Exploring light dark matter with the LDMX experiment

Bertrand Echenard
Caltech

University of Virginia – April 2019

Outline

Introduction

Light thermal dark matter
Direct detection and accelerators

Light dark matter at accelerators

Collider, fixed target and beam dump experiments
A few recent results

The LDMX proposal

Design and sensitivity
Physics program
Beamlines

Summary

Dark matter: an old puzzle

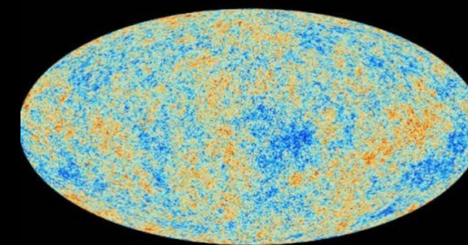
In 1933, Zwicky posited the existence of unseen "dark" matter after analyzing the velocity dispersion of galaxies in the coma cluster

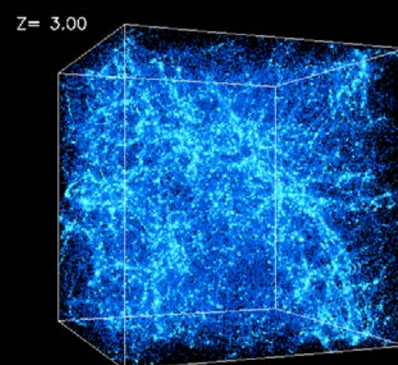
Coma cluster SDSS

Since then, we have collected strong evidence for dark matter

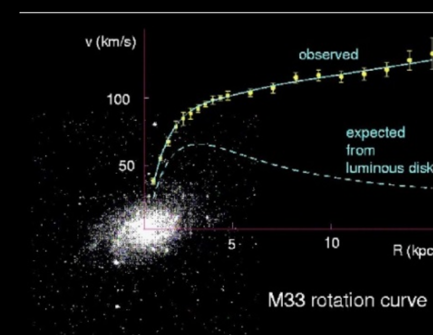
Lensing

CMB





Structure

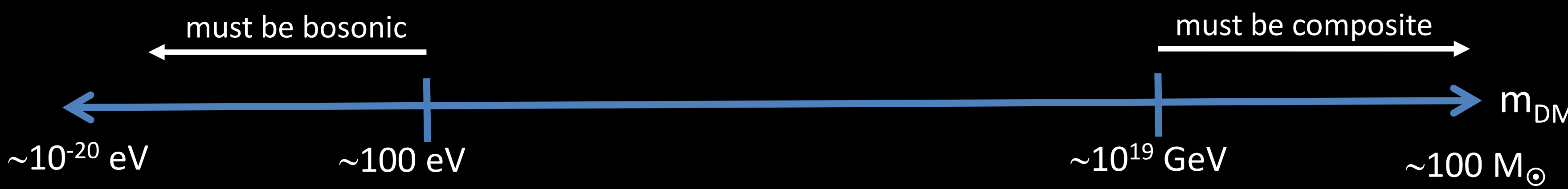


Rotation curve

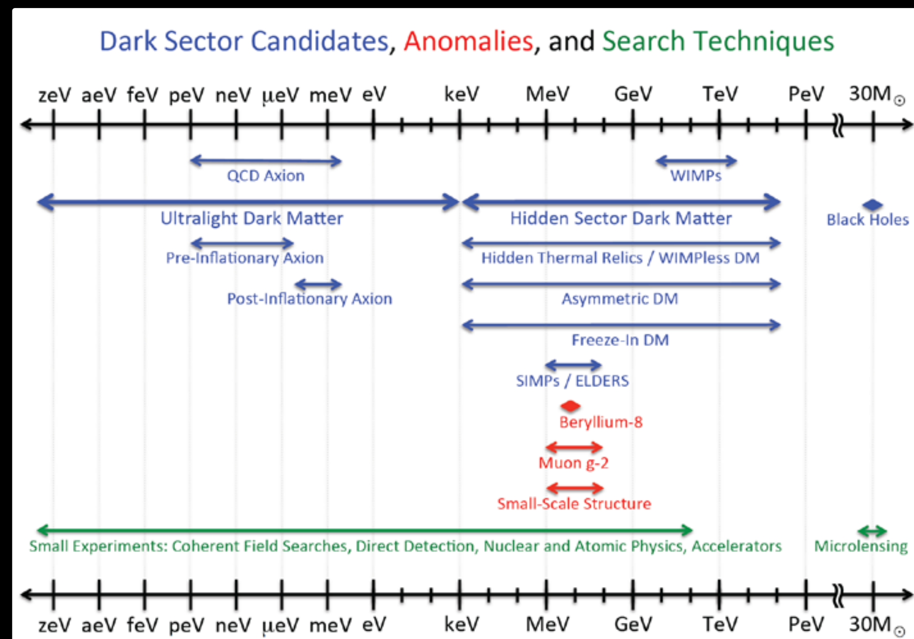
But we still know very little about its nature

One name, many faces

What we know: equation of state (ρ_{DM}), electrically neutral and interacts via gravity.



Bertone and Tait, arxiv:1810.01668



U.S. cosmic visions report

Need to make some assumption to start addressing the problem!

Thermal dark matter

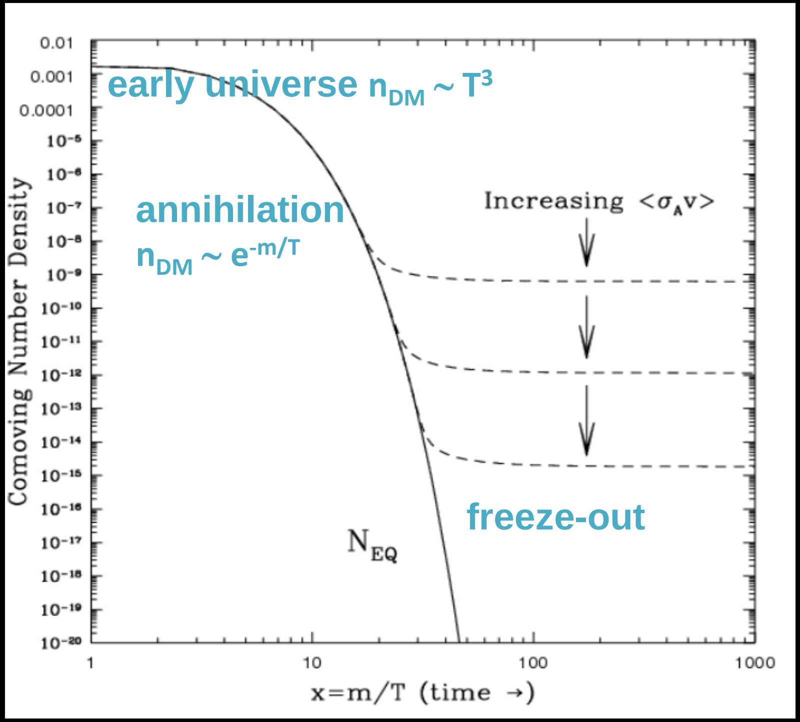
Thermal dark matter, originating as a relic in the early Universe, is arguably one of the most compelling paradigm

Simple: requires only that non-gravitational interaction rate between dark and familiar 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. Don't need to speculate too much!

Predictive: DM mass and coupling with SM set abundance → target



Thermal DM

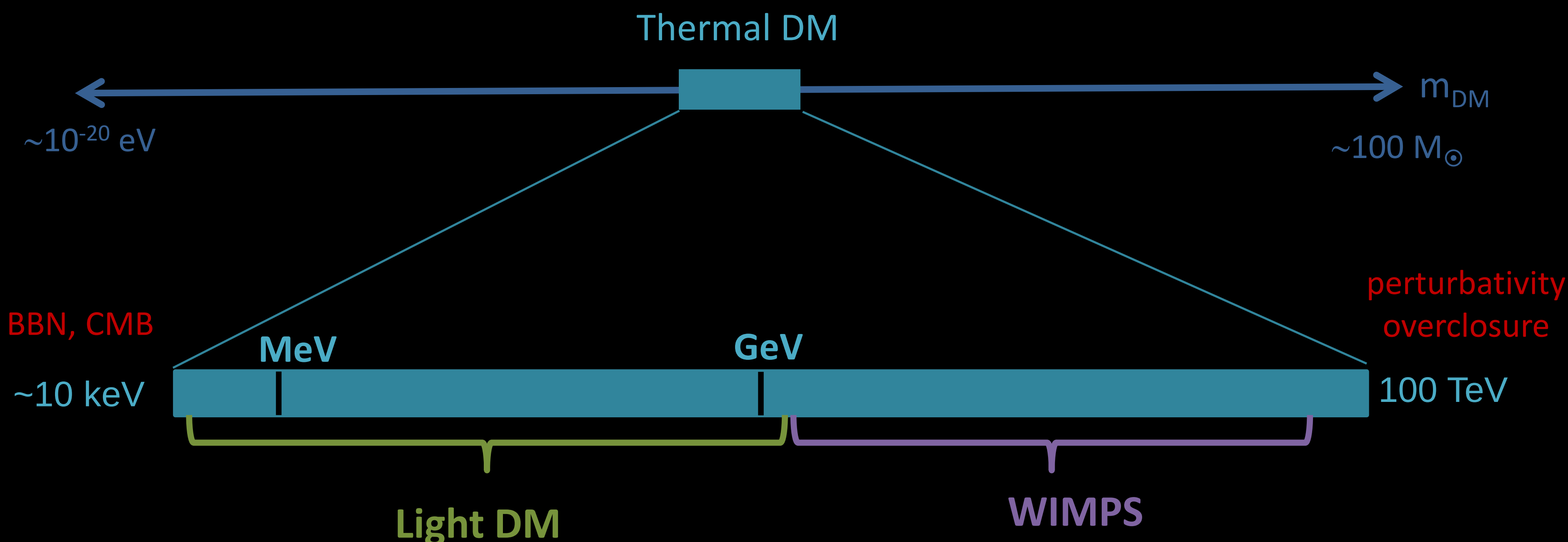
$\sigma v_{sym} \sim 3\text{x}10^{-26}\ cm^3s^{-1}$ (symmetric)

$\sigma v_{asym} > 3\text{x}10^{-26}\ cm^3s^{-1}$ (asymmetric)

There is a target!

Thermal dark matter

Thermal hypothesis also greatly restricts the range of allowed masses

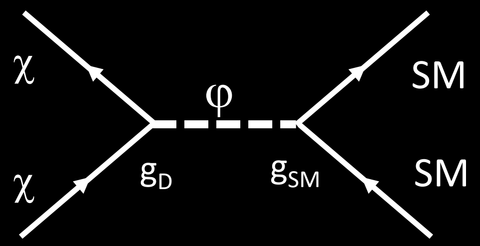


Thermal contact implies new mediator
Hidden sector light DM well-motivated model

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

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



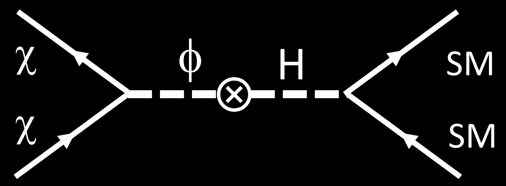
$$< \sigma v >_{relic} \sim \frac{g_D^2\, g_{SM}^2\, m_x^2}{m_\varphi^4} \qquad (m_\varphi \gg m_x)$$

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

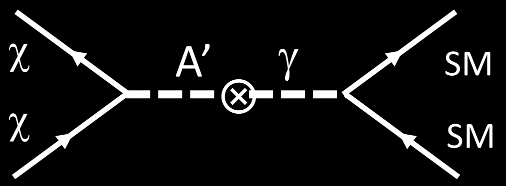
What kind of mediator?

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 hidden sectors.

Vector portal much less constrained that scalar one, so focus on this possibility.

Dark sector and vector portal

Dark sectors (DS)

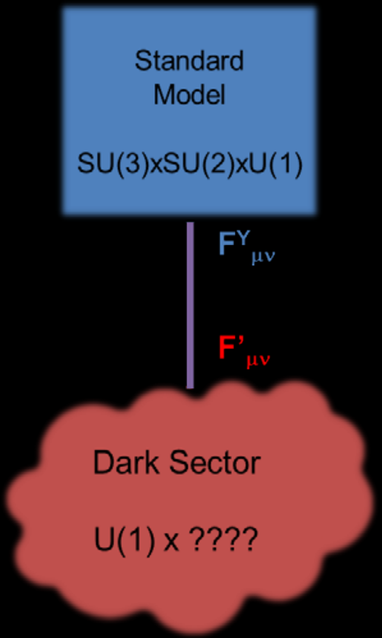
- New particles that don't couple directly to the Standard Model.
- Theoretically motivated: string theory and many other BSM scenarios (e.g. EW symmetry breaking) include dark sectors

Vector portal

- Dark sector with a new gauge group U(1)' and a corresponding gauge boson, the dark photon A'
- There is a generic interaction of the following form with the SM (kinetic mixing)

$$\Delta\mathcal{L} = \frac{\varepsilon}{2}\, F^{Y,\mu\nu}\, F'_{\mu\nu}$$

  between the SM hypercharge and U(1)' fields with a mixing strength ε
- After EWSB, there is a coupling between the dark photon and the photon (also the Z)

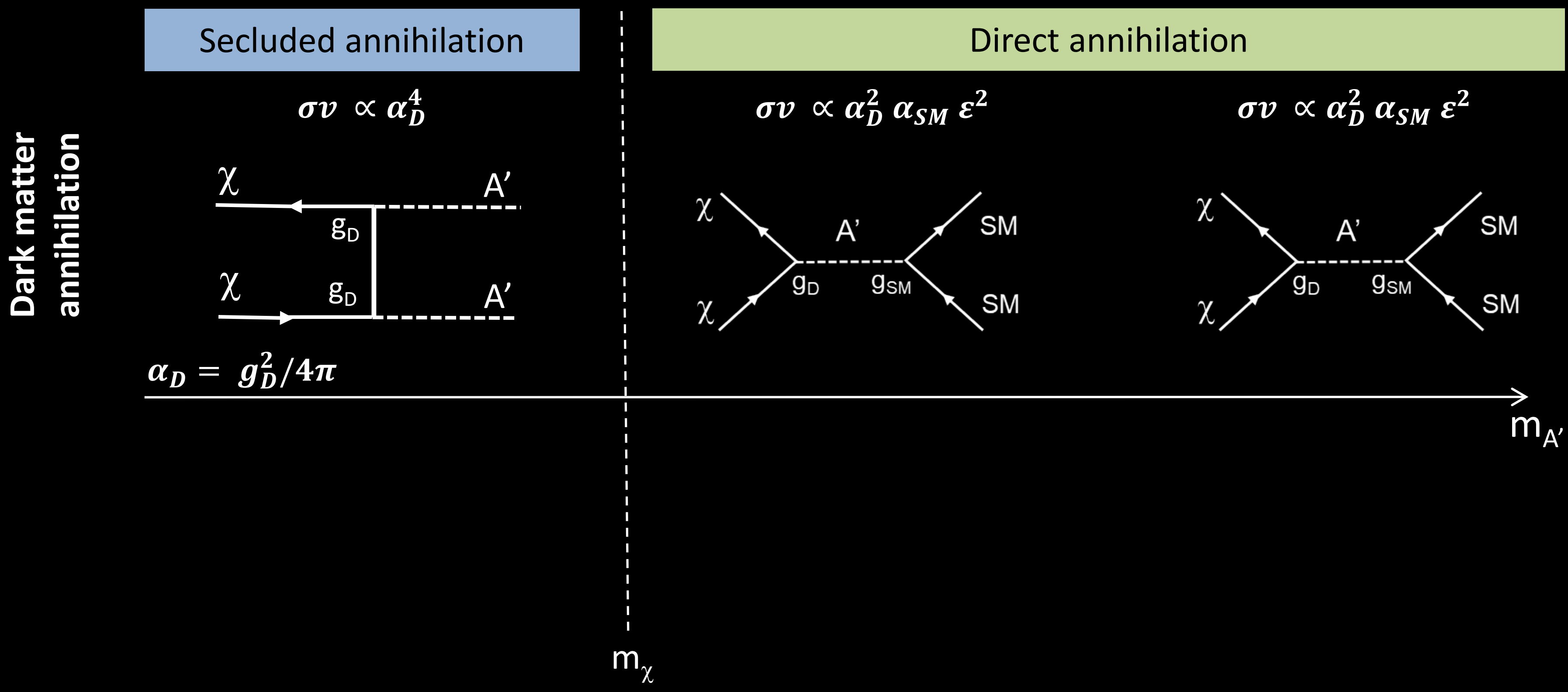


$$\Delta\mathcal{L} = \frac{\varepsilon}{2}\, F^{Y,\mu\nu}\, F'_{\mu\nu}$$

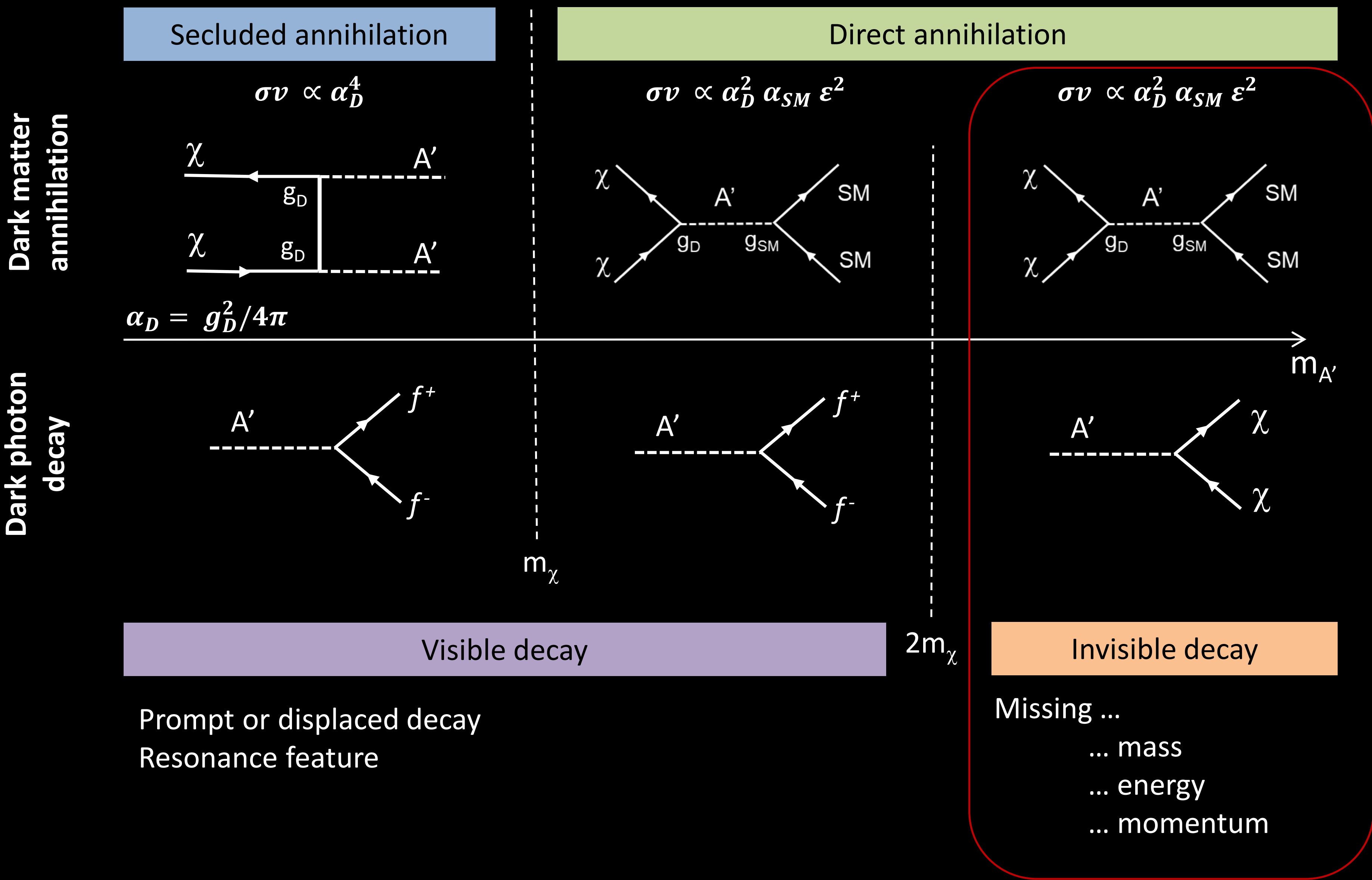
Holdom, Galison, Manohar

dark photon – SM fermion coupling with strength $\alpha' = \varepsilon^2\alpha$

Light DM production and decay



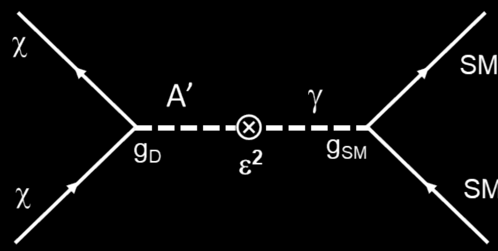
Production and decay



Representative benchmark scenario

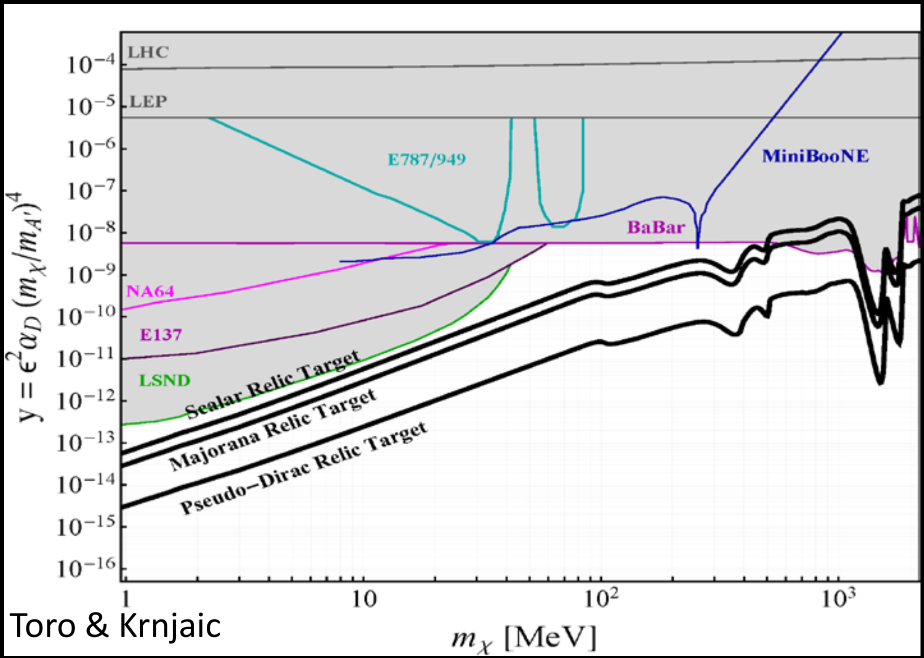
Hidden sector thermal LDM with vector portal.

Dark photon A' kinetically missing with strength ε



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

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



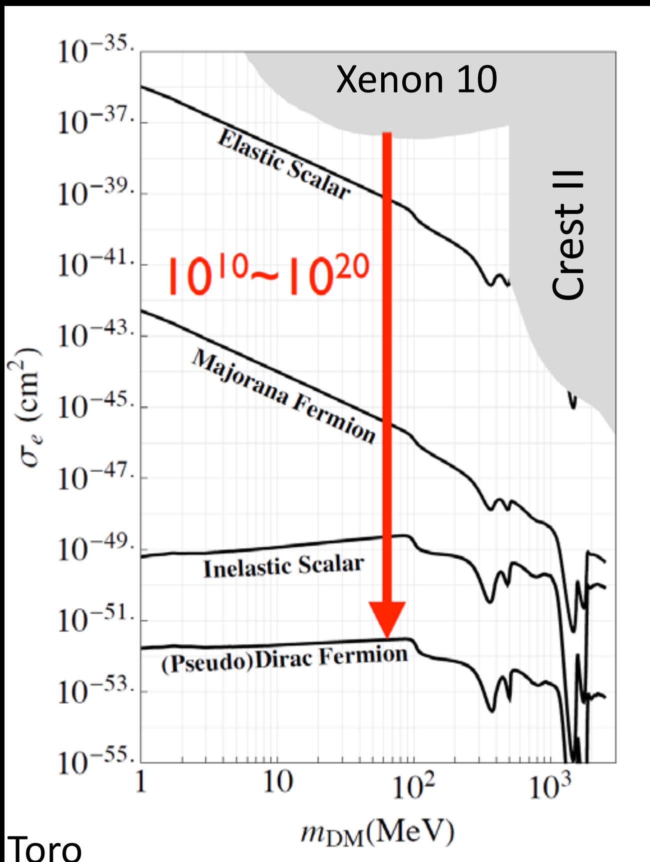
Toro & Krnjaic

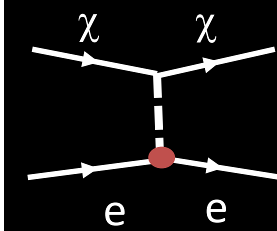
Conservative assumptions (α_D = 0.5 and m_A/m_χ = 3) made for plotting constraints from missing mass / momentum / energy experiments.

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

Why not direct detection?

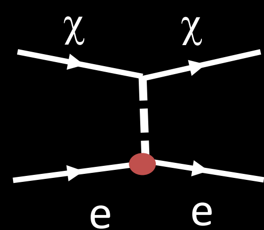
Direct detection targets





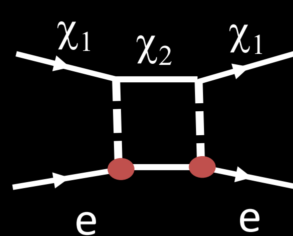
SCALAR

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



MAJORANA

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



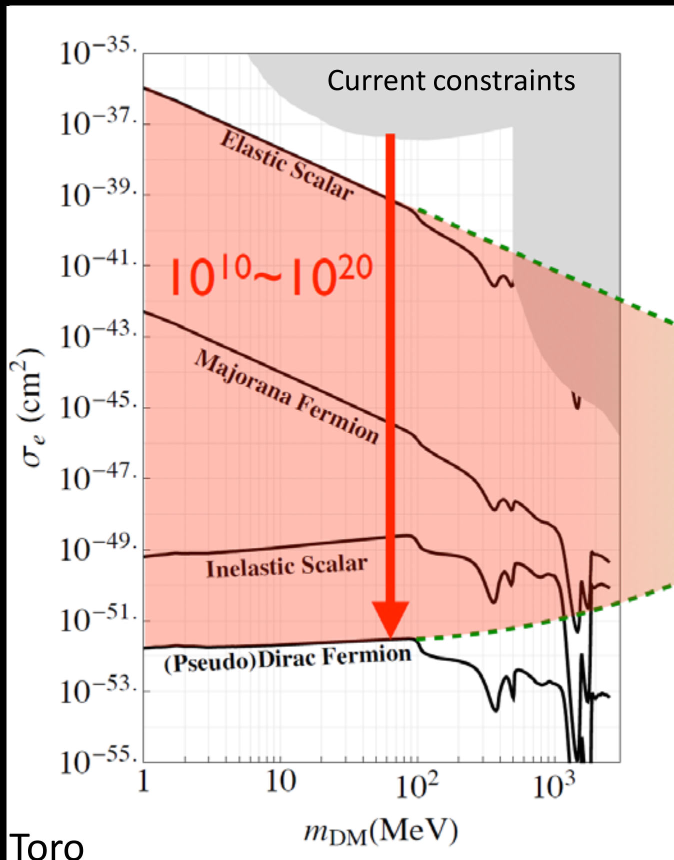
INELASTIC

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

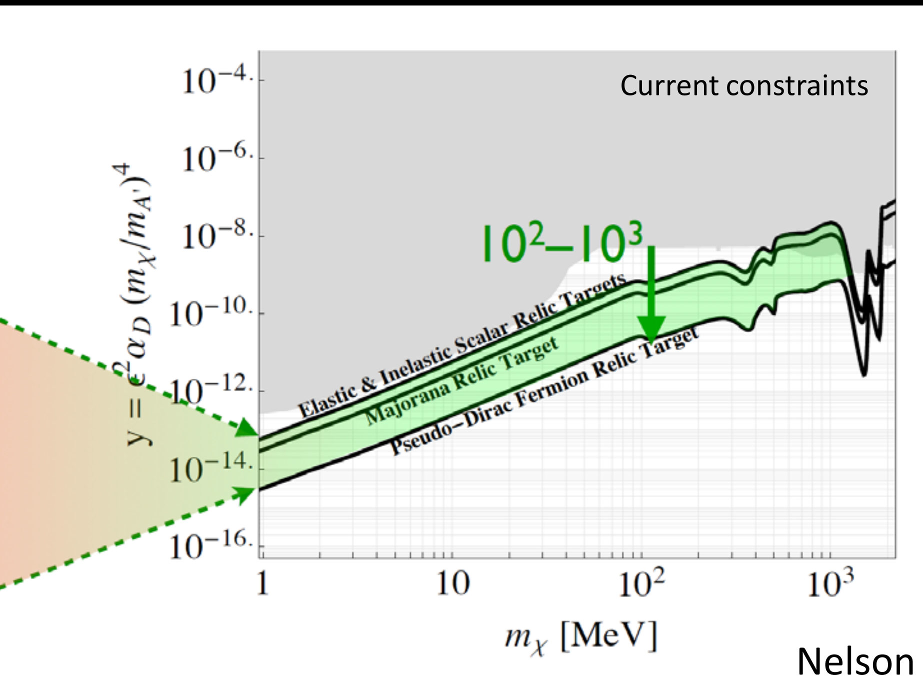
Is there a way to put these on the same footing?

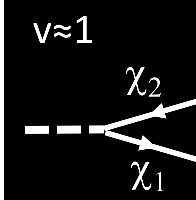
Why not direct detection?

Direct detection targets



Accelerator targets





Relativistic production at accelerators:
almost insensitive to spin and mass

Accelerators uniquely positioned to probe directly annihilating thermal LDM

More generally…

The scope of accelerator-based experiments is much more extensive, and encompass models such as

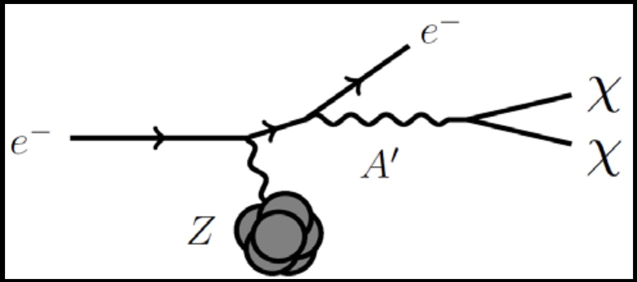
- Quasi-thermal DM, such as asymmetric DM and ELDER DM
- New long-lived resonances produced in the dark sector (SIMP)
- Freeze-in models with heavy mediators
- New force carriers coupling to electrons, decaying visibly or invisibly
- Milli-charged dark sector particles
- ….

In essence, exploring physics that couples to electrons in the sub-GeV mass range is well-motivated and important, and accelerator based experiments could generically probe a vast array of possibilities in addition to light thermal DM.

Light dark matter at accelerators

Maximizing dark matter sensitivity

Missing energy / momentum



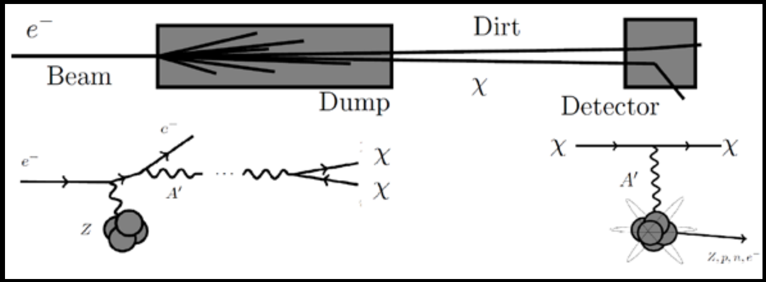
$\sigma \sim Z^2 \varepsilon^2 / m_A{}^2$

Large production yield for low mediator masses

Large "detection yield"

NA64
LDMX

Beam dump



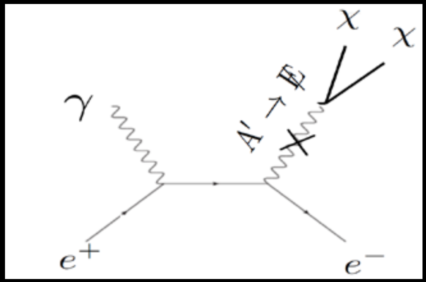
$\sigma \sim \alpha_D\, \varepsilon^4$

Probe dark sector coupling

Process suppressed by ε^4

E137
BDX
MiniBooNE
SHiP

Colliders



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

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

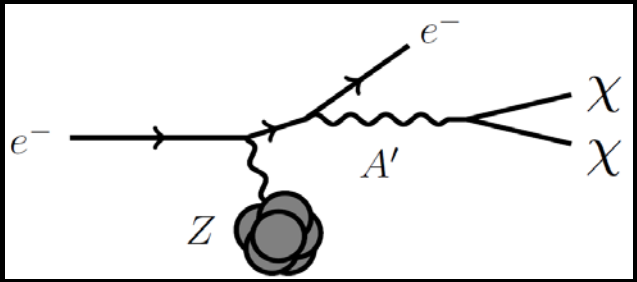
Large production yield on resonance

Best yield at high masses

BABAR
Belle (II)
PADME
LHCb (prompt)

Maximizing dark matter sensitivity

Missing energy / momentum



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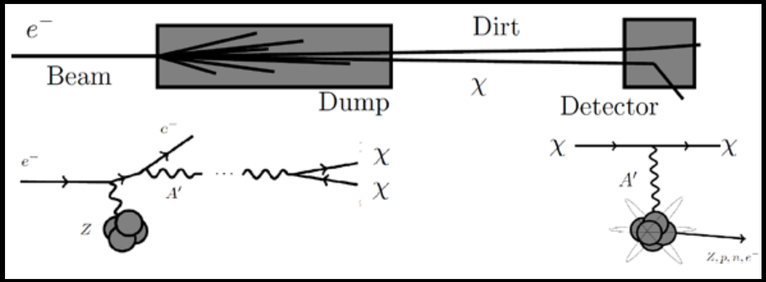

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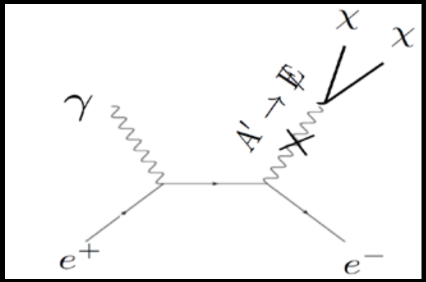

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$\sigma \sim \varepsilon^2/(s-m_A^2) \quad m_A \sim s$

Large production yield on resonance

Best yield at high masses

Accelerators can explore the physics in detail ($\varepsilon, m_{A'}, m_\chi, \alpha_D$),

direct detection needed to establish cosmological stability

Colliders

BABAR @ PEP II

Search for $e^+e^- \to \gamma A', A' \to$ invisible by tagging the recoil photon in “single photon” events.

Requires single photon trigger, only with a small fraction of the data (53/fb)

Exclude dark photon as explanation of $(g\text{-}2)_\mu$ anomaly

BELLE II @ SuperKEKB

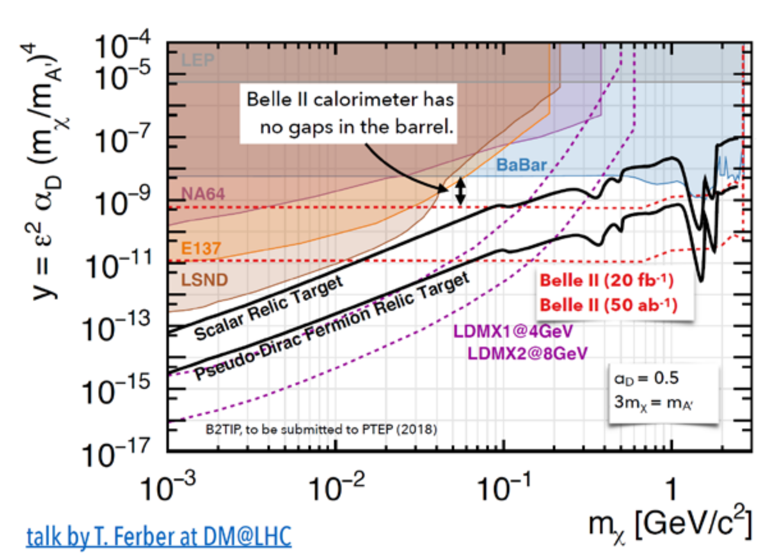
Search for same final state

Much larger data set by 2025 (50/ab)

Phase II (partial detector) ended last summer. Phase III with complete detector will start next summer.

BABAR @ PEP II

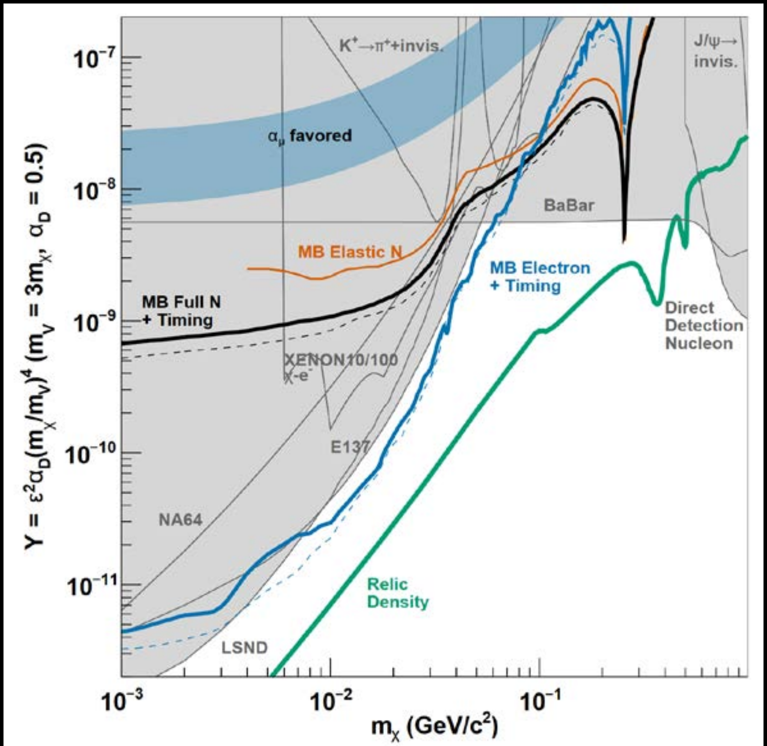
Belle II projected sensitivity



Proton beam dump

MiniBooNE

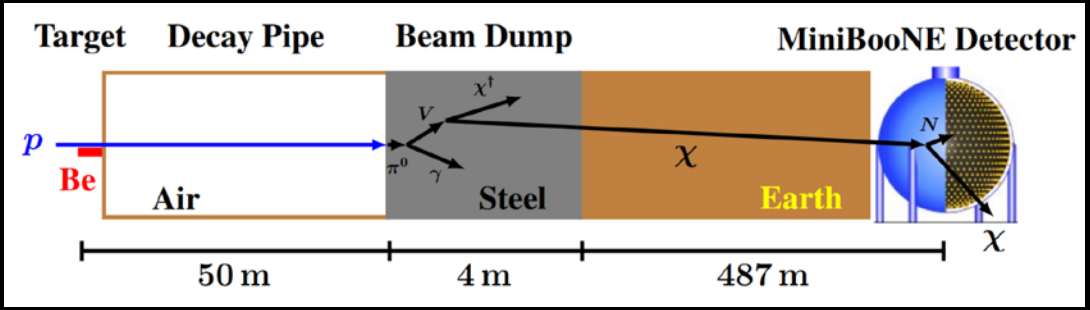
Phys. Rev. D 98, 112004 (2018)

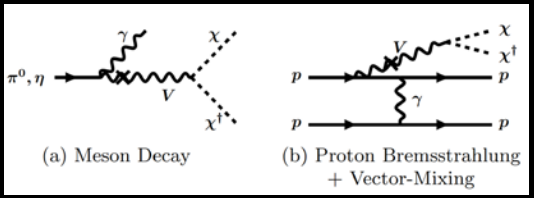


Probes quark coupling to dark matter

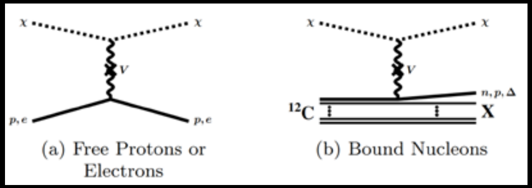
First dedicated dark matter search in proton beam dump experiments in 2013-2014 with 1.86×10^{20} POT

Bypass target to minimize neutrino production and use timing to further reject background.





Production scales as ε^2



Detection scales as $\alpha_D \varepsilon^2$

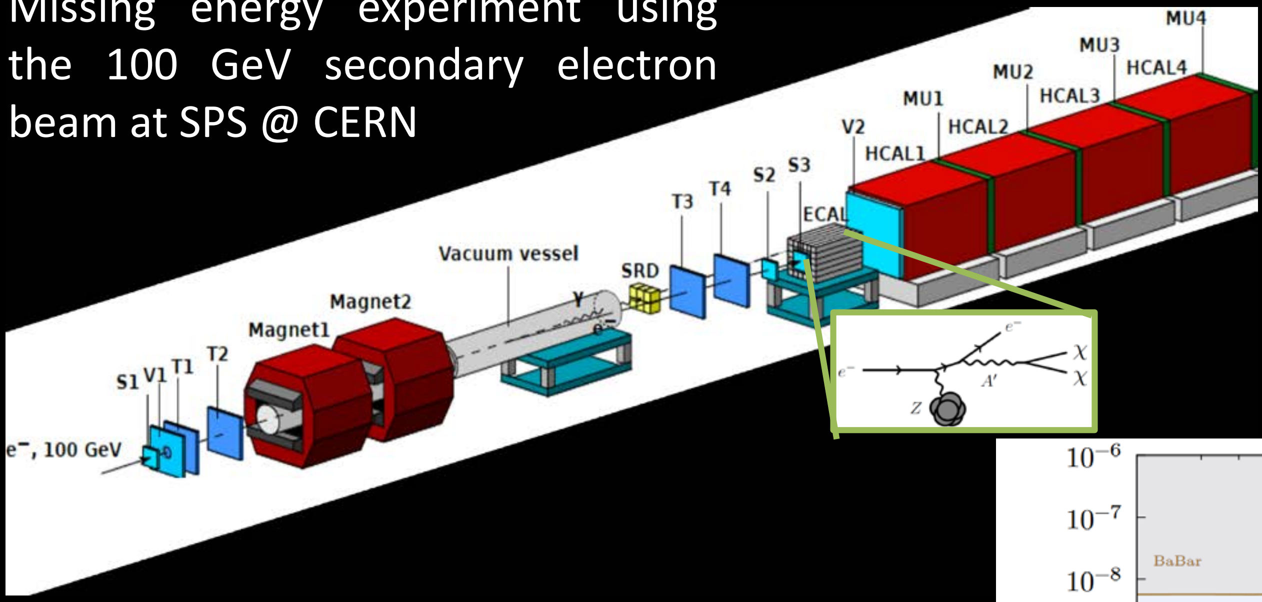
Proposal to continue DM searches with SBN program to improve by ~ an order of magnitude

SHiP, T2K, DUNE,… will also probe the vector and baryonic portals.

Missing energy

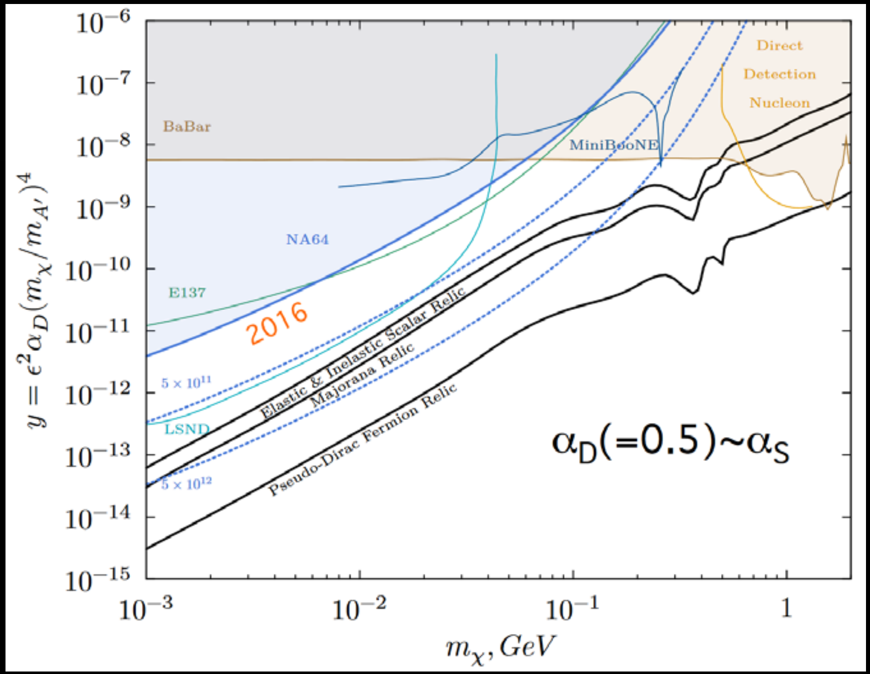
NA64 experiment

Missing energy experiment using the 100 GeV secondary electron beam at SPS @ CERN



- Tracking system to identify 100 GeV e-
- ECAL as active target
- HCAL and muon detector to veto hadronic reactions

PRD 97, 072002 (2018)



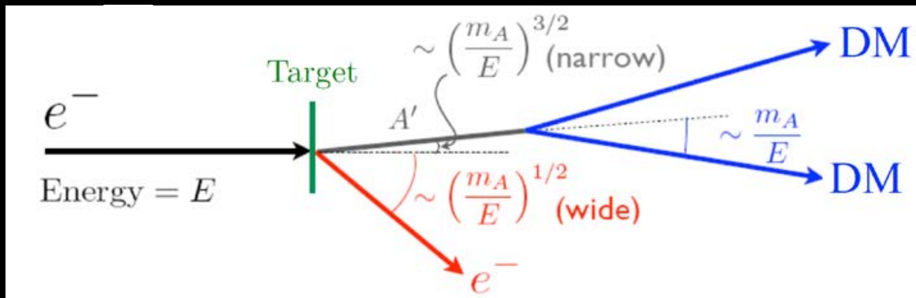
Results and future runs

2016 - 4.3×10^{10} EoT
2017 - 5.0×10^{10} EoT
2018 - ~2×10^{11} EoT

Approved run in 2021, goal 3×10^{11} EoT

The missing momentum approach: The LDMX experiment

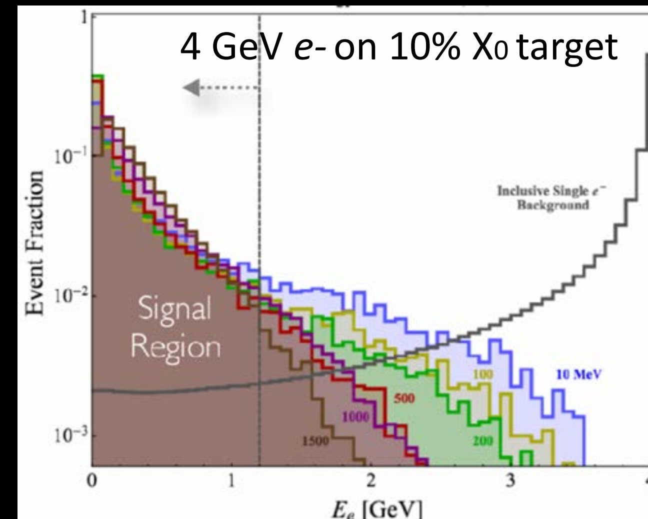
Missing momentum kinematics



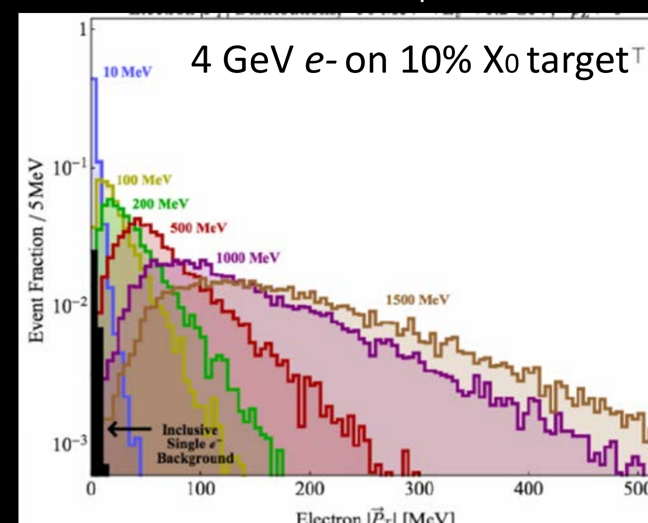
$$\frac{d\sigma}{dx} \propto \frac{\alpha^3}{\pi} \frac{\epsilon^2}{m_e^2 \cdot x + m_A^2 (1-x)/x}$$

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

Recoil energy



Recoil p_T,

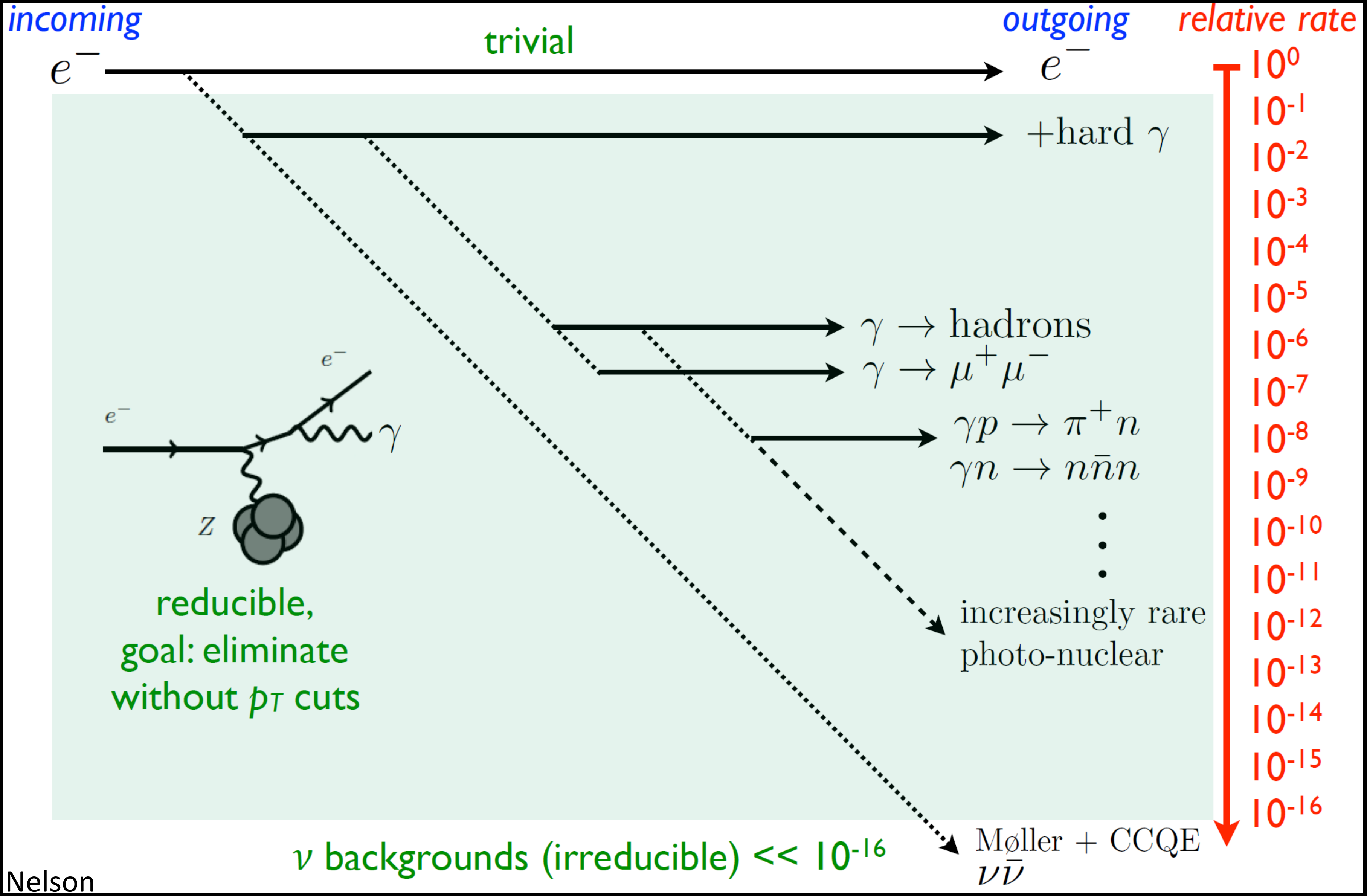


The kinematics is very different from bremsstrahlung emission.

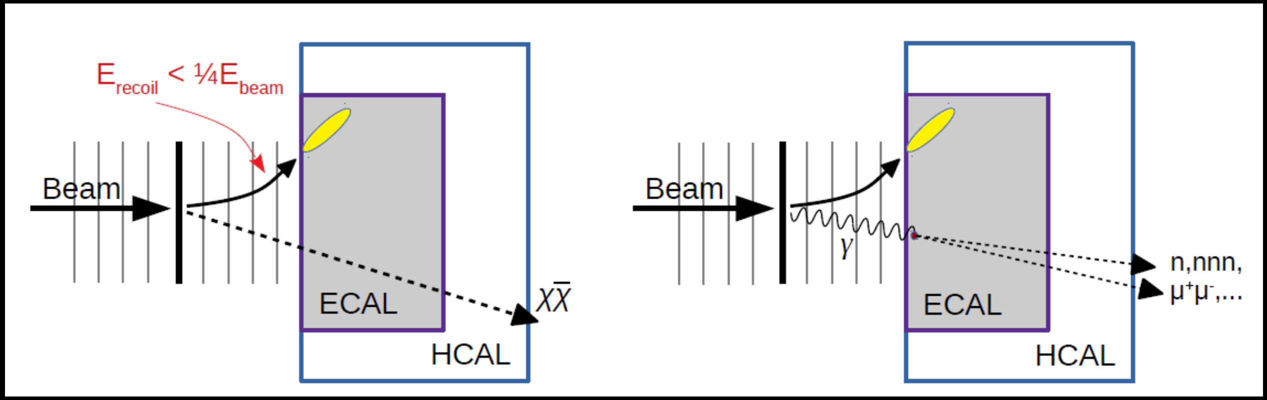
The A' is emitted at low angle and carries most of the energy:

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

Backgrounds



A successful missing momentum design



Beam allowing individual reconstruction of each incident electron

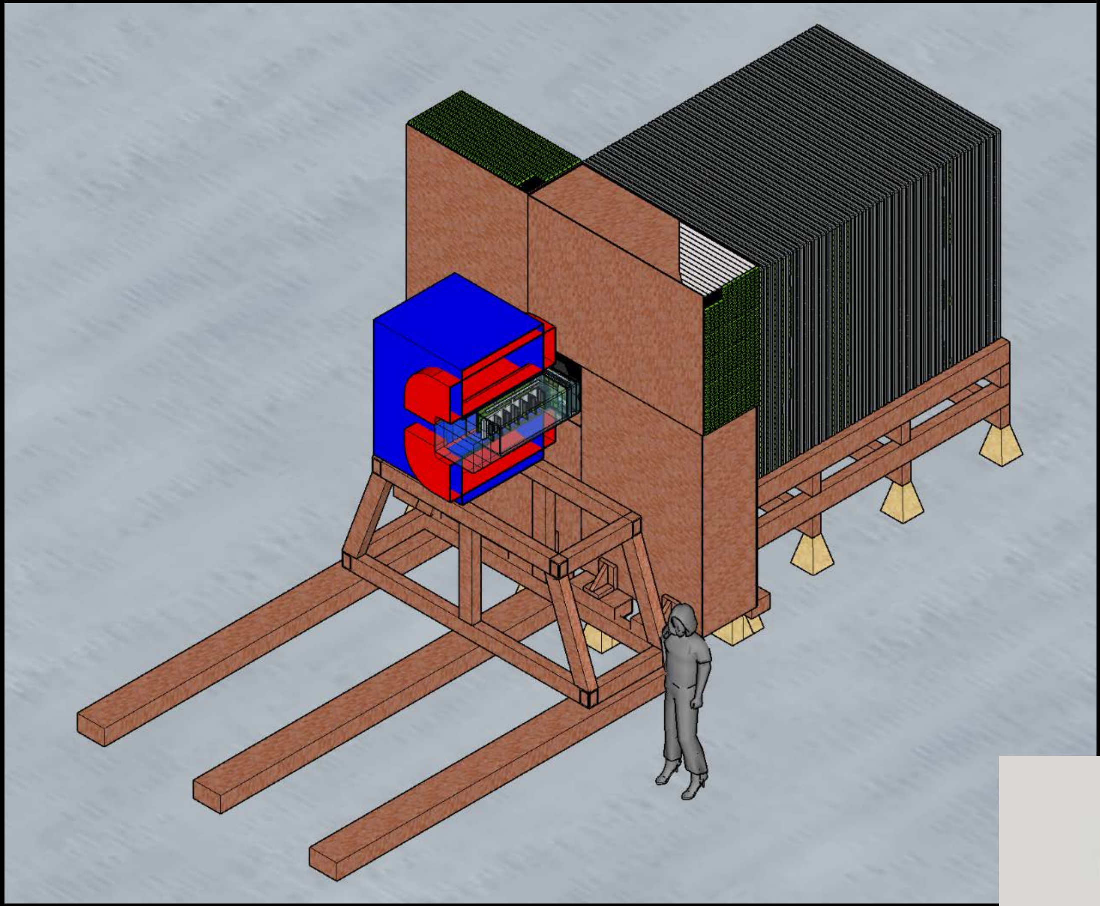
- A multi-GeV, low-current, high repetition rate (10^{16} EOT / year ≈ 1e / 3 ns) beam with a large beam spot to spread out the occupancy / radiation dose.
- Potential beamlines: S30XL @ SLAC, e-SPS @ CERN or CEBAF @ JLab.

Detector technology with high rate capabilities and high radiation tolerance

- Fast, low mass tracker to tag each electron with good momentum resolution
- Fast, granular, radiation hard EM calorimeter, and hermetic HCAL veto

The LDMX experiment has been proposed to realize these requirements in two phases: Phase-I with 10^{14} EOT, and Phase-II with 10^{16} EOT

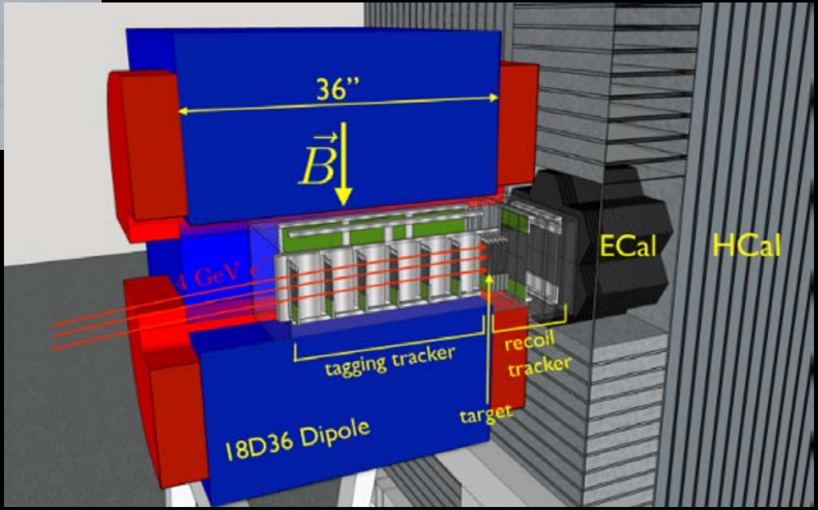
LDMX detector concept – Phase I



LDMX concept

- Magnet: 18D36 at SLAC
- Tracking: Silicon Vertex Tracker of HPS
- ECal: CMS high-granularity calorimeter
- HCal: scintillator/steel sampling calorimeter

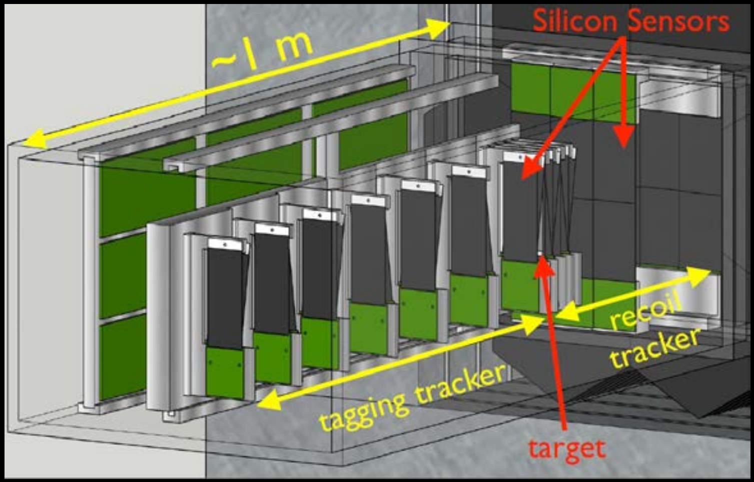
LDMX Whitepaper
arxiv:1808.05219



Tracking system

Two tracking systems:

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

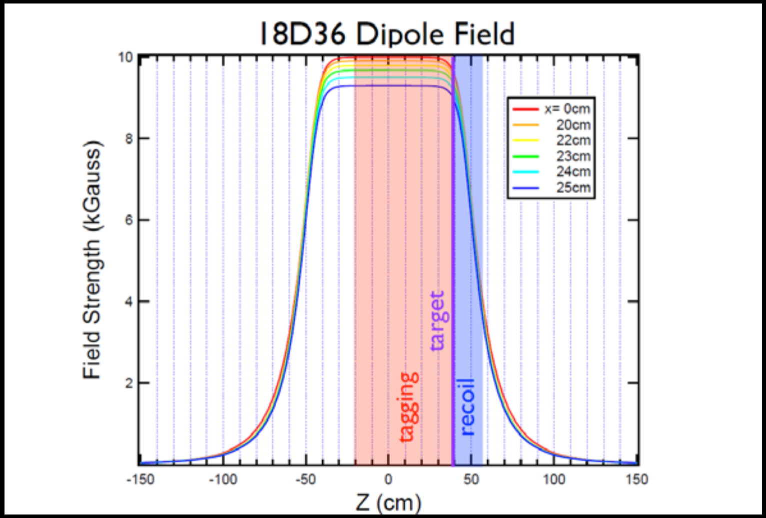


Single dipole magnet, two field regions

- 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

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

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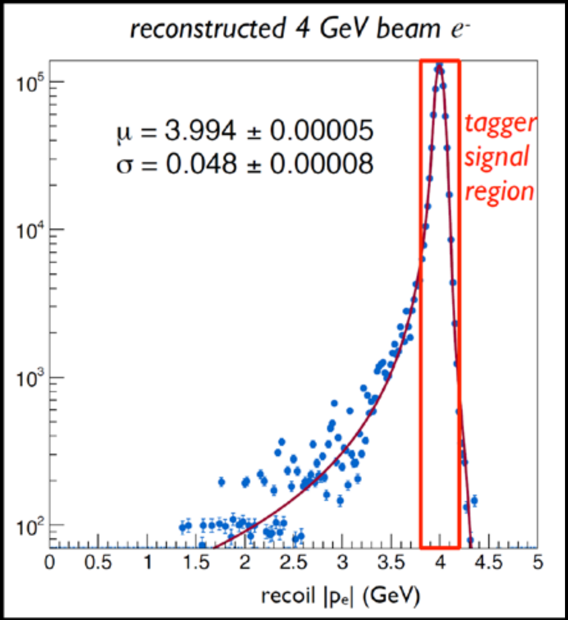
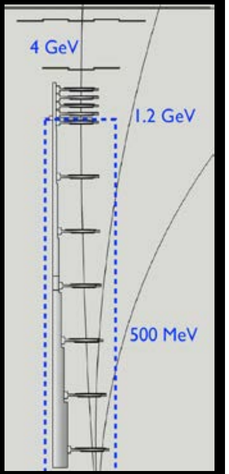
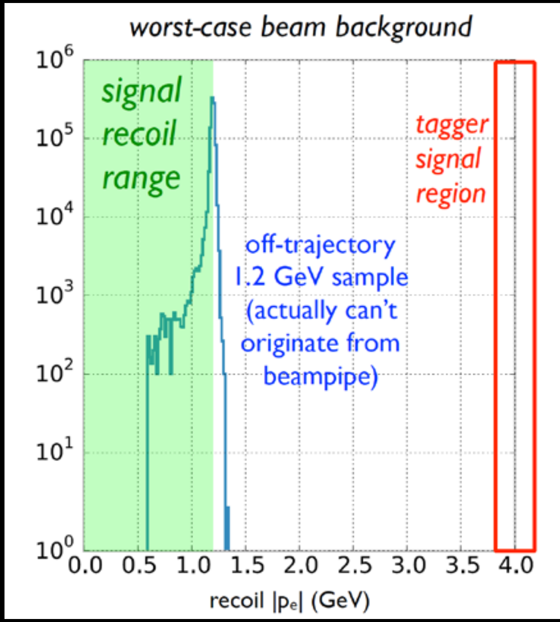


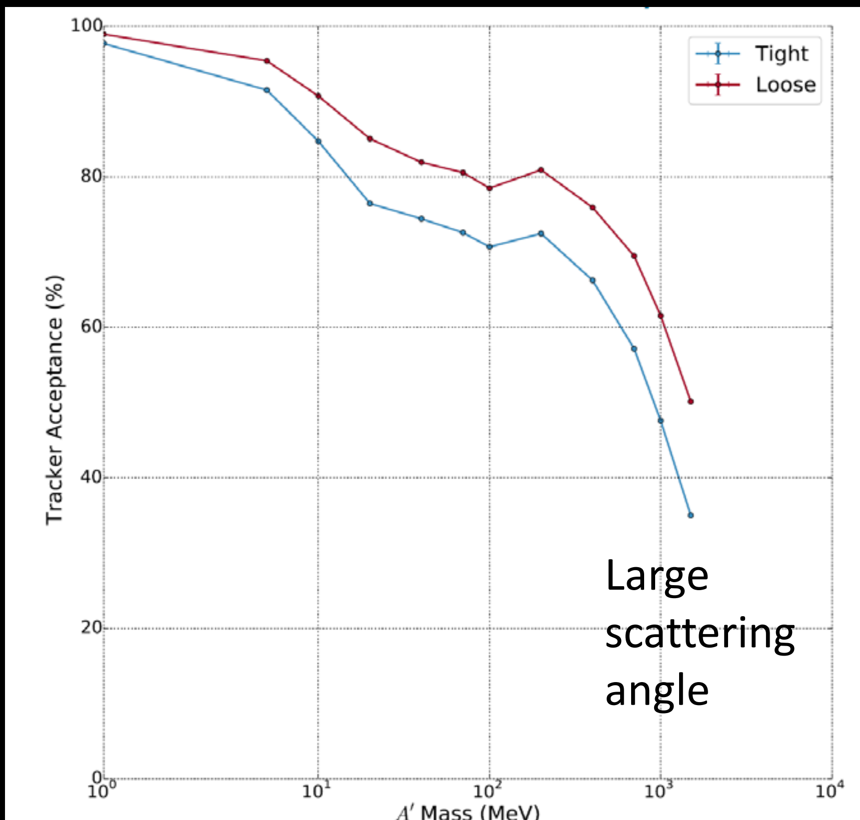


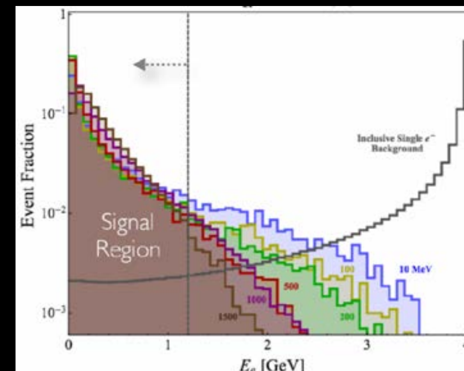


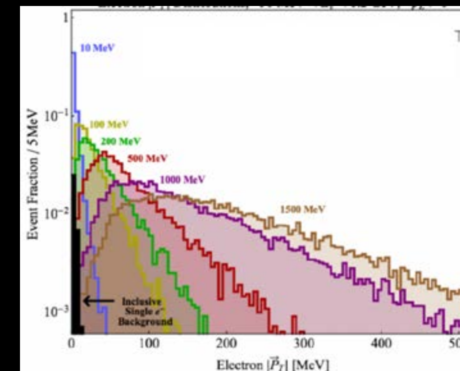
Tagging tracker efficiently rejects beam-induced background

Tracking system performance

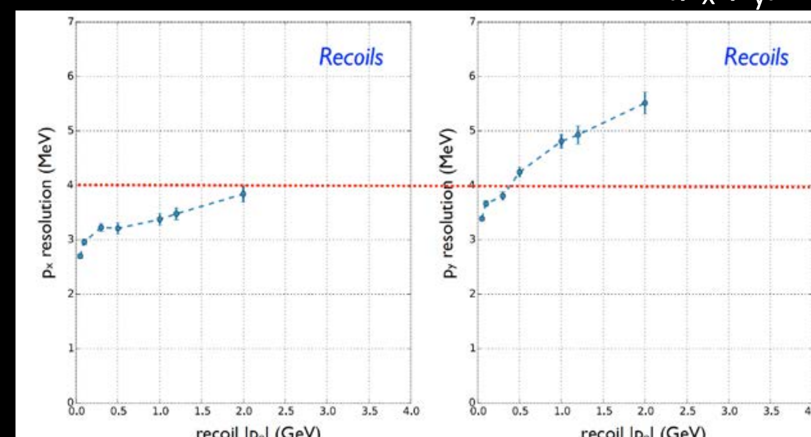
Acceptance for recoil electrons







Recoil momentum resolution (p_x,p_y)



Good acceptance, limited at high masses by kinematics (large angle scattering),

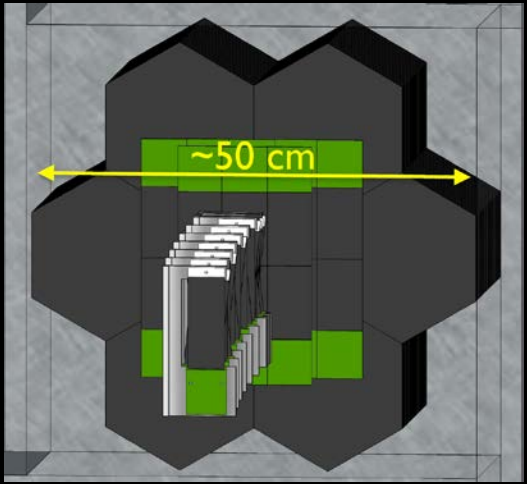
Recoil momentum resolution limited by multiple scattering in target

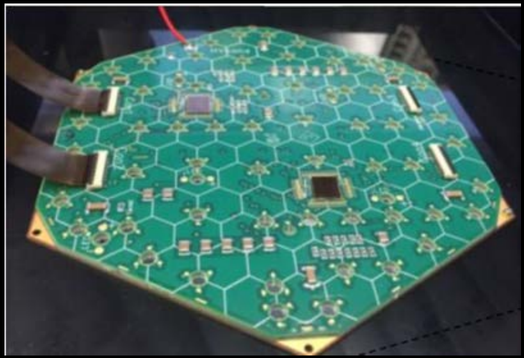
EM calorimeter

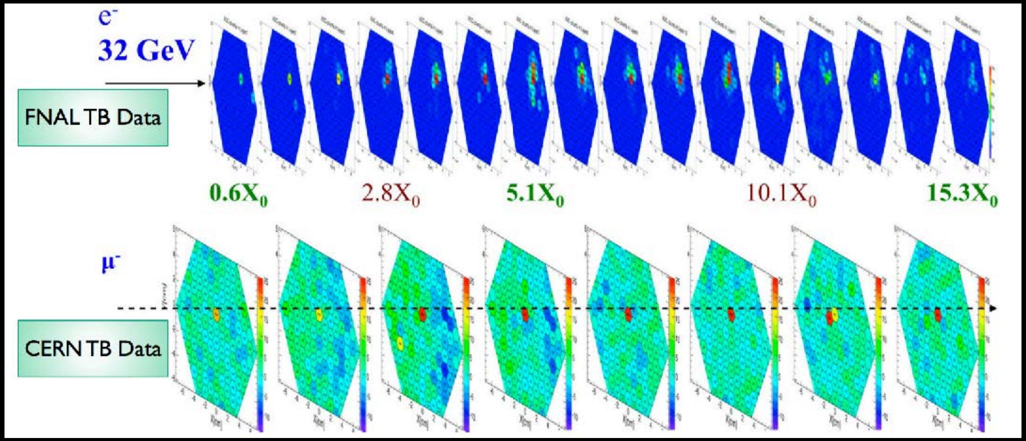
Si-W sampling calorimeter

- Fast, dense and radiation hard
- ~$40X_0$ deep for extraordinary containment
- High granularity, exploit transverse & longitudinal shower shapes to reject background events
- Provide fast trigger – accept event with ECal < 1.2 GeV

Currently developed for CMS ECal upgrade, adaptable to LDMX



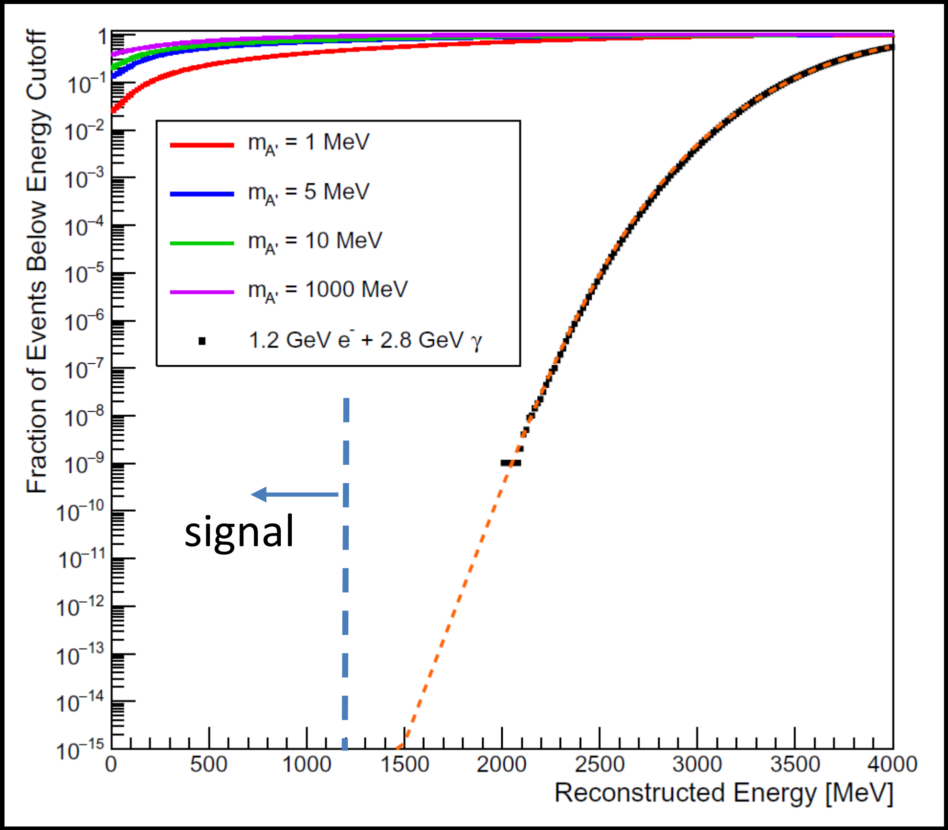




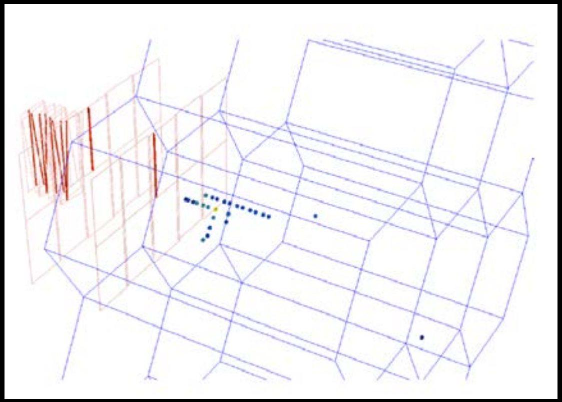
High granularity enables muon vs. electron discrimination, important to reject $\gamma \to \mu\mu$ bkg

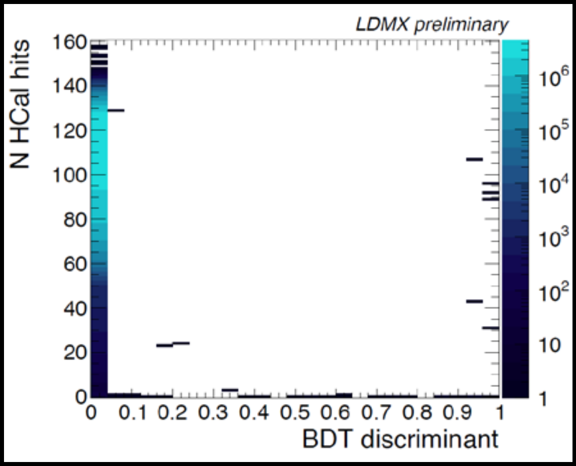
EM calorimeter

Bremsstrahlung bkg (1.2 GeV e- + 2.8 GeV γ)



Dimuon background ($\gamma^* \rightarrow \mu\mu$)





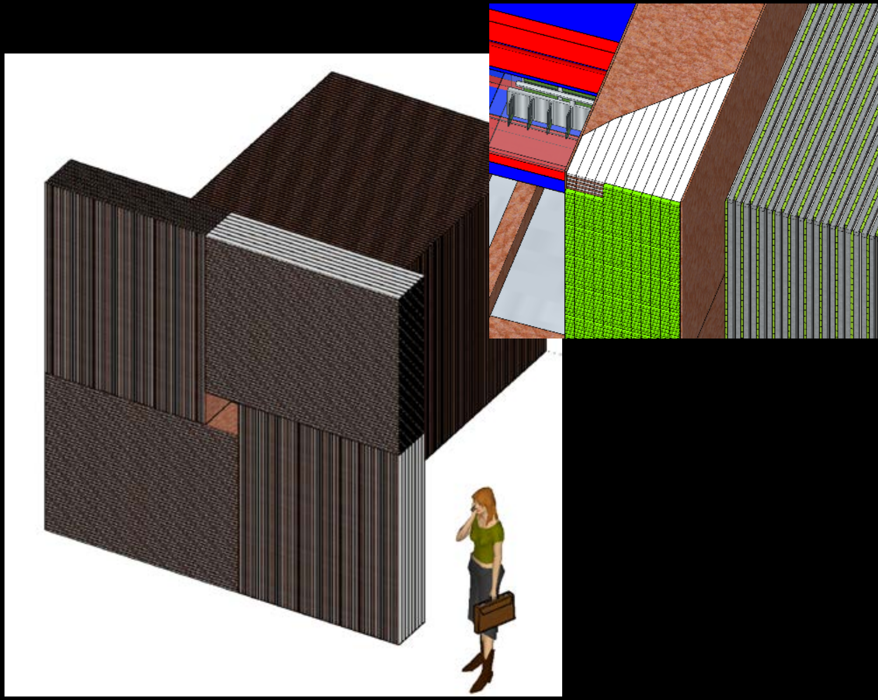
The ECal can efficiently reject background (e.g. 1.2 GeV e- + 2.8 GeV γ or dimuon production) from signal at the level required for Phase I.

Hadronic calorimeter

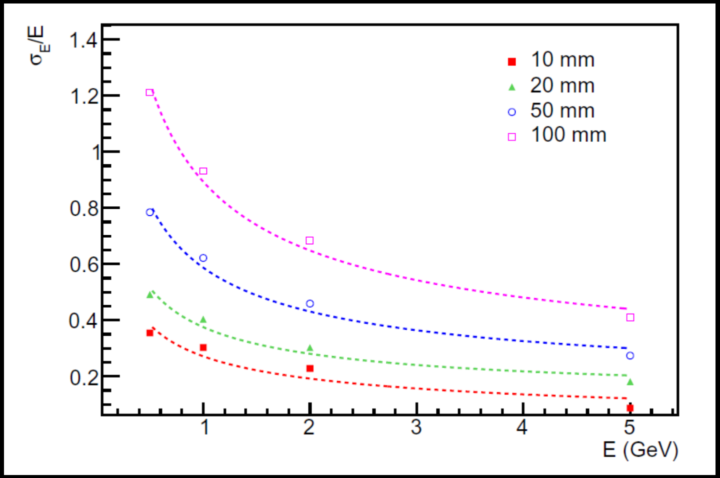
Steel / plastic scintillator sampling calorimeter

- Main role: veto hadronic PN events, in particular PN events emitting several hard neutrons (e.g. $\gamma n \rightarrow n\bar{n}n$) or many soft neutrons.
- Secondary role: physics with displaced signatures, electro-nuclear measurements and trigger, help with overall veto.
- Plastic scintillator bars with WLS fibers read out by SiPM and steel absorber.
- Back HCal (~13λ) and side HCal (~ 5λ), 2-3 m transverse size. Final design parameters still under study.

Current studies shows that the HCal can achieve the required veto efficiency while keeping decent energy resolution.



Energy resolution for pions



Trigger and DAQ

Trigger

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

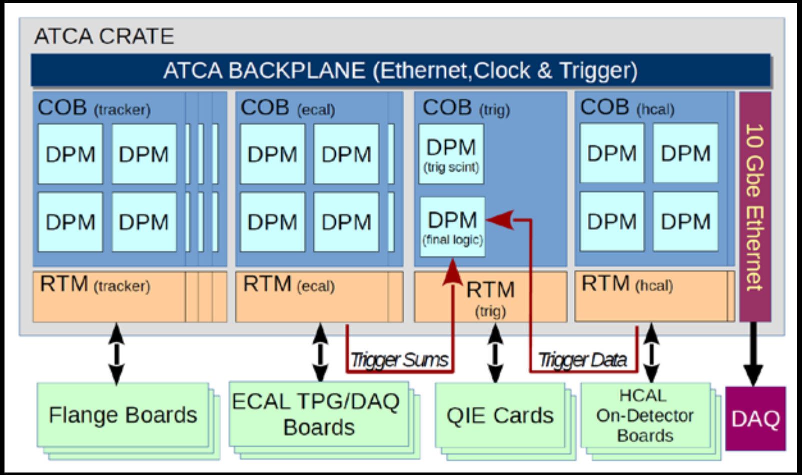
Signal efficiency 50-100% with 10^4 bkg rejection

n_{beam}	Fraction of Bunches (Signal)	Trigger Scintillator Efficiency	Missing Energy Threshold [GeV]	Calorimeter Trigger Efficiency	Rate [Hz]	Signal Inefficiency
1	36.8% (36.8%)	100%	2.50	99.2%	588	0.3%
2	18.4% (36.8%)	97.4%	2.35	98.0%	1937	1.7%
3	6.1% (18.4%)	92.4%	2.70	91.6%	1238	2.8%
4	1.5% (6.1%)	84.3%	3.20	77.2%	268	1.6%
Total					4000	8.8%

DAQ systems

- ACTA crate using the Reconfigurable Cluster Element (RCE) generic computational building block developed by SLAC. Re-use components and algorithms already developed for other experiments.

- DAQ rate of 25 kHz.

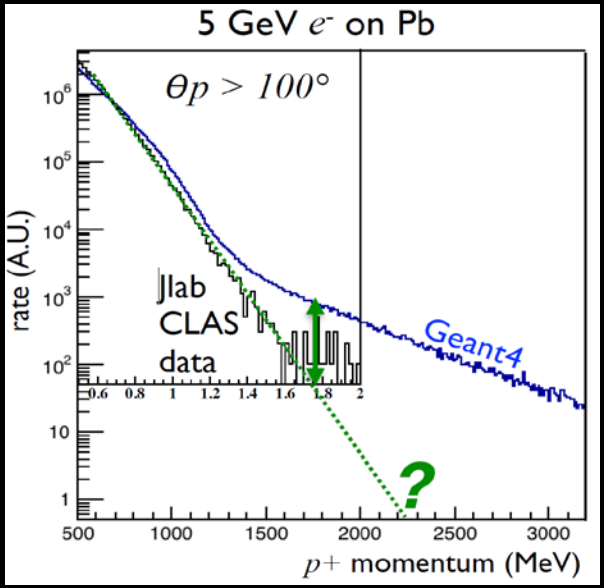


Improving Geant4 simulations

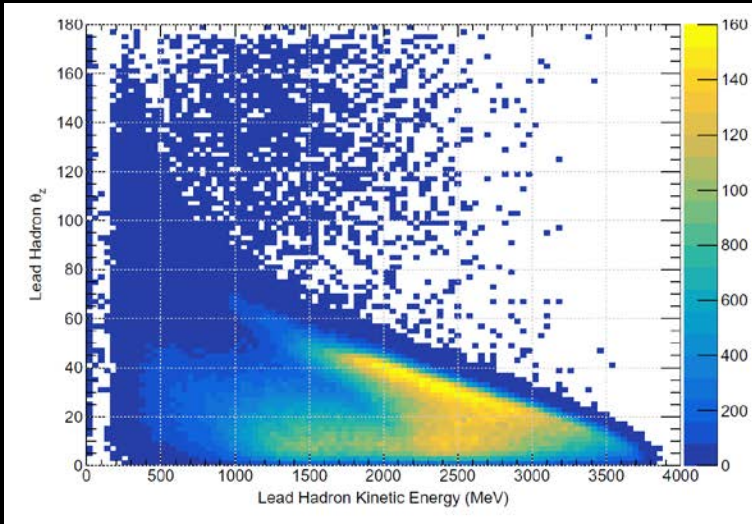
Several unphysical backgrounds were generated by Geant4, such as photo-nuclear events with hard, large angle hadrons.

Related to details of the Bertini cascade, on-going work to improve the physics model.

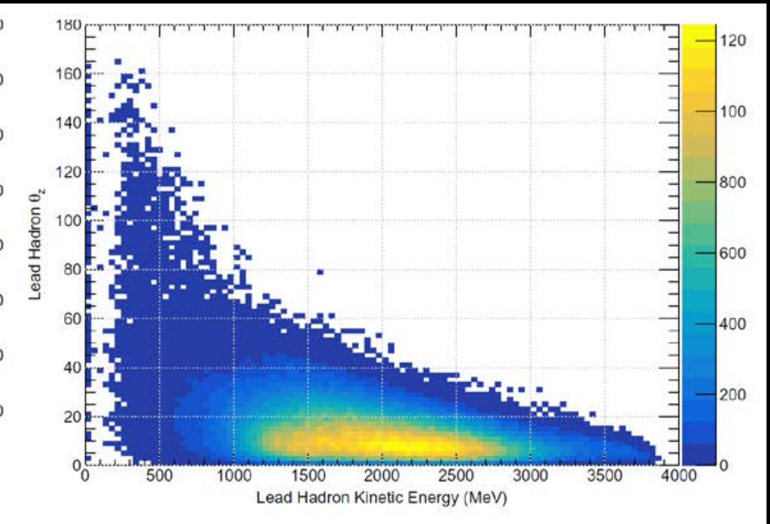
Re-weighing procedure used for whitepaper studies, new background samples with improved model generated for updated studies.



Original Geant4

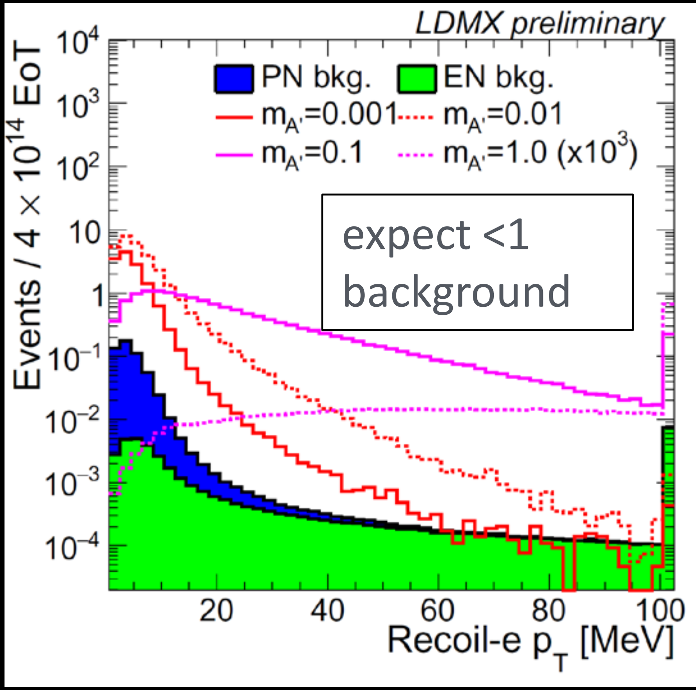


Improved Bertini cascade model

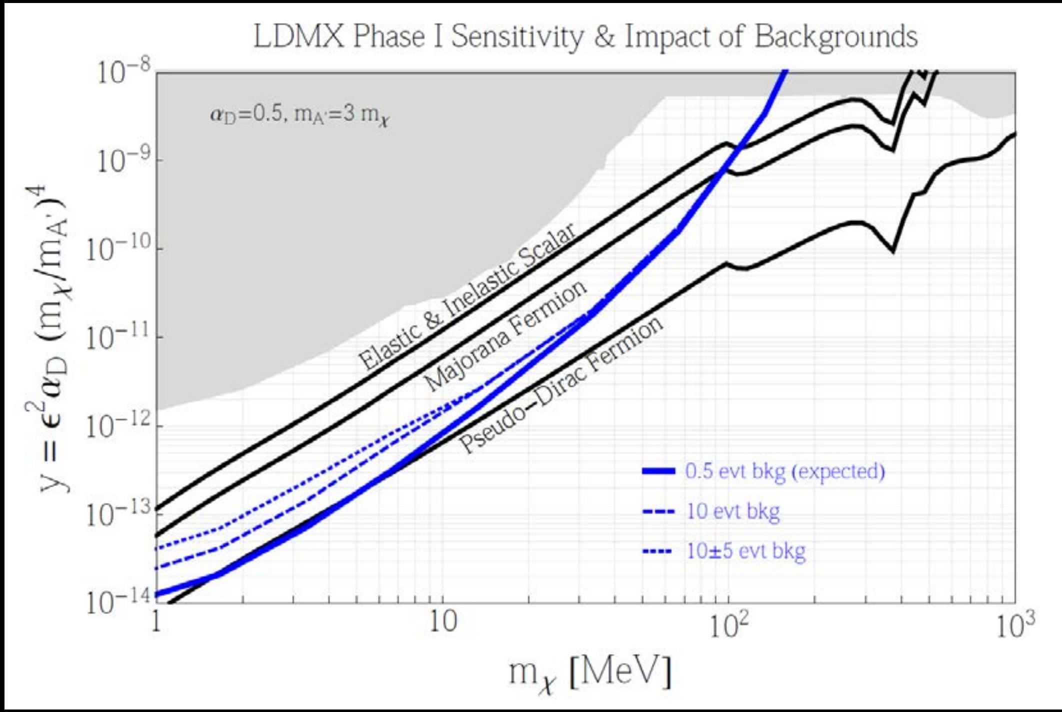


Phase I sensitivity

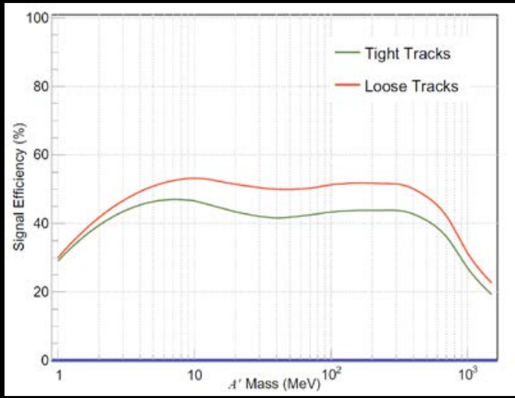
Recoil e^- p_T spectrum after all cuts



LDMX Phase I sensitivity ($4x10^{14}$ EOT @ 4 GeV)



Signal efficiency



Phase I probes scalar and Majorana targets below 100 MeV, grazes pseudo-Dirac target.

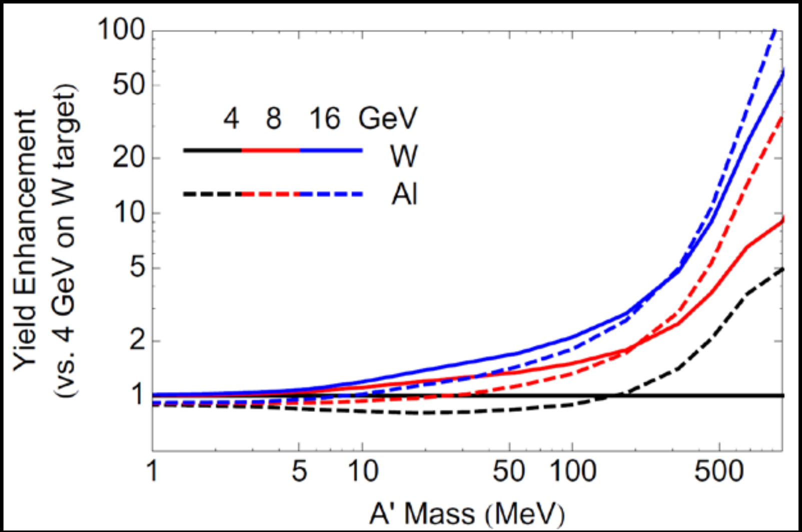
Additional improvements under study.

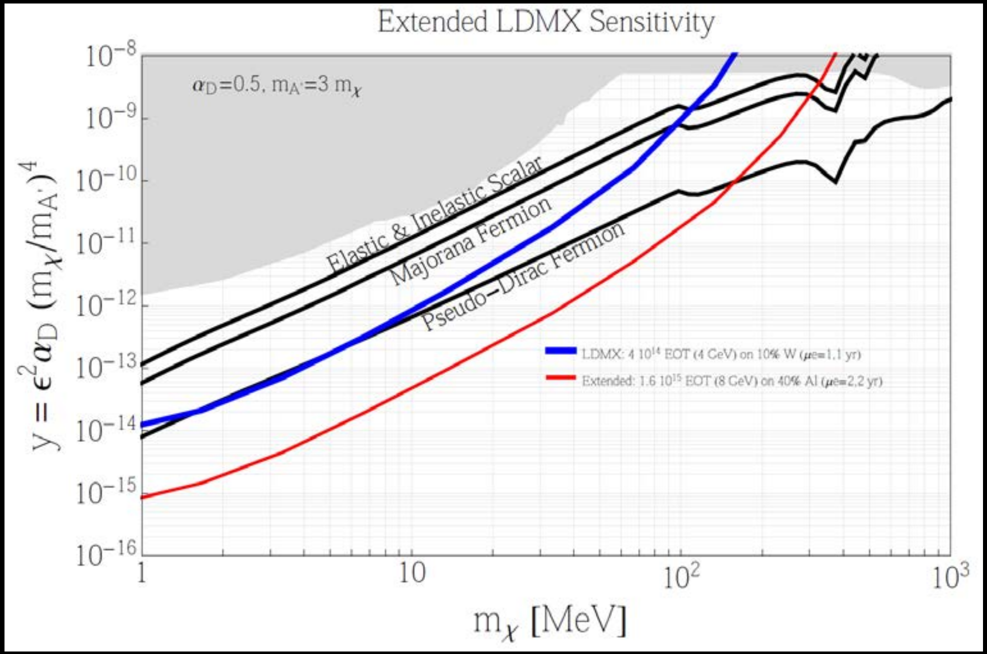
All details in whitepaper - arxiv:1808.05219.

Phase II upgrade

Several strategies are available for improving Phase I reach: increasing the beam energy, changing the target density or thickness.

Phase II could probe pseudo-Dirac target up to O(100) MeV.

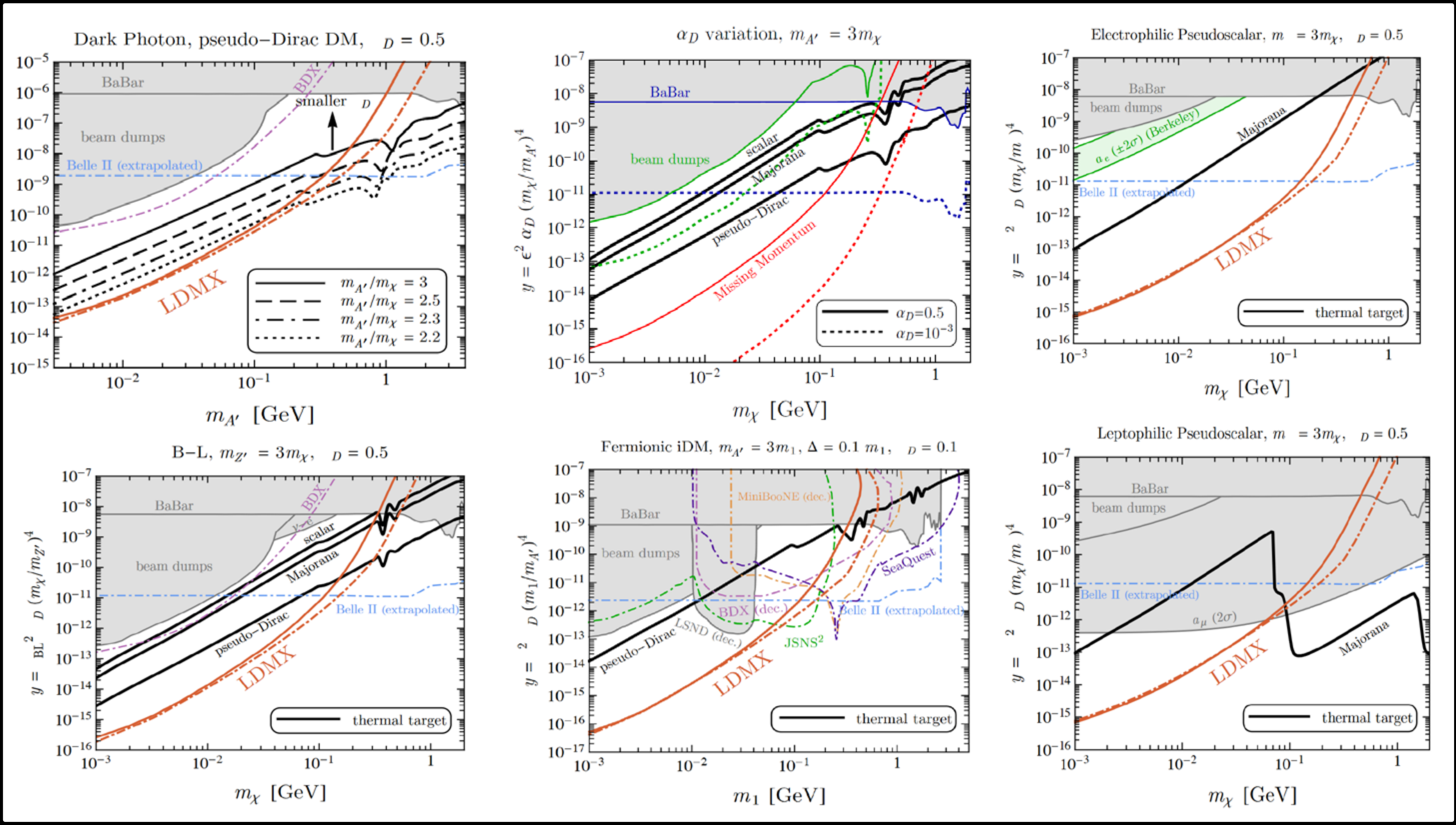




Mass Range [MeV]	Factor needed	E_e [GeV]	E_e Factor	Target $[X_0]$	Target Factor	μ_e	Years running	Factor achieved
$0.01 \leq M_\chi < 20$	2	4	1	0.15 W	1.5	1.5	1	~2
		4	1	0.1 W	1	1.5	1.5	
		4	1	0.15 W	1.5	1	1.5	
$20 \leq M_\chi < 75$	6	8	2	0.1 W	1	2	1.5	~6
		8	2	0.15 W	1.5	1	2	
		4	1	0.15 W	1.5	2	2	
$75 \leq M_\chi < 150$	80	8	4	0.4 W	4	2	3	~ 80
		8	4	0.4 Al	6	2	2	
		16	8	0.4 W	4	1.5	1.5	
		16	8	0.4 Al	4	1	2	
$150 \leq M_\chi < 300$	6×10^3	* 8	8	0.4 Al	13	2	4	$\sim 8 \times 10^2$
		16	45	0.4 W	4	2	4	$\sim 1 \times 10^3$
		16	45	0.4 Al	8	5	4	$\sim 7 \times 10^3$
		16	45	0.4 Al	8	10	2	$\sim 7 \times 10^3$

Variations on a theme

arxiv:1807.01730



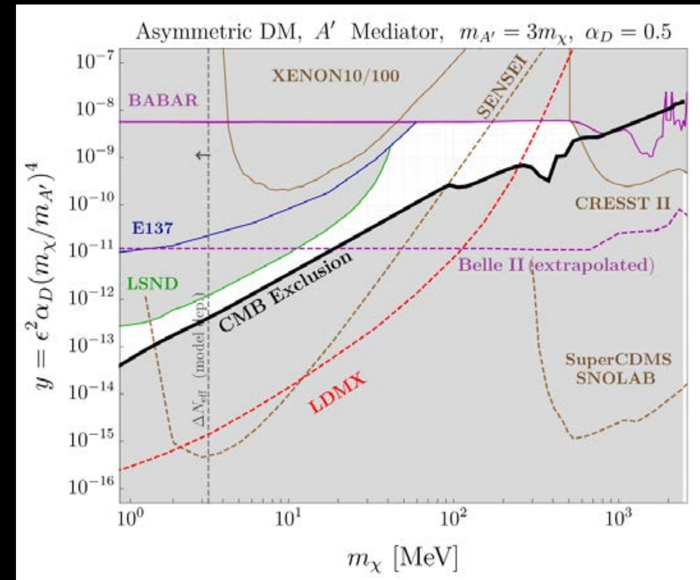
Sensitivity to a broad range of models and mild sensitivity to variation of parameters

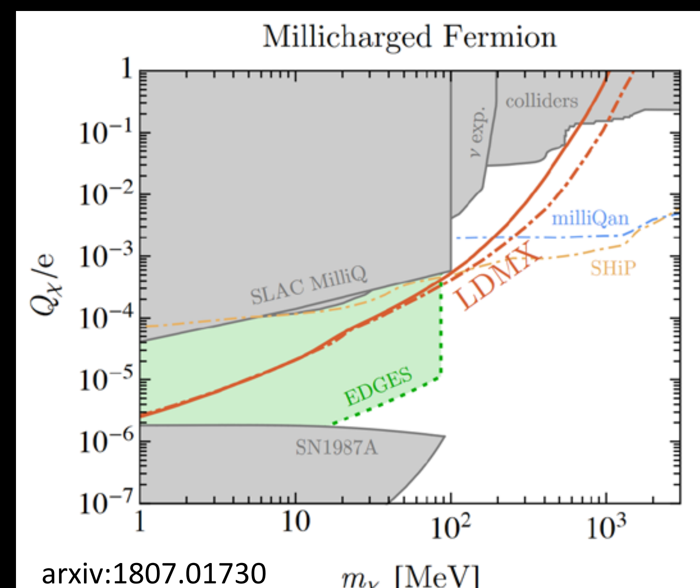
Sub-GeV BSM physics

Sample of BSM scenarios LDMX would be sensitive to:

- Asymmetric DM / ELDER
- Milli-charged fermions

arxiv:1807.01730



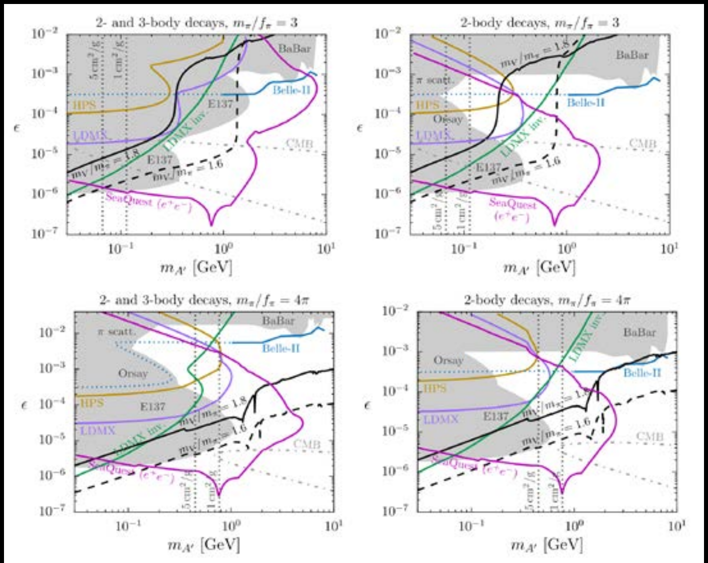


Sub-GeV BSM physics

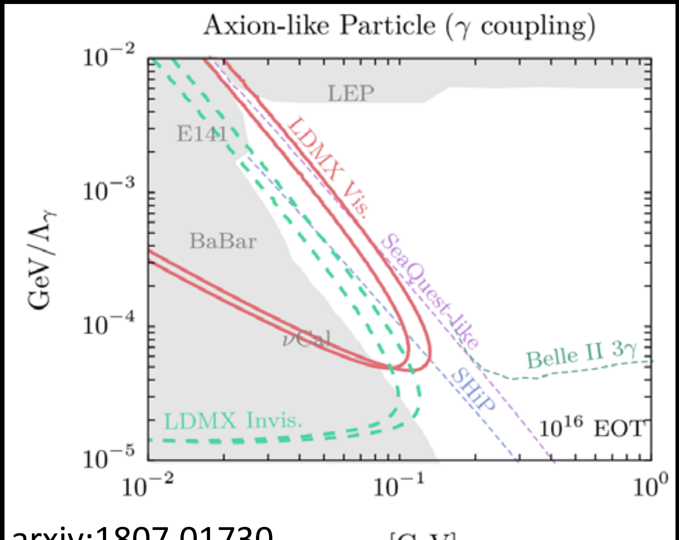
Sample of BSM scenarios LDMX would be sensitive to:

- Asymmetric DM / ELDER
- Milli-charged fermions
- Strongly interacting massive particles (SIMP) and displaced vertices
- Axion-like particles
- Generic visible and invisible mediator decays

Hidden sector vector meson decay



Berlin, Blinov, Gori, Schuster, Toro, 1801.05805



arxiv:1807.01730

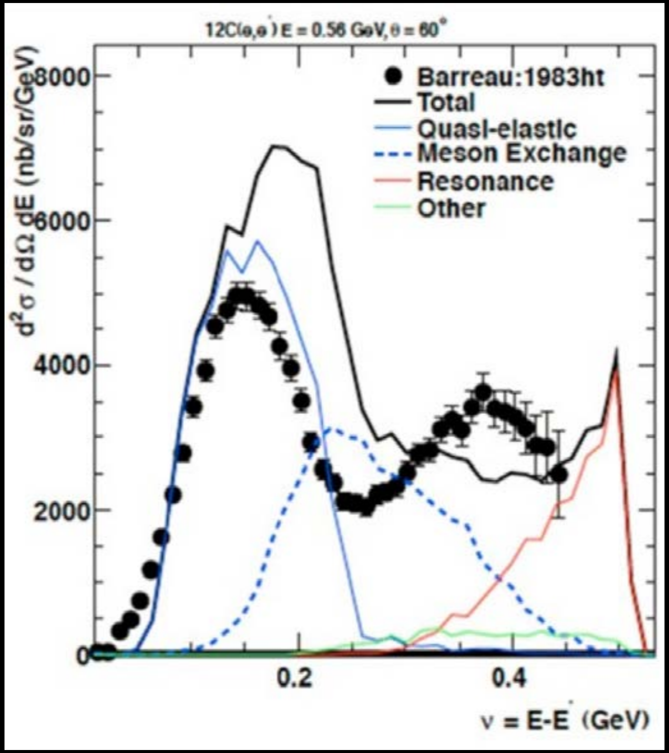
Sub-GeV BSM physics

Sample of BSM scenarios LDMX would be sensitive to:

- Asymmetric DM / ELDER
- Milli-charged fermions
- Strongly interacting massive particles (SIMP) and displaced vertices
- Axion-like particles
- Generic visible and invisible mediator decays

And can also provide useful electro-nuclear and photo-nuclear measurement for future neutrino experiments.

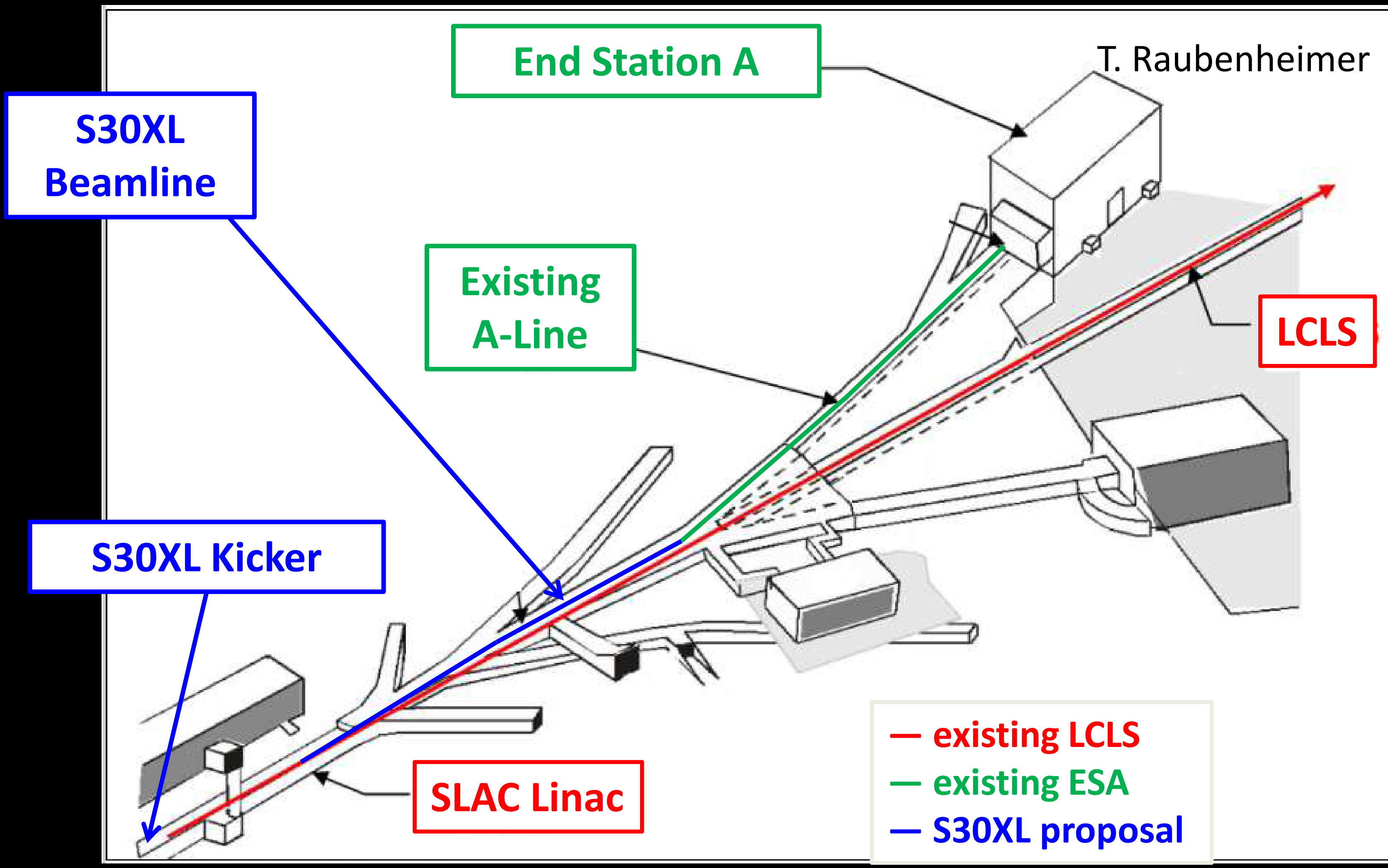
Electron scattering data needed to tune MC



T. Katori, 1304.6014

S30XL @ SLAC proposal

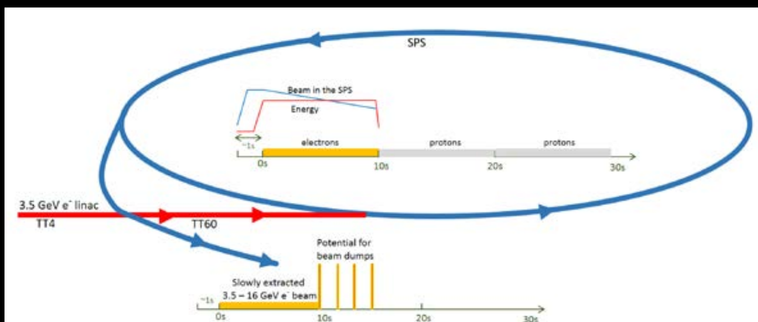
High rate, low-intensity (~1e-/bucket) beam extracted from LCLS-II



e-SPS @ CERN proposal

Possibility of a new multi-GeV Linac into SPS with high repetition rate and low current (arxiv:1805.12379).

Expression of interest to SPSC in October 2018 (https://cds.cern.ch/record/2640784) – see talks at PBC workshop.



Machine parameters:
- Energy: 3.5 – 16 GeV
- Bunch spacing: multiple of 5 ns
- Spill length: 10s in 30s super cycle
- Particles per bunch : 1 – 40

Conclusion

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

Among potential approaches, missing energy / momentum provide the best luminosity per sensitivity.

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. The experiment could also perform photonuclear & electronuclear measurements useful for planned neutrino experiments.

LDMX can complete this program within the next decade at reasonable cost, and potentially result in a groundbreaking discovery.

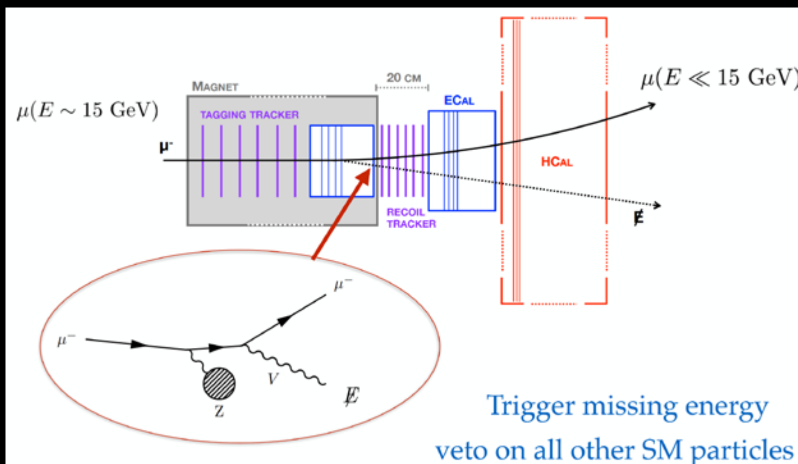
Extra material

LDMX-mu

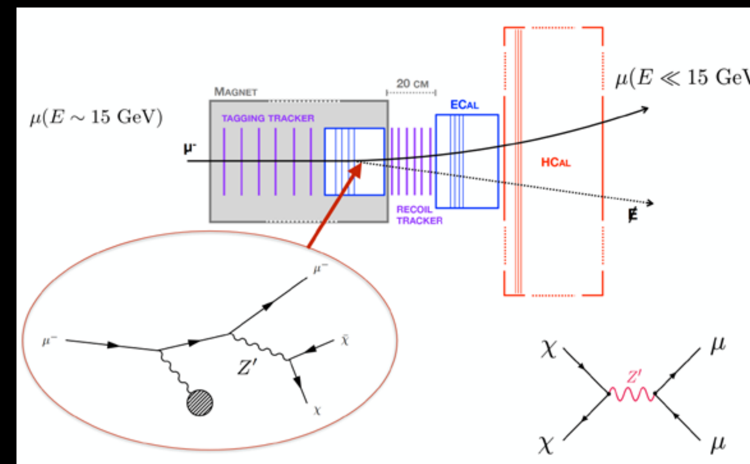
JHEP 1809 (2018) 153
arxiv:1804.03144

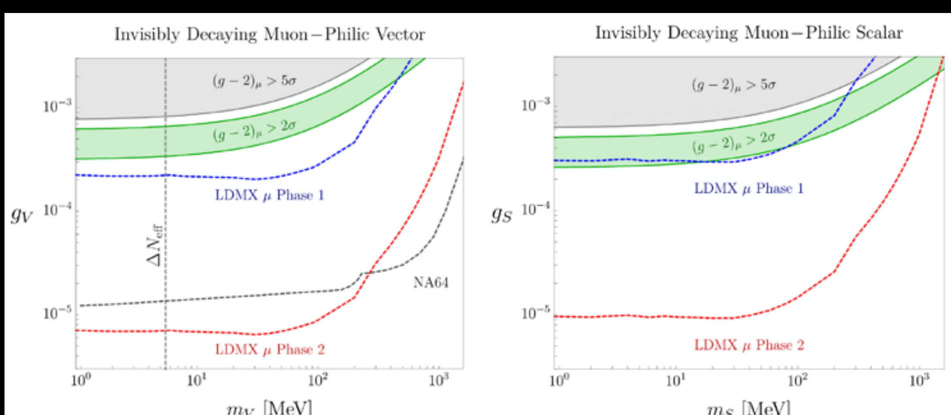
LDMX-like detector with a muon beam at FNAL

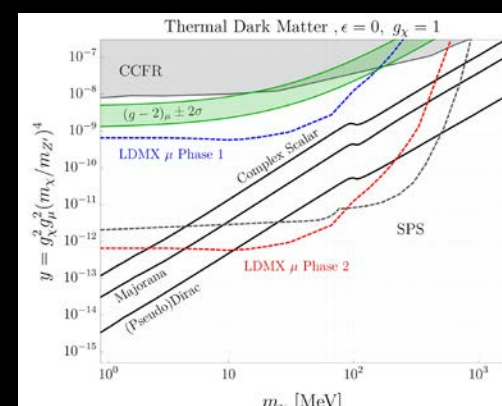
New light muon-philic particles



Muon-philic dark mediator







Secluded decay – WIMP next door

Consider case in which the DM-SM coupling was large enough to keep the two sectors in thermal equilibrium at early times (+renormalizable interactions)

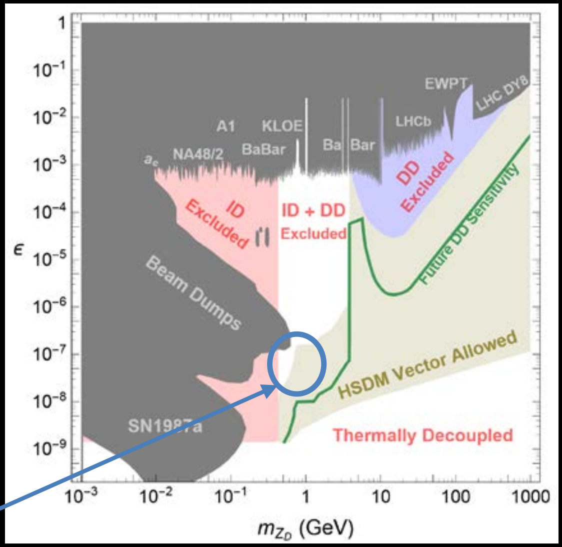
→ thermal equilibrium provides a minimal, UV-insensitive cosmological DM history that implies a minimum DM-SM coupling (with a few caveats….)

→ WIMP next door

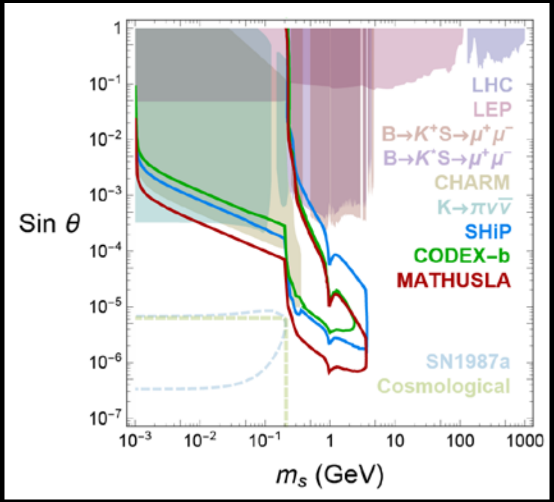
LDMX only sensitive to a small fraction of allowed parameter space for vector mediator (at most a few GeV)

Coupling to electrons only significant in a small mass range ($2m_e < m_S < 2m_\mu$) for scalar mediator

Vector mediator



Scalar mediator

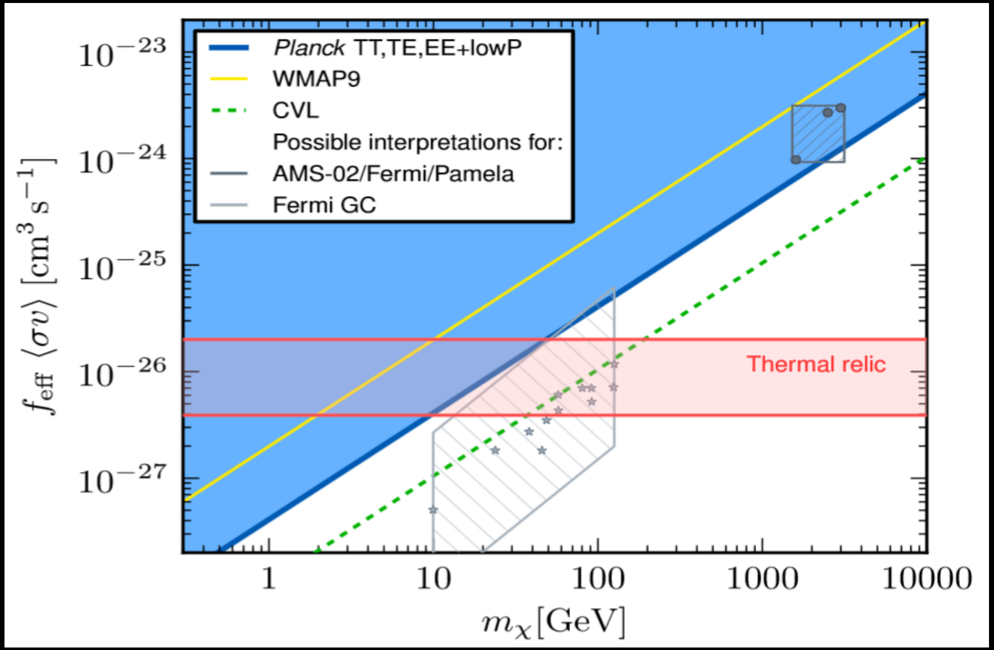


Evans, Gori & Shelton, arxiv:1712.03974

Cosmological constraints

Primordial DM annihilation injects energy in the CMB $\rightarrow$ distorts CMB spectrum

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



Planck collaboration, 1502.01589

Rules out Dirac fermion DM, which proceeds via s-wave annihilation.

Remaining possibilities

(1) p-wave annihilation

OR

(2) annihilation shuts off before CMB

Scalar, Majorana and inelastic DM are possible candidates

Proton beam dump

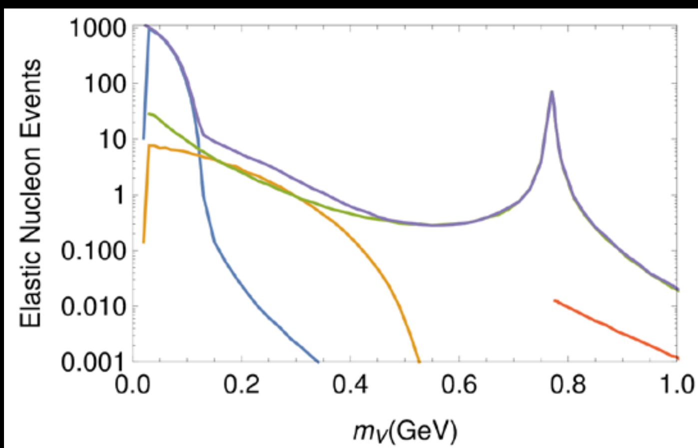
Future proton beam dump experiments

PRD 95 (2017) 035006

Name	Energy	POT	Detector Mass	Material	Distance	Angle	Efficiency
MiniBooNE-Beam Dump	8 GeV	2×10^{20}	400 tons	CH_2	490 m	0	0.35
T2K-ND280 (P0D)	30 GeV	5×10^{21}	6 tons	H_2O,Plastic	280 m	2.5^o	0.35
T2K-Super-K	30 GeV	5×10^{21}	50 kilotons	H_2O	295 km	2.5^o	0.66
SHiP	400 GeV	2×10^{20}	10 tons	LAr	100 m	0	0.5

+SBND,
DUNE,
…

Production modes



π^0 decays

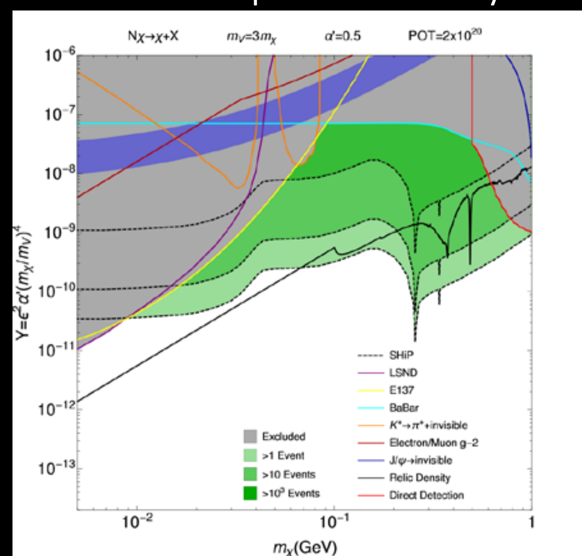
η decays

Bremsstrahlung (incl. ρ/ω mixing)

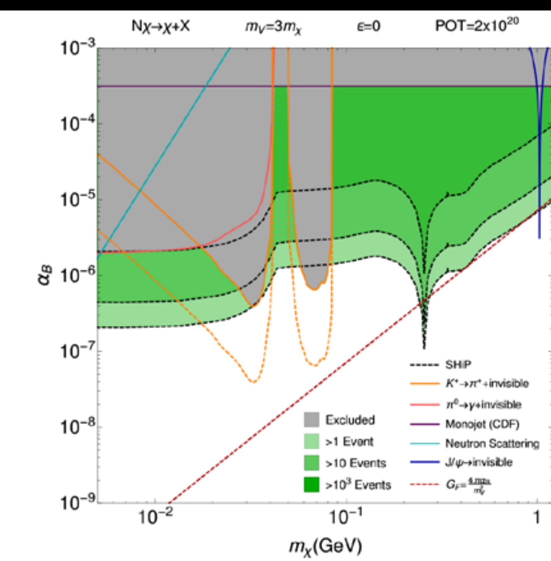
Parton

Total

SHiP vector portal sensitivity



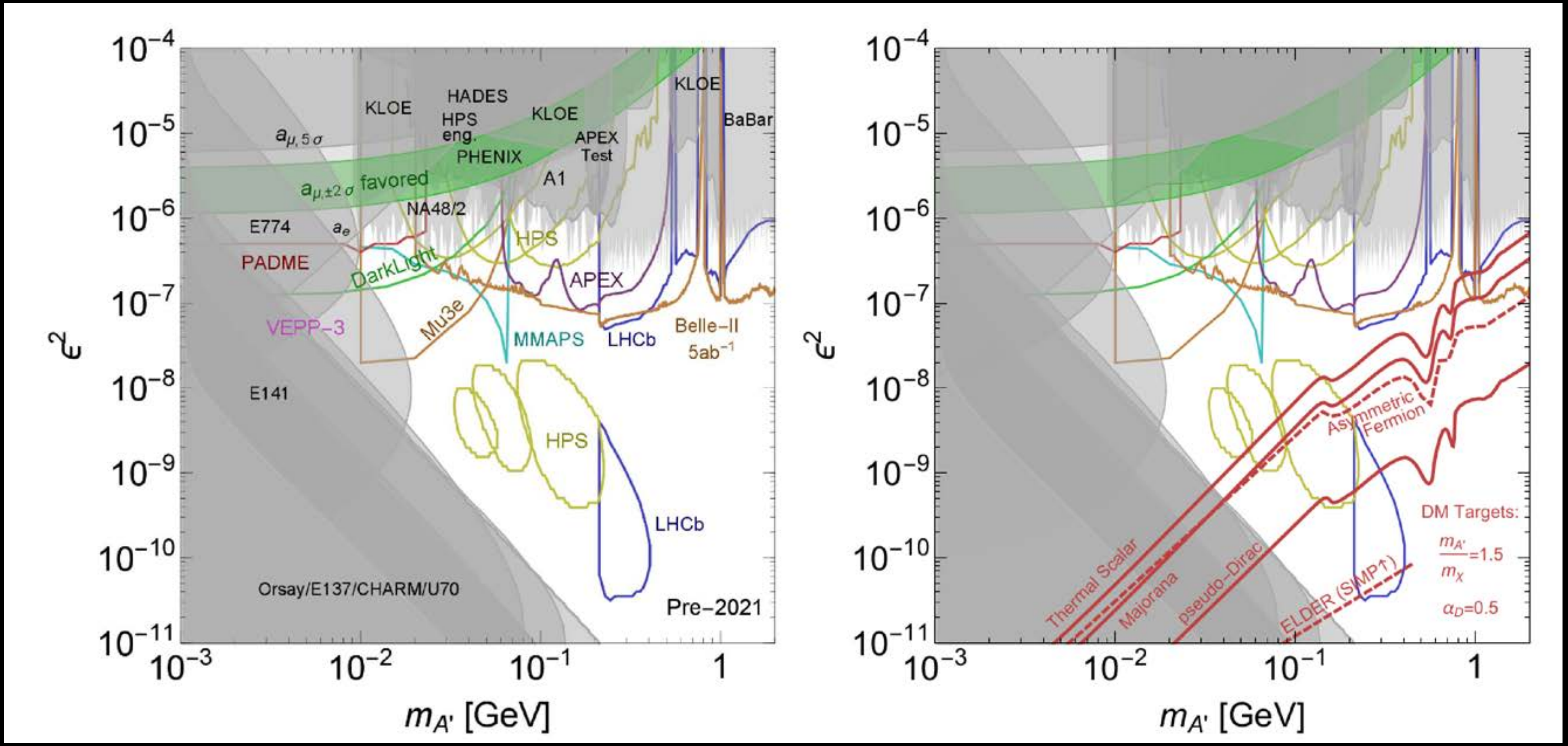
SHiP leptophobic sensitivity



Can probe vector portal and baryonic couplings

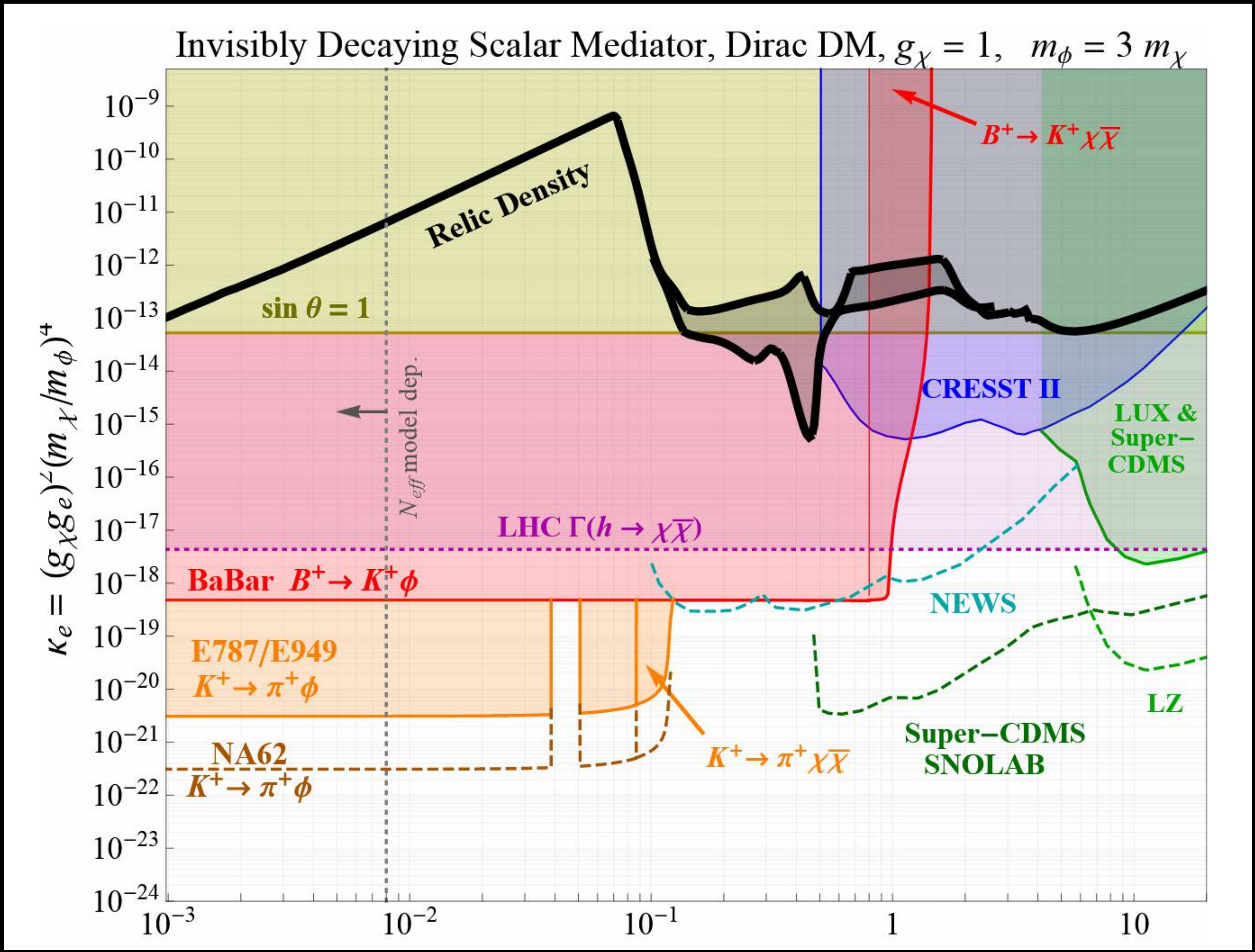
Sensitivity estimates

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

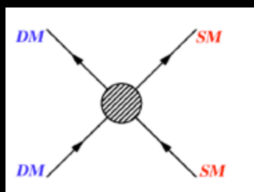
Scalar mediator



Krnjaic, arXiv:1512.04119

The WIMP miracle

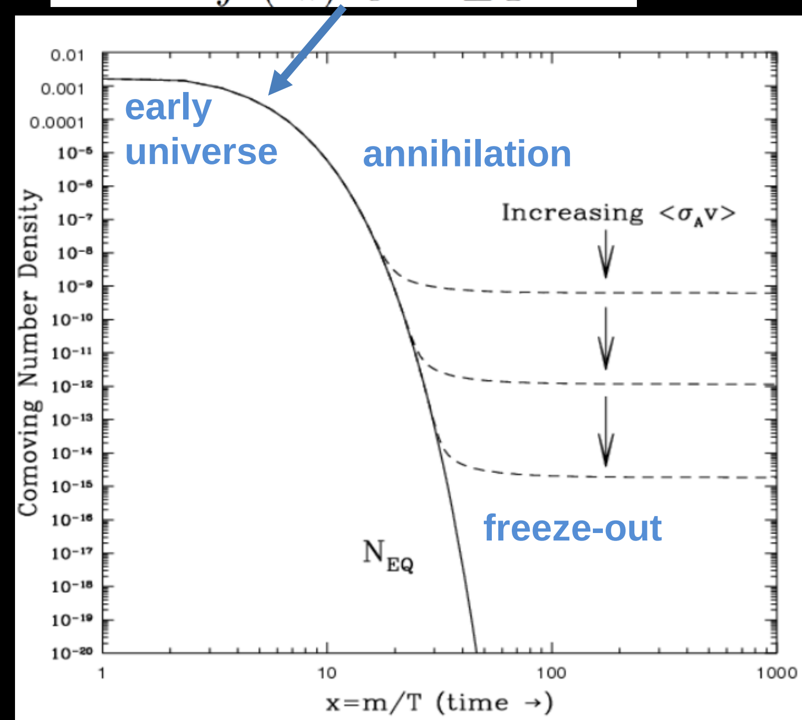
In early universe, dark matter particles are in thermal equilibrium with other standard model particles



$\mathrm{DM}\,\overline{\mathrm{DM}} \Leftrightarrow \mathrm{SM}\,\overline{\mathrm{SM}}$

$n_{DM} \sim T^3$

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



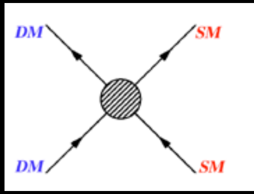
As the universe expands and cools, the DM number density becomes exponentially suppressed when $T \sim< m_{DM}$: $n_{DM} \sim e^{-m/T}$

The DM density becomes too low for annihilation process to keep up with expansion rate, and a DM abundance is left over to the present day (freezes out). The larger the annihilation cross-section, the smaller the relic density.

See e.g. Dev et al., arXiv:1311.5297

The WIMP miracle

In early universe, dark matter particles are in thermal equilibrium with other standard model particles



$DM\ \overline{DM} \Leftrightarrow SM\ \overline{SM}$

$n_{DM} \sim T^3$

As the universe expands and cools, the DM number density becomes exponentially suppressed when $T \sim< m_{DM}$: $n_{DM} \sim e^{-m/T}$

The DM density becomes too low for annihilation process to keep up with expansion rate, and a DM abundance is left over to the present day (freezes out). The larger the annihilation cross-section, the smaller the relic density.

And the WIMP miracle?

The observed DM density implies an averaged annihilation cross-section

$$\langle\sigma v\rangle \sim 3\times10^{-26}\ cm^3s^{-1}$$

The annihilation cross-section:

$$\sigma(DM\ DM \rightarrow SM\ SM) \sim \alpha^2/m^2_{DM}$$

For a typical weak-scale coupling, one find a mass scale

$$m_{DM} \sim 100\ GeV - 1\ TeV$$

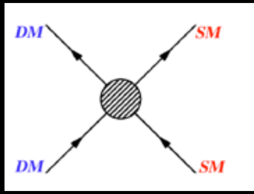
near the weak scale.

Thermal origin suggest both non-gravitational interactions and a mass scale in the vicinity of the weak scale

See e.g. Dev et al., arXiv:1311.5297

The WIMP miracle

In early universe, dark matter particles are in thermal equilibrium with other standard model particles



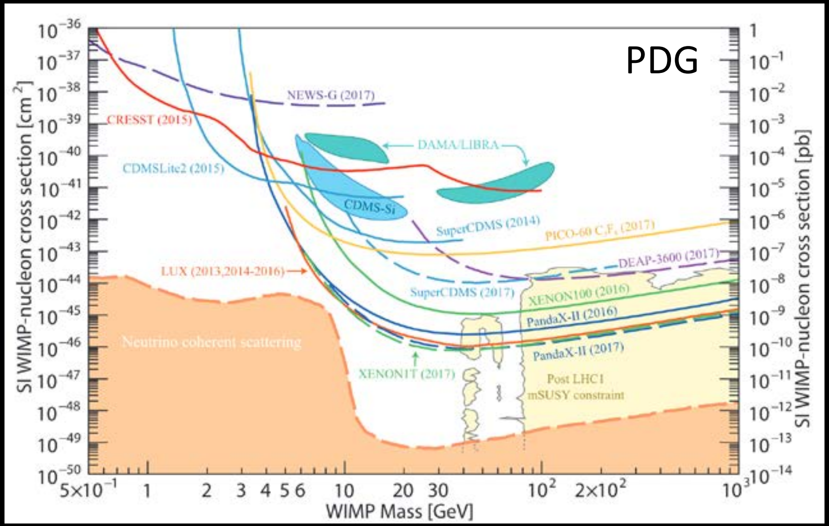
$$\mathrm{DM}\ \overline{\mathrm{DM}} \Leftrightarrow \mathrm{SM}\ \overline{\mathrm{SM}}$$

$$n_{DM} \sim T^3$$

As the universe expands and cools, the DM number density becomes exponentially suppressed when T ~< m_{DM} : $n_{DM} \sim e^{-m/T}$

The DM density becomes too low for annihilation process to keep up with expansion rate, and a DM abundance is left over to the present day (freezes out). The larger the annihilation cross-section, the smaller the relic density.

Limits on spin independent WIMP-nucleon cross-section



Null results from direct detection experiments and the LHC motivate the exploration of new ideas beyond the standard WIMP paradigm, such as the possibility of light dark sectors and light dark matter.

See e.g. Dev et al., arXiv:1311.5297