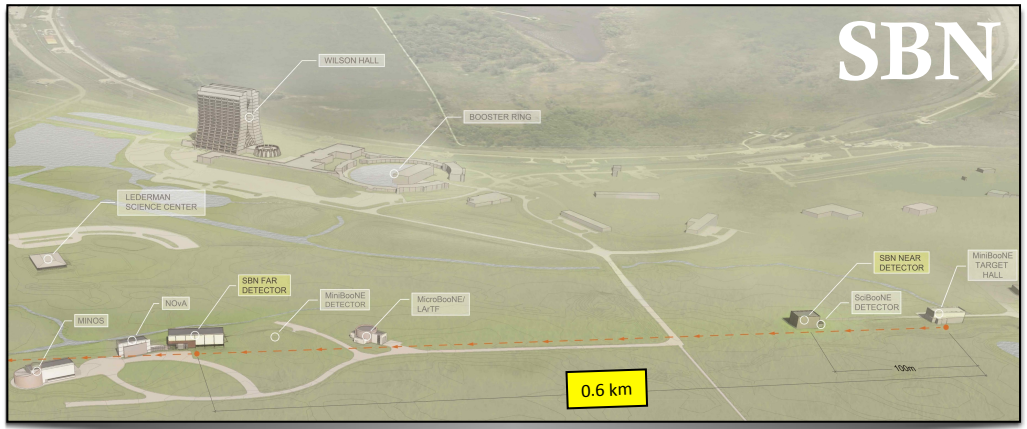
# Future SBN and LBN Physics Programs at Fermilab

short-baseline neutrino

long-baseline neutrino

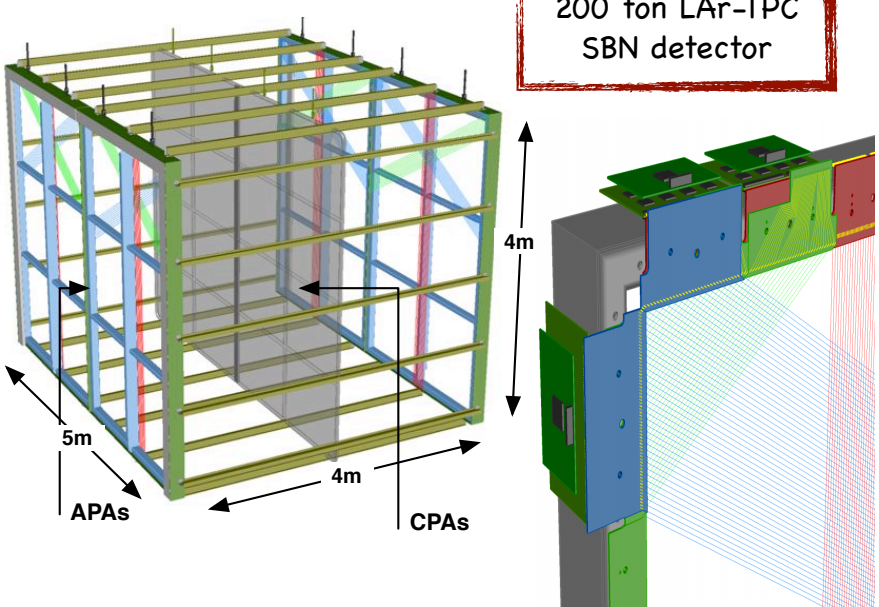
January 29, 2015

David Schmitz THE UNIVERSITY OF CHICAGO





200 ton LAr-TPC
SBN detector




34,000 ton LAr-TPC
LBN detector

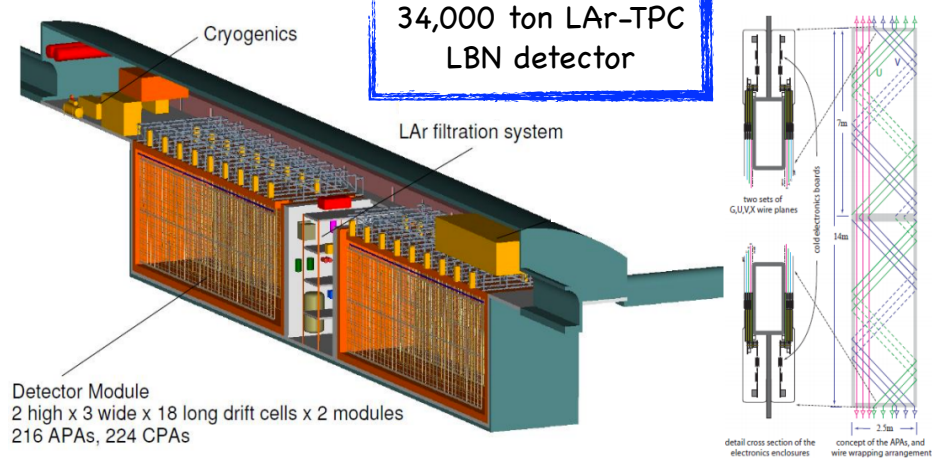



**FIGURE 16.** *Schematic of a 34-kt fiducial mass LArTPC design (left). The detector comprises two 17-kt fiducial mass LArTPC detectors. The design of a pair of Anode Plane Assemblies is shown at right.*

# The 2014 P5 Recommendations

Particle Physics Project Prioritization Panel (HEPAP subpanel)
http://www.usparticlephysics.org/p5/

**Building for Discovery**
Strategic Plan for U.S. Particle Physics in the Global Context

**Recommendation 12: In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.**

May, 2014

**Recommendation 15: Select and perform in the short term a set of small-scale short-baseline experiments that can conclusively address experimental hints of physics beyond the three-neutrino paradigm. Some of these experiments should use liquid argon to advance the technology and build the international community for LBNF at Fermilab.**

# Long-Baseline Physics Goals

MID 2020's AND BEYOND

- Test CP violation in the lepton sector
- Determine the mass ordering of the neutrinos
- Test the three-neutrino paradigm

Neutrino Mixing Matrix

flavor states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass eigenstates

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2$$

$$+ \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31} \frac{\sin(aL)}{aL} \Delta_{21} \cos(\Delta_{31} + \delta_{CP})$$

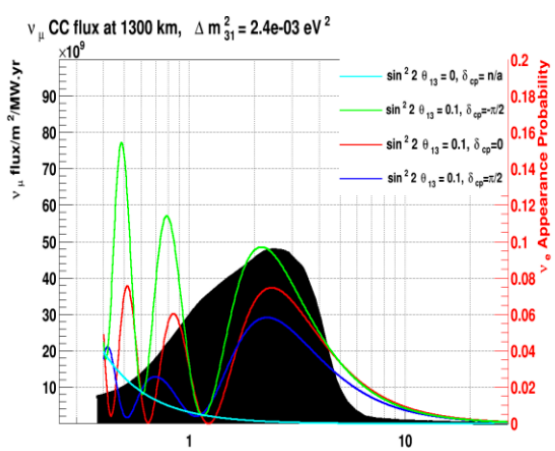
$$+ \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(aL)}{(aL)^2} \Delta_{21}^2$$

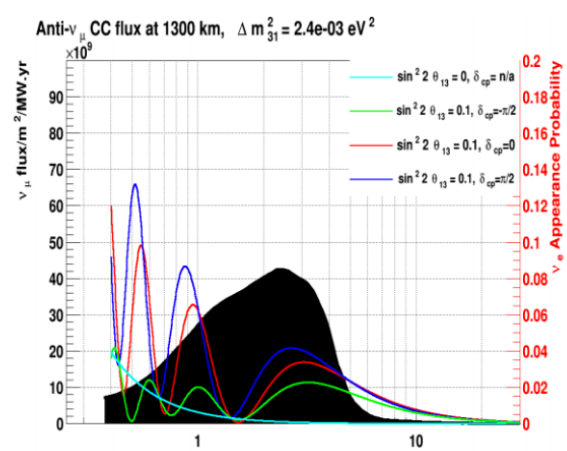
where, $\Delta_{ij} = \Delta m_{ij}^2 L/4E$, and $a = G_F N_e/\sqrt{2}$.

Beam-related and non-beam physics

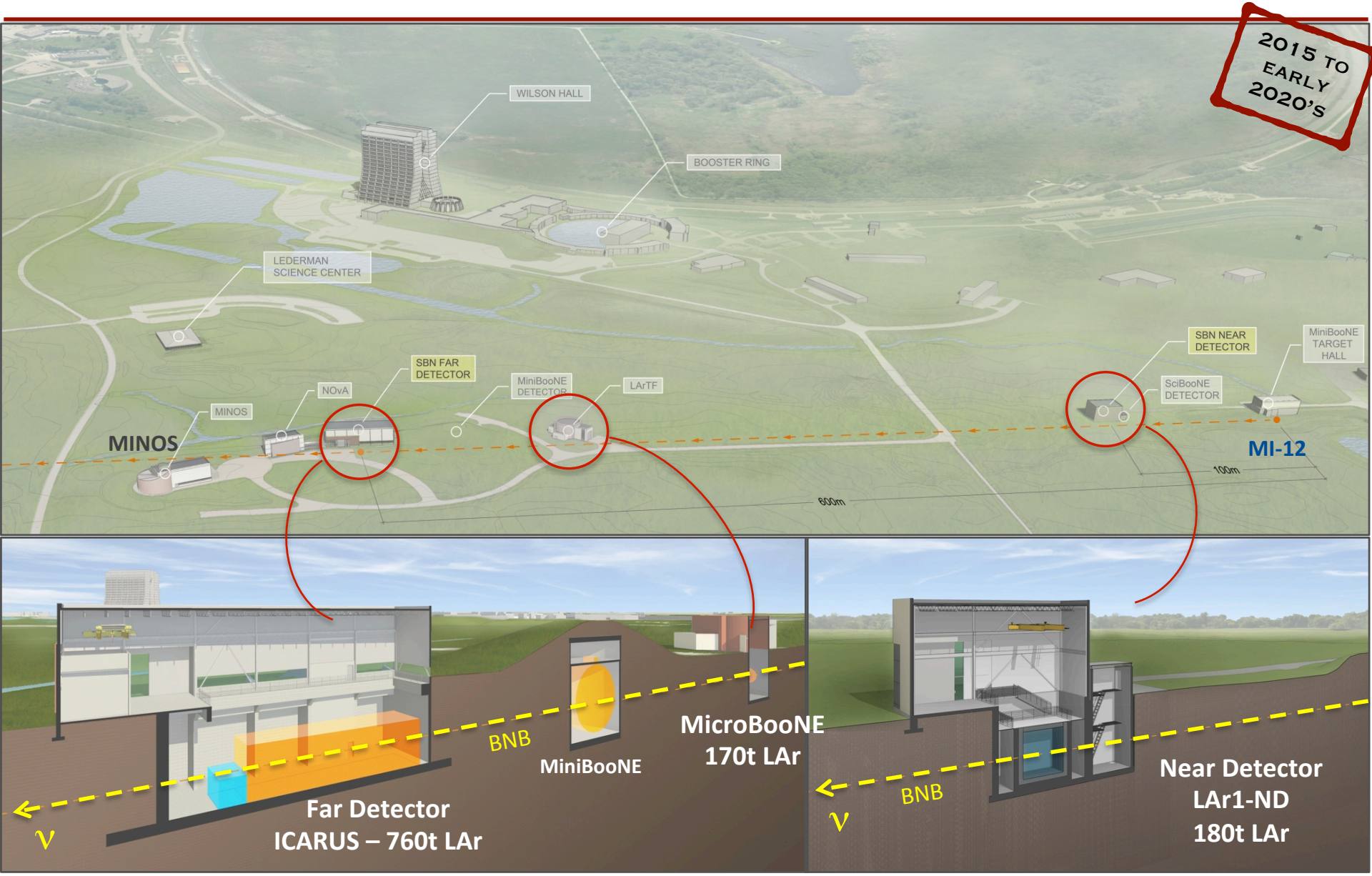
$\delta_{CP}$ and $a$ switch signs in going from $\nu_\mu \to \nu_e$ to $\bar{\nu}_\mu \to \bar{\nu}_e$

- Atmospheric neutrinos
- Nucleon decay
- Astrophysical neutrinos (core-collapse supernova)



# Fermilab Short-Baseline Neutrino Program



# SBN ⟺ LBN Physics Goals

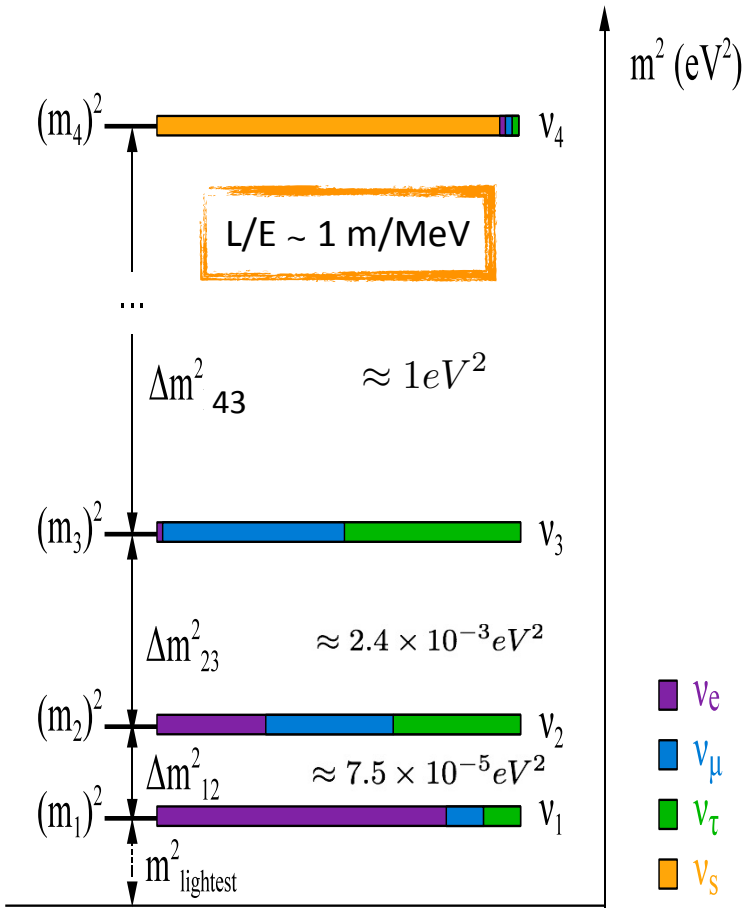
- The physics goals of SBN and LBN are complementary:
  - A major physics goal of LBN is to "test the 3-$\nu$ paradigm"
  - SBN will contribute directly to this question through either a major discovery or by ruling out light sterile neutrinos in a range hinted at by previous anomalies (~0.1 - 10 $eV^2$)
  - LBN measurements will depend upon good knowledge of the physics of $\nu$-Ar interactions
  - SBN will study these interactions in detail with millions of events in the relevant energy range
- Also, SBN a valuable demonstration of the LAr-TPC technology for precision neutrino physics

# Three-Neutrino Paradigm, Sterile Neutrinos

- Results from multiple experiments have hinted at a possible additional oscillation
- While each of the measurements alone lack the significance to claim a discovery, together they could be hinting at important new physics

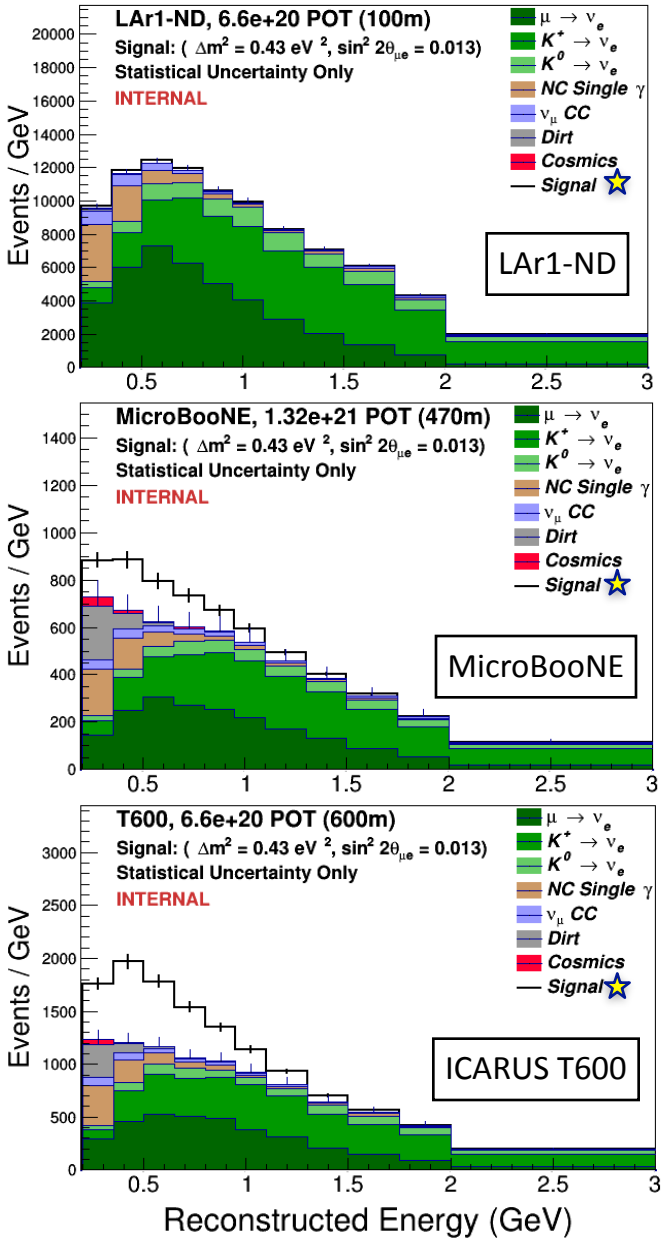
| Experiment | Type | Channel | Significance |
|---|---|---|---|
| LSND | DAR | $\bar{\nu}_\mu \to \bar{\nu}_e$ CC | $3.8\sigma$ |
| MiniBooNE | SBL accelerator | $\nu_\mu \to \nu_e$ CC | $3.4\sigma$ |
| MiniBooNE | SBL accelerator | $\bar{\nu}_\mu \to \bar{\nu}_e$ CC | $2.8\sigma$ |
| GALLEX/SAGE | Source - e capture | $\nu_e$ disappearance | $2.8\sigma$ |
| Reactors | Beta-decay | $\bar{\nu}_e$ disappearance | $3.0\sigma$ |

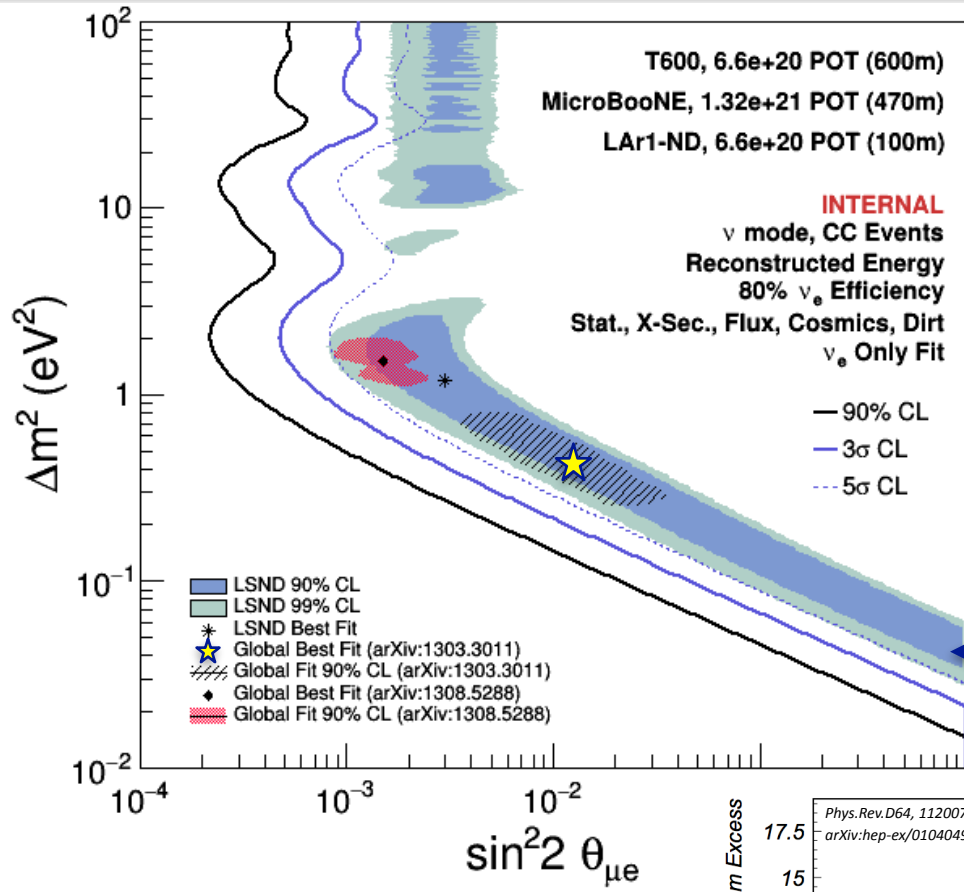
*K. N. Abazajian et al. "Light Sterile Neutrinos: A Whitepaper", arXiv:1204.5379 [hep-ph], (2012)*



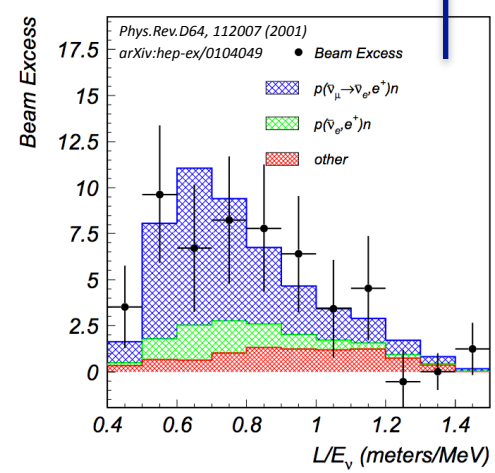

A discovery of light sterile neutrinos would, of course, have exciting implications for particle physics as well as cosmology

# SBN $\nu_e$ Appearance Sensitivity




LSND



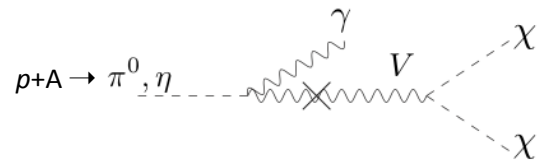

L ~ 600m

E ~ 600 MeV

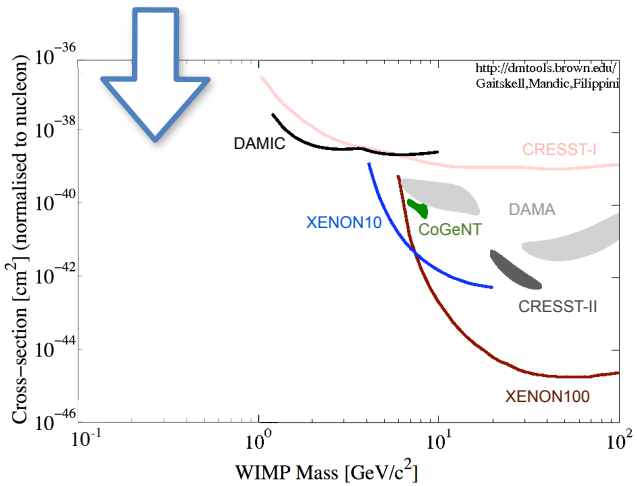
SBN@FNAL

# DM Opportunity with SBN Detectors

- Neutrino beam experiments running in beam-dump mode can perform Dark Sector searches, complementary to direct WIMP detection experiments
- Relativistic DM beam enables to search at lower DM masses, $M_X$ < 1 GeV
- For low mass WIMPs, however, need new mediator, $M_V$, to produce right relic density

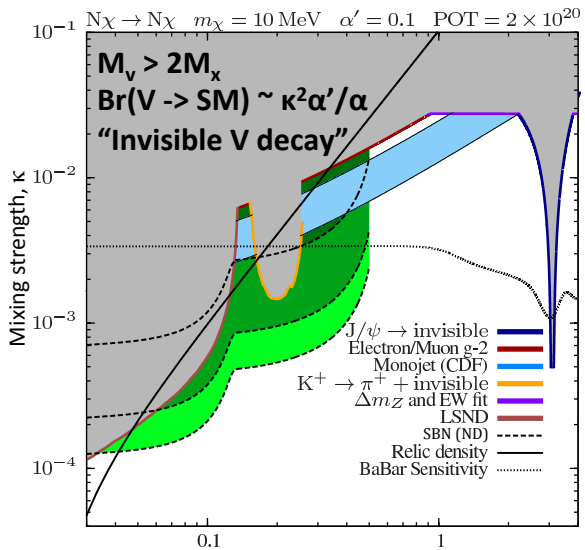



Beam-dump mode to suppress neutrino backgrounds (charged particles absorbed in dump w/o decay + no focusing)

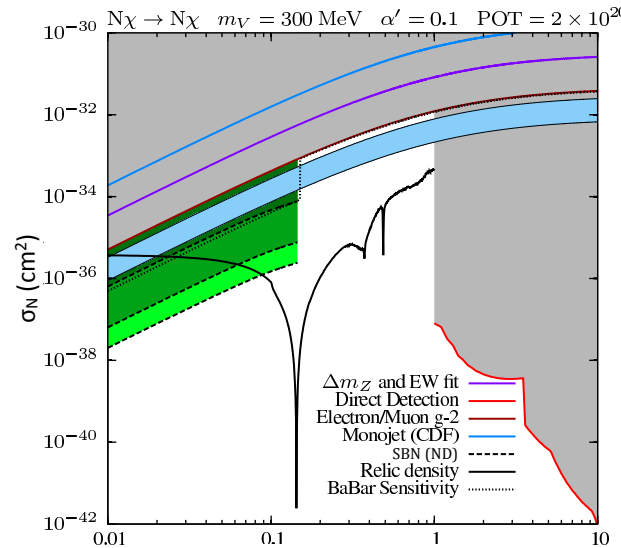



- Detect through elastic scattering of DM particle off electrons or nucleons in the neutrino detector, "Invisible V decays"
- Electron machine expts look for "Visible V decay" into SM particles
  - $M_V < 2M_X$
  - Br(V -> SM) ~ O(1)

## Proton beam-dump (SBN)




$M_V$ (GeV)



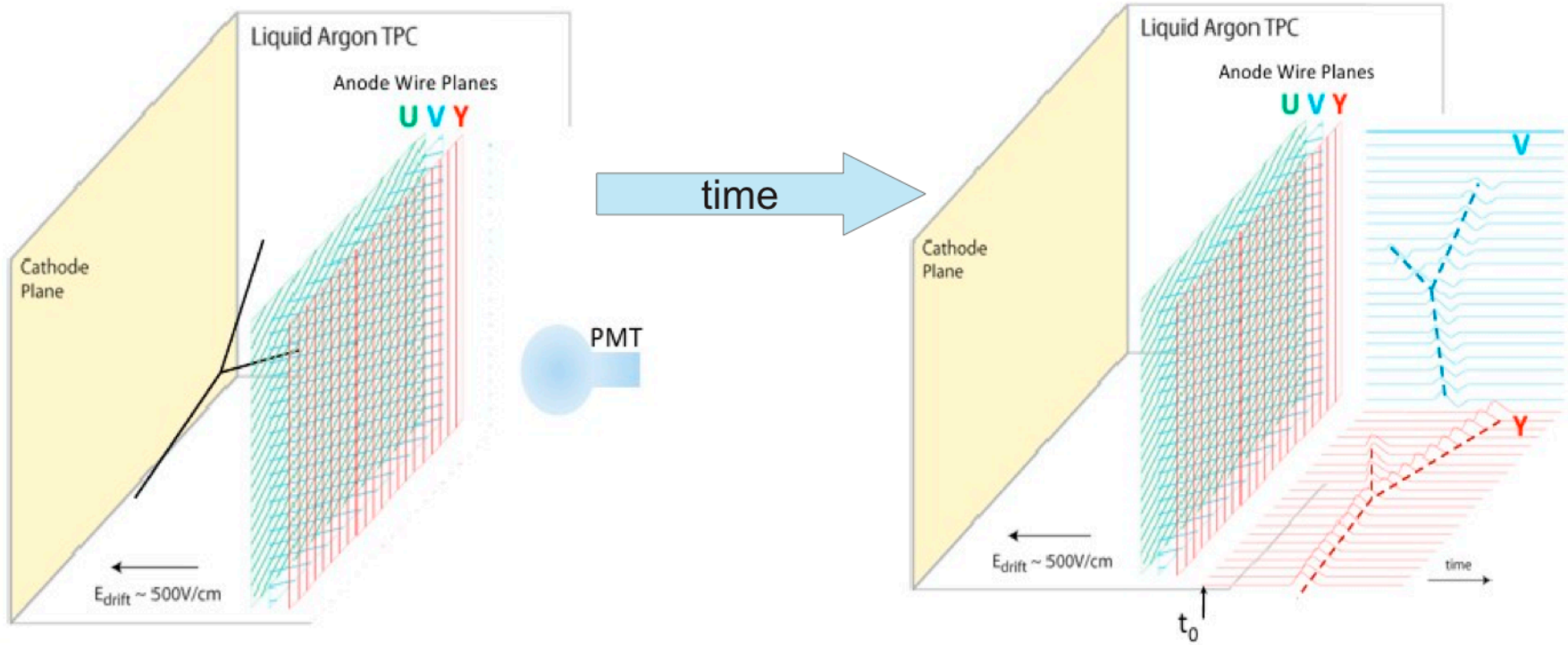

$M_X$ (GeV)

- Signal events: Dark Green > 1000; Green: 10-1000; Light Green: 1-10
- These are signal sensitivity plots. Actual measurement sensitivities/limits will depend on background rates and systematic errors.

# Backups

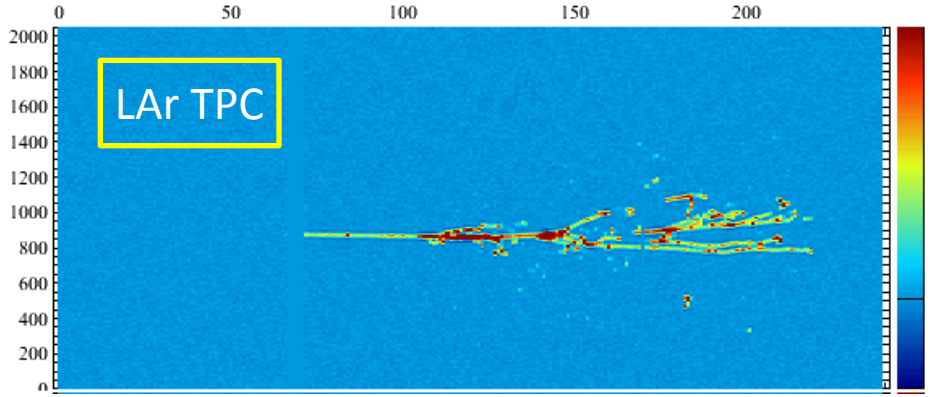
# How a LAr-TPC Works

- Charged particles in argon create electron-ion pairs and scintillation light.
- Electrons are drifted towards the anode wires.
- Multiple anode planes together with drift time allow 3D reconstruction.
- Collected charge allows calorimetric reconstruction.

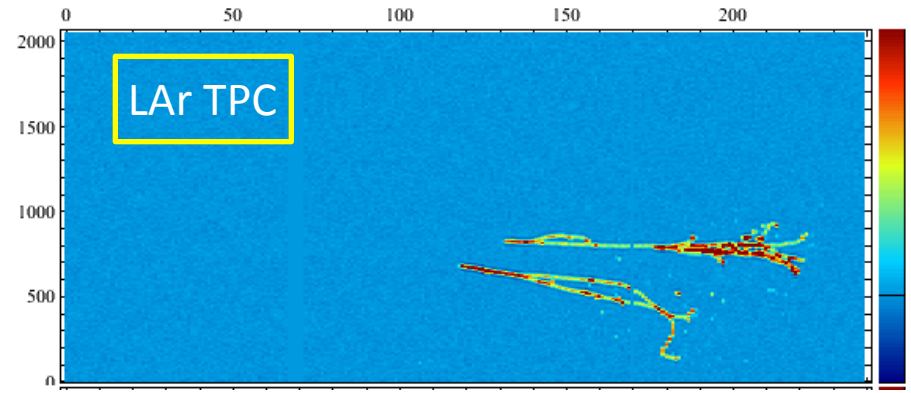


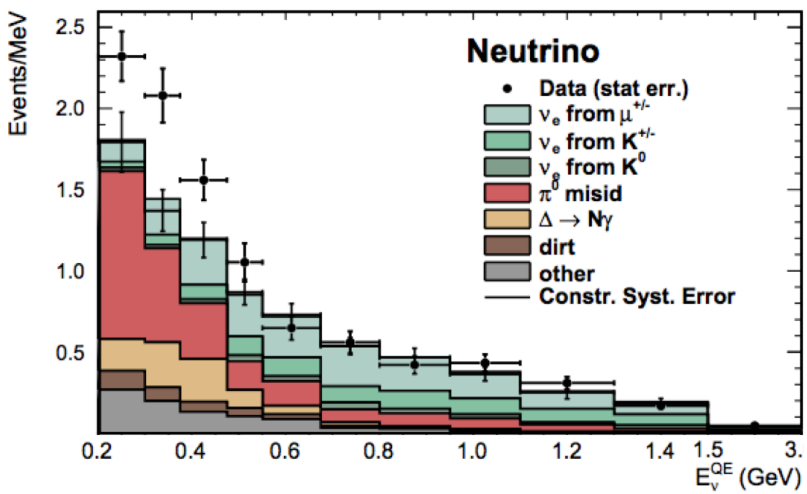
# Electron/photon separation with LAr-TPCs

1 GeV electron shower

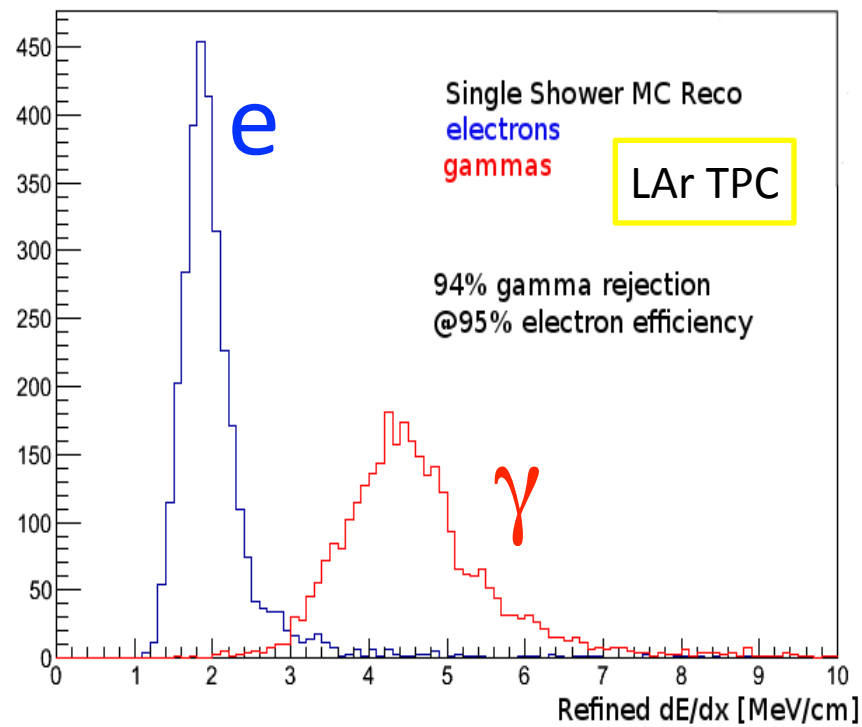



Decay of a 1 GeV $\pi^0$ to two photons.



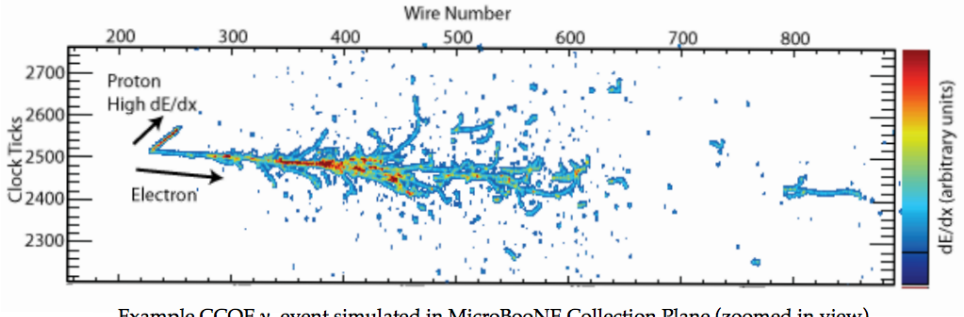




MiniBooNE

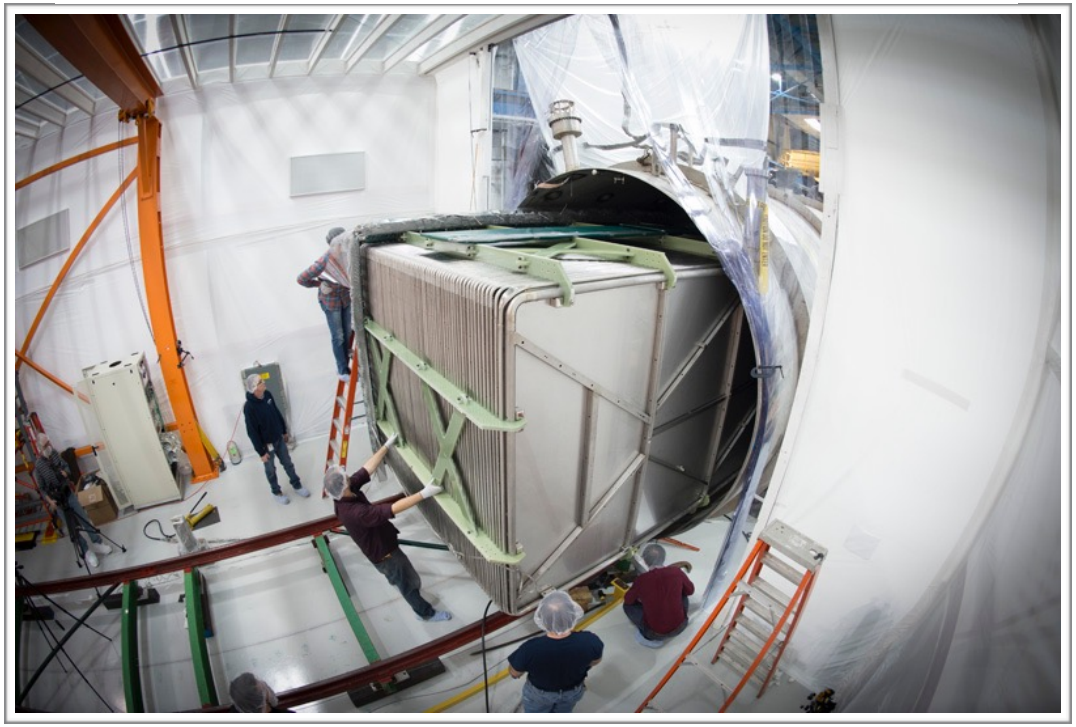


# MicroBooNE

- The first phase begins this year with MicroBooNE, installed in 2014 and coming online soon




Example CCQE $\nu_e$ event simulated in MicroBooNE Collection Plane (zoomed in view)

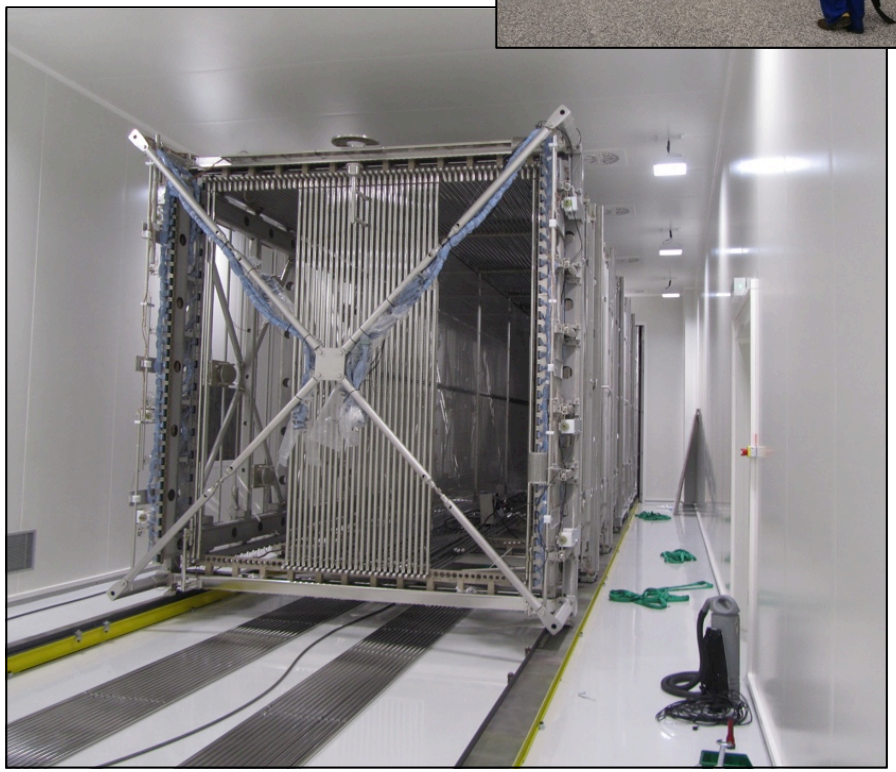


# ICARUS-T600, WA104

- Successfully operated at Gran Sasso in CNGS beam
  - Achieved electron lifetimes > 15 ms
  - Physics program including limits on sterile neutrinos
- ICARUS-WA104 project at CERN
  - Refurbish ICARUS-T600 w/ new cryostats, electronics, upgraded light collection
  - Move from Gran Sasso to CERN, Dec 2014
  - Refurbishing underway!
  - Schedule: TPC delivered to FNAL as soon as building available on-site, currently foreseen as early 2017

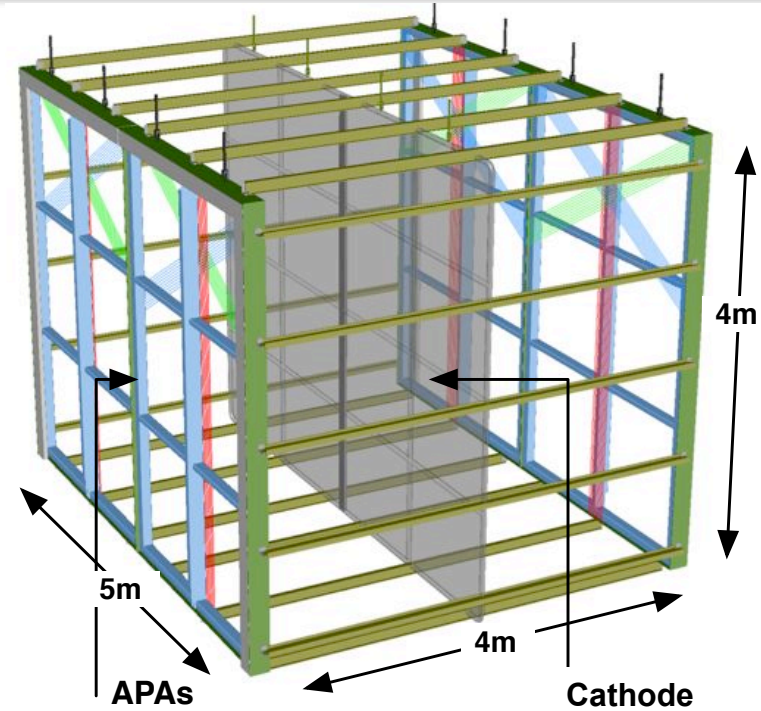
Ready to leave LNGS

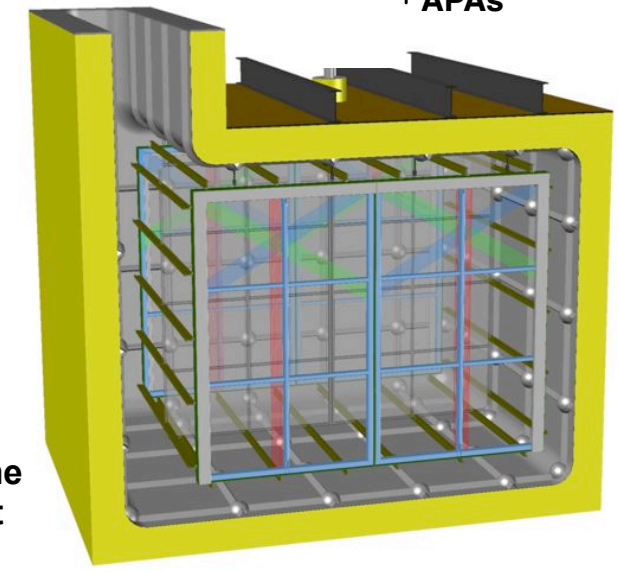
First T300 in Cleanroom at CERN

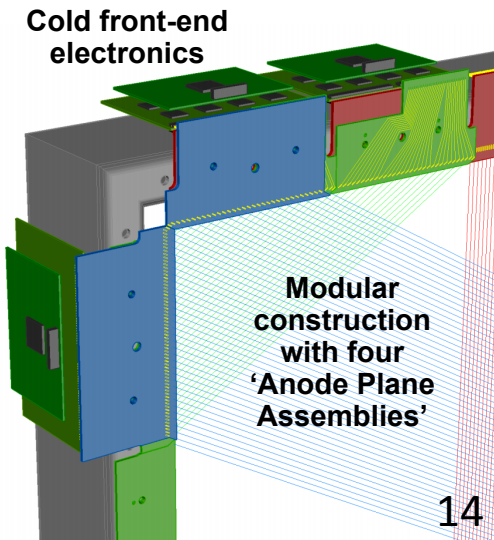


# LAr1-ND, T-1053

- A new detector, building on experience from ICARUS, MicroBooNE, 35ton, and based on current LBNE designs
- Provides an opportunity for prototyping baseline designs or developing alternative system designs
  - For example, LAr1-ND is an excellent test-bed for light collection concepts being developed for LBNF physics
- LAr1-ND approved at FNAL as T-1053 in summer 2014, now developing design, pursuing needed R&D



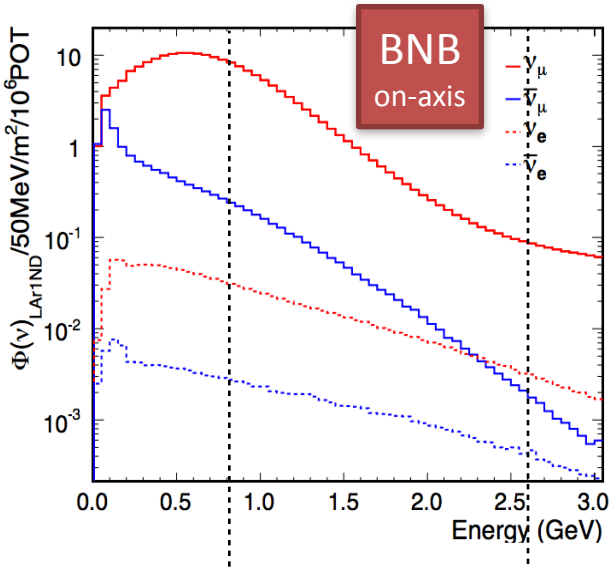
# SBN Timeline

- SBN is an opportunity to further develop the LAr-TPC technology and to **demonstrate its use in making precision measurements in neutrino physics**

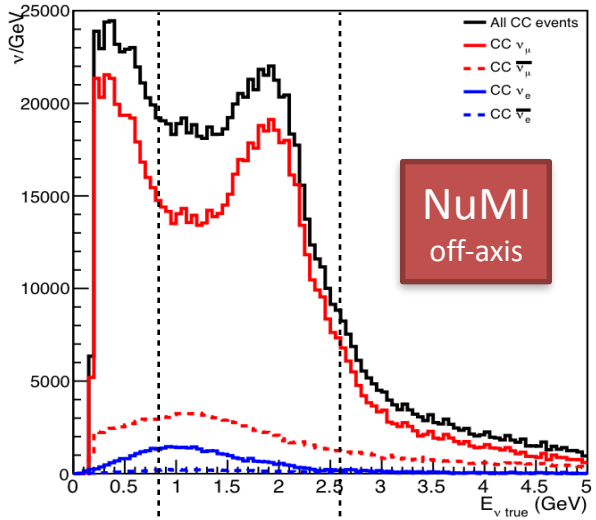
| *2015* | *2016* | *2017* | *2018* |
|---|---|---|---|
| *MicroBooNE running* | | | |
| *WA104 ICARUS-T600 refurbishment at CERN has begun*<br><br>*Develop ND technical designs & project schedules*<br><br>*Ground breaking on FD and ND buildings* | *ND and FD building construction completed*<br><br>*Complete T600 refurbishing*<br><br>*ND cryostat construction*<br><br>*ND TPC system construction*<br><br>*Cryogenics system fabrication* | *T600 arrives at Fermilab*<br><br>*T600 installation*<br><br>*ND active detector assembly and installation*<br><br>*Cryogenic system construction for ND and FD* | *Liquid Ar fill and commissioning*<br><br>*ND and FD running!* |

# Neutrino Interaction Physics and Event Reconstruction

- SBN detectors will provide huge data sets from the BNB on-axis and the NuMI off-axis fluxes
  - ND will record ~1.2M CC interactions in the fiducial volume per 2.2e20 pot, ~year of running (~7,000 $\nu_e$)
  - Large complementary samples in MicroBooNE and T600
  - Order 100k NuMI off-axis events in T600 per year
- High statistics, precision measurements of neutrino +Ar cross sections in the relevant energy range are an important component in reaching systematics at level of 1% in LBNF
- Large data sets will require that event reconstruction and analysis become fully automated
  - Precision testing of event reconstruction and identification techniques possible with large SBN data sets
  - This development for SBN physics will have direct impact for LBN in the future

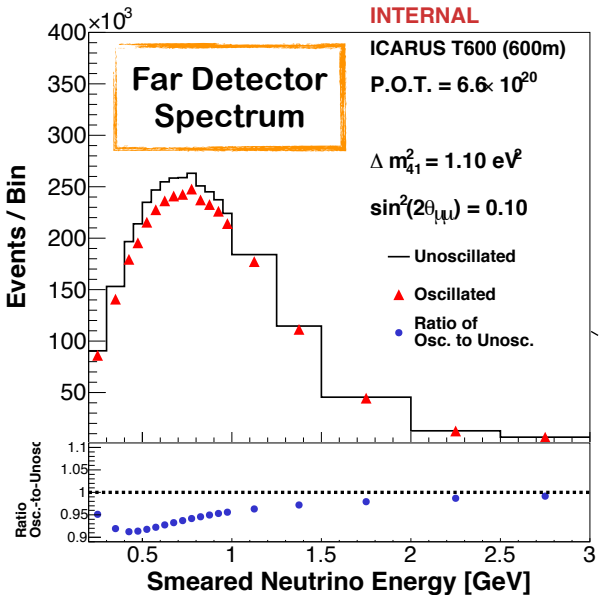


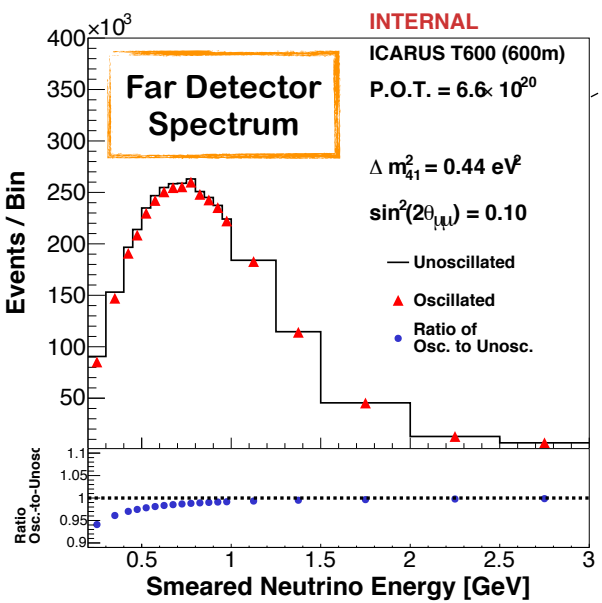

LBNF 2nd max 1st max

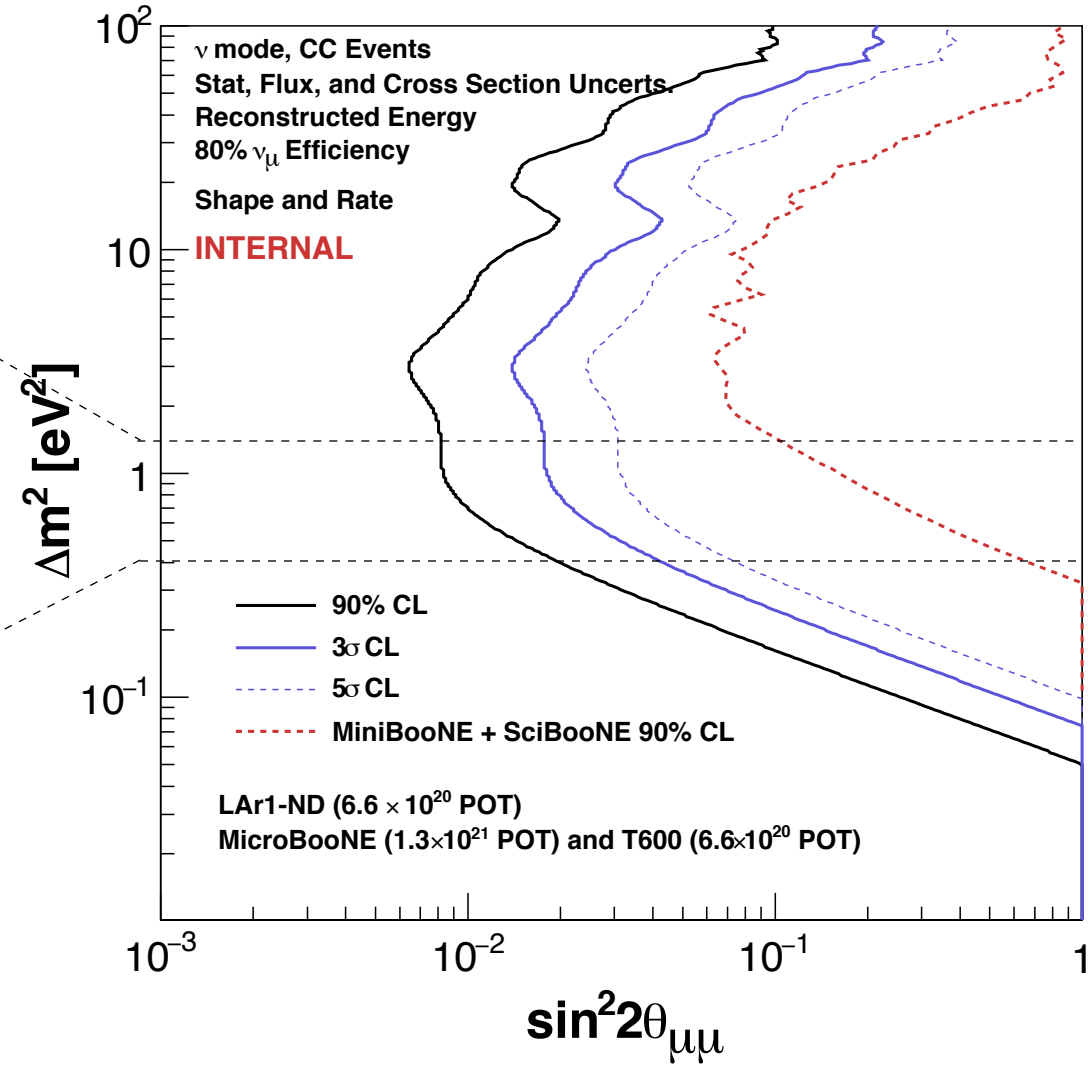



LBNF 2nd max 1st max

# SBN $\nu_\mu$ Disappearance Sensitivity



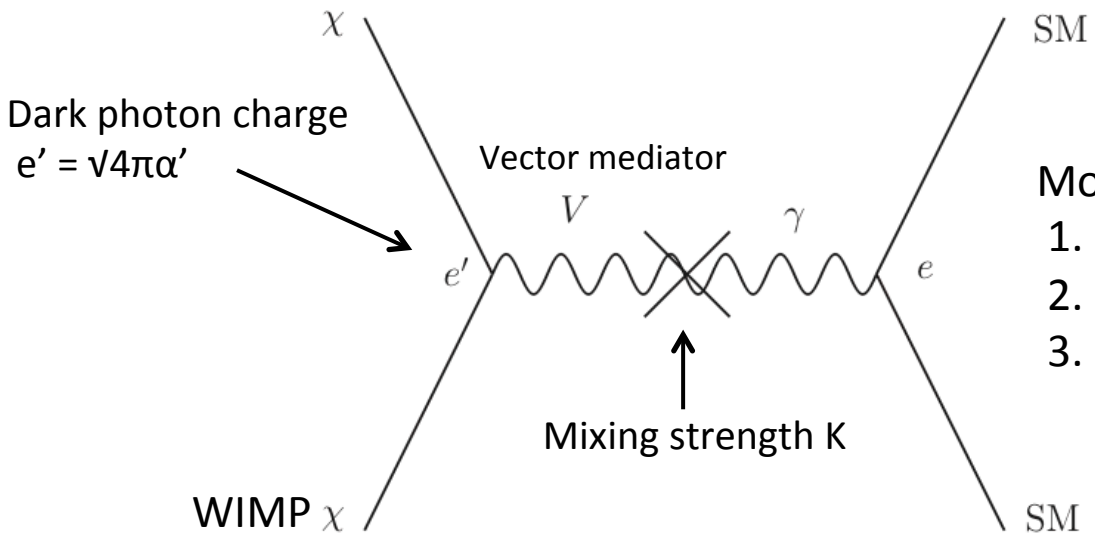
# Minimal U(1) Dark Force Vector Portal Model

## Opens up new annihilation channel for light WIMPs to achieve right relic density

B. Batell, M. Pospelov, A. Ritz Phys. Rev., vol. D80, p. 095024, (2009)

P. deNiveville, D. McKeen, A. Ritz, Phys.Rev.D86:035022 (2012)

$$\mathcal{L}_{\rm DM} = V_\mu \left( e\kappa J^\mu_{\rm em} + e' J^\mu_\chi \right) + \mathcal{L}_{\rm kin}(V,\chi) + \cdots$$




Model assumptions:

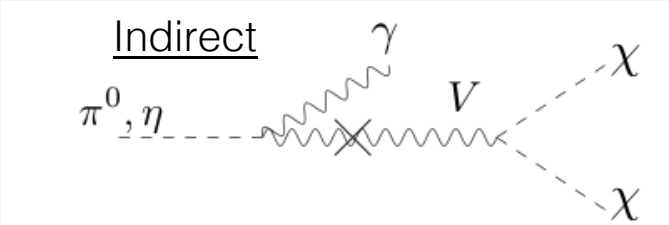
1. e = e' (perturbative regime)
2. K is small
3. $M_v > 2M_x$

Assuming thermal relic, if you know $m_\chi,\ m_V,\ \kappa,\ e'$ you know the present DM density

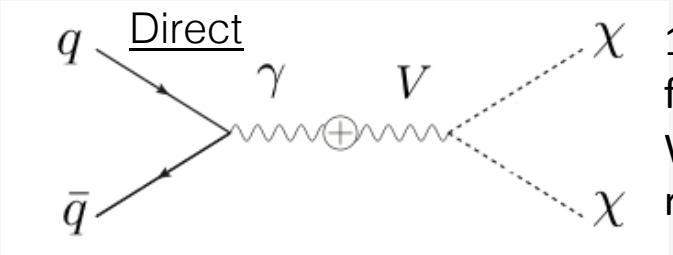
This is just one of many possible portal interactions, e.g. sterile neutrino, scalar, Higgs, etc

# Production:

- From proton-target interactions
- Requires intense beams with copious protons on target and variable energies (8 GeV, 120 GeV, etc)



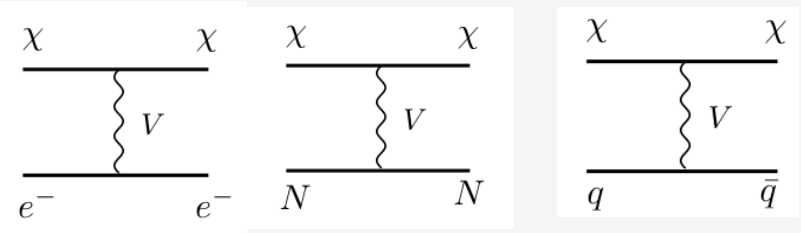

8 GeV




120 GeV for higher WIMP mass reach

# Detection:

- Elastic scattering off of nucleons, electrons, or DIS
- Require near, large, sensitive, well-understood detectors



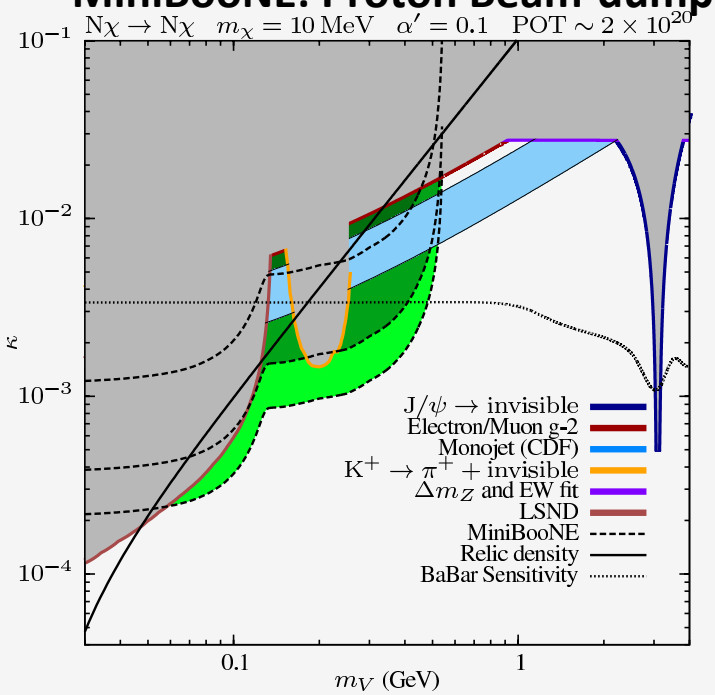

**Neutrino sources and detectors are ideal for Dark Sector particle searches!**

Run neutrino source in beam-dump mode to suppress the neutrino background (charged particles absorbed in dump w/o decay, no focusing)

7

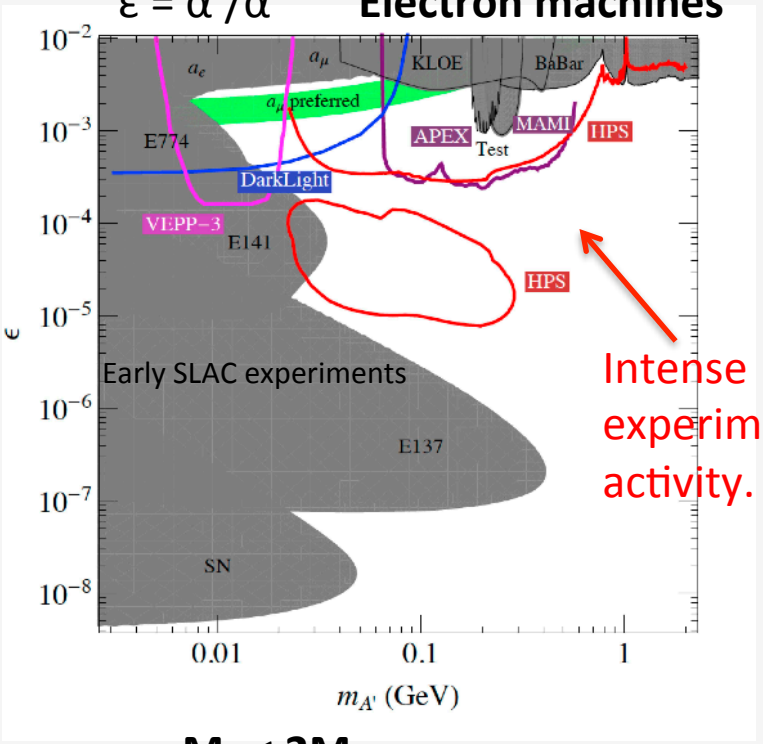
# Two Regimes for Light Mass Dark Matter Models: We Need to Investigate both Regimes!

**MiniBooNE: Proton Beam-dump**




**$M_V > 2M_\chi$**
**$Br(V \to SM) \sim \kappa^2\alpha'/\alpha$**
**"Invisible V decay"**

**$\varepsilon = \alpha'/\alpha$ Electron machines**




**$M_V < 2M_\chi$**
**$Br(V \to SM) \sim O(1)$**
**"Visible V decay"**

- Electron and Proton dump experiments compliment each other and extend the search for the hidden/dark sector!
- SNOMASS endorses proton beam-dump searches, and specifically MiniBooNE/MicoBooNE. These type of searches are detailed in the SNOMASS, LBNE, and Project X white papers.

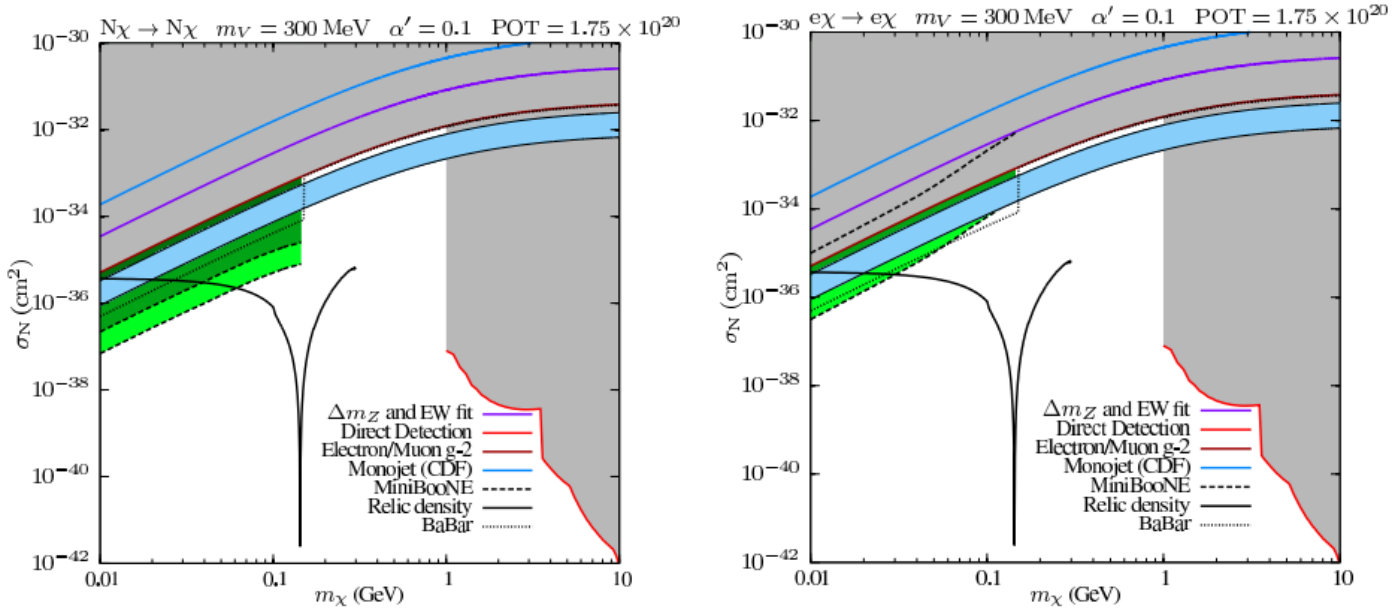
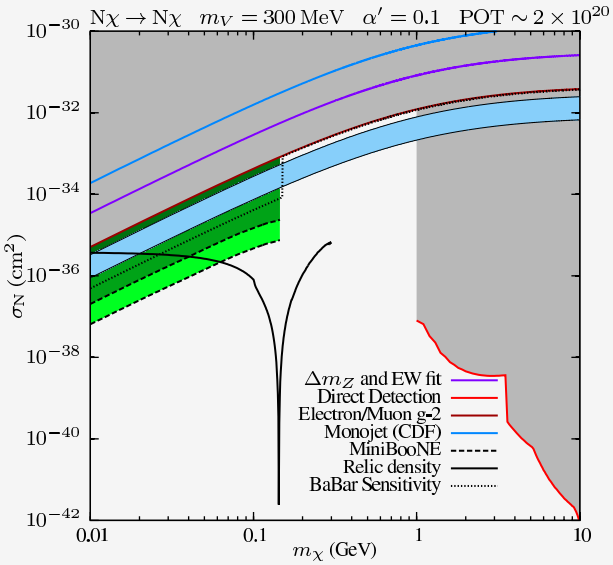


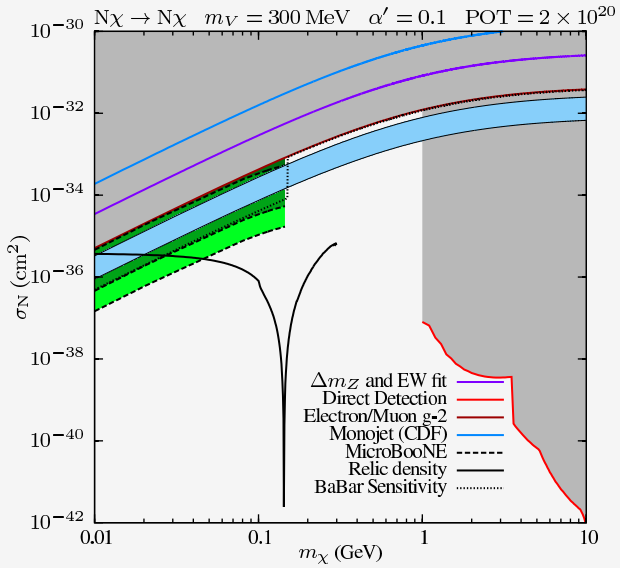

Figure 4: Regions of dark matter-nucleon scattering cross section (corresponding to non-relativistic spin-independent coherent scattering on nuclei) vs dark matter mass. In this plot we have fixed $m_V = 300$ MeV and $\alpha' = 0.1$. Constraints are shown from monojet searches ($pp \to j + \text{inv.}$) [44], excessive contributions to $(g-2)_\mu$ [21], precision electroweak measurements [38], a monophoton search ($e^+e^- \to \gamma + \text{inv.}$) [39, 40, 41] (labeled BaBar), and low-mass limits from dark matter direct detection experiments, DAMIC [46] (1-3 GeV), CDMSlite [47] (3-5 GeV) and XENON10 [43] (5-10 GeV). Note that a slightly stronger exclusion contour to XENON10 has recently been obtained by LUX [48]. The light blue band represents the region where the current $\sim 3\sigma$ discrepancy in $(g-2)_\mu$ is alleviated by the 1-loop contribution from the vector mediator [21]. The solid black line indicates where the relic density of the dark matter matches observations—the structure in this contour is due to $s$-channel $V^*$ resonant enhancement in the dark matter annihilation cross section for $m_\chi \sim m_V/2$. For $m_\chi > m_V$, new annihilation channels open up and this relation is modified. The left panel shows regions where we expect 1–10 (light green), 10–1000 (green), and more than 1000 (dark green) elastic scattering events off nucleons in the MiniBooNE detector with $1.75 \times 10^{20}$ POT. The right panel shows the same for elastic scattering off electrons.

# Signal Sensitivities for DM-NUCLEON Scattering (2E20 POT) Cross Section vs. Dark Matter Mass

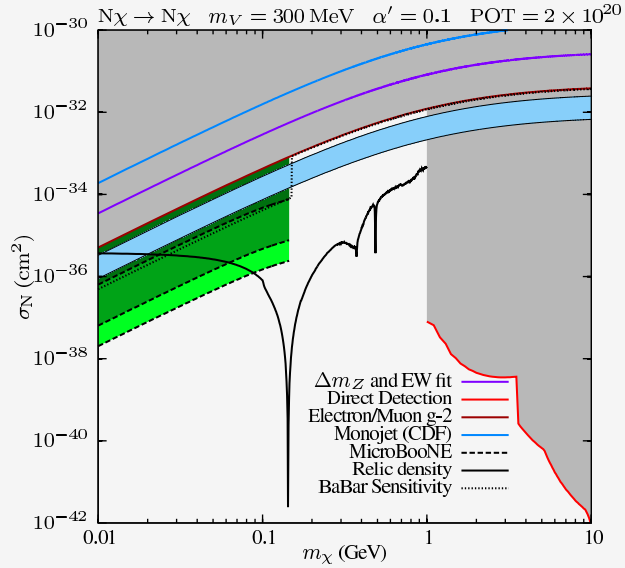
**MiniBooNE-$CH_2$**




**MicroBooNE-LAr**




**LAr1-NearDetector**

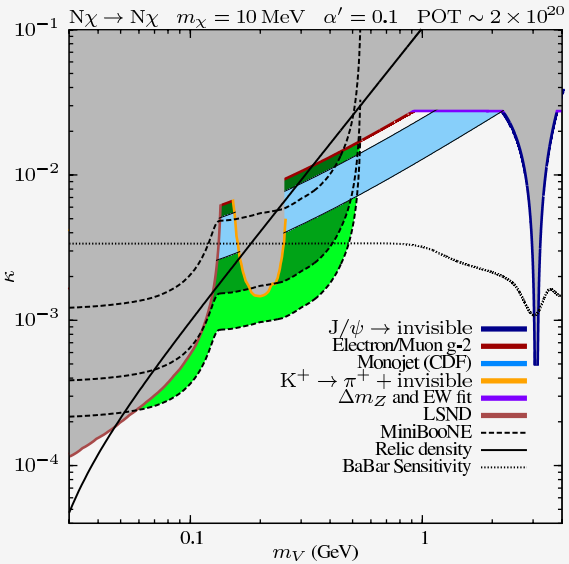



- Signal events: Dark Green > 1000; Green: 10-1000; Light Green: 1-10
- These are signal sensitivity plots. Actual measurement sensitivities/limits will depend on background rates and systematic errors.

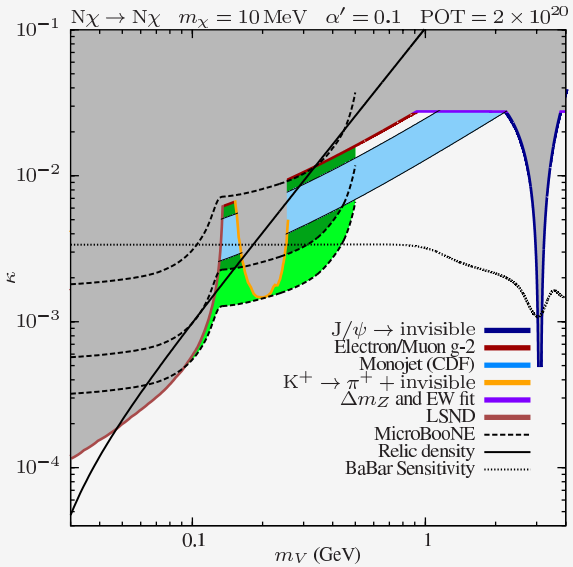
**These and following plots are for reasonable choices of $M_\chi$, $M_V$, and $\alpha' = 0.1$**
**Use of similar parameter values allow comparisons of different experiments.**

# Signal Sensitivities for DM-NUCLEON Scattering (2E20 POT)
# Mixing Strength vs. Vector Mediator Mass

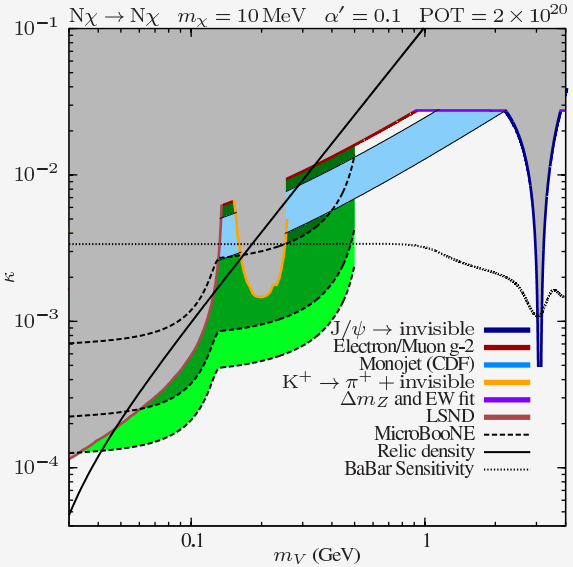
**MiniBooNE-$CH_2$**




**MicroBooNE-LAr**



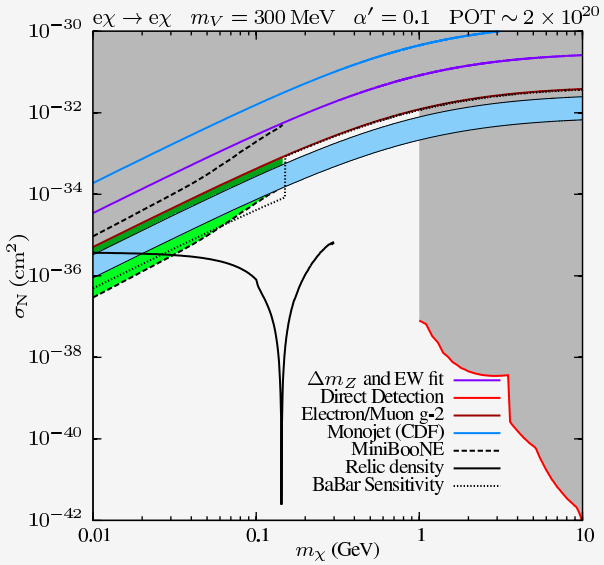

**LAr1-NearDetector**



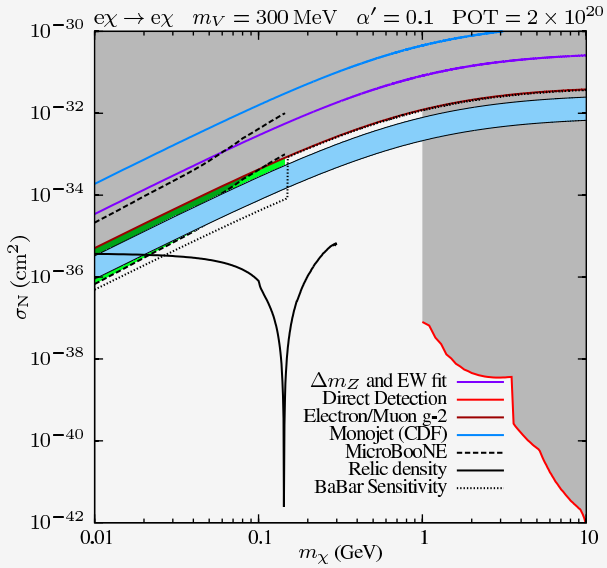

- Signal events: Dark Green > 1000; Green: 10-1000; Light Green: 1-10
- These are signal sensitivity plots. Actual measurement sensitivities/limits will depend on background rates and systematic errors.

# Signal Sensitivities for DM-ELECTRON Scattering (2E20 POT)
# Cross Section vs. Dark Matter Mass

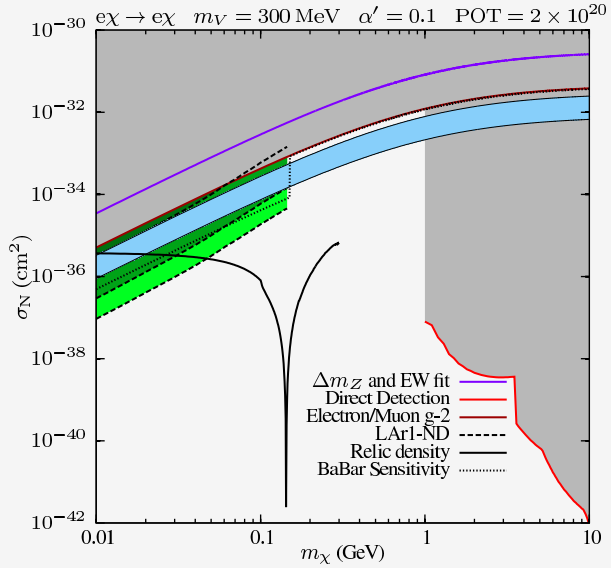
**MiniBooNE-$CH_2$**




**MicroBooNE-LAr**



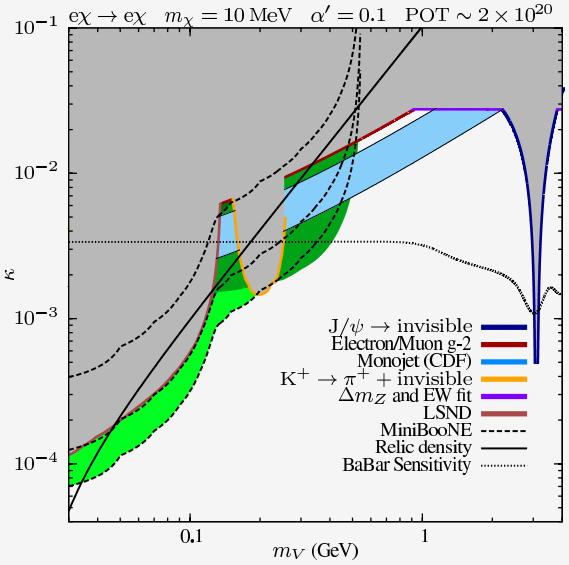

**LAr1-NearDetector**



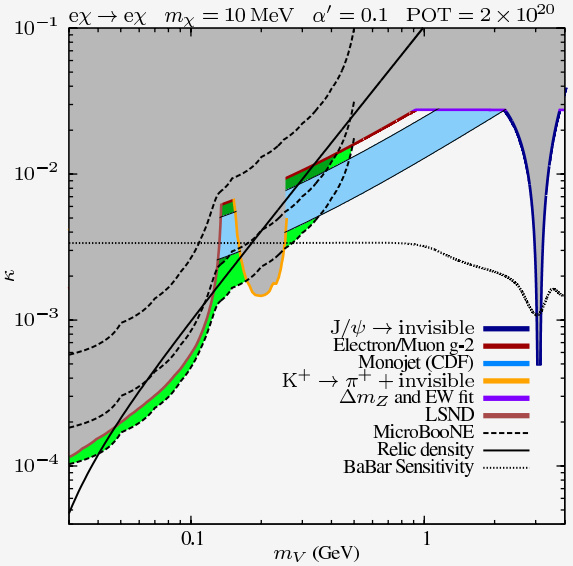

- Signal events: Dark Green > 1000; Green: 10-1000; Light Green: 1-10
- These are signal sensitivity plots. Actual measurement sensitivities/limits will depend on background rates and systematic errors.
- Electron signal sensitivity down due to lower cross sections. However, using direction information will significantly improve measurement sensitivity

# Signal Sensitivities for DM-ELECTRON Scattering (2E20 POT)
# Mixing Strength vs. Vector Mediator Mass

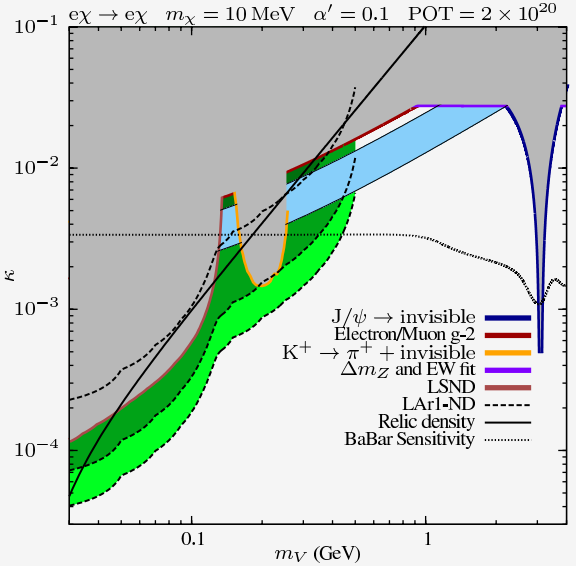
**MiniBooNE-$CH_2$**




**MicroBooNE-LAr**




**LAr1-NearDetector**




- Signal events: Dark Green > 1000; Green: 10-1000; Light Green: 1-10
- These are signal sensitivity plots. Actual measurement sensitivities/limits will depend on background rates and systematic errors.