

Fixed-target Dark Sector Searches

SLAC FPD Strategic Planning

Tim Nelson

26 September 2025

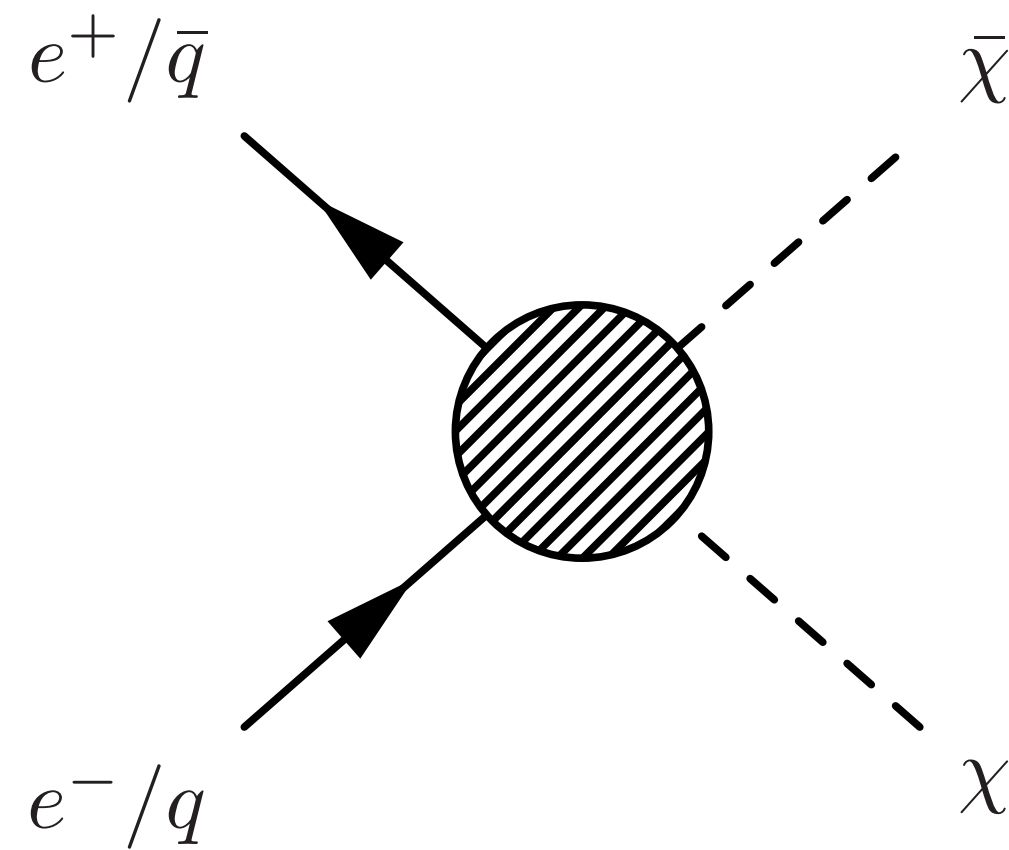
HPS

LDMX

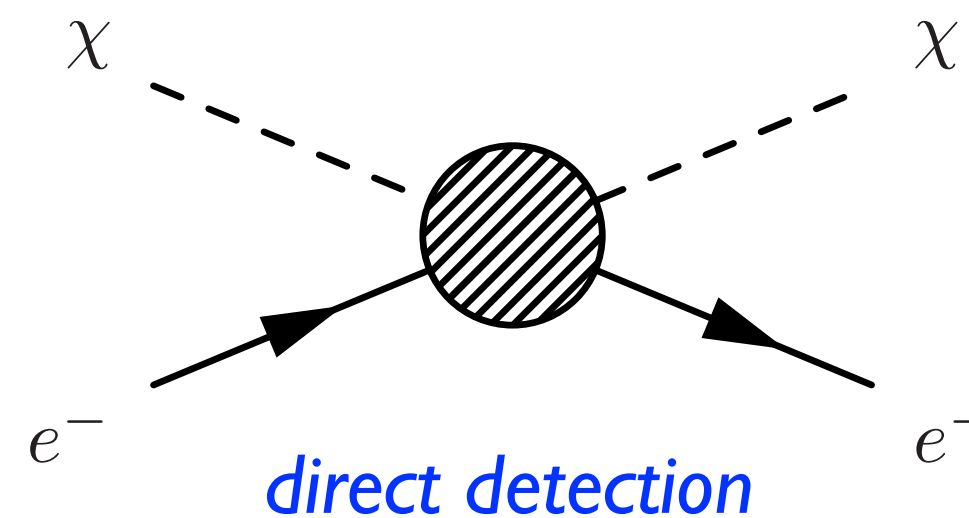
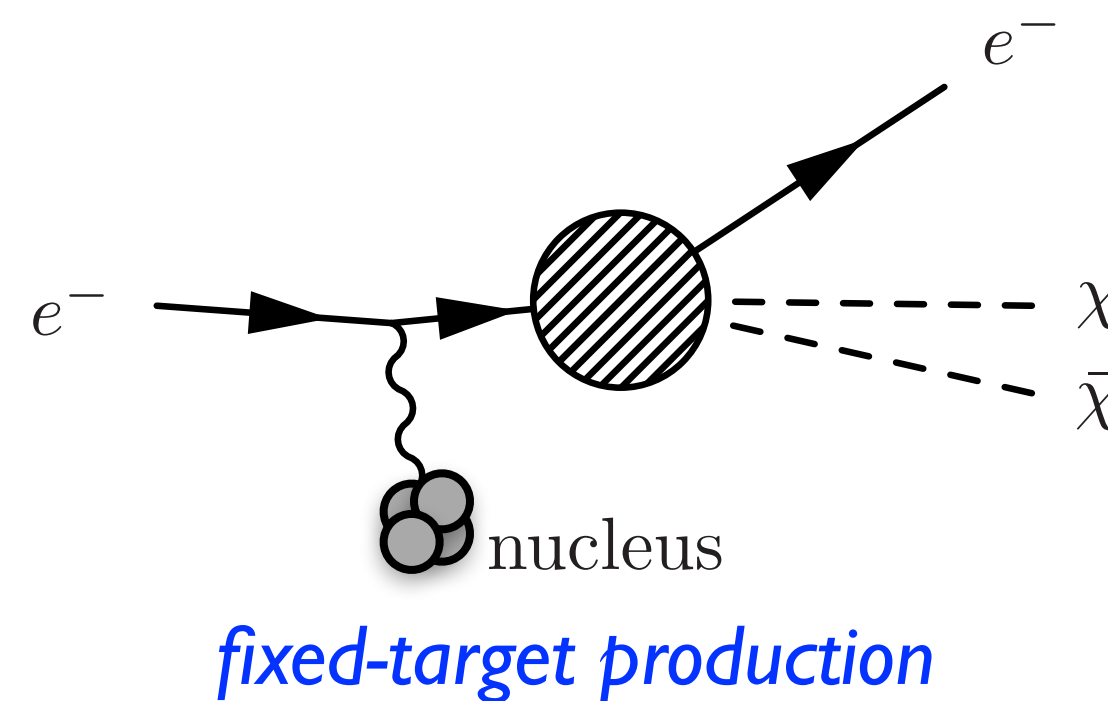
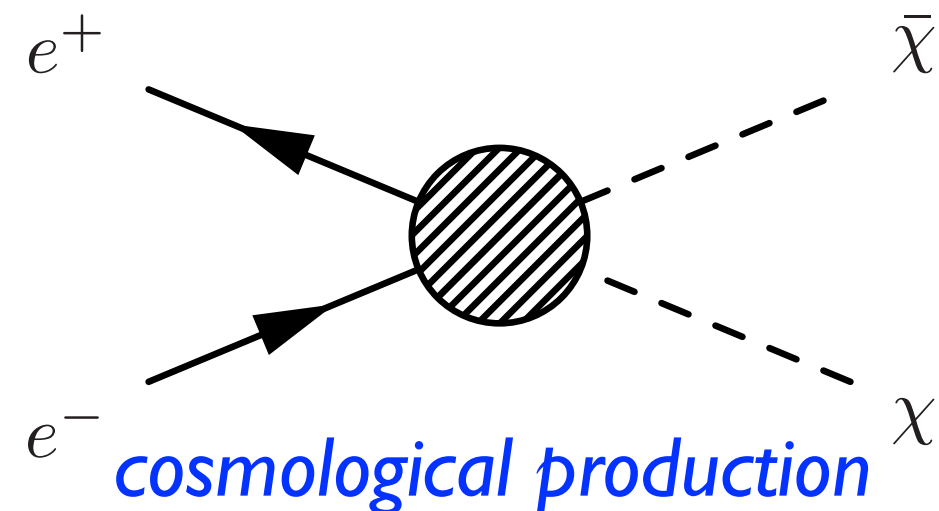
???

Key Objective: Sub-GeV Freeze-out Thermal Relics

Start with a simple ansatz for DM-SM interactions:



related by crossing symmetry



scale probed

$$q \sim m_\chi$$

origin of predictiveness

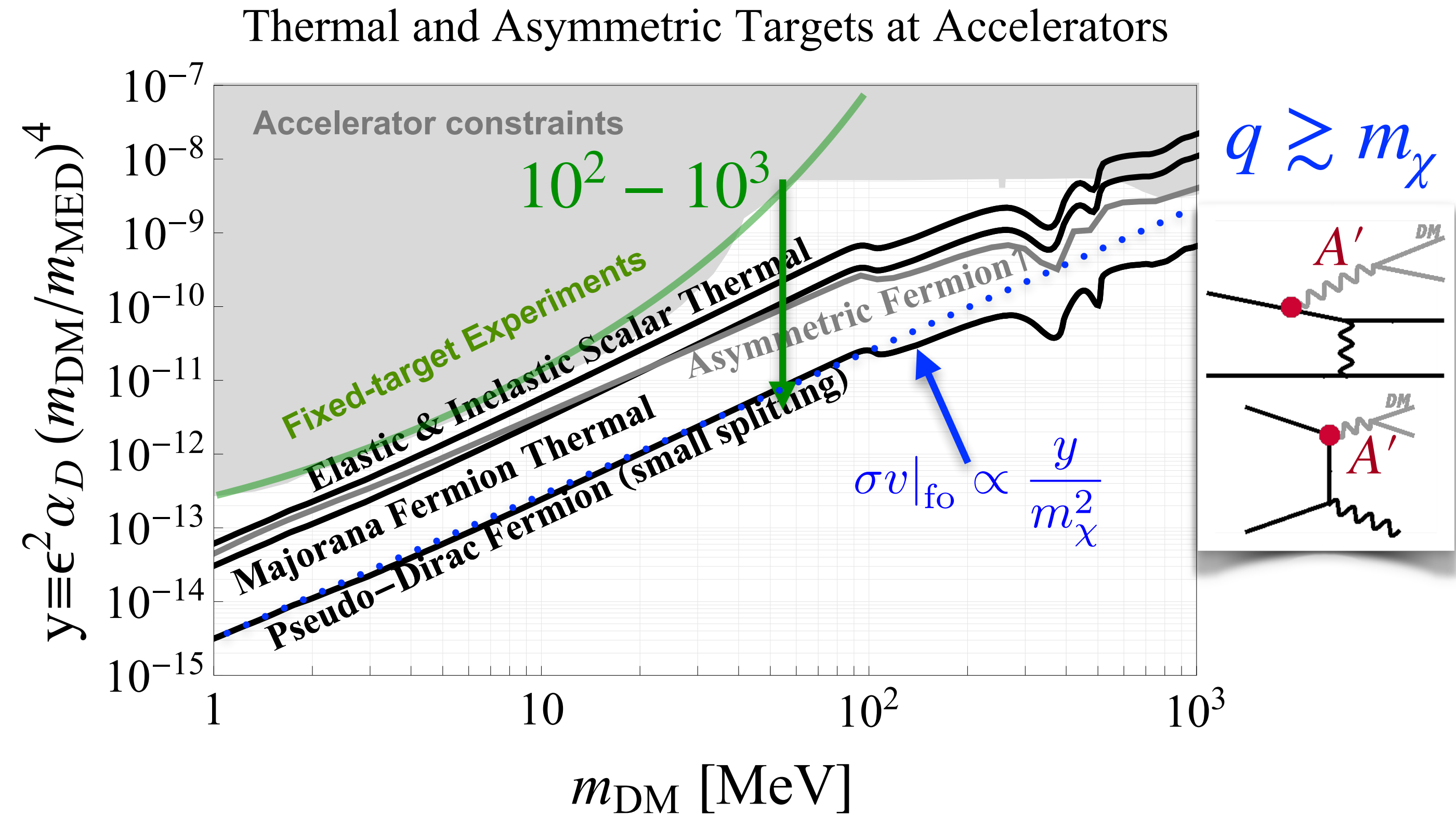
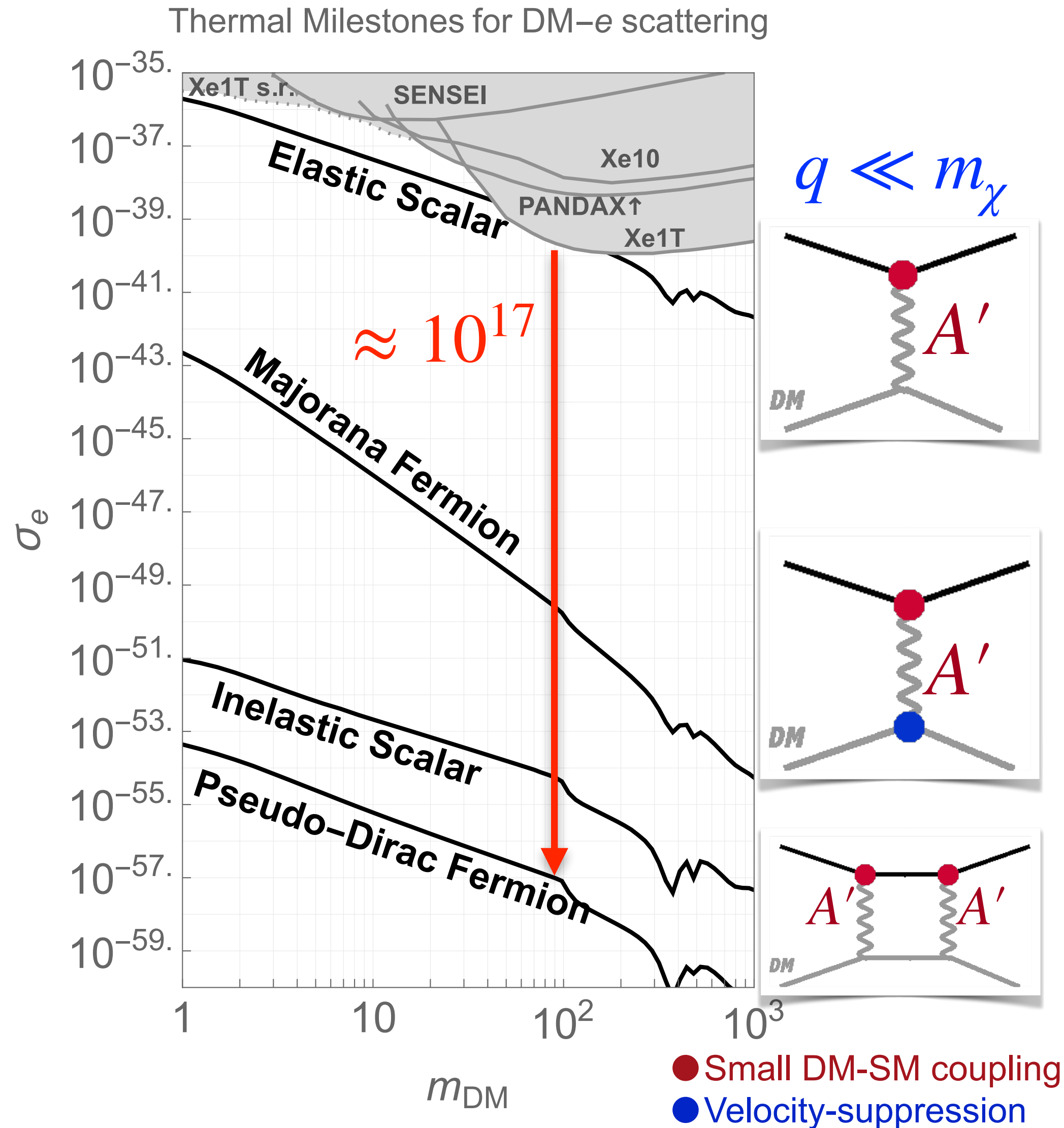
$$q \gtrsim m_\chi$$

origin of complementarity

$$q \ll m_\chi$$

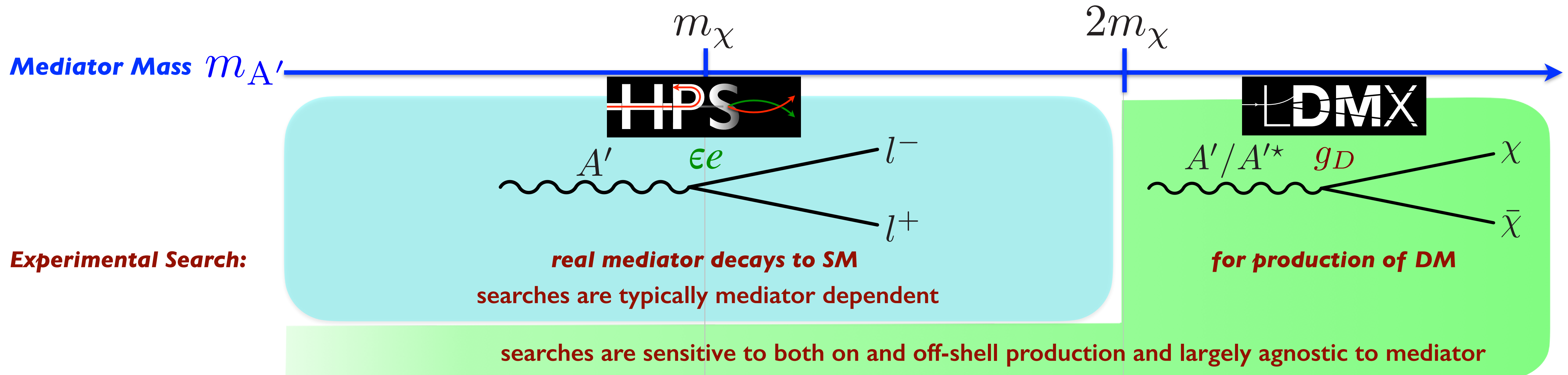
n.b. whatever the mediator is, it cannot be a known force for $M_\chi \lesssim 2 \text{ GeV}$

Concrete Example: Dark Photon Mediator (others are similar)

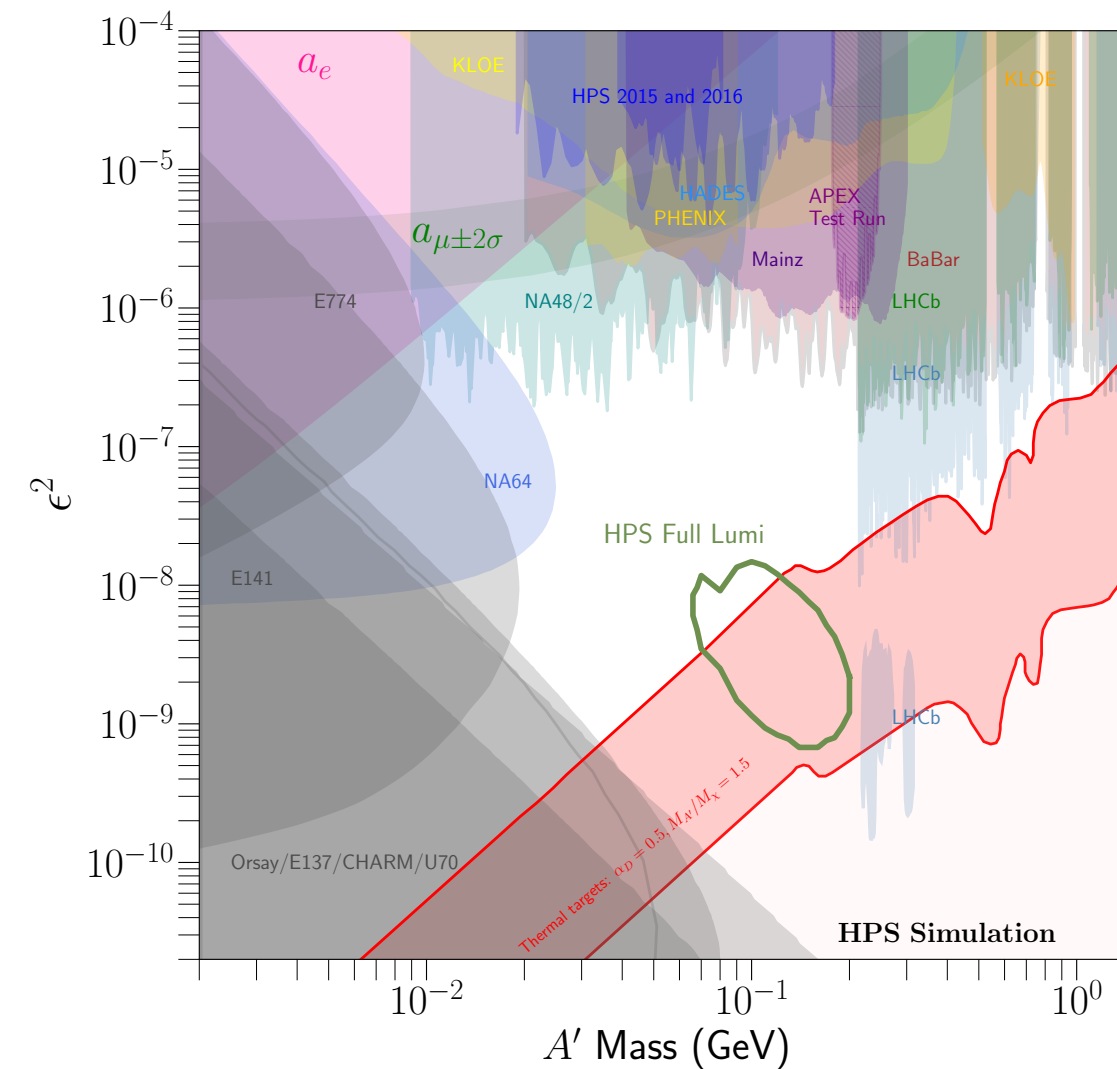


MeV-GeV freeze-out thermal relics are the “killer application” for accelerator searches.

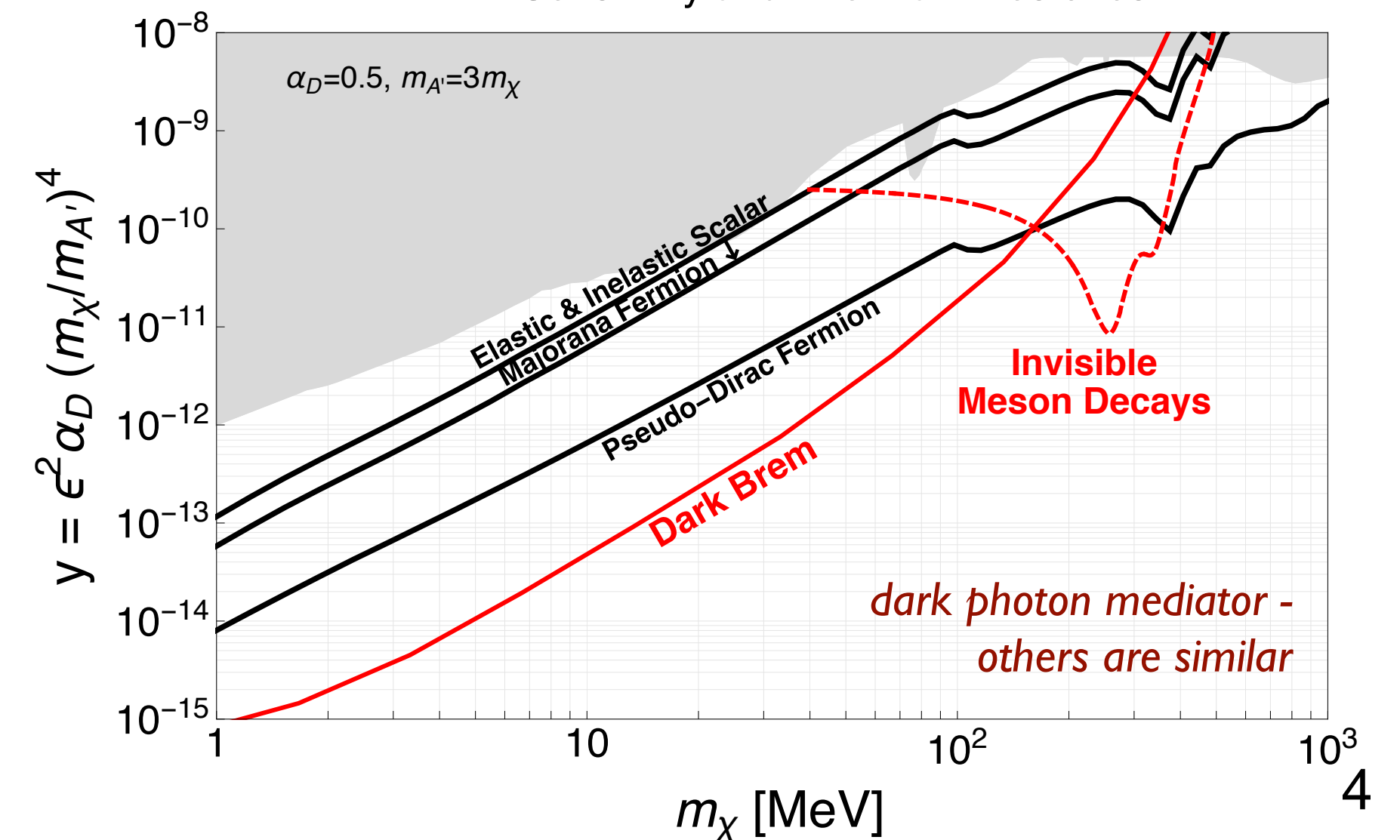
Fixed-target Dark Sector Search Strategies



HPS Sensitivity and Thermal Milestones



LDMX Sensitivity and Thermal Milestones



Theory Cross-cut and Community Landscape



SLAC theorists pioneered ideas, launching **APEX** (2010), **HPS** (2013), and inspiring many others.

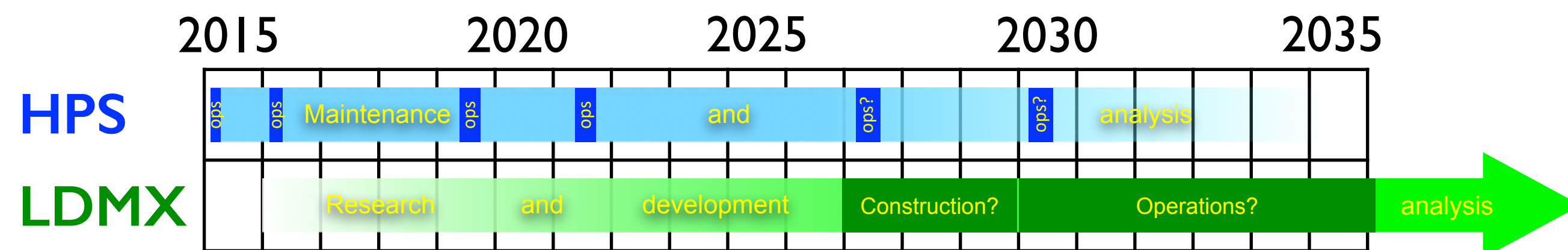
2014 P5 called for Small Projects Portfolio with DM and Physics of the Unknown science drivers.

In 2017, DOE launched **Basic Research Needs (BRN)** for **Dark Matter New Initiatives (DMNI)**.

BRN became basis for 2019 DMNI FOA: **LDMX** chosen for development.

2023 P5 creates a clearer mandate through R3 (ASTAE) with DMNI as first projects to consider for construction.

There are two active efforts at SLAC:



New Fixed-Target Experiments to Search for Dark Gauge Forces

James D. Bjorken,¹ Rouven Essig,¹ Philip Schuster,¹ and Natalia Toro²
¹Theory Group, SLAC National Accelerator Laboratory, Menlo Park, CA 94025
²Theory Group, Stanford University, Stanford, CA 94305
 (Dated: June 3, 2009)

Testing GeV-scale dark matter with fixed-target missing momentum experiments

Eder Izaguirre, Gordan Krnjaic, Philip Schuster, and Natalia Toro
 Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada, N2L 2Y5
 (Received 8 January 2015; published 22 May 2015)



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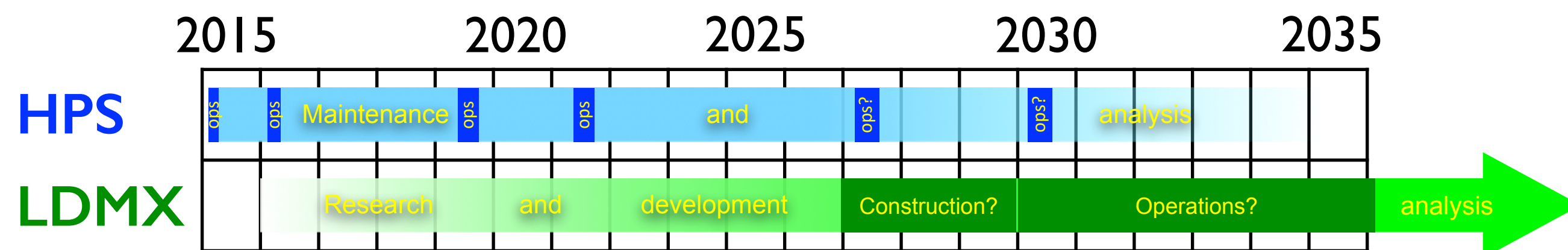
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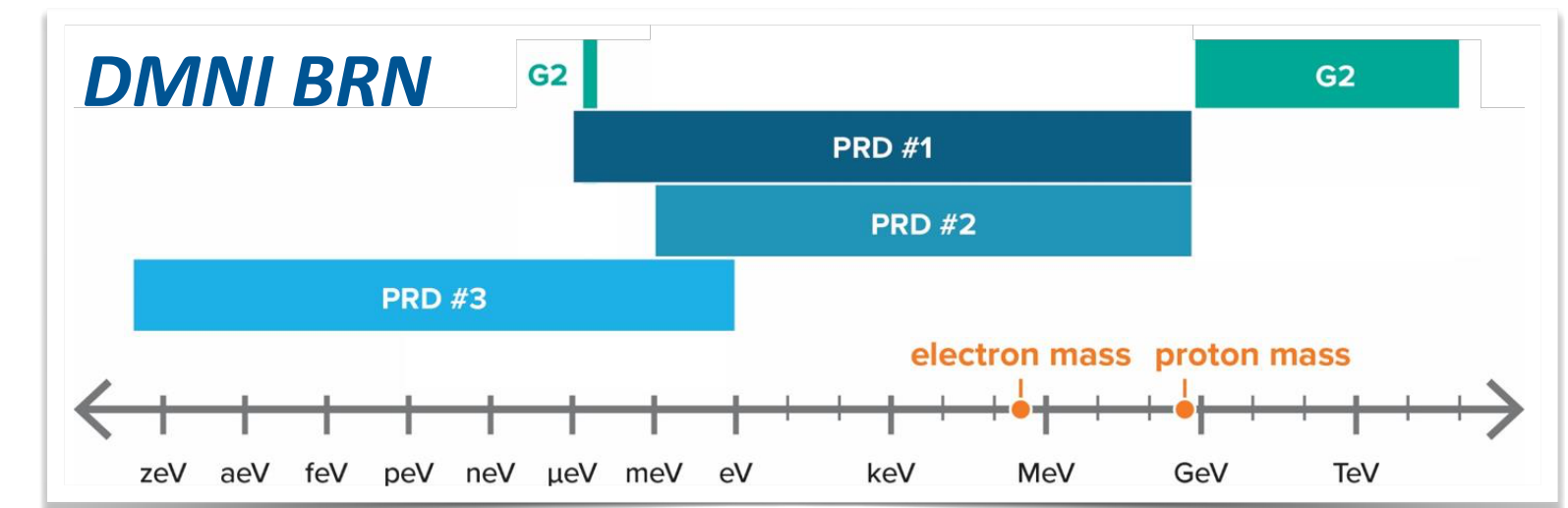
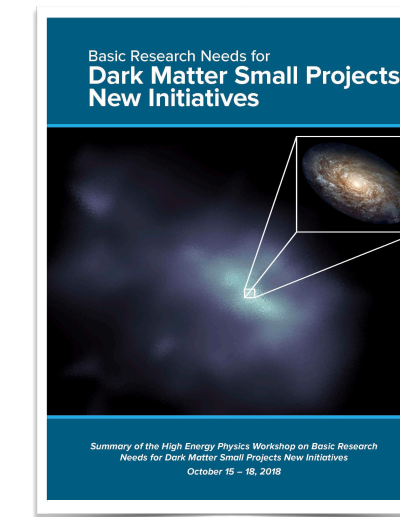
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2014 P5

Project/Activity	Scenarios			Science Drivers					
	Scenario A	Scenario B	Scenario C	Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown	Technique (Frontier)
Medium Projects									
LSST	Y	Y	Y		✓		✓		C
DM G2	Y	Y	Y			✓			C
Small Projects Portfolio	Y	Y	Y		✓	✓	✓	✓	All

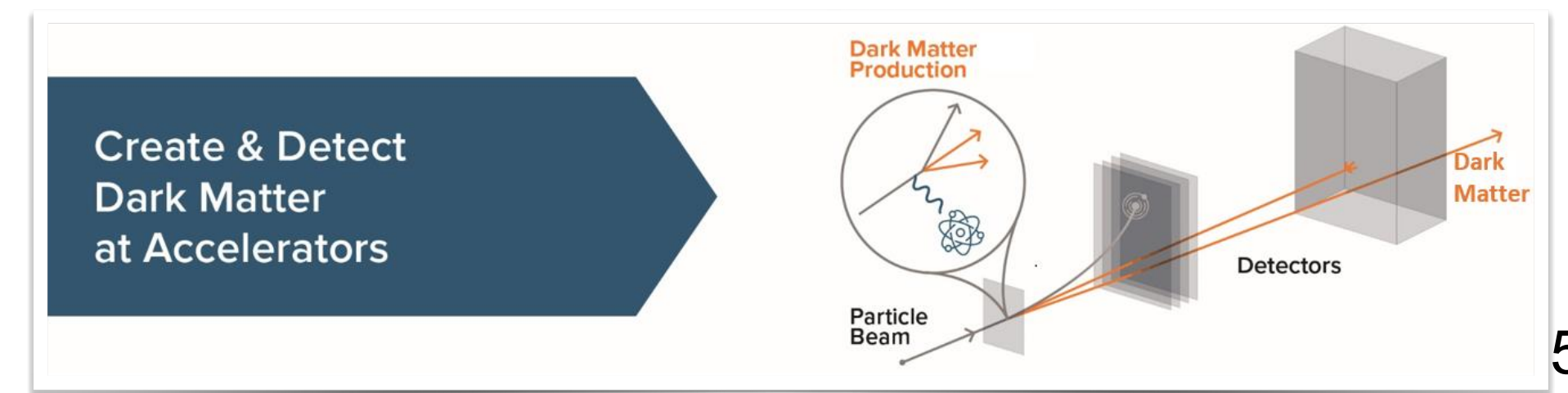
some reductions with



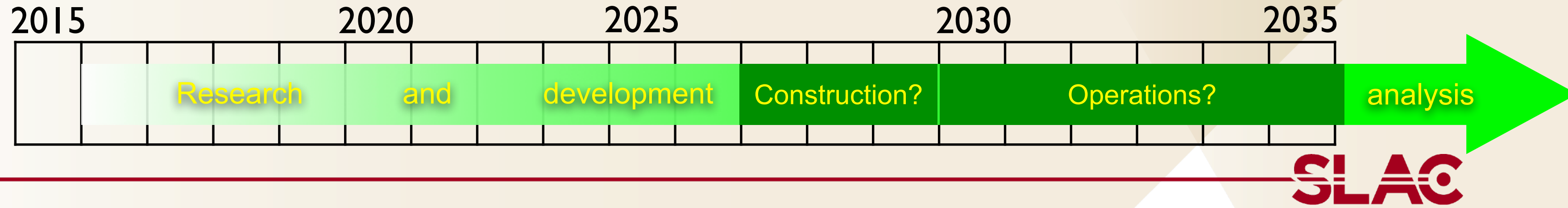
PRD 1: Create and detect dark matter particles below the proton mass and associated forces, leveraging DOE accelerators that produce beams of energetic particles.

LDMX → *Thrust 1 (near term):* Through 10- to 1000-fold improvements in sensitivity over current searches, use particle beams to explore interaction strengths singled out by thermal dark matter across the electron-to-proton mass range.

HPS → *Thrust 2 (near and long term):* Explore the structure of the dark sector by producing and detecting unstable dark particles.



Strategic Opportunity: LDMX

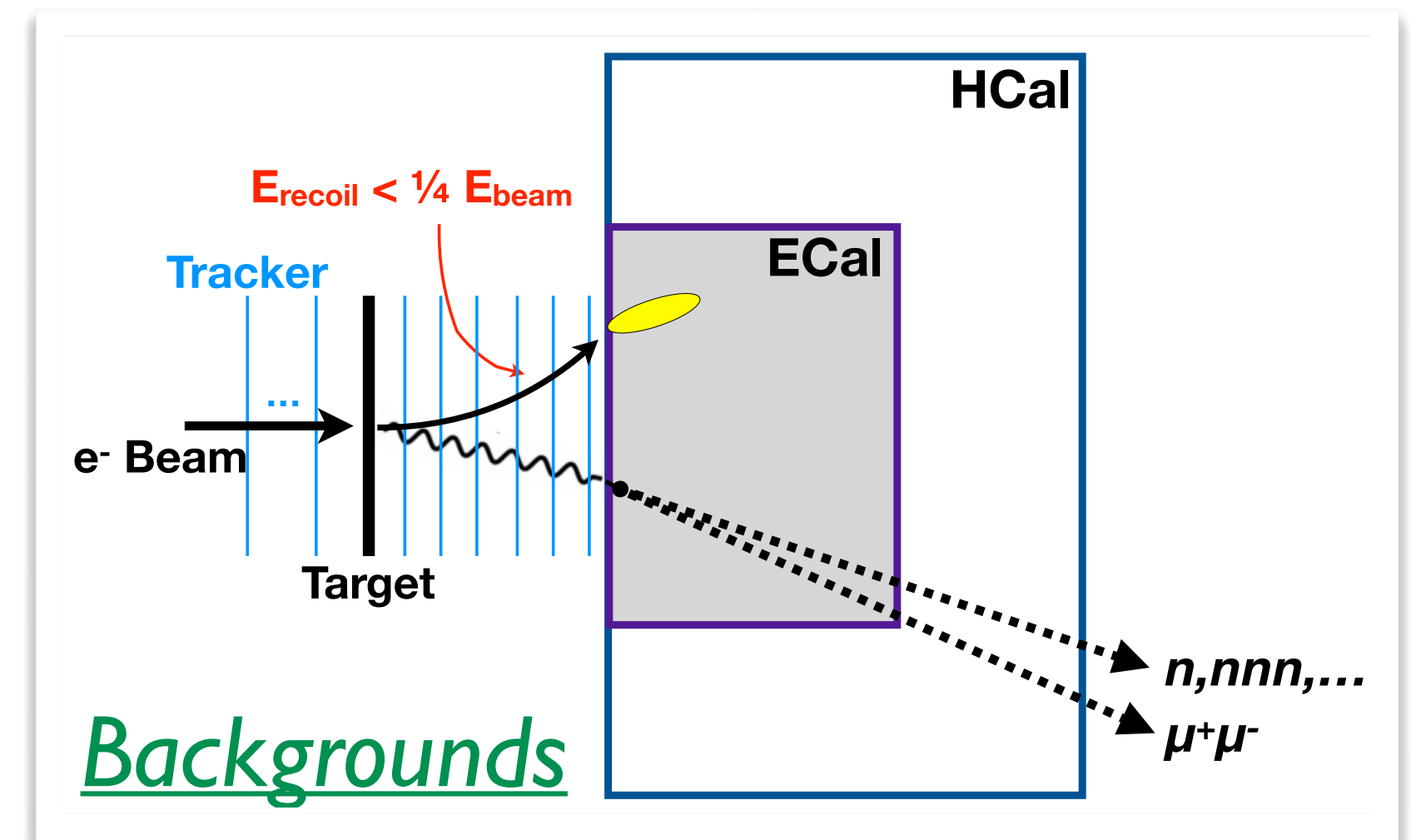
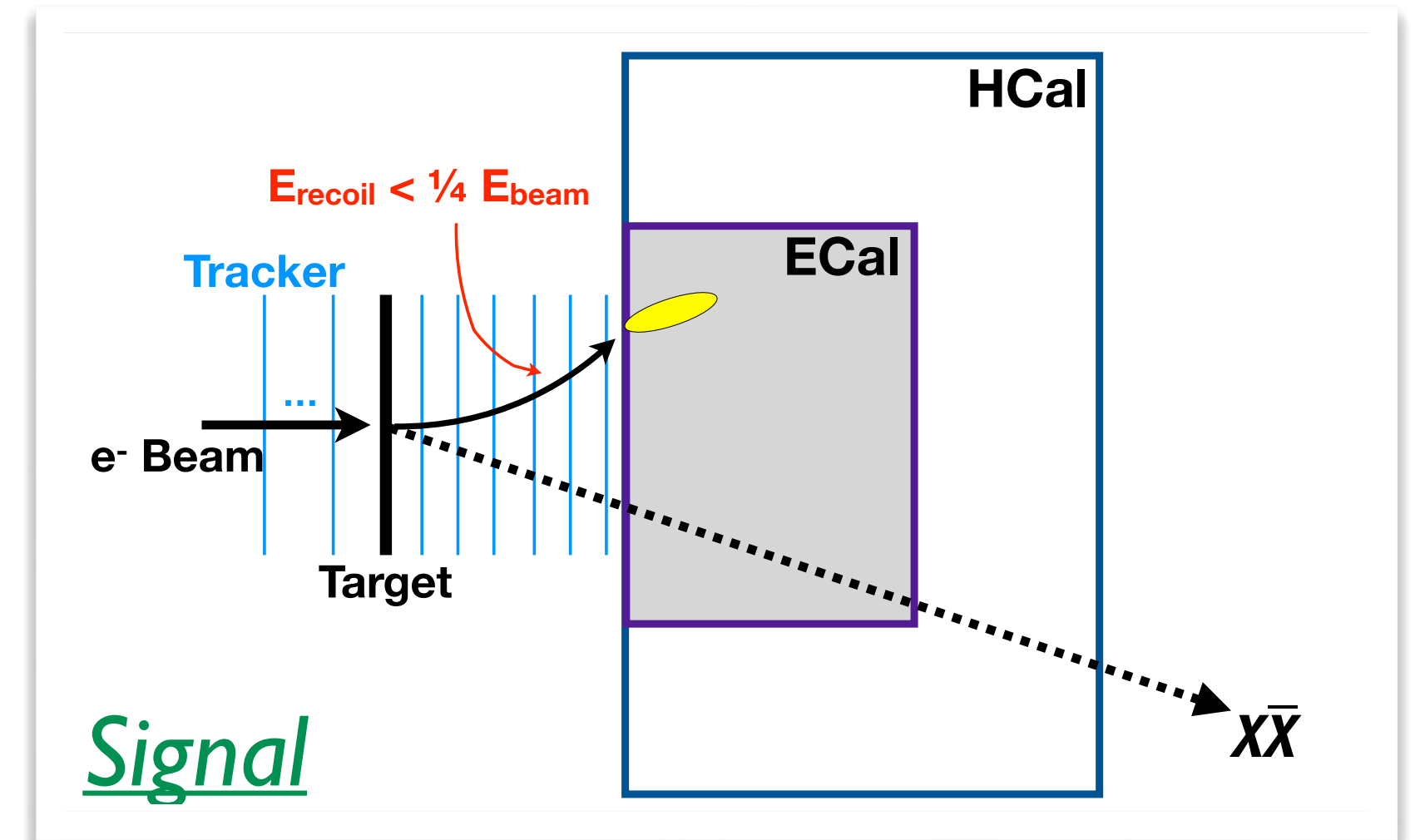
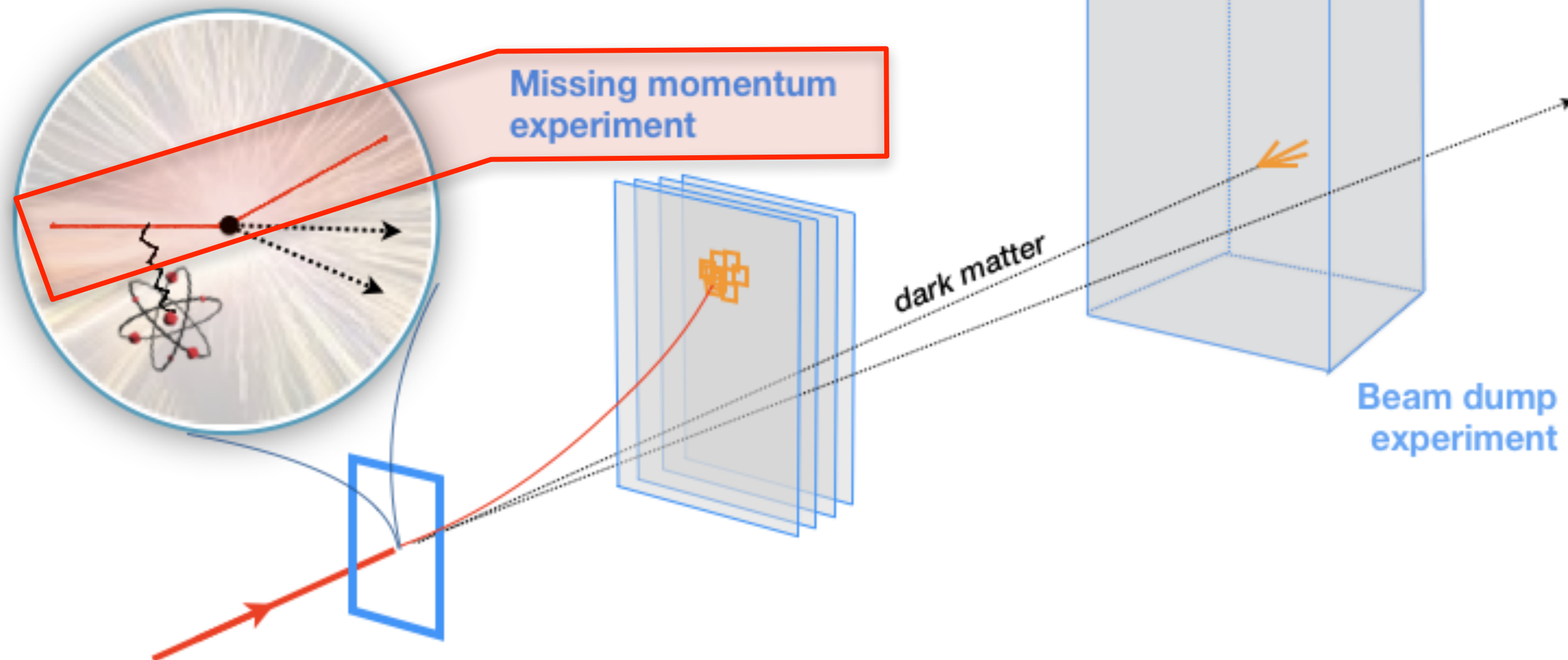


DMNI BRN Priority Research Direction 1

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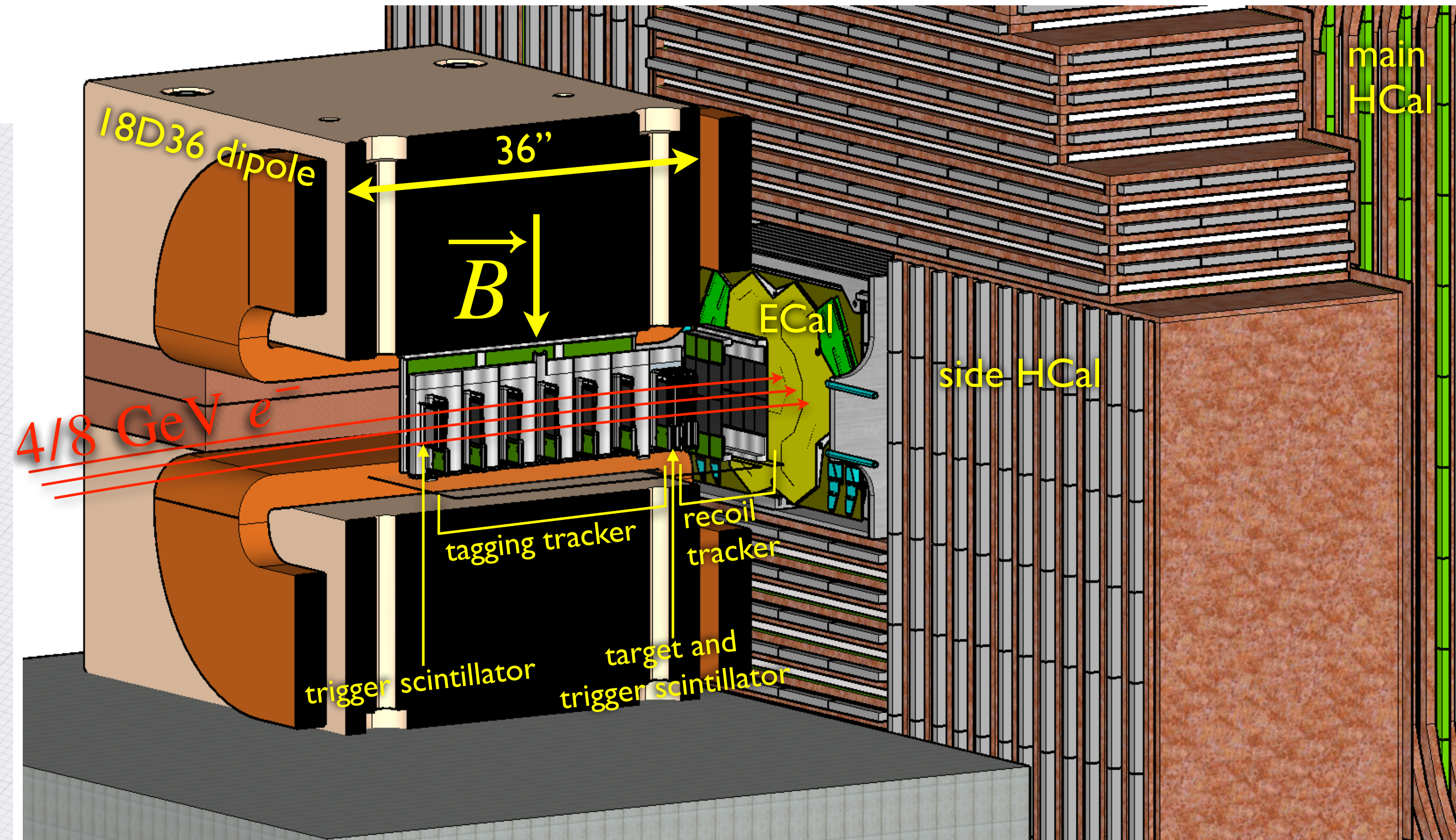
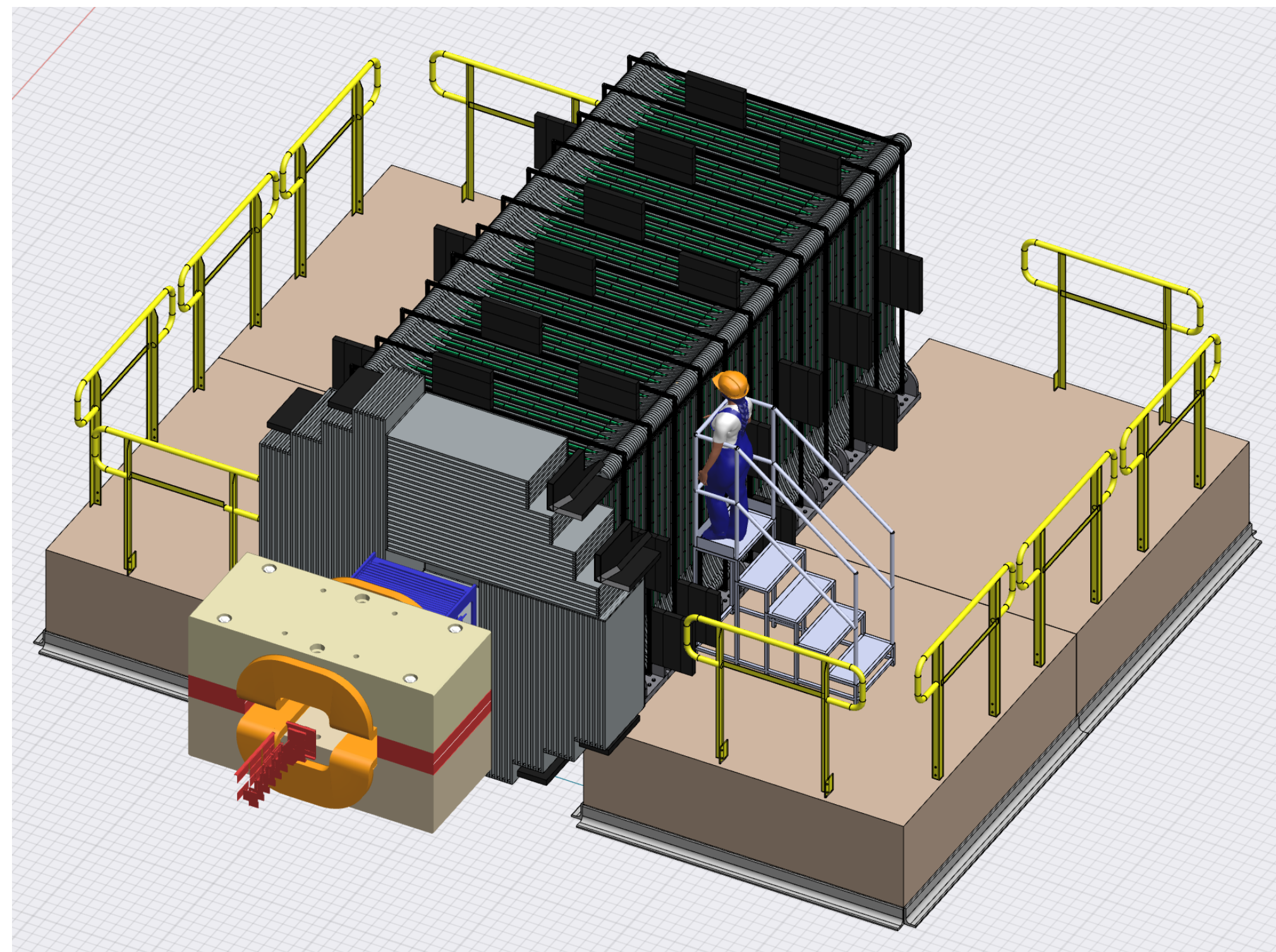
Missing momentum experiments, using modern detectors operating directly in a low-current lepton beam, identify dark matter production events based on the kinematics of visible particles recoiling from the production event. Such experiments in a continuous-wave electron beam offer a path to reach 1000-fold improvement in sensitivity over a broad mass range ...

RECREATING BIG BANG DARK MATTER PRODUCTION AT ACCELERATORS



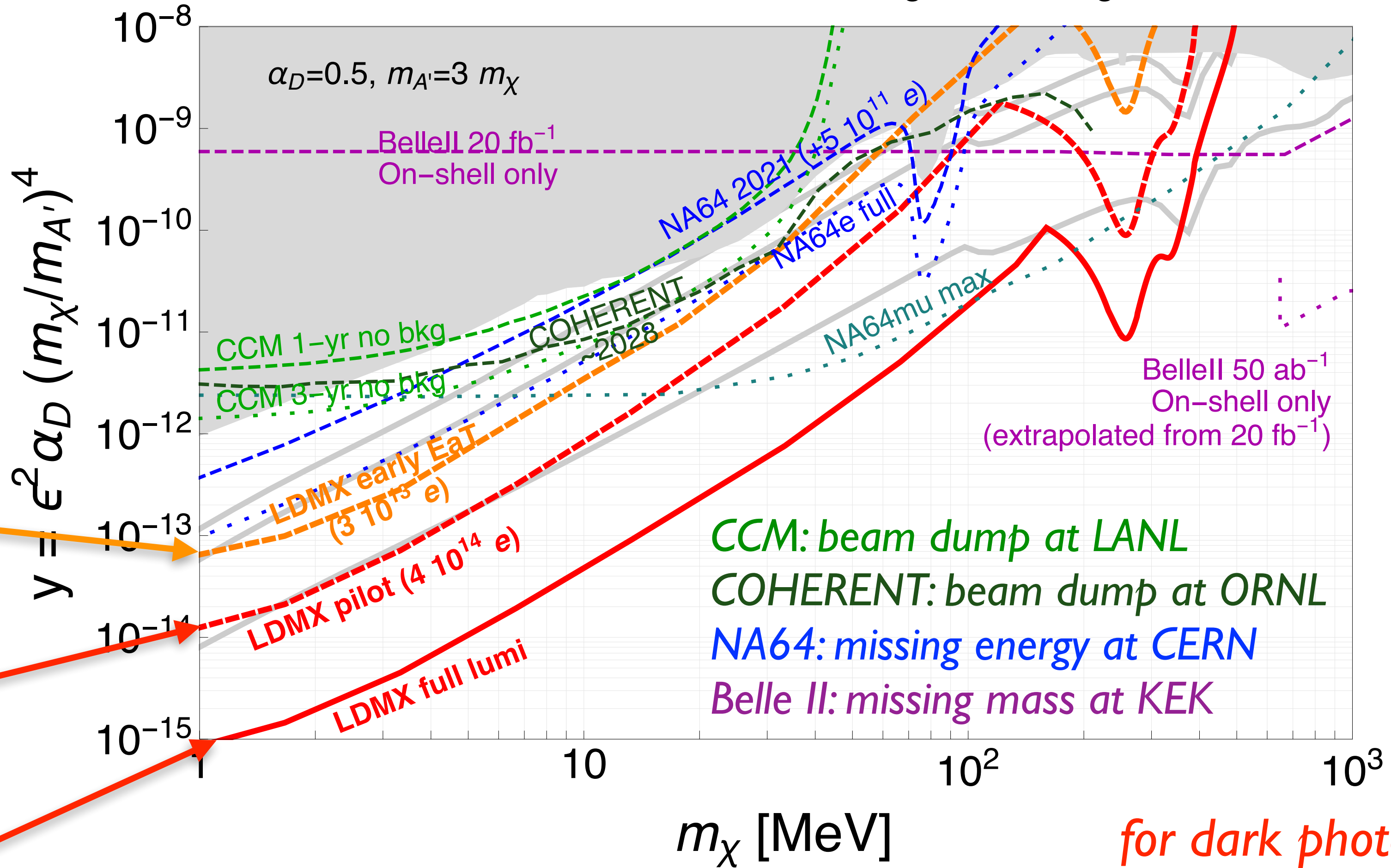
Strategic Opportunity: LDMX

LDMX Design Report [arXiv:2508.11833](https://arxiv.org/abs/2508.11833)



Strategic Opportunity: LDMX

LDMX and World Accelerator Light DM Program



10 days (1 e-/25 ns)
ECal as Target (EaT)
[arXiv:2508.08121](https://arxiv.org/abs/2508.08121)

135 days (1 e-/25 ns)
(10% X₀ tungsten)
JHEP 2020, 3 (2020)

~500 days (2 e-/25 ns)
(thicker target)
JHEP 2023, 92 (2023)

CCM: beam dump at LANL
COHERENT: beam dump at ORNL
NA64: missing energy at CERN
Belle II: missing mass at KEK

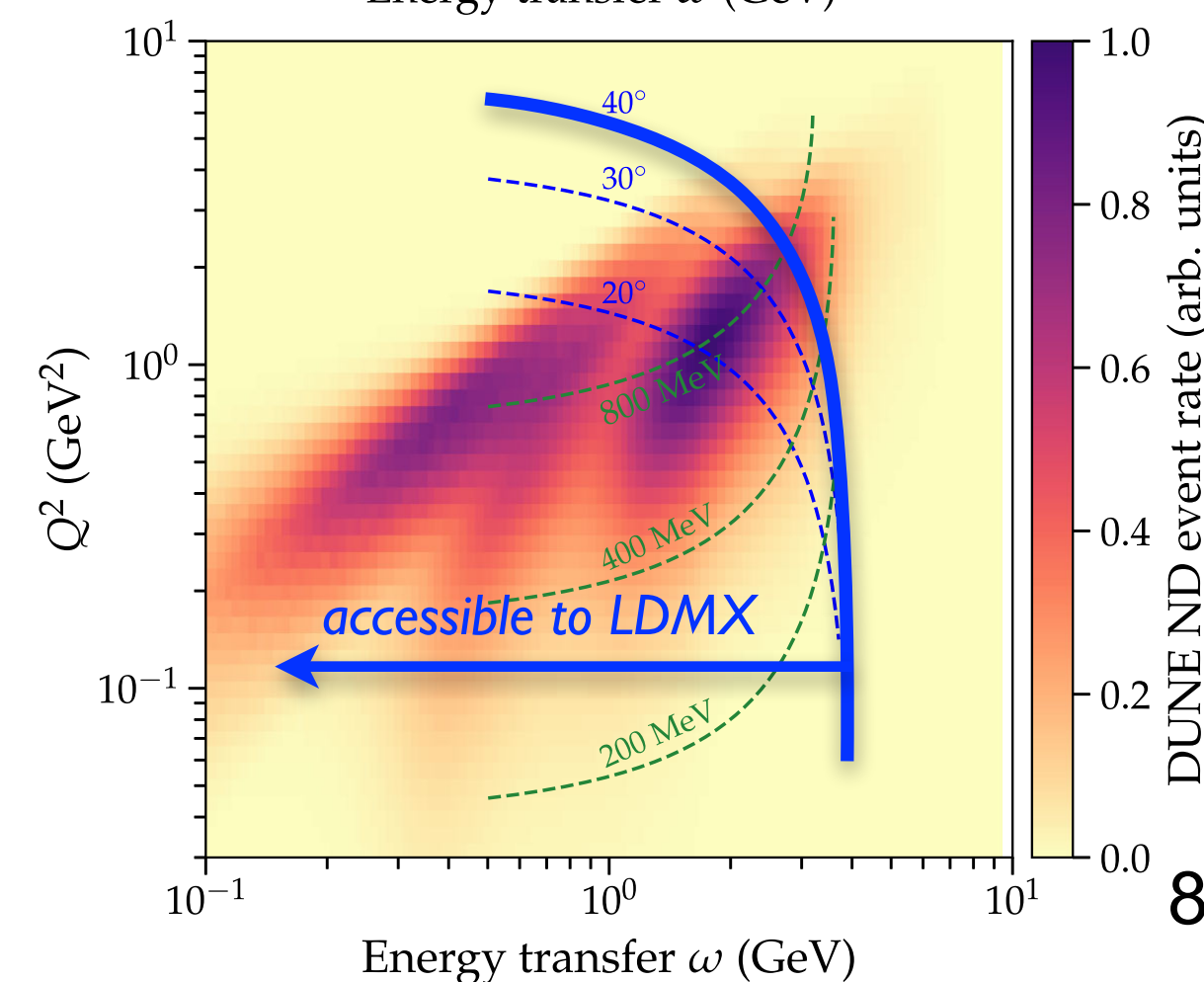
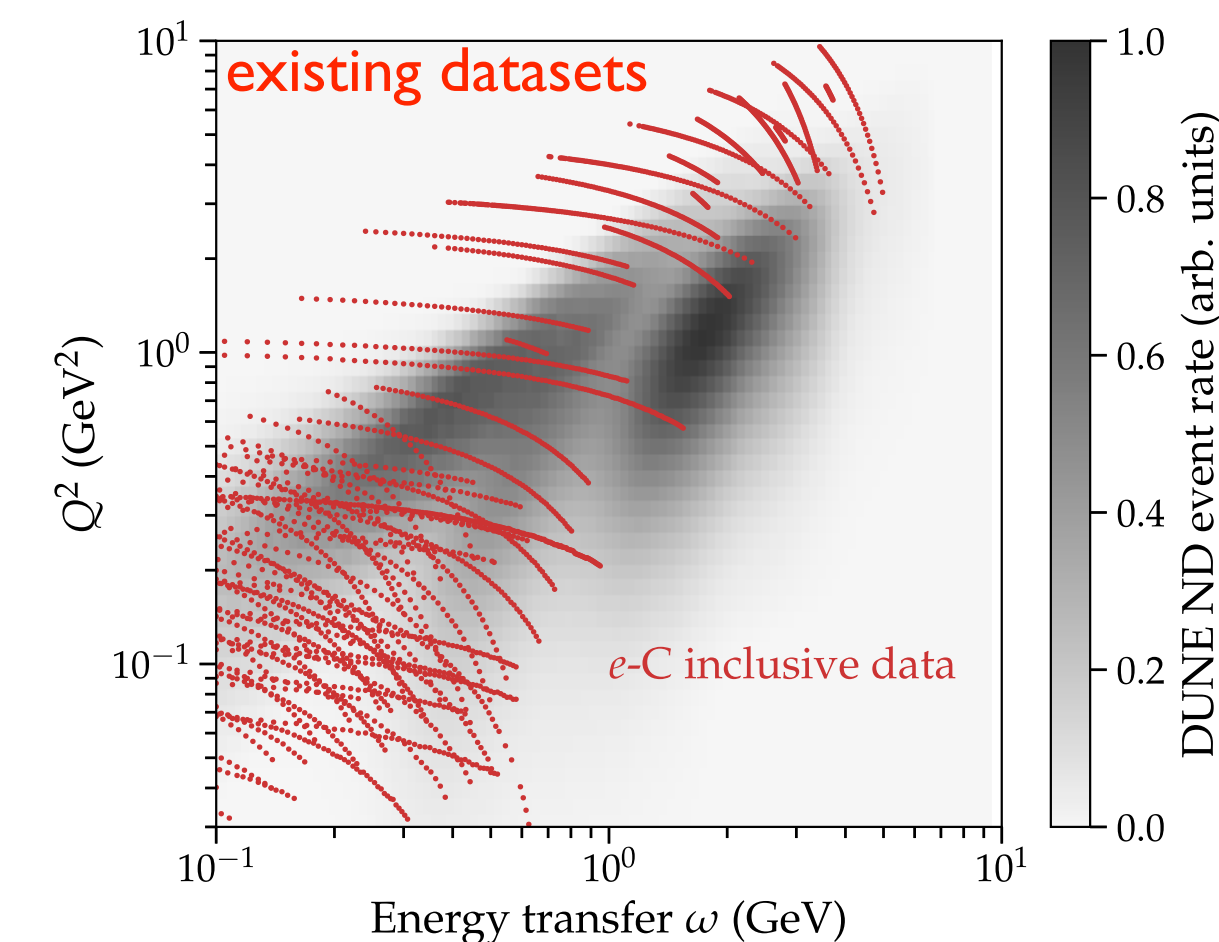
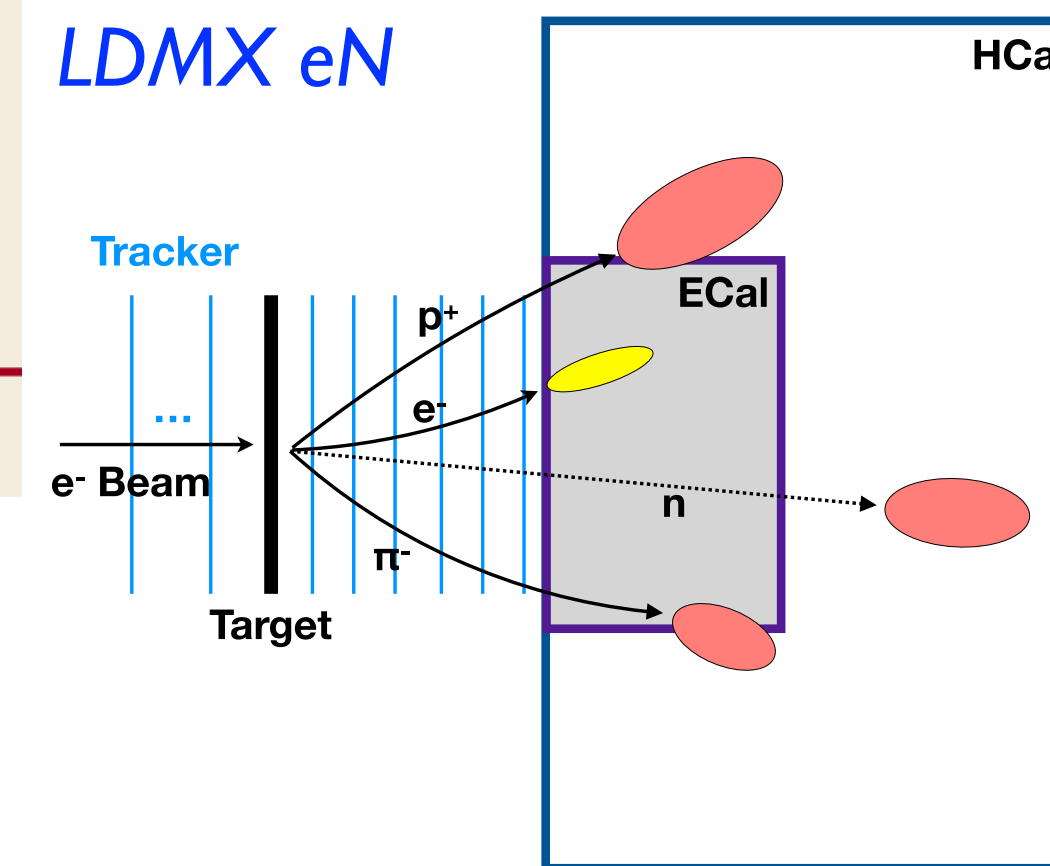
for dark photon mediator
(for other scenarios, see
[arXiv:1807.01730](https://arxiv.org/abs/1807.01730) [hep-ph])

Neutrino Cross-cut & Strategic Opportunity: LDMX eN Capabilities

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

- LDMX plans to run with Ti target to collect relevant data: Currently considering collecting entire dataset with this target!
- Studies to understand critical issues of triggering, acceptance, and particle identification.
- Have discussed what possible adaptations / upgrades might strengthen this program.
- There is an active effort, but much more to do than available effort.

Understanding what LDMX can do, and how it could be adapted or upgraded to better achieve the key goals, is an area for further exploration in developing the strategic plan around LDMX.



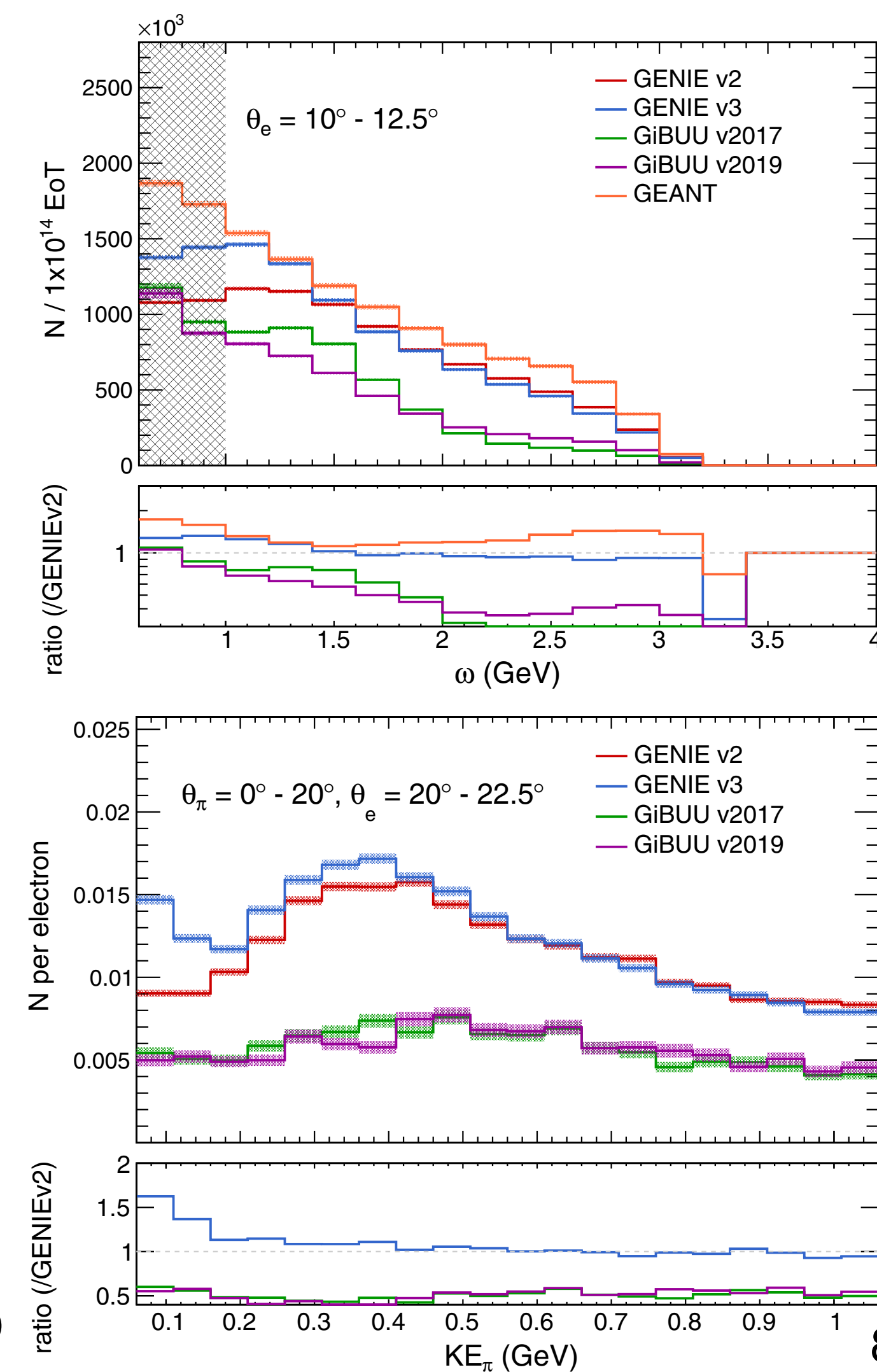
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MC modeling of LDMX observables

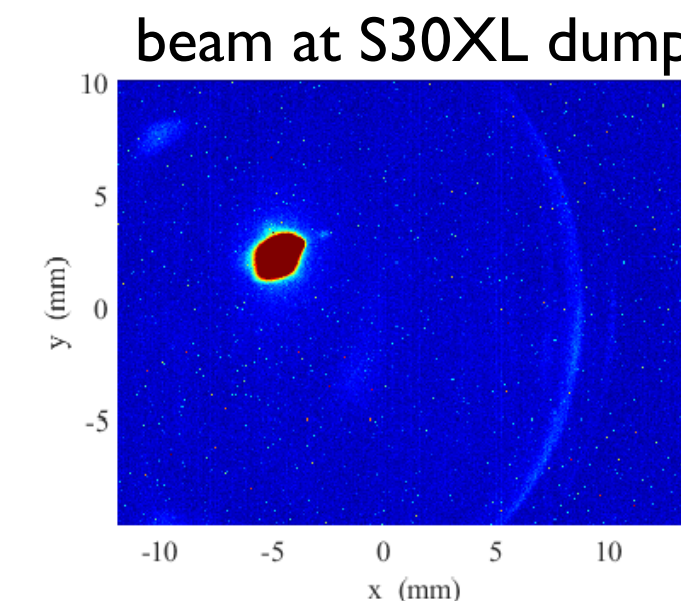
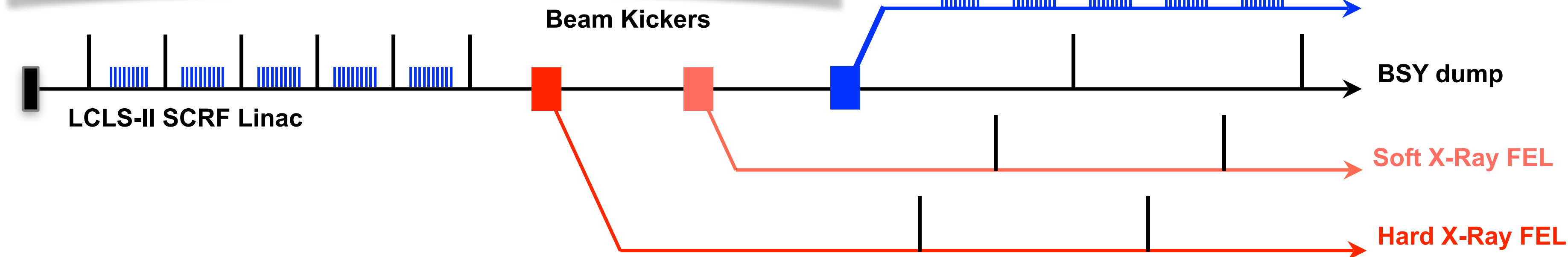
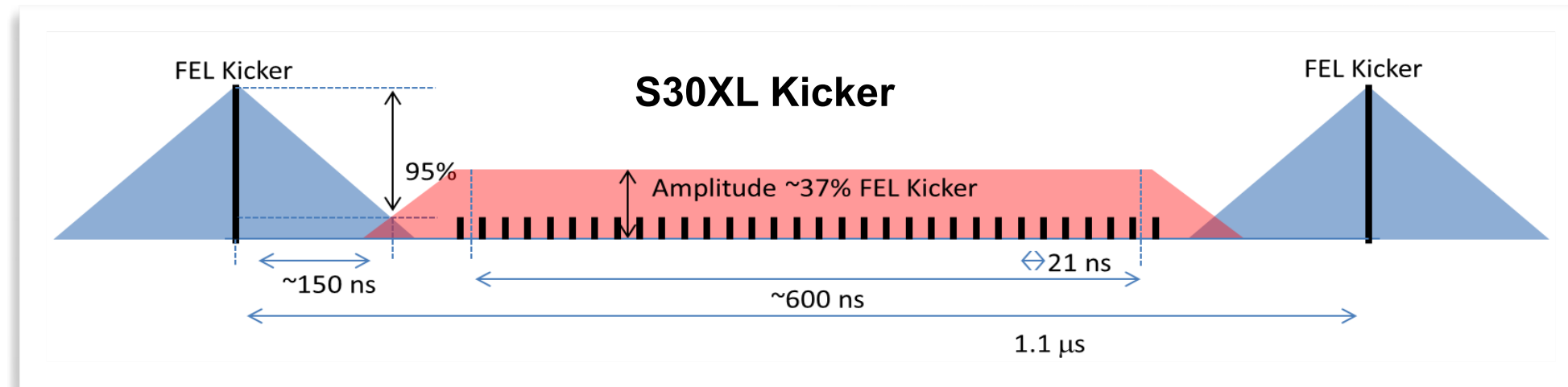
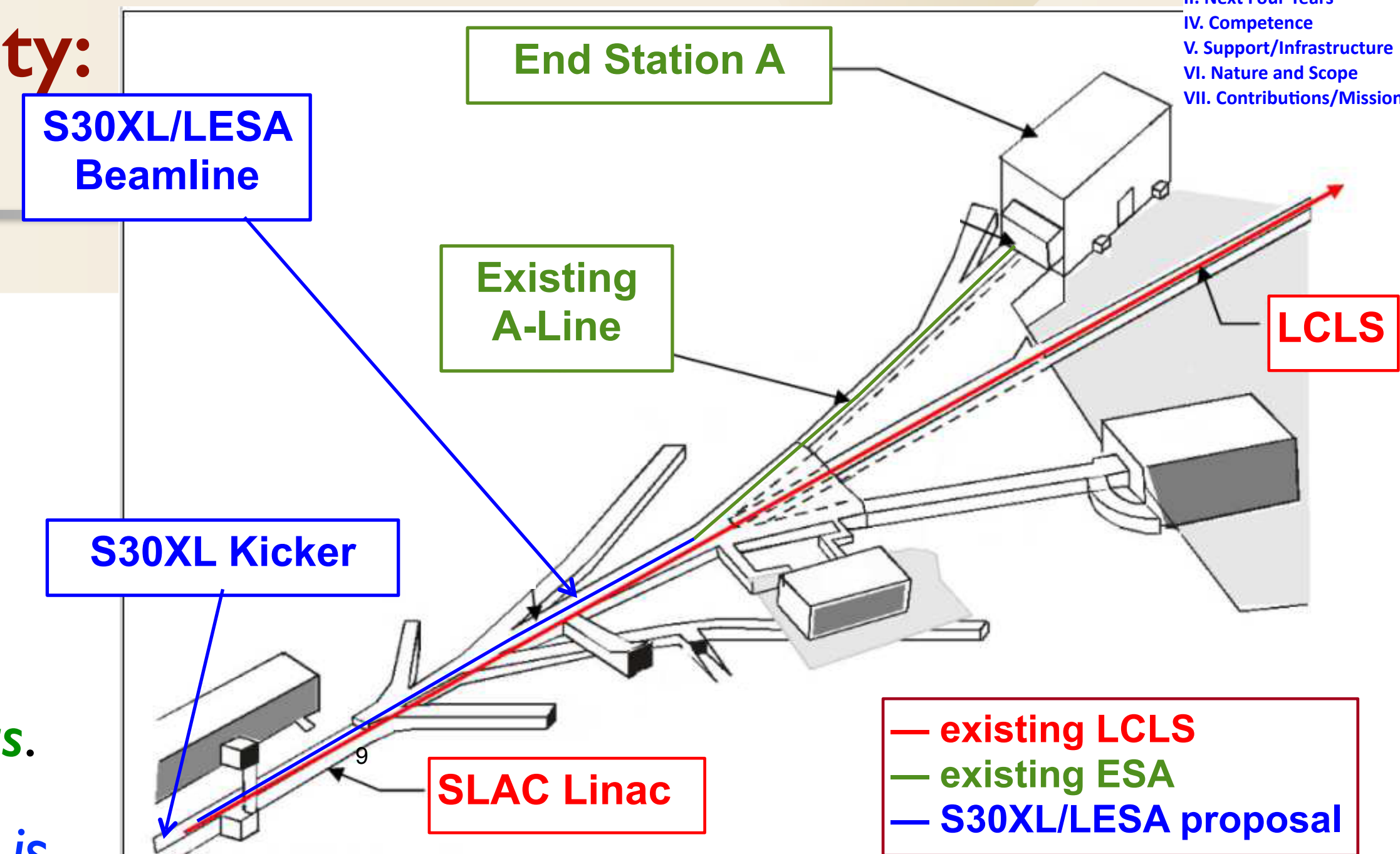


Accelerator Cross-cut & Strategic Opportunity: Linac to End Station A (LESA)

LCLS-II 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) AIP diverts ~60% of unused, low-charge bunches to LESA for LDMX and *other possible experiments*.

LESA is working to deliver beam to ESA in November, and LDMX is preparing a test slice of the detector to operate there in December.



Opportunities beyond LDMX?

...that leverage LESA

- new visible A' searches
 - ideas exist but there are many similar efforts
- dedicated eN experiment
 - physics goals and detector requirements need clarification

...that leverage both

- Adaptation/upgrade of LDMX for rare η decay dark sector / CPV program
 - physics goals and detector requirements need development
- Adaptation/upgrade of LDMX for dedicated eN physics program
 - physics goals and detector requirements need clarification

...that leverage LDMX

- M³ Missing Momentum with Muons @ FNAL
 - technical feasibility unclear
- physics reach needs to be better established

That leverage the neutrino program

- Dark sector searches with the DUNE ND
 - physics capabilities are somewhat narrow

ADDITIONAL SLIDES

Key Takeaways



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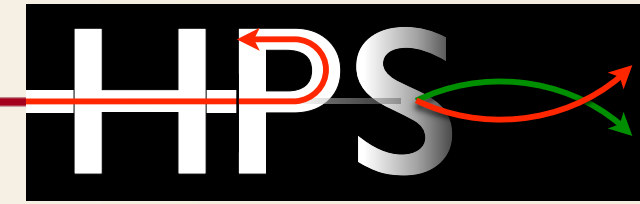
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The HPS Experiment in Hall B at JLab CEBAF



Compact e^+e^- spectrometer, immediately downstream of thin target

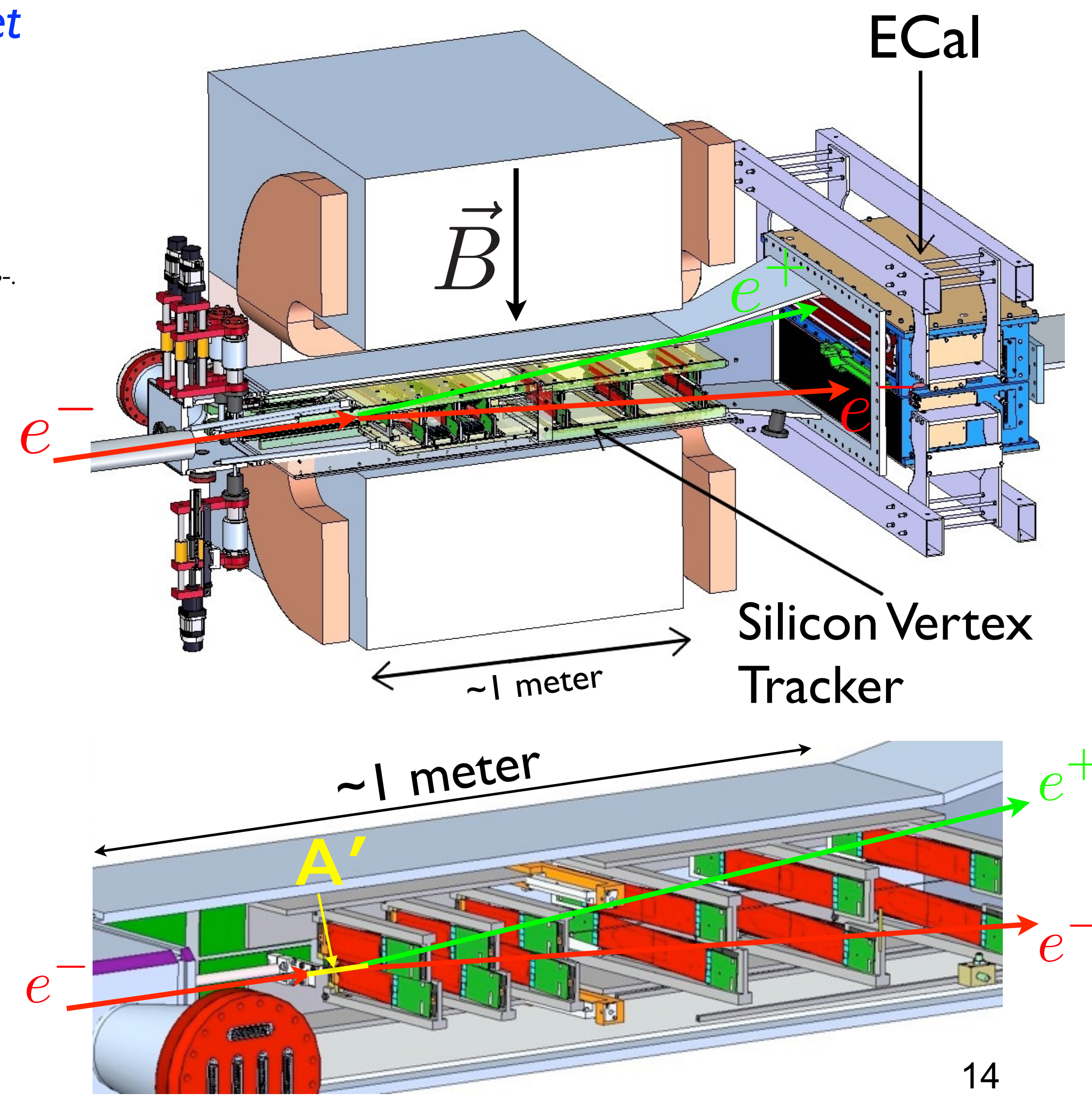
- Low-mass, high-rate (>5 MHz/mm²) silicon tracker (SVT) in vacuum allows vertexing long-lived A' to suppress SM tridents from target by factor $\sim 10^7$.
- PbWO₄ ECal trigger (JLab/INFN/Orsay) eliminates \gg MHz scattered single e^- .

Opportunistic engineering runs collected small samples of physics data in 2015 (1.17 pb⁻¹, 1.056 GeV) and 2016 (10.7 pb⁻¹, 2.3 GeV)

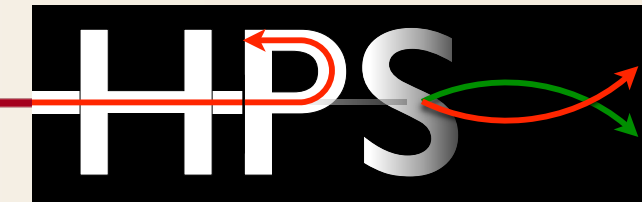
Analyses of 2015 data proved concept and motivated upgrades before first physics run in 2019.

- Added SVT layer closer to target using novel slim-edge sensors \Rightarrow improve vertex resolution ($\sim 2X$)
- Added positron hodoscope in front of ECal for positron-only trigger \Rightarrow increase trigger acceptance for events where e^- escapes along beam

Also motivated working on improvements in analyzing 2016 data.



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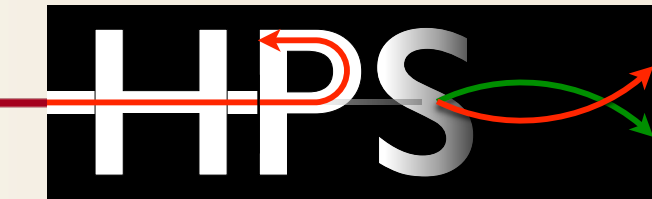
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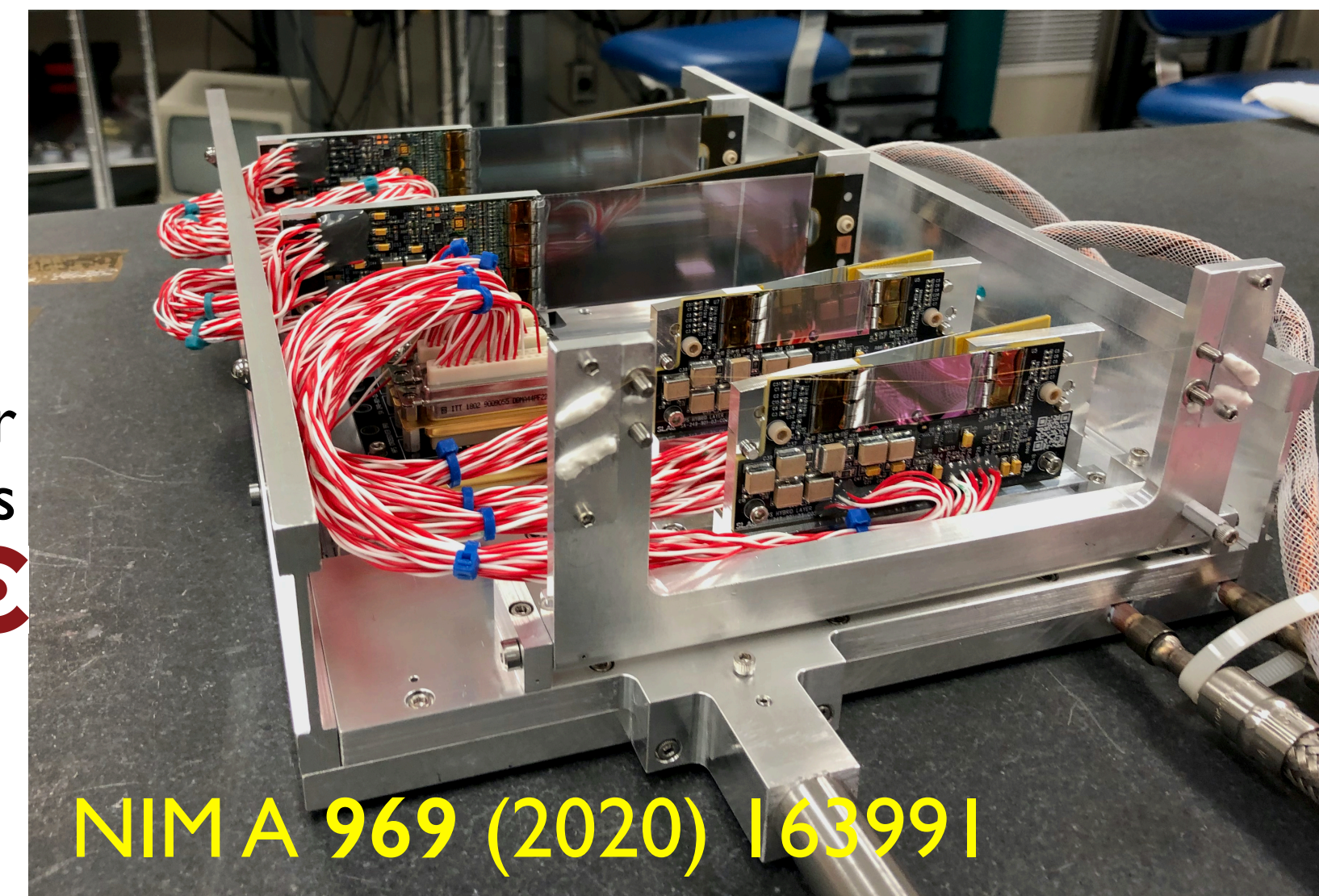
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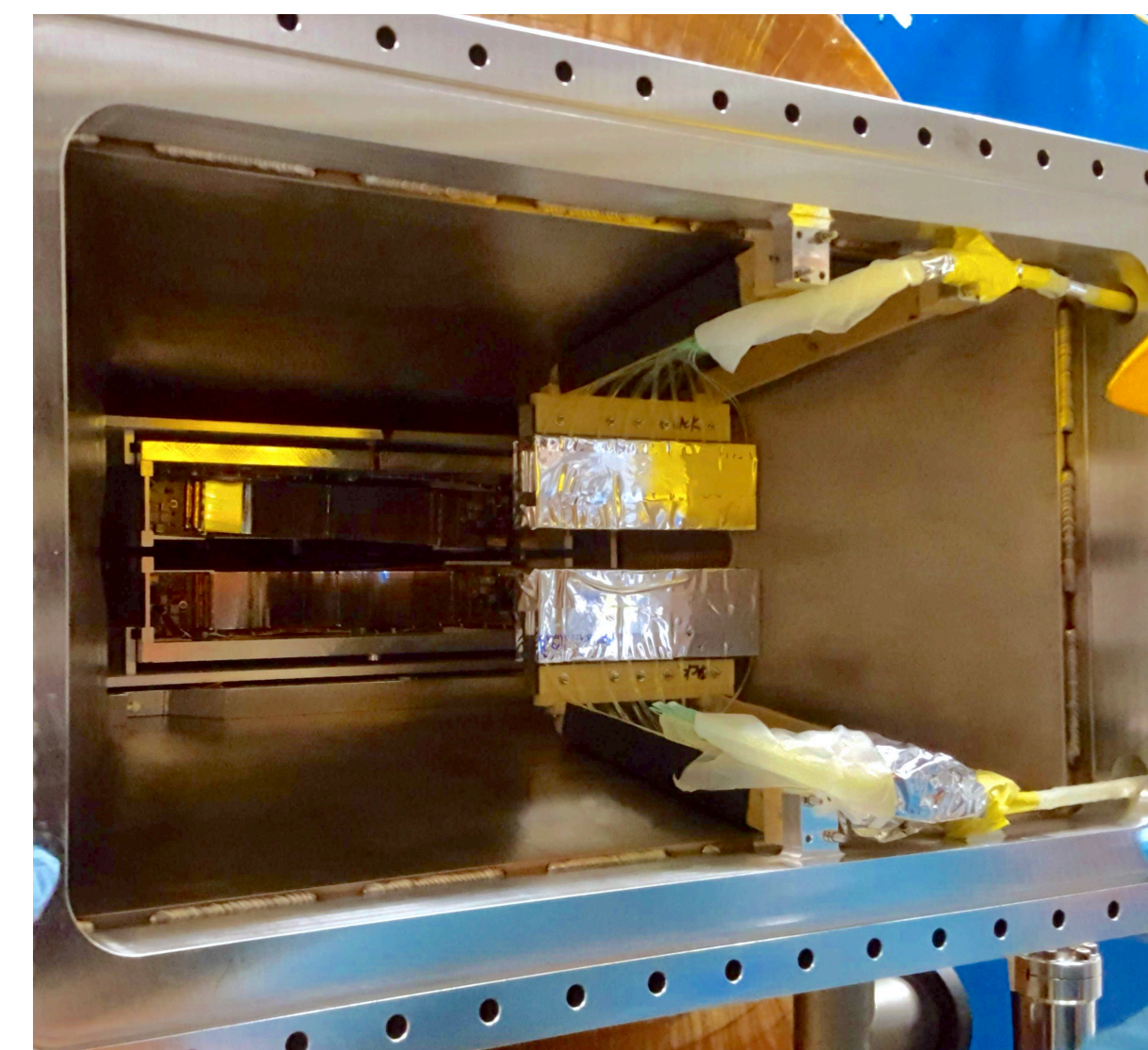
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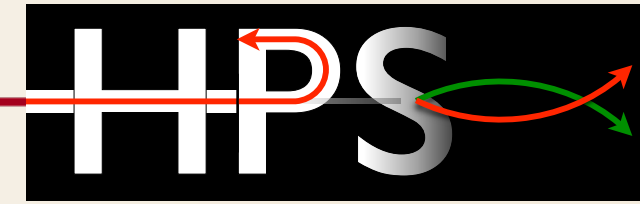
new inner
SVT layers
SLAC



positron
hodoscope
(JLab)



HPS Operations: 2019 — 2021



SVT Upgrade and first physics run just completed at beginning of FY20:

- 229 pb⁻¹ planned, 122 pb⁻¹ delivered. (53%)
- Beam delivery issues impacted data quality, damaged SVT

Additional time allocated in 2021 required keeping focus on operations

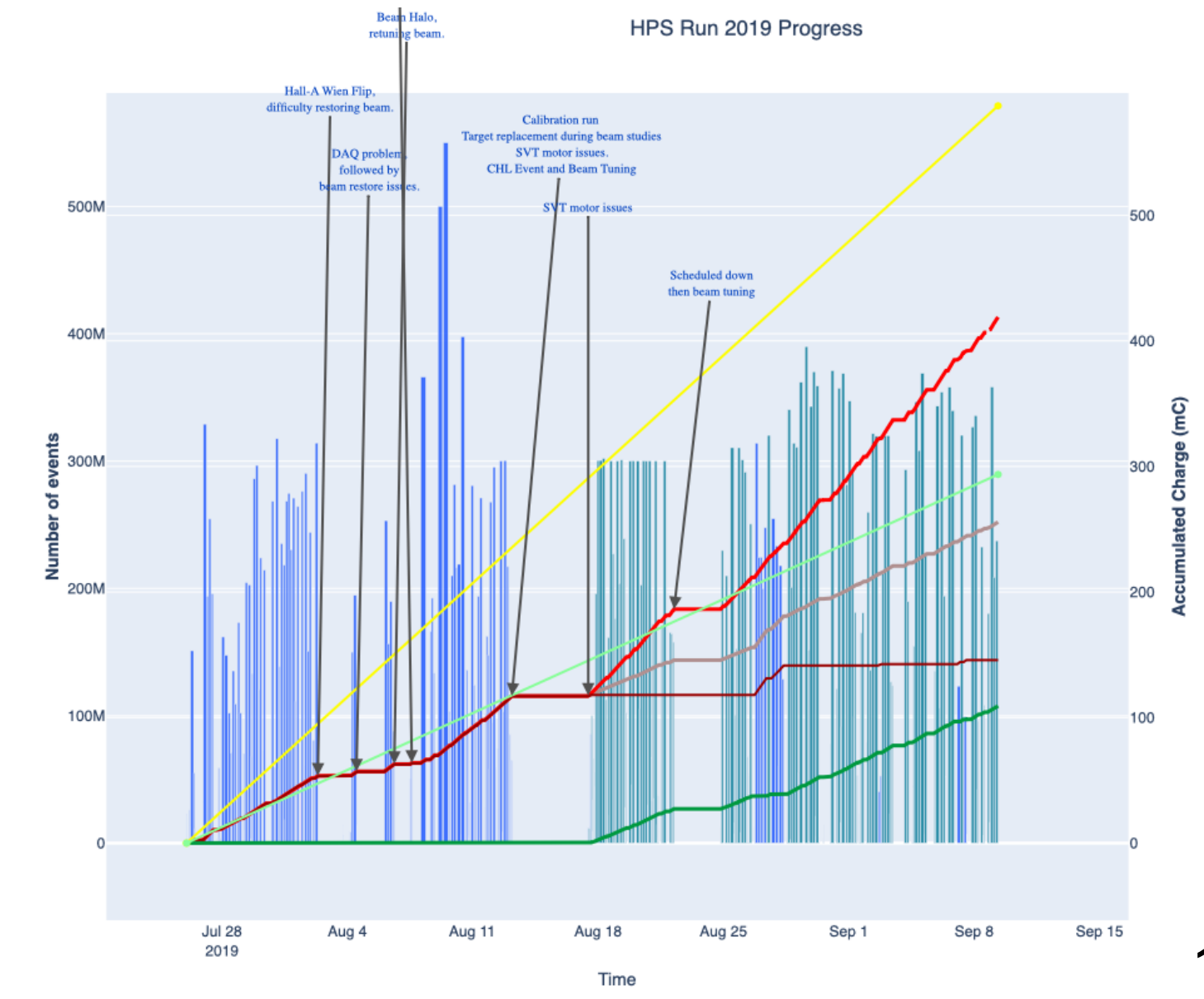
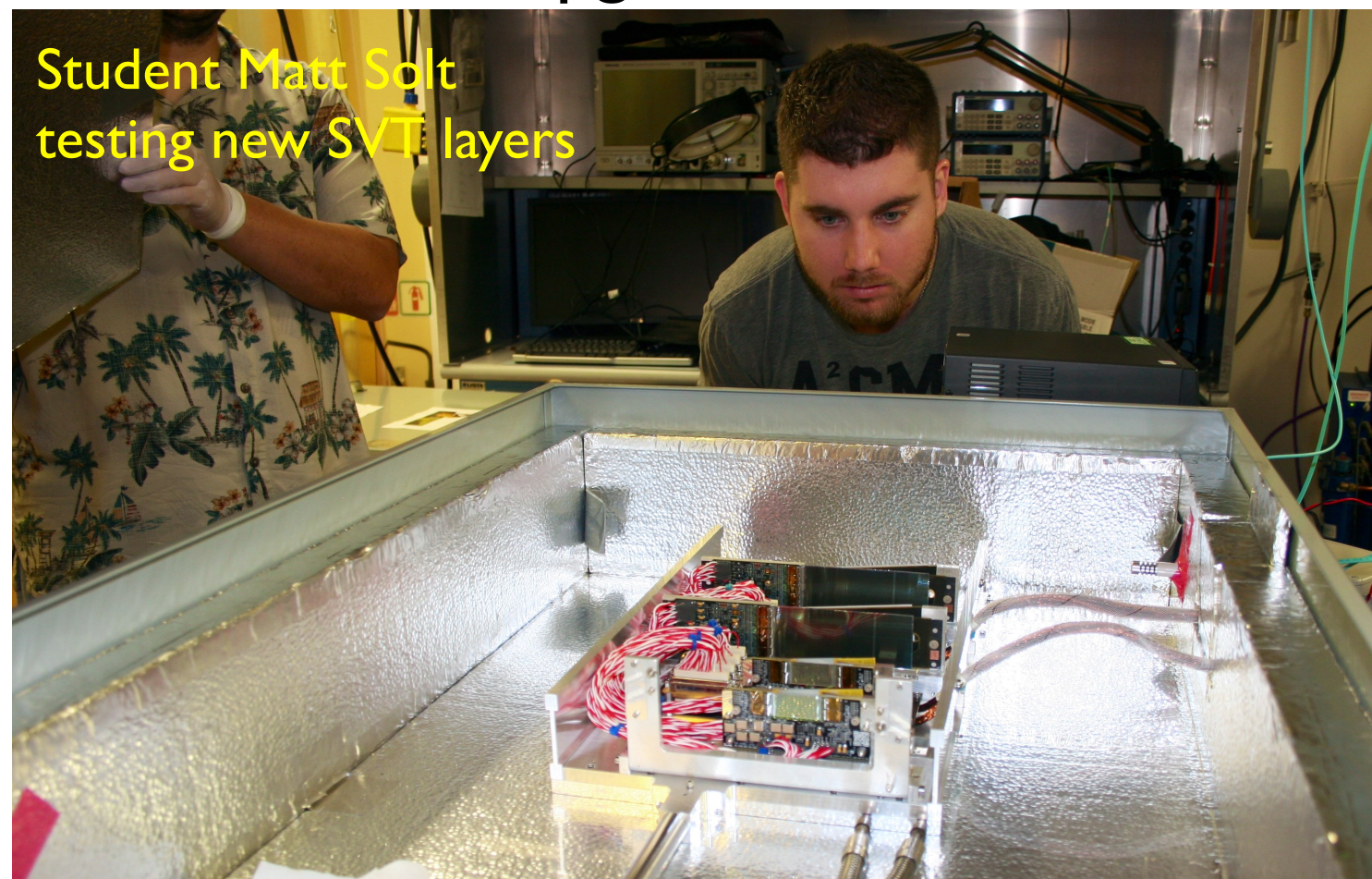
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- redesign and rebuild of slim-edge sensor modules

Despite pandemic restrictions/disruptions (travel/lab work, supply chain), 2021 was relatively smooth:

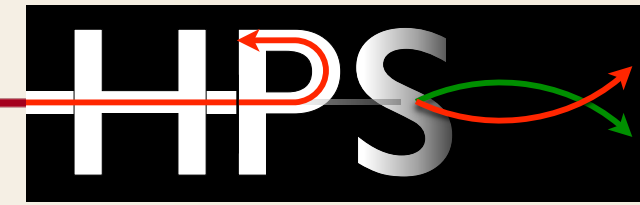
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2019 Upgrade and Run



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2020-2021 SVT Repairs



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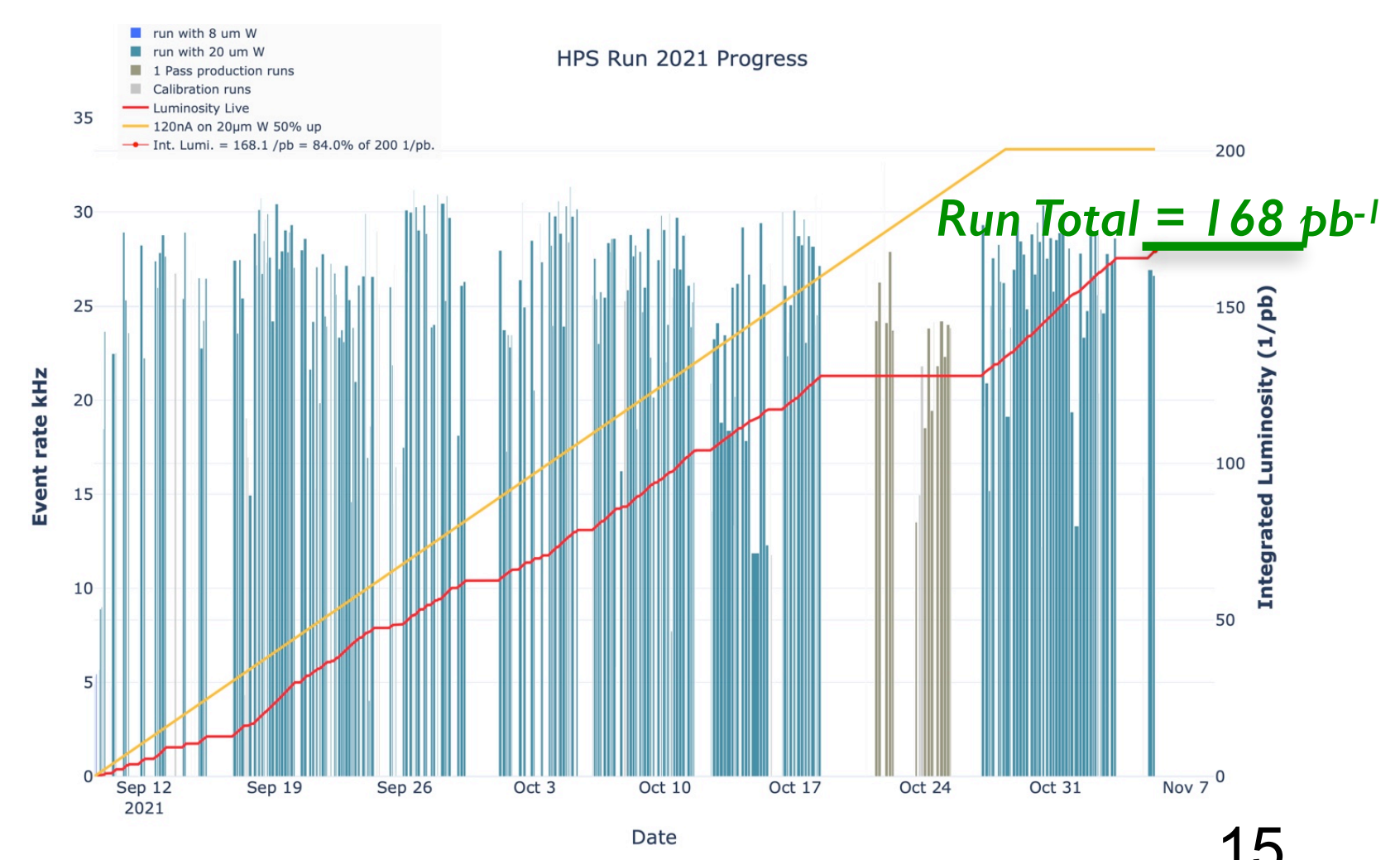
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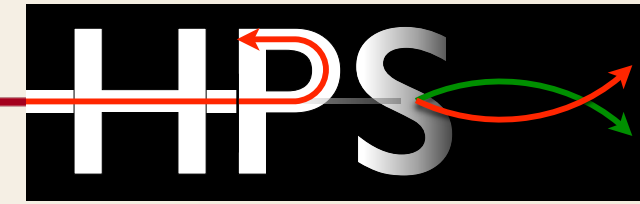
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students and postdocs installing the SVT (sans Tim)



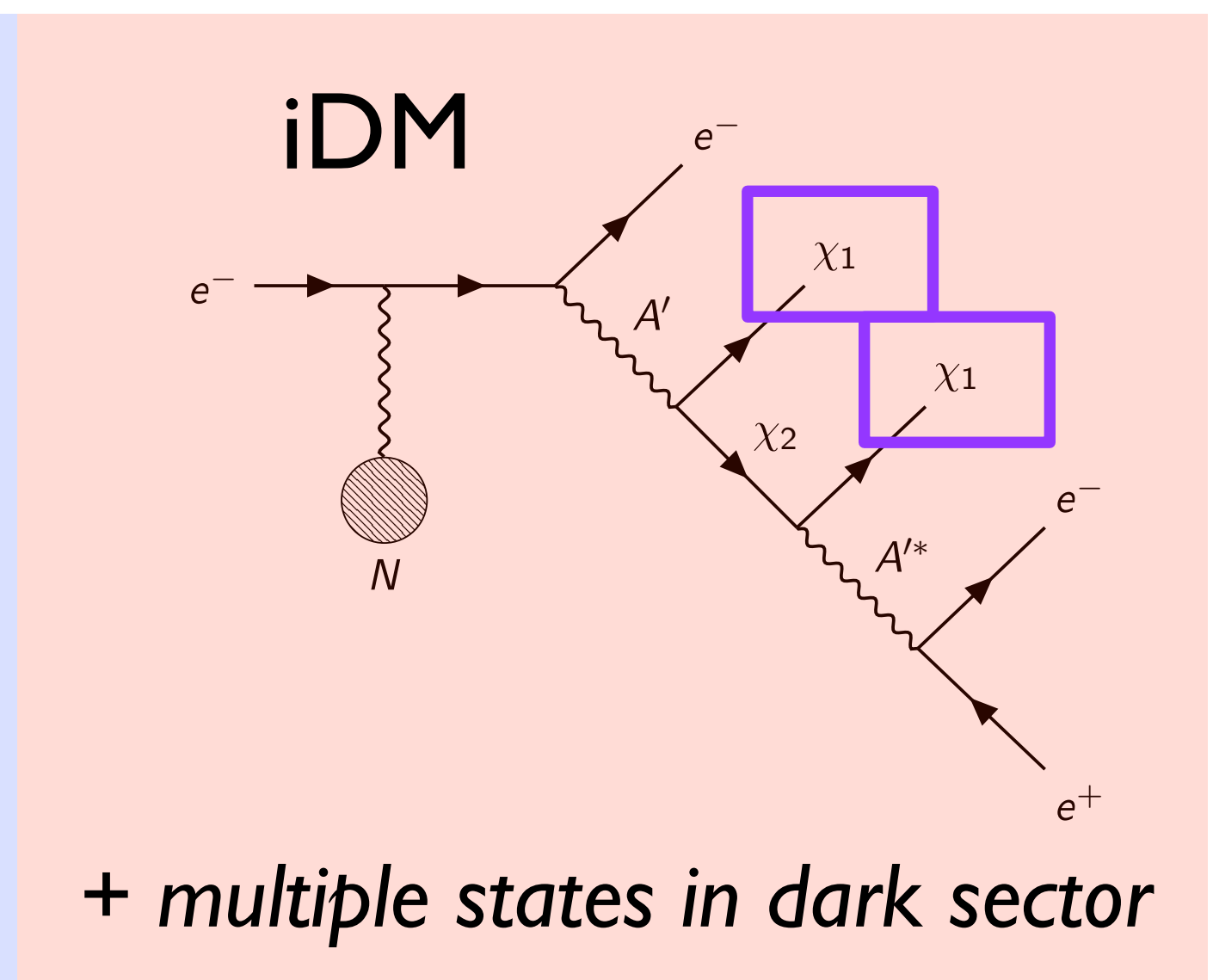
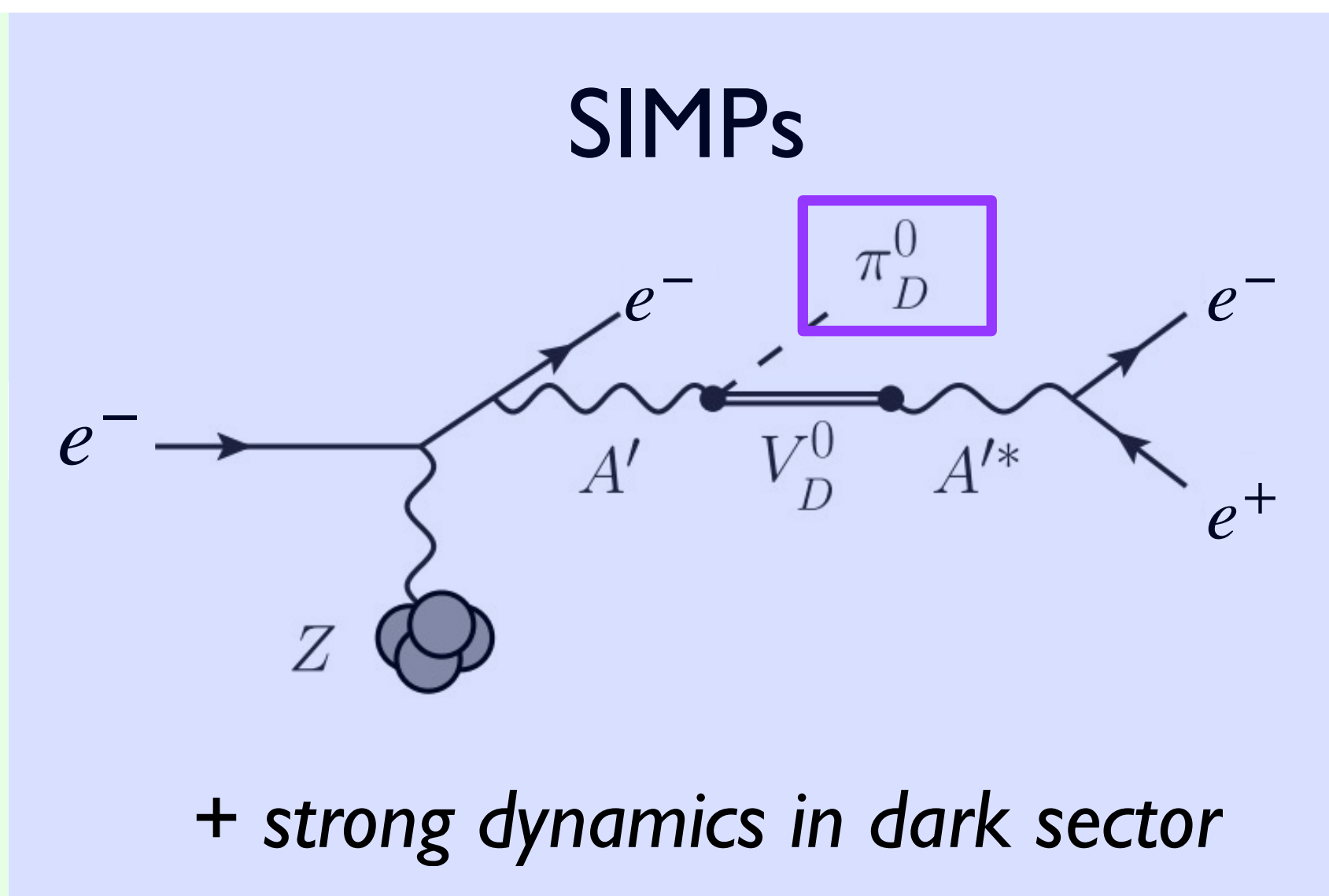
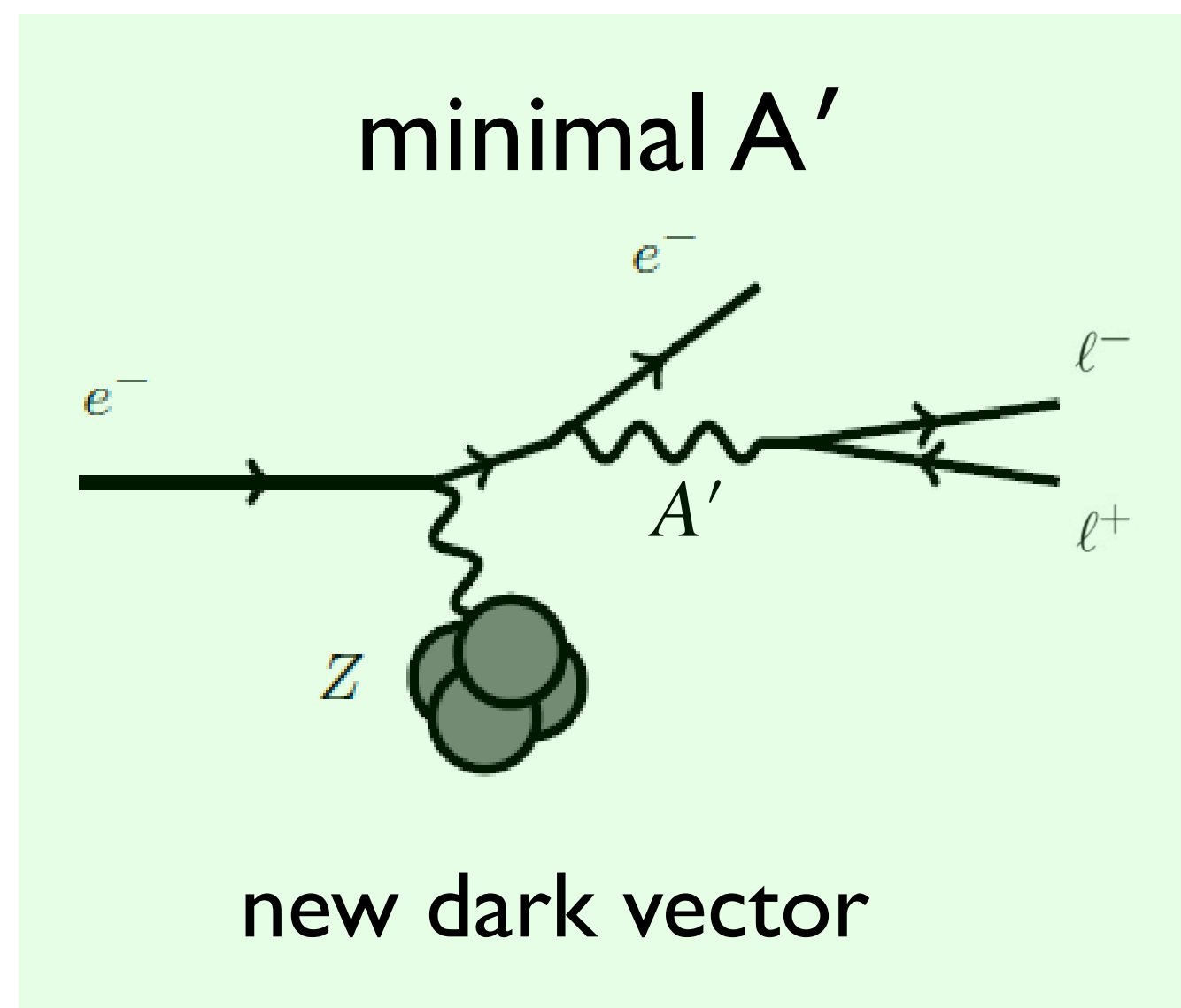
Evolving Landscape in Dark Sector Theory



Increasing interest in exploring richer dark sectors coupled to dark photons

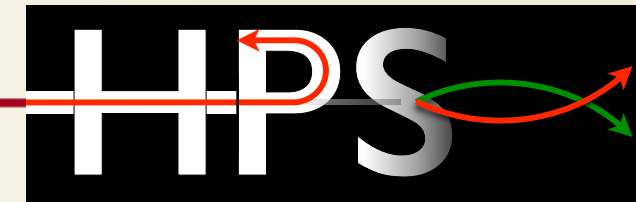
- Strongly Interacting Massive Particles:
⇒ resonant, displaced e^+e^- , \mathcal{E}
- inelastic DM with large mass splittings:
⇒ **non-resonant**, displaced e^+e^- , \mathcal{E}

	Signal			
Signature	Minimal A' $\epsilon^2 \gtrsim 10^{-7}$	Minimal A' $\epsilon^2 \lesssim 10^{-8}$	SIMPs	iDM
$x = \frac{ p_{e^+} + p_{e^-} }{E_{\text{beam}}}$	high	high	low	low
resonance	yes	yes	yes	no
prompt/displaced	prompt	displaced	displaced	displaced



HPS is sensitive to SIMPs, possibly also iDM.

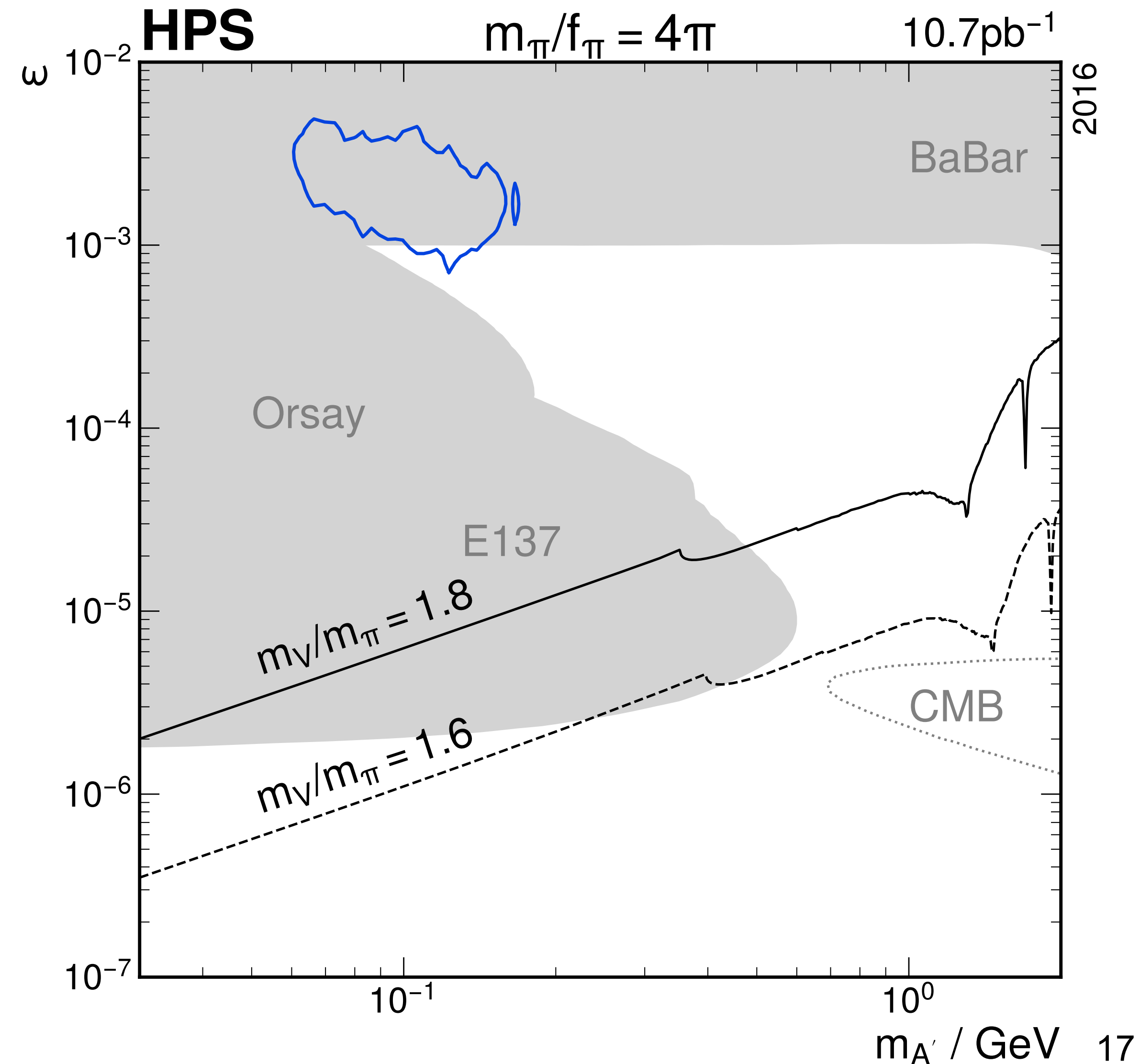
Work in Progress: SIMPs Search



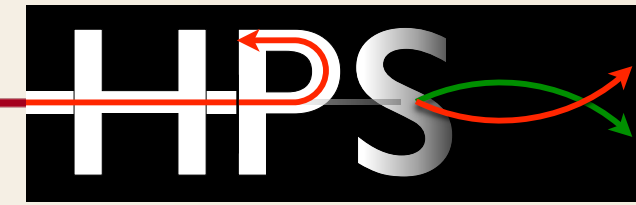
First search for SIMPs on 2016 data in review for publication

- A nice demonstration of how HPS program can be extended to address evolving dark sector physics
- We would like to return to some other scenarios (e.g. ALPs, iDM) to see what HPS can do there also.

Is there other physics potential in HPS data that we just haven't considered?



HPS Operations Plans and Sensitivity



With 105/180 days of approved operations remaining, status and future plans were reviewed by JLab PAC in July: HPS is re-approved with “A” rating.

Sensitivity for displaced A' search based on techniques from PRD used as benchmark for optimization:

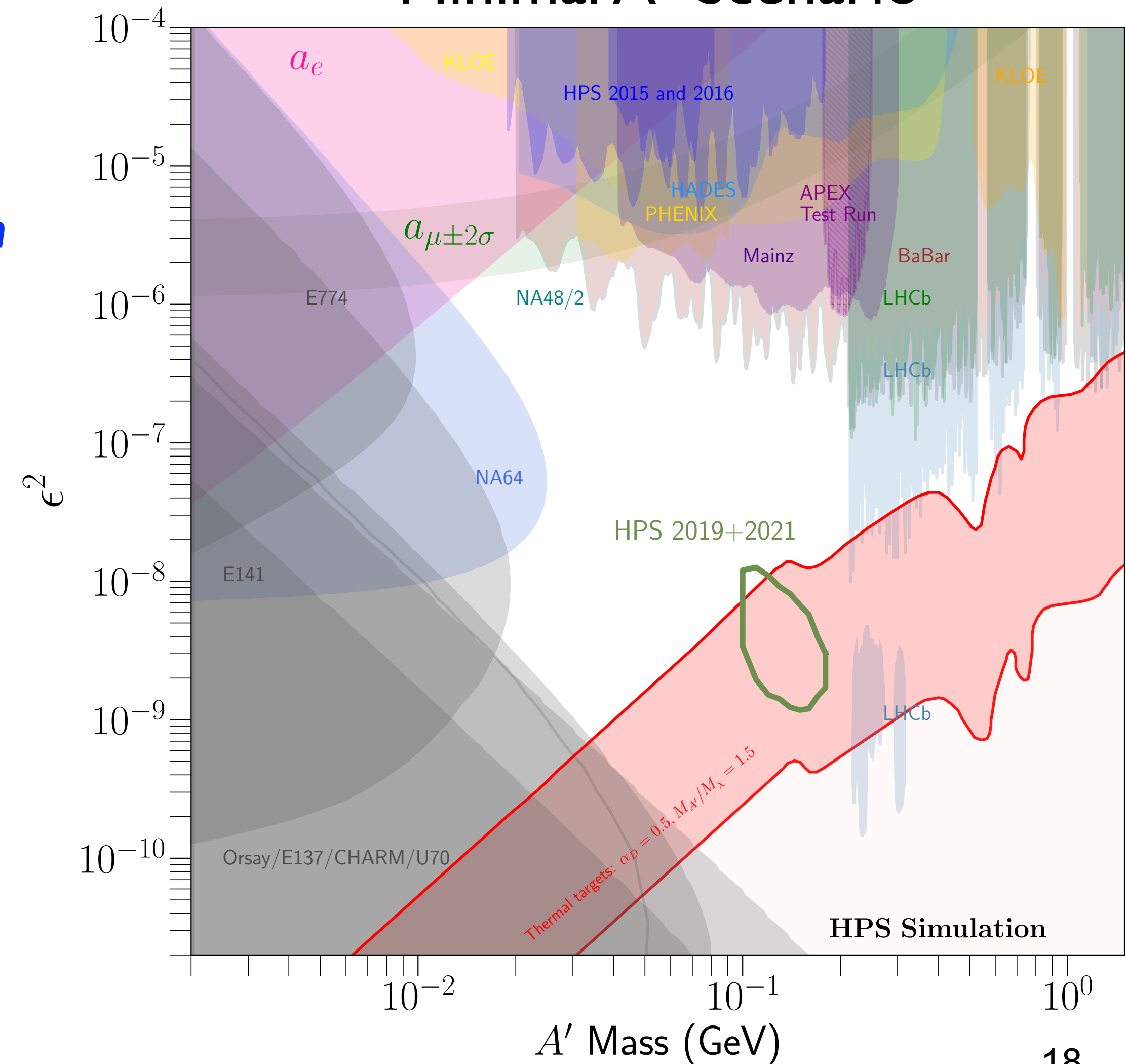
- existing data (75 days) opens up significant region of sensitivity
- future run plan (105 days) more than doubles this region

Optimum is ~7 weeks at ≈ 4 GeV and ~6 weeks at ≈ 2 GeV

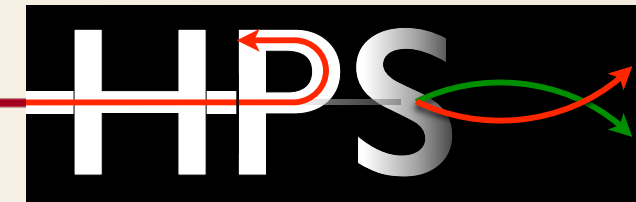
- HPS has requested and is planning 60 PAC days of 4 GeV running, to be followed by a final one-pass run at 2 GeV.

HPS is not close to saturating its sensitivity, which grows almost linearly even beyond approved time.

Minimal A' Scenario



HPS Operations Plans and Sensitivity



With 105/180 days of approved operations remaining, status and future plans were reviewed by JLab PAC in July: HPS is re-approved with “A” rating.

Sensitivity for displaced A' search based on techniques from PRD used as benchmark for optimization:

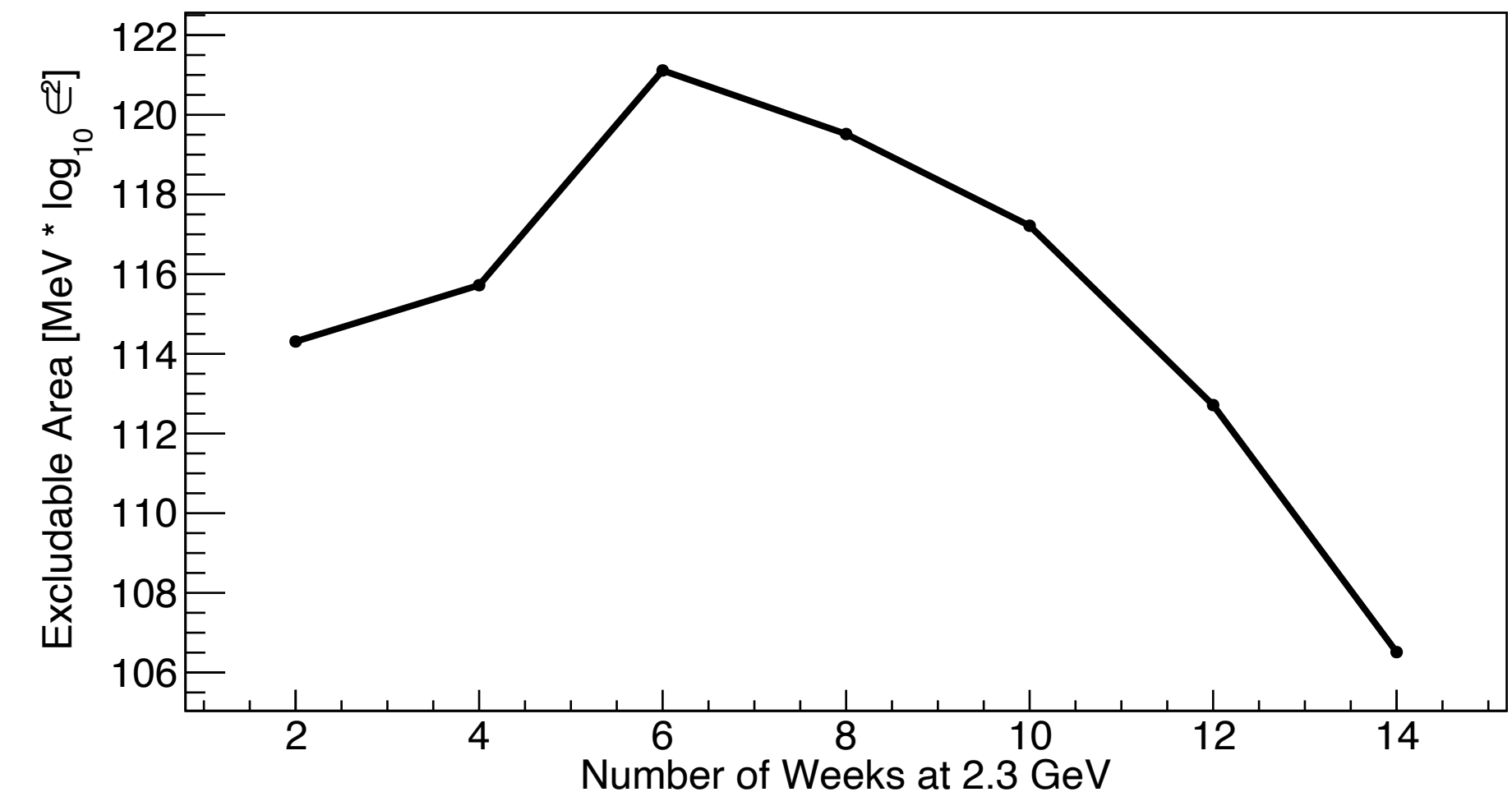
- existing data (75 days) opens up significant region of sensitivity
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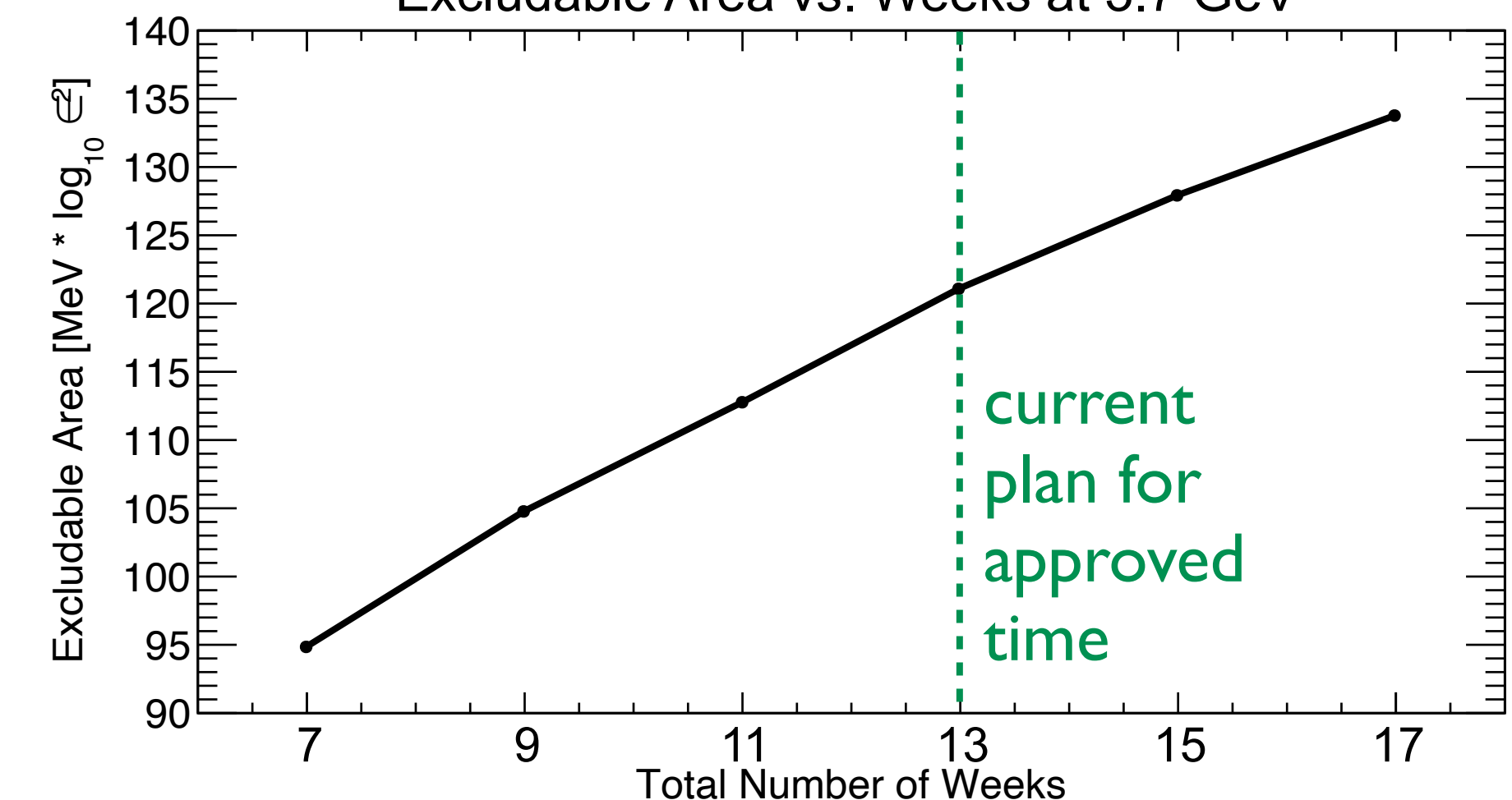
- HPS has requested and is planning 60 PAC days of 4 GeV running, to be followed by a final one-pass run at 2 GeV.

HPS is not close to saturating its sensitivity, which grows almost linearly even beyond approved time.

13 Total Weeks @ 2.3 and 3.7 GeV



Excludable Area vs. Weeks at 3.7 GeV



The LDMX Experiment

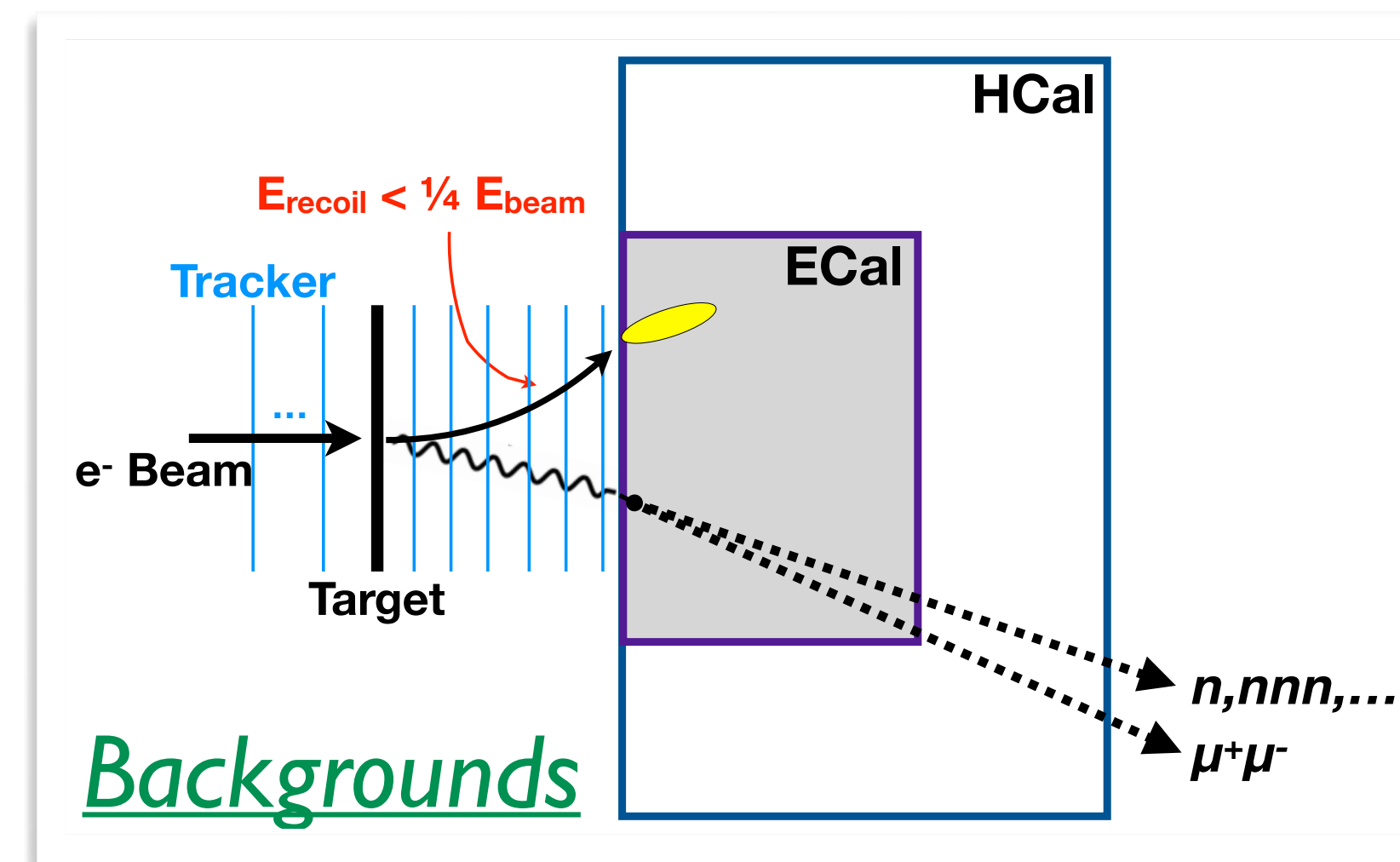
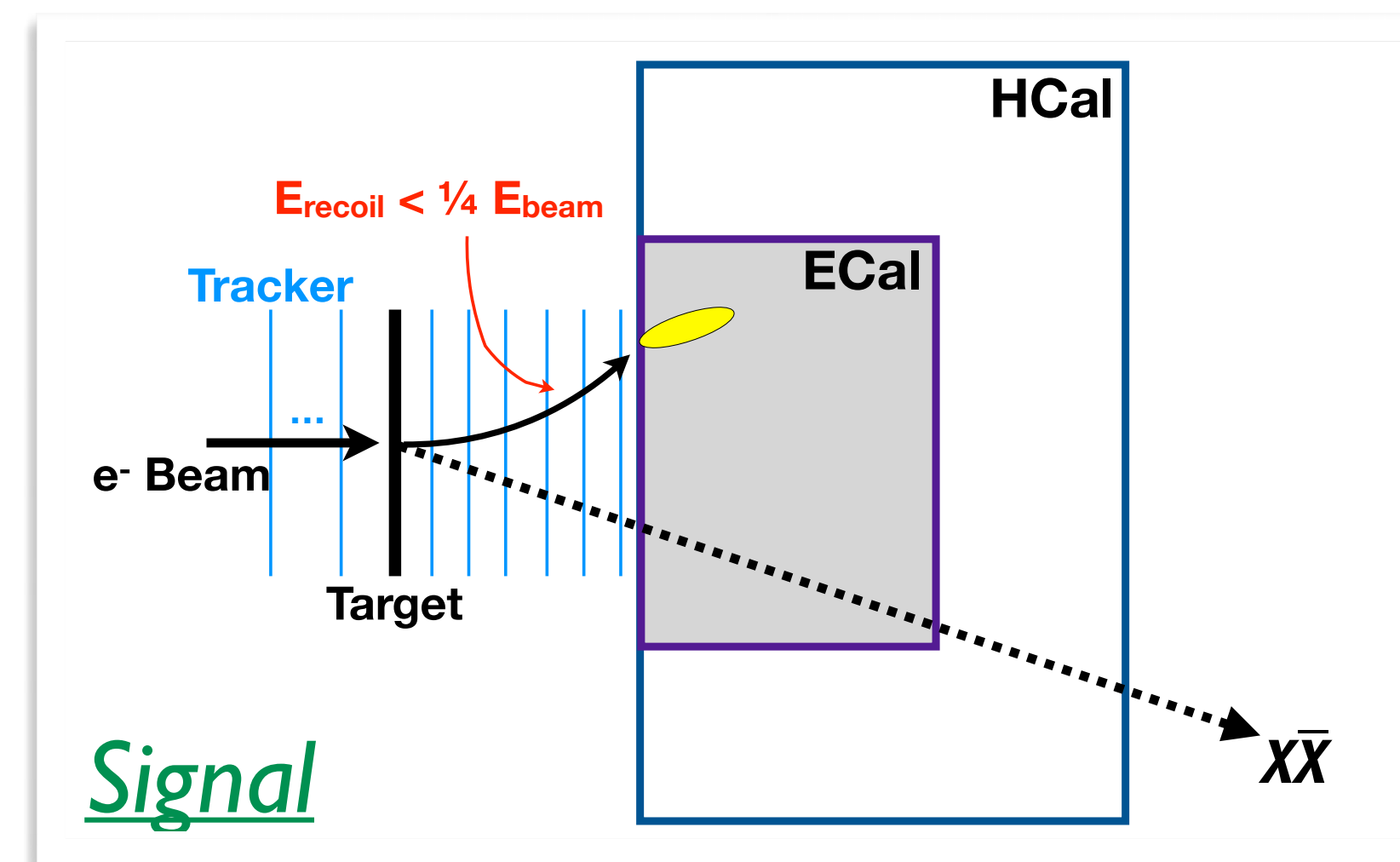
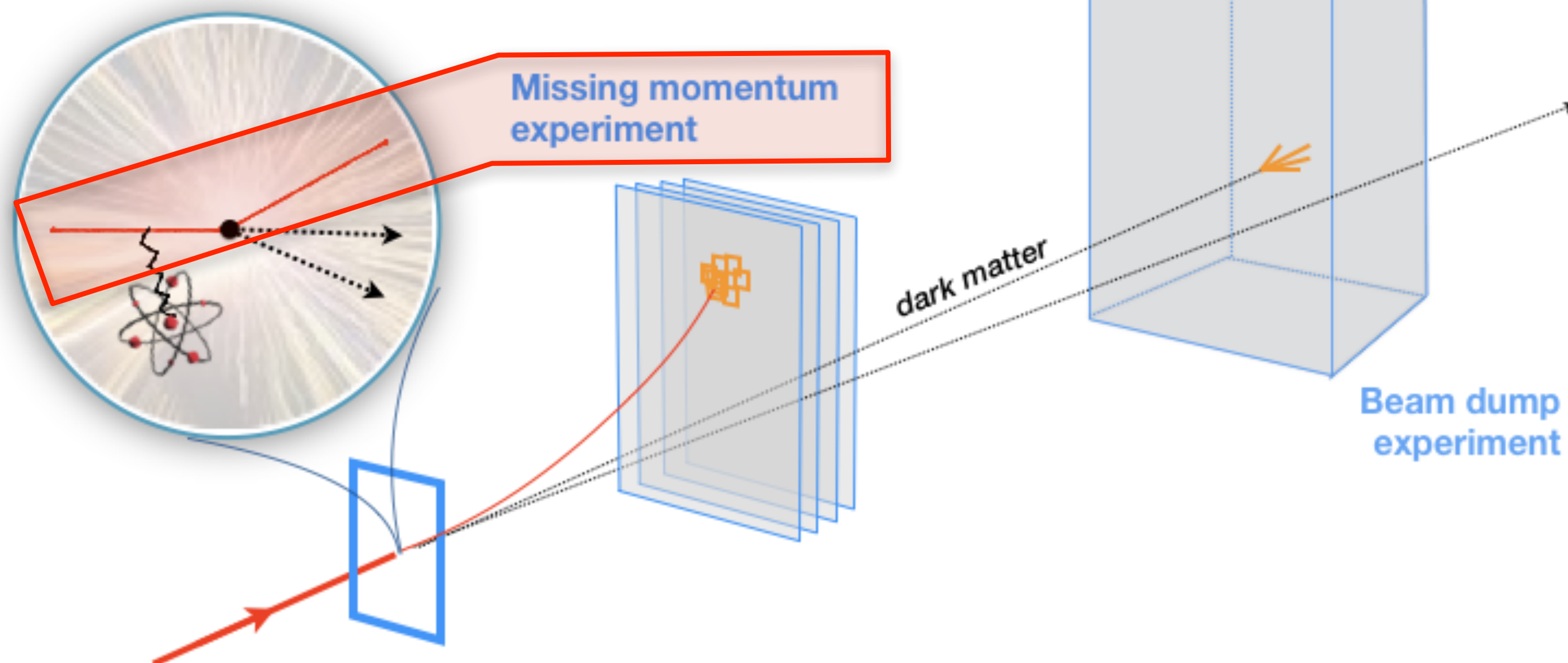


DMNI BRN Priority Research Direction 1

Thrust 1 (near term): Through 10- to 1000-fold improvements in sensitivity over current searches, use particle beams to explore interaction strengths singled out by thermal dark matter across the electron-to-proton mass range.

Missing momentum experiments, using modern detectors operating directly in a low-current lepton beam, identify dark matter production events based on the kinematics of visible particles recoiling from the production event. Such experiments in a continuous-wave electron beam offer a path to reach 1000-fold improvement in sensitivity over a broad mass range ...

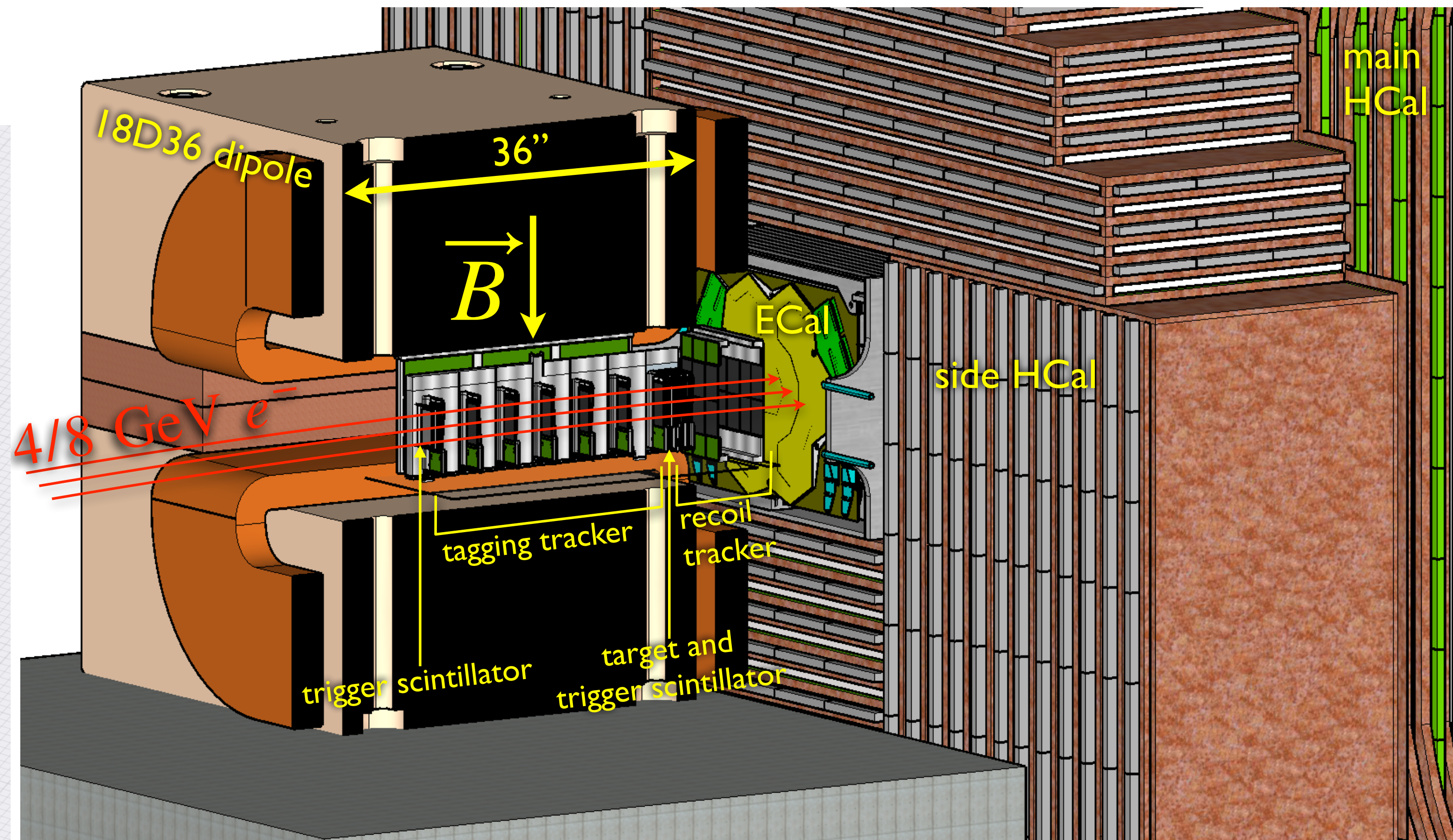
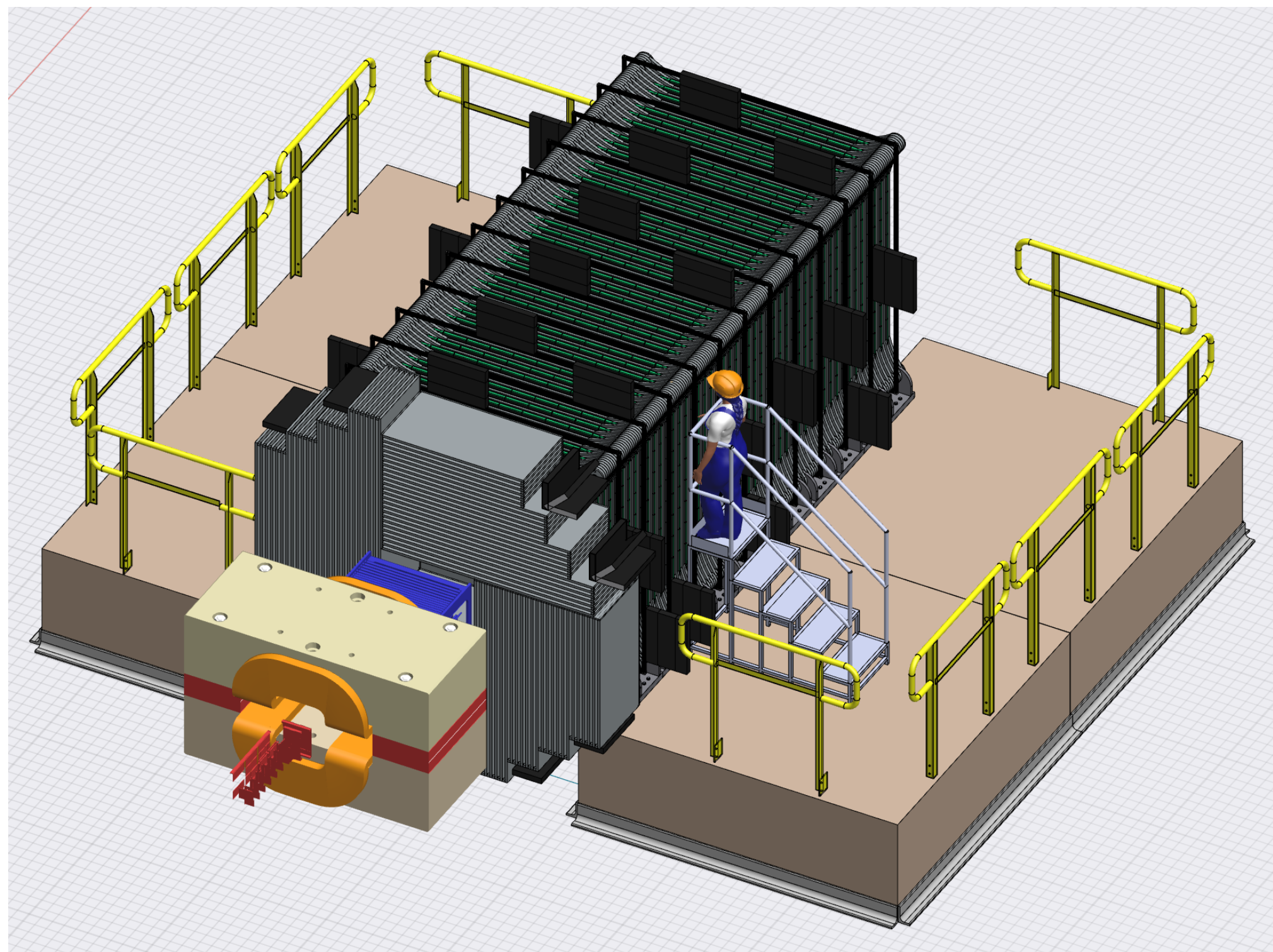
RECREATING BIG BANG DARK MATTER PRODUCTION AT ACCELERATORS



The LDMX Experiment



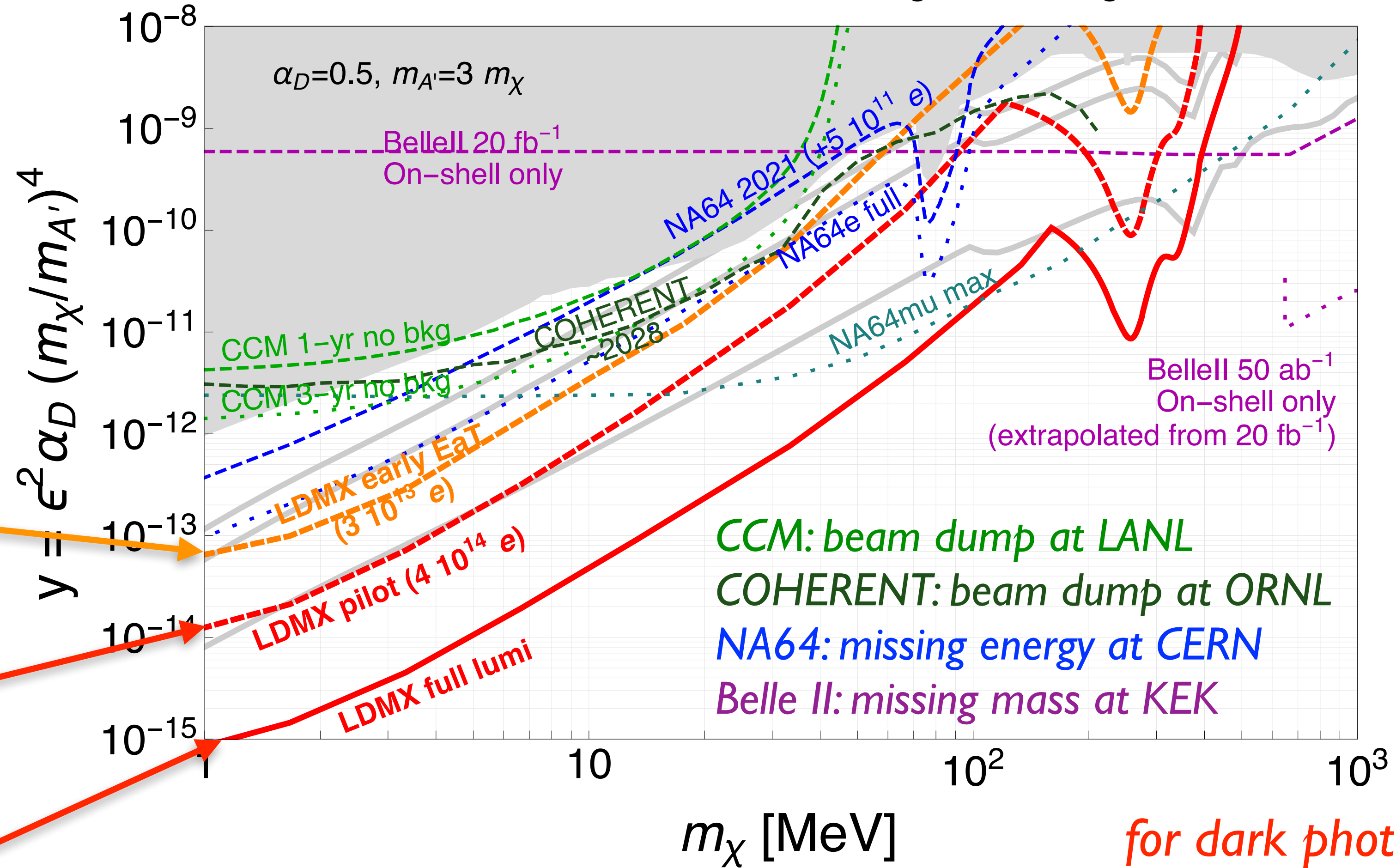
LDMX Whitepaper [arXiv:1808.05219](https://arxiv.org/abs/1808.05219)



The LDMX Experiment



LDMX and World Accelerator Light DM Program



10 days (1 e-/25 ns)
 ECal as Target (EaT)
 [paper in draft]

135 days (1 e-/25 ns)
 (10% X₀ tungsten)
 JHEP 2020, 3 (2020)

~500 days (2 e-/25 ns)
 (thicker target)
 JHEP 2023, 92 (2023)

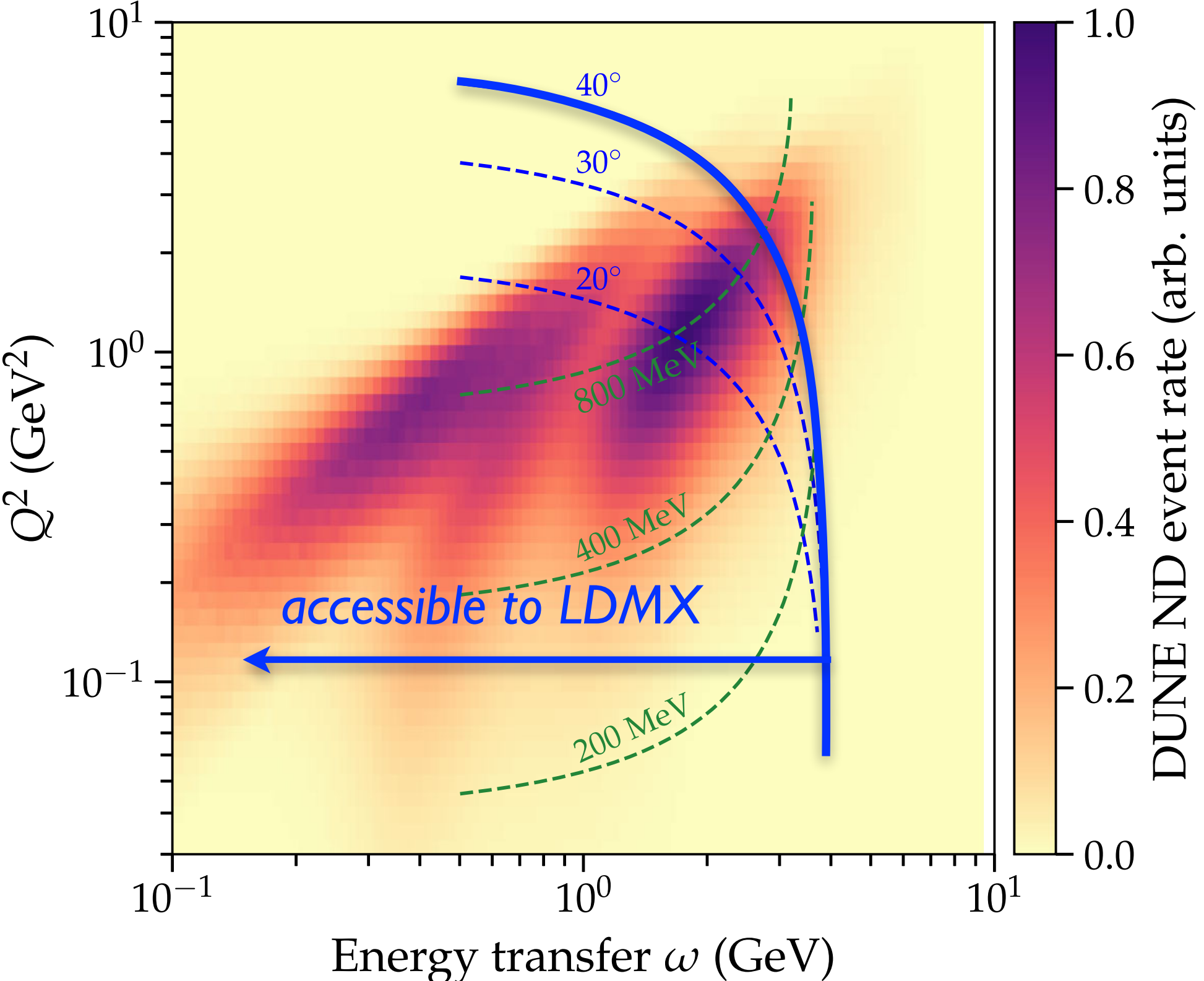
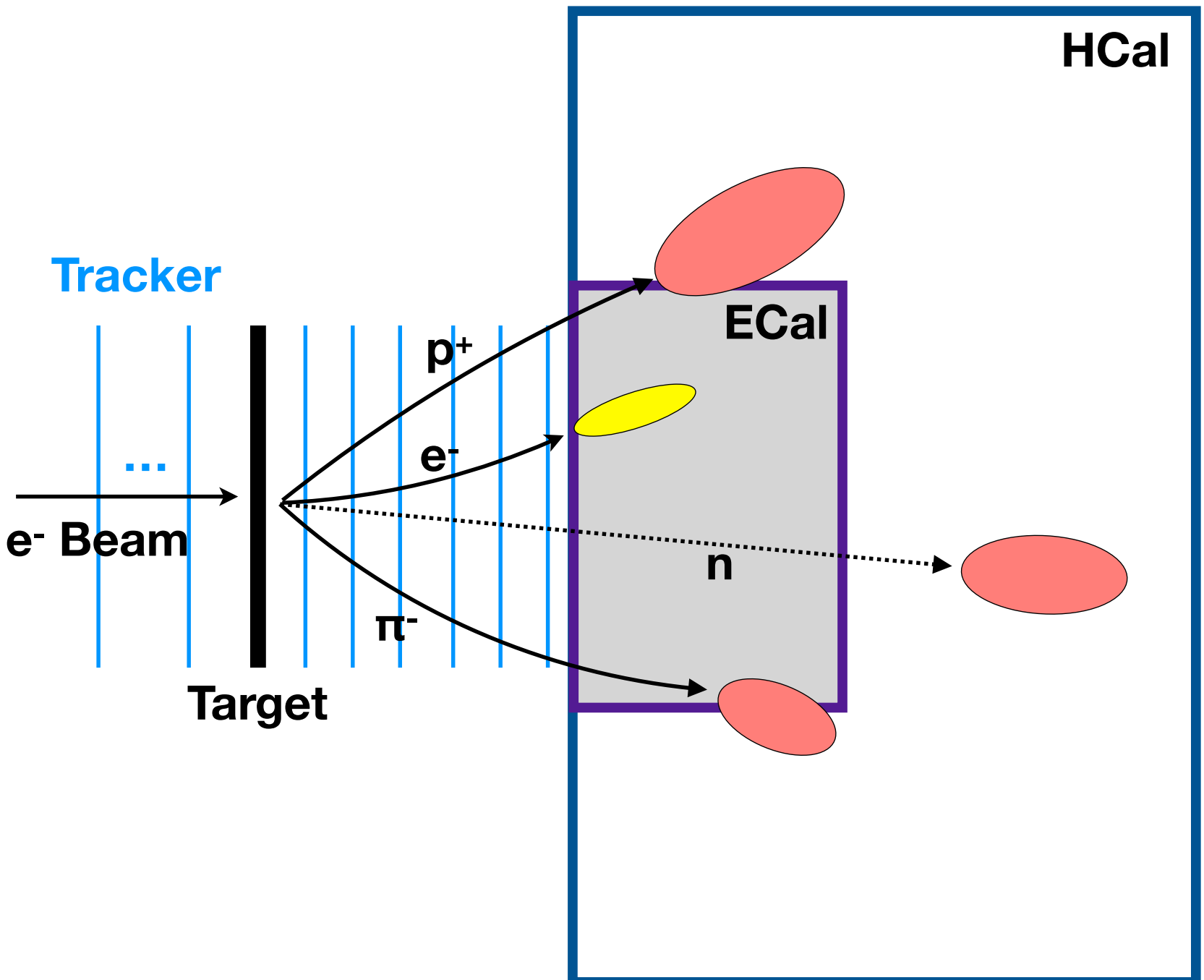
CCM: beam dump at LANL
 COHERENT: beam dump at ORNL
 NA64: missing energy at CERN
 Belle II: missing mass at KEK

for dark photon mediator
 (for other scenarios, see
[arXiv:1807.01730](https://arxiv.org/abs/1807.01730) [hep-ph])

The LDMX Experiment



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



PHYSICAL REVIEW D 101, 053004 (2020)

Linac to End Station A (LESA) at SLAC

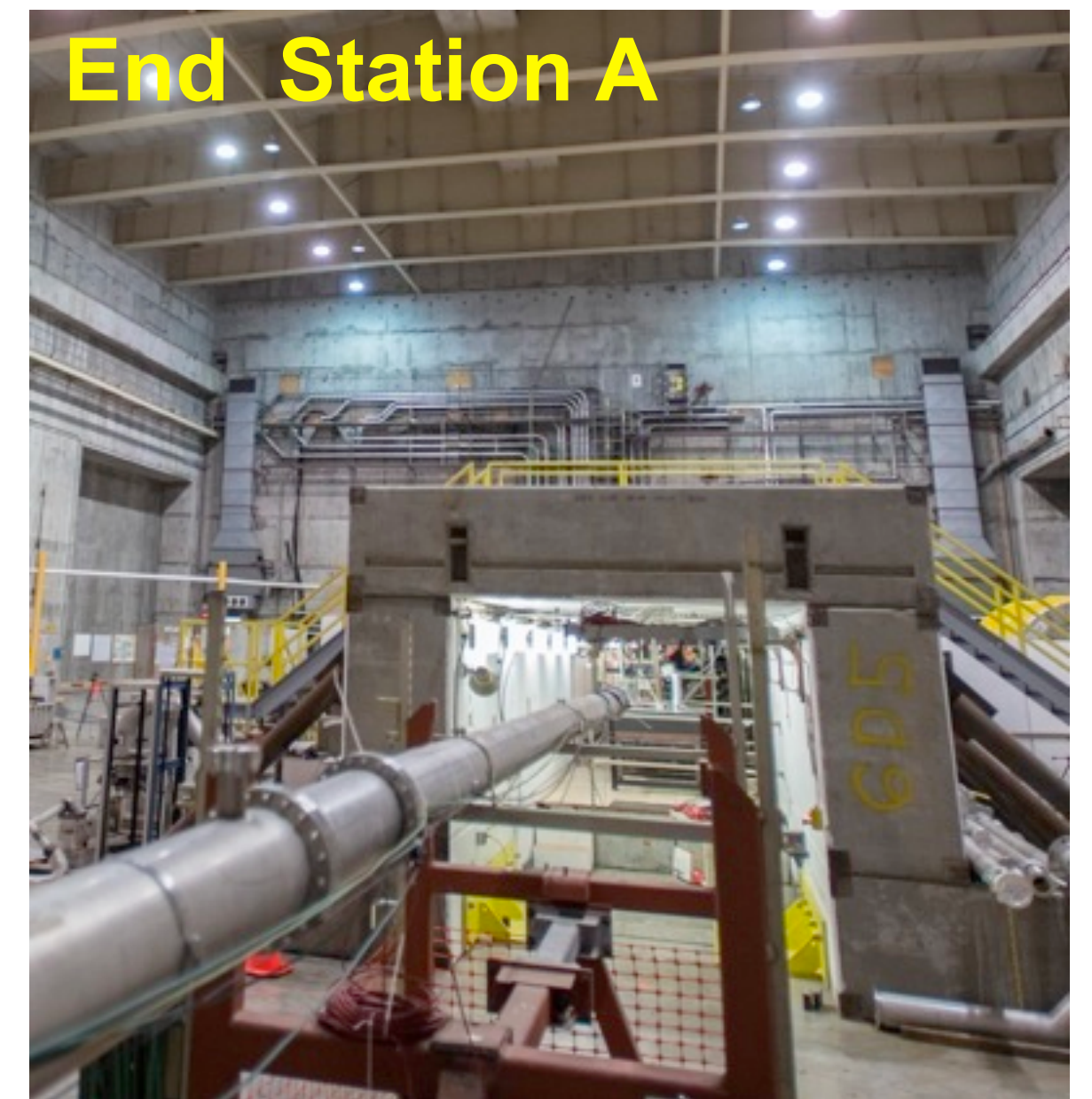
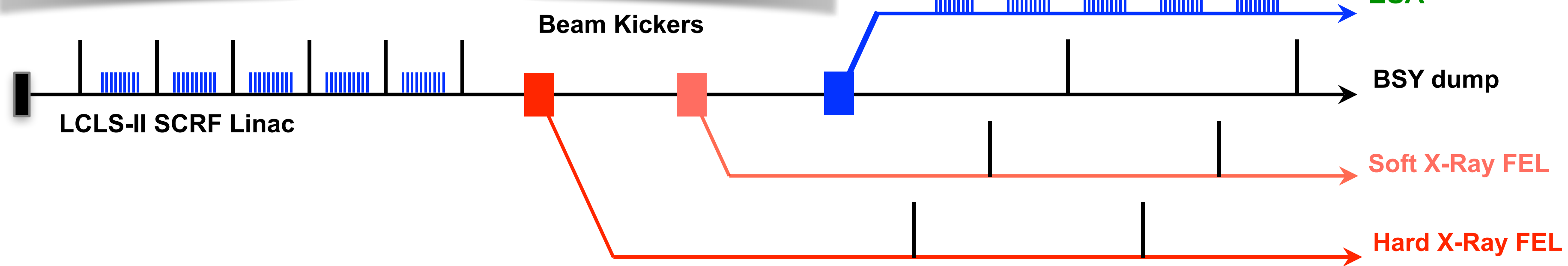
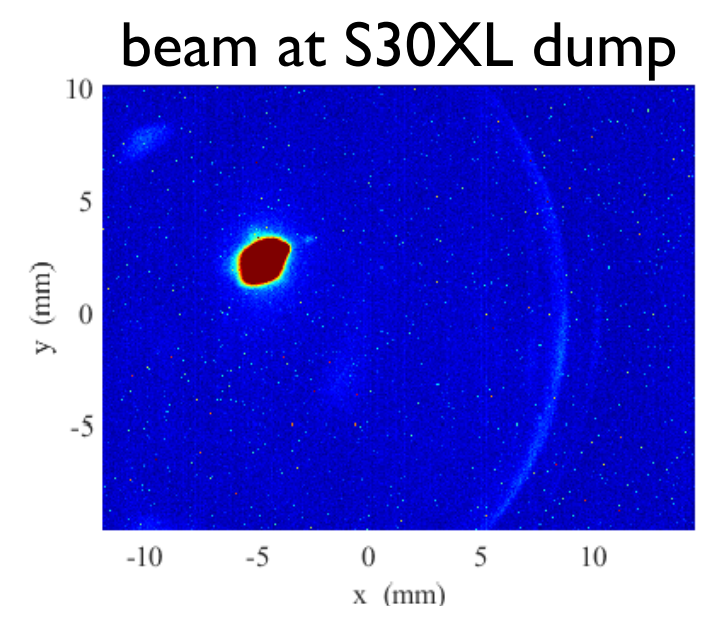
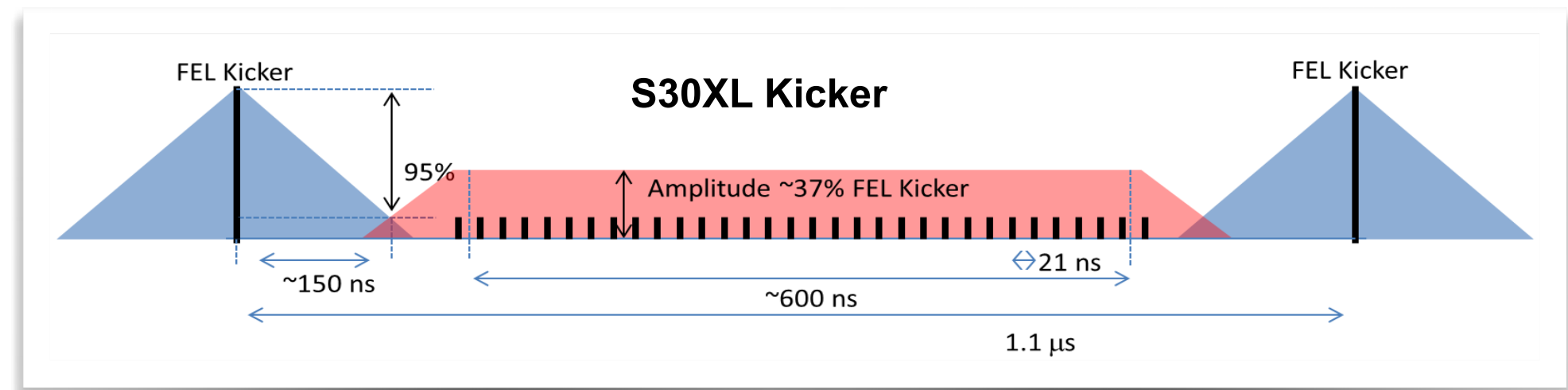
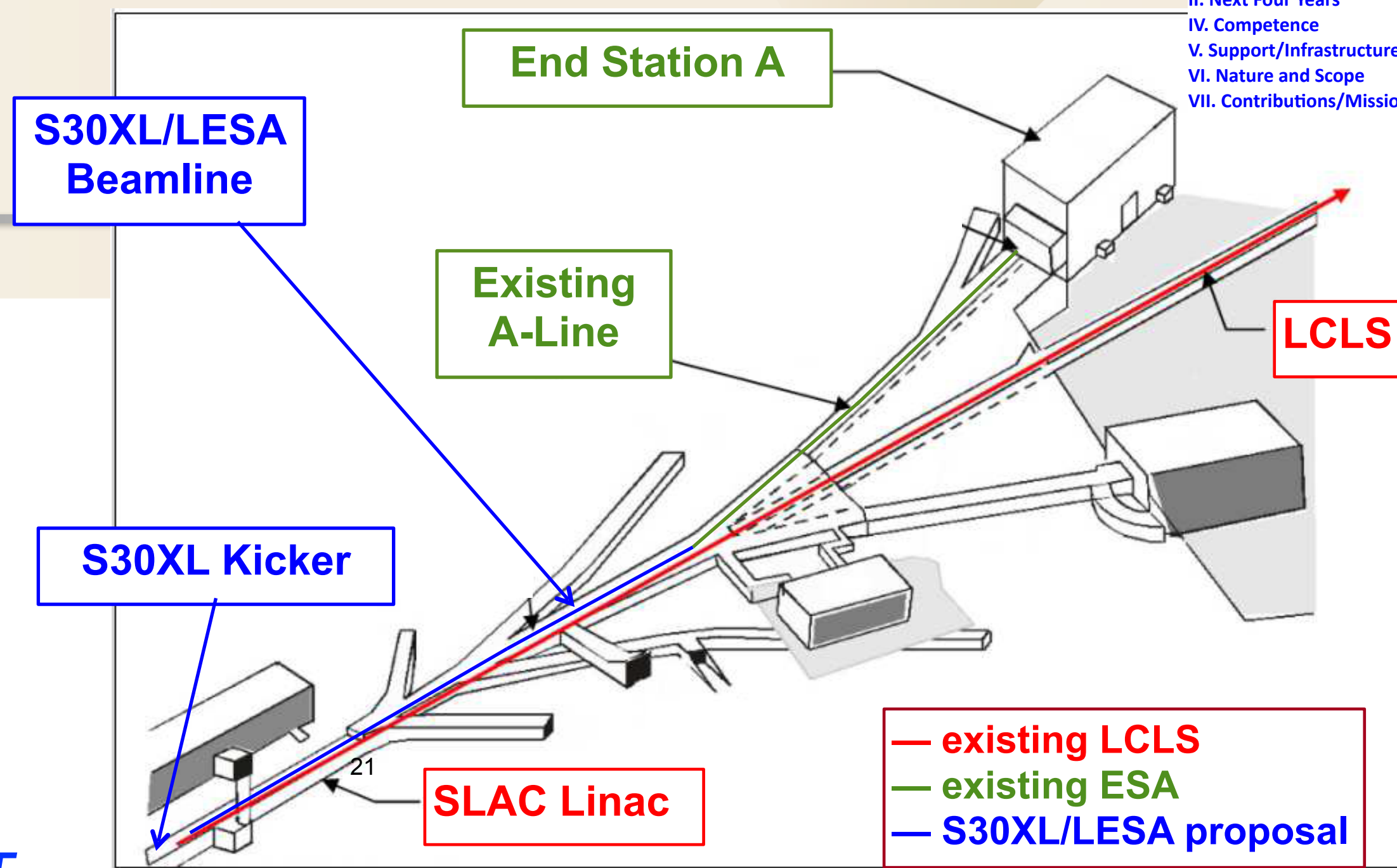
LCLS-II drive beam accelerates 186 MHz bunches

- ~5000 hours/year operation for photon science
- LCLS-II uses 929 kHz: >99% of bunches go to dump
- Sector 30 Transfer Line (S30XL) AIP diverts ~60% of unused, low-charge bunches to LESA for LDMX, test beam, and other expts.

S30XL is being commissioned alongside LCLS-II.

LESA construction ongoing, expects to deliver beam to ESA in FY25.

Natalia Toro is acting project lead: HPS also contributes effort.



LDMX Timeline



The most aggressive timeline currently possible starts construction in FY27, and therefore operation in FY30.

Assuming we are able to use $\mu = 2$ events as effectively as $\mu = 1$ events, full sensitivity requires 5 years of operation.

While this plan will face some pushback from HEP, the pace so far suggests that LDMX will probably be running until roughly 2035.

When will we be ready/able to ramp up effort on a new project?

Questions



Is there a well-motivated successor to HPS?

- Previous concepts have included:
 - “high-intensity HPS” which places HPS behind a dump. Extremely similar to DAMSA concept being developed at FNAL (Jae Yu, Juan Estrada, et al.).
 - HPS², a compact two arm spectrometer with much higher acceptance and better mass resolution.
 - Neither is suitable for LESA. What would an experiment designed for visible searches with no “dead zone” look like? How would it work?

Is there a well-motivated successor to LDMX?

- I am going to guess that after LDMX, dedicated beam dump experiments aimed at dark matter are going to be less attractive. Meanwhile, will be difficult to motivate a much larger and more expensive missing momentum experiment with electrons. What about muons, M³ at FNAL? Or millicharges?

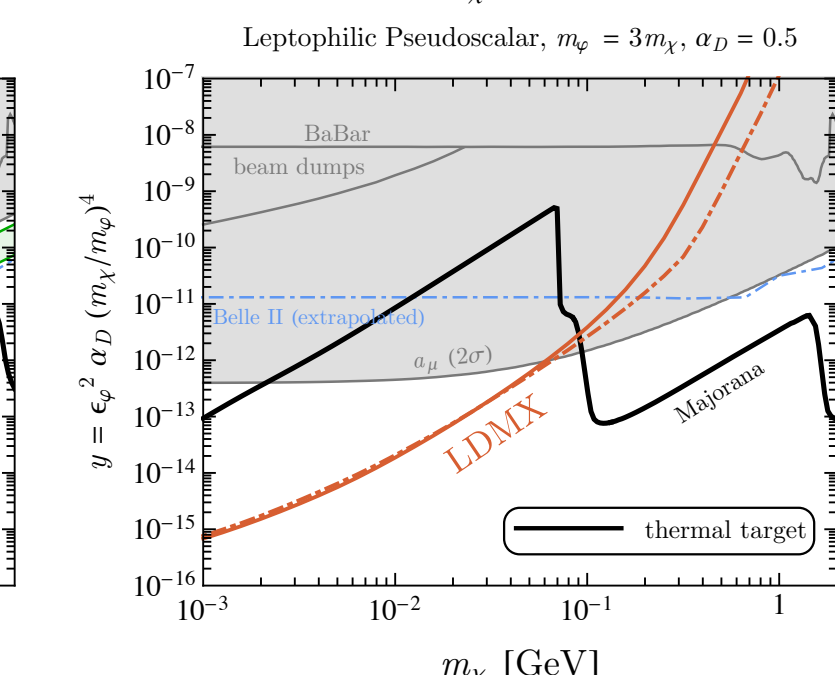
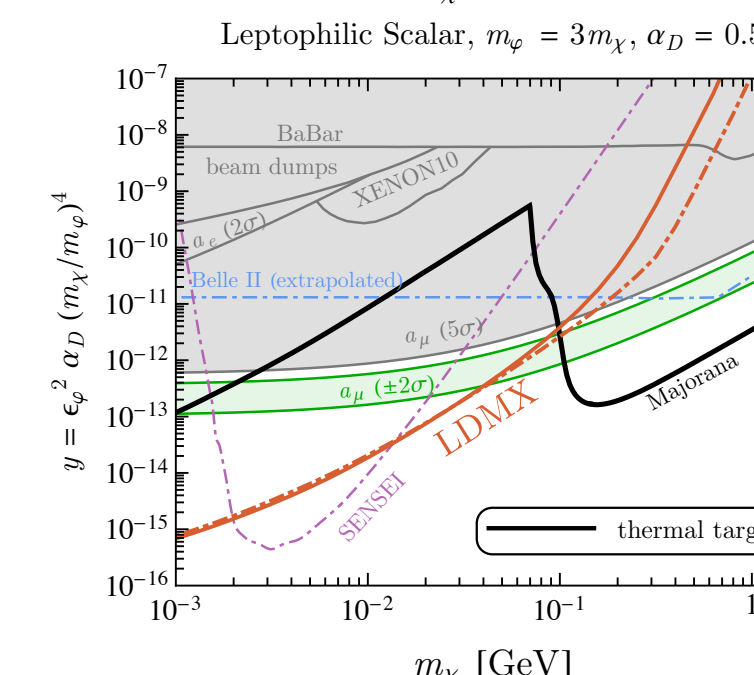
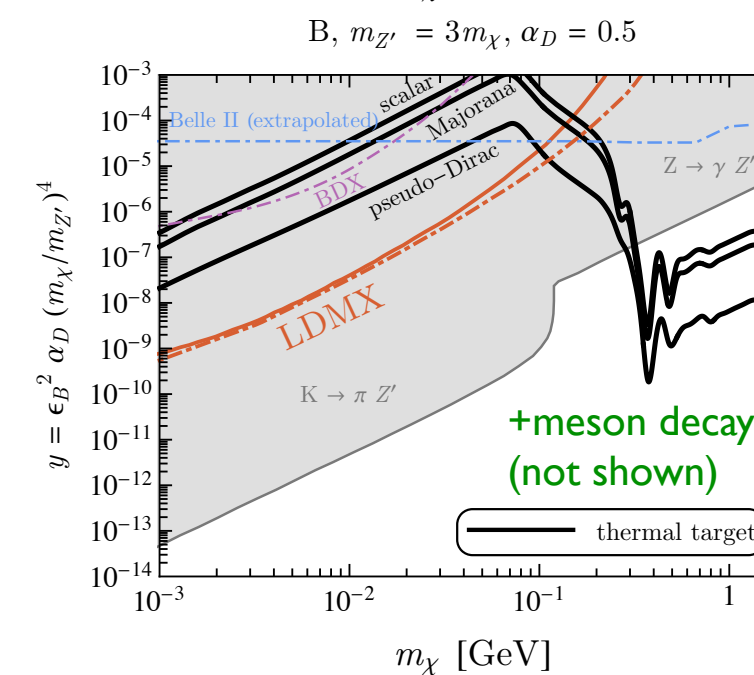
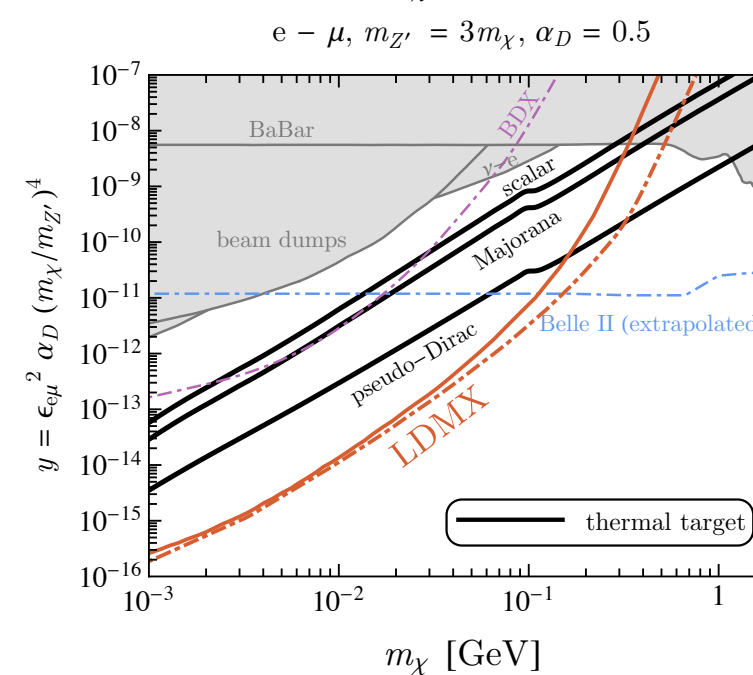
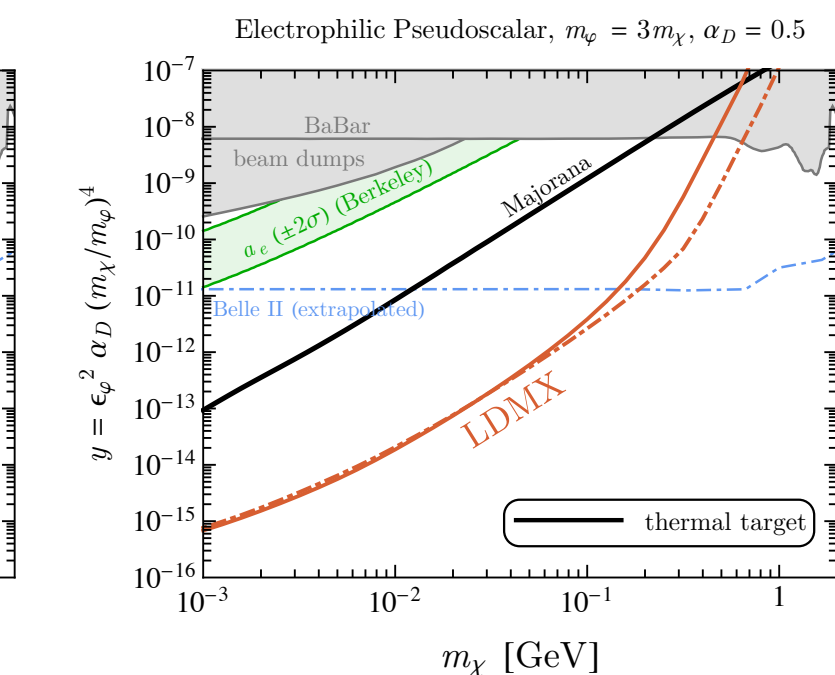
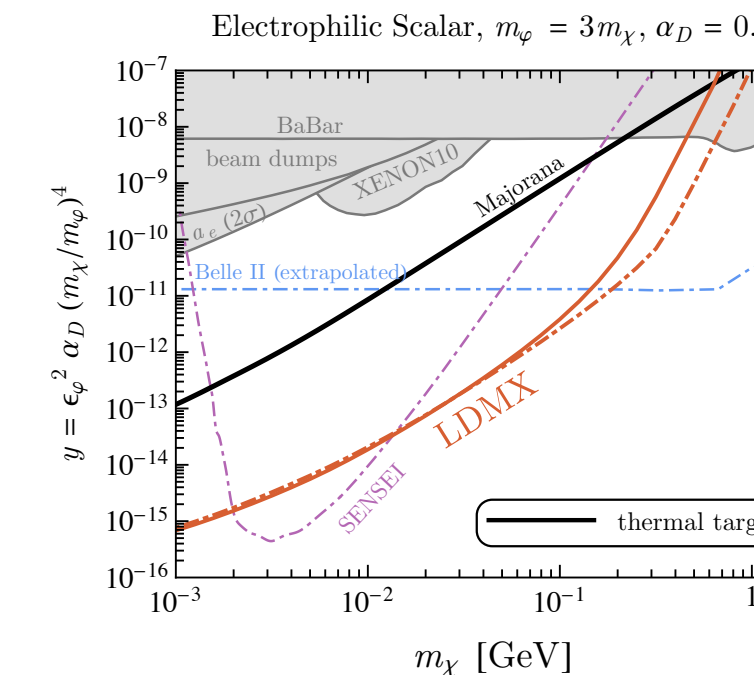
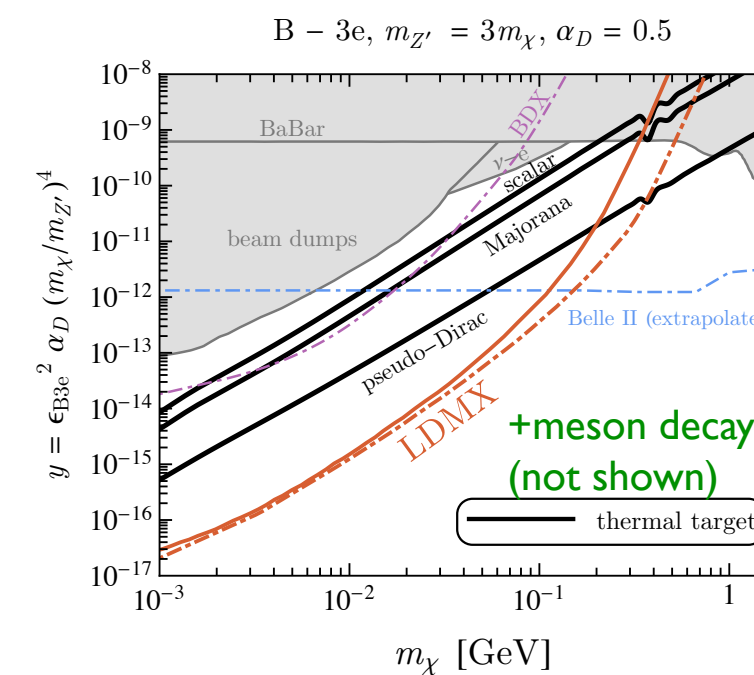
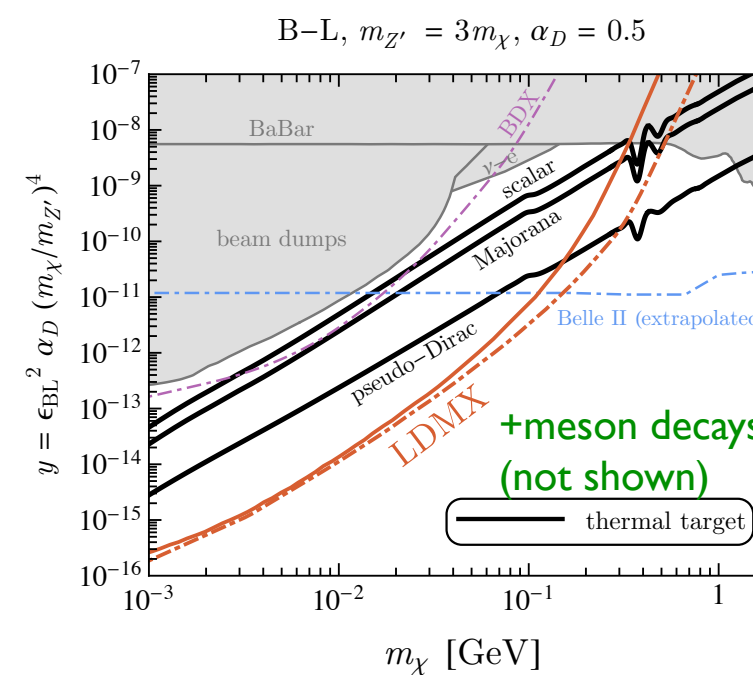
What will the interesting opportunities be at the neutrino near detectors?

What will the landscape look like in 2035? (need to skate to where the puck is going)

The Broader Palette of Dark Matter at LDMX

Invisible Signatures

- other mediators
- millicharged particles: arise from \sim 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)

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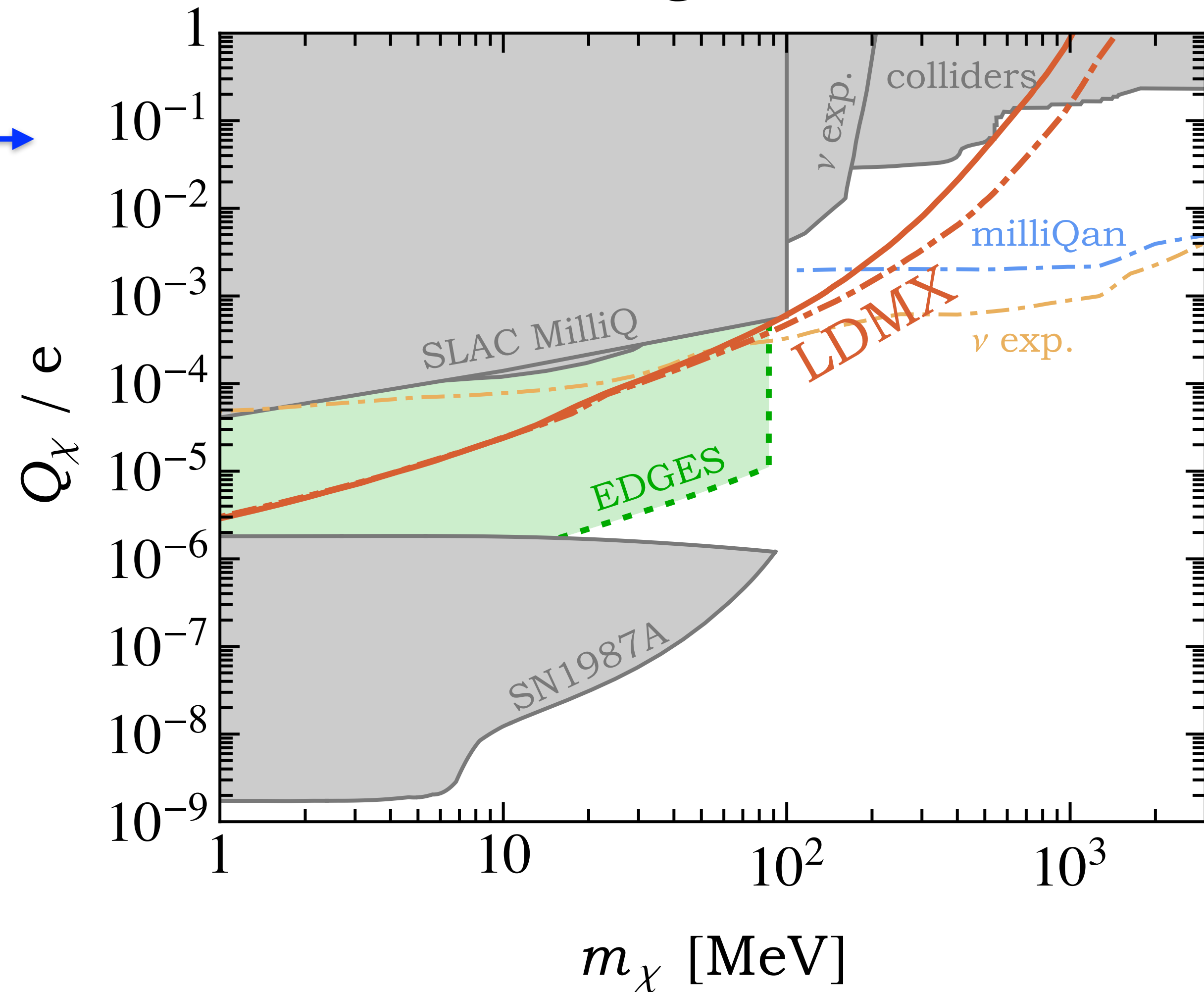
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Visible Signatures

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[arXiv:1807.01730](https://arxiv.org/abs/1807.01730) [hep-ph]

Millicharged Fermion



The Broader Palette of Dark Matter at LDMX

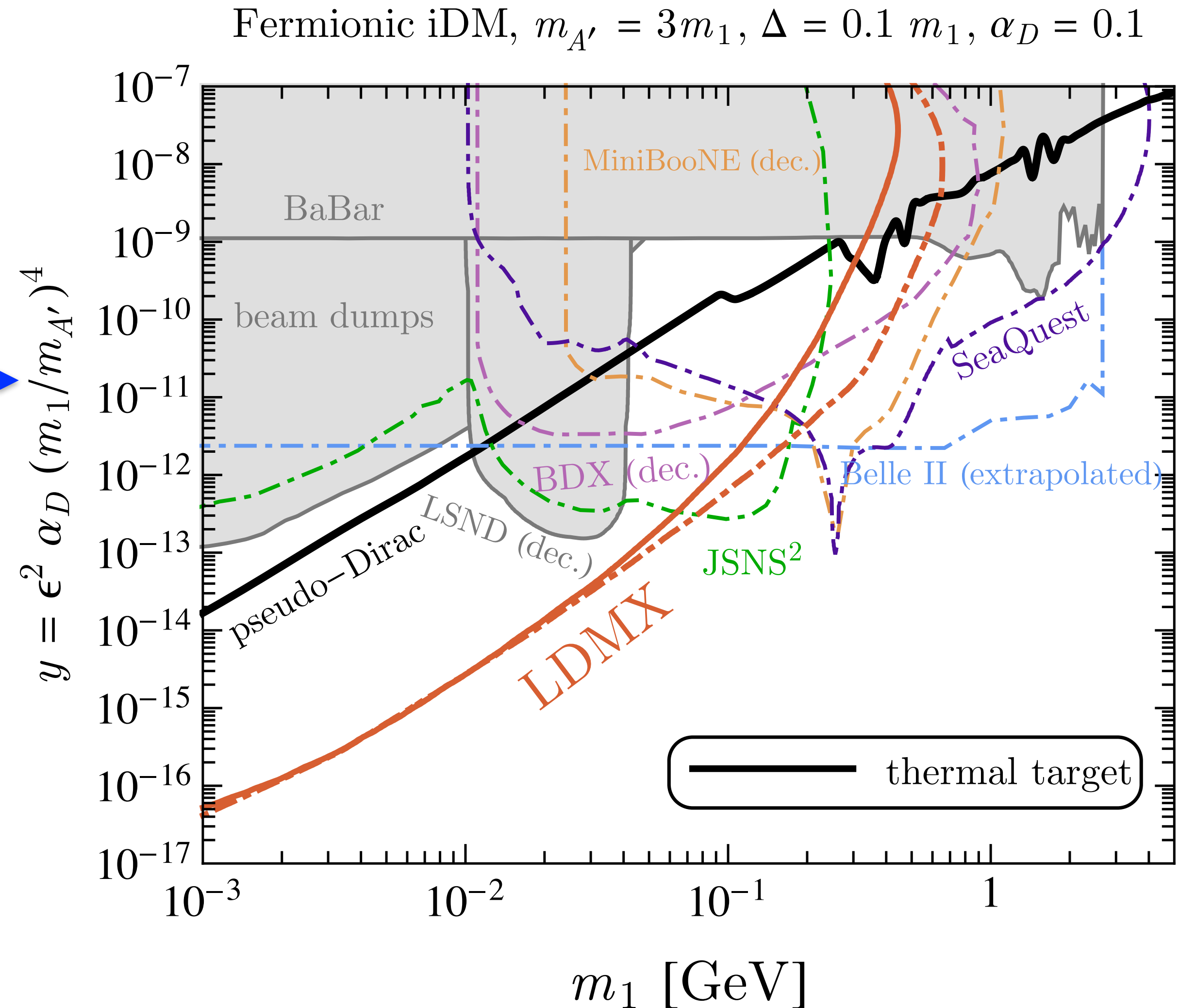
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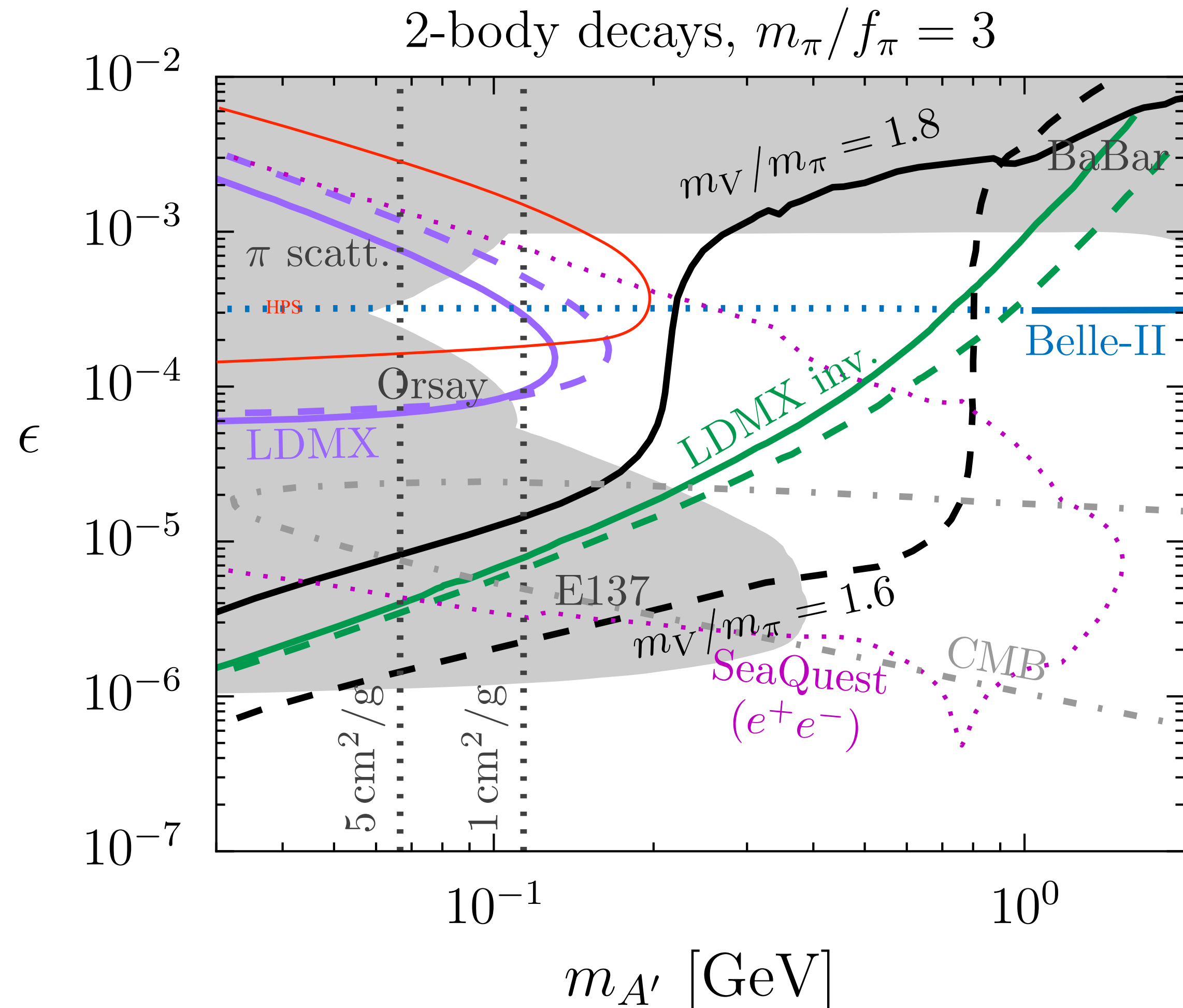
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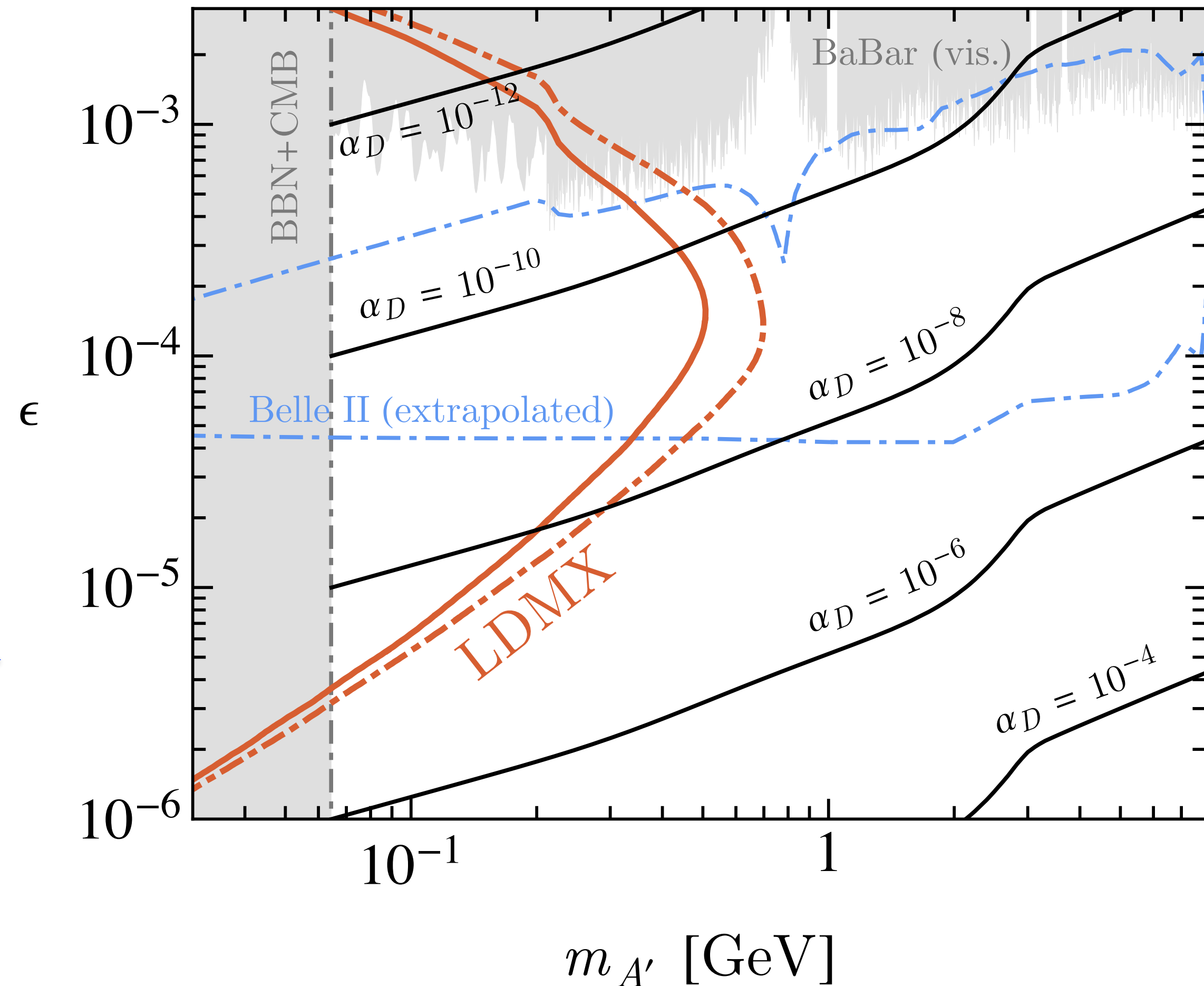
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Visible Signatures

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[arXiv:1807.01730](https://arxiv.org/abs/1807.01730) [hep-ph]

Low-Reheat Freeze-In, $m_{A'} = 15 T_{RH}$, $m_\chi = 10$ keV



The Broader Palette of Dark Matter at LDMX

Invisible Signatures

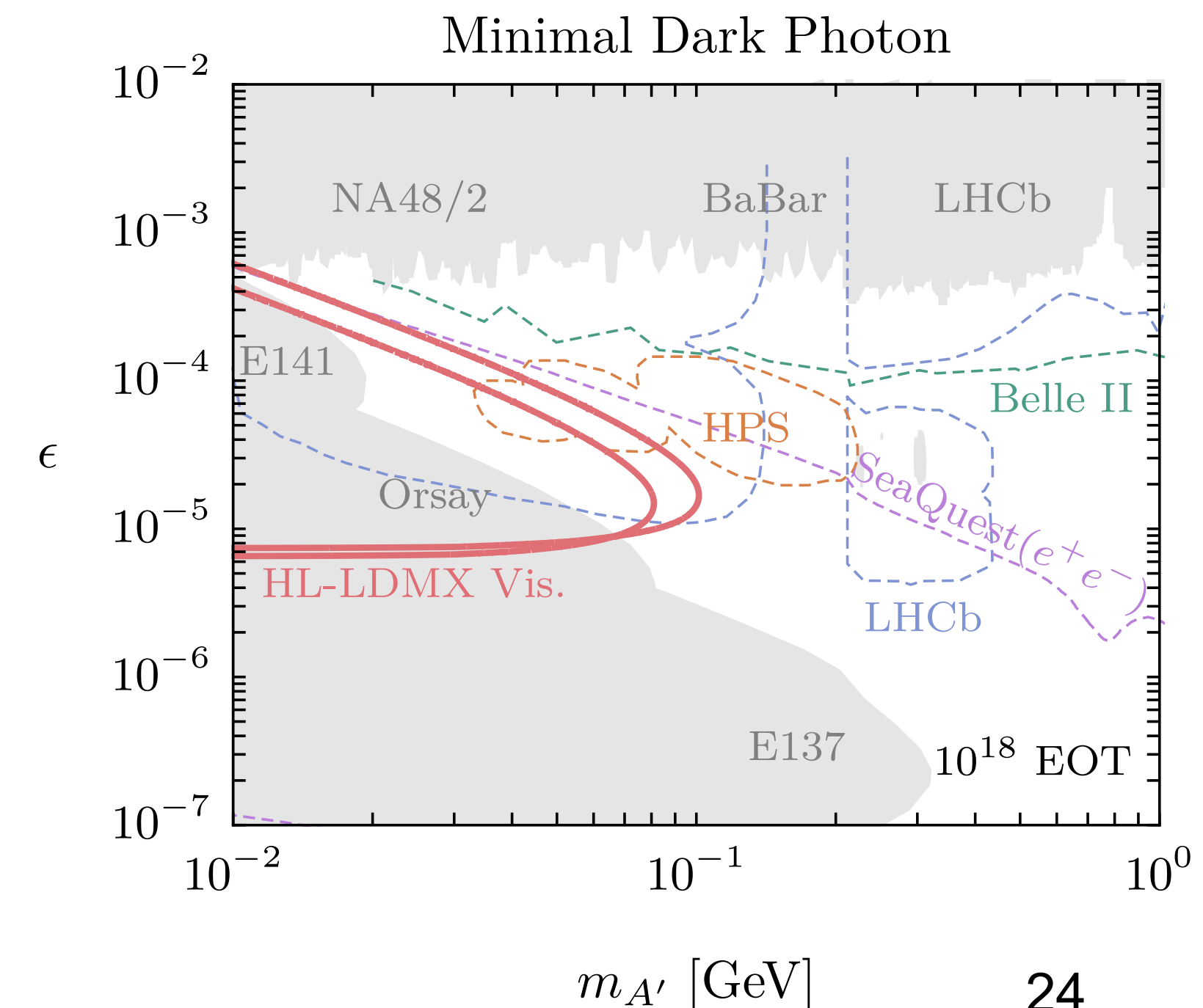
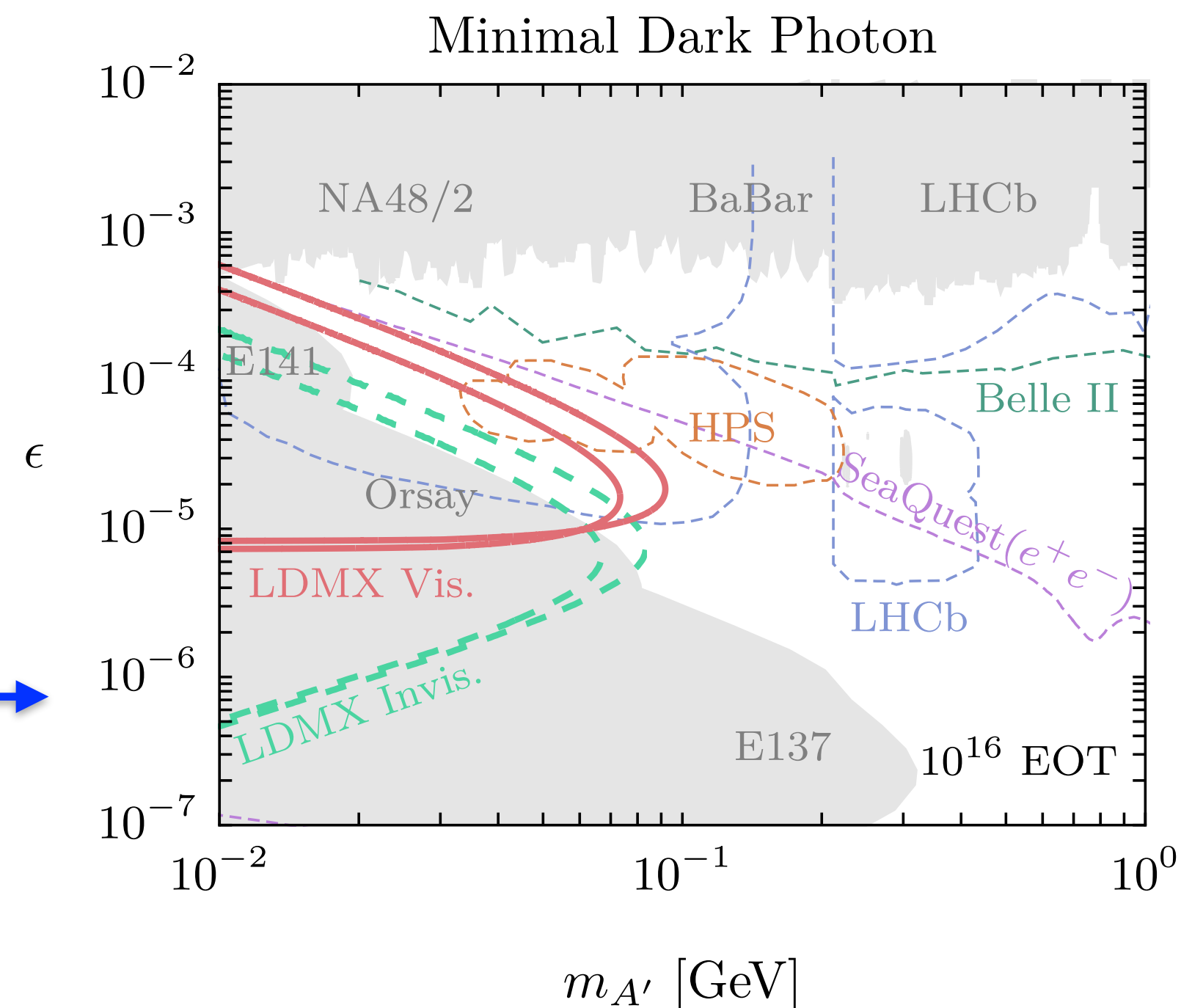
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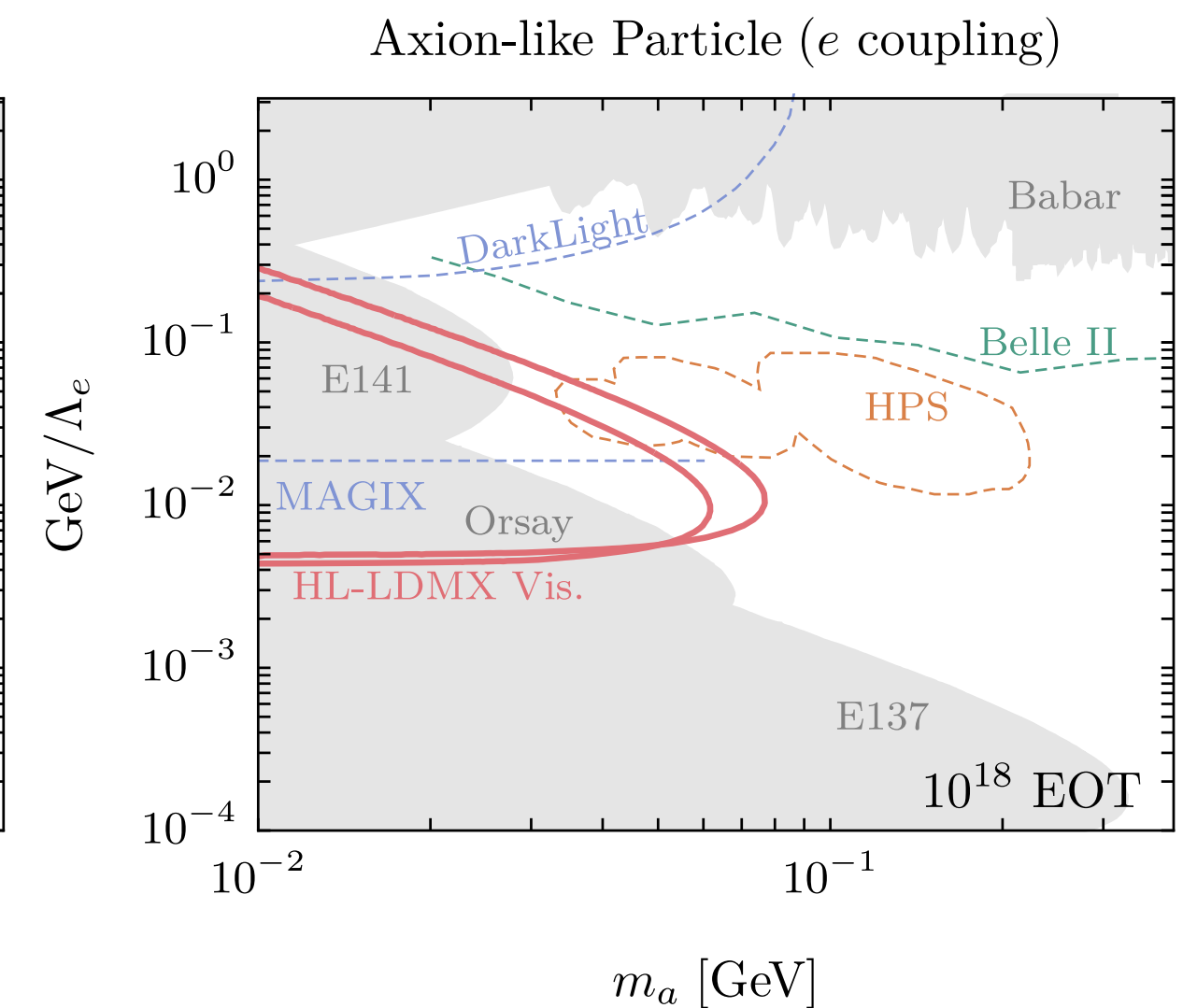
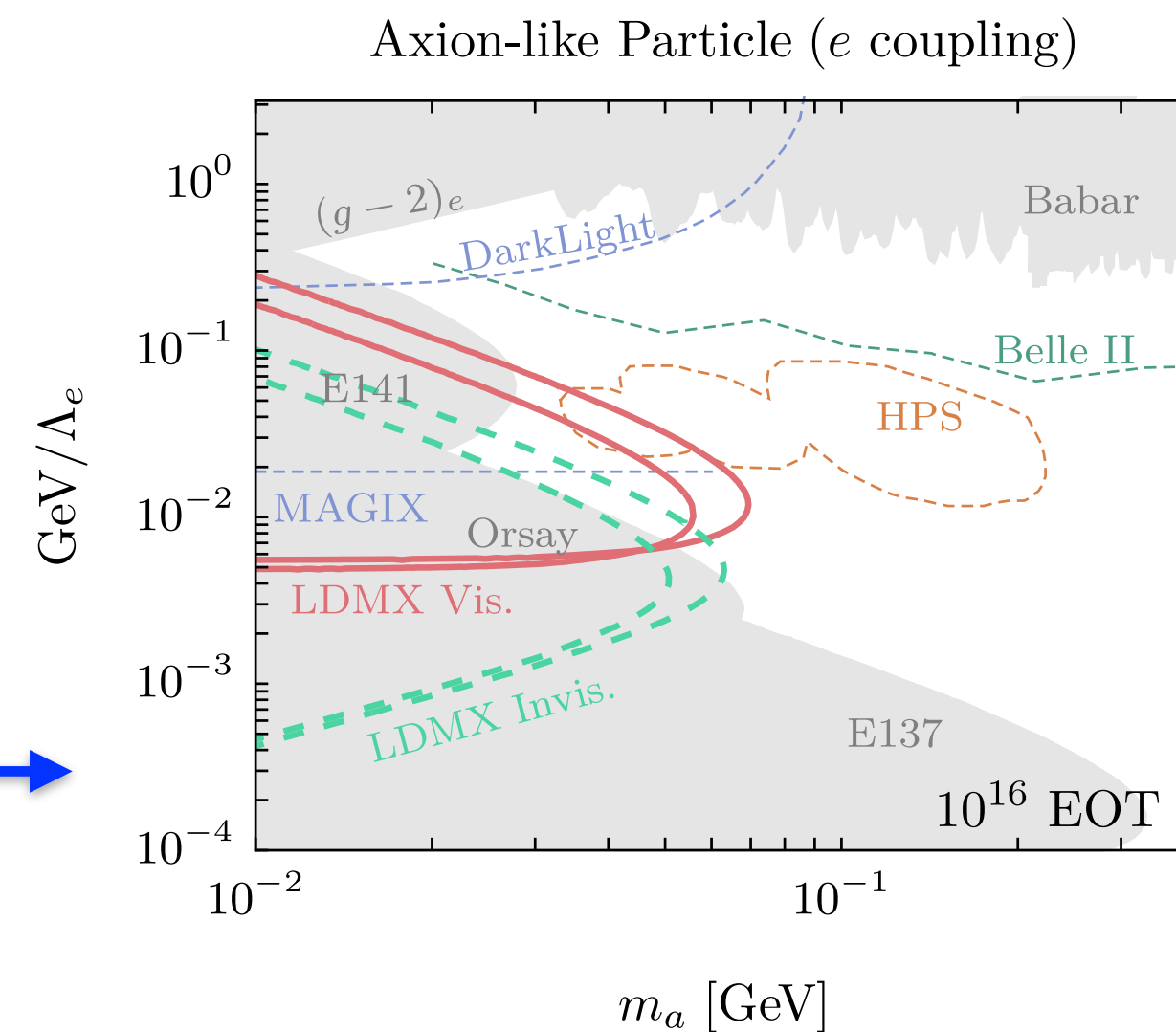
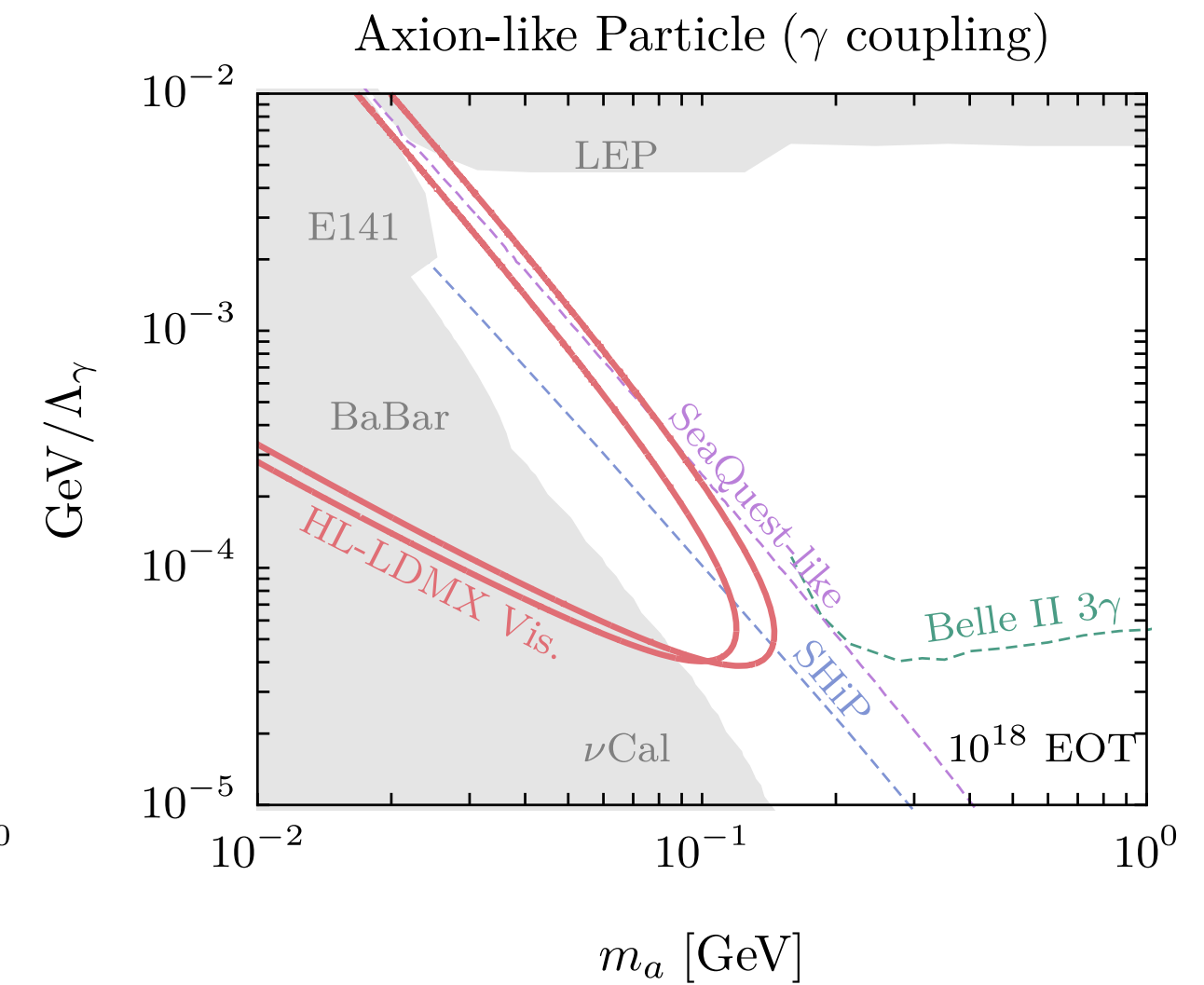
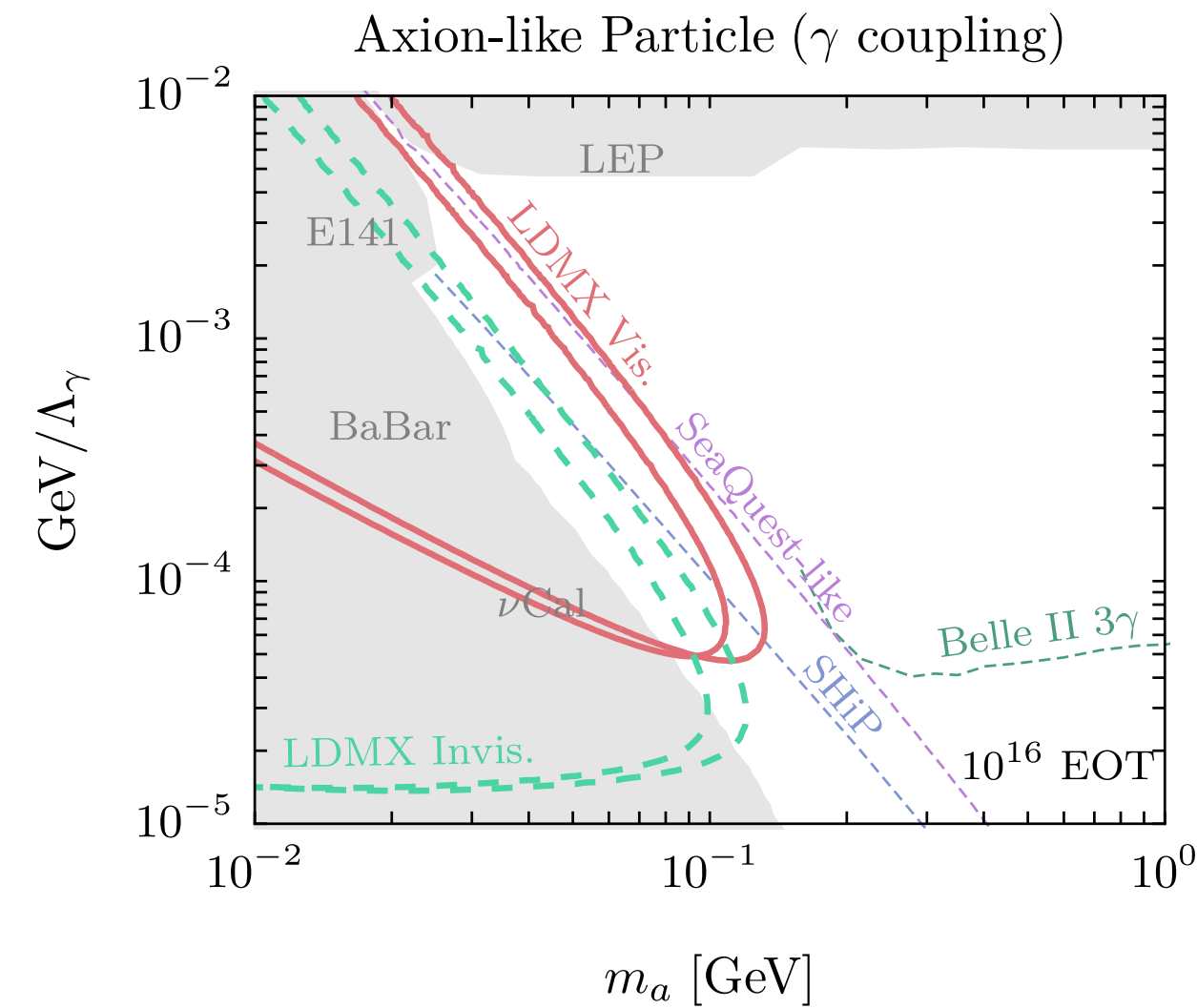
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2023 P5 creates a clearer mandate through ASTAE, calls out the DMNI portfolio as first set of projects to consider for construction.

Advancing Science and Technology through Agile Experiments

ASTAE §		P	P	P	P	P	P	
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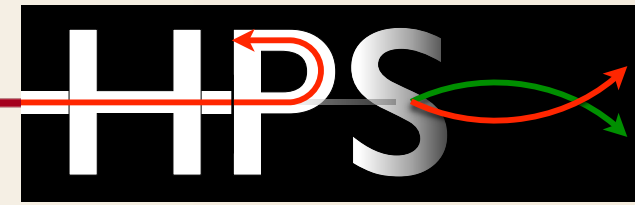
Recommendation 3: Implement a new small-project portfolio at DOE, **Advancing Science and Technology through Agile Experiments (ASTAE)**, across science themes in particle physics with a competitive program and recurring funding opportunity announcements. This program should start with the construction of experiments from the Dark Matter New Initiatives (DMNI) by DOE-HEP (section 6.2).

ASTAE

- For the ASTAE program to be agile, we recommend a **broad, predictable, and recurring (preferably annual) call for proposals**. This ensures the flexibility to target emerging opportunities and fields. A program on the scale of **\$35 million per year in 2023 dollars** is needed to ensure a healthy pipeline of projects.
- To preserve the agility of the ASTAE program, **project management** requirements should be outlined for the portfolio and should be adjusted to be commensurate with the scale of the experiment.
- A successful ASTAE experiment involves 3 phases: **design, construction, and operations**. A design phase proposal should precede a construction proposal, and construction proposals are considered from projects within the group that have successfully completed their design phase.
- The DMNI projects** that have successfully completed their design phase and are ready to be reviewed for construction, **should form the first set of construction proposals for ASTAE**. The corresponding design phase call would be **open to proposals from all areas of particle physics**.

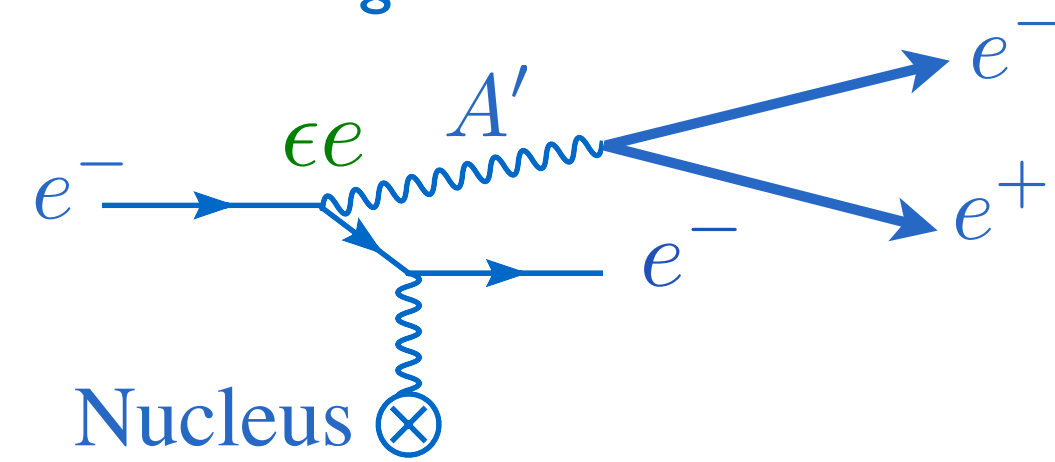
From LDMX perspective, this is the strongest statement we could have expected from P5.

Searching for Dark Photons Decaying Visibly to SM

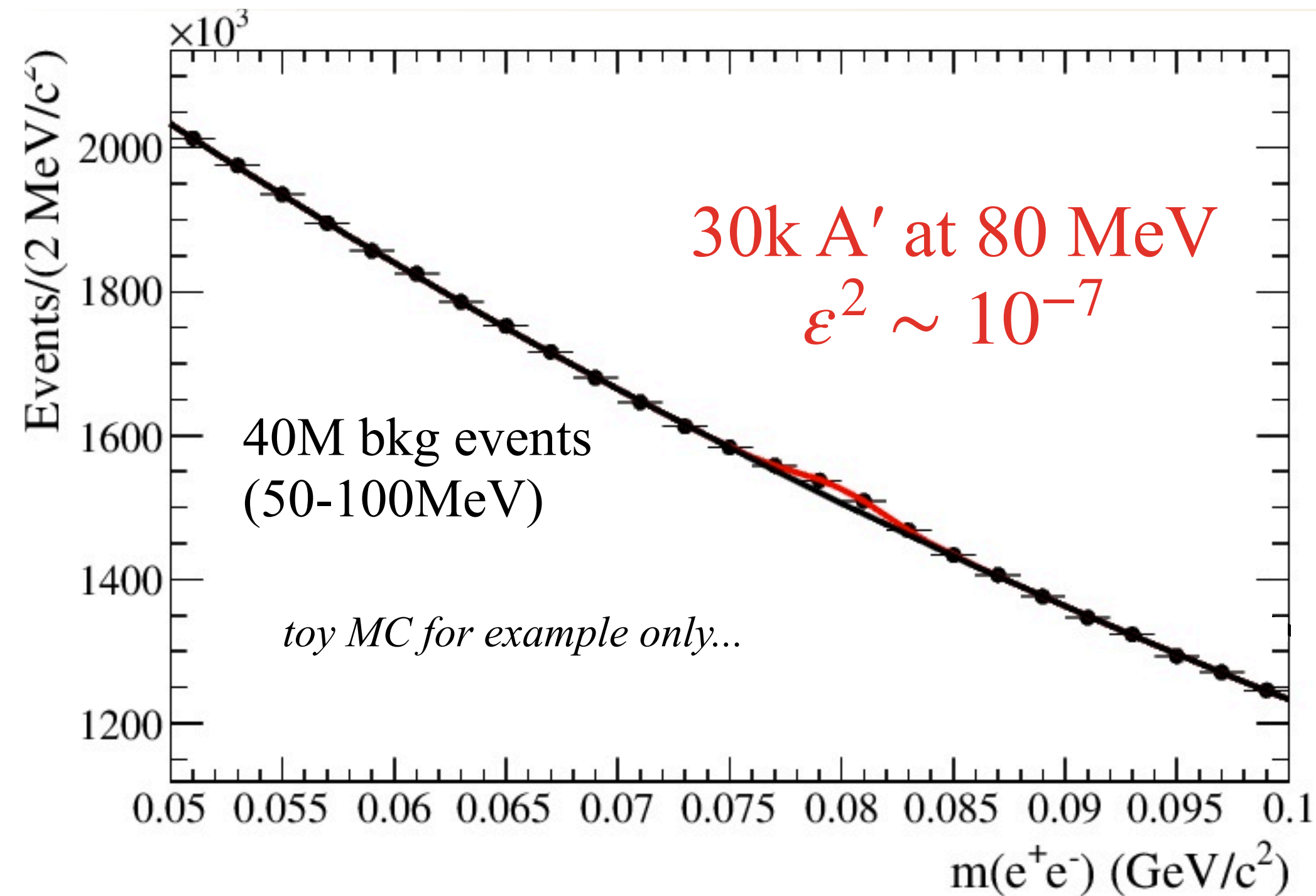
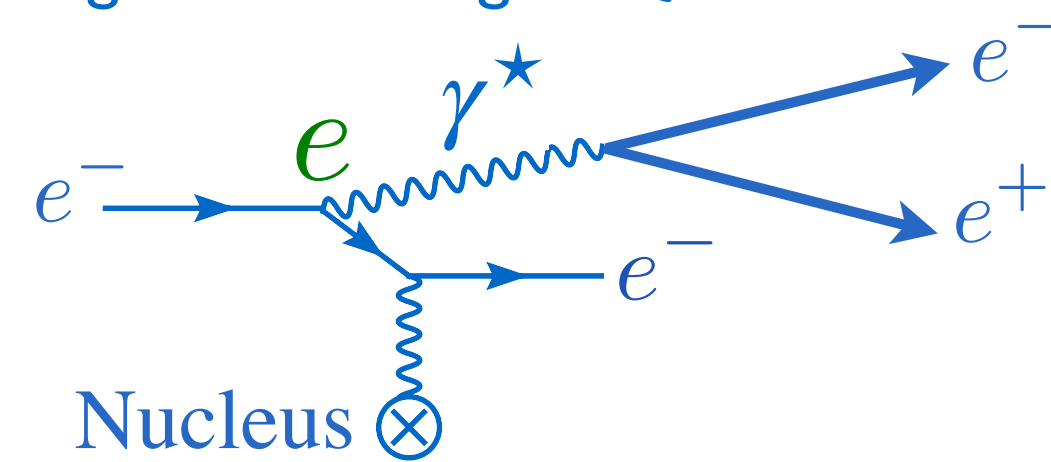


Many searches are simply for $m(l^+l^-)$ resonances.

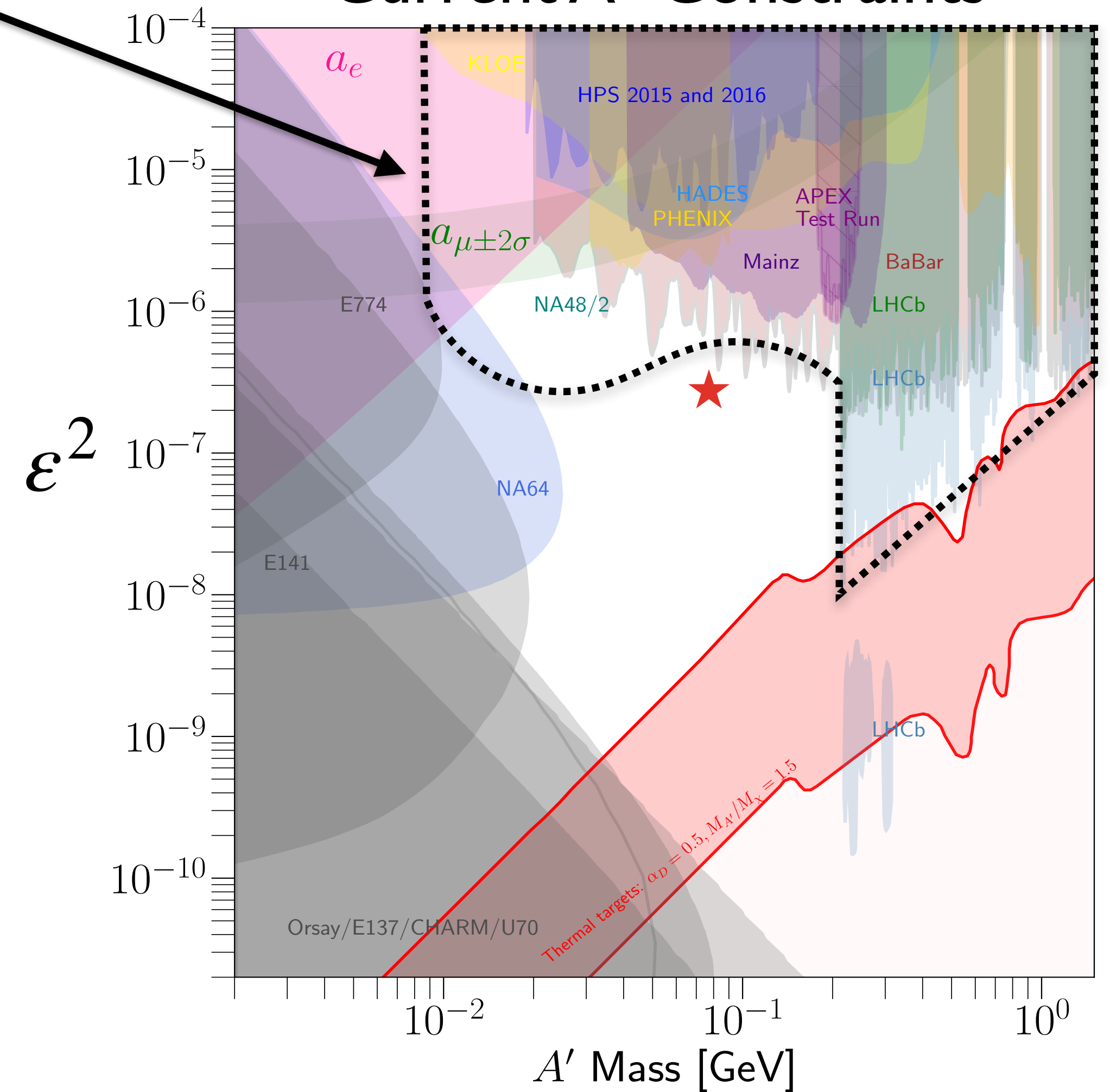
Minimal A' signal



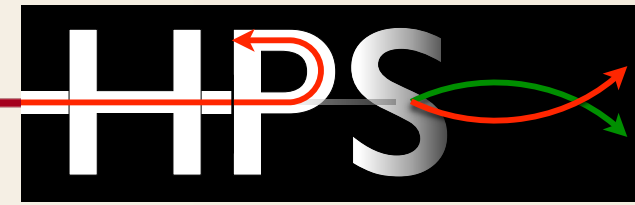
Background analogue: QED tridents



Current A' Constraints

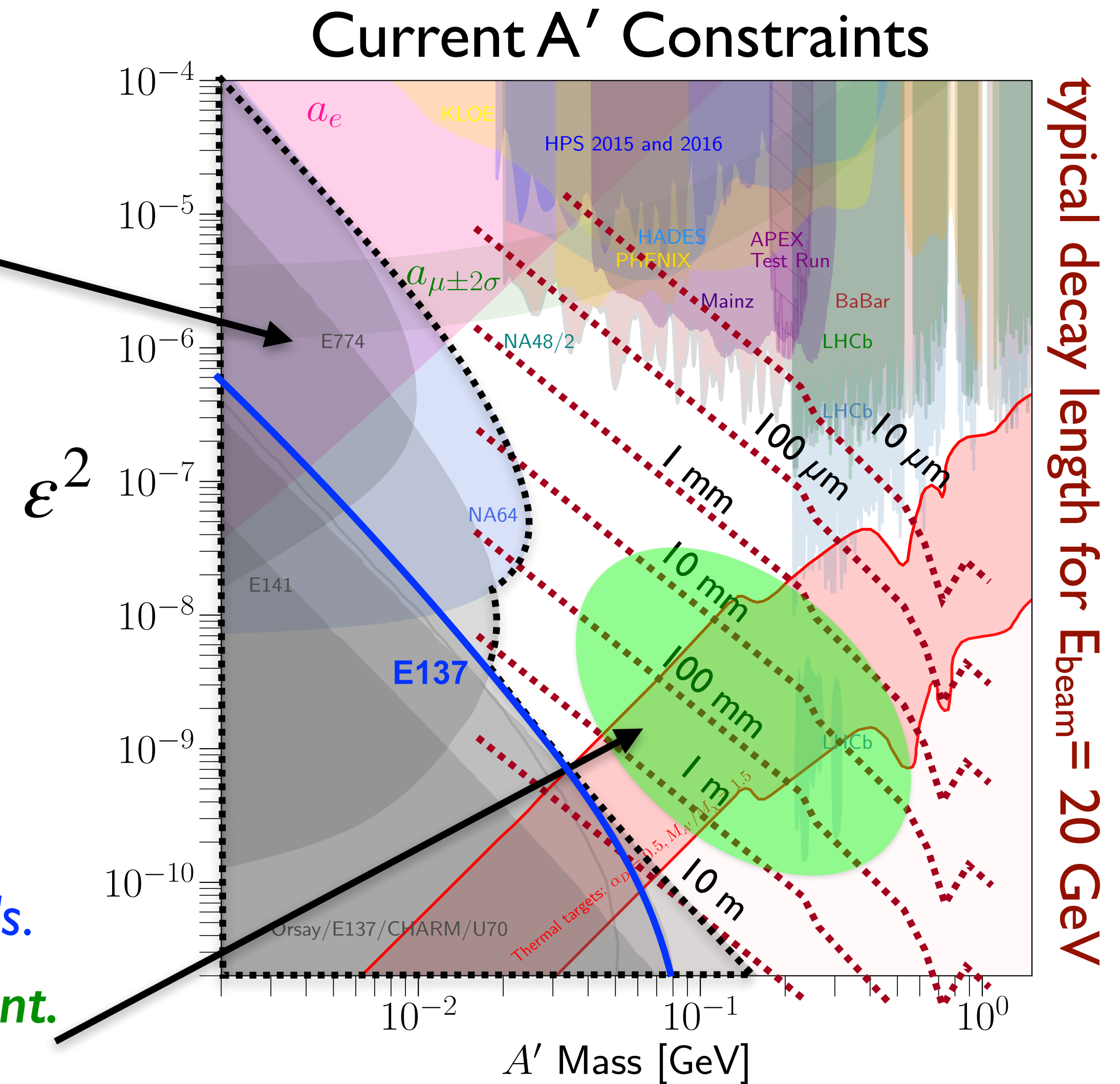
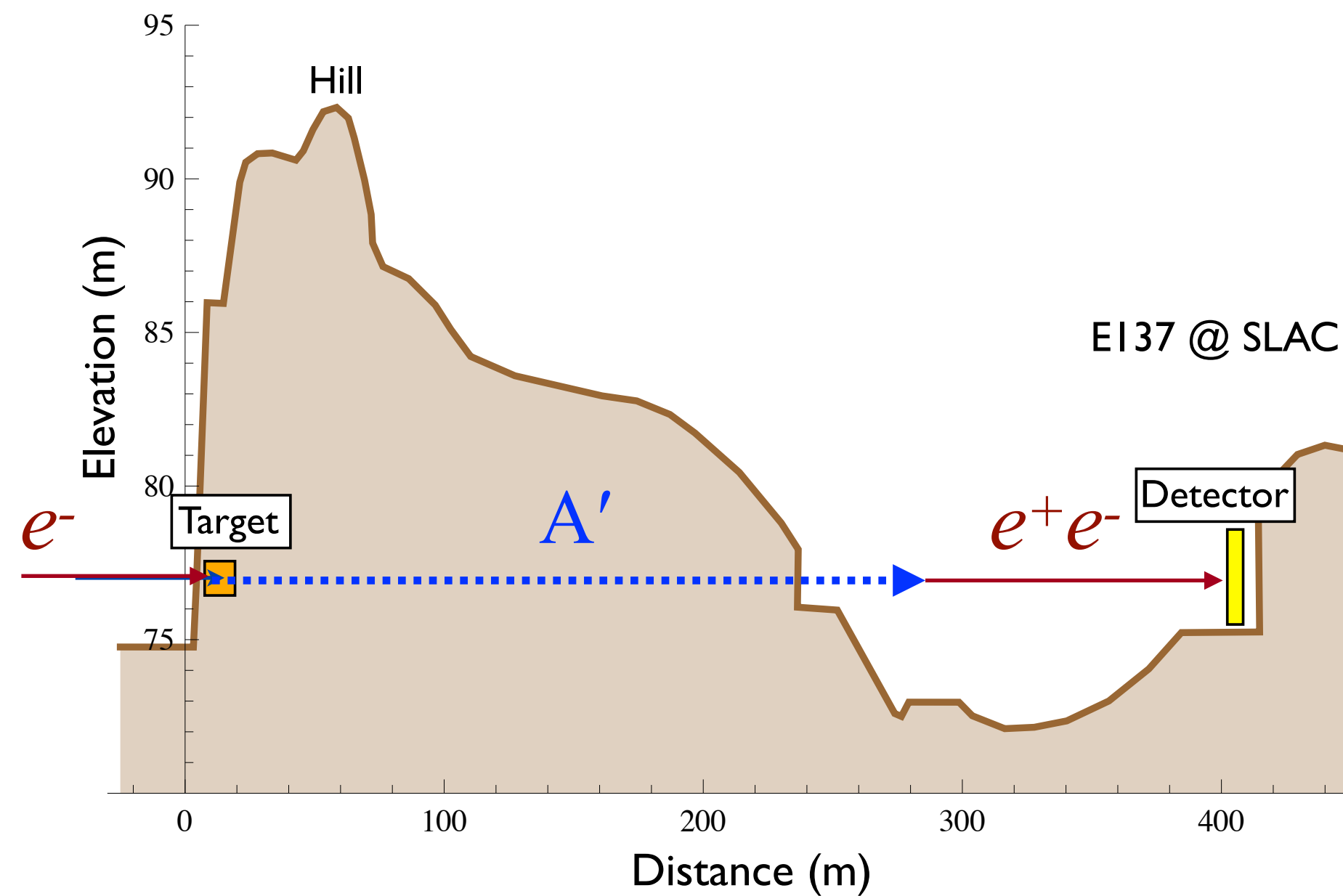


Searching for Dark Photons Decaying Visibly to SM



A' decay lengths are macroscopic at smaller couplings and masses: $\gamma_{CT} \propto \frac{1}{\epsilon^2 m_{A'}^2}$

Leads to sensitivity with beam dump experiments



Limited by depth of shield required to screen out backgrounds.

Intermediate couplings require decay length measurement.

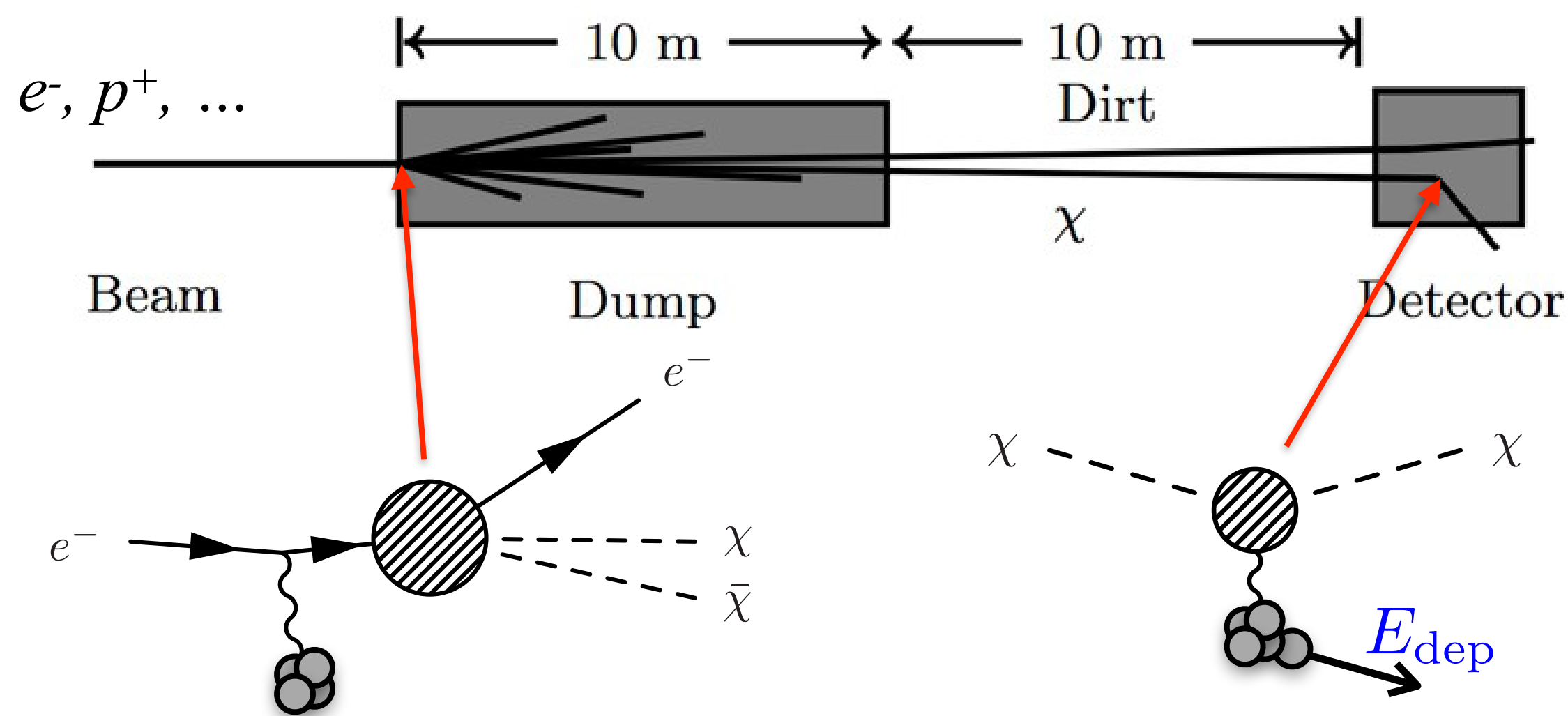
This is what HPS is designed to do.

typical decay length for $E_{beam} = 20 \text{ GeV}$

Fixed Target Dark Matter Search Approaches



Beam Dumps: Produce and re-scatter DM

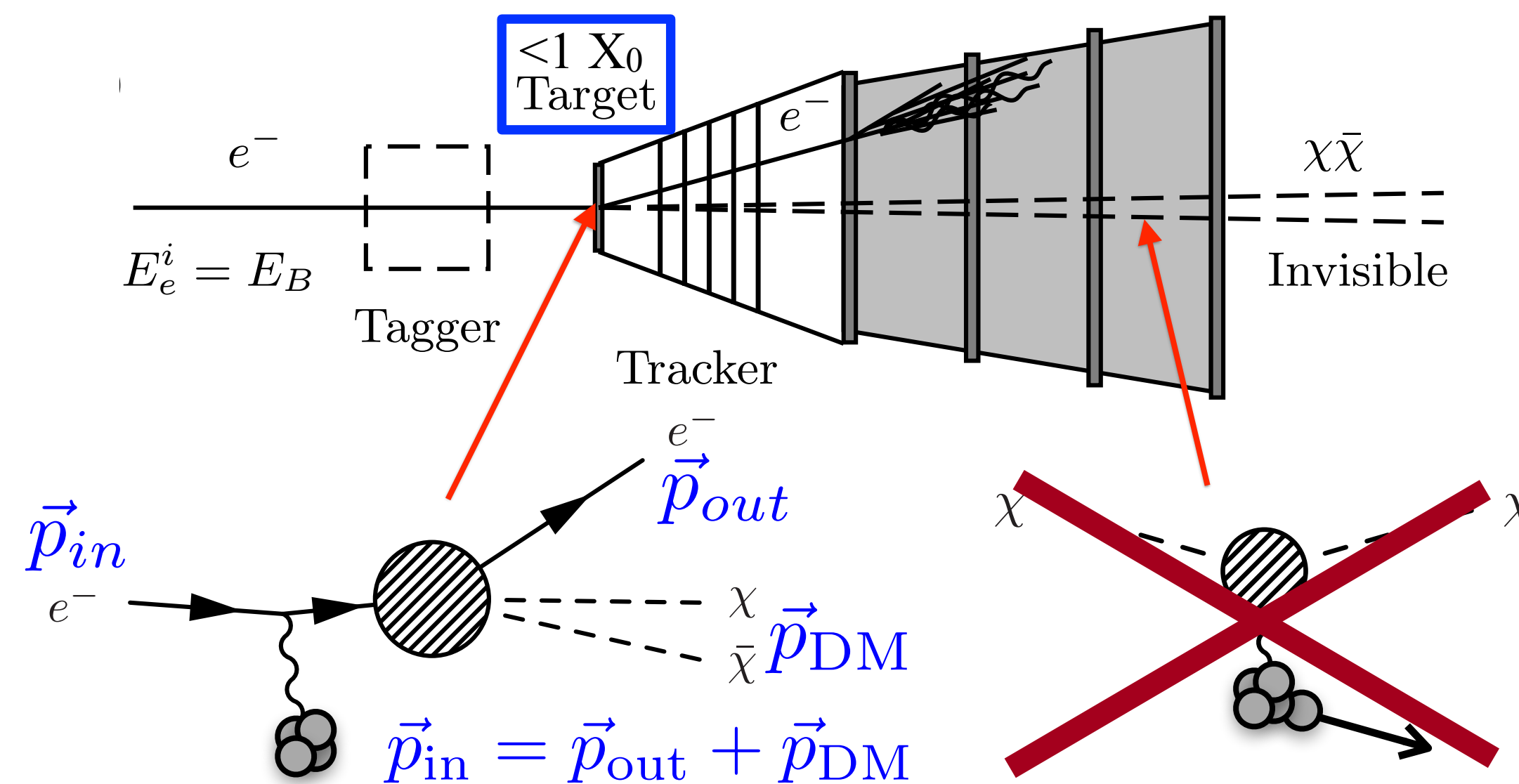


- new sensitivity with $\sim 10^{21}$ particles
- covers thermal targets with $\sim 10^{28}$ particles

Requirements:

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

Missing Momentum: Detect DM production



- new sensitivity for $\sim 10^{12}$ electrons
- covers thermal targets for $\sim 10^{16}$ electrons

Requirements:

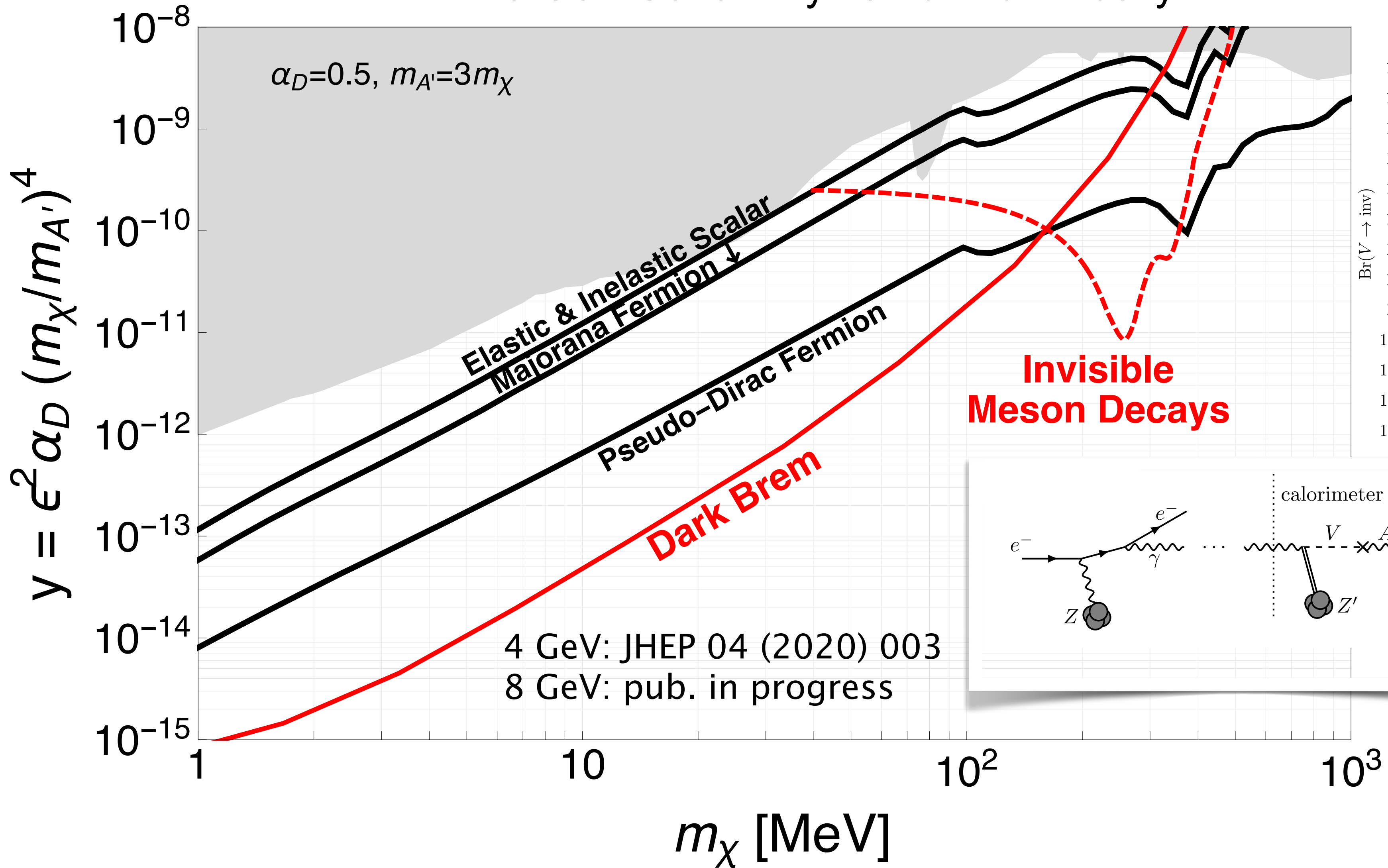
- high rate beam at $\sim 1 e^-/\text{bunch}$ (1 year = 3×10^{16} ns)
- fast, sensitive, detector systems
- (key backgrounds: $e^- \rightarrow e^- + \gamma$, $\gamma N \rightarrow \text{hadrons}$)

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

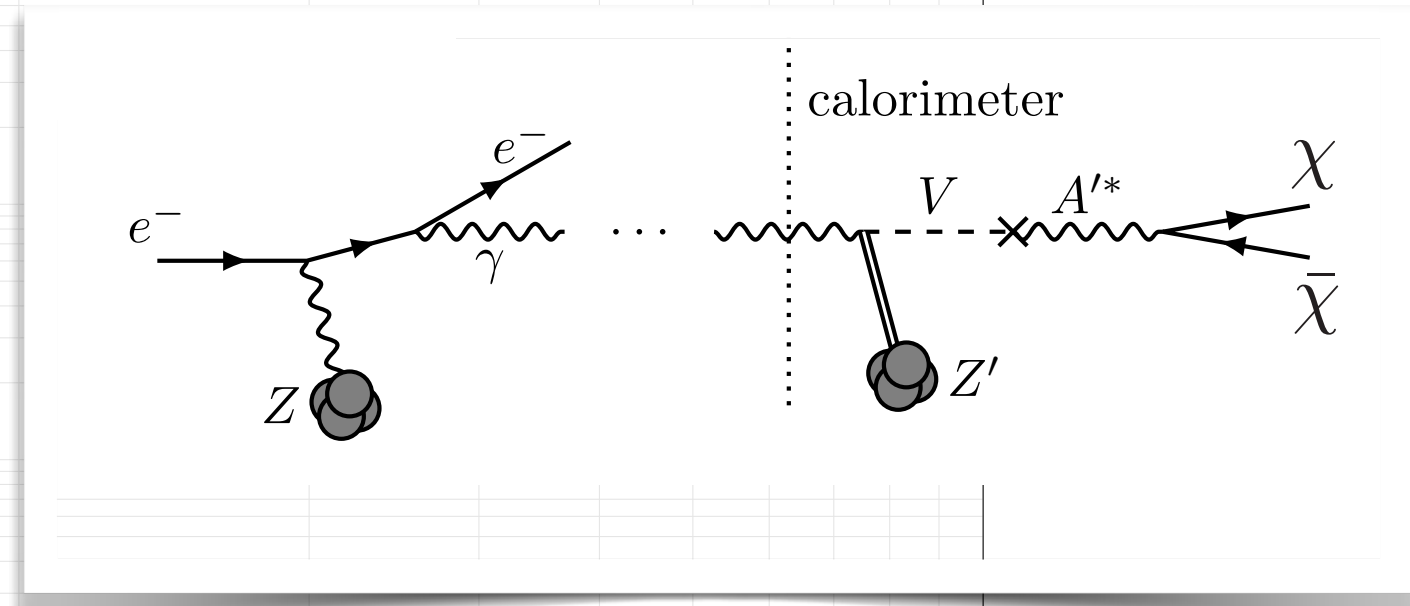
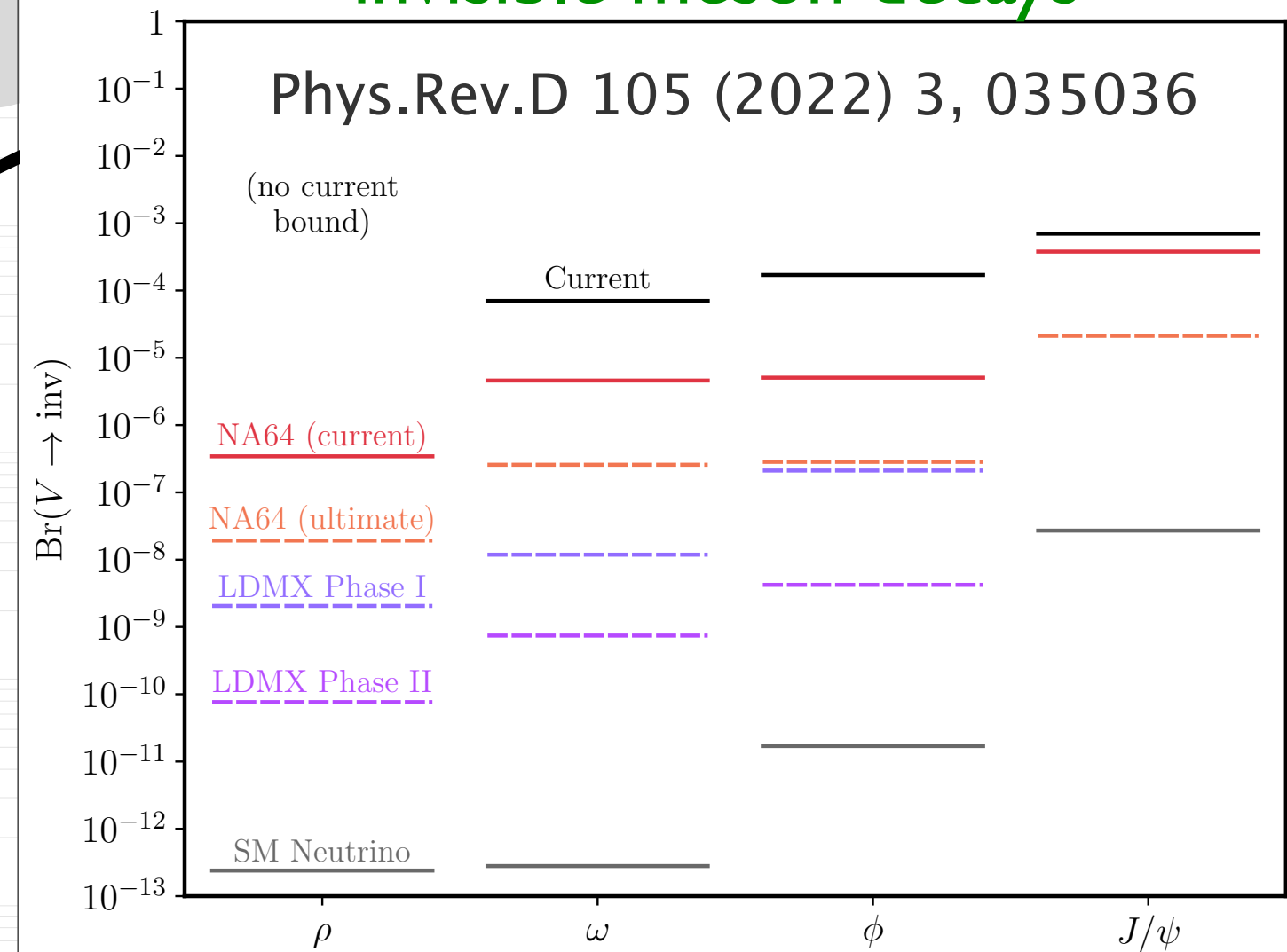
LDMX Sensitivity



LDMX 8 GeV Sensitivity w/ Full Luminosity

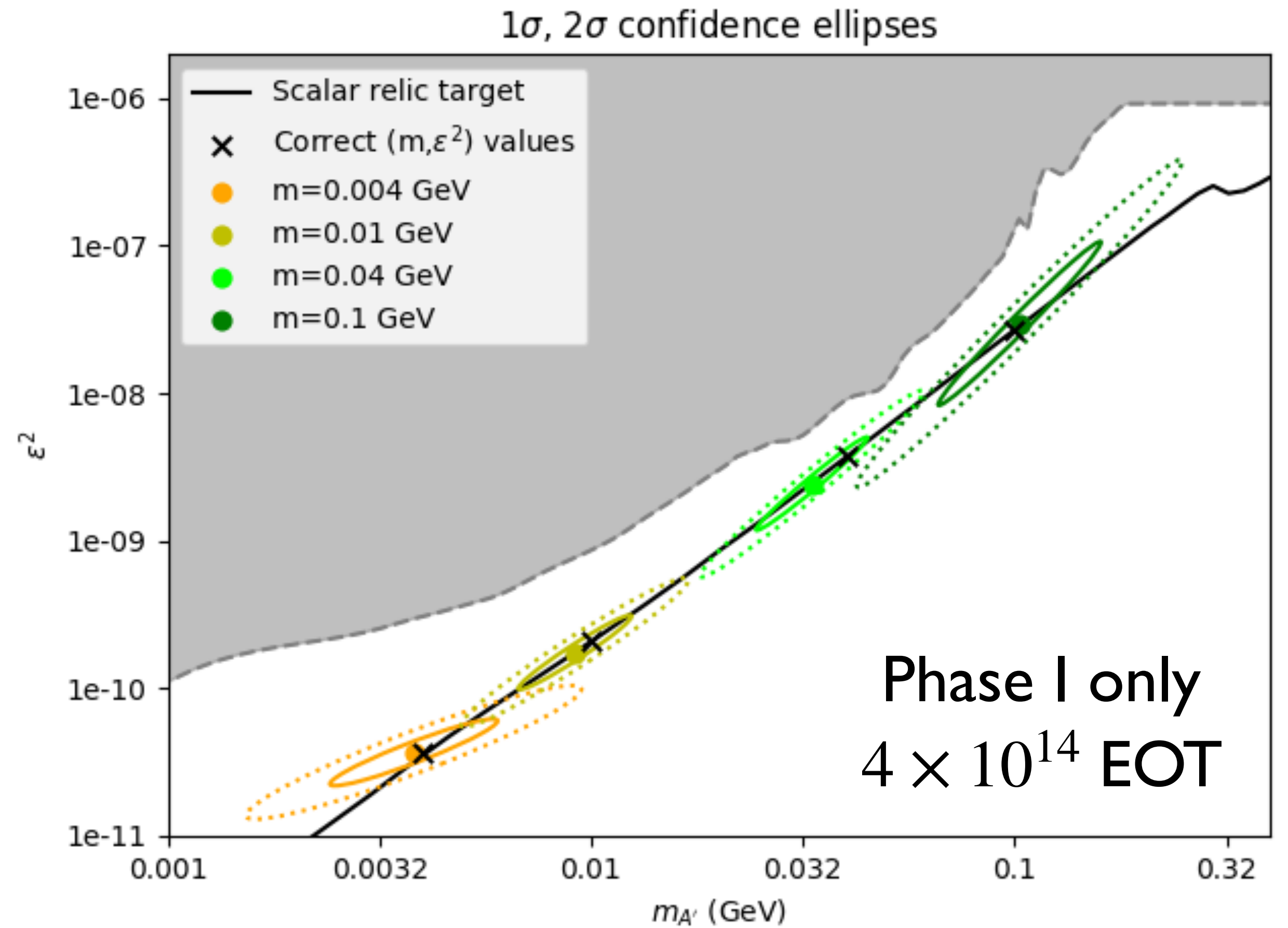
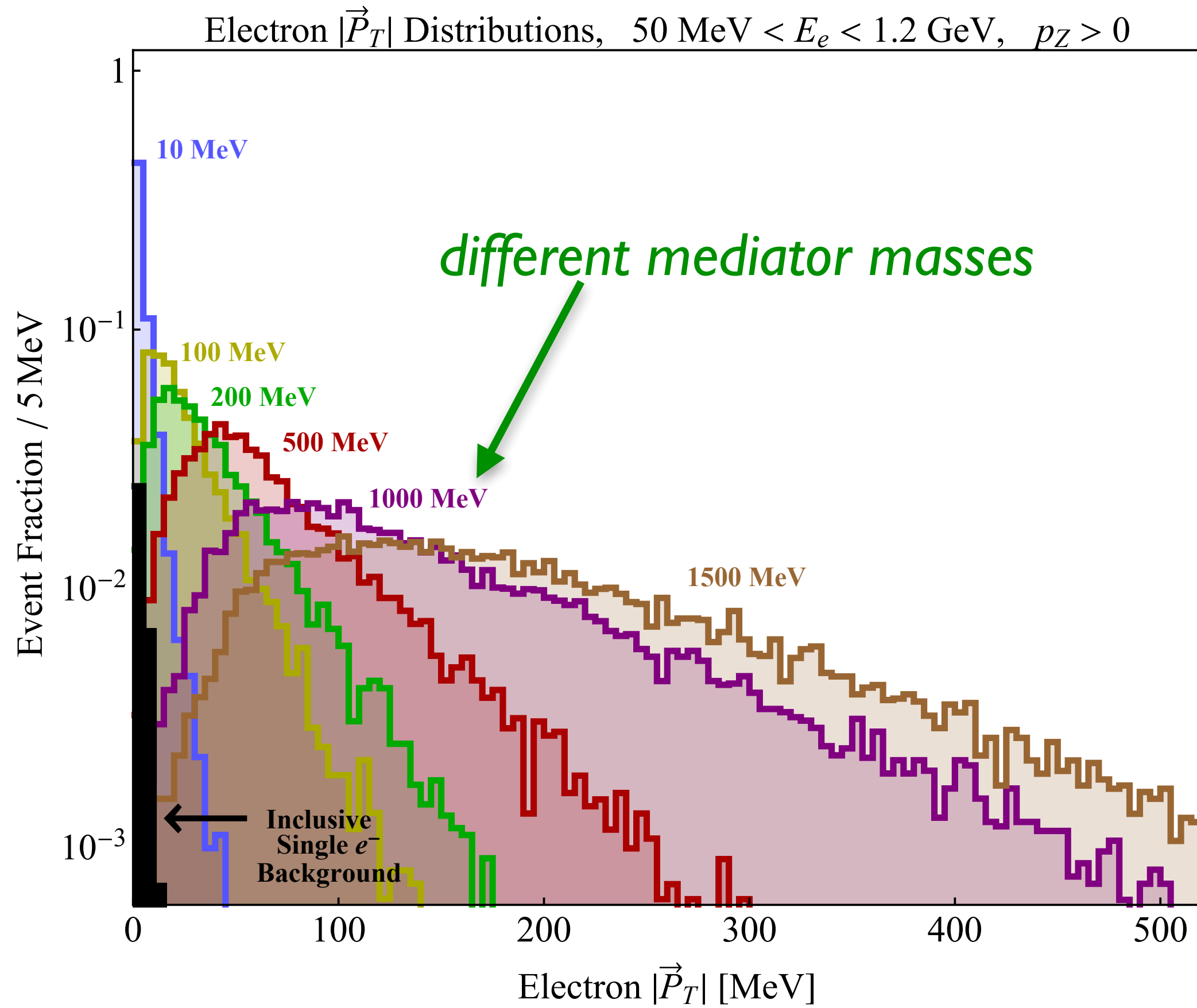


invisible meson decays



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

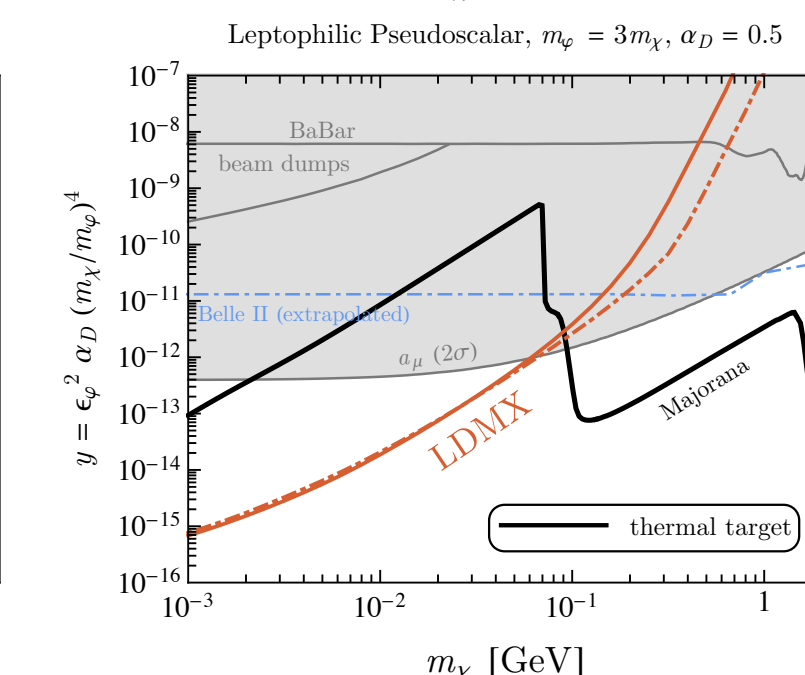
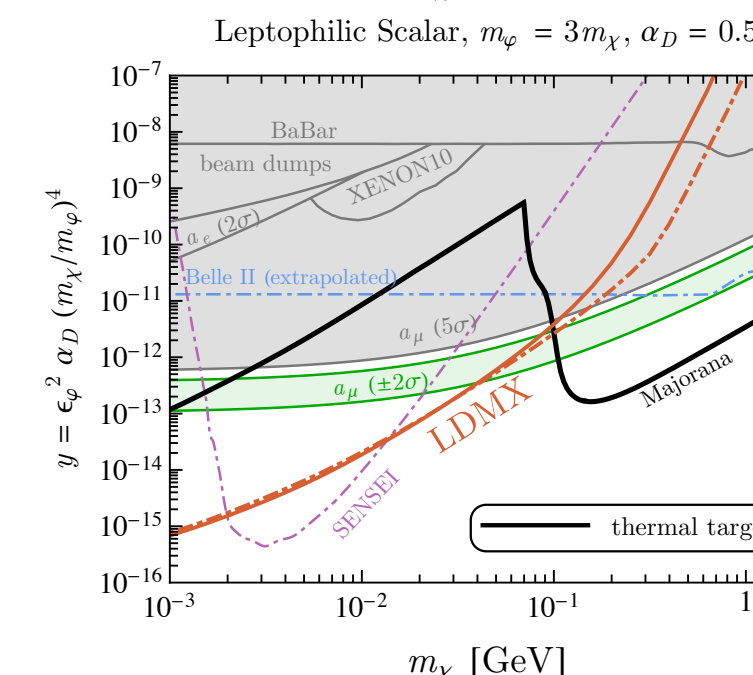
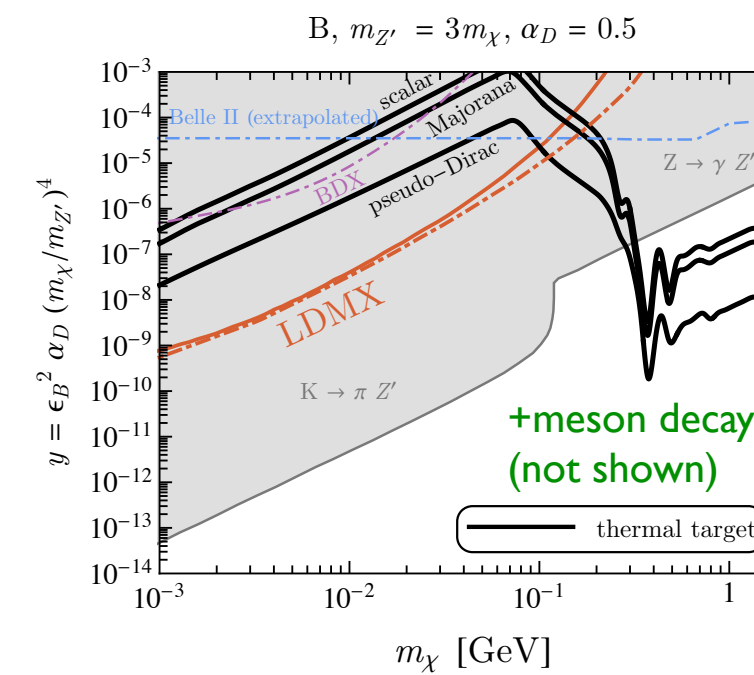
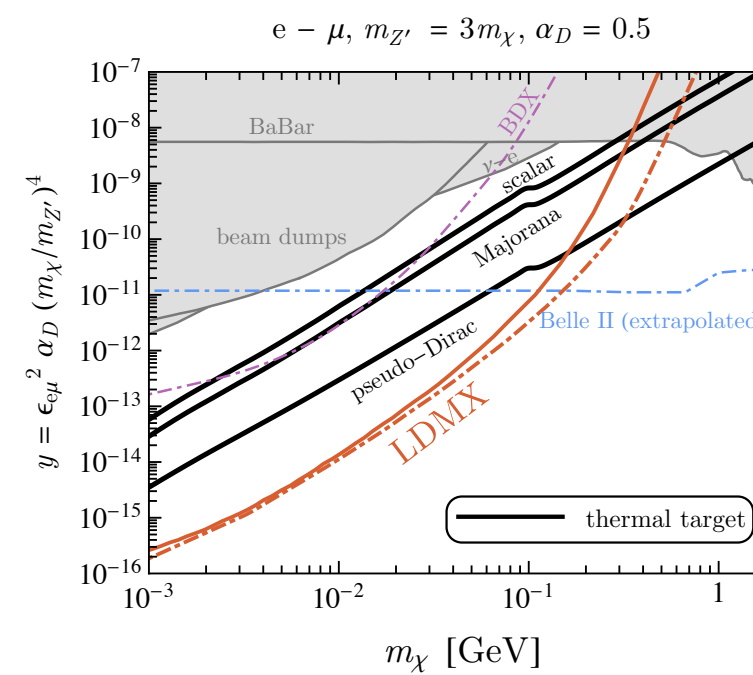
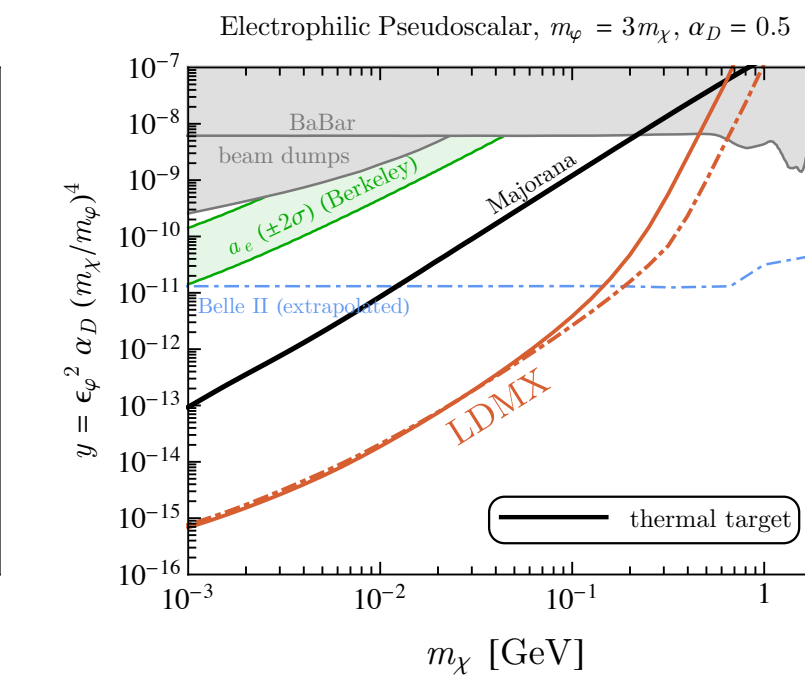
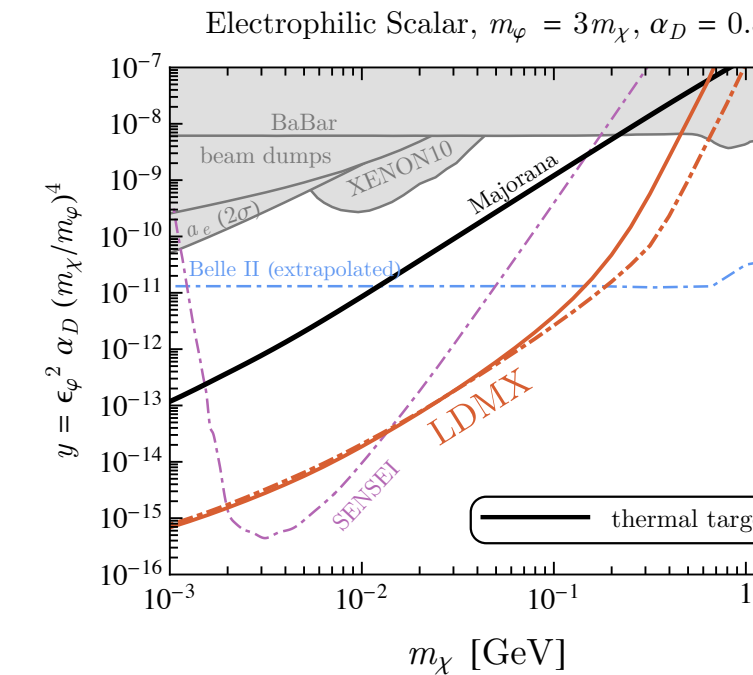
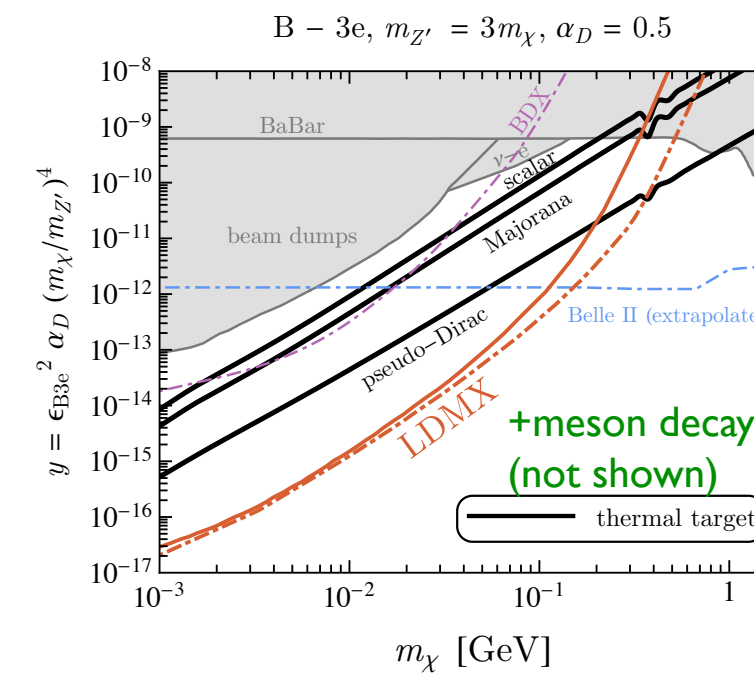
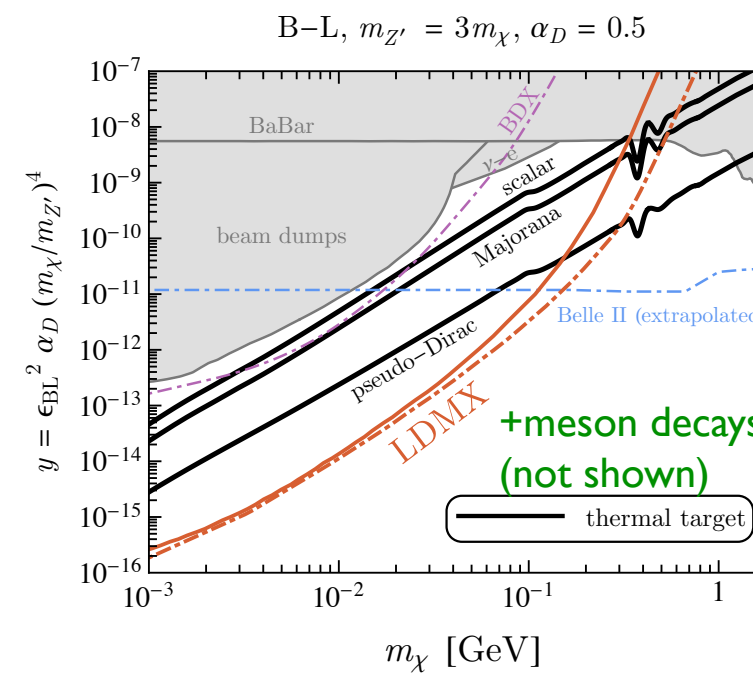
LDMX: Broader Physics Case

(other examples in backup)



Invisible Signatures

- different mediators \longrightarrow
- millicharged particles: arise from \sim 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](https://arxiv.org/abs/1807.01730) [hep-ph]
Phys. Rev. D 99, 075001 (2019)

LDMX: Broader Physics Case

(other examples in backup)



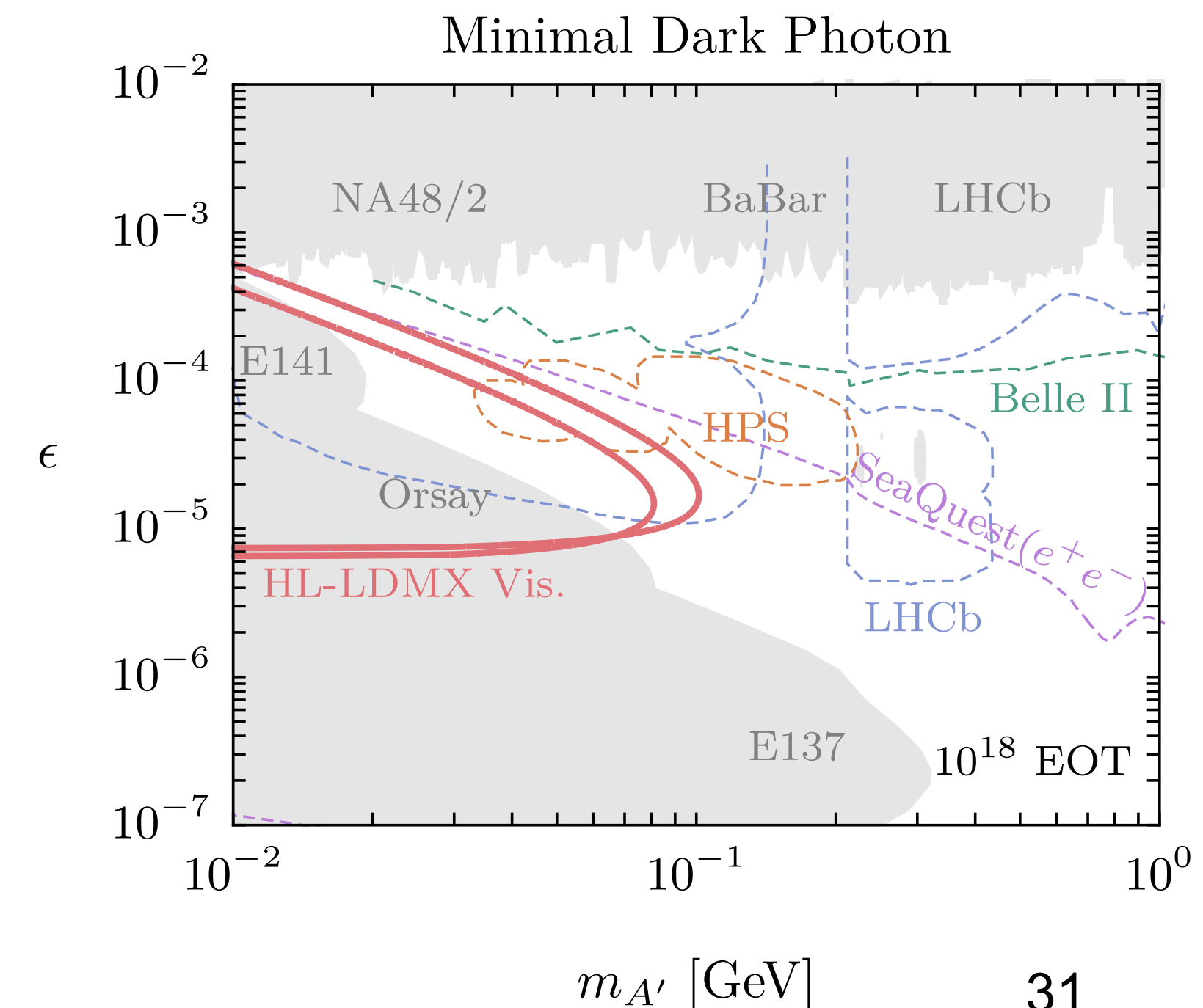
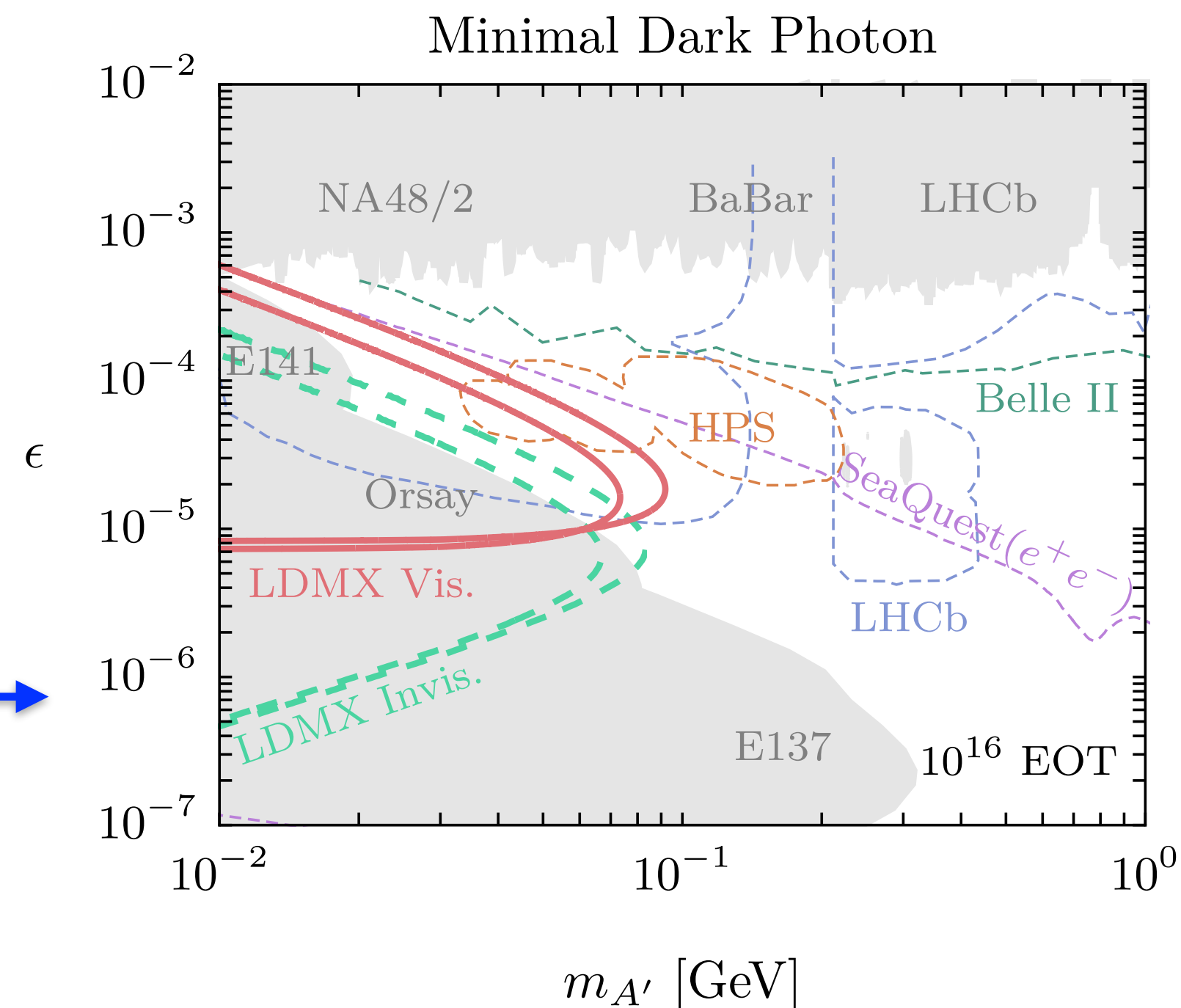
Invisible Signatures

- different mediators
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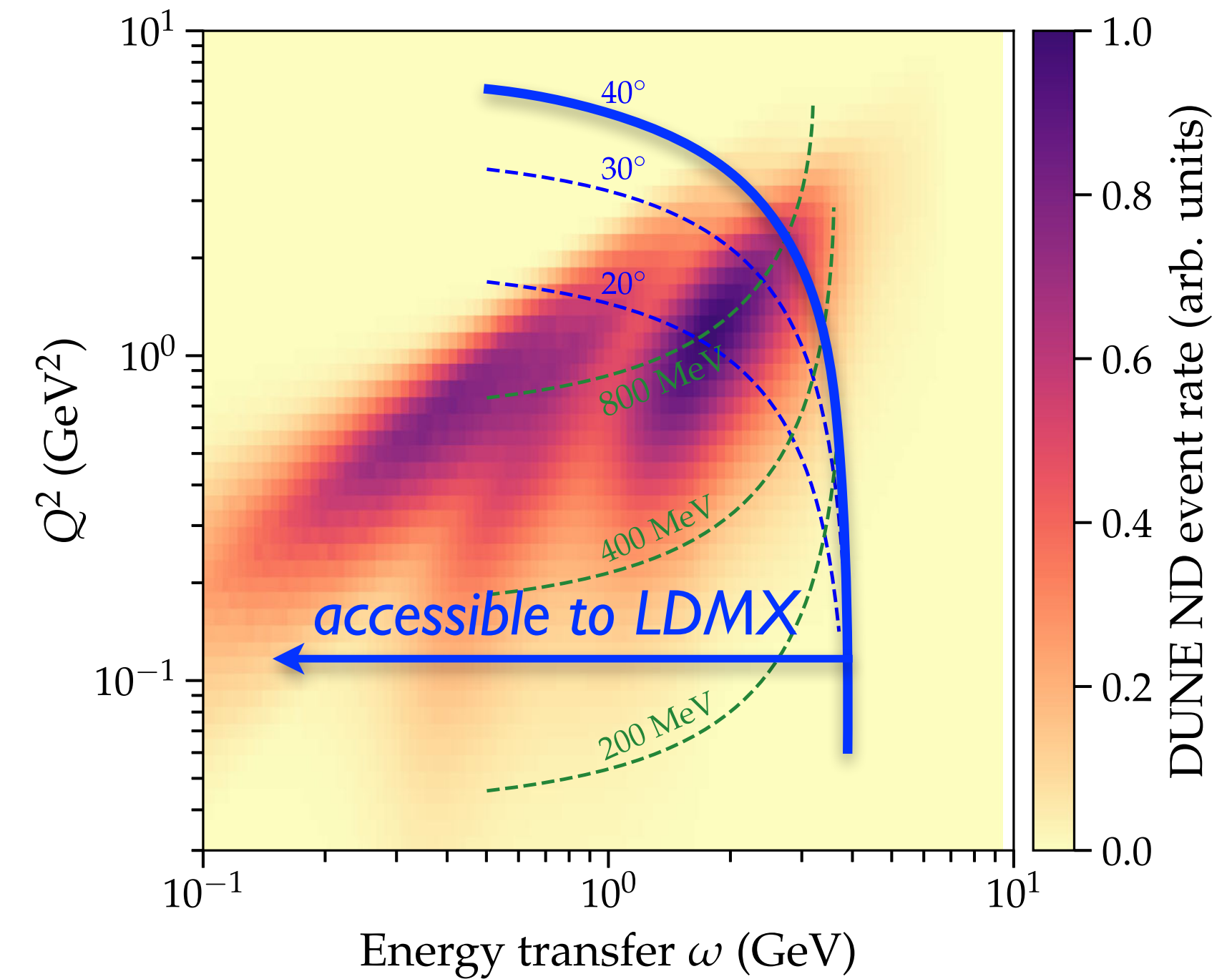
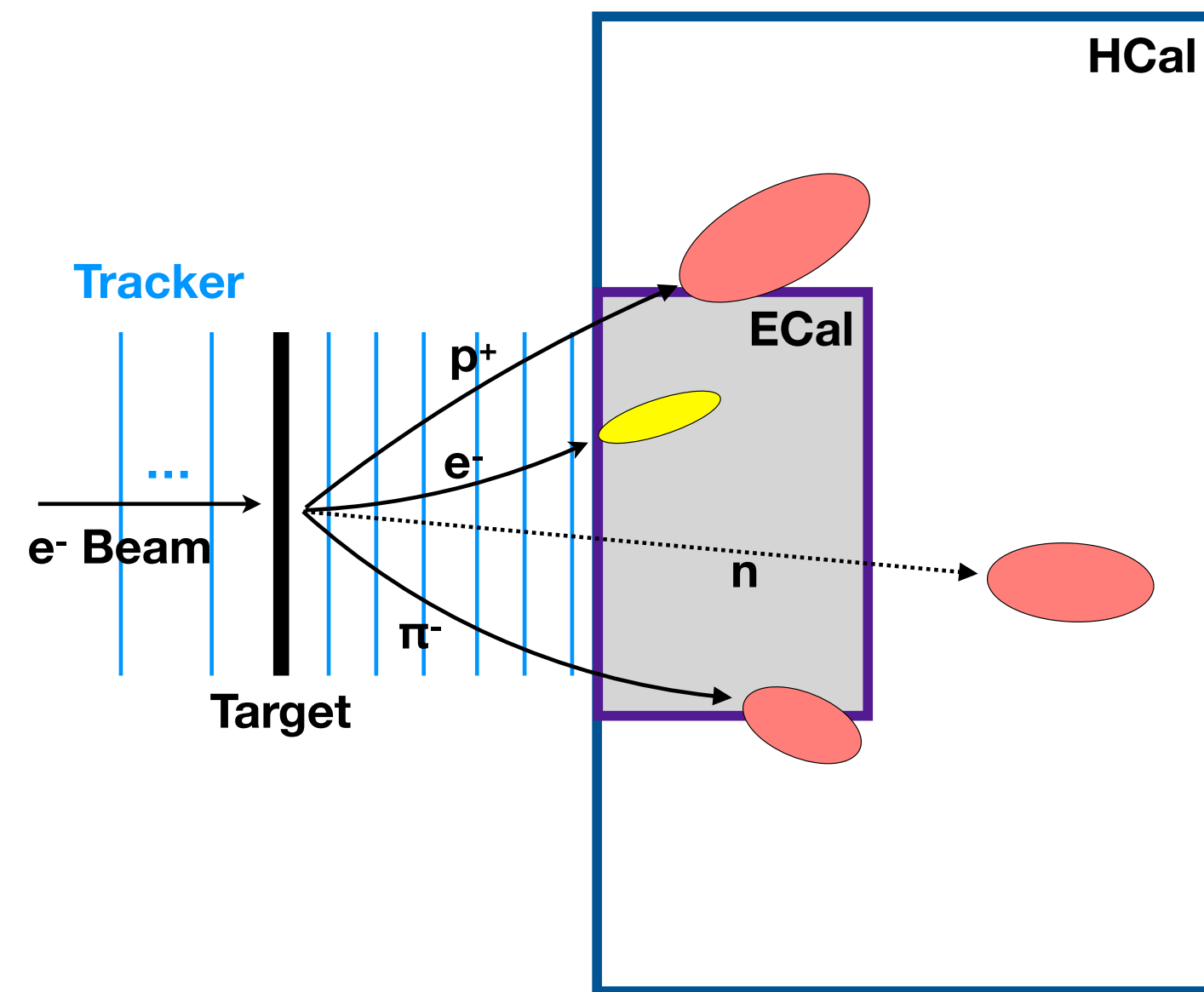


LDMX: Broader Physics Case

(other examples in backup)



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




PHYSICAL REVIEW D 101, 053004 (2020)

LDMX: Broader Physics Case



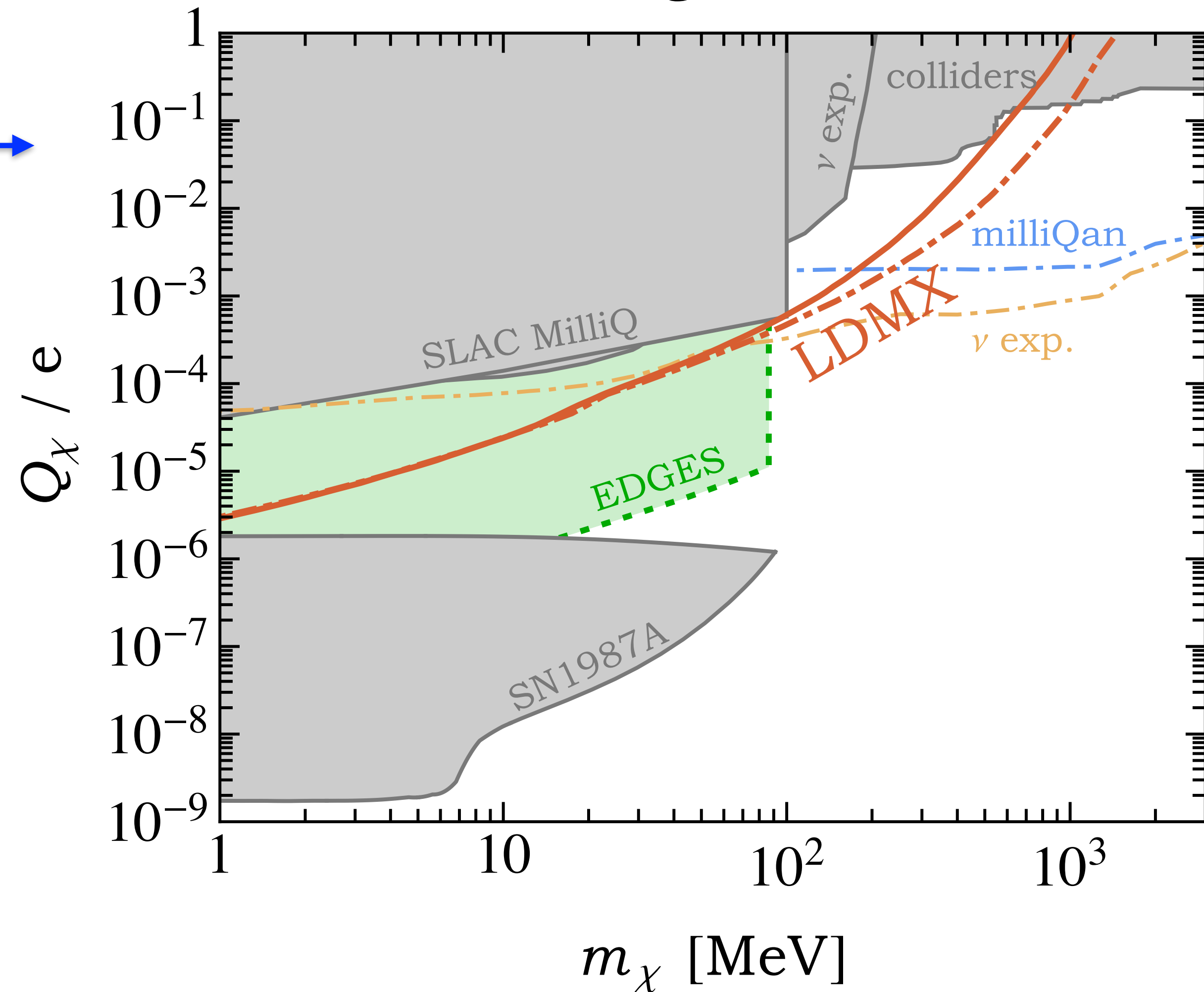
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Millicharged Fermion



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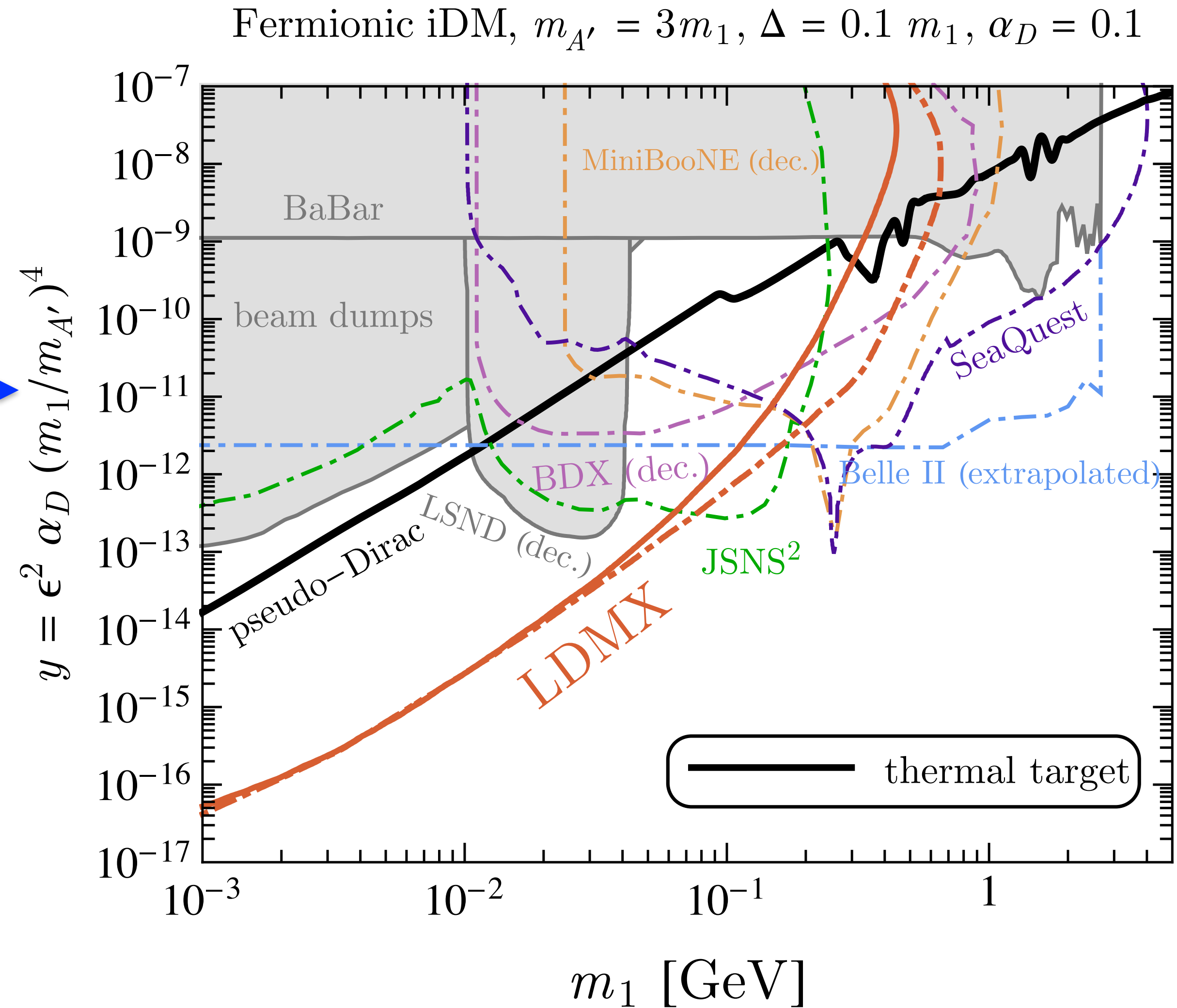


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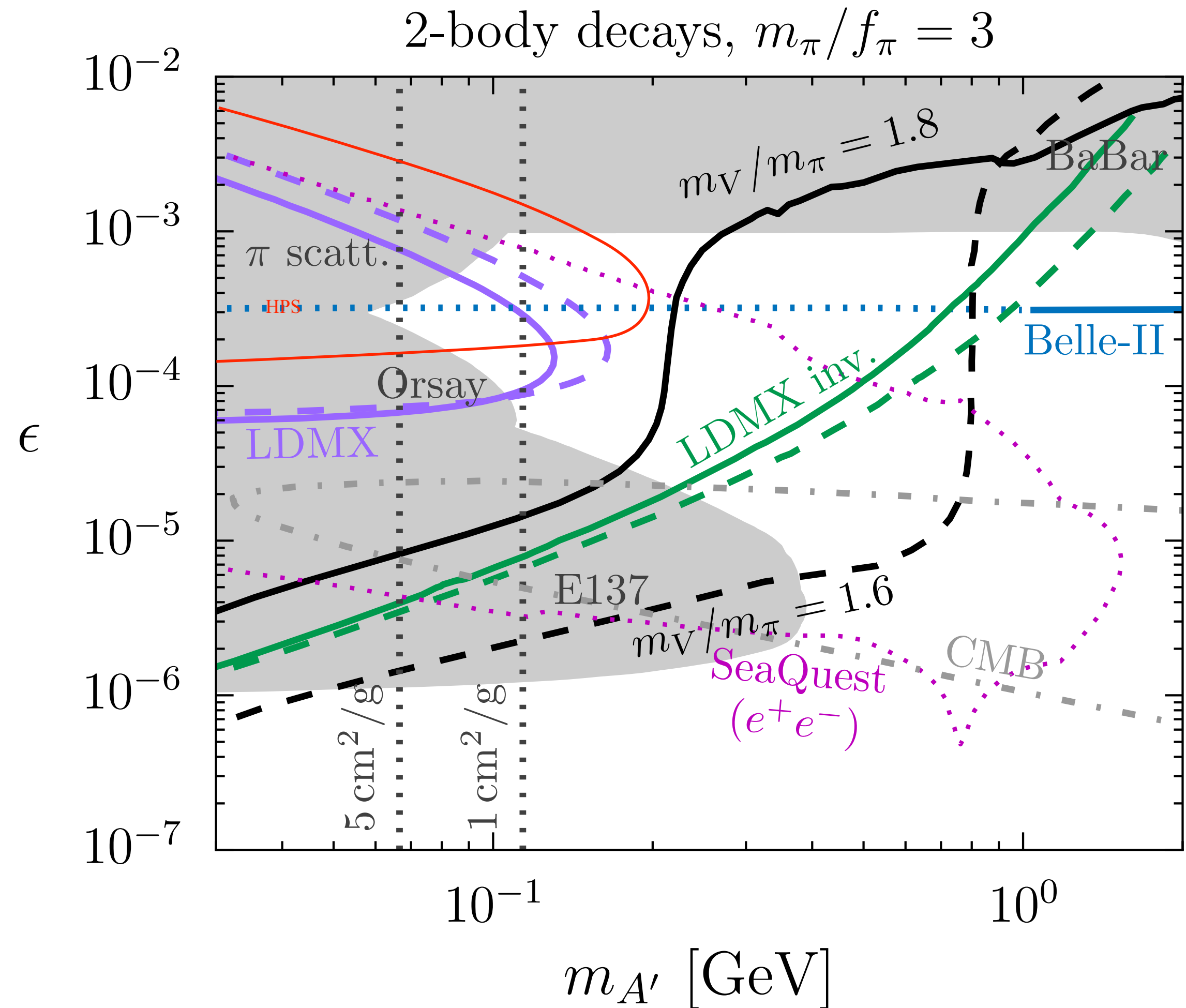


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LDMX: Broader Physics Case



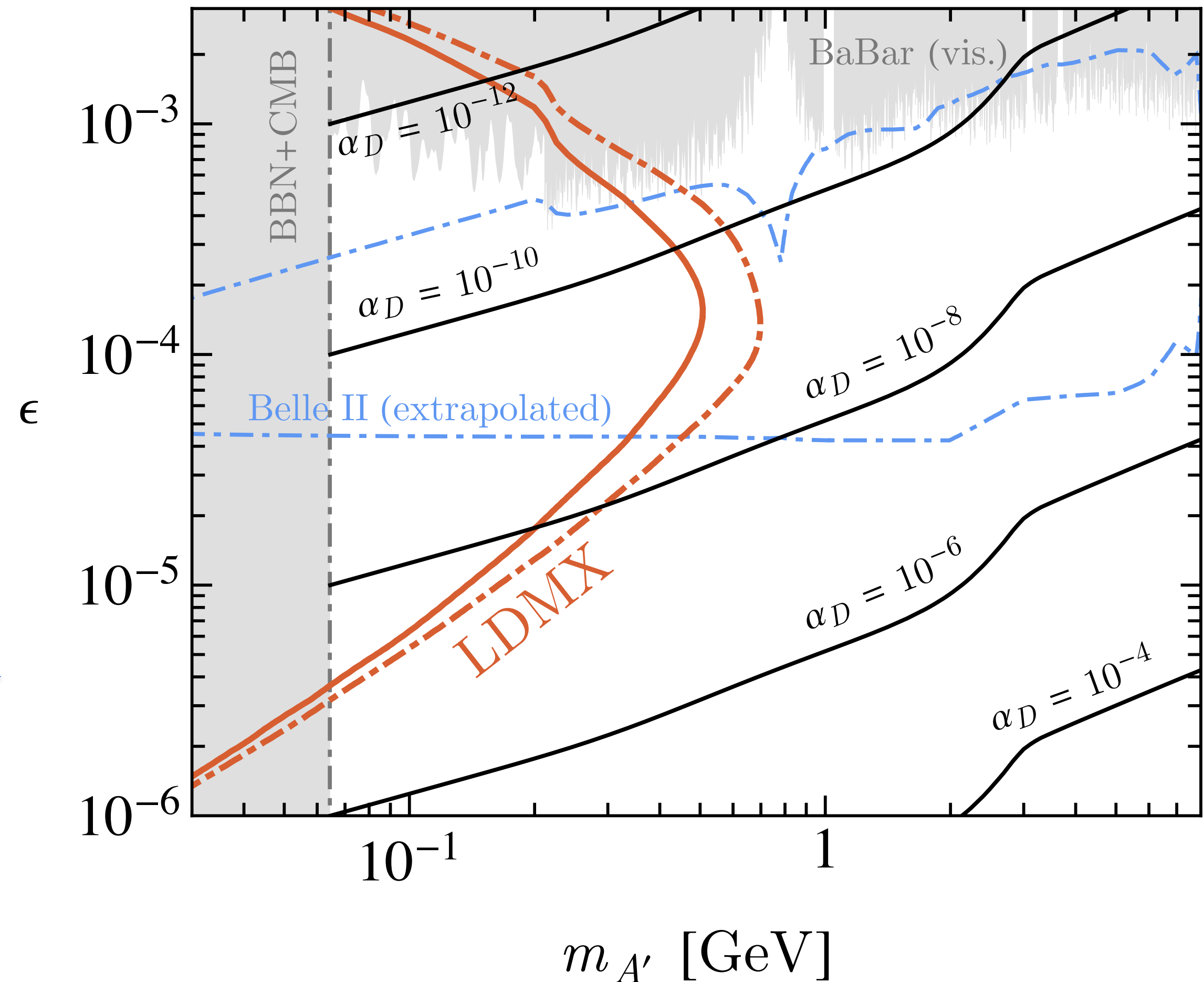
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Low-Reheat Freeze-In, $m_{A'} = 15 T_{RH}$, $m_\chi = 10$ keV



LDMX: Broader Physics Case



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