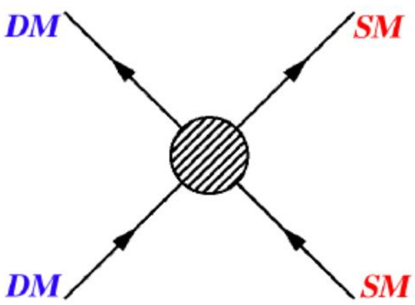
LDMX:
The Light Dark Matter eXperiment

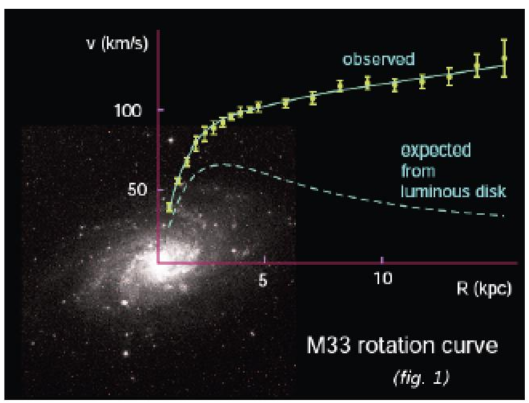
Craig Group
U. Virginia

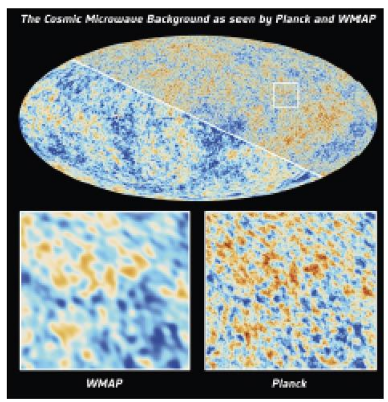


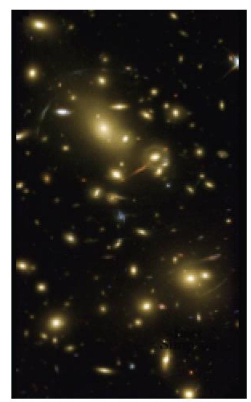
LDMX Collaboration

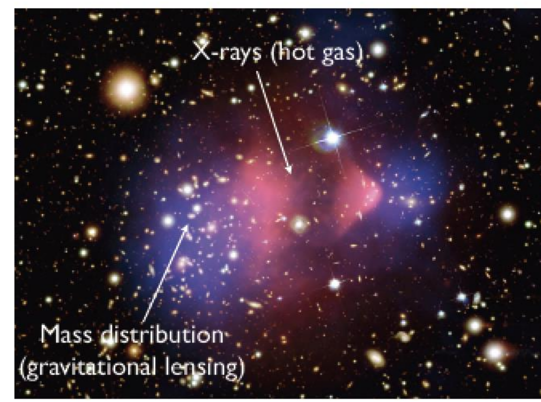
Motivation: Dark Matter is out there!

- Much evidence. (see below)
- Awaiting discovery of its particle nature!
- Few clues to its mass scale.
- WIMPs are the primary candidate, but phase space squeezed.
- Many new ideas on lighter (sub-GeV) dark matter.









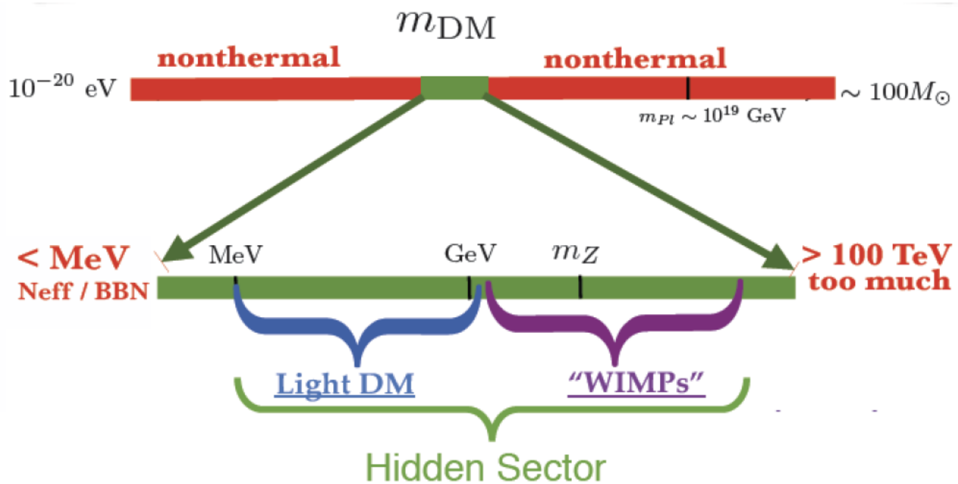
Galaxy Rotation Curves | CMB | Gravitational Lensing | The Bullet Cluster

Common assumption: thermal equilibrium

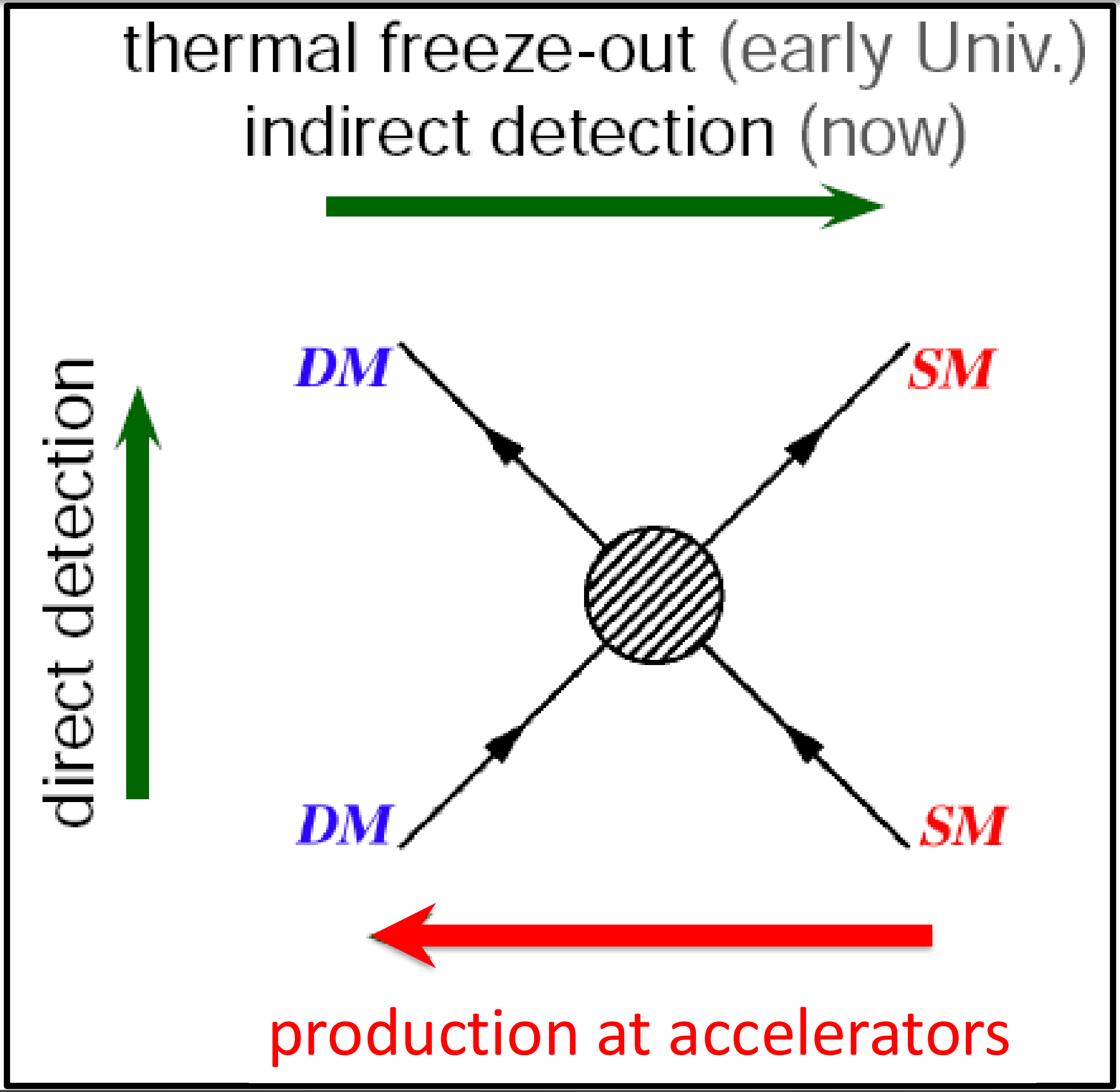
The dark matter mass is not well constrained by experiment!

Folding in assumptions about early universe cosmology we can motivate more specific mass scales

Thermal Equilibrium in early Universe narrows the viable mass range



Searching for Dark Matter



Common assumption: thermal equilibrium

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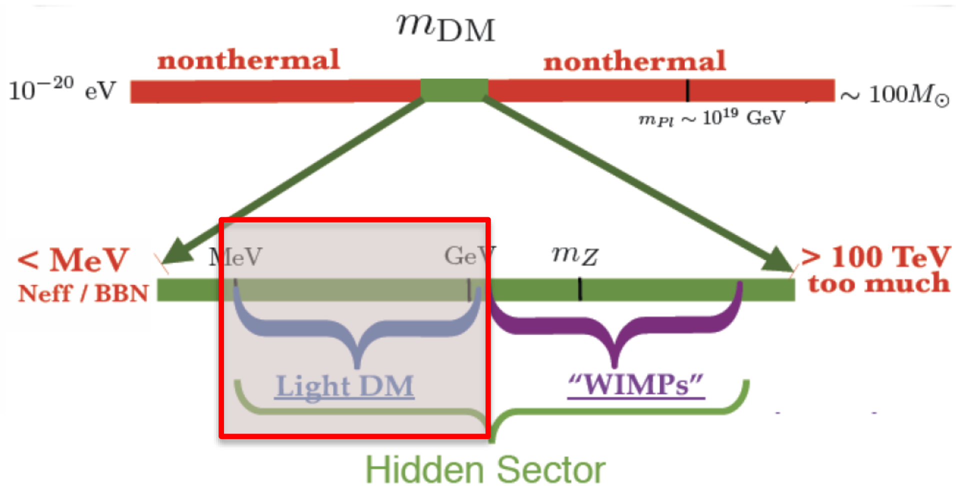
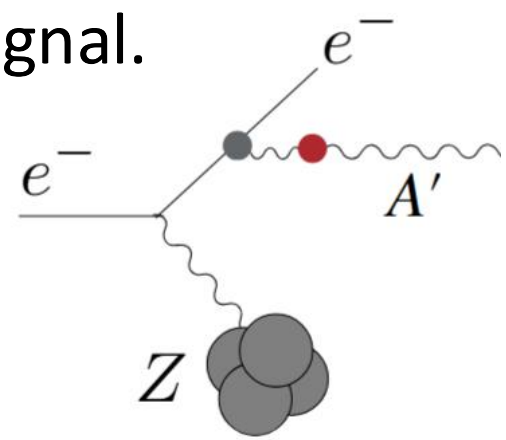


- Explorable with accelerator-based DM searches:
  - Collider – WIMP (but becoming constrained)
  - Fixed-target/beam-dump experiments - Light-DM
- Phenomenology of low-mass region [MeV-GeV] thermal DM is quite different from standard WIMP.

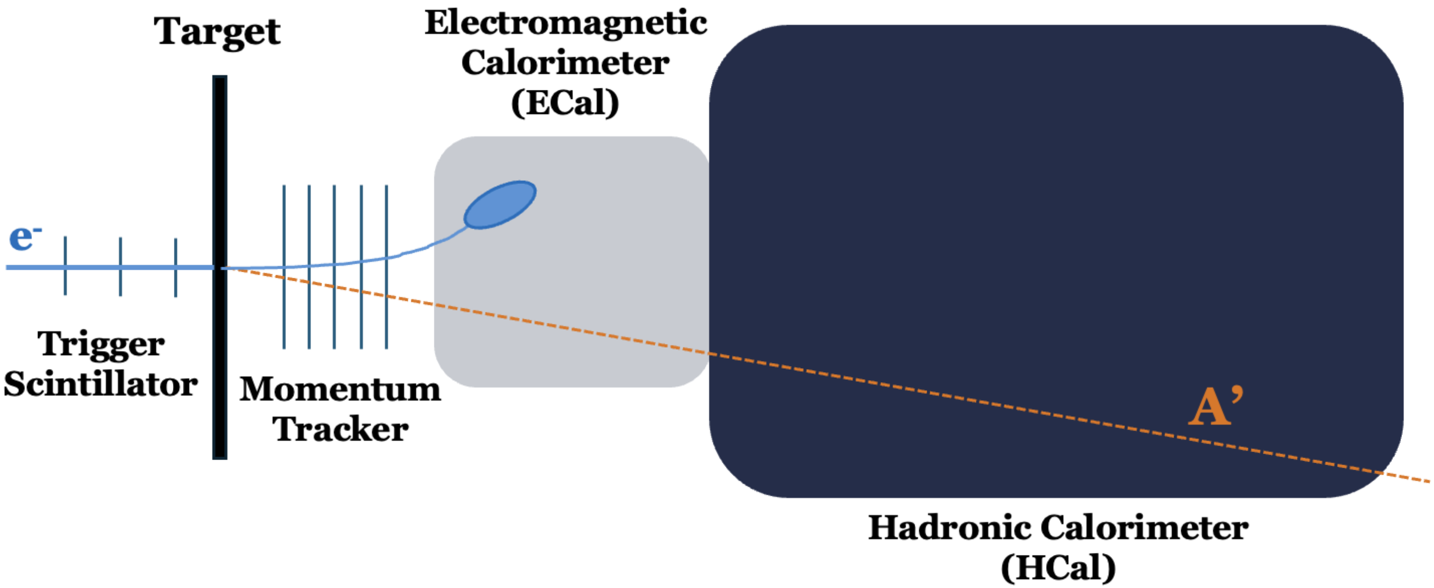
Benchmark Signal Model

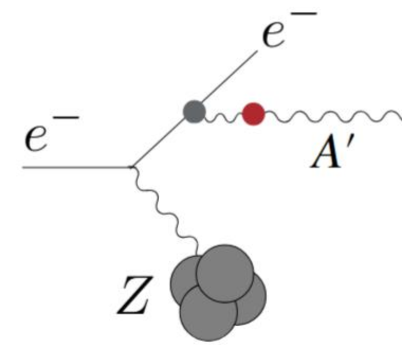
- Assuming a very simple benchmark model: a dark matter particle charged under a **U(1)** gauge field (i.e. "dark QED").
- **Dark photon :** A' as new light mediator
- Connects the "dark sector" to the Standard Model particles.
- **A' is a benchmark**. LDMX works for any model that would produce the missing energy signal.



LDMX and Missing Momentum

LDMX is designed to detect the missing energy and momentum signature.





Signal Event Signature:

- Single low energy electron with “missing” energy and momentum, and nothing else in calorimeters

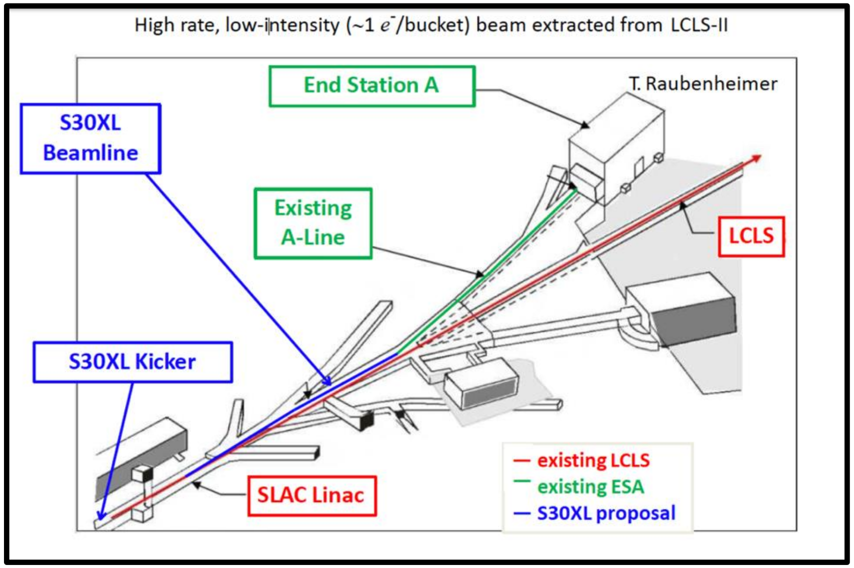
8 GeV e- Beam from LCLS-II

LCLS Linac Coherent Light Source

- Forefront of X-ray science.
- Strobe-like pulses are just a few millionths of a billionth of a second long, and a **billion times brighter** than previous X-ray sources.
- LCLSII produces x rays using an electron beam!

→ LSMX will use beam after the 8 GeV upgrade of LCLS and can be used parasitically without affecting LCLS-II experiments.

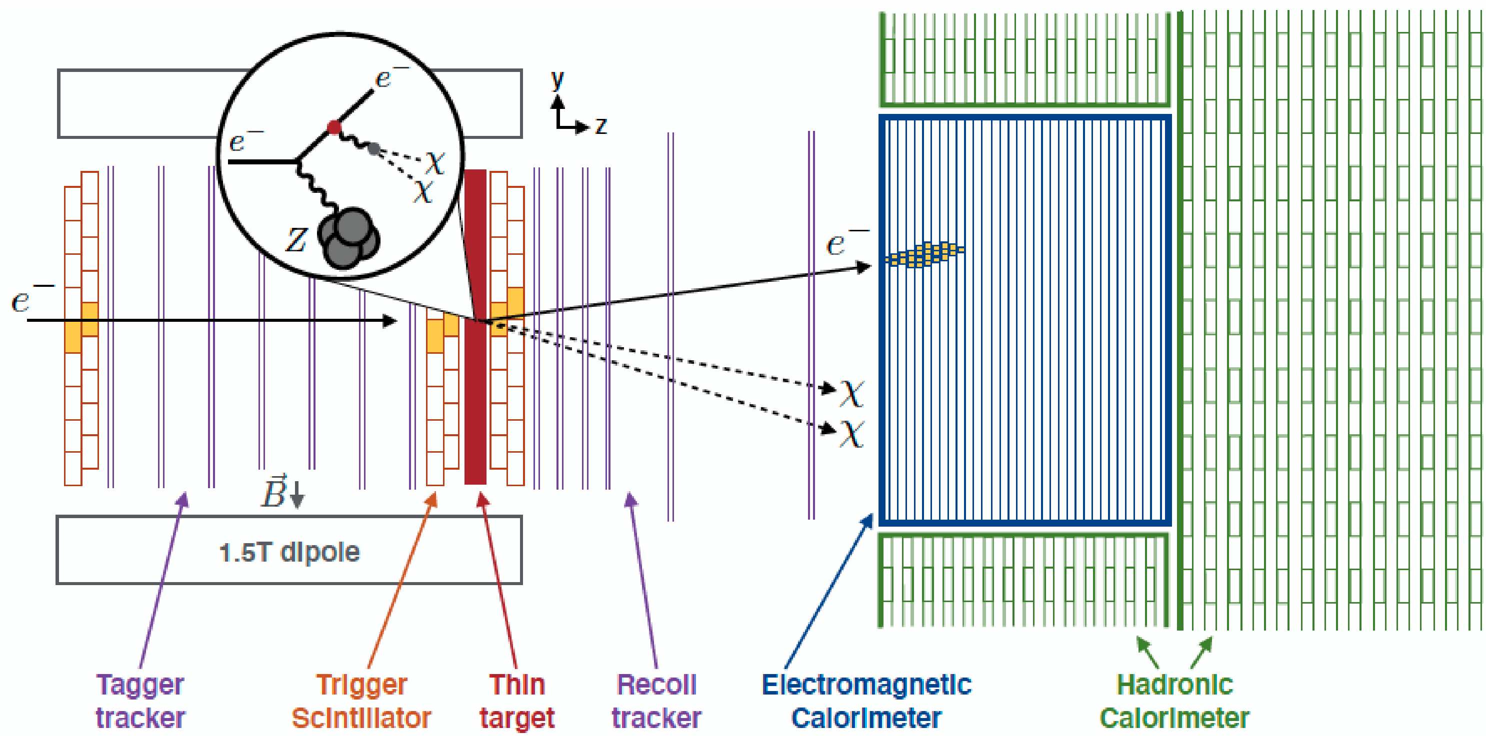
Transfer line to A-line and End Station A is constructed and operational!



Unique facility, providing low-energy CW beam for a variety of purposes: neutrino measurements, accelerator physics, and test-beam studies in addition to dark matter searches.

LDMX Detector

Experiment design relies heavily in proven technologies in other HEP experiments!



Tagging and Recoil Tracker

Simplified version of Silicon Vertex Tracker from HPS@Jlab (visible dark photon search)

Electromagnetic Calorimeter

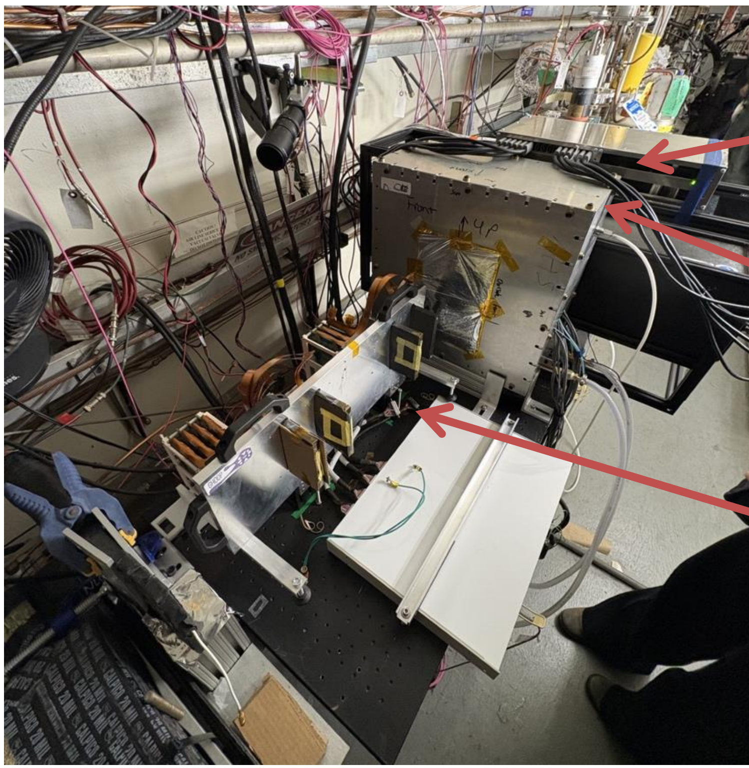
Draws on design of the CMS SiW HGCal (fast, radiation hard, dense, with high granularity for MIP tracking)

Hadronic Calorimeter

Inspired by Mu2e Cosmic Ray Veto (plastic scintillator with steel absorber: ~16 interactions lengths, optimized for veto of neutral hadrons)

LDMX and Missing Momentum

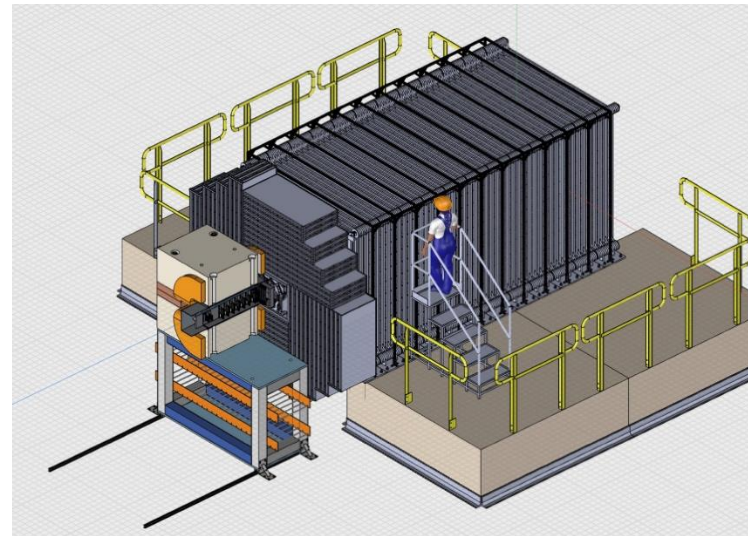
Components of LDMX are being built and tested today!
Example from recent test beam campaign at SLAC End Station A.



HCal Prototype

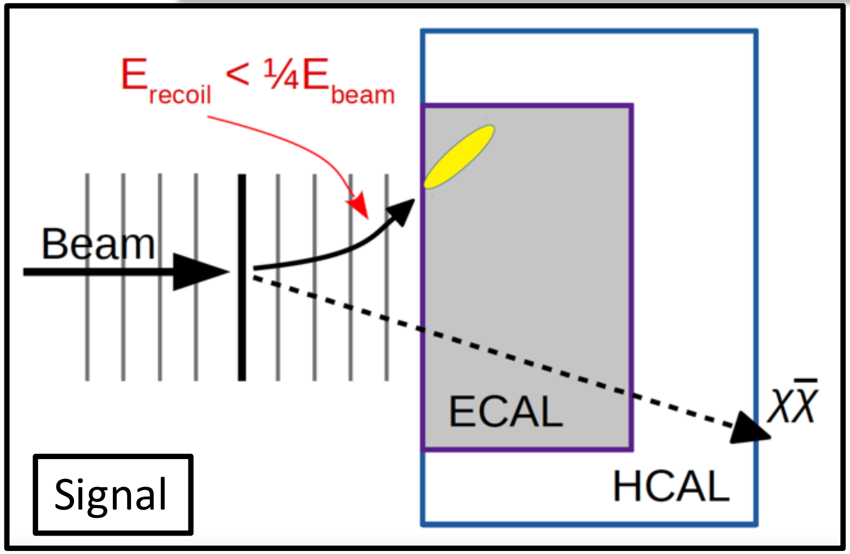
ECal Prototype

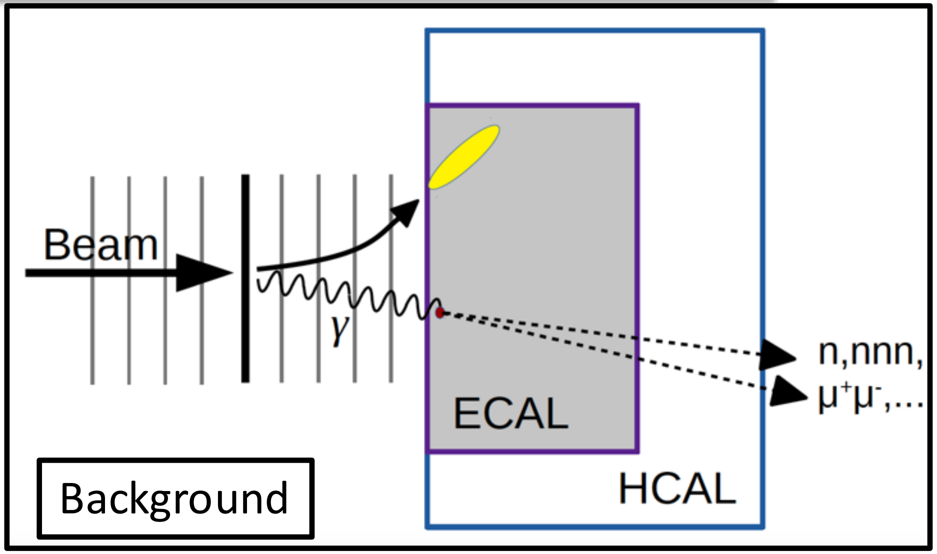
Trigger Scintillator Prototype



The LDMX Missing Momentum search could cover almost orders of magnitude of unexplored parameter space.

Signal and Primary Background

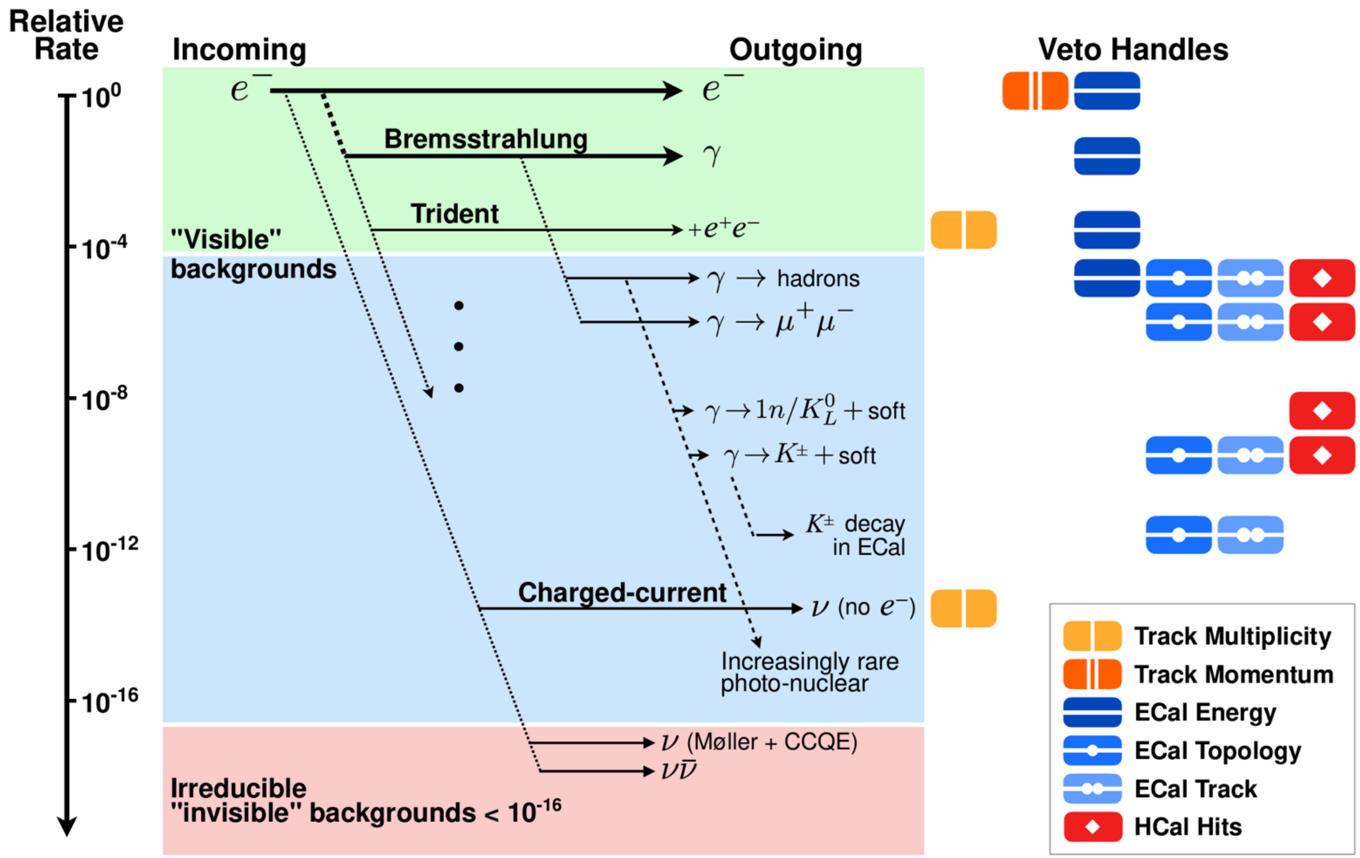




- Electron recoil is very different for signal and background (simple trigger)
- A' emitted at low angles and carries away most of the energy of the e-.
- HCAL designed to veto brem + photo-nuclear interactions:
  - Neutrons
  - Taus
  - Muons
  - …

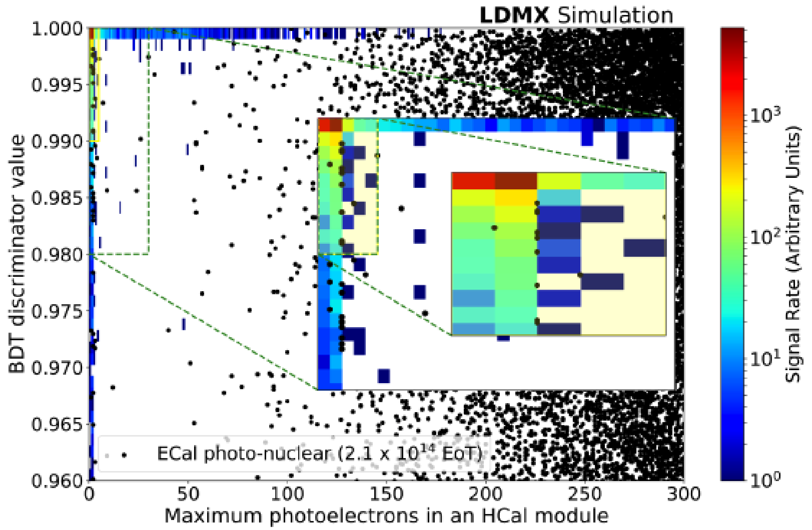
Background

- LDMX aims to be a zero-background search for light dark matter
- Backgrounds come in a large variety, and subsystems are optimized to veto them
- No fundamentally irreducible backgrounds at 10^{16} electrons on target (EoT)



Missing Momentum Analysis Strategy

- Trigger on missing energy.
- Combine ECal features into a Boosted Decision Tree (BDT) for Ecal veto.
- Veto on activity in Hcal.
- Additional vetoes on activity in trackers/ECal front layer.

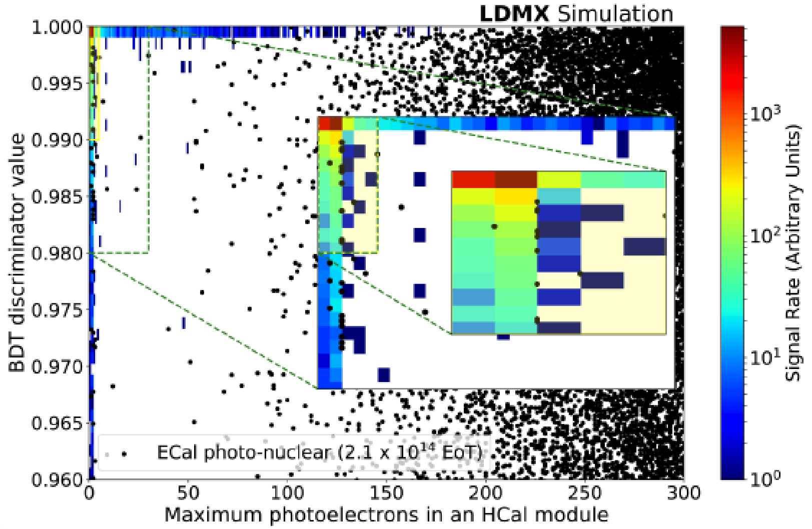


No background at 2e^14 EoT!

	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

Missing Momentum Analysis Strategy

- Trigger on missing energy.
- Combine ECal features into a Boosted Decision Tree (BDT) for Ecal veto.
- Veto on activity in Hcal.
- Additional vetoes on activity in trackers/ECal front layer.
- Save e- P_T to certify potential signal events and to estimate the dark photon mass.



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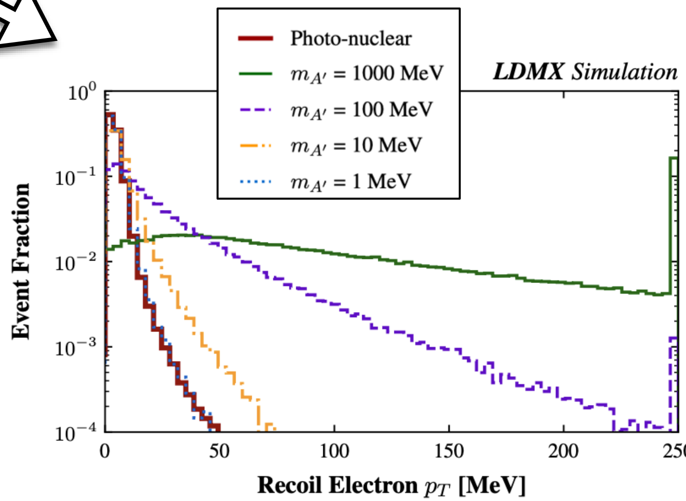
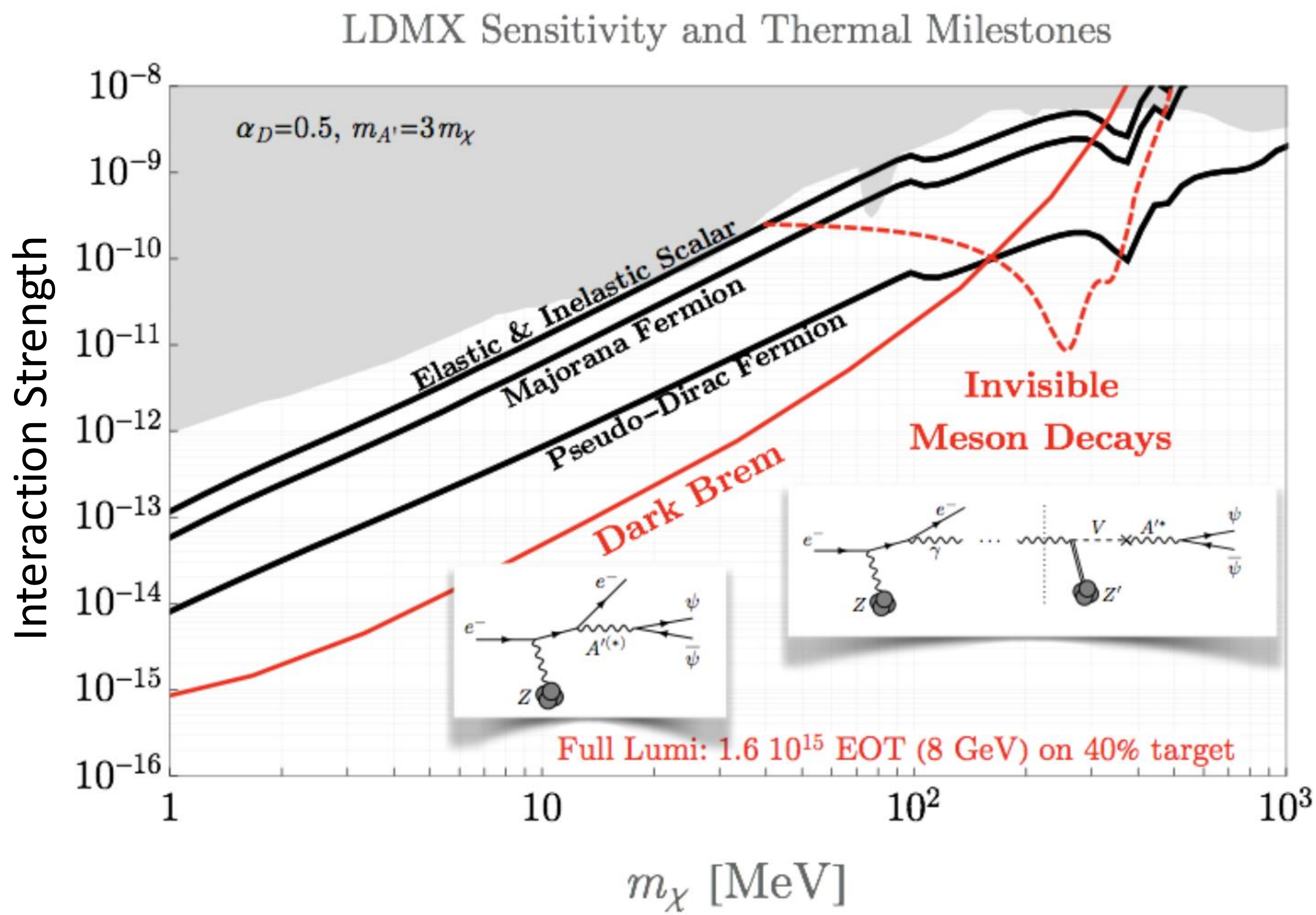


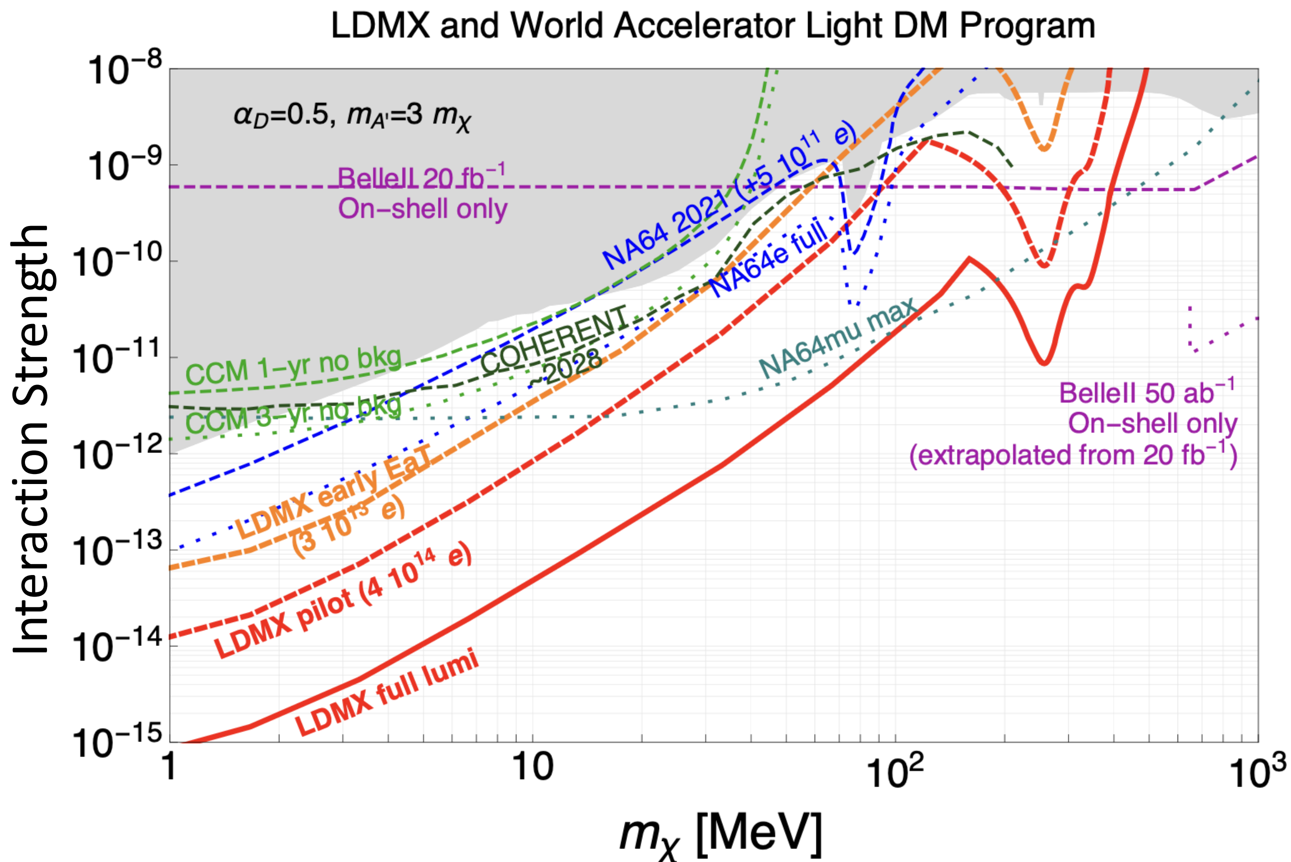
Expected Sensitivity



LDMX can probe all thermal targets up to a few hundred MeV.

https://arxiv.org/abs/1808.05219

Expected Sensitivity



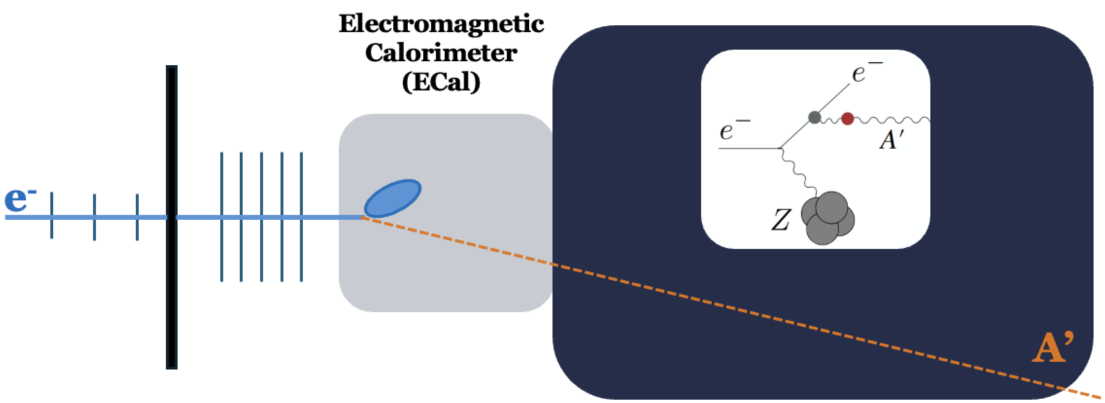
arXiv:2508.11833

Improve current sensitivity by several order of magnitude at low mass.

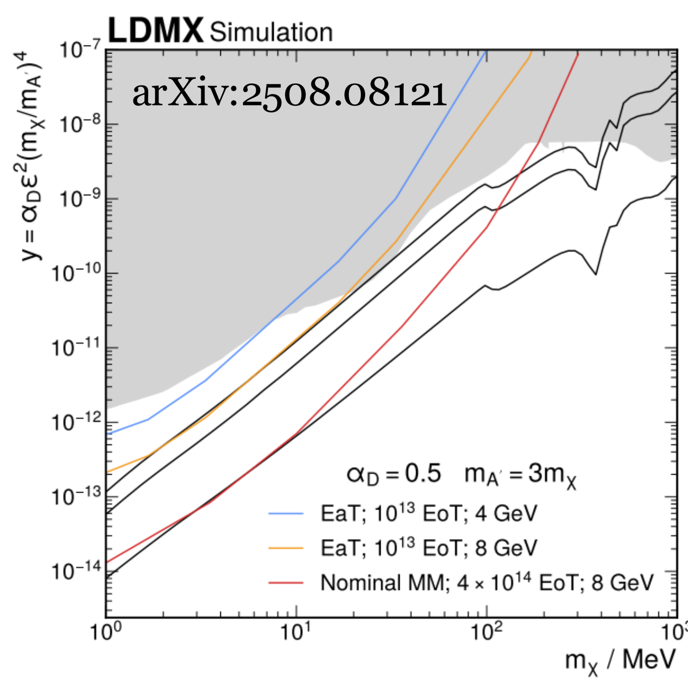
LDMX can also explore several complementary channels!

Electromagnetic Calorimeter as Target

- LDMX can search for DM beyond the missing momentum channel
- Early-run ECal-as-Target (EaT). Look for missing energy in ECal from dark brem at ECal front face

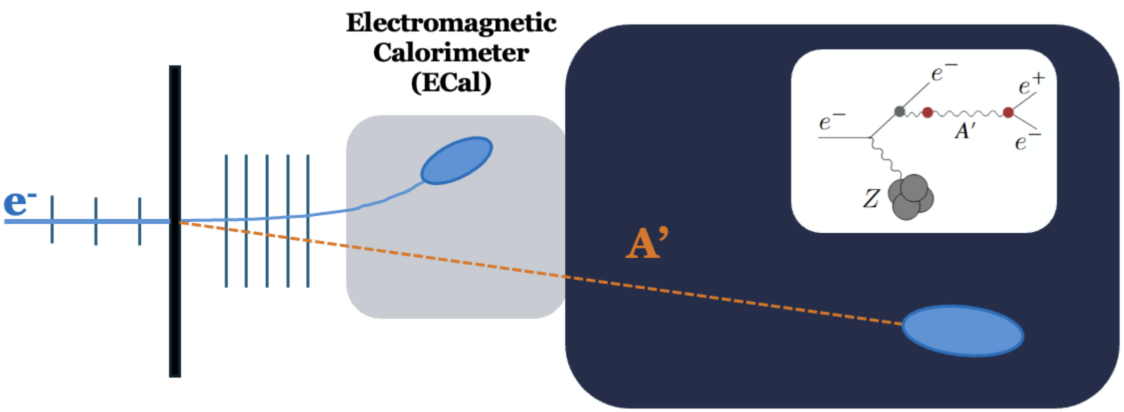


Allows LDMX to collect electrons-on-target while recoil tracker is still being commissioned and make use of electrons which do not interact in the target.

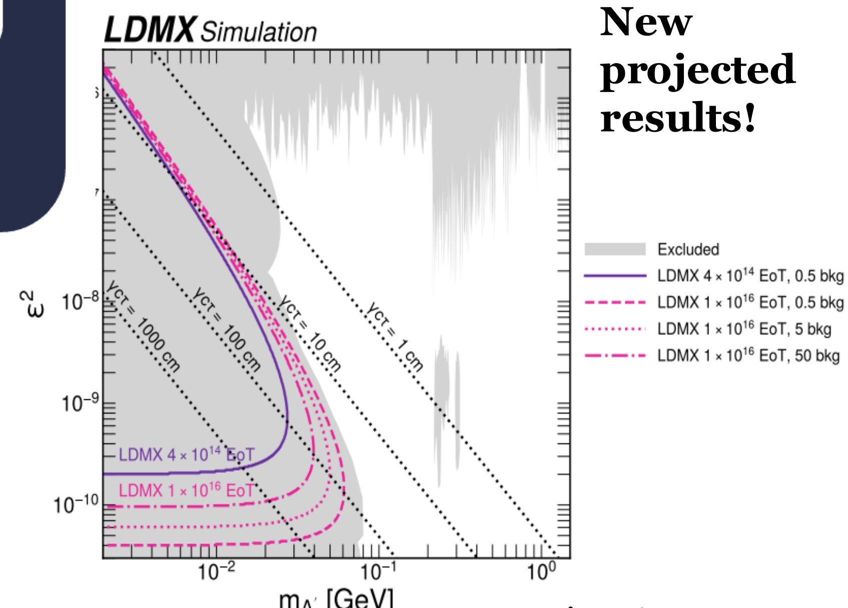


Visible A's

- We can also consider an alternative signal channel, where **$2m_{DM} > m_{A'} > 2m_e$**
- This allows the A' to decay **visibly into an electron-positron pair.** "Long-Lived-Particle" (LLP)
- New signal profile → <u>Soft recoil electron in ECal, displaced EM shower in HCal</u>



EaT boosts luminosity of missing momentum search, LLPs search expands LDMX's reach into entirely new thermal dark matter models.



New projected results!

arXiv:2604.14359

Visible ALPs

- We can also consider an alternative signal channel, where $\mathbf{2m_{DM} > m_{A'} > 2m_e}$
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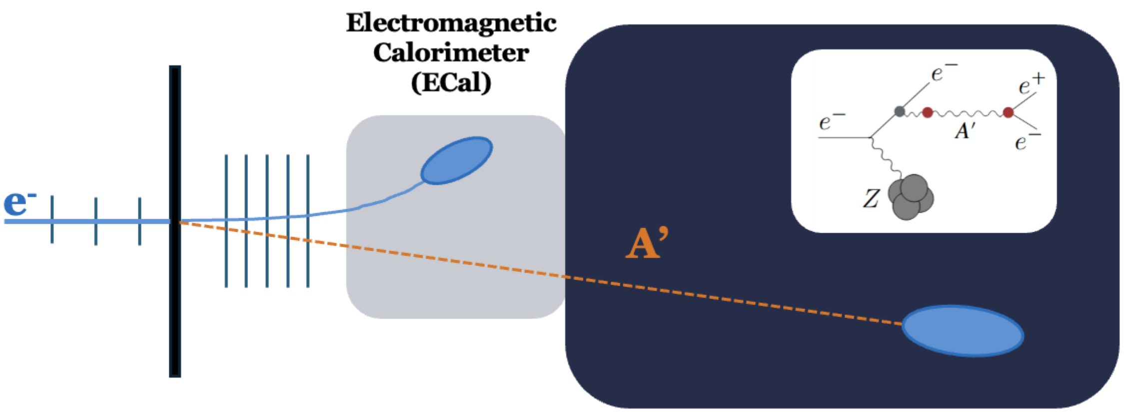
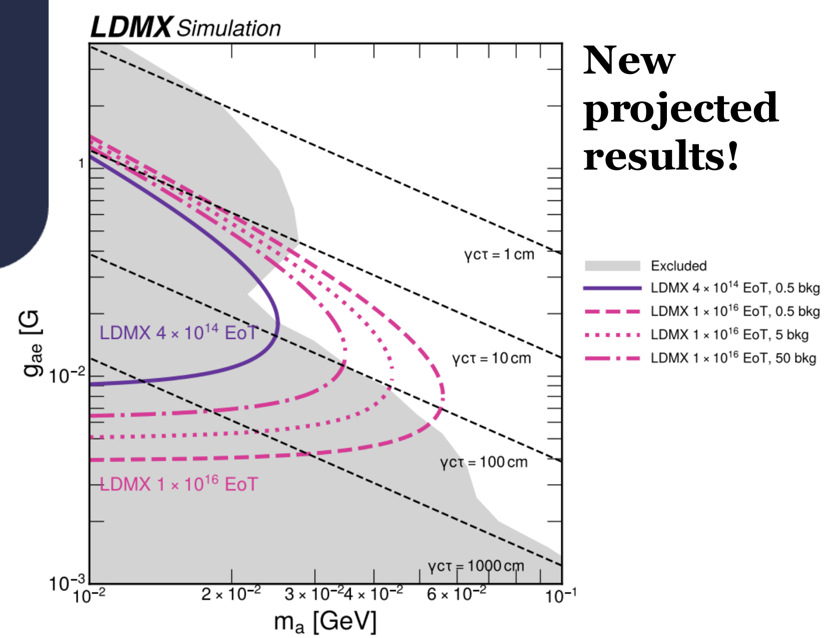
- New signal profile → <u>Soft recoil electron in ECal, displaced EM shower in HCal</u>





New projected results!

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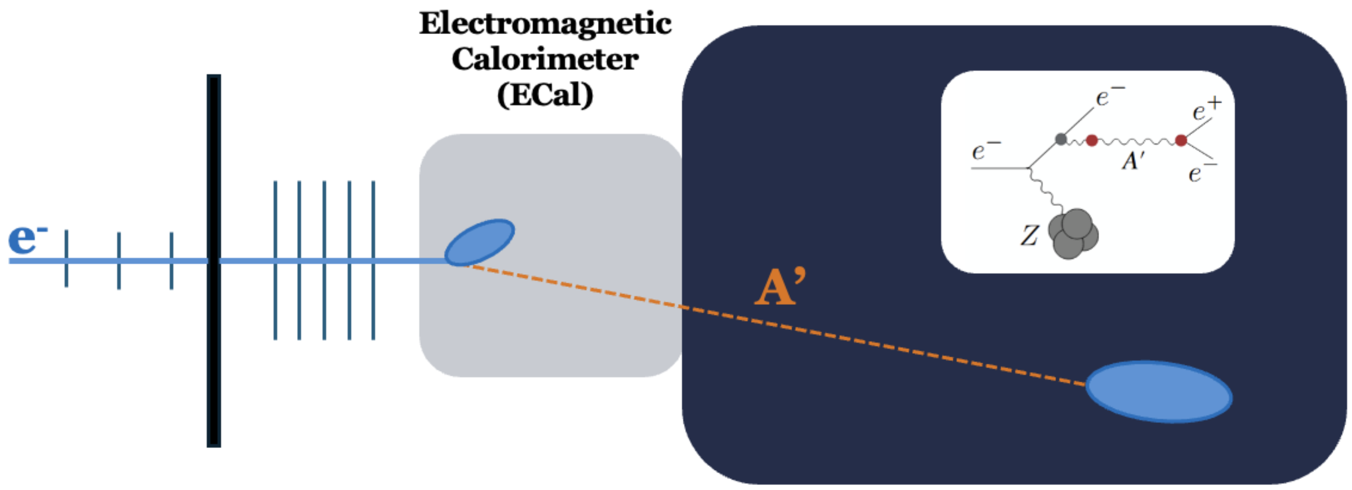
Ecal-as-target with visible LLPs

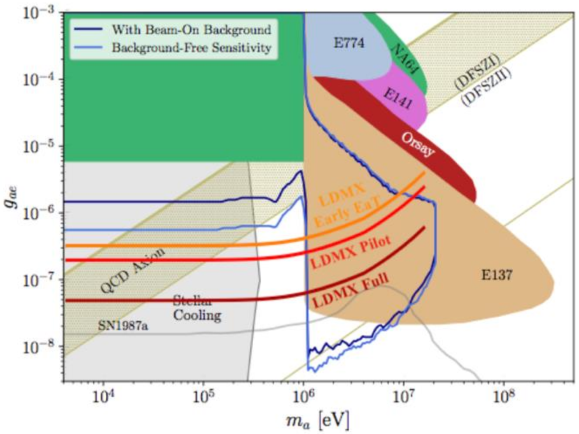


- Search for long-lived particles produced in the ECAL.
- Can increase sensitivity to both A' and ALP:
  - Signal increase: additional DM produced in ECAL
  - Improve sensitivity to higher coupling strength. (shorter decay lengths)

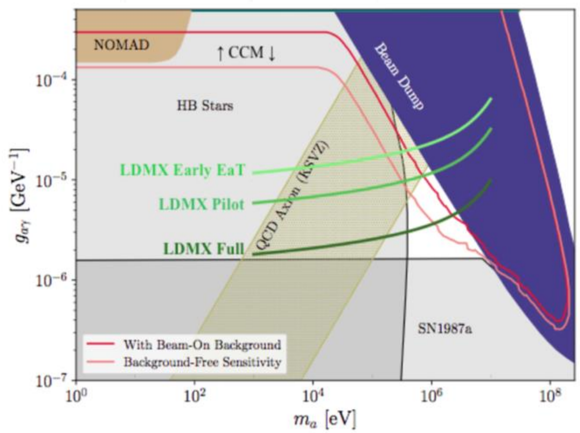
Currently being explored..

Other LDMX Opportunities

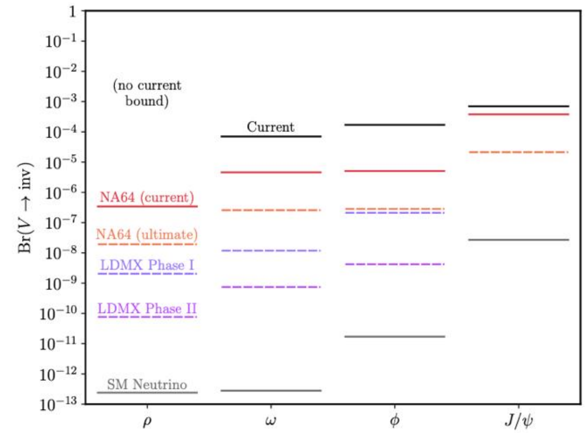
Sensitivity to QCD axions & ALPs via electron coupling



Sensitivity to QCD axions & ALPs via photon coupling



Sensitivity to fully-invisible decays of vector mesons



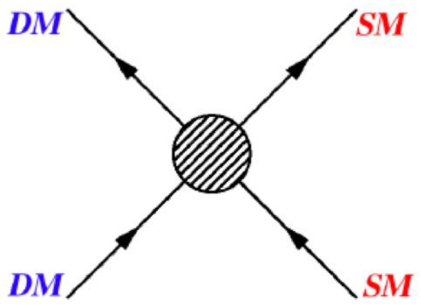
arXiv:2508.11833

Schuster, Toro & Zhou
Phys. Rev. D 105, 035306

- LDMX can carry out electron-nucleua scattering measurements to reduce modeling uncertainties for the neutrino physics program (DUNE).
- Beyond the dark photon model, missing momentum signature is sensitve to:
  - Spin-1 DM
  - ALPs
  - Milli-charged particles
  - …

Summary

- **LDMX, as designed, will improve the search sensitivity to sub-GeV dark matter by several orders-of-magnitude over existing limits.**
- Design report posted summer 2025: 2508.11833
- The experiment is designed and could be built very quickly. (less than 3 years)
- Working with DOE to establish funding profile in times of challenging financial constraints.



Thank you

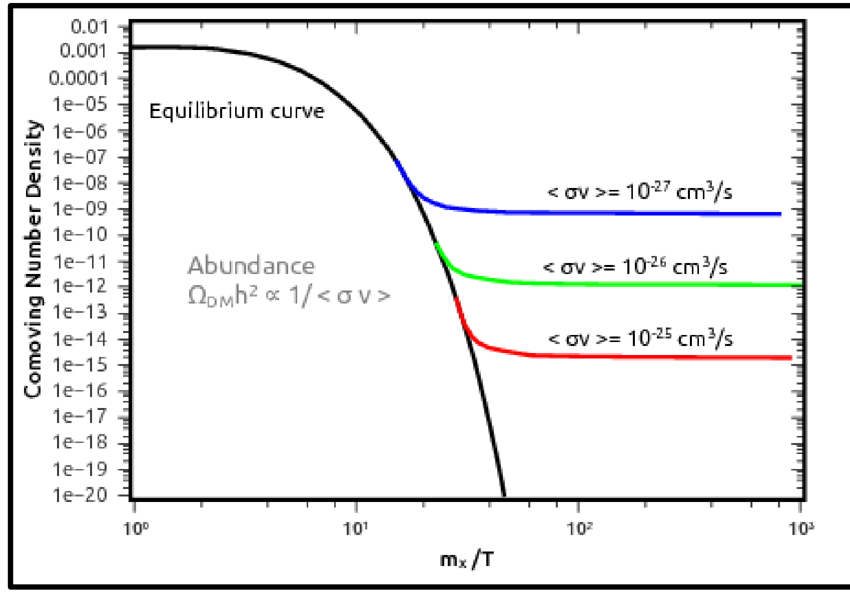
Bibliography

- LDMX concept: https://arxiv.org/abs/1808.05219
- Dark Matter, Millicharges, Axion and Scalar Particles, Gauge Bosons, and Other New Physics with LDMX: https://doi.org/10.1103/PhysRevD.99.075001
- A high efficiency photon veto for the Light Dark Matter eXperiment (4 GeV e- beam): https://doi.org/10.48550/arXiv.1912.05535
- Photon-rejection Power of the Light Dark Matter eXperiment in an 8 GeV Beam: https://doi.org/10.1007/JHEP12(2023)092
- Sensitivity of an early dark matter search using the electromagnetic calorimeter as a target for the Light Dark Matter eXperiment: https://doi.org/10.1007/JHEP12(2025)150
- Lepton-nucleus cross section measurements for DUNE with the LDMX detector: https://doi.org/10.1103/PhysRevD.101.053004
- Measurement of the LCLS-II dark current using the LDMX Trigger Scintillator Prototype: https://arxiv.org/abs/2601.08090
- Expected Sensitivity of the Light Dark Matter eXperiment to Long-Lived Dark Photons and Axion-Like Particles: https://arxiv.org/abs/2604.14359
- Design report: https://arxiv.org/abs/2508.11833

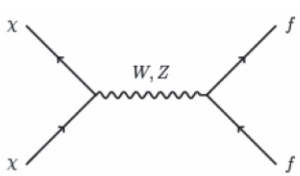
Thermal Dark Matter

Thermal dark matter, originating as a relic in the early Universe, is arguable one of the most compelling paradigms.

- **Simple**: Requires only that the there is a non-gravitational interaction.
- **Generic**: Applies to nearly all models with coupling large enough to detect.
- **Reasonable**: There is cosmological evidence (CMB) for a hot dense thermal phase of the Universe.
- **Predictive**: The DM mass and coupling to the the SM set the abundance. Abundance consistent with observed dark matter provides **experimental target**!



MeV-GeV thermal relic DM requires new, comparably light mediators to achieve required annihilation cross-section for thermal freeze-out.



$$\sigma v \sim \frac{\alpha^2 m_\chi^2}{m_Z^4} \sim 10^{-29}\mathrm{cm}^3\mathrm{s}^{-1}\left(\frac{m_\chi}{\mathrm{GeV}}\right)^2$$

(interaction rate)

Lee/Weinberg '79

Mass determination