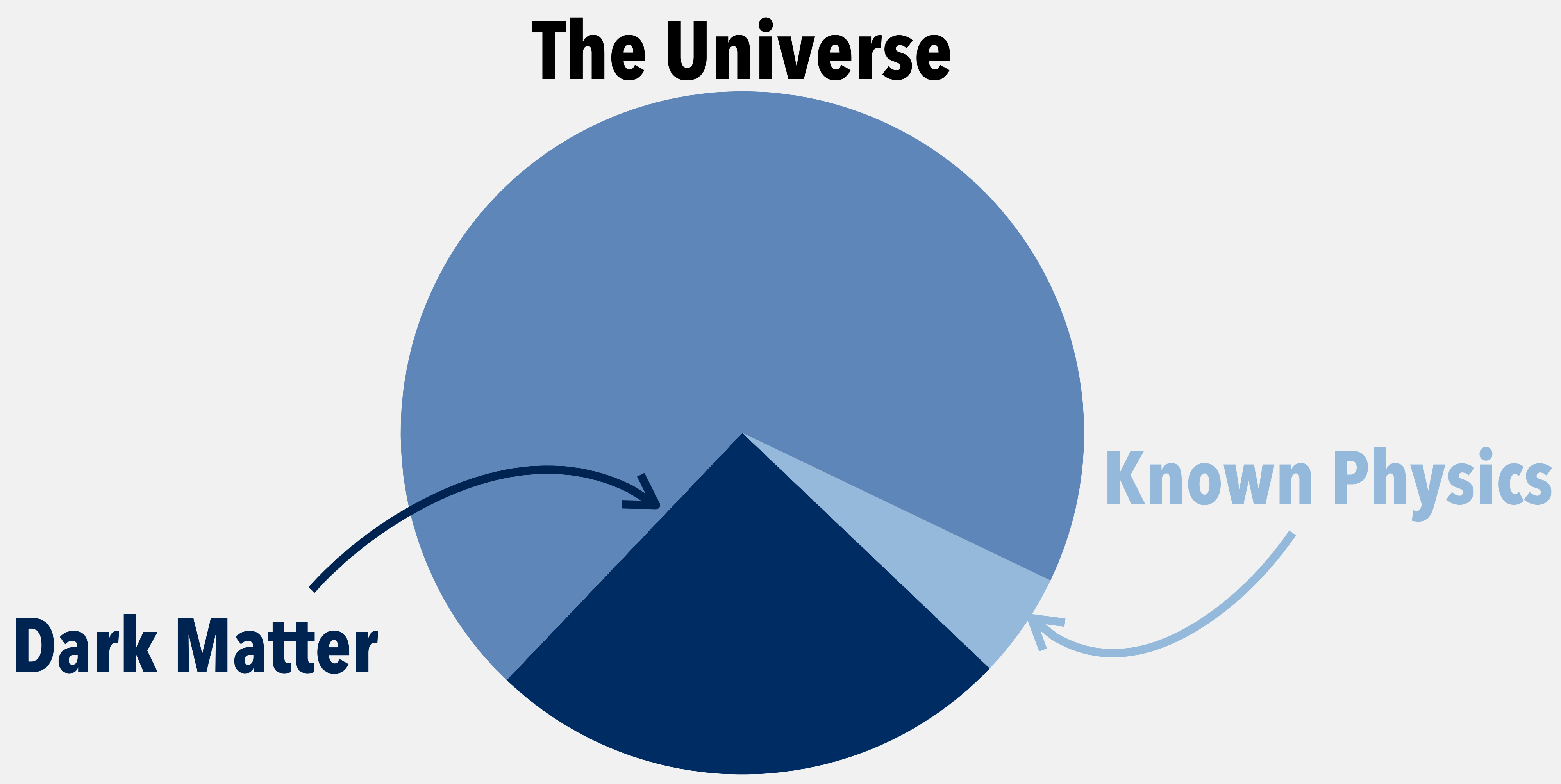
Search for Light Dark Matter (at Accelerators)

PPC 2018, Zurich

23 August 2018

Ruth Pöttgen

What is light? (in this talk)



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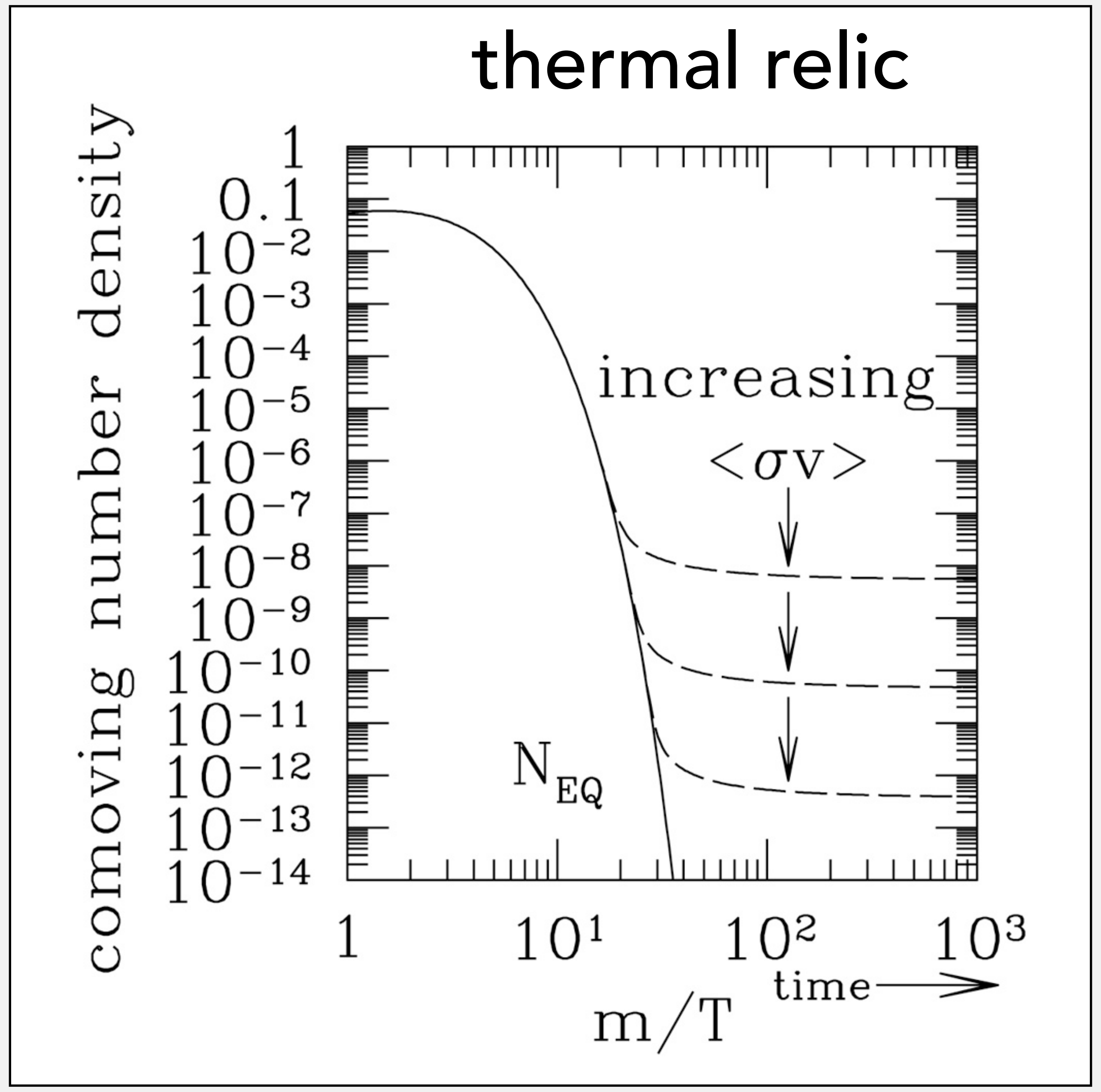

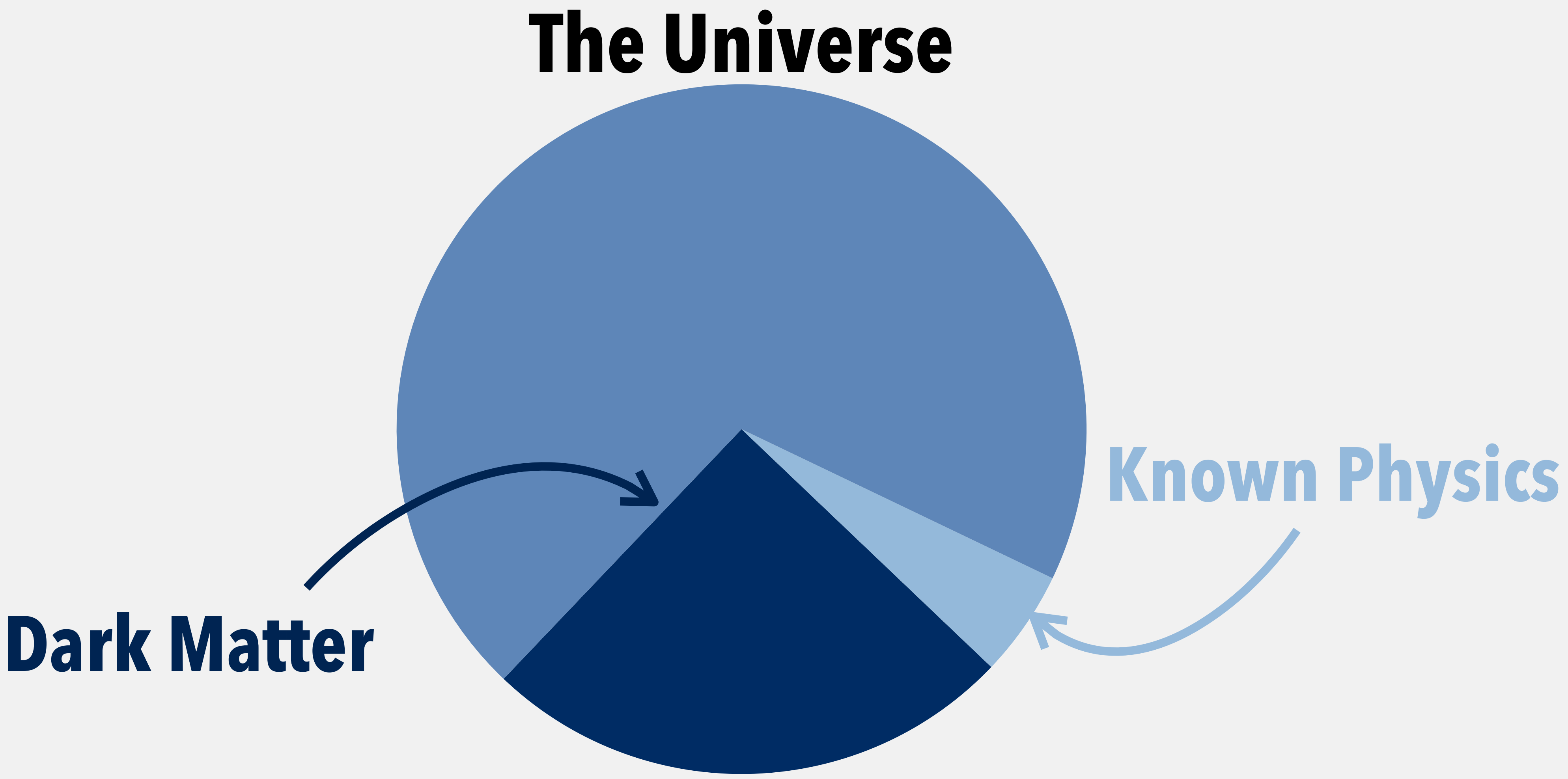

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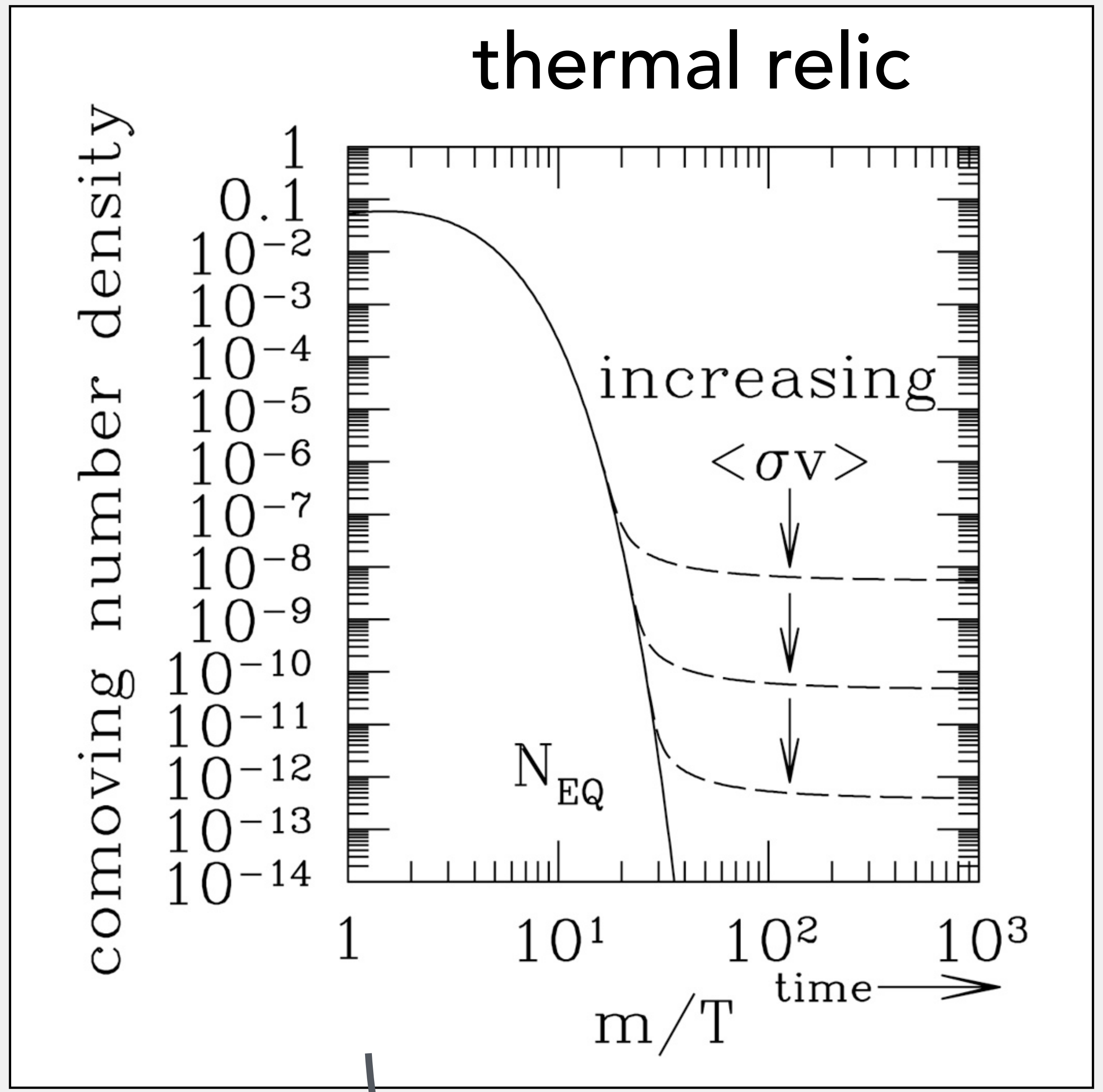

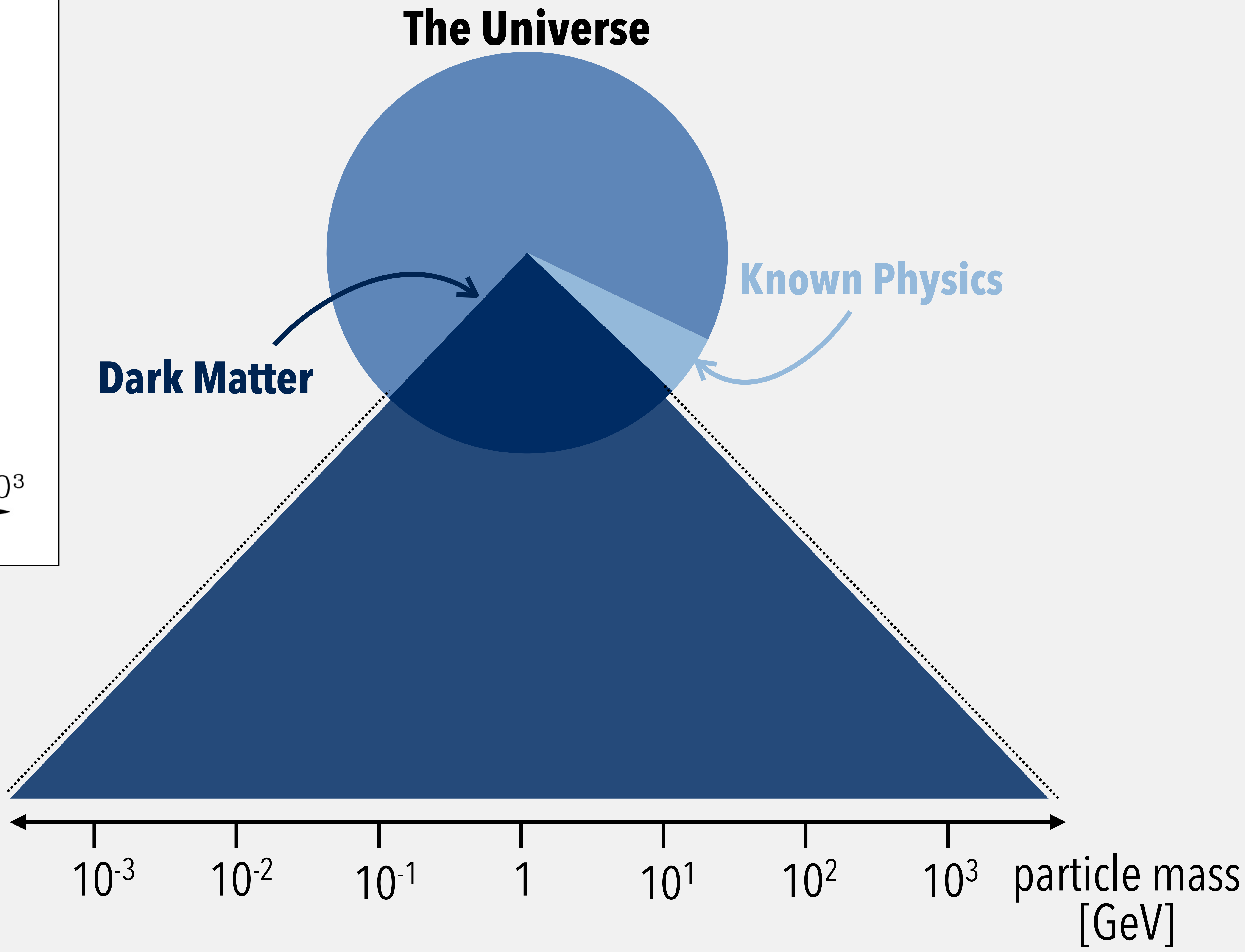

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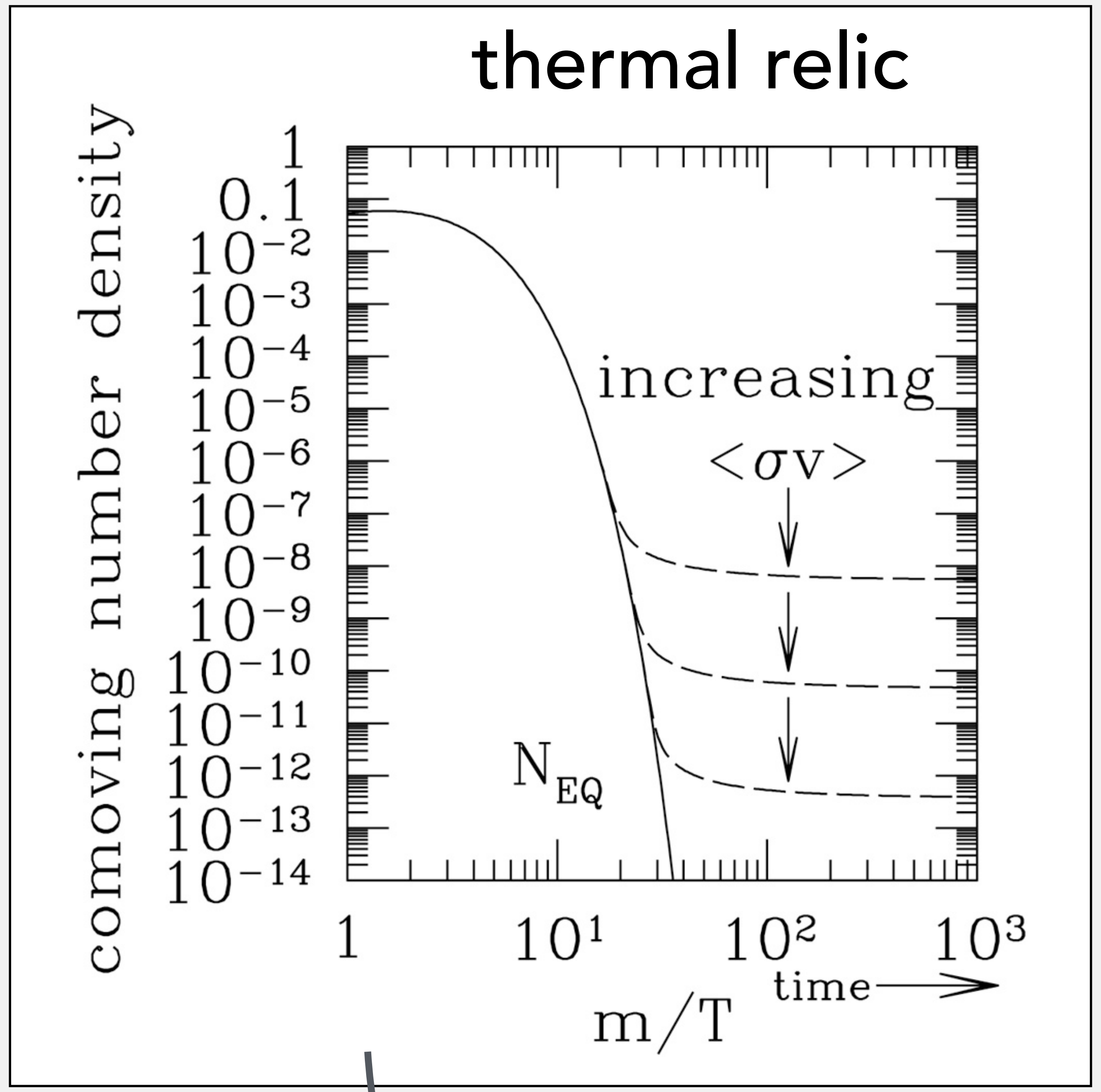

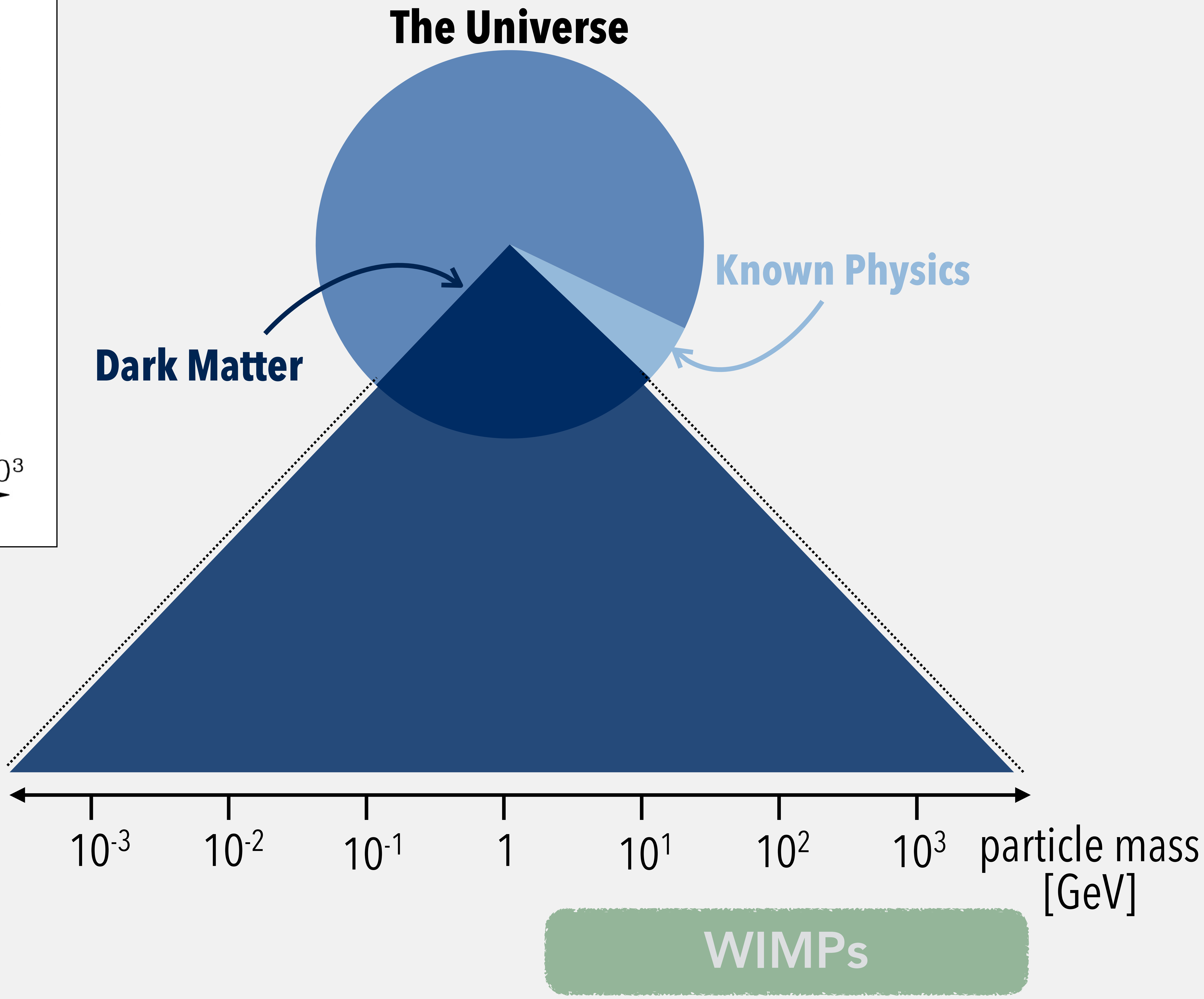

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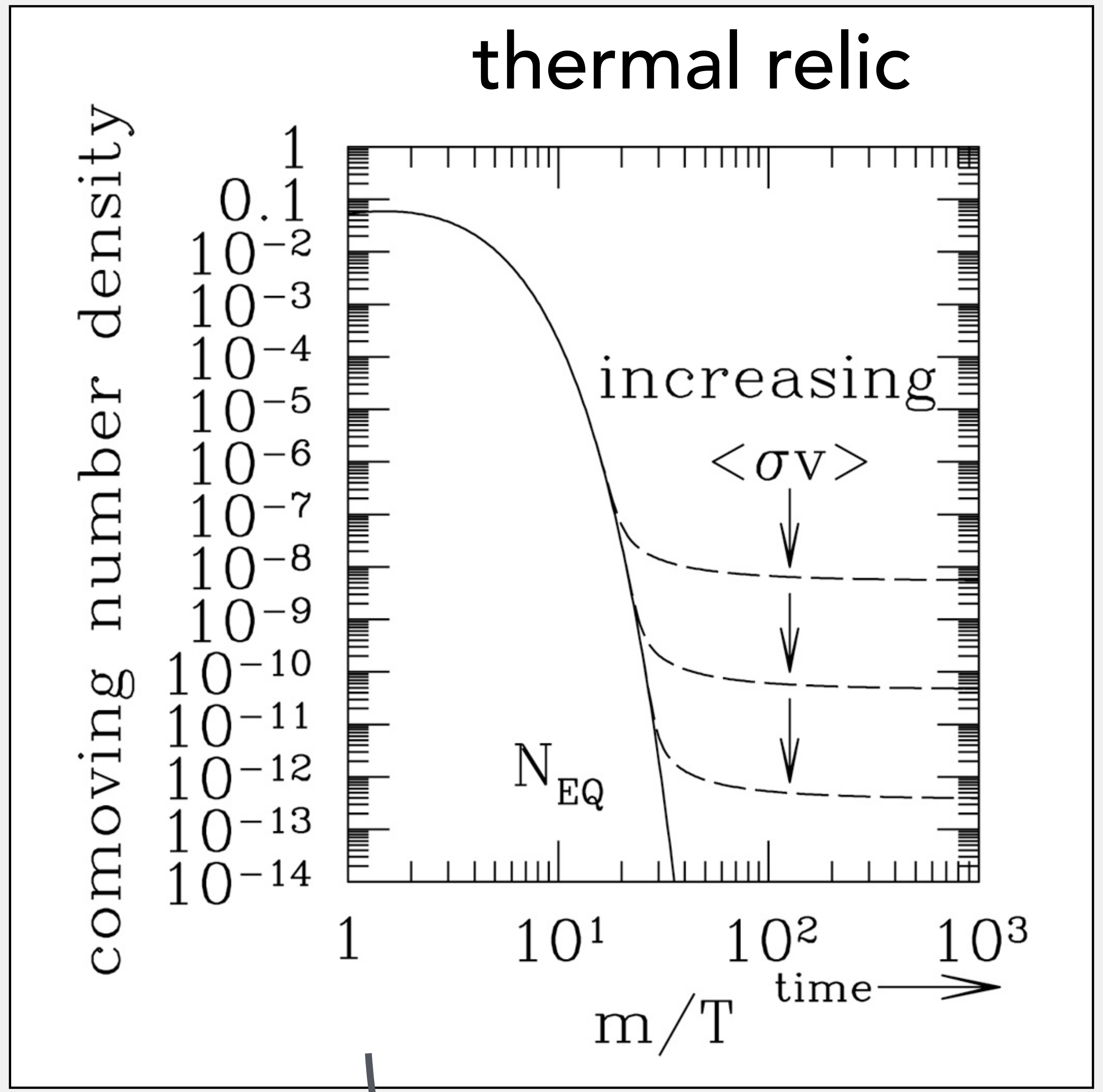

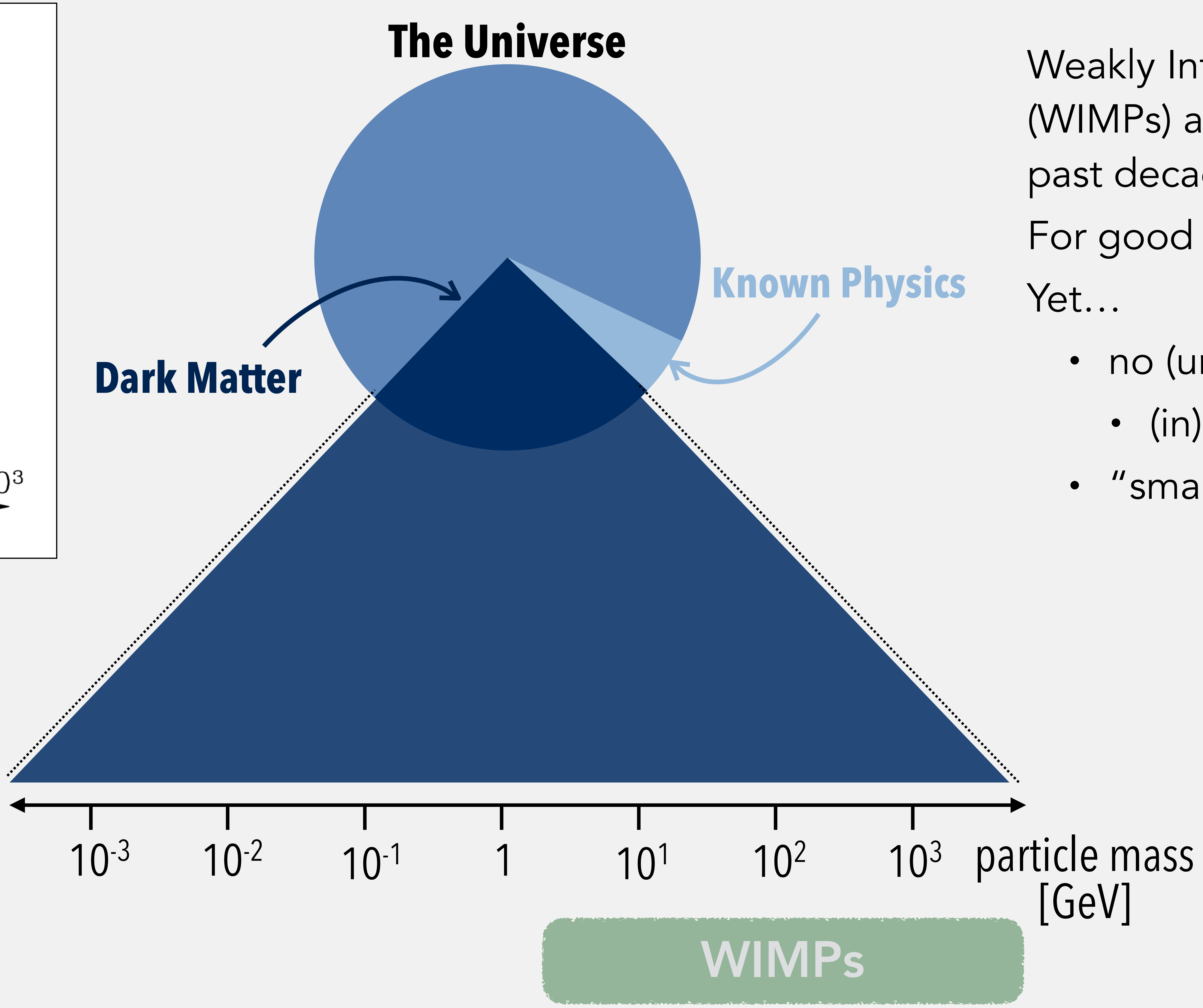

Weakly Interacting Massive Particles (WIMPs) at centre of attention in past decades.

For good reasons!

Yet…

- no (unambiguous) observation
  - (in)direct detection, LHC
- "small-scale crisis" of cold DM

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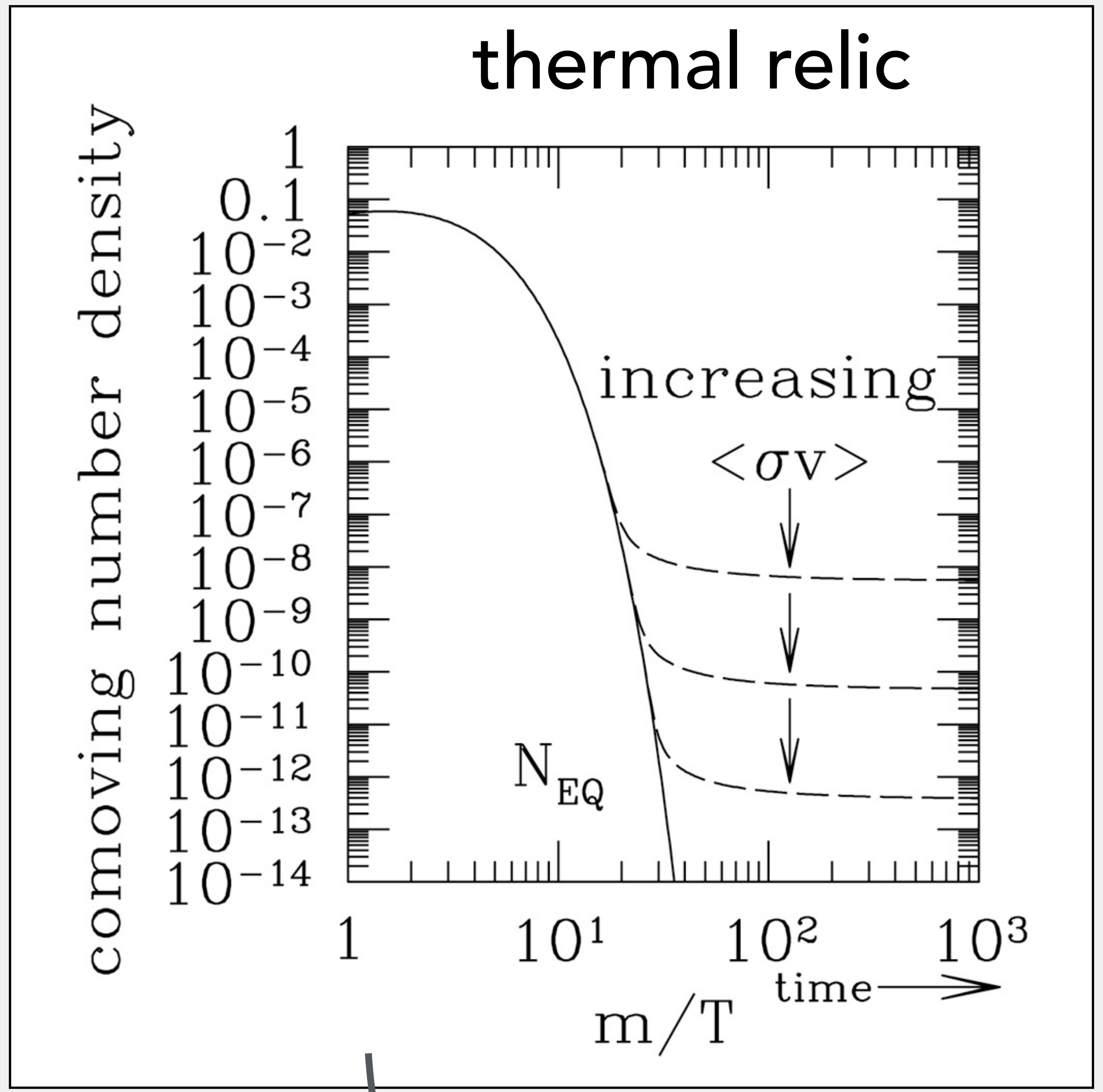

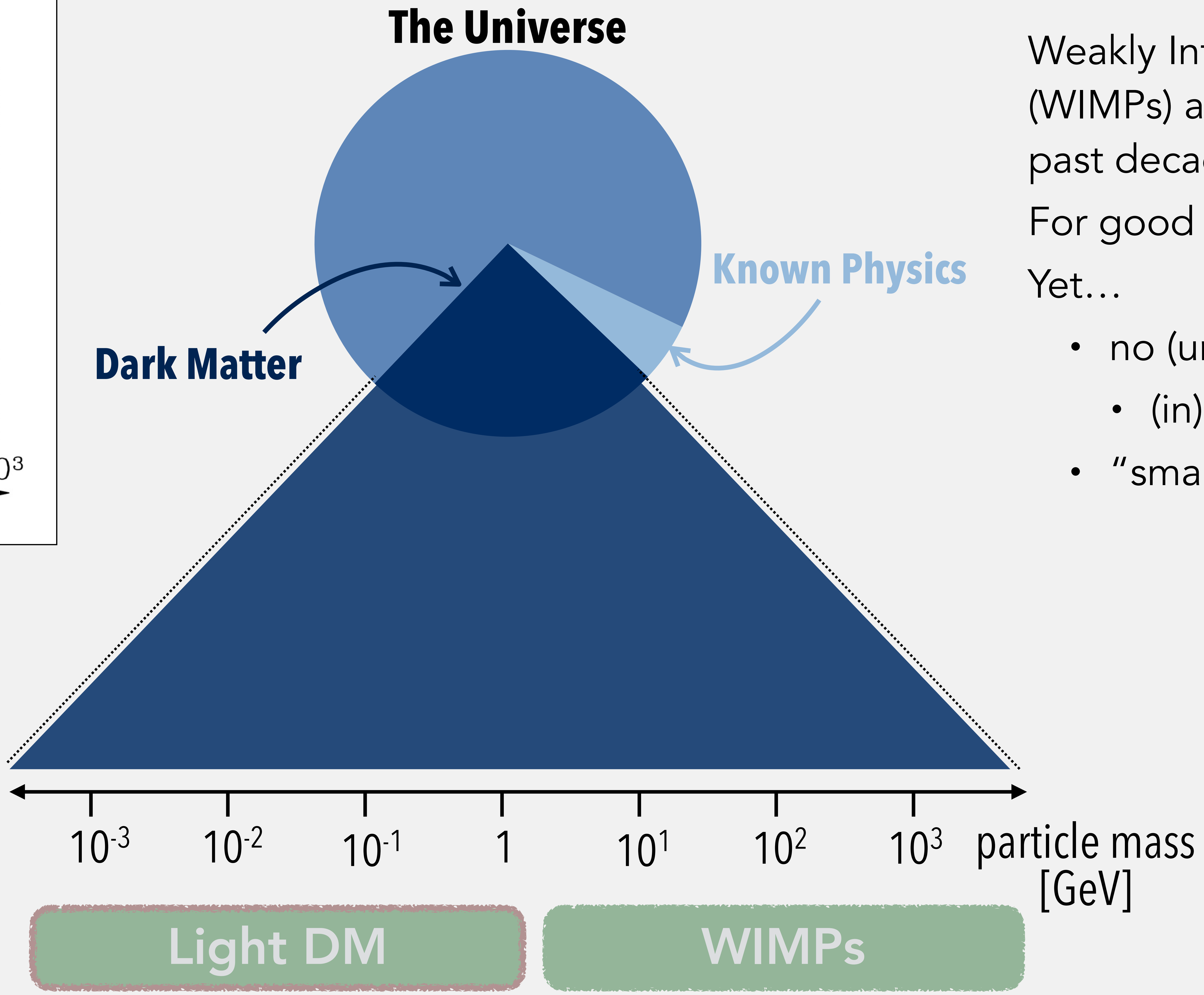

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Active Field

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	$E_{\rm beam}$ (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	$m_\chi < 0.06$	$y \gtrsim 10^{-13}$	started
DarkLight	LERF @ JLab	electron FT	0.17	MMass (& vis.)	$0.01 < m_{A'} < 0.08$	$\epsilon^2 \gtrsim 10^{-6}$	started
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 vis. disp.	$0.22 < m_{A'} < 9$ $m_{A'} < 2$	$\epsilon^2 \gtrsim 10^{-8}$ $\epsilon^2 \sim 10^{-14} - 10^{-}$	
Future international initiatives							
Belle II	SuperKEKB @ KEK	e^+e^- collider	~ 5.3	MMass (& vis.)	$0 < m_\chi < 10$	$\epsilon^2 \gtrsim 10^{-9}$	
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

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

Physics Beyond Colliders Annual Workshop

21-22 November 2017
CERN

Search...

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)

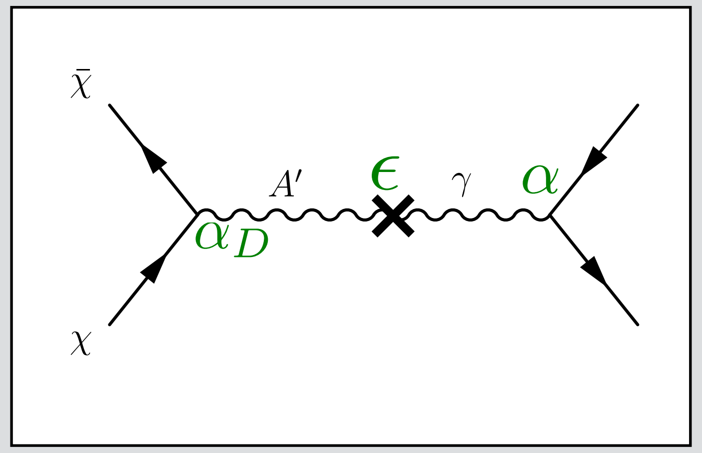
- annihilation into SM inefficient
  - overproduction of DM
- *Lee-Weinberg-bound*

introduce new, light mediator

- additional annihilation channel
  - correct relic abundance

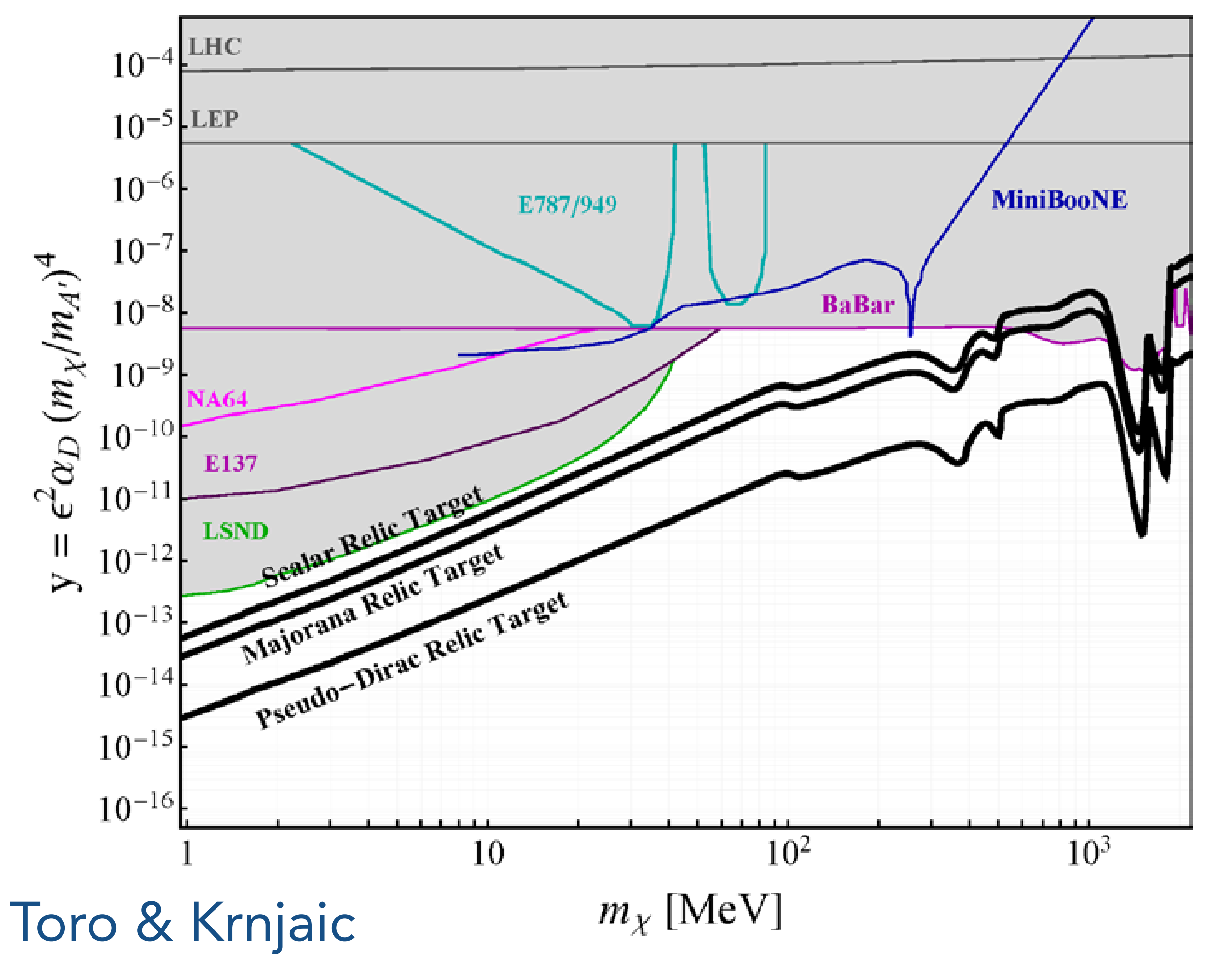
representative benchmark model: Dark Photon (A’)

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



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

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



Toro & Krnjaic

clear experimental *thermal targets*

conservative:

$$\alpha_D = 0.5 \qquad \frac{m_\chi^4}{m_{A'}^4} = \frac{1}{3}$$

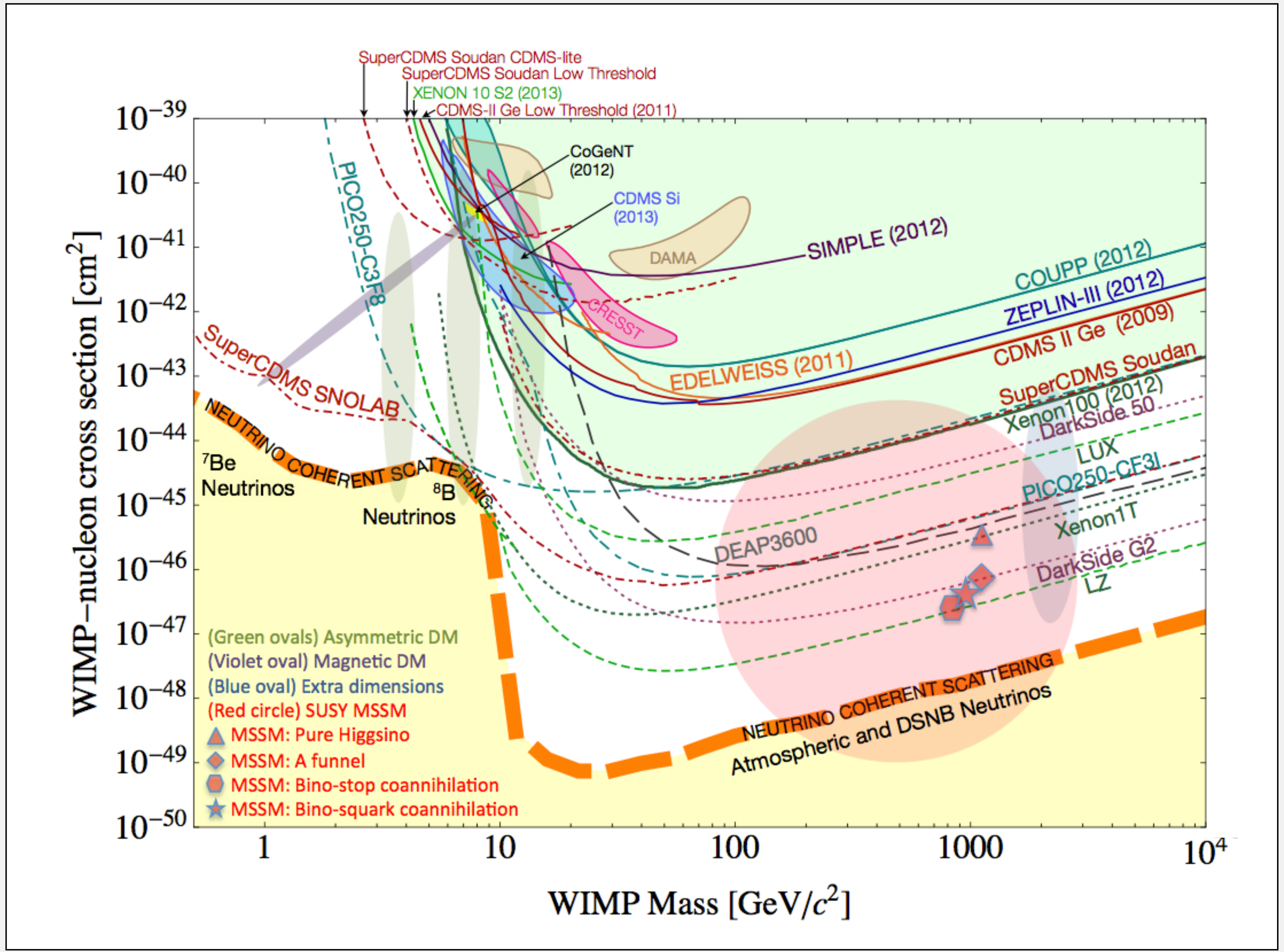
Direct Detection [talk this afternoon]

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

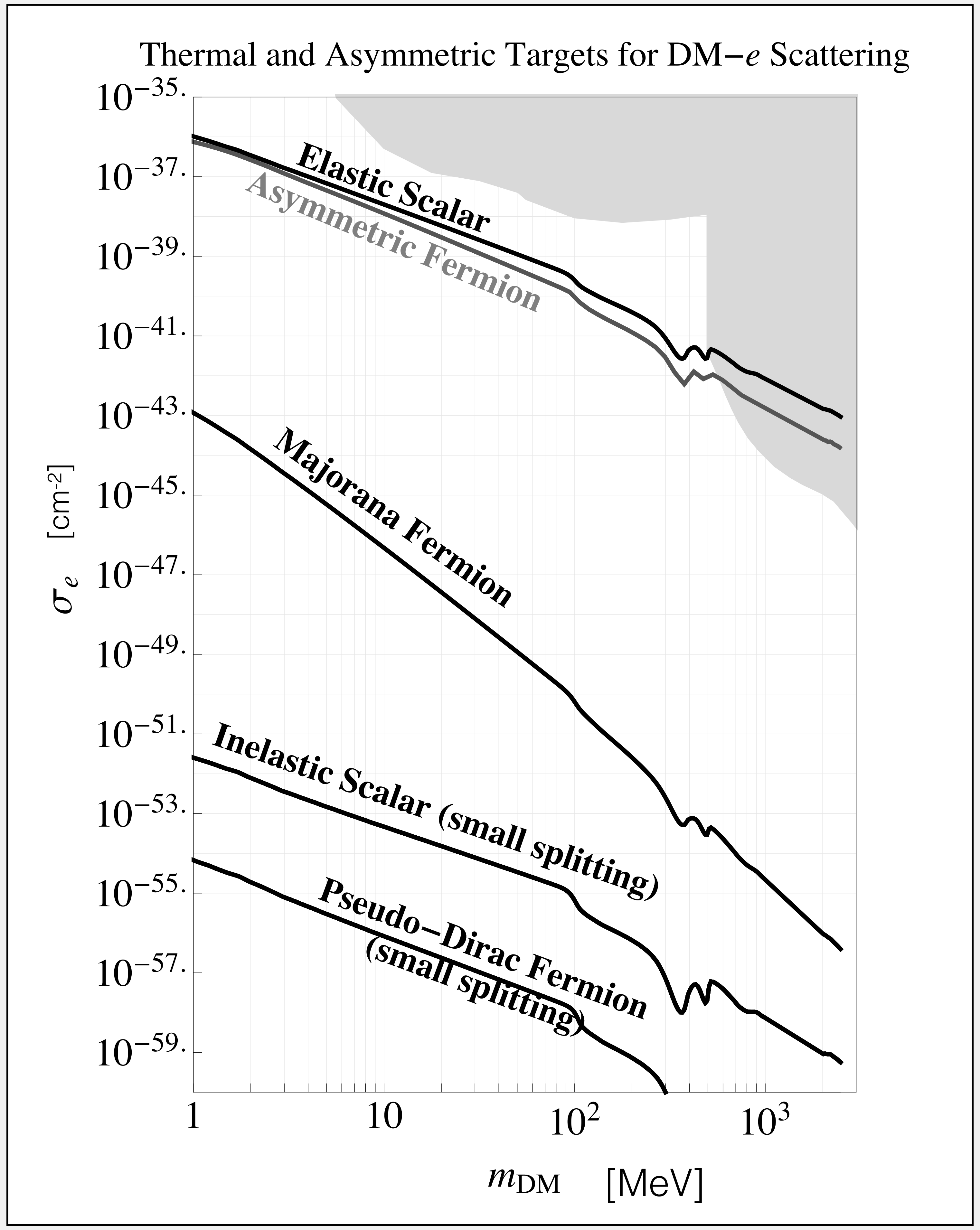
- needs lower energy threshold
  - examples:
    - electron-DM scattering
    - semiconductors



Why not just direct detection?

direct detection:

strong spin/velocity dependency



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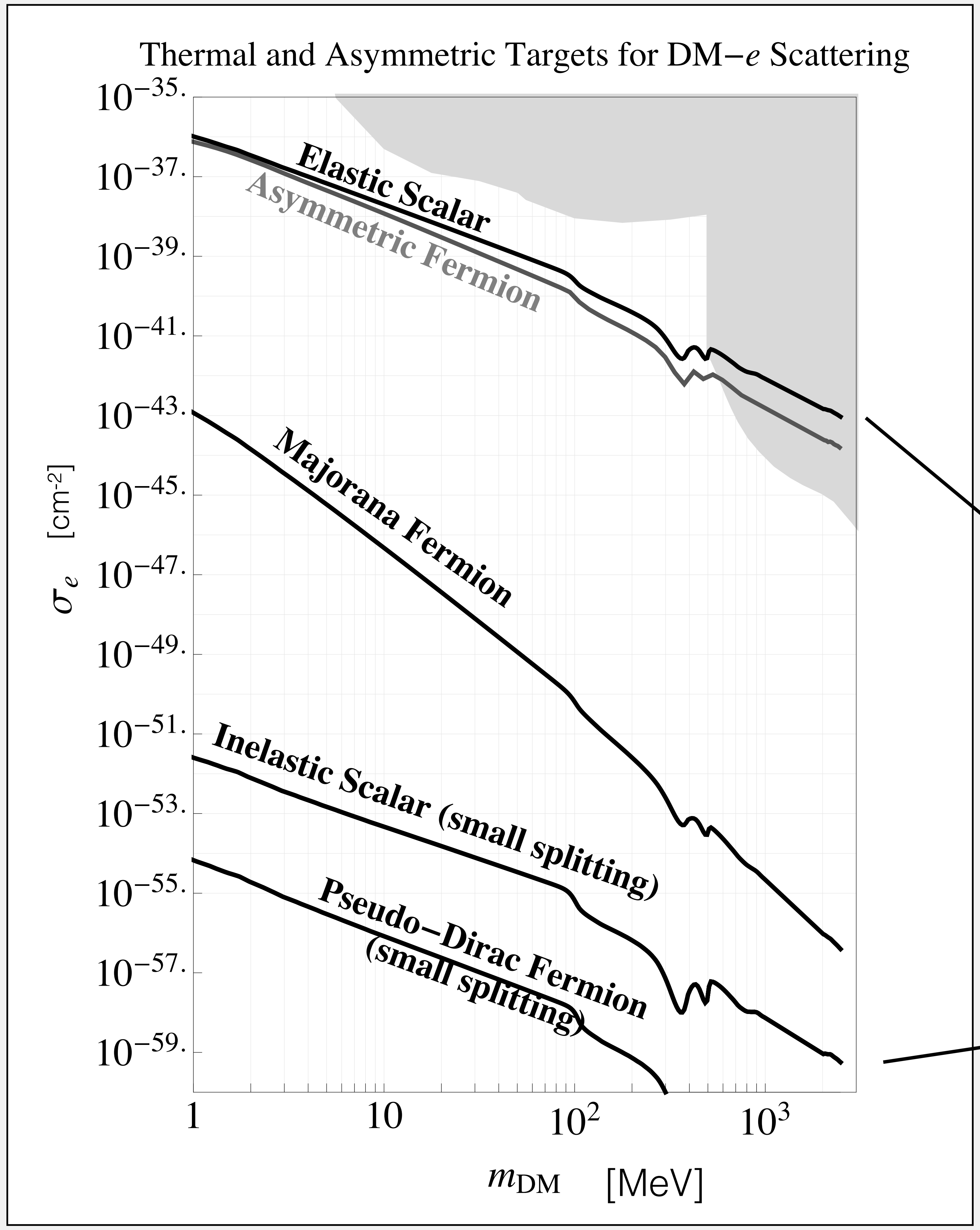
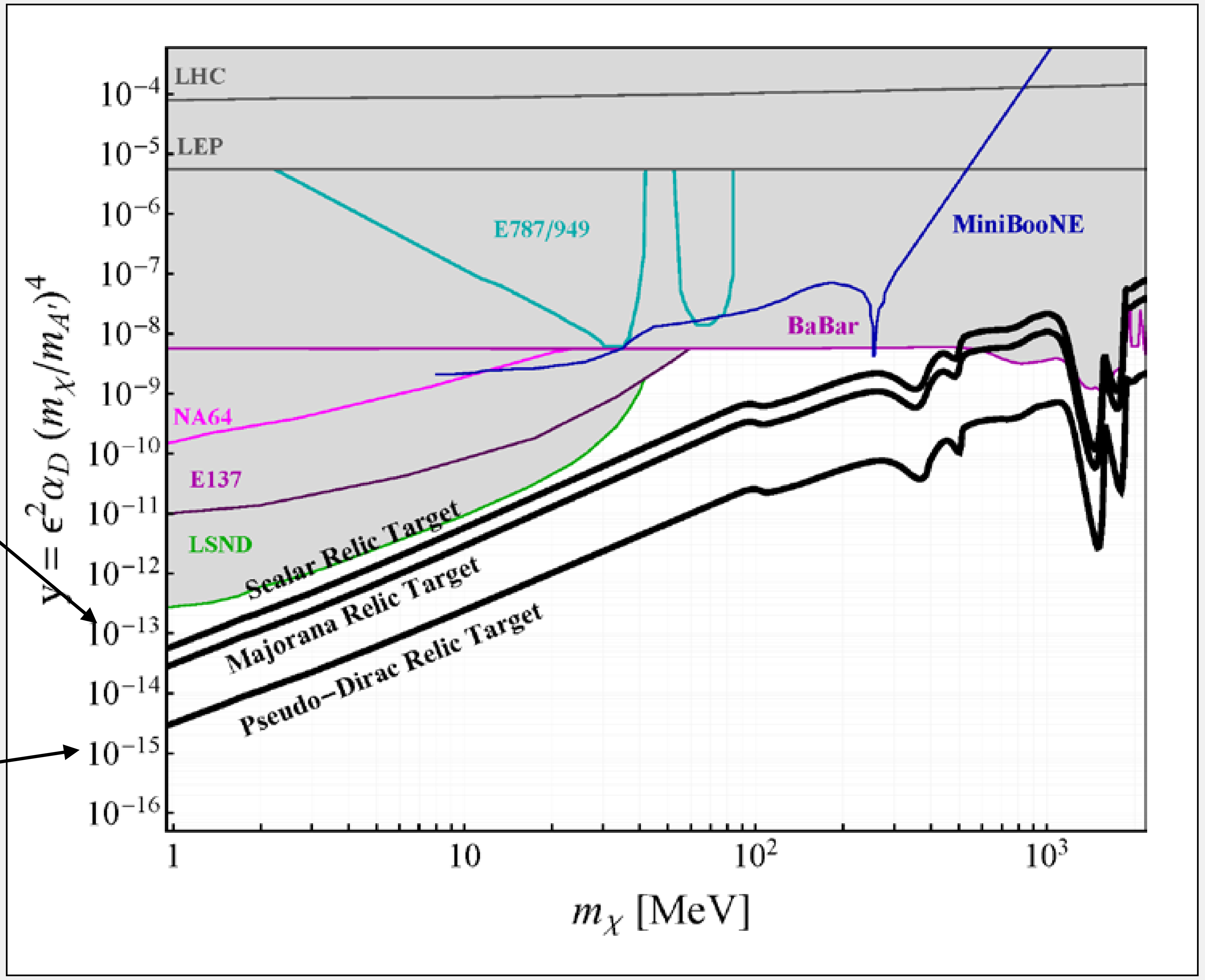


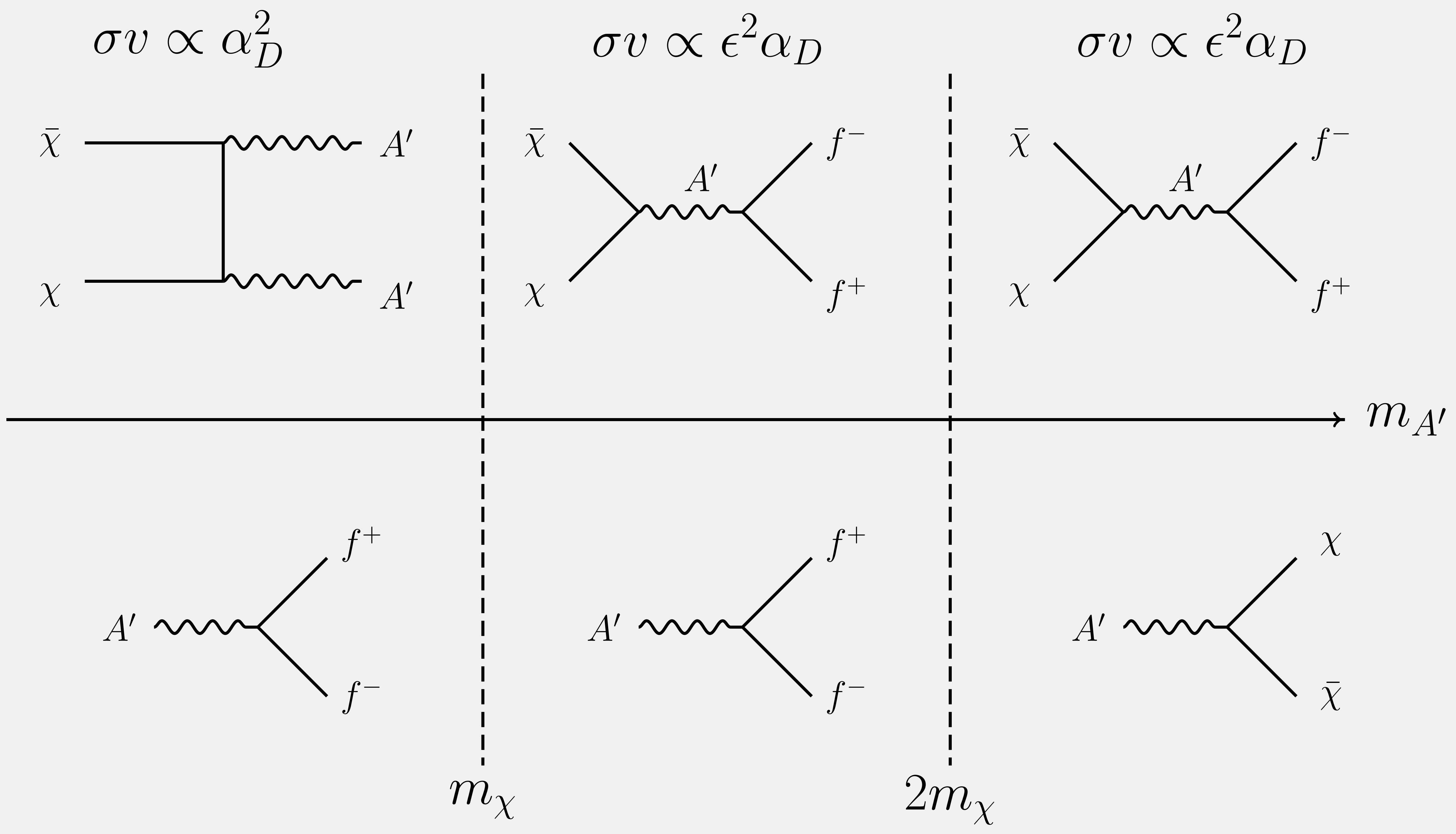
at accelerators: relativistic production

—> spin/velocity dependency reduced

all thermal targets in reach!

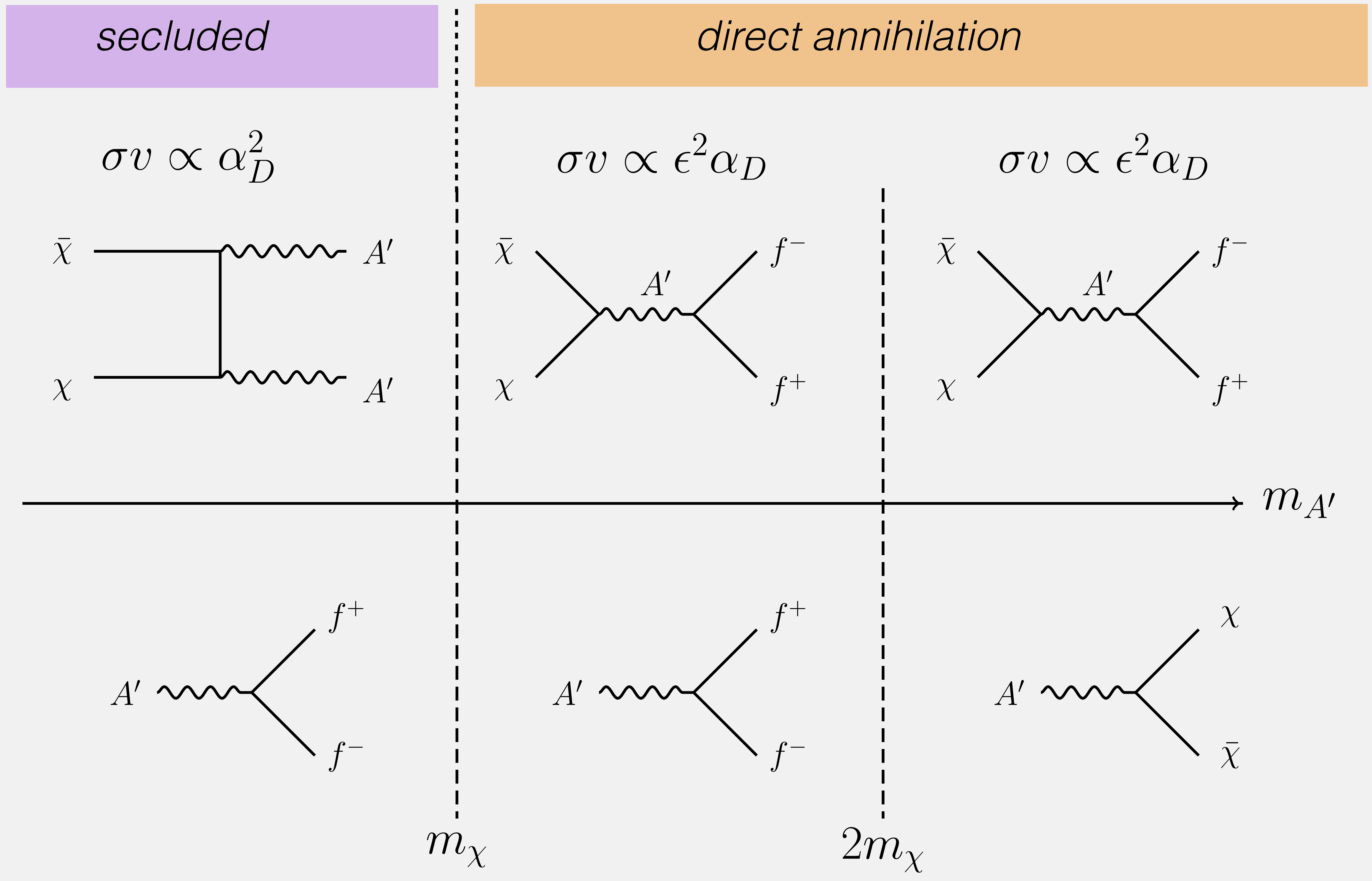


Signatures



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

Signatures



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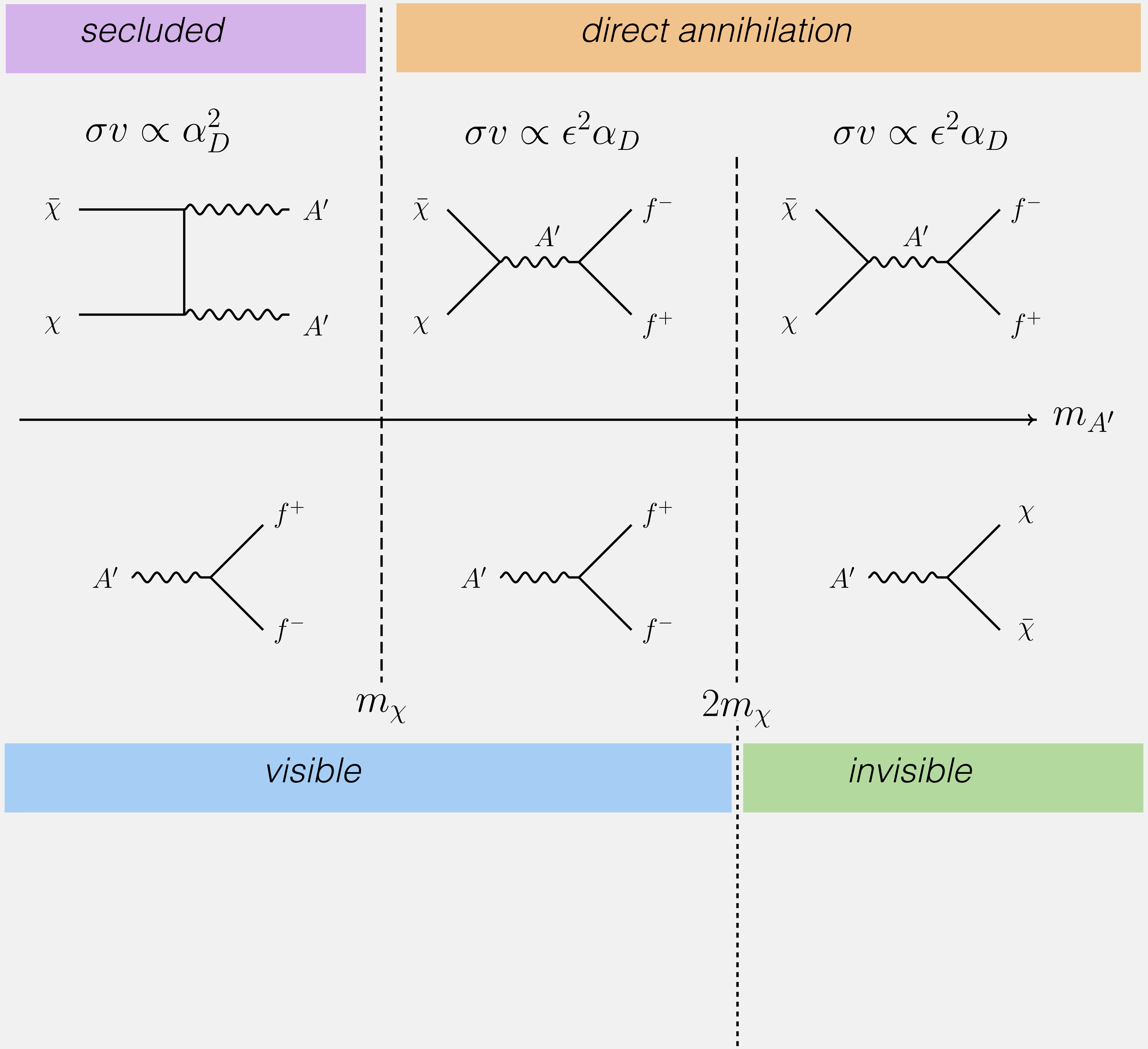
$2m_\chi$

Signatures



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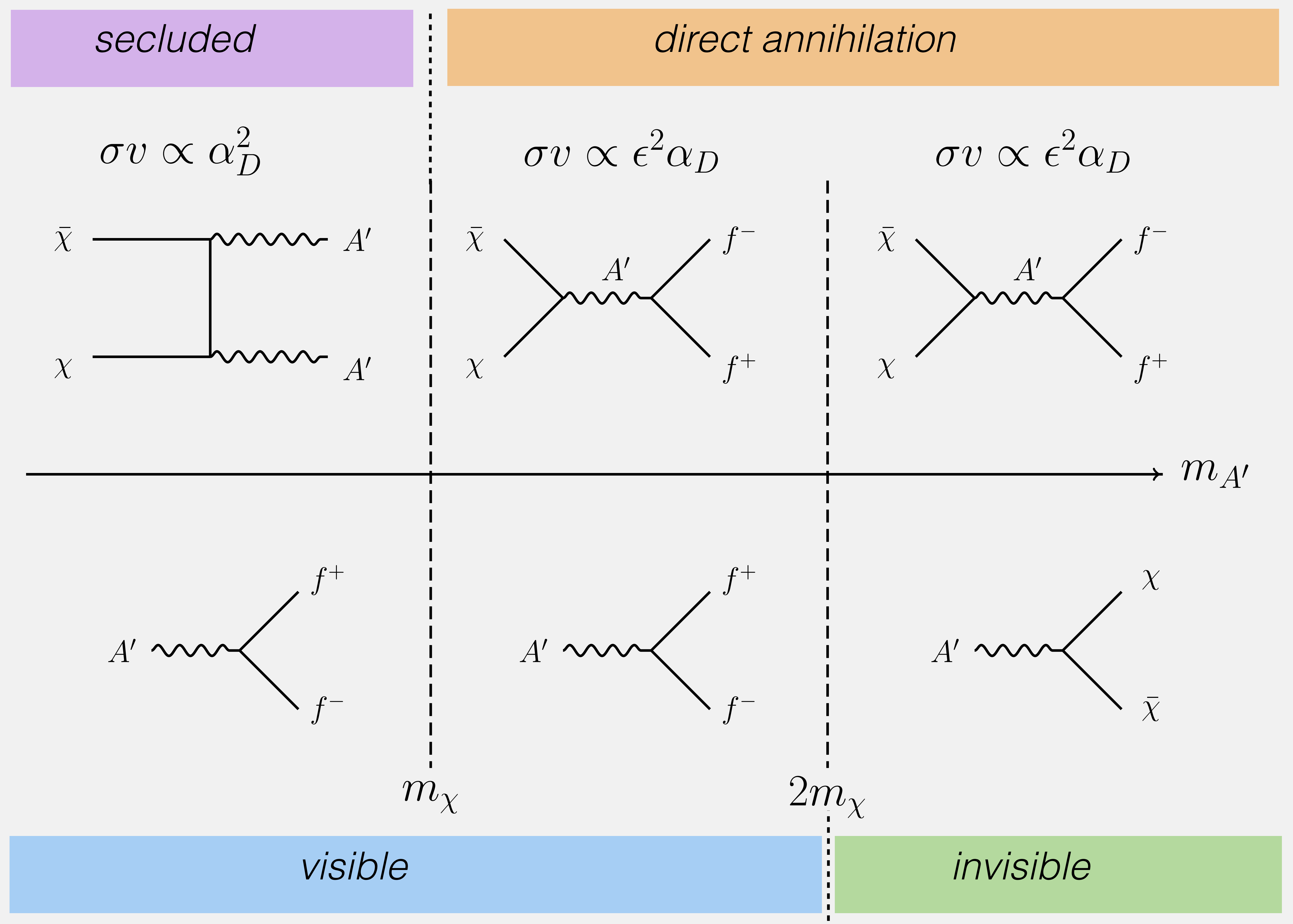
$\bar{\chi}$
χ
A'
A'
f^-
f^+
$m_{A'}$
m_χ
$2m_\chi$
visible
invisible

Signatures

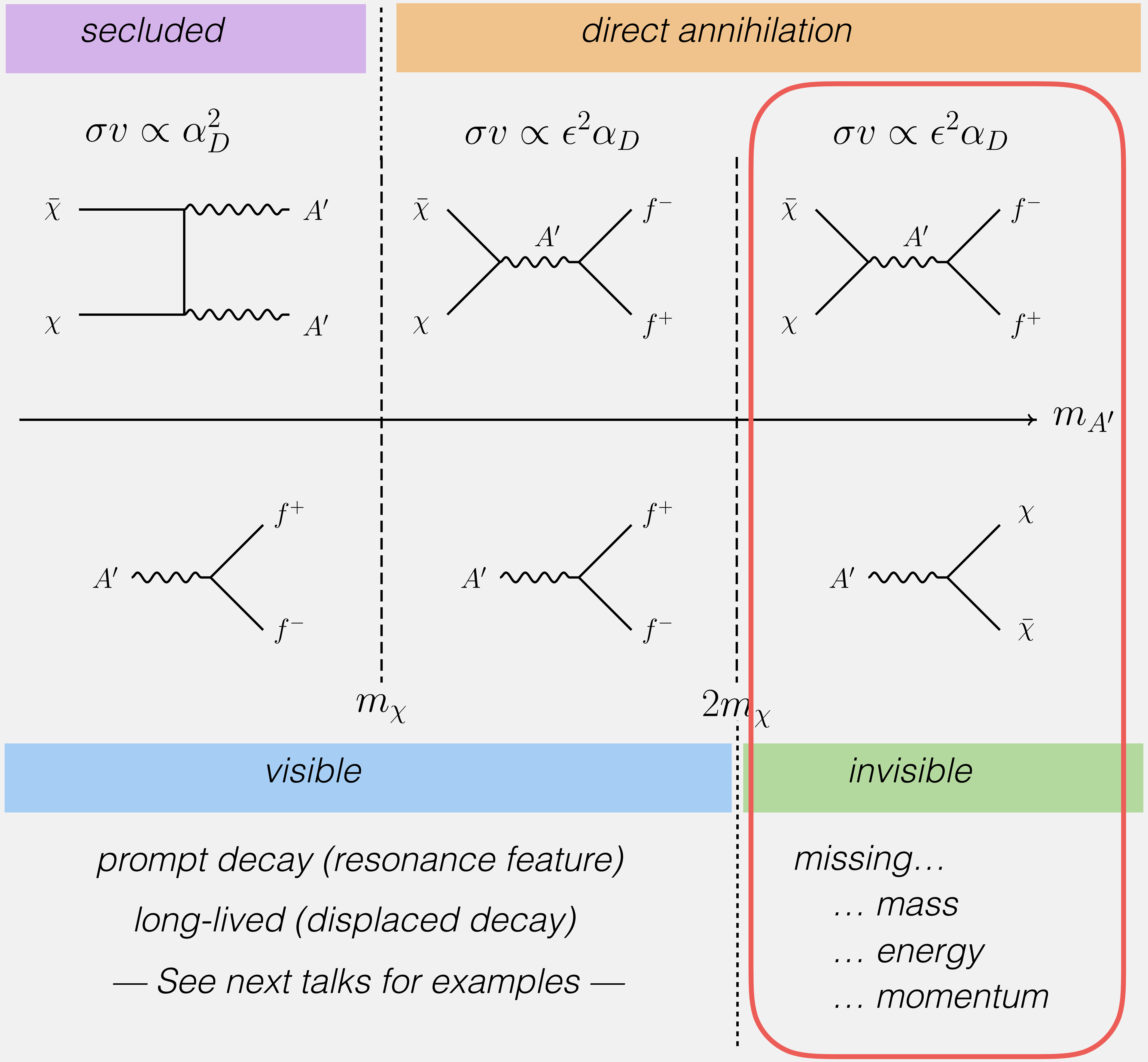


prompt decay (resonance feature)

long-lived (displaced decay)

— See next talks for examples —

Signatures


secluded
direct annihilation
$\sigma v \propto \alpha_D^2$
$\sigma v \propto \epsilon^2 \alpha_D$
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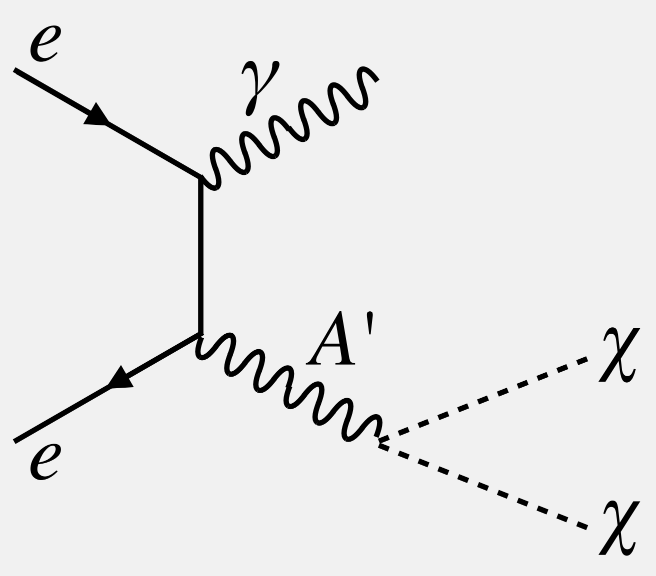
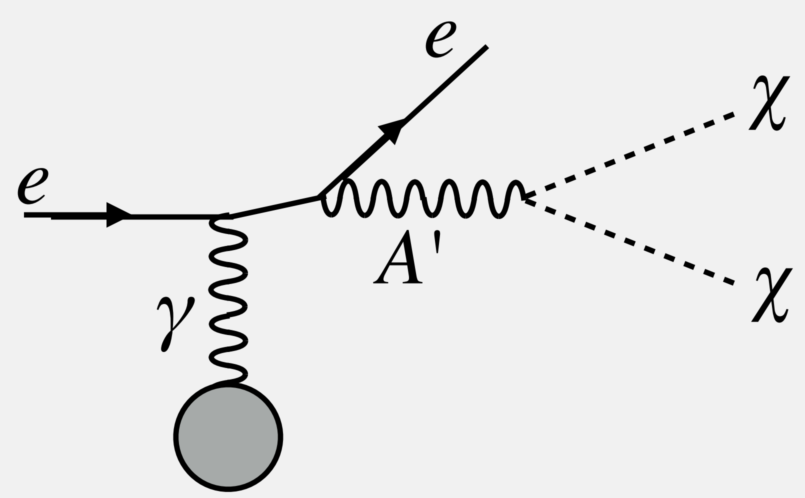
$\bar{\chi}$ χ A' A'
$\bar{\chi}$ χ A' f^- f^+
$\bar{\chi}$ χ A' f^- f^+
$m_{A'}$
A' f^+ f^-
A' f^+ f^-
A' χ $\bar{\chi}$
m_χ
$2m_\chi$
visible
invisible
prompt decay (resonance feature)
long-lived (displaced decay)
— See next talks for examples —
missing…
… mass
… energy
… momentum

Complimentary Approaches

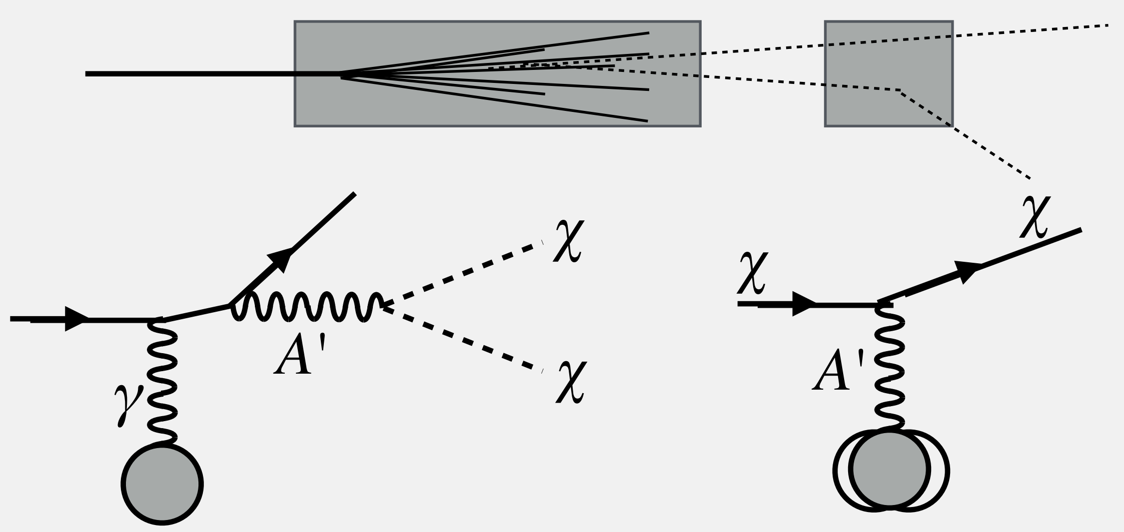
collider



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"**

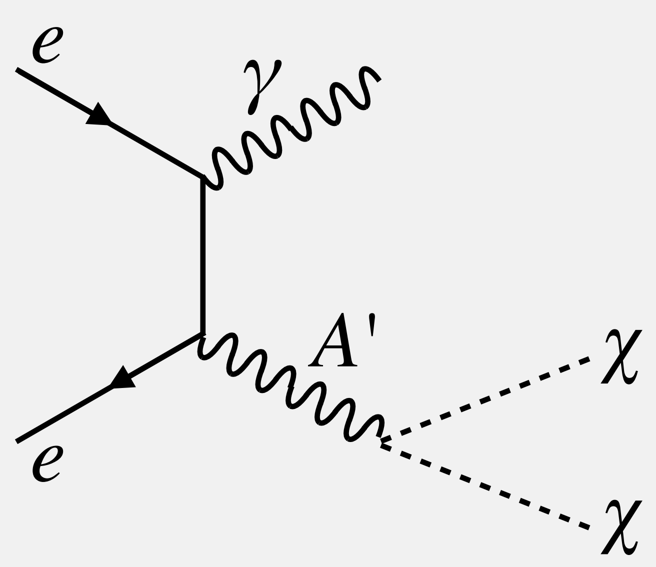
	collider	fixed target		beam dump	
examples (existing or planned)	**BaBar**	**PADME**	MMAPS	**E137**	SBNe/pi
	Belle II	**NA64**	VEPP3	LSND	**MiniBooNE**
	LHC	**LDMX**	DarkLight (II)	**BDX**	SHiP
mass range	0.1 - 10 GeV	MeV - GeV			

Collider Experiments (B-factories)

BABAR

@PEP-II

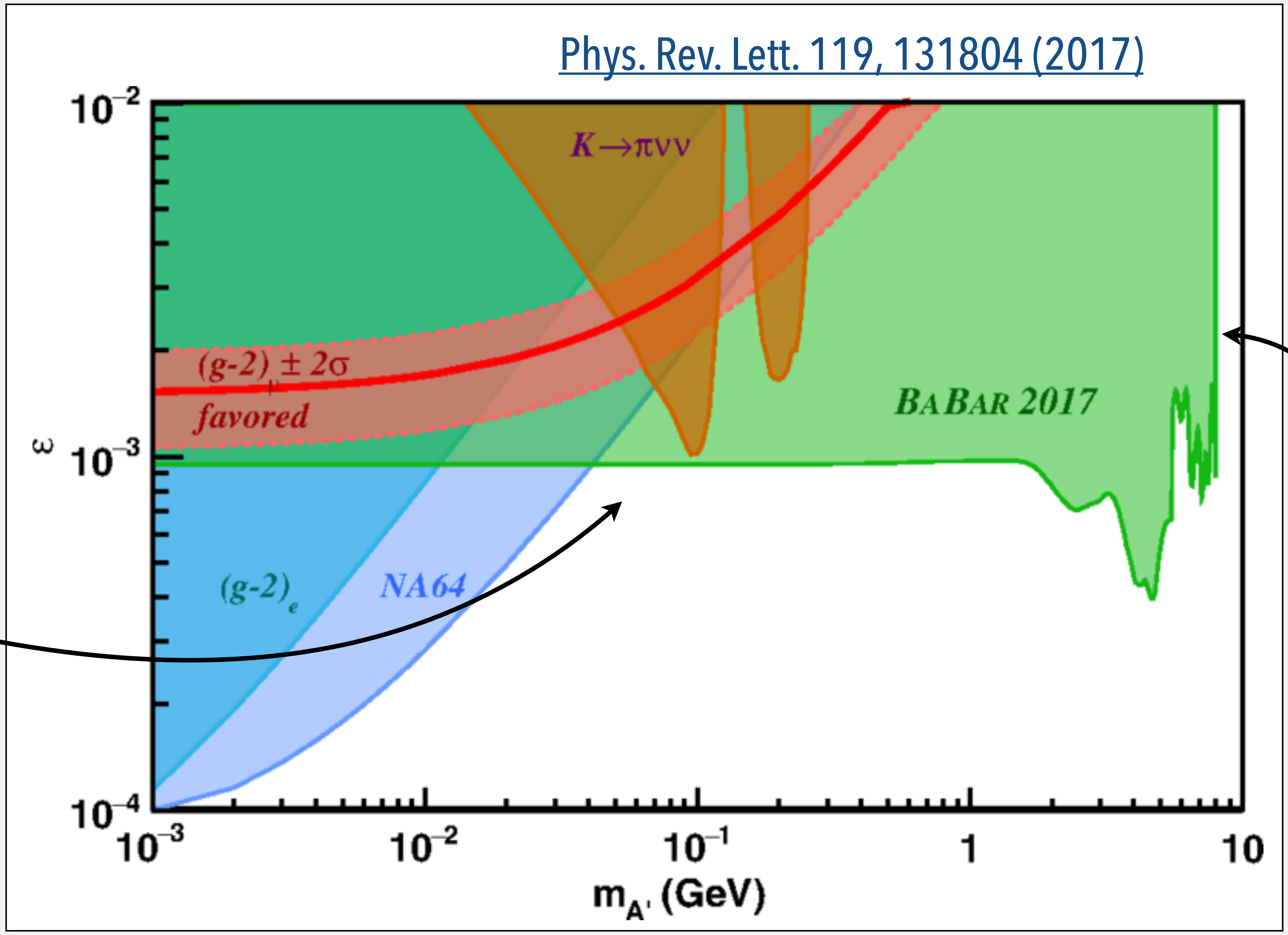
- asymmetric e^+/e^- collider at Υ(nS) resonances (~10 GeV)



need **single photon** trigger!

- implemented for final running period
  - 53/fb with "low mass" trigger (high energy)
  - 35.9/fb with "high mass"trigger (low energy)

$$E_\gamma = \frac{s - m^2_{A'}}{2\sqrt{s}}$$



cannot resolve different masses

limited by beam energy & trigger threshold

Belle II

@SuperKEKB

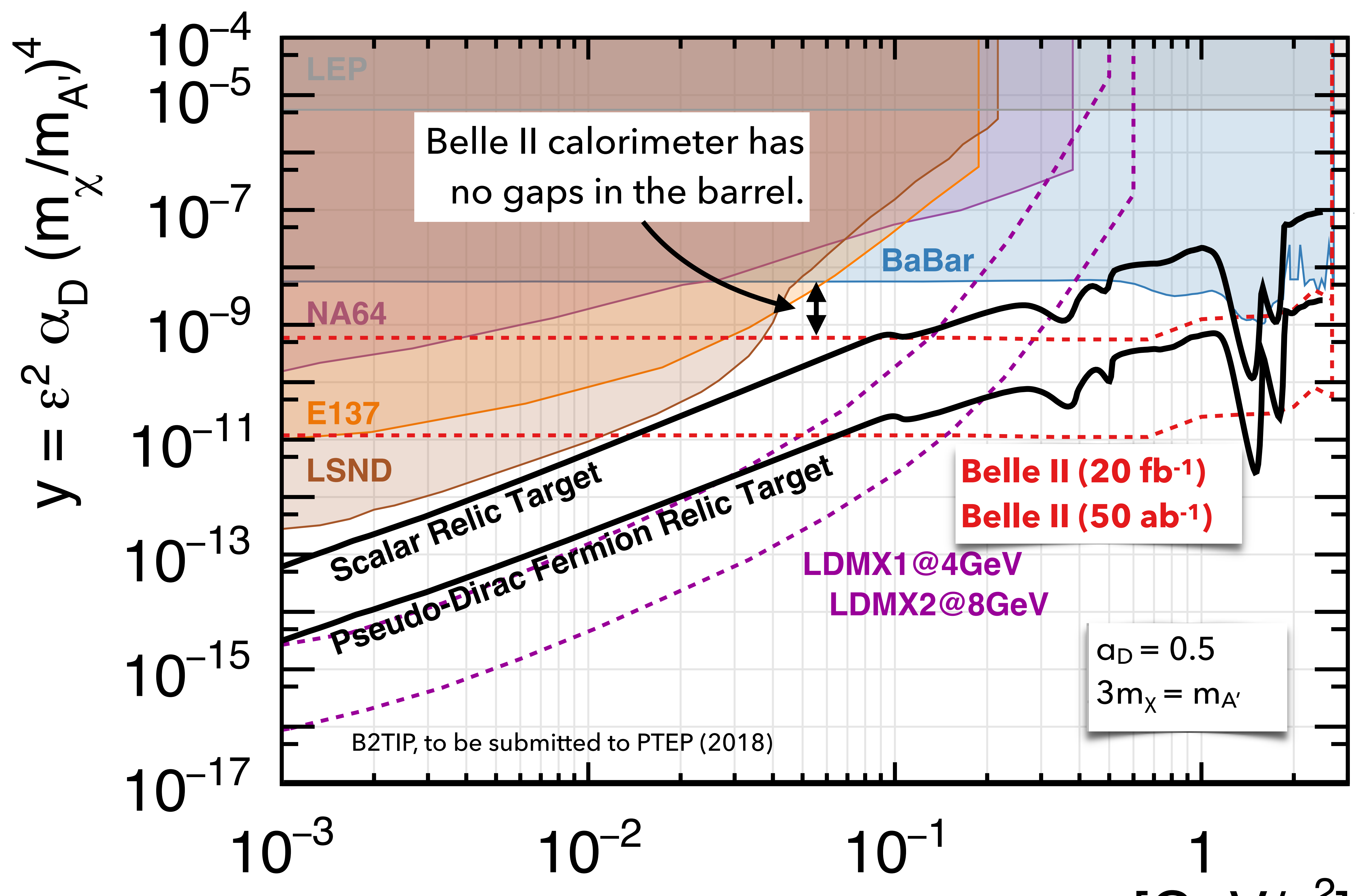
- e^+/e^- collider at 4.0/7.0 GeV (10.57 GeV)

Phase 2 data taking finished July 17th

- >0.5/fb collected

superior sensitivity for $m_\chi \geq O(100)$ GeV

projected sensitivity



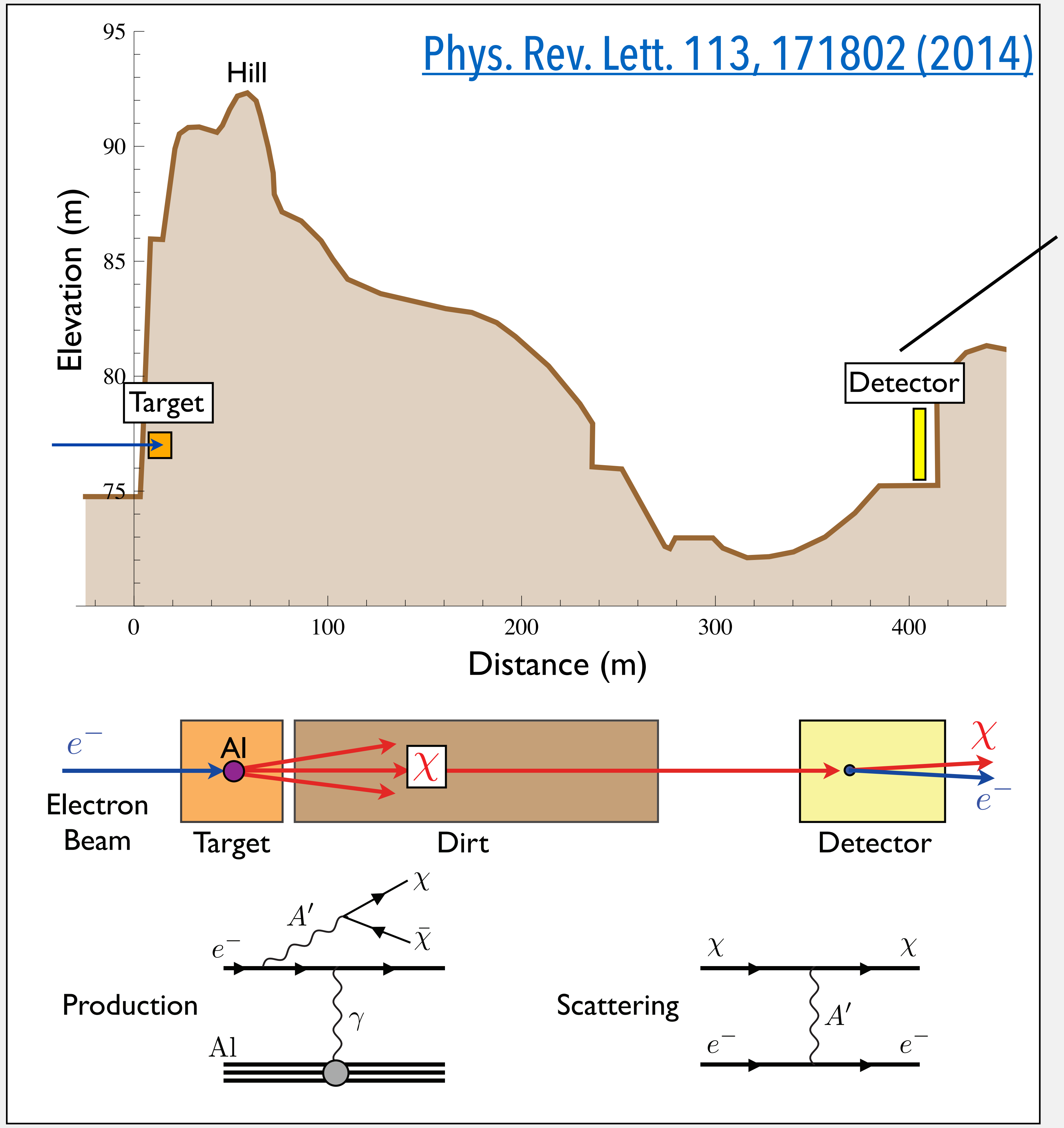
talk by T. Ferber at DM@LHC

Beam Dump Experiments

Electron Beam Dump

reanalysis of E137 data (1988), "proof of principle"

- search for neutral metastable penetrating particles
- 20 GeV electrons on SLAC beam dump, total of 2x10^{20} EoT



electromagnetic calorimeter

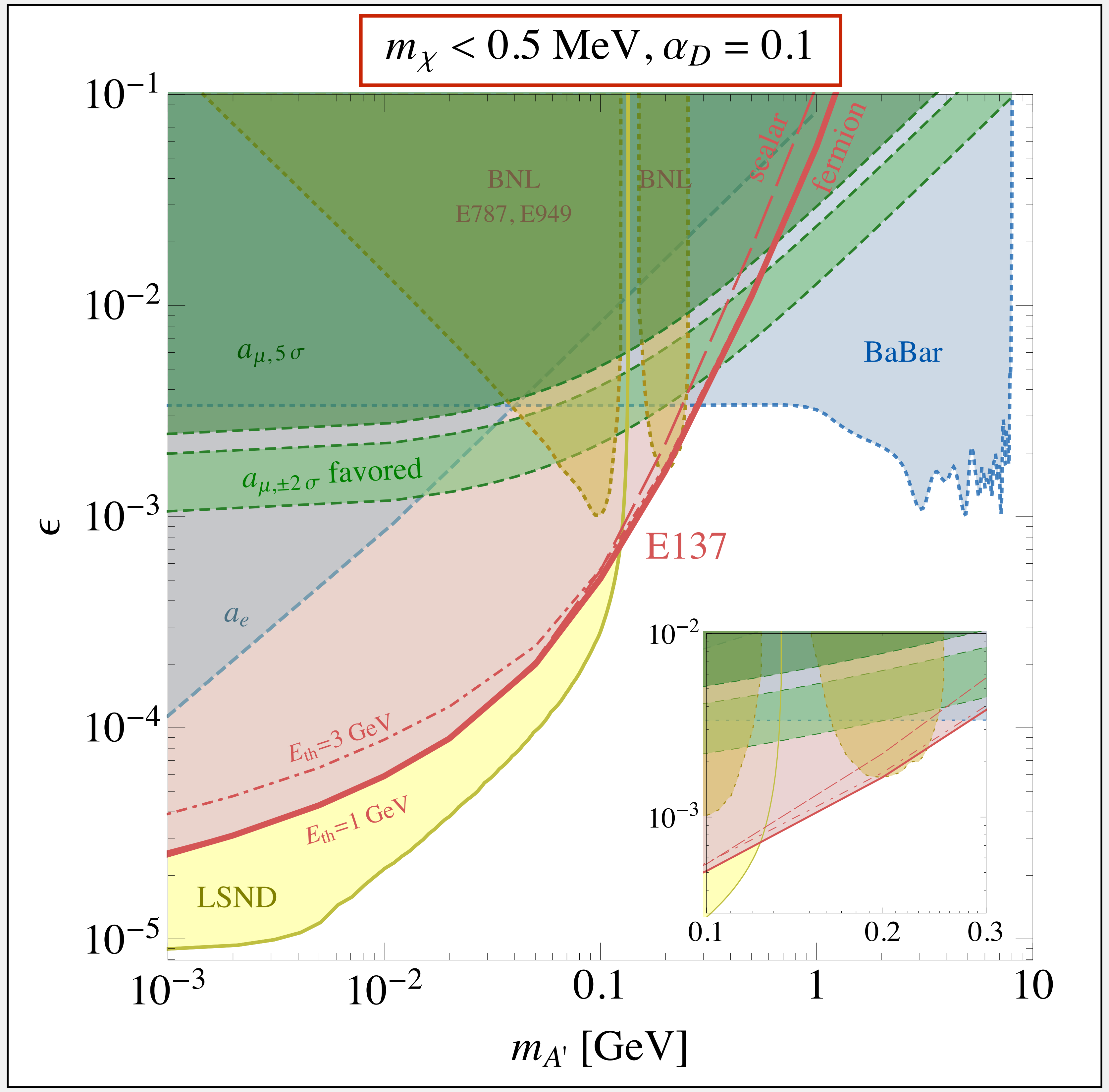
look for shower with:

- E > 1 GeV
- pointing back to dump

0 observed —> N_{95} = 3

Phys. Rev. D 38, 3375 (1988)

different parameter choice

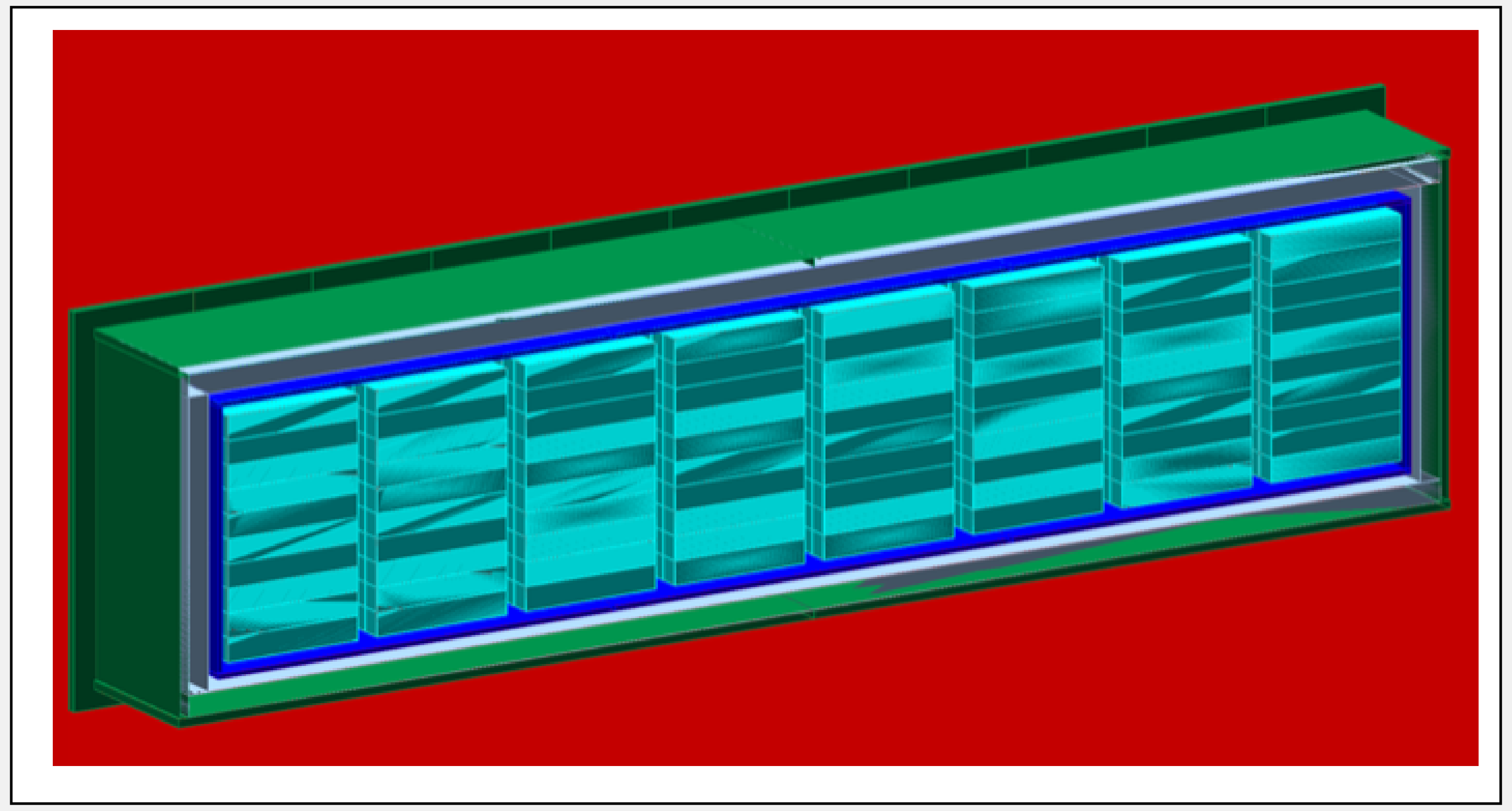


Phys. Rev. Lett. 113, 171802 (2014)

Electron Beam Dump

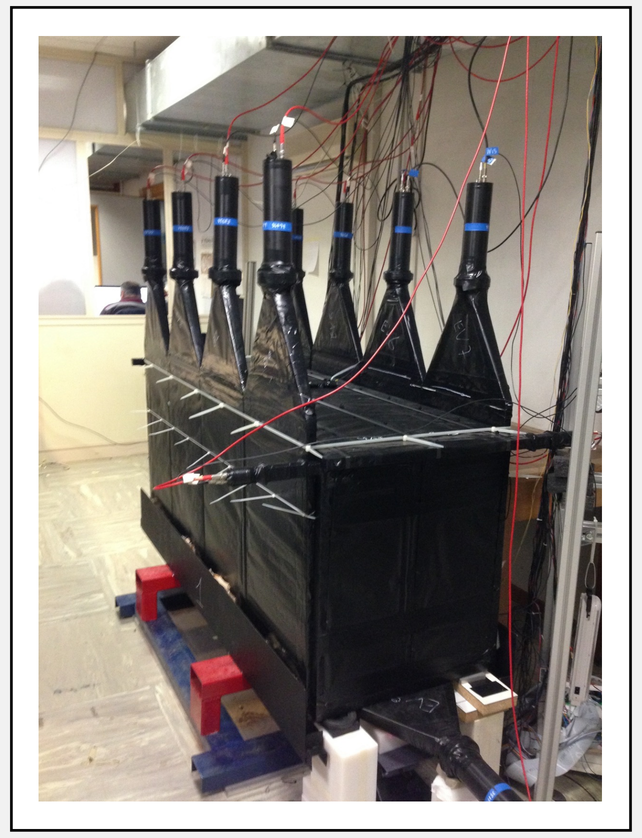
BDX - Beam Dump eXperiment [arxiv:1607.01390]

- **first** *dedicated* (electron) beam-dump experiment for LDM search
- conditionally approved for 41 weeks (~10^{22} EoT) @ 11 GeV (JLab)



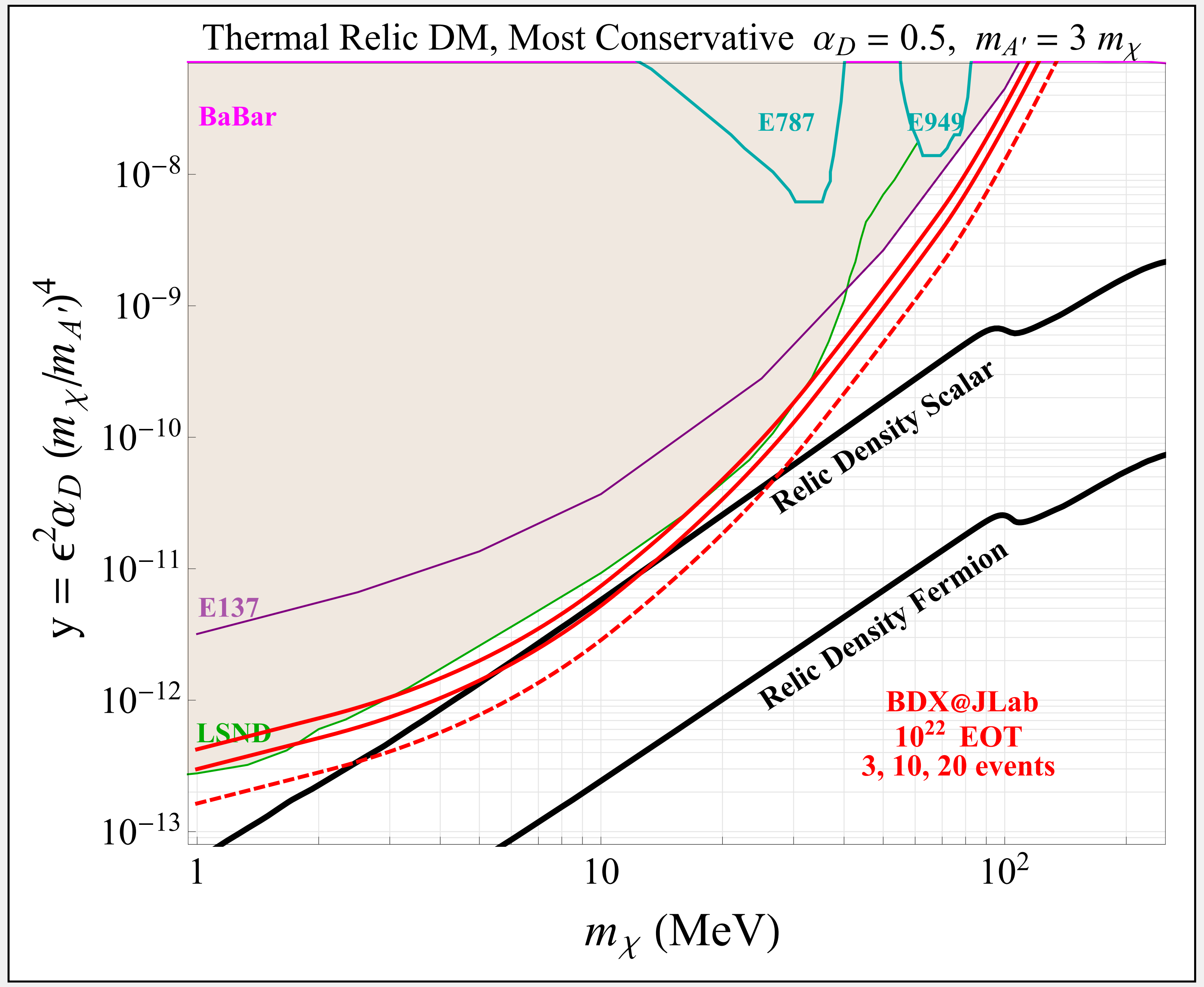
active veto sandwich
- inner & outer
- plastic scintillators

passive veto
- 5cm lead bricks



2 prototypes
- measured cosmic and beam background
- validated MC simulations and cosmic estimates

electromagnetic calorimeter
- CsI(Tl) crystals (from *Babar*) + SiPM readout
- measure ~GeV shower from X-e scattering
- ~MeV signal from inelastic X-nucleon scattering



300 MeV threshold

ultimately limited by irreducible neutrino background
- ~10 events in BDX life time

Proton Beam Dump

experiments with promising sensitivity Phys. Rev. D 95, 035006 (2017)

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

see dedicated talk in this session

+ several other current/future neutrino experiments

different production modes

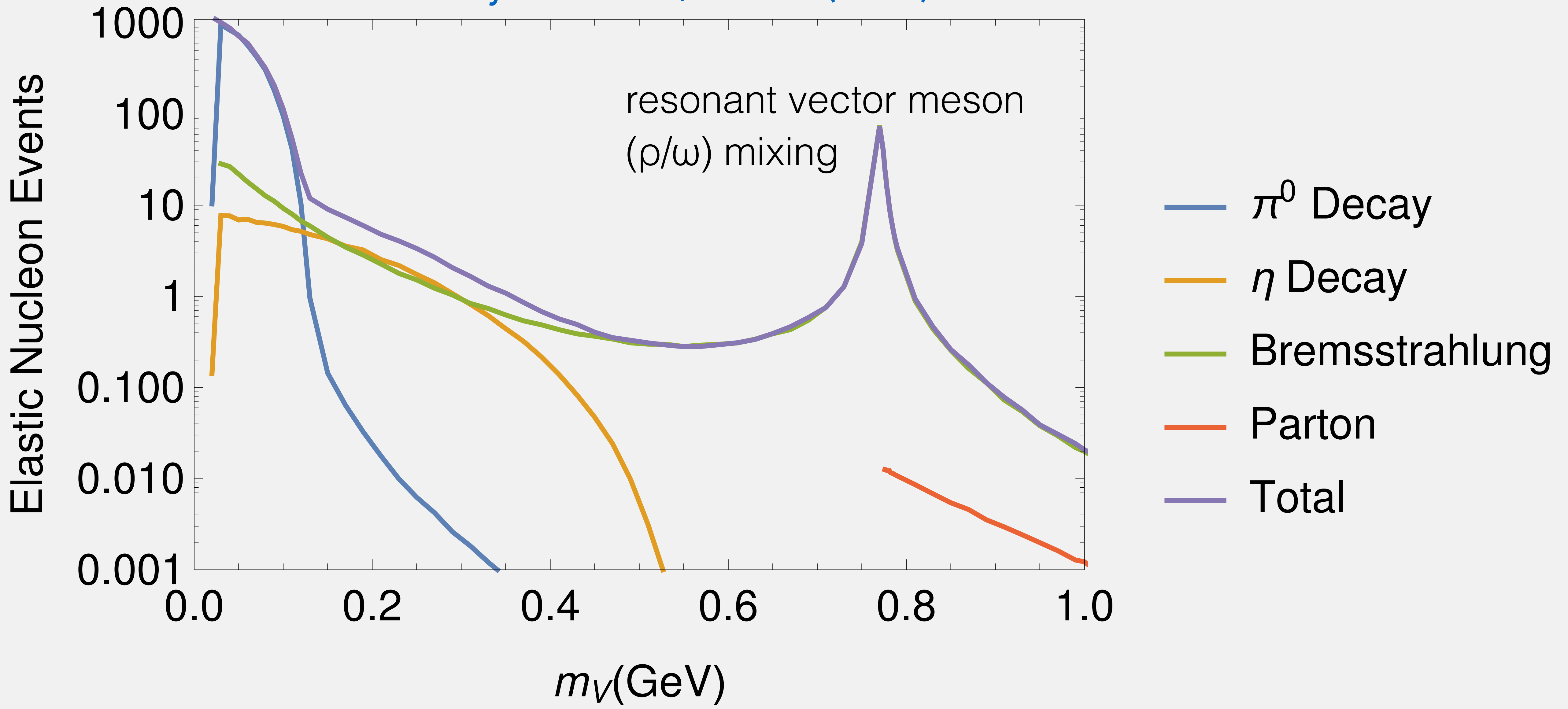
- radiative meson decay (low mass)
- bremsstrahlung with resonant mixing (intermediate mass)
- direct production (masses >1 GeV)

$$q\bar{q} \rightarrow A' \rightarrow \chi\bar{\chi}$$

generally “messier" —> higher beam backgrounds

MiniBooNE, 9 GeV

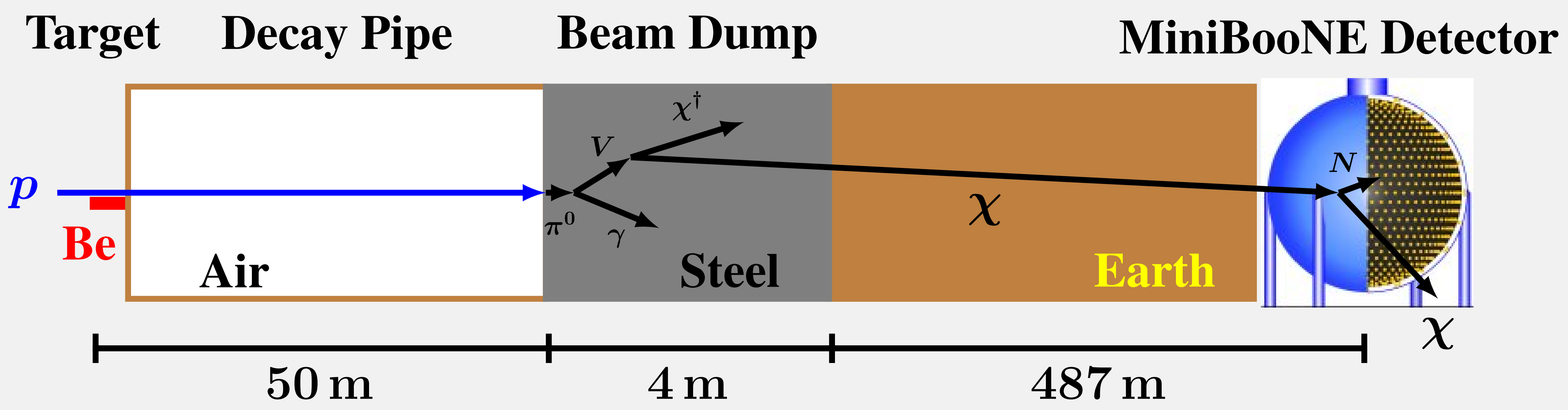
Phys. Rev. D 95, 035006 (2017)



MiniBooNE Search

dedicated run in 'beam-dump mode':

- Nov 2013 - Sep 2014, 1.86 x 10^{20} PoT, 8 GeV proton beam
- first dedicated DM search in proton beam-dump experiment
- well-understood experiment! (>10 years of operation)



12m diameter sphere

800t mineral oil CH_2 (450t fiducial)

~1300 PMTs to detect Cherenkov light

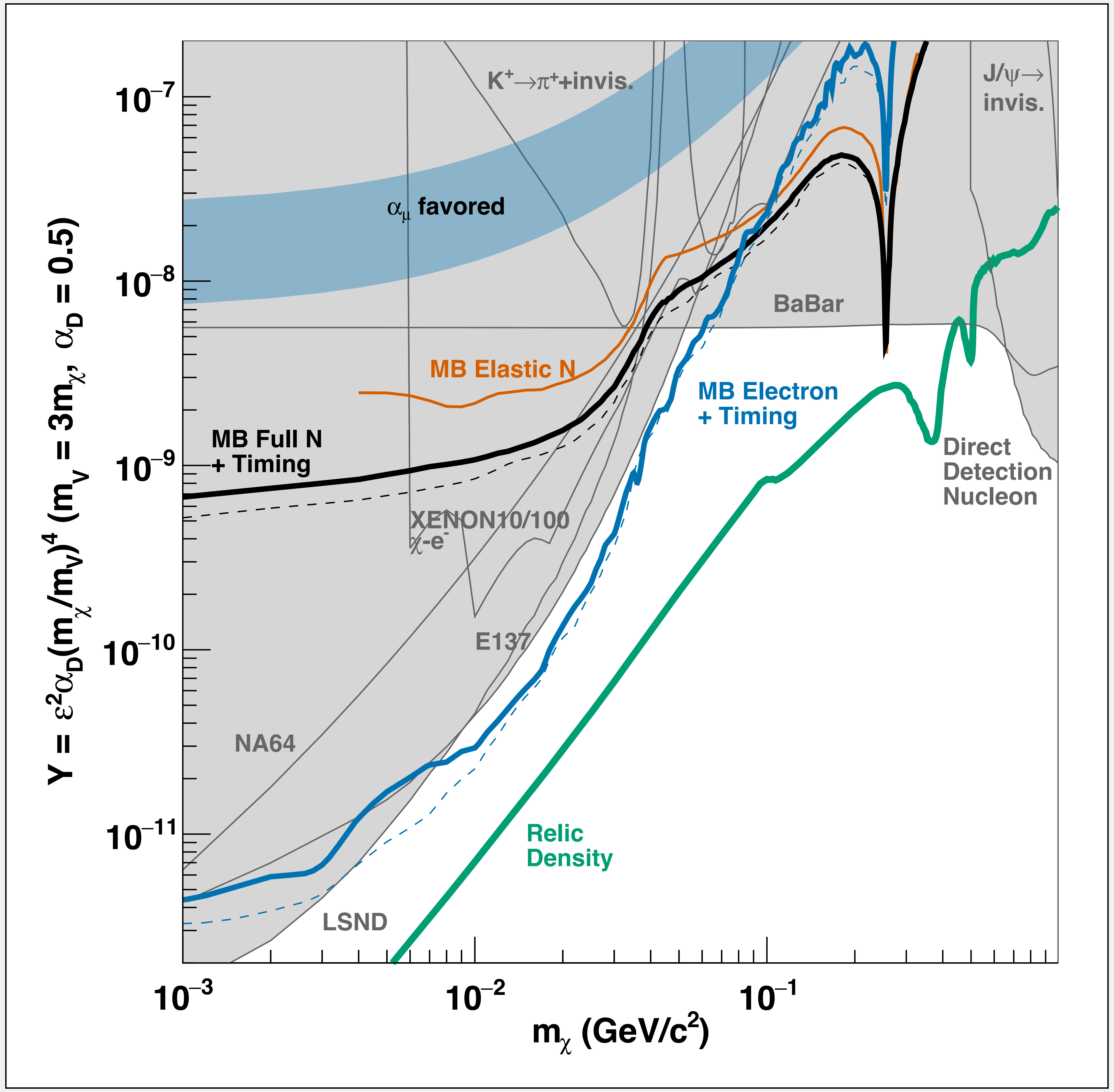
refined analysis published recently, additionally including

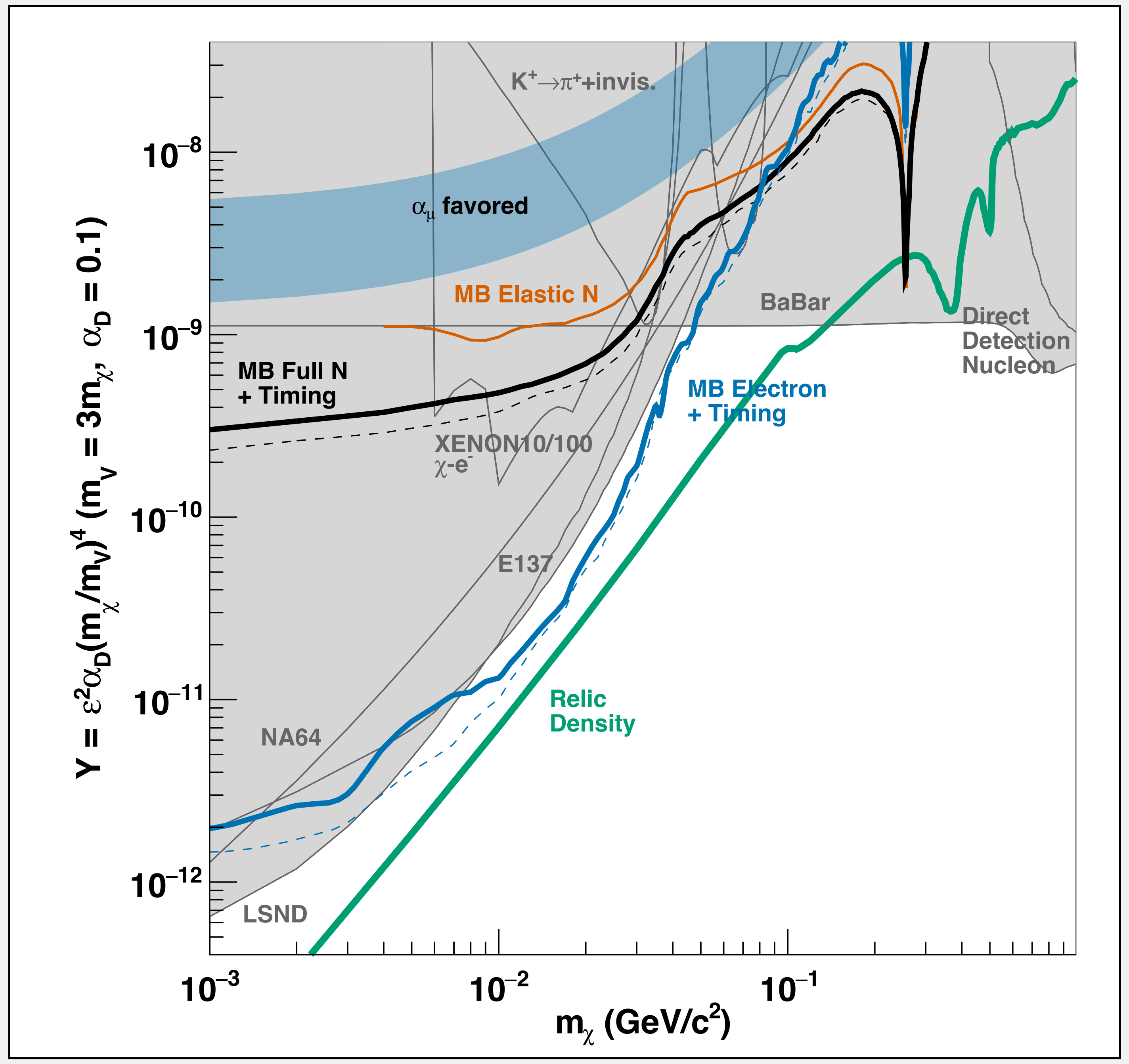
- neutral pion channel
- elastic electron scattering
- "time-of-flight"

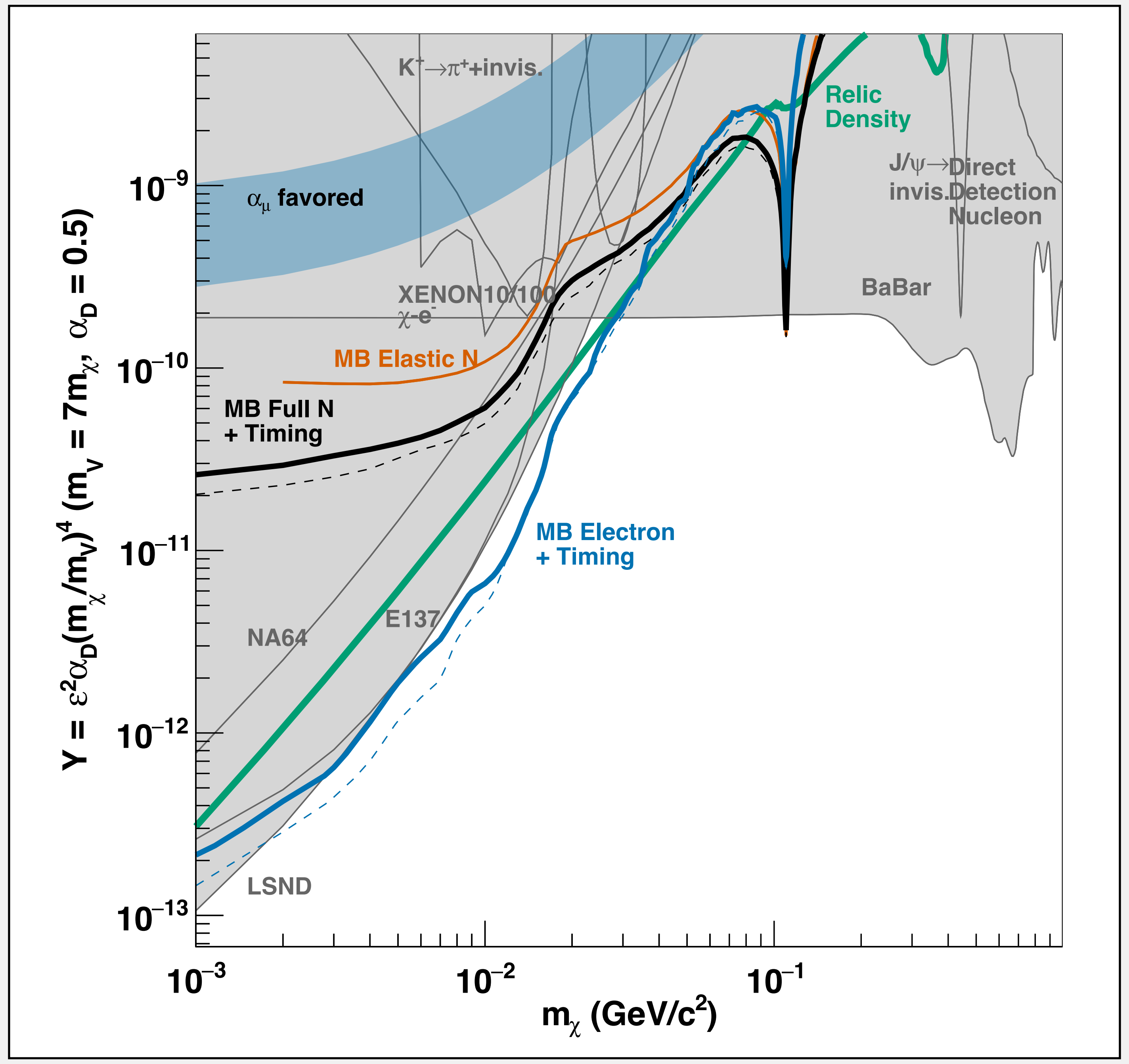
arxiv:1807.06137

MiniBooNE Results

arxiv:1807.06137







further increase in sensitivity requires special beam dump target, EoI received positive feedback from FNAL PAC

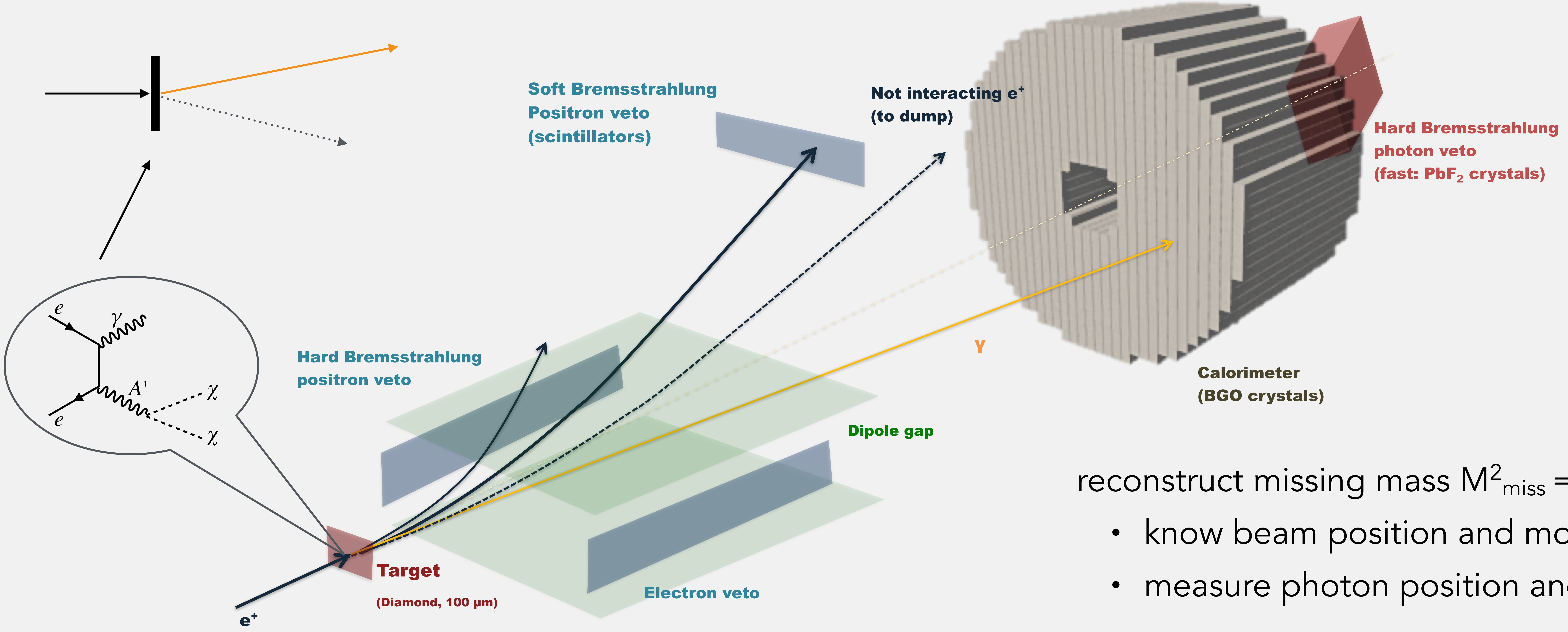
Fixed Target Experiments

PADME — Missing Mass

(positron annihilation into DM experiment)

550 MeV e^+ beam at DAΦNE beam test facility @ INFN

- first to look for annihilation in target —> single photon + nothing
- minimal assumption: some coupling of A' to electrons



reconstruct missing mass $M^2_{miss} = (p_{e+} - p_\gamma)^2$

- know beam position and momentum
- measure photon position and energy

clean environment due to vacuum chamber

PADME Projected Sensitivity

commissioning started in spring 2018,

data taking to start in September

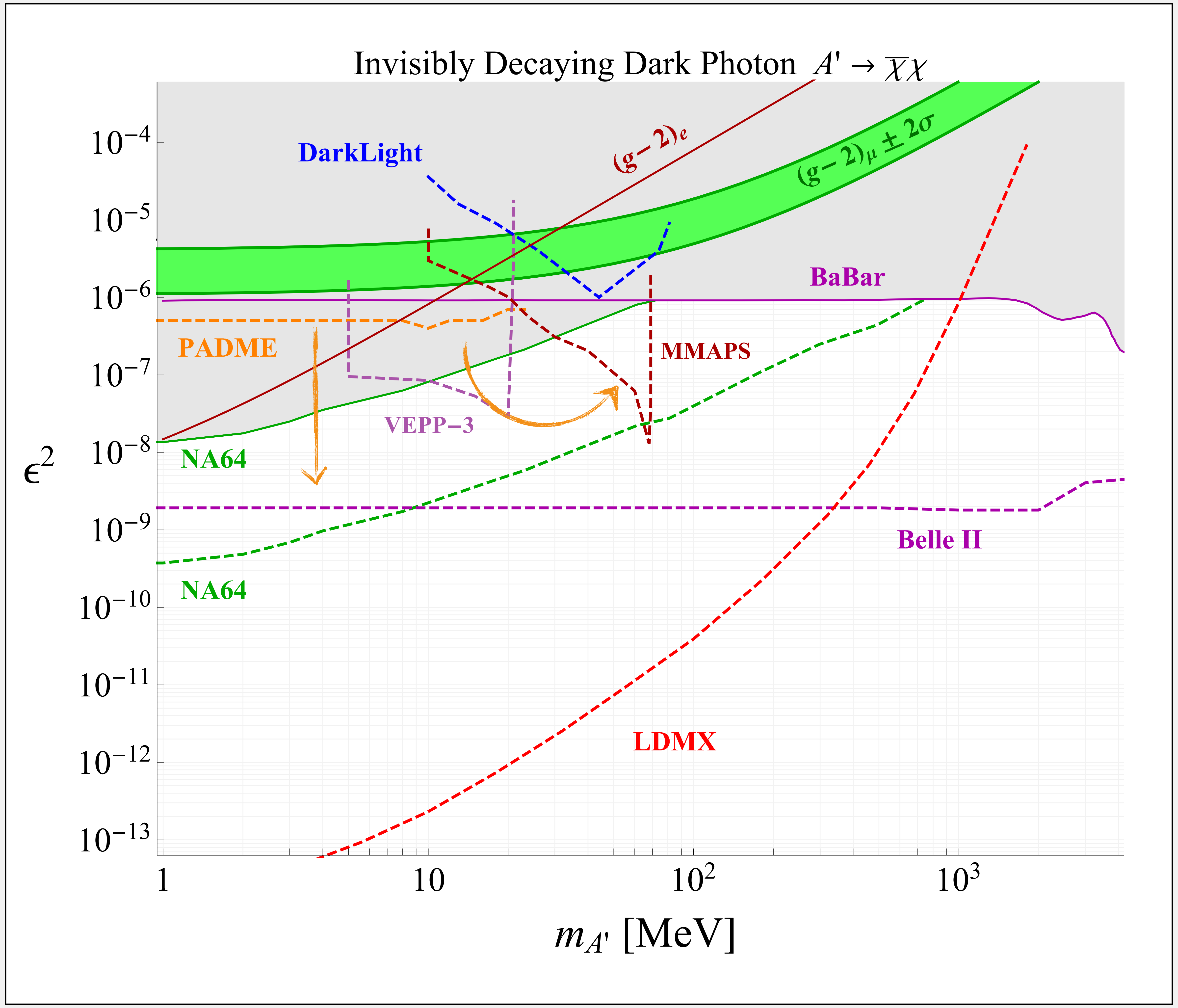
- sensitivity for 1-4 x 10^{13} positrons on target

sensitivity limited by duty factor (10^{-5})

- can potentially be improved by factor 2000@DAΦNE arxiv:1711.06877

mass reach (24 MeV) limited by beam energy

- proposal to move PADME to Cornell
  - 6 GeV beam energy —> $m_{A'}$ < 78 MeV
  - similar to MMAPS@Cornell
  - could run in early 2020s



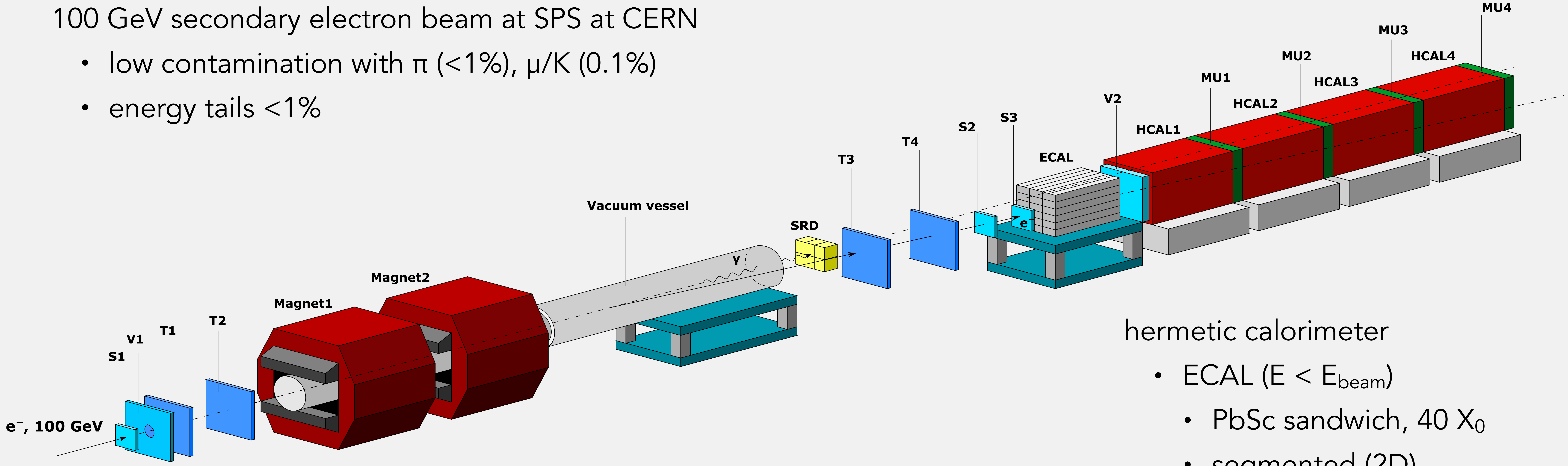
plans for a similar experiment in Novosibirsk (VEPP) — PADME just the first of a family of such experiments?

NA64 — Missing Energy

poster this afternoon!

100 GeV secondary electron beam at SPS at CERN

- low contamination with π (<1%), μ/K (0.1%)
- energy tails <1%



hermetic calorimeter

- ECAL ($E < E_{beam}$)
  - PbSc sandwich, 40 X_0
  - segmented (2D)
- HCAL (veto)
  - FeSc sandwich, 7 λ/module
  - WLS fibres in spirals (reduce leakage)

e^- tagging system

- tracker (100 GeV track)
  - magnetic field 7Tm
- synchrotron radiation detector (SRD)
  - particle ID (SR emission ~$1/m^4$)

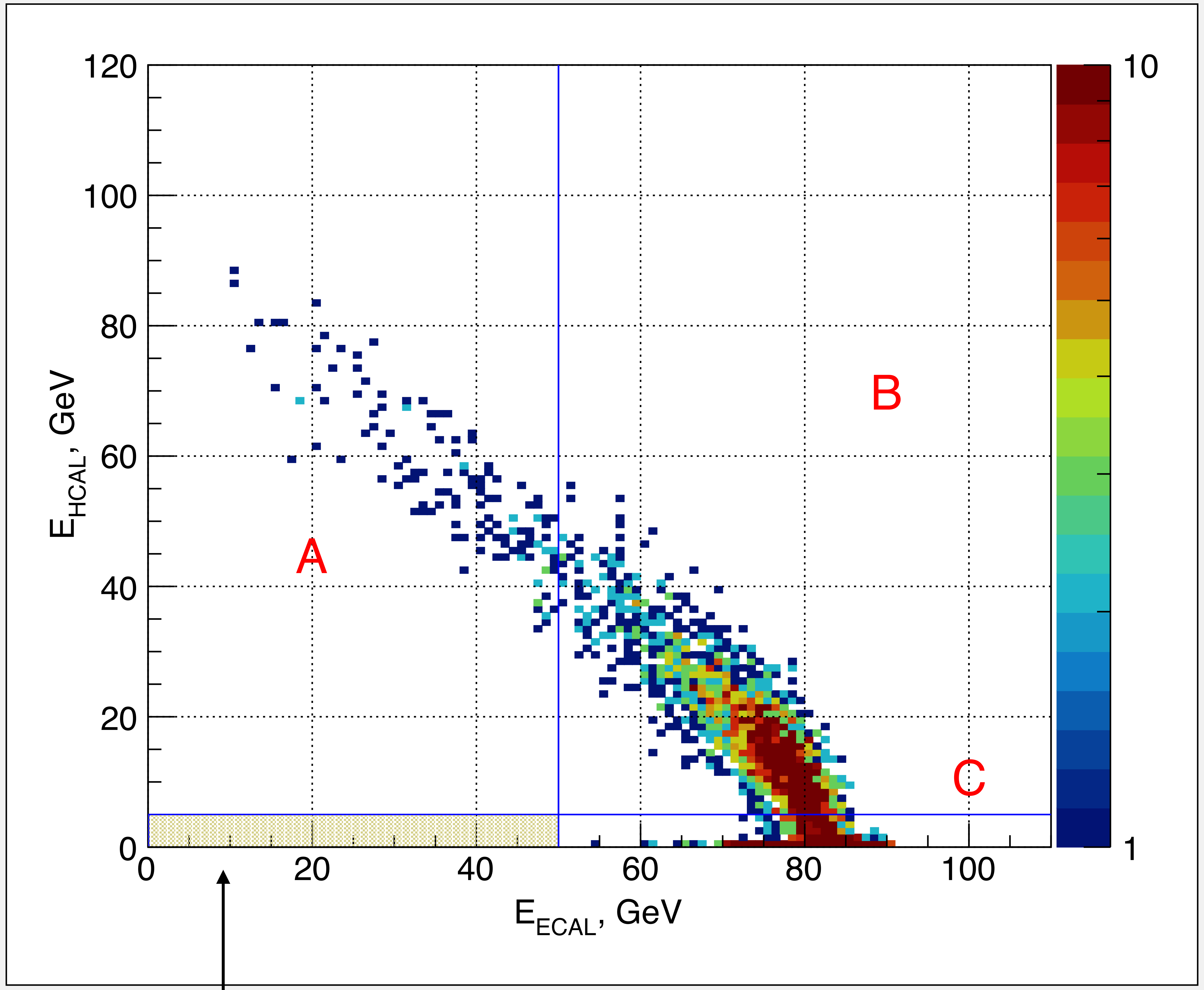
NA64 Results

poster this afternoon!

runs for invisible signature

- 2016: 4.3 x 10^{10} EoT [Phys. Rev. D 97, 072002 (2018)]
- 2017: 5.0 x 10^{10} EoT [analysis close to completion]
- 2018: ~2 x 10^{11} EoT [first results early 2019]

Background source	Estimated number of events, n_b
hermeticity: punchthrough γ's, cracks, holes	< 0.001
loss of hadrons from $e^- Z \to e^- + hadrons$	< 0.001
loss of muons from $e^- Z \to e^- Z\gamma; \gamma \to \mu^+\mu^-$	0.005 ± 0.001
$\mu \to e\nu\nu$, π, $K \to e\nu$, K_{e3} decays	0.02 ± 0.004
e^- interactions in the beam line materials	0.09 ± 0.03
μ, π, K interactions in the target	0.008 ± 0.002
accidental SR tag and e^- from μ, π, K decays	< 0.001
Total n_b	$\boxed{0.12 \pm 0.04}$



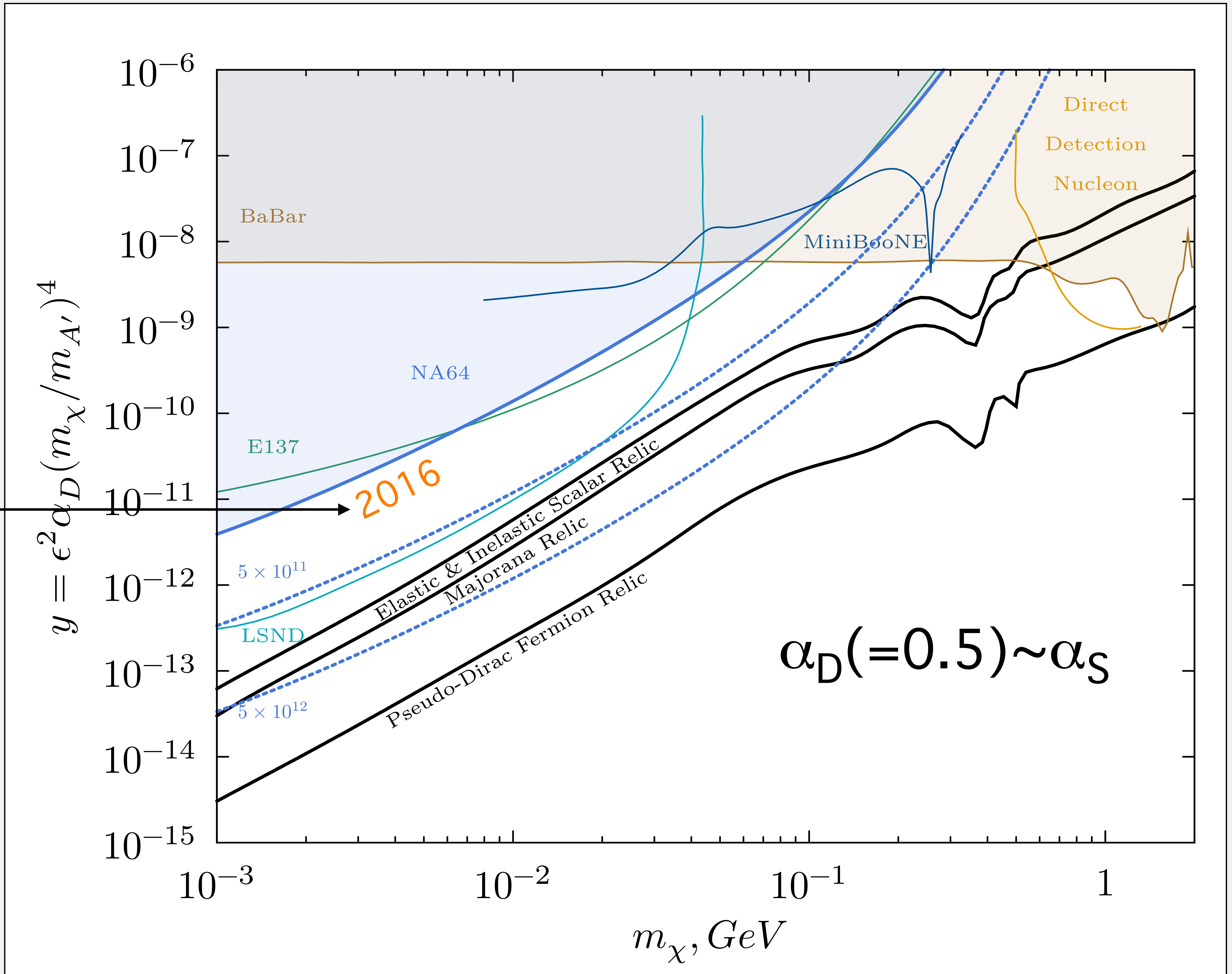
signal region (scaled up by 50 in y-direction)

NA64 Sensitivity

poster this afternoon!

exclusion bounds and projections

[Phys. Rev. D 97, 072002 (2018)]



[Report at SPSC, June 2018]

approved for running in 2021

target: another 3 x 10^{11} EoT

upgrade 2019/20 to tracker, ECal, electronics

—> improved performance at higher beam intensities

LDMX — Missing Momentum

(Light DM eXperiment)

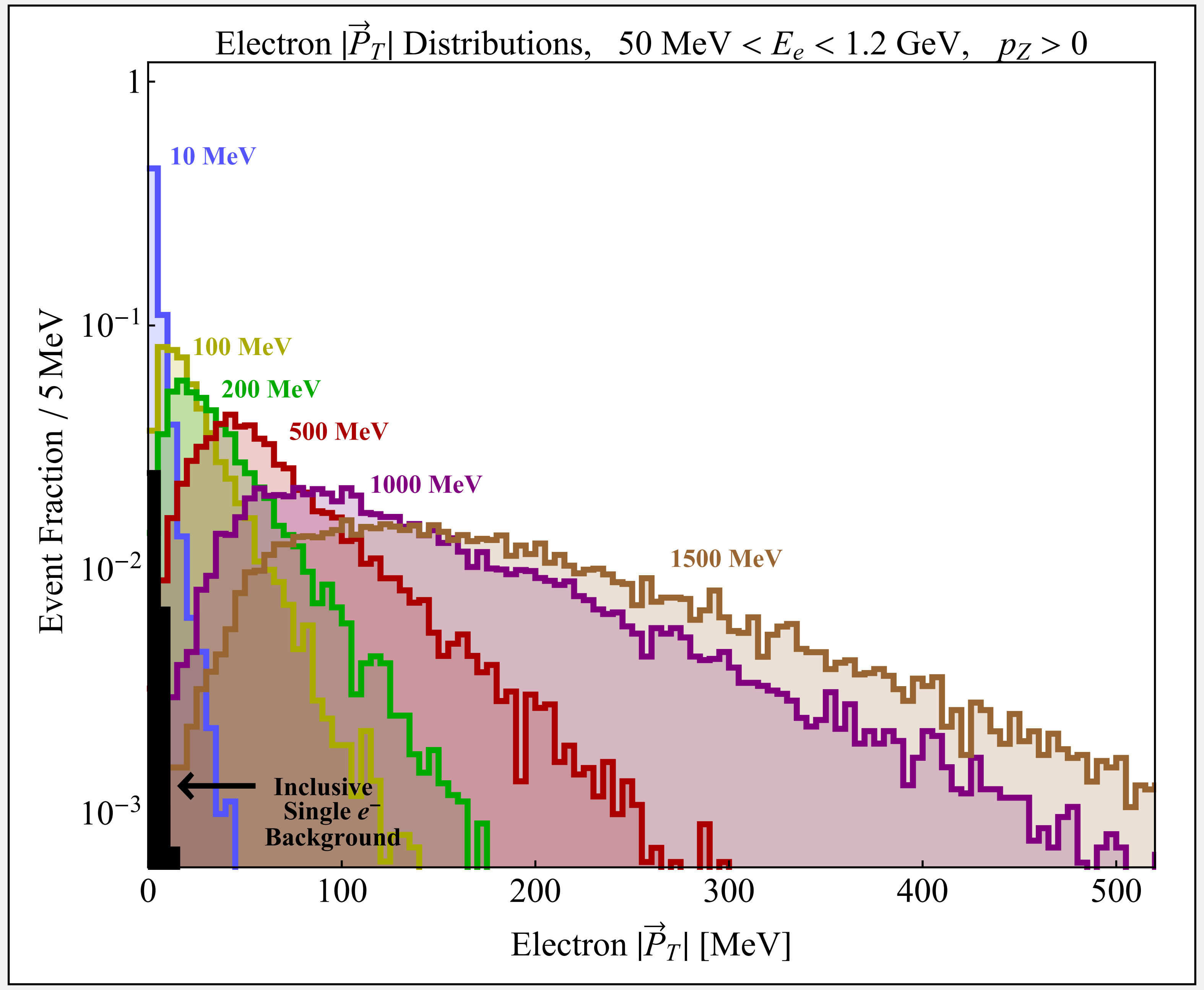
multi-GeV electron beam, not approved yet

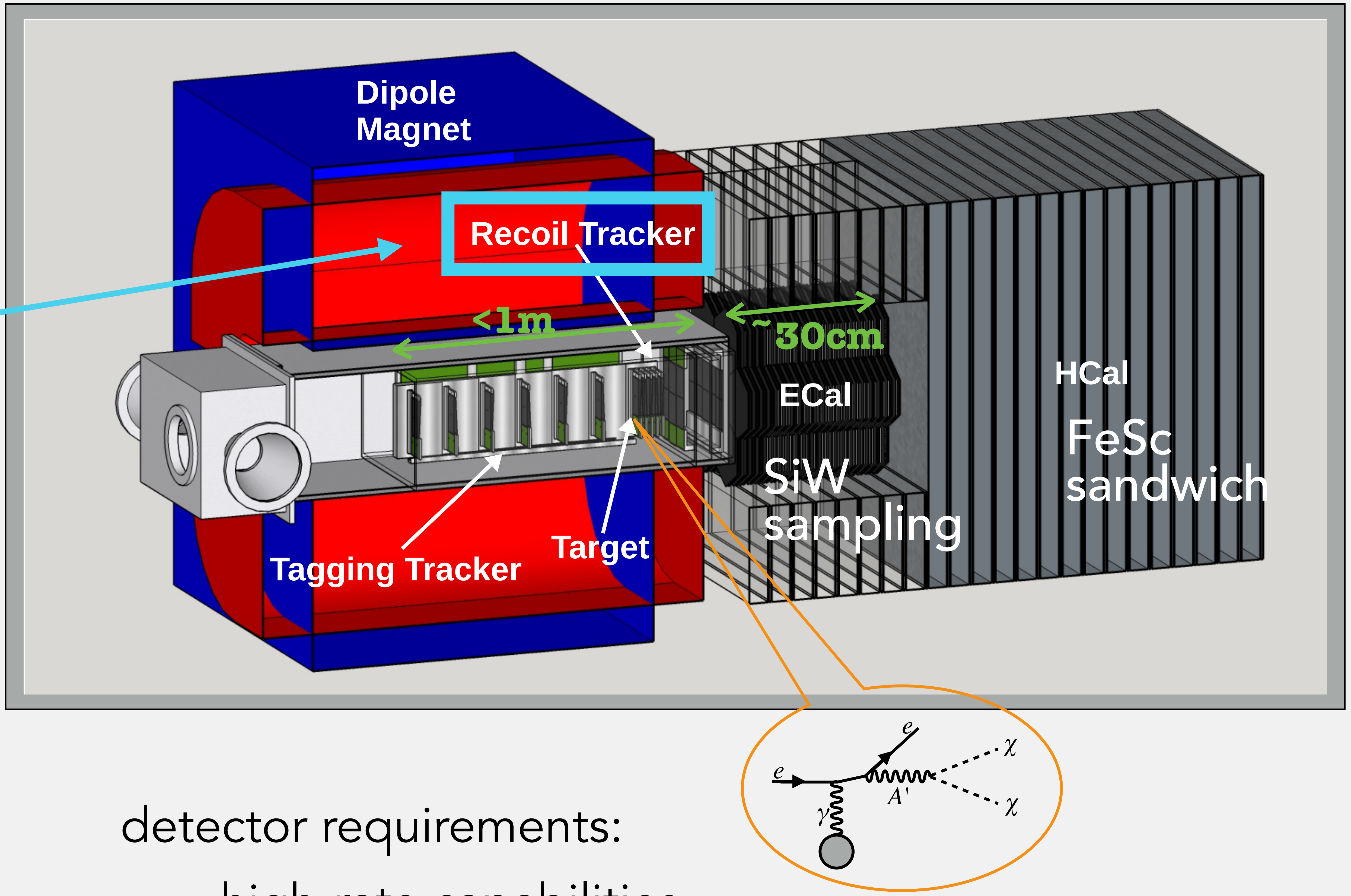
(default: 4/8 GeV@SLAC, parasitic at LCLS-II)

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

measure **missing momentum** (and energy)

- powerful additional handle





detector requirements:

- high-rate capabilities
- radiation hard

—> fast, low-mass tracking

—> fast, radiation hard, granular ECAL

—> efficient HCAL (veto)

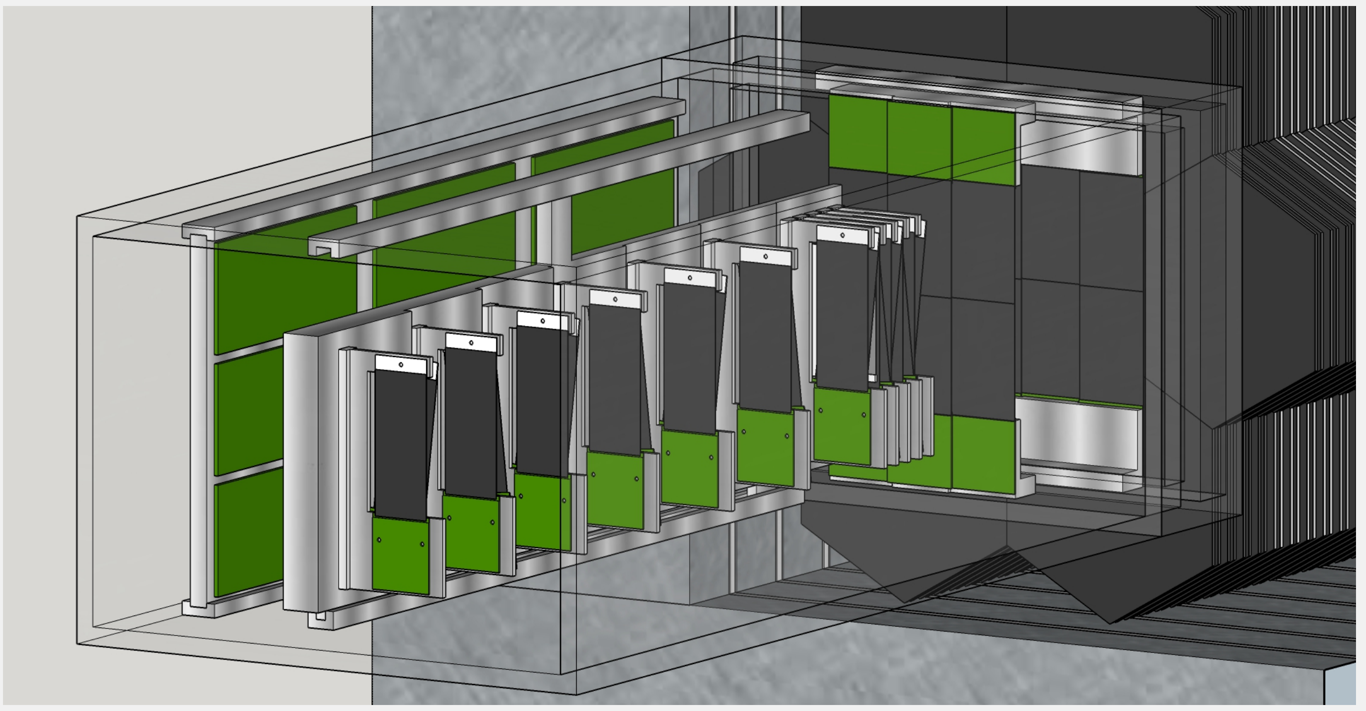
design paper new on arxiv! arxiv:1808.05219

LDMX Detector Design

leveraging techniques from existing/planned experiments

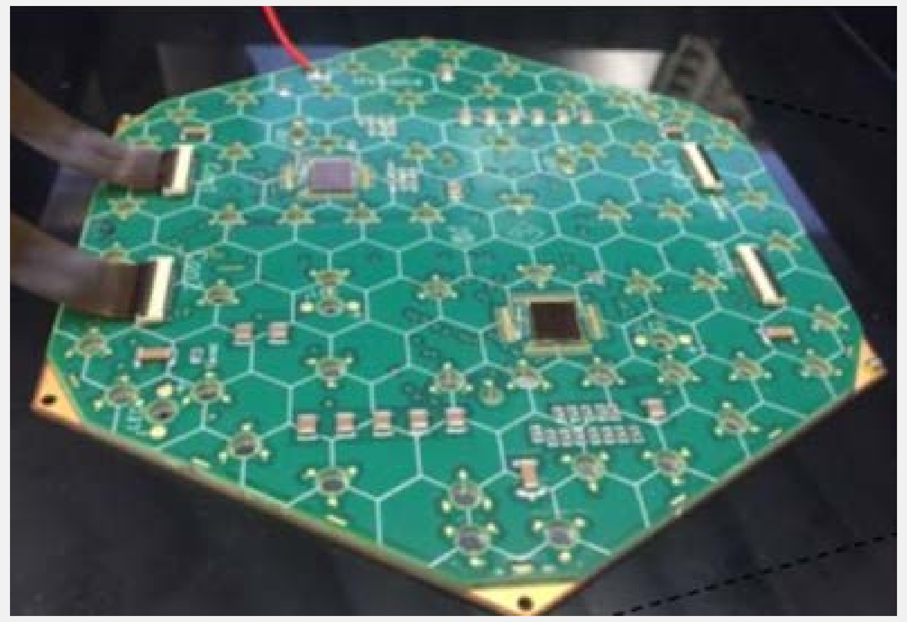
tracking

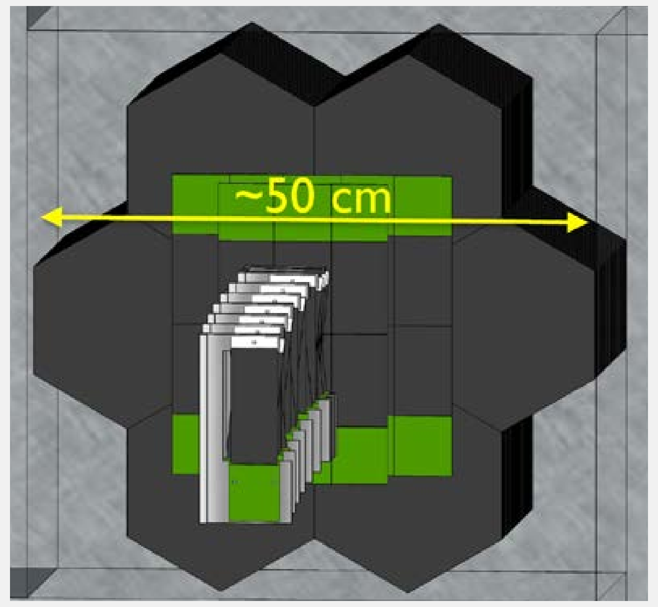
- simplified copy of Silicon Vertex Tracker (SVT) of HPS experiment@JLab (visible Dark Photon search)
  - fast (2ns hit time resolution)
  - radiation hard
  - technology well understood



ECal

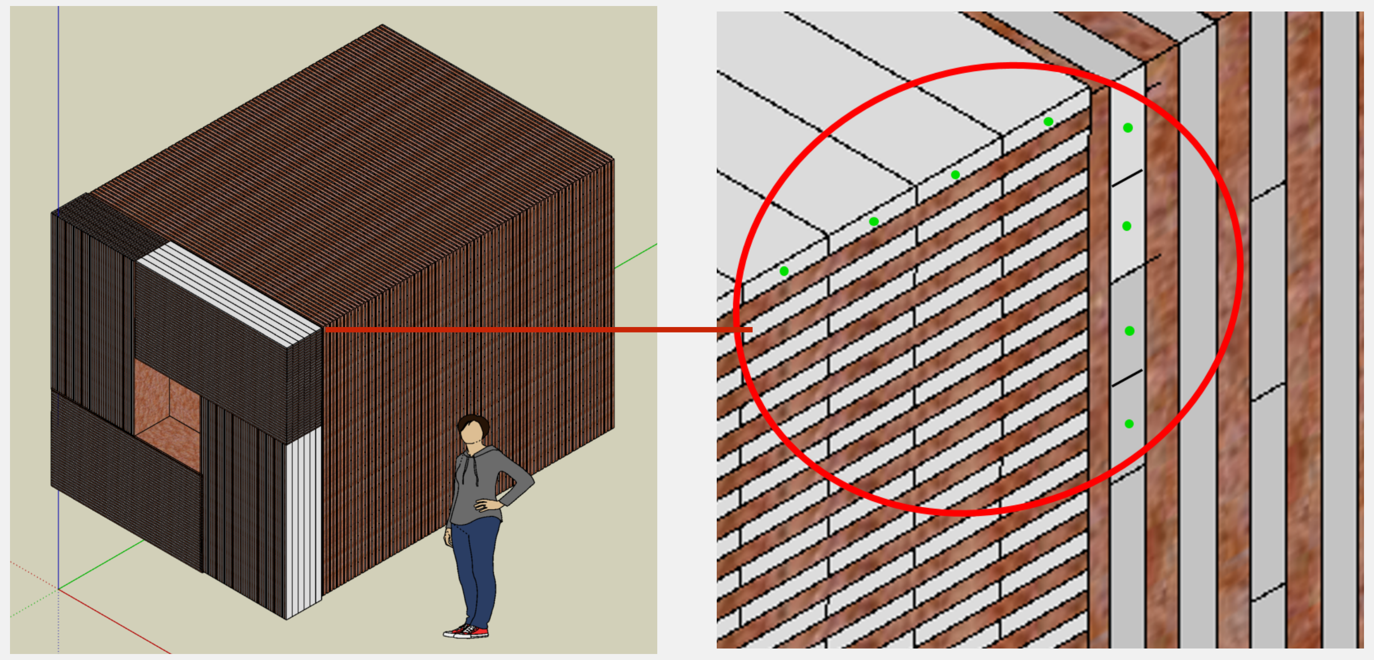
- draw on design of CMS forward SiW calorimeter upgrade
  - 32 layers with 7 modules each, 40 X_0
  - fast, radiation hard, dense
  - high granularity (MIP 'tracking')



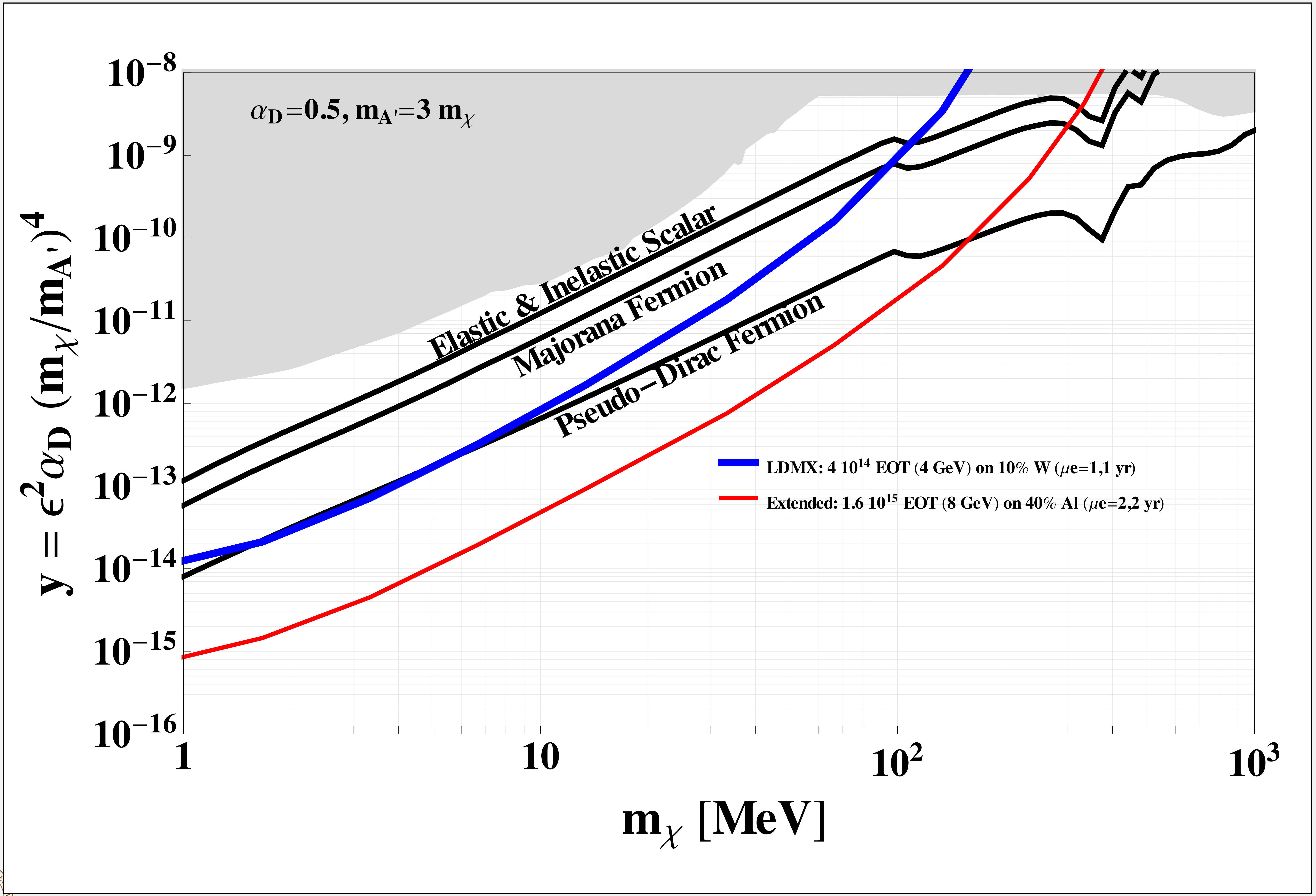


HCal

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



Projected Sensitivity



LDMX can explore a lot of new parameter space

sensitive to various thermal targets already with phase 1

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

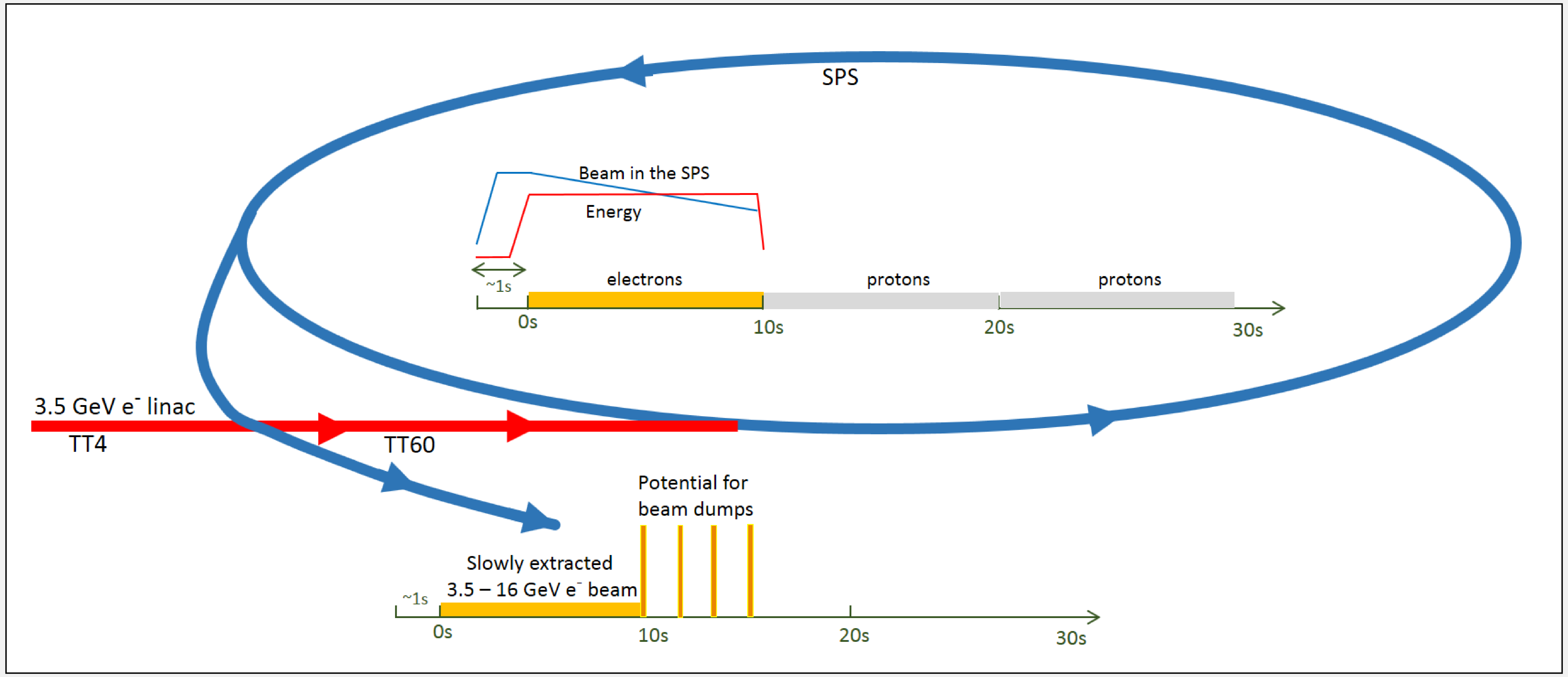
timescale: few years

A special beam…

requirements for an experiment like LDMX

- multi-GeV (ideally ~15 GeV)
- low current (resolve individual particles)
- large beam spot (separation of particles)
- high repetition rate (high integrated number of EoT)

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



- 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

Summary

broad interest in Dark Sector physics, many new initiatives

extension of DM search programme to low mass is

- well motivated!
- progressing on broad front with complementary experiments
  - new approaches in direct detection
  - various accelerator based experiments
    - different strengths/weaknesses
    - sensitive to variety of models (no time to talk about)

Thank you!

…and thanks to

Sergei Gninenko,

Venelin Kozhuharov,

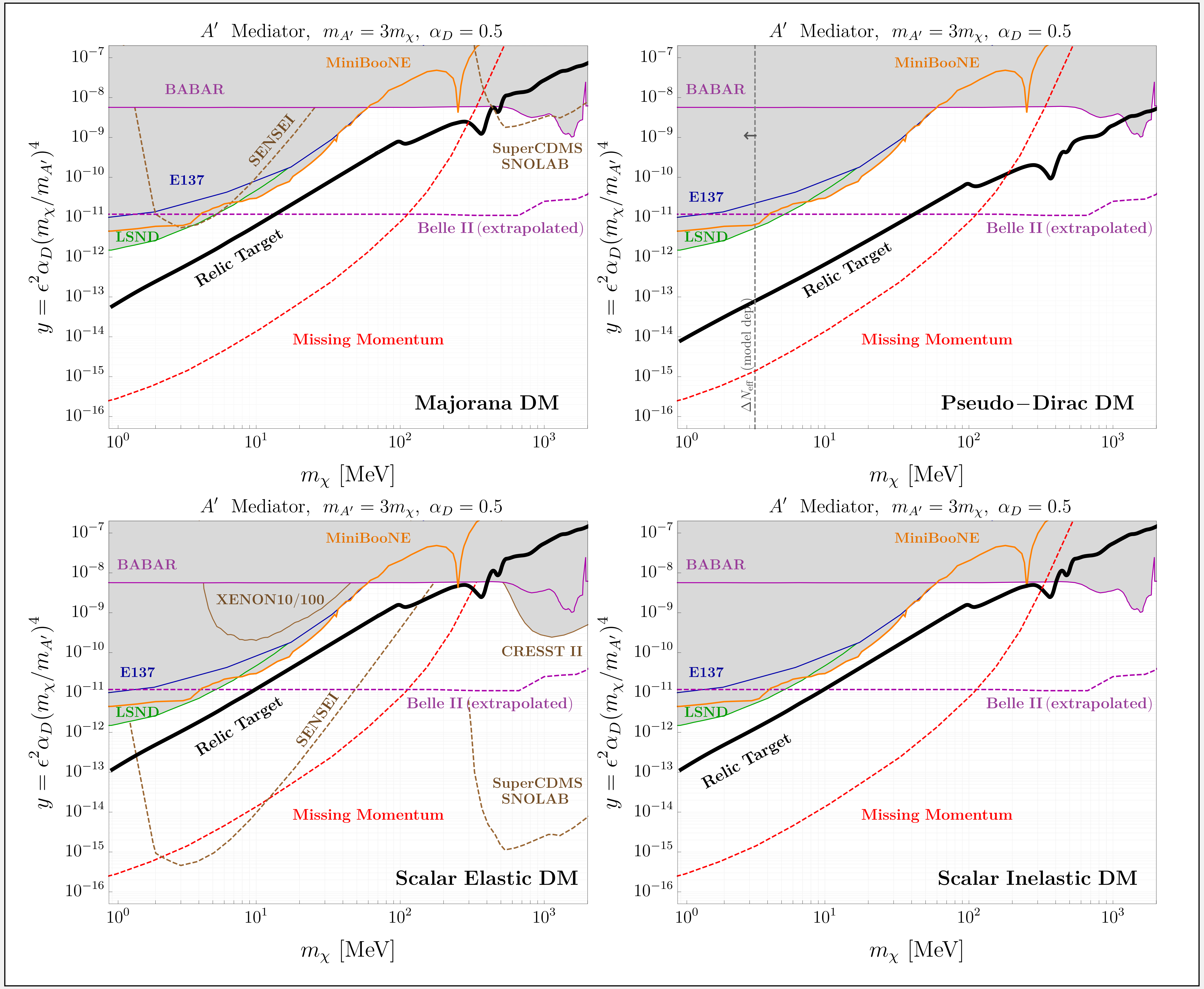
Remington Tyler Thornton

and my LDMX colleagues

for valuable input when preparing these slides

Additional Material

Various Future Projections



e-DM Scattering (Xe)

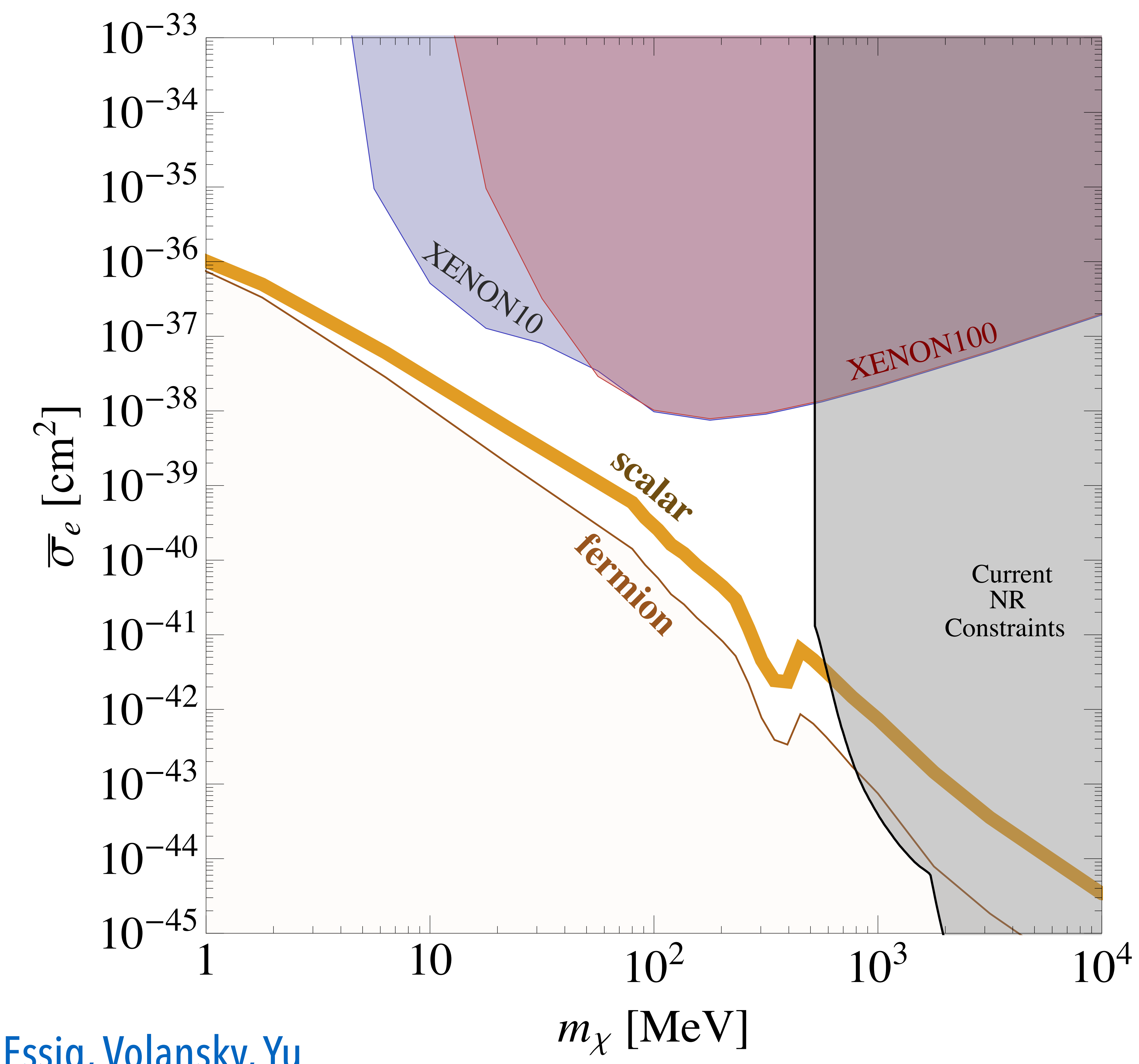
WIMP scattering ionises atom (ΔE ~ 10 eV)

- released electron can ionise further atoms
- electrons produce detectable photon signal

re-analysis of Xenon(10/100) data

[Phys. Rev. D 96, 043017 (2017)]

electron-scattering data can
cover new parameter space!



Essig, Volansky, Yu

SENSEI

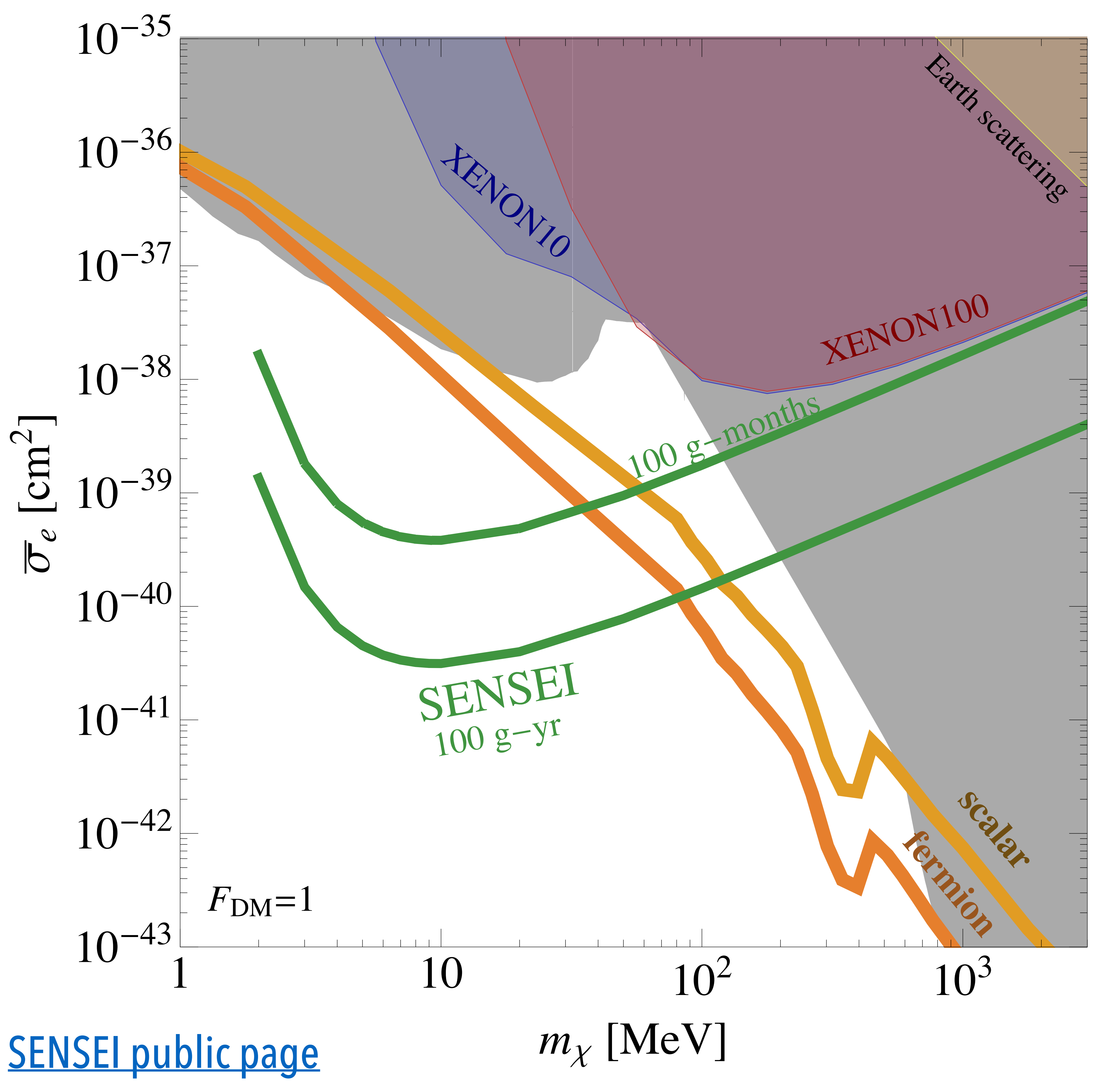
low band gap in Si: 1.1 eV

Skipper CCD as target

- readout noise dramatically reduced
- threshold ~few eV

Sub-**E**lectron-**N**oise **S**kipper CCD **E**xperimental **I**nstrument

100g detector can probe new parameter space in <<year



SENSEI public page

SENSEI

first results from low-exposure commissioning run at surface

0.019 gram-days (active mass: 0.071g)

already new parameter space explored

prototype now installed 100m underground
near MINOS experiment at FNAL

Phys. Rev. Lett. 121, 061803 (2018)