LDMX: The Light Dark Matter eXperiment

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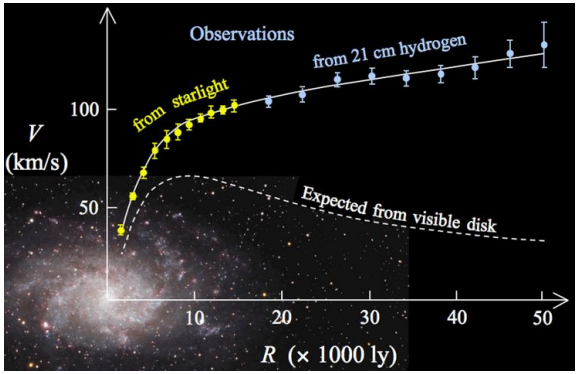
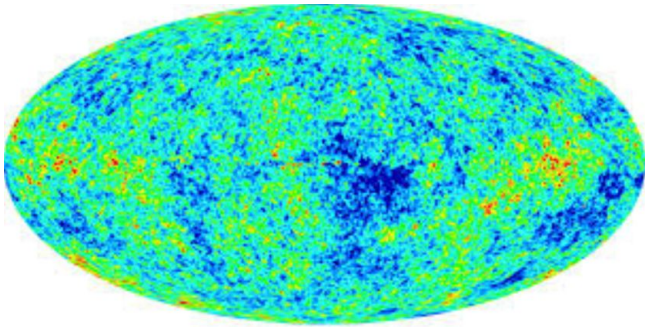
The Existence of Dark Matter

- There is clear evidence for the **existence of dark matter** (DM)
- The fundamental nature/origin of DM is a **central puzzle in particle physics**
- SM can't account for DM. What are some ideas for what DM could be?



Galactic Rotation Curves

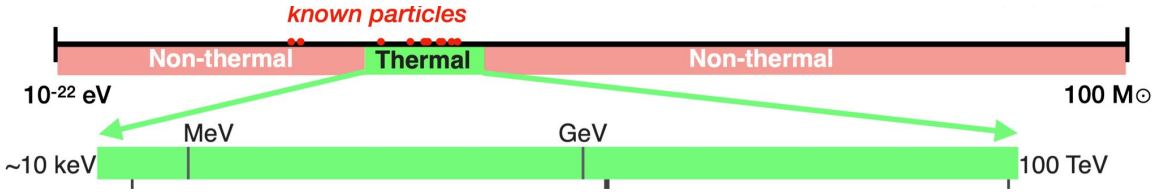
Gravitational Lensing



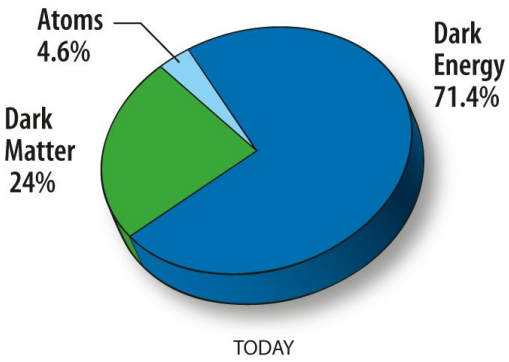
Cosmic Microwave Background

A Thermal Relic - Dark Matter

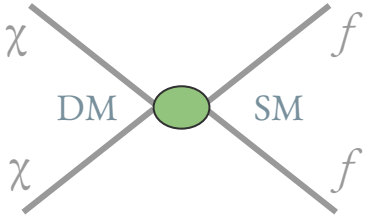
- Astrophysical evidence of DM does not constrain the mass scale very well
- **A thermal relic** - simple and predictive model of dark matter (DM)
- Thermal DM constrains DM mass to ~mass scale of SM particles and relates the annihilation cross-section to the observed relic abundance (~85%)



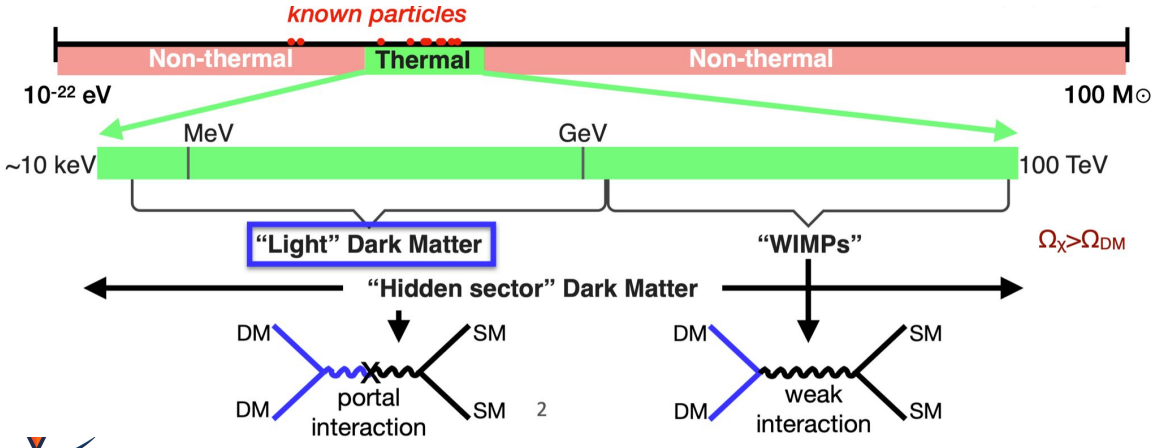
The range of (non-)thermal DM mass spans a range of ~(90)
7 orders of magnitude!

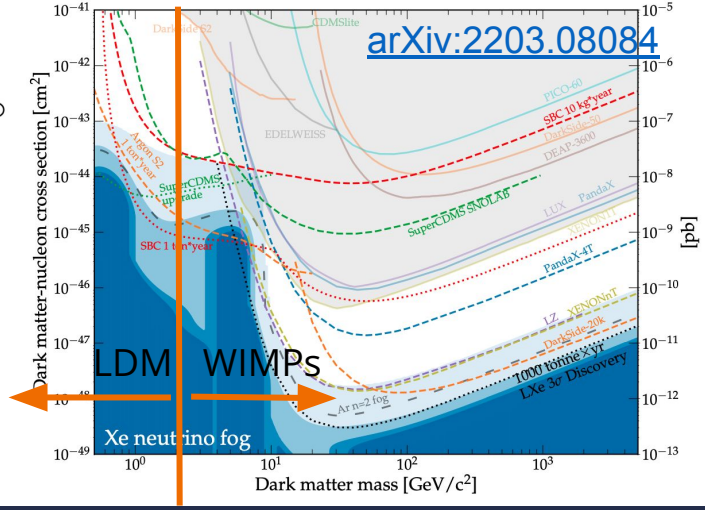


A Thermal Relic - WIMPs and LDM



- WIMPs are popular, but accessible parameter space is running out of room
- Increasing interest in expanding the thermal DM search to “Light” DM (LDM) in the MeV-GeV mass range
- LDM **requires non-SM “portal” interaction** due to the Lee-Weinberg Bound





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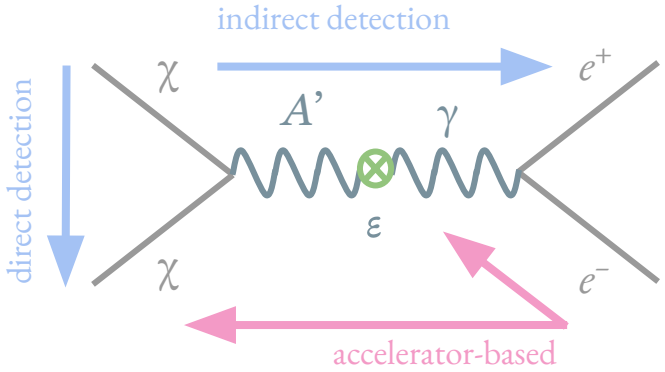
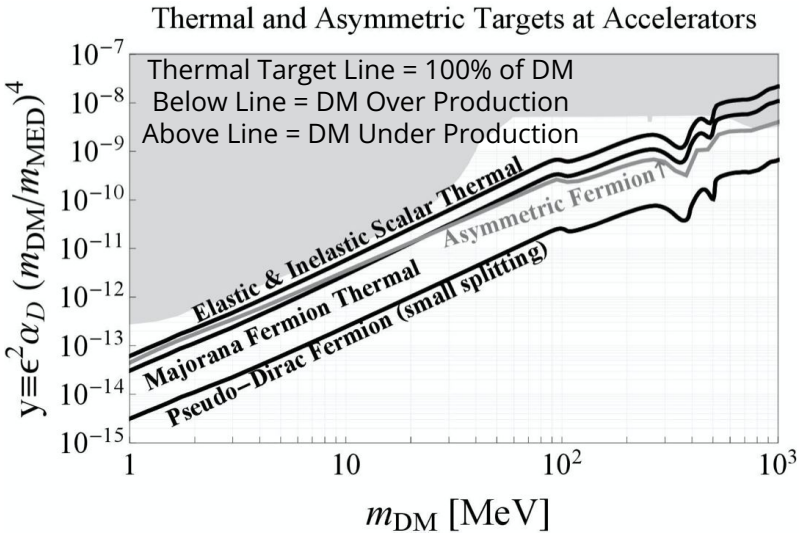
Light Dark Matter

- Simplest prediction includes a **dark photon** (heavy photon or A') that undergoes kinetic mixing with the SM photon
- Thermal prediction targets make **attainable predictions with accelerators**

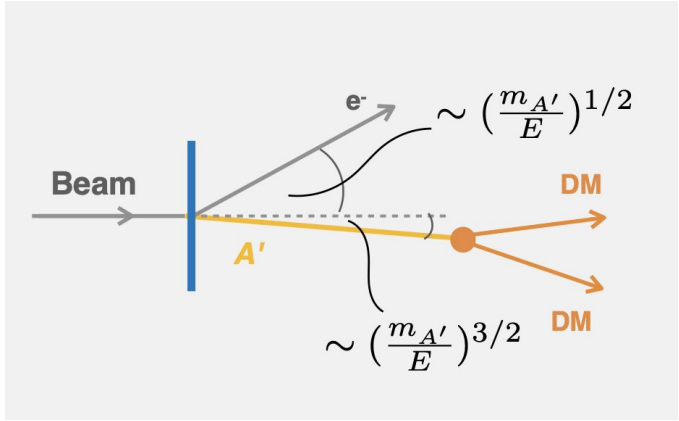


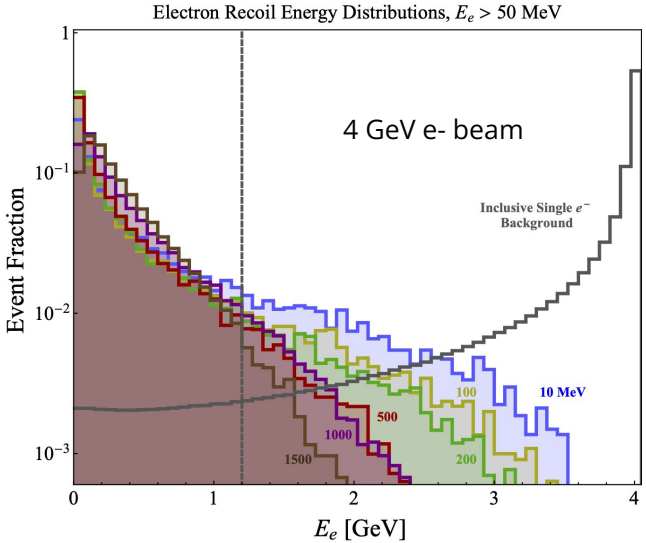
Kinetic Mixing $\epsilon F^{\mu\nu} F'_{\mu\nu}$

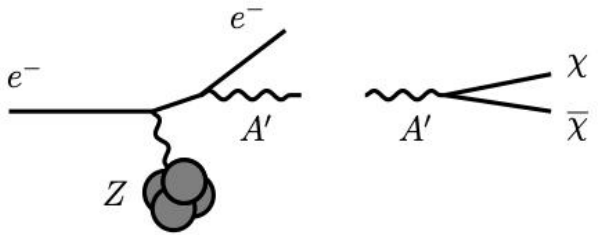


Dark Photon with a Fixed Target

- Fixed Target Signal Characteristics:
  - Dark bremsstrahlung A′ production, invisible decay
  - **A's take most of the beam energy; only visible final state particle is a soft recoil electron**

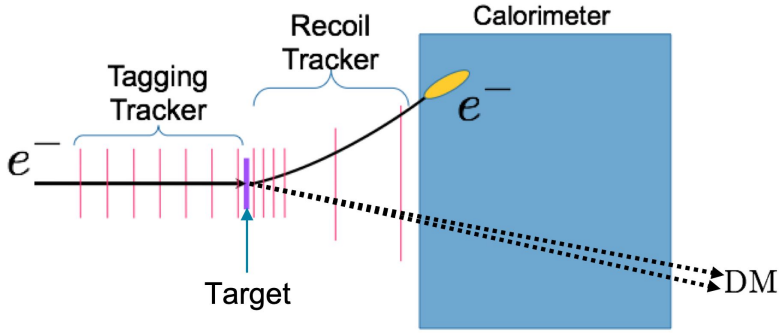




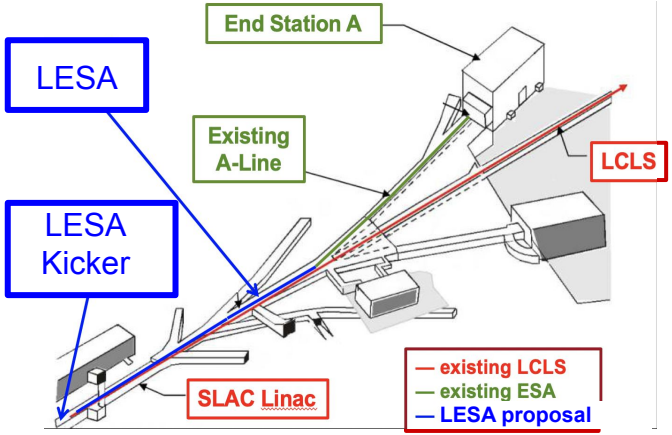


- Can probe this mechanism through a missing momentum search. We need…
  - High momentum resolution
  - High veto efficiency of SM backgrounds

LDMX Concept



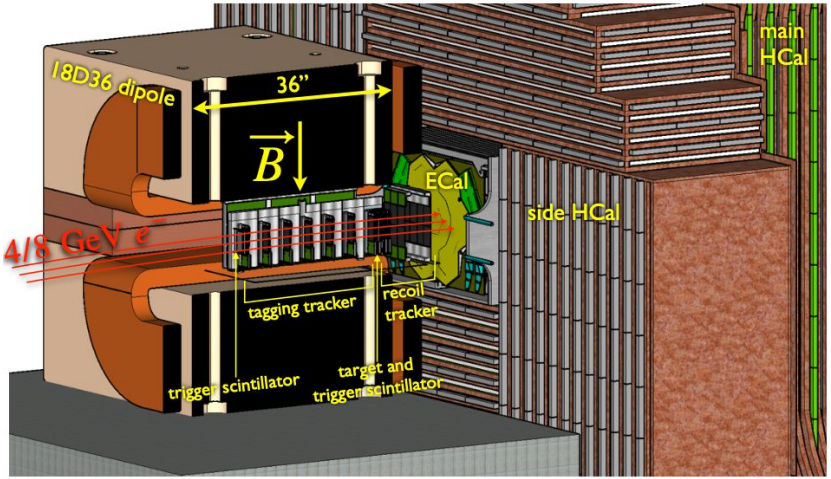
- Missing momentum and energy approach
  - DM production identified by missing energy/momentum in detector
  - Equipped for particle ID e/gamma
  - Recoil pT used as discriminator/identifier

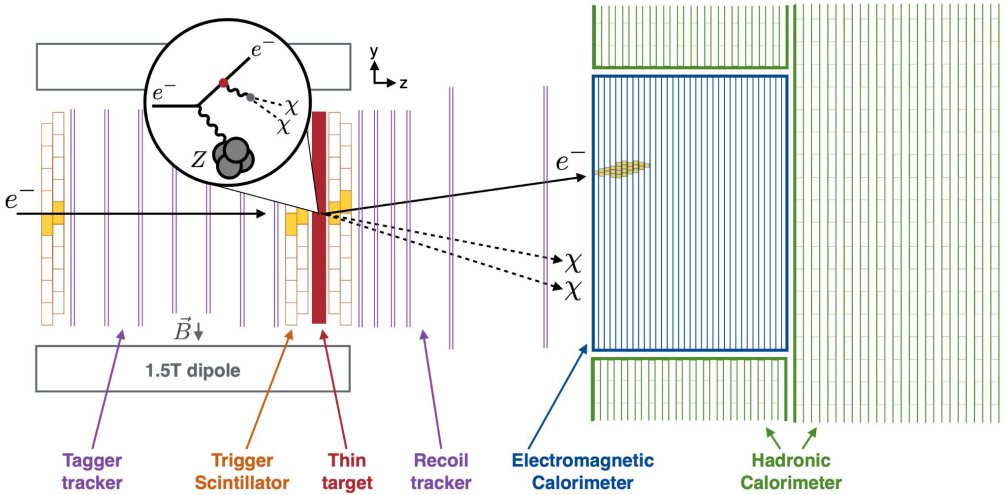


- 4 and 8 GeV e- beam provide by SLAC
  - Parasitically use the LCLS-II beam with a dedicated transfer line (LESA)
  - Individual tagging and reconstruction of up to 1e16 electrons
  - Low current, high repetition rate 37 MHz, μ = 1

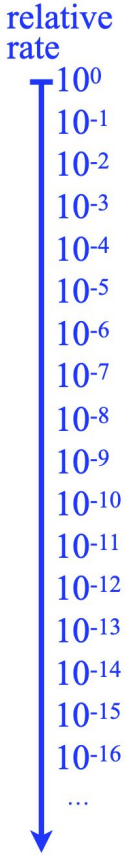
LDMX Design

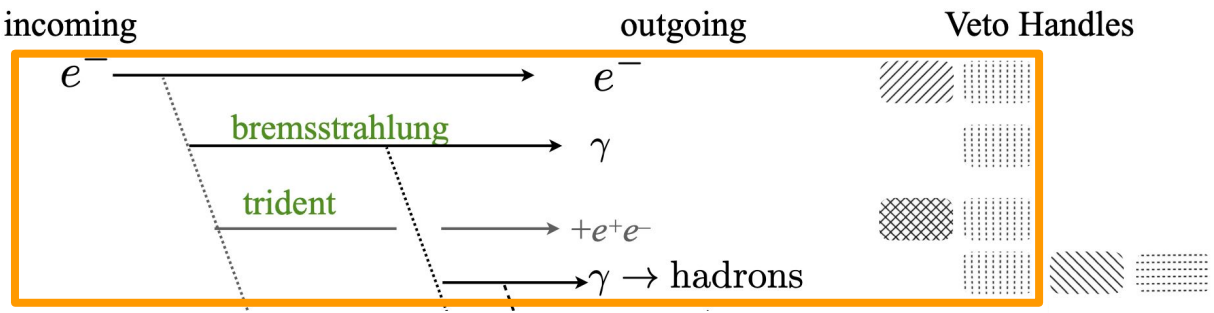
- Need hermetic detector designed for high rates and high radiation doses
  - **Tagging/recoil tracker**: fast with high momentum resolution and large acceptance, based on the Heavy Photon Search design arXiv:2212.10629v2
  - **Electromagnetic calorimeter**: fast, good energy resolution, and high granularity
  - **Hadronic calorimeter**: high veto efficiency of neutral hadrons

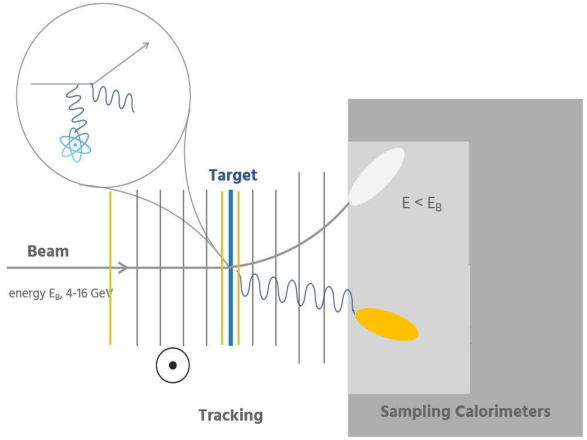


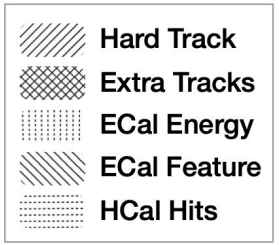


Backgrounds

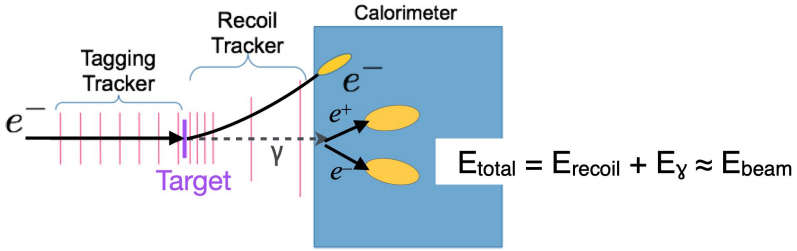




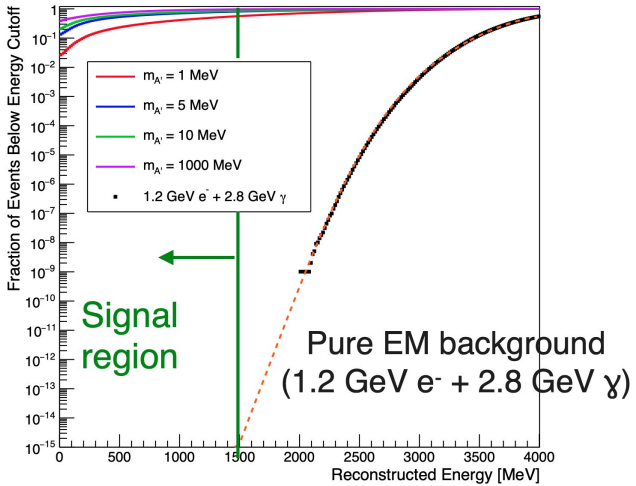


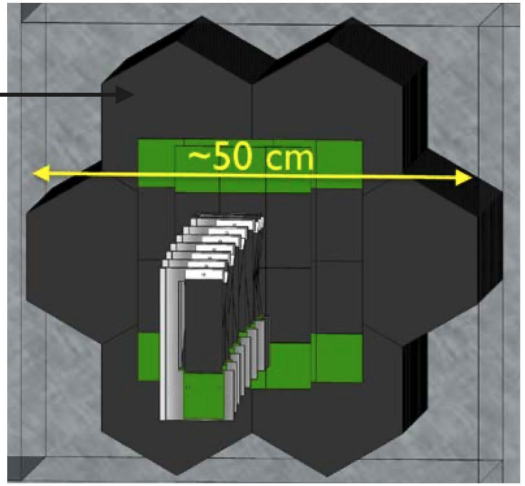


Electromagnetic Calorimeter



- 40 X0 Si-W sampling calorimeter (based on CMS HGCal upgrade)
  - Provides fast missing energy trigger
  - Dense, radiation hard, full shower containment, and high granularity





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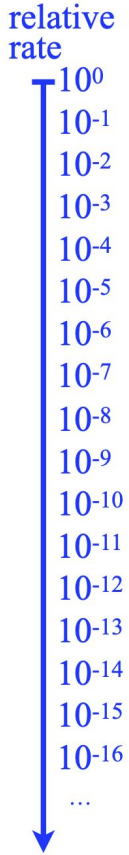
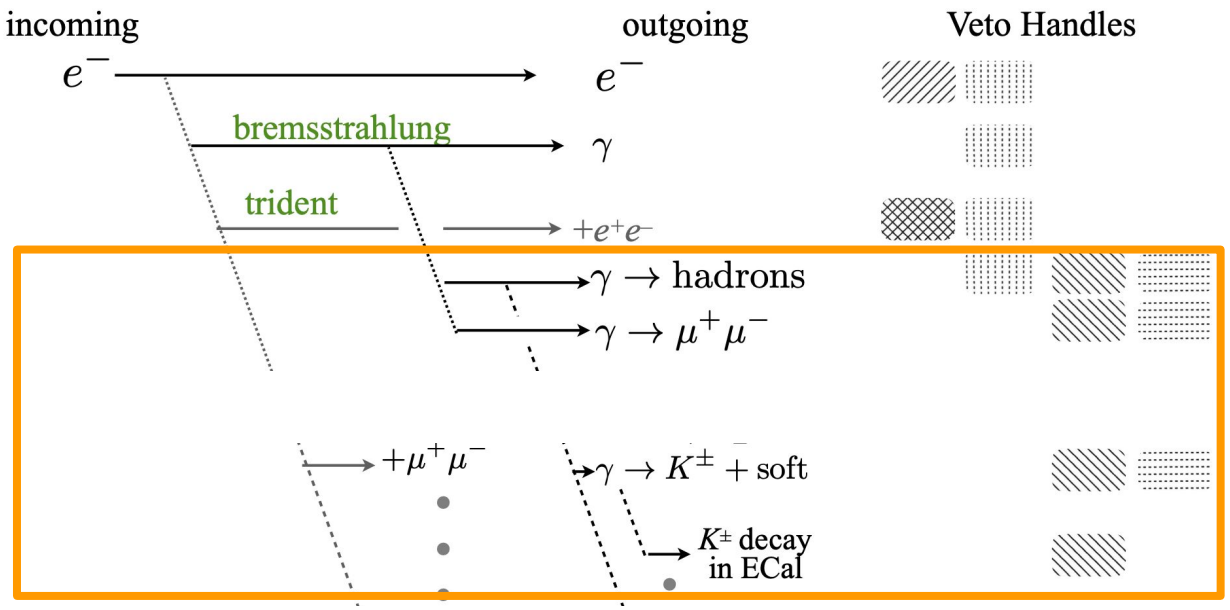
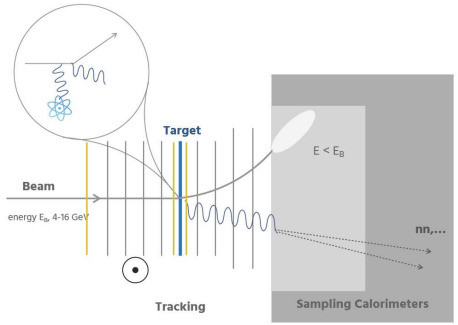
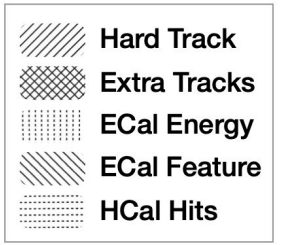


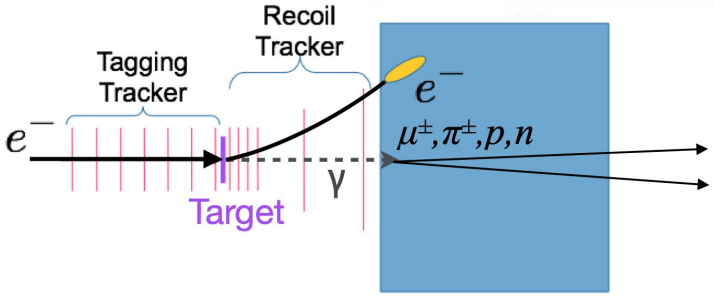


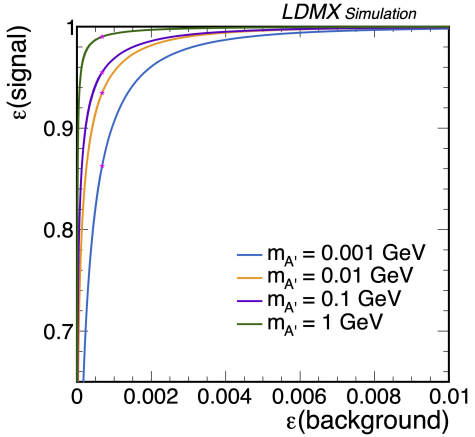




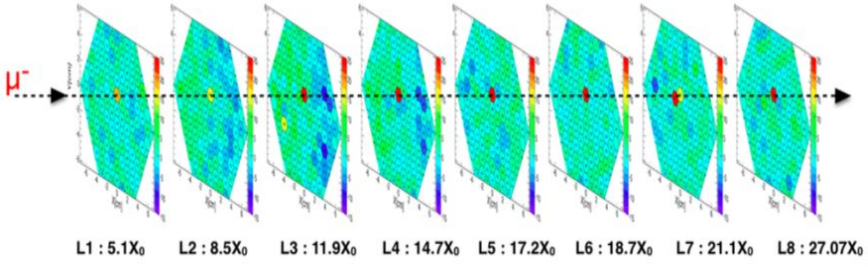
Ecal Veto

- More difficult to veto: Rare photon reactions that deposit low energy in the Ecal
  - Exploit longitudinal/transverse shower shapes and train a boosted decision tree (BDT)
  - High granularity Ecal enables MIP tracking

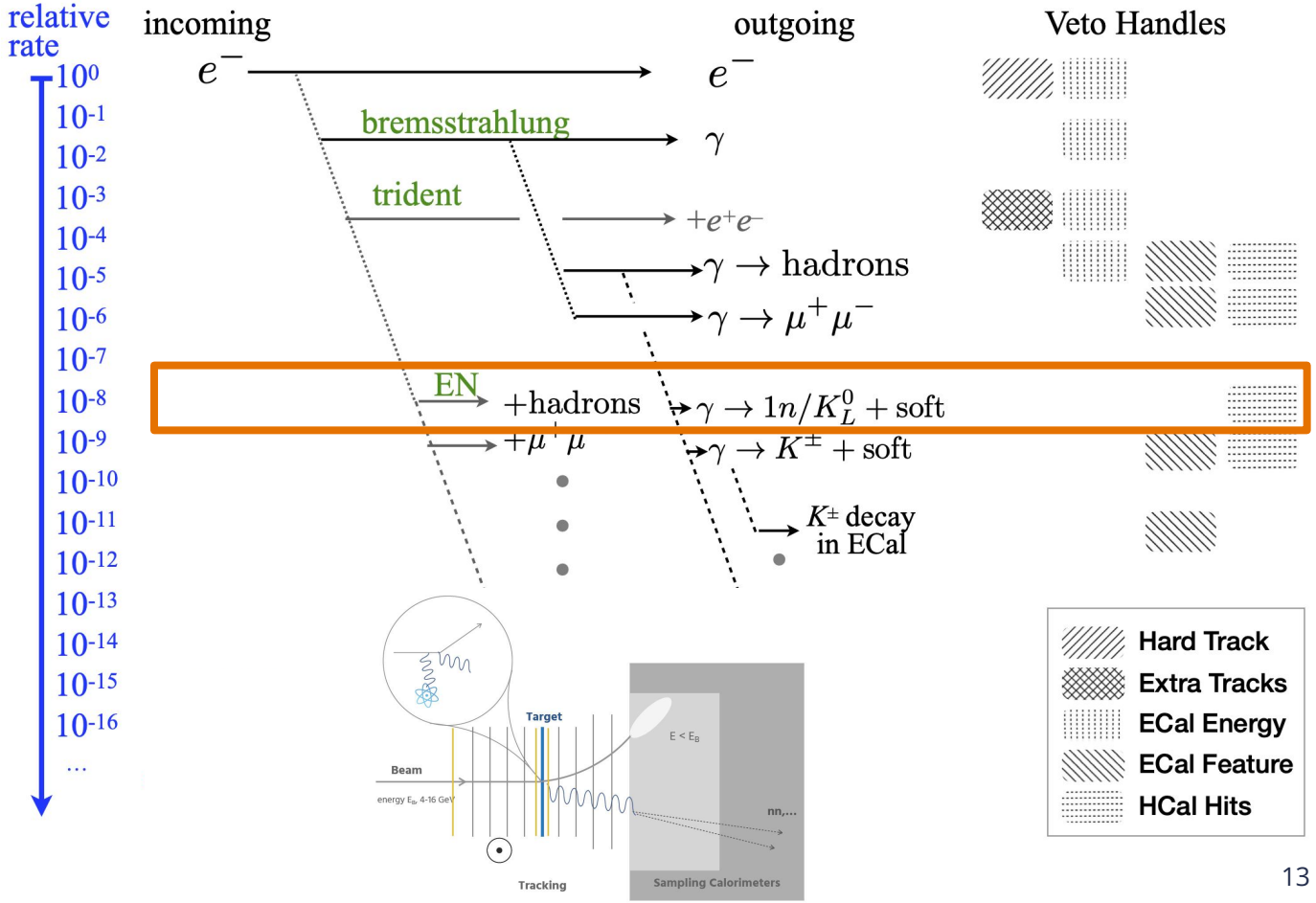




A.Martelli on behalf of CMS, arXiv:1708.08234

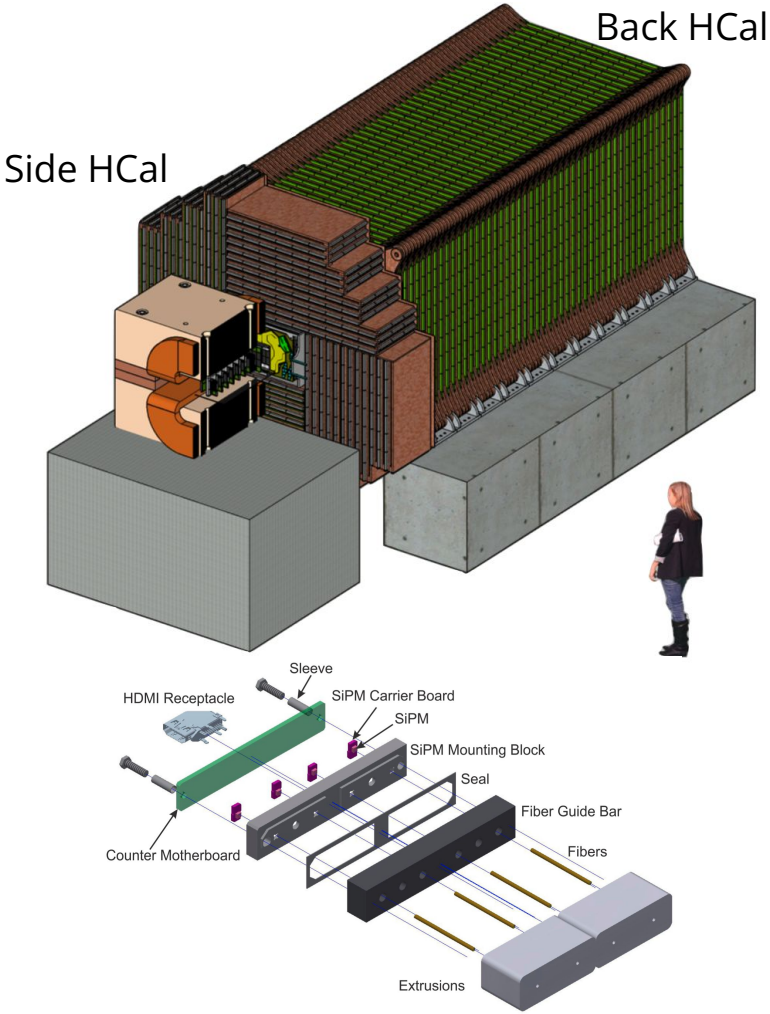


Backgrounds



Hadronic Calorimeter

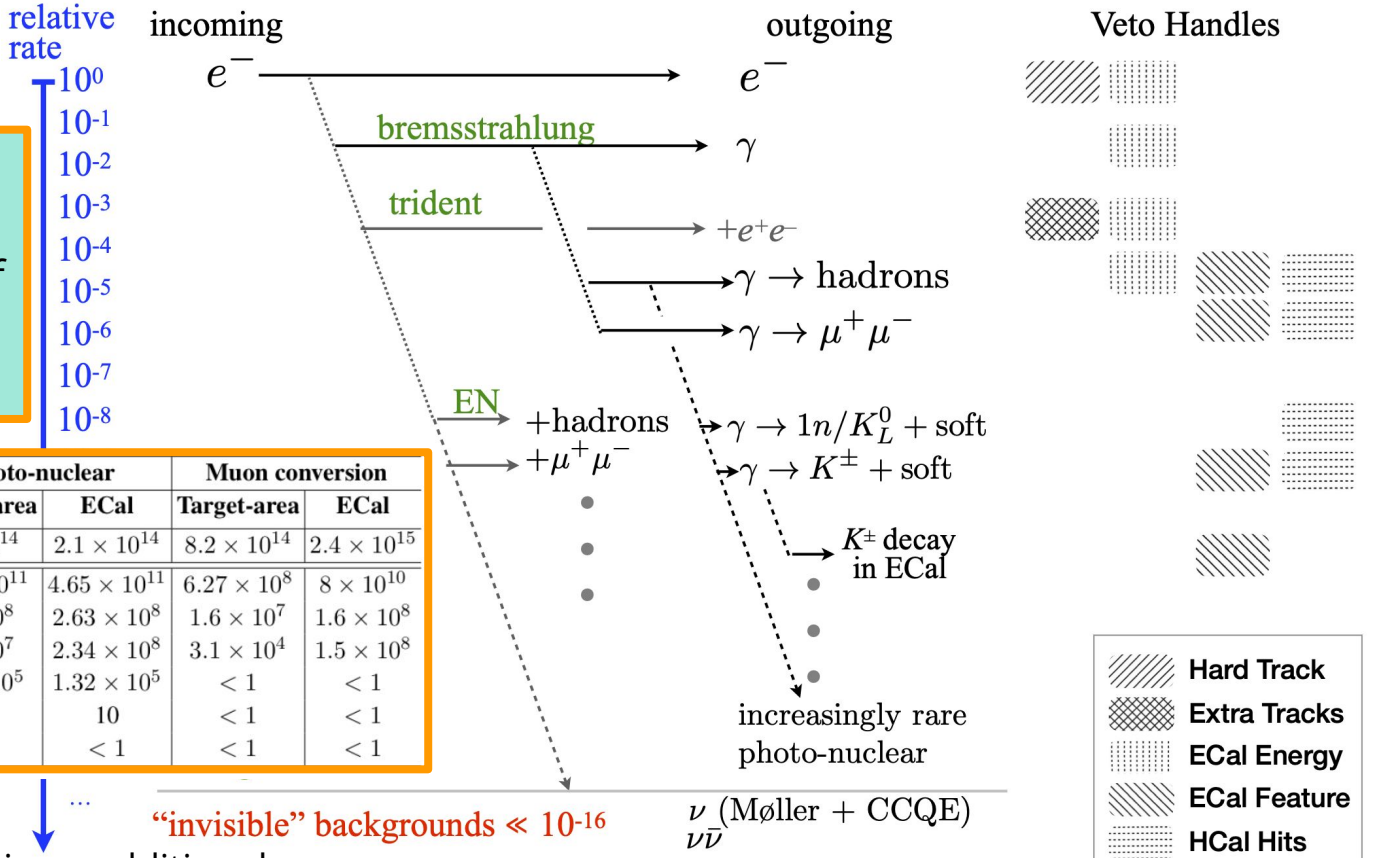
- Sampling calorimeter with segmented plastic/steel
  - Readout by wavelength shifting fibers and SiPMs (based on the Mu2e Cosmic Ray Veto design)
  - Highly efficient veto for PN processes that produce neutral hadrons. Desire 1e-6 rejection
  - Side HCal rejects wide angle bremsstrahlung and $\gamma \rightarrow \mu^+\mu^-$



Backgrounds

All systems combined: < 1 background event with signal efficiency of ~30-50% for O(1e14) EoT!

	Photo-nuclear		Muon conversion	
	Target-area	ECal	Target-area	ECal
EoT equivalent	4×10^{14}	2.1×10^{14}	8.2×10^{14}	2.4×10^{15}
Total events simulated	8.8×10^{11}	4.65×10^{11}	6.27×10^{8}	8×10^{10}
Trigger, ECal total energy < 1.5 GeV	1×10^{8}	2.63×10^{8}	1.6×10^{7}	1.6×10^{8}
Single track with $p < 1.2$ GeV	2×10^{7}	2.34×10^{8}	3.1×10^{4}	1.5×10^{8}
ECal BDT (> 0.99)	9.4×10^{5}	1.32×10^{5}	< 1	< 1
HCal max PE < 5	< 1	10	< 1	< 1
ECal MIP tracks = 0	< 1	< 1	< 1	< 1

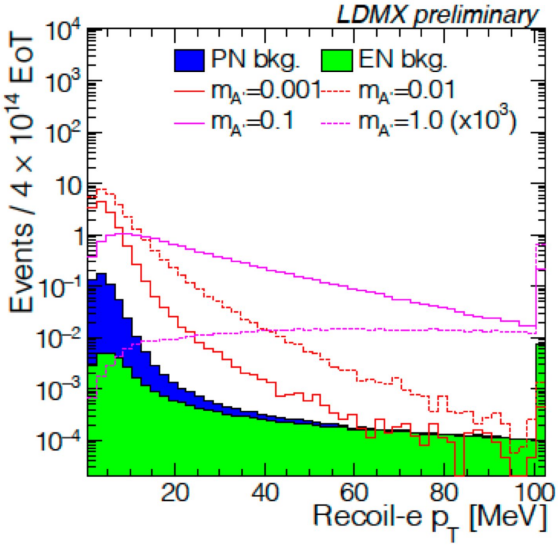


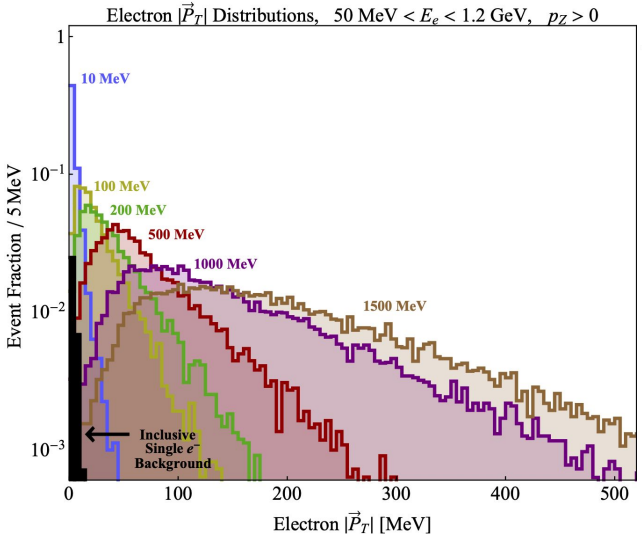
Recoil e- pT is an additional discriminator on backgrounds

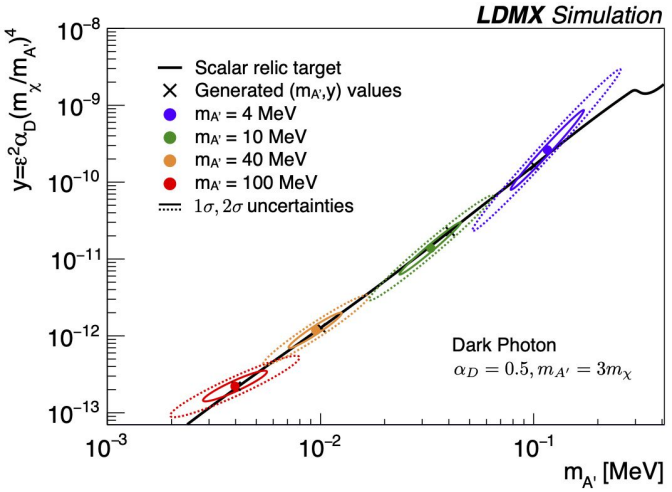
arXiv:1912.05535

Signal Kinematics

- Transverse momentum of recoil election is the last veto handle
- Currently not used in veto efficiency estimates, but as a backup discriminator
- Transverse momentum can also be used to constrain DM mass scale





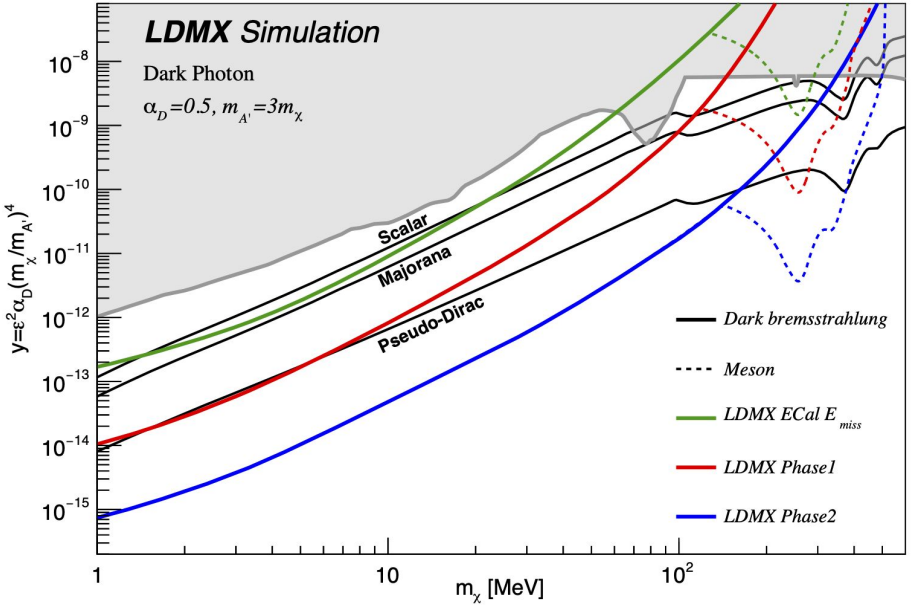


LDMX Sensitivity

$$2m_{DM} < m_{A'}$$

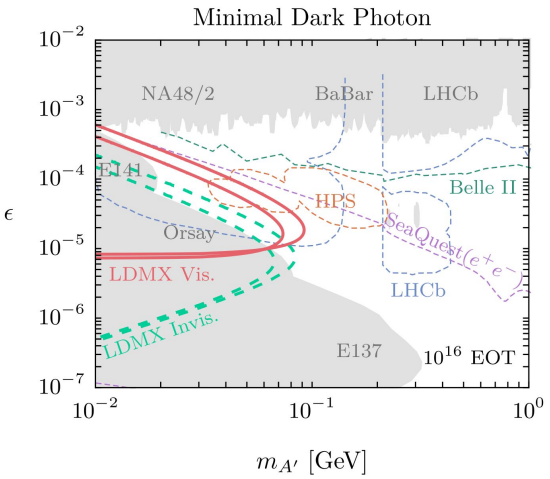
Phase 1: 4 GeV,
10^{14} electrons
Phase 2: 8 GeV,
10^{16} electrons

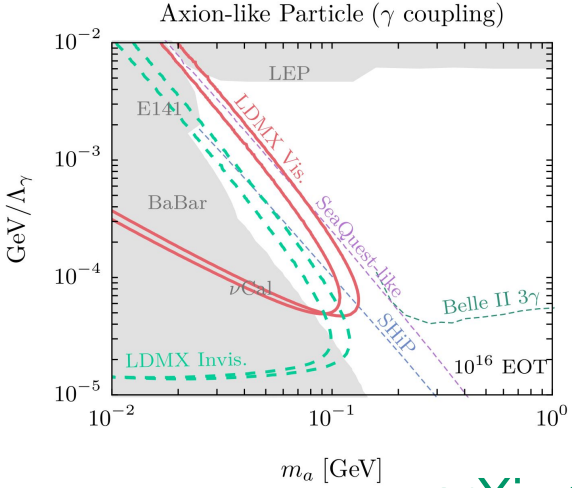
arXiv:1808.05219

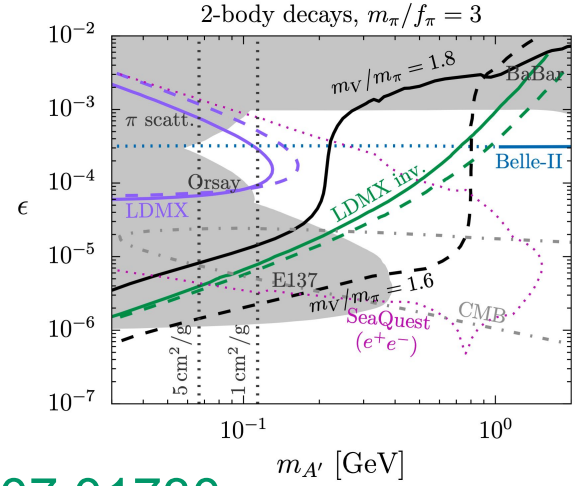


LDMX Visible Signatures

- Broad physics potential for LDMX beyond missing momentum search
  - Displaced visible decays - minimal dark photon, ALPs, SIMPs, etc.
  - Electronuclear measurements for neutrino physics arXiv:1912.06140





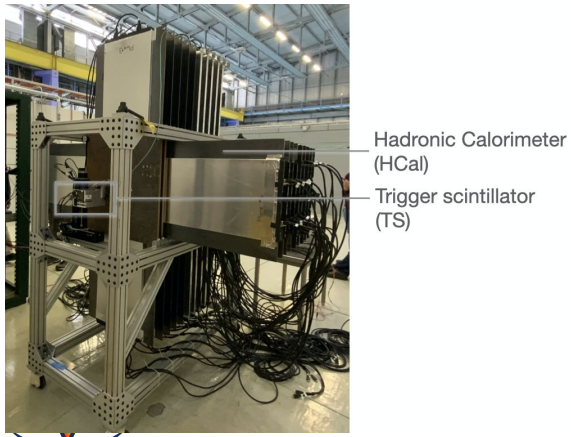


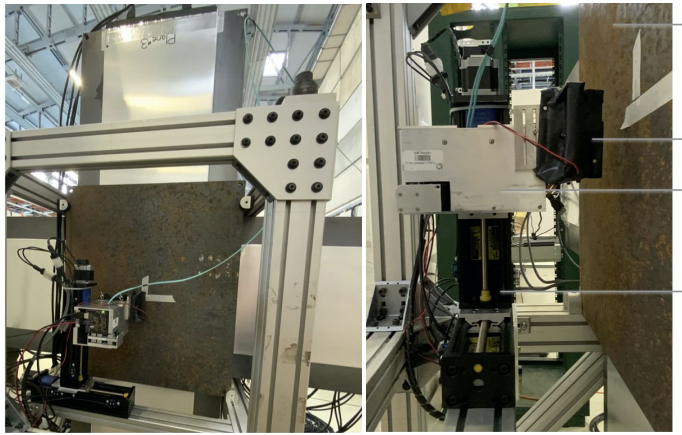
Projections are for 8 GeV and 16 GeV beams

arXiv:1807.01730

CERN Test Beam

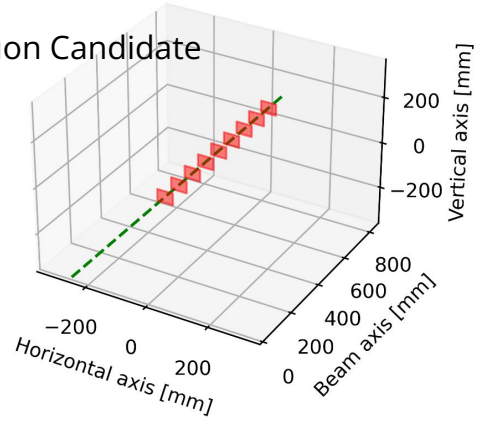
- Recent successful test beam at CERN PS in April 2022 with Hcal and trigger scintillator (TS) prototypes
- Demonstrated successful operations, readout & electronics, and basic physics capabilities of two subsystems

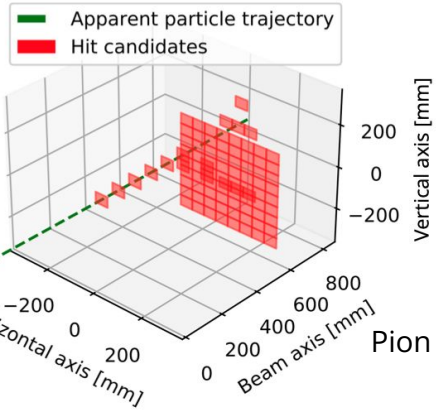




CERN Test Beam - Analysis

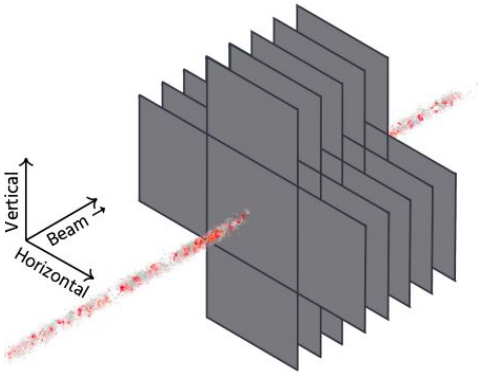
Muon Candidate



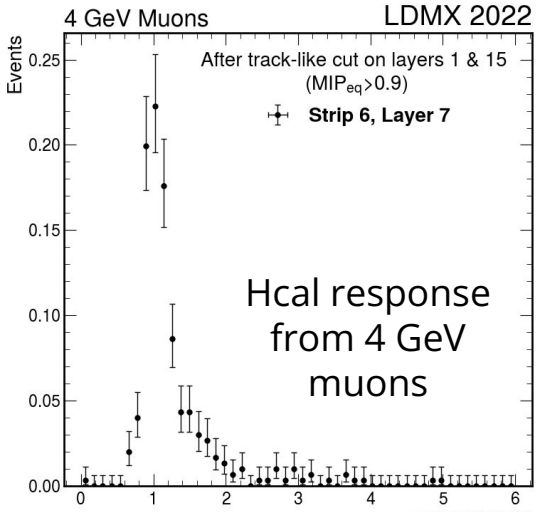


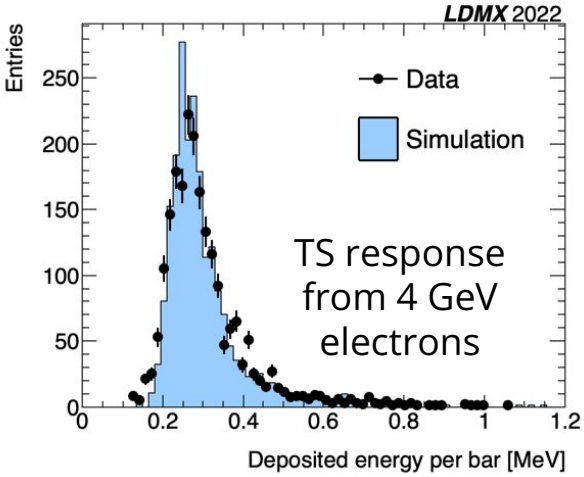
Pion Candidate

Beam & HCal orientation



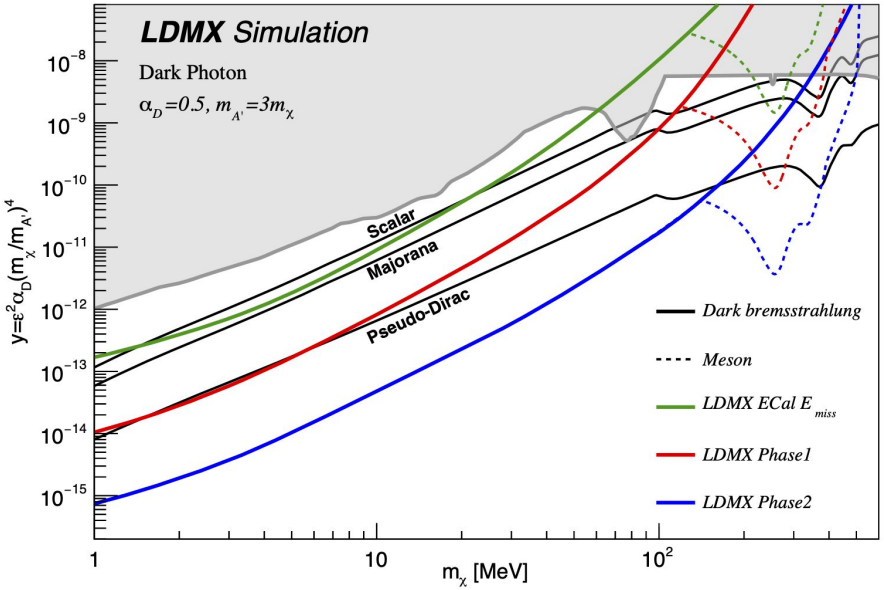
Preliminary results, data analysis is ongoing





Conclusion

- Thermal relic models offer plausible and predictive models of dark matter
- LDMX can conclusively probe many such models in the sub-GeV mass range through a missing momentum search
- LDMX offers a broader physics program for visible searches and neutrino measurements



Thank You!

Caltech

Fermilab

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TEXAS TECH UNIVERSITY

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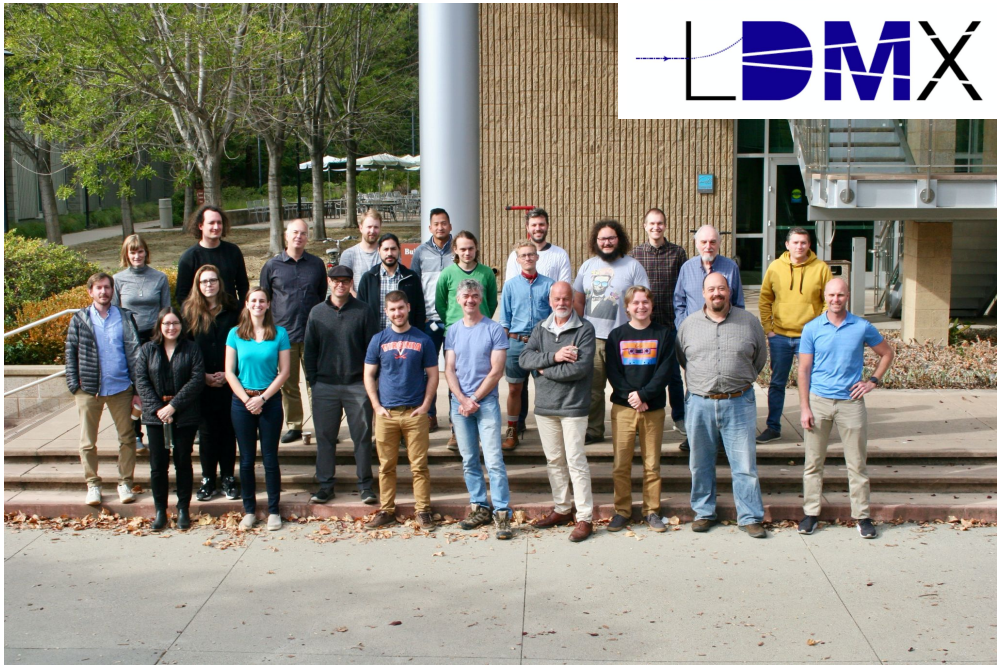
LDMX

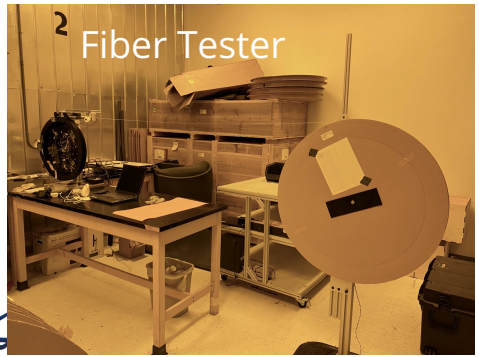


CERN Test Beam - Quad-bar Fabrication

Mu2e Cosmic Ray Veto (CRV) module factory at the
University of Virginia used for Hcal quad-bar fabrication

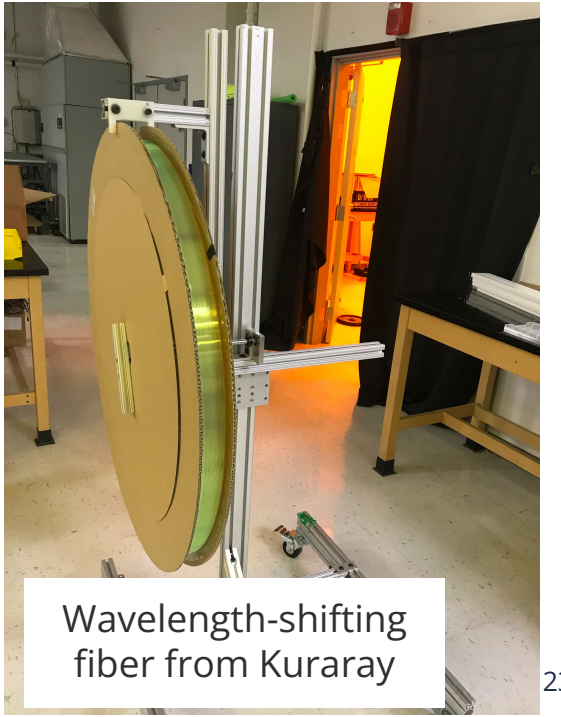
Inserting Fibers

Fiber Tester



Forming Quad-bars

Hcal Quad-bar

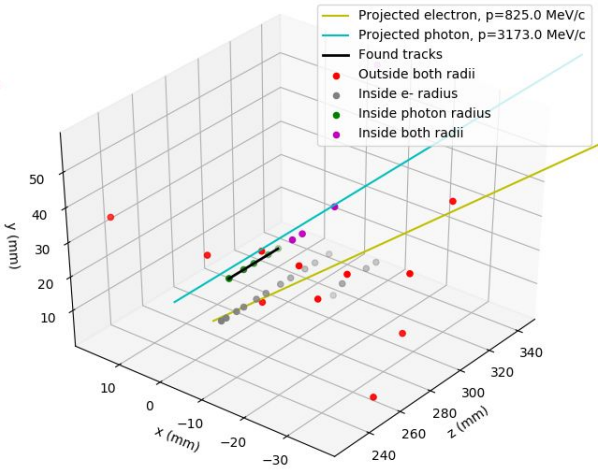


Wavelength-shifting fiber from Kuraray

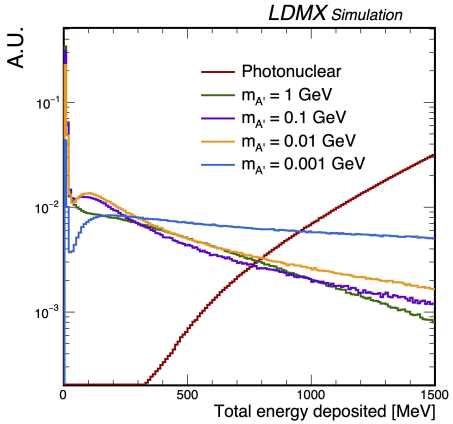
CERN Test Beam

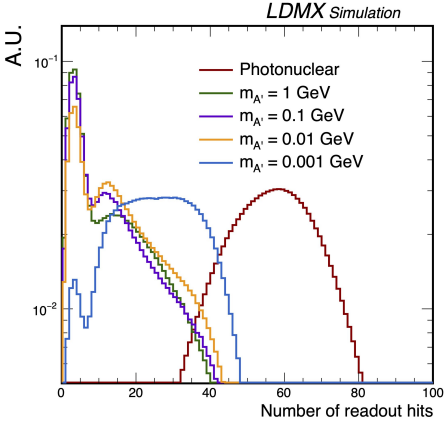
CERN PS T9 Beamline

Ecal BDT

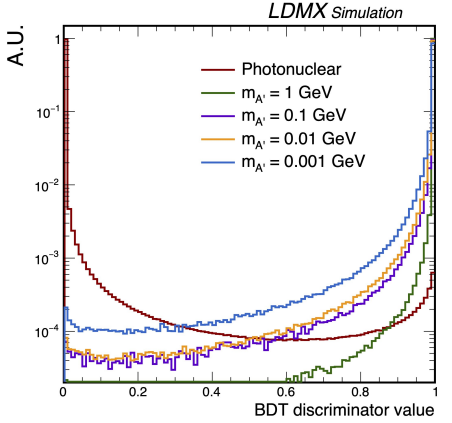


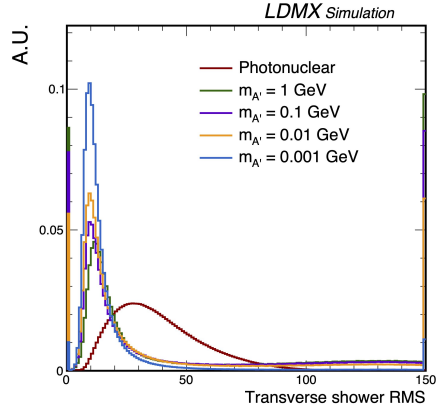
MIP Tracking





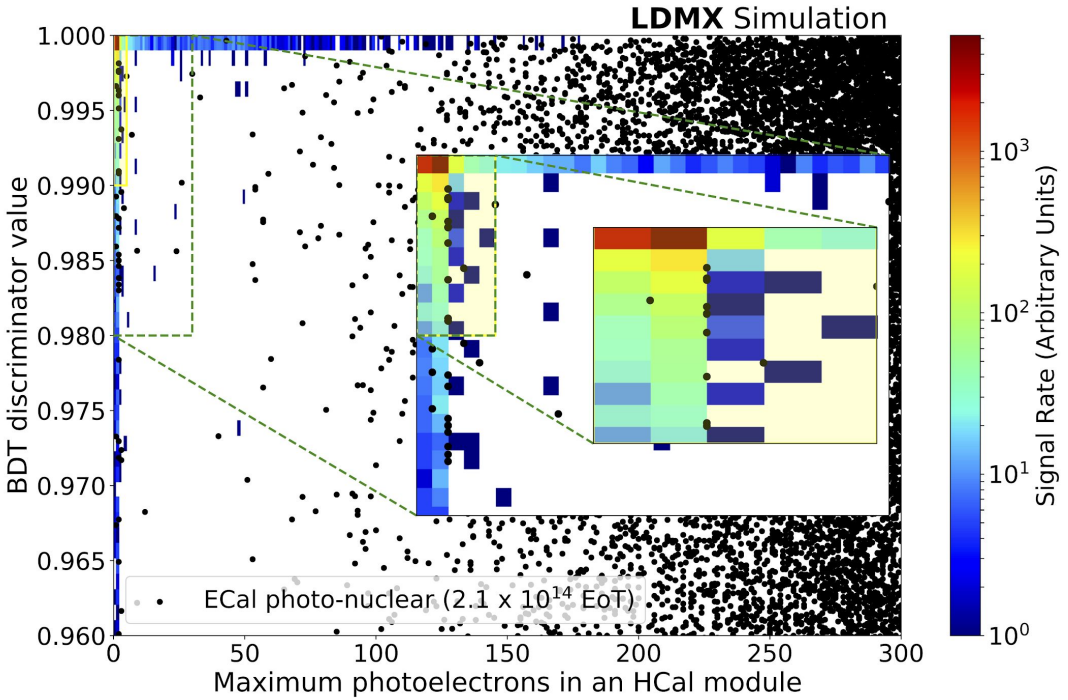
BDT Variables





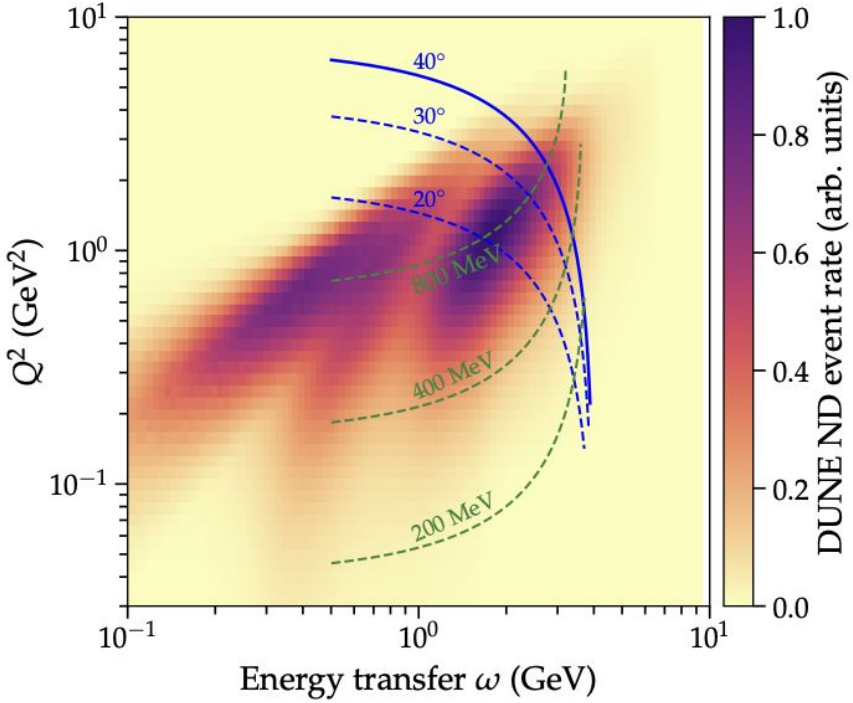
Ecal/Hcal Vetoes

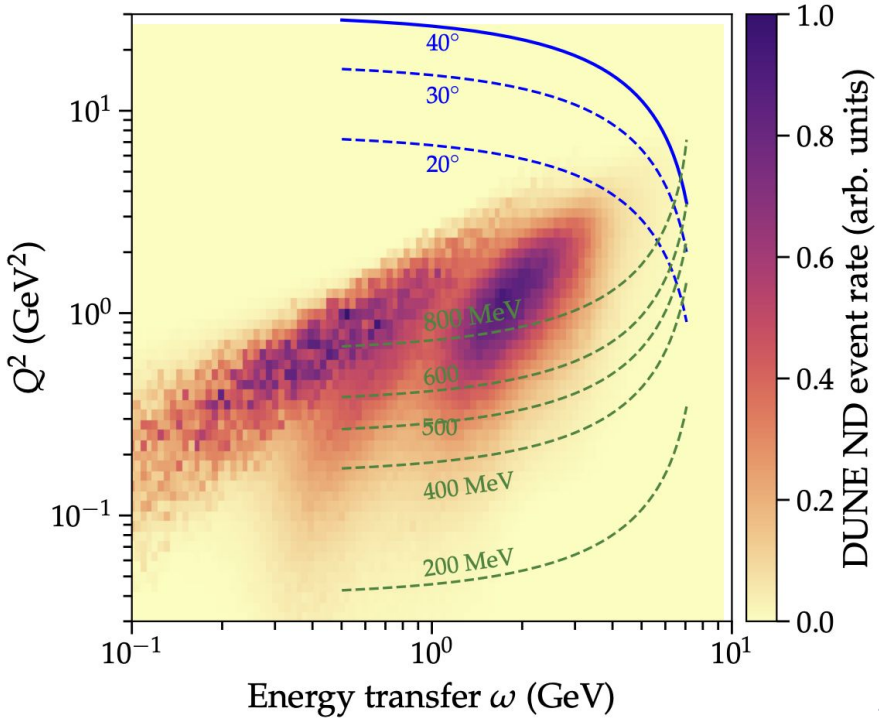
- Ecal BDT > 0.99
- Hcal max PEs is > 5



Electro-nuclear Scattering Measurements

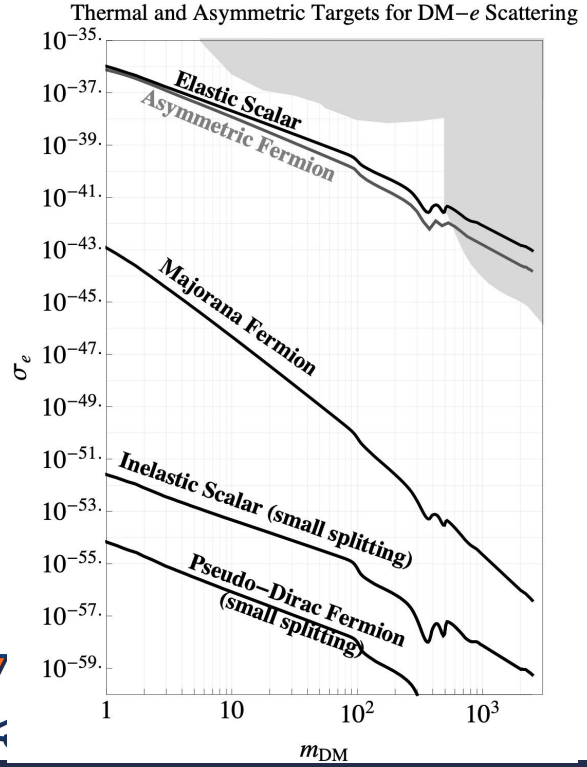
arXiv:1912.06140



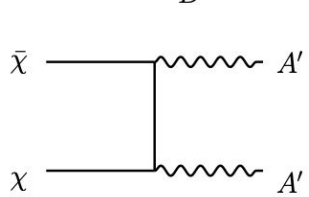


Advantage of DM Production at Accelerators

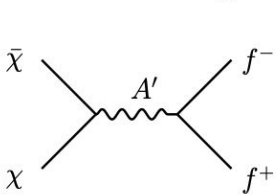
Non-relativistic vs semi-relativistic DM scattering

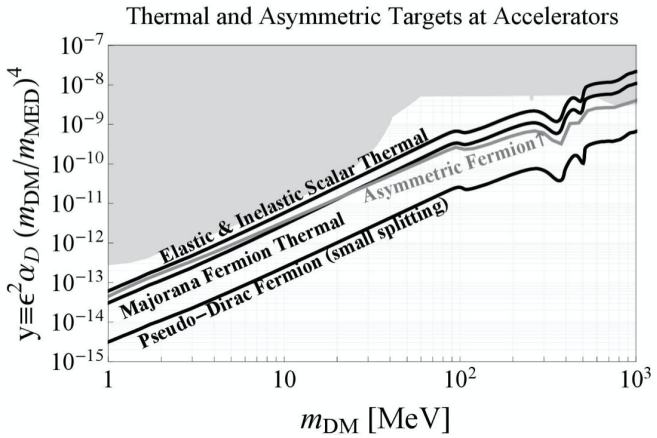


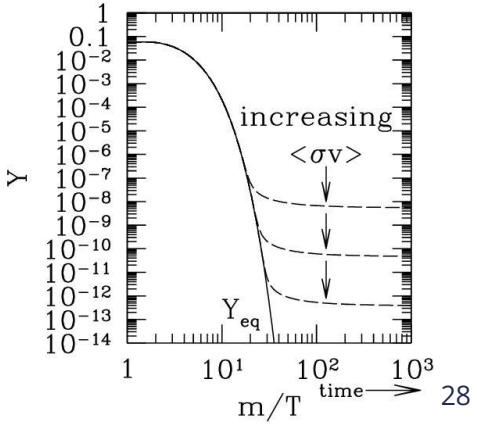
$\sigma v \propto \alpha_D^2$



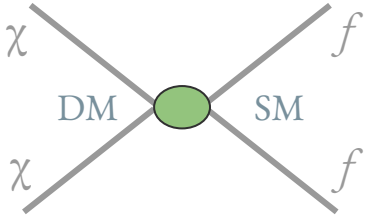
$\sigma v \propto \epsilon^2 \alpha_D$



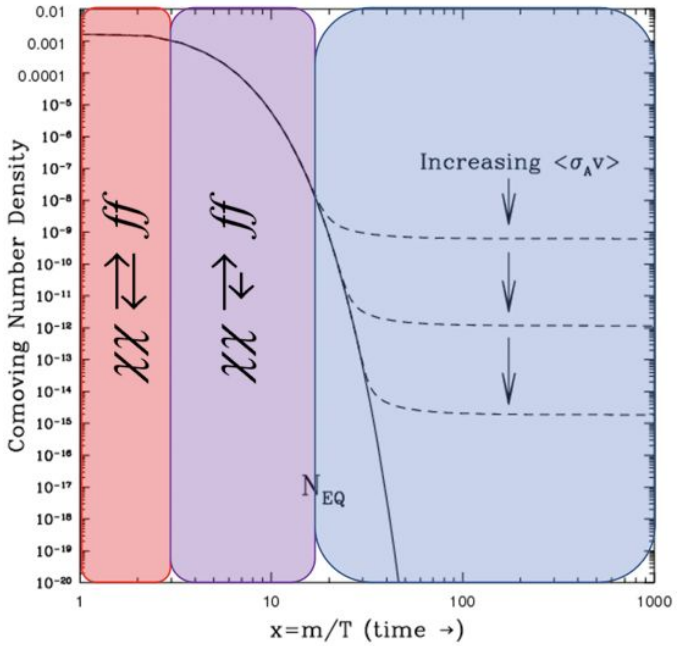




A Thermal Relic



arXiv:9506380



- What is a thermal origin of DM?
  - **1.** Assume DM was in thermal equilibrium with SM particles
  - **2.** The universe expands and cools such that DM pairs are no longer produced
  - **3.** The universe expands and cools such that DM annihilations cease
- The present DM density Ω_χ is related to the DM annihilation cross-section $\langle \sigma v \rangle$

$$\Omega_\chi \propto \frac{1}{\langle \sigma v \rangle} \rightarrow \langle \sigma v \rangle = 3 \times 10^{-26} \frac{\mathrm{cm}^3}{\mathrm{s}}$$

Any proposed mechanism must yield ≤ 85% DM!

Tracker and Trigger Scintillator

- Tagging tracker
  - Measures incoming beam electron
- Recoil tracker (based on Heavy Photon Search design) arXiv:2212.10629v2
  - Measures recoil electron and vetoes extra particles
- Trigger Scintillator
  - Arrays of scintillator bars provide fast count of incoming electrons
  - Used an input to the missing energy trigger