben Loer’s talk in this workshop

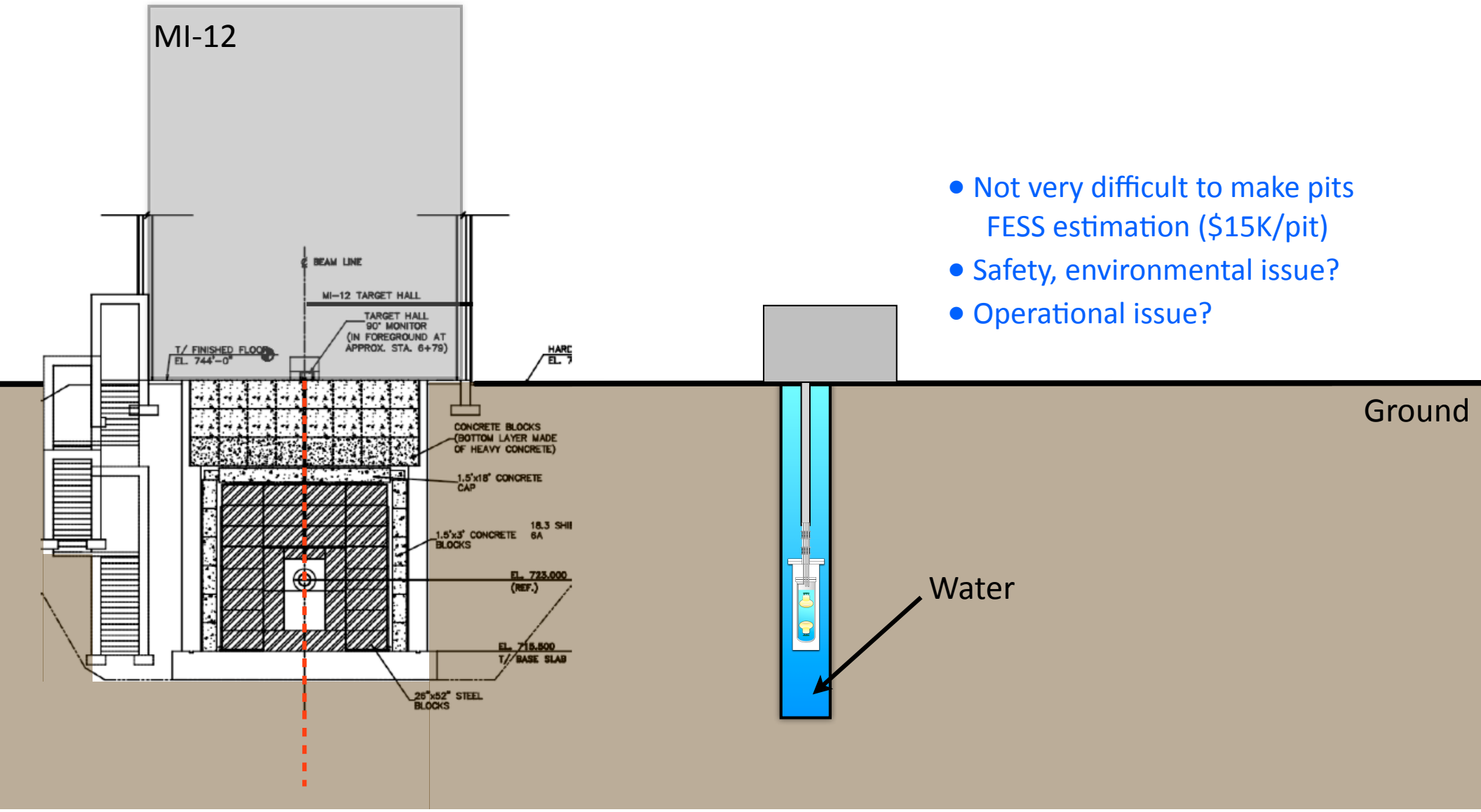


# Neutron Shielding Test Option 1



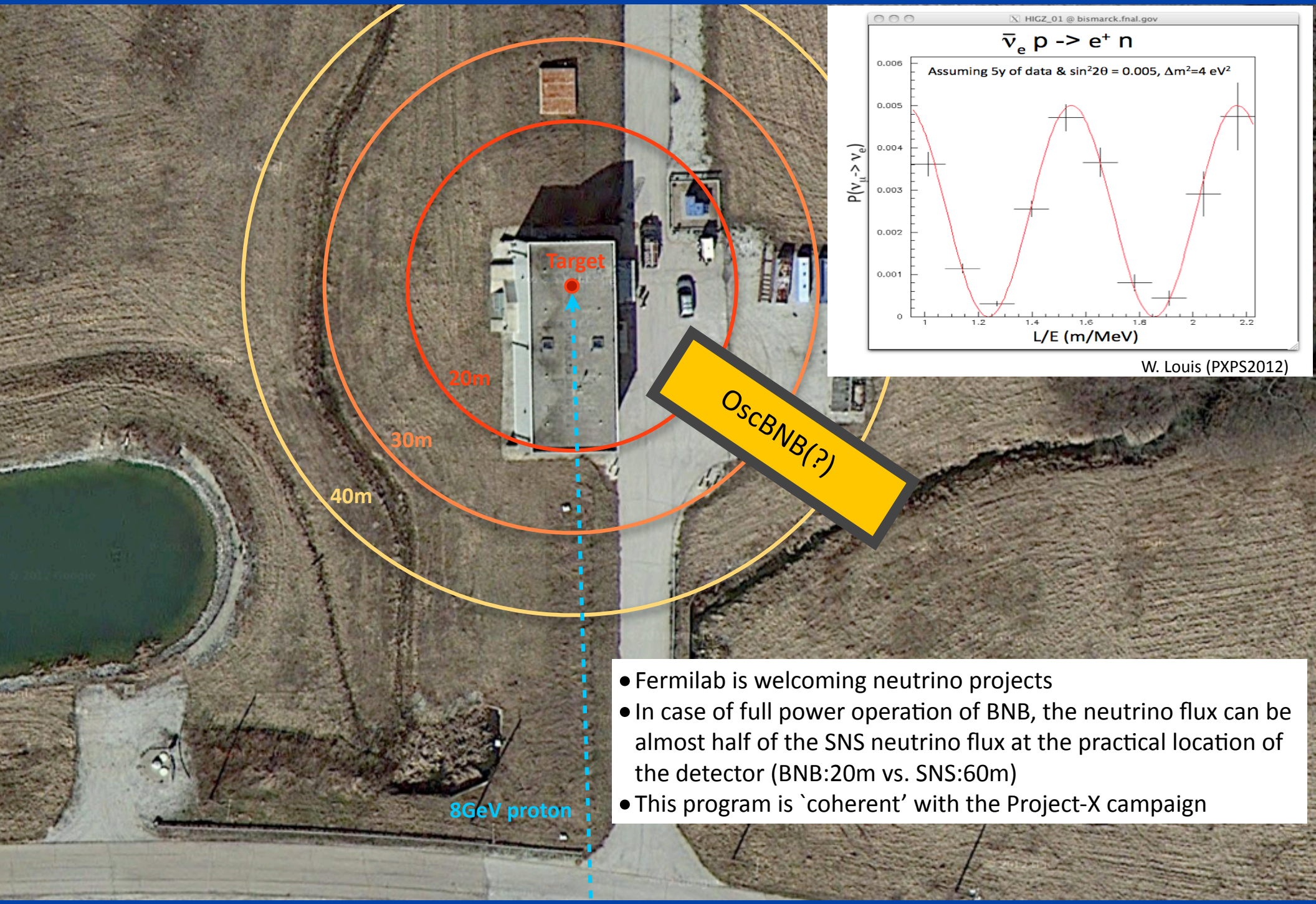

- Conceptually easy to build
- Fermilab has a lot of concrete blocks
- Cheaper option?
- Safety issue?

# Neutron Shielding Test Option 2




- Not very difficult to make pits
  FESS estimation ($15K/pit)
- Safety, environmental issue?
- Operational issue?

# OscBNB?







W. Louis (PXPS2012)

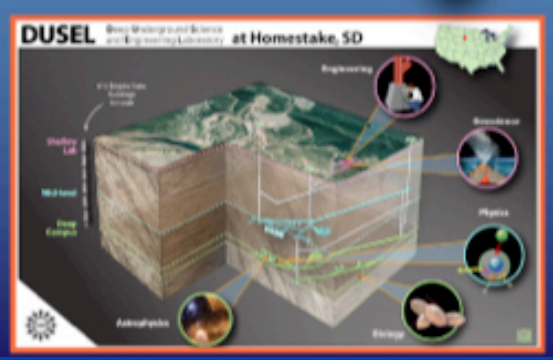
- Fermilab is welcoming neutrino projects
- In case of full power operation of BNB, the neutrino flux can be almost half of the SNS neutrino flux at the practical location of the detector (BNB:20m vs. SNS:60m)
- This program is `coherent' with the Project-X campaign

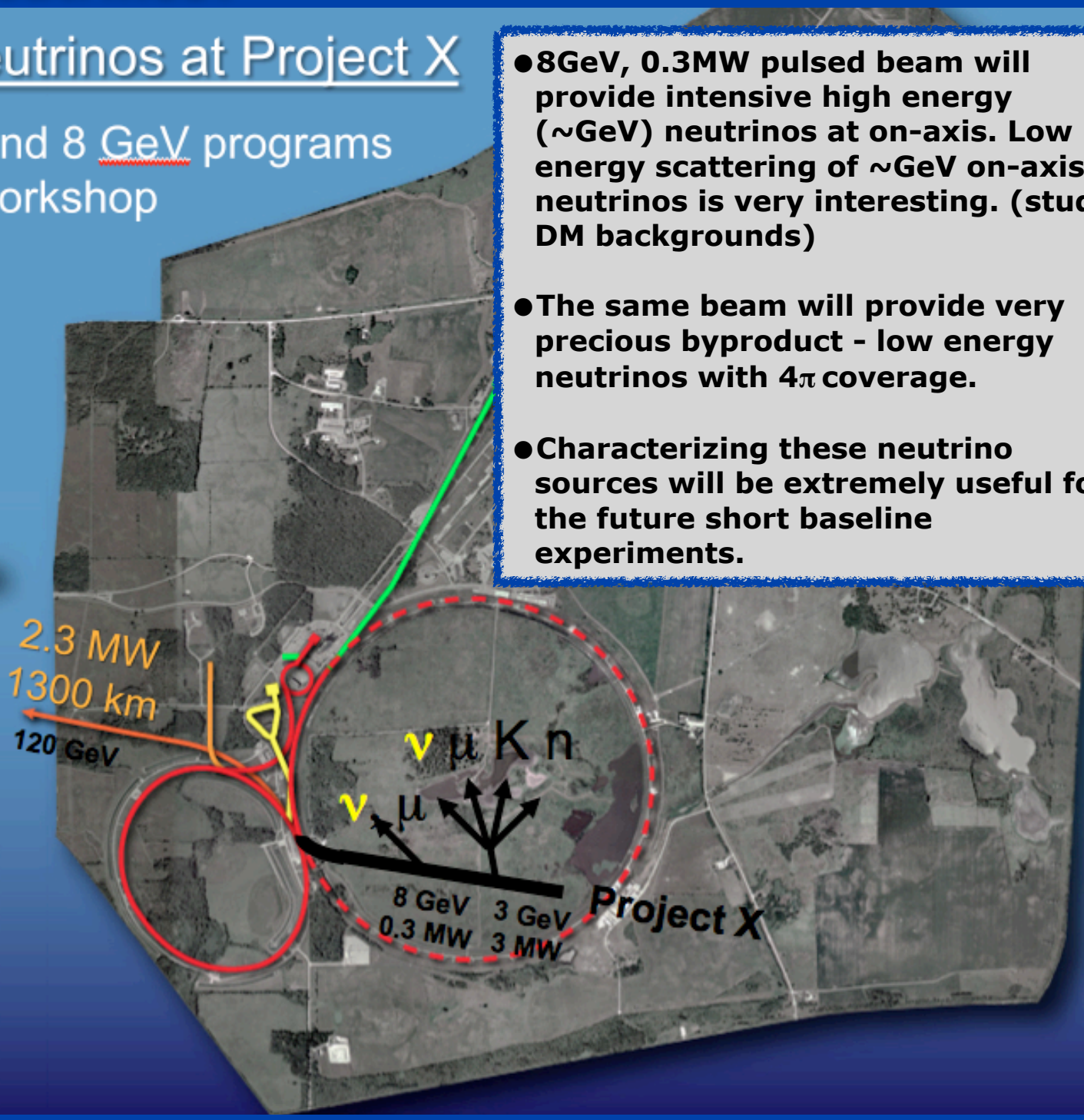
# Future of FOX neutrinos?

## Short Baseline Neutrinos at Project X

Exploring 3 GeV and 8 GeV programs
This workshop

- **8GeV, 0.3MW pulsed beam will provide intensive high energy (~GeV) neutrinos at on-axis. Low energy scattering of ~GeV on-axis neutrinos is very interesting. (study DM backgrounds)**
- **The same beam will provide very precious byproduct - low energy neutrinos with 4π coverage.**
- **Characterizing these neutrino sources will be extremely useful for the future short baseline experiments.**



# Project-X Stages

← Project X Campaign →

| Program: | Onset of NOvA operations in 2013 | Stage-1: 1 GeV CW Linac driving Booster & Muon, n/edm programs | Stage-2: Upgrade to 3 GeV CW Linac | Stage-3: Project X RDR | Stage-4: Beyond RDR: 8 GeV power upgrade to 4MW |
|---|---|---|---|---|---|
| MI neutrinos | 470-700 kW** | 515-1200 kW** | 1200 kW | 2450 kW | 2450-4000 kW |
| 8 GeV Neutrinos | 15 kW +0-50kW** | 0-42 kW* + 0-90 kW** | 0-84 kW* | 0-172 kW* | 3000 kW |
| 8 GeV Muon program e.g, (g-2), Mu2e-1 | 20 kW | 0-20 kW* | 0-20 kW* | 0-172 kW* | 1000 kW |
| 1-3 GeV Muon program, e.g. Mu2e-2 | ----- | 80 kW | 1000 kW | 1000 kW | 1000 kW |
| Kaon Program | 0-30 kW** (<30% df from MI) | 0-75 kW** (<45% df from MI) | 1100 kW | 1870 kW | 1870 kW |
| Nuclear edm ISOL program | none | 0-900 kW | 0-900 kW | 0-1000 kW | 0-1000 kW |
| Ultra-cold neutron program | none | 0-900 kW | 0-900 kW | 0-1000 kW | 0-1000 kW |
| Nuclear technology applications | none | 0-900 kW | 0-900 kW | 0-1000 kW | 0-1000 kW |
| # Programs: | 4 | 8 | 8 | 8 | 8 |
| Total max power: | 735 kW | 2222 kW | 4284 kW | 6492 kW | 11870kW |

* Operating point in range depends on MI energy for neutrinos.

** Operating point in range depends on MI injector slow-spill duty factor (df) for kaon program.

# Road Map to LowE-ν Intensity Frontier

**Far-off-axis BNB neutrino source is an extremely valuable resource to study beam background and neutrino flux**

**BNB Era**

- Understand beam-induced neutron background at the BNB target area and establish shielding methods (~2013)
- Propose coherent-NCvAS experiment to Fermilab Physics Advisory Committee (~2014)
- Coherent-NCvAS experiment (2017~2018)
- OscBNB experiment at Fermilab? (2018~)
  - One can imagine putting a full absorption target
  - Target is cheaper if it is not a spallation source

**Project-X Era**

- Neutrino flux and beam background study at BNB will be an important input to design the Project-X target
- BNB target station (MI-12) and detector infrastructure would still be very useful to test different target material
- The Project X stage-1 siting plan includes the option for a compressor ring which could drive a high power target for low energy neutrino experiments. (B.Tschirhart)
- A chance to design a detector close to source (4π coverage detector facilities?)

# Summary

- A lot of interesting physics cases in low energy neutrino interactions

- Coherent-NCvAS is a good first experiment which can test the total neutrino flux from the neutrino source
  - Largest interaction cross section (small detector volume)

- Fermilab has a well-defined low-energy neutrino source: BNB
  - It is a very valuable asset by two practical reasons
    1. New physics in low energy neutrino study
    2. Beam and target parameter input study for Project-X program

# Backup Slides

# Beam Parameters: BNB vs. SNS

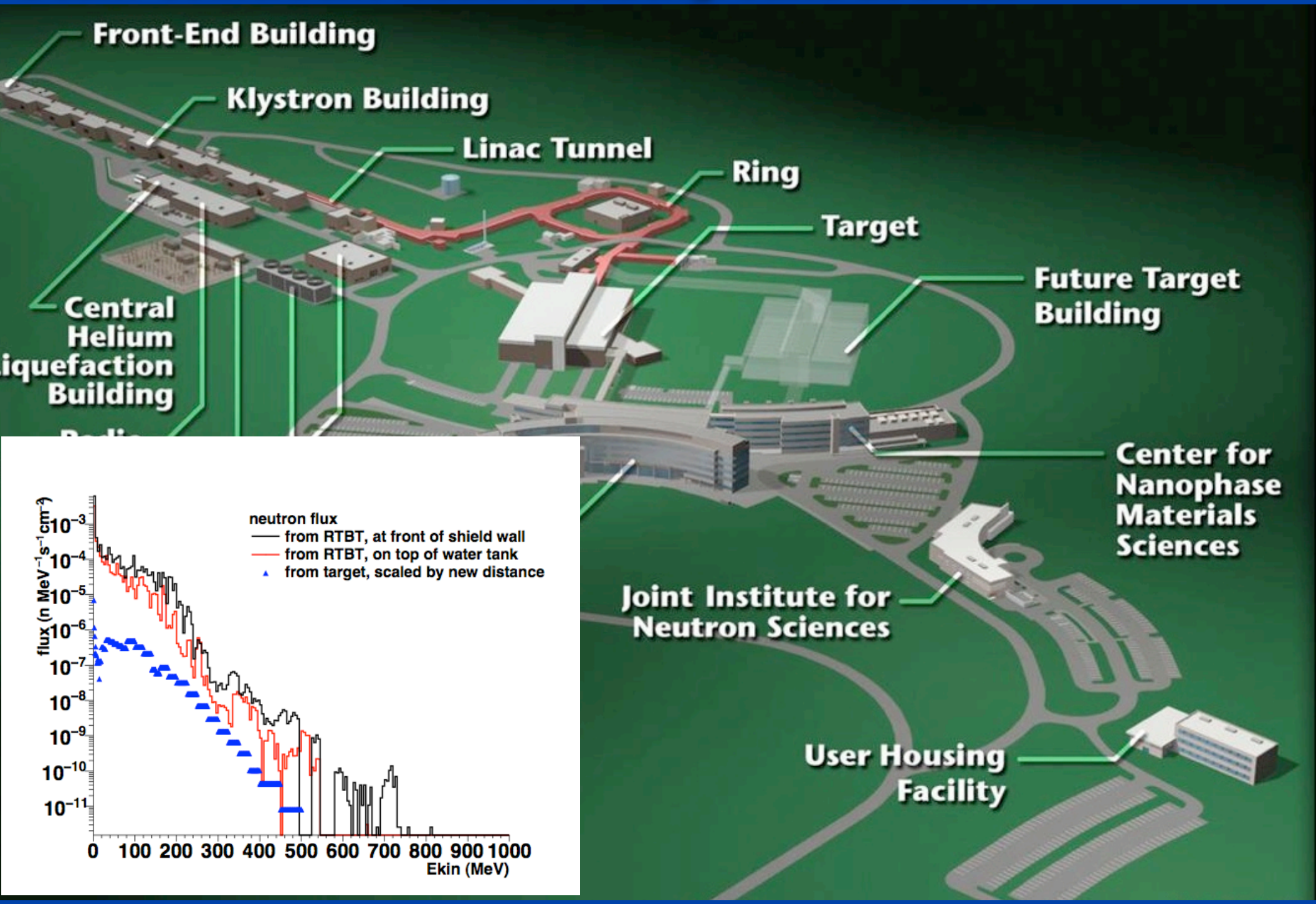
| | BNB (Fermilab) | SNS (Oak Ridge) |
|---|---|---|
| Proton beam energy | 8 GeV | 1 GeV |
| Intensity | $5 \times 10^{12}$ protons/pulse | $1.6 \times 10^{14}$ protons/pulse |
| Pulse duration | 1600 ns | 700 ns |
| Repetition rate | 5 Hz | 60 Hz |
| Total power | 32 kW | 1.4 MW |
| Target | Beryllium | Mercury |

**Neutrino flux at the practical location**

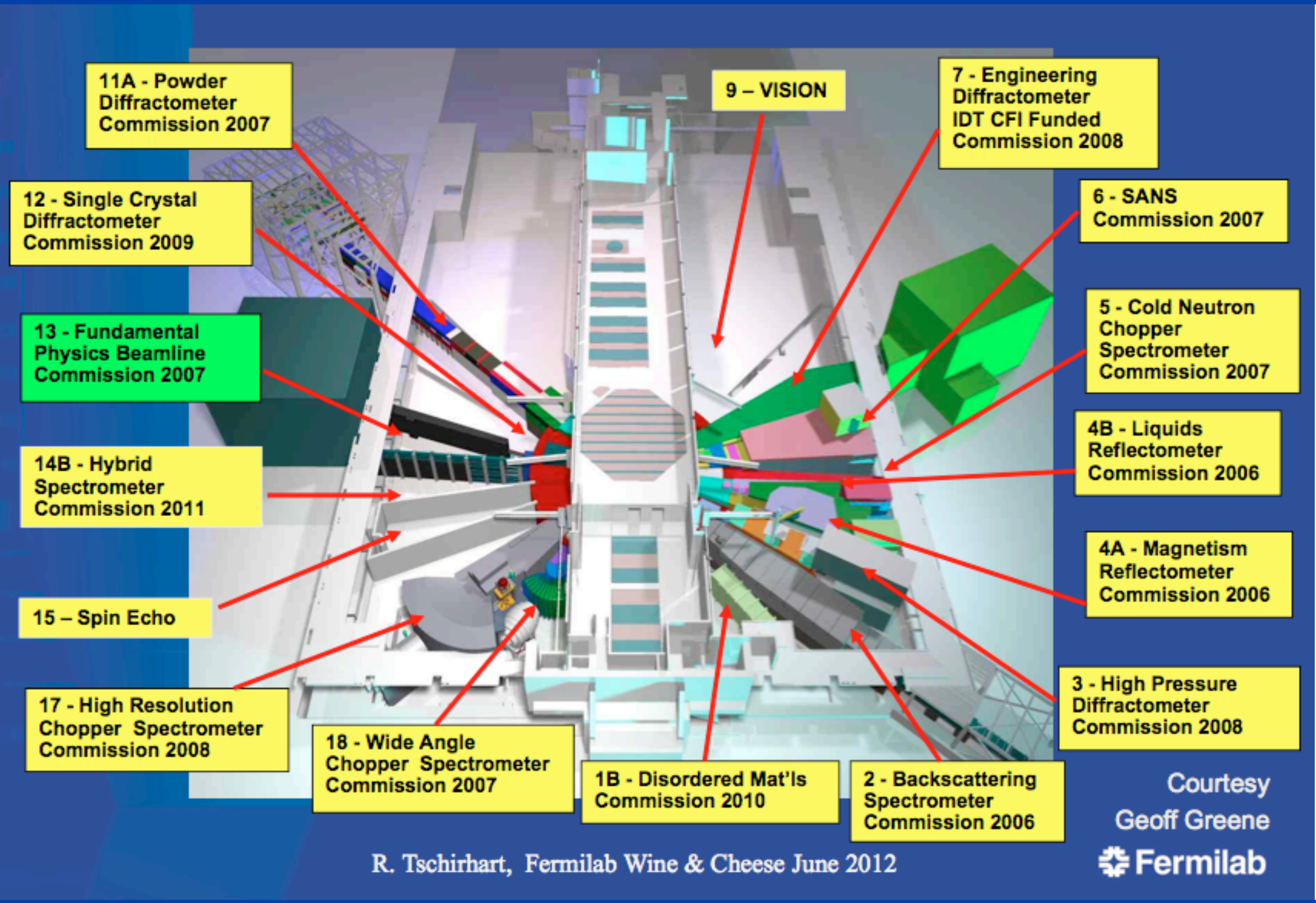
**BNB (@20m from the target) : $\phi \cong 5 \times 10^5$ ν/cm²/s**

**SNS (@60m from the target) : $\phi \cong 1 \times 10^6$ ν/cm²/s**

# Beam Coincident Neutron Background at SNS?



# ORNL SNS


11A - Powder Diffractometer Commission 2007
12 - Single Crystal Diffractometer Commission 2009
13 - Fundamental Physics Beamline Commission 2007
14B - Hybrid Spectrometer Commission 2011
15 – Spin Echo
17 - High Resolution Chopper Spectrometer Commission 2008
18 - Wide Angle Chopper Spectrometer Commission 2007
1B - Disordered Mat'ls Commission 2010
2 - Backscattering Spectrometer Commission 2006
3 - High Pressure Diffractometer Commission 2008
4A - Magnetism Reflectometer Commission 2006
4B - Liquids Reflectometer Commission 2006
5 - Cold Neutron Chopper Spectrometer Commission 2007
6 - SANS Commission 2007
7 - Engineering Diffractometer IDT CFI Funded Commission 2008
9 – VISION
Courtesy Geoff Greene
Fermilab
R. Tschirhart, Fermilab Wine & Cheese June 2012