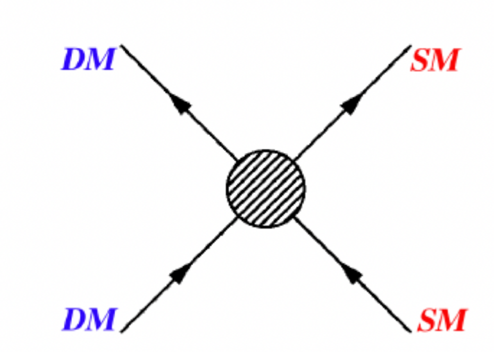
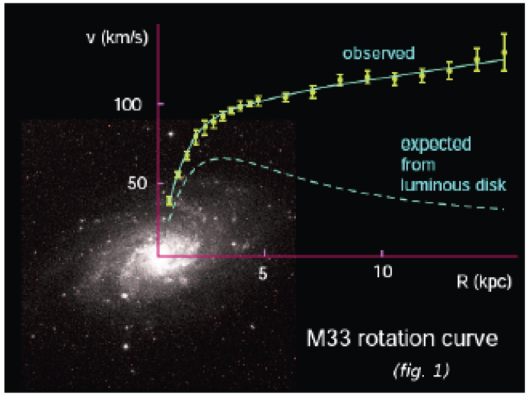
LDMX:
The Light Dark Matter eXperiment

Craig Group
Virginia

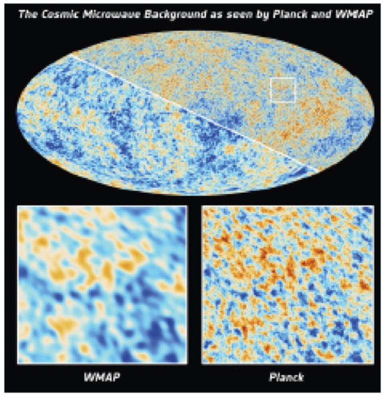


Motivation: Dark Matter is out there!

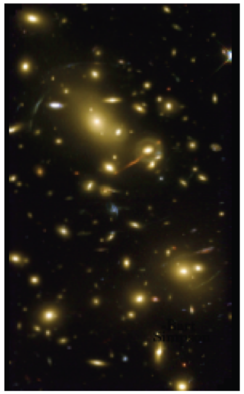
- Much evidence. (see below)
- Awaiting discovery of its particle nature!
- Few clues to its mass scale.
- WIMPs are the primary candidate, but phase space squeezed.
- Many new ideas on lighter (sub-GeV) dark matter.



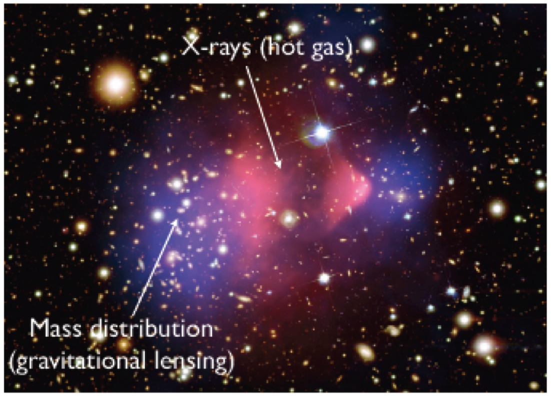
Galaxy Rotation Curves



CMB

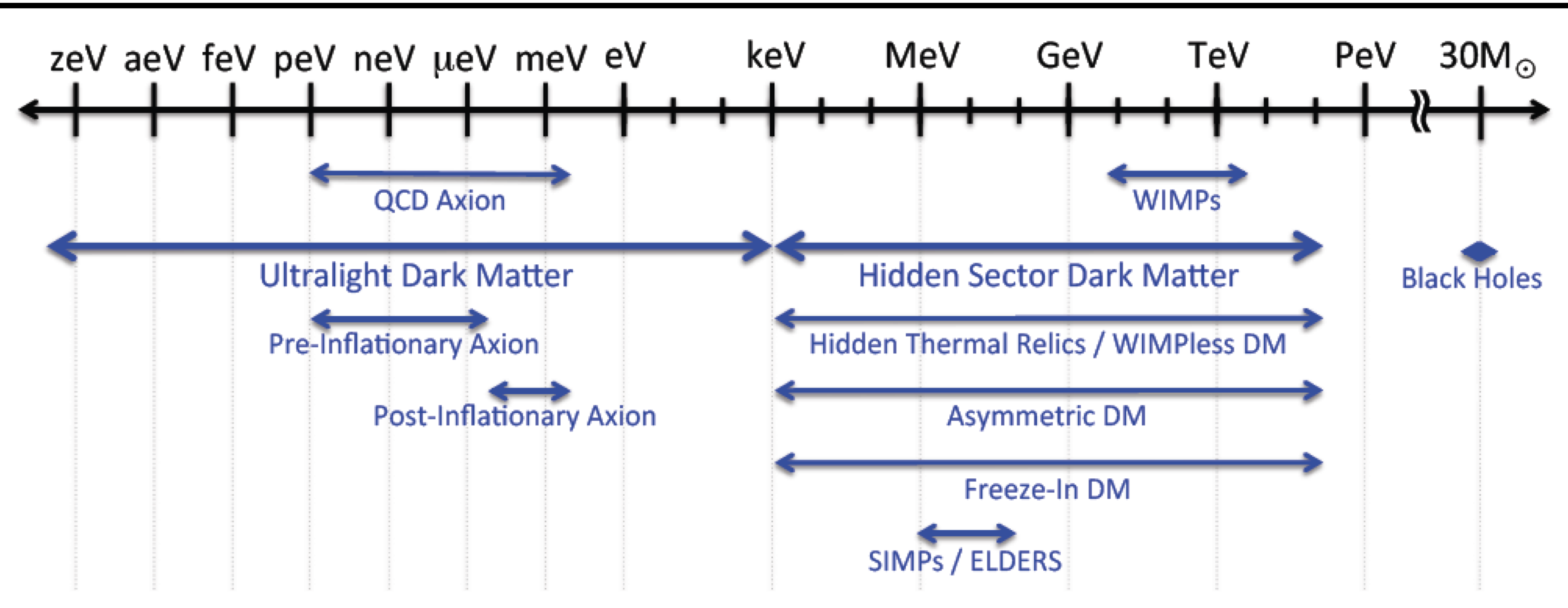


Gravitational Lensing



The Bullet Cluster

Candidates v/s Mass



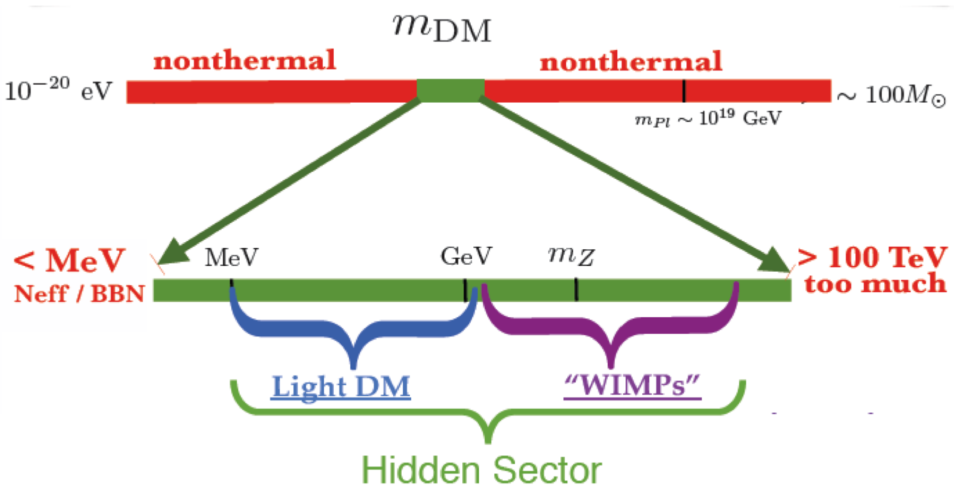
There is no shortage of dark matter candidates!

Until observed, we must explore all options…
but, some mass regions are better motivated than others.

Common assumption: thermal equilibrium

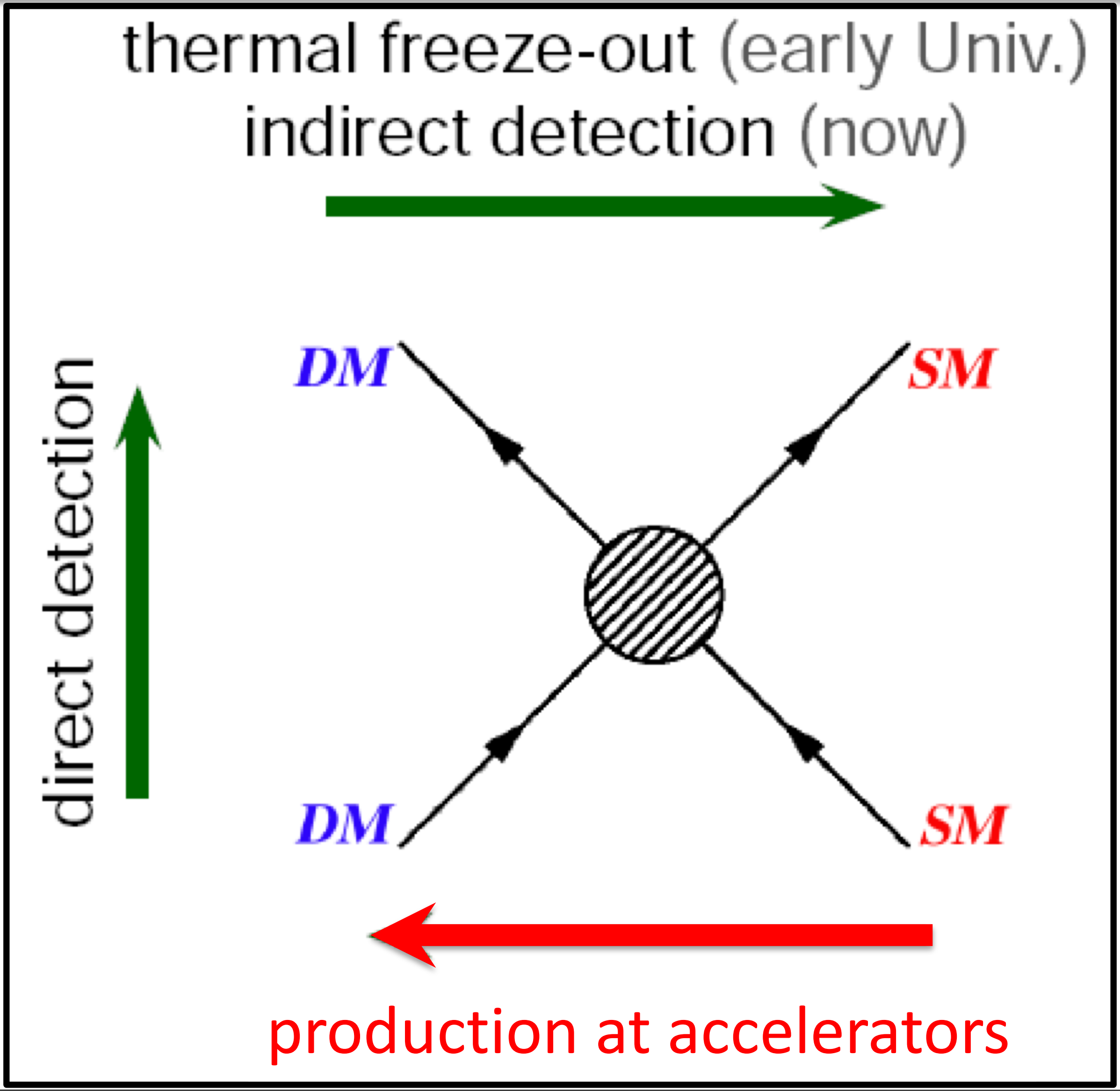
Folding in assumptions about early universe cosmology we can motivate more specific mass scales

Thermal Equilibrium in early Universe narrows the viable mass range



The dark matter mass is not well constrained by experiment!

Searching for Dark Matter



Common assumption: thermal equilibrium

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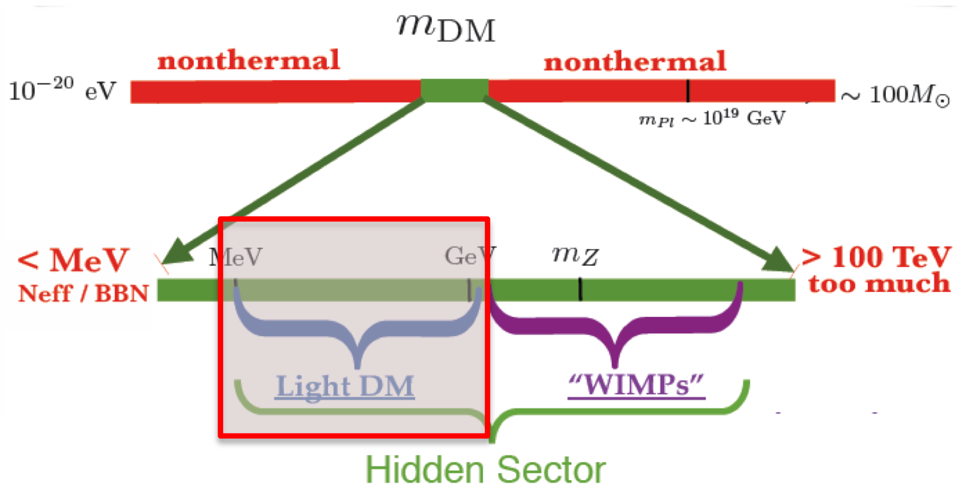
Thermal Equilibrium in early Universe narrows the viable mass range



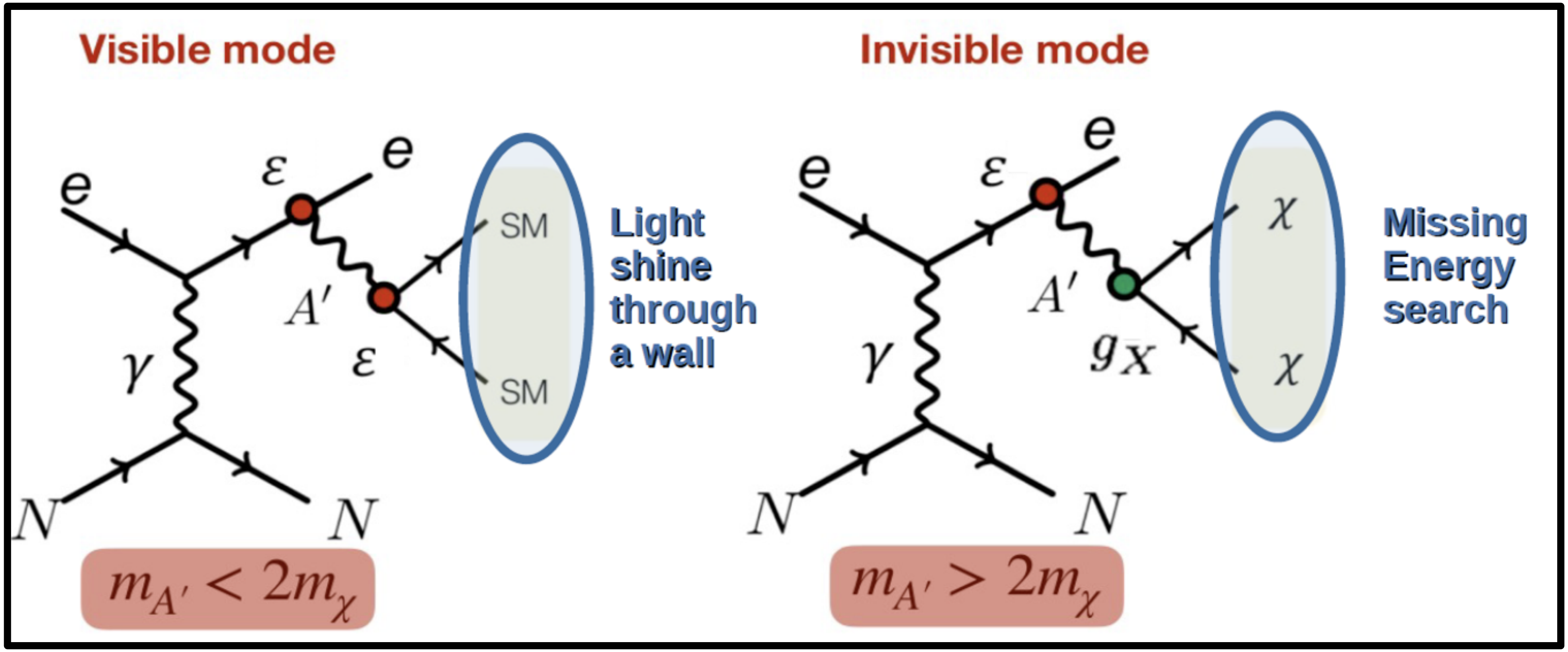
- Explorable with accelerator based DM searches:
  - Collider – WIMP (but becoming constrained)
  - Fixed-target/beam-dump experiments - Light-DM
- Phenomenology of low-mass region [MeV-GeV] thermal DM is quite different from standard WIMP.

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.

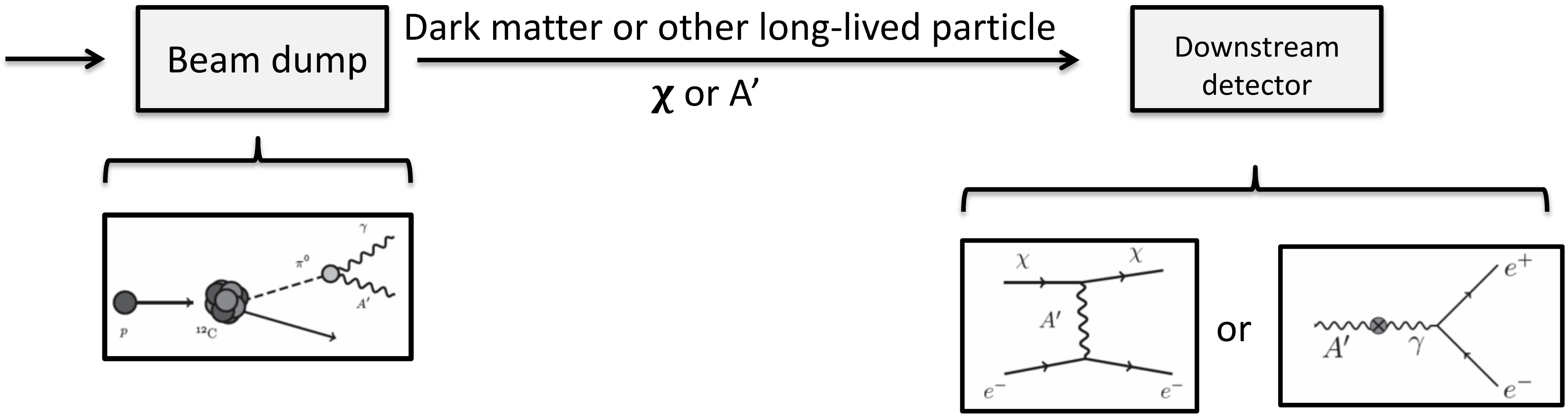
Searching for Dark Photons

- There have been several experiments that use “beam-dump” experiments to search for ”light shining through a wall”.
- Using a missing energy type experiment with the beam dump to probe the dark sector has recently gained favor.



Accelerator-based dark matter

- In the last decade, new ideas for accelerator-based searches for MeV - GeV dark matter.
- There have been a series of beam-dump experiments:

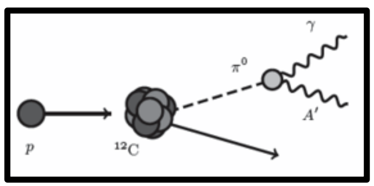


Accelerator-based dark matter

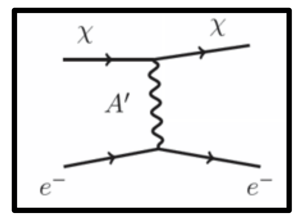
- In the last decade, new ideas for accelerator-based searches for MeV - GeV dark matter.
- There have been a series of <u>beam-dump experiments</u>:

→ Beam dump — Dark matter or other long-lived particle → Downstream detector

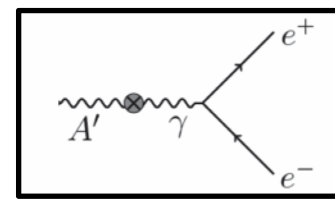
χ or A'



$\propto \varepsilon^2$



or



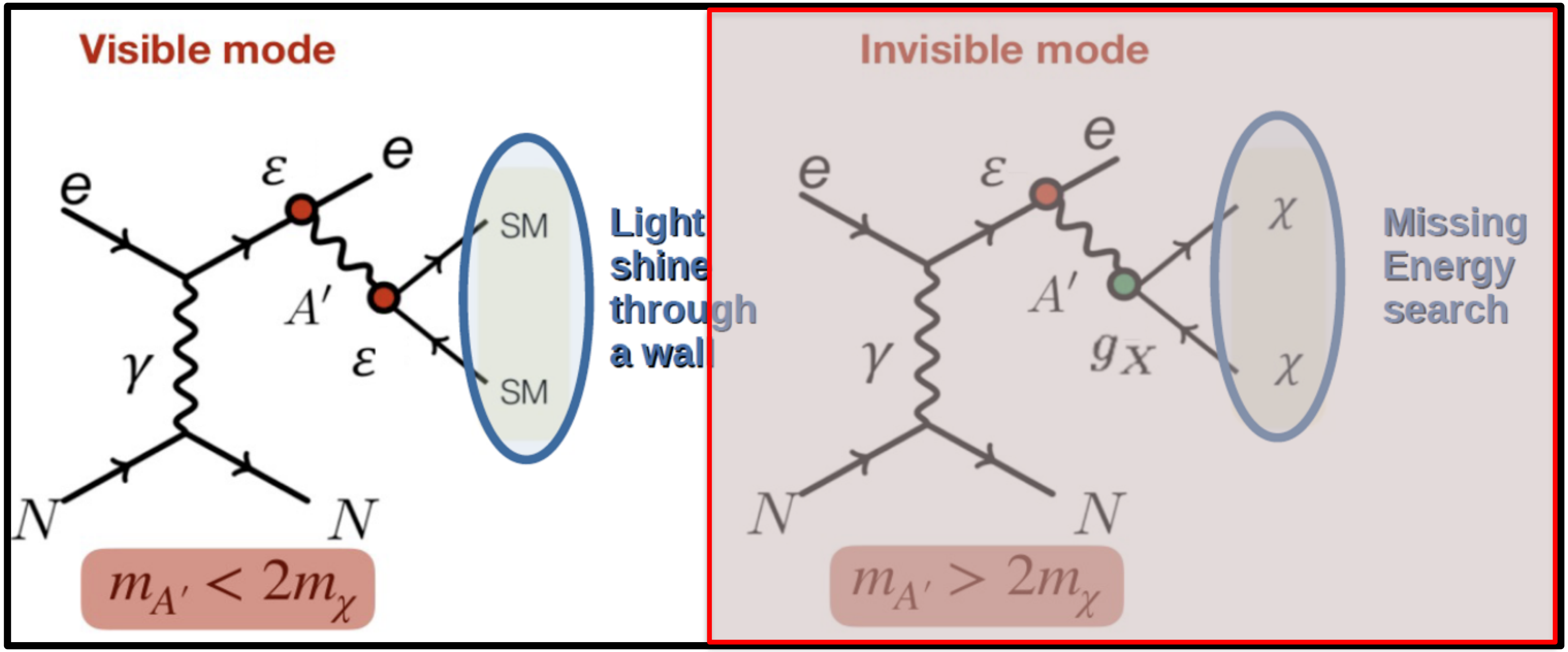
$\propto \varepsilon^2$

For both of these options the signal rate goes as ε^4.
Where ε is small - the mixing strength of the photon-dark photon coupling.

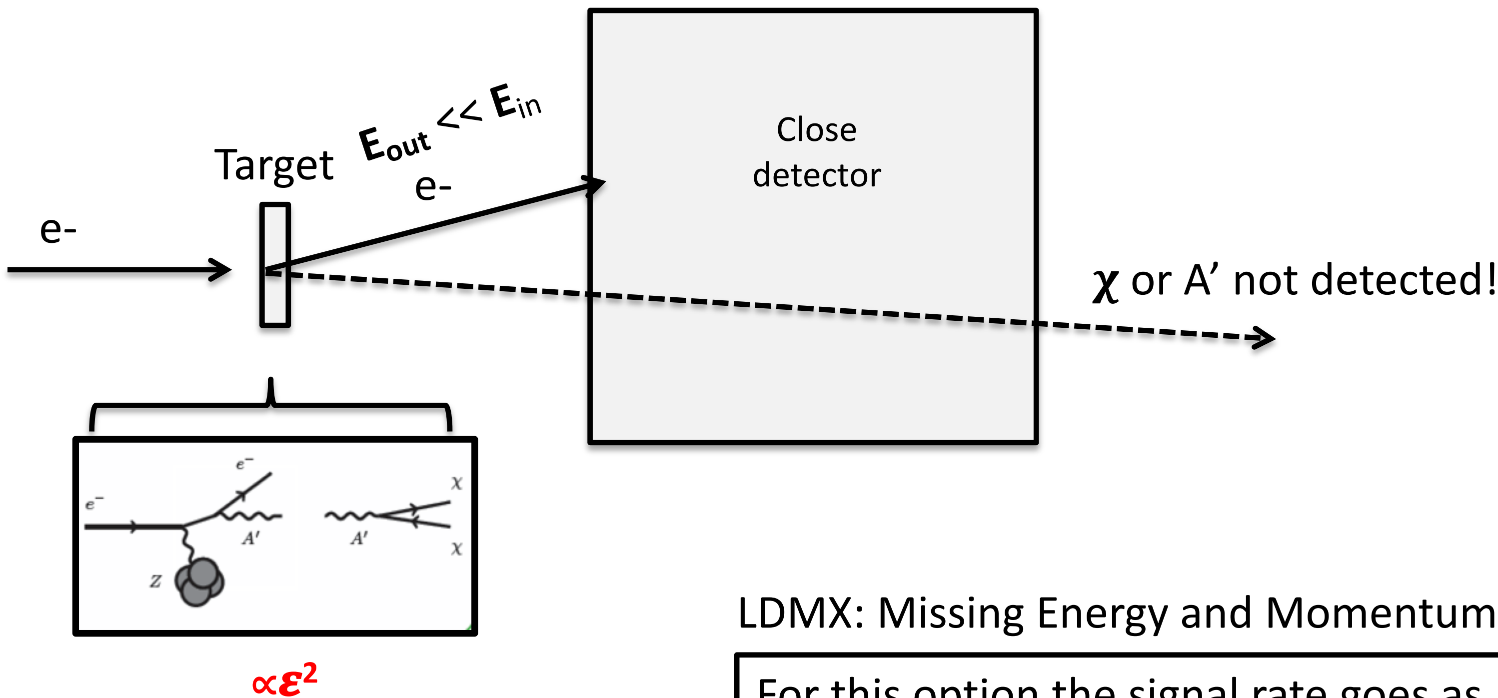
Examples: APEX and HPS at Jefferson Lab

Searching for Dark Photons

- There have been several experiments that use “beam-dump” experiments to search for ”light shining through a wall”.
- Using a missing energy type experiment with the beam dump to probe the dark sector has recently gained favor.



Missing Energy/Momentum Technique

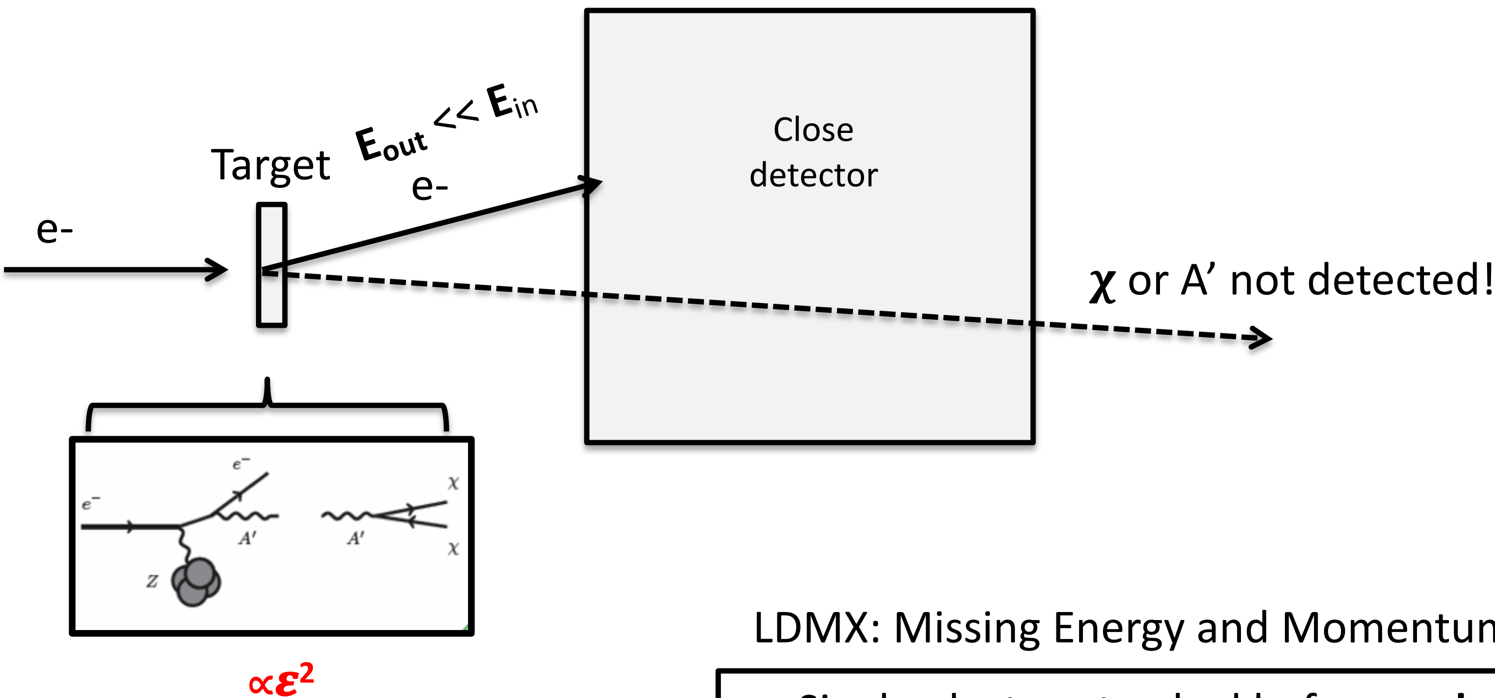


LDMX: Missing Energy and Momentum

For this option the signal rate goes as ε^2 – where ε is the mixing strength of the photon-dark photon coupling.

Higher rate than "light shining through a wall" experiments because you don't get the penalty from detecting the dark-sector particle.

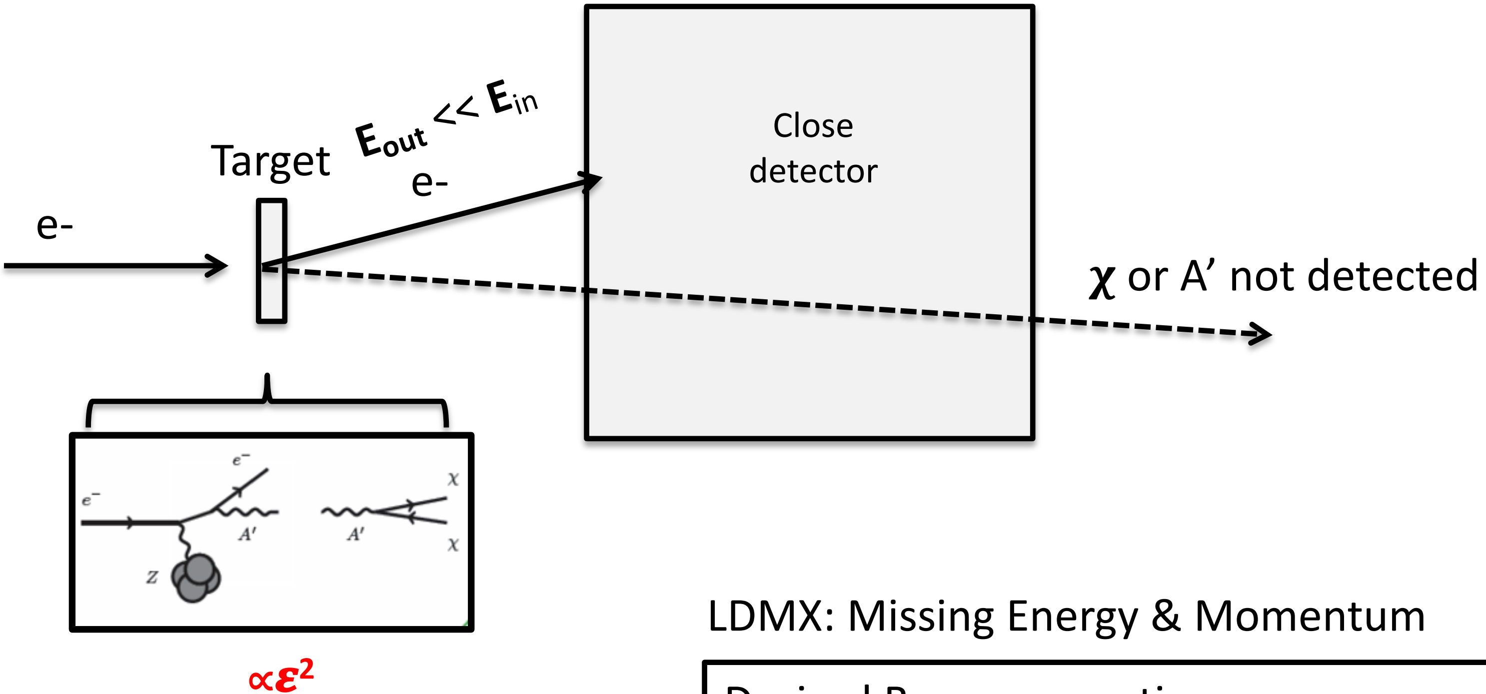
Missing Energy/Momentum Technique



LDMX: Missing Energy and Momentum

- Single electron tracked before **and after target**.
- Electromagnetic calorimeter
  - Measuring the recoil electron energy.
  - Particle ID.
- Hadronic calorimeter to veto primary background – photon bremstraulung.

Missing Energy/Momentum Technique



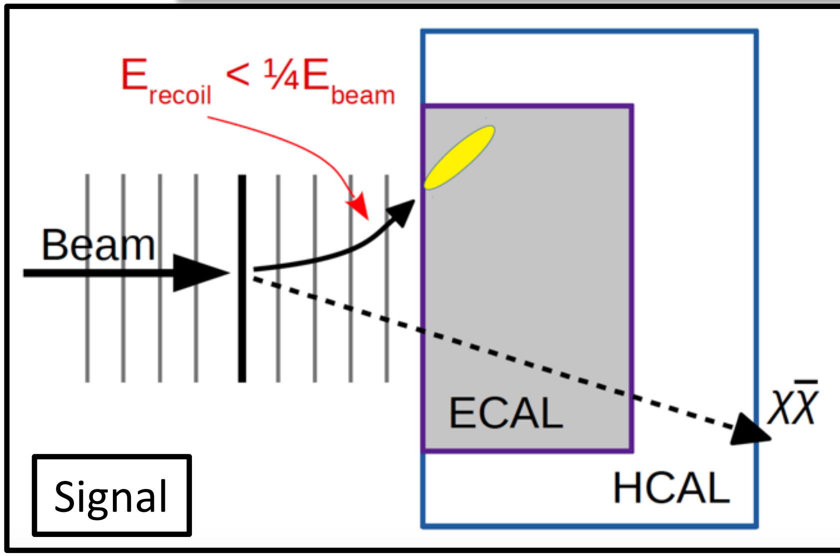
LDMX: Missing Energy & Momentum

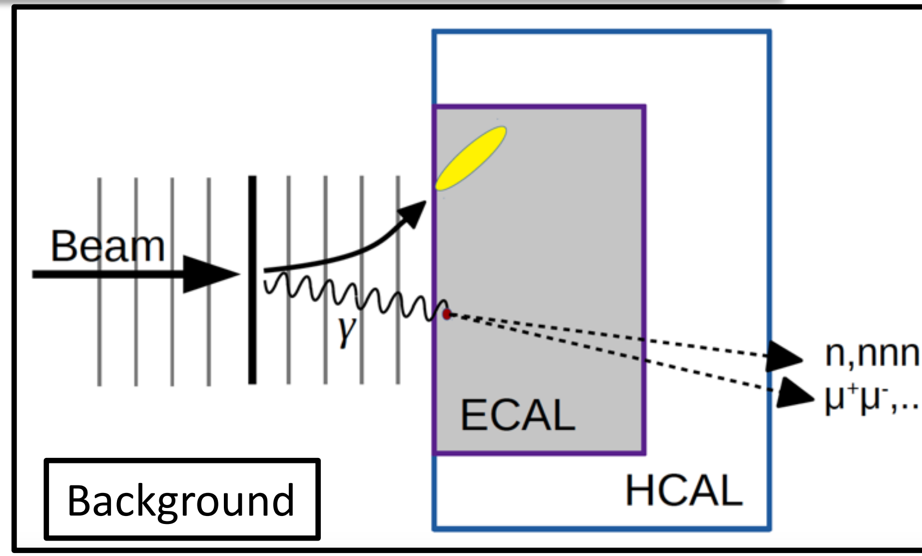
Desired Beam properties:

- **> 10^{14}** electrons at least 4 GeV
- **Few** electrons per bunch (<10)
- Beam with **high duty cycle** (many bunches)
- **Large** beam spot

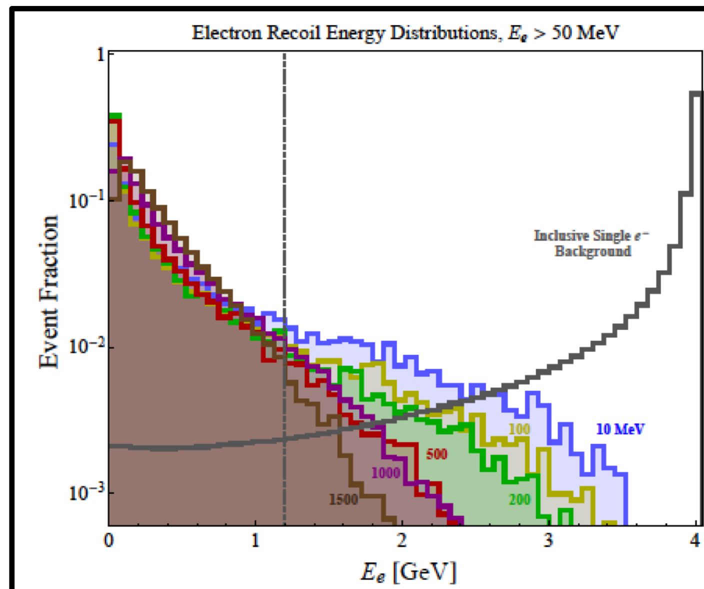
Need to be able to reconstruct **every** electron!

Signal and Primary Background



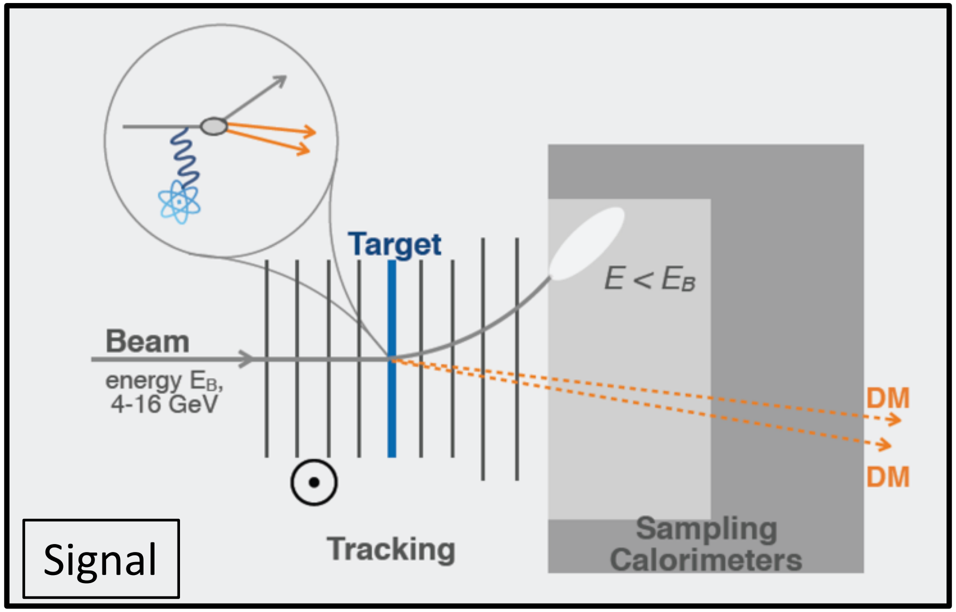


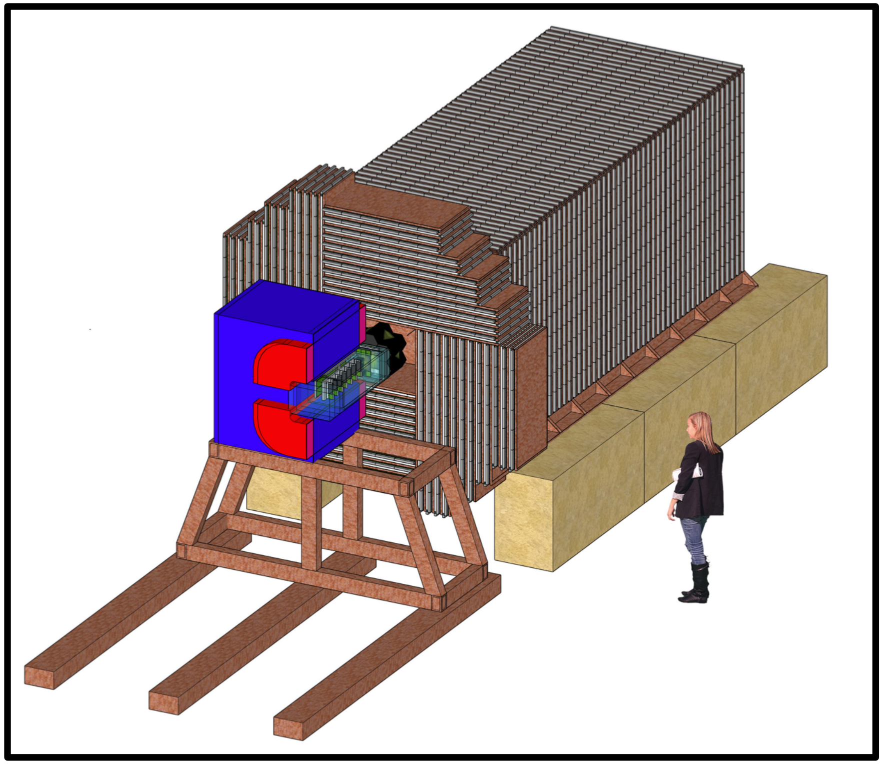
- E_{recoil} very different sig v/s bkg
- A' emitted at low angles and carries away most of the energy of the e-.
- HCAL for veto brem+photo-nuclear interactions:
  - Neutrons
  - Taus
  - Muons
  - …



LDMX Apparatus

LDMX Design Paper:
https://arxiv.org/abs/1808.05219





Smallish detector/experiment.

Small Collaboration:

LDMX Apparatus

LDMX Design Paper:
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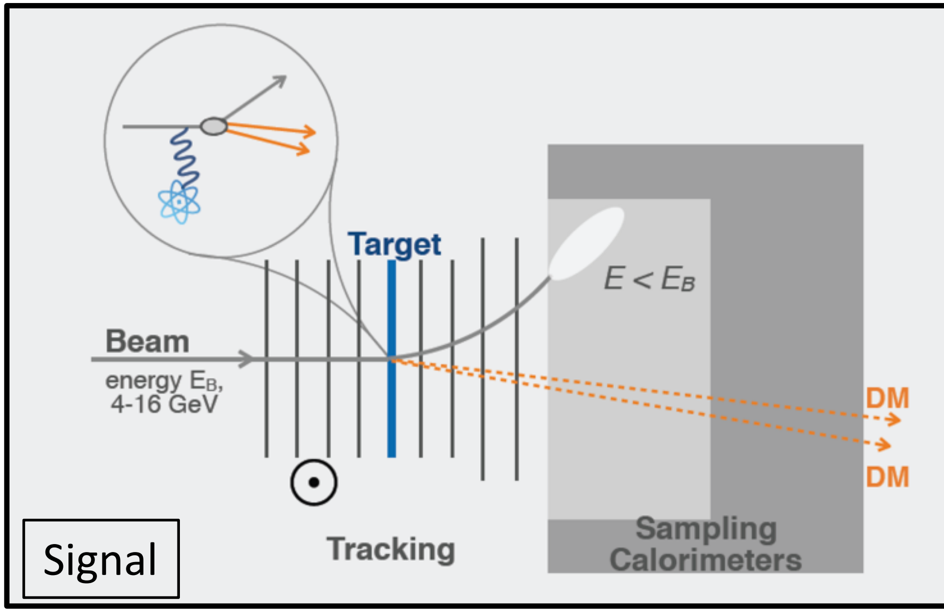
First LDMX Prototype!

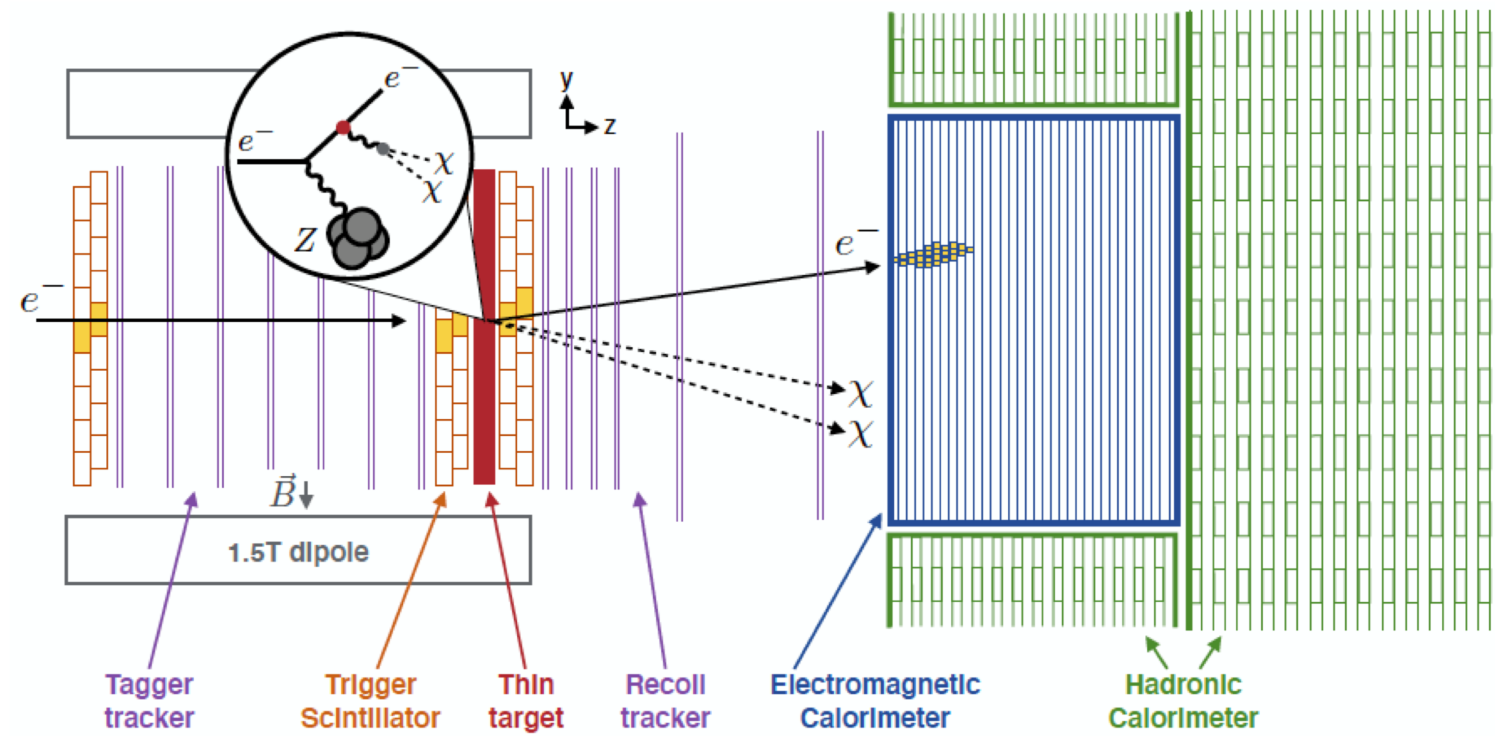


Smallish detector/experiment.

Small Collaboration:

Detector details

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

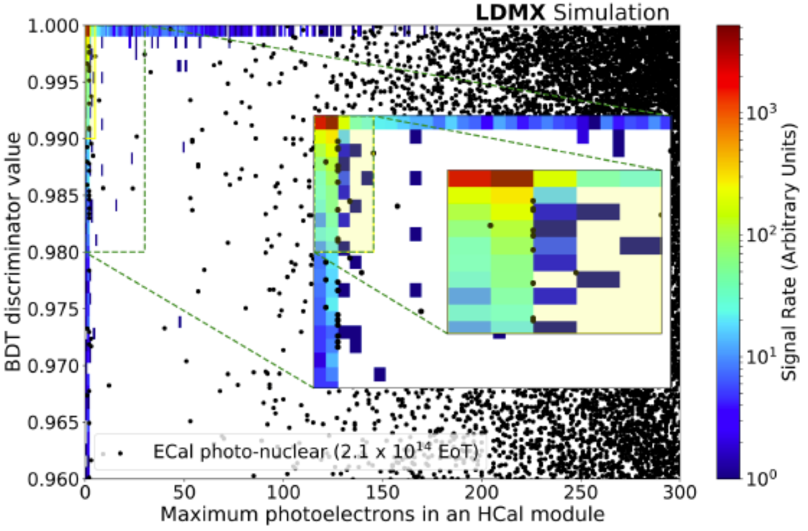
Draws on design of the CMS SiW HGCal (fast, radiation hard, dense, with high granularity for MIP tracking)

Hadronic Calorimeter

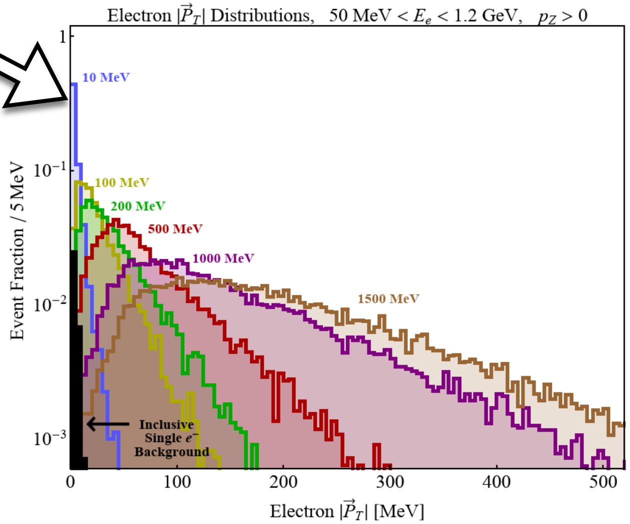
Inspired by Mu2e Cosmic Ray Veto (plastic scintillator with steel absorber: ~16 interactions lengths, optimized for veto of neutral hadrons)

Analysis Strategy

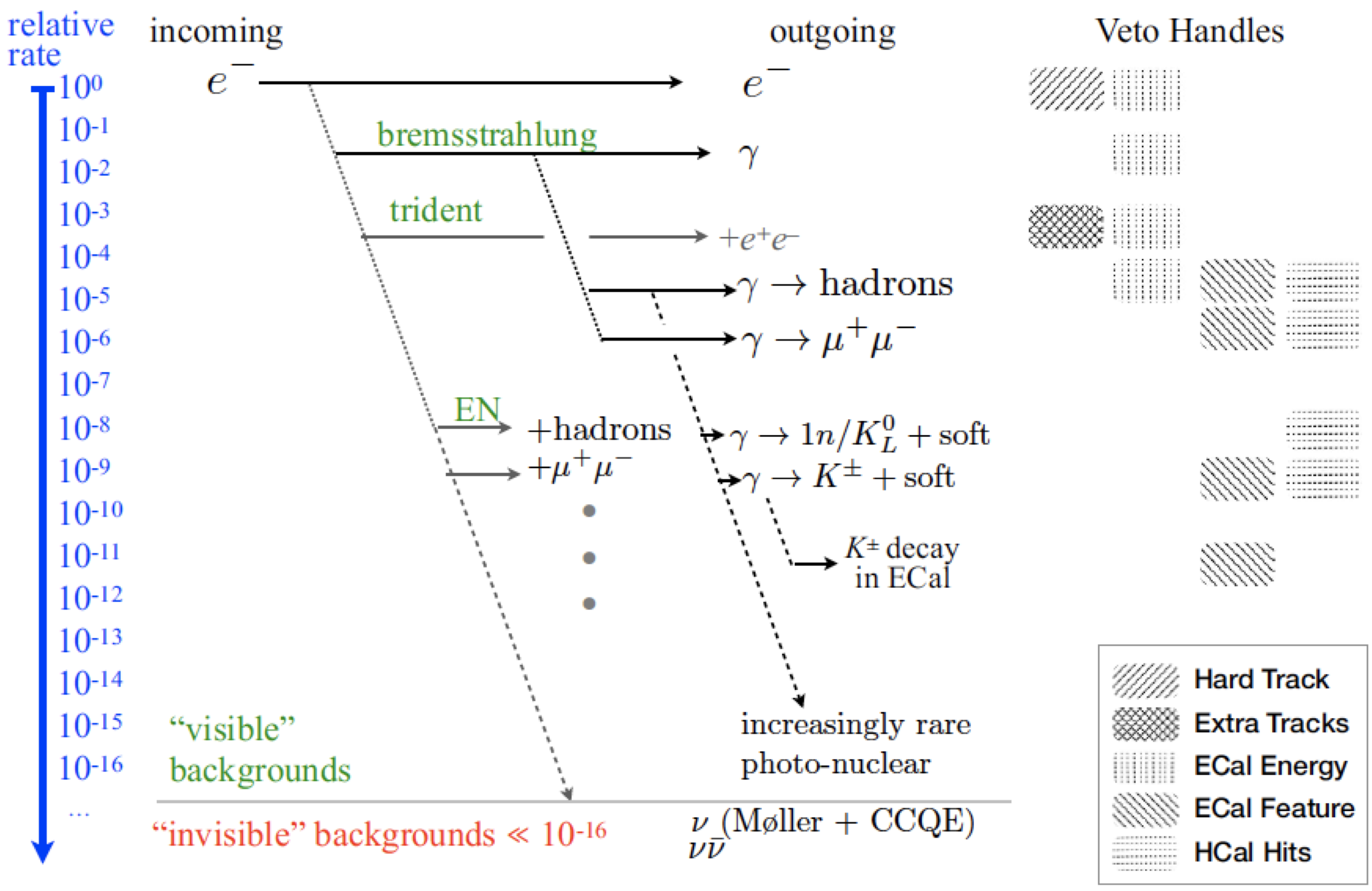
- Trigger on missing energy.
- Combine ECal features into a Boosted Decision Tree (BDT) for Ecal veto.
- Veto on activity in Hcal.
- Additional vetoes on activity in trackers/ECal front layer.
- Save e- P_T to certify potential signal events and to estimate the dark photon mass.



At 4 GeV **close to 0 background!**	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



Primary Backgrounds



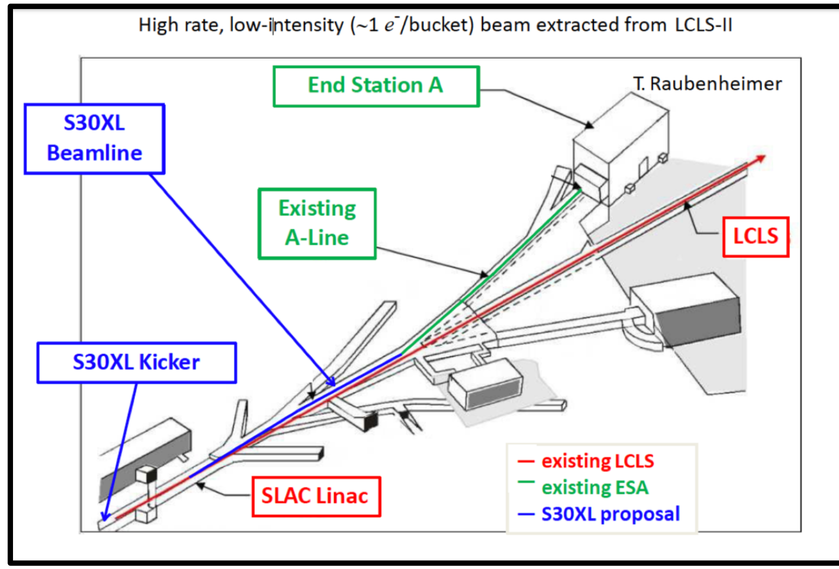
4 GeV Beam from LCLS-II

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 xrays using an electron beam!

→ 4-GeV superconducting (SC) linac (with a possibility of 8-GeV upgrade) can be used parasitically for other experiments.

Transfer line to A-line and End Station A



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.

Beam options

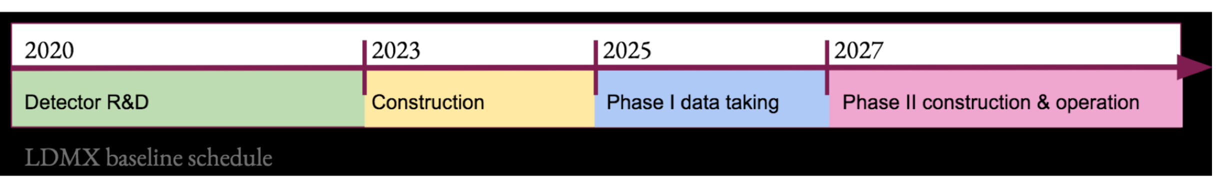
Location:

- LCLS-II at SLAC (most likely for first phase)
  - Requires dedicated transfer line (under construction)
  - 4 GeV or maximum 8 GeV, parasitic
- eSPS at CERN (later stage?)
  - e- back in CERN accelerators, next step for Xband linac developed for CLIC, accelerator R&D
  - 3.5 - 16 GeV, flexible beam parameters

- Experiment will likely be phased – improve current limits by ~100 with 4 GeV beam. Phase 1 - 4×10^{14} tagged electrons on target
  - At least another x10 looks possible **with higher energy** and $\sim 10^{16}$ e-.
    - Reduces a difficult background.
    - Large increase in production for higher mass hypotheses.

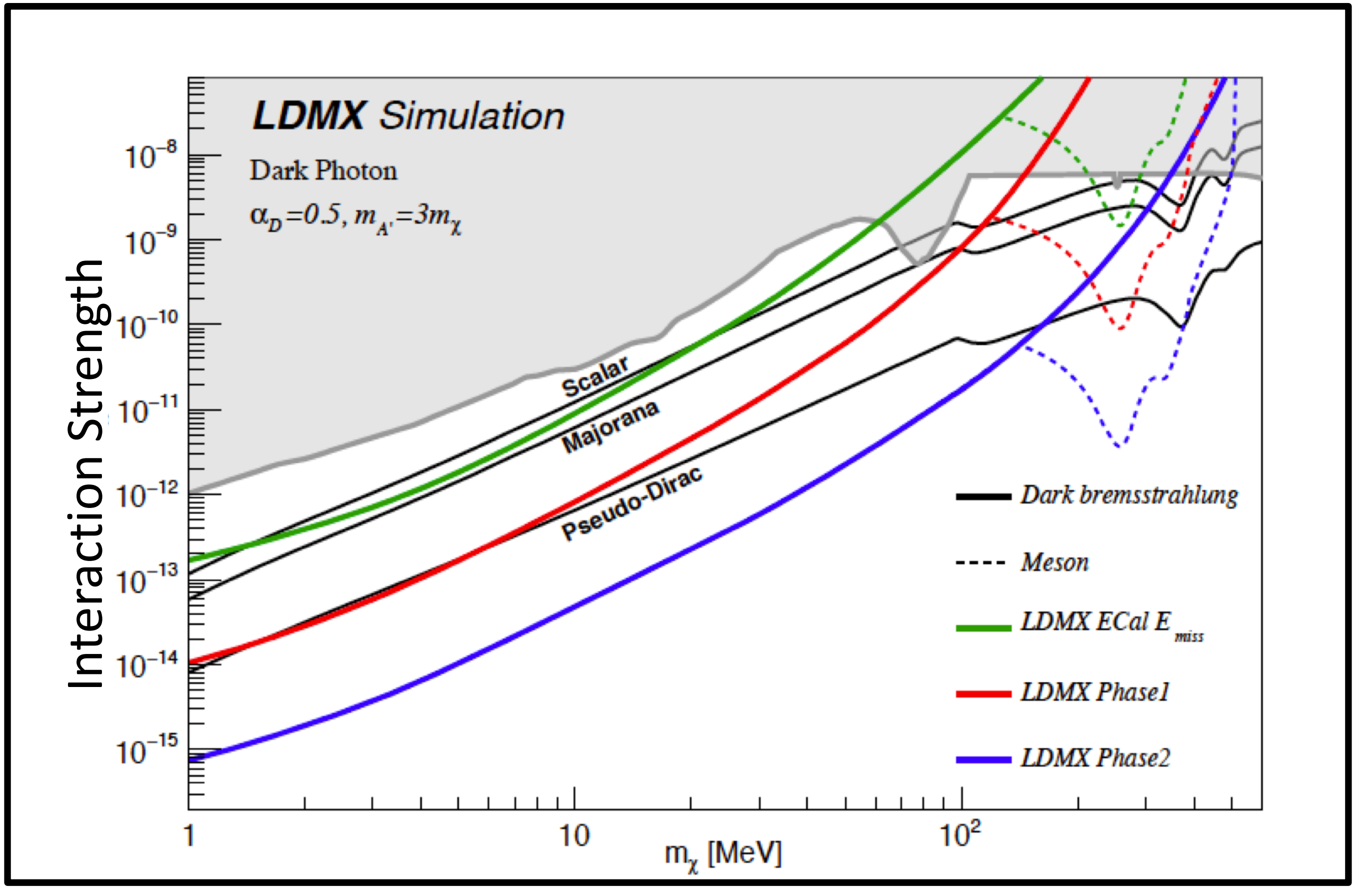
Reminder:

Desired Beam properties:
- **> 10^{14}** electrons at least 4 GeV
- Beam with **high-duty cycle**
- **Few** electrons per bunch (<10)
- **Large** beam spot



LDMX baseline schedule

Extended Sensitivity



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

With more electrons on target and a higher energy beam, LDMX can probe all thermal targets up to a few hundred MeV. https://arxiv.org/abs/1808.05219

Summary

- **LDMX will improve the search sensitivity to sub-GeV dark matter by several orders-of-magnitude over existing limits.**
- Technically, the experiment is designed and we could build it very quickly. <~3 years.
- Working with DOE to establish funding profile.

Hoping for major discoveries

in the mid 2020's!

Thank you

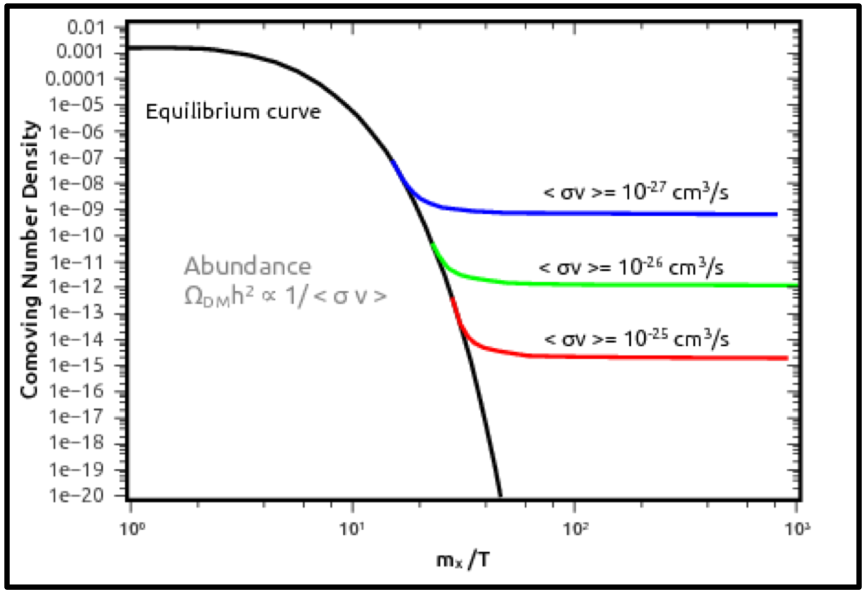
Bibliography

- LDMX concept: https://arxiv.org/abs/1808.05219
- **2020 JHEP: A high efficiency photon veto for the Light Dark Matter eXperiment**
- A. Berlin, N. Blinov, G. Krnjaic, P. Schuster, and N. Toro (2018), https://arxiv.org/abs/1807.01730. "**Dark Matter, Millicharges, Axion and Scalar Particles, Gauge Bosons, and Other New Physics with LDMX**"
- **Snowmass contribution: Current Status and Future Prospects for the Light Dark Matter eXperiment; https://arxiv.org/abs/2203.08192**

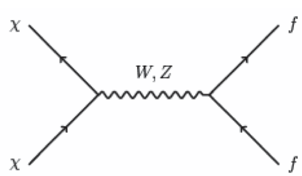
Thermal Dark Matter

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.

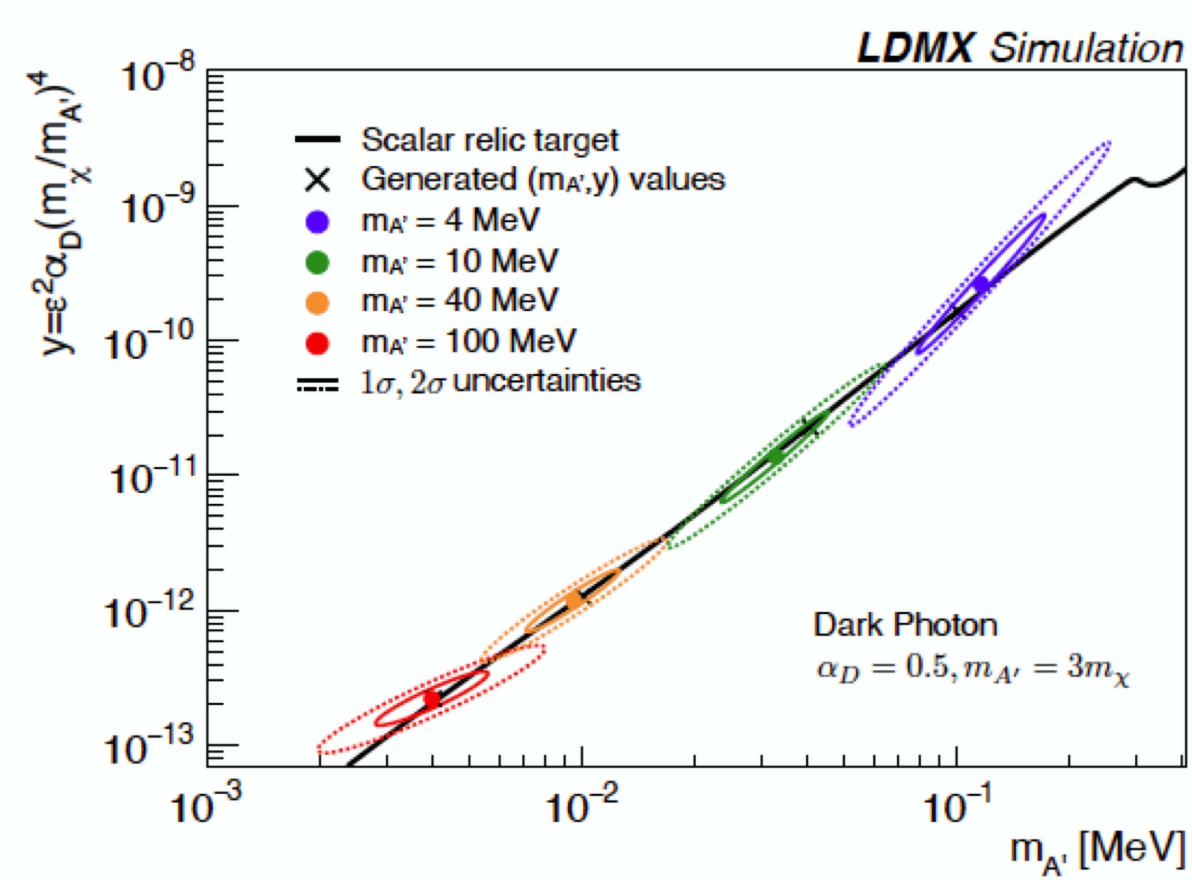


$$\sigma v \sim \frac{\alpha^2 m_\chi^2}{m_Z^4} \sim 10^{-29}\mathrm{cm}^3\mathrm{s}^{-1}\left(\frac{m_\chi}{\mathrm{GeV}}\right)^2$$

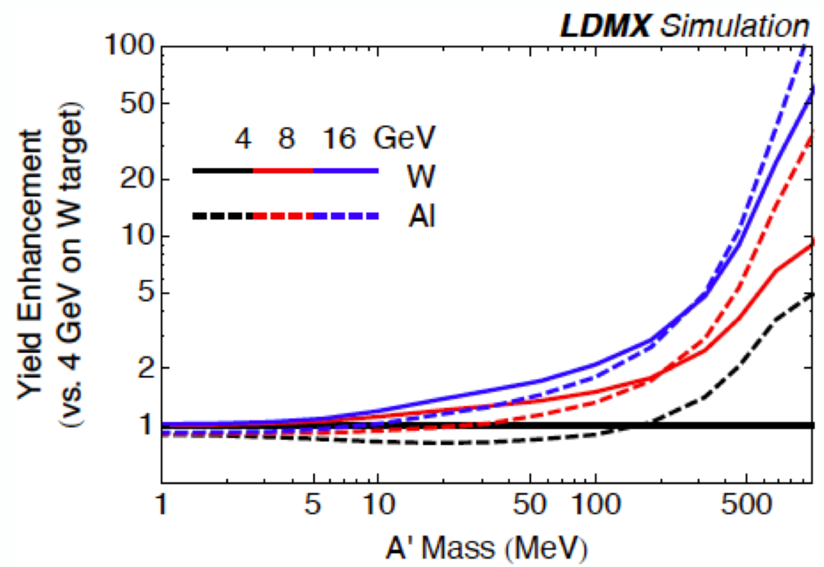
(interaction rate)

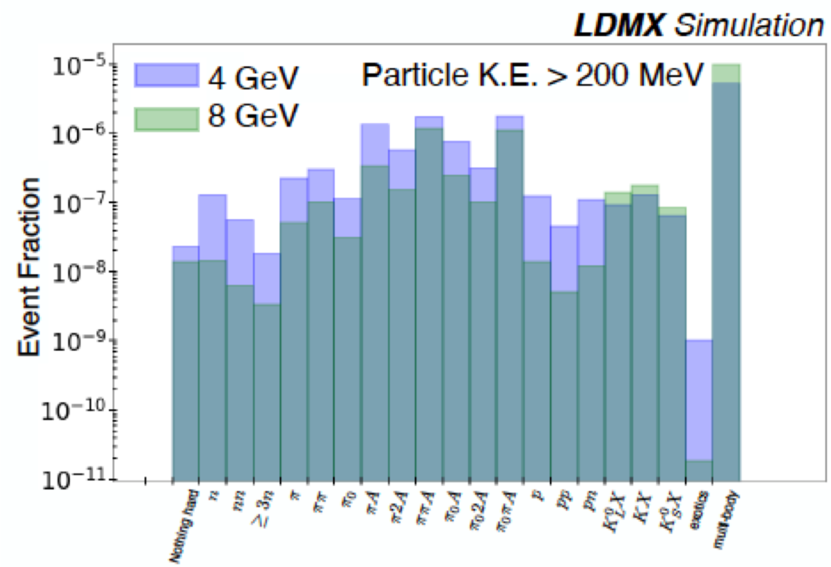
Lee/Weinberg '79

Mass determination

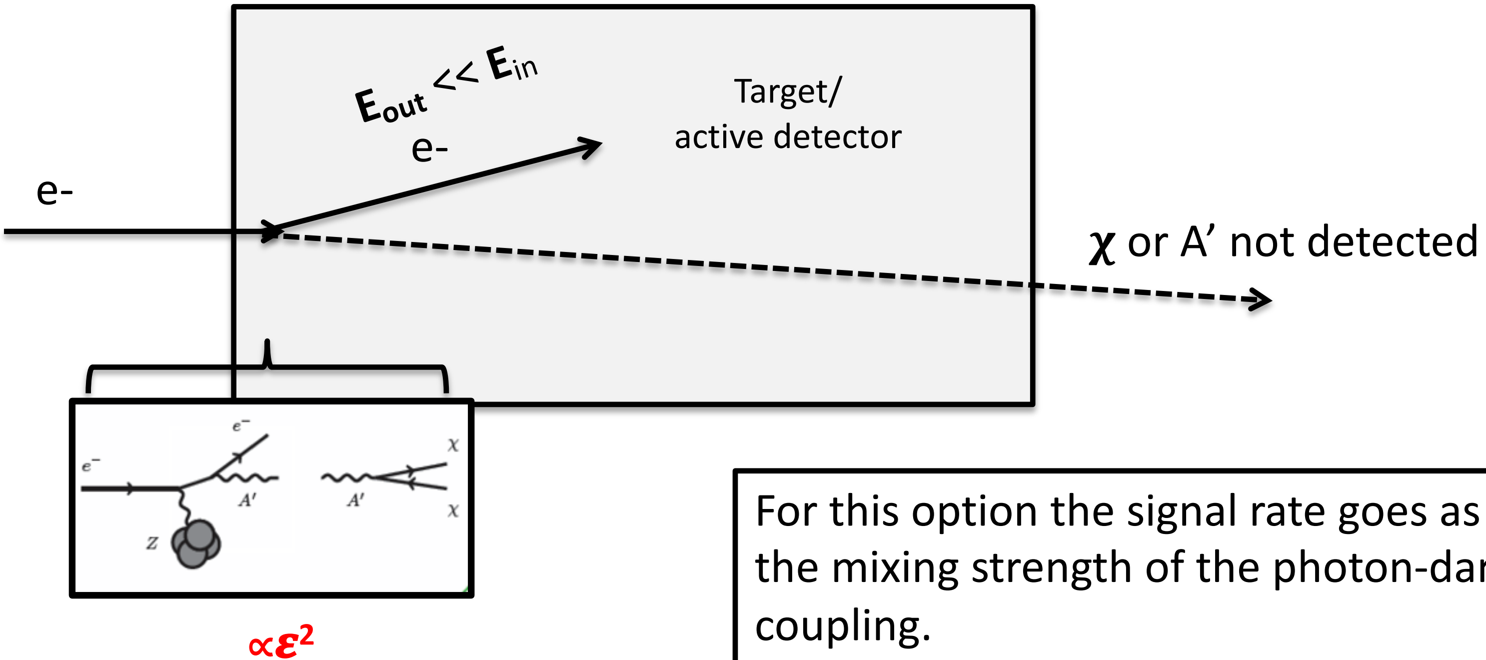


Higher energy is good!





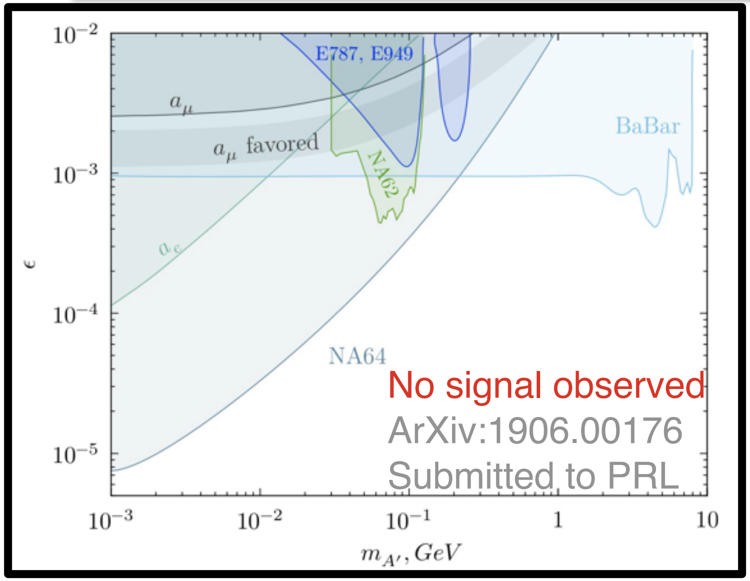
ECal as Target



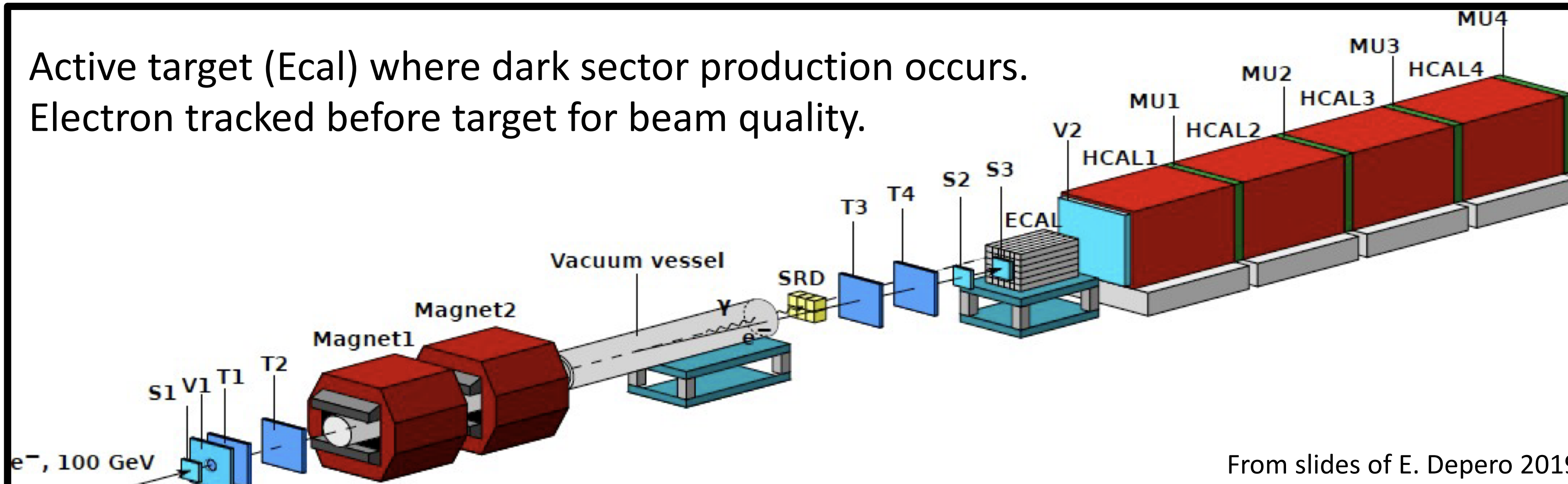
For this option the signal rate goes as ε^2 – where ε is the mixing strength of the photon-dark photon coupling.

Higher rate than "light shining through a wall" experiments because you don't get the penalty from detecting the dark-sector particle.

NA64 at CERN SPS



Active target (Ecal) where dark sector production occurs.
Electron tracked before target for beam quality.



From slides of E. Depero 2019