The LDMX experiment:

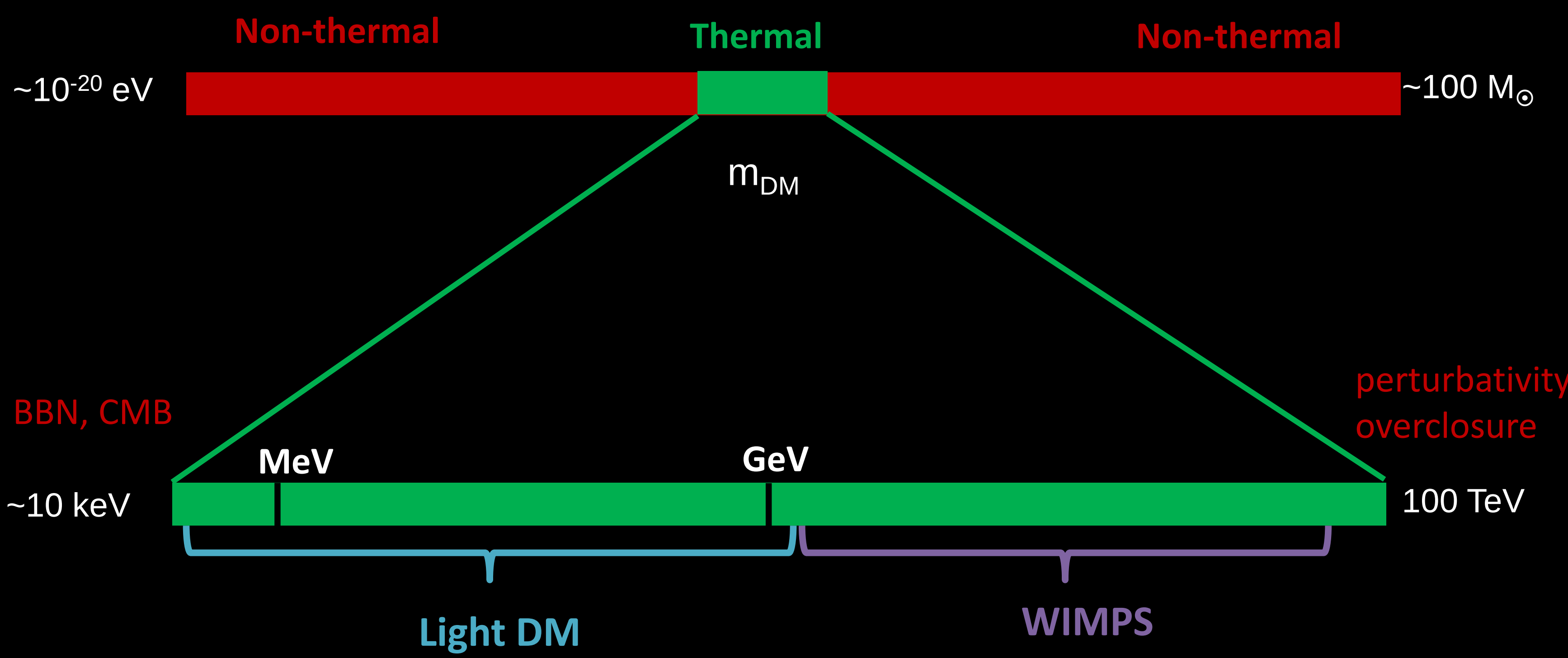
search for light dark matter and new sub-GeV particles

Bertrand Echenard - Caltech

Aspen – March 2018

Thermal dark matter

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



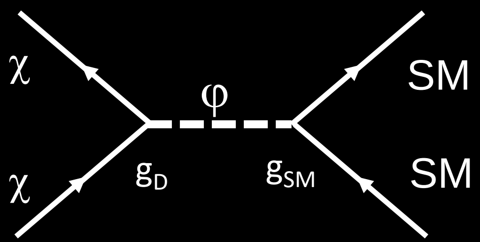
Thermal contact implies new mediator
Hidden sector light DM well-motivated model

Thermal freeze-out for weak scale masses
Driven DM searches for last ~30 years

Focus recently shifted to light DM as WIMP parameter space closes

Light thermal dark matter

Freeze-out scenario with light dark matter (χ) requires new light mediator to explain the relic density, or dark matter is overproduced



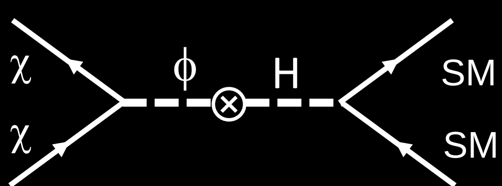
$$< \sigma v >_{relic} \sim \frac{g_D^2\, g_{SM}^2\, m_x^2}{m_\varphi^4} \qquad (m_\varphi \gg m_x)$$

$$m_\varphi^4 \sim \frac{g_D^2\, g_{SM}^2\, m_x^2}{<\sigma v>} \leq \frac{m_x^2}{<\sigma v>} \qquad \text{since } g \leq O(1)$$

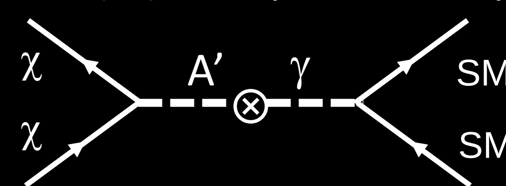
What kind of mediator?

Must be neutral under the SM and renormalizable. Simplest choices:

New scalar (ϕ) with Higgs coupling



New vector (A’) with photon coupling



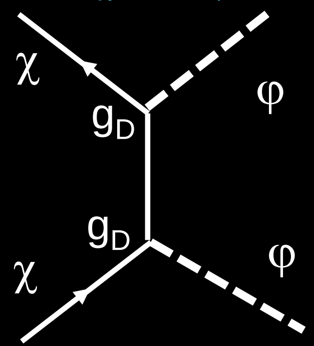
Naturally realized in the context of dark sectors

Light thermal dark matter

The DM / mediator mass ratio determines the type of annihilation and the mediator decay

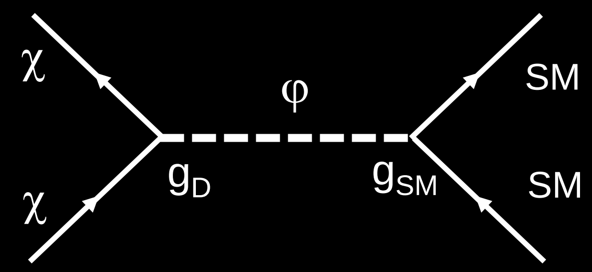
Secluded decay

$m_\chi > m_\varphi$



Direct annihilation

$m_\chi < m_\varphi$



Independent of mediator decays to SM

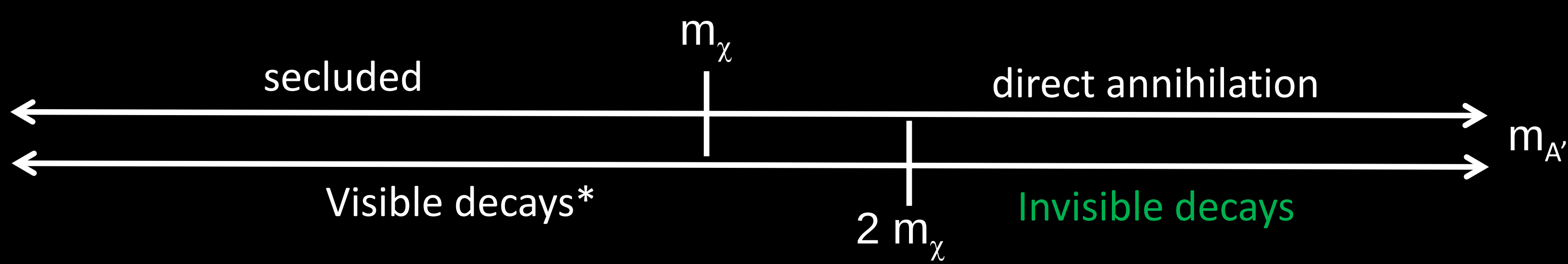
→ no specific target

Not further considered

Define specific target

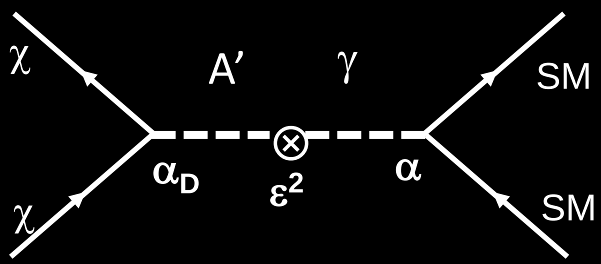
ruled out for scalar mediator**

Direct annihilation with vector mediator



*Look at extra material for visible decay constraints ** arXiv:1512.04119

Hidden sector thermal LDM with vector portal



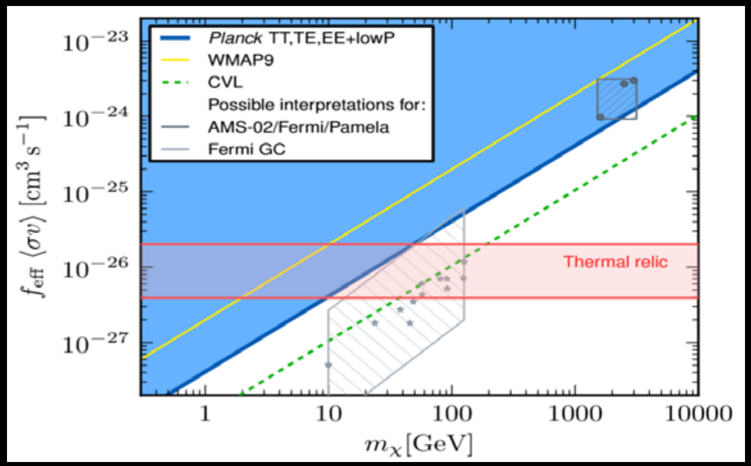
$$< \sigma v > \sim \alpha_D \varepsilon^2 \frac{m_x^2}{m_A^4} \sim \alpha_D \varepsilon^2 \frac{m_x^4}{m_A^4} \frac{1}{m_x^2} = y \frac{1}{m_x^2}$$

$$\boxed{y = \alpha_D\, \varepsilon^2 \frac{m_x^4}{m_A^4}}$$

Dimensionless variable

Cosmological constraints rule out Dirac fermion DM (s-wave annihilation).

Constraints on the self-annihilation cross-section at recombination x efficiency parameter



Planck collaboration, 1502.01589

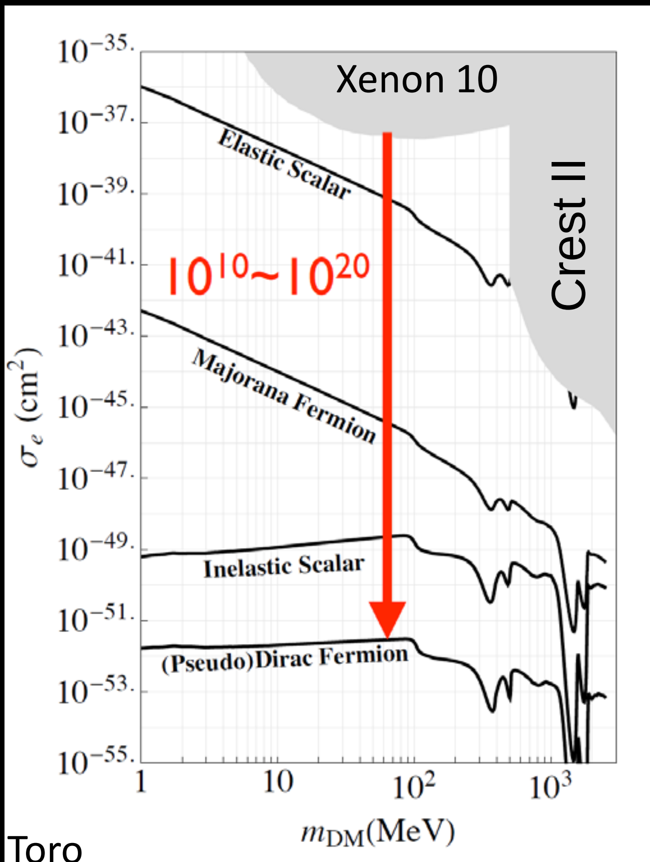
Definitive predictions as a function of mass and particle type !!!

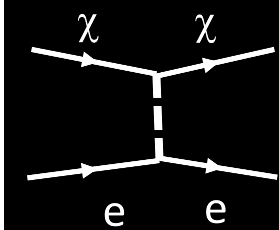
Scalar, Majorana and pseudo-Dirac (inelastic) DM are possible candidates

pseudo-Dirac DM: Dirac fermion whose two Weyl states are split by a small Majorana term

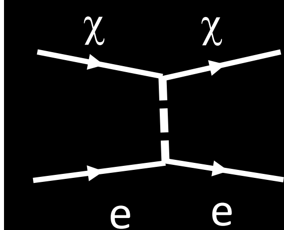
Direct detection and accelerators

Direct detection targets

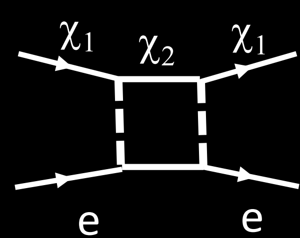




SCALAR
$\sigma_e \sim 10^{-39}$ cm^2



MAJORANA
$\sigma_e \sim 10^{-39} v^2$ cm^2 $v \sim 10^{-3}$

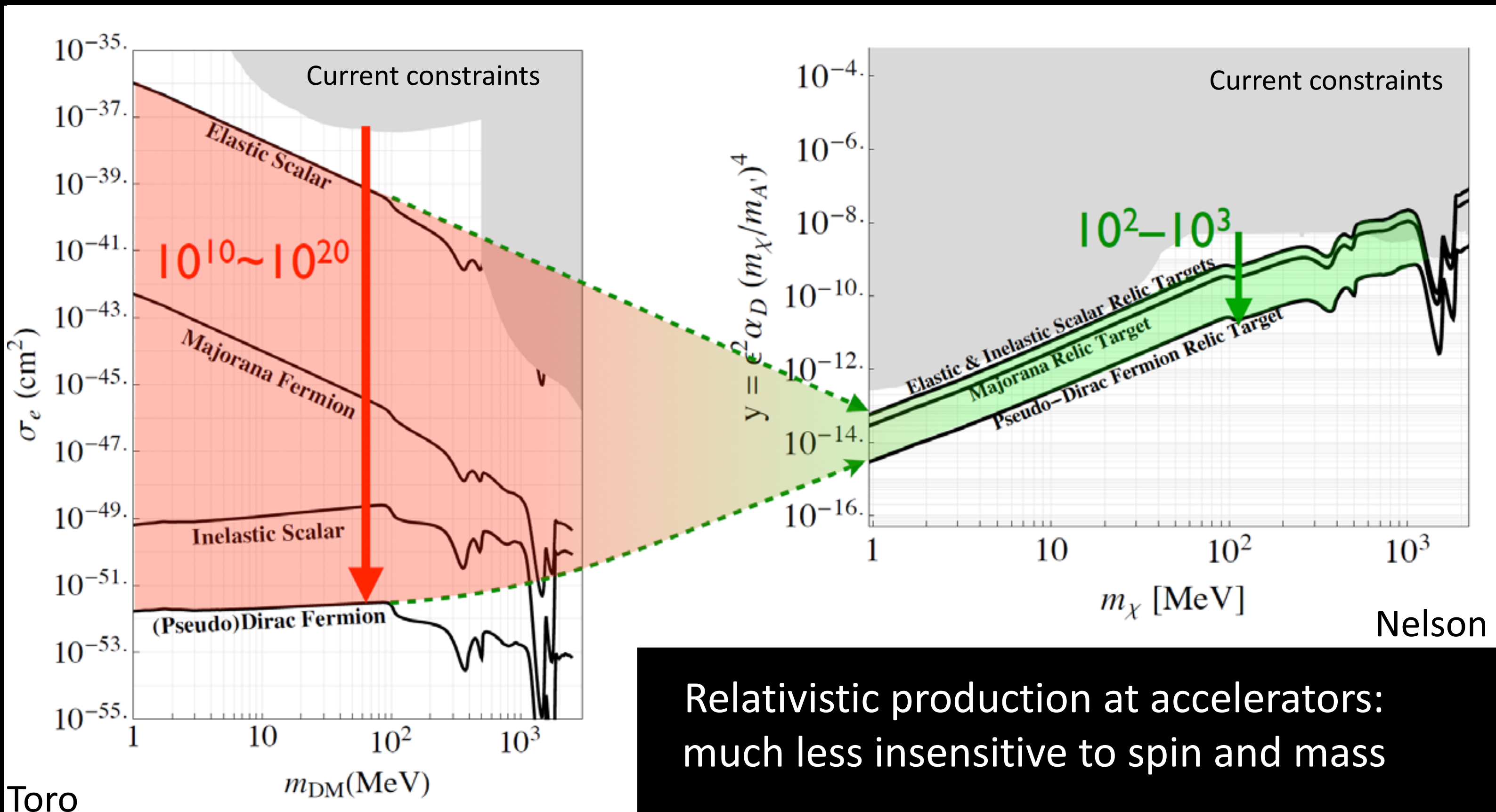


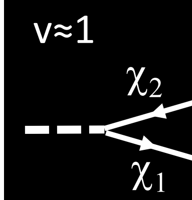
INELASTIC
$\sigma_e \sim 10^{-50}$ cm^2 loop diagram

Is there a way to put these on the same footing?

Direct detection and accelerators

Direct detection targets **Accelerator targets**



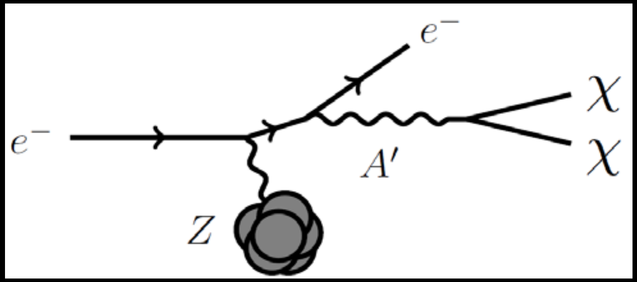


Relativistic production at accelerators:
much less insensitive to spin and mass

Accelerators uniquely positioned to robustly probe directly annihilating thermal LDM

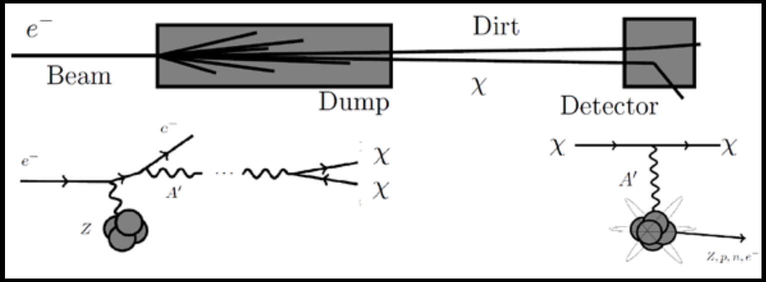
Accelerator approaches

Missing energy / momentum



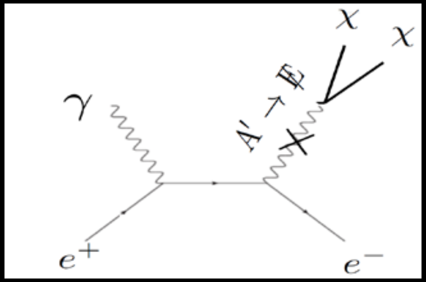
$\sigma \sim Z^2 \varepsilon^2 / m_A^2$

Beam dump



$\sigma \sim \alpha_D \varepsilon^4$

Missing mass



$\sigma \sim \varepsilon^2/s \quad m_A \ll s$

$\sigma \sim \varepsilon^2/(s-m_A^2) \quad m_A \sim s$

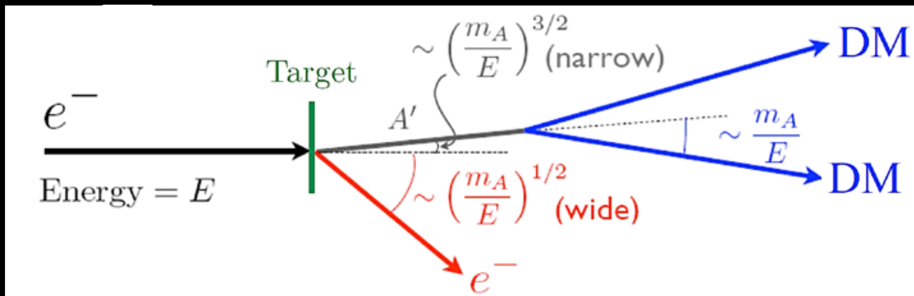
Fixed target
large dark photon yield production for low mediator masses

Missing energy/momentum:
large "detection" yield

Missing energy / momentum maximizes low mass dark matter production and detection. Missing mass provides best yield for larger masses.

Accelerators can access the physics in detail ($\varepsilon, m_{A'}, m_\chi, \alpha_D$),
Direct detection needed to establish cosmological stability

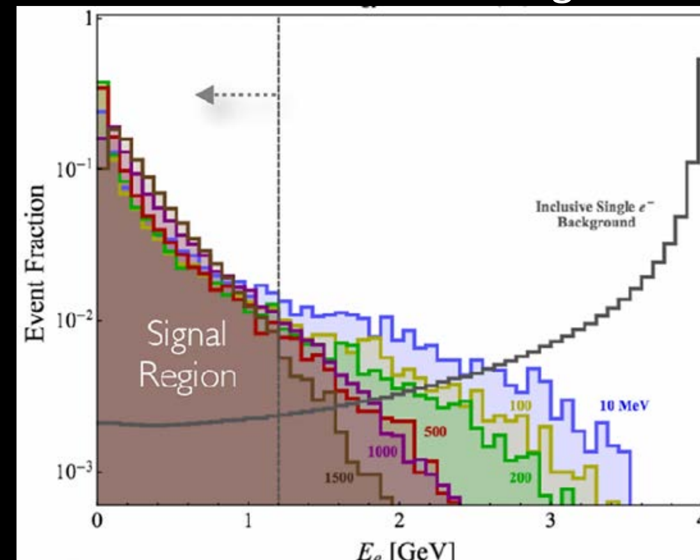
Missing momentum kinematics



$$\frac{d\sigma}{dx} \propto \frac{\alpha^3}{\pi} \frac{\epsilon^2}{m_e^2 \cdot x + m_A^2 (1-x)/x}$$

$$x = \frac{E_A}{E}$$

Recoil energy,
4 GeV *e-* on 10% X_0 target



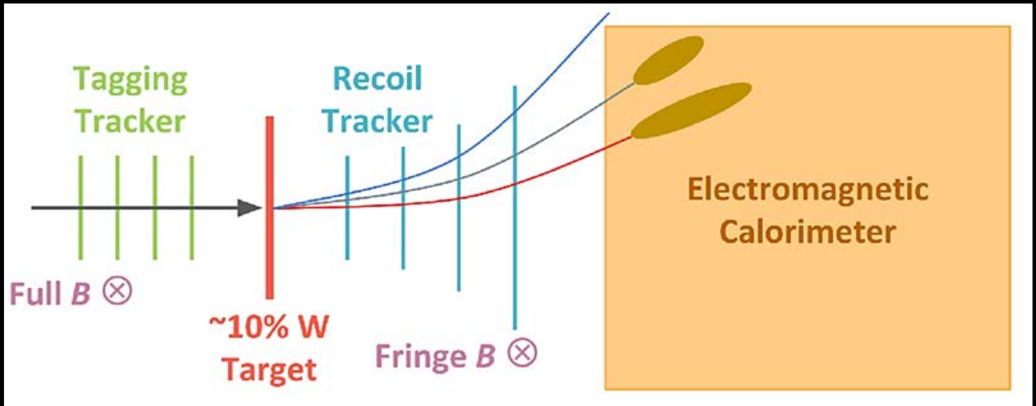
Bremsstrahlung suppressed by factor ~30 is signal region

The kinematics is very different from bremsstrahlung emission.

The A' is emitted at low angle and carries most of the energy, so

- large missing energy, the recoil electron is soft
- large missing p_T, the recoil electron is emitted at large angle

A successful missing momentum design



Beam allowing individual reconstruction of each incident electron

- A multi-GeV, low-current, high repetition rate (10^{16} EOT / year ≈ 1e / 3 ns) beam with a large beam spot to spread out the occupancy / radiation dose.
- DASEL @ SLAC (4/8 GeV) or CEBAF @ JLab (up to 12 GeV) are candidates

Detector technology with high rate capabilities and high radiation tolerance

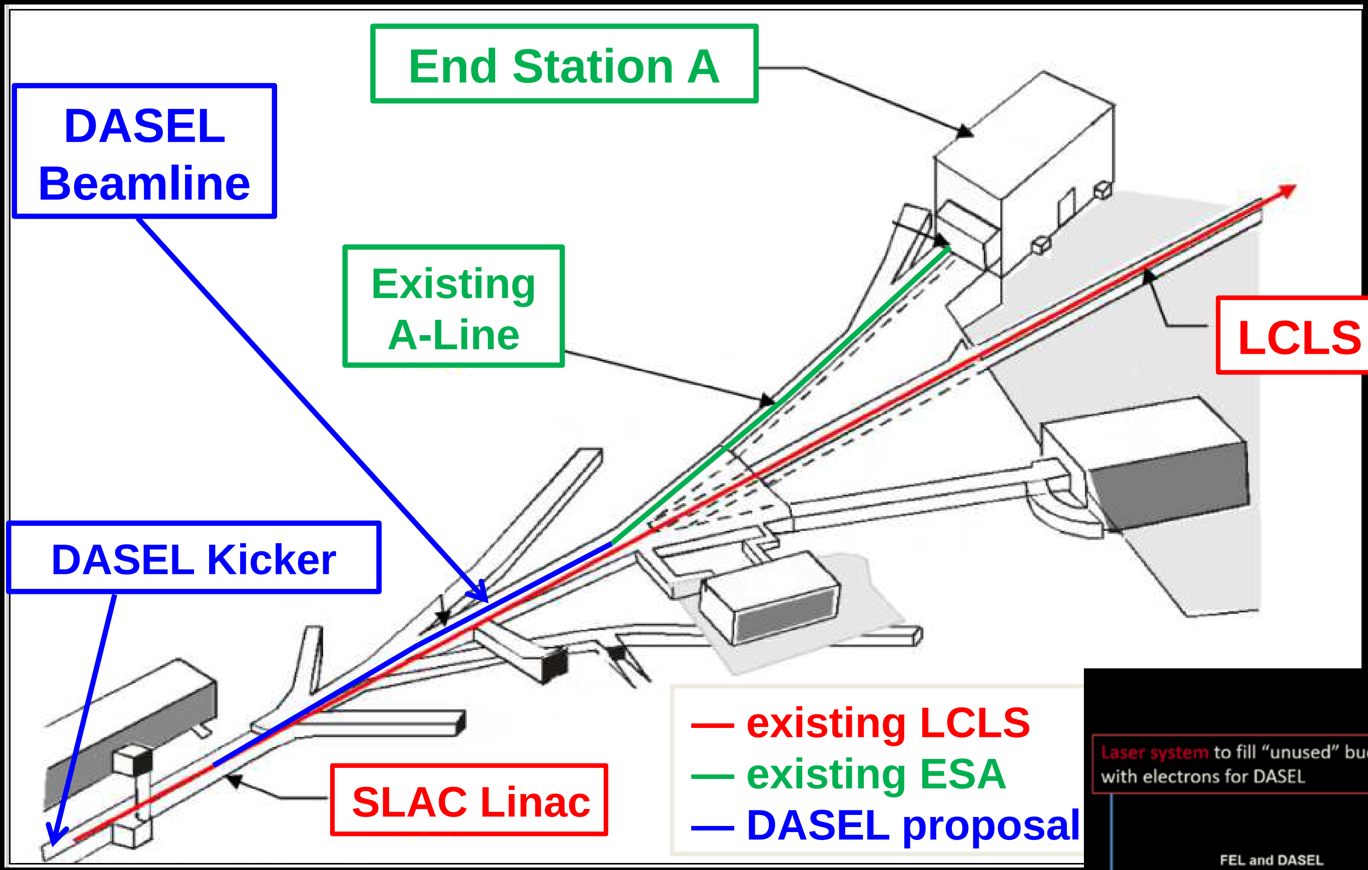
- Fast, low mass tagger / recoil tracker to tag each electron with good momentum resolution
- Fast, granular, radiation-hard EM calorimeter

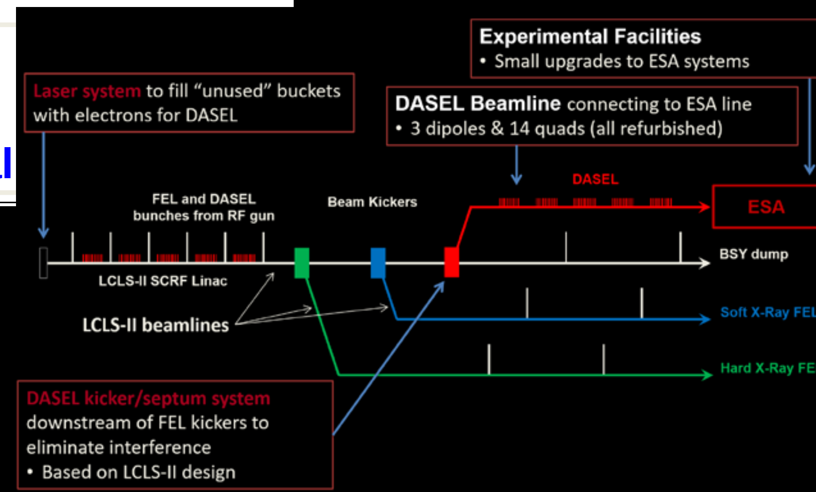
The LDMX experiment has been proposed to realize these design requirements in two phases: Phase-I with 10^{14} EOT (1e- / 25 ns) , and Phase-II with 10^{16} EOT (1e- / 3 ns)

DASEL proposal

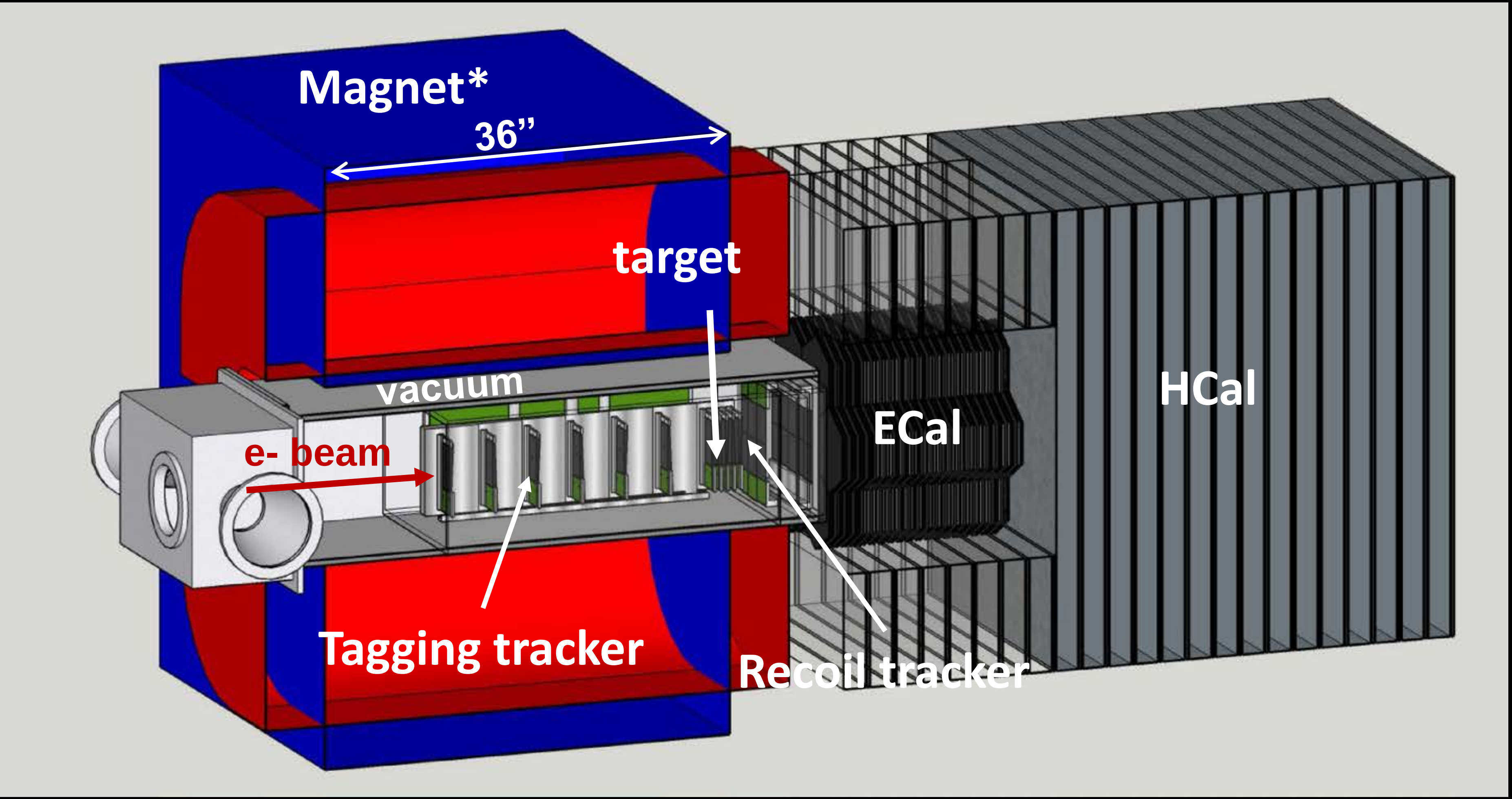
DASEL (Dark Sector at LCLS)

T. Raubenheimer



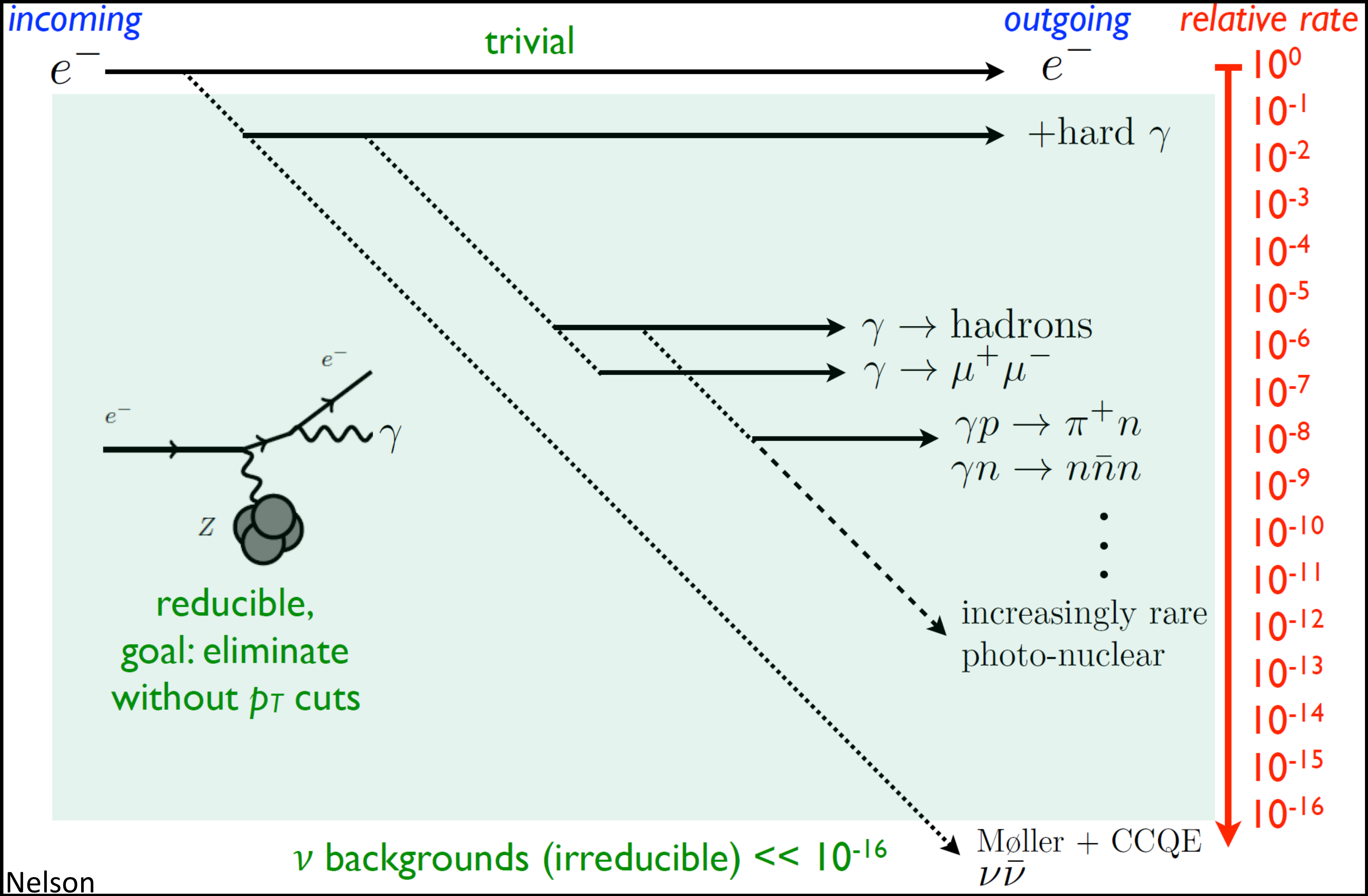


LDMX detector concept – Phase I



* 36’’ magnet readily available at SLAC

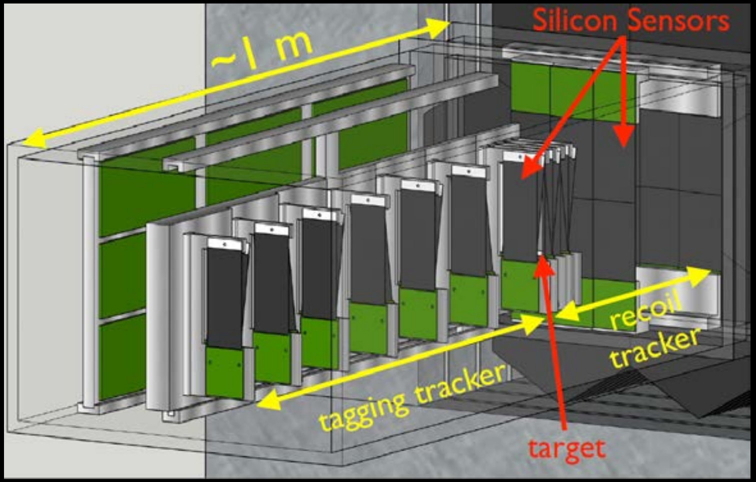
Fighting the backgrounds



Tracking system

Two tracking systems:

- Tagging tracker to measure incoming e-
- Recoil tracker to measure scattered e-

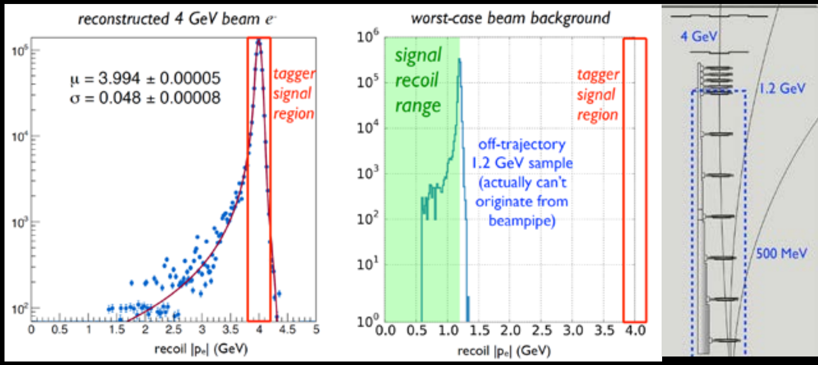


Single dipole magnet, two field regions

- Tagging tracker placed in the central region for p_e = 4 GeV,
- Recoil tracker in the fringe field for p_e ~ 50 – 1200 MeV

Silicon tracker similar to HPS SVT

- Fast (2ns hit time) and radiation hard



Tungsten target between the two trackers

- 0.1-0.3 X_0 thickness to balance between signal rate and momentum resolution
- Scintillator pads at the back of target to veto empty events

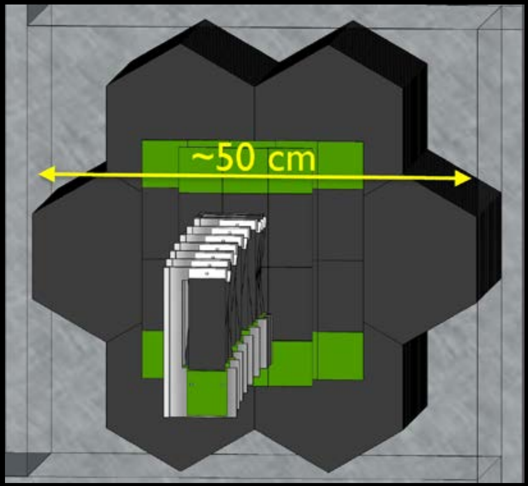
Tagging tracker efficiently rejects beam-induced background while keeping a good acceptance for the signal (50% - 95% depending on the A’ mass)

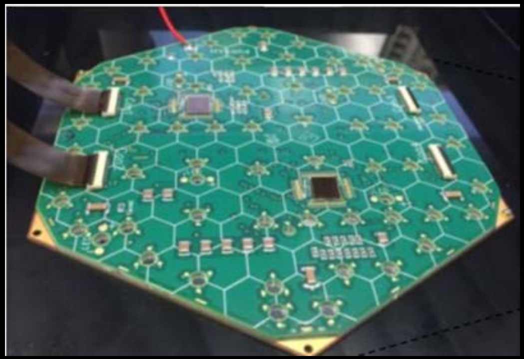
EM calorimeter

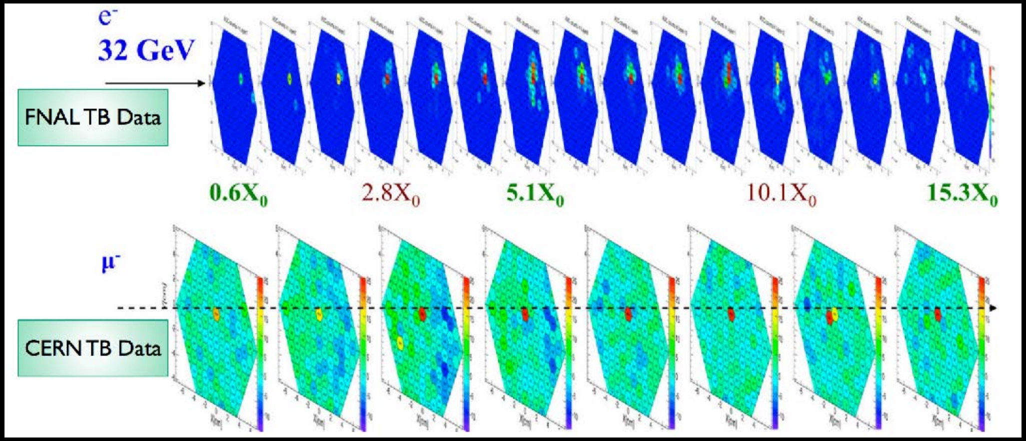
Si-W sampling calorimeter

- Fast, dense and radiation hard
- 40 X_0 deep for extraordinary containment
- High granularity, exploit transverse & longitudinal shower shapes to reject background events
- Can provide fast trigger

Currently developed for CMS upgrade, adaptable to LDMX

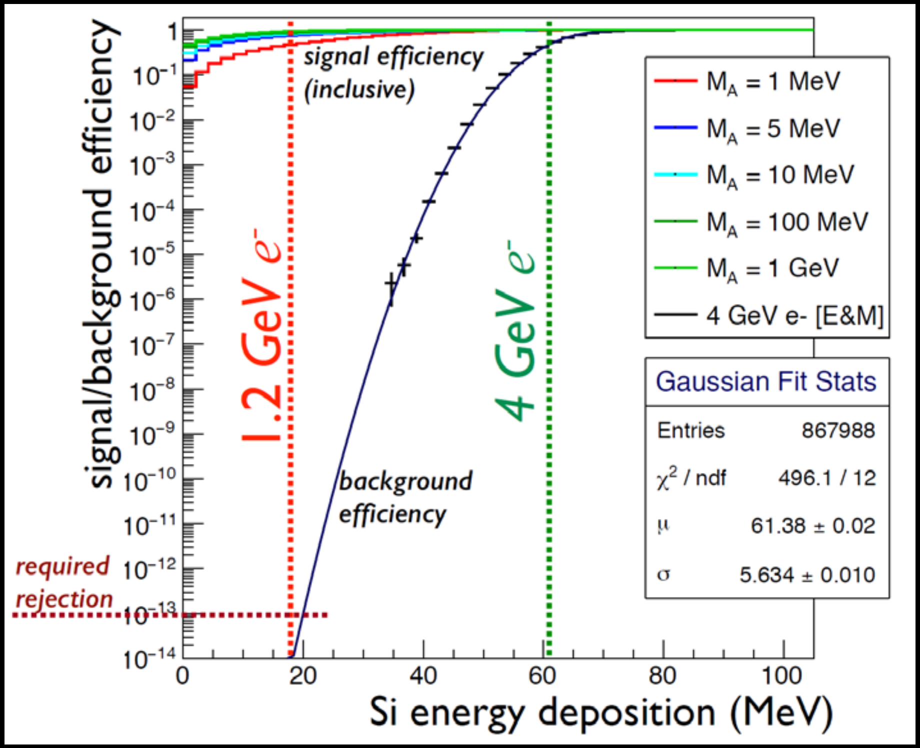






High granularity enables muon vs. electron discrimination, important to reject $\gamma \rightarrow \mu\mu$ bkg

EM calorimeter



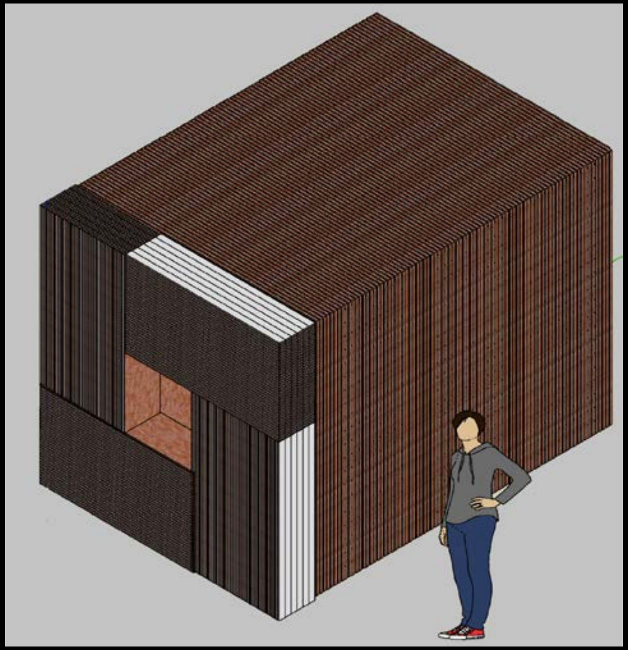
Preliminary studies show that even without using shower shape, the ECAL can reject EM background (4 GeV e- + γ) from signal (E_e < 1.2 GeV) at the level required for Phase I.

On-going work to include shape information and substantially improve the ECAL performance

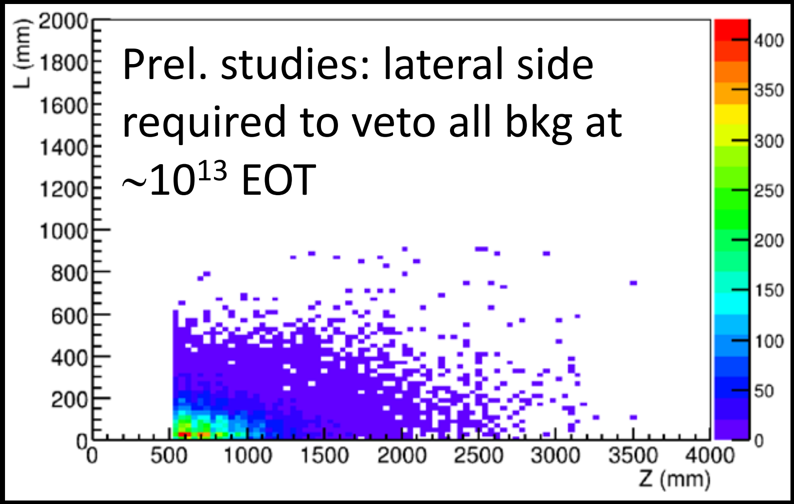
Hadronic calorimeter

Steel / plastic scintillator sampling calorimeter

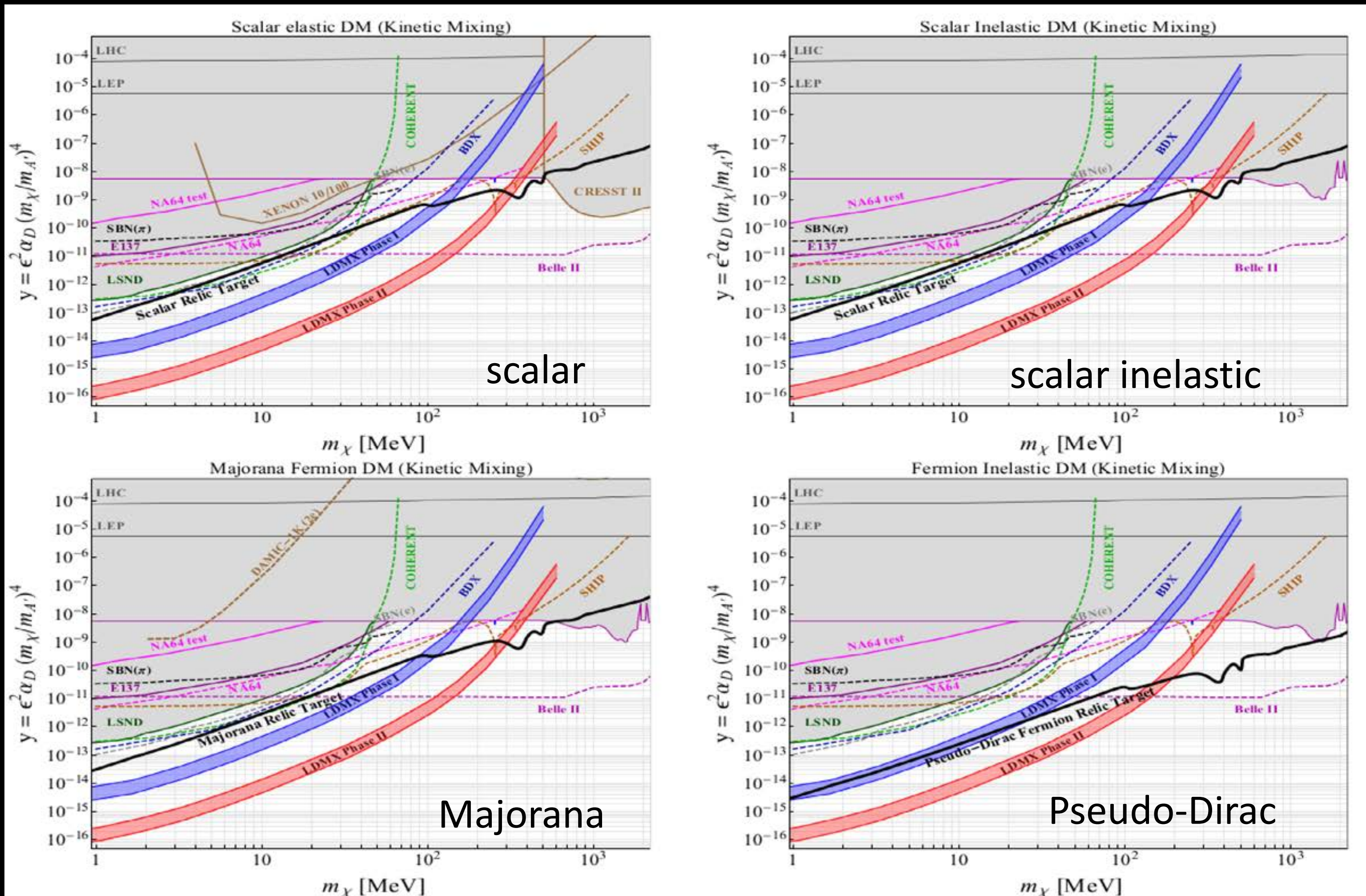
- Surround ECAL as much as possible
- Catch hadrons from PN events, in particular PN events emitting several hard neutrons (e.g. $\gamma n \rightarrow n\bar{n}n$) or many softer neutrons
- Catches wide angle bremsstrahlung, and generally helps with overall veto



On-going studies to determine the best design parameters and general layout. Scintillator read out by SiPM and WLS fibers.



Sensitivity estimates

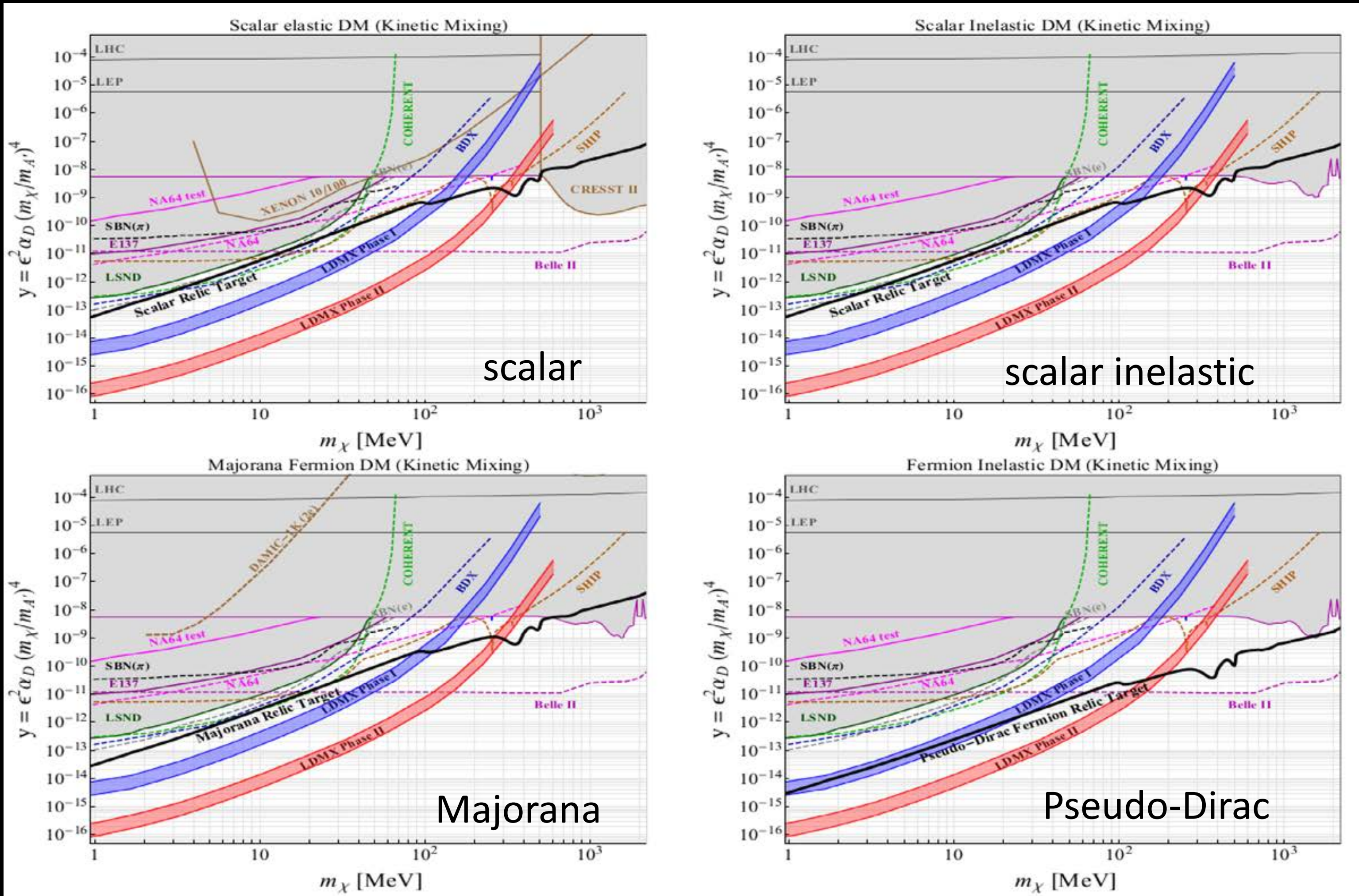


No bkg
α_D = 0.5
m_A/m_χ = 3

The parameters α_D = 0.5, m_A/m_χ = 3 lead to the weakest constraints, i.e. conservative exclusion regions.

For smaller values of α_D or larger mass ratio, the constraints go down while the targets are invariant.

Sensitivity estimates



No bkg
$\alpha_D = 0.5$
$m_A/m_\chi = 3$

Phase I 10^{14} EOT @ 4 GeV probes scalar, Majorana and scalar inelastic DM

Phase II 10^{16} EOT @ 8 GeV probes Pseudo-Dirac DM

Unprecedented sensitivity surpassing all existing and projected constraints by orders of magnitude for DM masses below a few hundred MeV.

And many other interesting possibilities…

LDMX would be sensitive to a much broader array of physics!

The experiment could be seen as an ultra-short baseline beam dump experiment, which would be sensitive to a broad array of physics:

- Quasi-thermal DM, such as asymmetric DM and ELDER DM
- New long-lived resonances produced in the dark sector (e.g. SIMP)
- New force carriers coupling to electrons, decaying visibly or invisibly (incl. A’)
- Milli-charged dark sector particles (EDGES)
- Axions
- ….

and could perform photonuclear & electronuclear measurements useful for future neutrino experiments.

In essence, LDMX could generically probe a vast array of possibilities in addition to light thermal DM in the sub-GeV mass range.

LDMX collaboration

SLAC NATIONAL ACCELERATOR LABORATORY — Norman Graf, Jeremy McCormick, Takashi Maruyama, Omar Moreno, Tim Nelson, Philip Schuster, Natalia Toro

UCSB — Owen Colegrove, Joe Incandela, Gavin Niendorf, Alex Patterson, Melissa Quinnan

UNIVERSITY OF MINNESOTA — Josh Hiltbrand, Jeremy Mans, Reese Petersen, Michael Revering

Fermilab — Gordan Krnjaic, Nhan Tran, Andrew Whitbeck

Caltech — Bertrand Echenard, David Hitlin

UC SANTA CRUZ — Robert Johnson

LUND UNIVERSITY — Torsten Åkesson, Ruth Pottgen

Take away messages

The thermal paradigm is arguably one of the most compelling DM candidate, and the broad vicinity of the weak scale is a good place to be looking – logical extension of WIMP

Accelerator based experiments are in the best position to decisively test all simplest scenarios of light dark matter - and could reveal much of the underlying dark sector physics together with direct detection experiments

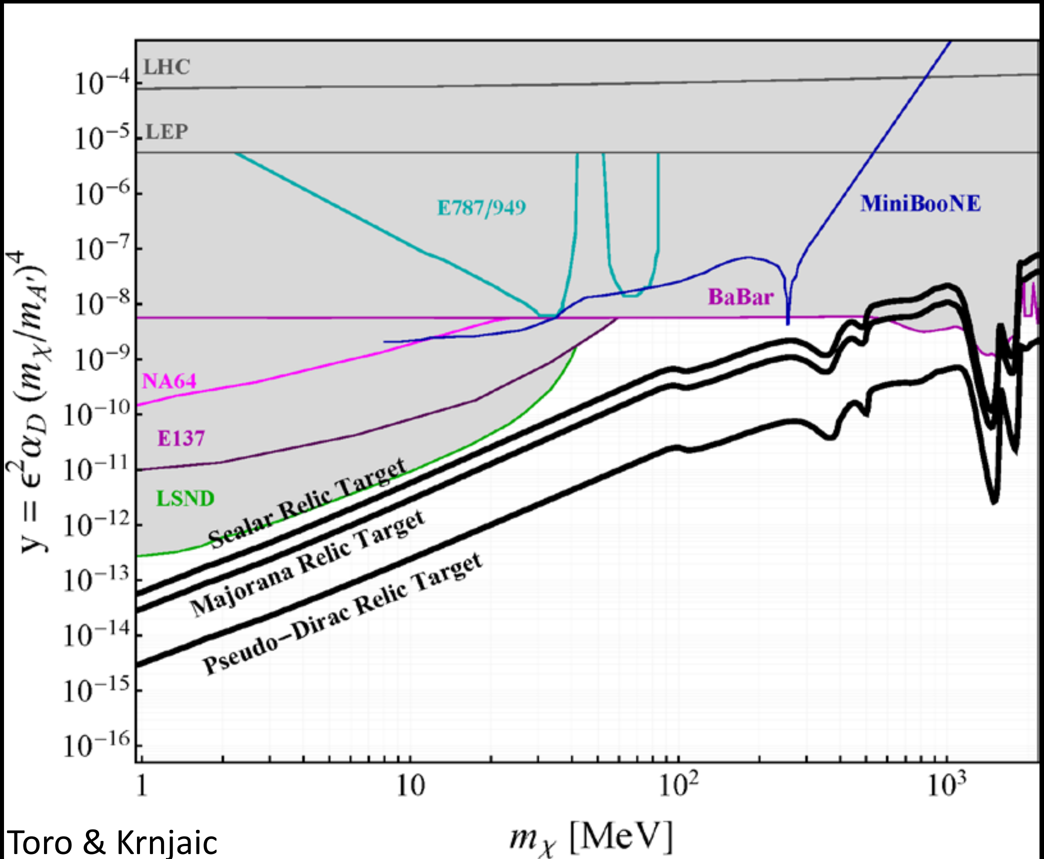
LDMX would offer unprecedented sensitivity to light DM, surpassing all existing and projected constraints by orders of magnitude for DM masses below a few hundred MeV.

More generally, the experiment will be able to explore a broad array of sub-GeV physics, and could also perform photonuclear & electronuclear measurements useful for planned neutrino experiments.

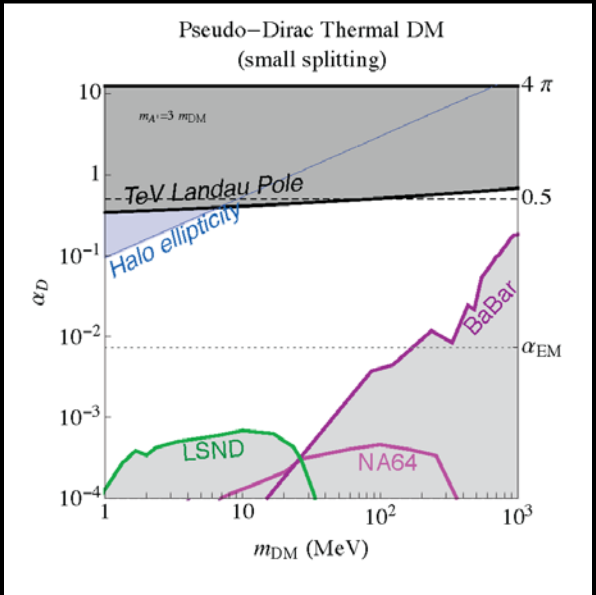
We are currently writing a comprehensive "design study" paper and we hope to be ready for publication in the coming months. Stay tuned…

Extra material

Current constraints



Toro & Krnjaic



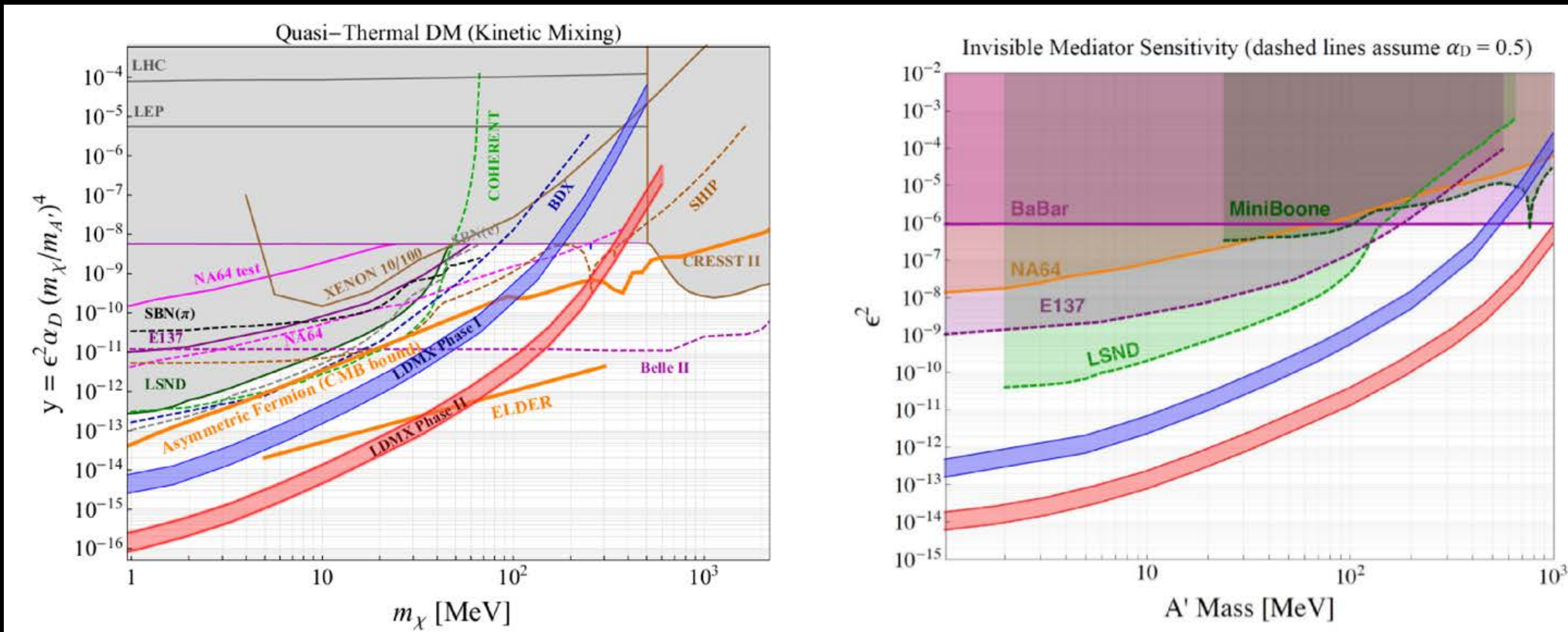
Some assumptions need to be made to plot constraints from missing mass / momentum / energy experiments. We pick very conservative parameters: α_D = 0.5 and m_A/m_χ = 3.

These parameters lead to weak(est) constraints. For smaller values of α_D or larger mass ratio, the constraints go down while the targets are invariant.

pseudo-Dirac DM: Dirac fermion whose two Weyl states are split by a small Majorana term

Sensitivity estimates

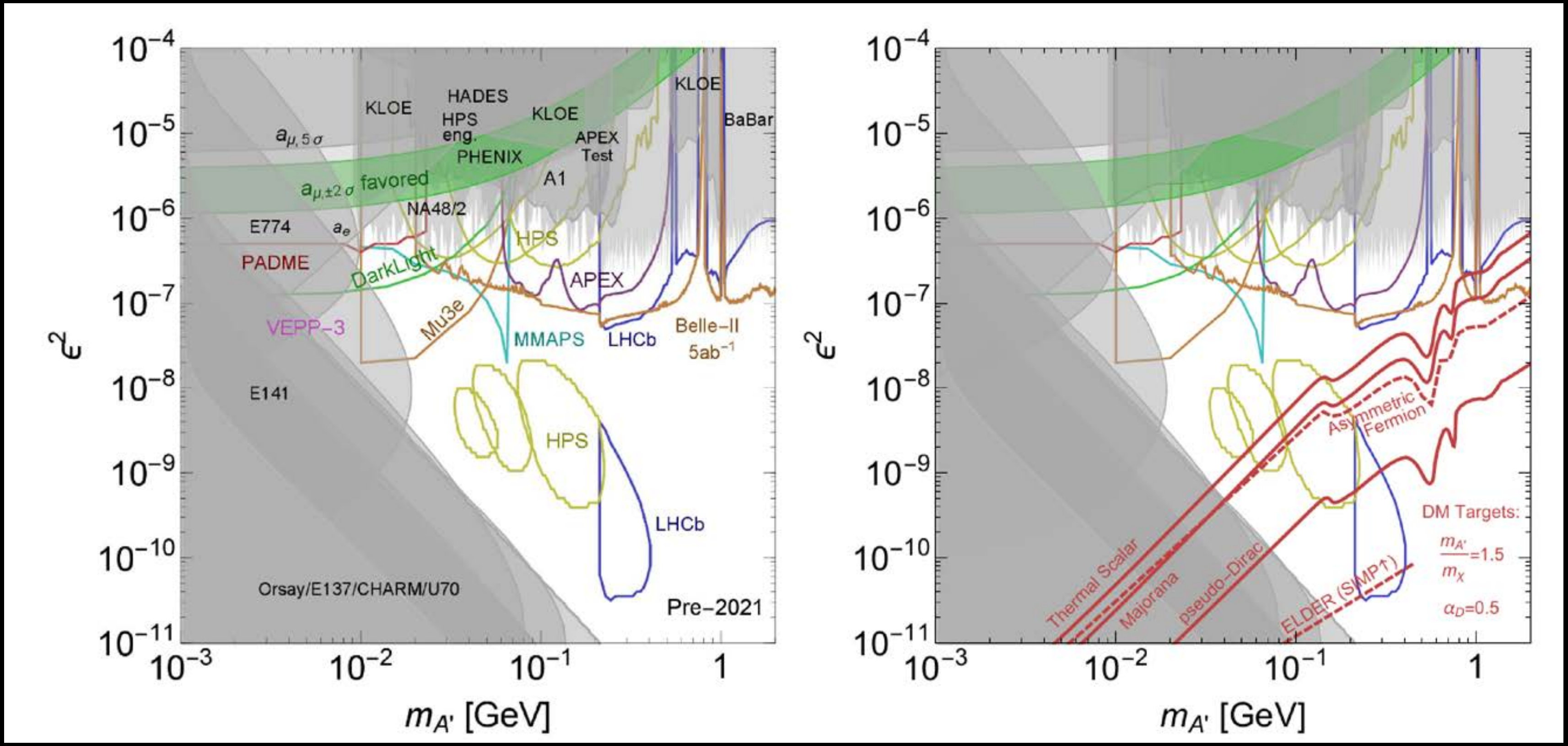
US cosmic vision report arXiv: 1707.04591



LDMX can also explore DM with quasi-thermal origins, e.g. asymmetric DM or SIMP/ELDER scenarios, and improve the sensitivity on invisible A' decays.

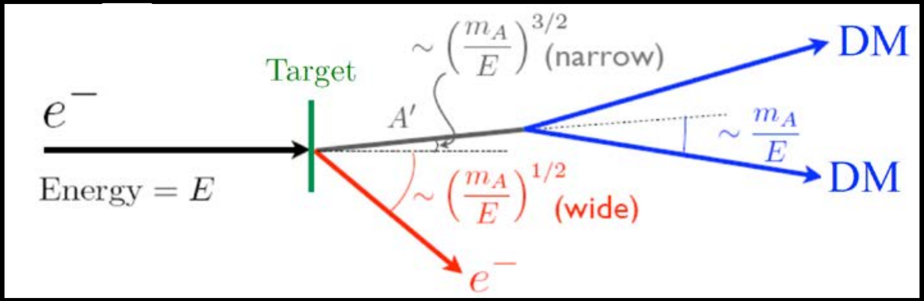
Visible decays

Toro & Essig



Visible decays searches ($m_\chi < m_{A'} < 2m_\chi$) will start probing the thermal DM, asymmetric and ELDER targets in the near future as well

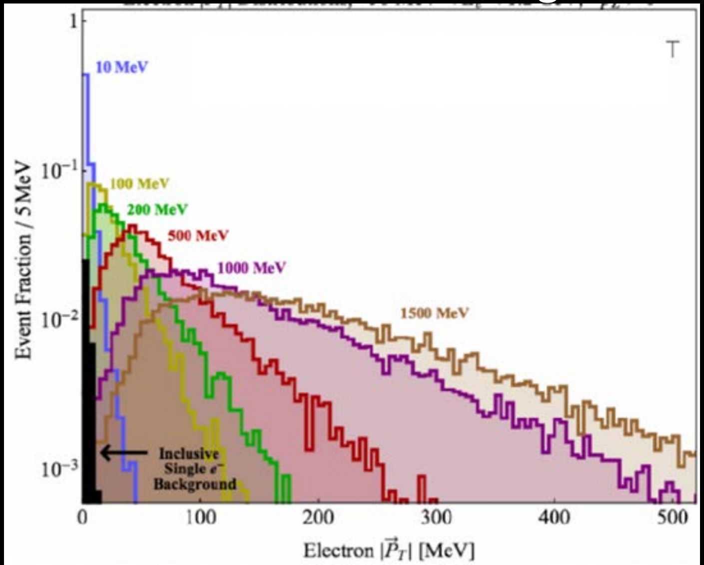
Missing momentum kinematics



$$\frac{d\sigma}{dx} \propto \frac{\alpha^3}{\pi} \frac{\epsilon^2}{m_e^2 \cdot x + m_A^2(1-x)/x}$$

$$x = \frac{E_A}{E}$$

Recoil p_T,
4 GeV *e-* on 10% X_0 target



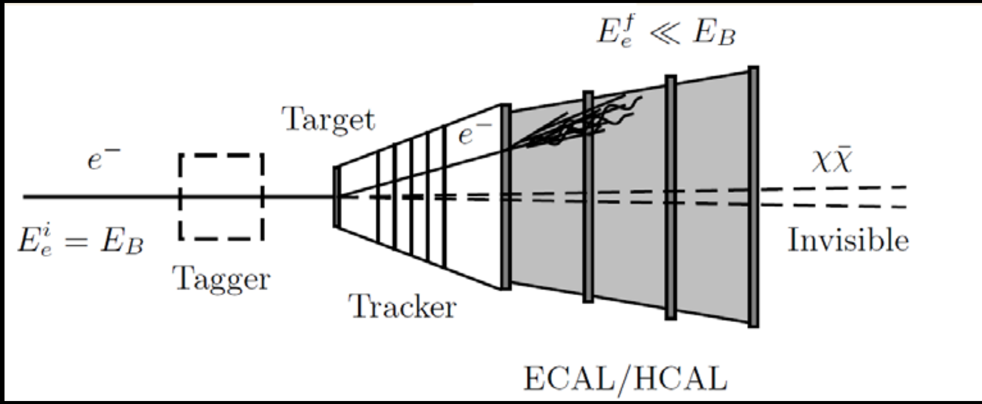
Clear separation from
Bremsstrahlung background

The kinematics is very different from bremsstrahlung emission.

The A’ is emitted at low angle and carries most of the energy, so

- large missing energy, the recoil electron is soft
- large missing p_T, the recoil electron is emitted at large angle

Missing energy / momentum



Missing energy:

- Higher signal yields / EOT
- Greater acceptance
- Backgrounds beyond 10^{14} EOT might require e-γ identification

Missing momentum:

- Reconstruct outgoing electron, better bkg rejection
- p_T spectrum sensitive to $m_{A'}/m_{\chi}$
- Lower signal yield / ETO

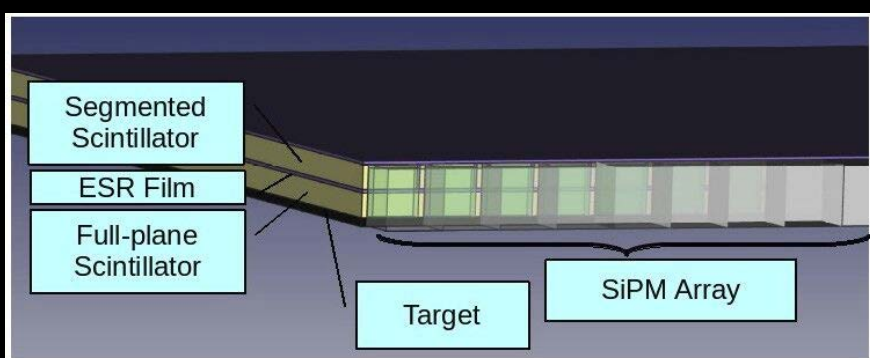
A missing momentum experiment can also perform a missing energy measurement!

Trigger

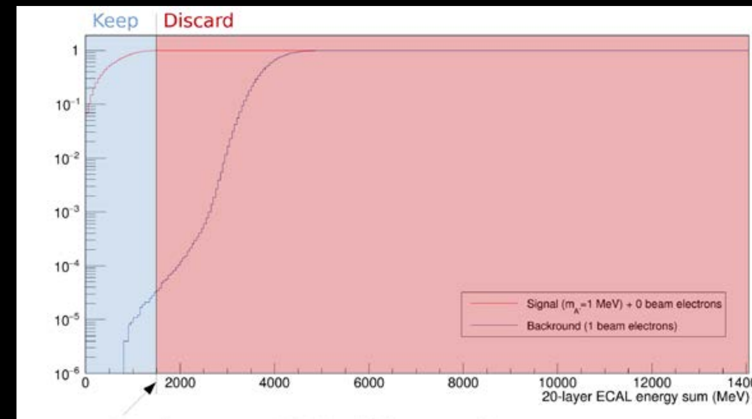
Trigger systems

- Reject beam-energy backgrounds (non-interacting e-, bremsstrahlung,…)
- Sum energies of the first 20 layers of Ecal
- Scintillator behind target to suppress empty events

Signal efficiency 50-100% with 10^{-4} bkg rejection



Sum energies of the first 20 layers of Ecal with recoil electron E < 1.2 GeV



Signal acceptance