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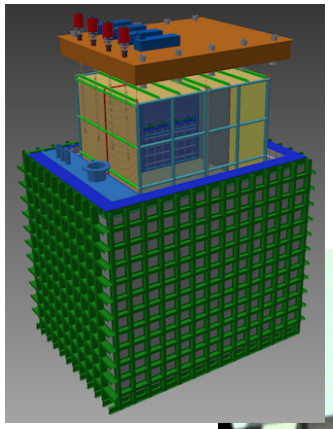
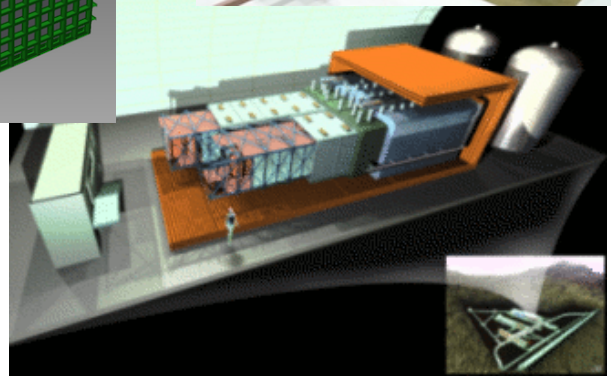
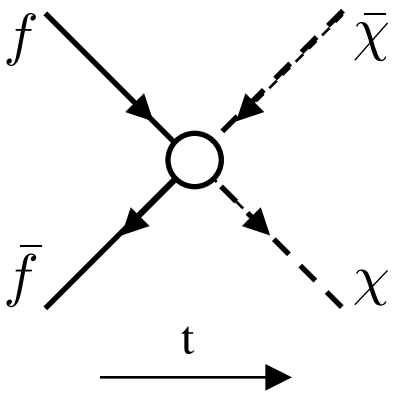
Future Dark Matter Searches at the Fermilab Short Baseline Neutrino Experimental Program

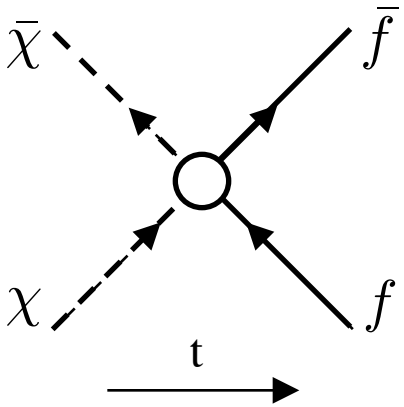


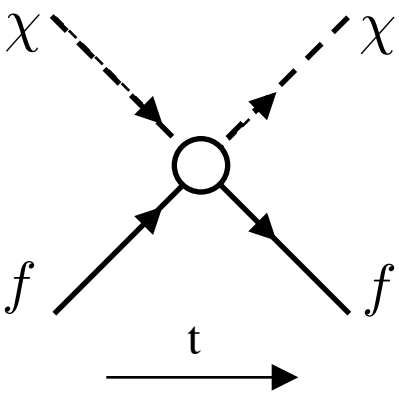


R.L. Cooper
NMSU

How To Look For Dark Matter







Collider Production

- Can cover most of mass range
- Signal is lack of a signal (Missing E_T)

Annihilation

- Energetic particle /antiparticle signals
- Also gamma rays (e.g., 511 keV)

Scattering

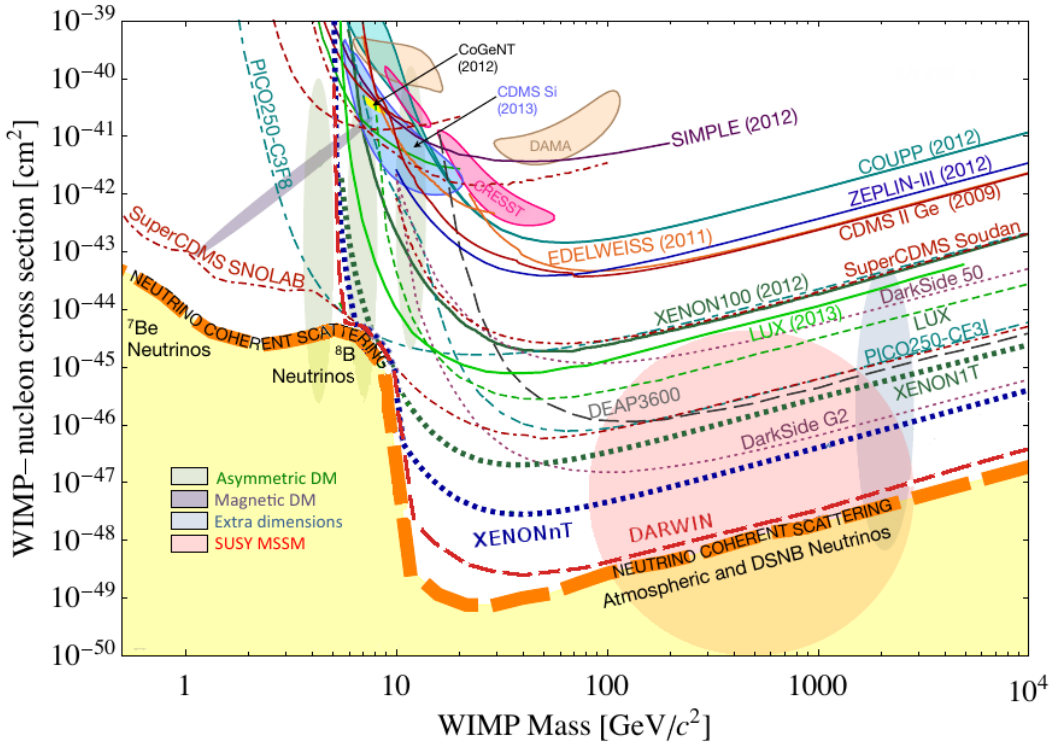
- Galactic halo DM scatters in detector
- Very low energy deposits

Where Are We With Direct Searches?

"WIMP Miracle"

- Electroweak scale masses (~100 GeV) and cross sections (10^{-38} cm^2) give correct relic abundances
- Conflicting claims, mostly ruled out phase space
- A rich dark sector easily bypasses "miracle"

Dark Matter Sensitivity



[1]G.L. Baudis, *Phys. Dark Univ.* **4** (2014) 50. arXiv:1408.4371 [astro-ph].

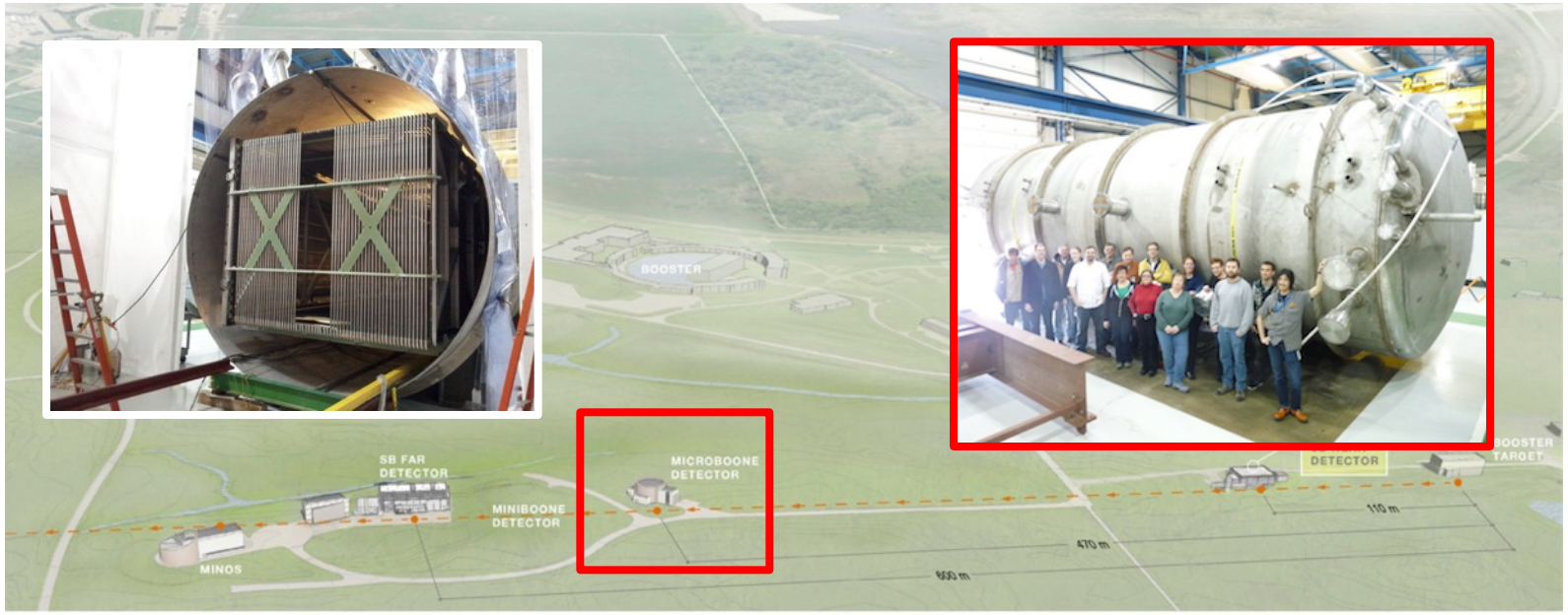
The Short Baseline Neutrino Program

- Suite of 3 liquid argon LAr time-projection chambers (TPCs) to search for sterile neutrino oscillations on the Fermilab Booster Neutrino Beamline (BNB)

[1]SBN Proposal. arXiv:1503.01520 [physics.ins-det].

The Short Baseline Neutrino Program

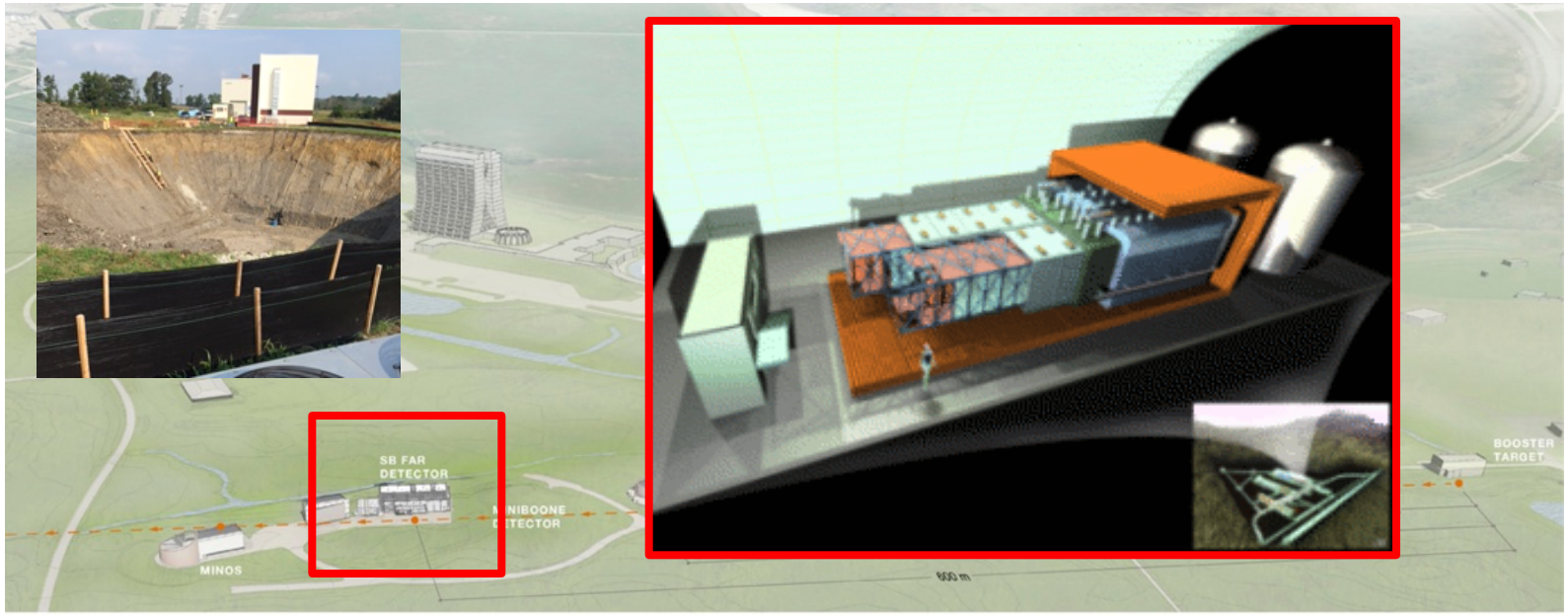
- **MicroBooNE** 170 ton LAr, 32 × 8” PMTs, 8250-wire TPC
- Operates 470 m from BNB neutrino production target
- Has been operating since late-2015



[1]MicroBooNE website. http://www-microboone.fnal.gov.

The Short Baseline Neutrino Program

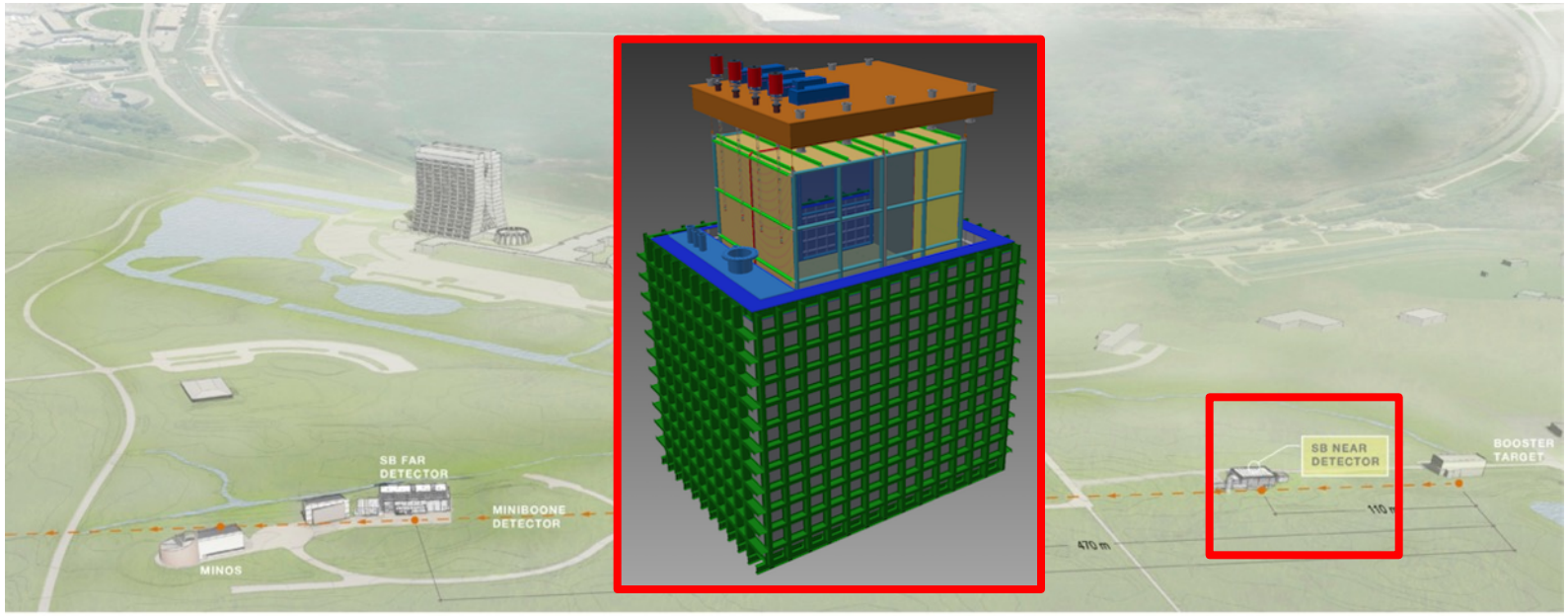
- **ICARUS T-600** 2× 300 ton LAr TPCs (600 ton total volume)
- Has operated at CERN from 2010-2014; move to FNAL in 2017
- Will operate at 700 m from BNB target



[1]ICARUS website. http://icarus.lngs.infn.it.

The Short Baseline Neutrino Program

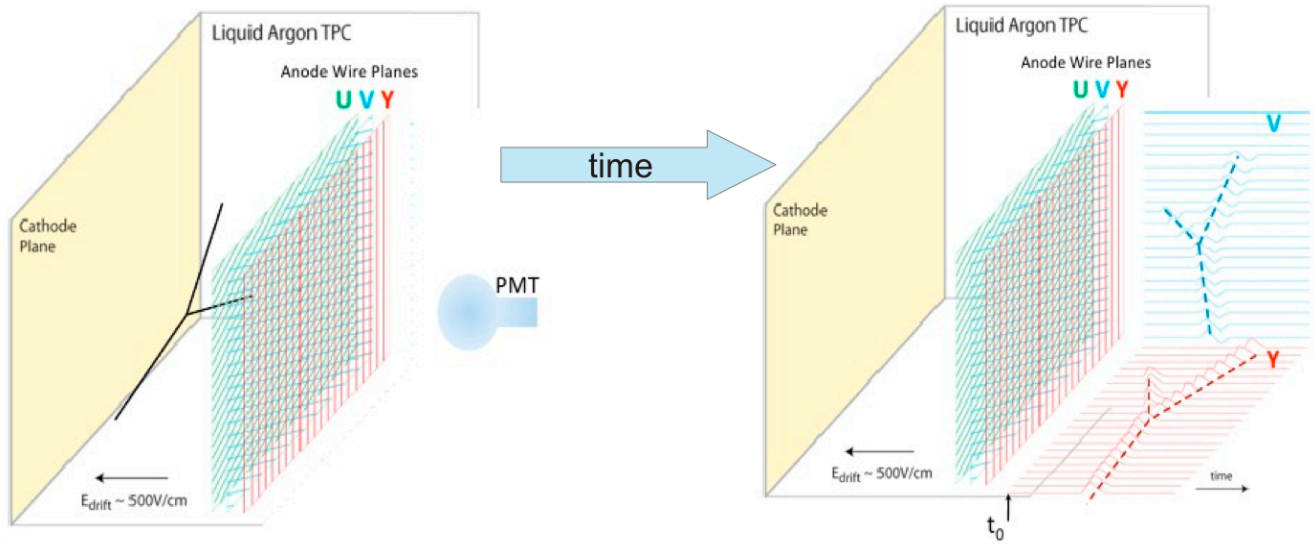
- **SBND (formerly LAr1-ND)** 260 ton LAr (112 ton active volume)
- Design being finalized; 120 × 8” PMTs (similar to MicroBooNE)
- Will operate at 110 m from BNB target



[1]SBND website. http://sbn-nd.fnal.gov.

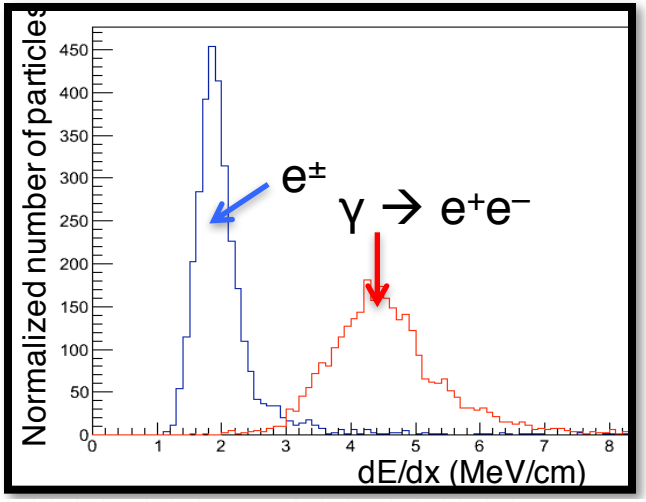
How a TPC Works in a Nutshell

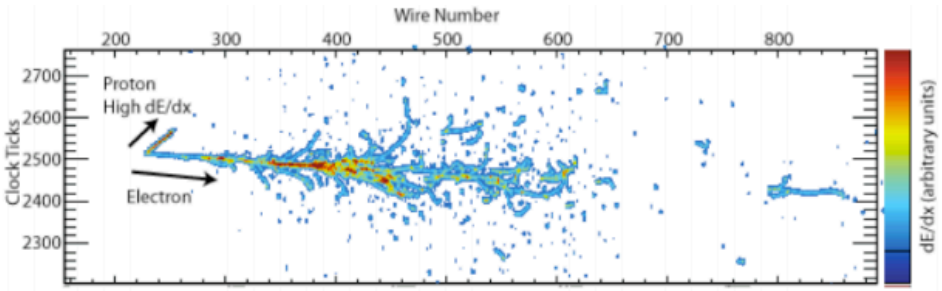
- Particle interaction creates ionization tracks (or points)
- Externally applied electric field drifts free ionized charge at (millisecond per meter) scale velocities
- Fine array of induction and collection wires collect 2D signal
- Light flash in photon detection system sets t_0 → <u>3D reconstruction</u>

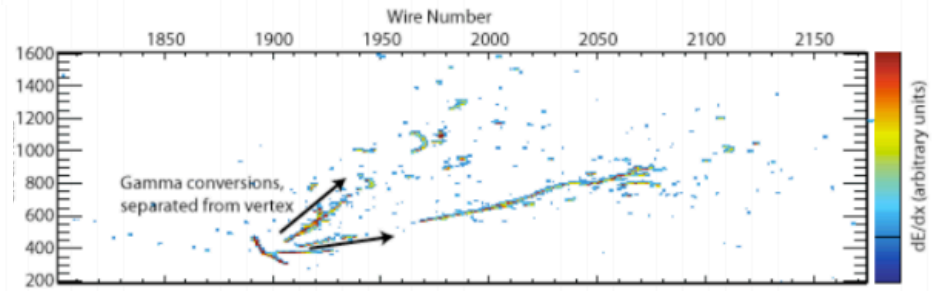


LAr Performance

- LAr TPCs offer unprecedented separation of tracks from vertices
- dE/dx particle ID for an EM shower
  - **LOW dE/dx → single e^+/e^-**
  - **HIGH dE/dx → e^+e^- pair from converted photon**
- TPC can measure vertex / track separation
- Identify converting gamma ray or a candidate neutral particle decay





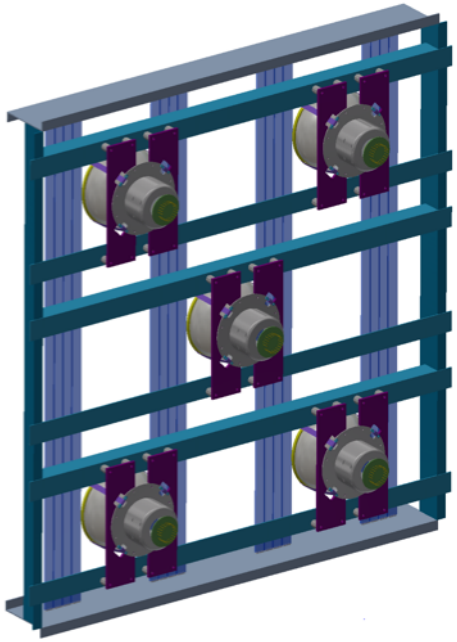


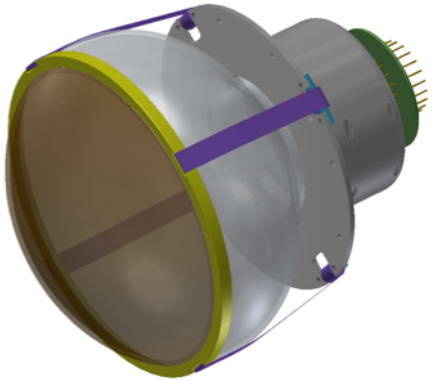
OK, Great! More Reasons for LAr?!

- Very long ionized electron drift lengths for scalable, large TPCs (read: DUNE)
- High scintillation output with easily separable short / long lifetimes
  - Scintillation is fast enough to approach ns-level timing resolution
- ”Easy” to purify
- Low-energy ^{39}Ar beta decay is only significant radio-impurity
- Relatively abundant and inexpensive (compared to LXe)
  - LAr and water (and maybe organic scintillator) are only technologies scalable to 10-100 kton scale
- The ability to construct large-scale, fine-grained tracking TPCs for a full 3D reconstruction and particle identification through *dE/dx* is a game changing opportunity for rare searches

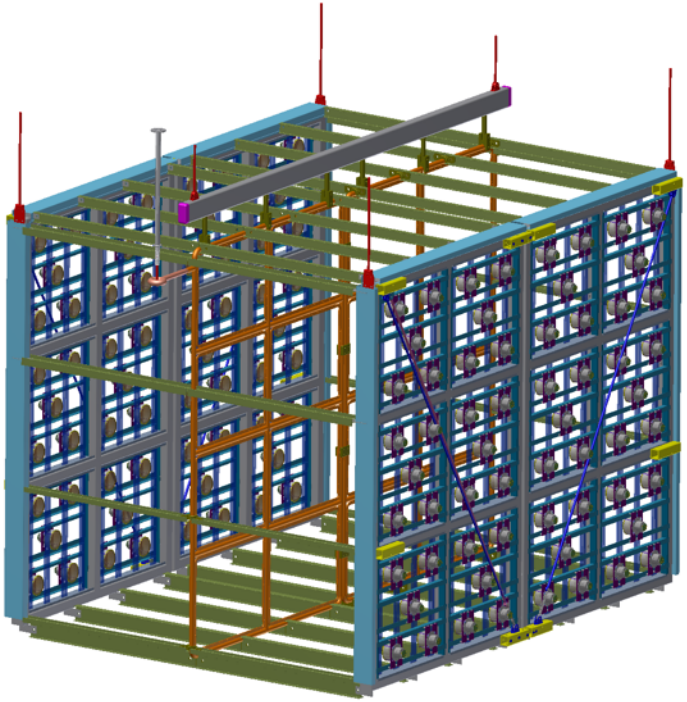
LAr is No Panacea

- Millisecond drift times present serious problems correlating to BNB
- BNB pulse width is 1.6 μs; Constructed of 81X 20 ns RF “buckets”
- Prompt scintillation is our only hope





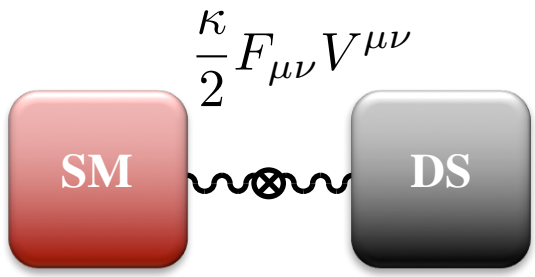
Proposed SBND photon detection system elements (120 PMTs total)

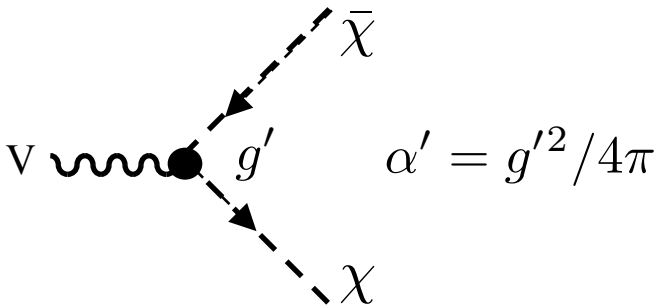


Minimal Vector Portal Model

An Initial Motivator

- Extends the familiar dark photon concept; new *lighter* mediator bypasses Lee-Weinberg bound to allow adequate DM annihilation
- U(1) vector mediator kinematically mixed
- Requires 4 parameters: m_χ, m_V, κ, g'

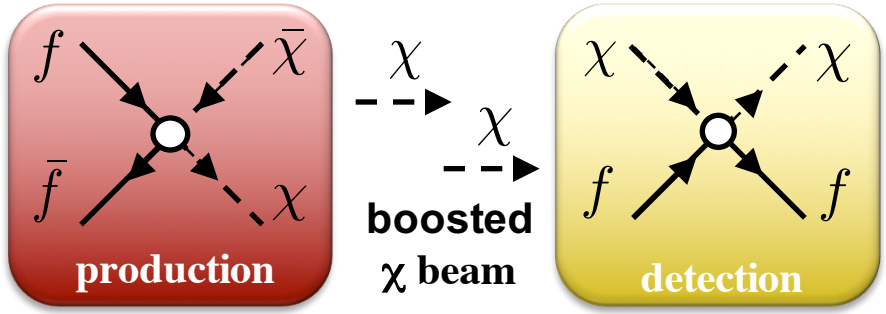


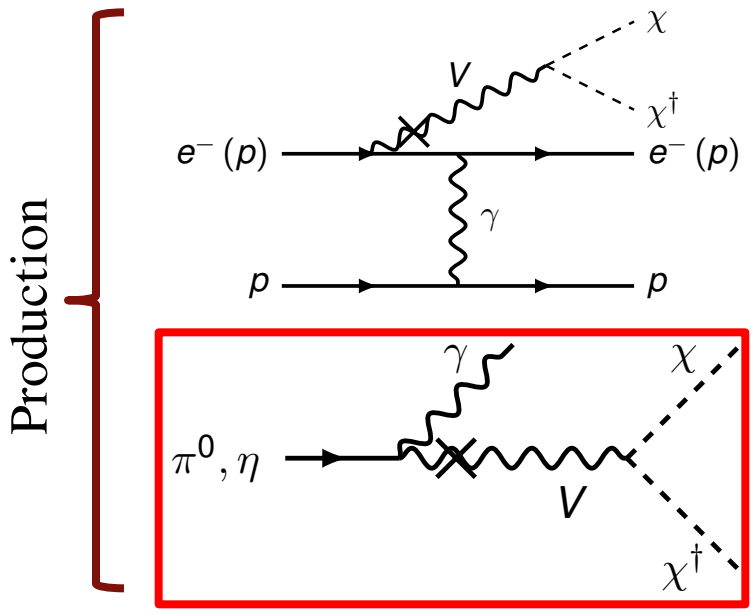


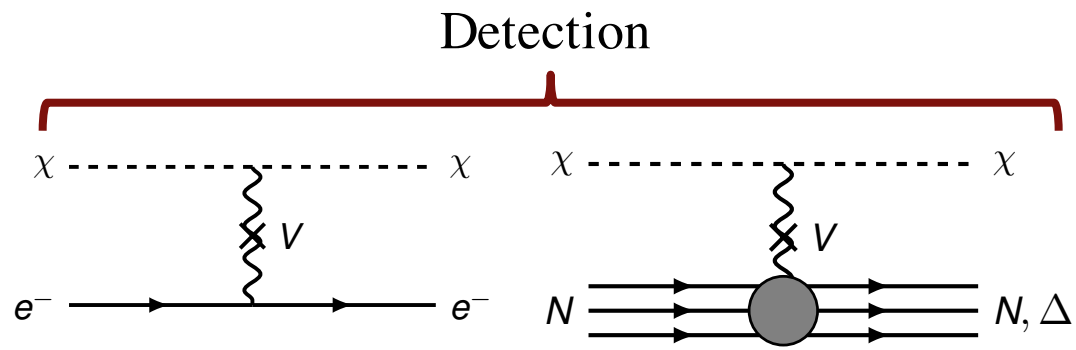
[1]C. Boehm & P. Fayet, *Nucl. Phys.* **B683** (2004) 219. arXiv:hep-ph/0305261 [hep-ph].
C. Boehm et al., *Phys. Rev. Lett.* **92** (2004) 101301. arXiv:astro-ph/0309686 [astro-ph].

Dark Matter Beam and Detector

- High-energy production and scattering detection





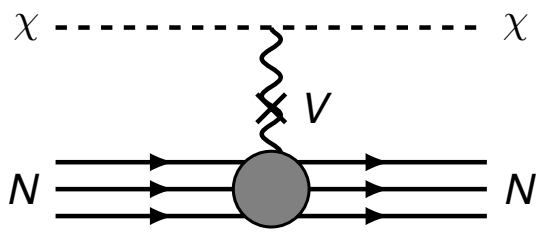


[1]B. Batell et al., *Phys. Rev. Lett.* **113** (2014) 171802. arXiv:1406.2698 [hep-ph].
P. deNiverville et al., *Phys. Rev.* **D84** (2011) 075020. arXiv:1107.4580 [hep-ph].

Neutrino Backgrounds

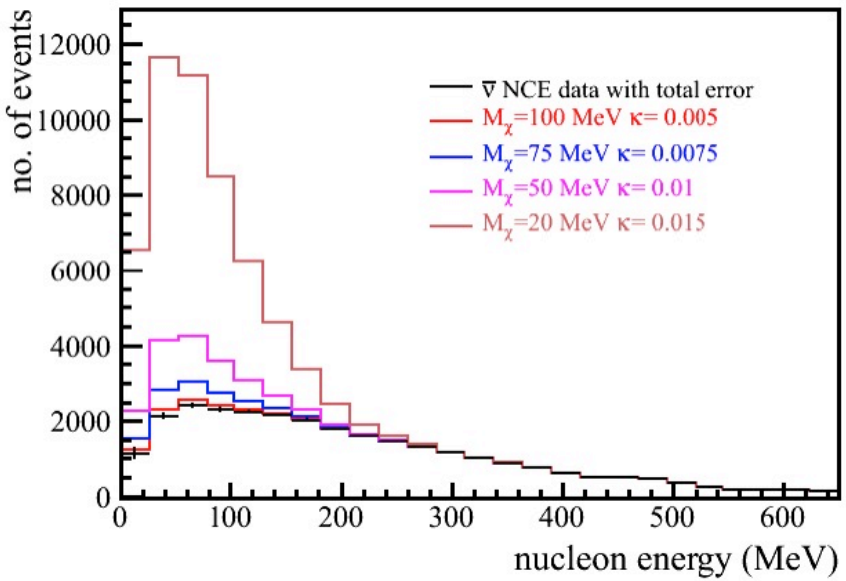
A Lesson from MiniBooNE

- Consider nucleon elastic scattering



- Same as ν NC elastic
  → **MUST SUPPRESS ν**

MiniBooNE Antineutrino Data Set with DM Models and Efficiencies



[1] A.A. Aguilar-Arevalo et al., *Phys. Rev.* **D82** (2010) 092005. arXiv:1007.4730 [hep-ex].
A.A. Aguilar-Arevalo et al., *Phys. Rev.* **D91** (2014) 012004. arXiv:1309.7257 [hep-ex].

Neutrino Backgrounds

A Lesson from MiniBooNE

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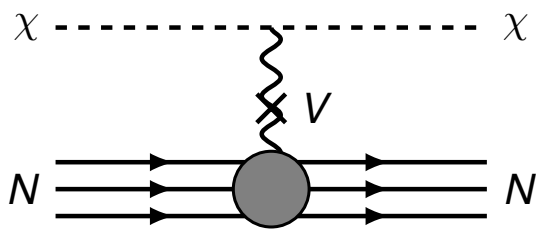

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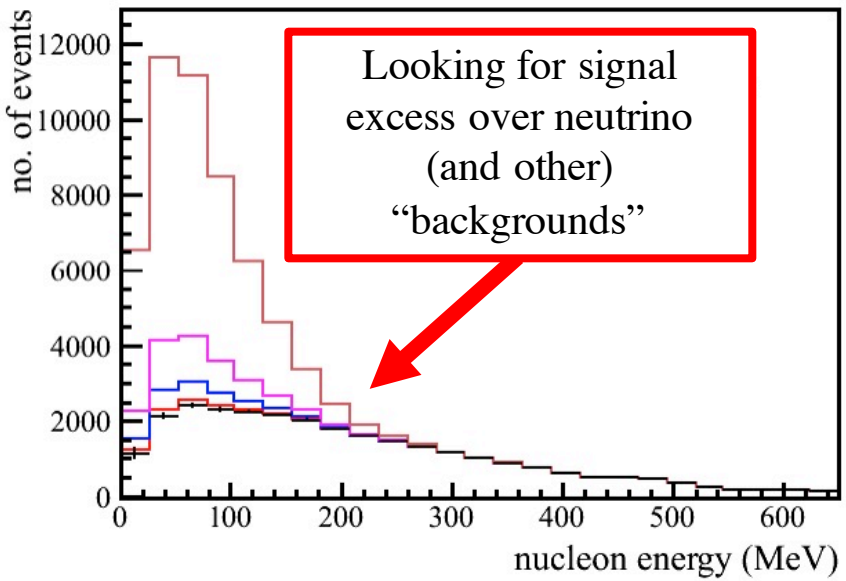
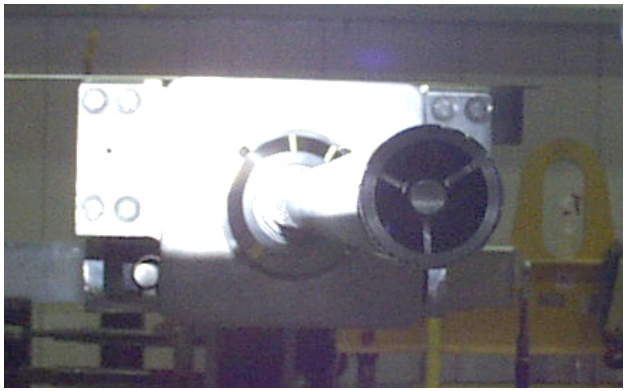
MiniBooNE Antineutrino Data Set with DM Models and Efficiencies

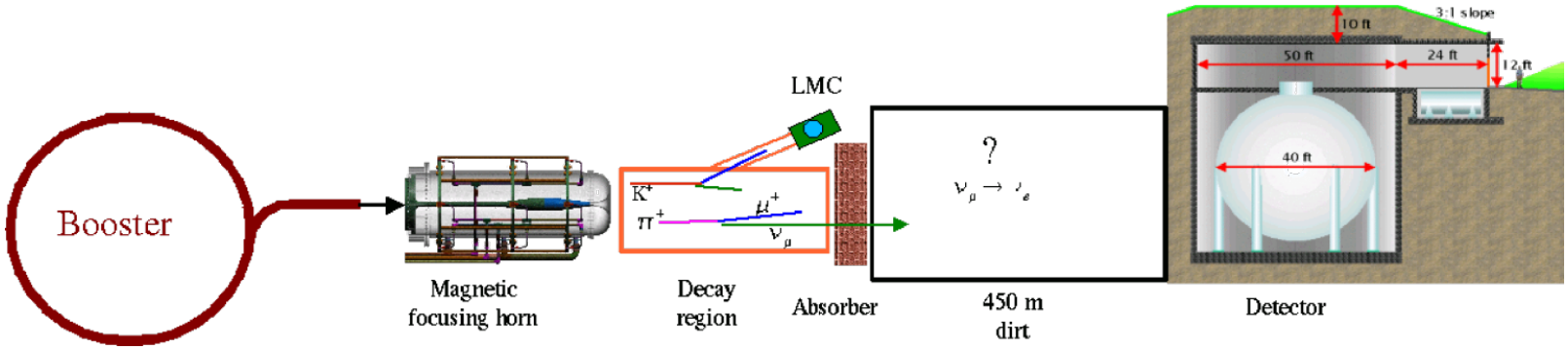


[1] A.A. Aguilar-Arevalo et al., *Phys. Rev.* **D82** (2010) 092005. arXiv:1007.4730 [hep-ex].
A.A. Aguilar-Arevalo et al., *Phys. Rev.* **D91** (2014) 012004. arXiv:1309.7257 [hep-ex].

The Booster Neutrino Beamline (BNB)

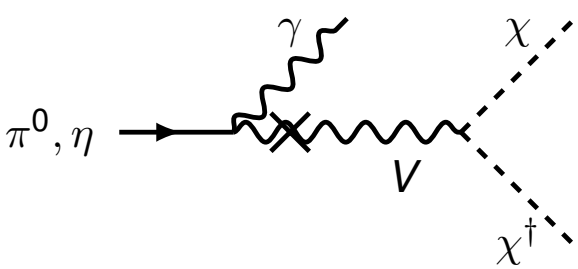
- 8.9 GeV Booster protons to BNB endstation (or Main Injector)
- At BNB, protons strike Be target (1.8 radiation lengths)
- Typical operation: 2×10^{20} protons on target (POT) per year





How To Suppress ν and Produce χ

- ν_μ from π^+ → don't let "escape" into air, absorb them in material
- χ from π^0, η: short lifetimes ($\tau \sim 10^{-16}$ s) → decays before absorption in material

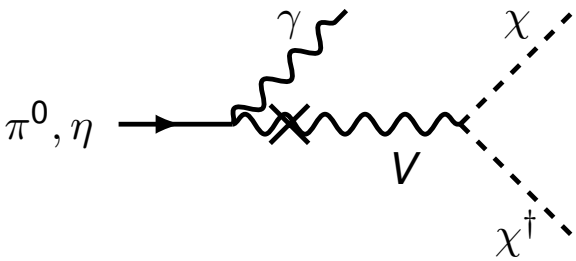


- Bypass Be target, hit steel beam stop
- Neutrino flux suppression factors of 1/44 demonstrated by MiniBooNE (see R. Tayloe talk about MiniBooNE)

Our Primary Sensitivity

- A "beam" of dark matter traveling through meters of dirt requires invisible decays

$$m_V > 2m_\chi$$



- Want final state of V decays to prefer pairs of χs

$$V \to \chi\chi^\dagger$$

- SM final state suppression

- Minimal vector portal model initially motivated run

- Not the only viable model (e.g. leptophobic dark matter)

[1]B. Battell et al., *Phys. Rev.* **D90** (2014) 115014. arXiv:1405.7049 [hep-ph].

SBN and MiniBooNE Signal Estimates

- For all configurations, assume 50 m beam dump, 2×10^{20} POT

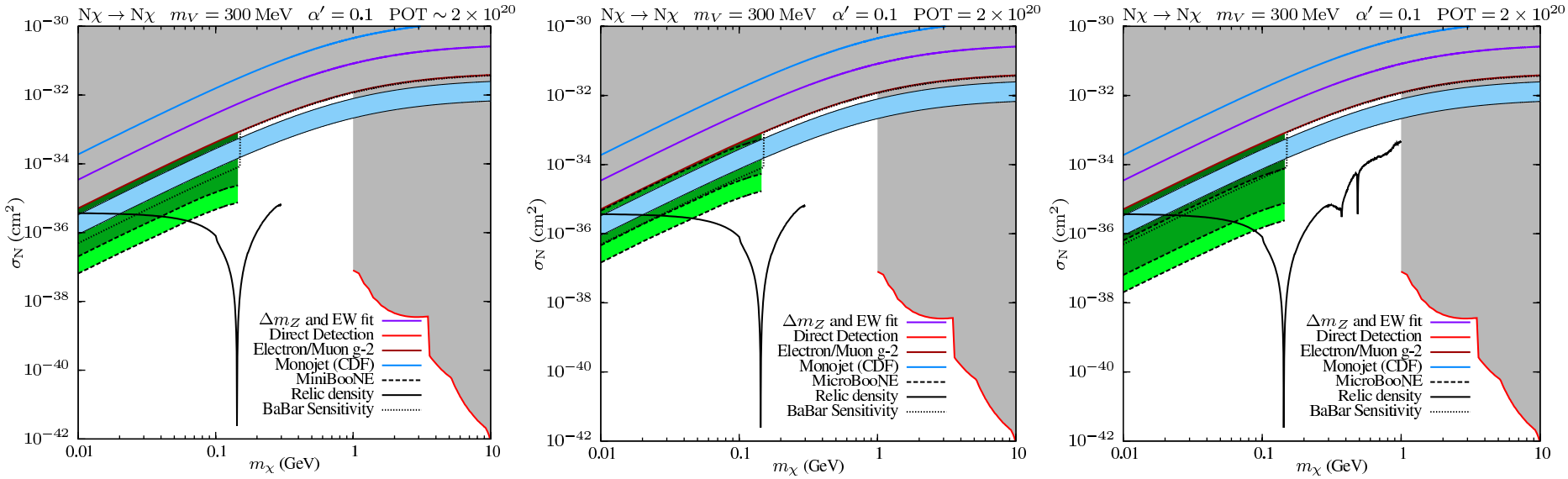
	MiniBooNE	MicroBooNE	SBND
Distance from 50m Dump (m)	500	420	50
Analysis Fiducial Mass (tons)	450	60	40
Efficiency (N or e^-)	30%	60%	60%
Approximate scaling[1]	1.0	0.38	17.7
DM-N signal[2]	**1,326**	**503**	**23,500**
ν-N elastic background[3]	406+/-80	40	2,500
DM-e^- signal[2]	**4.8**	**1.8**	**85.0**
ν-e^- elastic background[3]	~0.6	< 0.1	~10

[1]Sensitivity plots contain other scaling factors, e.g., $1/r^2$ distance scaling, energy, etc.
[2]Assume $M_\chi = 50$ MeV, and $\sigma = 8 \times 10^{-36}$ cm^2.
[3]Contains beamdump neutrino flux suppression 1/44, POT, efficiency, and $\cos\theta_{e\text{-beam}} > 0.98$ cut

Signal Sensitivity DM-N (2×10^{20} POT)

Cross Section vs. DM Mass

MiniBooNE | **MicroBooNE** | **SBND**



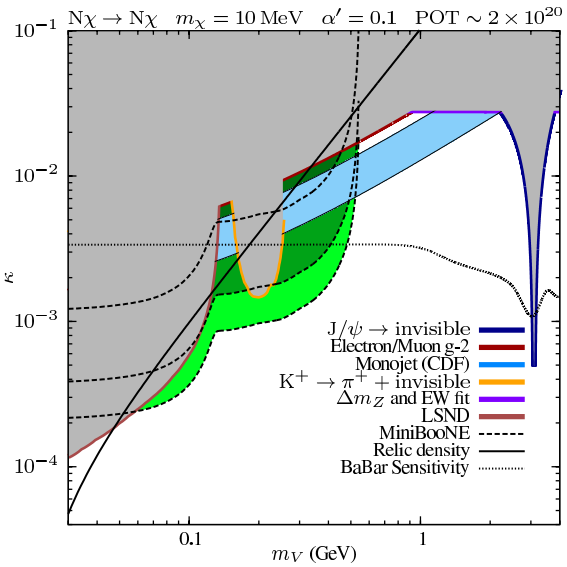
1-10 events | 10-100 events | 100-1000 events

- **Signal** sensitivity only → background and systematics ignored

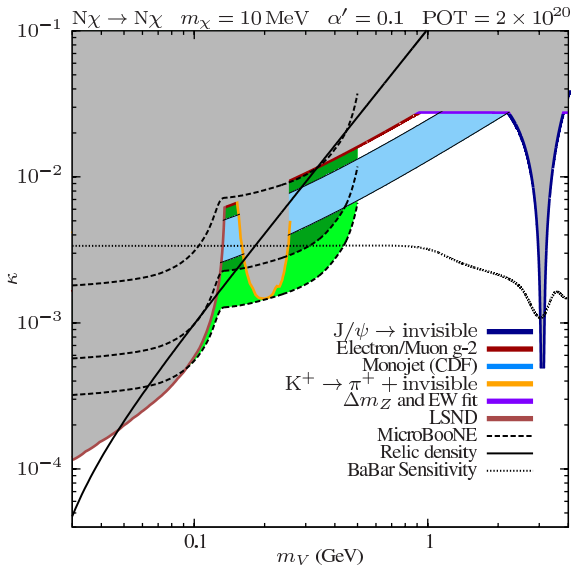
Signal Sensitivity DM-N (2×10^{20} POT)

Mixing Strength vs. Vector Mediator Mass

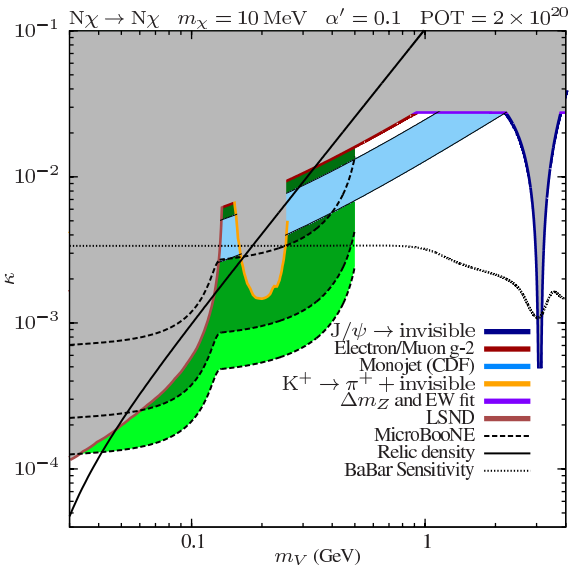
MiniBooNE



MicroBooNE



SBND



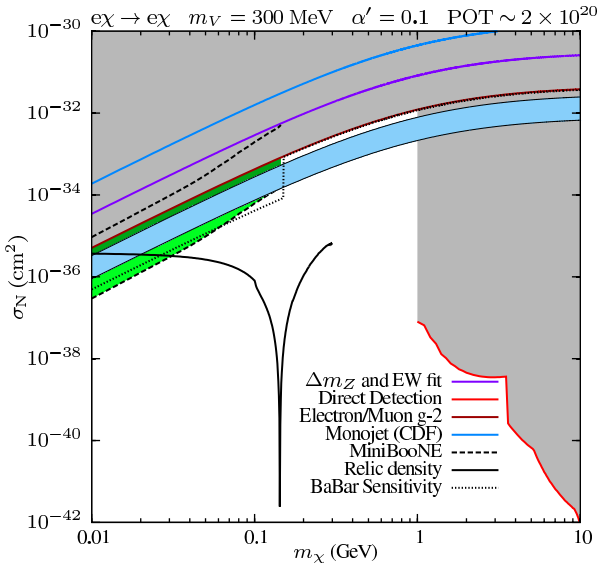
1-10 events 10-100 events 100-1000 events

- **Signal** sensitivity only → background and systematics ignored

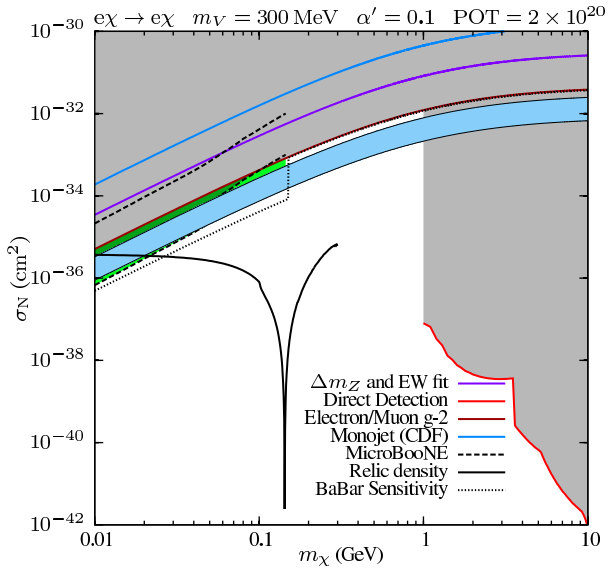
Signal Sensitivity DM-e$^-$ (2×10^{20} POT)

Cross Section vs. DM Mass

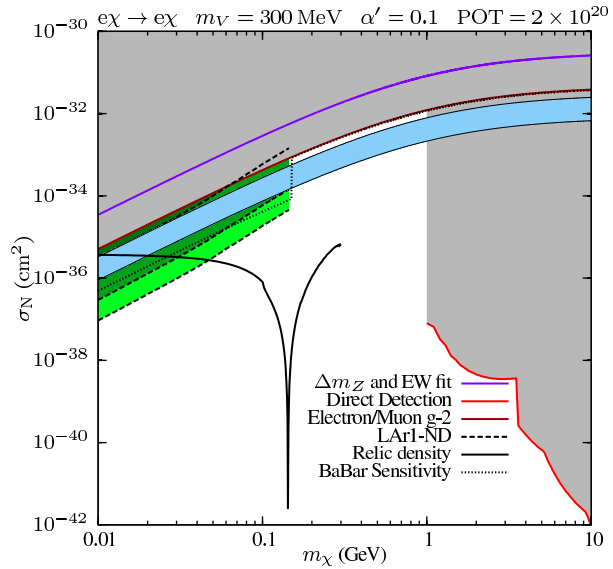
MiniBooNE



MicroBooNE



SBND



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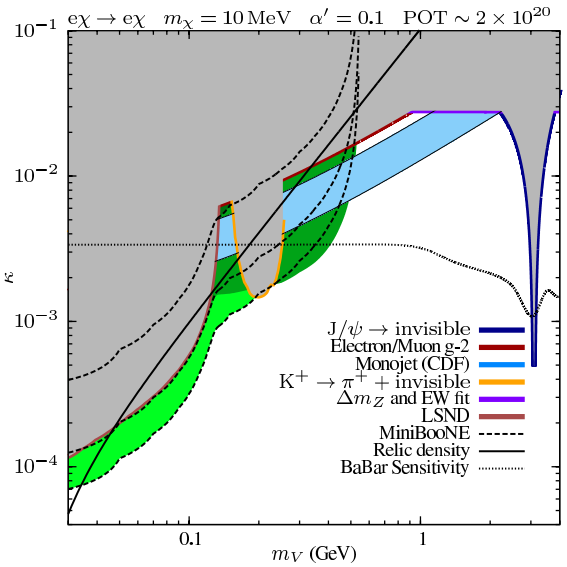
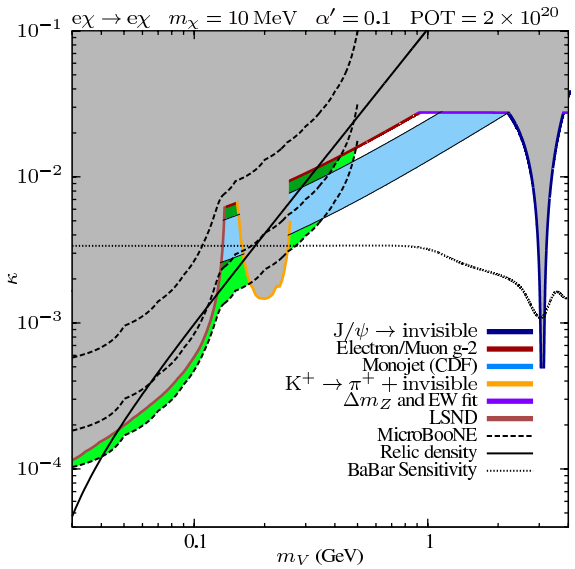
Mixing Strength vs. Vector Mediator Mass

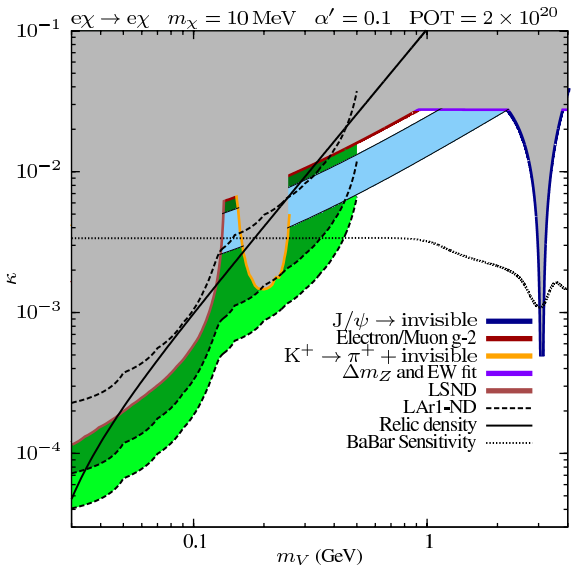
MiniBooNE



MicroBooNE



SBND



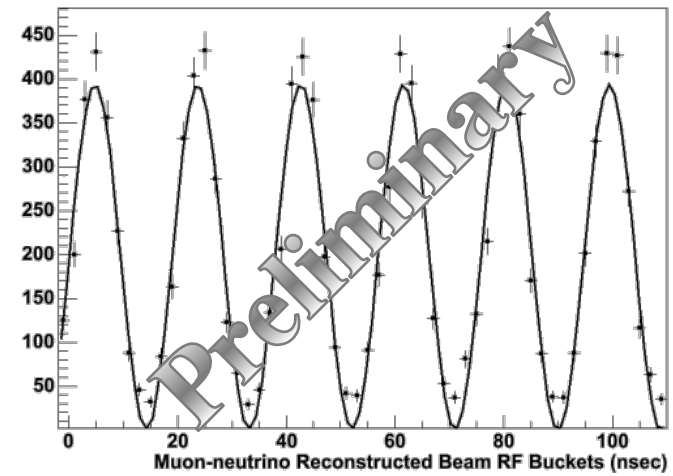
1-10 events 10-100 events 100-1000 events

- **Signal** sensitivity only → background and systematics ignored

Dark Matter Propagation Time

- χ is massive so travels the 500 m slower than c ($m\chi$ = 120 MeV, E = 1.5 GeV → 6 ns delay over 500 m drift)
- SBND drift is 50 m, sensitive to higher mass dark matter; complementary
- Beam – 81 RF bunches
- MiniBooNE has prompt Cherenkov timing response and excellent PMT coverage

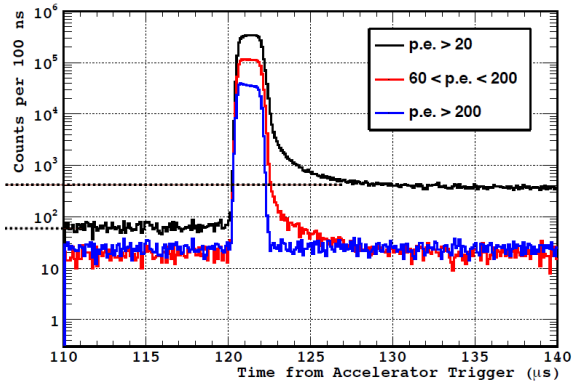
MiniBooNE Muon Reconstruction (RF Buckets)

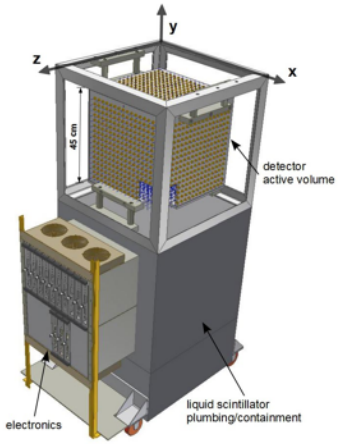


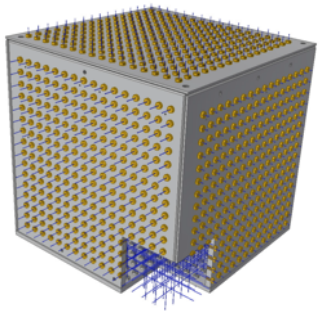
- Is LAr scintillation and PMT coverage sufficient for ns-scale resolution in SBN?

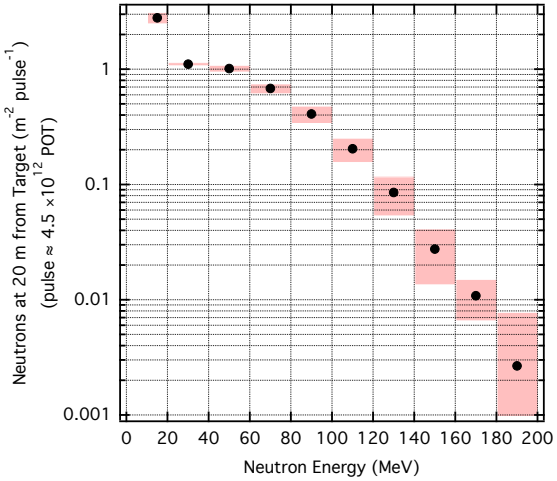
Beam-Related ”Dirt” Backgrounds

- Neutrons produced in surrounding rock by beam neutrinos can penetrate deep within detector
- Background not subtractable
- SciBath is 80 L liquid scintillator neutron tracking detector
- Proven record for measuring neutrons backgrounds at BNB (e.g., SciBooNE near SBND site, results forthcoming)



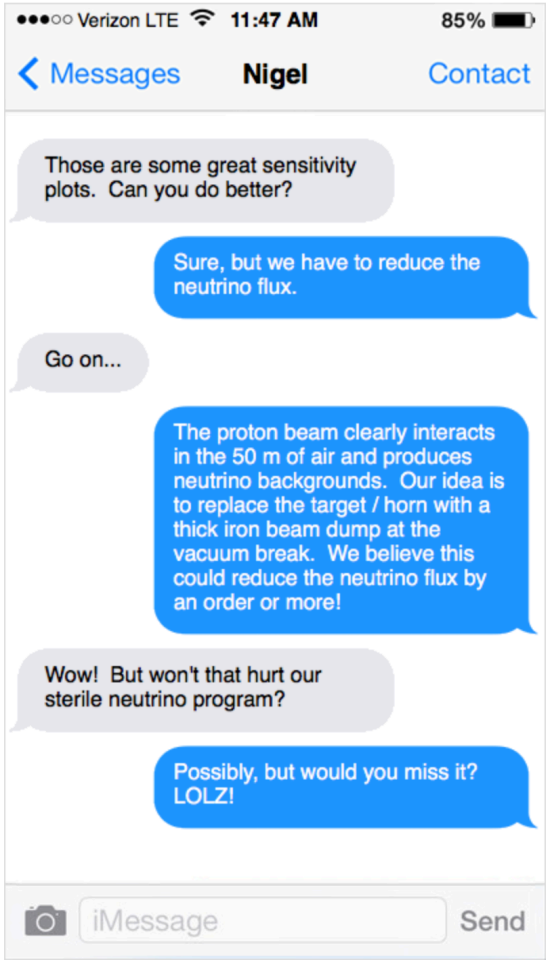






Future Improvements in Beam Dump

- Future DM search must reduce neutrino backgrounds
- Current beam dump goes through 50 m of air.
- A thick iron target could significantly reduce the neutrino flux relative to the DM production
- $1/r^2$ DM flux reduction, but significant S/B increase



Easy, it's just a joke!

Conclusions

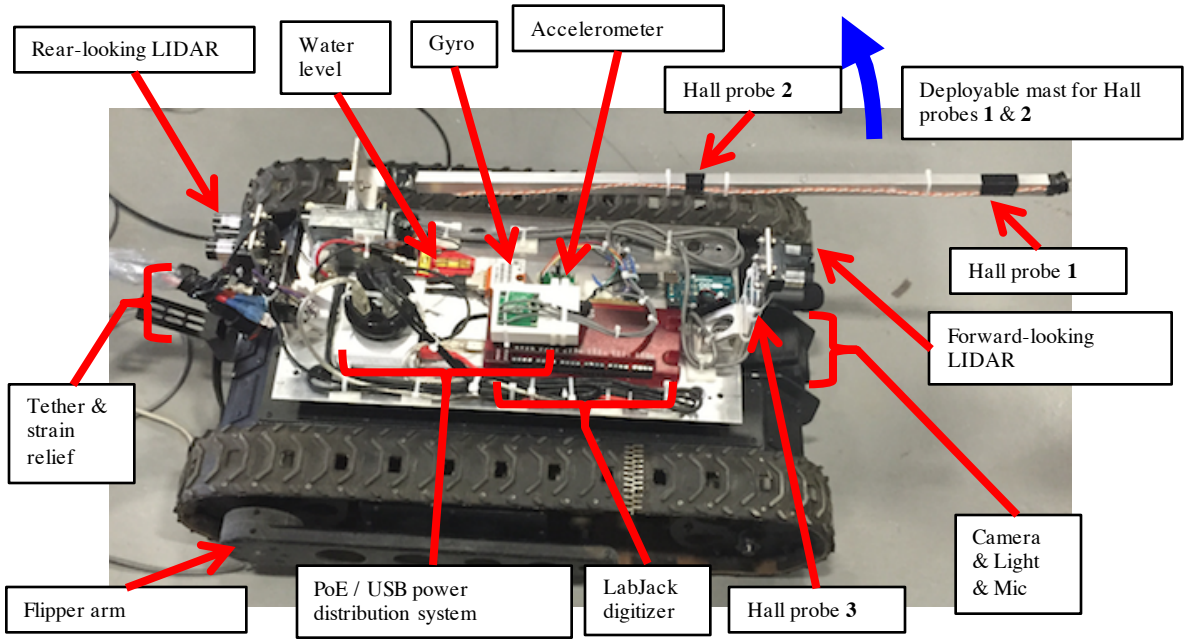
- MiniBooNE has paved the way for Light Mass Dark Matter searches at the Fermilab BNB → a new proton beam dump result
- The Short Baseline Program is approved and will build SBND and ICARUS near and far detectors to complement MicroBooNE
- SBN will use a trio of LAr TPCs with unprecedented 3D track reconstruction and EM shower particle ID
- SBND (in particular) has a high sensitivity to DM-Nucleon and DM-electron elastic scattering channels
- Fast timing resolution is one of the major challenges

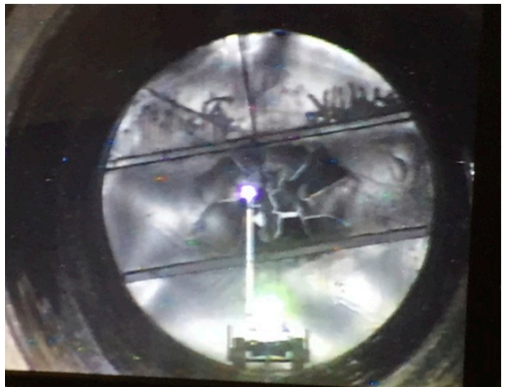
BACKUPS

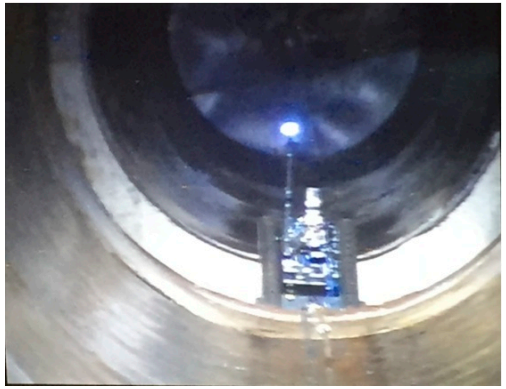
Beampipe Survey with FRED

- **FRED**: **F**inding **R**adiation **E**vidence in the **D**ecay pipe

- Visual and magnetic field survey
  → no anomalies







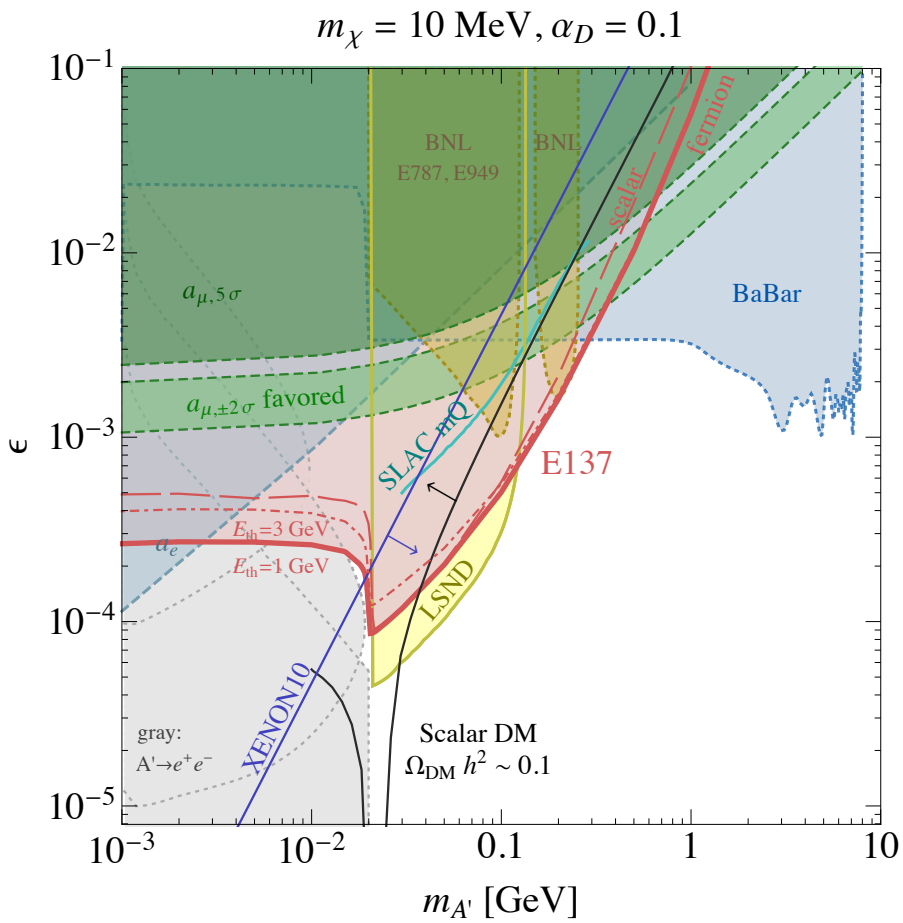
Current Limits

Invisible

- $m_V > 2m_\chi$
- Final state V decays prefer to go to pairs of χs

$$V \to \chi\chi^\dagger$$

- SM final states suppressed
- We need these for χ beams



[1]B. Battell et al., *Phys. Rev. Lett.* **113** (2014) 171802. arXiv:1406.2698 [hep-ph].

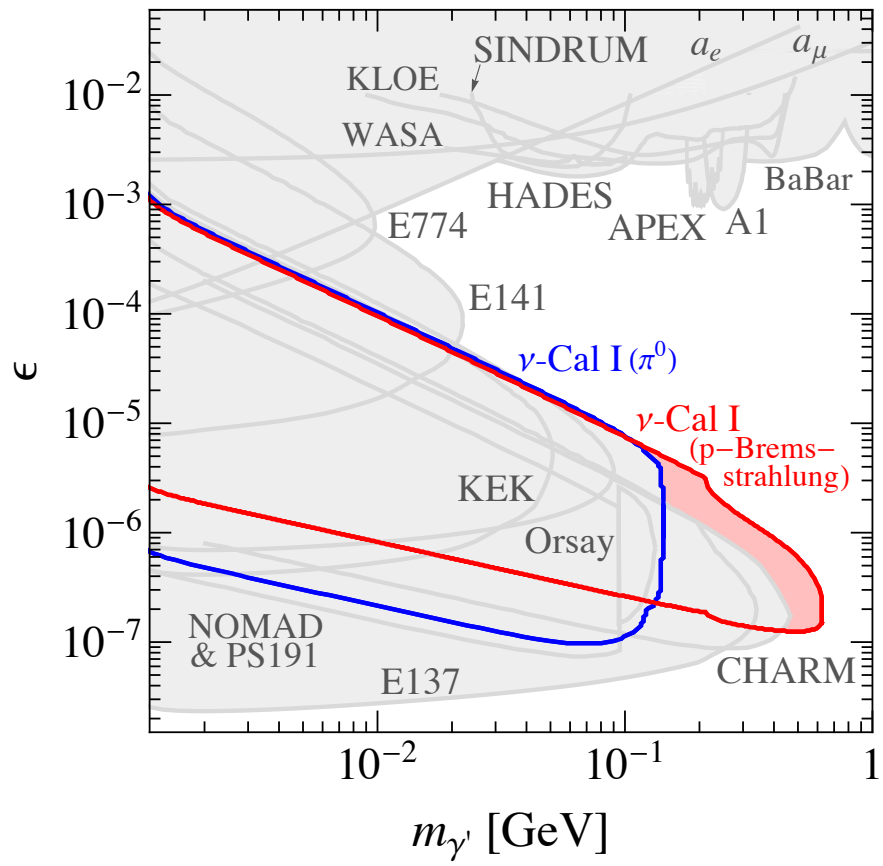
Current Limits

Visible

- $m_V > 2m_\chi$
- Final state V decays are visible SM model particles, e.g.,

$$V \to \ell^- \ell^+ \to \gamma\gamma$$

- Can't produce pairs of χs



[1] J. Blümlein & J. Brunner, *Phys. Lett.* **B4** (2014) 320. arXiv:1311.3870 [hep-ph].