Searches for New Physics at an Upgraded Fermilab Accelerator Complex: PIP2-BD and SBN-BD

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Snowmass 2021 Community Summer Study

Seattle, WA

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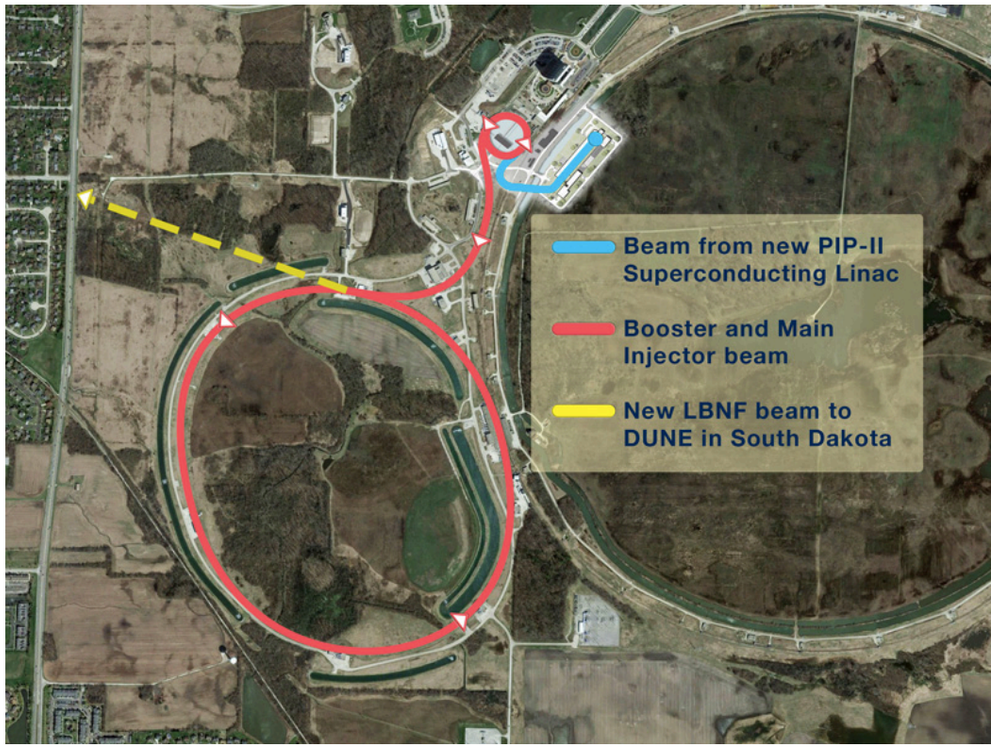
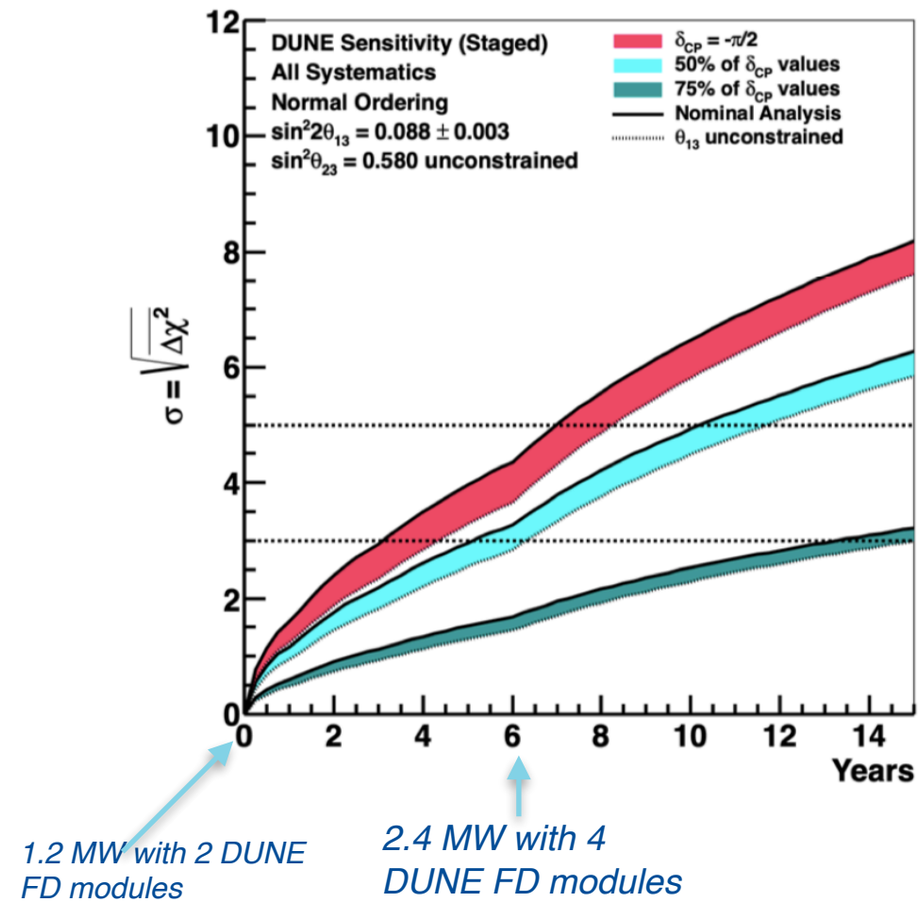
The PIP-II Project

- DUNE major component of US particle physics program in next ~decade
- Upgrade to the current Fermilab accelerator complex driven by DUNE physics goals
- Among highest power ~GeV proton beams in the world
  - Capable of 1.6 MW at 800 MeV proton energy CW
  - Small percentage of protons (1.1%) needed to support DUNE
- Can we leverage existing upgrade plans to search for other exciting physics at Fermilab?
  - O(1 GeV) stopped-pion neutrino source program leveraging the available beam
  - Opportunity to build facility to maximize high-energy physics impact
  - PIP2-BD White Paper: https://arxiv.org/pdf/2203.08079.pdf
  - SBN-BD White Paper: https://arxiv.org/pdf/2203.08102.pdf





SBN-BD:O(10) GeV Beam Dump Program using PIP-II at Fermilab

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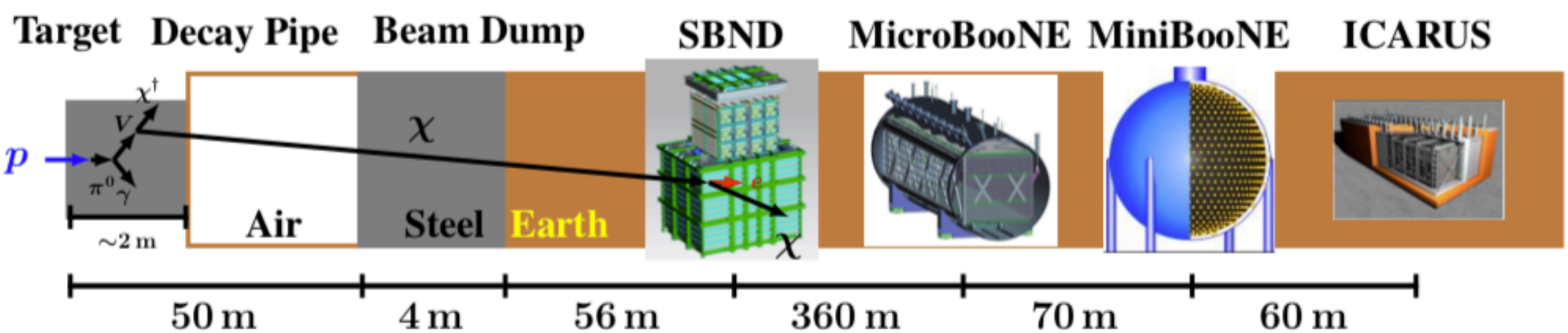
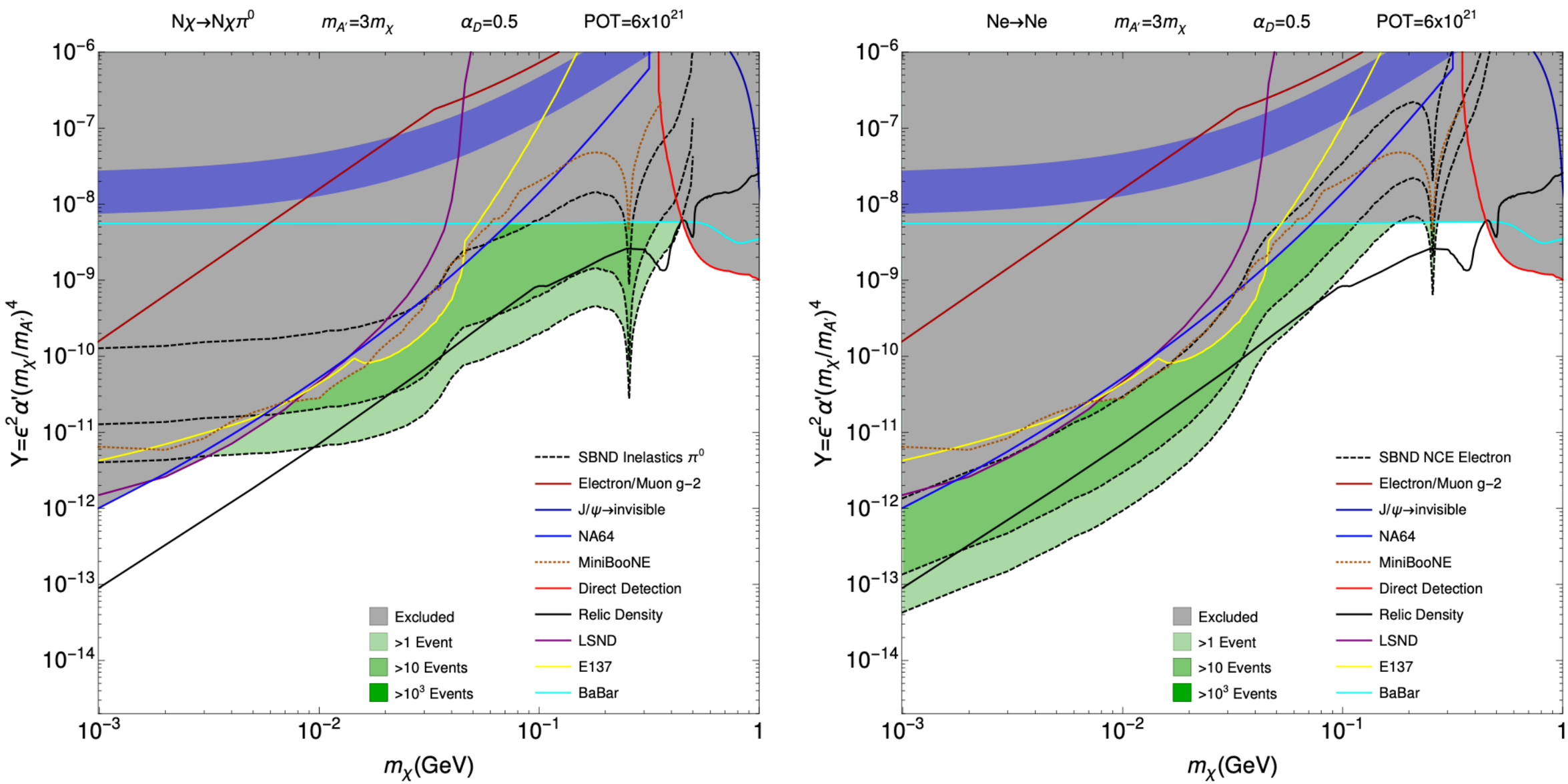
Leveraging PIP-II with a BNB Beam Dump Station: SBN-BD

- sub-GeV accelerator produced dark matter search possible with new dedicated beam dump station at the BNB within 100 m of the SBN Near Detector (SBND)
  - Possibility of running concurrently with existing neutrino beam program
  - Pioneering search for accelerator produced sub-GeV dark matter performed by MiniBooNE
- Increase in Booster power to 160 kW in the PIP-II era provides extra protons beyond needs of SBN, DUNE
- Assume five year run in beam dump mode delivers 6×10^{21} Proton on Target (POT)



Dark Matter Searches with SBN-BD

- Two searches possible with NCπ^0 and NC-electron scattering using 5 year run of SBND in beam dump mode



P. deNiverville, LANL

PIP2-BD: O(1) GeV Beam Dump Program using PIP-II at Fermilab

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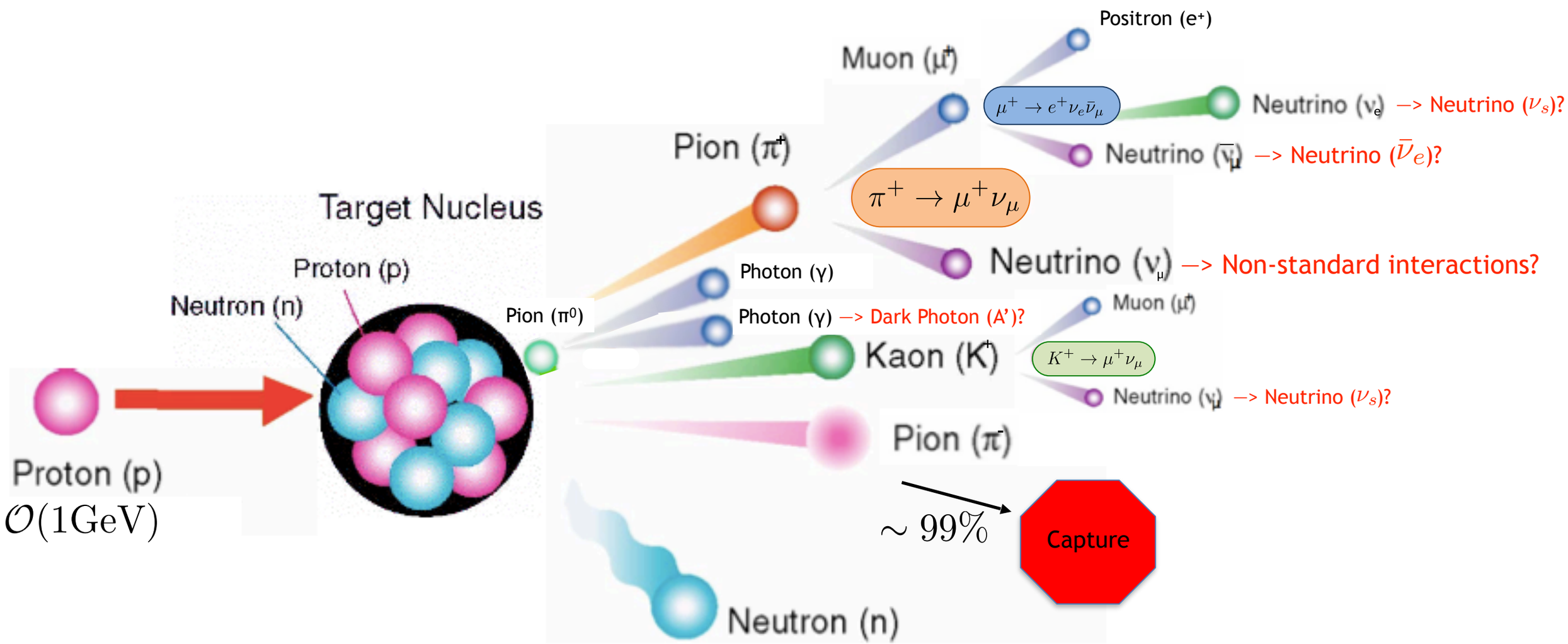
Stopped-pion (or decay-at-rest) neutrino source



ν_μ with pion decay lifetime (~26 ns), ν_e and anti-ν_μ with muon decay lifetime (2.2 μs)

Such a source possible at Fermilab if PIP-II coupled to an accumulator ring!

Creating a stopped-pion source with PIP-II: PIP2-BD

- Low mass dark sector searches are enabled at PIP-II with the addition of an accumulator ring on PIP-II, further upgrading the FNAL accelerator complex
  - We have studied three possible accelerator scenarios that enable dark sector searches
  - PIP-II Accumulator Ring (PAR), Compact PIP-II Accumulator Ring (C-PAR), and Rapid Cycling Synchrotron Storage Ring (RCS-SR)
- PAR and C-PAR are realizable in the timeframe of the start of the PIP-II accelerator (late 2020's)
- RCS-SR is a further upgrade on the timescale of the Booster Replacement

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

Current/Planned Stopped Pion Sources Worldwide

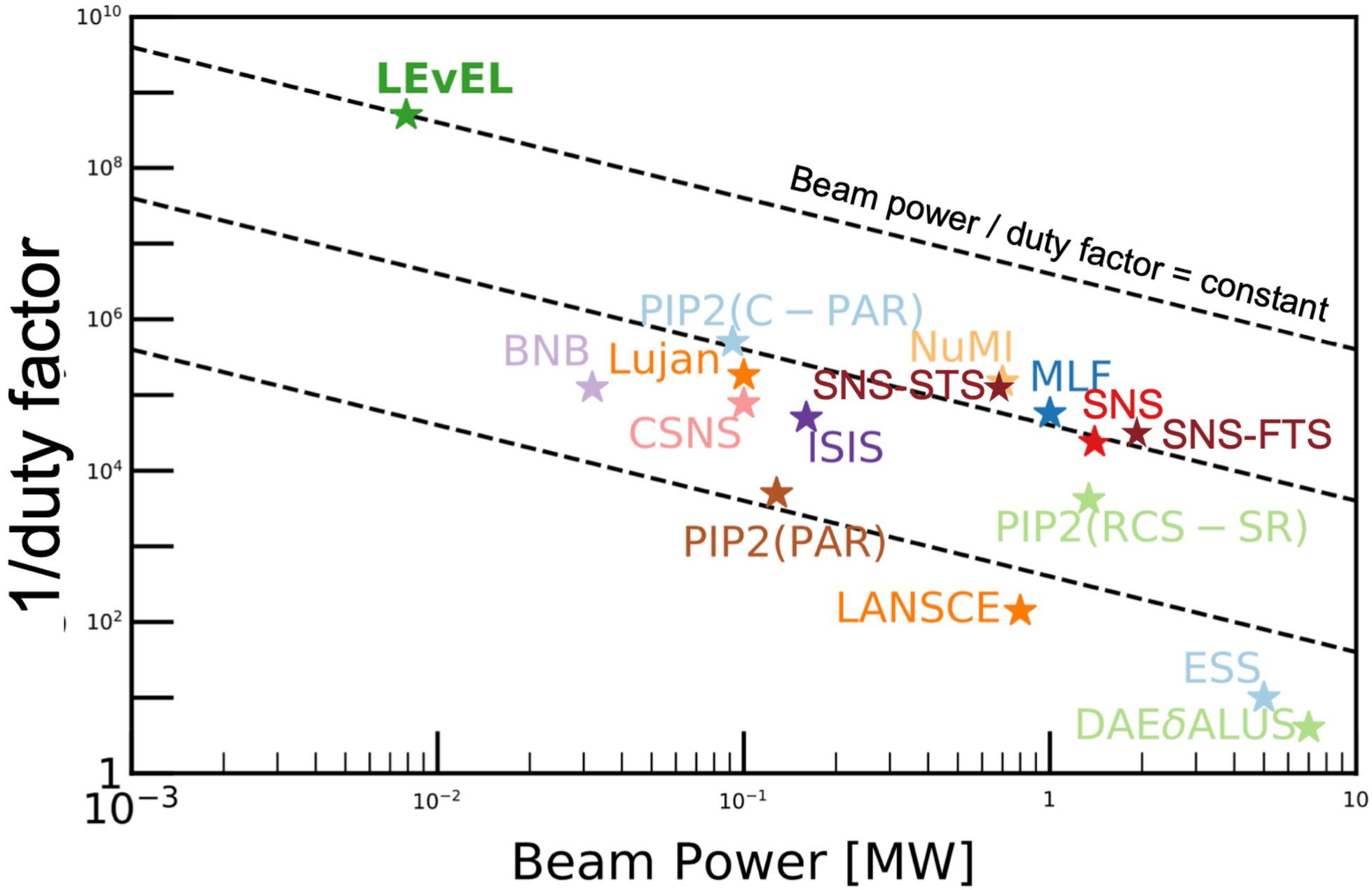


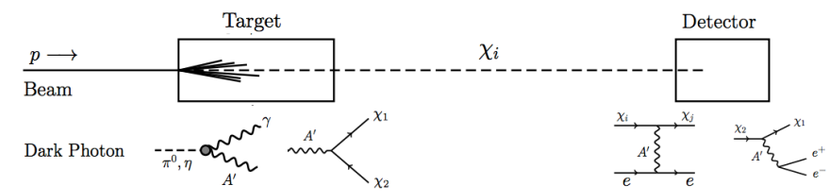
Figure adapted from arxiv:2103.00009

Physics available with O(1 GeV) stopped-pion source

- Light dark matter (LDM) / dark sector searches
  - Decay and/or scattering signatures

Will focus here!

- Axion-like particle (ALP) searches
  - Coupling to photons and e+/e-



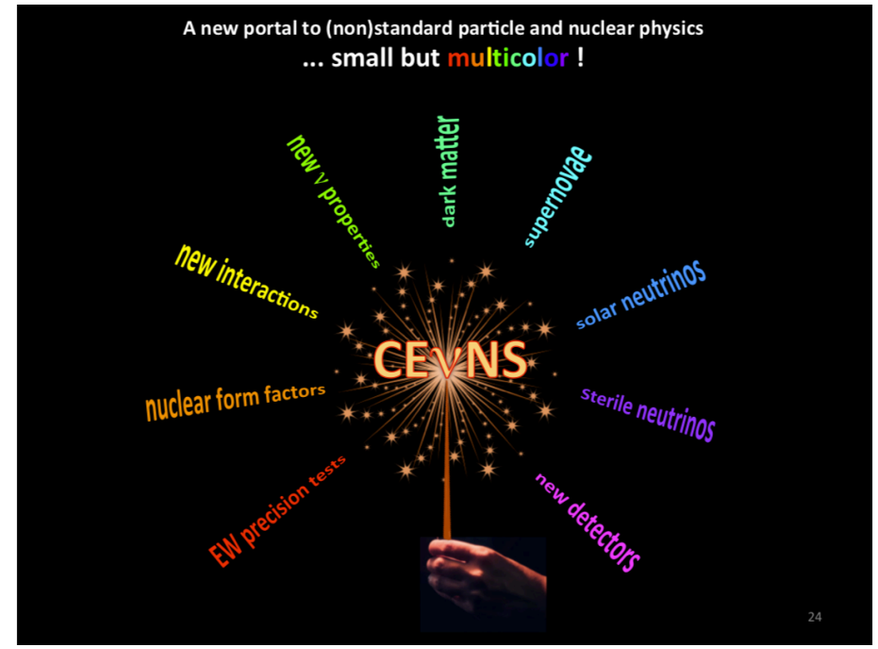
- Coherent elastic neutrino-nucleus scattering (CEvNS)

- Light Sterile Neutrino Searches
  - Both appearance and disappearance possible

- Searches for Non-standard interactions (NSIs), tests of the Standard Model

- Neutrino Cross Section Measurements

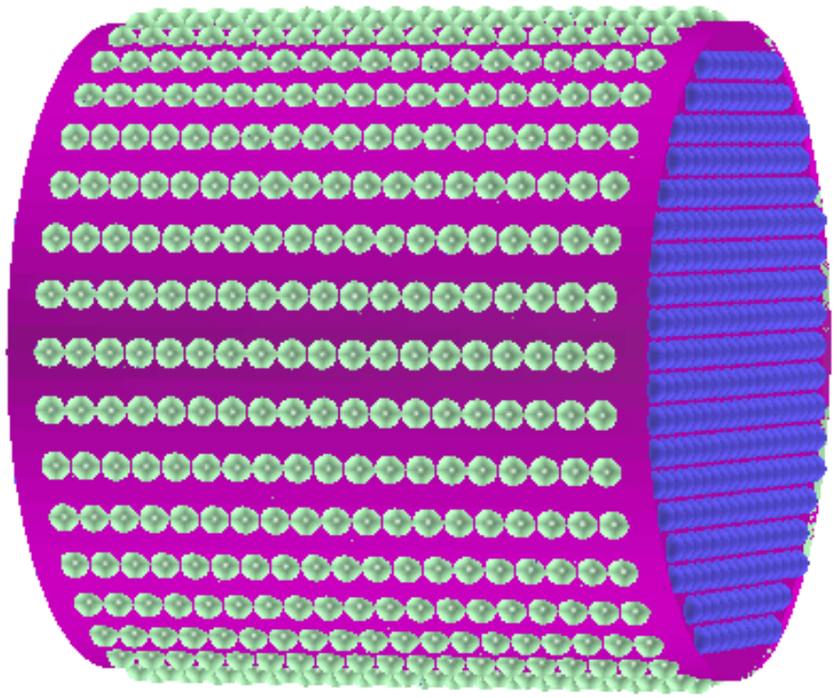
- Neutrino-Electron Scattering (LSND-like), MeV-scale



E. Lisi, NuINT 2018

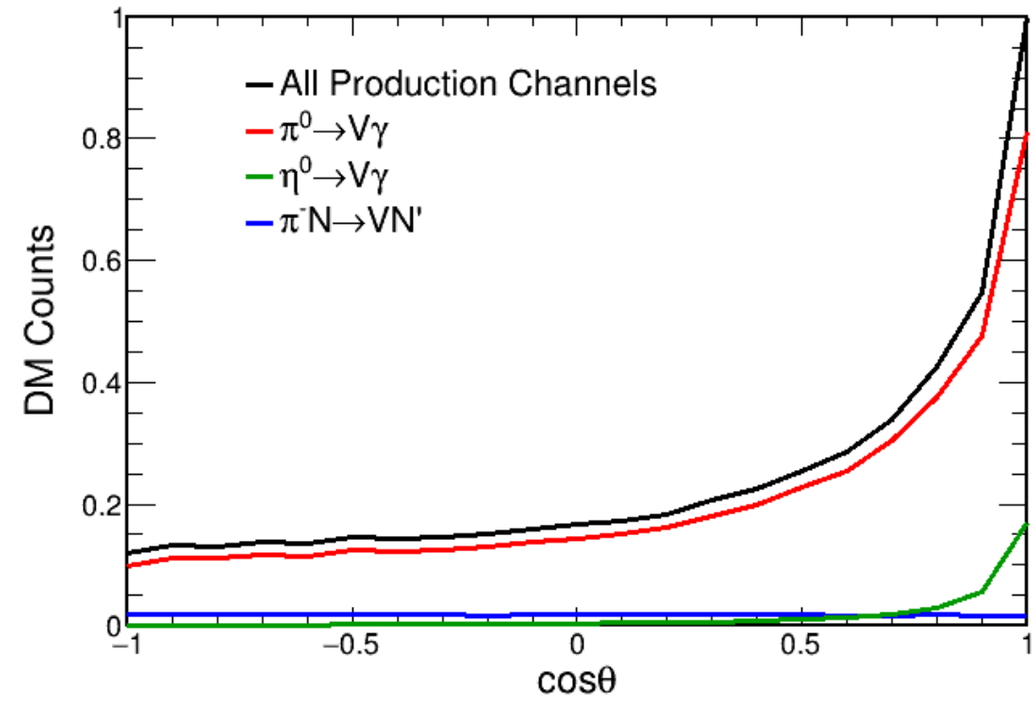
Proposed Detector at PIP-II

- Single-phase, scintillation only liquid argon (LAr) detector
- Fiducial volume - 4.5 m right cylinder inside box, **~100 tons LAr**
- Surround sides and endcaps of detector volume with TPB-coated 8” PMTs
  - TPB-coated reflector on sides and endcaps for photocoverage gaps
- Preliminary simulations suggest 20 keVnr threshold achievable with this detector
- Existing experiments such as COHERENT and CCM are key for testing many of the experimental techniques to successfully reach the physics goals of a 100-ton scale detector
- Fermilab-funded LDRD to study dark sector searches at proposed stopped-pion facility using PIP-II

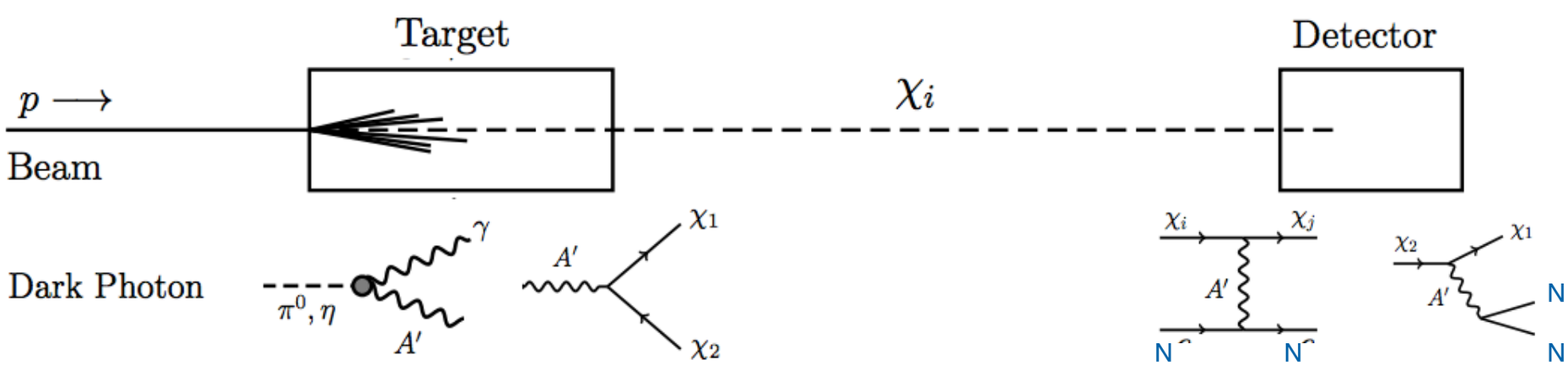


Vector Portal Light Dark Matter (LDM)

- Proton-target collisions produce dark sector mediators (V) between SM and dark sector (χ)
  - sub-GeV dark matter particle
- Produced dark matter particles boosted towards forward direction
- Signature in detector is low-energy nuclear recoil
  - Understanding beam-related backgrounds important!



Phys. Rev. D 102 (2020) 5, 052007

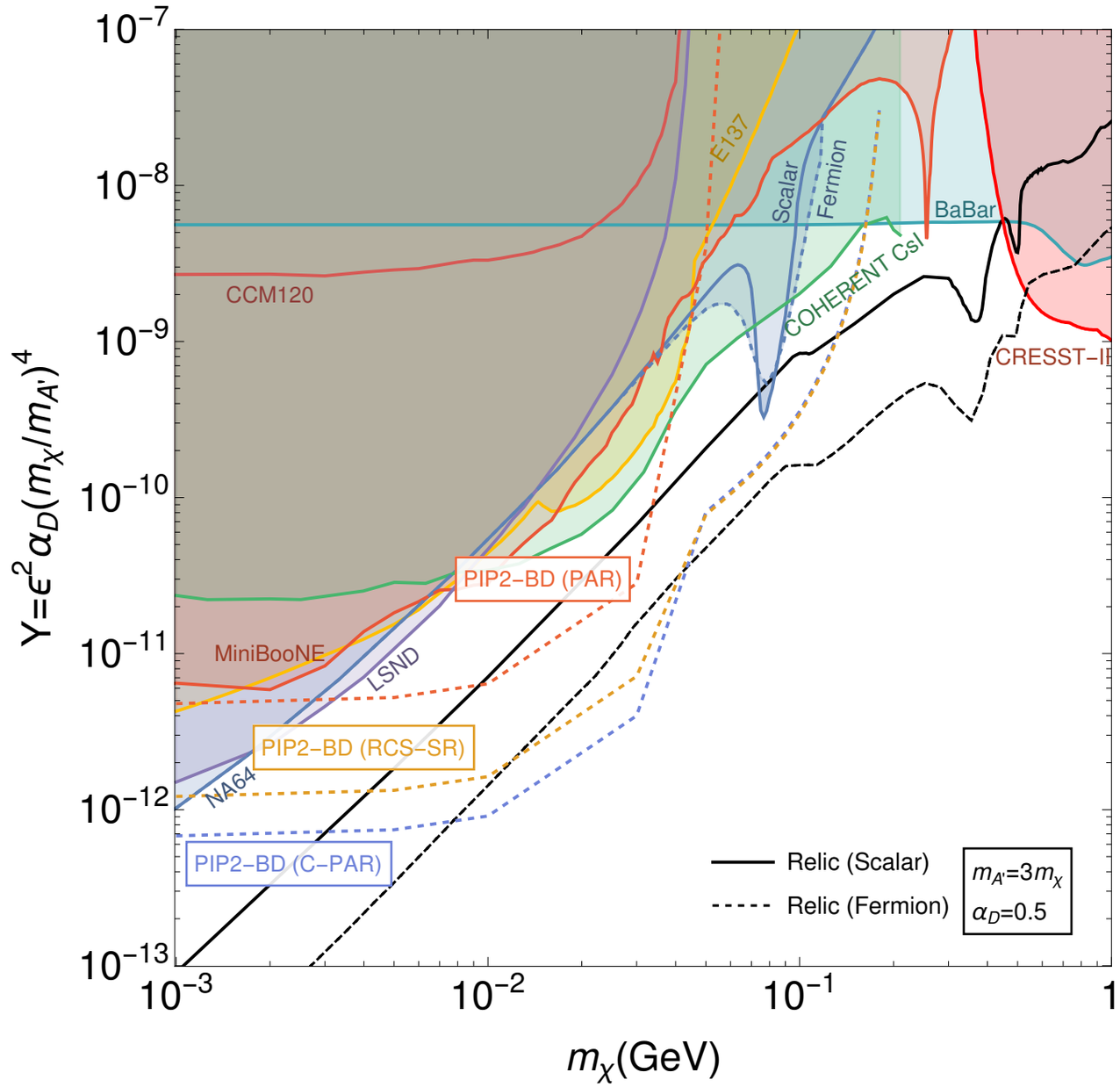


P. deNiverville et al., Phys. Rev. D 92 (2015) 095005

B. Dutta et al., Phys. Rev. Lett 124 (2020) 121802

PIP2-BD Vector Portal sub-GeV DM Search

- Stopped-pion neutrino sources place strong limits on LDM
  - Produced by proton collisions with fixed target
  - π^0 and η decay into light dark matter
  - Detector located on axis, 18 m downstream from target
  - 20 keVnr threshold
  - Backgrounds simulated using custom Geant4-based simulation
  - DM generated using BdNMC
    - 90% C.L. curves computed using simulated backgrounds and scaling the DM event rate with ϵ^4
  - 5 year run for each accelerator scenario

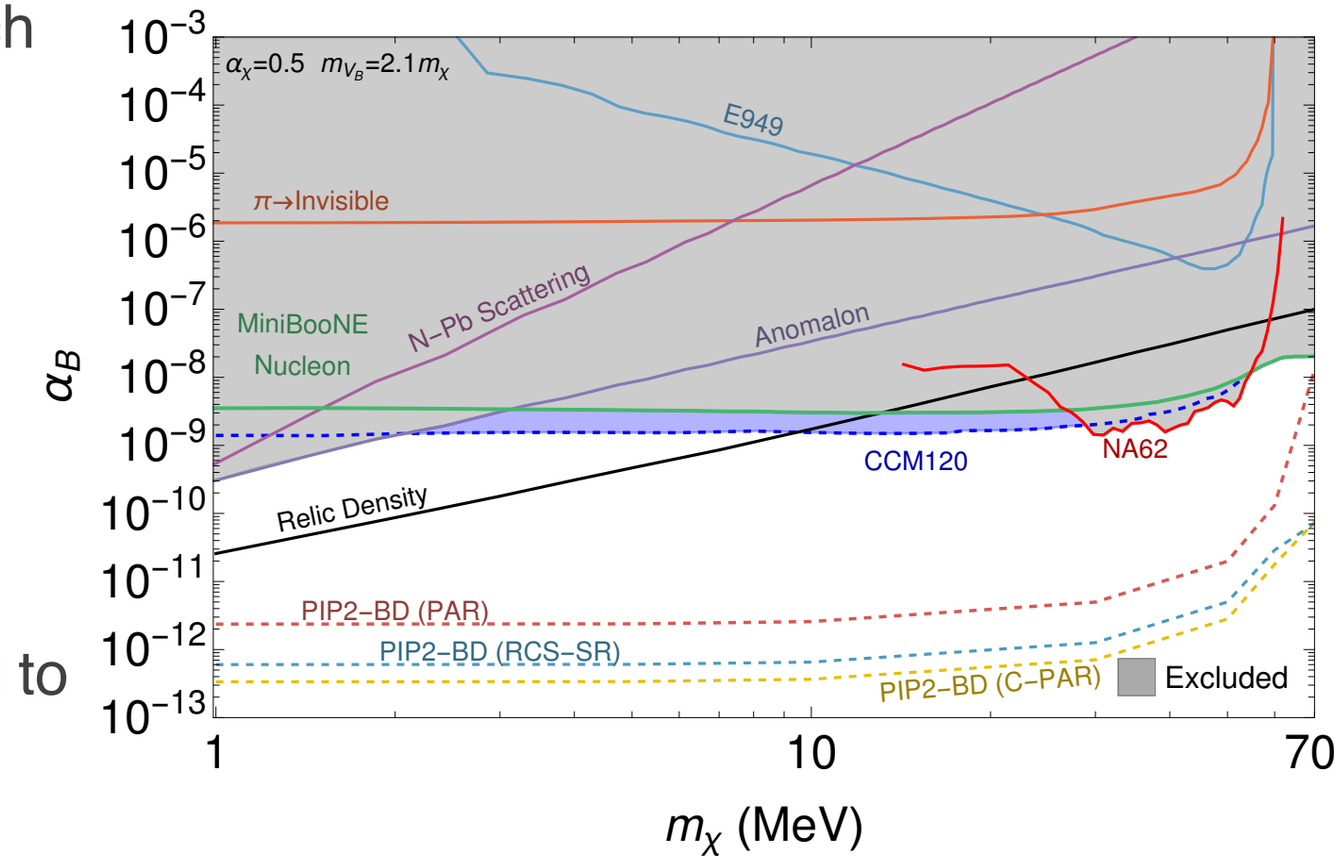


PIP2-BD Leptophobic DM Search

- Dark sector model couples to quarks rather than leptons
  - Example dark matter scenario for which proton beam searches provide robust sensitivity

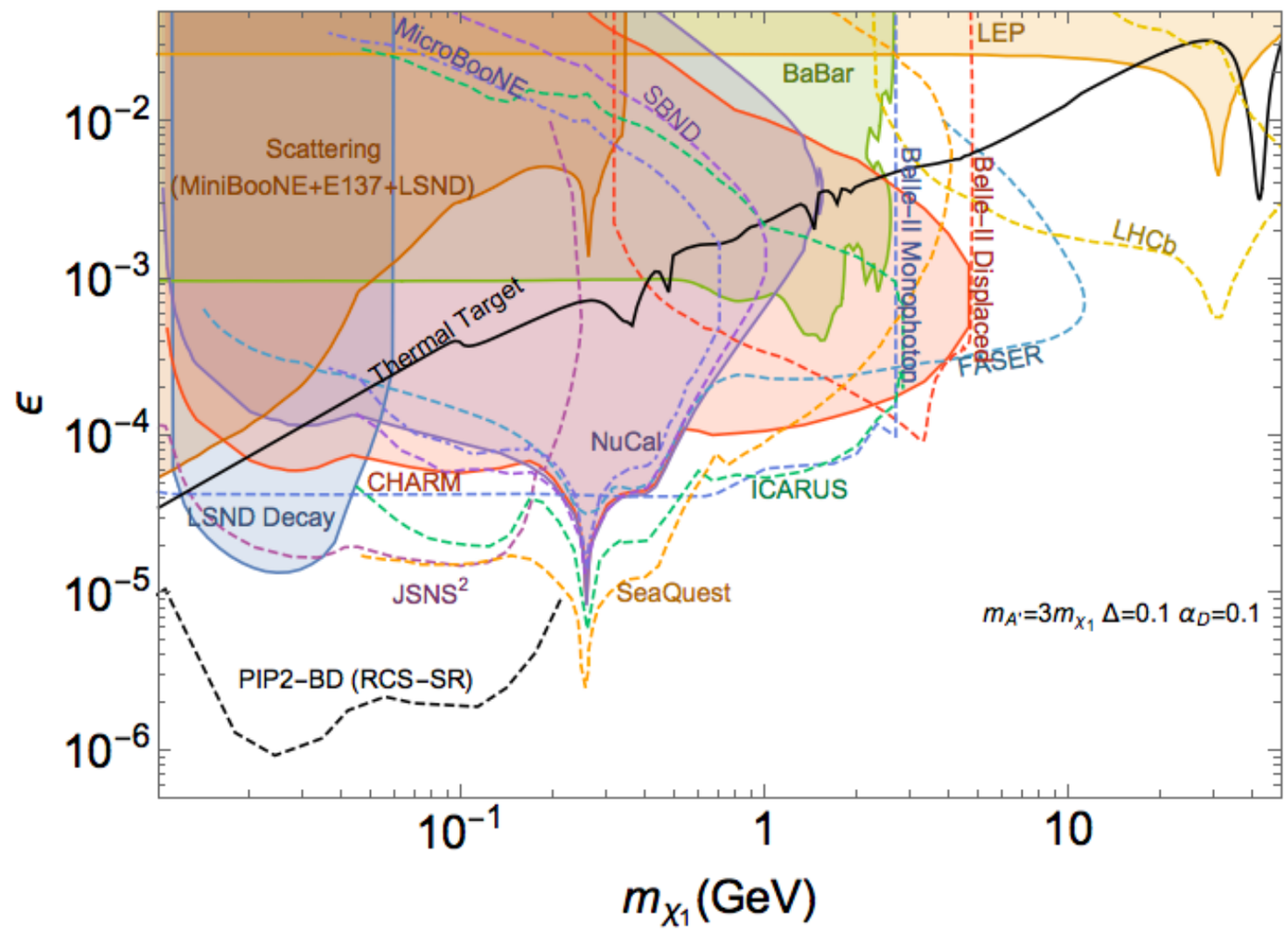
$$\mathcal{L}_B \supset -A_B^\mu (g_B J_\mu^B + g_\chi J_\mu^\chi + \varepsilon_B e J_\mu^{\mathrm{EM}})$$

- Model predicts the same DM nuclear recoil energy distributions as the vector-portal model
  - Rate scales with as $\alpha_\chi \alpha^2_B$ as opposed to ε^4
- Same procedure to compute 90% C.L. as for vector-portal model
- 5 year run with the 3 accelerator scenarios



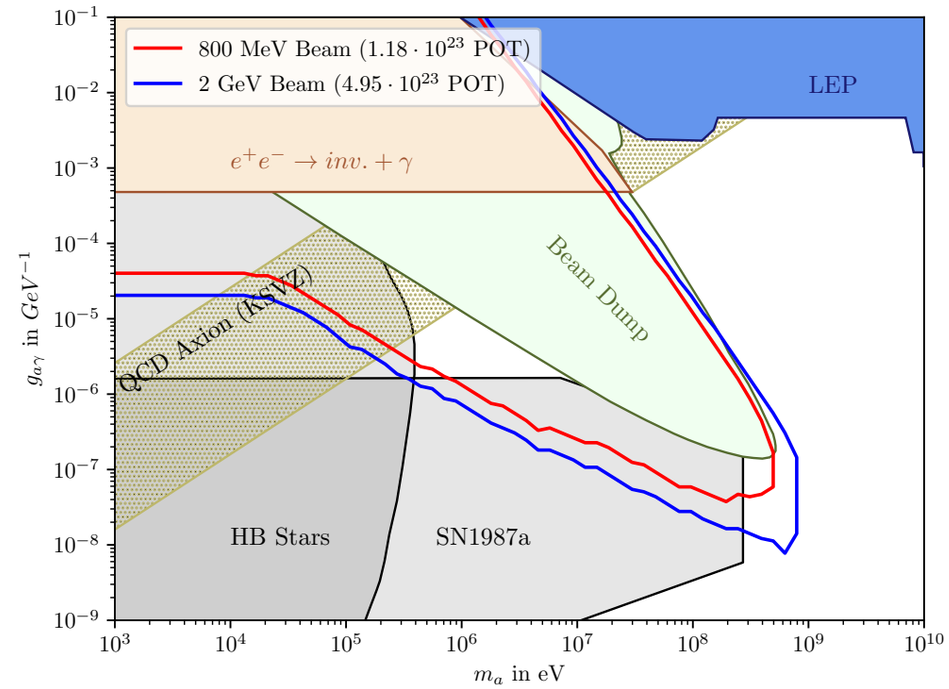
PIP2-BD Inelastic dark matter search

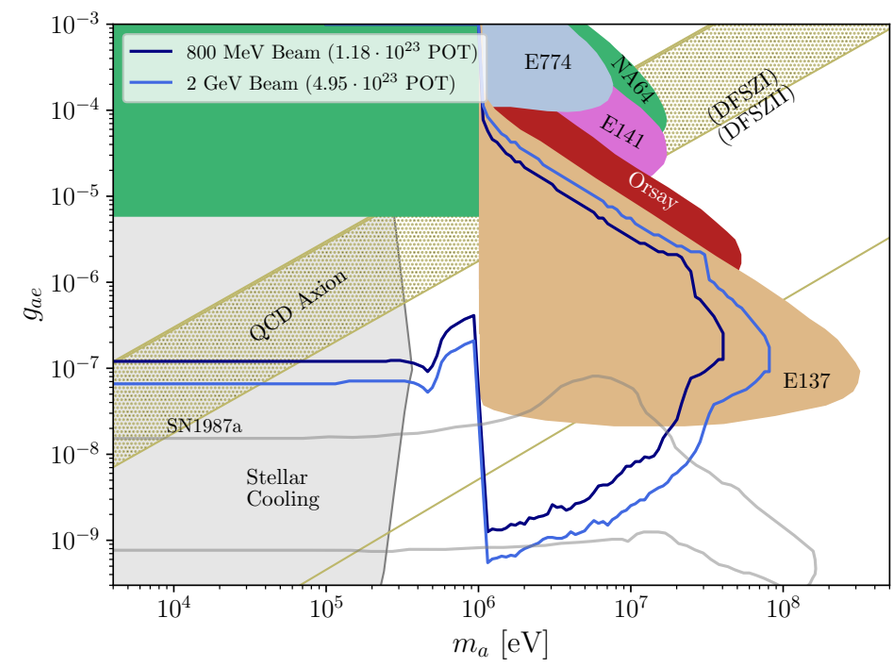
- Extend minimal vector portal scenario to include two DM particles χ_1 and χ_2
- Require $\Delta = (m_{\chi_2} - m_{\chi_1})/m_{\chi_1} > 0$
- Possibility of χ_2 decay into e+e-
- If decay not kinematically allowed, DM observation also possible through its up- or down-scattering off of electrons in the detector
- Plot 3 event sensitivity through BDMNC for 5 years of data taking
  - Expected backgrounds not yet quantified



PIP2-BD Axion-like particles (ALP) search

- ALPs that couple to photons can be produced in the beam dump via Primakoff process, detectable via inverse Primakoff process or decay into two photons
- ALPs coupling to electrons detectable via inverse Compton, e+e- conversion, or decay to e+e-
- For PIP2-BD, obtain photon flux and e+/e- flux produced in the target above 100 keV
- Compute background-free event sensitivities
- 75% sensitivity assumed based off of search using the Coherent Captain-Mills (CCM) experiment





A. Thompson, A. Karthikeyan, B. Dutta, TAMU

Summary

- Completion of PIP-II will support initial 1.2 MW beam to LBNF
- Concurrent upgrades to the Booster allow for a proton beam dump based dark sector program using existing SBN detectors
- Further upgrades in the form of an accumulator ring could produce a stopped-pion neutrino source on par with the most powerful in the world
- Stopped-pion sources provide access to a host of physics opportunities such as through CEvNS and searches for the dark sector
- **Can build stopped-pion neutrino program with facility optimized and dedicated to HEP searches**
- Preliminary studies using a 100 ton liquid argon detector show the ability for leading probes on accelerator-produced dark sector model searches
- We are looking to grow our collaboration! If you're interested in this effort or have questions, please contact us

Backup

More Information

- PIP2-BD White Paper
- SBN-BD White Paper
- White Paper on RCS option at Fermilab

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]

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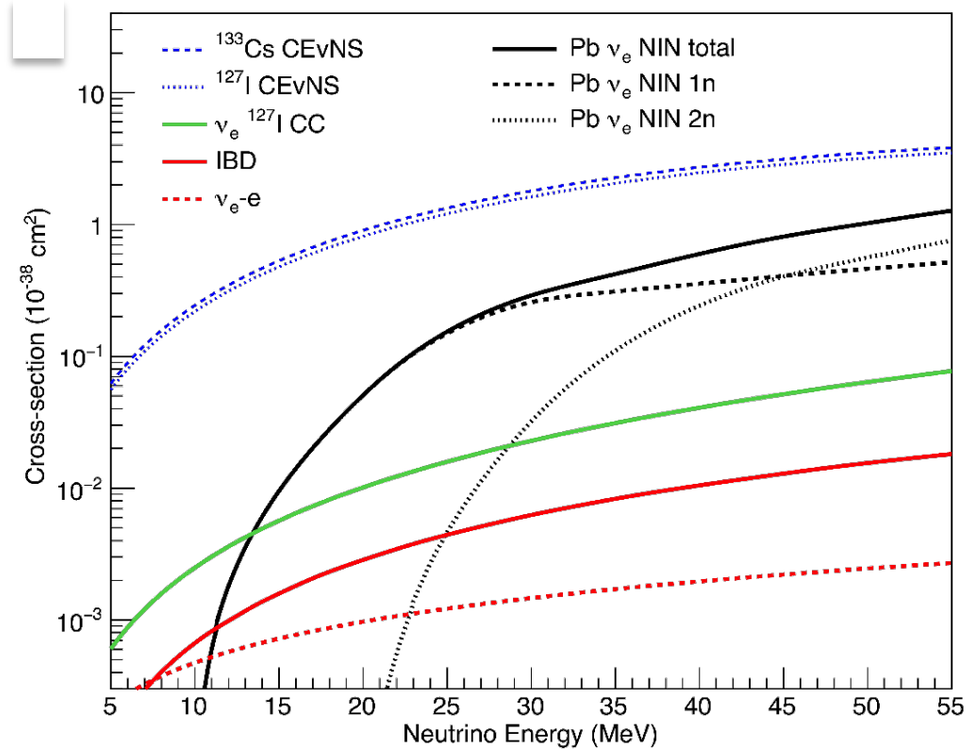
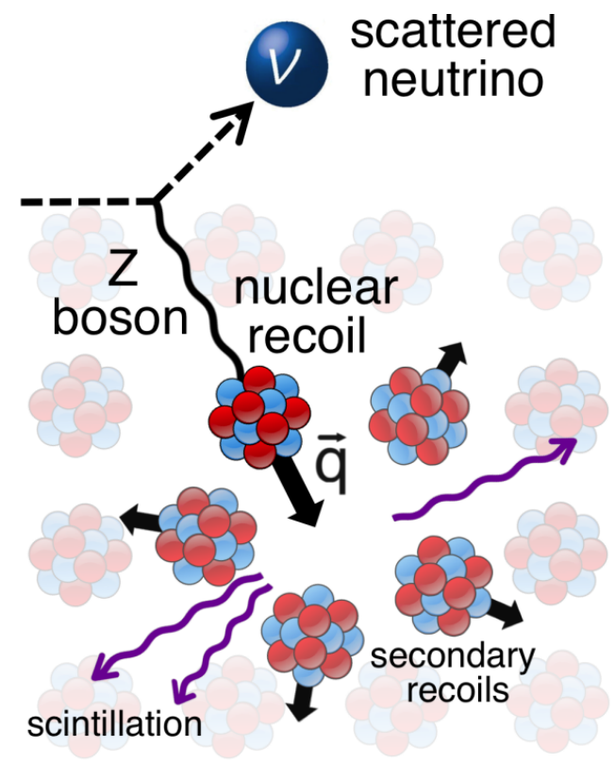
Thank you!

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

- First mentioned by Freedman in 1974
- First detected by COHERENT Collaboration with CsI[Na] target in 2017 at SNS at ORNL
- Neutrino interacts coherently with nucleons in target nucleus
- Signature is very-low-energy nuclear recoil
  - O(10 keV) for O(10 MeV) neutrino
- Largest low-energy neutrino cross section on heavy nuclei
- Distinct N^2 dependence of cross section





D. Akimov et al. (COHERENT). Science 357, 1123-1126 (2017)

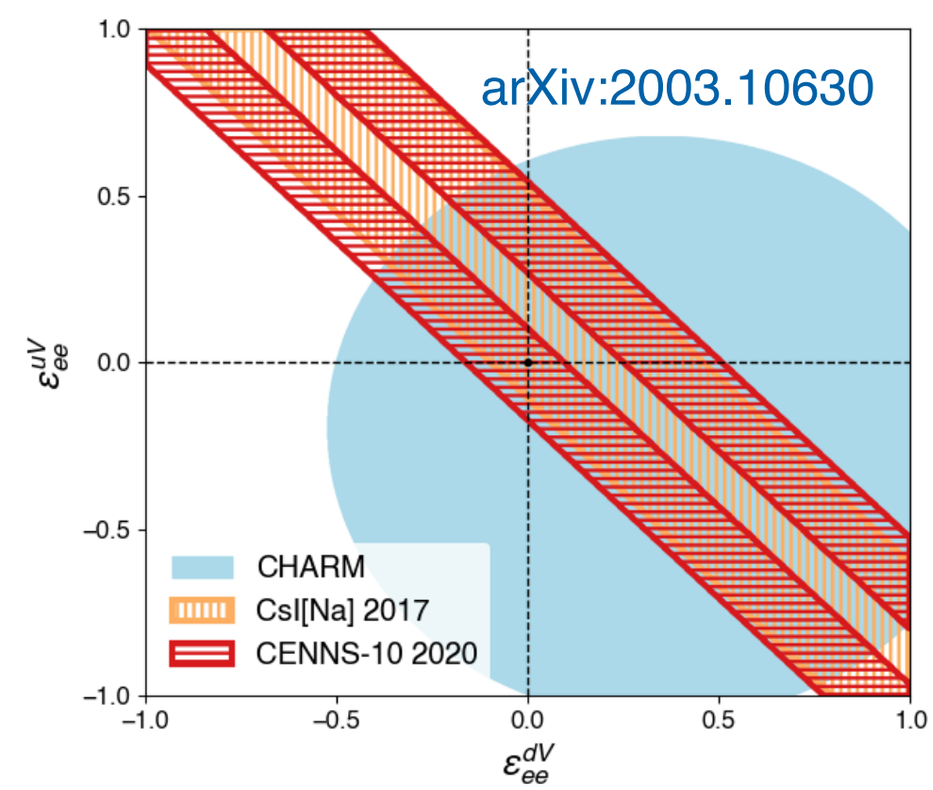
Neutrino non-standard interactions (NSI)

- Addition to SM Lagrangian as modification of weak charge

$$\mathcal{L}_{\mathrm{NSI}} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \epsilon^{f,P}_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P f)$$

$$Q_W^2 \to Q_{\mathrm{NSI}}^2 = 4\left[N\left(-\frac{1}{2} + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV}\right) + Z\left(\frac{1}{2} - 2\sin^2\theta_W + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV}\right)\right]^2$$

- CEvNS sensitive to both non-universal and flavor changing neutral currents
  - Place limits on NSI parameter space with CEvNS measurements
- Neutrino-electron scattering also sensitive to NSI



J. Barranco et al., Phys. Rev. D 76 (2007)

J. Billard, J. Johnston, B. Kavanagh arXiv:1805.01798

PIP2-BD Sterile neutrino search

- Two identical, O(100 ton) detectors at L = 15 m and L = 30 m from target
- Optimize facility to reduce beam-correlated backgrounds to negligible levels
- Assume 1:1 signal/background for remaining beam-uncorrelated backgrounds
- Off-axis
- 630 kW beam power at 800 MeV, 75% uptime
- 20 keVnr threshold with 70% efficiency above threshold
- 9% normalization systematic uncertainty correlated between two detectors
  - 36 cm path length smearing

CEvNS-based Sterile Neutrino searches

- A PIP2-BD neutrino source provides unique tool to search
  - Three flavors of neutrinos, with the ν_μ separated in time from the ν_e and anti-ν_μ
  - Using CEvNS, there are several disappearance searches available
    - Monoenergetic ν_μ disappearance at 30 MeV
    - Summed disappearance of ν_μ ,ν_e and anti-ν_μ to ν_s
    - Constrain ν_μ -> ν_e oscillation parameters

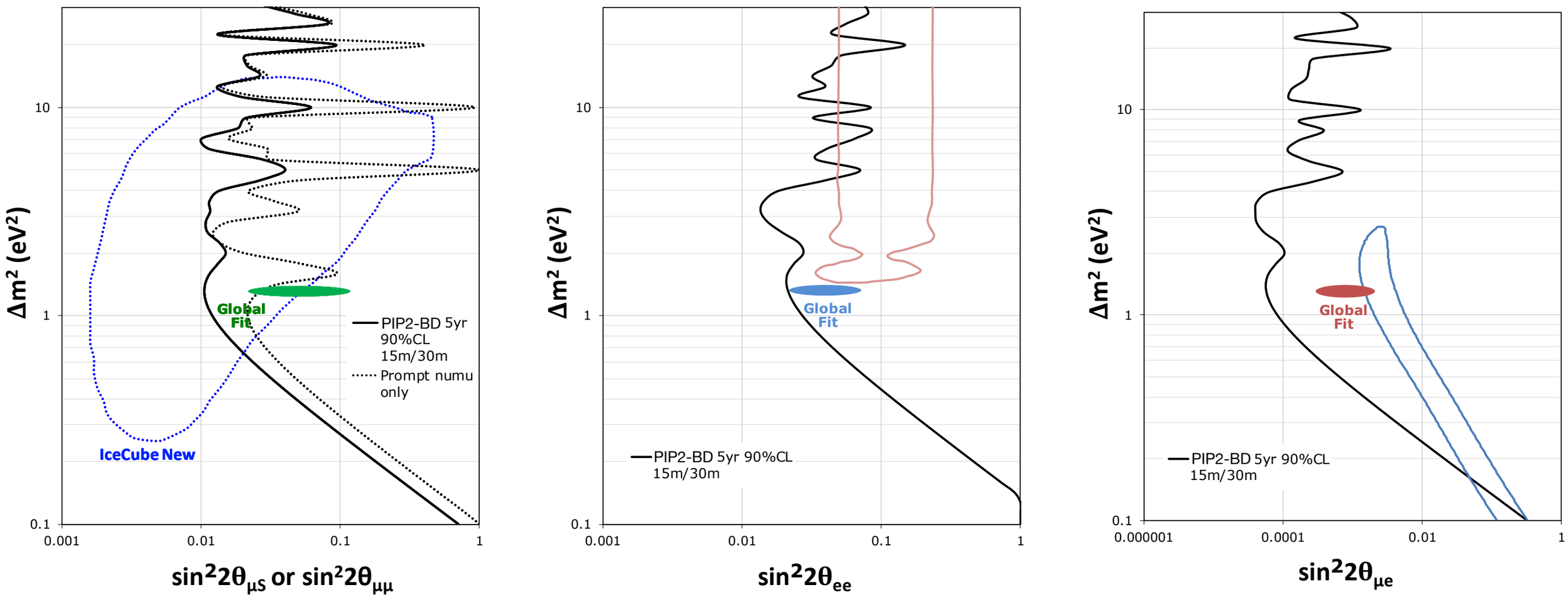


FIG. 13. PIP2-BD 90% confidence limits on active-to-sterile neutrino mixing compared to existing ν_μ disappearance limits from IceCube [45] and a recent global fit [46], assuming a 5 year run (left). Also shown are the 90% confidence limits for ν_μ disappearance (left), ν_e disappearance (middle), and ν_e appearance (right), assuming the $\bar{\nu}_\mu$ and ν_e can be detected with similar assumptions as for the ν_μ.

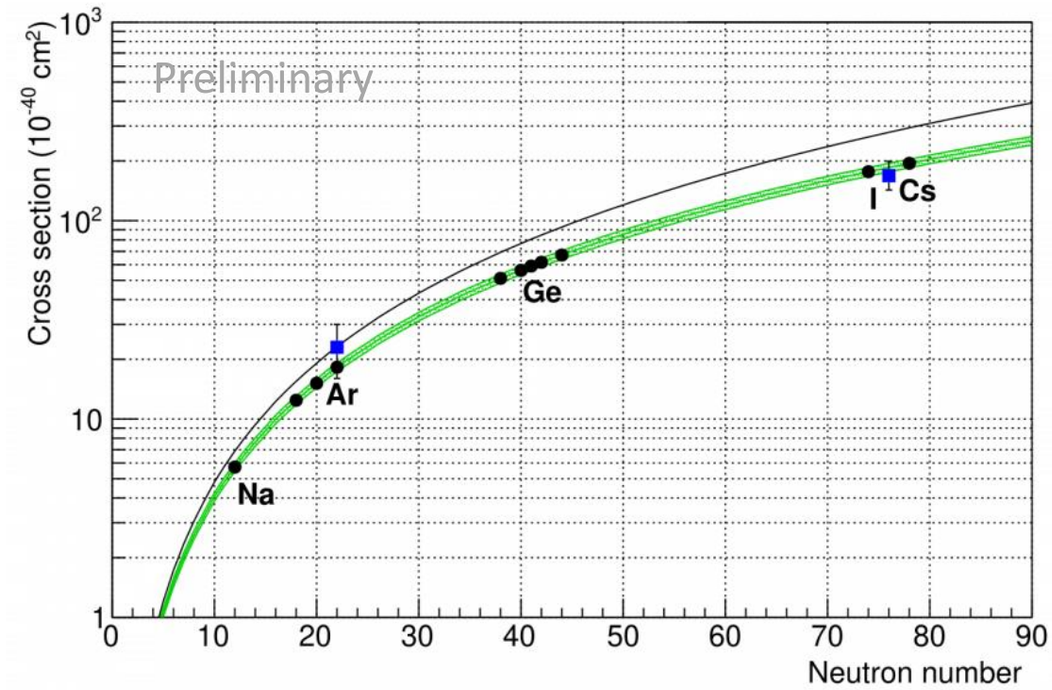
Requires separation of prompt, delayed neutrinos!

Backgrounds for CEvNS-based physics searches with LAr

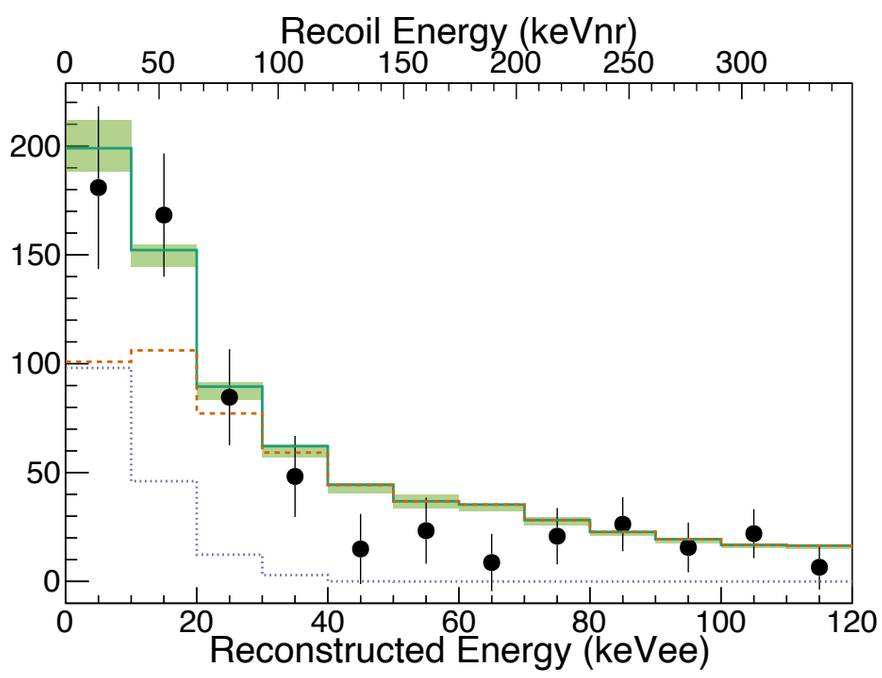
- Main backgrounds to a low-threshold physics search in LAr:
  - Beam-related backgrounds (likely fast neutrons produced by the proton collisions with target)
    - Mitigate with lower Z target material, less neutrons produced than spallation neutron sources with high Z material and shielding
      - Shielding is a challenge, other measurements show this is an achievable goal in building a facility
  - Cosmogenically produced ^{39}Ar
    - Rates of 1 Bq/kg in atmospheric argon, a steady-state background
    - Mitigate with pulsed beam timing or acquiring argon with low ^{39}Ar content (underground argon)
      - Use in direct detection DM experiments show rate lowered to ~1 mBq/kg
- Electron-recoil backgrounds also mitigated by PSD

Liquid Argon (LAr) for CEvNS-based new physics detection

- Large scintillation yield of 40 photons/keV
- Well-measured quenching factor
  - Conversion between nuclear recoil response and scintillation response
- Strong pulse-shape discrimination (PSD) capabilities for electron/nuclear recoil separation
- First CEvNS detection on argon at >3σ significance by COHERENT!
- Move toward precision physics and new physics searches with large detectors



D. Pershey, Magnificent CEvNS 2020



D. Akimov et al. (COHERENT), Phys. Rev. Lett. 126 (2021) 1, 012002