Coherent Elastic Neutral Current Neutrino Nucleus Scattering Measurement at Fermilab

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Short Baseline Neutrino Workshop
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Outline

- Coherent Elastic Neutral Current Neutrino Nucleus Scattering (Coherent-NCvAS)
- Dark Matter
- Neutrino Sources for the coherent-NCvAS
- Detector R&D at Fermilab
- Summary

Coherent-NCvAS

The first prediction of Coherent-NCvAS

The first convincing evidence of neutral current from CERN (1973)

$$\bar{\nu}_\mu + e \longrightarrow \bar{\nu}_\mu + e$$

Coherent Elastic Neutral Current Neutrino Nucleus Scattering

A straightforward calculation given the existence of weak neutral current

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Coherent effects of a weak neutral current

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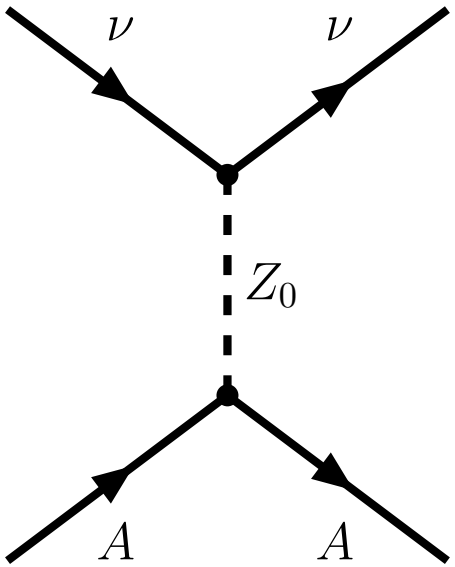
(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \rightarrow \nu + A$ should have a sharp coherent forward peak just as $e + A \rightarrow e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm^2 on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \rightarrow \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

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

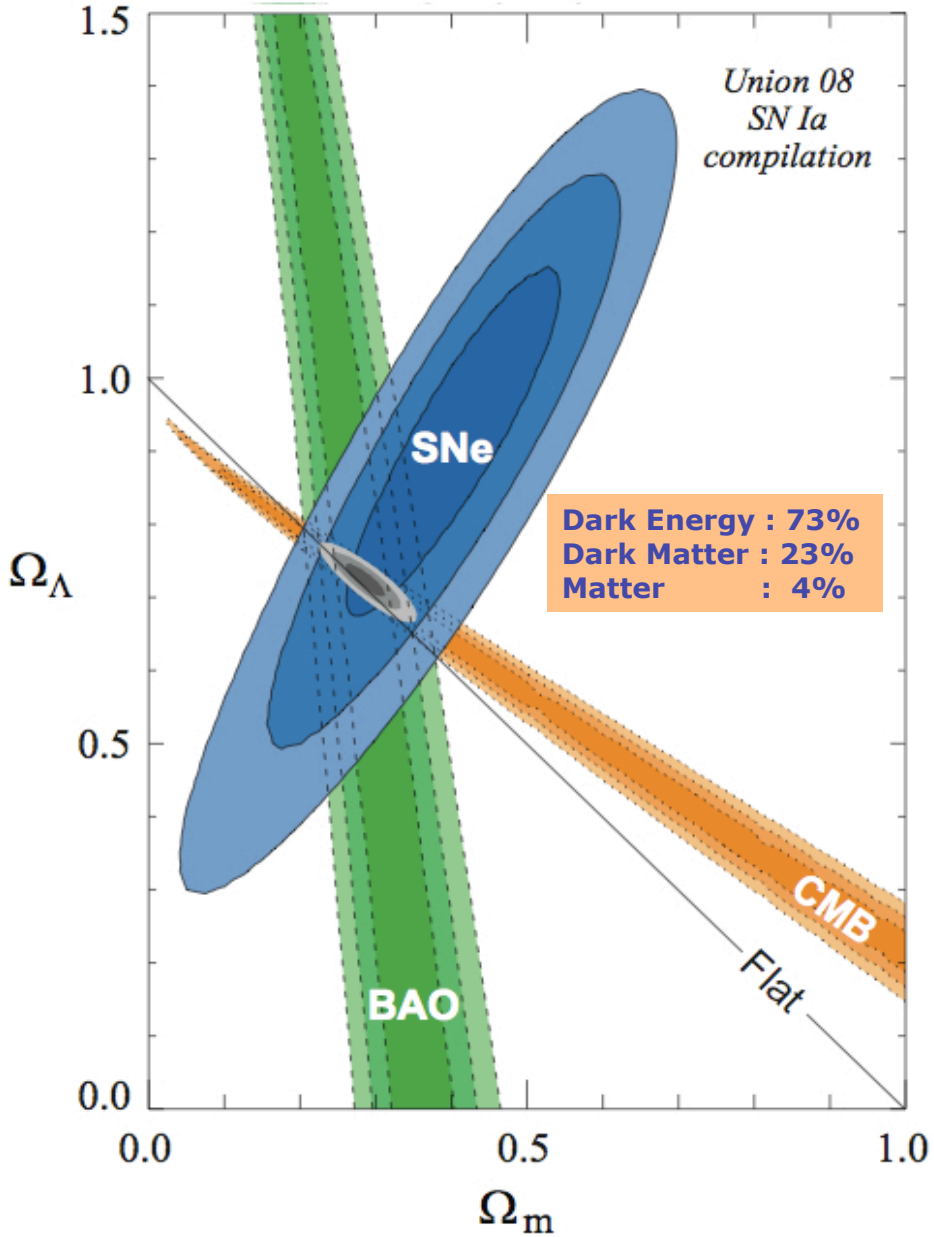
Requires a ton-scale detector with ~10 keV energy threshold

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

Recent innovation of Dark Matter detector technology makes it possible to access coherent-NCvAS

Dark Matter

Dark Matter



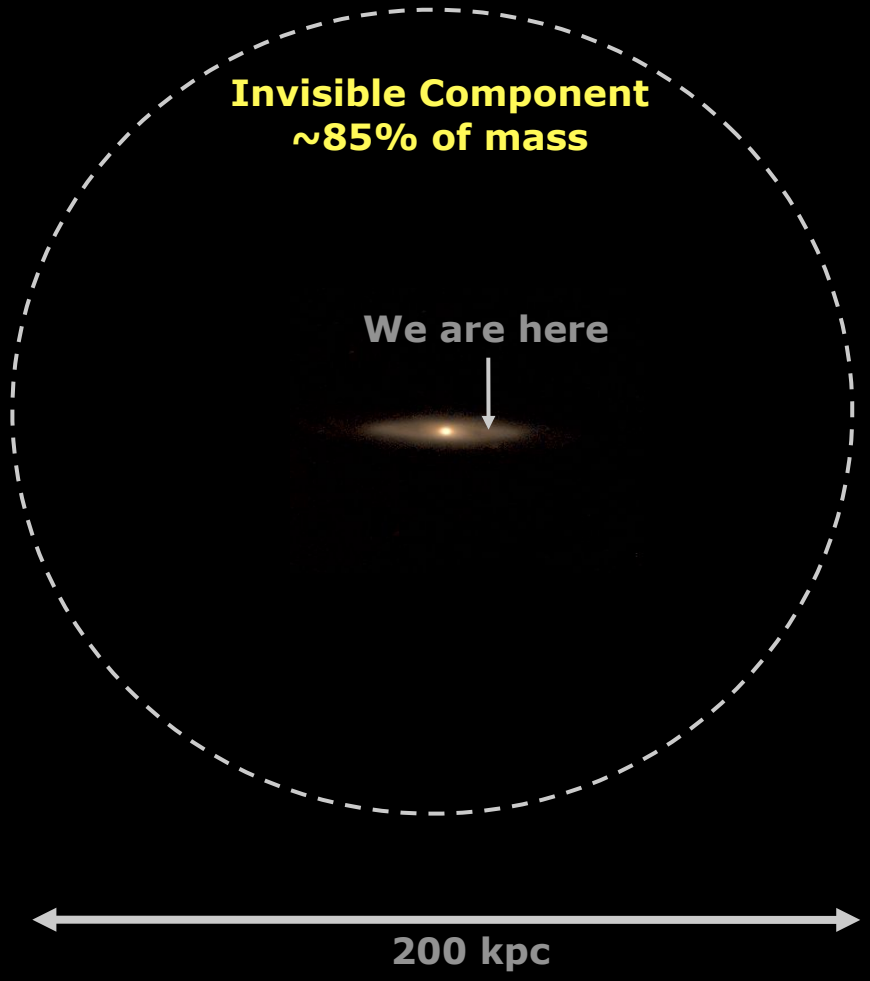
- We know that the Dark Matter is stable / non-baryonic / nonrelativistic / interacts gravitationally
- We don't know what it actually is: mass / coupling / spin / composition / distribution in the Universe …
- Cosmology suggests to probe EW scale

$$\Omega_{DM} \sim \langle \sigma_A v \rangle^{-1}$$

$$\sigma_A = \alpha^2 / M^2_{EW}$$

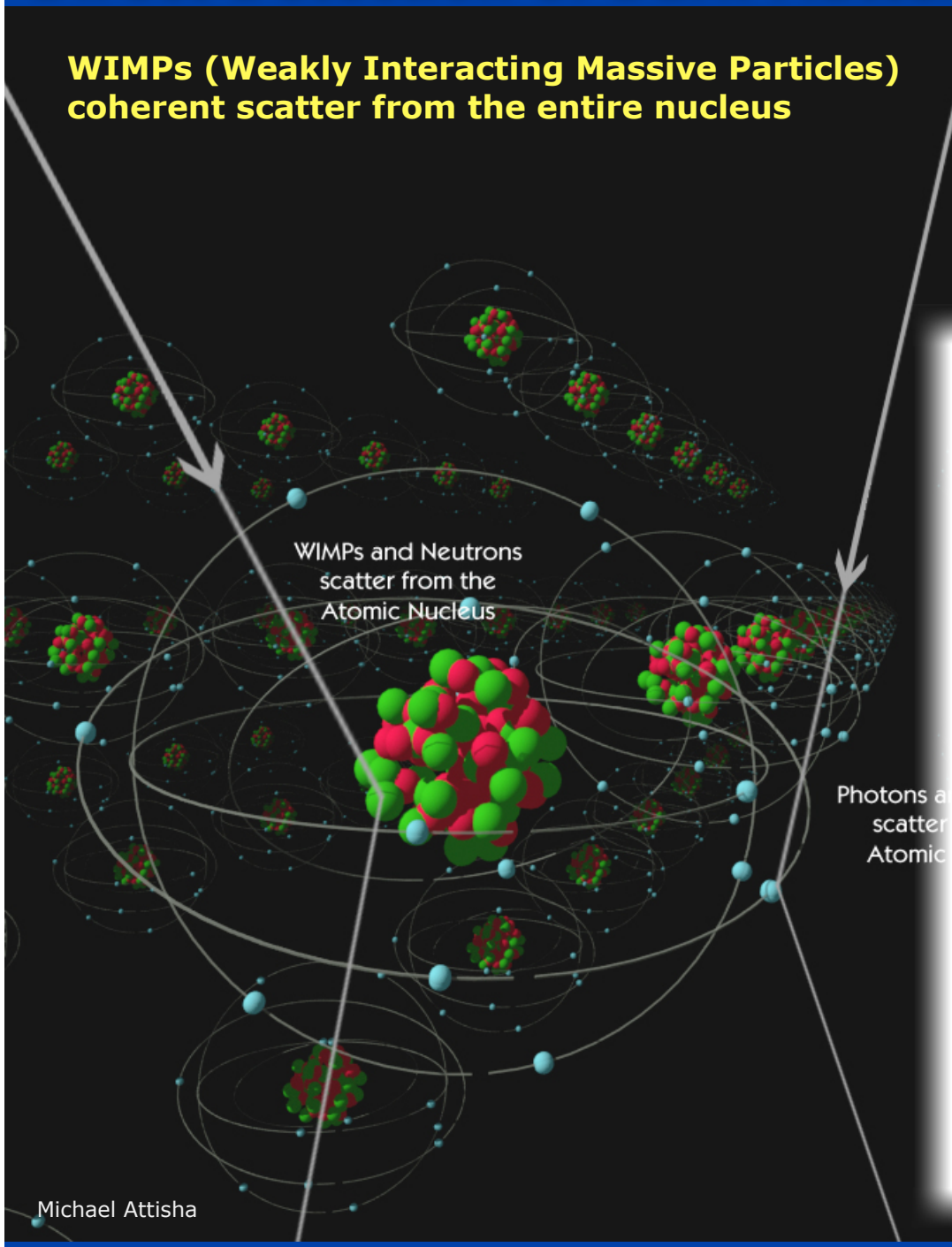
- SUSY model provides electroweak scale stable neutral particle
- However Dark Matter is not necessarily a SUSY particle.

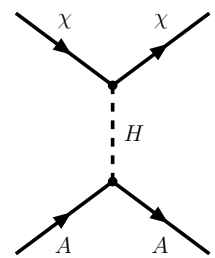
Dark Matter Distribution



Direct Detection of Dark Matter

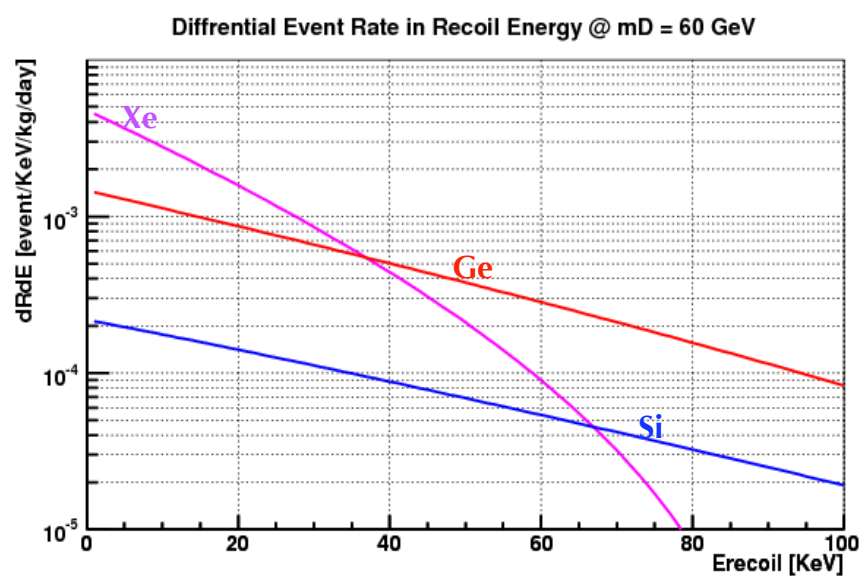
WIMPs (Weakly Interacting Massive Particles) coherent scatter from the entire nucleus





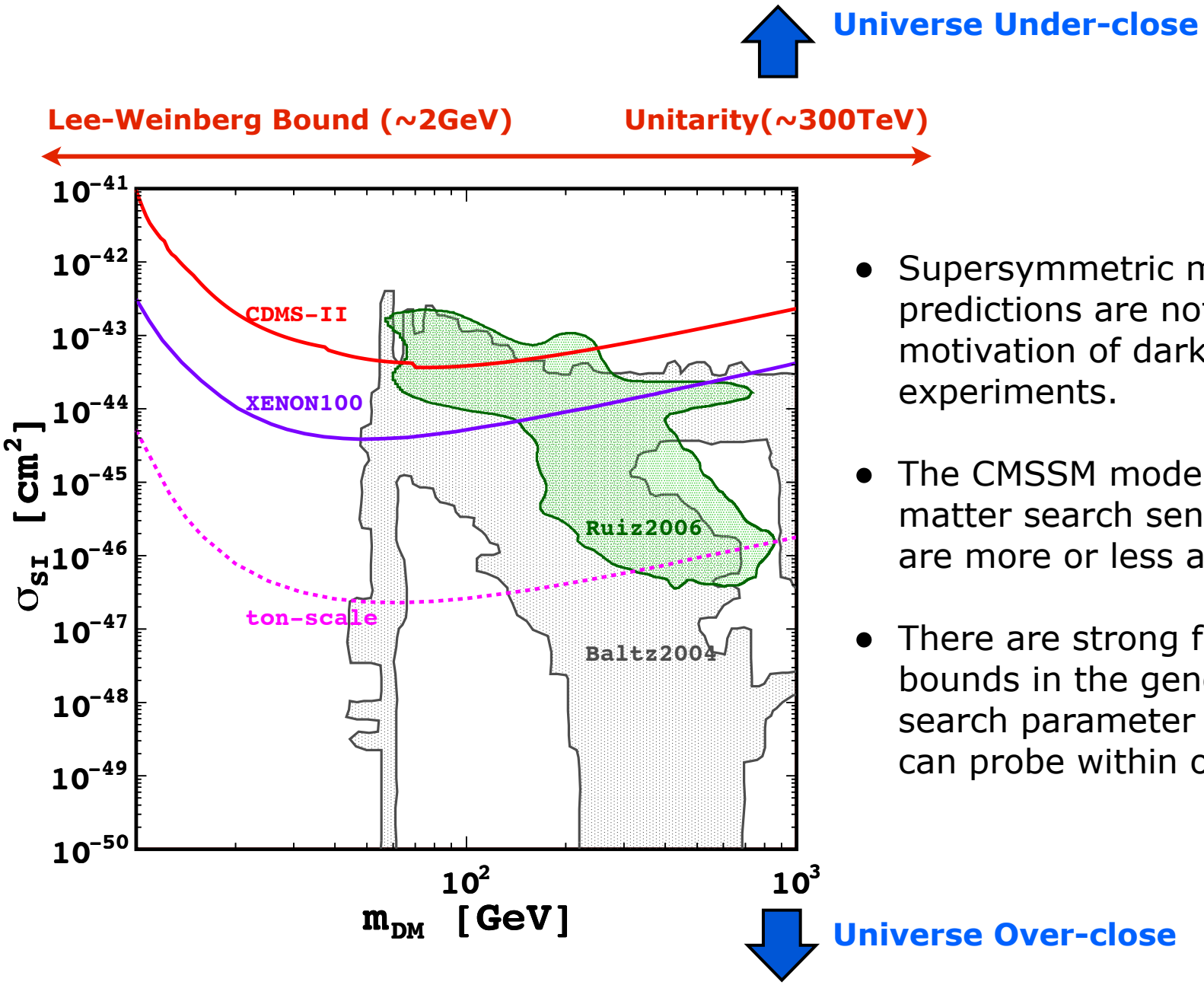
$$\sigma_{\chi N} \simeq \frac{4}{\pi}\mu^2[Zf_p + (A-Z)f_n]^2$$

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



Michael Attisha

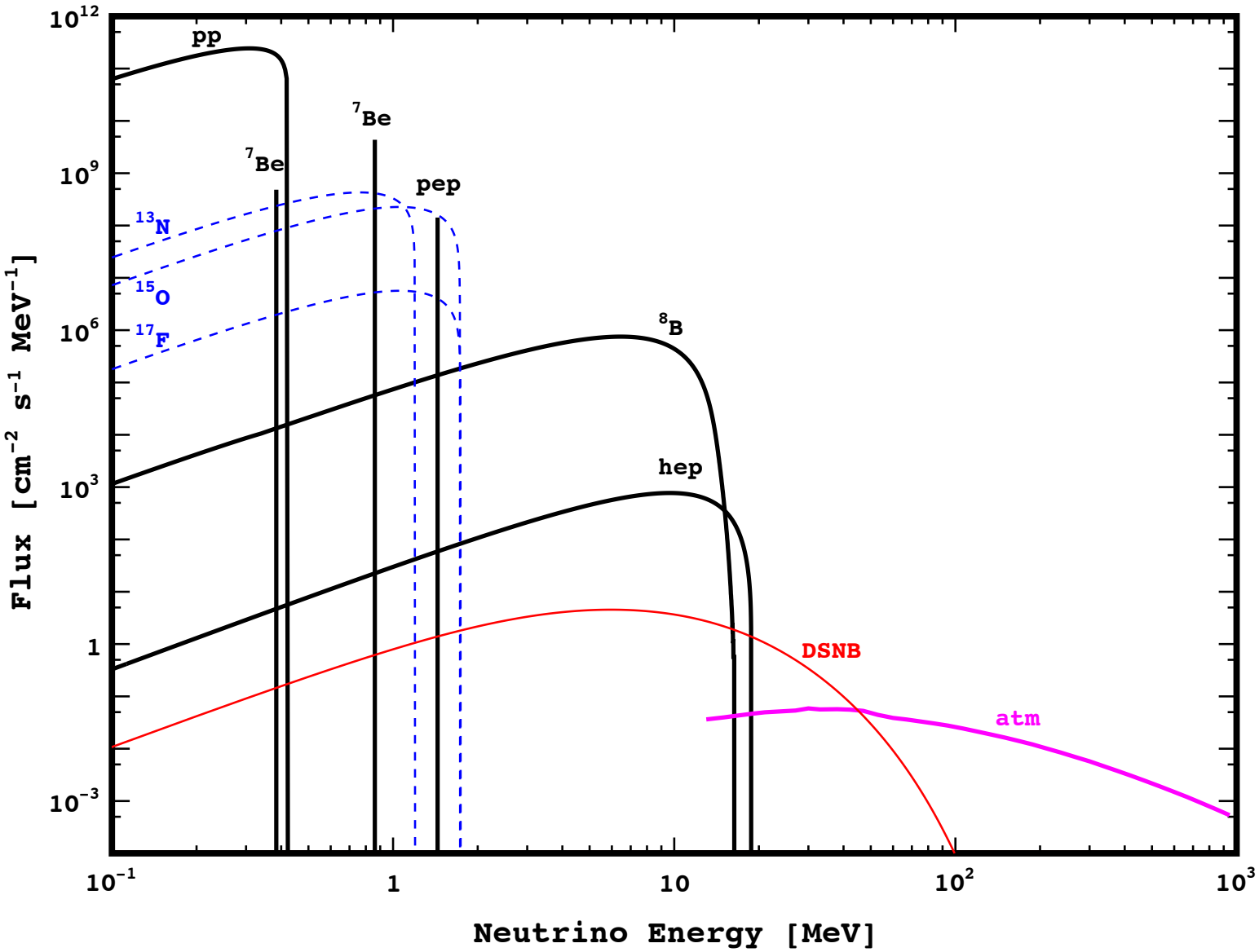
Sensitivity of Dark Matter Search



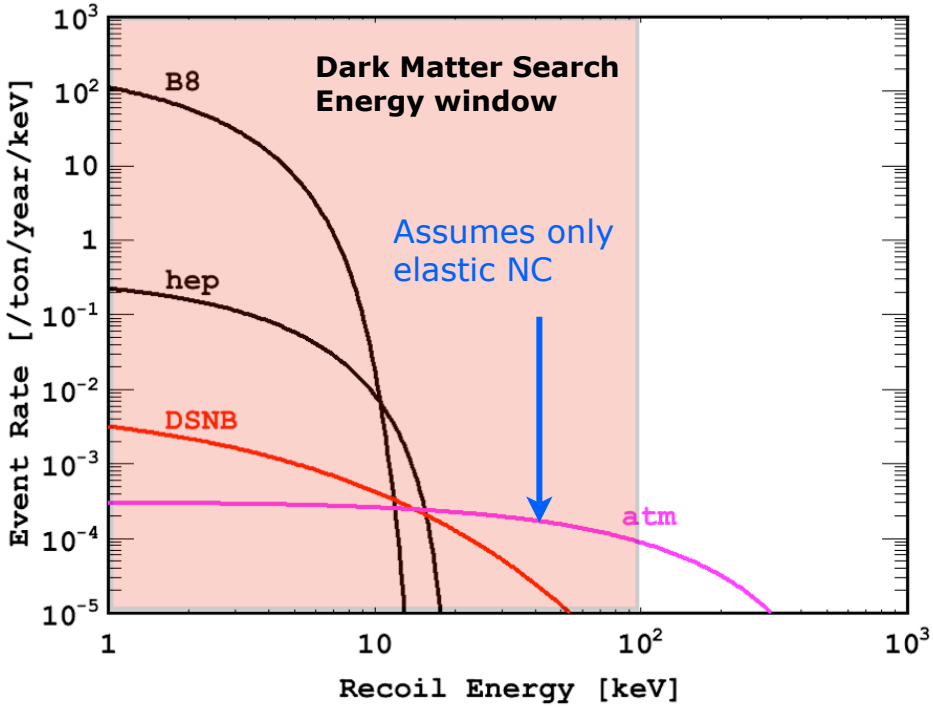
- Supersymmetric model predictions are not the major motivation of dark matter search experiments.
- The CMSSM models in the dark matter search sensitivity plots are more or less a wall paper.
- There are strong fundamental bounds in the generic WIMP search parameter space that we can probe within our generation.

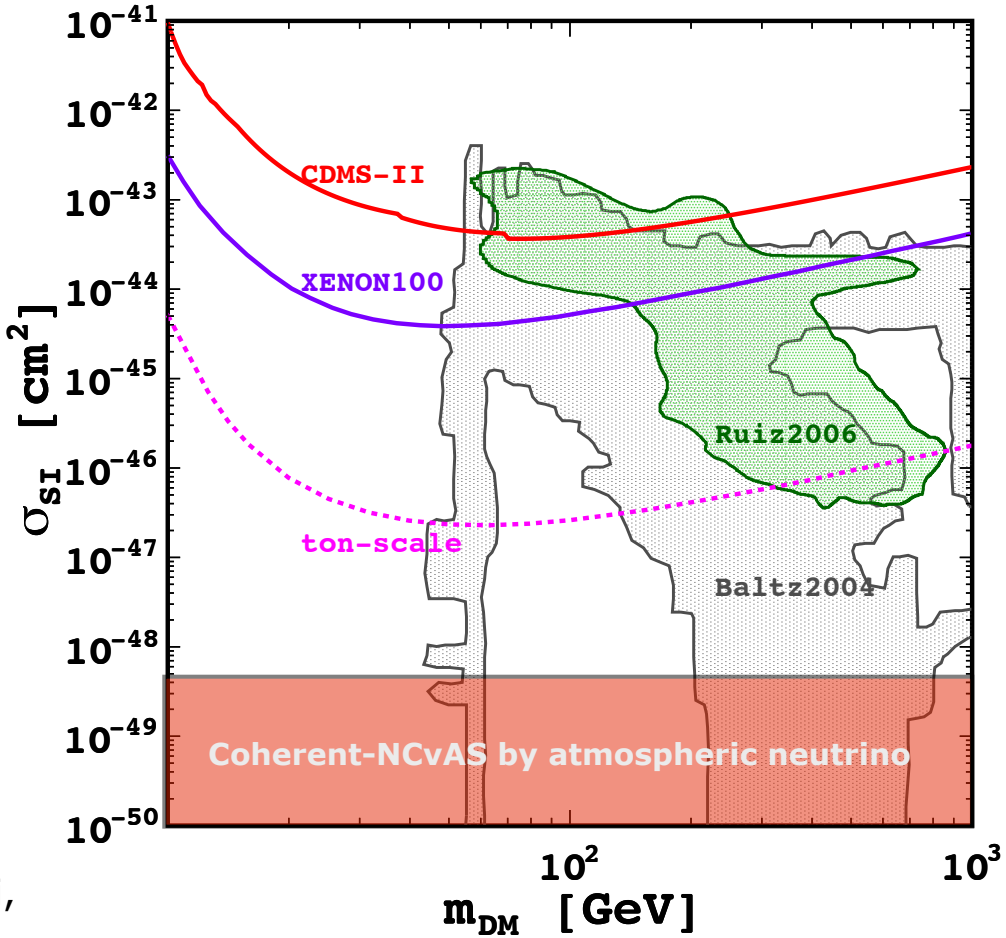
Irreducible Backgrounds

Neutrinos from Astrophysical Origin



Irreducible Backgrounds





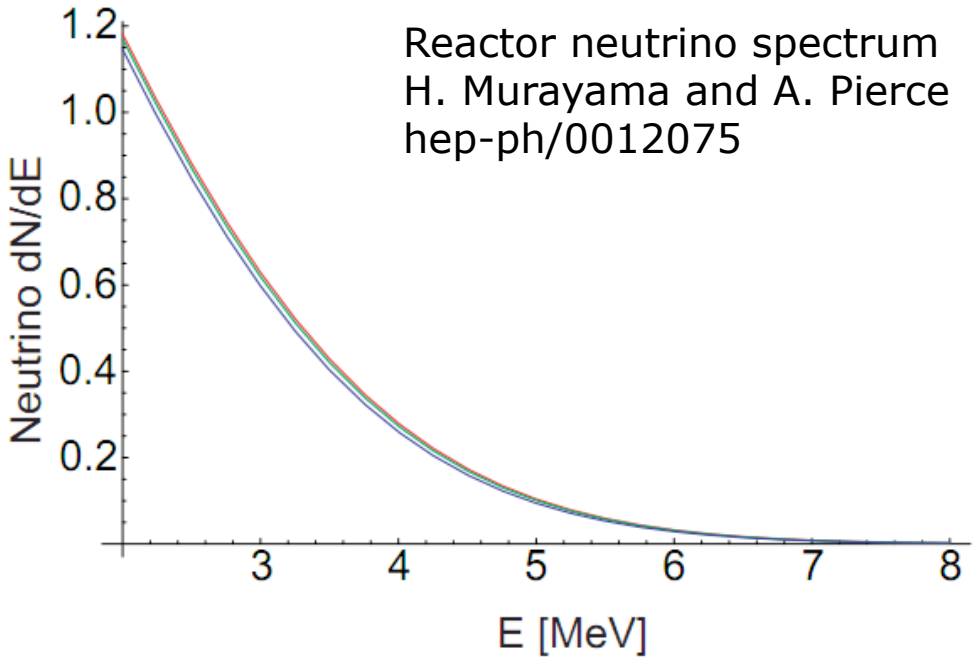
- Coherent scattering of atmospheric neutrino is an irreducible background in the future *O*(10 ton) scale dark matter experiments (see Strigari, arXiv:0903.3630)

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

Sensitivity of Dark Matter detectors will be saturated out by irreducible neutrino backgrounds: No zero-background experiments

Neutrino Sources for Coherent-NCvAS

Reactor Neutrinos



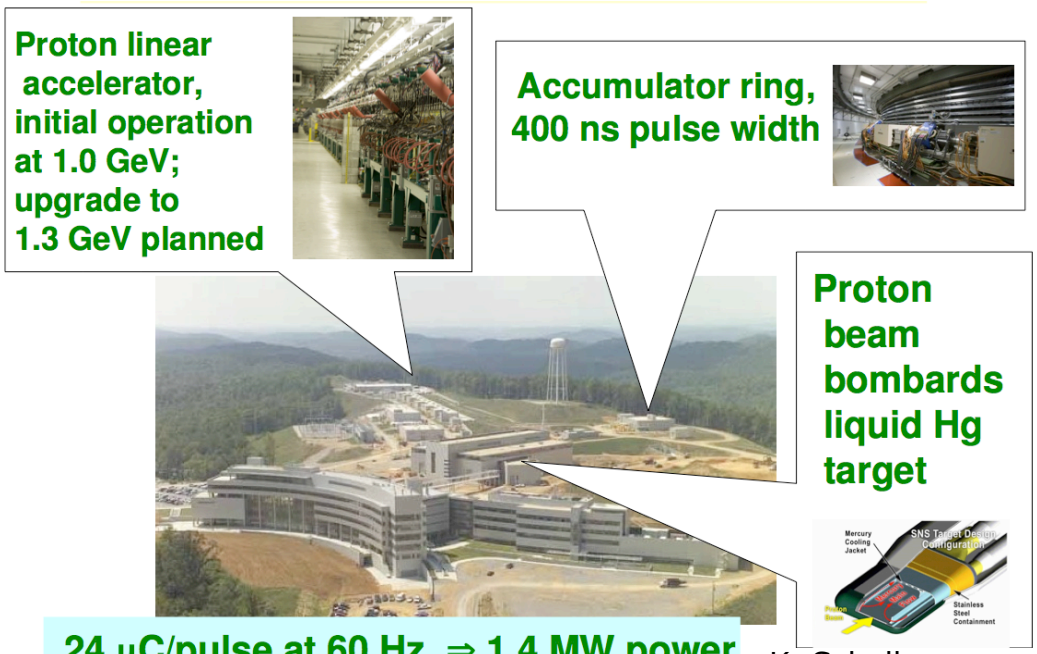
$$E_{max} \simeq \frac{2E_\nu^2}{M} < \mathrm{keV}$$

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

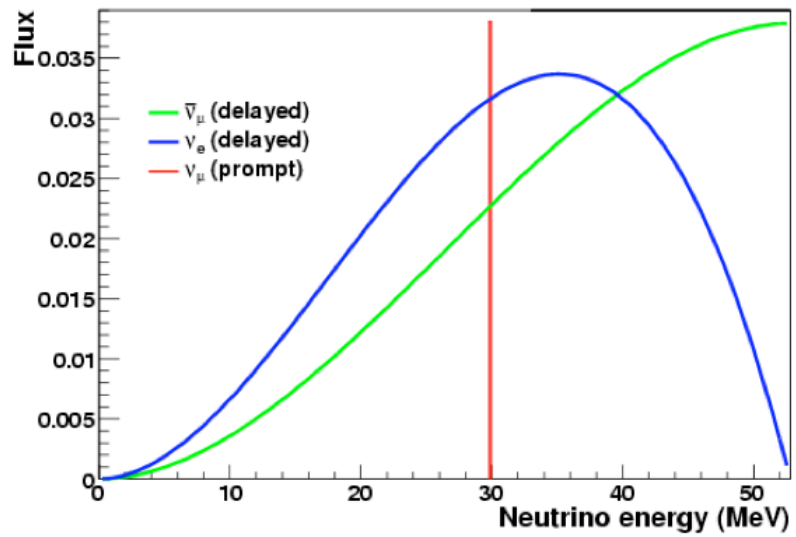
- Ultra-clean, kg-size, ~10 eV threshold detector
- Need to overcome steady state backgrounds and detector noise
- Reactor off-time can be used for background subtraction
- Detector development is challenging for a realistic experiment

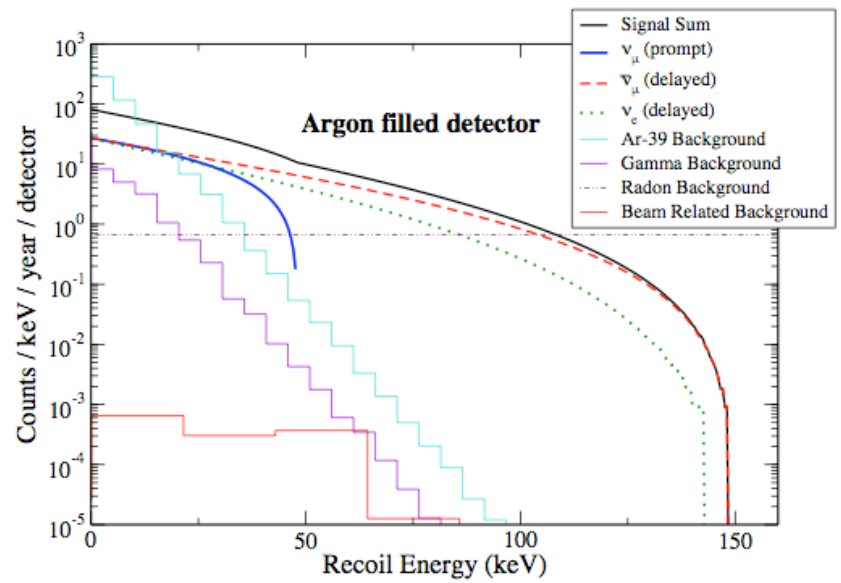
Neutrino Source from Stopping Pions

- 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



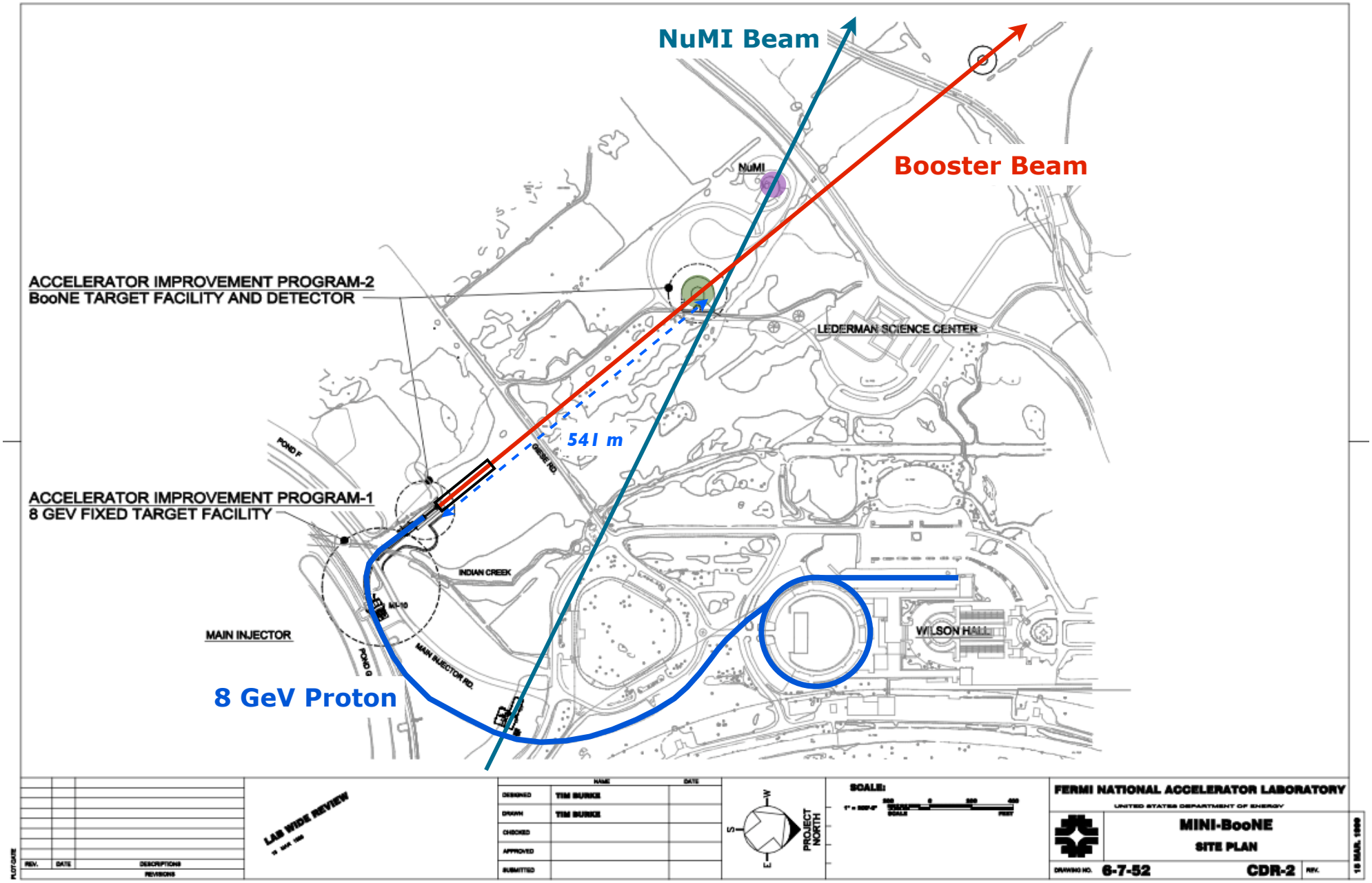
K. Scholberg





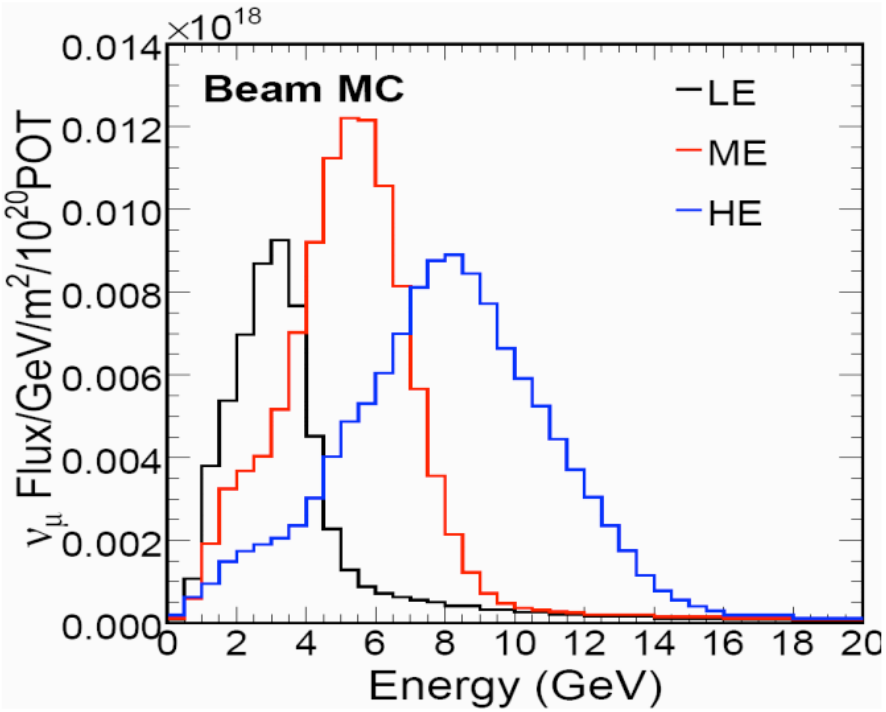
- Flux ~ 10^7/sec/cm^2 at 20m from the target
- 60 Hz pulsed source
- Steady state background rejection factor ~10^{-4}
- Expected event rate in a single-phase 500kg LAr detector: ~890events/year of detection (E_{th}> 20 keV) at the proposed experiment site (46m from SNS target)

Neutrino Sources at Fermilab



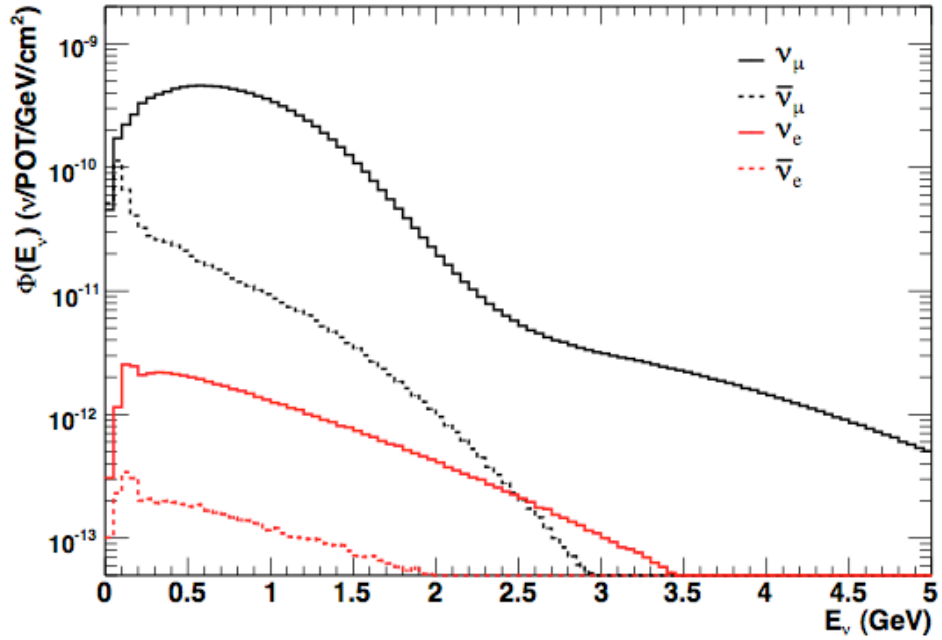
On-aXis Neutrinos

- **NuMI Beam**



1040m from the NuMI target with the horns separated by 10m and the target inside the first horn (LE), or retracted 1m (ME) or 2.5m (HE). (arXiv:0709.2737)

- **Booster Beam**

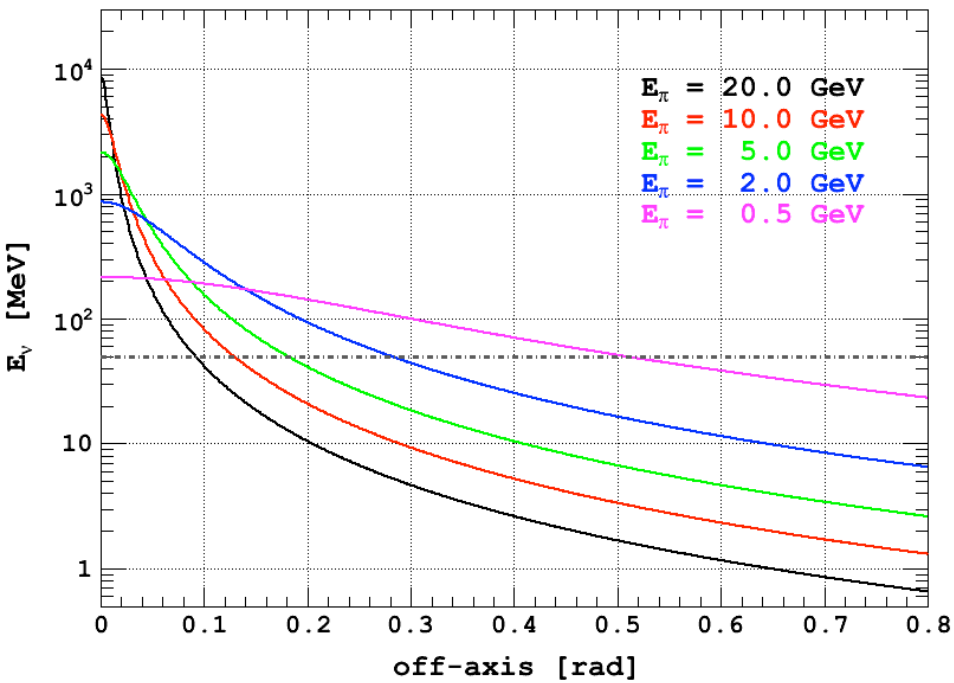


Total predicted flux at the MiniBooNE detector by neutrino species with horn in neutrino mode. (arXiv:0806.1449)

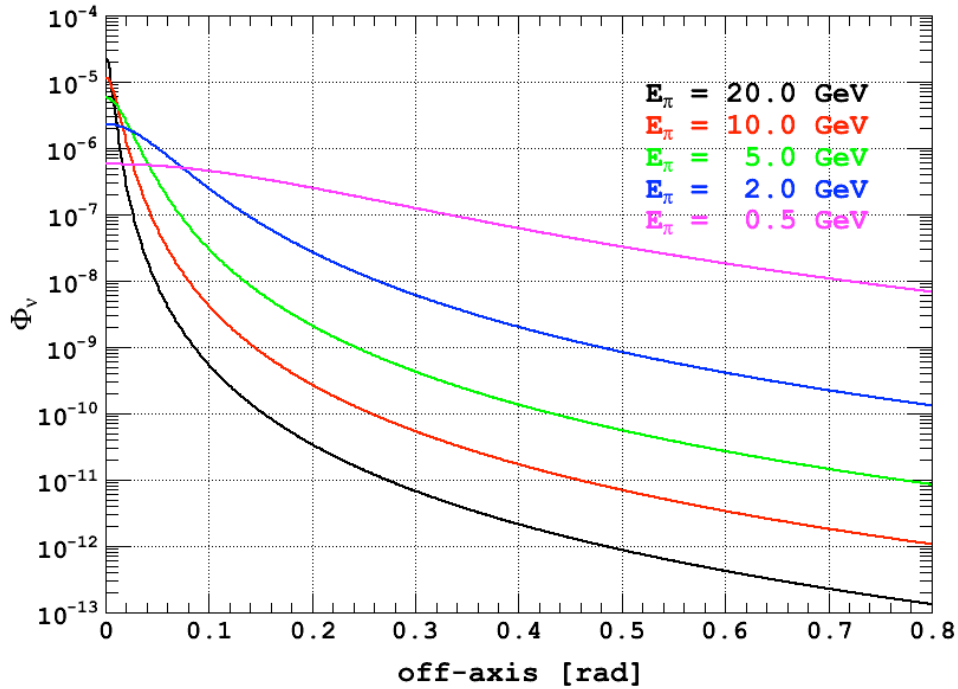
- **Neutrino energy of order GeV**
- **Too high energy for a pure coherent-NCvAS study (need below 50MeV)**
- **But possibly OK for low energy (<100 keV) neutrino scattering study**

Off-aXis Neutrinos

- **Neutrino Energy at Off-aXis**



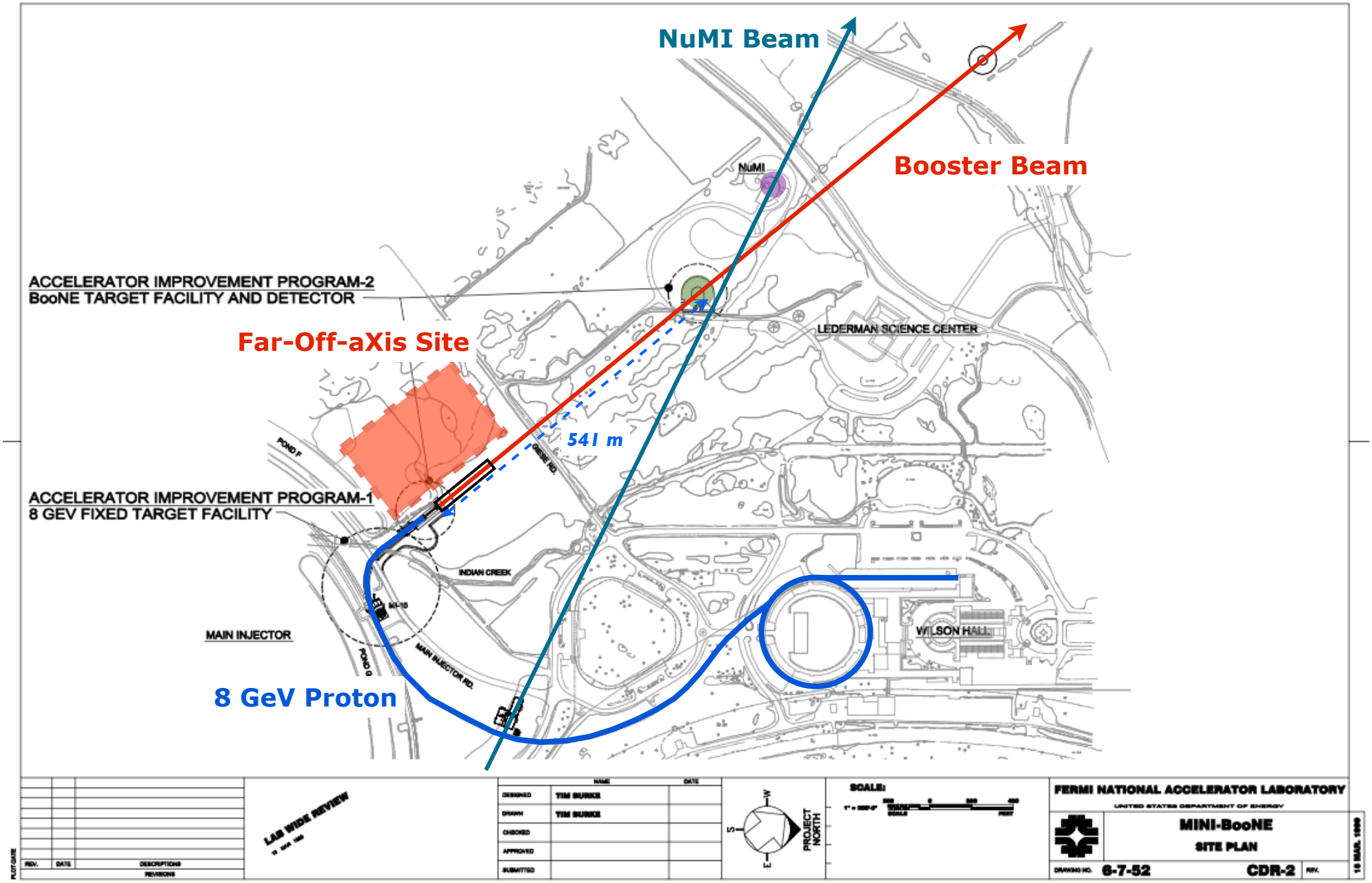
- **Neutrino Flux at Off-aXis**



- It is well known that the energy of neutrino beam is lower and narrower at the off-axis

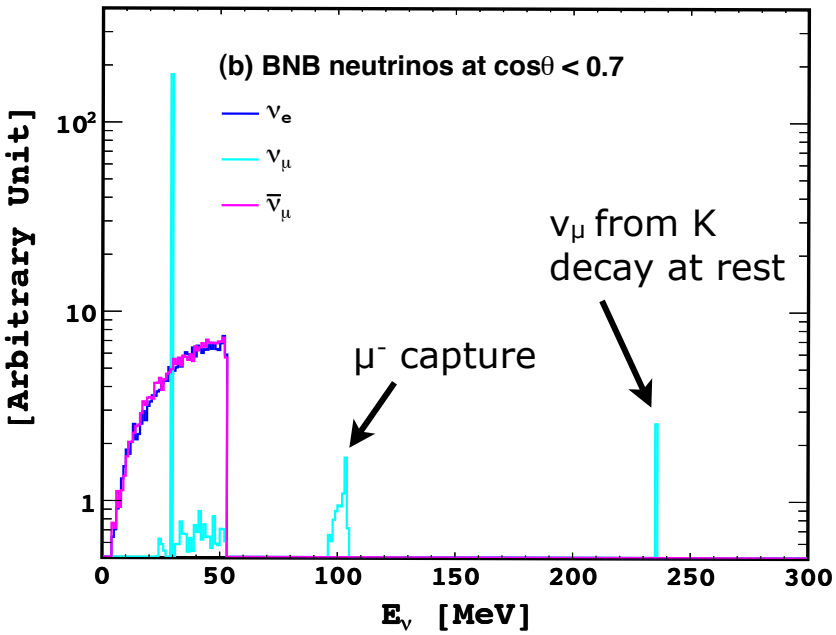
- The neutrino energy is still order of GeV scale at small off-axis angle (see John Cooper's talk (2011-05-13) in this workshop)

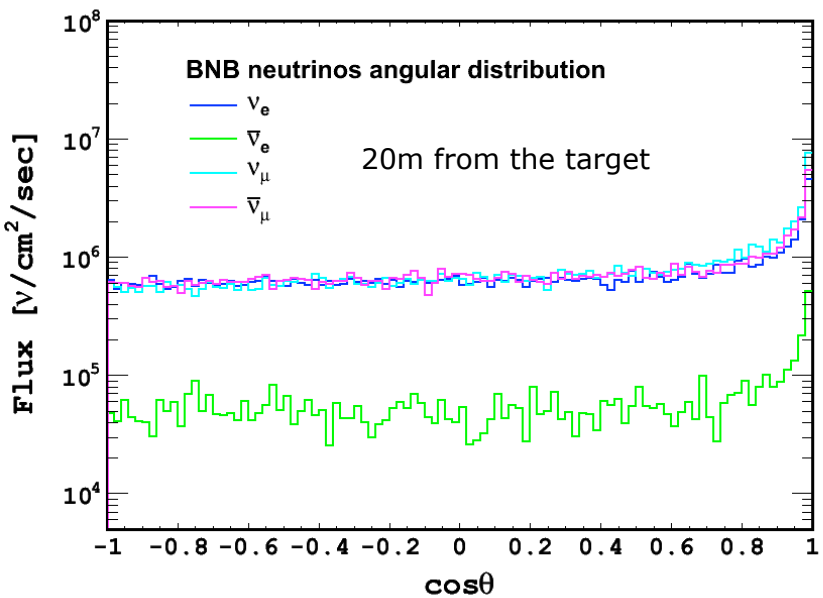
Far-Off-aXis Neutrinos



Far-Off-aXis (FOX) Neutrinos

From Booster Beam MC (S. Brice)





Beam MC Configuration

- Use standard Booster Beam MC
  - release stopping pion cuts in the original MC
- 8 GeV, 5Hz 5×10^{12} Protons on Be target
  - 32 kW max power (NUMI beam on 8 kW)
- 173 kA horn current neutrino mode
- 20m from the target

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

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad E(\nu_\mu) = 29.9 \text{ MeV}$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \qquad \text{delay} = 2.2\ \mu s$$

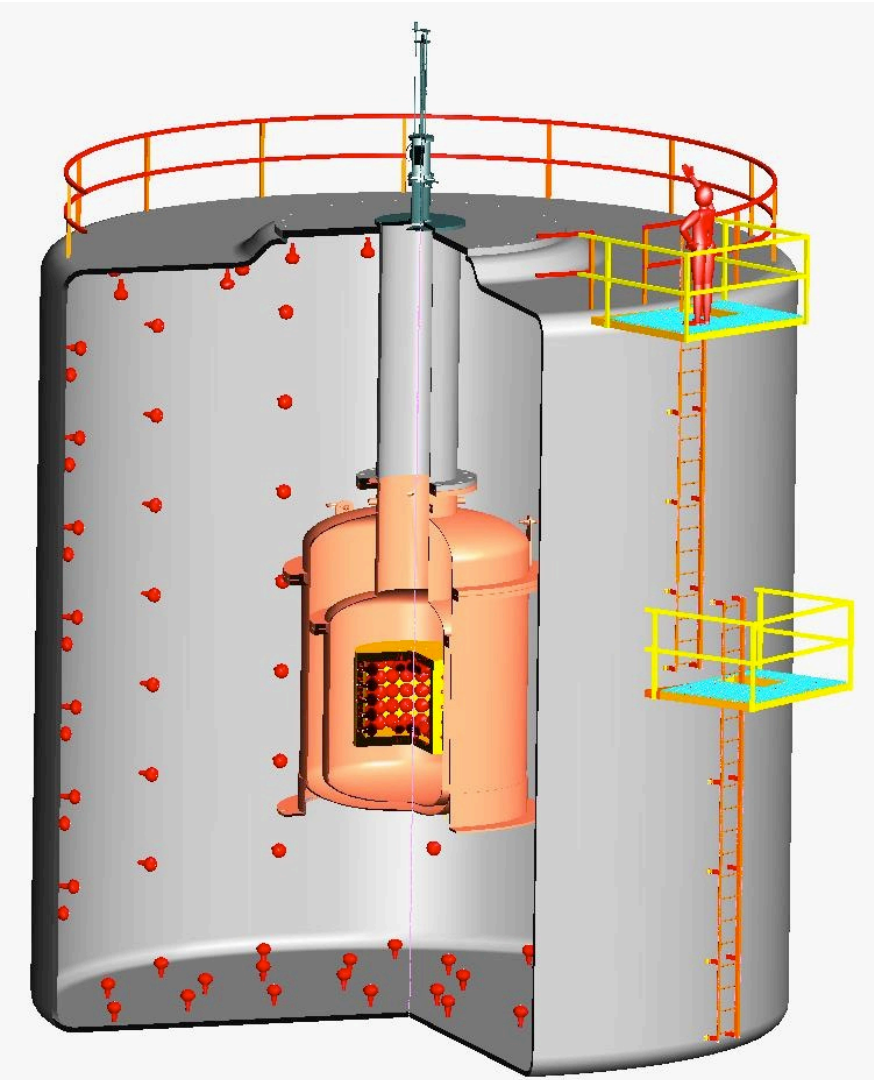
⇨ **$\phi \sim 5\times10^5$ ν/cm²/s (@cosθ<0.5)**

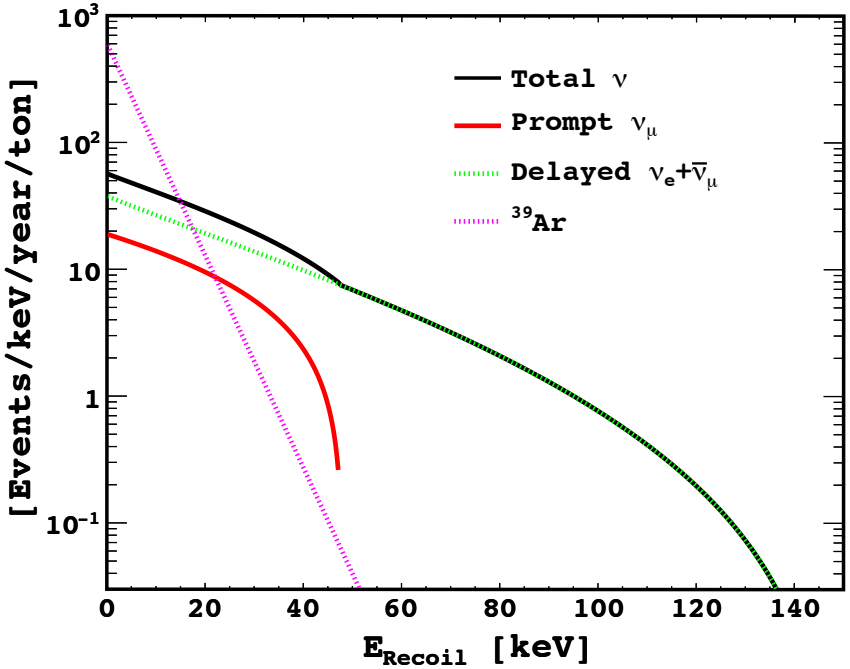
- Systematic uncertainties of the neutrino flux estimation should be checked in detail
- Beam correlated muons and neutrons at the detector site should be evaluated

* ν_e spectrum does not accurately follow the 3-body muon decay kinematics where the post-processing of Booster Beam MC does not apply in this low energy region. However the total flux should not be affected.

Expected Coherent-NCvAS Event Rates at FOX

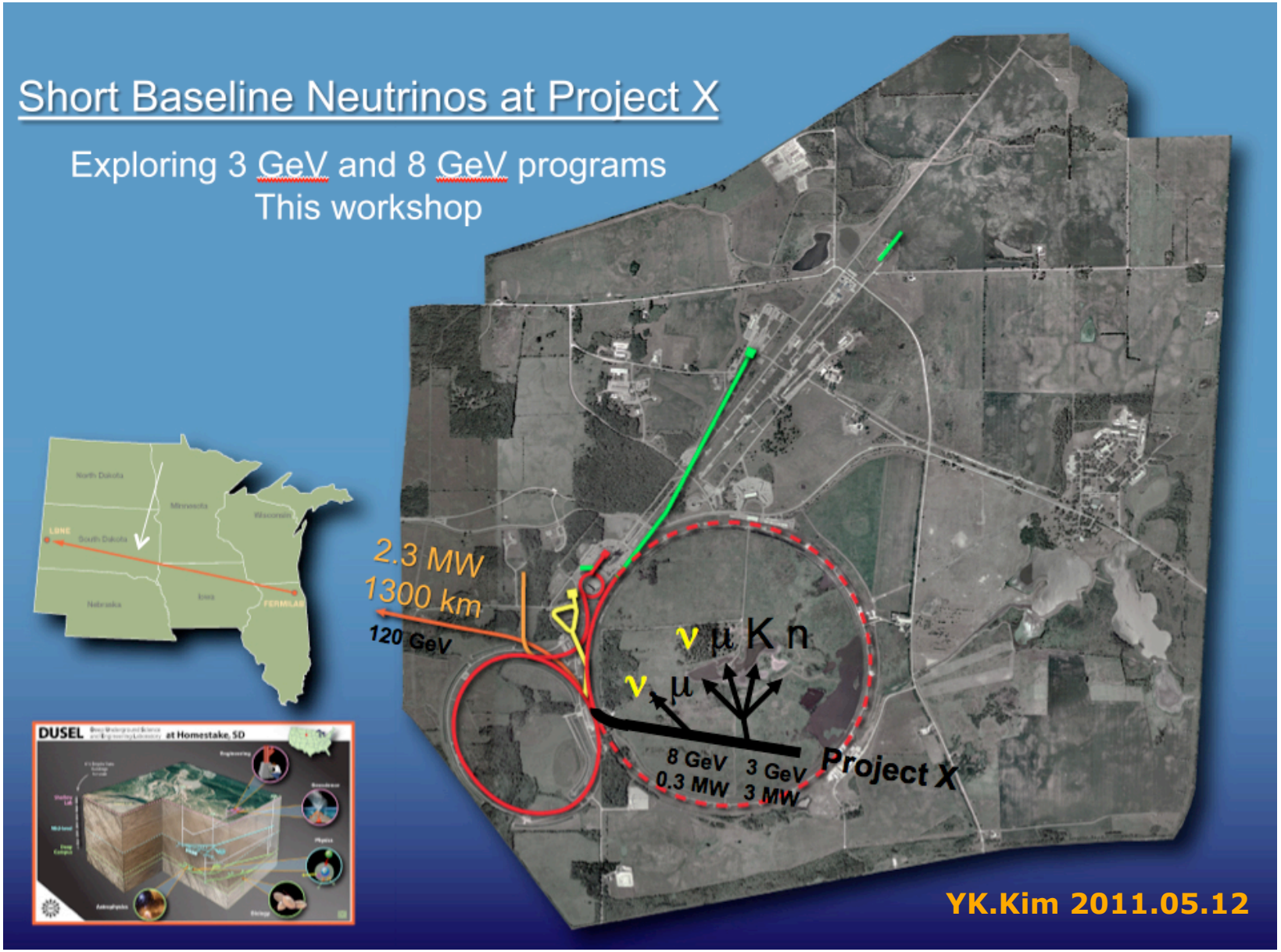
If we believe the FOX Booster Beam MC results, a ton-scale single phase LAr detector will perform the first ever observation of the coherent-NCvAS at Fermilab





- 20m from the target
- Steady state background rejection factor ~10^{-5}
- Use pulse shape discrimination of nuclear recoil (fast) and electron recoil (slow) signal in LAr (see Boulay and Hime: astro-ph/0411358)
- Well known detector technology (DEAP/CLEAN)
- Expected Event Rate in a single-phase 1-ton LAr detector: ~200evt/year (E_{th}> 30 keV) w/ full-power operation (w/ NUMI: ~50 evt/year)

Future of FOX neutrinos?



→ see C.Polly's talk in this workshop as well (2011.05.14)
→ Alternative options; see DAEδALUS J.Conard talk in this workshop (2011.05.14)

Detector R&D
at
Fermilab

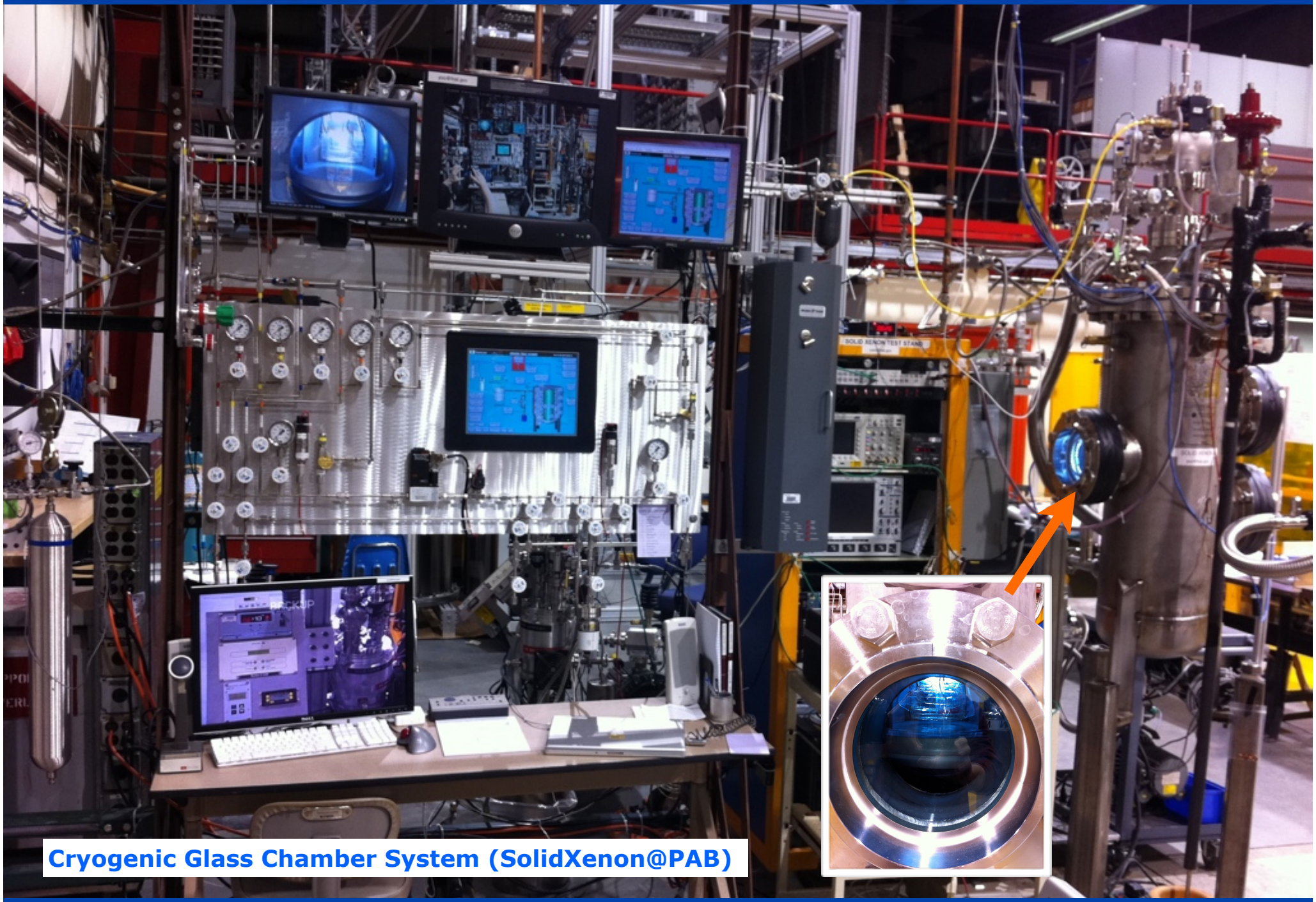
Fermilab Noble Gas Detector R&D Facility

Fermilab Noble Gas Detector R&D Facility

Noble Gas Purification Tower (Darkside@PAB)

Liquid Argon Purity Demonstrator (LAPD@PC4)

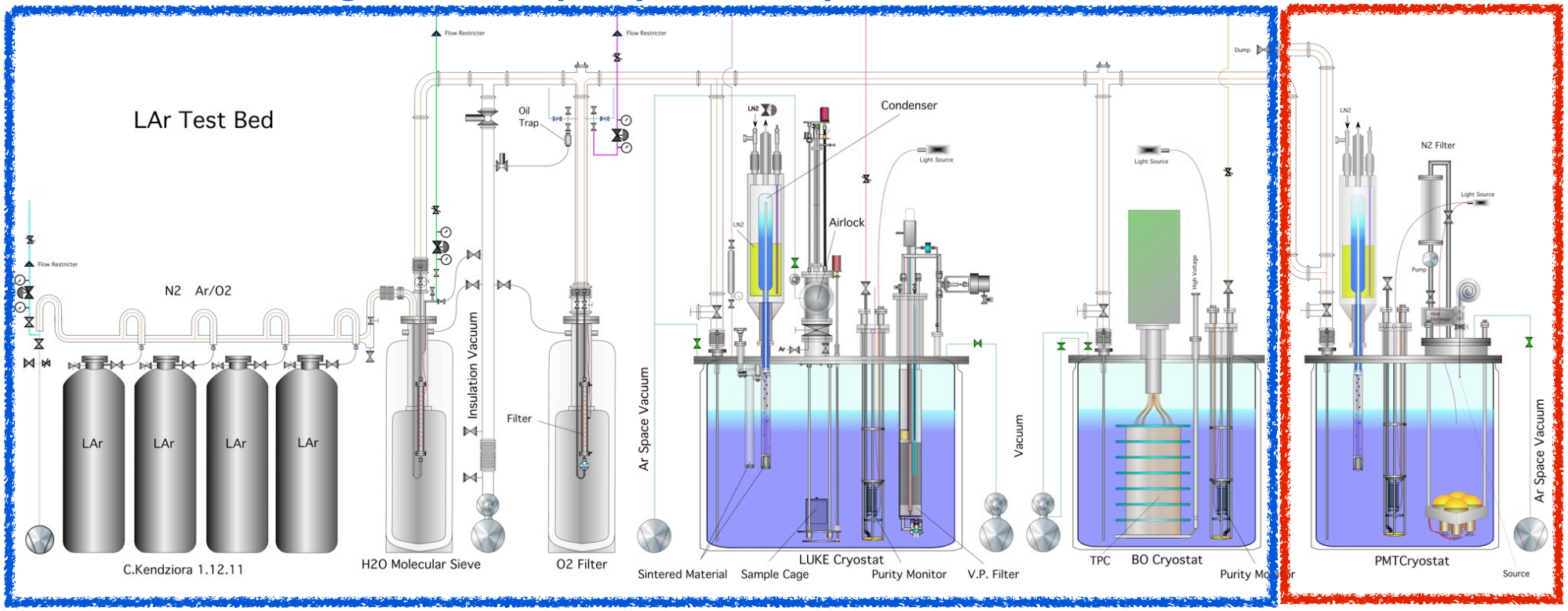
Fermilab Noble Gas Detector R&D Facility



Cryogenic Glass Chamber System (SolidXenon@PAB)

Prototype Detector Test Chamber

Existing LAr electro-purity test facility at Fermilab PAB **New Addition**



- Existing LAr test chamber system demonstrated 20ppt level of purity control on electronegative elements (H_2O and O_2)
- N_2 contamination above ~ppm in LAr is known to affect pulse shape discrimination of nuclear recoil events (see 2010 JINST 5 P06003 by WArP collaboration)
- The chamber will be used for PMT characterization and N_2 contamination control in ~300kg size of LAr
- Understand design issues of prototype detector

Summary

- Coherent-NCvAS has never been observed since its first prediction in 1974
- Dark Matter Search experiments will face irreducible coherent-NCvAS neutrino backgrounds. It will be interesting to study neutrino interactions at sub-MeV range of nuclear recoils.
- There is a well defined low energy (<50MeV) neutrino source at Fermilab which might be useful for coherent-NCvAS experiment.
- Further R&D within Project-X neutrino program (8GeV-0.3MW proton beam) can open up new endeavors and opportunities of future short baseline projects.
- Detector R&D efforts at Fermilab have just started.