

Coherent Elastic Neutrino Nucleus Scattering

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NuInt12

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Coherent Elastic Neutrino Nucleus Scattering

Coherent Elastic (Neutral Current) Neutrino Nucleus Scattering: CENNS

first prediction by D.Z. Freedman (1974)

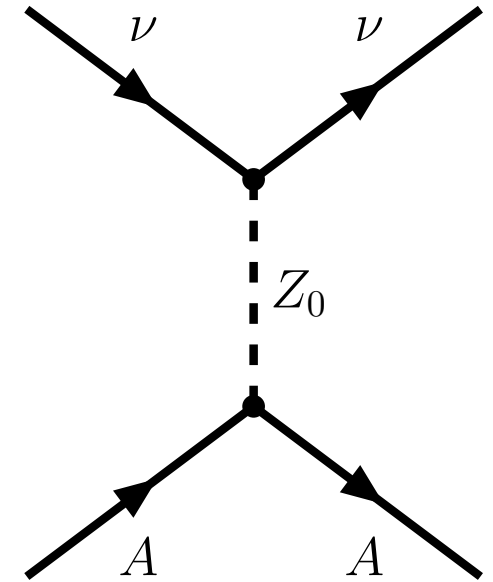
$$\mathcal{L}_{eff} = \frac{G_F}{\sqrt{2}} l^\mu j_\mu$$

Cross section for zero-momentum transfer limit

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

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

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



Differential cross section for finite momentum transfer

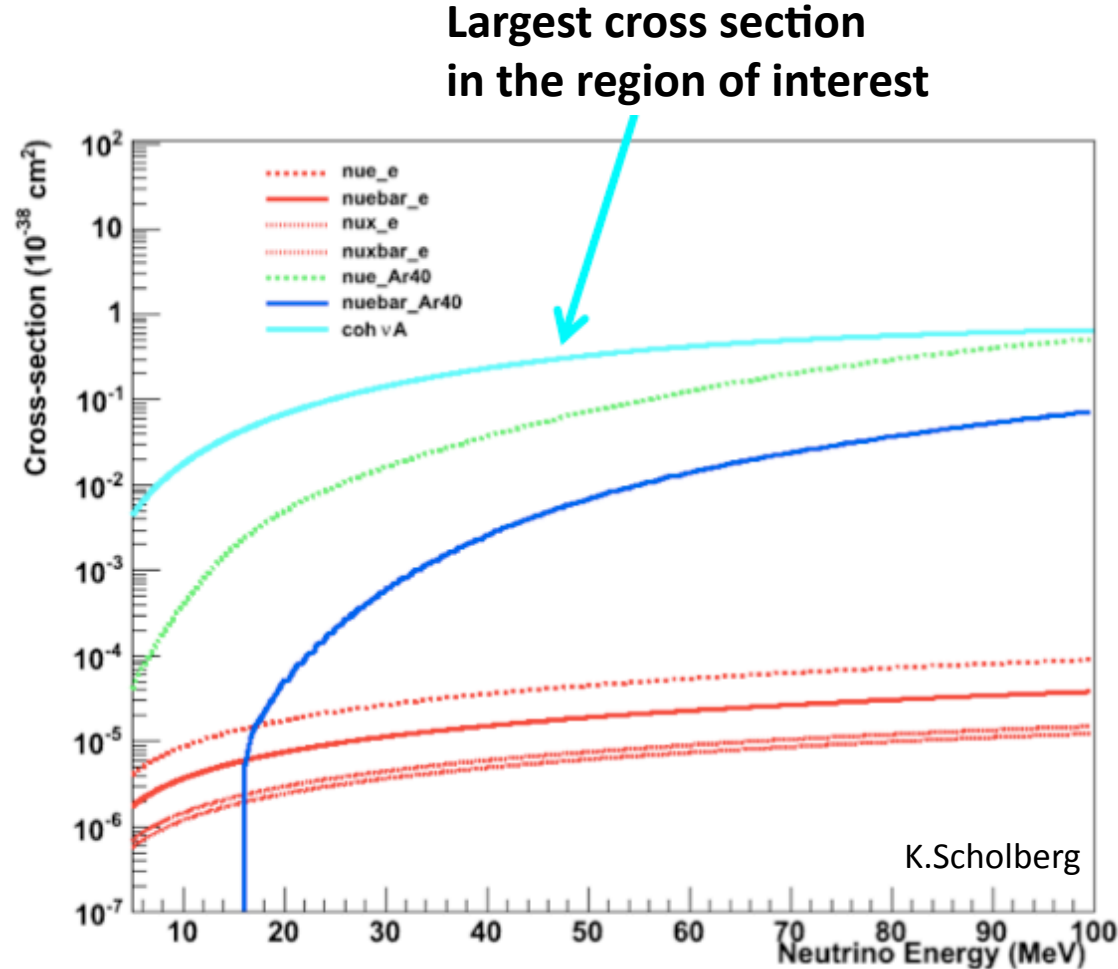
$$\frac{d\sigma}{dE} = \frac{G_F^2}{4\pi} [(1 - 4 \sin^2 \theta_w)Z - (A - Z)]^2 M \left(1 - \frac{ME}{2E_\nu^2}\right) F(Q^2)^2$$

Requirements of the CENNS

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

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

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



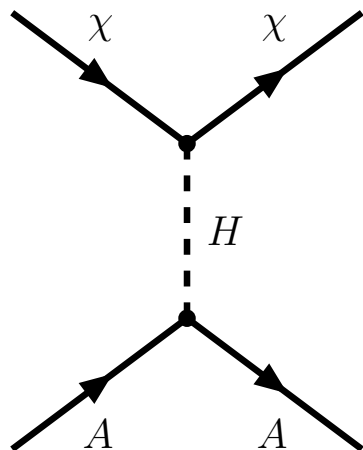
Requires a ton-scale detector with ~ 10 keV energy threshold

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

- It's 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 scattering of neutrinos:
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* !

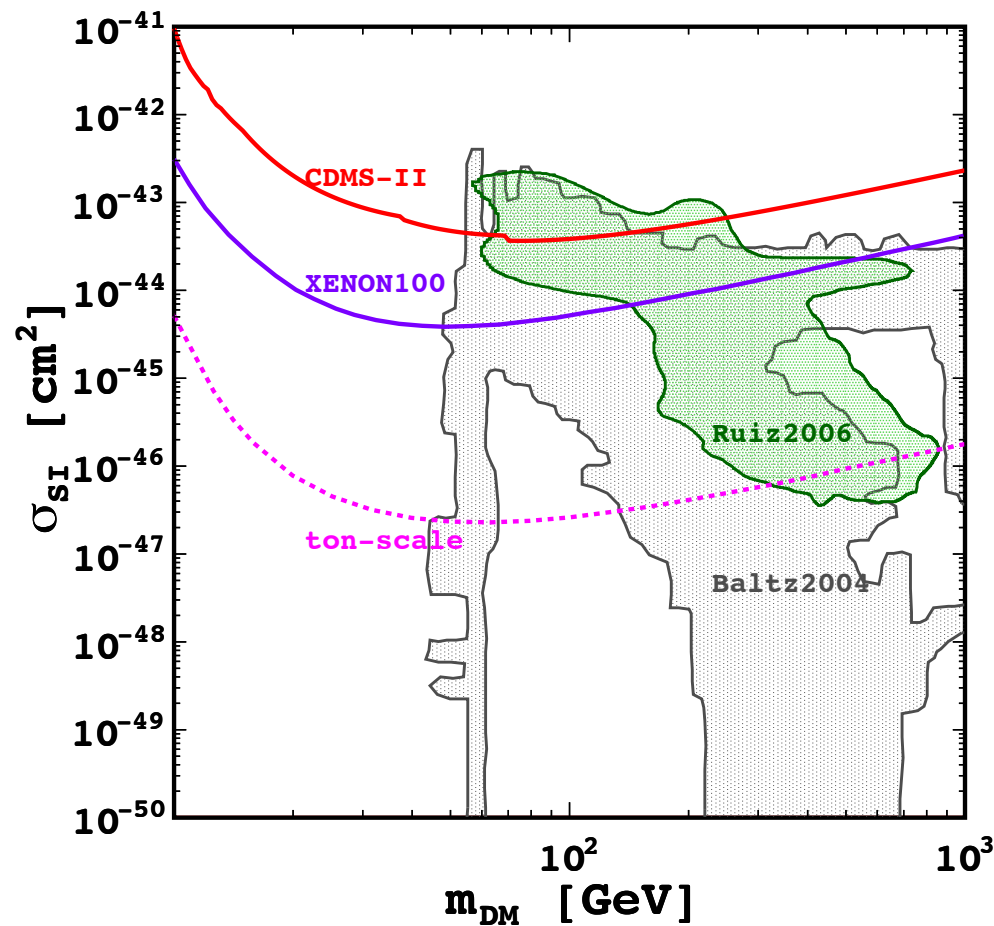
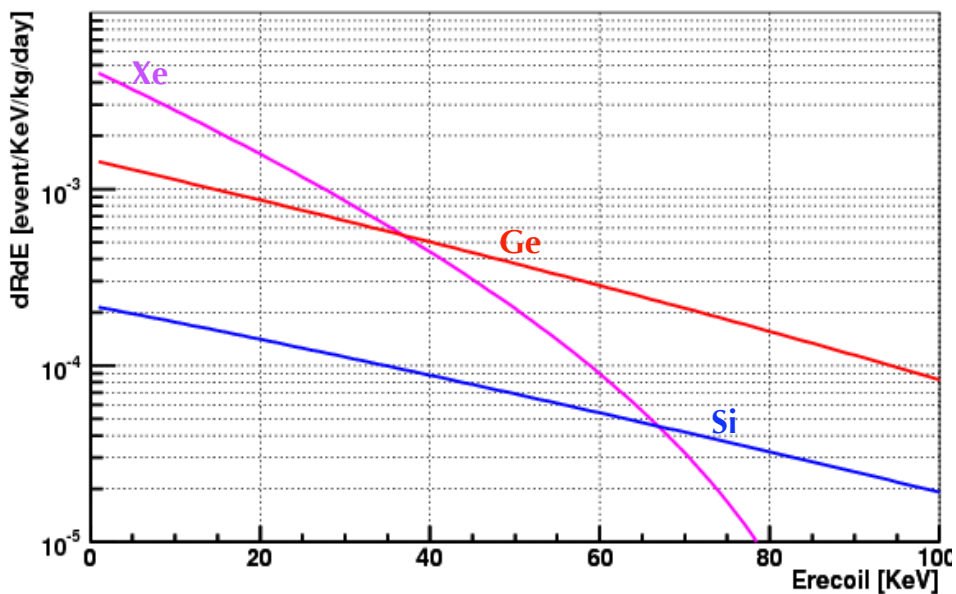
Dark Matter Search



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

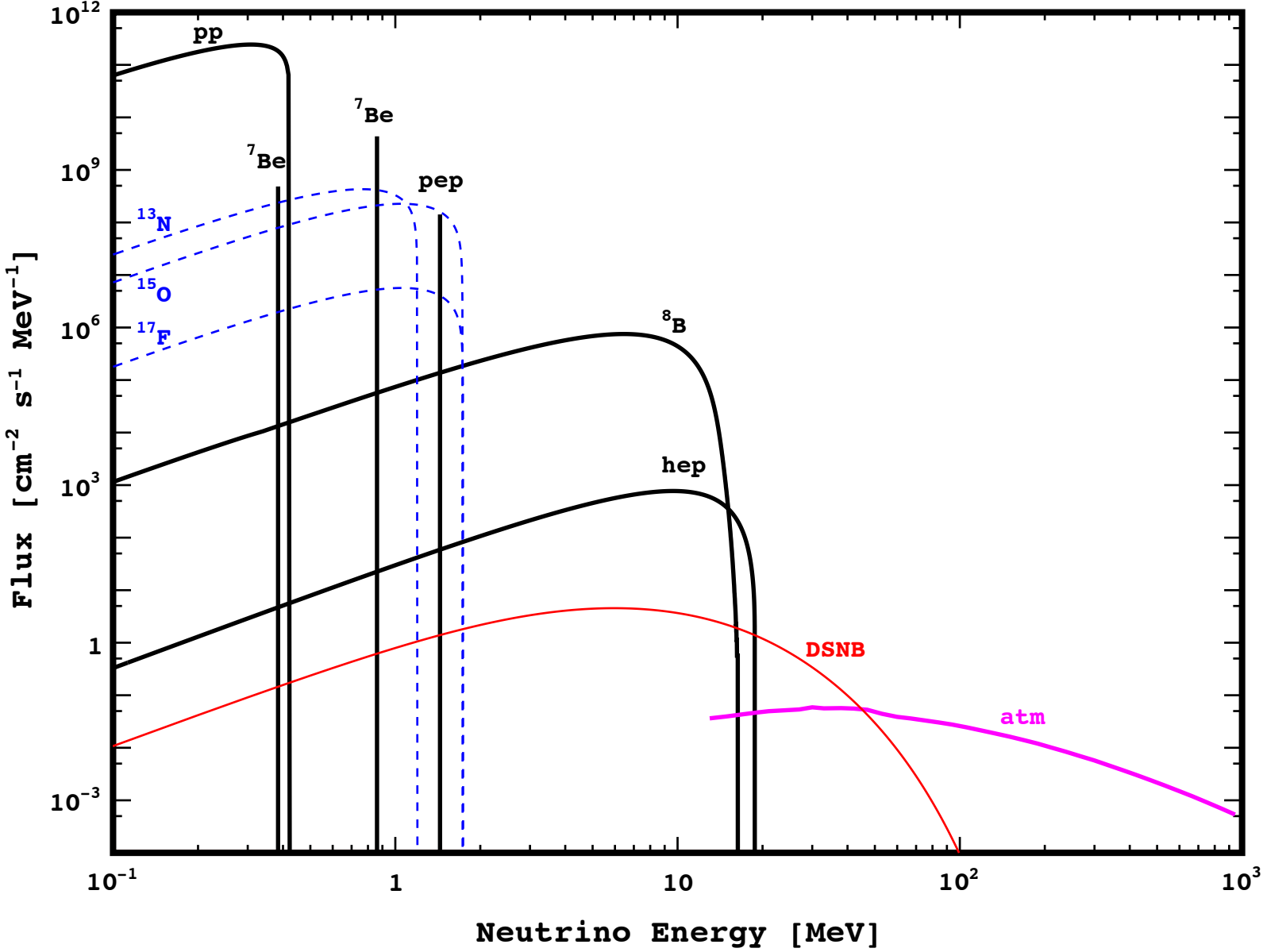
$$\frac{dR}{dE} = \frac{\sigma_0}{m_\chi} \frac{A^2}{2\mu_n^2} F_A^2(E) \times \rho_0 \int_{v_m} \frac{f(v)}{v} dv$$

Differential Event Rate in Recoil Energy @ $m_D = 60$ GeV

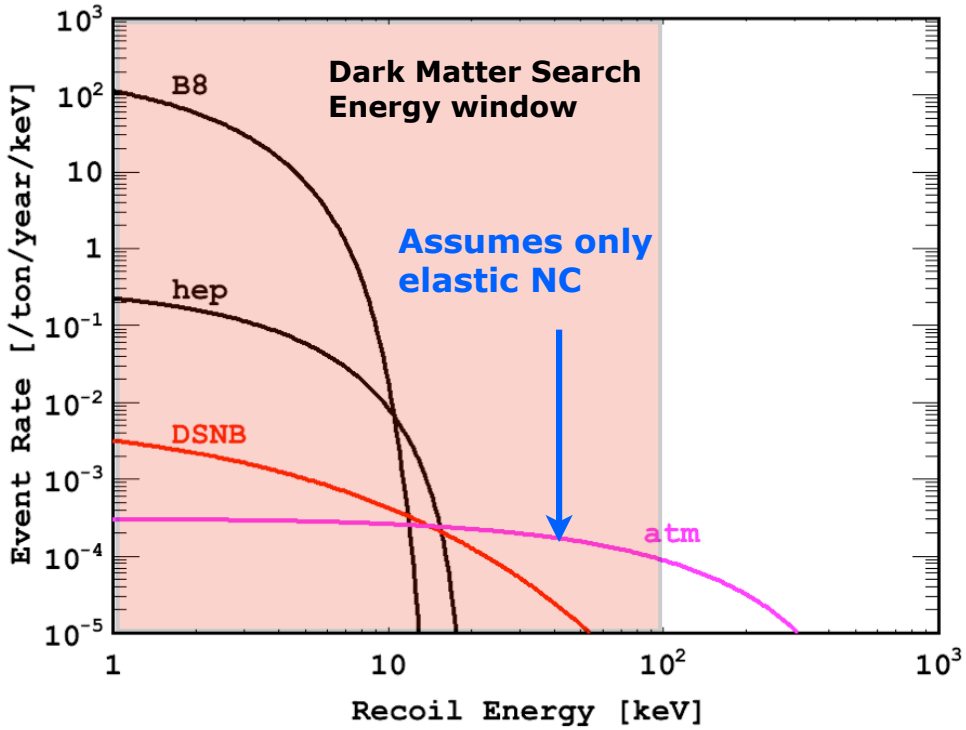


Irreducible Backgrounds

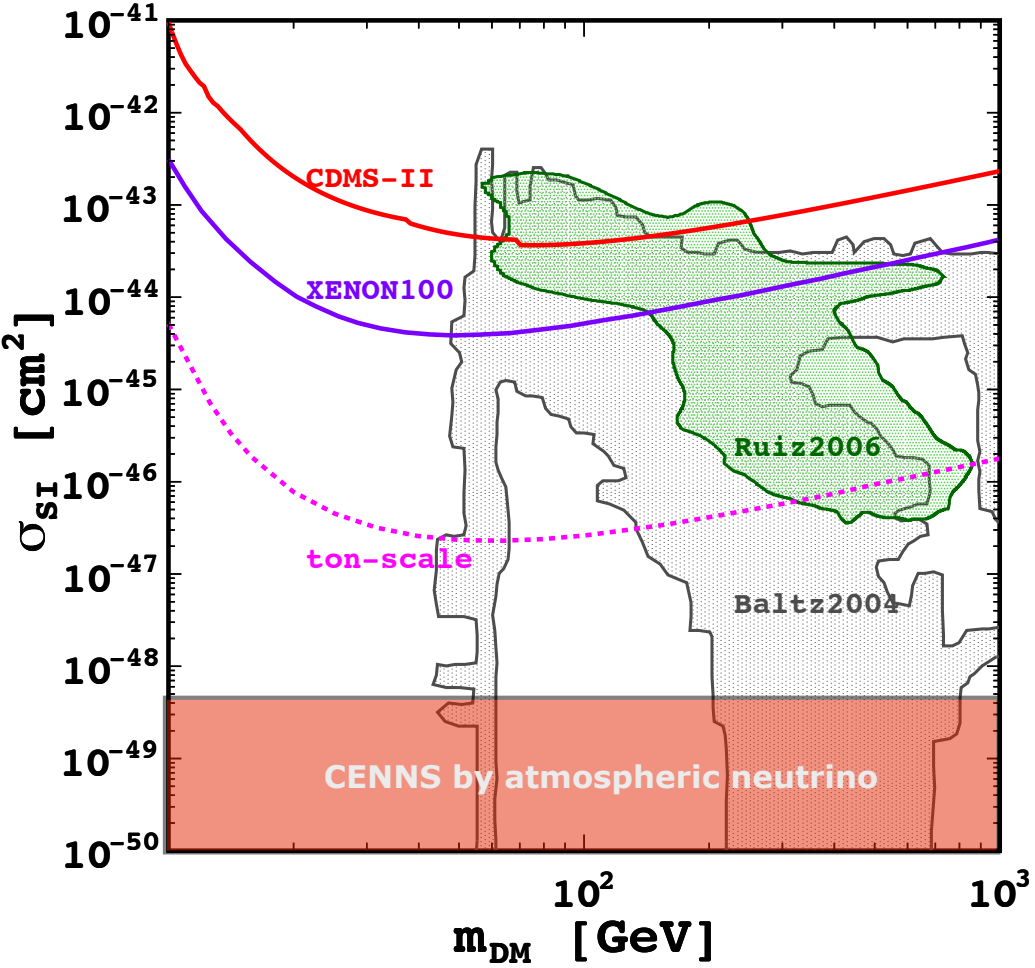
Neutrinos from astrophysical origin



Irreducible Backgrounds

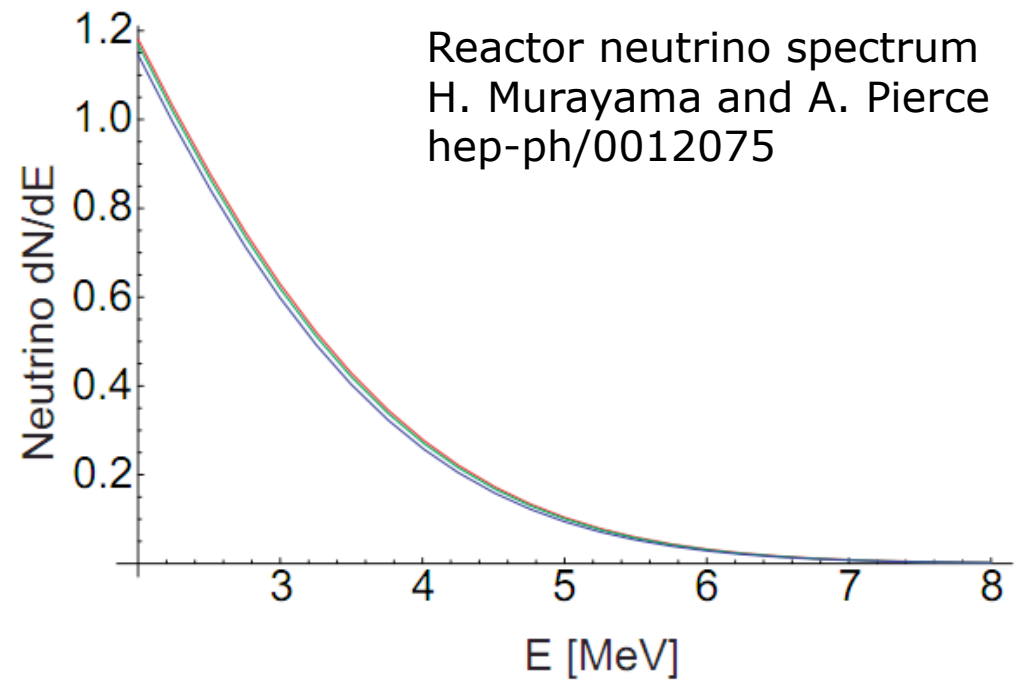


- Coherent scattering of atmospheric neutrino is an irreducible background in future $O(10 \text{ ton})$ scale dark matter experiments (see Strigari, arXiv:0903.3630)
- What about the inelastic interaction tail by high energy neutrinos?



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

Reactor Neutrinos



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

$$\Phi = 10^{20} \bar{\nu}_e / \text{sec} / 4\pi R^2 \quad (\Phi = 10^{12} \bar{\nu}_e / \text{sec} / \text{cm}^2 @ 20 \text{ m})$$

- Ultra-clean, kg-size, ~ 10 eV threshold detector
- Need to overcome steady state backgrounds and detector noise
- Reactor off-time can be used for background subtraction
- Detector development is challenging for a realistic experiment

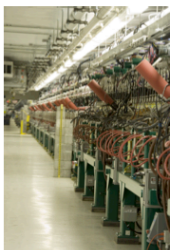
CLEAR Proposal: SNS at ORNL

- ν SNS at Oak Ridge National Lab

F. Avignone and Y. Efremenko, J. Phys. G, 29 (2003) 2615-2628

- See **CLEAR** proposal : K. Scholberg *et al.*, hep-ex:0910.1989

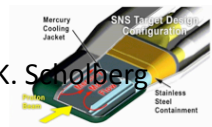
Proton linear accelerator, initial operation at 1.0 GeV; upgrade to 1.3 GeV planned



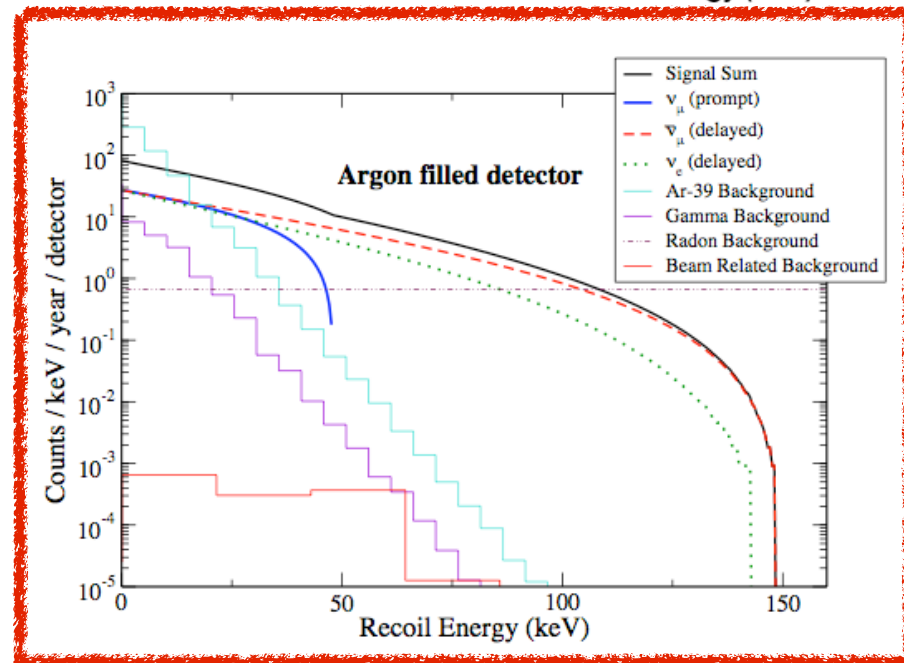
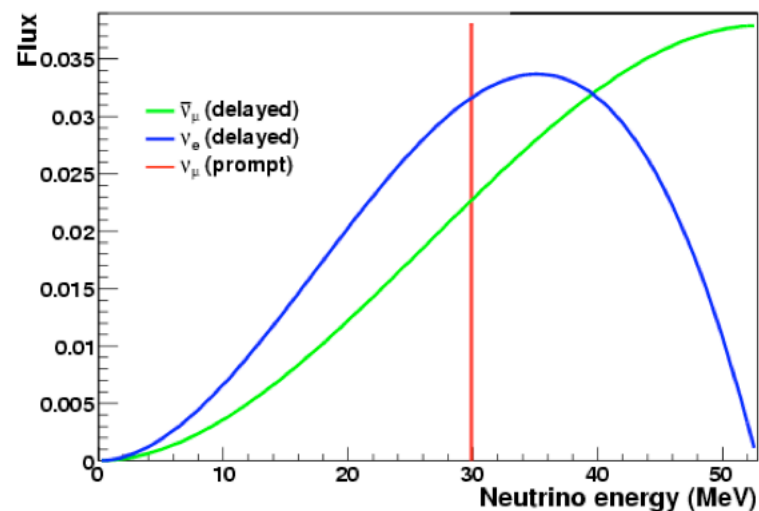
Accumulator ring, 400 ns pulse width



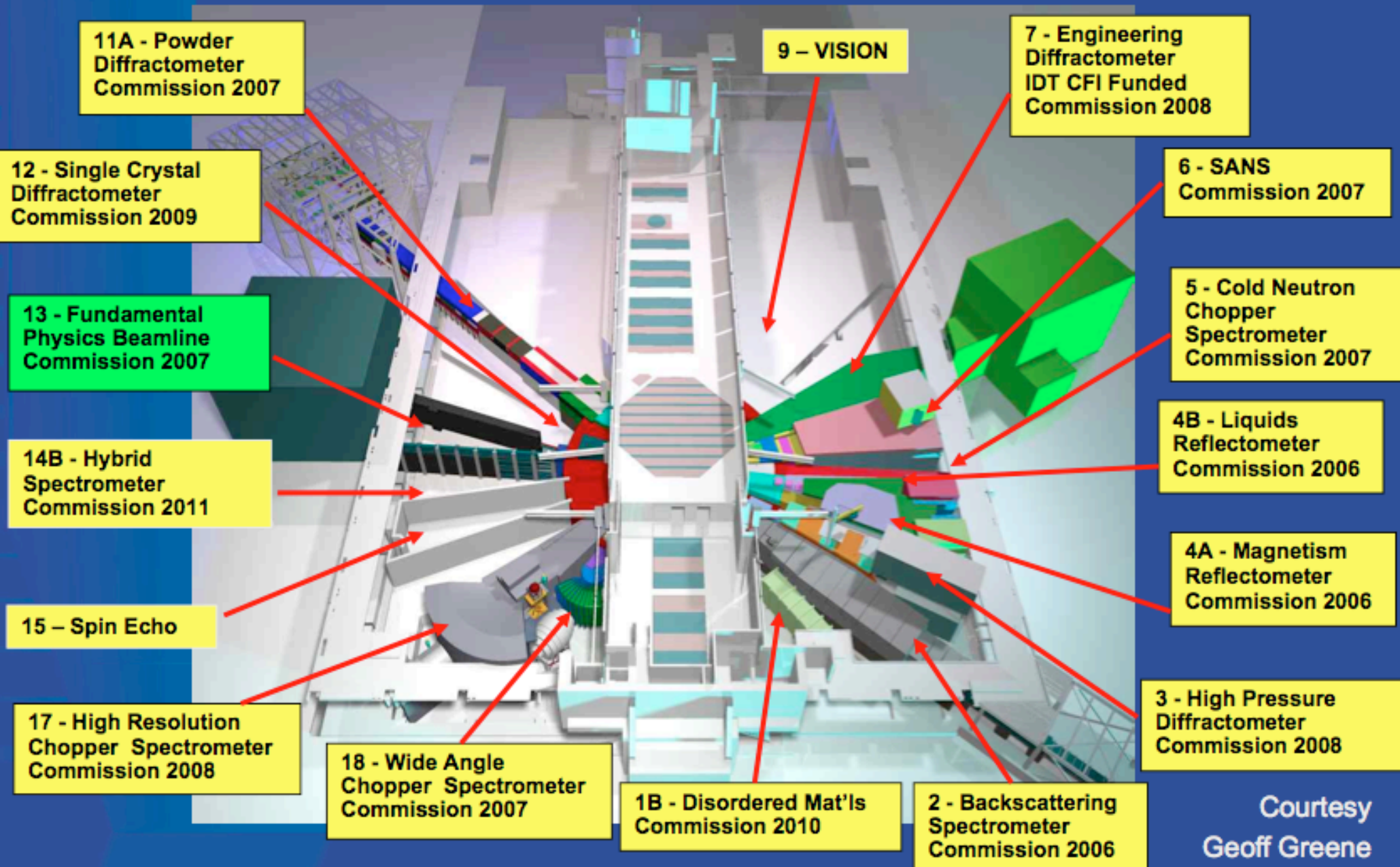
Proton beam bombards liquid Hg target



24 μC /pulse at 60 Hz \Rightarrow 1.4 MW power



- Flux $\sim 2 \times 10^6/\text{sec}/\text{cm}^2$ at 46m from the target
- Steady state background rejection factor $\sim 10^{-4}$
- Expected event rate in a single-phase 500kg LAr detector: ~ 400 events/year of detection ($E_{\text{th}} > 30$ keVnr)



R. Tschirhart, Fermilab Wine & Cheese June 2012

Courtesy
Geoff Greene
 Fermilab

Neutrinos at Fermilab



MI-12 Target Building Area



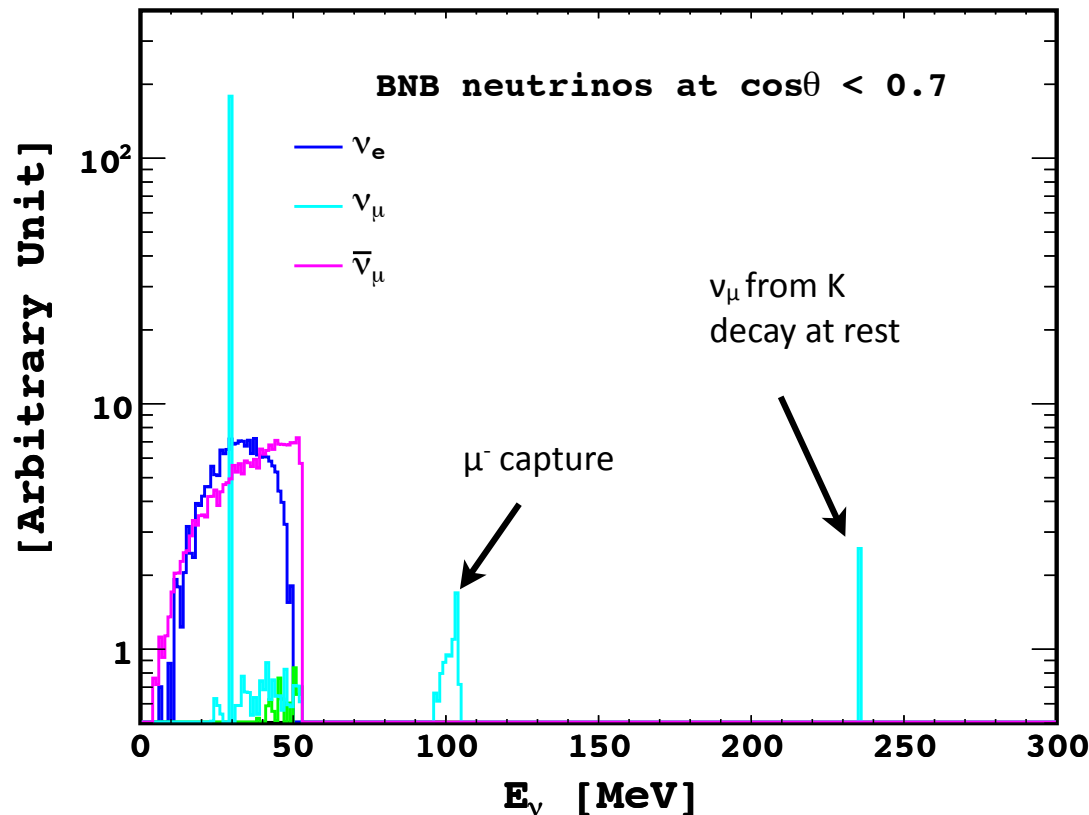
Far-Off-aXis (FOX) Neutrinos at BNB

Beam MC Configuration

- Use standard Booster Beam MC
 - release stopping pion cuts in the original MC
- 8 GeV, 5Hz 5×10^{12} Protons on Beryllium target
 - 32 kW max power
- 173 kA horn current neutrino mode

arXiv:0806.1449

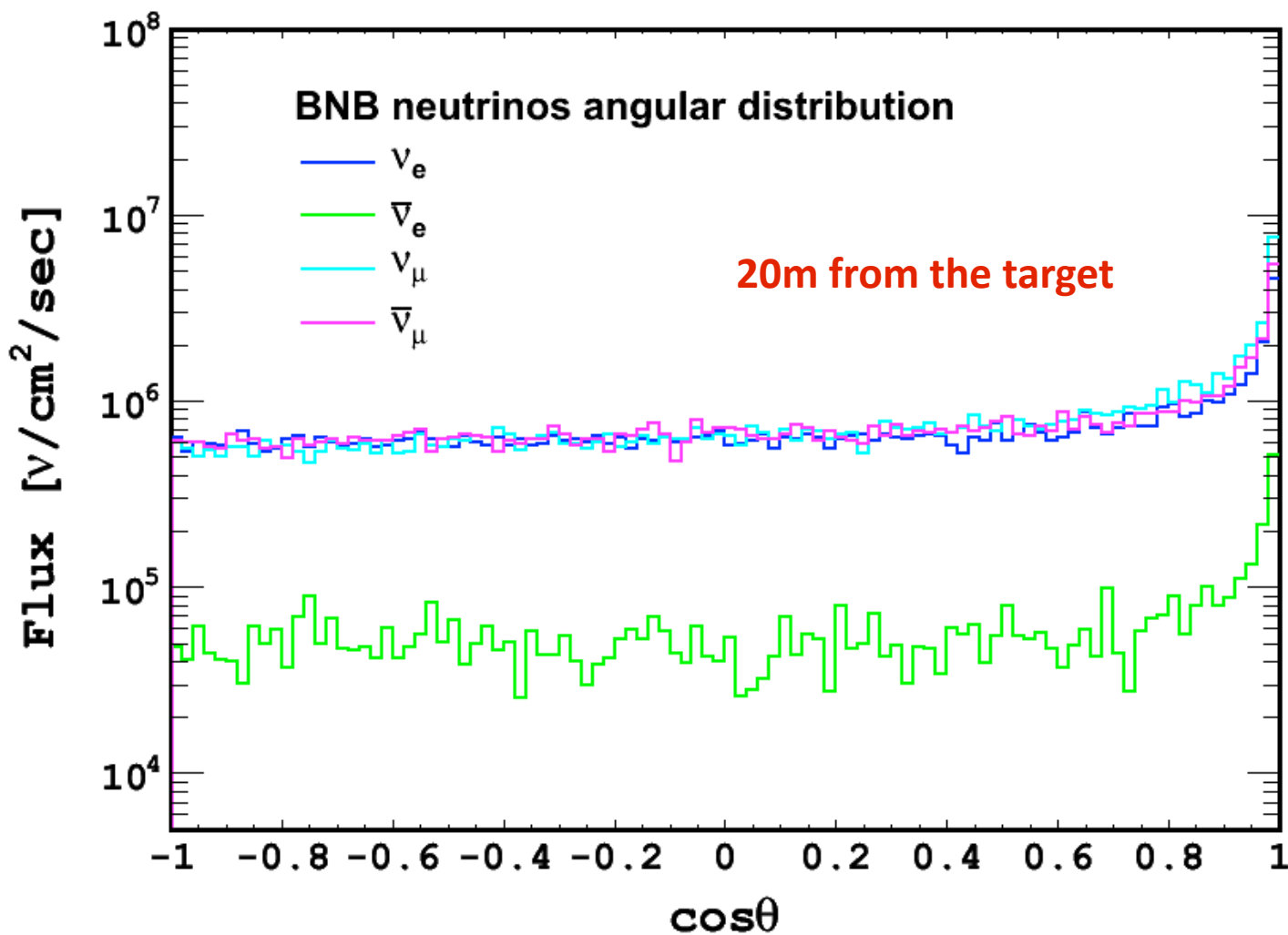
From Booster Beam MC (S.Brice)



Particle	Lifetime (ns)	Decay mode	Branching ratio (%)
π^+	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
μ^+	2197.03	$e^+ + \nu_e + \bar{\nu}_\mu$	100.0

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

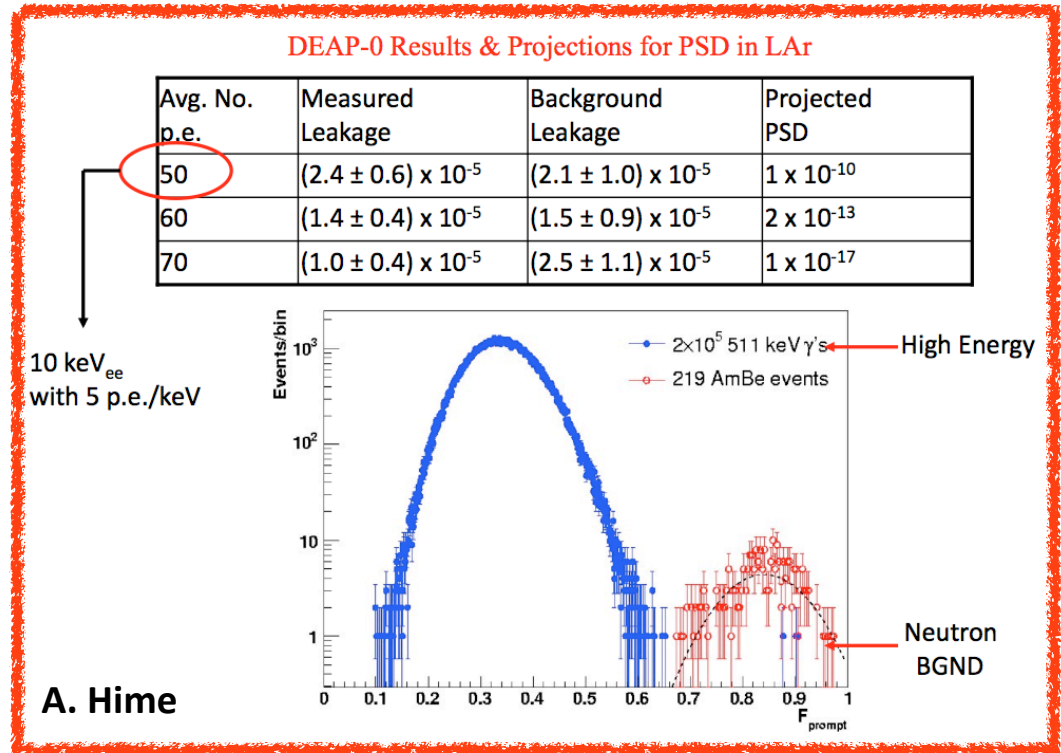
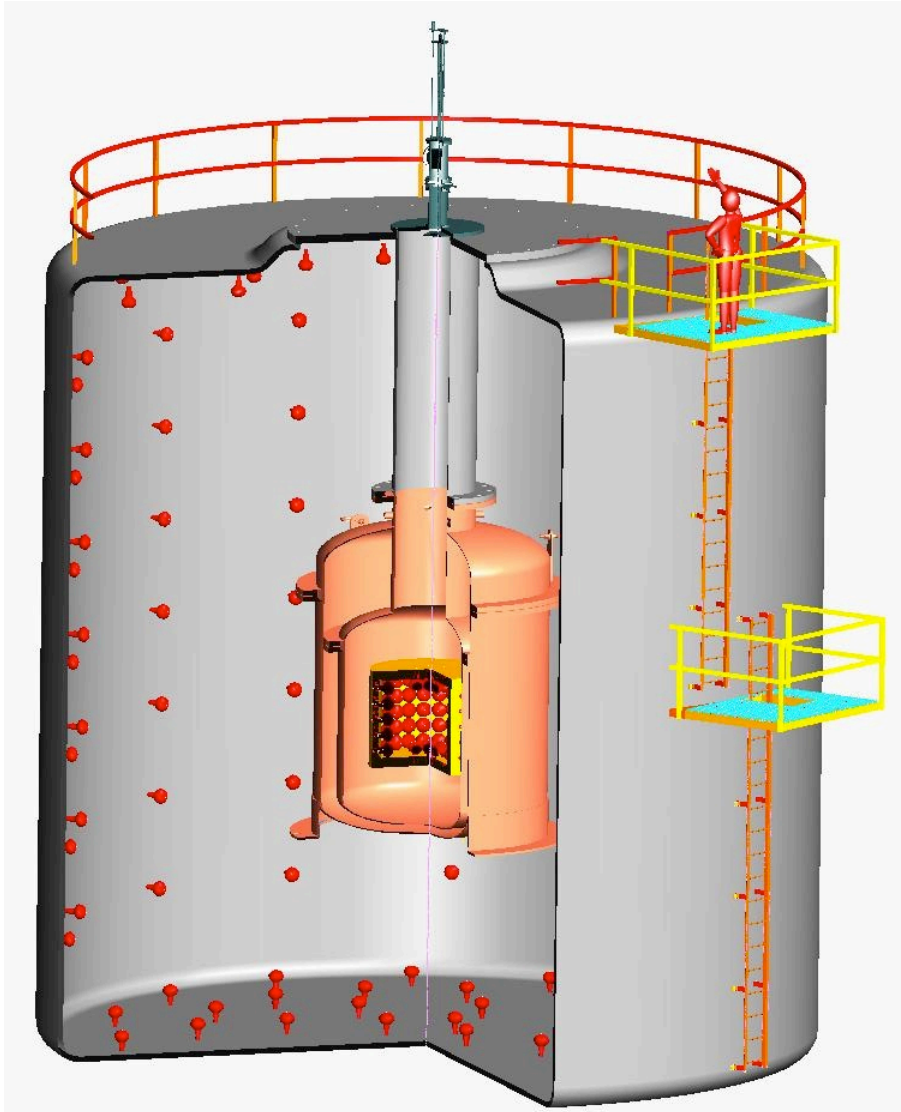
Far-Off-aXis (FOX) Neutrinos at BNB



- $\phi \cong 5 \times 10^5 \text{ v/cm}^2/\text{s} @ 20\text{m} (\cos\theta < 0.5)$ (cf. $\phi(\text{SNS}) \cong 10^7 \text{ v/cm}^2/\text{s} @ 20\text{m}, 1 \times 10^6 \text{ v/cm}^2/\text{s} @ 60\text{m}$)
- Systematic uncertainties of the neutrino flux estimation should be checked in detail

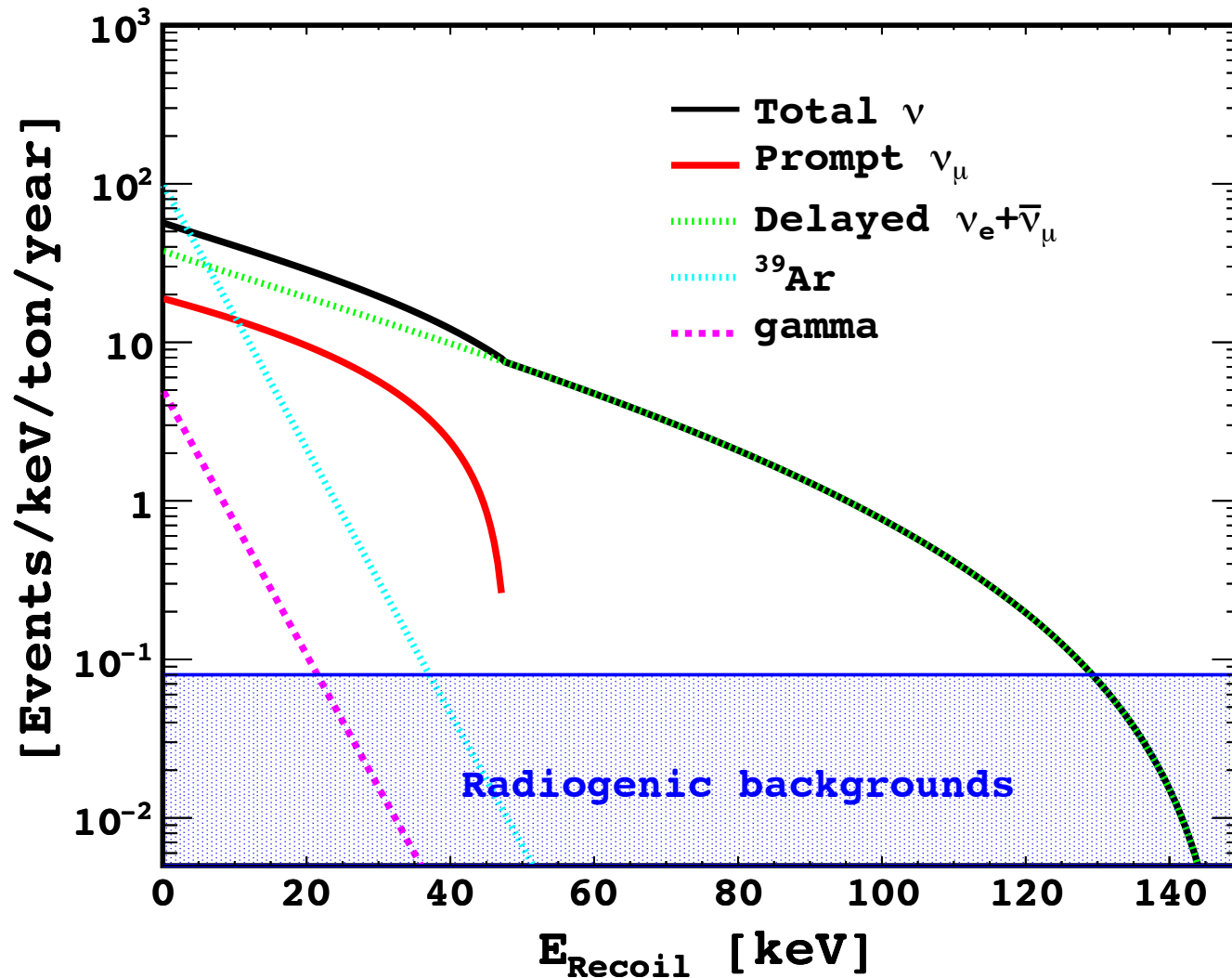
Low Energy Threshold LAr Neutrino Detector

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



- 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 ($\tau = 269\text{yr}$) ^{39}Ar beta decay (1kBq/ton) wouldn't be a serious issue due to duty factor of pulsed beam & Pulse Shape Discrimination (PSD)

Expected CENNS Event Rates at FOX

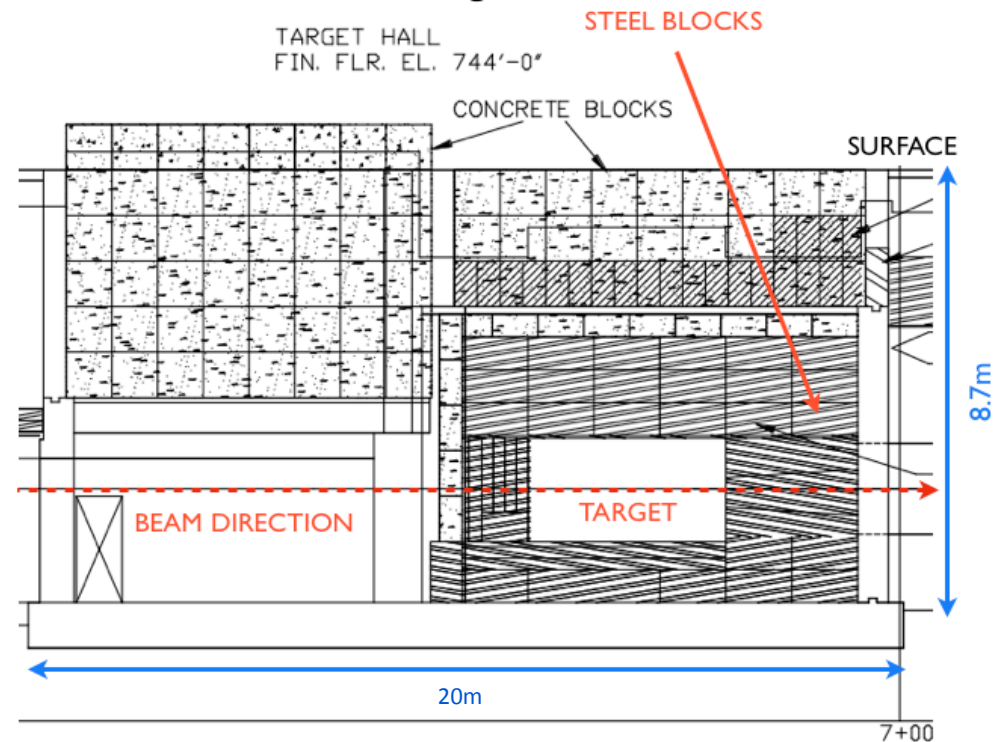


- 20m from the target ($\phi \approx 5 \times 10^5$ v/cm²/s)
- Steady state background rejection factor $\sim 10^{-5}$ (Total exposure: ~ 300 sec/year)
- Expected event rate in a single-phase 1-ton LAr detector: ~ 200 evt/year ($E_{\text{th}} > 30$ keV @ 32kW)
- **Beam-induced neutron backgrounds ?**

BNB Target Radiation Shielding



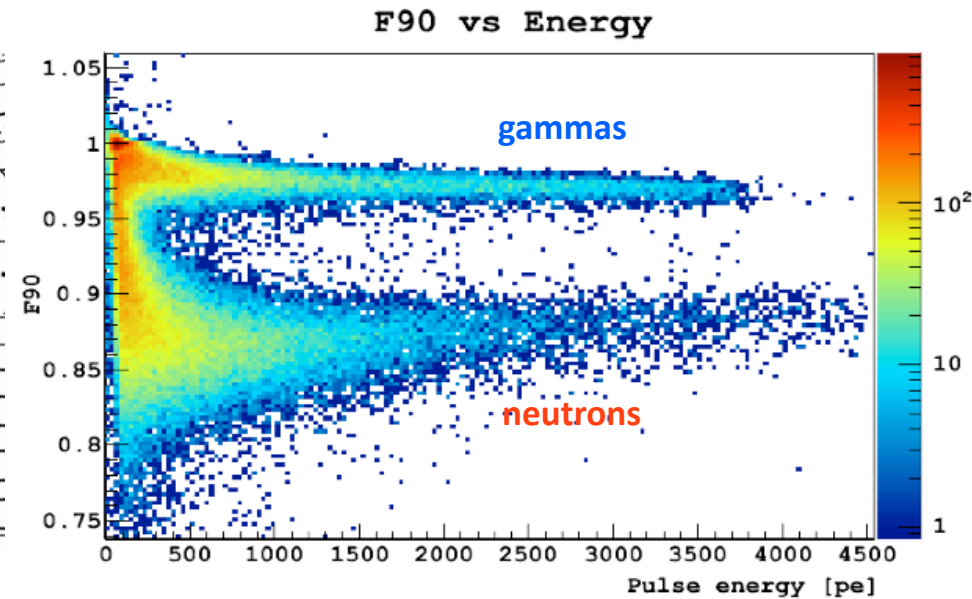
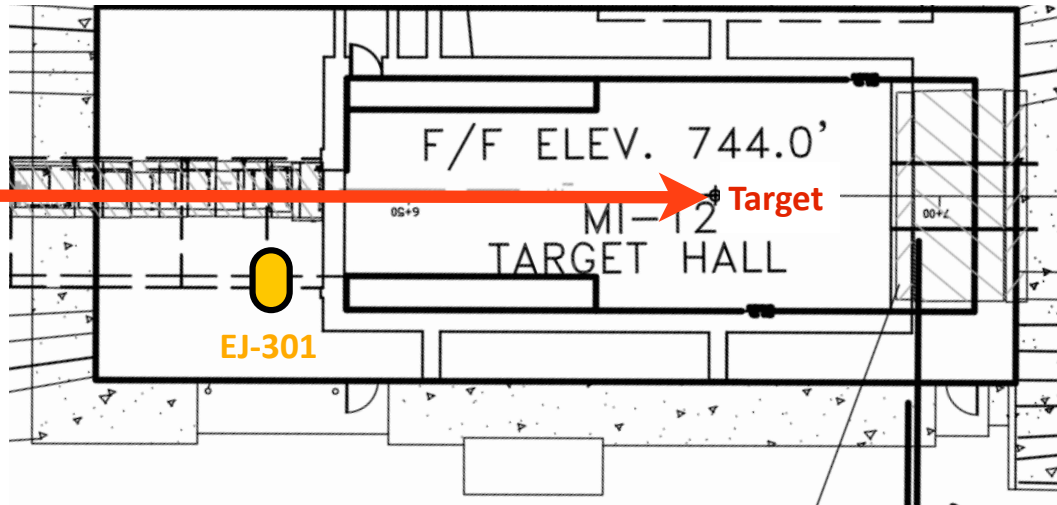
MI-12 Radiation Shielding



- 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: $N_n = (5 \times 10^{12} \text{ pot/pulse}) \times (30 \text{ neutrons/proton}) = 1.5 \times 10^{14} \text{ neutrons/pulse}$
 $\phi_n(\text{@surface}; R=640\text{cm w/ iron \& concrete shielding}) = \sim 102 \text{ neutrons/pulse/m}^2$
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 (~kg) Commercial Liquid Scintillator (@target building surface)



Muon Veto



Gamma Shielding



Neutron Shielding

- No (or rare, if any) beam-induced muons
- Gammas are easy to shield (lead blocks)
- Neutron shielding wasn't easy
- High flux of neutrons are detected in the target building

SciBath-768 Neutral Particle Detector

Initial Survey : Feb 2012

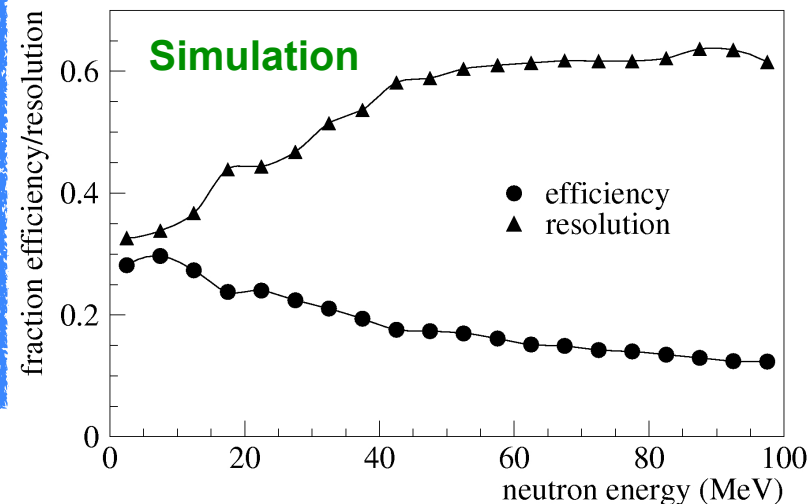
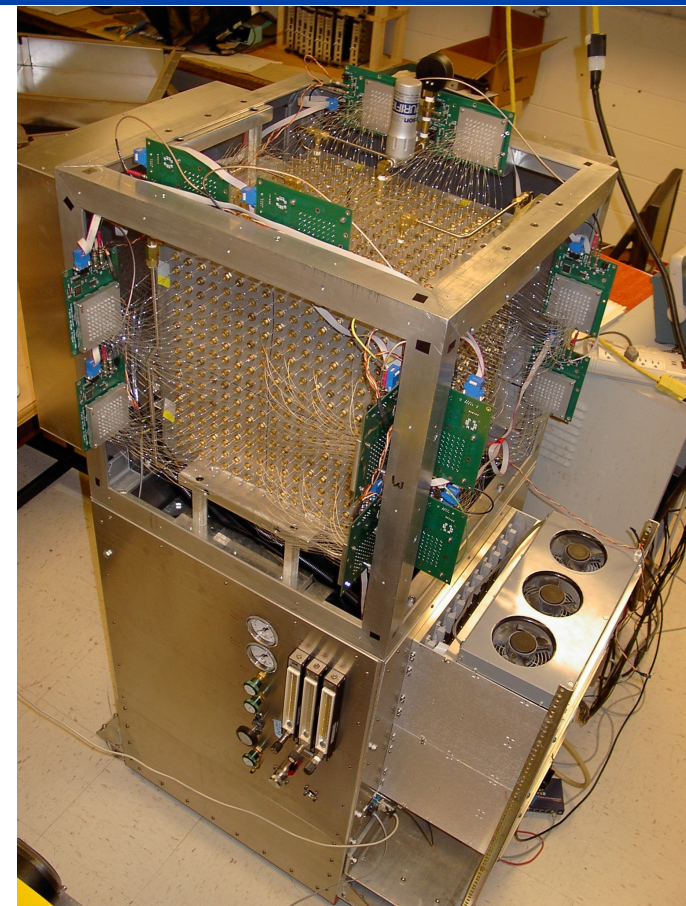
- Commercial 5"D EJ-301 neutron detector
- Establish logistics of data taking procedure at the target building
- Measure beam induced event rate

SciBath (Indiana University)

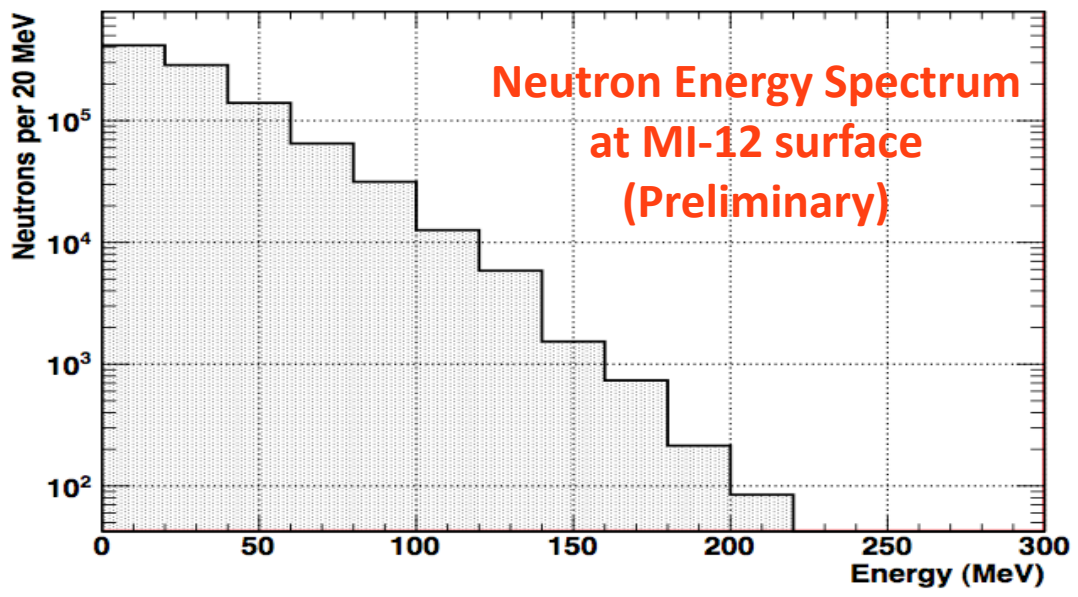
- $(45\text{cm})^3$ volume containing
- 82 liters (70kg) of liquid scintillator:
mineral oil, 11% pseudocumene, + PPO
- 3 16x16 grids, in x,y,z (768 total), 2.5cm spacing, 1.5mm wavelength-shifting (WLS) fibers (UV->blue)
- coupled to clear plastic fibers, routed to readout:
- 12 Hamamatsu 64-anode PMTs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

Goal

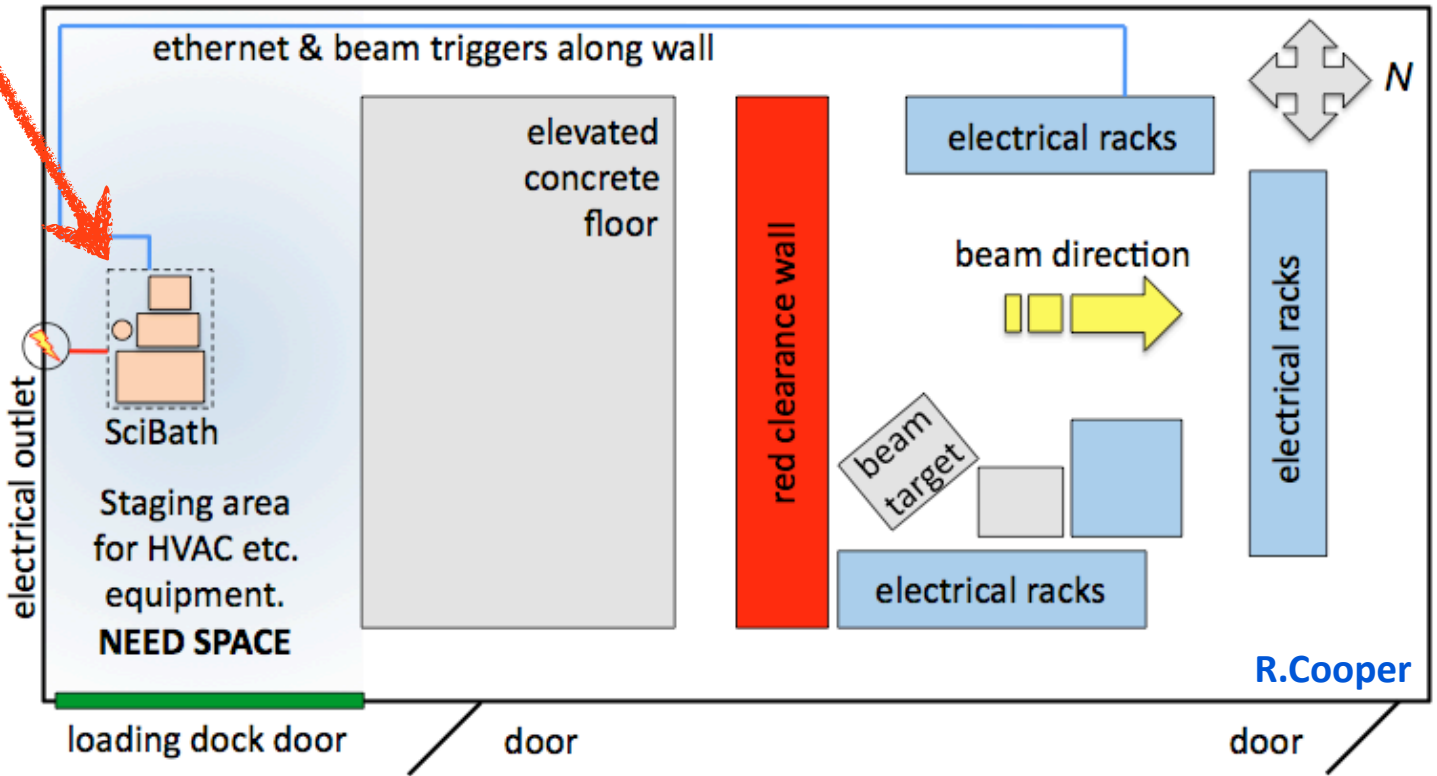
- Beam induced neutron background measurement
- Measure energy spectrum of the neutrons
- cosmic-induced fast neutron flux measurement



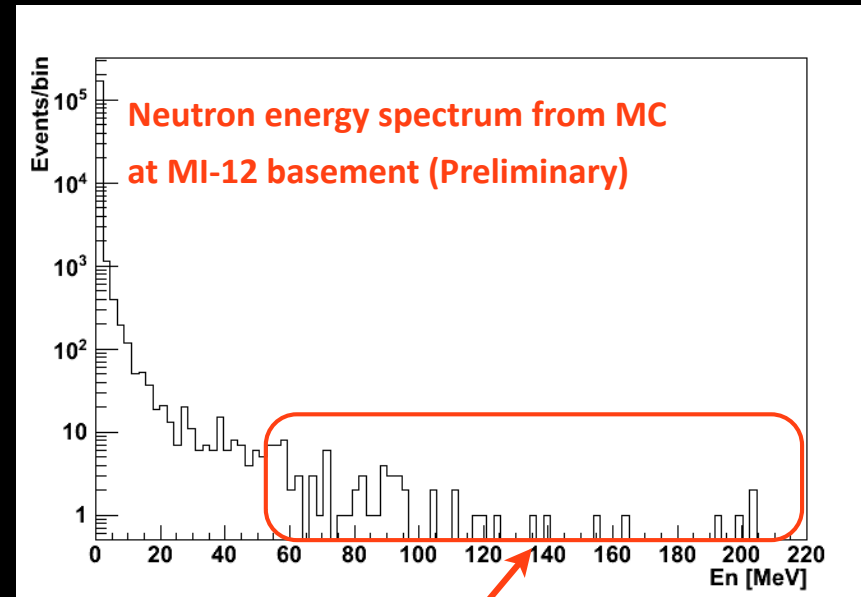
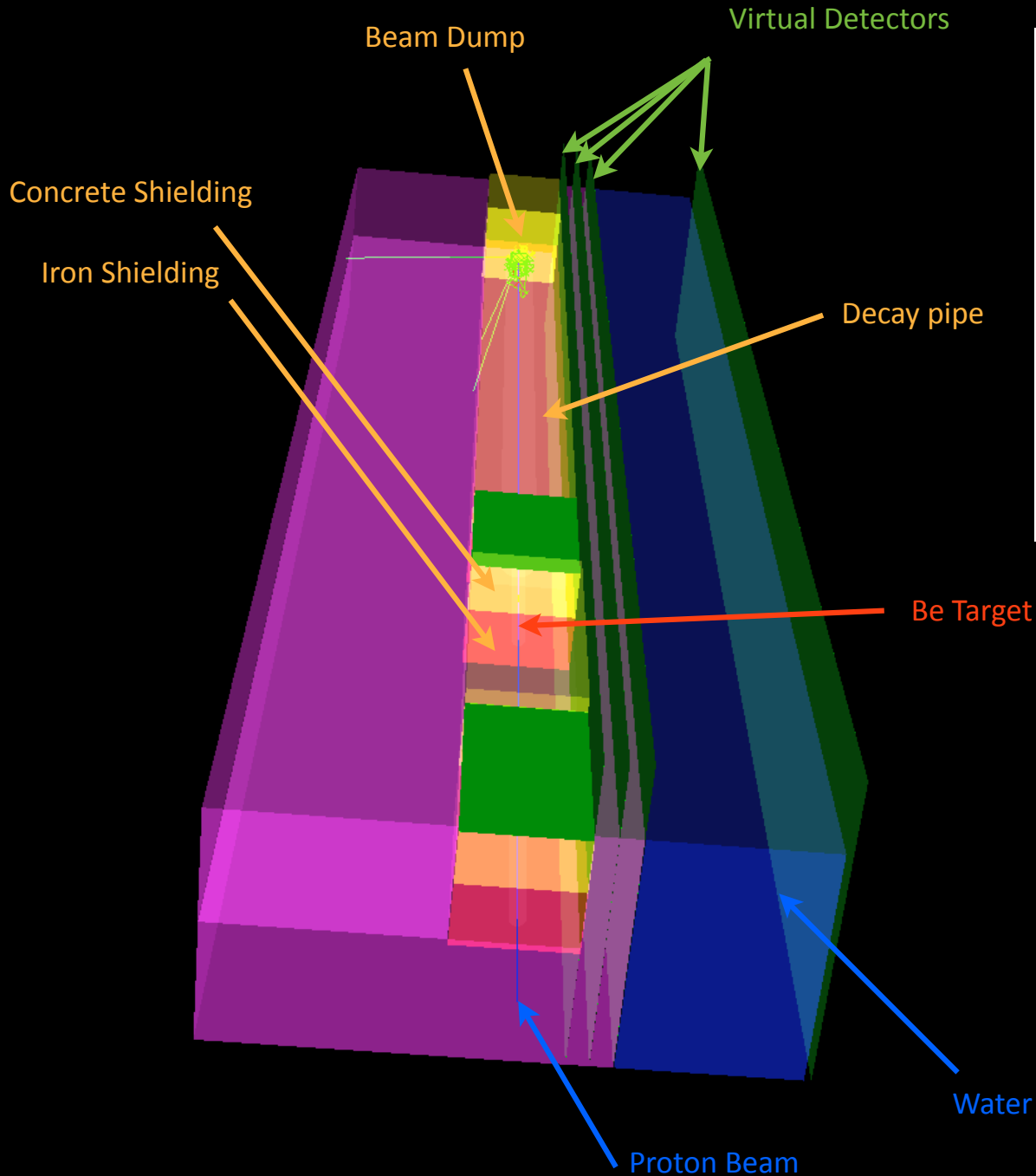
SciBath at BNB Target Building (Feb~Apr 2012)



- Pre-beam, in-beam, off-beam backgrounds measurements
- Data taking: Feb~Apr 2012
- Neutron flux and spectrum measurement (preliminary)
 $\phi_n = \sim 1 \text{ n/pulse/m}^2$



Beam Background Simulation



These fast neutrons are notorious ones

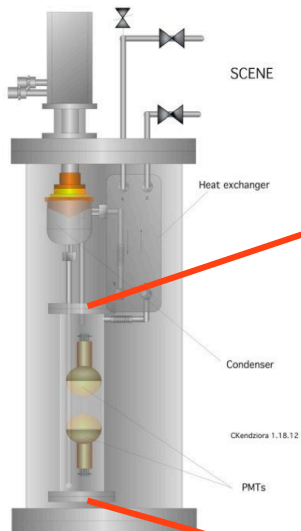
Fast Neutrons

- 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

Low Energy Threshold LAr Detector Development



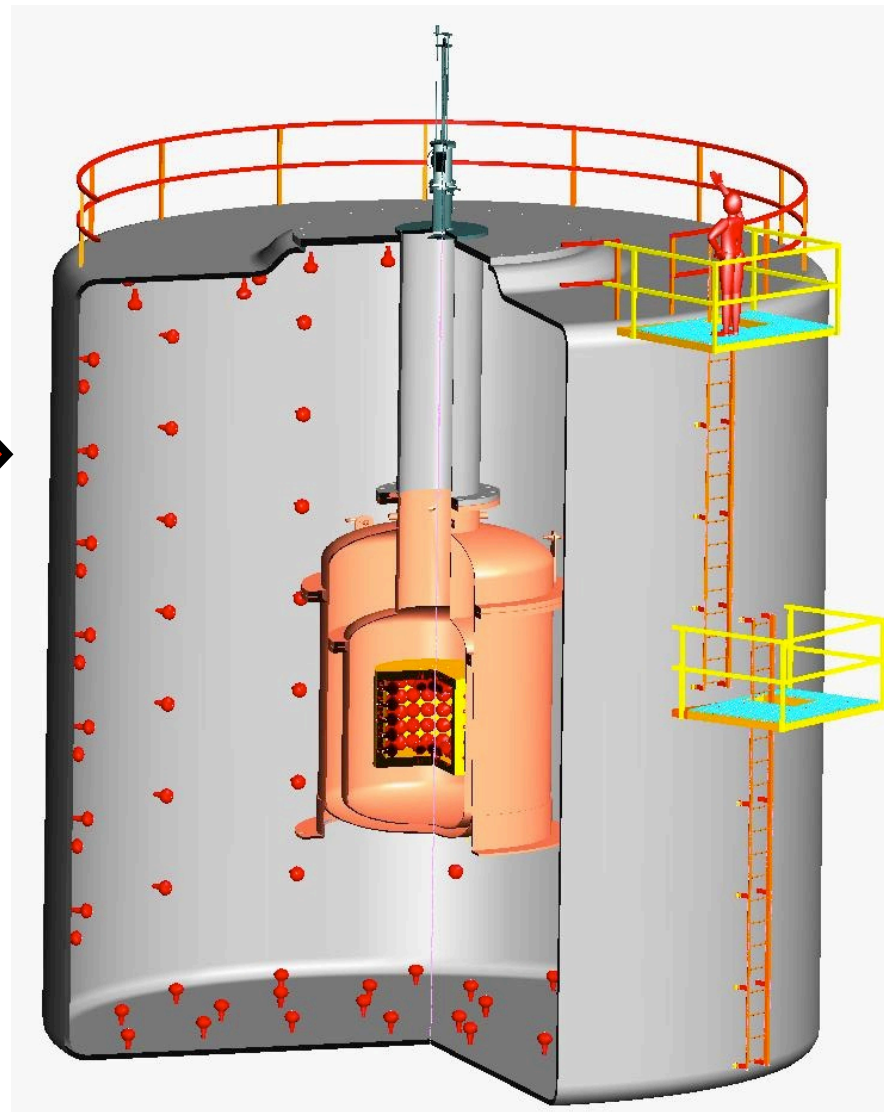
1-kg detector 2012

- Operational experience
- Measure scintillation light efficiency of nuclear recoils in LAr



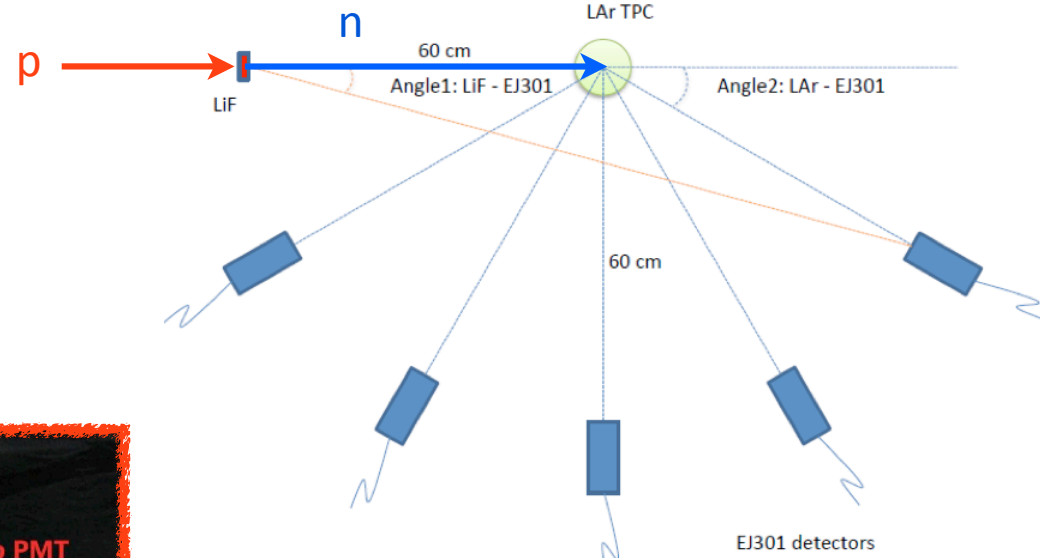
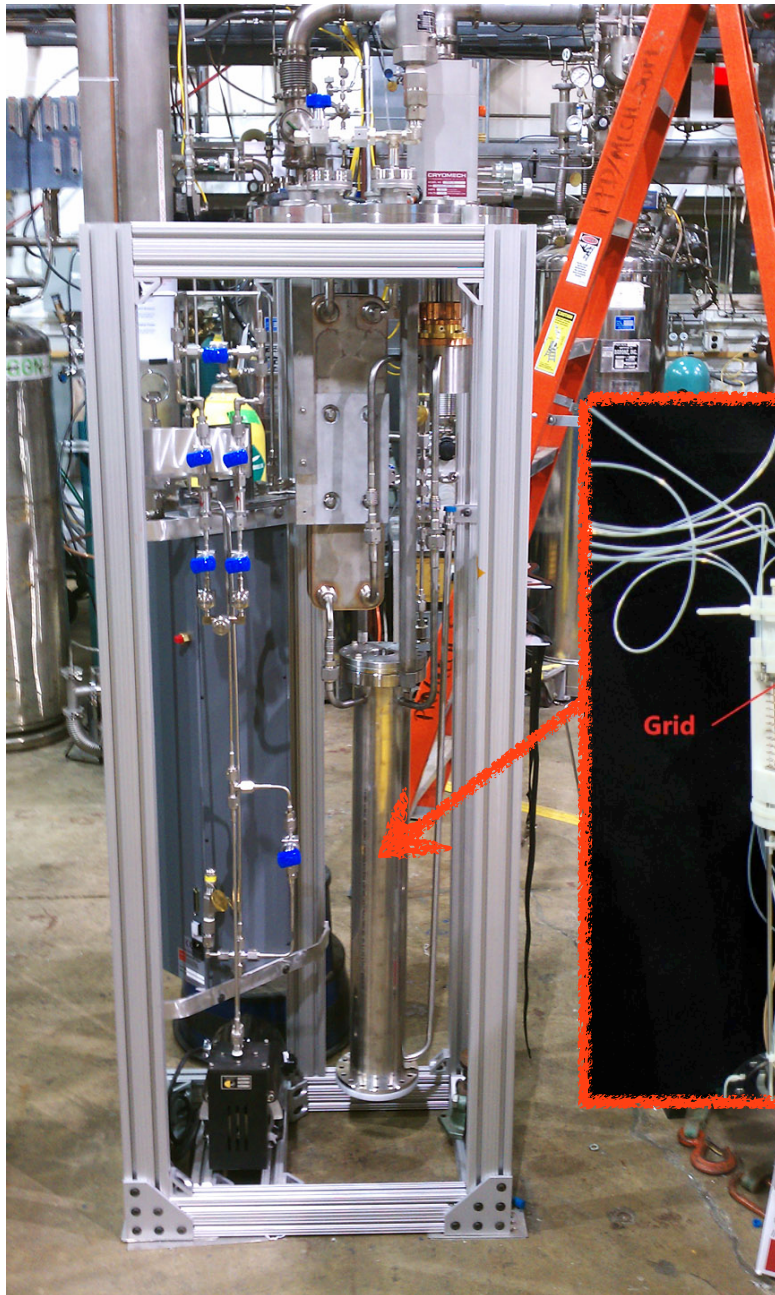
10-kg detector 2013

- Study beam induced neutron shielding near the beam target
- Characterize the BNB neutron backgrounds in LAr target
- Understand design issues of the ton-scale detector



**Ton-scale detector
for the CENNS experiment**

1-kg LAr Detector

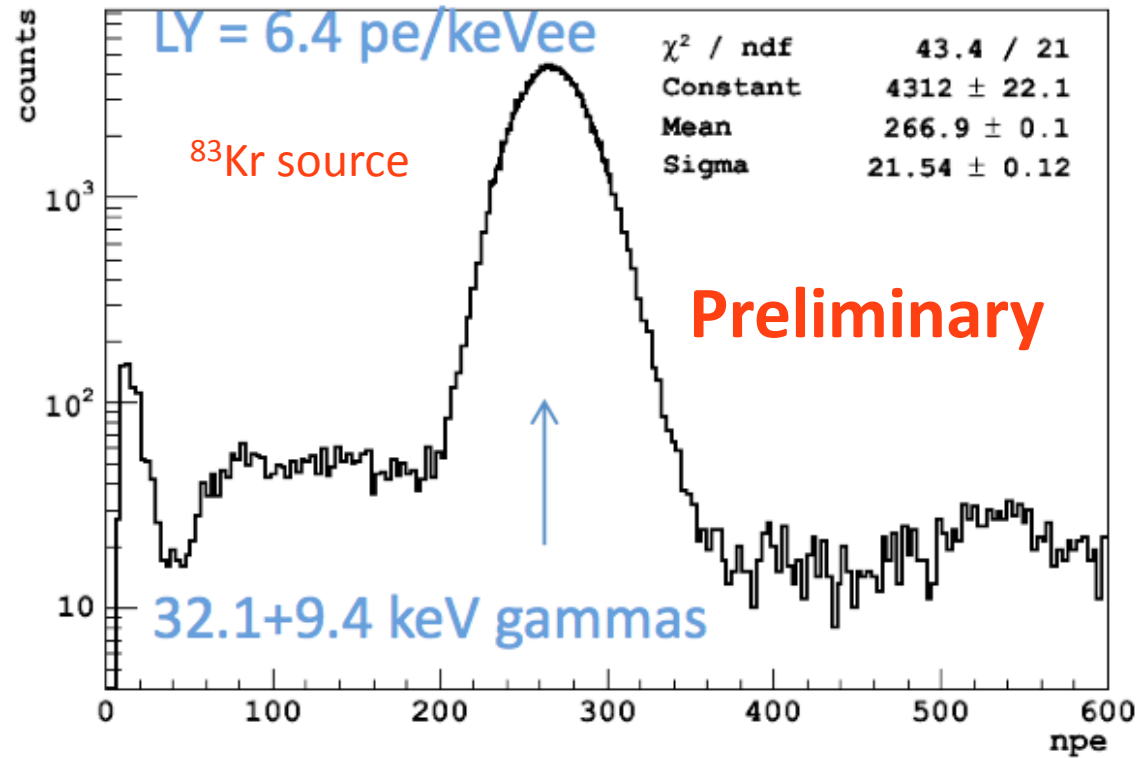


1-kg LAr prototype detector

- SCENE Collaboration: (CENNS+DarkSide)
SCintillation Efficiency of Noble Elements
- Goals:
Measure scintillation light yield
in low-energy (<50 keV) nuclear recoils
- Can run in single-phase mode
or dual phase TPC mode
- Use pulsed neutron beam
at University of Notre Dame

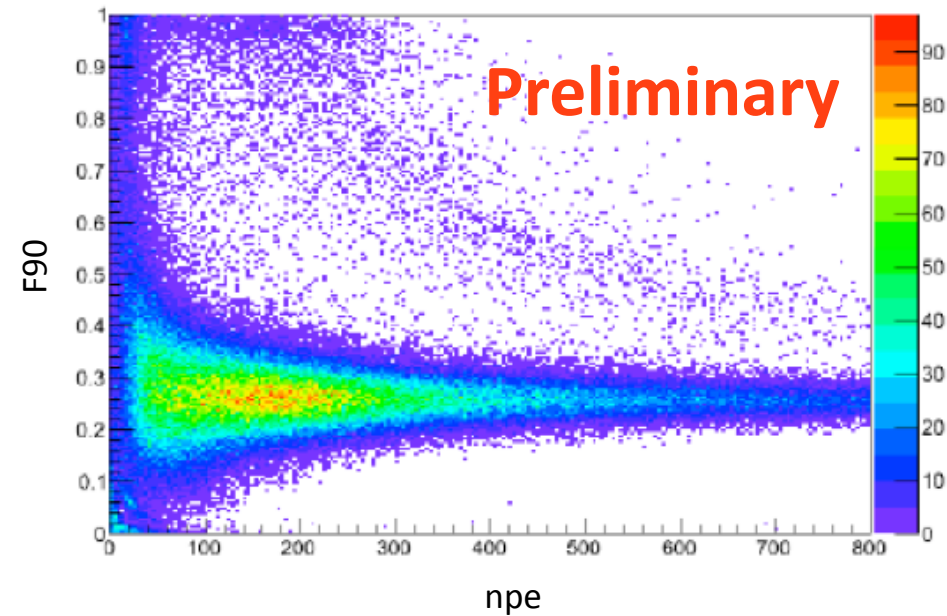
1-kg Detector Performance

Gamma Light Yield (single phase)

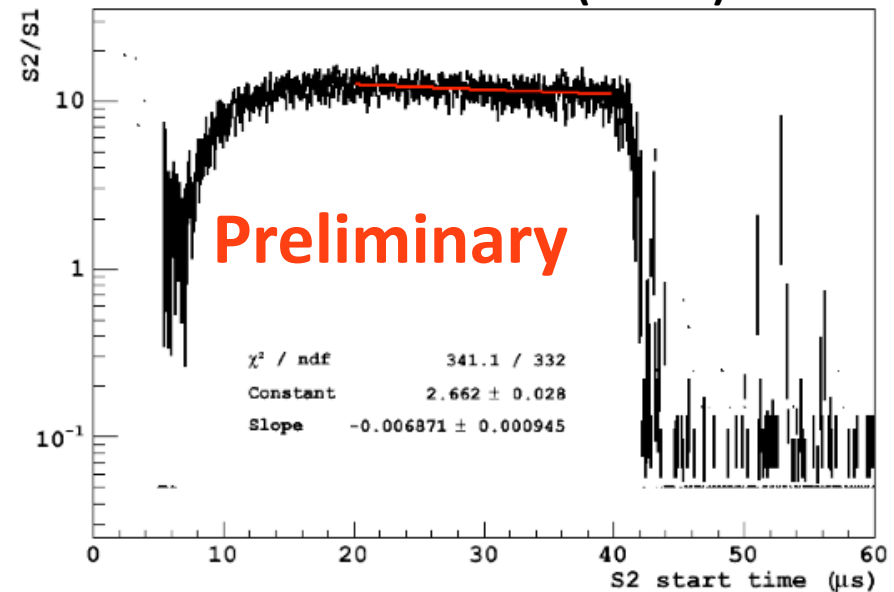


- Detector performance is good enough to carry out in-beam measurement
- Date taking at the end of 2012 and early 2013

Pulse Shape Discrimination



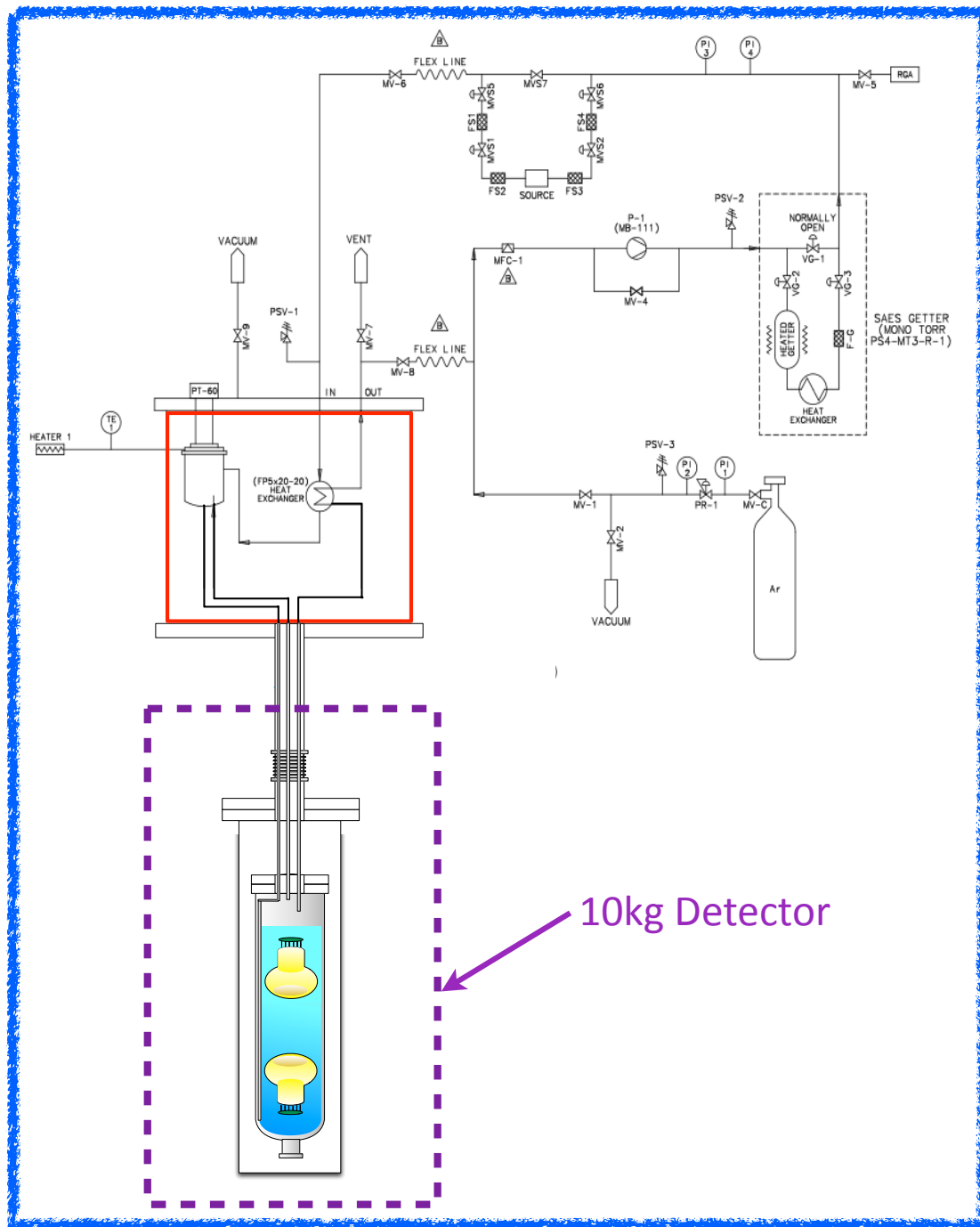
Electron Drift time (145us)



10-kg Detector

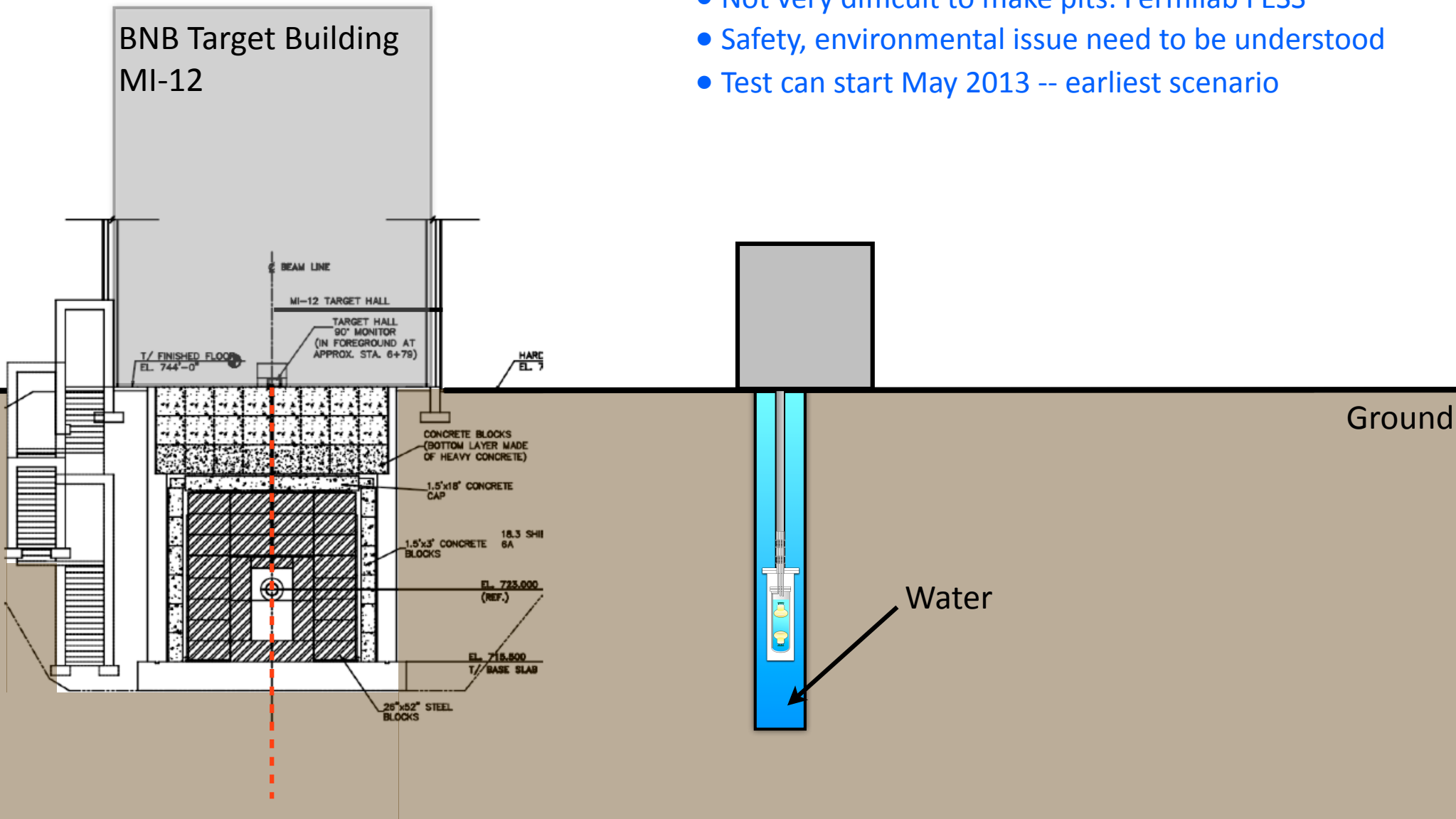
10-kg prototype detector

- Goals:
 - Neutron background study at BNB area
 - 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

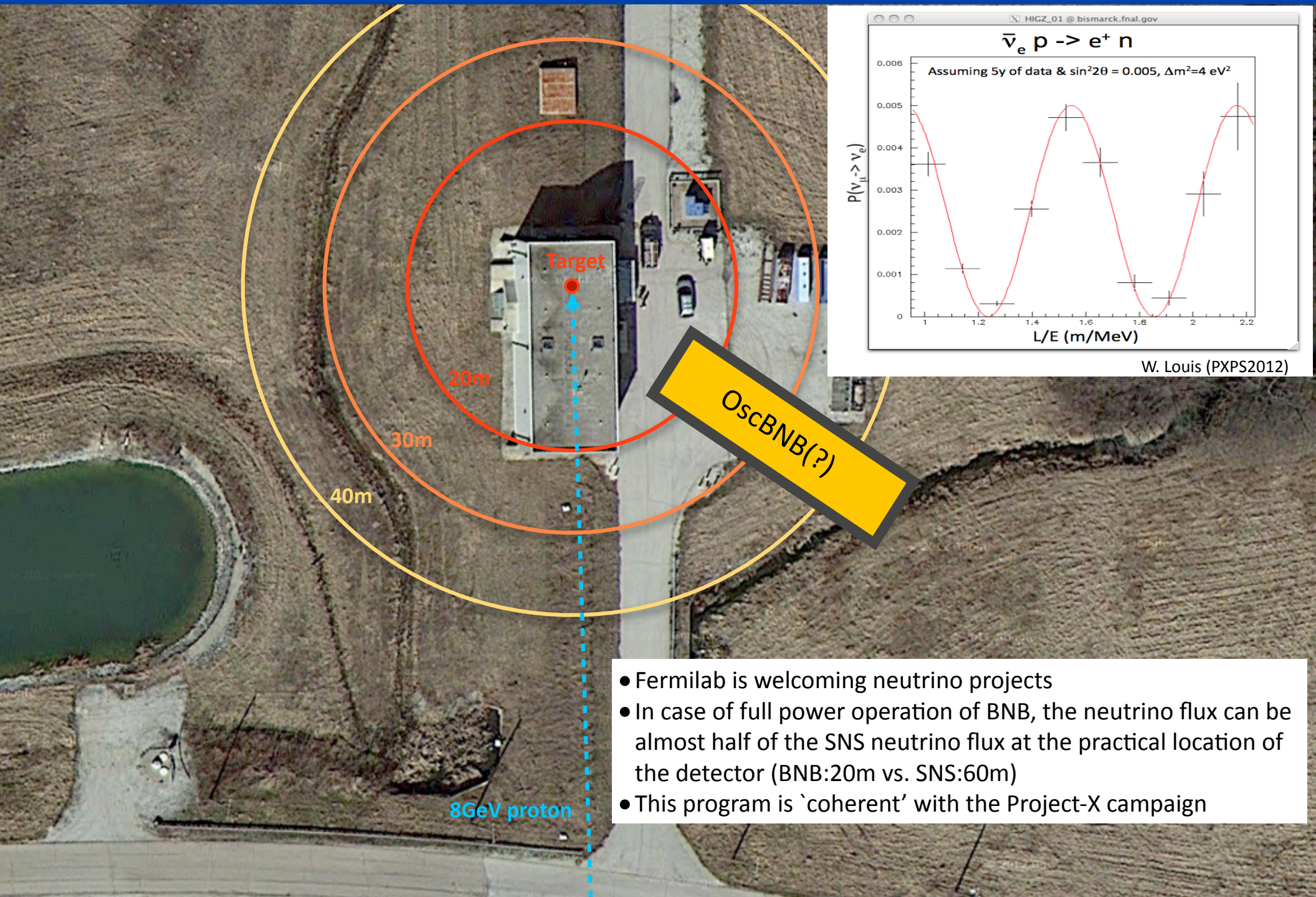


Neutron Shielding Test Option

- Not very difficult to make pits: Fermilab FESS
- Safety, environmental issue need to be understood
- Test can start May 2013 -- earliest scenario



OscBNB?



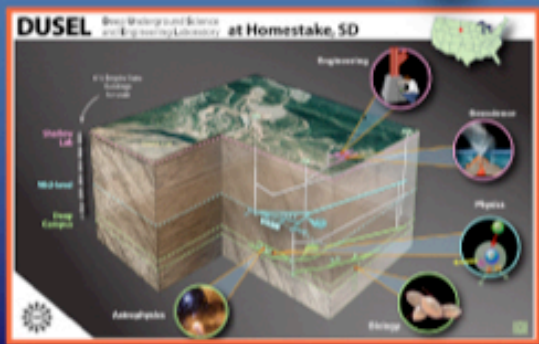
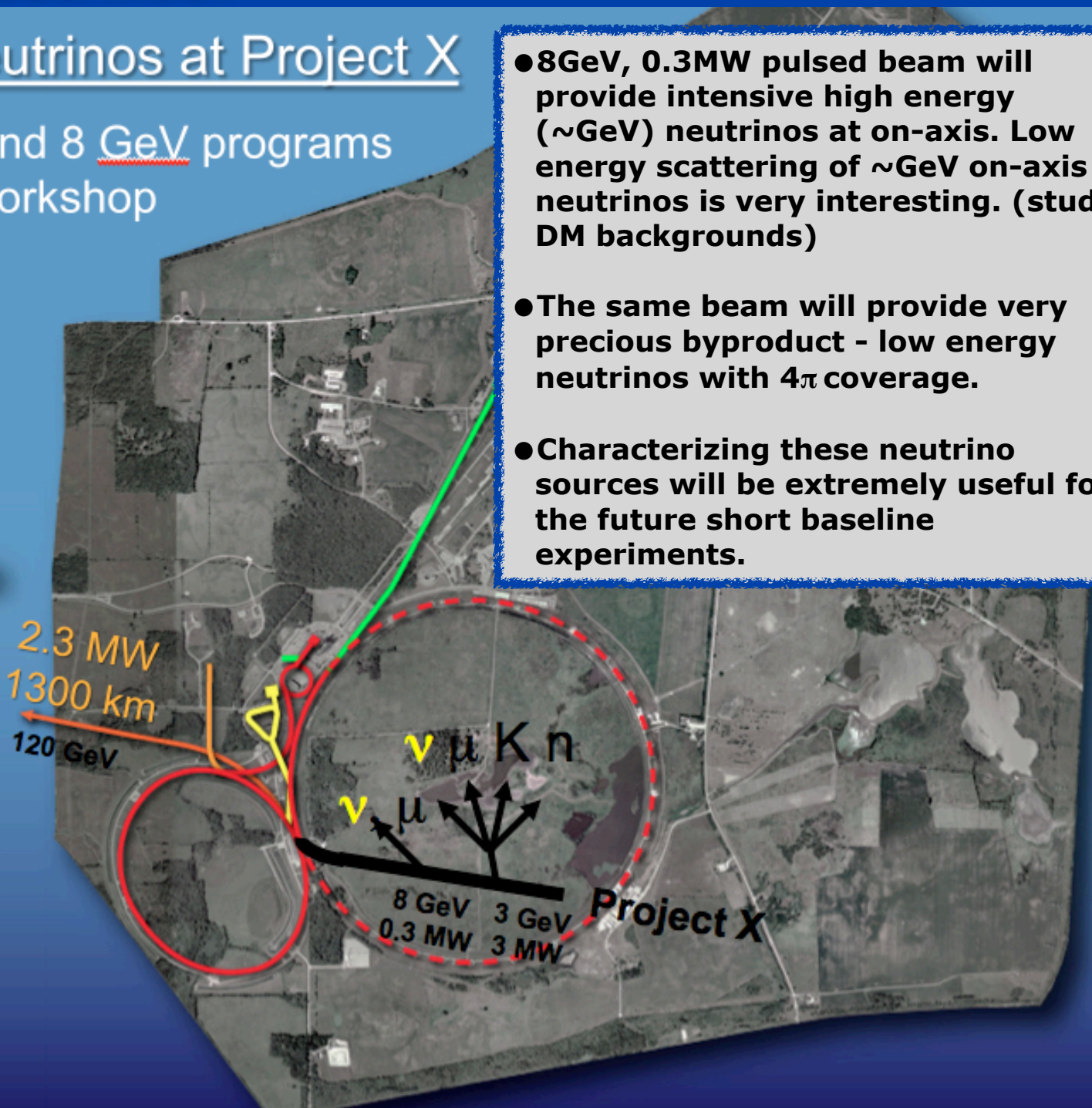
- Fermilab is welcoming neutrino projects
- In case of full power operation of BNB, the neutrino flux can be almost half of the SNS neutrino flux at the practical location of the detector (BNB:20m vs. SNS:60m)
- This program is 'coherent' with the Project-X campaign

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 (\sim GeV) neutrinos at on-axis. Low energy scattering of \sim 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.

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 CENNS experiment to Fermilab Physics Advisory Committee (~ 2014)
- CENNS experiment (2017 \sim 2018)
- OscBNB experiment at Fermilab? (2018 \sim)
 - 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.
- A chance to design a detector close to source (4π coverage detector facilities?)

- **A lot of interesting physics cases in low energy neutrino interactions**
More details: <https://indico.fnal.gov/conferenceDisplay.py?confId=5926>
- **Coherent scattering of neutrinos 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
- **CENNS Collaboration**

Fermilab, Duke University, Indiana University, University of Florida, North Carolina State University, University of Houston, UCLA, LANL, INFN (Italy)

*** We are welcoming new collaboration**