LDMX: The Light Dark Matter eXperiment

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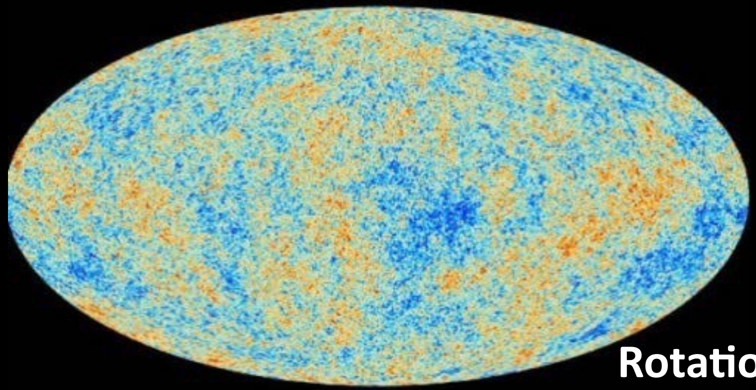
Dark Matter (DM): Evidence

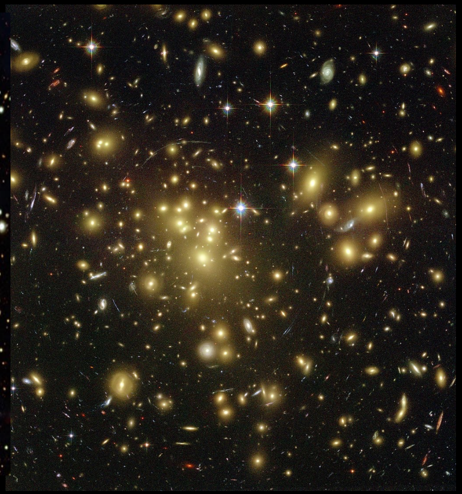
- Much observational evidence for existence of Dark Matter (DM).
- Lambda CDM: 5% Ordinary matter, 27% Dark Matter, 68% Dark Energy.
- But the nature and mass scale of this matter remains unknown.

Cosmic Microwave Background

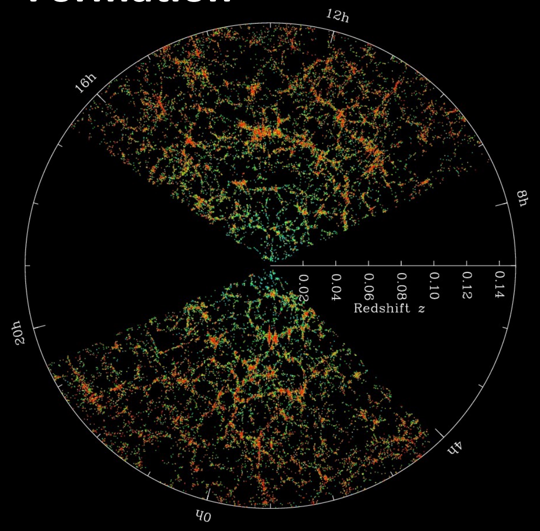


Bullet Cluster

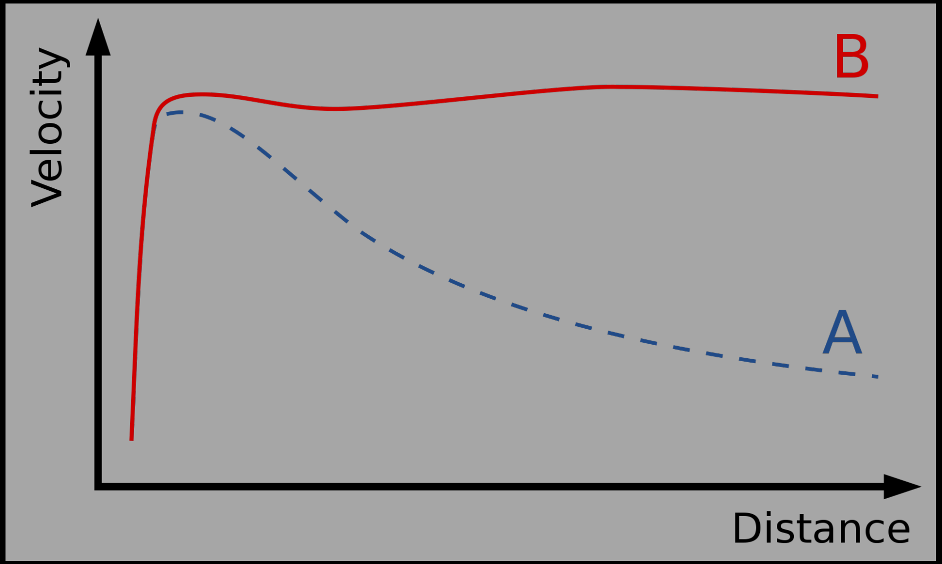
Lensing



Large Scale Structure Formation



Rotation Curves

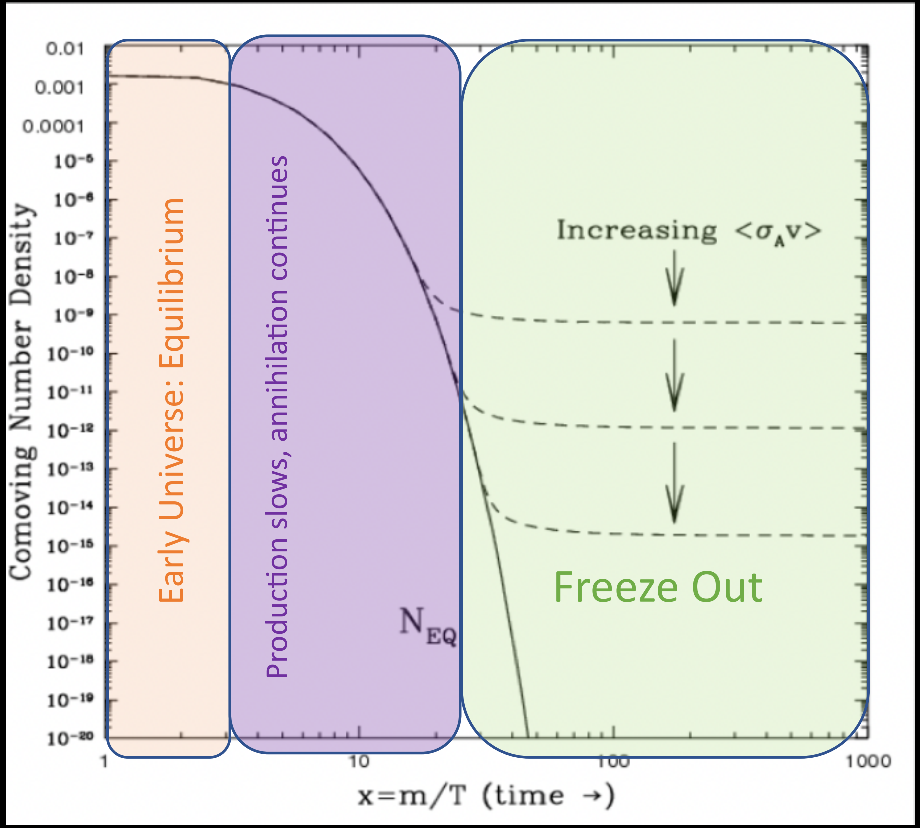


Thermal Dark Matter

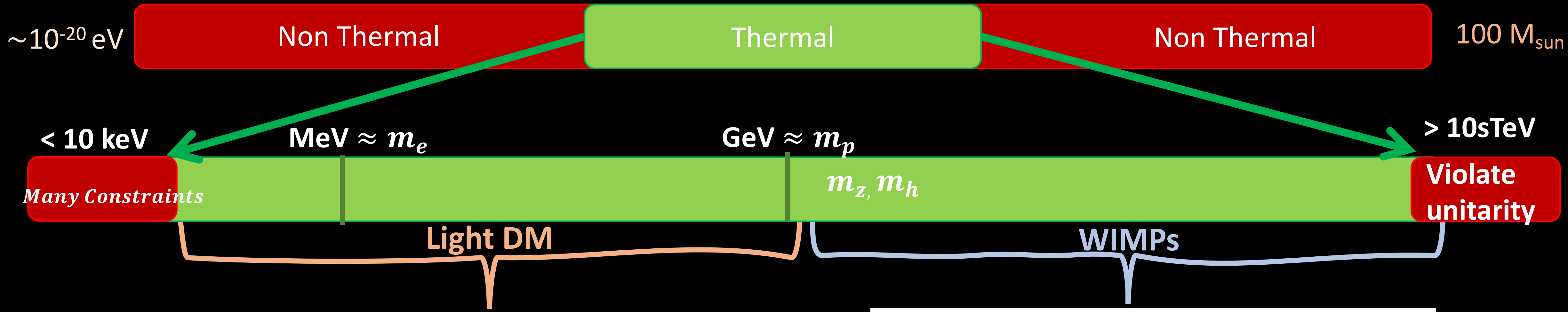
- Discovering the particle nature of Dark Matter is one of the most pressing challenge facing elementary particle physics.
- Among the simplest possibilities is one in which DM arose as a thermal relic from the hot Early Universe.

- **Simple:** Requires only that non-gravitational interaction rate between DM and ordinary matter exceed the Hubble expansion. Compatible with nearly all UV scenarios.
- **Generic:** Applies to nearly all models with coupling large enough to allow detection (rare counter-example: axion).
- **Reasonable:** Evidence from CMB and BBN for hot and dense thermal phase of early Universe.
- **Predictive:** DM mass and coupling with SM set abundance → target

Implies a minimum annihilation rate $\langle \sigma v \rangle \sim 10^{-26}\ cm^3 s^{-1}$



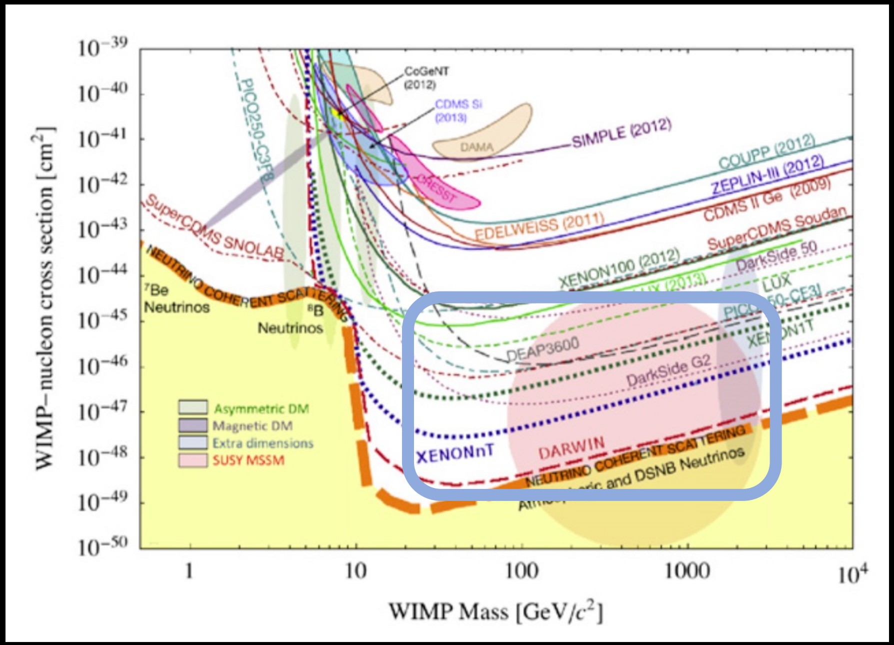
The allowed mass range over which DM can thermalize with the SM in the early universe and yield the observed relic abundance via annihilation:



Searching for WIMPs of ~ GeV-TeV has been focus detection experiments to date.

Next gen (e.g. SuperCDMS, LZ or LHC) experiments will cover a large portion of the remaining parameter space.

The lower mass range of MeV - GeV, where the most stable forms of ordinary matter are found, has remained stubbornly difficult to explore with existing experiments.



Light Dark Matter (LDM)

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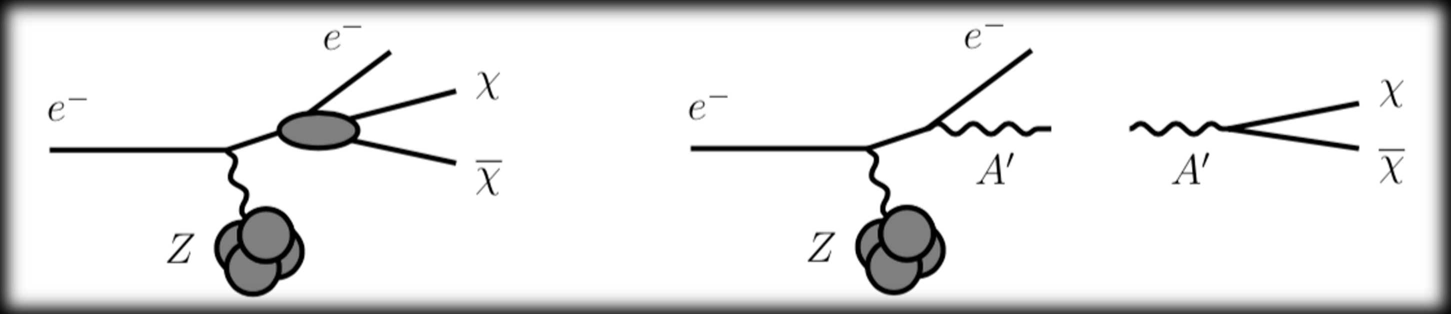
In the MeV-GeV mass range, viable models of LDM have the following properties:

- **Light Forces:** Require light force carriers to mediate an efficient annihilation rate for thermal freeze-out
- **Neutrality:** Both the DM and mediator must be singlets under the full SM gauge group.
- **Benchmark Physics Model:**
  - DM is charged under a new *U(1)'* gauge field;
  - Mediated by a *U(1)'* gauge boson (dark photon, *A'*) .
  - *Connects Dark Sector to Standard Model Particles.*
- Vector portal much less constrained than scalar one, so focus on this possibility.



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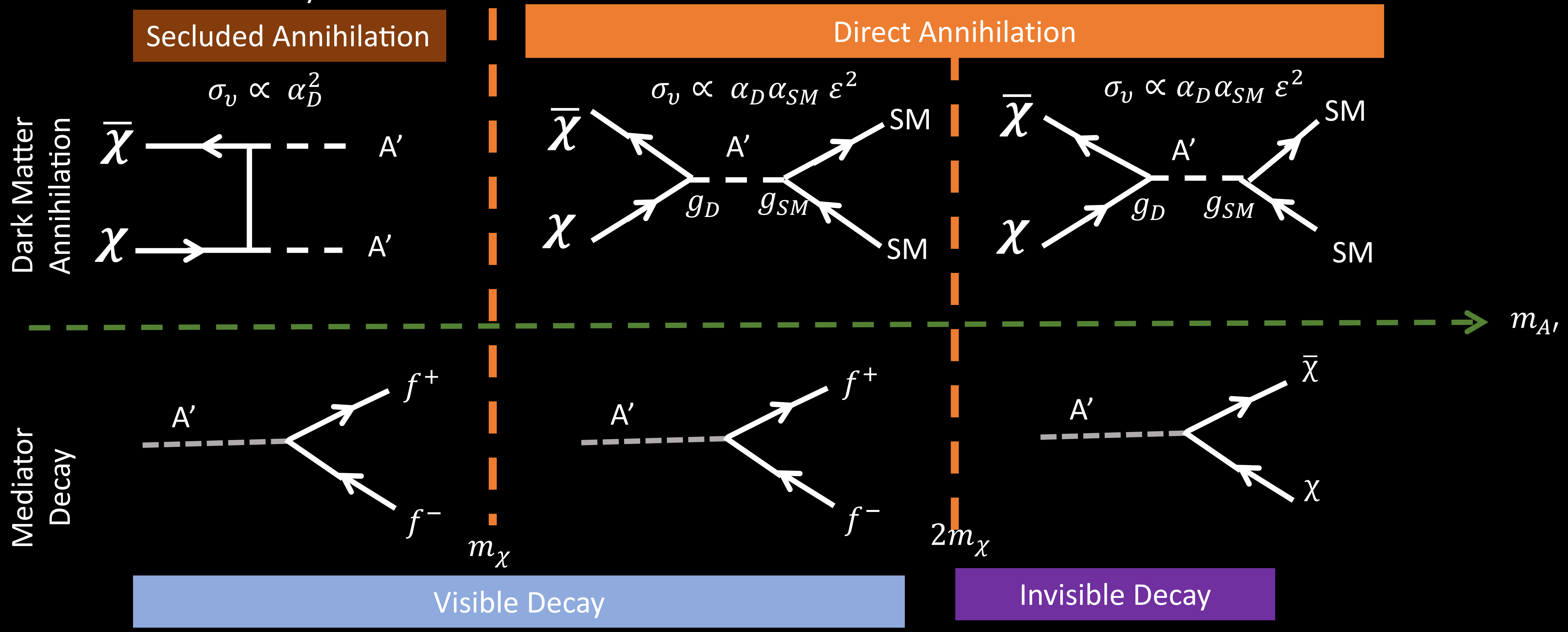
Production & Decay

Direct annihilation – predictive!

Constrained by CMB data



Resonance, prompt or displaced decay

➔ Missing energy, mass or **momentum**

Thermal Targets

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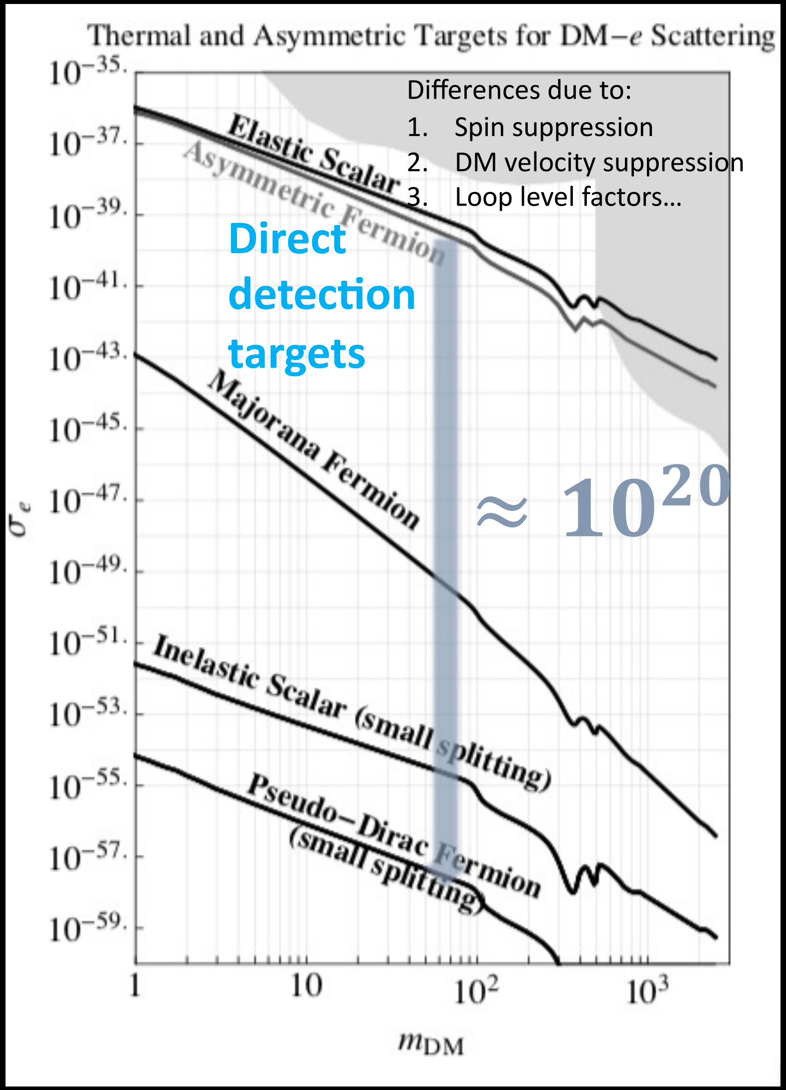
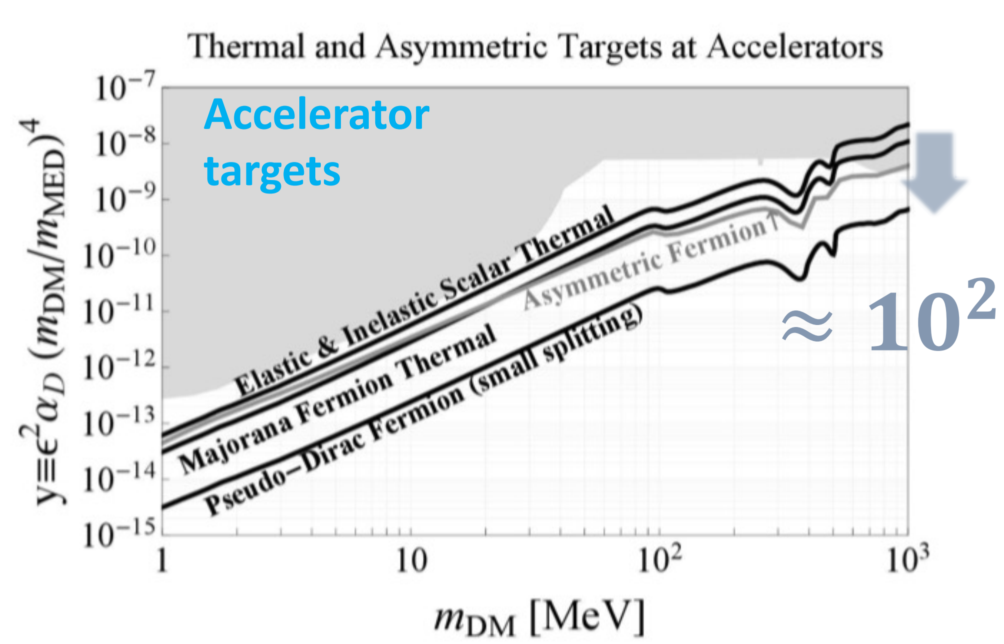


σe = electron-recoil direct detection cross section

Dimensionless interaction strength y:

$$\sigma v(\chi\chi \to A'^* \to ff) \propto \epsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} = \frac{y}{m_\chi^2} \quad , \quad y \equiv \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4 .$$

For given m_χ there is a unique value of y compatible with thermal freeze-out independent of the individual values of α_D, ε and $m_\chi/m_{A'}$.



Targets share same parametric dependence on y

Accelerators uniquely positioned to probe directly annihilating thermal LDM

Relativistic production at accelerators: almost insensitive to spin and mass

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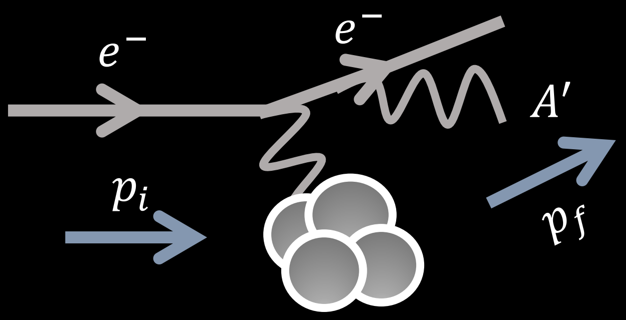
- High-luminosity measurement of missing momentum in multi-GeV electron fixed-target collisions, through both direct DM and mediator particle production.
- Will explore DM interactions with electrons to a level of sensitivity needed to test many of the most predictive thermal DM scenarios over nearly the entire sub-GeV mass range.



$$p_f - p_i = p_{missing}$$

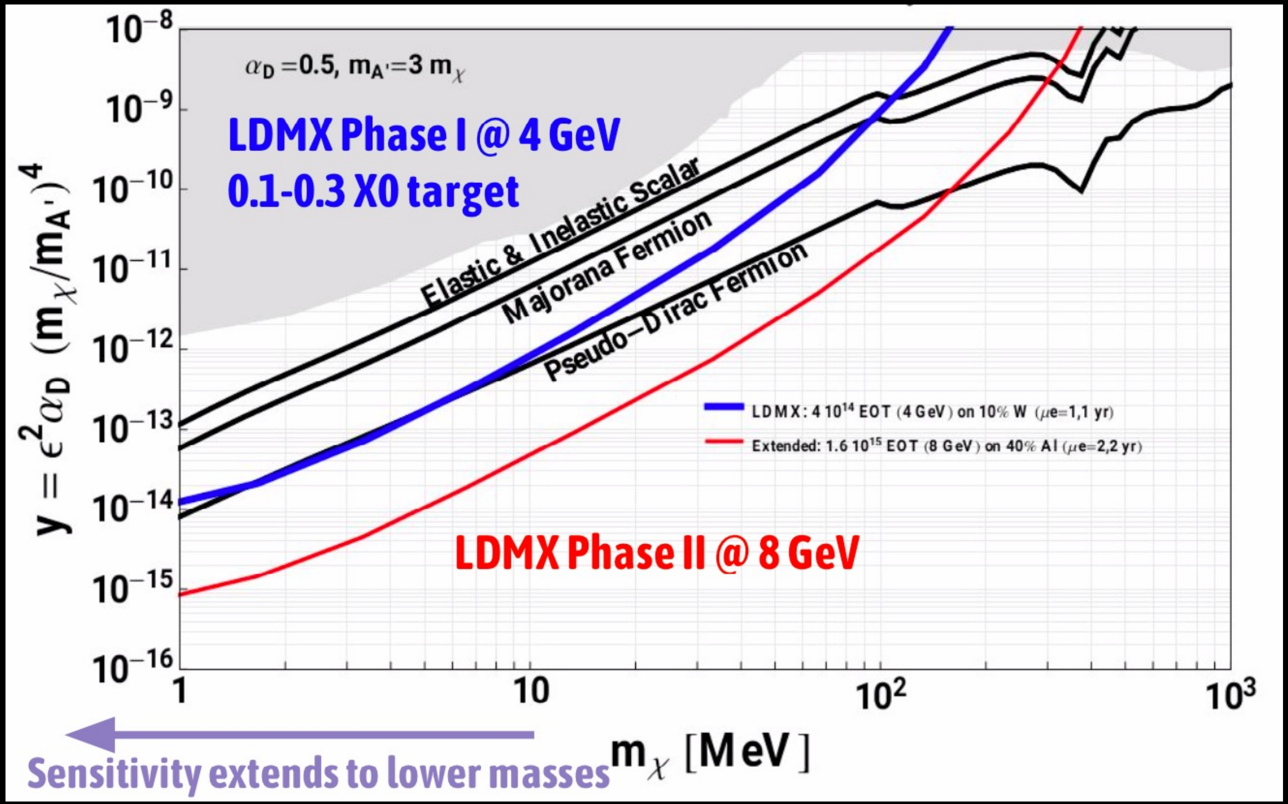
Phase I:

- Total required luminosity of 0.8 pb^{-1} i.e 4×10^{14} tagged electrons on target (EOT).
- Utilize establish detector technology to gain strong physics results.

Phase II:

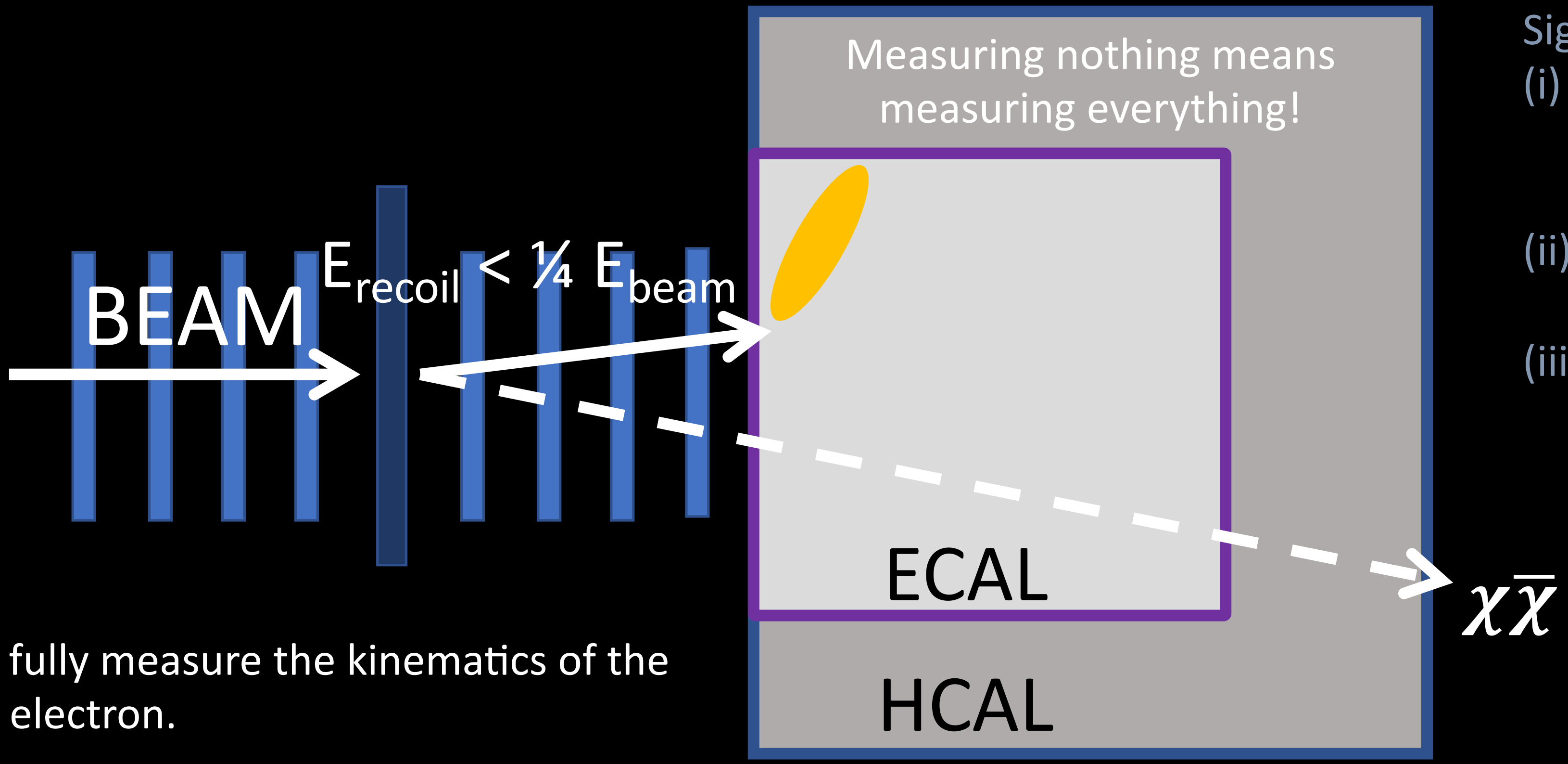
- Higher luminosity running at 8 GeV energies --> 10^{16} EOT

Physics Reach



Missing Momentum

An electron beam incident on a thin target can produce dark matter particles through a "dark bremsstrahlung" process, in which most of the incident electron's energy is typically carried away by the invisible dark matter.

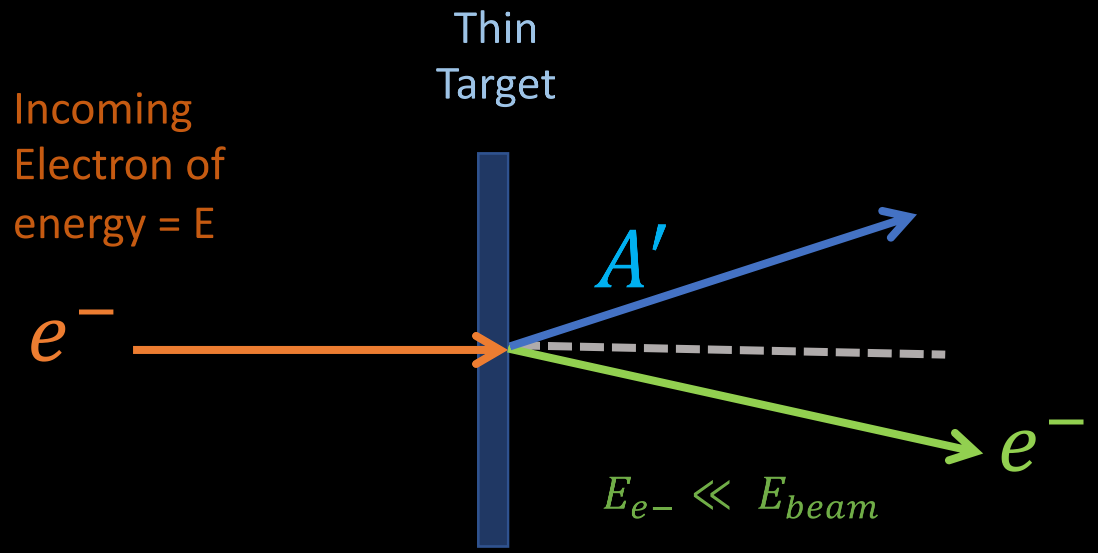


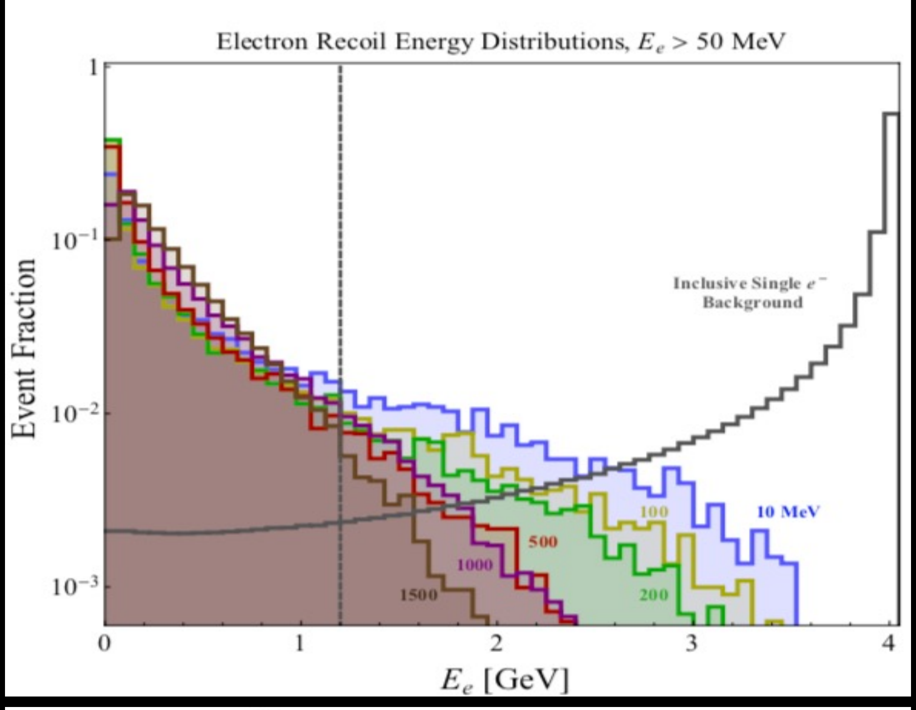
Signature:

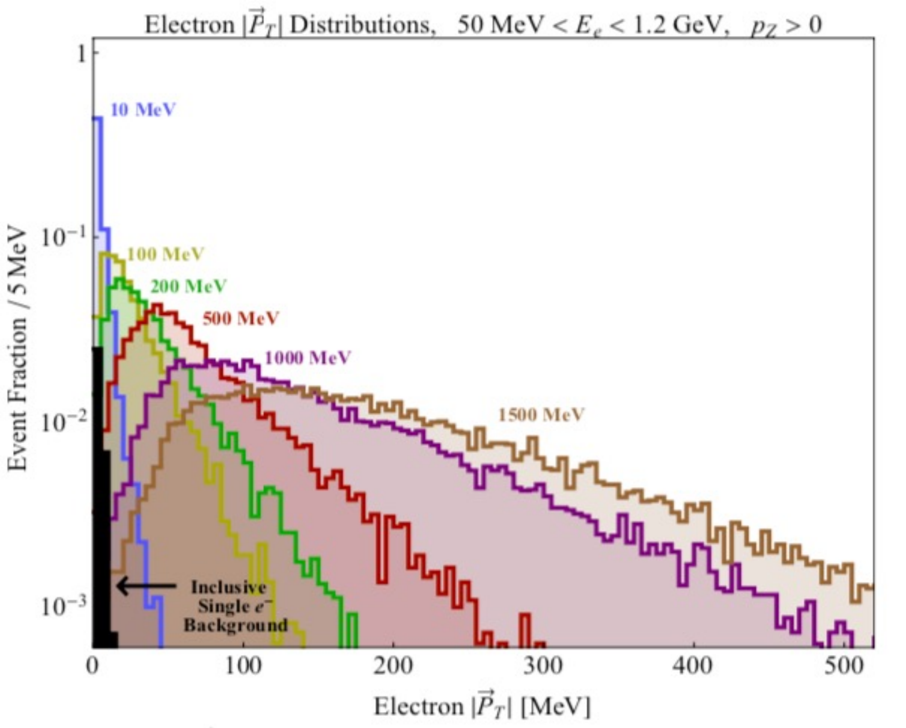
(i) Substantial energy loss by the electron (e.g. recoil with <30% of incident energy),
(ii) Potentially large transverse momentum kick, and
(iii) absence of any additional visible final-state particles that could carry away energy lost by the electron.

Goal: to fully measure the kinematics of the recoiling electron.

Kinematics







Darksstrahlung kinematics and rates differ from SM bremsstrahlung.
A' takes most of the beam energy.:

- Large missing energy, soft recoil electron
- Large missing p_T, large angle recoil electron

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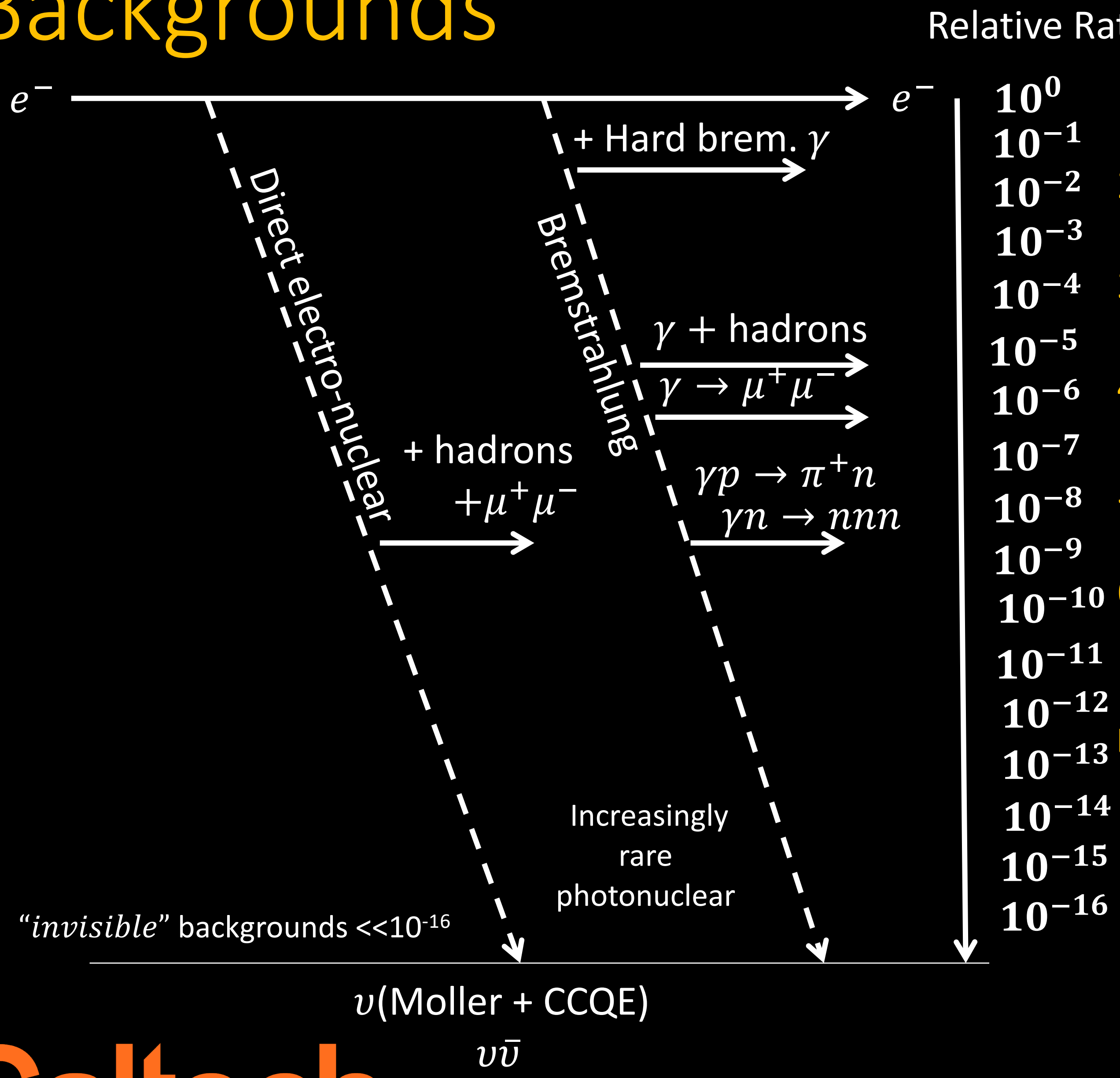
Backgrounds



1. Beam Impurities: check recoil corresponds to a clean 4 GeV beam electron.
2. Electrons which don't interact in target: Most deposit ≈ 4GeV shower in Ecal.
3. Hard Brem.: 2 showers in the Ecal, with combined shower energy ≈ 4 GeV . Must measure photon accurately.
4. Hard bremsstrahlung + photo-nuclear reaction in the target or Ecal: wide range of final states
5. Photon conversion to muons: one or two "tracks" passing through the calorimeter
6. Electron Nuclear

Photon Rejection Paper: **A High Efficiency Photon Veto for the Light Dark Matter eXperiment (https://arxiv.org/abs/1912.05535)**

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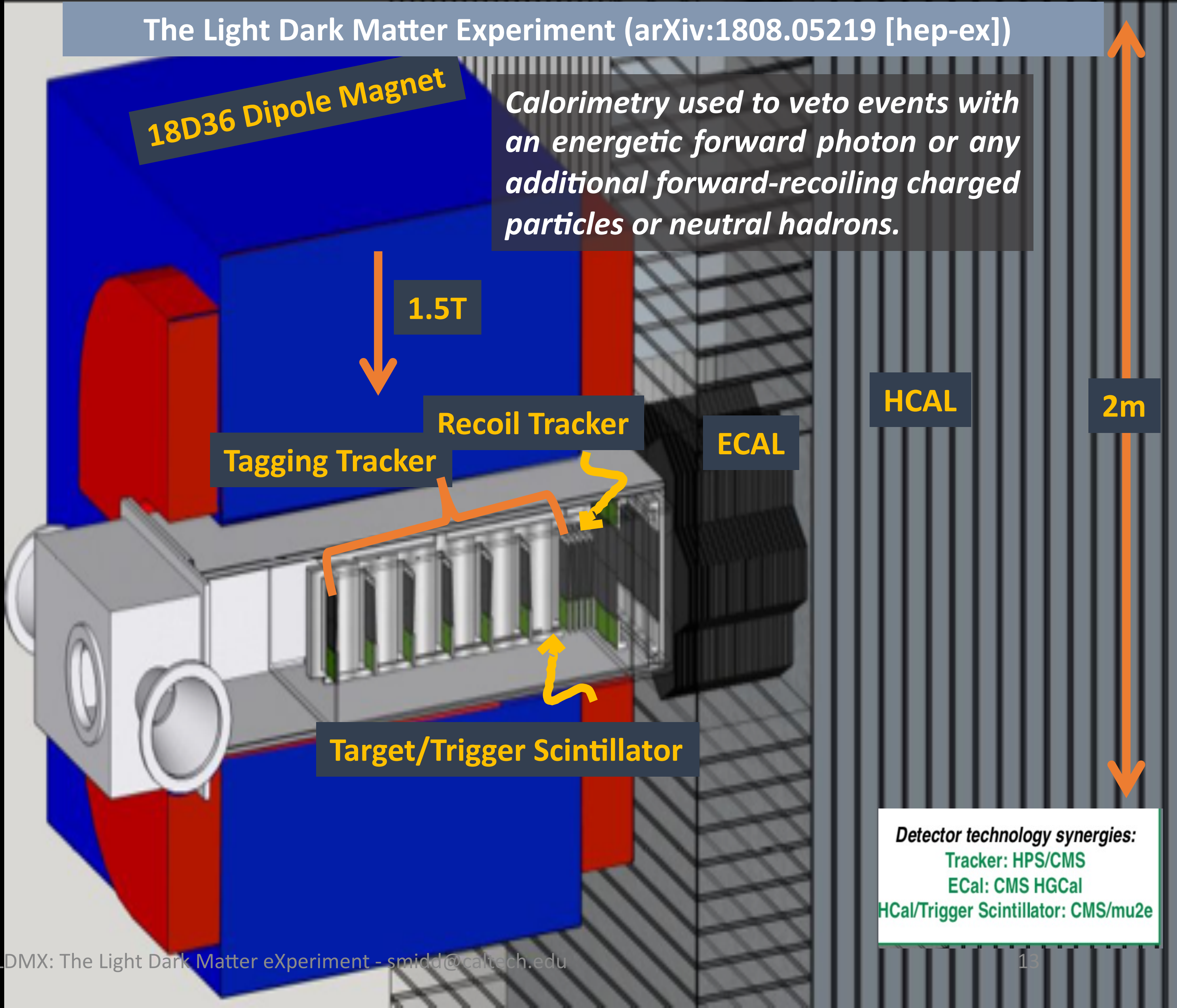
The Apparatus

Two goals:

1. Measure the distinguishing properties of DM production
2. Reject potential backgrounds for this process.

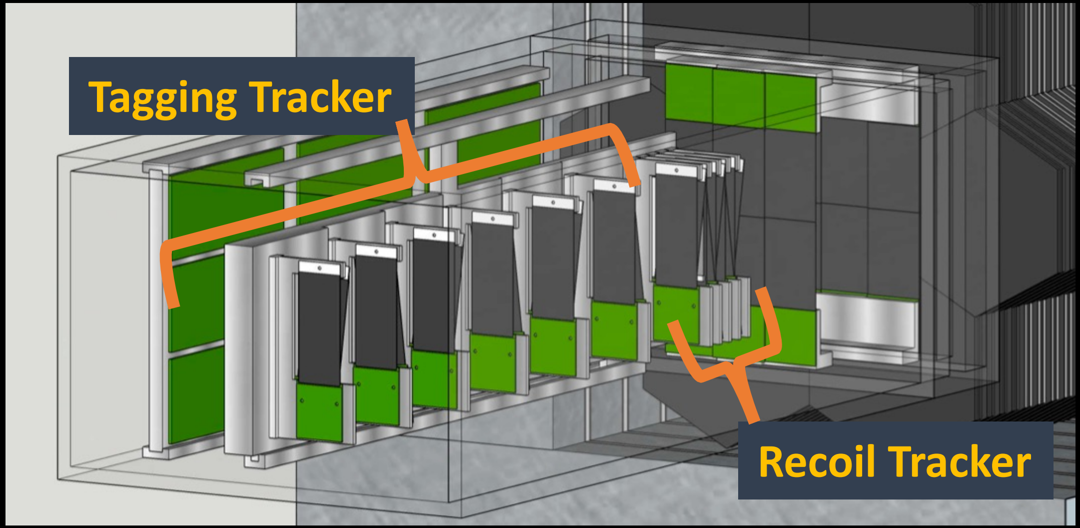
LDMX reconstructs kinematics of each beam electron both upstream and downstream of low mass target using low-mass tracking detectors in magnetic field.

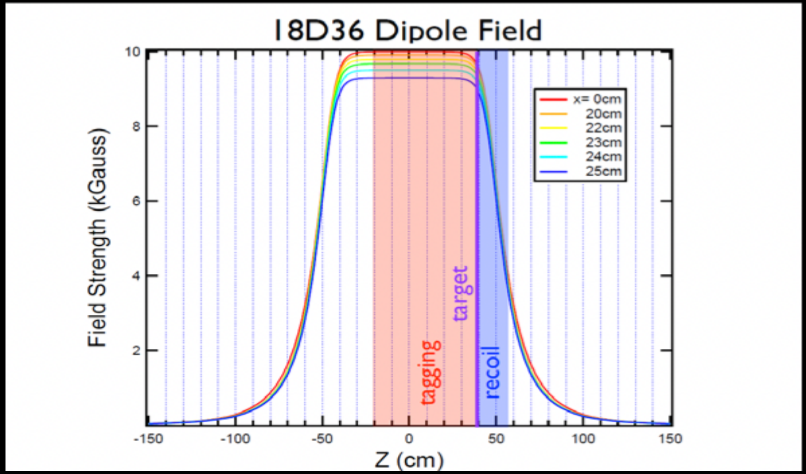


Phase I Detectors: Tracking System

- **Two tracking systems:**
  - Tagging tracker to measure incoming electron
  - Recoil tracker to measure scattered electron
- **Silicon tracker similar to HPS SVT**
  - Fast (2ns time resolution)
  - Meets radiation tolerance requirements

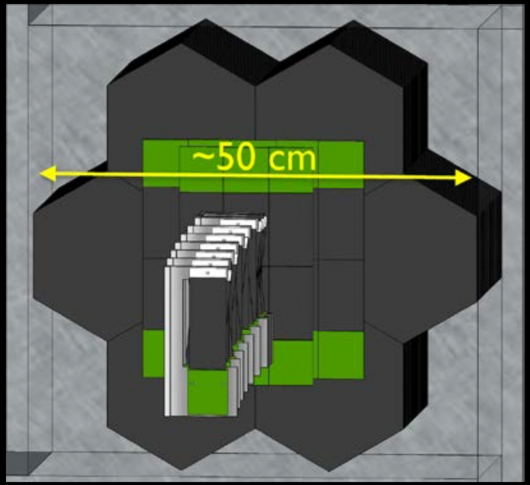
- Tagging Tracker:
  - 7 measuring stations, 2 sensors at small angle stereo
  - Use to select off-energy electrons
- Recoil Tracker:
  - 4 stations composed of sensor pairs at small angle stereo and "axial only" layers





Phase I Detectors: The ECAL

- **Utilizes Si-W calorimeter technology designed for CMS upgrade:**
  - Fast, dense, granular for high occupancies - allows for exploitation of both longitudinal and transverse shower shapes.
  - Deep ($40X_0$) for extraordinary EM containment.
  - Can provide fast trigger for tracks (-3μs).
  - Capable of MIP tracking – helps background rejection.
  - Easily withstands the effective fluence of 10^{13} n/cm^2 from 10^{14} EOT.

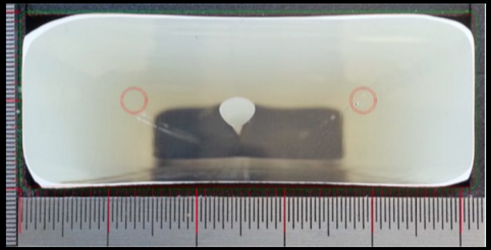


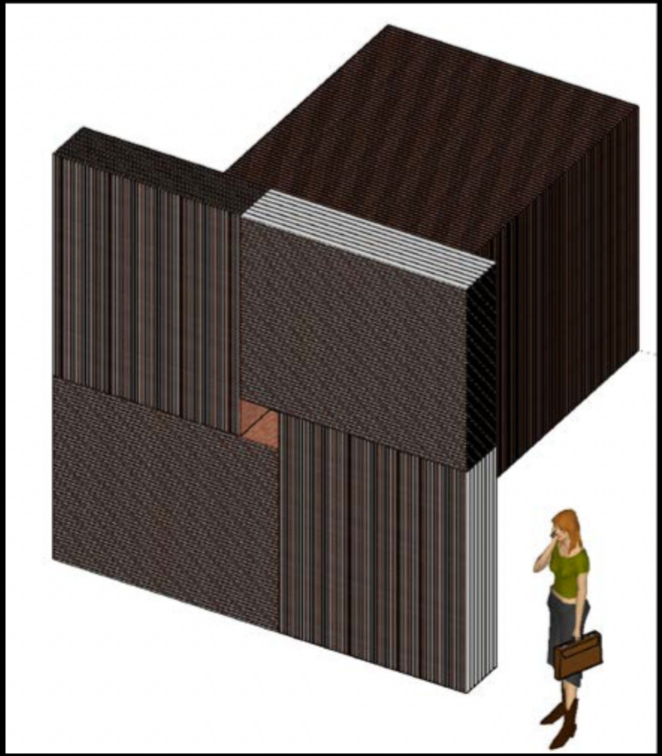
Phase I Detectors: The HCAL

Plastic scintillator bars with WLS fibers read out by SiPM and steel absorber – based on Mu2e technology:

- 2 important regions:
  - Back HCAL (~13λ)
  - Side HCal (~ 3.5λ), 3 m transverse size.

- Must veto hadronic Photo-Nuclear (PN) events, in particular PN events emitting several hard neutrons (e.g. $\gamma n \rightarrow n\bar{n}n$) or many soft neutrons.
- Can also help with: displaced signatures, electro-nuclear measurements and trigger and overall veto.





Other Physics Possibilities

Assumed very simple benchmark physics model

However….

- LDMX also has sensitivity to a broad range of New Physics – anything which can couple to electrons and produce missing momentum can be detected:
  - Quasi-thermal DM, such as asymmetric DM and ELDER DM
  - New long-lived resonances produced in the dark sector (SIMP)
  - Freeze-in models with heavy mediators
  - New force carriers coupling to electrons, decaying visibly or invisibly (i.e. ALPs)
  - Milli-charged dark sector particles

i.e. could generically probe a vast array of possibilities in addition to light thermal DM.

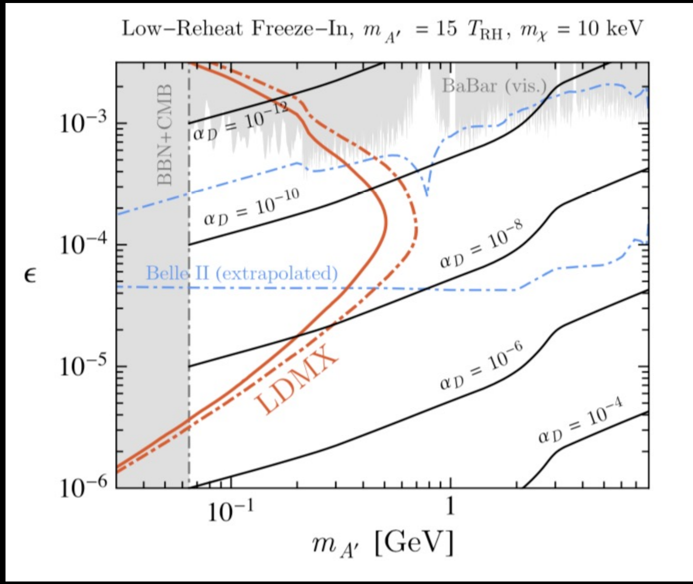
Dark Matter, Millicharges, Axion and Scalar Particles, Gauge Bosons, and Other New Physics with LDMX *Phys.Rev.D* 99 (2019) 7, 075001

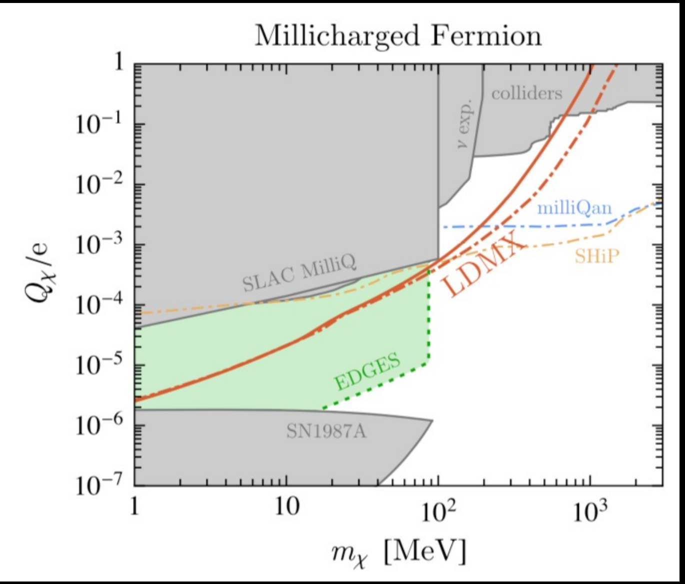
- Electro-nuclear measurements for DUNE: LDMX coverage in the relevant kinematic window is excellent

See: "Lepton-Nucleus Cross Section Measurements for DUNE with the LDMX Detector" (https://arxiv.org/abs/1912.06140)

Other Physics Possibilities

LDMX





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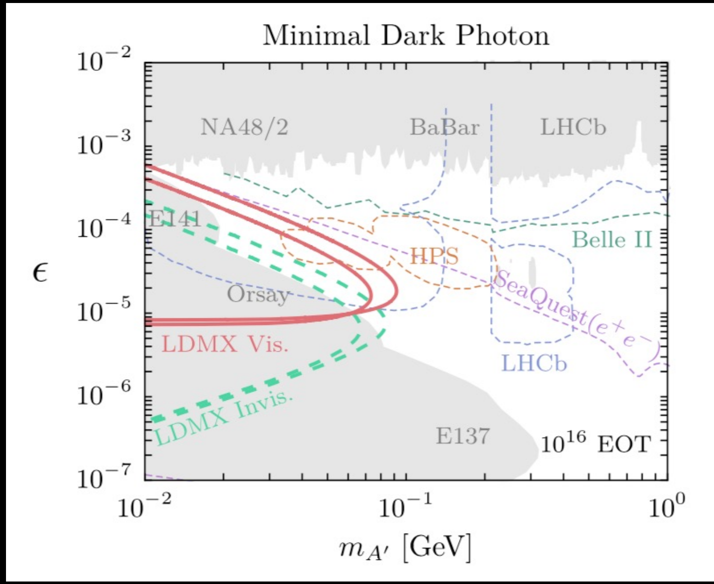

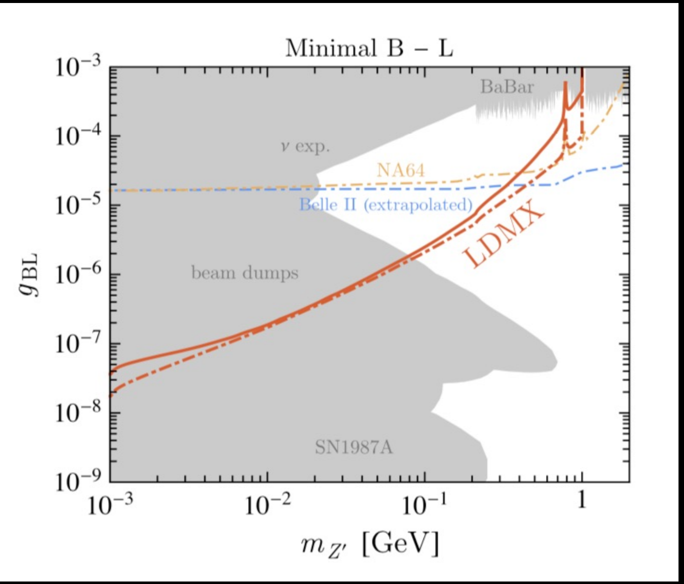

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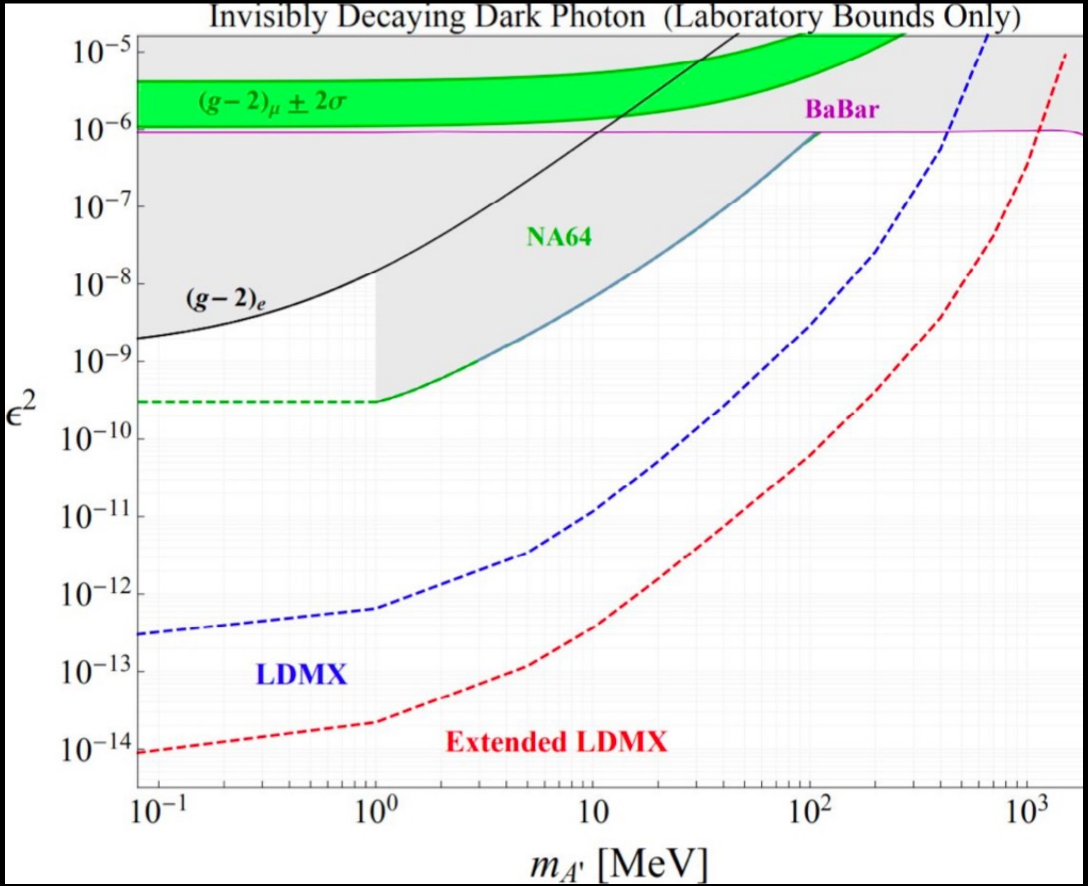
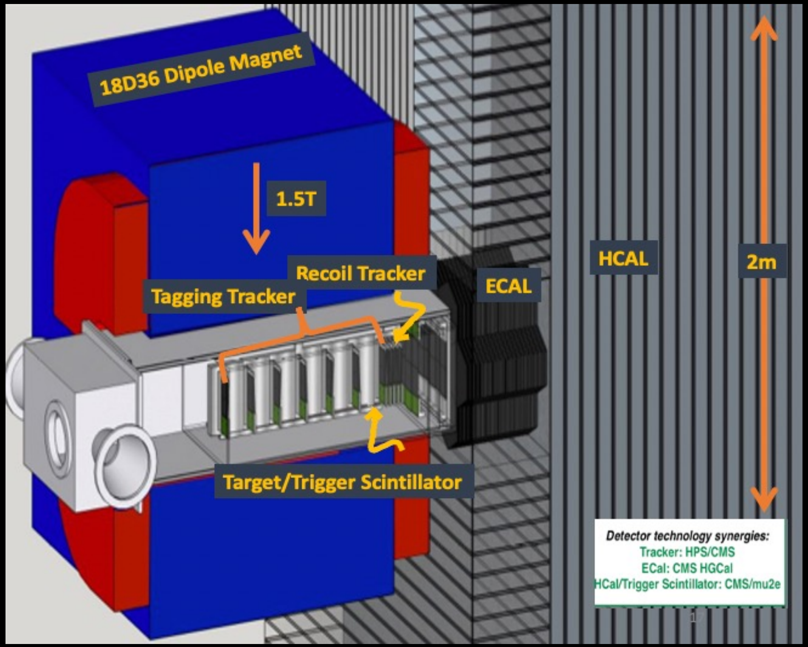
Summary & Outlook

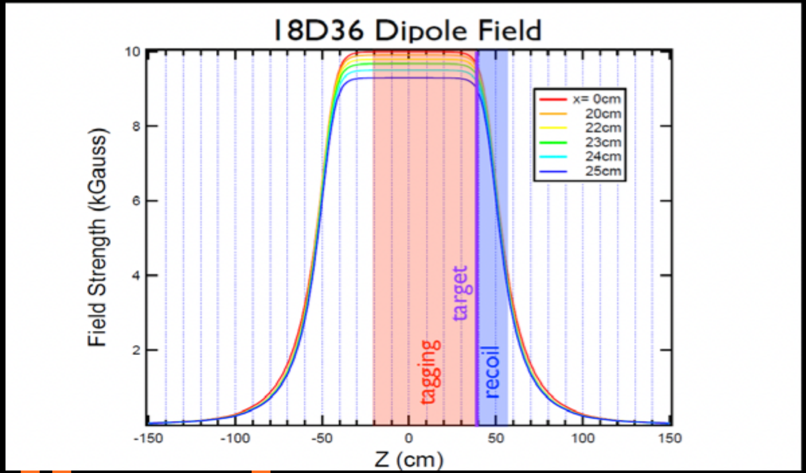
- The thermal paradigm is arguably one of the most compelling DM candidate: LDM less explored.
- Accelerator-based experiments have unique sensitivity in the MeV-GeV range.
- LDMX can reach all thermal targets over most of the MeV-GeV range and probe other physics models.
- Among potential approaches, missing energy / momentum provide the best luminosity per sensitivity.
- **Broad physics potential:** LDMX can probe sub-GeV dark sectors that couple weakly to electrons, and the physics of photo- and electro-nuclear collisions.
- LDMX can complete this program within the next few years at reasonable cost, and potentially result in a groundbreaking discovery.

Physics Reach



Phase I Detectors: Tracking System





- **Single dipole magnet, two field regions**
  - Tagging tracker placed in the central region for p_e = 4 GeV,
  - Recoil tracker in the fringe field for p_e ~50 – 1200 MeV
  - Recoil: Weak magnetic field allows use of events in which a soft, wide-angle recoil electron does not penetrate into the ECal.
  - Tagging: Strong field for rejection of stray low-energy particles from beam halo with very high efficiency

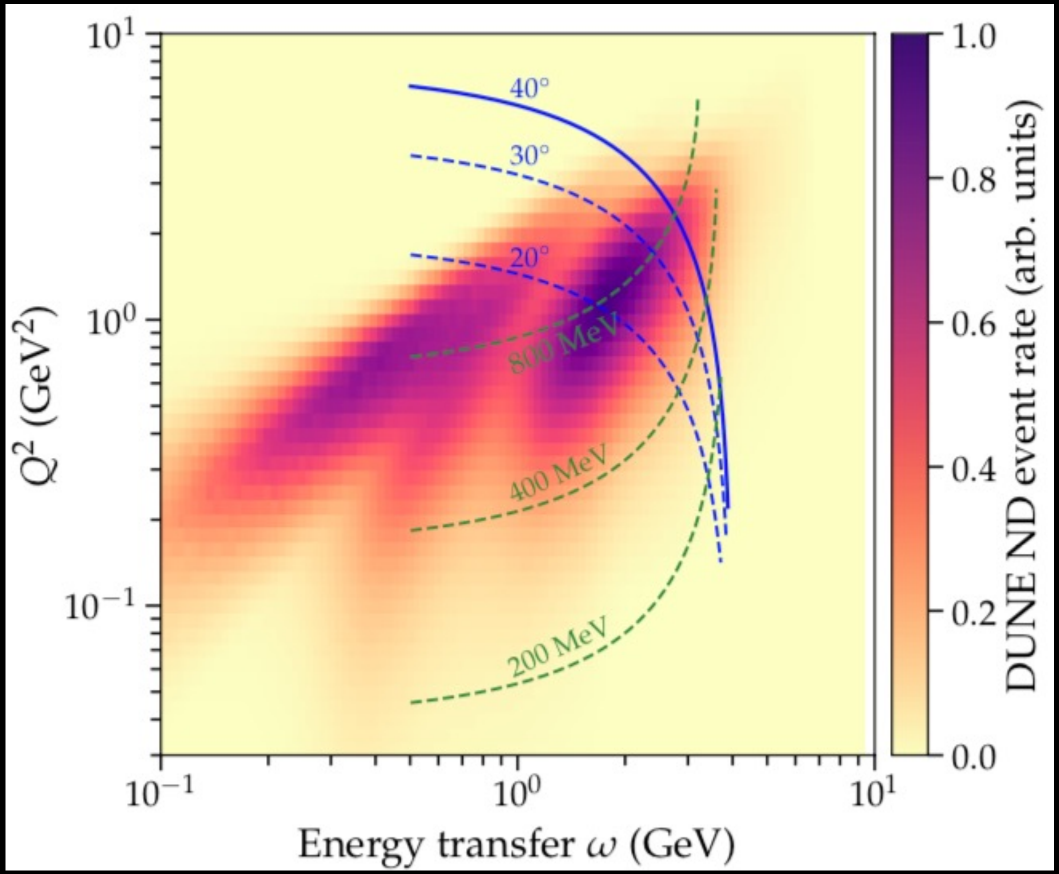
- **Tungsten target between the two trackers**
  - ~$0.1X_0$ thickness to balance between signal rate and momentum resolution
  - Scintillator pads at the back of target to veto empty events

Electro-Nuclear Measurements

LDMX coverage in the relevant kinematic window is excellent

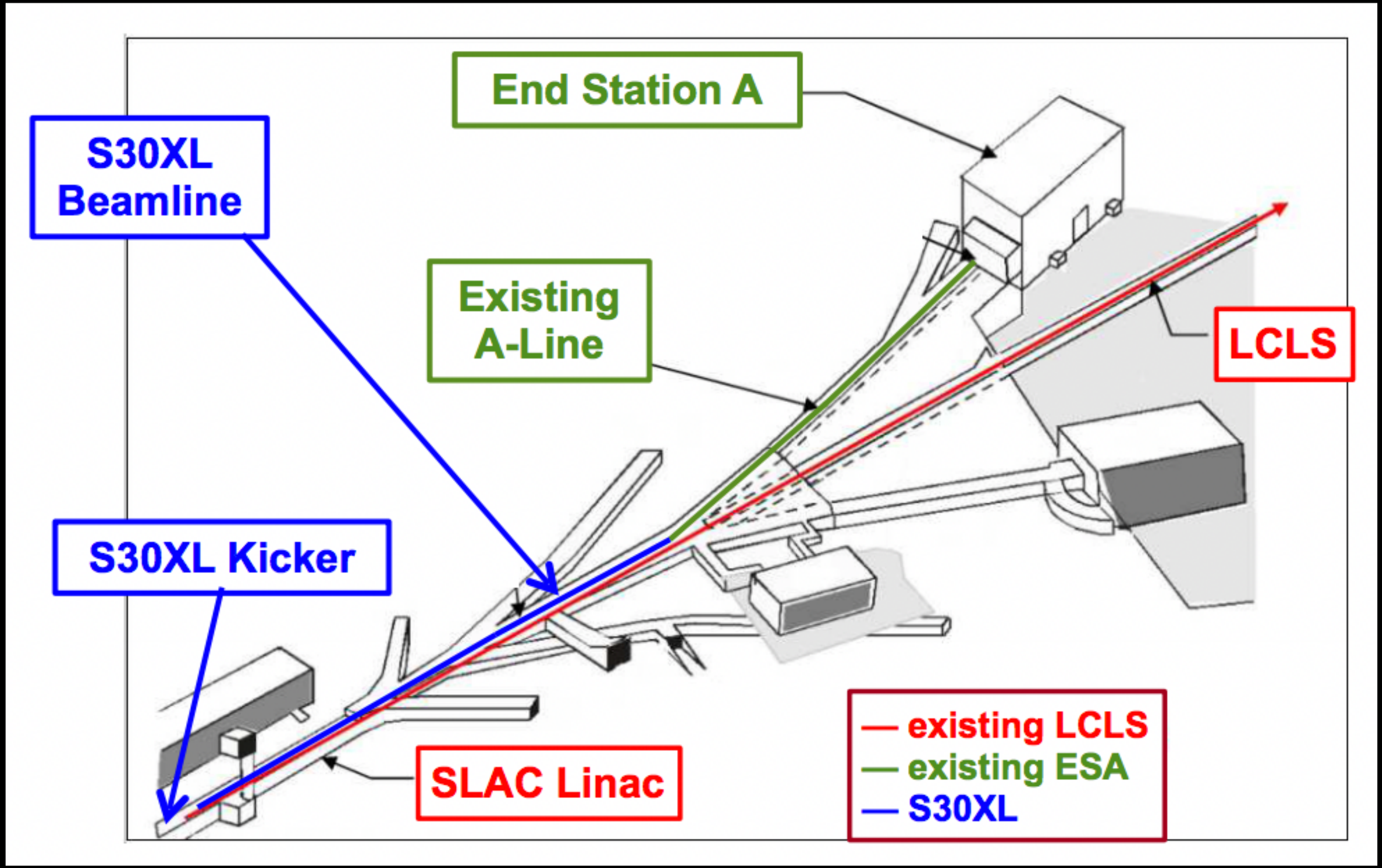
See: "Lepton-Nucleus Cross Section Measurements for DUNE with the LDMX Detector" (https://arxiv.org/abs/1912.06140):

- DUNE: Measure effects of δ_{CP} and mass hierarchy, requiring high precision - must understand how neutrinos interact with nuclei!
- Neutrino-nucleus interactions in the relevant energy range (between 500 MeV and 4 GeV) are complex.
- Different mechanisms of interaction yield comparable contributions to the cross-section.
- Electron scattering offers controlled kinematics and large statistics.
- Can study specific scattering processes and diagnose currently obscured by the quality of the neutrino scattering data
- LDMX: 4GeV electrons, precision tracker, calorimeters with near 2π acceptance from forward beam axis out to ~40° angle, low reconstruction threshold.



LCLS-II Transfer lines

LCLS-II @ SLAC; new beamline under construction. High rate, low intensity beam extracted from LCLS-II:

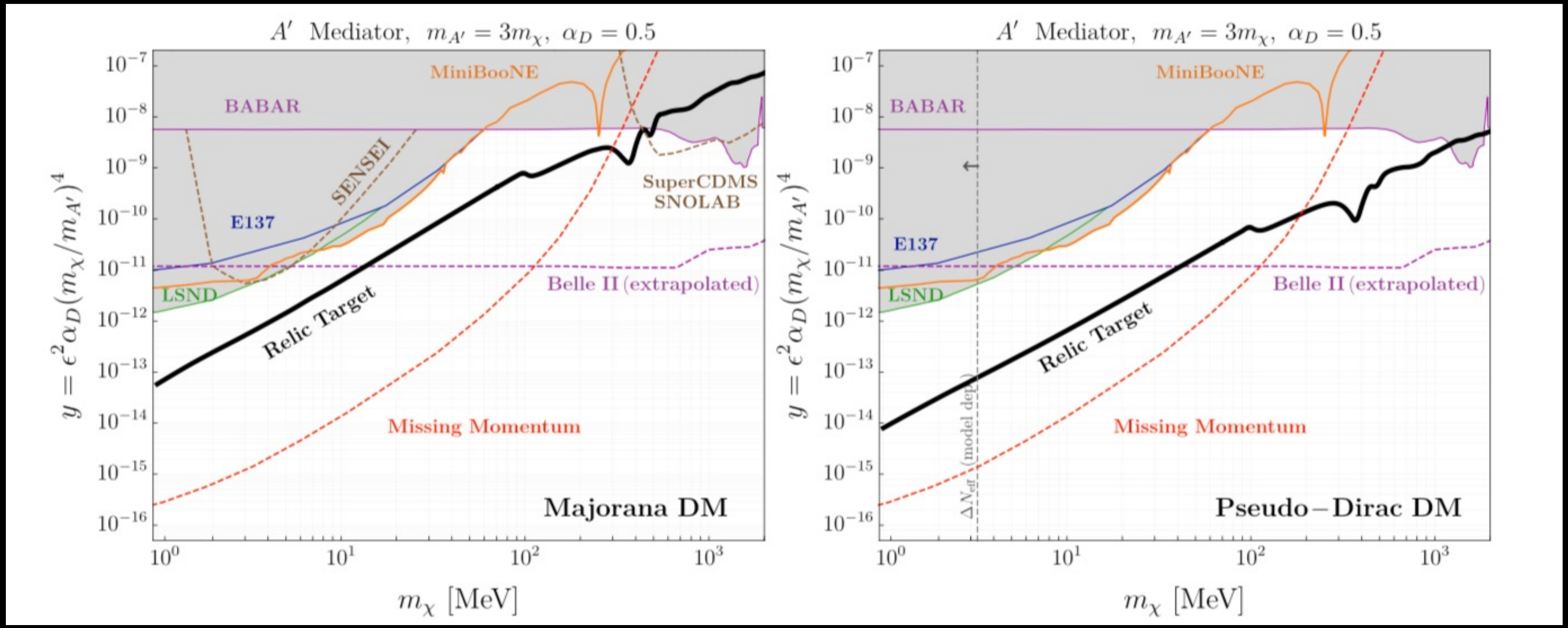


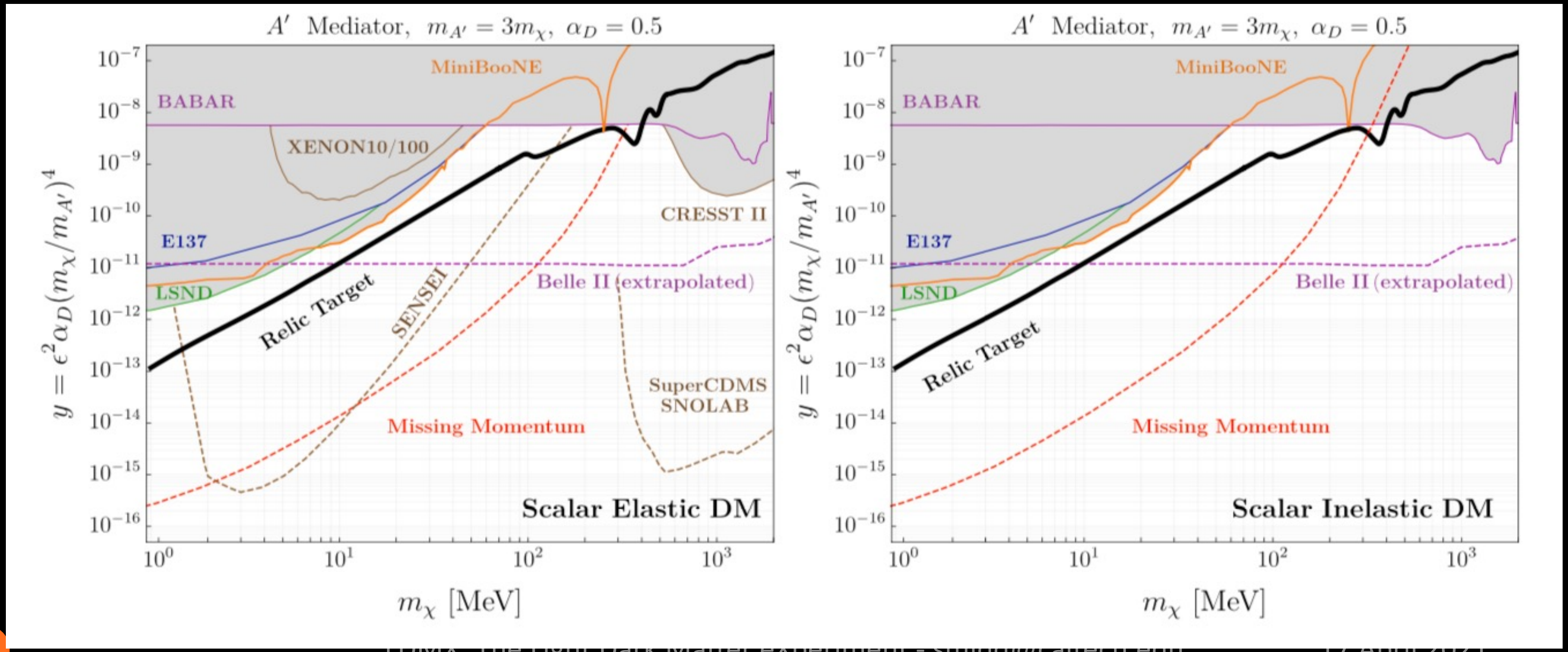
Unique facility providing low energy CW beam for a variety of purposes:

- Neutrino measurements
- Test beam
- Accelerator physics
- DM searches

Parameter Space

LDMX





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