Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

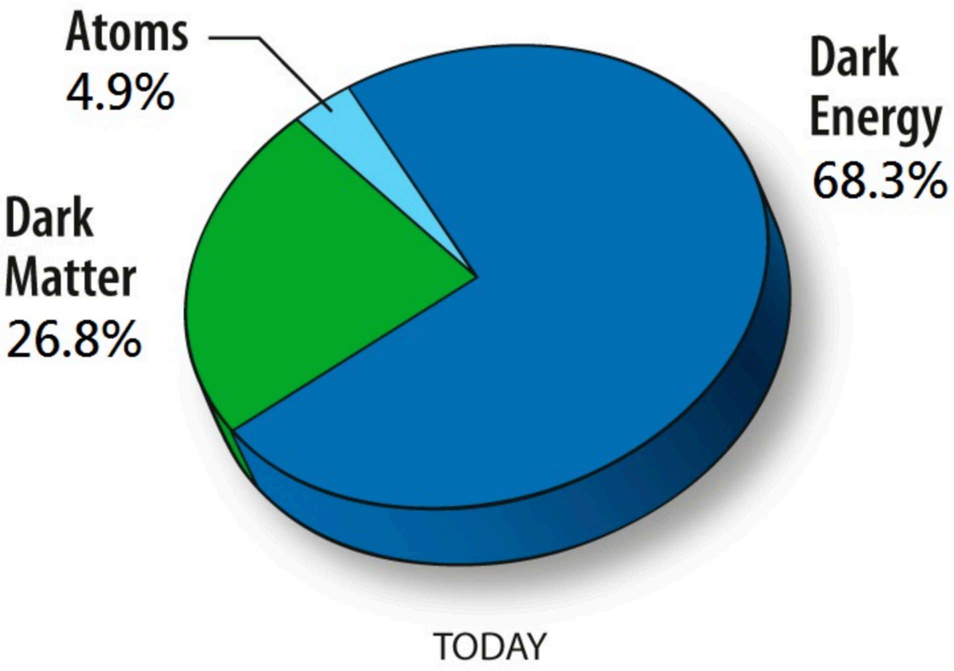
New Proton Beam Dump Experiments at Fermilab: PIP2-BD and SBN-BD

Matt Toups, Fermilab

Mitchell Conference on Collider, Dark Matter, and Neutrino Physics 2022

Wed 25 May 2022

Mass/Energy Content of the Universe



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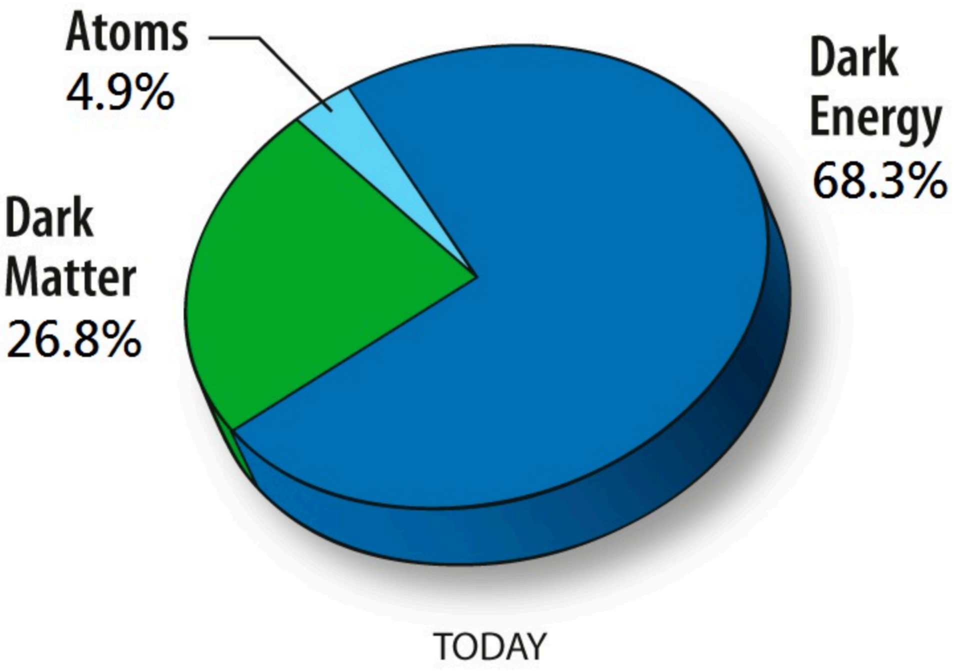
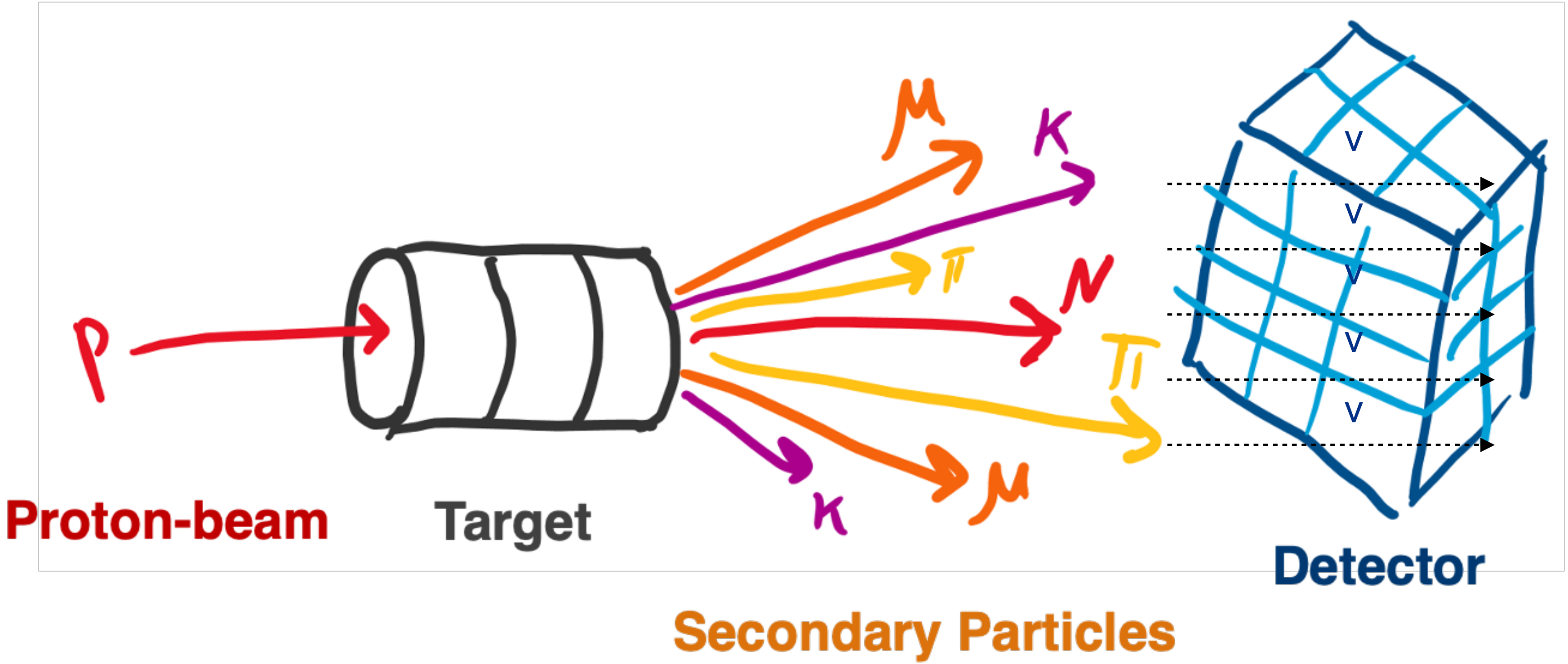
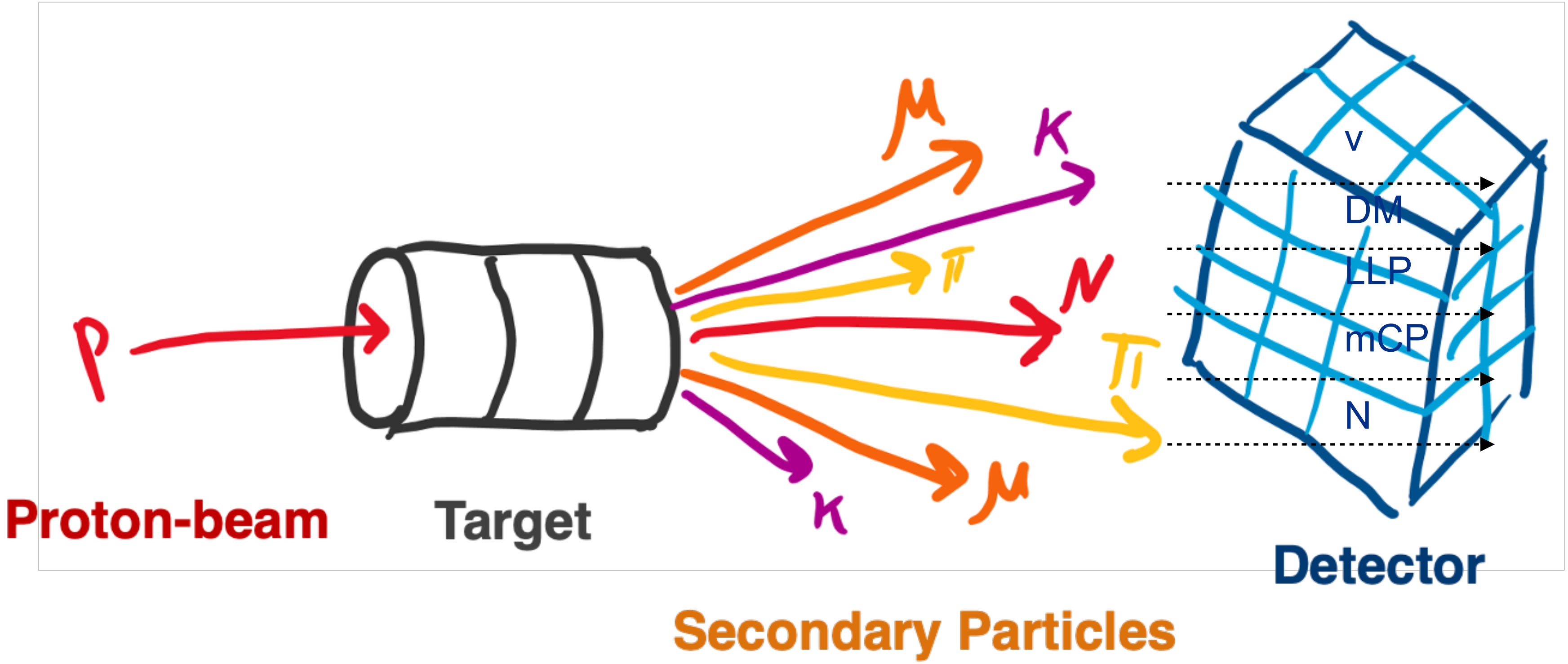


Where is the New Physics?

Accelerator-based neutrino beams



Accelerator-based new physics beams



Dark Sectors

- Focus on energy scales relevant for accelerator neutrino facilities (up to ~GeV)
- New physics should be neutral ("dark") under SM forces (EM, weak, strong)
- Connects to SM through finite list of "portal" operators, enabling systematic exploration

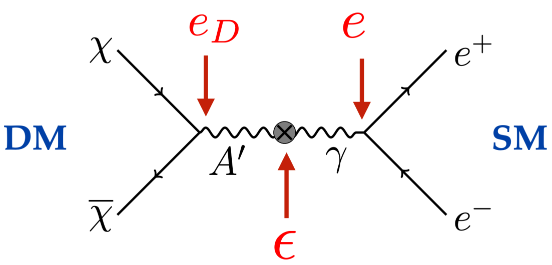
$B_{\mu\nu}$	x	$\epsilon/2\, F'^{\mu\nu}$	Vector portal
$\|h\|^2$	x	$\mu S + \lambda\|\phi\|^2$	Higgs portal
hL	x	$y_N N$	Neutrino portal

- Also of interest: axion portal, gauging SM global symmetries

Dark Sectors - Light Dark Matter

- Minimal models can explain the thermal relic abundance of dark matter and predict sub-GeV dark matter that can be produced and detected at accelerator-based neutrino facilities

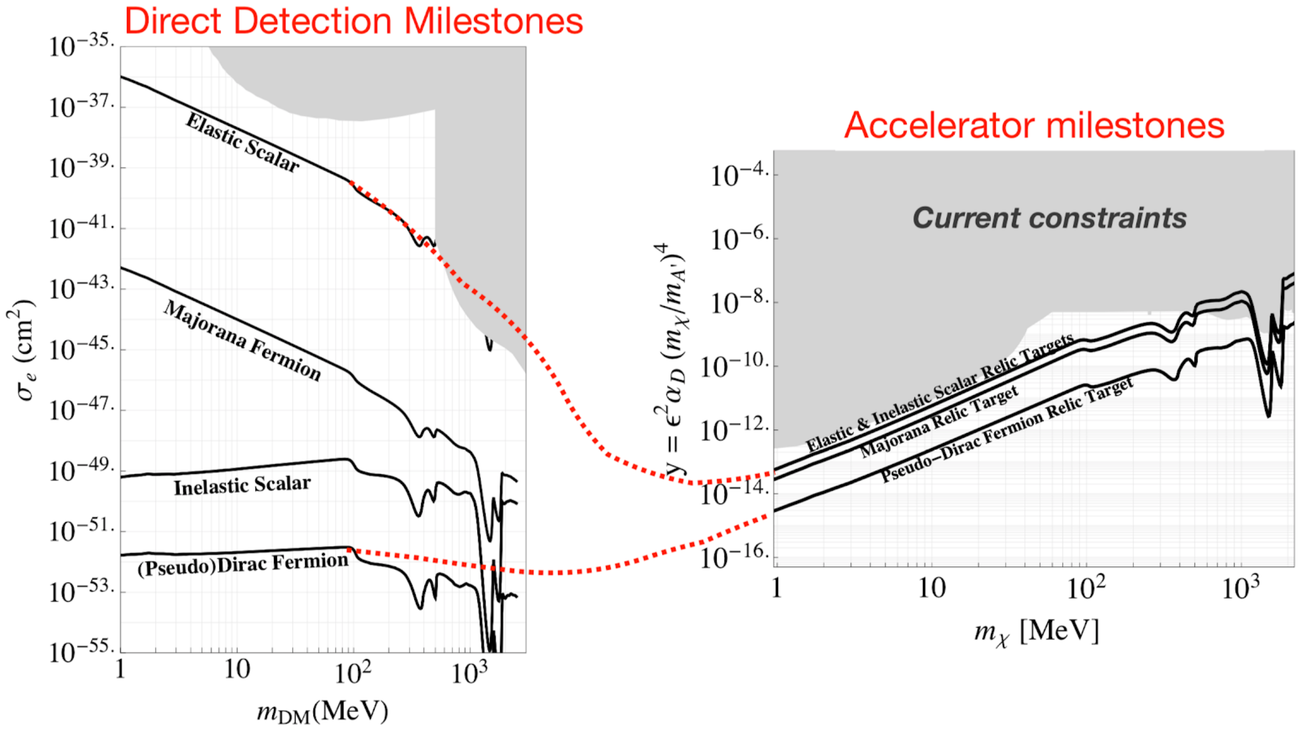
- Representative model: vector portal kinetic mixing with $m_{A'} > m_\chi$



$$\sigma v \propto \epsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} \equiv \frac{y}{m_\chi^2}$$

- Minimum SM coupling ϵ required for thermal freeze out

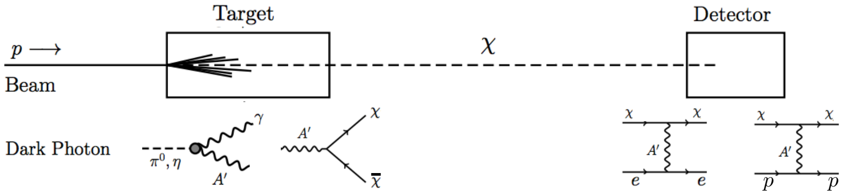
Dark Sectors - Light Dark Matter

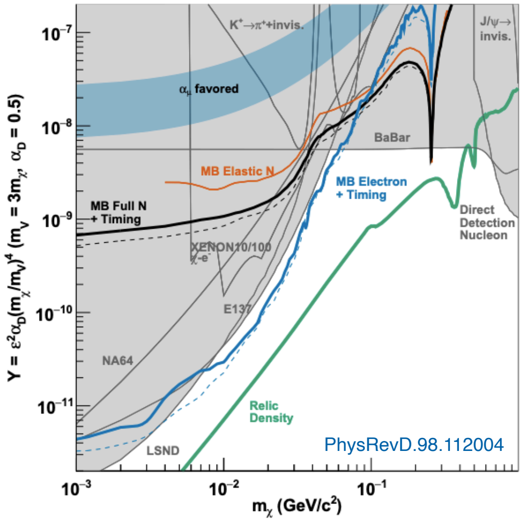


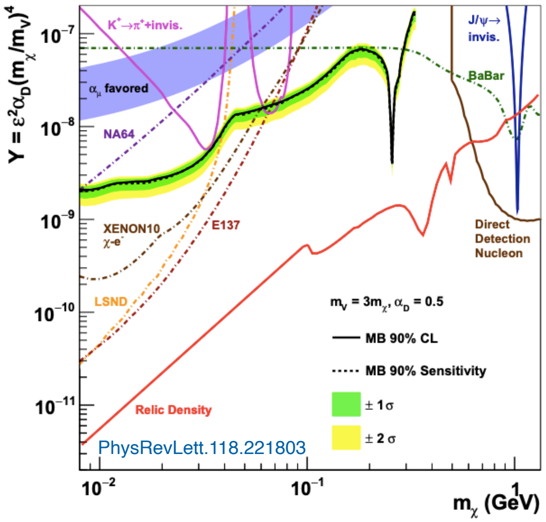
Wide class of models that can explain the cosmological dark matter abundance accessible to accelerator-based searches

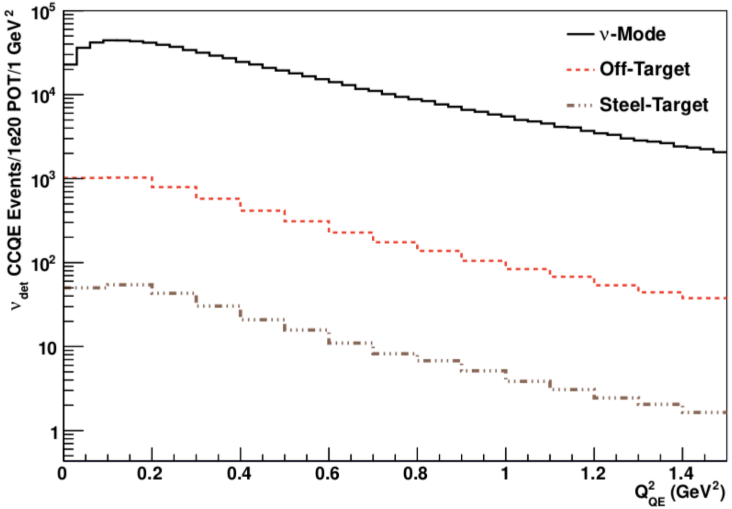
Dark Sector Searches on the Booster Neutrino Beamline at Fermilab

MiniBooNE-DM pioneered accelerator-produced dark matter rescattering searches for benchmark models such as vector portal dark matter by running off target in beam dump mode

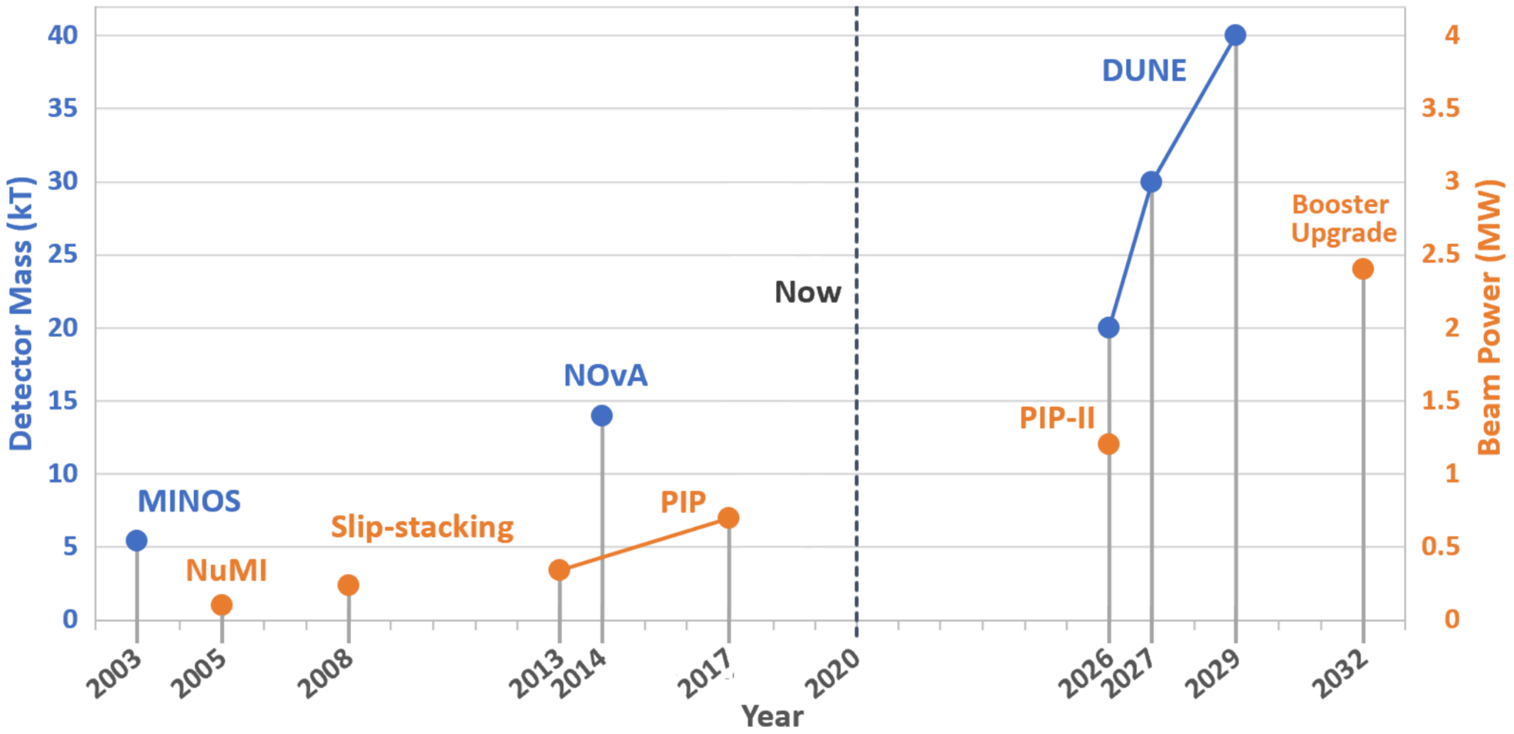








Fermilab Long-Baseline Neutrino Program



JINST **14** P07021 (2019)

PIP-II Upgrade of Fermilab Accelerator Complex

PIP-II Upgrade of Fermilab Accelerator Complex

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PIP-II Schedule

Mar 2018
Approve Alternative Selection (CD-1)

Dec 2020
Approve Scope, Cost, Schedule (CD-2)

Jan 2027
Shutdown Complex Operations For Booster Connection

Mar 2021
Approve Long-Lead Procurements (CD-3a)

Sep 2024
Linac Tunnel Occupancy

Jan 2027
SRF Linac Comm. Begins

2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028

Jul 2020
Cryoplant Bldg. Construction Approved

Apr 2022
Approve Technical Construction (CD-3 review) ✅

Dec 2028
Project Completion
Start of Operations
(Early CD-4)

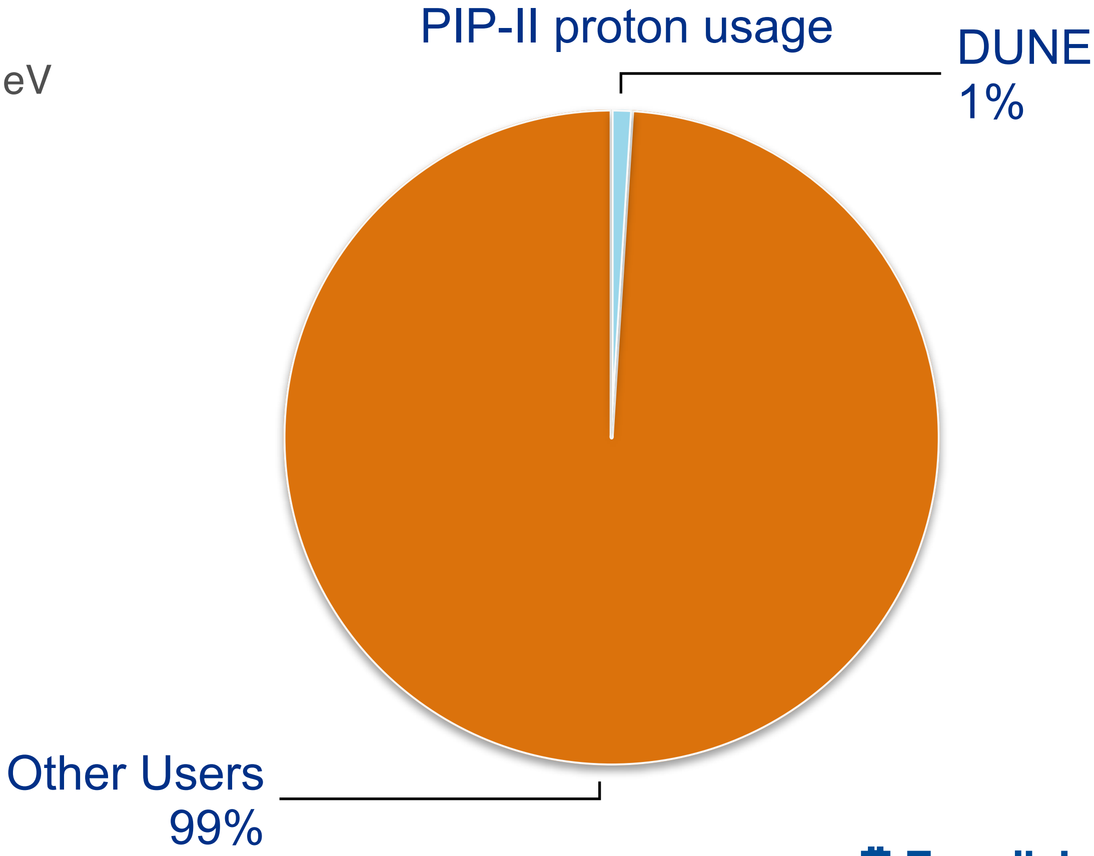
Mar 2019
Linac Complex Ground-Breaking

PIP-II Linac

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

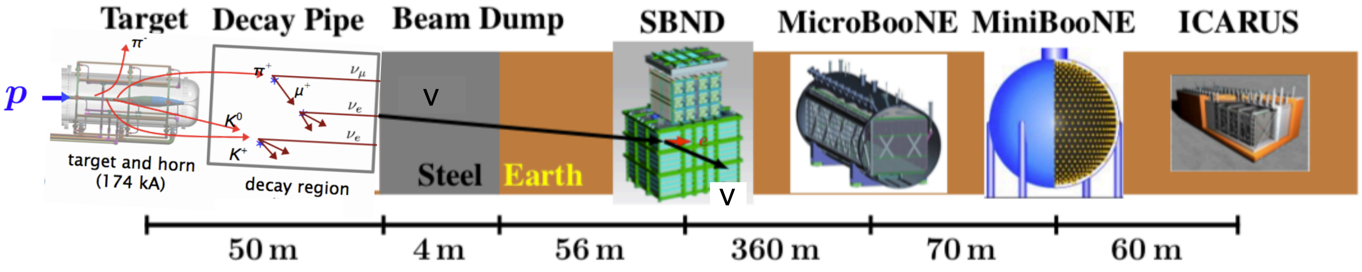
Key high-level metrics for SC LINAC:

- Capable of 2 mA @ 800 MeV (1.6 MW)
- DUNE only uses 1.1% of this beam to achieve its physics goals
- Proton beam is ~continuous wave



SBN-BD

Current short-baseline neutrino program uses horn-focused, decay-in-flight neutrino beam:



→ Target limited to 35 kW, but up to 80 kW available in PIP-II era in excess of DUNE needs

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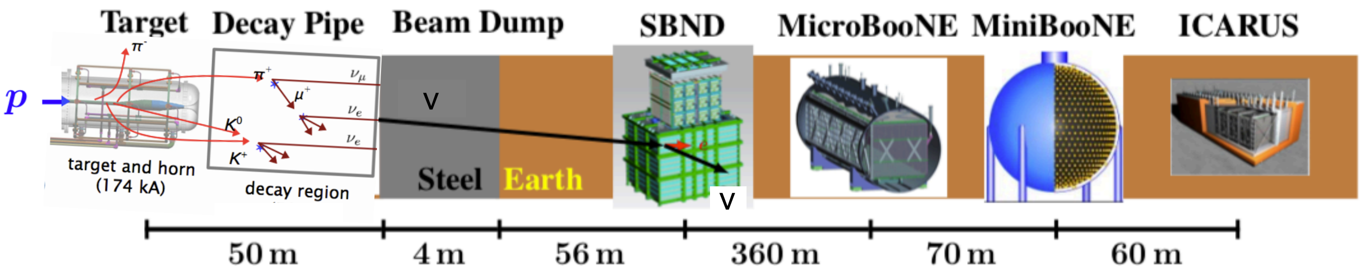
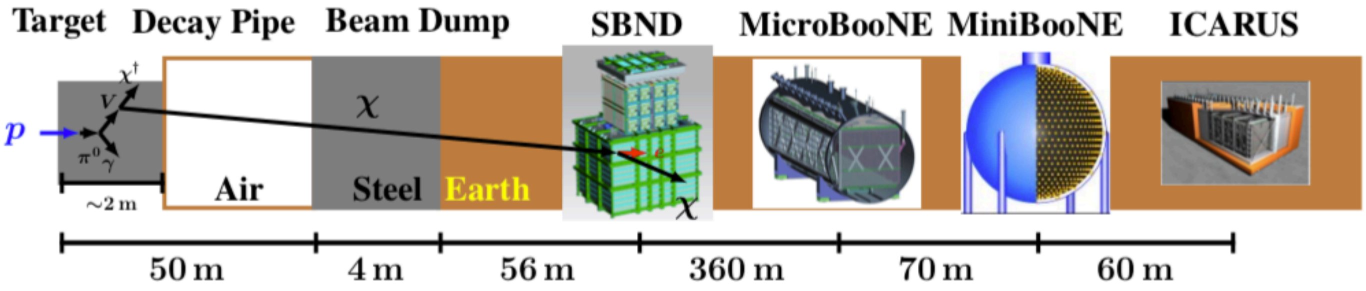


→ Target limited to 35 kW, but up to 80 kW available in PIP-II era in excess of DUNE needs

Impinging proton beam on absorber enables dark sector search program:



→ With kicker magnets and second target station, can run concurrently with the above

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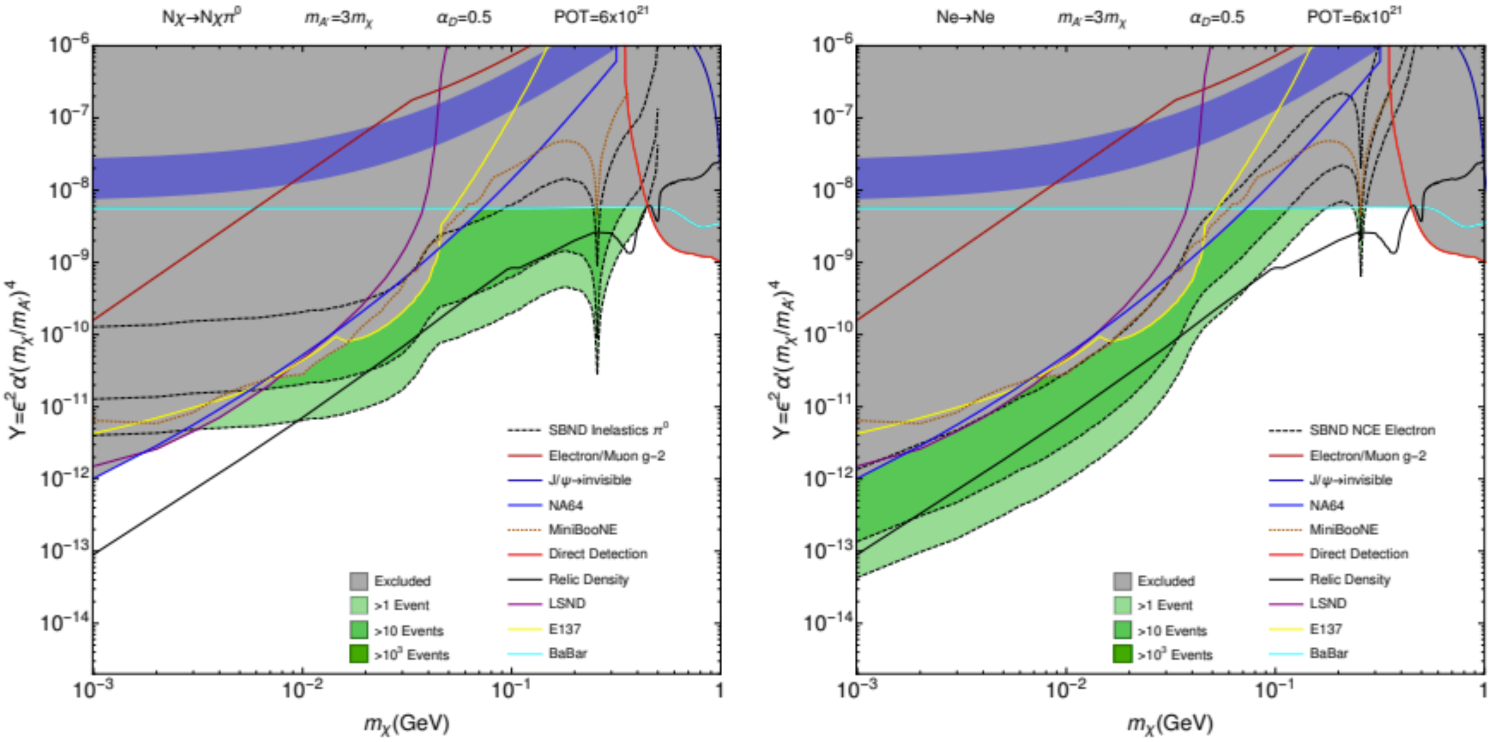
SBN-BD Event Sensitivities



- Setup also has sensitivity to other DS models, e.g. hadrophilic DM

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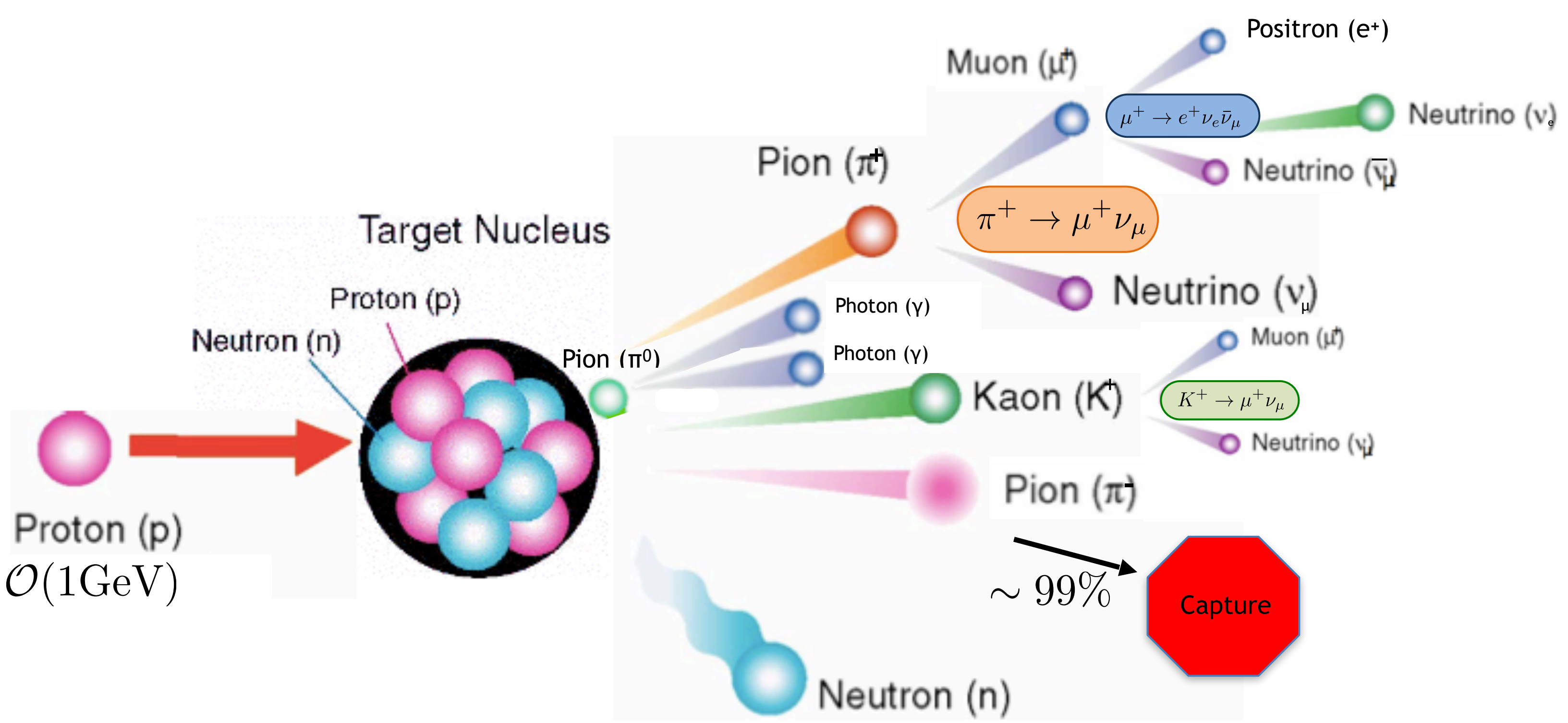
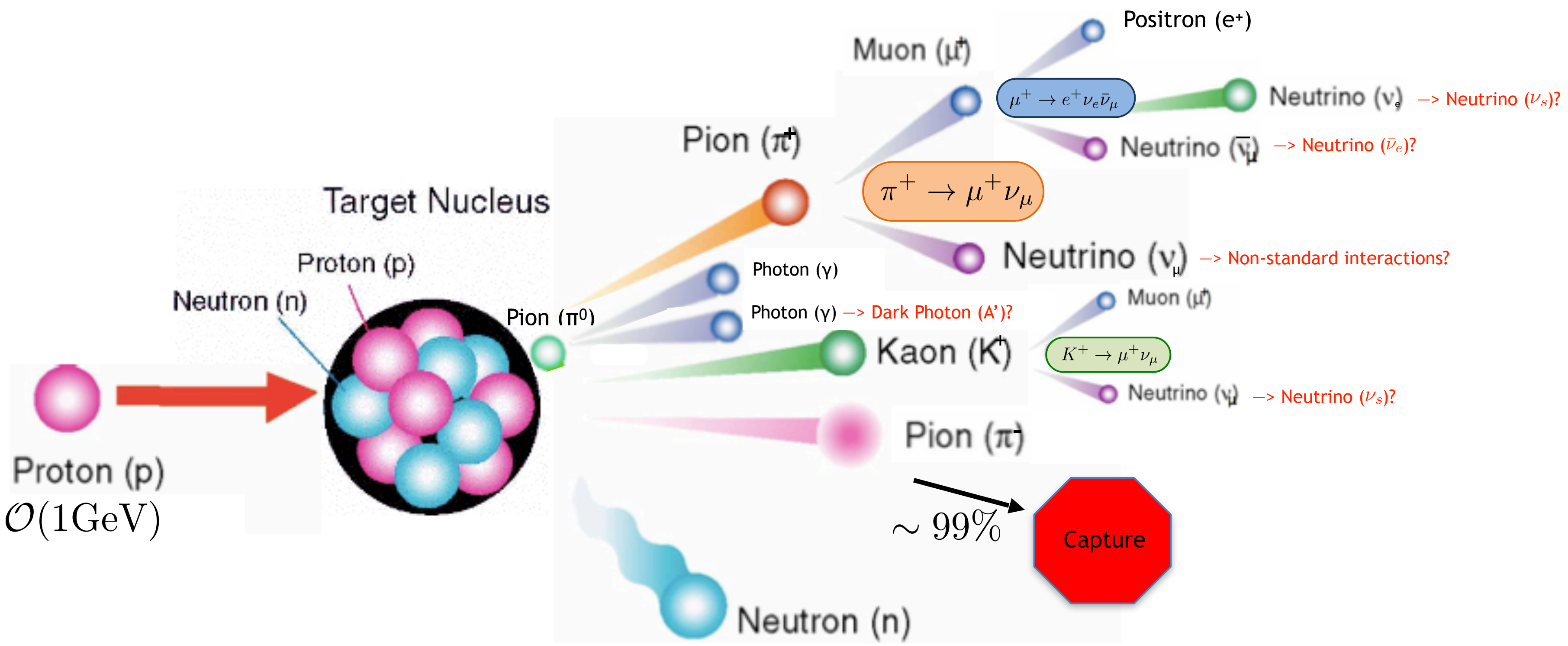
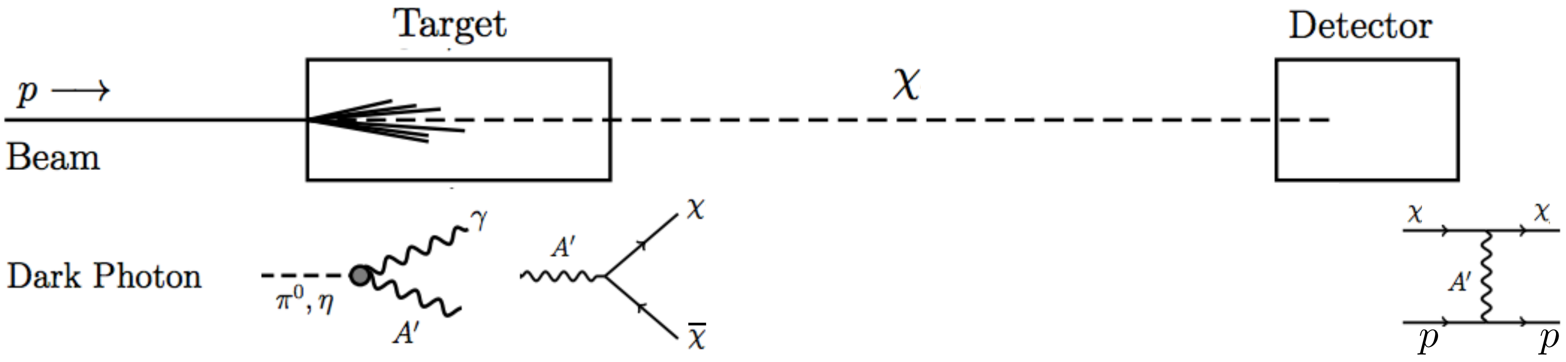
GeV Proton Beam Dumps



BSM Physics at GeV Proton Beam Dumps



Pion Decay-at-rest Sources as BSM Factories: Challenges

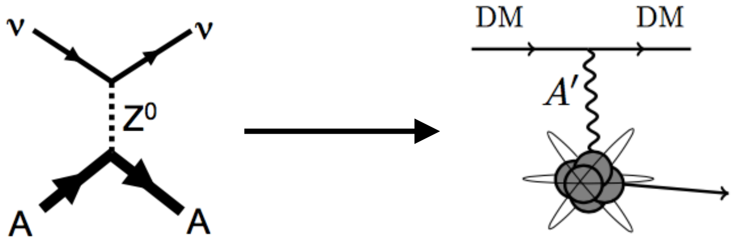


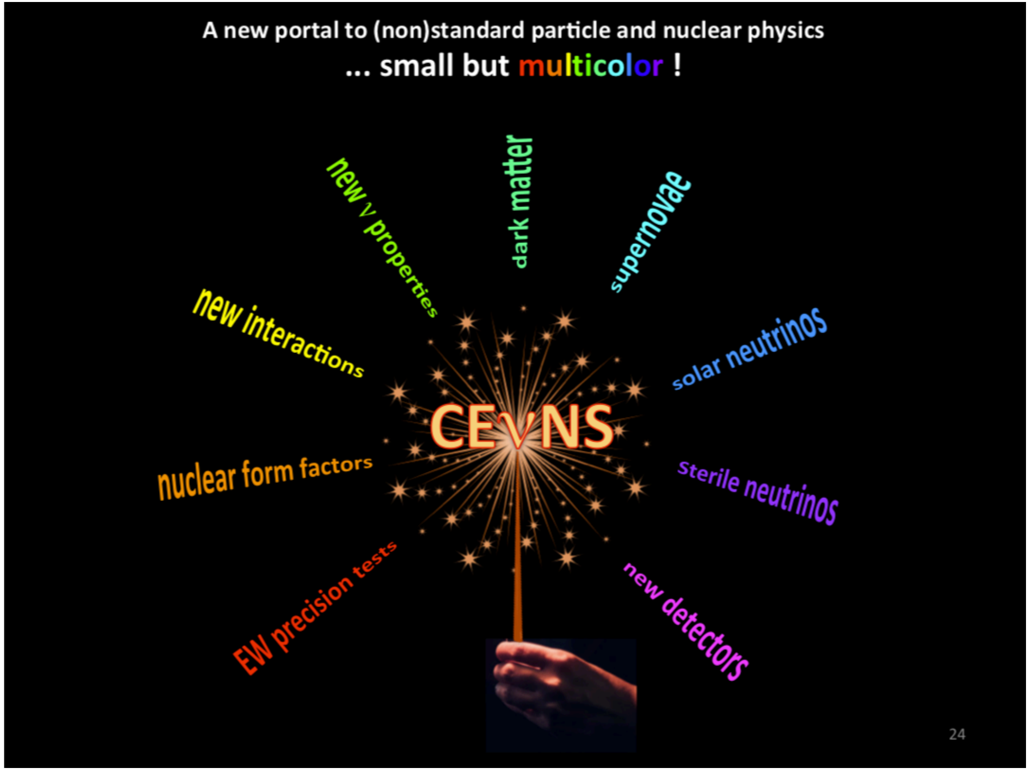
- Low energy nuclear recoil signal —> need low, O(1-10 keVnr) detector thresholds
- Rare signals —> need large beam exposures
- Steady state backgrounds —> need pulsed beams with low, O(10^{-6}-10^{-4}) duty factor
- Beam-related backgrounds —> adequate shielding (neutrons)
  —> beam timing (neutrons, neutrinos)

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

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

New HEP tool to probe neutrino properties and search for BSM physics

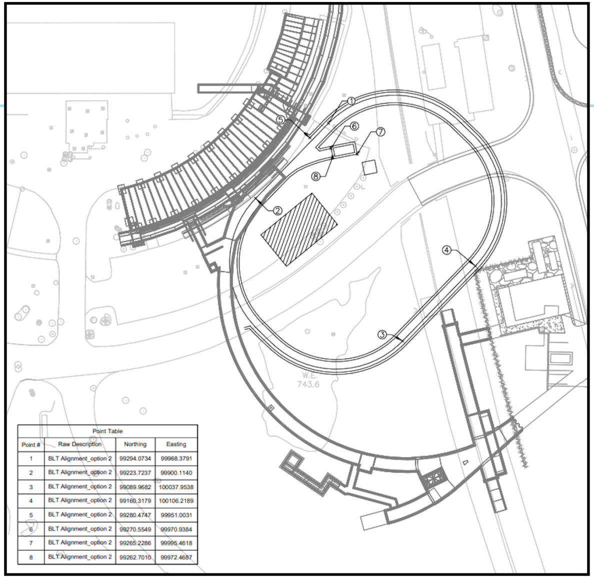




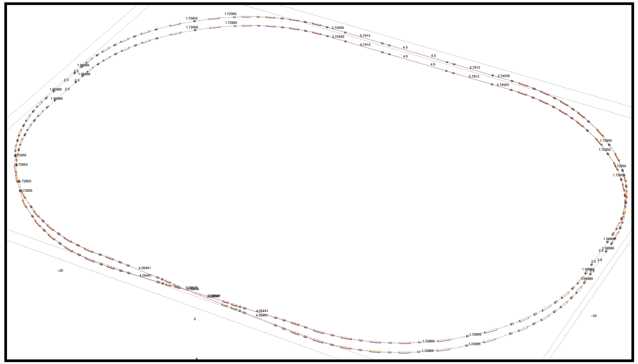
Eligio Lisi, NuINT 2018

PIP-II Accumulator Ring (PAR)

- Forward-looking design of the PIP-II linac includes provisions that facilitate future upgrades, including:
  - CW multi-user mode of operation
  - Increase in beam energy to 1 GeV and beyond
  - Stub in the beam transfer line to the Booster to provide beam to other users
- Extension of the PIP-II beam transfer line tunnel would allow co-location of an accumulator ring for modest cost that can be realized within the decade
  - Provides a dark sector program on Day 1 of PIP-II operation
  - Enables injecting 1 GeV beam in Booster as a pathway to higher LBNF beam power

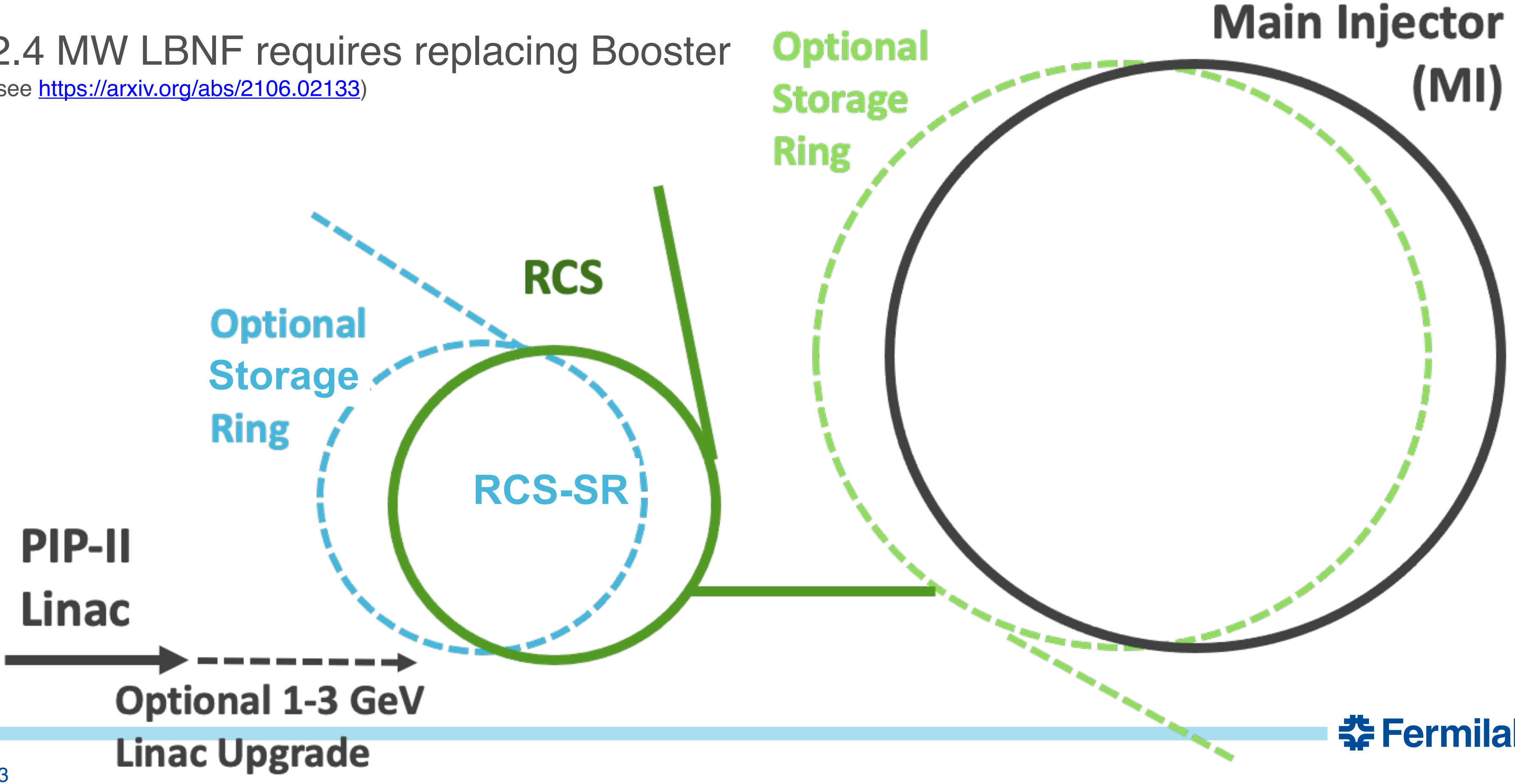


Point Table			
Point #	Raw Description	Northing	Easting
1	BLT Alignment_option 2	99294.0734	99968.3791
2	BLT Alignment_option 2	99223.7237	99900.1140
3	BLT Alignment_option 2	99089.9682	100037.9538
4	BLT Alignment_option 2	99160.3179	100106.2189
5	BLT Alignment_option 2	99280.4747	99951.0031
6	BLT Alignment_option 2	99270.5549	99970.9384
7	BLT Alignment_option 2	99265.2286	99995.4618
8	BLT Alignment_option 2	99262.7010	99972.4687



Rapid Cycling Synchrotron (RCS) Booster Replacement

2.4 MW LBNF requires replacing Booster
(see https://arxiv.org/abs/2106.02133)

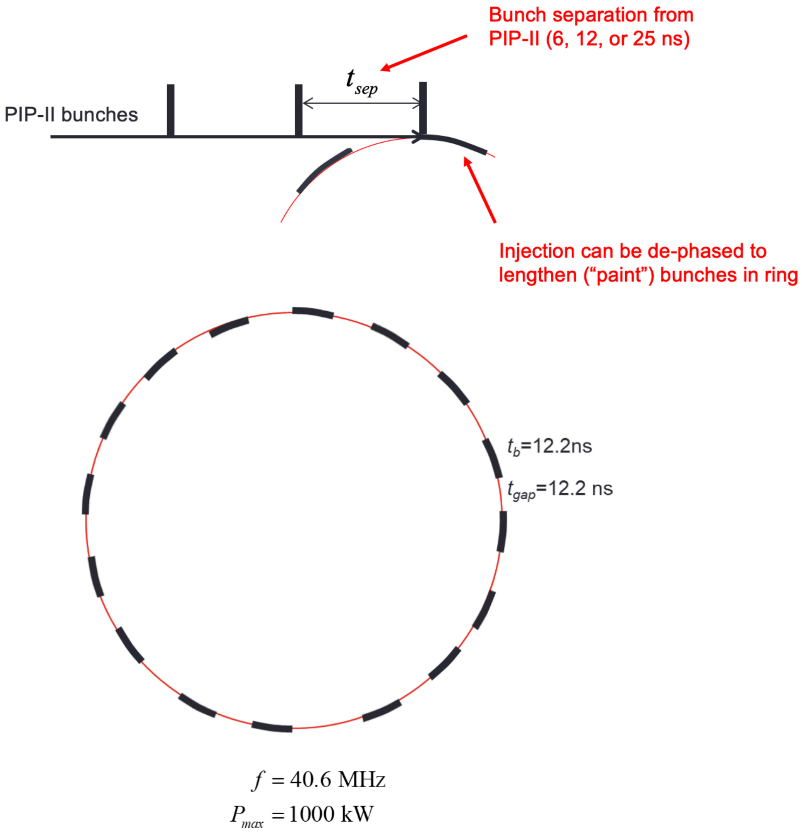


Compact PIP-II Accumulator Ring (C-PAR)

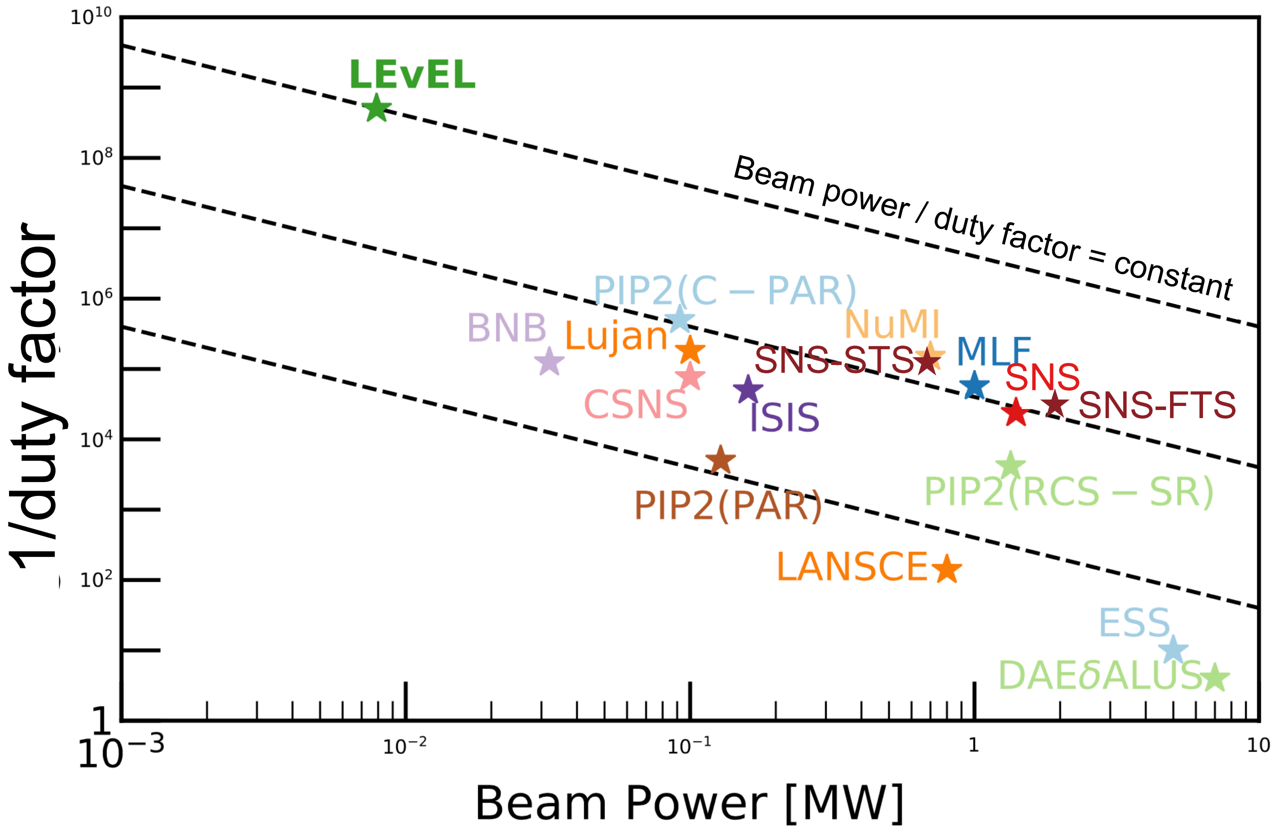
- Proposed Advanced Muon Facility calls for a compact 100 m accumulator ring for a future charged lepton flavor violation experiment using PIP-II

- Provides very short proton pulses of ~20 ns at O(100 Hz)

- Would also support a dark sector search program at a proton beam dump facility



Pion Decay-at-rest Accelerator Facilities



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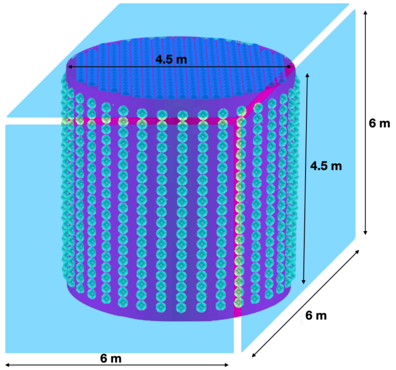
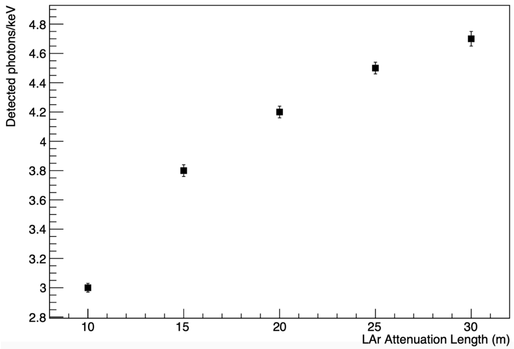
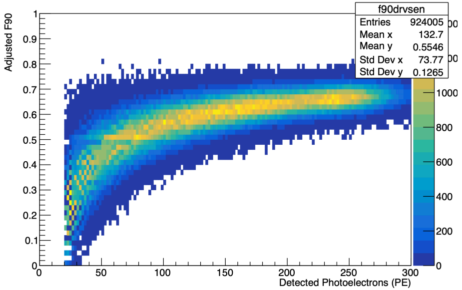
PIP2-BD

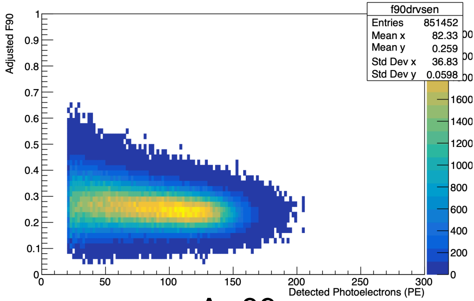
- Single-phase, 100 ton scintillation only liquid argon detector
  - Same technology as CENNS-10, Coherent CAPTAIN-Mills (CCM)
- Cylindrical volume with 1294 TPB-coated PMTs and TPB-coated reflectors on sides and end caps
- Geant4-based simulation of detector response indicate a 20 keVnr threshold is achievable
- Instrumental effects (PMT noise) and Ar-39 also taken into account







CEvNS recoils

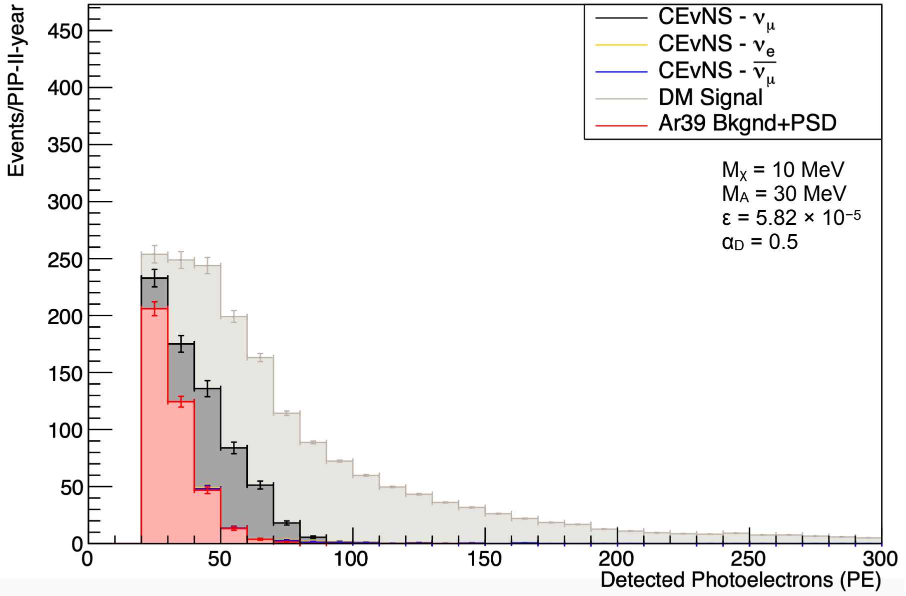


Ar-39

Vector Portal Kinetic Mixing Light Dark Matter Search

- PIP2-BD located 18 m downstream of the dump, on axis
- Geant4-based simulation of proton beam dump used to generate neutrino backgrounds and light meson distributions
- BdNMC used to generate dark matter nuclear recoils in the detector, then fed into the full detector simulation
- Rate-only sensitivity calculated using:

$$\Delta\chi^2 = \frac{N_{\rm sig}^2}{N_{\rm bkg} + \sigma^2 N_{\rm CEvNS}^2}$$



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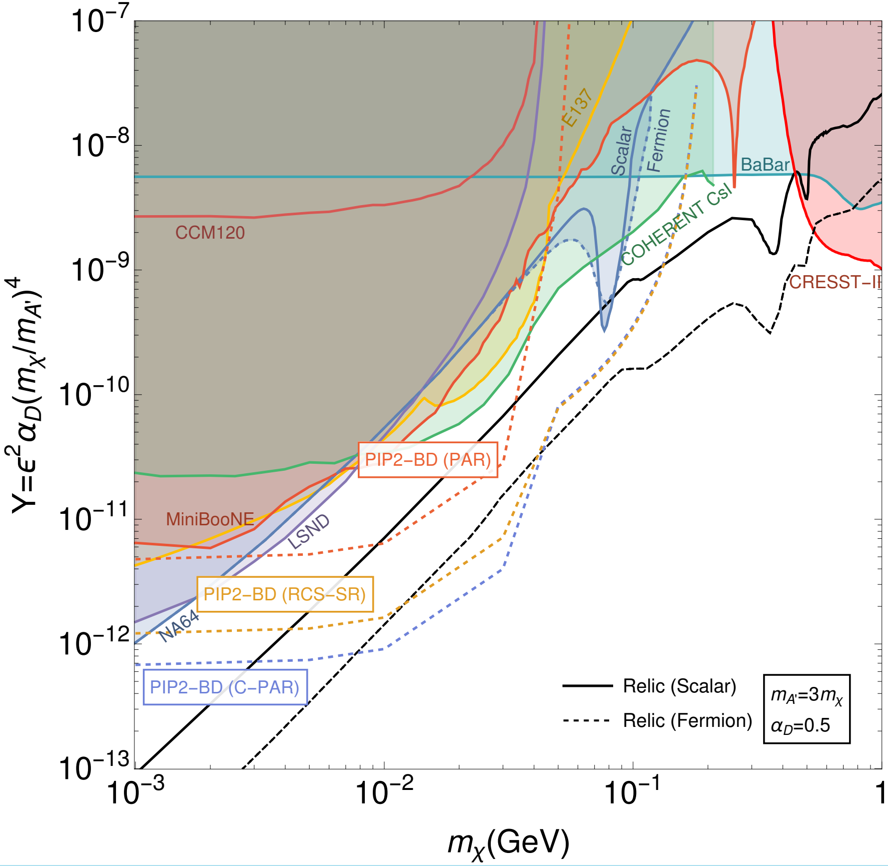
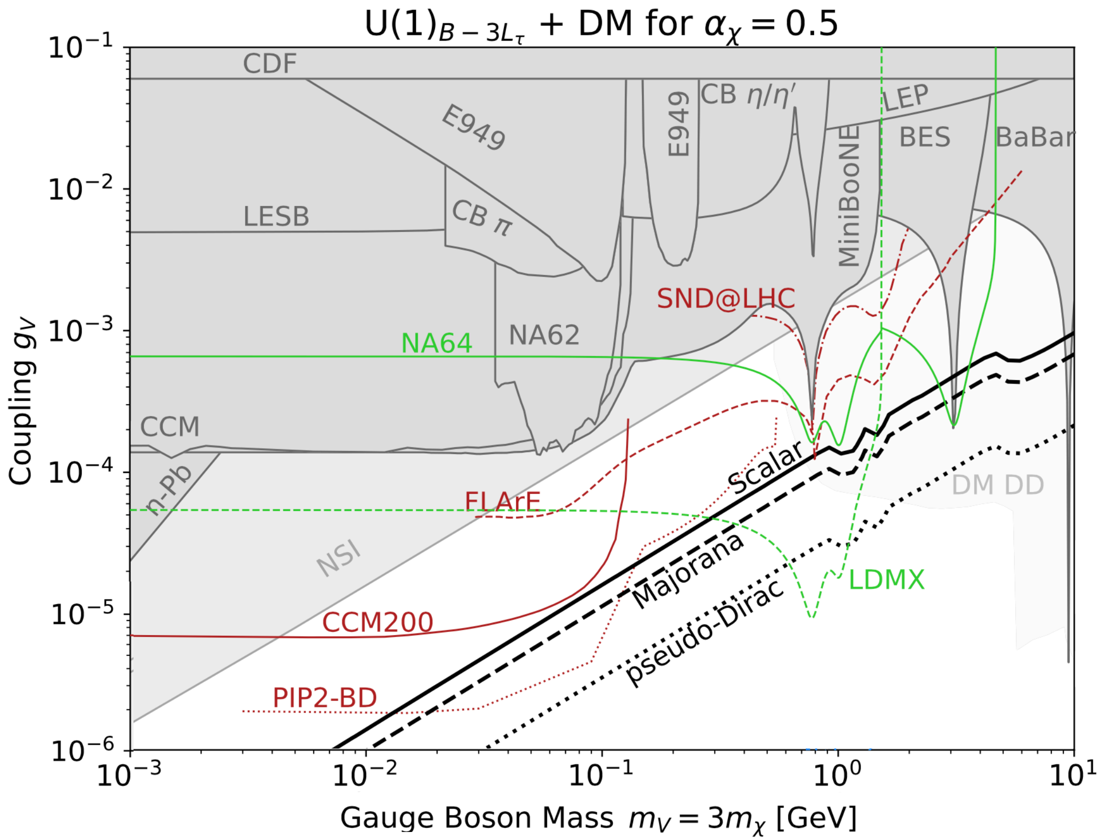
Vector Portal Kinetic Mixing 90% C.L. Sensitivities



Facility	Beam energy (GeV)	Repetition rate (Hz)	Pulse length (s)	Beam power (MW)
PAR	0.8	100	2×10^{-6}	0.1
C-PAR	1.2	100	2×10^{-8}	0.09
RCS-SR	2	120	2×10^{-6}	1.3

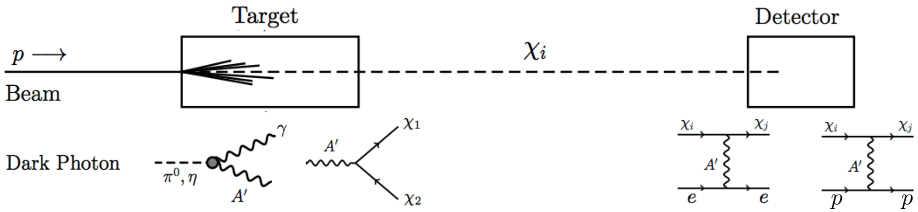
Hadrophilic Dark Matter 90% C.L. Sensitivities

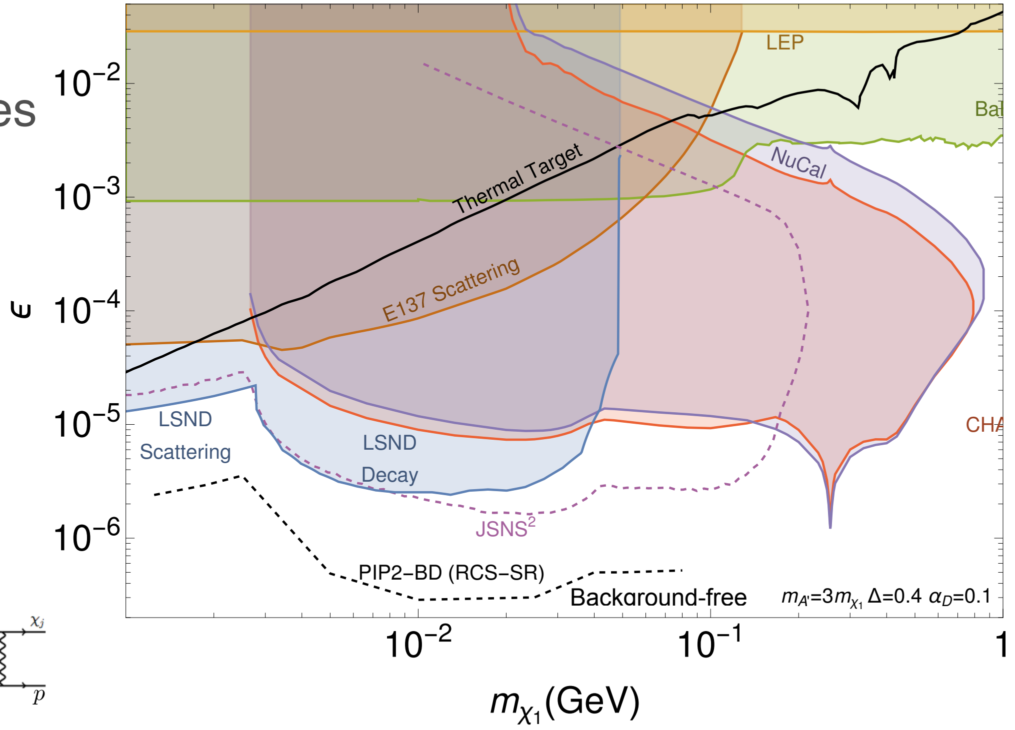


Inelastic Dark Matter 95% C.L. Sensitivities

- Adding an additional dark matter species with a small mass splitting brings in a richer set of phenomenology

- Detection channels now include both scattering and decay signatures



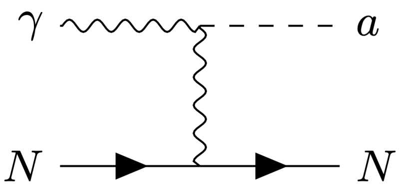


Axion-like Particles (ALPs)

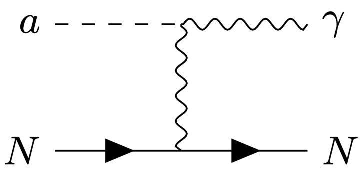
- ALPs can couple to photons and electrons produced in the beam dump
  - Excellent sensitivity due to intense source + large, low-threshold detector nearby

$$\mathcal{L}_{\mathrm{ALP}} \supset -\frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} - g_{ae}\, a\, \bar{e}\, i\gamma_5\, e$$

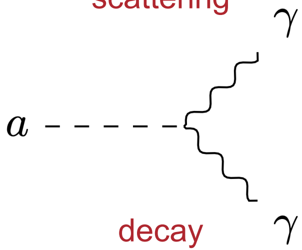
- Photon coupling example:



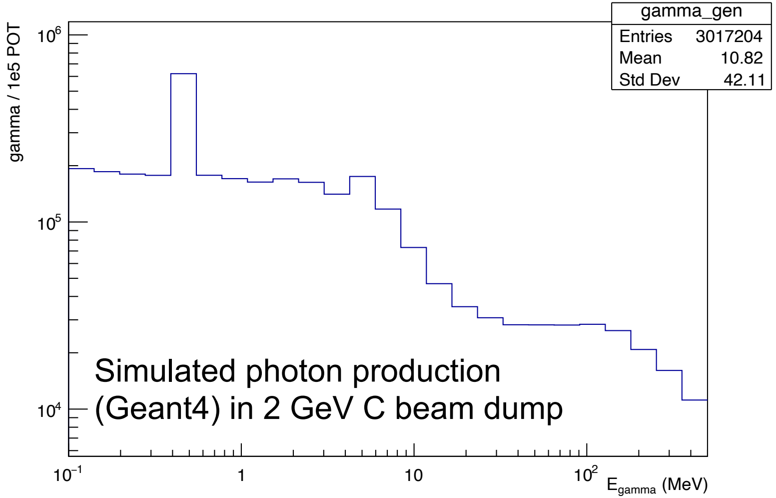
production



scattering

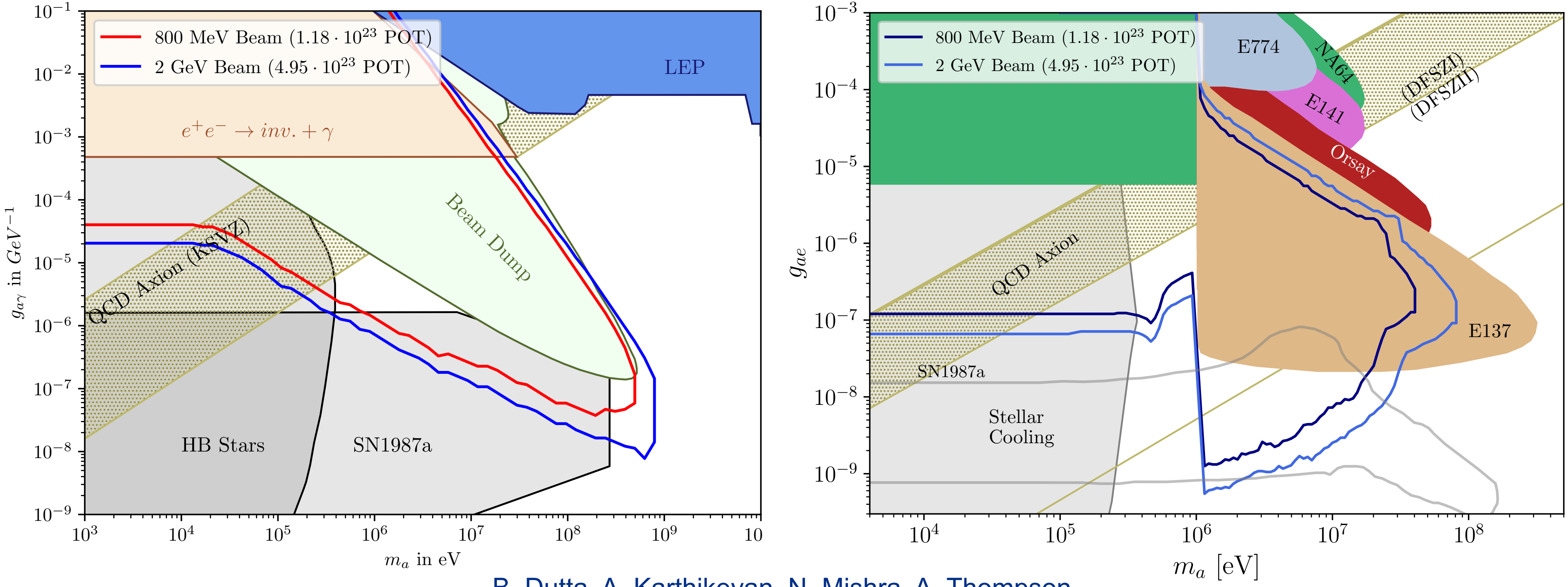


decay



- Following studies in CCM, assume 75% efficiency above 100 keV

Background-free 90% C.L. Sensitivities



B. Dutta, A. Karthikeyan, N. Mishra, A. Thompson

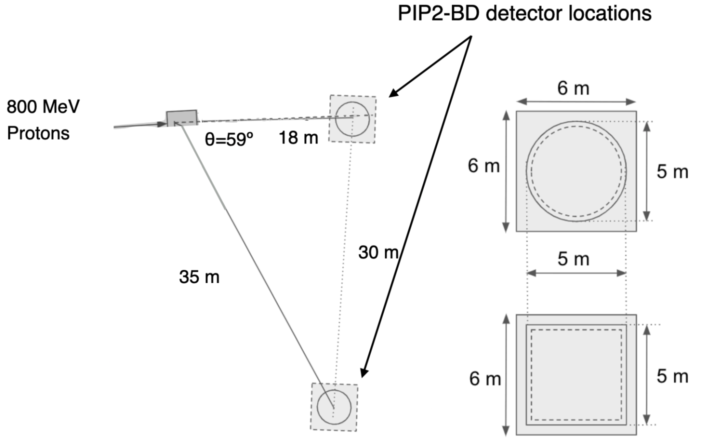
Sterile Neutrinos

- CEvNS-based search provides smoking-gun evidence for sterile neutrinos
  - Three flavors of neutrinos, with the mono-energetic ν_μ separated in time from the ν_e and anti-ν_μ

$$\sin^2 2\theta_{\mu S} = 4U_{\mu 4}^2 U_{S4}^2 = 4U_{\mu 4}^2\left(1 - U_{e4}^2 - U_{\mu 4}^2\right)$$

$$\sin^2 2\theta_{eS} = 4U_{e4}^2 U_{S4}^2 = 4U_{\mu 4}^2\left(1 - U_{e4}^2 - U_{\mu 4}^2\right)$$

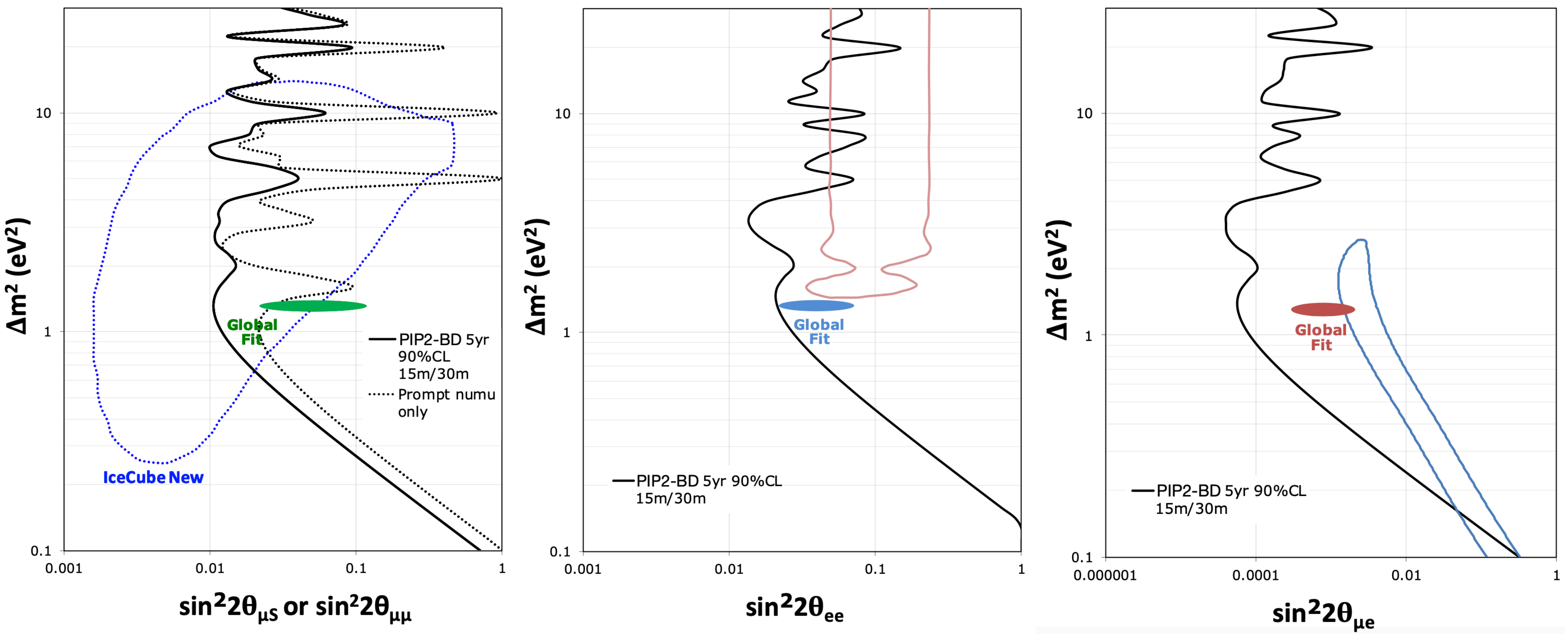
- Leverage advantages of dedicated HEP beam dump facility
  - Flexible detector positioning
    - Near/far setup to cancel flux normalization systematics
  - Low Z target to increase neutrino flux
  - Neutron shielding to reduce beam-correlated backgrounds to negligible levels



or DUNE PRISM moveable detector concept

- Two identical PIP2-BD detectors at L = 15, 30 m from target
  - 20 keVnr threshold with 70% efficiency above threshold
  - 1:1 signal/background for beam-uncorrelated backgrounds
  - 9% correlated normalization systematic uncertainty
    - 36 cm path length smearing

90% C.L. Rate-only Sensitivities (C-PAR)



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Conclusion

Exciting prospect for discovering accelerator-produced light dark matter over the coming decade

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

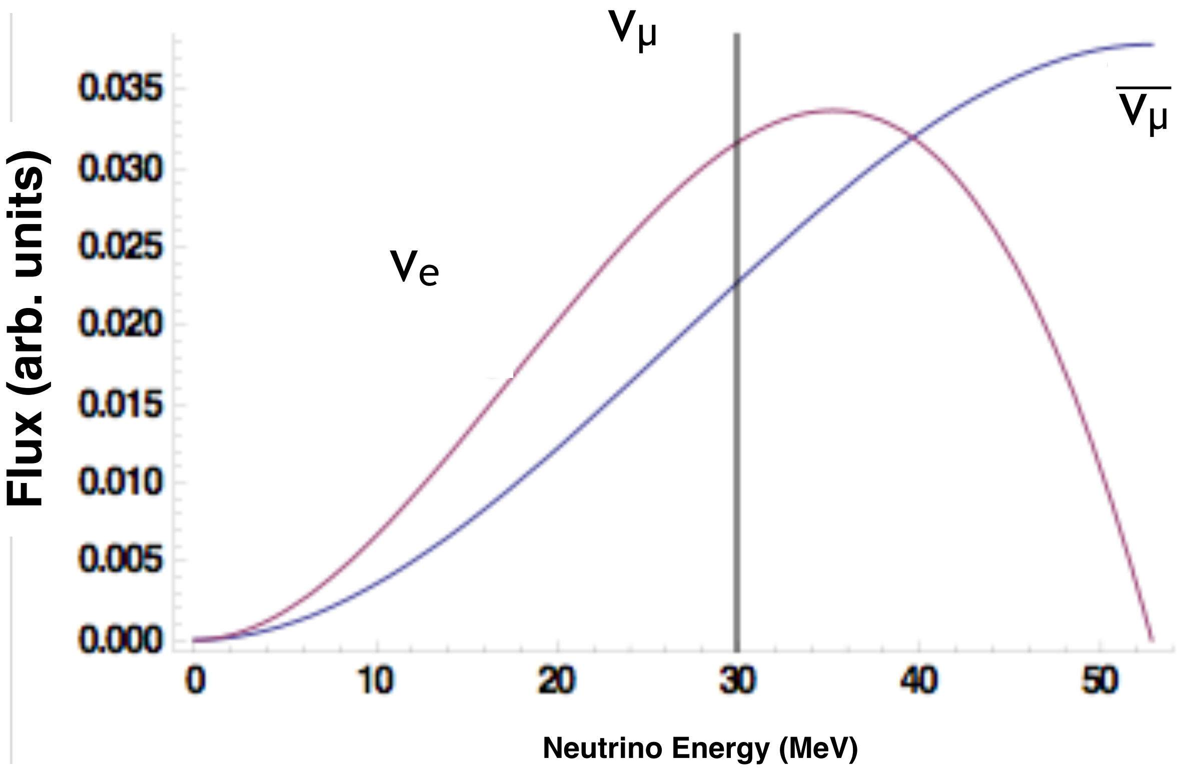
The PIP-II Accumulator Ring could enable a GeV-scale proton beam dump program to be realized within the decade along with a clear upgrade path

- Key feature of such a beam dump facility at Fermilab is that it can be designed for and dedicated to HEP searches

Thank you for your attention!

Backups

Stopped pion decay-at-rest neutrino flux



Booster Replacement Physics Opportunities

Accelerator upgrade will be driven by science priorities

Many ideas on the table spanning a range of physics topics

Opportunity to define future program alongside DUNE

Experiment	Dark Sectors	ν Physics	CLFV	Precision tests	R&D
Lepton flavor violation: μ-to-e conversion					
Lepton flavor violation: μ decay					
PIP2-BD: ~GeV Proton beam dump					
SBN-BD: ~10 GeV Proton beam dump					
High energy proton fixed target					
Electron missing momentum					
Nucleon form factor w/ lepton scattering					
Electron beam dumps					
Muon Missing Momentum					
Muon beam dump					
Physics with muonium					
Muon collider R&D and neutrino factory					
Rare decays of light mesons					
Ultra-cold neutrons					
Proton storage ring for EDM and axions					
Tau neutrinos					
Proton irradiation facility					
Test-beam facility					

https://arxiv.org/abs/2203.03925

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