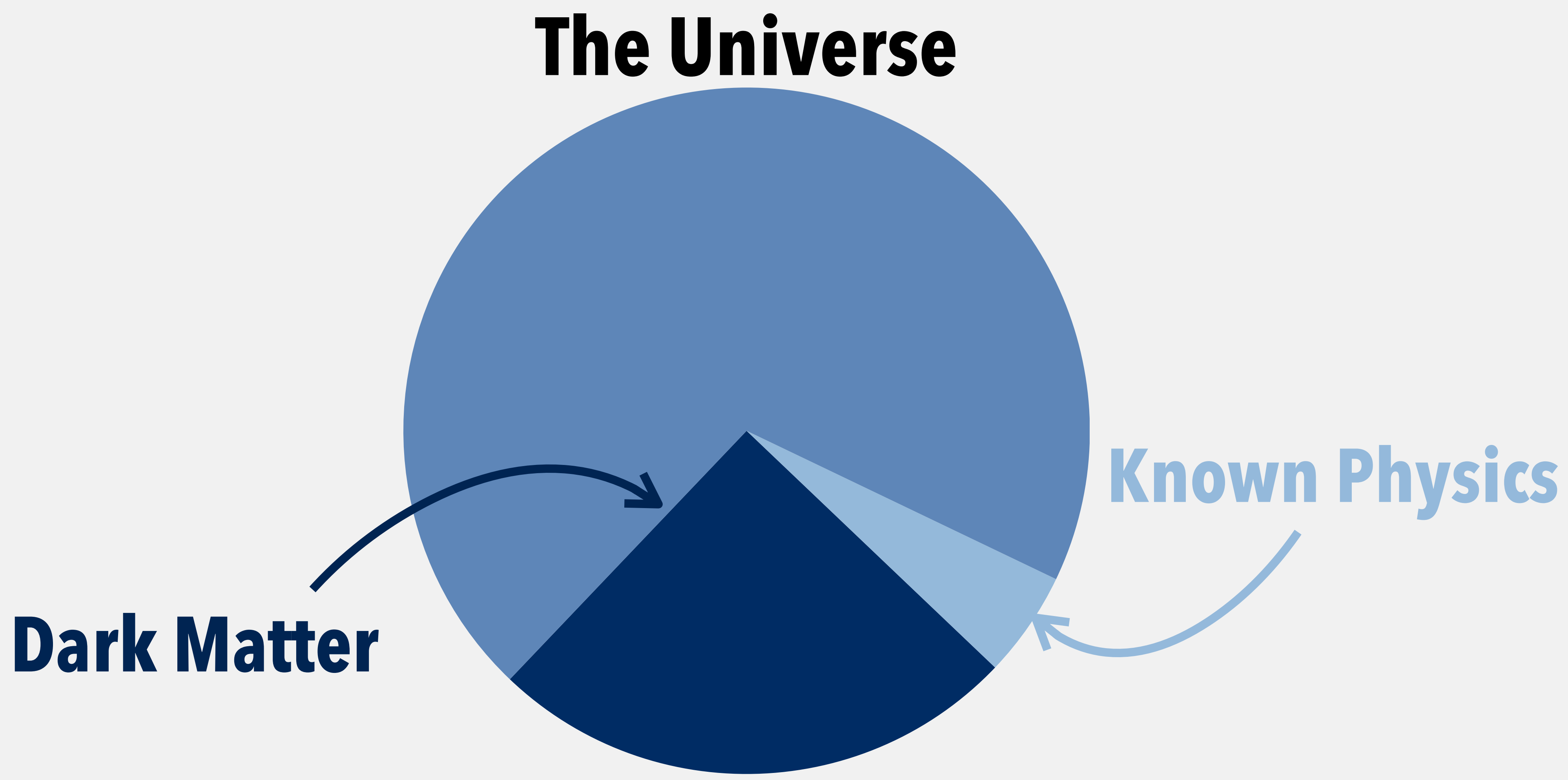
The Light Dark Matter eXperiment

Next Frontiers in the Search for Dark Matter

Workshop at GGI, September 2019

Ruth Pöttgen

What is light? (in this talk)



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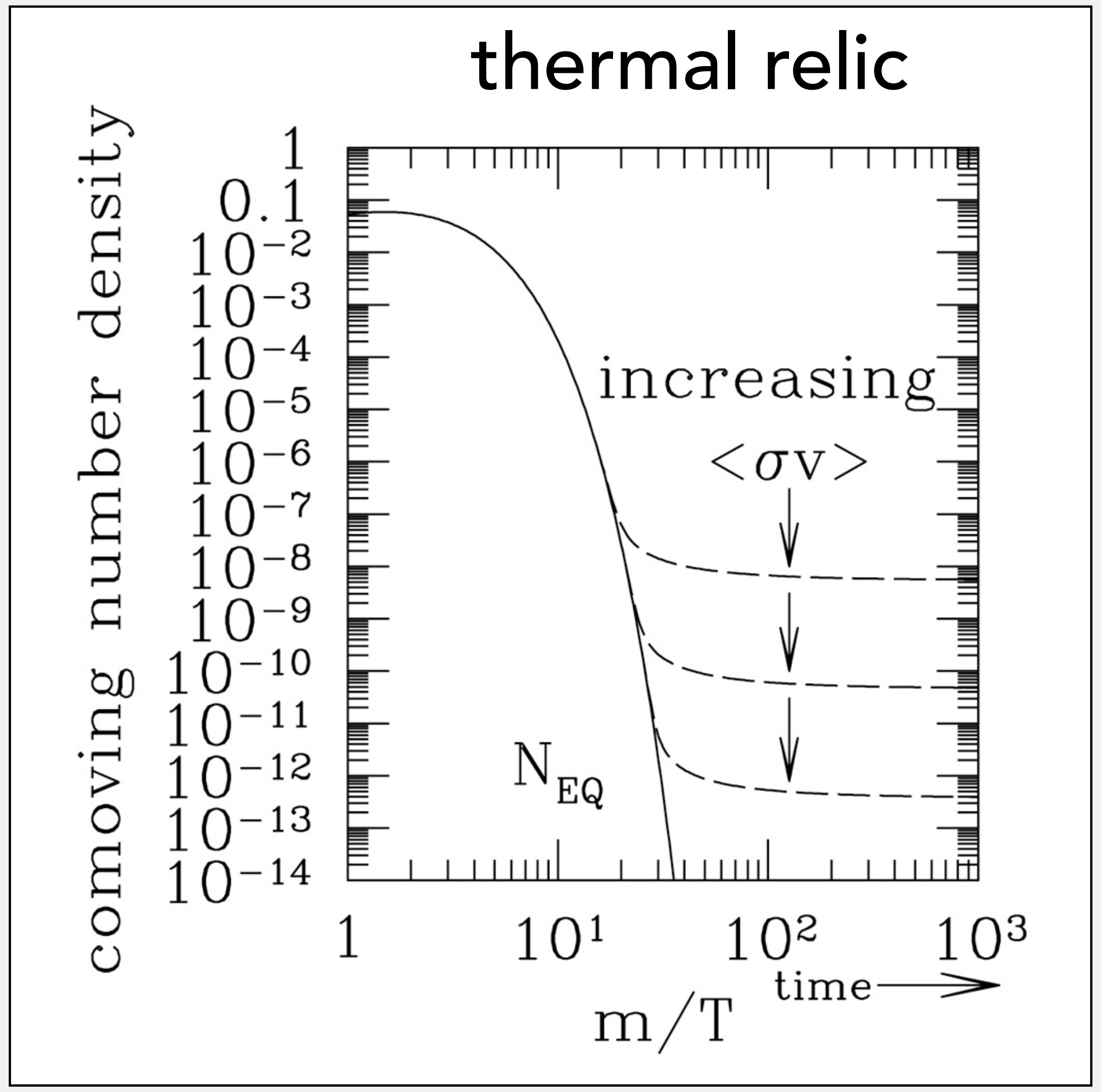

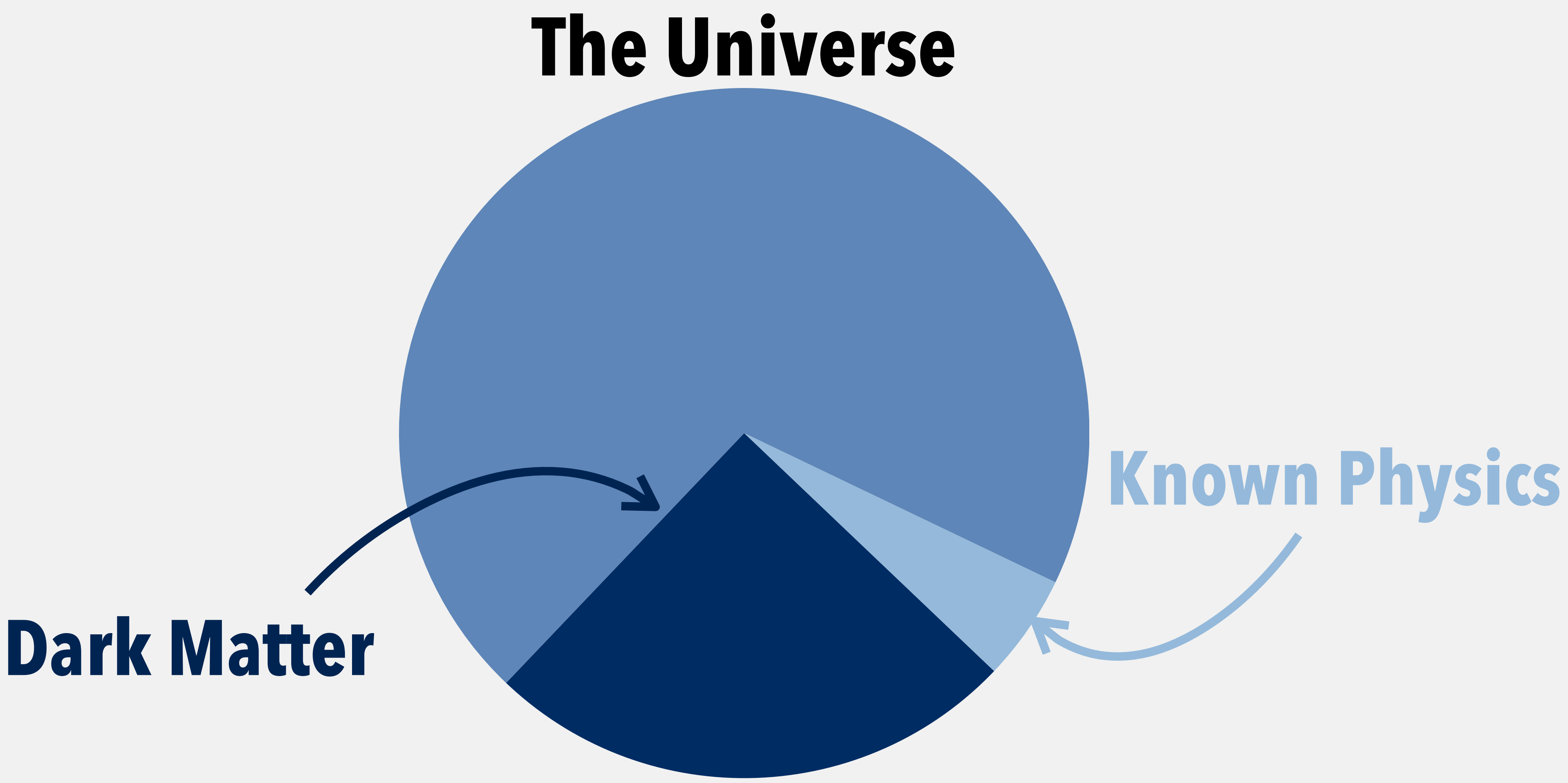

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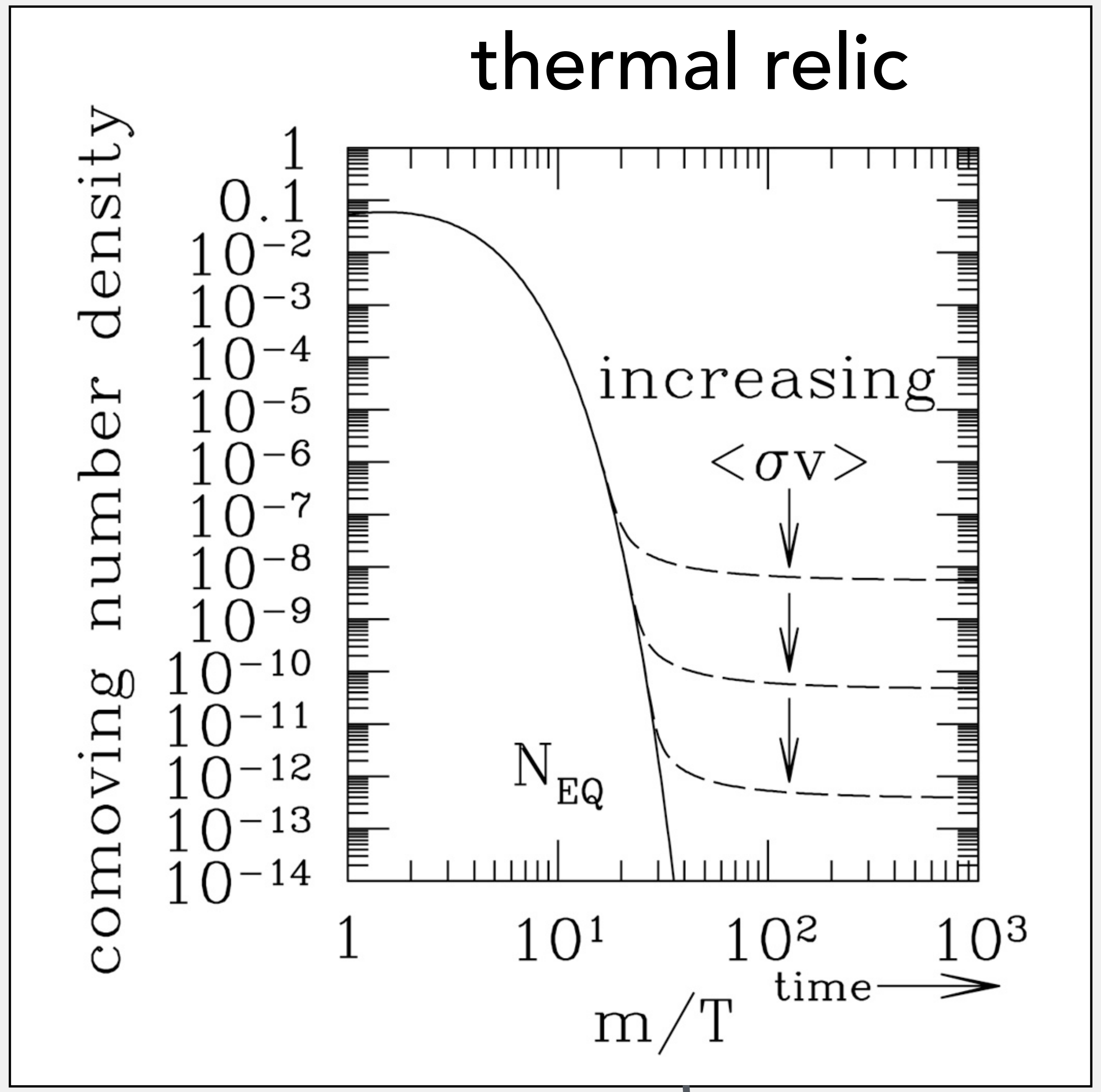

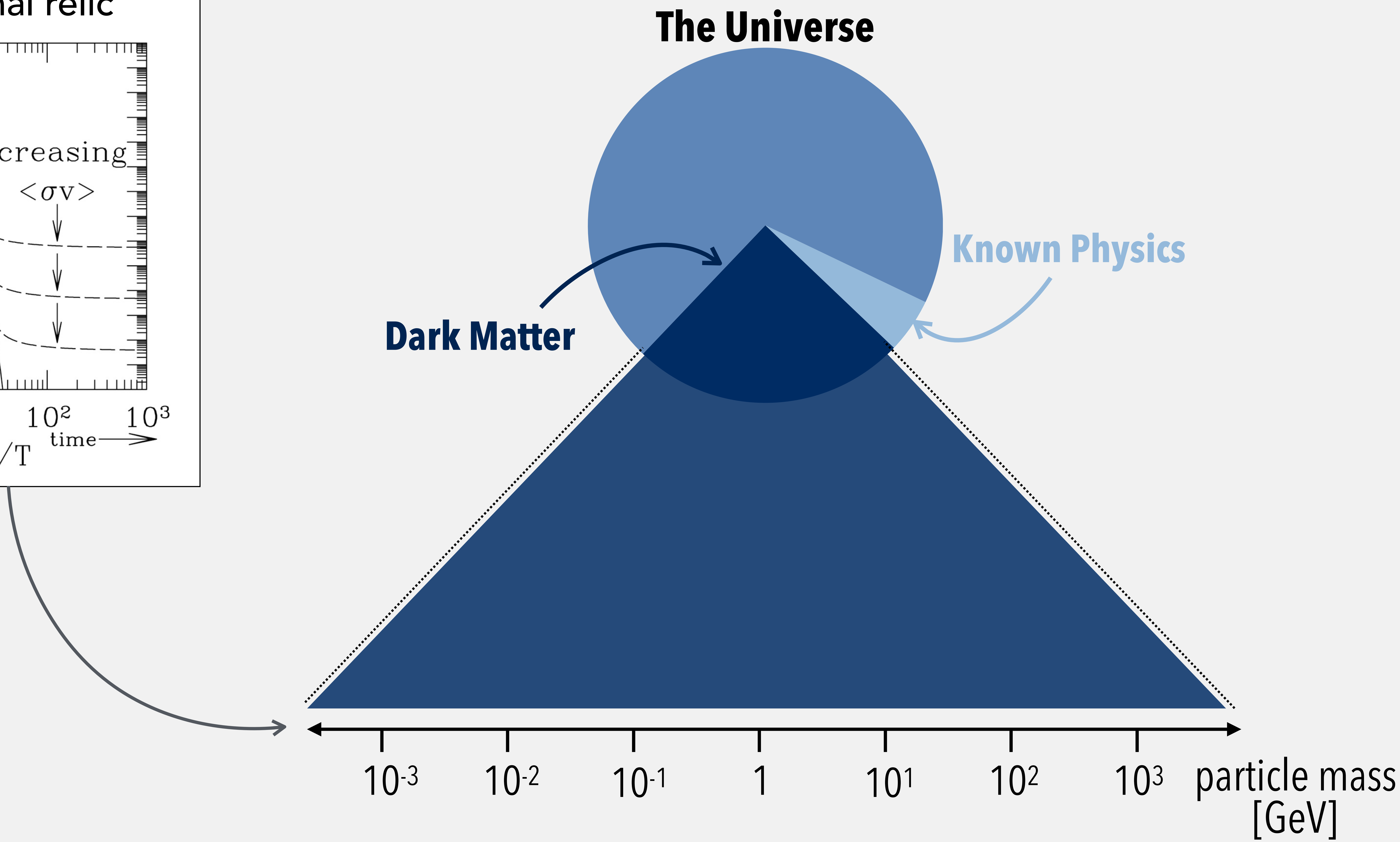

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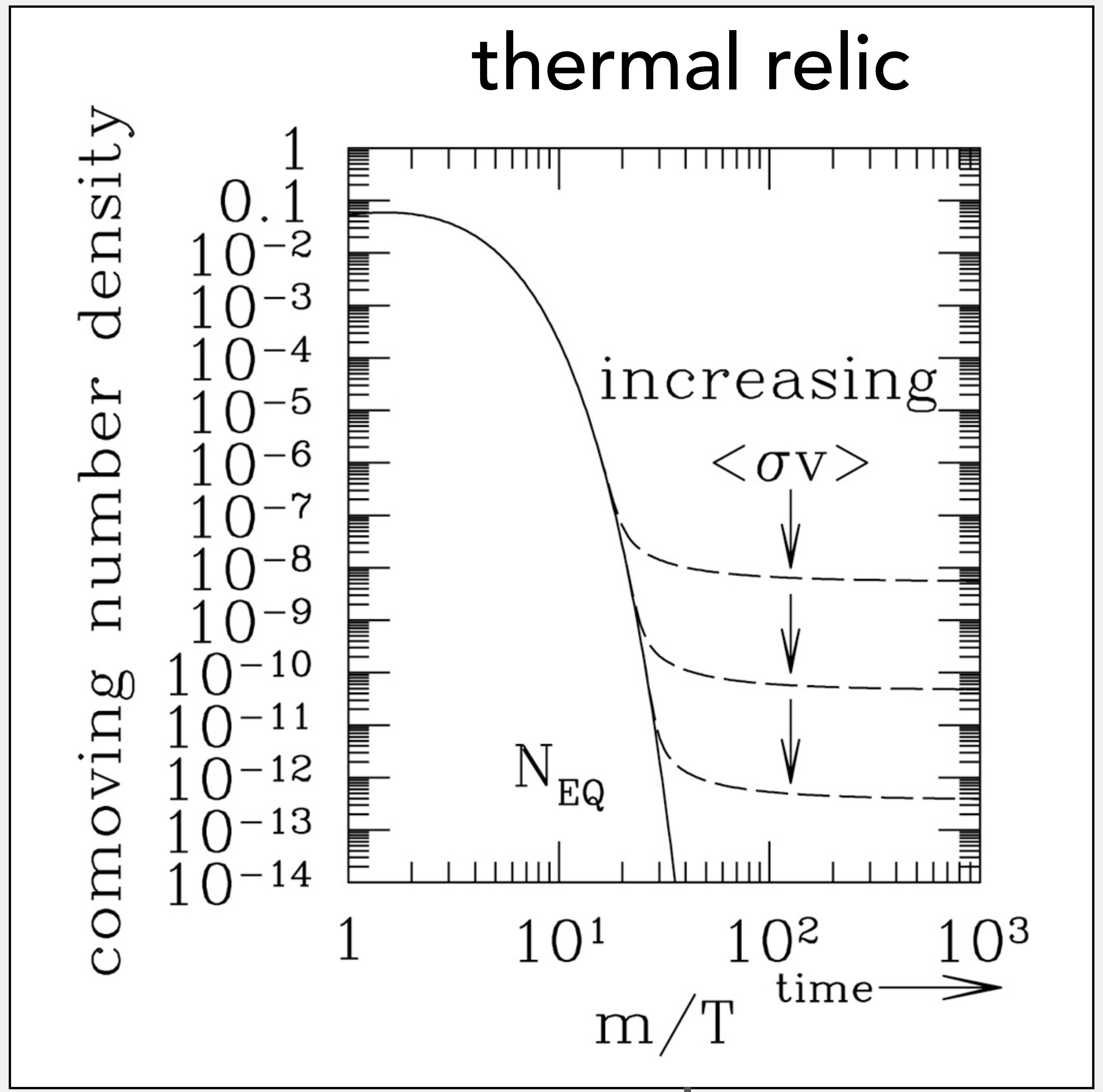

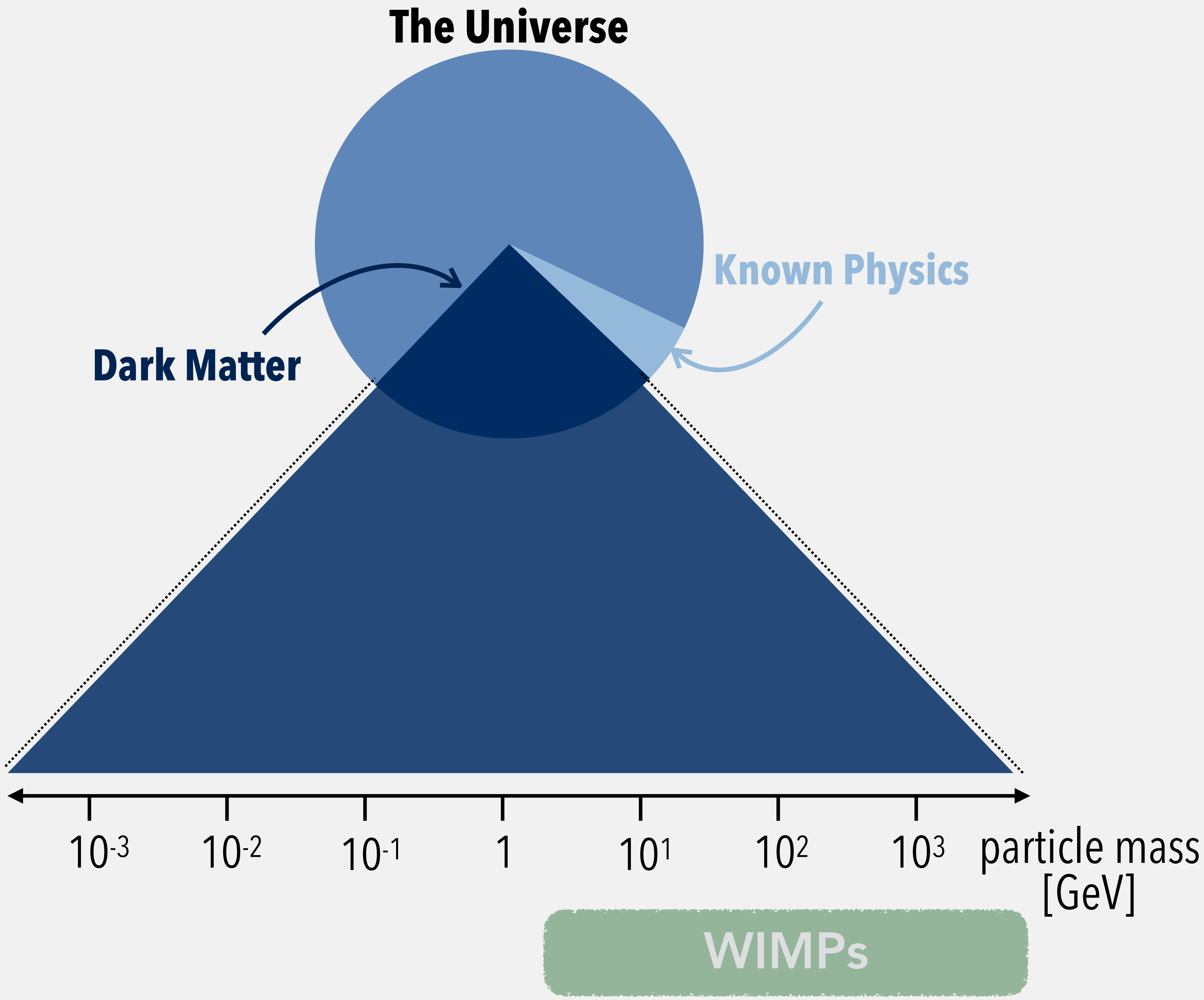

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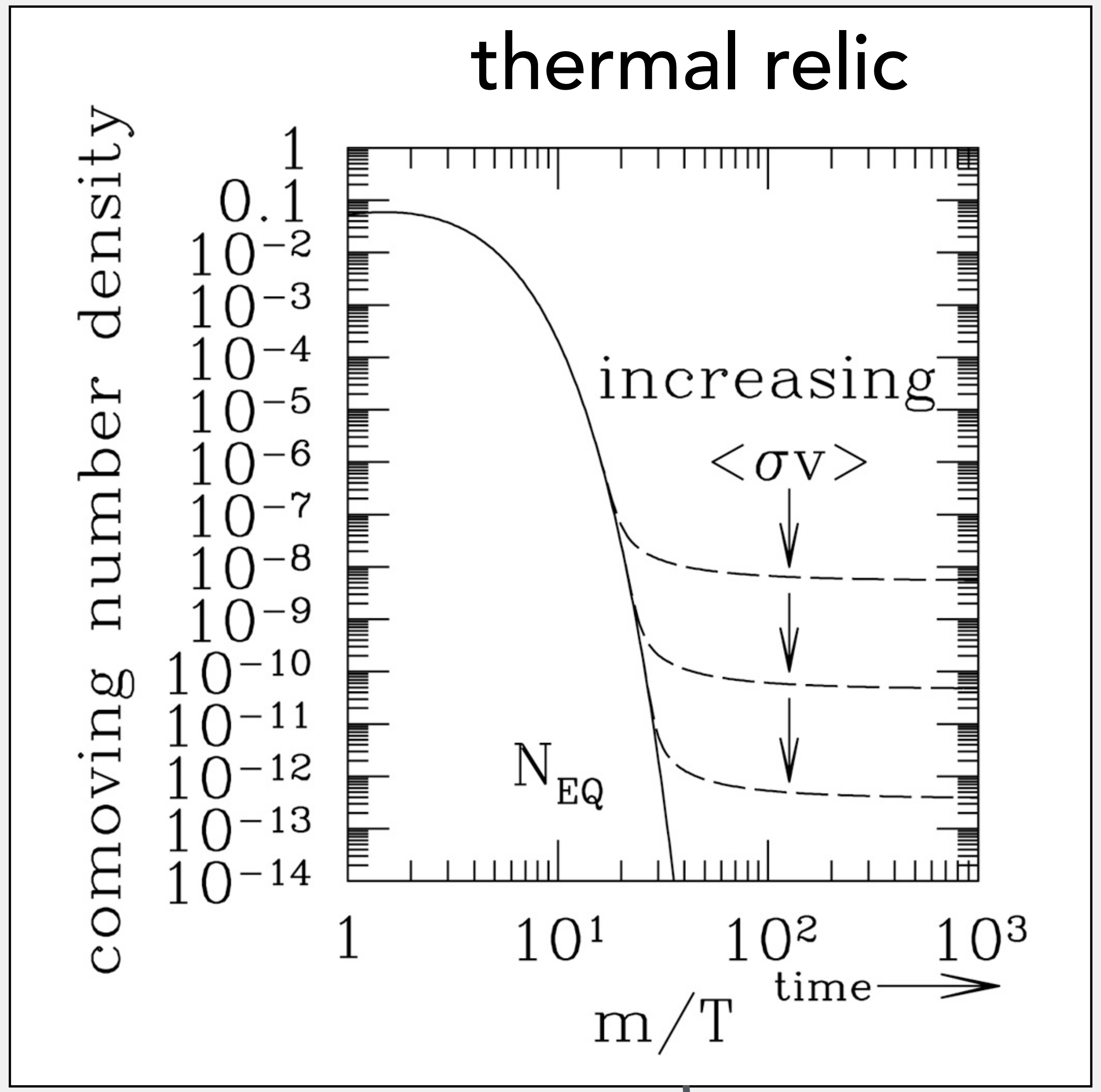
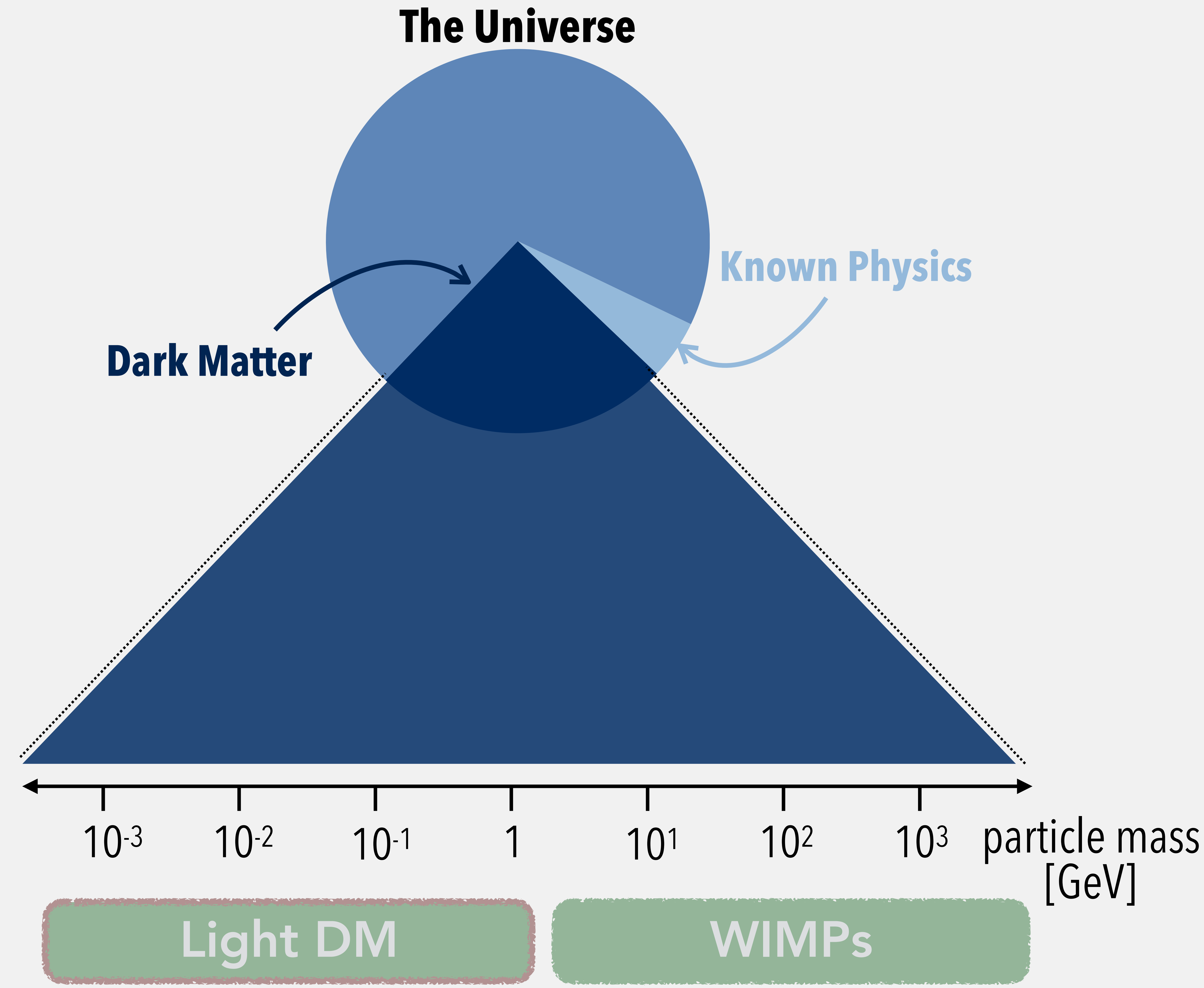




How to realise LDM

starting point: thermal relic assumption

- restricts viable mass range
- **minimum** annihilation cross section
  - otherwise overproduction of DM

if WIMPs 'too light' (m_χ< few GeV)

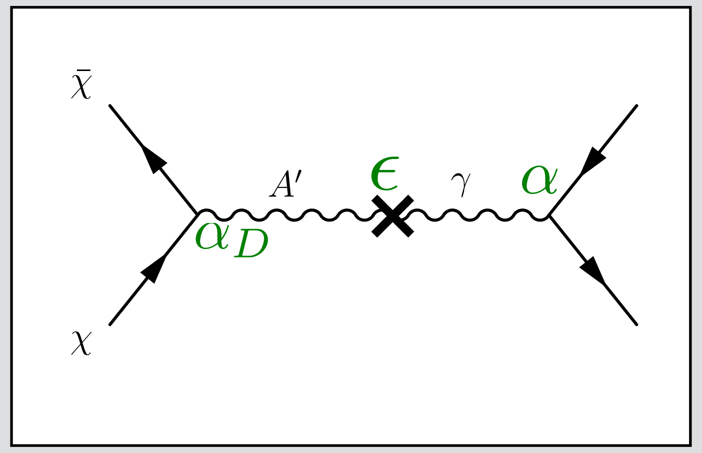
- annihilation into SM inefficient
  - overproduction of DM
- *Lee-Weinberg-bound*

introduce new, light mediator

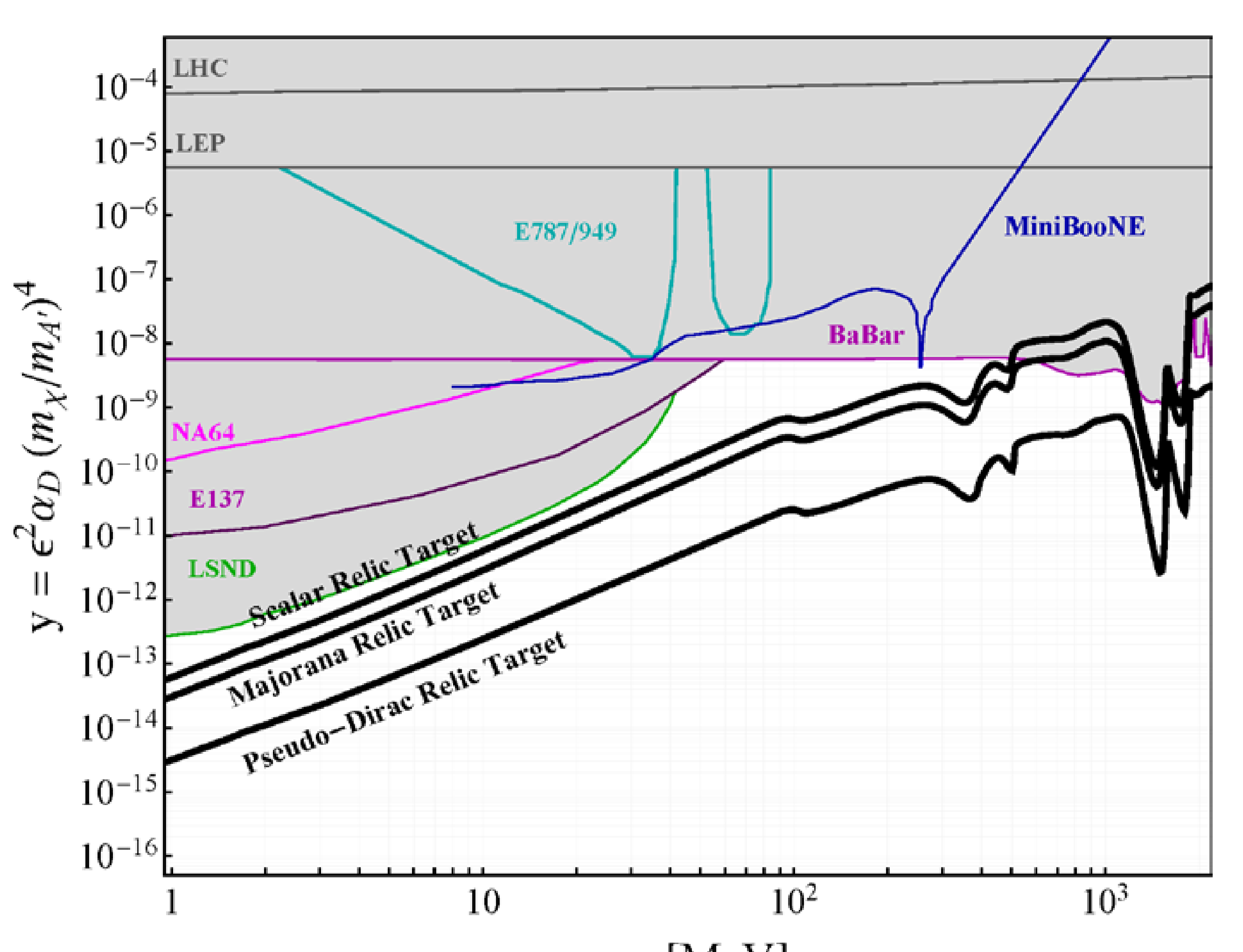
- additional annihilation channel
  - correct relic abundance

representative benchmark model: Dark Photon (A')

- vector mediator
- kinetically mixes with photon (**ε**)
- annihilation cross section



$$\sigma v \sim \alpha_D \varepsilon^2 \frac{m_\chi^2}{m_{A'}^4} \sim \alpha_D \varepsilon^2 \frac{m_\chi^4}{m_{A'}^4} \frac{1}{m_\chi^2} \sim y \frac{1}{m_\chi^2}$$



Toro & Krnjaic

$$y = \alpha_D \varepsilon^2 \frac{m_\chi^4}{m_{A'}^4}$$

clear experimental *thermal targets*

conservative:

$$\alpha_D = 0.5 \qquad \frac{m_\chi}{m_{A'}} = \frac{1}{3}$$

Active Field

arxiv:1608.08632

Dark Sectors 2016 Workshop: Community Report

arxiv:1707.04591

US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report

Experiment	Machine	Type	E_{beam} (GeV)	Detection	Mass range (GeV)	Sensitivity	First beam
Future US initiatives							
BDX	CEBAF @ JLab	electron BD	2.1-11	DM scatter	$0.001 < m_\chi < 0.1$	$y \gtrsim 10^{-13}$	2019+
COHERENT	SNS @ ORNL	proton BD	1	DM scatter	$m_\chi < 0.06$	$y \gtrsim 10^{-13}$	
DarkLight	LERF @ JLab	electron FT	0.17	MMass (& vis.)	$0.01 < m_{A'} < 0.08$	$\epsilon^2 \gtrsim 10^{-6}$	
LDMX	DASEL @ SLAC	electron FT	4 (8)*	MMomentum	$m_\chi < 0.4$	$\epsilon^2 \gtrsim 10^{-14}$	
MMAPS	Synchr @ Cornell	positron FT	6	MMass	$0.02 < m_{A'} < 0.075$	$\epsilon^2 \gtrsim 10^{-8}$	
SBN	BNB @ FNAL	proton BD	8	DM scatter	$m_\chi < 0.4$	$y \sim 10^{-12}$	
SeaQuest	MI @ FNAL	proton FT	120	vis. prompt	$0.22 < m_{A'} < 9$	$\epsilon^2 \gtrsim 10^{-8}$	
				vis. disp.	$m_{A'} < 2$	$\epsilon^2 \sim 10^{-14} - 10^{-8}$	
Future international initiatives							
Belle II	SuperKEKB @ KEK	e^+e^- collider	~ 5.3	MMass (& vis.)	$0 < m_\chi < 10$	$\epsilon^2 \gtrsim 10^{-9}$	2018
MAGIX	MESA @ Mami	electron FT	0.105	vis.	$0.01 < m_{A'} < 0.060$	$\epsilon^2 \gtrsim 10^{-9}$	2021-2022
PADME	DAΦNE @ Frascati	positron FT	0.550	MMass	$m_{A'} < 0.024$	$\epsilon^2 \gtrsim 10^{-7}$	2018
SHIP	SPS @ CERN	proton BD	400	DM scatter	$m_\chi < 0.4$	$y \gtrsim 10^{-12}$	2026+
VEPP3	VEPP3 @ BINP	positron FT	0.500	MMass	$0.005 < m_{A'} < 0.022$	$\epsilon^2 \gtrsim 10^{-8}$	2019-2020
Current and completed initiatives							
APEX	CEBAF @ JLab	electron FT	1.1-4.5	vis.	$0.06 < m_{A'} < 0.55$	$\epsilon^2 \gtrsim 10^{-7}$	2018-2019
BABAR	PEP-II @ SLAC	e^+e^- collider	~ 5.3	vis.	$0.02 < m_{A'} < 10$	$\epsilon^2 \gtrsim 10^{-7}$	done
Belle	KEKB @ KEK	e^+e^- collider	~ 5.3	vis.	$0.1 < m_{A'} < 10.5$	$\epsilon^2 \gtrsim 10^{-7}$	done
HPS	CEBAF @ JLab	electron FT	1.1-4.5	vis.	$0.015 < m_{A'} < 0.5$	$\epsilon^2 \sim 10^{-7}$**	2018-2020
NA/64	SPS @ CERN	electron FT	100	MEnergy	$m_{A'} < 1$	$\epsilon^2 \gtrsim 10^{-10}$	started
MiniBooNE	BNB @ FNAL	proton BD	8	DM scatter	$m_\chi < 0.4$	$y \gtrsim 10^{-9}$	done
TREK	K^+ beam @ J-PARC	K decays	0.240	vis.	N/A	N/A	done

https://home.cern/scientists/updates/2016/05/cern-launches-physics-beyond-colliders-study-group

CERN launches Physics Beyond Colliders study group

We are pleased to announce the kick-off workshop of the "Physics Beyond Colliders" Study Group which has recently been set up by CERN Management. The workshop will be held at CERN, Geneva, on September 6-7, 2016.

The aim of the workshop is to explore the opportunities offered by the CERN accelerator complex and infrastructure to get new insights into some of today's outstanding questions in particle physics through projects complementary to high-energy colliders and other initiatives in the world. The focus is on fundamental physics questions that are

arxiv:1901.09966

Physics Beyond Colliders at CERN Beyond the Standard Model Working Group Report

arxiv:1902.00260

Physics Beyond Colliders

CERN-PBC-REPORT-2018-003

Summary Report of Physics Beyond Colliders at CERN

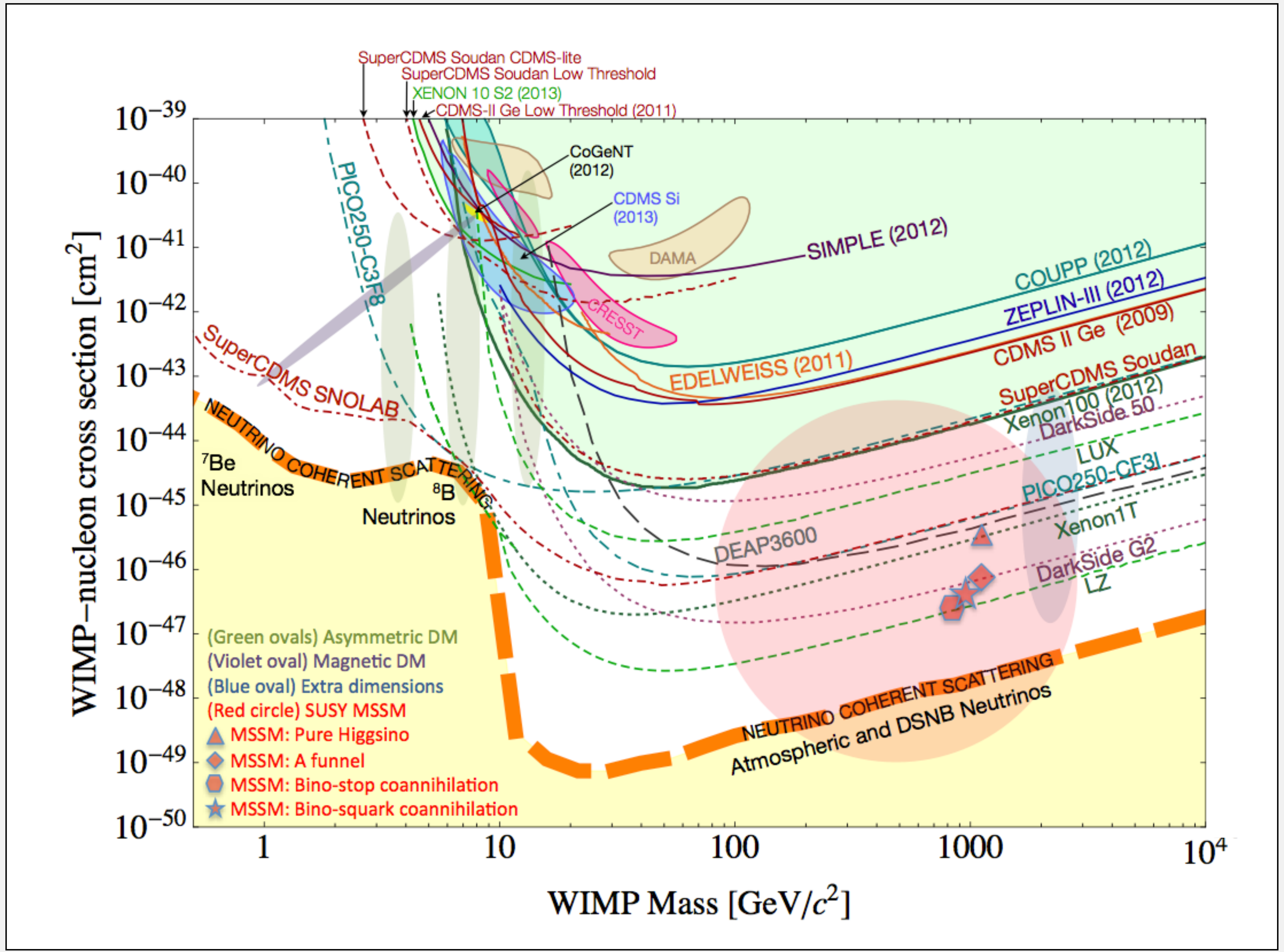
Direct Detection

Direct detection: **nuclear** recoil due to WIMP scattering

- sensitivity drops quickly below few GeV

Many new ideas in recent years to get to lower masses

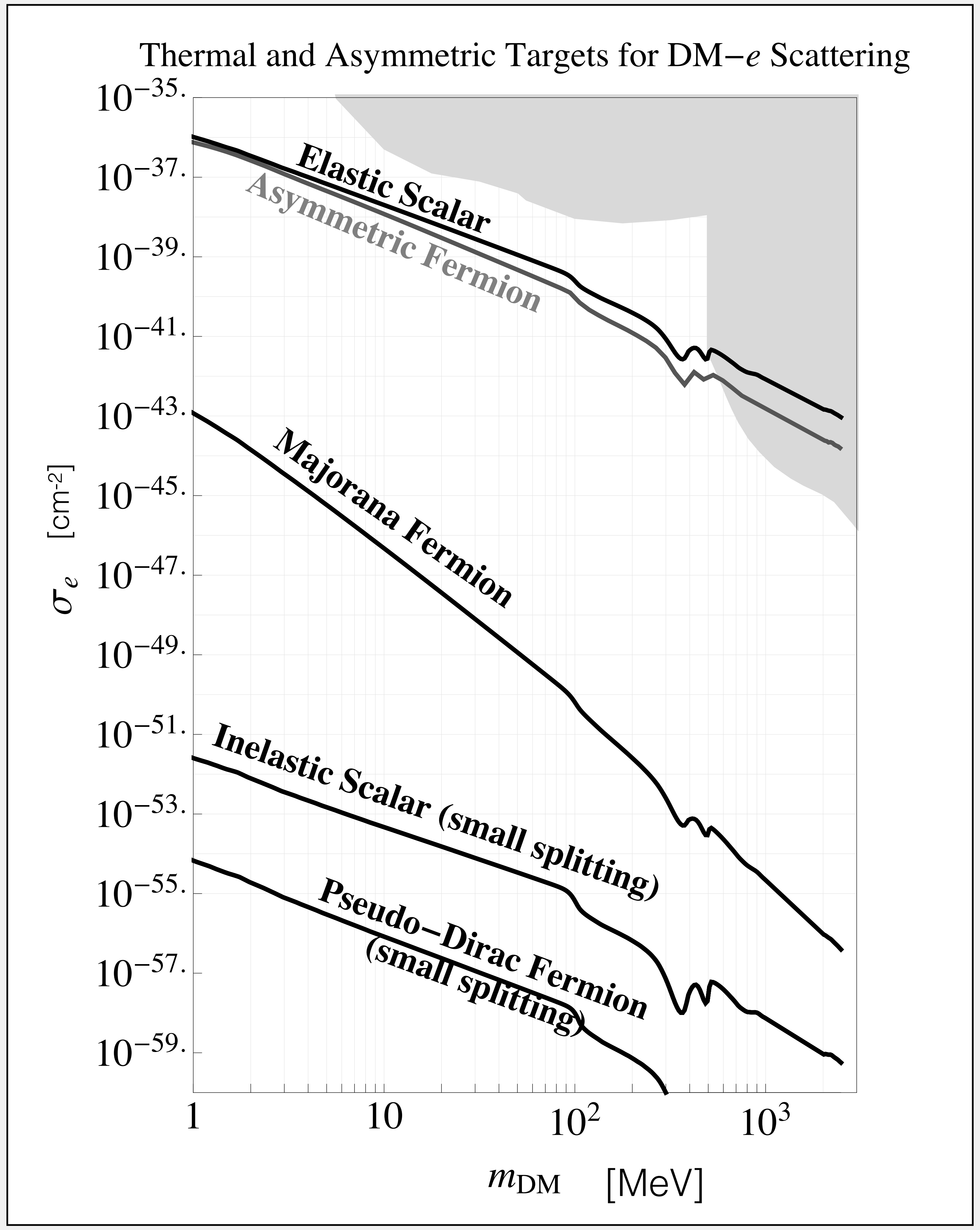
- needs lower energy threshold
  - examples:
    - electron-DM scattering
    - semiconductors



Why not only direct detection?

direct detection:

strong spin/velocity dependency



Why not only direct detection?

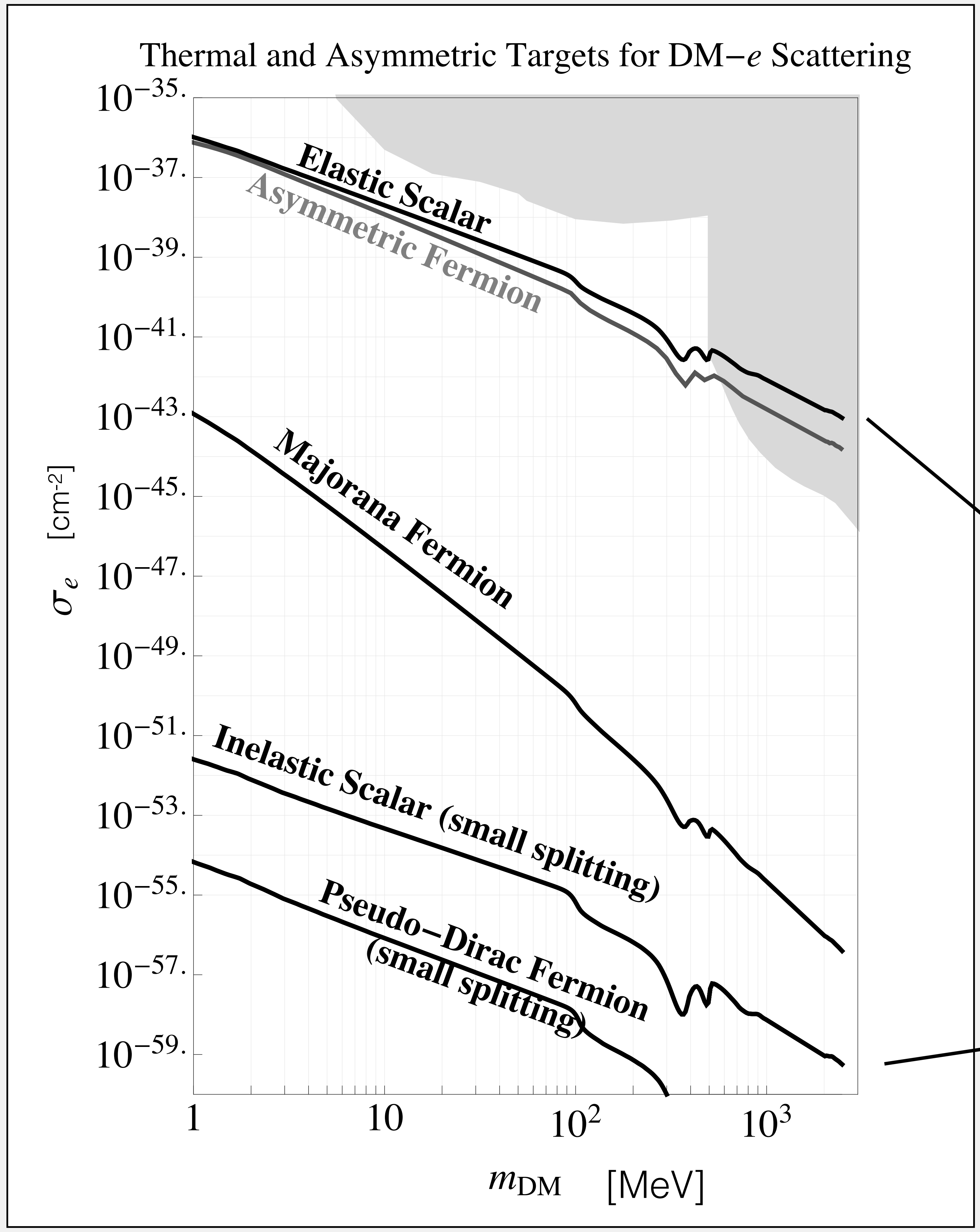
direct detection:

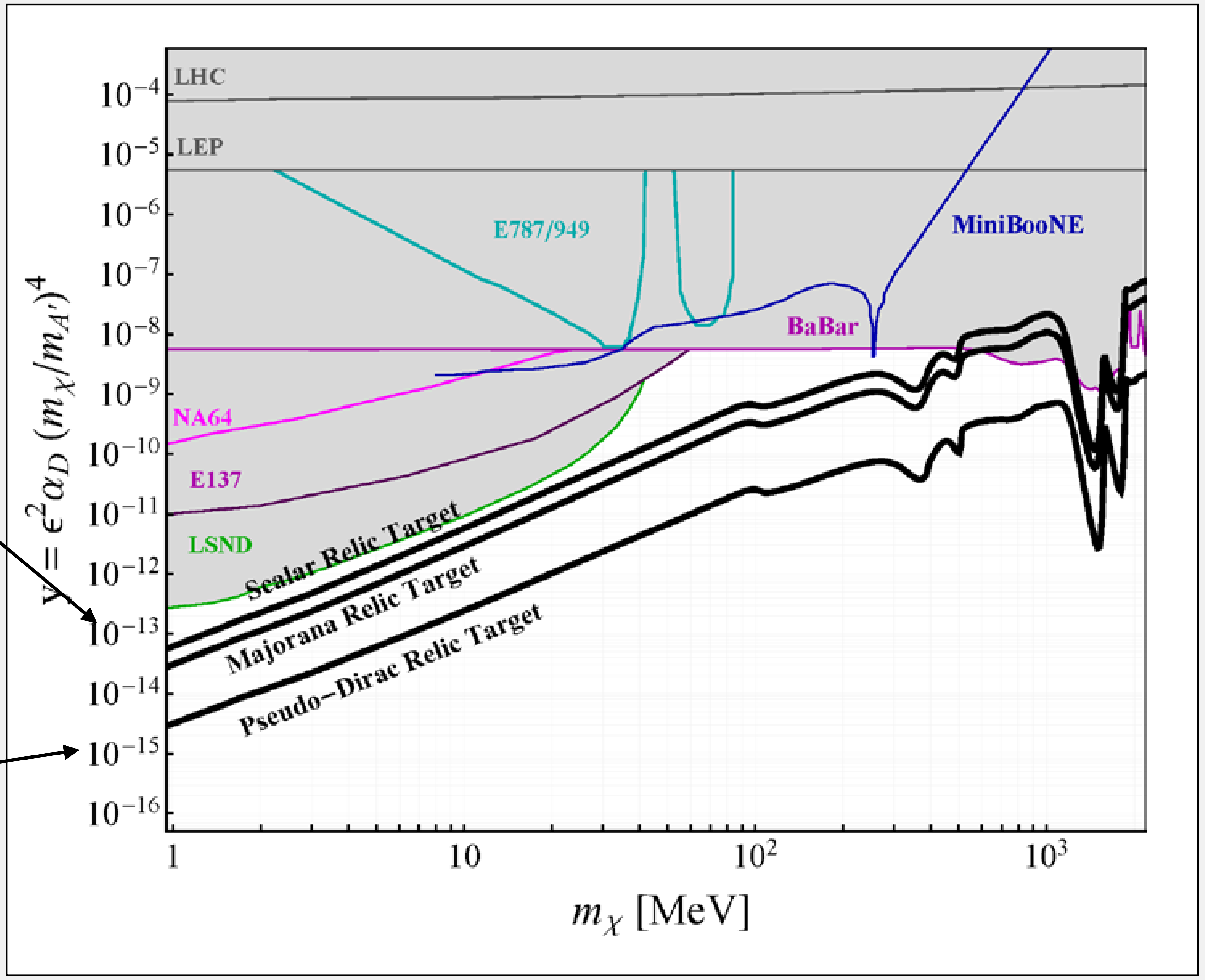
strong spin/velocity dependency

at accelerators: relativistic production

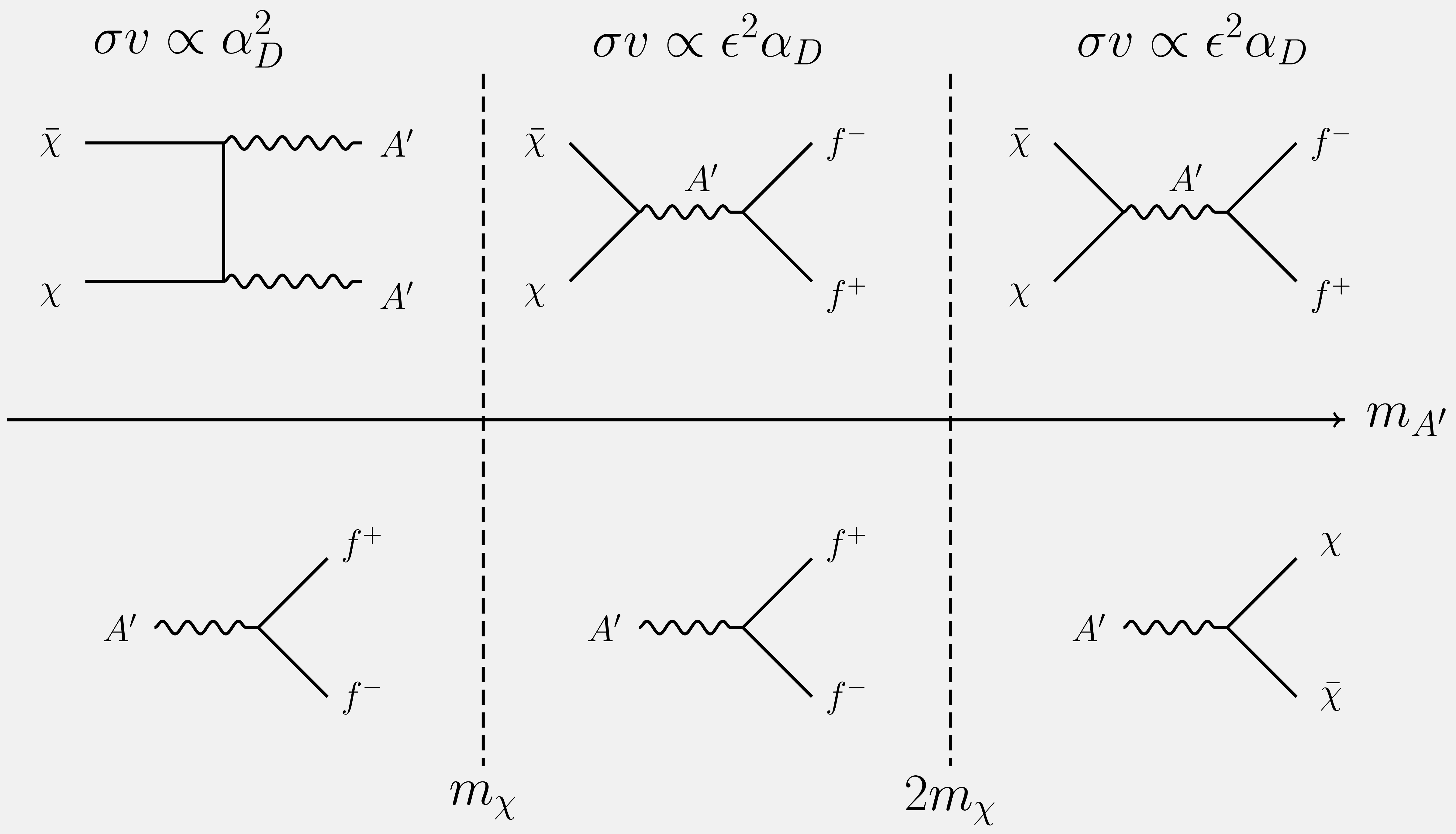
—> spin/velocity dependency reduced

all thermal targets in reach!





Signatures


$\sigma v \propto \alpha_D^2$
$\sigma v \propto \epsilon^2 \alpha_D$
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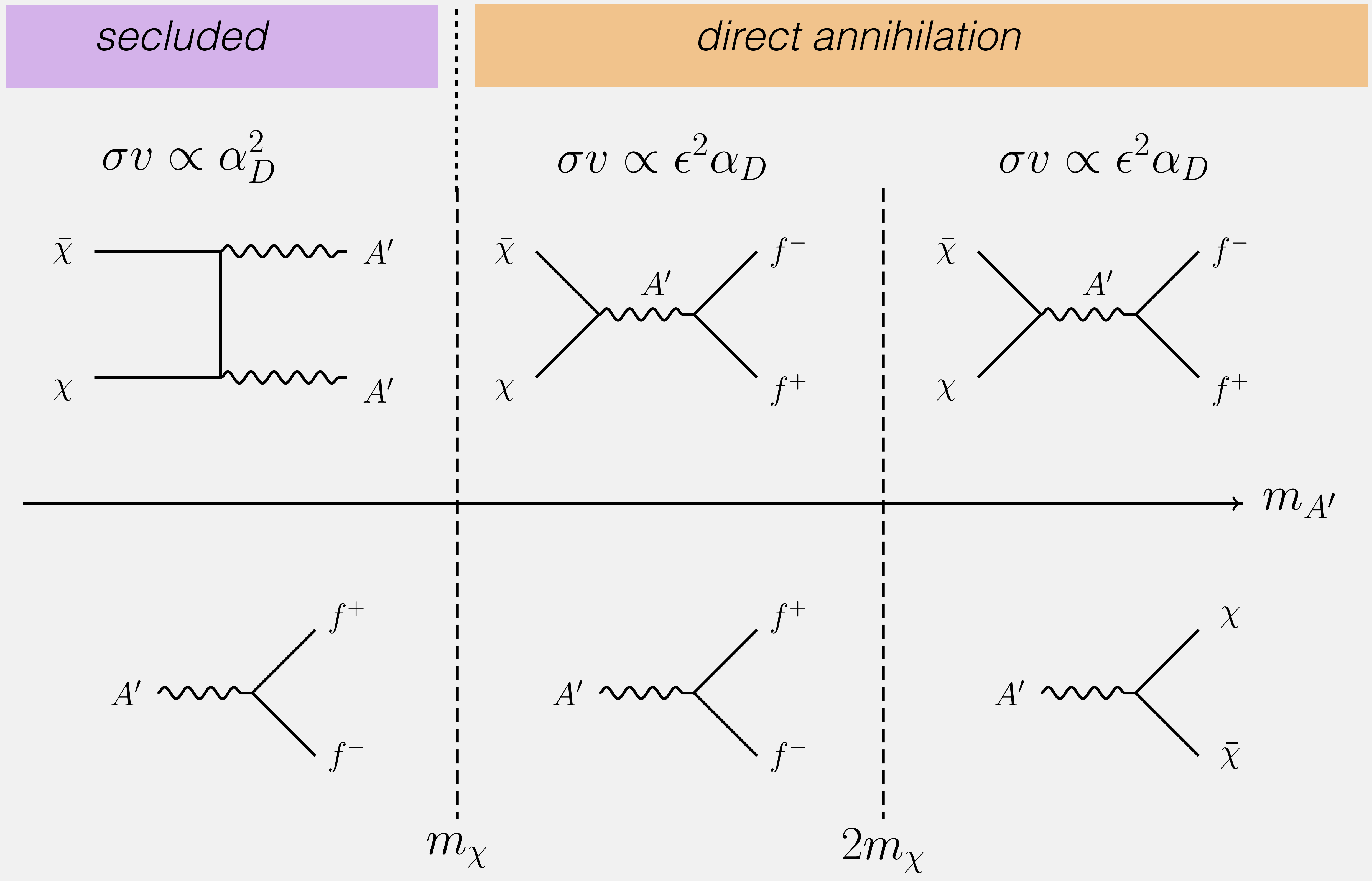
$\bar{\chi}$
χ
A'
A'
f^-
f^+
$m_{A'}$
f^+
f^-
χ
$\bar{\chi}$
m_χ
$2m_\chi$

Signatures



secluded
direct annihilation
$\sigma v \propto \alpha_D^2$
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$\bar{\chi}$
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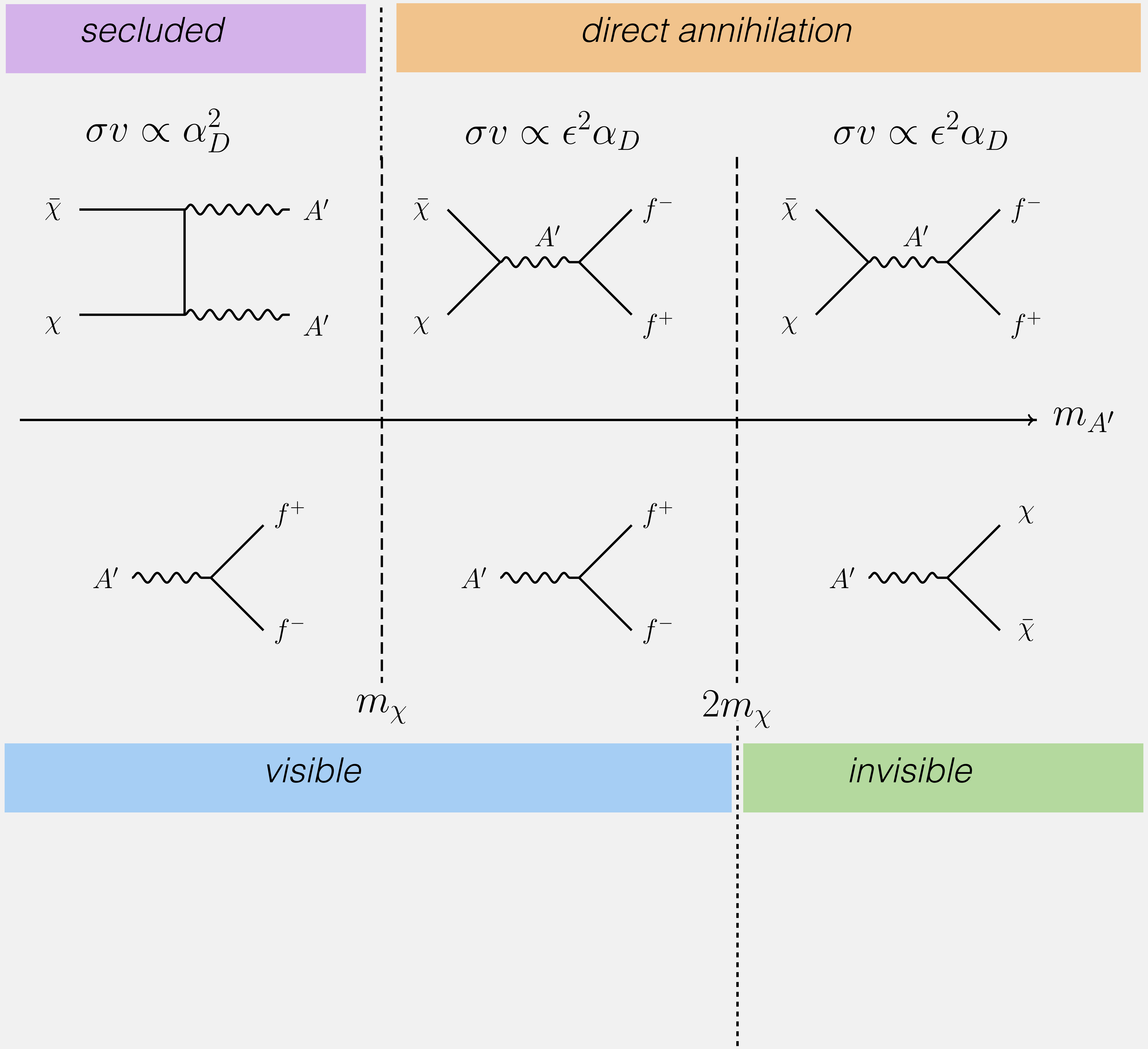
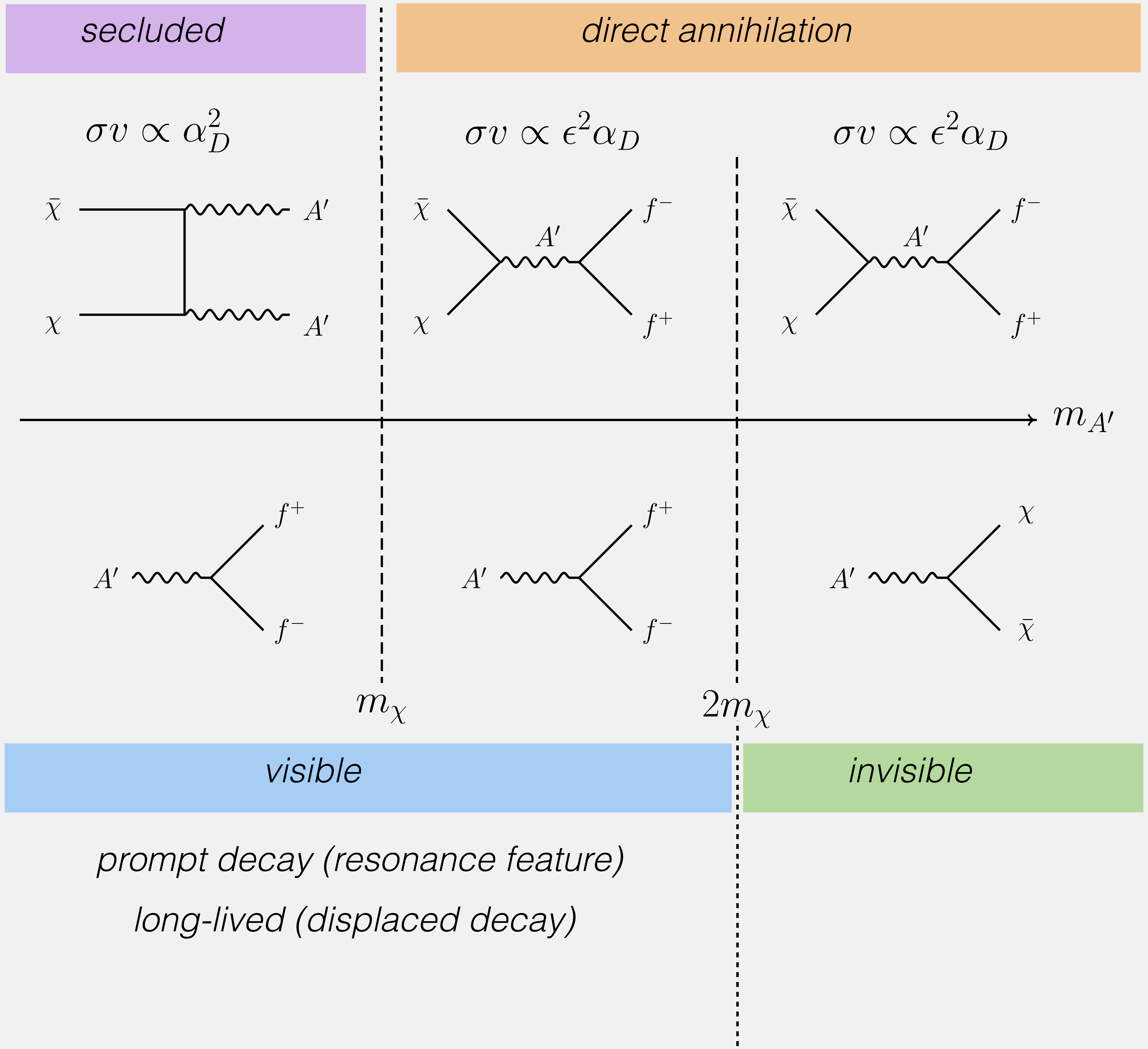


secluded
direct annihilation
σv ∝ α_D^2
σv ∝ ε^2 α_D
σv ∝ ε^2 α_D
χ̄
χ
A′
f−
f+
m_A′
m_χ
2m_χ
visible
invisible

Signatures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prompt decay (resonance feature)
long-lived (displaced decay)

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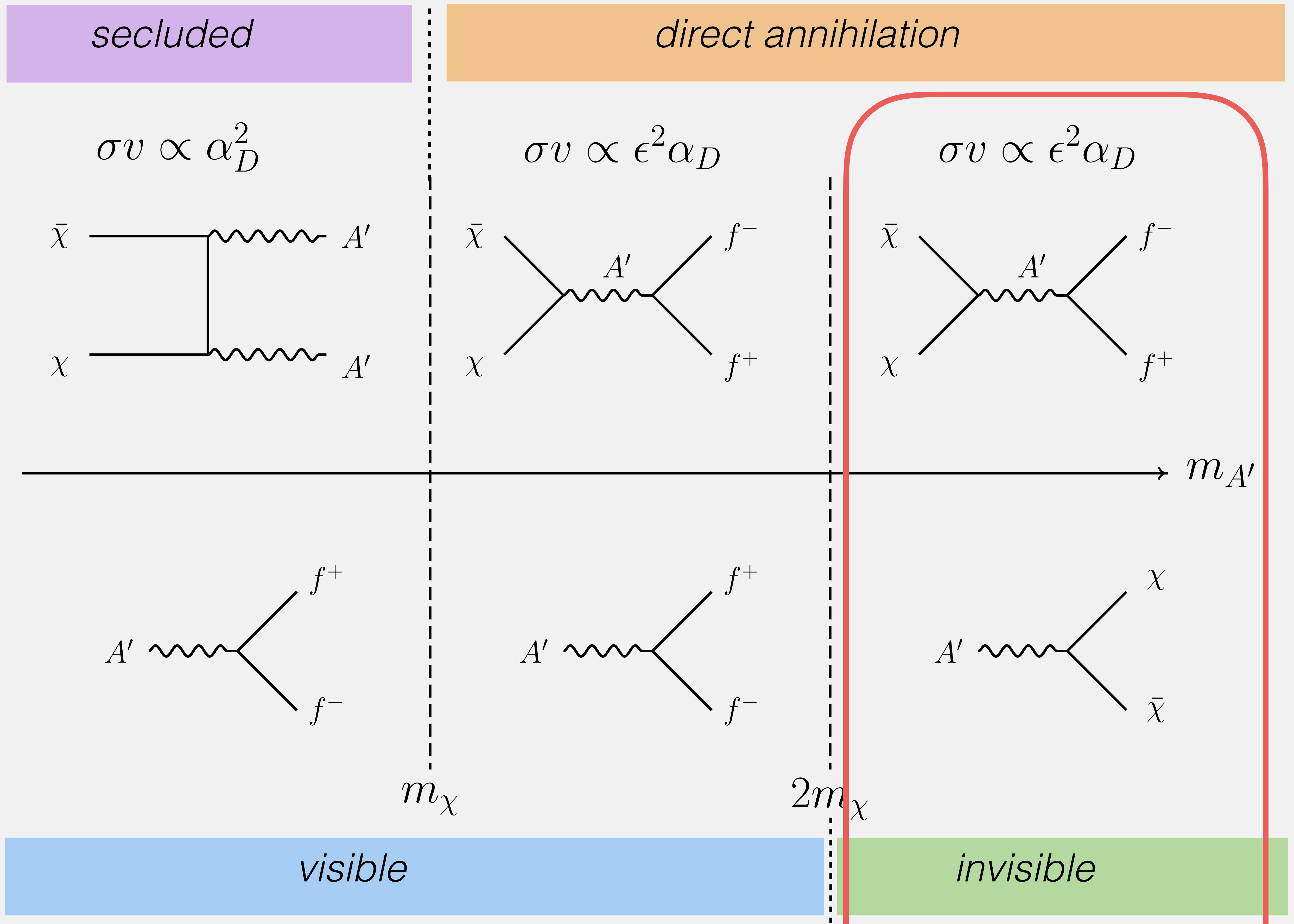


prompt decay (resonance feature)

long-lived (displaced decay)

missing…

… mass

… energy

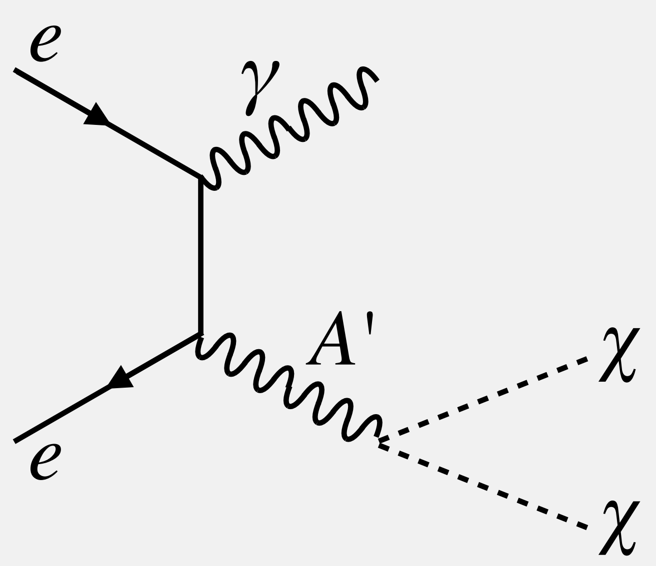
… momentum

Accelerator Searches

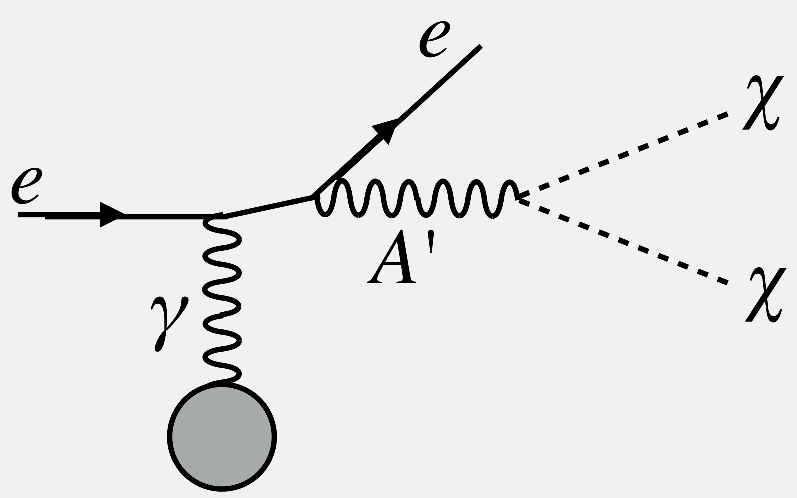
thermal origin of Dark Matter —> production mechanism at accelerators/colliders

Complimentary Approaches

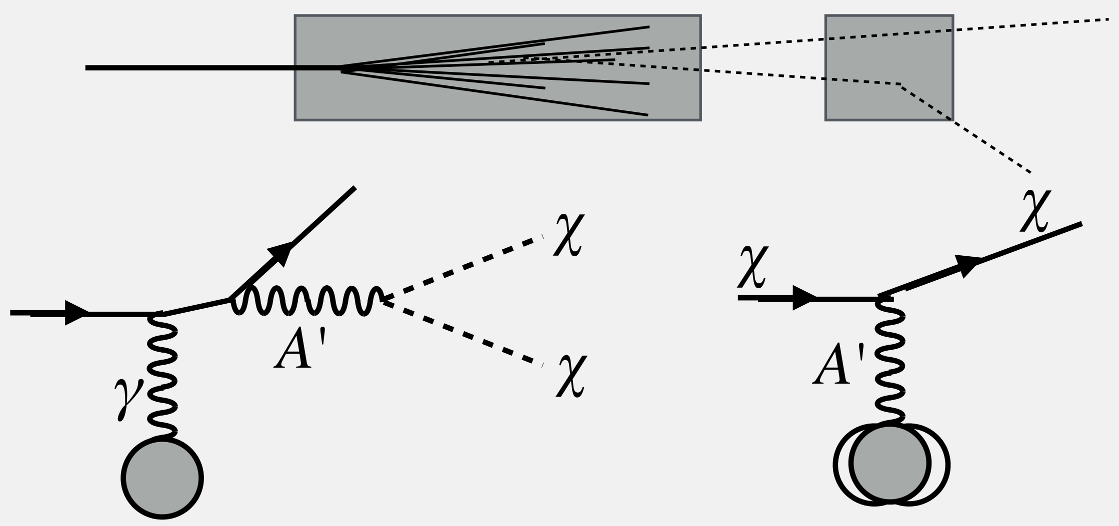
collider



fixed target



beam dump



$\sigma_{\text{coll}} \propto \frac{\varepsilon^2}{E_{\text{cm}}^2}$ << $\sigma_{\text{FT}} \propto \frac{Z^2\varepsilon^2}{m_{\text{A'}}^2}$ $N \propto \varepsilon^2(1-\varepsilon^2) \approx \varepsilon^2$ >> $N \propto \varepsilon^4$

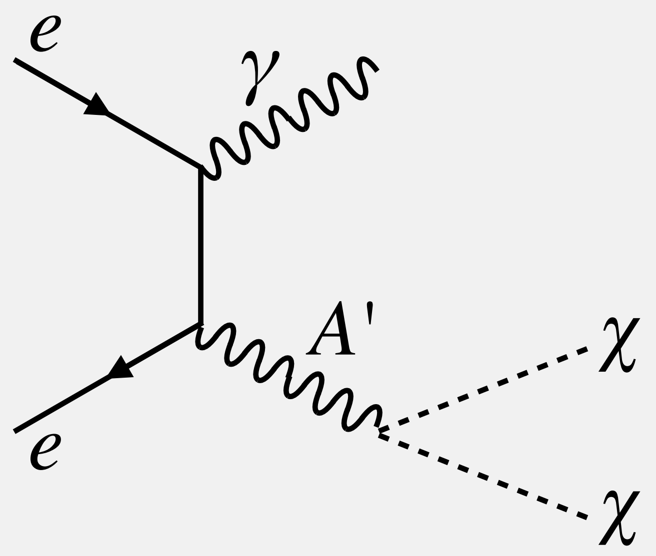
but **"direct DM detection"**

	collider	fixed target		beam dump	
examples (existing or planned)	BaBar	PADME	MMAPS	E137	SBNe/pi
	Belle II	NA64	VEPP3	LSND	MiniBooNE
	LHC	**LDMX**	DarkLight (II)	BDX	SHiP

mass range 0.1 - 10 GeV MeV - GeV

Complimentary Approaches

collider



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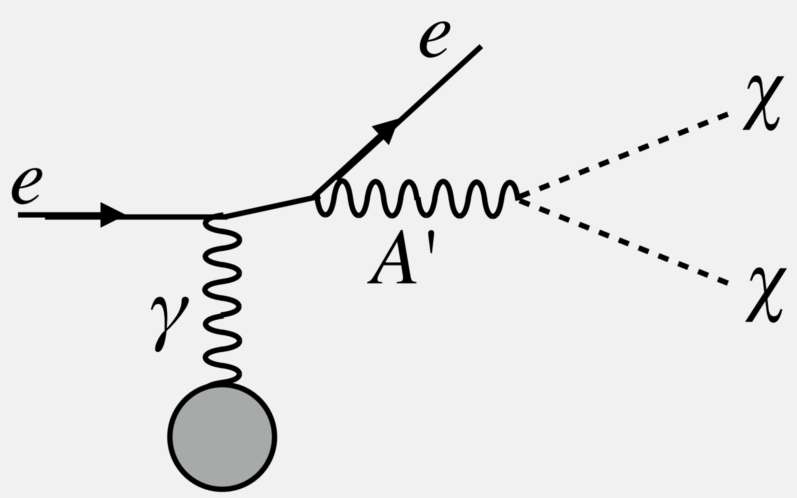
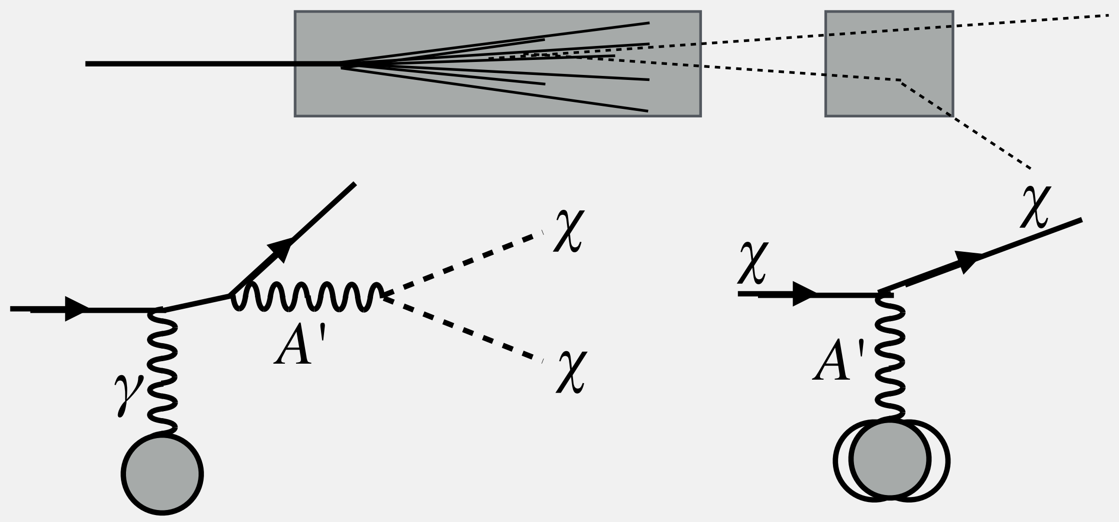


beam dump



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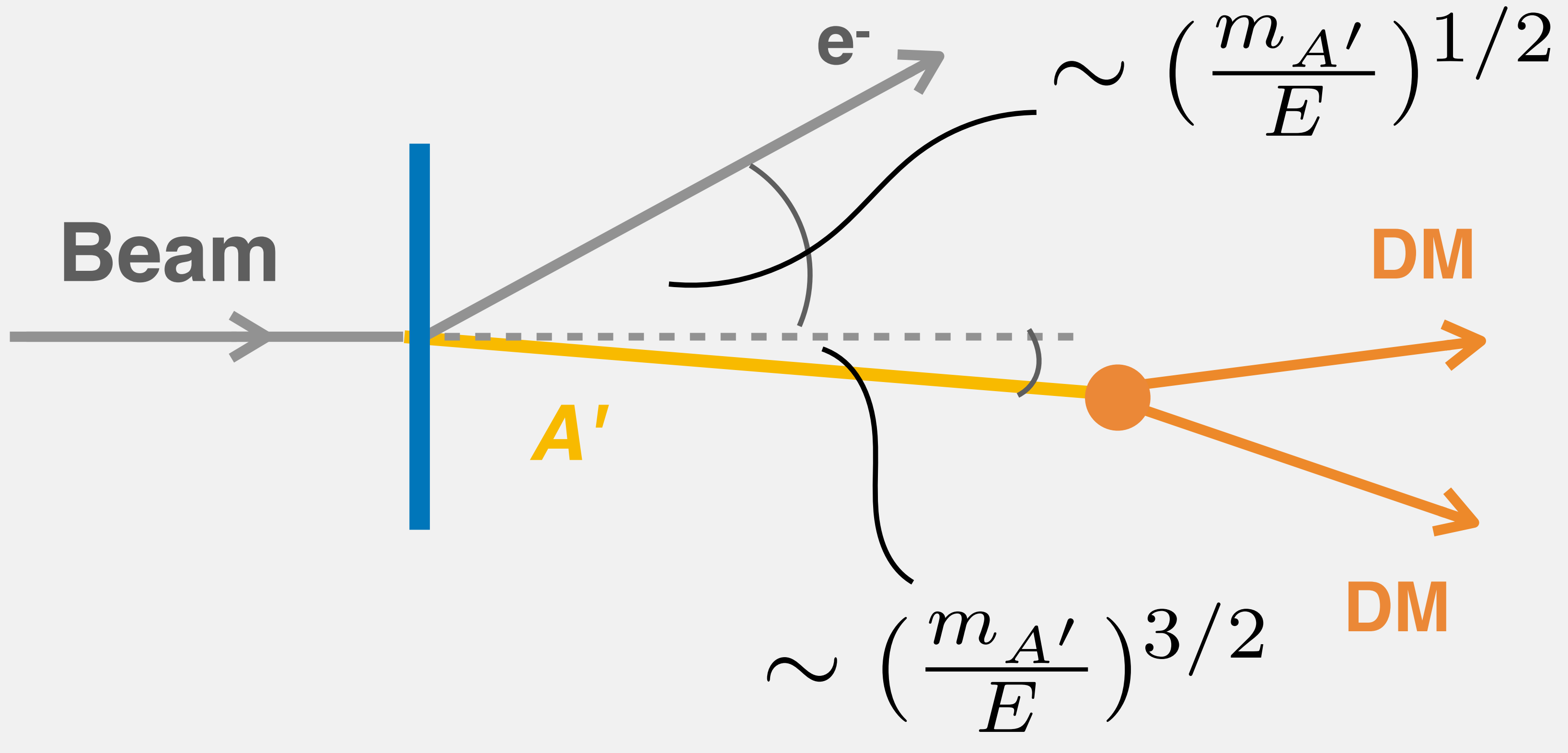
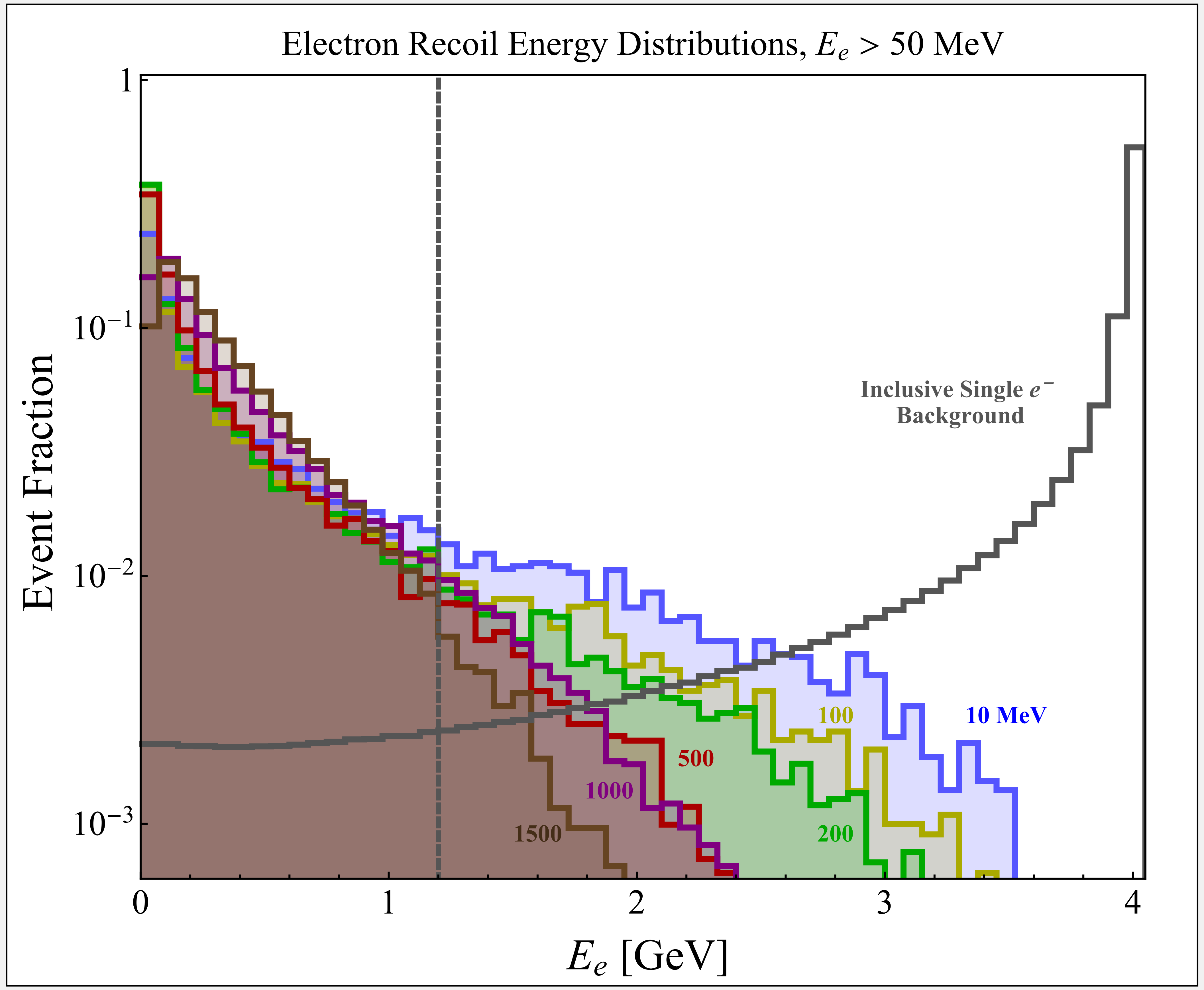
Kinematics

very different from SM bremsstrahlung (main background)





Mediator carries most of the energy

—> soft recoil electron, large missing energy

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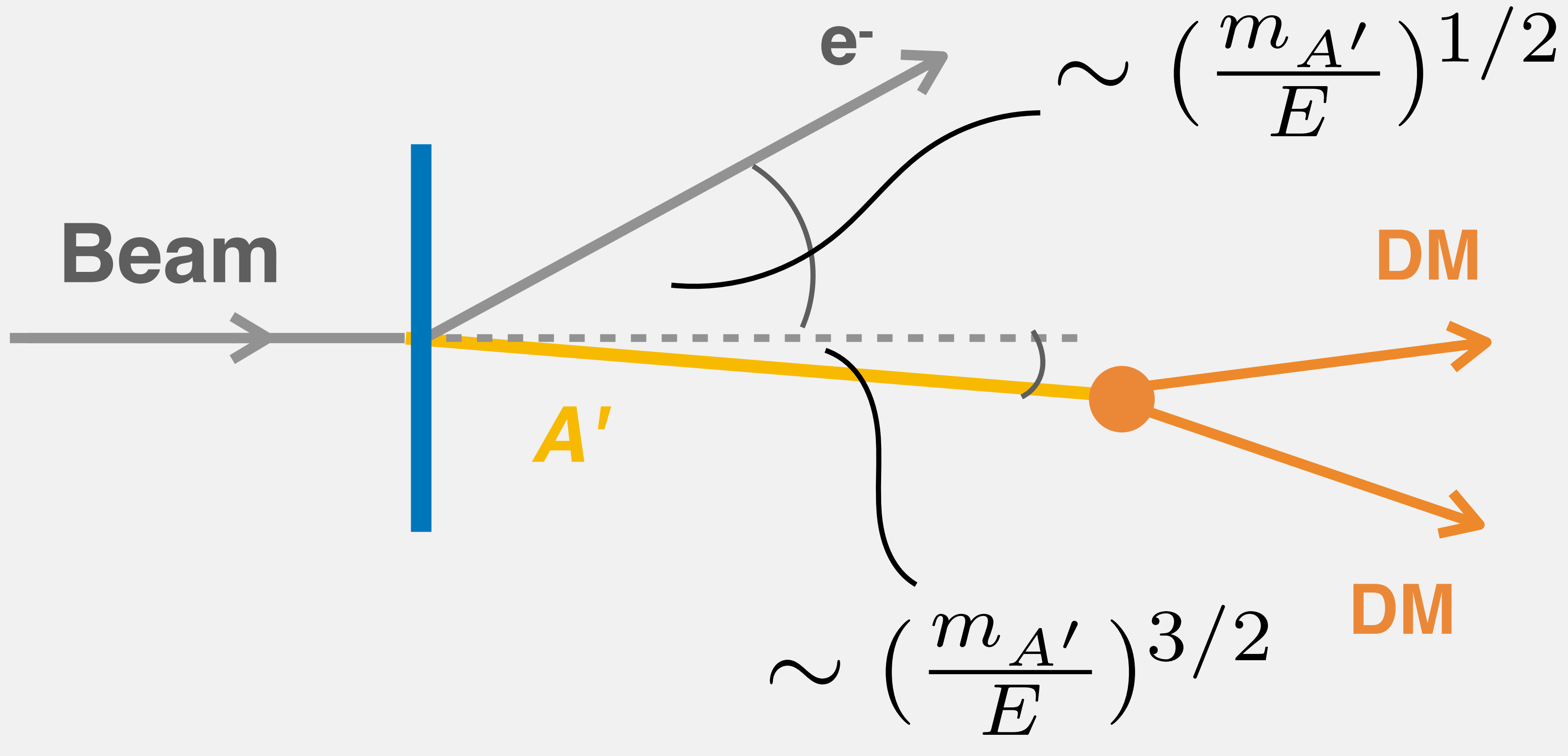
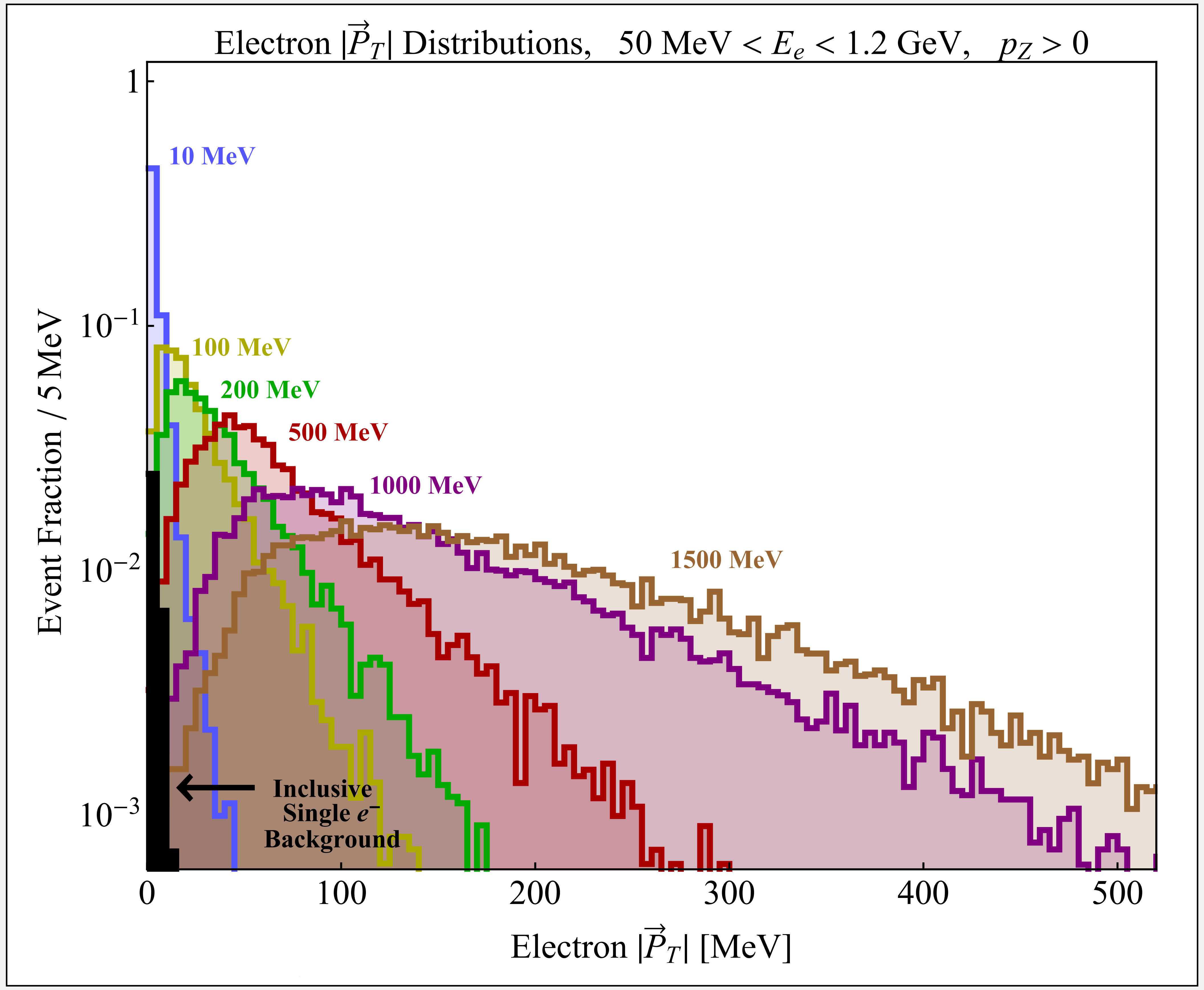




Mediator carries most of the energy

—> soft recoil electron, large missing energy

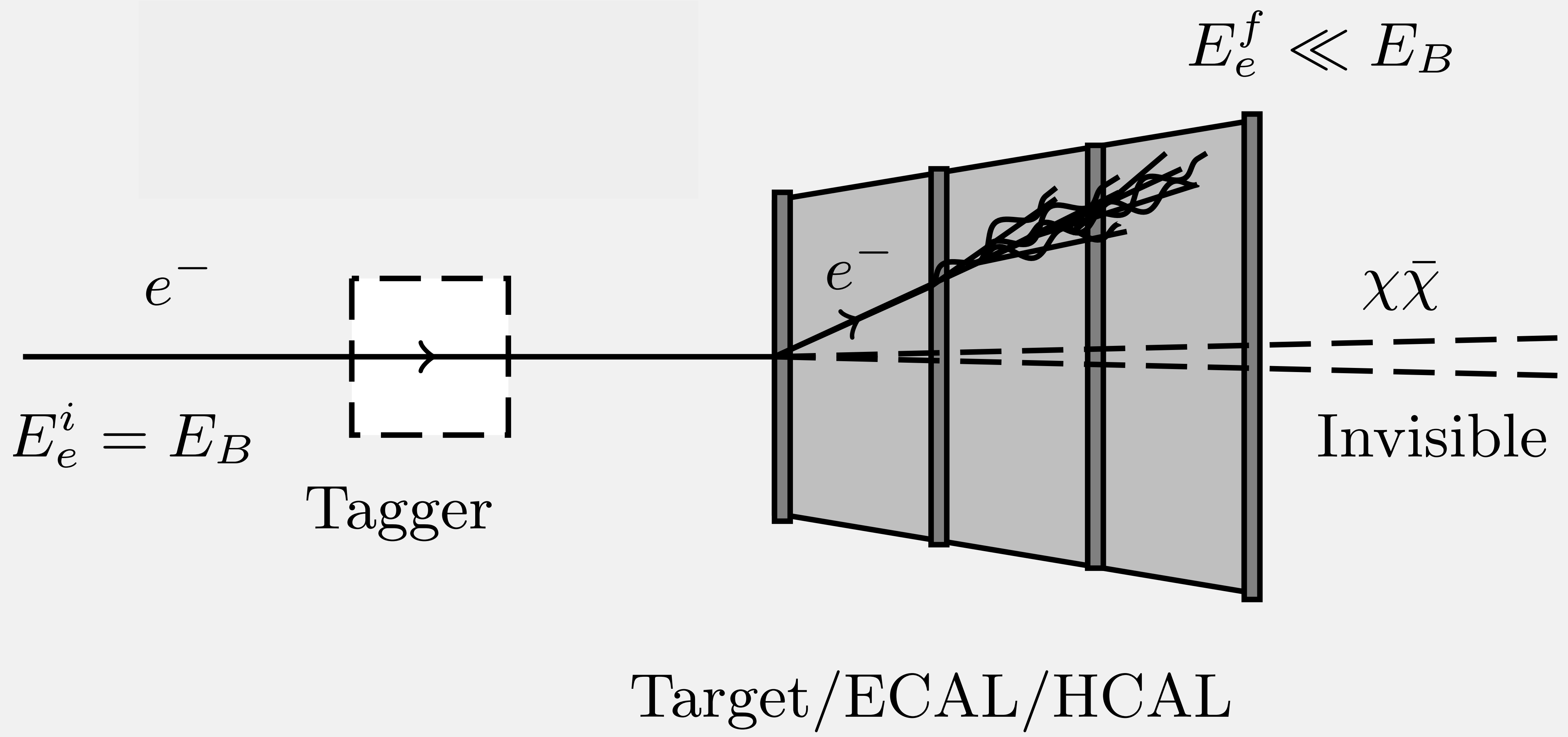
Recoil electron gets transverse 'kick'

—> large missing transverse momentum

measurement of p_T: strong discriminator AND information about (missing) mass!

Two Approaches

missing energy

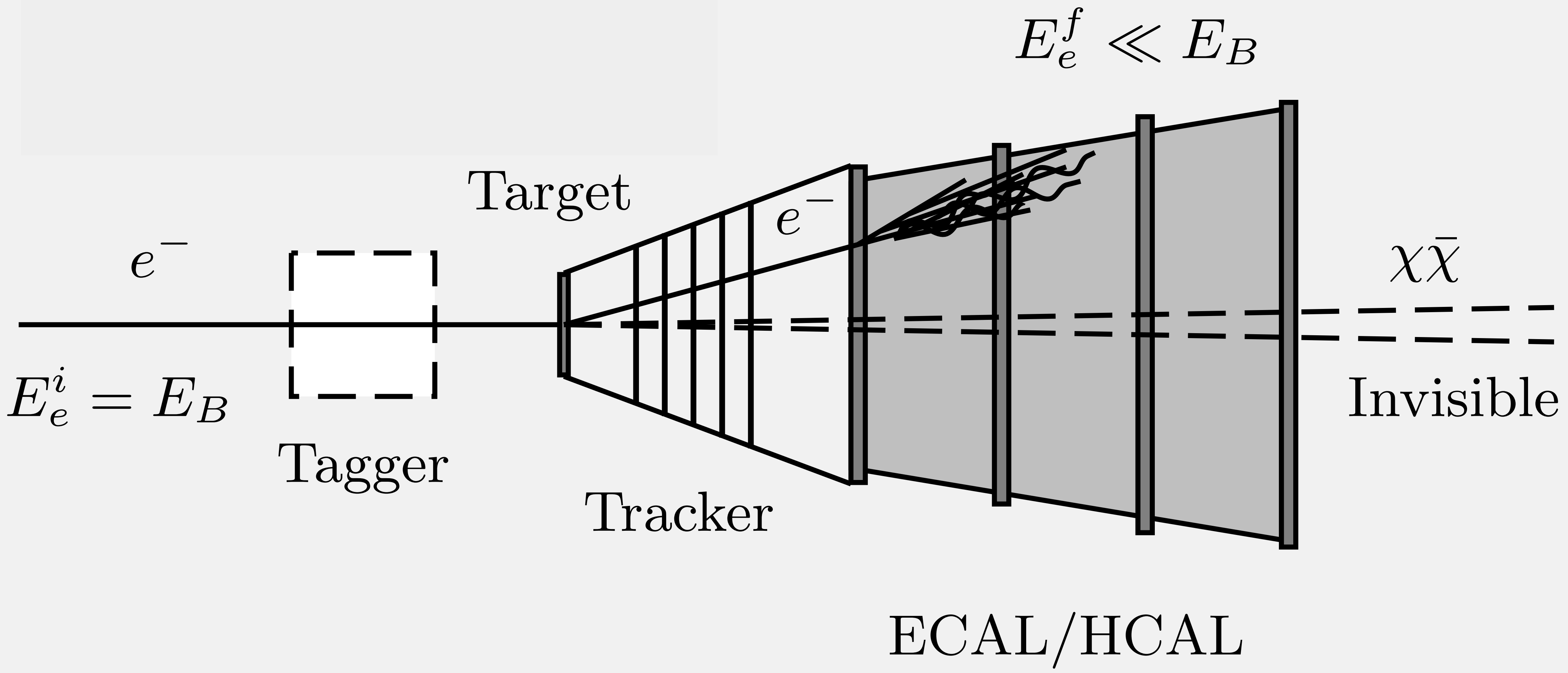


higher signal yield/EoT (thicker target)

greater signal acceptance

no e-γ particle ID

missing momentum



includes missing energy

p_T as discriminator & *signal identifier*

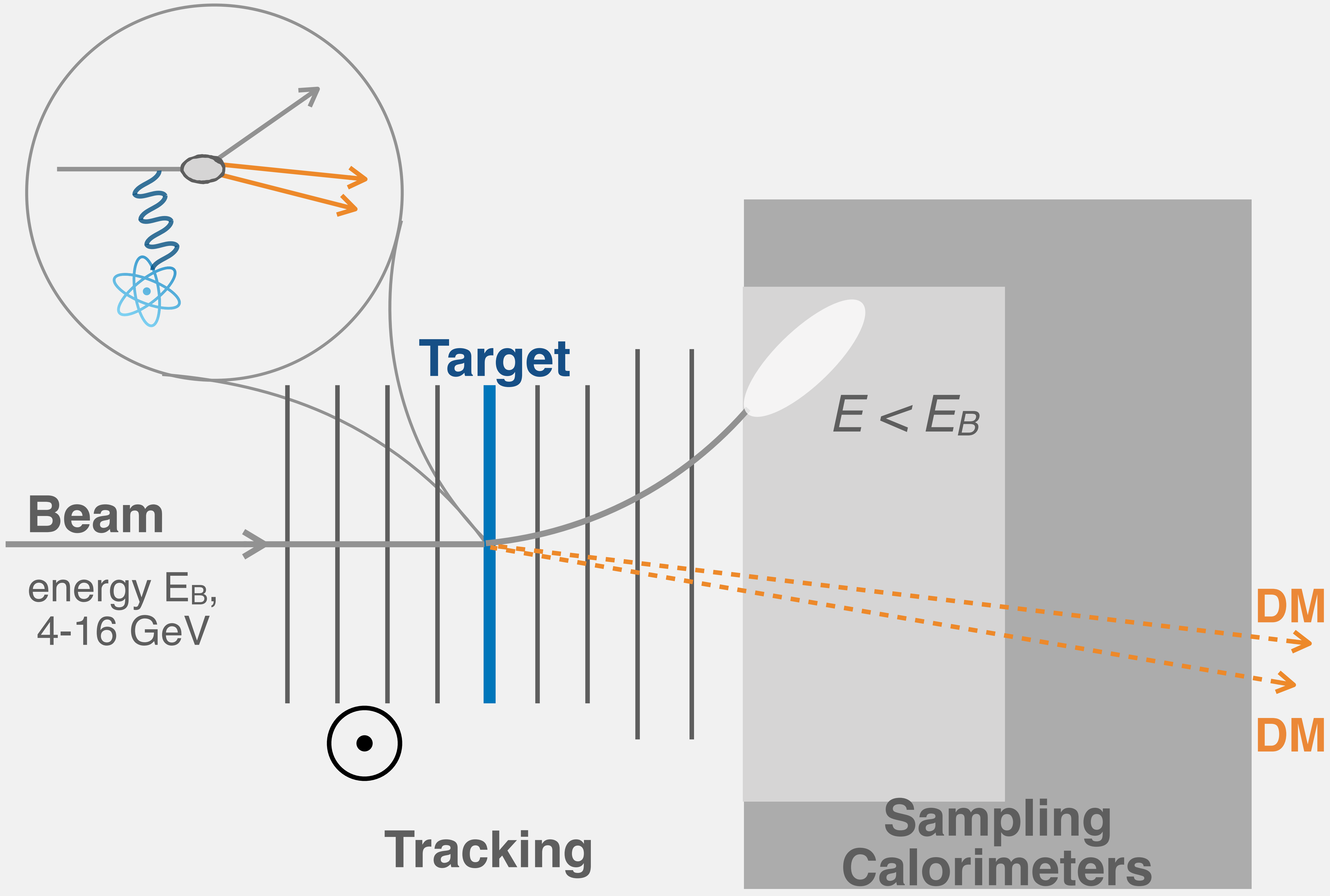
e-γ particle ID

LDMX

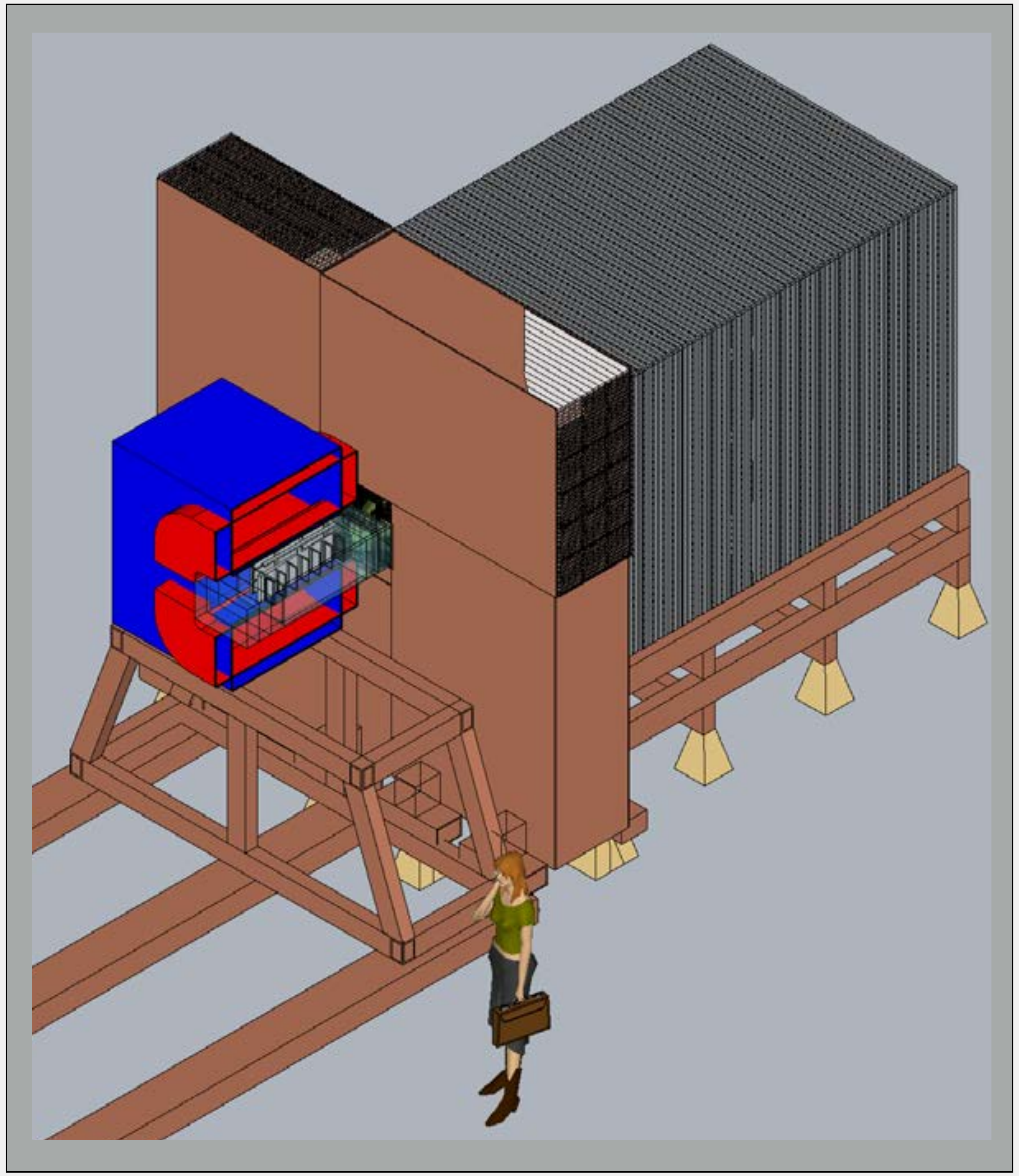
design paper arxiv:1808.05219

Caltech Fermilab Lunds Universitet University of Minnesota UCSB University of California Santa Barbara SLAC National Accelerator Laboratory University of Virginia

Light Dark Matter eXperiment

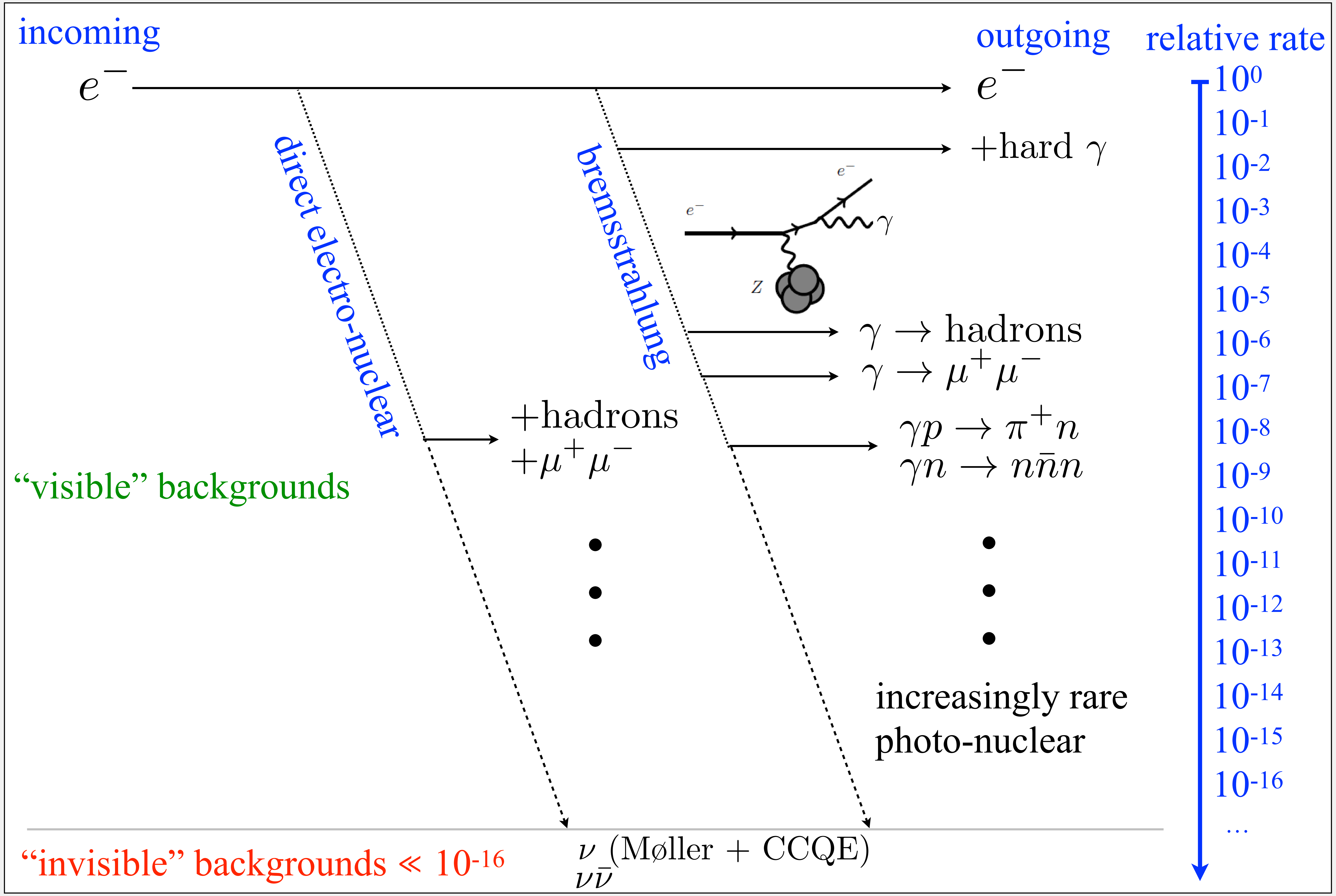


individually measure up to 10^{16} electrons on target (EoT), missing energy & *missing (transverse) momentum*



small-scale experiment

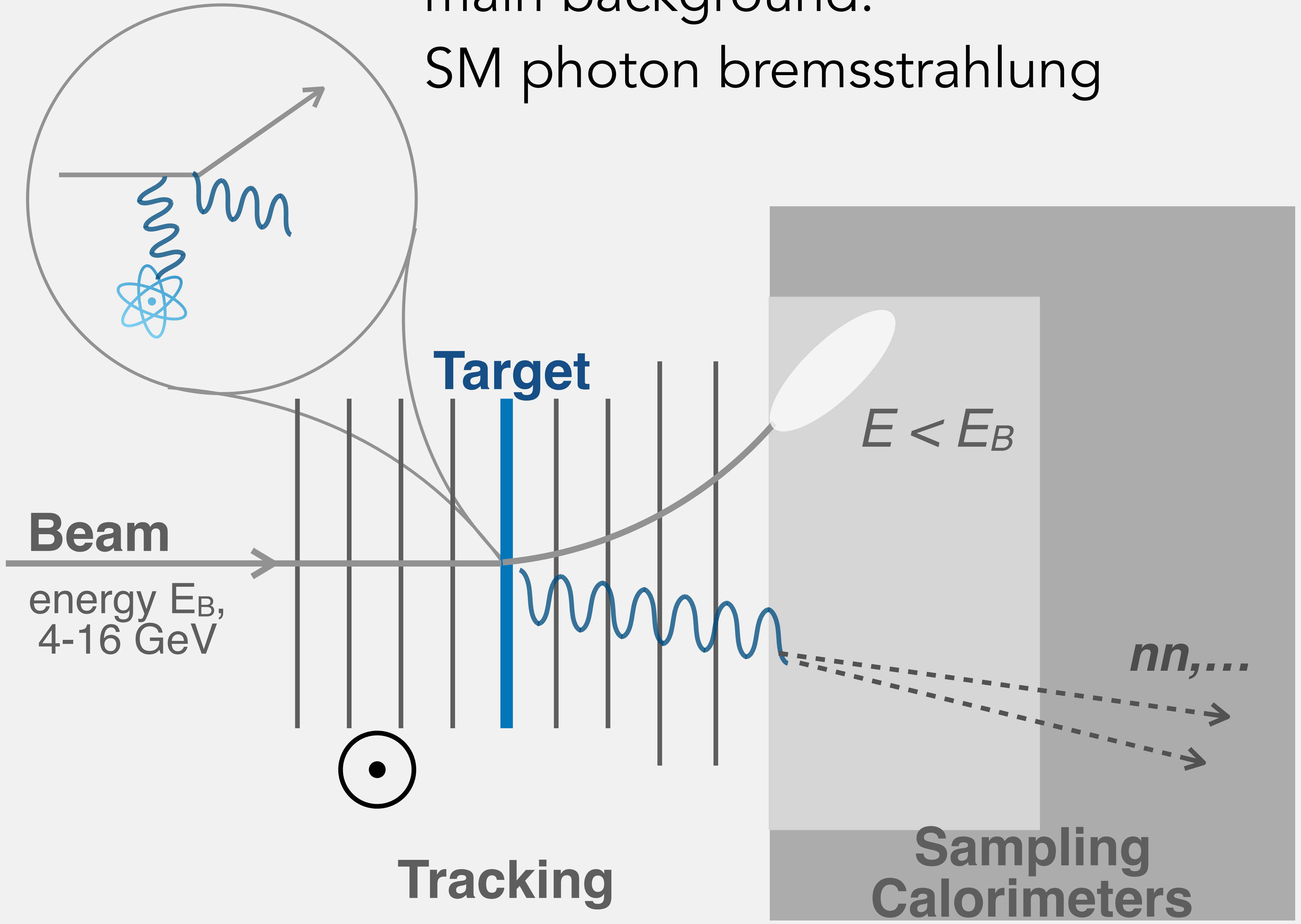
Backgrounds



essentially only
instrumental backgrounds

Background Challenges

main background:
SM photon bremsstrahlung



particularly challenging:

photo-nuclear reactions producing *neutral final states* (relative rate: ~10^{-9})

—> most design work recently on HCal to optimise rejection power, obtained first funding for R&D/ prototype (testbeam 2020)

Tracking

simplified copy of Silicon Vertex Tracker (SVT) of HPS experiment@JLab (visible Dark Photon search)

- fast (2ns hit time resolution)
- radiation hard
- technology well understood

tagging tracker

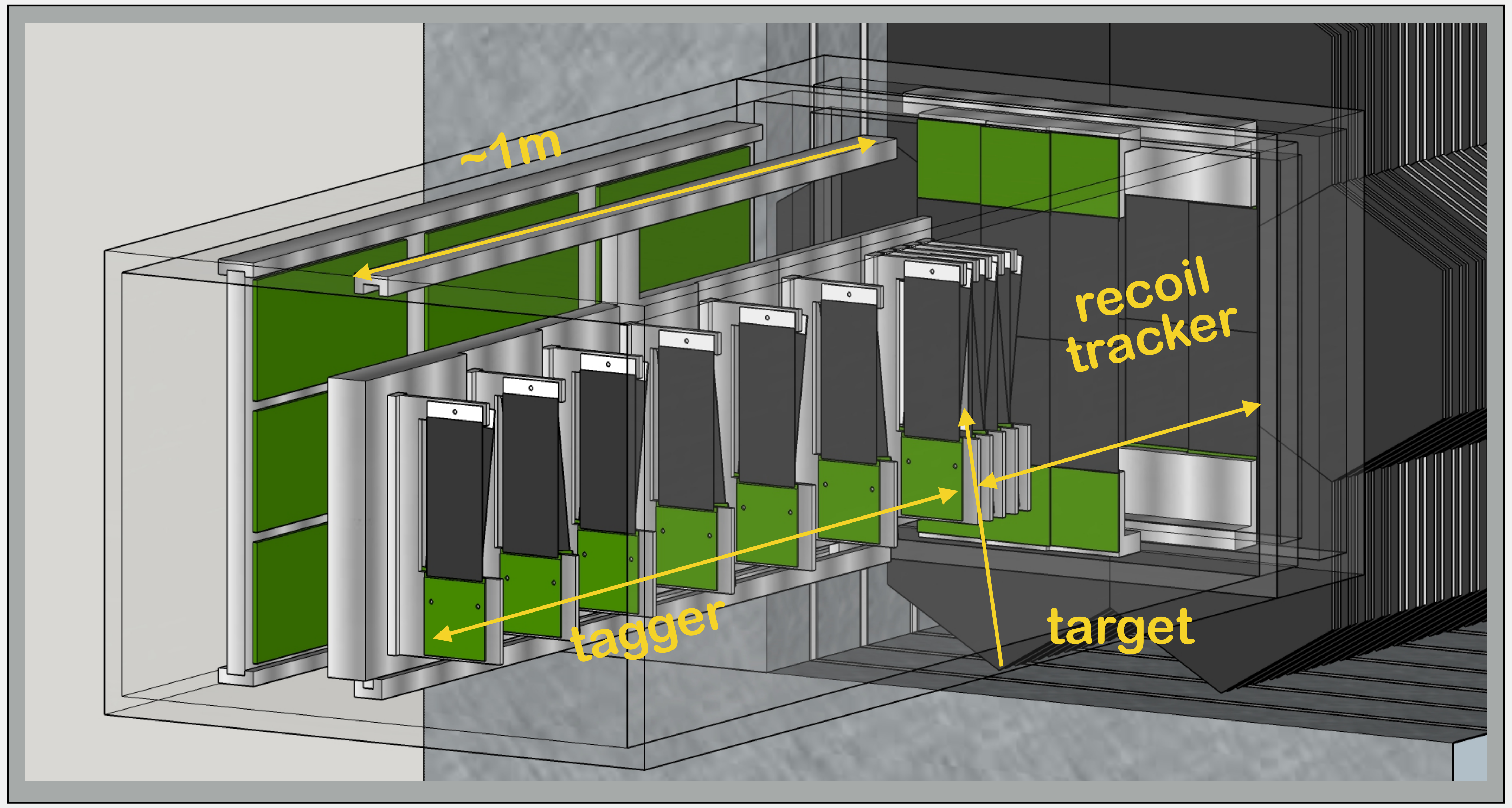
- in 1.5T dipole field
- measure incoming electron
  - momentum filter
  - impact point on target

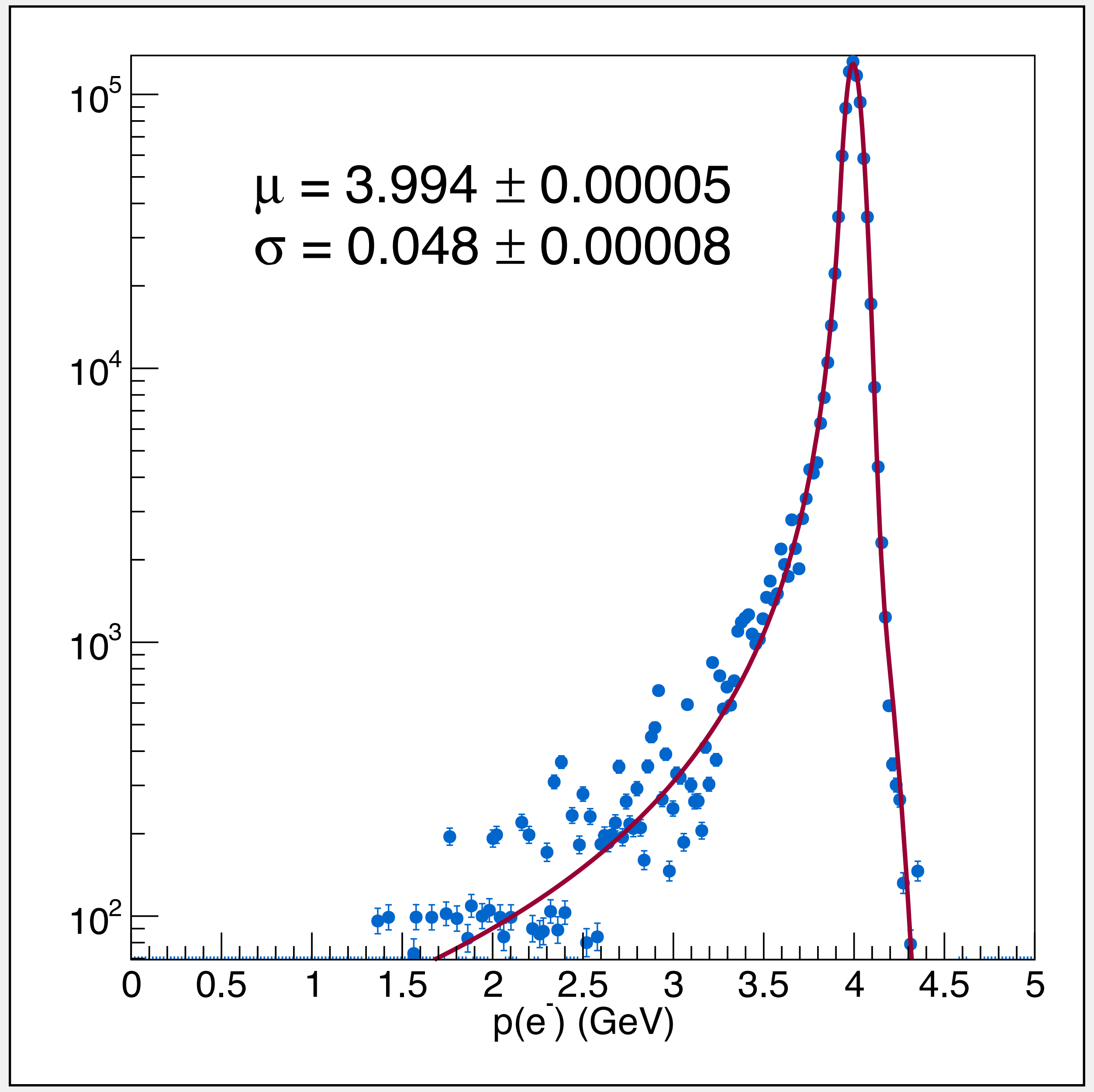
recoil tracker

- in fringe field
- measure recoil electron

target

- ~0.1 - 0.3 X_0 tungsten
- balance signal rate & momentum smearing

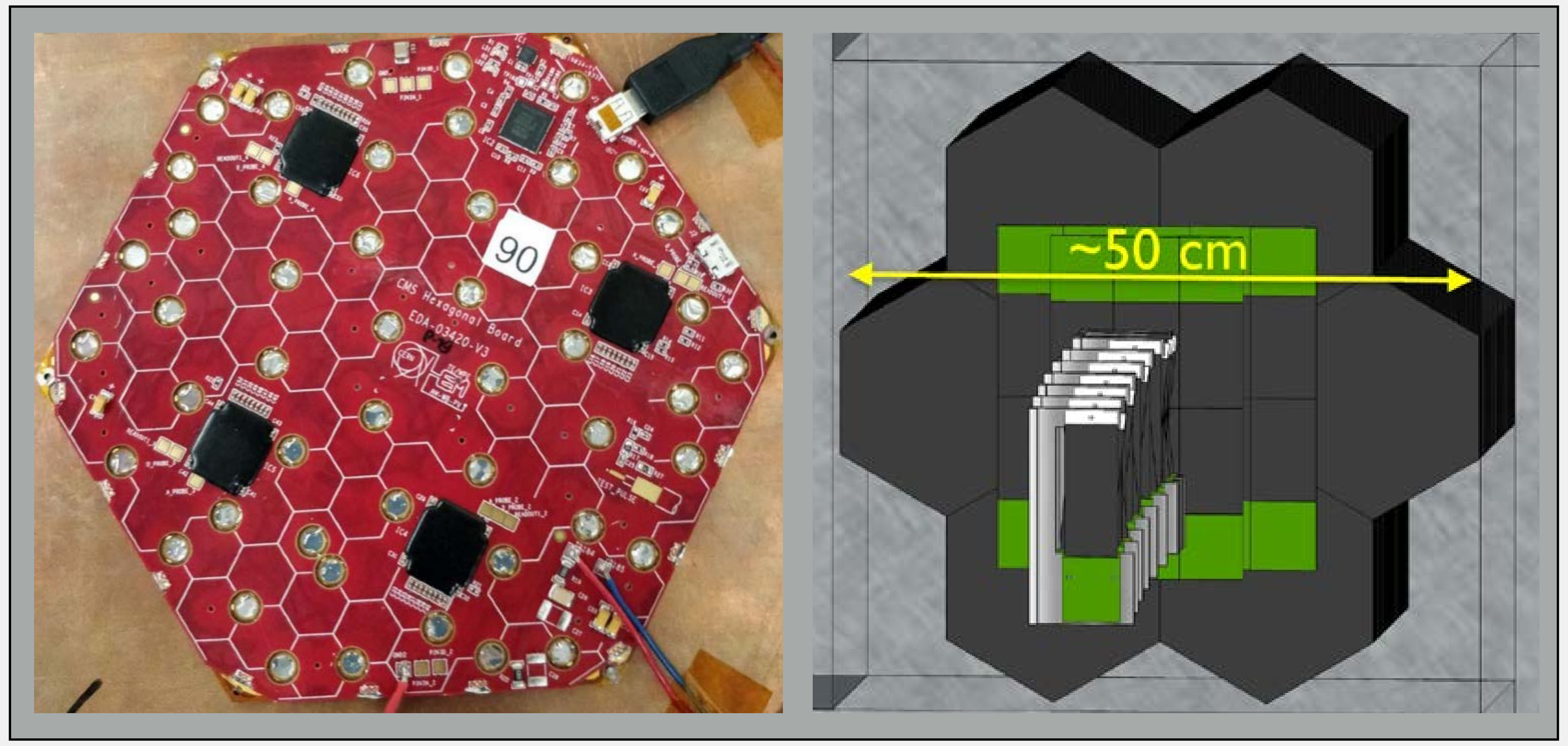


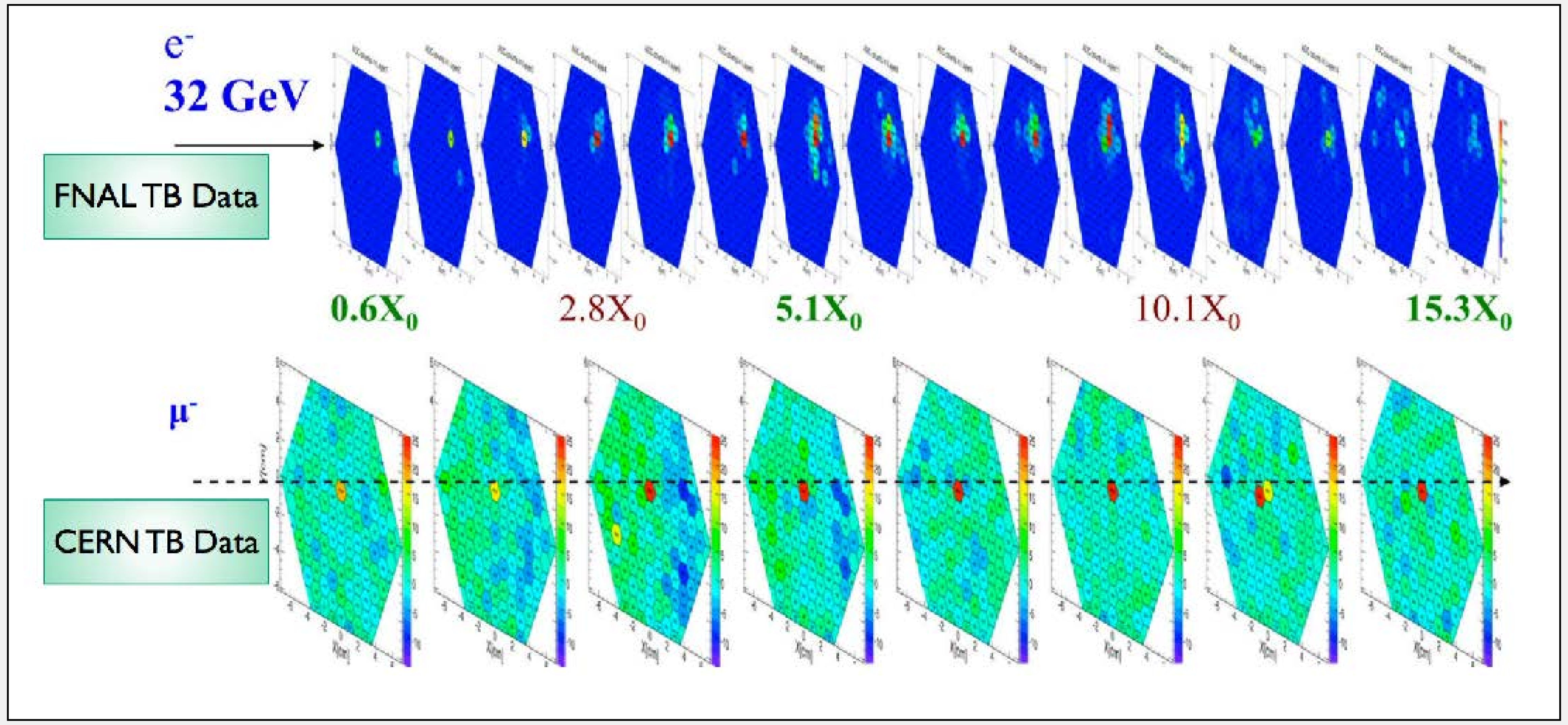


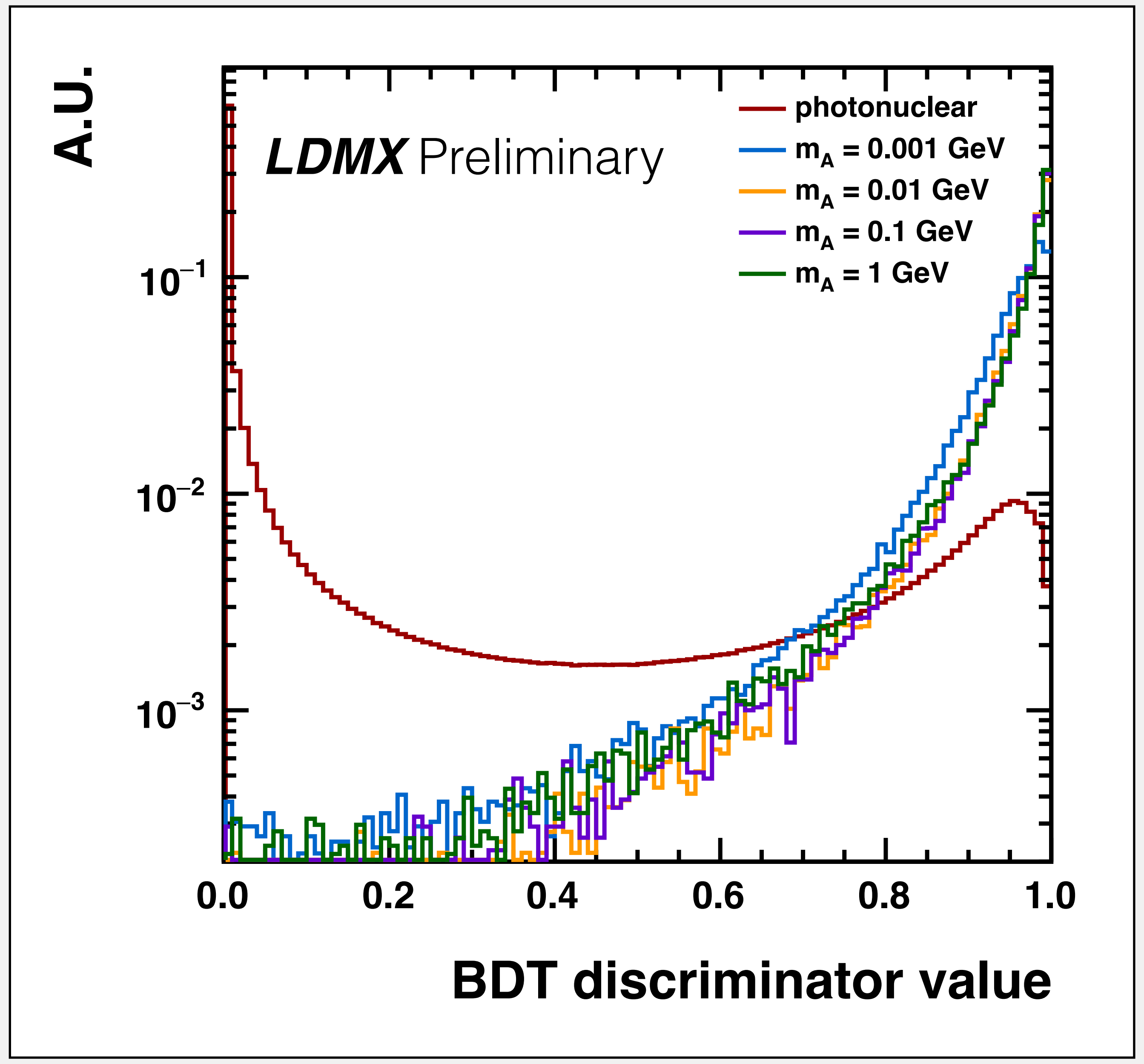
Electromagnetic Calorimeter

ECal

- draw on design of CMS forward SiW calorimeter upgrade
  - 32 layers with 7 modules each, 40 X_0
  - fast, radiation hard, dense
  - high granularity (MIP 'tracking')
    - potentially increase granularity in central module



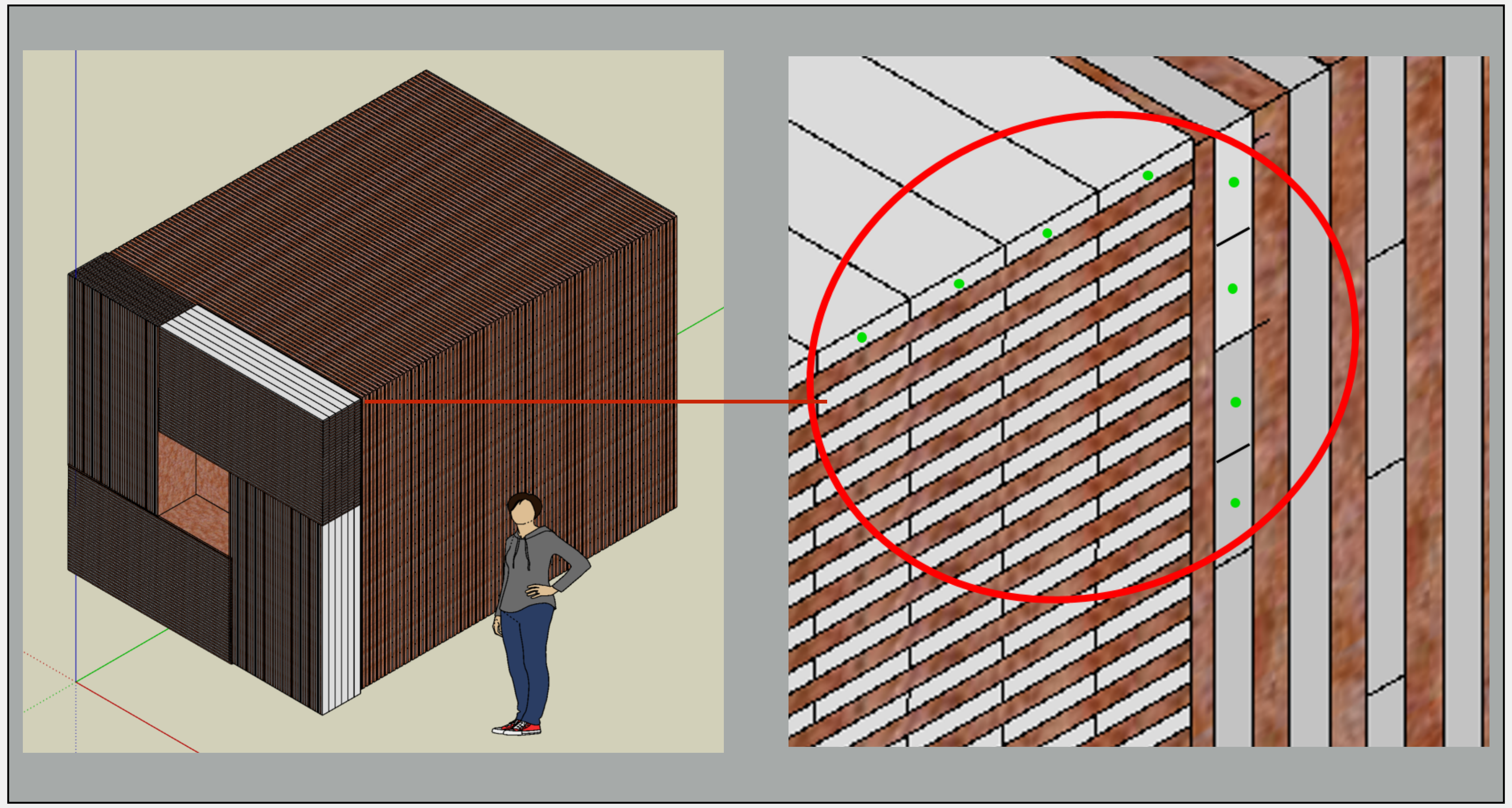




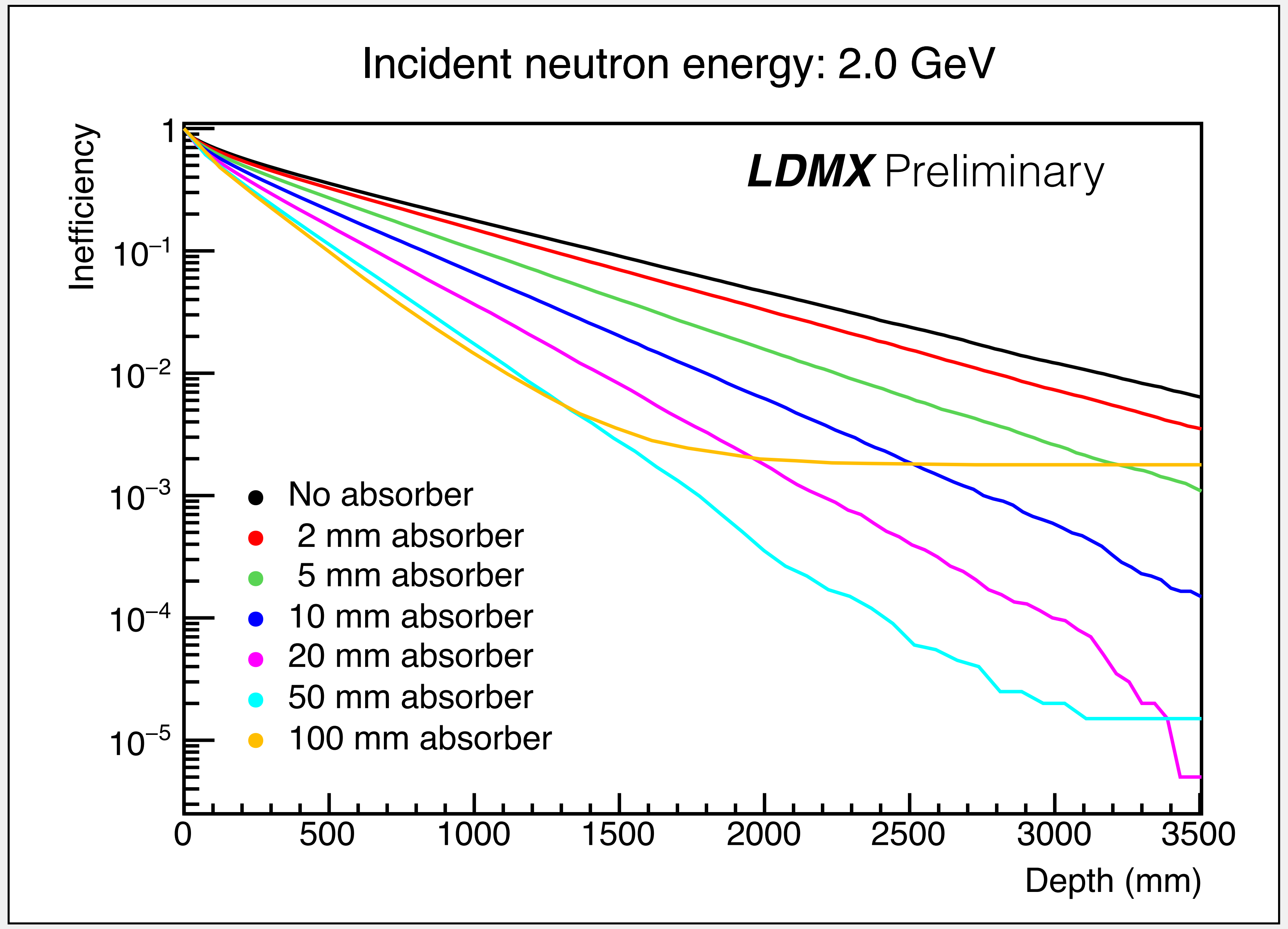
Hadronic Calorimeter

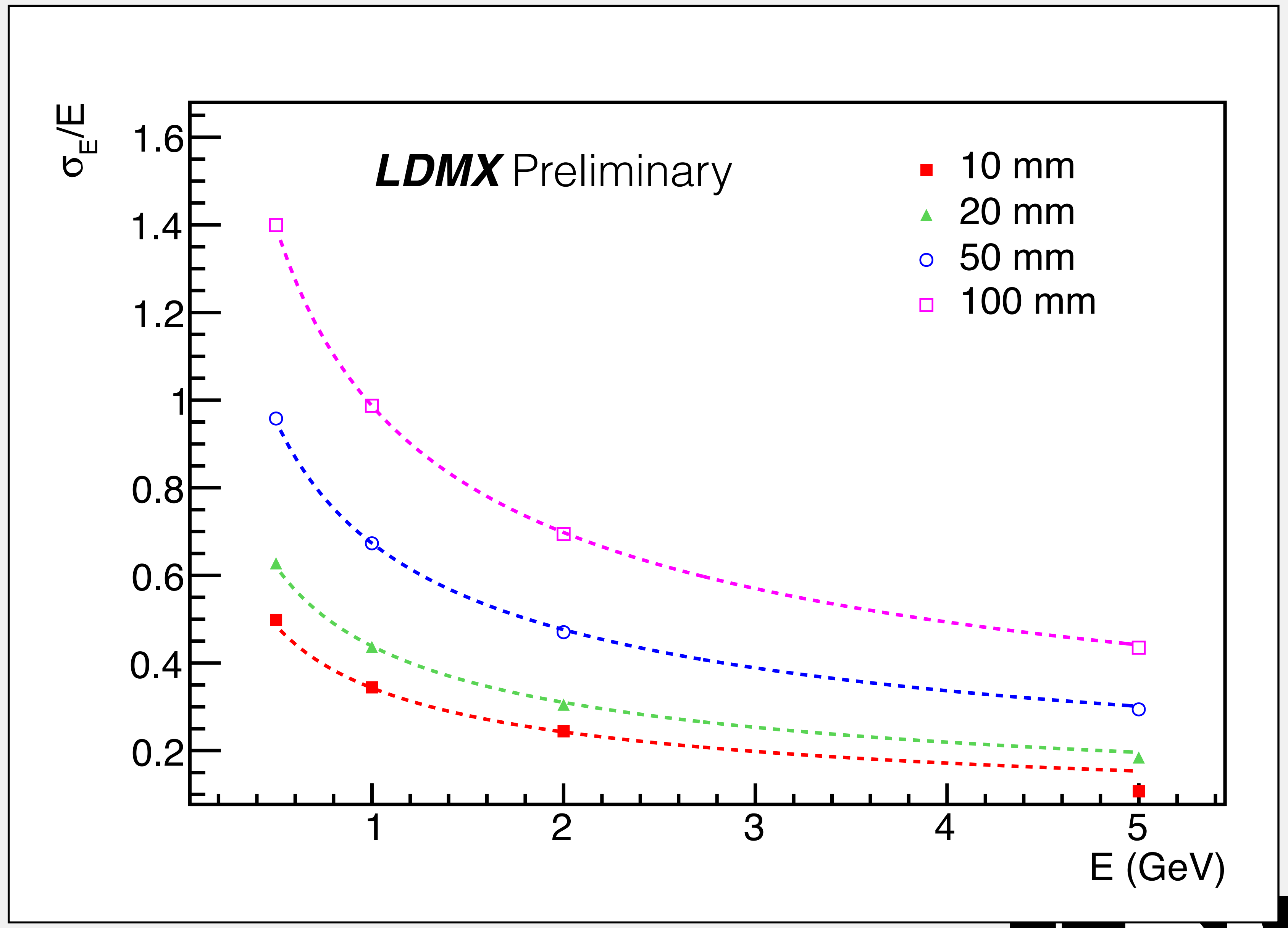
HCal

- need highly efficient **veto** for low- and high-energy neutrons
- plastic scintillator with steel absorber
- surround ECal as much as possible (back and side)



preliminary simulation studies show potential to get close to 0 background in phase 1, while retaining decent energy resolution





A special beam…

beam **energy** ideally 4 GeV < E_B < 20 GeV

looking for extremely rare signal
—> need very large statistics

goal: 10^{14} - 10^{16} EoT in few years

—> beam with **high duty-cycle**

resolve individual particles
—> **low number** of electrons per bunch (≤10)
—> **large beam spot**

options:

default: transfer line from LCLS-II @ SLAC

- 4/8 GeV
- 46 MHz (186MHz?)

alternative (?): CEBAF @ JLab (≤12 GeV)

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resolve individual particles
—> **low number** of electrons per bunch (≤10)
—> **large beam spot**

options:

default: transfer line from LCLS-II @ SLAC
- 4/8 GeV
- 46 MHz (186MHz?)

alternative (?): CEBAF @ JLab (≤12 GeV)

triggered idea of having a **new Linac into SPS@CERN**,
quickly became active field of study arxiv:1805.12379

eSPS at CERN

get e- back in CERN accelerators, next step for X-band linac developed for CLIC, accelerator R&D

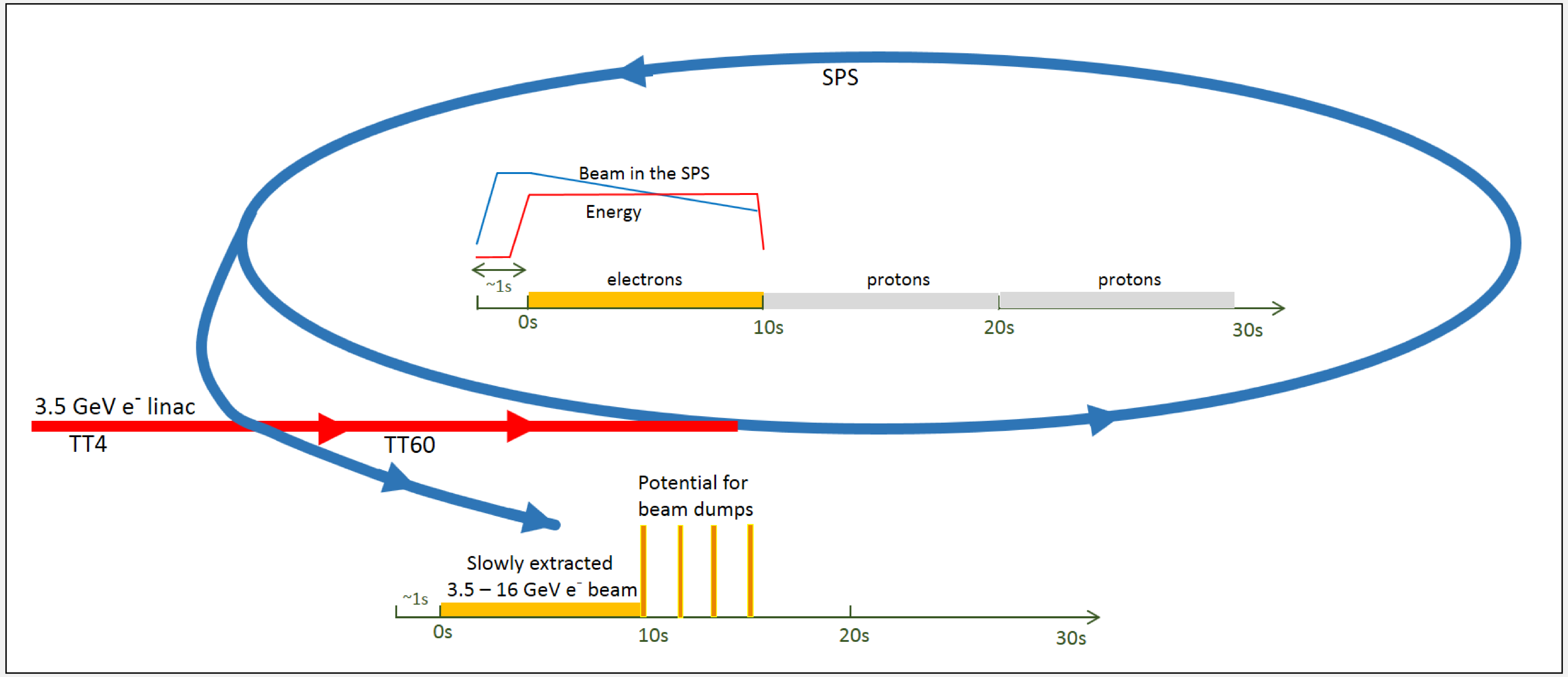
Expression of interest to SPSC in October 2018 https://cds.cern.ch/record/2640784

Input to Strategy Update (#36)

- 3.5 GeV Linac as injector to SPS
- large number of electrons can be filled within 2s
- slow extraction over 10s
- can run in parallel with other SPS programme

flexible parameters:

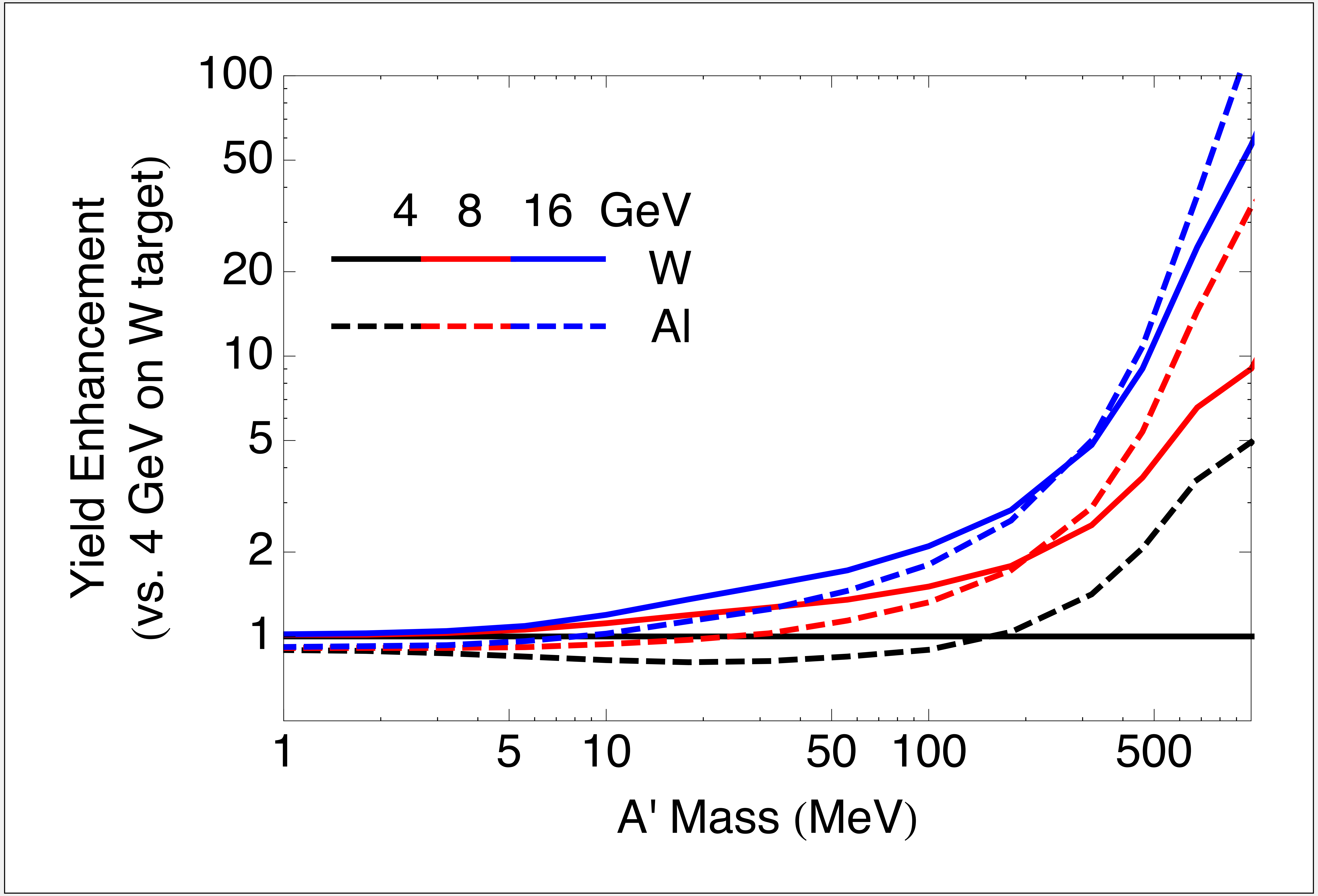
- energy: 3.5 - 16 GeV
- electrons per bunch: 1 - 40
- bunch spacing: multiples of 5 ns
- adjustable beam size



optimal catering for LDMX-like experiment

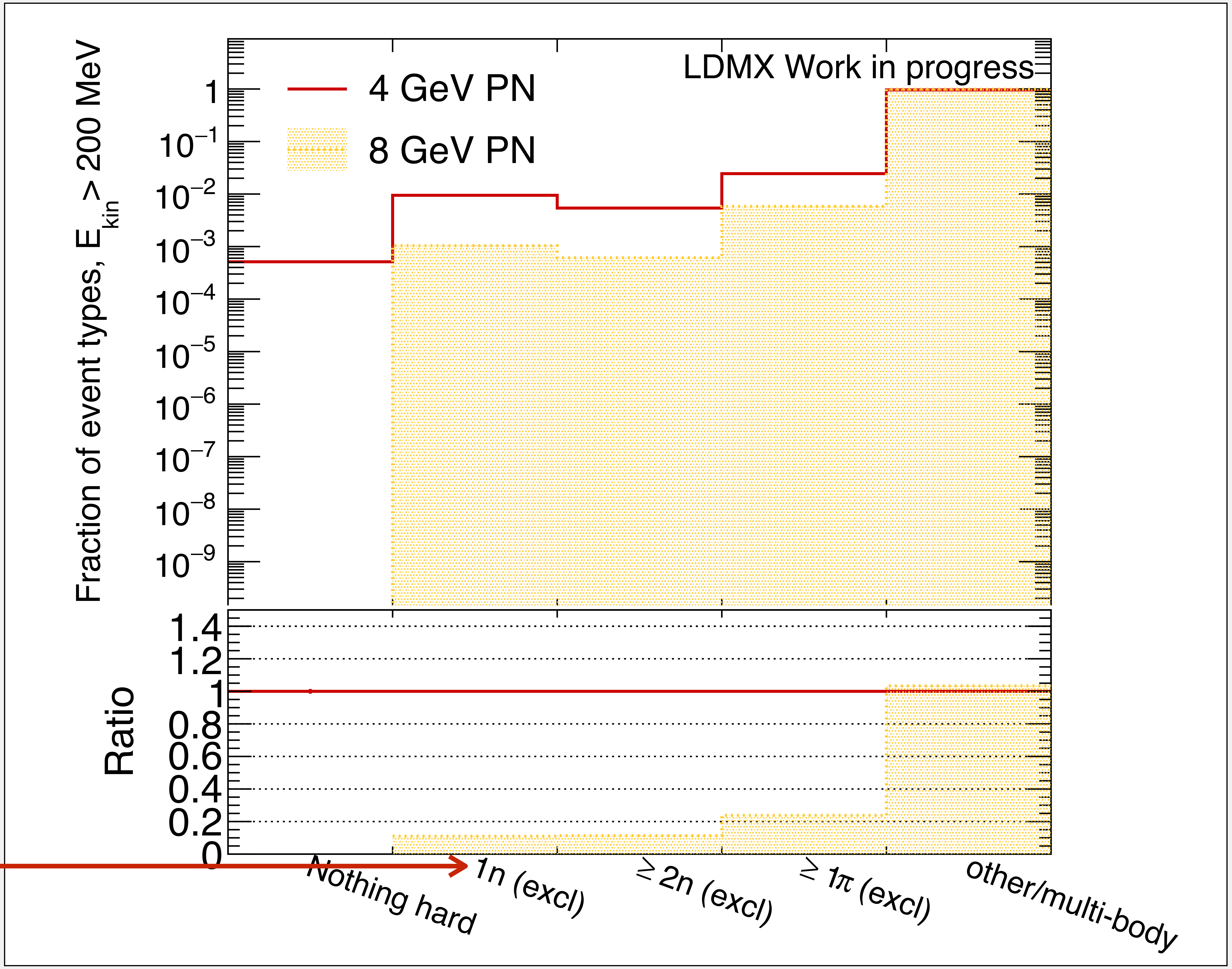
Why higher energy?

increased signal yield



Why higher energy?

improved background rejection possibilities



particularly critical

Analysis Strategy

trigger on missing energy

+ combine ECal features into a BDT

+ veto on activity in HCal

+ additional vetoes on activity in trackers/ECal front layer

---

at 4 GeV: **close to 0-background** for 4e14 EoT
based on simulation studies

important:

several handles not exploited yet, in particular p_T!

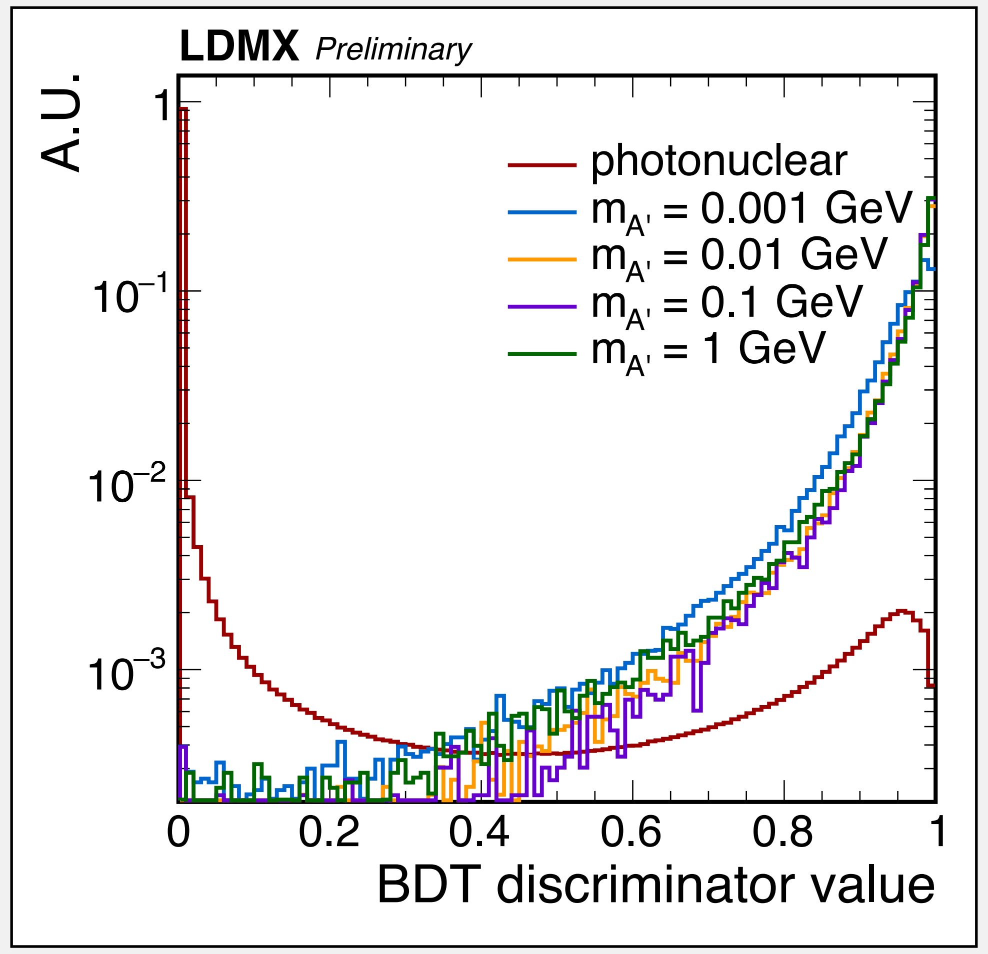
HCal optimisation ongoing

things get easier at higher energy!

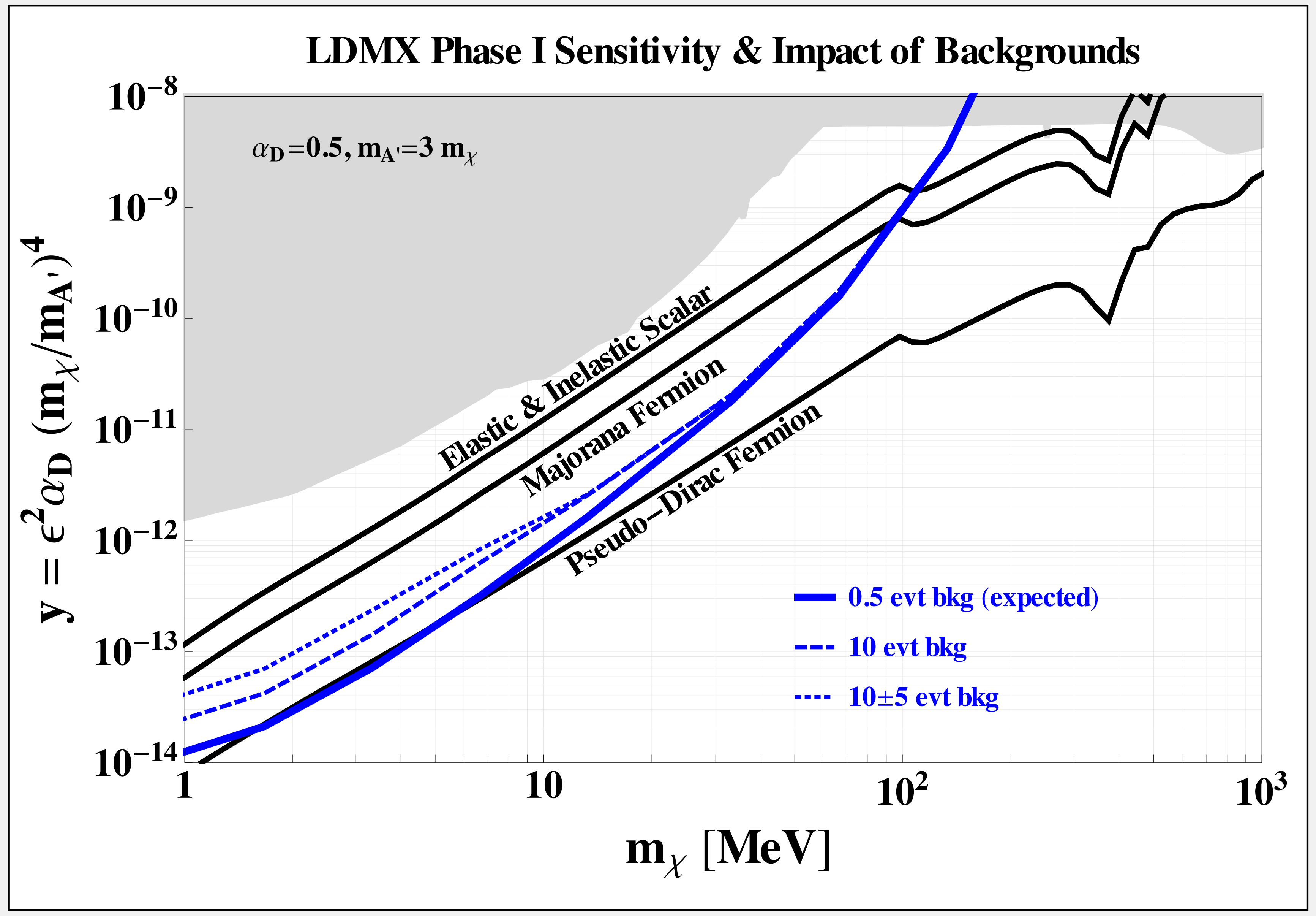
with data:

redundancy in vetoes —> data control samples, verify rejection

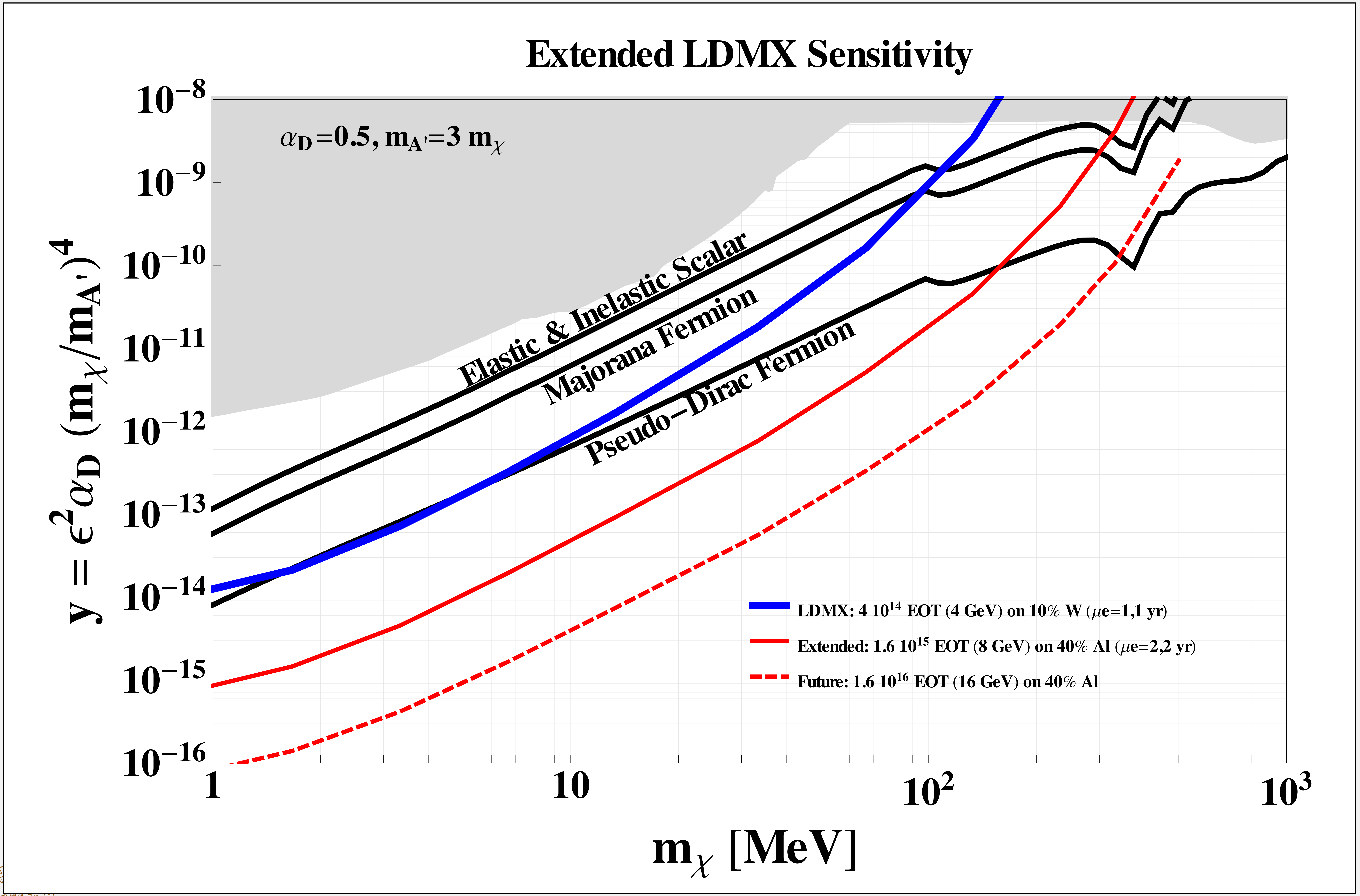
comprehensive kinematic information —> establish signal-likeness



arxiv:1808.05219



Projected Sensitivity



LDMX can explore a lot of new parameter space

sensitive to various thermal targets already with "pilot run"

ultimately potential to probe all thermal targets up to O(100) GeV

timescale: few years

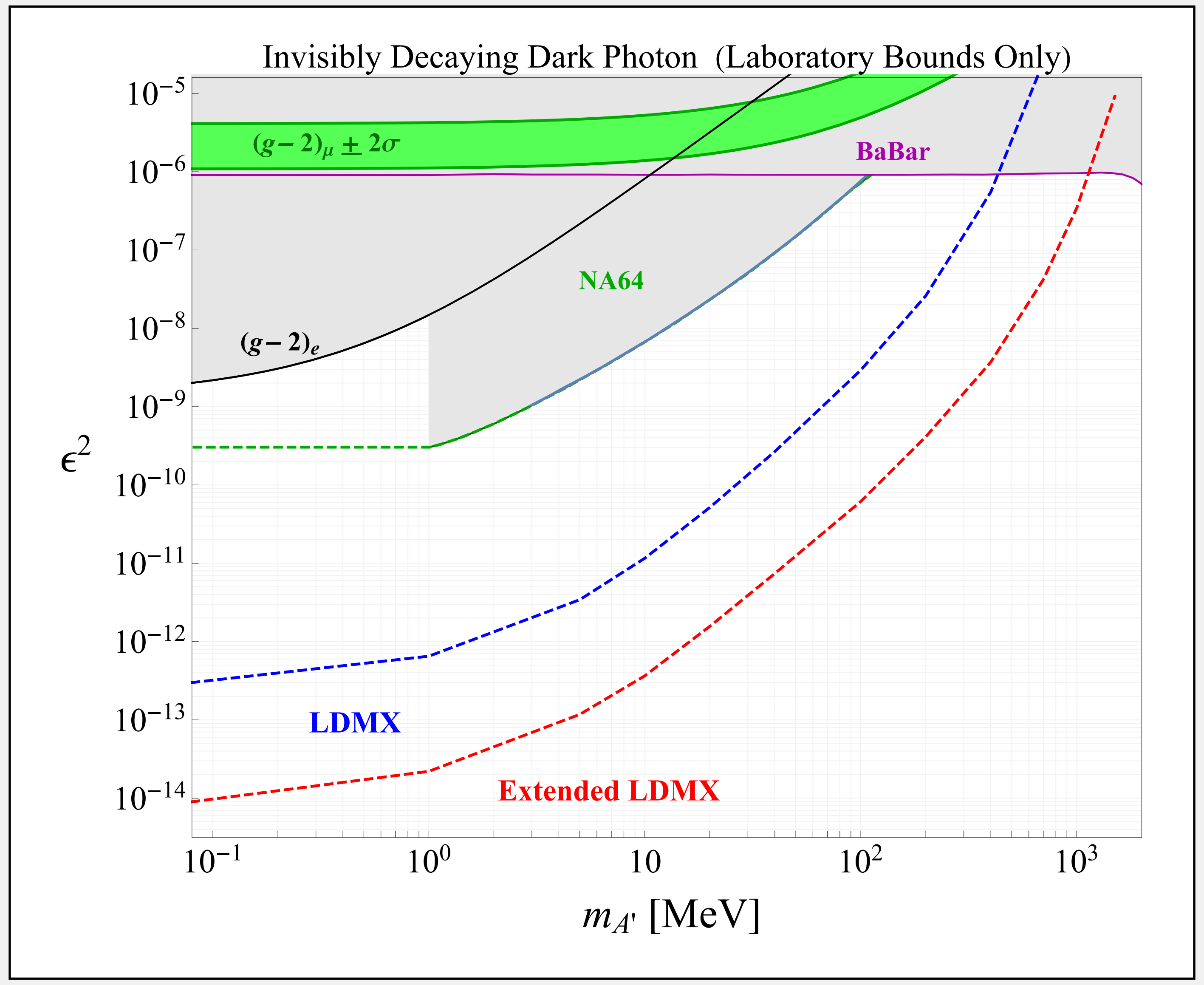
Further Potential

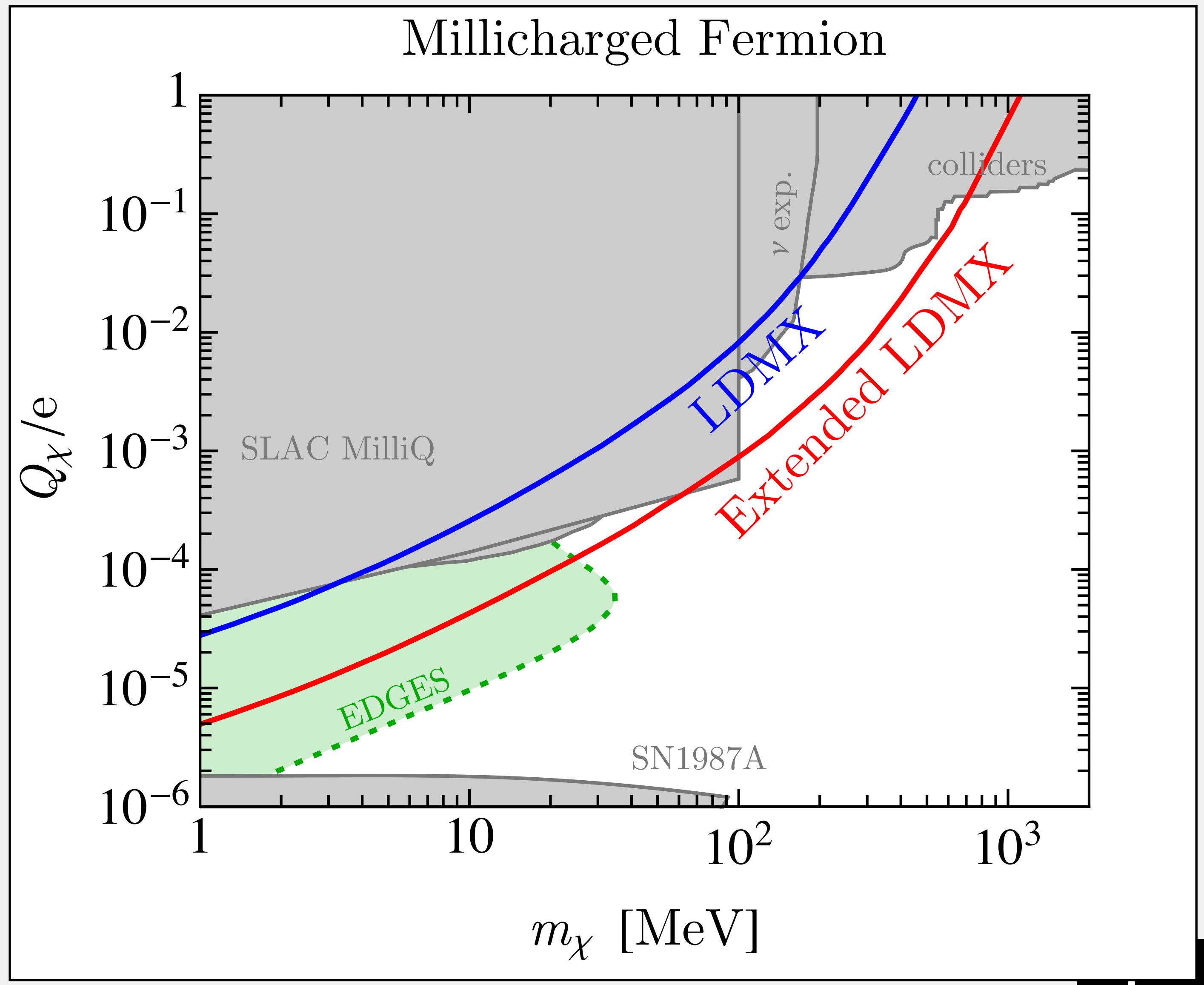
also sensitive to

- DM with quasi-thermal origin (asymmetric, SIMP/ELDER scenarios)
- new invisibly decaying mediators in general (A' one example)
- displaced vertex signatures (e.g. co-annihilation, SIMP)
- milli-charged particles

(more in Berlin, Blinov, Krnjaic, Schuster, Toro **arxiv:1807.01730**)

in addition: *measurement* of photo- and electro-nuclear processes (for neutrino experiments)





Summary

broad interest in Dark Sector physics, many new initiatives

- light, thermal relic Dark Matter well motivated
- fixed-target, missing-momentum approach provides outstanding sensitivity
- LDMX the only such experiment on the horizon
  - start of data-taking in early 2020s
- potential to probe thermal targets in MeV - GeV range
  - complements direct detection
- more generally, sensitive to broad range if sub-GeV physics

Thank you!

Additional Material

Various Future Projections