The Light Dark Matter eXperiment (LDMX)

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On Behalf of the LDMX Collaboration

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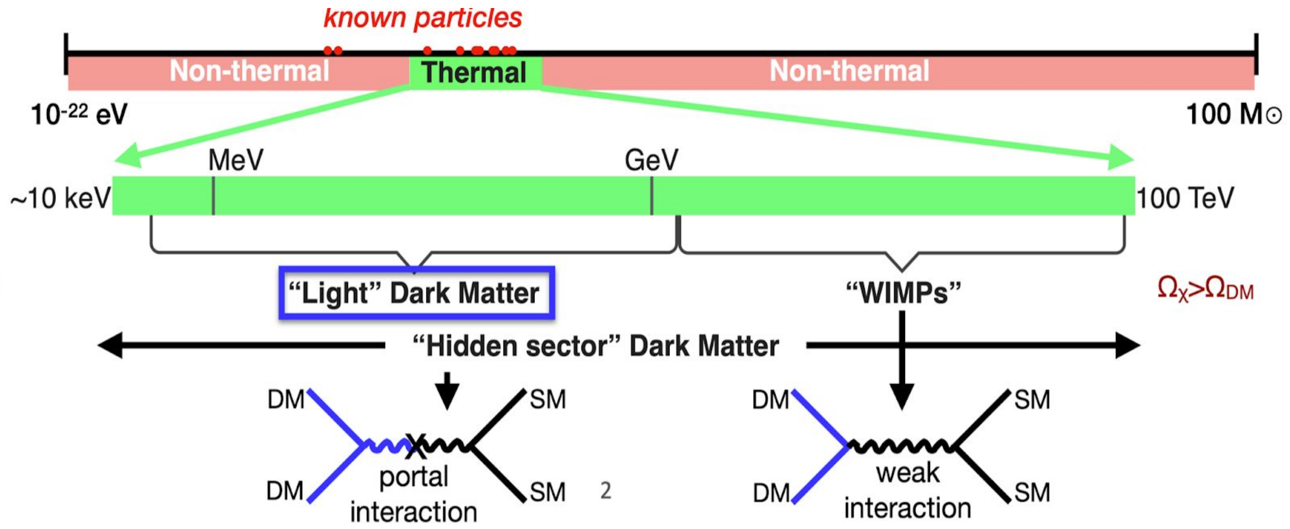
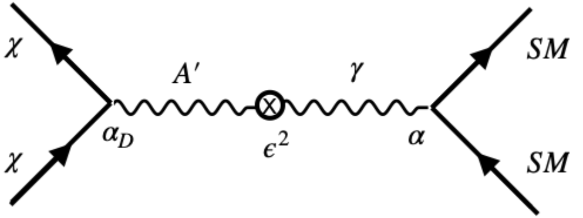
Light Dark Matter (LDM)

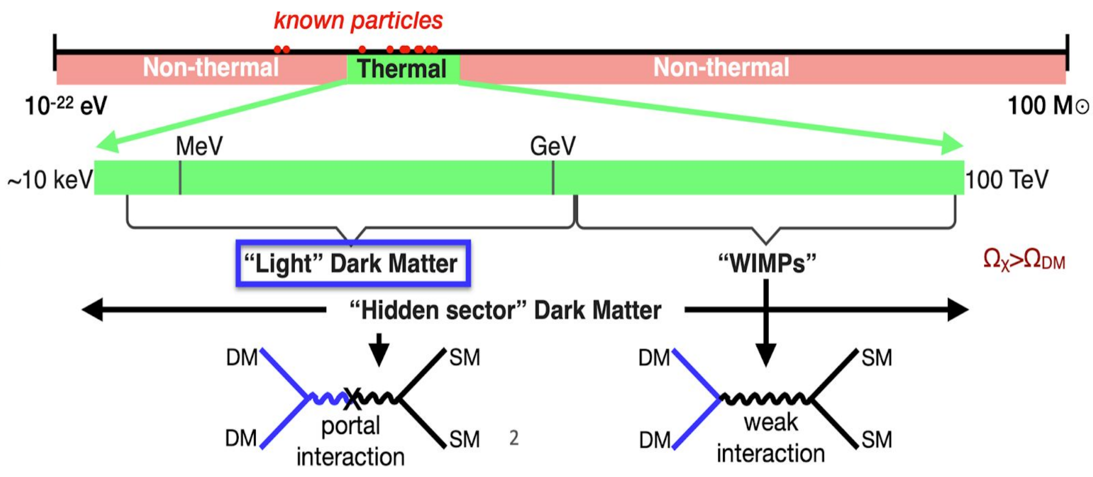
- Thermal relic DM model works for keV to TeV range
- Two categories for thermal dark matter: WIMPs & LDM
  - Still viable parameter space for WIMPs is dwindling, leading to the rise of “light” dark matter research



Light Dark Matter (LDM)

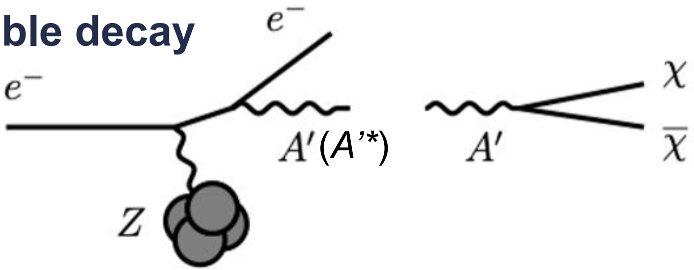


- Thermal relic DM model works for keV to TeV range
- Two categories for thermal dark matter: WIMPs & LDM
  - Still viable parameter space for WIMPs is dwindling, leading to the rise of "light" dark matter research
- Important benchmark is vector portal with dark photon (A') kinetically mixing with SM photon
- Accelerator experiments provide generic probe for LDM independent of portal and type of DM particle



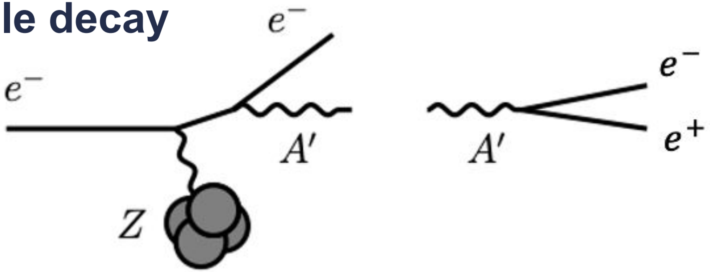
Dark Photon Signatures

Invisible decay



- $m_{A'} > 2m_\chi$ or off-shell production
  - Decays into DM particles that don’t interact with detector
- For LDMX, characterized by some missing energy/momentum in the detector as a whole

Visible decay



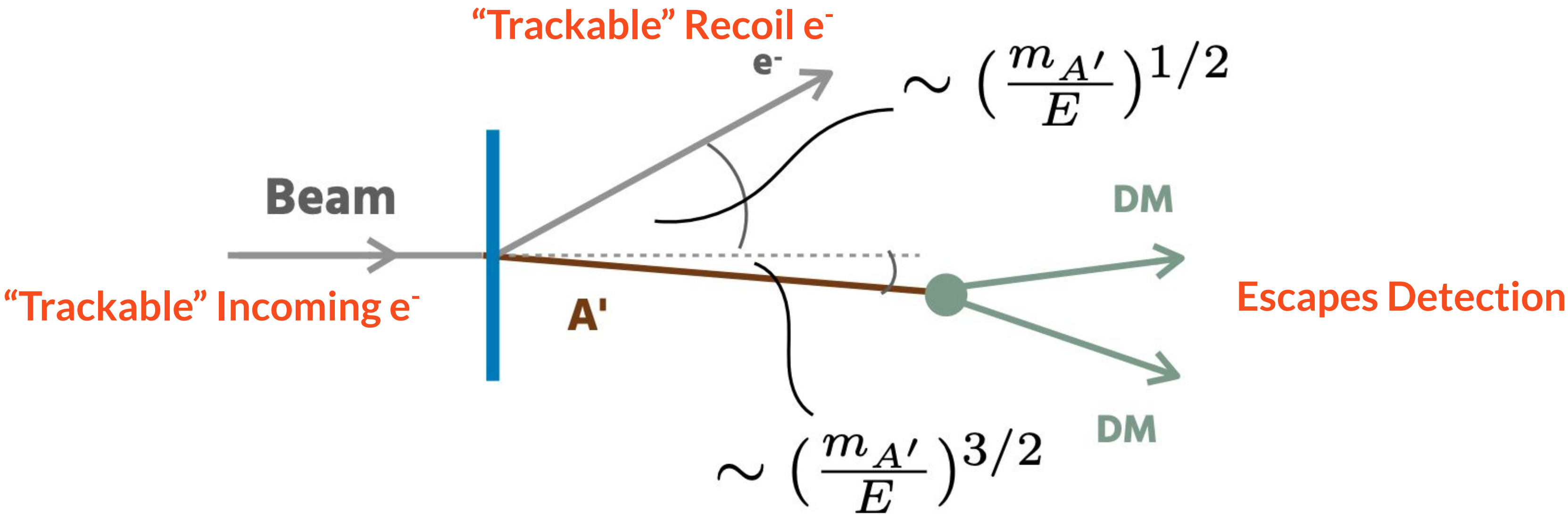
- $2m_e < m_{A'} < 2m_\chi$
  - Decays into SM particles
  - Long-lived
- For LDMX, characterized by a displaced, sudden appearance of energy deposited in some downstream part of the detector

Dark Photon Kinematics at a Fixed Target Experiment

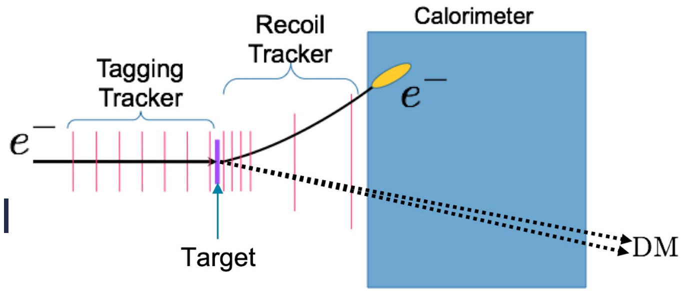
Fixed target signal characteristics:

→ Dark bremsstrahlung A’ production (invisible decay)

→ **A’s take most of the beam energy; only visible final state particle is a soft recoil electron**

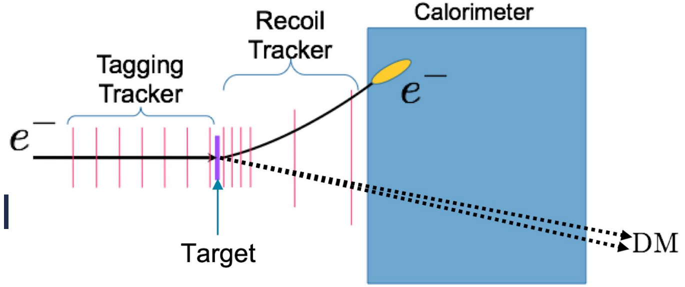


LDMX Concept



- Look for missing momentum (and energy) in recoil electron
  - Use detectors to identify the missing momentum & energy → DM production!
  - Particle ID
  - Transverse momentum of recoil e^- used as discriminator/identifier

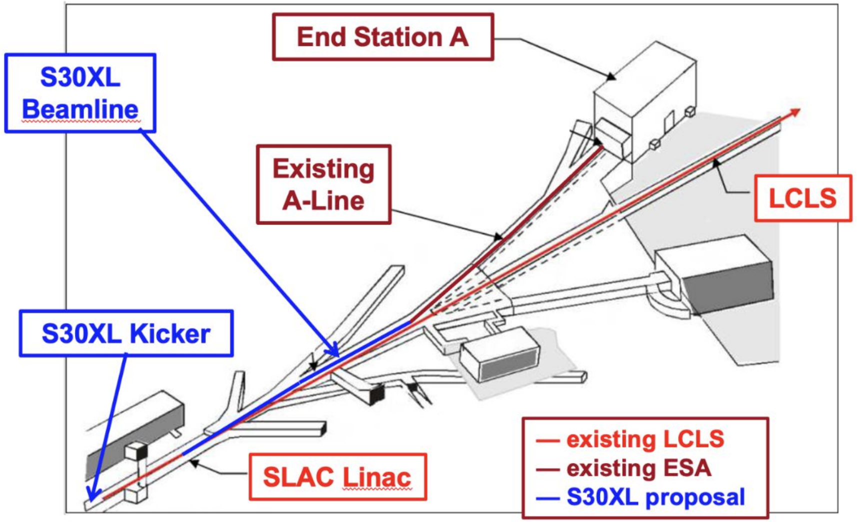
LDMX Concept



- Look for missing momentum (and energy) in recoil electron
  - Use detectors to identify the missing momentum & energy → DM production!
  - Particle ID
  - Transverse momentum of recoil e^- used as discriminator/identifier

- e^- beam provided by SLAC
  - Planning on 4 GeV and 8 GeV runs

- Must be able to tag and reconstruct every electron
  - Do this for up to 1e16 electrons
  - Use low current, high repetition rate of 37 MHz, μ = 1 to a few

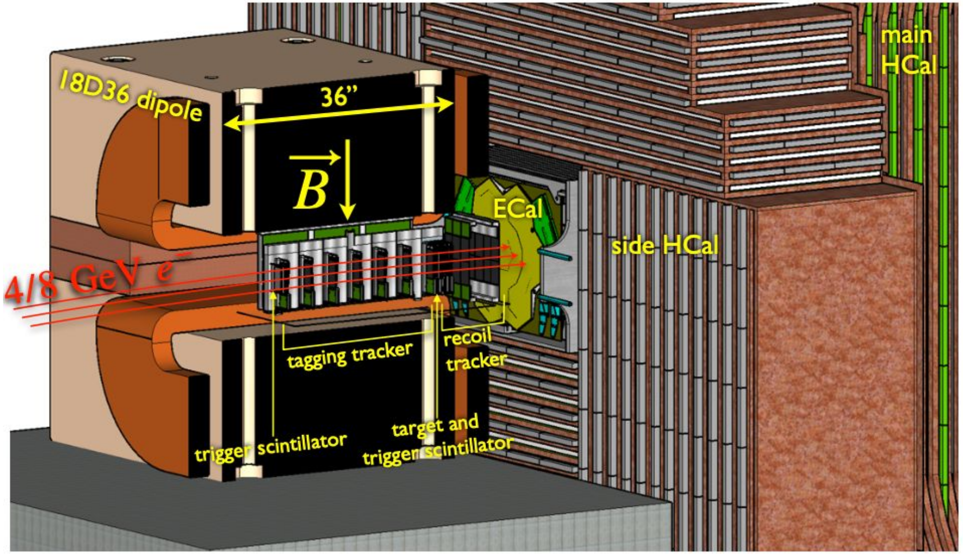


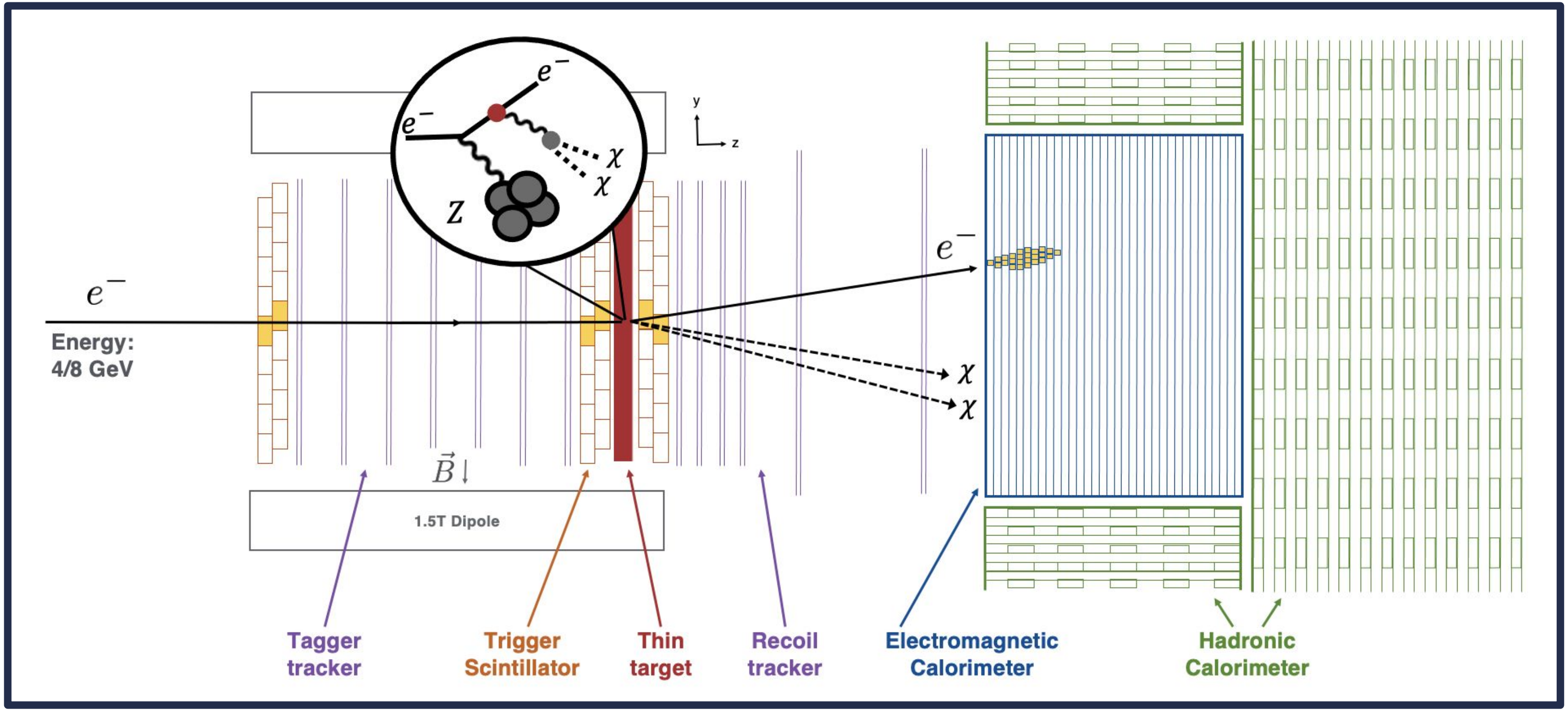
LDMX Design

Basically dumping the beam onto our detector!

⟶ Need hermetic, radiation tolerant detector designed for high beam rates

- **Tagging tracker**: low acceptance and high resolution at beam energy
- **Recoil tracker**: large acceptance and high resolution at low particle momenta
- **Trigger Scintillator**: scintillator bars provide fast, accurate count of incoming electrons
- **Electromagnetic calorimeter**: fast, good energy resolution, and high granularity
- **Hadronic calorimeter**: high veto efficiency of neutral hadrons





Tagging and Recoil Tracker

Simplified version of Silicon Vertex Tracker from HPS at JLab (visible dark photon search)

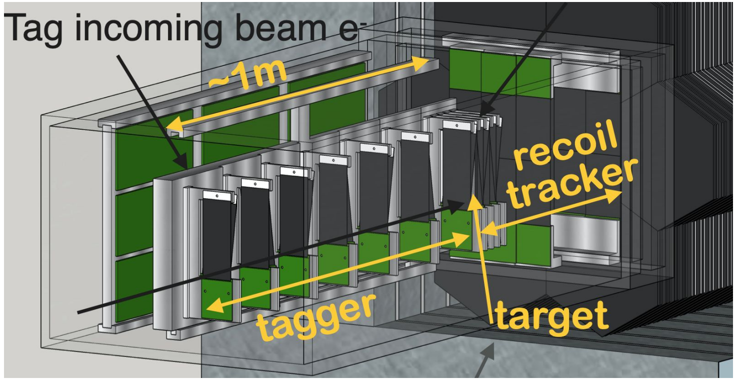
Electromagnetic Calorimeter

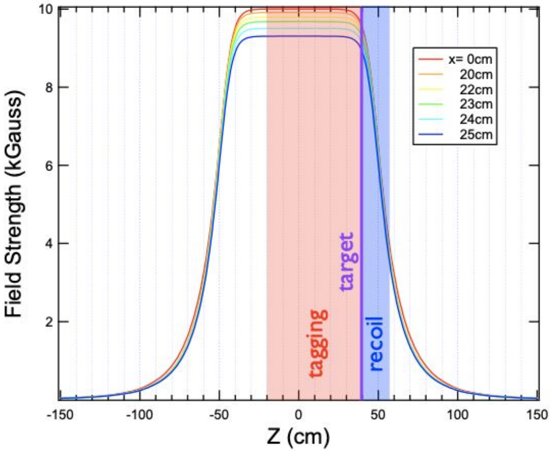
Draws on design of CMS Si-W HGCal

Hadronic Calorimeter

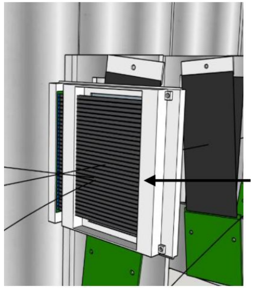
Will be built at UVA! Inspired by Mu2e Cosmic Ray Veto

Trackers and Trigger Scintillator





- Tagging tracker
  - Measures incoming beam electron
- Recoil tracker
  - Measures recoil electron and vetoes extra particles
- Trigger Scintillator
  - Arrays of scintillator bars provide fast count of incoming electrons
  - Used as an input to the missing energy trigger

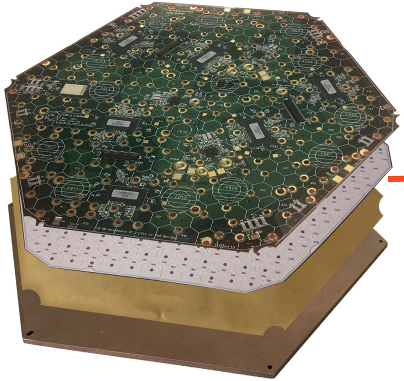


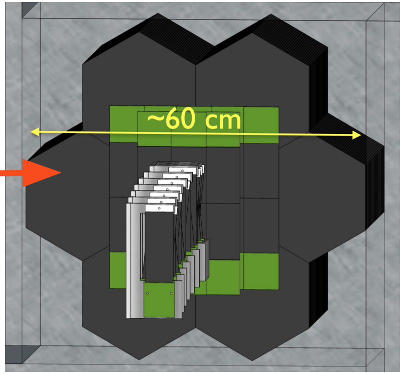
Scintillator pads around target

Electromagnetic Calorimeter (Ecal)

10.17181/CERN.IV8M.1JY2

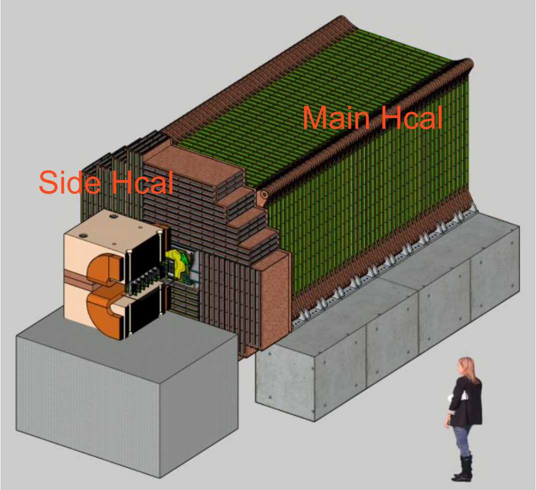
- Si-W sampling calorimeter (based on CMS HGCal upgrade)
  - ~ 40 X_0 depth (34 Si layers) for extraordinary shower containment
- Provides fast missing energy trigger (E < 1.5 GeV for 4 GeV beam)
- High granularity - transverse and longitudinal shower shapes can be exploited to reject backgrounds
- Capable of MIP tracking to further improve background rejection

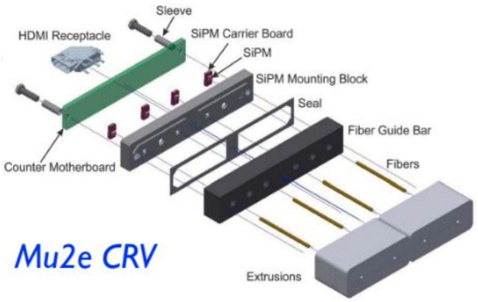


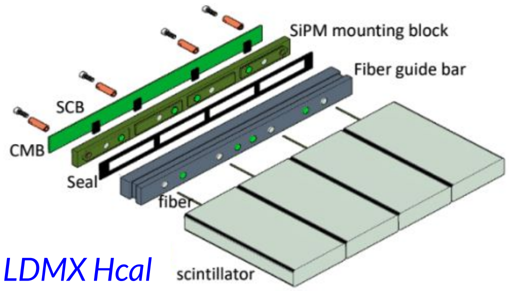


Hadronic Calorimeter (Hcal)

- Segmented scintillator/steel sampling calorimeter
  - 96 layers of 20 (25) mm of polystyrene (Fe) → ~17λ
- Main Hcal detects neutral hadrons (mostly K_L, n) produced in photonuclear reactions, and MIPs
- Side Hcal rejects wide angle brem and γ→μ+μ-
- Extruded scintillator bars with inserted wavelength-shifting fibers, read out with SiPMs

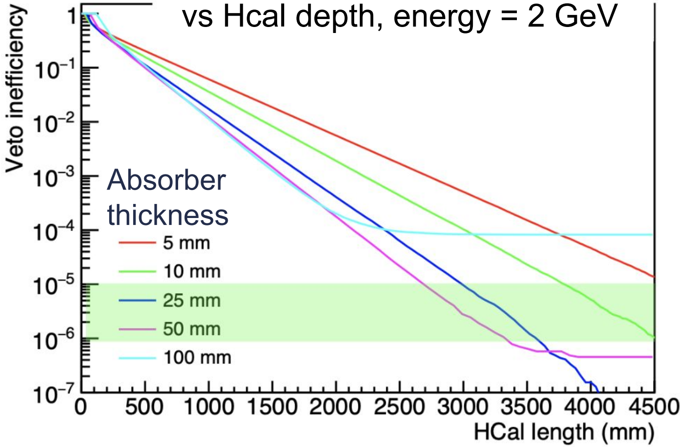


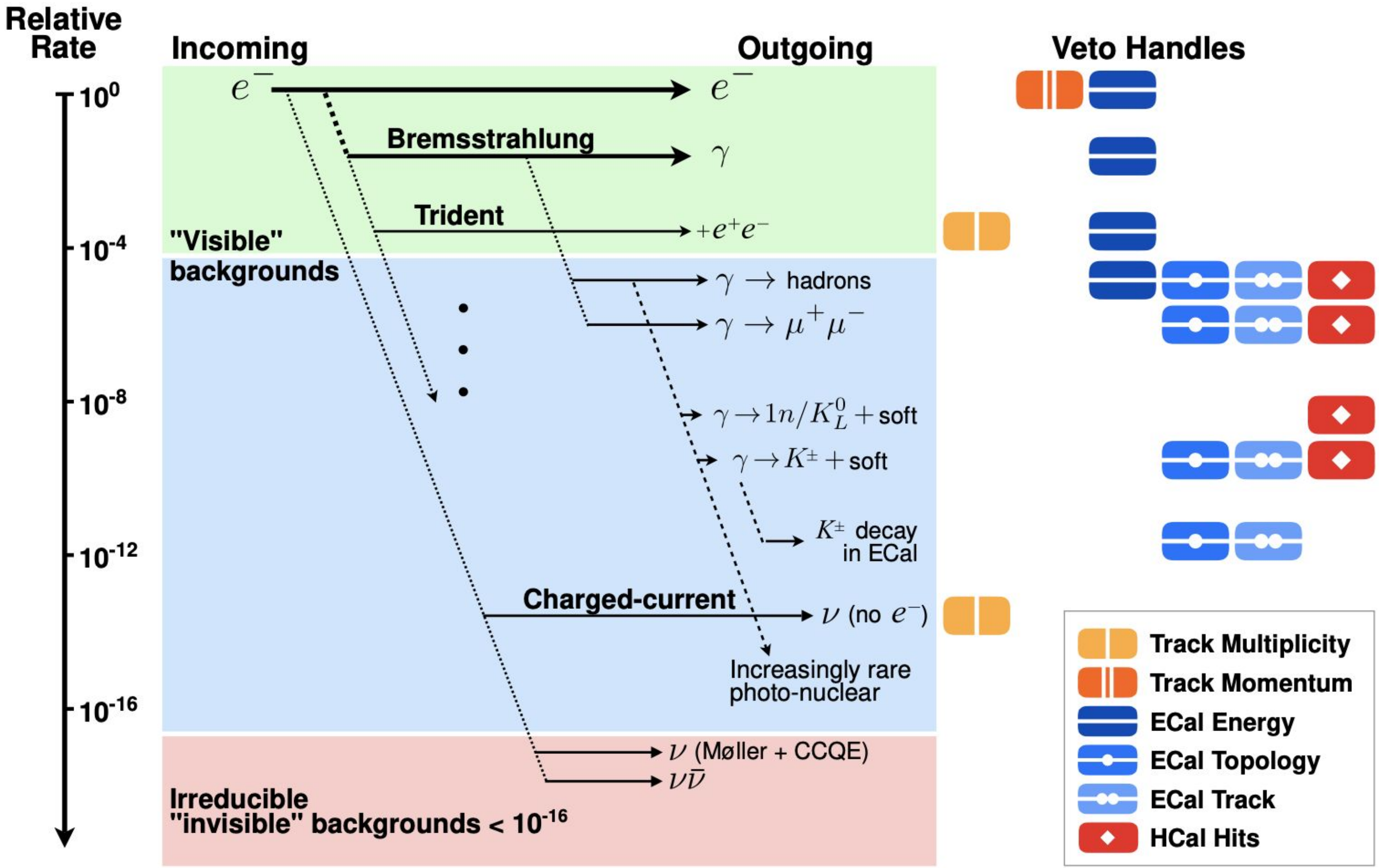




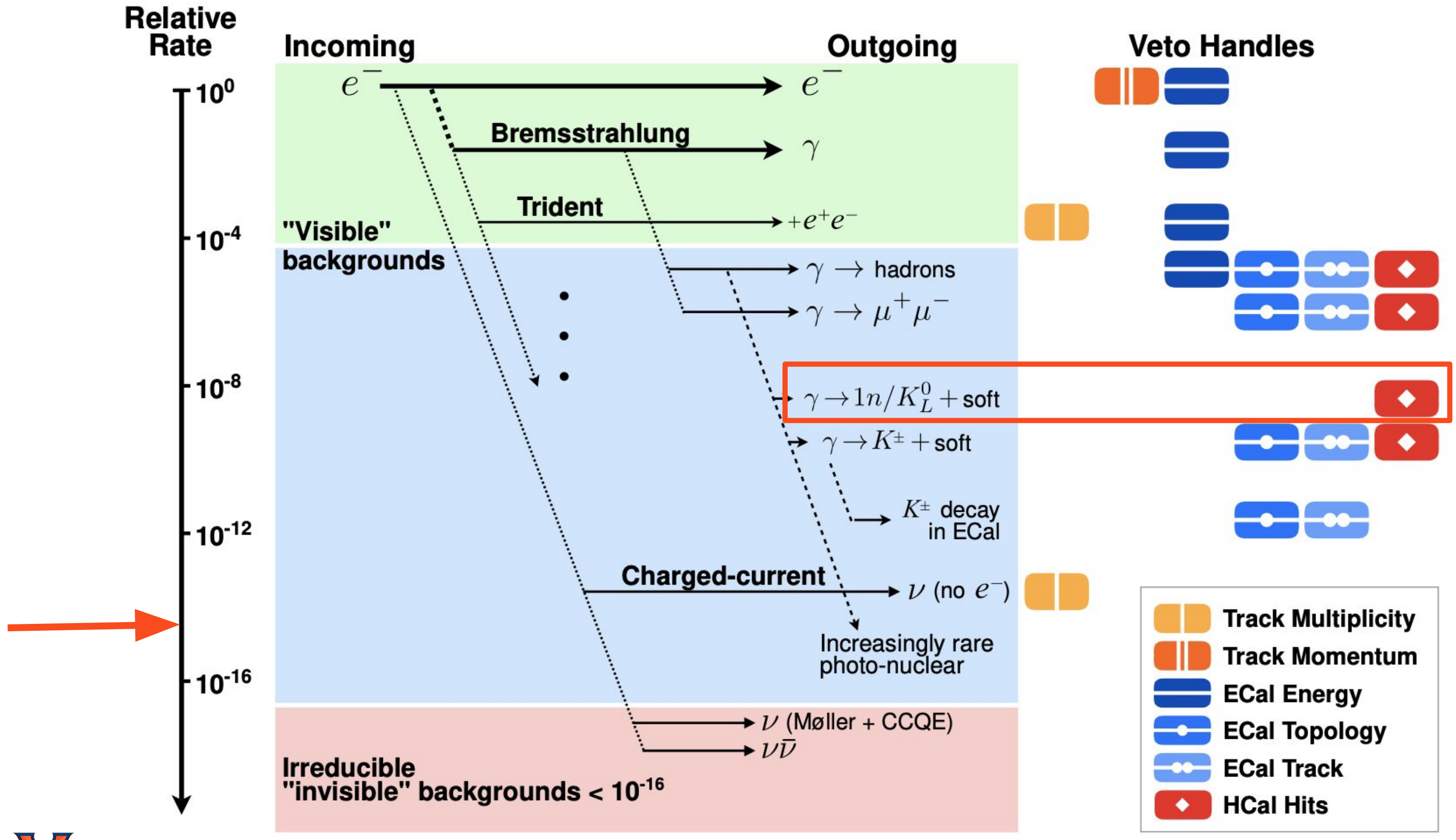
10.18130/0nf5-sw49

Single neutron veto inefficiency vs Hcal depth, energy = 2 GeV





Relative Rate
Incoming
Outgoing
Veto Handles
10^0
10^{-4}
10^{-8}
10^{-12}
10^{-16}
e^-
e^-
Bremsstrahlung
γ
Trident
$+e^+e^-$
"Visible" backgrounds
$\gamma \rightarrow$ hadrons
$\gamma \rightarrow \mu^+\mu^-$
$\gamma \rightarrow 1n/K^0_L +$ soft
$\gamma \rightarrow K^\pm +$ soft
$K^\pm$ decay in ECal
Charged-current
ν (no e^-)
Increasingly rare photo-nuclear
ν (Møller + CCQE)
$\nu\bar{\nu}$
Irreducible "invisible" backgrounds < 10^{-16}
Track Multiplicity
Track Momentum
ECal Energy
ECal Topology
ECal Track
HCal Hits


Relative Rate
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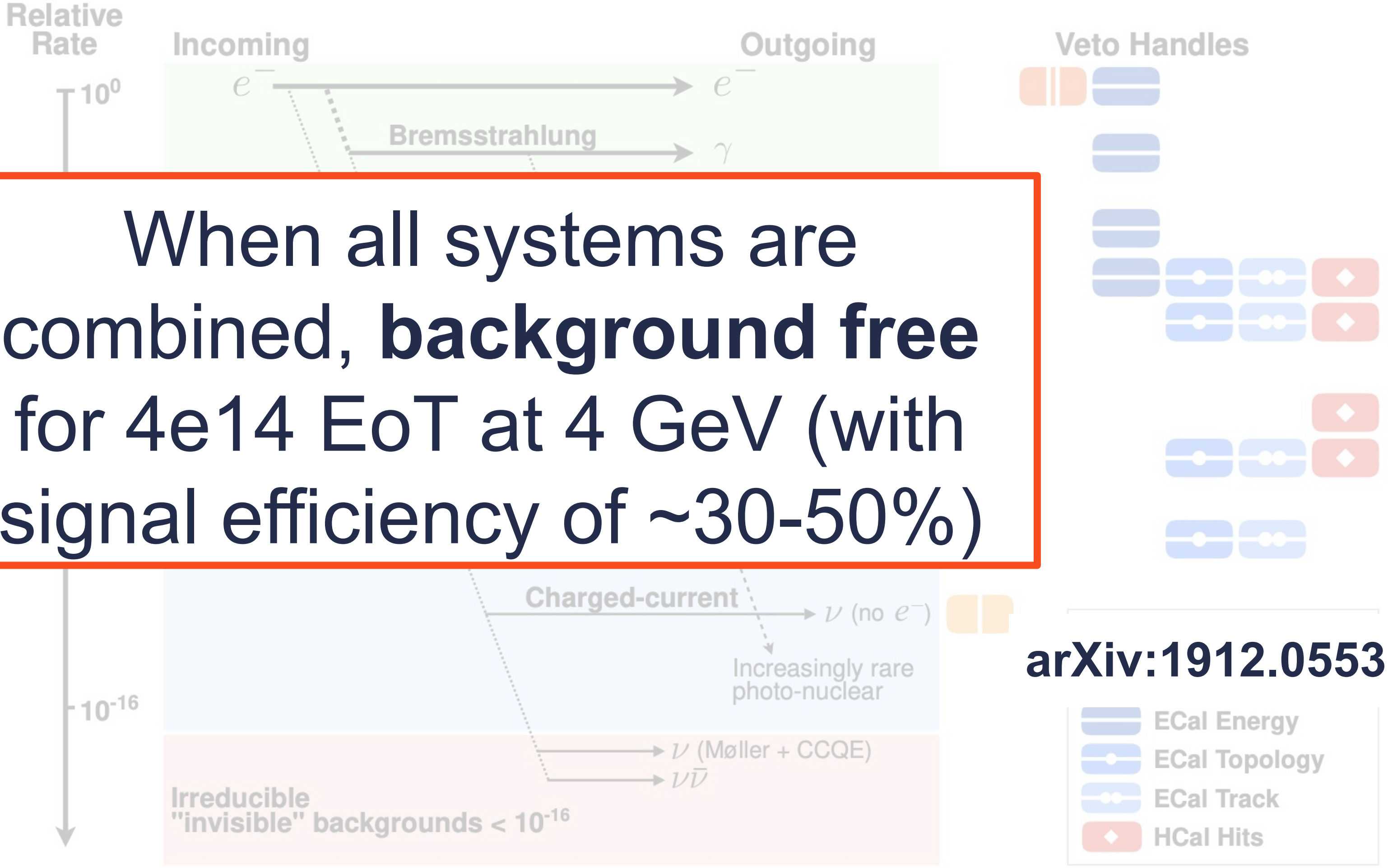

When all systems are combined, **background free** for 4e14 EoT at 4 GeV (with signal efficiency of ~30-50%)

arXiv:1912.05535

Projected Sensitivity

- LDMX is able to reach ALL thermal targets!
    - Even with some background included for the 8 GeV/1e16 EoT run, clearly pass all the benchmark models, so we will be able to exclude all of them
- Within a few weeks of running, LDMX could begin to reach the first thermal targets

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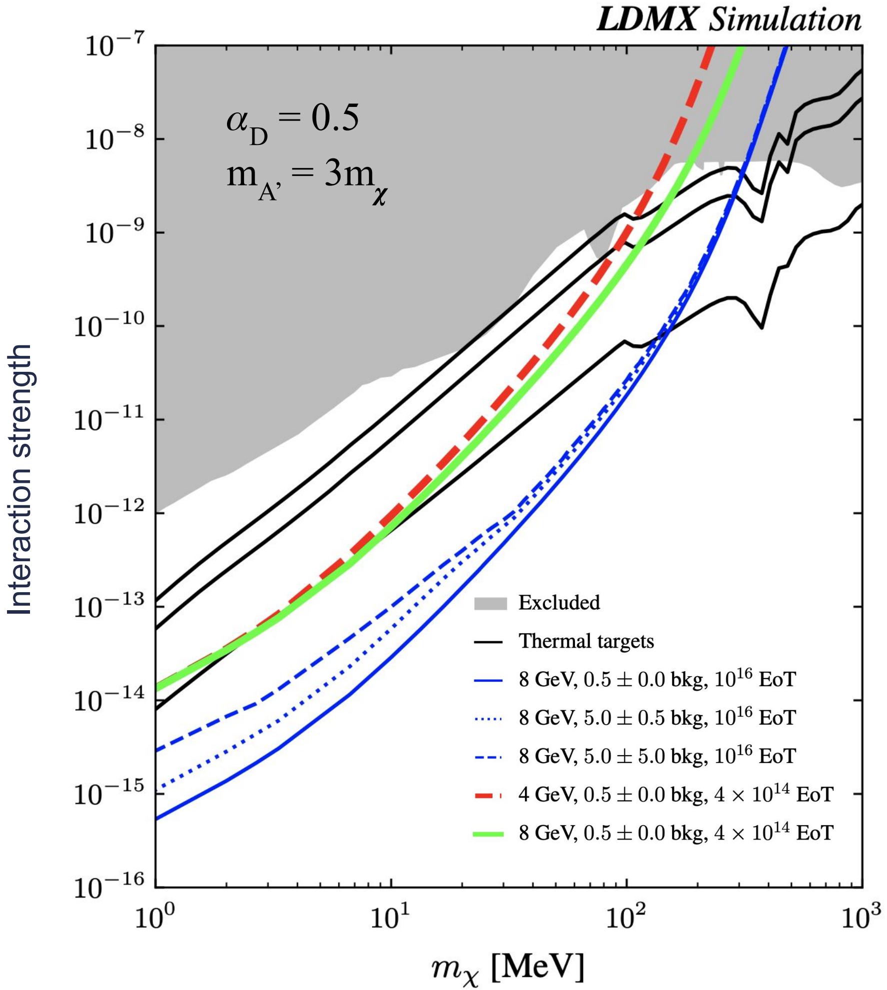
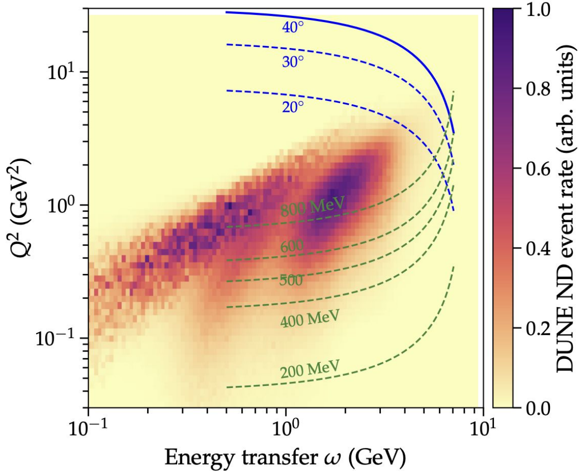


Additional Physics Program: Neutrino Cross-Sections

- LDMX offers a broader physics program beyond a missing momentum search for LDM
- Small angle acceptance (nearly hermetic) and fully reconstructing final/initial states allows for several unique measurements
  - Electro-nuclear scattering measurements of interest to neutrino experiments such as DUNE



8 GeV

Simulated event distribution for charged-current muon neutrino scattering on argon

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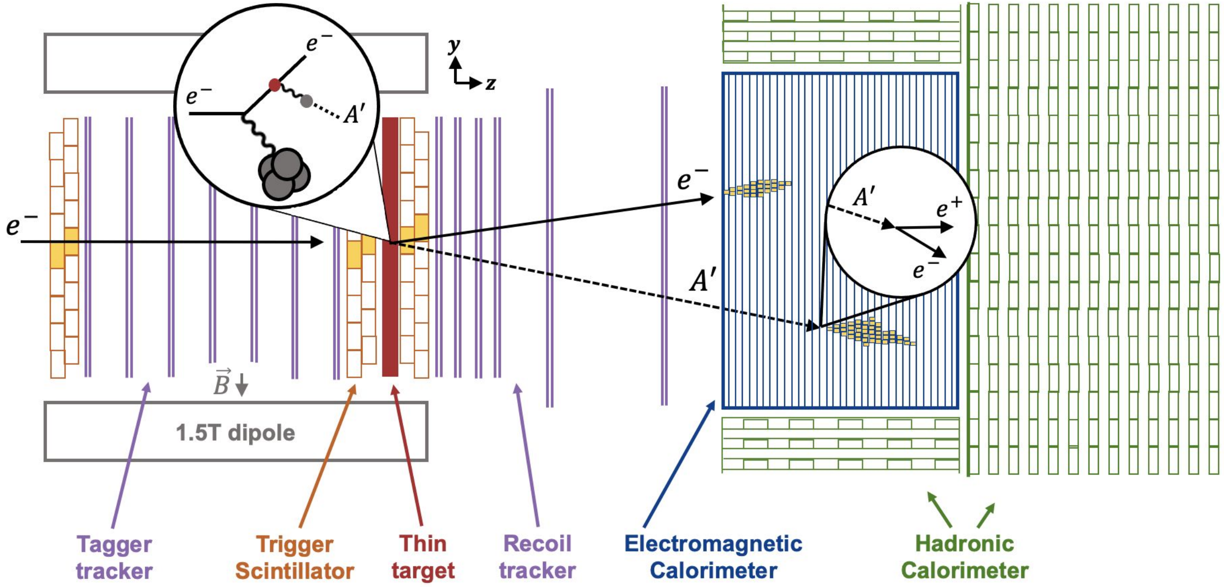
Additional Physics Program: Visible Signatures

- LDMX offers a broader physics program beyond a missing momentum search for LDM
- Many models could be tested (minimal dark photon, ALPs, SIMPS, etc.)



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Conclusions

- Thermal DM is a simple and compelling scenario, and MeV-GeV scale is a logical place to look - extension of WIMPs!
- LDMX will be able to provide world-leading sensitivity to sub-GeV DM and is able to test many LDM scenarios along the way
  - Impressive physics discovery potential and guaranteed deliverables
- The experiment is ready to move forward with the construction phase
- LDMX could be taking data in 2-3 years after establishing the funding profile and **make a major discovery shortly thereafter**

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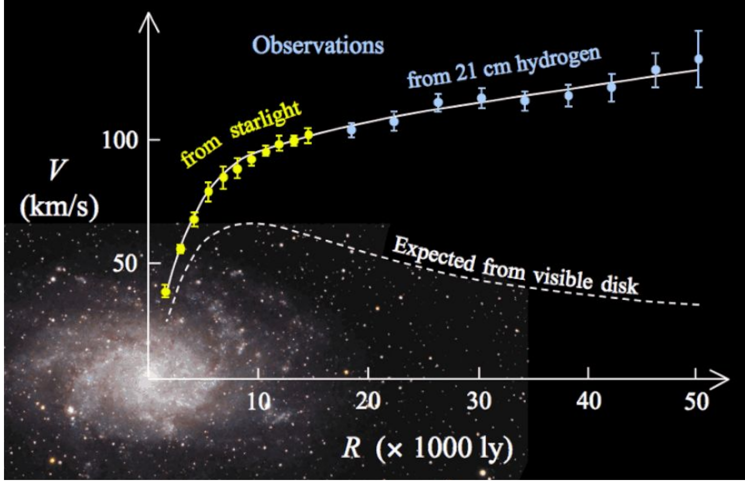
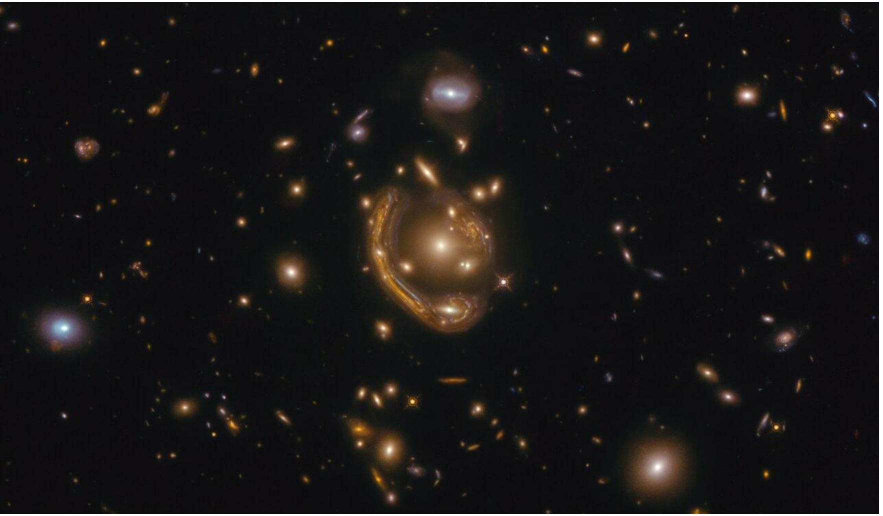
Backup

Evidence for Dark Matter

- Strong case for the existence of dark matter (DM)
  - Galaxy rotation curves
  - Gravitational lensing
  - Cosmic Microwave Background anisotropy
  - Cluster collisions

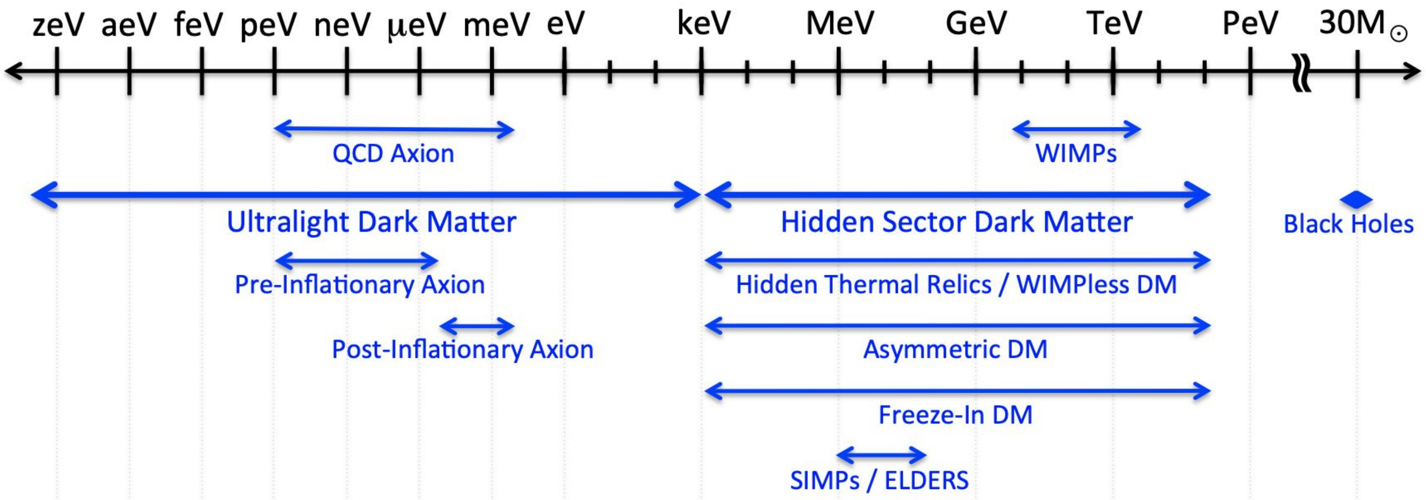




- No detection (yet!) - the origin and nature of DM is a key puzzle for particle physics
  - Standard model does not include dark matter
  - How do we narrow down a search region to determine what DM is?

Trying to Understand Dark Matter

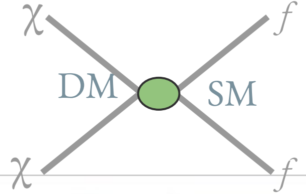
- What do we know?
  - Interacts gravitationally
  - Cosmological abundance
  - Limited interactions with known (SM) matter
- We don't know the mass of the DM



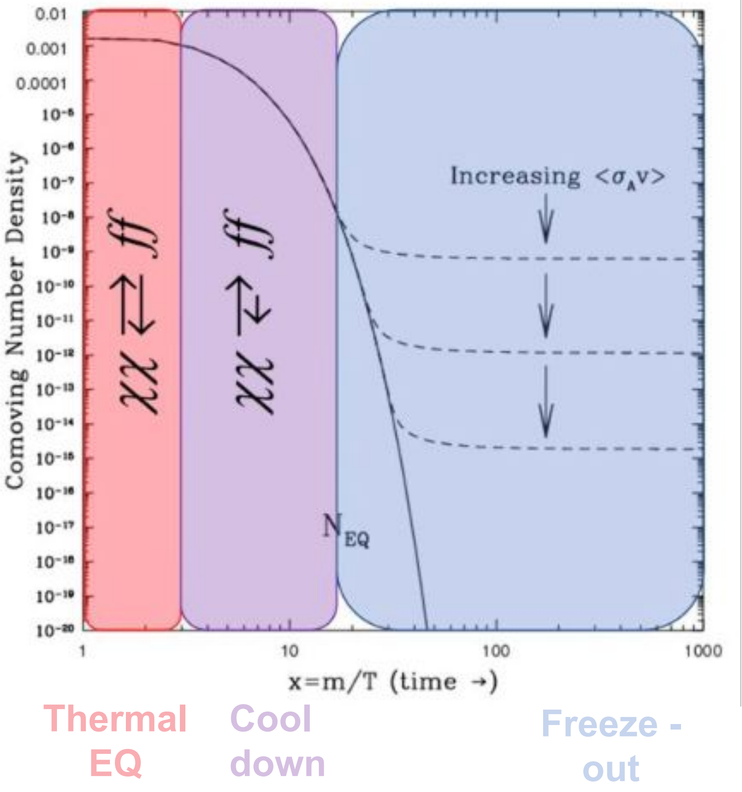
Thermal Dark Matter

- Assume we are dealing with ***particle-like DM***
- DM and SM particles in **thermal equilibrium** in the very early universe
- As universe cools and expands, **DM pairs are no longer in equilibrium**, resulting in decreasing amount of interactions
- Universe expands and cools enough such that DM is too dilute to interact → **freeze-out**
- The current relic density Ω_χ is related to the annihilation cross section $\langle \boldsymbol{\sigma v} \rangle$

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

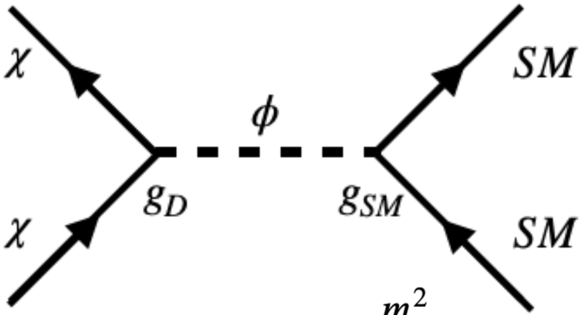


arXiv:9506380

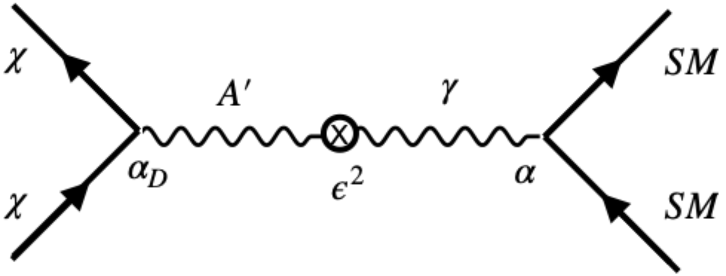


Light Thermal Dark Matter - Hidden Sector

- DM could belong to some "hidden sector" that is secluded from the SM
- Sub-GeV DM requires an additional non-SM interaction to maintain the correct relic abundance
  - Mediated by new massive gauge boson



$$< \sigma v > \sim g_D g_{SM} \frac{m_\chi^2}{m_\phi^4}$$



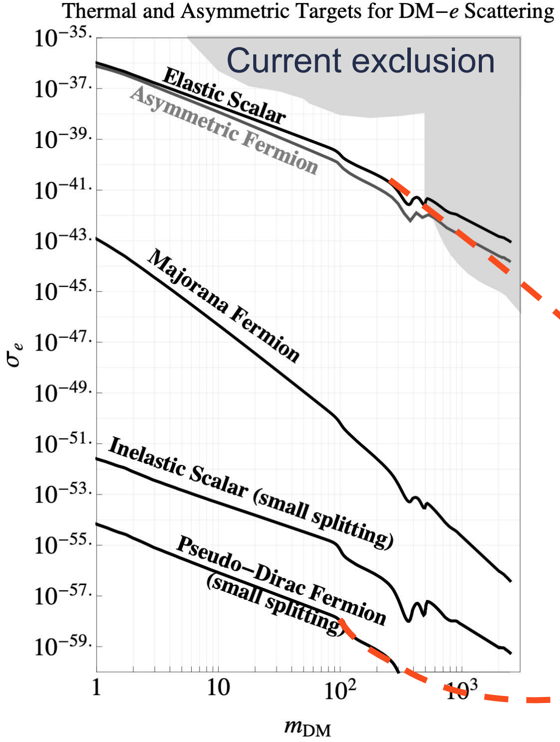
$$\alpha_D = \frac{g_D^2}{4\pi}$$

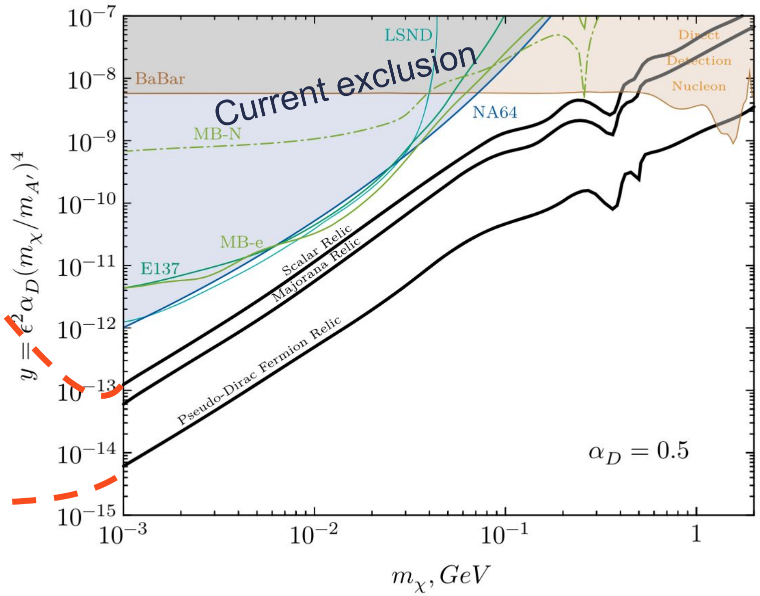
$$\epsilon F^{\mu\nu} F'_{\mu\nu}$$

- Additional spin-one gauge boson (**dark photon** or **A'**)
  - neutral under SM
  - Hidden, broken symmetry $\boldsymbol{U(1)_D}$
- Kinetically mixing with SM $\mathbf{U(1)_Y}$ with factor ϵ
- Visible and invisible final states

Advantage of DM Production at Accelerators

- LDM production at accelerators is fairly independent of the DM model, especially when compared to direct detection
  - ALL “thermal targets” for sub-GeV dark matter models are much more accessible for accelerator experiments

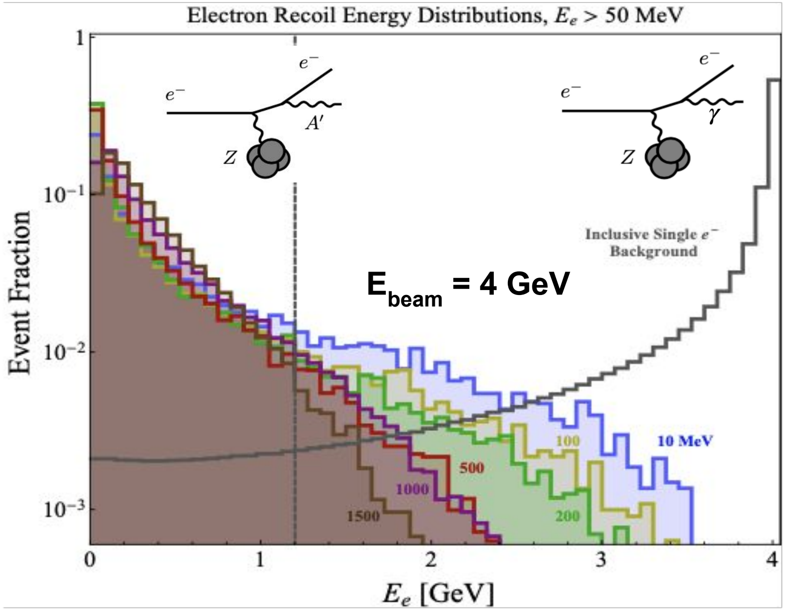


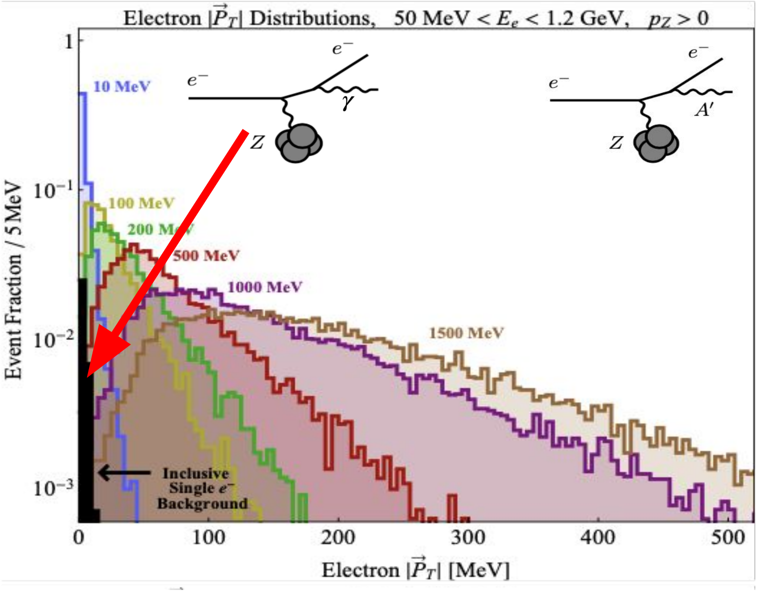


Key difference is the non-relativistic (DM-e) vs relativistic (accel.) DM scattering

$$\Omega_\chi \propto \frac{1}{\langle \sigma v \rangle}$$

Dark Photon Kinematics at a Fixed Target Experiment

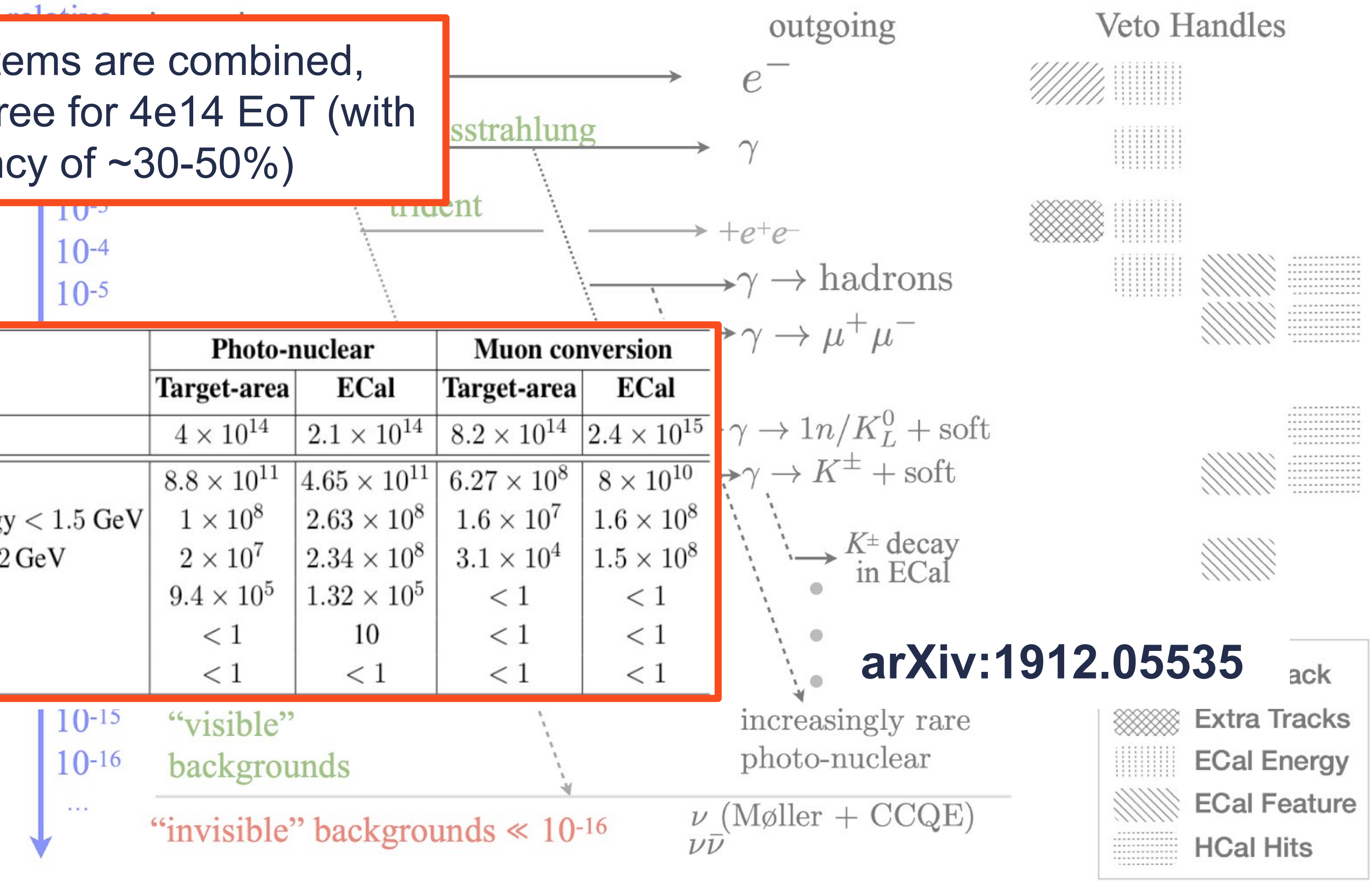




- **A'→χχ carry away most of the beam energy and escape undetected**
  - Opposite behavior for the bremsstrahlung emission
- **Recoil electron p_T spectrum depends strongly on $m_{A'}$ for signal**
  - Signal identification or extra handle for background rejection

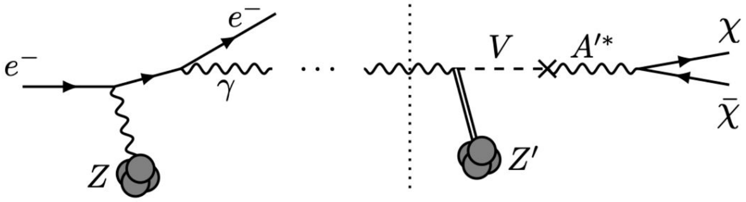
When all systems are combined, background free for 4e14 EoT (with signal efficiency of ~30-50%)

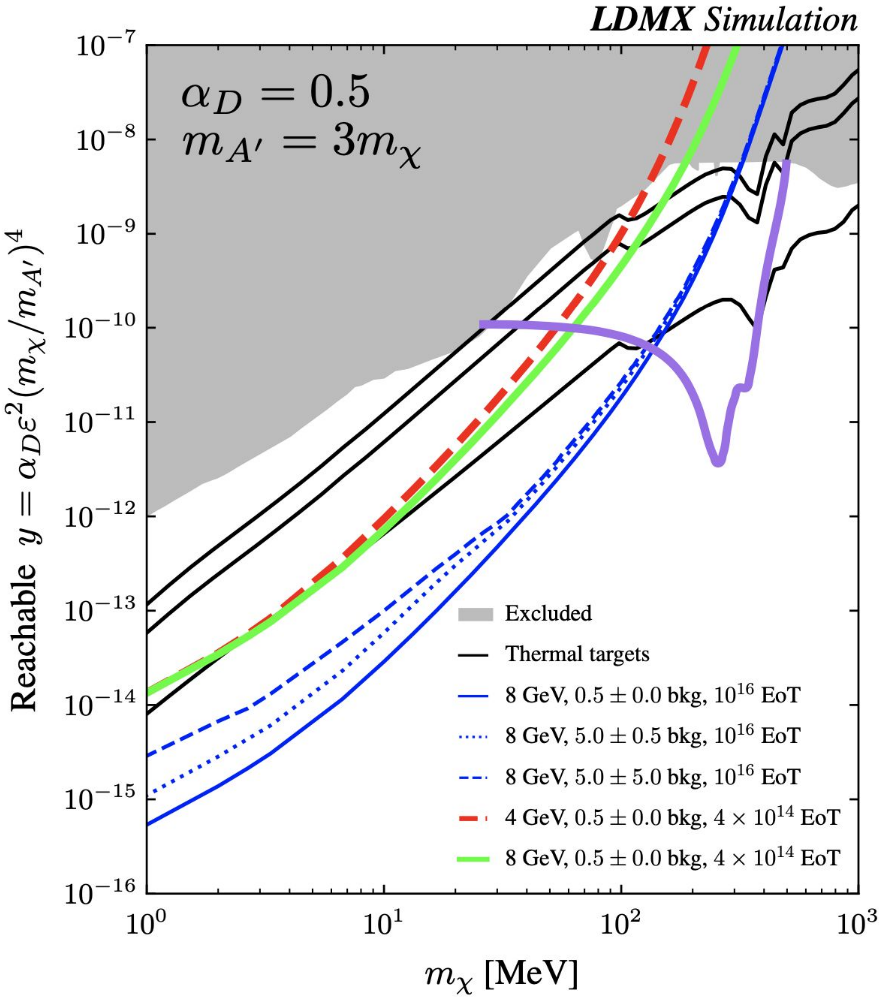
	Photo-nuclear		Muon conversion	
	Target-area	ECal	Target-area	ECal
EoT equivalent	4×10^{14}	2.1×10^{14}	8.2×10^{14}	2.4×10^{15}
Total events simulated	8.8×10^{11}	4.65×10^{11}	6.27×10^{8}	8×10^{10}
Trigger, ECal total energy < 1.5 GeV	1×10^{8}	2.63×10^{8}	1.6×10^{7}	1.6×10^{8}
Single track with $p < 1.2$ 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



arXiv:1912.05535

Gain additional sensitivity from invisible meson decay channel





Advantages of 8 GeV Beam

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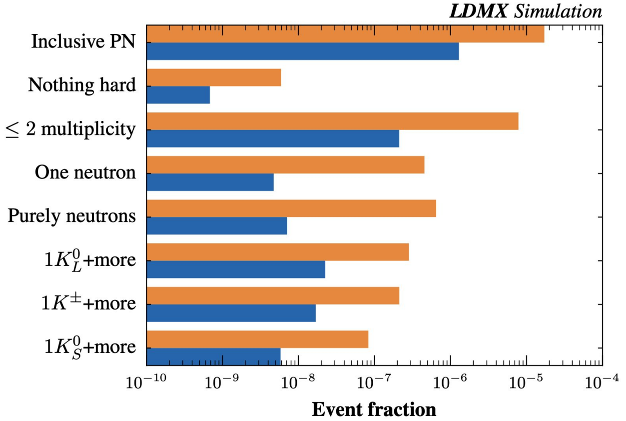


Overall reduction of PN events that pass the trigger and higher multiplicity

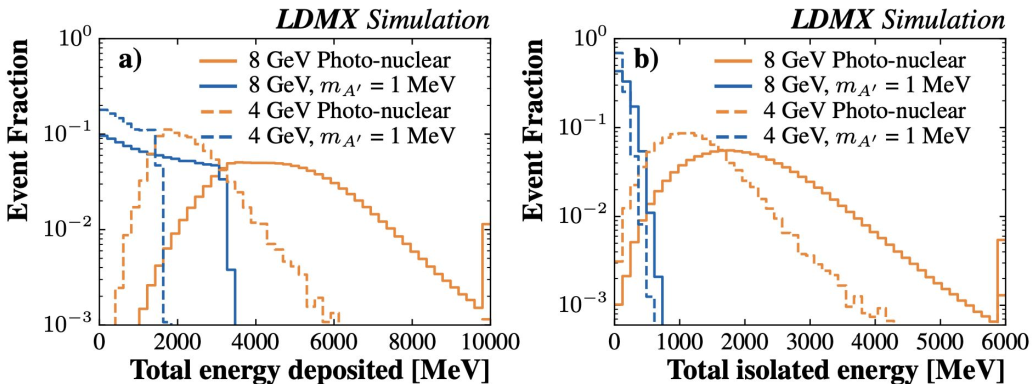
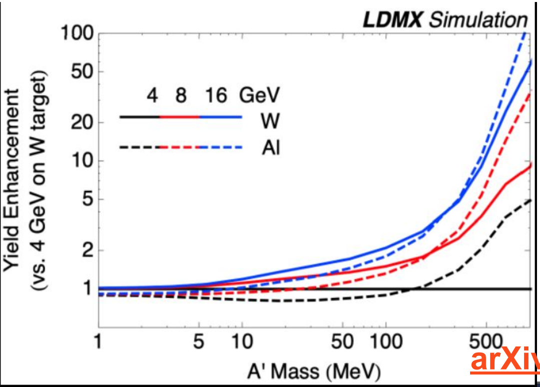


	Photo-nuclear		Muon conversion	
	Target-area	ECal	Target-area	ECal
EoT Equivalent	2.00×10^{14}	2.00×10^{14}	2.00×10^{14}	2.00×10^{14}
Trigger (front ECal energy < 3160 MeV)	7.57×10^{7}	4.43×10^{8}	2.37×10^{7}	8.12×10^{7}
Total ECal energy < 3160 MeV	2.73×10^{7}	7.27×10^{7}	1.76×10^{7}	6.06×10^{7}
Single track with p < 2400 MeV/c	3.03×10^{6}	6.64×10^{7}	5.32×10^{4}	5.69×10^{7}
ECal BDT (85% eff. $m_{A'} = 1$ MeV)	1.50×10^{5}	1.04×10^{5}	< 1	< 1
HCal max PE < 8	< 1	2.02	< 1	< 1
ECal MIP tracks = 0	< 1	< 1	< 1	< 1



arXiv:1808.05219

Higher signal cross-section