Probing the Dark Sector using an Beam Dump Facility at Fermilab in the PIP-II Era

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Fermilab Neutrino Seminar

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Overview

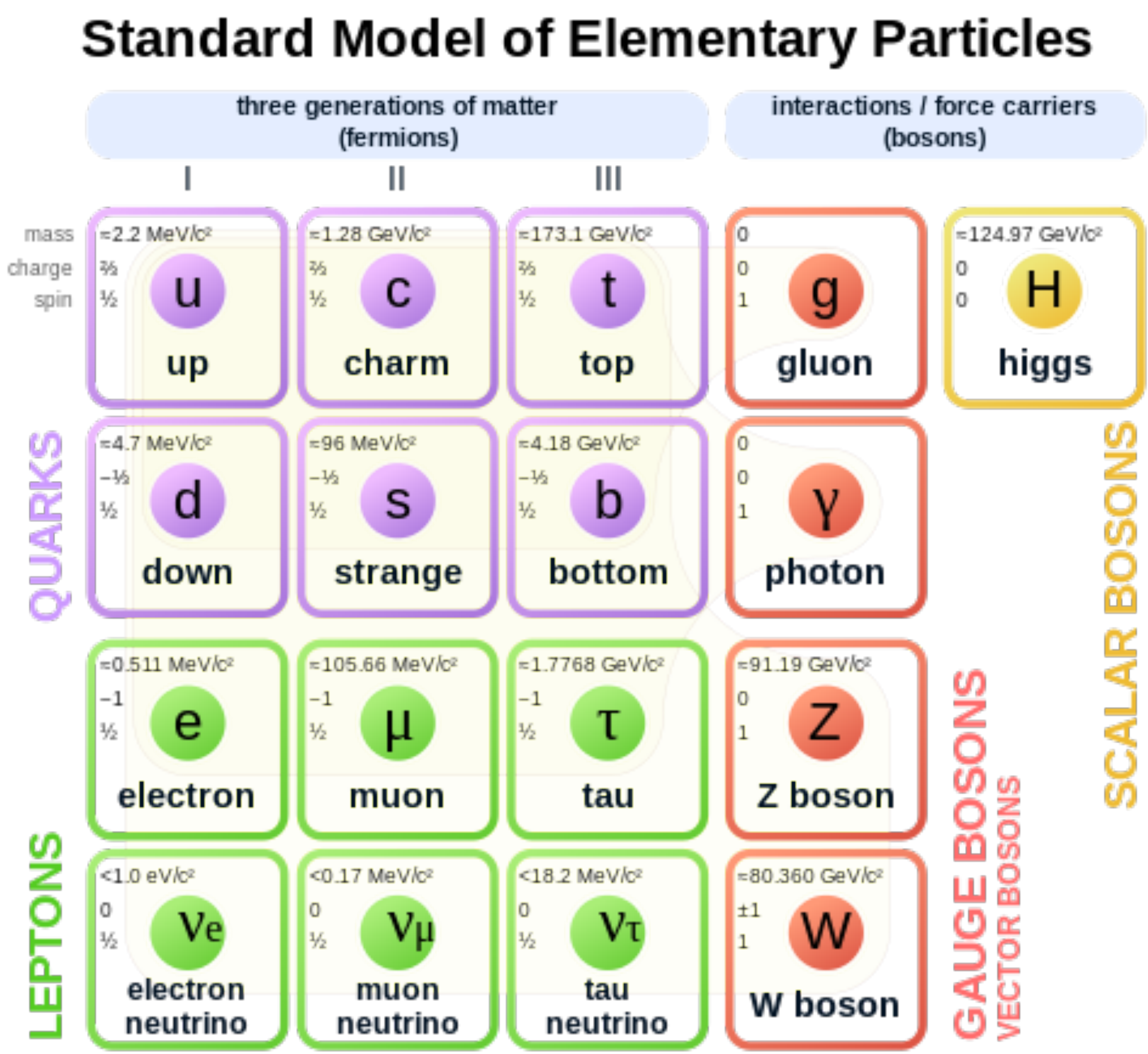
- What do we know about the possibility of new physics beyond the Standard Model of Particle Physics?

- How can the Fermilab Accelerator Complex answer be used to answer these questions?

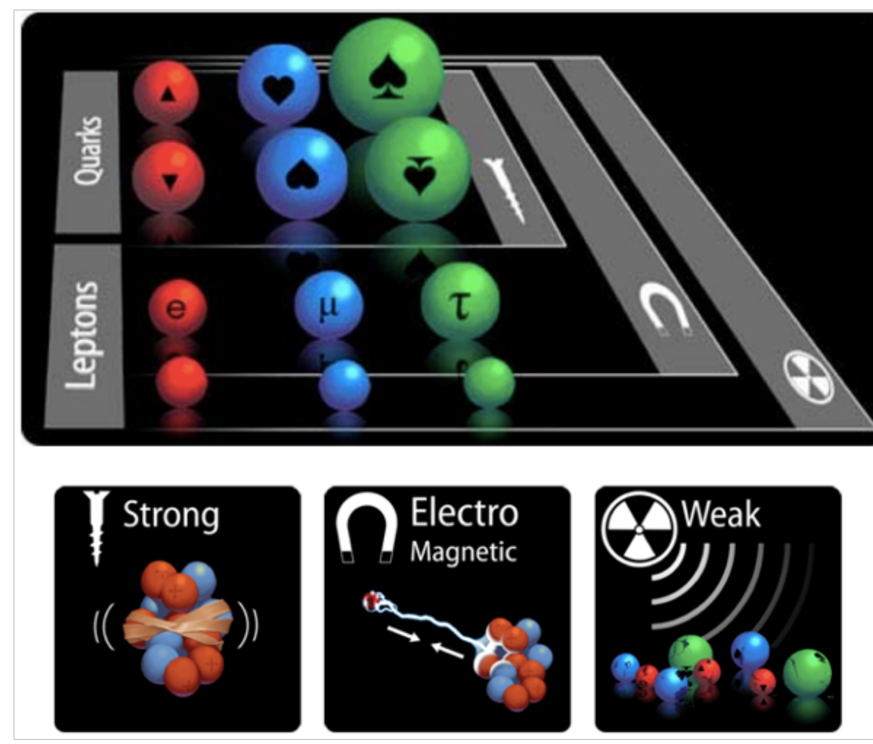
- How can we leverage the accelerator upgrades for dark sector searches moving forward with a new high-power particle beam?

What do we know about the possibility of new physics beyond the Standard Model of Particle Physics?

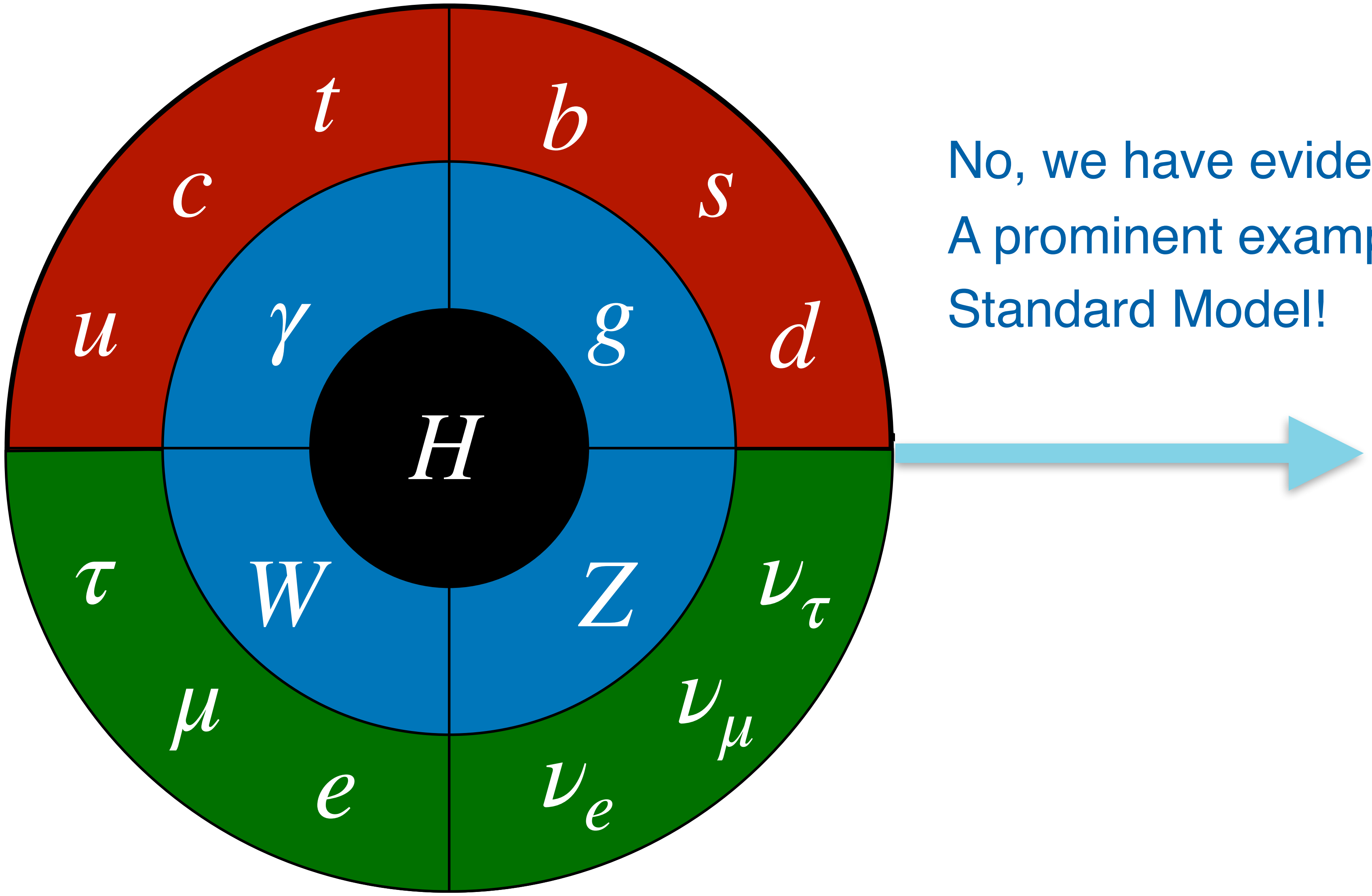
The Standard Model of Particle Physics



- The Standard Model is the theory that describes all fundamental matter and particle interactions
- It has proven remarkably successful since it was established, but there are still open questions surrounding this picture
  - Neutrino mass?
  - Particle/antiparticles behave in the same way?



Is the SM Complete?

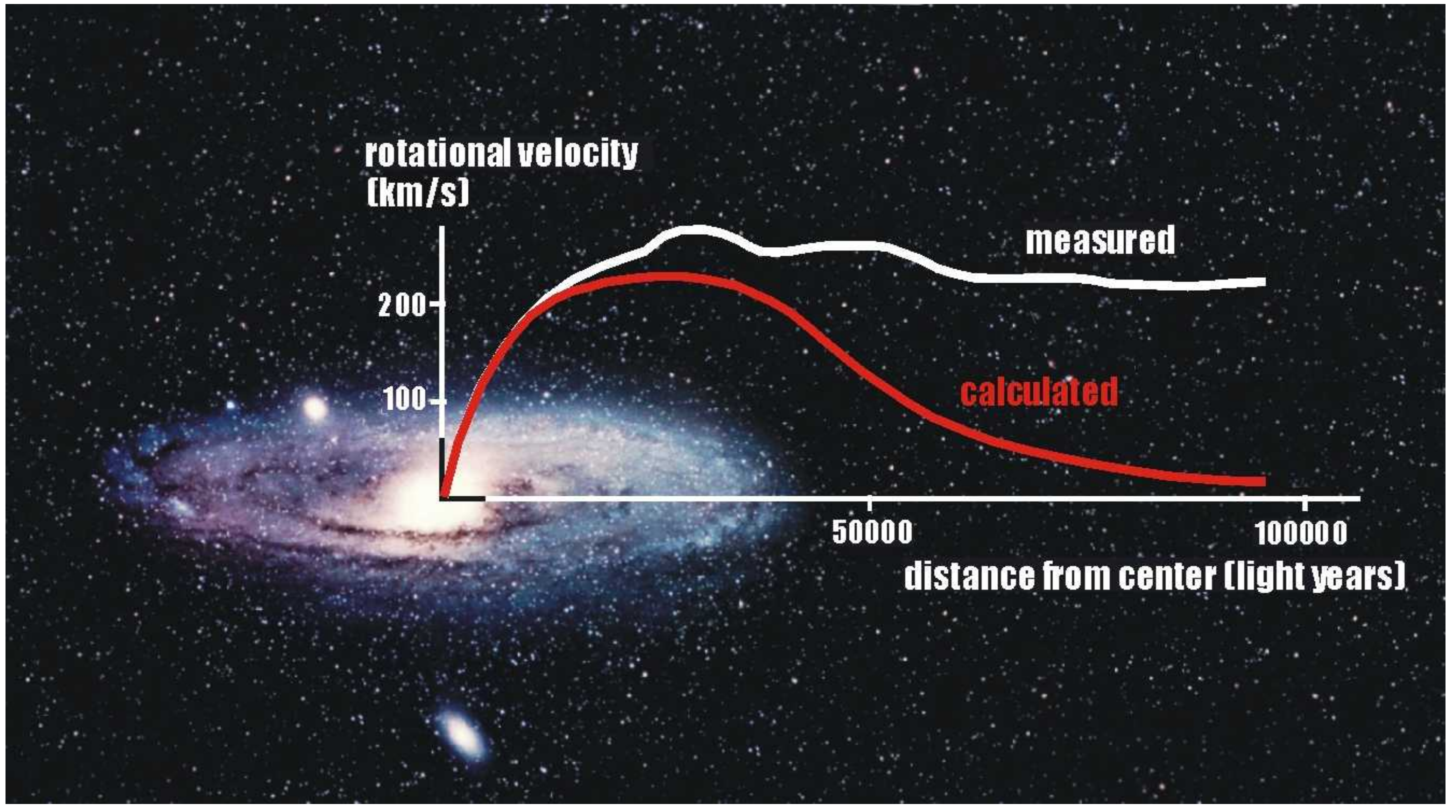


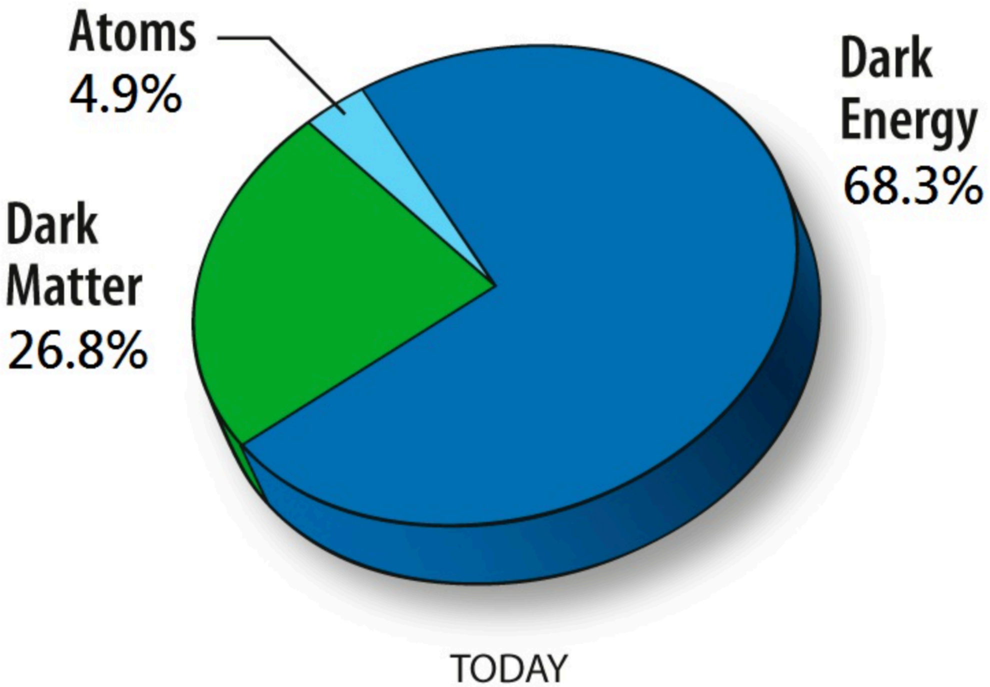
No, we have evidence that it is incomplete!
A prominent example of physics beyond the Standard Model!

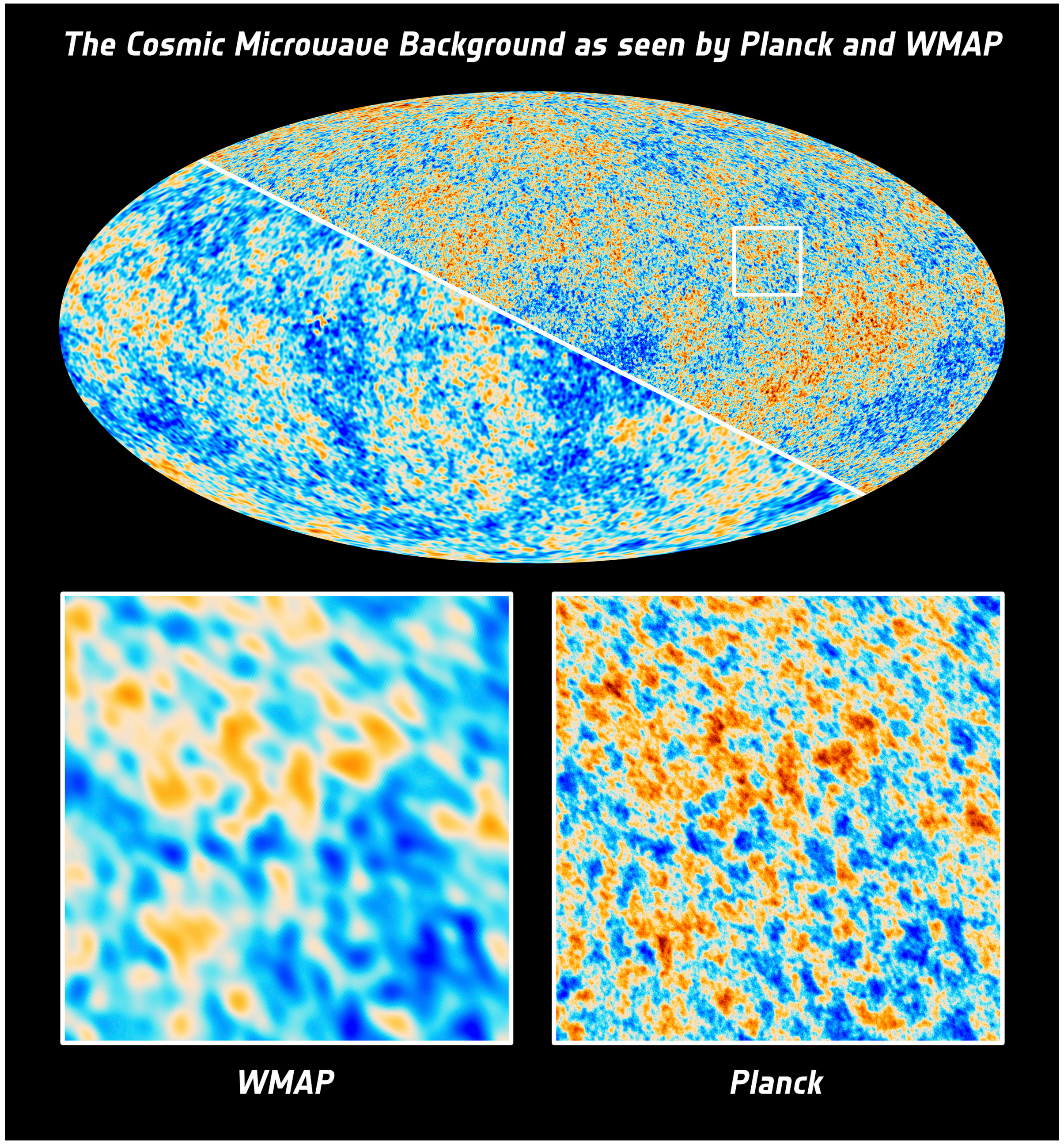
Dark matter

arXiv:2209.04671

Dark Matter Observations



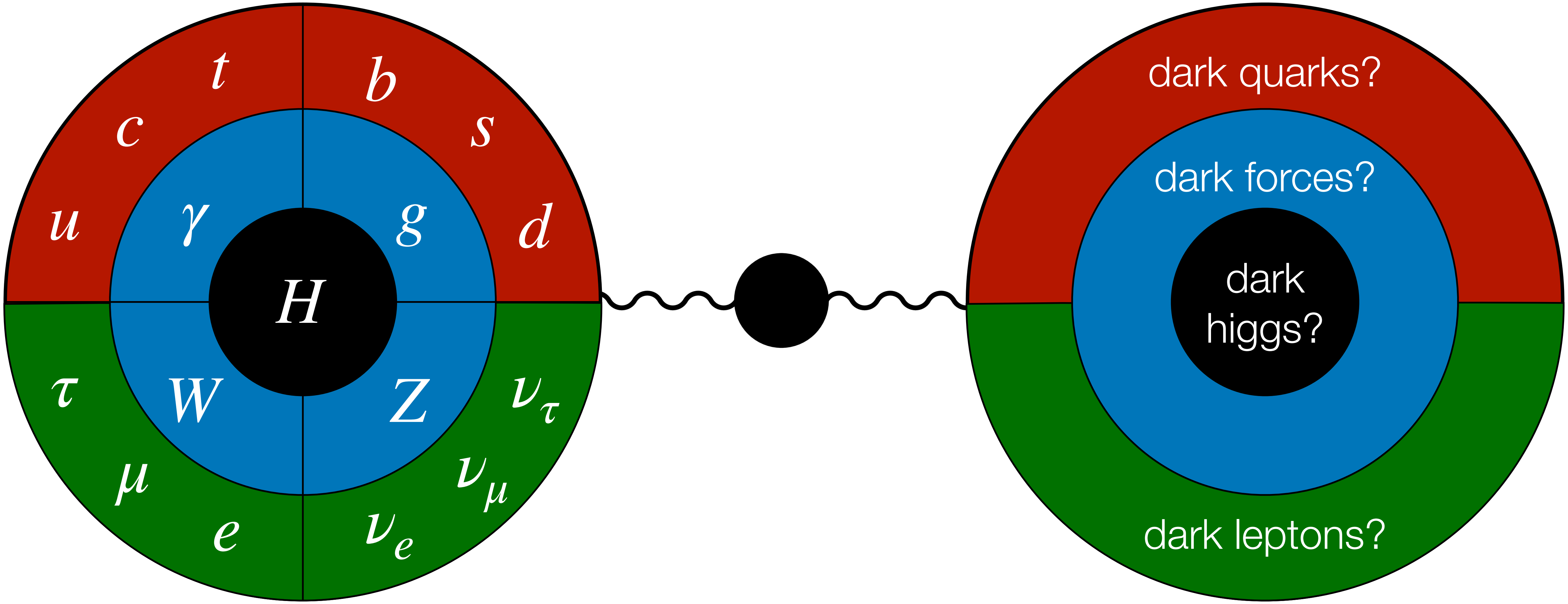




CMB measurements by Planck and WMAP

An Entire Dark Sector?

- A dark sector is motivated by the existence of dark matter



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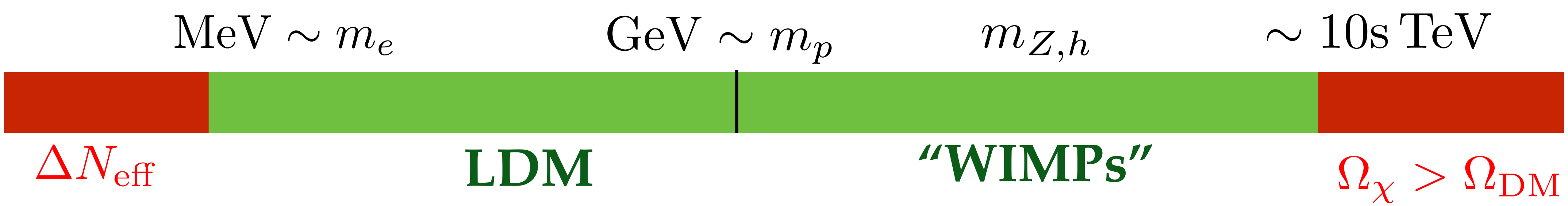
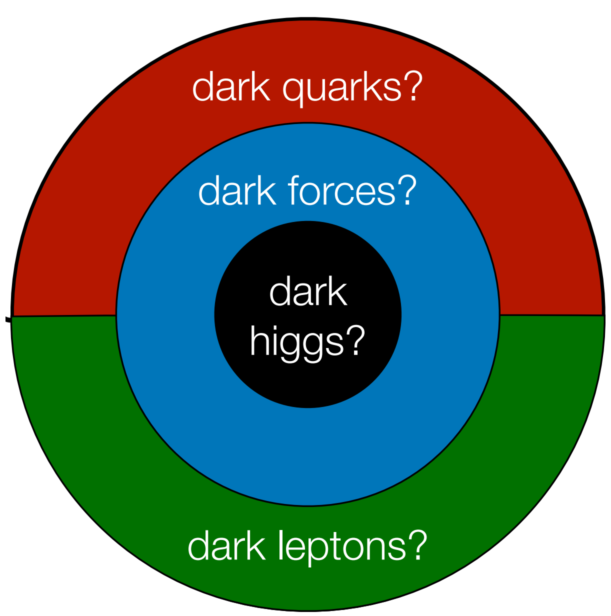
Current Landscape of Dark Matter and Dark Sector Searches



- Allowed range of dark sector space is very large
- For sub-GeV dark matter, the new physics is theorized to be neutral under SM forces
  - A finite set of operators serve as a portal to a possible dark sector



Vector portal (“dark force, dark photon”)

Higgs portal (“dark Higgs, dark scalar”)

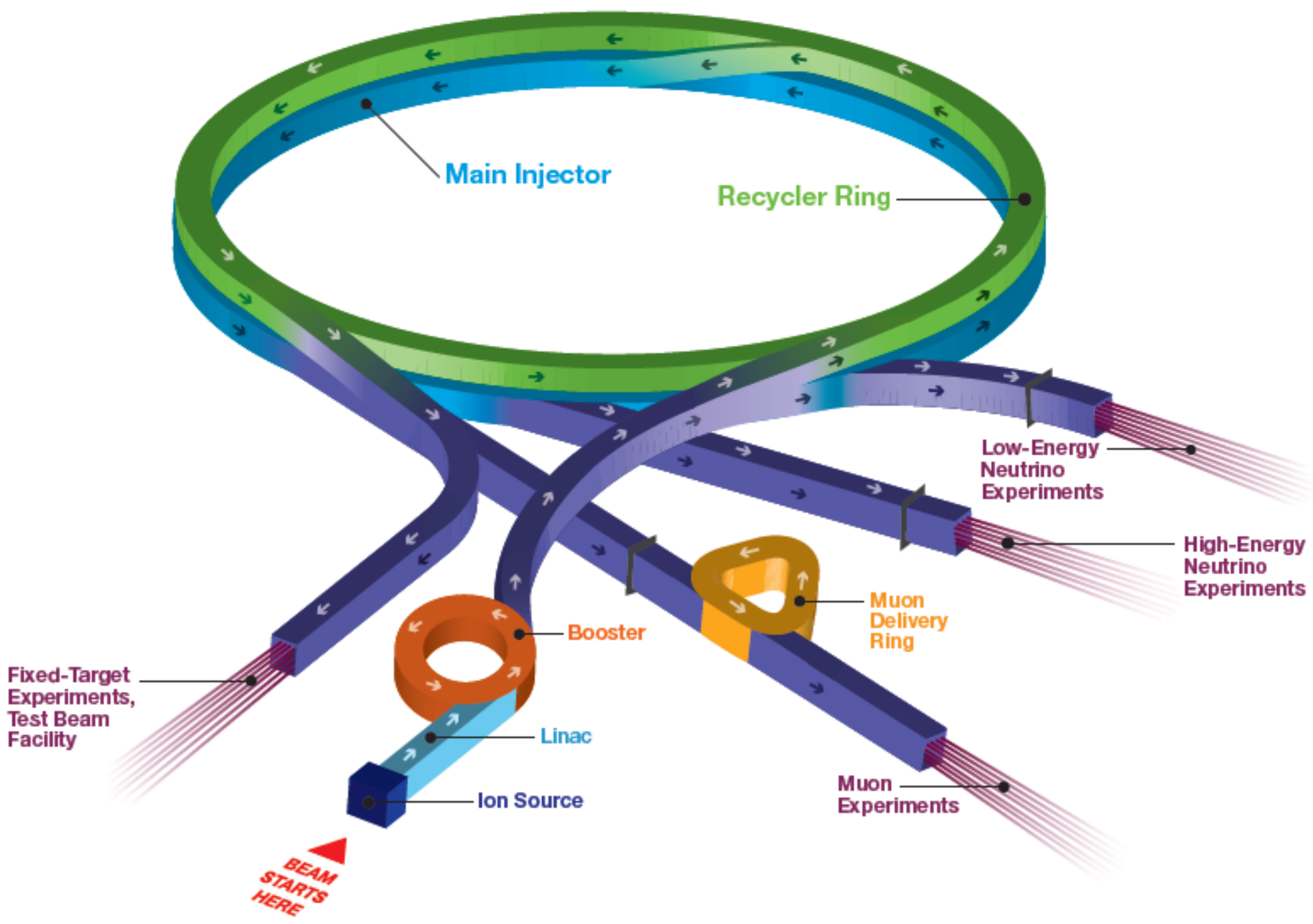
Neutrino portal (“dark lepton, heavy neutral lepton”)

Axion portal (“axion-like particle”)

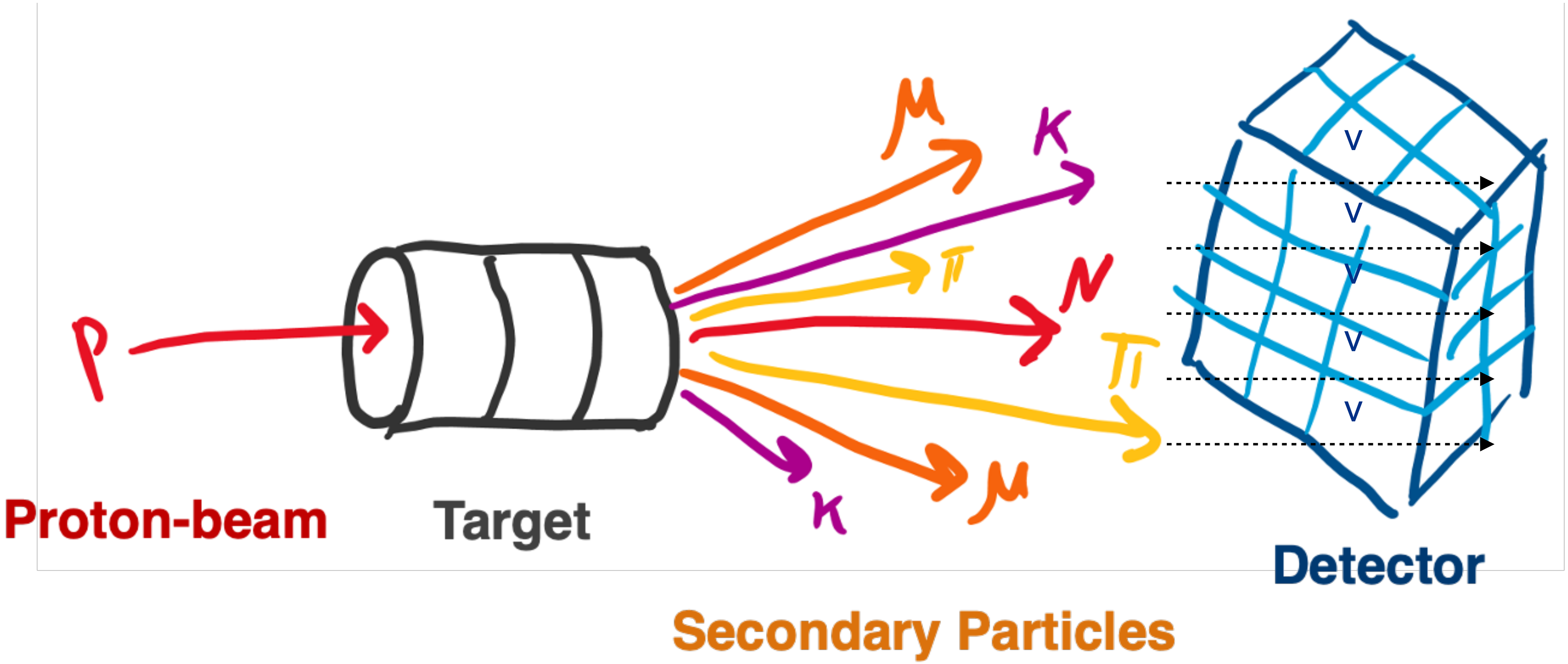
How can the Fermilab Accelerator Complex be used to answer some of these questions?

The Current Fermilab Accelerator Complex

- The current Fermilab accelerator complex hosts energetic beams of particles that can be used to answer some of these questions

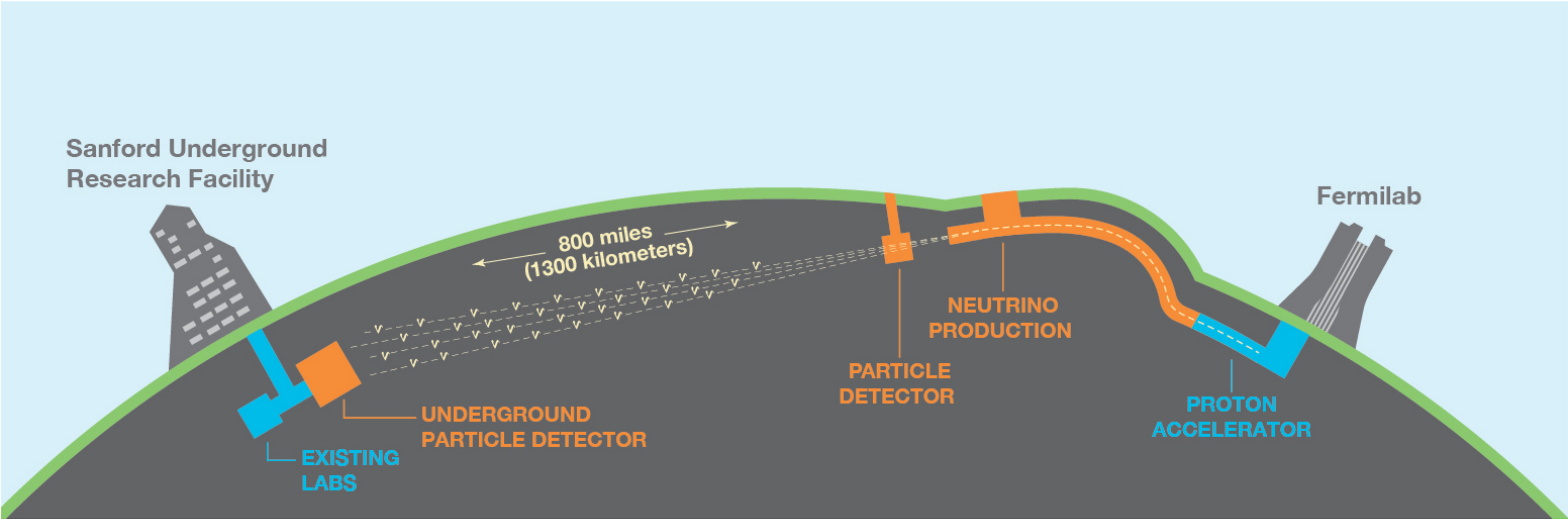


Particle Production with Energetic Proton Beams



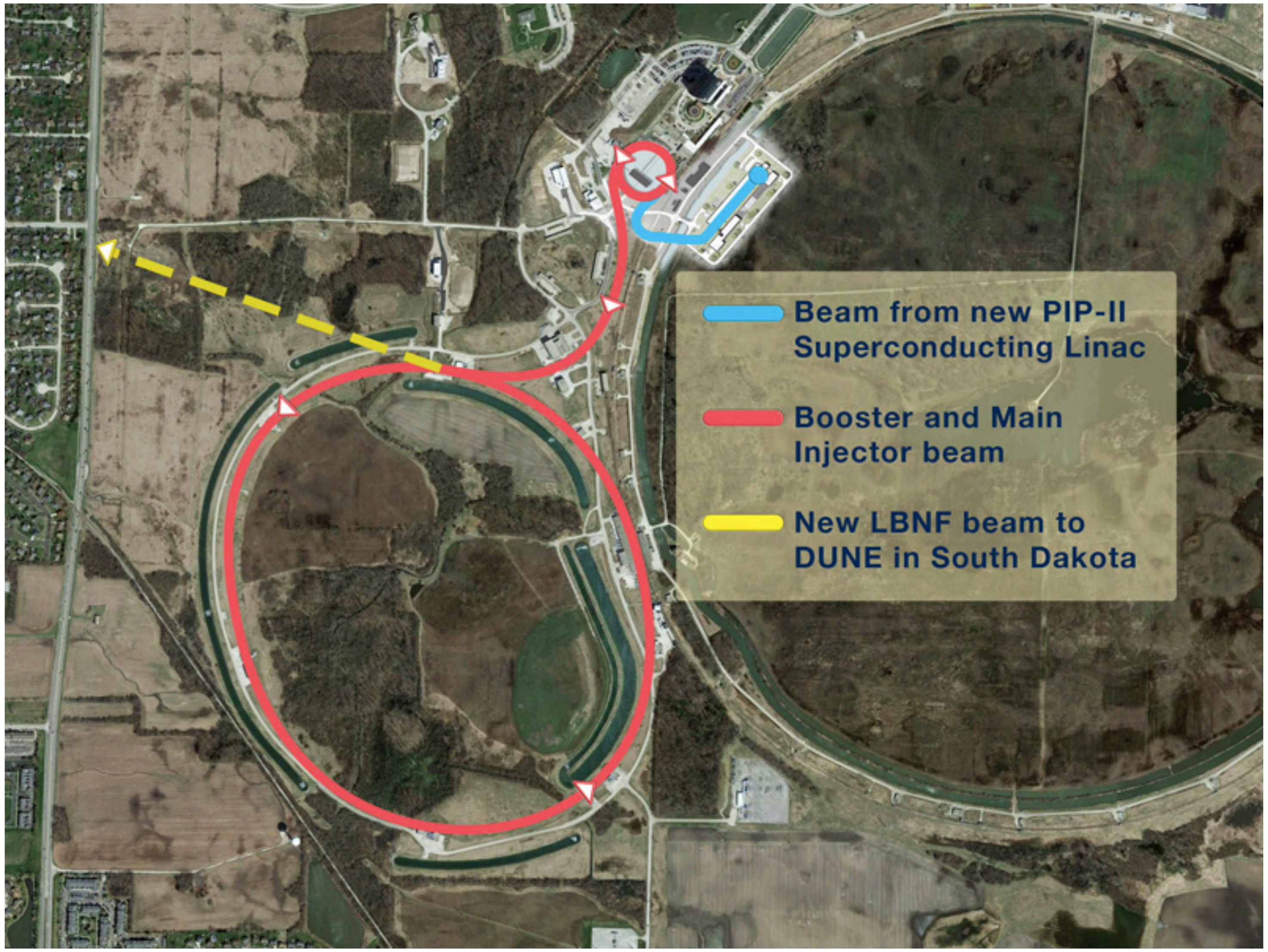
The Deep Underground Neutrino Experiment (DUNE)

- DUNE can provide input on the neutrino mass, the matter/antimatter asymmetry, and is a laboratory for Beyond the Standard Model (BSM) physics
- DUNE consists of a high intensity neutrino beam and near detector complex at Fermilab, including a liquid argon detector
- Large, deep underground liquid argon far detectors at SURF in Lead, SD



The Proton Improvement Plan II (PIP-II) Project

- The physics goals of DUNE require an upgrade of the accelerator complex
- The PIP-II project will make the Fermilab Accelerator Complex among the highest power ~GeV proton beams in the world
  - Completion date around the end of this decade
  - DUNE only requires a small fraction of the available protons
  - These upgrades open the door to other exciting physics searches, as you will see in the rest of this talk!



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PIP-II Timeline

We are here!

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

Mar 2018
Approve Alternative Selection (CD-1)

Mar 2019
Linac Complex Ground-Breaking

Jul 2020
Cryoplant Bldg. Construction Approved

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

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

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

Sep 2024
Linac Tunnel Occupancy

Jan 2027
Shutdown Complex Operations For Booster Connection

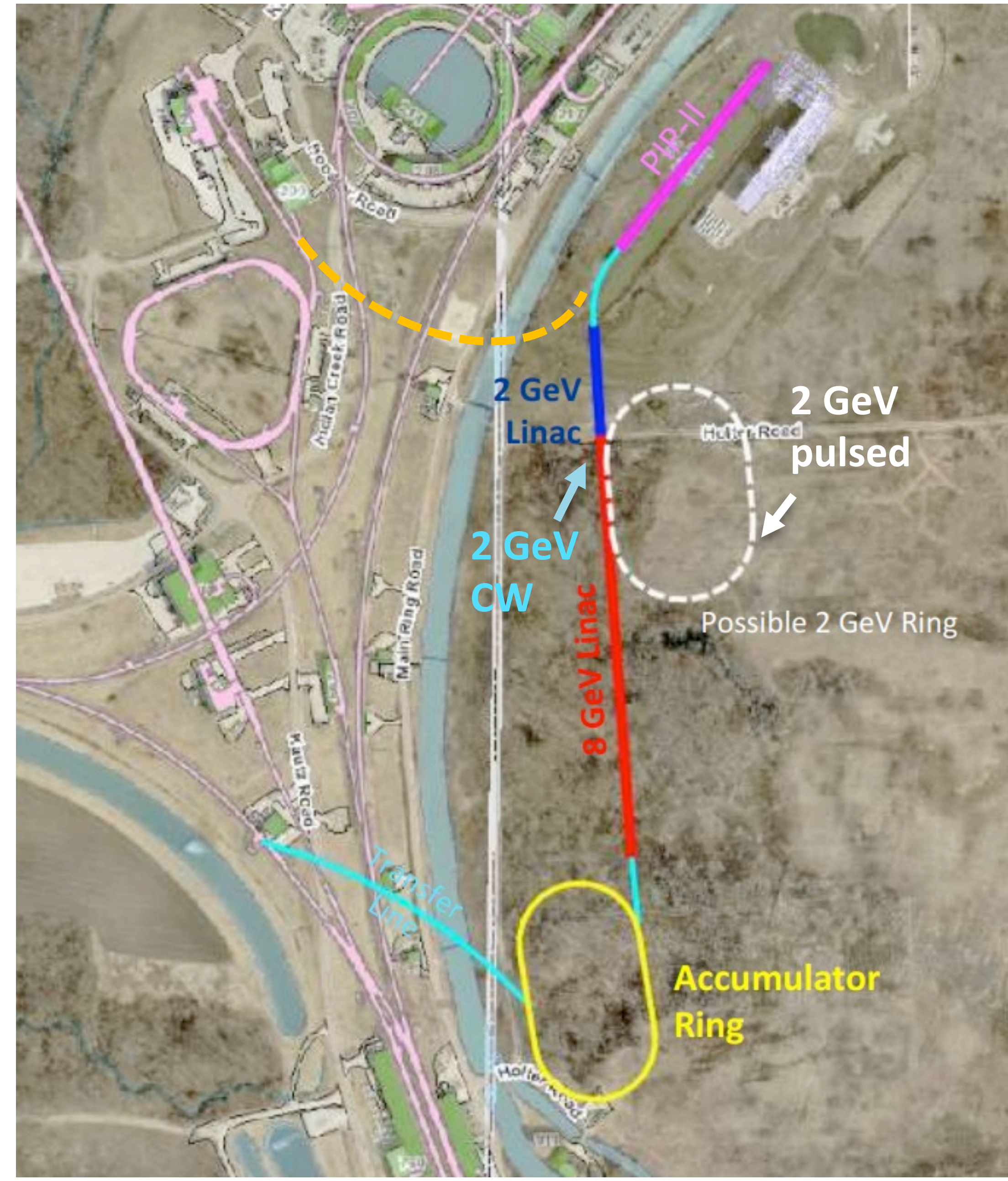
Jan 2027
SRF Linac Comm. Begins

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

The view from my office!

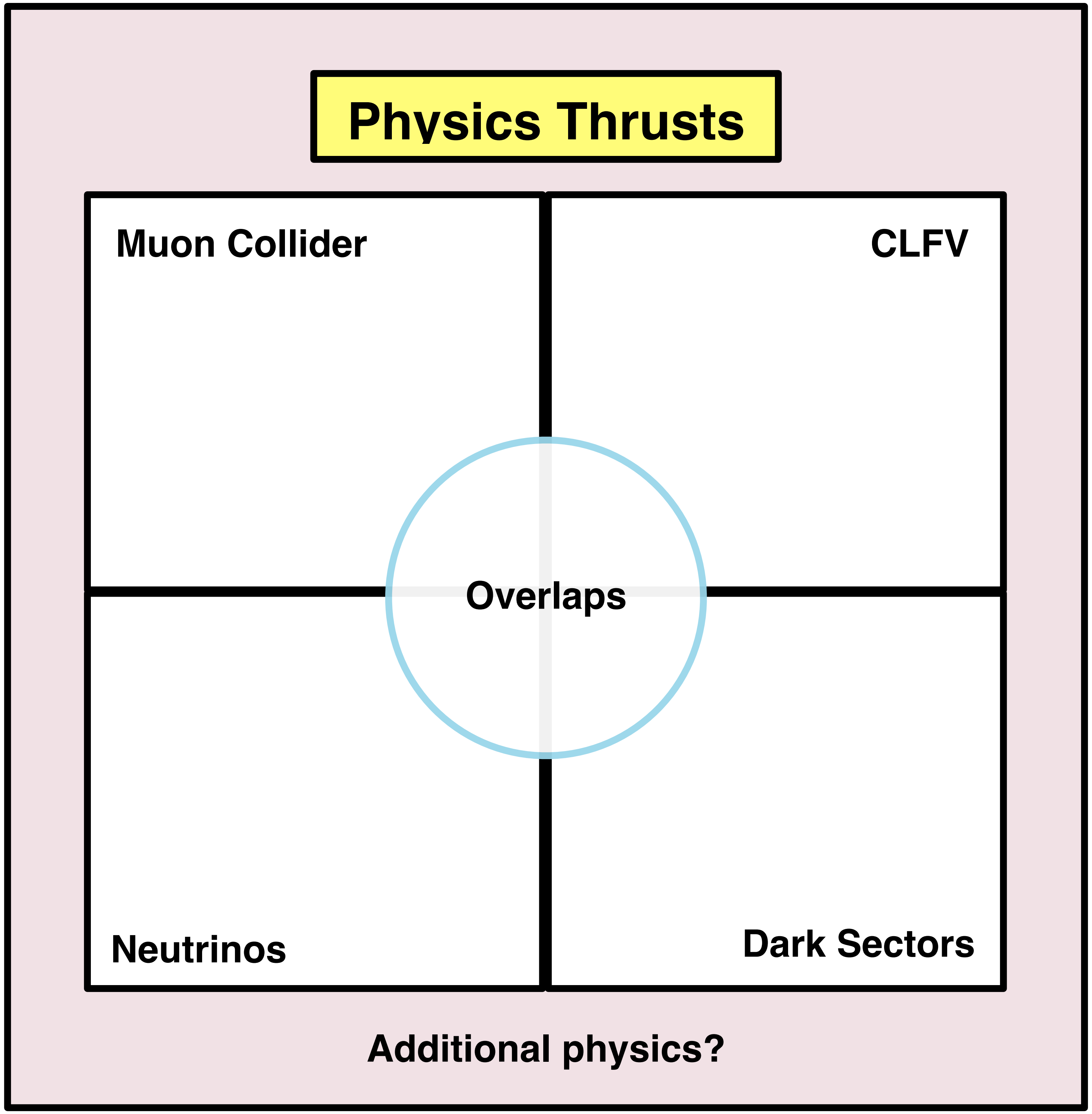
The Fermilab Accelerator Complex Evolution (ACE)

- Upgrades to the Main Injector and LBNF Target station in the early 2030s (ACE-MIRT) to improve the cycle time providing a path to multi-MW class beams for DUNE
- Establish project to replace the Fermilab Booster in late 2030's (ACE-BR)
  - Provide reliable platform for the future of the FNAL Accelerator Complex replacing the current synchrotron
- Next generation possibilities include a higher energy linac and an accumulator ring



Highlighting a lot of the possibilities of ACE!

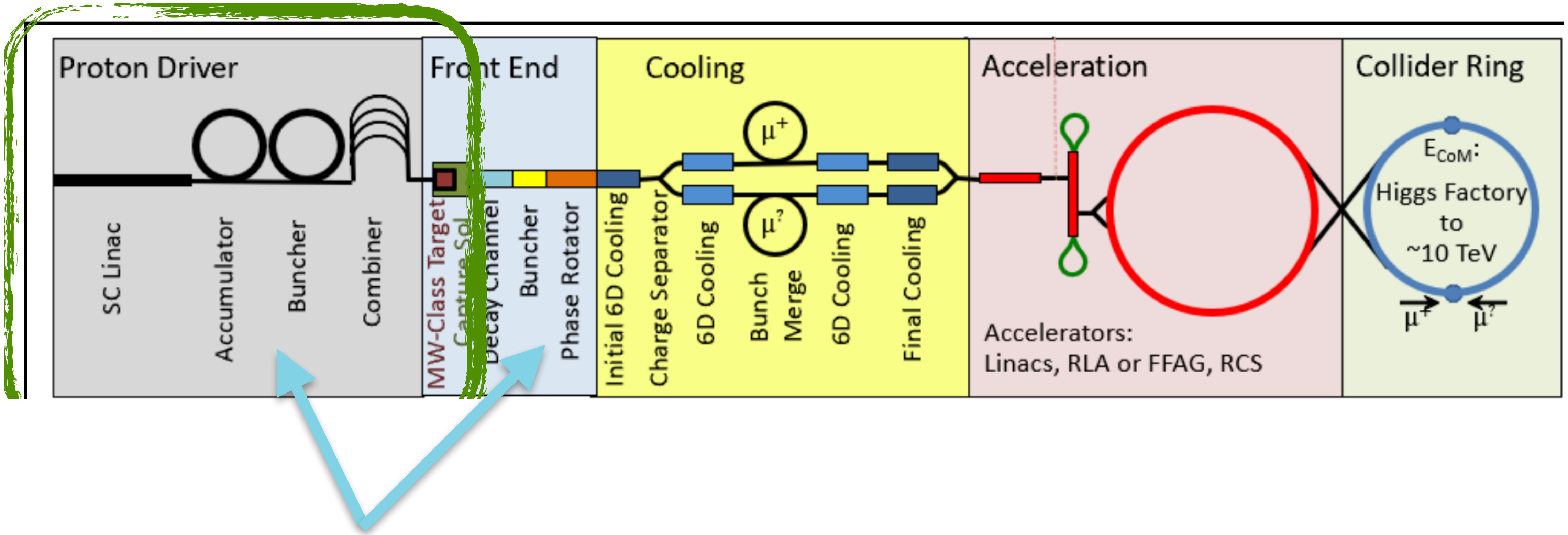
Physics Possible with ACE



There are opportunities in several physics sectors for Fermilab via ACE to provide world-leading capabilities

Future Muon Collider R&D

- T here are discussions about the next large-scale collider project after the Large Hadron Collider at CERN
- One possibility being considered is a muon collider
- The synchrotron replacements envisioned under ACE are similar to those needed for a muon collider and could represent an R&D opportunity at Fermilab towards this goal



Similar to ACE scenario

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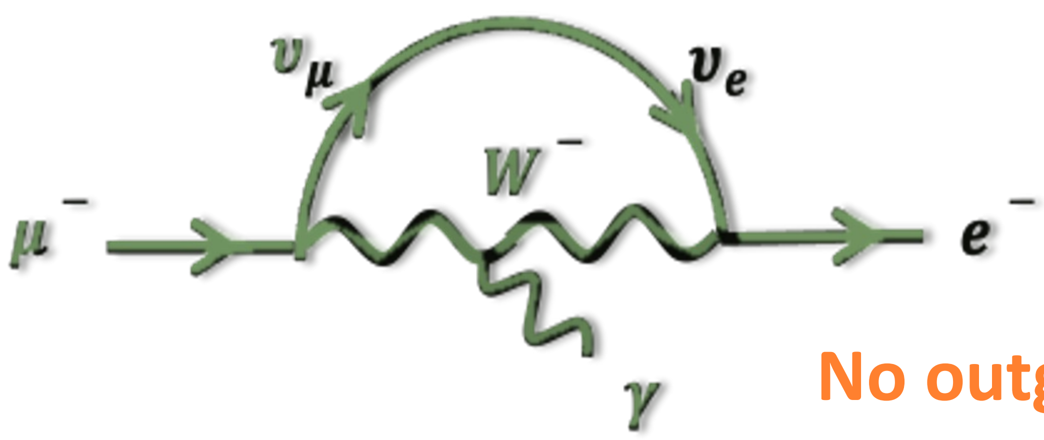
Charged Lepton Flavor Violation (CLFV)

- Possibility that the lepton flavor number in interactions is not conserved
- Represents another clear signature of Beyond the Standard Model physics!
- Improving on current limits requires high-intensity muon beams
  - The proton beams at Fermilab can also produce muon beams!



No outgoing neutrinos!

The Standard Model predicts: $\mathcal{B}(\mu \to e\gamma) \sim 10^{-54}$

$$R_{\mu \to e} = \frac{\Gamma\left(\mu^- + N(Z,A) \to e^- + N(Z,A)\right)}{\Gamma\left(\mu^- + N(Z,A) \to \nu_\mu + N(Z-1,A)\right)} < 6 \times 10^{-17} \text{ (90\% CL)}$$

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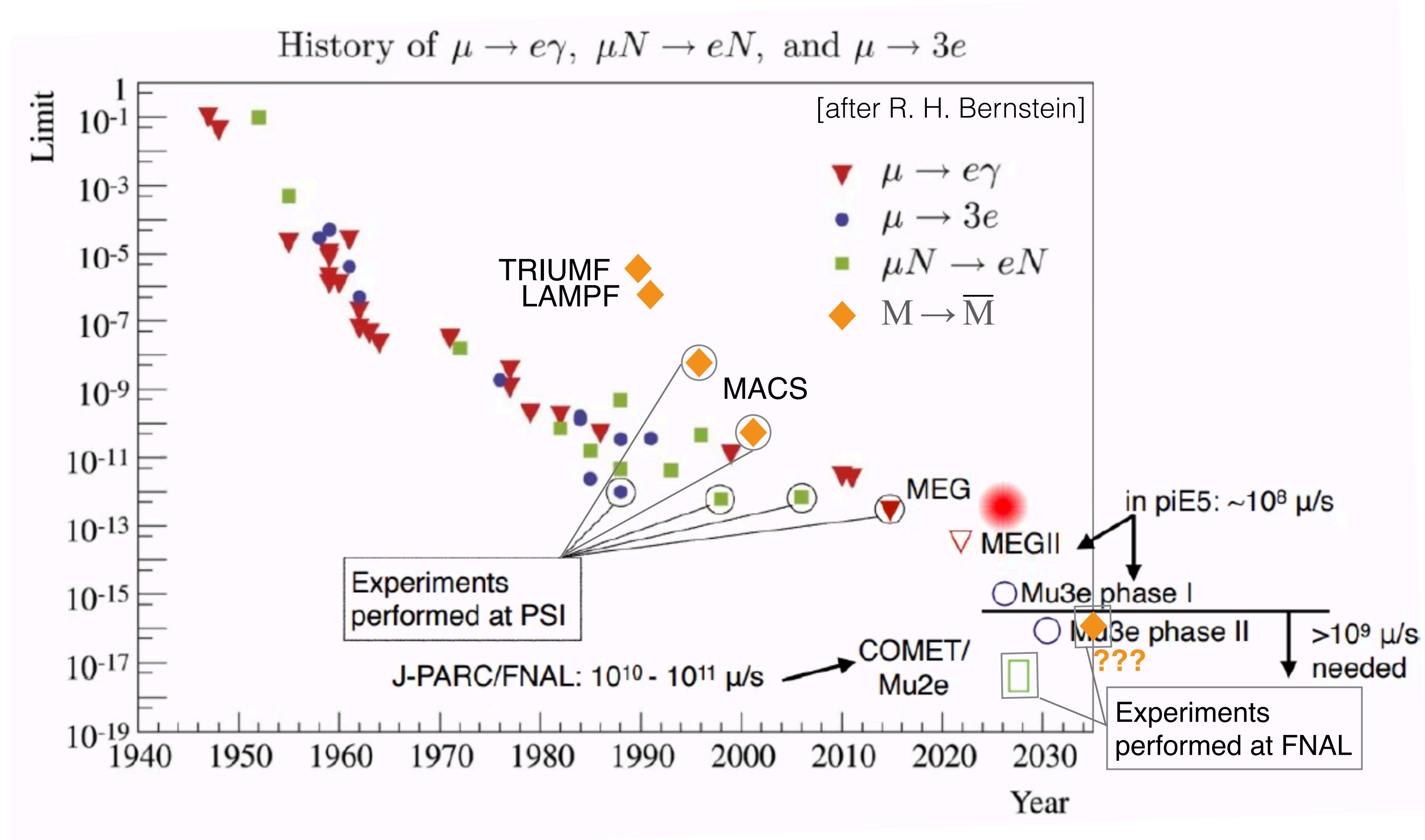
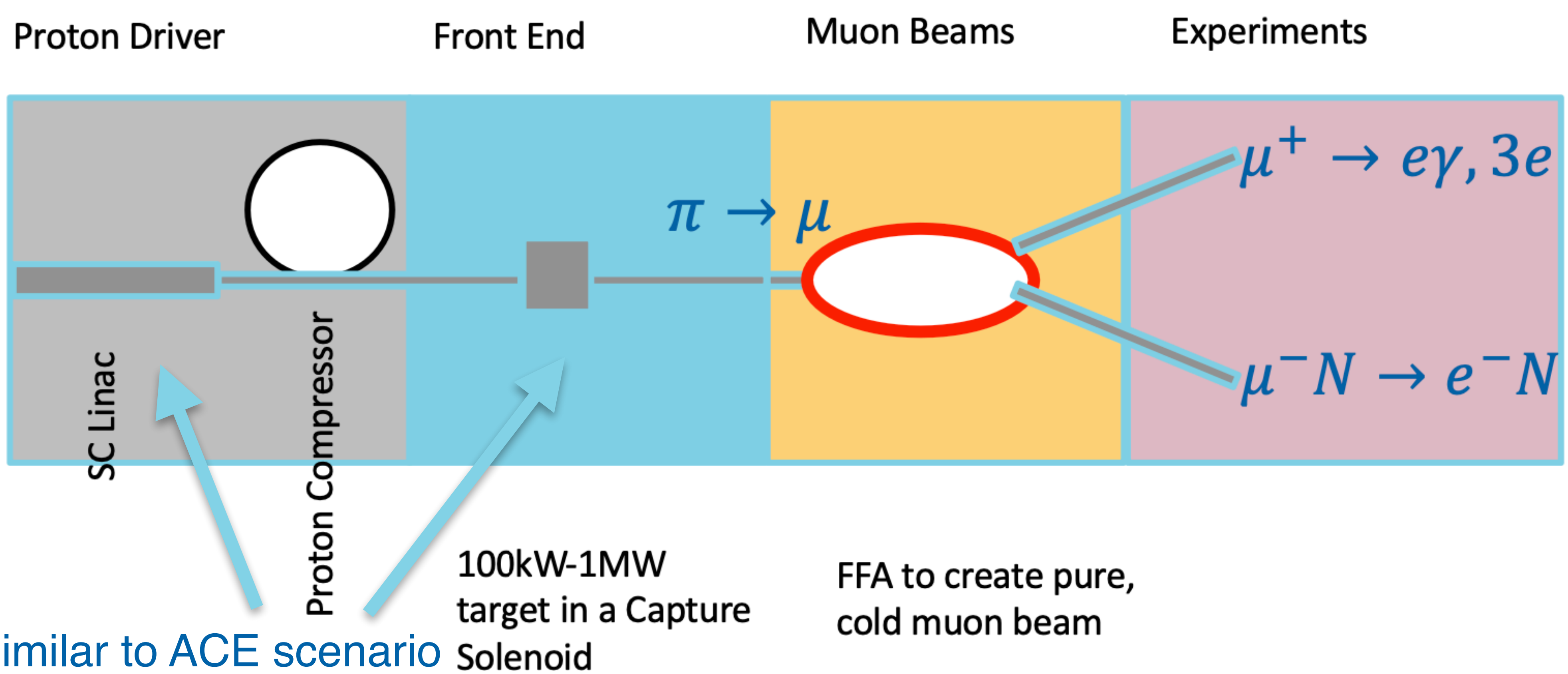
Muon Physics and Mu2e-II

- Opportunity at Fermilab to improve on existing CLFV limits through experiments such as Mu2e and Mu2e-II using PIP-II and ACE



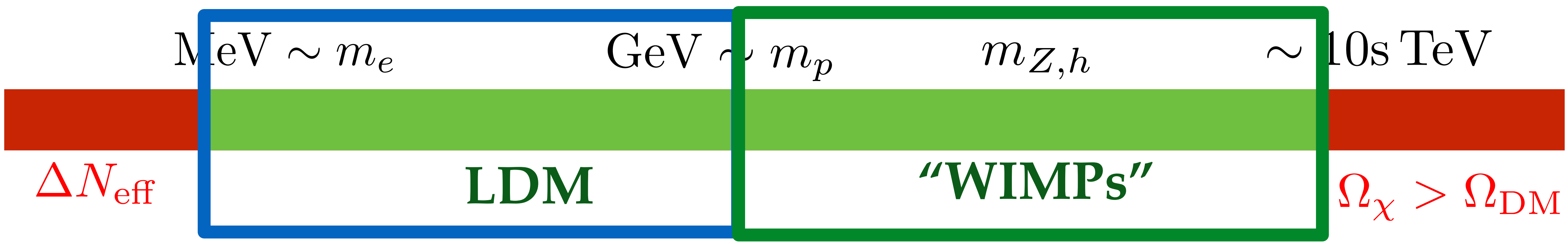


Similar to ACE scenario

How can we leverage the accelerator upgrades for dark sector searches moving forward with a new high-power particle beam?

Why accelerator-based dark sector searches?

- GeV-scale dark matter candidates (“WIMPs”) well covered by direct detection dark matter experiments
- Experiments based at high intensity particle beams well equipped to search for sub-GeV scale dark sector

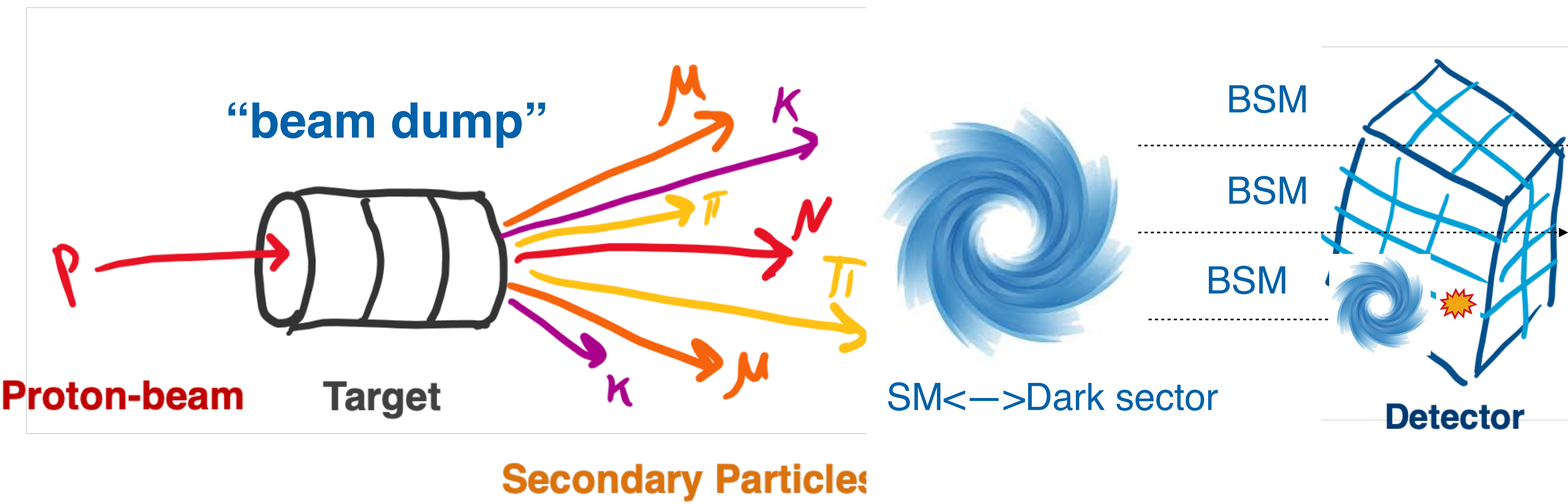


The energetic beams at Fermilab represent opportunities here!

Well covered by direct detection dark matter experiments

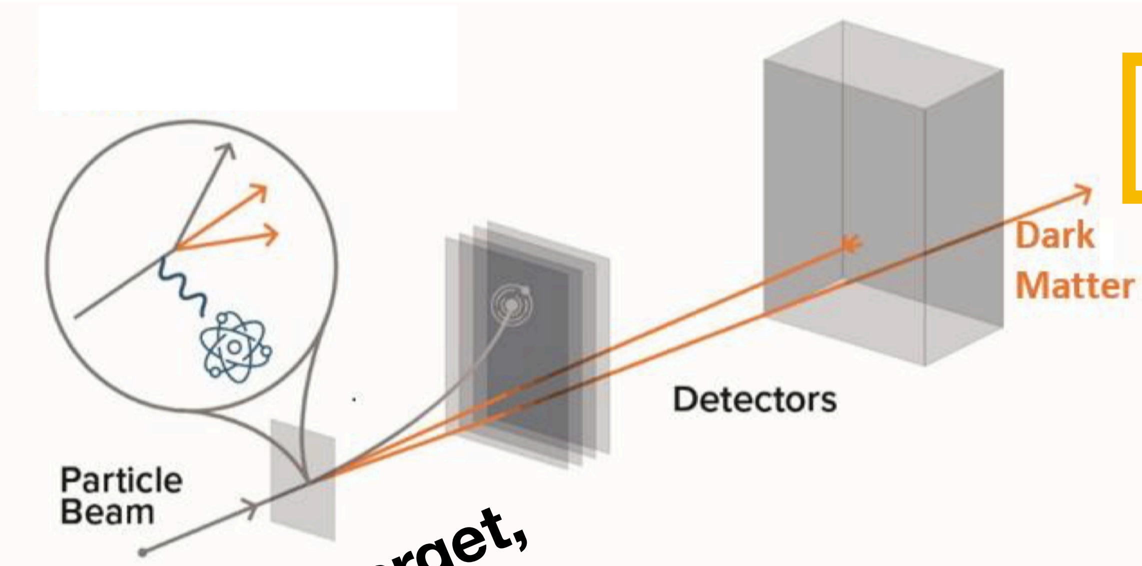
BSM signatures at accelerator facilities

- Accelerator-based facilities with intense particle beams represent an excellent opportunity to search for dark sectors and other BSM physics
- BSM-physics signatures possible in some models through similar channels as neutrino production from accelerator-based neutrino beams



Searching for Dark Sectors at Beam Dump Experiments

Production of dark matter

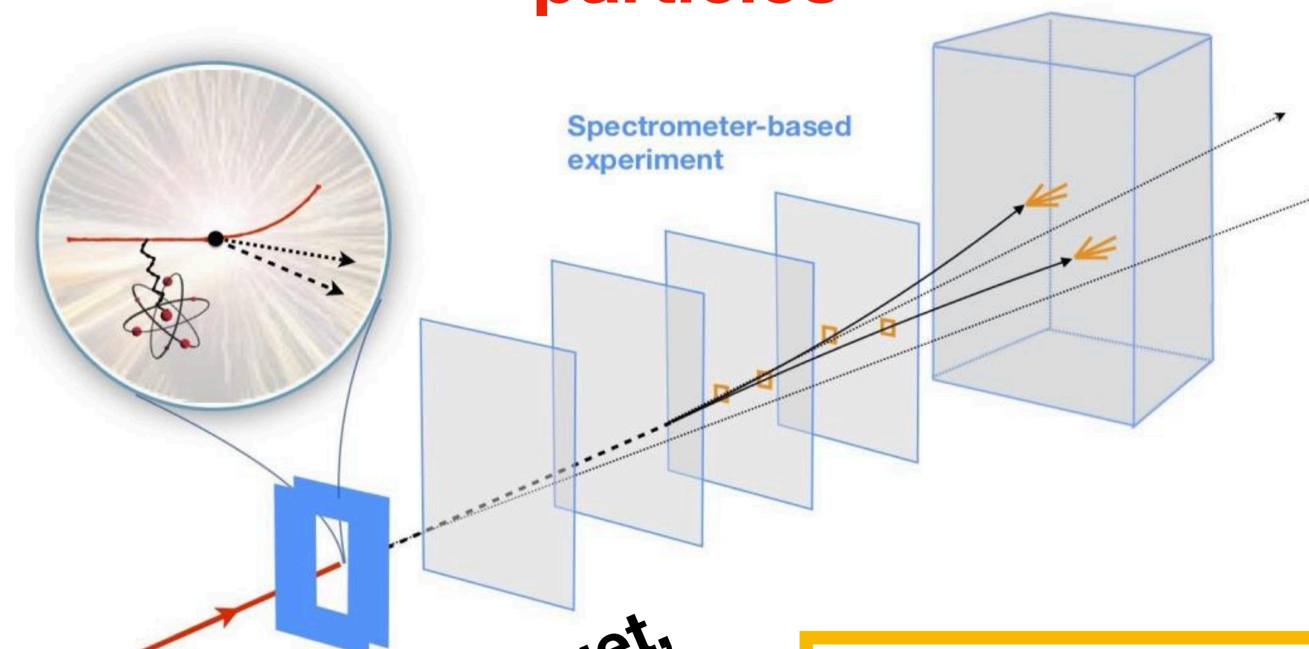


2. **Re-scattering**

A. B. **fixed target, colliders**

1. **Missing energy/ momentum/mass**

Production of unstable dark sector particles



1. 2. **fixed target, colliders**

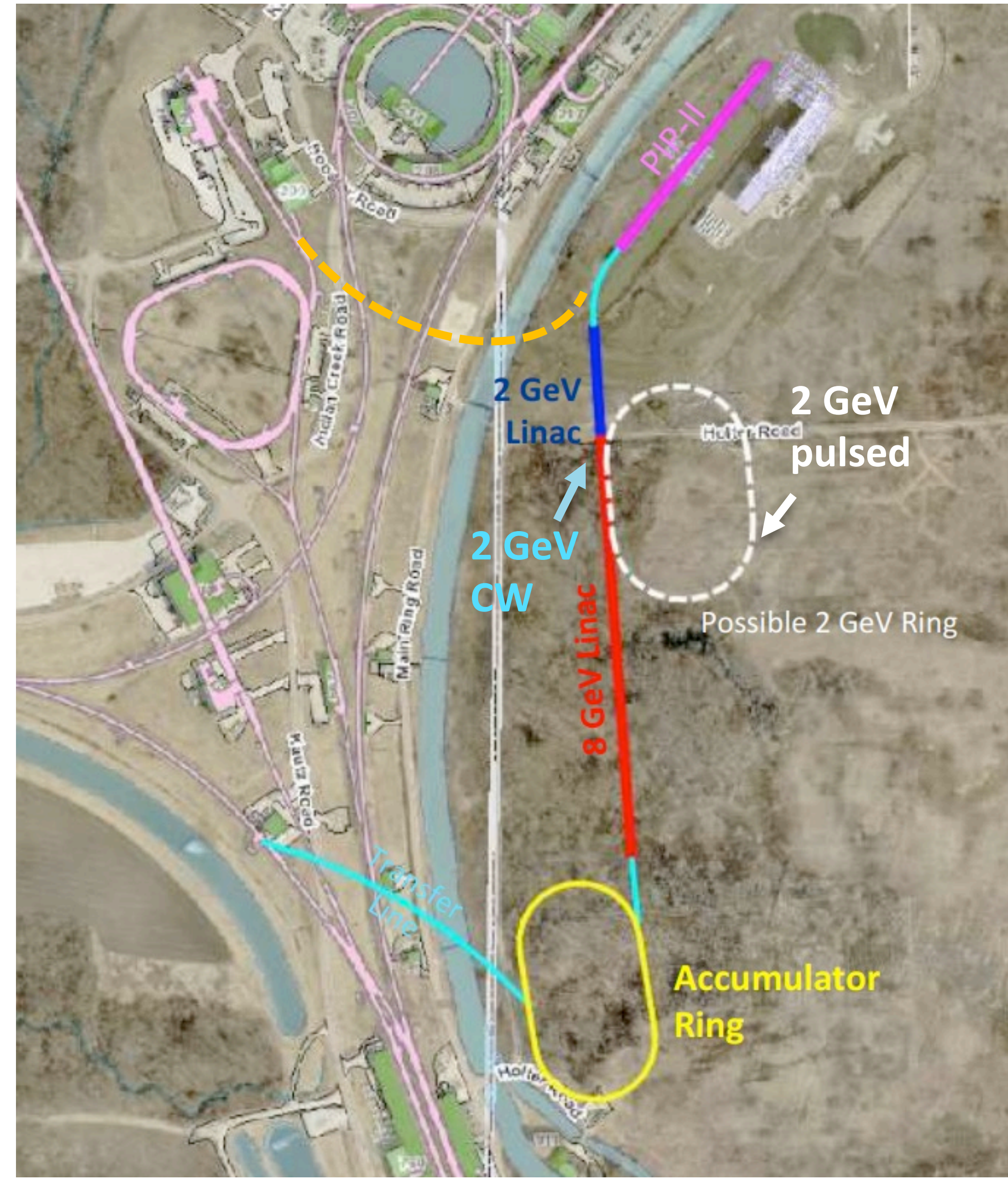
3. **Visible decay products**

- Breadth of ideas within a program important!
  - In case of discovery, allows for studying dark sector mass and interaction strength
  - Will focus here on ideas for methods 2 and 3 across visible energy detection thresholds!

Adapted from S. Gori

Integrating a dark sector search program at Fermilab

- There are many potential sitings for a dark sector search plan representing different accelerator configuration possibilities
  - Can use both continuous and bunched beams
- Take advantage of all of these scenarios for complementary approaches to re-scattering and decay dark sector searches
  - Pair detectors with the accelerator upgrades to create a dark sector search experimental program at Fermilab

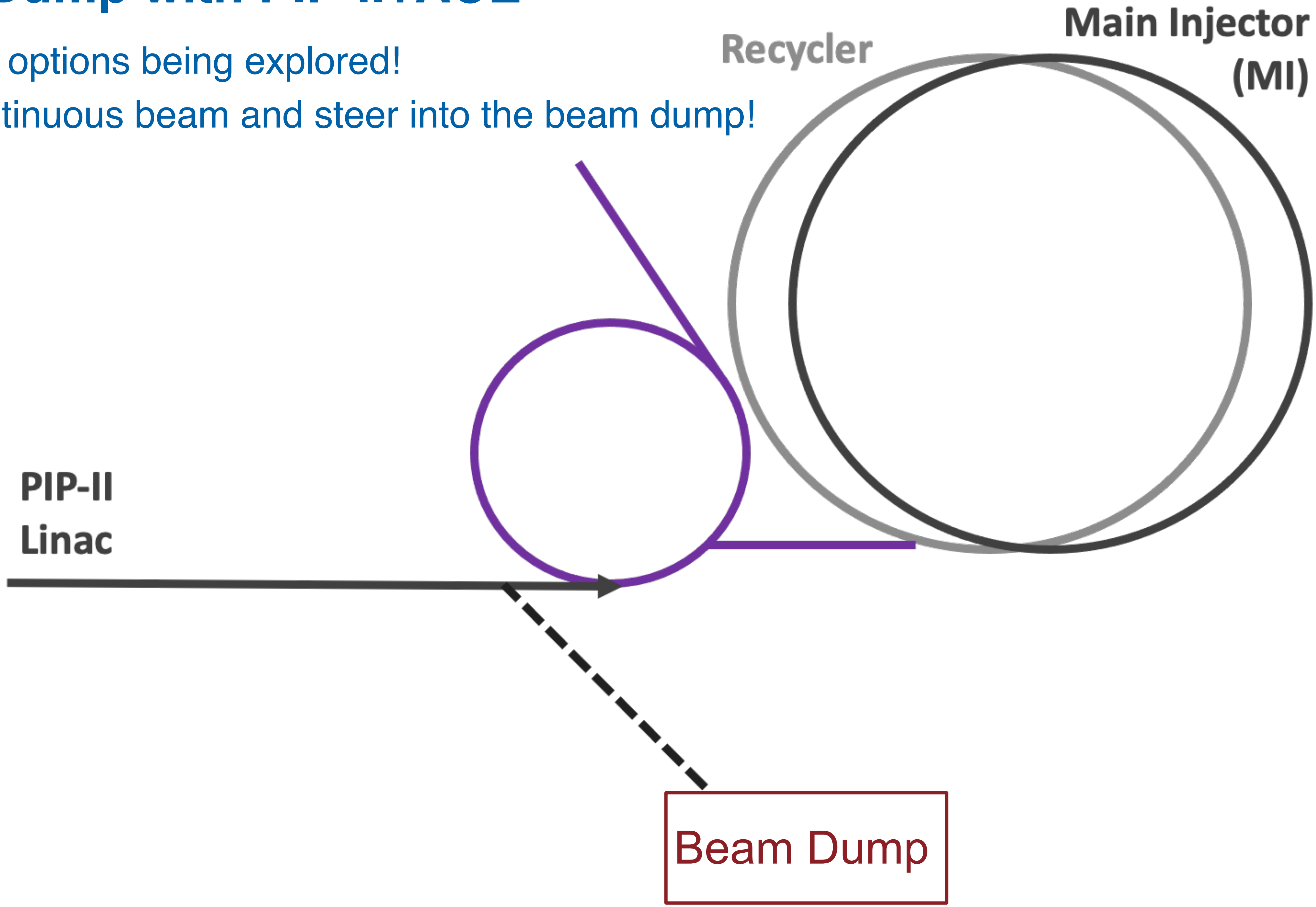


This diagram highlights a lot of the possibilities!

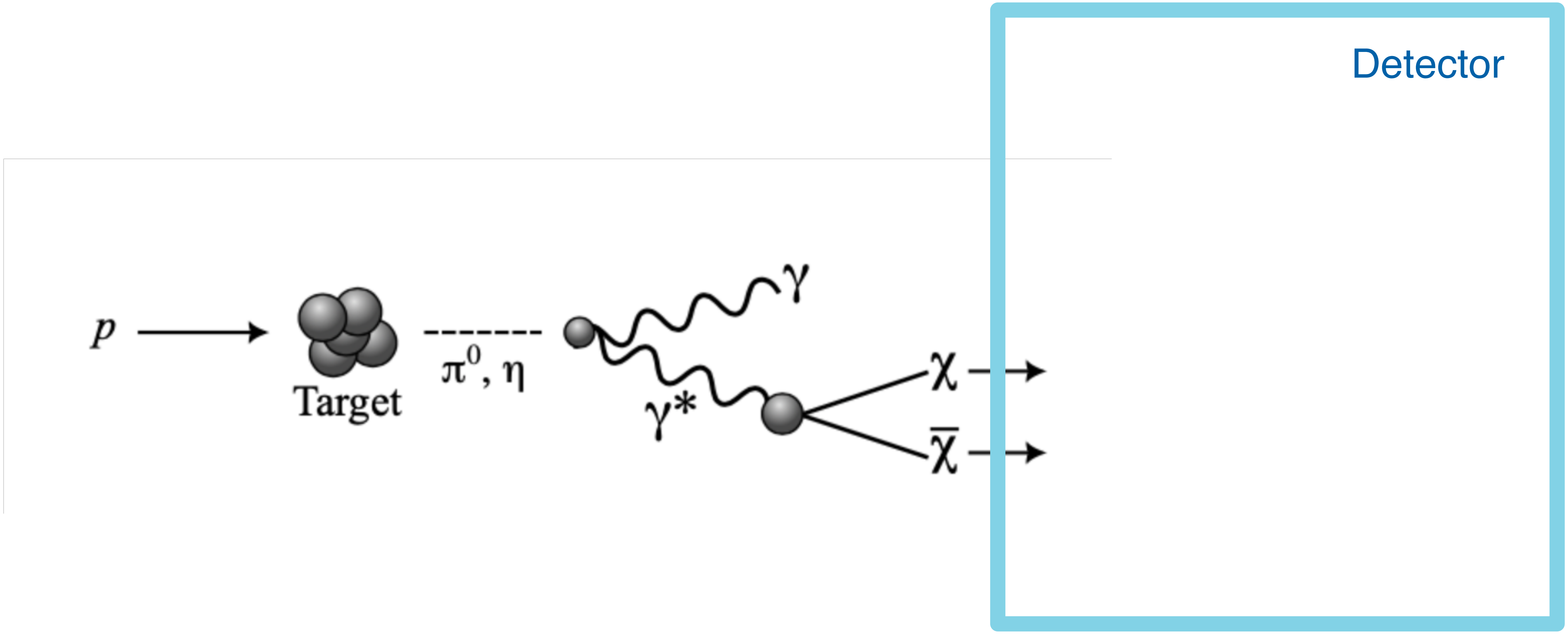
Beam Dump with PIP-II+ACE

Two main options being explored!

1. Take continuous beam and steer into the beam dump!



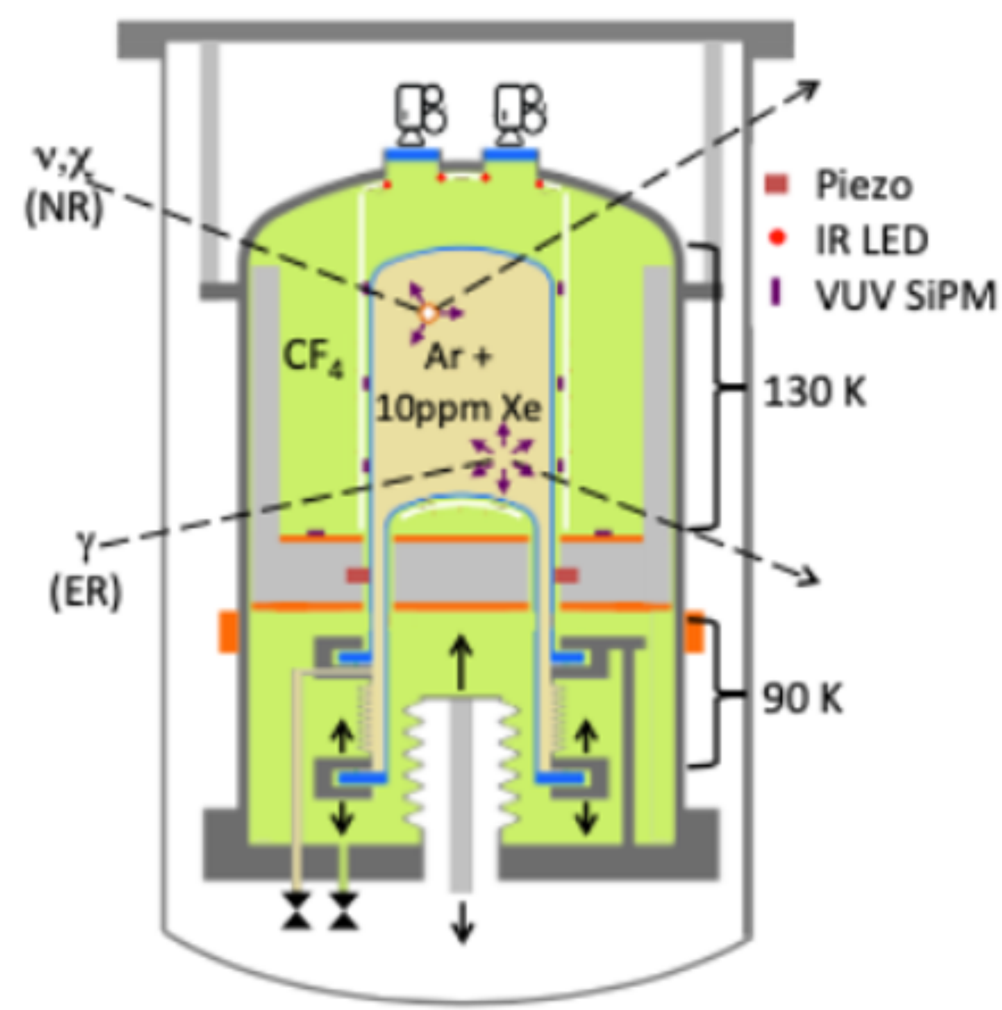
Dark sector re-scattering signature at PIP-II: millicharged particles



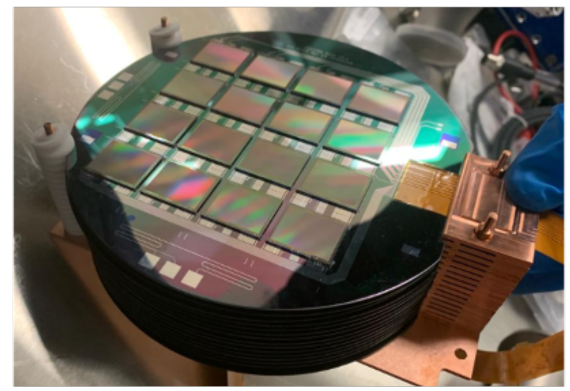
- Millicharged particles arise from extensions of the Standard Model that include a massless dark photon
- Millicharged particles are produced in high energy collisions at particle accelerators

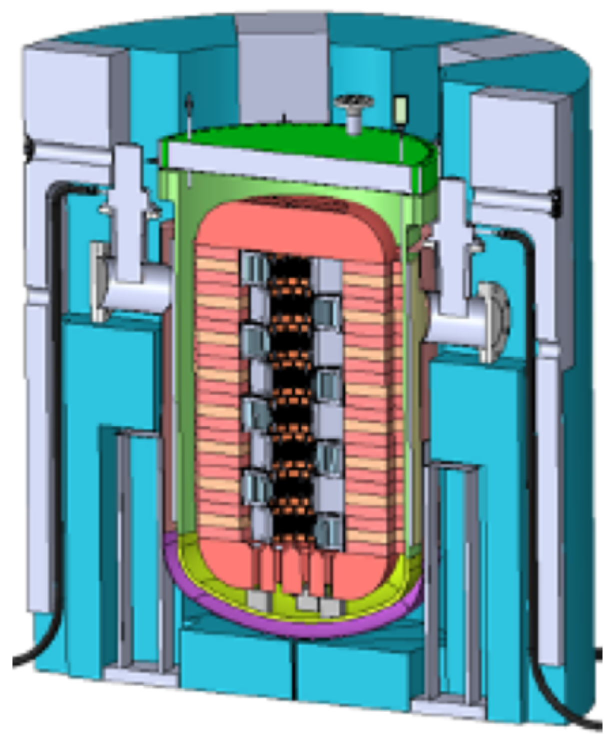
Re-scattering experiments using PIP-II continuous beam

- Significant progress on developing new detector technologies for direct detection dark matter searches
- Opportunity to leverage these technologies for dark sector searches at high-intensity beams such as millicharged particles



Scintillating Bubble Chamber (SBC)





Silicon skipper-CCD detectors

Cryogenic micro-calorimeters

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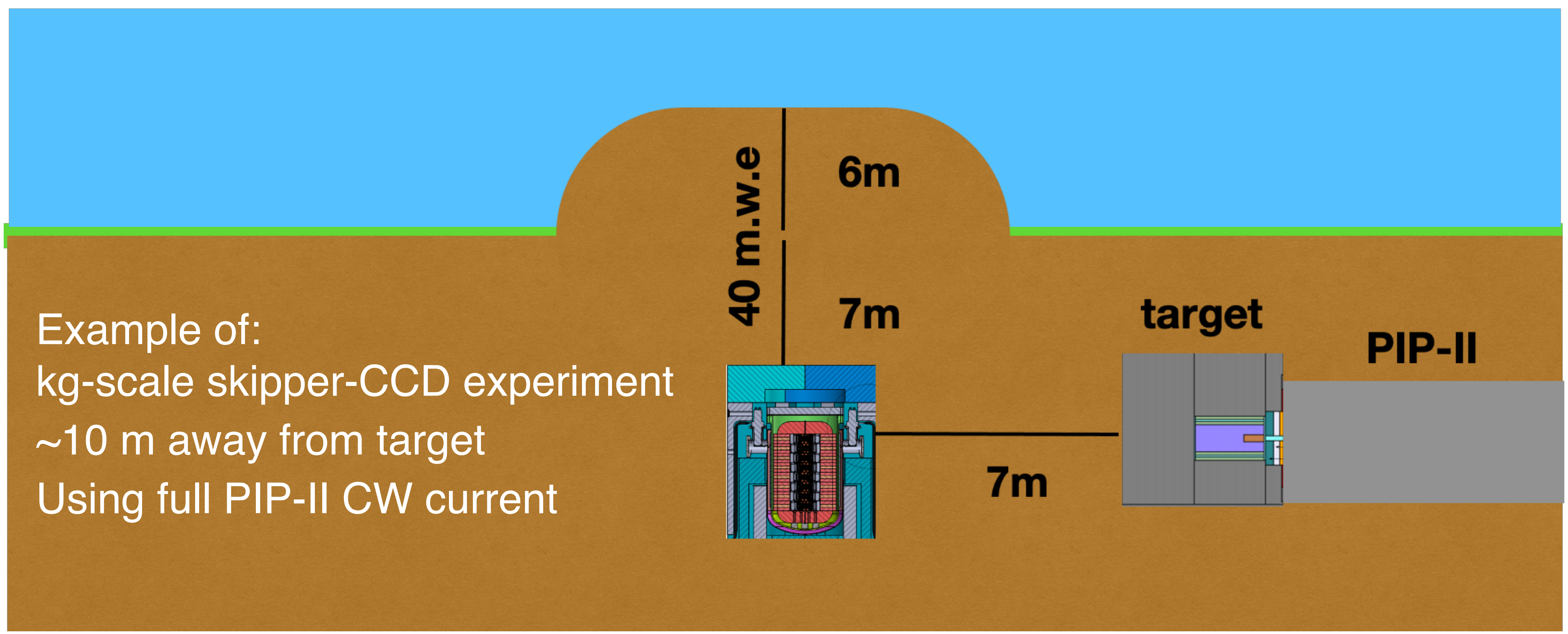
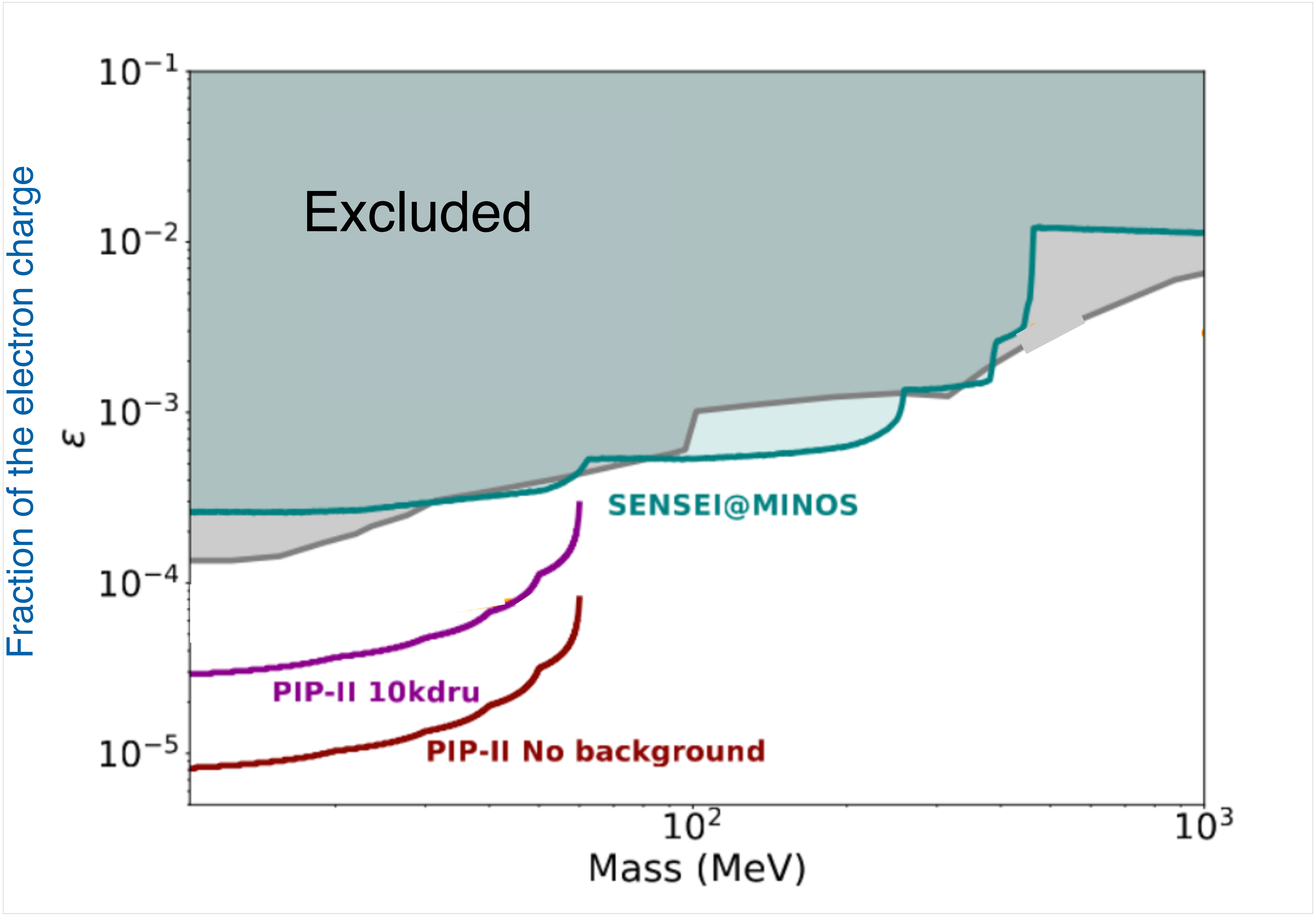
Experimental siting at PIP-II Beam Dump

- What are we interested in when siting a potential dark sector search experiment at a PIP-II beam dump?
  - Detector close to the beam dump
  - Shallow underground lab with sufficient shielding from cosmic backgrounds
  - Ability to implement multiple experiments at one time



Expected limits for skipper-CCD detectors at PIP-II CW



SENSEI@MINOS results: L. Barak et al., arXiv:2305.04964

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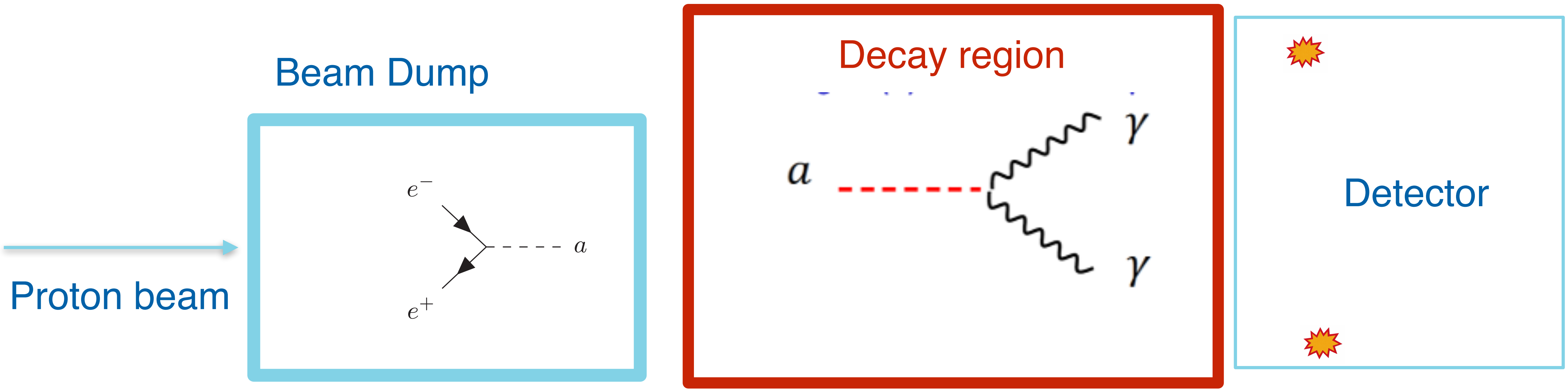
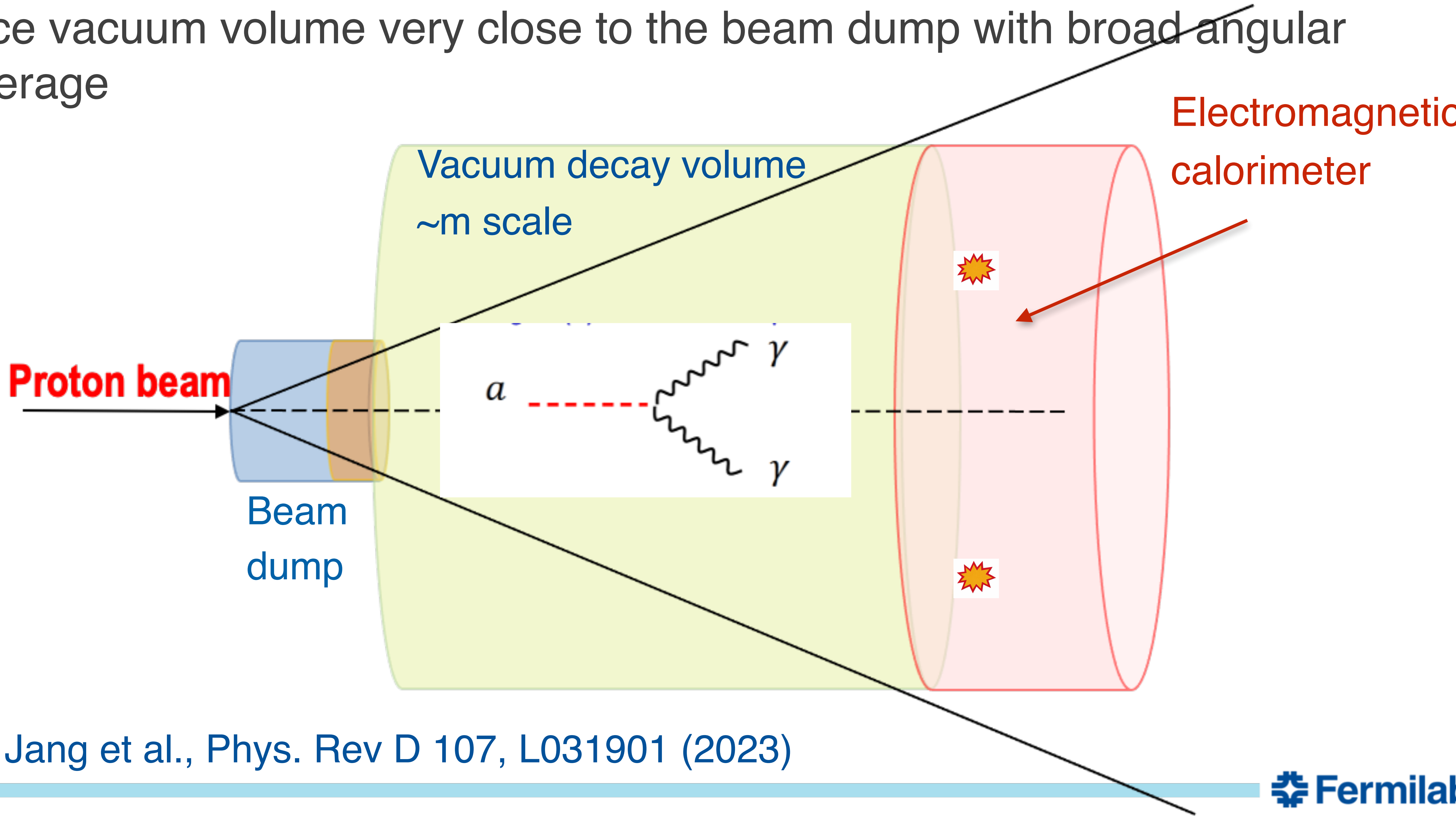
Visible decay dark sector signatures: Axion-like particles



- Some axions are predicted dark sector particles in models that extend the Standard Model
- Axion like particles (ALPs) also produced through copious EM interactions that arise from beam dump collisions
- ALPs are a viable dark matter candidate related to unanswered questions around the strong nuclear force

The DAMSA Experiment Concept

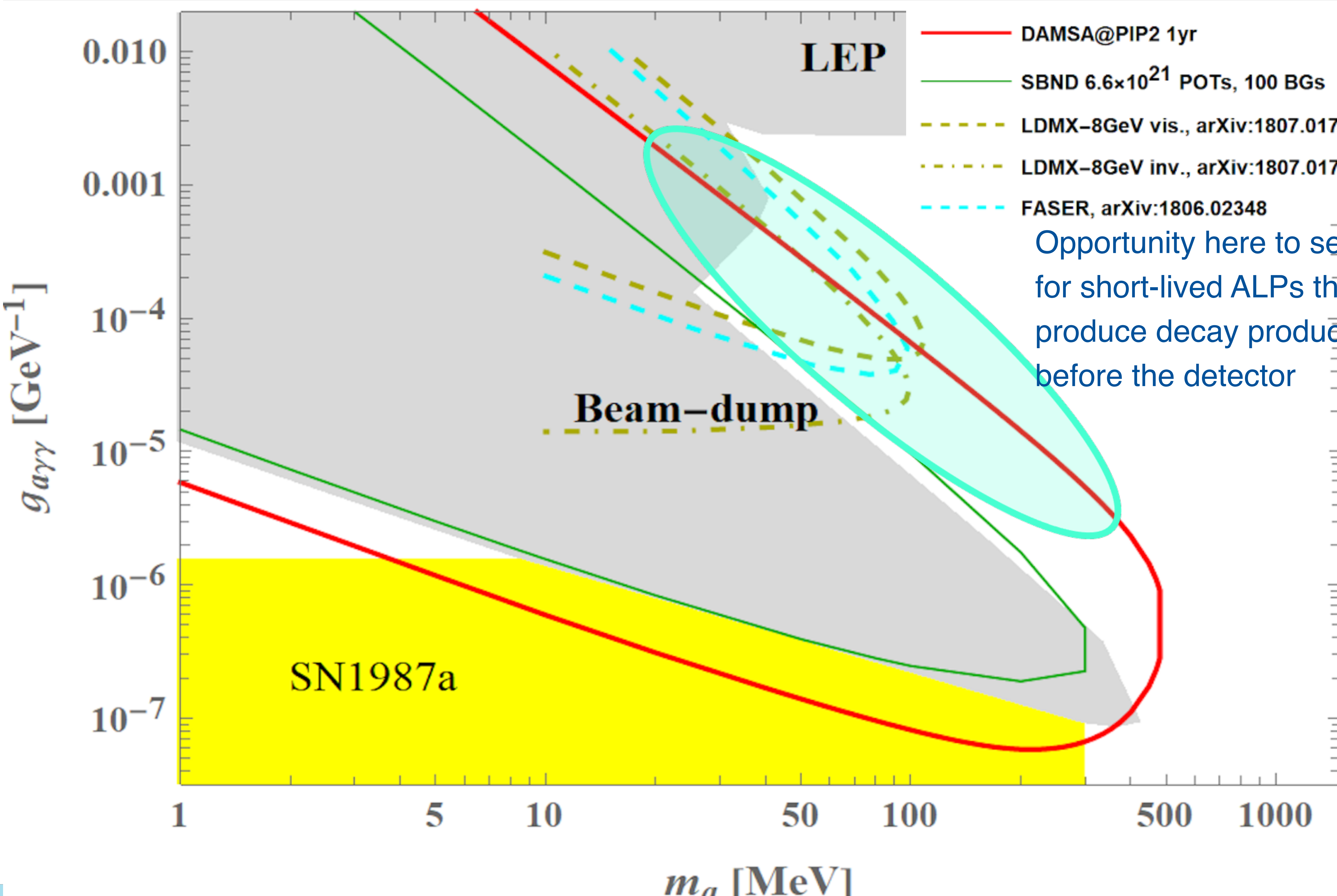
- Dump-produced Aboriginal Matter Searches at an Accelerator (DAMSA)
- Search for axion like particles decaying to two photons, along with possibilities for dark photon decay to e+/e- searches
- Place vacuum volume very close to the beam dump with broad angular coverage



W. Y. Jang et al., Phys. Rev D 107, L031901 (2023)

DAMSA Sensitivity to axion-like particles

Adapted from W. Y. Jang et al., Phys. Rev D 107, L031901 (2023)



ALP coupling to photons

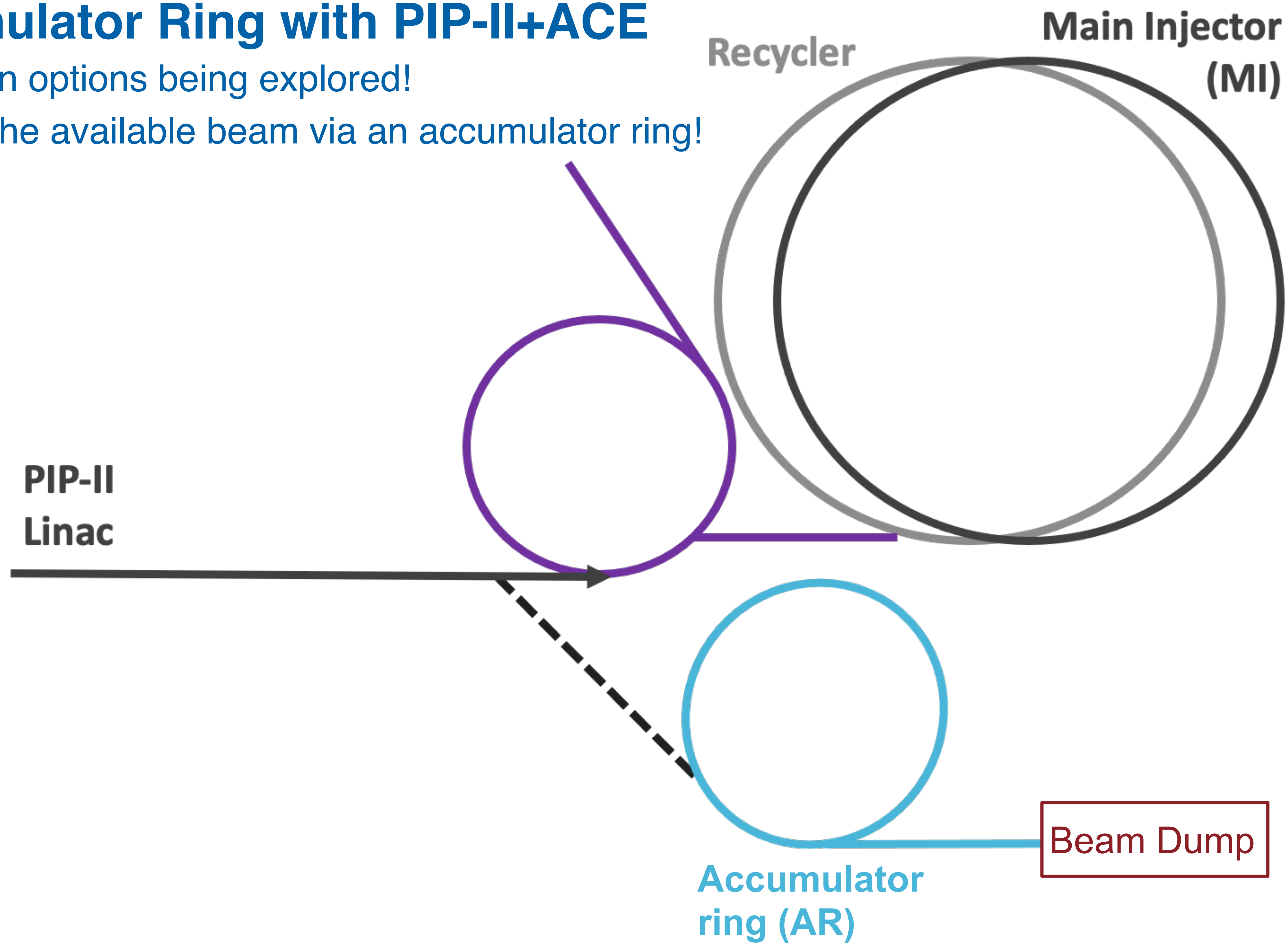
Opportunity here to search for short-lived ALPs that produce decay products before the detector

How can we extend this program even further using the opportunities afforded under ACE?

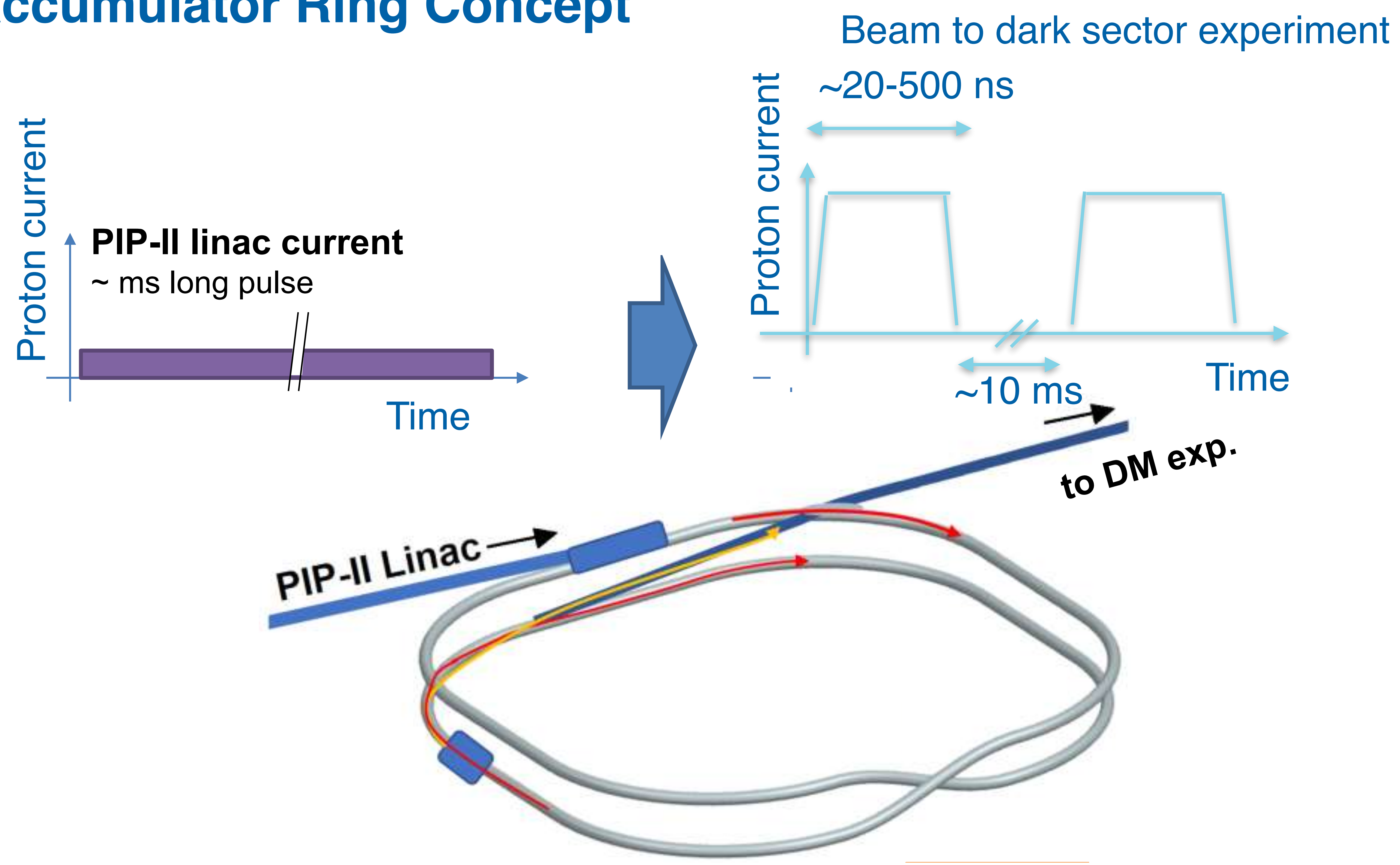
Accumulator Ring with PIP-II+ACE

Two main options being explored!

2. Bunch the available beam via an accumulator ring!



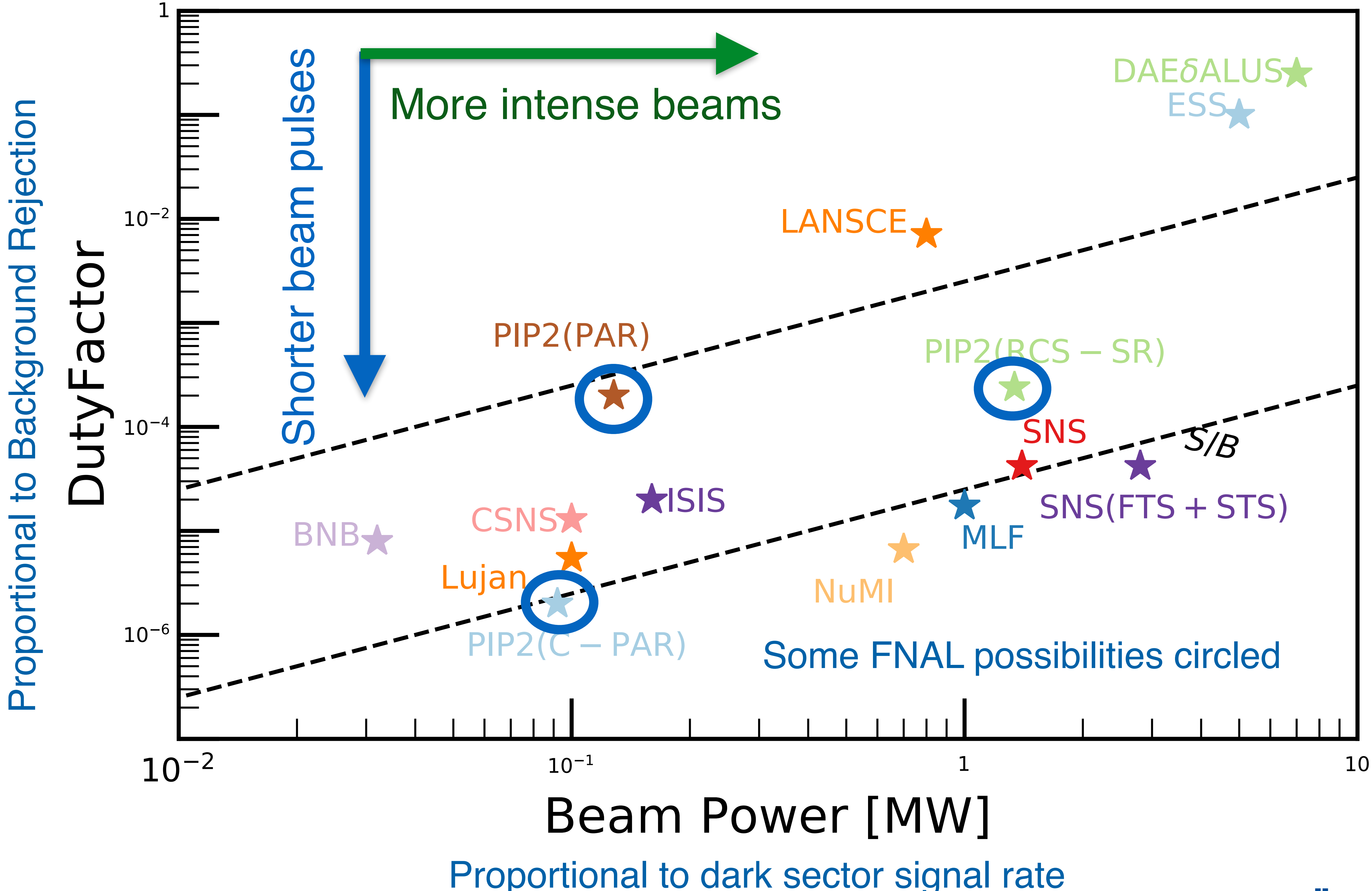
Accumulator Ring Concept



Allows precise knowledge of beam timing!

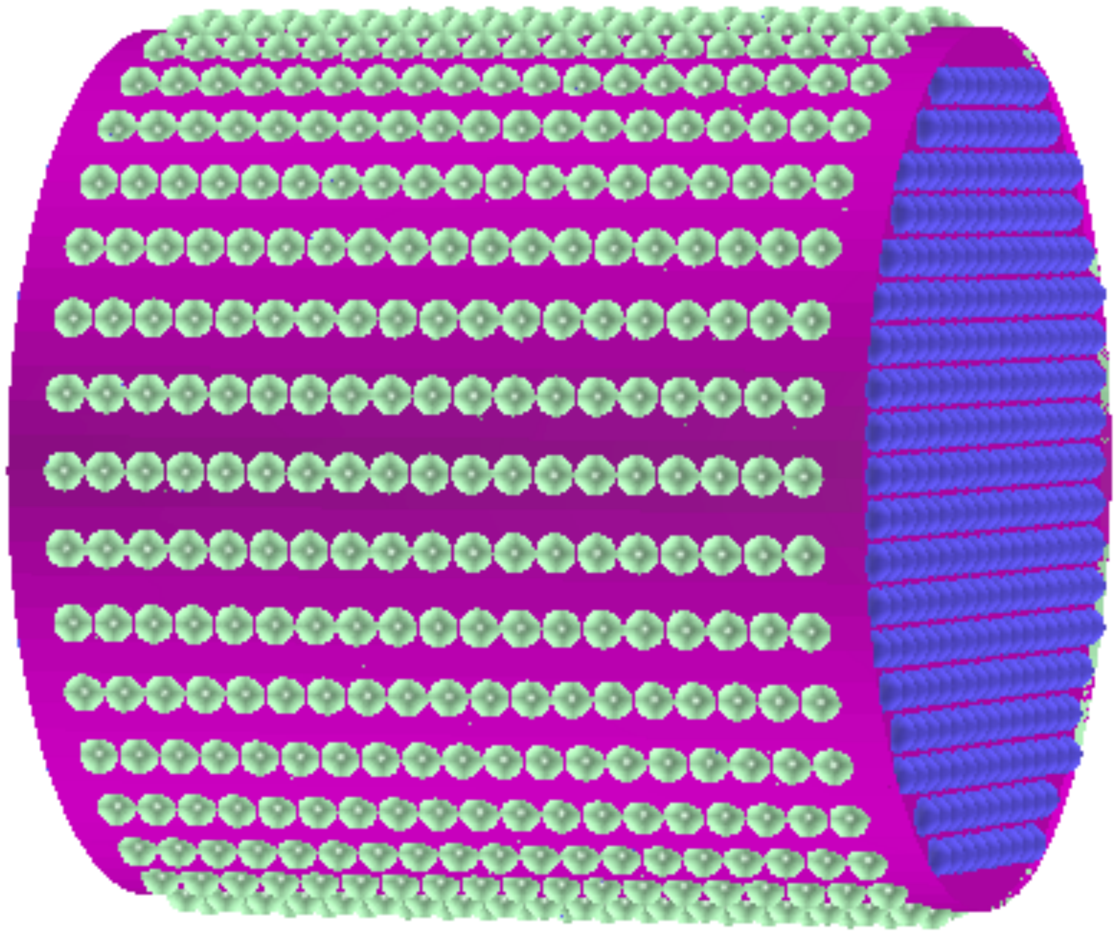
Important for reducing backgrounds that are not related to the beam itself!

PIP-II + ACE Accumulator Ring Scenarios



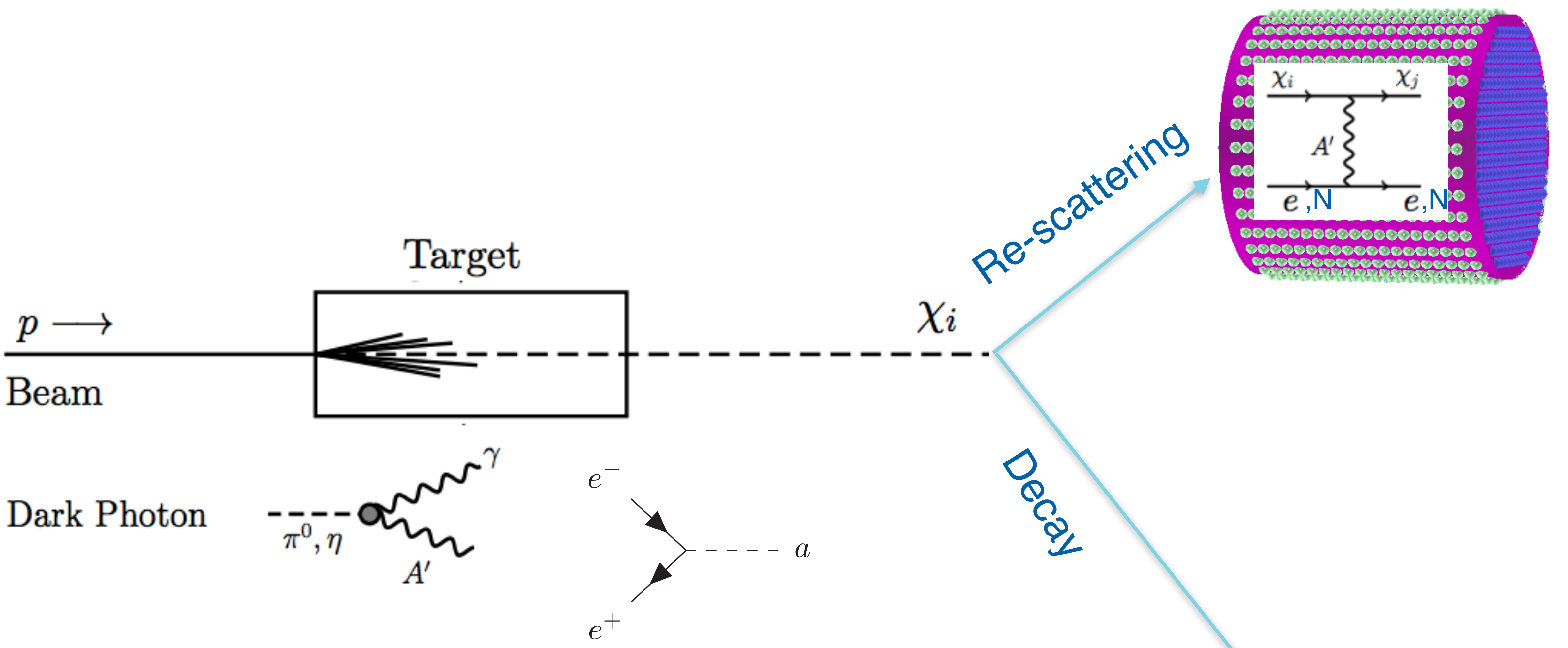
Experimental Ideas: The PIP2-BD Concept

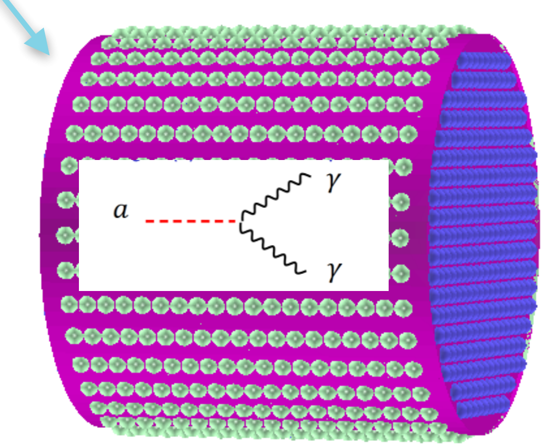
- 100 tonne liquid argon (LAr) scintillation detector instrumented with 1200 photomultiplier tubes (PMTs)
- These detectors provide excellent dark sector search capabilities with the improved timing capabilities afforded by the PIP-II beam bunched by an accumulator ring which allows powerful background rejection capabilities



Rendering of PIP2-BD detector concept

PIP2-BD can measure both re-scattering and decay signatures

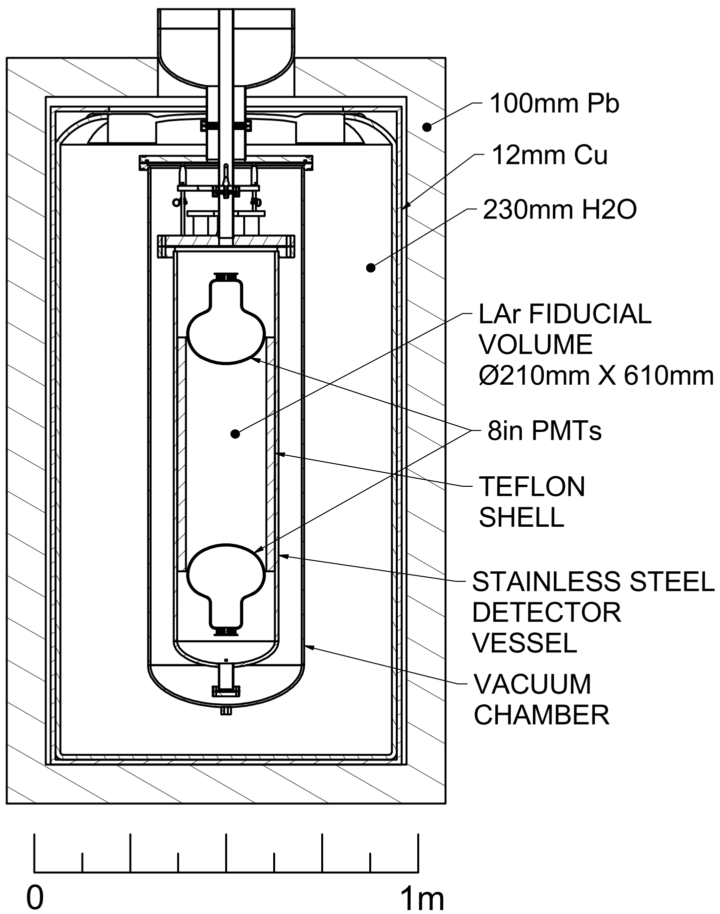




This is enabled by the broad range of energies detectable by the liquid argon technology used by PIP2-BD!

PIP2-BD represents the next generation of a successful technology

- The capability for measuring re-scattering signatures with liquid argon was pioneered by the 24 kg COH-Ar-10 detector operating at the high-intensity proton beam at the Spallation Neutron Source at Oak Ridge National Laboratory
- Currently building a tonne-scale detector COH-Ar-750 to probe into the re-scattering parameter space

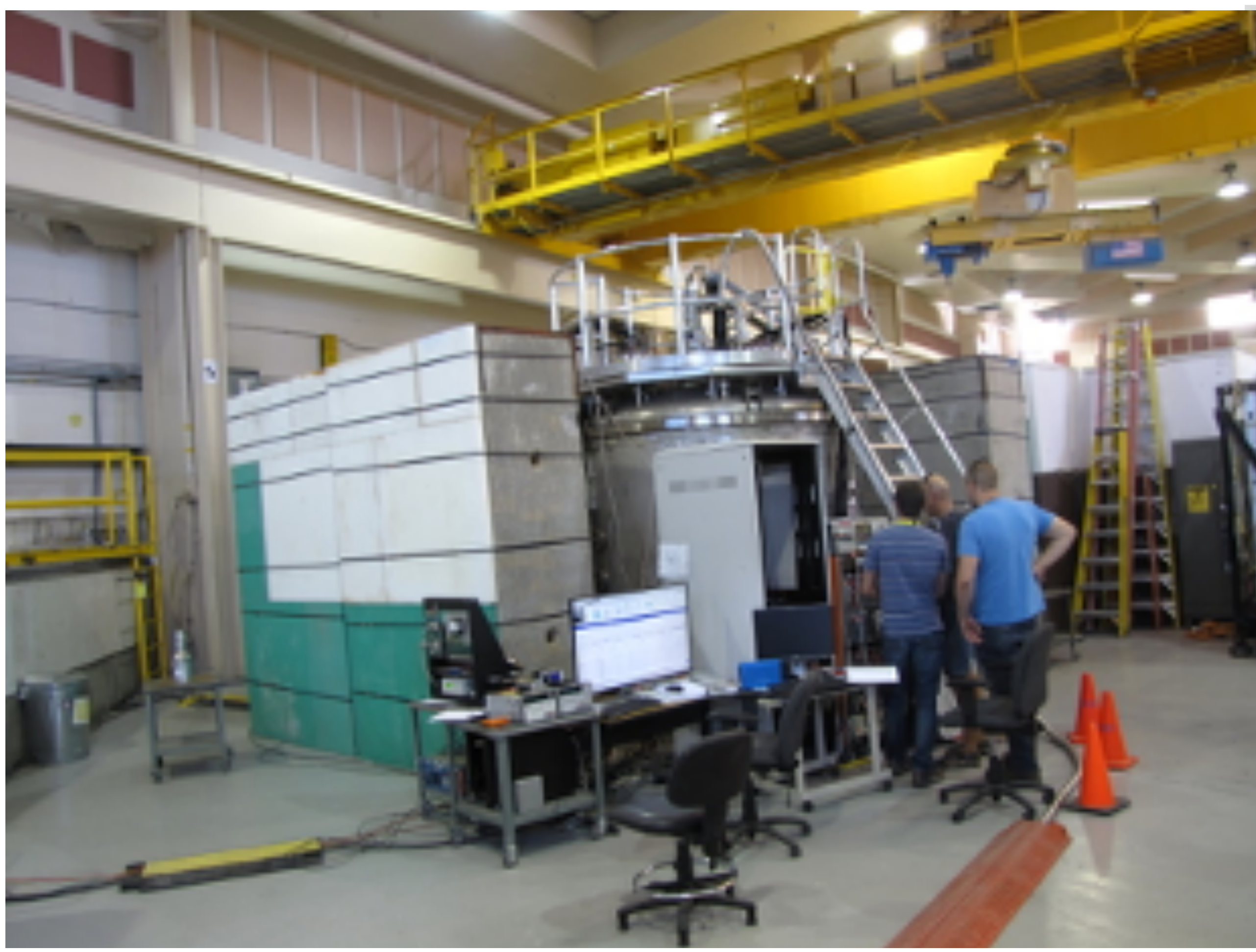


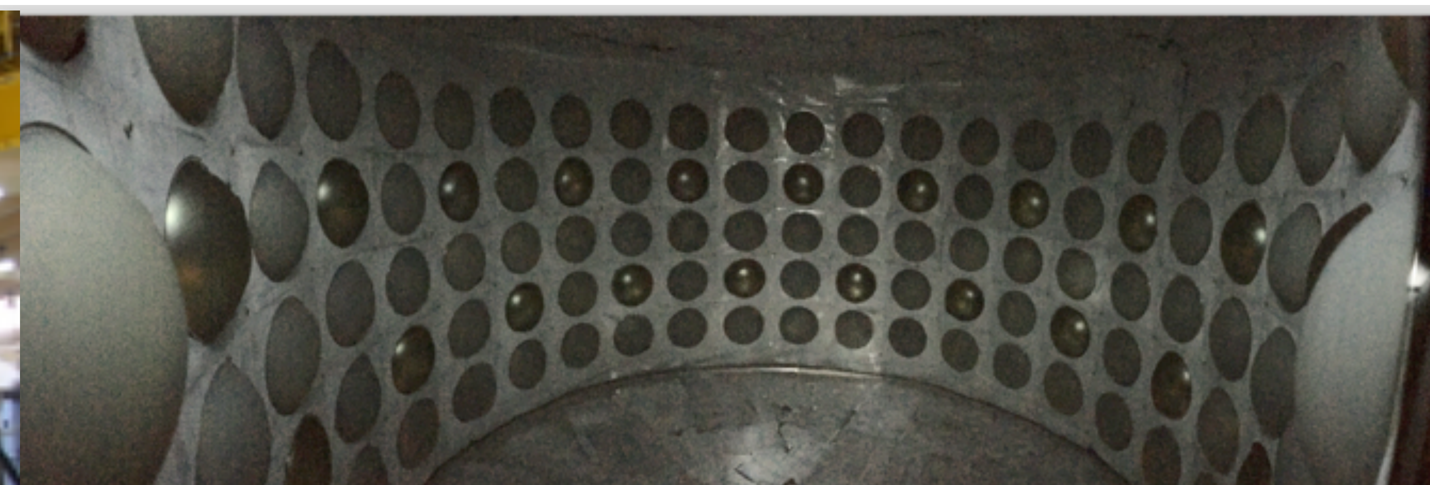
My past life!

Re-scattering search capabilities: Phys. Rev. Lett 130 051803 (2023)

PIP2-BD represents the next generation of a successful technology

- The Coherent Captain Mills (CCM) experiment located at the proton beam at the Lujan Center at Los Alamos National Laboratory uses liquid argon technology at the 10-tonne scale to probe decay signatures



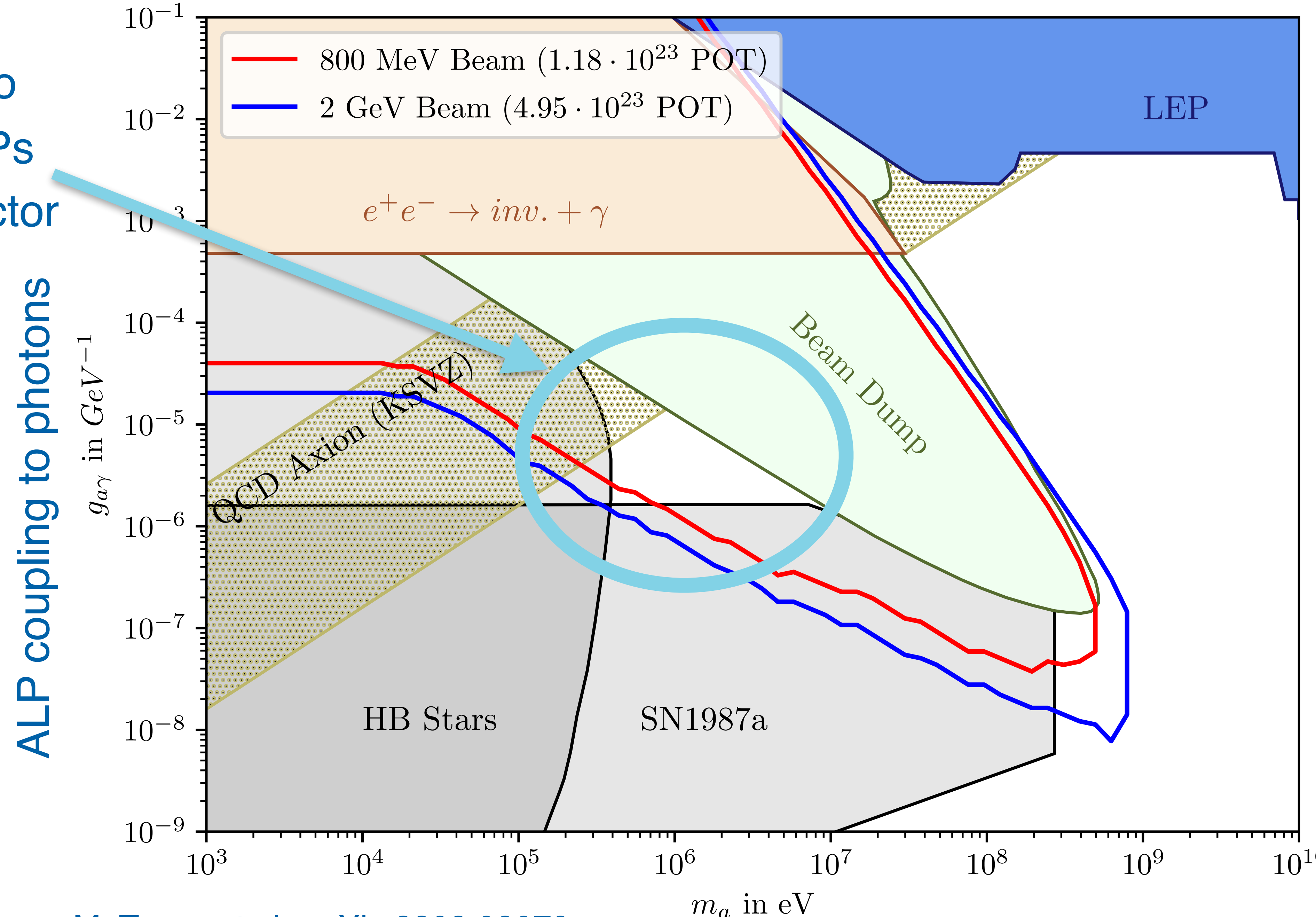


First decay signature results:
Phys. Rev. D 107, 095036 (2023)

Dark sector decay searches at PIP2-BD

- PIP2-BD provides sensitivity to the other interesting region relating to the QCD axion that is not covered by terrestrial or astrophysical sources

Opportunity in this space to search for longer-lived ALPs that decay inside the detector



M. Toups et al., arXiv:2203.08079

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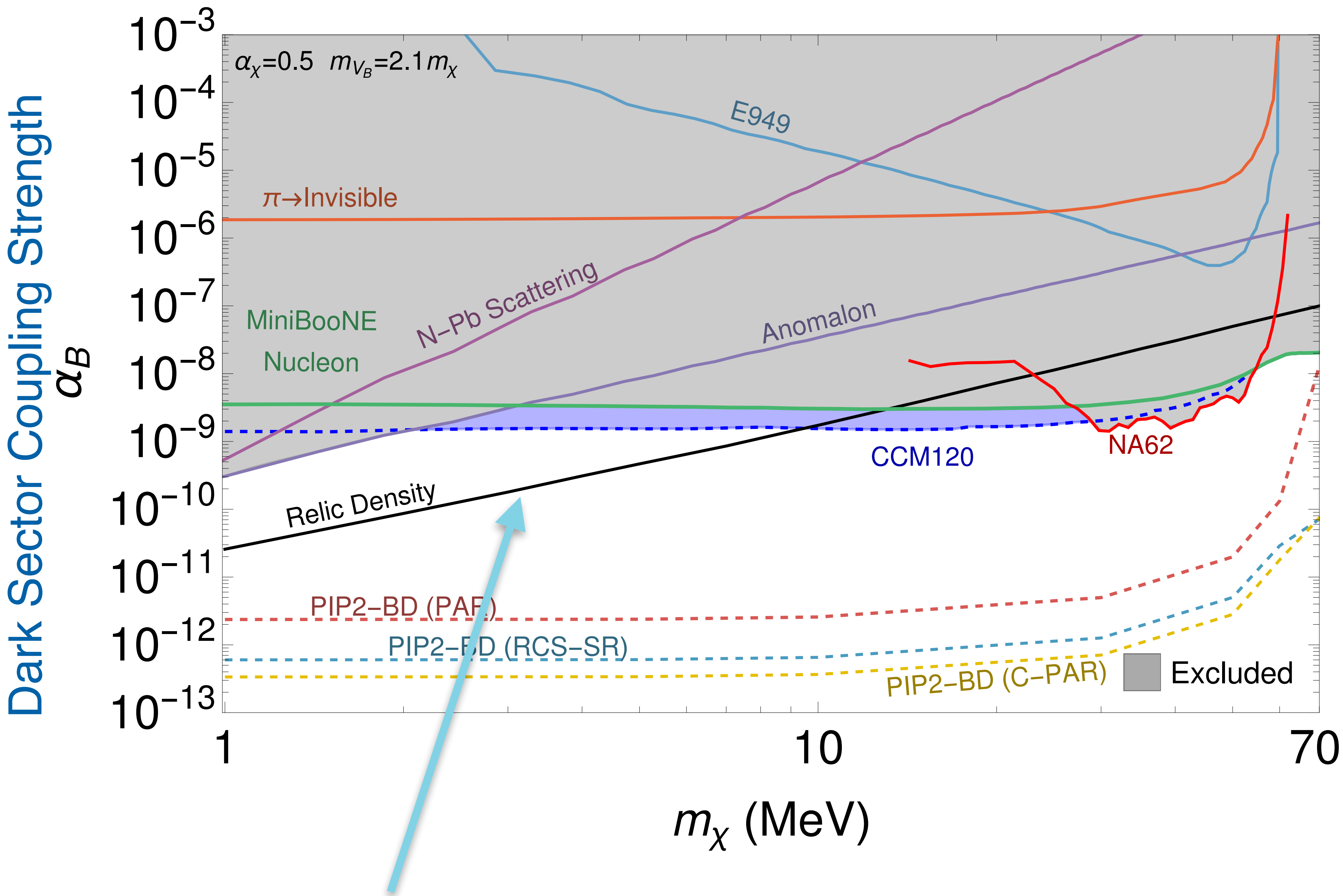
PIP2-BD Dark sector re-scattering search

- Can probe light dark matter scenarios both coupling to leptons or not
- Same production mechanism, but opportunity to provide world-leading searches with energetic beams such as those at Fermilab

M. Toups et al., arXiv:2203.08079



Experimental target for cosmological DM

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What's next: The 2023 P5 report and the ASTAE program

Exploring the Quantum Universe

- The 2023 P5 report recommended the formation of a portfolio for small experiments called ASTAE

5.1.3 – New Initiative: A Portfolio of Agile Projects to Search for Direct Evidence of New Particles

the hidden sectors through the Vector and Heavy Neutral Lepton portals. At Fermilab, PIP-II is expected to make many more protons than needed for DUNE, and we anticipate proposals for experiments using the excess protons. These experiments should compete in the portfolio for agile projects (see Recommendation 3a and Section 6.2).

- Directly suggests exploring possibilities using the excess protons at PIP-II under this program and specifically for dark sector searches

Recommendation 3: Create an improved balance between small-, medium-, and large-scale projects to open new scientific opportunities and maximize their results, enhance workforce development, promote creativity, and compete on the world stage.

In order to achieve this balance across all project sizes we recommend the following:

a. Implement a new small-project portfolio at DOE, Advancing Science and Technology through Agile Experiments (ASTAE), across science themes in particle physics with a competitive program and recurring funding opportunity announcements. This program should start with the construction of experiments from the Dark Matter New Initiatives (DMNI) by DOE-HEP (section 6.2).

b. Continue Mid-Scale Research Infrastructure (MSRI) and Major Research Instrumentation (MRI) programs as a critical component of the NSF research and project portfolio.

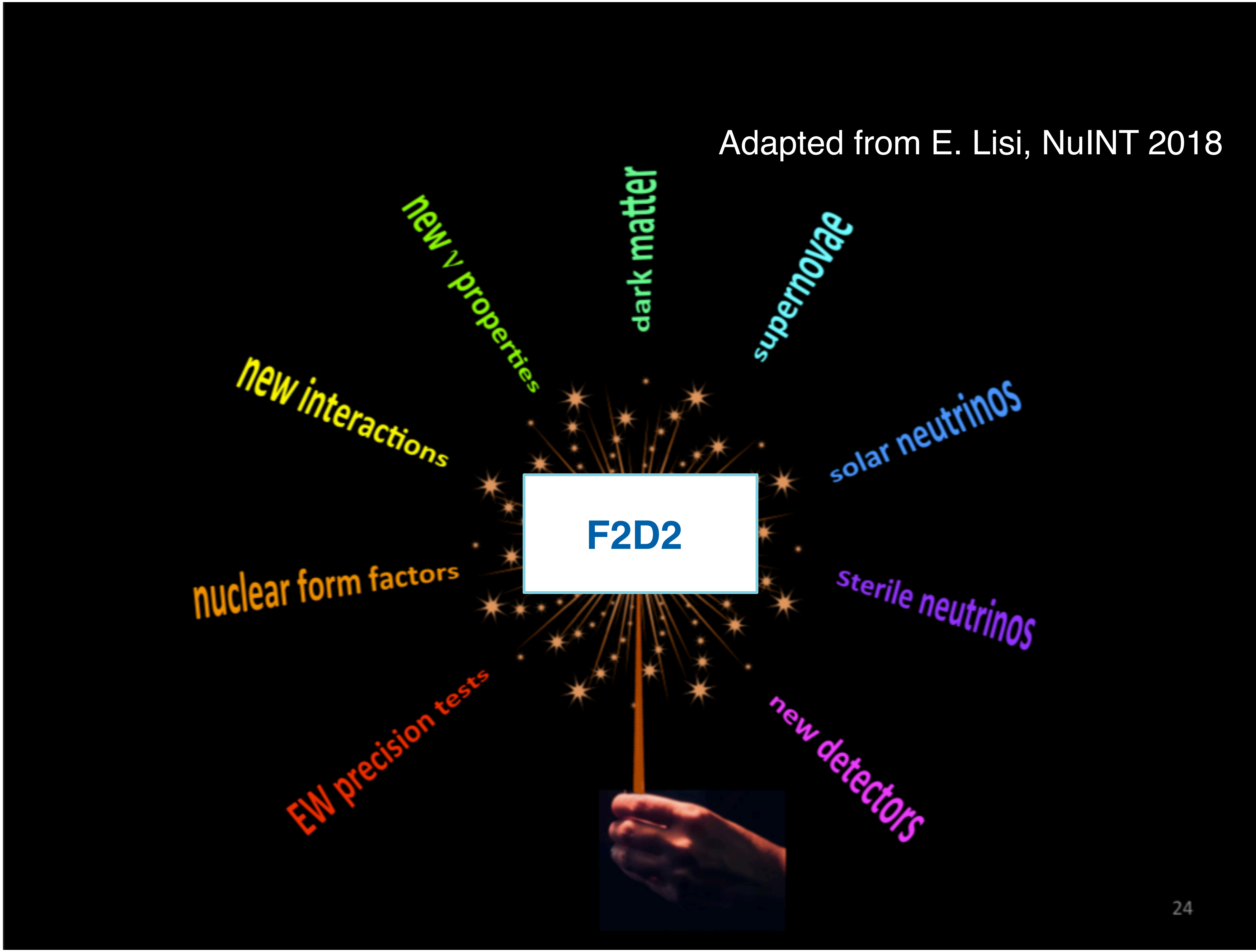
The Fermilab Facility for Dark Matter Discovery (F2D2)

- PIP-II beam dump facility to host dark sector ASTAE experiments
- White paper from a workshop held at Fermilab in May 2023 on the physics program and possible experiments hosted at F2D2
  - DAMSA: Very short baseline beam dump experiment
  - OSCURA: Skipper CCD, low threshold
  - PIP2-BD: 100t LAr Scintillator
  - And other opportunities
- Based on this work, Fermilab is forming a task force to develop a more detailed picture of what would be required to realize these opportunities
  - See K. Burkett's Jan. 2024 Fermilab PAC talk

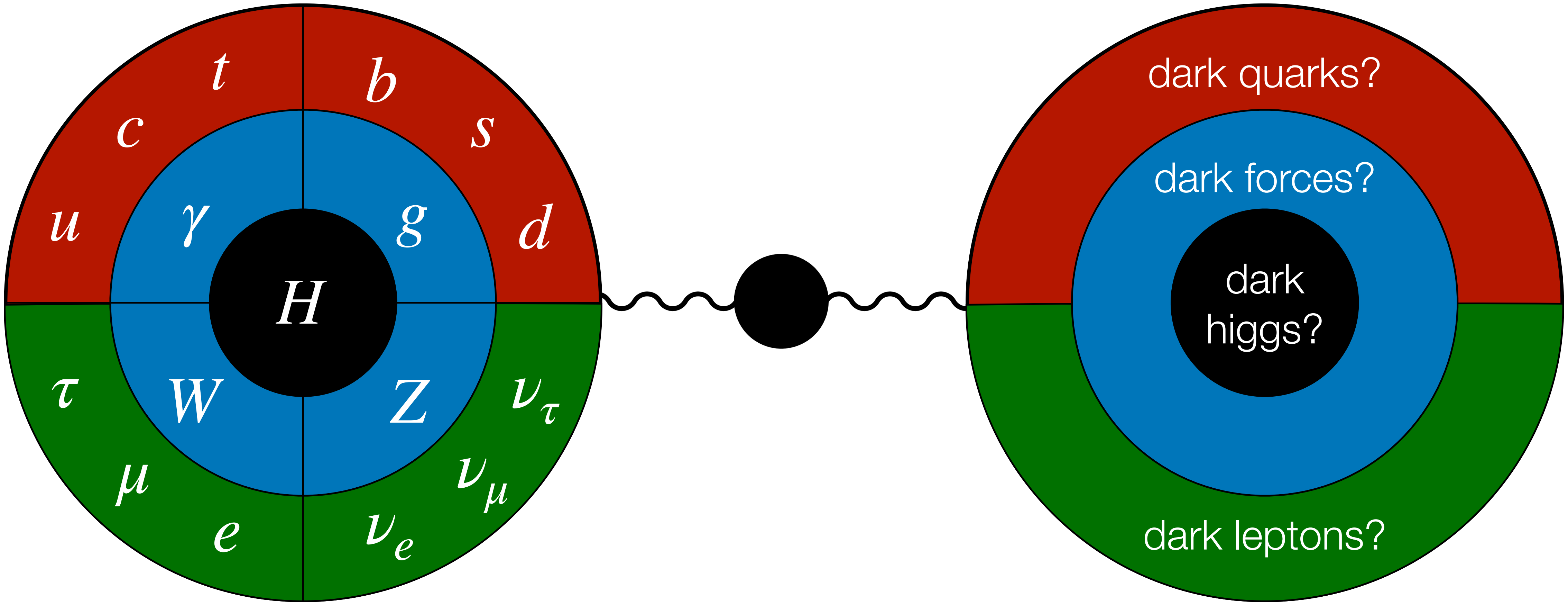
Physics Opportunities at a Beam Dump Facility at PIP-II at Fermilab and Beyond

A. A. Aguilar-Arevalo[1], J. L. Barrow[2], C. Bhat[3], J. Bogenschuetz[4], C. Bonifazi[5,6], A. Bross[3], B. Cervantes[1], J. D'Olivo[1], A. De Roeck[7], B. Dutta[8], M. Eads[9], J. Eldred[3], J. Estrada[3], A. Fava[3], C. Fernandes Vilela[10], G. Fernandez Moroni[3], B. Flaugher[3], S. Gardiner[3], G. Gurung[4], P. Gutierrez[11], W. Y. Jang[4], K. J. Kelly[8], D. Kim[8], T. Kobilarcik[3], Z. Liu[2], K. F. Lyu[2], P. Machado[3], R. Mahapatra[8], M. Marjanovic[11], A. Mastbaum[12], V. Pandey[3], W. Pellico[3], S. Perez[13], J. Reichenbacher[14], D. Rodrigues[13,15], A. Sousa[16], B. Simons[3,9], D. Snowden-Ifft[17], C.- Y. Tan[3], M. Toups[3], N. Tran[3], Y.-T. Tsai[18], R. G. Van de Water[19], R. Vilar[20], S. Westerdale[21], J. Yu[4], J. Zettlemoyer[3], and R. Zwaska[3]

arXiv:2311.09915


Adapted from E. Lisi, NuINT 2018
new ν properties
dark matter
supernovae
new interactions
solar neutrinos
F2D2
nuclear form factors
sterile neutrinos
EW precision tests
new detectors
24

Exciting opportunities to uncover new physics using the accelerator facilities at Fermilab in the next decade-plus with the opportunities provided by PIP-II and ACE!



The future is light and dark!

Thank you!

Fermilab