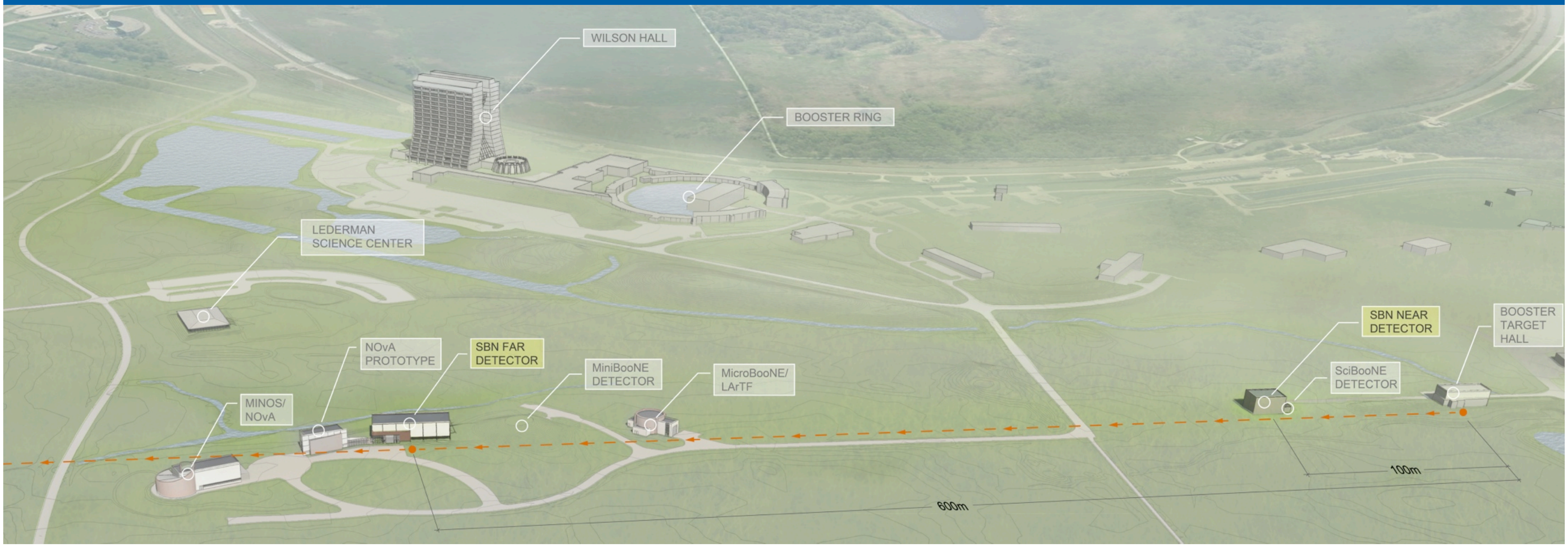

Future Searches with Proton Fixed Target Experiments

R.G. Van de Water (LANL, P-25 Subatomic Physics)

US Cosmic Visions Workshop

March 24, 2017

Outline

- Physics case for Proton beam dump DM searches
  - A number of portals uniquely tested by proton beams
  - MeV to GeV a good place to look for DM
- Current proton beam dump searches, strategy, and shortcomings
  - Lessons learned from doing a real beam dump DM search with MiniBooNE
- Near term improved searches at FNAL
  - BNB 8 GeV protons, Short Baseline Neutrino (SBN) program
  - Main Injector (MI) Dump – higher energy 120 GeV protons
  - SeaQuest (see Liu talk)
- Summary

Where Are We With Direct Searches?

"WIMP Miracle"

What about here

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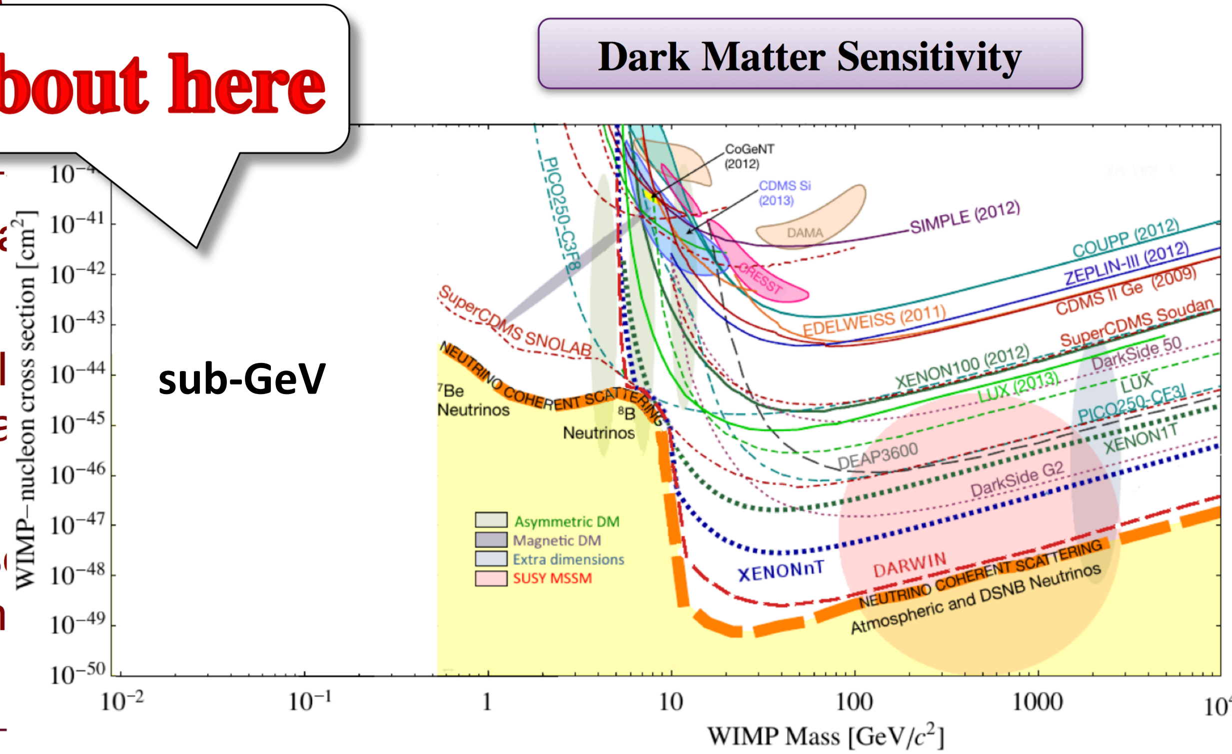


[1]G.L. Baudis, *Phys. Dark Univ.* **4** (2014) 50. arXiv:1408.4371 [astro-ph].

- Direct detection experiments >GeV mass threshold due to slow moving galactic halo DM, and low energy detection limits.
- **Solve by producing boosted DM with proton beamline. Method has experienced much recent theoretical and experimental activity.**

Physics Case for Proton Beam Dump DM searches

- Provide couplings to copious number of nucleons, mesons, and photons from decay or Bremstrhalung.
  - probes both leptonic and leptophobic models
- Probe Vector, Neutrino, and Higgs portal models.
- Coupled with a large/near neutrino detector, proton dump experiments are able to directly search for invisible modes, i.e. direct production and detection of DM.
- High energy proton collisions boosts DM final state energy, accesses higher DM mass and kinematics.
  - sensitive to DM mass from a few MeV up to few GeV

Portals to the Dark Sector

$$(AS + \lambda S^2)H^\dagger H$$ Higgs Portal

$$yLHN$$ Neutrino portal

$$-\frac{\kappa}{2}B_{\mu\nu}V^{\mu\nu}$$ Vector Portal

- Only three *renormalizable* portals in the Standard Model
- S, N, V_μ may mediate interactions between dark sector and SM

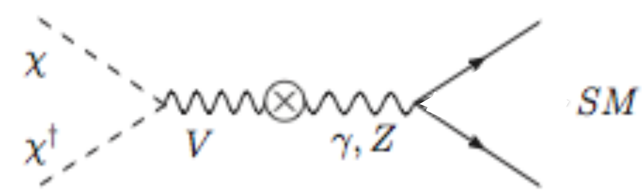
Vector Portal Dark Matter

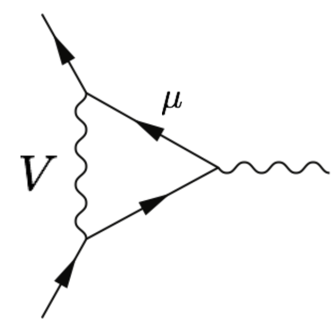
[Pospelov, Ritz, Voloshin]
[Arkani-Hamed, Finkbeiner, Weiner, Slatyer]

$$\mathcal{L} \supset |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4}(V_{\mu\nu})^2 + \frac{1}{2} m_V^2 (V_\mu)^2 - \frac{\kappa}{2} V_{\mu\nu} F^{\mu\nu} + \ldots$$

$$D_\mu = \partial_\mu - i g_D V_\mu$$

- Dark photon mediates interaction between DM and SM
- 4 new parameters: $m_\chi, m_V, \kappa, \alpha'$ $\quad (V = A',\ \kappa = \epsilon,\ \alpha' = \alpha_D)$
- Scalar DM annihilation is p-wave, CMB ok
- Experimental signatures
  $M_V > 2 M_x$ (invisible mode, neutrino experiments ideal)
  $M_V < 2 M_x$ (visible modes, e+e-, etc)
- Dark photon can address g-2 anomaly





Leptophobic Dark Matter [Batell, deNiverville, McKeen, Pospelov, Ritz]

- It is possible that dark matter couples dominantly to quarks

- **Many constraints are evaded - proton beams have a significant advantage!**

- Simplified model (based on local $U(1)_B$ baryon number)

$$\mathcal{L} = i\bar{\chi}\gamma^\mu D_\mu \chi - m_\chi \bar{\chi}\chi - \frac{1}{4}(V_B^{\mu\nu})^2 + \frac{1}{2}m_V^2 (V_B^\mu)^2 + \frac{g_B}{3} V_B^\mu \sum_i \bar{q}_i \gamma_\mu q_i + \ldots$$

$$D^\mu = \partial^\mu - i g_B q_B V_B^\mu$$

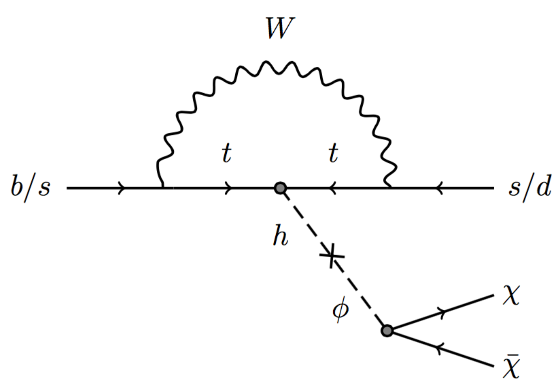
- 4 new parameters: $m_\chi, m_V, \alpha_B, q_B$

- $U(1)_B$ is "safe" - preserves approximate symmetries of SM (CP, P, flavor)

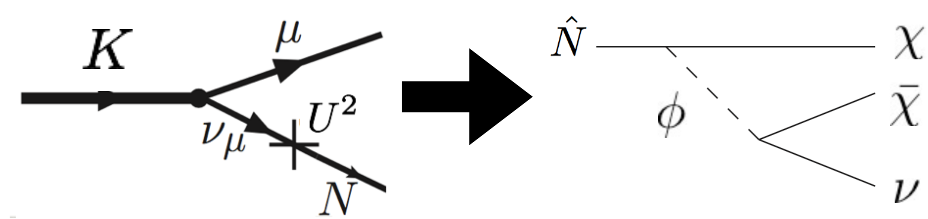
- Gauge anomalies can be cancelled by new states at the weak scale

Higgs & Neutrino portals

- It is possible that DM interacts through Higgs or Neutrino portal
- **Proton beams allow for significant production of dark sector states through these portals via, e.g., meson decays**



Higgs portal
[see e.g. Krnjaic '16]



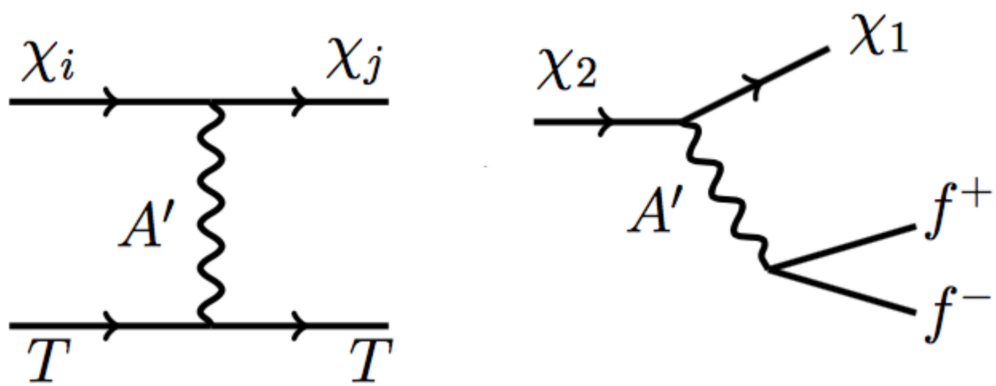
Neutrino portal
[see e.g. Bertoni, Ipek, McKeen, Nelson '14]

- Signatures include rare meson decays with missing energy

Inelastic Dark Matter

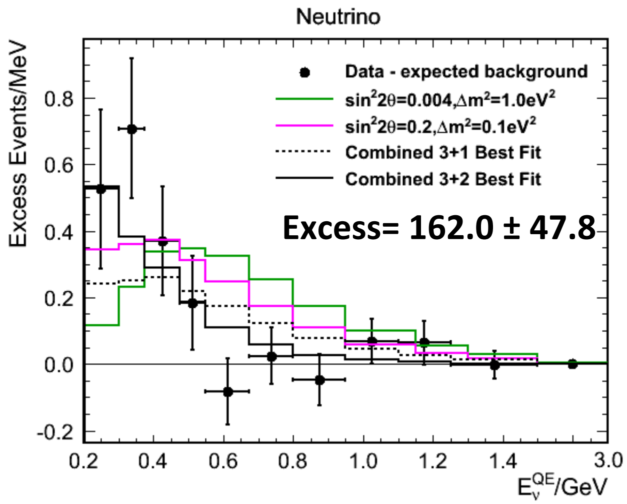
[Tucker-Smith, Weiner]
[Izaguirre, Kahn, Krnjaic, Moschella]

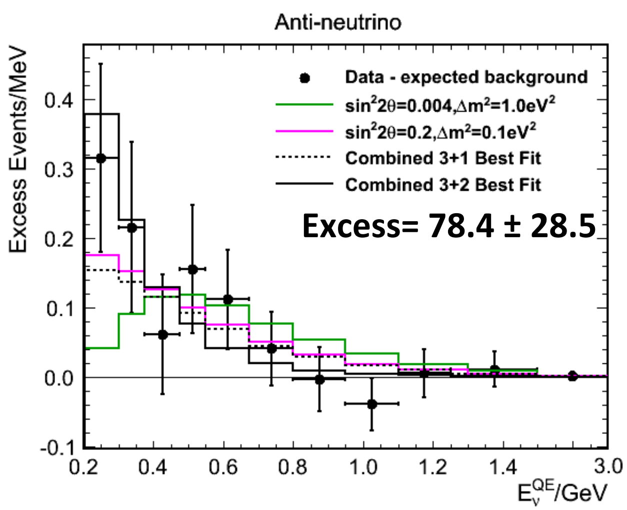
- The DM particle, χ_1 , interacts by transitioning to a heavier state χ_2
- This can lead to new signatures involving the decay of the excited state

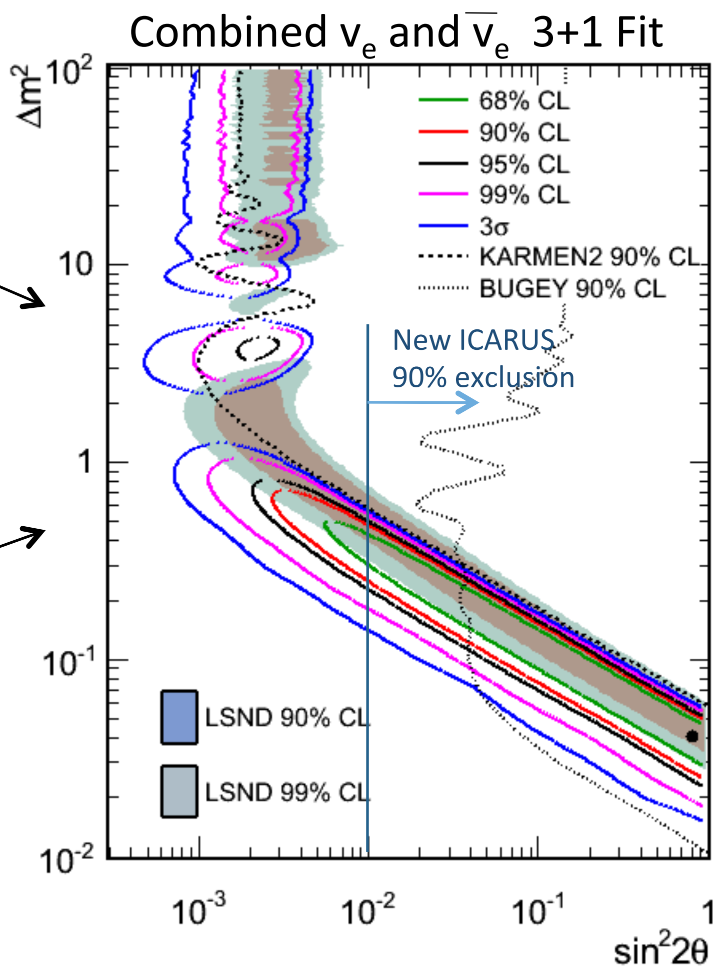


- Can help evade constraints from direct detection and CMB
- **Proton fixed target experiments, like MiniBooNE, MicroBooNE, SBND will have significant sensitivity to such signatures.**
- These signatures are striking! No neutral current neutrino background

MiniBooNE appearance results to be tested by Short Baseline Neutrino (SBN): If not oscillations, what is it?







- Combined ν_e and $\bar{\nu}_e$ Event Excess from 200-1250 MeV = 240.3+-34.5+-52.6 (3.8σ)
- **Possible first hint of sterile neutrinos and/or coupling to the dark sector….**

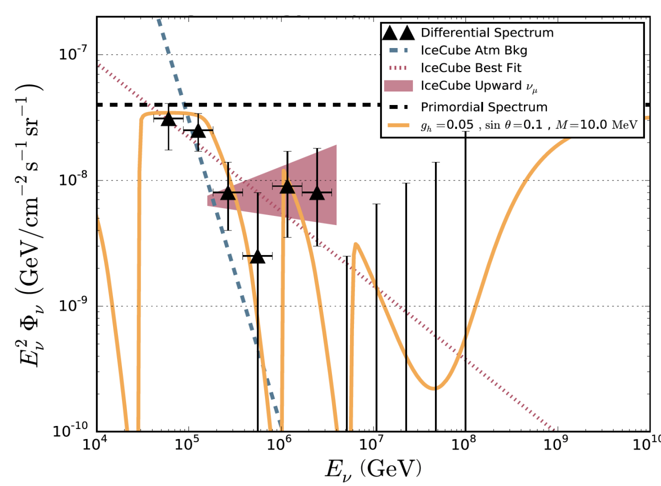
Possible Experimental Signatures of Dark Sector

(Cherry, Friedland, Shoemaker arXiv:1605.06506)

- Assume LSND/MiniBooNE anomaly ~1 eV^2 sterile neutrino.
- Assume sterile neutrinos are self interacting and gives standard neutrino's an effective interaction through oscillations.
- Predicts ~MeV scale dark sector mediator.
- Explains IceCube lack of high energy neutrinos.

increase m_ν

absorption moves to low-E



increase m_ϕ → absorption move to high-E

Resonant absorption at:

$$E_\nu = \frac{m_\phi^2}{2m_{\nu_i}}$$

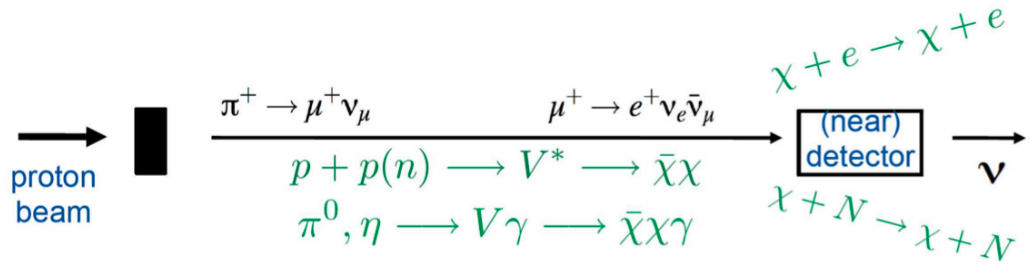
Cherry, Friedland, IMS [1605.06506]

(from I. Shoemaker)

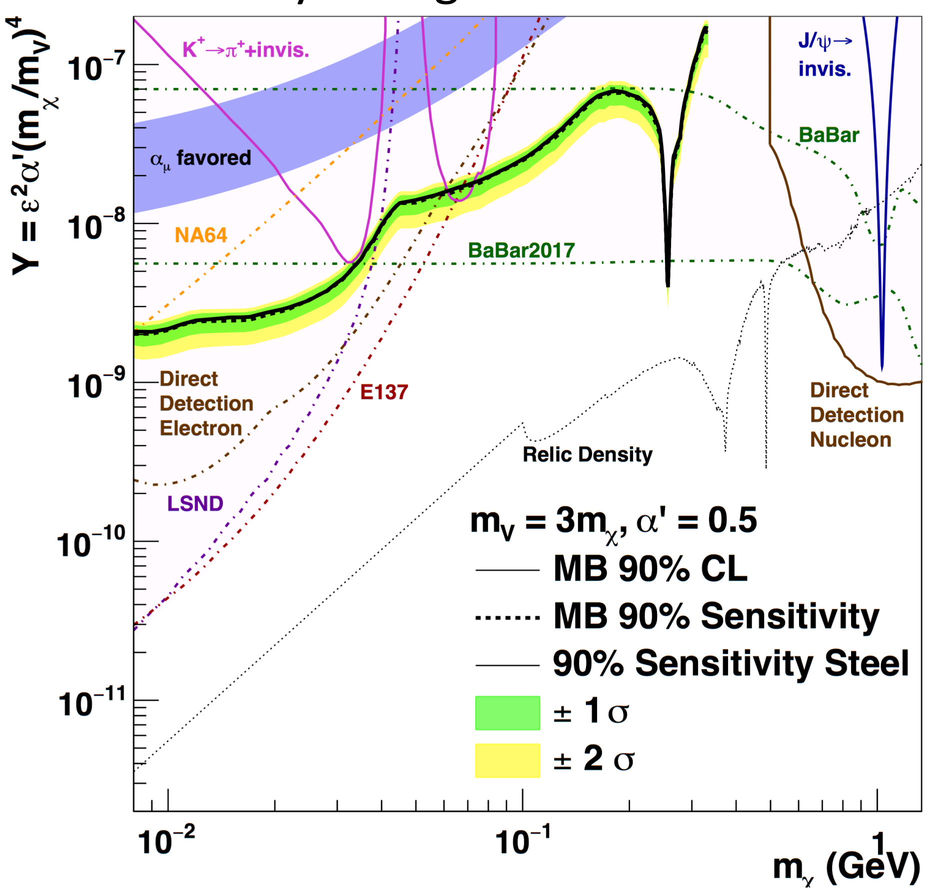
Why are neutrino experiments (e.g. MiniBooNE) useful for new particle searches?

- Require lots of protons on target: MiniBooNE has a total of ~2E10^{21} @ E_{proton}= 8GeV.
- Detector needs to be close to source (for rate), but far enough away too minimize beam related backgrounds. MB is 500m from target.
- Massive detector (MB ~1 Kton oil).
- Good particle identification (MB reconstructs p, n, μ, e, γ).
- Good event reconstruction (for MB E_t > 35 MeV and absolute timing ~nsec).
- Good cosmogenic background rejection, especially below 200 MeV.
- Run parasitic, cost burden shared with neutrino project.

MiniBooNE Sub-GeV Dark Matter Results



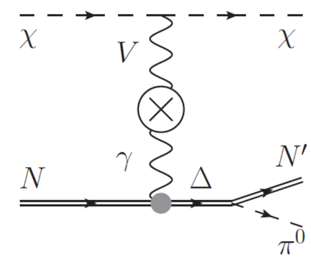
- MiniBooNE performed a dedicated proton beam dump search, **proving it is feasible** and yielding direct DM limits in an un-explored region.



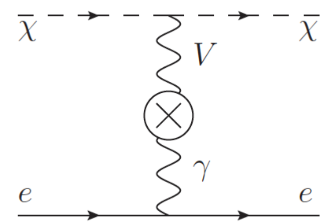
- **NCE results arXiv: 1702.02688 PRL and PRD soon.**
- **See Cooper's talk for details.**
- **Based on 50m absorber running.**
- **Ongoing analysis of π^0 and electron scattering channels.**

Next Analyses in MB Data Set

- Inelastic DM resonance scattering $\Delta \rightarrow \pi^0$ where NCπ^0 ν-scattering is main background
  - π^0 is a clean detection signal
  - Beam-uncorrelated backgrounds expected to be small
  - Expect better sensitivity than nucleon-DM elastic scattering



- Elastic DM-electron scattering where Standard Model predicted ν-e is main background
  - Like ν-e is very forward peaked
  - Expect better sensitivity than nucleon-DM elastic scattering

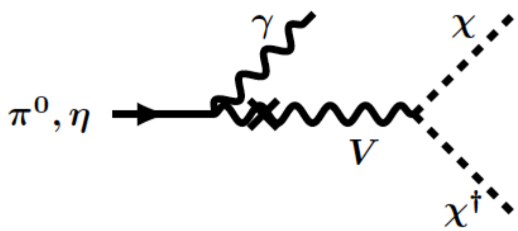


- RF spill-event timing
  - Massive DM will be delayed relative to ν backgrounds
  - Predictable timing spectrum vs. dirt which is flat in time
  - Timing is even applicable to ν-oscillation data to separate e-γ

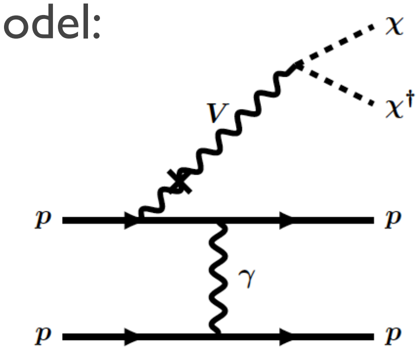
BdNMC

[deNiverville, Chen, Pospelov, Ritz]
https://github.com/pgdeniverville/BdNMC/releases

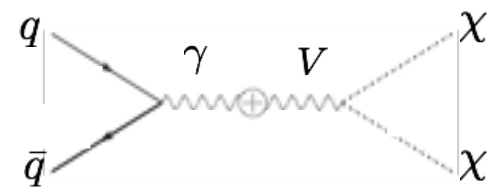
- Publicly available proton beam fixed target DM simulation tool developed by Patrick deNiverville (U.Victoria) and collaborators. **Used for all the sensitivities in this talk and for the recent MiniBooNE DM result.**
- Detailed DM production model:



Neutral mesons decays

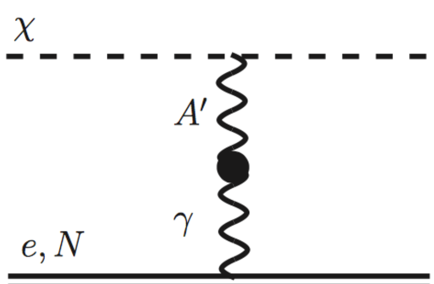


Bremsstrahlung + vector meson mixing

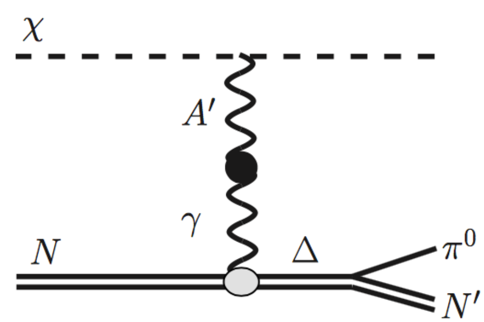


Direct production

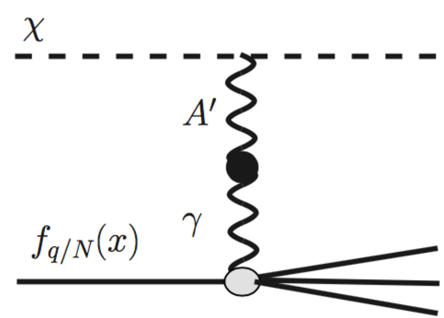
- Several DM scattering processes included



Elastic NC nucleon or electron scattering



Inelastic NC neutral pion -like scattering

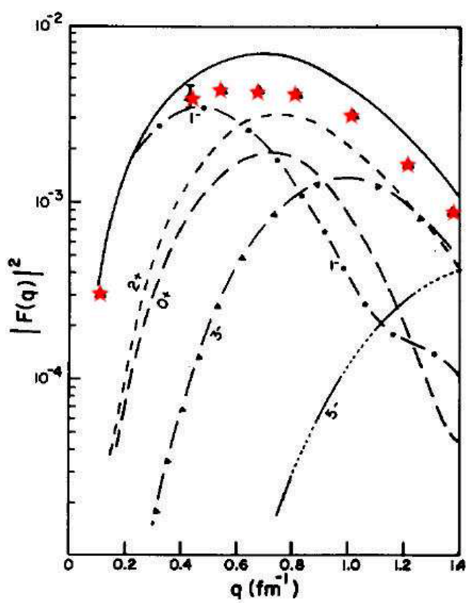


Deep Inelastic scattering

Improving DM Nuclear Modeling (S. Pastore, J. Carlson, LANL)

Nuclear Effects in Searches for Light Dark Matter

^{40}Ca form factor for the giant resonance region

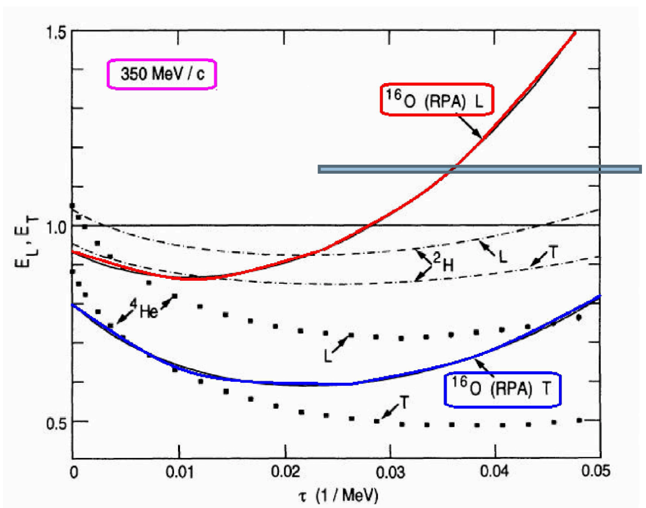


Hammersteing *et al.* PRL49(1974)235

★ = EXPT / Z^2 = EXPT/400

solid line includes contributions from all the states in the energy region $\sim$ 10 to 25 MeV

Euclidean longitudinal and transverse responses



Pandharipande *et al.* PRC49(1994)789

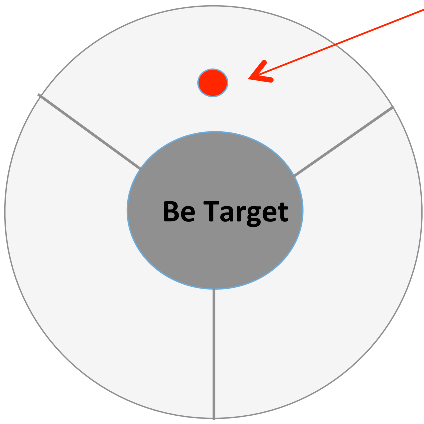
Longitudinal $\sim \boldsymbol{\sigma}_i \cdot \mathbf{q}\, \boldsymbol{\tau}_i \cdot \mathbf{T}$
Transverse $\sim \boldsymbol{\sigma}_i \times \mathbf{q}\, \boldsymbol{\tau}_i \cdot \mathbf{T}$

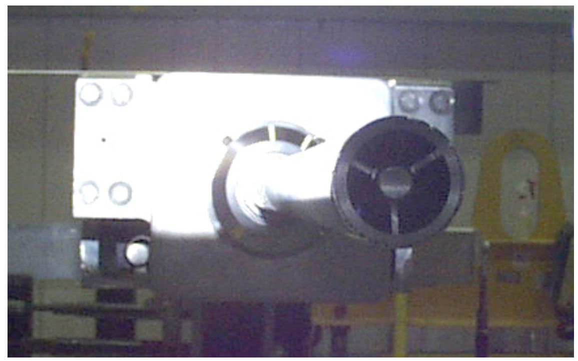
Nuclei respond differently to different (DM) coupling, *e.g.*, significant enhancement of spin-longitudinal over spin-transverse response at low energies $\lesssim$ 25 MeV

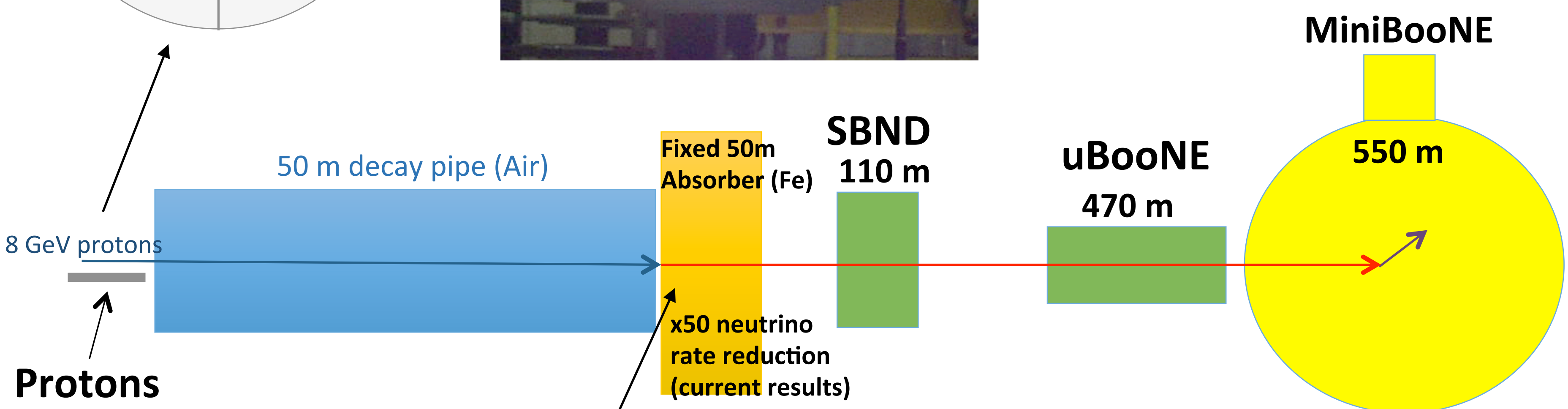
Coherent quantum effects can increase the magnitude of the cross-section by a large factor at low nuclear excitation energy (high DM mass)

Beam Dump Running: A Unique Capability of the Booster Neutrino Beamline (BNB) to Search for Sub-GeV Dark Matter (FREE!)

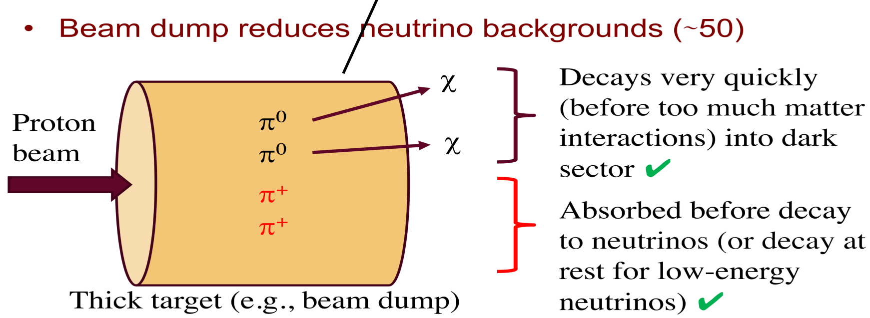
- Beam spot position in beam off target mode (~1 mm spread).
- Target is 1 cm diameter, with 1 cm air gap





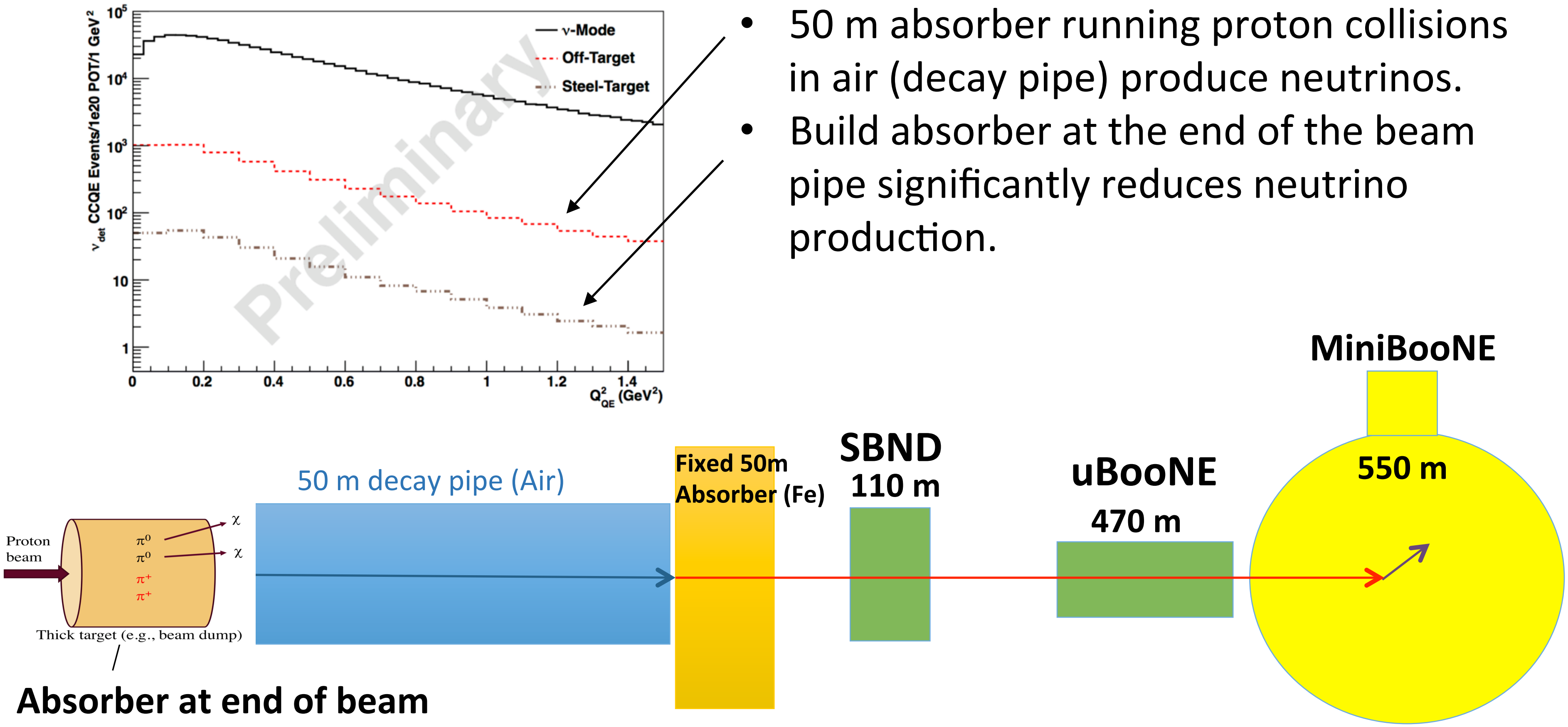


Protons bypass Be Target and Horn



x50 reduced neutrino rate in MiniBooNE enhances sensitive search for neutral current processes such as DM scattering.

Future of BNB sub-GeV DM Searches
What an Improved Beam Dump will do...



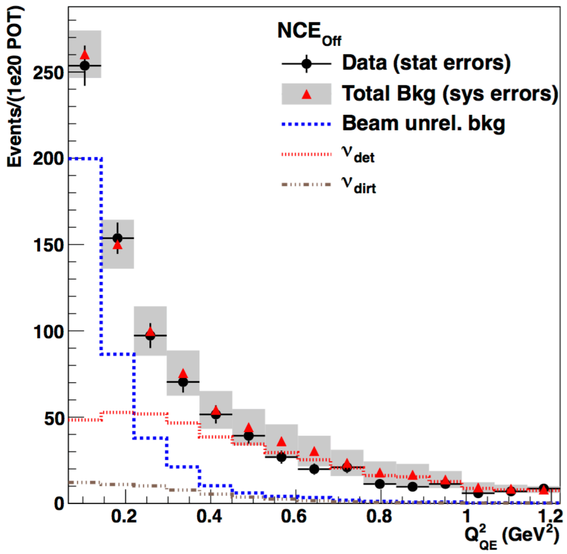
- 50 m absorber running proton collisions in air (decay pipe) produce neutrinos.
- Build absorber at the end of the beam pipe significantly reduces neutrino production.

Absorber at end of beam pipe reduces neutrino rate by x1000 (instead of x50)

x1000 reduced neutrino rate in MiniBooNE enhances sensitive search for neutral current processes such as DM scattering.

x1000 reduction in neutrino backgrounds!

Future of sub-GeV DM Searches: What an improved Beam Dump would do for MiniBooNE recent results

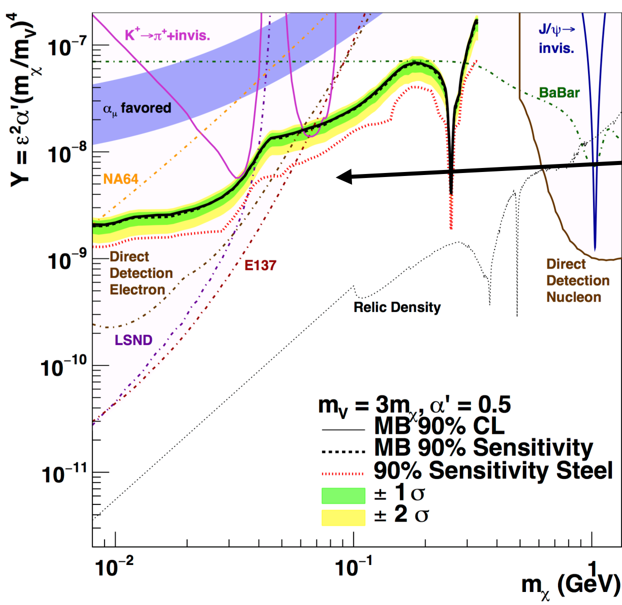


NCE Channel

	#events	uncertainty
BUB	697	
ν_{det} bkg	775	
ν_{dirt} bkg	107	
Total Bkg	1579	14.3% (pred. sys.)
Data	1465	2.6% (stat.)

Sys error ~1%

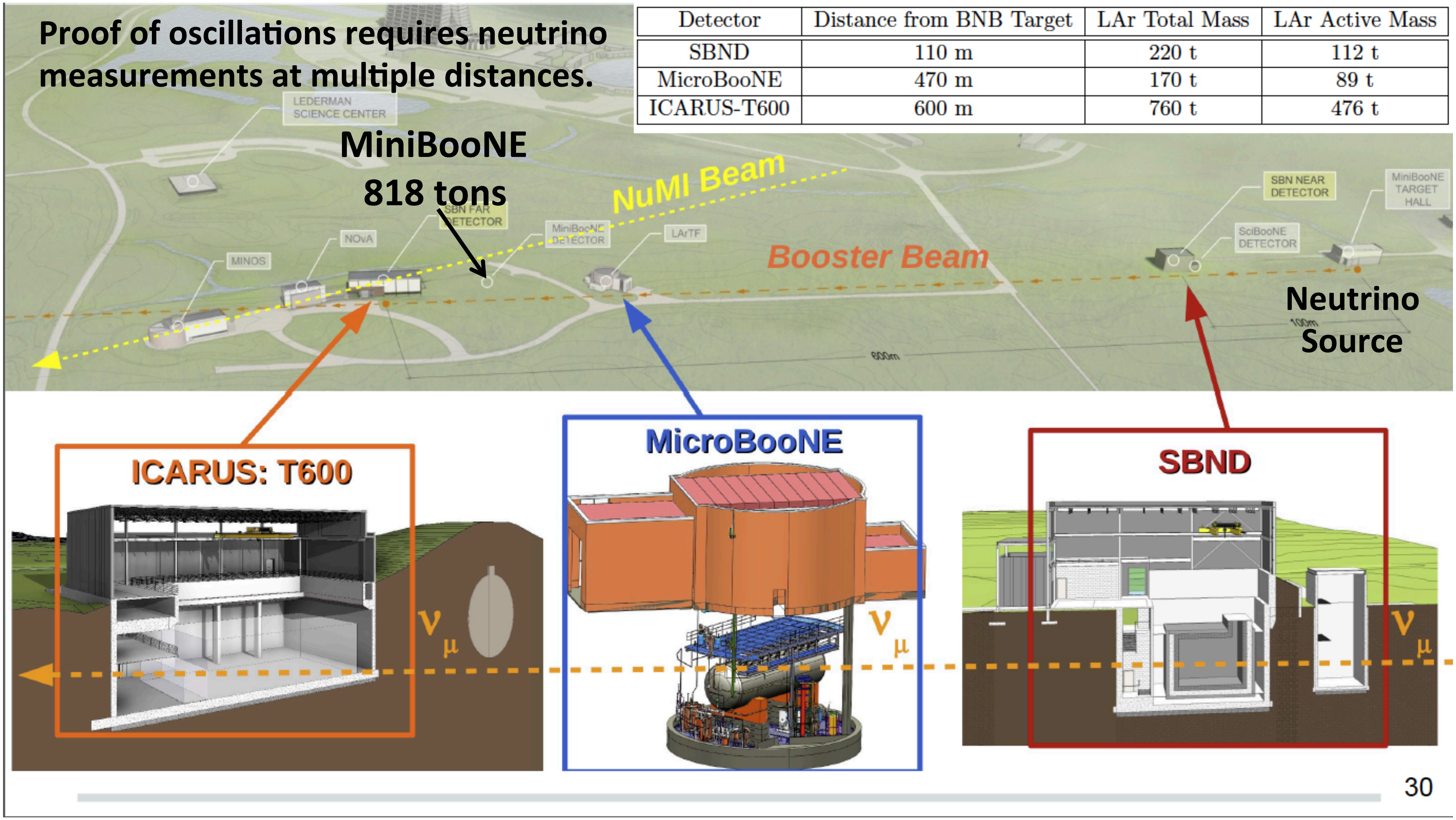
x20 rate reduction= 44 events reduces relative sys error ~1%



- Only a factor of ~2 improvement in sensitivity (red) due to cosmogenic backgrounds (BUB).
- However, π^0 and electron final state channels have extremely small BUB, so will see significant improvement (later slides).

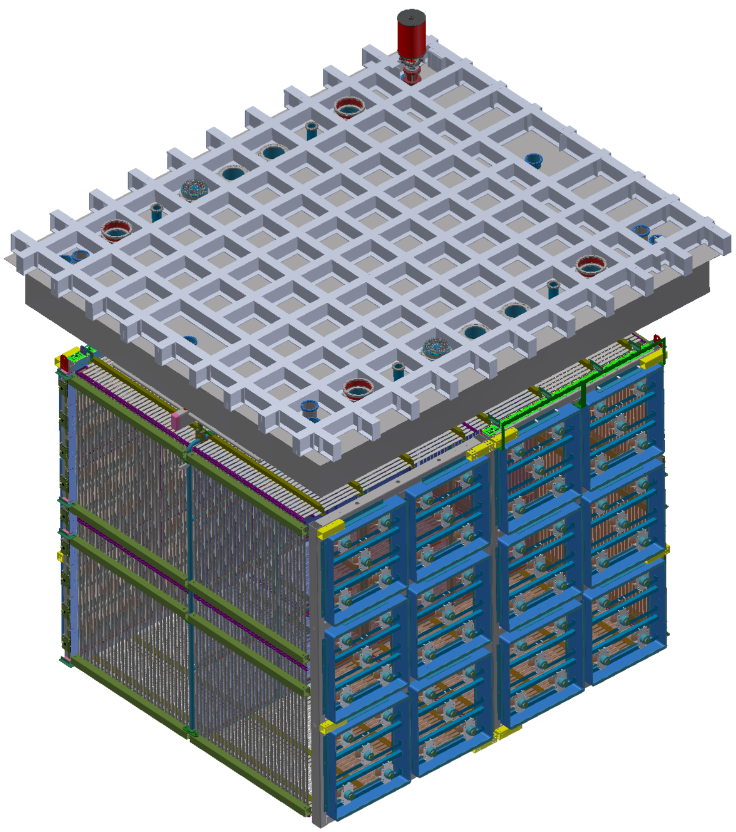
LSND/MiniBooNE have motivated the DOE/HEP Short Baseline Neutrino (SBN) Program which will begin operations in 2018

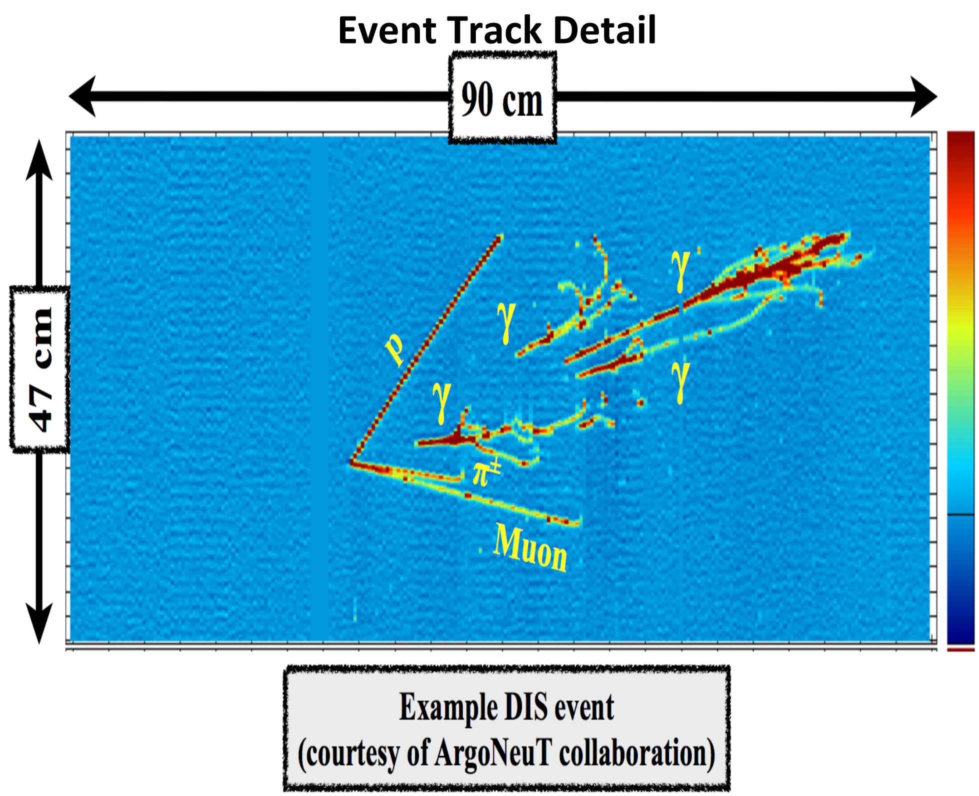
Detector	Distance from BNB Target	LAr Total Mass	LAr Active Mass
SBND	110 m	220 t	112 t
MicroBooNE	470 m	170 t	89 t
ICARUS-T600	600 m	760 t	476 t



International Program with ~250 collaborators (and growing)

SBND Detector: 112 tons LAr TPC 4 x 4 x 5 m, 11000 TPC wires, 2 m drift distance. Measure high statistics neutrino event rate at 110 m position which is used to normalize far detector to test LSND/MB oscillations.





- Integrated cosmic ray tracker and photon detection system (PDS) will significantly reduce cosmogenic backgrounds.
- PDS will achieve ~nsec timing improving DM sensitivity M> 70 MeV (time of flight)
- Detector to start running in neutrino mode 2019.

Future (~few years) of Proton Beam Dump sub-GeV DM Searches

- Entire SBN (Short Baseline Neutrino) program can search for low-mass DM
  - Thee LAr TPC detectors at various distance and sizes.
  - LAr TPCs would have exceptional sensitivity to π^0 and e-DM
- SBND (near detector) will have factor x9 the MiniBooNE signal rate
  - SBND is x4 smaller (445 t → 112 t fiducial)
  - SBND is x5 closer to 50 m beam dump (491 m → 110 m)
  - SBND has x2 higher efficiency
  - Including non flat $1/r^2$ effects
- However, to suppress neutrino background and achieve the highest sensitivity requires a beam dump absorber at the BNB proton beam vacuum exit
  - Most ν backgrounds come from proton beam interacting in 50 m of decay pipe air.
  - Improved beam dump suppresses of neutrino background by x1000!

SBN Beam Dump Upgrade Option

- **Option 1**
  - Design, optimize, build a target block (iron, tungsten, hybrid, etc) that replaces current horn/target (removable).
  - **Pros**: Inexpensive ~ $1M, excellent neutrino suppression
  - **Cons**: Can only run after SBN neutrino run > 3yrs.

Proton beam pipe

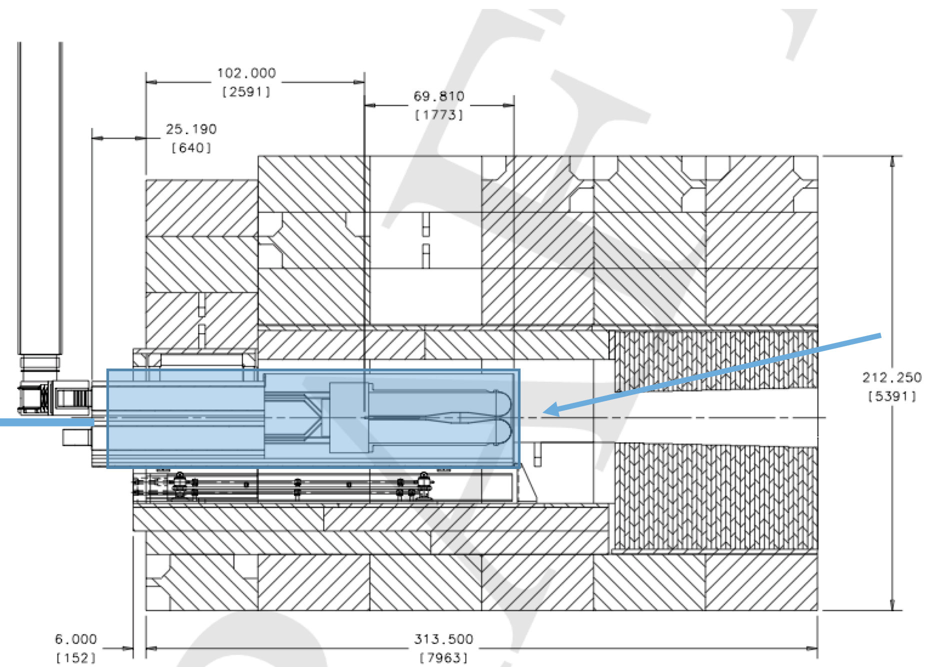


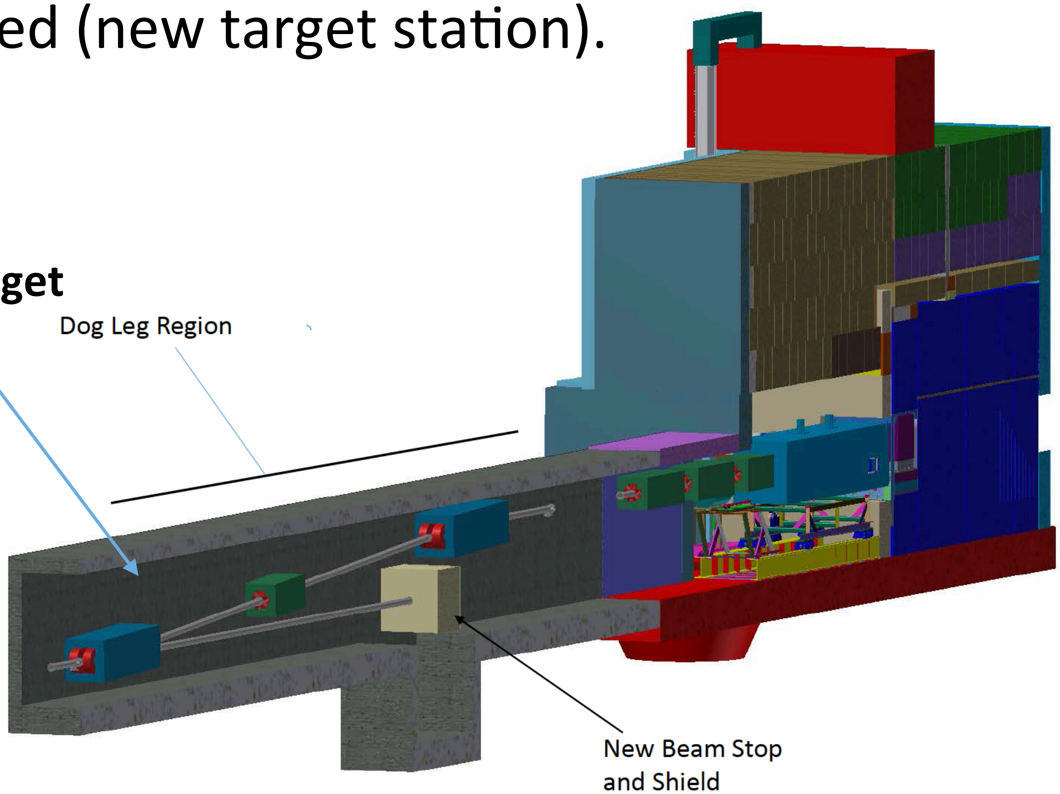
Figure 3.9: An elevation view of the target pile, including the horn, adjuster module, shielding steel. The stripline extends upward at the left.

- Replace neutrino horn/target with Fe Target block
- Protons directly enter absorber

SBN Beam Dump Upgrade Option

- **Option 2**
  - Design, optimize, build a target block (iron, tungsten, hybrid, etc) and new target station on the beam line.
  - **Pros**: Run concurrently with neutrino run, more flexible design. Excellent neutrino suppression.
  - **Cons**: More expensive ~$5M, as extensive shielding required (new target station).

Kicker magnet steers beam to neutrino horn/target or beam dump



DM Scattering Signal Comparisons:

	MiniBooNE (Actual) 50m beam dump	SBND 50m beam dump	**SBND Improved beam dump**
Beam off Target Run	1.86E20POT, 50m dump	2E20POT, 50m dump	2E20POT, 0m dump
Distance from Dump (m)	491	60	110
Analysis Fiducial Mass (tons)	445	112	112
Efficiency (nucleon or electron)	35%	60%	60%
Approximate scaling (*)	1.0	29	8.6
DM-nucleon/pi0 signal (**)	**24/10**	**533/250**	**177/83**
ν-nucleon background (***)	882	25600	446
ν-pi0 background (***)	135	3915	68
DM-electron signal (**)	**0.4**	**7.0**	**2.7**
ν-electron background (****)	0.6	17.4	0.3

- (*) 1/r2 x mass x eff x non flat pi0 distribution
- (**) **Signal point M_x= 100 MeV, Mv= 300 MeV, and Y= 10^{-8} .**
- (***) Actual nucleon/pi0 analysis. 0m dump with x17 reduction (CCQE muon from Tyler).
- (****) BeamDump factor 1/44, POT, efficiency, and electron cut $\cos\theta_{beam}$ > 0.98.

DM Scattering Signal Comparisons:

	MiniBooNE (Actual) 50m beam dump	SBND 50m beam dump	SBND Improved beam dump
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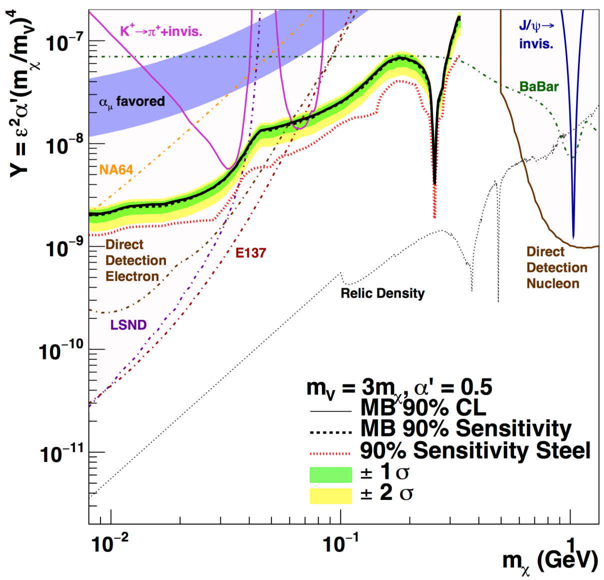
Analysis Fiducial Mass (tons)	445	112	112
Efficiency (nucleon or electron)	35%	60%	60%
Approximate scaling (*)	1.0	29	8.6
DM-nucleon/pi0 signal (**)	**0.7/0.9**	**15/24.5**	**5.3/8.3**
ν-nucleon background (***)	882	25600	446
ν-pi0 background (***)	135	3915	68
DM-electron signal (**)	**59**	**1711**	**507**
ν-electron background (****)	0.6	17.4	0.3

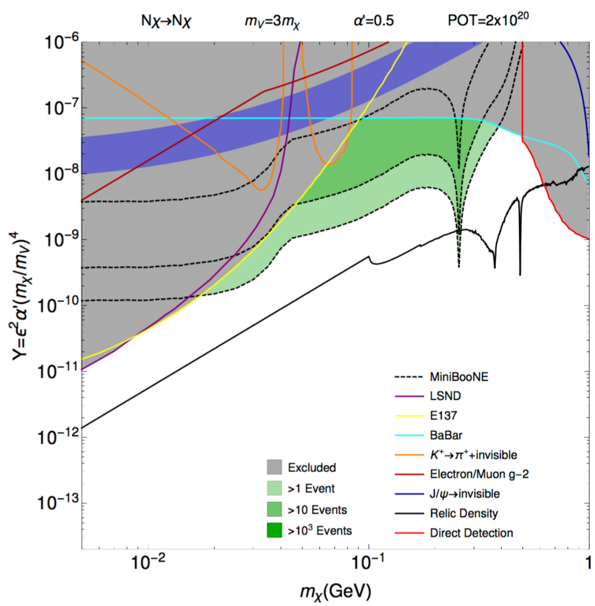
- (*) 1/r2 x mass x eff x non flat pi0 distribution
- (**) **Signal point M_x= 10 MeV, Mv= 30 MeV, and Y= 10^{-10}** .
- (***) Actual nucleon/pi0 analysis. 0m dump with x17 reduction (CCQE muon from Tyler).
- (****) BeamDump factor 1/44, POT, efficiency, and electron cut $\cos\theta_{beam} > 0.98$.

Improved DM Search with SBND: Nucleon Channel

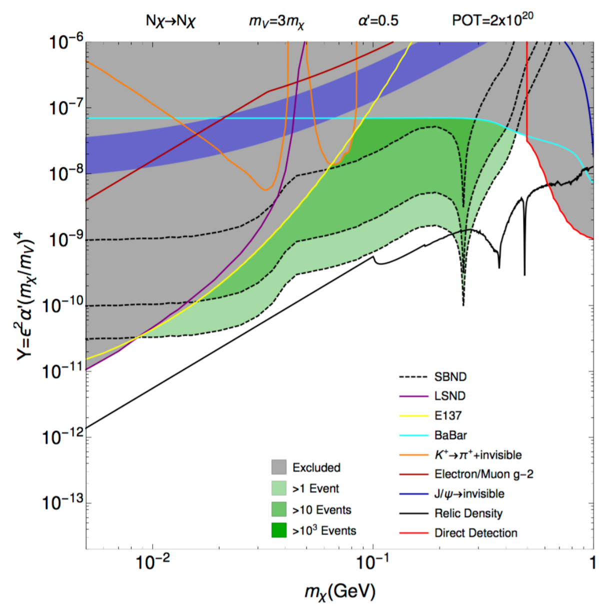
MiniBooNE-Actual



MiniBooNE

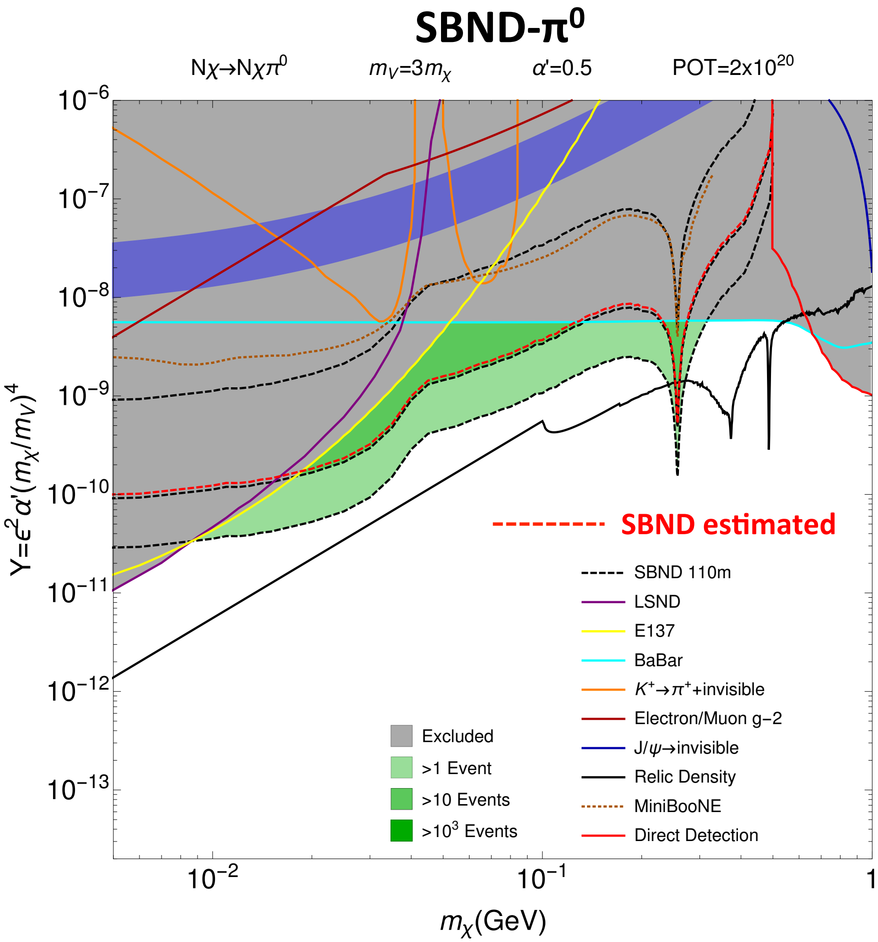


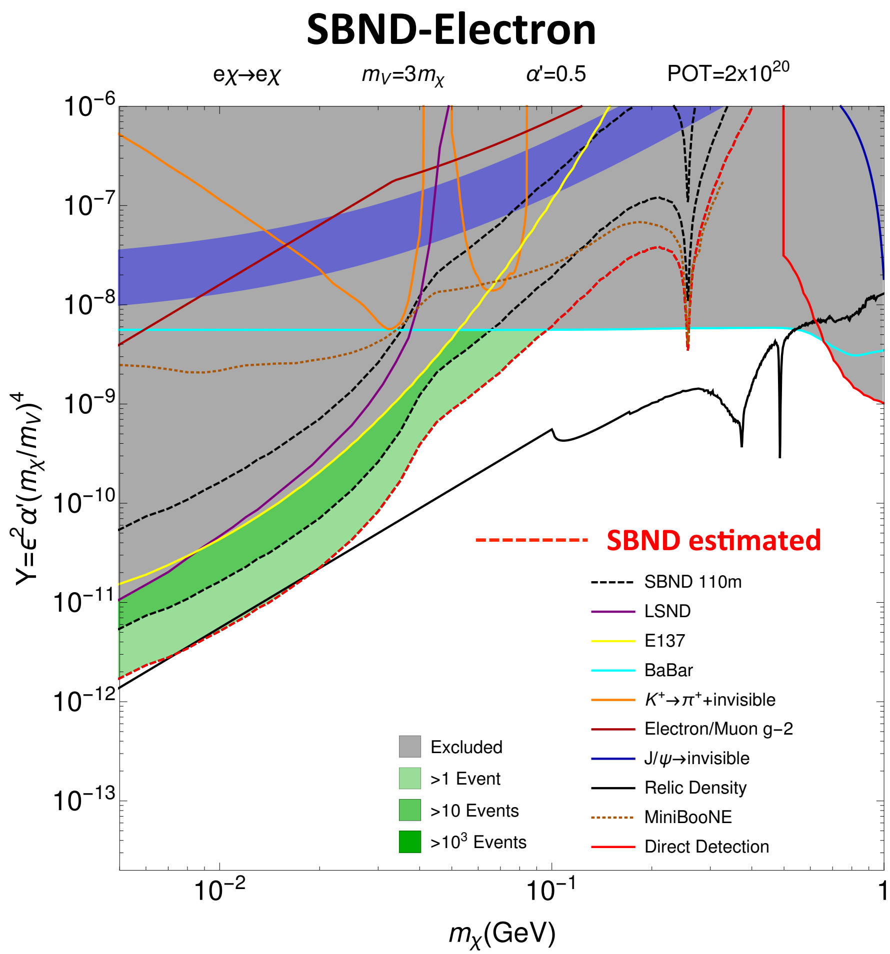
SBND (110m)



- Signal events: Dark Green > 1000; Green: 10-1000; Light Green: 1-10
- SBND will have an order magnitude better signal sensitivity over MB due to proximity of source, but +/-3300 event background given systematic error (13%).

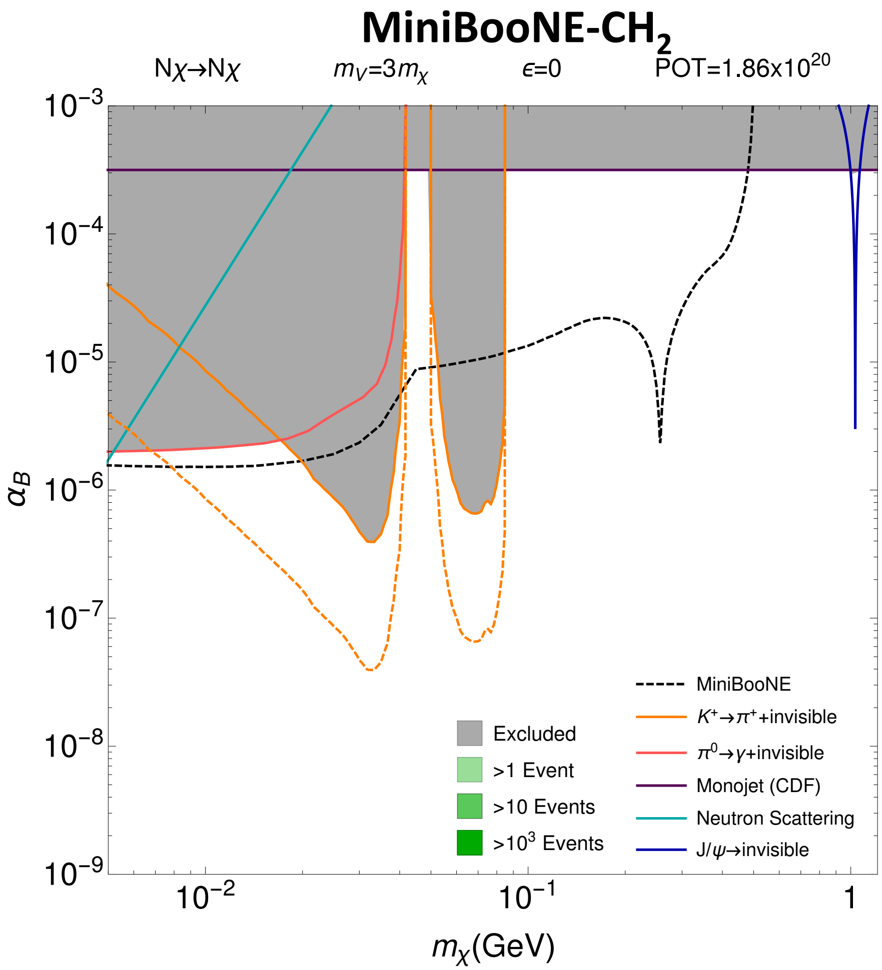
DM Search with SBND: π^0 and Electron Channel and Improved Beam Dump

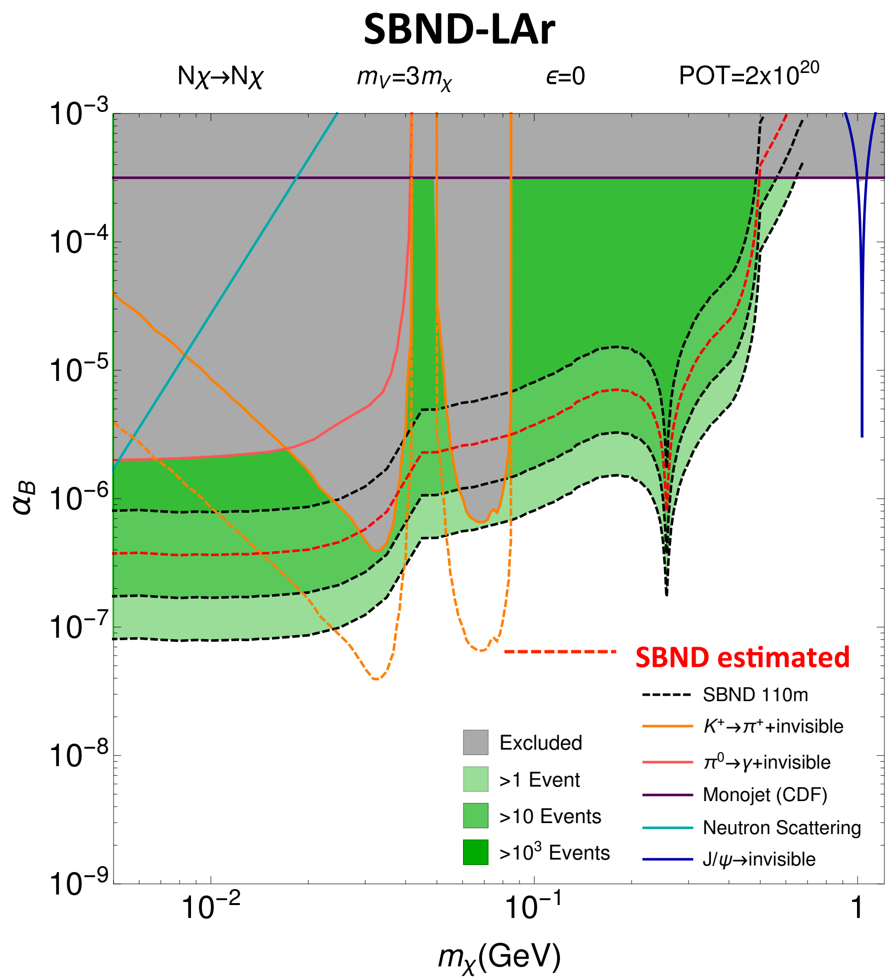




- Signal and background estimates robust, based on MB lessons
- π^0 good at high mass, electron at low mass -- compliment each other!
- **Working on event timing ~2 nsec, improve sensitivity for DM mass > 70 MeV**
- SBND order magnitude better than MB, but needs improved dump to reduce backgrounds!

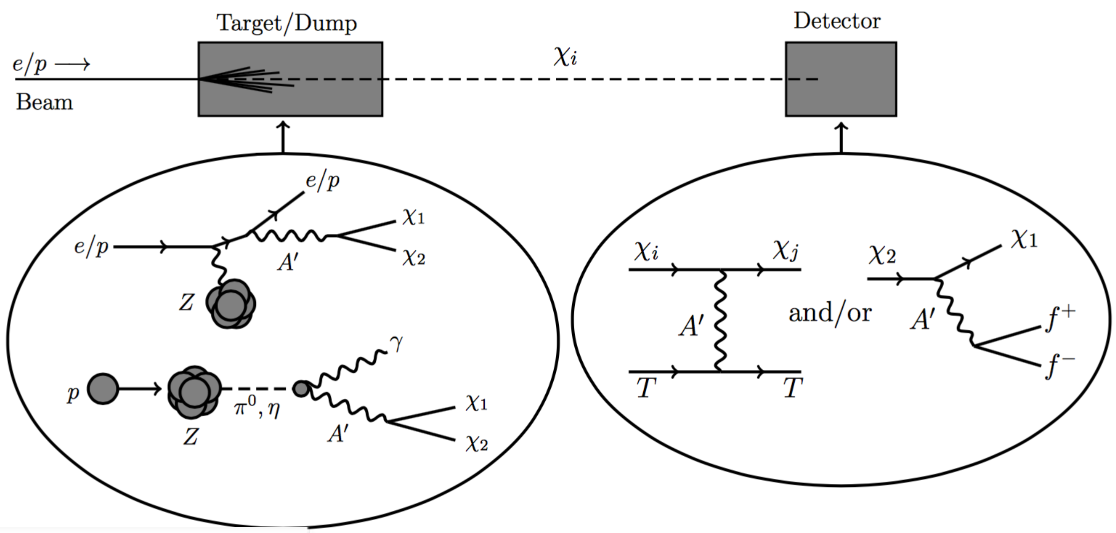
SBND Leptophobic Searches with Improved Beam Dump

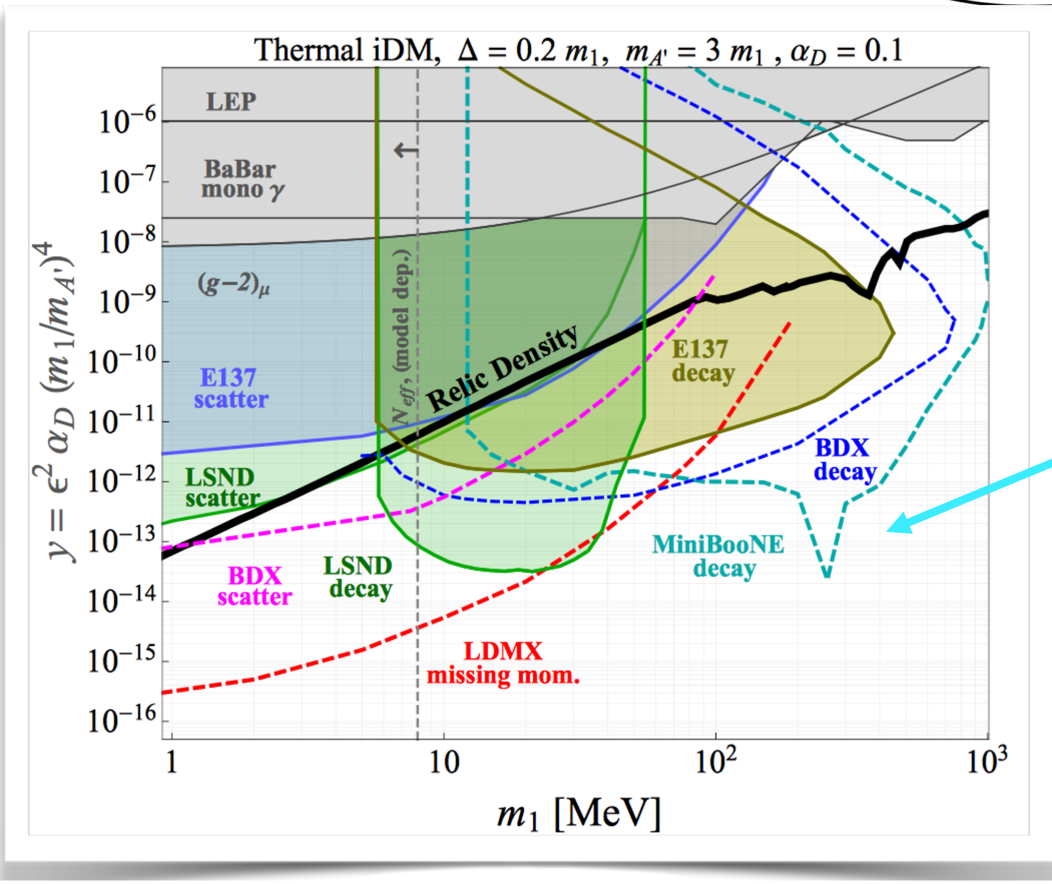




- Proton dump can significantly probe leptophobic models!

Inelastic DM



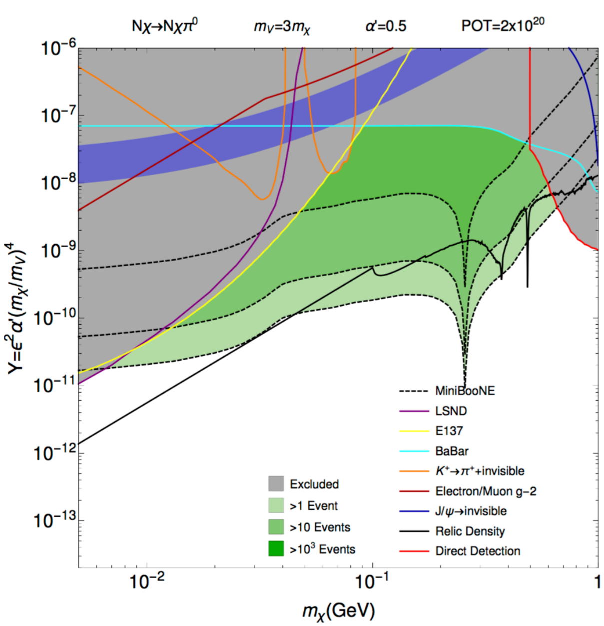


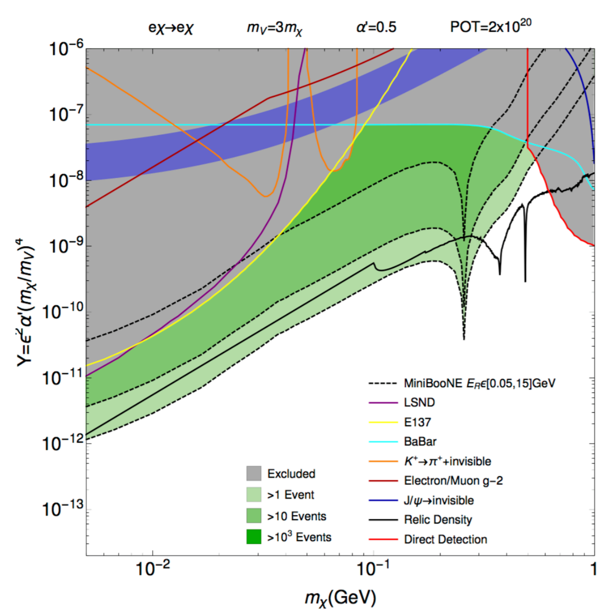
MiniBooNE sensitivity with current beam dump

[Izaguirre, Kahn, Krnjaic, Moschella]

120 GeV Main Injector Proton Dump Option

- Move or build a new MiniBooNE-like down stream of the MI 120 GeV Dump
- **Pro's**: Significant sensitivity improvement in both DM mass and coupling. Tests relic density limits.
- **Cons**: Current yearly limit of 120 GeV/c protons to the MI absorber, which is limited by groundwater, is 2.5E19 protons. No experience with background estimates, systematic errors, etc. Might be done for < $10M ??



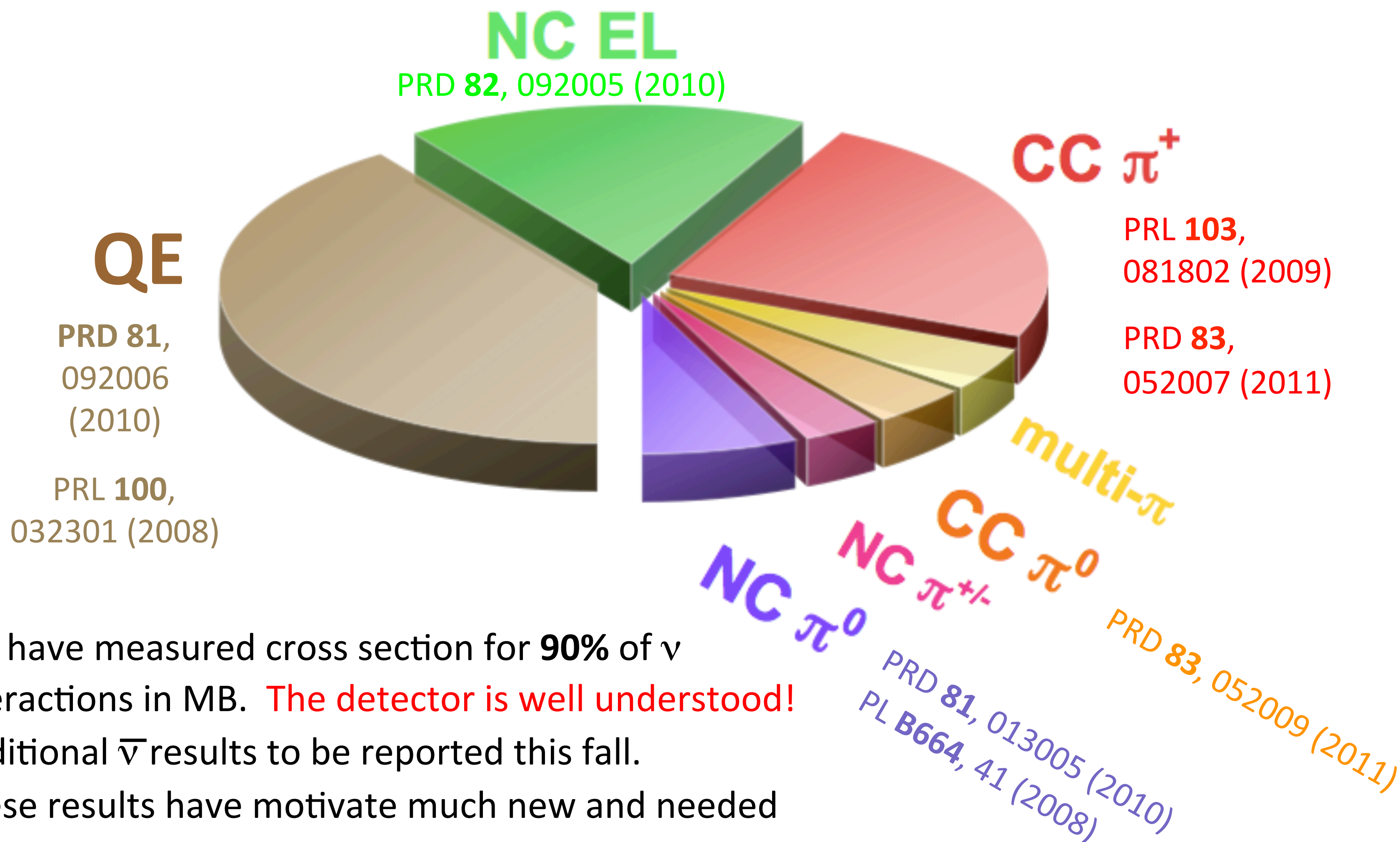


Proposed SBN sub-GeV Dark Matter Search

- **SBND will achieve an order of magnitude** improvement in signal sensitivity relative to MiniBooNE
  - Test vector portal relic density limits in the MeV to GeV range.
  - Significant test of leptophobic and inelastic DM models.
- **Requires deployment of a dump/absorber** at the end of the beam pipe to significantly reduce neutrino backgrounds
  - Leverage investment in SBN detectors (start running 2018)
  - Option 1 (replace horn/target with absorber) ~$1M
  - Option 2 (new target station) ~$5M.
- **Systematic errors and sensitivity estimates are robust** based on the recent successful MiniBooNE DM search.

Backups....

Ten Years of MiniBooNE Running: Cross Section Results

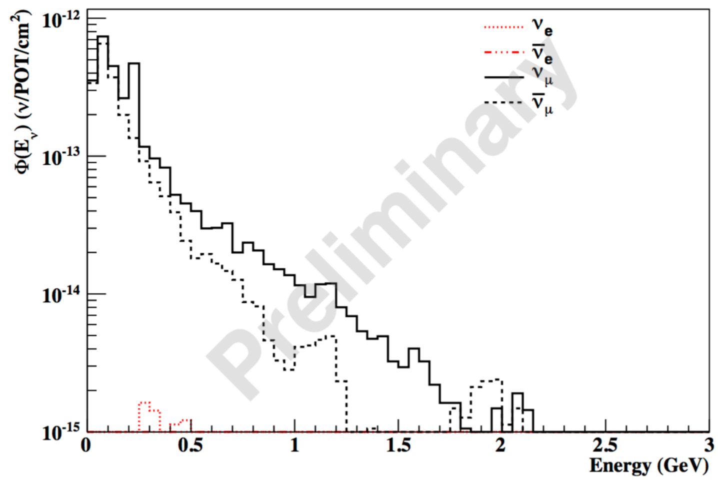


- We have measured cross section for **90%** of ν interactions in MB. The detector is well understood!
- Additional $\bar{\nu}$ results to be reported this fall.
- These results have motivate much new and needed theoretical work on neutrino nucleus scattering.

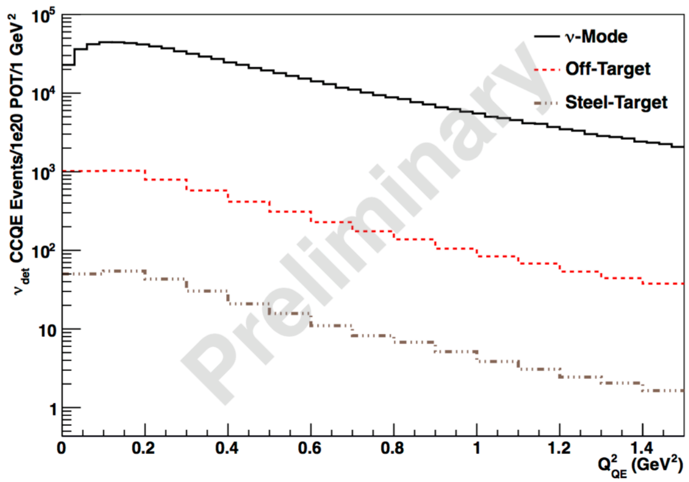
Future of sub-GeV DM Searches
What an Improved Beam Dump will do...

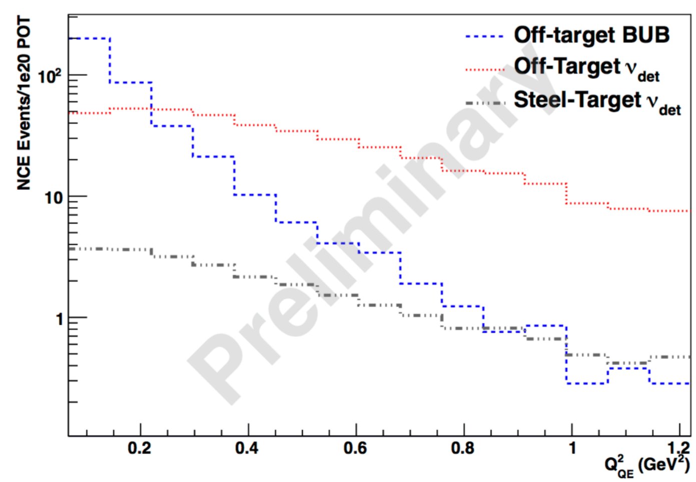
Dedicated Iron Beam Dump at BNB

- Some ν backgrounds come from proton beam scraping
- Proton beam interacts in 50 m of decay pipe air
- CCQE event rate suppressed by $\sim$ 1000 compared to ν-Mode



Reduction ~x20 relative to beam off target

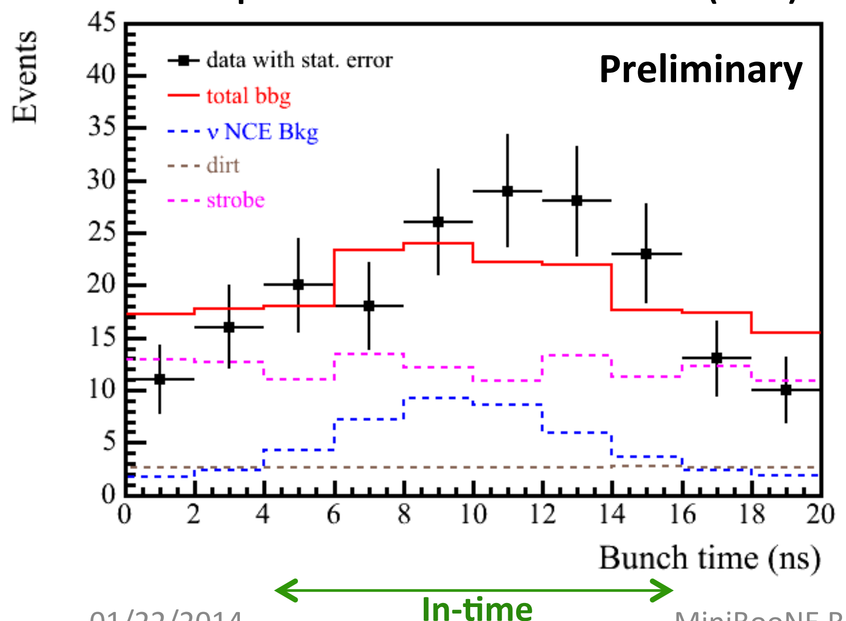




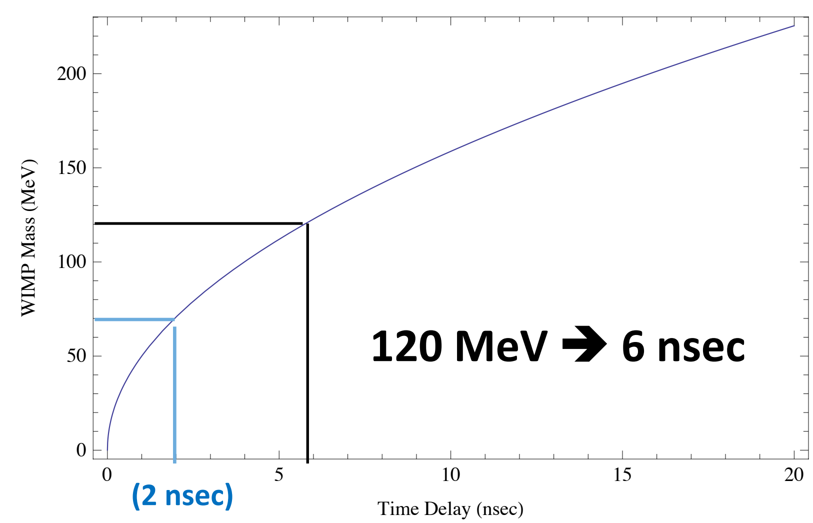
Neutral Current Data Timing for 3.19×10^{19} POT Beam-Dump Mode

- Neutrino NCE events have 4.2 nsec timing resolution.
- Beam-unrelated and neutrino dirt interactions are flat in time.
- **In-time (4-16 nsec) region** rejects flat backgrounds, enhances M_{DM} < 120 MeV.
- **Out-time (0-4; 16-20 nsec) region** rejects NCE bkgs, enhances M_{DM} > 120 MeV
- **Pi0 timing ~2 nsec, sensitive to DM mass > 70 MeV (1σ time separation)**

NC Sample Reconstructed Event Time (nsec)

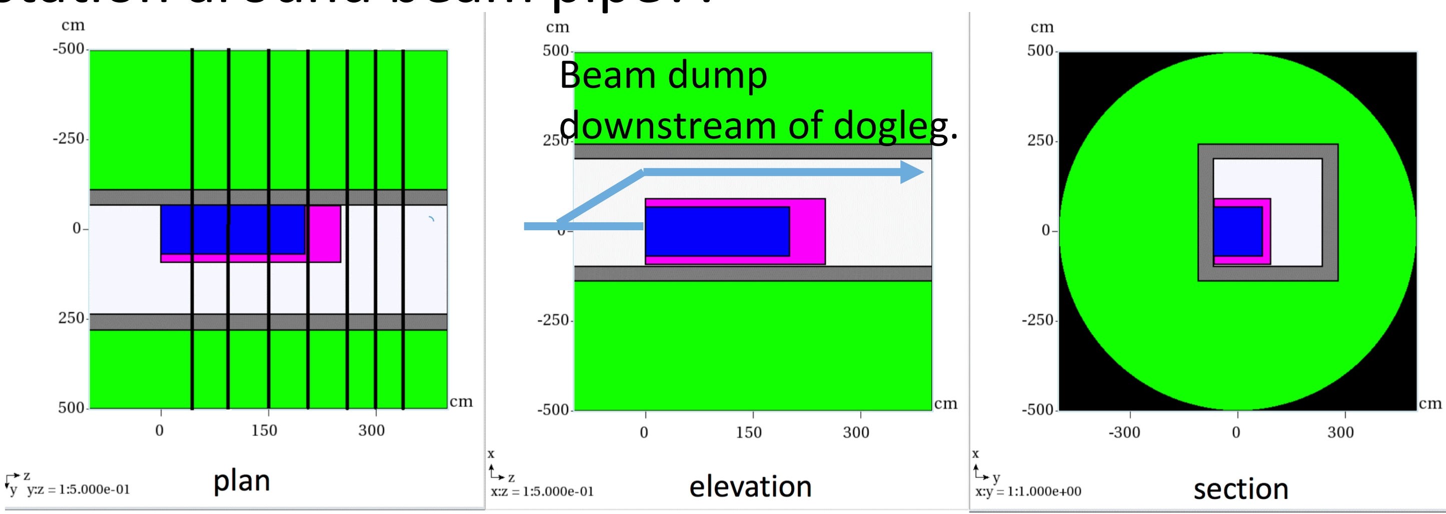


Dark Matter Mass vs. Time Delay (for typical energy 1.5 GeV)



DM Proposal Options

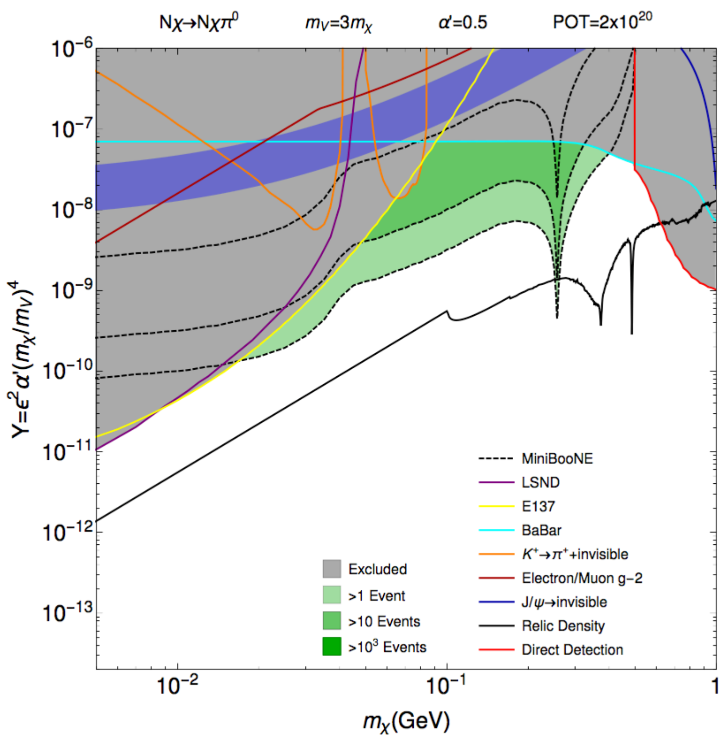
- **Option 3**
  - Design, optimize, build a target block (iron, tungsten, hybrid, etc) at the dog leg in the beam tunnel.
  - Pros: run concurrently with nu.
  - Cons: medium expensive ~$1M. Two meter lower than nu beam direction. Fit will be tight. Radiation and ground water issues (Tom K investigating). Build target station around beam pipe??



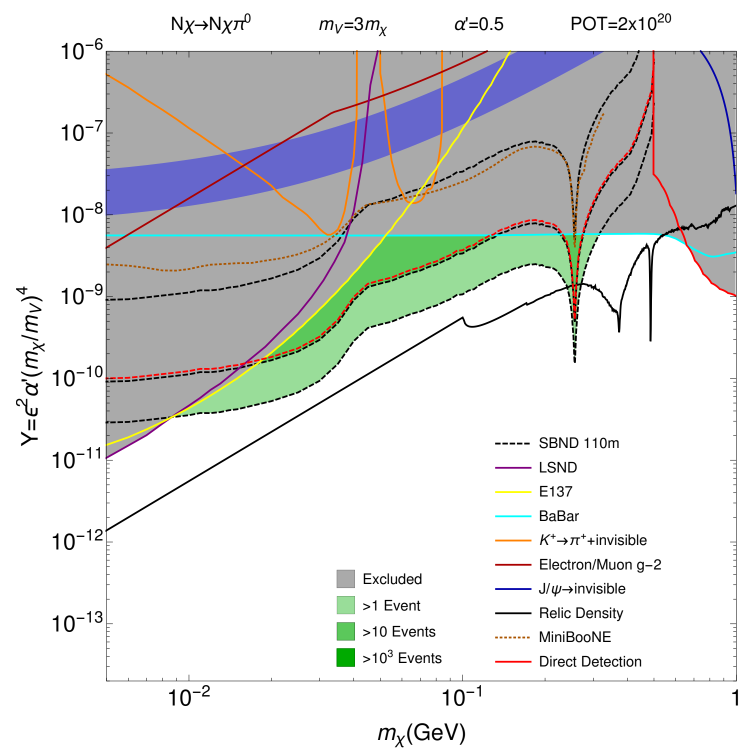
- modeling a 4’4”x4’4”x2m iron dump, surrounded by 10” of borated poly on three side, up against the concrete wall on the fourth, and 50cm downstream.

Improved DM Search with SBND: pi0 Channel

MiniBooNE-CH_2

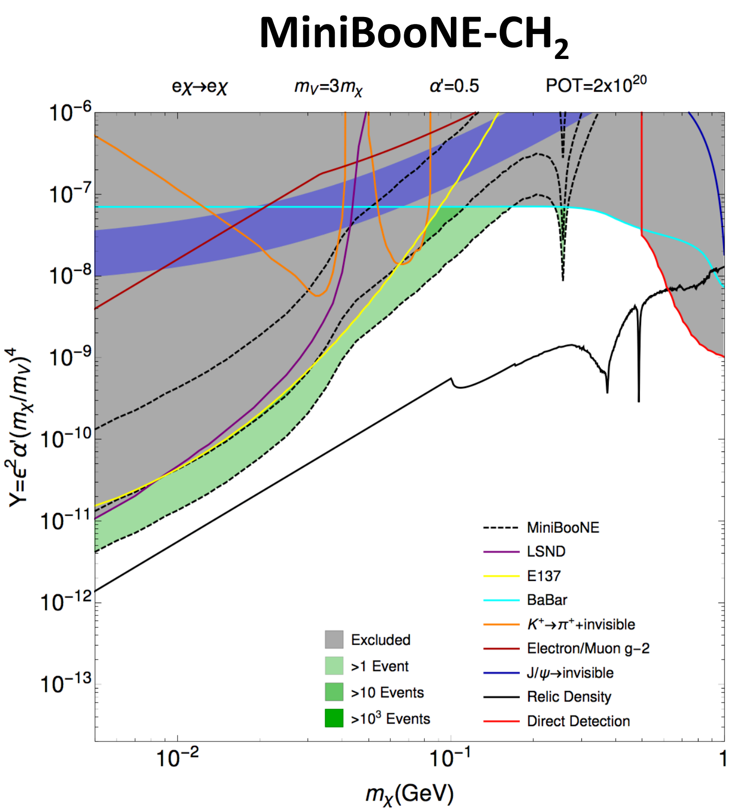


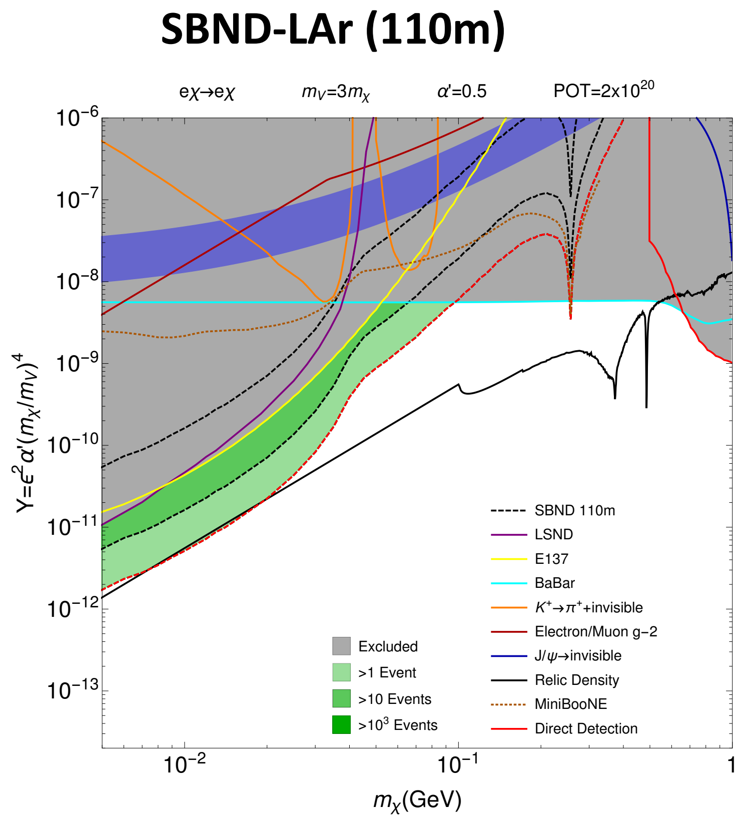
SBND-LAr (110m)



- Signal events: Dark Green > 1000; Green: 10-1000; Light Green: 1-10
- Nucleon and Pi0 channel similar signal sensitivity. However, pi0 channel has very little BUB.
- Assume 13% sys error, no BUB, 50m Dump: MiniBooNE +/-17 events, SBND +/- 820 events
- Assume 13% sys error, no BUB, 0m Dump: MiniBooNE +/-1 events, SBND +/- 12 events
- Pi0 channel benefits from 0m steel dump due to lack of BUB. Should be true for e channel

Improved DM Search with SBND: Electron Channel





- Signal events: Dark Green > 1000; Green: 10-1000; Light Green: 1-10
- Electron channel does well at low DM mass (??)
- Assume 13% sys error, no BUB, 50m Dump: MiniBooNE << 1 events, SBND +/- 4 events
- Assume 13% sys error, no BUB, 0m Dump: MiniBooNE << 1 events, SBND << 1 events
- Electron channel benefits from 0m steel dump, gets to relic density line for DM mass < 40 MeV

Dotted Red Line – Estimated Background Sensitivity: Red Stars - signal points slide 14 and 15
Top Plots: SBND 60m (beam off target onto 50m dump)
Bottom Plots: SBND 110m (steel dump at current horn/target)