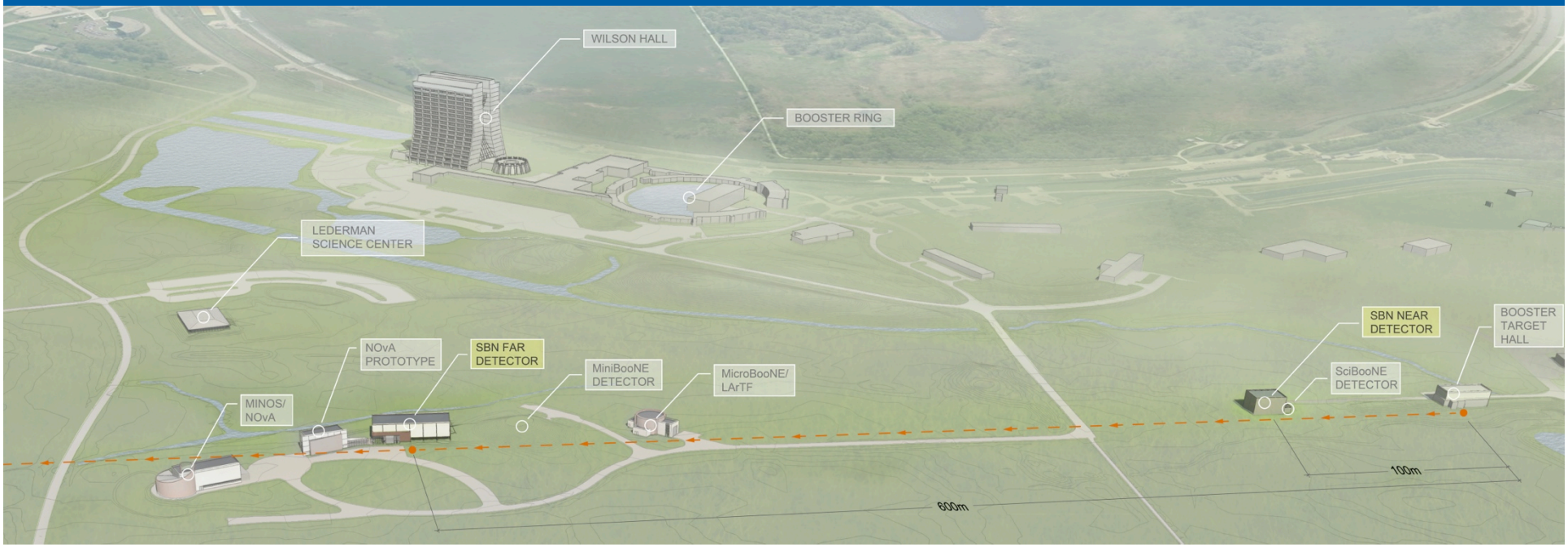


Next Step in Accelerator Sub-GeV Dark Matter Searches at FNAL: An Expression of Interest to Improve the BNB Beam Dump for SBN

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

FNAL PAC Nov 16-17, 2017

Outline

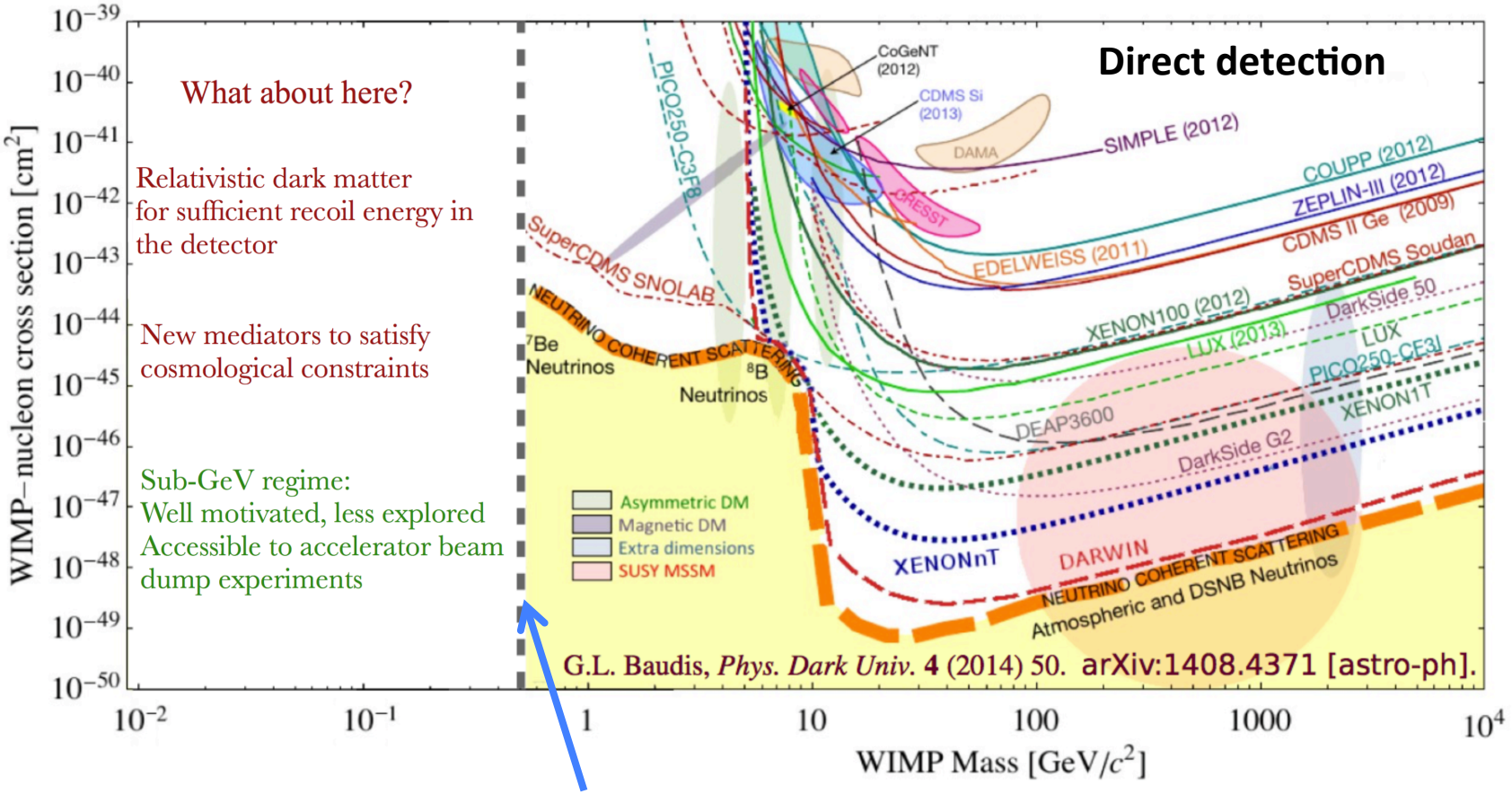
- **New Directions**: DOE call for new initiatives in Dark Matter (DM) searches.
- **Motivation** for proton beam dump dark matter searches
  - New models predict MeV to GeV an excellent place to look for DM, can test relic density limits.
  - Many dark matter portals uniquely tested by proton beams.
  - Neutrino experiments ideal with intense proton beams and large sensitive near detectors.
- **Order of magnitude improved dark matter searches**
  - Plans to upgrade 8 GeV BNB beam dump, leverage **SBN** detectors, begin testing relic density limits.
  - Future possibilities with 120 GeV protons (backup slides).

Cosmic Vision Workshop (March 2017)

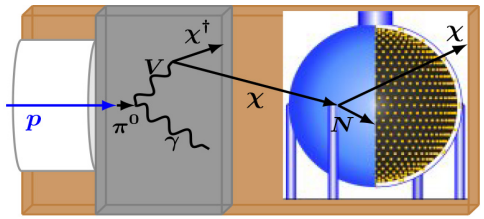
- **DOE charge: New DM search initiative (see slide 26 for details)**
  - "To respond to the 2014 P5 report recommendations in the search for dark matter particles and maintaining a diversity of project scales in our program, DOE Office of High Energy Physics (HEP) is interested in identifying new, small projects for dark matter searches in areas of parameter space (i.e. mass ranges or types of particles) not currently being (or on track to be) explored. HEP is asking for community input in the spring 2017 timeframe in order to plan the program forward. Input is requested on the possibilities for small (the whole project is ~ $10 million or less) dark matter projects in unexplored parameter space. A community workshop, followed by a White Paper would be a good path to provide the input needed. We encourage you to collect information from the community, including theorists and experimentalists involved in non-accelerator and accelerator-based efforts."

- **Accelerator DM Search: One of five recommendations from US Cosmic Visions, New Ideas in Dark Matter 2017, Community Report arXiv:1707.04591**
  - Accelerator experiments can both produce and detect new particles, such as dark matter and the particles mediating new interactions. This unique ability has enabled beam dump, missing mass/energy, and visible mediator search experiments to achieve world-leading sensitivity to highly sought-after dark matter scenarios. Building on these proven techniques and exploiting existing US accelerator facilities, a small number of fixed-target experiments can broadly explore sub-GeV dark matter and associated forces with sufficient sensitivity to test all predictive thermal DM scenarios. This focused effort is based on established detector technology, with a number of modest-cost proposals ready for funding now to achieve significant science in the next few years.

Experimental Motivation for sub-GeV Dark Matter Searches



- **Direct detection ~GeV threshold limit due to slow moving galactic halo DM.**
- **Access sub-GeV threshold with accelerator boosted DM. Method has experienced much recent theoretical and experimental activity.**

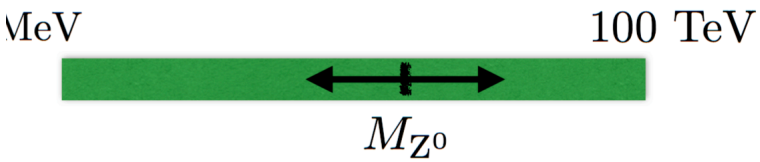


Theoretical Motivation for sub-GeV DM Search: sub-GeV DM and Light Mediators

Dark Matter

Thermal relic sharp target (contact with SM)

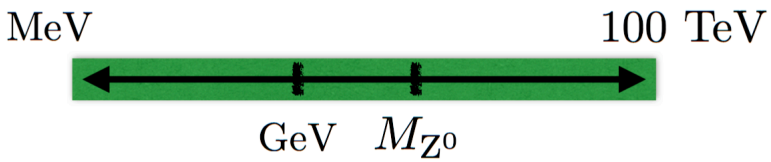
Hypothesis:
tightly tied to EWSB



WIMPs!

Correct relic density requires
Lee-Weinberg mass limit > 2 GeV

Hypothesis:
weakly tied to EWSB



Light thermal DM
same mass range as SM: MeV - TeV

Thermal contact implies
light mediator!

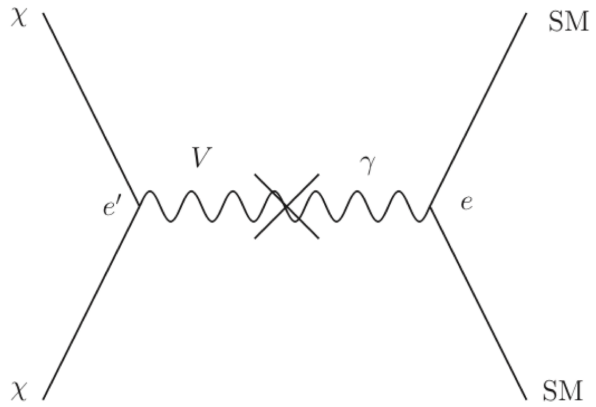
Vector Portal Dark Matter (Dark Photon)

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

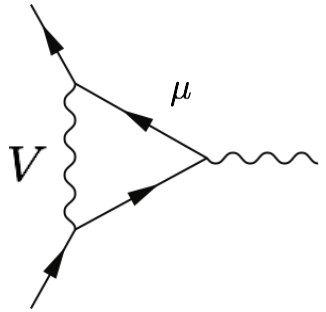
$$\mathcal{L} \supset |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4}(V_{\mu\nu})^2 + \frac{1}{2} m_V^2 (V_\mu)^2 - \frac{\kappa}{2} V_{\mu\nu} F^{\mu\nu} + \ldots$$

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

- Dark photon mediates interaction between DM and SM
- 4 new parameters: $m_\chi, m_V, \kappa, \alpha'$
- Dark photon charge $e' = \sqrt{4\pi\alpha'}$
- Kinetic mixing strength $\kappa = \epsilon$



- Experimental signatures
  $M_V > 2\ M_x$ (invisible mode, neutrino experiments ideal)
  $M_V < 2\ M_x$ (visible modes, e+e- final states, etc)



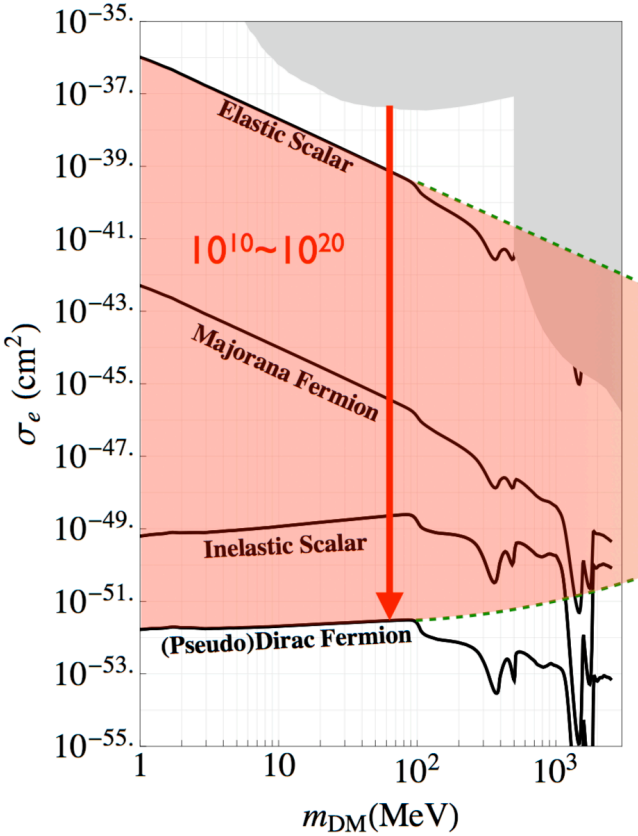
- Dark photon can address g-2 anomaly
- Other dark sector portals: Neutrino and Higgs models

Motivation for sub-GeV DM Search: Probing Relic Density Limits

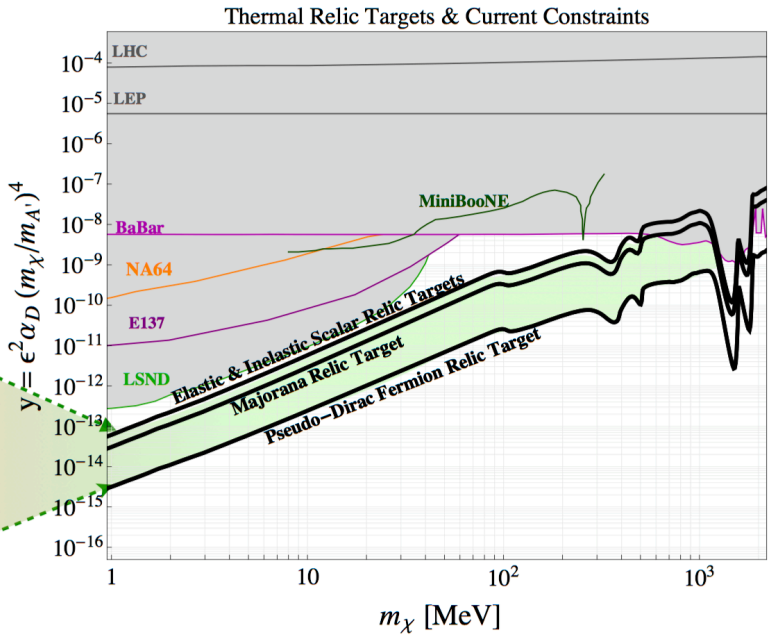
Boosted accelerator Dark Matter improves reach testing relic density limits

The Thermal Target

Halo DM 'beam': non-relativistic probe



Accelerator DM beam: relativistic DM



Couplings vs mass targets more tightly spaced when probed by relativistic beams

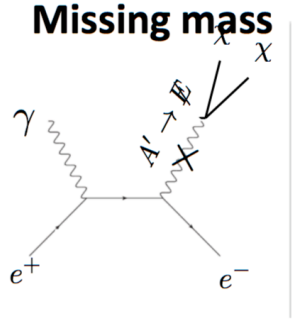
Sensitive to **any** thermal relic

Closing in on well defined goal post!

Many Techniques to Search for sub-GeV DM

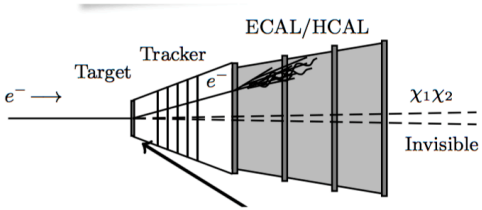
Probing the thermal relic target with accelerator-based experiments

Missing mass

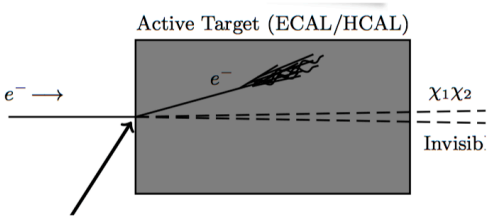


Resonance signal, rate gives coupling information

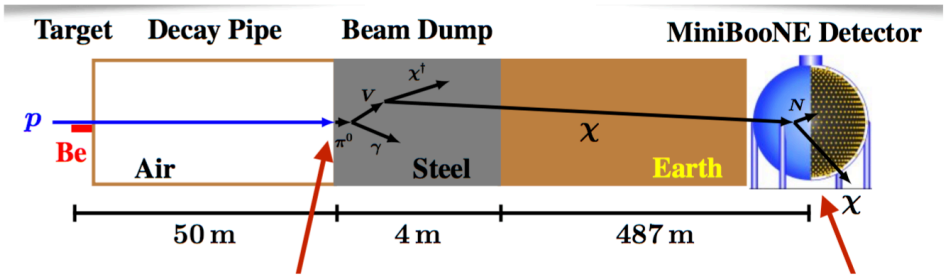
Missing energy / missing momentum



Best yield scaling with luminosity

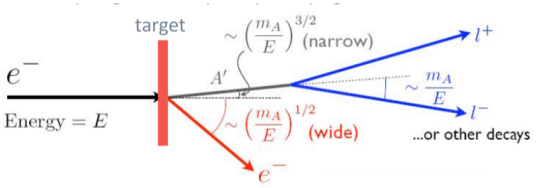


Proton / electron beam dump



Probes DM interaction twice

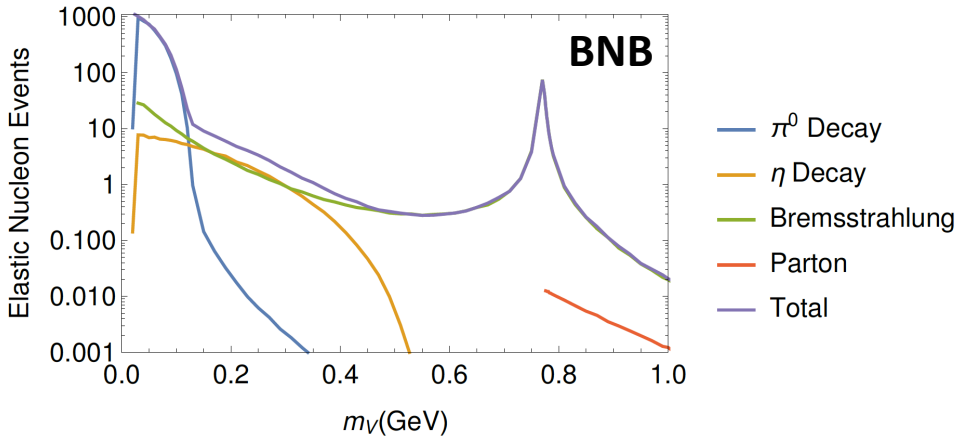
Searches for the mediator



Complementary to DM searches

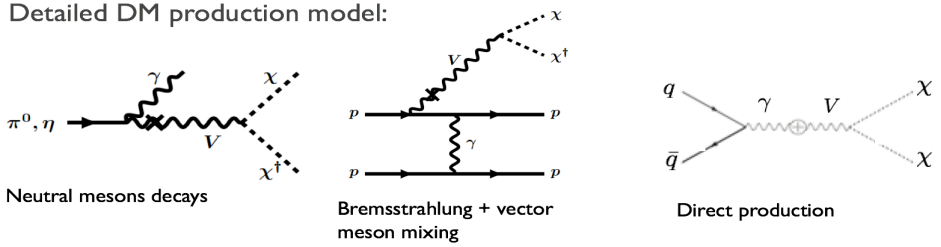
Production and Detection of DM at BNB (8 GeV)

- Couplings to copious number of nucleons, mesons, and photons from decay or Bremsstrahlung.

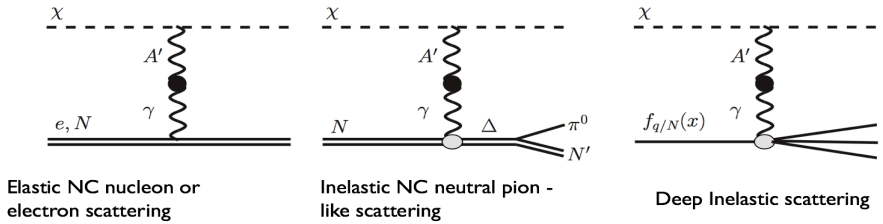


- Many production/detection channels (detailed BdNMC generator [deNiverville, Chen, Pospelov, Ritz])

- Detailed DM production model:

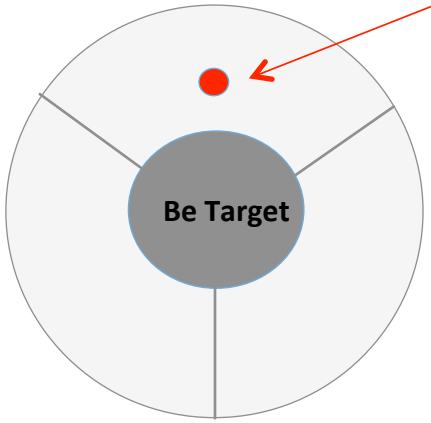


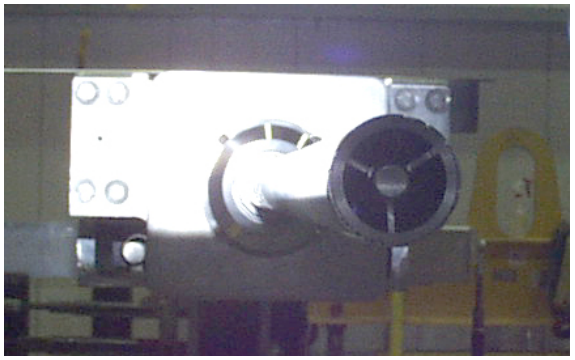
- Several DM scattering processes included

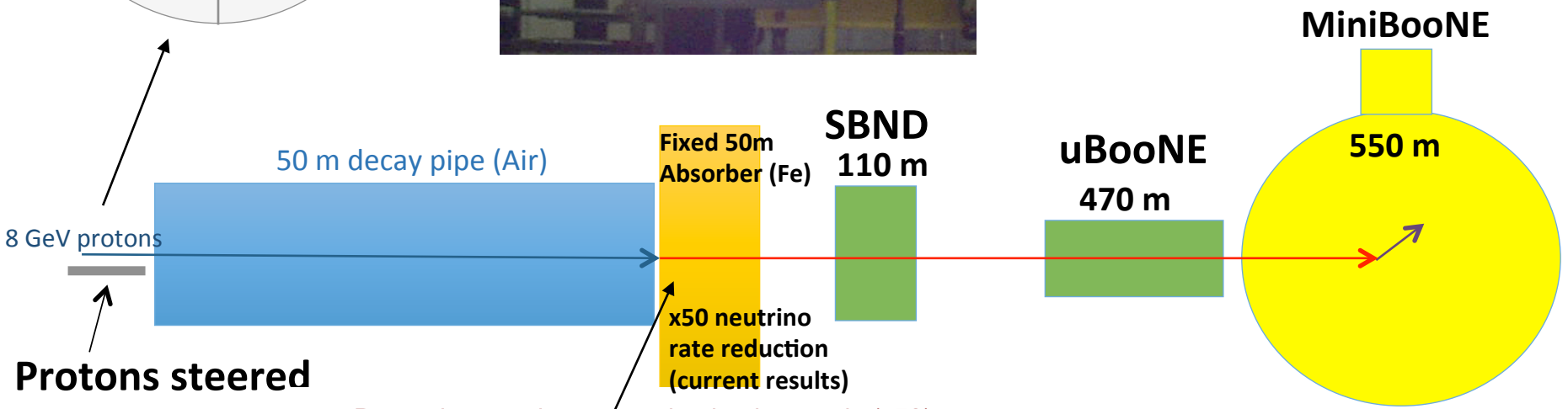


Beam Dump Running: A Unique Capability of the Booster Neutrino Beamline (BNB) to Search for Sub-GeV Dark Matter (FREE!)

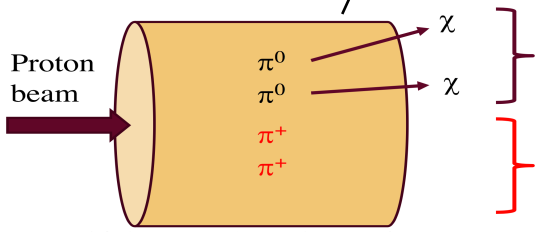
- Beam spot position in beam off target mode (~1 mm spread).
- Target is 1 cm diameter, with 1 cm air gap







- Beam dump reduces neutrino backgrounds (~50)

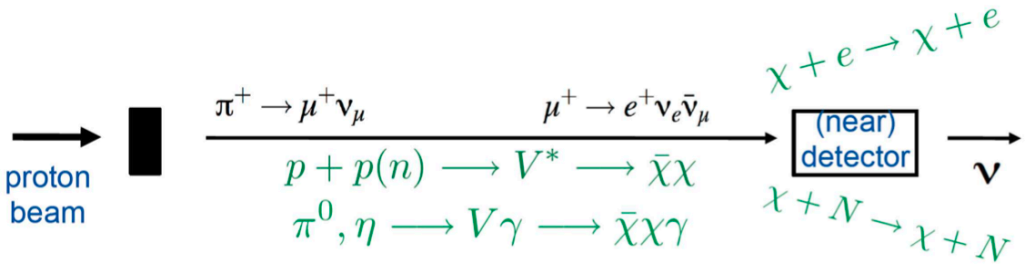


Decays very quickly (before too much matter interactions) into dark sector ✔

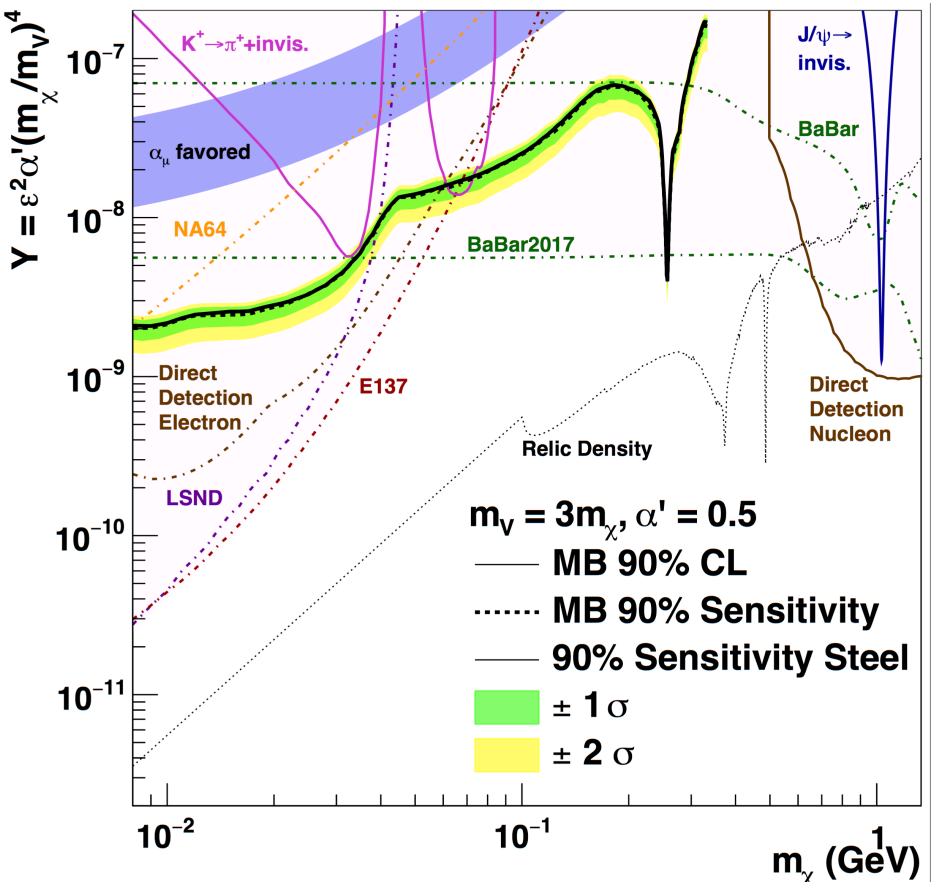
Absorbed before decay to neutrinos (or decay at rest for low-energy neutrinos) ✔

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

MiniBooNE Sub-GeV Dark Matter Results



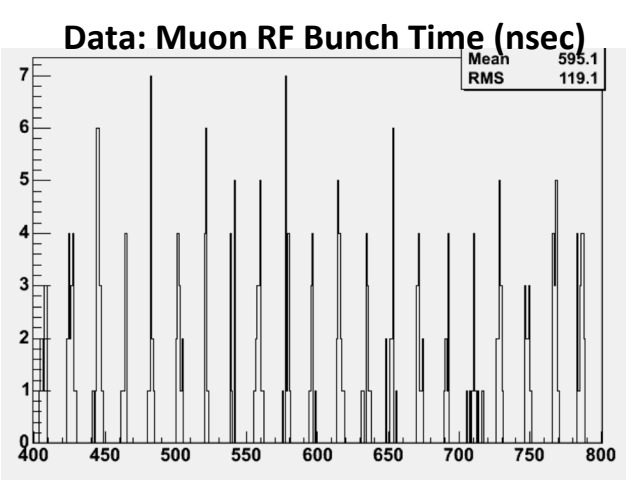
- **MiniBooNE performed a dedicated proton beam dump search**, proving it is feasible and yielding direct DM limits in an un-explored region**.**

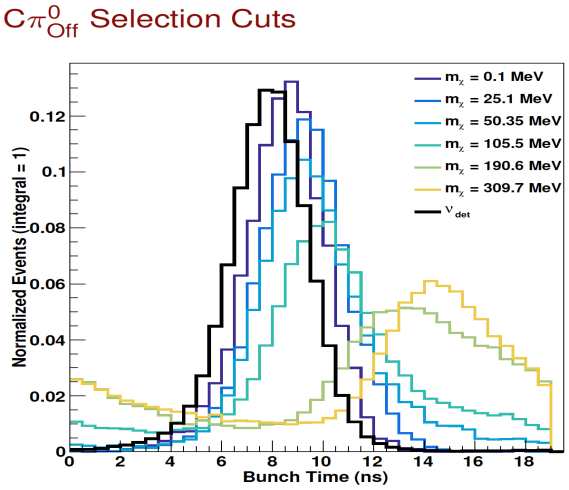


- **Nucleon Neutral Current Scattering: Phys. Rev. Lett. 118, 221803 (2017) – Editors Selection!**
- Based on 50m absorber running 1.86E20 POT.
- Constrained backgrounds with neutrino muon CCQE and NCE. Systematic error cancellation 30% -> 13%.
- **Achieved goal of covering most of the g-2 space.**

Next Analyses from MiniBooNE-DM Data Set: More Lessons Learned and Publications!

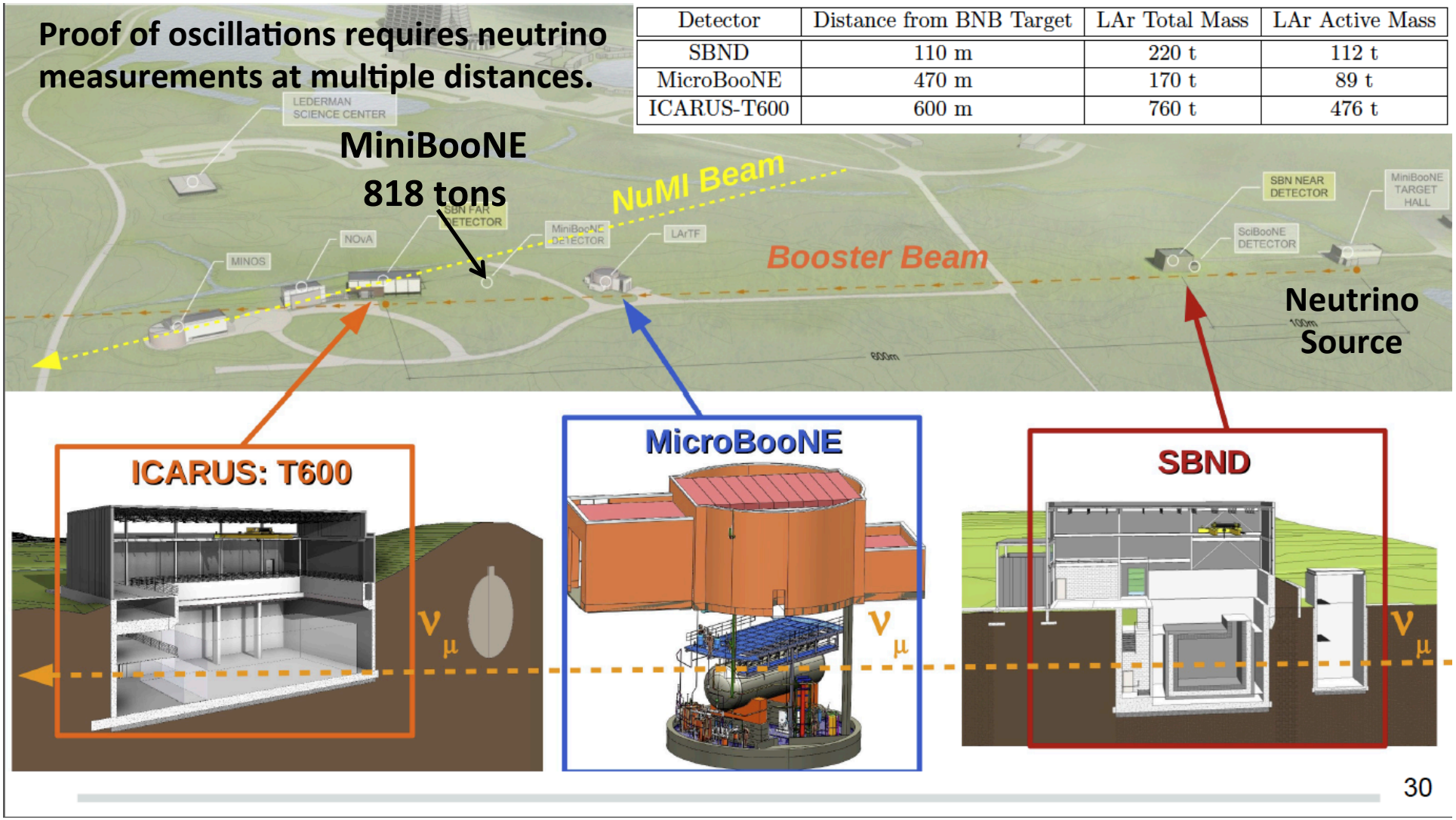
- Inelastic DM resonance scattering $\Delta \rightarrow \pi^0$ where NCπ^0 ν-scattering is main background
  - π^0 is a clean detection signal, excellent sensitivity, stats limited
  - Beam-uncorrelated backgrounds expected to be small
- Elastic DM-electron scattering where Standard Model predicted ν-e is main background
  - Like ν-e is very forward peaked, excellent sensitivity, stats limited
- Beam RF spill event timing
  - Massive DM (> 50 MeV) will be delayed relative to ν backgrounds
  - CCQE e and NC π^0 reconstructed timing resolution ~1 nsec.





LSND/MiniBooNE have motivated the DOE/HEP Short Baseline Neutrino (SBN) Program which will begin operations in 2019

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

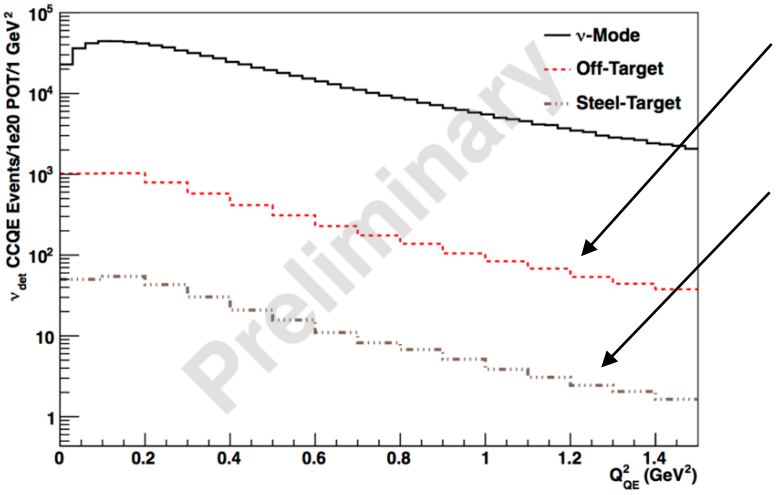


International Program with ~250 collaborators (and growing) → **Many students will need PhD topics!**

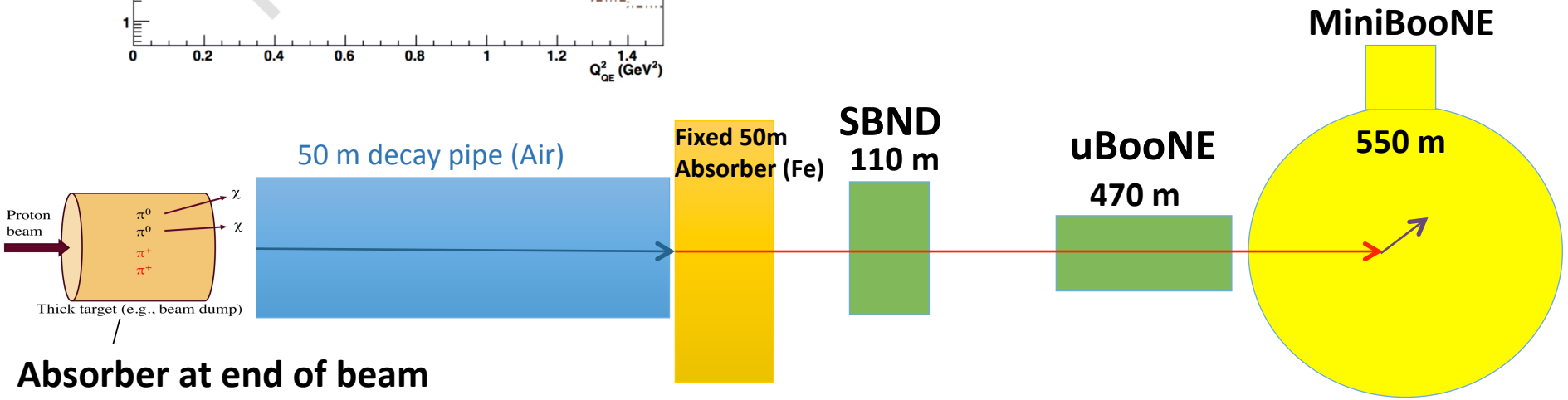
Future of Proton Beam Dump sub-GeV DM Searches

- 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 good sensitivity to π^0 and e scattering.
  - uB and ICARUS measure/reduce systematics.
- 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 beam dump (550 m → 110 m)
  - SBND has x2 higher efficiency
  - Include non flat $1/r^2$ effects
- However, require beam dump absorber at the BNB proton beam vacuum exit to maximize S/B
  - Most ν backgrounds from proton beam interactions in 50 m decay pipe air.
  - Improved beam dump reduce neutrino background by x1000!

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.



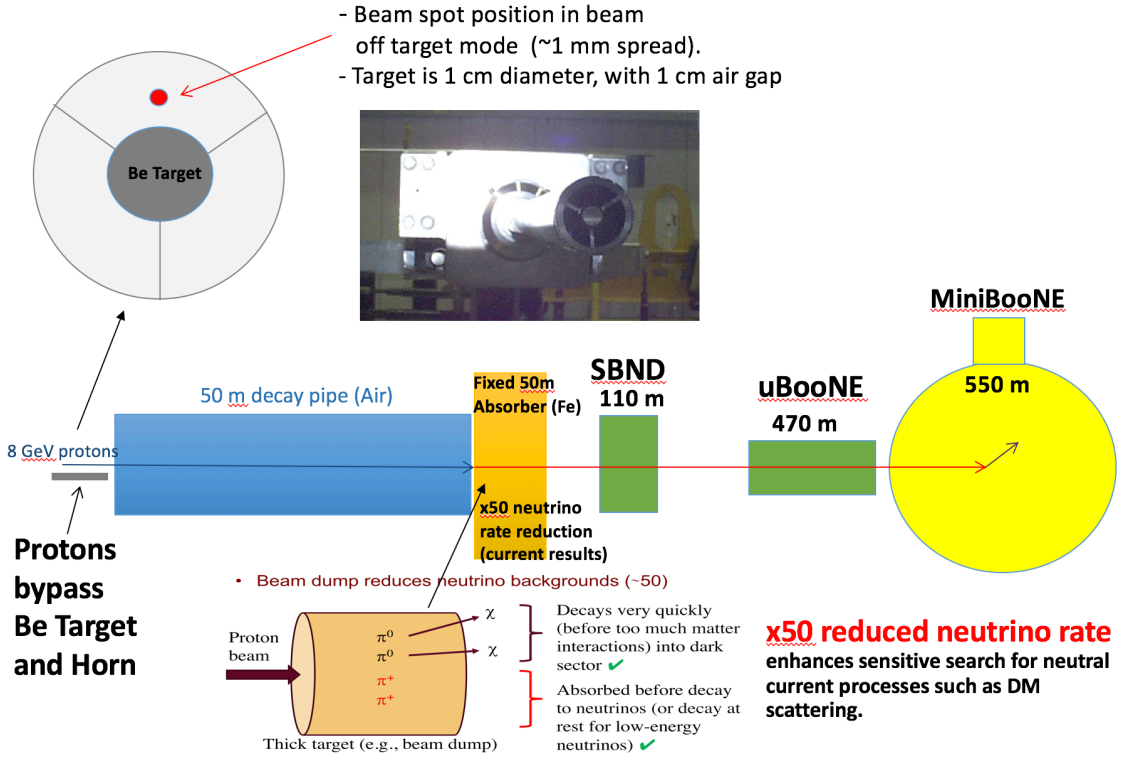
Absorber at end of beam pipe reduces neutrino rate by x1000 (instead of x50)

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

x1000 reduction in neutrino backgrounds!

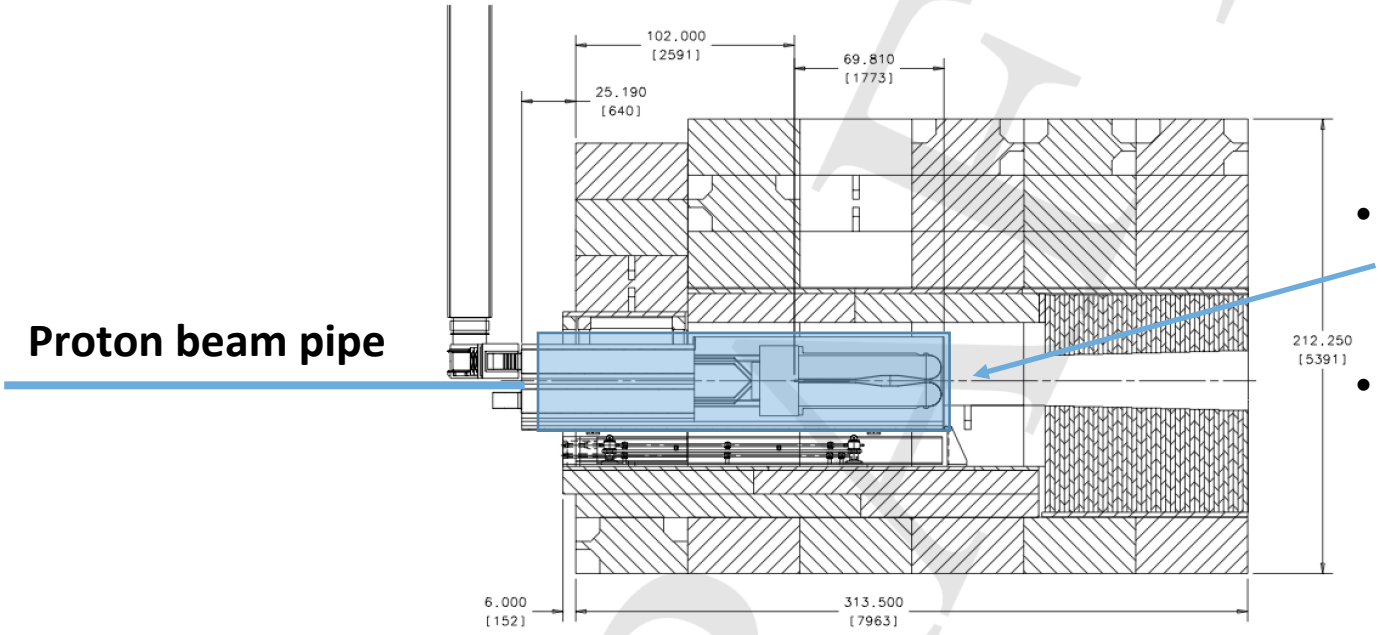
SBN Beam Dump Option

- **Option 0**
  - Run beam to 50 m absorber similar to MiniBooNE-DM run.
  - **Pros**: Cheap, and can do it today! Recently installed kicker magnet allows simultaneous neutrino running.
  - **Cons**: Only x50 neutrino flux reduction, minimal improved sensitivity for SBND.



SBN Beam Dump Upgrade Option

- **Option 1**
  - Design, optimize, build a target block (iron, tungsten, hybrid, etc) that replaces current horn/target (removable).
  - One year run (including target swap) to collect 2E20 POT.
  - **Pros**: Inexpensive ~ $1M, excellent neutrino suppression
  - **Cons**: Can only run after SBN neutrino run > 3yrs.

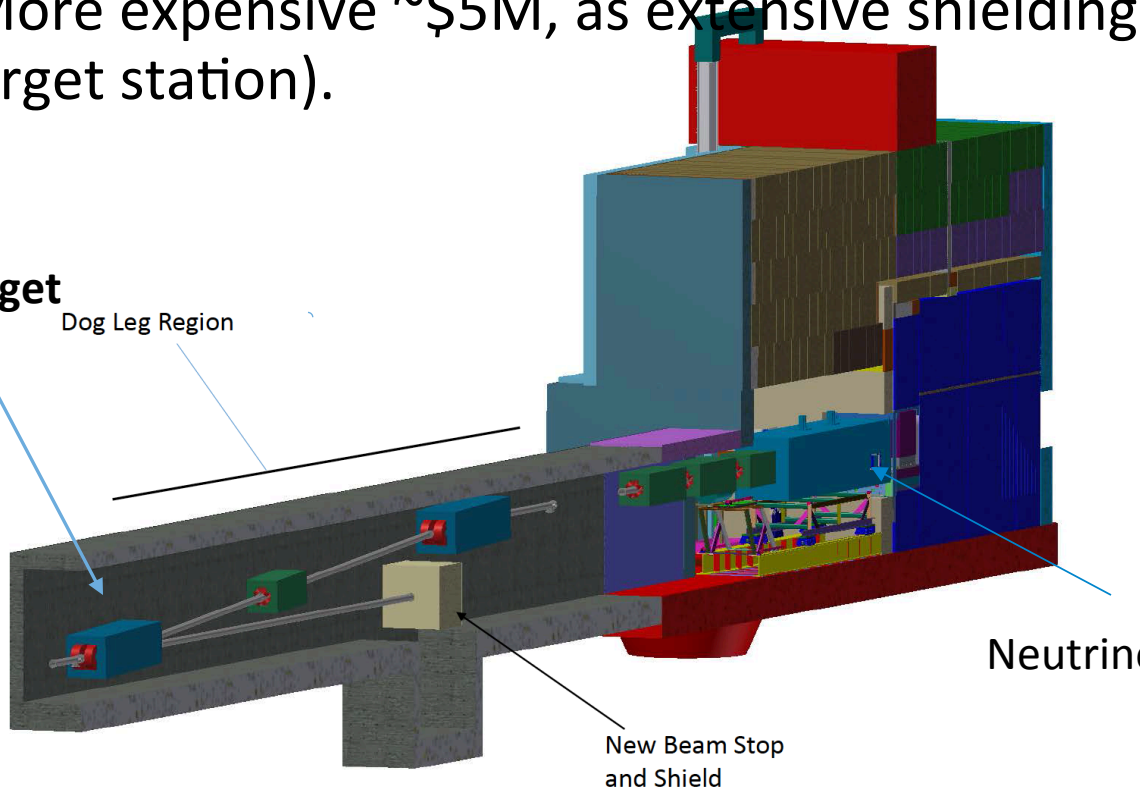


- **Replace neutrino horn/target with Fe Target block**
- **Protons directly enter absorber**

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

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.
  - One year construction, multi-year run collect 6E20 POT.
  - **Pros**: Run concurrently (opportunistically) with neutrino run, more flexible design. Excellent neutrino suppression.
  - **Cons**: More expensive ~$5M, as extensive shielding required (new target station).

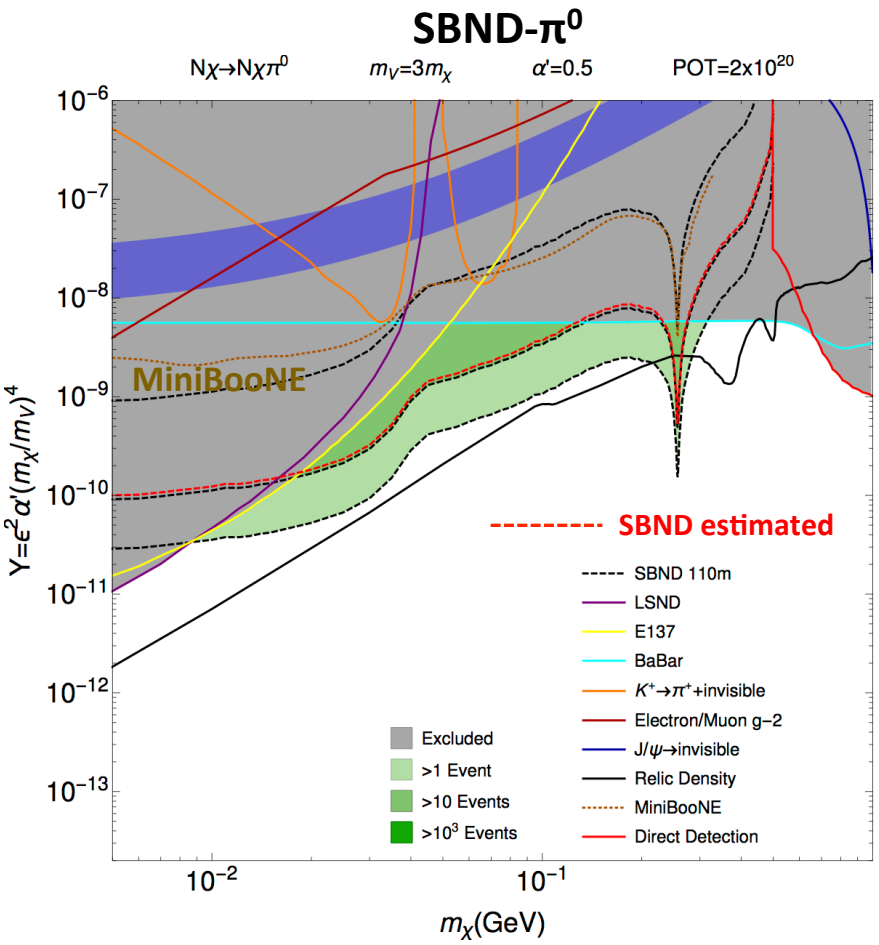


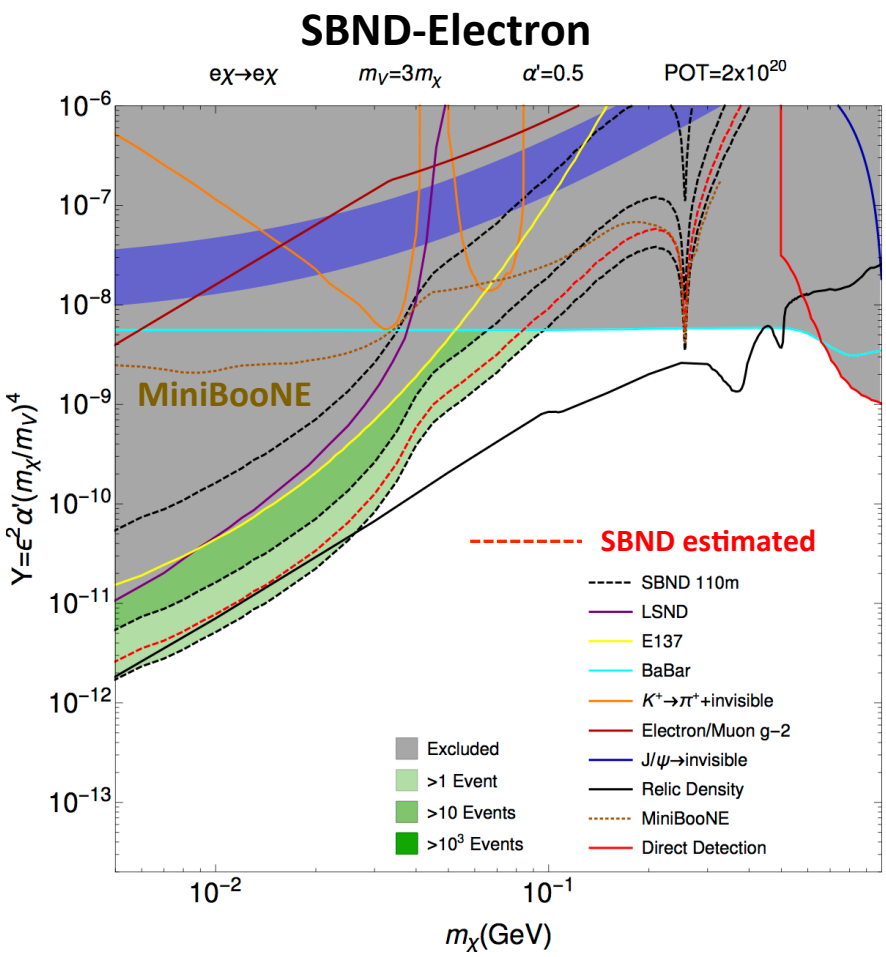
DM Scattering Signal Comparisons:

	MiniBooNE (Actual) 50m beam dump	SBND Option 0	**SBND Option 1&2**
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 (pi0/electron)	35%	60%	60%
Approximate scaling (*)	1.0	29	8.6
DM-pi0 signal (**)	10	290	86
ν-pi0 background (***)	135	3915	68
pi0 signal/background	**~1/10**	**~1/10**	**~1/1**
DM-electron signal (**)	0.4	11.6	3.4
ν-electron background (****)	0.6	17.4	0.3
electron signal/background	**~1/1**	**~1/1**	**~10/1**

- (*) 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.
- (****) Includes electron cut $\cos\theta_{beam} > 0.98$.

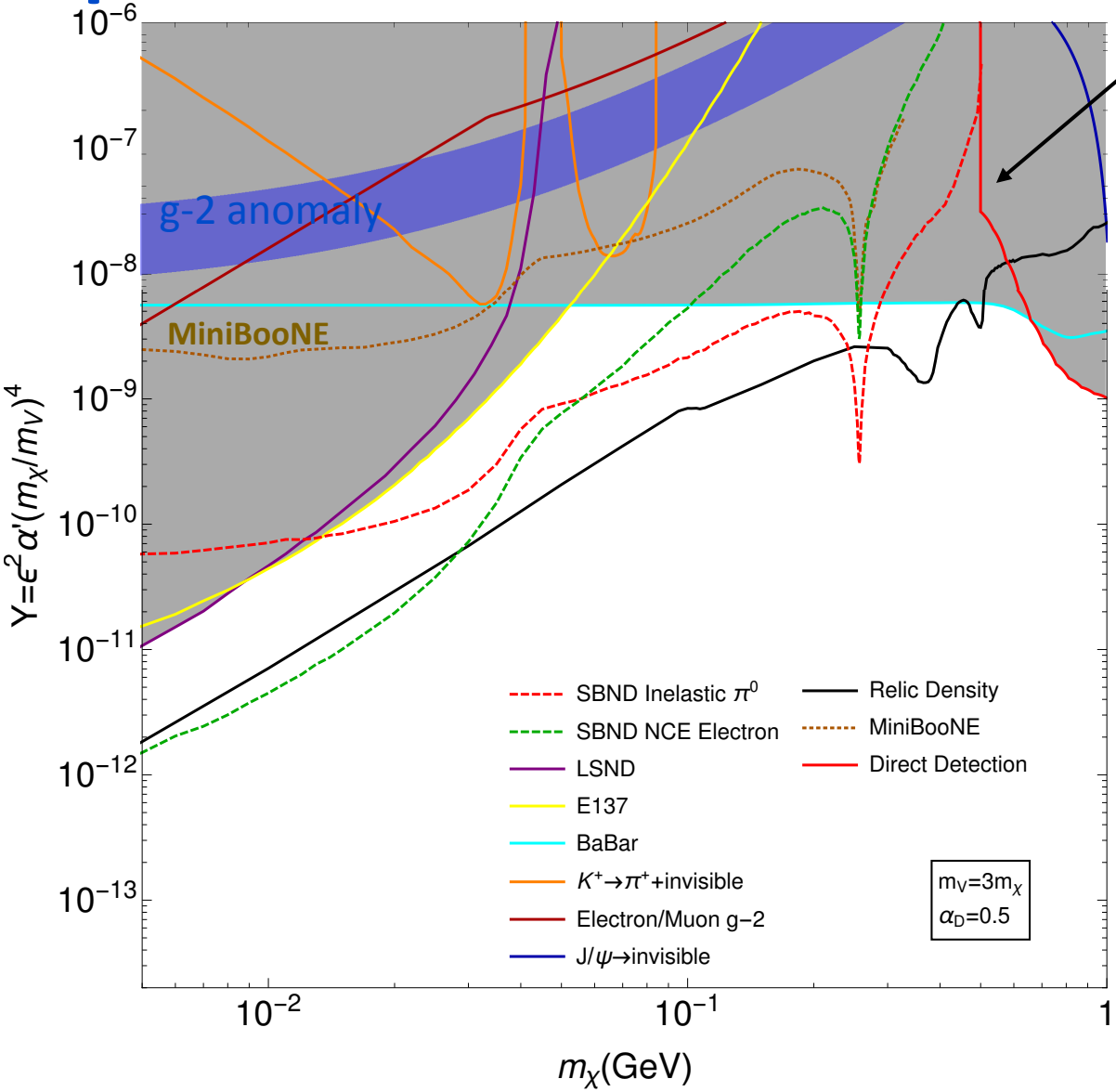
DM Search with SBND: π^0 and Electron Channel and Improved Beam Dump: Option 1 with 2.0E20 POT





- Signal and background estimates robust, based on MB lessons
- π^0 good at high mass, electron at low mass -- compliment each other!
- Event timing ~1 nsec relative to beam will improve sensitivity for DM mass > 50 MeV
- **SBND order magnitude better than MB, but needs improved dump to reduce backgrounds!**

More Protons with a Dedicated Dump: Option 2 with 6.0E20 POT



Direct Detection Lower Limits

- **SBND with improved beam dump will probe scalar relic density line.**
- π^0 (high mass) and electron (low mass) channels complement each other.
- Including beam timing will improve DM search for masses > 50 MeV.

Growing Interest in DM Searches at FNAL: PI's from MiniBooNE-DM, SBN and Theory

Next Step in Accelerator Sub-GeV Dark Matter Searches at FNAL: An Expression of Interest to Improve the BNB Beam Dump for SBN

Submitted to the FNAL PAC Nov, 2017

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Future SBN sub-GeV Dark Matter Search

- **SBND can achieve an order of magnitude** improvement in DM signal sensitivity relative to MiniBooNE-DM
  - Test vector portal relic density limits in the MeV to GeV range.
  - Test other models: leptophobic, inelastic, higgs and neutrino portals.
- **Requires deployment of a dump/absorber** at the end of the beam pipe to significantly reduce neutrino backgrounds
  - Leverage investment in SBN detectors, significantly expand physics scope at reasonable cost.
  - 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.

Request to the PAC:

- Given a positive response from the FNAL PAC and management, work will continue to further elaborate the physics case and technical requirements outlined in this EOI with the goal of developing a proposal to seek DOE funding for small scale dark matter initiatives, should the opportunity arise.
- Will pursue other funding opportunities such as NSF, LANL-LDRD, international, etc.

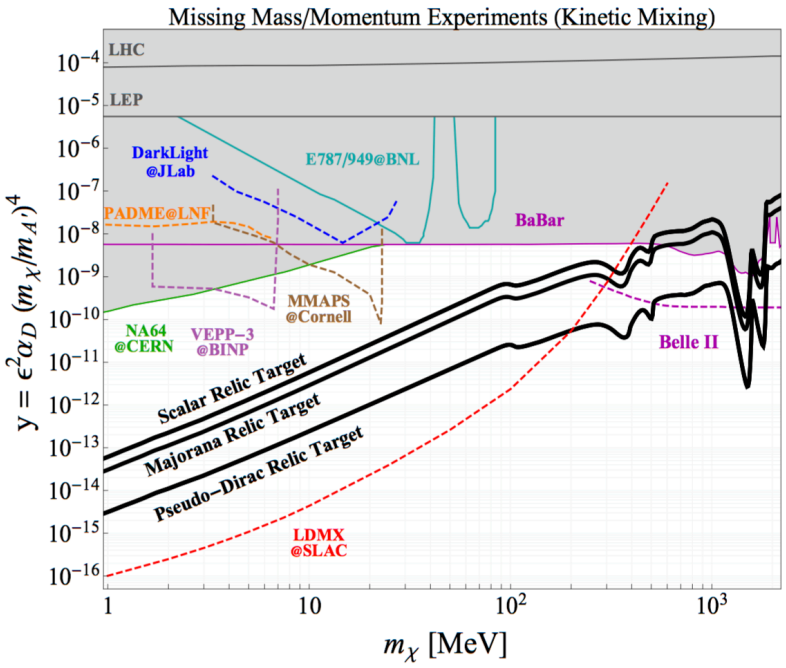
Backups….

DM Community Organizing Itself for New Push: Cosmic Vision Workshop (March 2017)

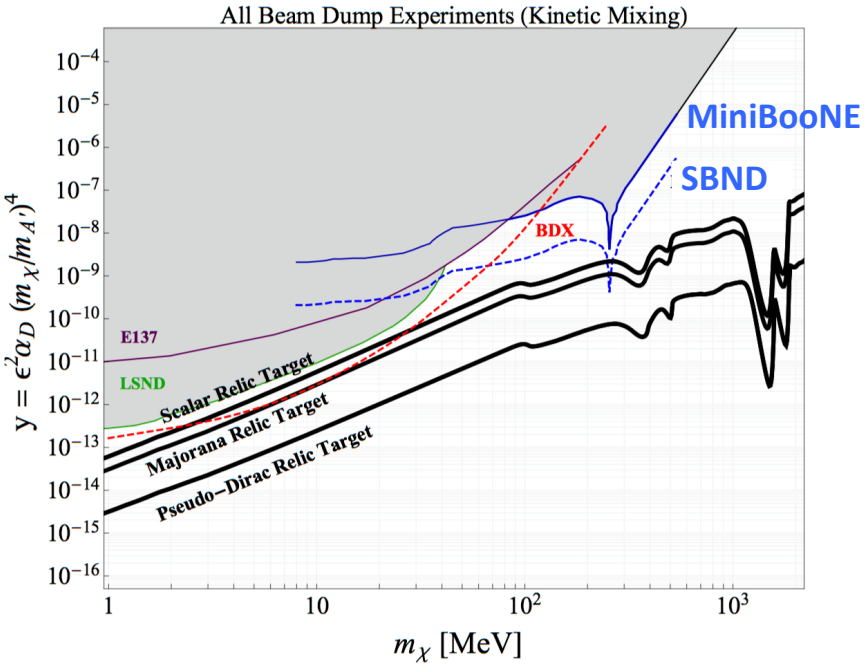
- US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report **arXiv:1707.04591**
  - Describe science case for new/lightly-explored parameter search. e.g. sub-GeV <-> portal vector model, milli-eV, etc.
  - Describe experiments that can cover new parameter space.
  - **Prioritize search opportunities, not experiments.**
- DOE requested the report and are currently reviewing to decide if/when call for proposals
  - US based, under $10 million. International cooperation allowed, but junior partner.
  - Funding will come from IF, CF, NSF, etc. Augmented funding welcomed e.g. LDRD, international, etc.
  - **Prefer experiments that can be mounted near term (~few years). Use of existing lab infrastructure preferred.**

Many Techniques to Search for sub-GeV DM: Long Road to Relic Density Limits

Missing mass / momentum / energy



Beam dump



Robust exploration of thermal targets
Big discovery space!

Either discover DM, or demonstrate that it is not in thermal contact with SM!

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 – Bench Mark Model

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

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)

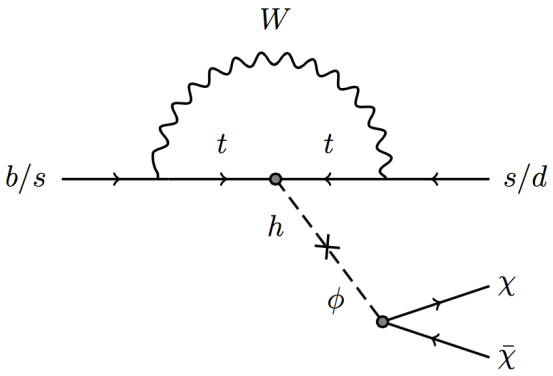
$$\mathcal{L} = i\bar{\chi}\gamma^\mu D_\mu \chi - m_\chi \bar{\chi}\chi - \frac{1}{4}(V_B^{\mu\nu})^2 + \frac{1}{2}m_V^2 (V_B^\mu)^2 + \frac{g_B}{3} V_B^\mu \sum_i \bar{q}_i \gamma_\mu q_i + \dots$$

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

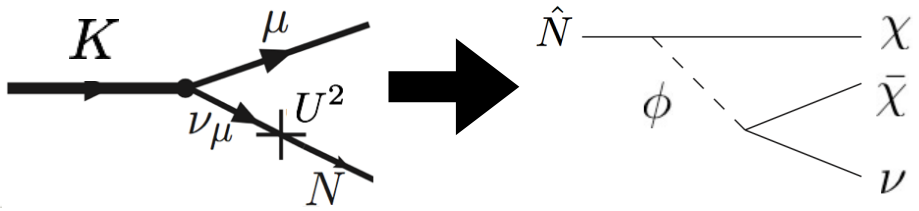
- 4 new parameters: $m_\chi, m_V, \alpha_B, q_B$
- $U(1)_B$ is "safe" - preserves approximate symmetries of SM (CP, P, flavor)
- Gauge anomalies can be cancelled by new states at the weak scale

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]



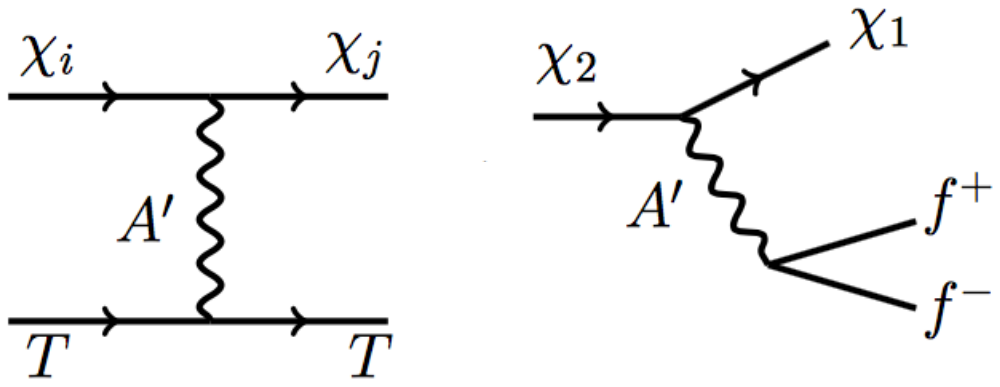
Neutrino portal
[see e.g. Bertoni, Ipek, McKeen, Nelson '14]

- Signatures include rare meson decays with missing energy

Inelastic Dark Matter

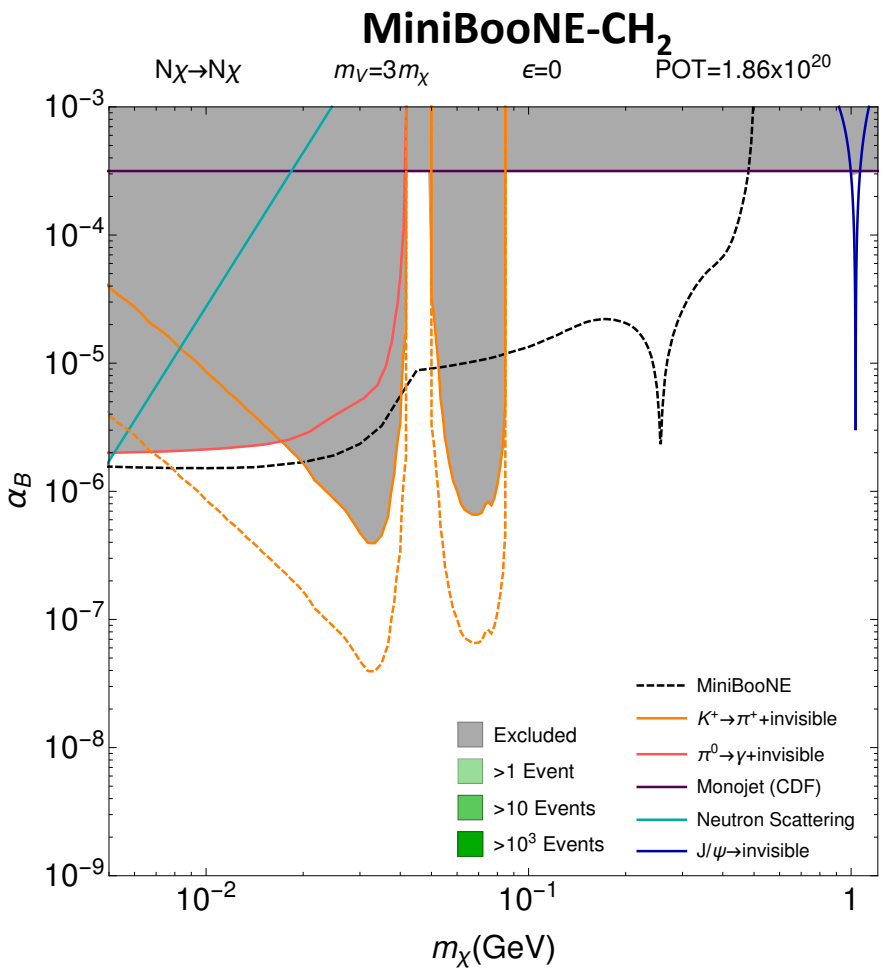
[Tucker-Smith, Weiner]
[Izaguirre, Kahn, Krnjaic, Moschella]

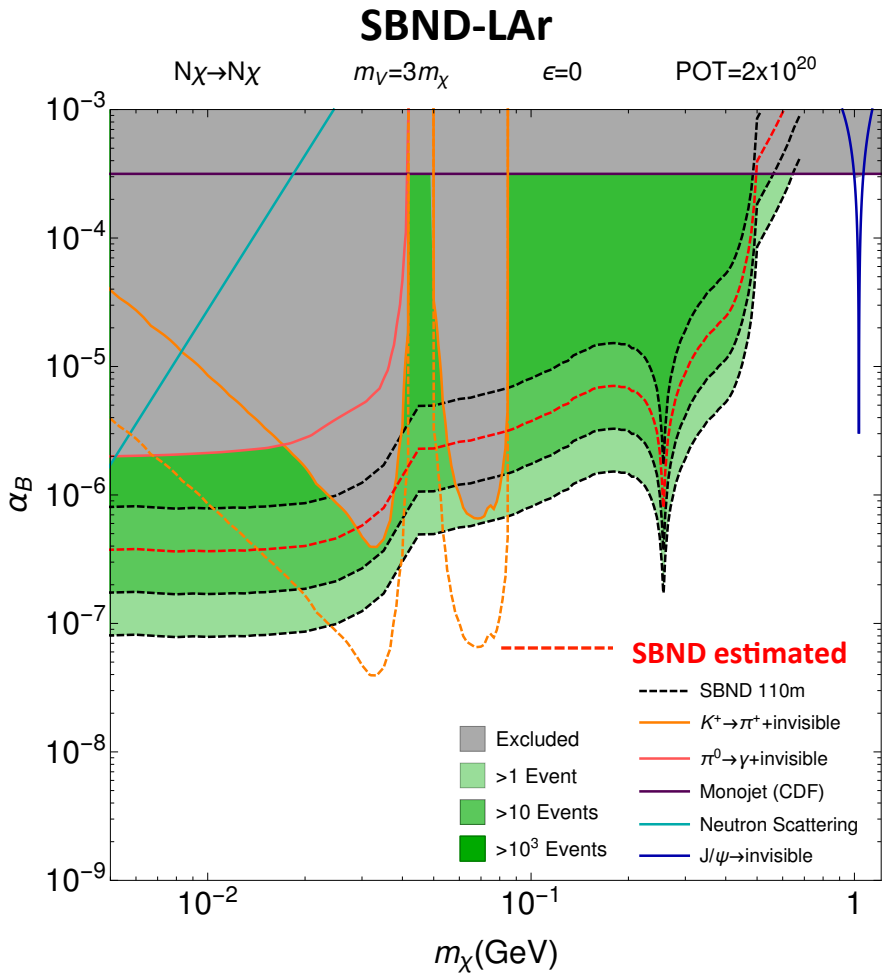
- The DM particle, χ_1, interacts by transitioning to a heavier state χ_2
- This can lead to new signatures involving the decay of the excited state



- 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

SBND Leptophobic Searches with Improved Beam Dump: Few searches, mostly open parameter space!

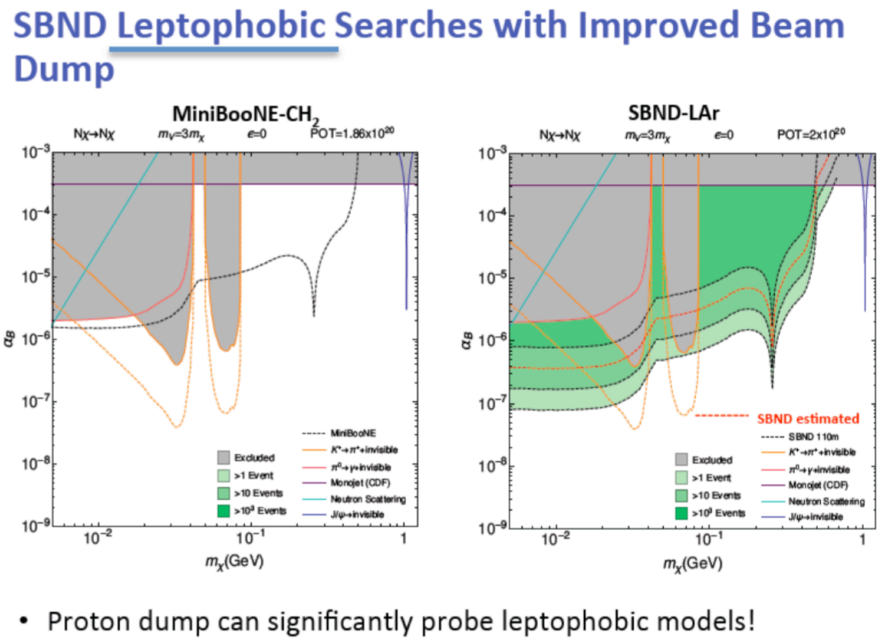


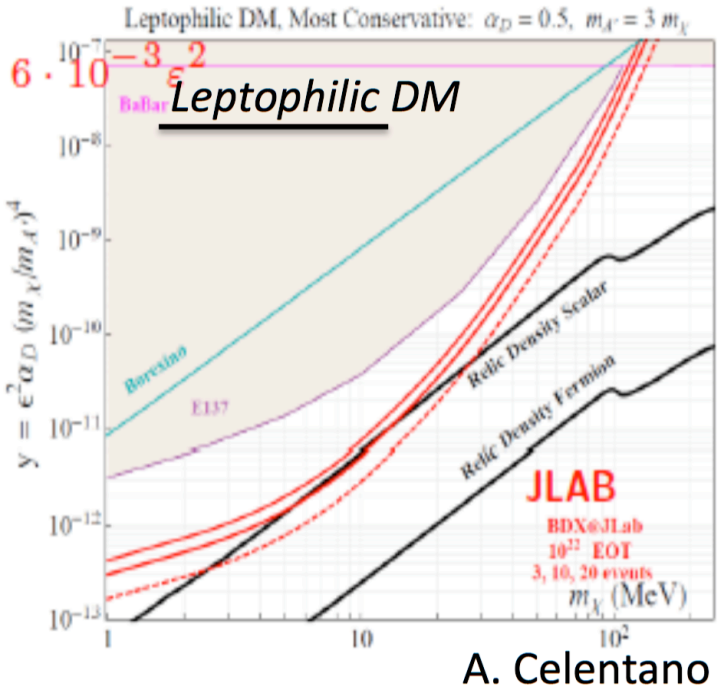


- Proton dump can significantly probe leptophobic models!

Motivation for sub-GeV DM Search

Complementarity between proton and electron beams



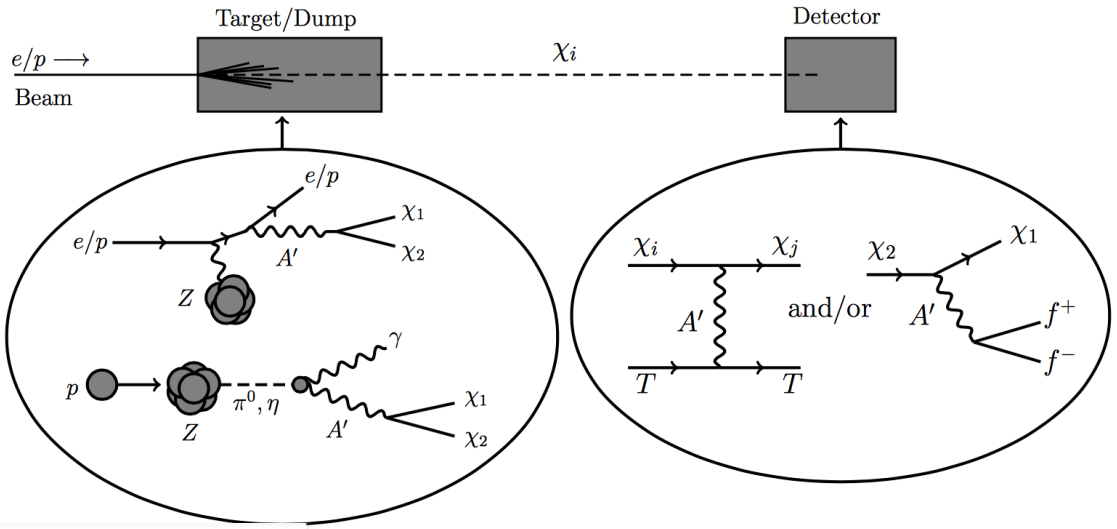


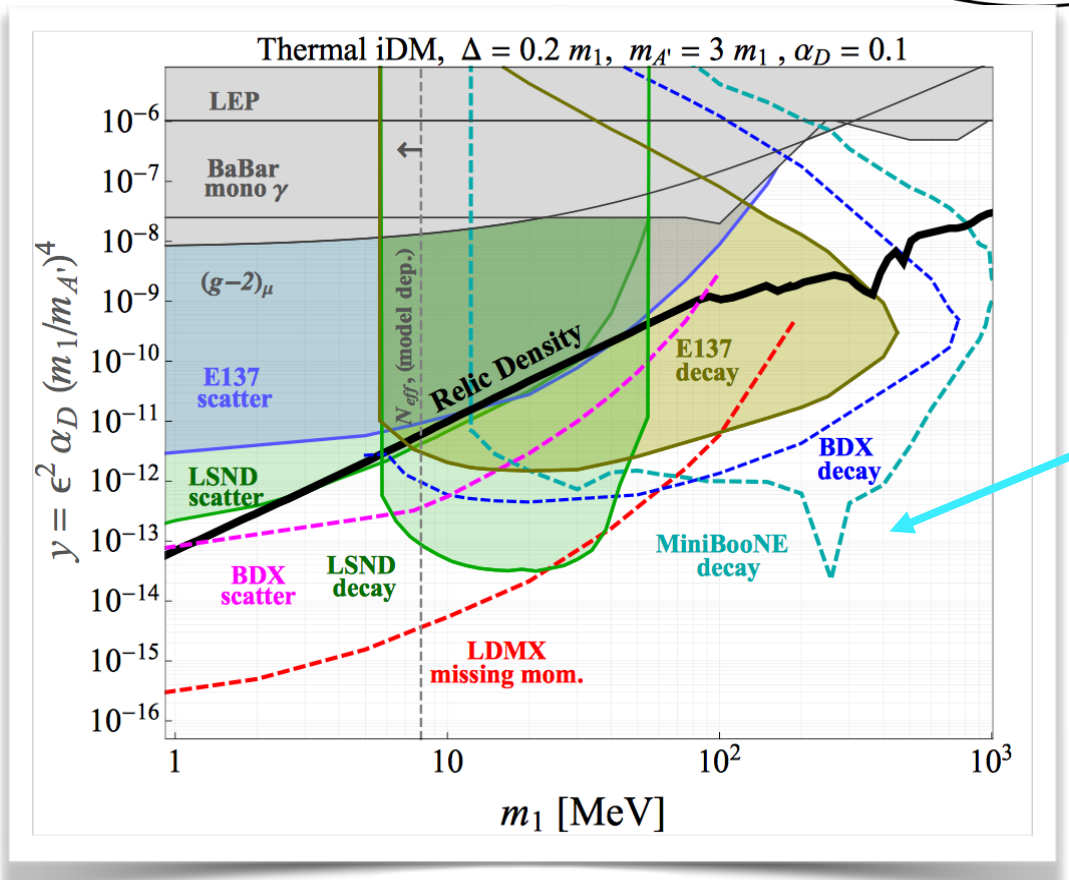
A. Celentano

Electron beam probes lepton couplings
Proton beam probes hadronic couplings
Both couplings are possible

Inelastic DM

More models, more opportunity...

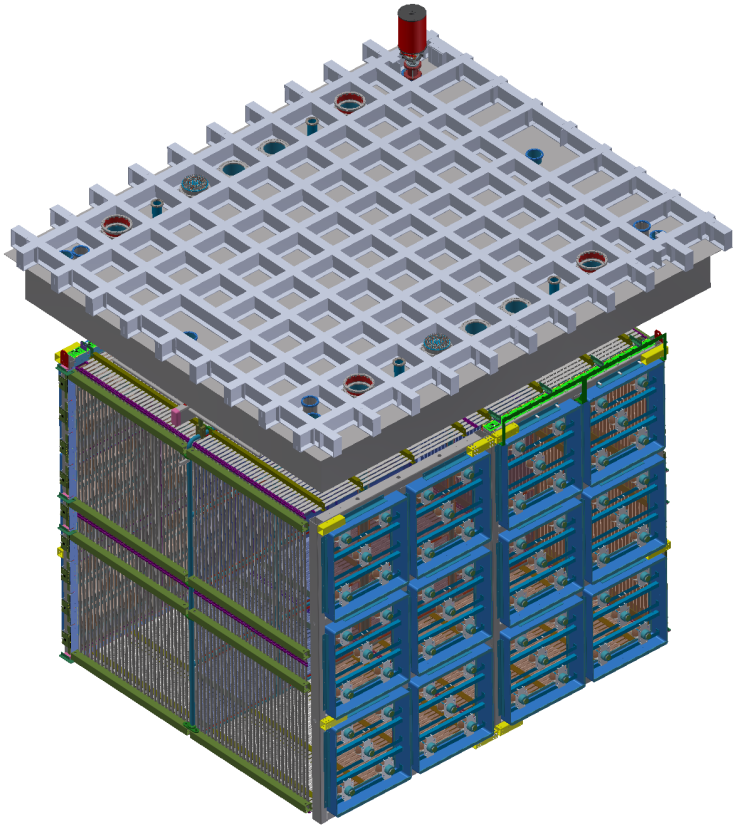


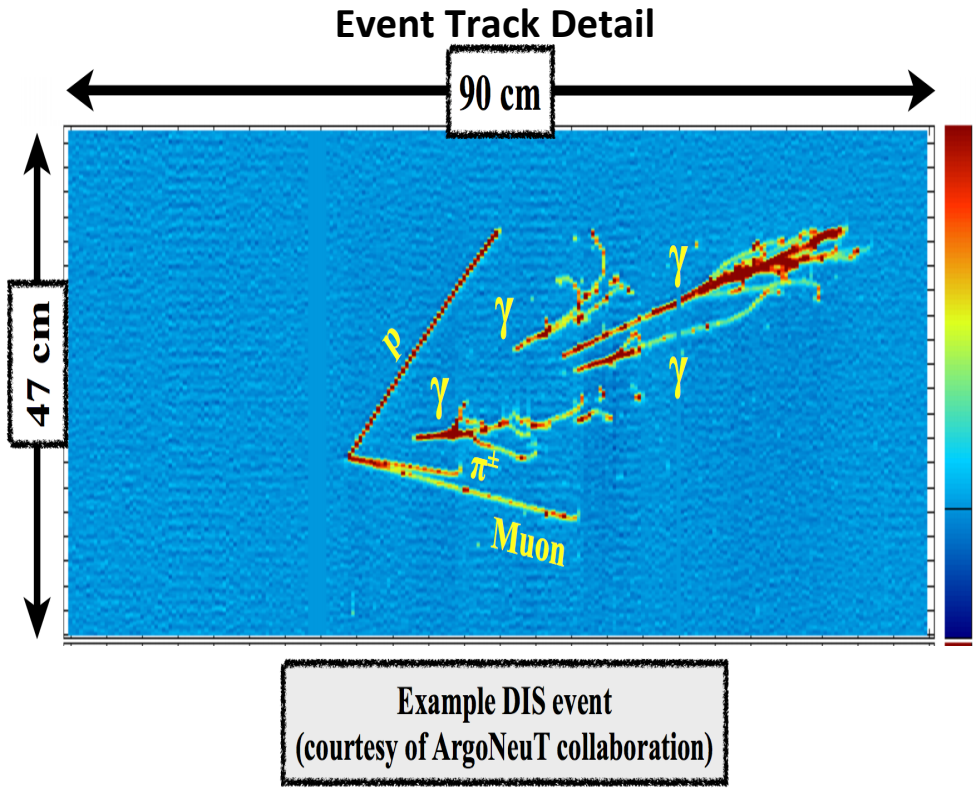


MiniBooNE sensitivity with current beam dump

[Izaguirre, Kahn, Krnjaic, Moschella]

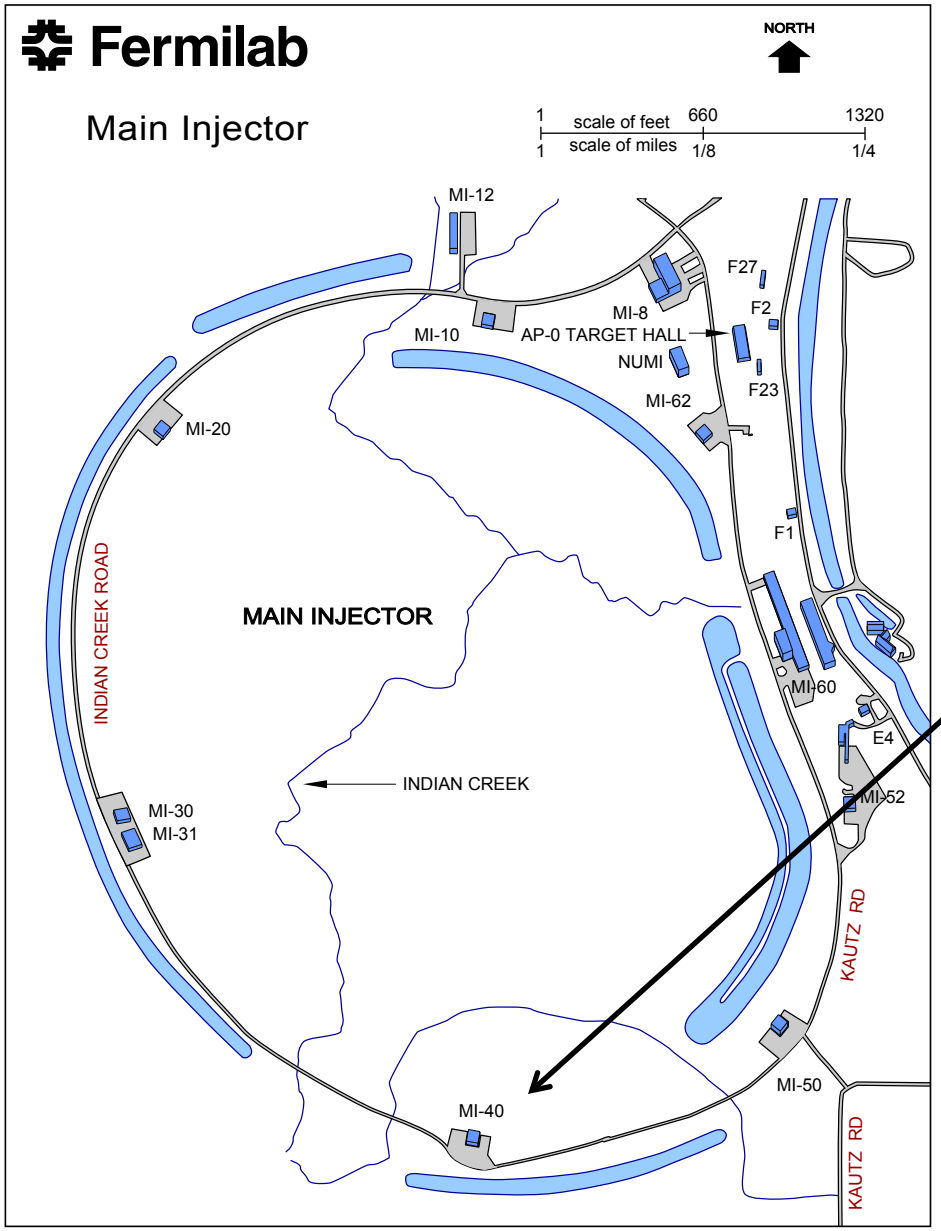
SBND Detector: 112 tons LAr TPC 4 x 4 x 5 m, 11000 TPC wires, 2 m drift distance. Measure high statistics neutrino event rate at 110 m position which is used to normalize ICARUS far detector to test LSND/MB oscillations.

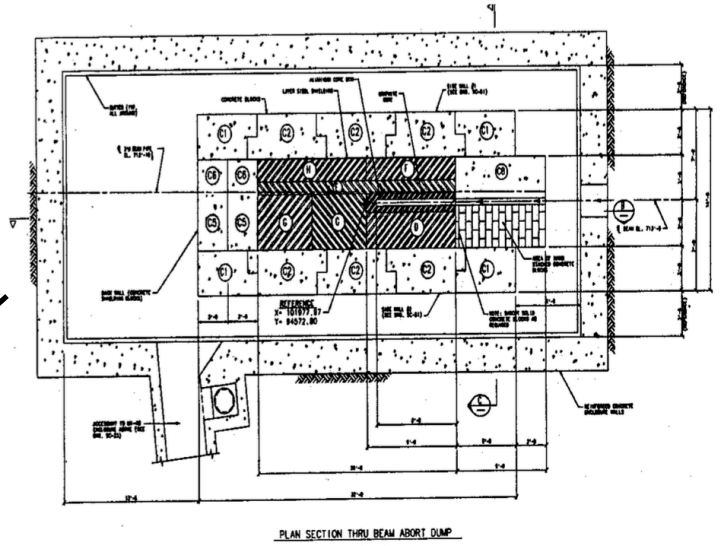




- Overburden, 98% coverage cosmic ray tracker, and 120 8” PMT photon detection system (PDS) will significantly reduce cosmogenic backgrounds.
- PDS will achieve ~nsec timing improving DM sensitivity M> 50 MeV (time of flight)
- Detector to start running in neutrino mode 2020.

MI40 Abort 120 GeV Beam Dump

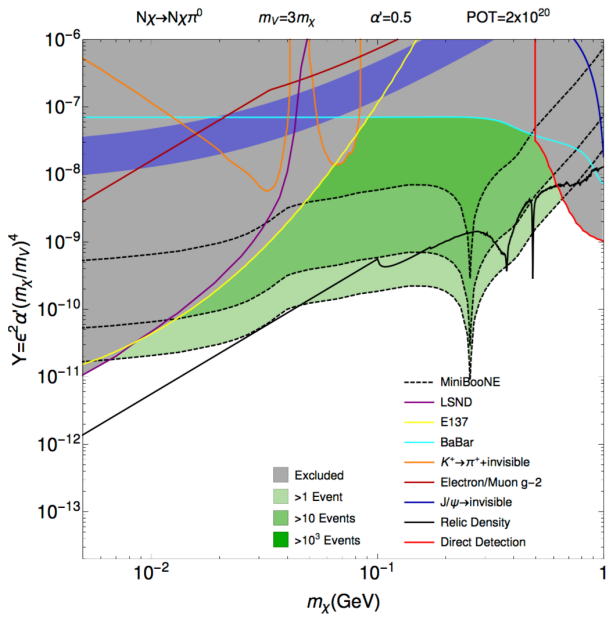


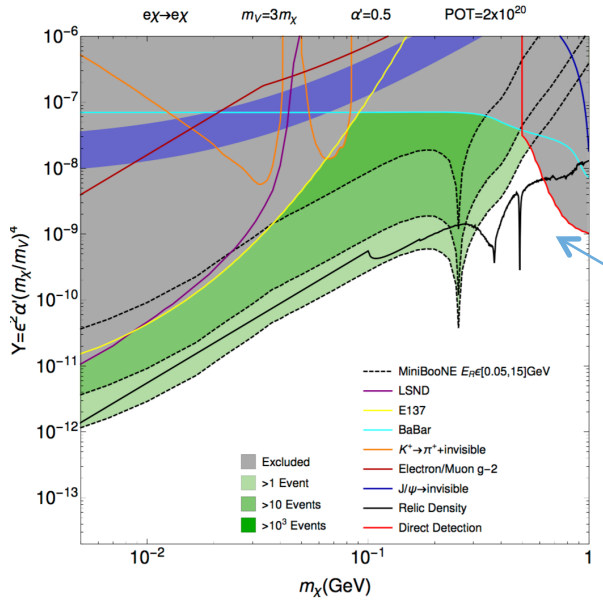


Radiation requirements limits to 2.5E19 POT/year

120 GeV Main Injector Proton Dump Option

- Move or build a new MiniBooNE (or NOvA)-like detector down stream of the MI 120 GeV Dump (MI40).
- **Pro's**: Significant sensitivity improvement in both DM mass and coupling. Significant test of scalar relic density limits. Complete overlap with direct searches above a few GeV.
- **Cons**: Current proton limit to the MI absorber is 2.5E19 POT/year (limited by groundwater). Need to build a detector ($$). Minimal experience estimating backgrounds, systematic errors, etc.





Better coverage at higher mass