Light Dark Matter with the Missing Momentum Technique

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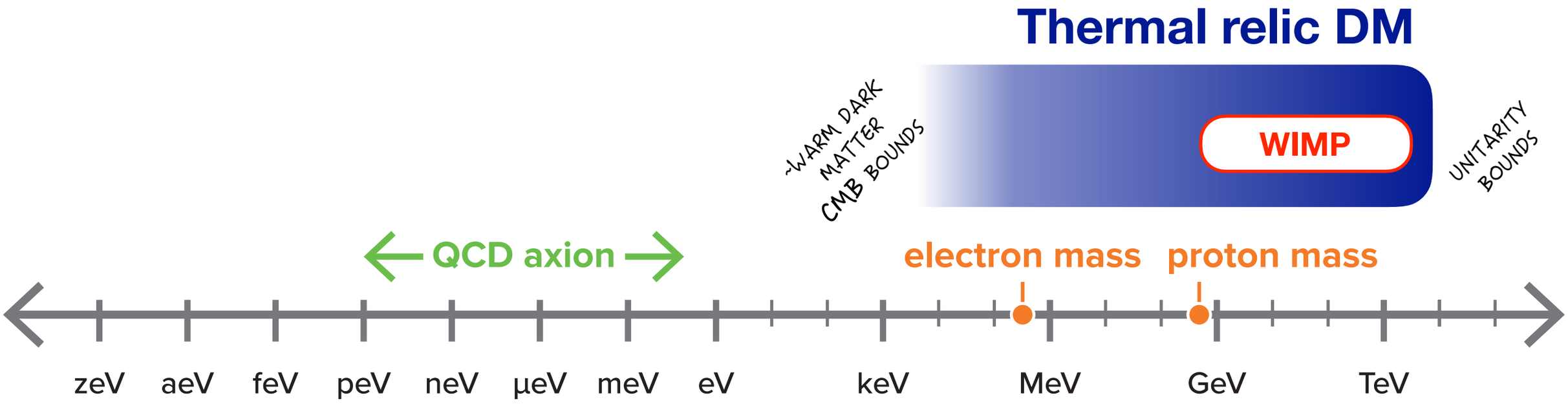
Fermilab Physics Advisory Committee meeting

January 17, 2019

Outline

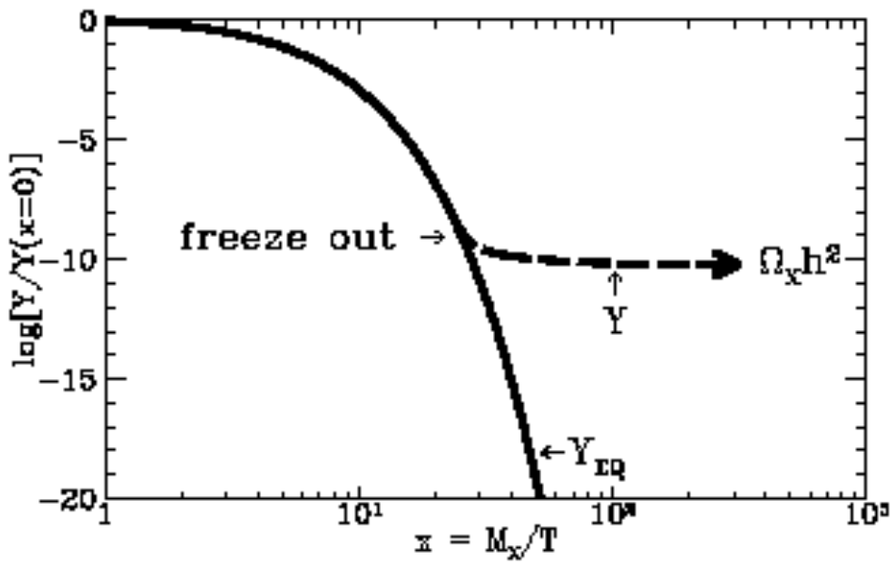
- **New initiatives in dark matter and the Basic Research Needs process**
- **The missing momentum technique physics program**
- **Light Dark Matter eXperiment**
- **Missing momentum with muon beams, LDMX-M³**

The state of dark matter



The existing G2 dark matter program is very successful but has yet to understand the **particle nature of dark matter**

Thermal freeze out dark matter remains a compelling paradigm for origin of DM in early universe over **MeV to TeV mass range**



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New initiatives in dark matter

- **Exciting new initiatives in DM to complement the G2 program**
  - New ideas looking for **sub-GeV DM** with
    - **accelerator-based experiments**
    - **direct detection methods**
    - **Searches for ultralight wave-like dark matter < eV**

- **Cosmic Visions workshop (March 2017)** enumerated a wide range of novel ideas in dark matter
  - Workshop agenda: https://indico.fnal.gov/event/13702/
  - Resulting white paper: https://arxiv.org/abs/1707.04591
    US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report

    - LDMX talk: *https://indico.fnal.gov/event/13702/session/9/contribution/133*

Basic Research Needs (BRN) Study

- Next: **DOE Basic Research Needs** study for small dark matter projects
  - Oct 2018, https://orau.gov/hepbrn2018/default.htm
  - See summary report at HEPAP by R. Kolb for more information
    https://science.energy.gov/~/media/hep/hepap/pdf/201811/RKolb-HEPAP_201811.pdf

  - Procedure started in 2001-2002 by DOE Basic Energy Sciences (BES)

  - DM Small projects: first time BRN process has been used in DOE HEP

The BRN does not:

- Recommend anything
- Advise DOE
- Prioritize projects
- Rank PRD opportunities

The BRN does:

- Describe SCIENCE OPPORTUNITIES

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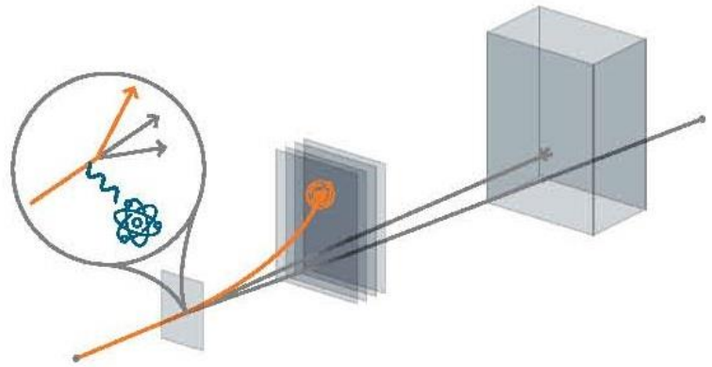
Charge:

- Identify science opportunities for new directions and areas of parameter space that will provide high impact science return and advancement for DM particle detection.
- Determine the high impact science opportunities which could be pursued by small projects (approximately $5M to $15M in Total Project Cost) that could be ready to start within the next few years, and in which DOE's laboratory infrastructure and/or technology capabilities are required to be realized.
- Suggest opportunities that could be pursued by future small projects, which also require DOE capabilities, but need further technology development before project initiation.

BRN Priority Research Directions

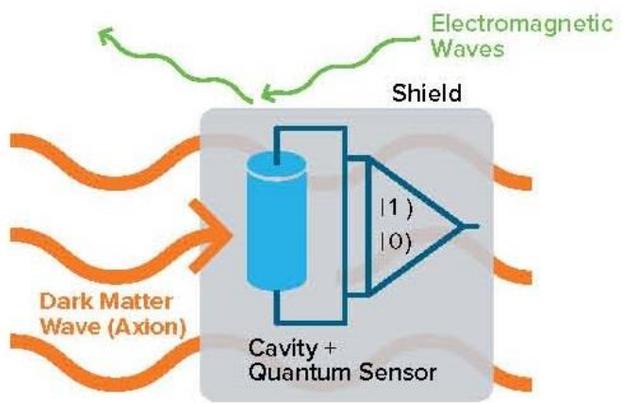
Three Priority Research Directions

Create & Detect Dark Matter at Accelerators



Detect Galactic Dark Matter Underground

Detect Wave Dark Matter in the Laboratory



https://science.energy.gov/~/media/hep/hepap/pdf/201811/RKolb-HEPAP_201811.pdf

https://science.energy.gov/~/media/hep/hepap/pdf/201811/BRN_Dark-Matter-Brochure_HEPAP_201811.pdf

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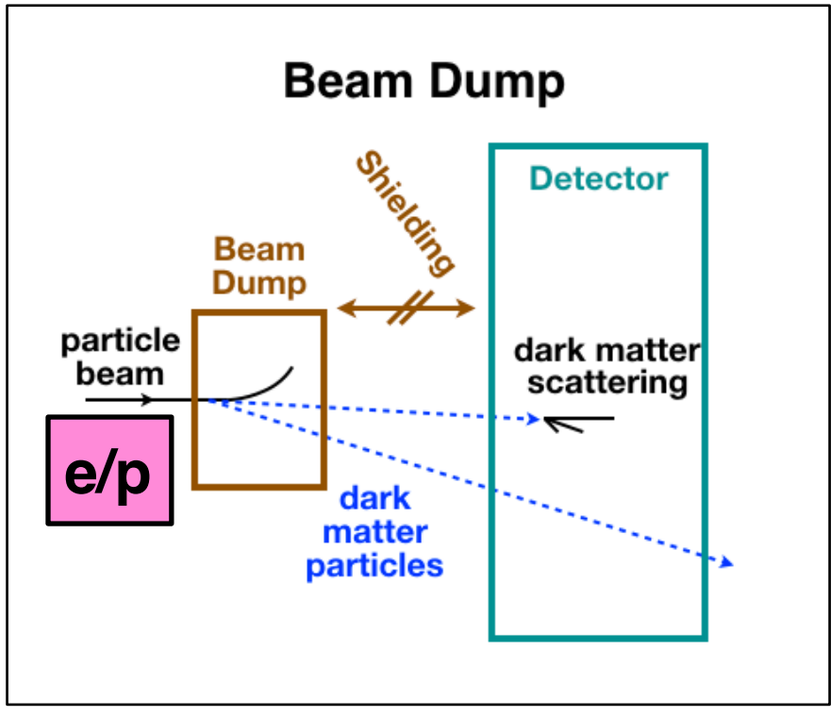
Accelerator dark matter program

Define two thrusts for the priority research direction:
Create and detect dark matter at accelerators

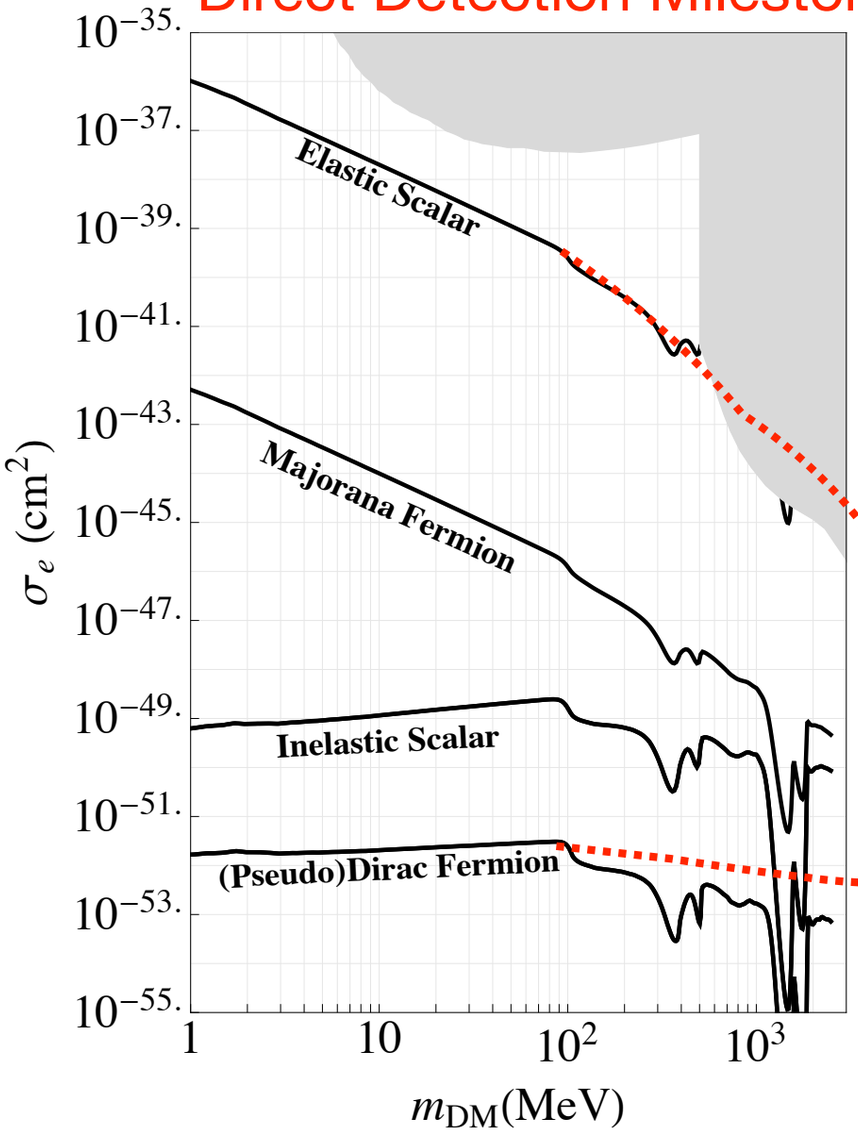
- **Thrust 1 (near-term)**: explore interaction strengths singled out by **thermal dark matter** through 10-1000-fold improvements in sensitivity
  - **Beam dump experiments** like MiniBooNE
    n.b. Proton beam dump program presented at Nov 2017 Fermilab PAC meeting
    https://indico.fnal.gov/event/15726/session/3/material/0/0.pdf
  - **Missing momentum experiments (electrons or muons)**

- **Thrust 2 (near-term and long-term)**: Explore the structure of the dark sector by producing and detecting **unstable** dark particles.
  - **Spectrometers** like SeaQuest

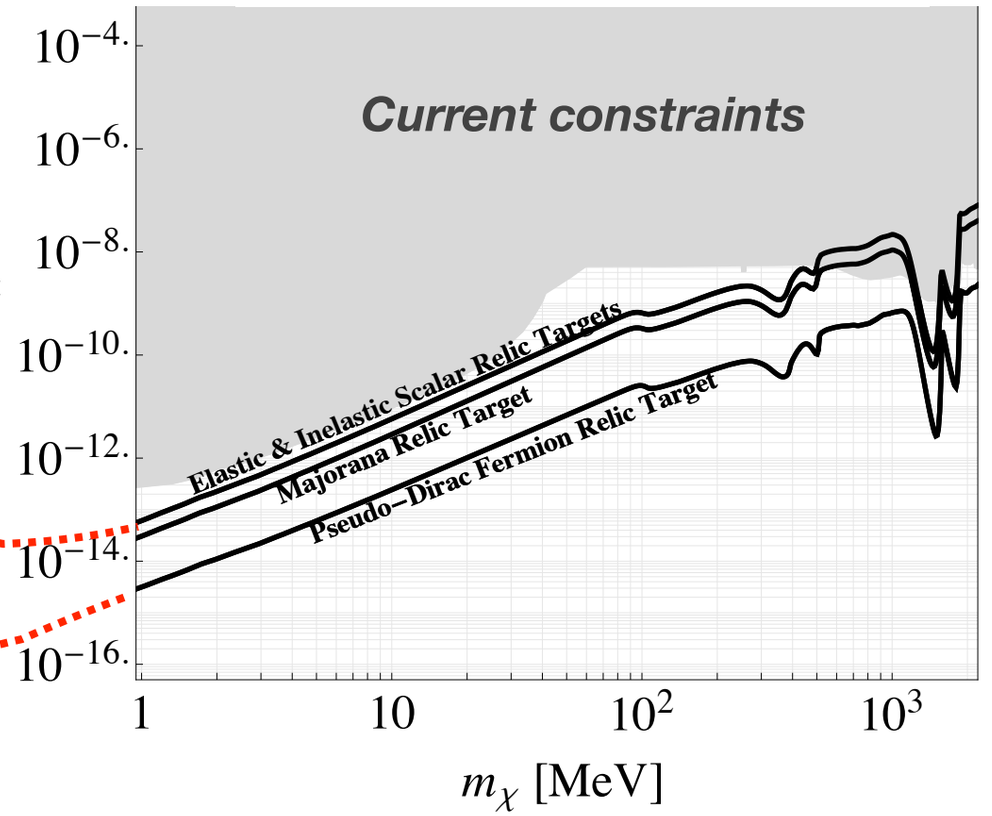


Thermal relic dark matter

Direct Detection Milestones



Accelerator milestones

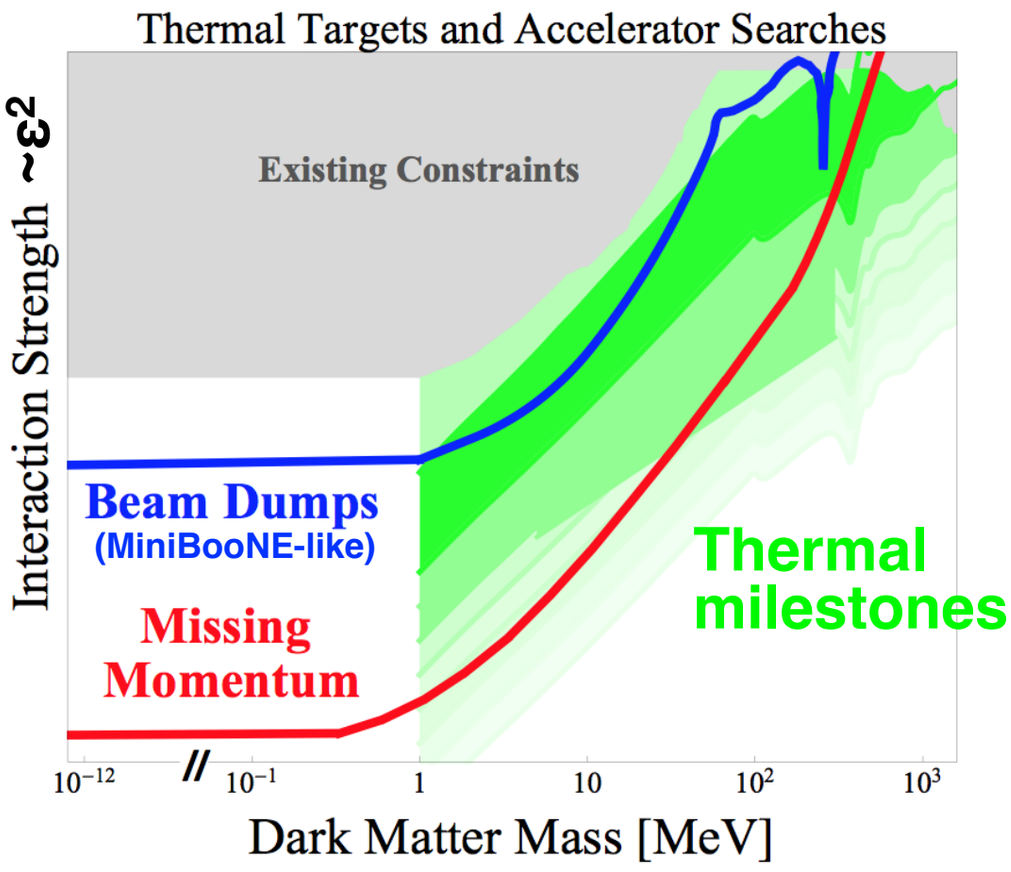


Accelerator program has good complementarity with direct detection

covers loop-suppressed and velocity-dependent couplings

The missing momentum physics program

Beam dump and **missing momentum experiments** have nice complementarity across different types of signals and probe different couplings



Missing momentum experiments typically have better coupling sensitivity because experiments scale as ε^2 instead of ε^4

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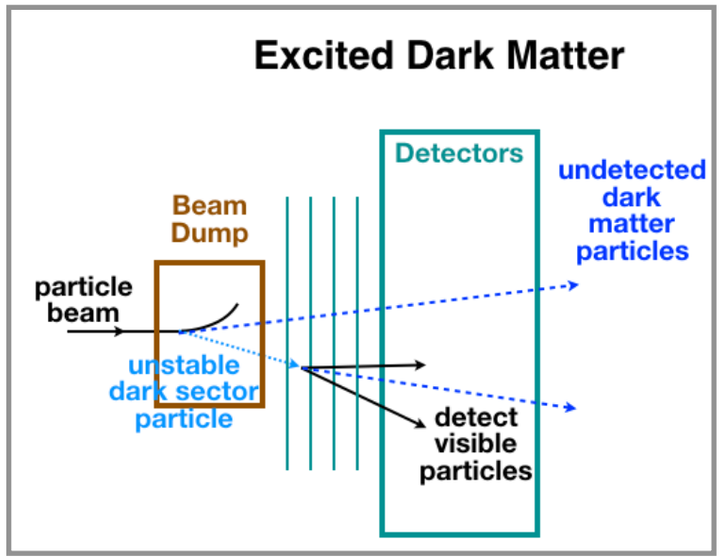

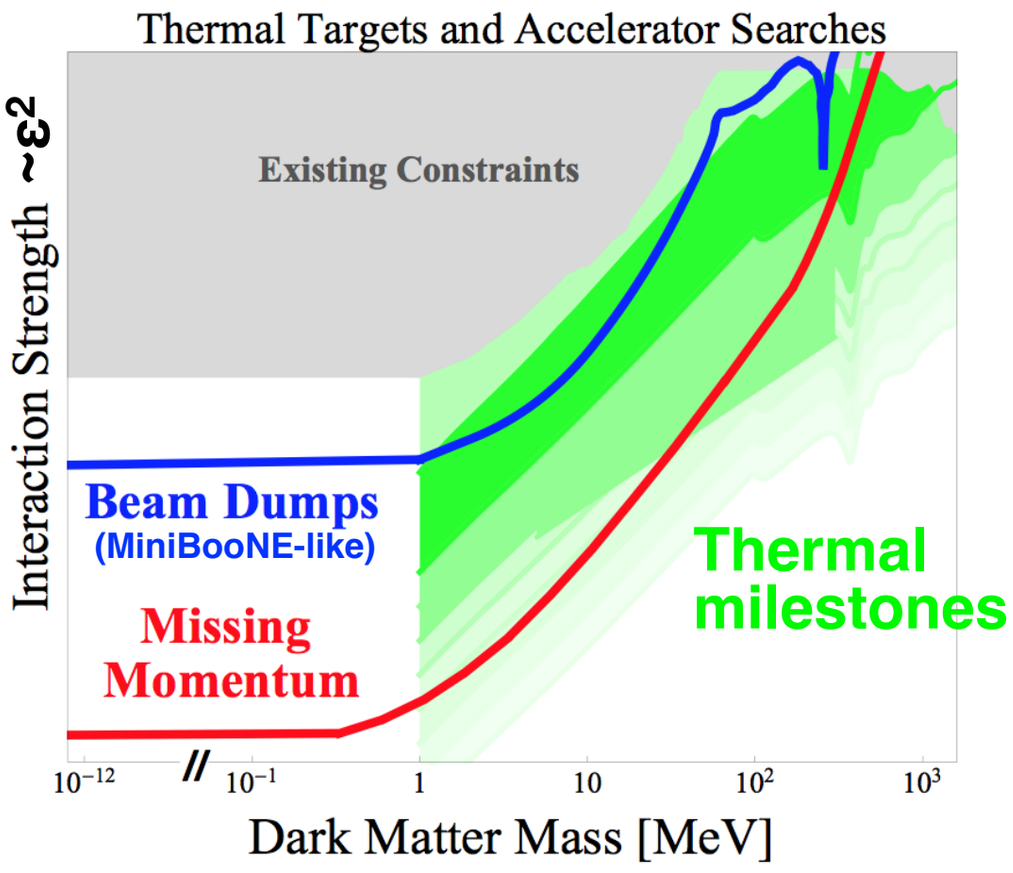

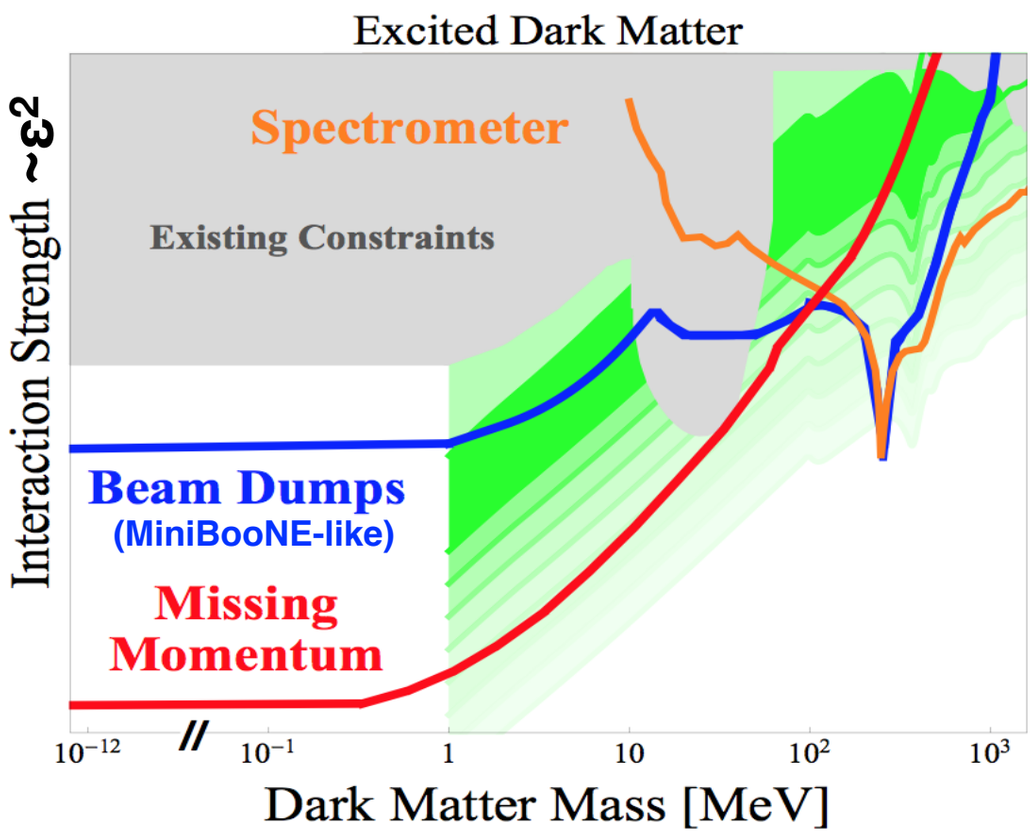

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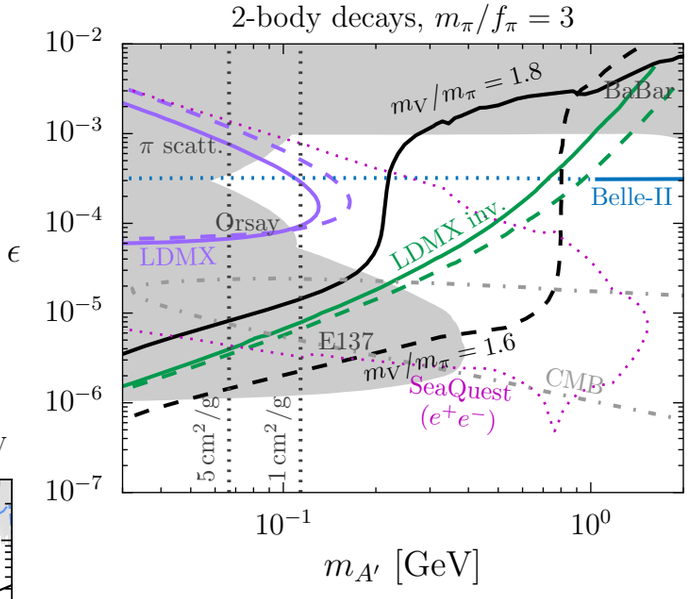
The missing momentum physics program

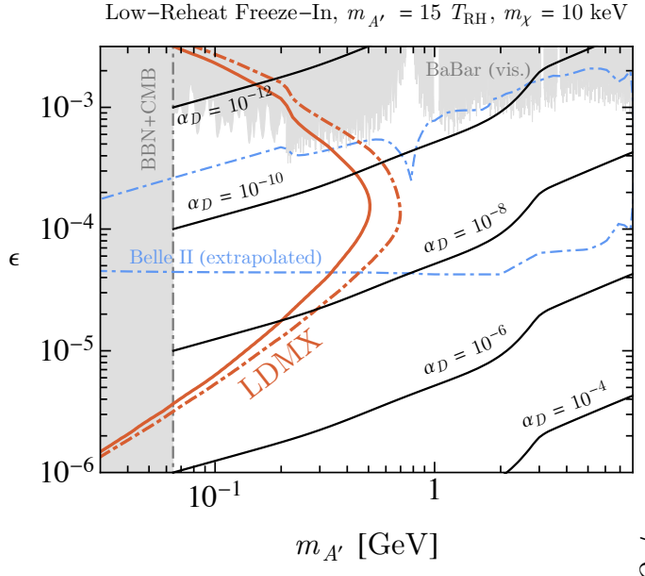
Much **broader physics program** for missing momentum experiments beyond thermal freeze-out dark matter milestones

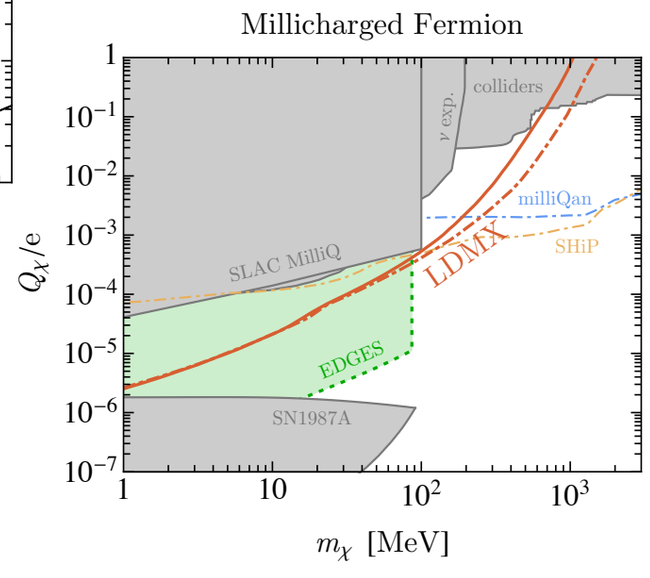
https://arxiv.org/pdf/1807.01730.pdf

(A. Berlin, N.B., G.K., P. Schuster, N. Toro)

- Long-lived and millicharged particles
- Strongly interacting DM models (SIMPs)
- Freeze-in DM
- Muon-specific couplings
  - B-L gauge boson models
  - $(g\text{-}2)_\mu$ and light new physics
  - More on this later!
- Potential connection to neutrino program
  - Measurements of lepton-nucleon measurements to improve v-N modeling (studies on-going)







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The Light Dark Matter eXperiment (LDMX)

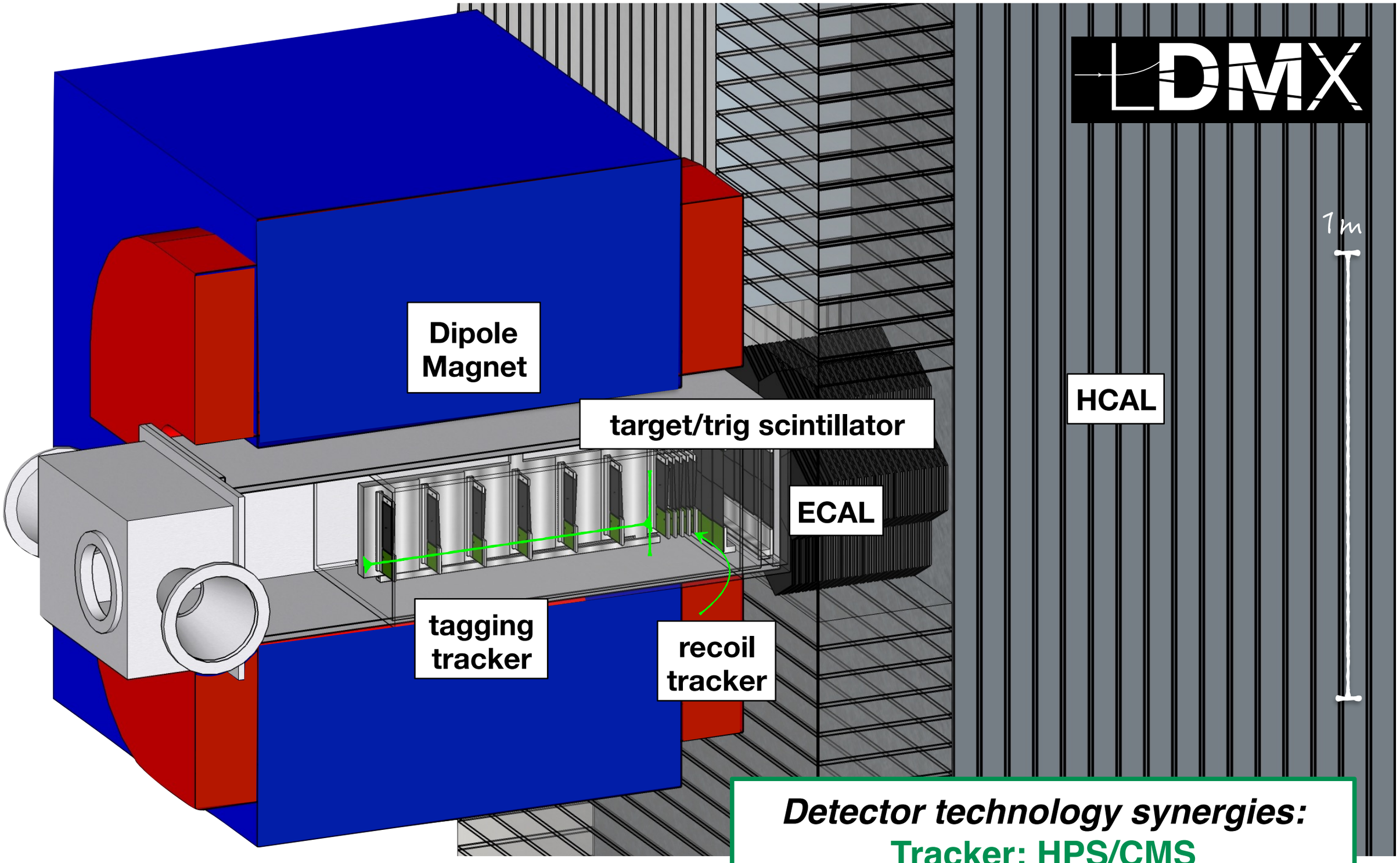
LDMX is an experimental concept developed for the missing momentum technique with electron beams

- Potential beamlines: JLab CEBAF, SLAC S30XL (proposed), CERN eSPS (proposed)

- **Experimental requirements**
  - High momentum resolution tracking system
  - Radiation hard, high precision electromagnetic calorimeter
  - Wide angle, high efficiency hadronic and MIP veto
  - Fast LHC-style electronics, ~50 MHz

STRONG FERMILAB SYNERGY!

- **White paper: https://arxiv.org/abs/1808.05219**
  - **Full GEANT studies demonstrating viability of missing momentum technique**
- LDMX institutions:
  - Caltech, Fermilab, Lund, SLAC, Texas Tech, UCSB, UMinnesota
  - Thank you to fellow LDMX colleagues for their support and studies!



Detector technology synergies:

Tracker: HPS/CMS

ECal: CMS HGCal

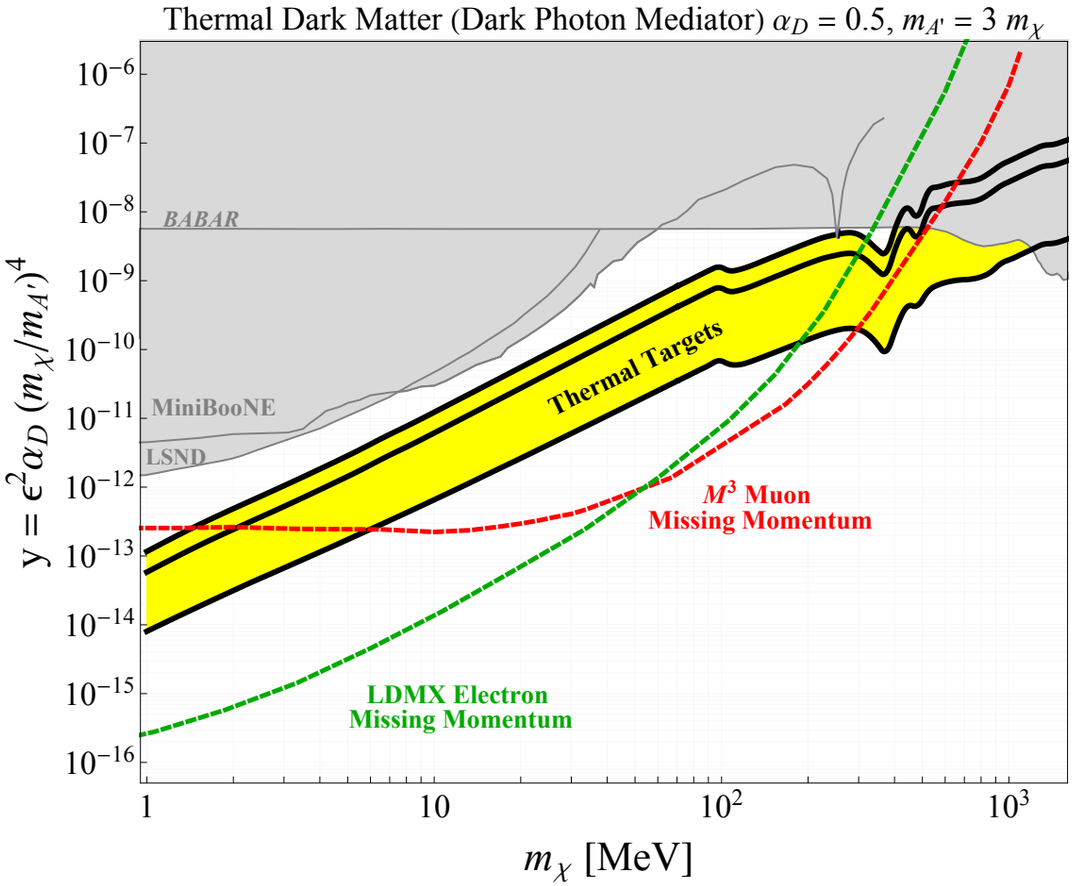
HCal/Trigger Scintillator: CMS/mu2e

https://arxiv.org/abs/1804.03144

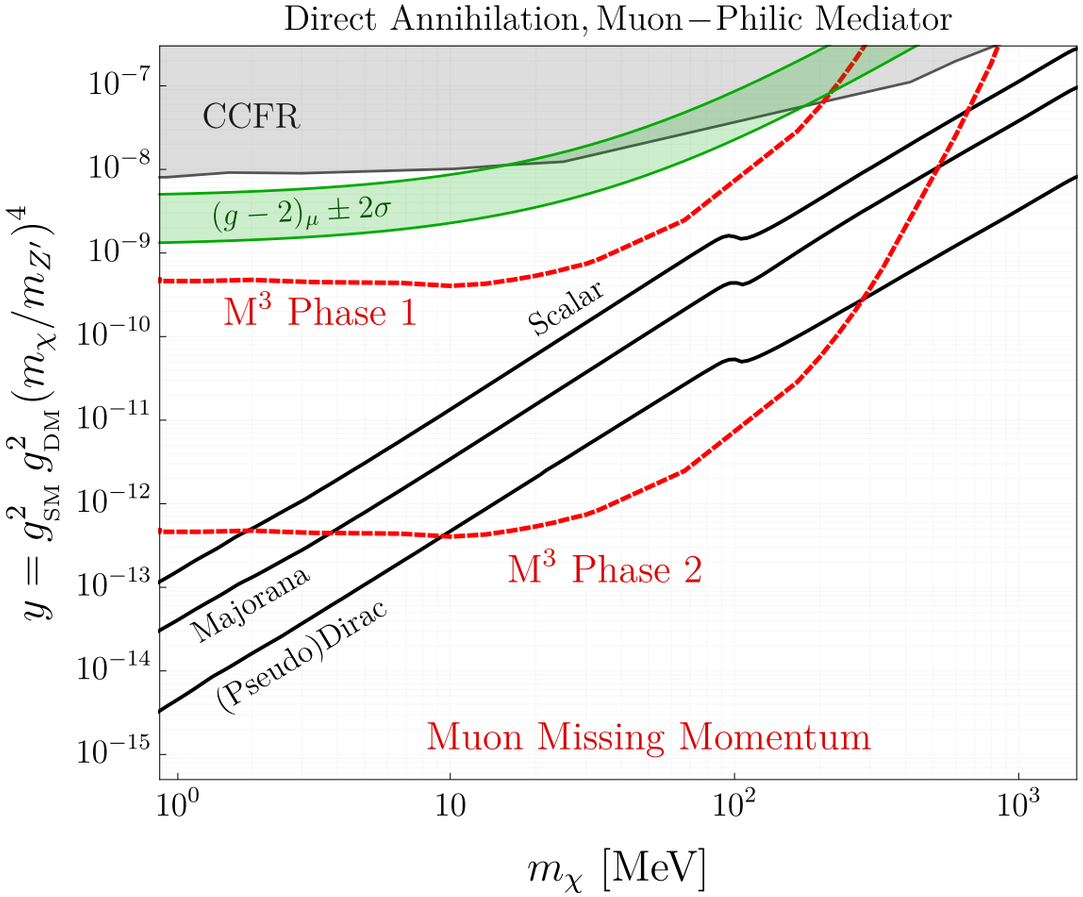
M³: Muon Missing Momentum

Muon beam missing momentum experiment good complement to electron beam experiment

For thermal DM milestones (lepton flavor universal), Muon Missing Momentum (M³) experiments have sensitivity to higher dark matter masses (> ~100 MeV)



Muon beams provide model-independent probe of light new physics contributing to $(g\text{-}2)_\mu$ anomaly



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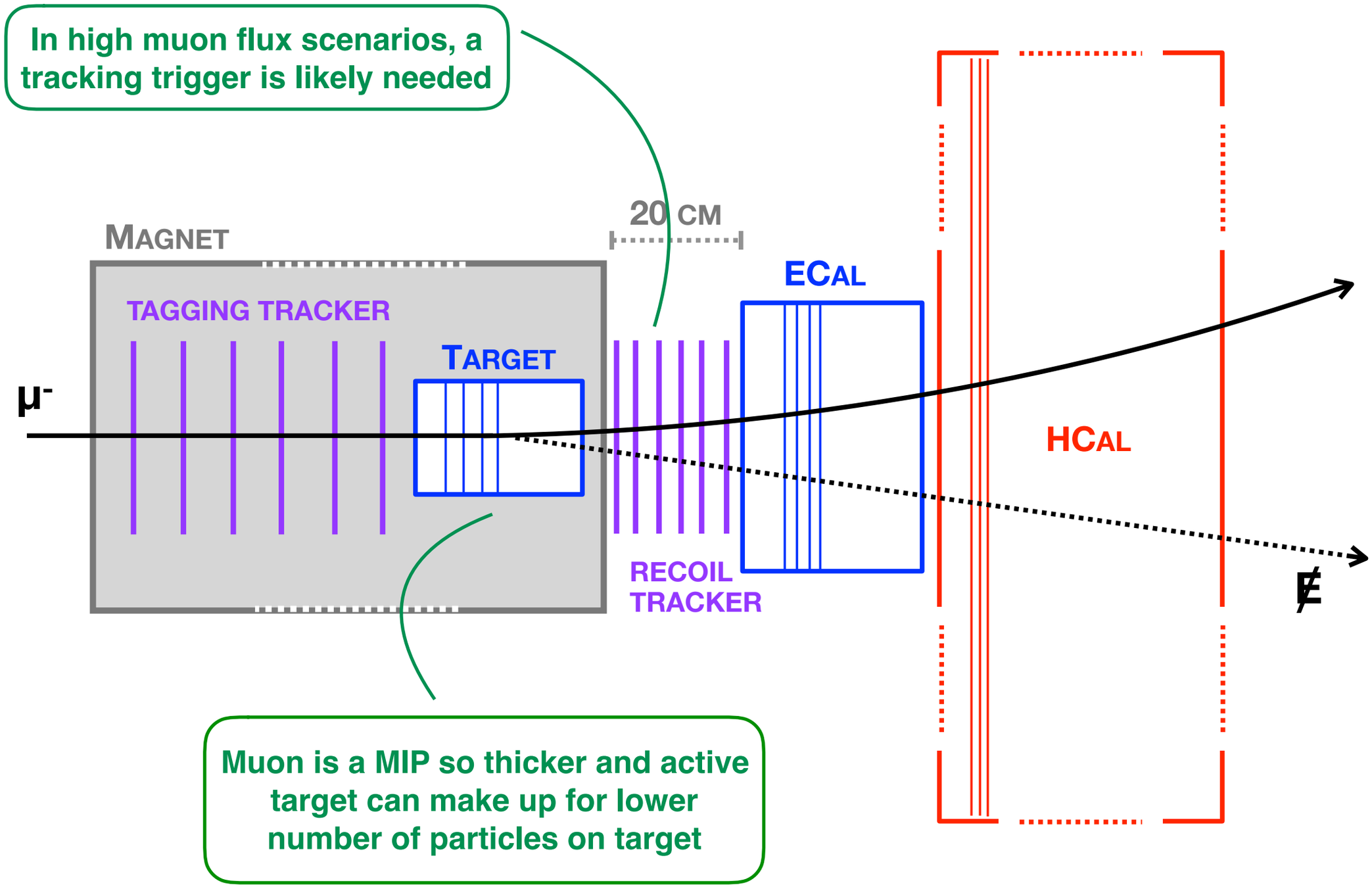
LDMX-M³



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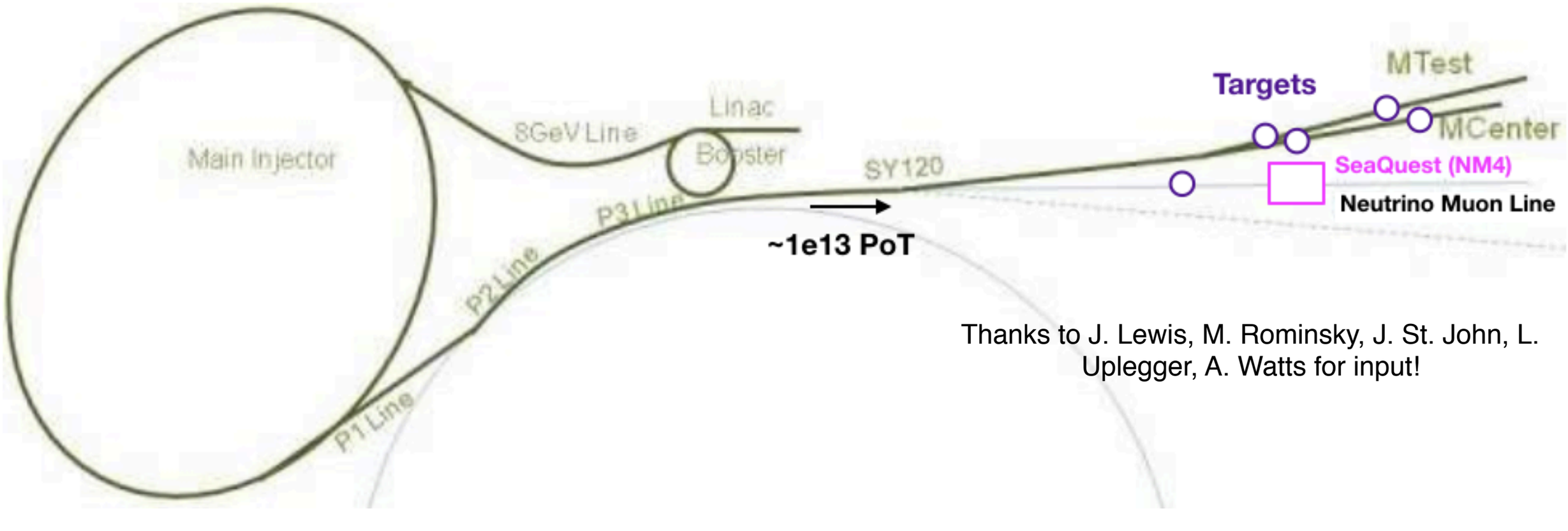
Muon beams with the Fermilab Accelerator Complex



Thanks to J. Lewis, M. Rominsky, J. St. John, L. Uplegger, A. Watts for input!

Muon beam for LDMX-M^3 could be provided by Fermilab Accelerator Complex

- Phase 1: 10^{10} muons on target, meson beamline to MTest/MCenter
- Phase 2: 10^{13} muons on target, Neutrino-Muon beamline to NM4 (SeaQuest)

Need sim. studies, measurements to understand muon beam capabilities

10^8-10^9 MoT "Phase 0" exp. may also yield physics starting on the 1-2 year timescale!

Fermilab and missing momentum synergies

Scientific and technological expertise for missing momentum program has **strong synergy with Fermilab capabilities**

- Intellectual leadership in this physics program
  - GK, NB originators and drivers of the LDMX physics program
  - NT, AW (formerly FNAL) drivers of the LDMX experimental concept; simulation studies and calorimeter/electronics expertise
  - YK, GK, NT, AW are originators of the M^3 concept at Fermilab
- LDMX detector synergy - current involvement
  - HCal employs mu2e scintillator fabricated in Fermilab Scintillator Fabrication Facility and electronics from mu2e cosmic ray veto (FNAL eng.)
  - Target scintillator deploys CMS HCal electronics (FNAL eng.)
  - Trigger leadership from Fermilab/CMS expertise (NT)
- Muon beamline synergy: Fermilab accelerator complex is the only place in the US that can provide the necessary beam
  - Proposal to the CERN Physics Beyond Colliders group (NA64-like)

Summary and Outlook

- **Accelerator-based DM experiments** are exciting tool to explore new initiatives in **sub-GeV dark matter**
  - **Fermilab** plays crucial role in proton beam dumps, missing momentum experiments, and spectrometers
  - **DOE BRN study** (~month timescale) highlights accelerator DM program

- **LDMX is developed experimental concept** demonstrating feasibility of **missing momentum technique**
  - **Fermilab** plays crucial role in intellectual development of the physics program and the several of the detector subsystems

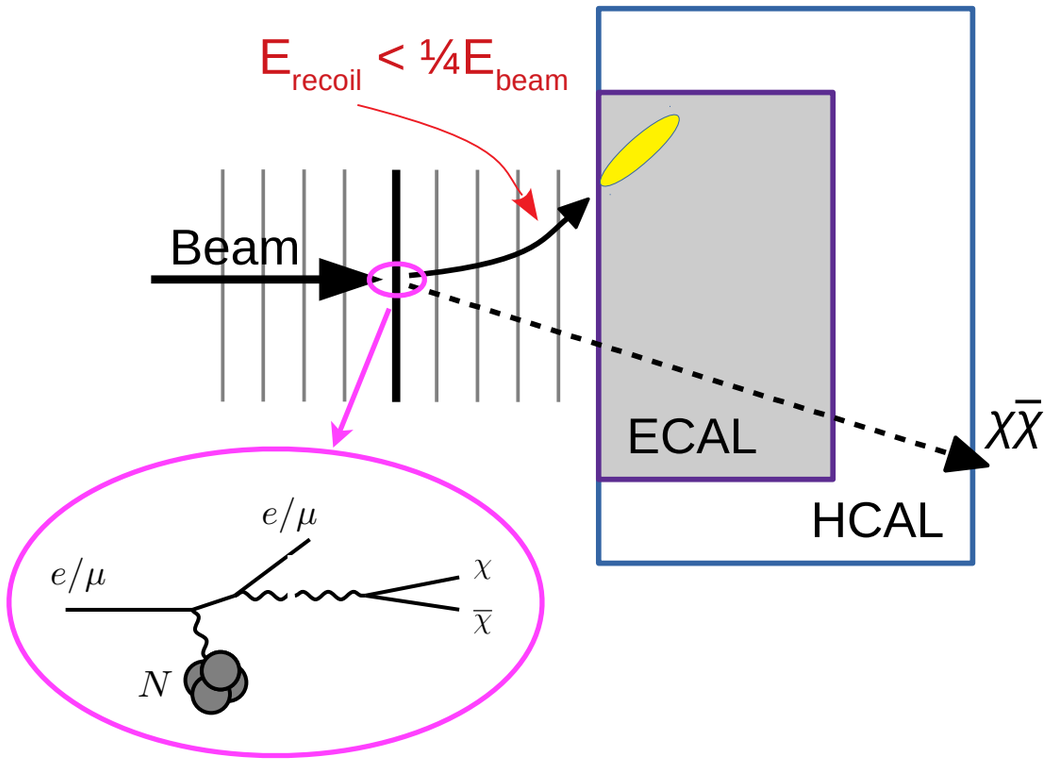
- **Muon missing momentum (LDMX-M^3)** uniquely probes muon couplings and heavier dark matter candidates with the Fermilab Accelerator Complex

We expect the PAC to comment on Fermilab's role in driving the LDMX(-M^3) physics program and detector development and the study muon beamline capabilities

Backup

The missing momentum technique

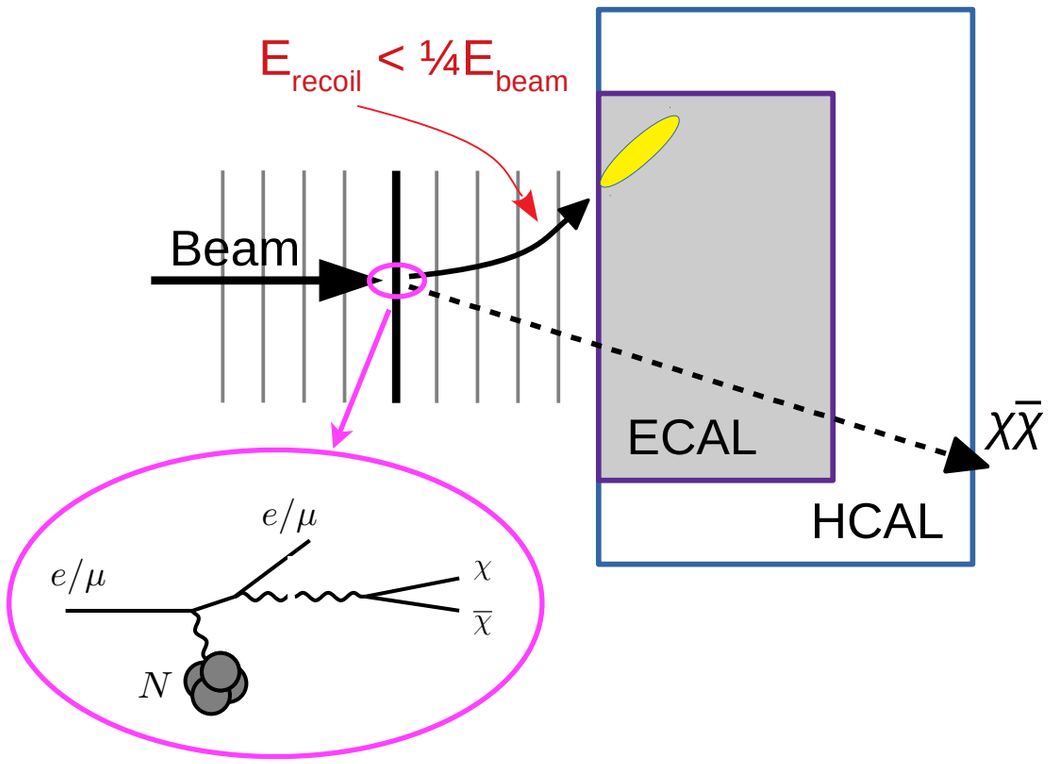
Signal



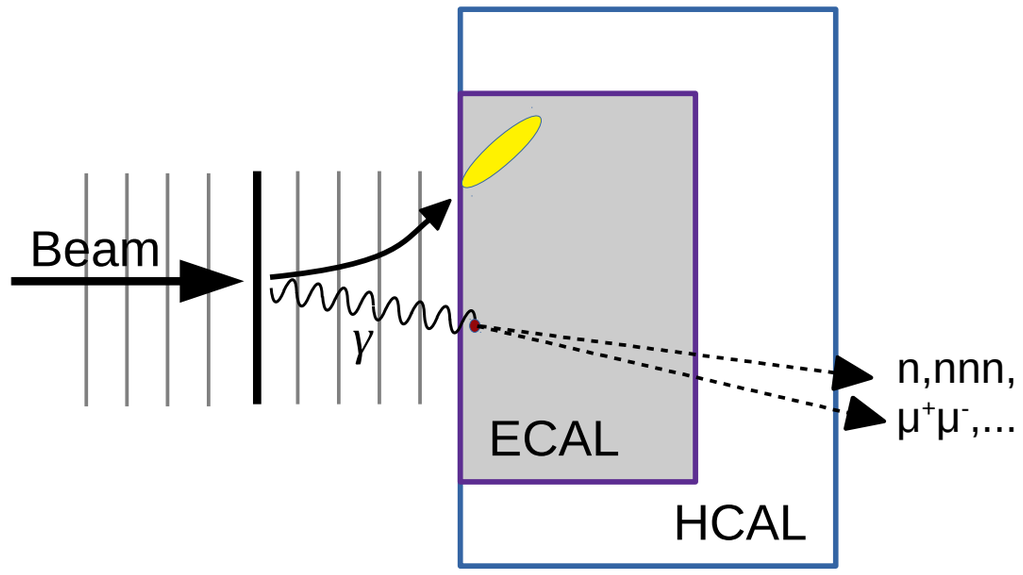
Incoming beams of ~single O(10) GeV electrons or muons
Beam rates: to achieve thermal milestones, need rates at ~50 MHz scale

The missing momentum technique

Signal



Background



Backgrounds come from rare SM processes that escape detection

Hard Bremsstrahlung + photon-nucleon

Hard Bremsstrahlung + muon pair conversion

Electron-nucleon

LDMX white paper results

Full GEANT simulation study to understand feasibility of the LDMX physics program with an electron beam

- Detailed simulation and calculation of photonuclear, electronuclear, and muon conversion backgrounds including improvements to GEANT modeling
- A first baseline detector concept simulating detector performance requirements and geometry