Proton Fixed-Target Dark Sector Searches at Fermilab

Matt Toups, Fermilab

15 Dec 2020

PIP-II will support a world-leading neutrino program @ FNAL

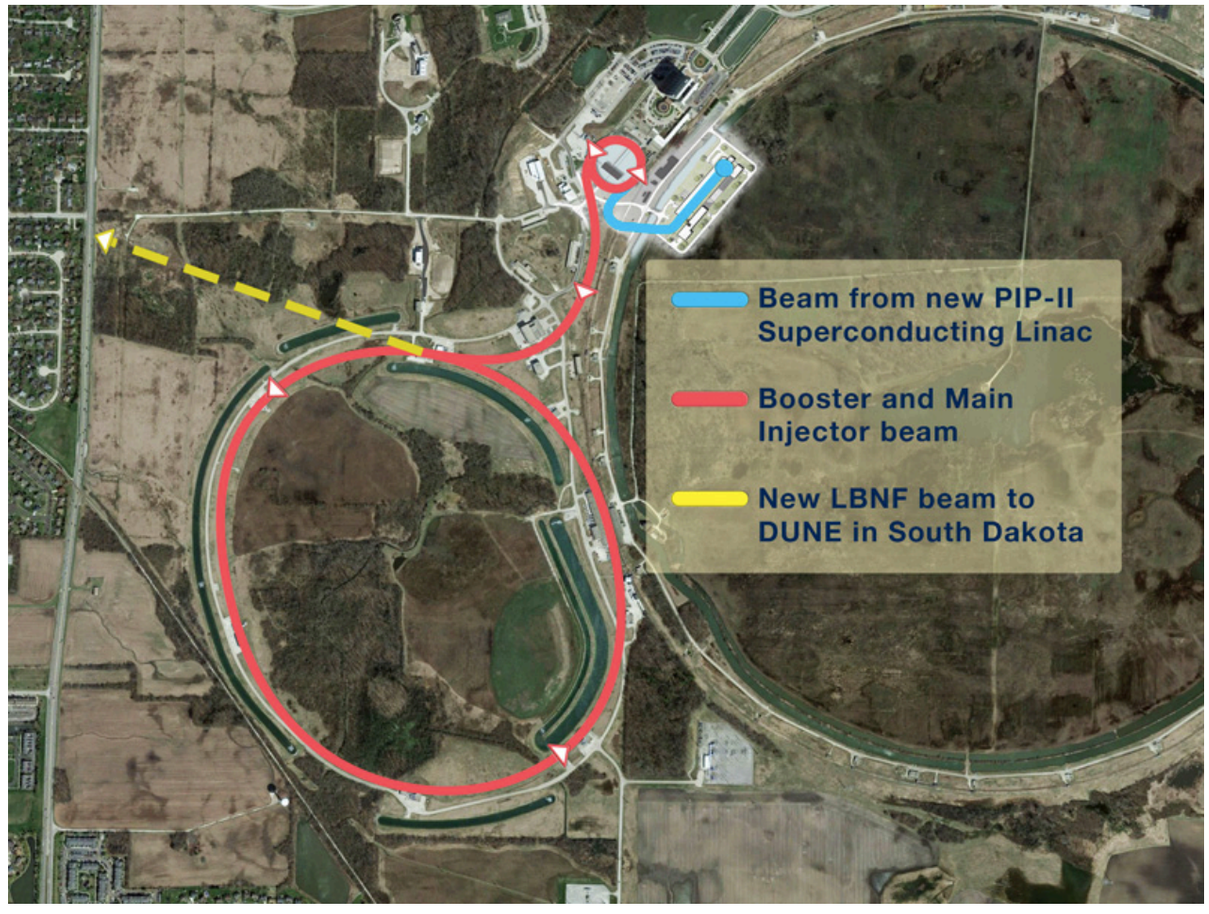
- Expected LINAC commissioning in FY27
  - In July, broke ground on the first building for PIP-II

- Will be among the highest-power ~GeV proton beams in the world

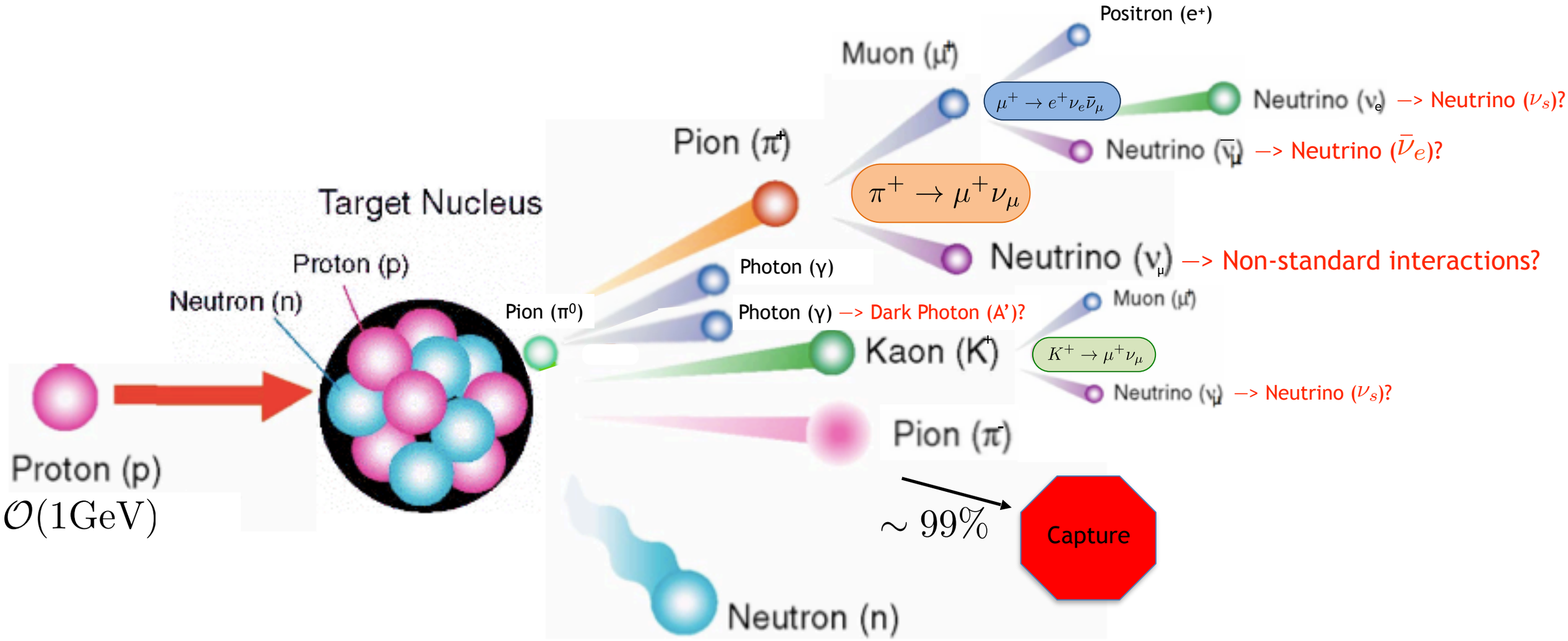
- Key high-level metrics for SC LINAC:
  - Capable of 2 mA @ 800 MeV (1.6 MW)

  - DUNE only uses 1.1% of this beam to achieve its physics goals

- How can we best leverage this advanced beam facility to search for new physics?

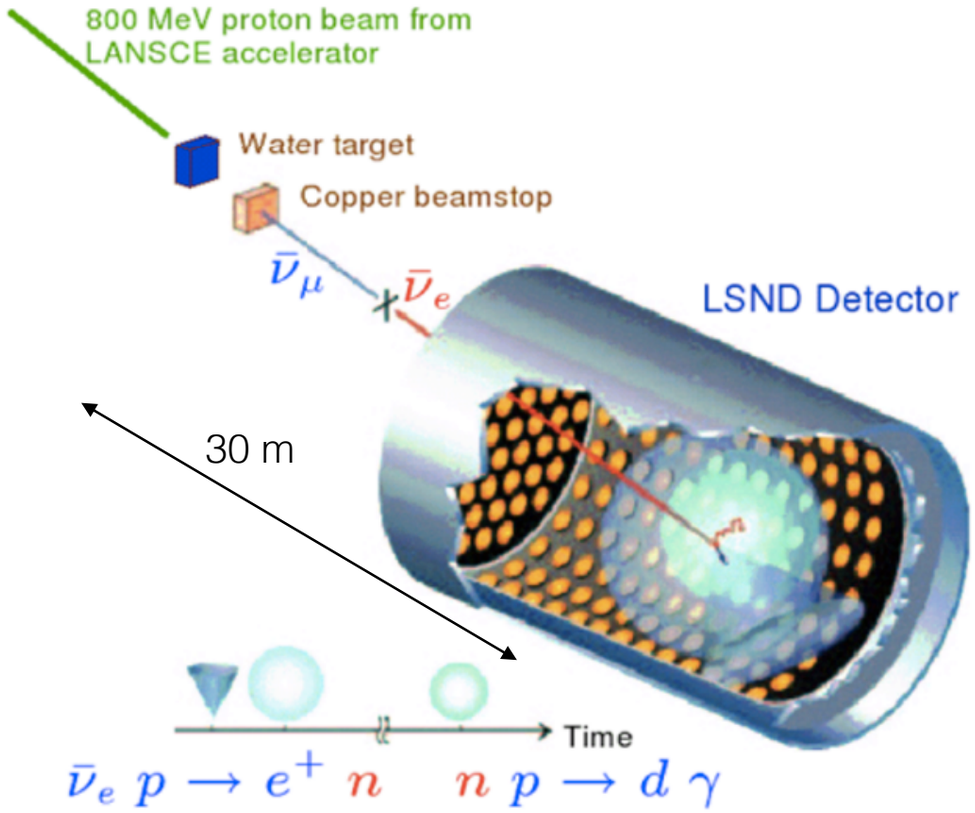


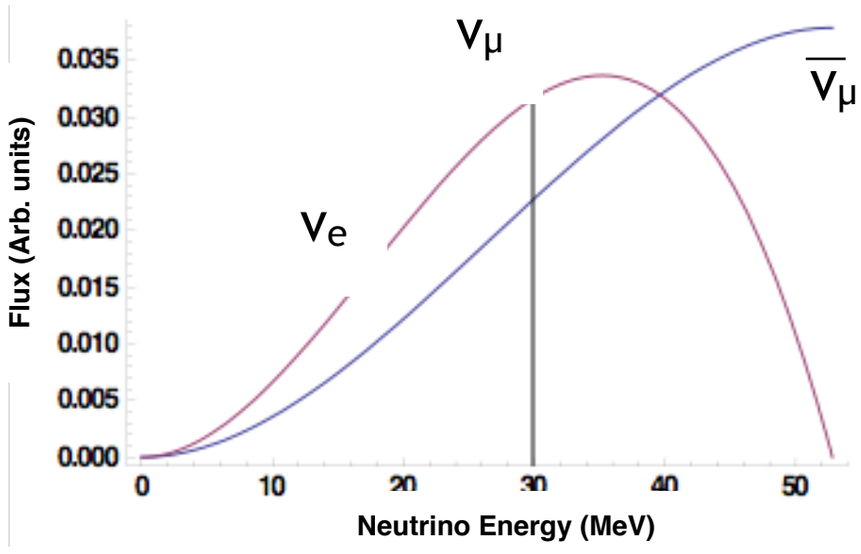
PIP-II is <u>simultaneously</u> capable of driving a MW-class GeV-scale proton fixed target program and a 2.4 MW beam line for DUNE

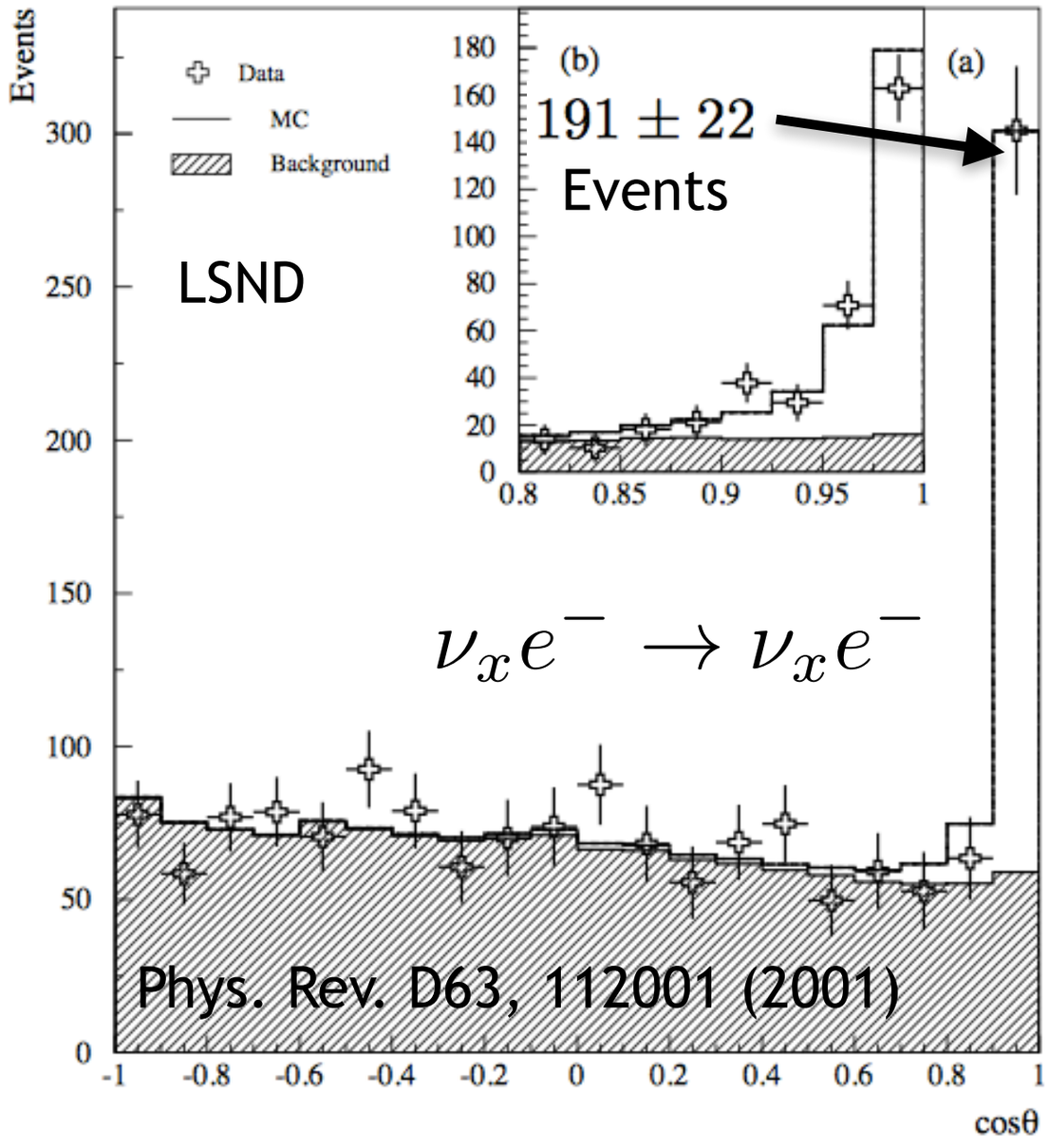


Excellent opportunity for a proton beam dump facility at Fermilab dedicated to HEP that more fully utilizes PIP-II infrastructure as well as the existing accelerator complex

Past Experiments: LSND







~2e23 POT, 7% duty factor

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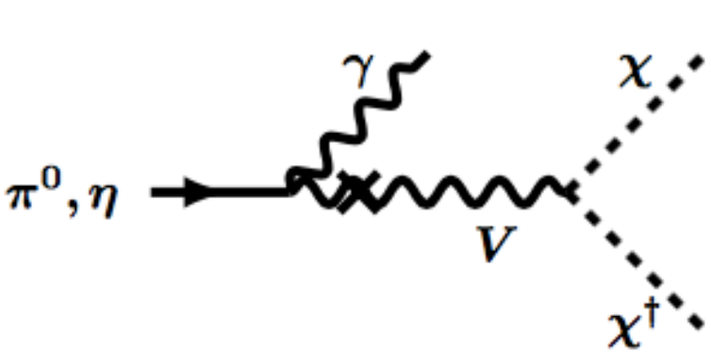
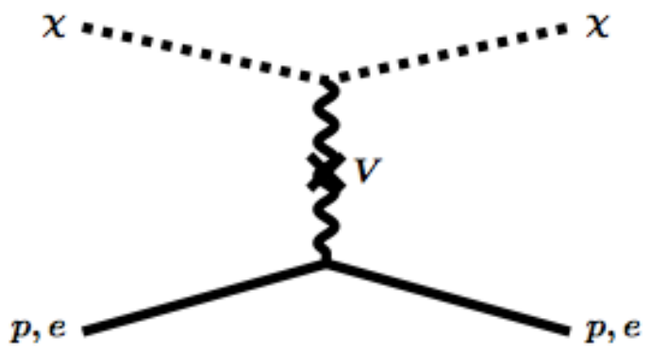
New Theoretical Directions: Thermal Light Dark Matter

- Recent theoretical work has highlighted not only the viability of sub-GeV dark sectors models to explain the cosmological dark matter abundance but also that a broad class of these models can be tested with accelerator-based, fixed-target experiments, which complement growing activity in sub-GeV direct dark matter detection
- Benchmark vector portal (kinetic mixing) model:

$$\mathcal{L}_V = \mathcal{L}_\chi - \frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_V^2 V_\mu V^\mu - \frac{\epsilon}{2} F_{\mu\nu} V^{\mu\nu},$$

$$\mathcal{L}_\chi = \begin{cases} i\bar{\chi} \not{D} \chi - m_\chi \bar{\chi} \chi & \text{Dirac fermion,} \\ |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 & \text{Complex scalar,} \end{cases}$$





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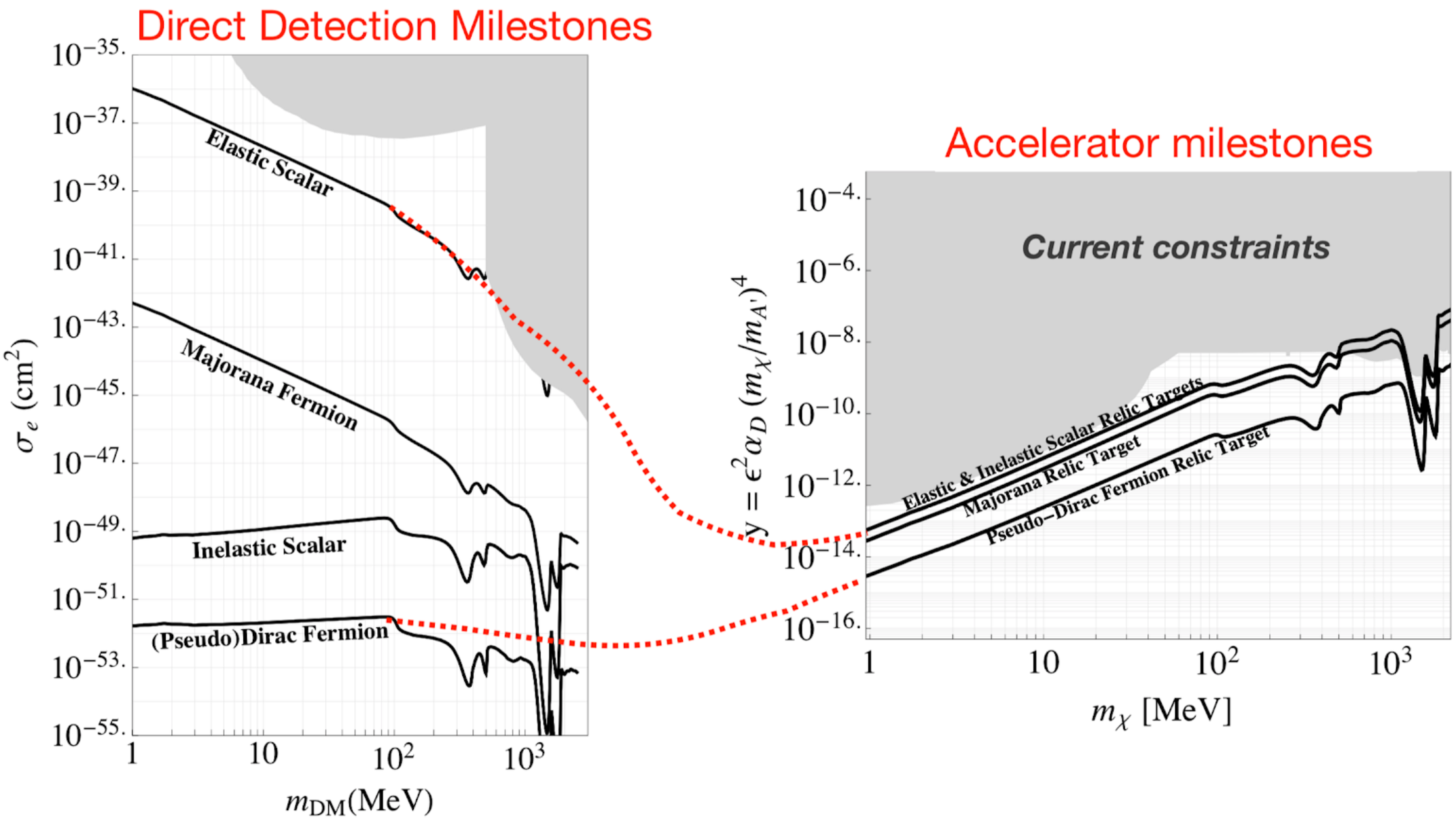
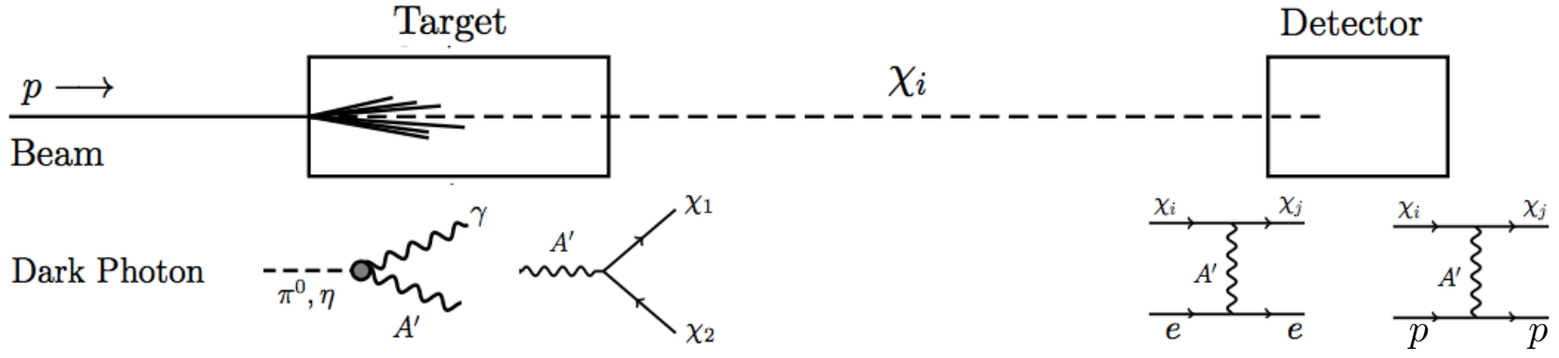
Accelerator-based light dark matter (LDM) searches

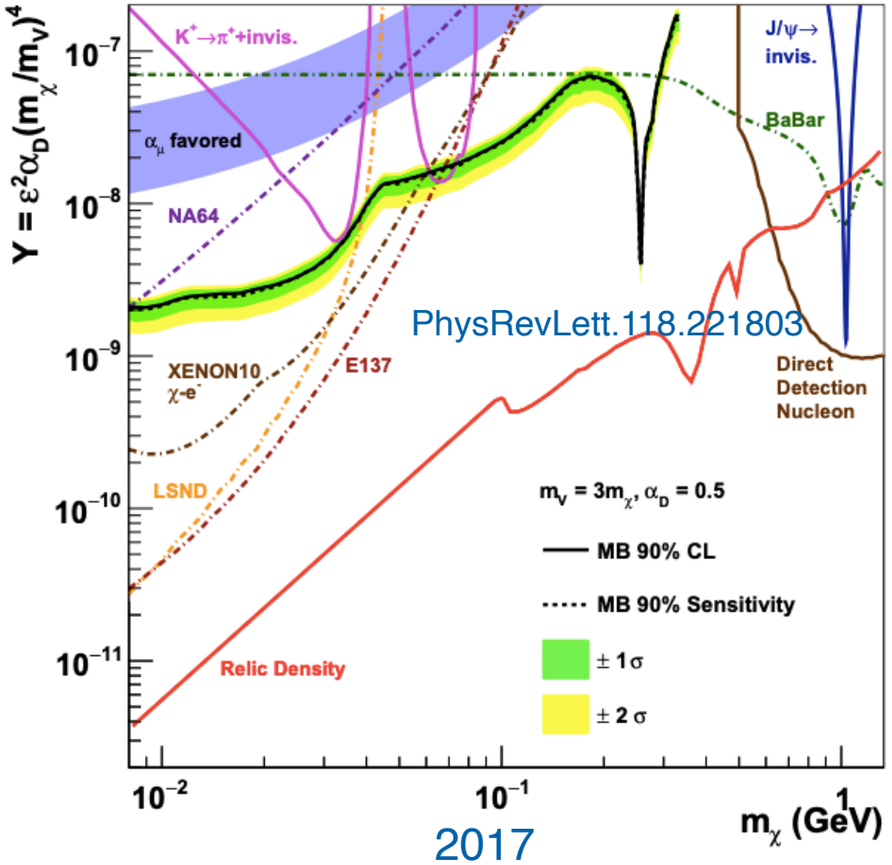


Wide class of models that can explain the cosmological dark matter abundance accessible to accelerator-based searches

MiniBooNE-DM accelerator-based LDM searches

MiniBooNE-DM collaboration ran off-target, impinging protons from the Booster Neutrino Beamline on the hadron absorber at the end of the tunnel, pioneering these types of searches at Fermilab





PhysRevLett.118.221803

2017

MiniBooNE-DM accelerator-based LDM searches

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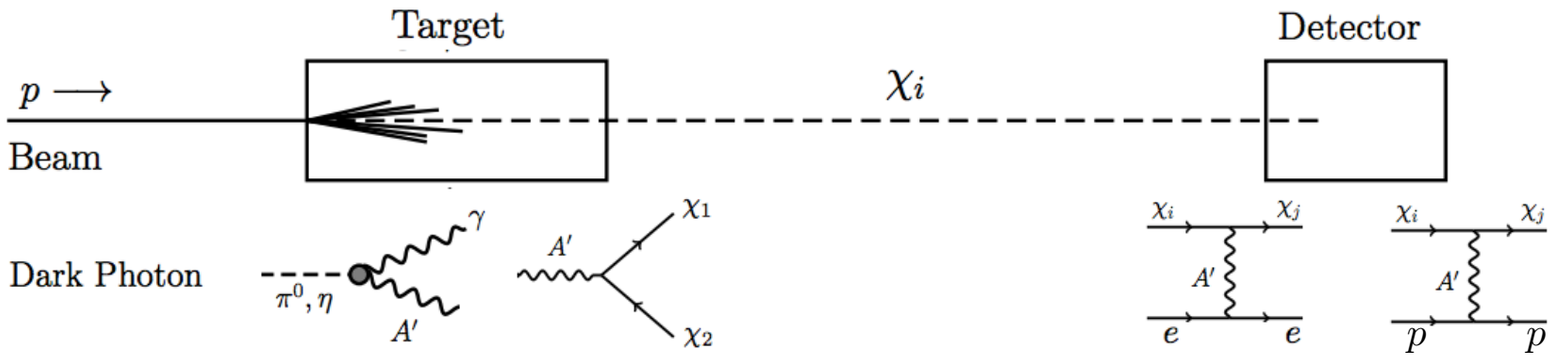

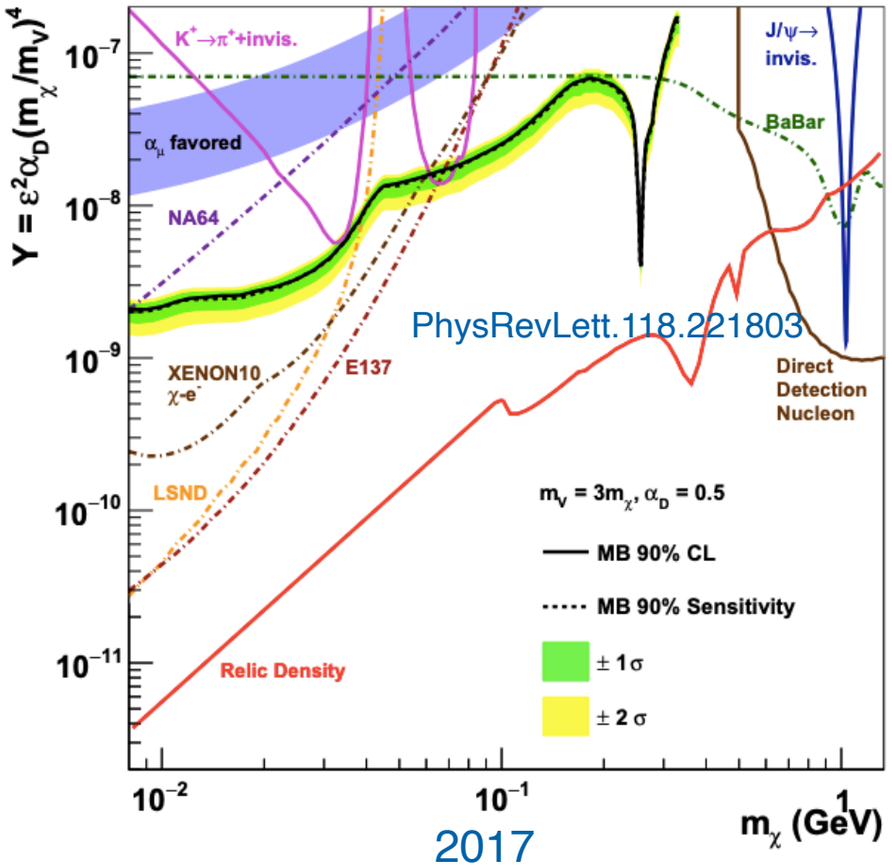

PhysRevLett.118.221803

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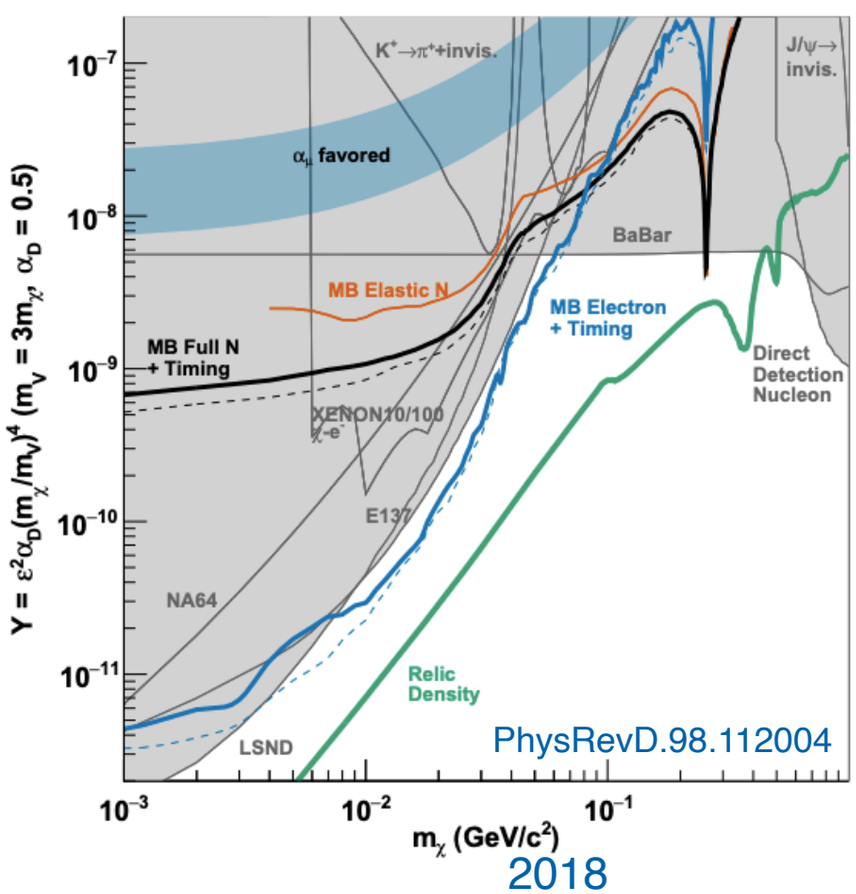

PhysRevD.98.112004

2018

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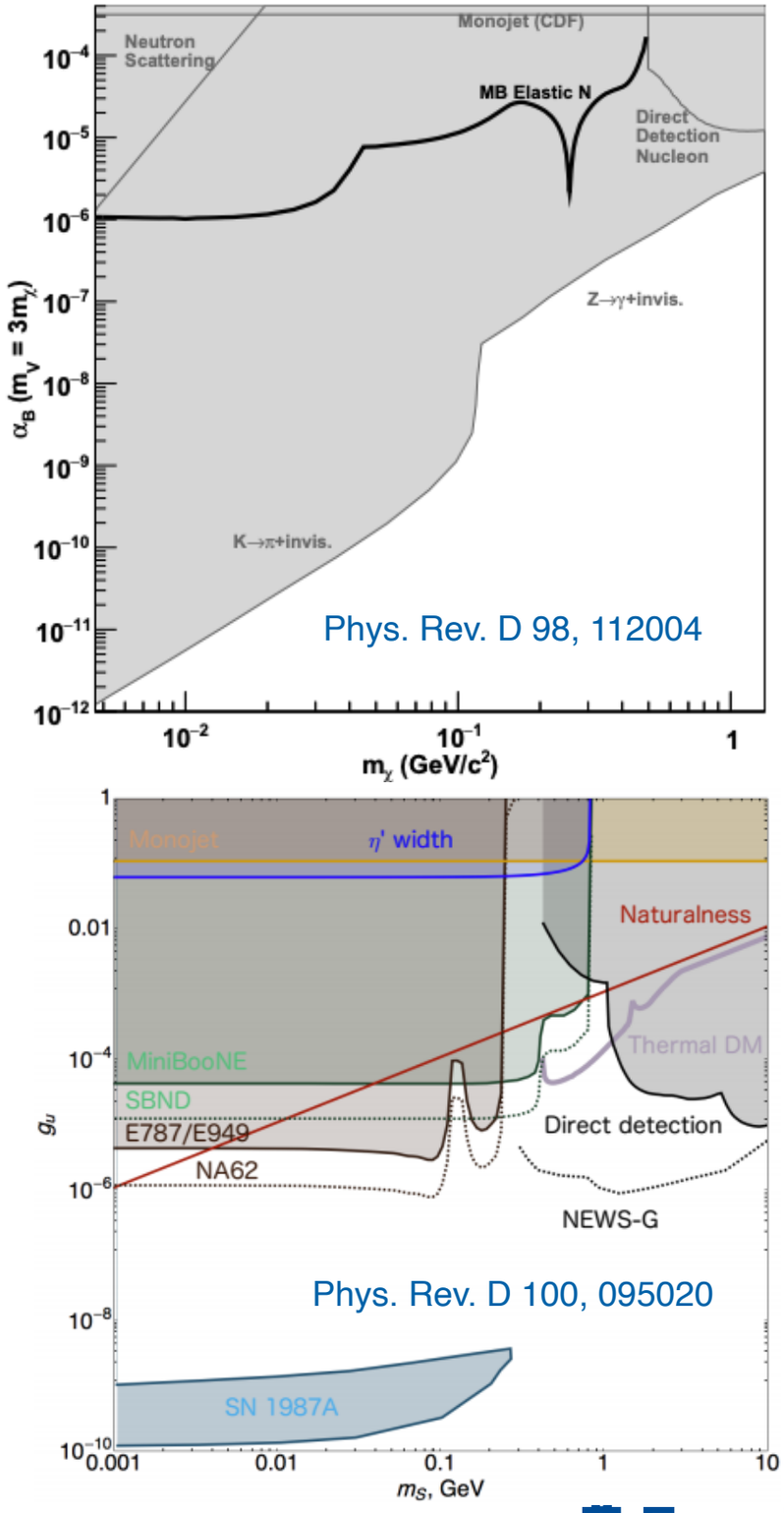
Beyond the Benchmark Vector Portal Model

- While benchmark model provides robust experimental search targets, a wide range of dark sector models can be probed at accelerator-based fixed target experiments
  - Searches based on proton and electron beams can have unique sensitivity to these

- For example, MiniBooNE-DM also set limits on leptophobic dark matter

- Calculations also indicate sensitivity to hadrophilic dark matter on the BNB



New HEP Tools: Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

- Studied by Freedman in 1974
- First detected by COHERENT collaboration in 2017 with CsI[Na] detector and then subsequently in 2020 with a 24 kg liquid argon (LAr) scintillation-only detector
- Neutrino interacts coherently with nucleons in target nucleus, giving a strong enhancement to the cross section at low energies
- However, must be able to detect low energy nuclear recoils
  - O(10 keV) for O(10 MeV) neutrino

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

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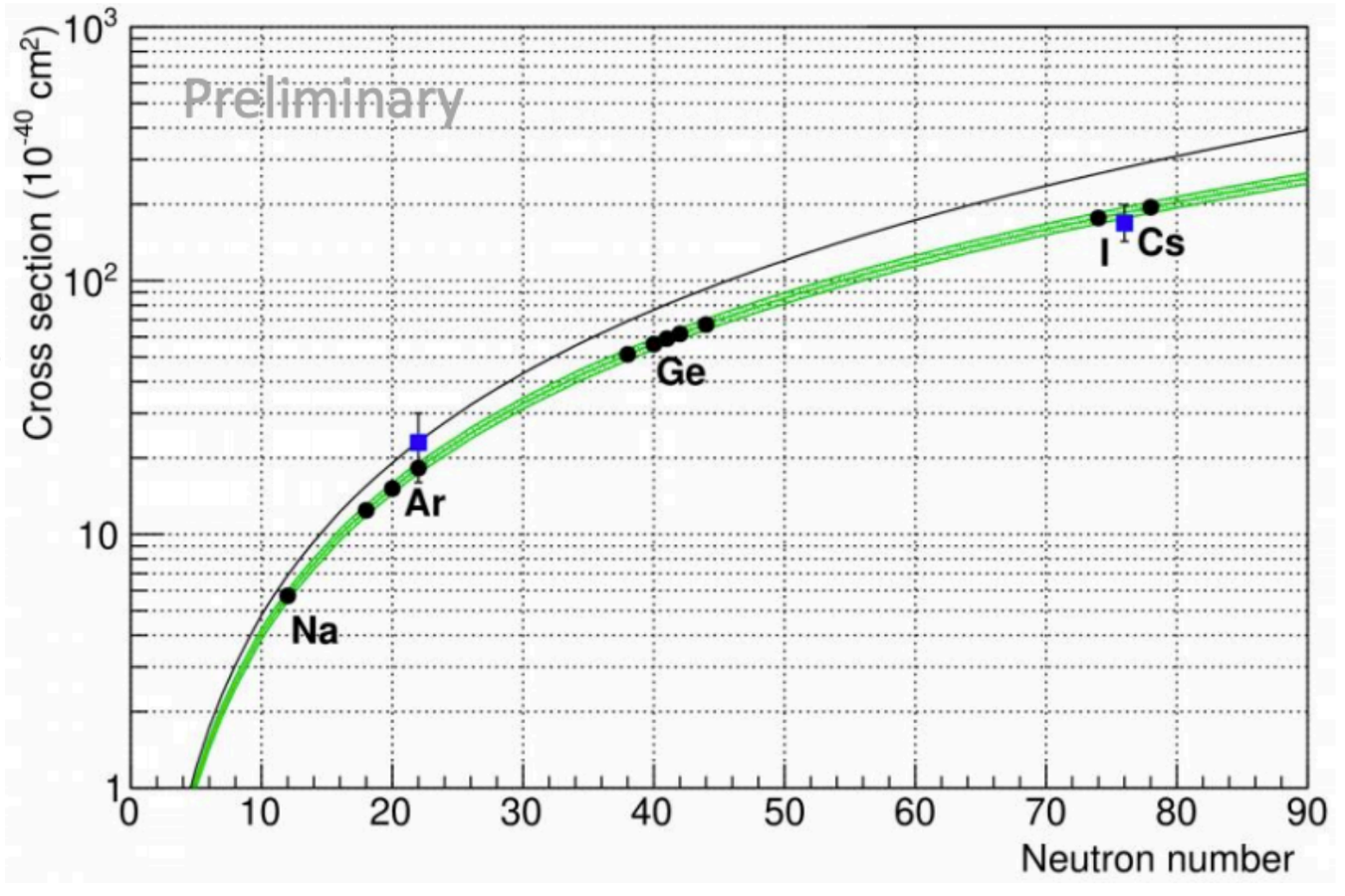
(Received 15 October 1973; revised manuscript received 19 November 1973)

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



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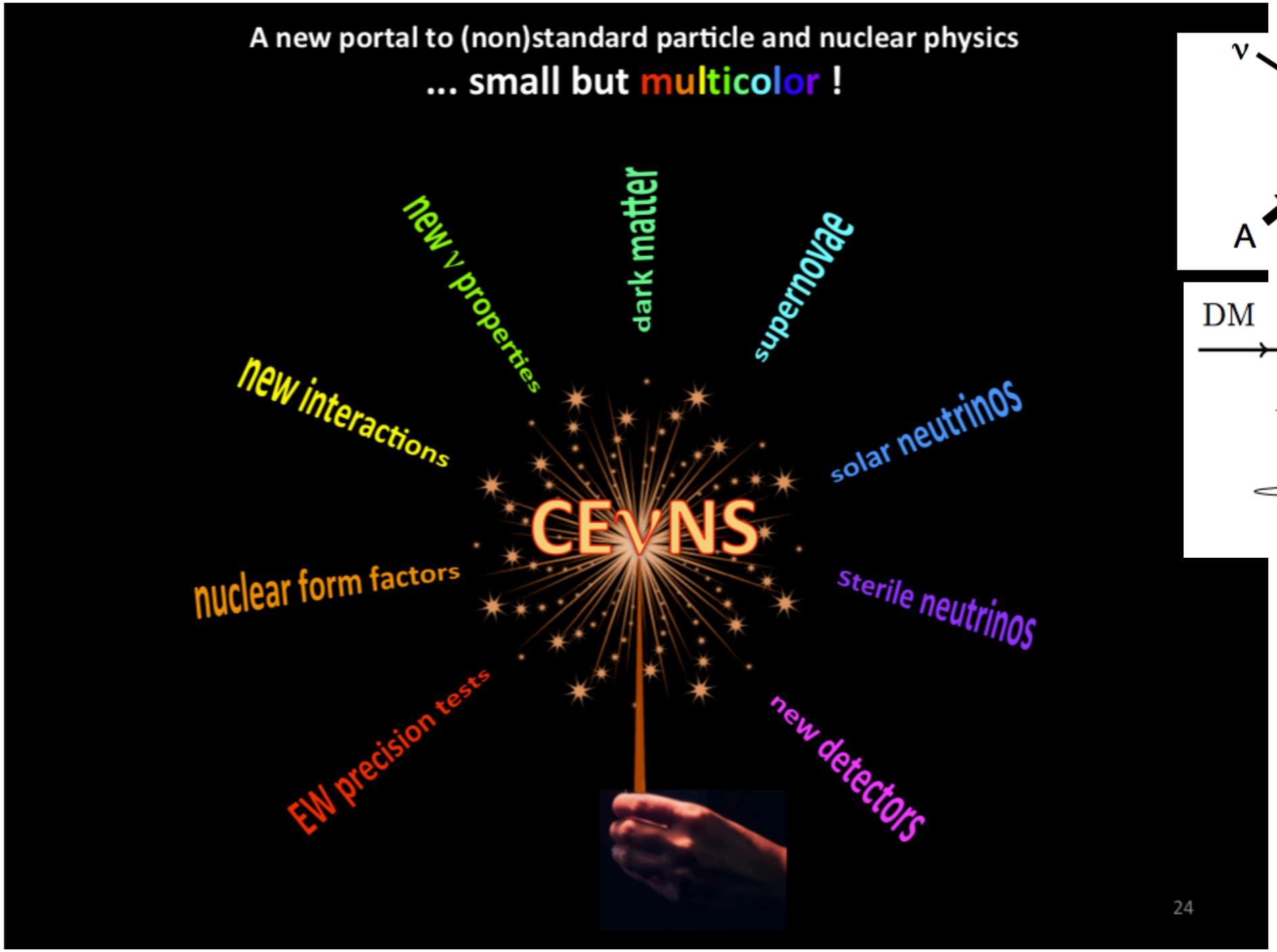
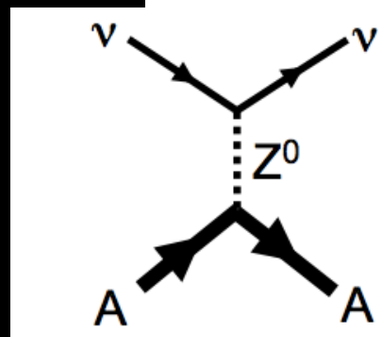
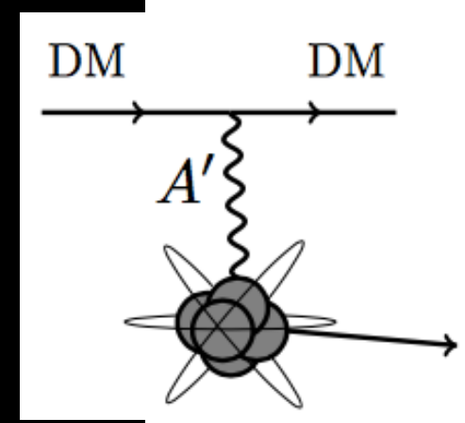




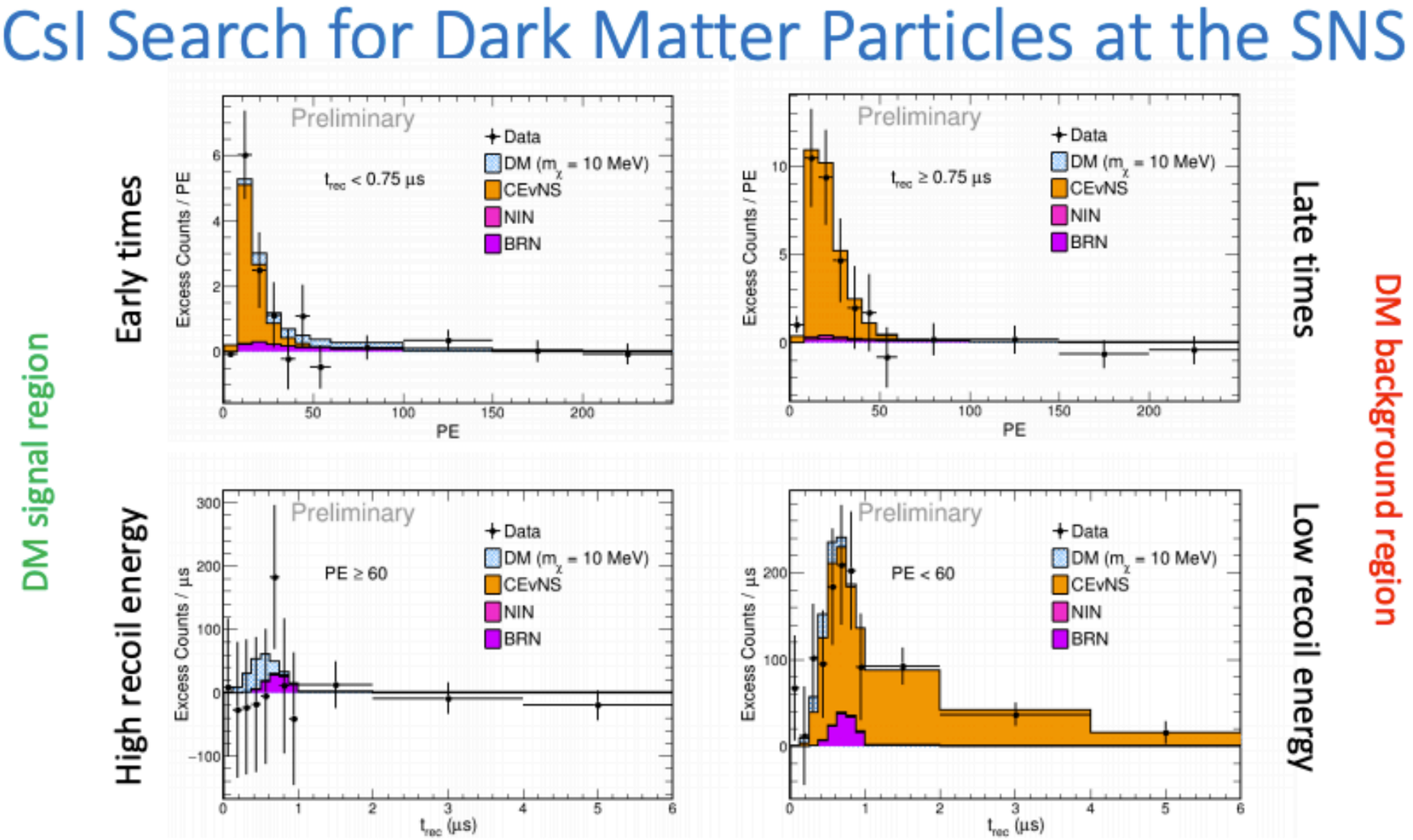


Eligio Lisi, NuINT 2018

Dark matter searches can target (essentially) the same experimental signature

COHERENT Dark Sector Search at the SNS at ORNL

- SNS provides 1.4 MW, 1 GeV proton beam at 60 Hz with 350 ns FWHM
- Recent search for an excess of events above CEvNS signal with 14 kg CsI[NA] detector based on ~4e23 POT



D. Pershey, Magnificent CEvNS 2020

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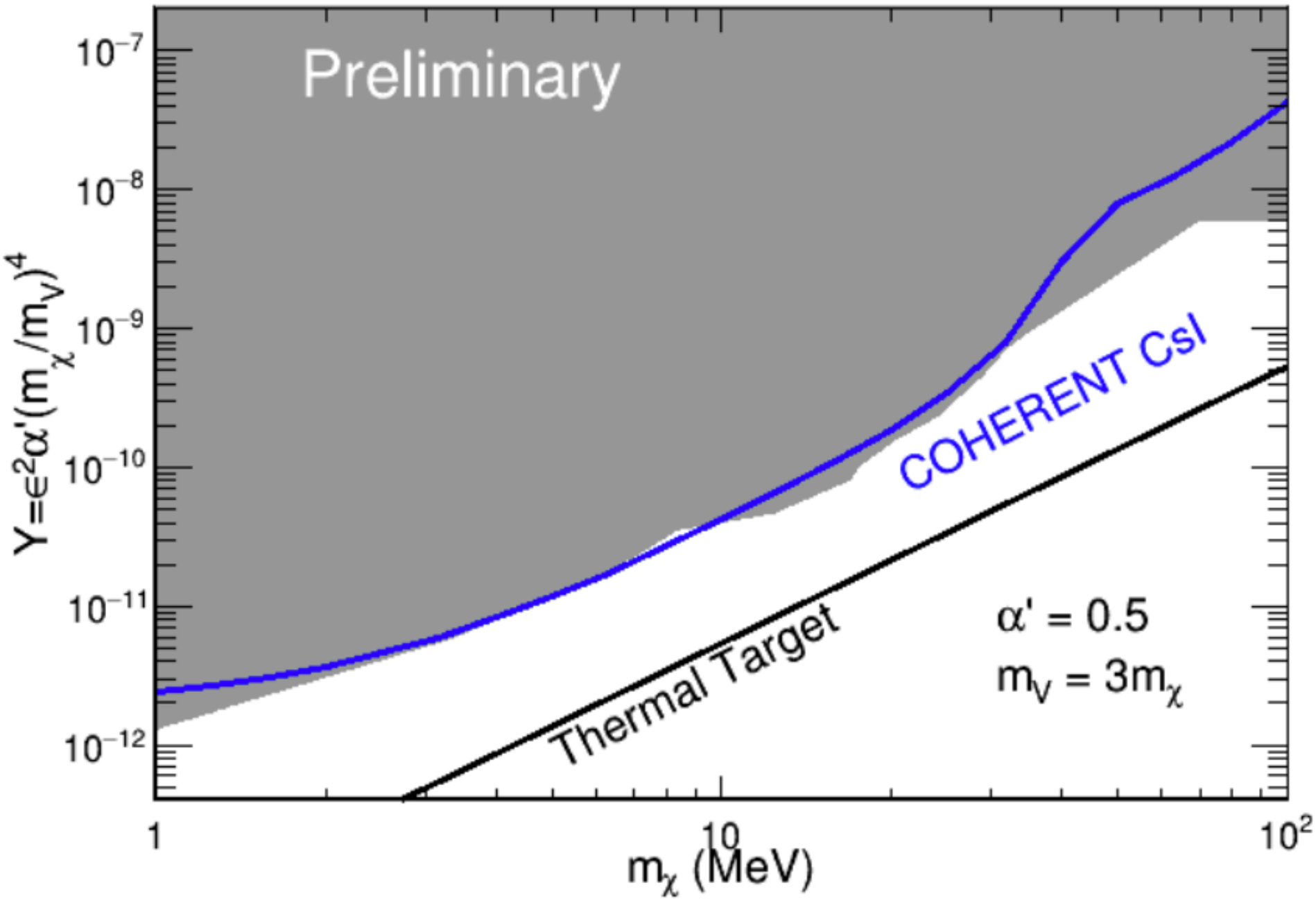
COHERENT Dark Sector Limits with CsI[Na]



D. Pershey, Magnificent CEvNS 2020

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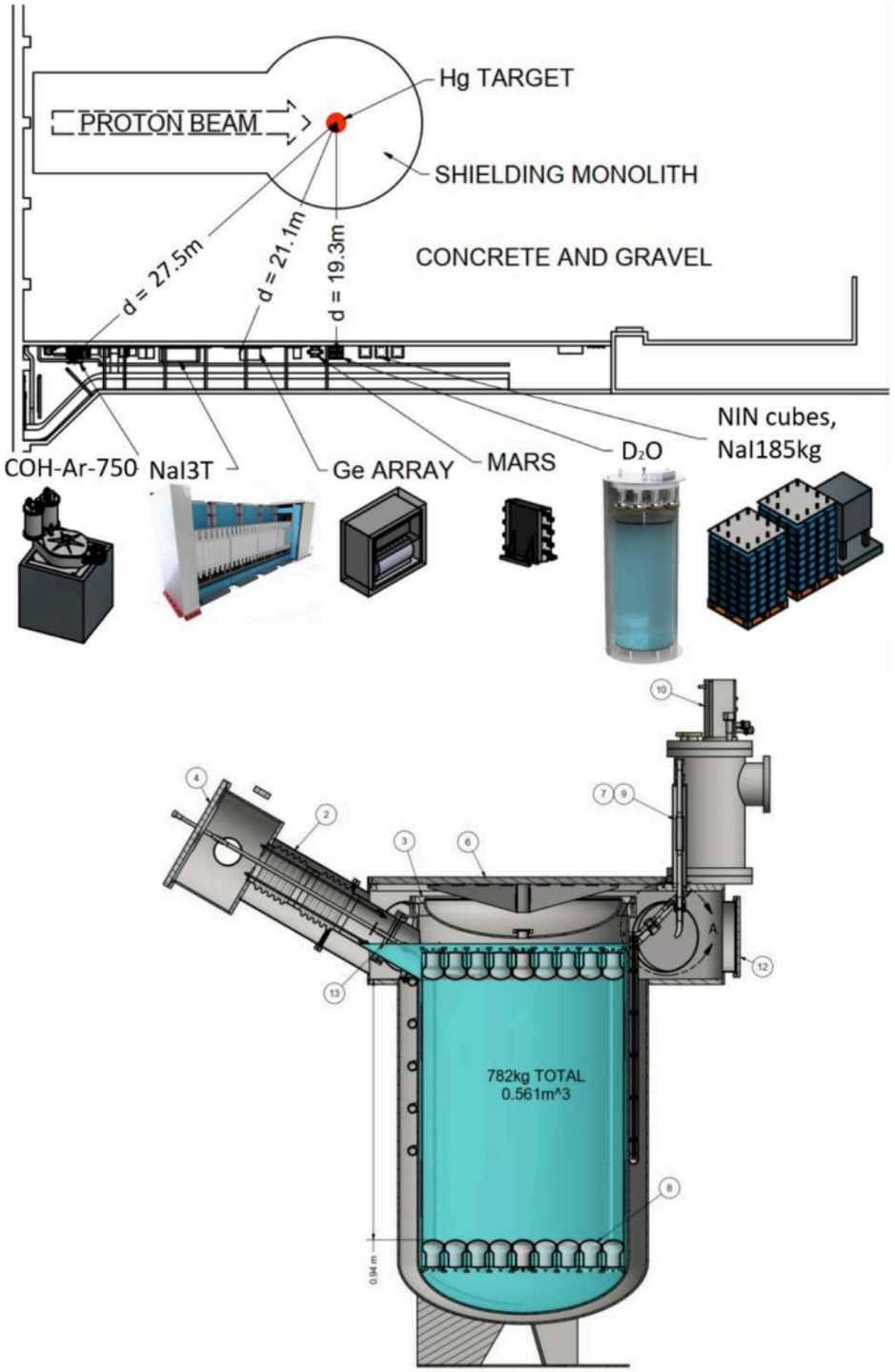
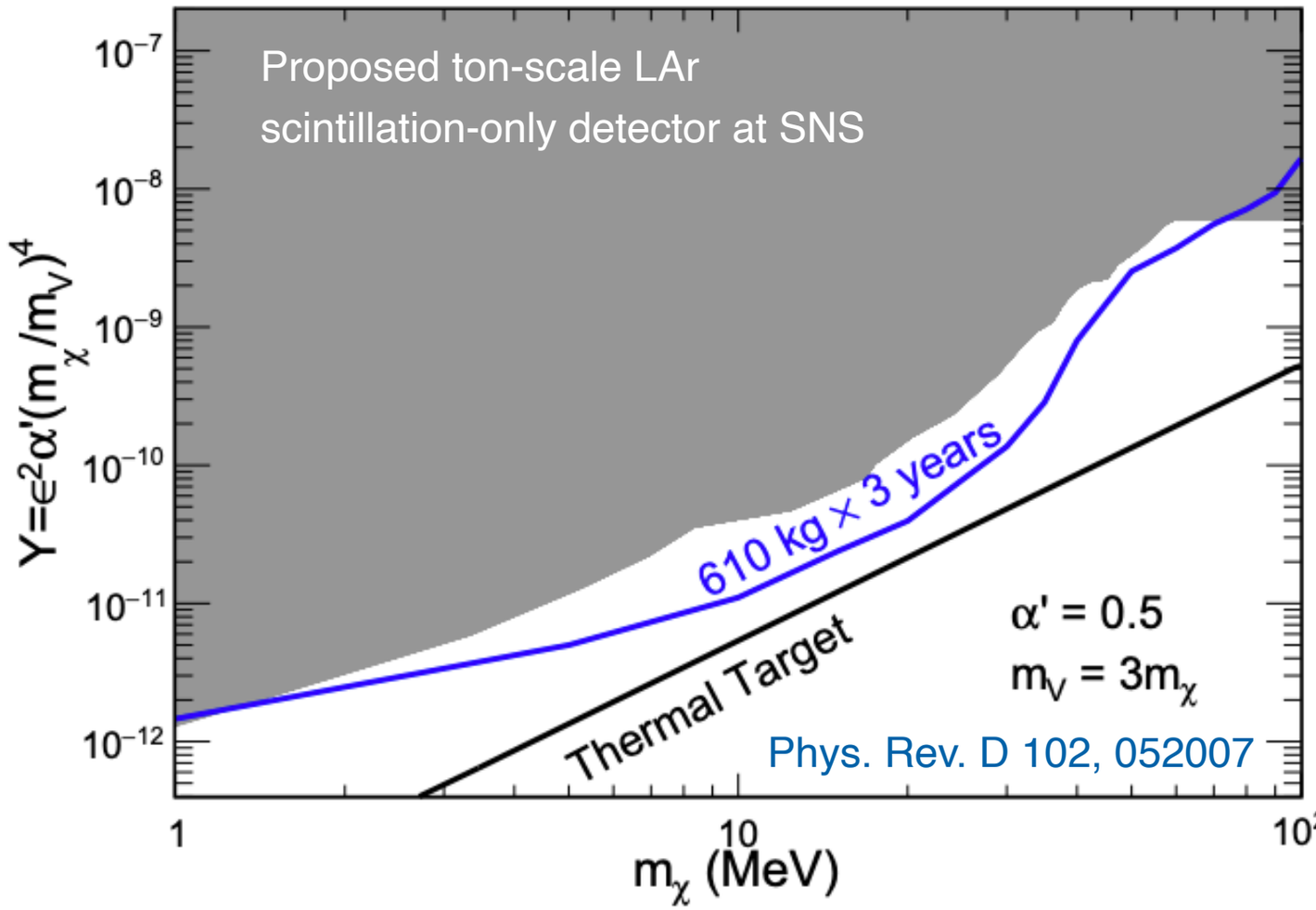
COHERENT Dark Sector Projections with LAr

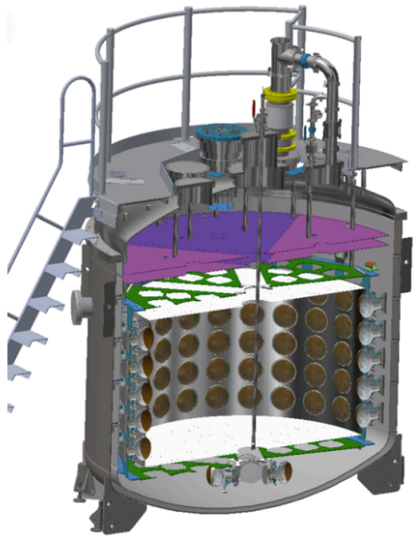


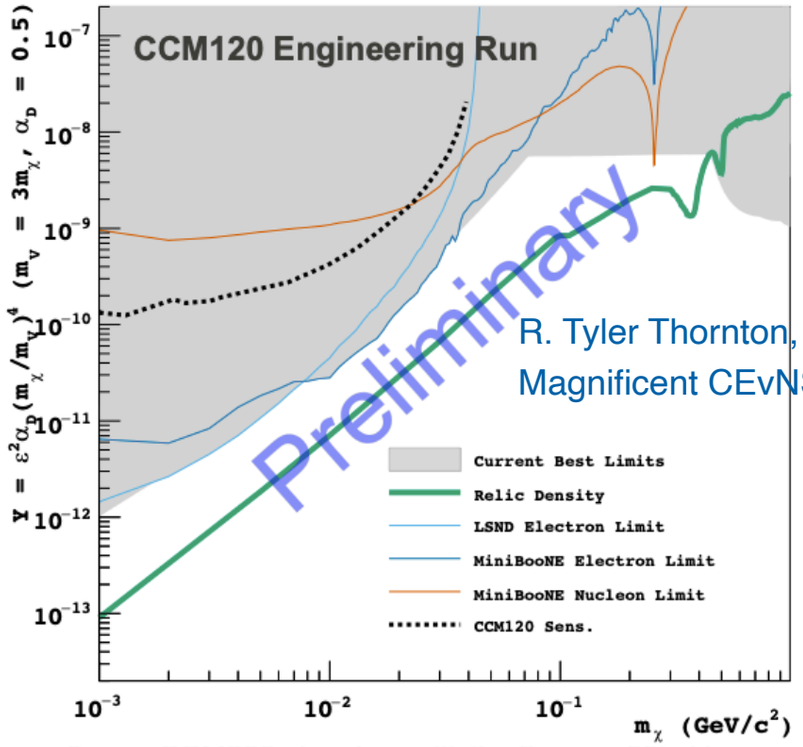


Even located on axis with 50 ton-years of exposure, search is still statistically limited

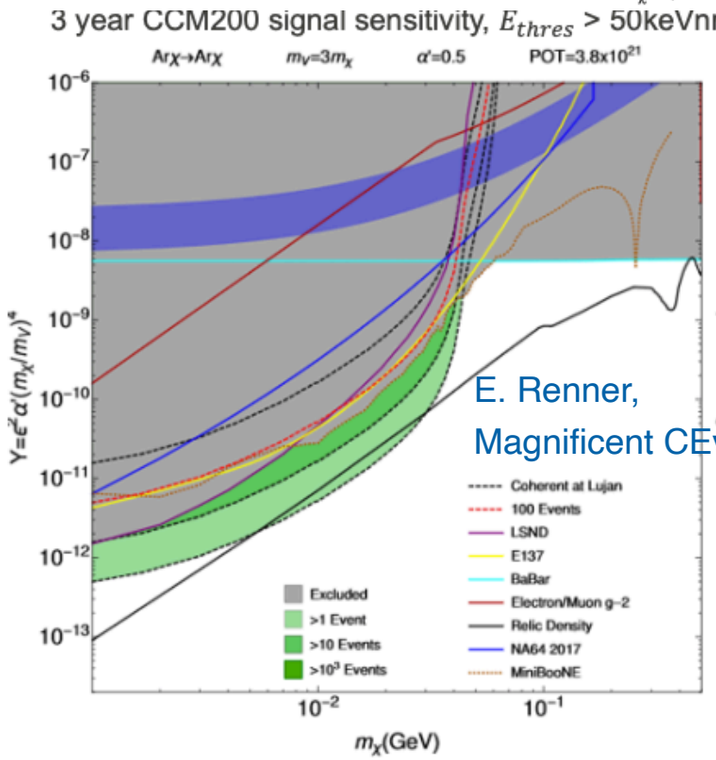
Coherent CAPTAIN-Mills (CCM) Experiment

- Operating at Lujan Center at LANL
  - 80 kW, 20 Hz, 270 ns beam width
- 10-ton single-phase scintillation-only LAr detector
- Initial engineering run of 1.5 months already shows the potential for scaling up this type of detector for dark sector searches
- Experiments such as CCM are key for testing many of the experimental techniques to successfully reach the physics goals of large-scale scintillation-only LAr detector





R. Tyler Thornton, Magnificent CEvNS 2020



E. Renner, Magnificent CEvNS 2020

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Fixed-Target Searches for New Physics with O(1 GeV) Proton Beams at Fermi National Accelerator Laboratory

M. Toups,[1,*] R.G. Van de Water,[2,*] Brian Batell,[3] S.J. Brice,[1] Patrick deNiverville,[2] Jeff Eldred,[1] Roni Harnik,[1] Kevin J. Kelly,[1] Tom Kobilarcik,[1] Gordan Krnjaic,[1] B. R. Littlejohn,[4] Bill Louis,[2] Pedro A. N. Machado,[1] Z. Pavlovic,[1] Bill Pellico,[1] Michael Shaevitz,[5] P. Snopok,[4] Rex Tayloe,[6] R. T. Thornton,[2] Jacob Zettlemoyer,[1] and Bob Zwaska[1]

[1] *Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*
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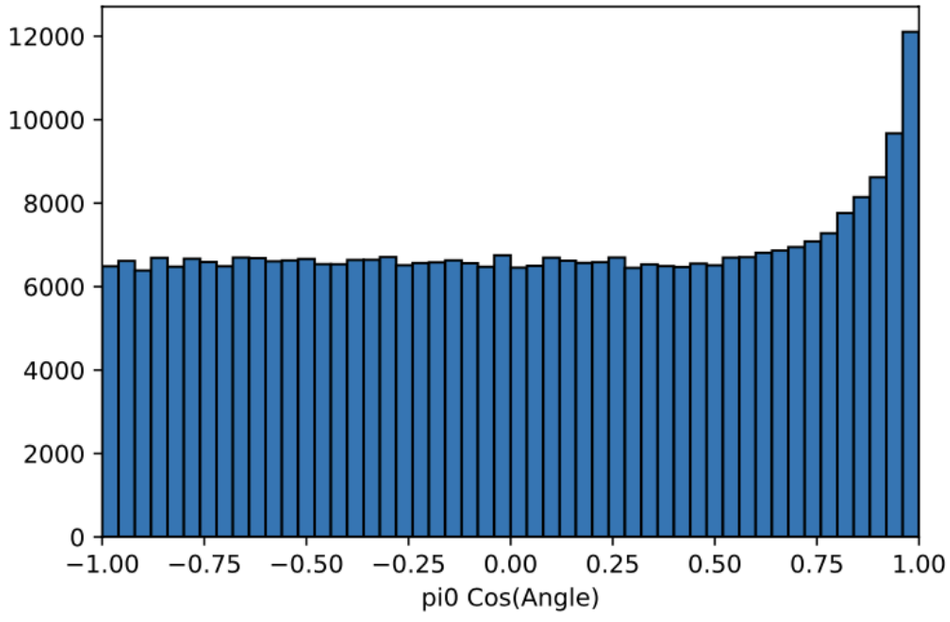
[6] *Indiana University, Bloomington, IN 47405, USA*

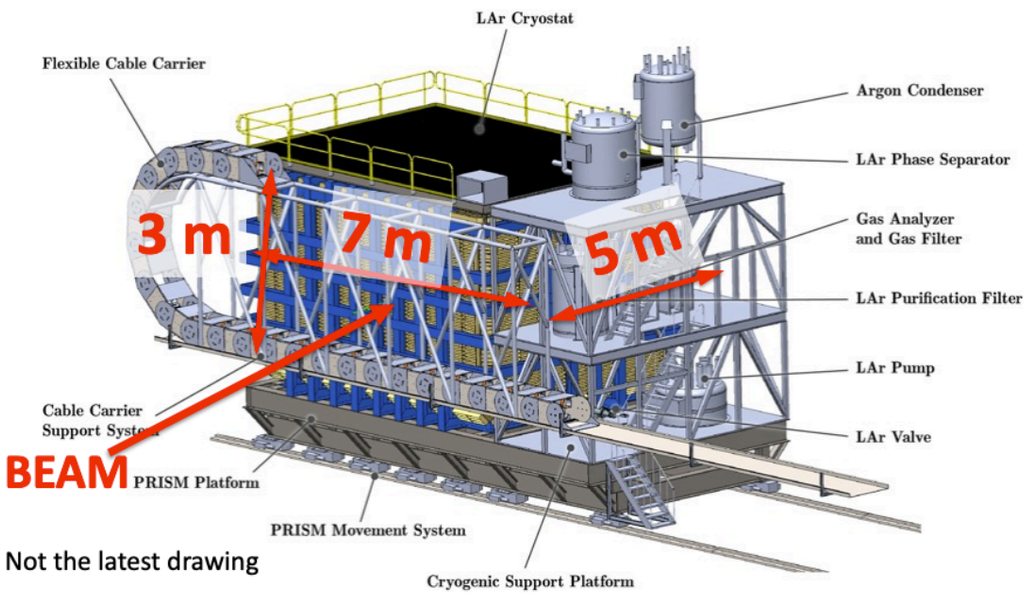
Advantages of a PIP-II driven Proton Beam Dump Facility at FNAL

- Can be designed from the ground-up for HEP
  - Suppress rather than maximize neutron production via shielding and choice of low-Z target to reduce beam-related backgrounds
    - Low-Z target also increases production of pions per incoming proton and thus DM signal



- Experimental hall can be built to allow for large mass detectors at flexible locations to optimize sensitivity to DM
  - Studies indicate importance of larger mass detectors, utilizing the angular dependence of the dark matter flux, and reduced flux uncertainty (which can be addressed with relative measurements at different angles using identical or moveable detectors) for these DM searches

P. deNiverville



M. Weber, D. Dwyer DUNE CDR review, 7-8-9 July 2020

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Accumulator Ring (Pulsed Proton Beam) is Essential

- Steady-state background reduction (and characterization) via accelerator timing is also essential for these DM (and CEvNS-based) searches in large detectors near the surface
- Booster Accumulator Ring (BAR) will compress proton pulses (300-400 ns pulse width goal) and reduce the duty factor to the level of 10^{-5}
  - Initial operation at 100 kW, 100 Hz, 0.8 GeV protons
  - Modest upgrades to PIP-II and the BAR would allow for 1 GeV proton energy and increases the available beam power to 240 kW while increasing the power to LBNF
- Ultimately, if an accumulator ring is constructed as part of the Booster replacement (e.g. as an injector to an RCS), >2.4 MW could be delivered to LBNF and the available beam power for an O(1 GeV) fixed target program could be increased to the MW scale

Technology	BAR	BAR Upgrade	RCS Accumulator Ring
Intensity	1e13 protons/spill	1.5e13 protons/spill	3.6e13 protons/spill
Repetition Rate	100 Hz	100 Hz	120 Hz
Proton Energy	0.8 GeV	1 GeV	2 GeV
Beam Power	130 kW	240 kW	1.4 MW
Pulse Width	300-400 ns	300-400 ns	300-400 ns
Timescale	2027	Late 2020's-early 2030's	in the 2030s

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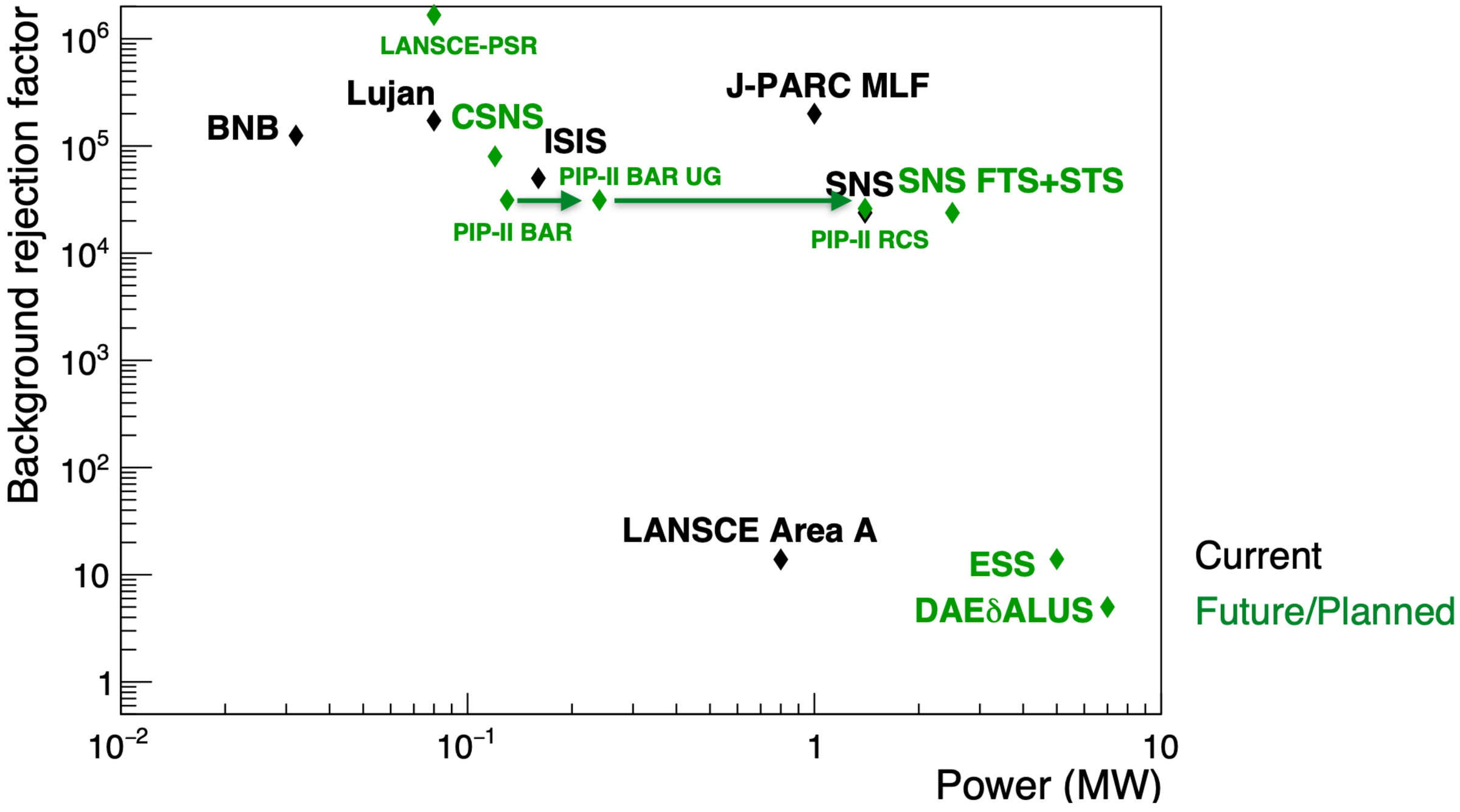
Evolution of Fermilab 1 GeV Proton Beam Dump Facility



Plot via K. Scholberg

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Fermilab Proton Beam Dump DM Event Sensitivities

- Sensitivities assume a 630 kW 1 GeV proton beam impinging on a low-Z target
- We consider a 100-ton LAr scintillation detector placed 18 m downstream from the target with a 50 keV recoil energy threshold and an efficiency of 70%
- Assuming a 5-year run with a 75% uptime, we compute event sensitivities for 4.6 x 10^{23} protons-on-target
- Not only probes benchmark scalar DM model, but also Majorana fermion, pseudo-Dirac fermion DM, etc.

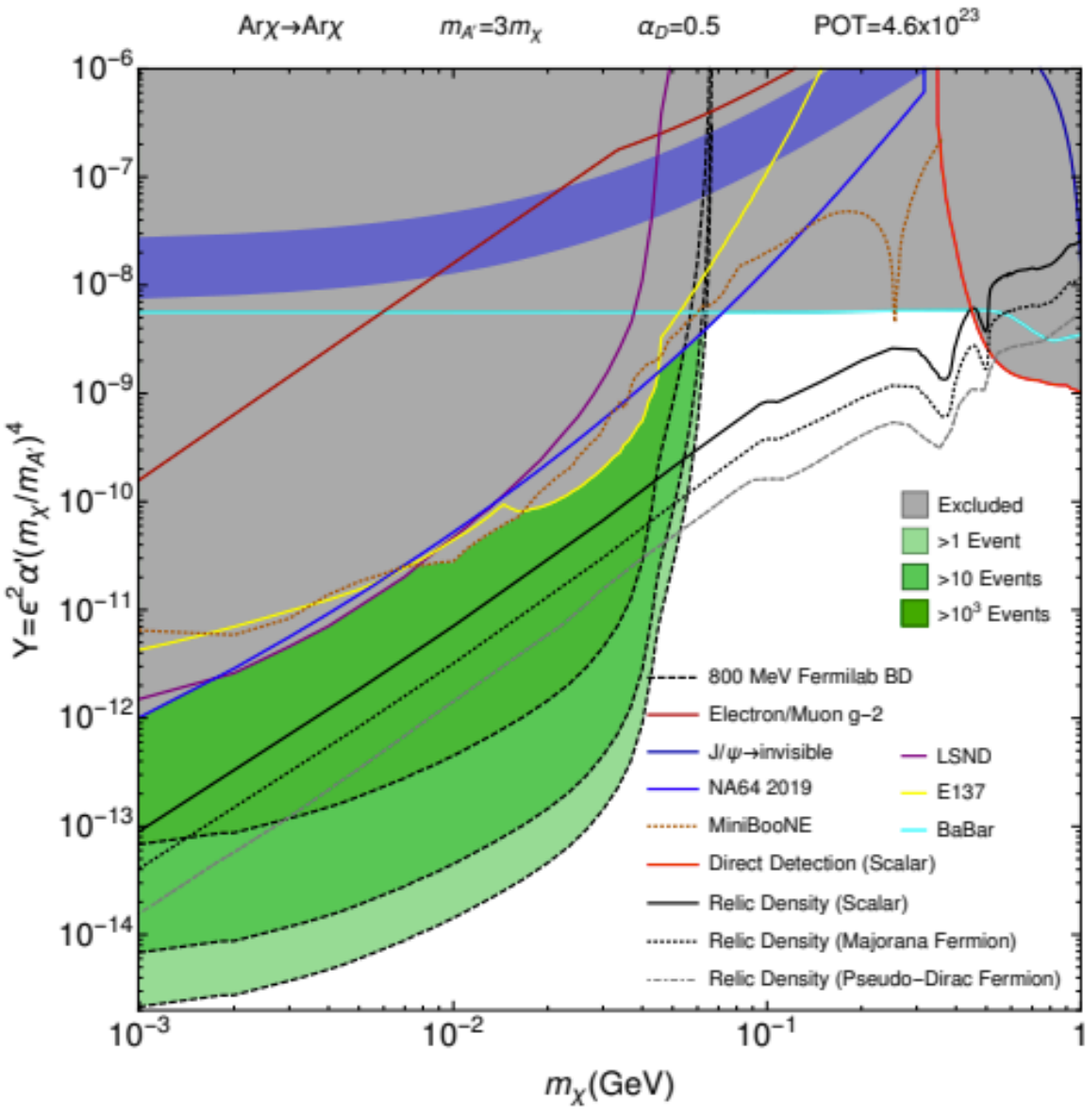
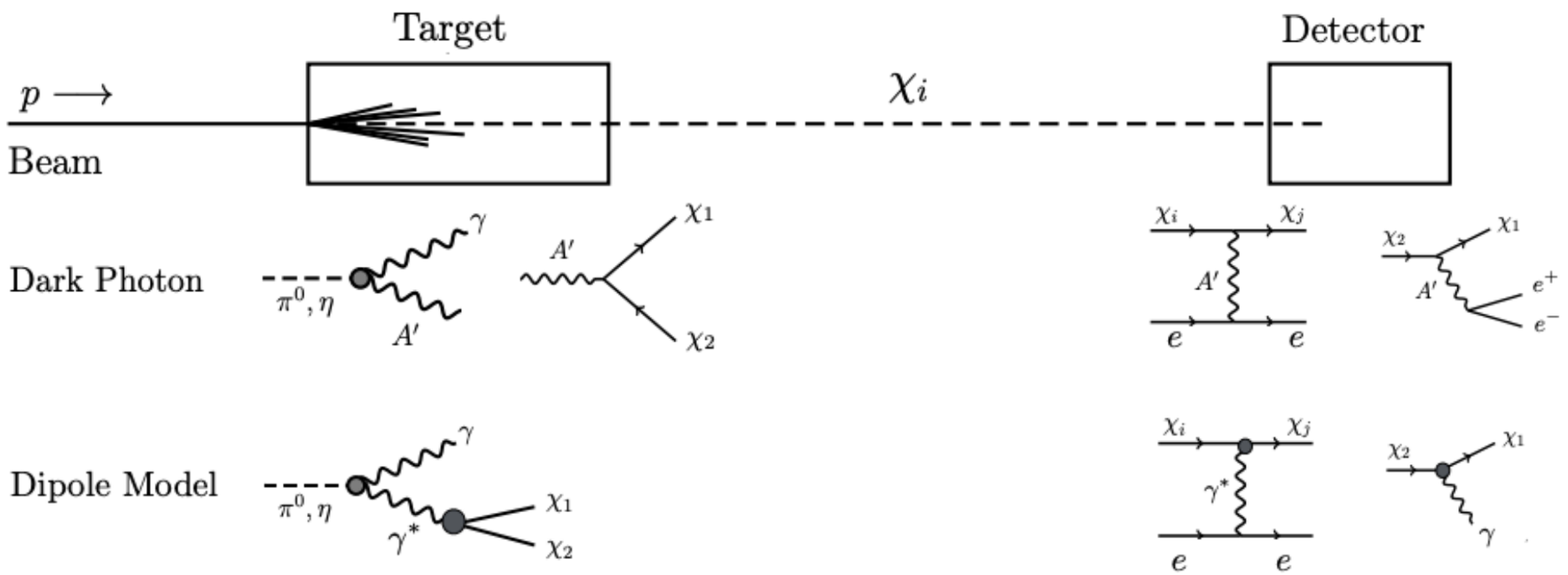


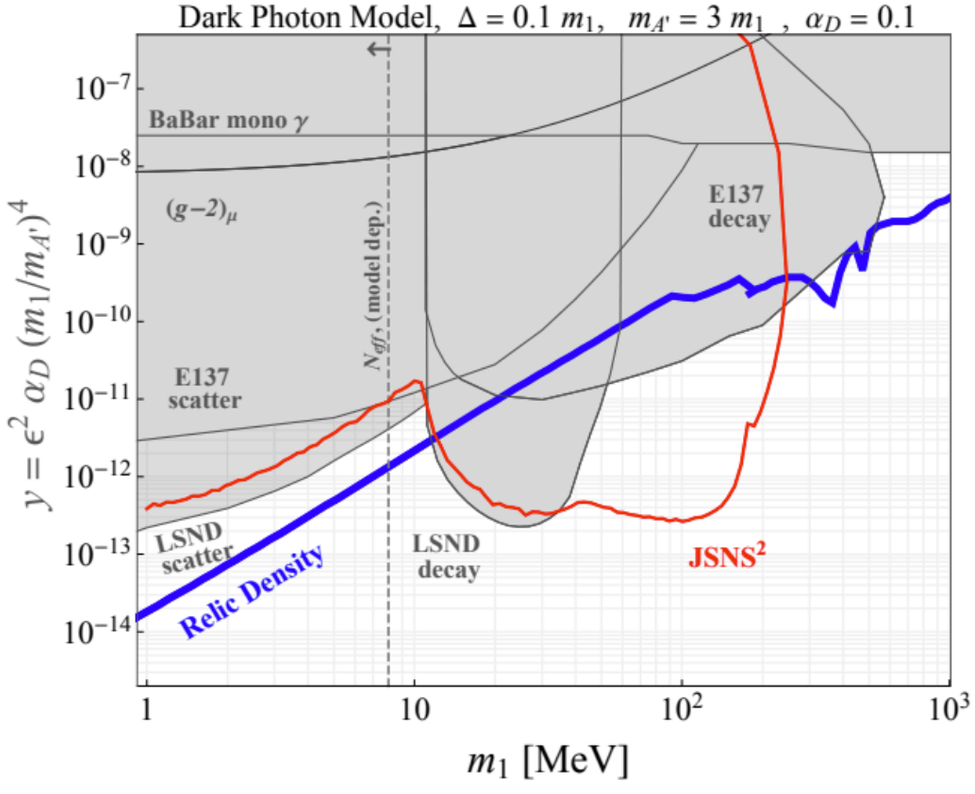
FIG. 1. Fermilab beam dump facility argon recoil event sensitivity curves for 4.6×10^{23} protons on target compared to thermal relic density targets and existing 90% exclusion limits as a function of the dimensionless scaling variable $Y = \epsilon^2\alpha(m_\chi/m_{A'})^4$, assuming $\alpha = 0.5$ and $m_A = 3m_\chi$.

Probing DM Particle Nature in Beam Dump Scattering Experiments



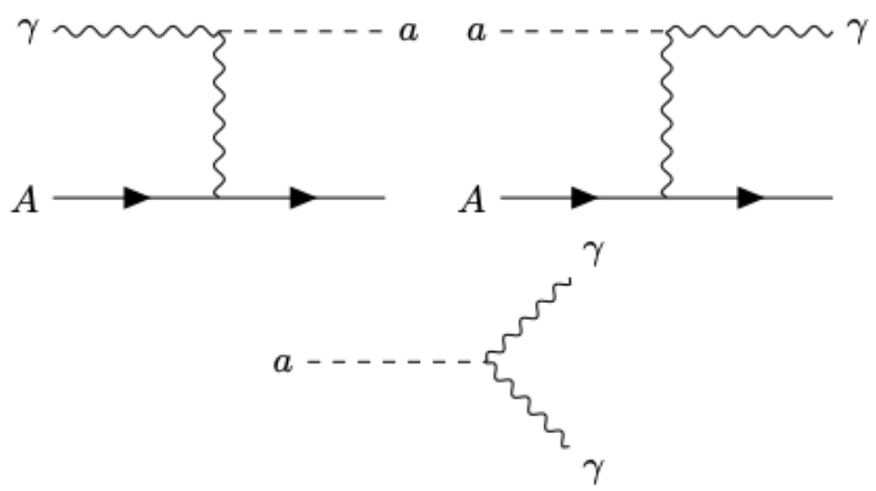
- Unique scattering signatures of some DM models can extend the sensitivity of beam dump searches quite significantly

- Studies performed for LSND and JSNS^2 illustrate the power of these searches
  - See, for example, Phys. Rev. D 98, 075020



Other Detectors, other models

- Focused on baseline large-scale LAr scintillation-only detector scenario for vector portal light dark matter search

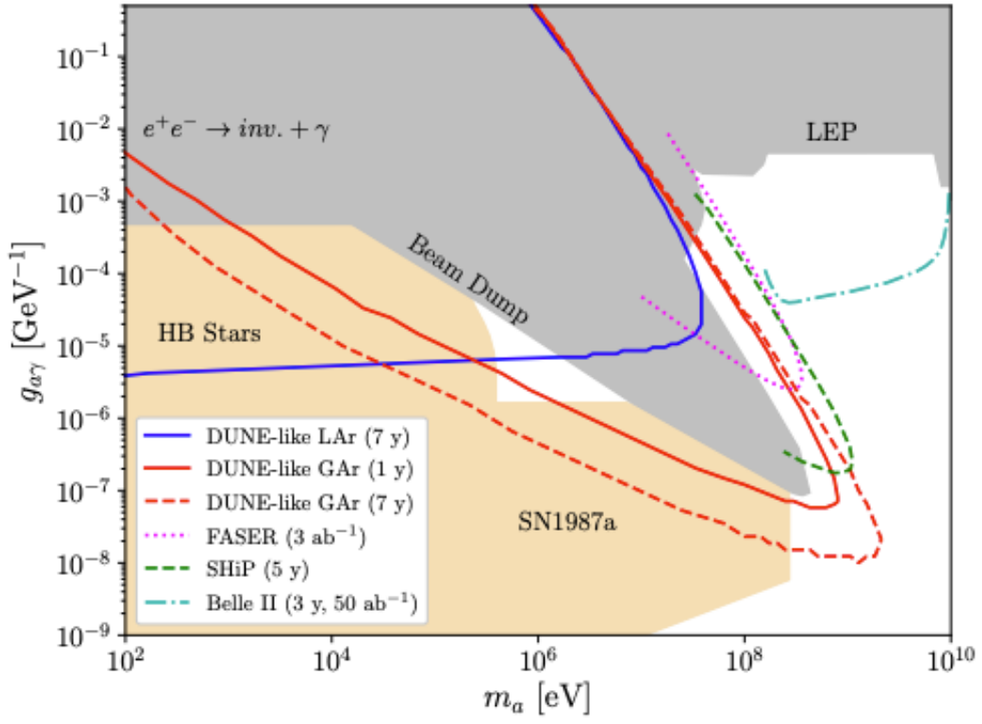


- Can also site additional detectors at such a facility to probe other dark sector models

- Hydrocarbon-based liquid scintillator detector
  - See previous slide

- Axion-like particles

- Etc.



Summary

- PIP-II LINAC at Fermilab capable of driving among the highest-power ~GeV proton beams in the world
  - Can simultaneously support multi-MW high energy beams for LBNF/DUNE (which uses only 1.1% of full beam capacity) and intense low (~GeV) energy protons beam
- Excellent opportunity for a proton beam dump based dark sector (and neutrino physics) program at Fermilab that more fully utilizes PIP-II infrastructure as well as the existing BNB complex, but requires a pulsed proton beam
- The Booster Accumulator Ring could enable this GeV-scale proton beam dump program to be realized within the decade along with a clear upgrade path
  - Key feature of such a beam dump facility at Fermilab is that it can be designed for and dedicated to HEP searches

Thank you