New Physics With Lepton Beams

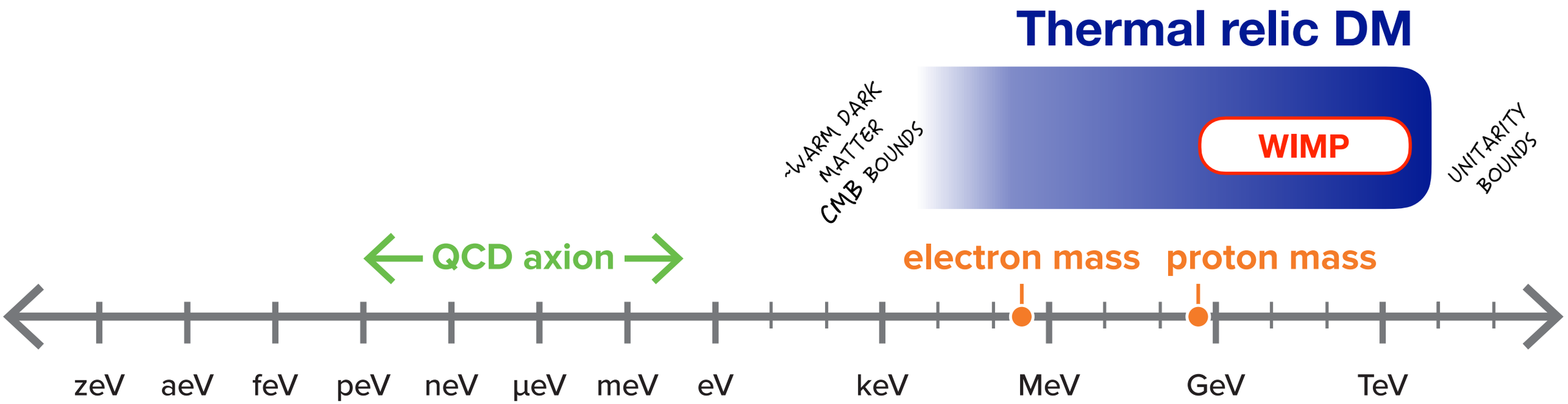
Gordan Krnjaic, Nhan Tran

Booster Replacement Science Opportunities, May 19, 2020

Outline

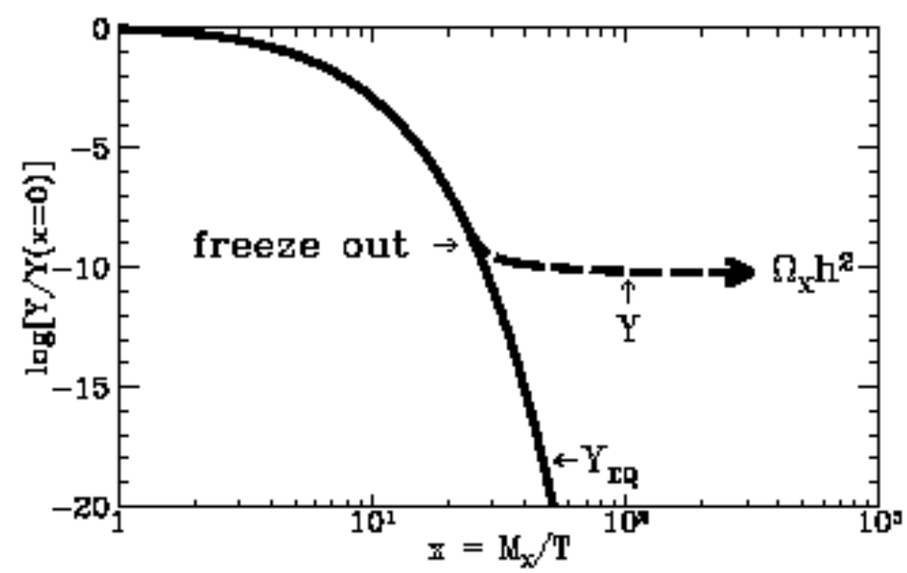
- **Motivation Overview**
- **Beam Dumps (electron, positron, muon)**
- **Spectrometer (electron)**
- **Missing momentum (electron, muon)**

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**



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

  - **European Community (2019)**
    - Physics Briefing Book https://arxiv.org/abs/1910.11775
    - CERN Physics Beyond Colliders https://arxiv.org/abs/1902.00260

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

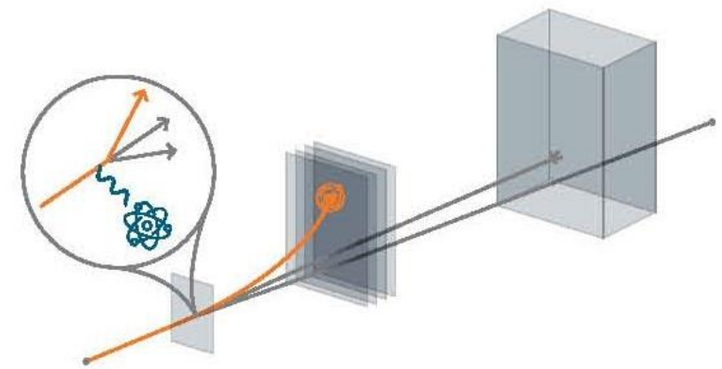
The BRN does not:
- Recommend anything
- Advise DOE
- Prioritize projects
- Rank PRD opportunities

The BRN does:
- Describe SCIENCE OPPORTUNITIES

BRN Priority Research Directions

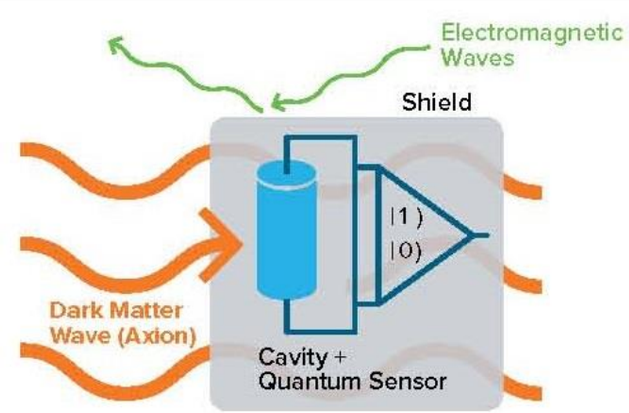
Three Priority Research Directions

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

Accelerator dark matter program

Define two thrusts for the priority research direction:
Create/detect dark sector particles @ accelerators

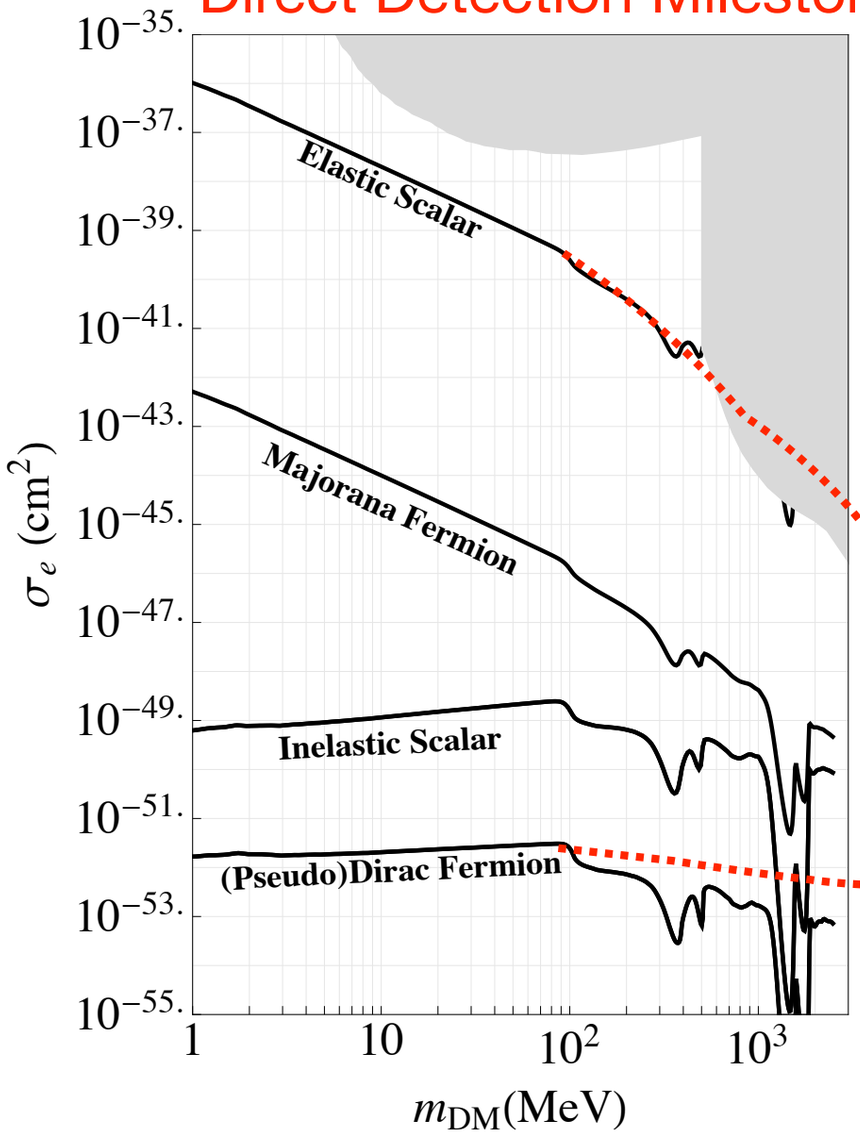
- **Thrust 1 (near-term)**: Explore interaction strengths motivated by **thermal dark matter** through 10-1000-fold improvements in sensitivity

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

  - **Techniques for both thrusts**
  - **Beam dump experiments** (electron positron muon)
  - **Spectrometers** (electron)
  - **Missing momentum experiments** (electrons/muons)

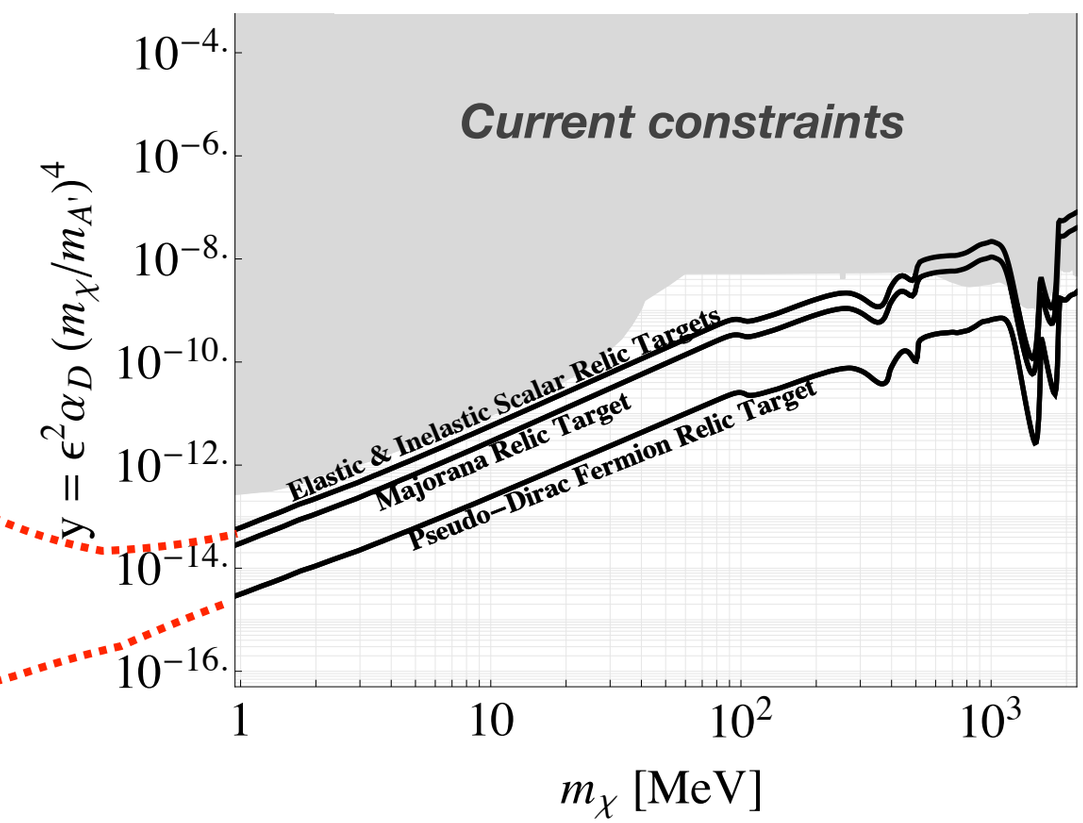
Key Milestone: Thermal relic dark matter

Direct Detection Milestones



Cosmic Visions Report

Accelerator milestones



Accelerator program has good complementarity with direct detection

covers loop-suppressed and velocity-dependent couplings

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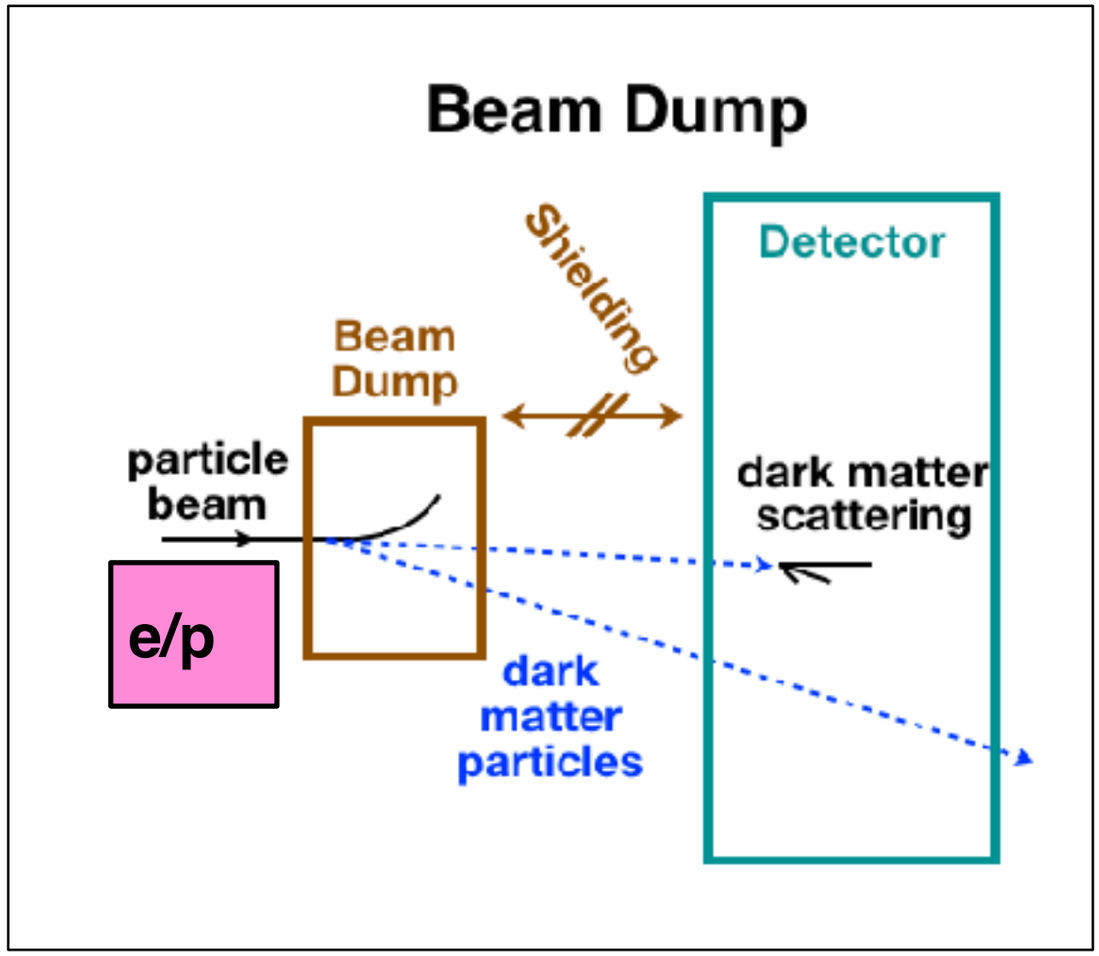
Beam Dump Technique

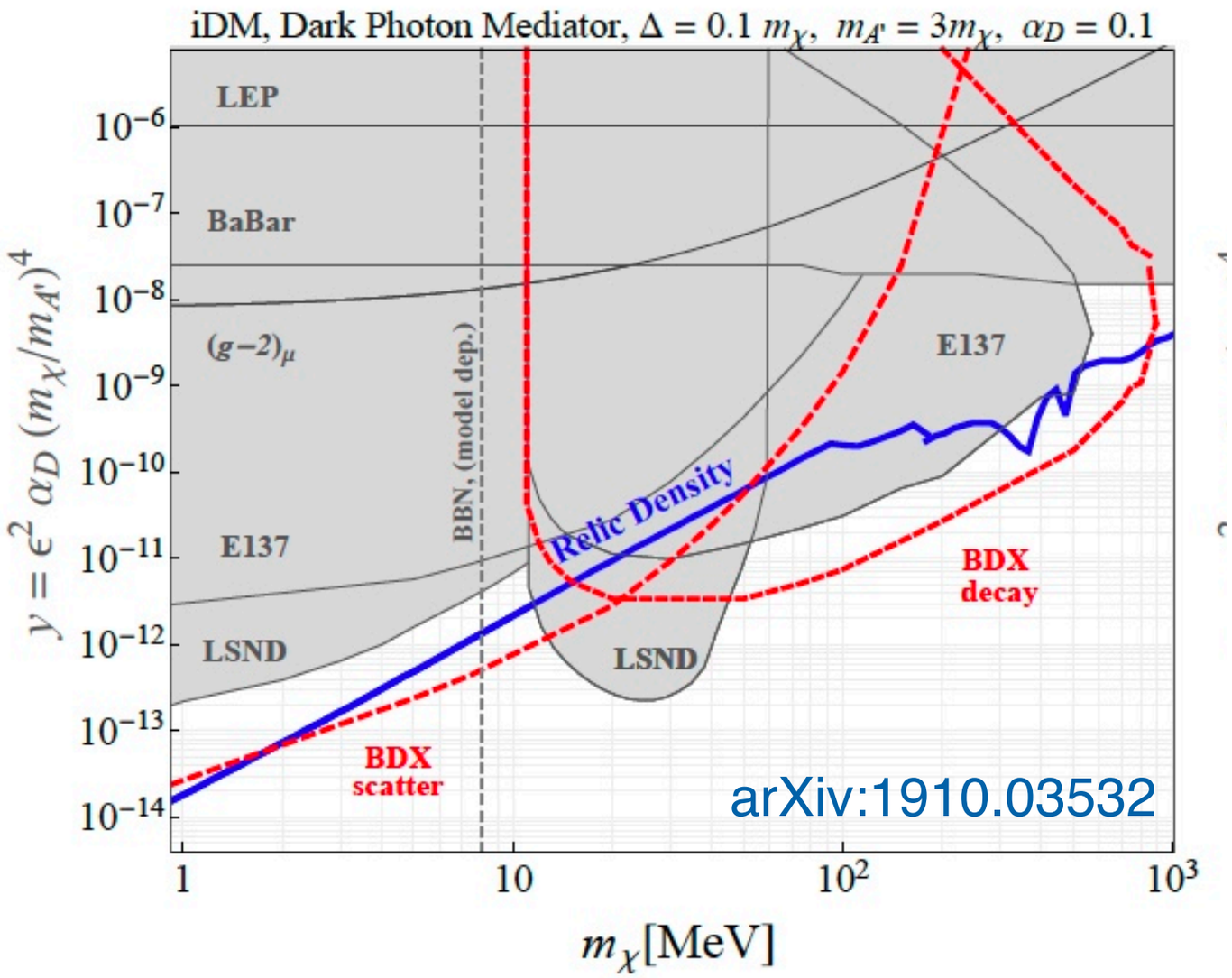


(or unstable decays)

Signal scales as production x detection = (coupling)^4

Incoming beams of ~single O(10) GeV electrons, positrons, muons
Beam rates: to achieve thermal milestones, need ~ 1e22 EOT (electron)

Electron Beam Dumps

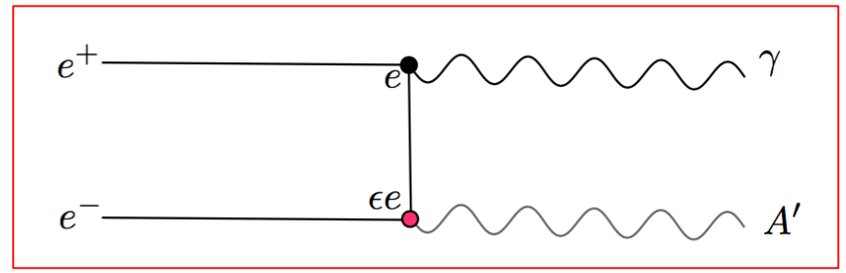


11 GeV e- beam, high current ~ 100 uA, 1e22 EOT/year

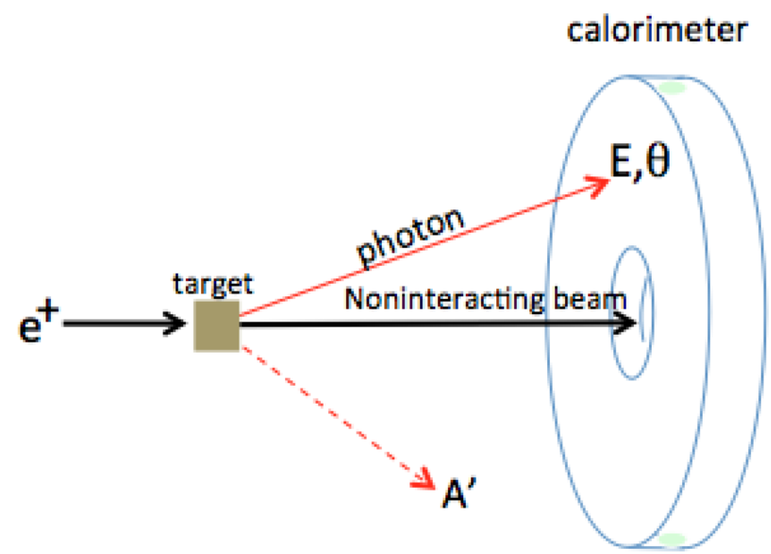
Sensitivity to thermal DM (Thrust 1), unstable "friends" (Thrust 2)

Positron Beam Dumps

Process of interest:



Hardware:



- E_{beam} = 1.8 -- 5.3 GeV
- I_{beam} ~ 2.3 nA at target
- quasi-CW during ~millisecond spills @ 60H
- pulse structure: 168ns

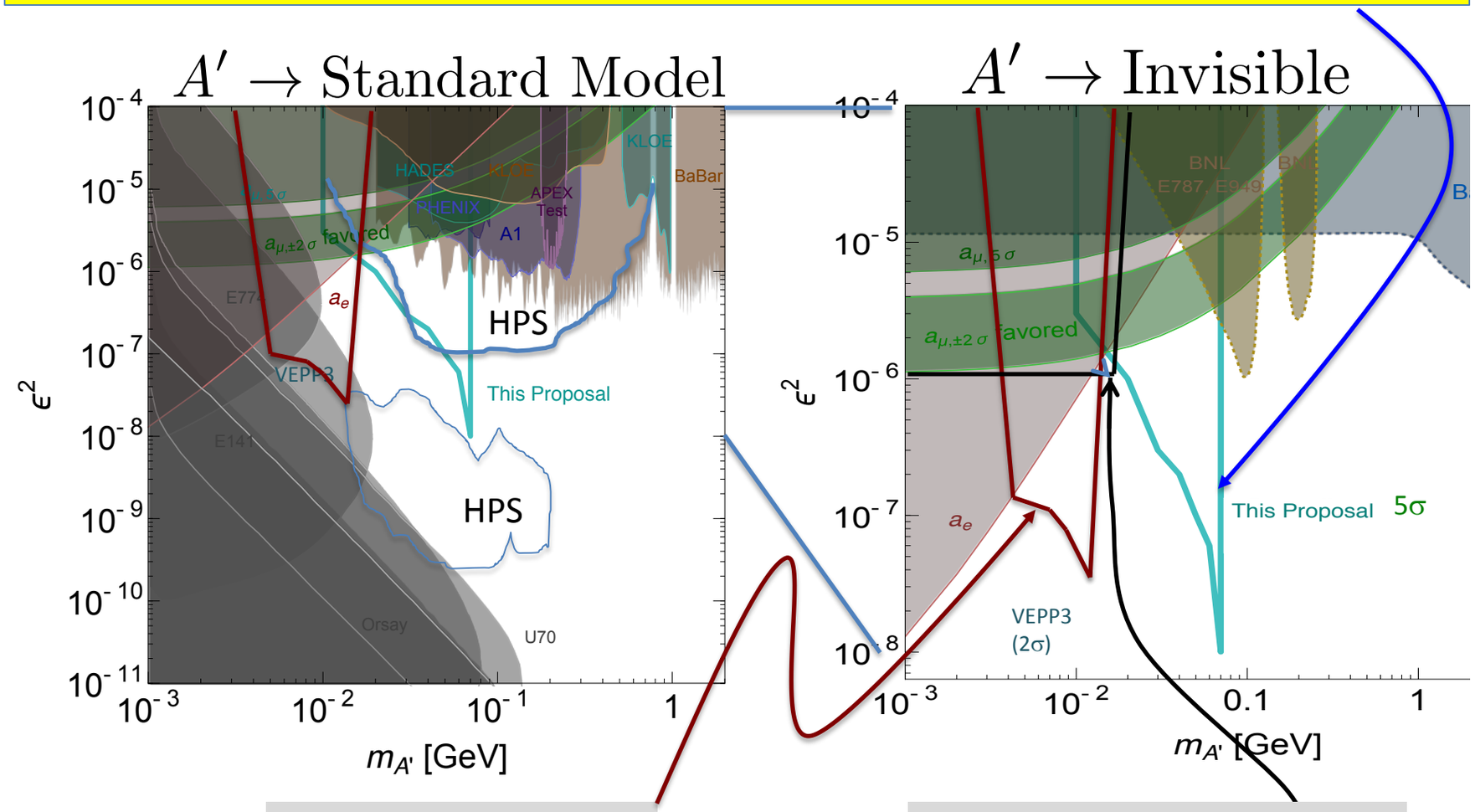
Fixed target, calorimeter 10m downstream.

Source: Jim Alexander

Positron Beam Dumps

Based on GEANT4 simulation with all bkgs and pileup included

E_{beam}=5.3GeV, I^{avg}_{beam}=2.3nA, Lumi = 1.0×10^{34}, T = 10^7sec, 5-sigma excl

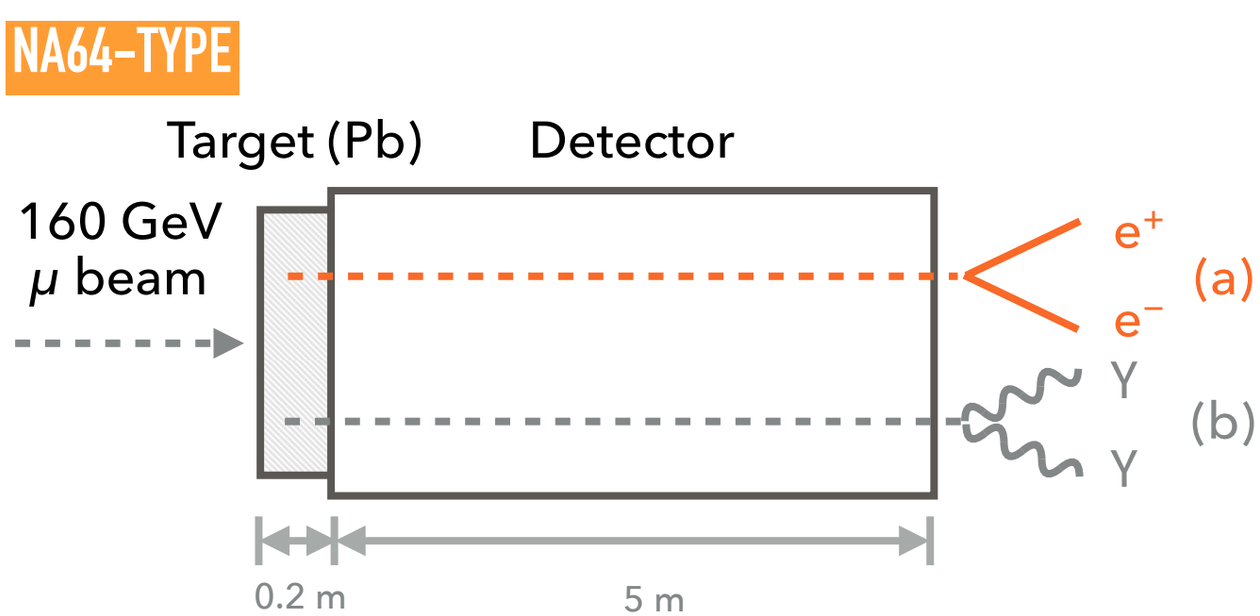


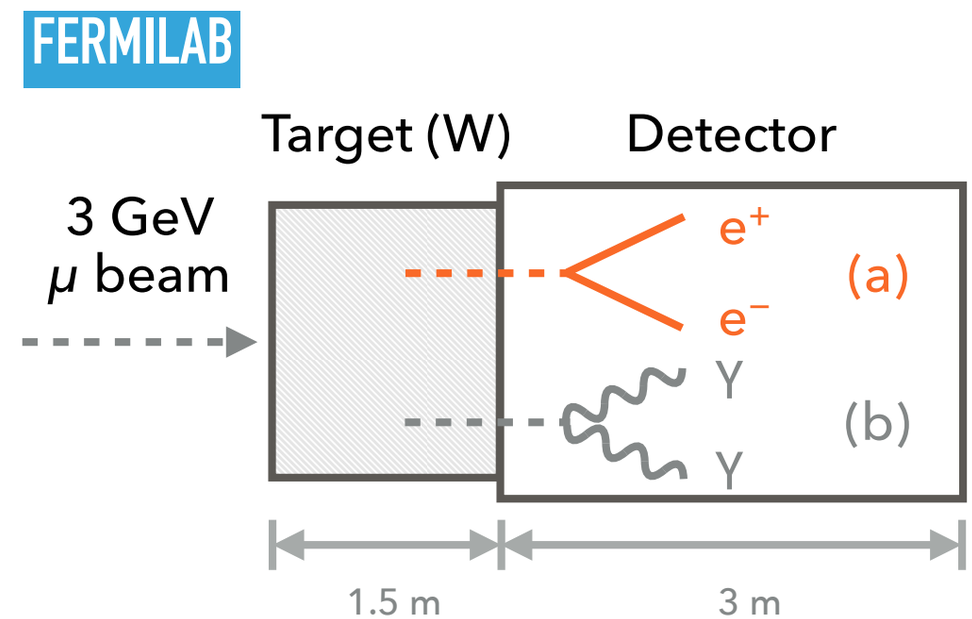
Novosibirsk (proposed)

PADME @ Frascati (proposed)

Source: Jim Alexander

Muon Beam Dumps



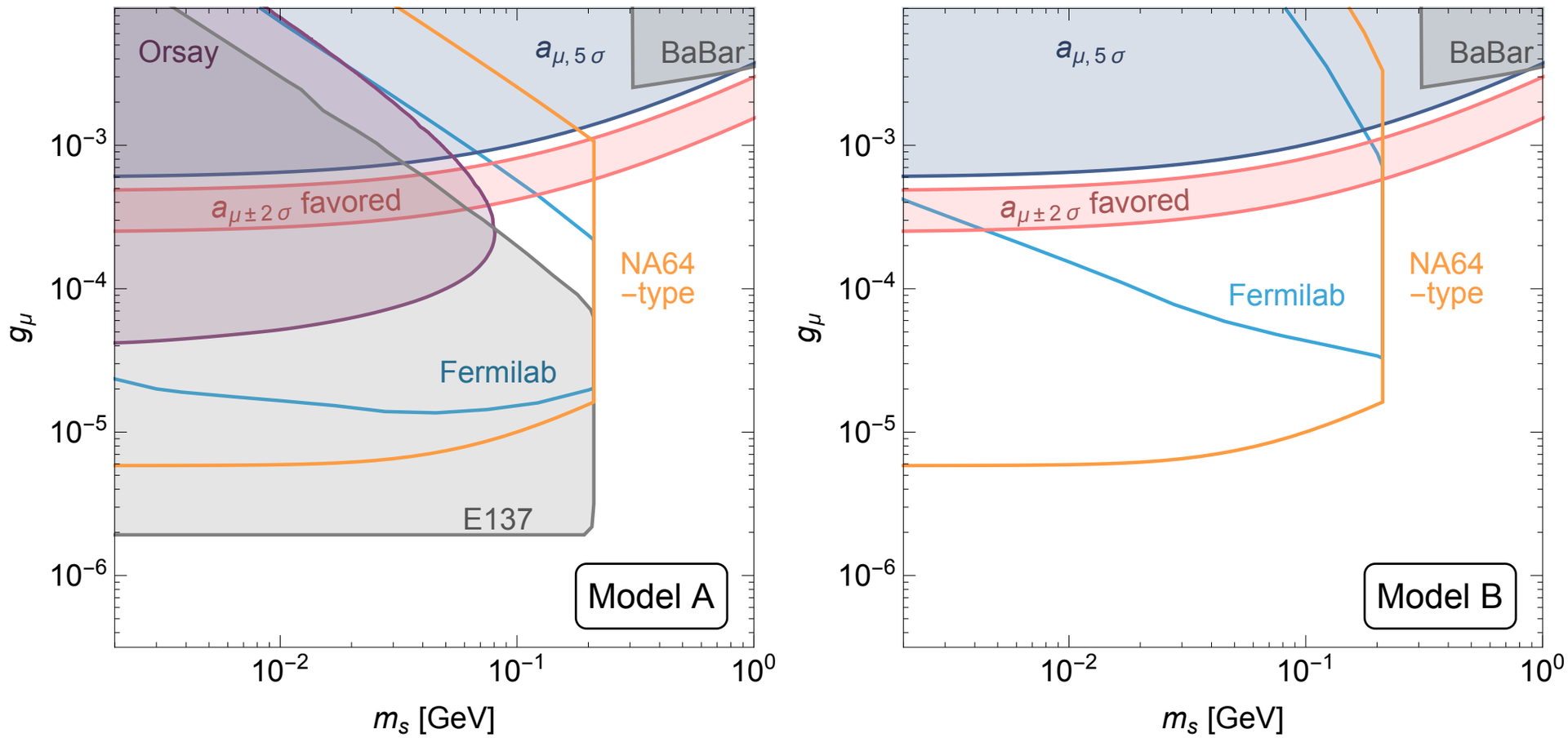


Chen, Pospelov, Zhong 1701.07437

1-100 GeV beams, ~1e13 muons/year

Sensitivity to unstable dark sector particles (Thrust 2)

Muon Beam Dumps



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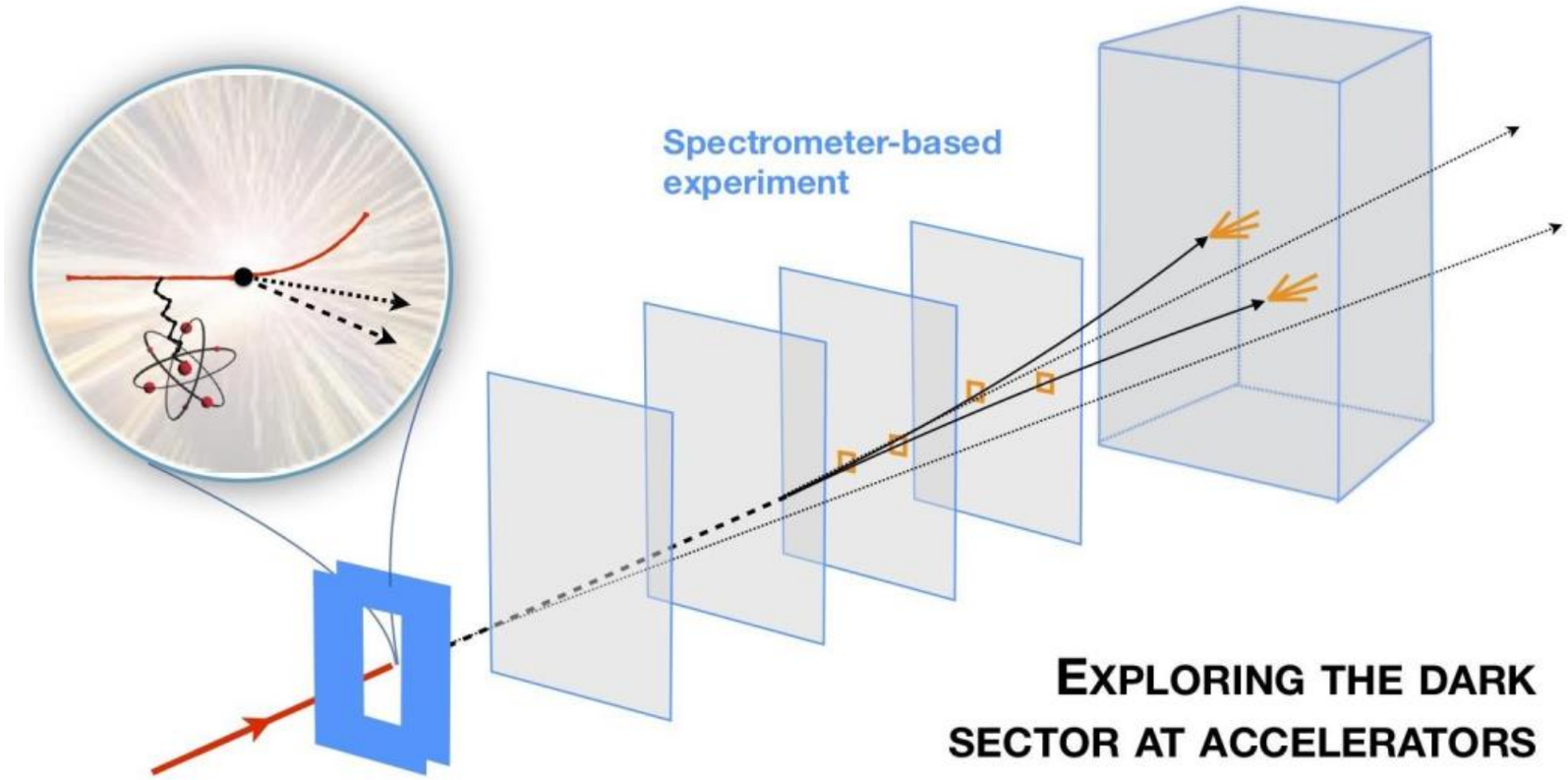
Electron Spectrometer



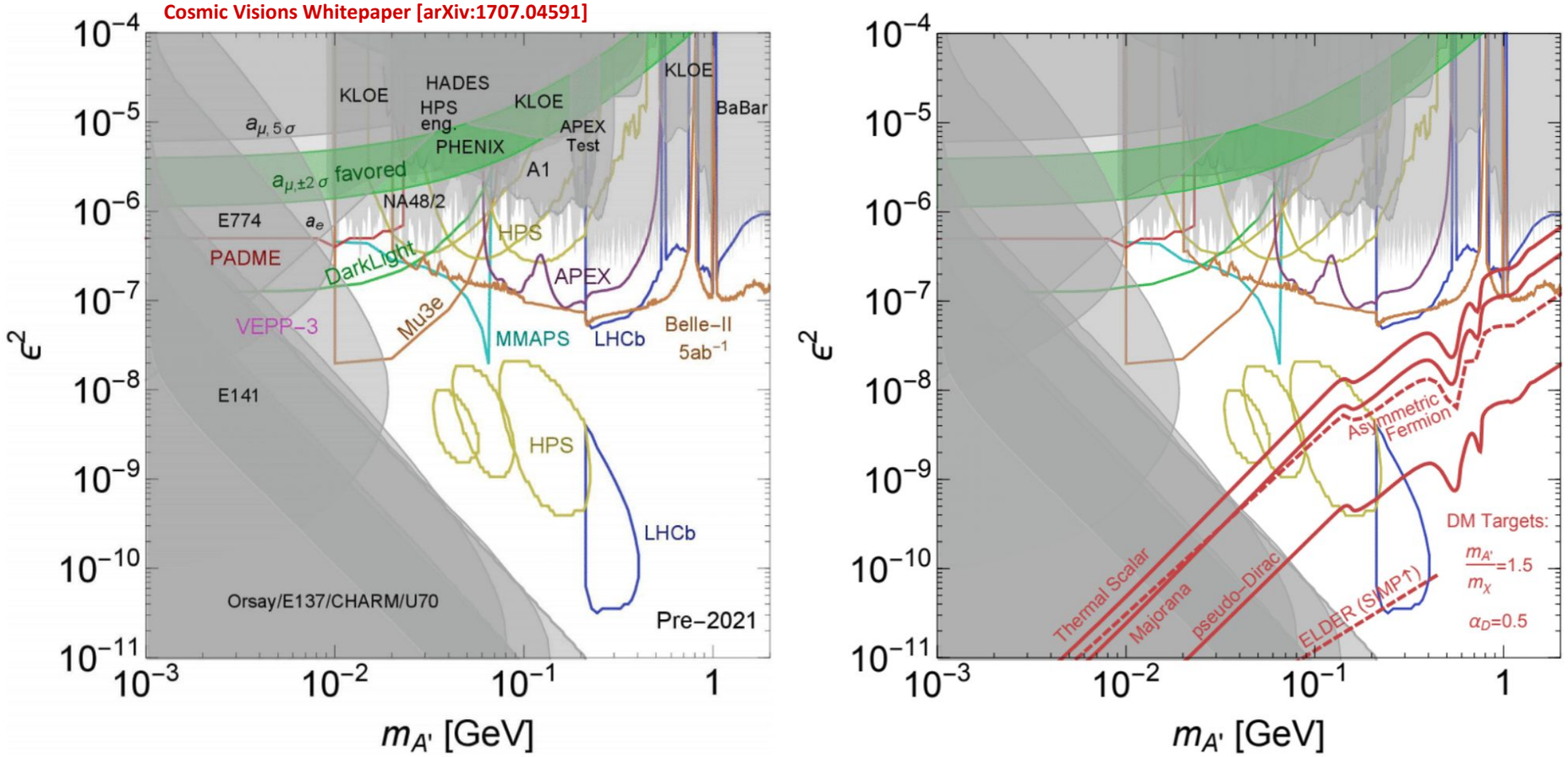
DOE BRN Report

Produce unstable particles, track daughter particles downstream
Same signal scaling as beam dumps ~ (coupling)^4

Lower current ~ nA-100 nA (often to reduce BGs)

Electron Spectrometer

Cosmic Visions Whitepaper [arXiv:1707.04591]



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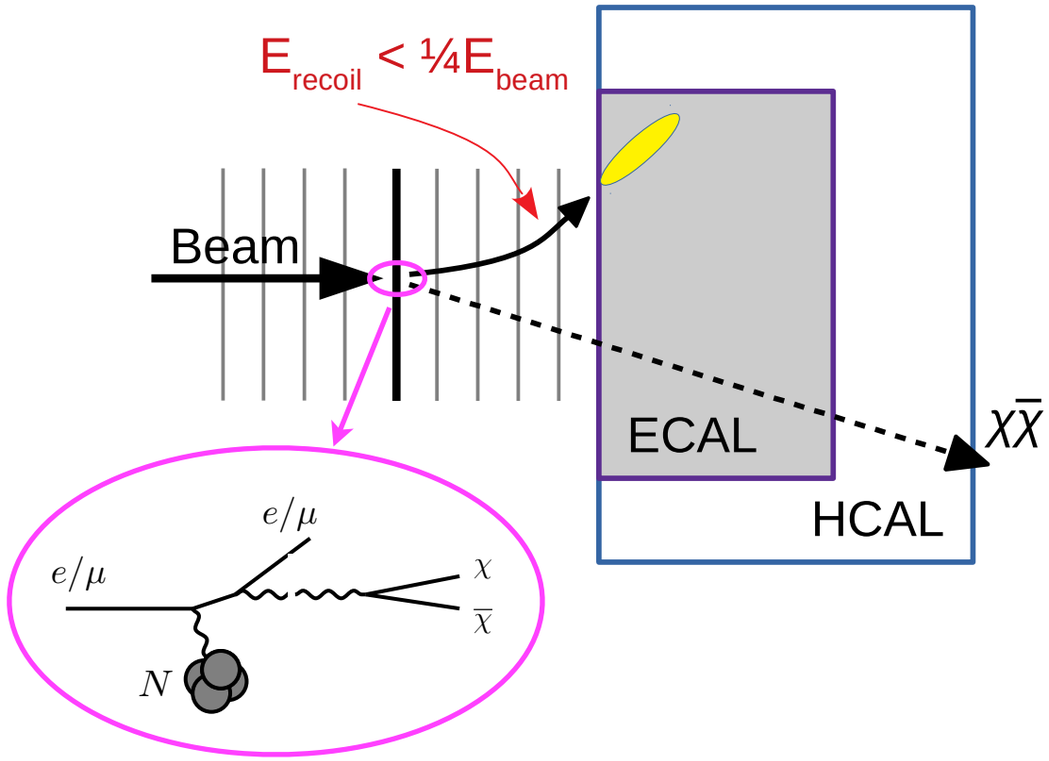
Electron Missing Momentum

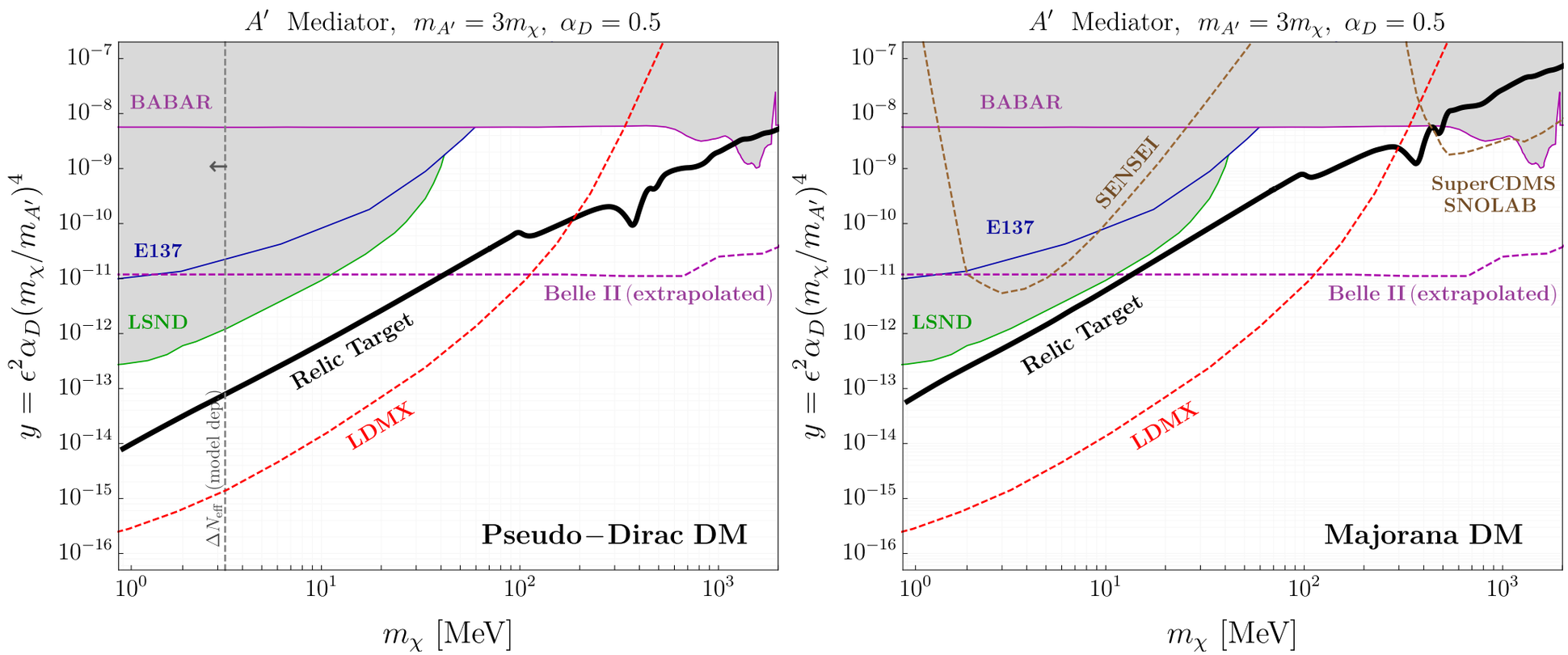


Best for invisible Particles

Signal scales as production only = (coupling)^2

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

Electron Missing Momentum



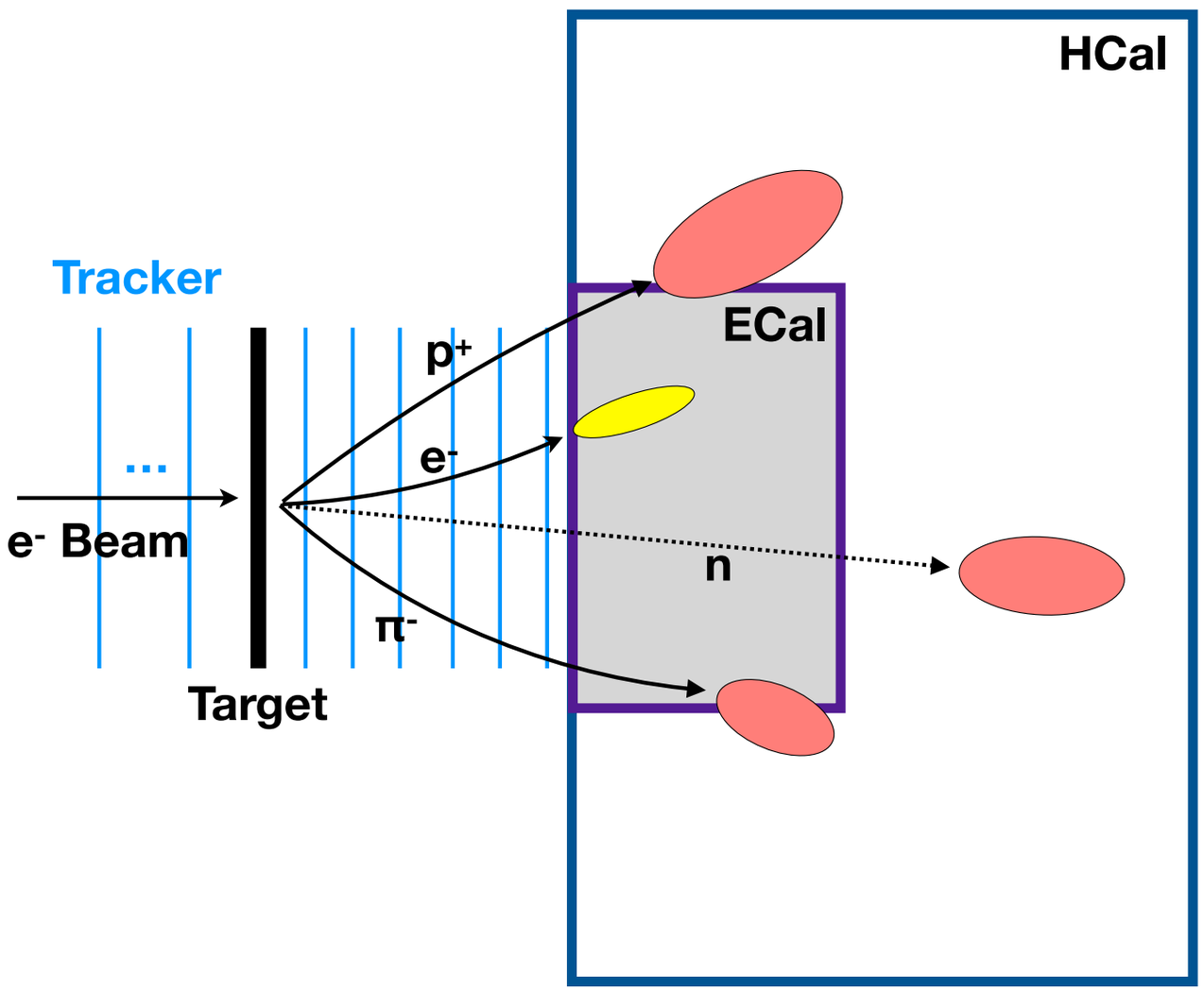
Signal scales as production only = (coupling)^2

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

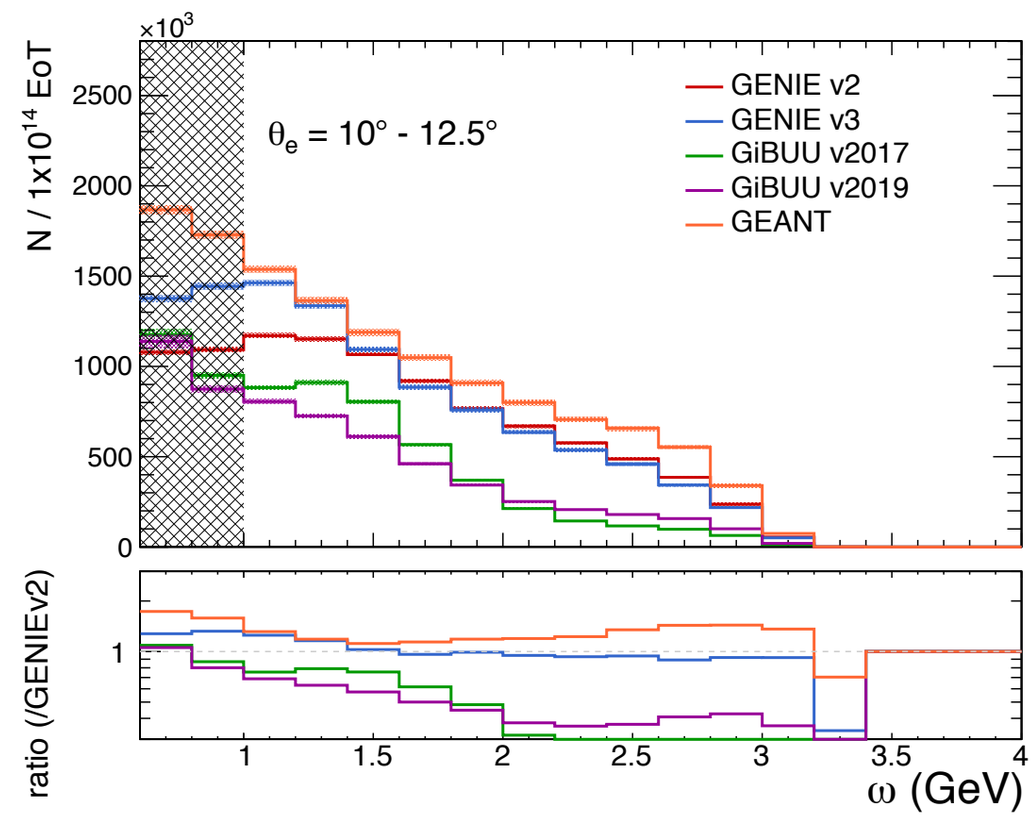
arxiv:1807.01730

Lepton-nucleon scattering for DUNE

Electron-nucleon scattering at ~several GeV matches well with the DUNE lepton-nucleon cross section phase space



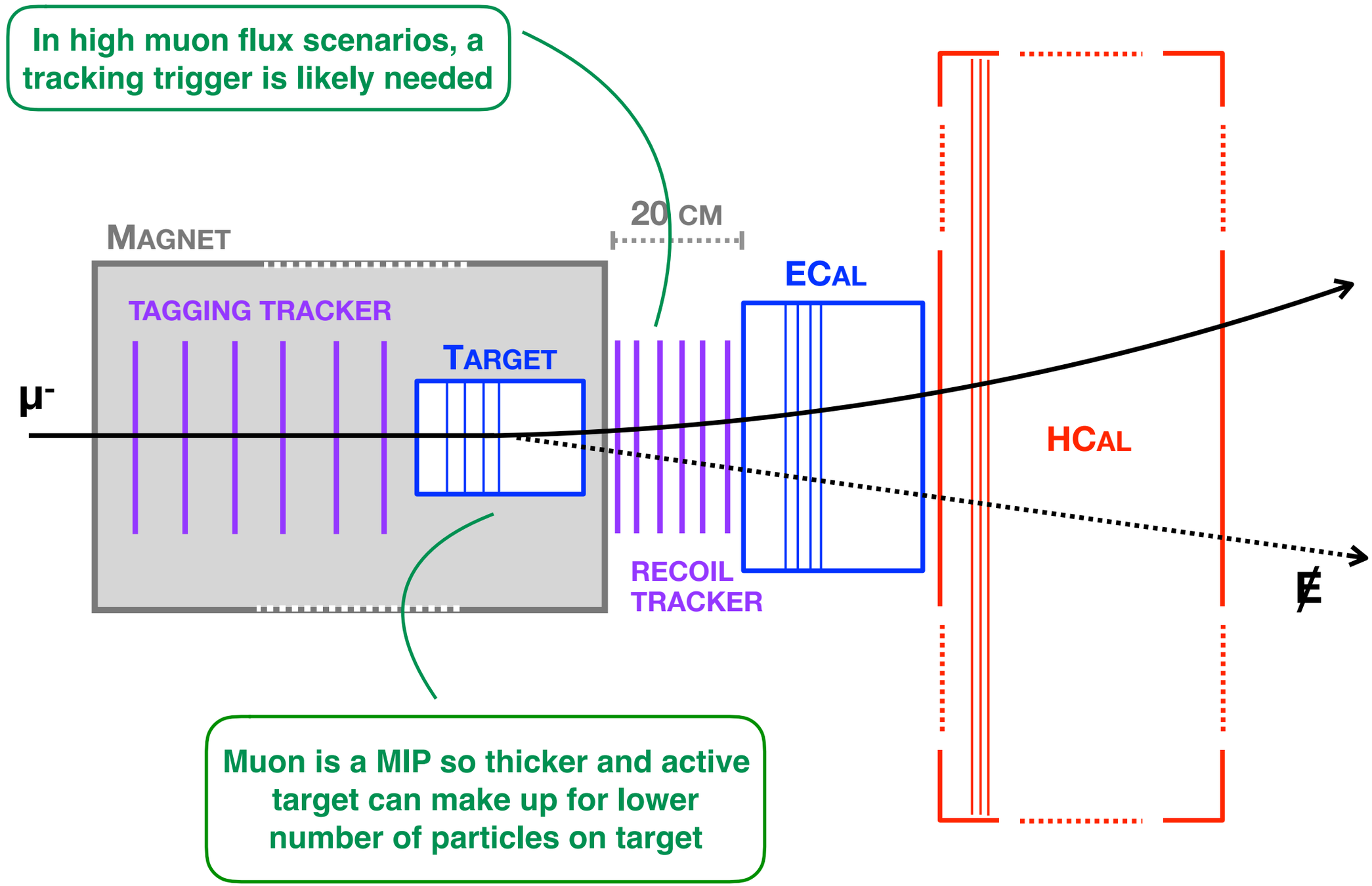
Electrons energy transfer



Measurements help to constrain electron-nucleon MC models

arxiv:1912.06140

Muon Missing Momentum



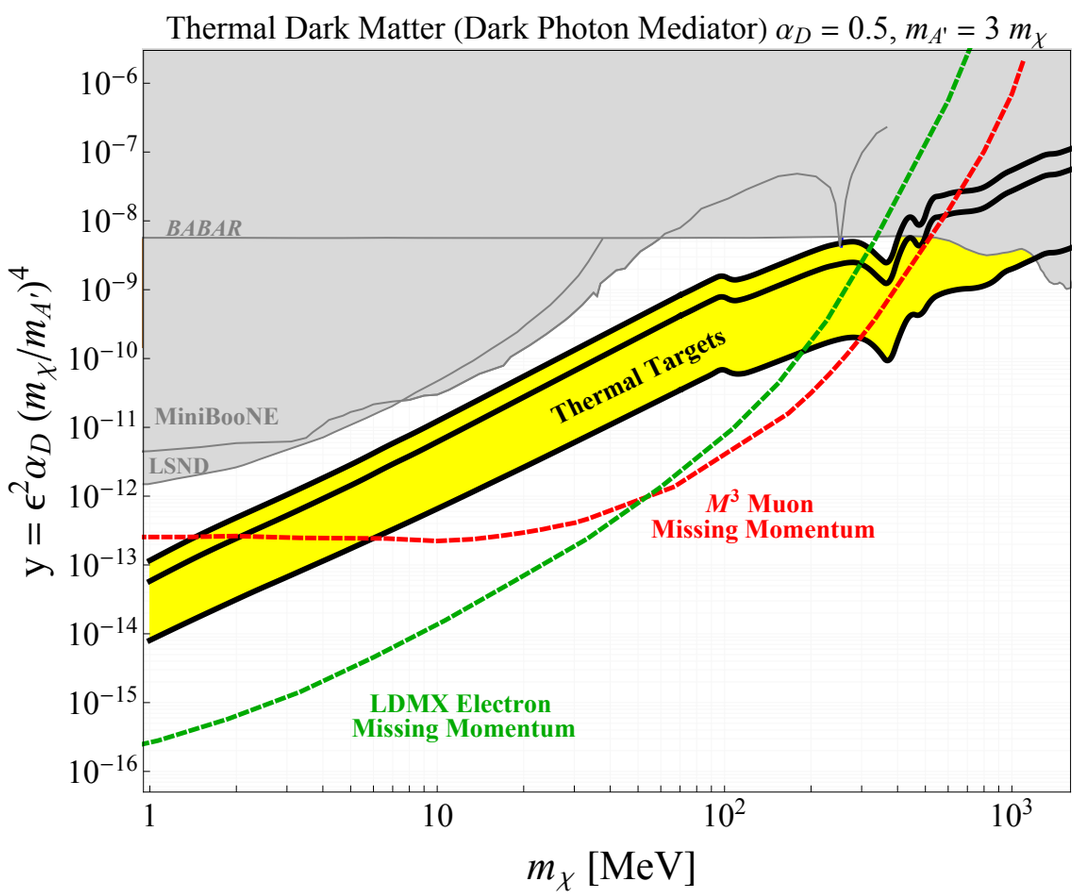
Muon Missing Momentum

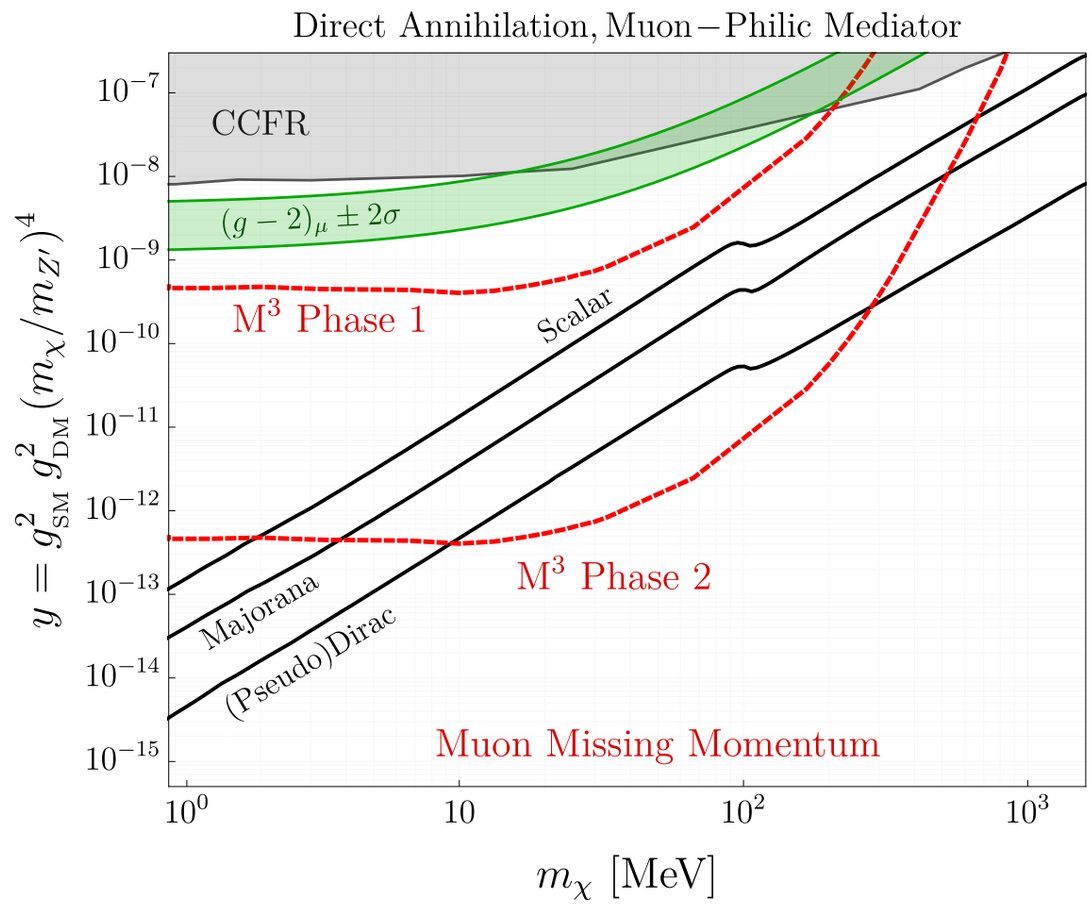
https://arxiv.org/abs/1804.03144

Muon beam missing momentum experiment good complement to electron beam experiment

For thermal DM milestones (lepton flavor universal), Muon Missing Momentum (M^3) 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





Missing momentum (broad physics program)

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

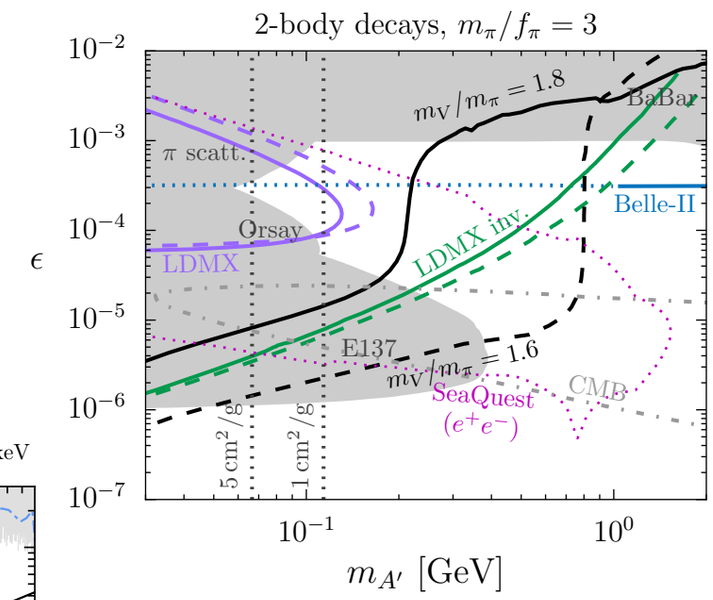
https://arxiv.org/pdf/1807.01730.pdf

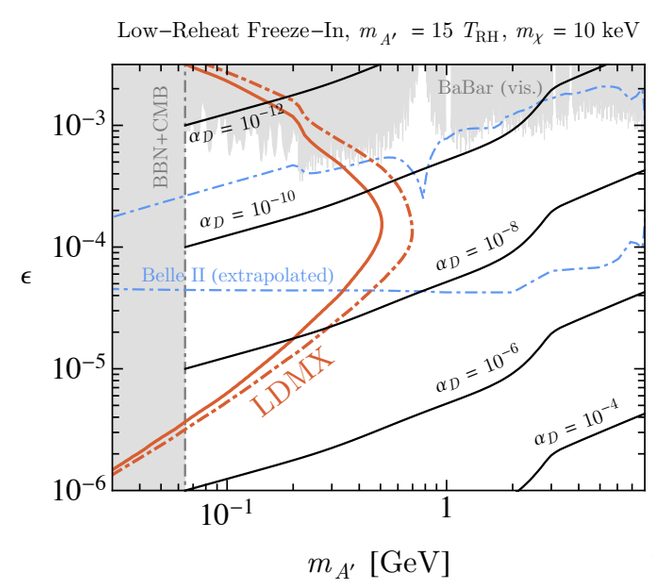
(A. Berlin, N.B., G.K., P. Schuster, N. Toro)

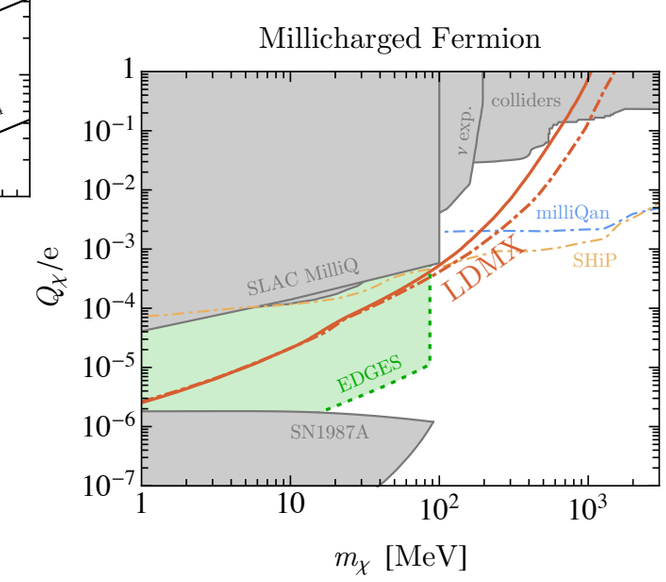
- Long-lived and millicharged particles
- Strongly interacting DM models (SIMPs)
- Freeze-in DM

- 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 ν-N modeling (studies on-going)







Summary and Outlook

- **Accelerator-based DM experiments** are exciting tool to explore new initiative in **sub-GeV dark matter + unstable "friends"**

- **Beam Dumps (electron, positron, muon)**
  can explore both production and decay, (g-2)

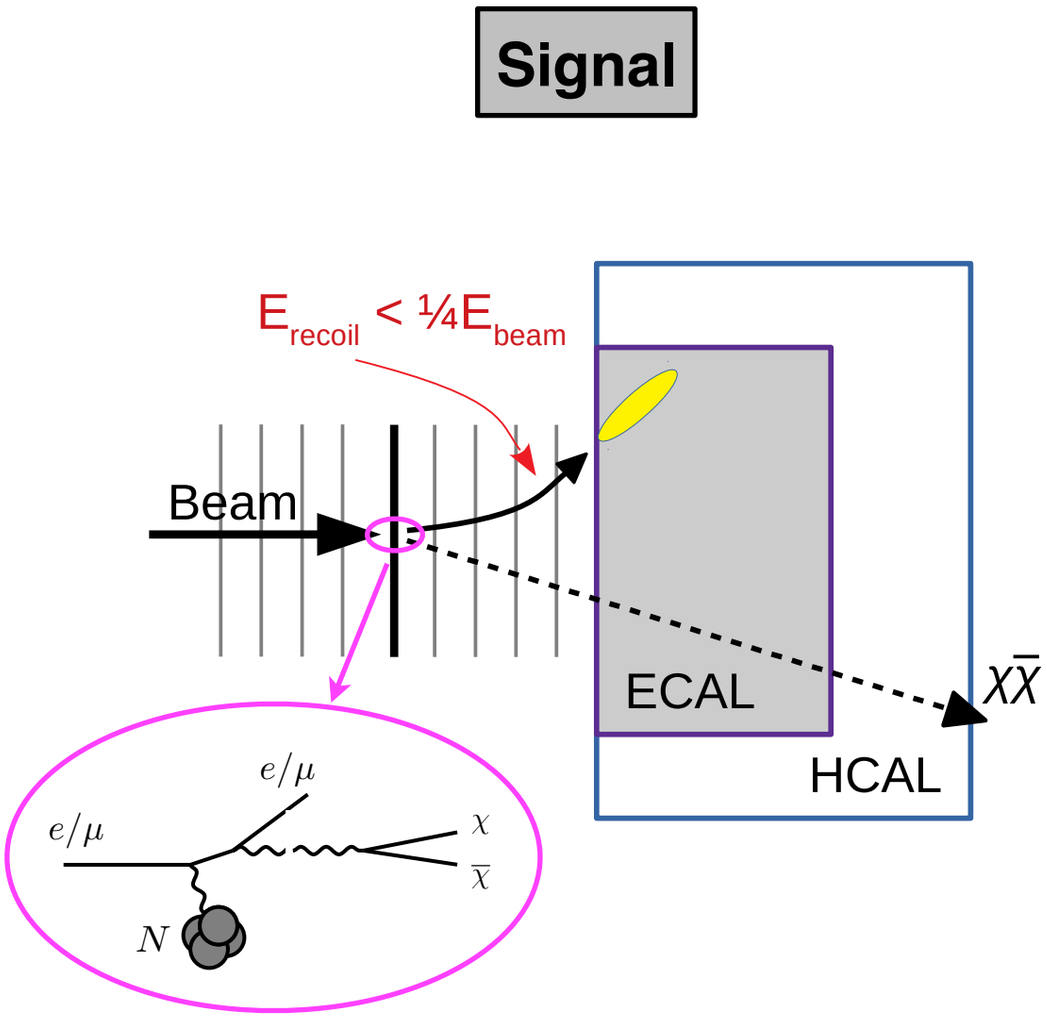
- **Spectrometer (electron)**
  visible dark sectors with compact baselines

- **Missing Momentum (electron)**
- best for scaling and overall sensitivity

- **Missing Momentum (muon)**
- muonic couplings (g-2); heavier recoiling particle

Backup

The missing momentum technique



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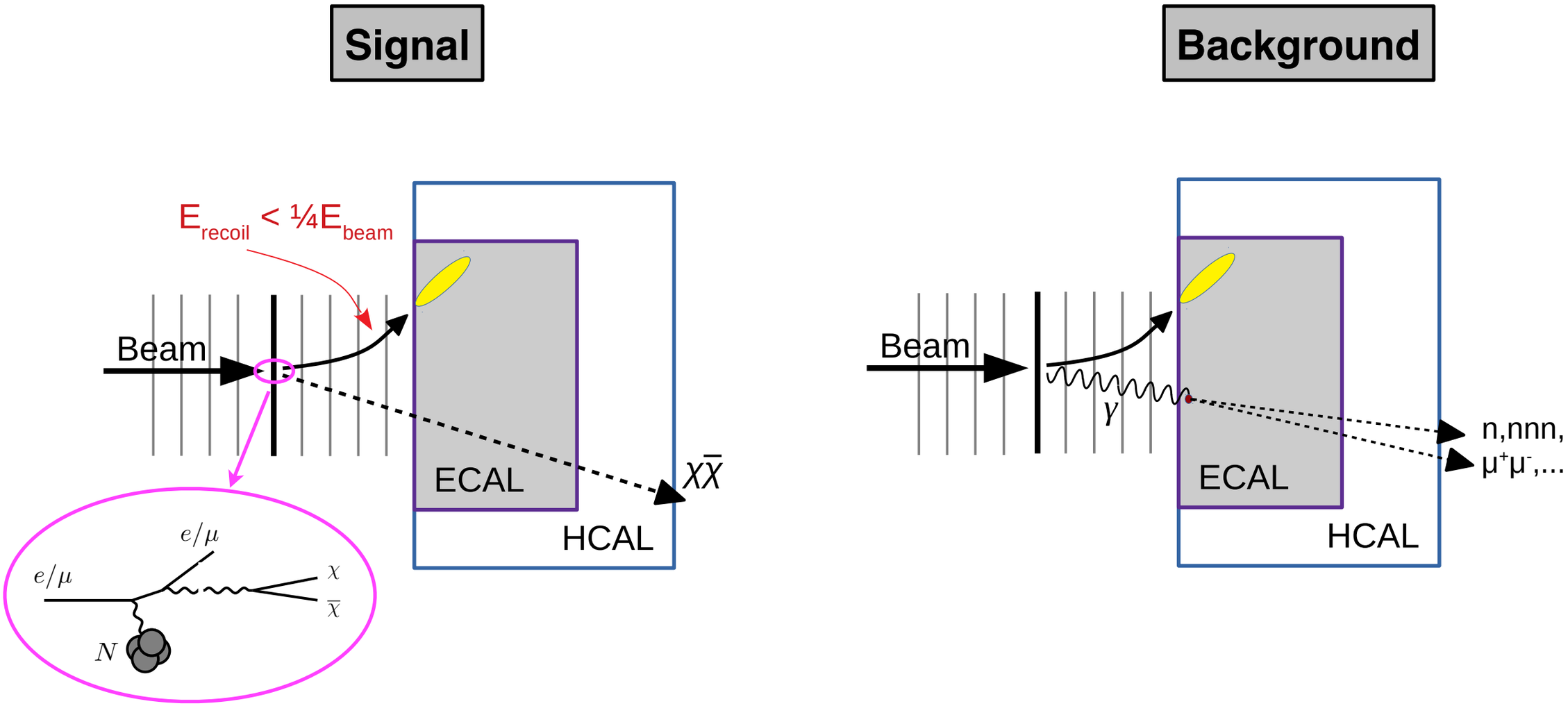

Backgrounds come from rare SM processes that escape detection

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