Fermilab

light dark matter at accelerators

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Precision science working group
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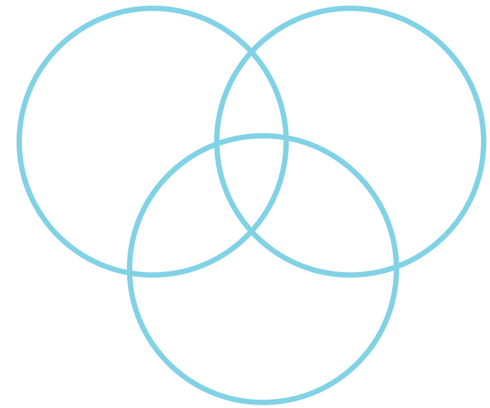
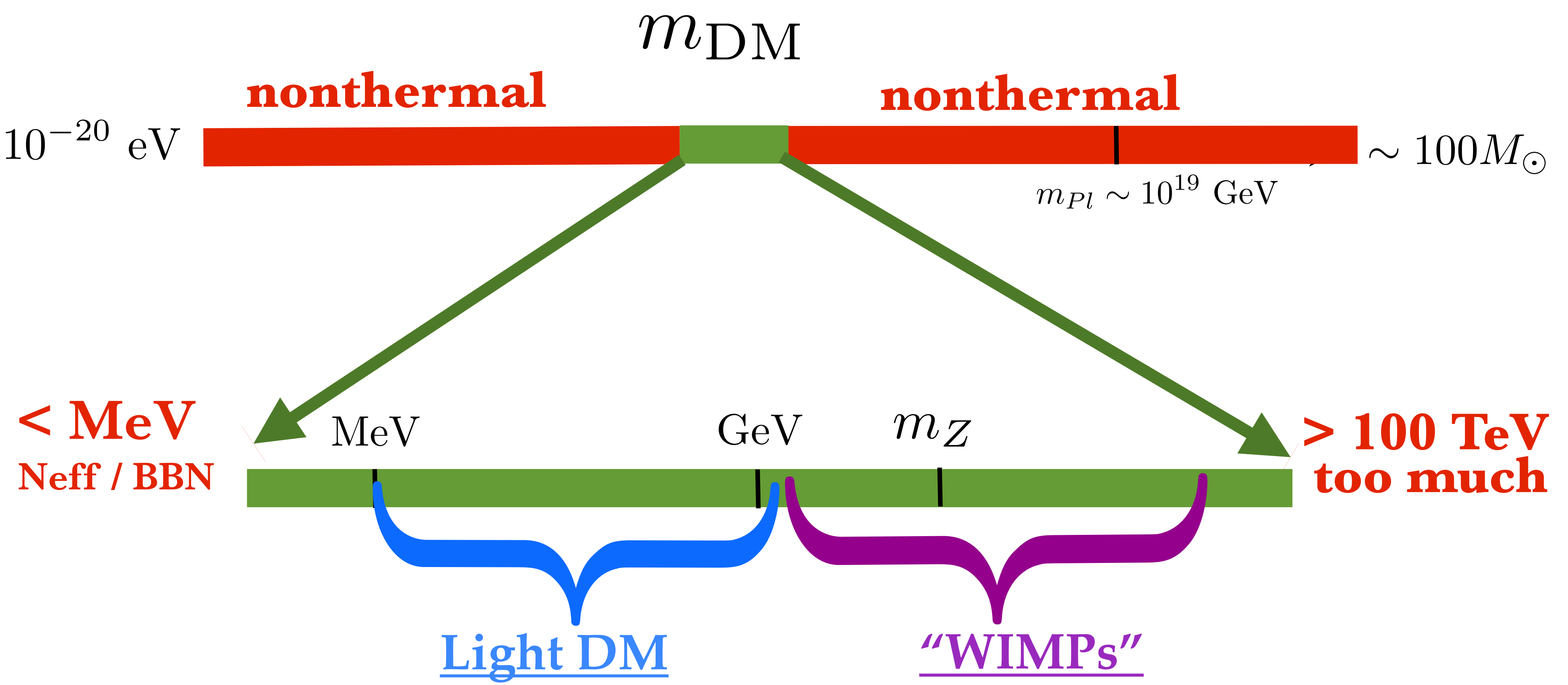
Experiments which use **high intensity** beams to uncover the nature of **light dark matter** using **LHC detector** technologies by suppressing **extremely rare** SM processes



You can find much more material on these types of experiments at *New Ideas in Dark Matter* workshop, working group 3 https://indico.fnal.gov/conferenceDisplay.py?confId=13702

Thermal Equilibrium

UV insensitive, Predictive, Minimum SM interaction



Thermal Equilibrium: Generic, Easily Realized

If interaction rate exceeds Hubble expansion

$$\mathcal{L}_{\text{eff}} = \frac{g^2}{\Lambda^2}(\bar{\chi}\gamma^\mu\chi)(\bar{f}\gamma_\mu f)$$

$$H \sim n\sigma v \qquad \Longrightarrow \quad \frac{T^2}{m_{Pl}} \sim \frac{g^2 T^5}{\Lambda^4}\bigg|_{T=m_\chi}$$

Equilibrium is easily achieved in the early universe if

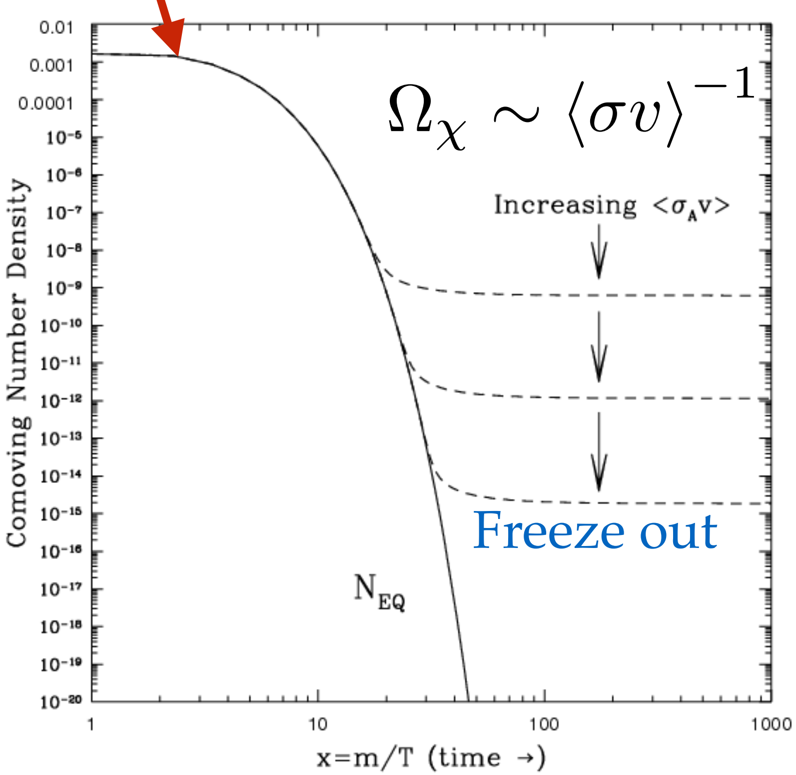
$$g \gtrsim 10^{-8}\left(\frac{\Lambda}{10\,\text{GeV}}\right)^2\left(\frac{\text{GeV}}{m_\chi}\right)^{3/2}$$

Applies to nearly all models with couplings large enough for detection (rare counterexample: QCD axion DM)

Dark Matter: Freeze Out of Equilibrium

DM in Eq. is overproduced, need to annihilate it away!

$$n_{\mathrm{DM}}^{(\mathrm{eq.})} = \int \frac{d^3p}{(2\pi)^3} \frac{g_i}{e^{E/T} \pm 1} \sim T^3$$



Griest et. al. 1992

Symmetric Thermal DM

Observed density requires

$$\sigma v_{\mathrm{sym}} \sim 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

Asymmetric Thermal DM:

Just need to deplete antiparticles

$$\sigma v_{\mathrm{asym}} > 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

Rate can be bigger, but not smaller

Either way, there's a target!

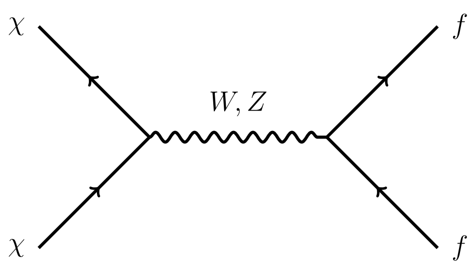
< GeV DM Model Building

DM must be a SM singlet

Else would have been discovered (LEP…)

Even if it weren't, freeze out still needs new forces

DM overproduced unless there are light new "mediators"



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

Lee/Weinberg '79

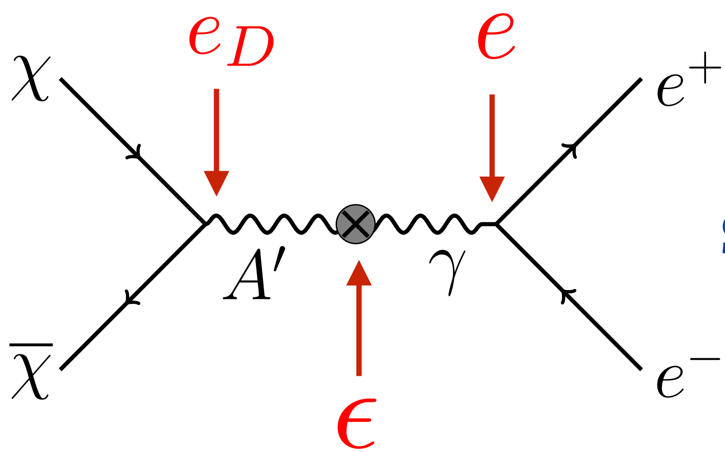
Simplicty: can't use higher dimension operators

Requires renormalizable interactions

Representative Model: Dark QED

$$\alpha_D \equiv \frac{e_D^2}{4\pi}$$

DM



SM

$$\alpha \equiv \frac{e^2}{4\pi}$$

DM charged under new force: $e_D \sim e$

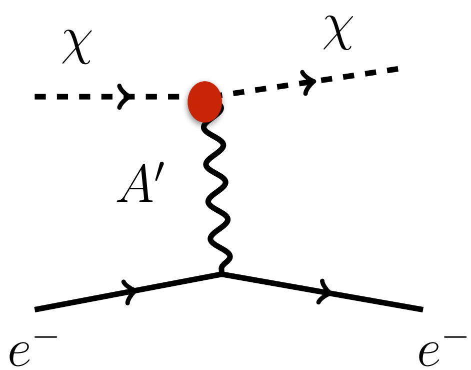
Allowed small *A′*-photon mixing: $\epsilon \ll 1$

SM acquires small charge under *A′*: $e\epsilon$

Not the only model, but qualitatively similar to all viable choices

Classify Viable Models by DD Scattering?

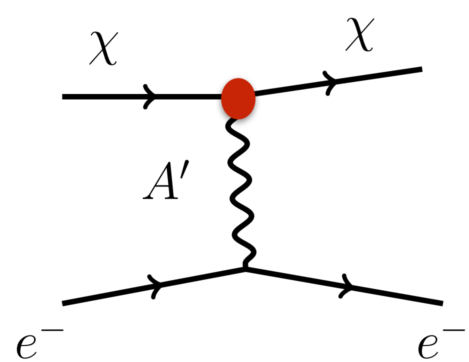
Scalar DM



$$A'_\mu \chi^* \partial_\mu \chi$$

$$\sigma_e \sim 10^{-39} \mathrm{cm}^2$$

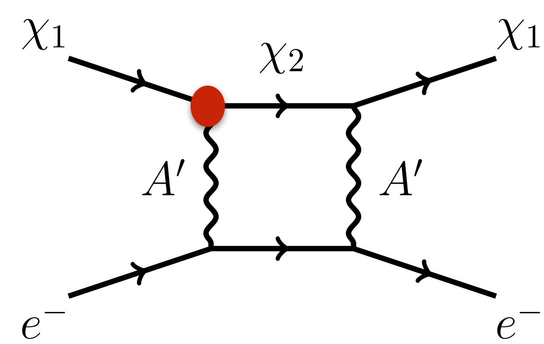
Majorana DM



$$A'_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi$$

$$\sigma_e \sim 10^{-39}\, v^2\, \mathrm{cm}^2$$
$$\sim 10^{-45}\, \mathrm{cm}^2$$

Pseudo-Dirac DM inelastic



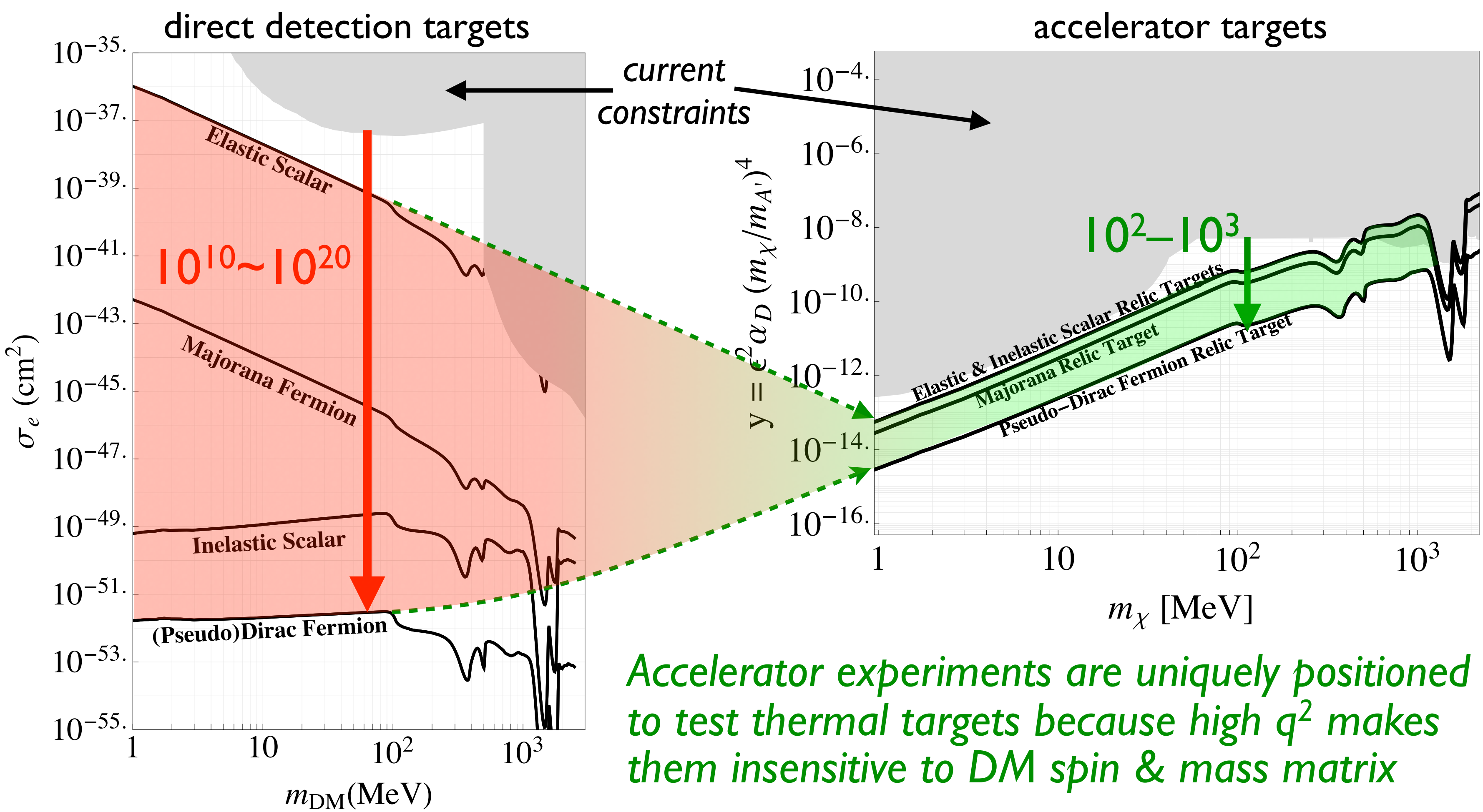
$$A'_\mu \bar{\chi}_1 \gamma^\mu \chi_2$$

$$\sigma_e \sim 10^{-48}\, \mathrm{cm}^2$$

Very different cross sections despite similarity @ high energy

Each ● interaction can realize thermal annihilation at *T* ~ *M*

DARK MATTER TARGETS AT ACCELERATORS



Accelerator experiments are uniquely positioned to test thermal targets because high q^2 makes them insensitive to DM spin & mass matrix

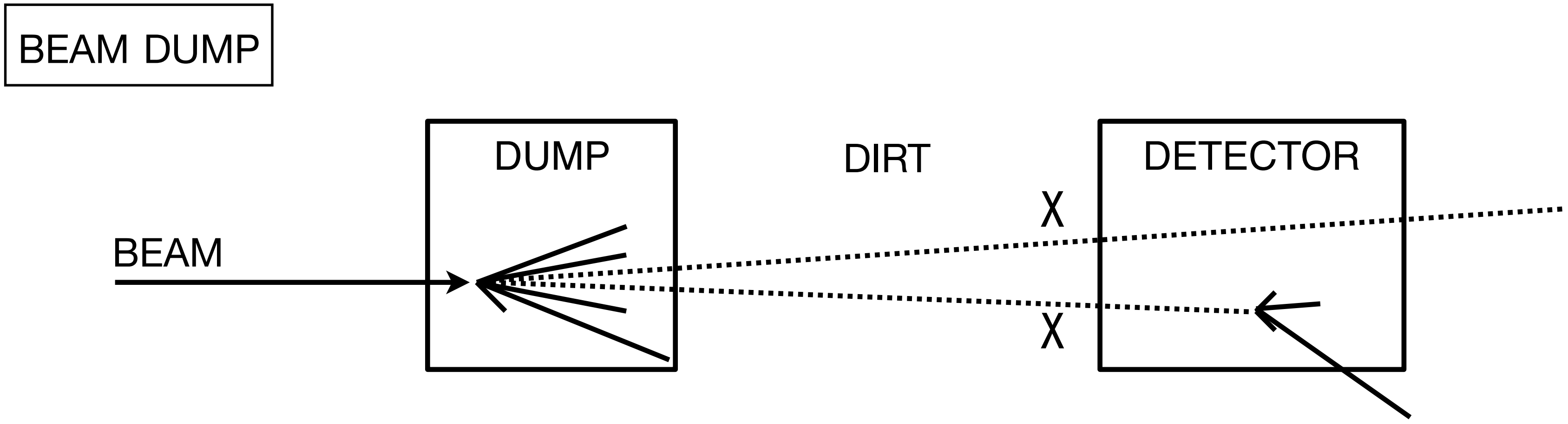
Dark matter at accelerators

Beam dump:

- proton/electron/muon beam dumps: MiniBoone

Missing mass/momentum/energy:

- LHC, monojet
- B-factories, monophoton
- electron/positron fixed target



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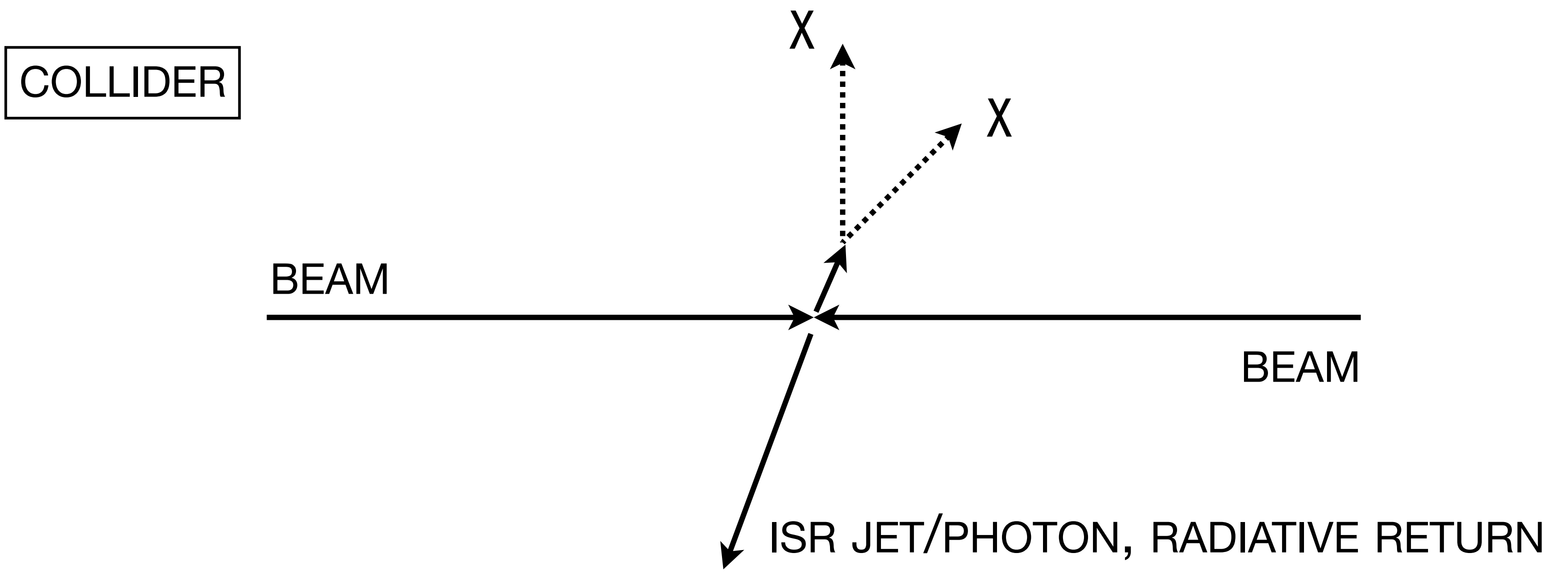

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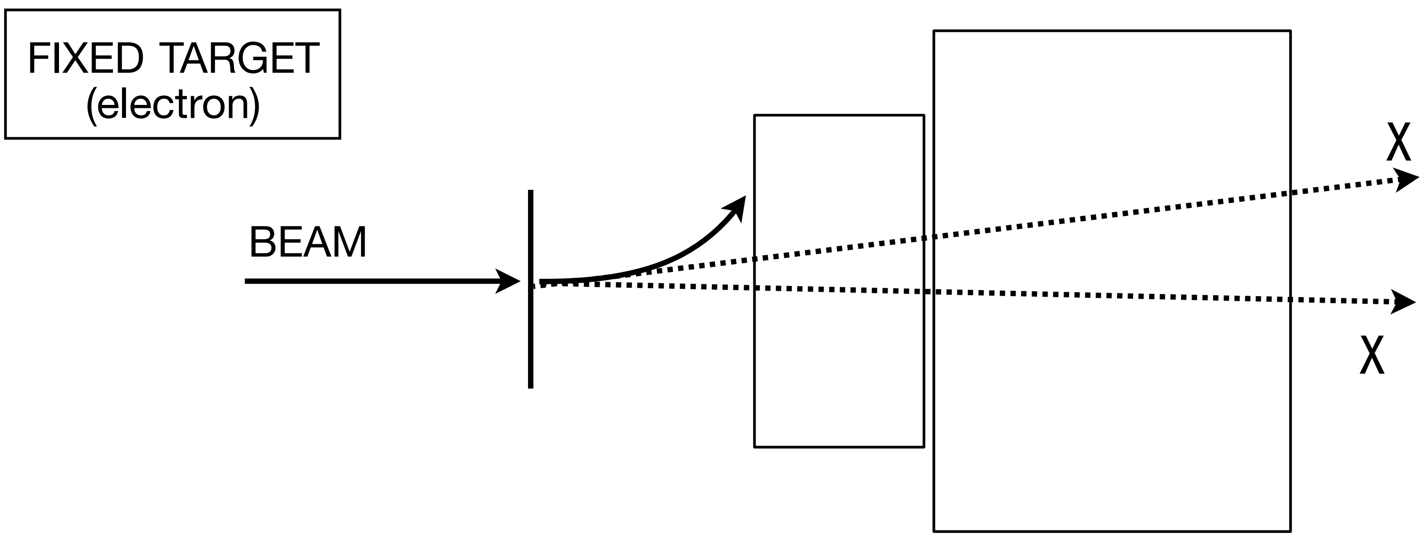
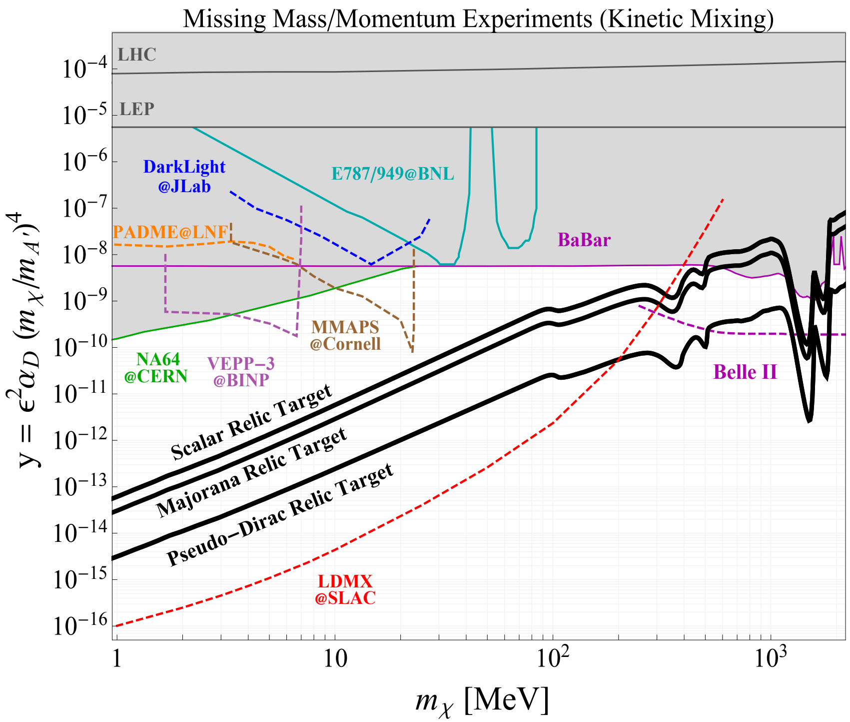


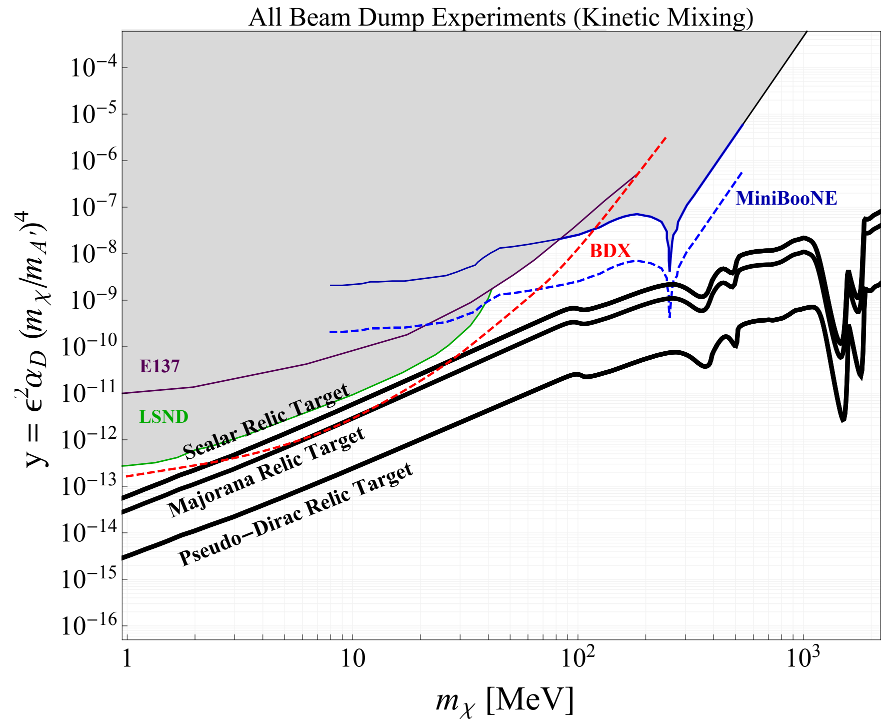
Accelerator Technique Comparison

SOURCE

Missing mass / momentum / energy



Beam dump

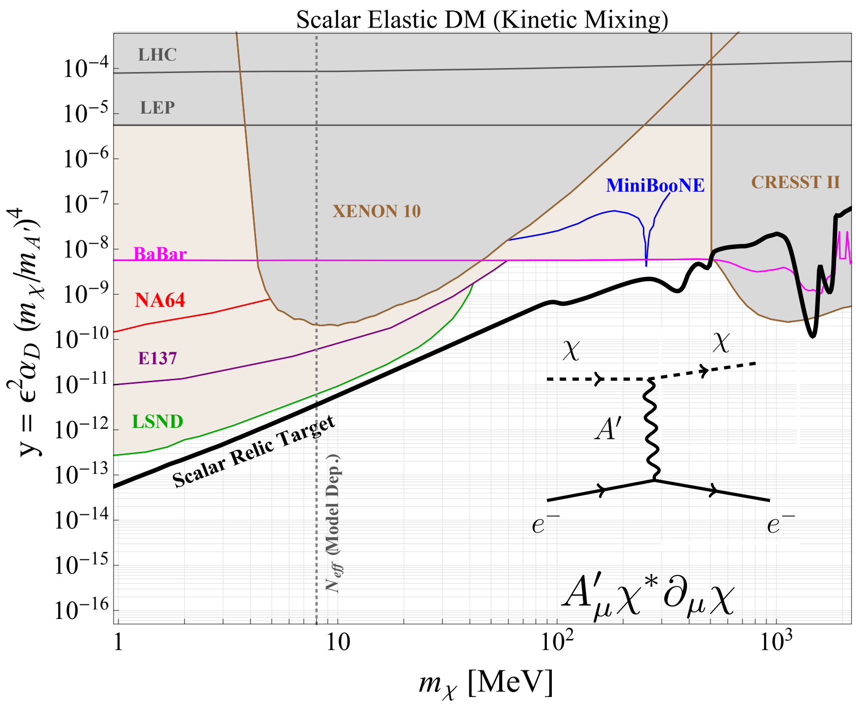


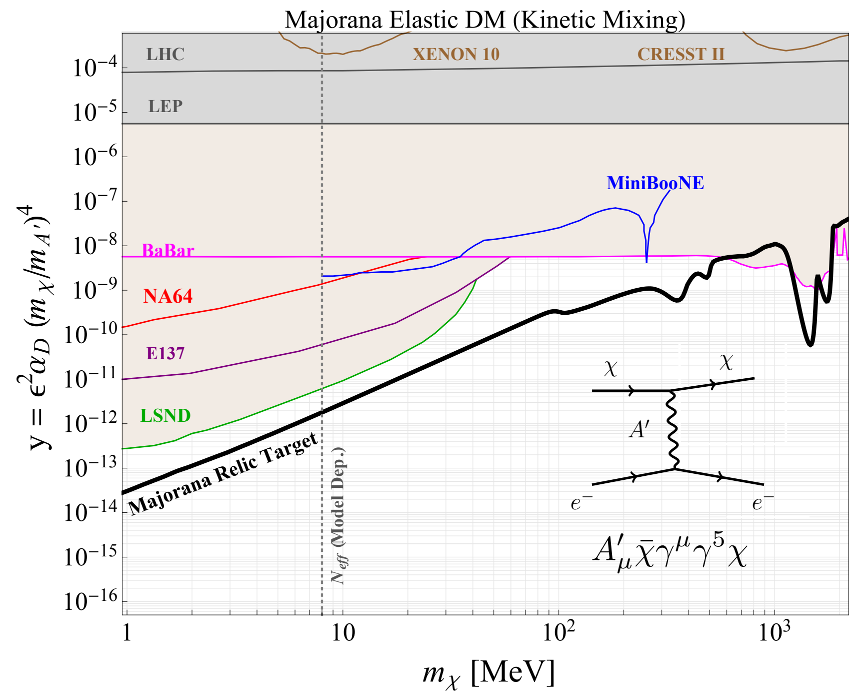
ELECTRON FIXED TARGET (LDMX) A STRONG CANDIDATE FOR ACHIEVING LIGHT THERMAL DARK MATTER TARGETS

Beam requirements: low current (~single electron), high repetition rate
Phase 1/2: $4\times10^{14}/10^{16}$ EoT, O(5-25ns)
Energy: several GeV ~ 10s GeV

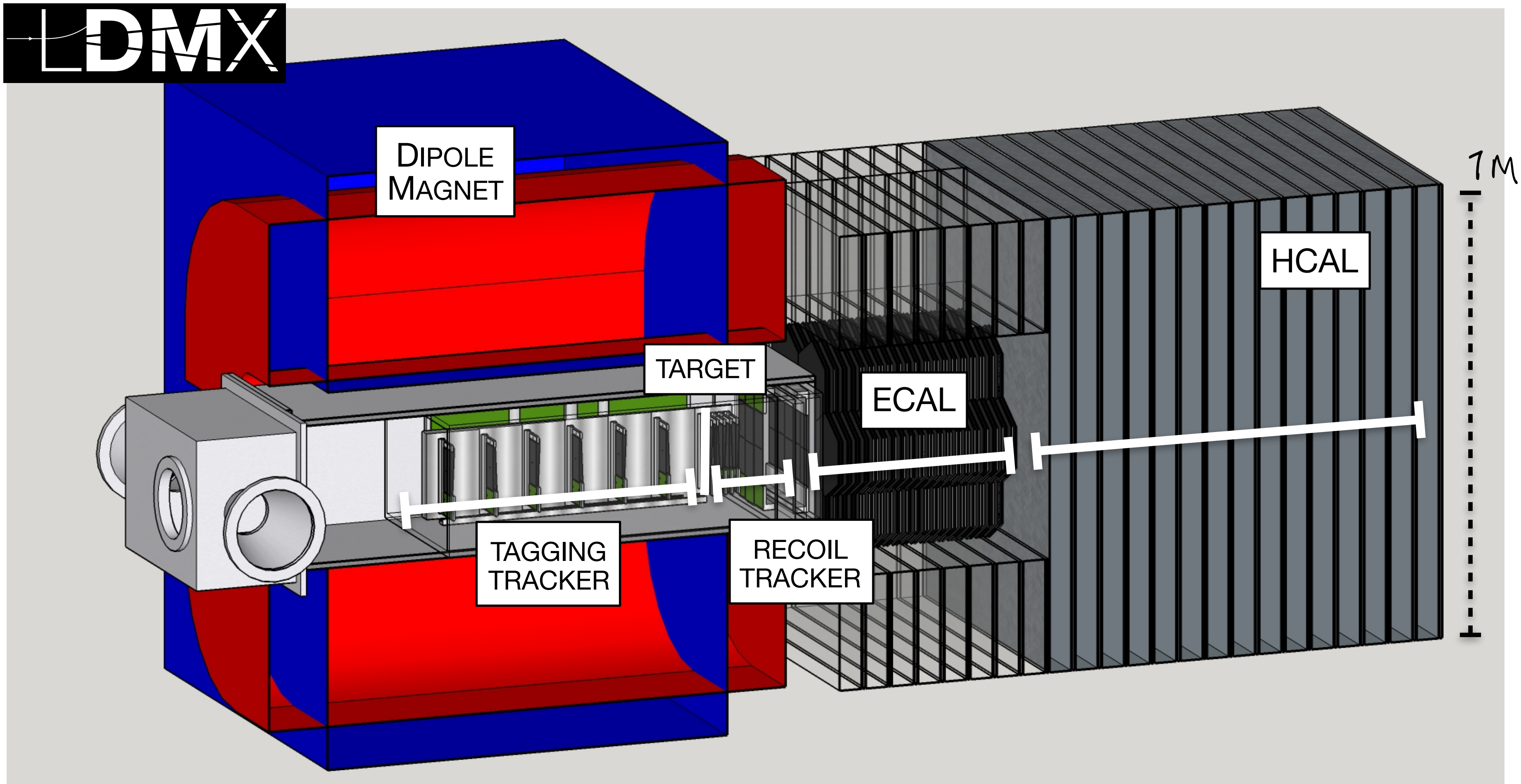
proposed beam, DASEL, at LCLS-II, to meet specs

COMPLEMENTARITY



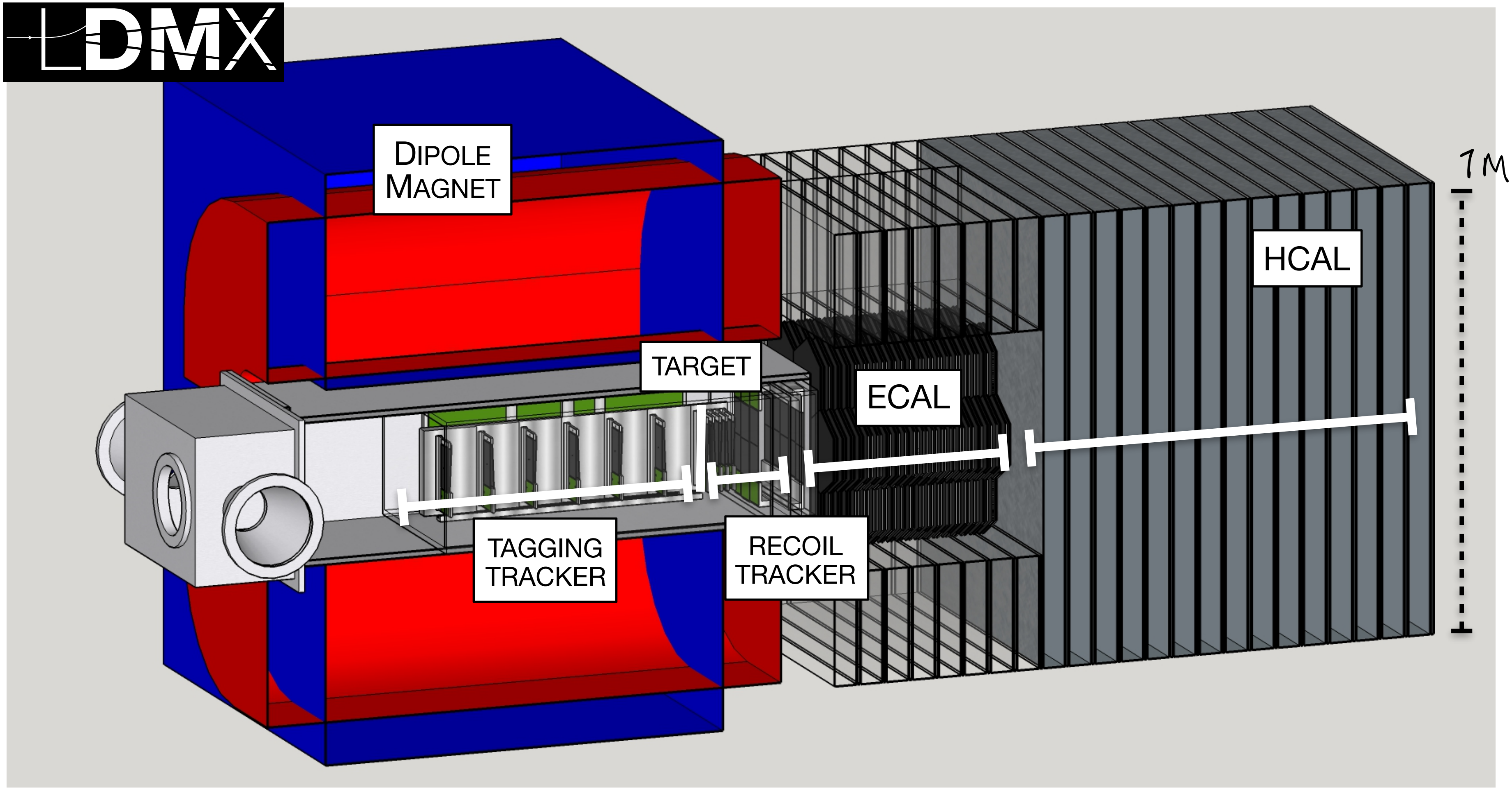


Light Dark Matter eXperiment



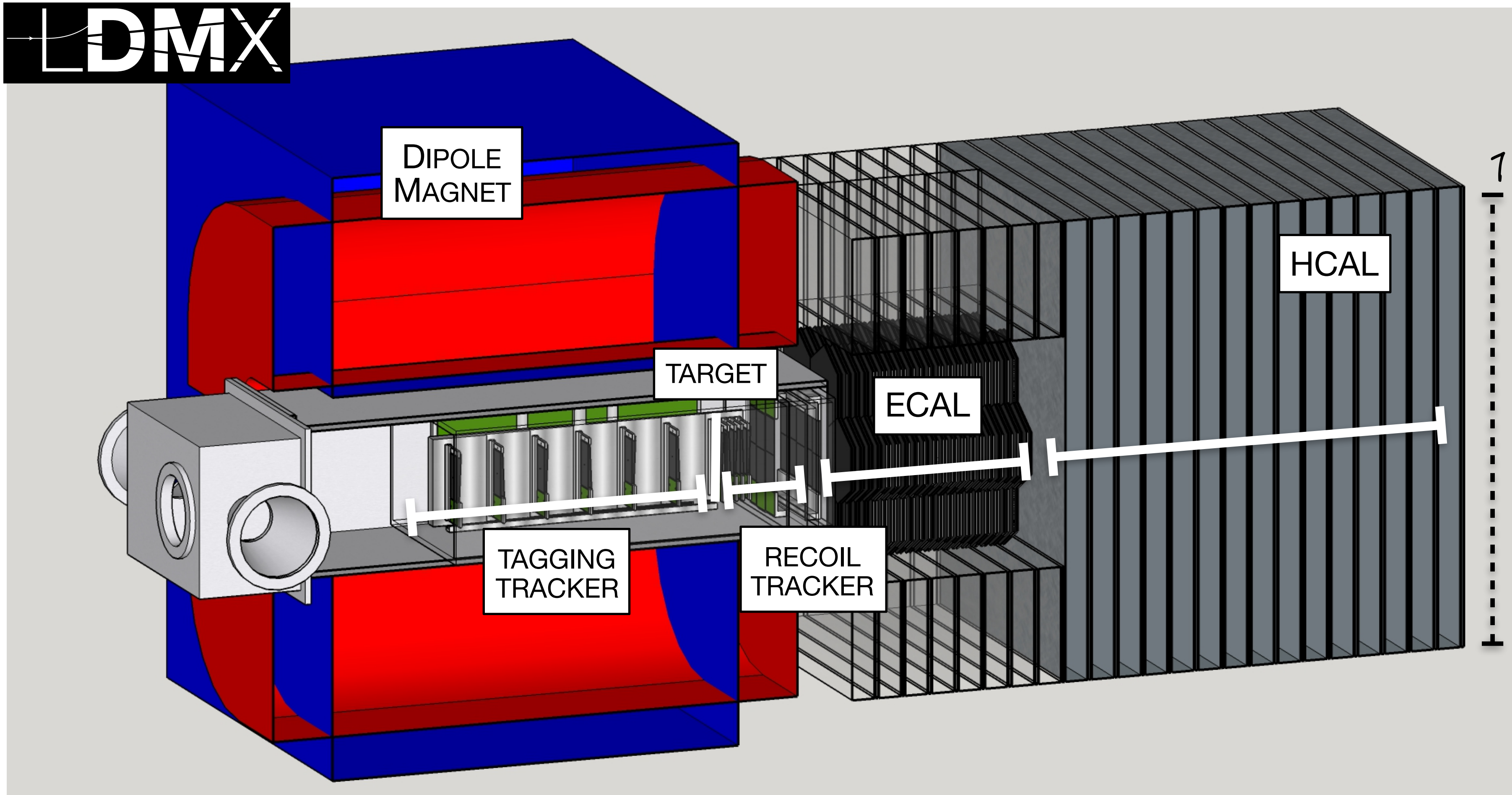
Trackers based on HPS experiment
Tagging tracker makes sure we have 4 GeV electrons coming in

Light Dark Matter eXperiment



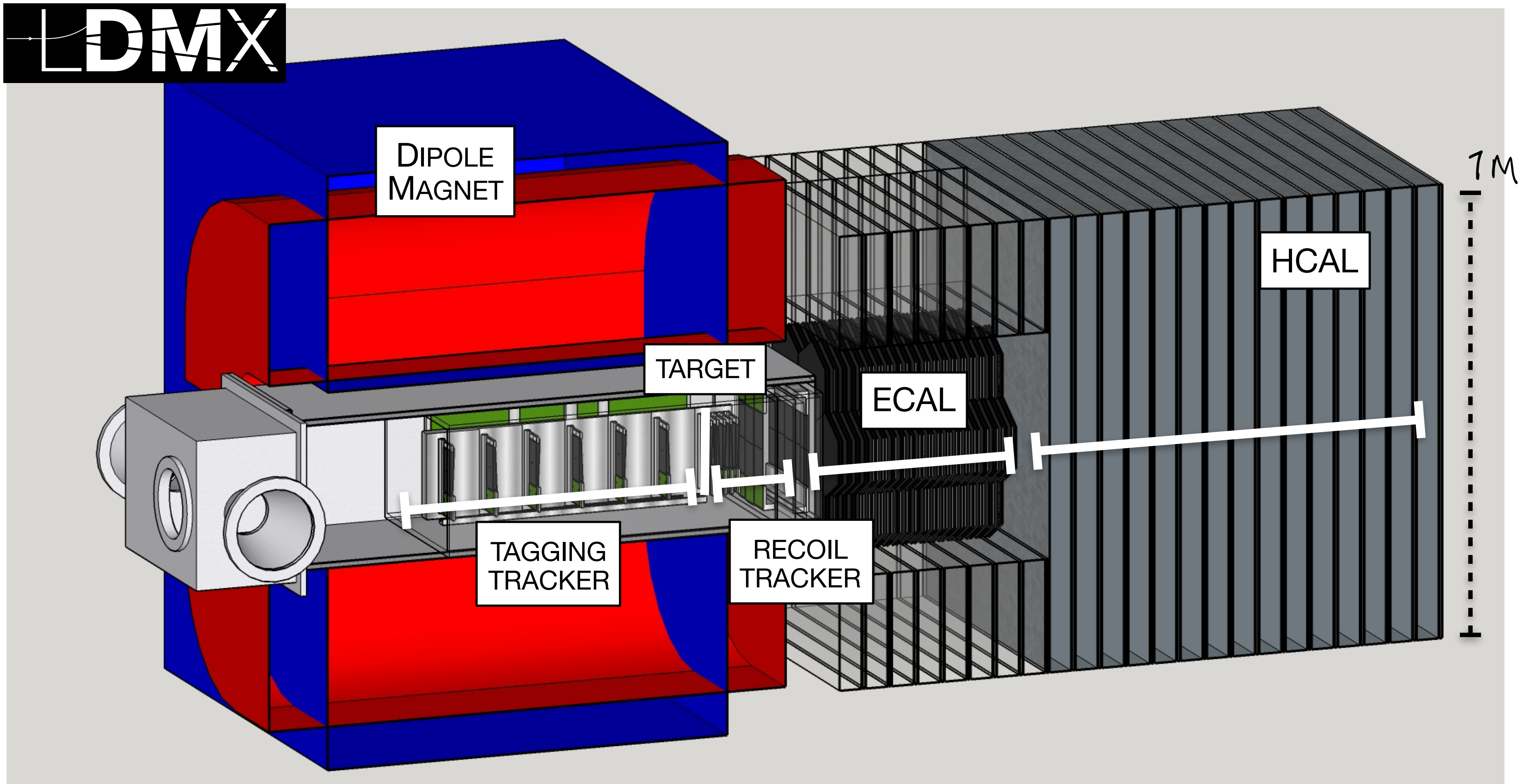
Trackers based on HPS experiment
Recoil tracker measures the recoil electron p_T

Light Dark Matter eXperiment



ECAL is based on CMS phase 2 calorimetry
[W/Si sampling calorimeter]
Si calorimeter has high radiation tolerance and good MIP tracking

Light Dark Matter eXperiment



Hcal is Fe/Scintillator sampling calorimeter

high sampling fraction is good for high efficiency neutron detection

Synergy with LHC calorimeter readout electronics

SUMMARY

Light thermal dark matter: simple, predictive, accessible

A new class of experiments aimed at definitively exploring the light thermal dark matter phase space with **accelerators**

- Complementary to direct detection experiments like Sensei

Fixed target, neutrino, beam-dumps, colliders

- Broad program of production/scattering/decay searches
- Fixed target electron beam experiment, **LDMX**, is a promising approach

NO LOSE THEOREM: GENUINE OPPORTUNITY TO DISCOVER/FALSIFY

BACKGROUND REDUCTION