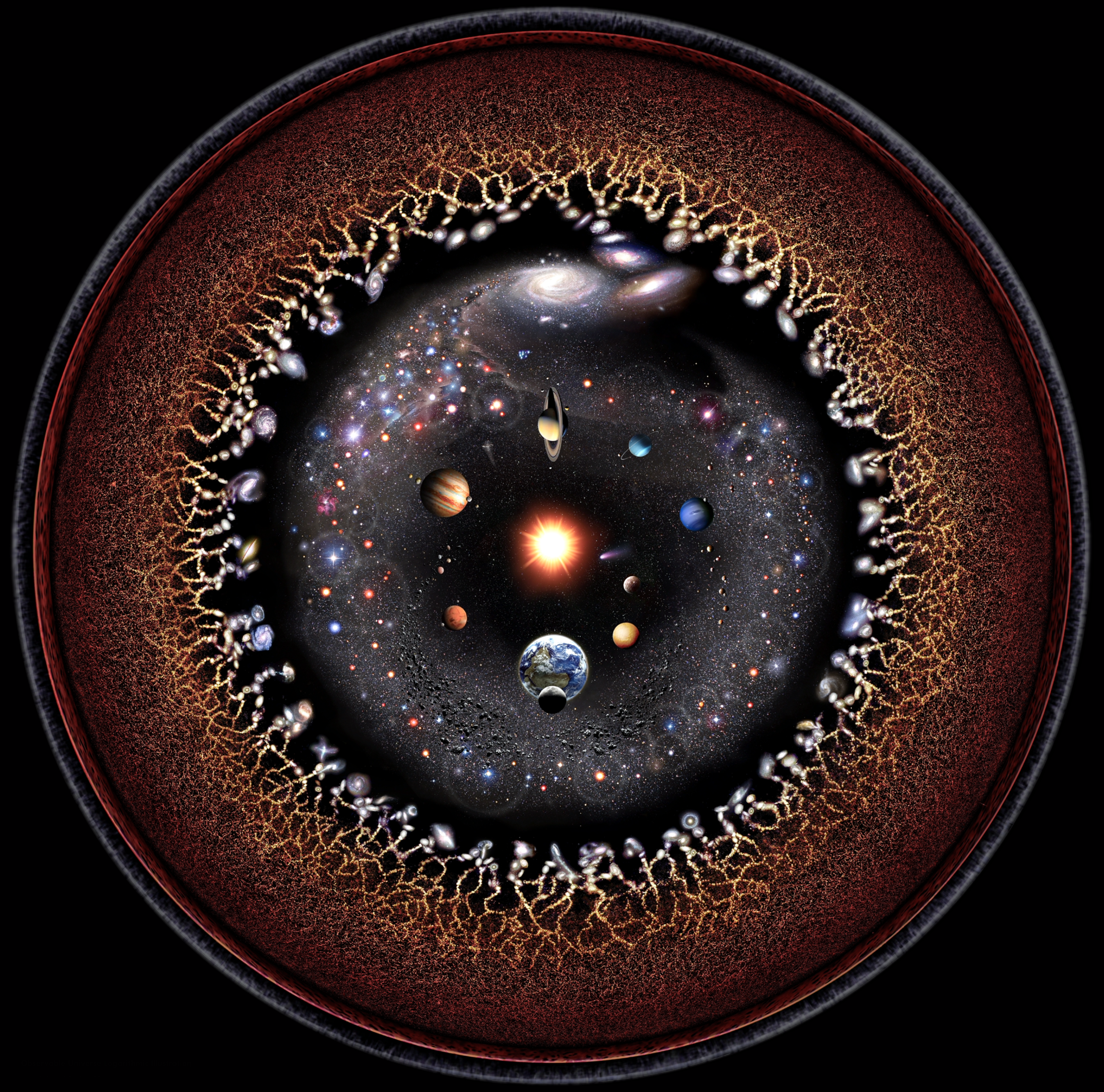
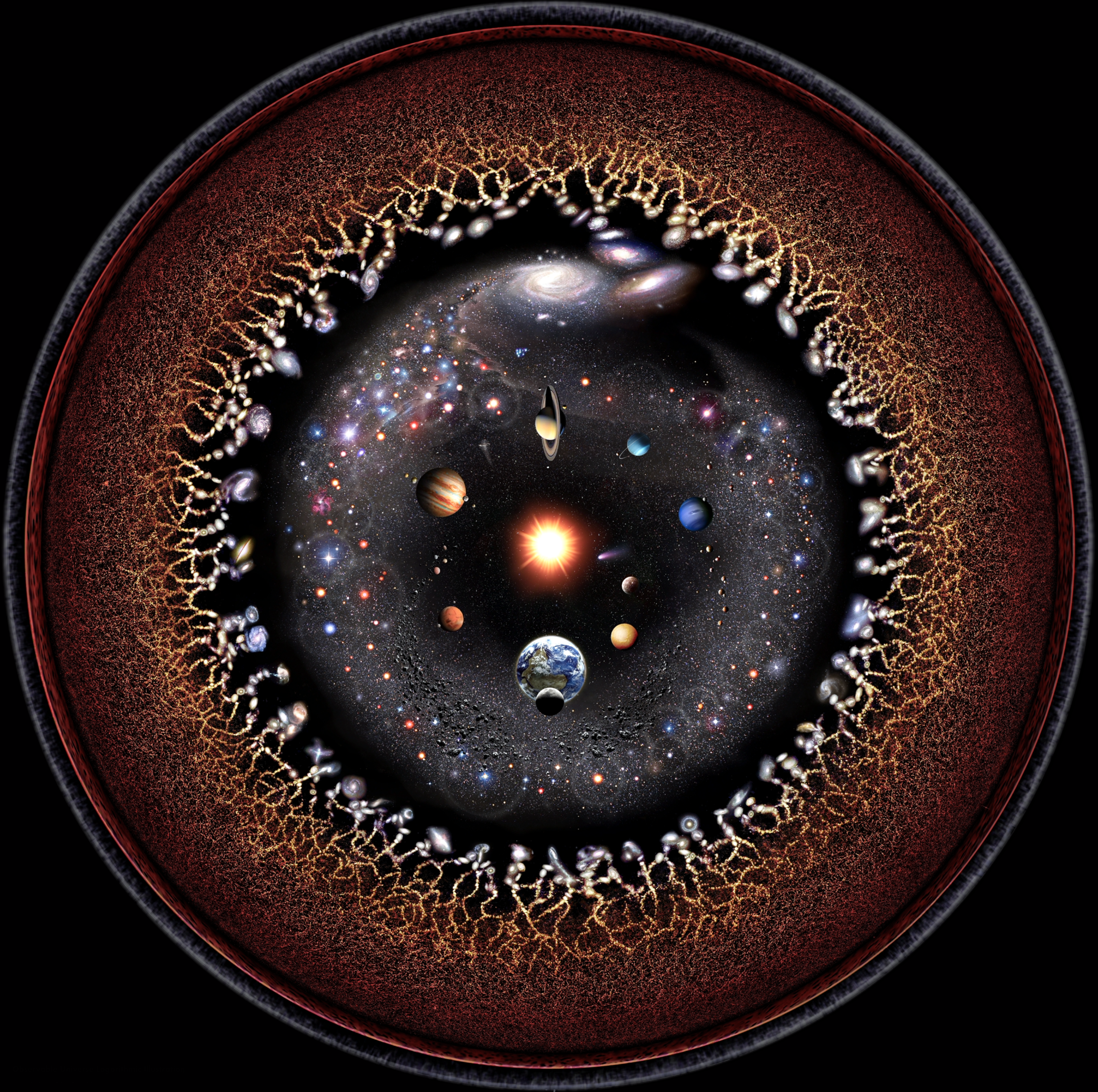


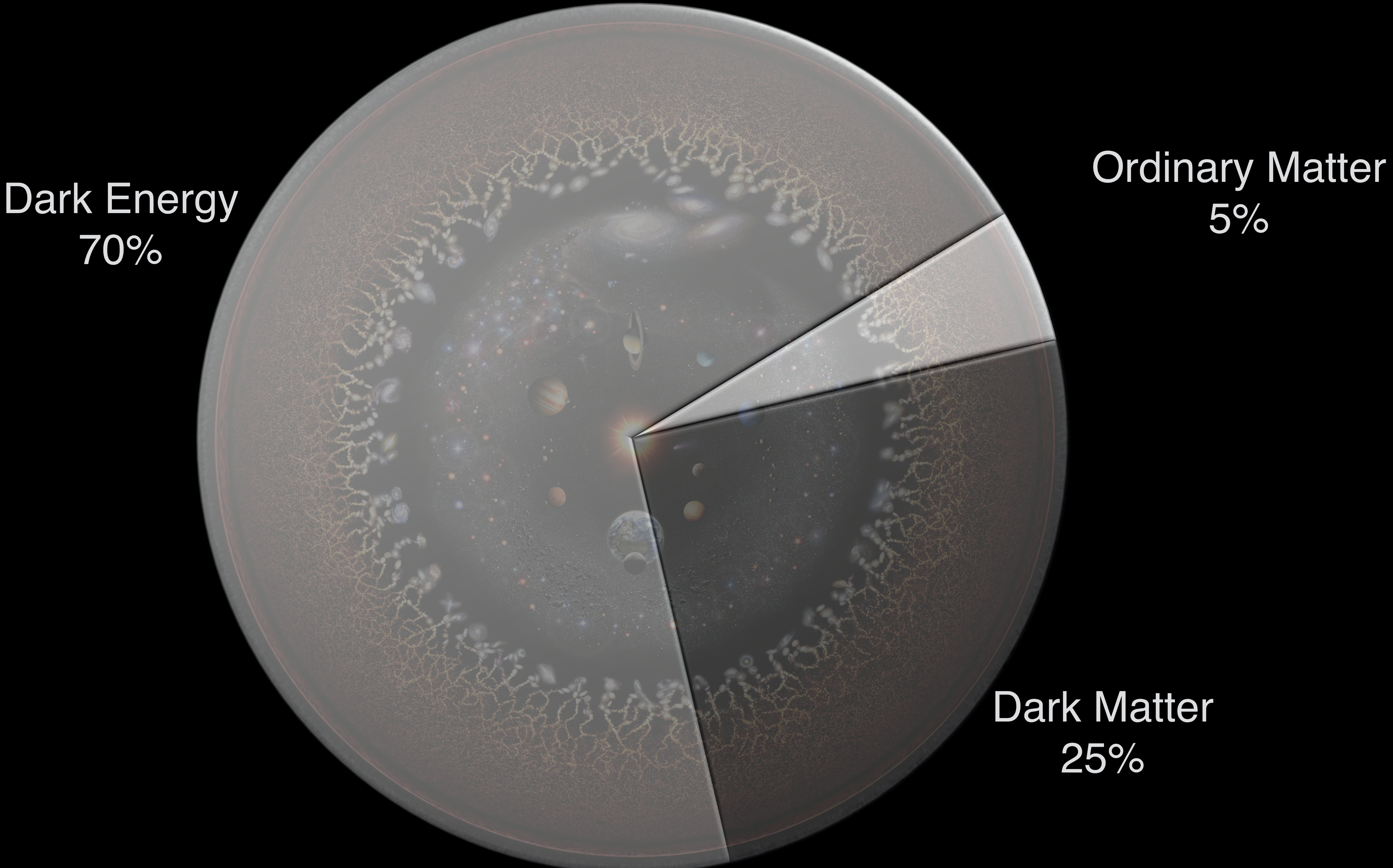
Light in the Dark
Opening a new window to the Dark Sector

UVA HEP Seminar

14 November 2019

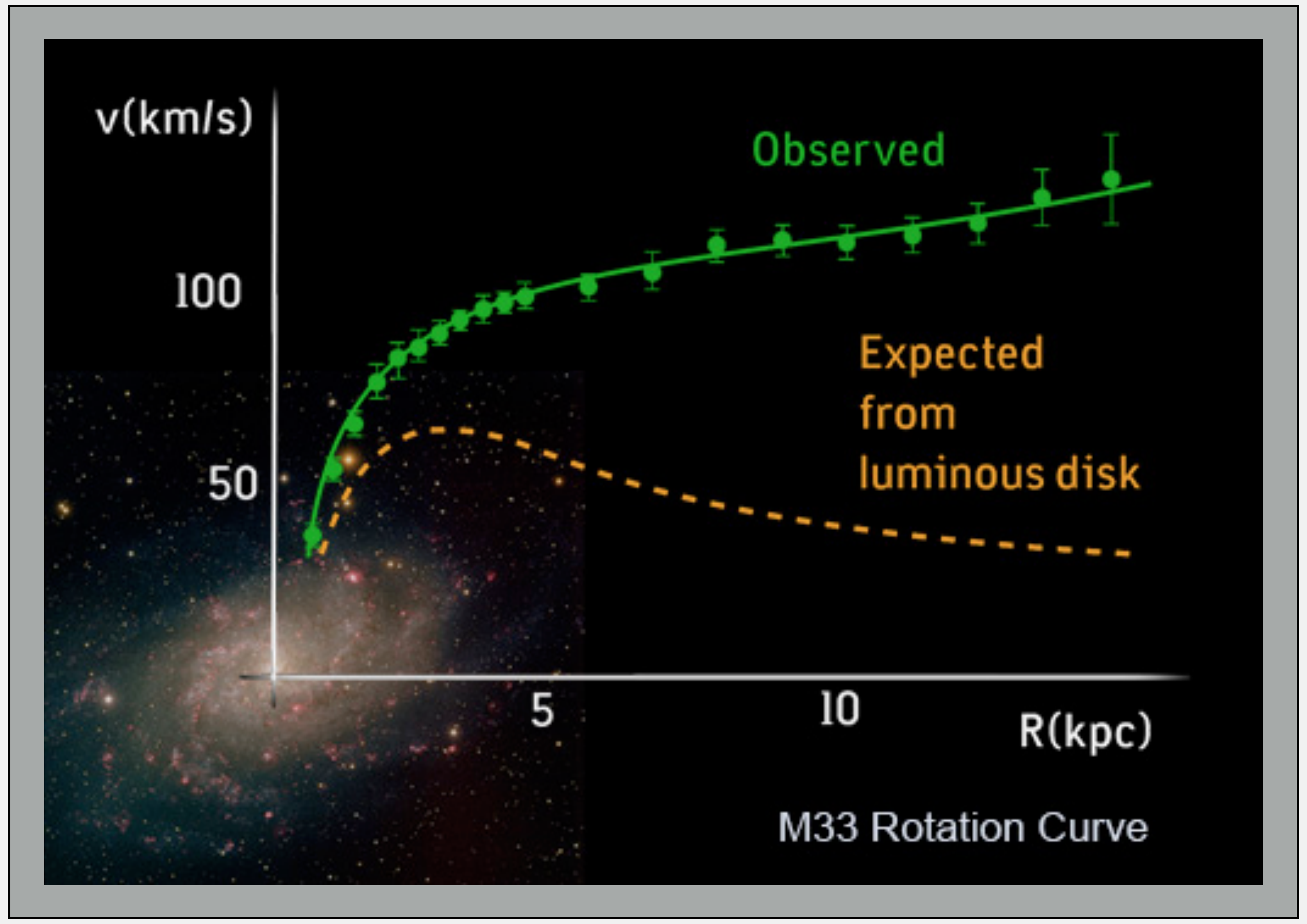
Ruth Pöttgen, Lund University




Dark Energy
70%
Ordinary Matter
5%
Dark Matter
25%

How do we know Dark Matter is there?

Rotation Curves



stars in the outer parts of many galaxies rotate much faster than expected based on gravitation from visible matter

shown by Vera Rubin in the 1970s for hundreds of galaxies

first observation of "dunkle Materie" (dark matter) in 1930(s)

(often attributed to F. Zwicky, 1933, studied Coma Cluster)

but actually first mentioned by Knut Lundmark in 1930

(see L. Bergström's presentation in April 2015)

Über die Bestimmung der Entfernungen, Dimensionen, Massen und Dichtigkeiten für die nächstgelegenen anagalaktischen Sternsysteme.

Von Knut Lundmark.

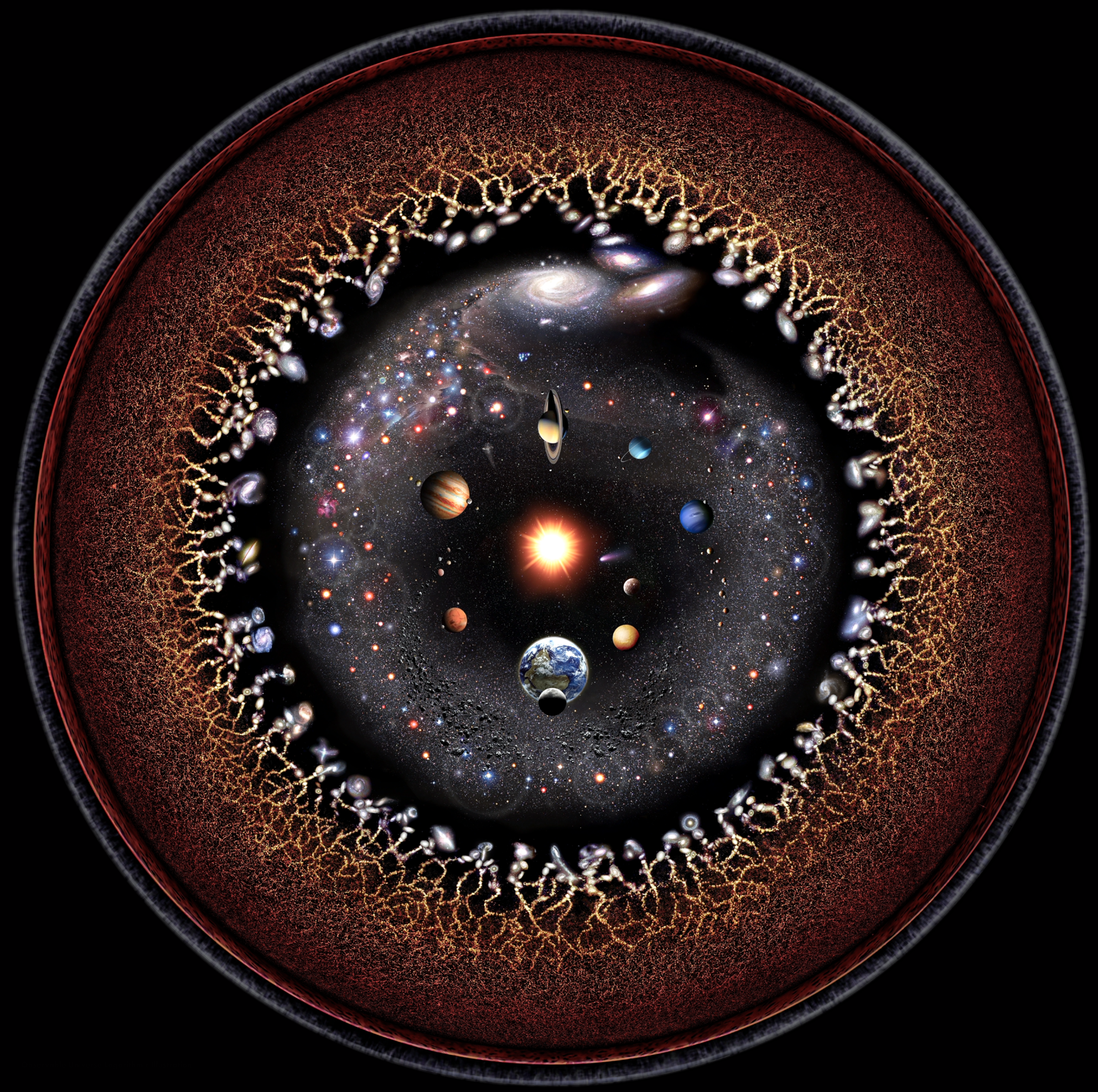
Tabelle 4.

Objekt	Verhältnis: (Leuchtende + dunkle Materie) / Leuchtende Materie	Mittlere Zahl der Sterne für ^{3} Lichtjahre
Messier 81	100 : 1 (?)	0.20 (?)
N. G. C. 4594	30 : 1	0.042
Andromedanebel	20 : 1	0.006
Messier 51	10 : 1	0.012
Milchstraßensystem	10 : 1	0.08
Messier 33	6 : 1	0.026

Dark Matter, a known unknown

ample **evidence** for existence of non-luminous form of matter

- all based on **gravitational** effects
- observed on vastly different scales (single galaxies up to entire Universe)



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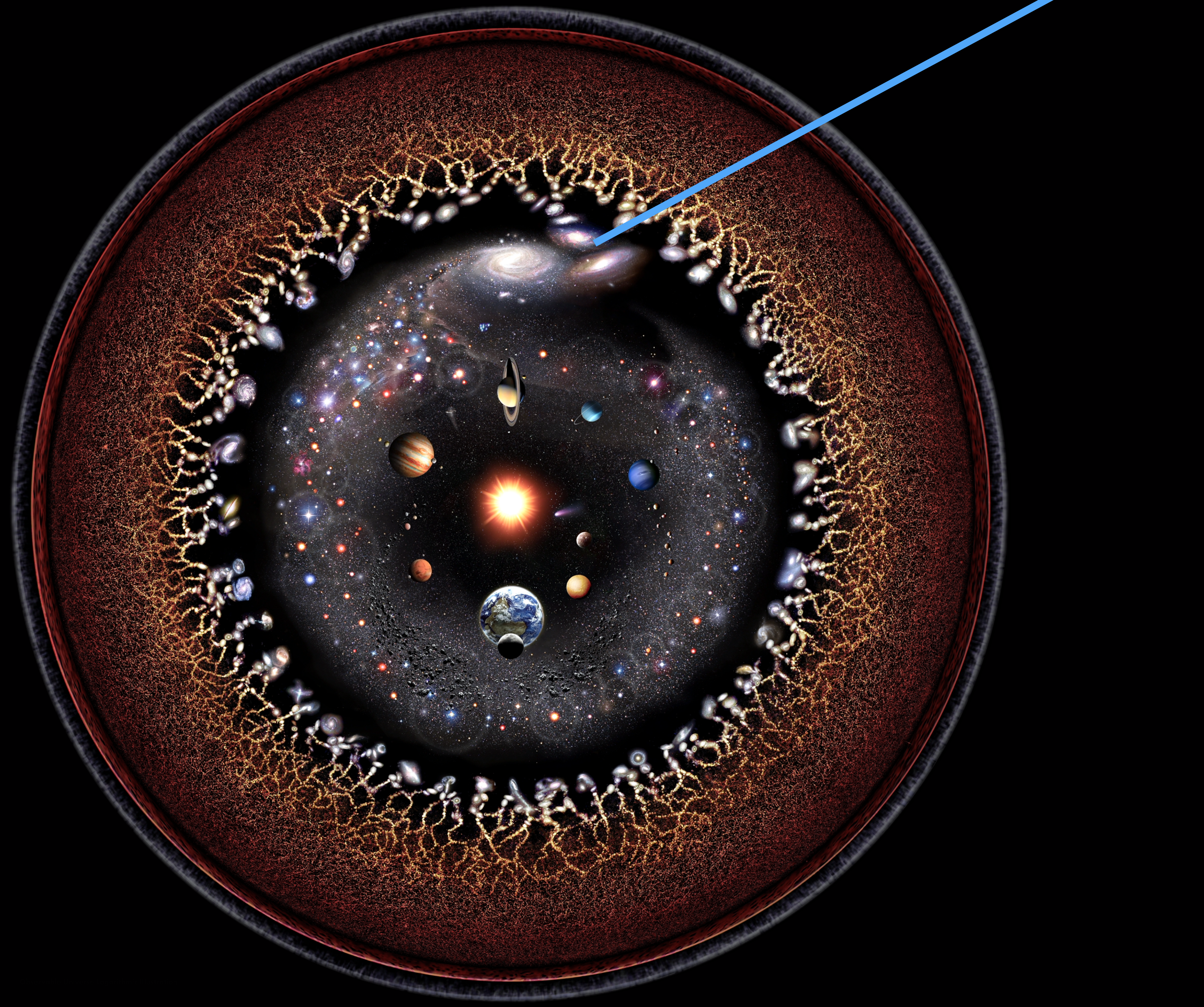

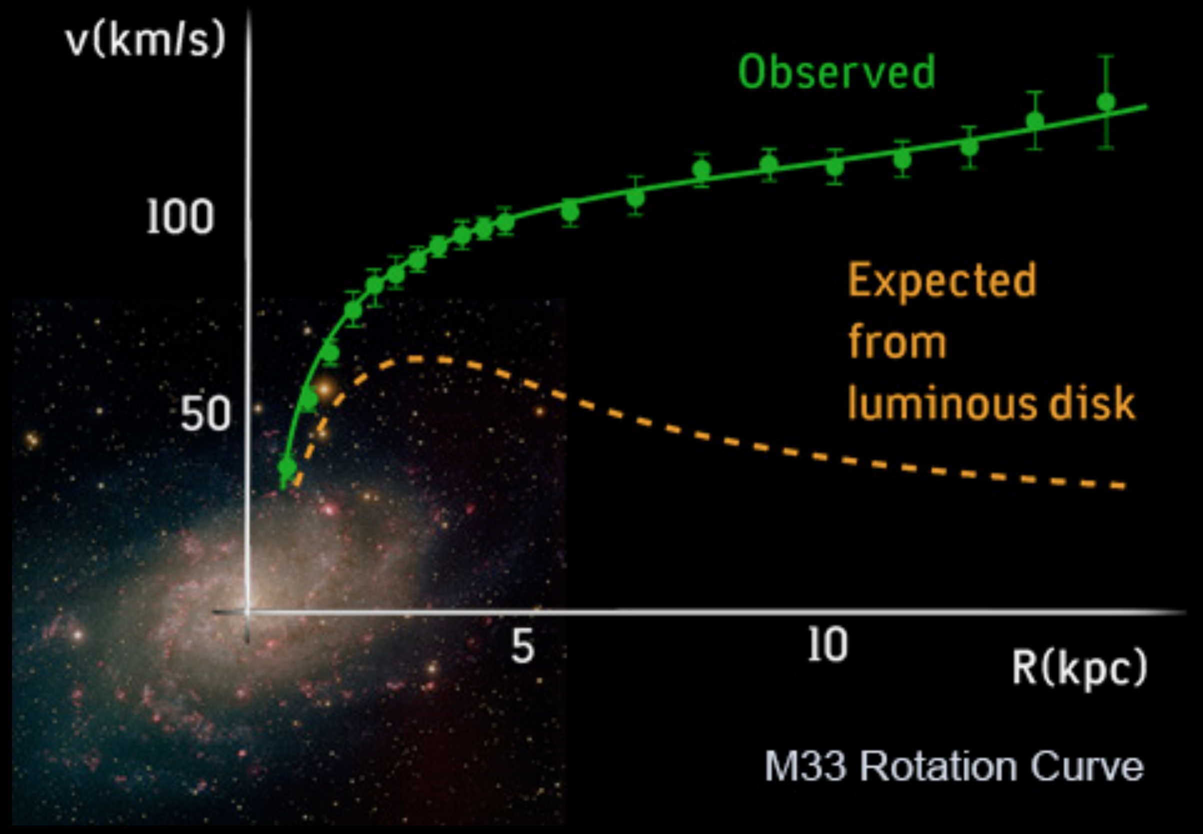

M33 Rotation Curve

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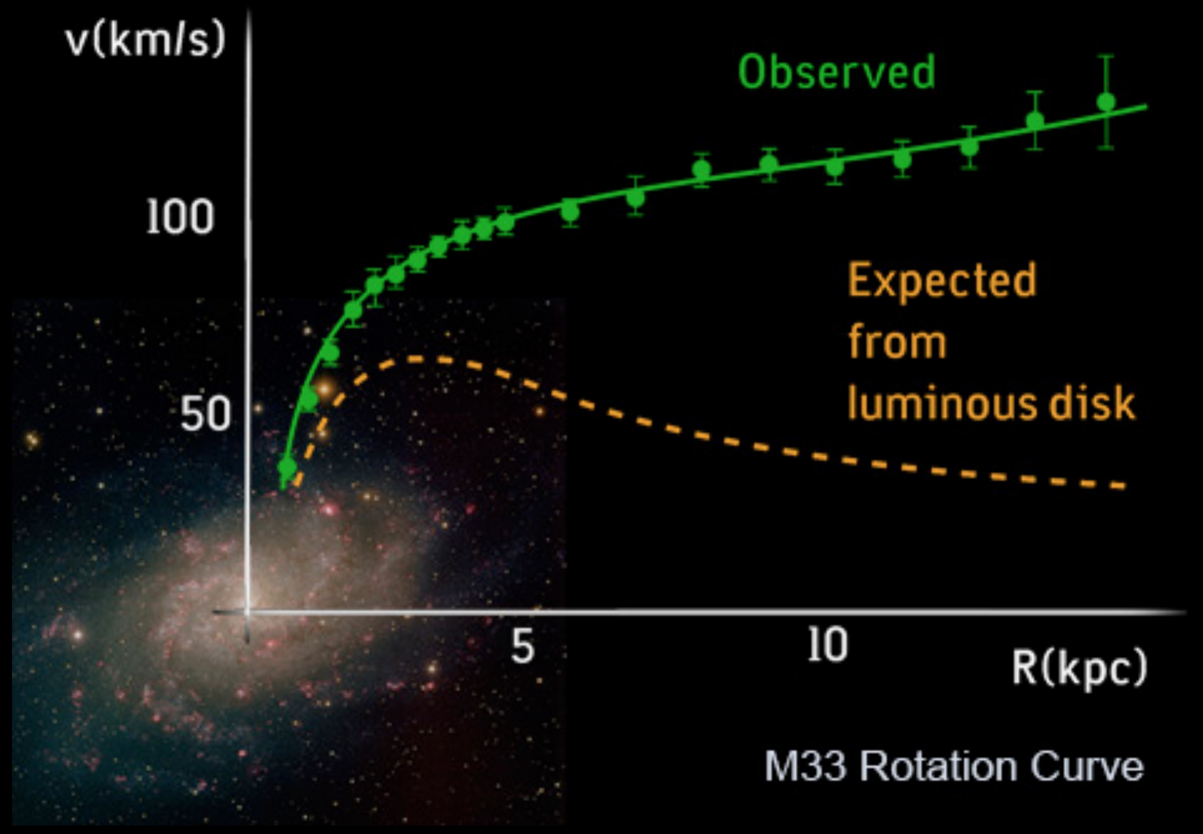

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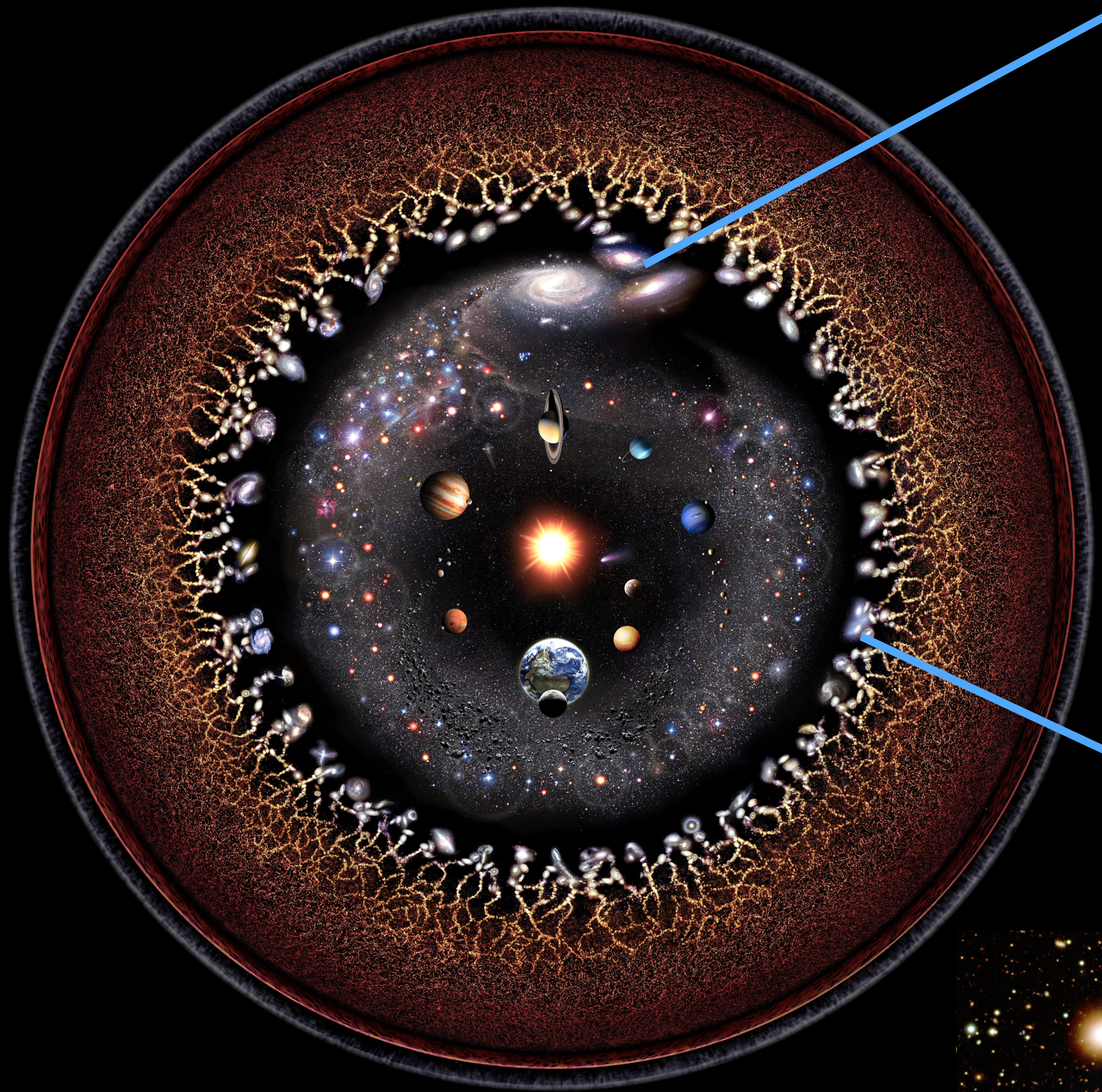
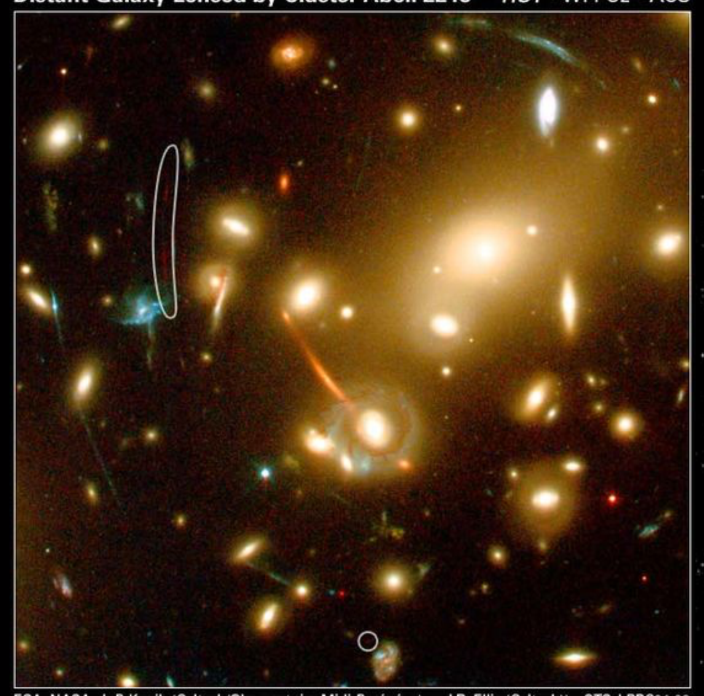
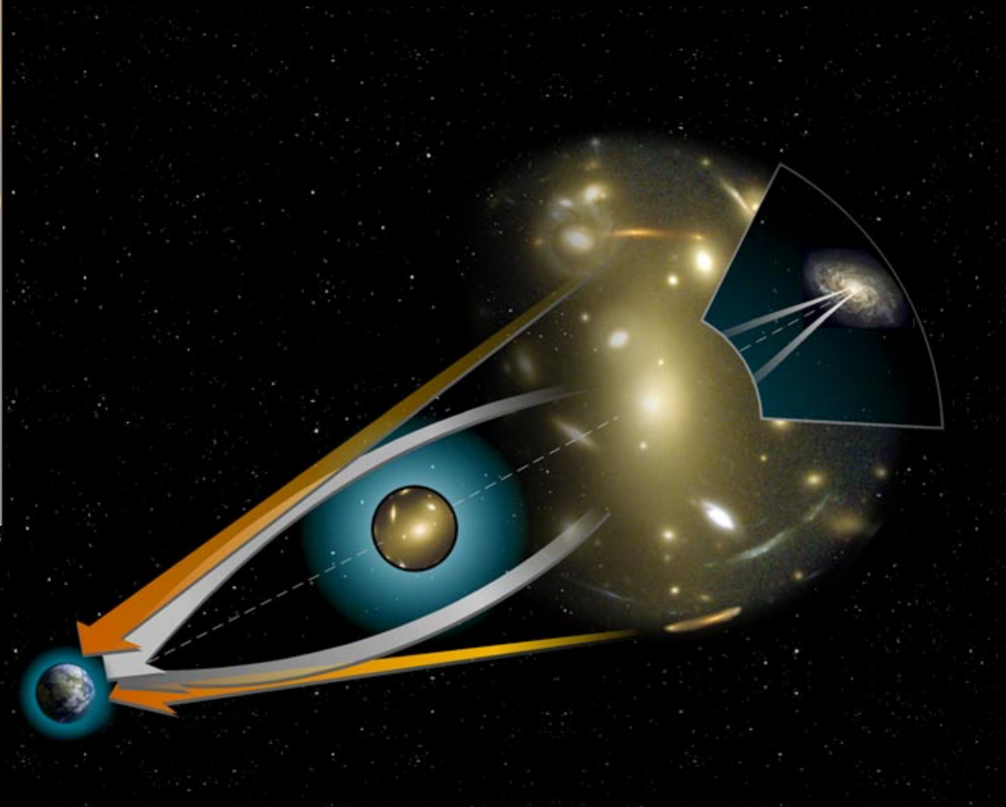
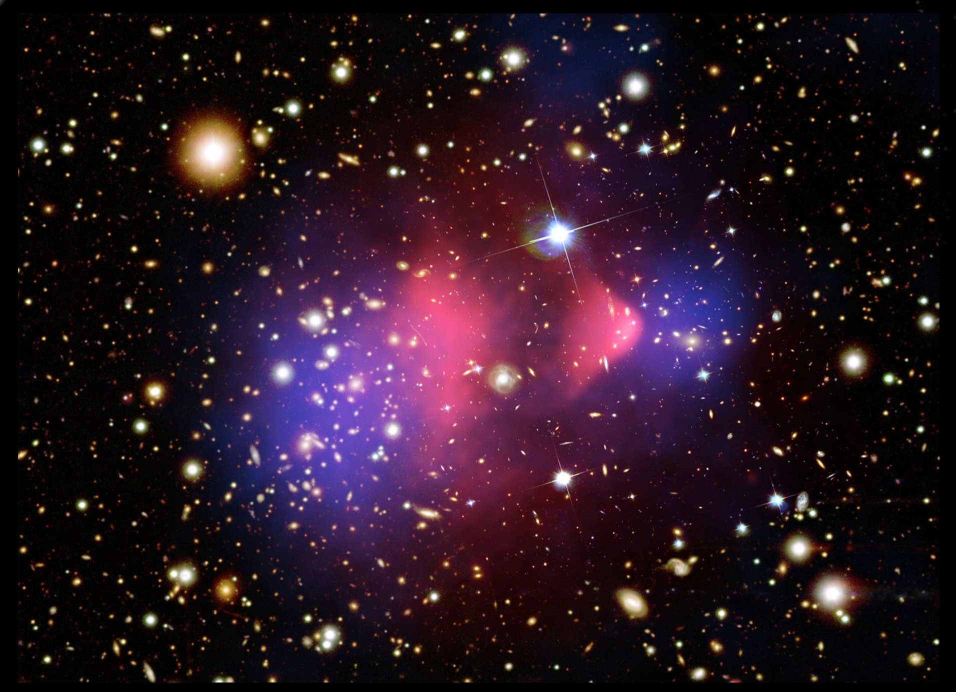


Distant Galaxy Lensed by Cluster Abell 2218 *HST* • WFPC2 • ACS



ESA, NASA, J.-P. Kneib (Caltech/Observatoire Midi-Pyrénées) and R. Ellis (Caltech) STScI-PRC04-08





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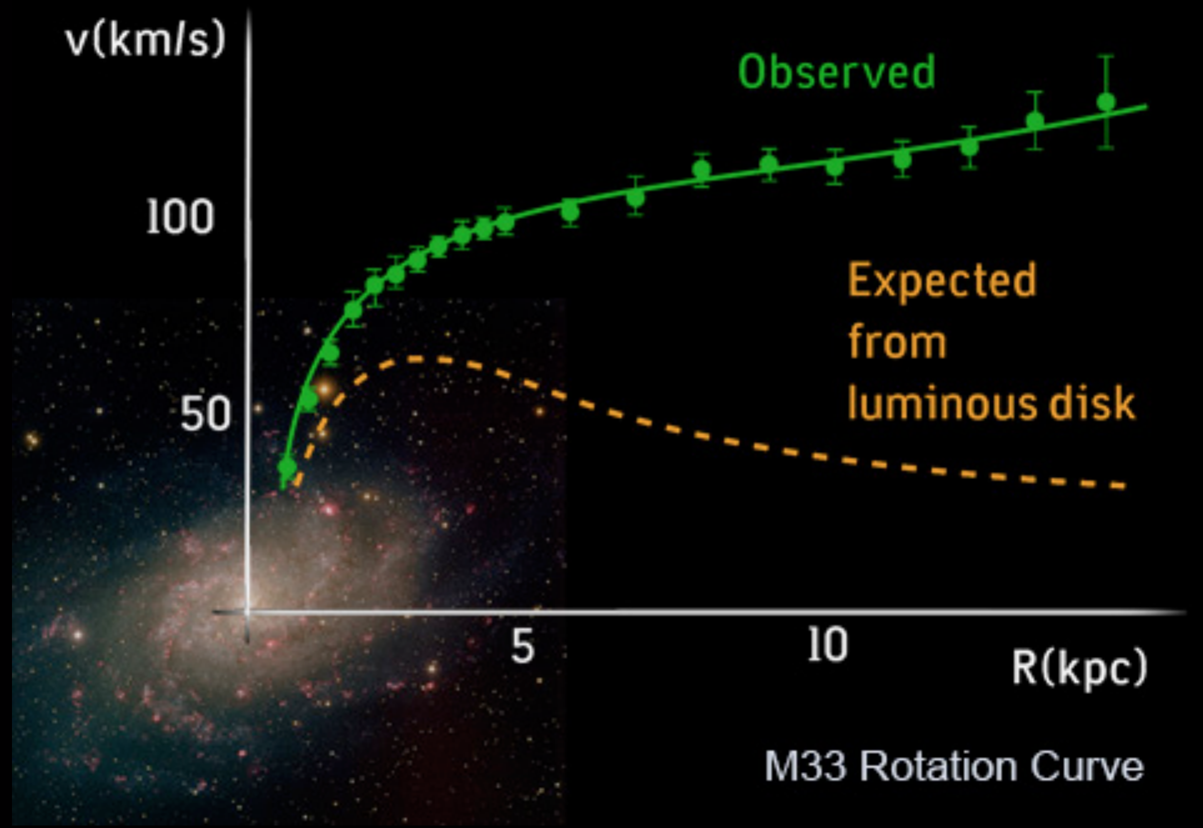

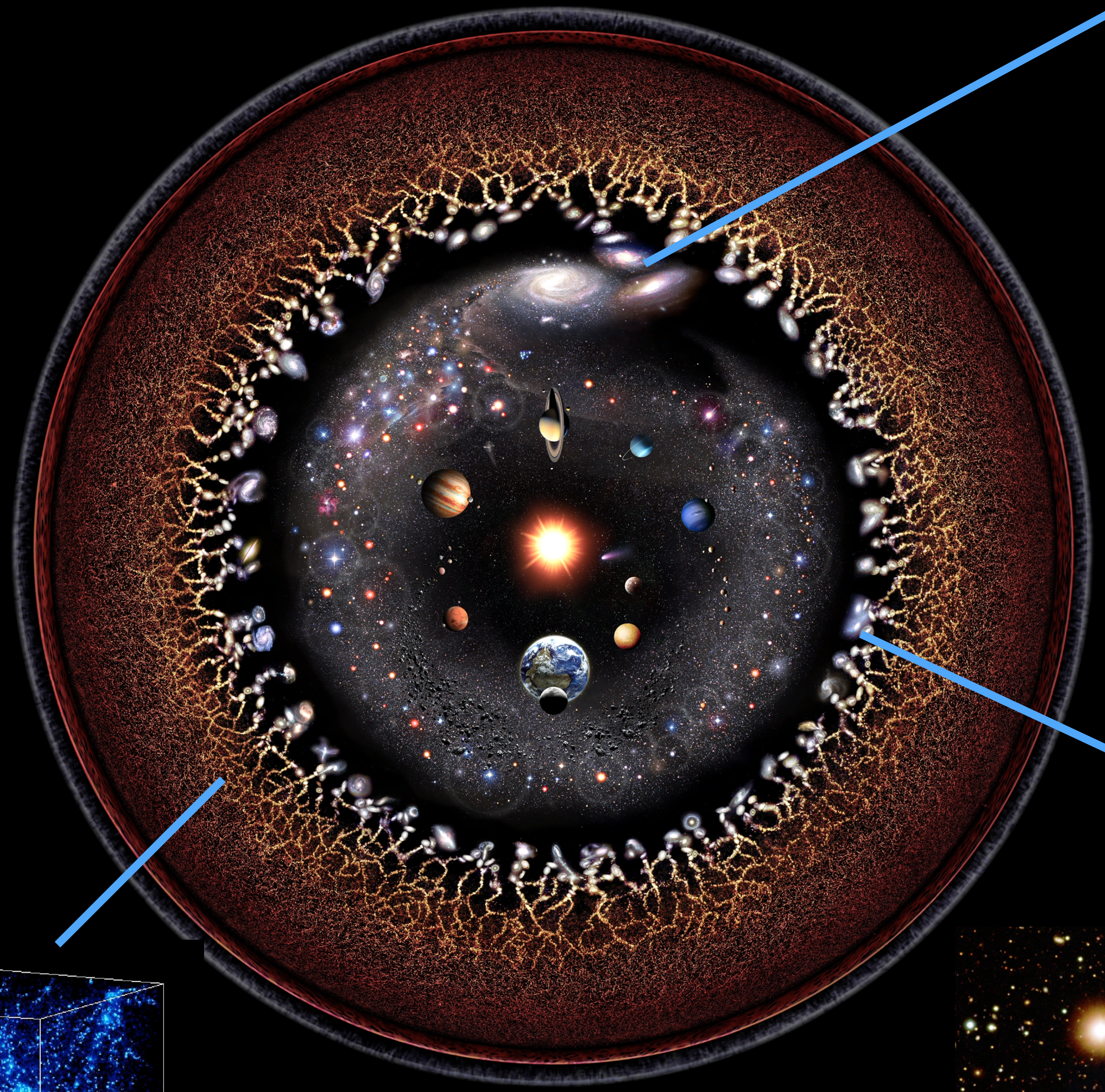

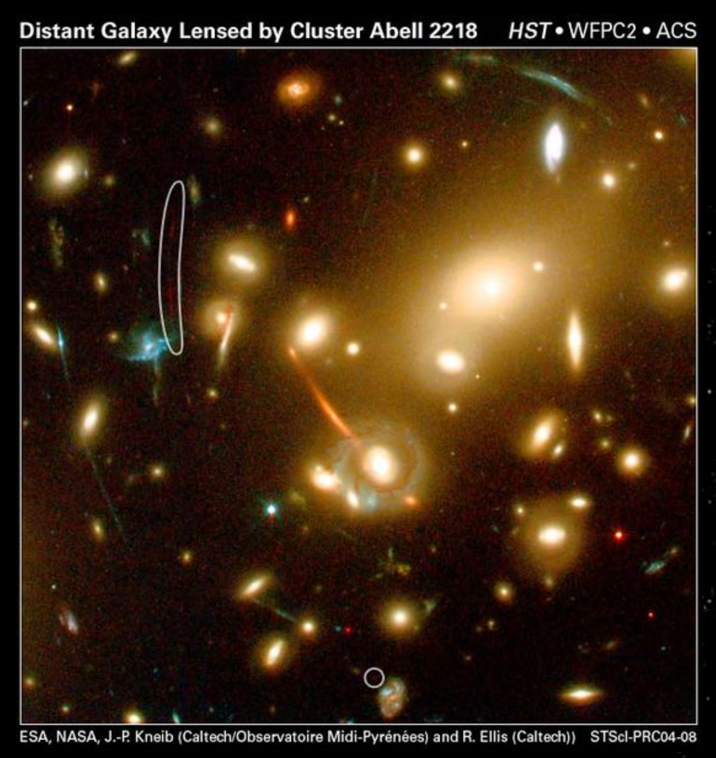

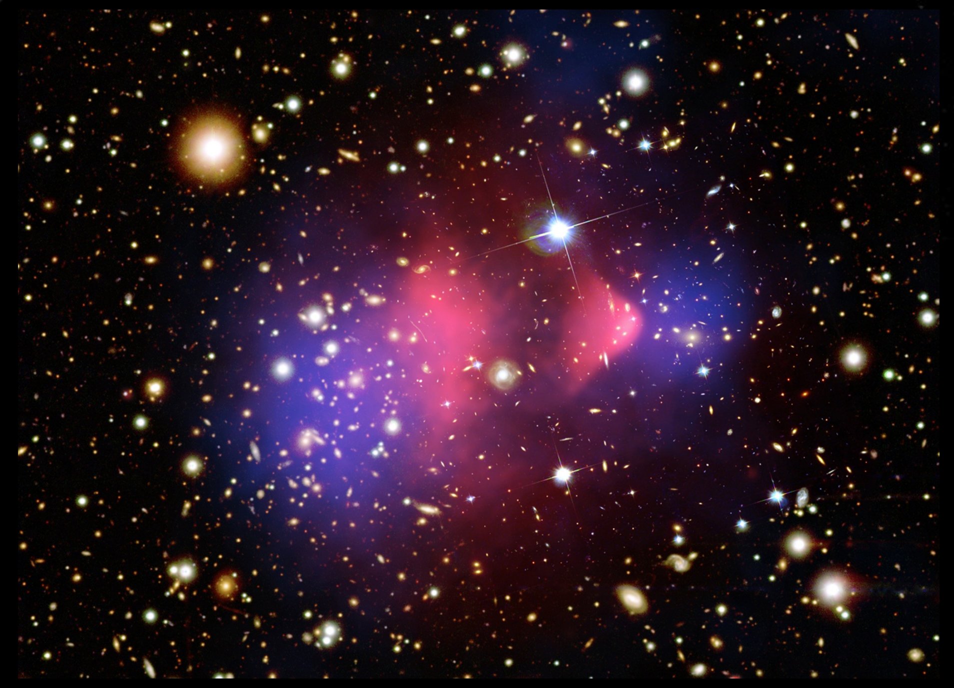

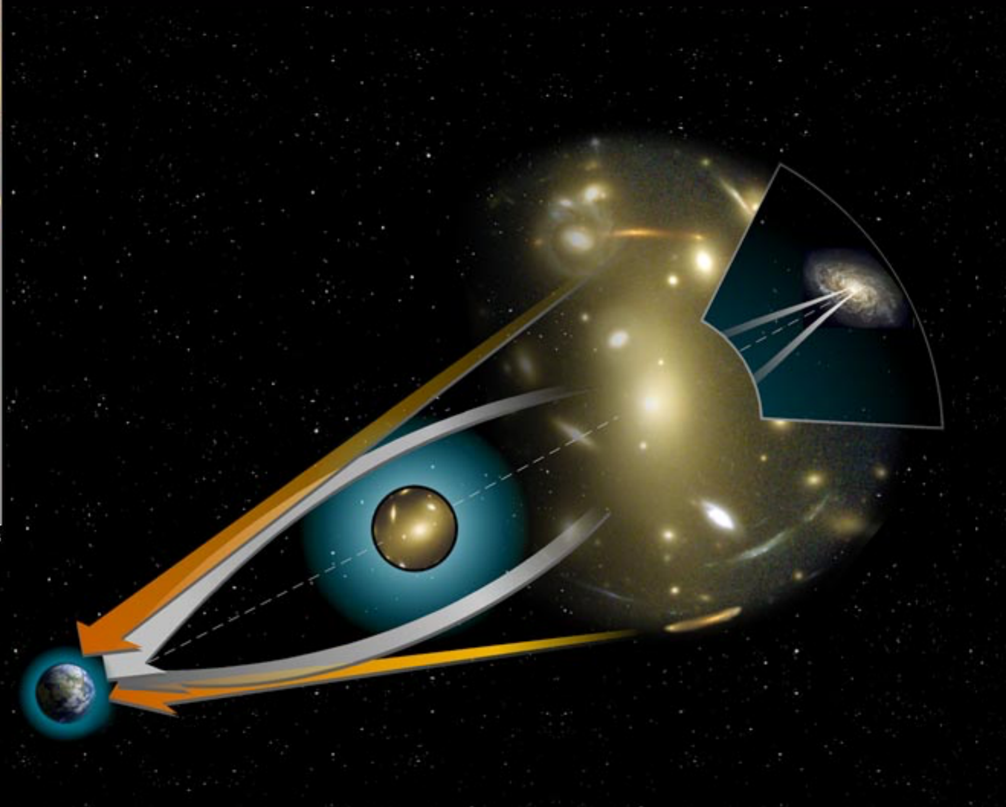

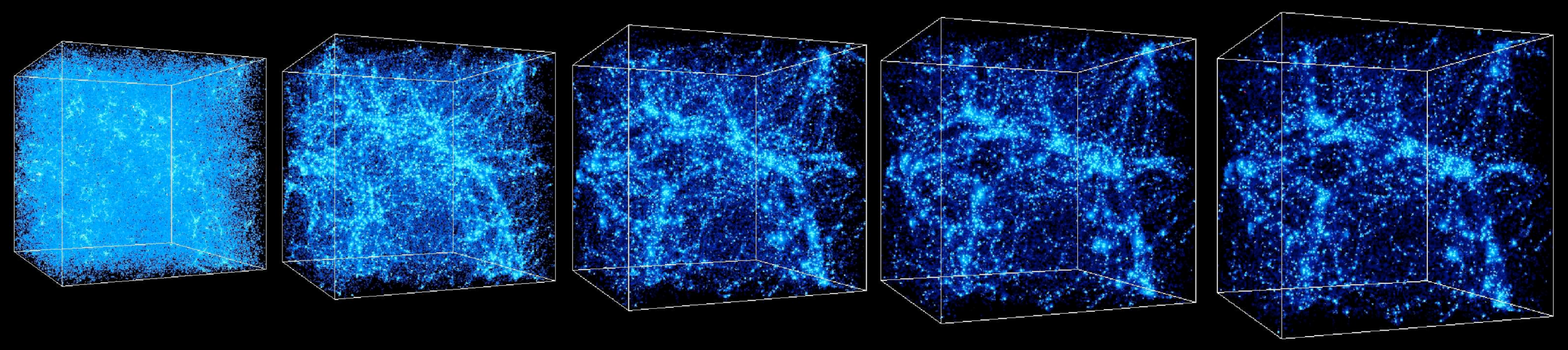

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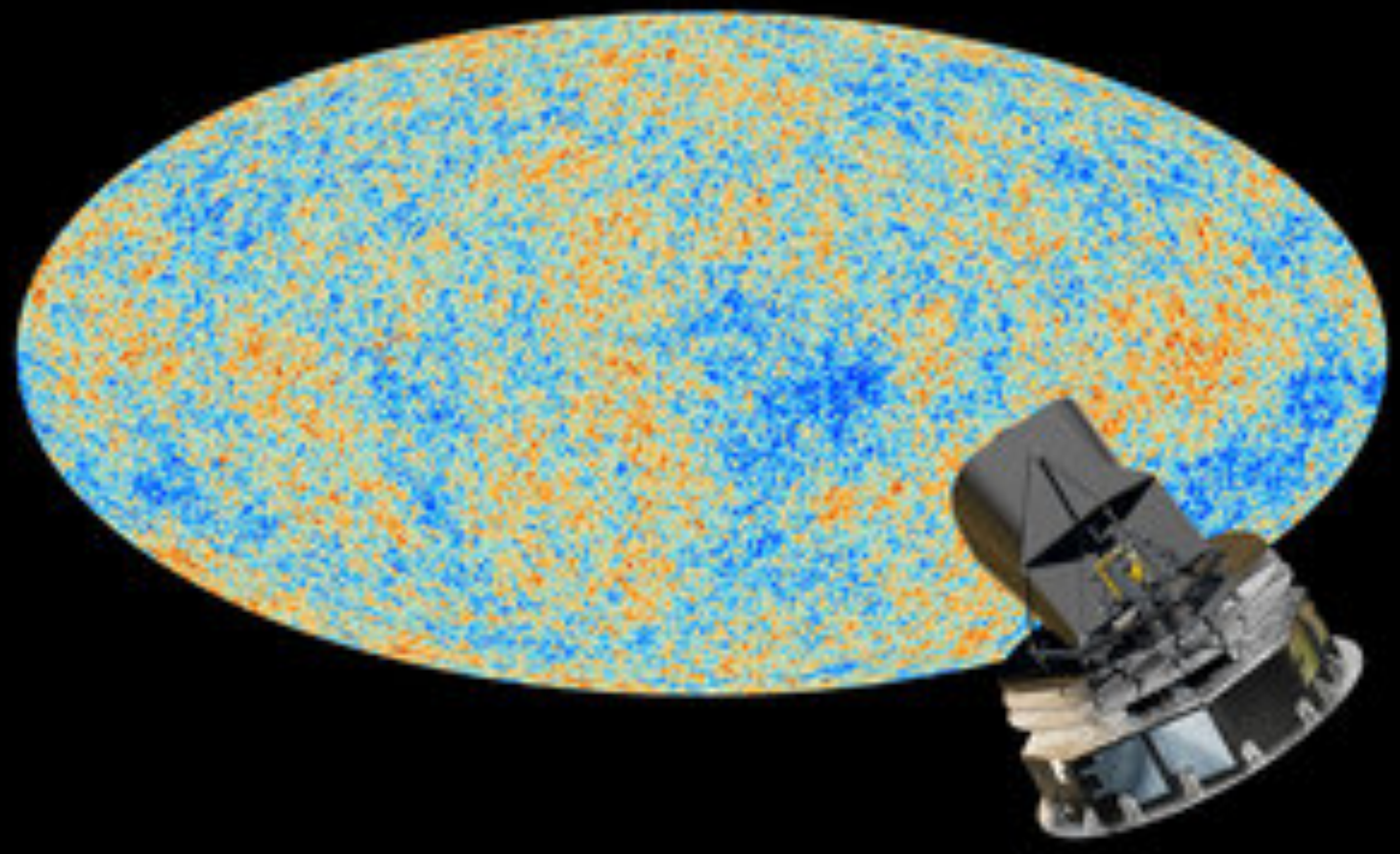
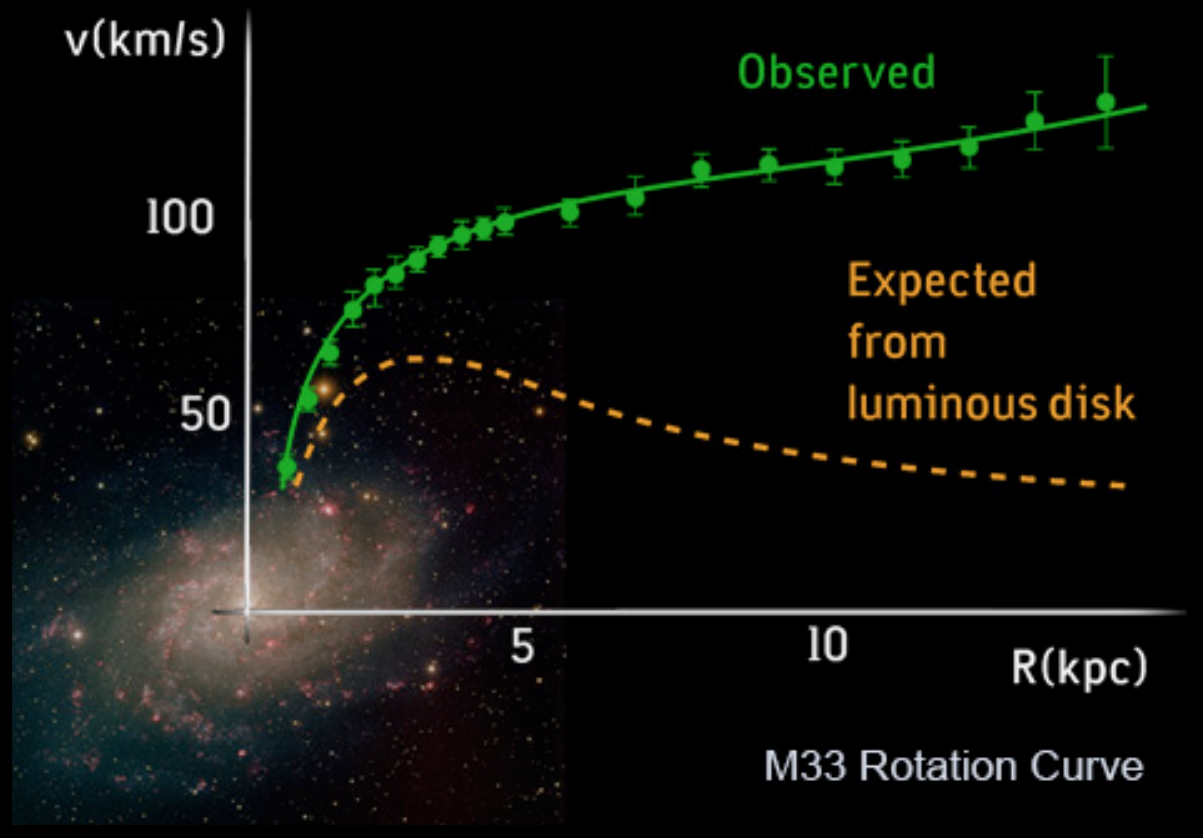
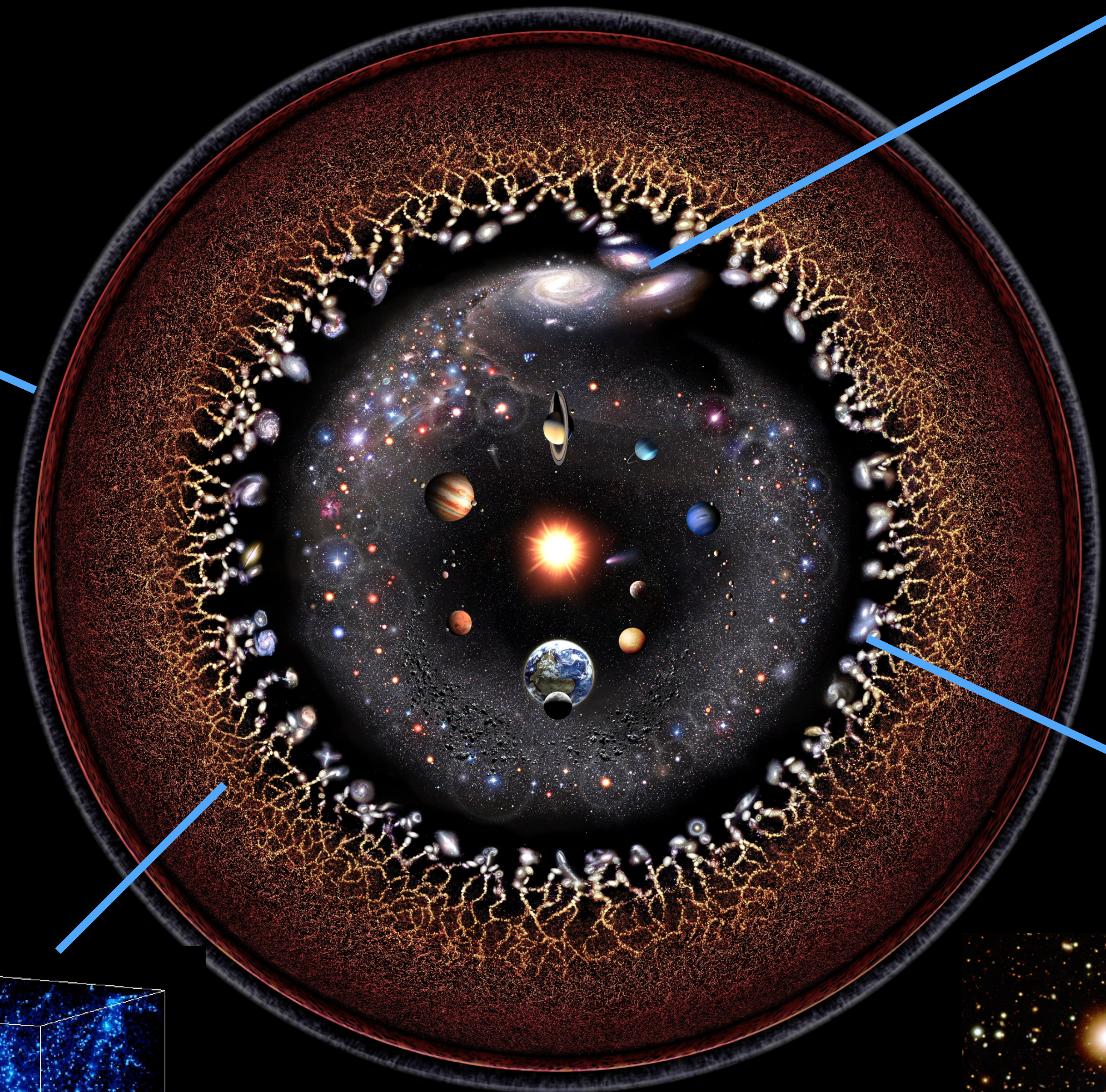
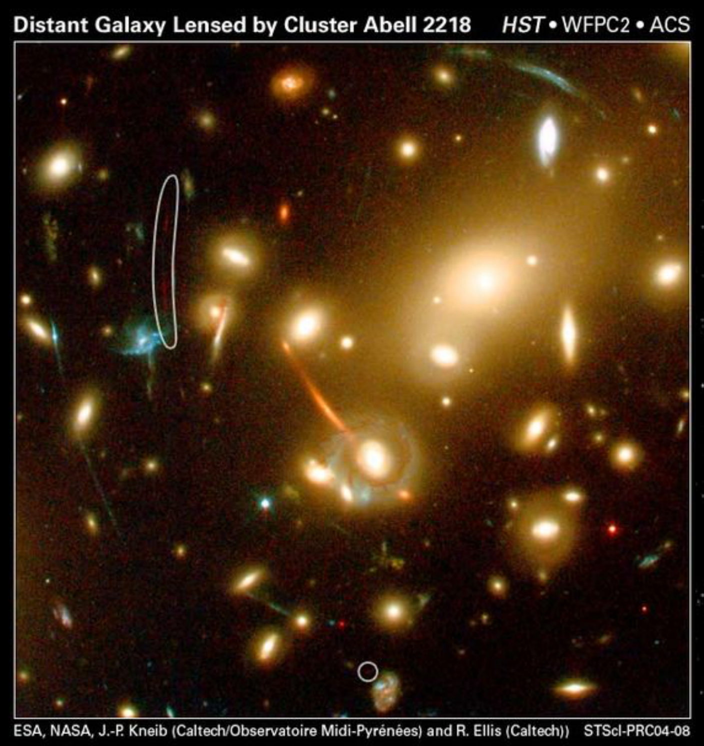
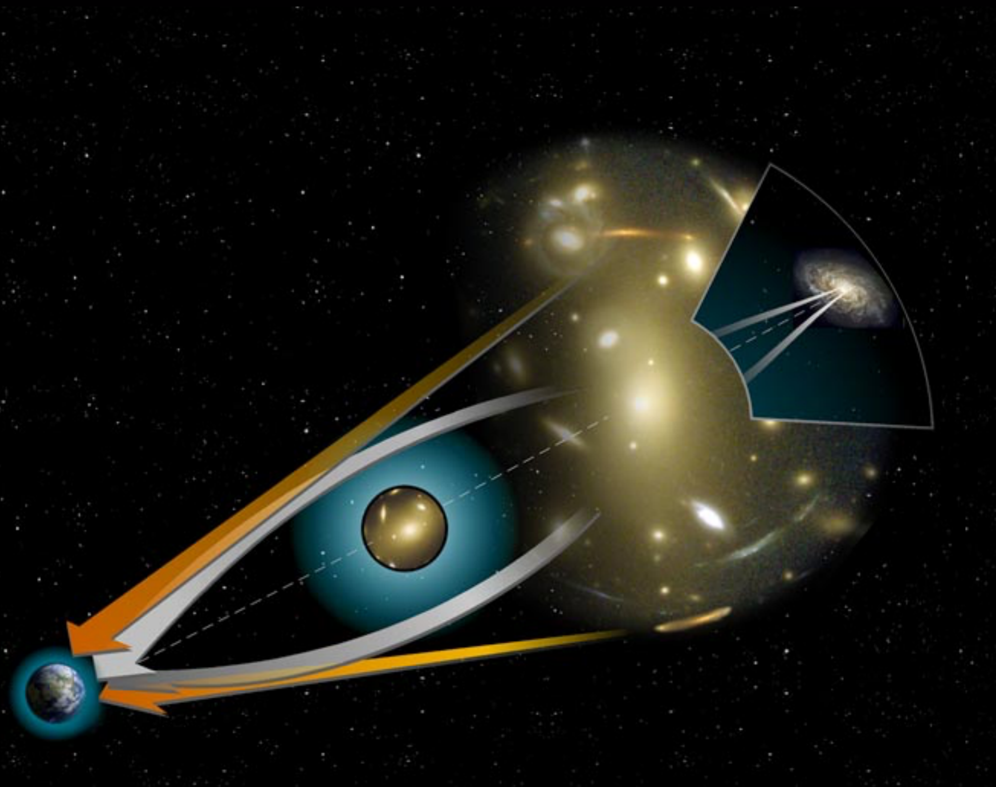
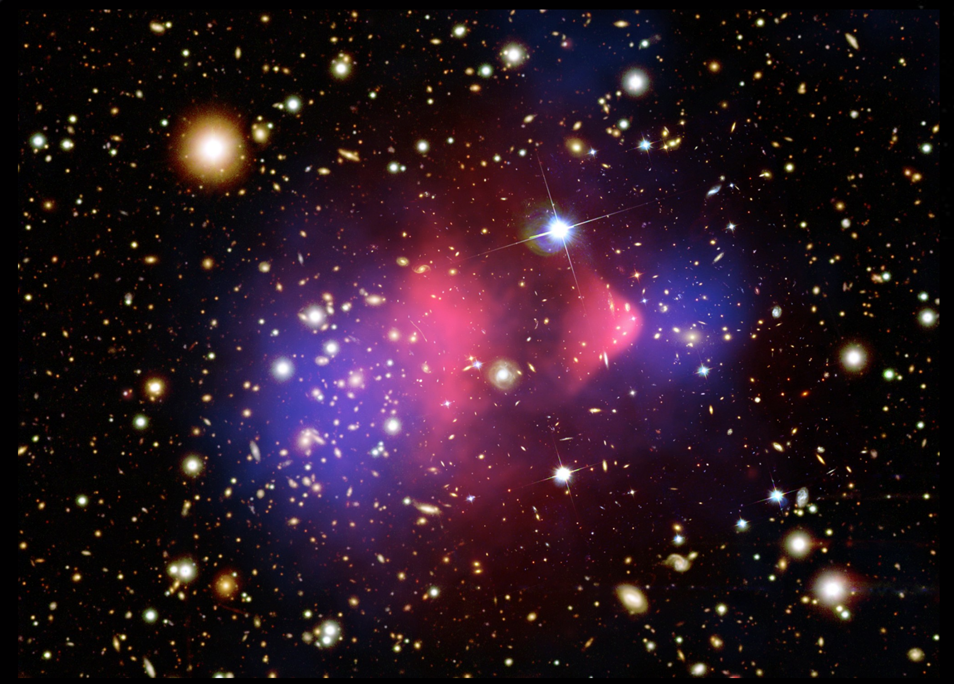


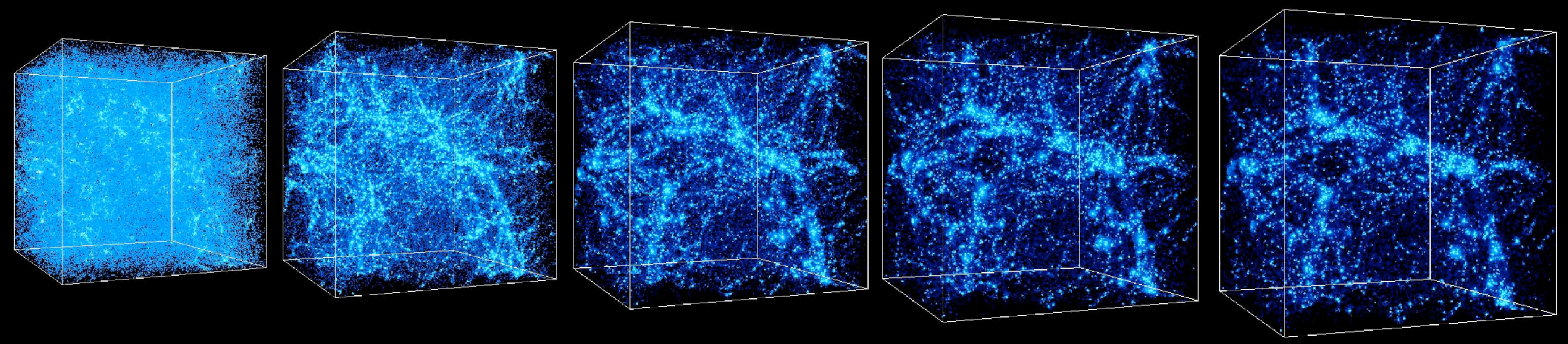








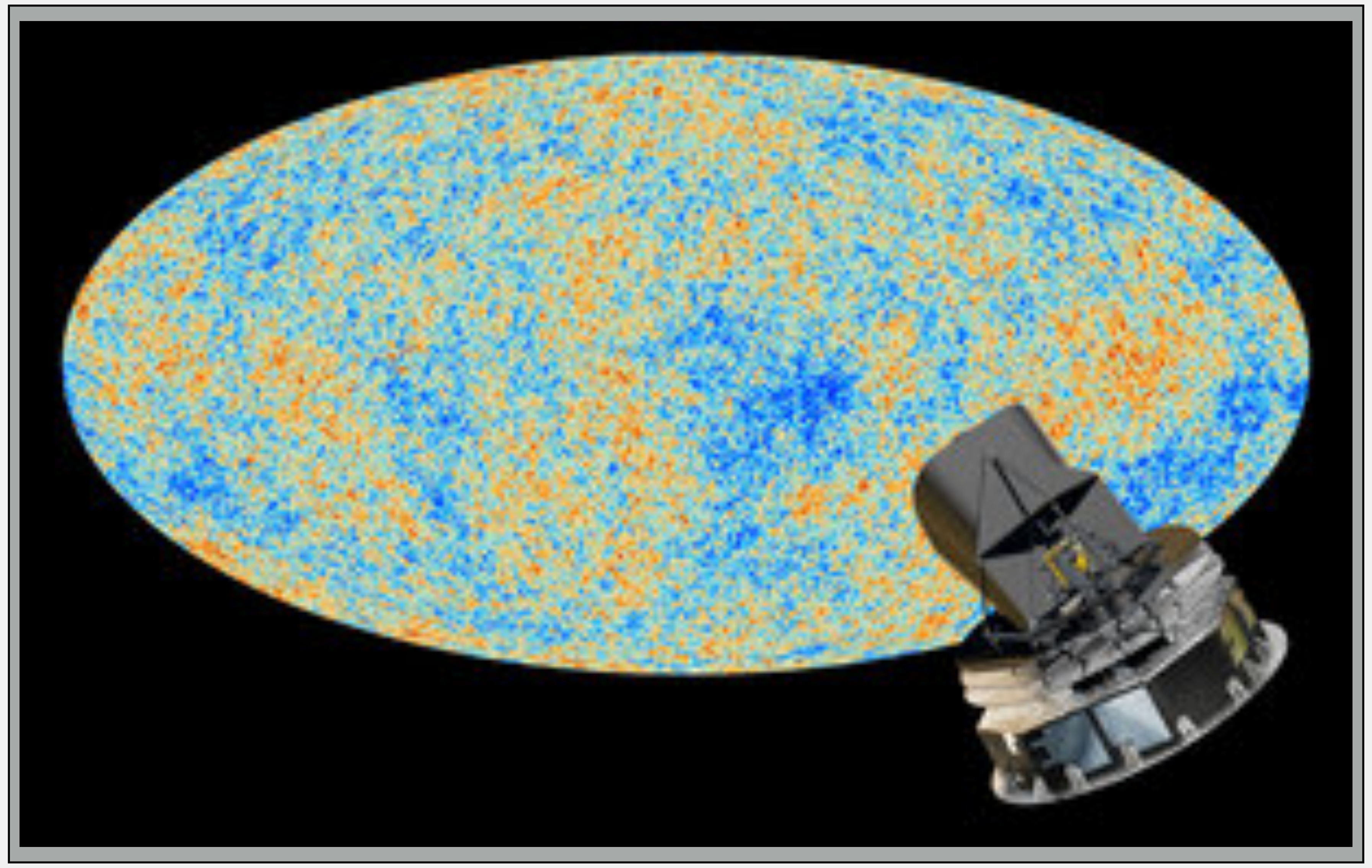


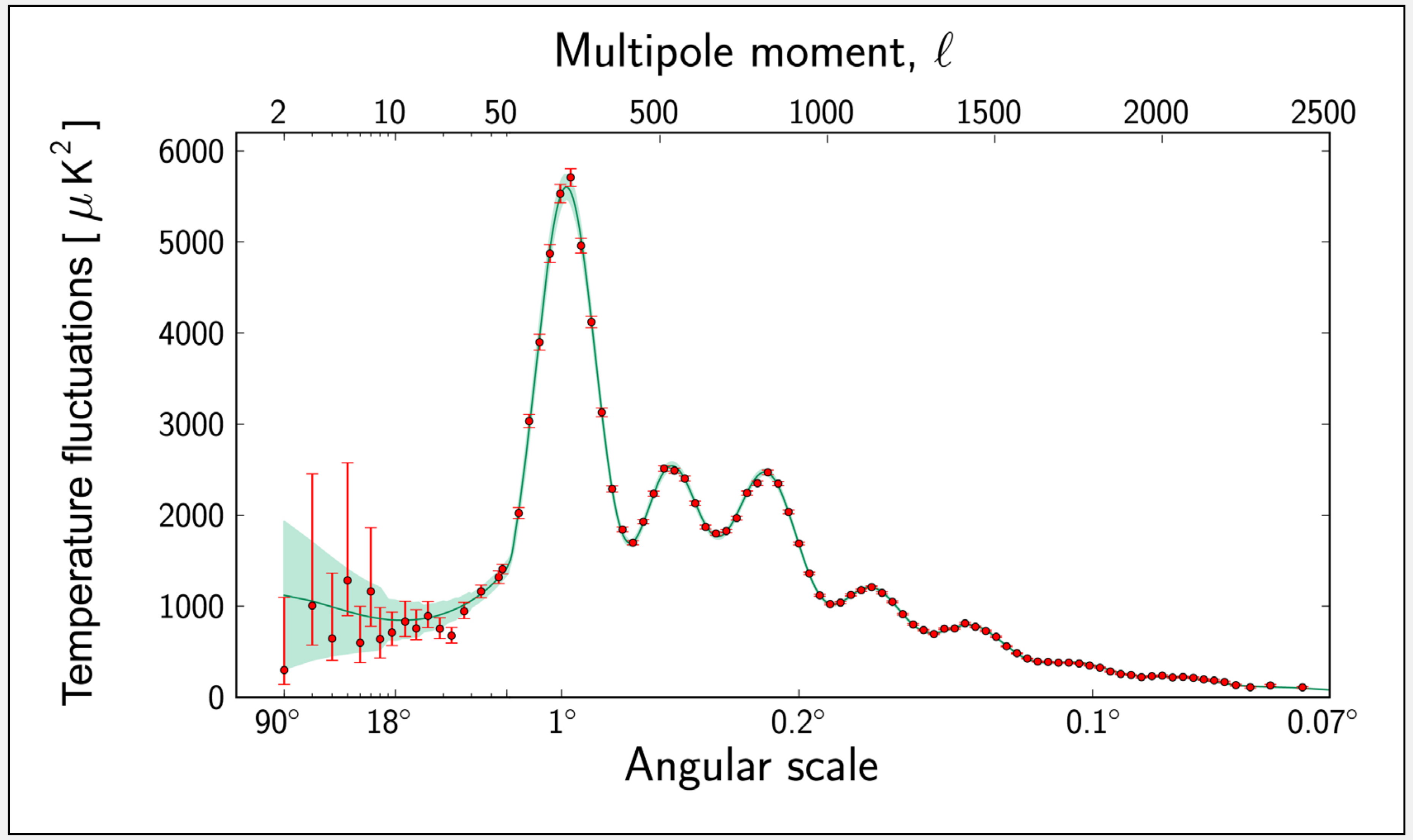


Cosmic Microwave Background

radiation from shortly after the big bang

- density fluctuations in early Universe encoded in temperature fluctuations of CMB
- measured most recently by ESA PLANCK satellite





position/height of peaks contains information about composition of the Universe

Nobel Prize 2019 for J. Peebles

This is how we know how much Dark Matter there is in the Universe.

What Particles could Dark Matter be made of?

What Particles?

Some basic requirements

- electrically neutral (dark!)
- stable on cosmological timescales
- **massive**

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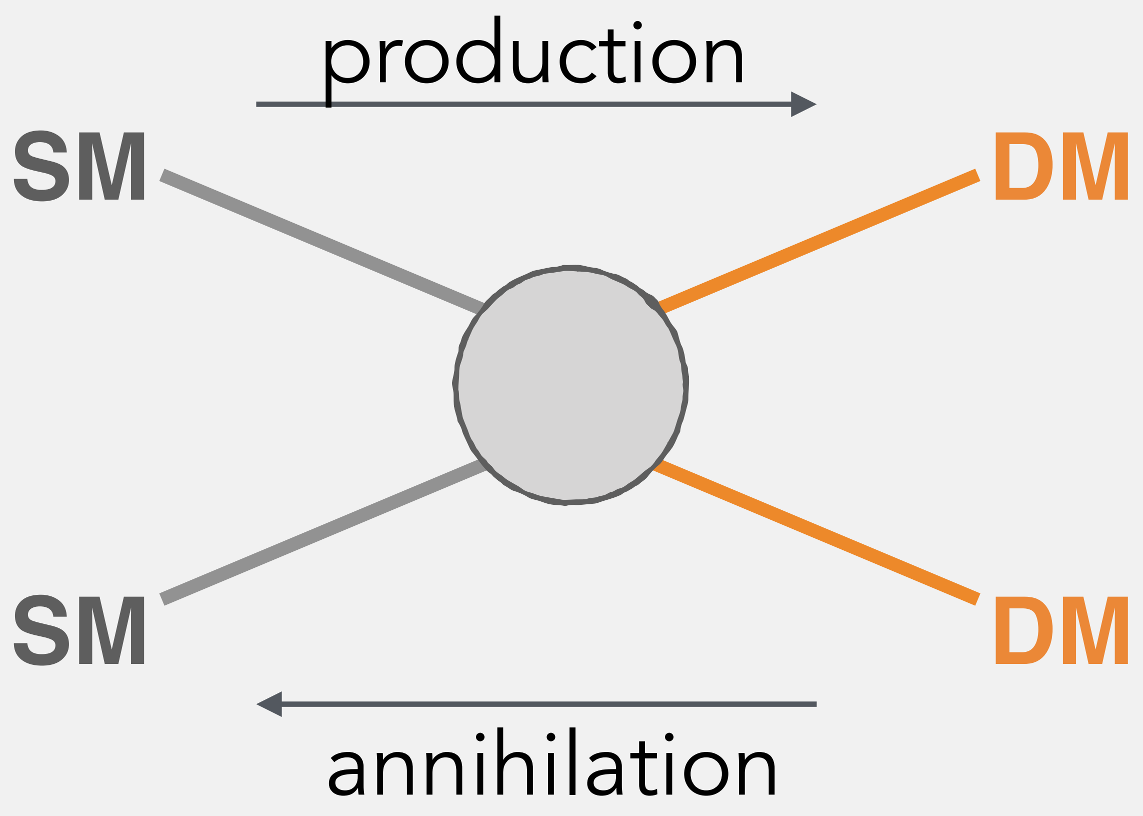

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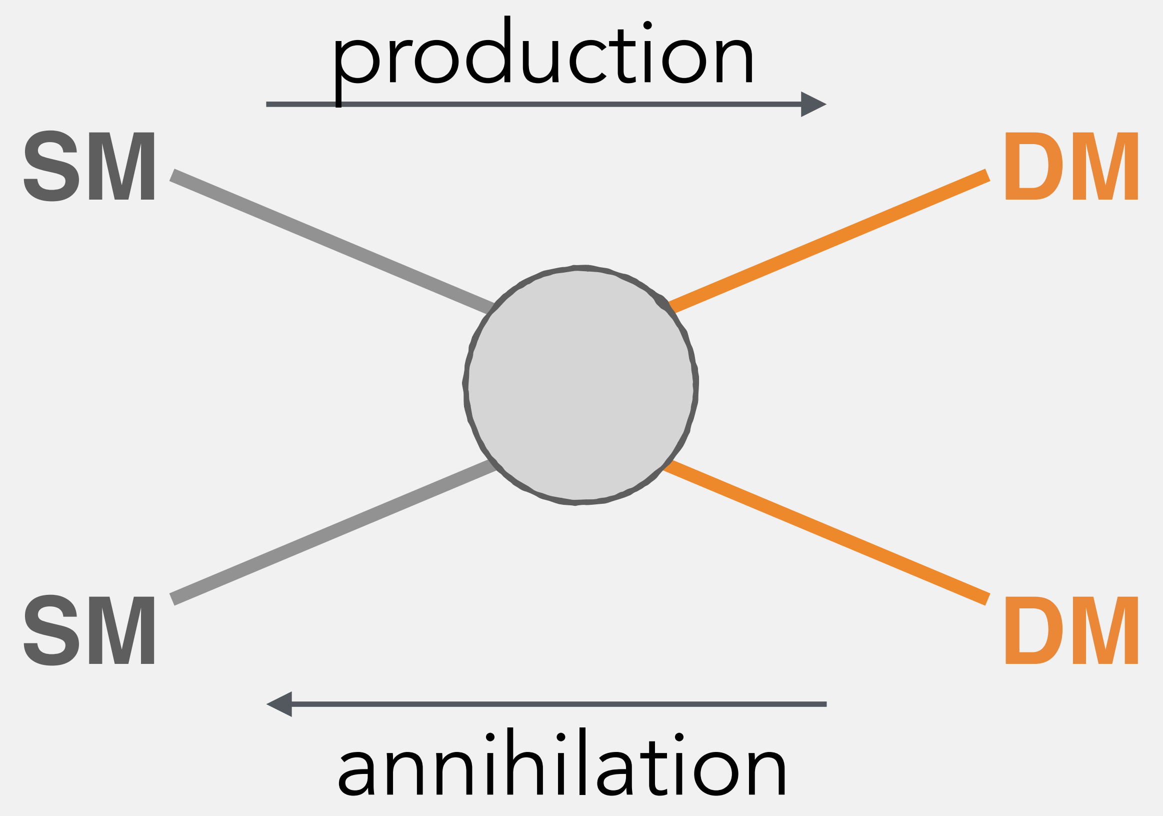

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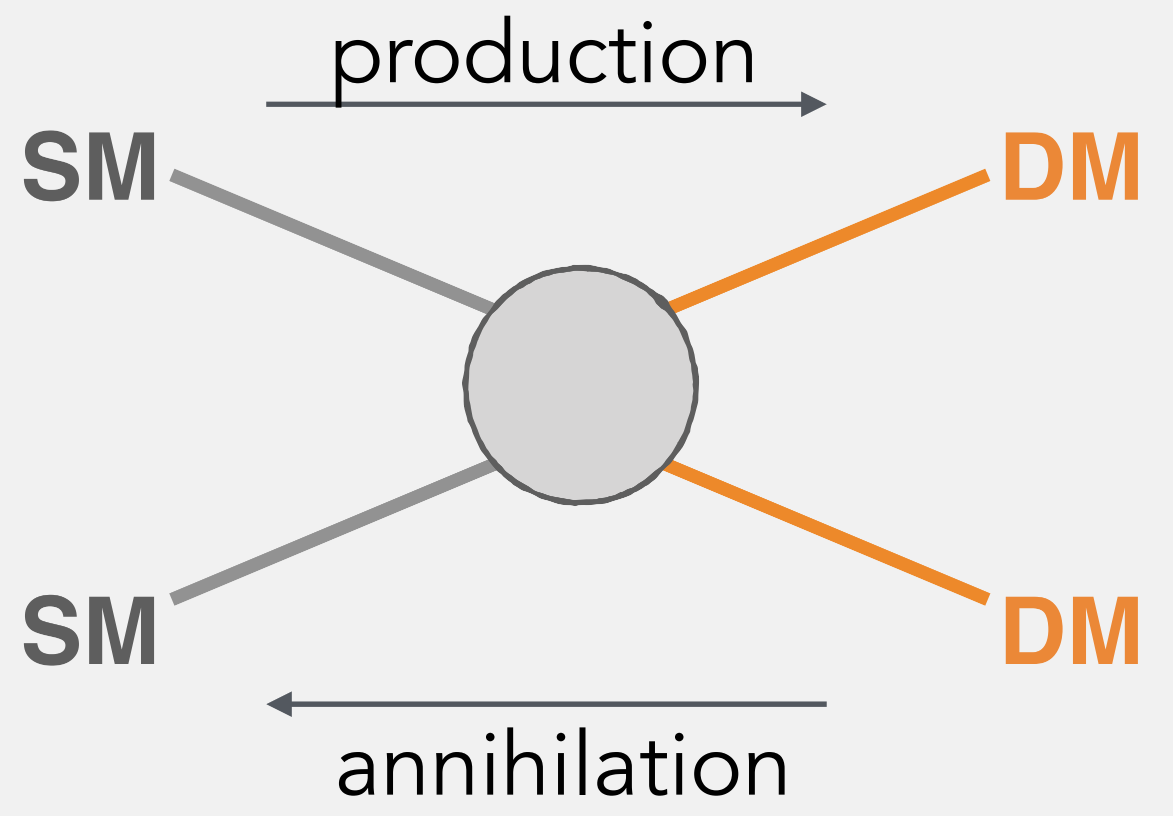

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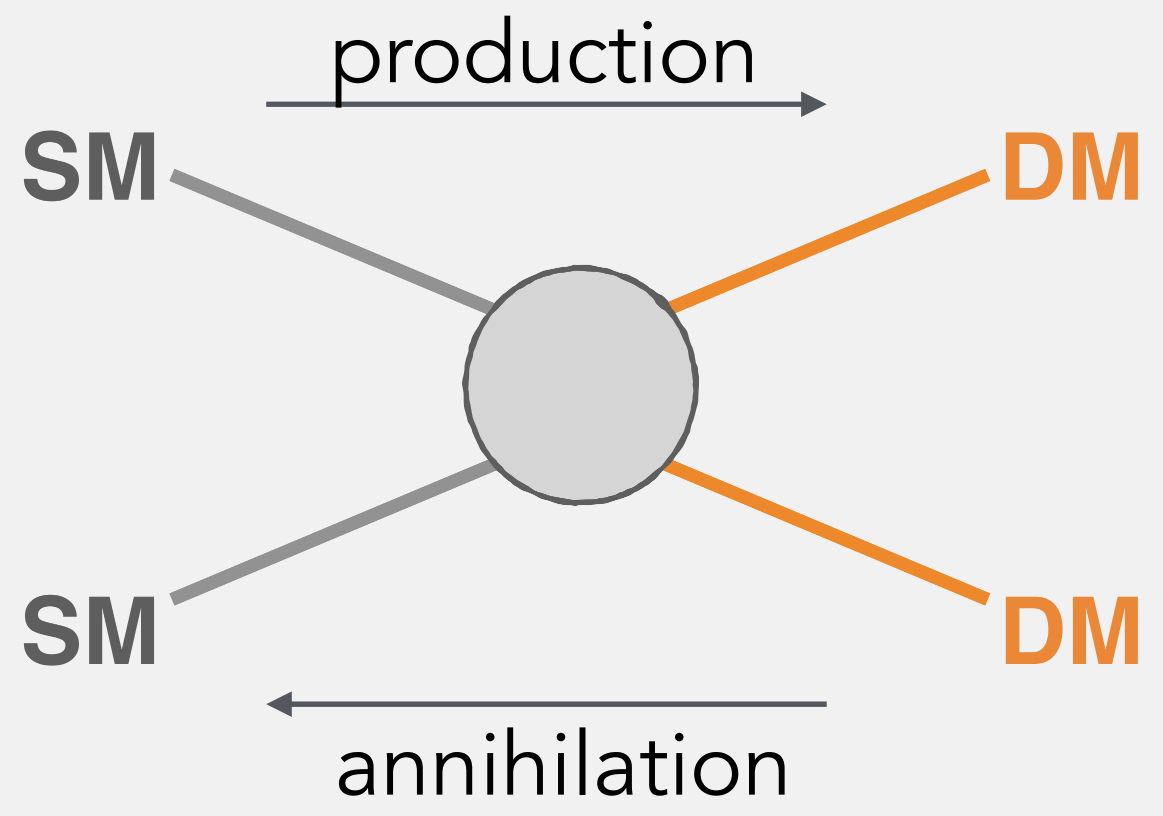

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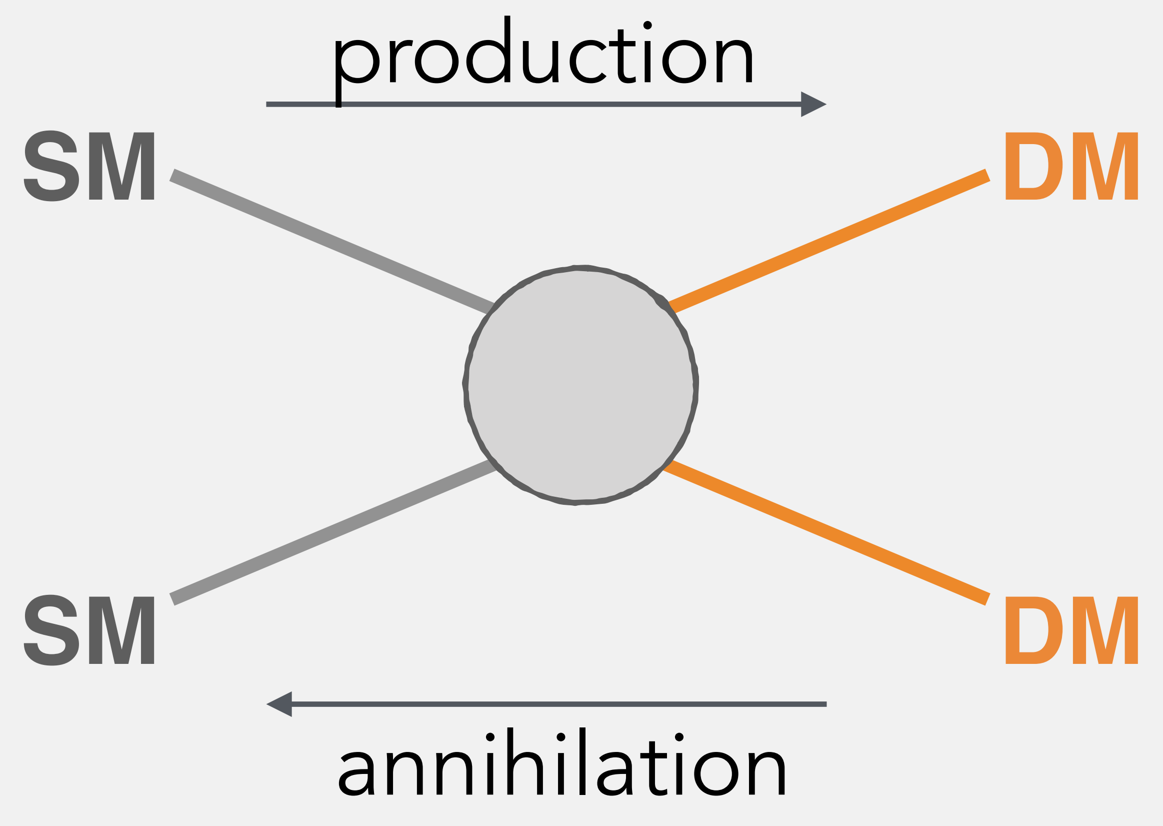

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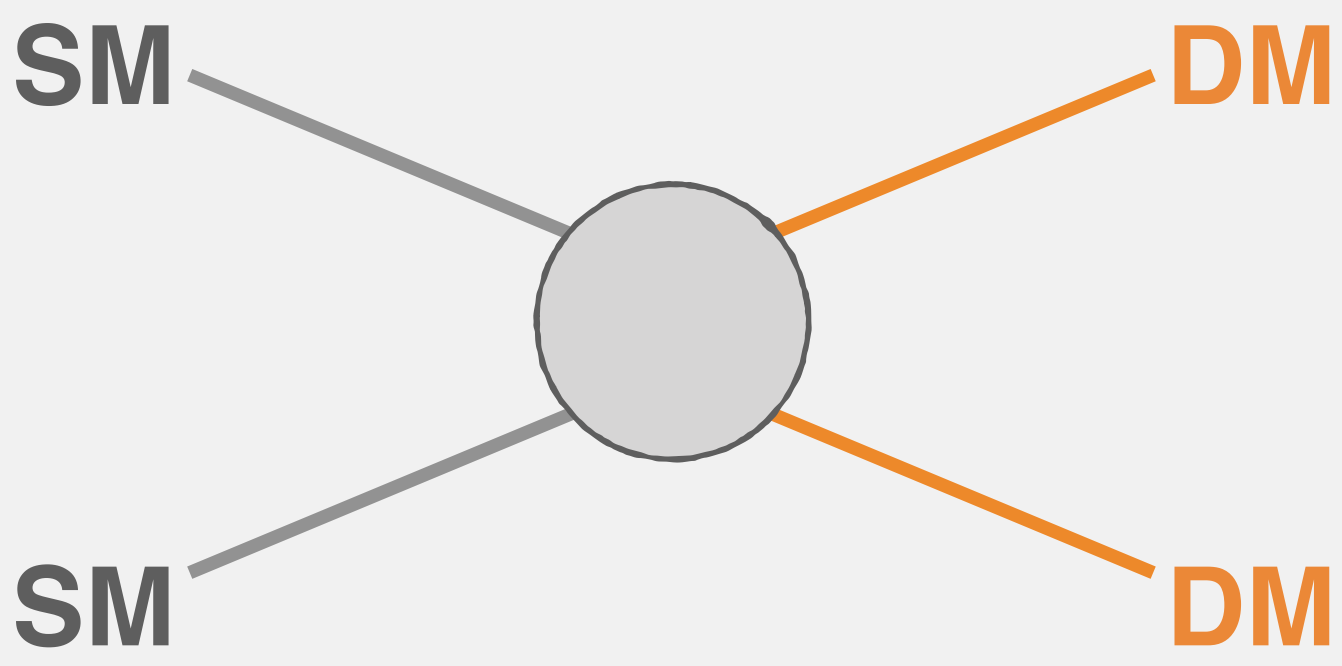
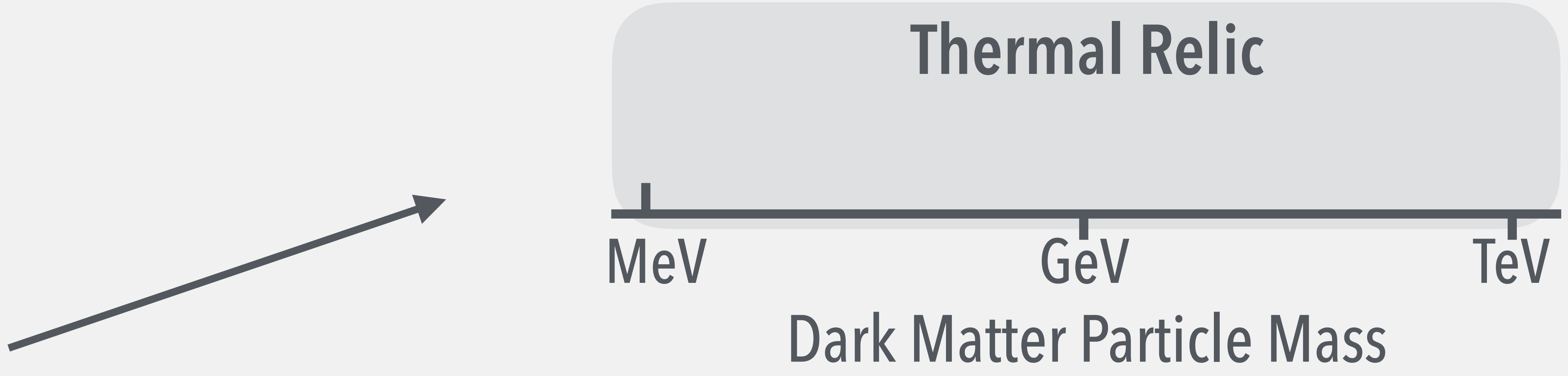
below: problems with BBN, structure formation, ΔN_{eff}

above: too much DM

Searches for Thermal Relic DM





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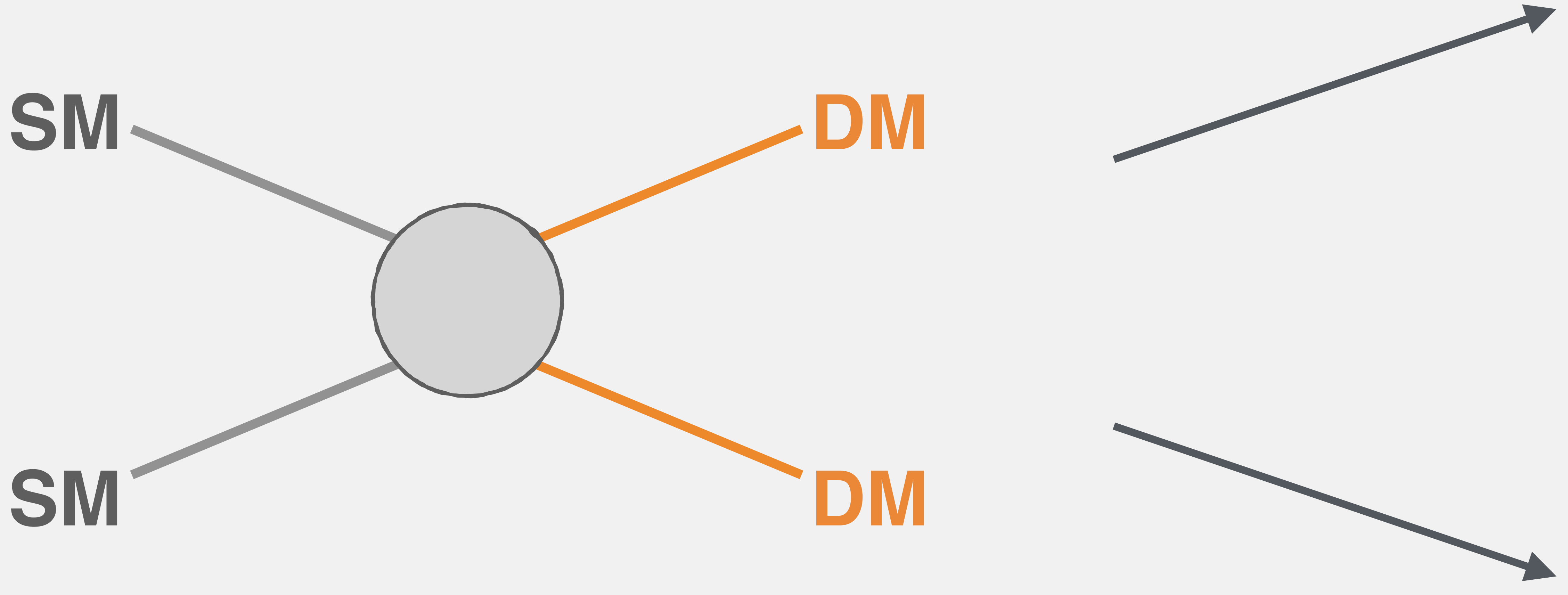

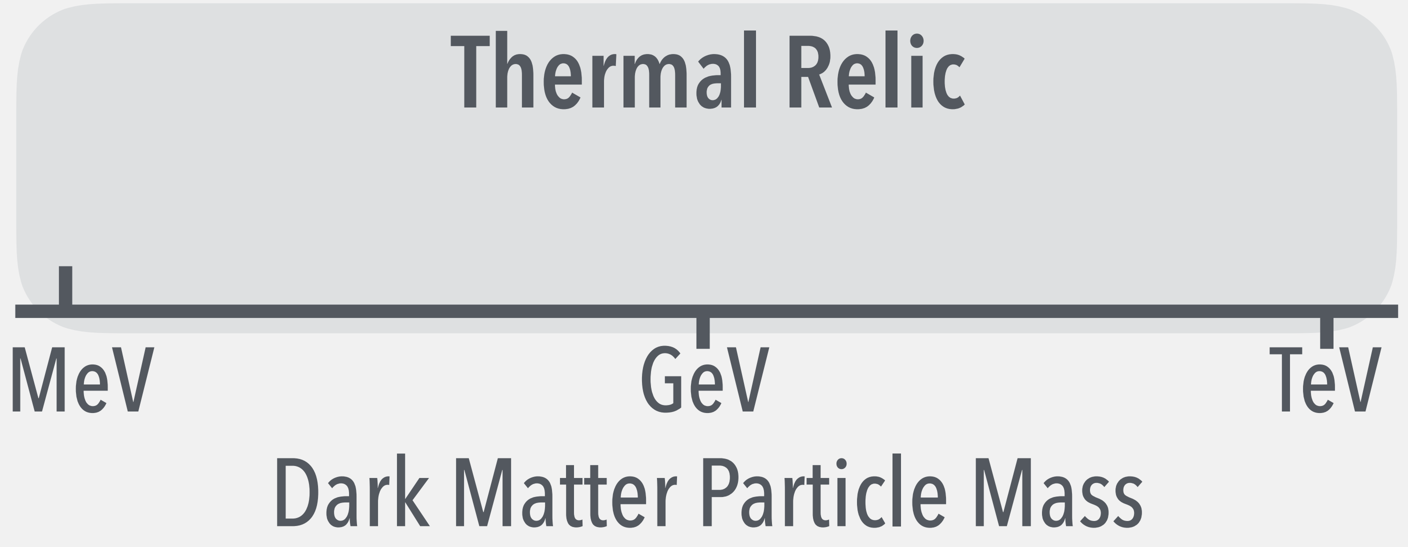

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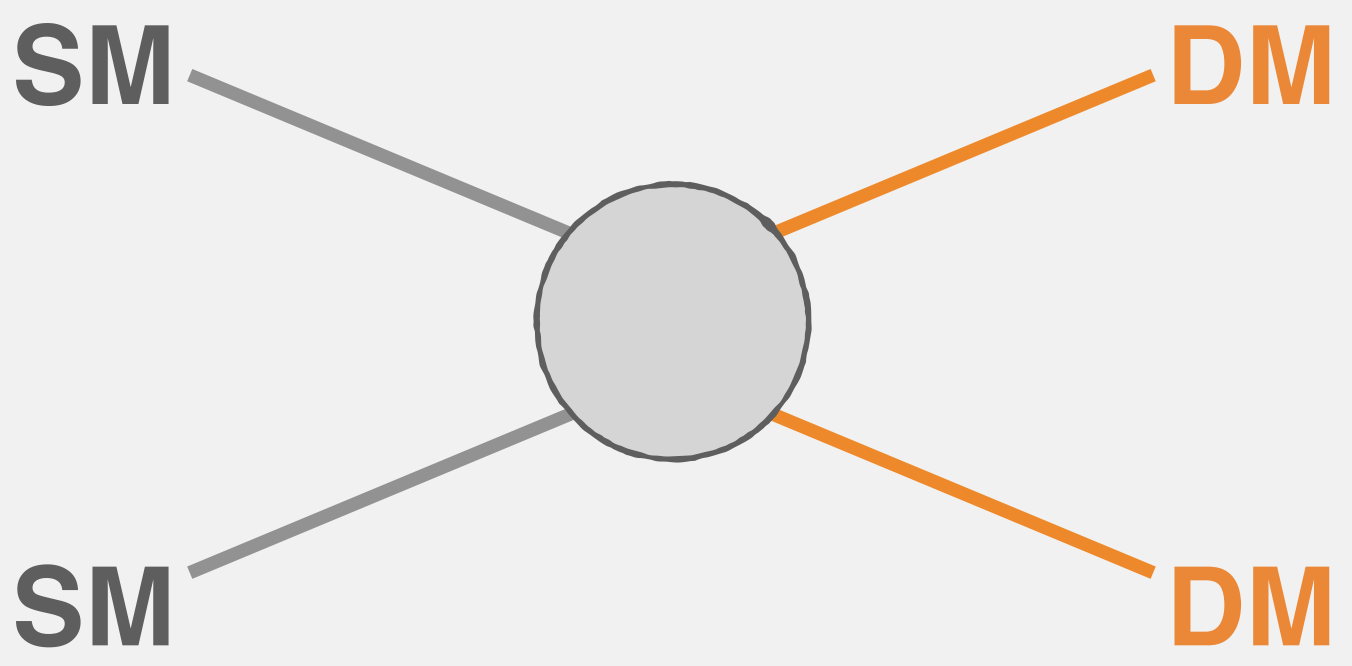

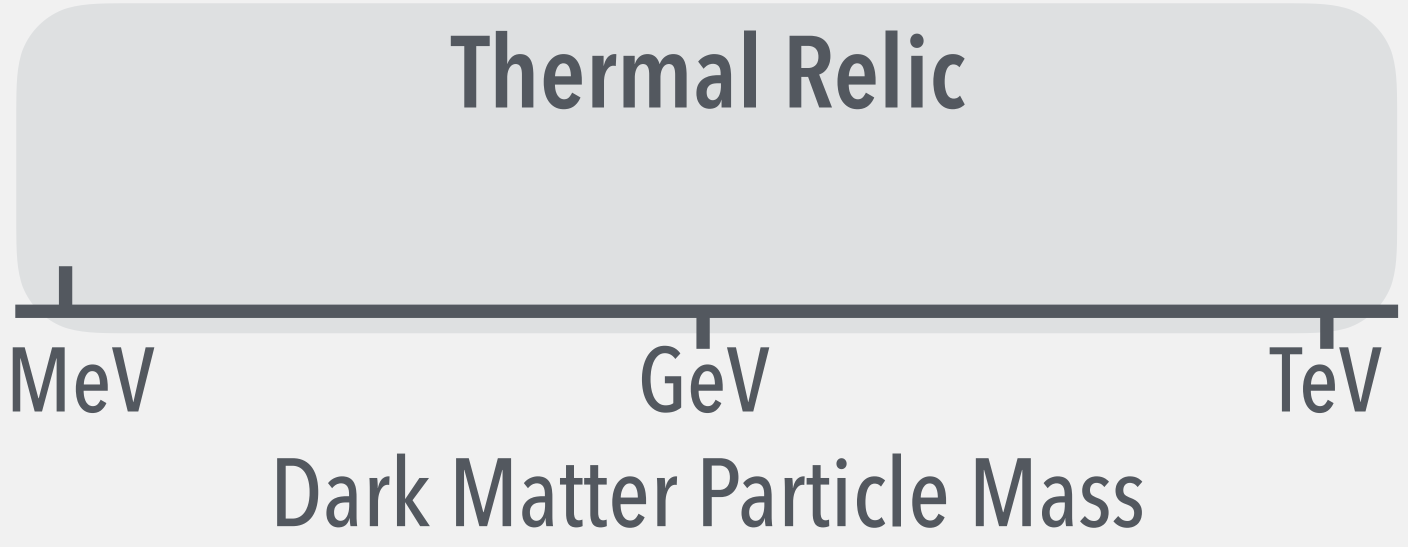

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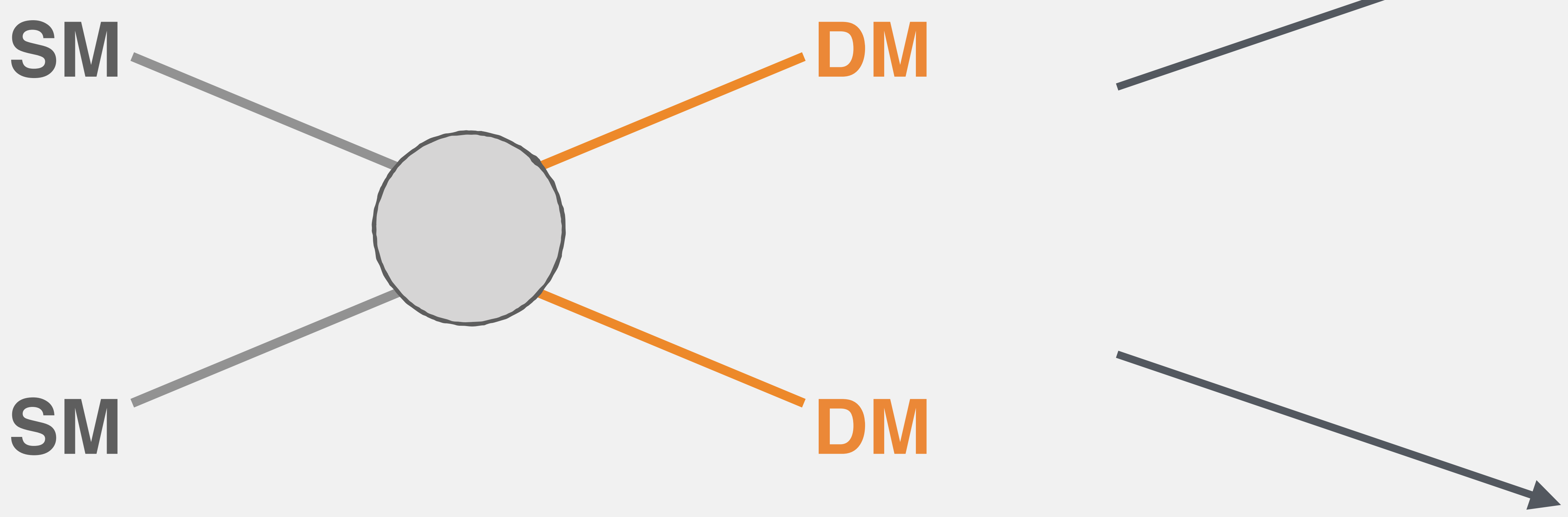

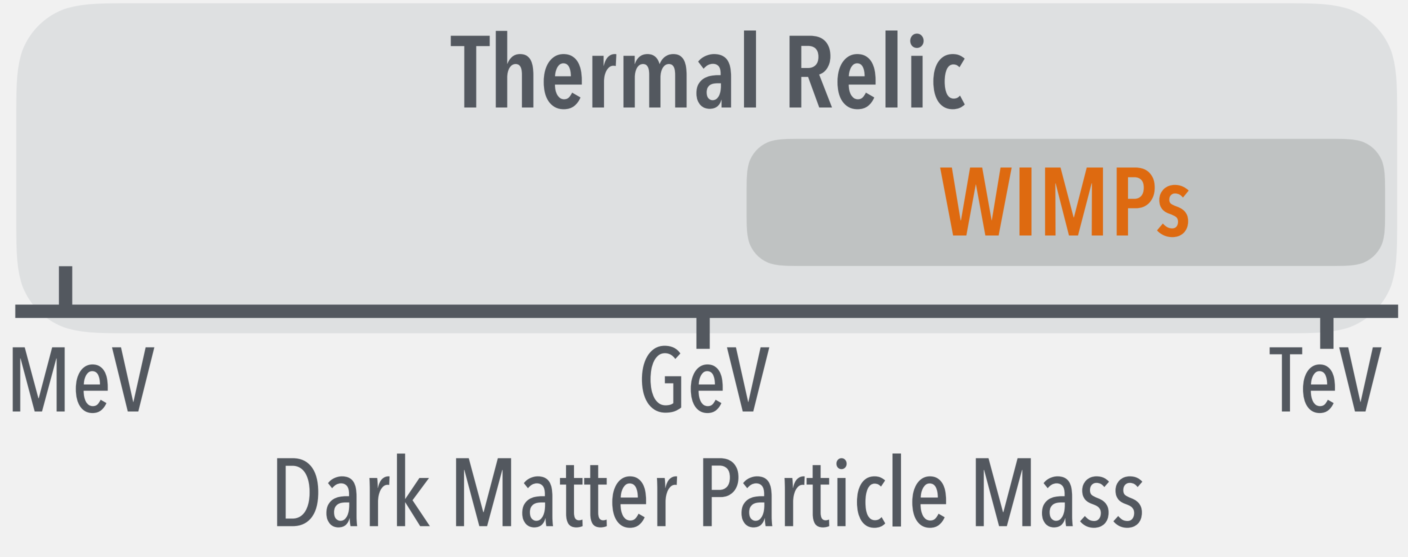

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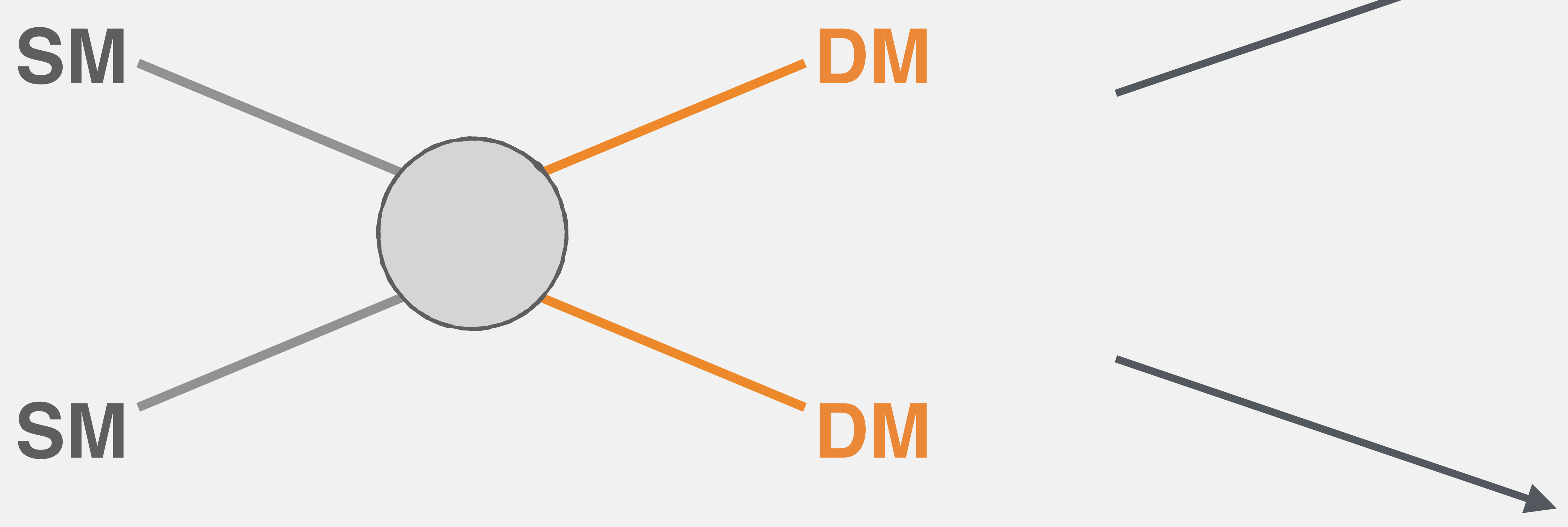

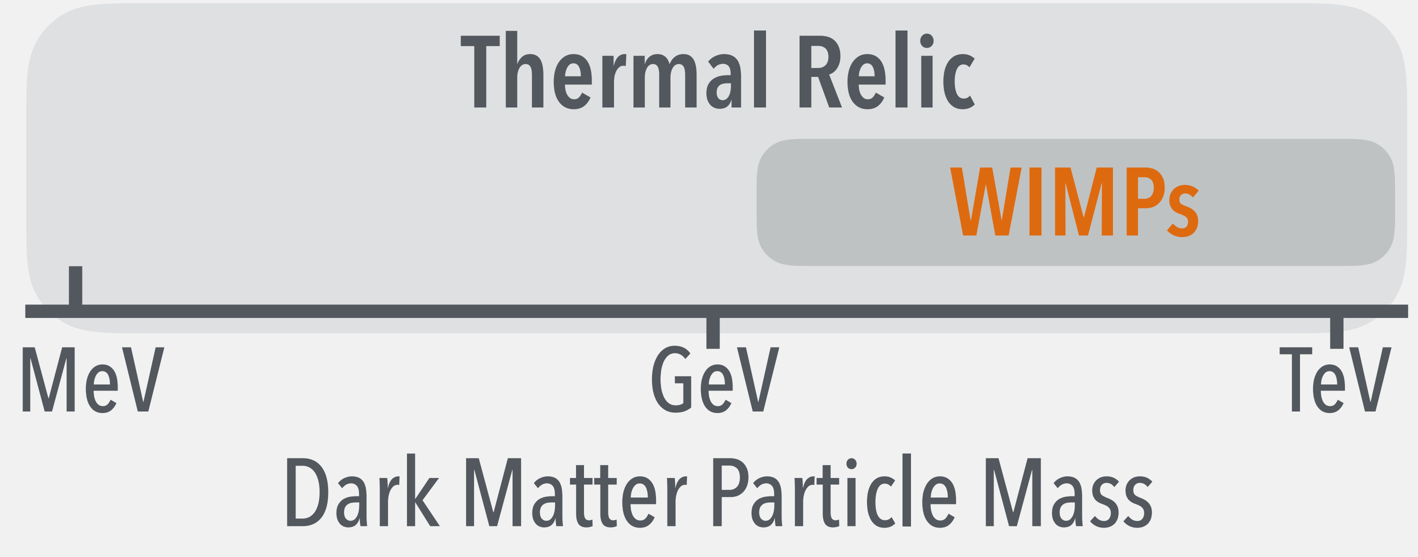

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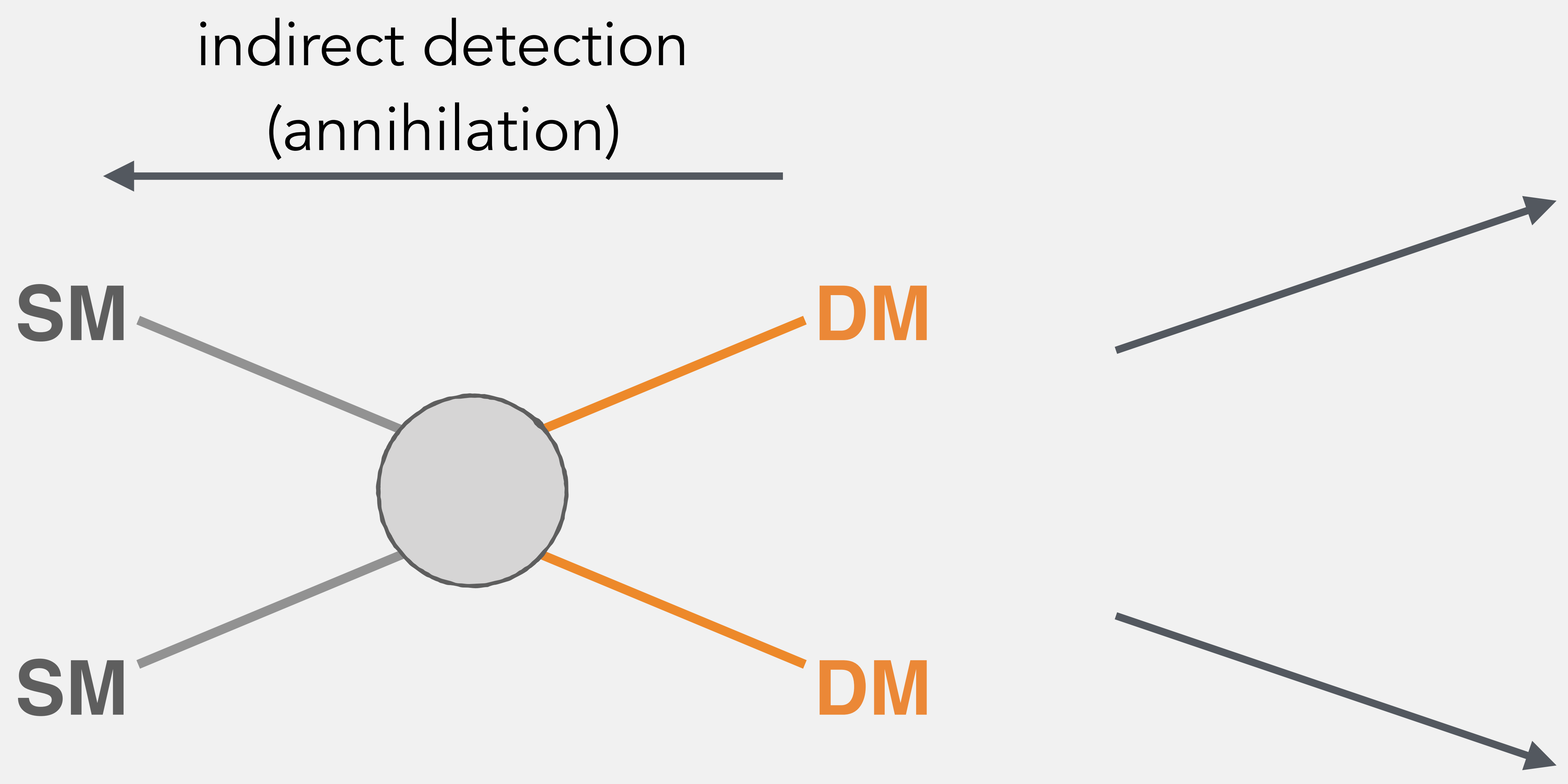

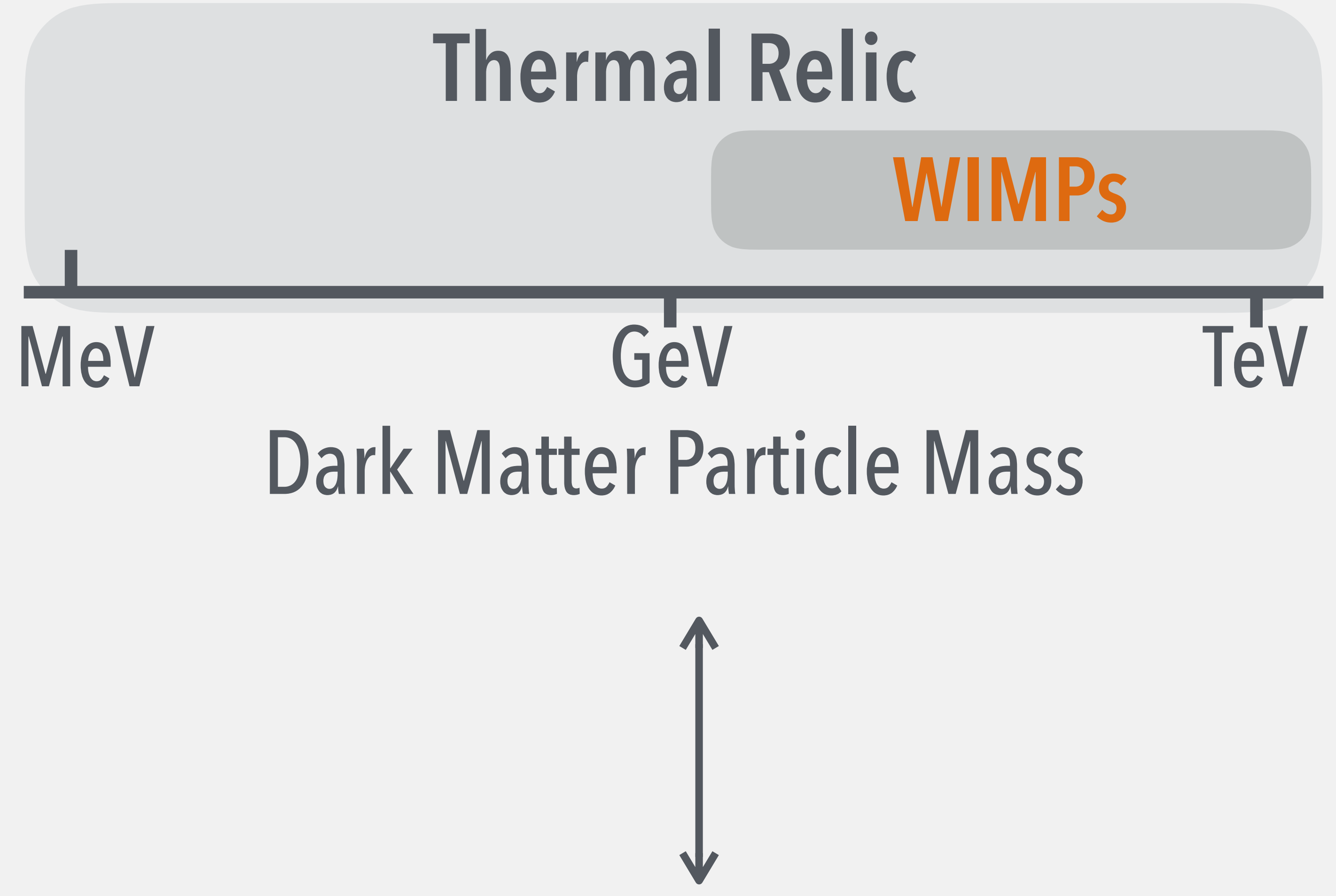

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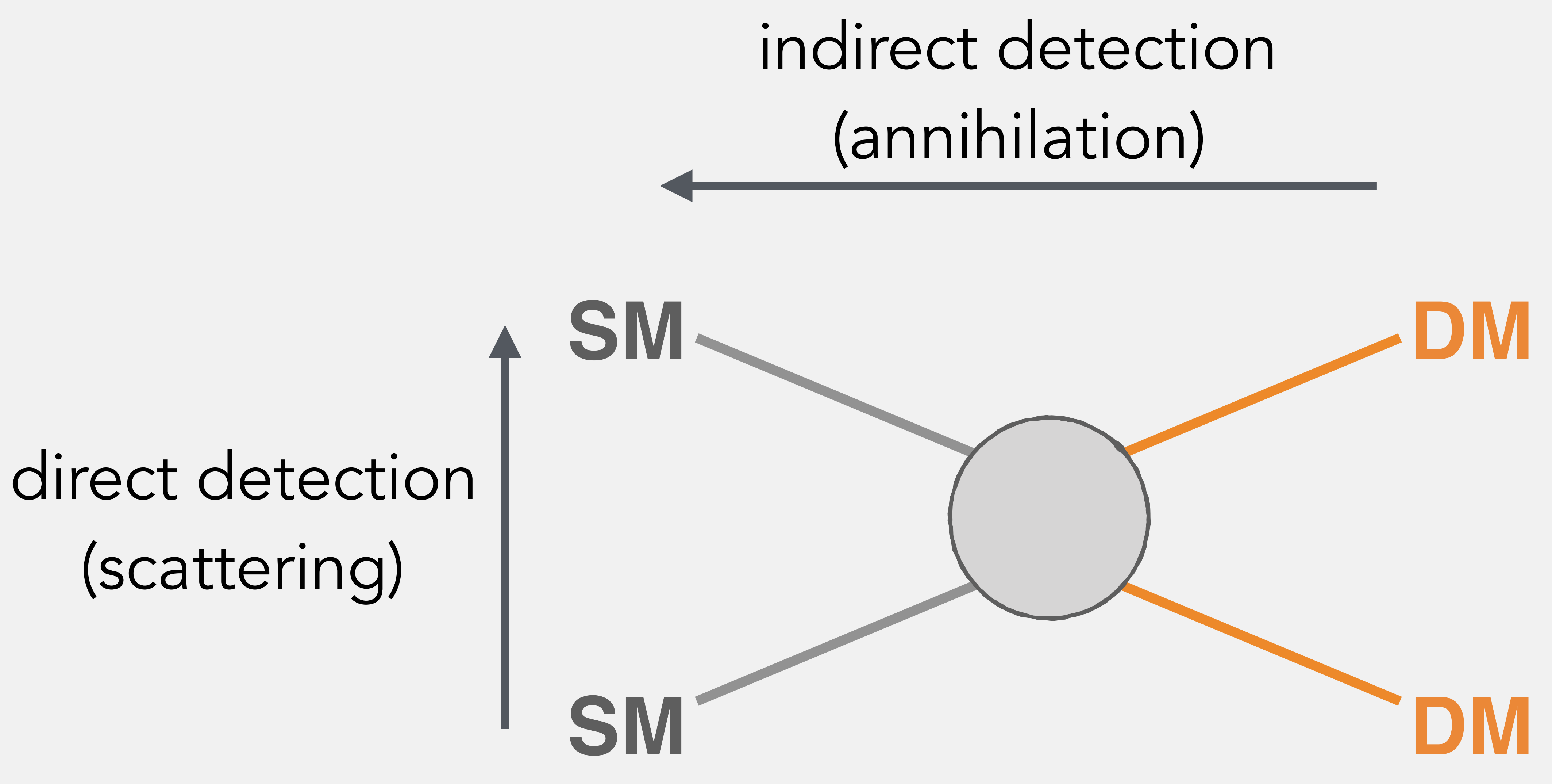

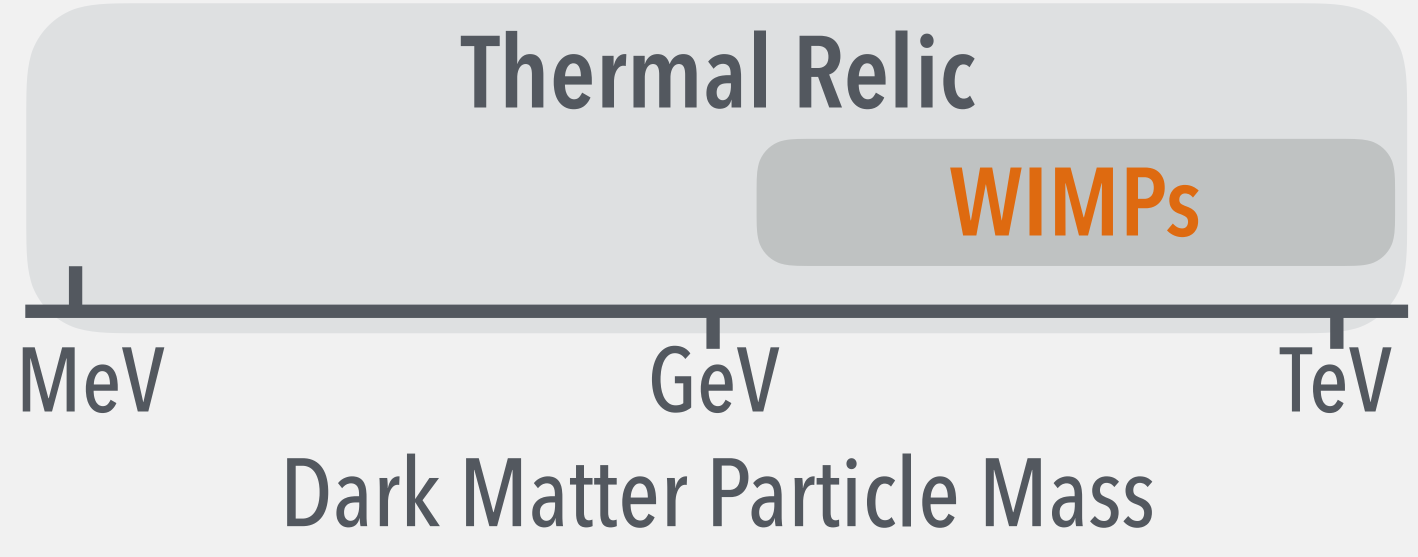

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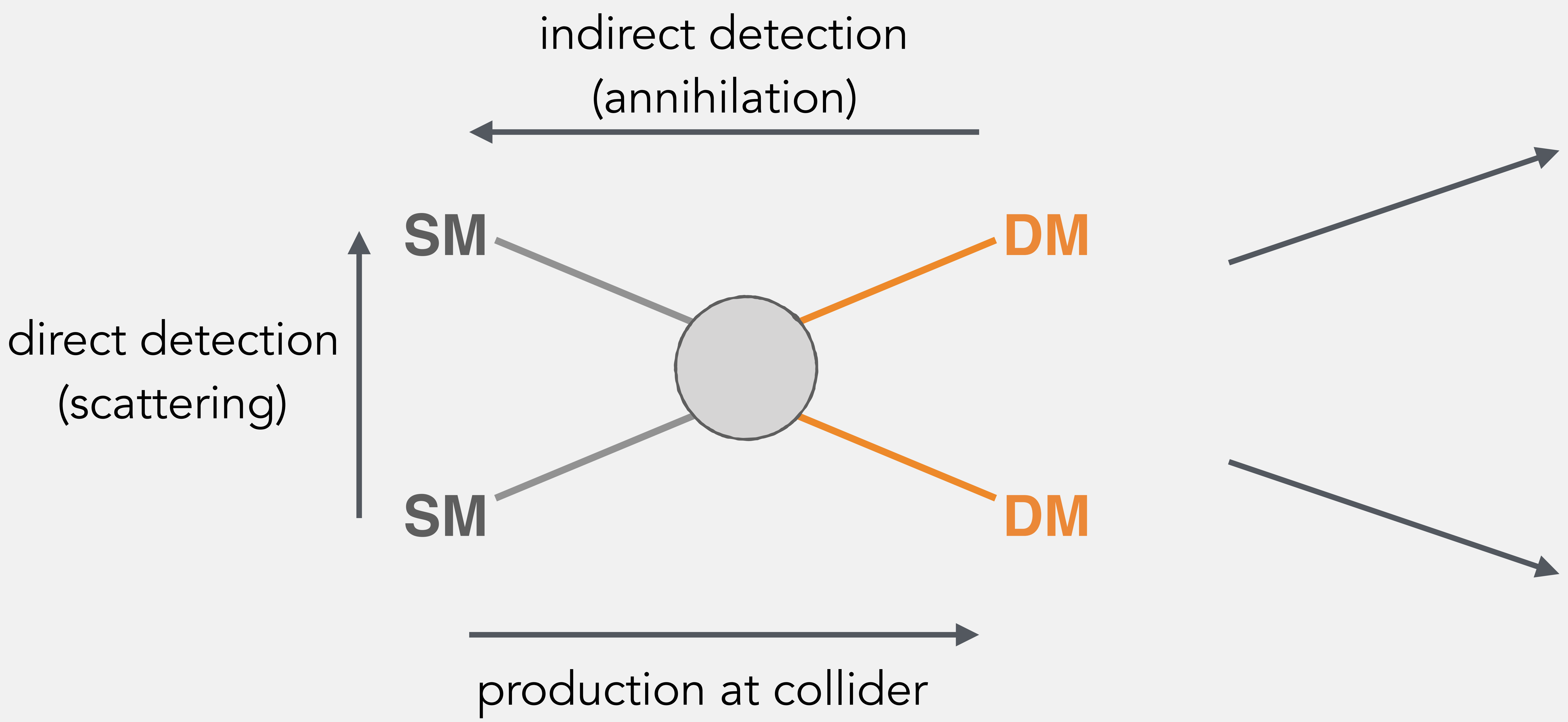

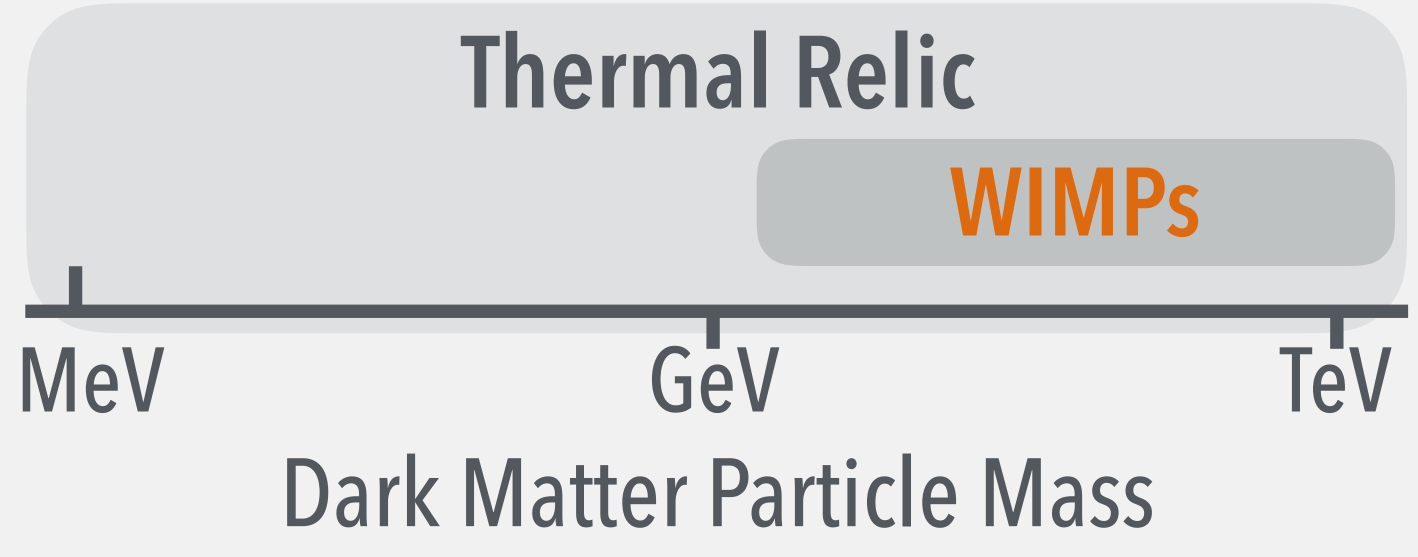

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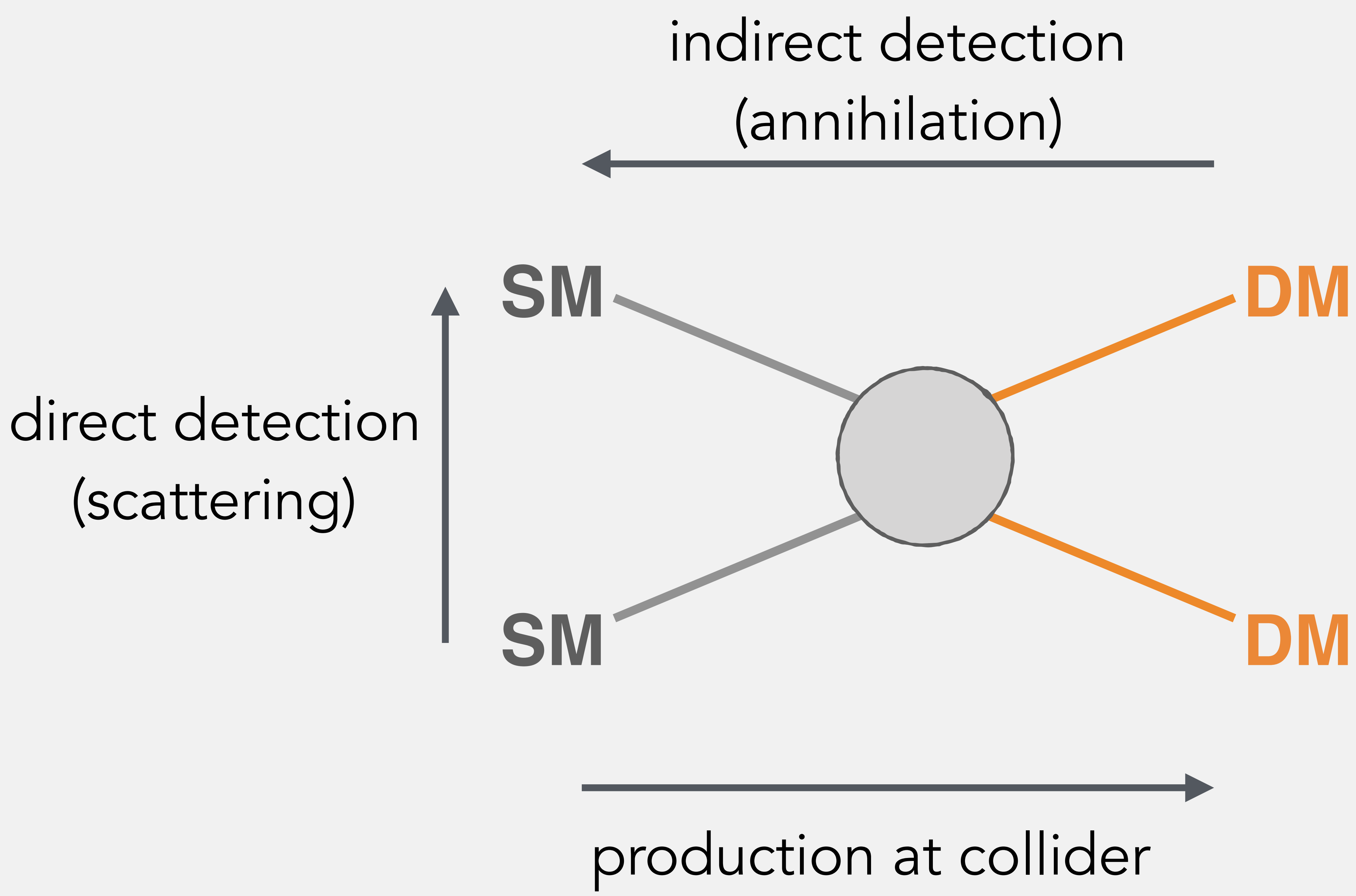

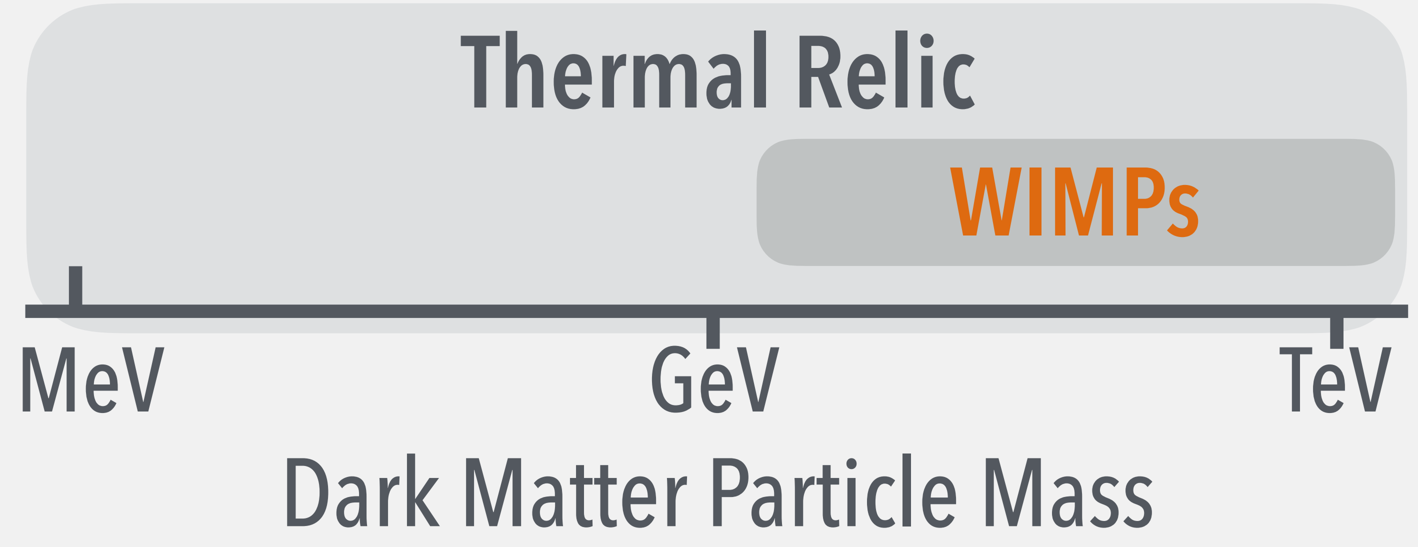

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No observation so far.

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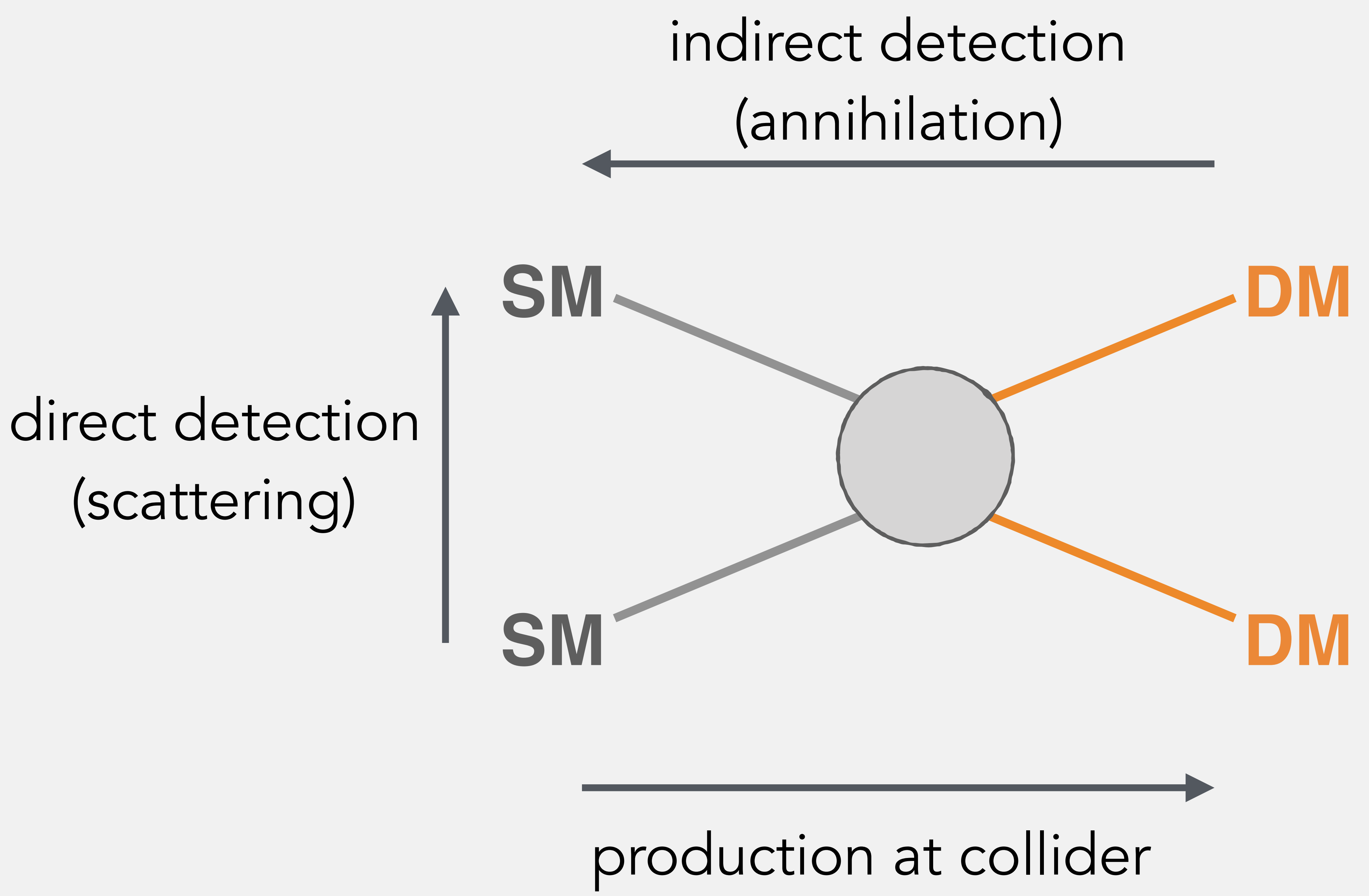

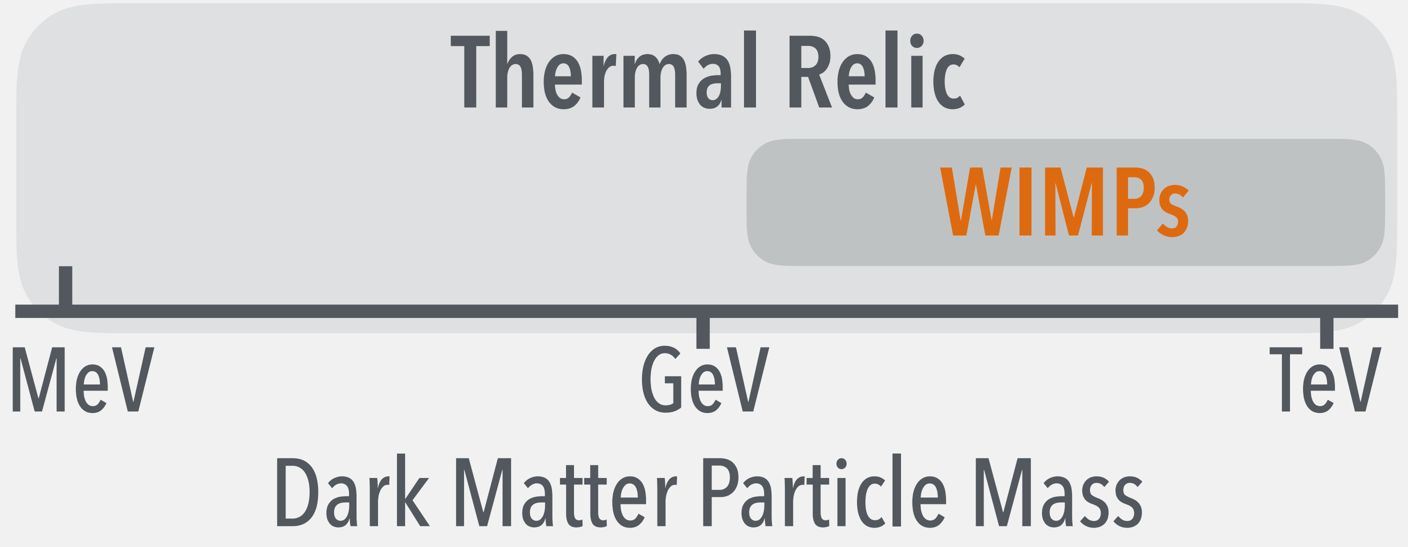

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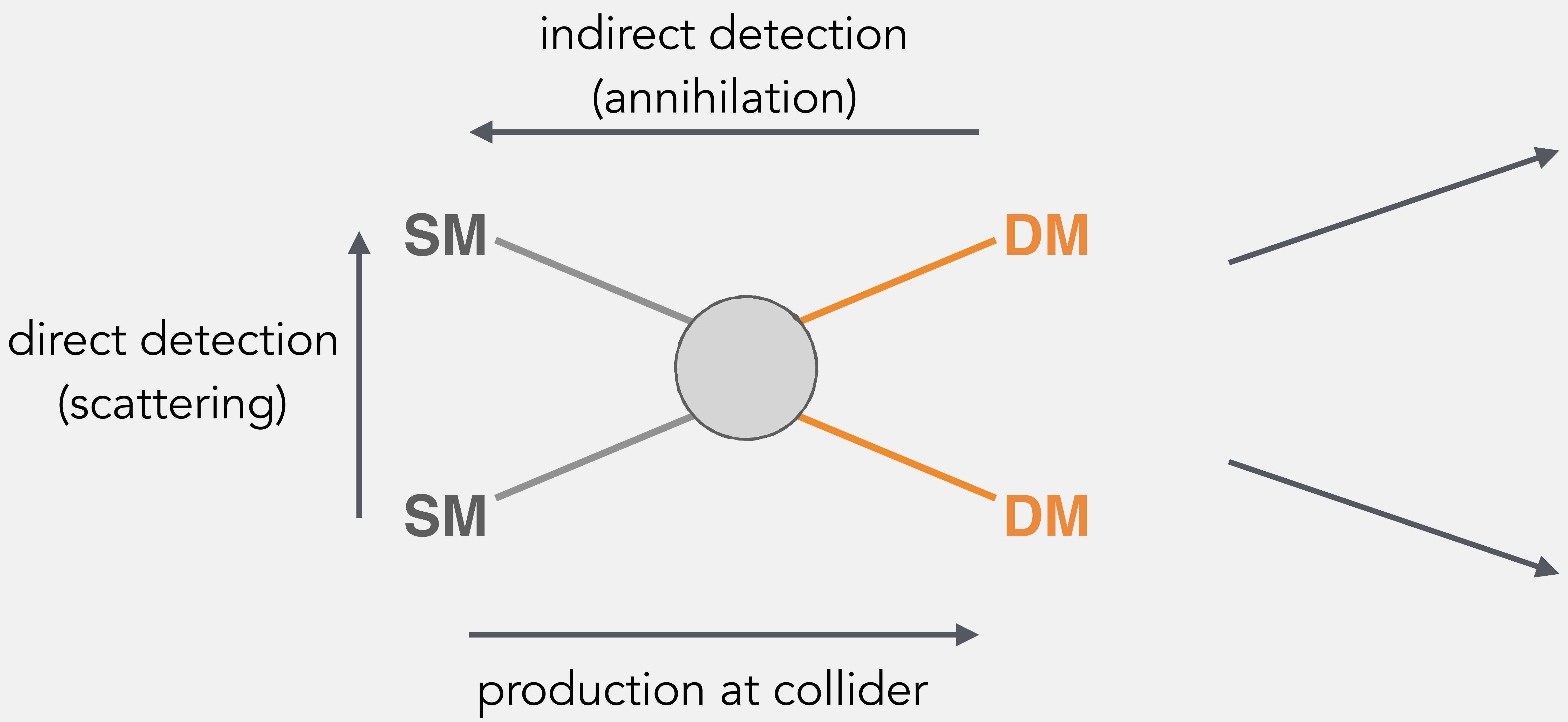

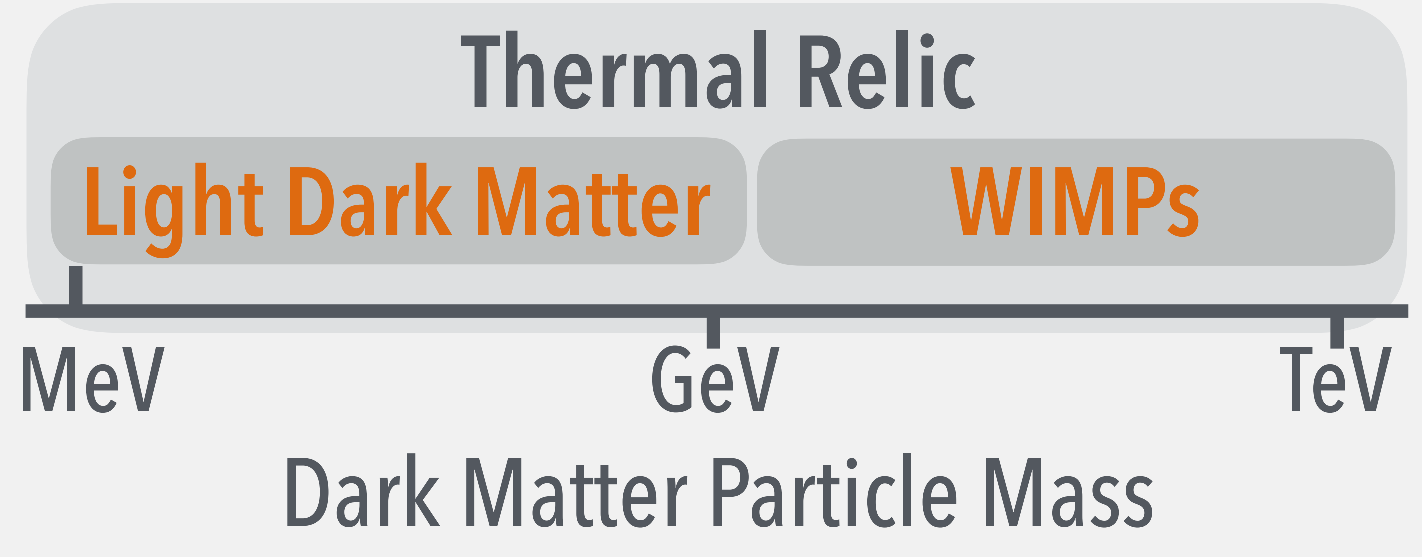

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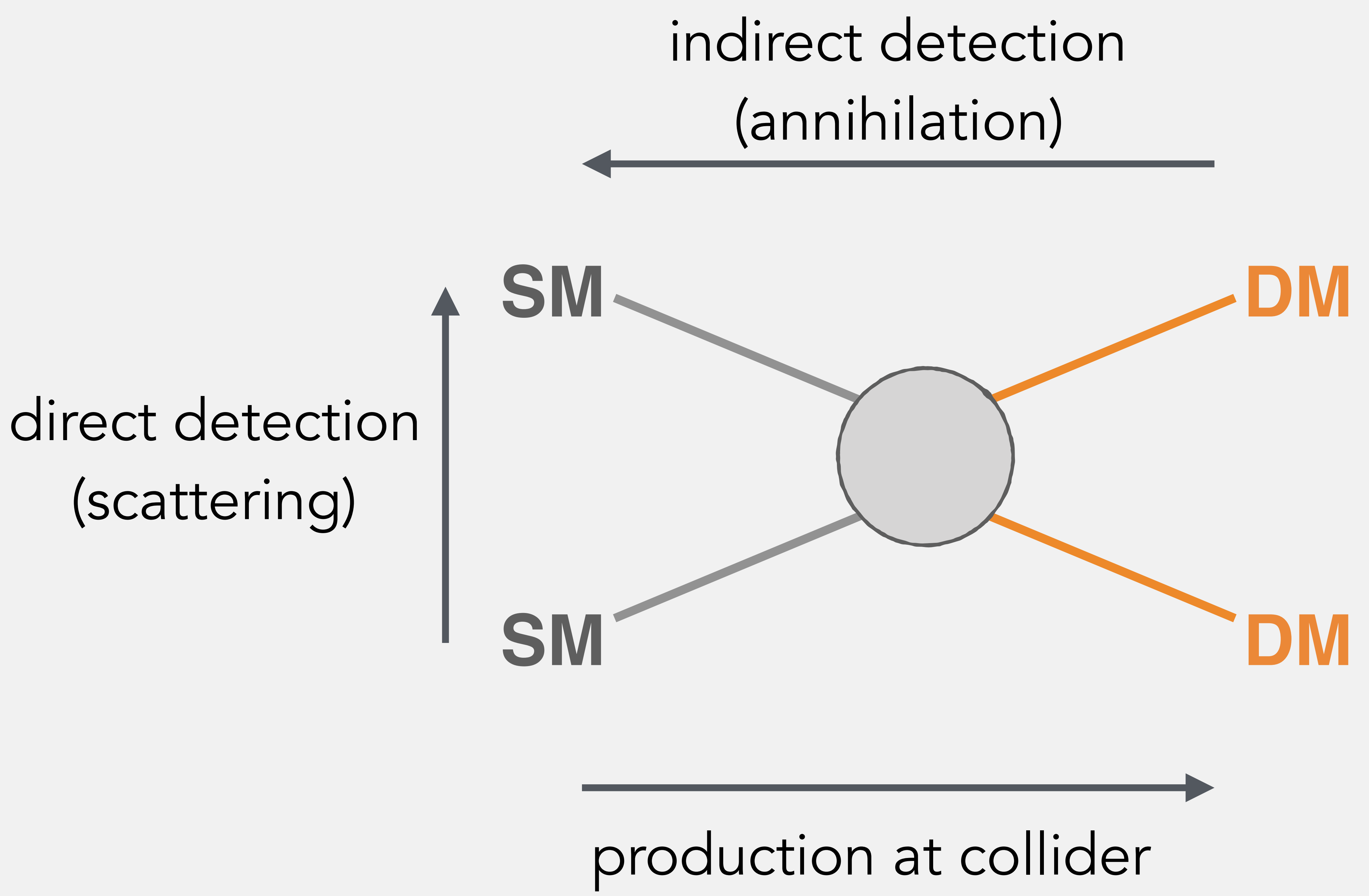

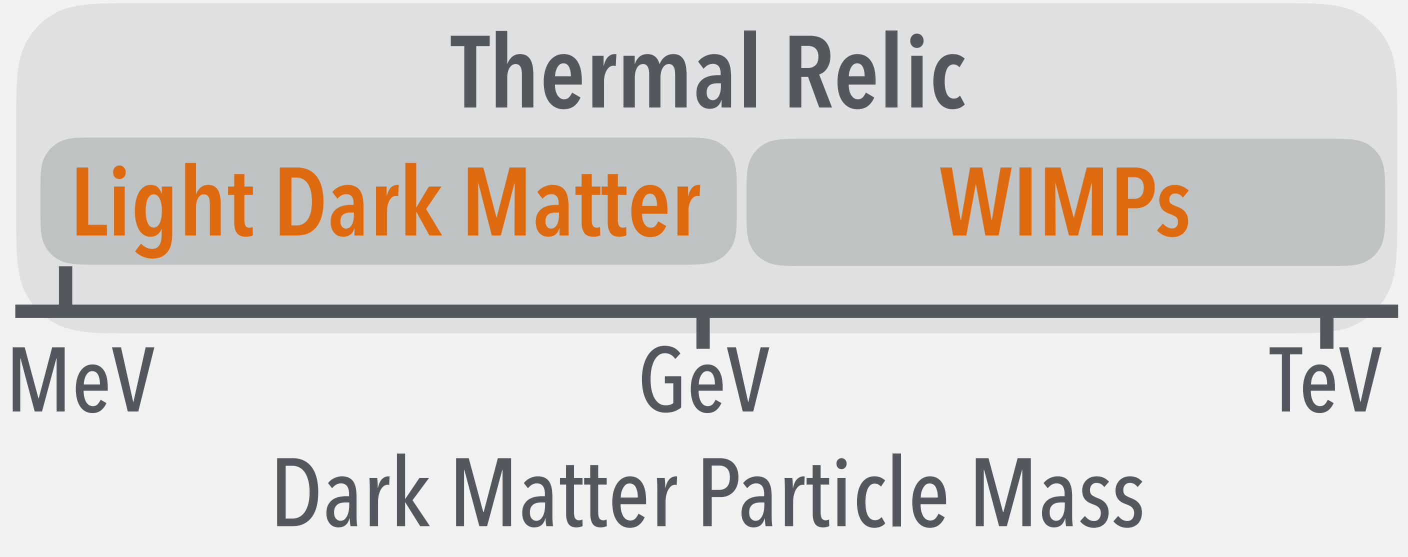

Some *non-gravitational* interaction!
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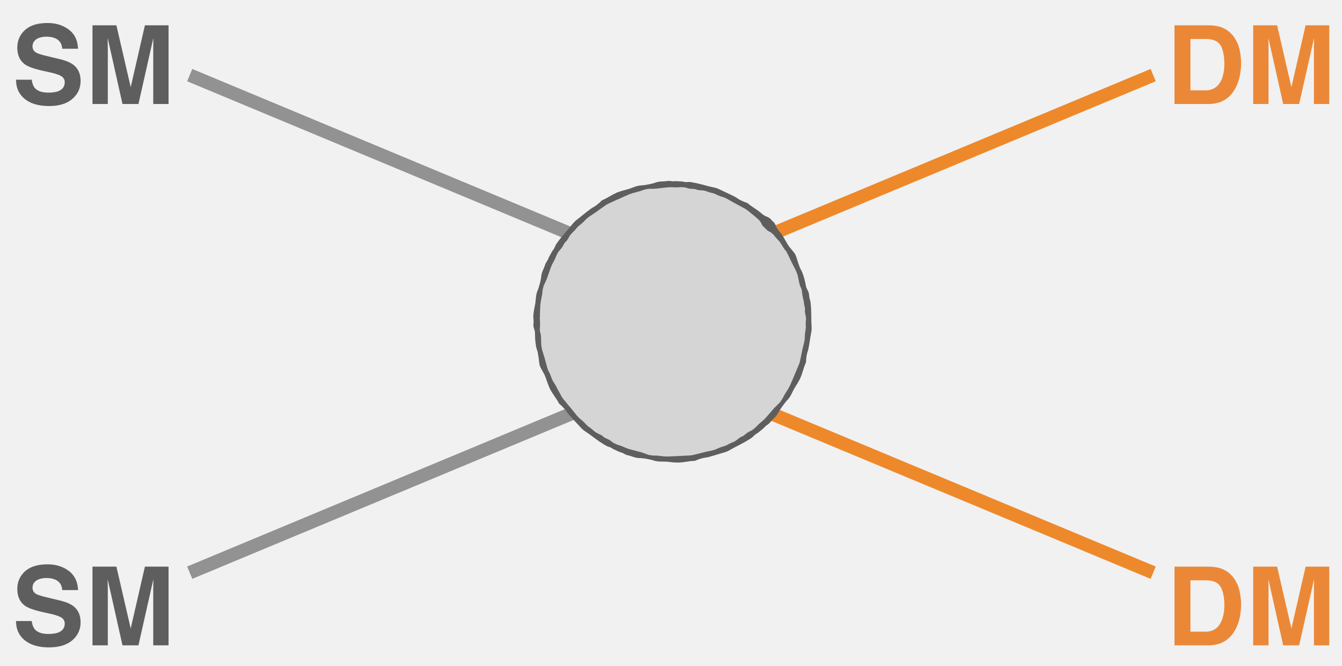
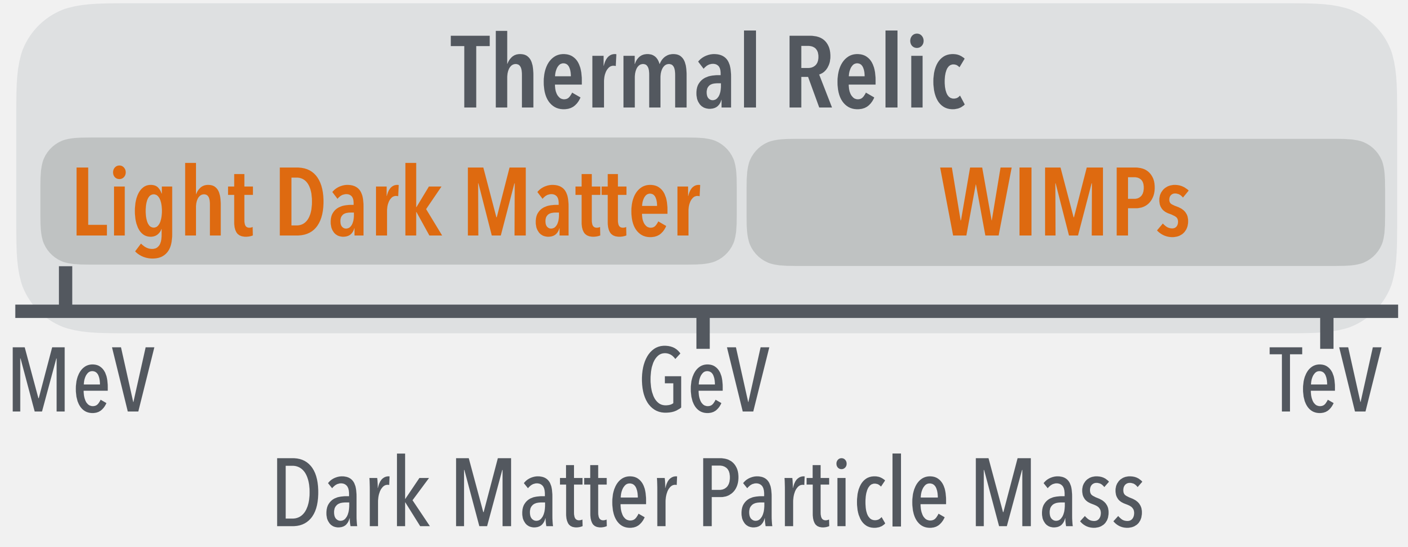
new feeble interaction

~known weak interaction of Standard Model

Searches for Thermal Relic DM





Some *non-gravitational* interaction!

(i.e. we might detect it in experiments)

new feeble interaction

~known weak interaction of Standard Model

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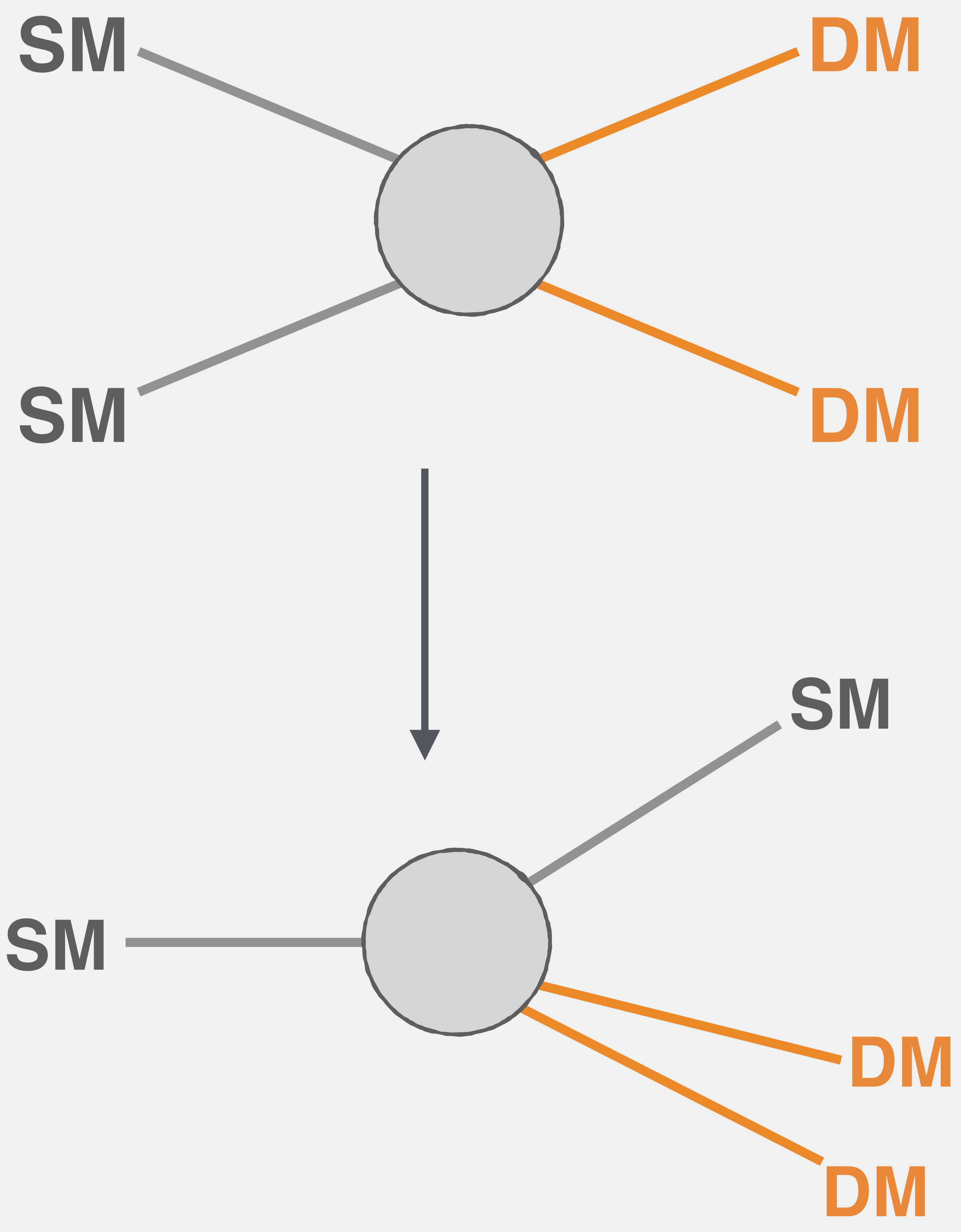

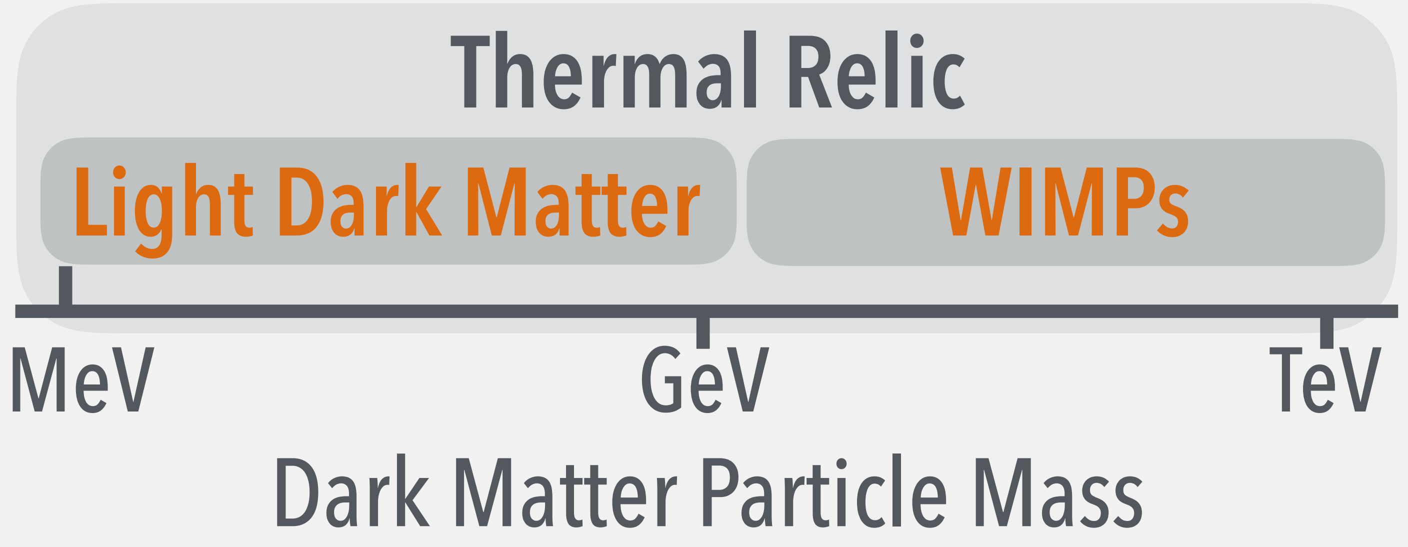

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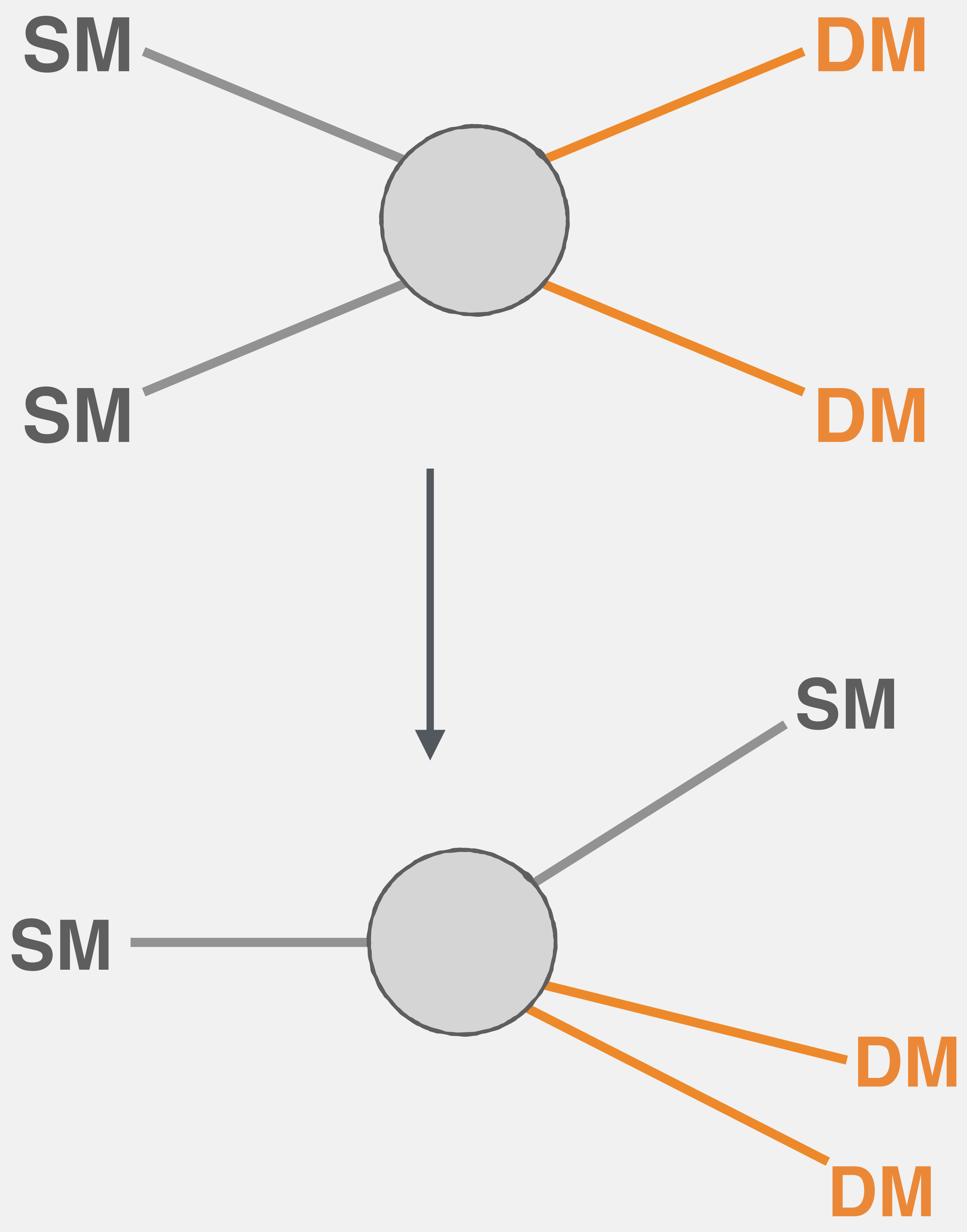
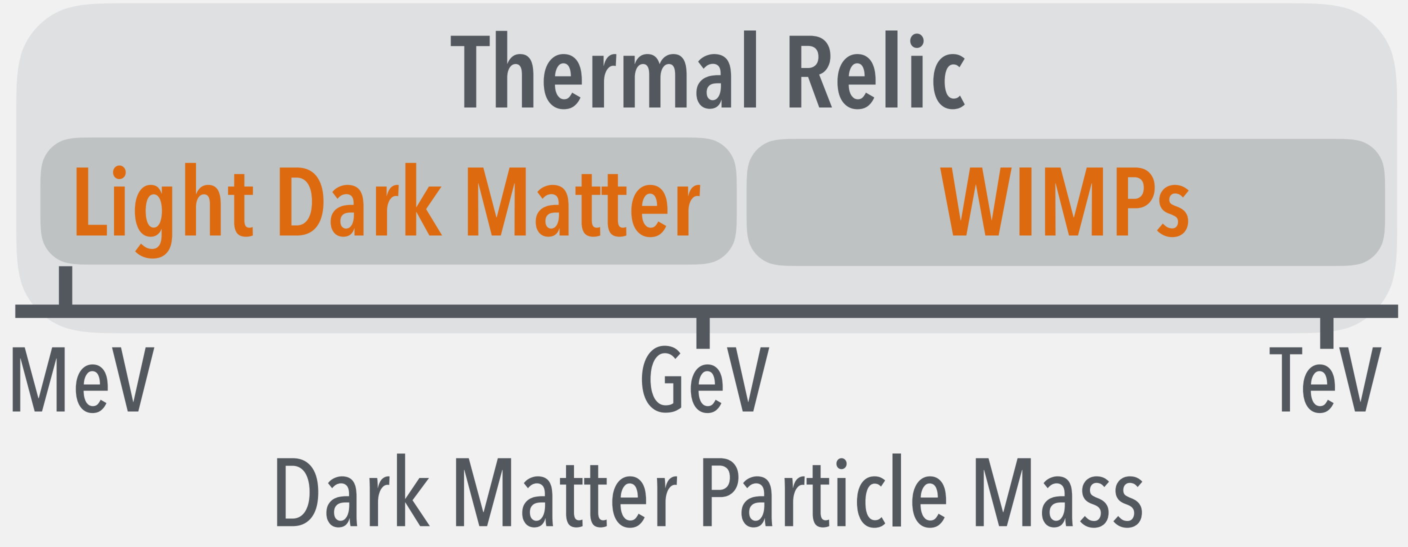


production mechanism at accelerators



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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)

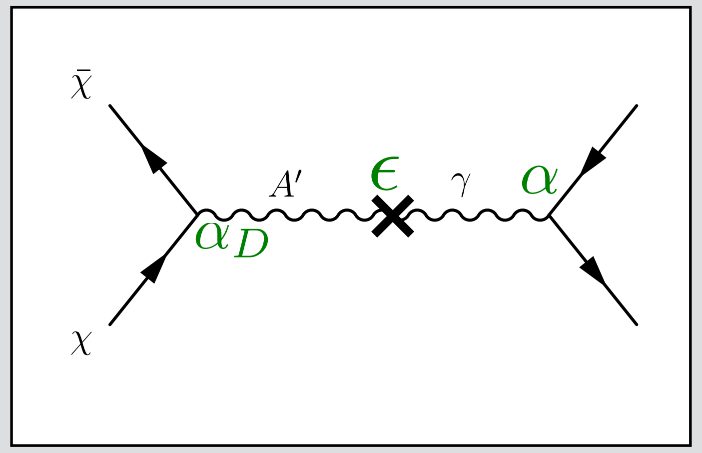
- annihilation into SM inefficient
  - overproduction of DM
- *Lee-Weinberg-bound*

introduce new, light mediator

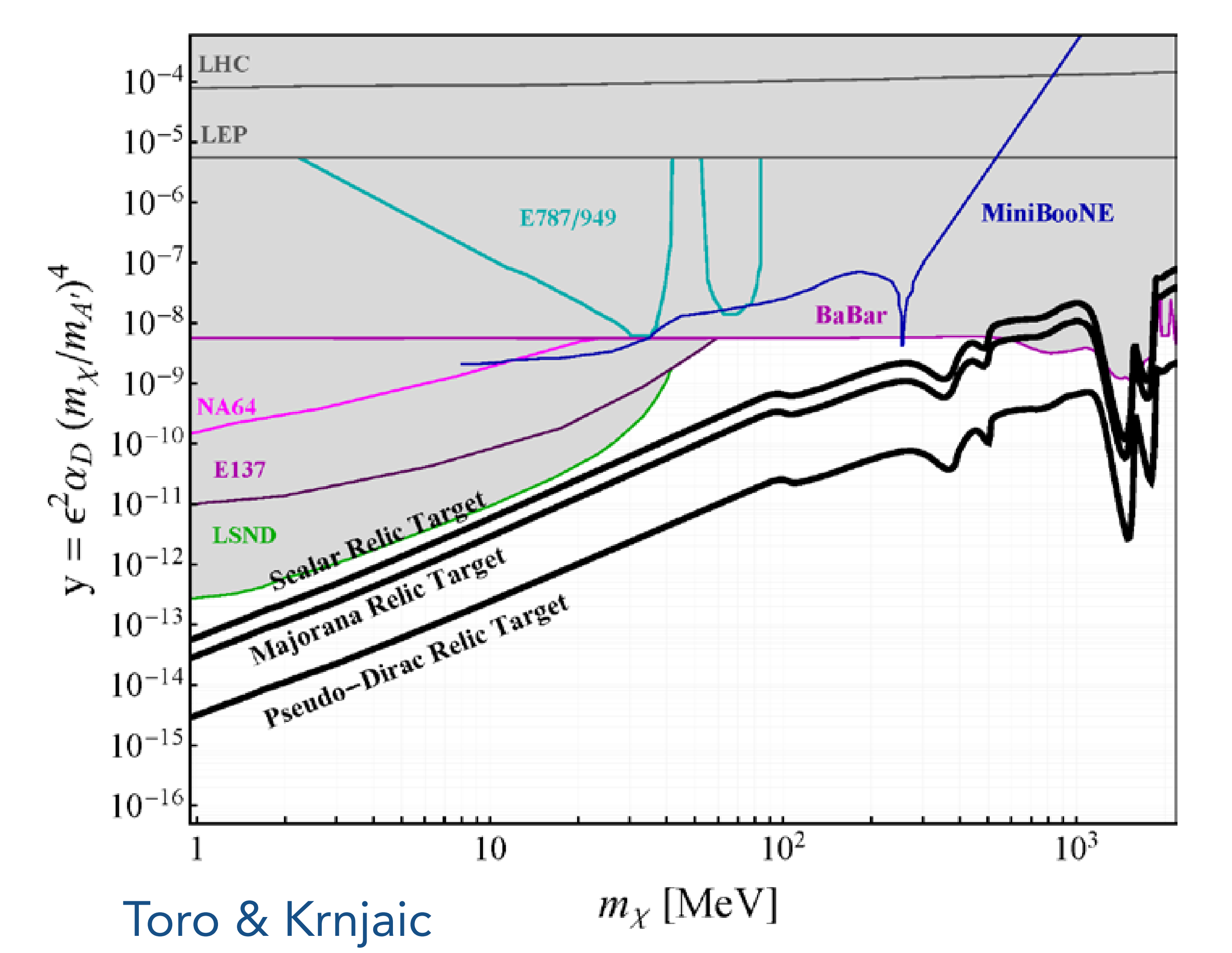
- additional annihilation channel
  - correct relic abundance

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:

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

Sub-GeV Dark Matter Detection

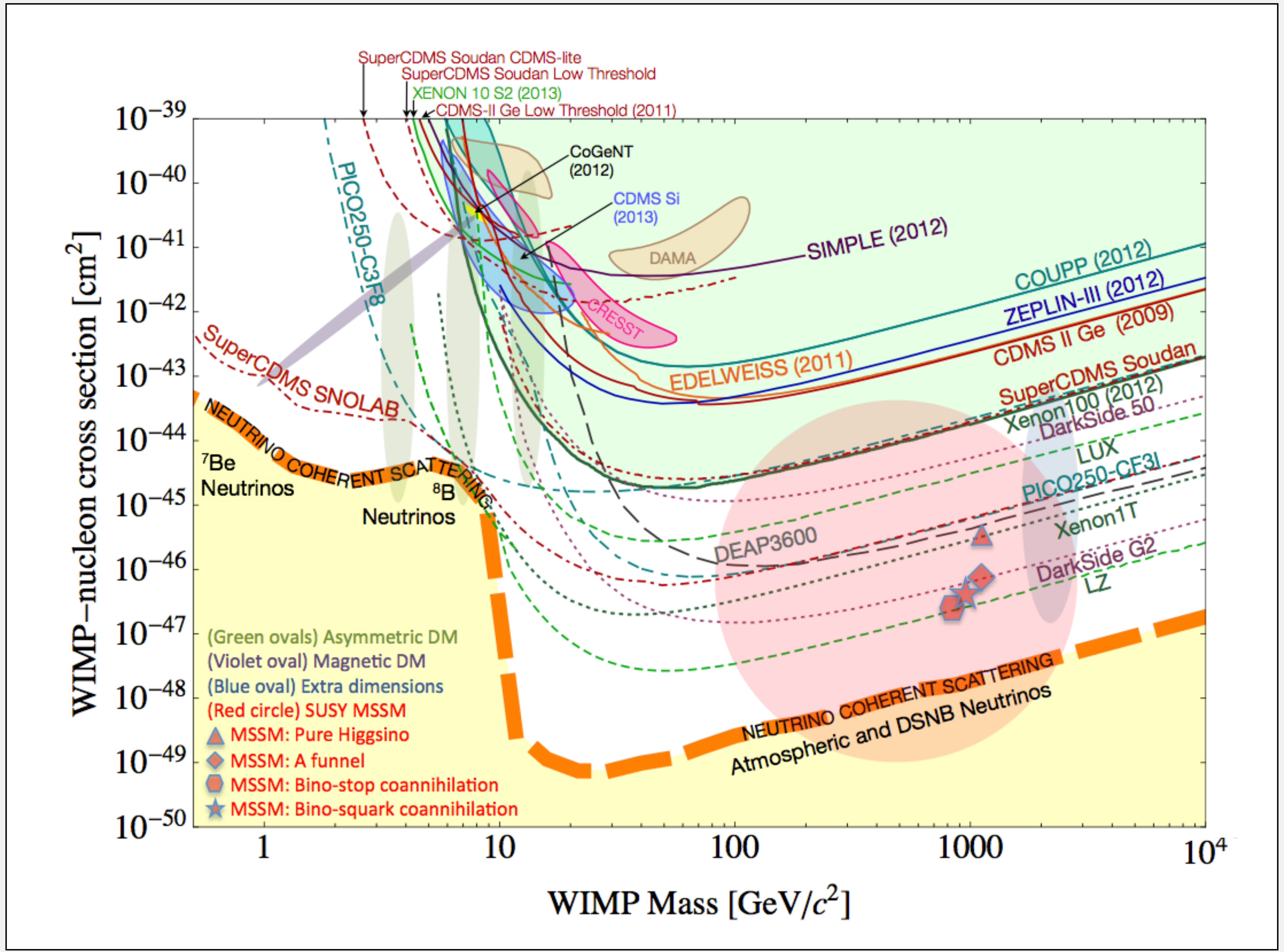
Direct Detection

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

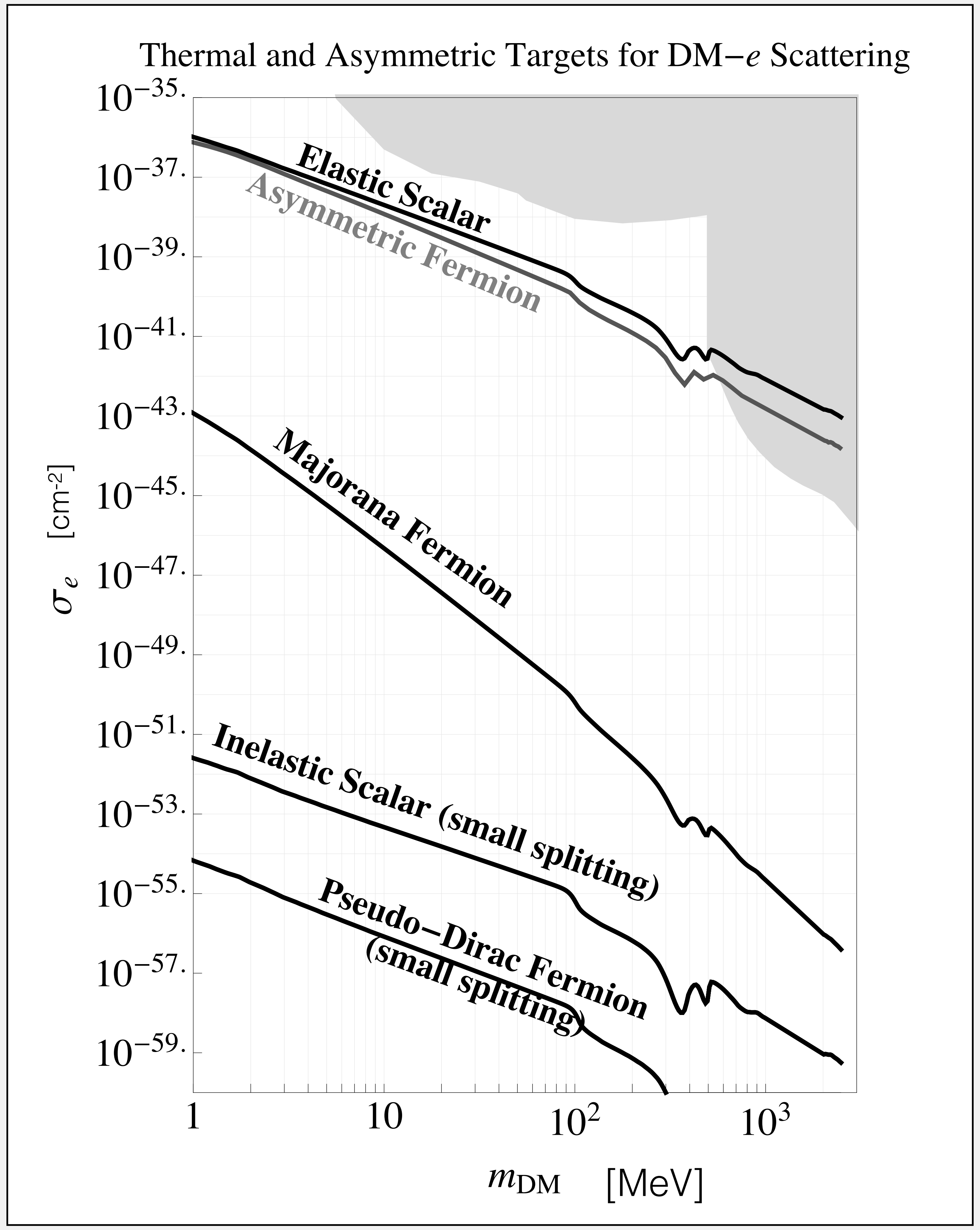
- needs lower energy threshold
  - examples:
    - electron-DM scattering
    - semiconductors



Why not only direct detection?

direct detection:

strong spin/velocity dependency



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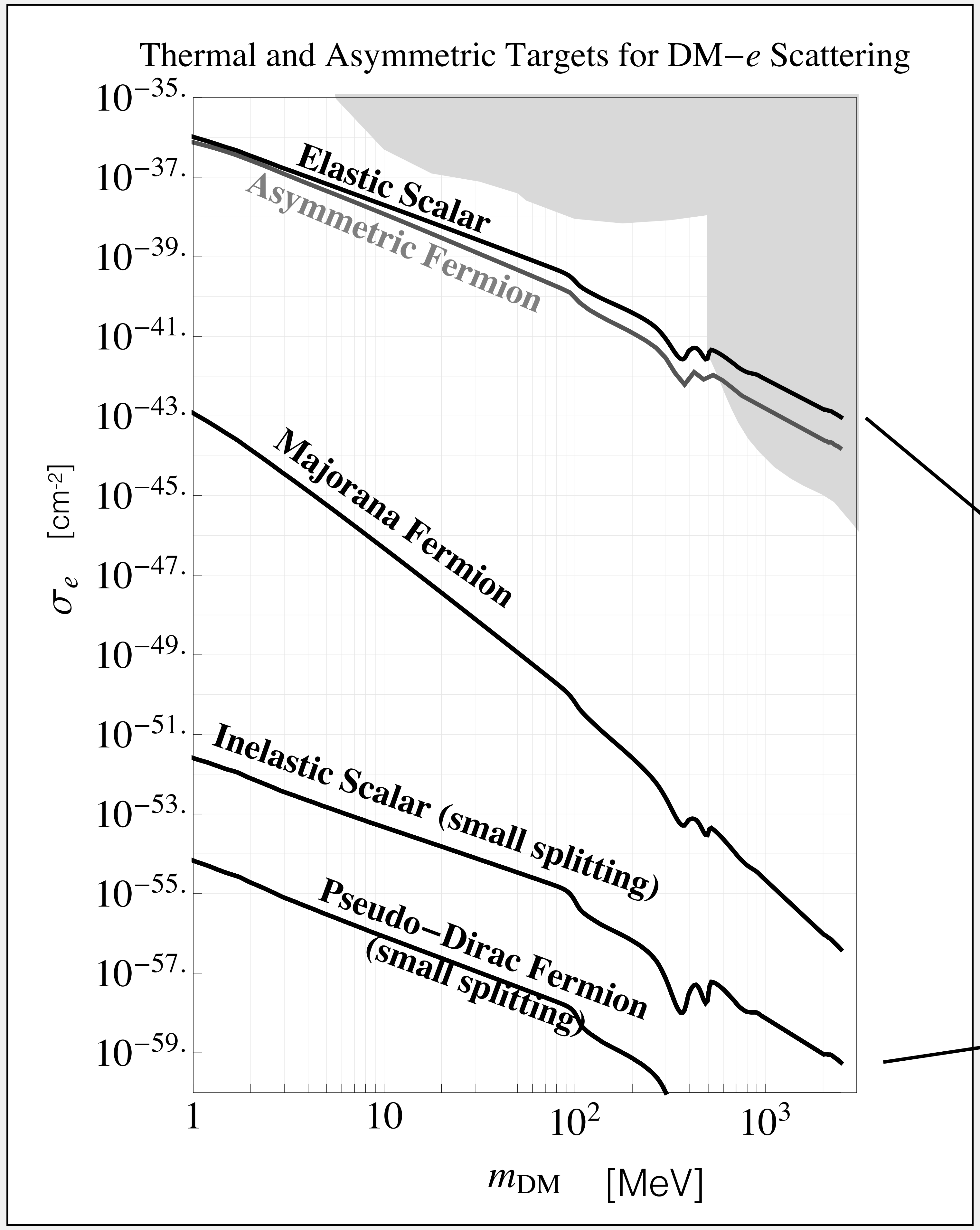
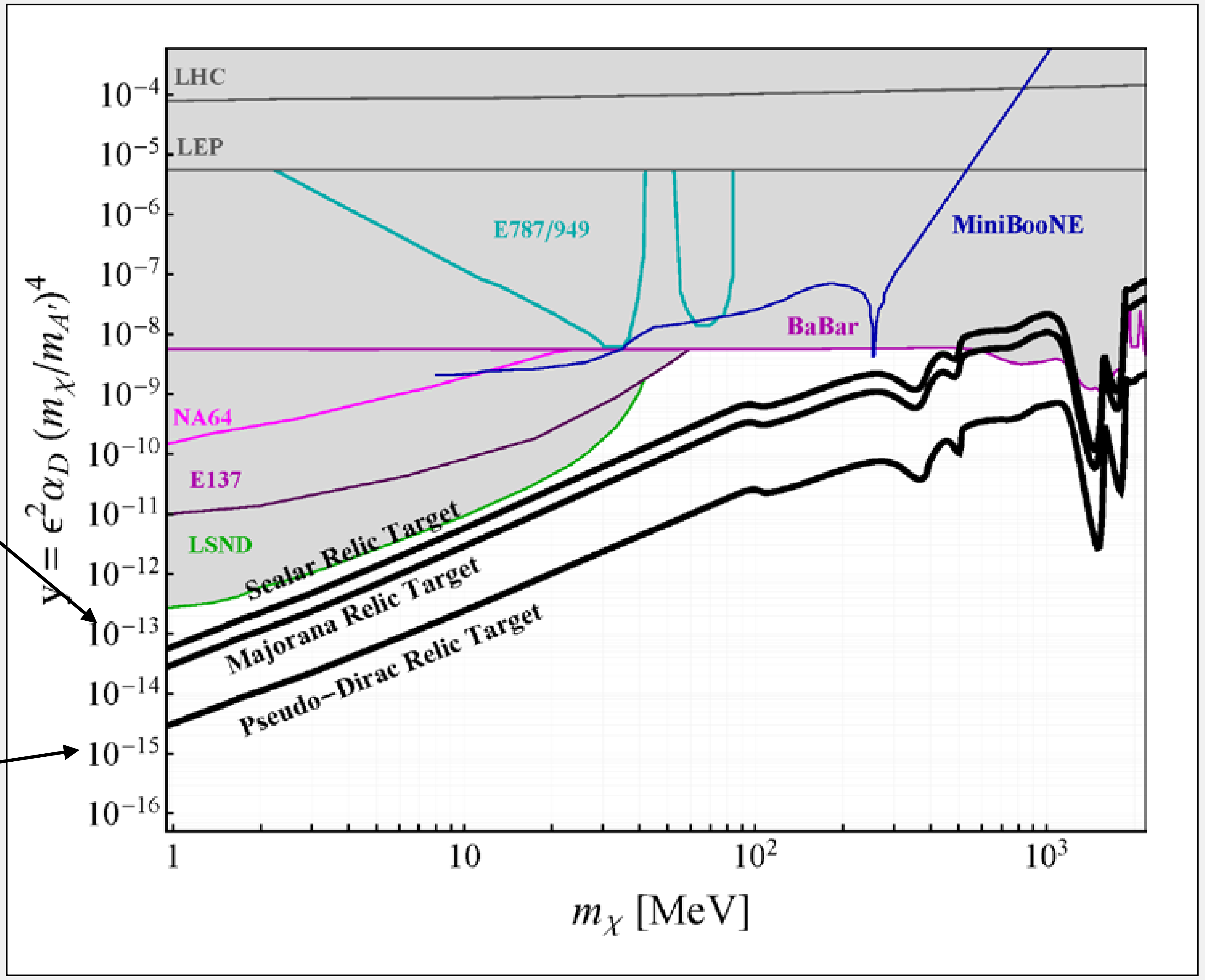


at accelerators: relativistic production

—> spin/velocity dependency reduced

all thermal targets in reach!



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 vis. disp.	$0.22 < m_{A'} < 9$ $m_{A'} < 2$	$\epsilon^2 \gtrsim 10^{-8}$ $\epsilon^2 \sim 10^{-14} - 10^{-8}$	
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

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

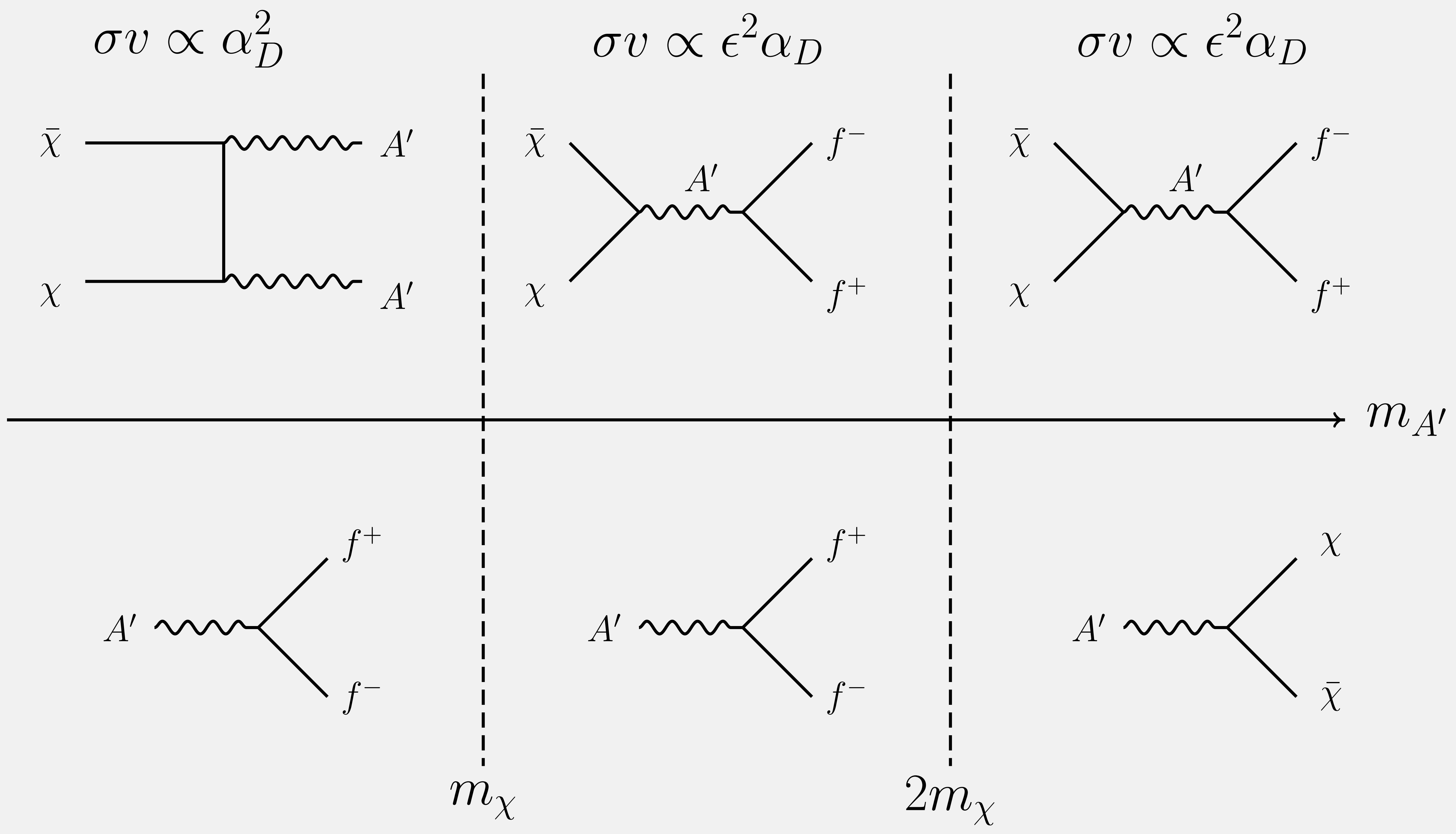
Physics Beyond Colliders at CERN Beyond the Standard Model Working Group Report

arxiv:1902.00260

CERN-PBC-REPORT-2018-003

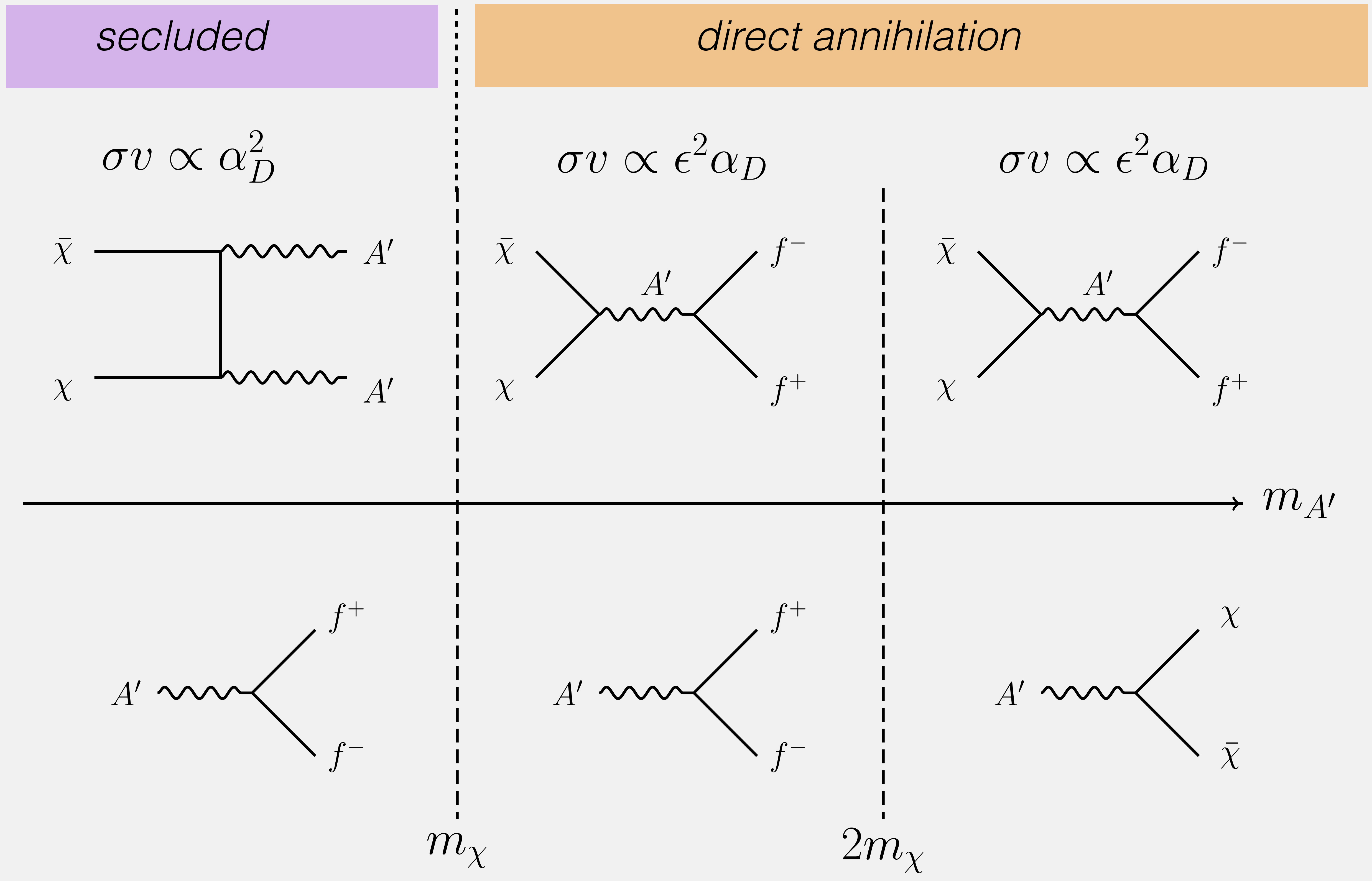
Summary Report of Physics Beyond Colliders at CERN

Signatures



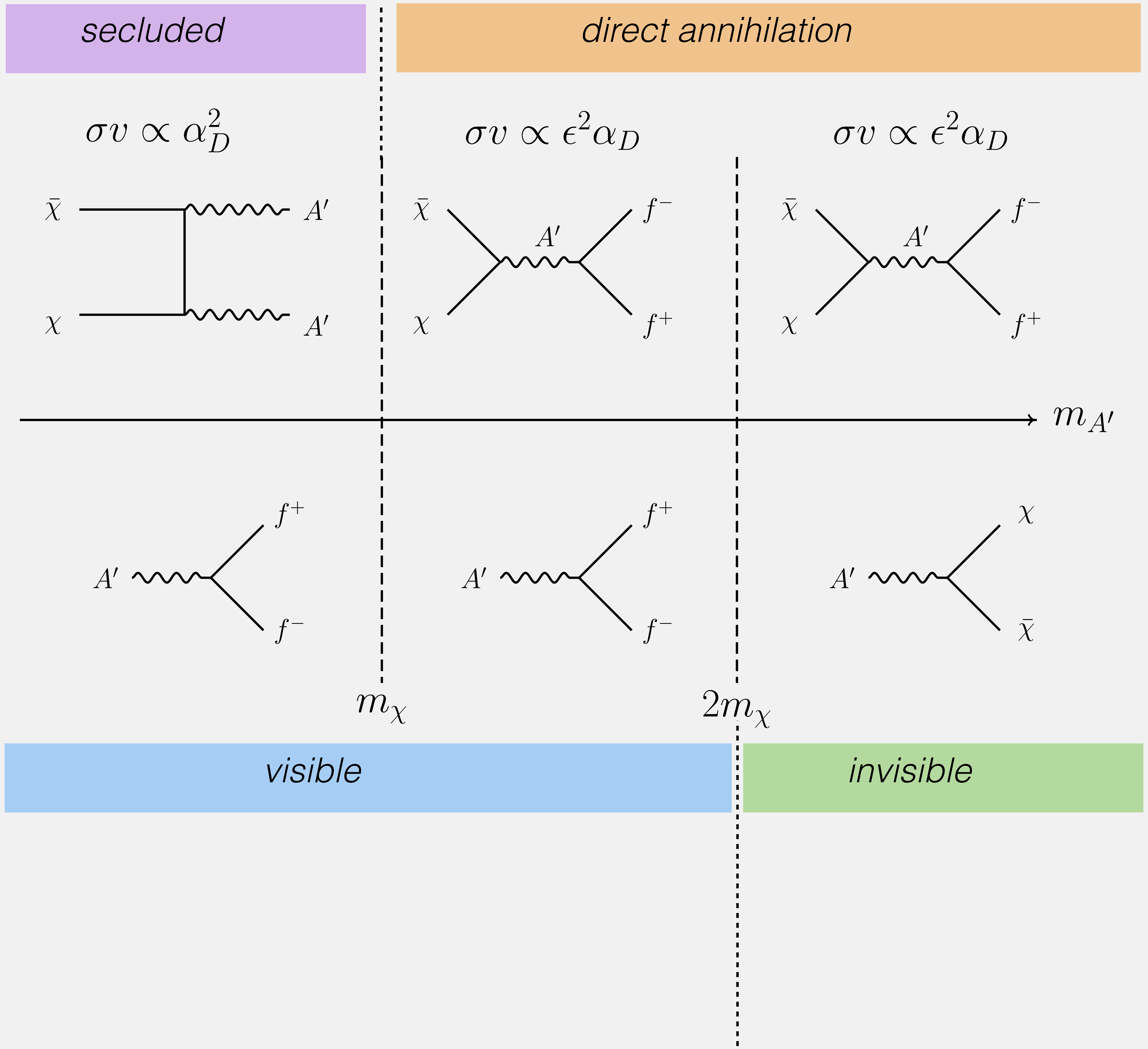
$\sigma v \propto \alpha_D^2$
$\sigma v \propto \epsilon^2 \alpha_D$
$\sigma v \propto \epsilon^2 \alpha_D$
$\bar{\chi}$
A'
χ
A'
$\bar{\chi}$
f^-
A'
χ
f^+
$\bar{\chi}$
f^-
A'
χ
f^+
$m_{A'}$
f^+
A'
f^-
f^+
A'
f^-
χ
A'
$\bar{\chi}$
m_χ
$2m_\chi$

Signatures



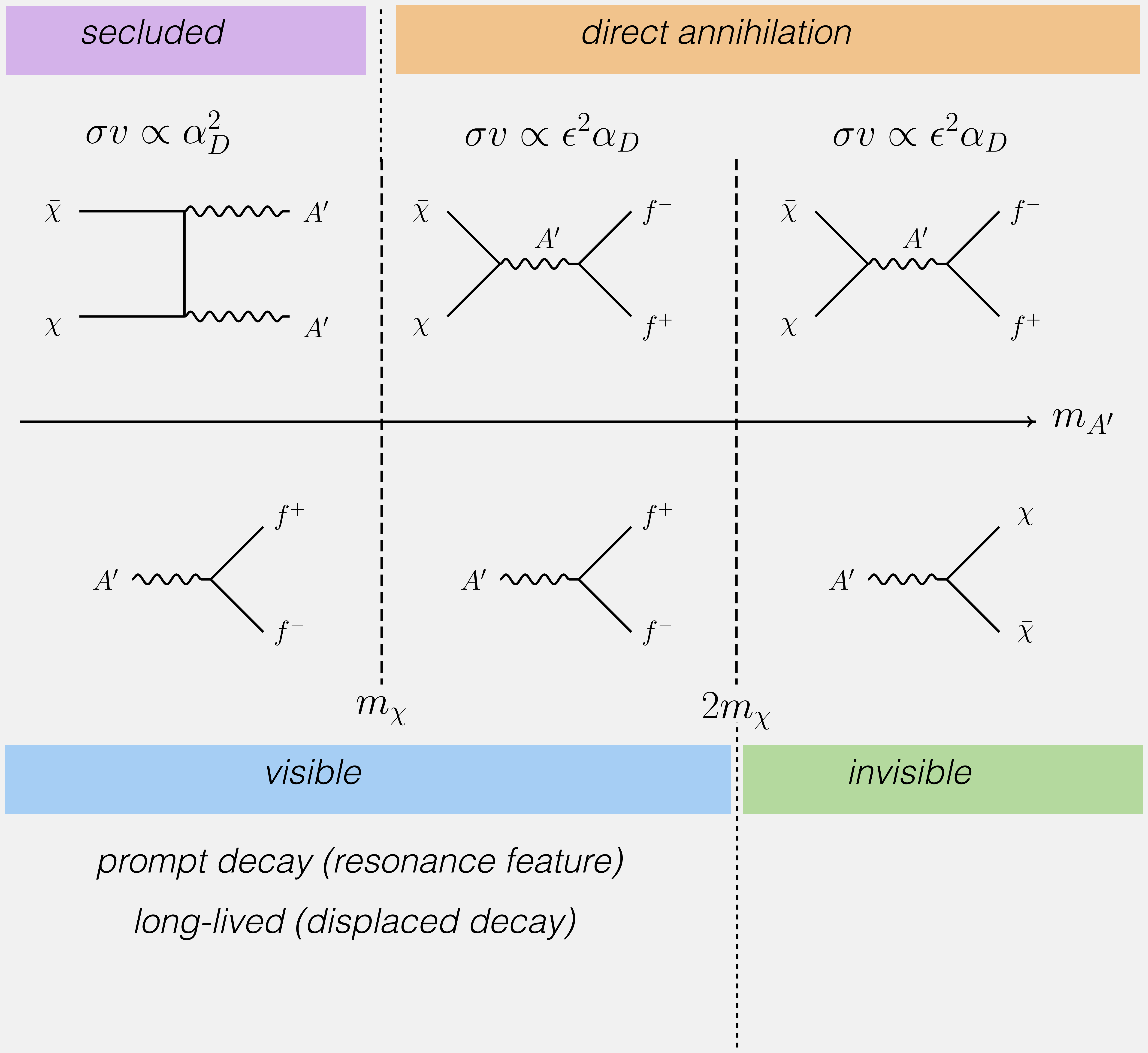
secluded
direct annihilation
$\sigma v \propto \alpha_D^2$
$\sigma v \propto \epsilon^2 \alpha_D$
$\sigma v \propto \epsilon^2 \alpha_D$
$\bar{\chi}$
χ
A'
A'
f^-
f^+
$m_{A'}$
f^+
f^-
χ
$\bar{\chi}$
m_χ
$2m_\chi$

Signatures



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

Signatures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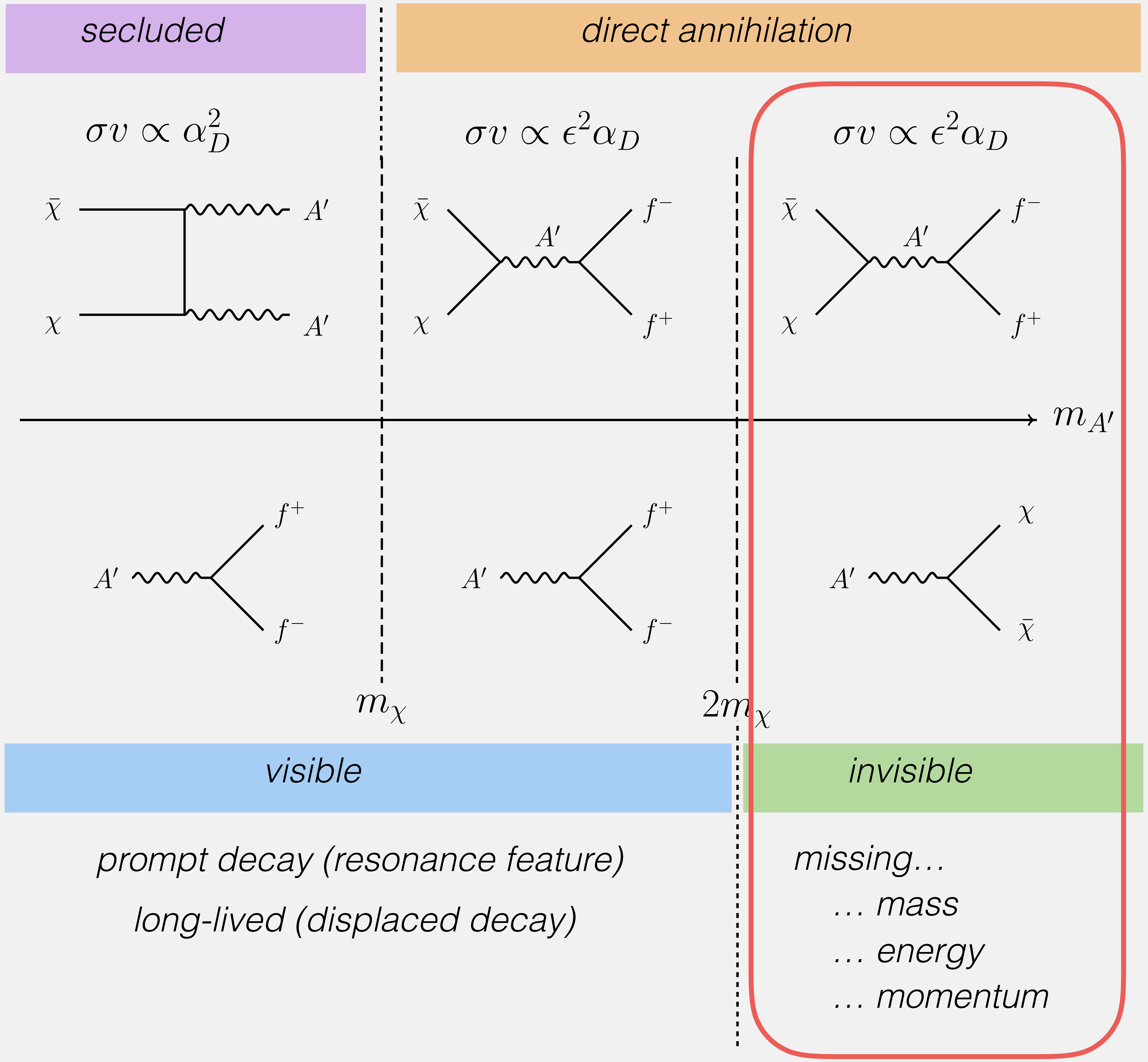
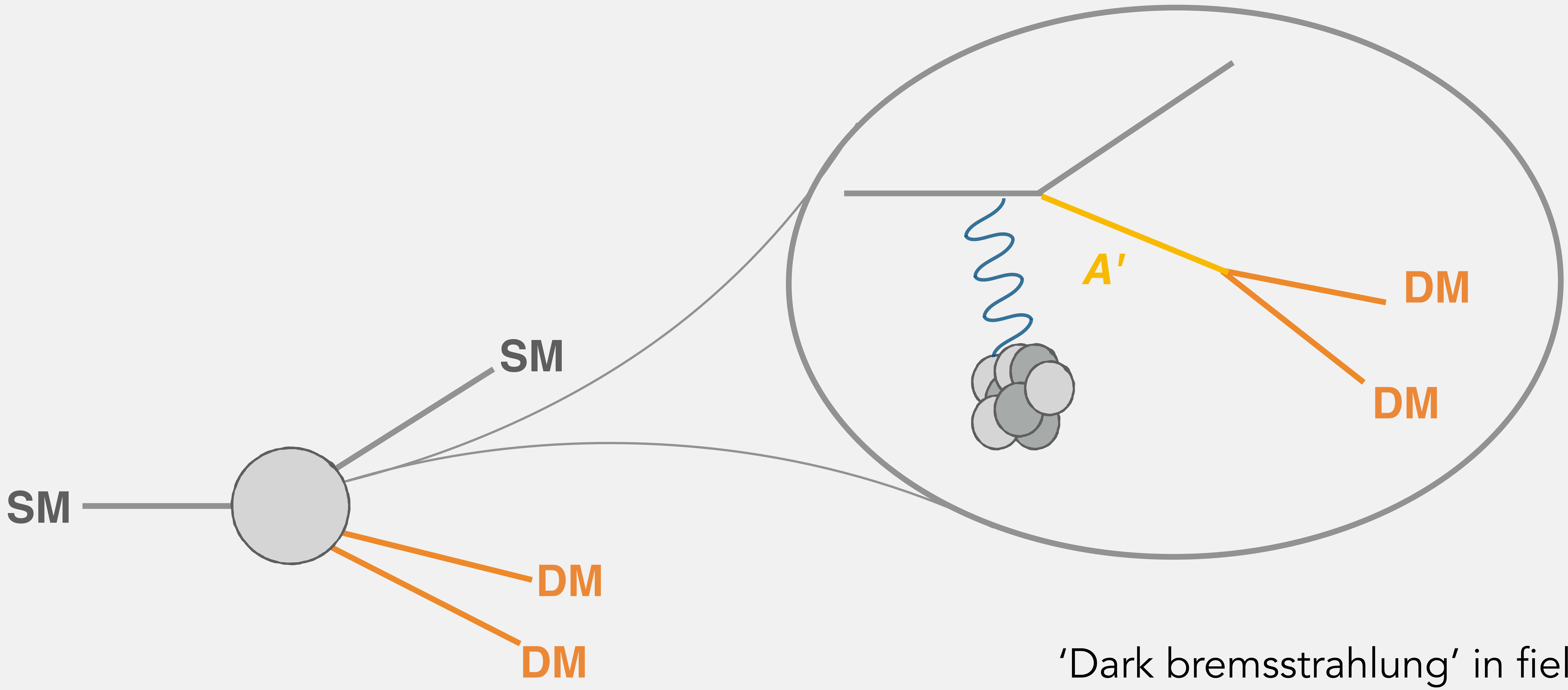
$\bar{\chi}$
χ
A'
f^-
f^+
$m_{A'}$
m_χ
$2m_\chi$
visible
invisible
prompt decay (resonance feature)
long-lived (displaced decay)

Signatures


secluded
direct annihilation
σv ∝ α_D^2
σv ∝ ε^2 α_D
σv ∝ ε^2 α_D
χ̄
χ
A′
A′
f−
f+
m_A′
f+
f−
χ
χ̄
m_χ
2m_χ
visible
invisible
prompt decay (resonance feature)
long-lived (displaced decay)
missing…
… mass
… energy
… momentum

Fixed-Target Missing Energy/Momentum

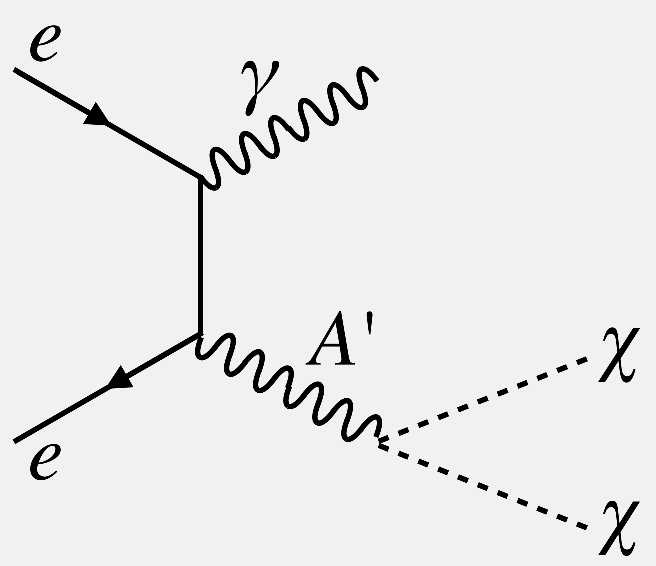
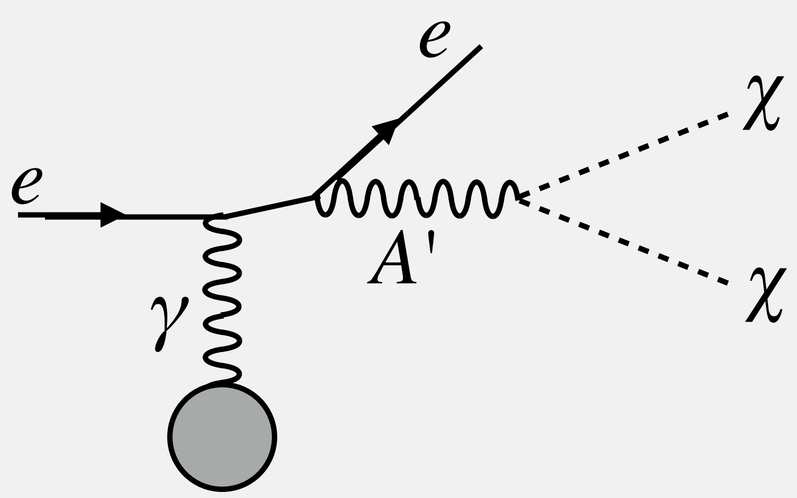
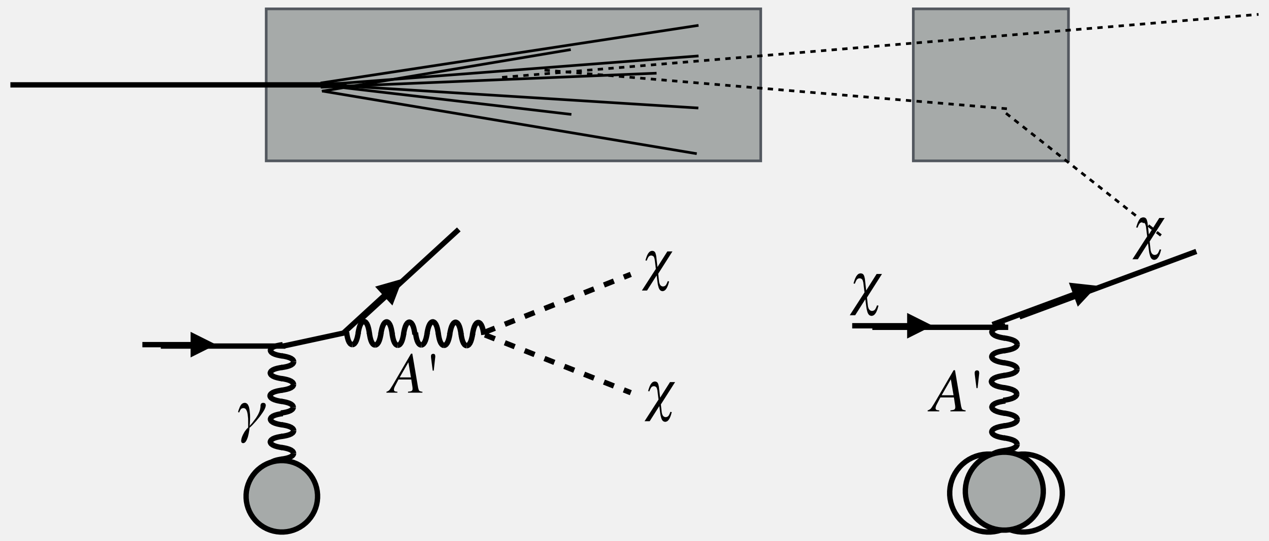
Accelerator Production



'Dark bremsstrahlung' in field of a nucleus

Main background: 'ordinary' bremsstrahlung of a SM photon

Complimentary Approaches

collider	fixed target	beam dump
		

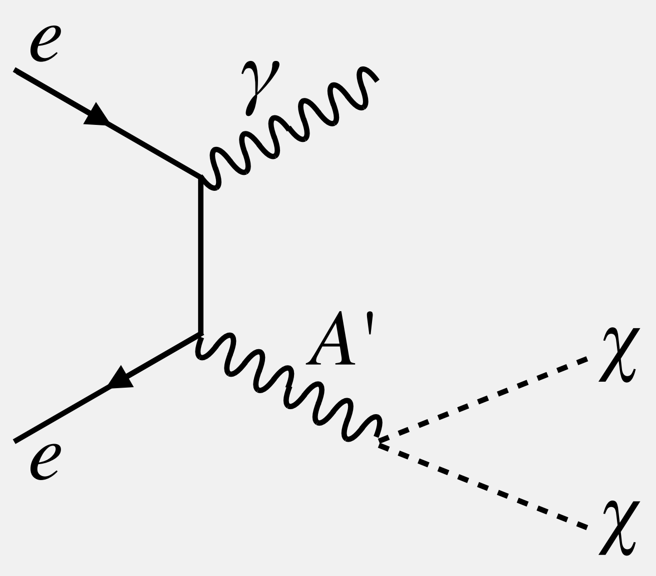
$\sigma_{\mathrm{coll}} \propto \frac{\varepsilon^2}{E_{\mathrm{cm}}^2}$ $\ll$ $\sigma_{\mathrm{FT}} \propto \frac{Z^2\varepsilon^2}{m_{\mathrm{A'}}^2}$ $N \propto \varepsilon^2(1-\varepsilon^2) \approx \varepsilon^2$ $\gg$ $N \propto \varepsilon^4$

but **“direct DM detection”**

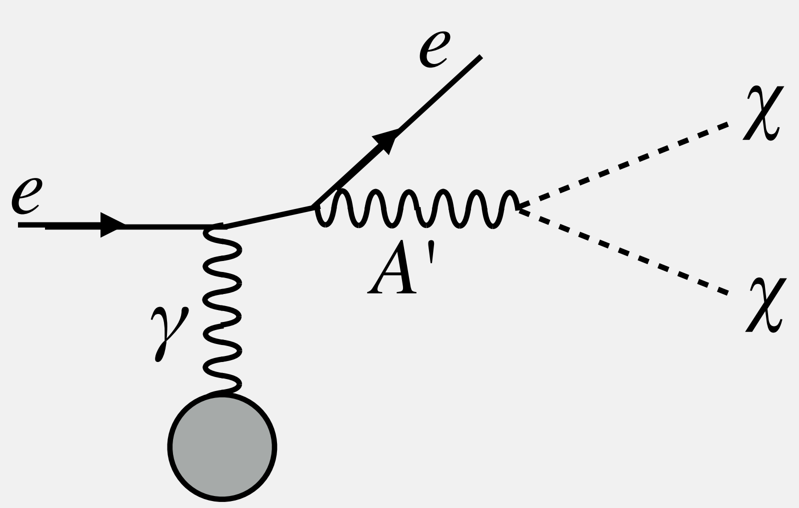
examples (existing or planned)	BaBar Belle II LHC	PADME NA64 **LDMX**	MMAPS VEPP3 DarkLight (II)	E137 LSND BDX	SBNe/pi MiniBooNE SHiP
mass range	0.1 - 10 GeV	MeV - GeV			

Complimentary Approaches

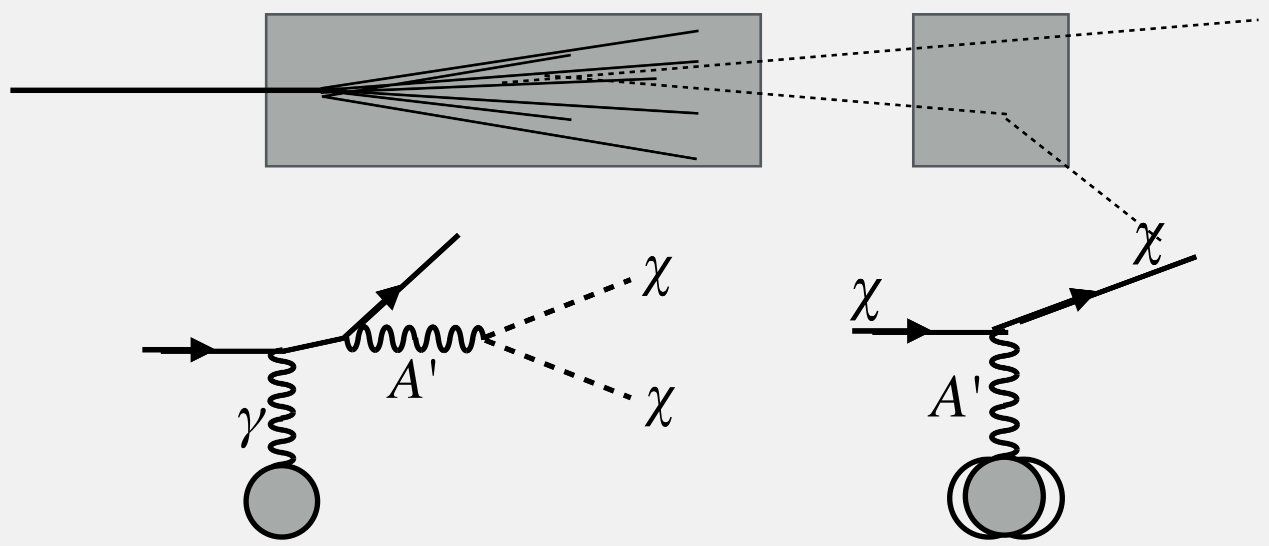
collider



fixed target



beam dump



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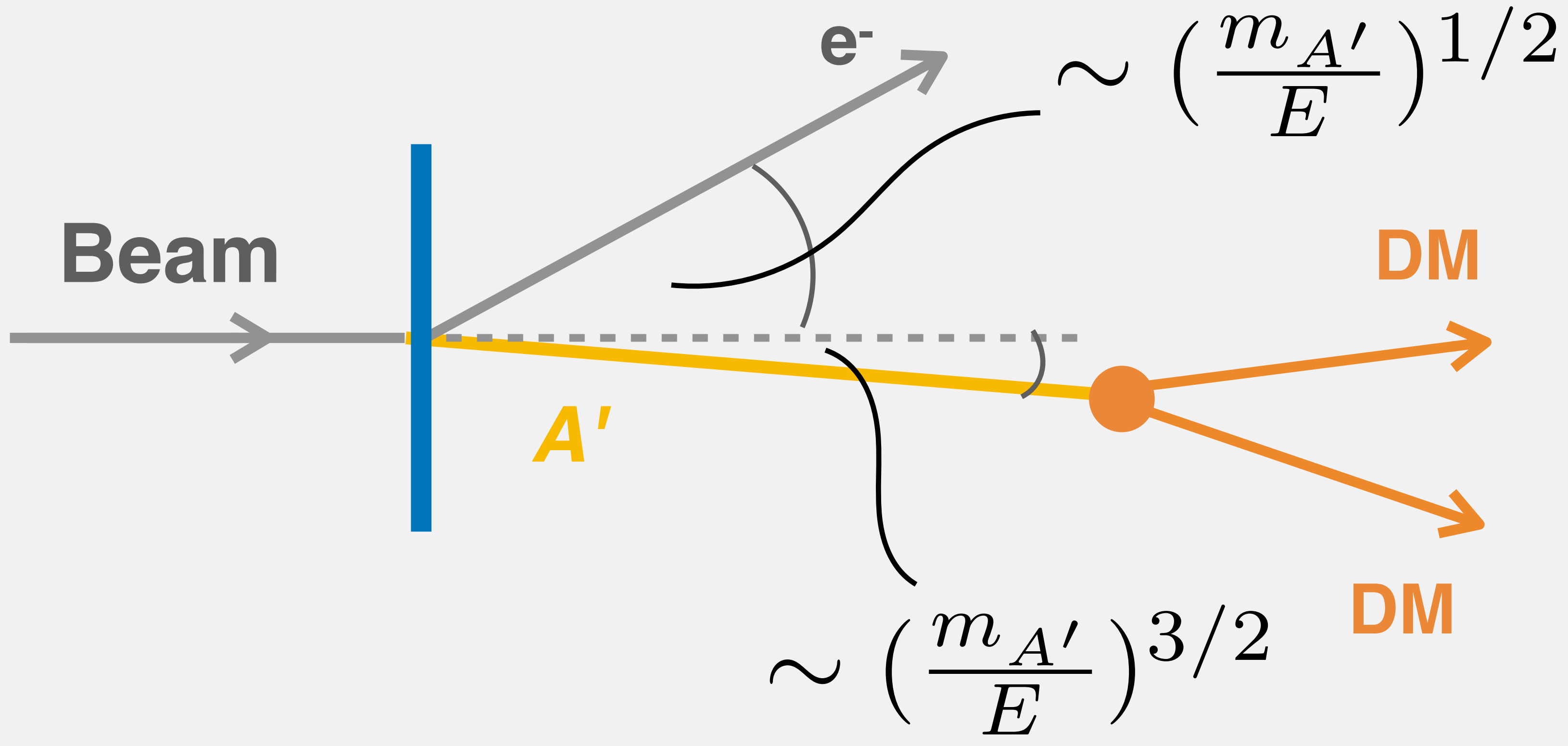
but **"direct DM detection"**

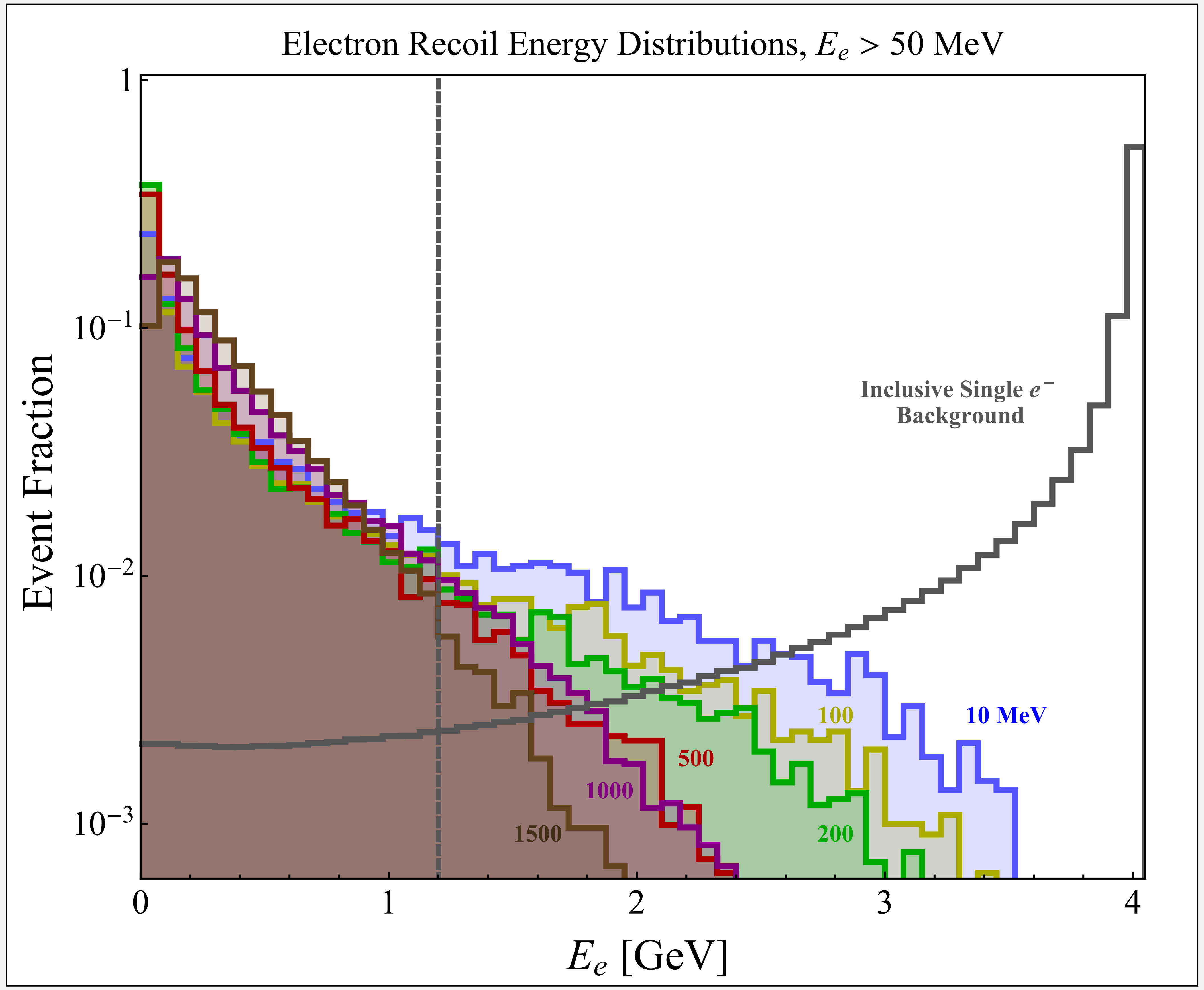
examples (existing or planned)	collider	fixed target		beam dump	
	BaBar	PADME	MMAPS	E137	SBNe/pi
	Belle II	NA64	VEPP3	LSND	MiniBooNE
	LHC	**LDMX**	DarkLight (II)	BDX	SHiP

mass range 0.1 - 10 GeV MeV - GeV

Kinematics

very different from SM bremsstrahlung
(main background)





Mediator carries most of the energy
—> soft recoil electron, large missing energy

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very different from SM bremsstrahlung
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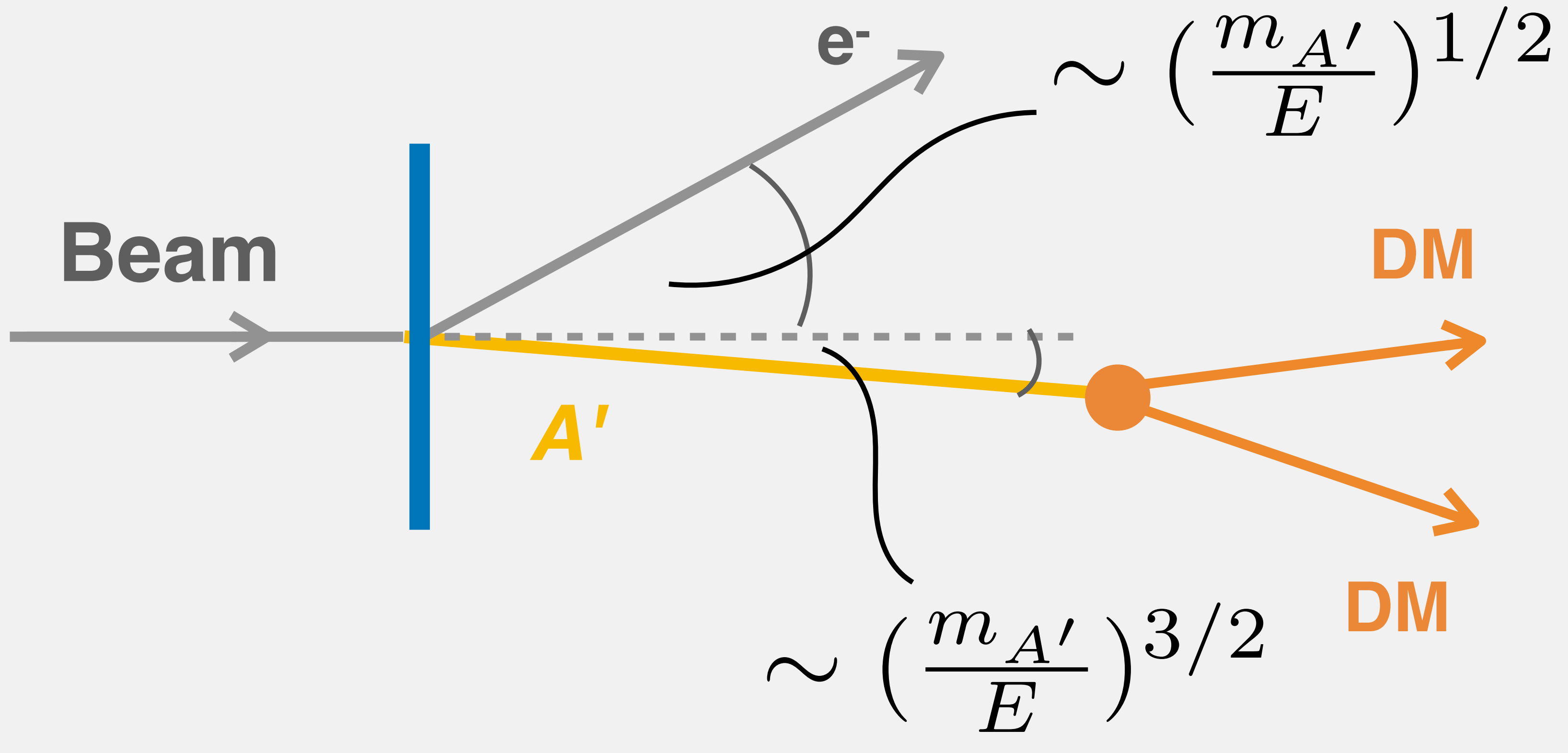
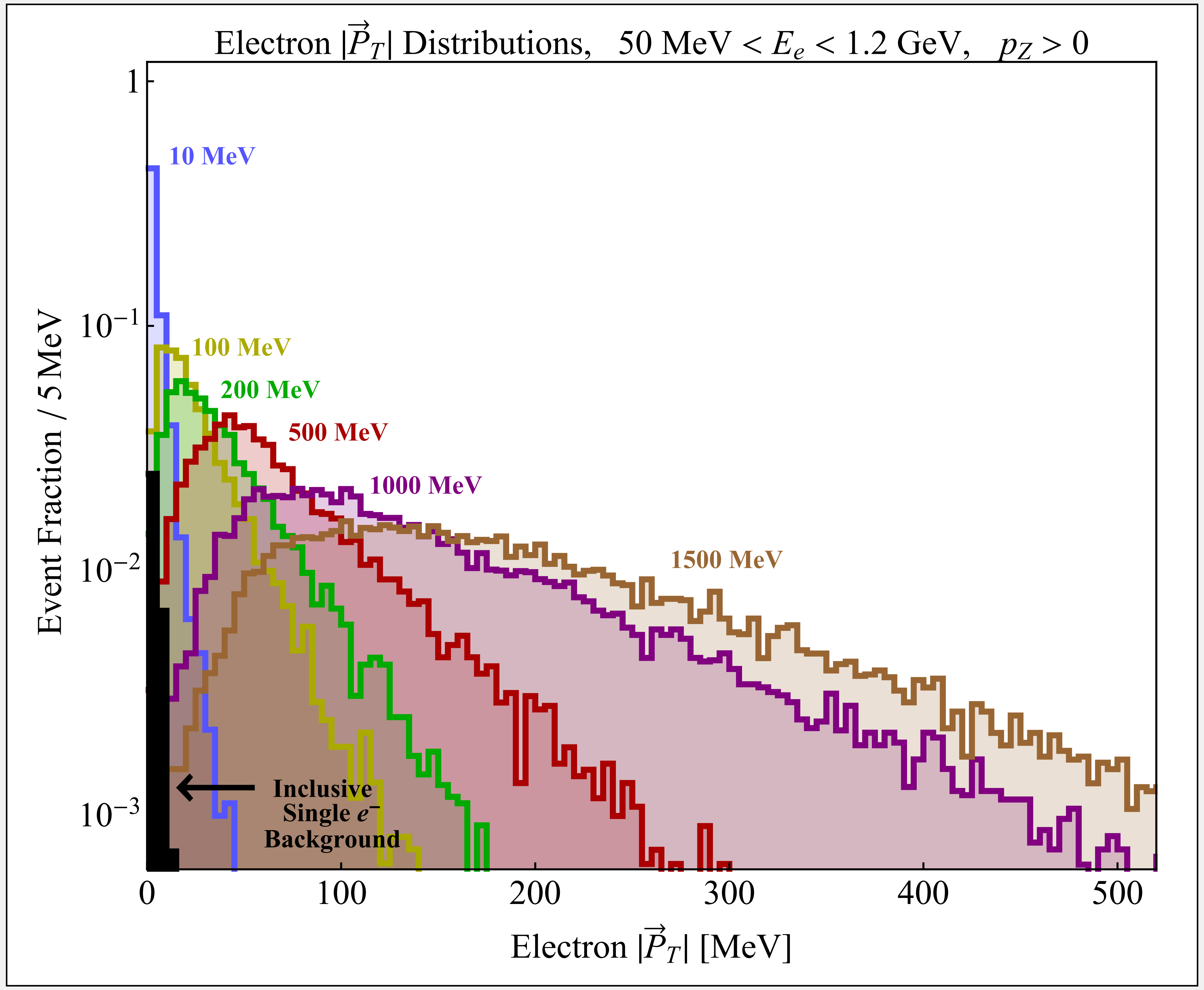




Mediator carries most of the energy
—> soft recoil electron, large missing energy

Recoil electron gets transverse 'kick'
—> large missing transverse momentum

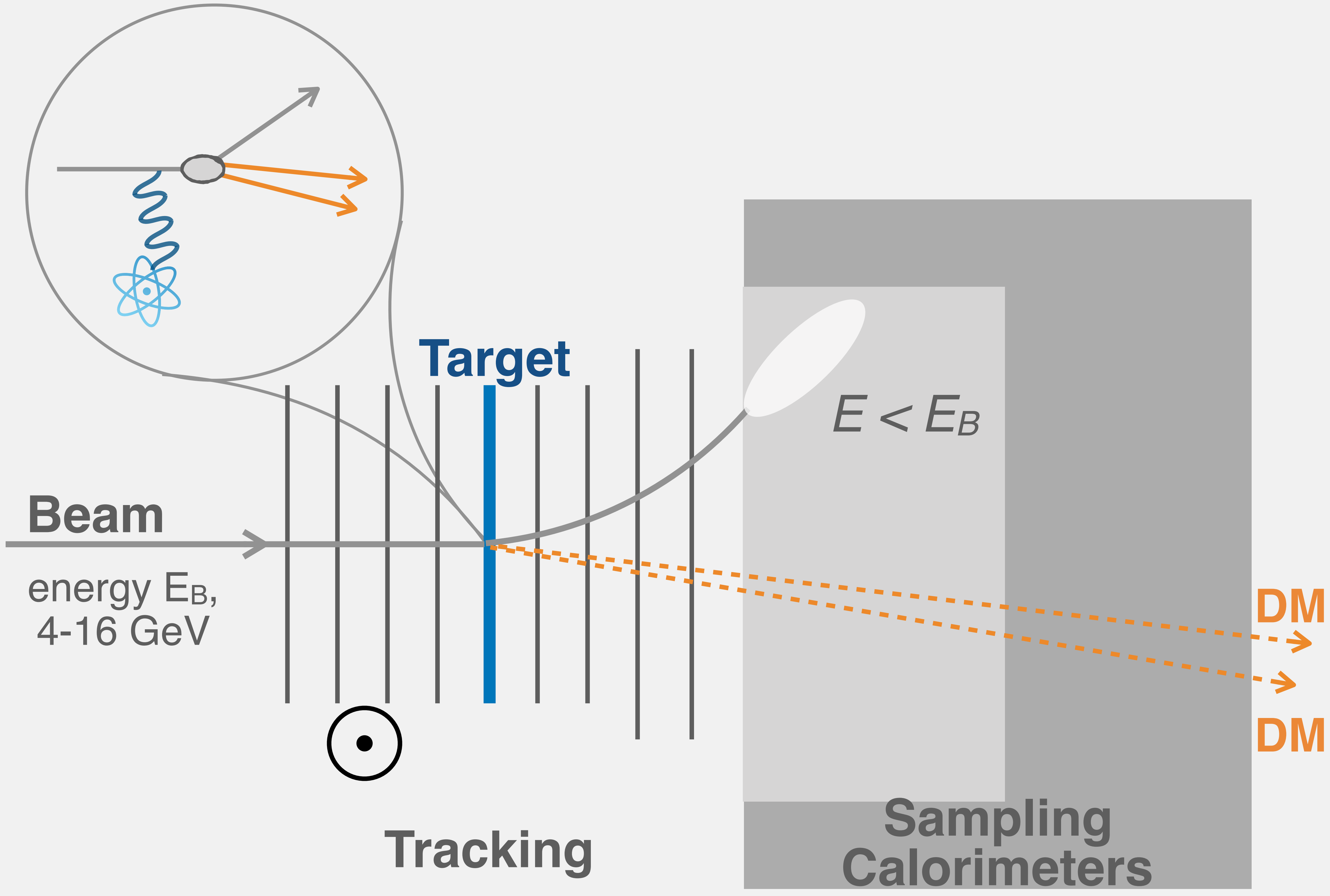
measurement of p_T: strong discriminator
AND information about (missing) mass!

LDMX

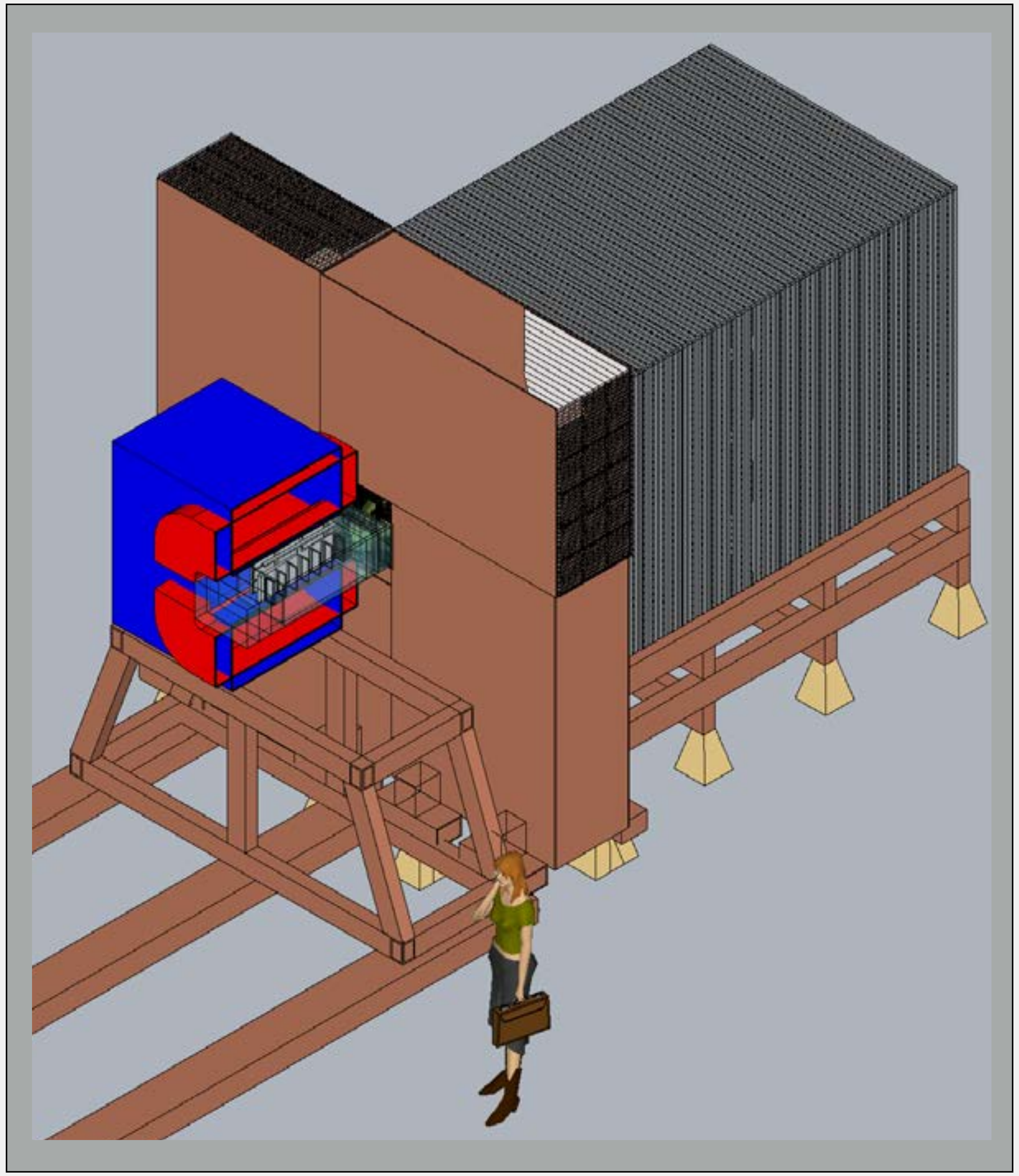
design paper arxiv:1808.05219

Caltech Fermilab Lunds Universitet University of Minnesota UCSB SLAC 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

The Beam

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} electrons in few years

—> beam with **high duty-cycle**

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

options (still an open question):

SLAC (*default*, first stage)
dedicated transfer line from LCLS-II
(Linac Coherent Light Source)

CERN (later stage)
new Linac injecting electrons into SPS
(Super Proton Synchrotron)

S30XL @ LCLS-II @ SLAC

https://confluence.slac.stanford.edu/display/MME/Publications+and+Presentations

(Sector 30 Transfer Line)

Goal: Parasitically extract low-current, high-rate electron beam from LCLS-II linac

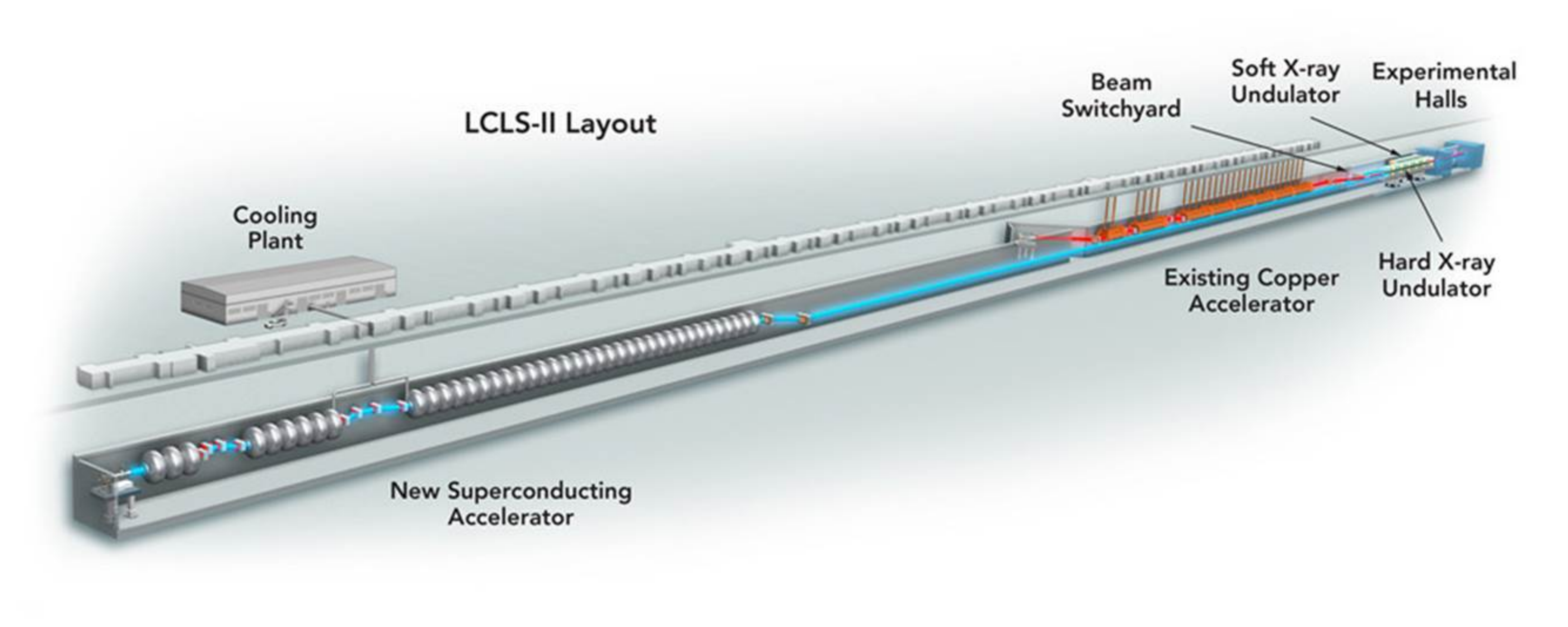
Physics program spans dark matter physics (LDMX), neutrino physics (electro-nuclear scattering as reference), test beam program…

energy: 4 (8) GeV

bunch frequency: 46 MHz (186 MHz)

4×10^{14} EoT year 1

parasitic



S30XL @ LCLS-II @ SLAC

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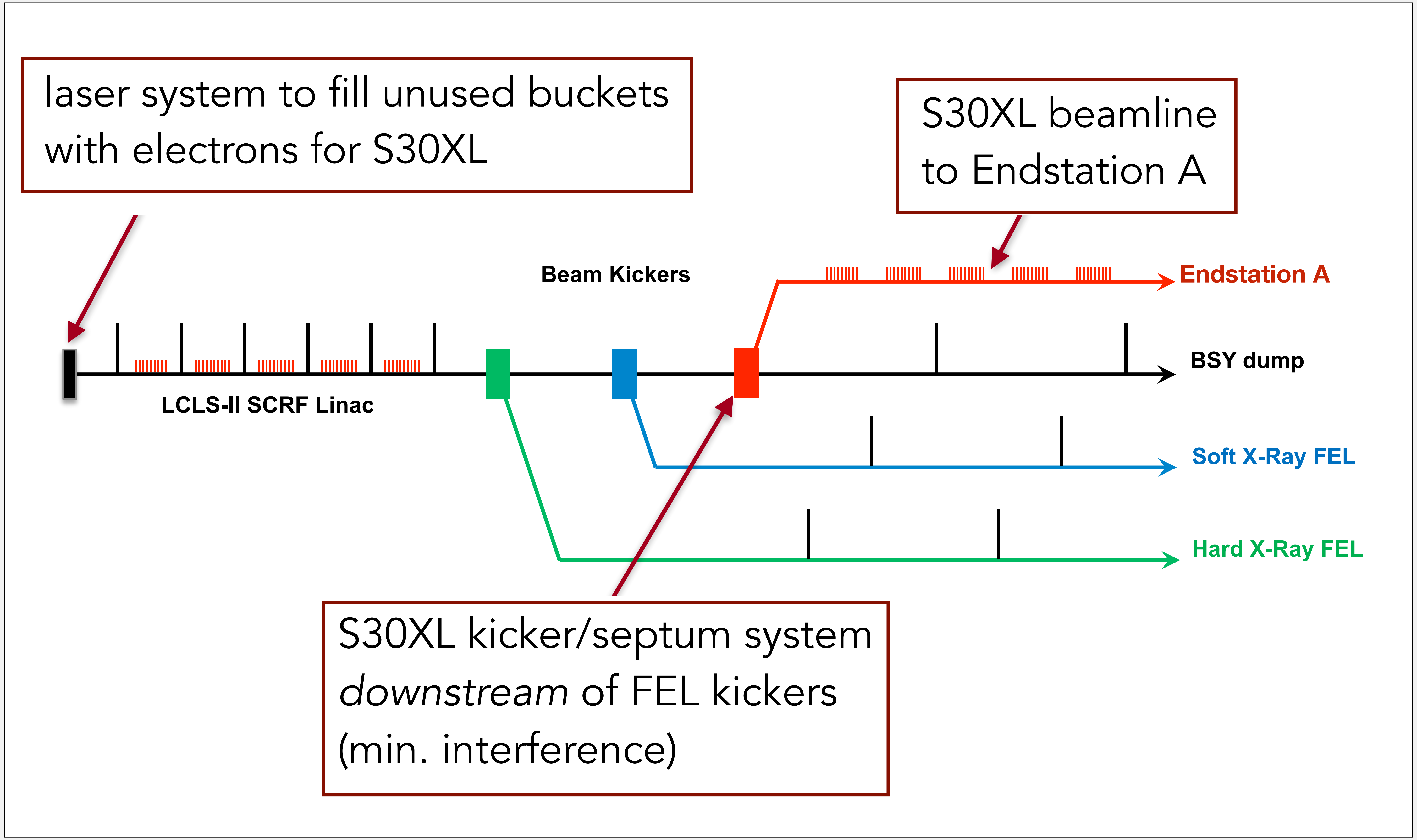
(Sector 30 Transfer Line)

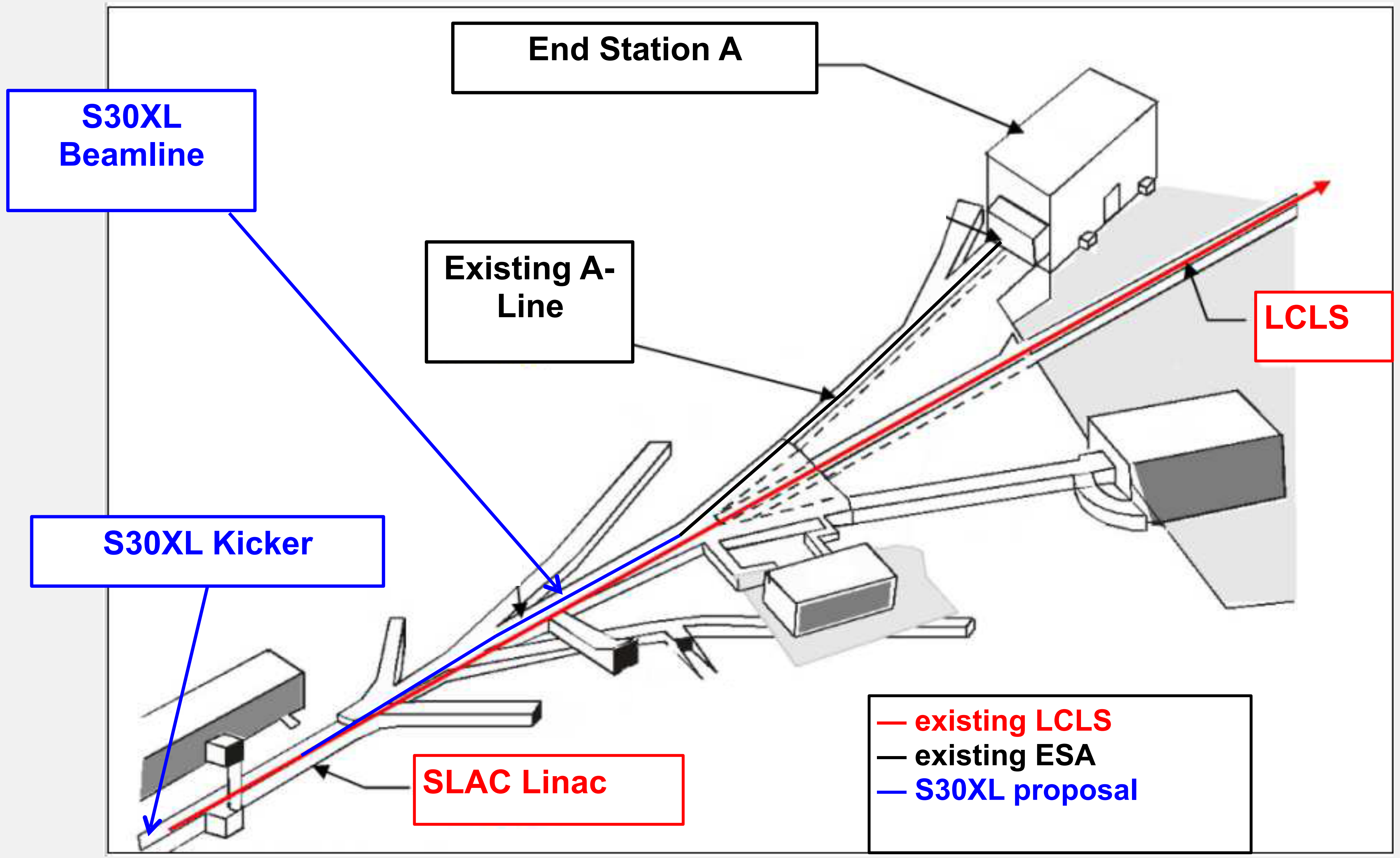


S30XL @ LCLS-II @ SLAC

(Sector 30 Transfer Line)

Staged approach:

- first: S30 Accelerator Improvement Project (kicker & ~100m beamline – ending in beam switchyard)
  - Design underway following funding in FY19; release of construction funding expected after successful review (~early January)
  - Installation timeframe: depends on LCLS-II downtime schedule
  - Enable characterization of dark current, long-pulse kicker demonstration, single-electron QED tests, and high-rate single electron test beam
- second: additional ~100m beamline to connect to existing End Station A line, potentially laser system



eSPS at CERN

arxiv:1805.12379 arxiv:1905.07657

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

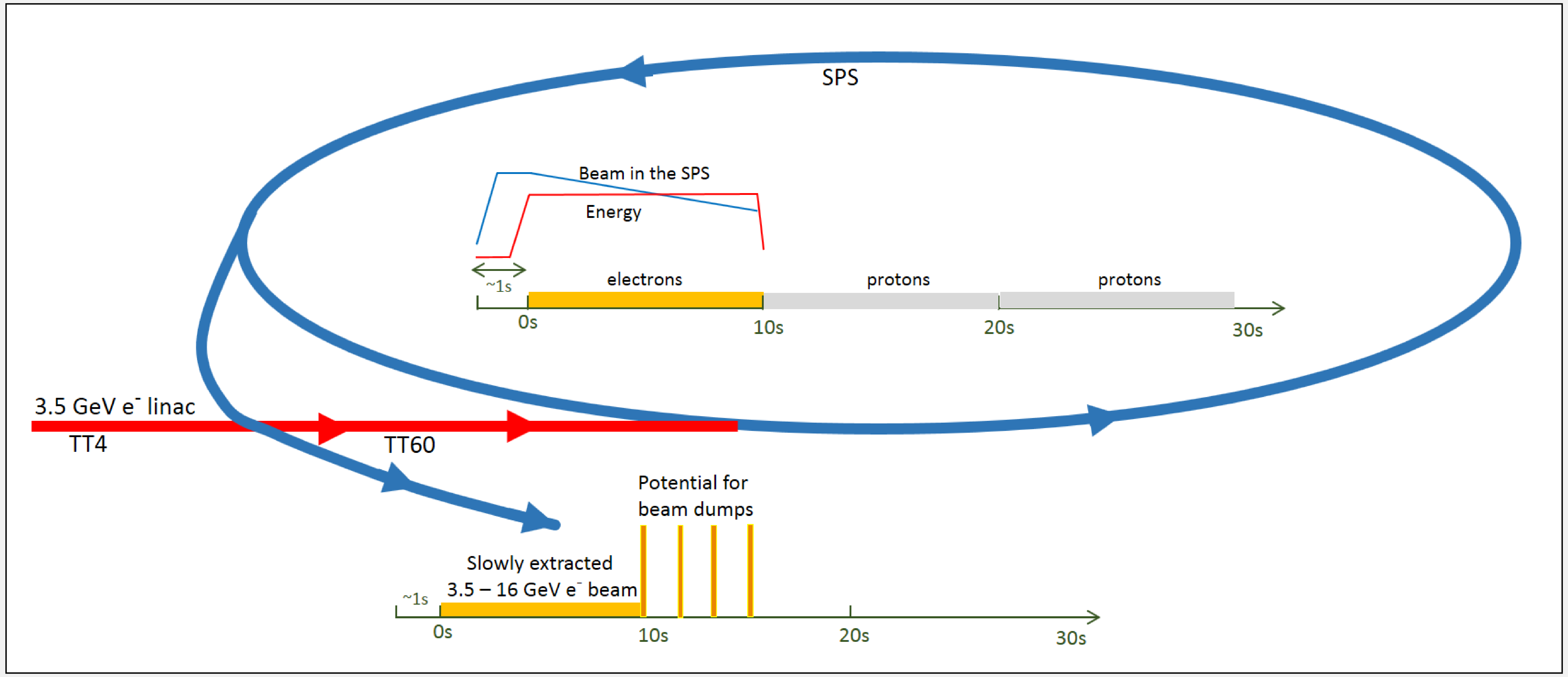
Idea ~2 years ago, quickly picked up momentum

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:

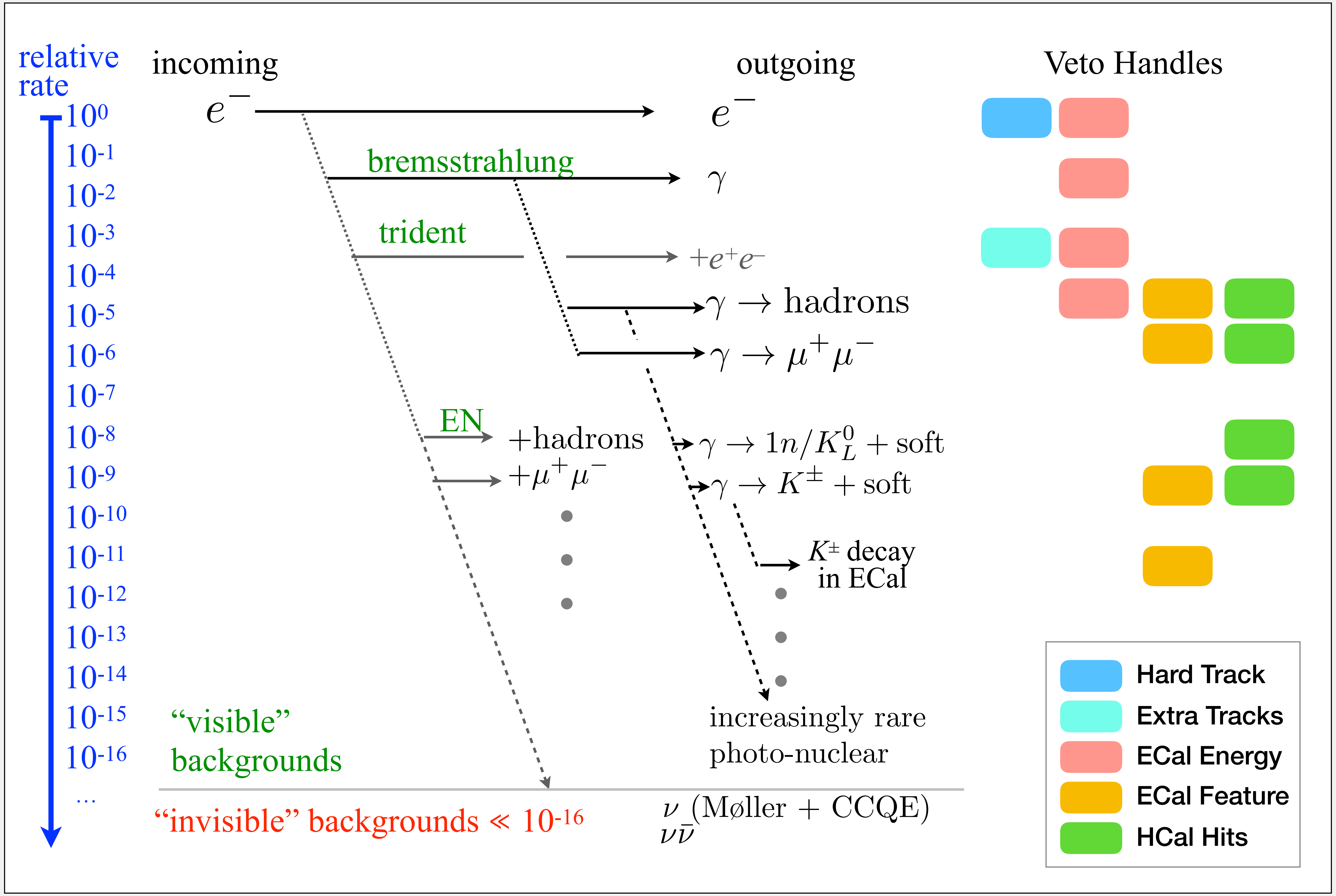
- energy: 3.5 - 16 GeV
- electrons per bunch: 1 - 40
- bunch spacing: multiples of 5 ns
- adjustable beam size



optimal catering for LDMX-like experiment

Backgrounds and Detectors

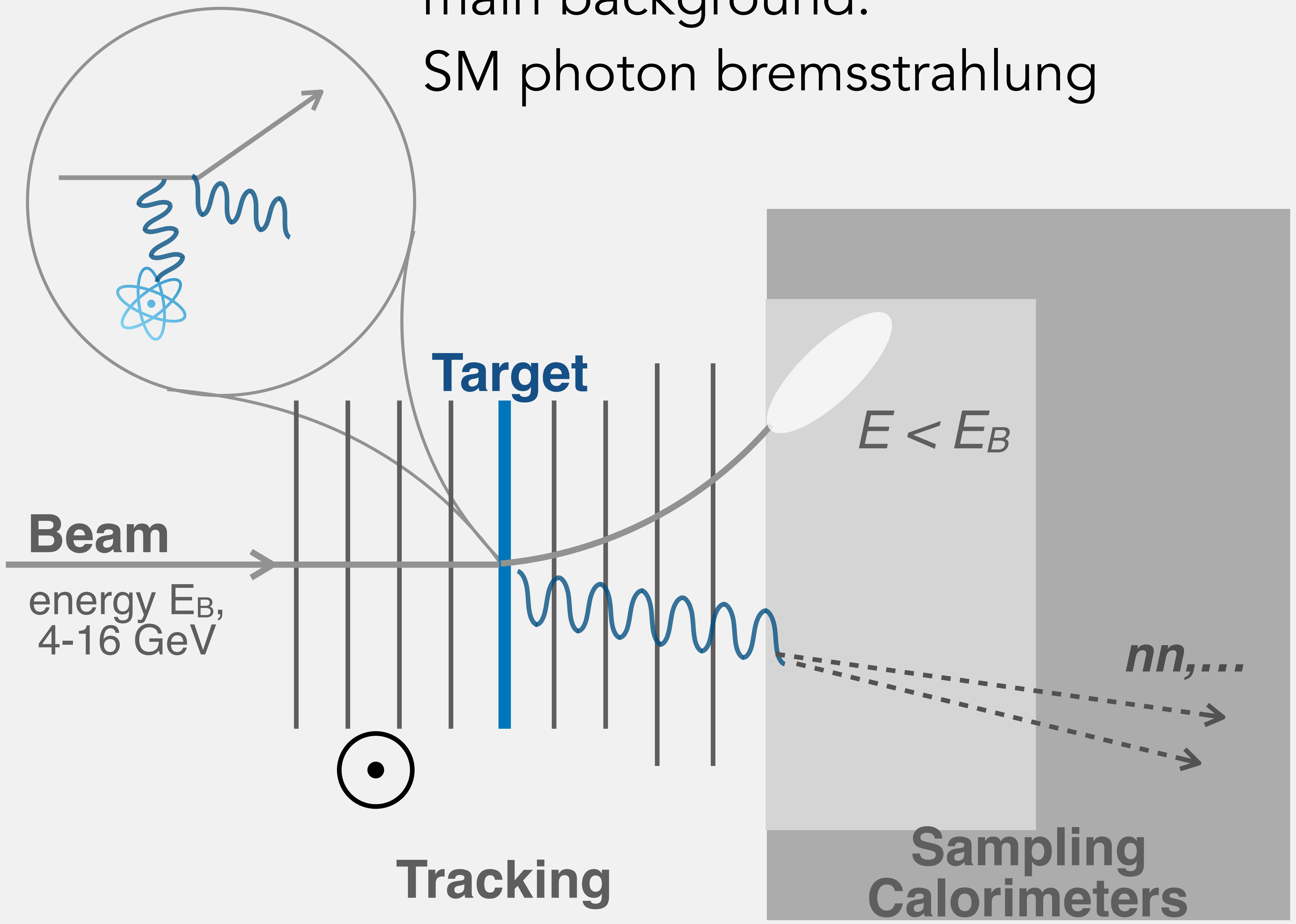
Backgrounds



essentially only instrumental backgrounds

Background Challenges

main background:
SM photon bremsstrahlung

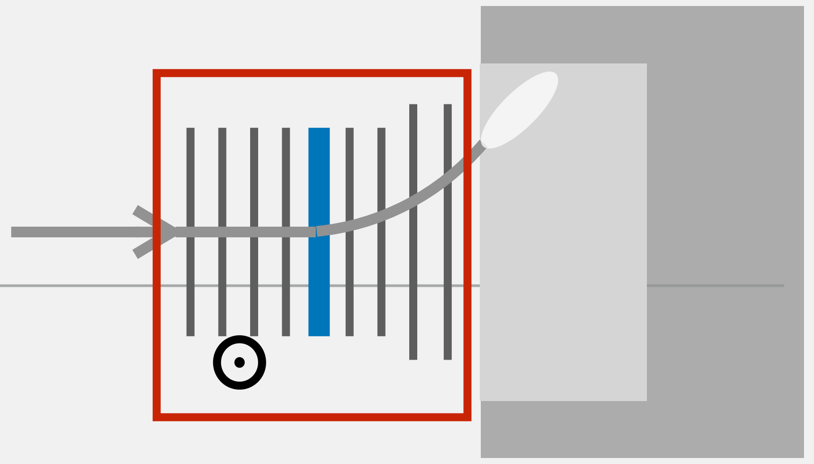


particularly challenging:

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

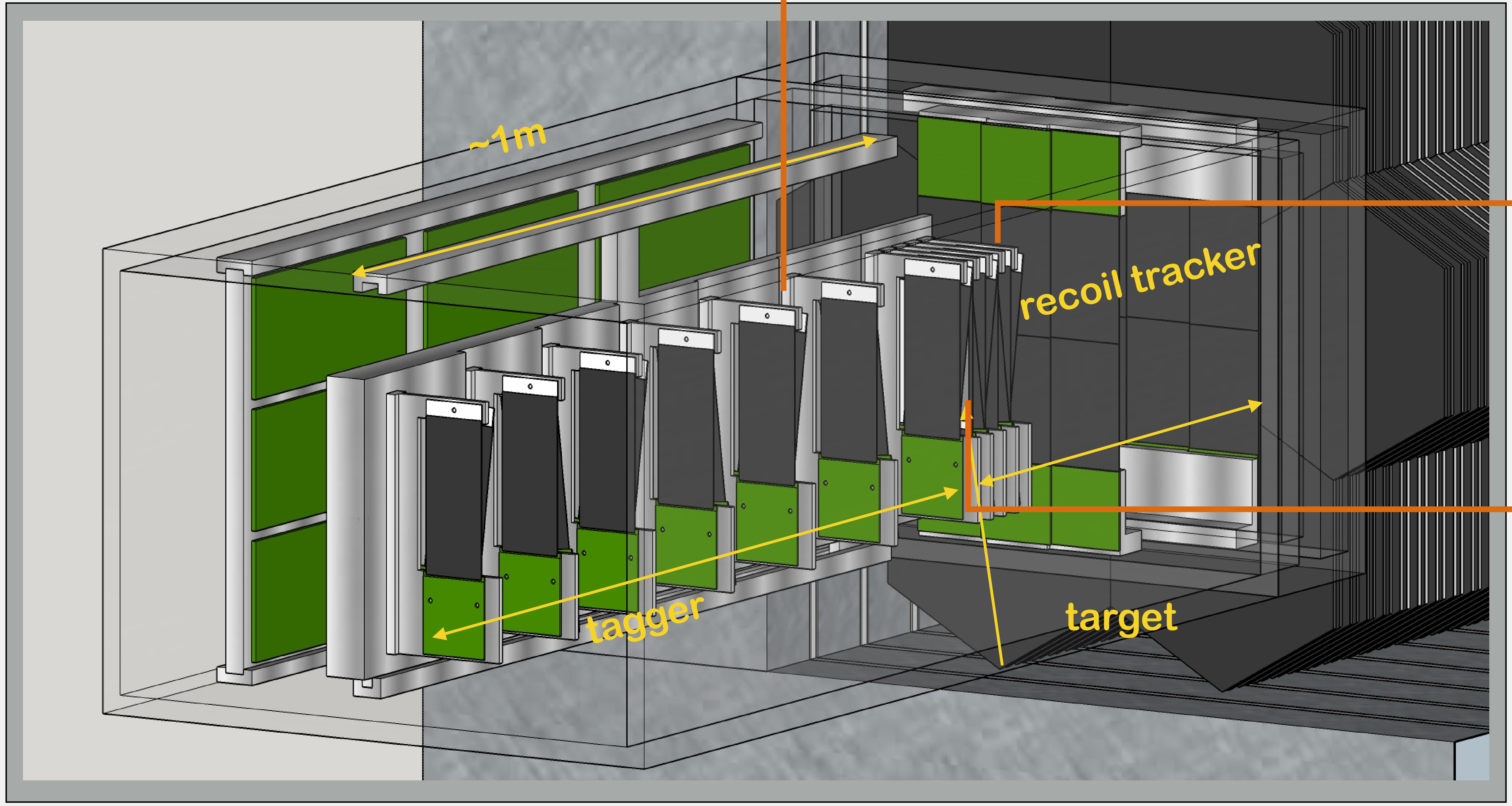
—> most design work (with UVA!) recently on HCal to optimise rejection power

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

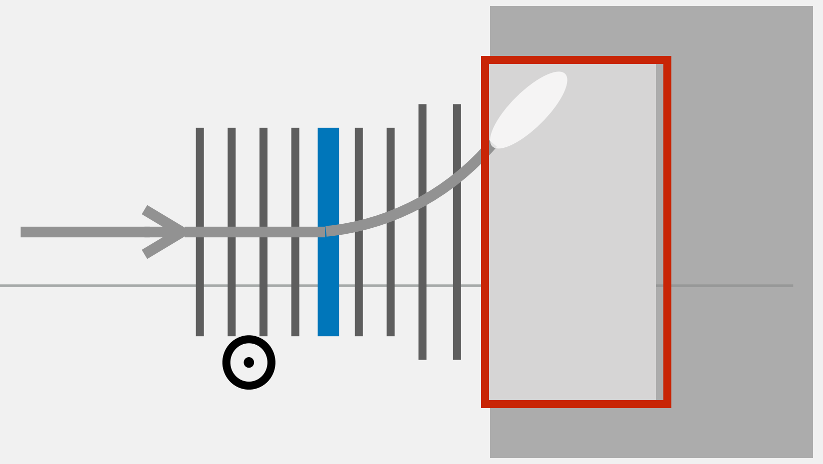
recoil tracker

- in fringe field
- measure recoil electron

target

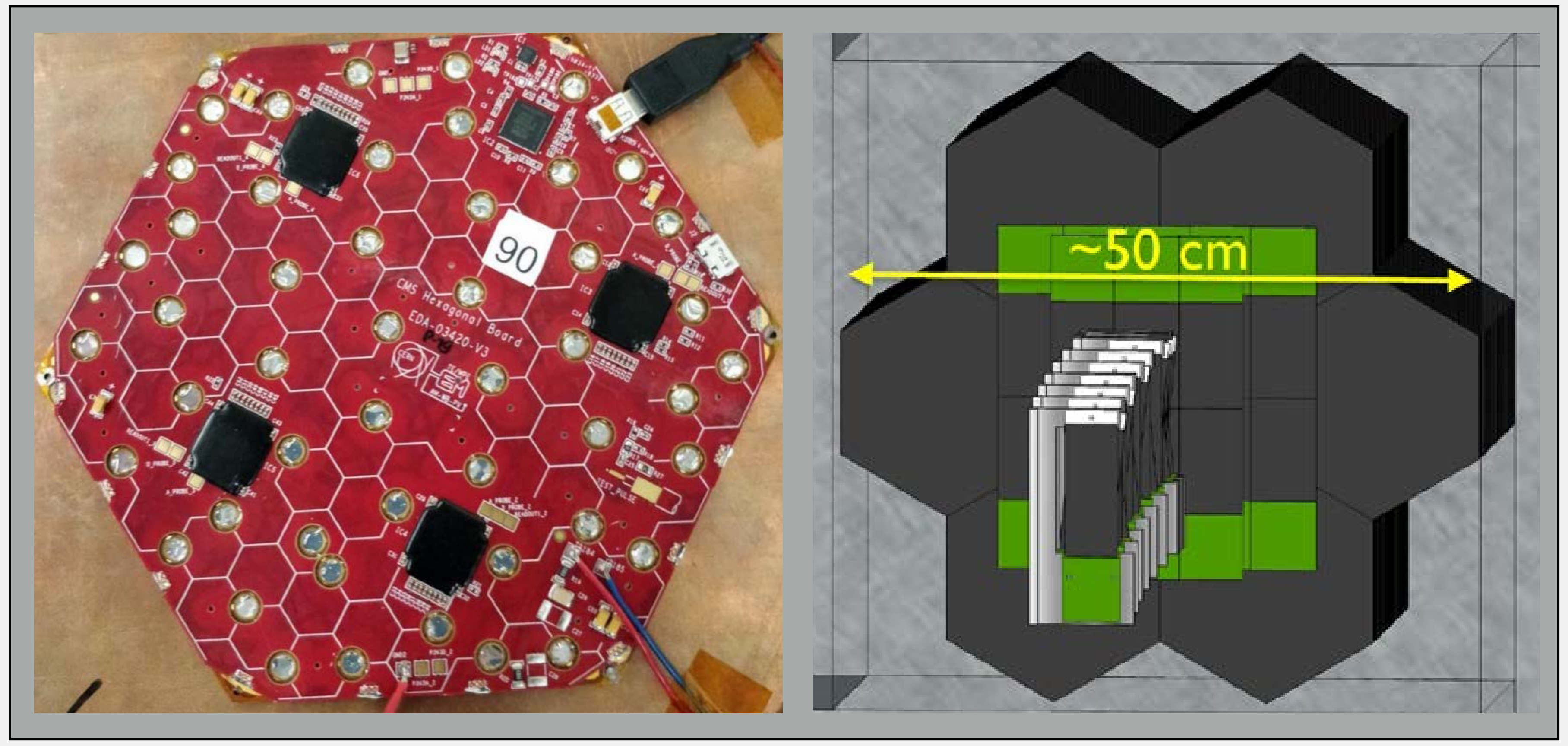
- ~0.1 - 0.3 X_0 tungsten
- balance signal rate & momentum smearing

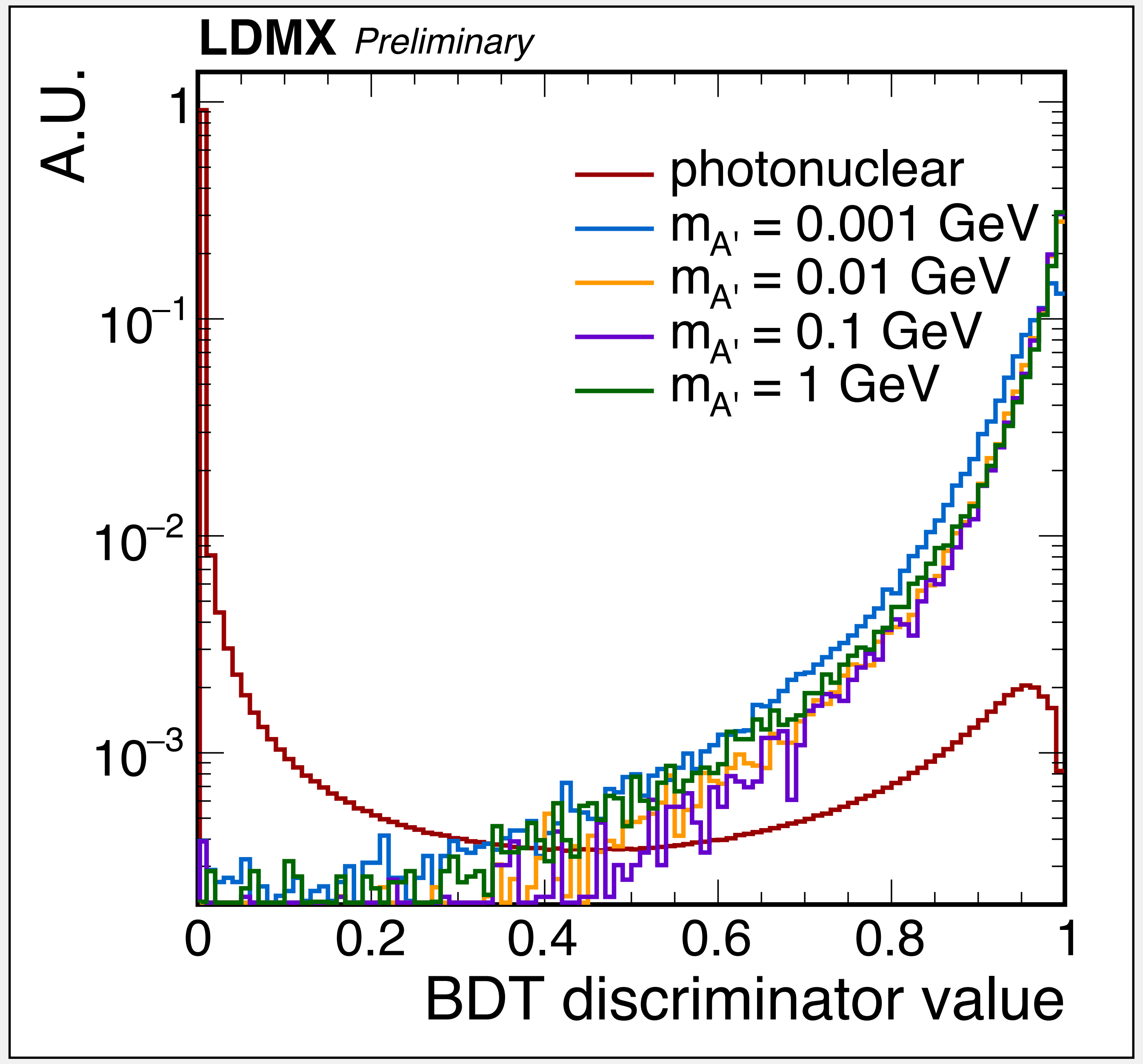
Electromagnetic Calorimeter

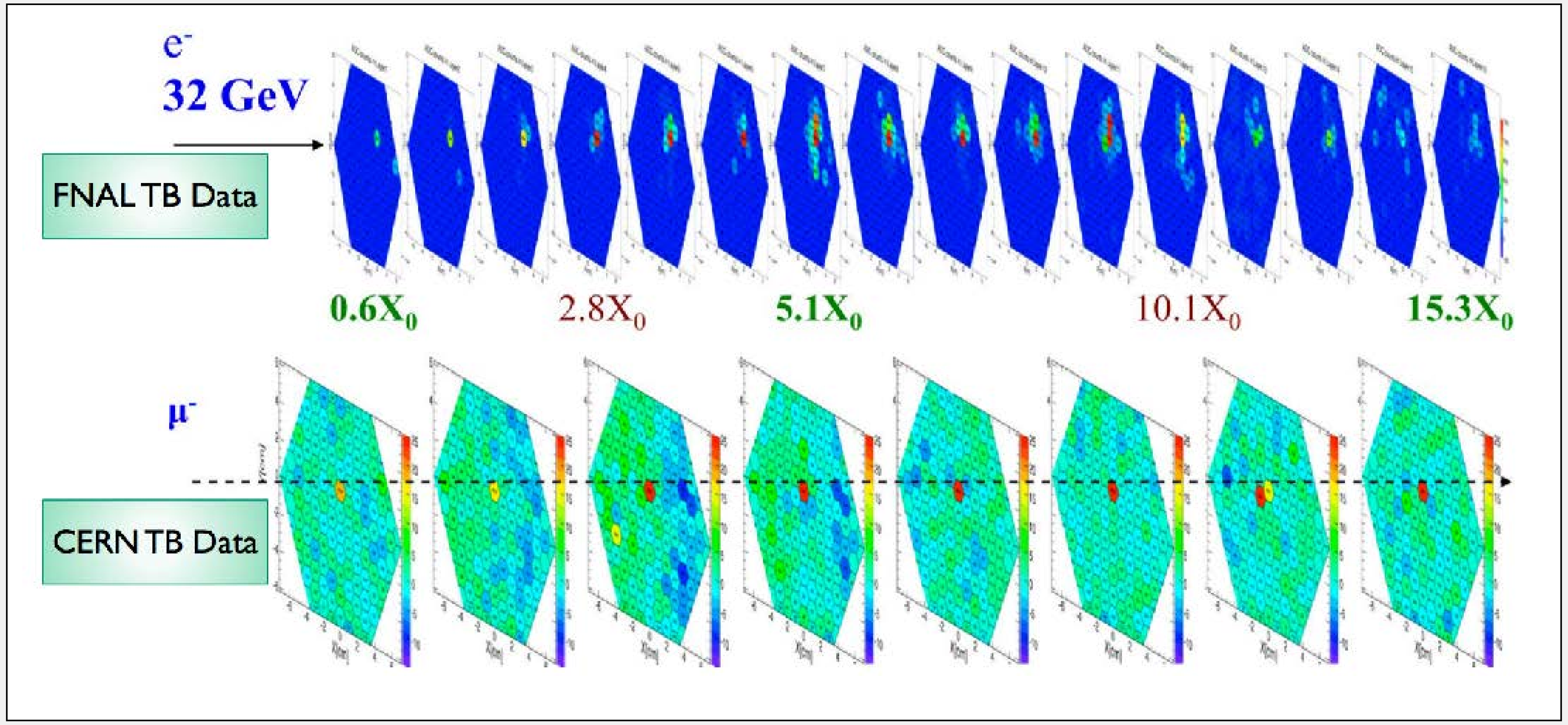


ECal

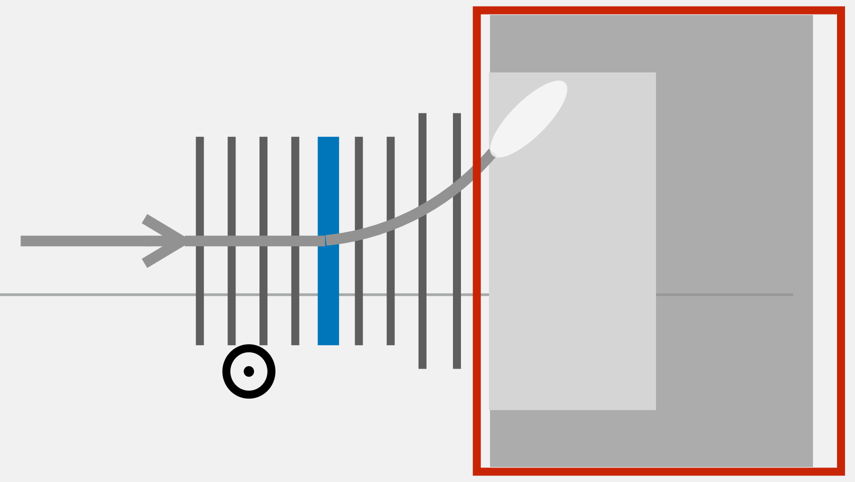
- draw on design of CMS@LHC forward SiW calorimeter upgrade
  - fast, radiation hard, dense
  - 40 radiation lengths (>30 layers)
  - high granularity ('tracking' of minimum ionising particles, MIP)
    - potentially increase granularity in central module





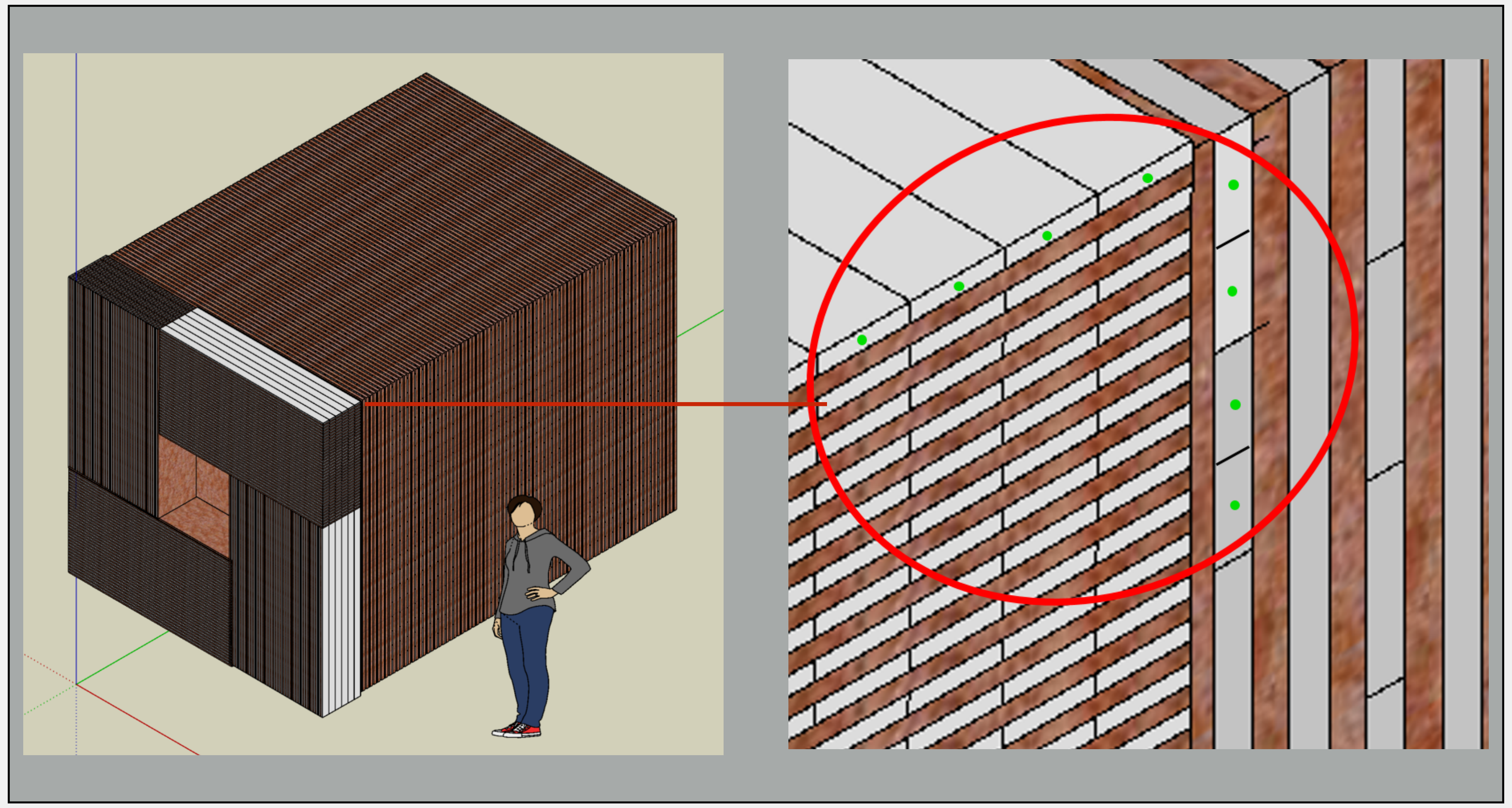


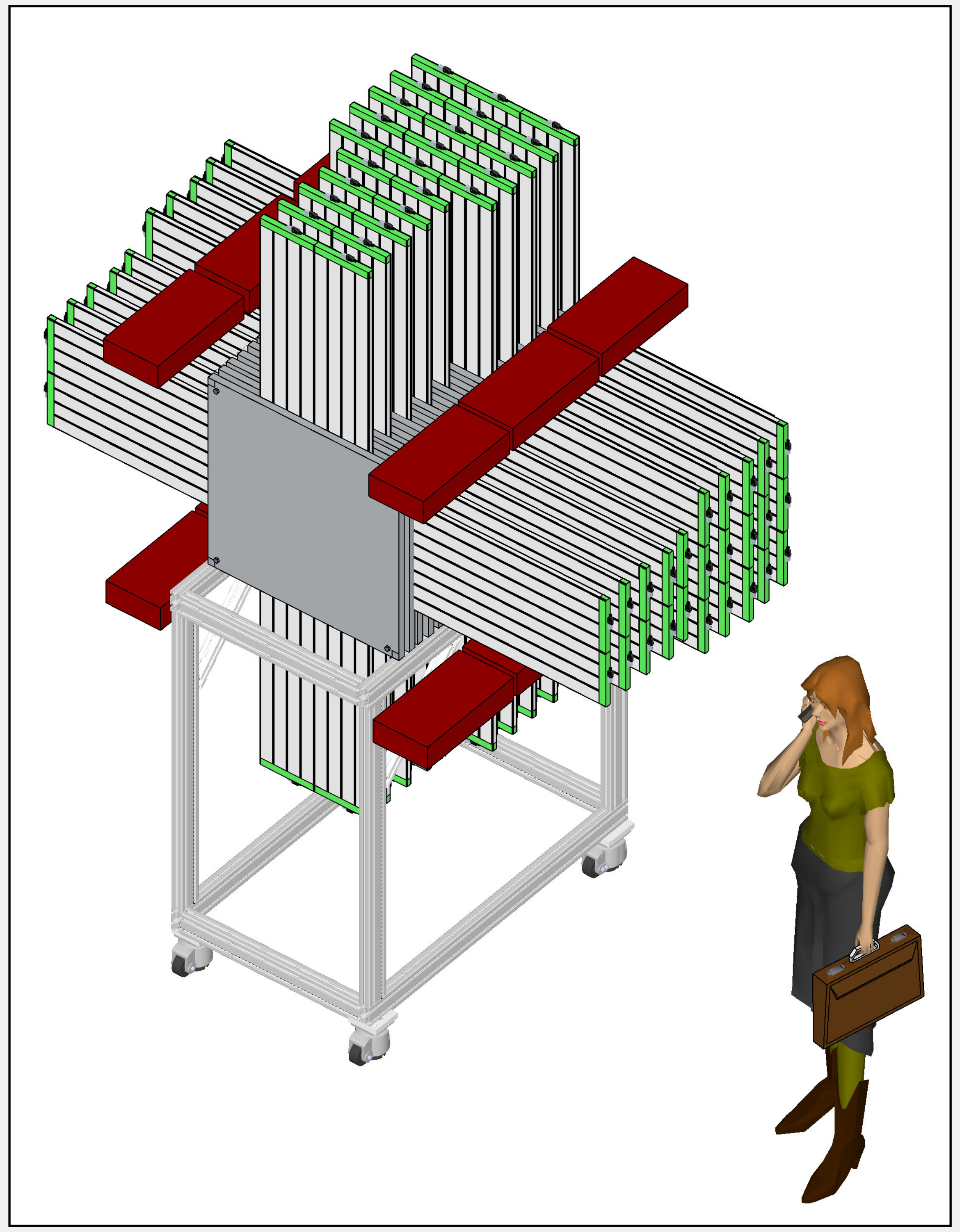
Hadronic Calorimeter



HCal

- highly efficient **veto** of low- and high-energy neutrons
- surround ECal as much as possible (back and side)
- plastic scintillator with steel absorber (inspiration from Minos/**Mu2e**/CMS)





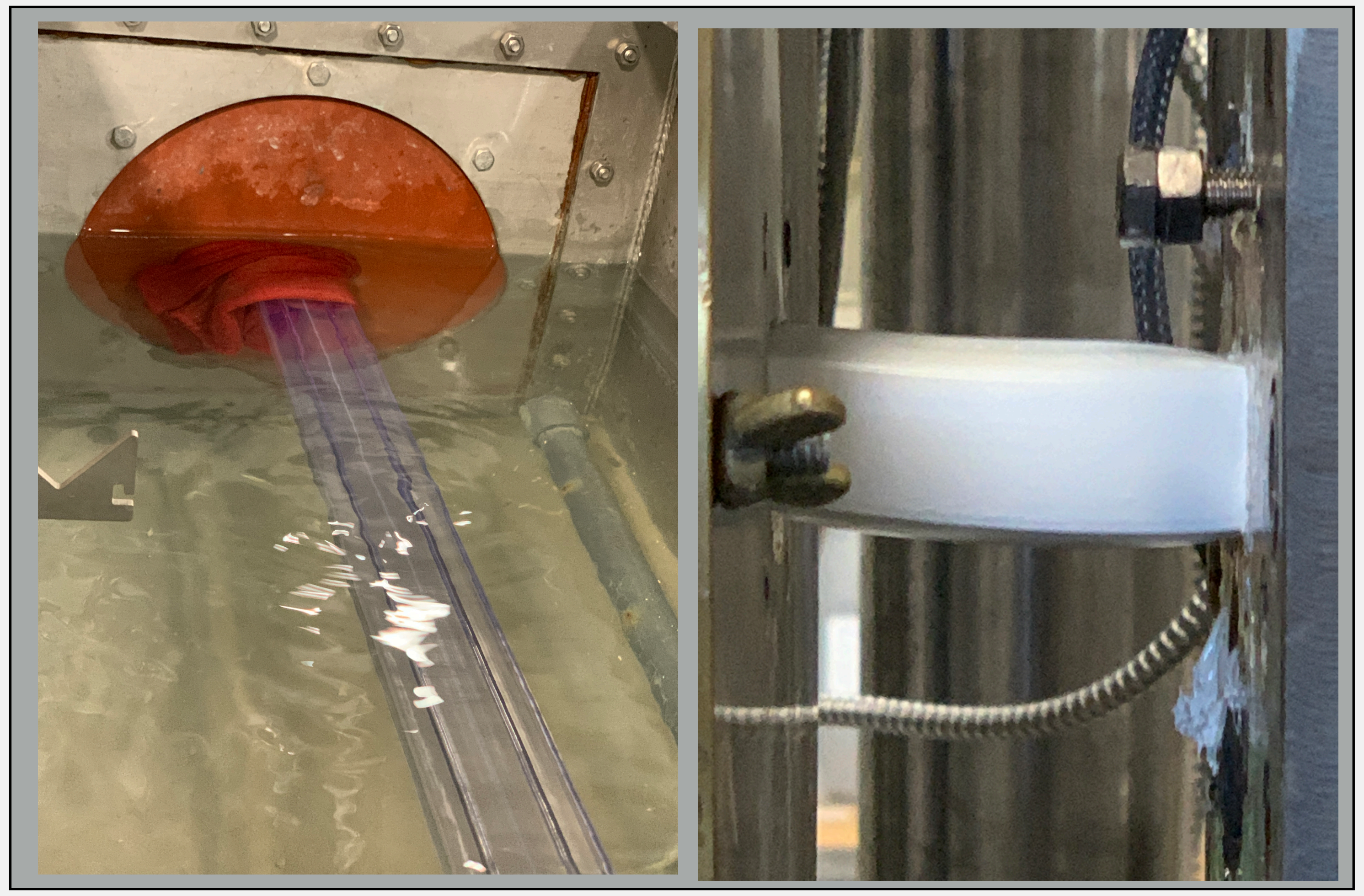
Testbeam

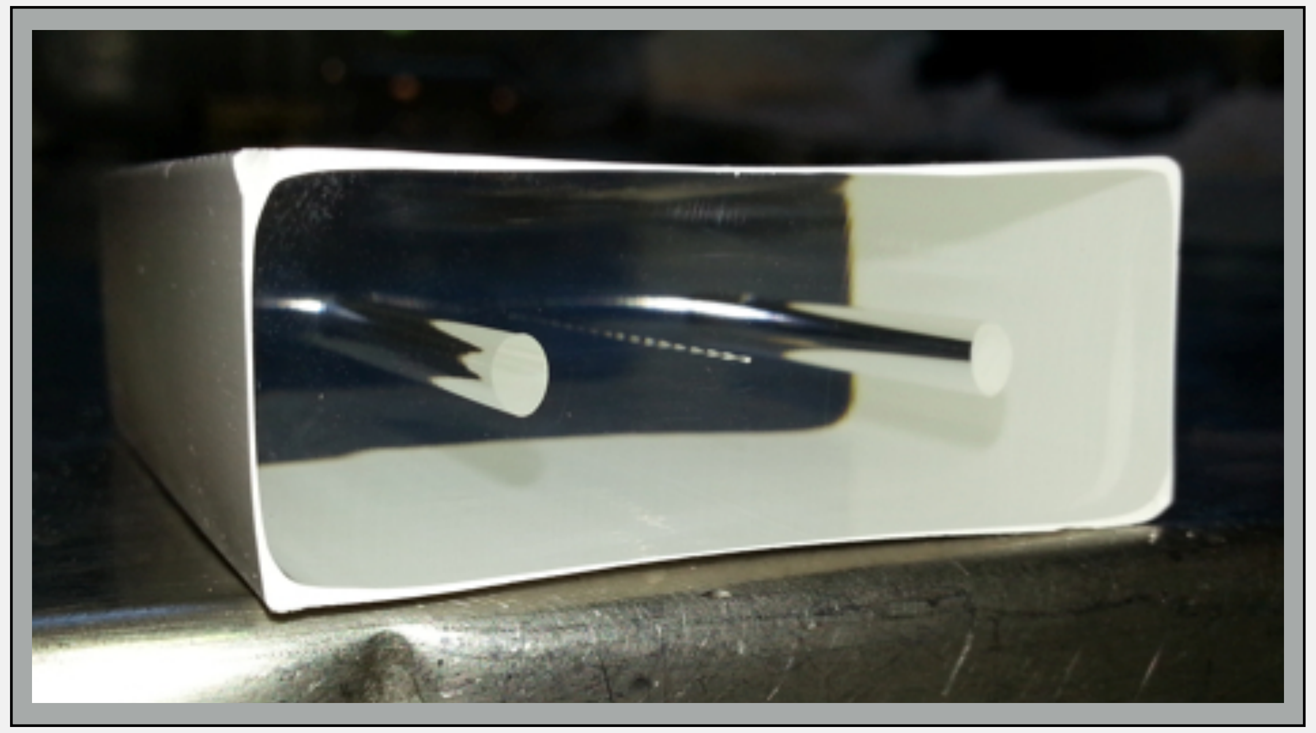
- obtained first funding from Swedish sources for R&D/prototype
- planned for fall 2020
- prototype layout coming together

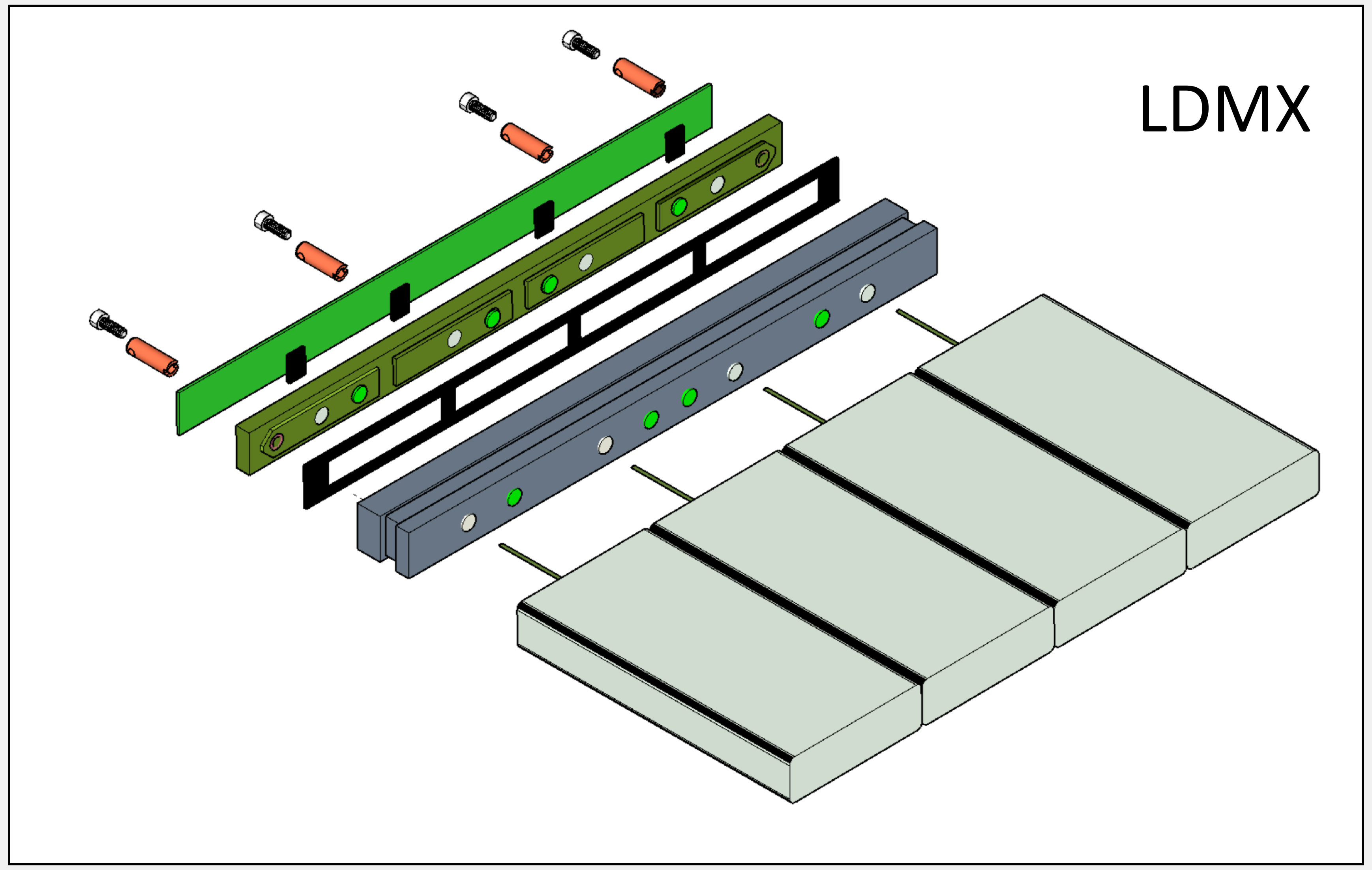
Hadronic Calorimeter

Scintillator bars: based on Mu2e cosmic ray veto that UVA group is building

- great to have this first-hand expertise for LDMX!
- bars extruded at FNAL with one hole in the middle for fiber (Mu2e uses two holes)
- LDMX probably going to use quad-bar units instead of di-bars







Hadronic Calorimeter

Benchmark example:

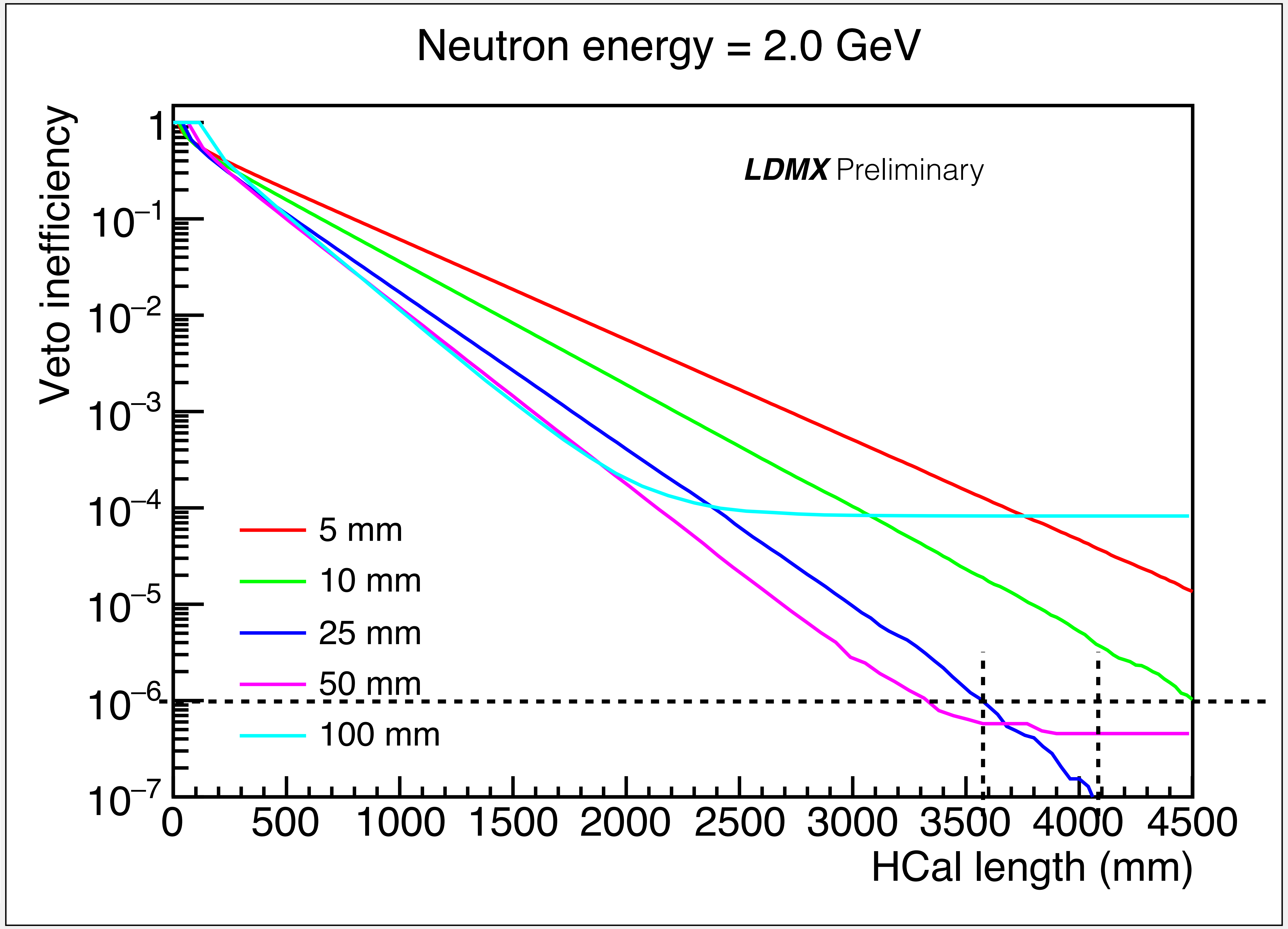
veto inefficiency of at most 10^{-6} for single neutrons (~15λ)

Absorber thickness?

- too thick: neutrons 'get stuck'
  —> no signal in scintillator
- too thin: detector needs to be very large

Currently assuming 25mm, 4m deep, transverse size 2-3m

"Side HCal" around the ECal: Similar configuration, few λ deep



Finalisation of design parameters ongoing

Analysis Strategy

trigger on missing energy

+ combine ECal features into a BDT
+ veto on activity in HCal
+ MIP tracking in ECal (**new!**)

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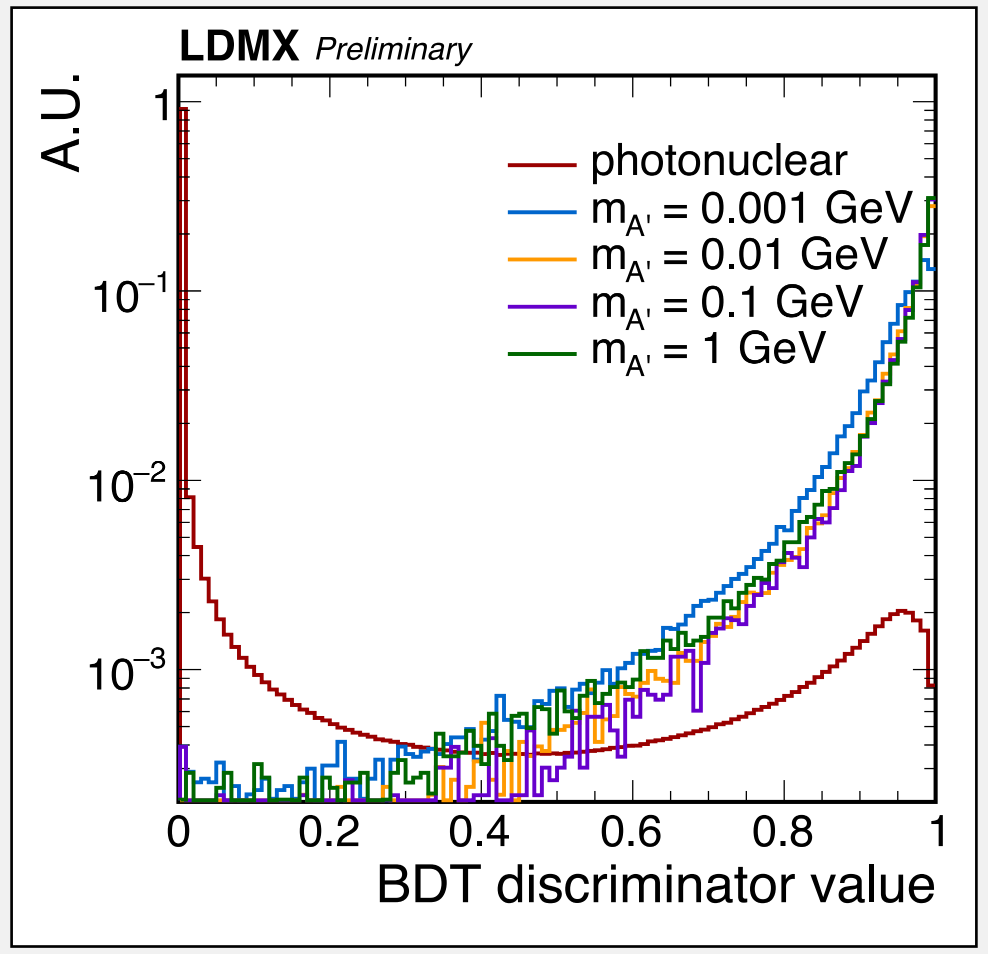
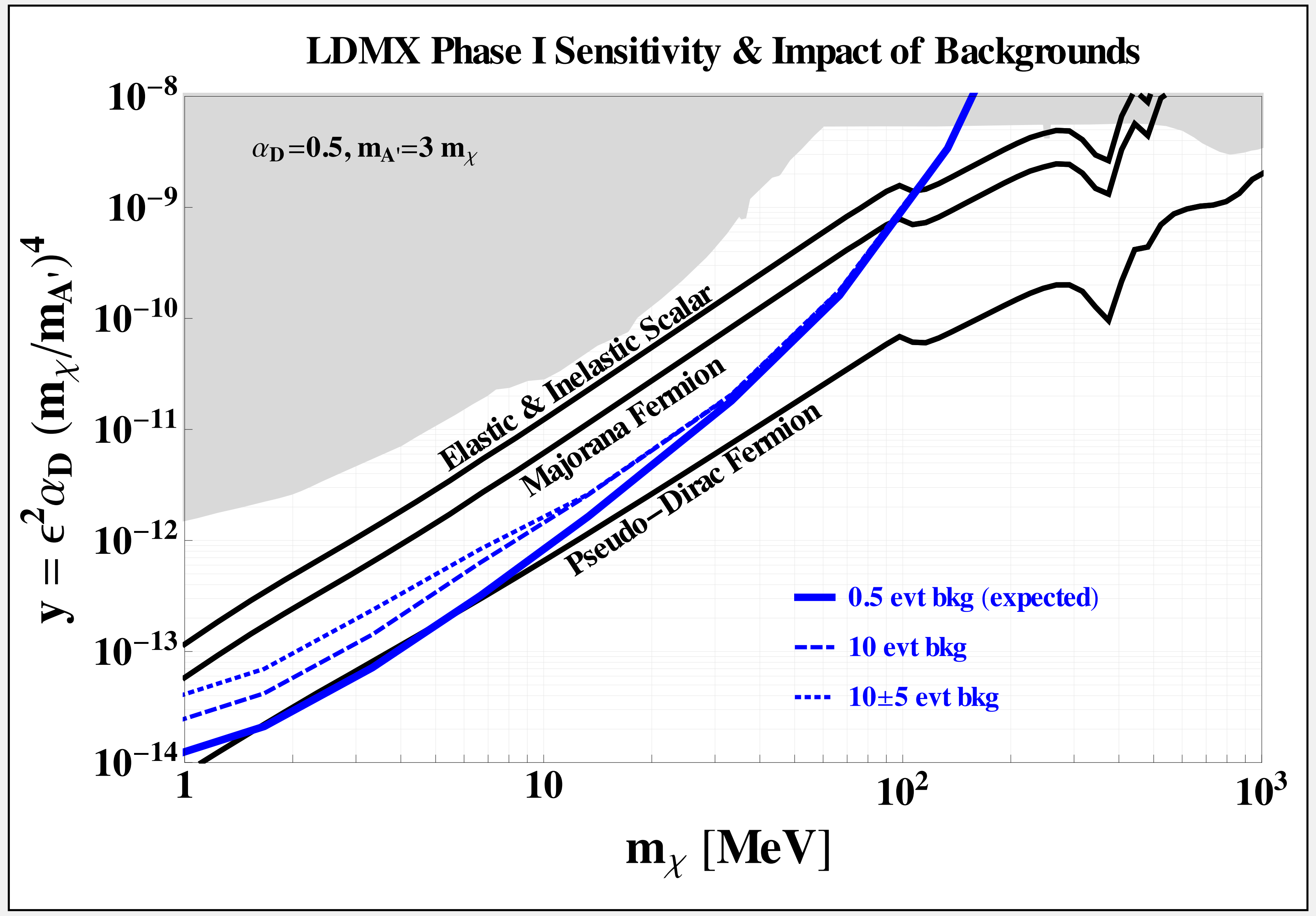
at 4 GeV: **close to 0-background** for 4e14 EoT
based on simulation studies



arxiv:1808.05219



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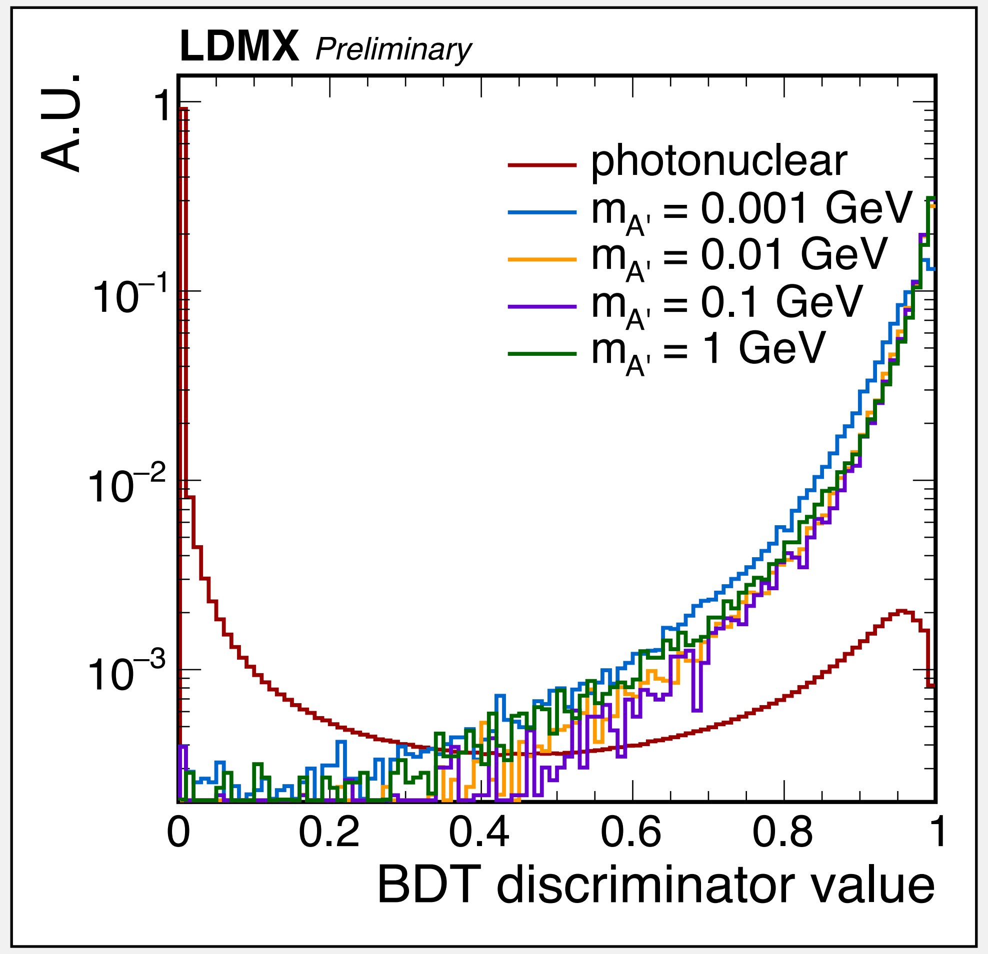
important:

several handles not exploited yet, in particular p_T!

HCal optimisation ongoing

things get easier at higher energy!



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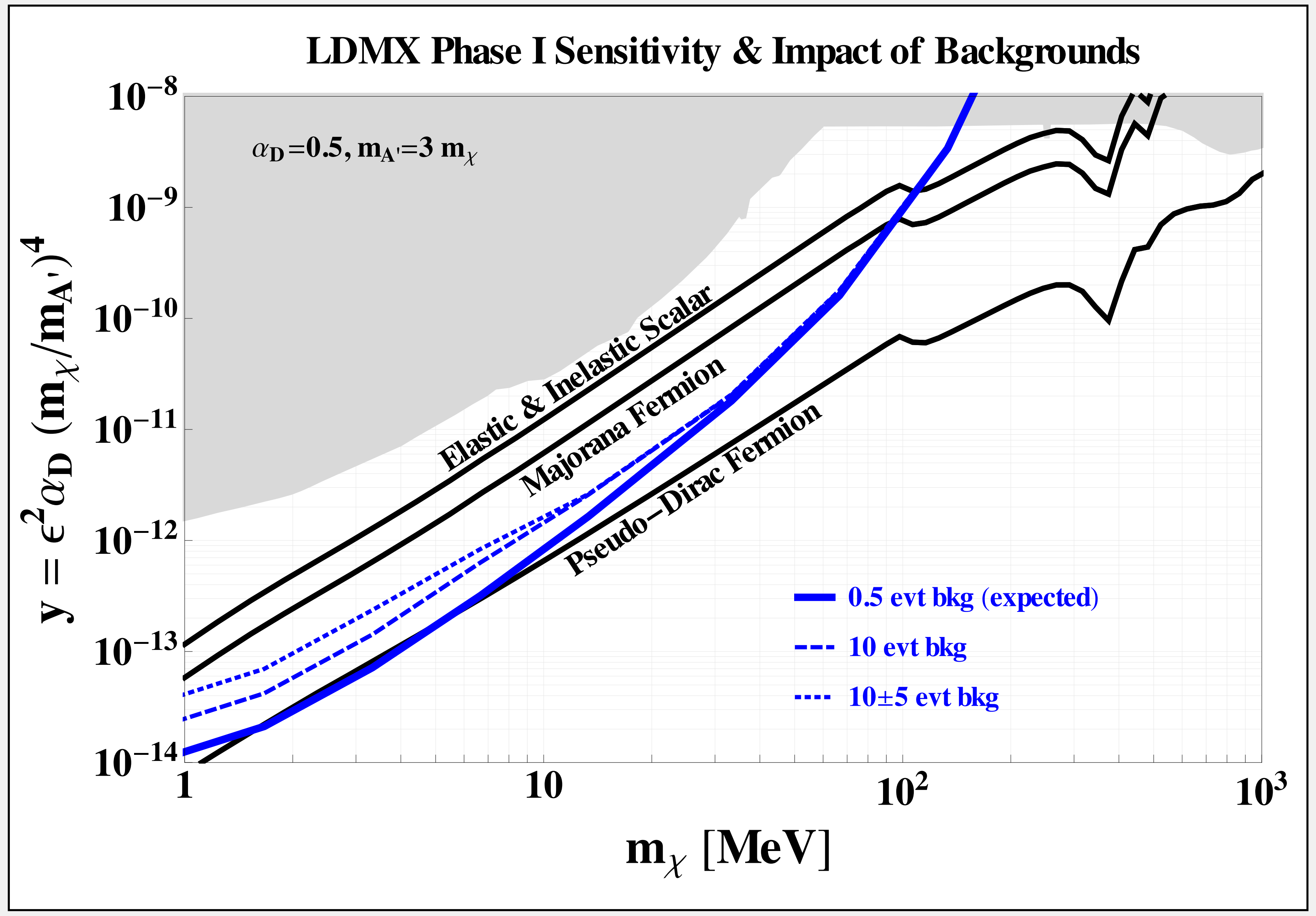

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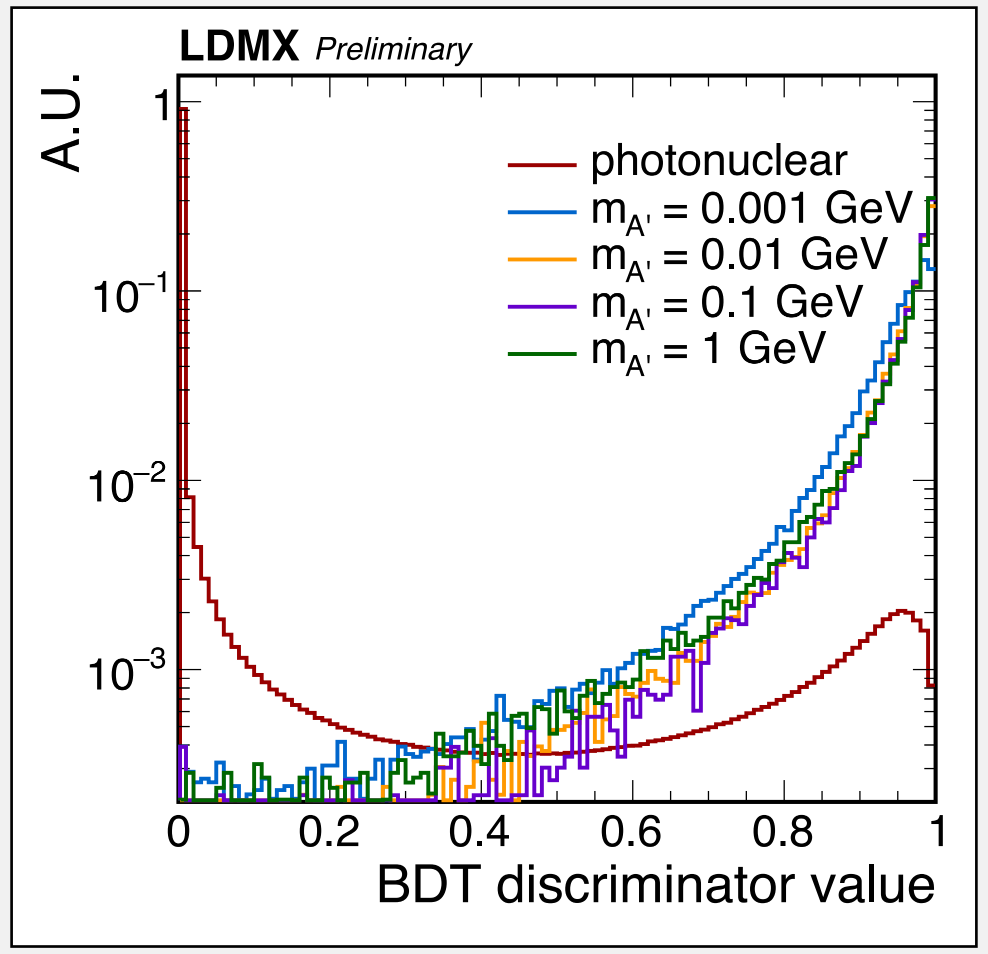

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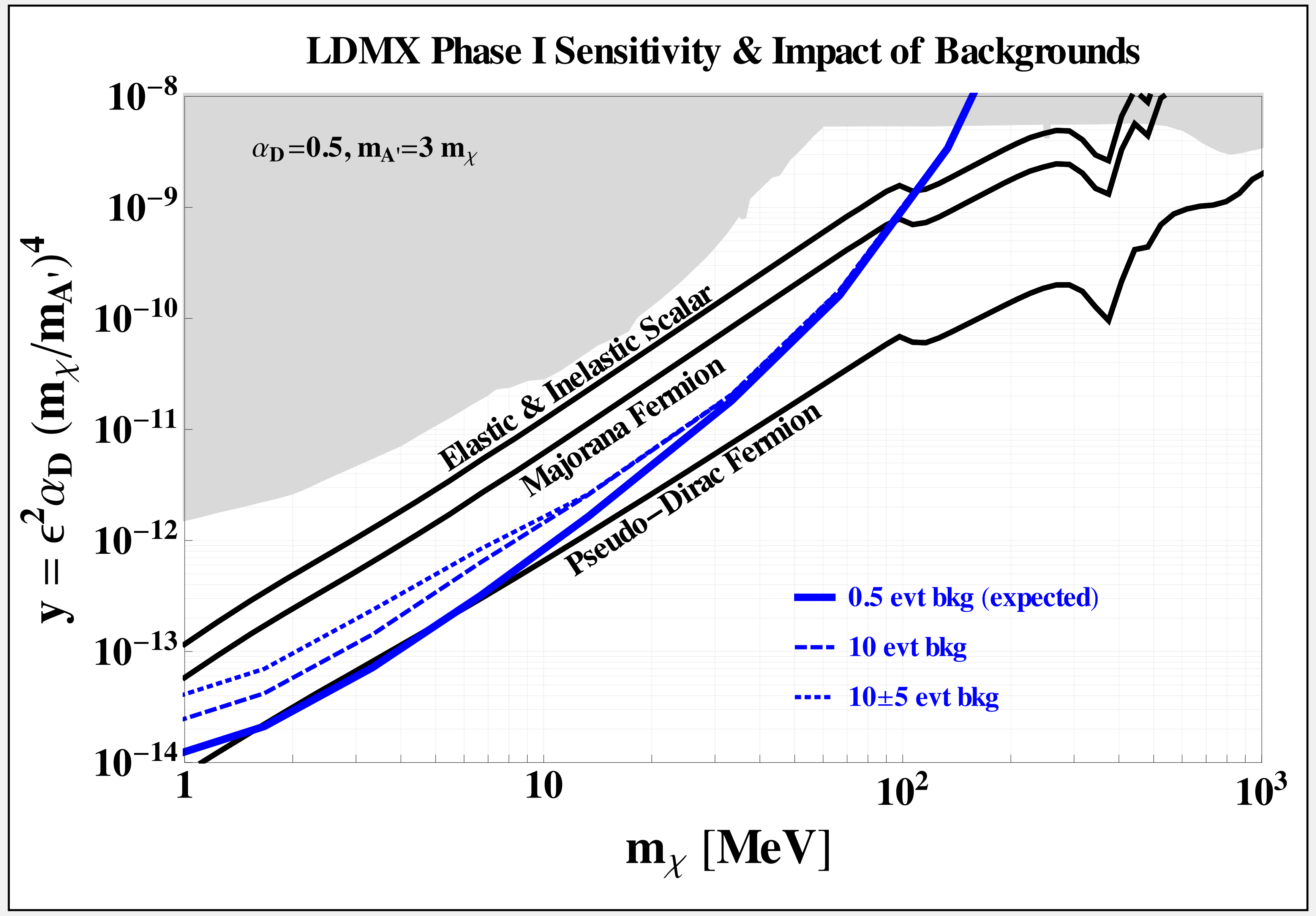


with data:
redundancy in vetoes —> data control samples, verify rejection
comprehensive kinematic information —> establish signal-likeness

Funding

US: Awaiting outcome of application for R&D funding submitted in spring

Europe: Some funding awarded during summer/fall

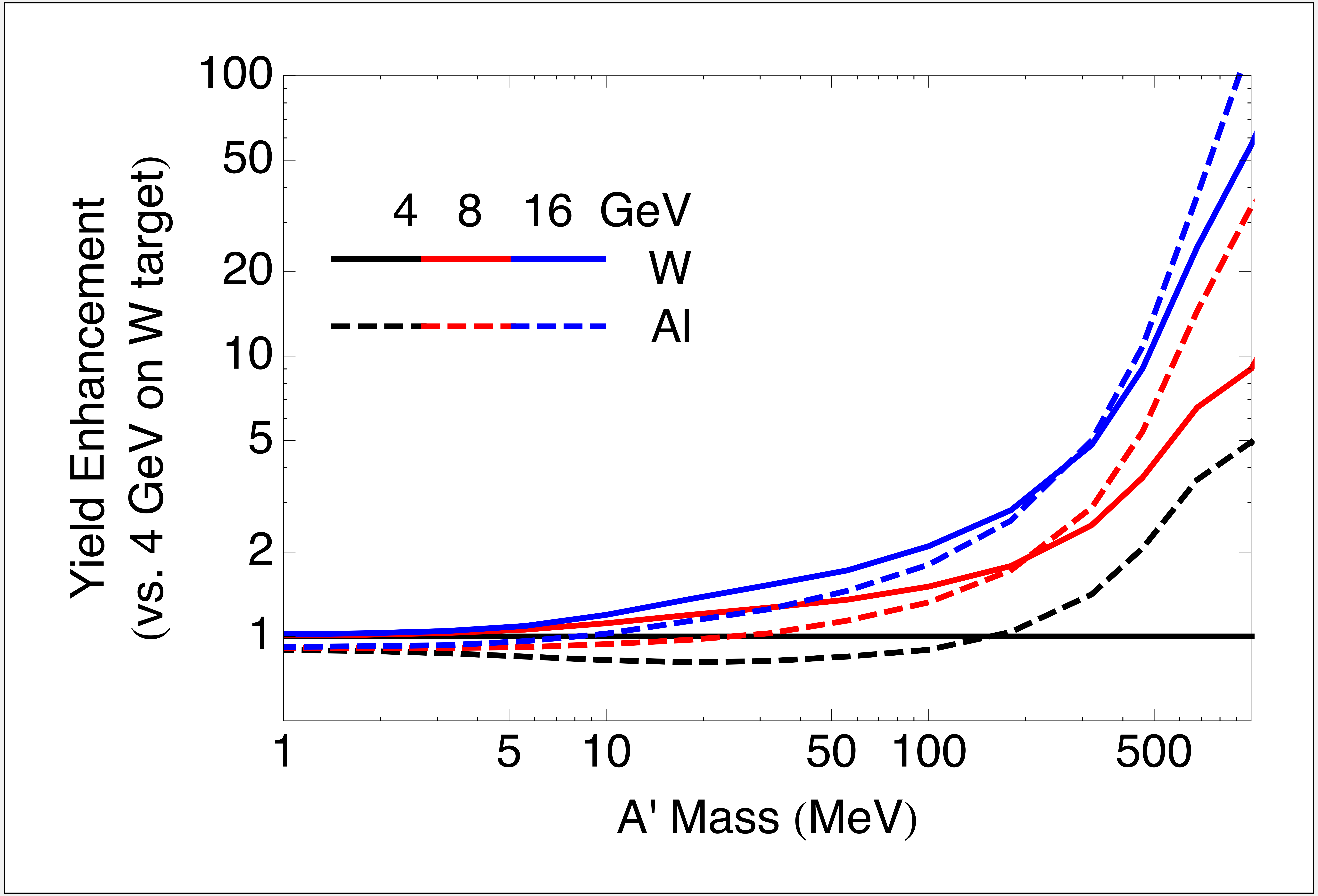
- support for HCal prototype/testbam
  - Crafoord Foundation + Royal Physiographic Society Lund
- project grant for research programme on LDMX from Knut and Alice Wallenberg Foundation
- individual support from Swedish Research Council

—> Things are moving along!

Going Beyond

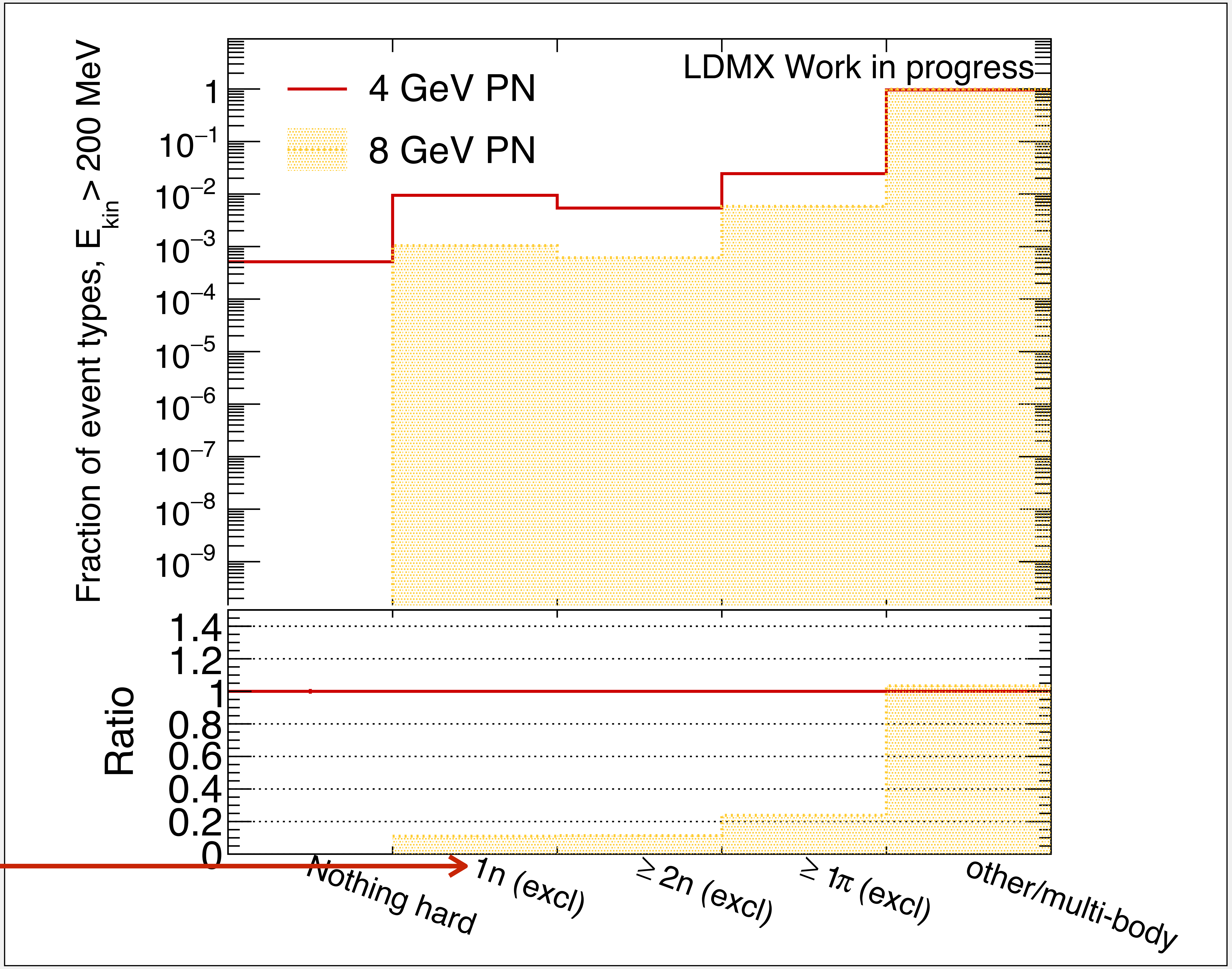
Why higher energy?

increased signal yield



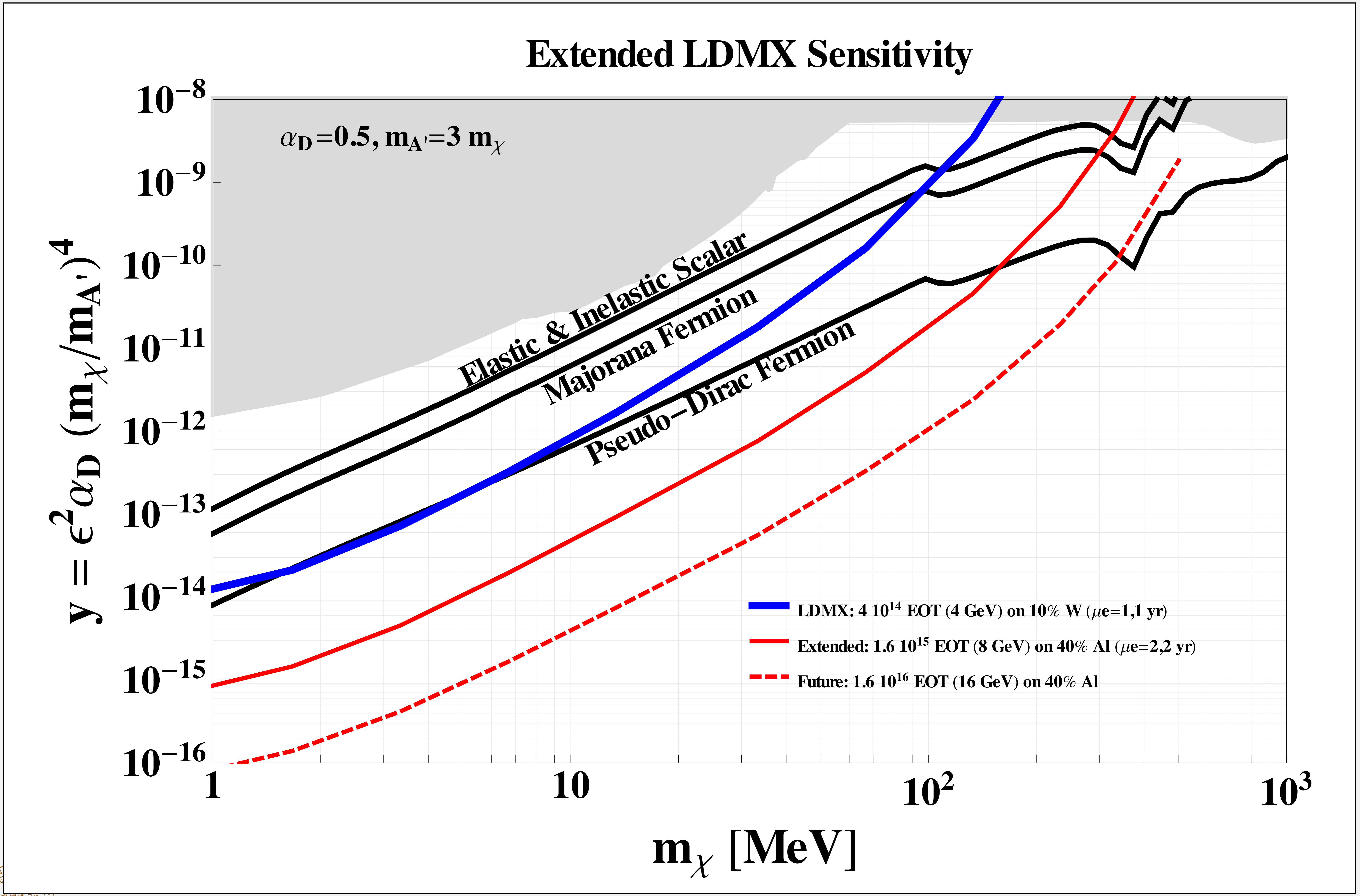
Why higher energy?

improved background rejection possibilities



particularly critical

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

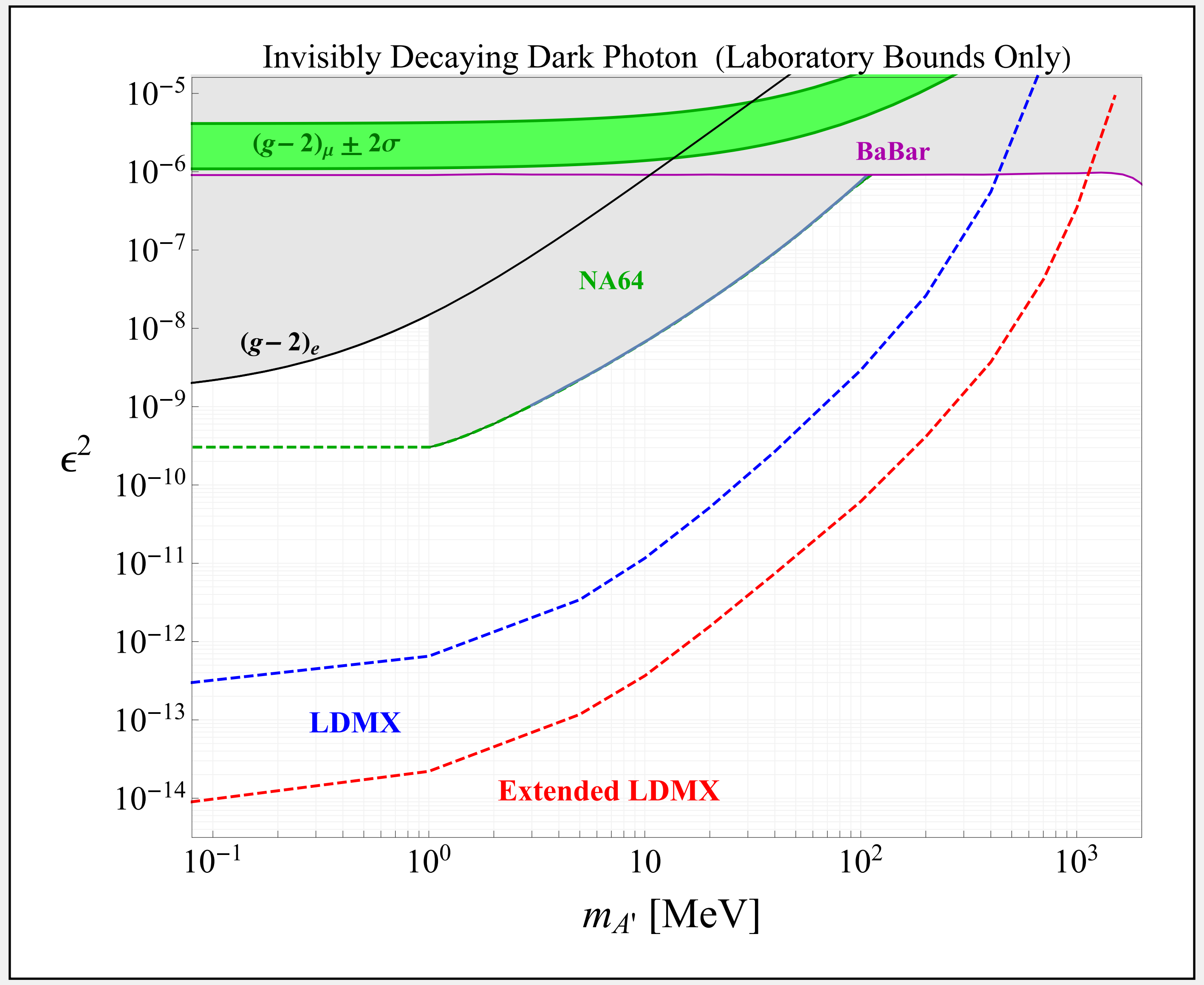
Further Potential

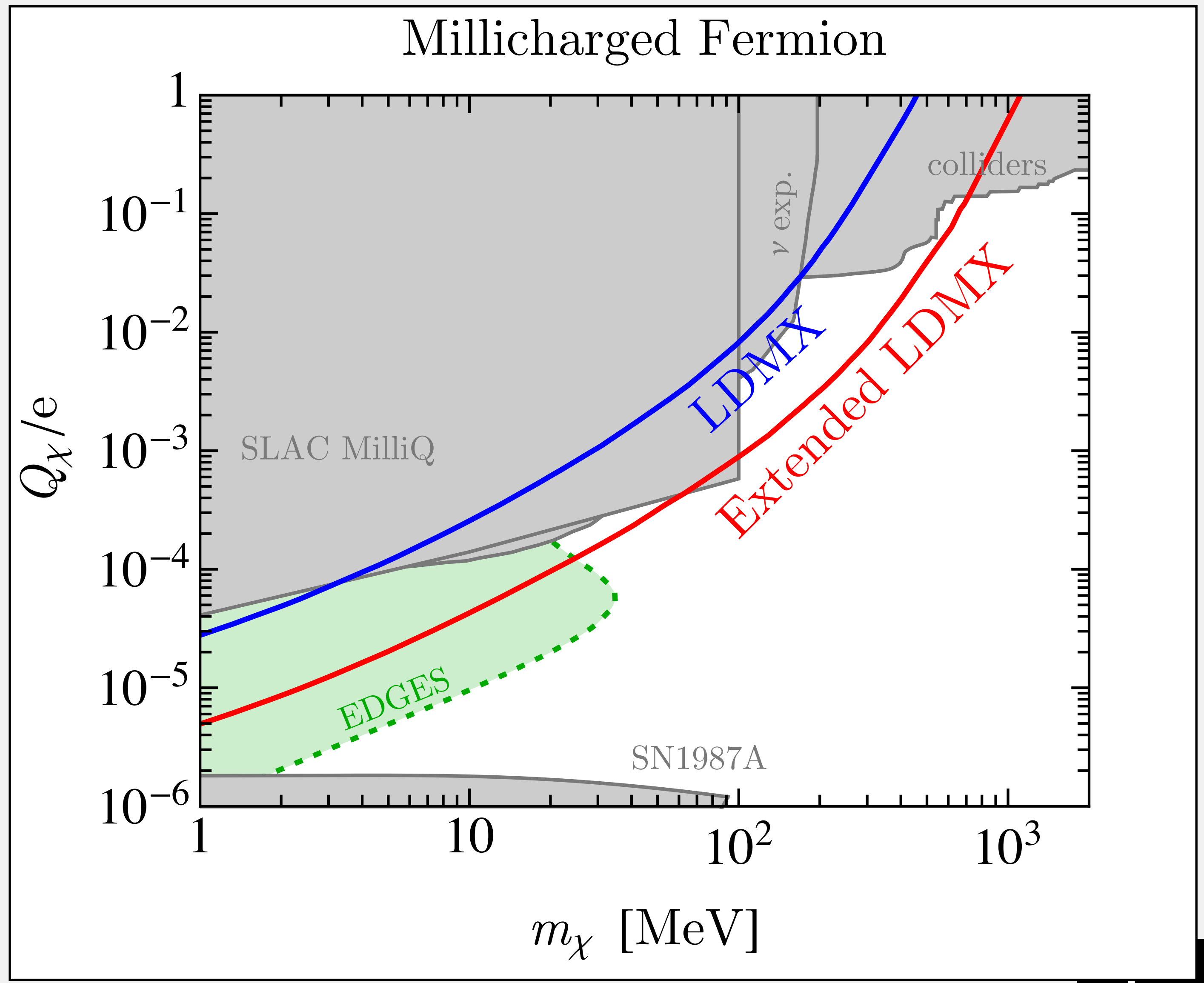
also sensitive to

- 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

- More than 5 times as much Dark Matter as normal matter
- Light, thermal relic Dark Matter well motivated
- Broad interest in Dark Sector physics, many new initiatives
- LDMX can achieve outstanding sensitivity (within a few years)
- Potential to probe thermal targets in MeV - GeV range
- First funding coming in

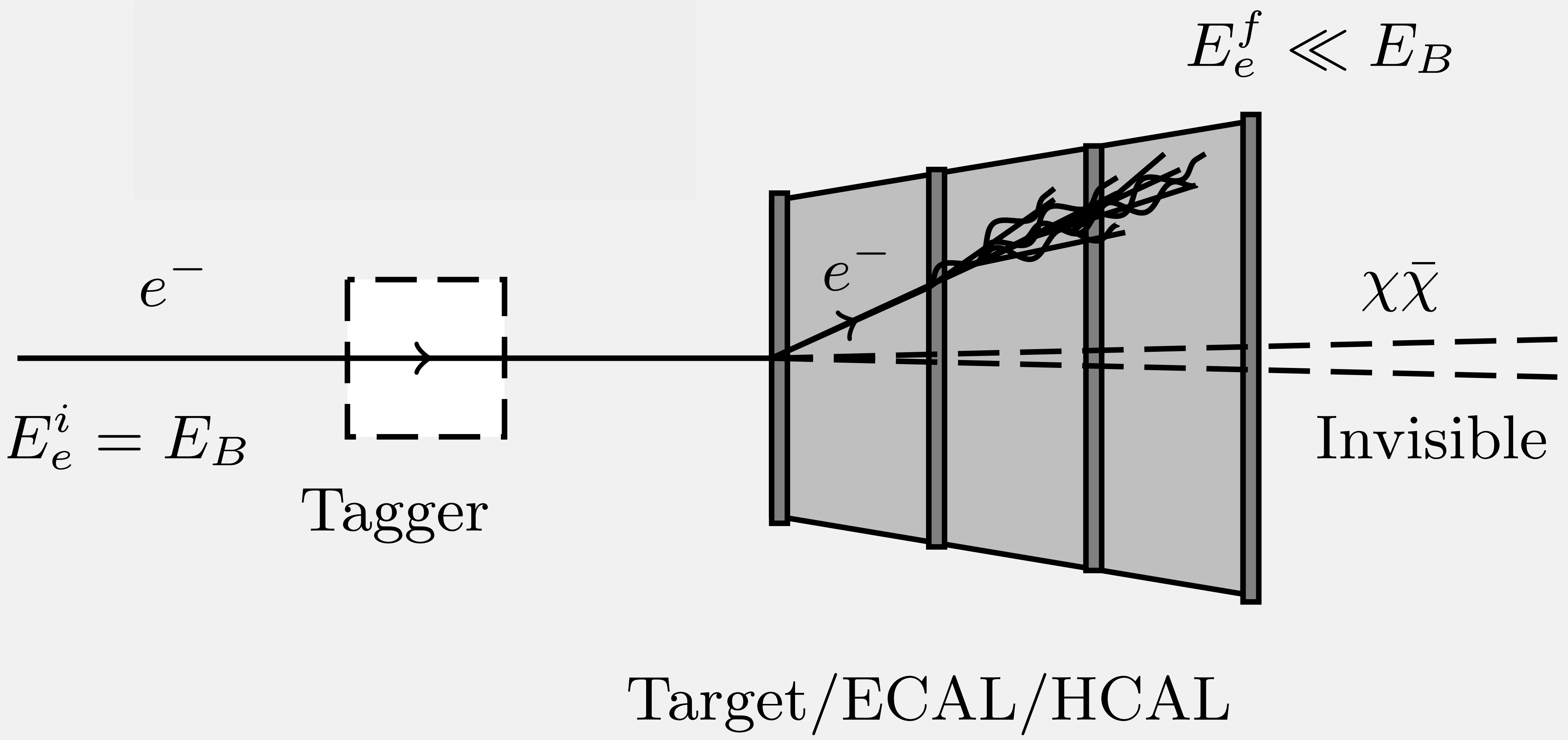
The next few years will be exciting!

Thank you!

Additional Material

Two Approaches

missing energy

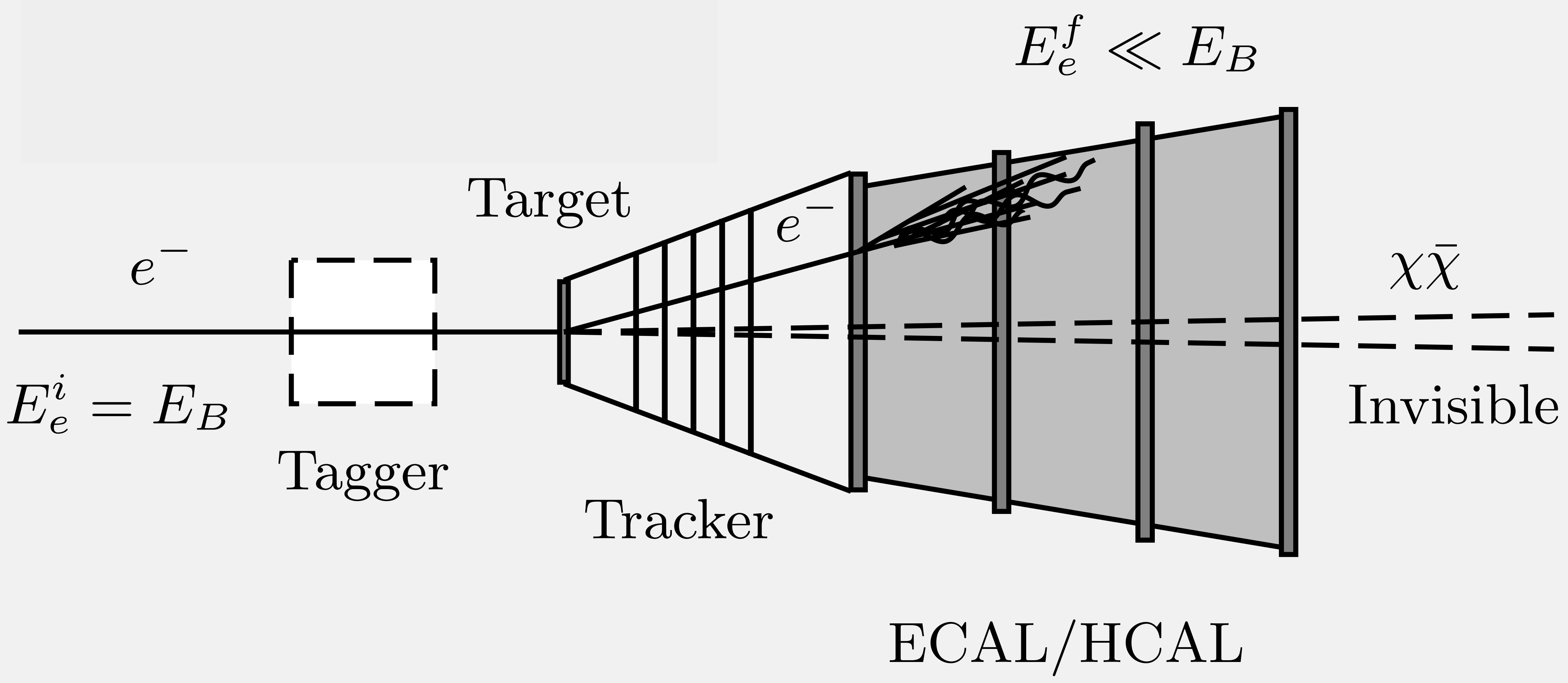


higher signal yield/EoT (thicker target)

greater signal acceptance

no e-γ particle ID

missing momentum

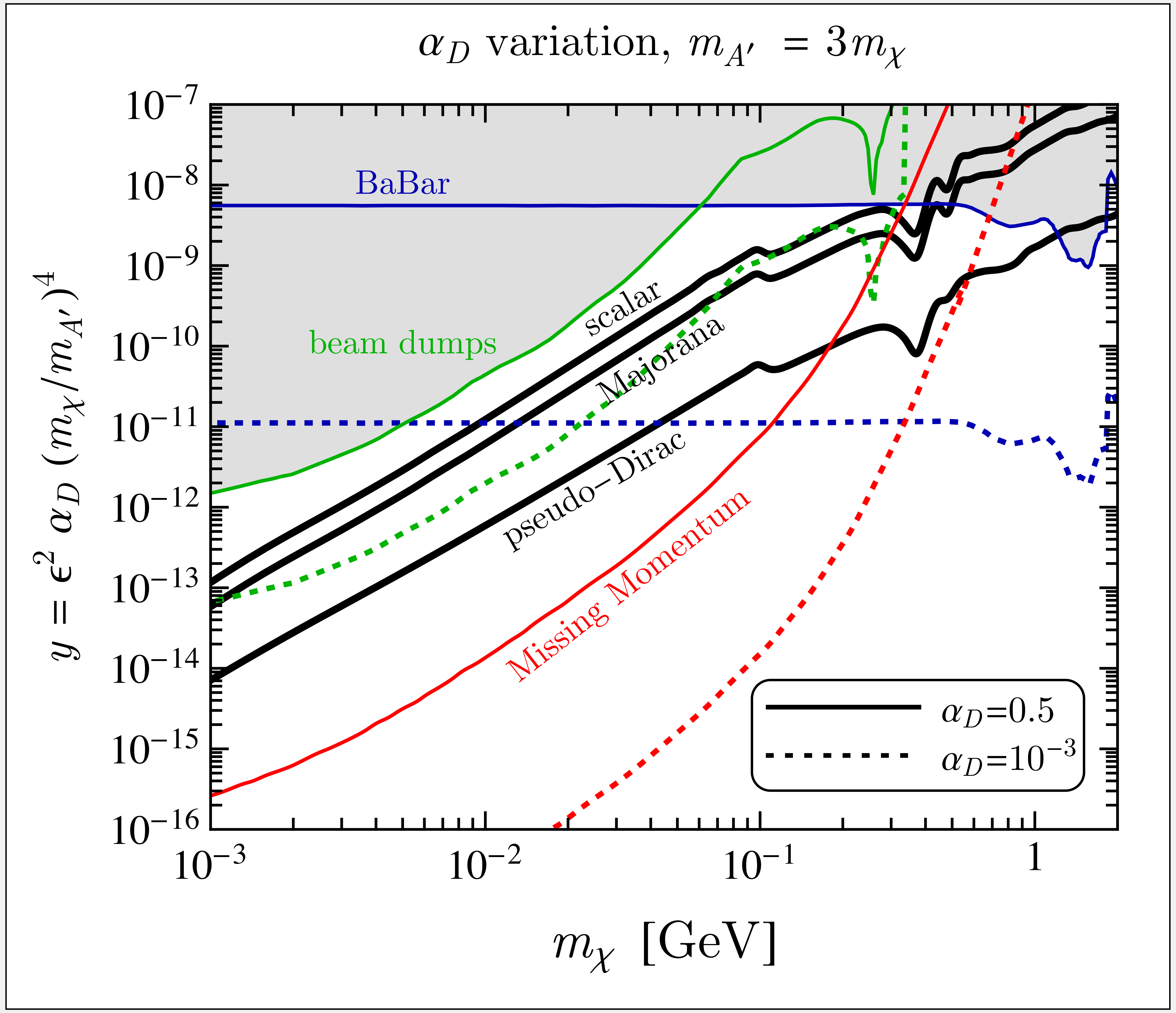


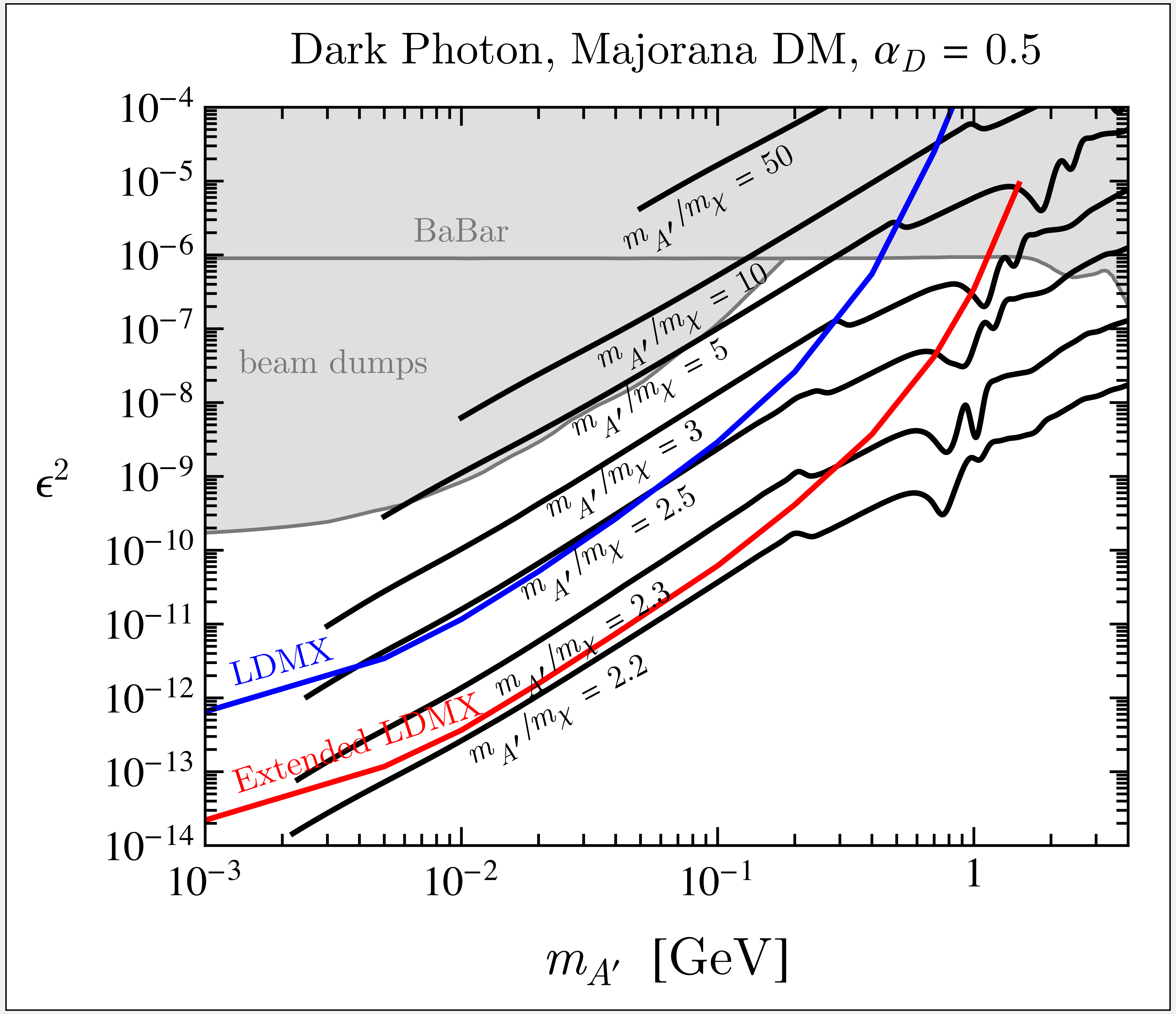
includes missing energy

p_T as discriminator & *signal identifier*

e-γ particle ID

Parameter Dependence





Various Future Projections