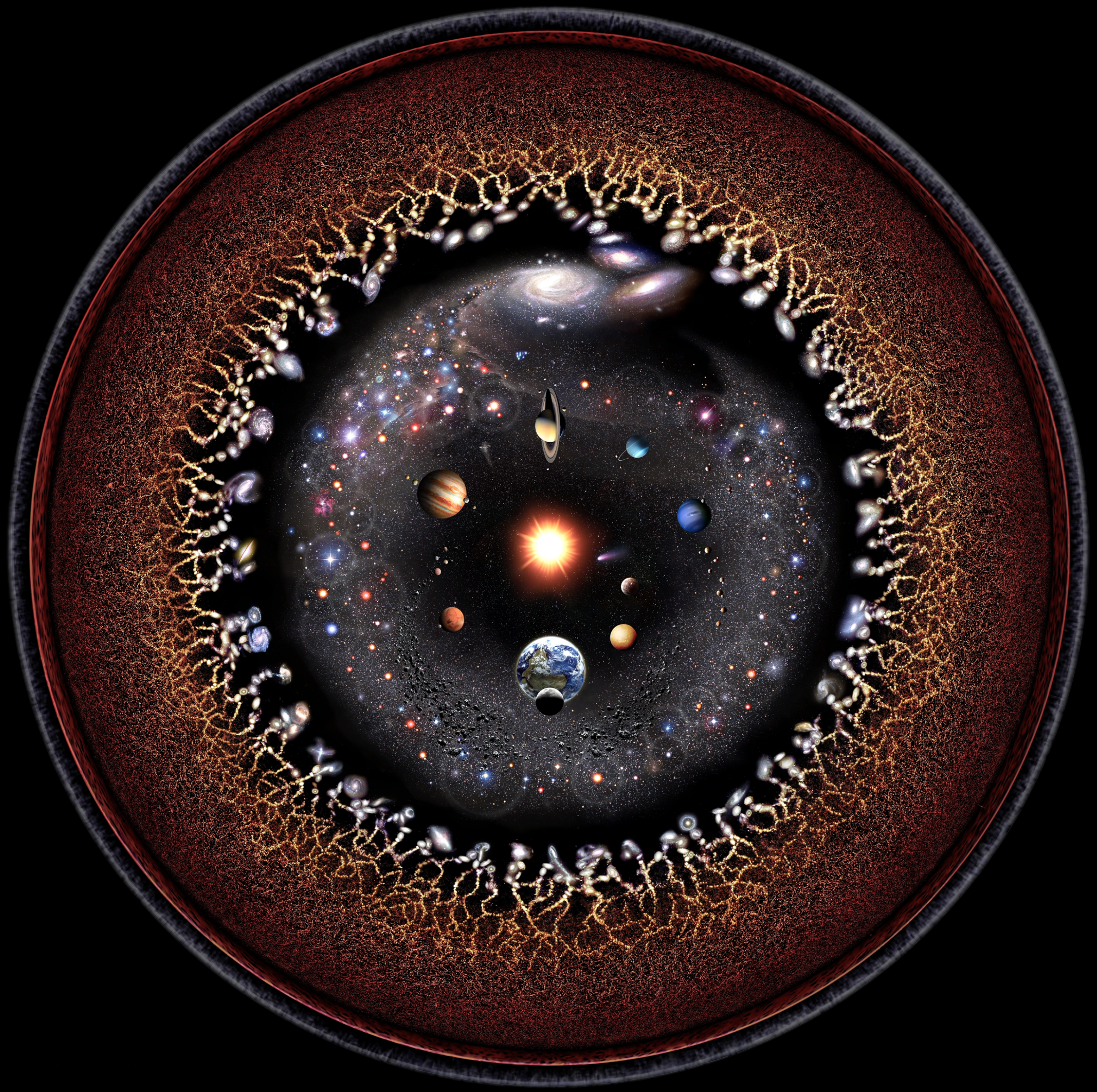
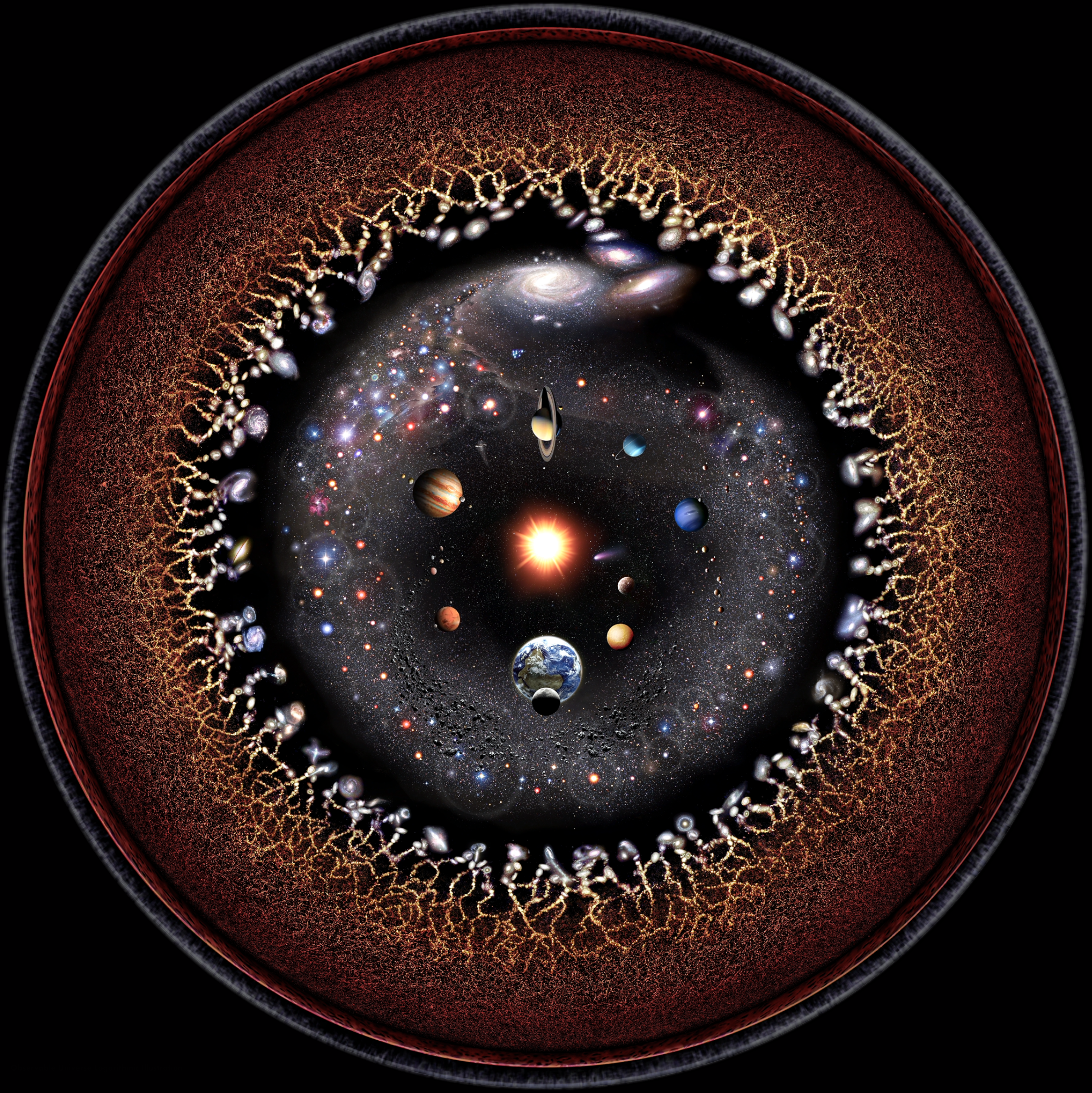
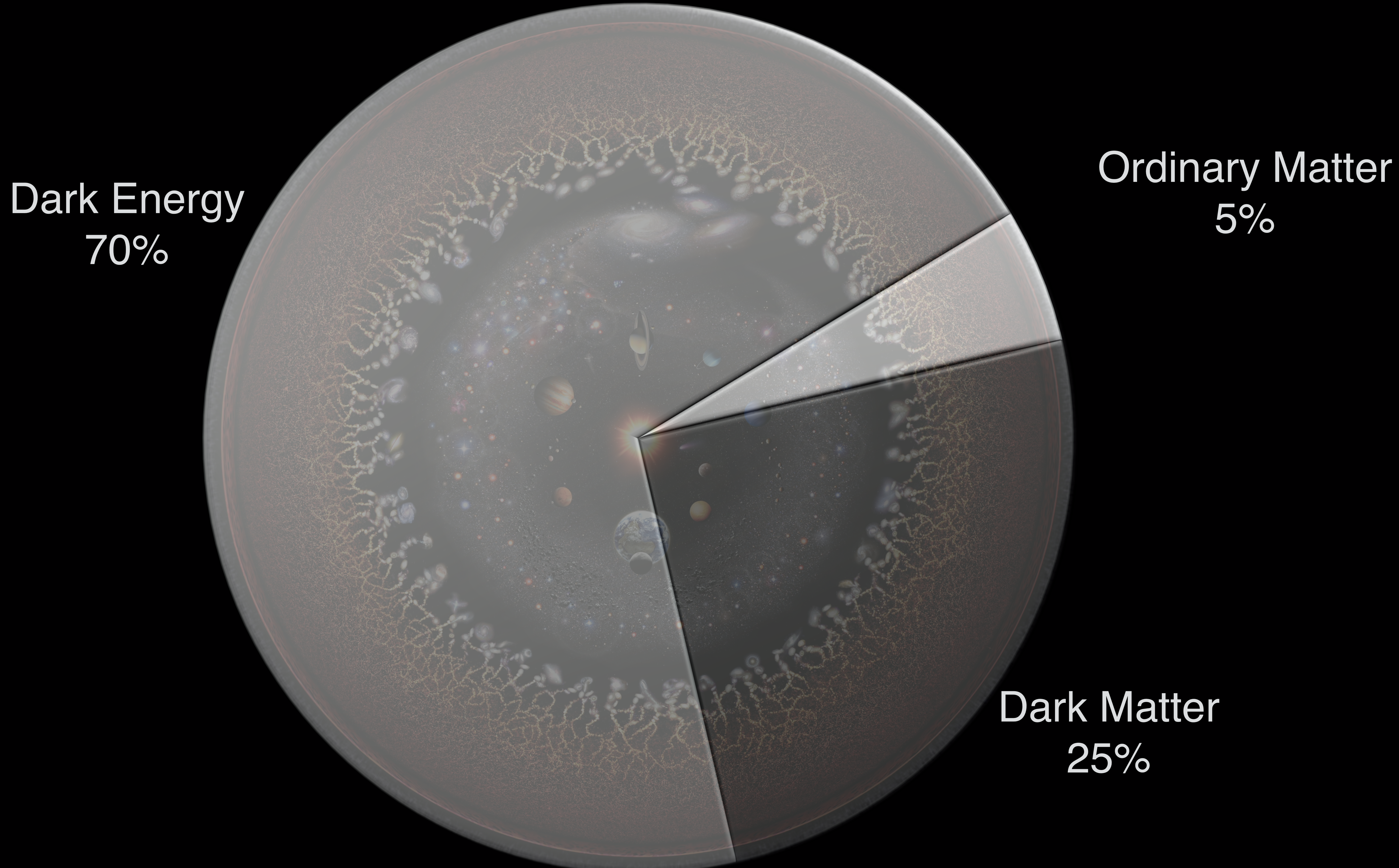


Search for Light Dark Matter at Accelerators

58. International Winter Meeting on Nuclear Physics
Bormio, 24 January 2020

Ruth Pöttgen

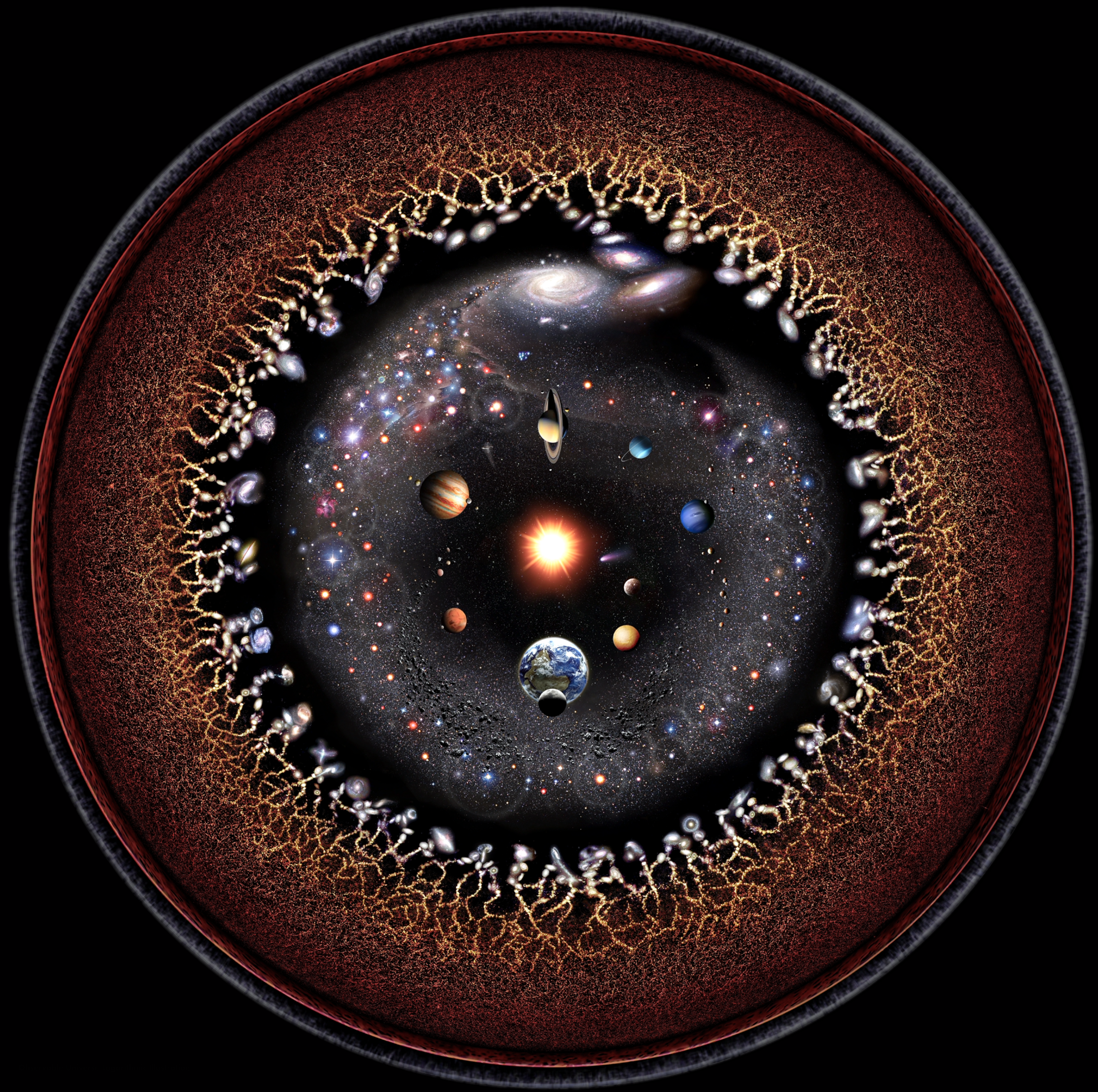



Dark Energy
70%
Ordinary Matter
5%
Dark Matter
25%

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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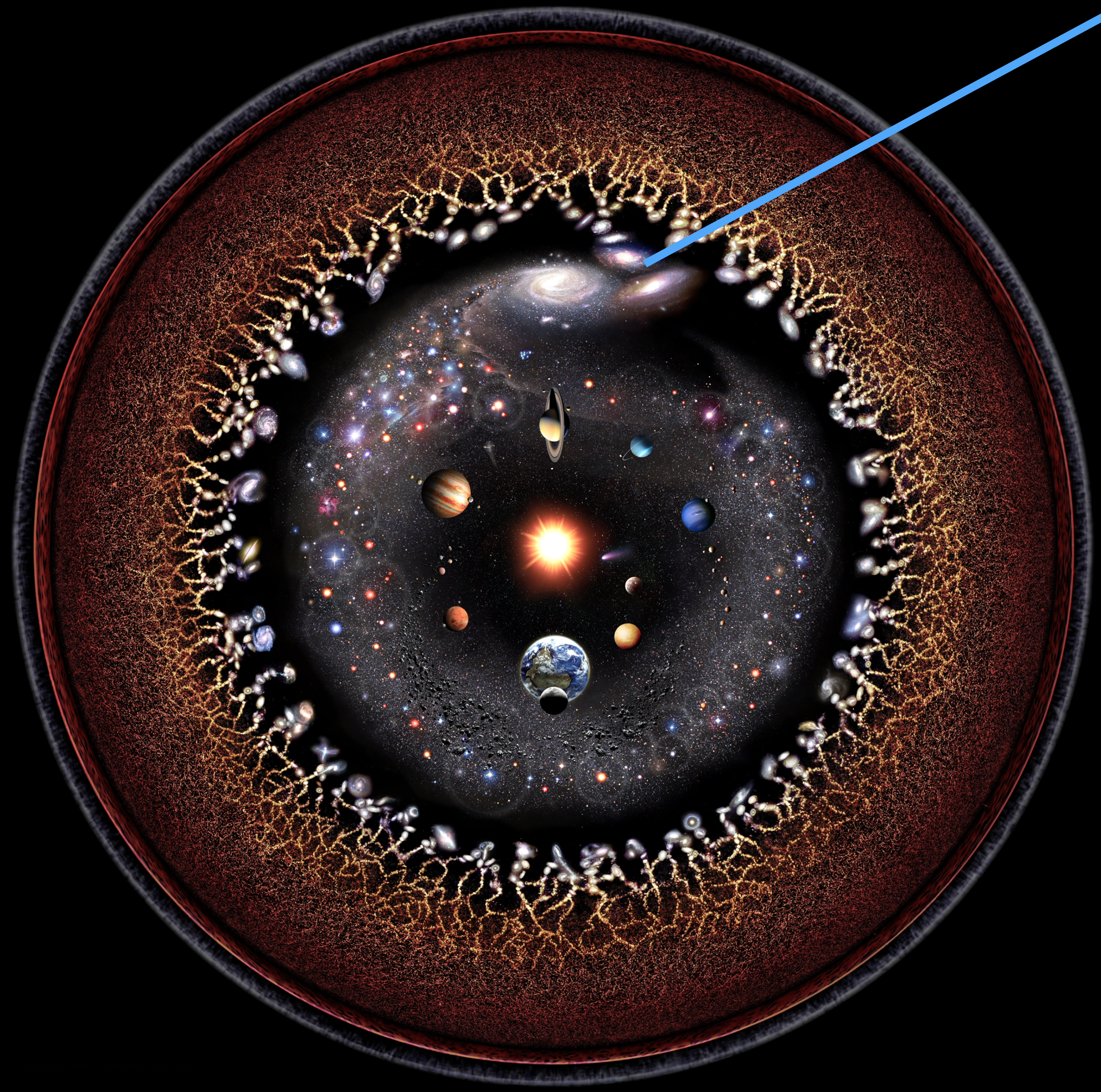

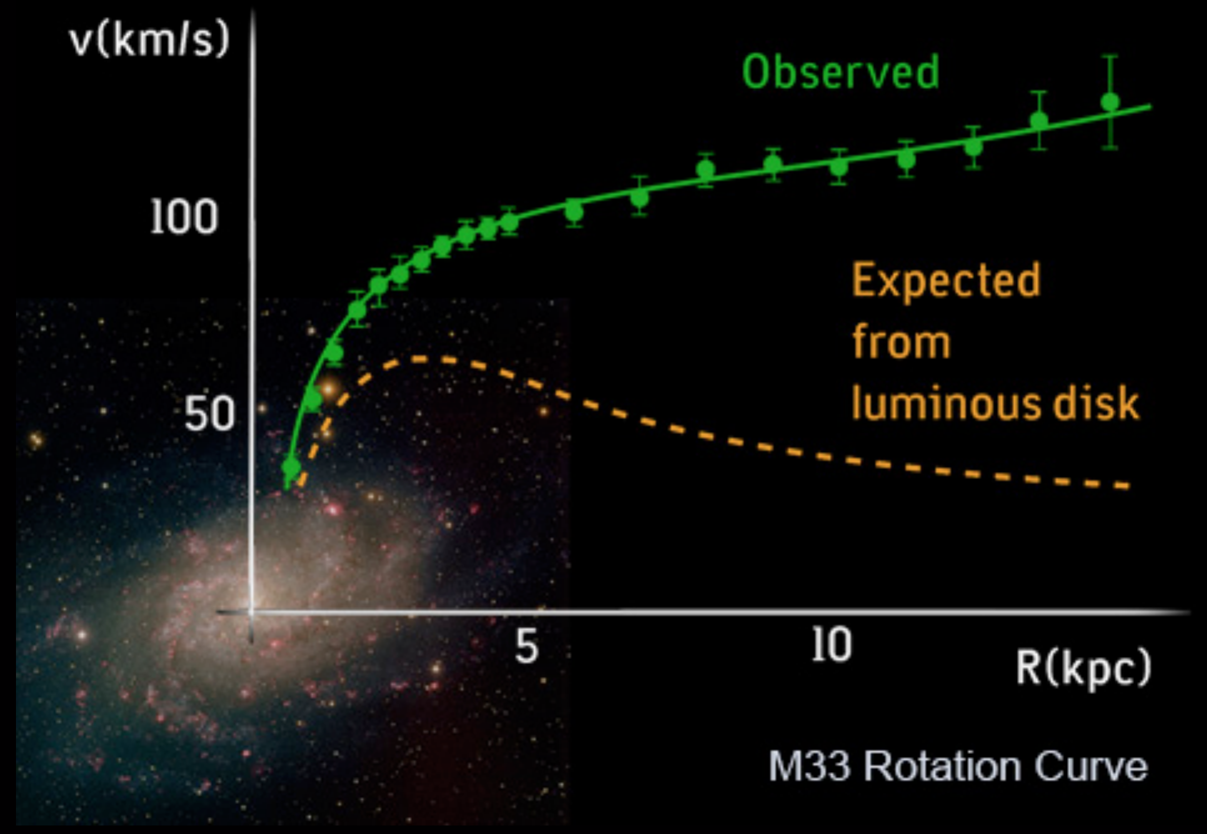

M33 Rotation Curve

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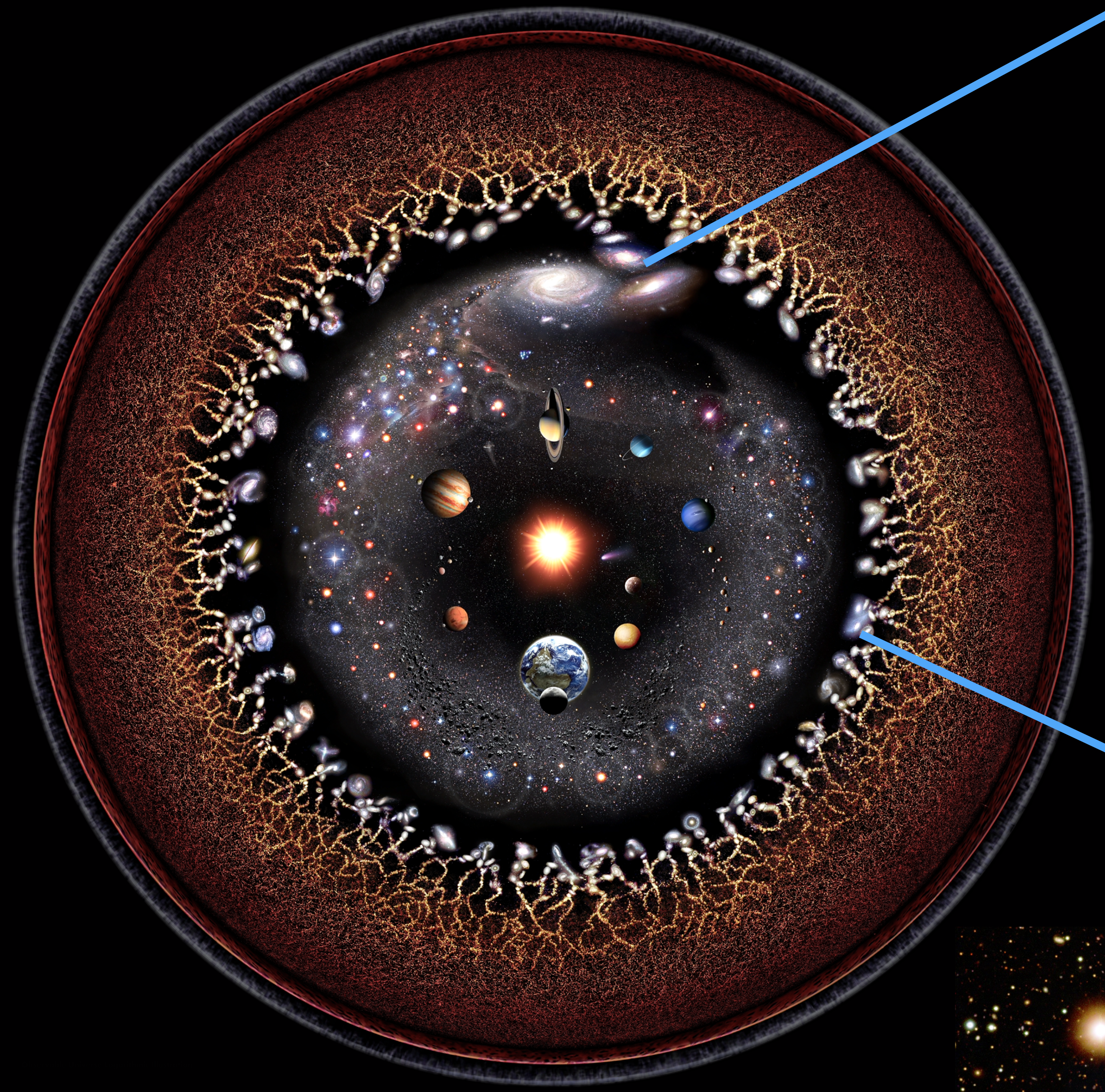

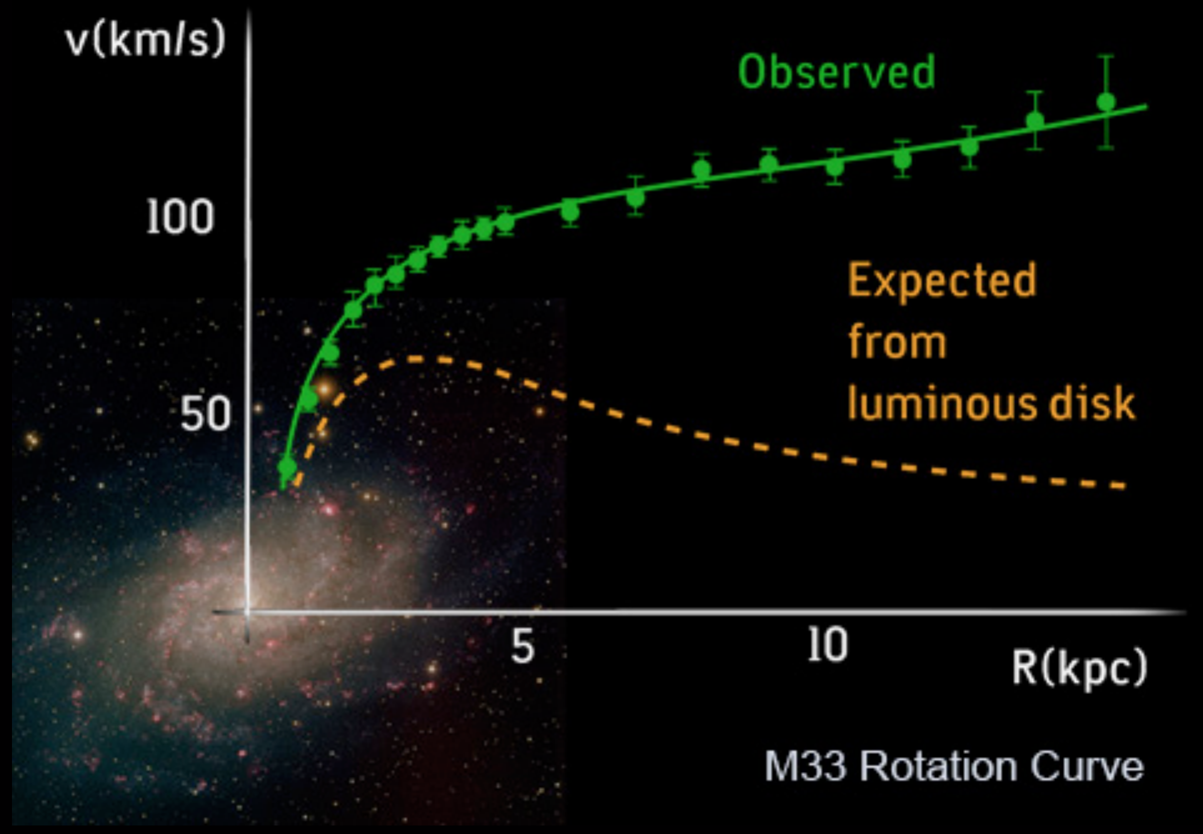

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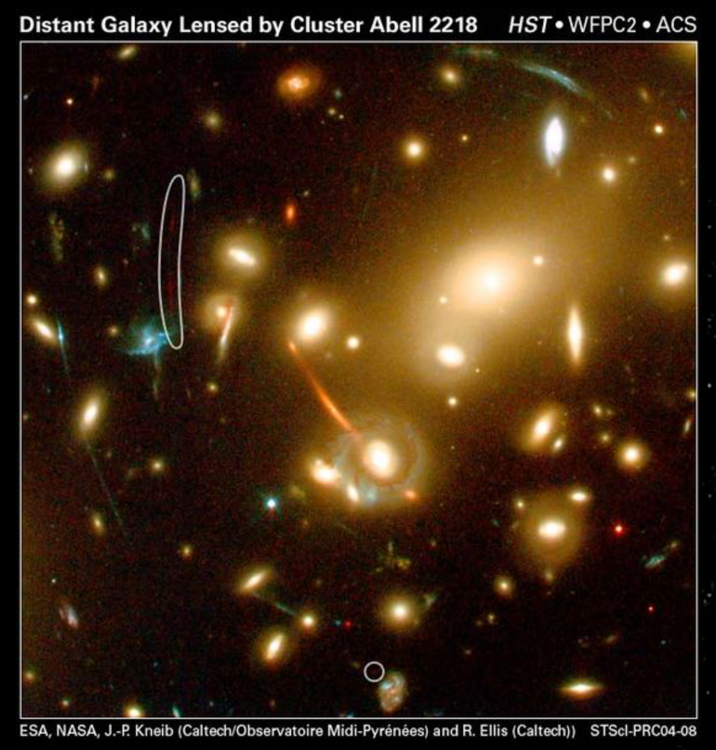

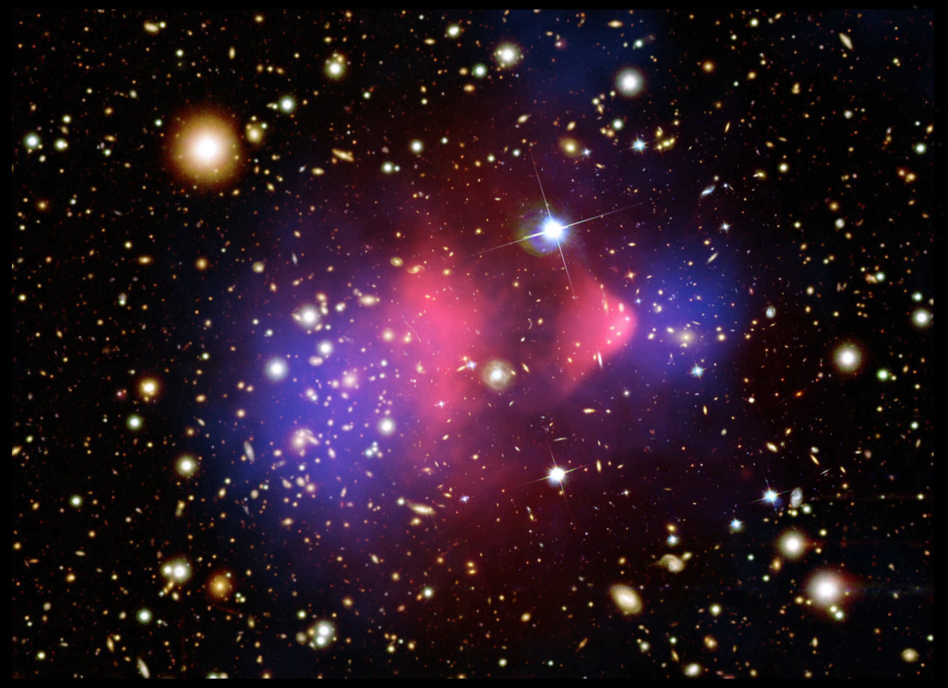

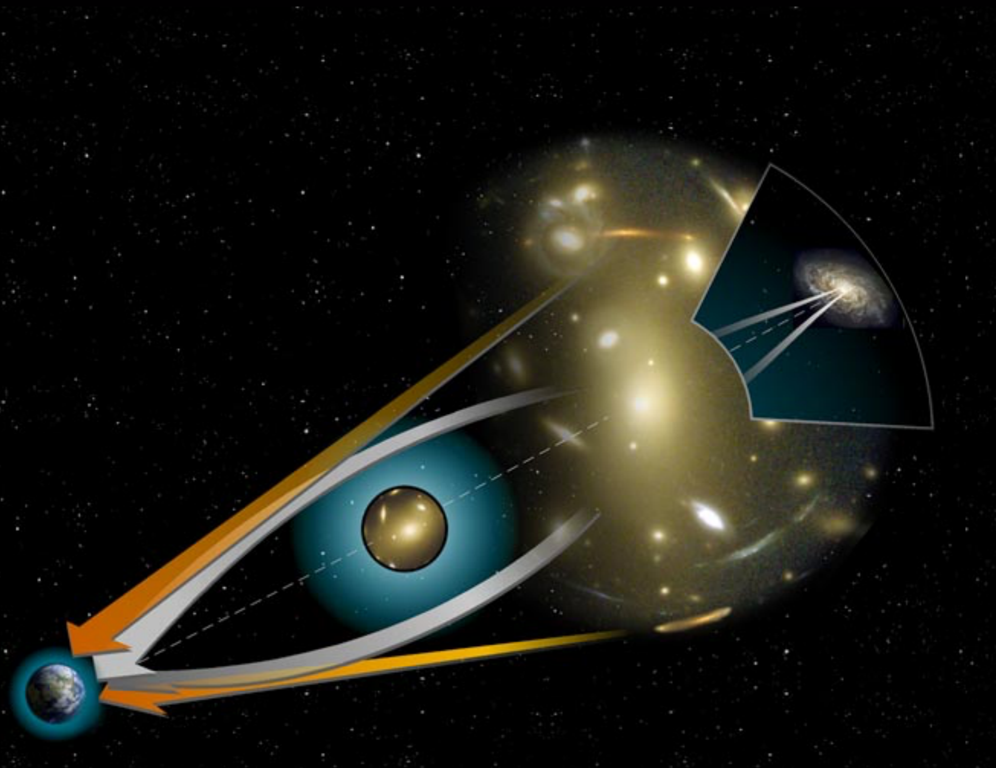

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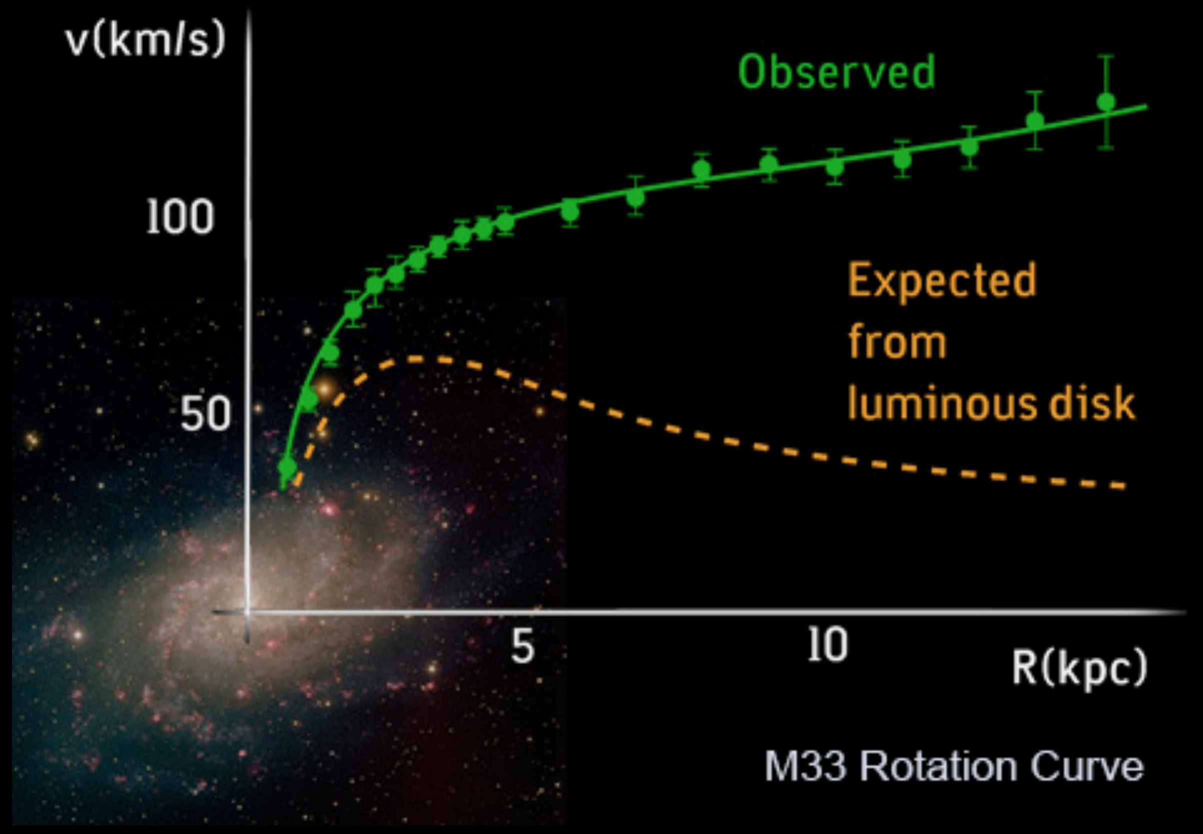

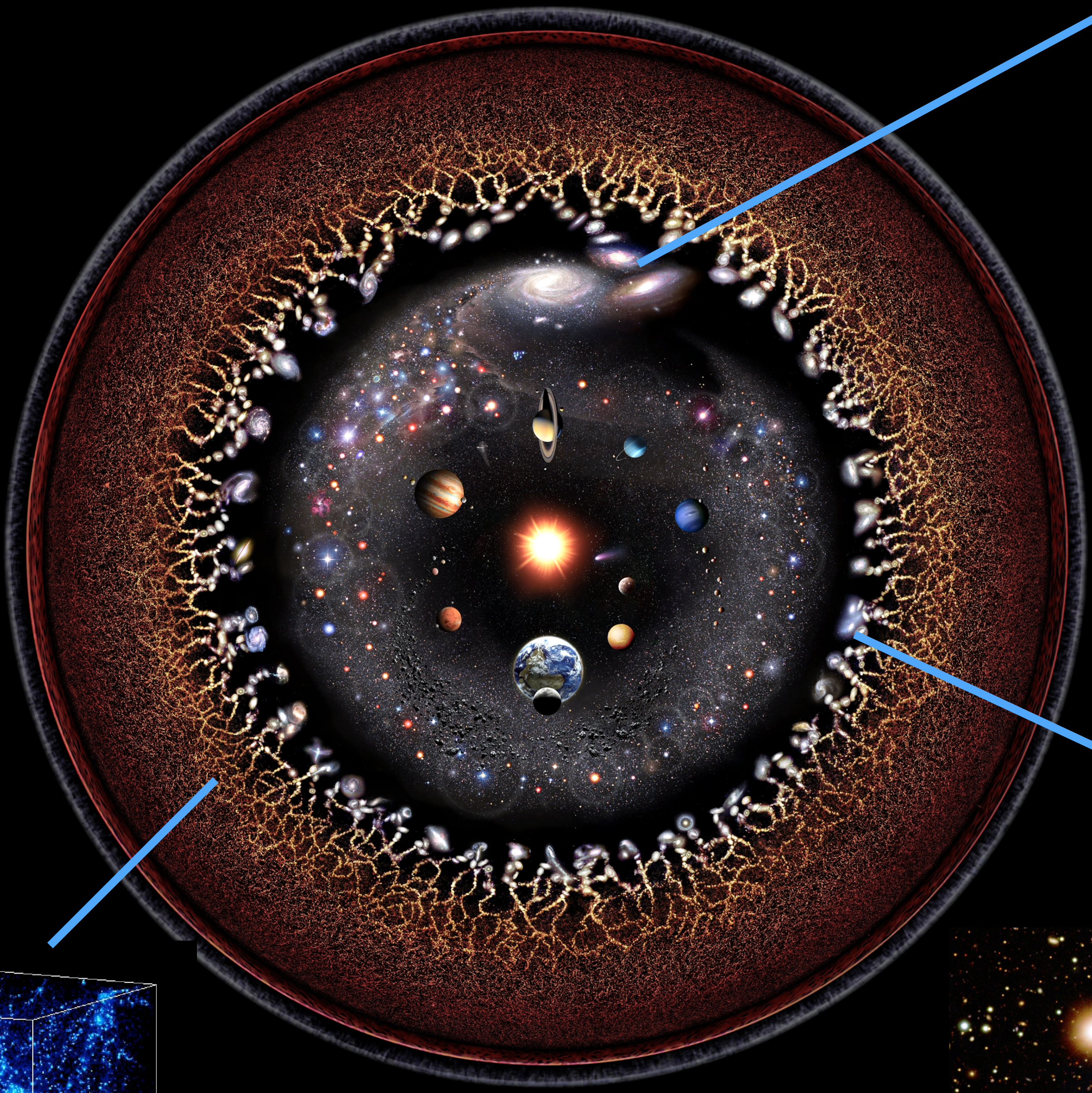

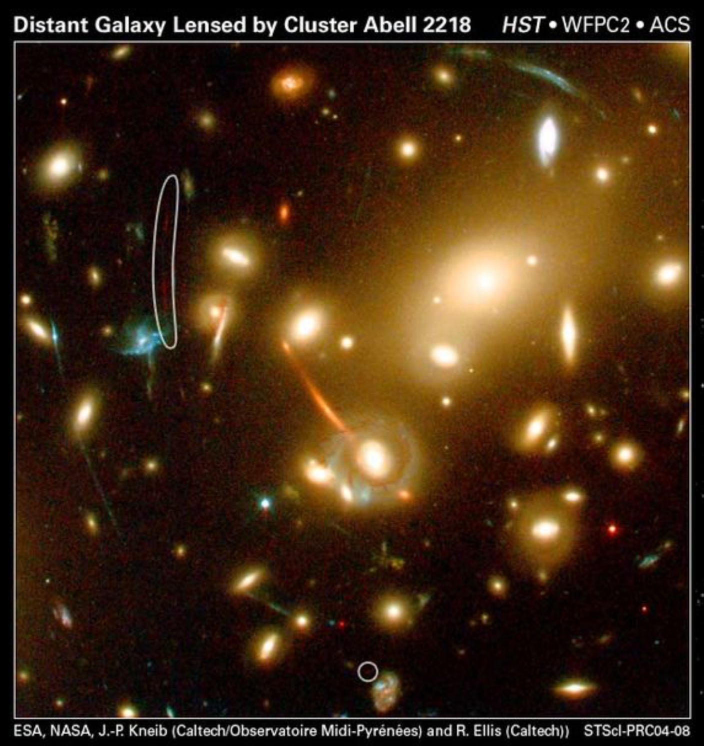

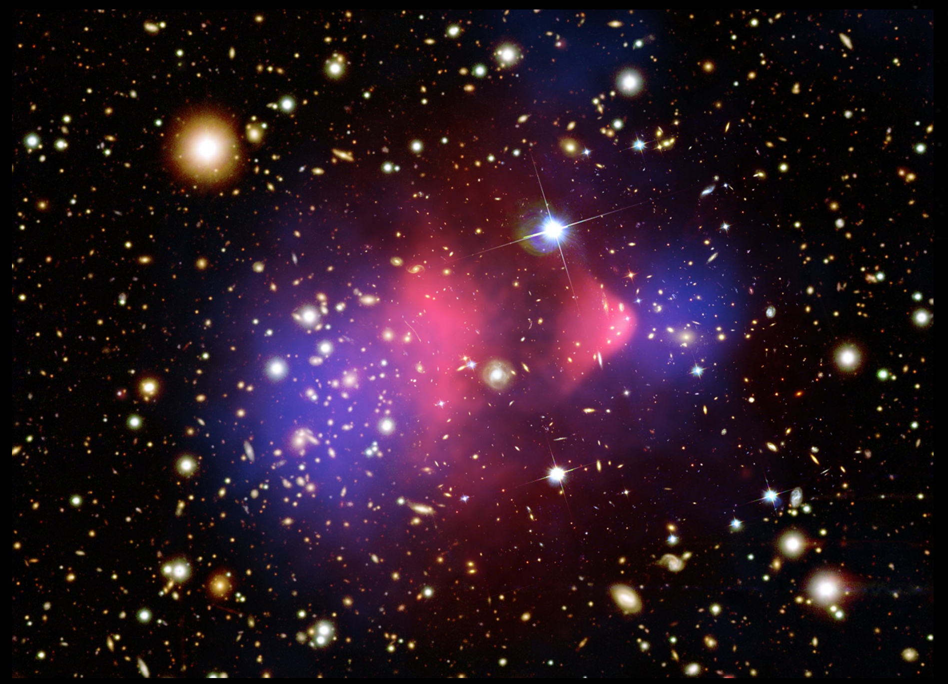

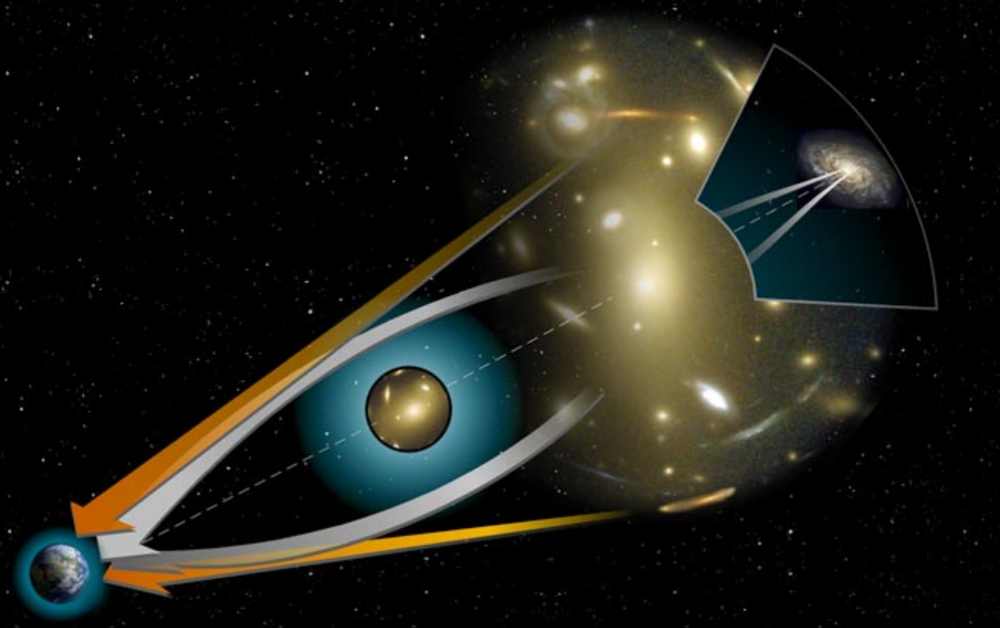

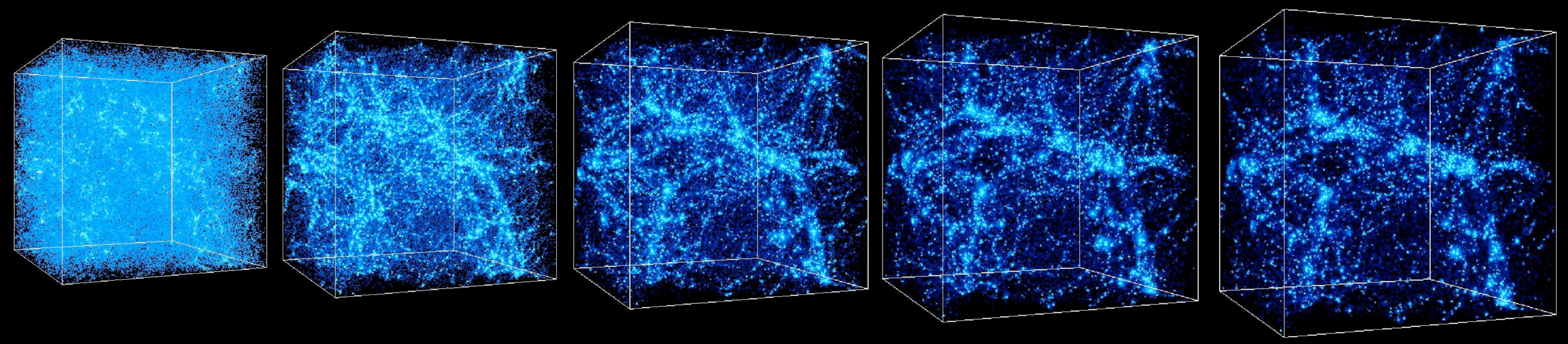

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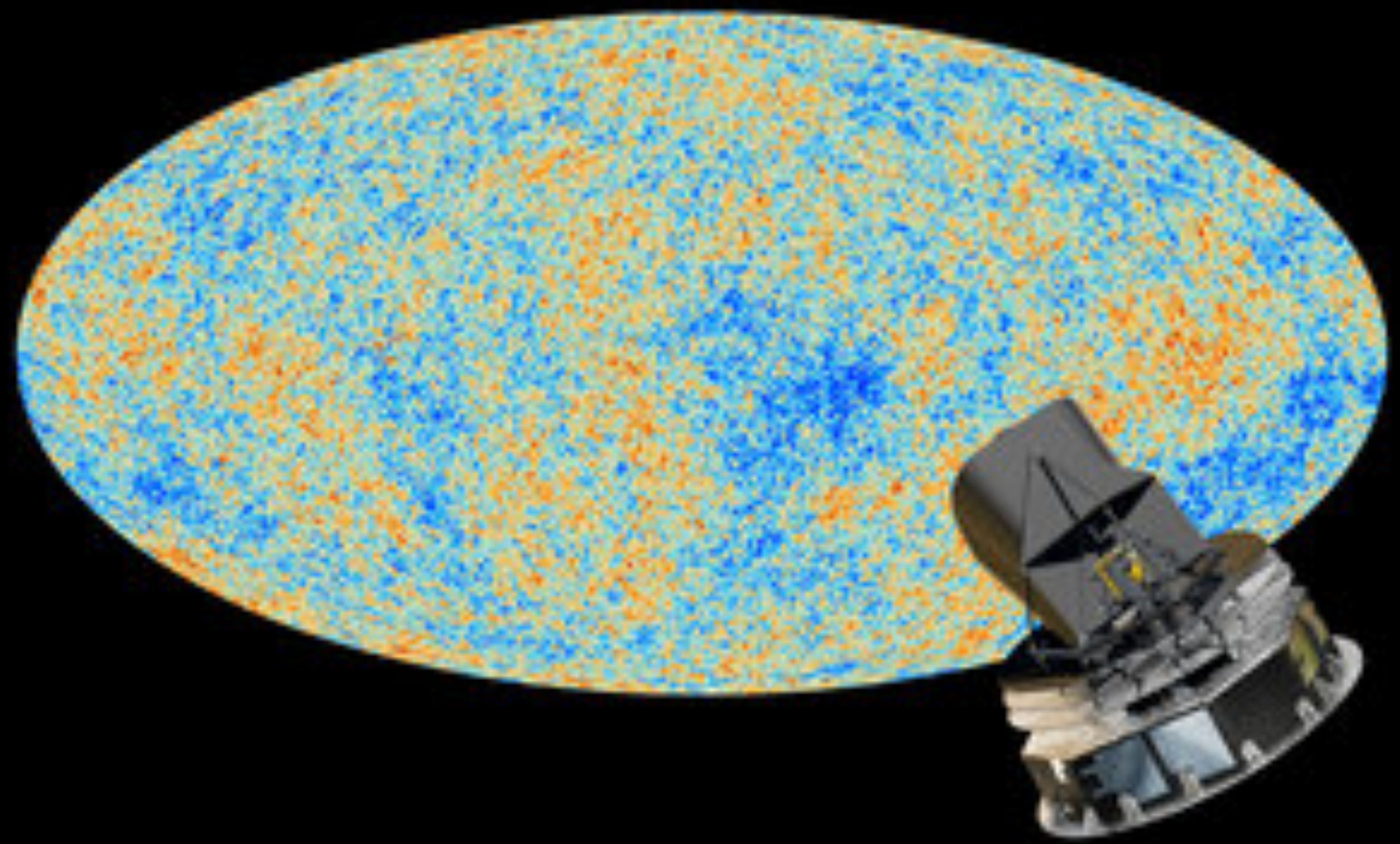

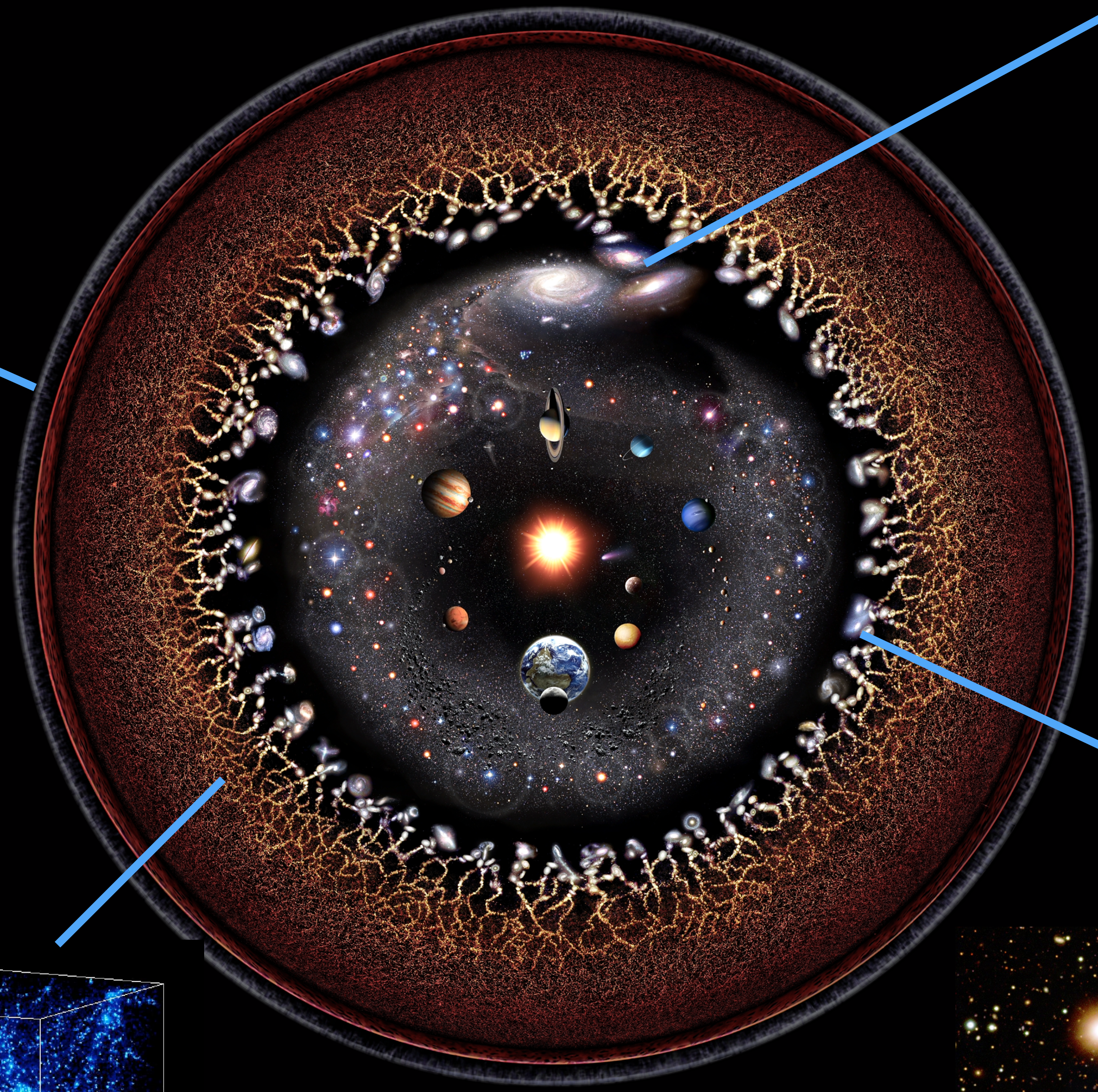

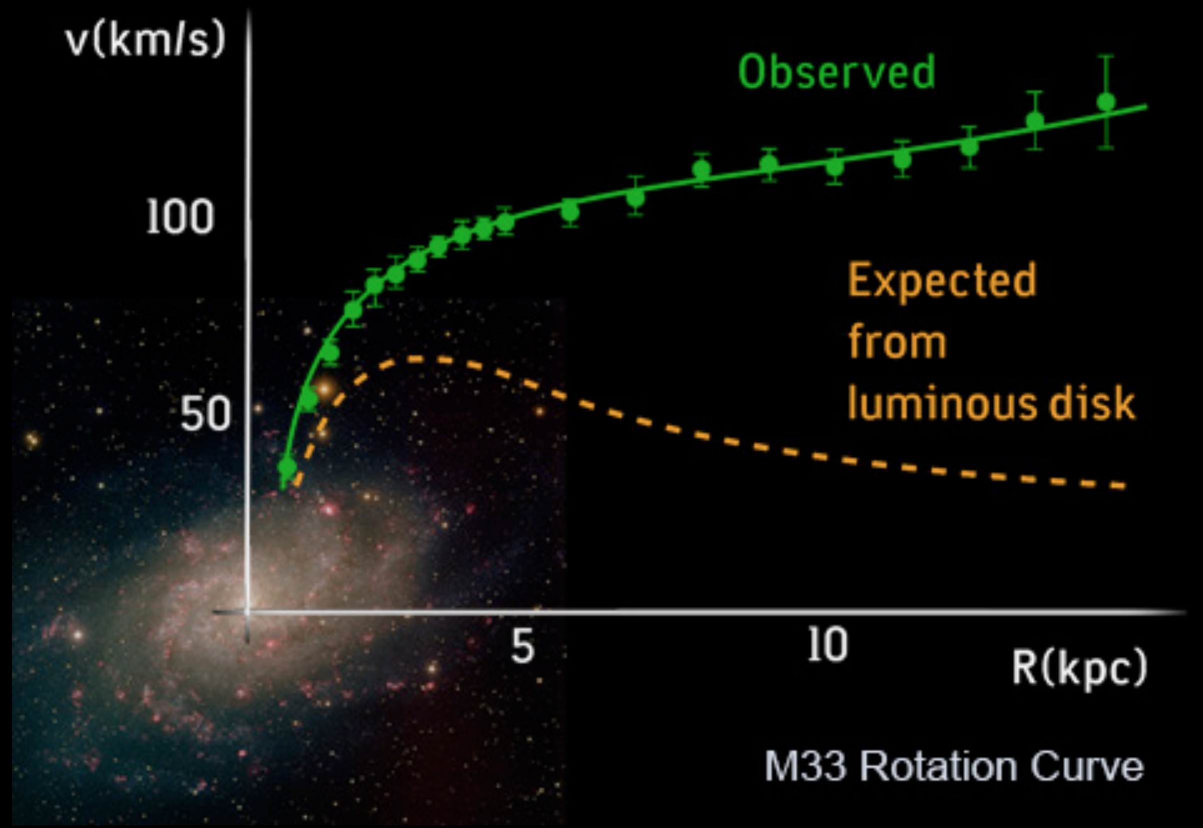

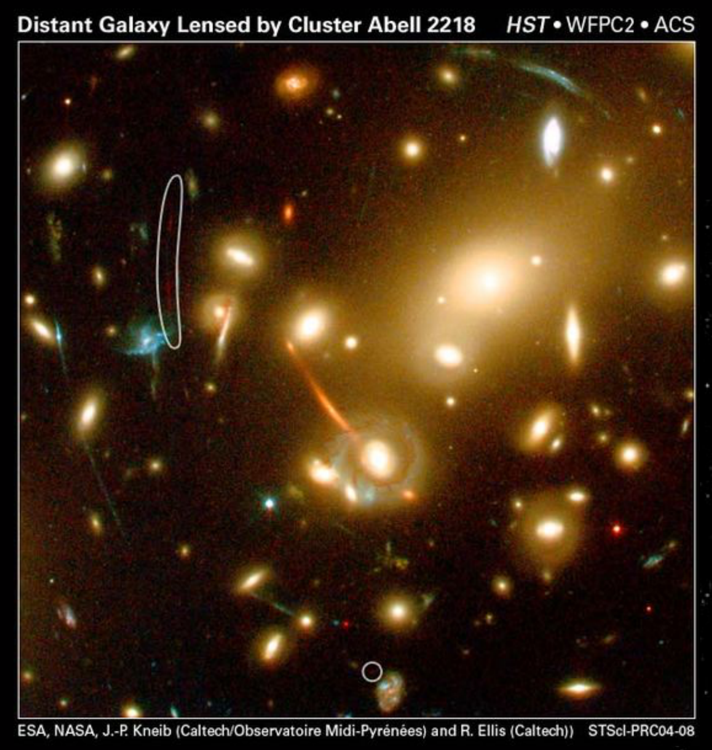

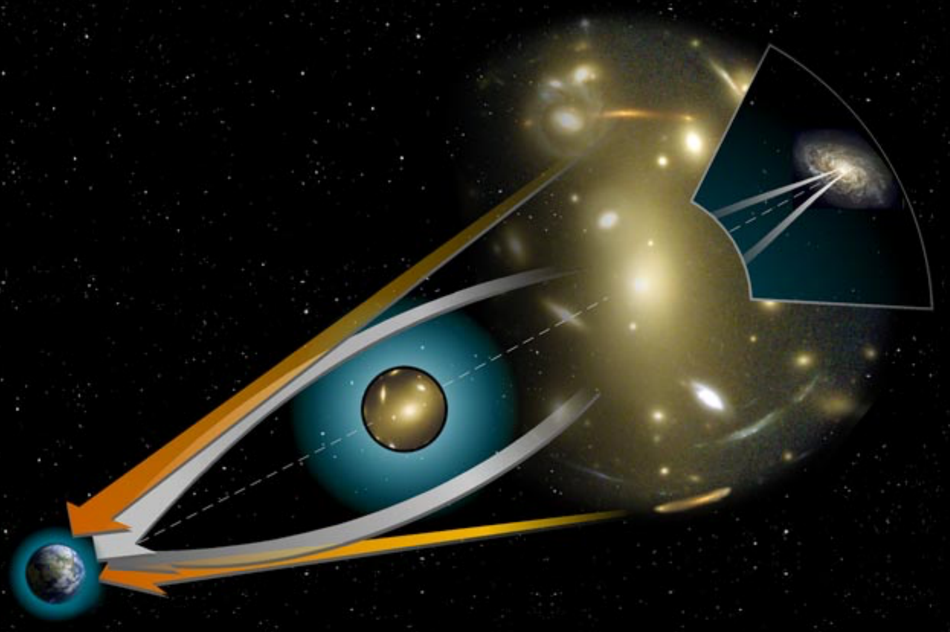

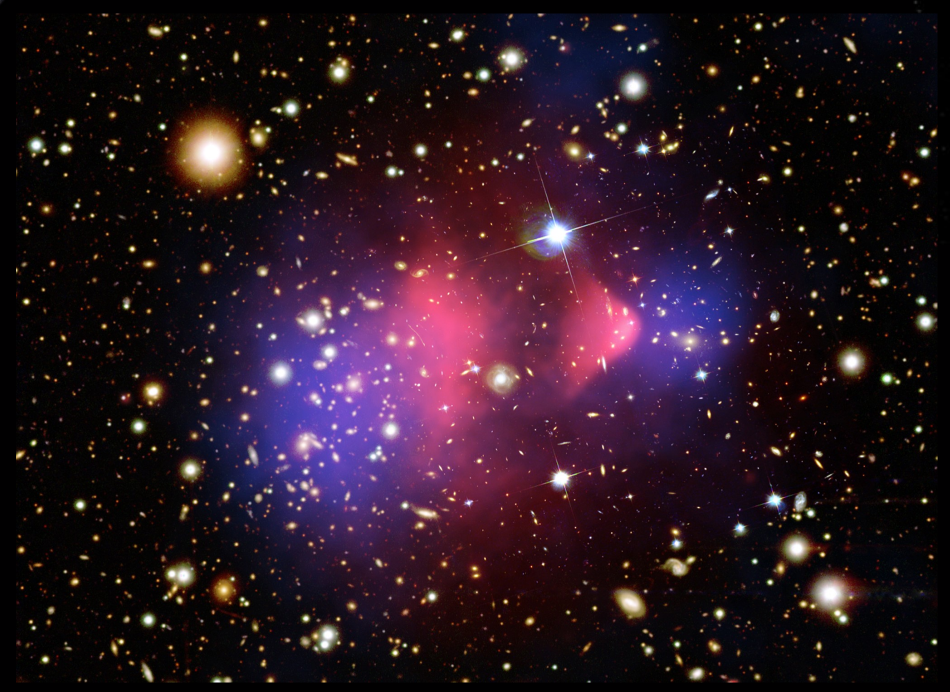

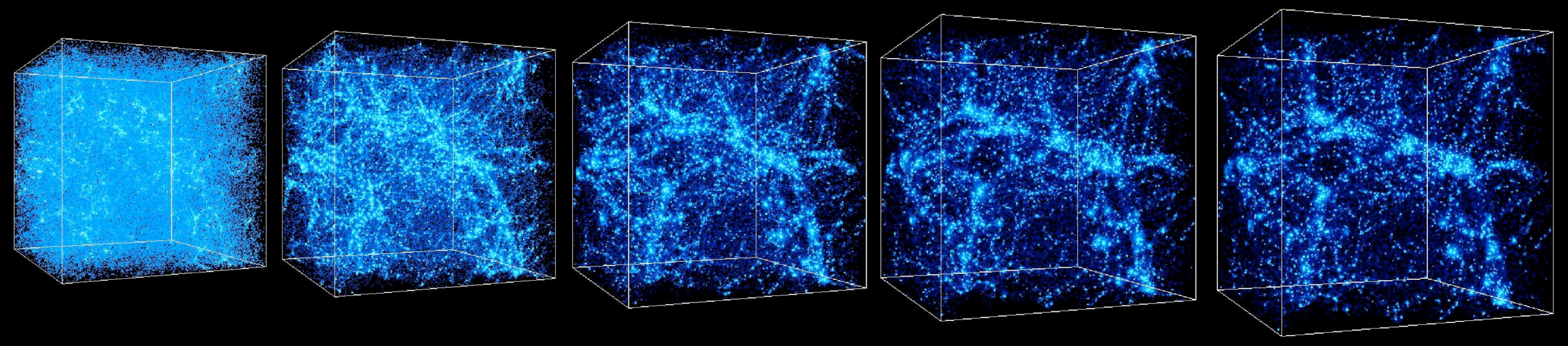

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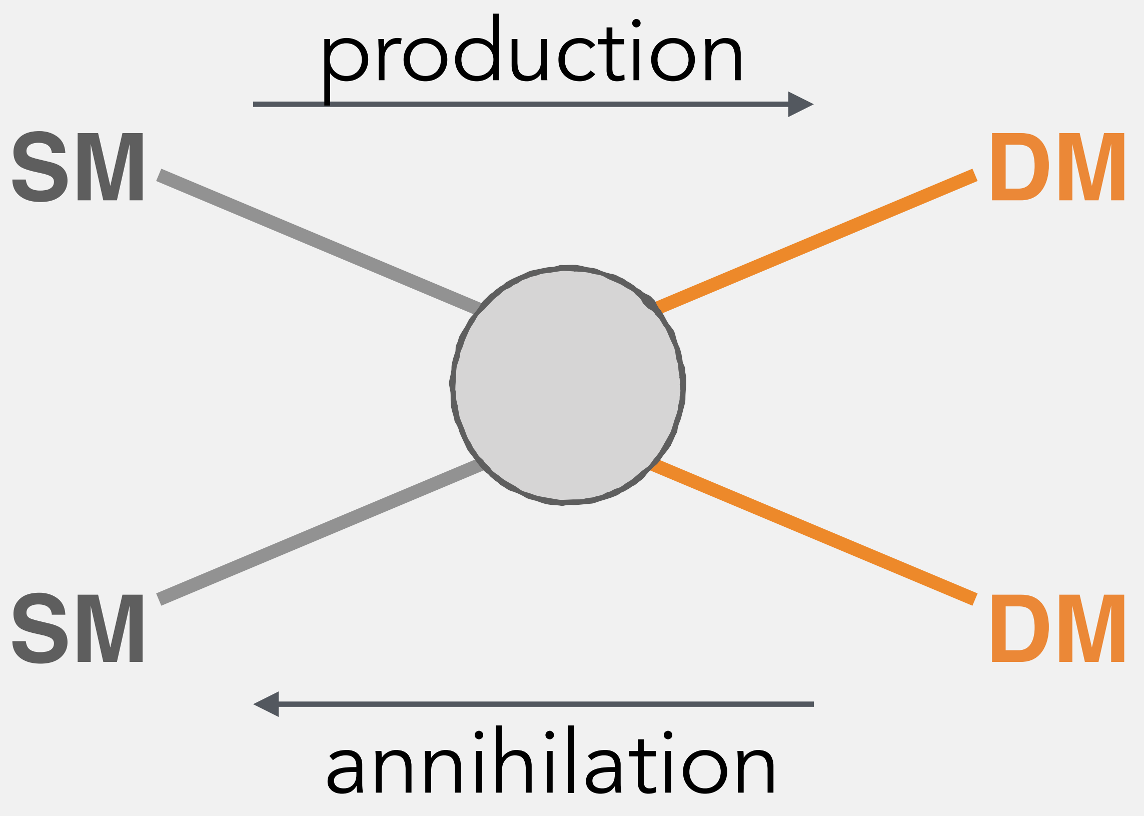

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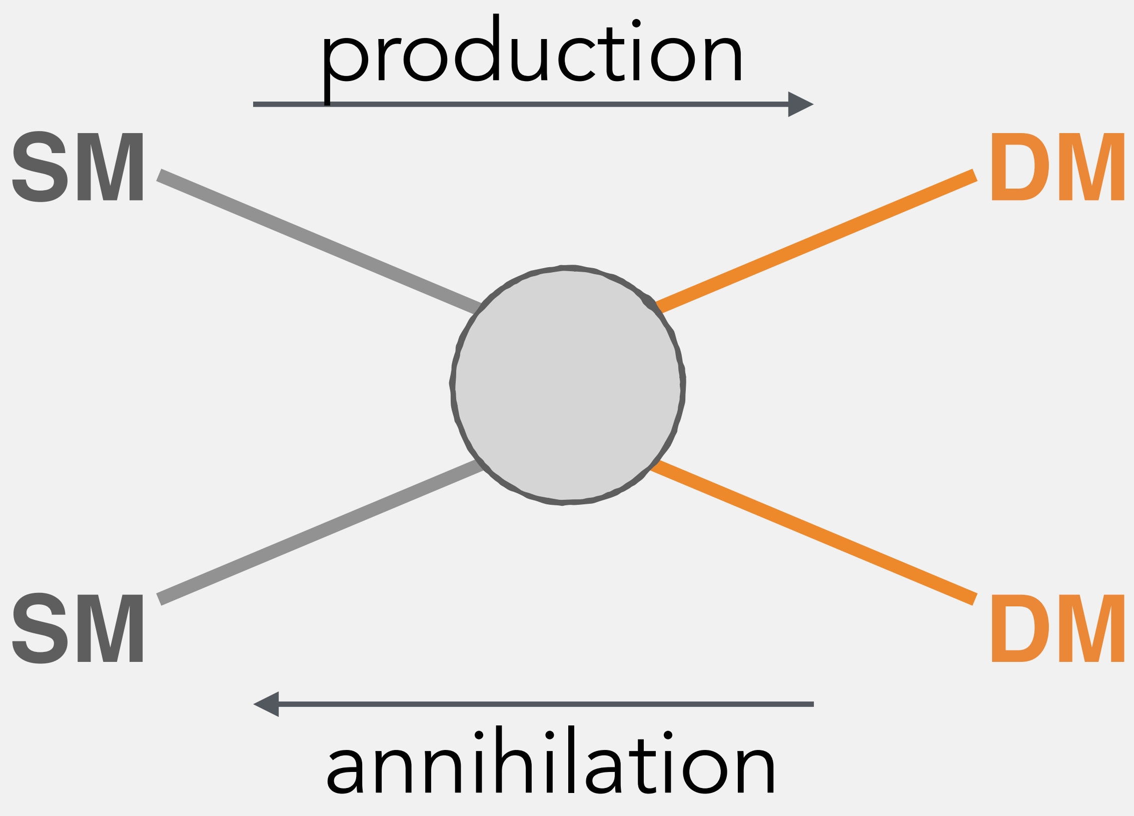

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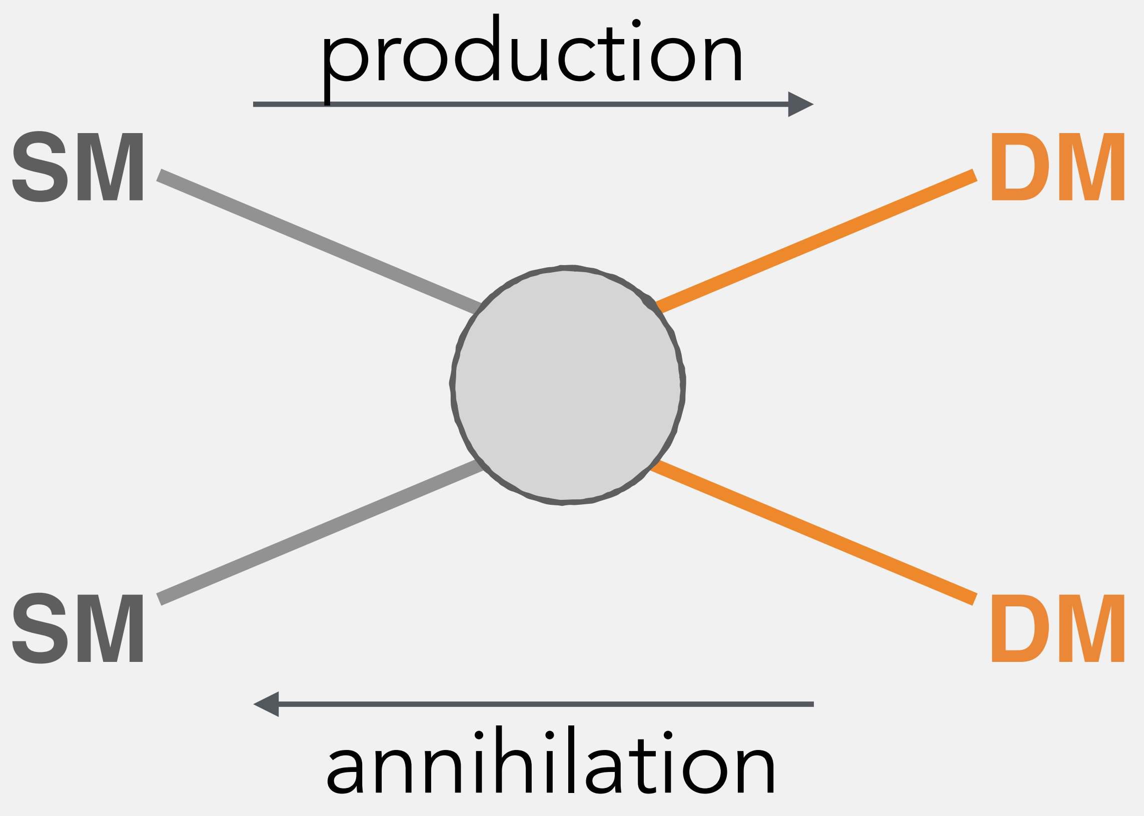

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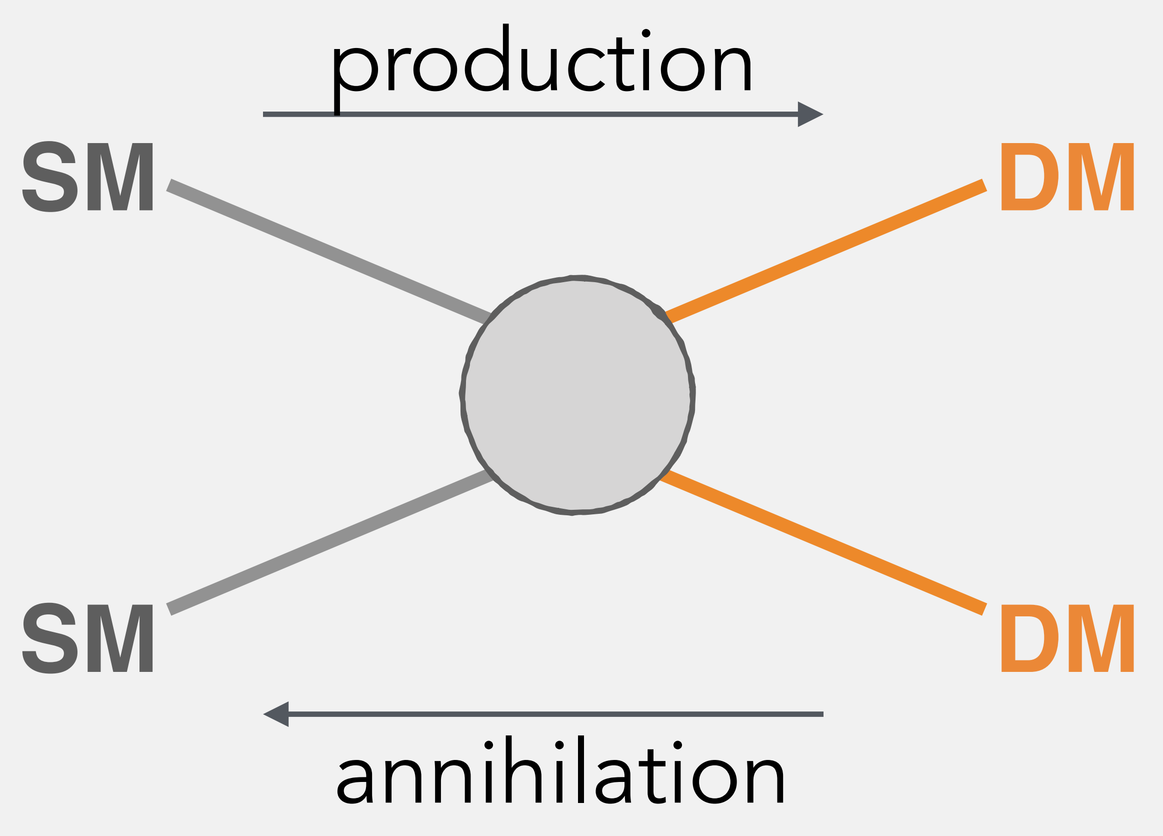

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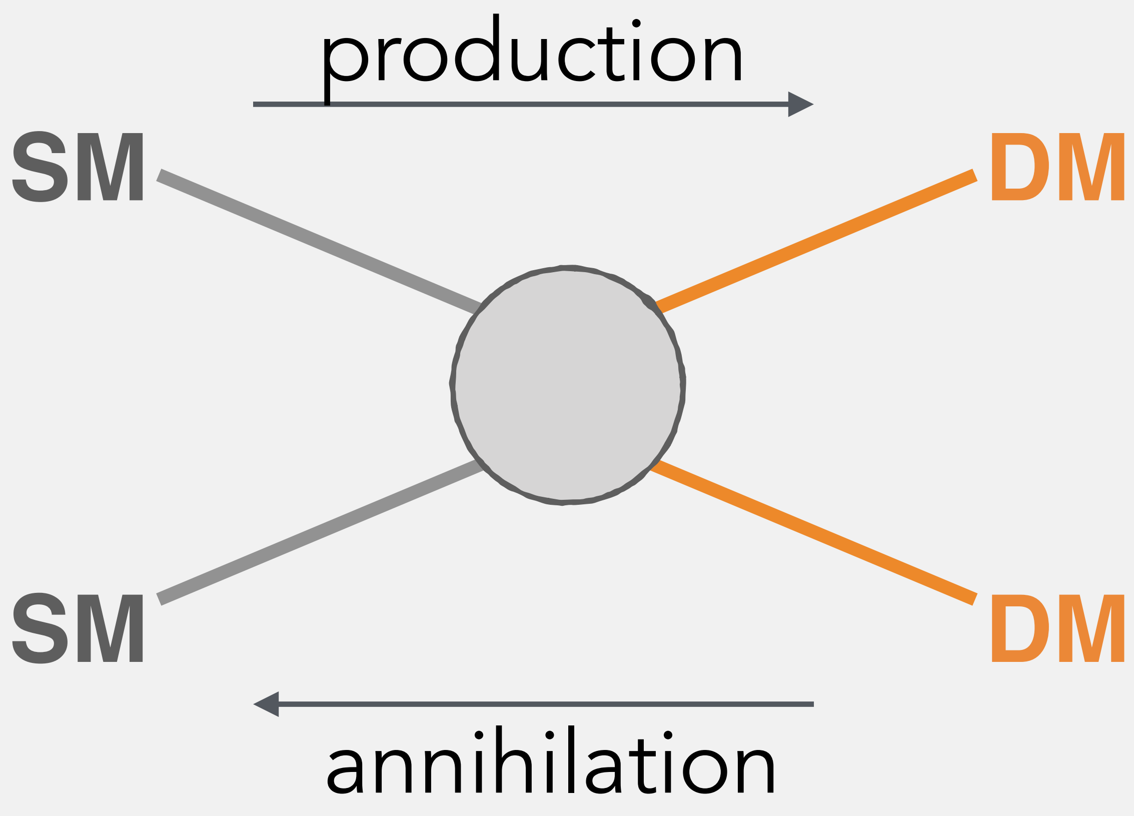

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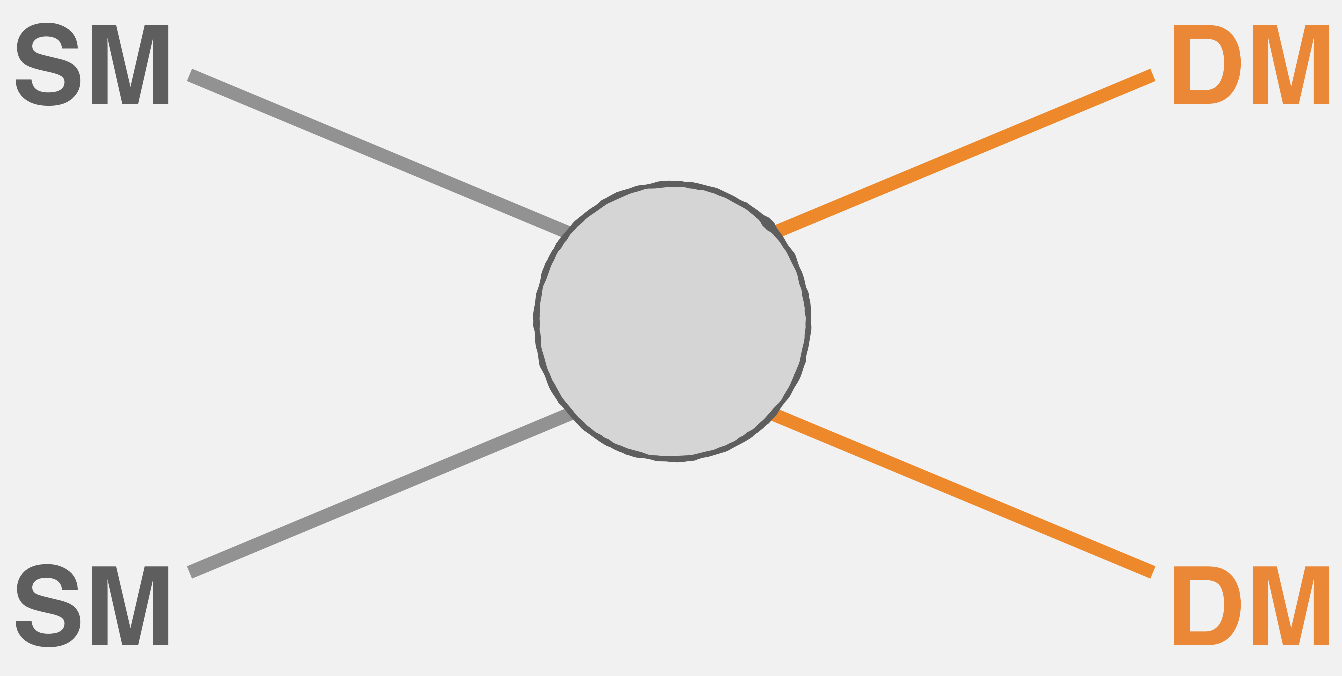
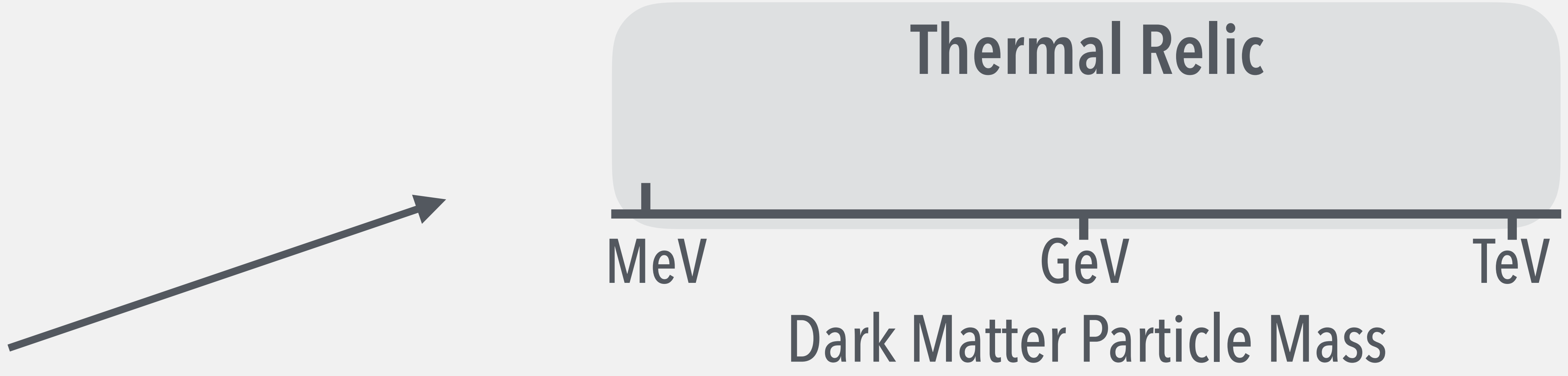
above: too much DM

Searches for Thermal Relic DM





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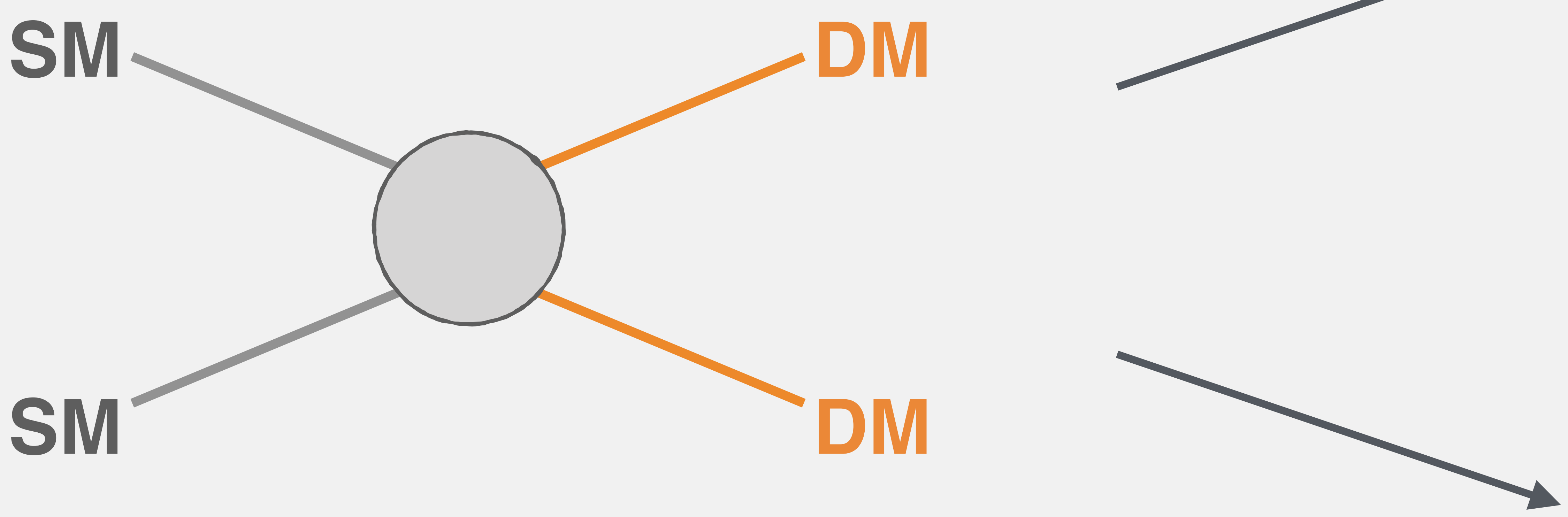

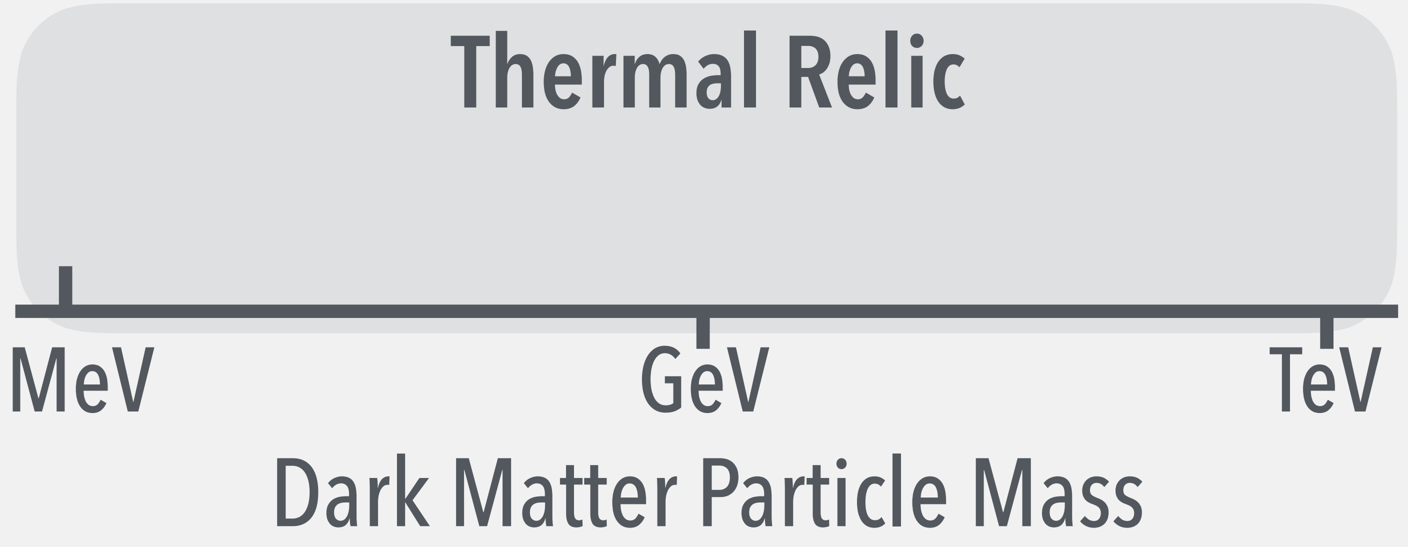

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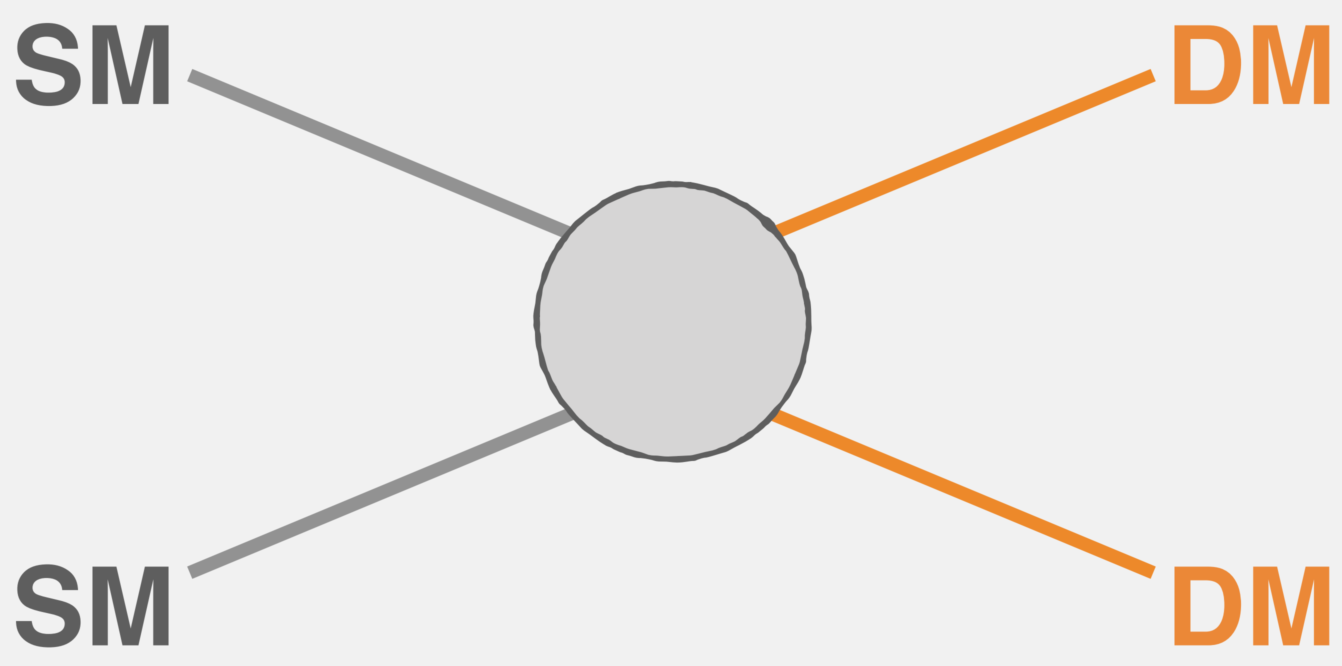

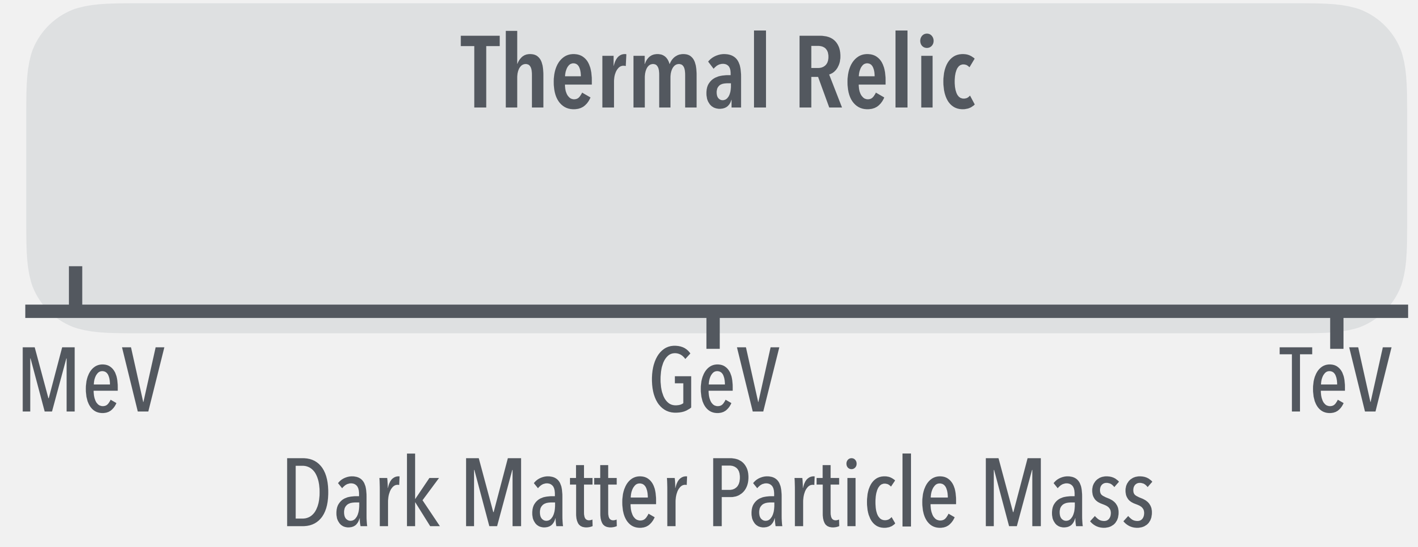

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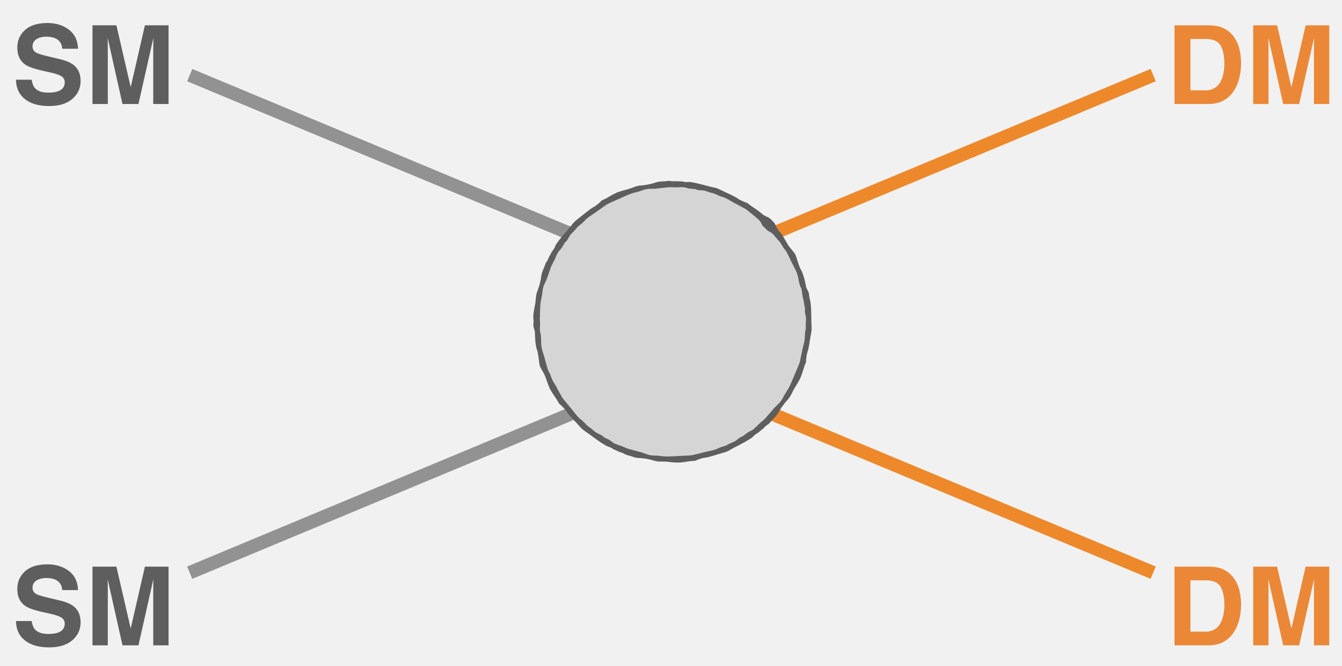

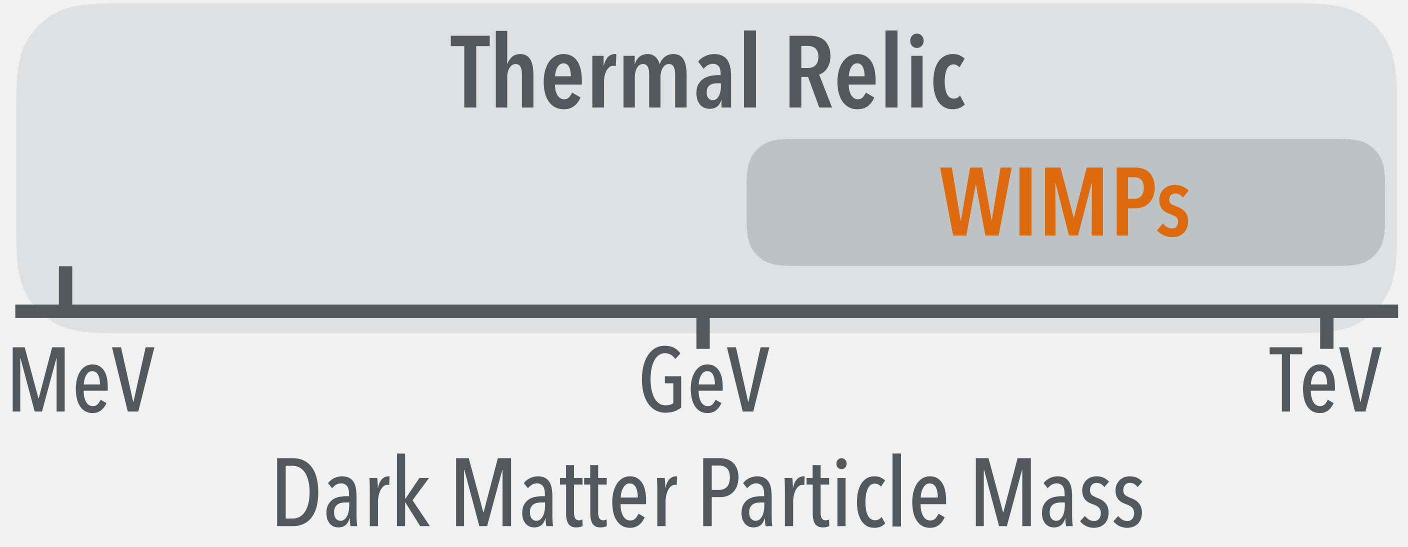

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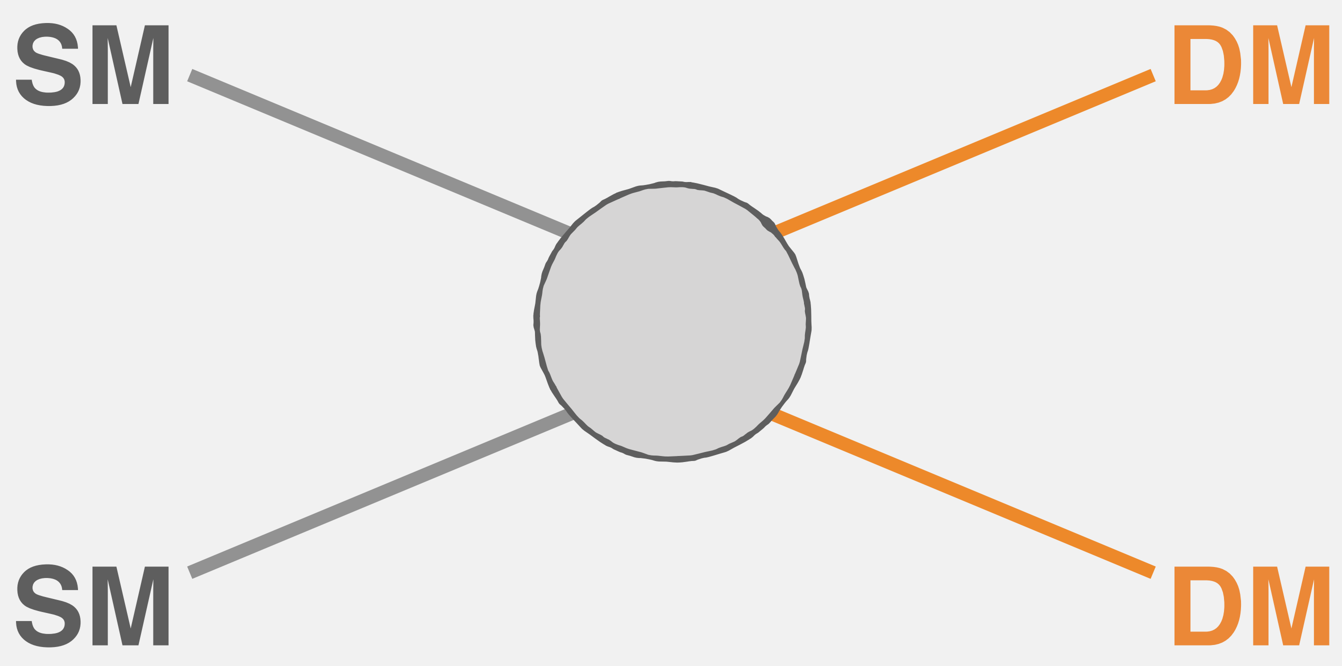

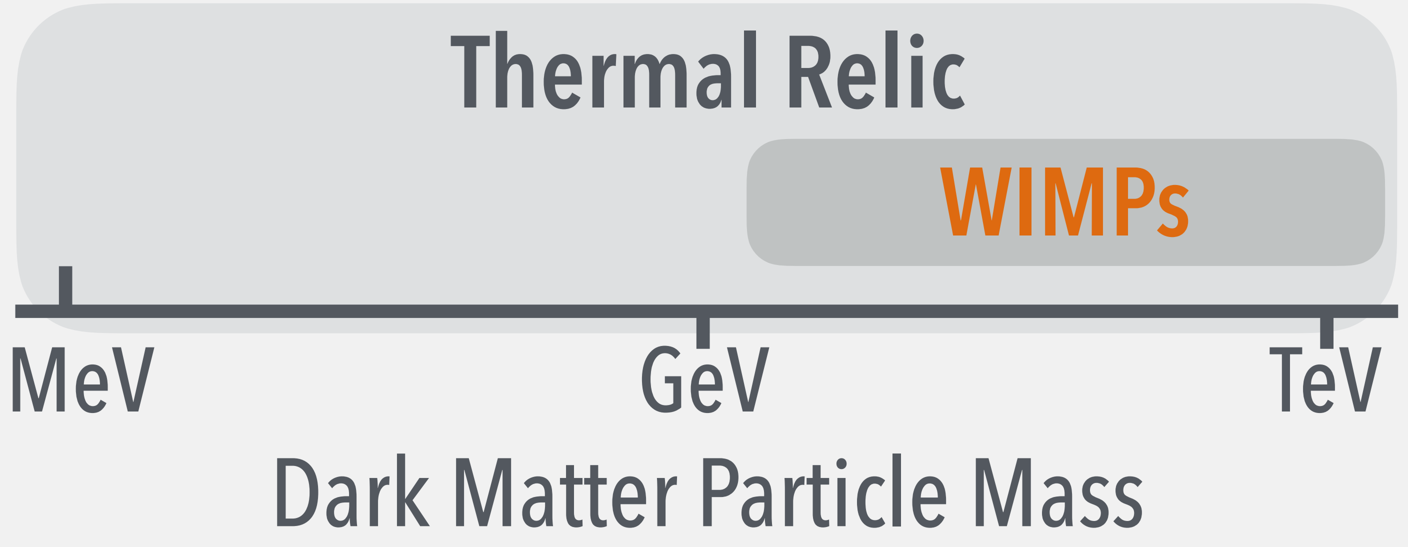

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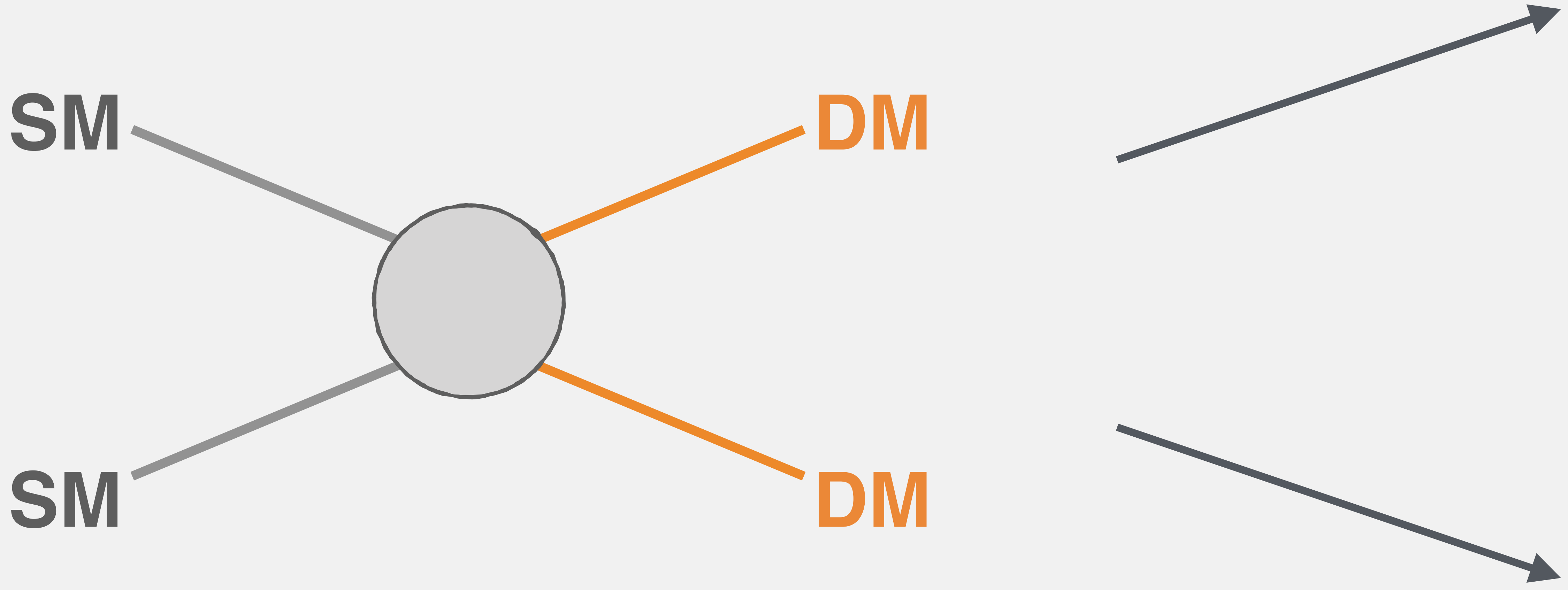

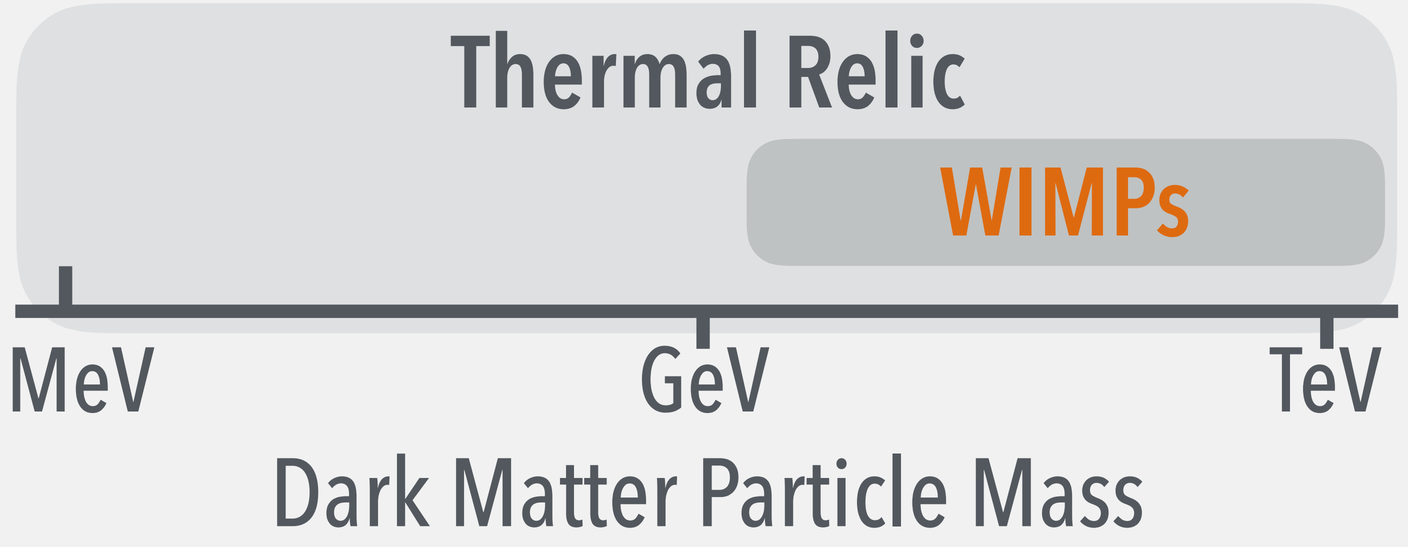

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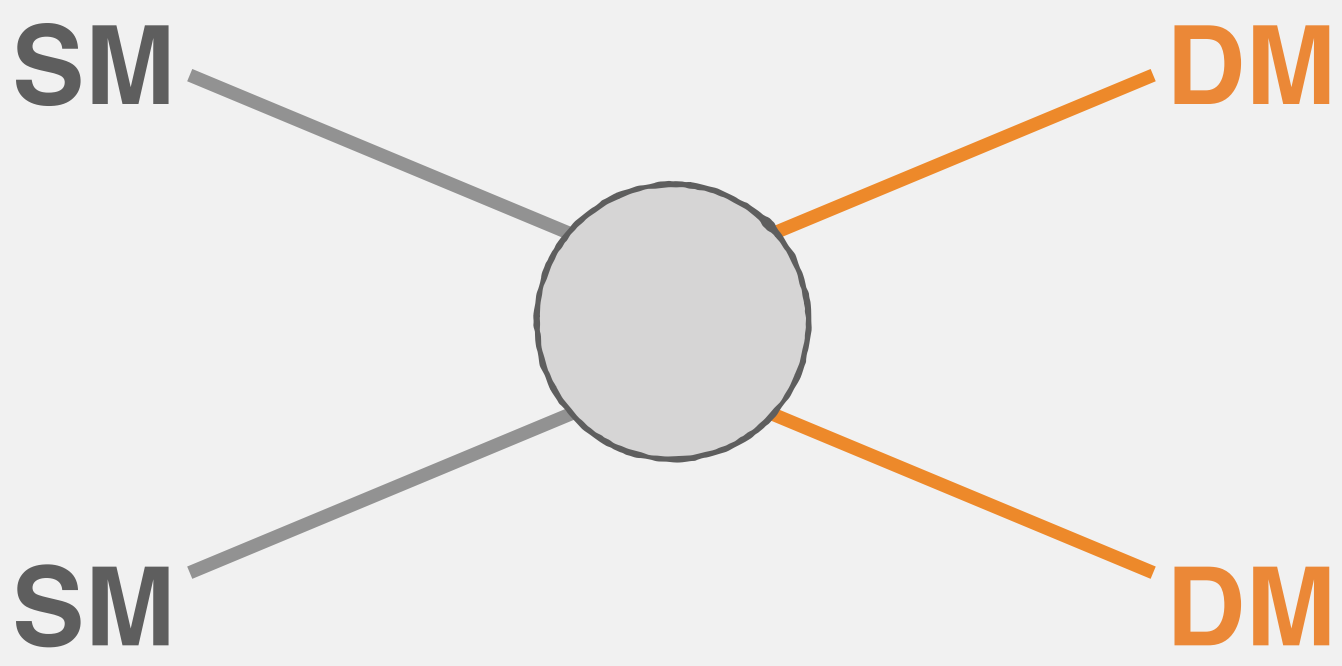

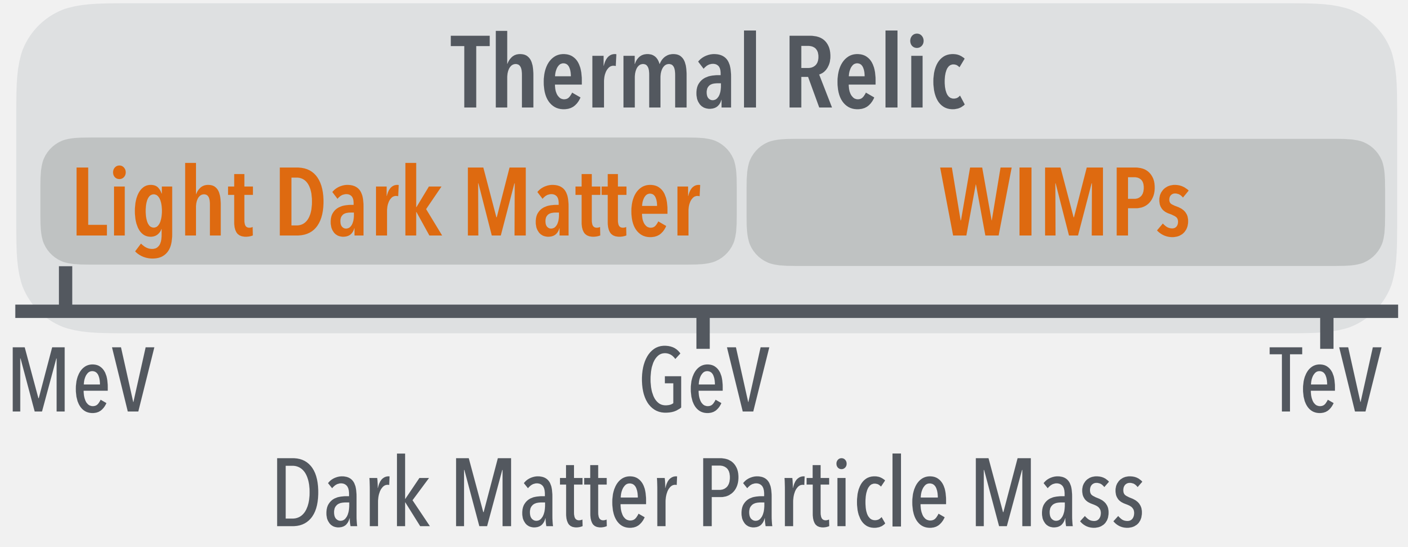

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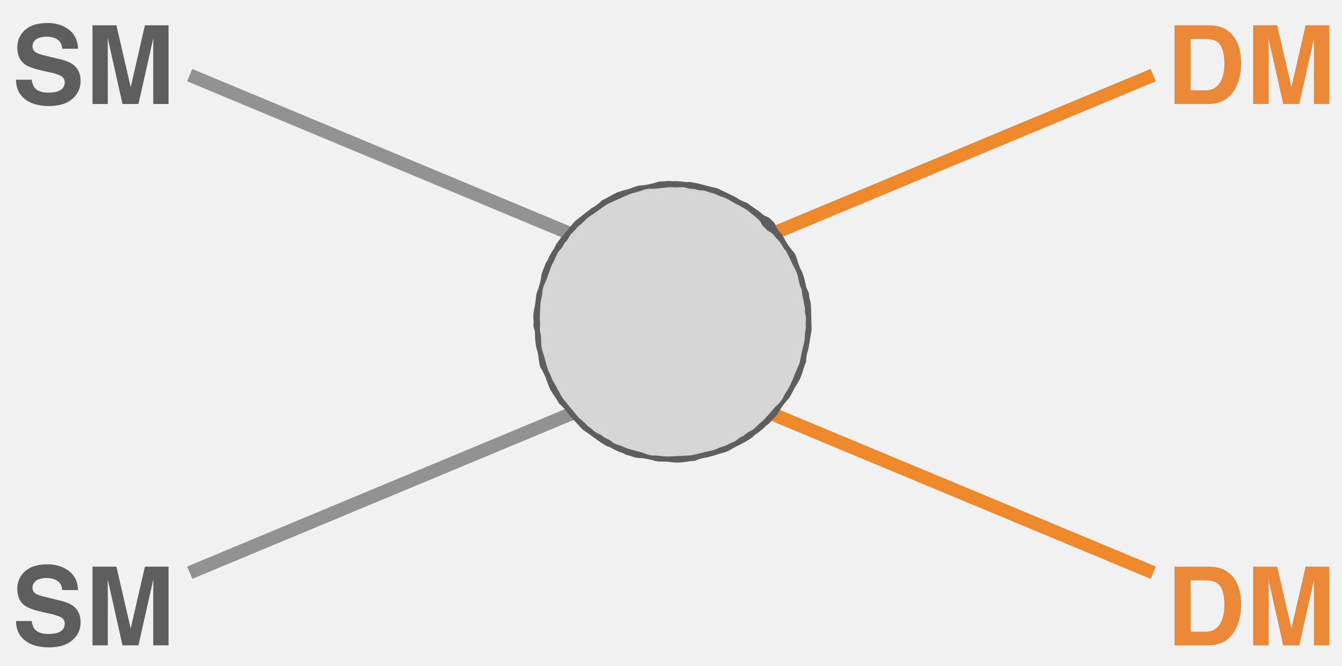

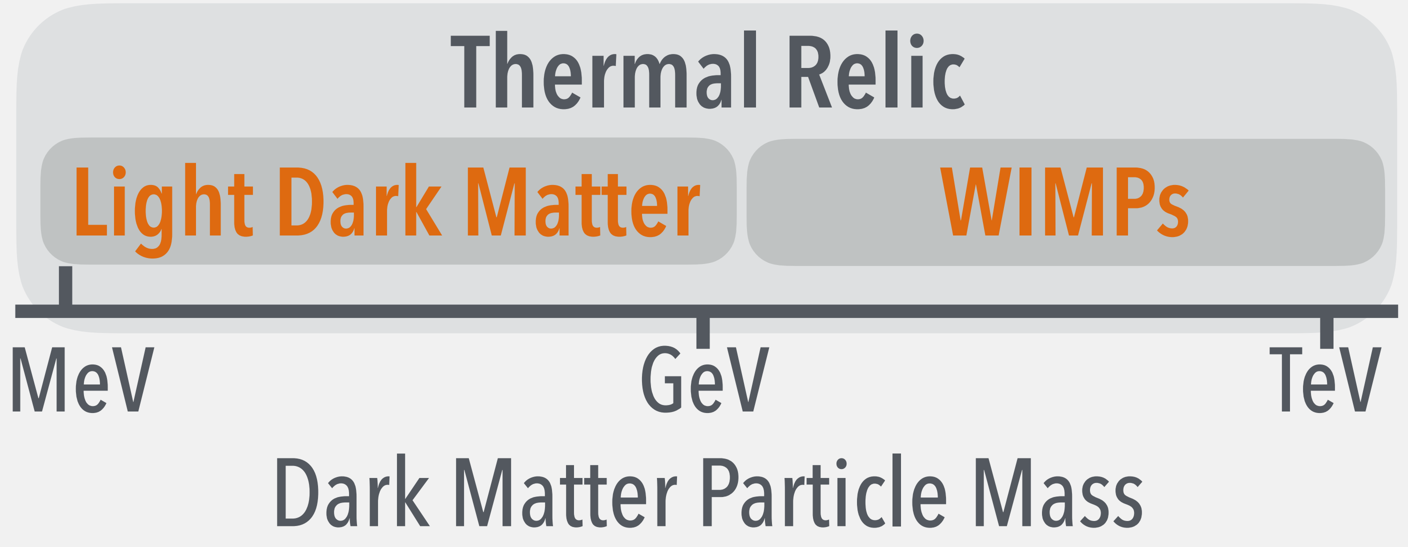

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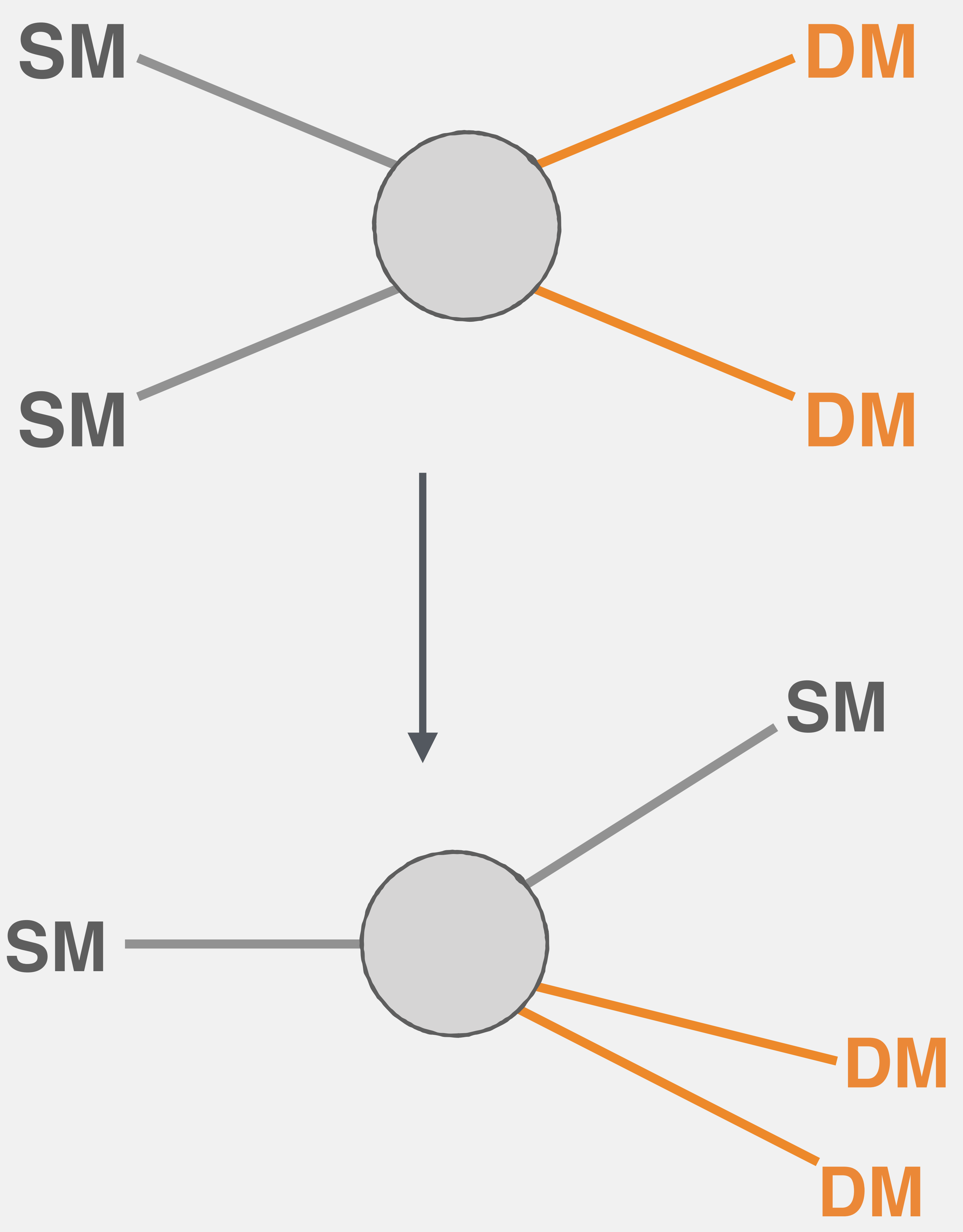

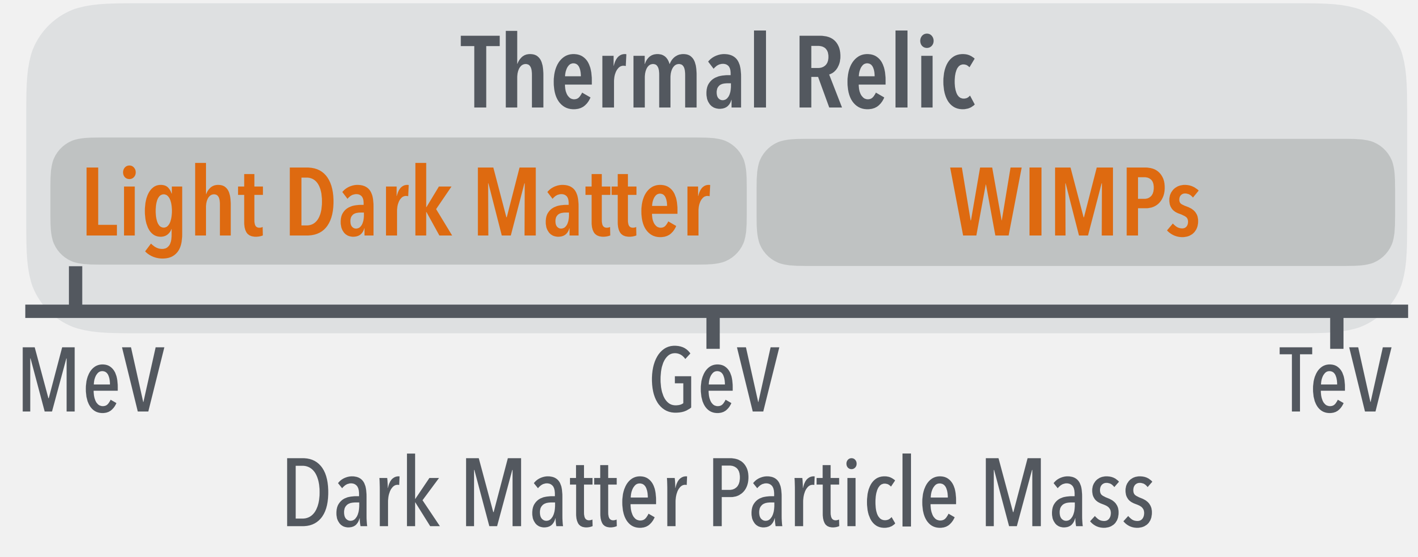

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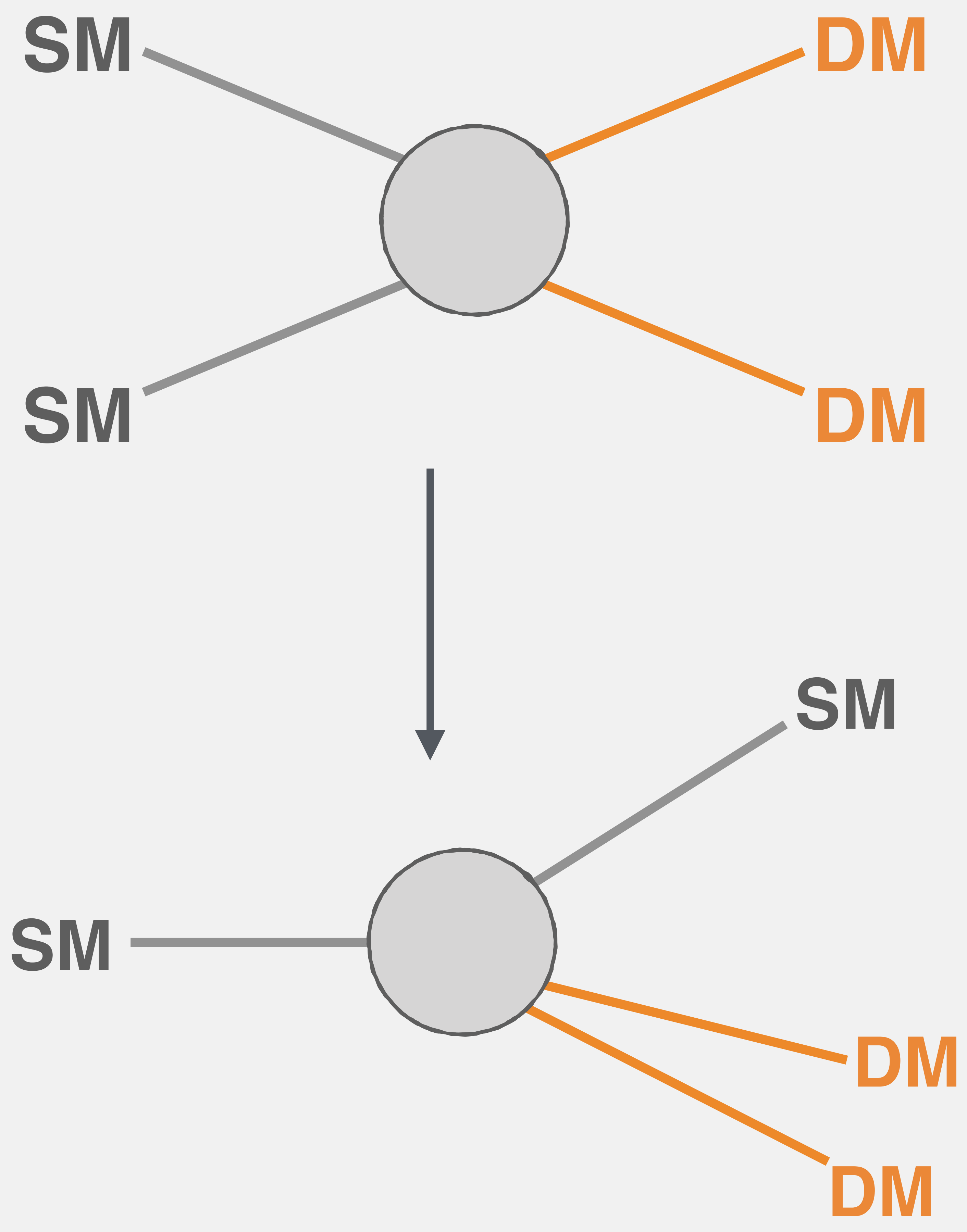
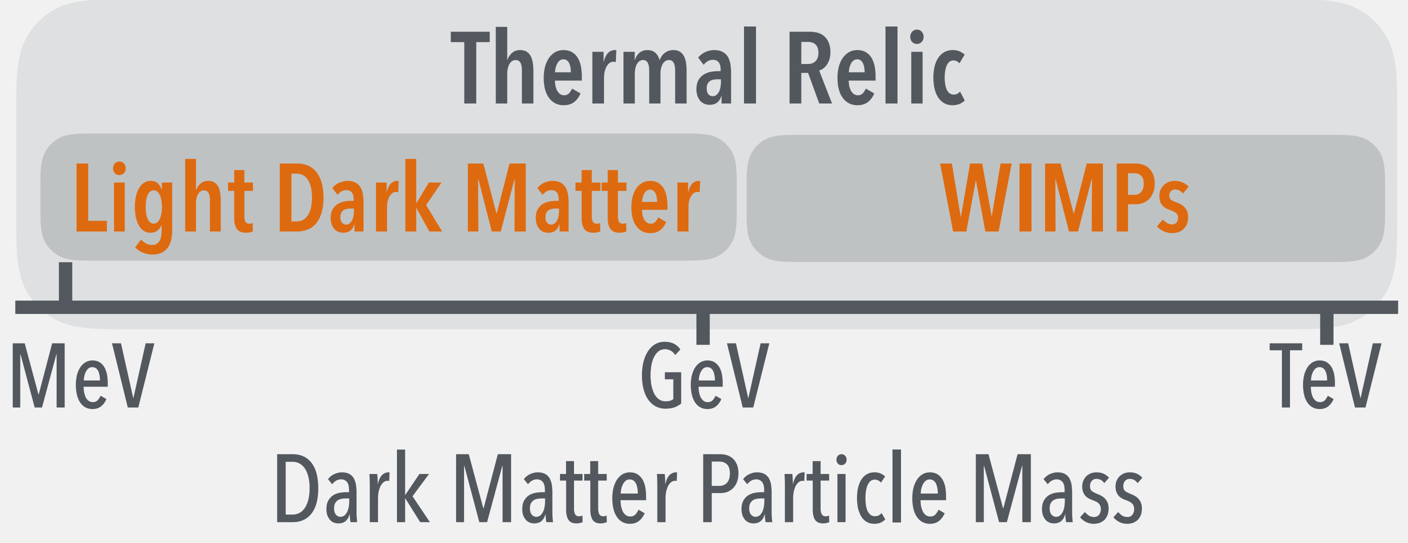


production mechanism at accelerators



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Active Field

arxiv:1608.08632

Dark Sectors 2016 Workshop: Community Report

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

arxiv:1707.04591

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	$m_\chi < 0.06$	$y \gtrsim 10^{-13}$	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	$m_\chi < 0.4$	$\epsilon^2 \gtrsim 10^{-14}$	2020+
MMAPS	Synchr @ Cornell	positron FT	6	MMass	$0.02 < m_{A'} < 0.075$	$\epsilon^2 \gtrsim 10^{-8}$	2020+
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.	$m_{A'} < 2$	$\epsilon^2 \sim 10^{-14} - 10^{-}$	
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.	$0.01 < m_{A'} < 0.060$	$\epsilon^2 \gtrsim 10^{-9}$	
PADME	DAΦNE @ Frascati	positron FT	0.550	MMass	$m_{A'} < 0.024$	$\epsilon^2 \gtrsim 10^{-7}$	
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

Basic Research Needs for Dark Matter Small Projects New Initiatives October 15 – 18, 2018

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

CERN Physics Beyond Colliders

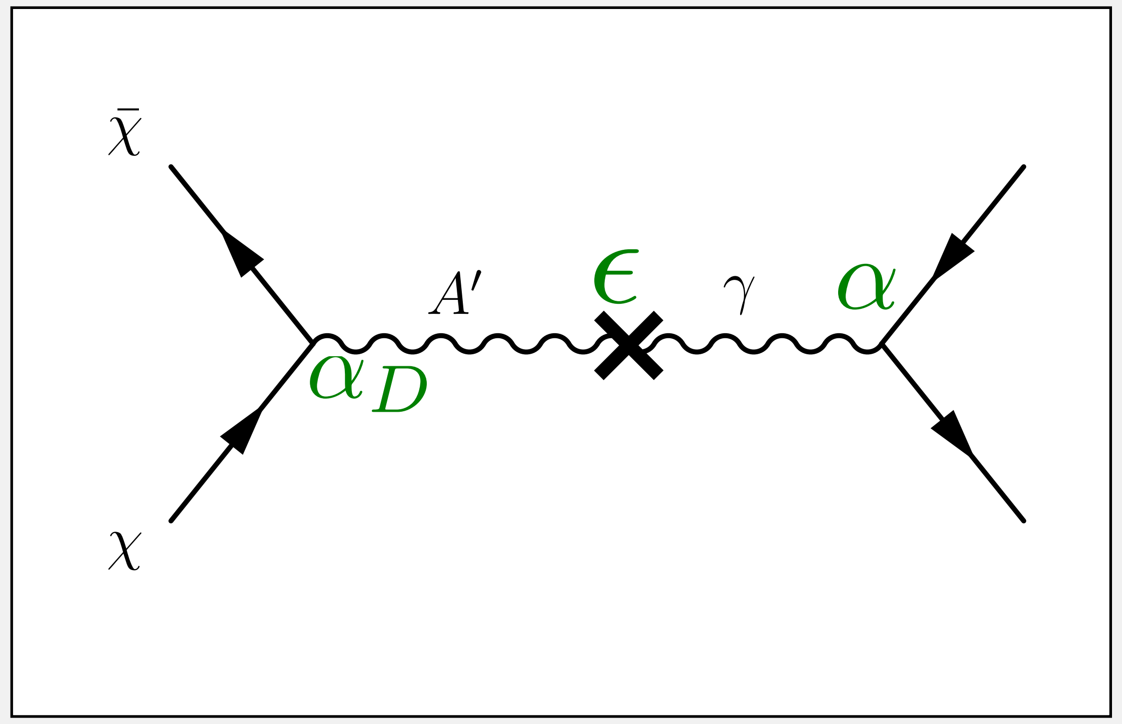
21-22 November 2017
CERN

Search...

How to realise LDM

representative benchmark model: Dark (Heavy) Photon (A')

- spin-1 particle, mass $m_{A'} \neq 0$ (MeV - GeV)
- mixes with photon (ε)

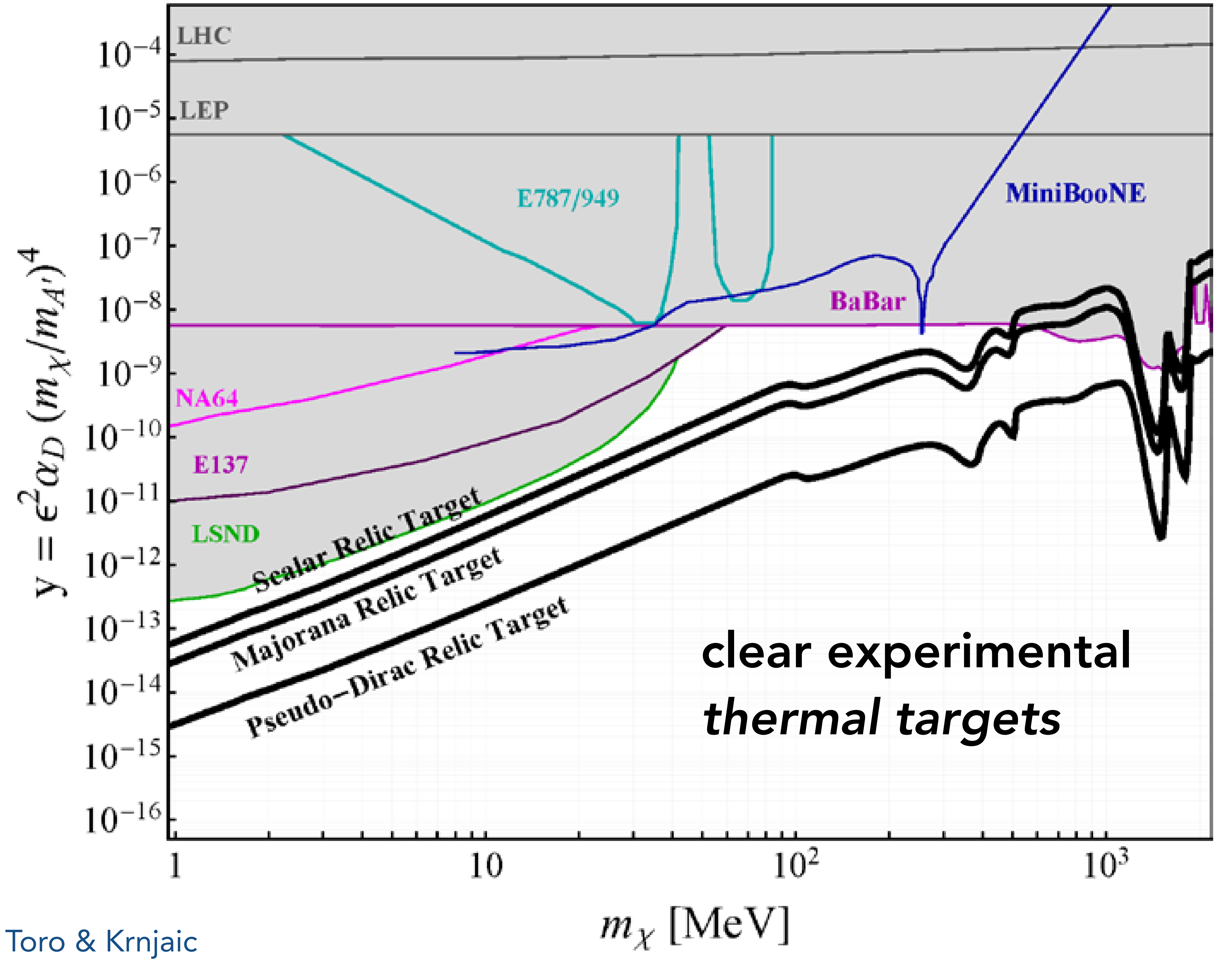


$$\sigma v \sim \alpha_D \varepsilon^2 \frac{m_\chi^2}{m_{A'}^4} \sim \alpha_D \varepsilon^2 \frac{m_\chi^4}{m_{A'}^4} \frac{1}{m_\chi^2} \sim y \frac{1}{m_\chi^2}$$

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

interaction strength

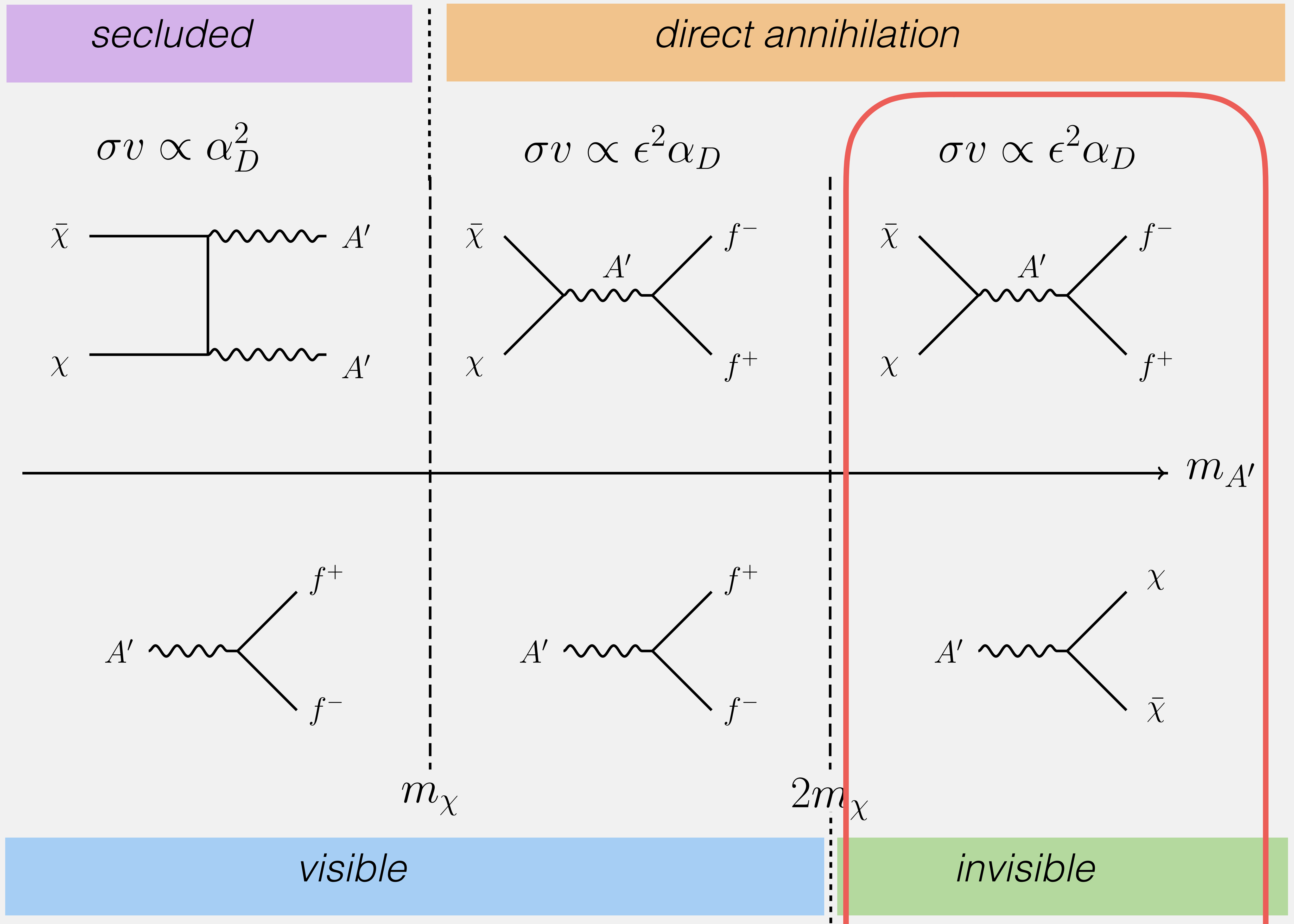
conservative: $\alpha_D = 0.5 \quad \frac{m_\chi}{m_{A'}} = \frac{1}{3}$



clear experimental *thermal targets*

Toro & Krnjaic

Signatures



prompt decay (resonance feature)

long-lived (displaced decay)

missing…

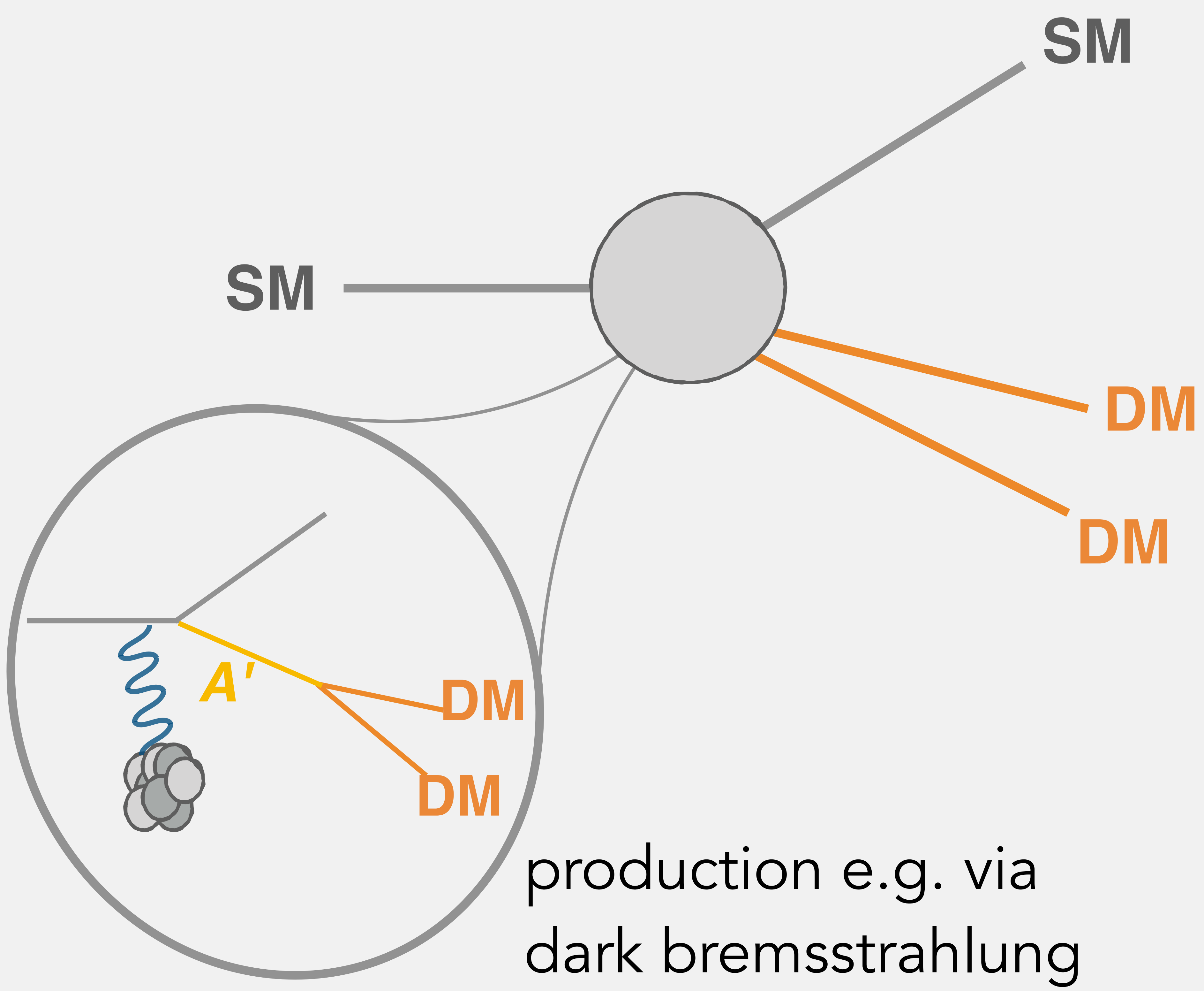
… mass

… energy

… momentum

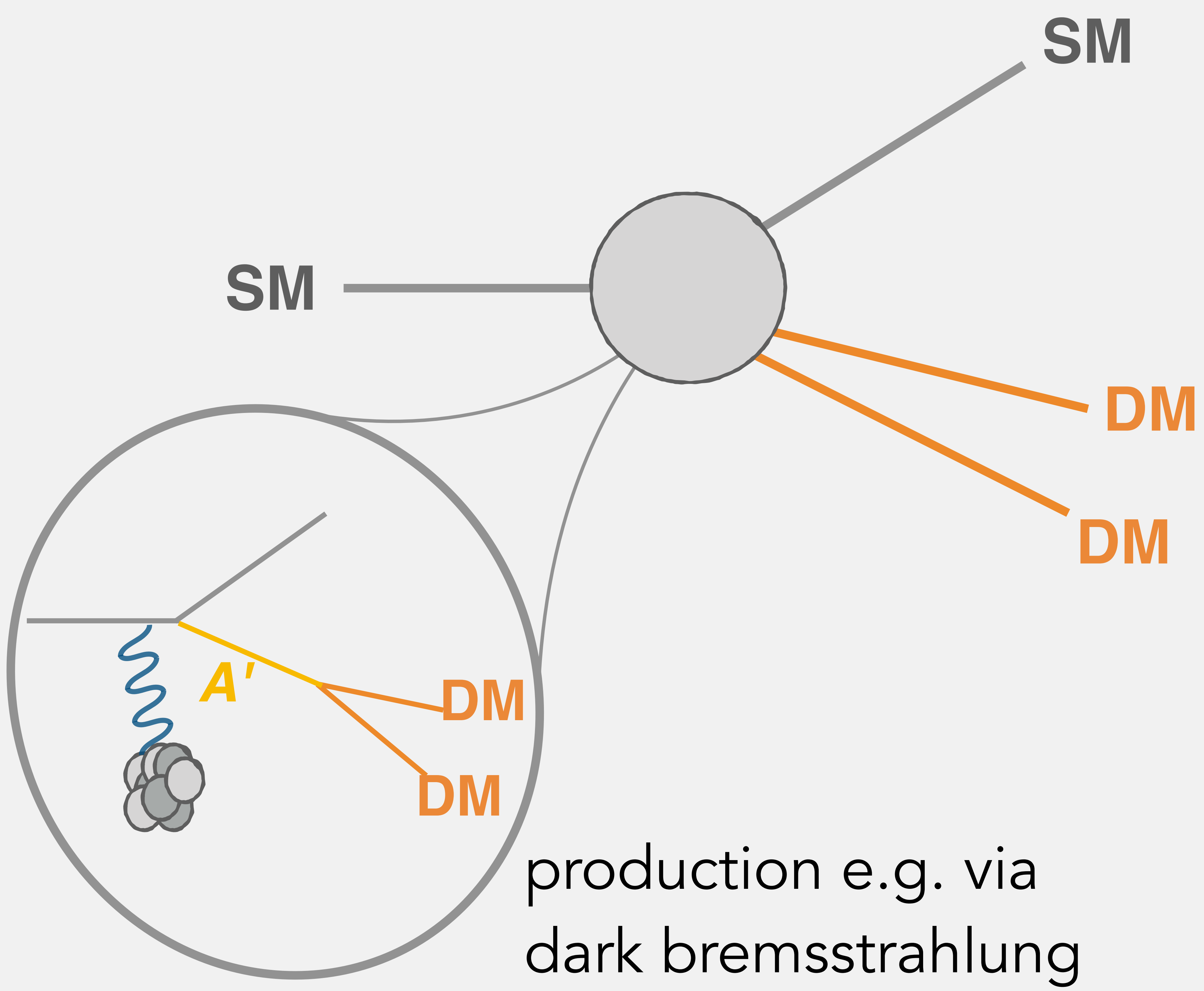
rescattering

Accelerator Searches



production e.g. via
dark bremsstrahlung

Accelerator Searches

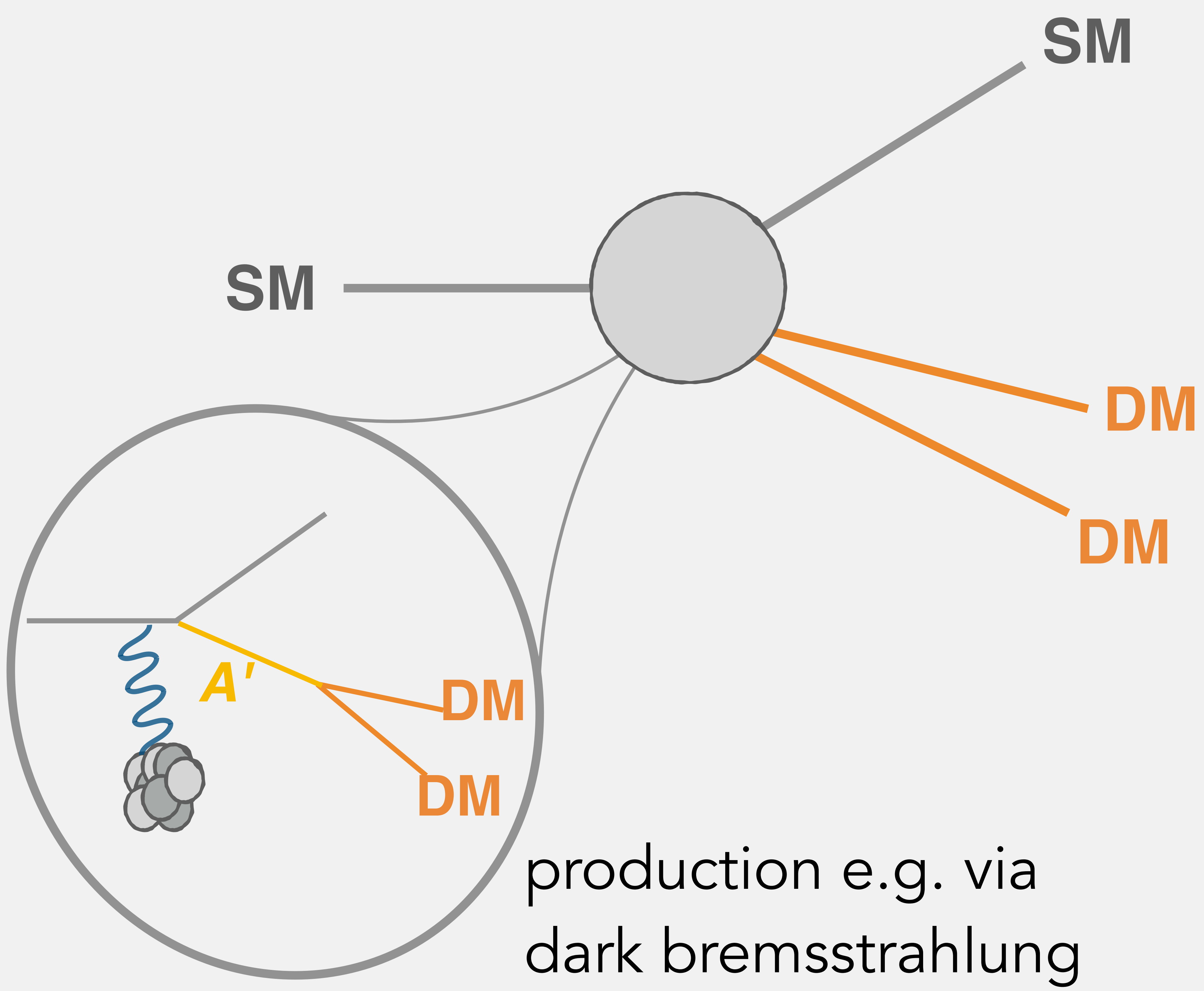


production e.g. via
dark bremsstrahlung

Fixed Target

DM escapes, measure scattered SM particle, $N_{sig} \sim \varepsilon^2$
NA64(++), **LDMX**, PADME, MMAPS, VEPP3, DarkLightII…

Accelerator Searches



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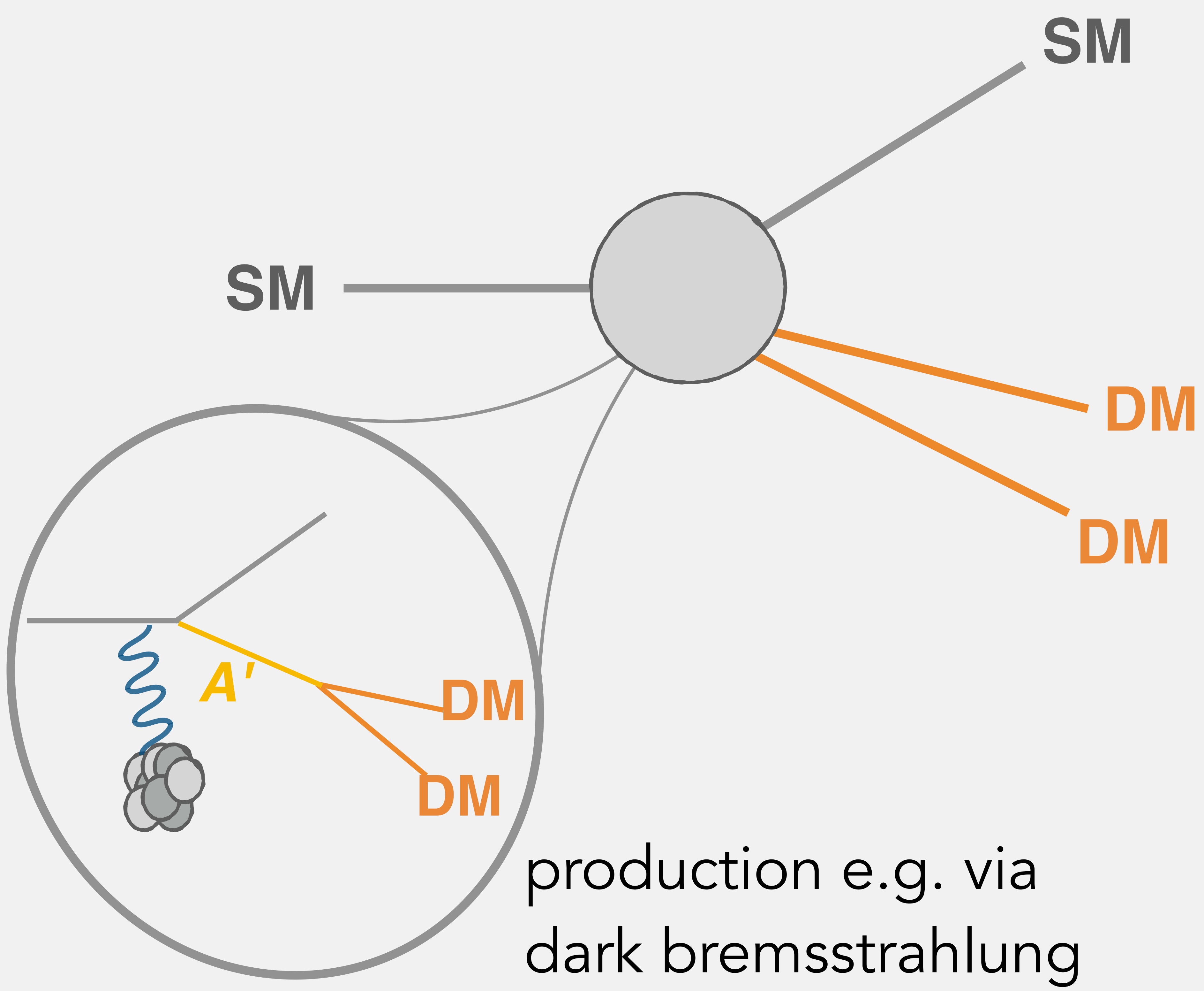
Beam Dump

detect DM rescattering, $N_{sig} \sim \varepsilon^4$

E137, **BDX**, LSND, **MiniBooNE**, SHiP, SBNe/pi…

Accelerator Searches



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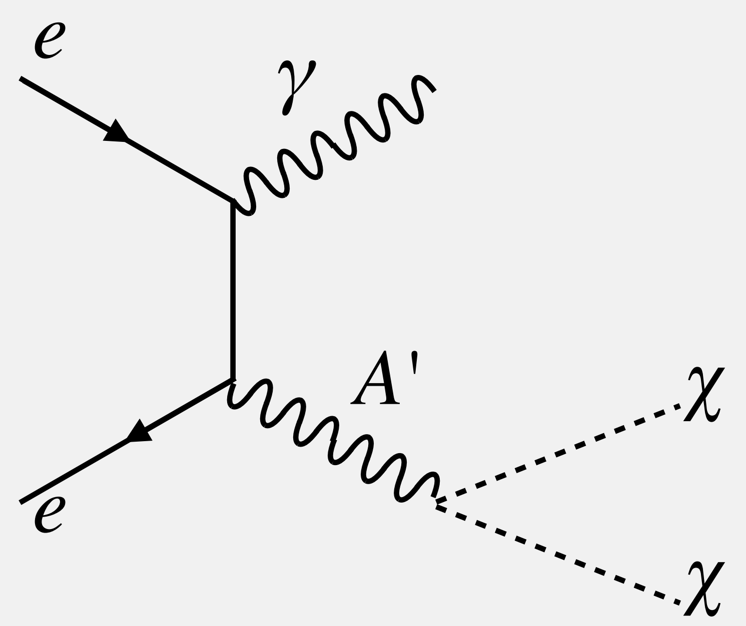
Beam Dump

detect DM rescattering, $N_{sig} \sim \varepsilon^4$

E137, **BDX**, LSND, **MiniBooNE**, SHiP, SBNe/pi…

production e.g. via
dark bremsstrahlung

also: *colliders* ('mono-photon')
BaBar, Belle II, LHC
[not in this talk]

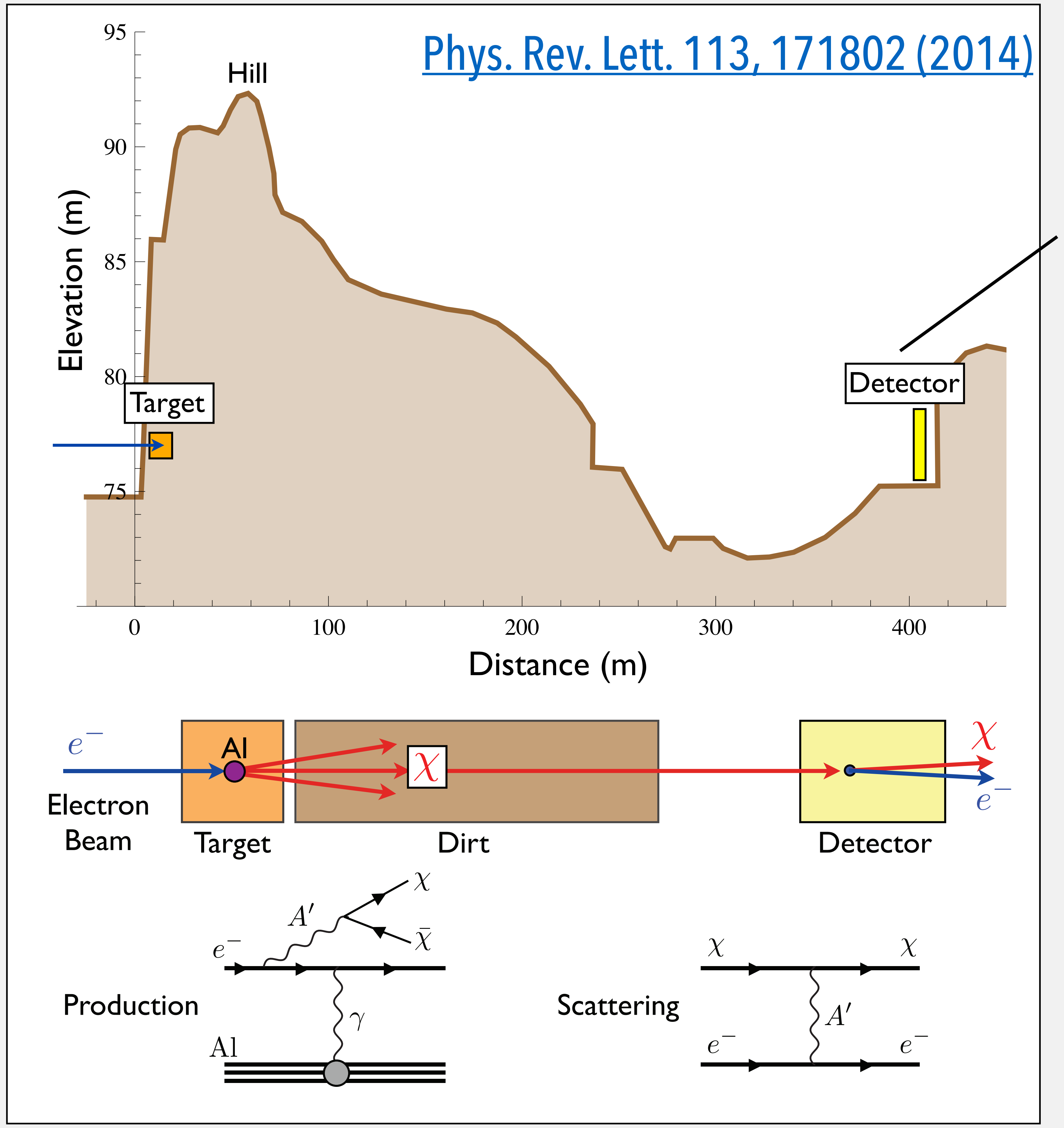


Beam Dump Experiments

Electron I: E137

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

- search for neutral metastable penetrating particles
- 20 GeV electrons on SLAC beam dump, total of 2×10^{20} EoT



electromagnetic calorimeter

look for shower with:

- E > 1 GeV
- pointing back to dump

0 observed —> $N_{95} = 3$

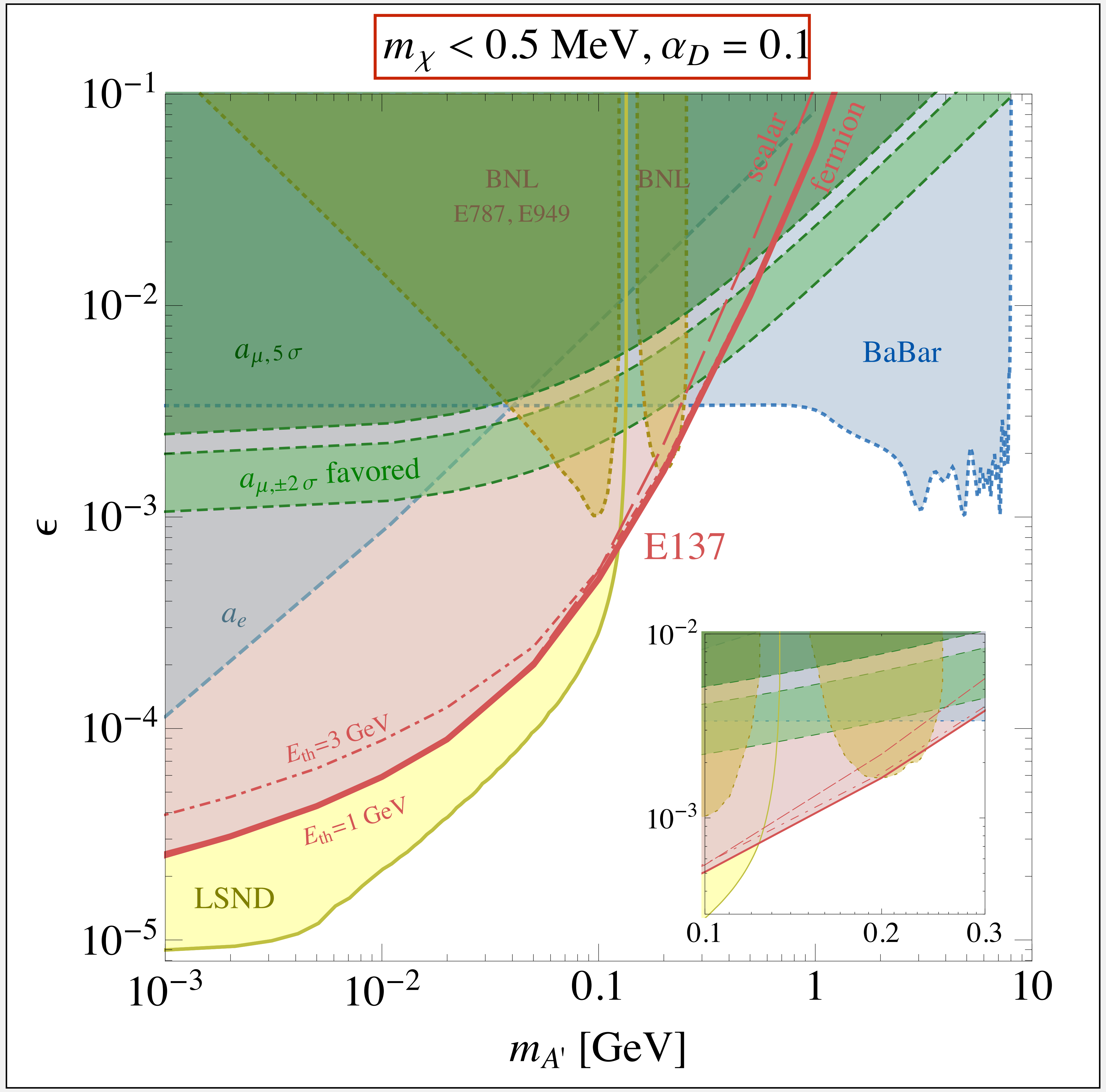
Phys. Rev. D 38, 3375 (1988)

Electron I: E137

first reanalysis assuming dark bremsstrahlung production:

- detailed simulation of original detection threshold/ trigger, including systematic studies

[Phys. Rev. Lett. 113, 171802 (2014)](https://doi.org/10.1103/PhysRevLett.113.171802)



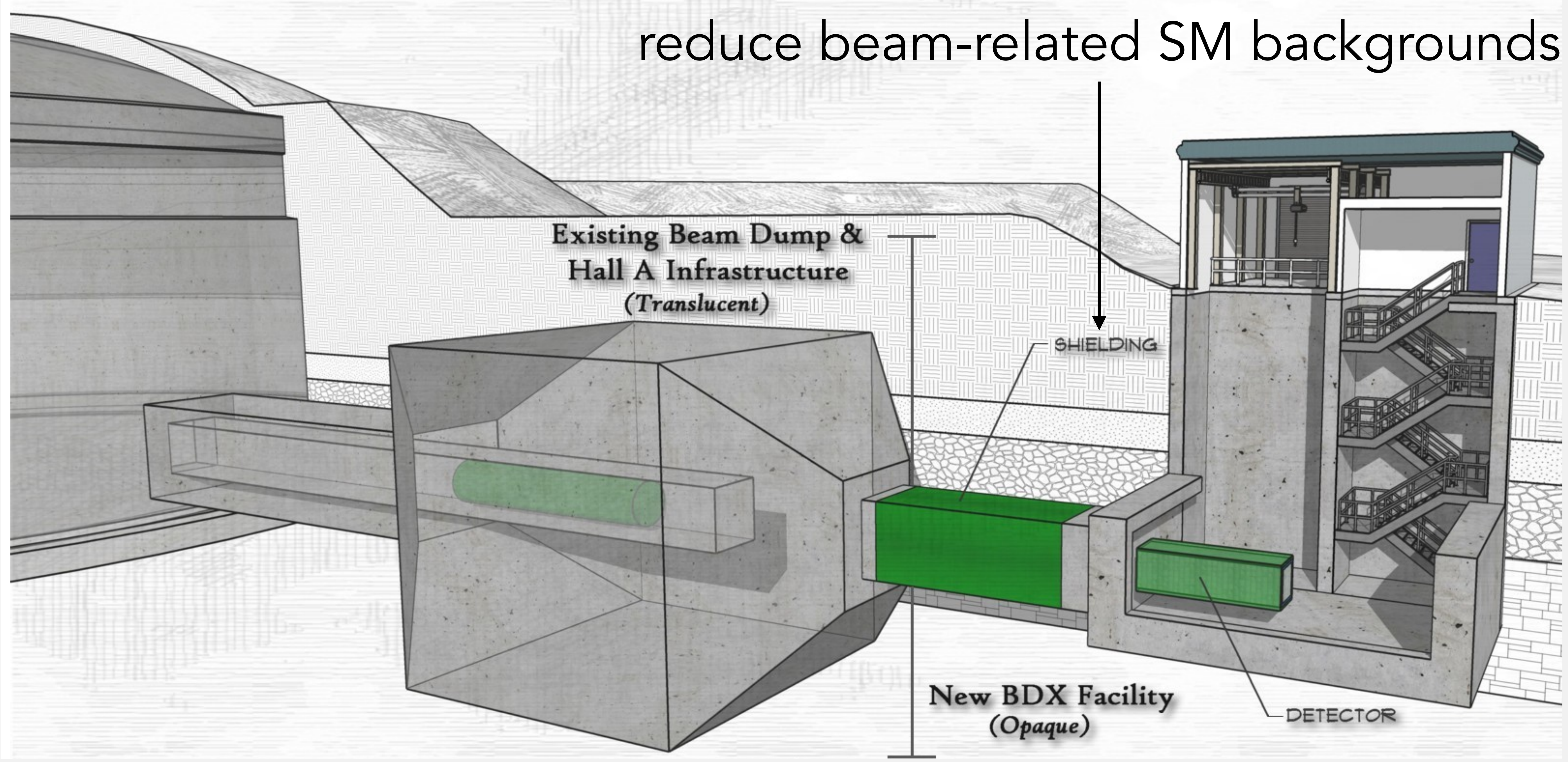
more recent re-interpretation including e^+e^- annihilation channel from secondary positrons

[Phys. Rev. Lett. 121, 041802 (2018)](https://doi.org/10.1103/PhysRevLett.121.041802)

Electron II: BDX

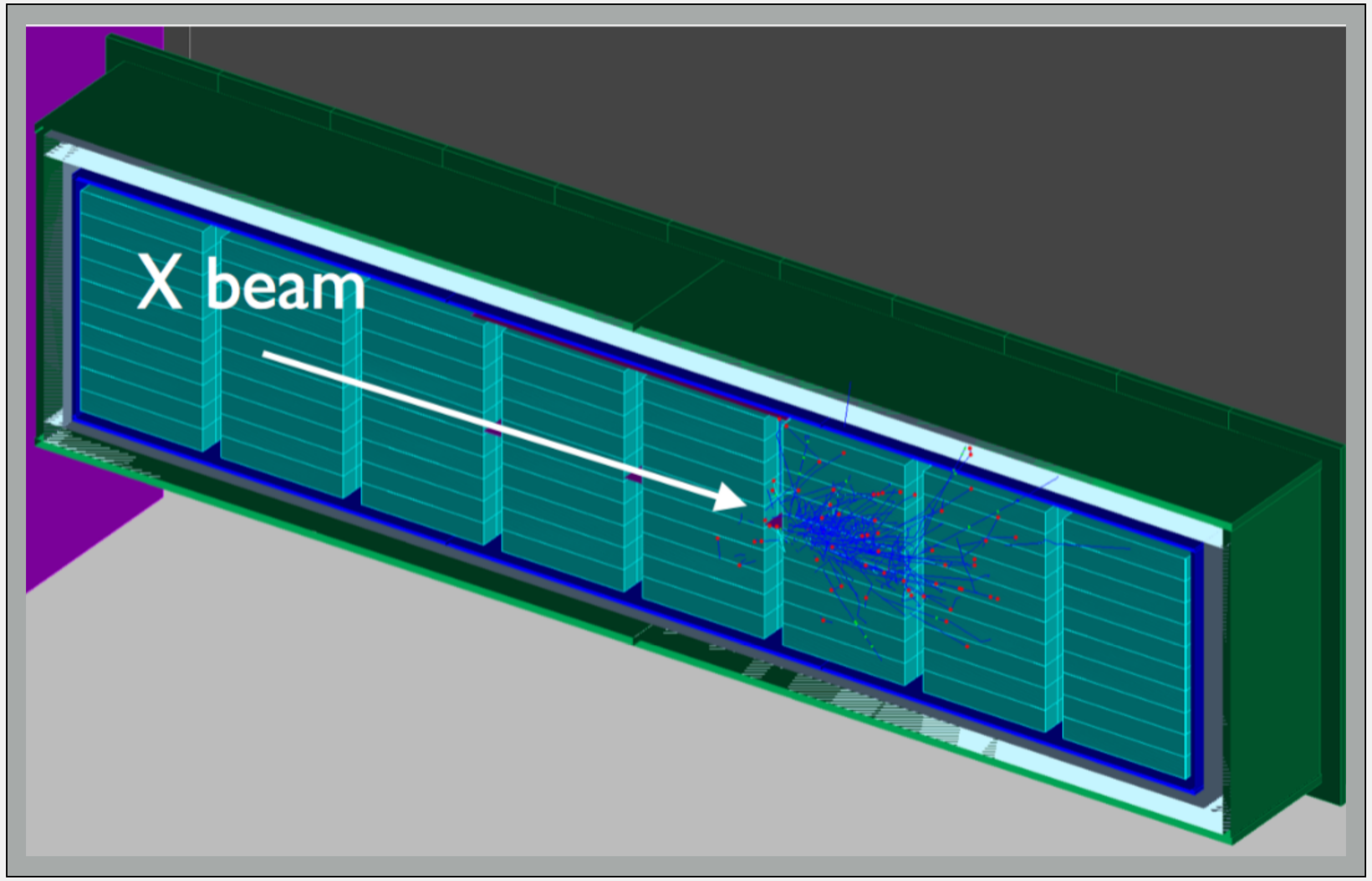
BDX - Beam Dump eXperiment arxiv:1607.01390

- **first** *dedicated* (electron) beam-dump experiment for LDM search
- approved for 285 days (~10^{22} EoT) @ 11 GeV (CEBAF@JLab)
- detector ~20m behind Hall A beam dump, new experimental hall
- sizeable overburden to reduce cosmic backgrounds (~10m water equivalent)



Electron II: BDX — Detector

arxiv:1607.01390



active veto sandwich

- inner & outer
- plastic scintillators

passive veto

- 5cm lead bricks

homogeneous electromagnetic calorimeter

- 800 CsI(Tl) crystals, total interaction volume 0.5 m^3
- SiPM readout
- measure ~GeV shower from X-e scattering
- ~MeV signal from inelastic X-nucleon scattering

2 prototypes

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

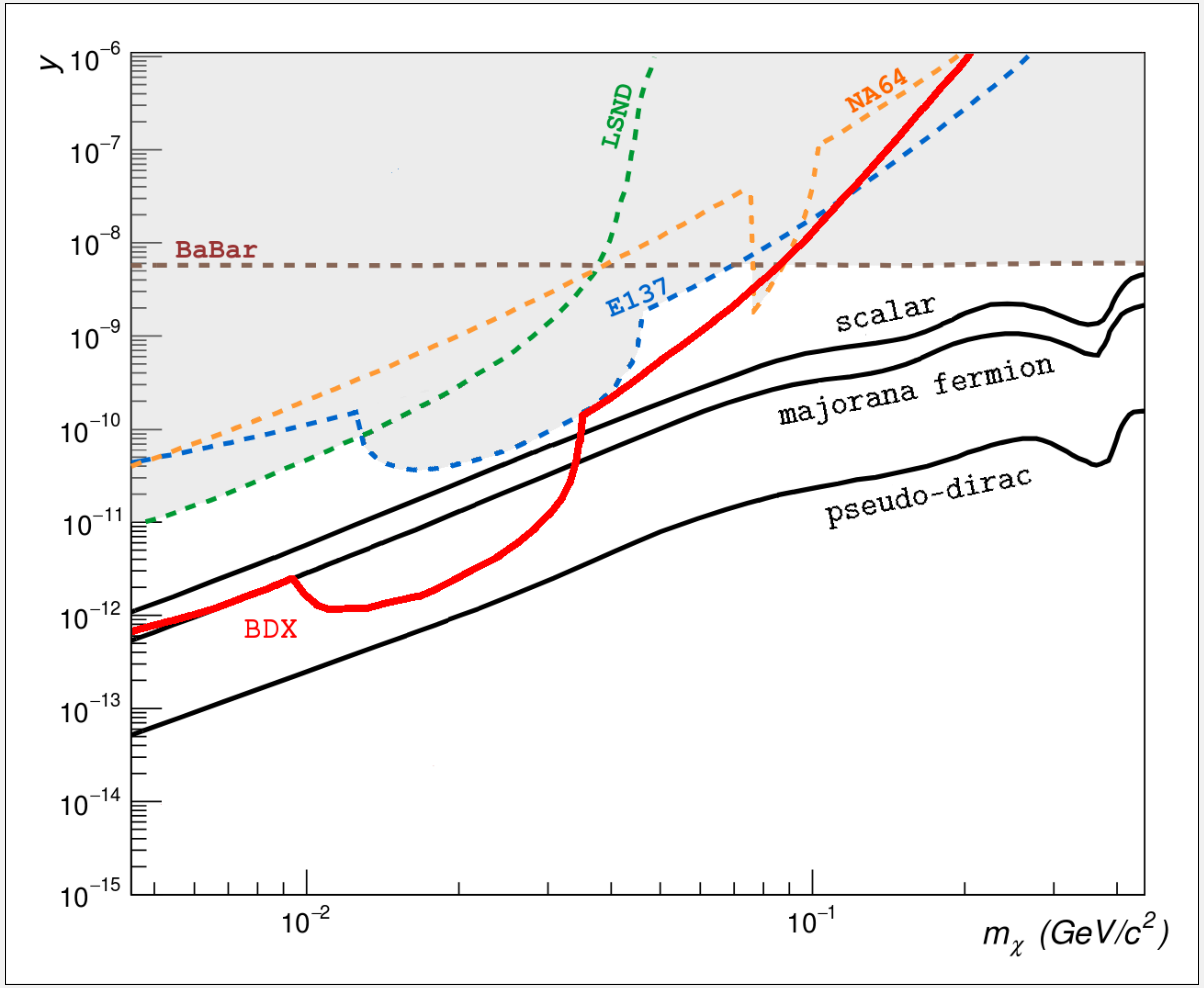
Electron II: BDX — Sensitivity

expected backgrounds (350 MeV energy threshold)

- cosmogenic backgrounds: 0
- neutrino backgrounds: ~5 events

sensitivity shown

- for $\alpha_D = 0.5 \quad \frac{m_\chi}{m_{A'}} = \frac{1}{3}$
- includes annihilation channel discussed in [Phys. Rev. Lett. 121, 041802 (2018)]



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

+ several other current/future neutrino experiments

different production modes

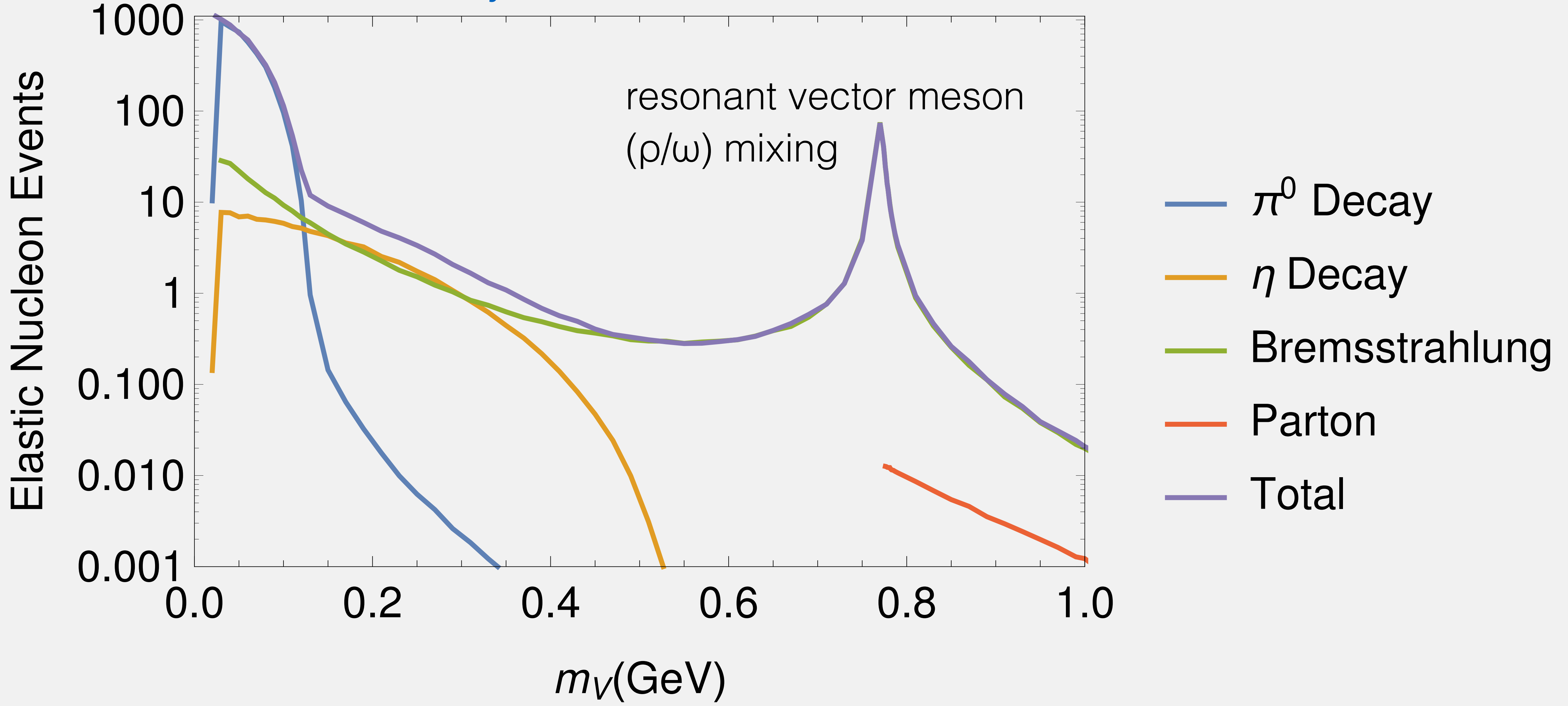
- radiative meson decay (low mass)
- bremsstrahlung with resonant mixing (intermediate mass)
- direct production (masses >1 GeV)

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

generally “messier" —> higher beam backgrounds

MiniBooNE, 9 GeV

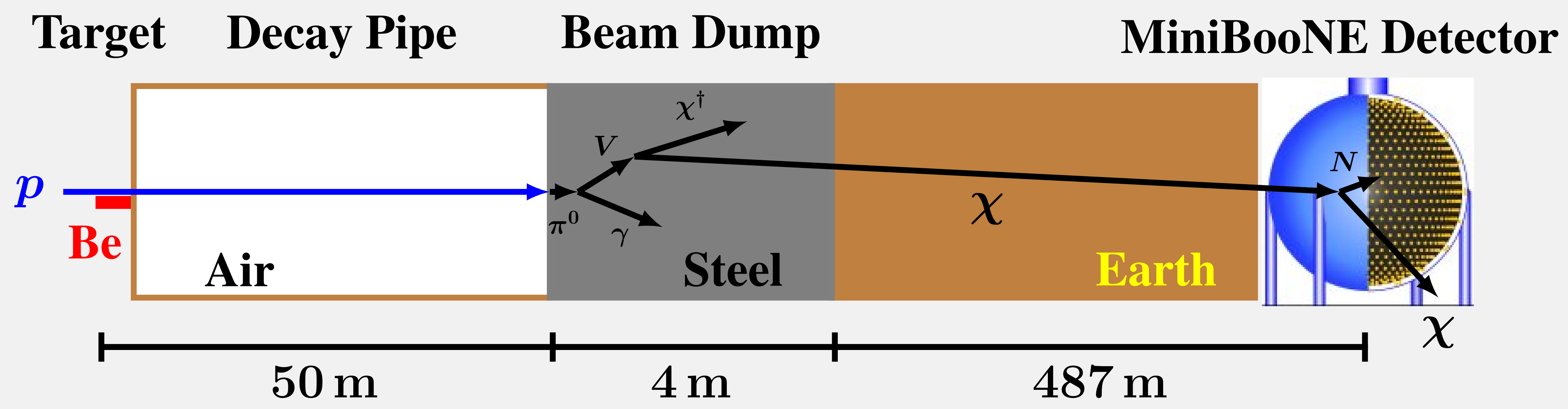
Phys. Rev. D 95, 035006 (2017)



Proton: MiniBooNE

dedicated run in 'beam-dump mode':

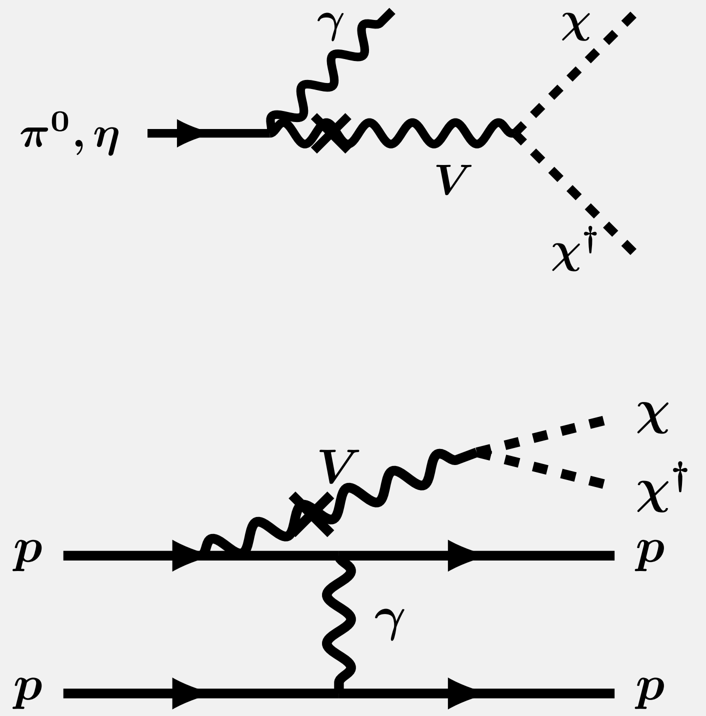
- Nov 2013 - Sep 2014, 1.86 x 10^{20} PoT, 8 GeV proton beam
- first dedicated DM search in proton beam-dump experiment
- well-understood experiment! (>10 years of operation)

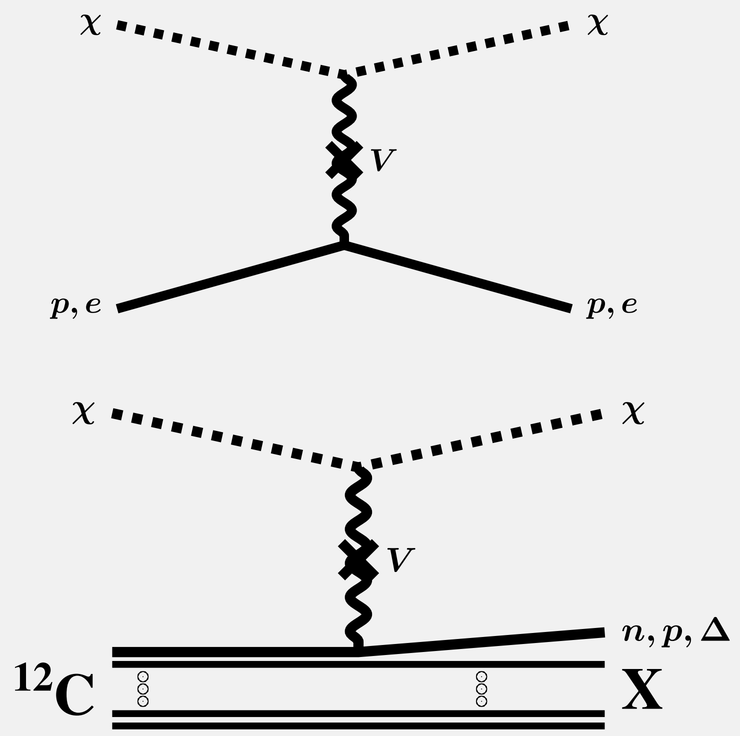


12m diameter sphere

800t mineral oil CH_2 (450t fiducial)

~1300 PMTs to detect Cherenkov light





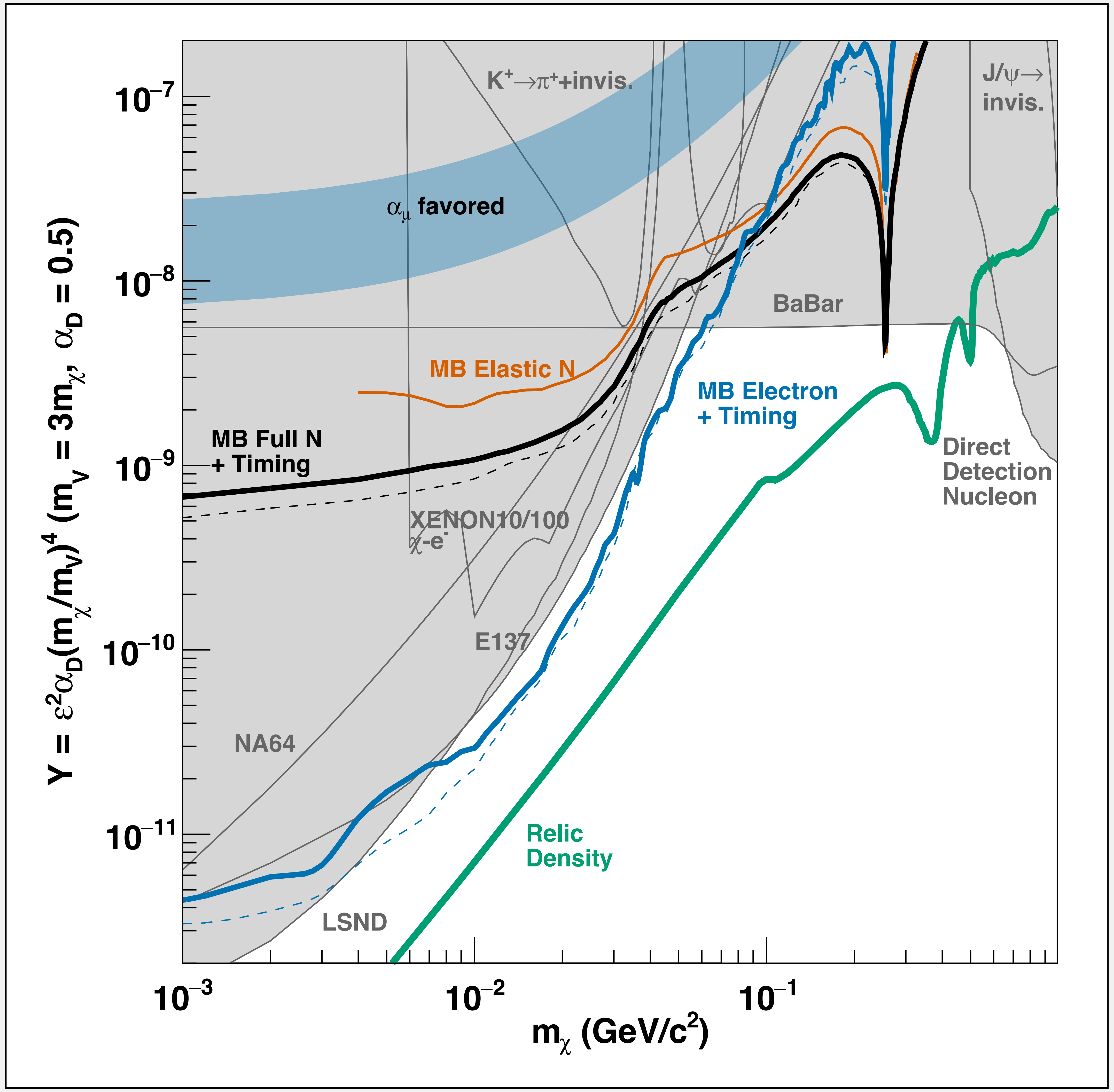
refined analysis published, additionally including

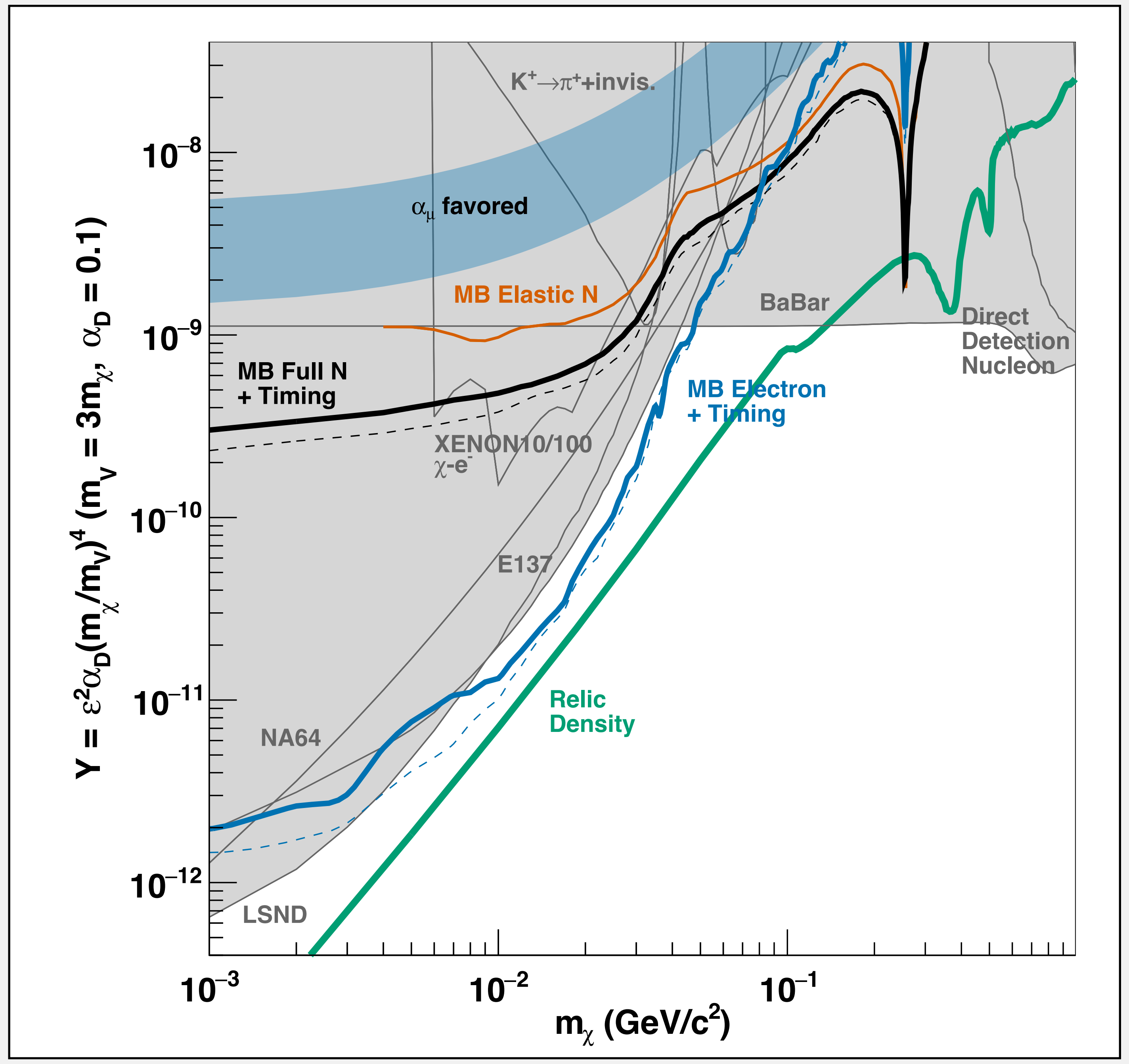
- neutral pion channel
- elastic electron scattering
- "time-of-flight"

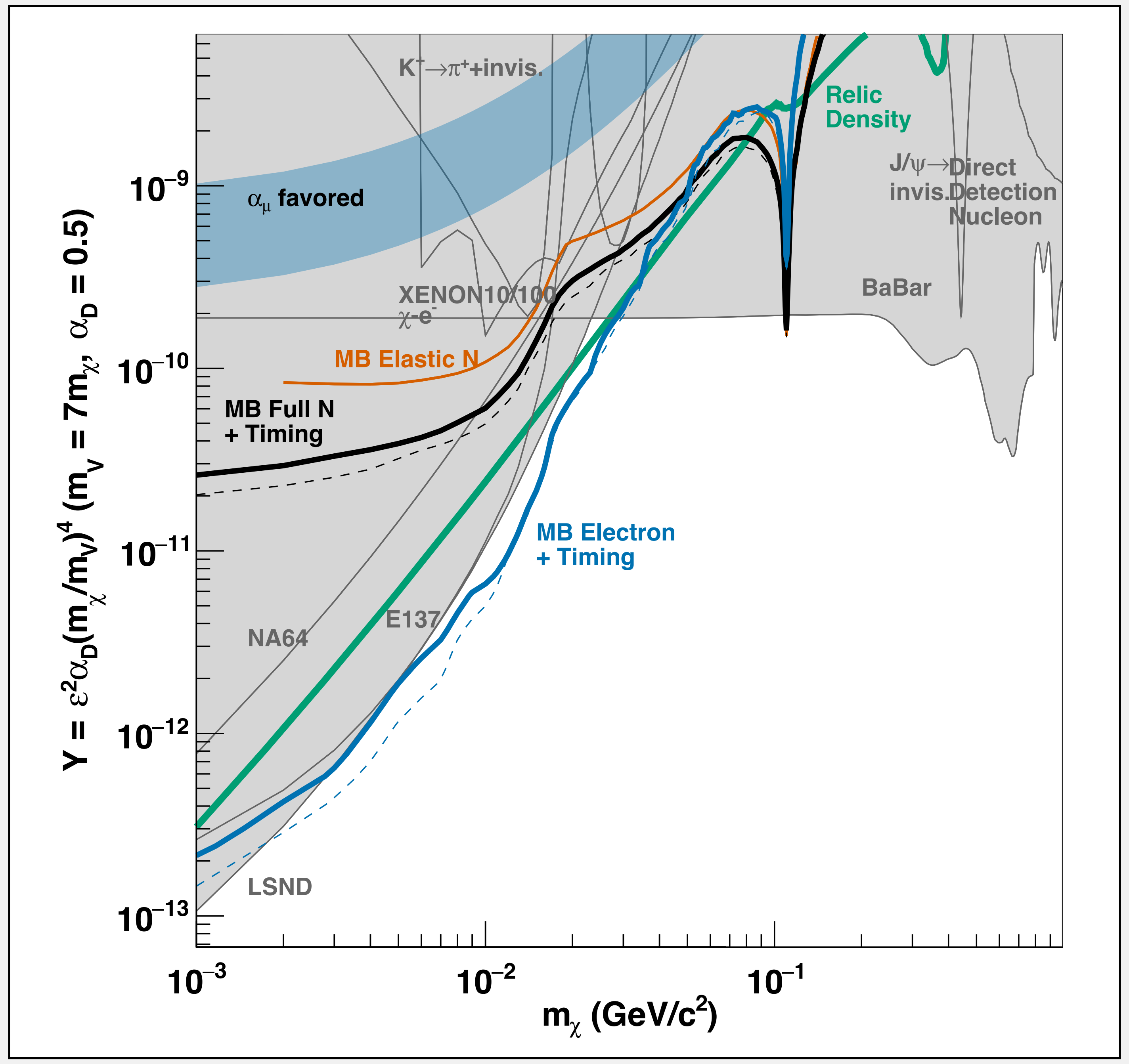
arxiv:1807.06137

Proton: MiniBooNE Results

arxiv:1807.06137





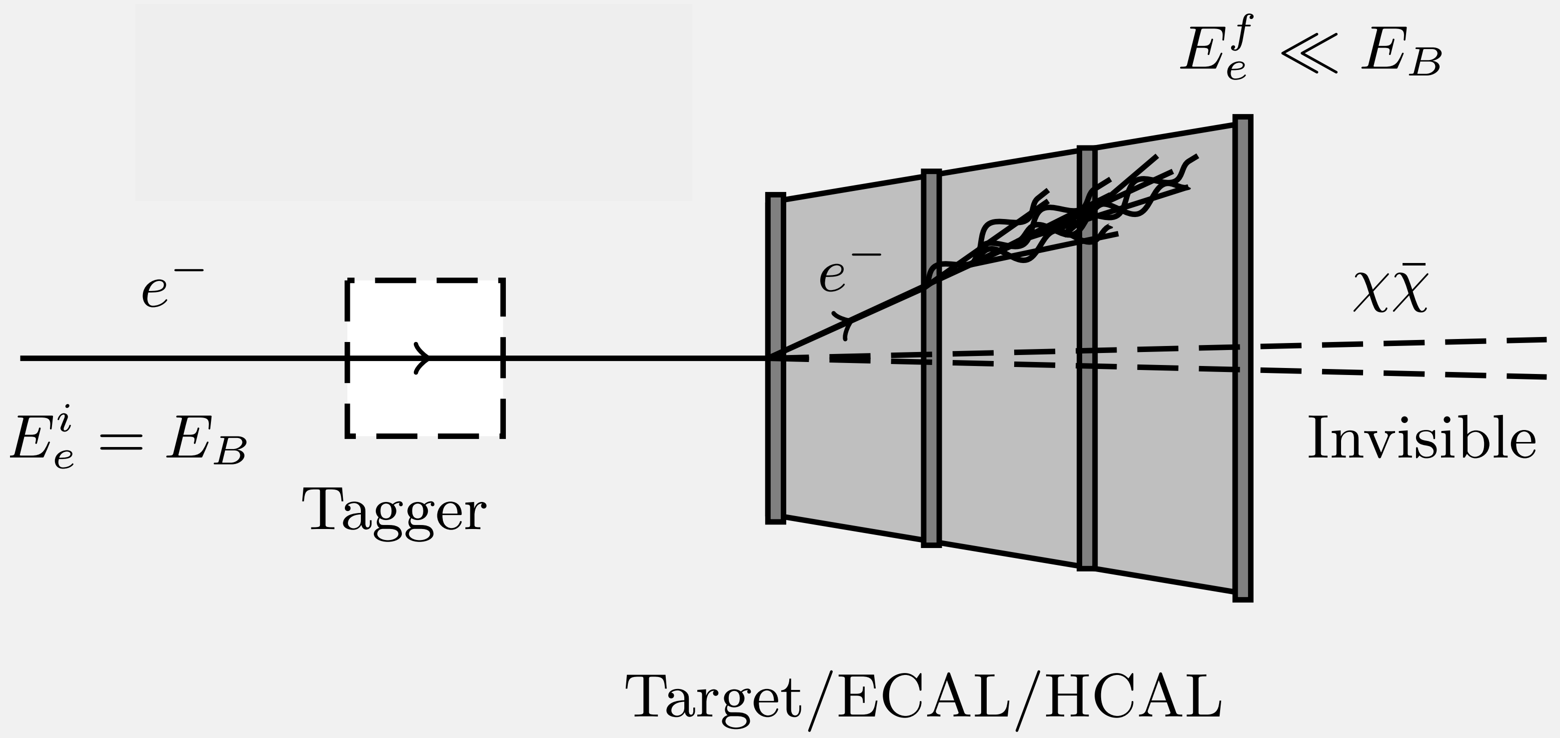


change of parameter values moves limits relative to thermal targets

Fixed Target Experiments

Complementary Approches

<u>missing energy</u>

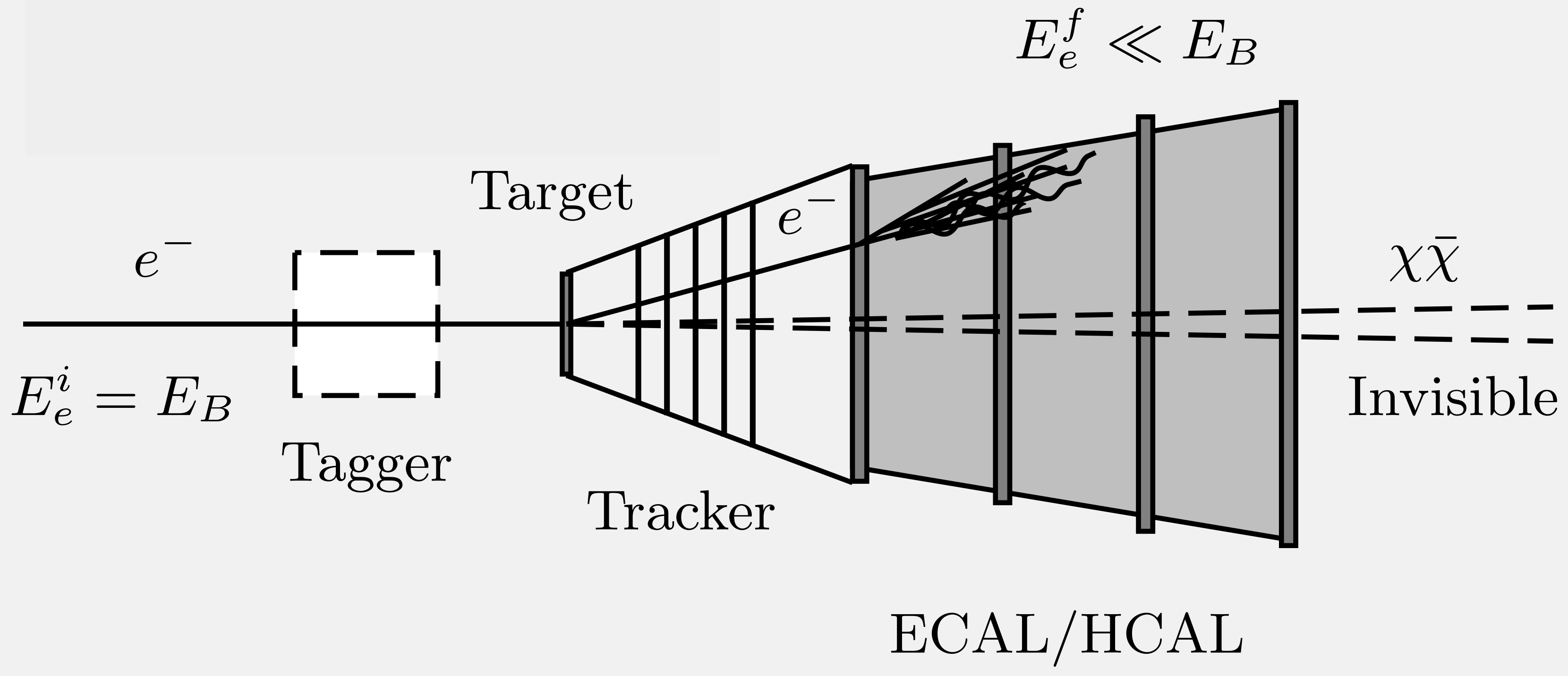


higher signal yield/EoT (thicker target)

greater signal acceptance

no e-γ particle ID

<u>missing momentum</u>



includes missing energy

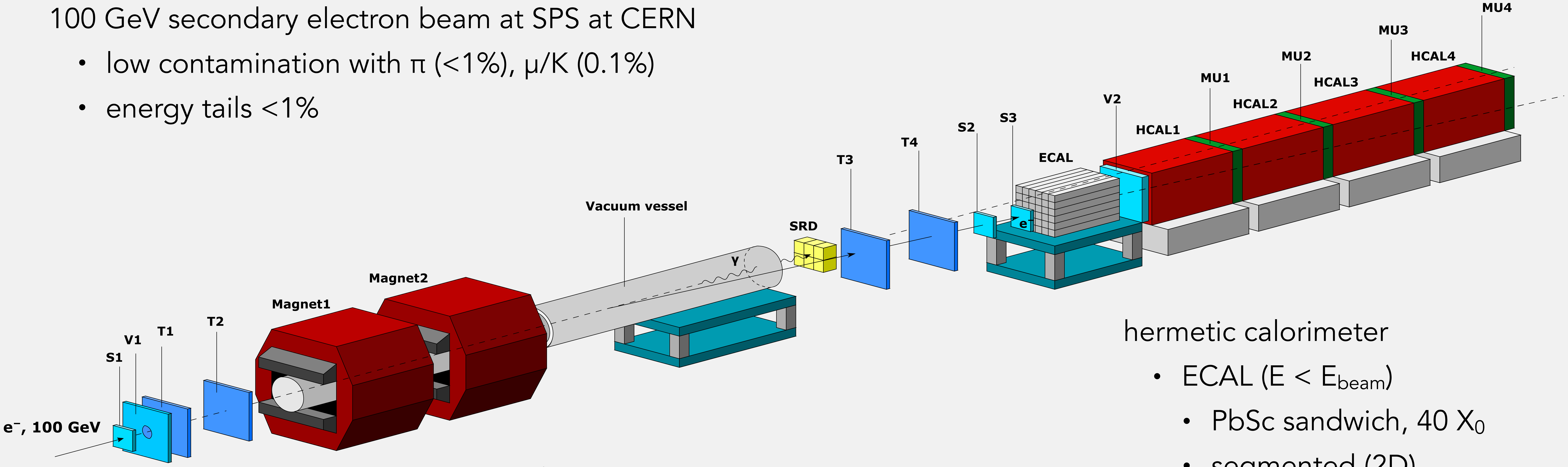
p_T as discriminator & *signal identifier*

e-γ particle ID

NA64 — Missing Energy

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

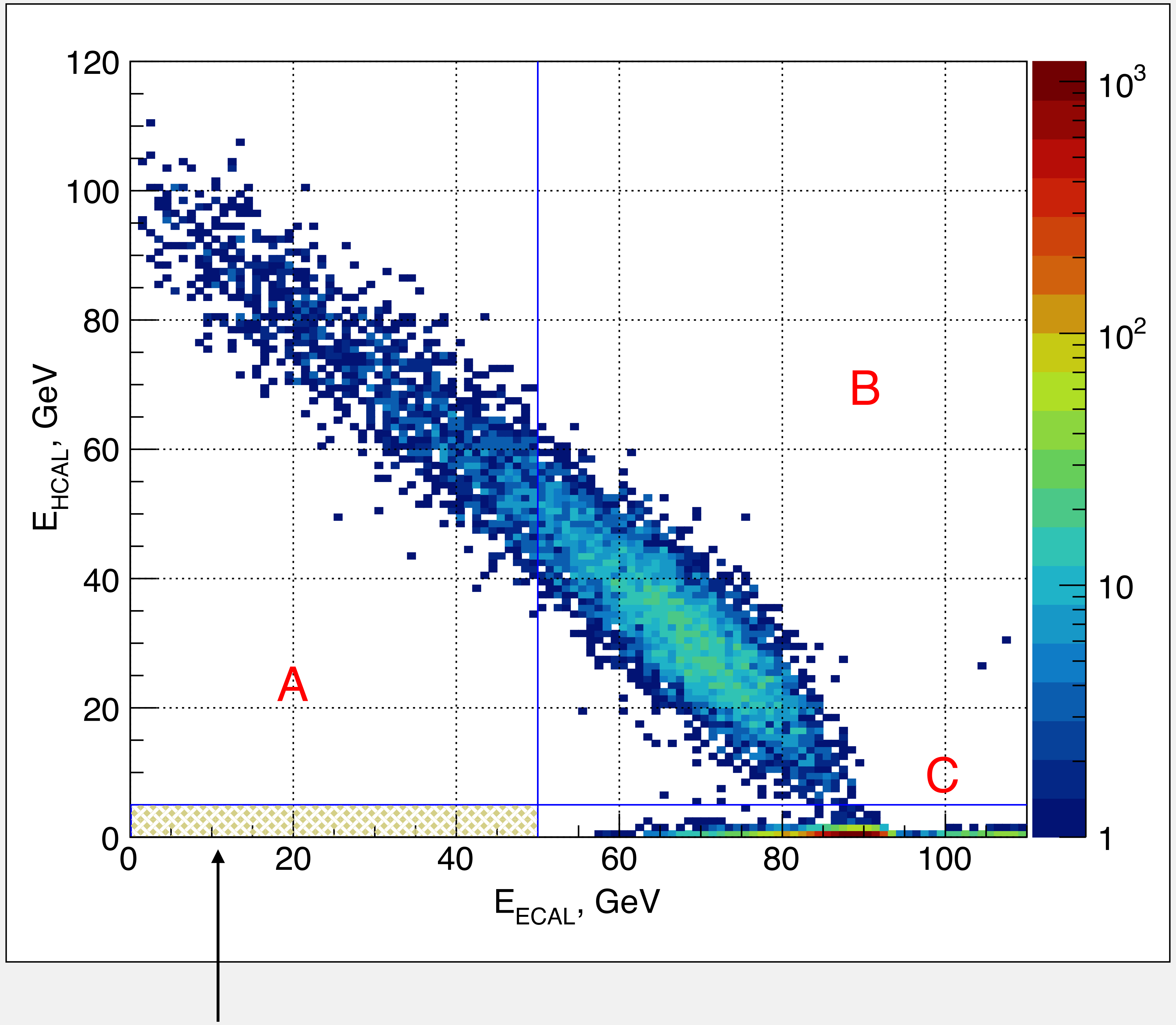
- tracker (100 GeV track)
  - magnetic field 7Tm
- synchrotron radiation detector (SRD)
  - particle ID (SR emission ~$1/m^4$)

NA64 Results

runs for invisible signature

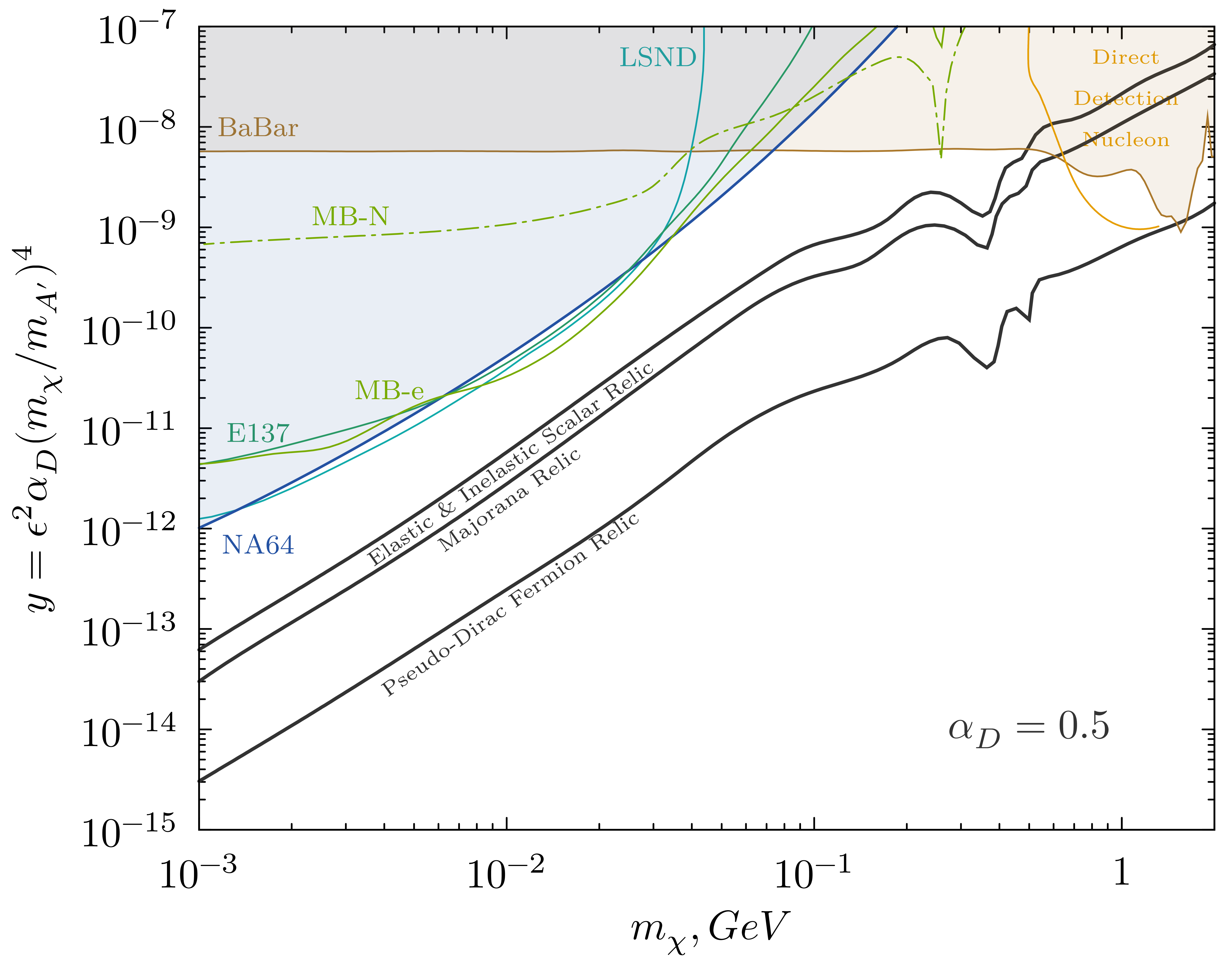
- 2016: 4.3 x 10^{10} EoT [Phys. Rev. D 97, 072002 (2018)]
- 2017: 5.4 x 10^{10} EoT
- 2018: 1.87 x 10^{11} EoT
- total: 2.84 x 10^{11} EoT [Phys. Rev. Lett. 123, 121801 (2019)]

Background source	Background, n_b
(i) Dimuons	0.024 ± 0.007
(ii) π, $K \to e\nu$, K_{e3} decays	0.02 ± 0.01
(iii) e^- hadron interactions in the beam line	0.43 ± 0.16
(iv) e^- hadron interactions in the target	<0.044
(v) Punch-through γ's, cracks, holes	<0.01
Total n_b (conservatively)	0.53 ± 0.17



signal region (scaled up by 5 in y-direction)

NA64 Sensitivity



[Phys. Rev. Lett. 123, 121801 (2019)]

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 (planned)

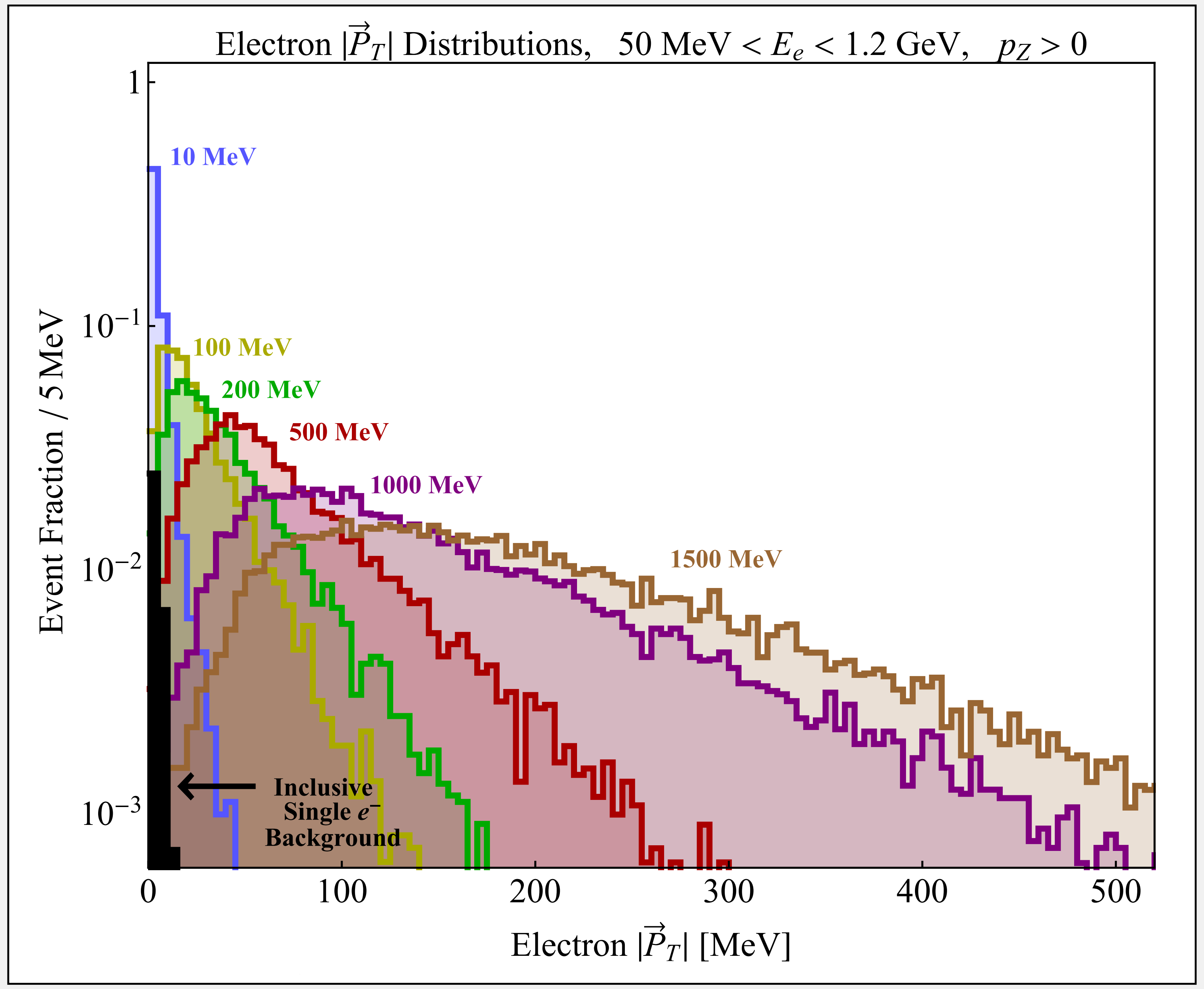
default: **4/8 GeV**@SLAC, parasitic at LCLS-II

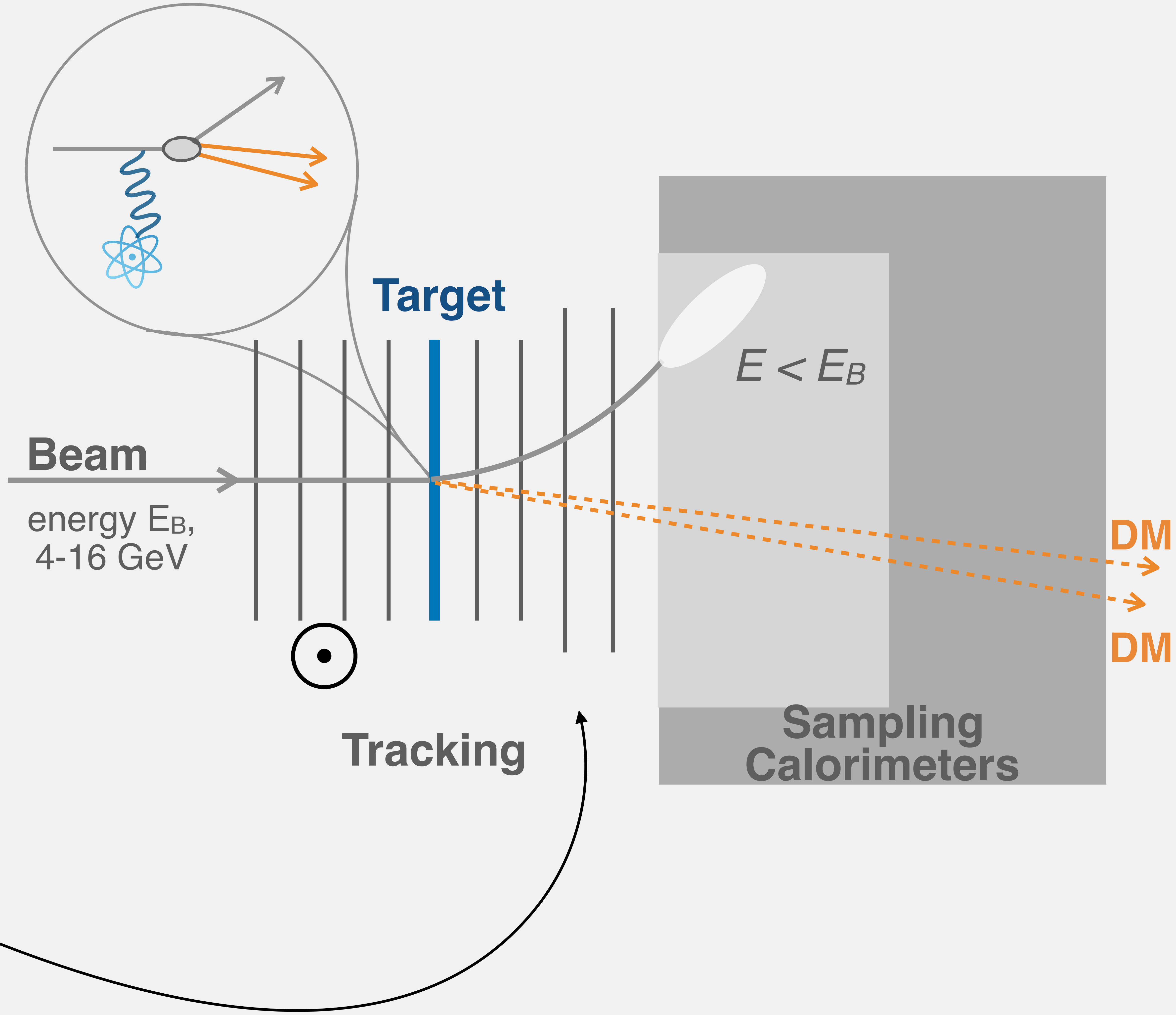
(potential alternative at CERN, up to 20 GeV)

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

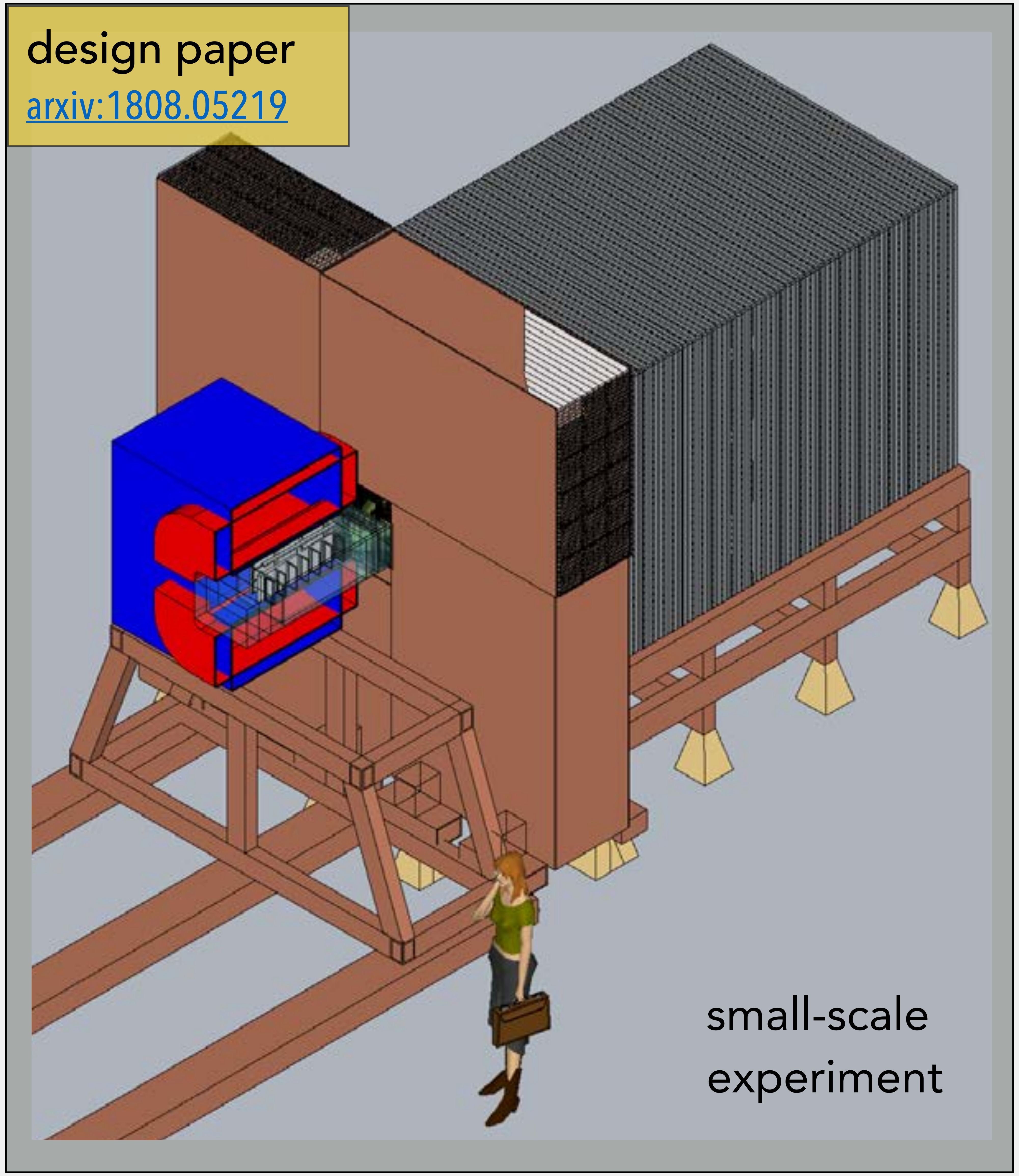
measure **missing momentum** (and energy)

- powerful additional handle





LDMX — Detector



leveraging techniques from existing/planned experiments

tracking

- simplified copy of Silicon Vertex Tracker (SVT) of HPS experiment@JLab
  - tagging tracker in 1.5T field
  - recoil tracker in fringe field
  - $0.1X_0$ W target

ECal

- draw on design of CMS forward SiW calorimeter upgrade
  - fast, radiation hard, dense
  - high granularity (MIP 'tracking')

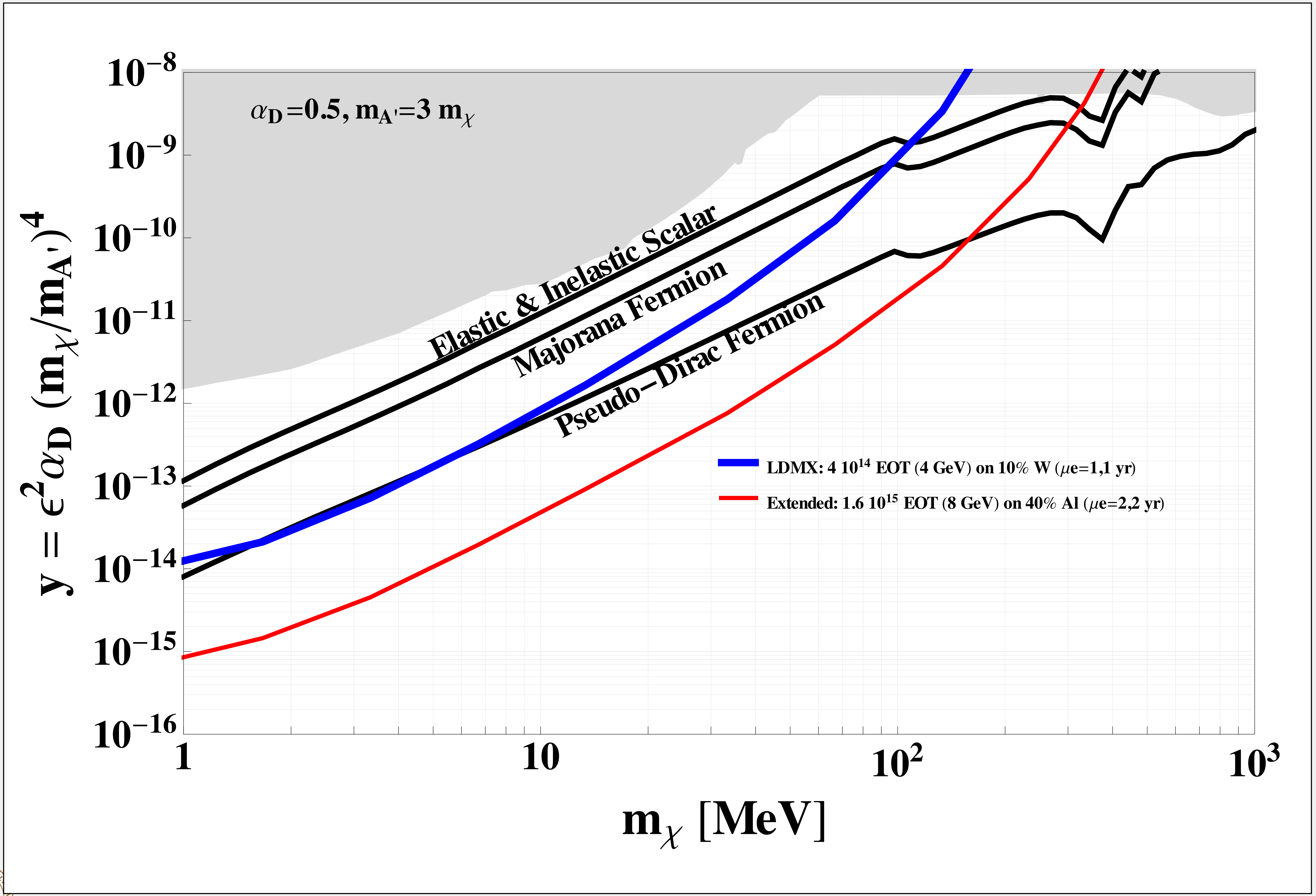
HCal

- need highly efficient neutron **veto**
- plastic scintillator, steel absorber (like Minos, Mu2e)

expect **close to 0 background** for $4x10^{14}$ EoT

photon-veto
arxiv:1912.05535

LDMX — Projected Sensitivity



LDMX can explore a lot of new parameter space

sensitive to various thermal targets already with **pilot run**

further potential to probe all thermal targets up to O(100) MeV

timescale: few years

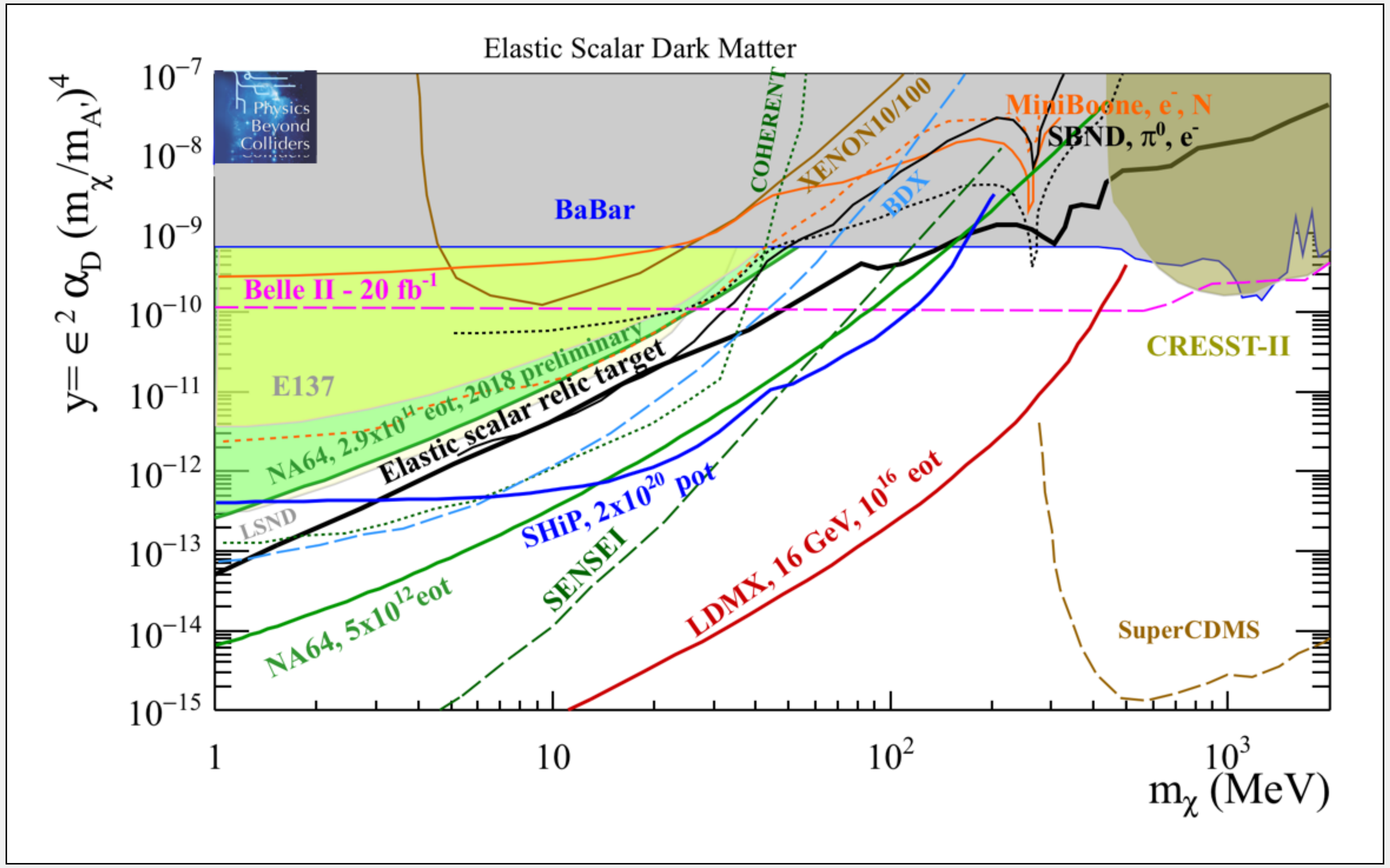
Summary

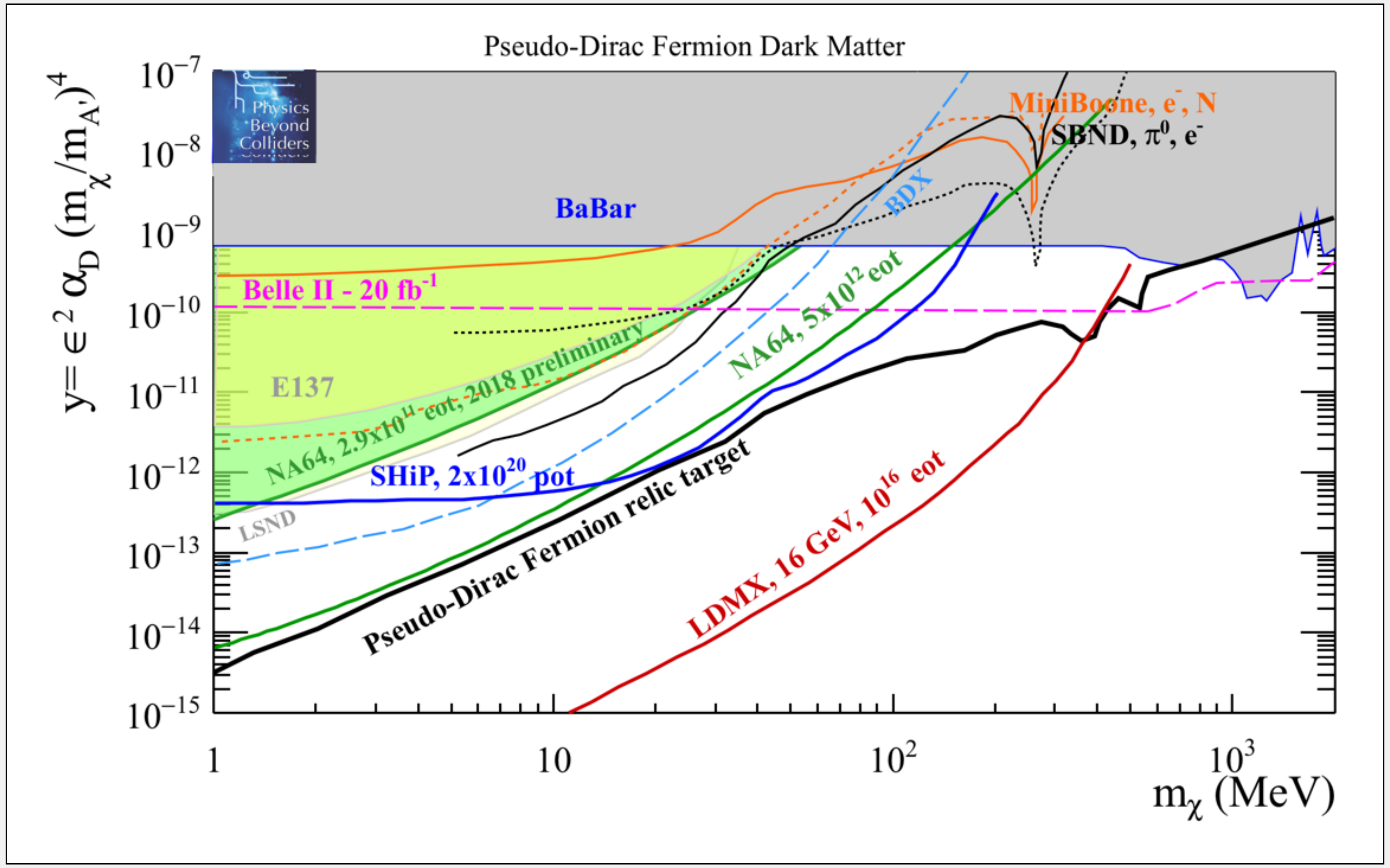
broad interest in Dark Sector physics, many new initiatives

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
    - could only cover some examples here
    - sensitive to variety of models (no time to talk about)

Lots going on and more to come!





https://arxiv.org/abs/1901.09966

Thank you!

Additional Material

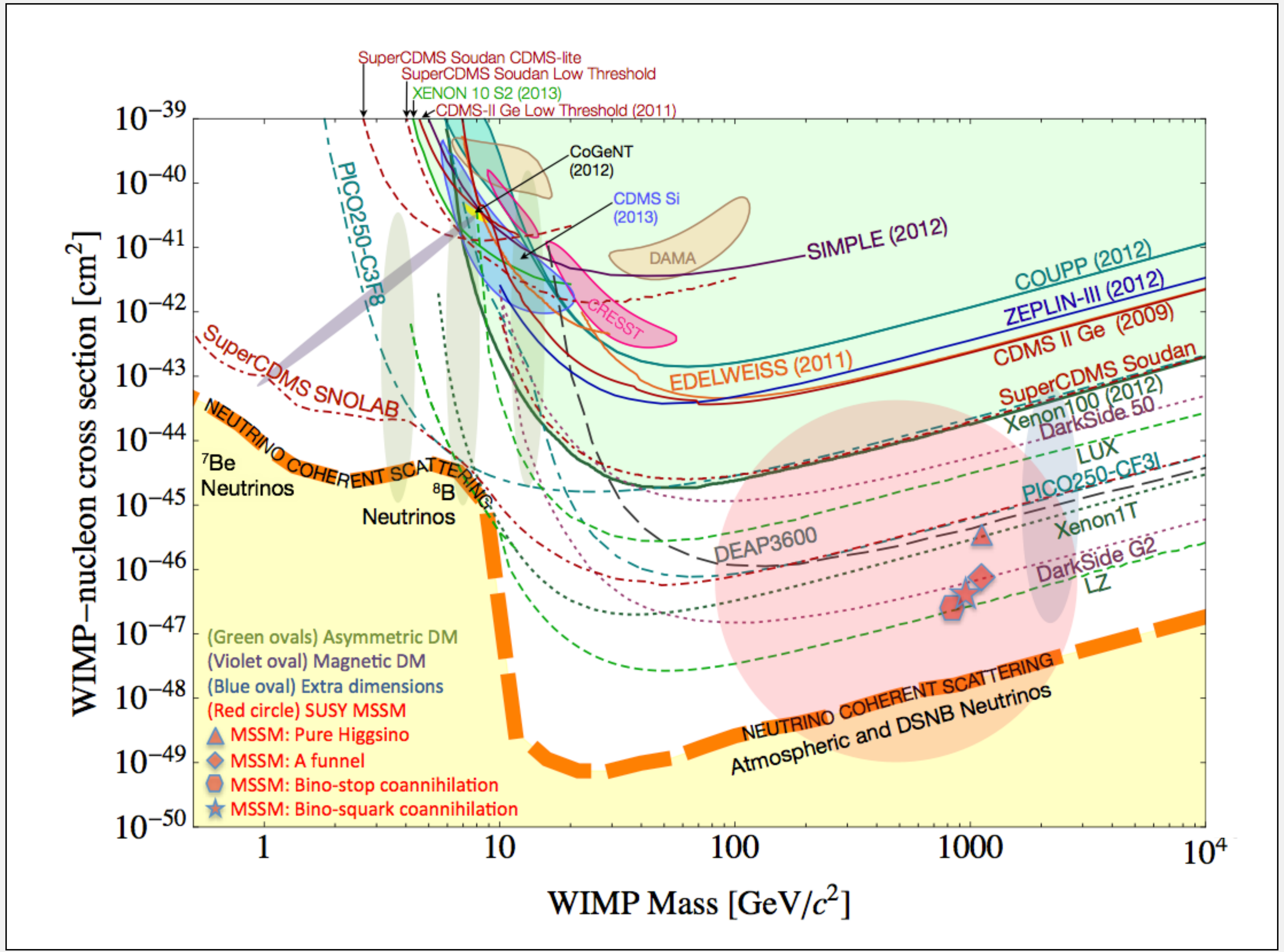
Direct Detection

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

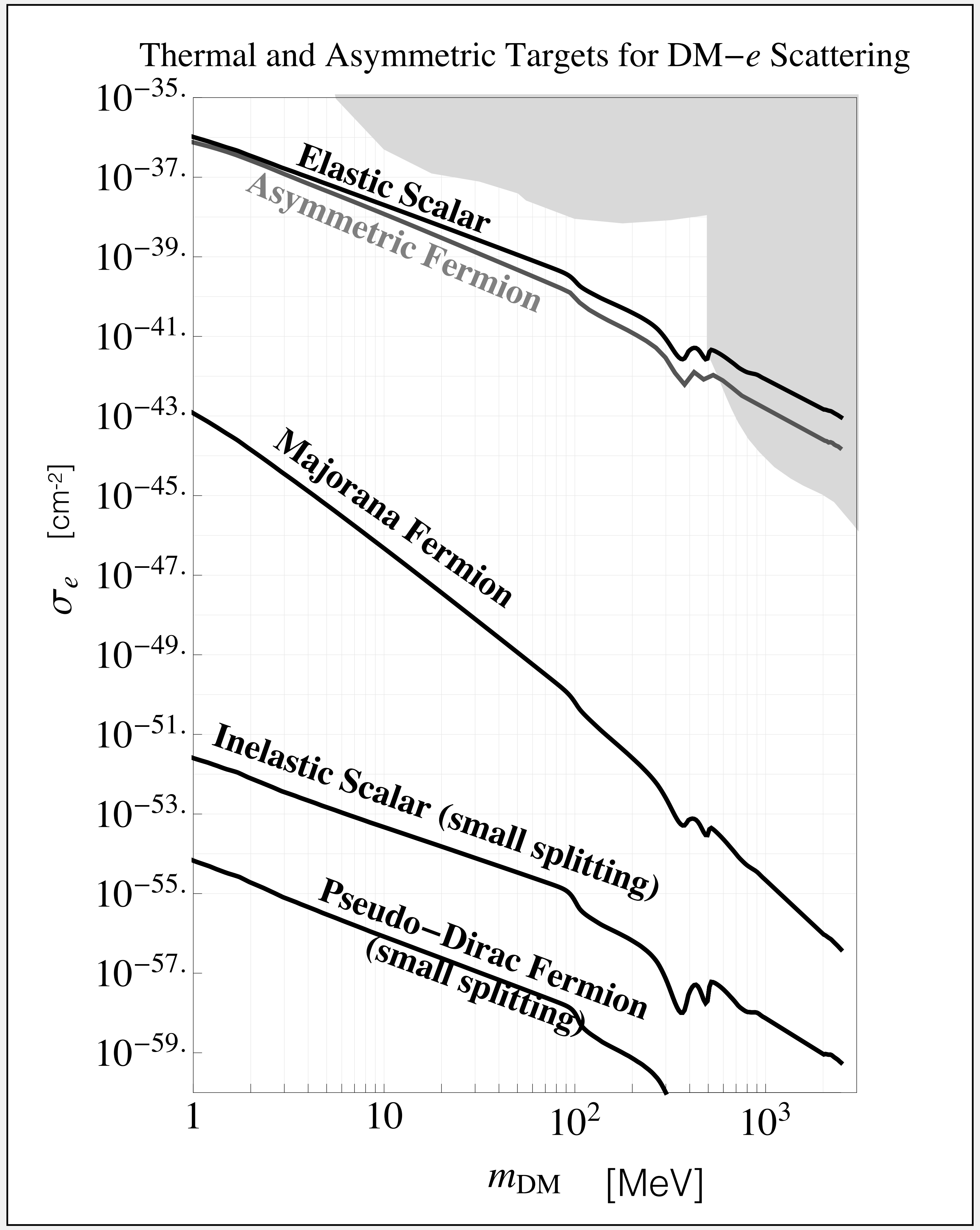
- needs lower energy threshold
  - examples:
    - electron-DM scattering
    - semiconductors



Why not just direct detection?

direct detection:

strong spin/velocity dependency



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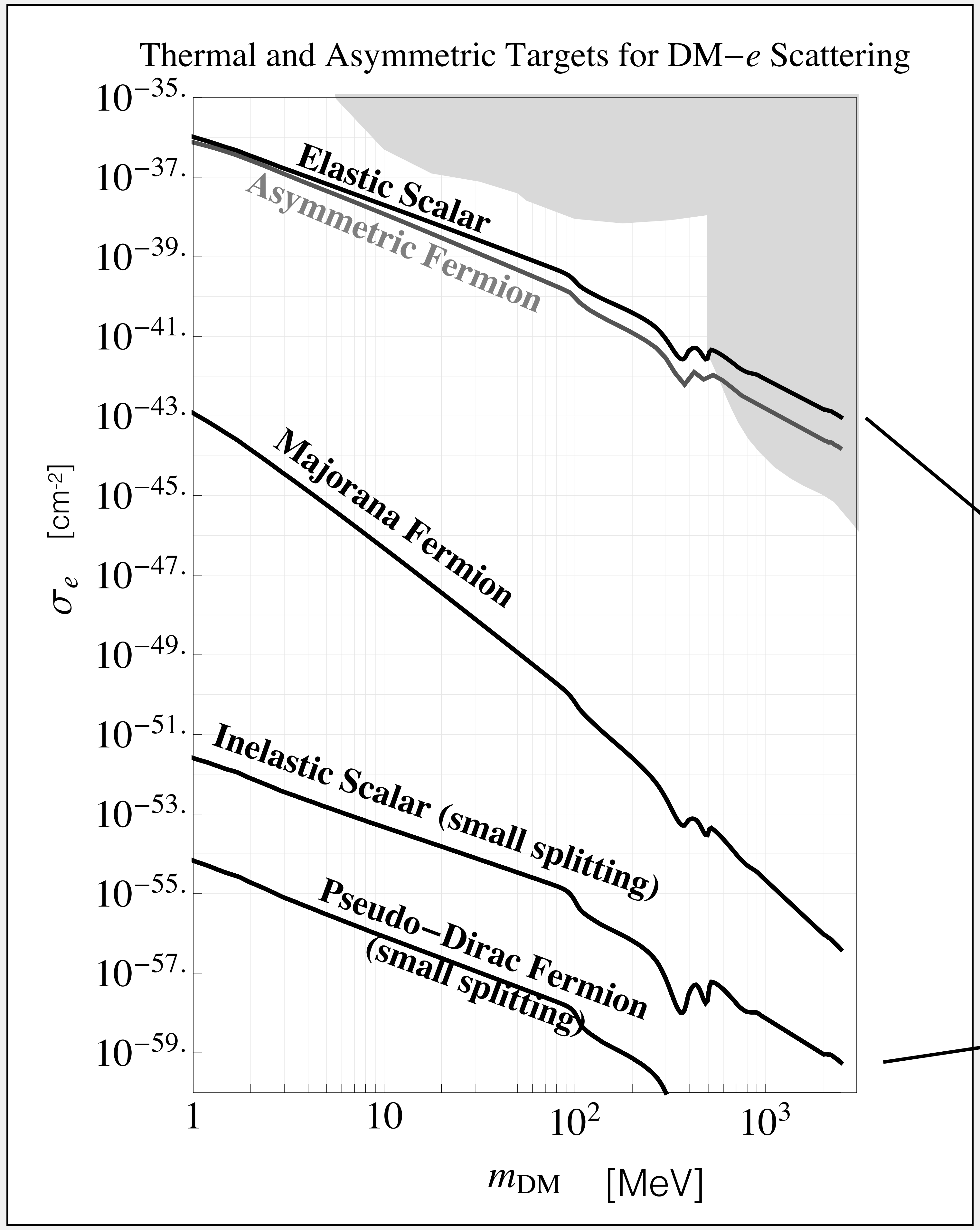
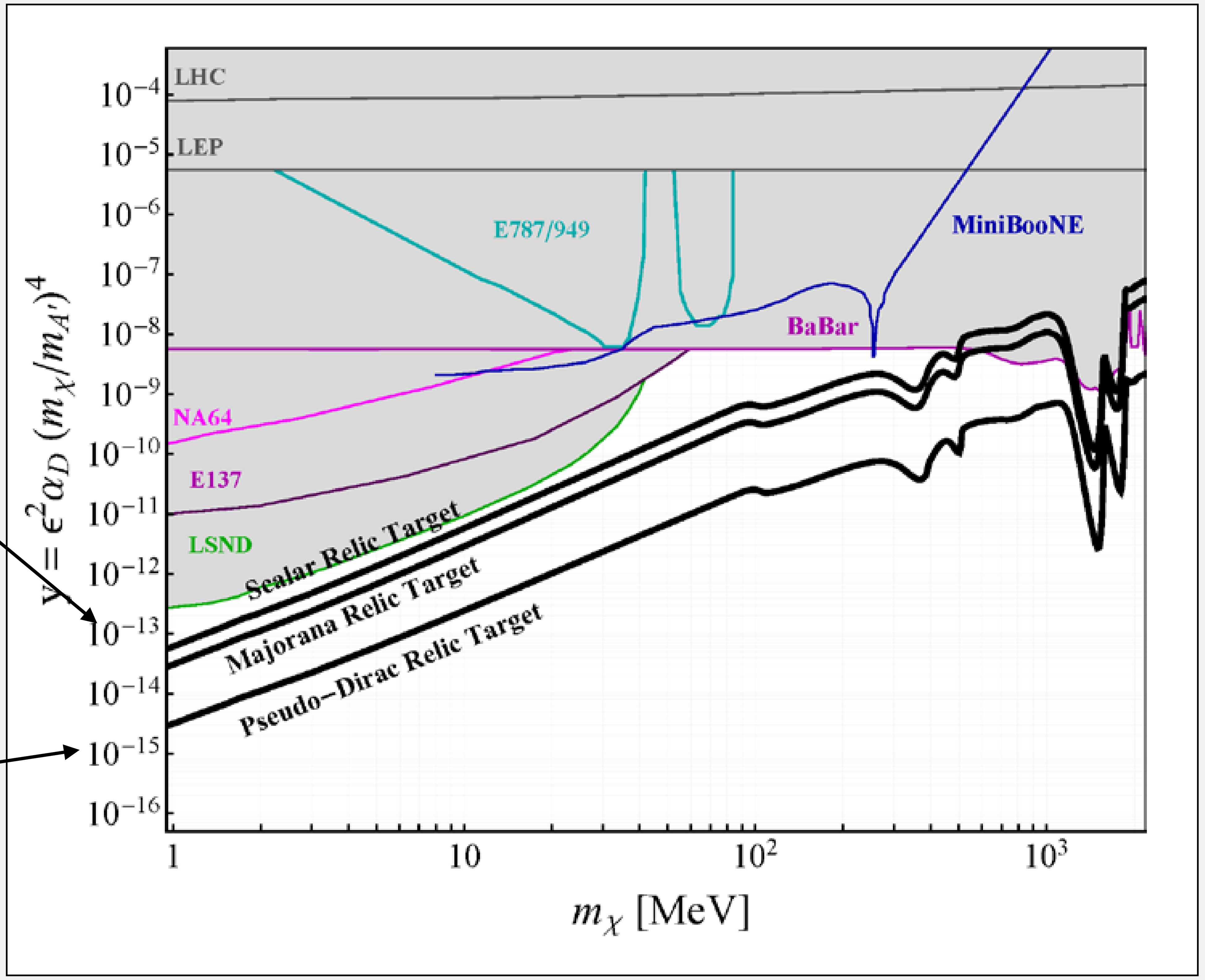


at accelerators: relativistic production

—> spin/velocity dependency reduced

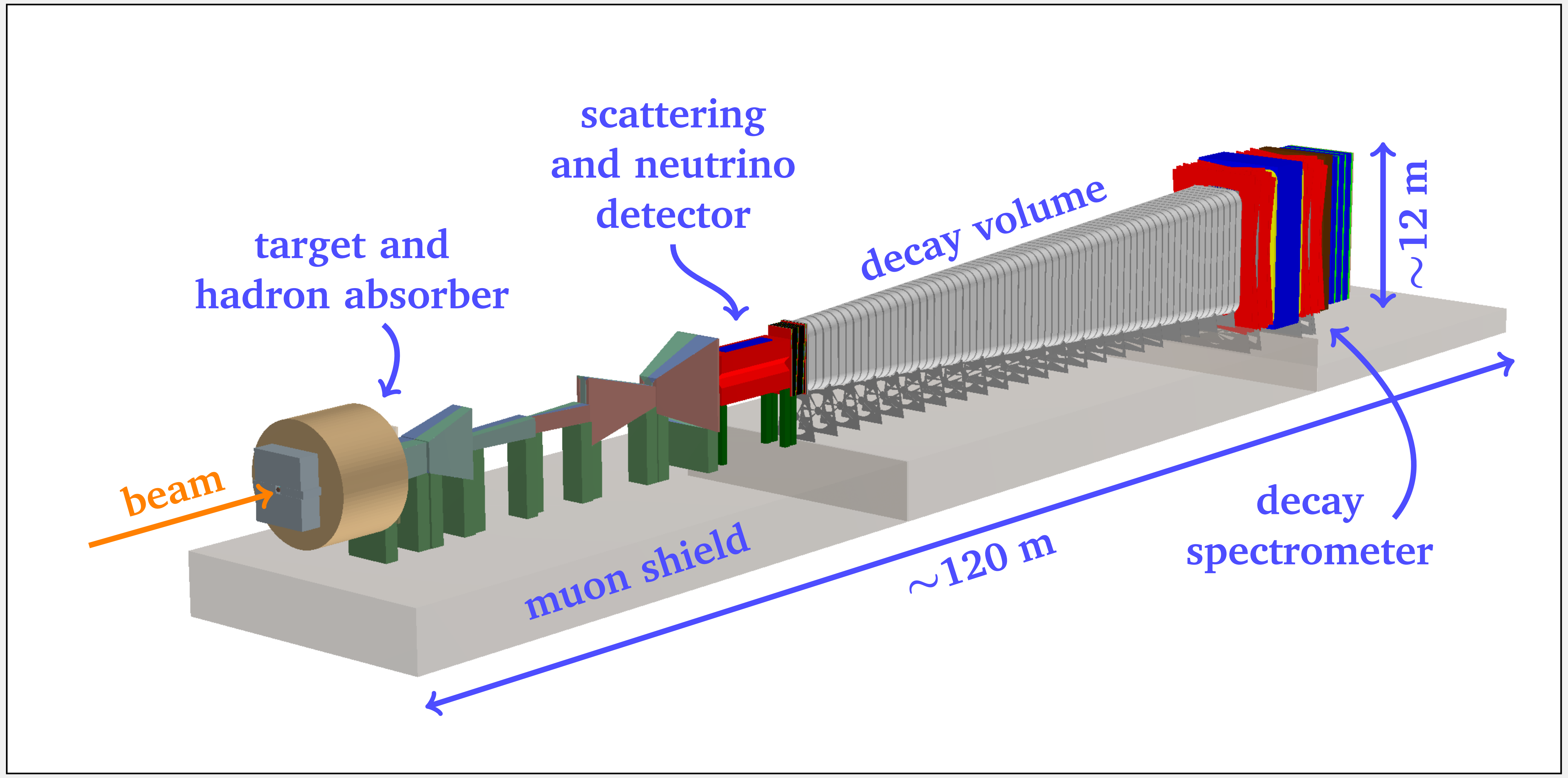
all thermal targets in reach!



Proton II: SHiP — Search for Hidden Particles

proposed experiment at CERN (Beam Dump Facility at SPS)

- Comprehensive Design Study report in Dec 2019 CERN-SPSC-2019-049
- 400 GeV proton beam, goal: 2×10^{20} POT in 5 years
- search for weakly coupled long-lived particles (decay volume + spectrometer)
- complementary for neutrino scattering and LDM search



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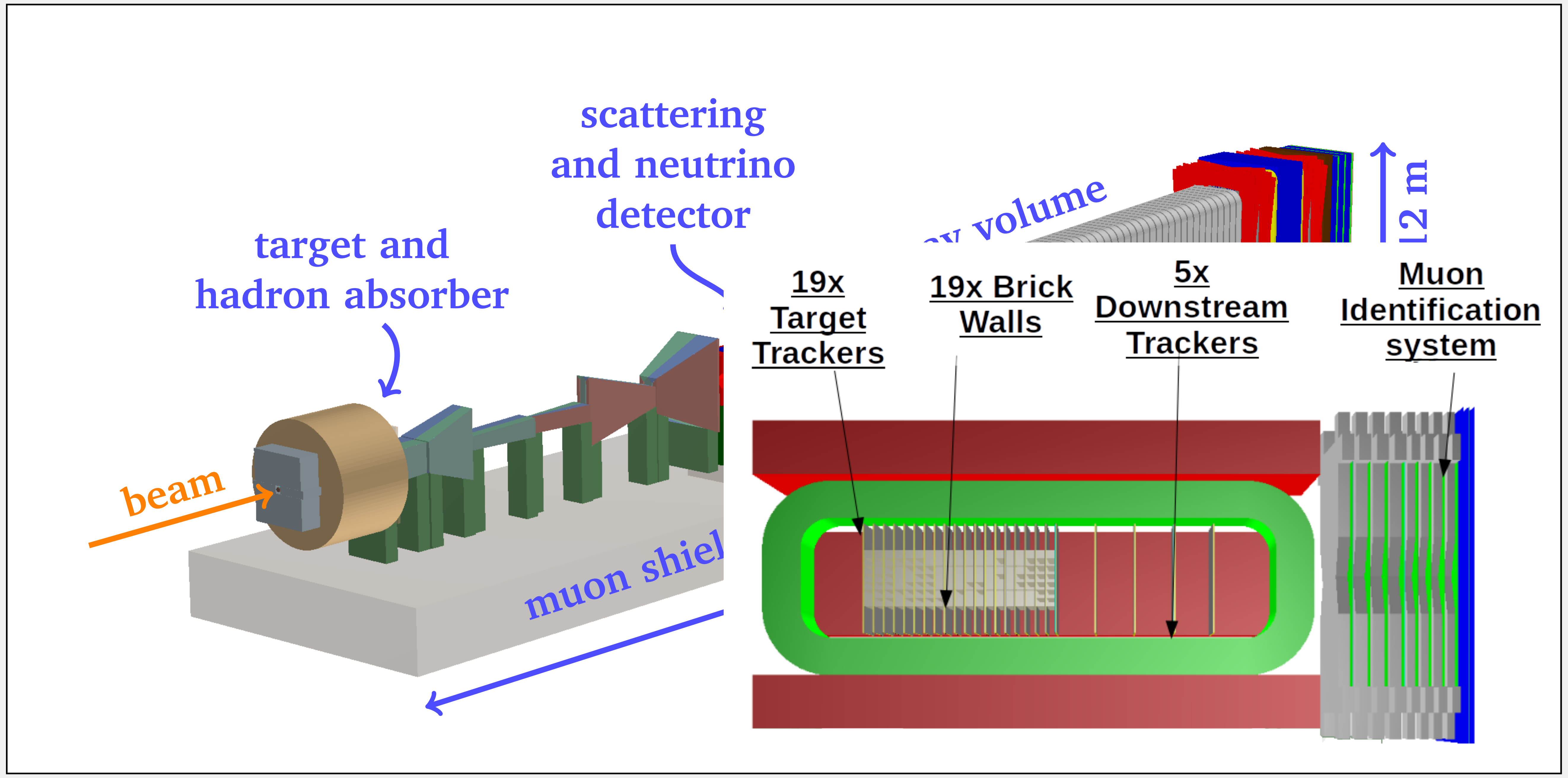


SND:

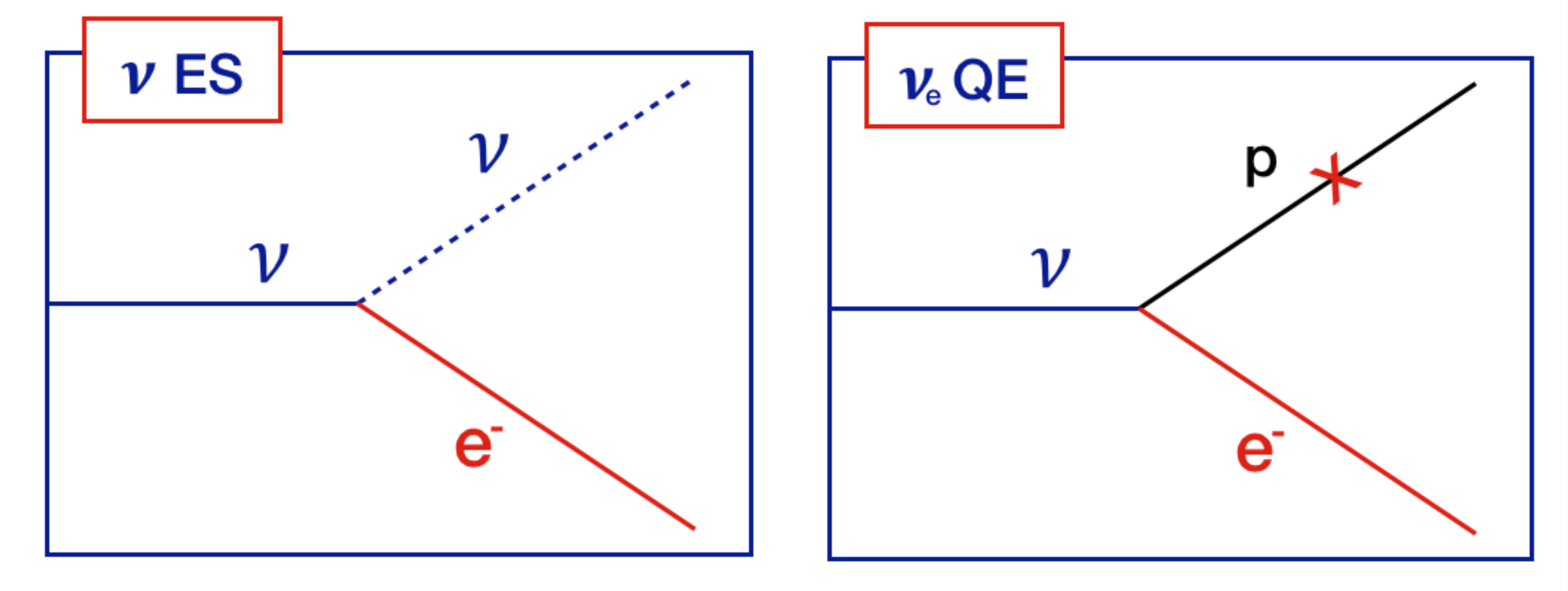
- precision spectrometer (1.2T field) + muon detector
- spectrometer: layers of absorber, nuclear emulsion, tracking (total absorber mass: 8t)
- detect showers induced by electrons from elastic LDM scattering
- nuclear emulsions provide topological discrimination against neutrino backgrounds

Proton II: SHiP — Sensitivity

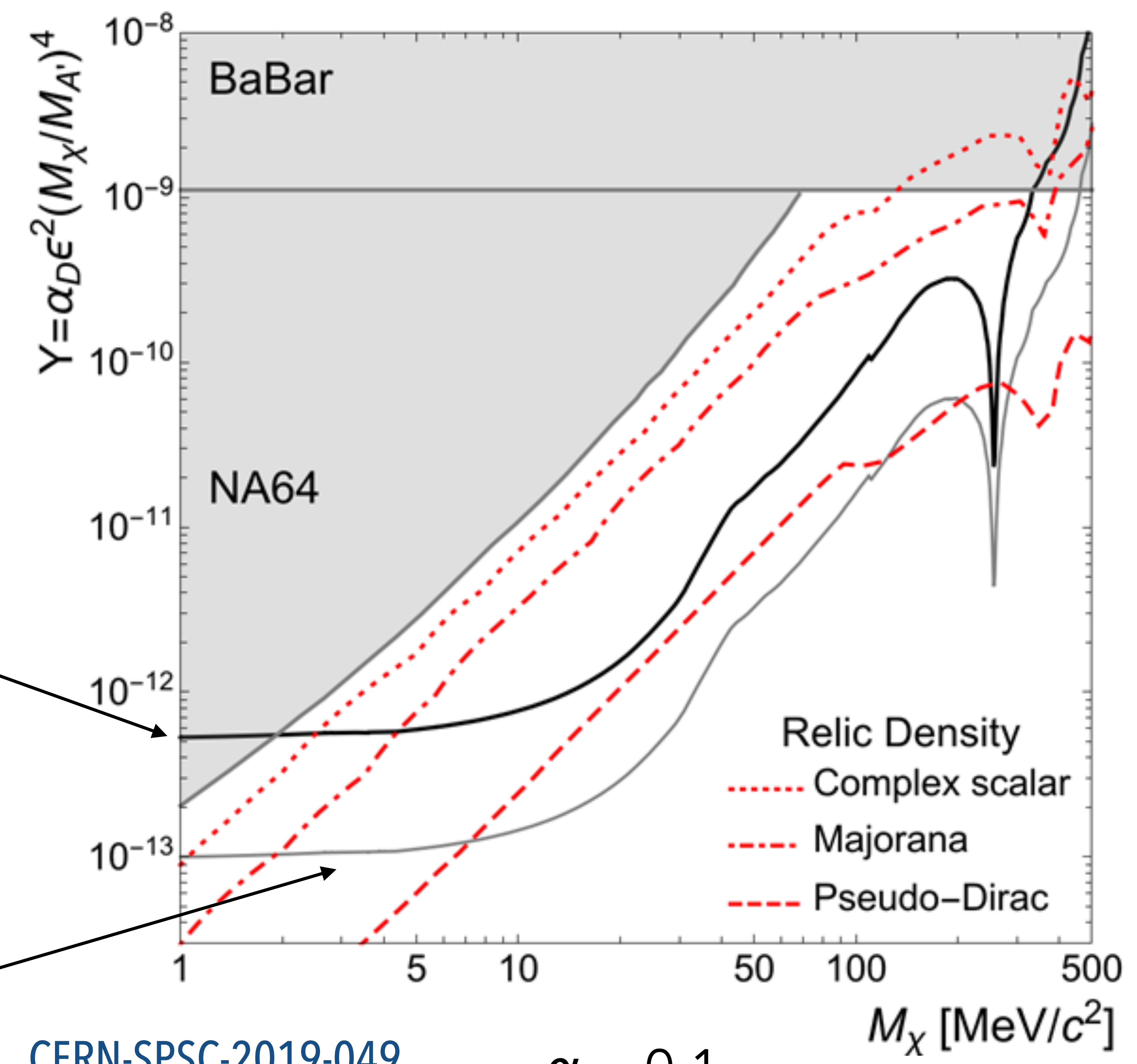
full simulation of neutrino backgrounds for 2x10[20] POT

CERN-SPSC-2019-049

	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	all
Elastic scattering	81	45	56	35	217
Quasi - elastic scattering	245	236			481
Resonant scattering	8	126			134
Deep inelastic scattering	-	14			14
Total	334	421	56	35	846



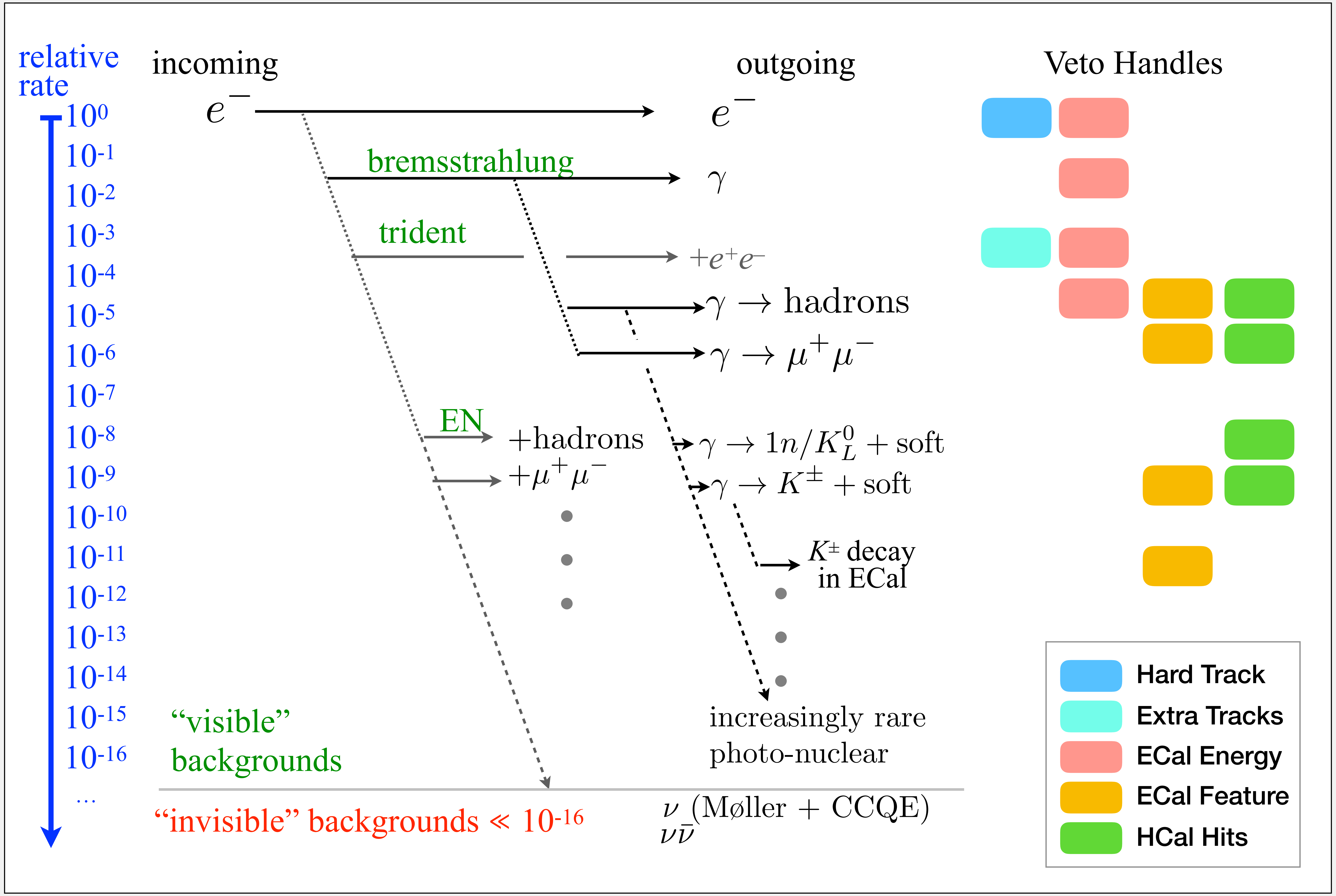
0 background



CERN-SPSC-2019-049

α_D=0.1

LDMX: Backgrounds



essentially only instrumental backgrounds

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

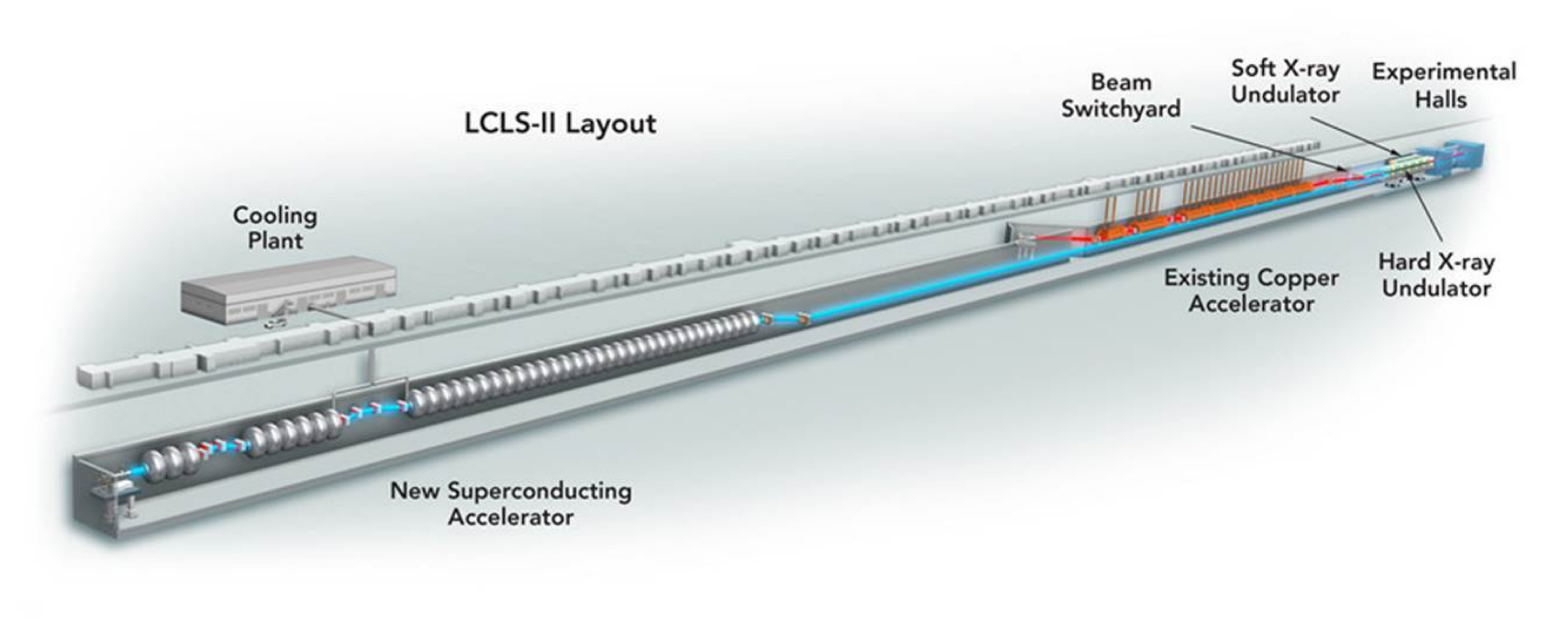
Physics program spans dark matter physics (LDMX), neutrino physics (electro-nuclear scattering as reference), test beam program…

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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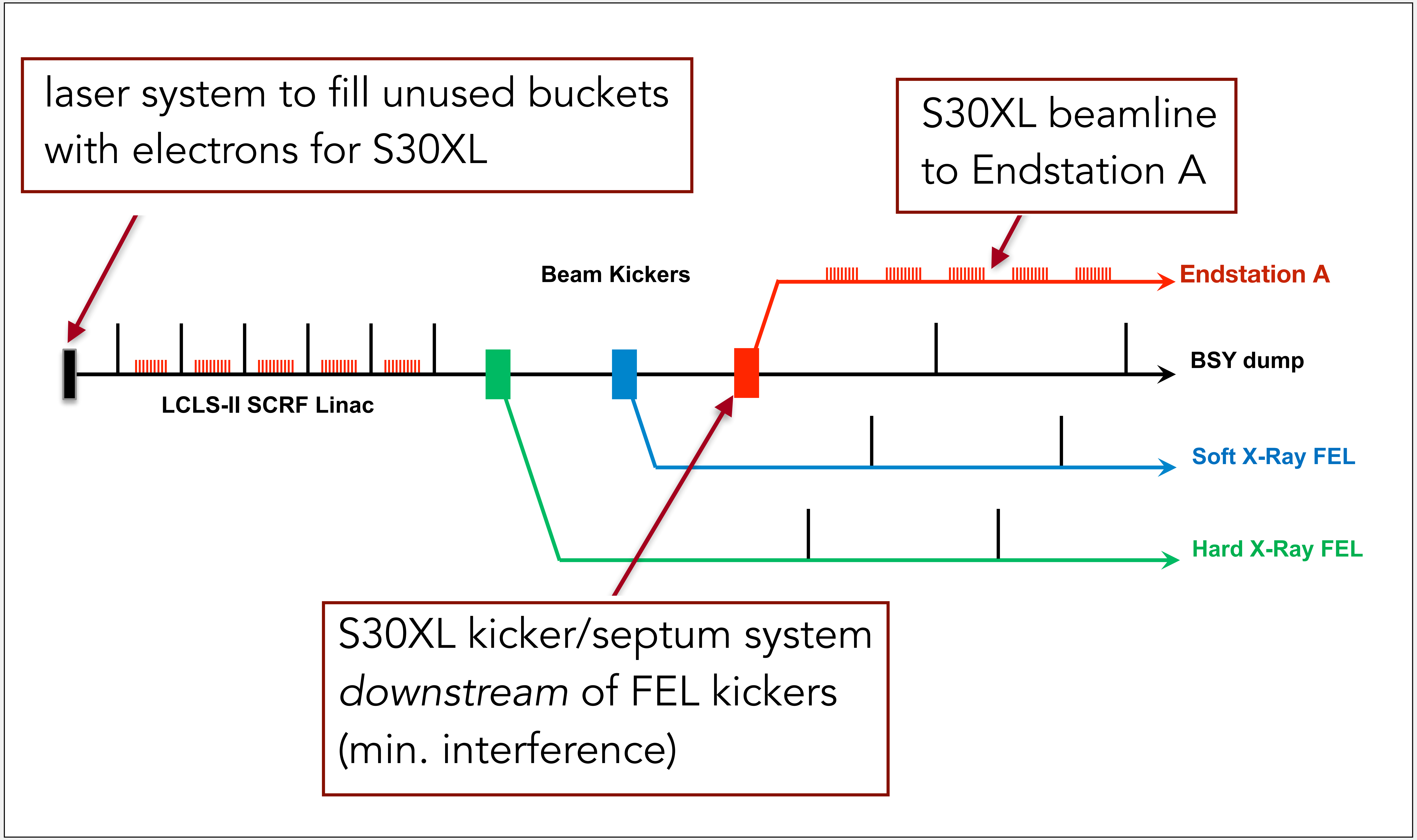
(Sector 30 Transfer Line)

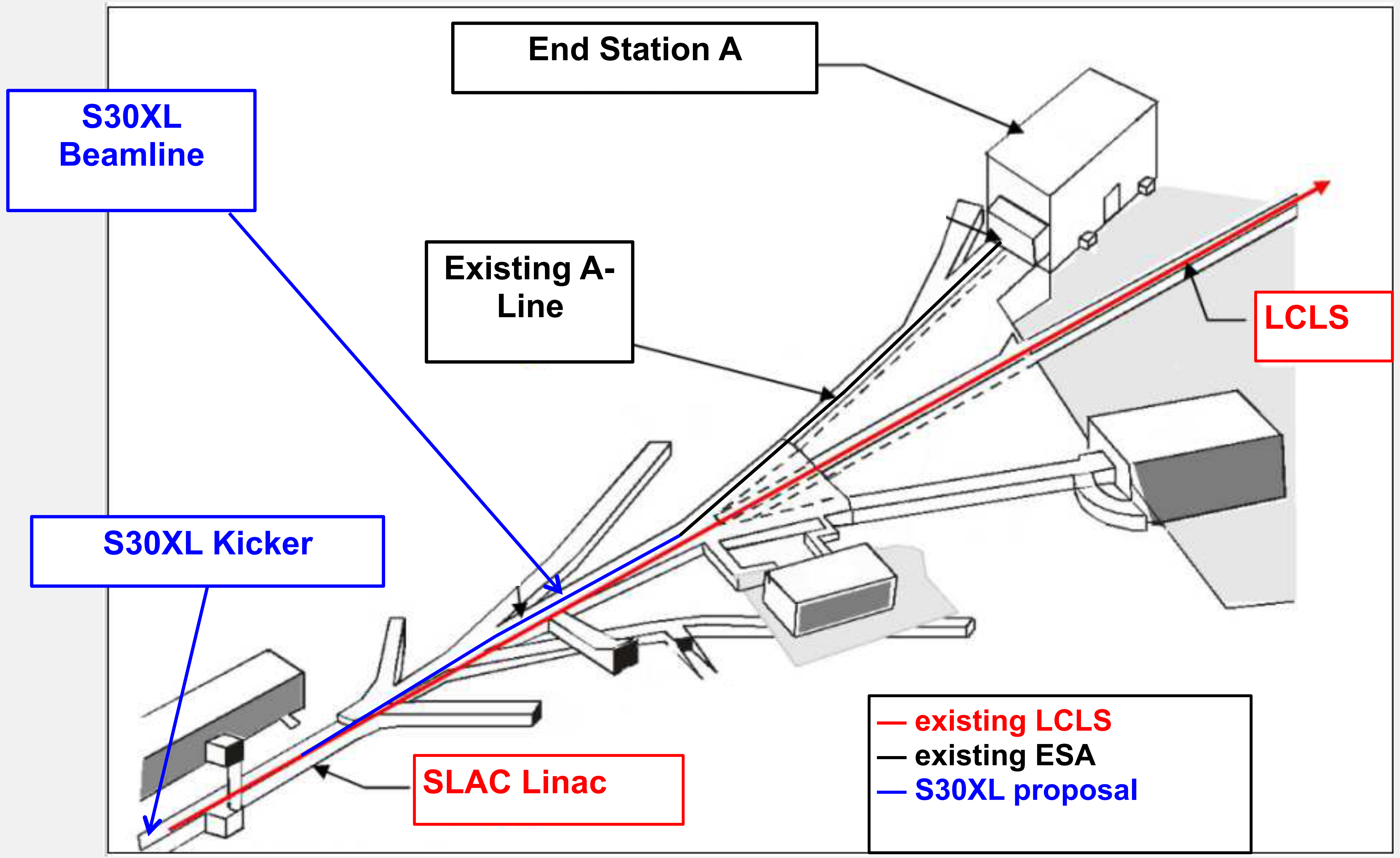


S30XL @ LCLS-II @ SLAC

(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

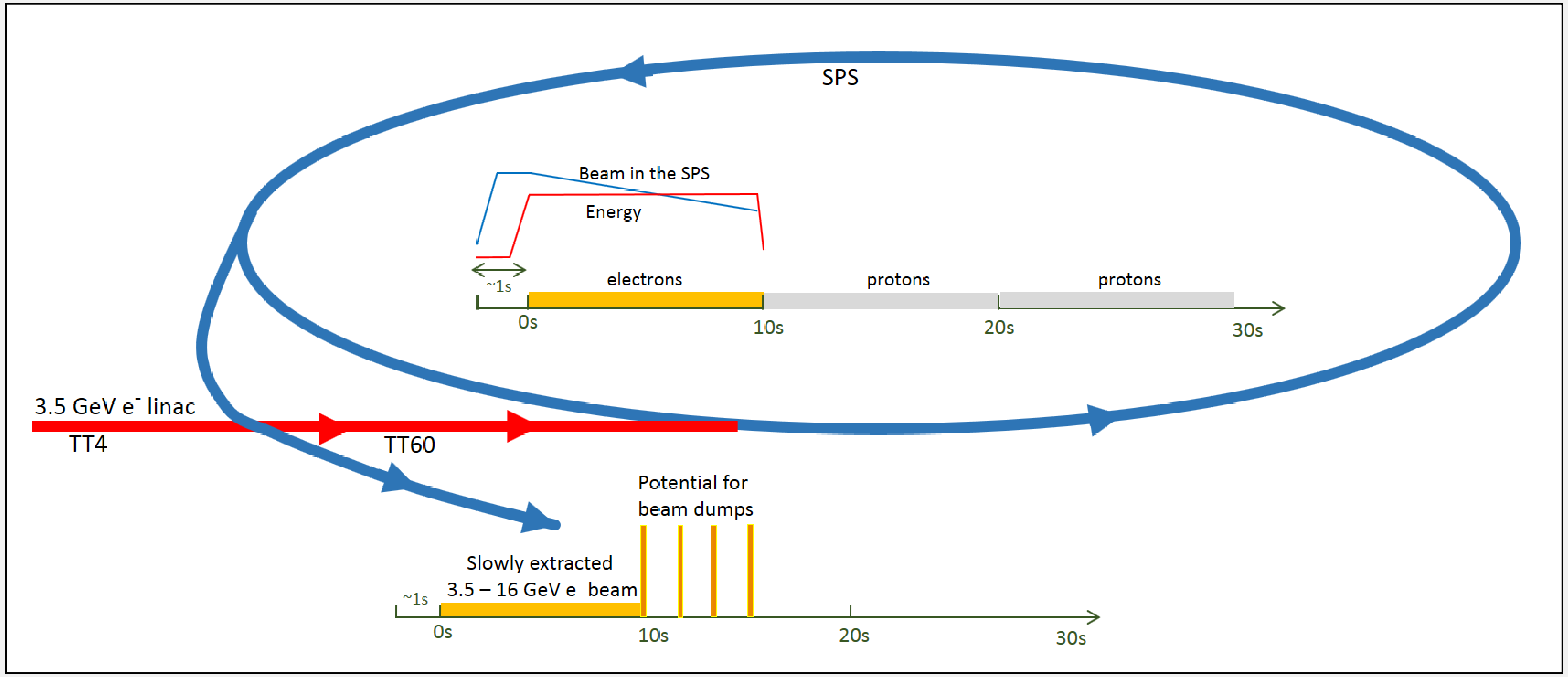
Idea ~2 years ago, quickly picked up momentum

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

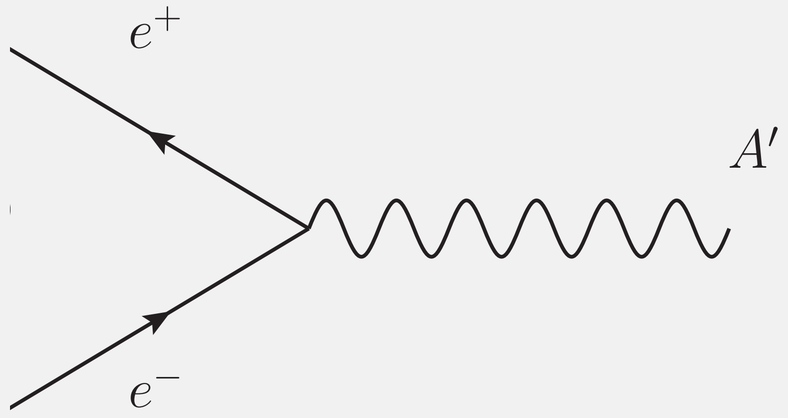


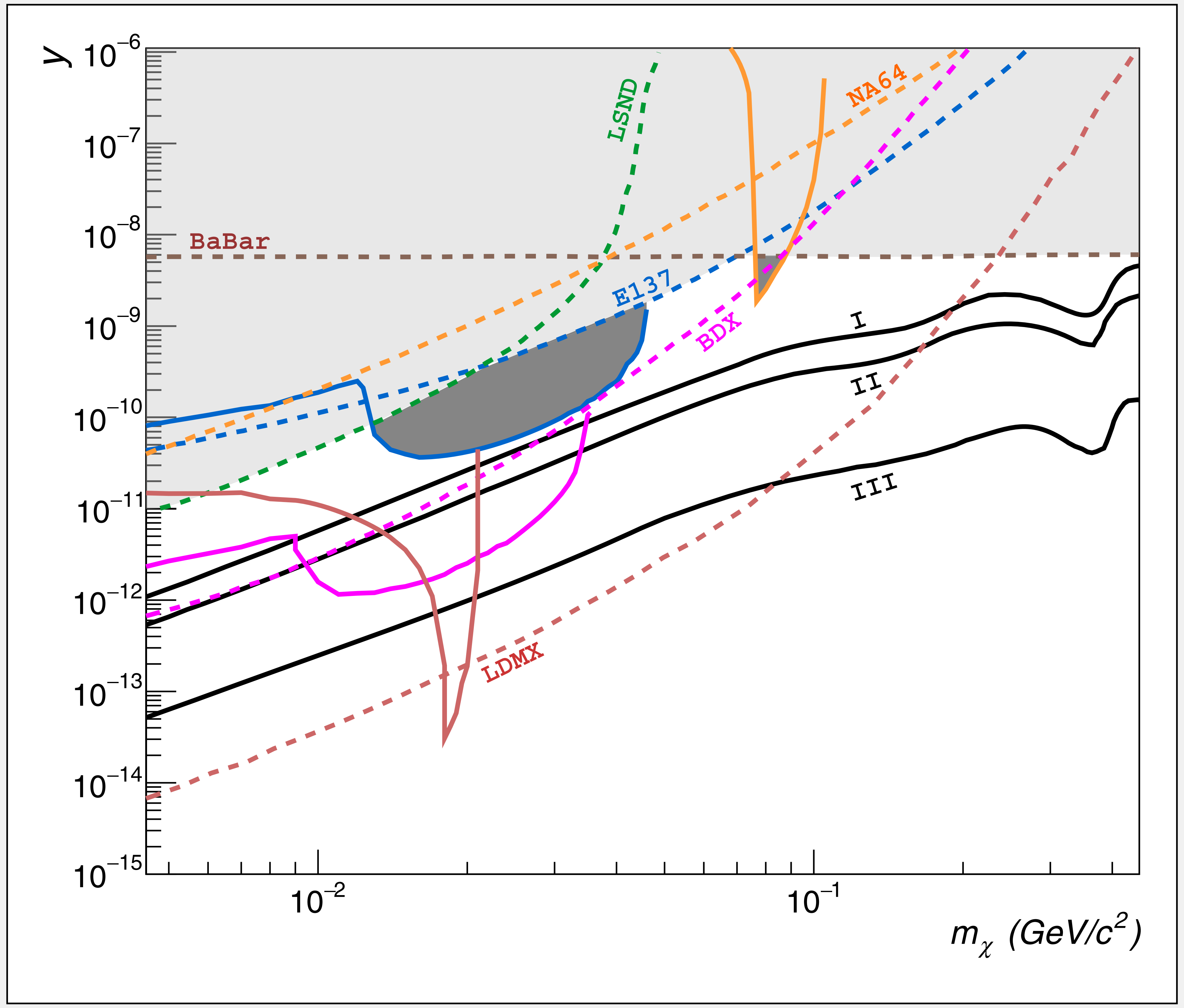
optimal catering for LDMX-like experiment

Electron I: E137

new reanalysis of E137 data [Phys. Rev. Lett. 121, 041802 (2018)]

- focus on secondary positrons
- new resonant production from e^+e^- annihilation





Various Future Projections