Light dark matter and the LDMX experiment

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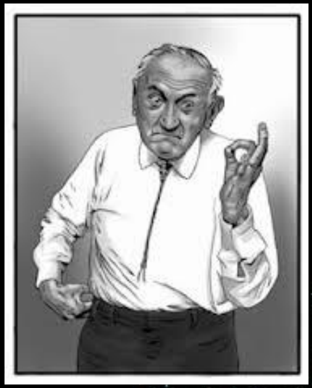
University of Oregon – April 2023

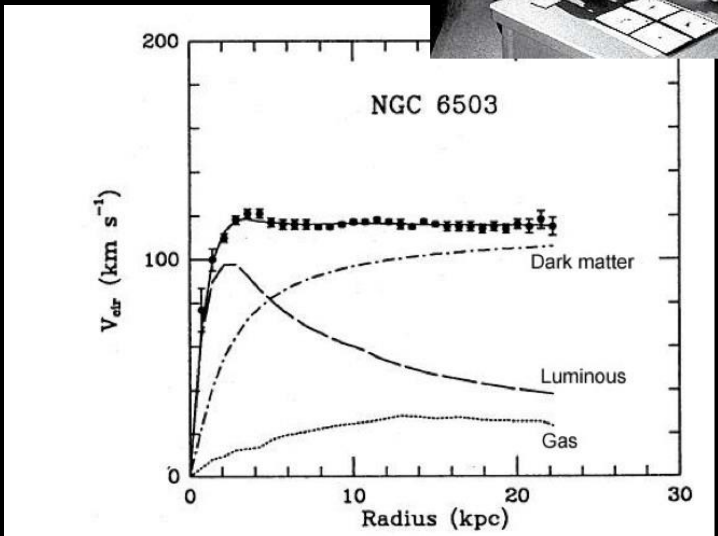
Dark matter: an old puzzle

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



Coma cluster SDSS

In the 1970s, Vera Rubin measured the rotation curves of many spiral galaxies. She observed a flat curve at large radii, indicating the presence of dark matter

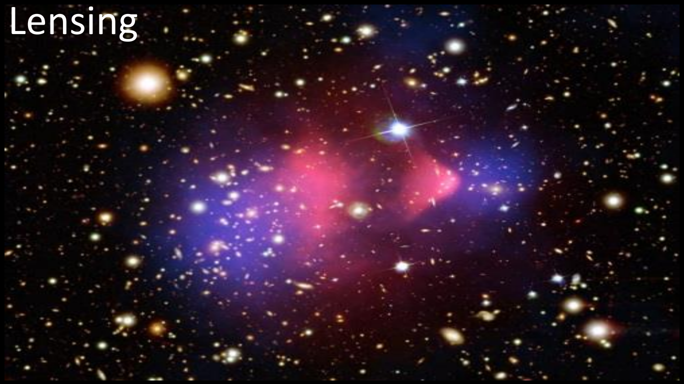


K.G. Begeman, A.H. Broels, R.H. Sanders. 1991. Mon.Not.RAS 249, 523.

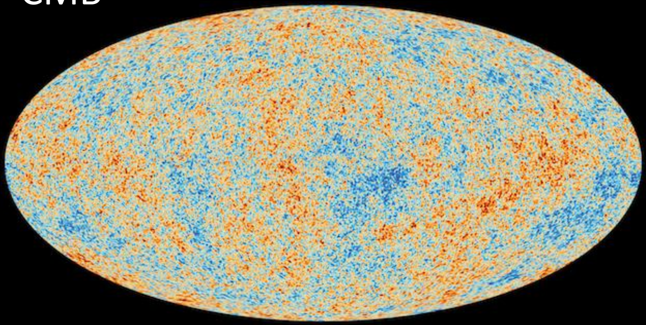
Dark matter: an old puzzle

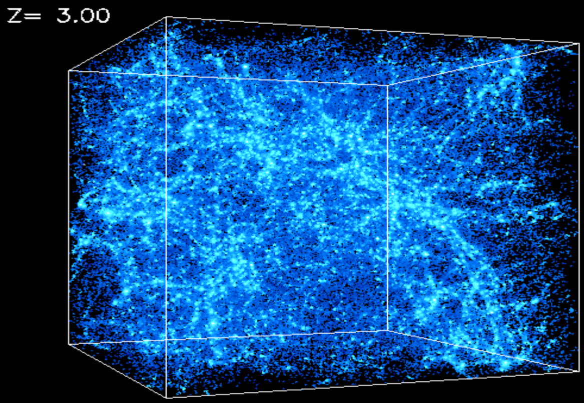
Many recent astrophysical probes have arrived to the same conclusion: about 85% of the total mass in the universe is unseen

Lensing

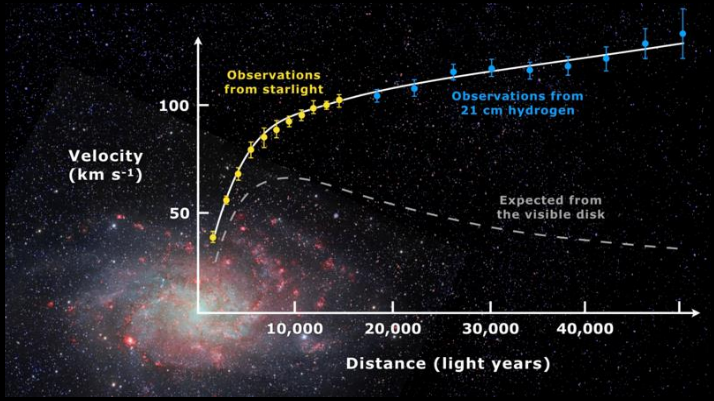


CMB





Structure formation



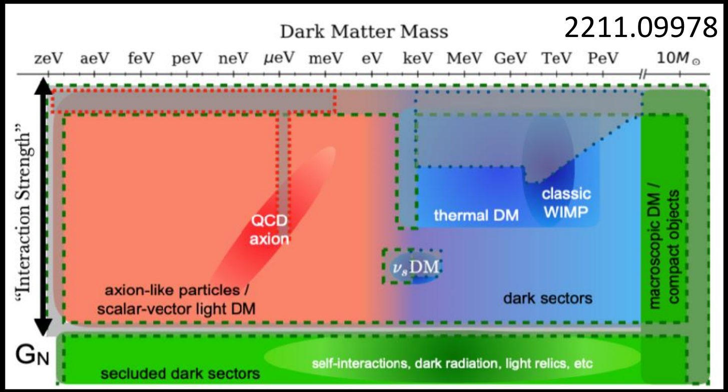
Rotation curve

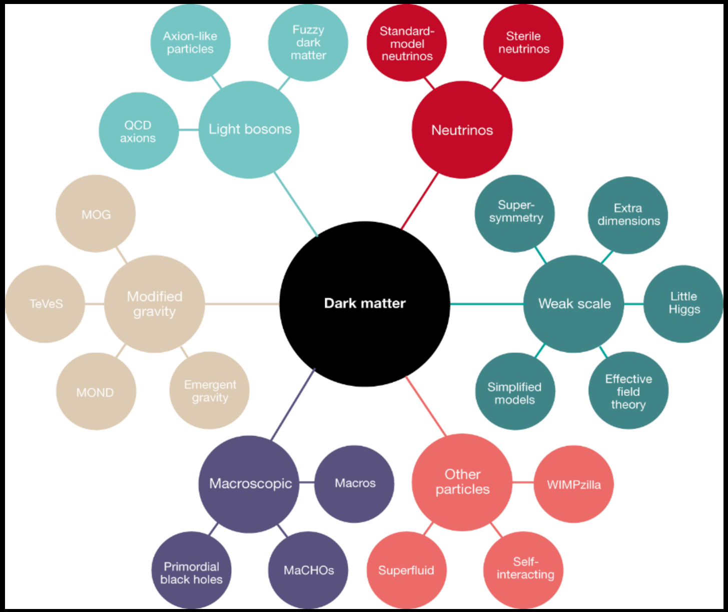
A vast array of possibilities

We still know relatively little about DM:

- **Abundance:** Ω_{DM} ~ 0.26
- **Mass:** about 80 (60) orders of magnitude of mass range for bosons (fermions)
- **Interactions:** gravitational interaction, a self-interaction is possible if it is not too strong - other interactions with ordinary matter possible as long as they do not involve emission of photons

A vast range of possibilities





Bertone and Tait, Nature 562, 51–56 (2018)

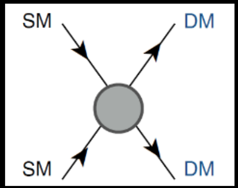
Dark matter flowchart

Adapted from 1807.01730

Was DM in thermal equilibrium with SM?

No → **How was it produced**

- **initial conditions:** axion, primordial BH,…
  Vast parameter space
- **Feeble coupling with thermal bath:** sterile ν, freeze-in,…



Difficult to test due to small coupling

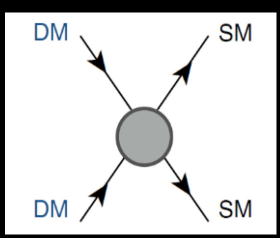
Yes → **Was DM abundance depleted into visible matter**

No → **Stable dark state**

Often tension with Neff, BBN, LSS / non standard cosmology

Yes →

Direct annihilation: WIMP, MeV-GeV relic,…



Thermalizes with SM - predictive models

Indirect annihilation: Secluded DM, SIMP, …

Thermalizes with particle that thermalizes with SM - Search for mediators

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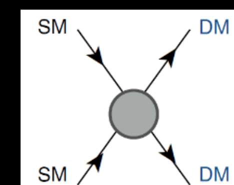

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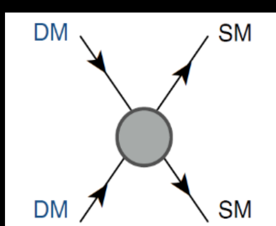

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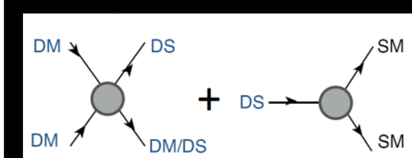
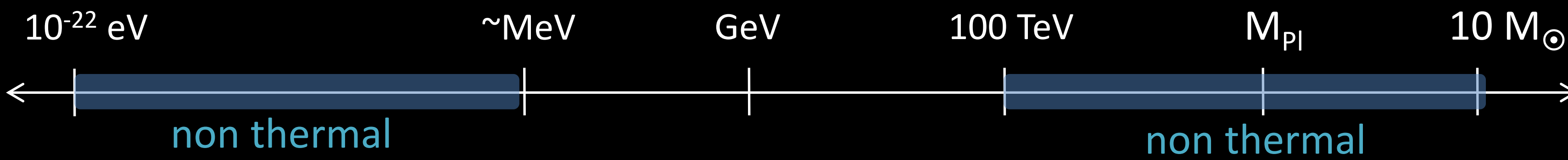


Thermalizes with particle that thermalizes with SM - Search for mediators

Thermal dark matter:
Simple and generic, only requires non-gravitational interaction larger than the Hubble expansion rate

WIMP and light DM

Thermal hypothesis greatly restricts the range of DM masses from ~ MeV – 100 TeV



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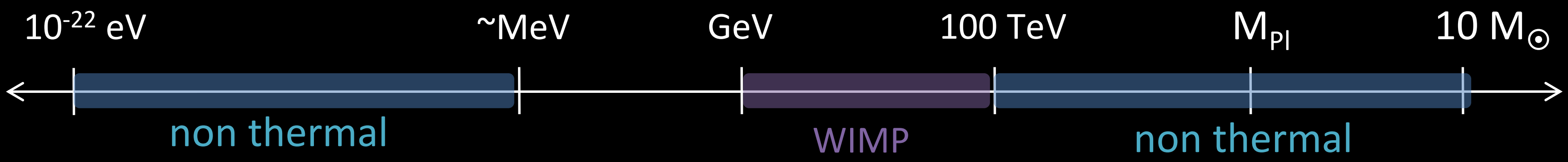


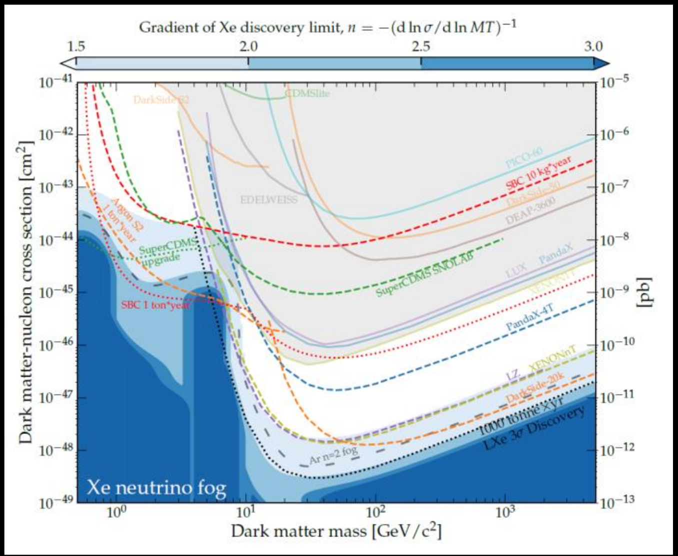
WIMP – the miracle

The observed DM density implies an averaged annihilation cross-section

$$\langle \sigma v \rangle \sim 3 \cdot 10^{-26}\ cm^3 s^{-1}$$

For a typical weak-scale coupling, one finds a mass scale m_{DM} ~100 GeV – 1 TeV, near the weak scale.

No WIMP has been unambiguously observed so far, but searches continue….



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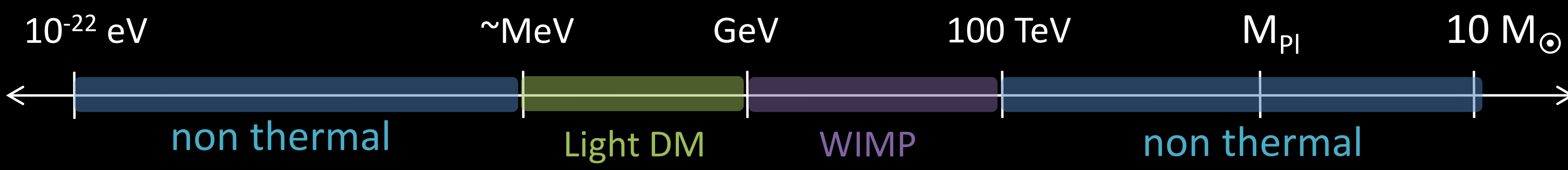
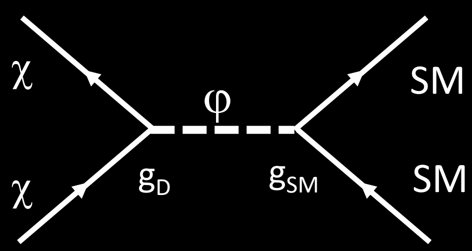


Light DM – new mediator

Thermal DM allows mass down to ~MeV, but requires a new light mediator to explain the relic density, or dark matter is overproduced (Lee Weinberg bound)



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

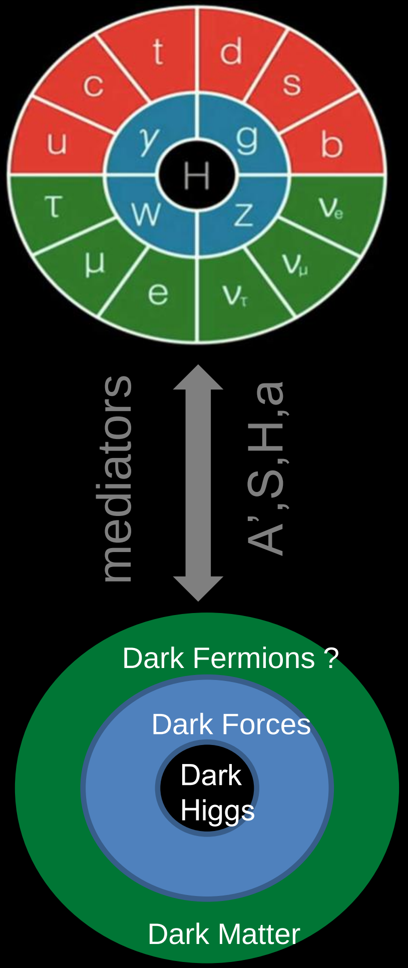
$$m_\varphi^4 < \sigma v > \sim g_D^2\, g_{SM}^2\, m_x^2 \leq m_x^2 \qquad \text{since } g \leq O(1)$$

New mediator must be neutral under the SM interactions.
Naturally realized in the context of hidden sectors

Hidden sectors

What are hidden sectors (HS) / dark sectors (DS)

- Simply put, they are new particle(s) that don't couple directly to the SM
- But they can couple indirectly via new mediator particles through so-called "portals" – see next slide
- Dark sector structure could be rich, including many new fermions and bosons with complicated DS interactions. After all, the SM is non-trivial, and there is no reason for the dark sector to be simple.
- Theoretically motivated: many BSM scenarios (e.g. EWSB) and string theory include dark sectors
- Dark matter could reside in dark sector



Shift the focus from high-energy to high-intensity / low-coupling

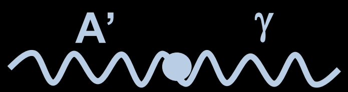
Portals and hidden sector dark matter

There are a only few indirect interactions allowed by Standard Model symmetries between the DS - SM – the "portals". The lowest dimension portals include:

Dim=4

Vector (+variants)
$\varepsilon B^{\mu\nu} A'_{\mu\nu}$

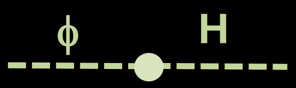
New gauge boson A' (dark photon) mixing with SM photon/Z via kinetic mixing strength ε



Dim=4

Scalar
$H^2 (\mu\phi + \lambda\phi^2)$

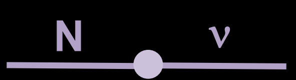
New dark scalar ϕ mixing with SM Higgs



Dim=4

Fermion
yHNL

New heavy neutral lepton mixing with left-handed SM doublets and the Higgs boson



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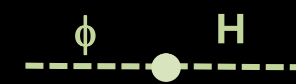

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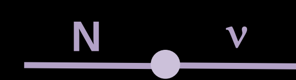
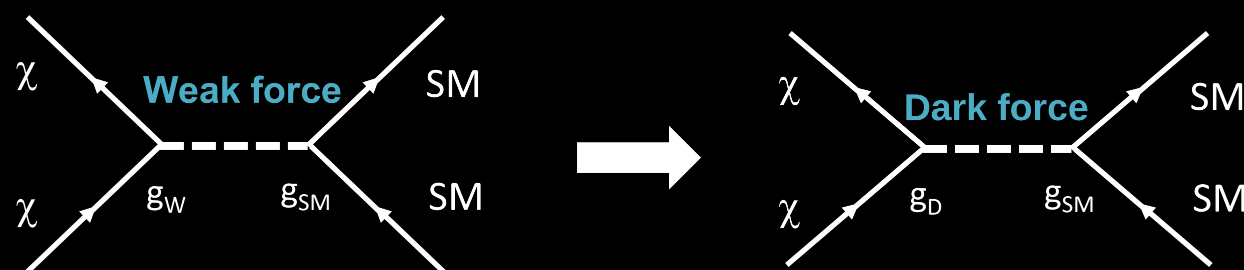


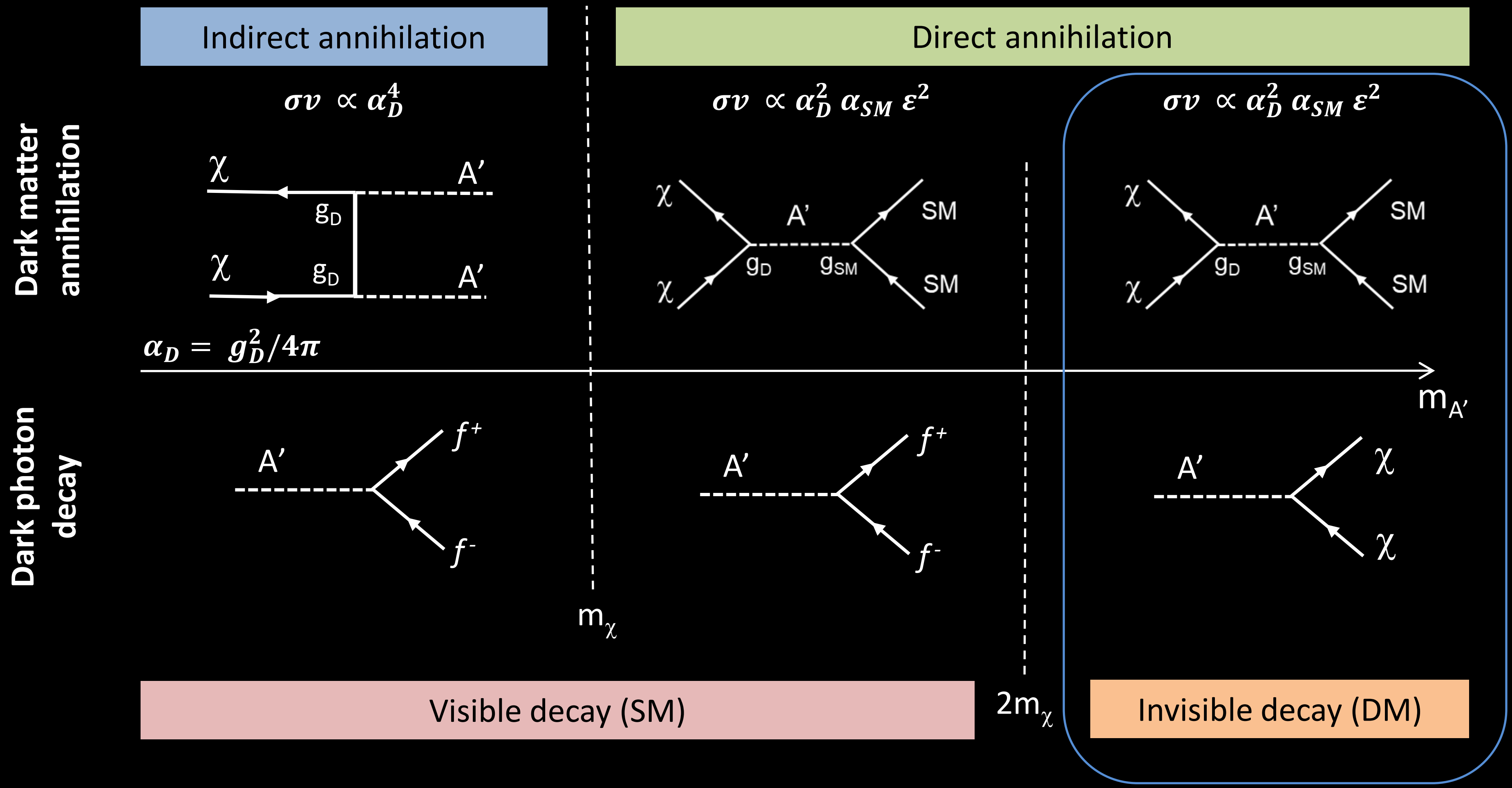
Hidden sector light dark matter

Same story as WIMP for new mediator



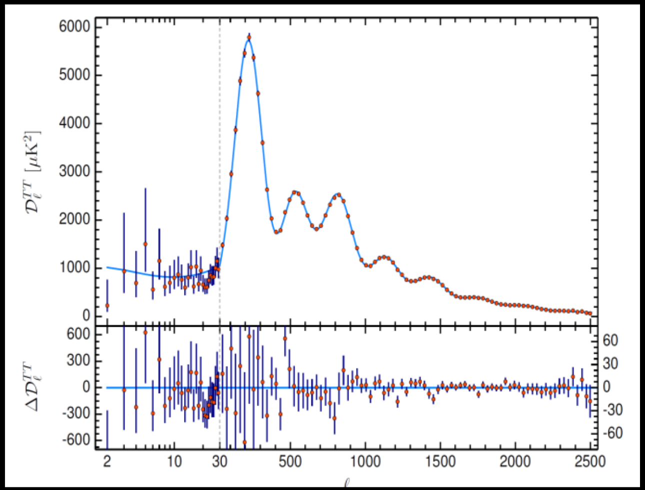
Light DM signatures

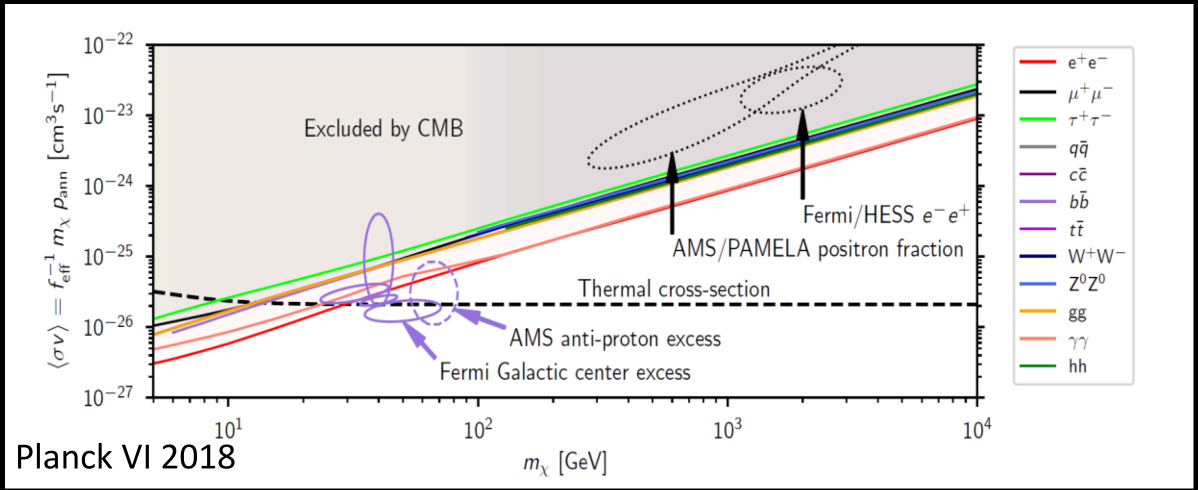
Scalar portal is excluded by rare meson decays for direct annihilation, and we will focus on the vector case for the remainder of this talk



Cosmological constraints

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





Planck VI 2018

Rules out DM masses below ~10 GeV but probe temperatures << freeze-out temperature

Allow models where annihilation rates decrease at low temperatures:

- p-wave annihilation – velocity suppressed (scalar and Majorana fermion DM)
- Inelastic co-annihilation – two states split by Δ mass, shuts off before CMB since heavy state has decayed (inelastic scalar or pseudo-Dirac fermion DM)

Exclude s-wave annihilation – no velocity suppression (Dirac fermion DM)

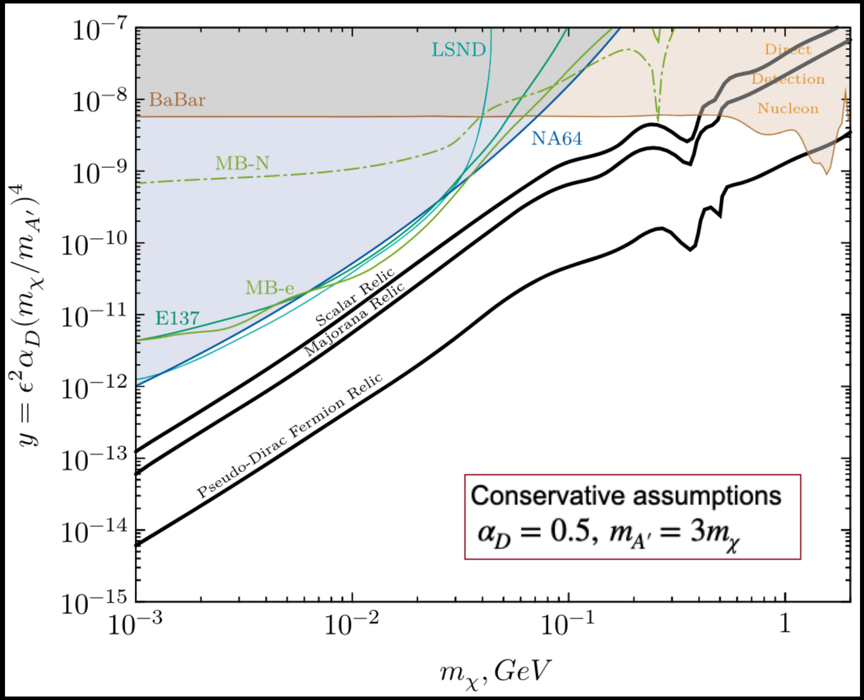
Hidden sector light dark matter

Benchmark scenario: light dark matter via vector portal

Very interestingly, the DM relic density for direct annihilation via the vector portal depends only on the mass, spin and dark sector couplings

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

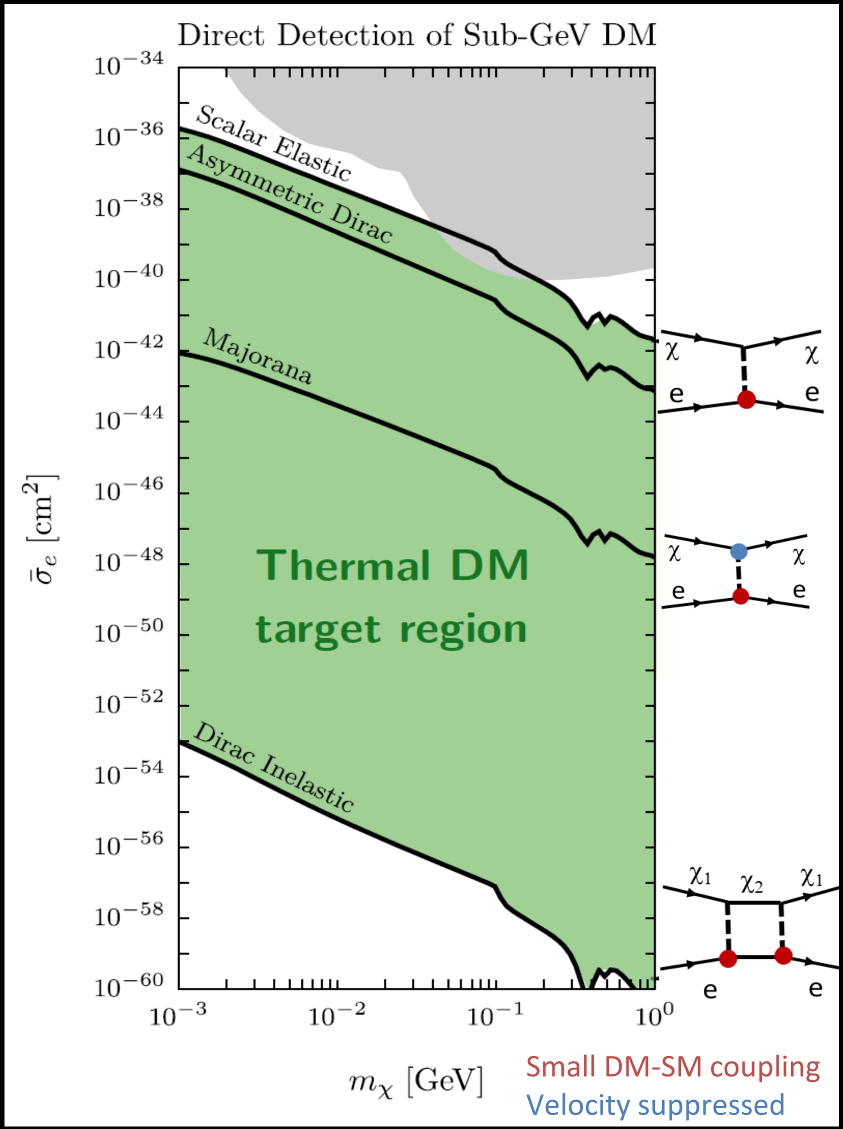
Dimensionless variable $$y = \alpha_D\, \varepsilon^2 \frac{m_x^4}{m_A^4}$$



Hidden sector light DM defines sharp targets, accessible in laboratory

Light dark matter at accelerators

Why accelerators?



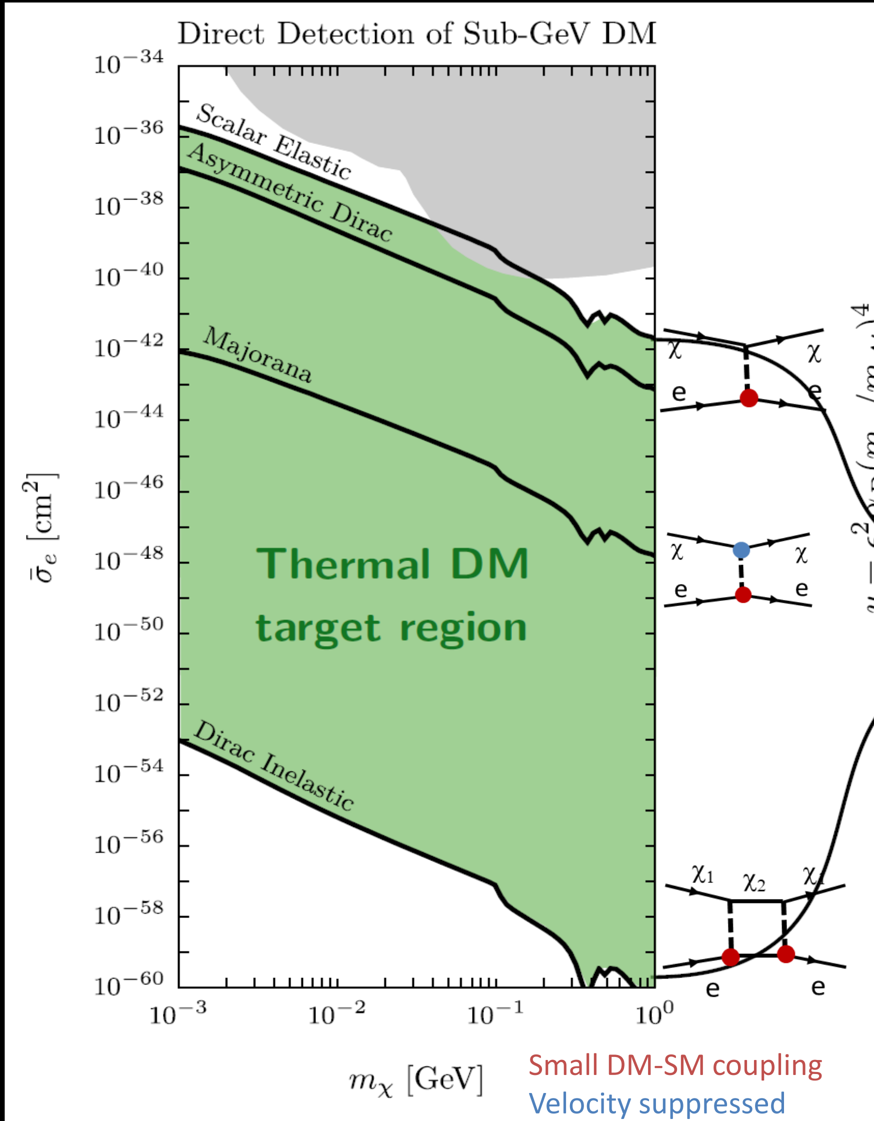
Direct detection capabilities are strongly dependent on the nature of dark matter

Some of the effects that suppress non-relativistic annihilation also suppress non-relativistic scattering

Predictions for scalar elastic and asymmetric Dirac DM are within reach of planned experiments

Majorana DM may be accessible with future generation of experiments (low threshold LXe)

Why accelerators?



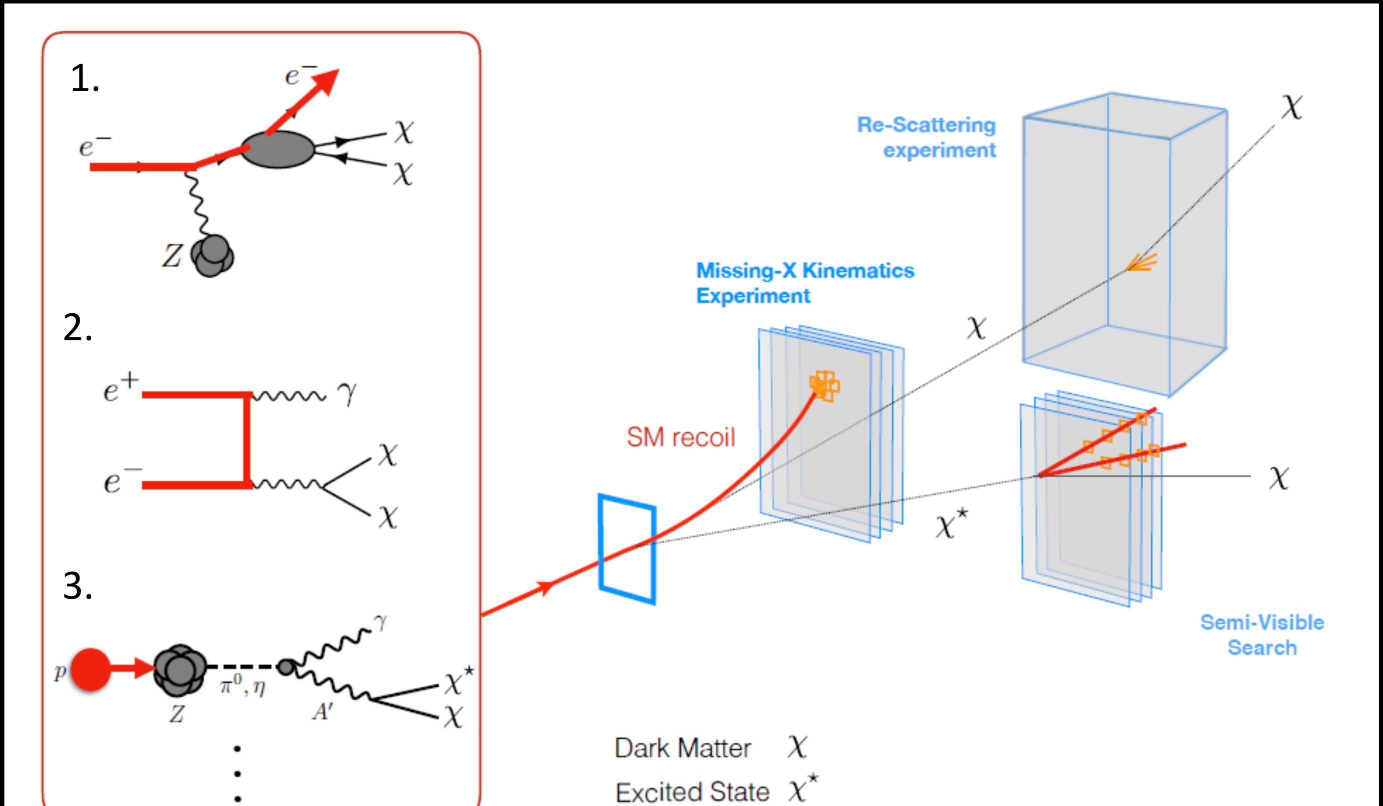
Relativistic production at accelerators: almost insensitive to spin and mass

Need direct detection to confirm cosmological nature

Searches at accelerators

Main techniques to produce light DM at accelerator

1. Bremsstrahlung-like DM production off beam leptons / proton beam
2. Electron-positron annihilation
3. Meson decays



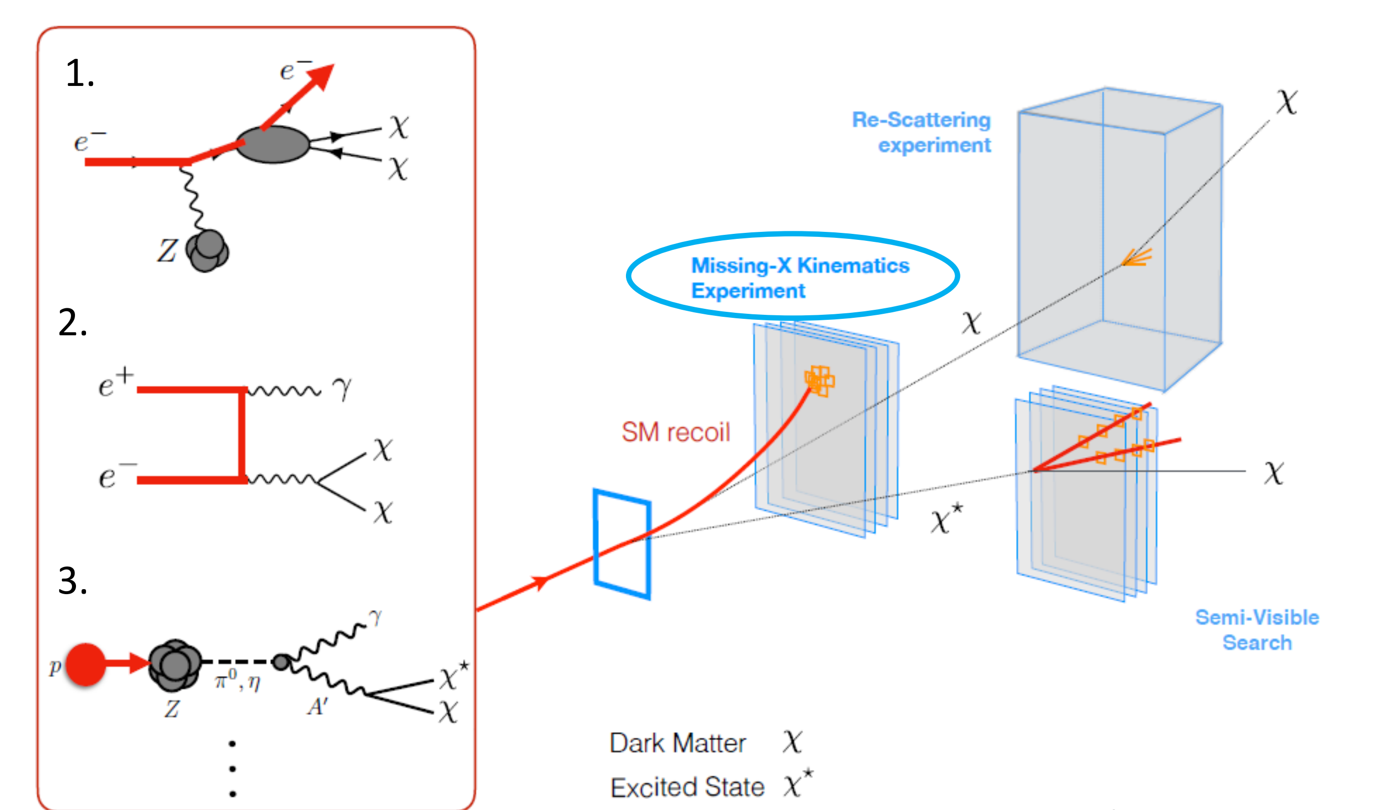
Taken from 2207.00597

Searches at accelerators

Main techniques to detect light DM at accelerator

Missing energy/momentum/mass: observe all but DM particle and use kinematic to reconstruct DM signature.

Large signal yield (coupling^2) but need excellent veto to remove large SM background



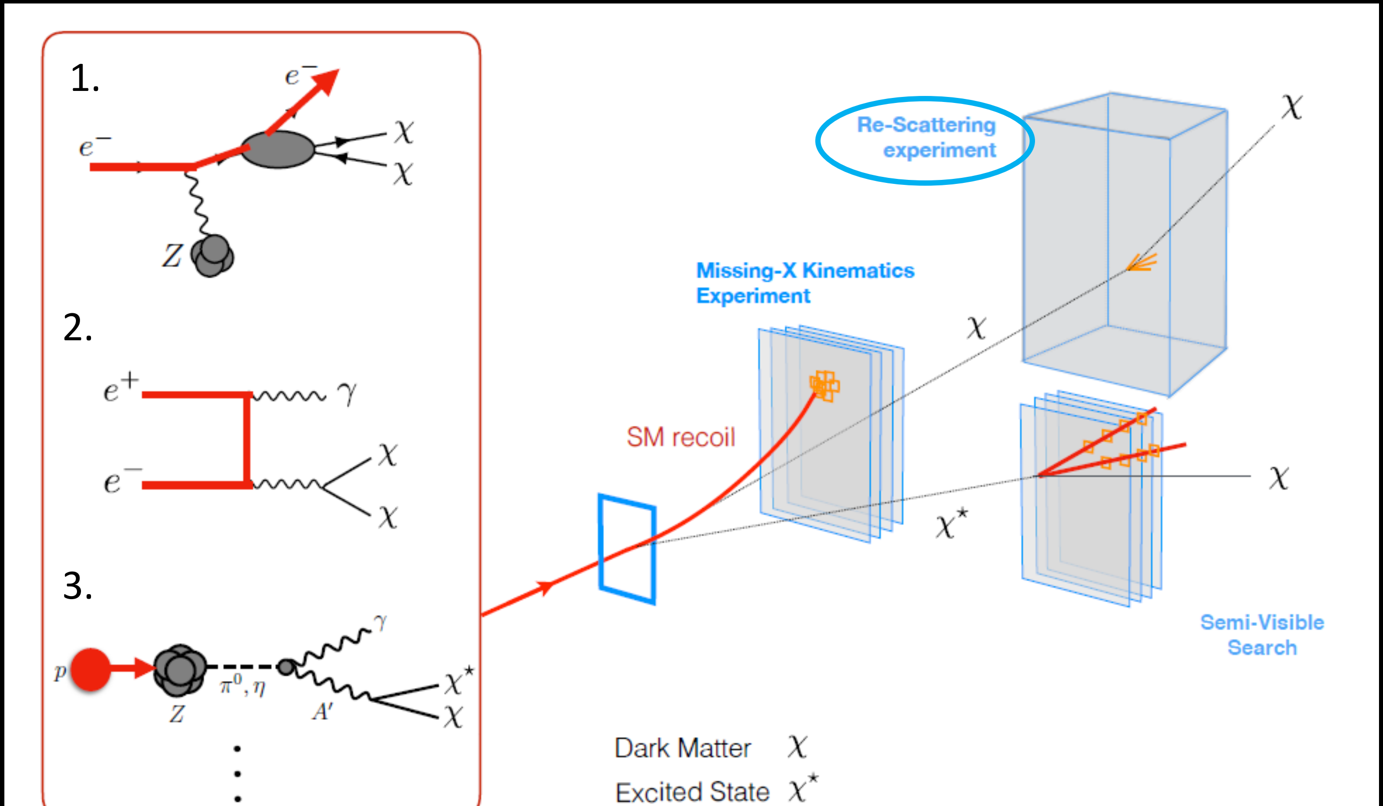
Taken from 2207.00597

Searches at accelerators

Main techniques to detect light DM at accelerator

Re-scattering: produce dark matter in target and identify DM signal in downstream detector.

Sensitive to dark sector physics but rates very suppressed (coupling^4)



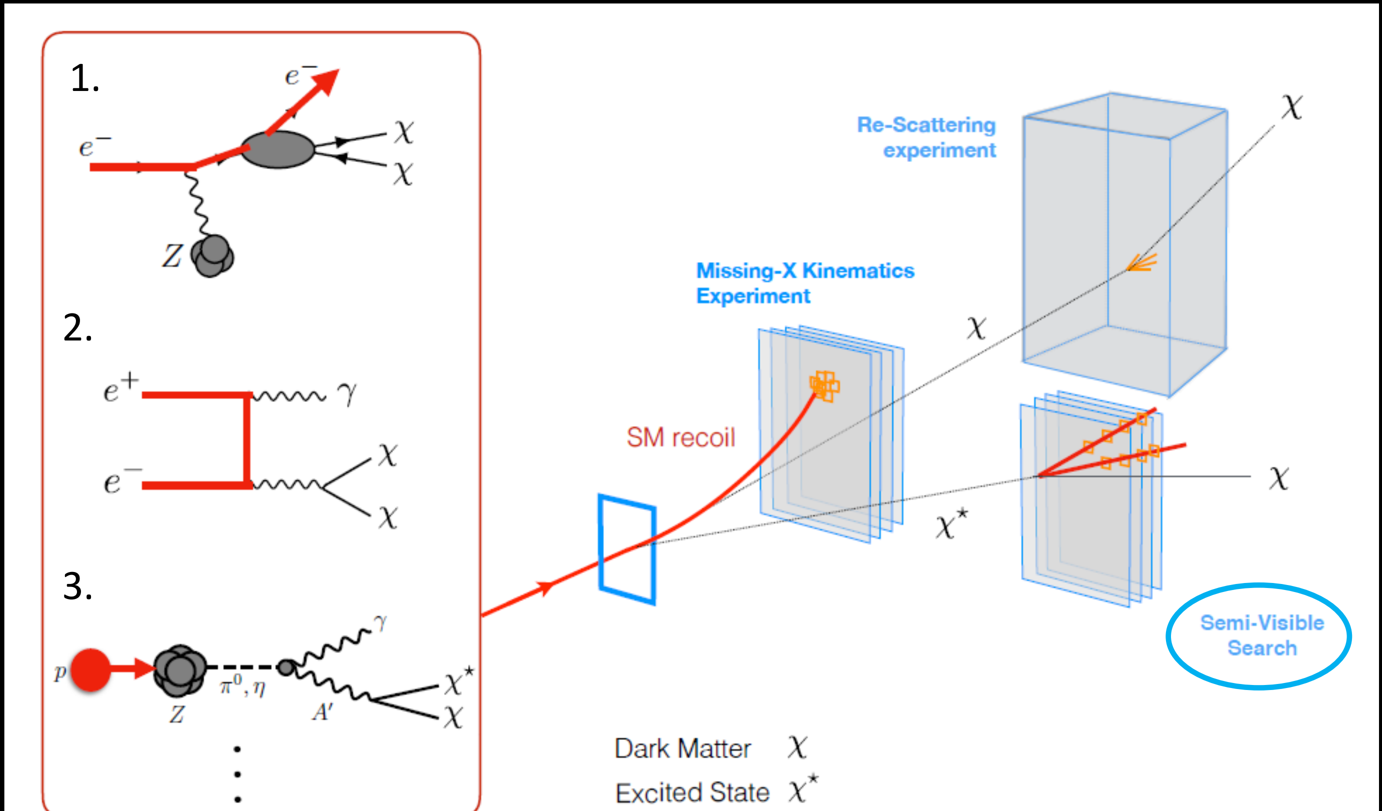
Taken from 2207.00597

Searches at accelerators

Main techniques to detect light DM at accelerator

Semi-visible search: Search for visible states produced by transitions between dark sector states.

Signature are model dependent $\rightarrow$ vast parameter space to probe



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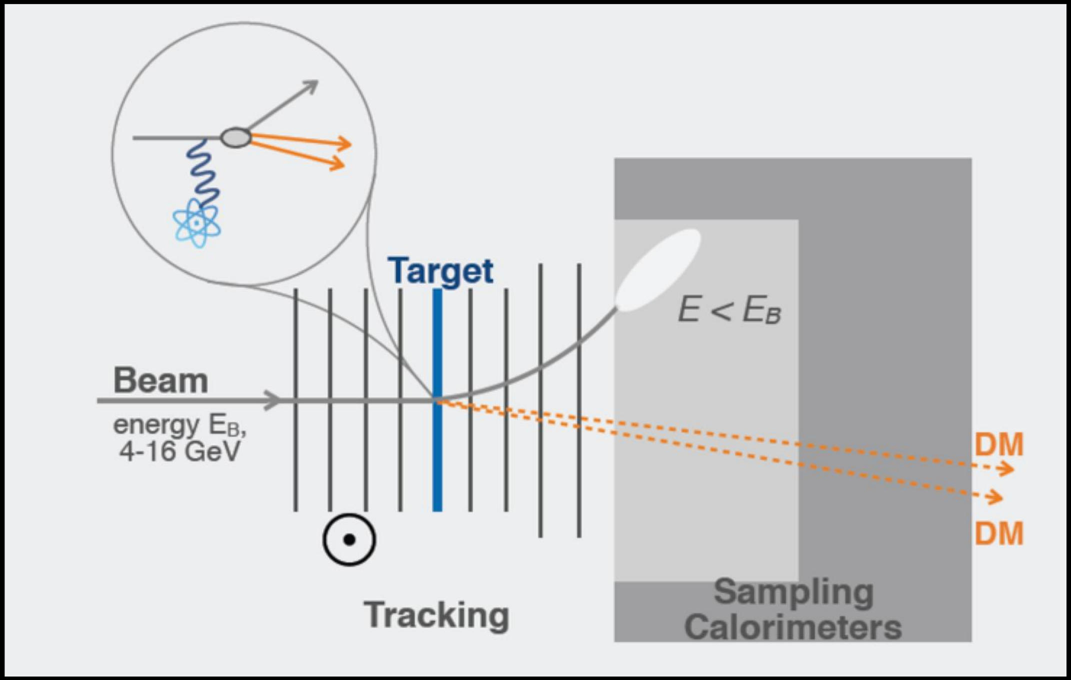
The missing momentum approach:
The LDMX experiment

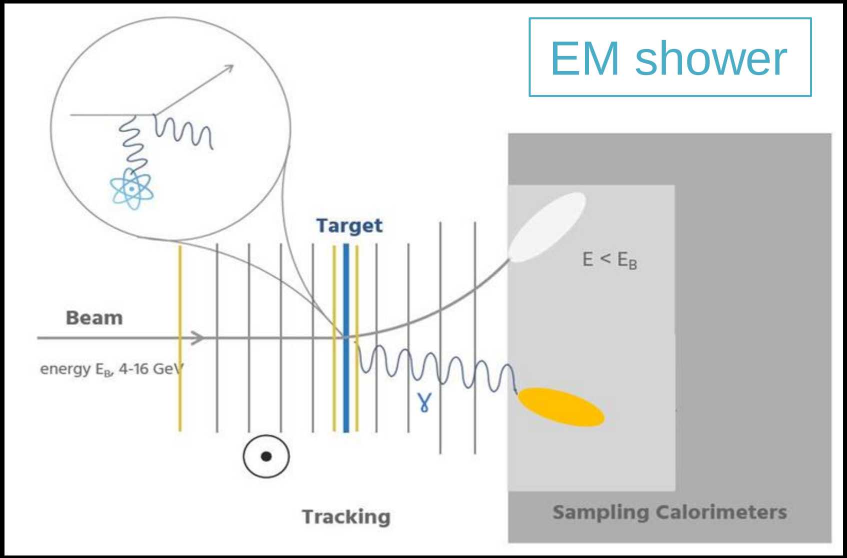
LDMX concept

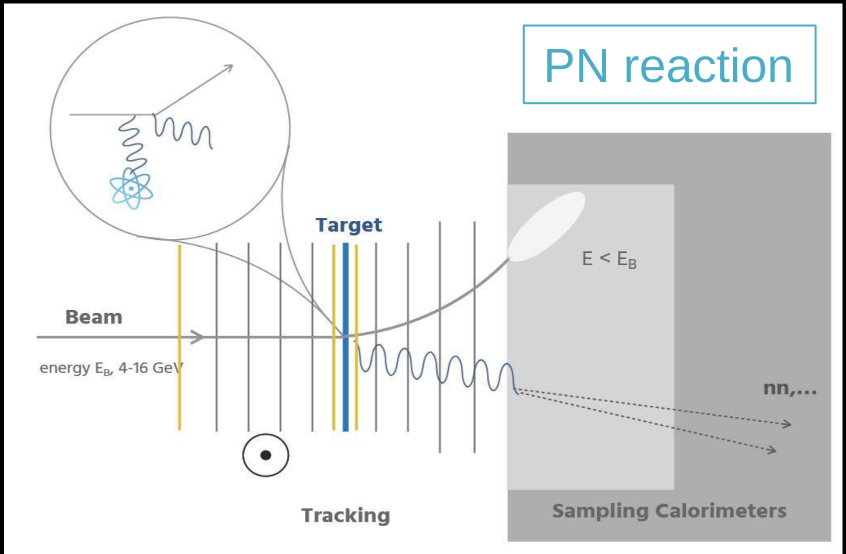
LDMX (Light Dark Matter eXperiment) proposes to produce DM in electron-nucleus interactions and use the "missing momentum" approach to identify this process with **unique capability to probe the thermal targets in the sub-GeV region**

Individually measure electron scatterings on a thin target. Signal is identified as a deflected electron and nothing else in the detector to balance the transverse momentum (similar to missing energy but with additional information about direction)



Background processes





Major background:

- Radiated photon produces an electromagnetic shower in the calorimeter
- Very large rate, vetoed by measuring the total energy in the calorimeter

Challenging background:

- Radiated photon induced photo-nuclear interaction producing a few neutral particles
- Small rate, but difficult to identify (require large hadronic calorimeter to detect the neutrals)

Signal kinematics

The recoil electron kinematics is very different between the signal and background processes

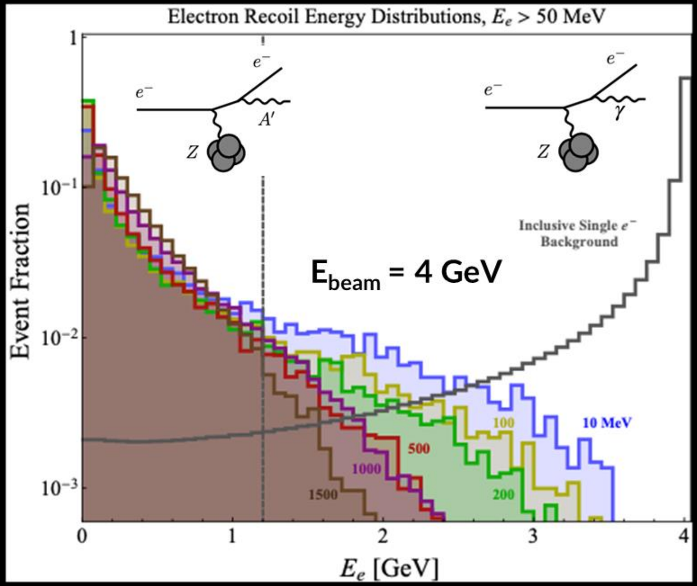
The A’ is emitted at low angle and carries most of the energy:

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

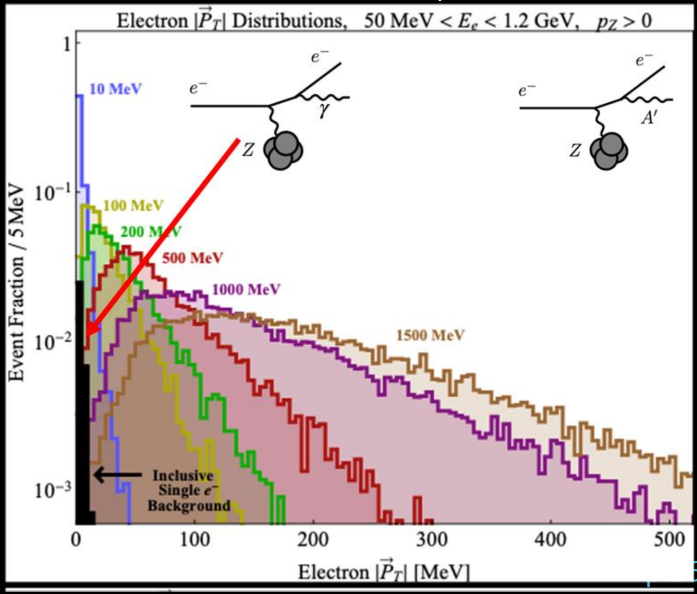
The electron recoil momentum offers additional handle to reject backgrounds or to measure the signal properties

- Clear advantage over missing energy measurement

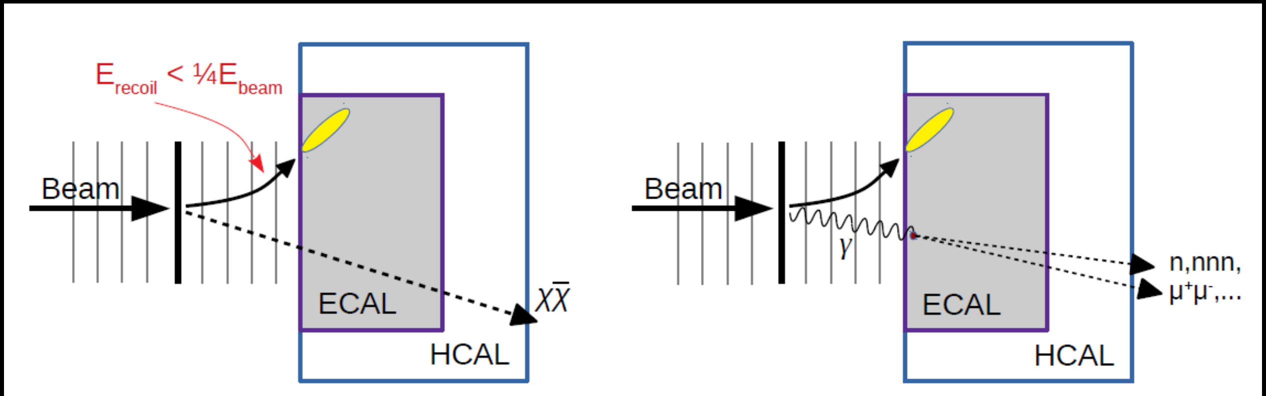
Recoil energy



Recoil p_T



Ingredients to build LDMX



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.
- Provided by the LESA beamline under construction at SLAC

Detector technology with high rate capabilities, high radiation tolerance and excellent hermiticity

- Fast, low mass tracker to tag each electron with good resolution
- Fast, granular, hermetic EM calorimeter, and hermetic hadronic calorimeter

LESA @ SLAC

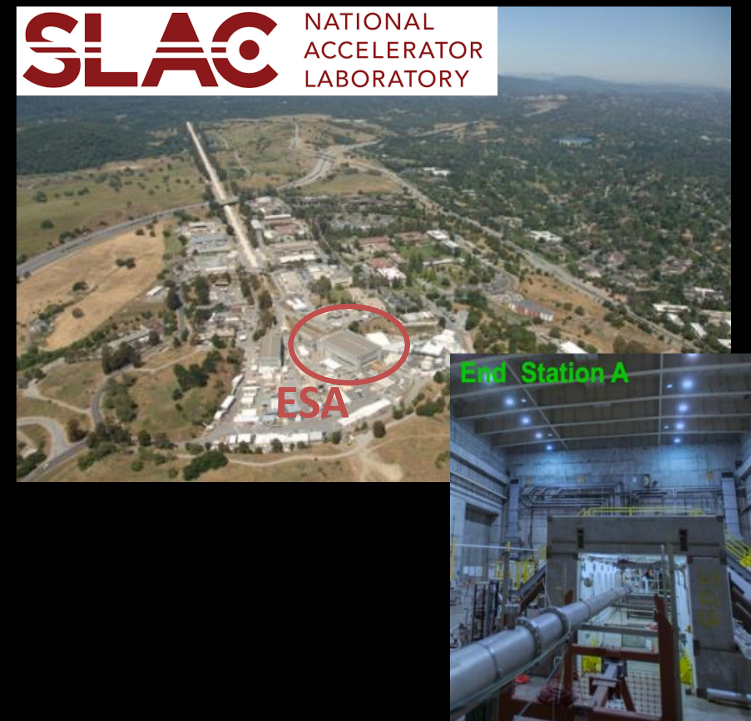
LCLS-II beam at SLAC:

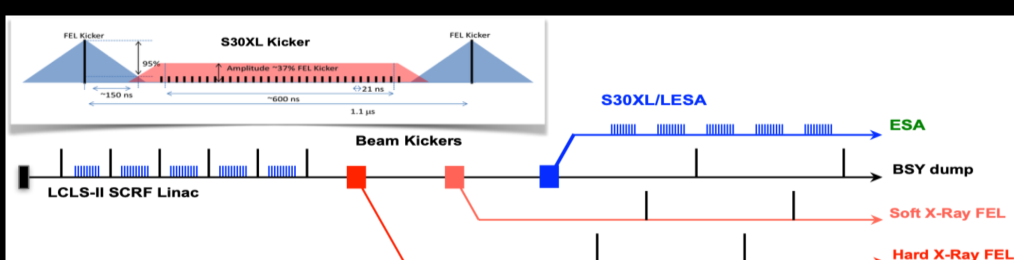
- Linac Coherent Light Source, a free electron laser producing femtoseconds X-ray pulses for multi-purpose science (material, biology, chemistry, optics,…)
- **~ 99% of electrons are unused**

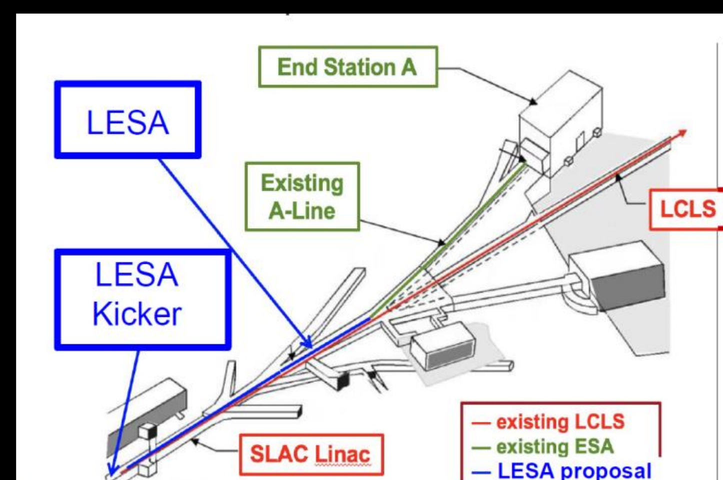
LESA: new beamline to drive ~60% of unused low-charge bunches to End Station A – **completely parasitic to LCLS operation**

LESA beamline installation and commissioning is planned for FY24-25

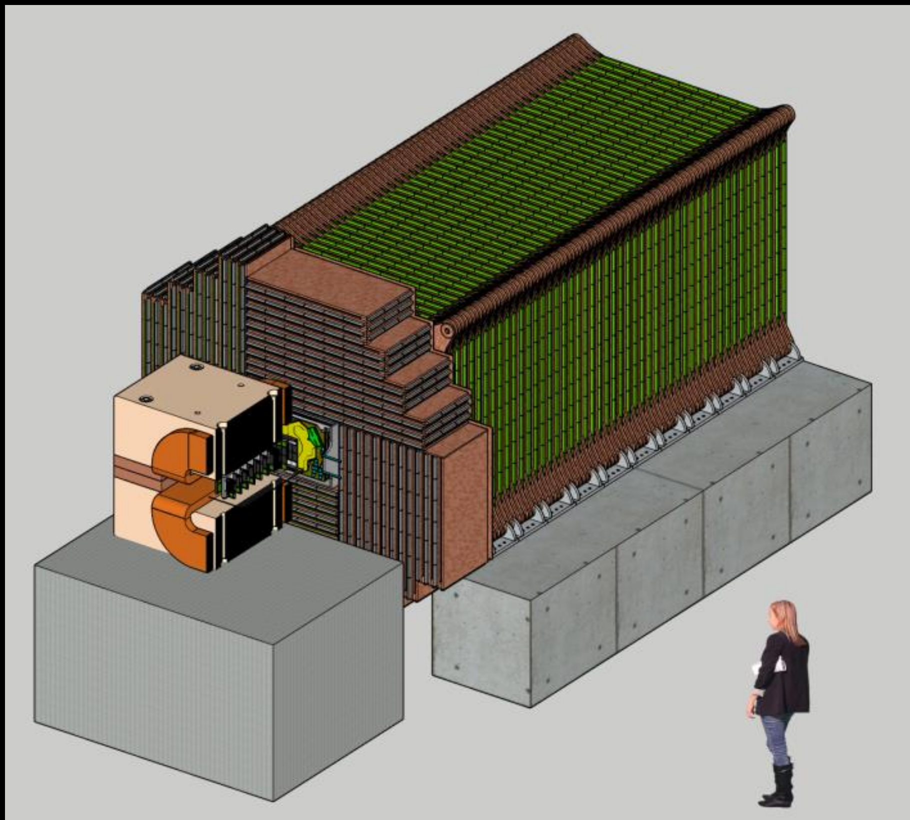
- Early commissioning of LDMX with low-current CW in FY25
- LCLS-II upgrade to 8 GeV in FY27-28

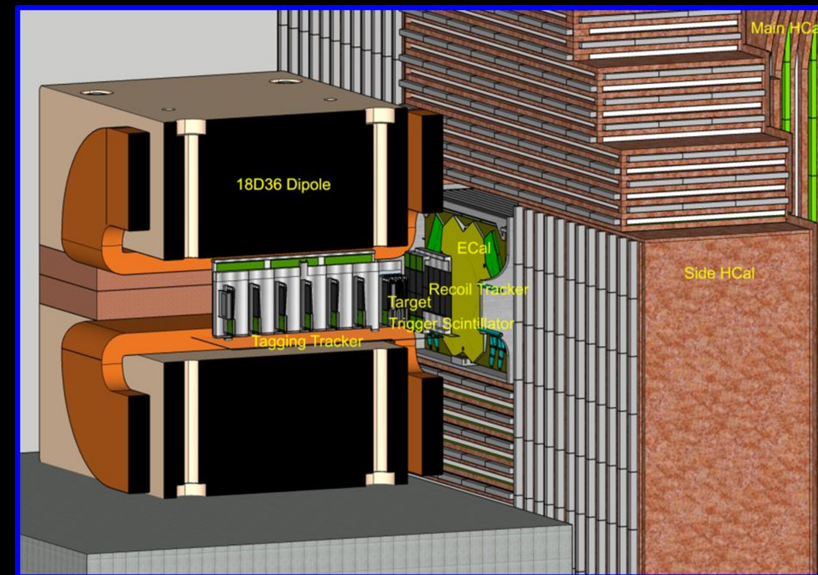






LDMX experiment





LDMX whitepaper: https://arxiv.org/abs/1808.05219

Detector concept

- **Tagger Tracker** with low acceptance and high resolution at beam energy
- **Recoil Tracker** with large acceptance and high resolution at low particle momenta
- **Trigger scintillator** for fast electrons-per-bunch counting
- **Electromagnetic calorimeter** with fine granularity for EM/Had shower shapes and MIP tracking
- **Hadronic calorimeter** with very low energy veto threshold for neutral hadrons

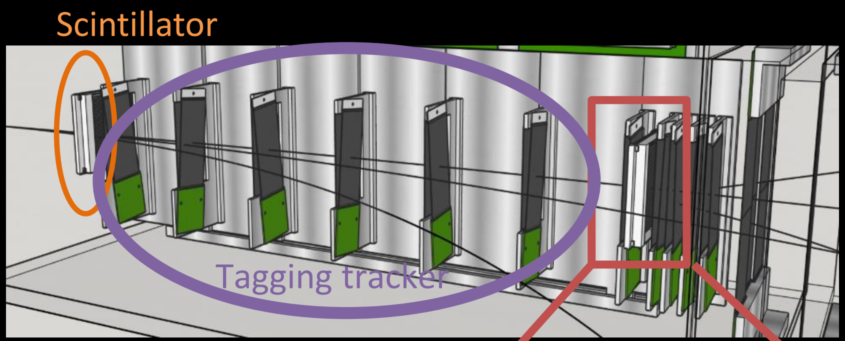
Tracking and target system

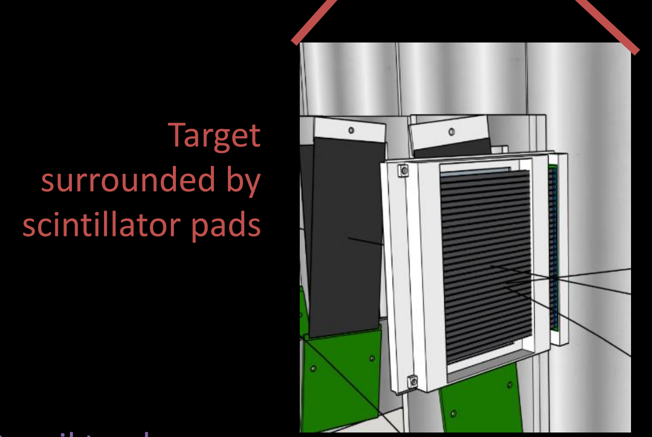
Tracking system

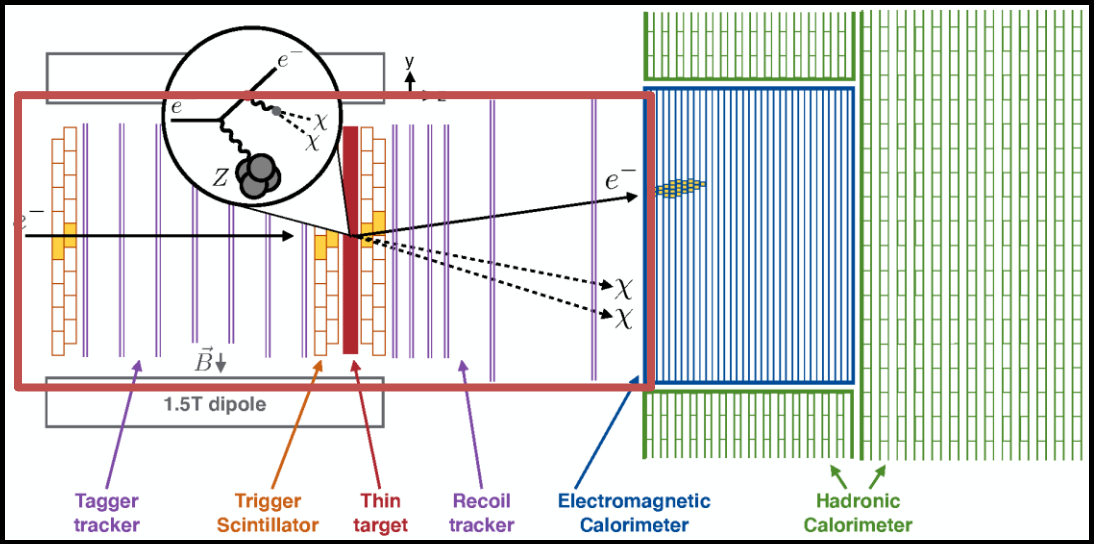
- Tagging tracker to measure incoming e-
- Recoil tracker to measure scattered e-
- Silicon tracker similar to HPS SVT
- Fast (2ns hit time) and radiation hard

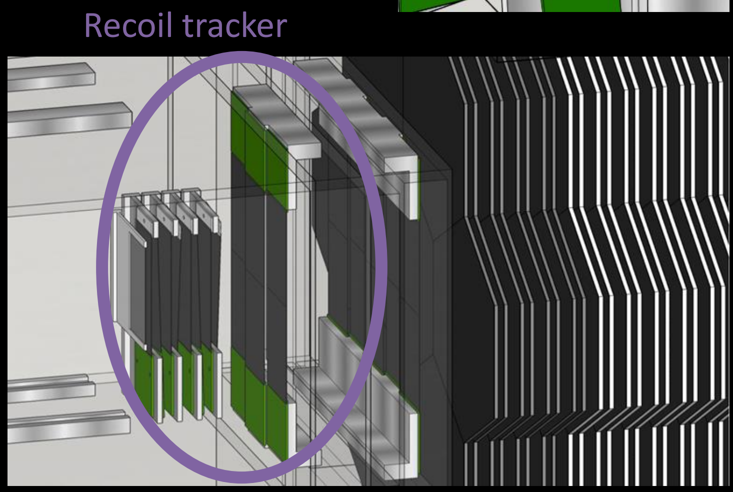
Tungsten target and scintillator planes

- Scintillator pads to count # incoming electrons
- Thin target to balance between signal rate and momentum resolution, potentially active target





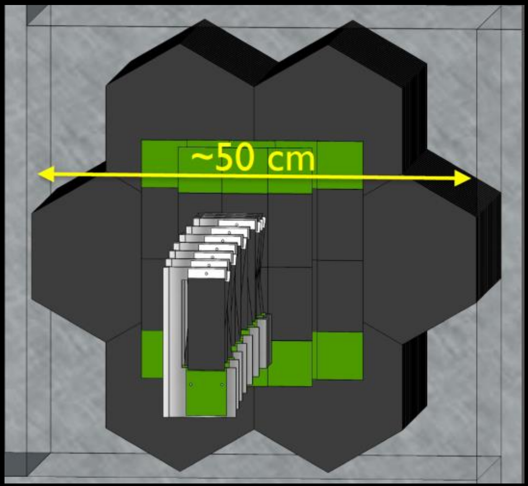


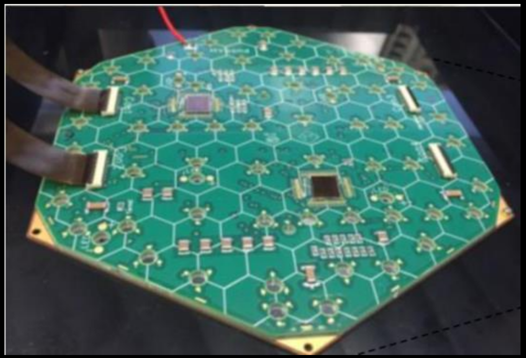


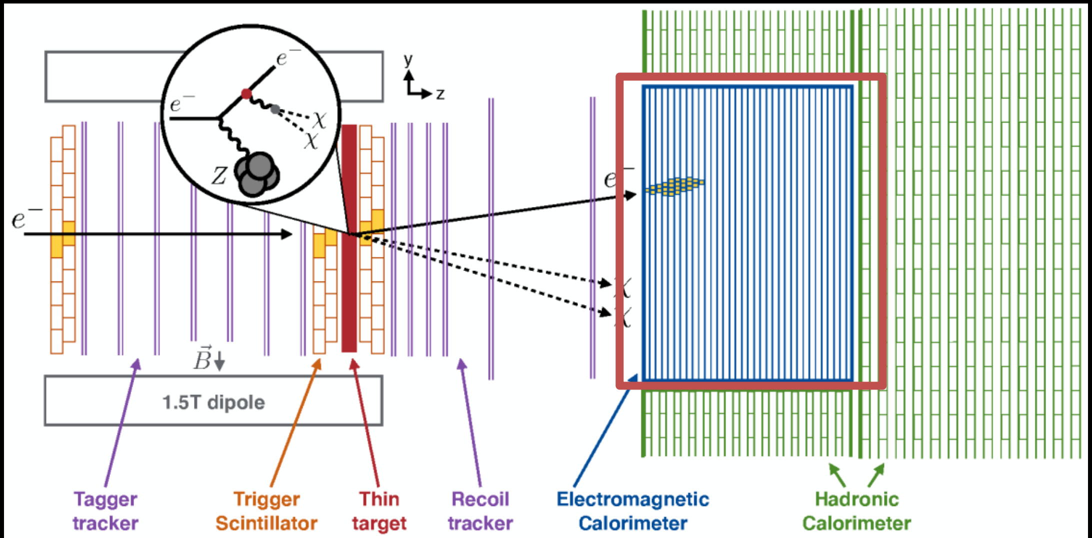
Electromagnetic calorimeter

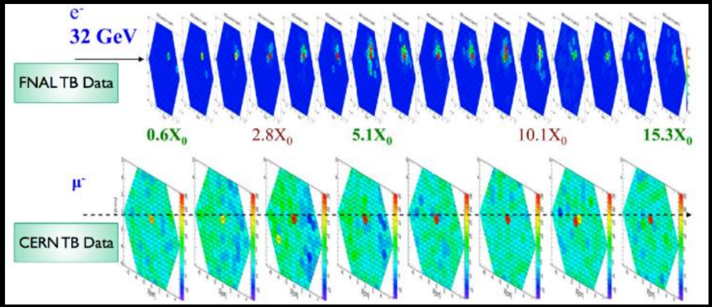
Electromagnetic calorimeter

- Based on CMS Phase-II forward high granularity calorimeter (HGC) upgrade
- Tungsten-Silicon sampling calorimeter: $\sigma(E)/E \sim 20\%/\sqrt{E}$
- High granularity enables track reconstruction
- Significant depth: 40 X_0
- Radiation hard
- Provides a fast energy trigger: E < 1.2 GeV





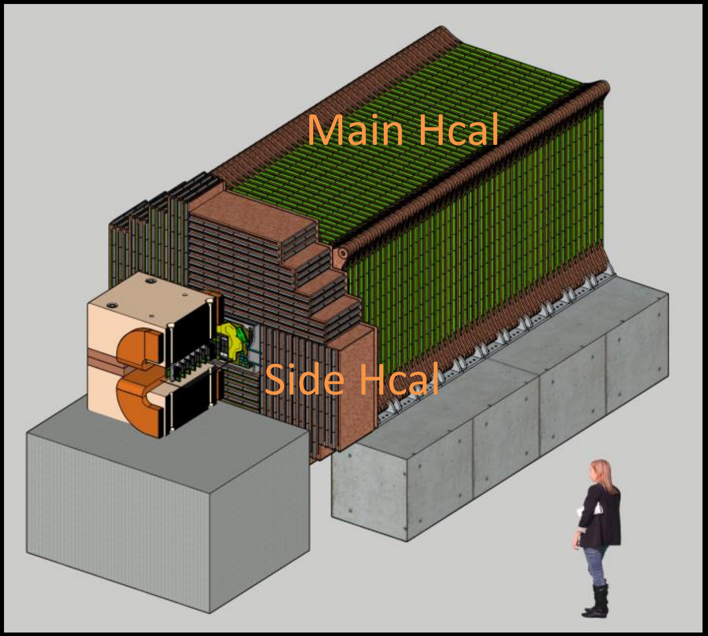


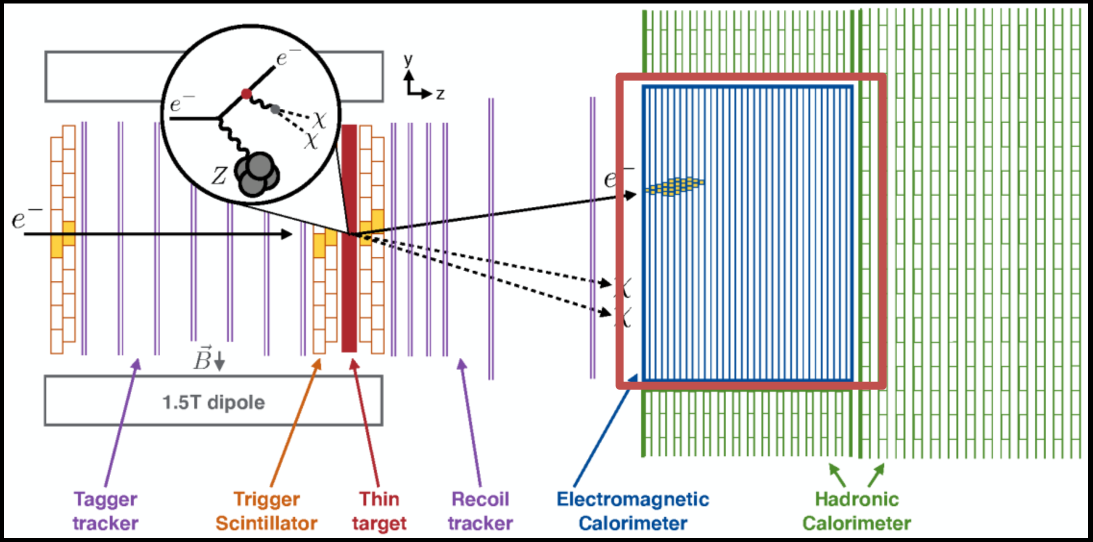


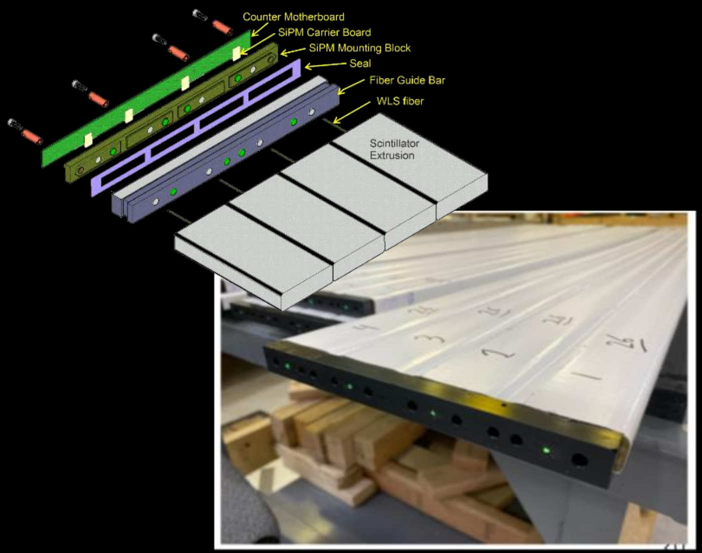
Hadronic calorimeter

Hadronic calorimeter

- Detects neutral hadrons/neutrons produced in photonuclear reactions, EM showers escaping ECal, and MIPs (muons)
- Iron-scintillator sampling calorimeter: 96 layers of 20/25 mm polystyrene / Fe
- Extruded 5x2 cm^2 scintillator bars with inserted wavelength-shifting fibers, read out with Silicon Photomultipliers - developed for Mu2e cosmic ray veto

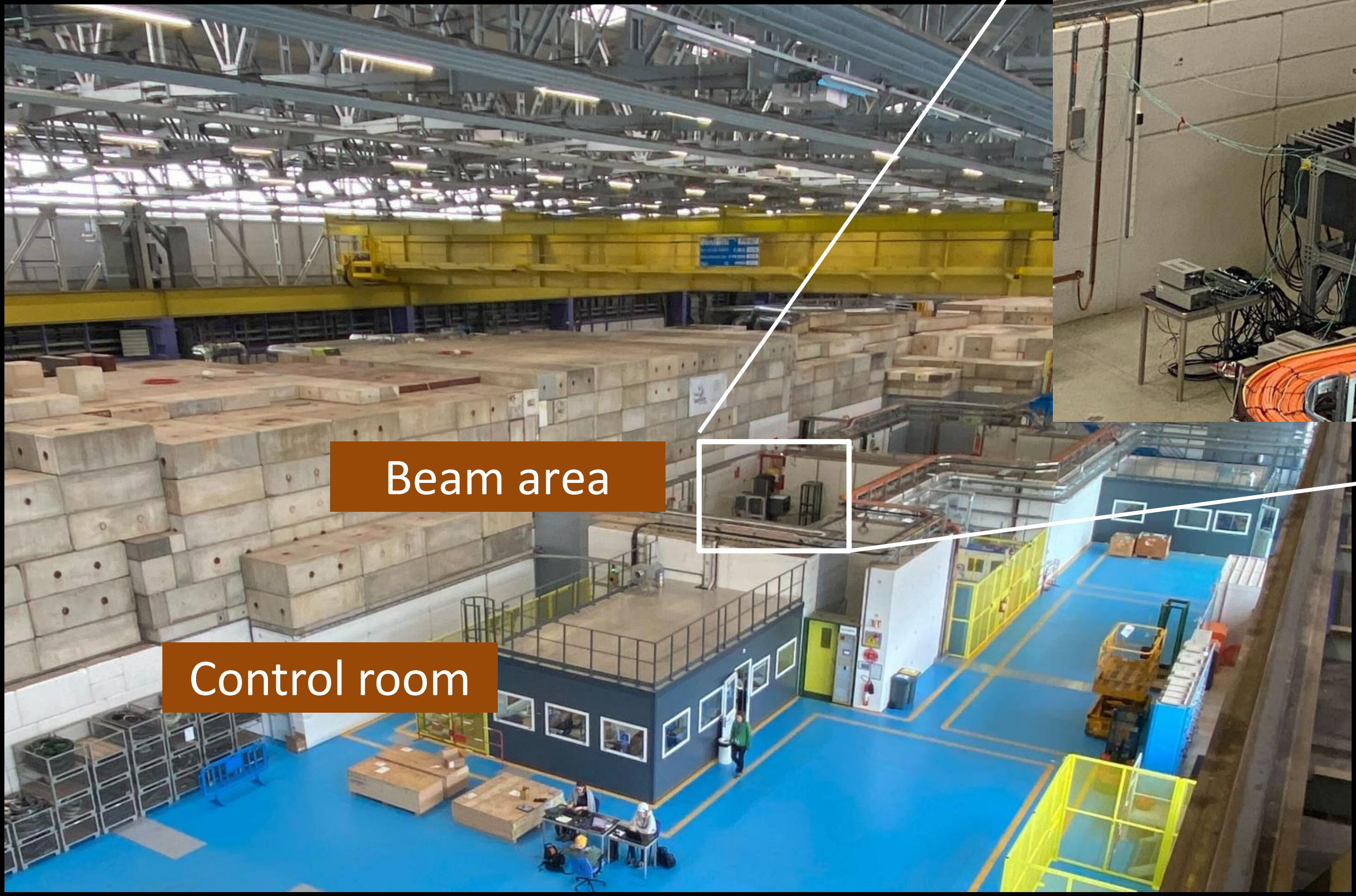






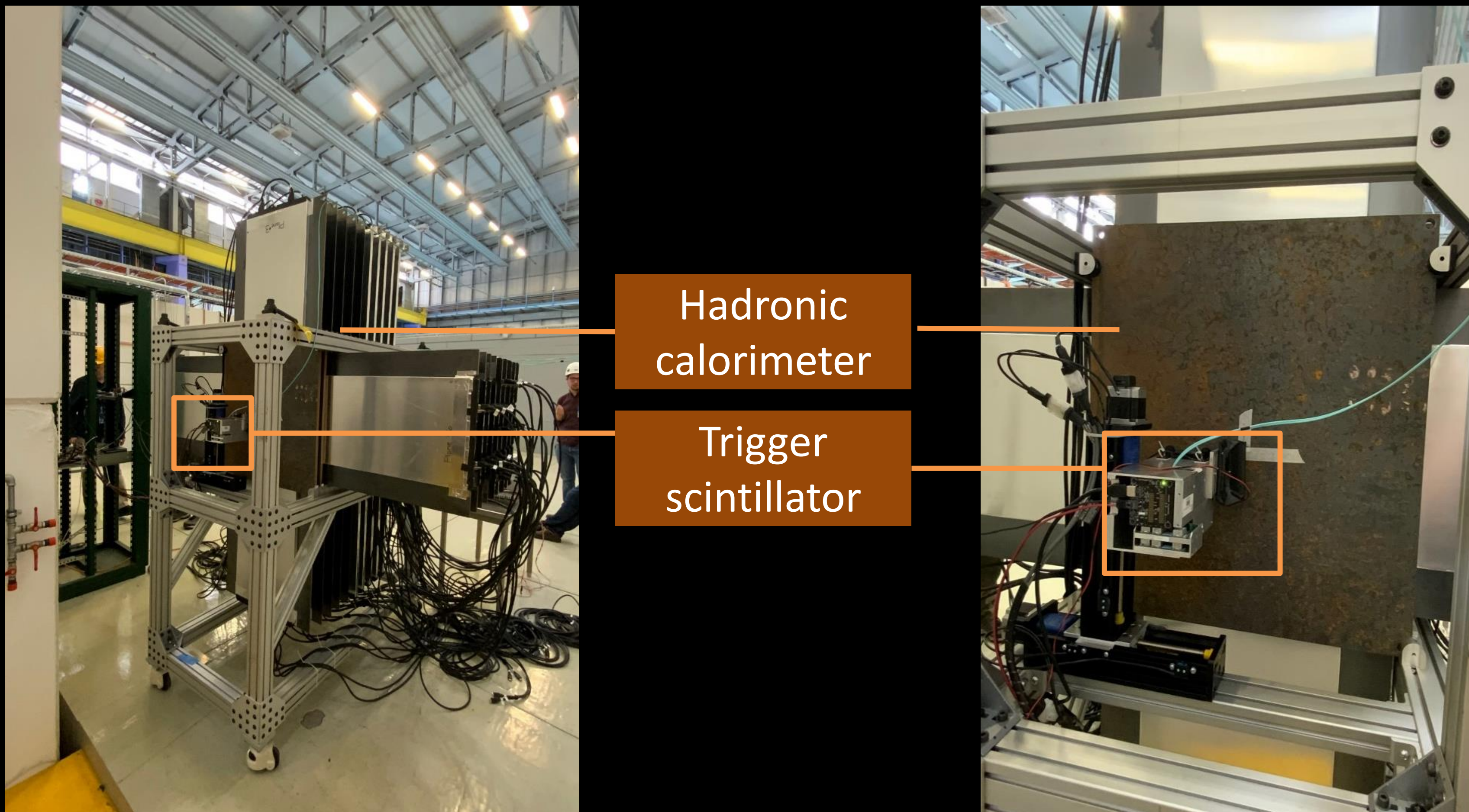
Prototype and test beam at CERN

Hadronic calorimeter and trigger scintillator prototypes have been tested at the CERN T9 beam line



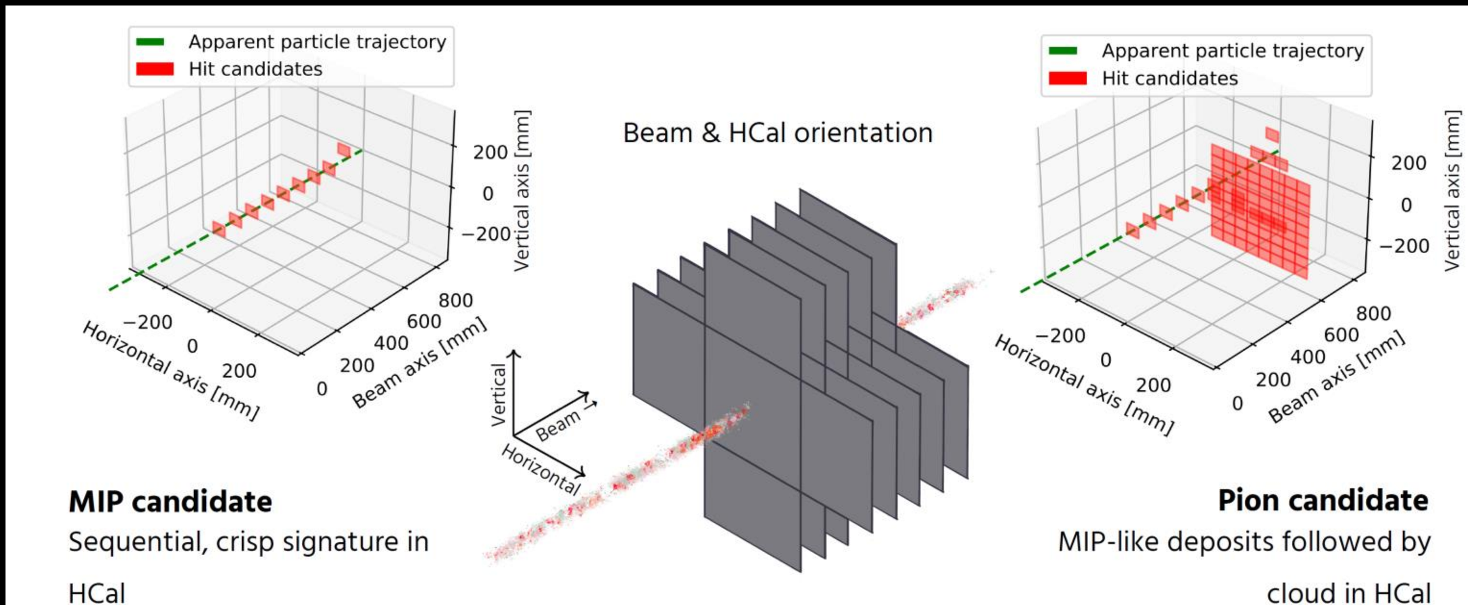
Collected million of events with hadron / electron beams from ~200 MeV – 8 GeV

Prototype and test beam at CERN

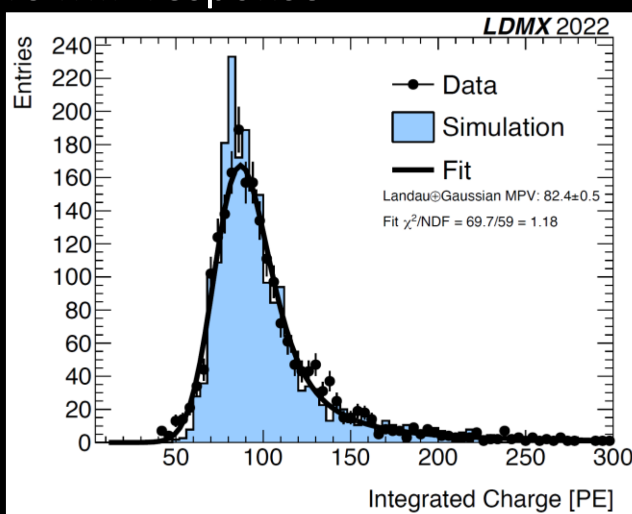


Hadronic calorimeter prototype with 19 layers of 25mm absorber and trigger scintillator prototype with two layers of plastic scintillator

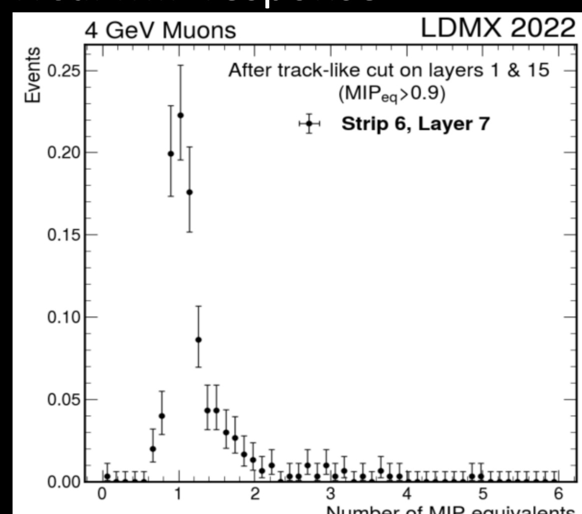
Prototype and test beam at CERN



TS MIP response



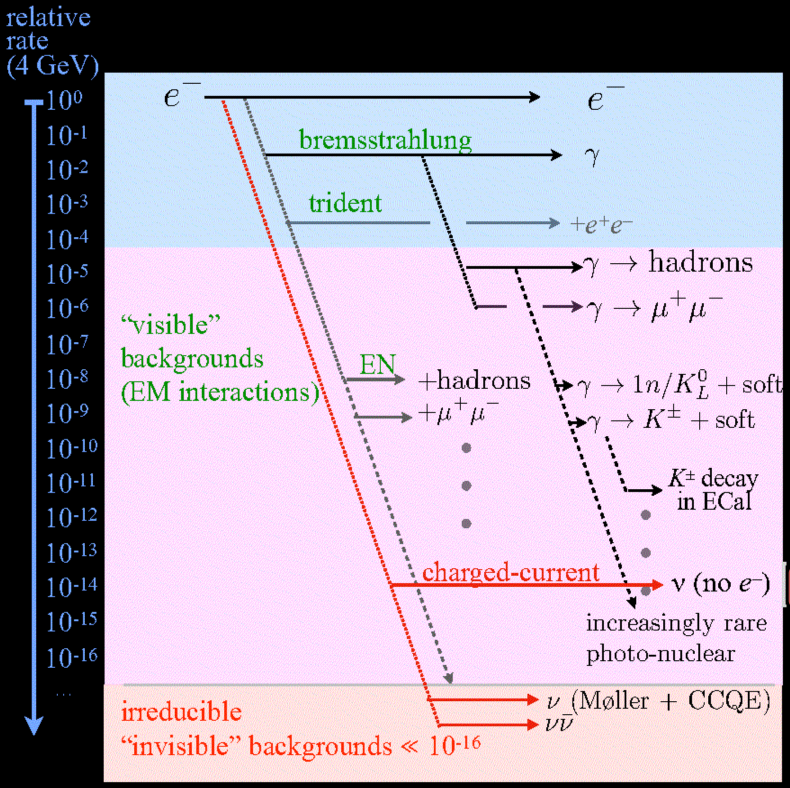
HCal MIP response



Very successful data taking campaign

On-going data analysis

Background and vetoes



Recoil tracker – exactly one track
Remove electro-nuclear & rare invisible ν processes

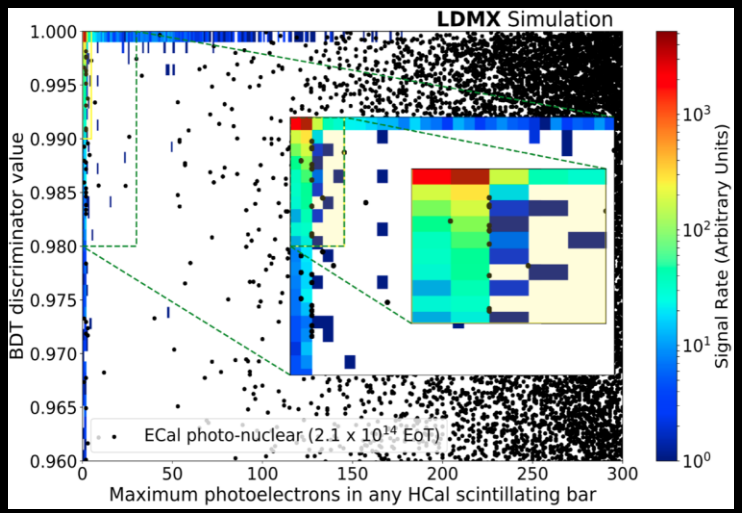
ECAL Veto
BDT using shower features leveraging ECal granularity

HCAL Veto
Remove event with neutral escaping the ECal

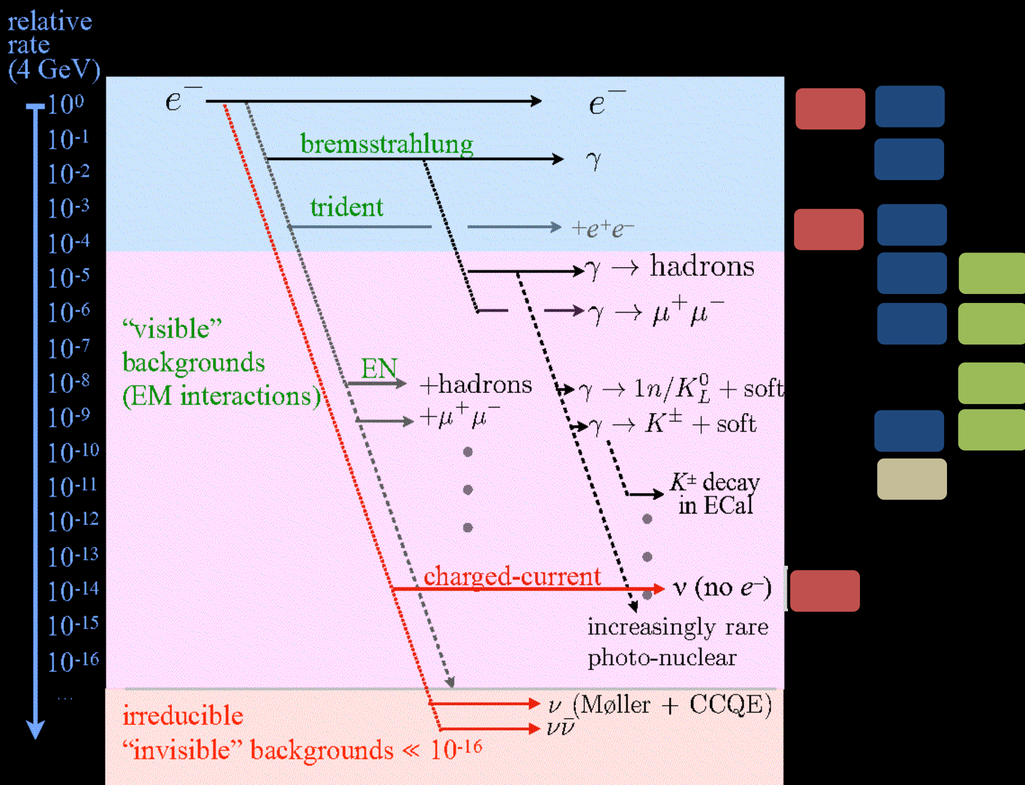
MIP Tracking in ECAL
Veto isolated track around photon direction

Electron P_T
Unused, additional handle in case of unexpected bkg

Ecal and HCal veto



Background and vetoes



Recoil tracker – exactly one track
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Remove event with neutral escaping the ECal

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Veto isolated track around photon direction

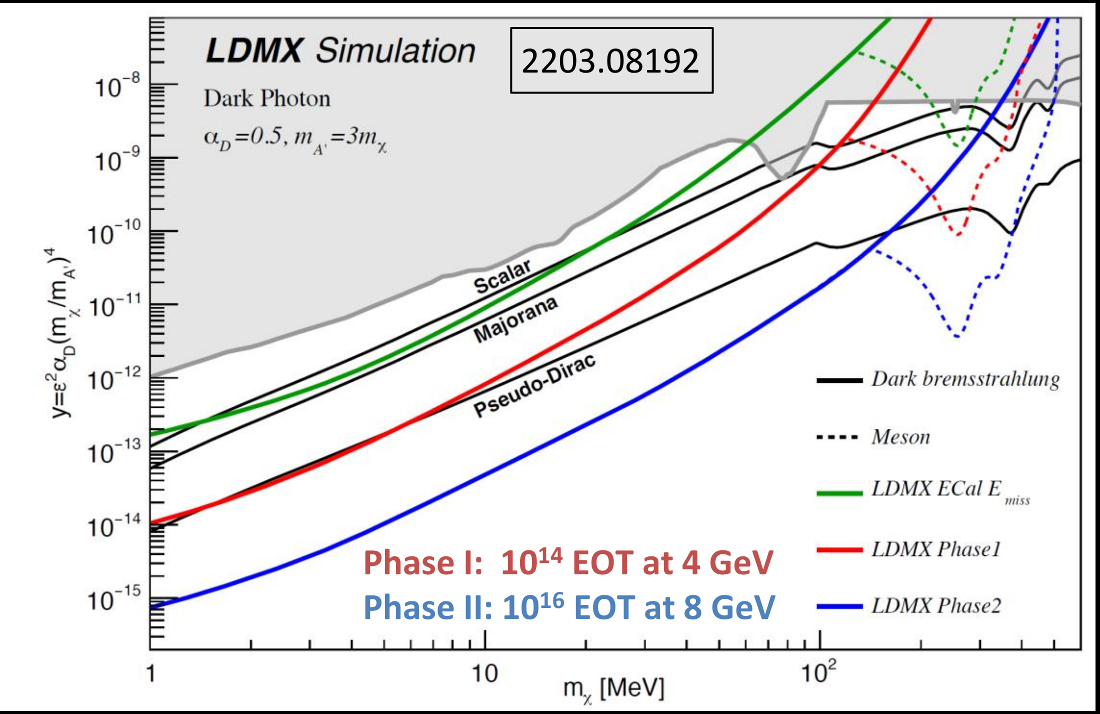
Electron P_T
Unused, additional handle in case of unexpected bkg

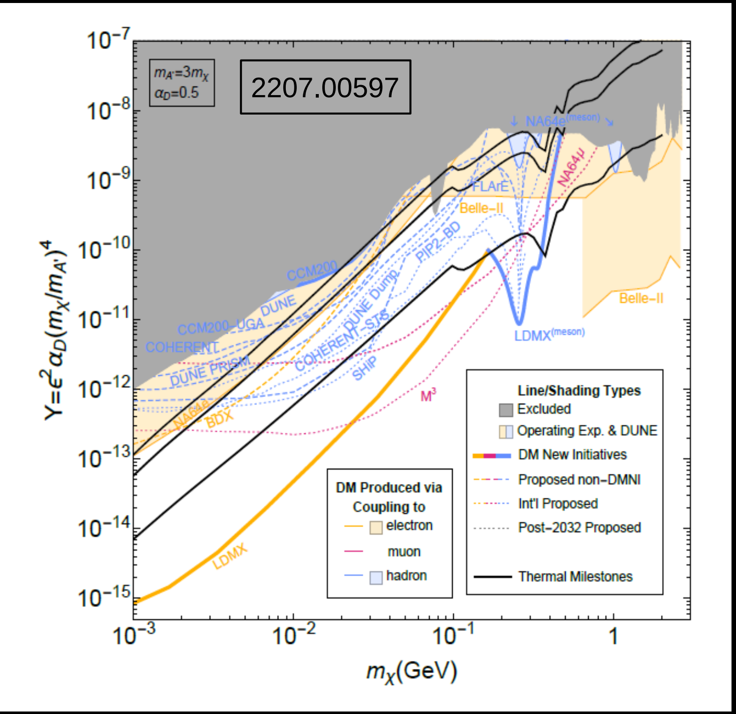
Extensive simulation studies show that the search remains **background free** up to $4\text{x}10^{14}$ EOT (on-going study for 8 GeV)

	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}	4.7×10^{11}	6.3×10^{8}	8×10^{10}
Trigger, ECal total energy < 1.5 GeV	1×10^{8}	2.6×10^{8}	1.6×10^{7}	1.6×10^{8}
Single track with $p < 1.2$ GeV	2×10^{7}	2.3×10^{8}	3.1×10^{4}	1.5×10^{8}
ECal BDT (> 0.99)	9.4×10^{5}	1.3×10^{5}	< 1	< 1
HCal max PE < 5	< 1	10	< 1	< 1
ECal MIP tracks $= 0$	< 1	< 1	< 1	< 1

JHEP04(2020)003 and 2203.08192

LDMX sensitivity



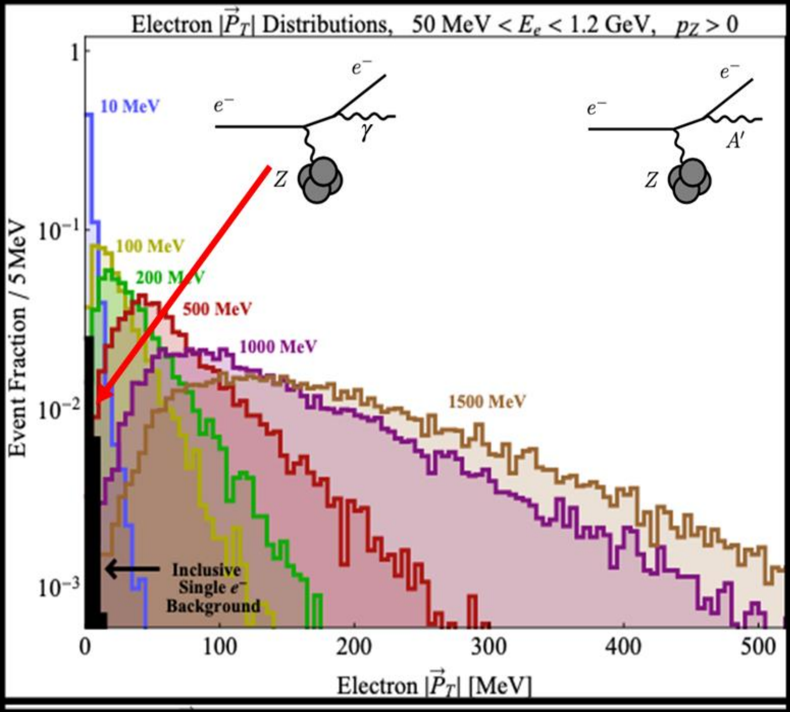


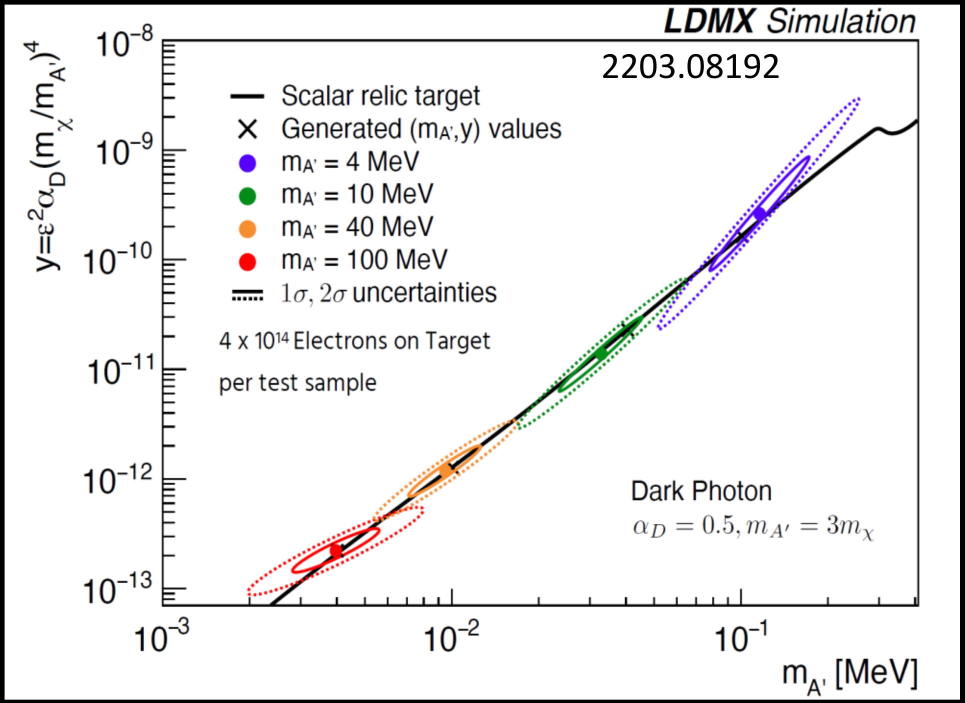
LDMX can probe all thermal targets up to a few hundreds of MeV

Unparalleled sensitivity in the low mass region - missing energy approach becomes limited by rare ν background

LDMX sensitivity

Estimate DM mass from electron p_T spectrum





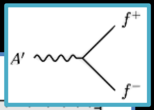
LDMX can provide information about the DM mass and coupling in case of an observation – unique capability of missing momentum approach

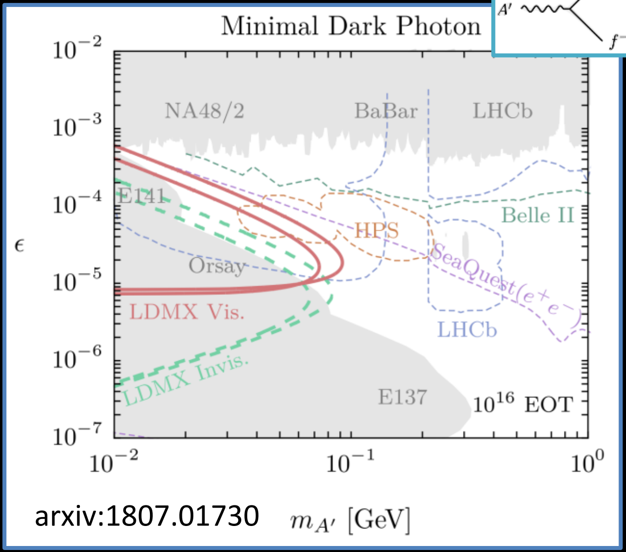
More generally

LDMX would also be sensitive to many other BSM physics scenarios, such as:

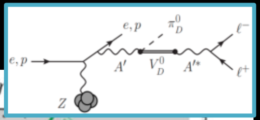
- New force carriers coupling to electrons, decaying visibly or invisibly
- Quasi-thermal DM, such as asymmetric DM and ELDER DM
- New long-lived resonances produced in the dark sector (SIMP)
- Freeze-in models with heavy mediators
- Axion like particles
- Milli-charged dark sector particles

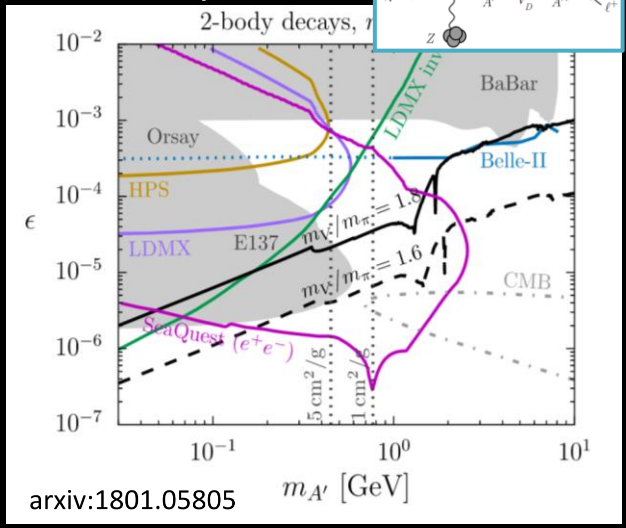
Visible dark photon decay





SIMP decay





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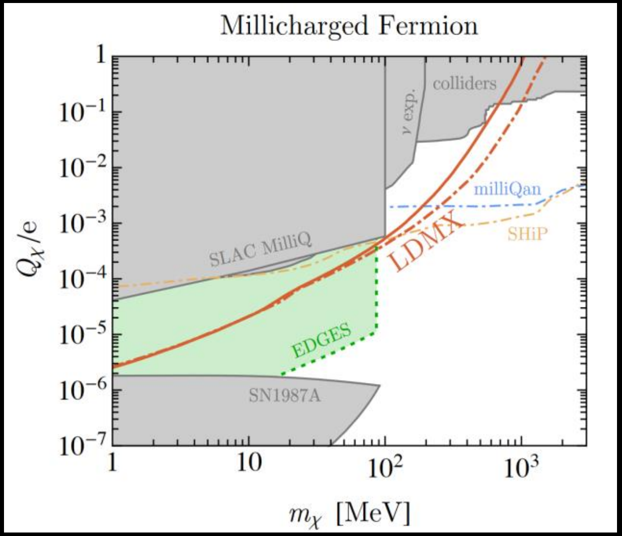
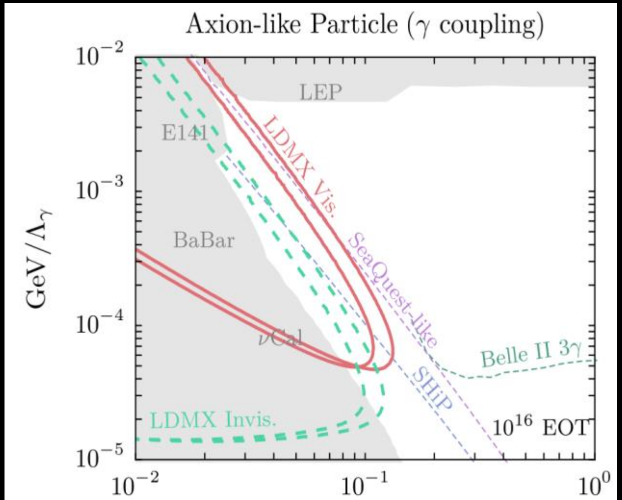
- Milli-charged dark sector particles

LDMX could explore a vast array of sub-GeV physics with unique sensitivity





arxiv:1807.01730

Electro-nuclear interactions and neutrino physics

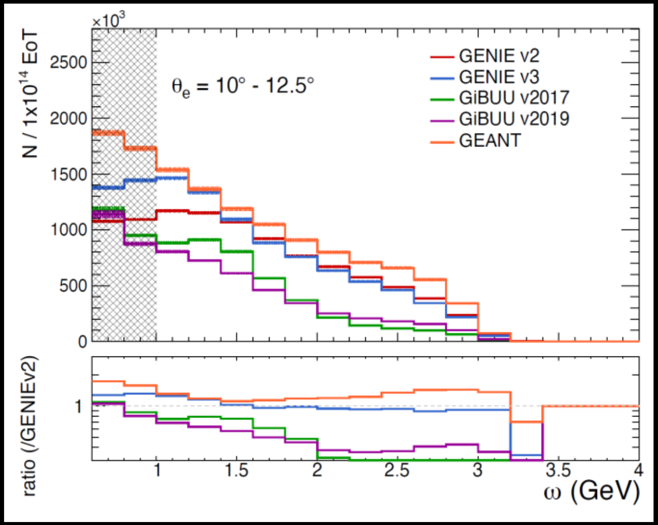
Electro-nuclear measurements (eN) can be related to neutrino-nuclear interactions (νN) and constrain nuclear models

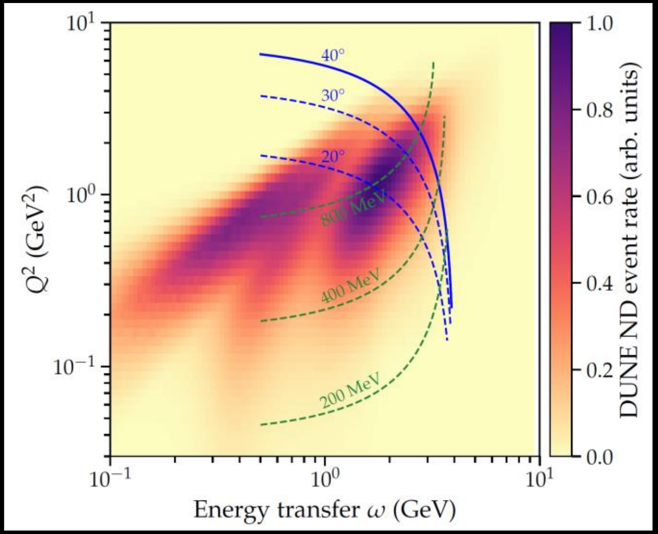
Current generators predictions for neutrino interactions disagree widely over phase space covered by LDMX.

LDMX measurements would constrain lepton-nucleon interaction models in the same phase space

- Full forward acceptance, nearly hermetic
- Fully reconstructed initial and final state
- Excellent neutron detection efficiency

LDMX could also provide useful information for neutrino experiments





PhysRevD.101.053004

Conclusion

Thermal dark matter is a simple and compelling scenario, and the MeV-GeV scale is a good place to explore – logical extension of WIMP

LDMX provides world-leading sensitivity to sub-GeV DM and can test many predictive light DM scenarios

LDMX has also impressive sensitivity to:

- Visible signatures of mediators and dark sector particles
- Broad range of new physics models with missing momentum signatures
- Important electron scattering measurements to constrain neutrino cross-section uncertainties for DUNE

The experiment is ready to move forward with the construction phase

- Dark Matter New Initiatives R&D funding has been very productive
- LESA Beamline construction is underway at SLAC
- A test-beam run at CERN has validated key detector developments

LDMX could be taking data in 2-3 years after establishing the funding profile, and potentially make a groundbreaking discovery shortly thereafter

Thank you for your attention

Questions?

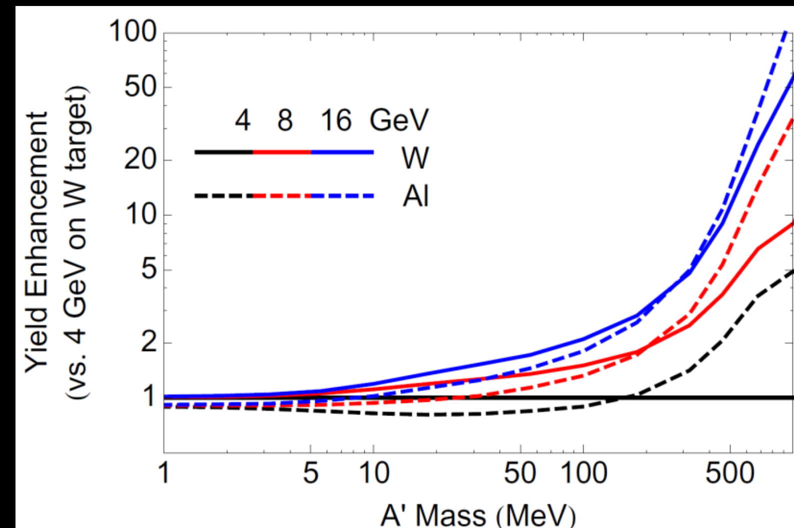
@ C. Group and son

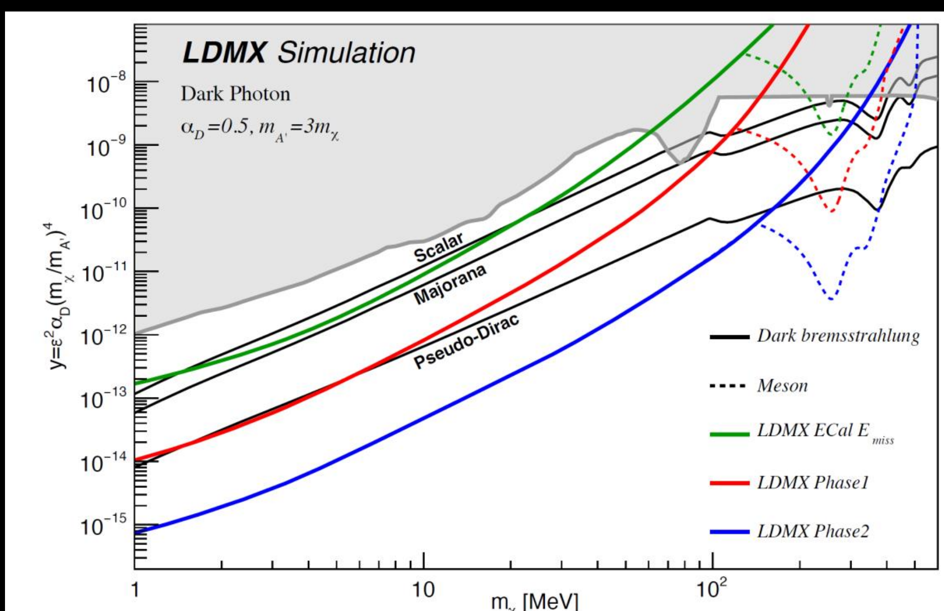
Extra Material

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(300) MeV.





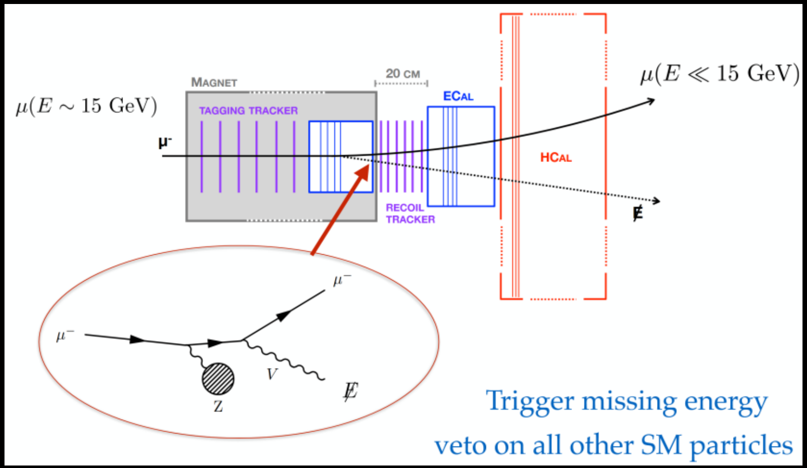
Mass Range [MeV]	Factor needed	E_e [GeV]	E_e Factor	Target $[X_0]$	Target Factor	μ_e	Years running	Factor achieved
$0.01 \le M_\chi < 20$	2	4	1	0.15 W	1.5	1.5	1	~2
		4	1	0.1 W	1	1.5	1.5	
		4	1	0.15 W	1.5	1	1.5	
$20 \le M_\chi < 75$	6	8	2	0.1 W	1	2	1.5	~6
		8	2	0.15 W	1.5	1	2	
		4	1	0.15 W	1.5	2	2	
$75 \le M_\chi < 150$	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	
$150 \le M_\chi < 300$	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	$\sim 7 \times 10^3$

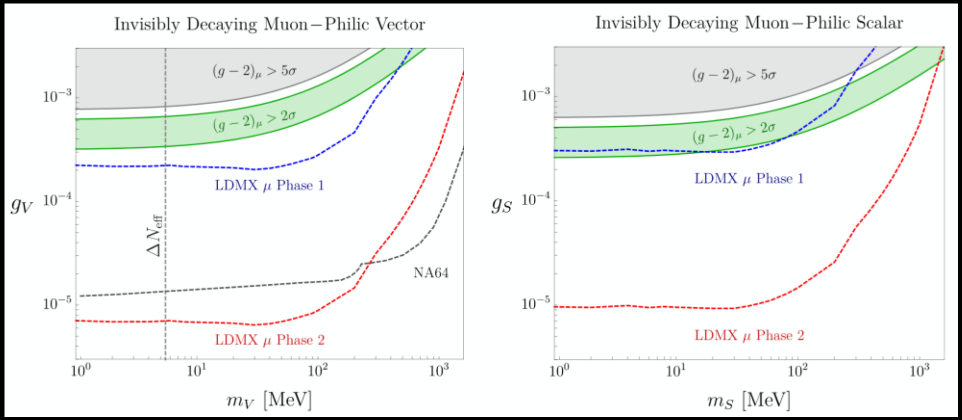
LDMX-mu

JHEP 1809 (2018) 153
arxiv:1804.03144

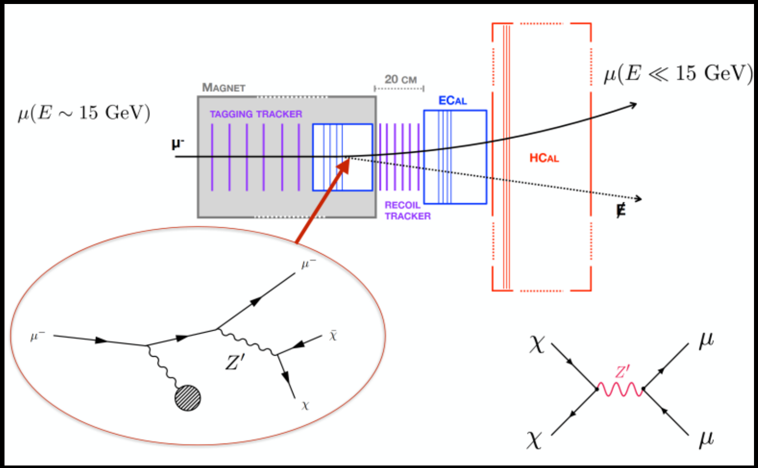
LDMX-like detector with a muon beam at FNAL

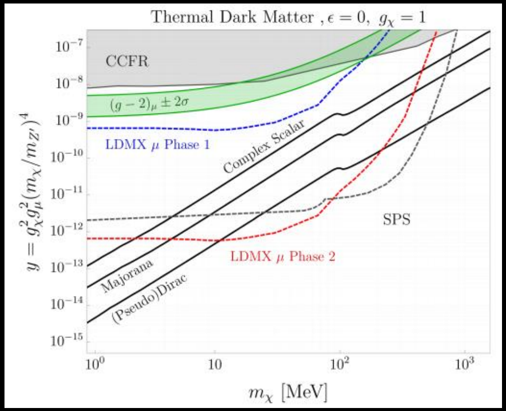
New light muon-philic particles





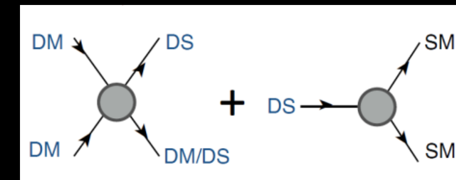
Muon-philic dark mediator





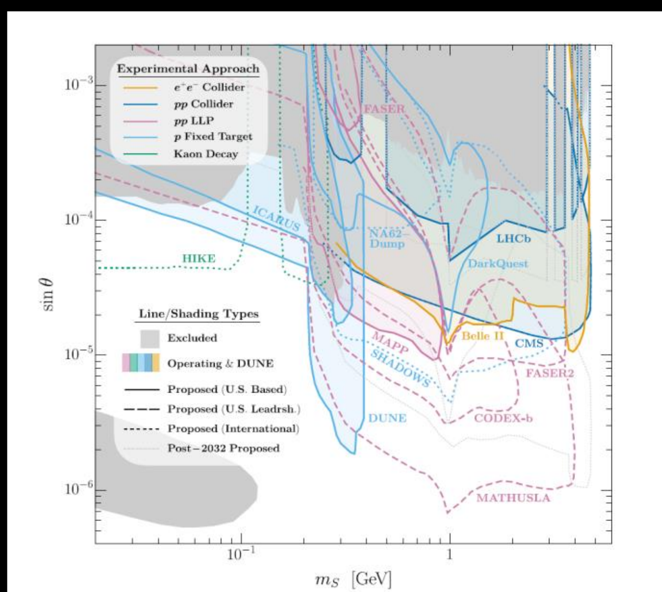
Secluded dark matter

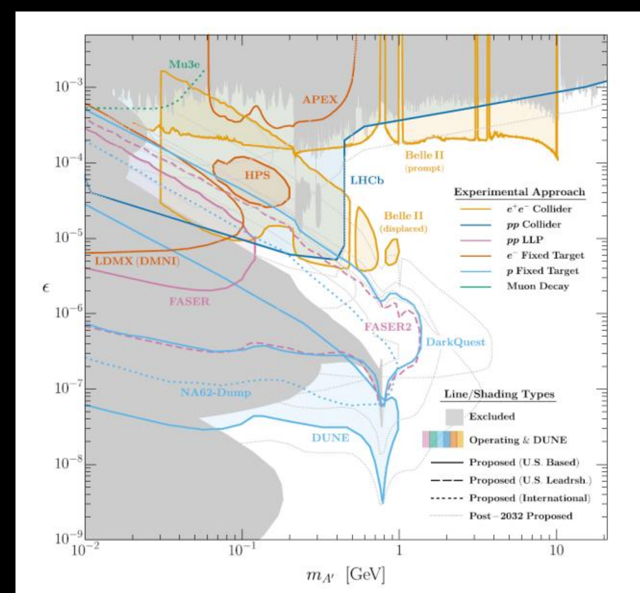
Dark matter annihilates into pair of mediators when $m_{DM} > m_{MED}$, followed by mediator decay to SM particles.



Annihilation cross-section depends only on dark sector physics, but thermal equilibrium requires a minimal DM-SM coupling

→ broad region of parameter space compatible with light DM hypothesis





B. Batell et al., 2207.06905

Freeze-in DM

DM abundance initially vanishes and slowly builds up over time via feeble DM-SM coupling

- DM produced in thermal era but never in thermal equilibrium

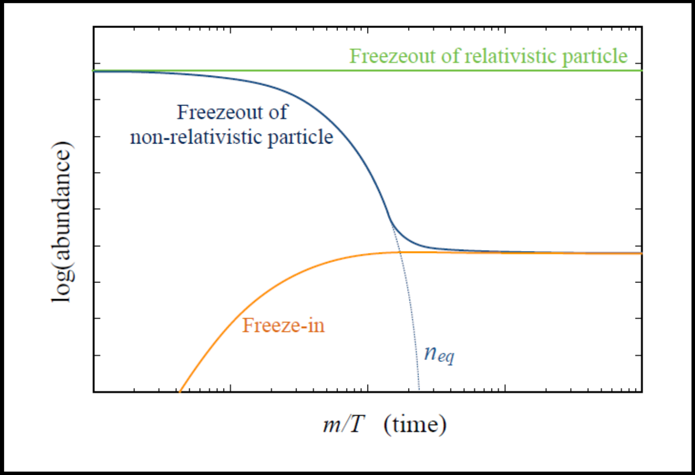
Dark sector realization requires extremely small couplings

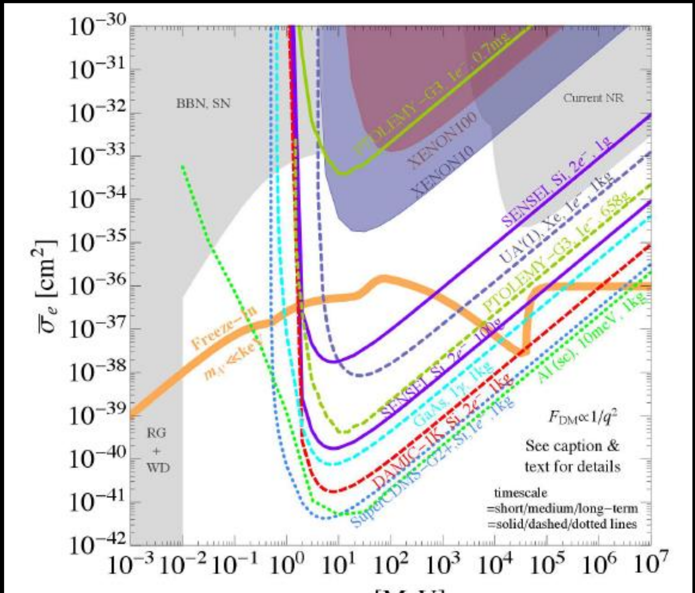
- typically at a level unobservable for any experiment

But for m_{DM} < 1 MeV, freeze-in also require mediator mass < 10^{-10} eV

- Small mediator mass and low momentum transfer boosts the electron-DM scattering cross-section → potentially detectable process

T. Lin 1904.07915



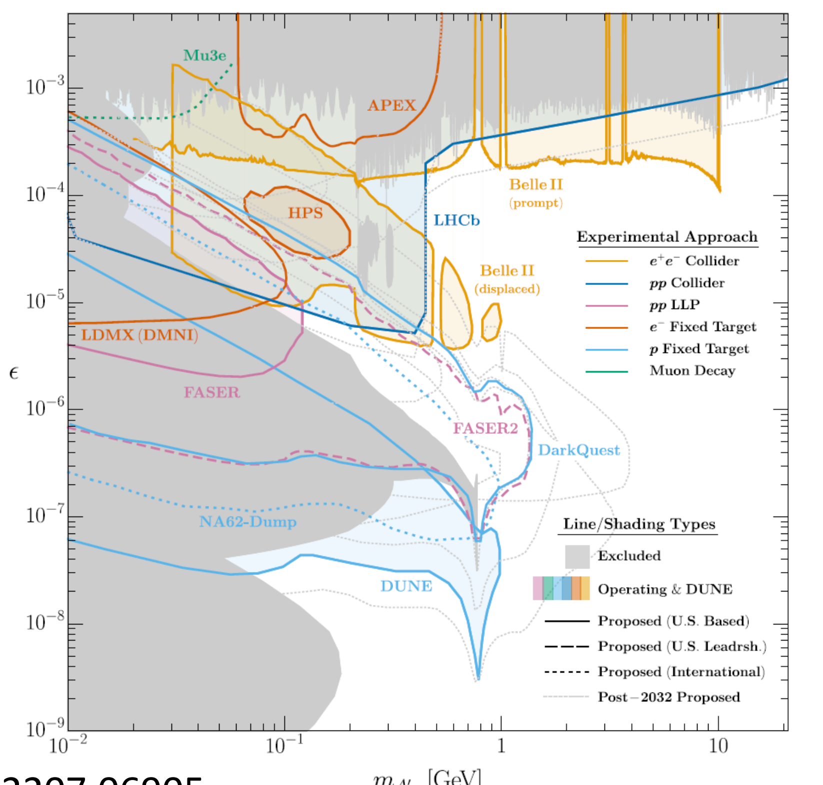


1707.04591

Visible dark photon decays

Non-minimal models motivate generic search for visible mediator decays

Constraints on dark photon kinetic mixing



2207.06905

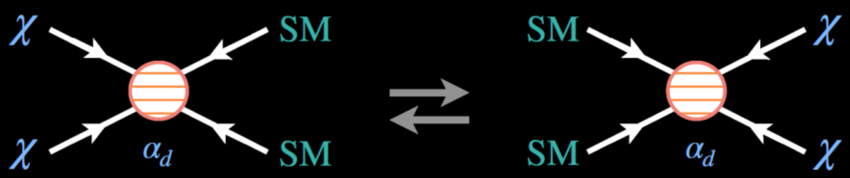
Collider typically probe parameter space "from the top" – larger coupling and wide range of masses

Beam dump / fixed target probe longer lifetimes → lower masses and couplings

Region below ~1 GeV will be significantly constrained by upcoming experiments (both colliders and beam dump / fixed target)

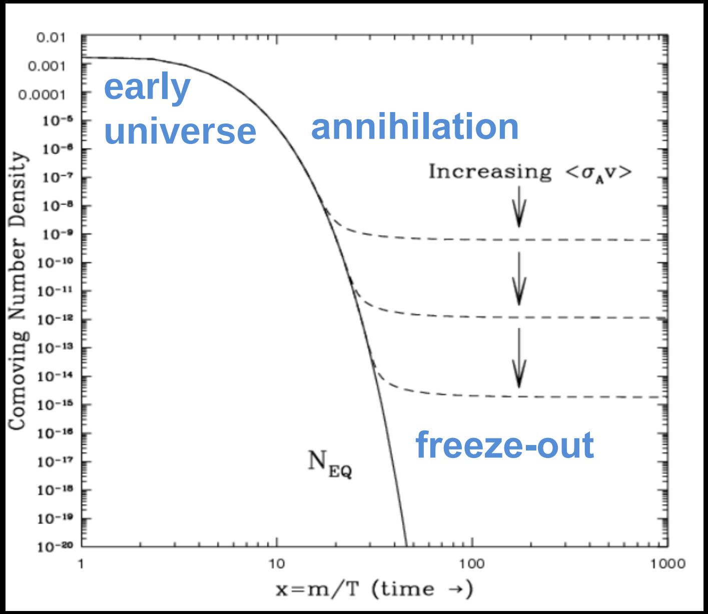
Thermal dark matter

Early universe:
DM particles are in thermal equilibrium with SM particles



Annihilation:
Universe expands and cools, DM number density becomes exponentially suppressed when T < ~m_{DM} : n_{DM} ~ $e^{-m/T}$

Freeze-out:
DM density becomes too low for annihilation process to keep up, freezing out a DM abundance over to the present day



Number density

$$\frac{dn}{dt} = -\langle\sigma v\rangle\left(n^2 - n_{eq}^2\right) - 3Hn$$

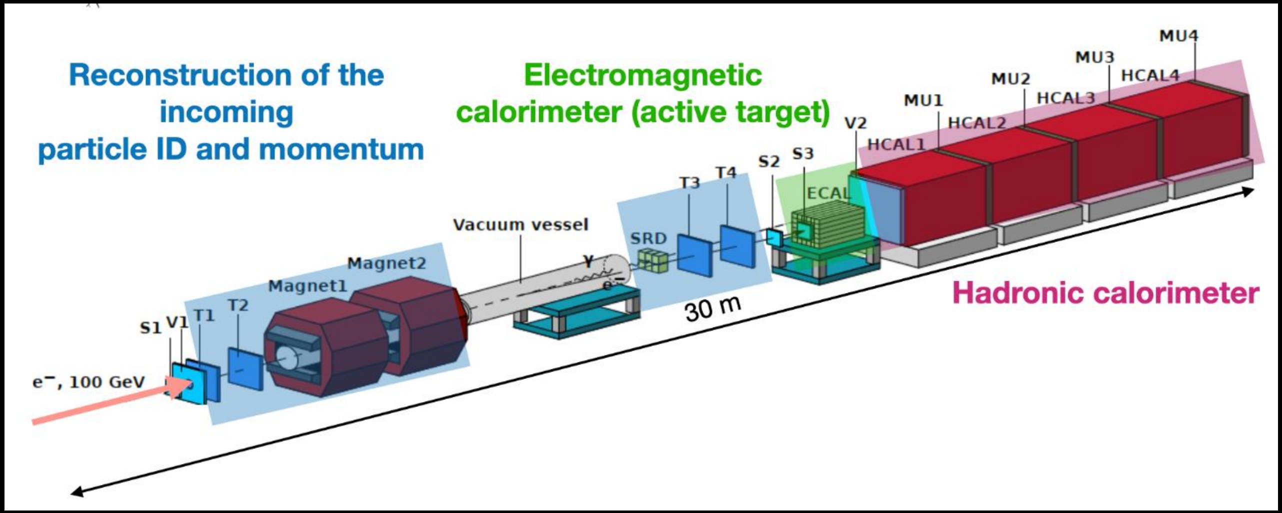
Freeze-out when the two scales are equal

$$n_{eq}^f \approx H^f \,/\, \langle\sigma v\rangle$$

$$\Omega\,\rho_c \sim {T_0^3}/{T_f^3}\; m\, n_{eq}^2$$

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

Also planned run with muon beam and proposed run with hadron beams