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Light Dark Matter eXperiment: A Discovery Experiment for sub-GeV Dark Matter

Tim Nelson - SLAC

P5 Town Hall @ BNL – April 12, 2023

LDMX
UC SANTA BARBARA
Caltech
Carnegie Mellon University
Fermilab
Lund University
University of Minnesota
SLAC National Accelerator Laboratory
Stanford University
Texas Tech University System
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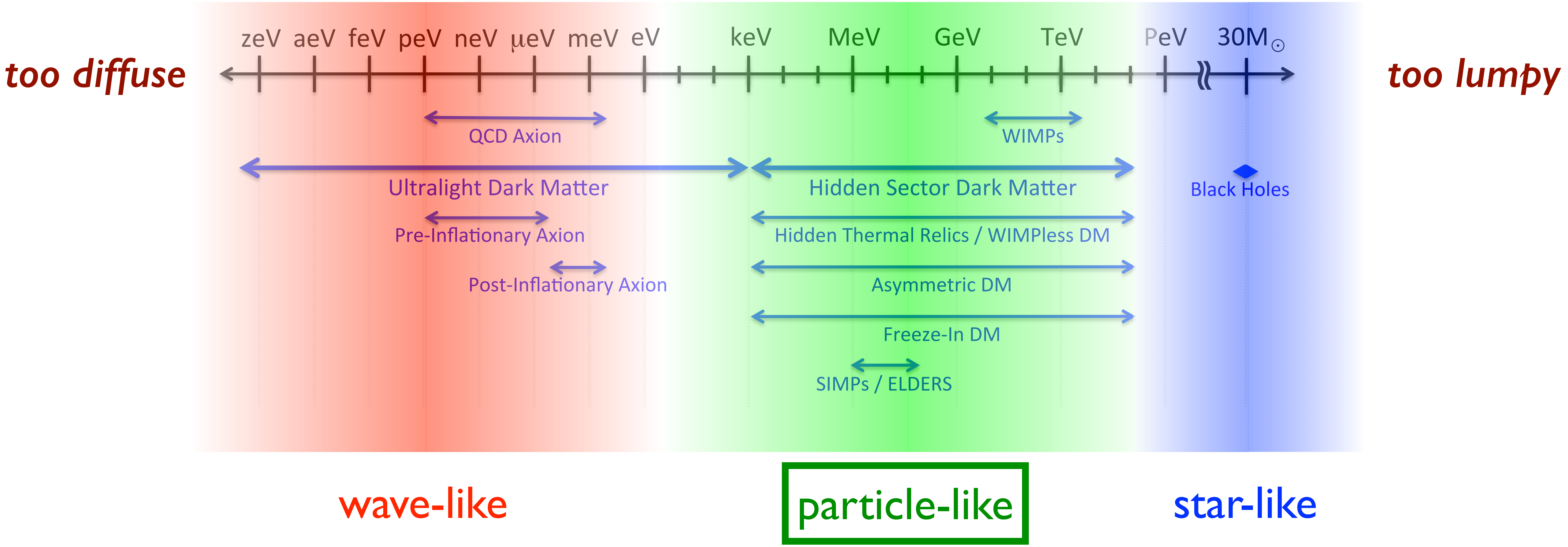
Dark Matter Landscape

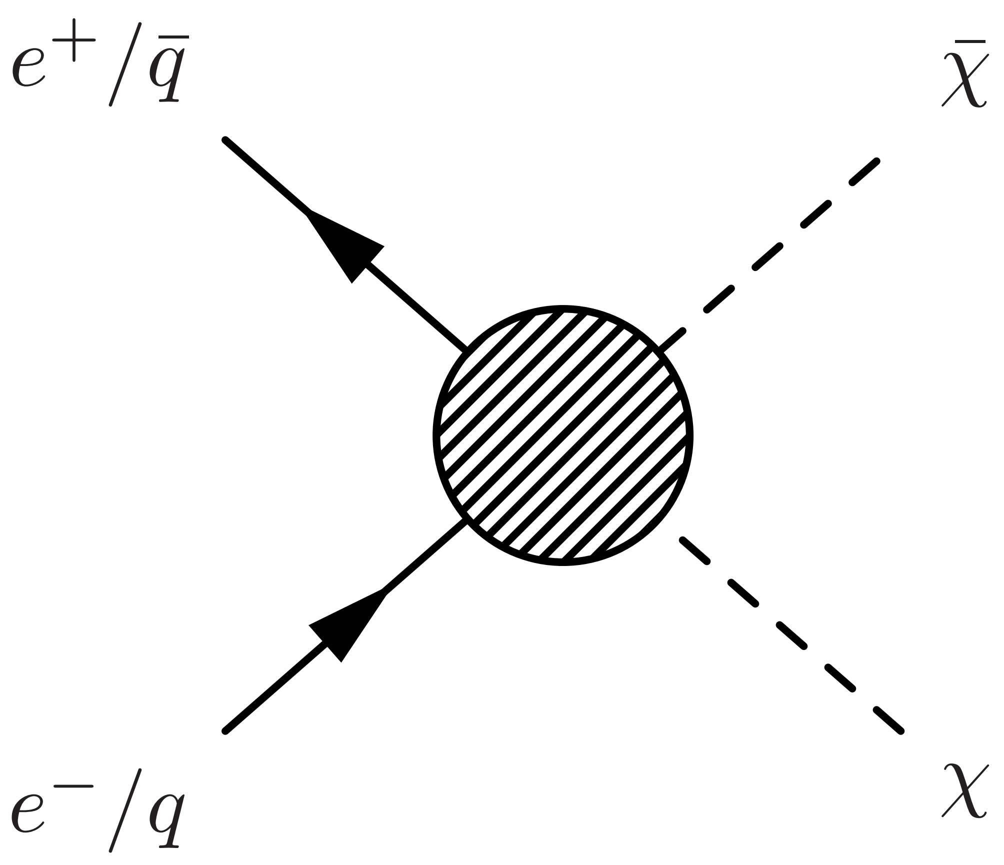
Everything we know about the mass of Dark Matter arXiv:1707.04591 **[hep-ph]**



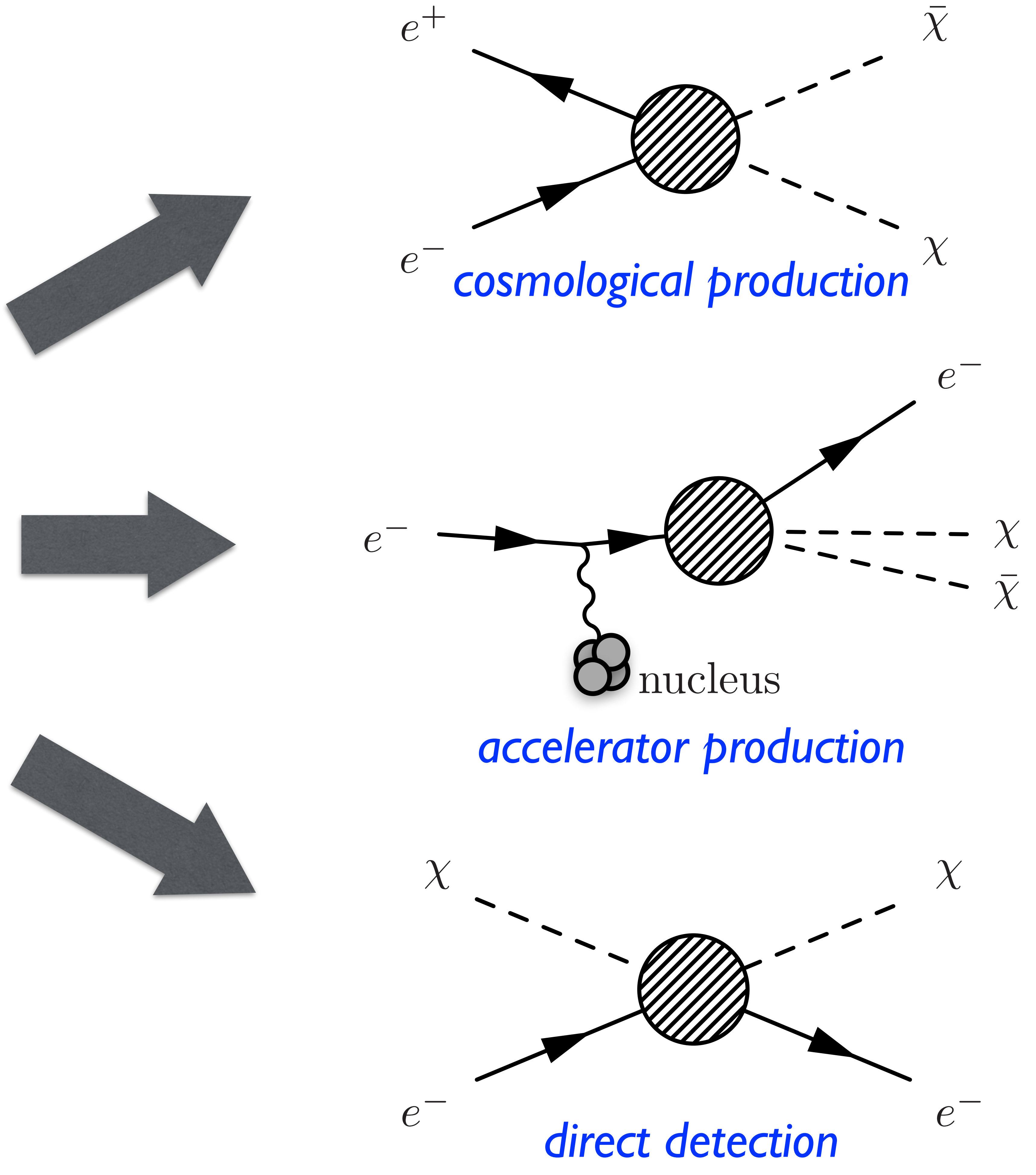
Thermal relics are an important class of dark matter where sub-GeV region is still relatively unexplored.

Thermal Relics

Start with a simple ansatz for DM-SM interactions:



related by crossing symmetry



scale probed

$q \sim m_\chi$

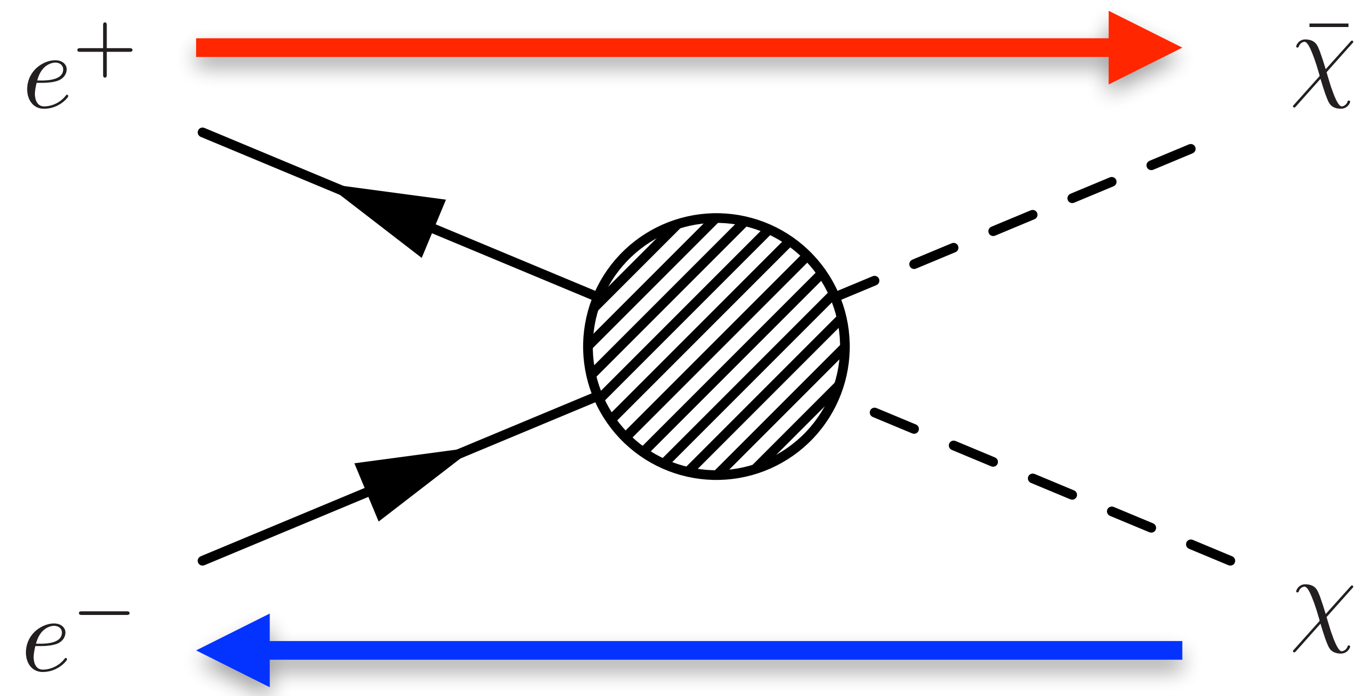
origin of predictiveness

$q \gtrsim m_\chi$

origin of complementarity

$q \ll m_\chi$

cosmological production

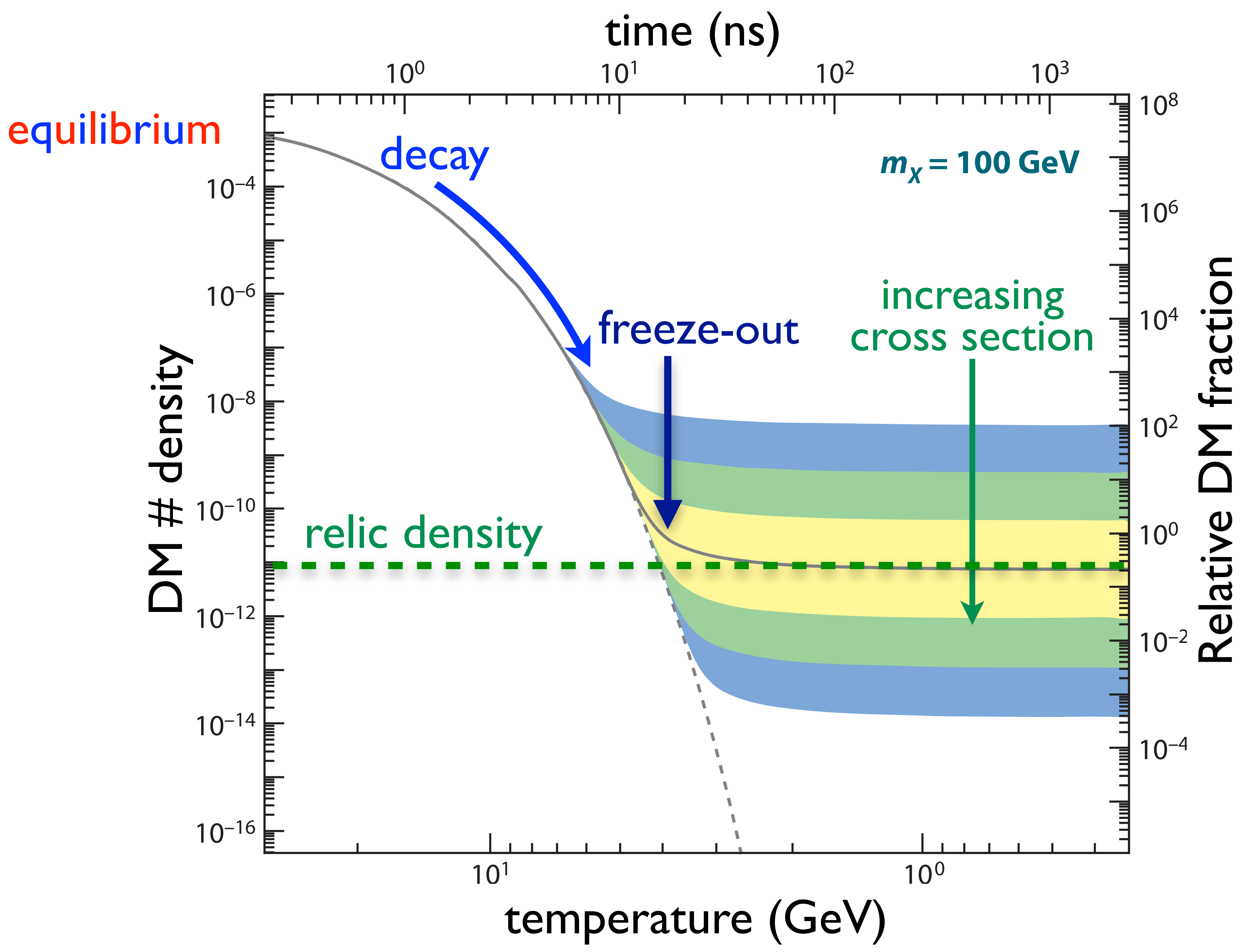


$$\sigma v = \frac{1}{16\pi^2}\frac{\bar{\mathcal{M}}(s)}{s}$$

at freeze-out:

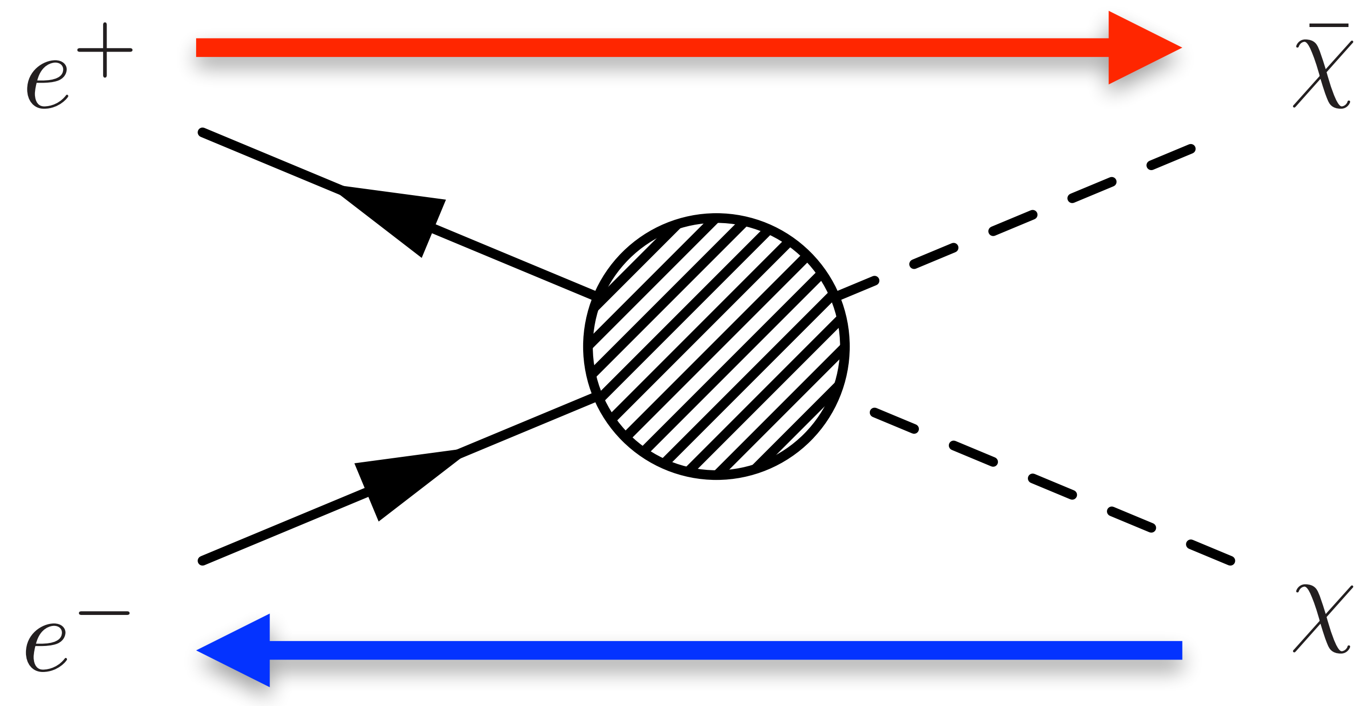
$$s_{\rm fo} \approx (2m_\chi)^2$$
$$\sigma v = 3\cdot 10^{-26}{\rm cm}^3/s$$

$$\Rightarrow |\bar{\mathcal{M}}(s_{\rm fo})|^2 = 10^{-6} m_\chi^2/{\rm GeV}^2$$

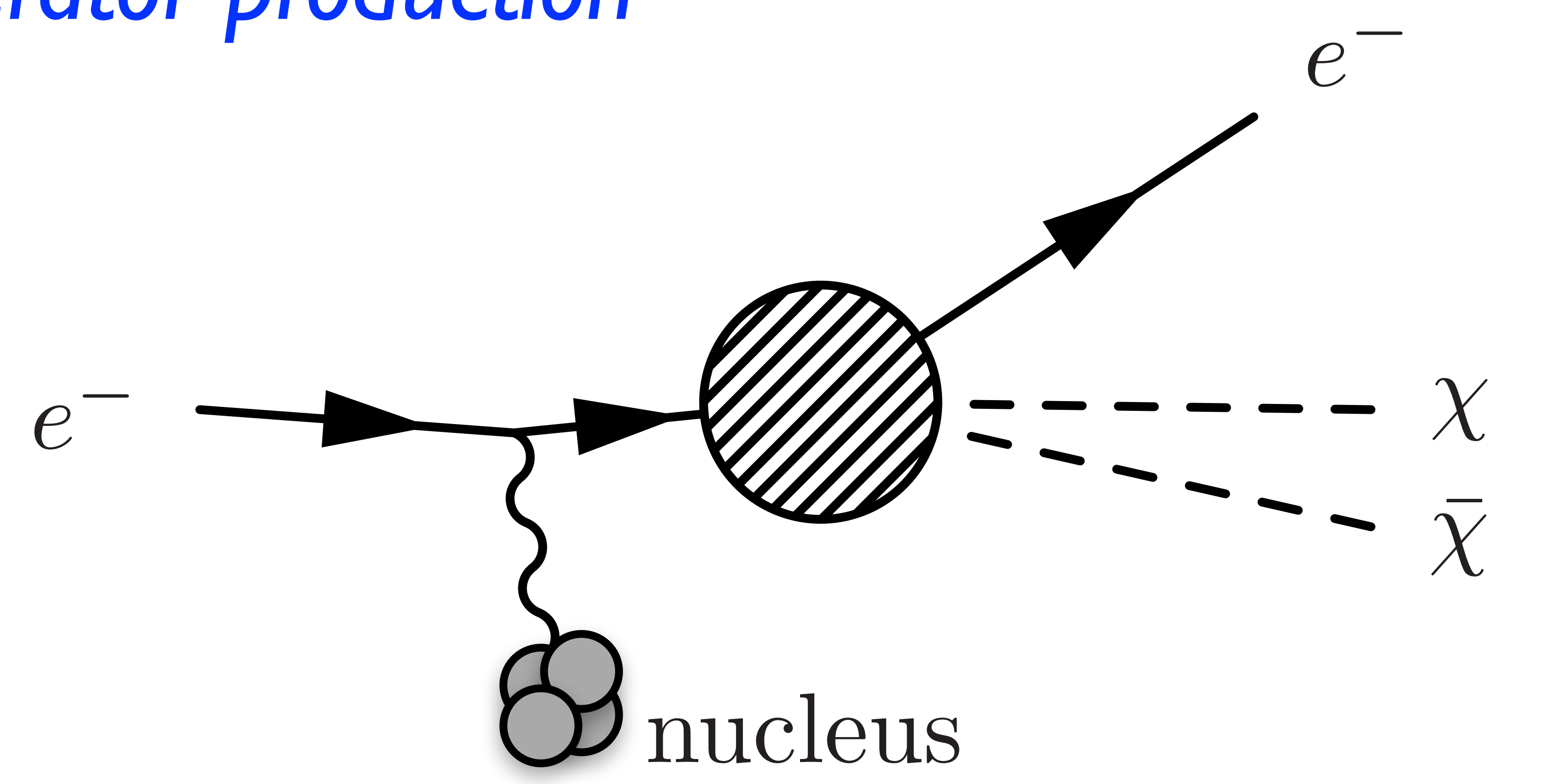


Accelerator Experiments and Freeze-out Thermal Relics

cosmological production



accelerator production



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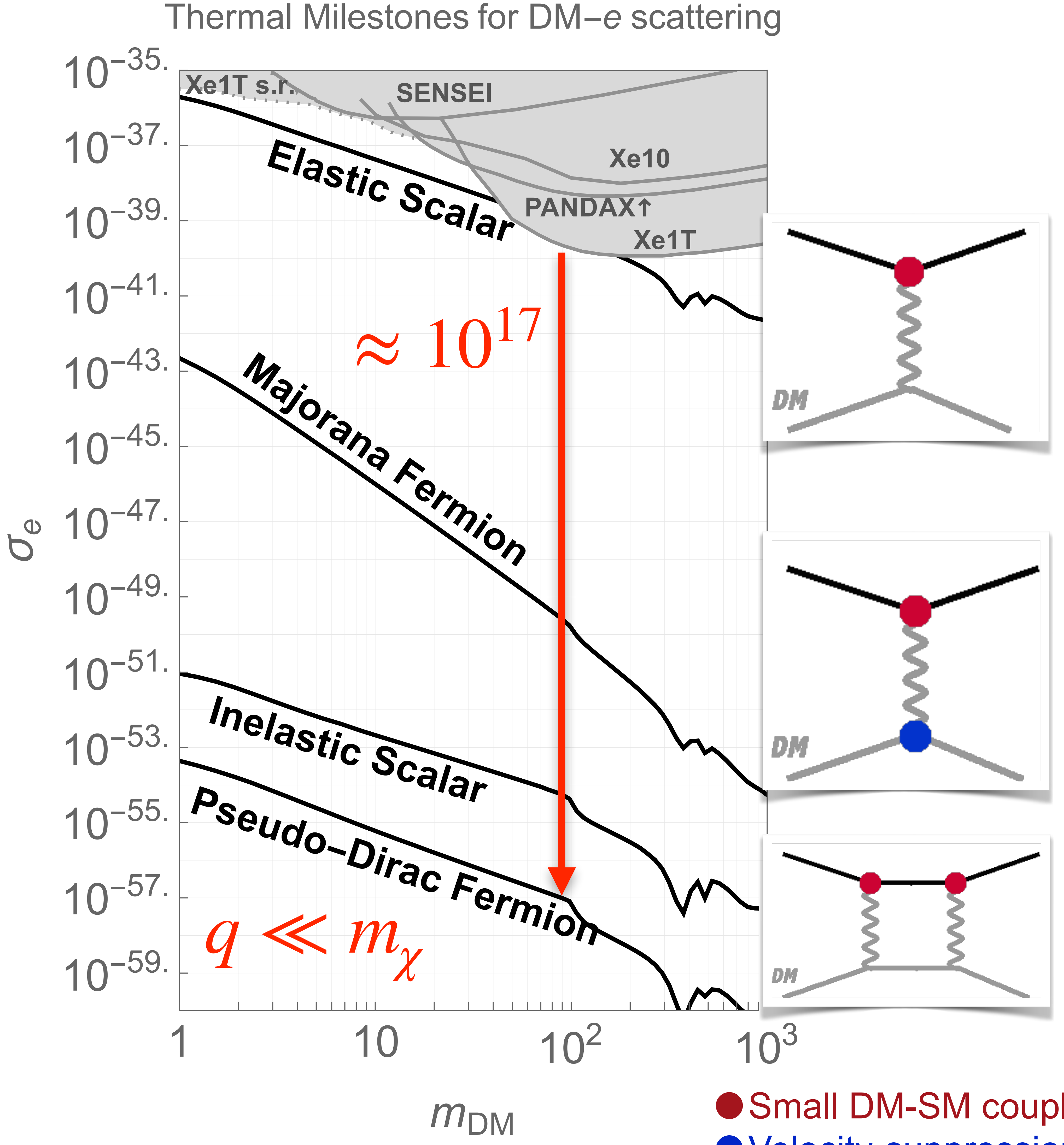
for production at $s \approx s_{\rm fo}$:

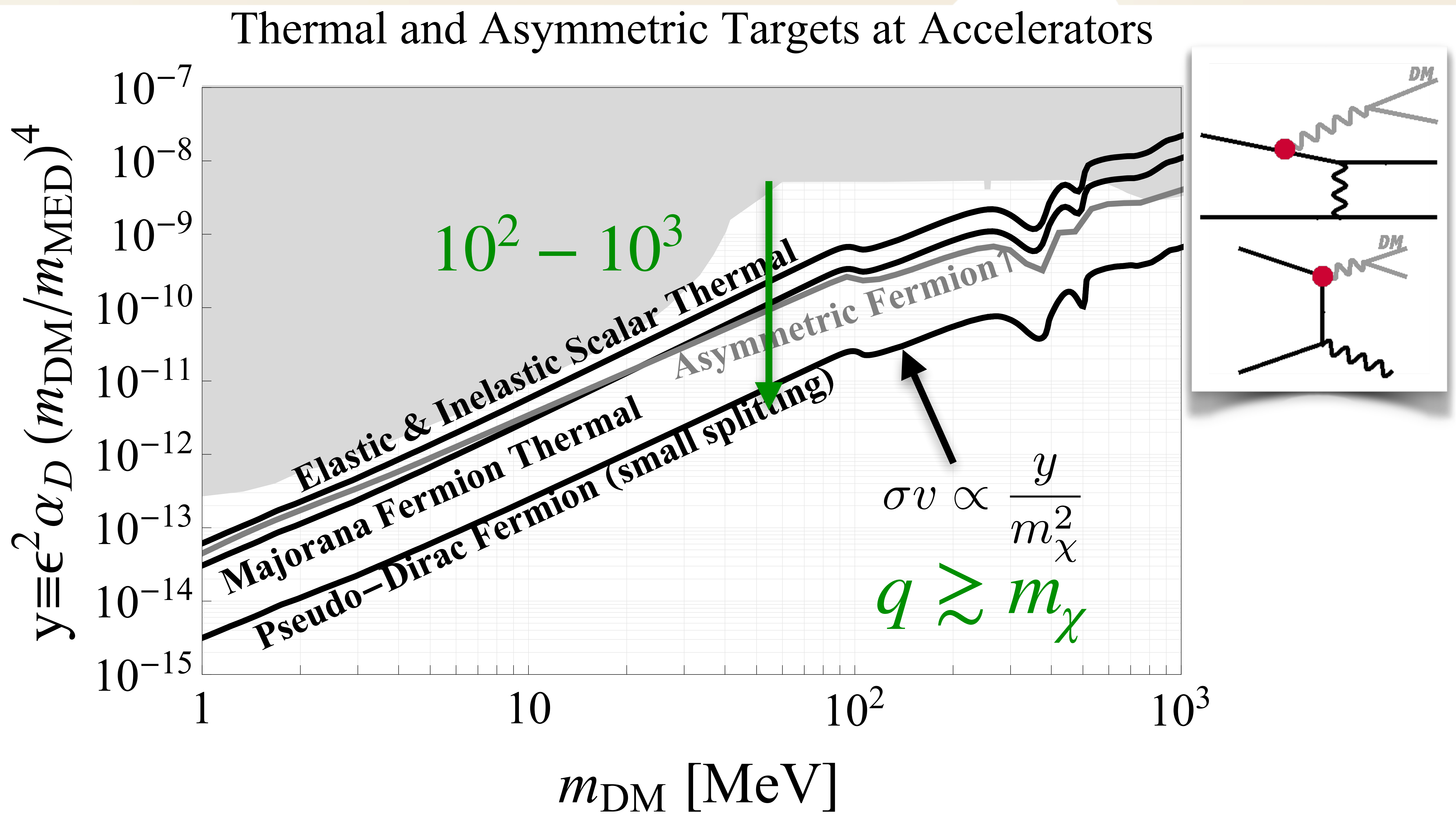
$$\frac{\sigma_{\chi\bar{\chi}}}{\sigma_{\rm brem}} \approx \frac{|\mathcal{M}|^2}{e^2}\frac{1}{48\pi^2}\frac{(2m_\chi)^{-2}}{m_e^{-2}} f_{\rm coh} \approx 2\cdot 10^{-15} f_{\rm coh}$$

where $f_{\rm coh}$ is $\mathcal{O}(1)$ for $m_\chi \lesssim 100$ MeV

Since smaller cross sections result in DM overabundance, an accelerator experiment with ~10^{16} electrons has generic ability to produce sub-GeV freeze-out thermal relics.

Concrete Example: Dark Photon Mediator





● Small DM-SM coupling
● Velocity-suppression

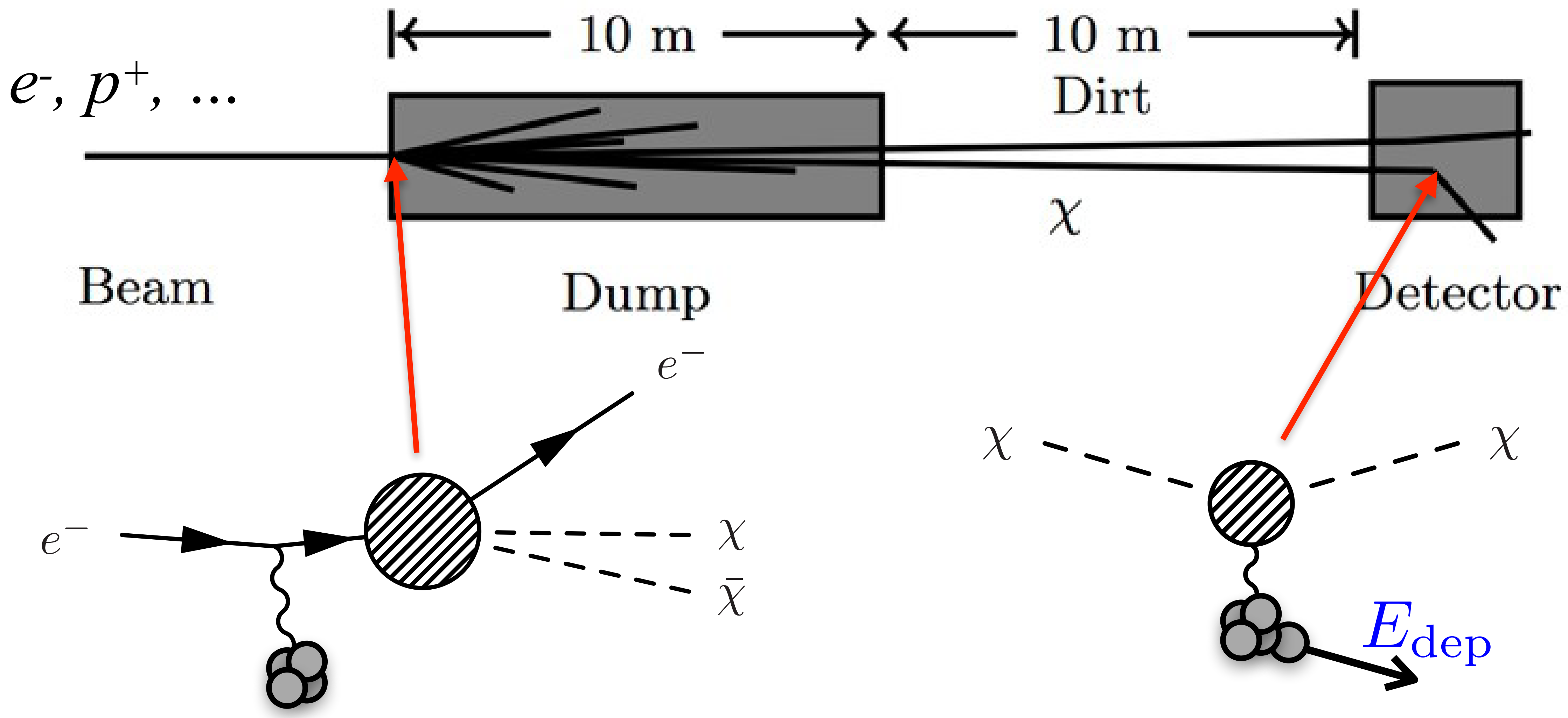
relativistic production ⇒ no suppression

MeV-GeV freeze-out thermal relics are the "killer application" for accelerator searches.

"Big Idea 1" of Snowmass RF6

Fixed Target Dark Matter Search Approaches

Beam Dumps: Produce and re-scatter DM

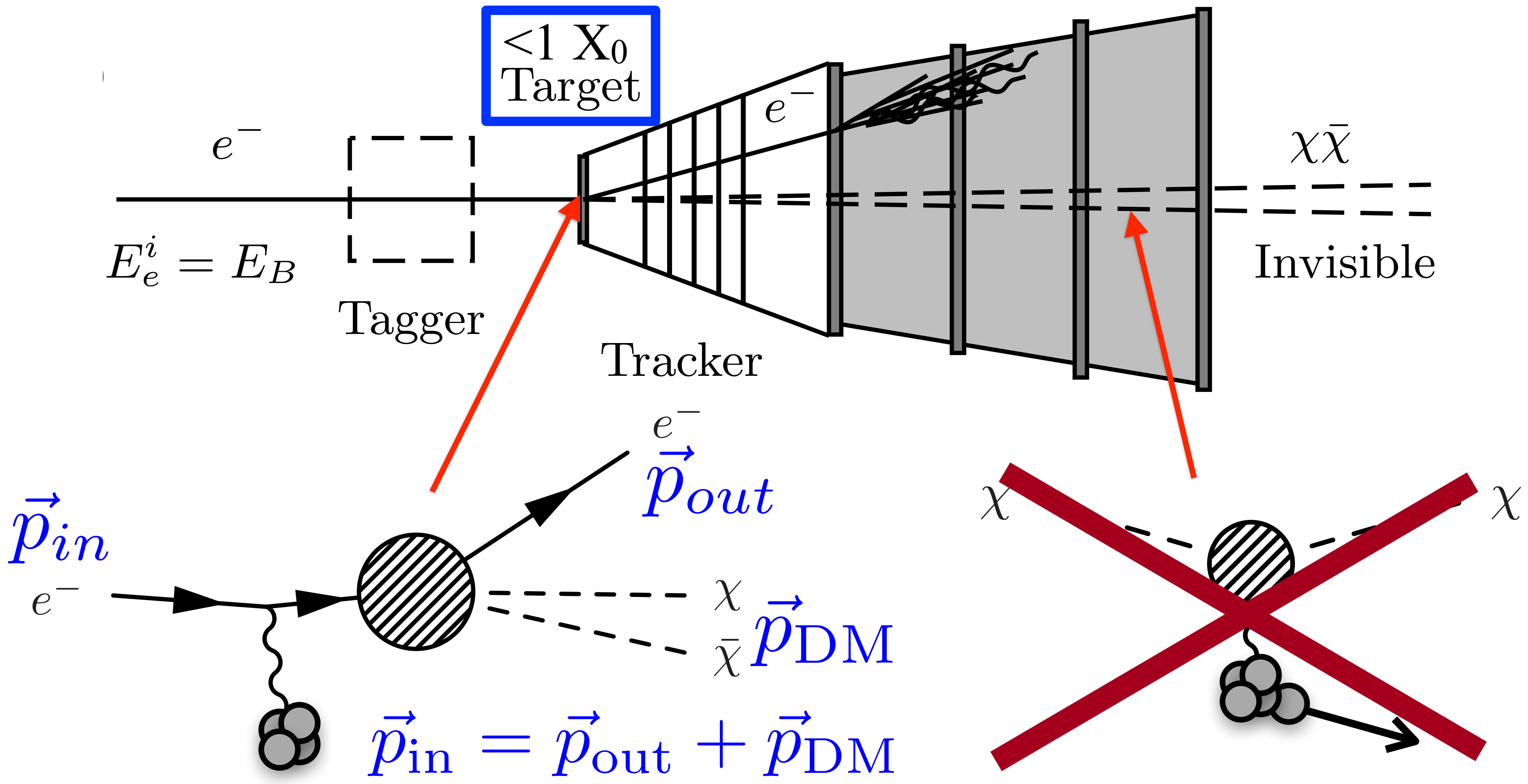


- new sensitivity with ~10^{21} particles
- covers thermal targets with ~10^{28} particles

Requirements:

- most powerful and energetic beam available
- most massive detector available
- (key background: neutrinos)

Missing Momentum: Detect DM production



- new sensitivity for ~10^{12} electrons
- covers thermal targets for ~10^{16} electrons

Requirements:

- high rate beam at ~1e^-/bunch (1 year = 3×10^{16} ns)
- fast, sensitive, detector systems
  (key backgrounds: $e^- \to e^- + \gamma$, $\gamma N \to$ hadrons)

Both approaches work, but only missing momentum feasibly covers all thermal targets

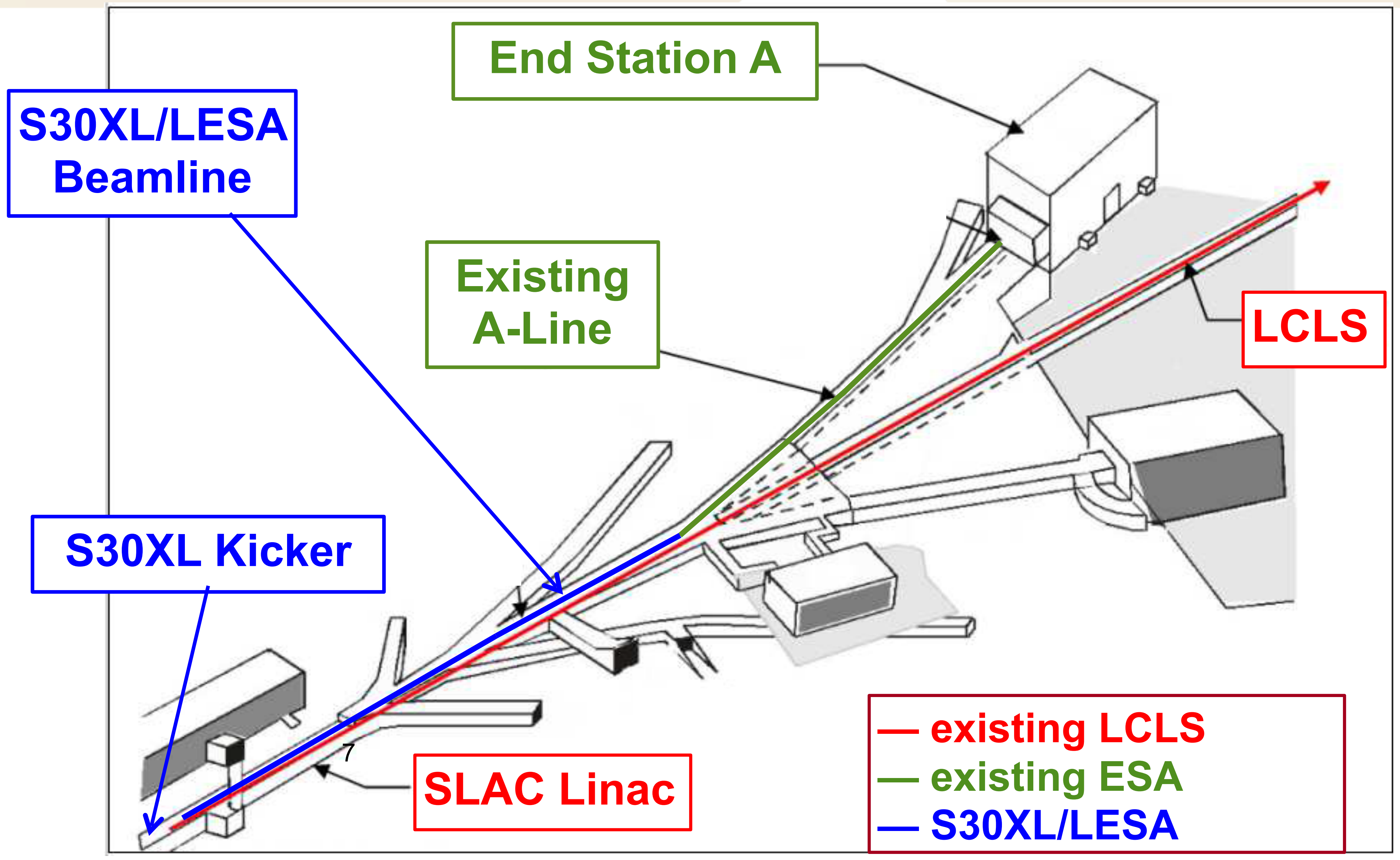
Linac to End Station A (LESA) at SLAC

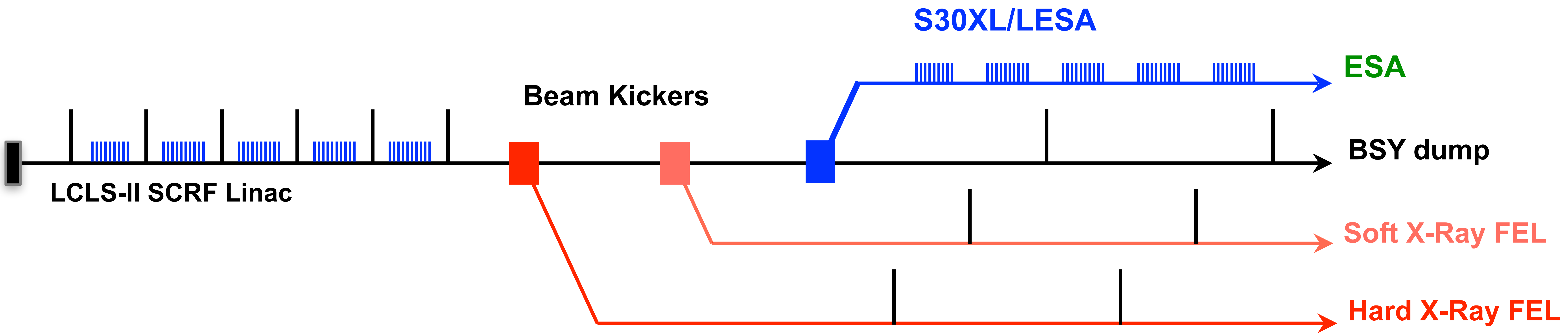
LCLS-II 4/8 GeV drive beam accelerates 186 MHz bunches

- ~5000 hours/year operation for photon science
- LCLS-II uses 929 kHz: >99% of bunches go to dump
- Sector 30 Transfer Line (S30XL) diverts ~60% of unused, low-charge bunches to LESA with LDMX as a primary user.

S30XL AIP is currently under construction alongside LCLS-II.

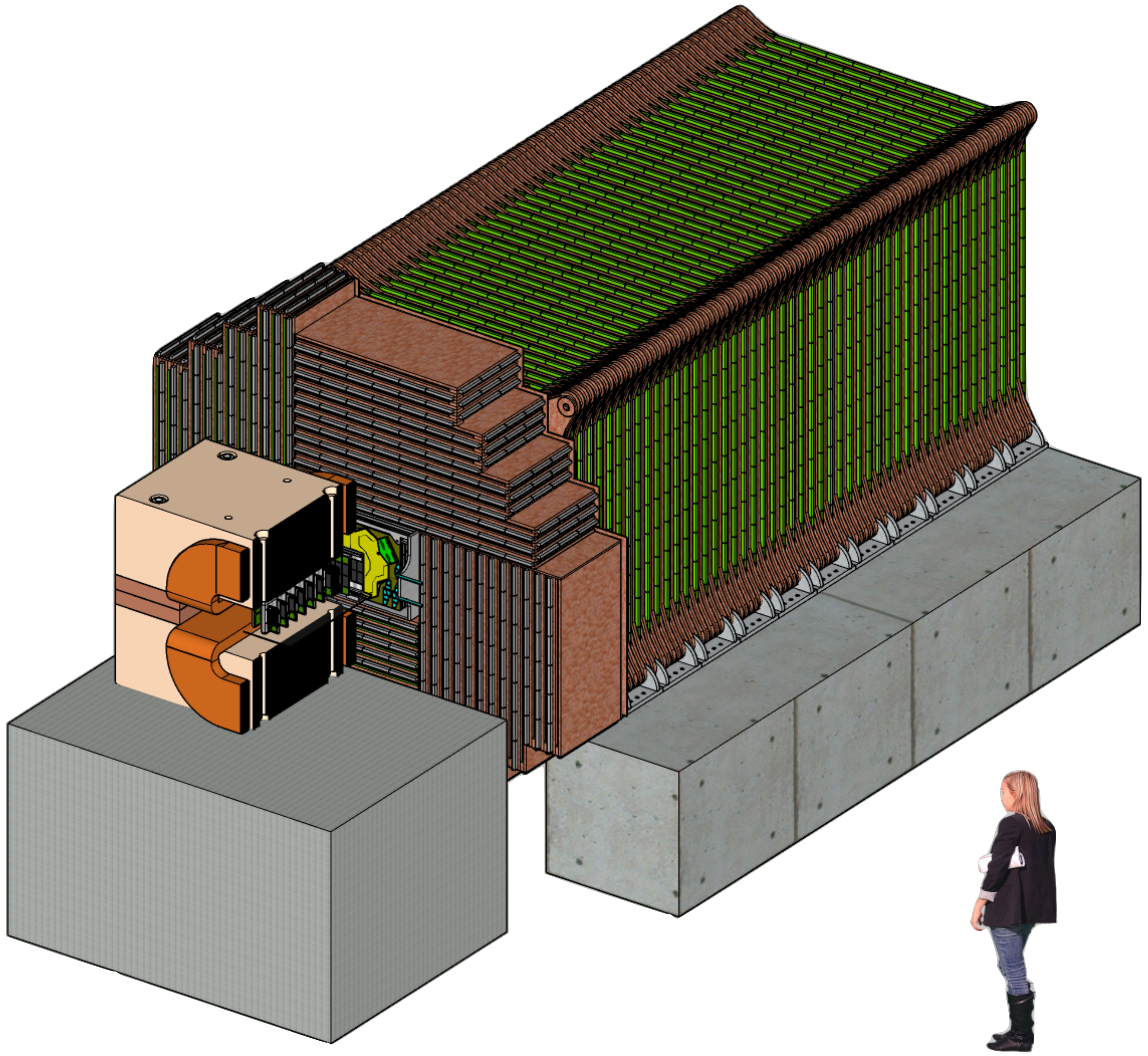
LESA is expected to deliver beam to End Station A in FY25.

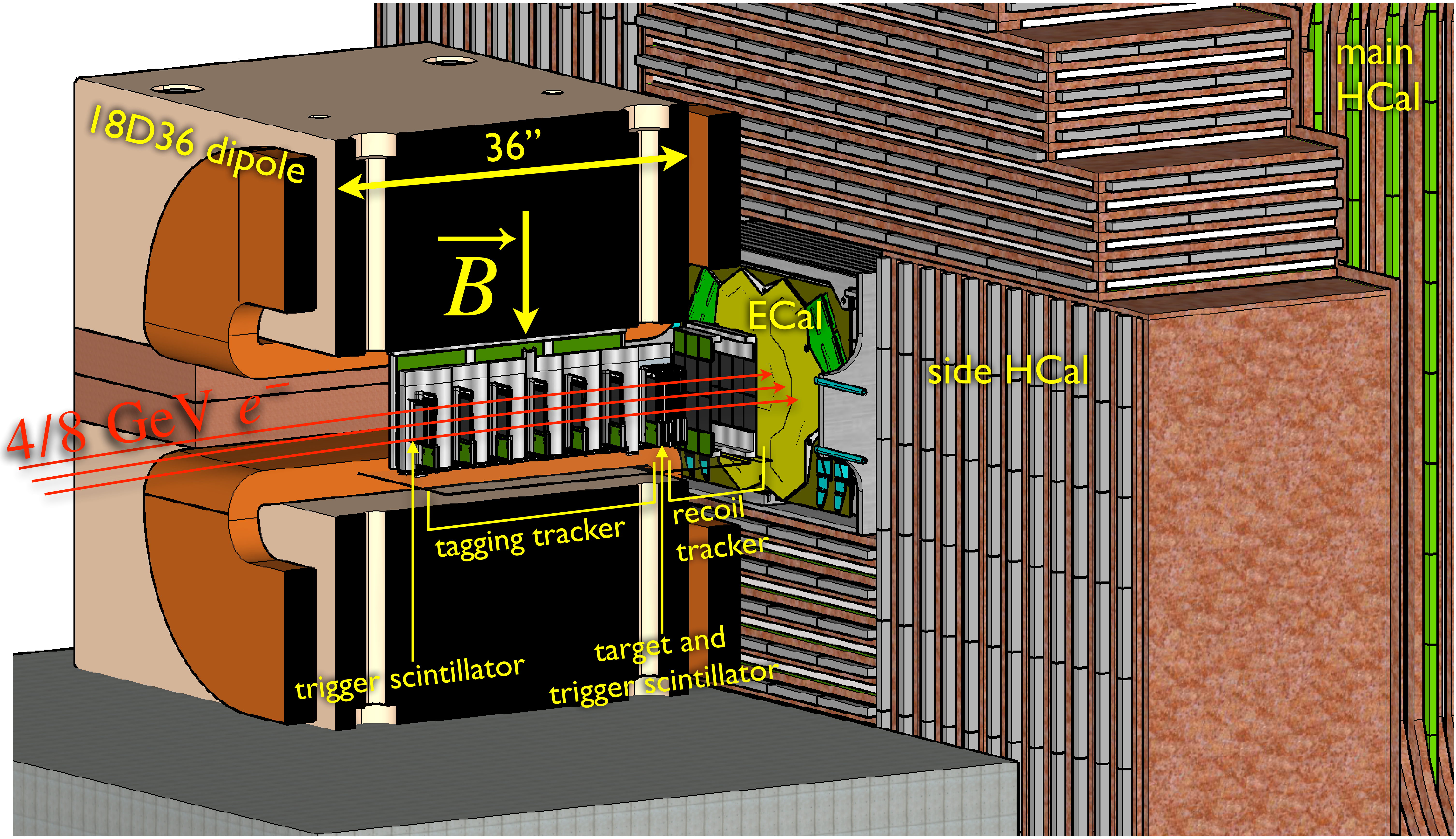




Light Dark Matter eXperiment

LDMX Whitepaper arXiv:1808.05219



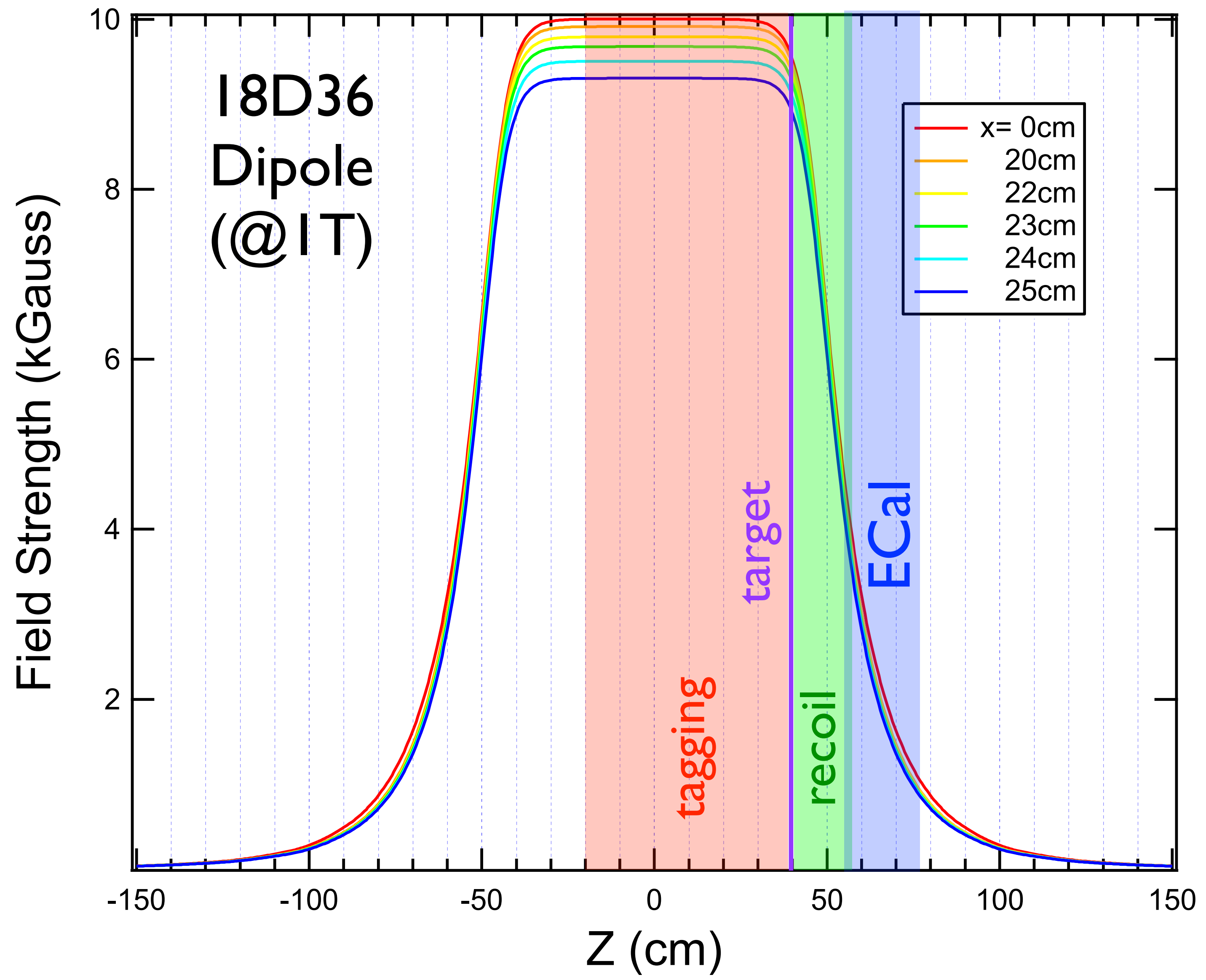


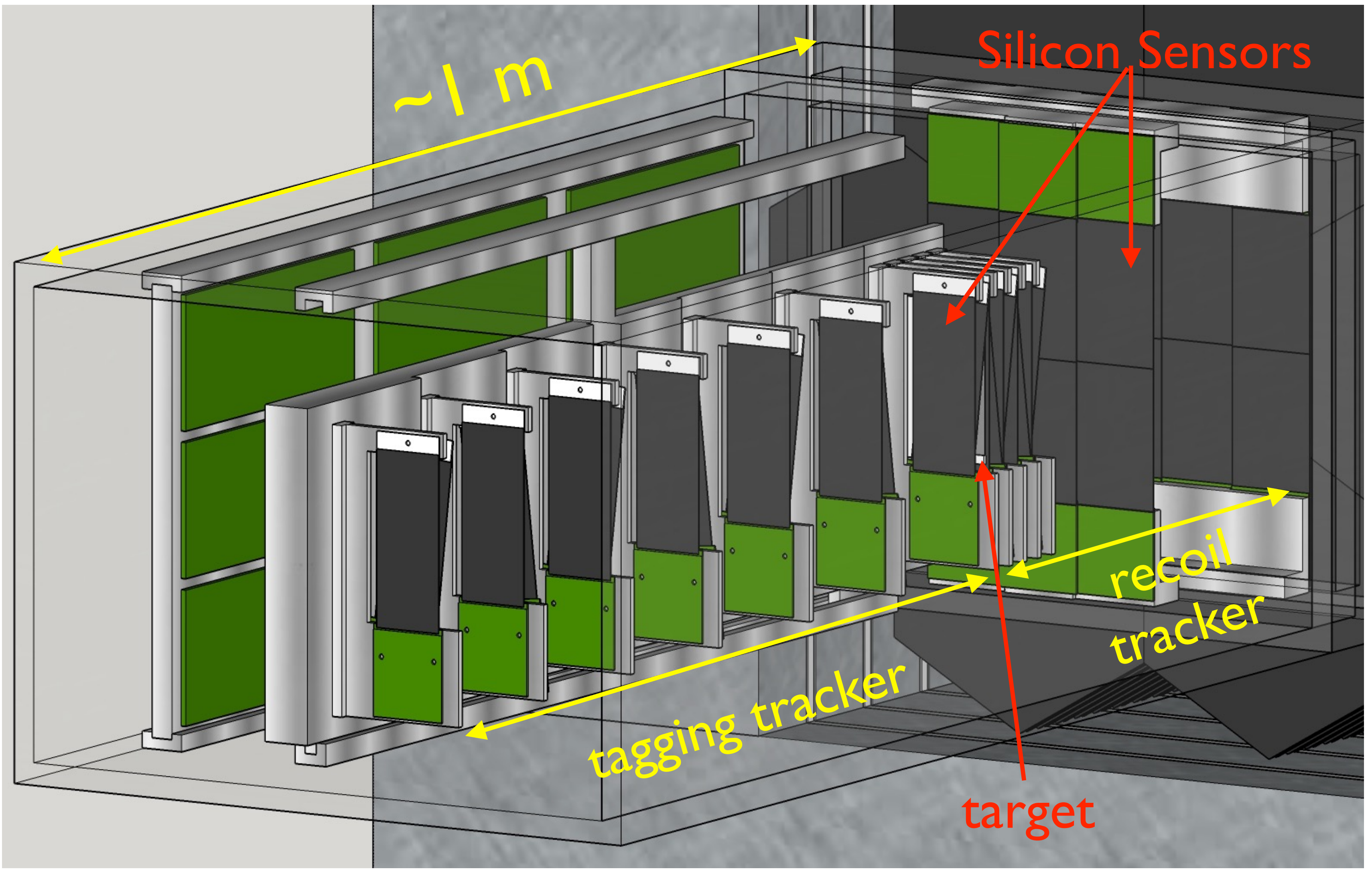
LDMX is an electron missing momentum experiment designed for up to 10^{16} electrons

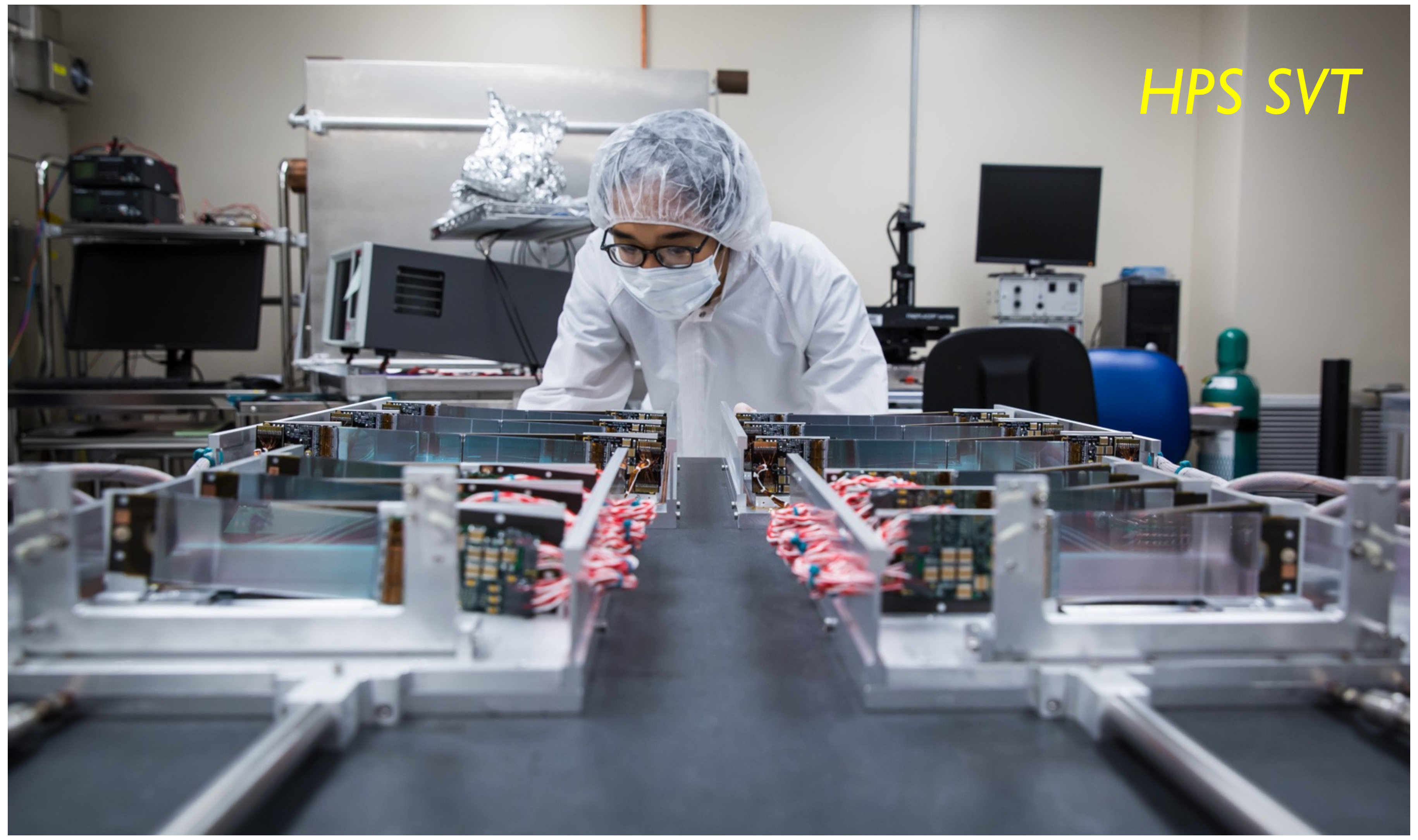
LDMX Detector Subsystems

Tracking based on HPS (orig. CMS)

- refurbish existing dipole
- reuse HPS designs for detector modules and readout







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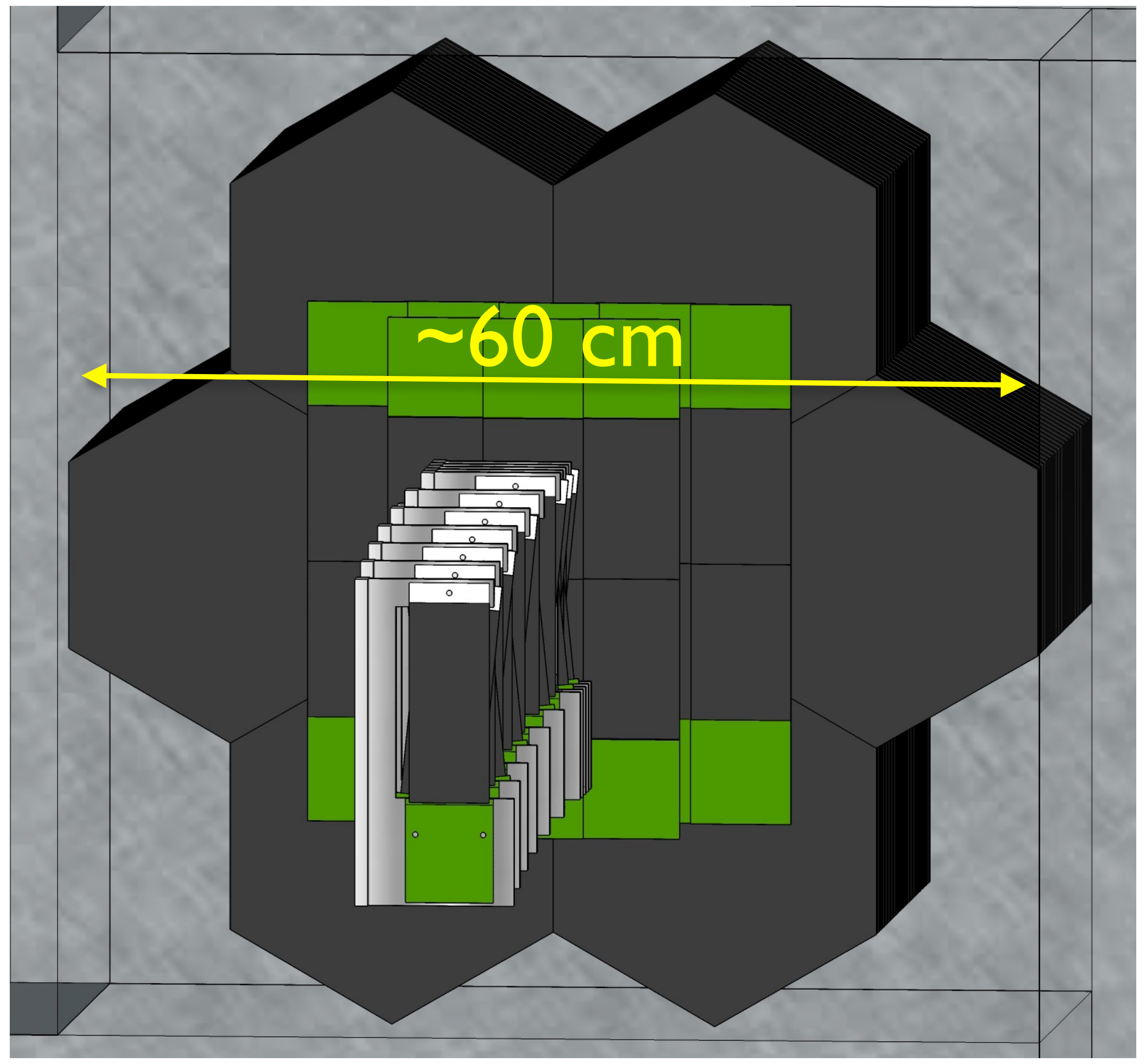
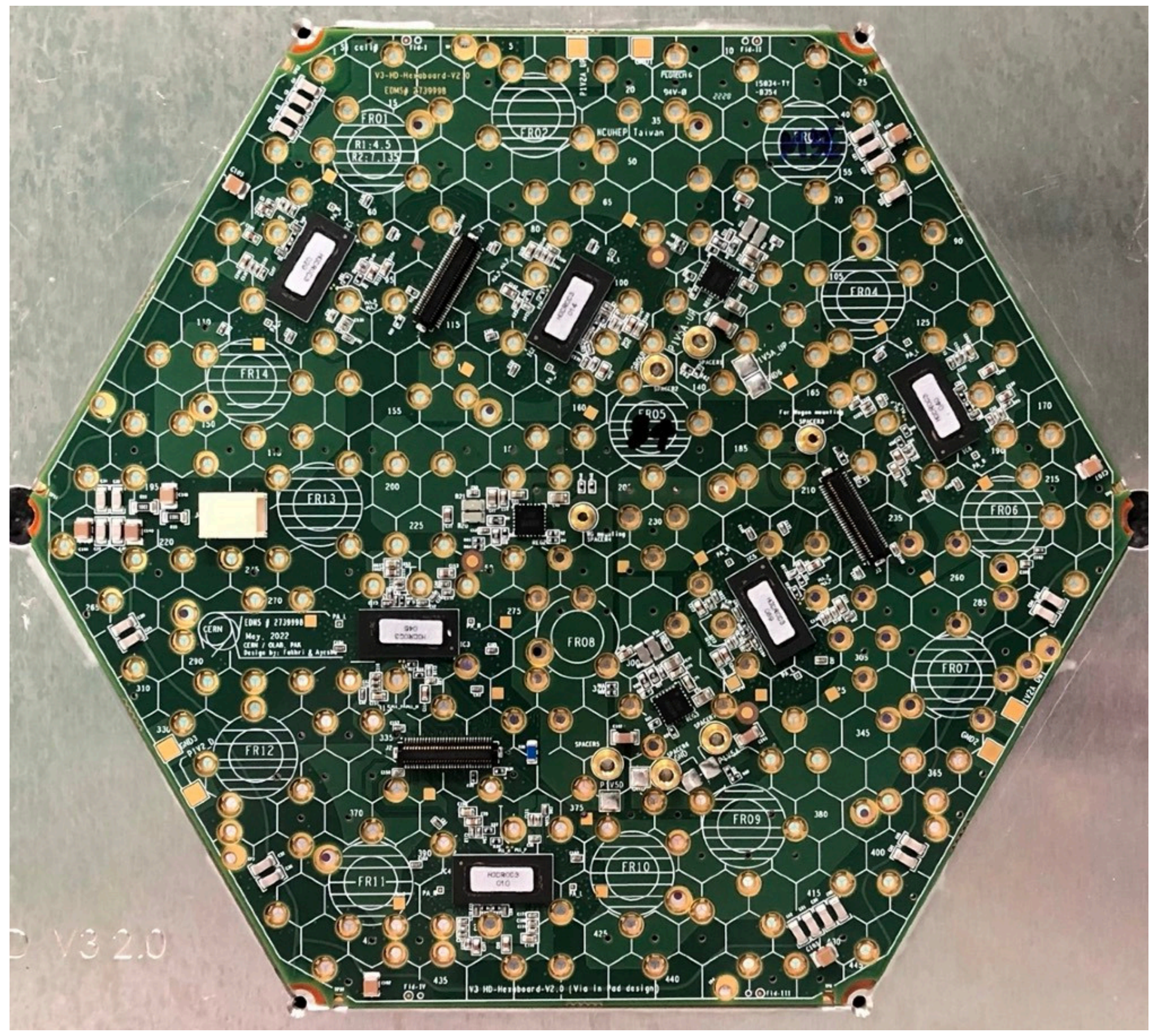
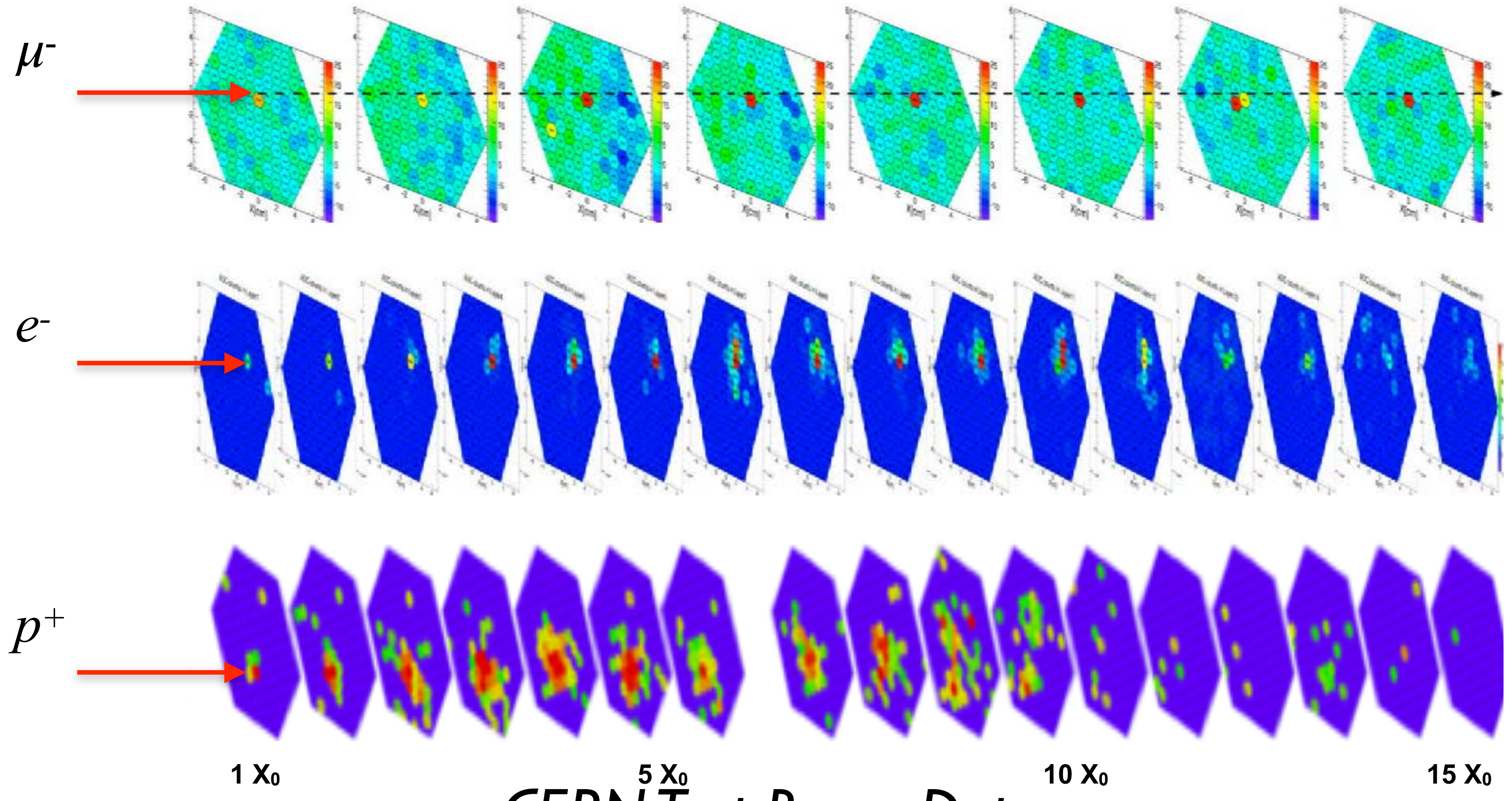
ECal based on CMS

- silicon/tungsten High Granularity Calorimeter for Phase 2 upgrade
- powerful for rejection of rare backgrounds

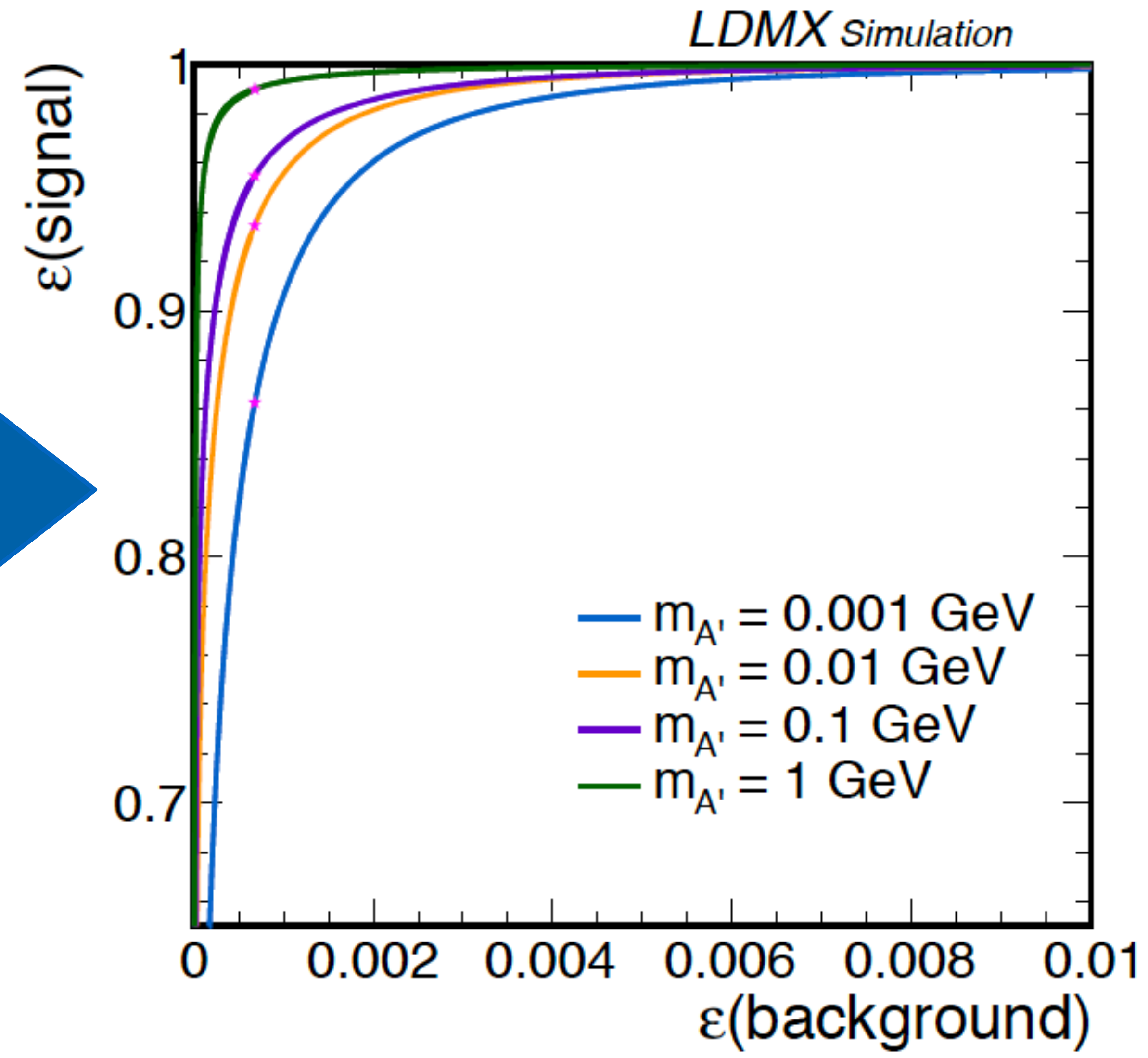






CERN Test Beam Data

Boosted **D**ecision **T**ree



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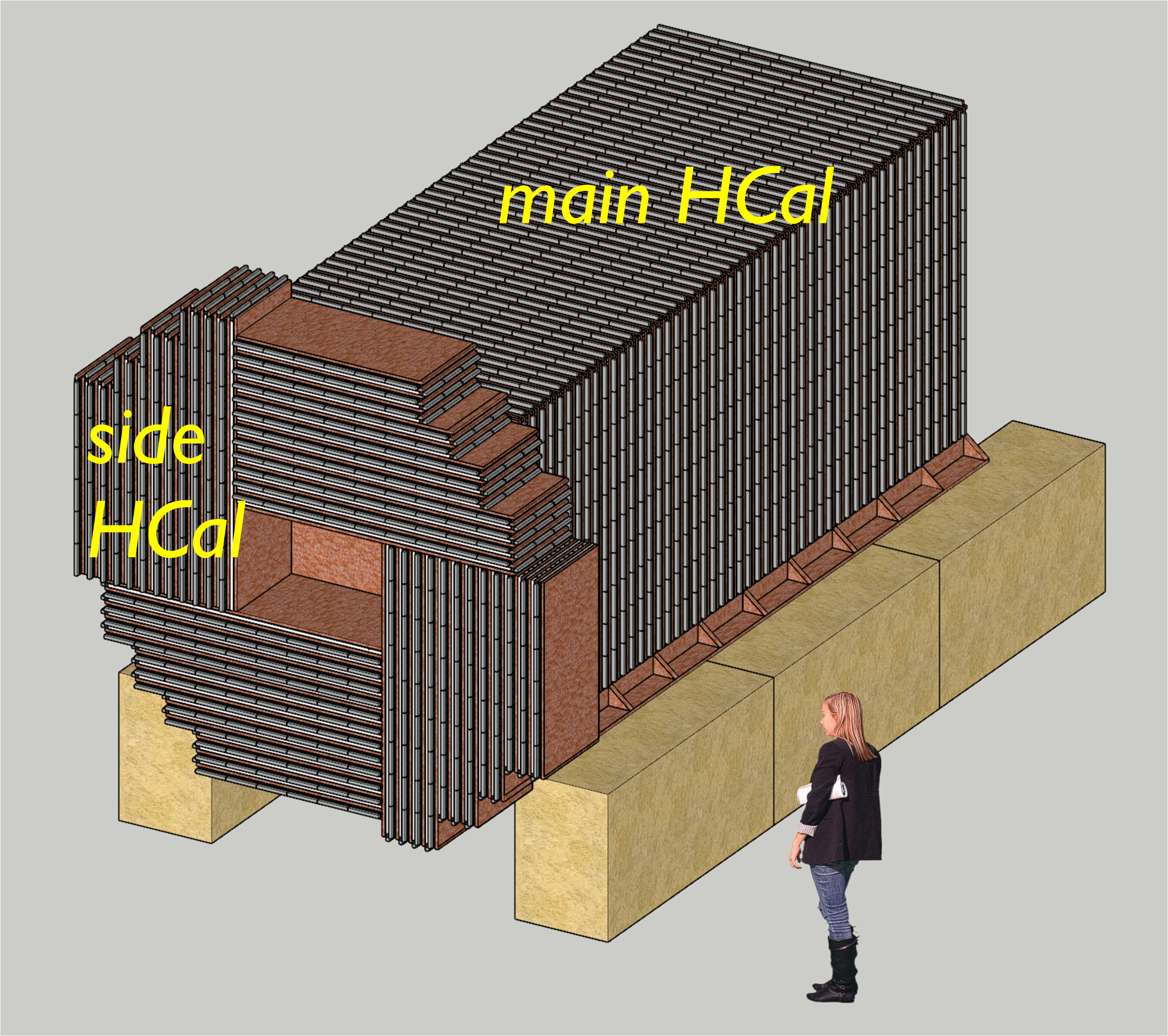
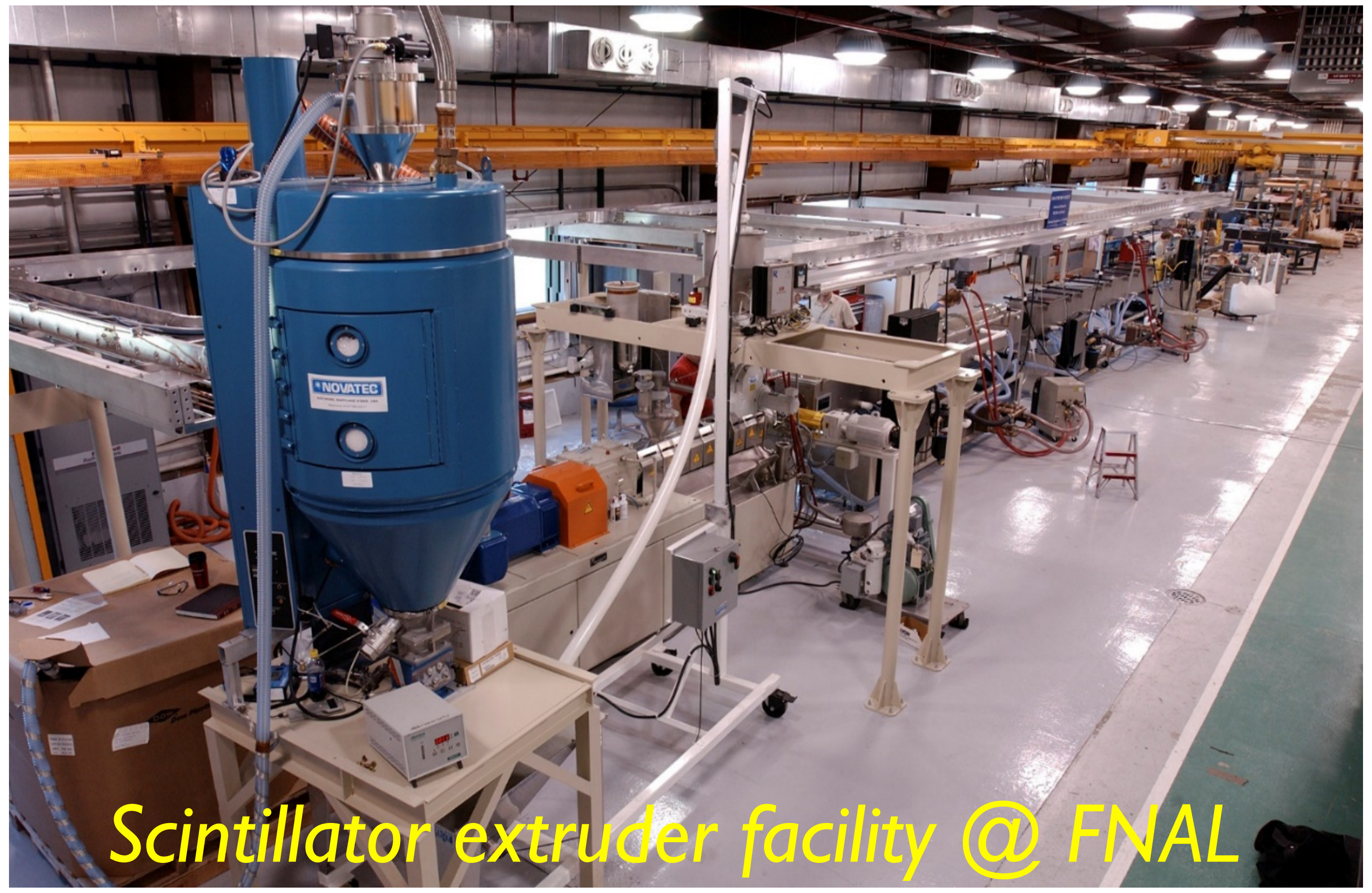
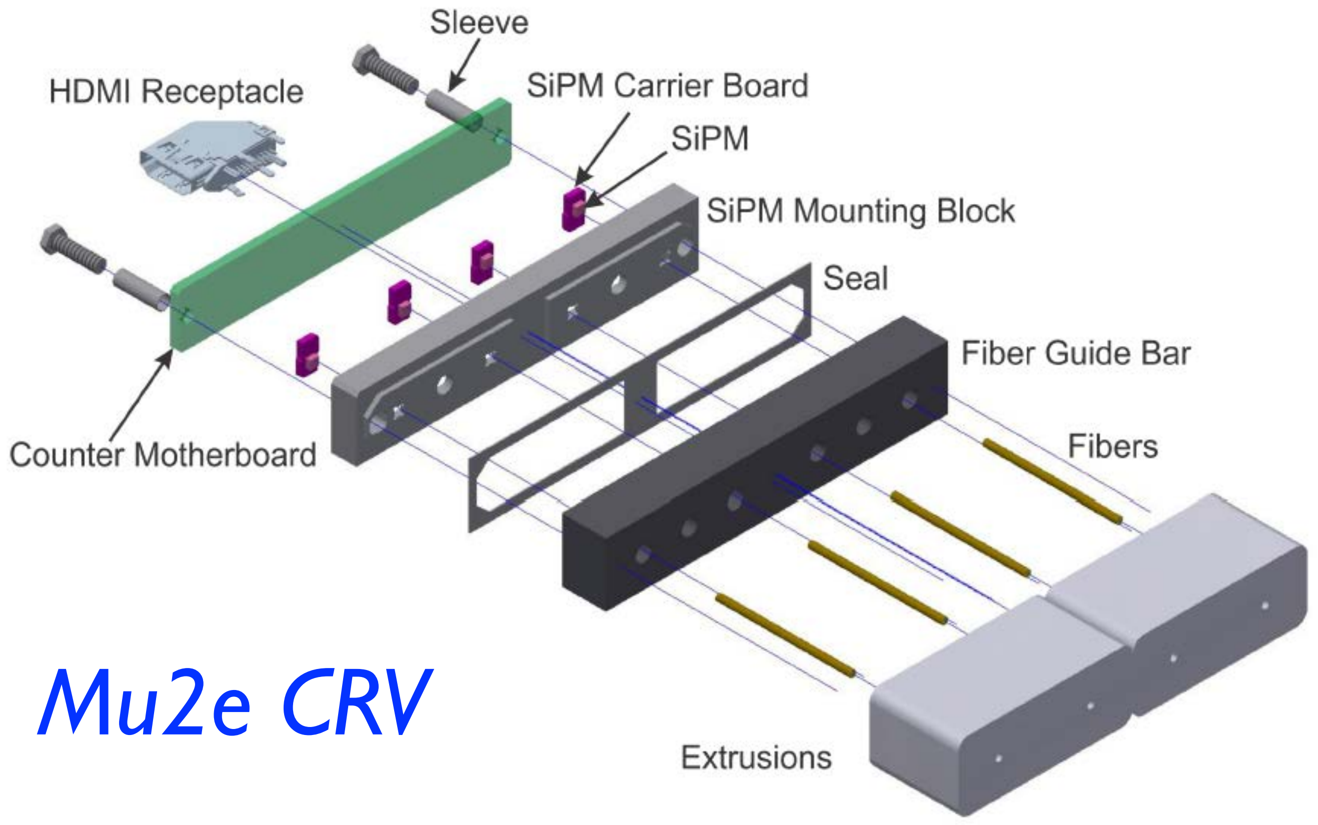
HCal based on Mu2e Cosmic Ray Veto

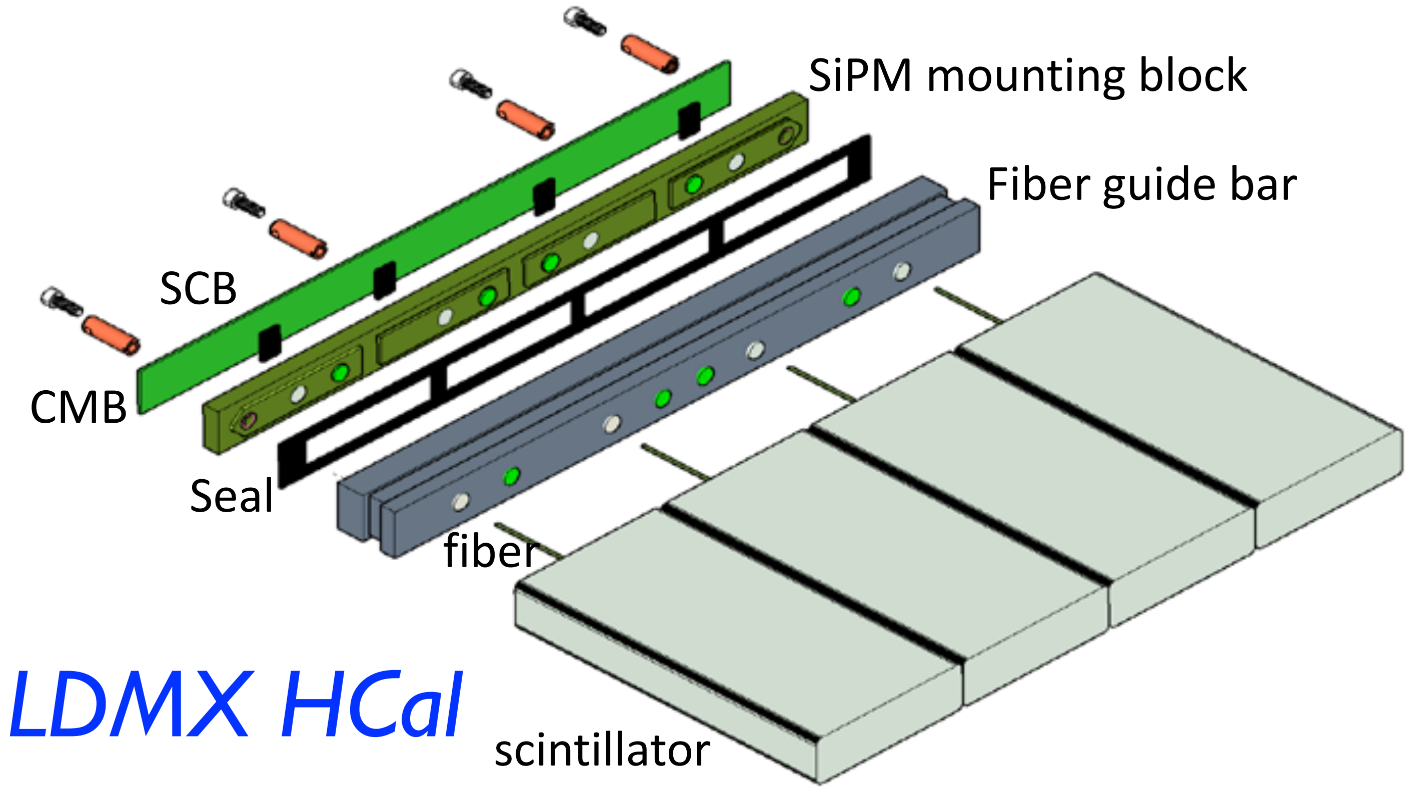
- extruded plastic scintillator/iron
- low veto threshold for neutrons







Mu2e CRV



LDMX HCal

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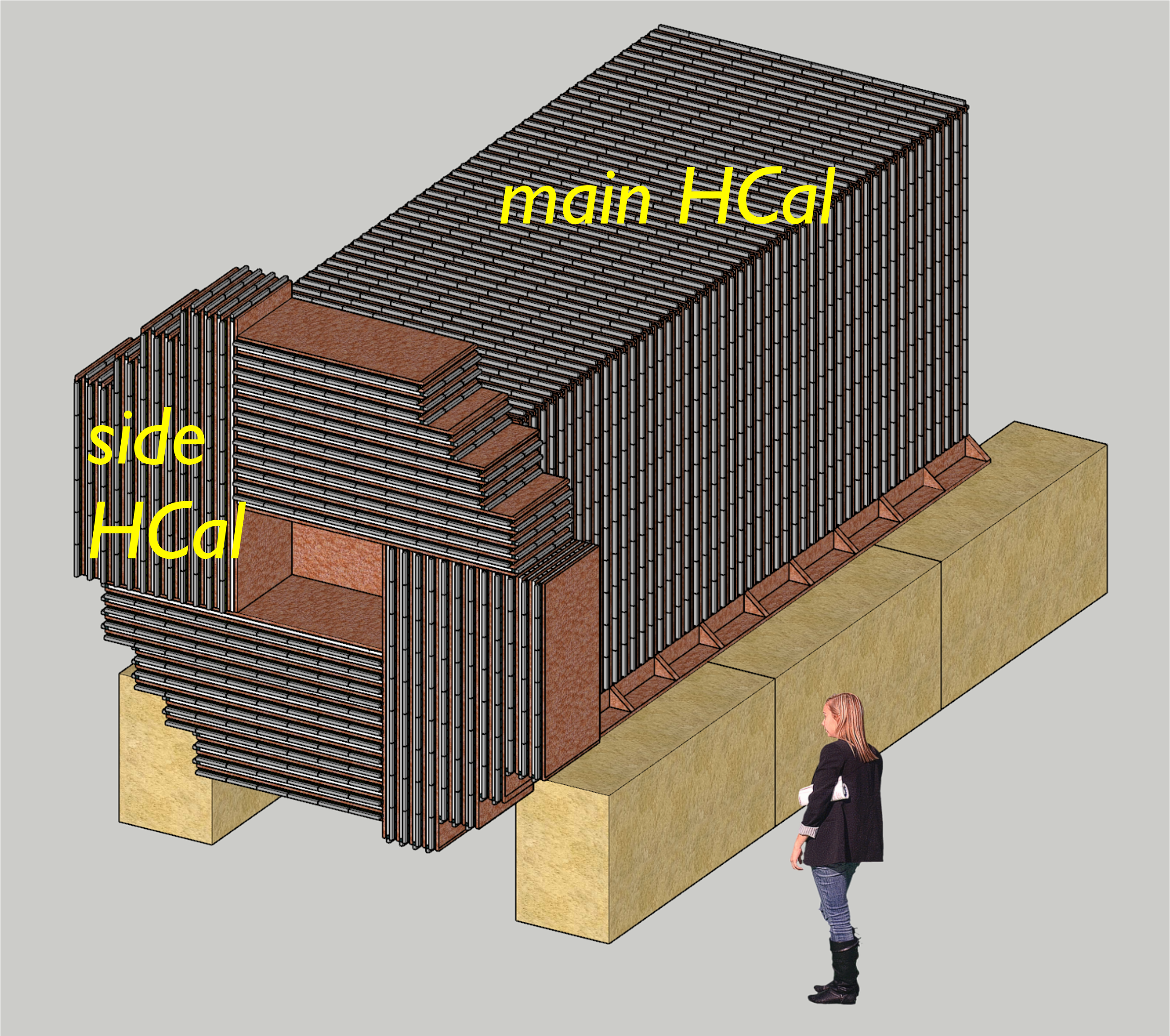
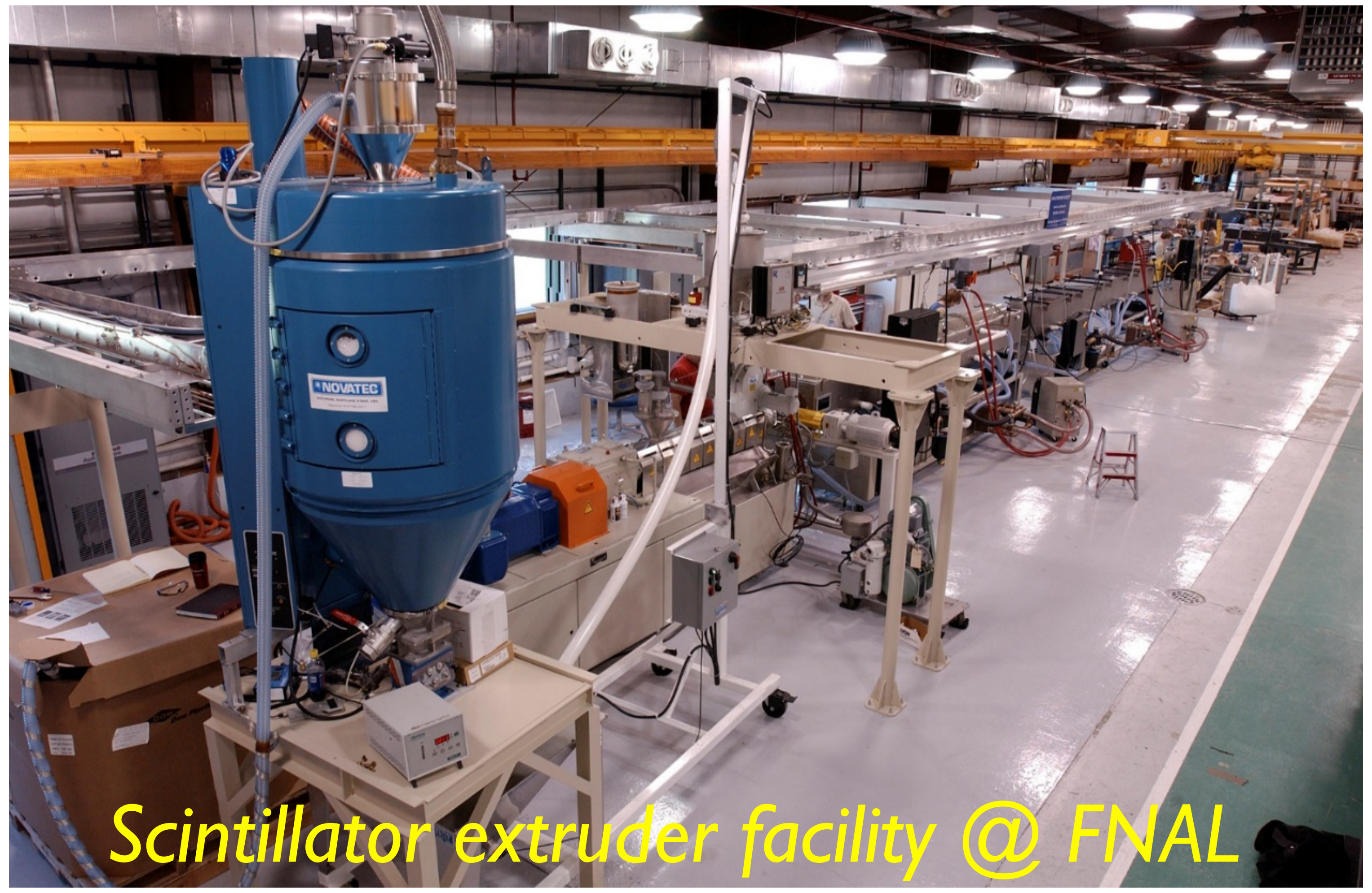
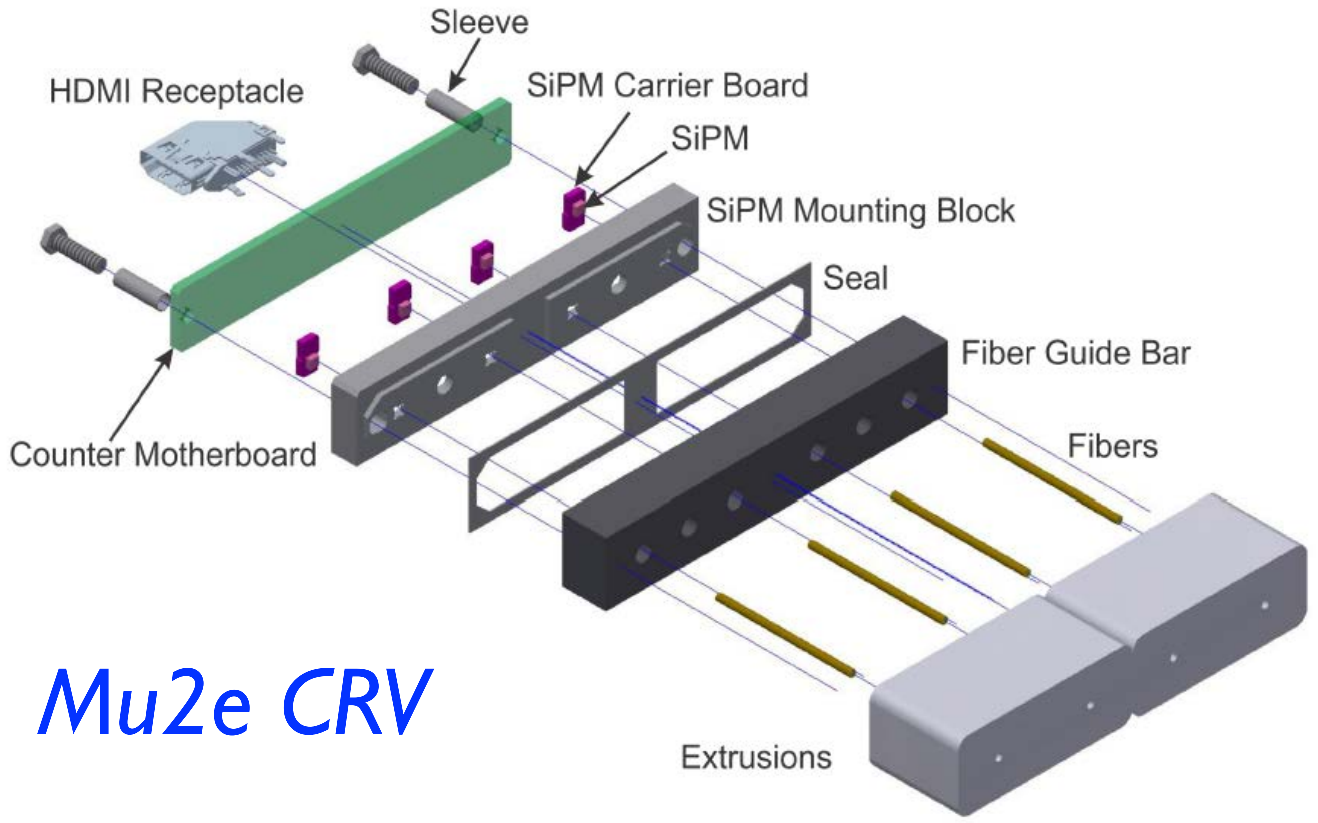
re-using existing technologies, LDMX is inexpensive, shovel ready







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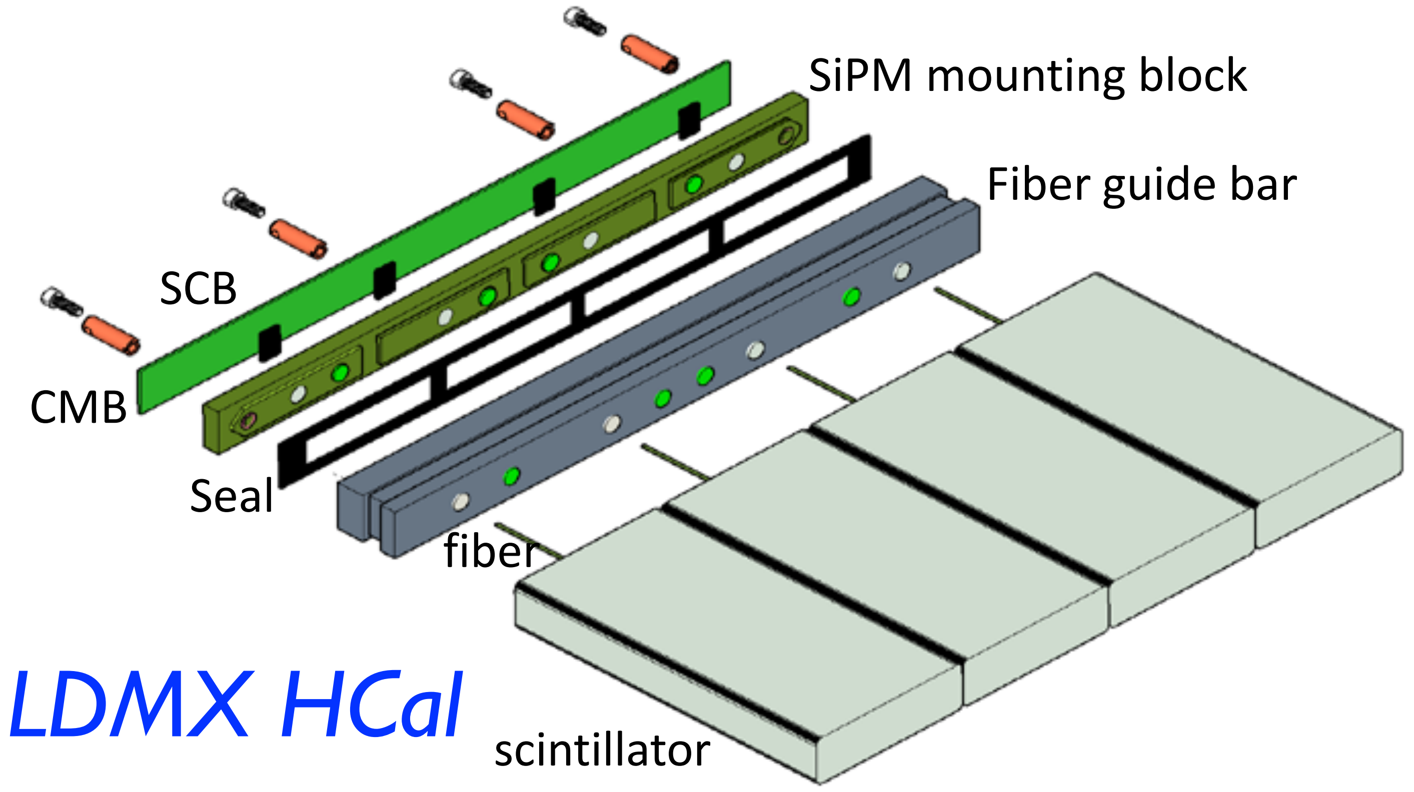
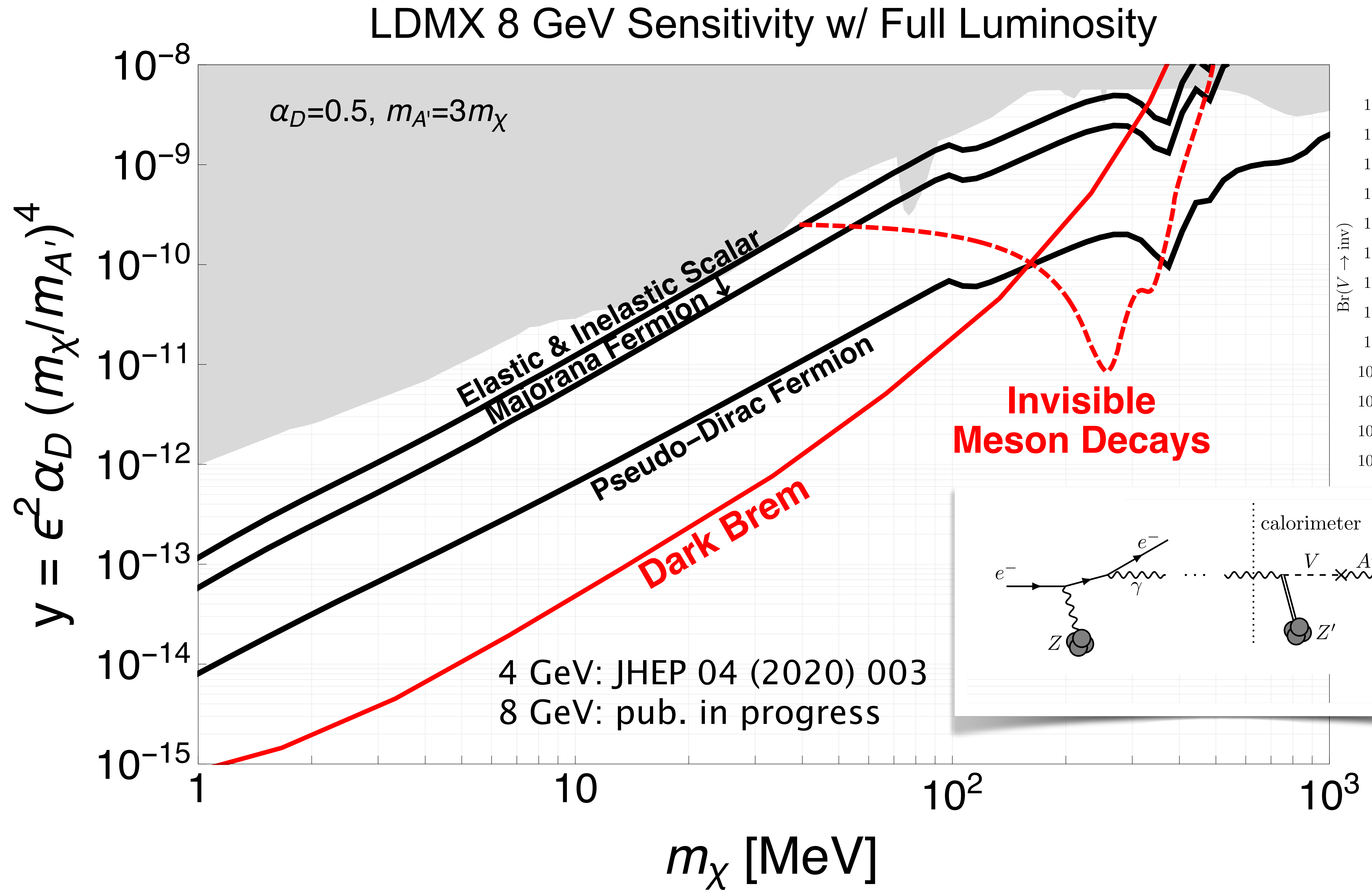
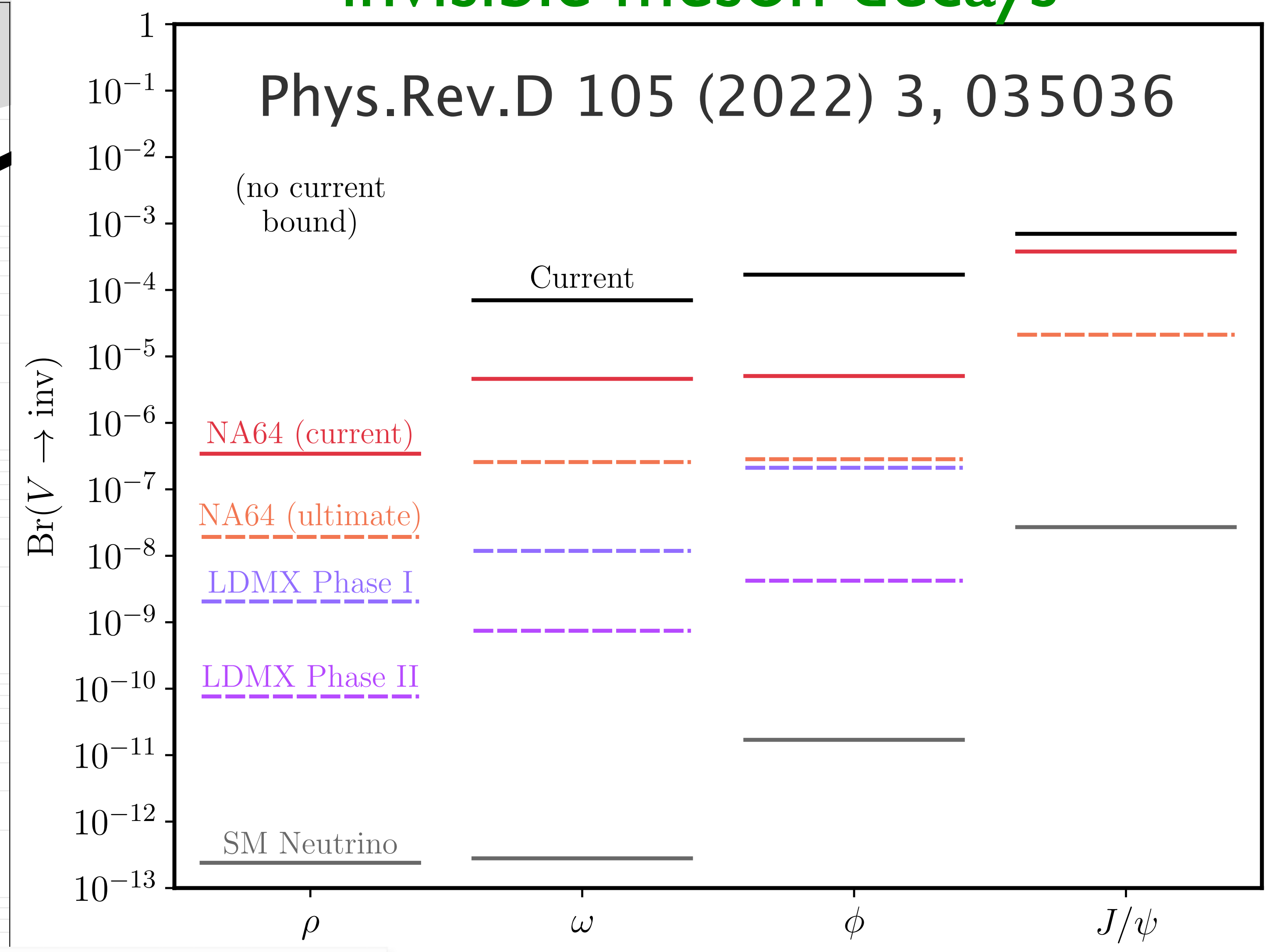


LDMX HCal

LDMX Sensitivity

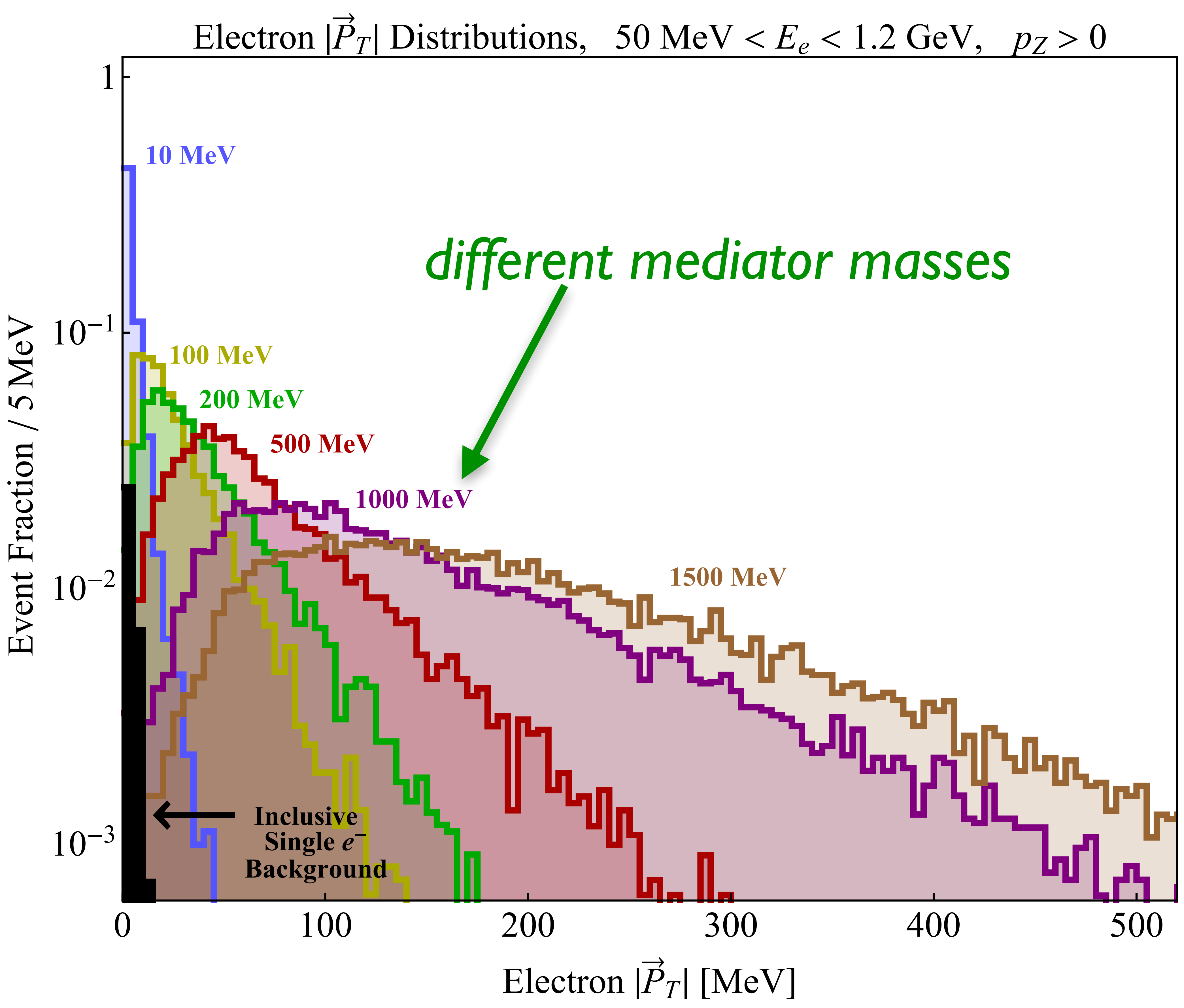


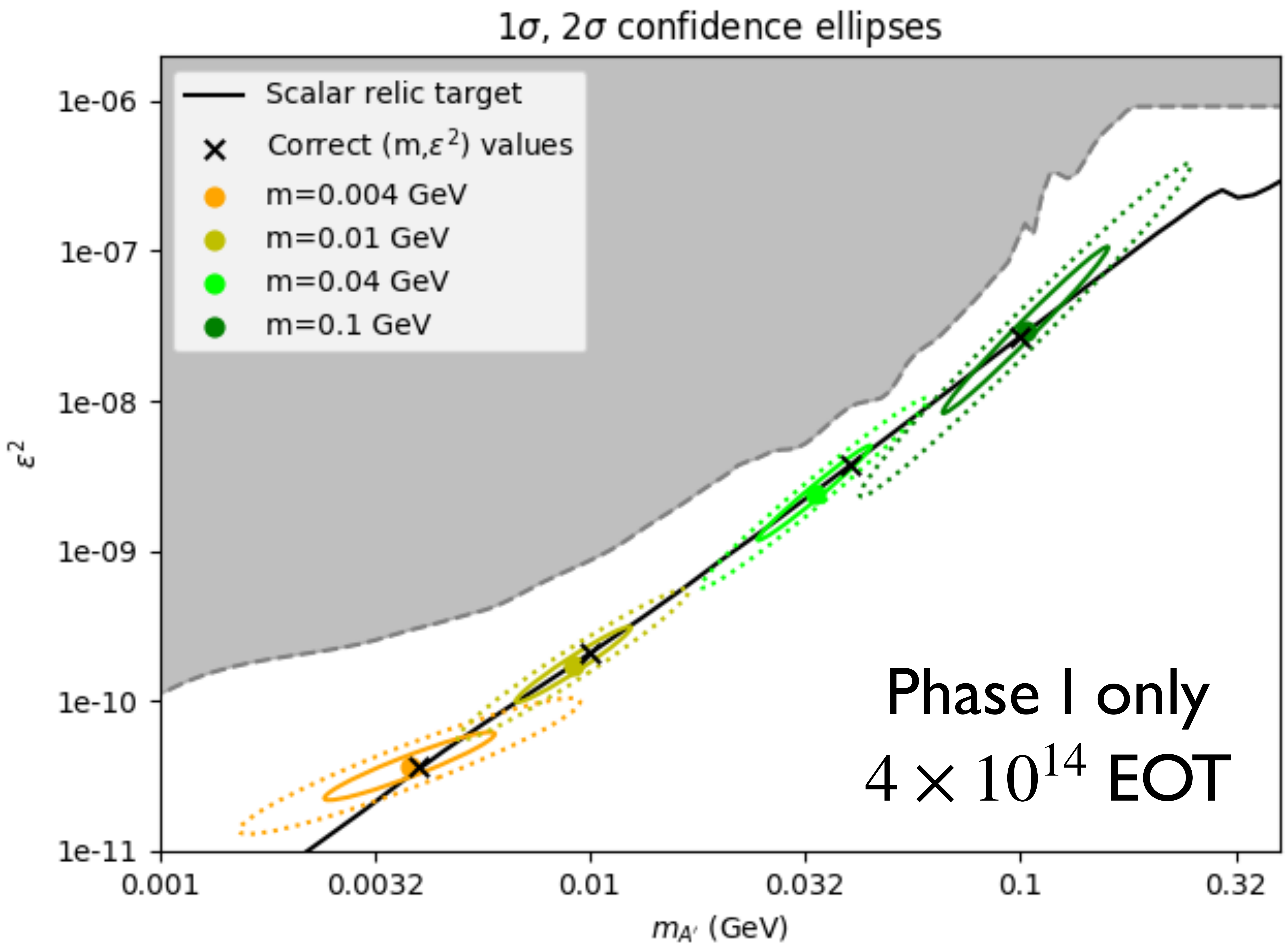
invisible meson decays



probes hadronic couplings in mass range relevant to freeze-out

LDMX Sensitivity



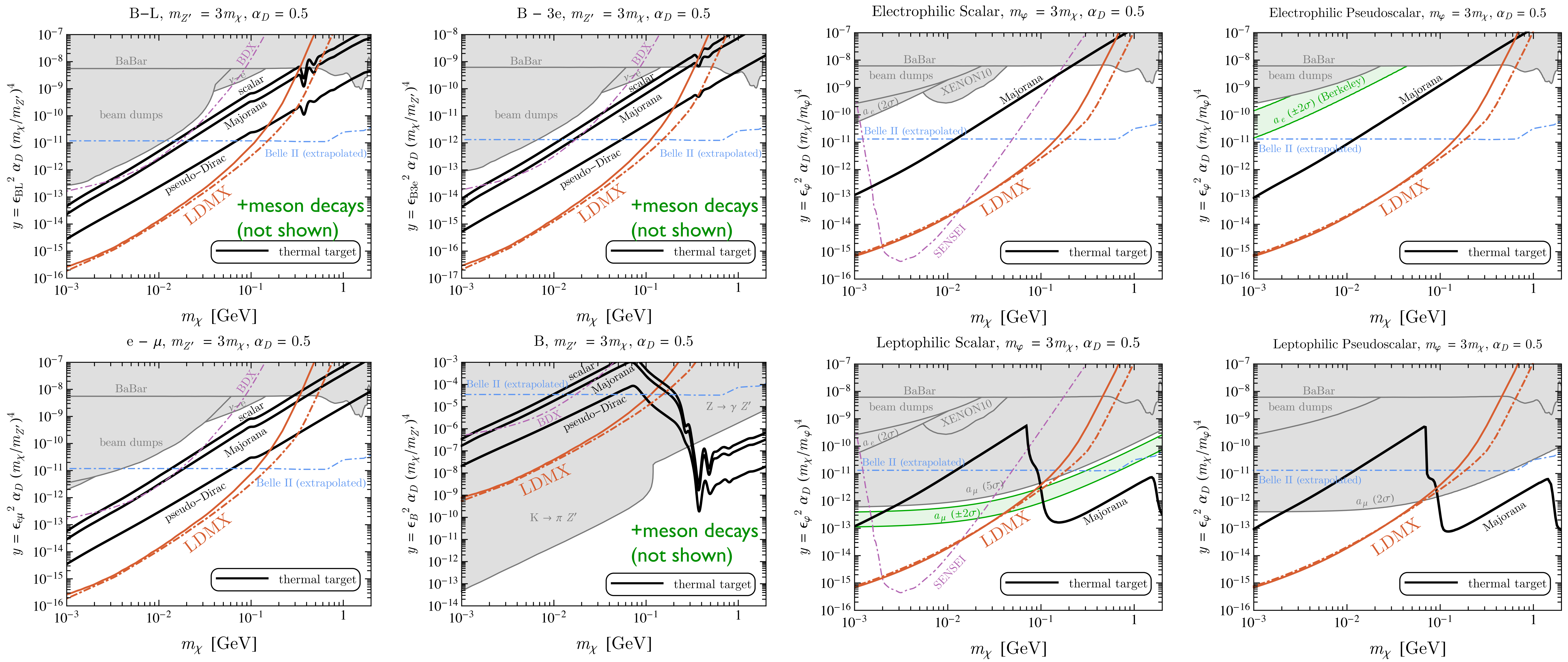


Fit to Δp_T spectrum of recoiling electron allows measurement of mediator mass

LDMX: Broader Physics Case
(other examples in backup)

Invisible Signatures

- different mediators →
- millicharged particles:
  arise from ~massless dark photons and
  thrust into spotlight by EDGES anomaly
- inelastic Dark Matter (iDM):
  large mass-splittings in dark states
- Strongly Interacting Massive Particles (SIMPs):
  a confining interaction in the dark sector
  (both visible and invisible signatures)
- freeze-in DM



Visible Signatures

- Dark Photons
- Axion-like particles (ALPs)

arXiv:1807.01730 [hep-ph]
Phys. Rev. D 99, 075001 (2019)

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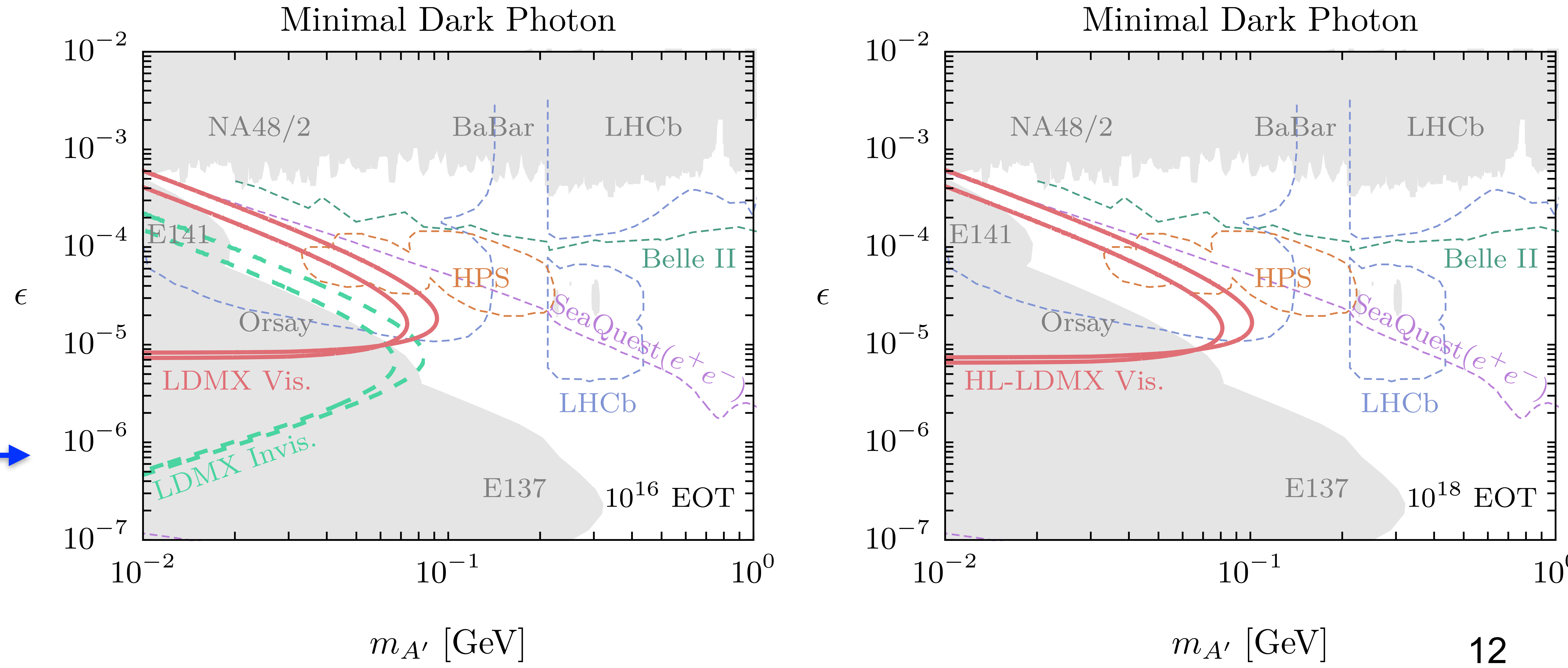

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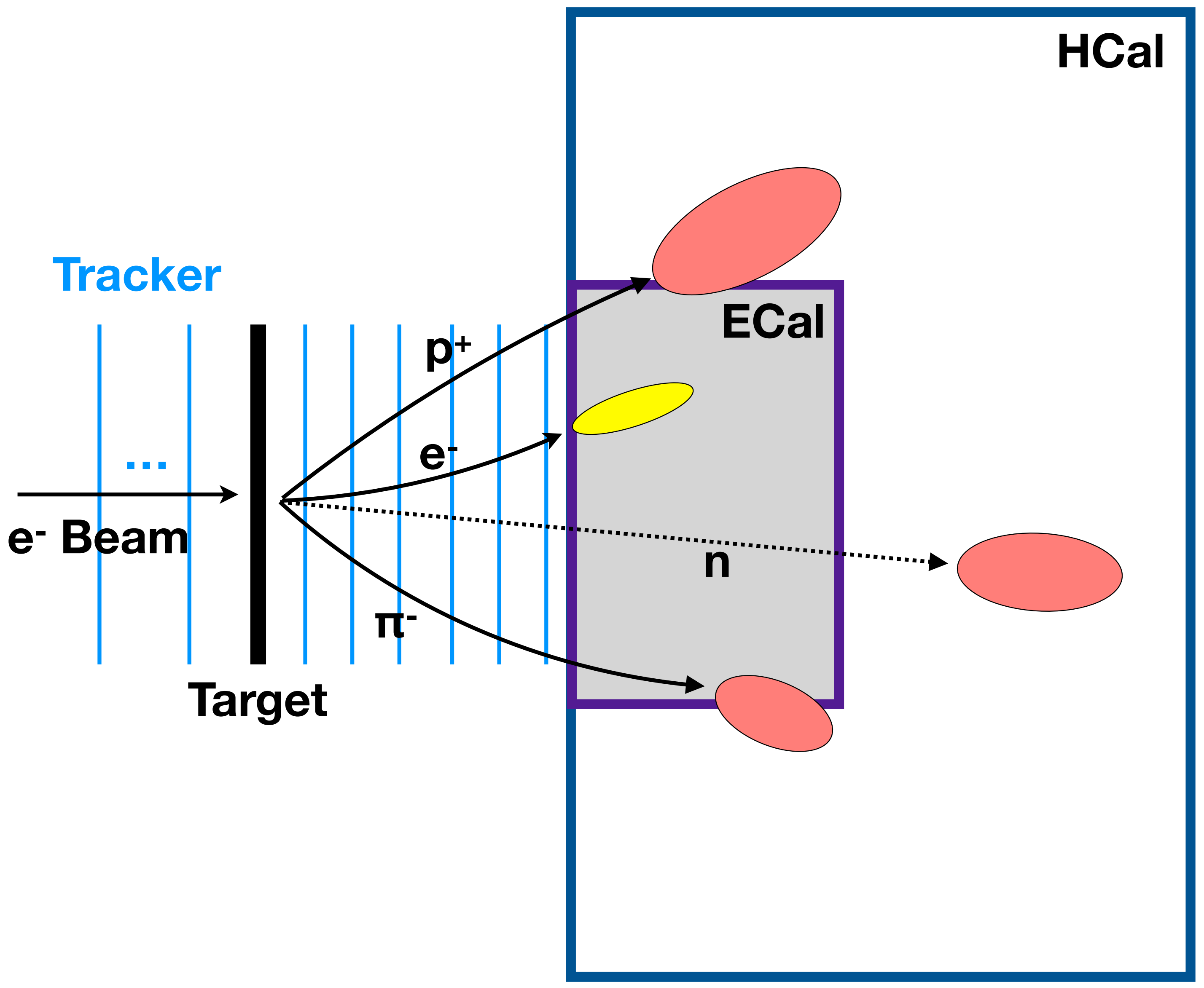
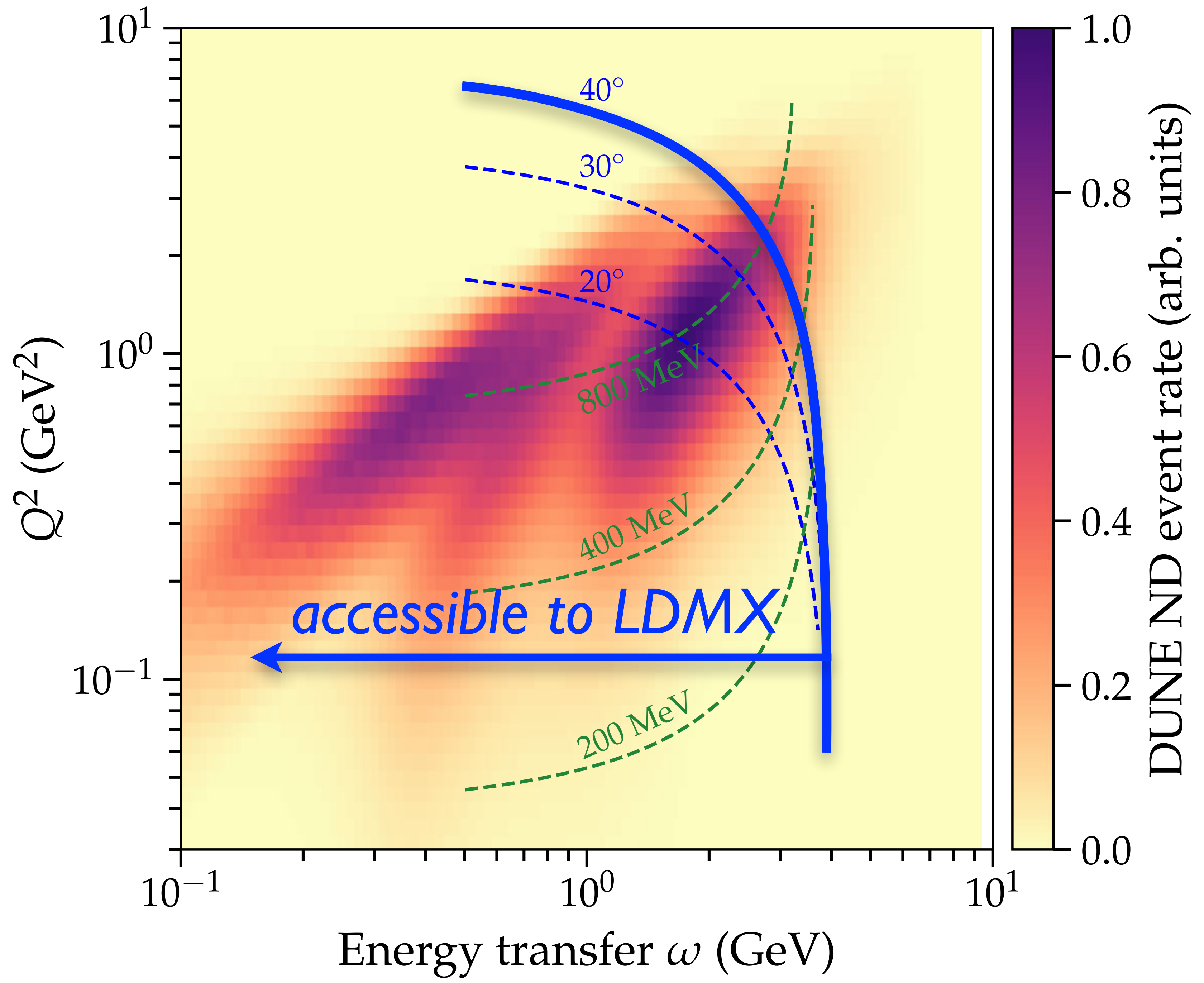
LDMX also enables measurements of electron-nucleon cross-sections that would be critical to the neutrino program





PHYSICAL REVIEW D 101, 053004 (2020)

Status, Budget and Schedule

2018 DMNI Basic Research Needs report identifies1000-fold sensitivity improvement for accelerator experiments for MeV-GeV freeze-out thermal relics as "Thrust 1 of Priority Research Direction 1" and calls out unique capability of electron missing momentum technique to achieve this goal.

2020 LDMX selected for development as a two-year DMNI pre-project, awarded at $1.5 M, currently stretched out through FY24 ($1.55M to date).

LDMX design and project execution plan is mature, design report in draft. We are ready now!

Budget (for FY23 start from FY22 DMNI Review)

Current Cost Estimate for the LDMX Project						
WBS	Item	M&S Total (K$)	Labor Total (K$)	Total (K$)	Cont. (K$)	Total w/ Cont. (K$)
1	LDMX Detector	5,179	8,241	13,420	4,090	18,842
1.1	Beamline	192	842	1,034	504	1,538
1.2	Trigger Scintillator	208	95	303	85	388
1.3	Tracker	541	1,738	2,279	747	3,026
1.4	ECal	1,655	1,151	2,806	717	3,522
1.5	HCal	1,499	906	2,405	654	3,059
1.6	Trigger/DAQ	449	1,887	2,336	748	3,085
1.7	Computing	481	0	481	169	650
1.8	Installation	123	439	562	249	811
1.9	Management	30	1,184	1,214	216	1,430
	Risk Contingency				1,332	1,332

Schedule summary (from FY22 DMNI Review)

- Earliest possible project start in FY25
- Construction and installation in 3 years
  $\Rightarrow$ Operations beginning in FY28
- LDMX will achieve new sensitivity with only weeks of data
- Full luminosity achieved in 5 years

LDMX program can be completed in a decade

Summary

- With modest effort, a program of small experiments can achieve broad sensitivity to particle- and wave-like dark matter below the WIMP mass range, including highly motivated scenarios with specific targets.
- Direct detection and small-scale accelerator based experiments have complementary sensitivity to sub-GeV dark matter, with simple DM freeze-out scenarios implying clear predictions for accelerator signals.
- Freeze out of the observed DM abundance implies DM production at accelerators with interaction strengths within reach of a missing momentum search for DM production with ~10^{16} electrons.
- LDMX is a missing momentum search for production of dark matter with definitive discovery potential for MeV-GeV freeze-out thermal relics and the ability to explore the properties of the dark sector.
- LDMX also has groundbreaking sensitivity for DM candidates with other thermal histories and dark sector physics beyond DM. In addition, LDMX does important "bread-and-butter" physics for the neutrino program.
- LDMX deploys technologies developed for other experiments and free electron beam provided by LCLS-II to realize the experiment with minimal risk and cost
- An endorsement of these smaller experiments is very important to the DM search program, where specific efforts with high scientific impact should be called out regardless of scale.

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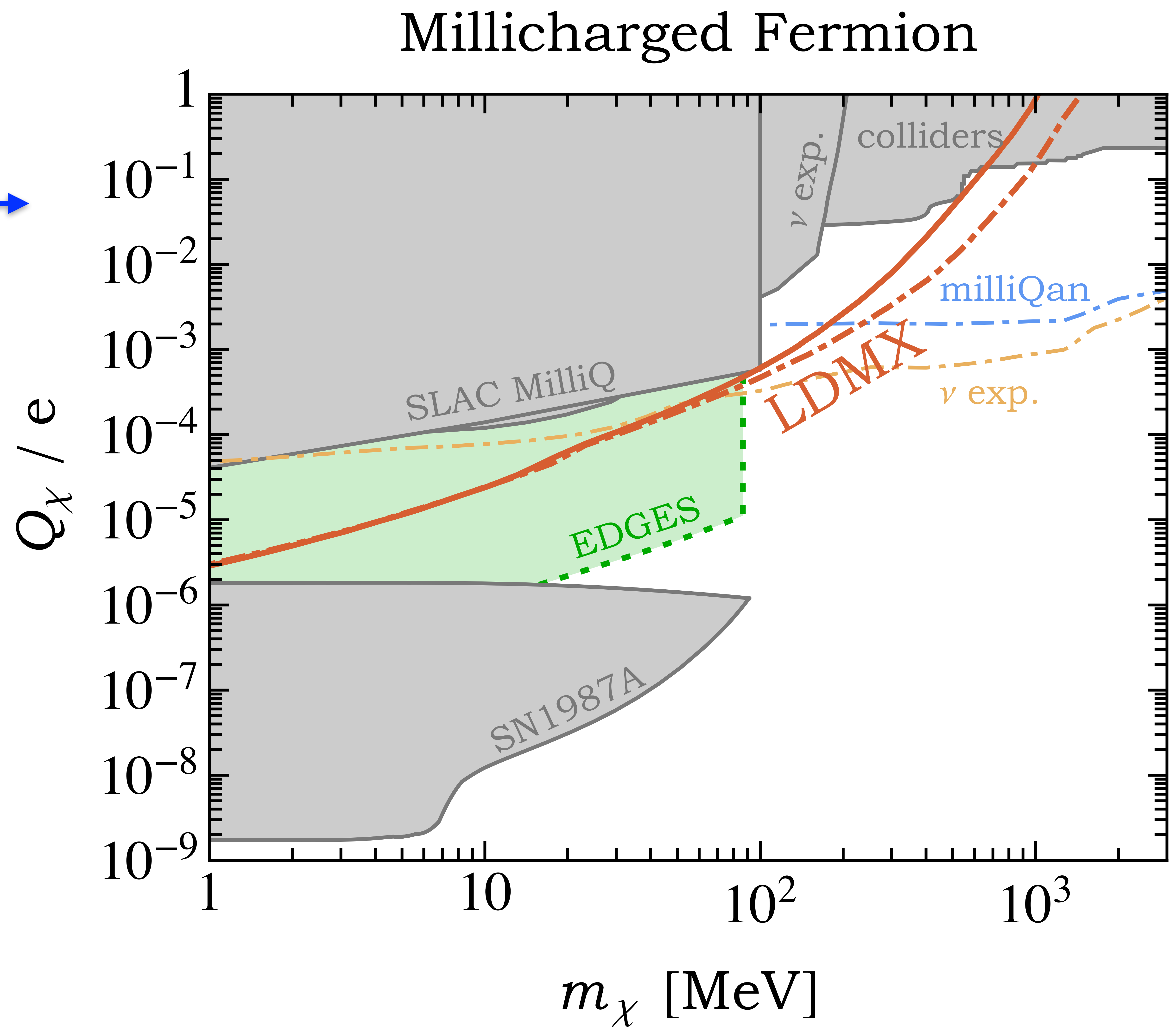

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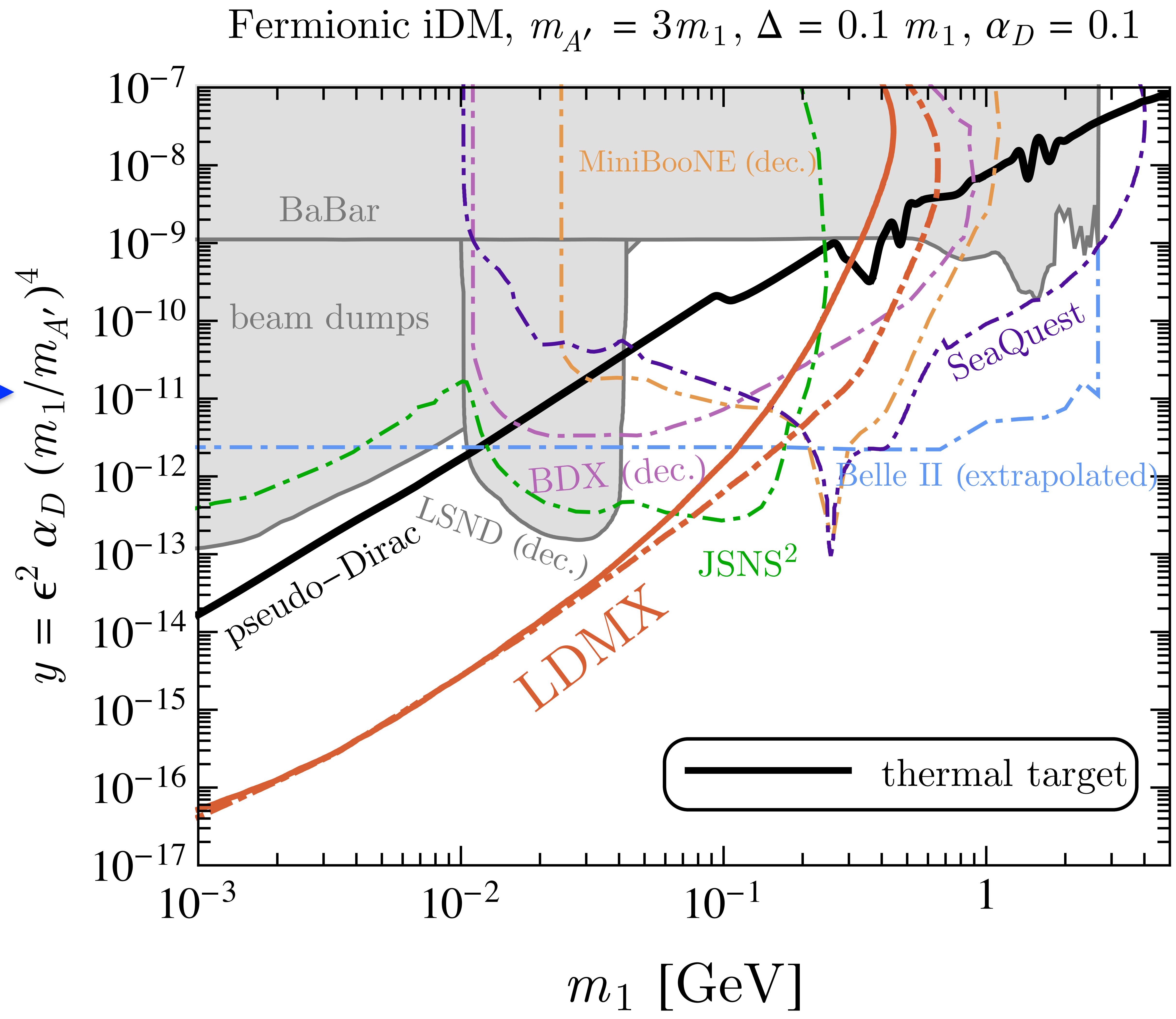

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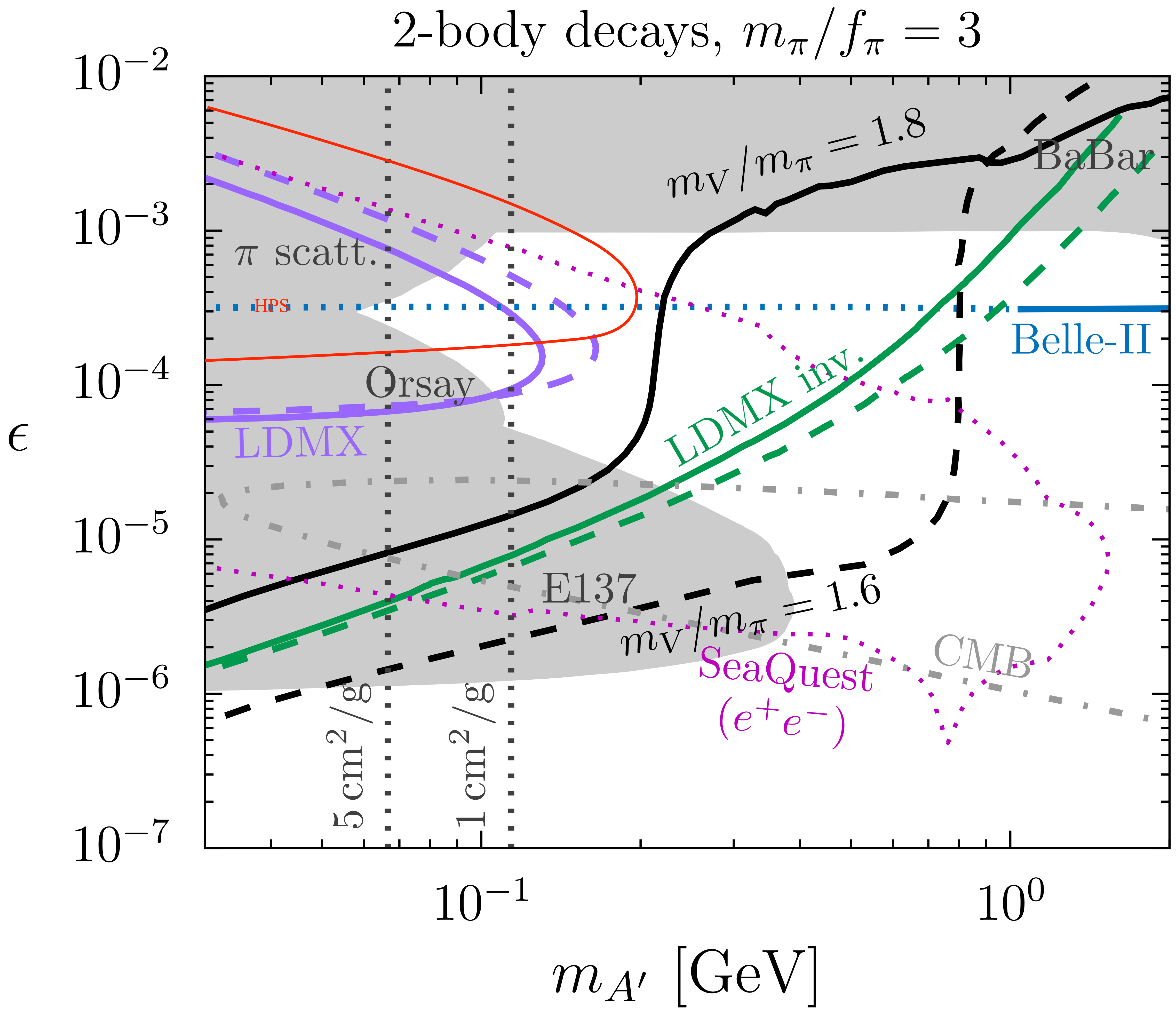

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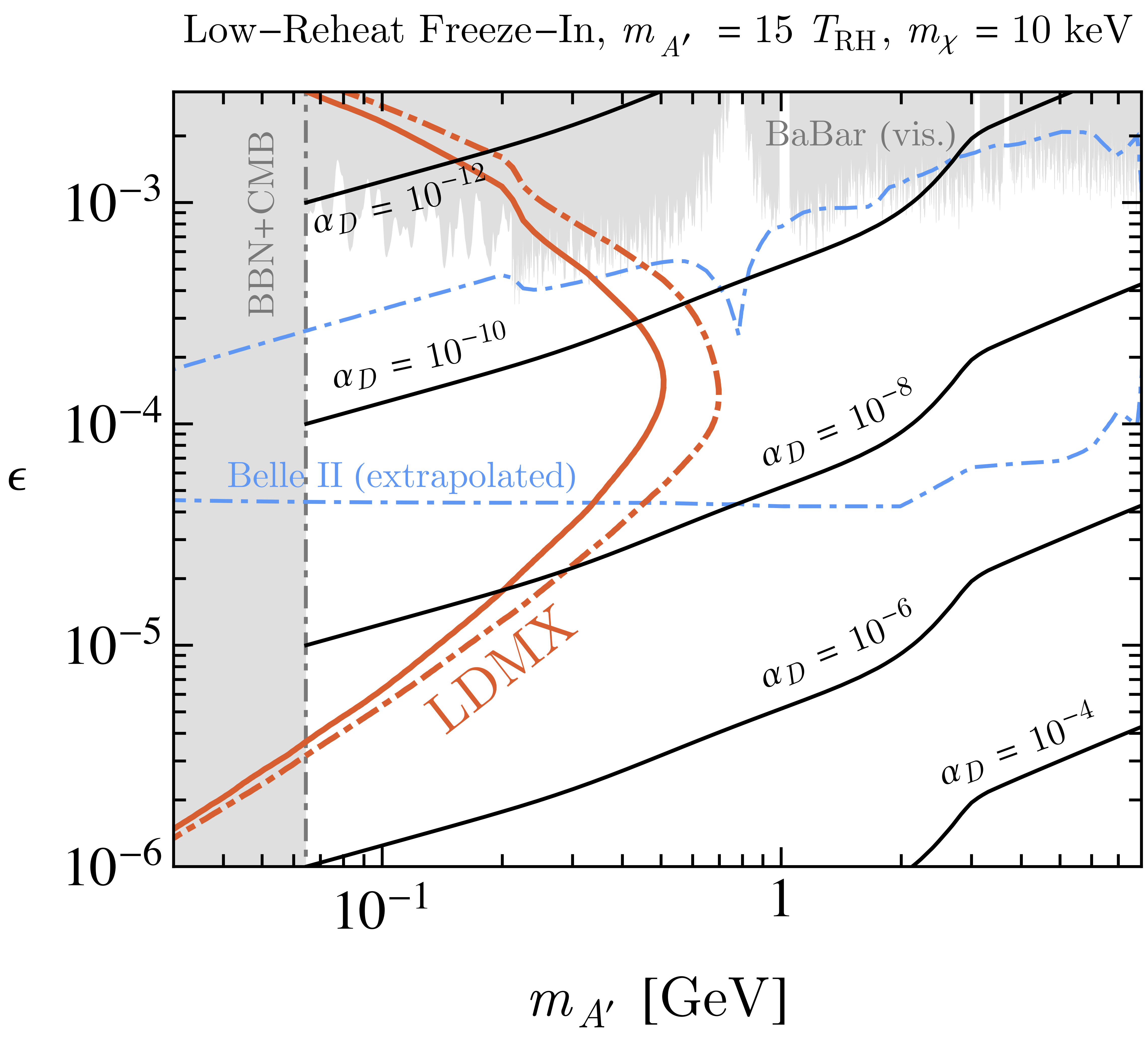

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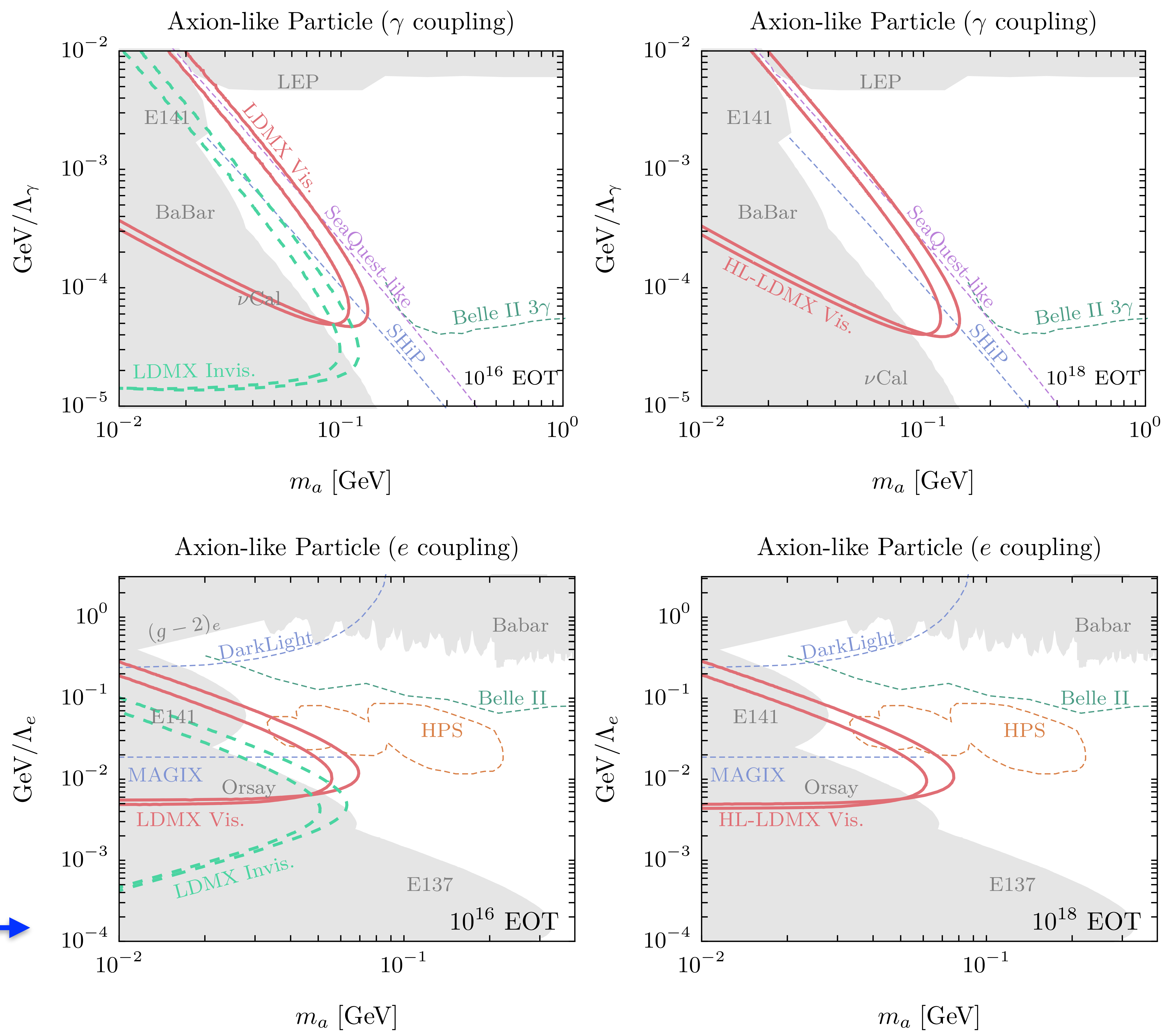


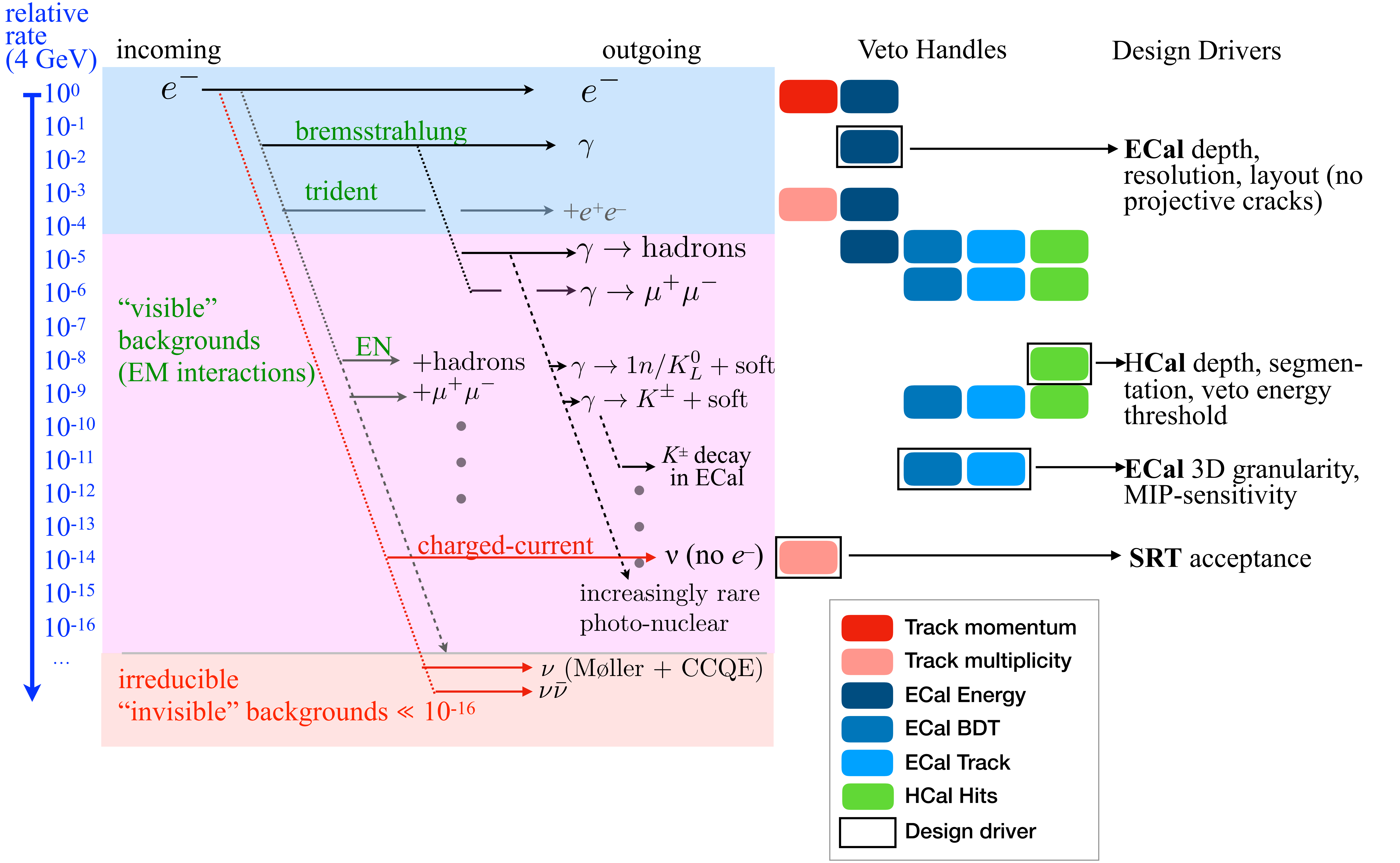
arXiv:1807.01730 [hep-ph]
Phys. Rev. D 99, 075001 (2019)

Missing Momentum Design Drivers: Backgrounds

Gaussian energy fluctuations

Rare reactions → products escape ECal and/or anomalous energy deposition

Irreducible prompt $\not{E}$

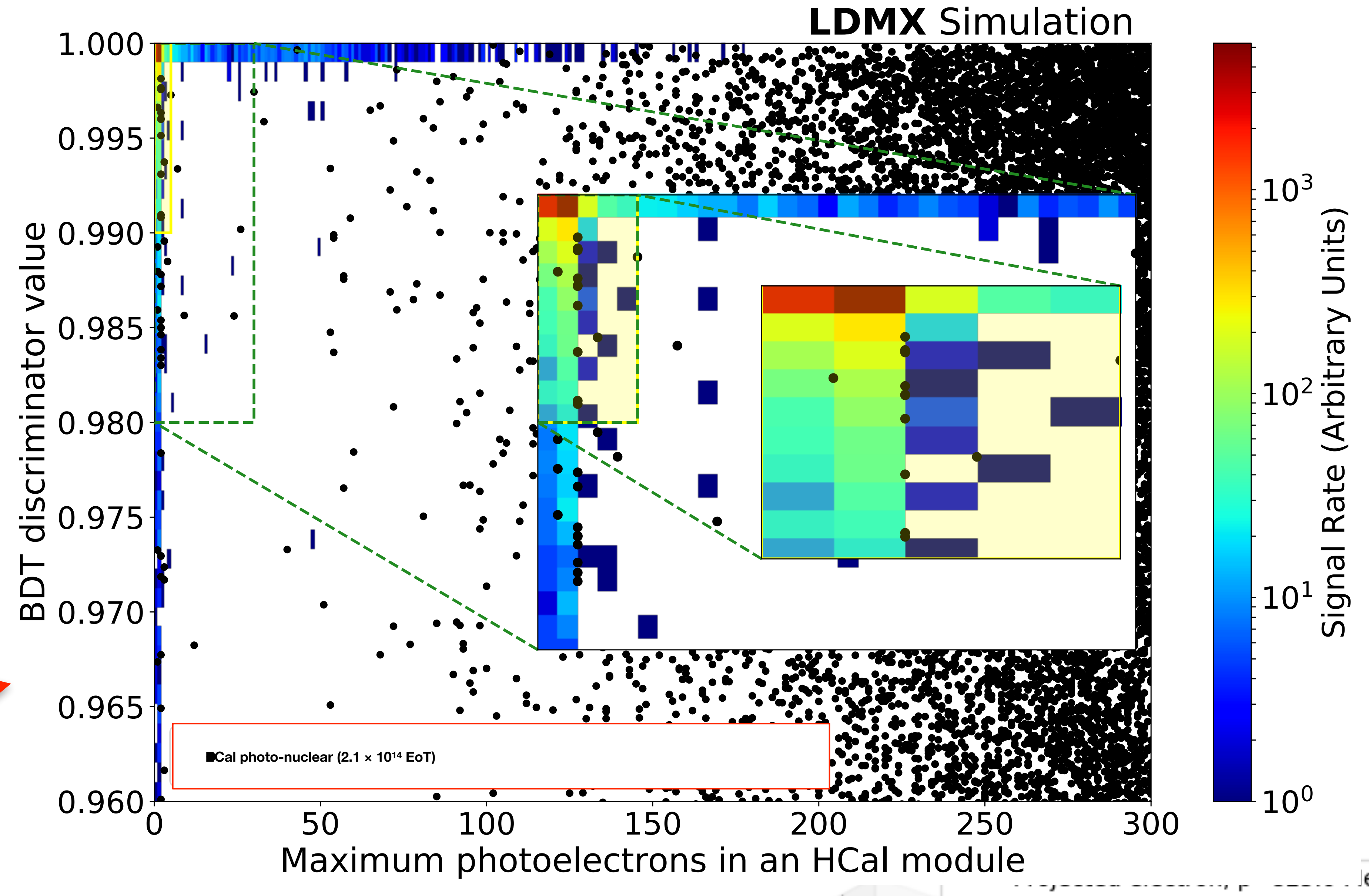


LDMX Phase I Sensitivity (4 GeV)

Initial LCLS-II operation provides 4 GeV beam,
1 year ≈ 4000 hours operation $\Longrightarrow$ 4×10¹⁴ e⁻

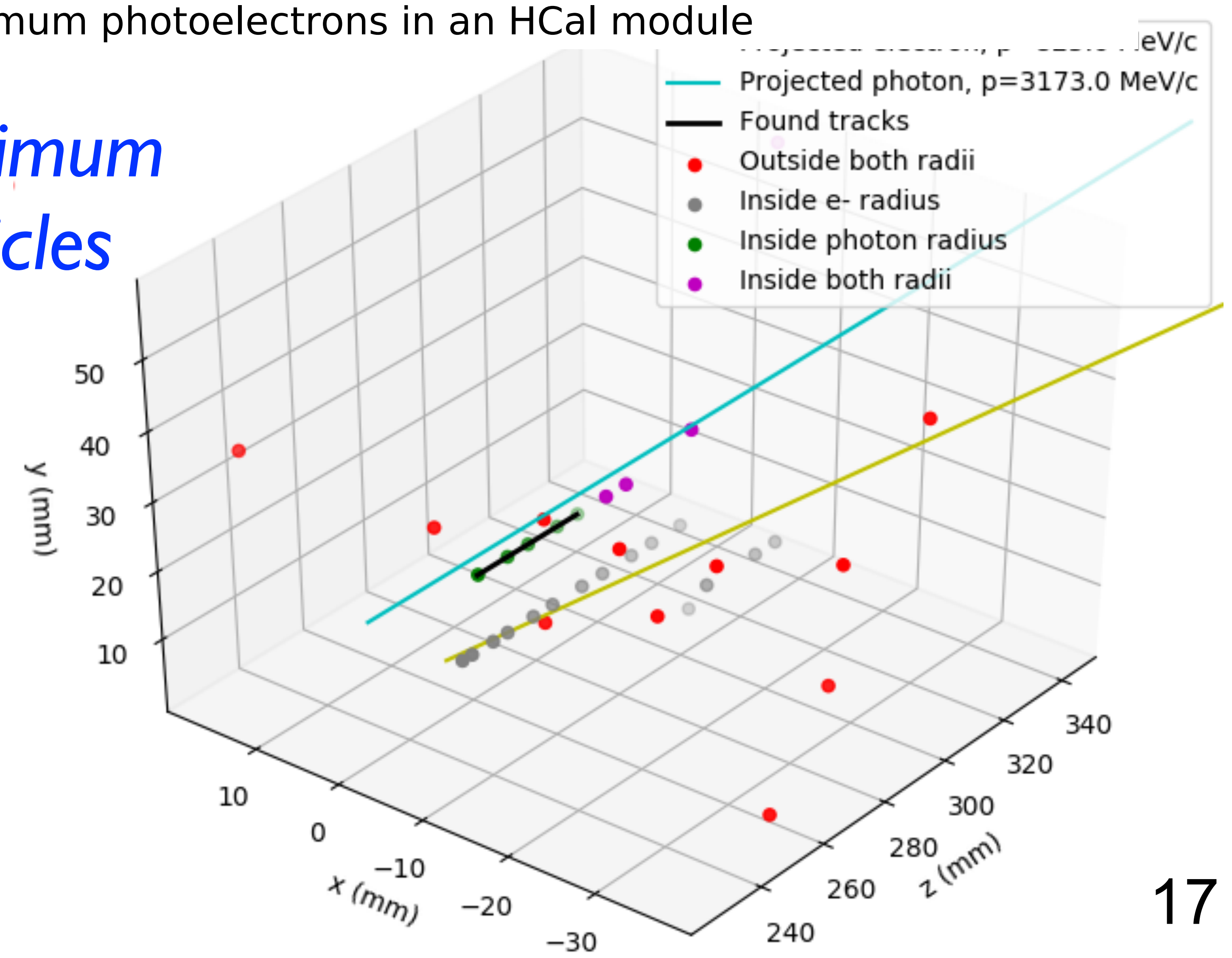
Analysis strategy developed on full simulation JHEP 04 (2020) 003

	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



- have put major development work into GEANT 4 photonuclear modeling: also studying variation among simulation tools (FLUKA, PHITS, MCNP)
- p_T can always be used to eliminate remaining backgrounds but also allows reconstruction of mediator mass
- Most difficult backgrounds strongly suppressed with 8 GeV beam

Tracking minimum ionizing particles in ECal



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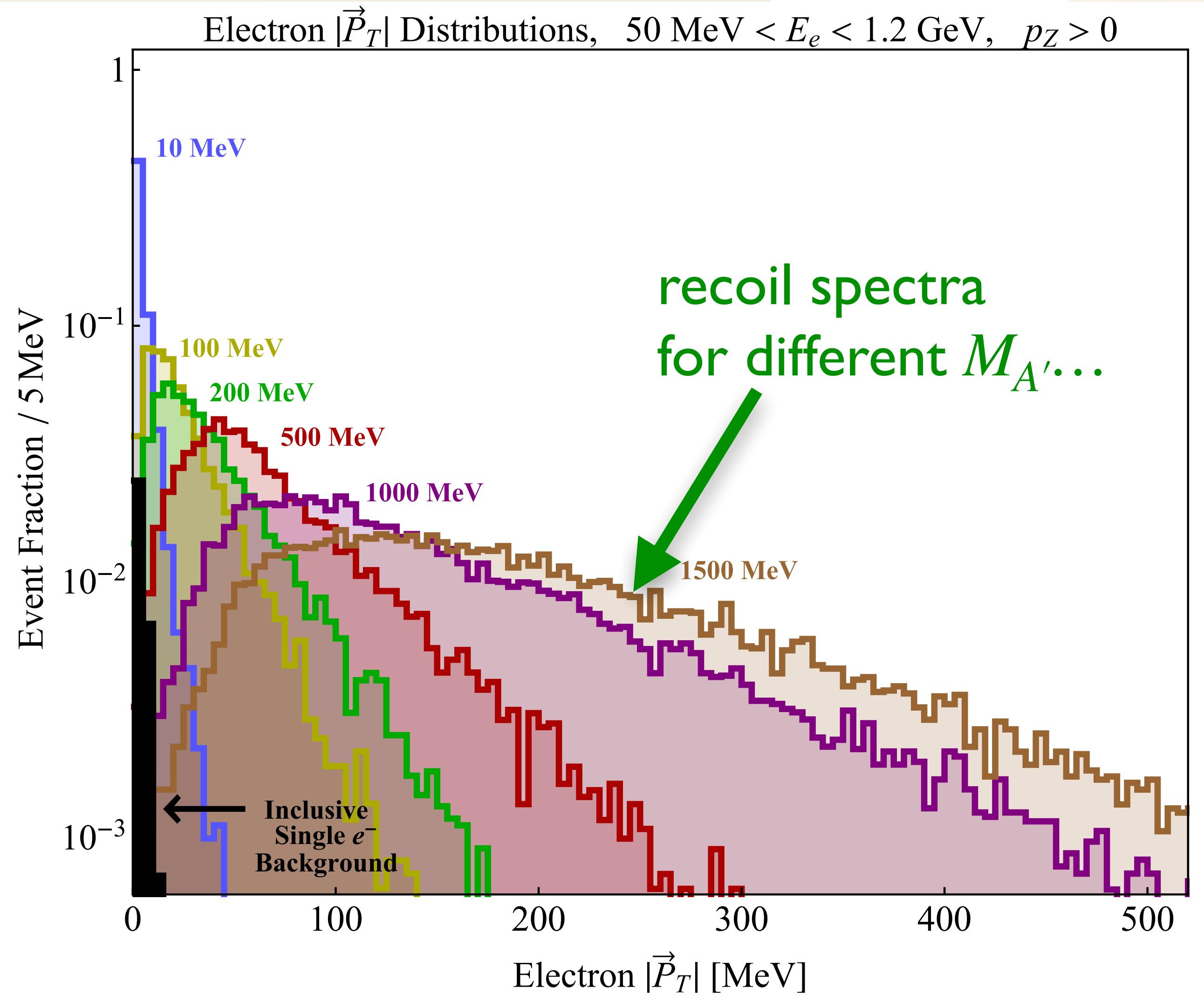

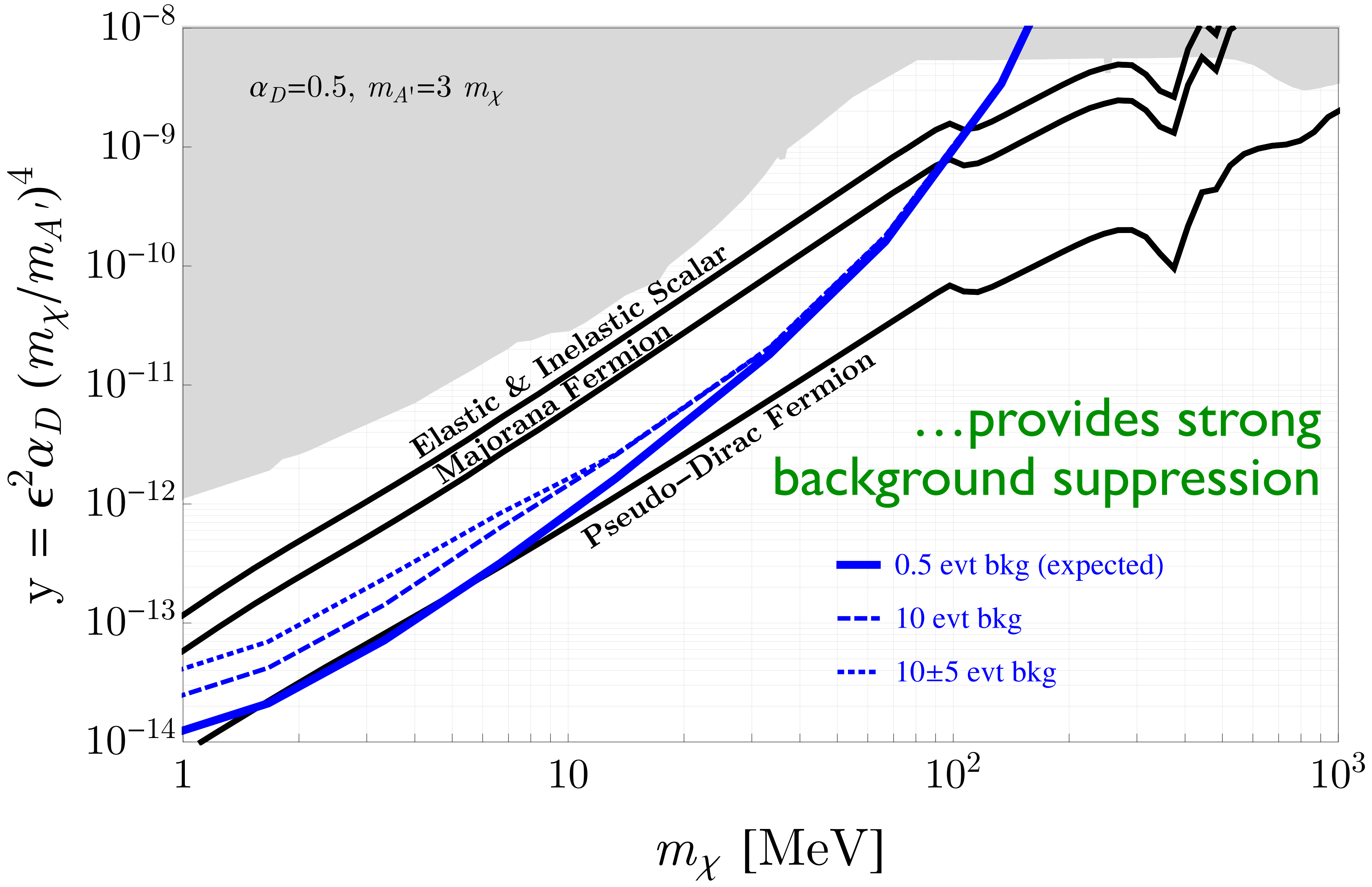

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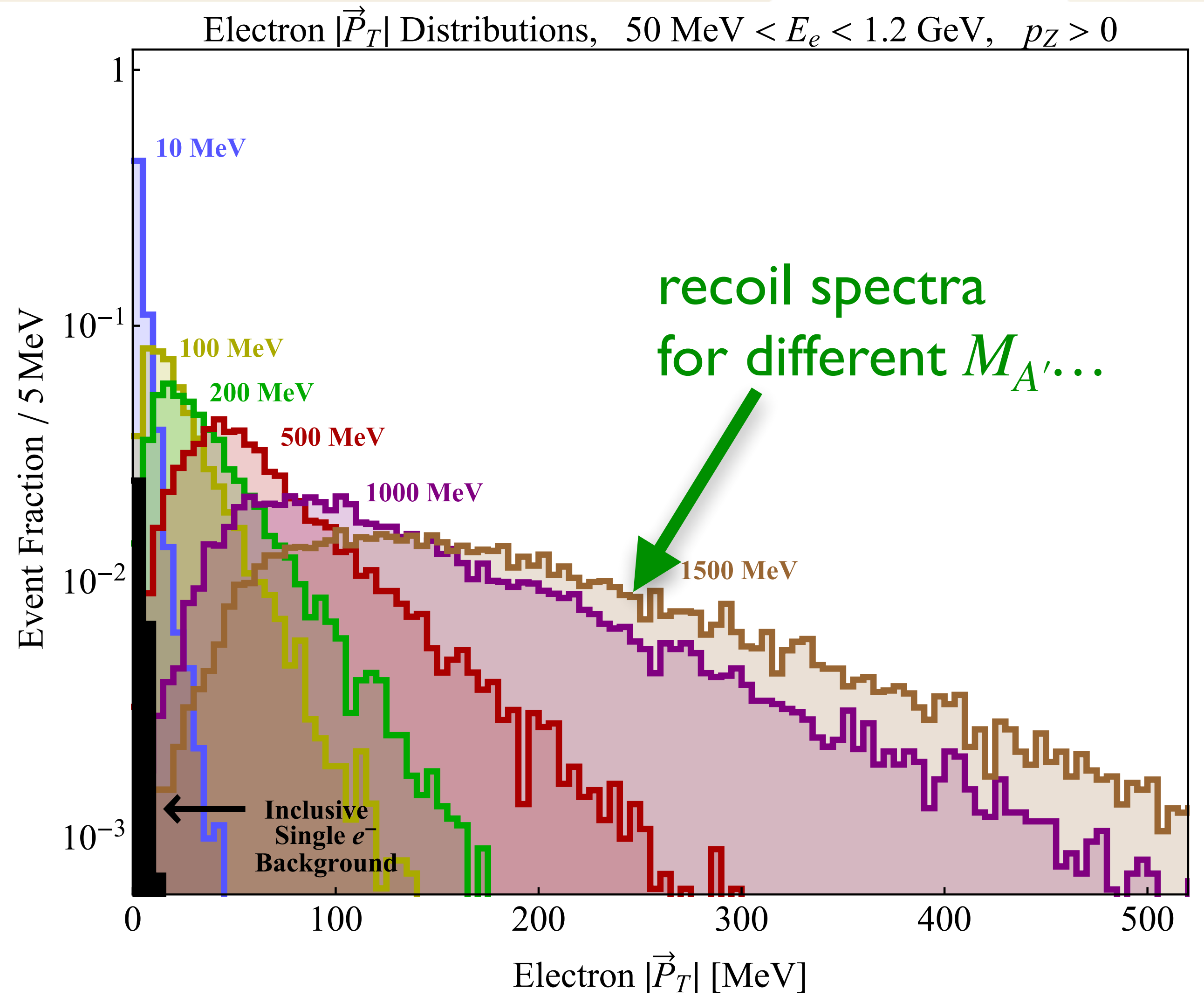
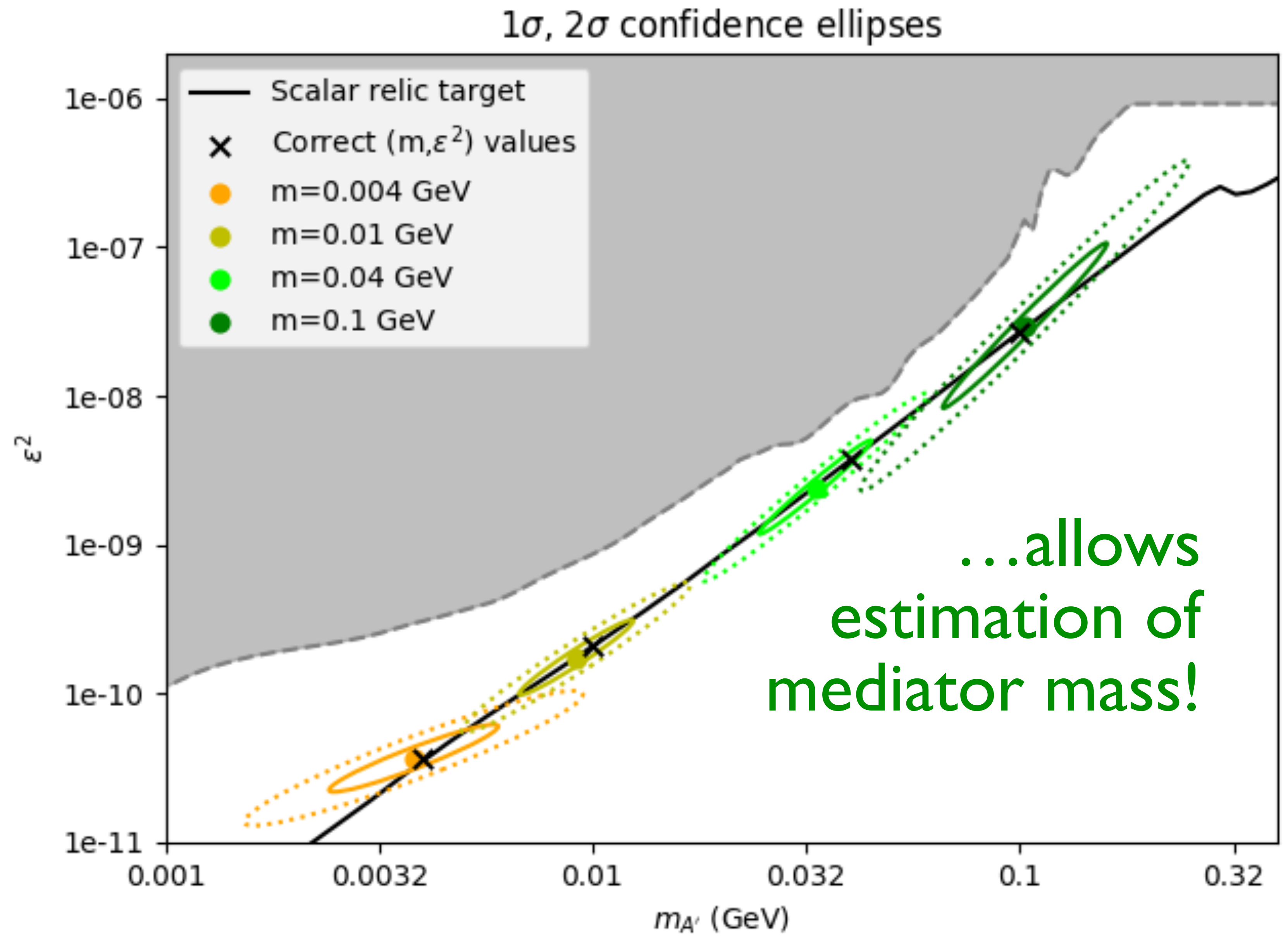
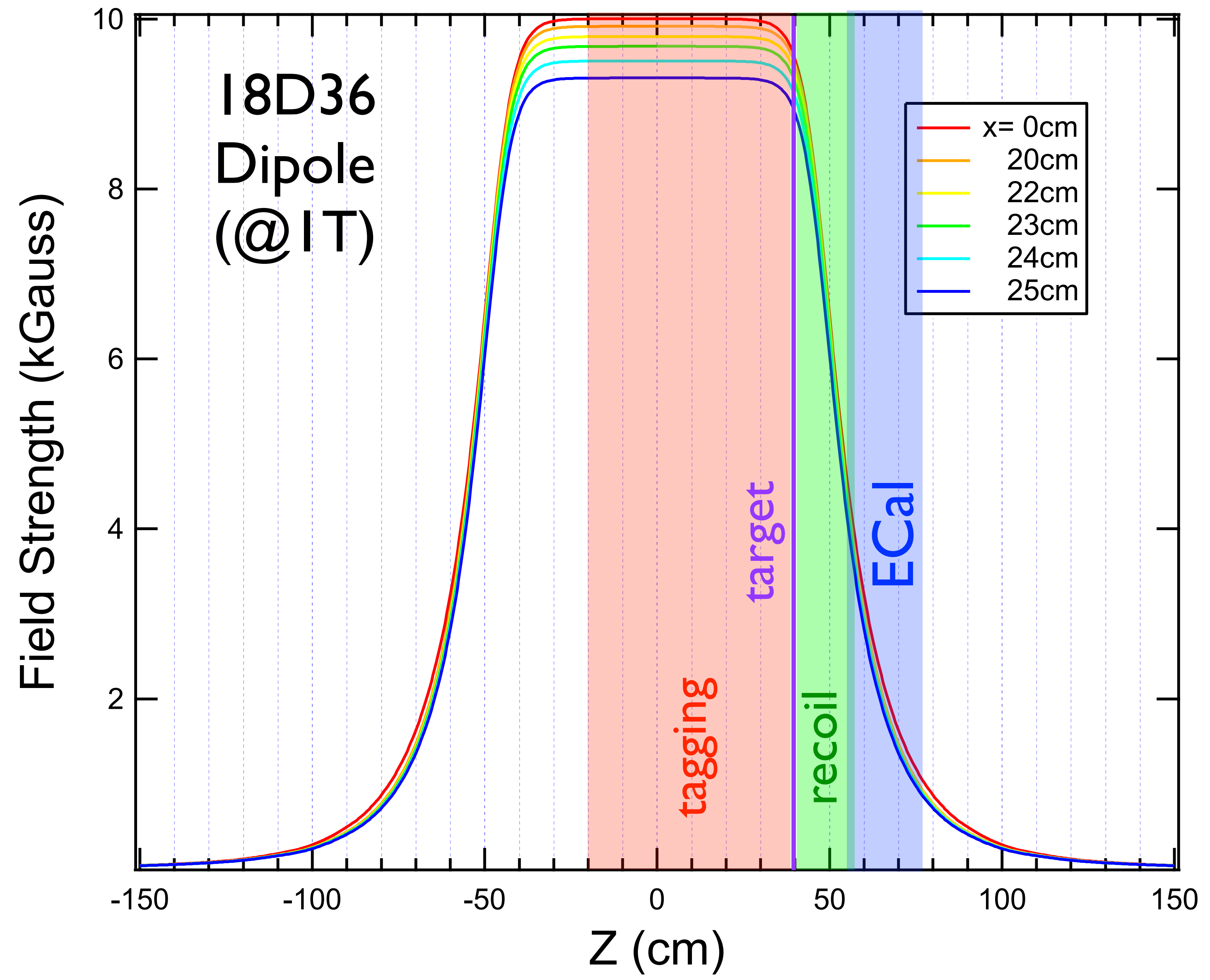




LDMX Subsystems and Technology Choices

WBS 1.1 – Beamline and Magnet: (SLAC core competency)

- final section of beam pipe with vacuum window
- common dipole magnet provides high(low) field for incoming(recoiling) e^-



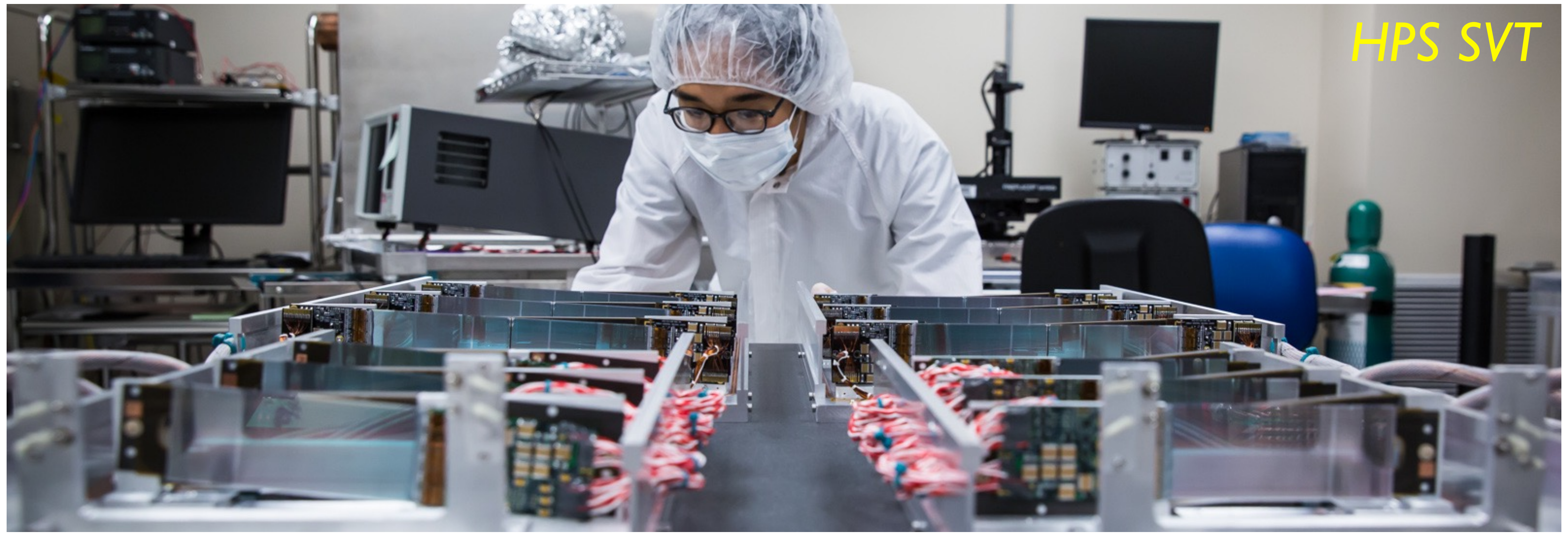
WBS 1.3 – Trackers: (from HPS Silicon Vertex Tracker built at SLAC)

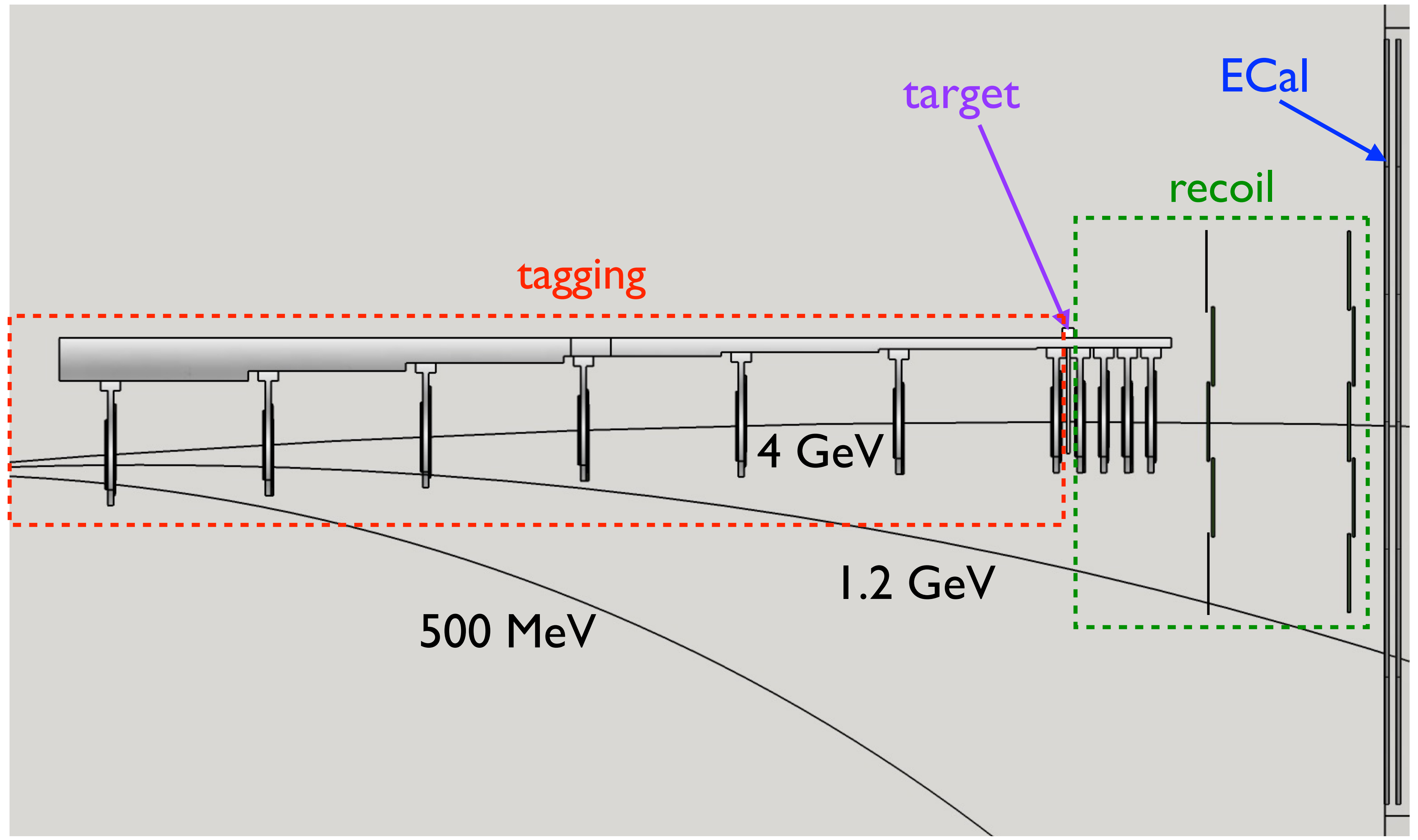
Tagging Tracker: long, narrow, in uniform 1.5 T field for p_e = 4 GeV

- 7 double-layers provide robust tag of incoming electrons

Recoil Tracker: short, wide, in fringe field for p_e = 0.05 - 1.2 GeV

- 4 double-layers + 2 axial-only layers provide good acceptance, Δp_T resolution limited by multiple scattering in target

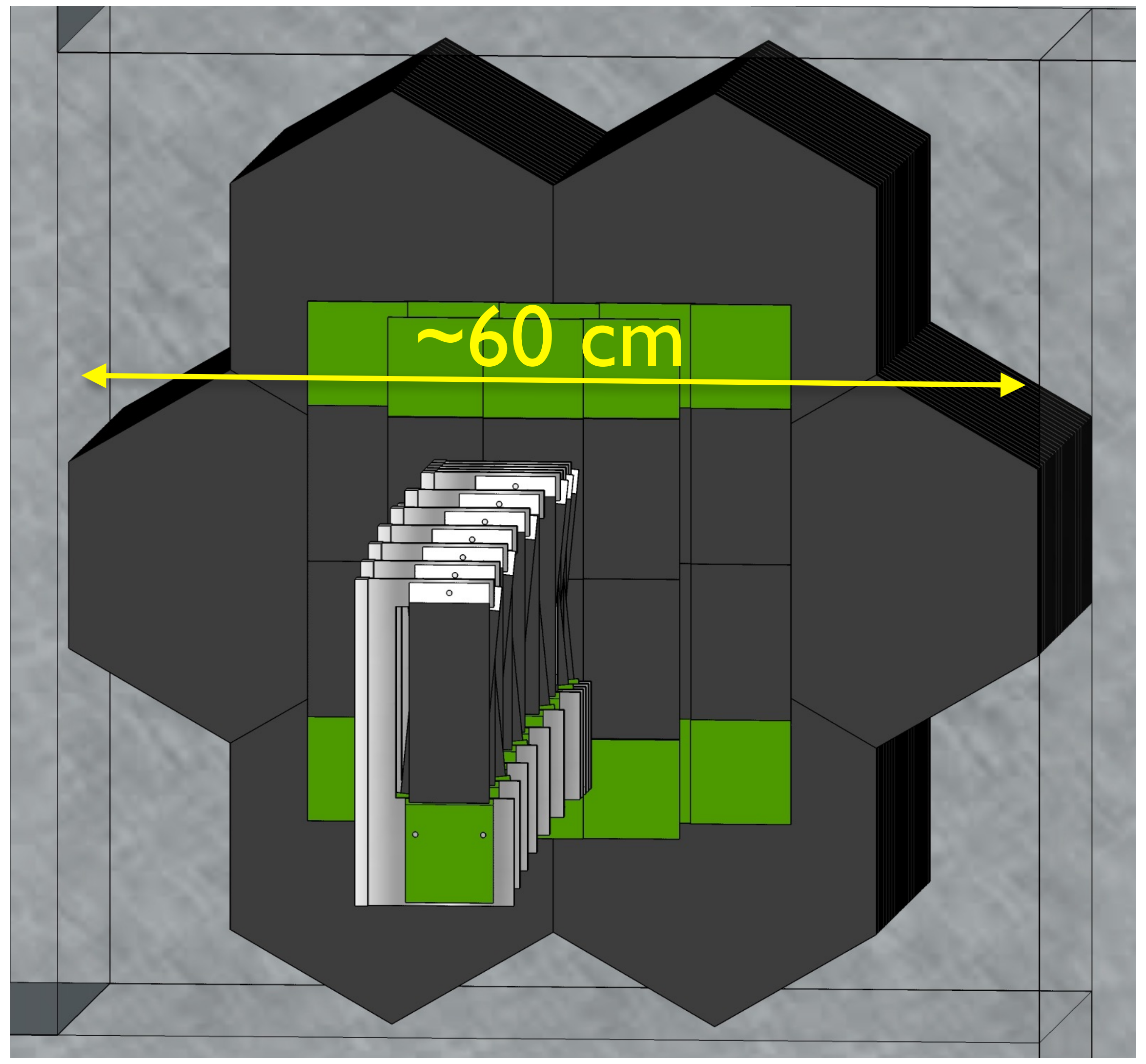


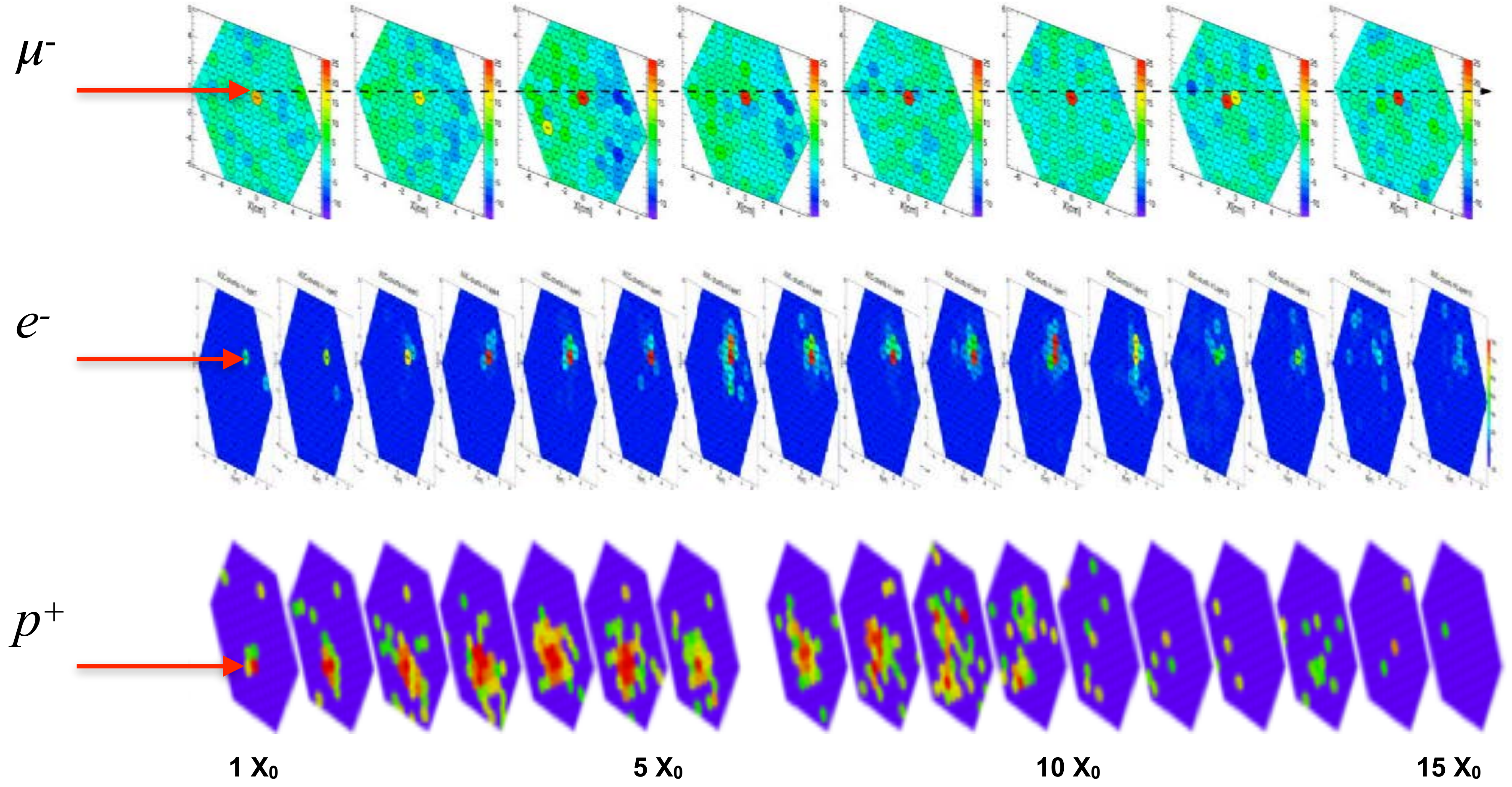


LDMX Subsystems and Technology Choices

WBS 1.4 – ECal: from CMS HGCal (UCSB – Incandela, U. Minn. – Mans)

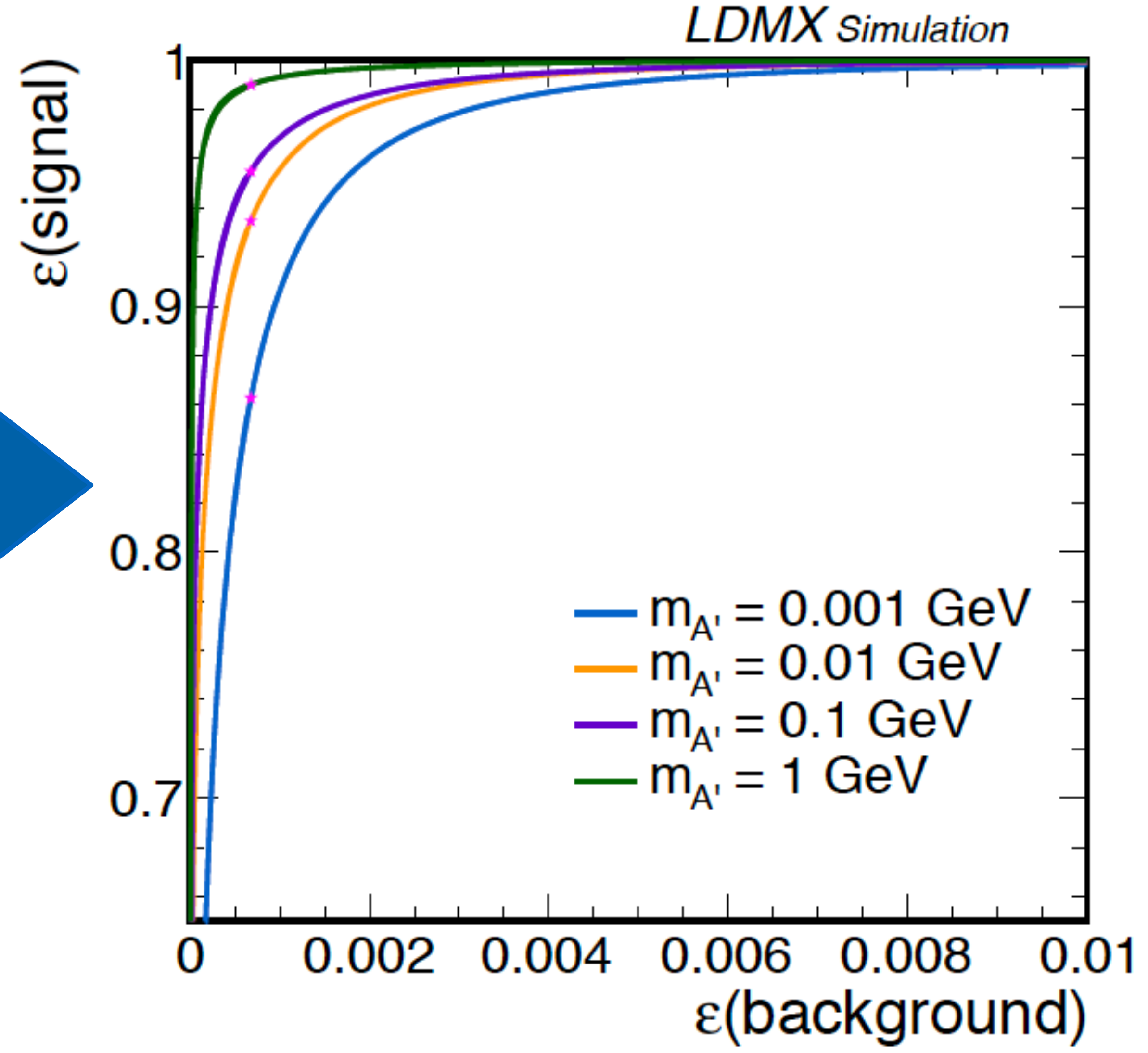
- Si-W sampling calorimeter: fast, dense, high radiation tolerance
- 40 X_0 deep: excellent containment of EM showers
- Granularity and MIP sensitivity: imaging and MIP tracking are powerful for rejecting rare backgrounds (e.g. photonuclear reactions and $\gamma \rightarrow \mu\mu$)
- designed to provide fast trigger (here using ECal energy < 0.3 E_{beam})

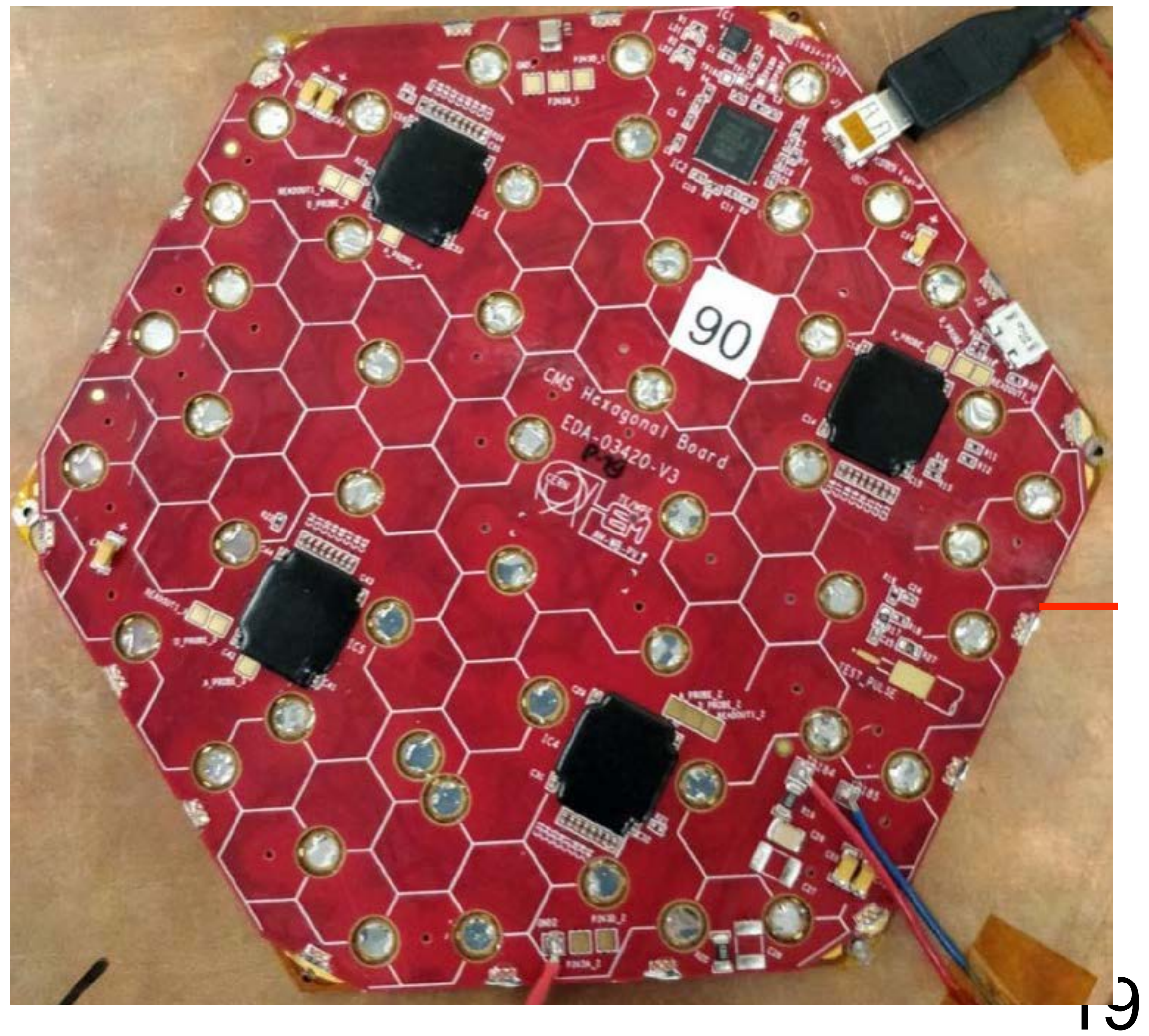




CERN Test Beam Data

Boosted Decision Tree

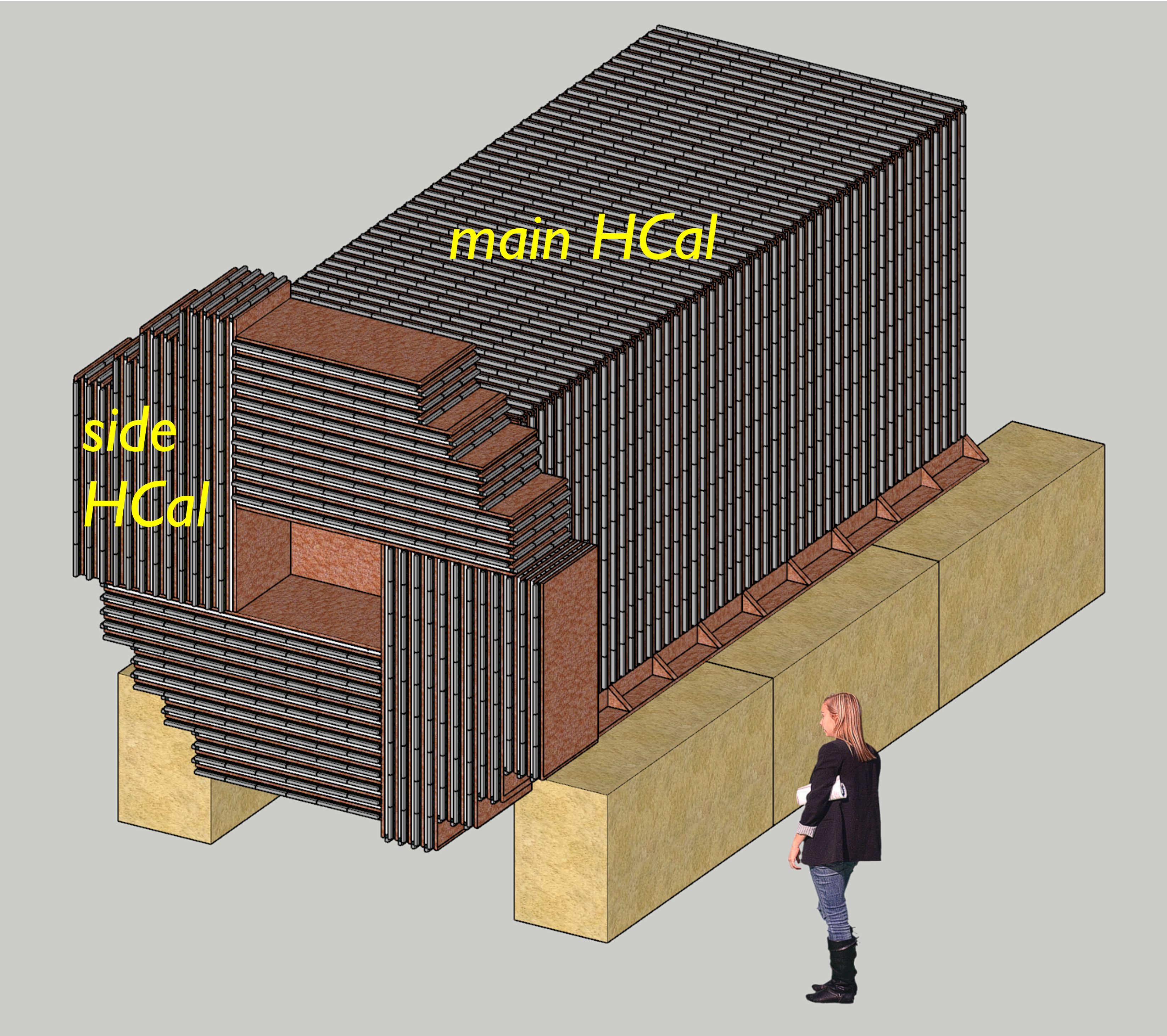


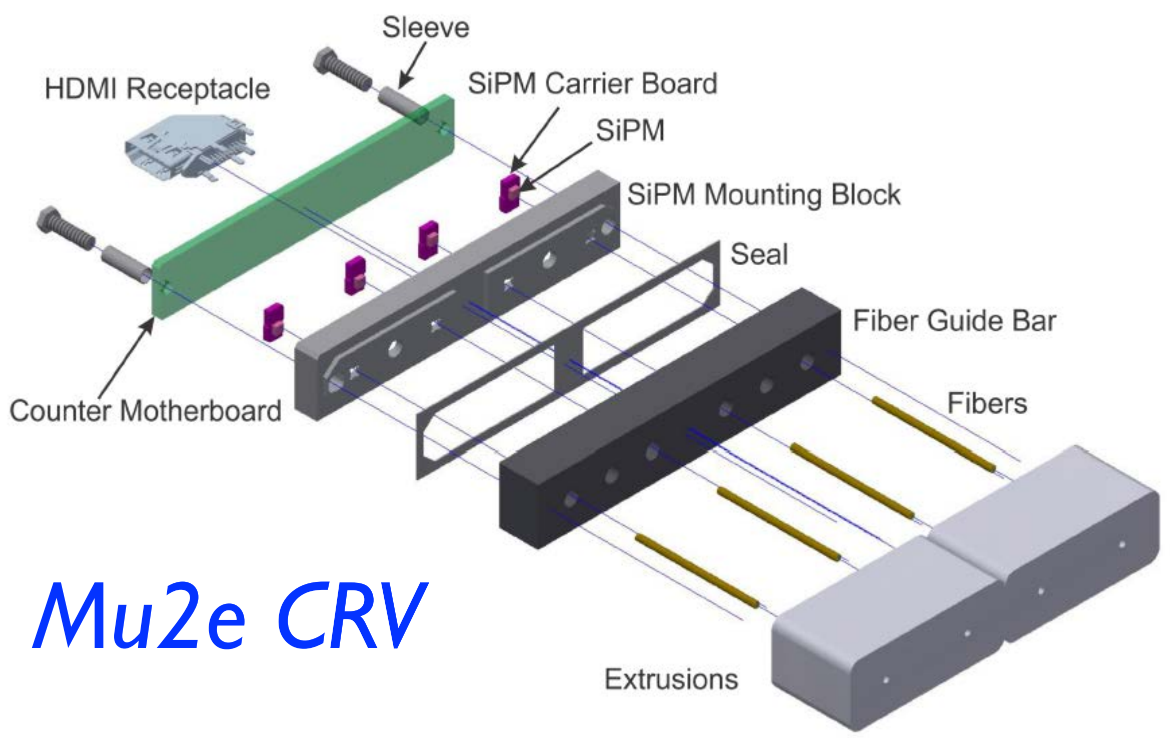


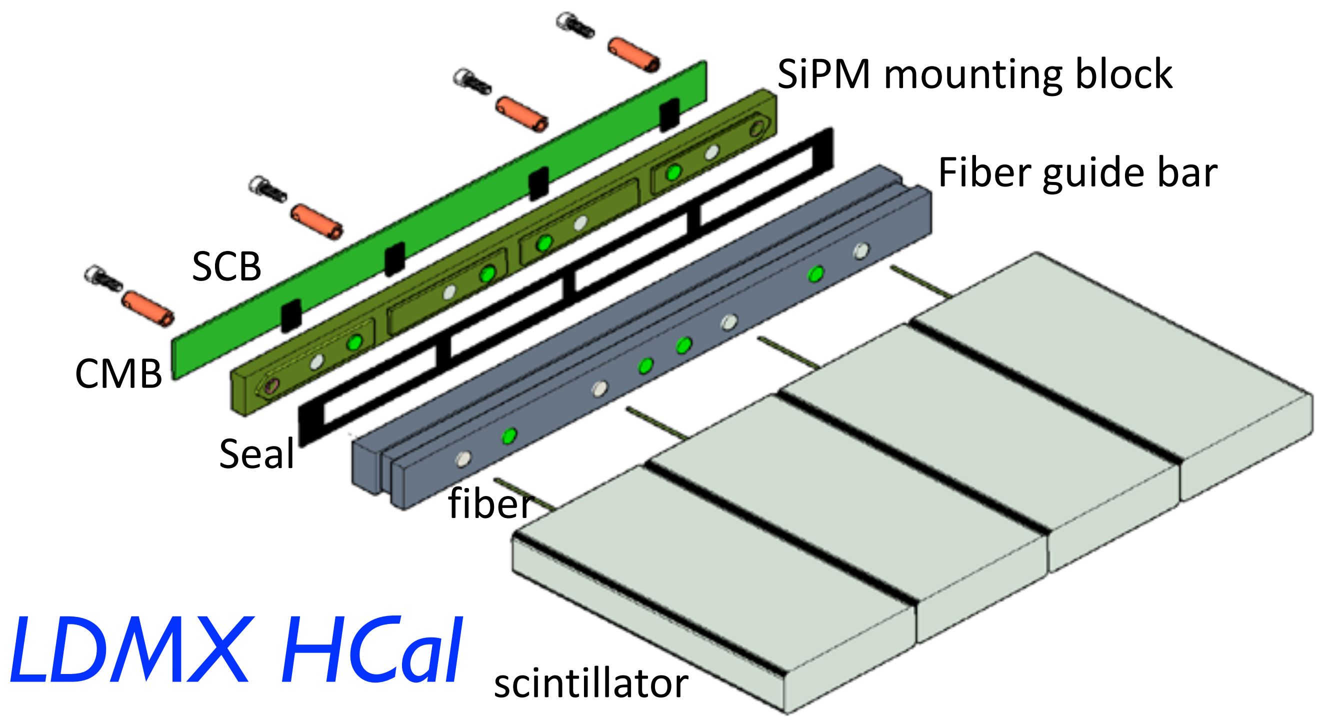
LDMX Subsystems and Technology Choices

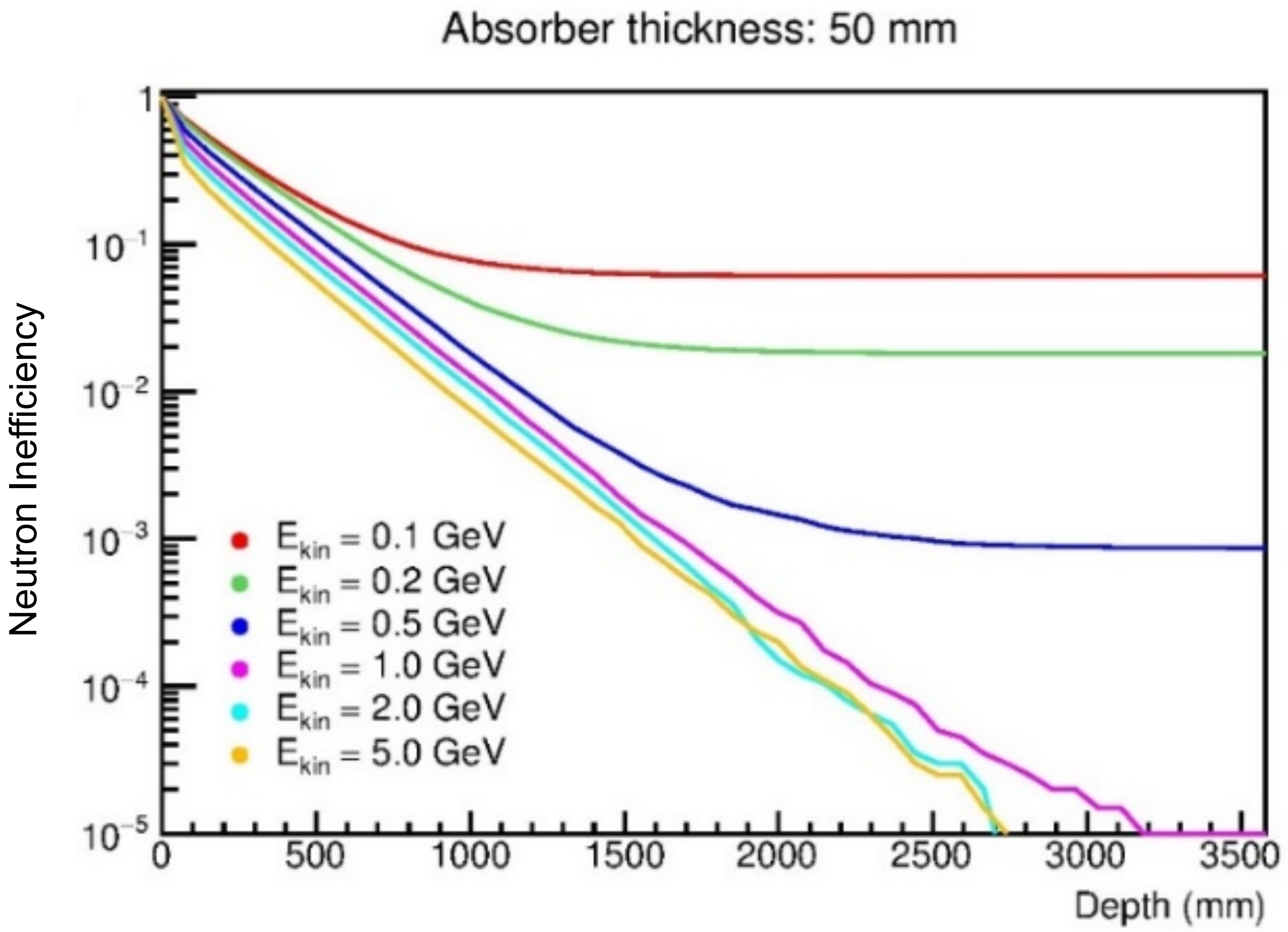
WBS 1.5 – HCal: from Mu2e Cosmic Ray Veto (UVA – Group)

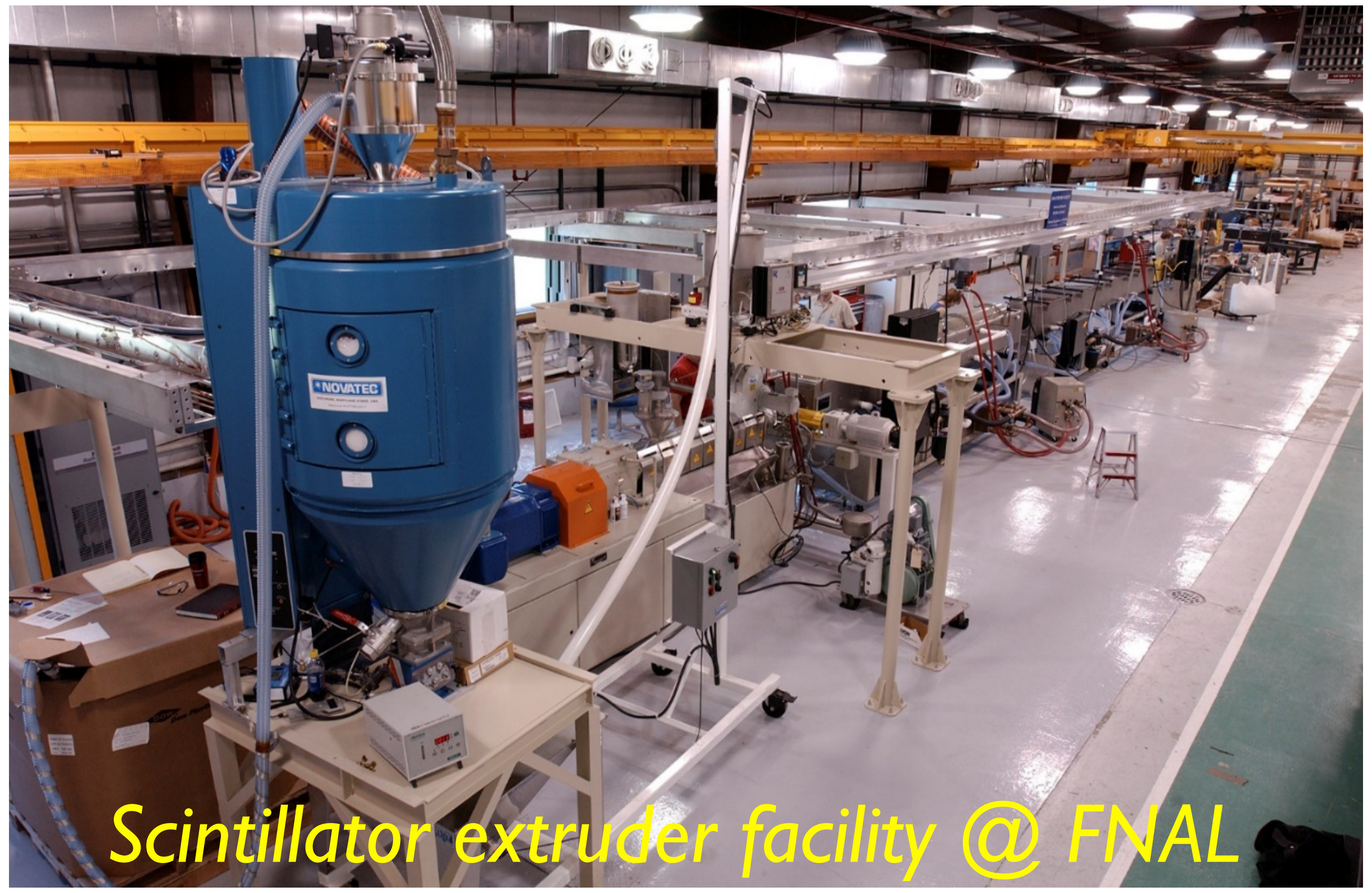
- extruded polystyrene scintillator with WLS fibers and SiPM readout
- main HCal: sufficient depth for rare events with very hard neutrons ($E_n \sim E_\gamma$)
- side HCal: important for high-multiplicity final states and wide-angle brems







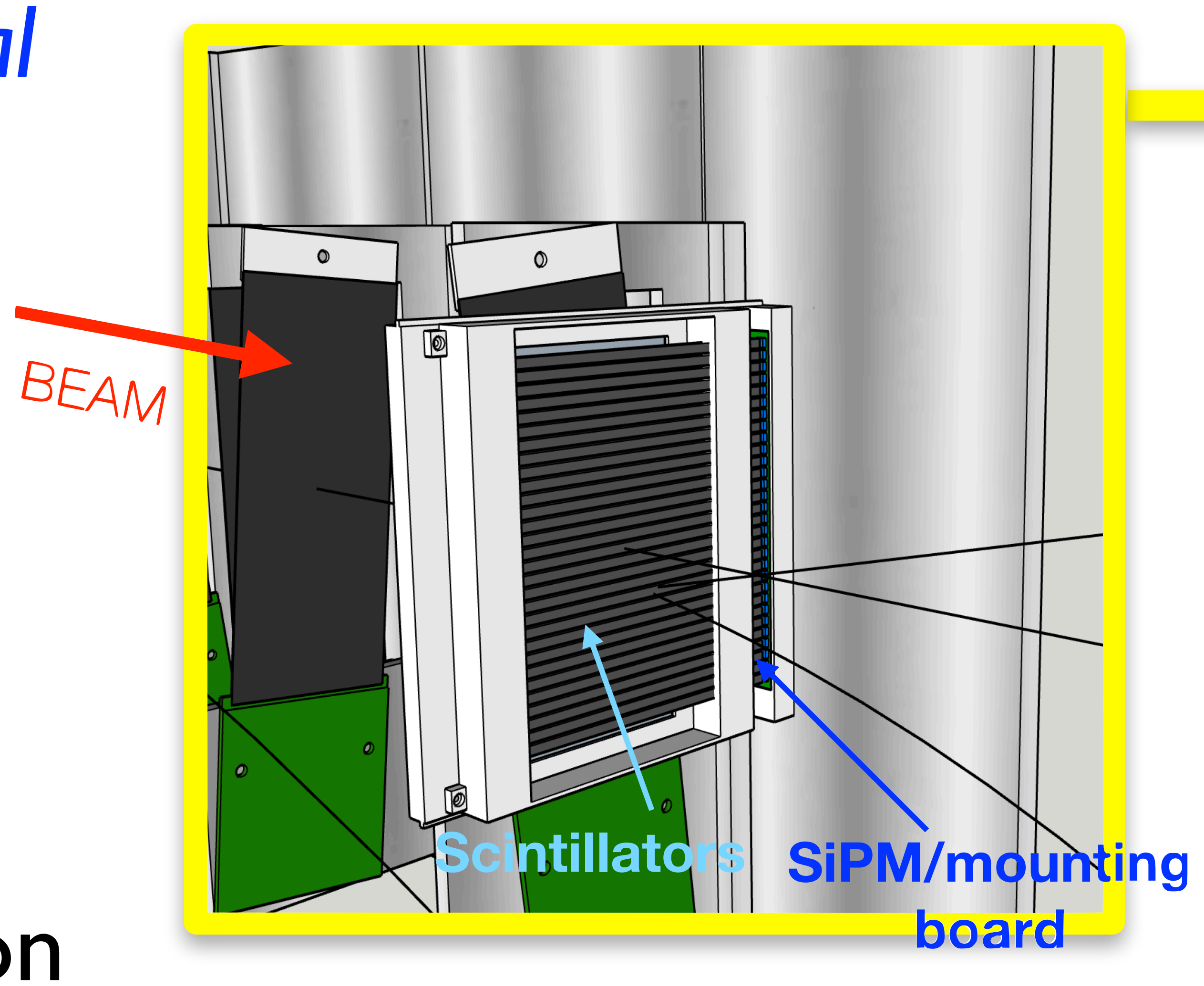


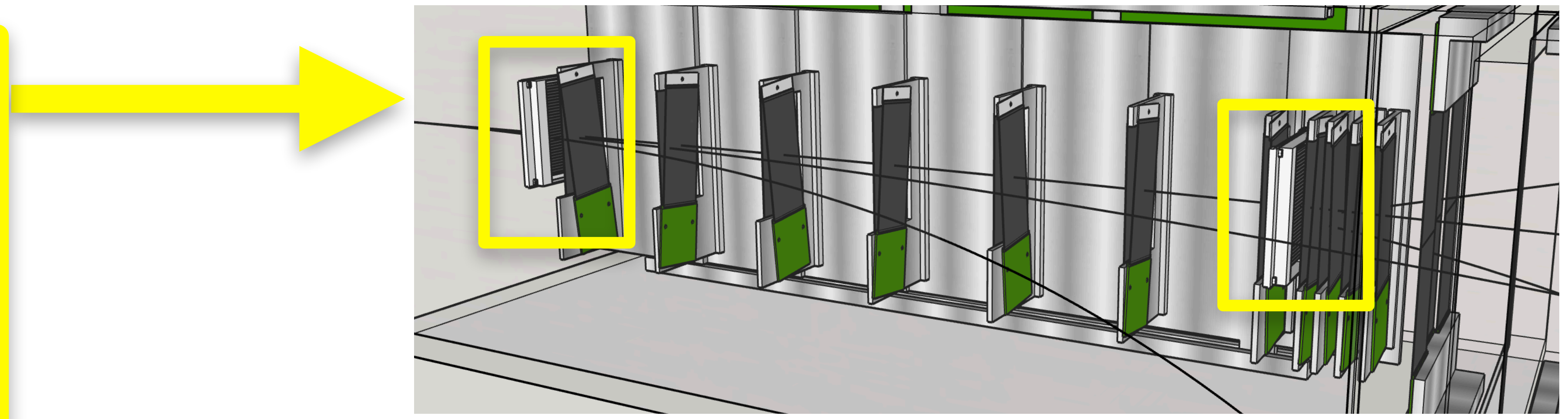


LDMX Subsystems and Technology Choices

WBS 1.2 – Trigger Scintillator: from CMS HCal

- Low-energy ECal trigger requires knowledge of n_e/pulse
- layers of segmented scintillators provides fast estimate of n_e
- also considering segmented LYSO active target: provides additional information about hard interactions in the target



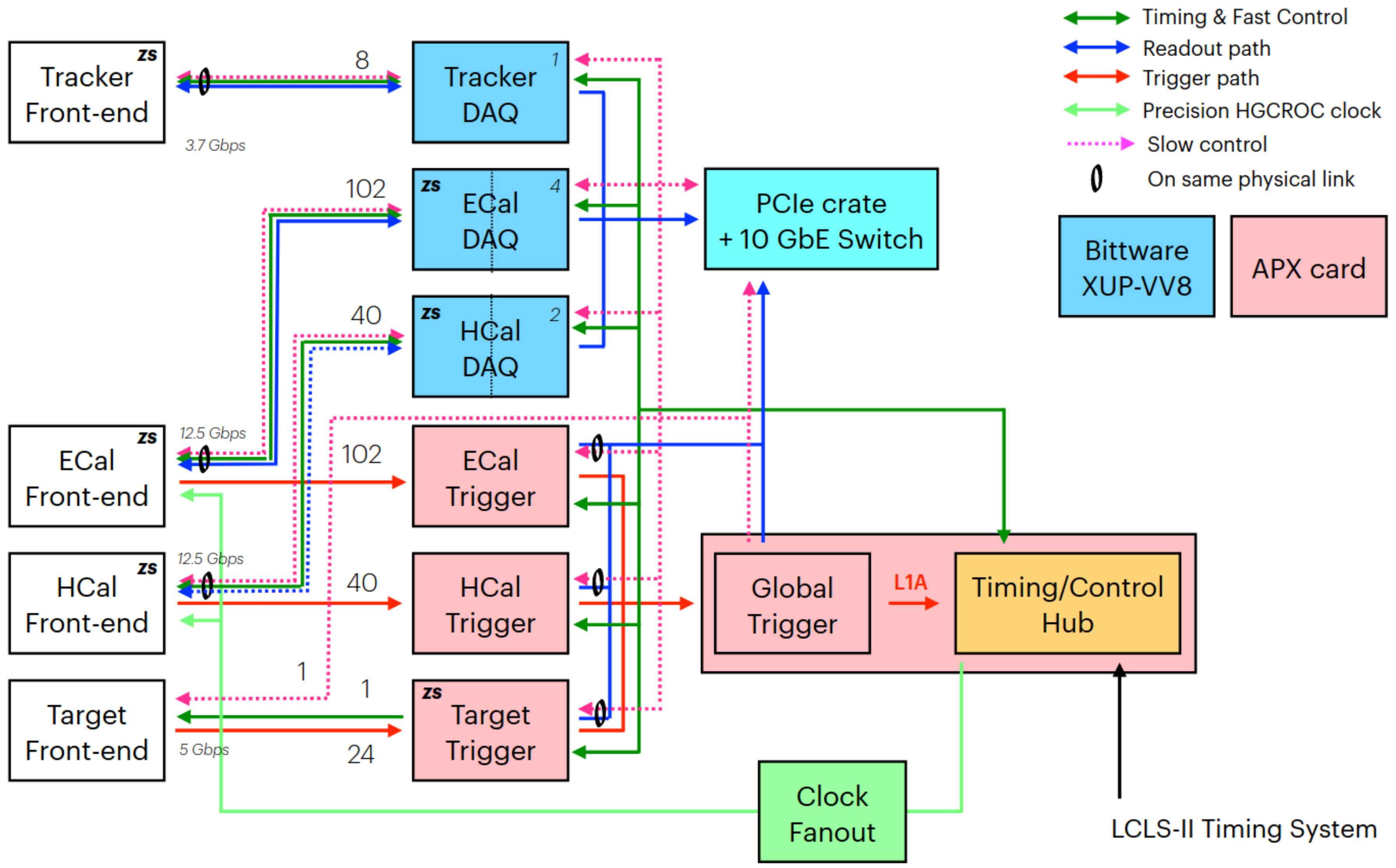


4 GeV trigger summary

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%

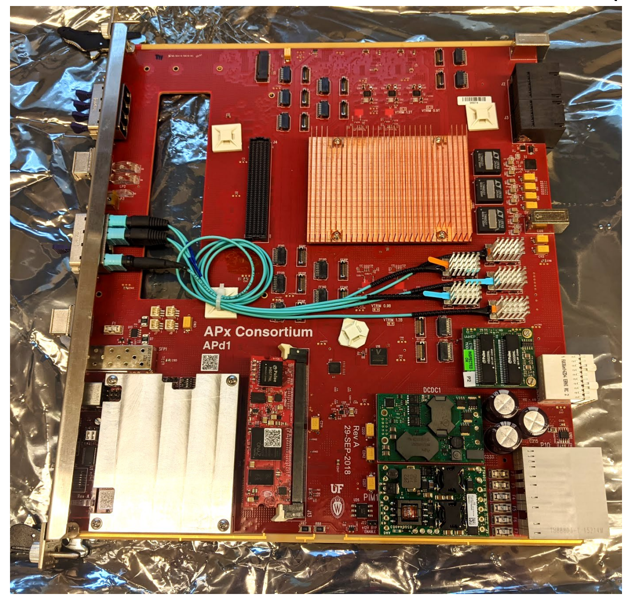
WBS 1.6 – Trigger and DAQ: from SLAC/FNAL tech

- back end DAQ based on PCIe FPGA platform developed at SLAC
- trigger DAQ based on APx DAQ developed for CMS



Bittware XUP-VV8

Advanced Processor demonstrator (APd)



LDMX Subsystems and Technology Choices

WBS 1.7 – Computing and Software

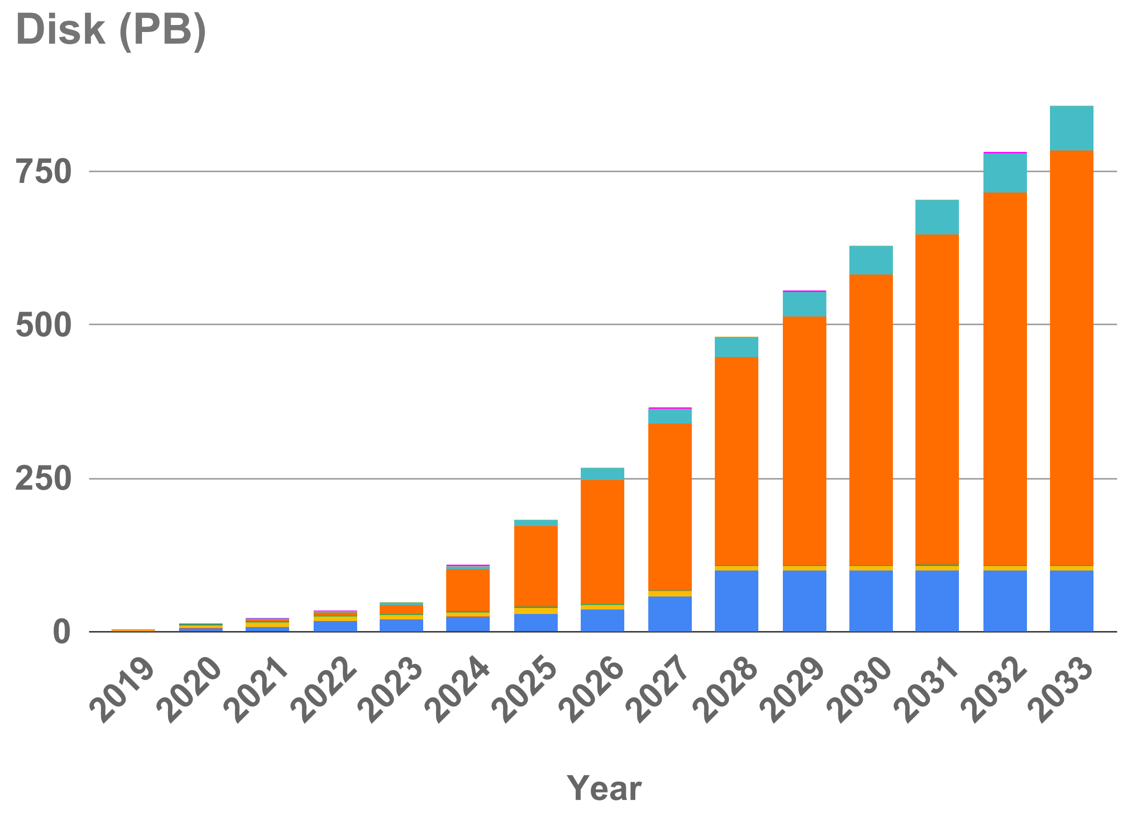
LDMX requires significant computing resources: Datasets and MC will total ~8 PB (disk+tape) after filtering and require ~15M CPU hours to process.

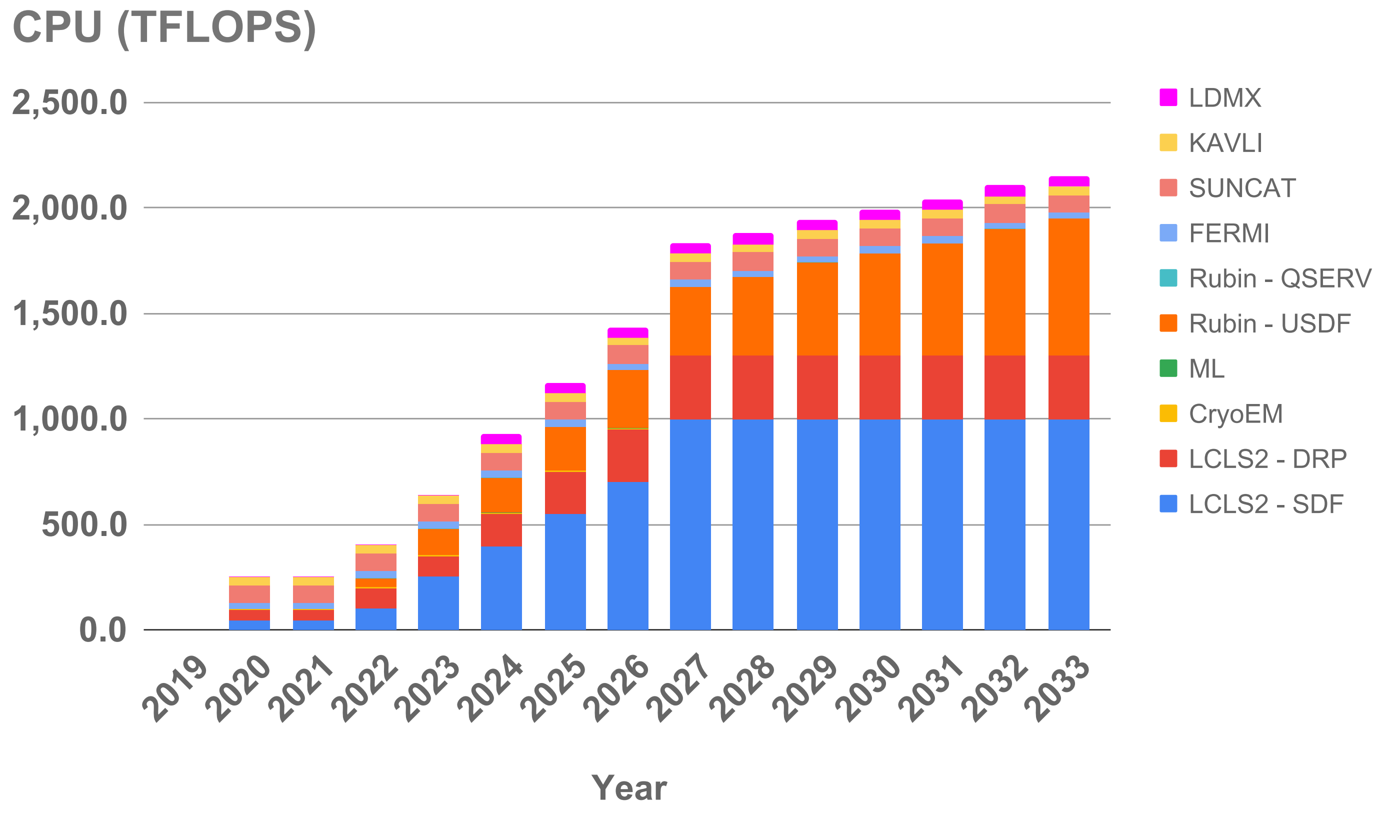
- SLAC Shared Scientific Data Facility (SDF)
- LDMX distributed computing pilot project:
  Lightweight Distributed Computing System (LDCS)
  arXiv:2105.02977 **[hep-ex]**

ldmx-sw: C++ software framework for event generation and reconstruction

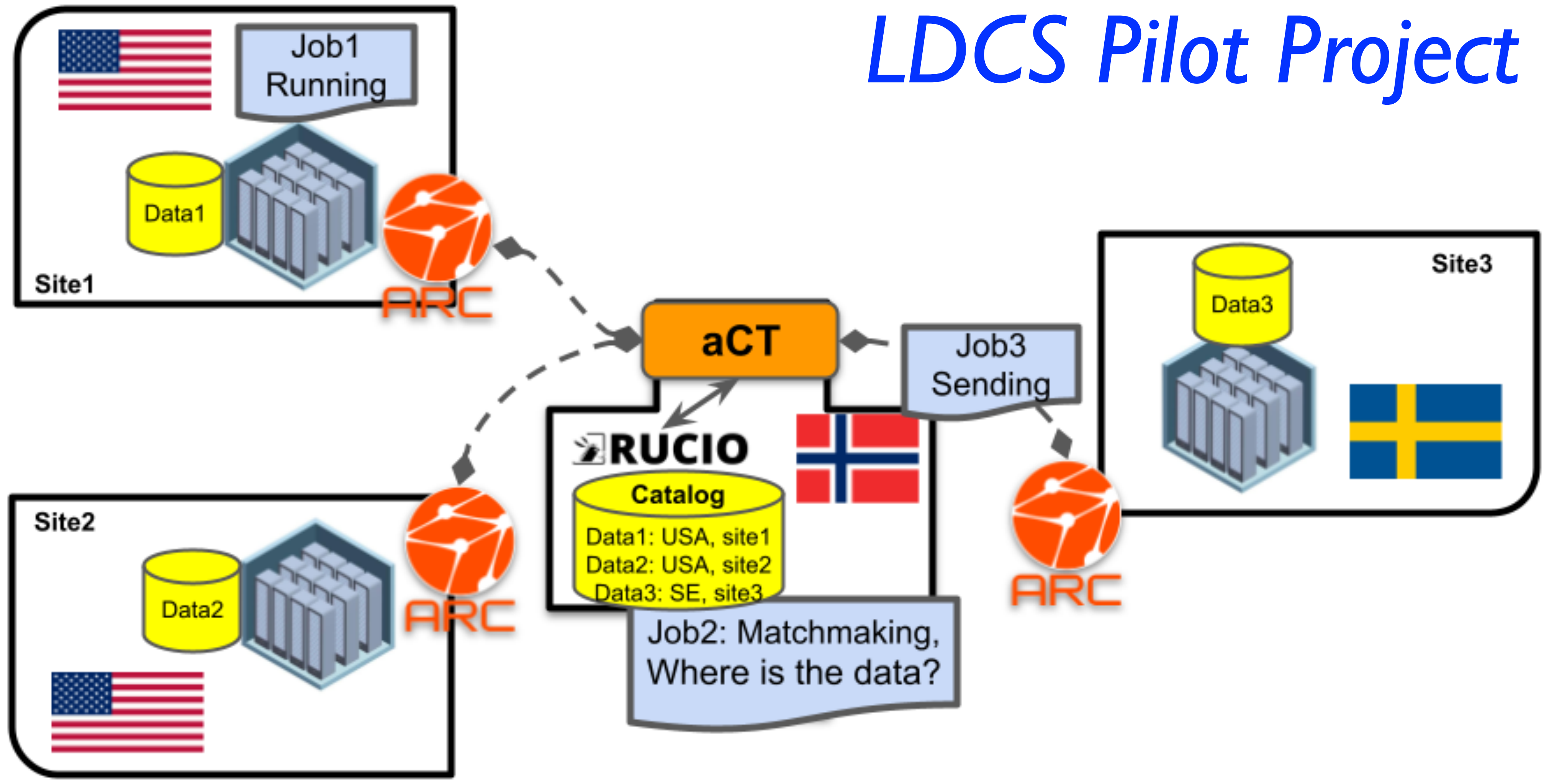
https://github.com/LDMX-Software/ldmx-sw/

SLAC Shared Scientific Data Facility (SDF)





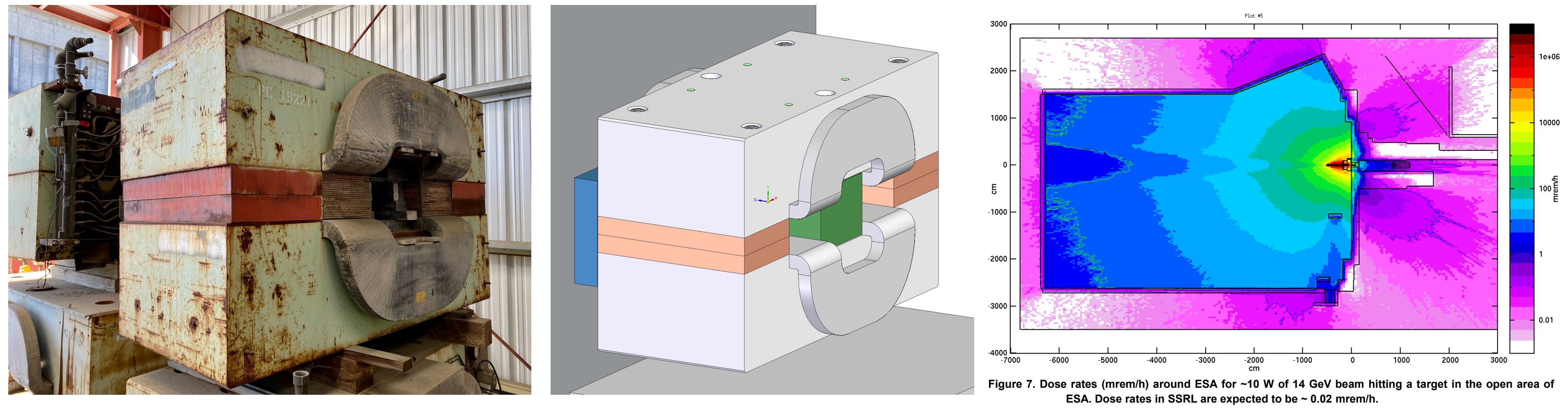
LDCS Pilot Project



LDMX DMNI Project Plan: technical development

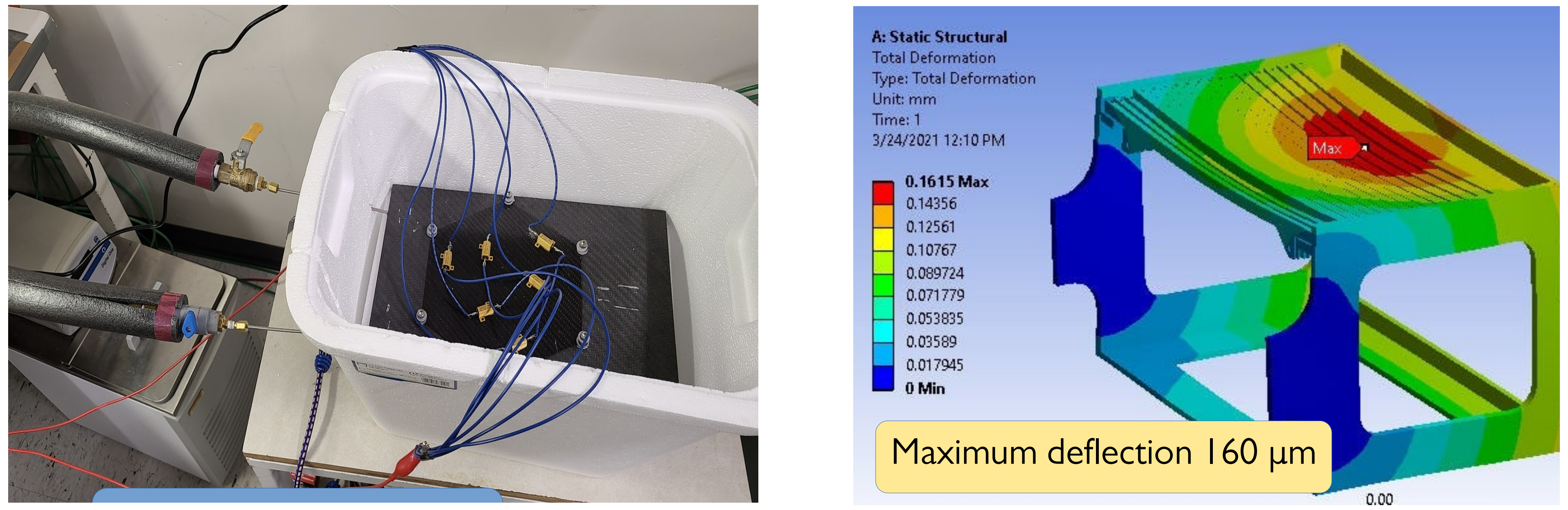
LDMX DMNI project consists of development work required to adapt existing technologies and prepare a design report and execution plan ready to be reviewed and baselined for a small project fabrication, as well as final engineering work that enables the immediate start of construction.

Beamline: magnet design and radiation studies



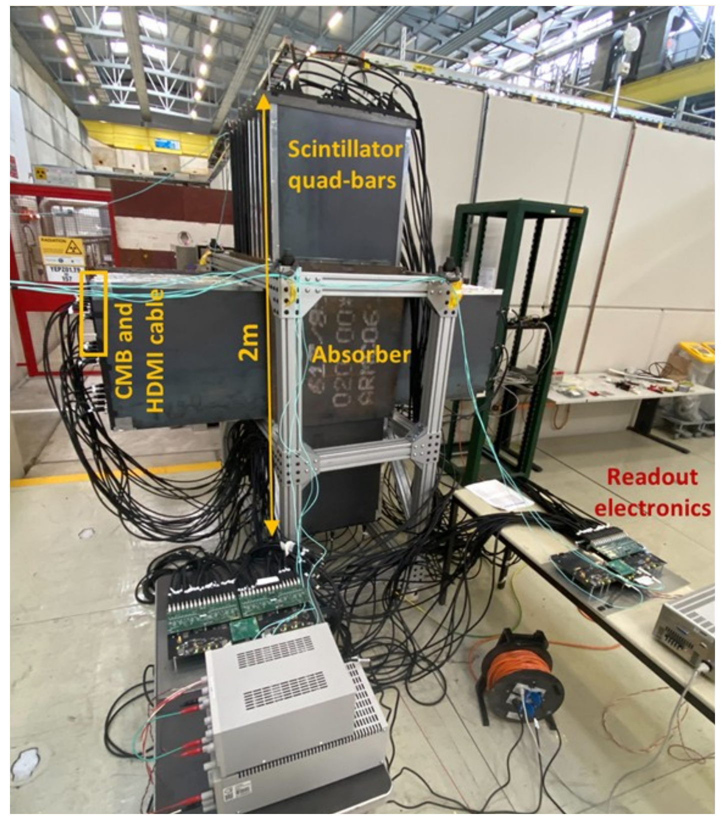
ECal/HCal/Trigger Scintillator: readout prototypes

ECal cooling tests and mechanical studies

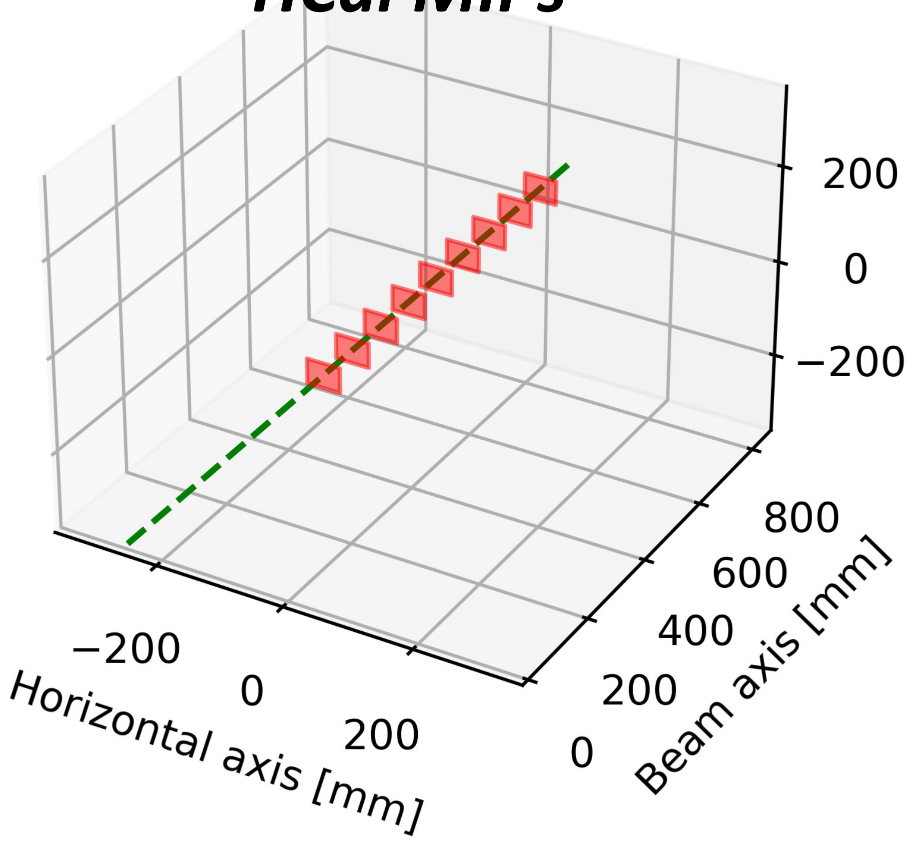


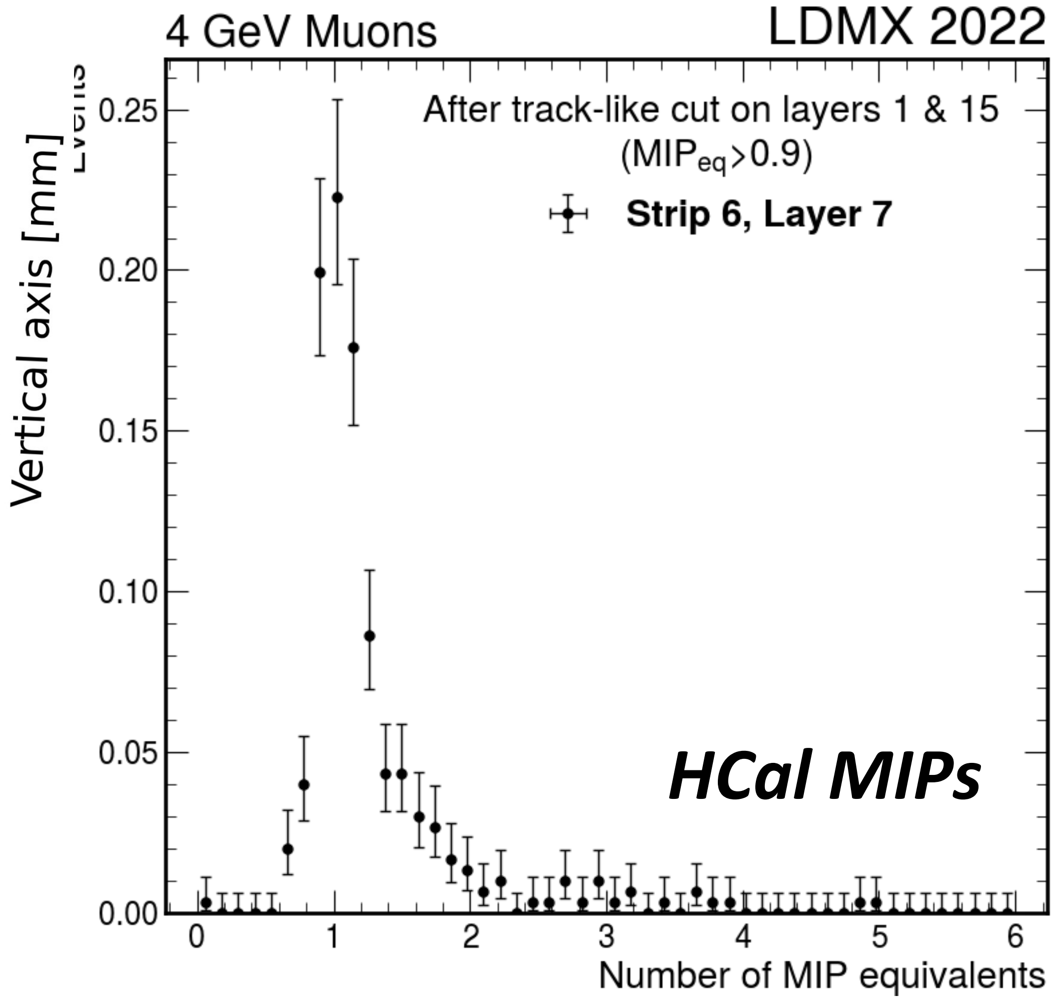
LDMX Test Beam at CERN

HCal prototype



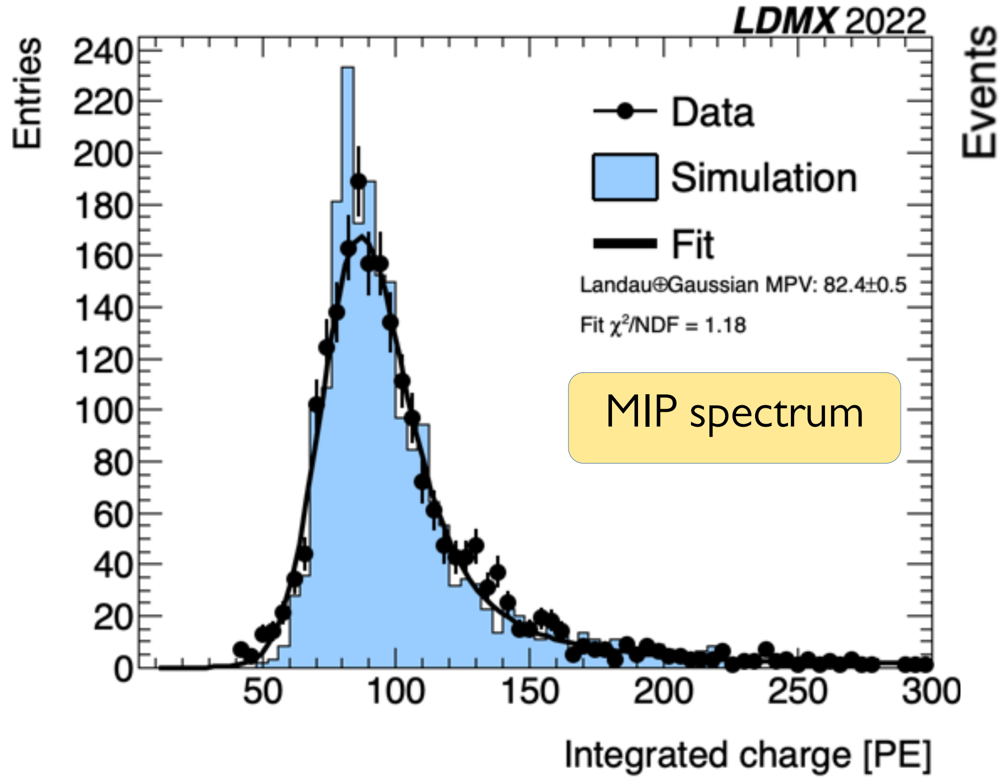
HCal MIPs





Trigger Scintillator (TS) prototype

TS MIPs



TS PE spectrum