

Dark matter and RPF

- experimental landscape -

Nhan Tran, Fermilab

May 18, 2022

Snowmass rare and precision measurement frontier workshop, Cincinnati

Outline

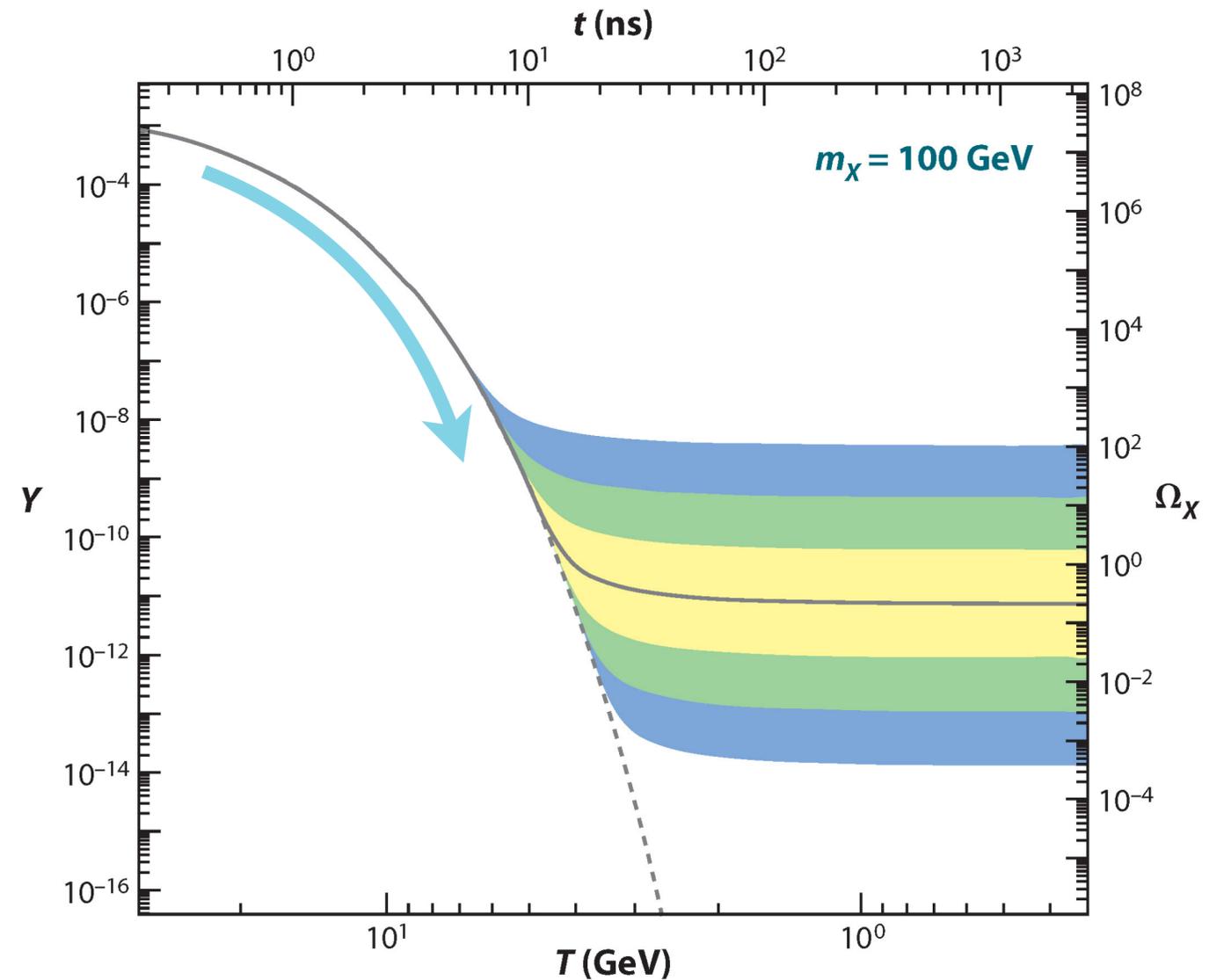
- Dark sector physics motivators
- Why and how to look for dark sectors at accelerators
- Experimental approaches - schematic organization
- Takeaway messages and discussion

Physics drivers

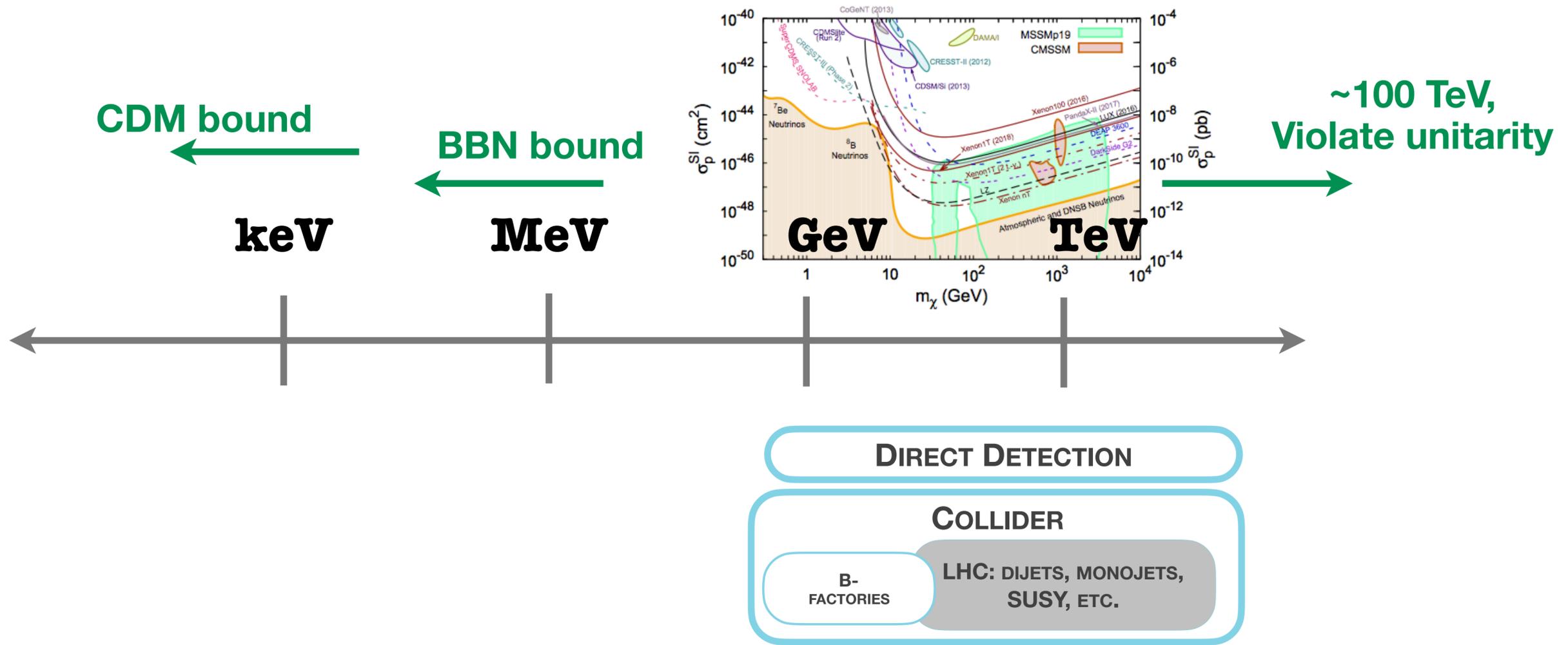
- **Dark matter** exists
 - Thermal freeze-out DM narrows the mass range to \sim MeV-TeV
 - Provides clear milestones
 - WIMP searches thus far no discovery
- **Dark sectors** can solve many experimental/theoretical puzzles
 - Dark sectors mean SM-neutral forces (typically $< \sim$ GeV)
 - Can include dark matter
 - For parts of phase space, visible (SM) final states needed for discovery

Thermal Freeze-Out Dark Matter

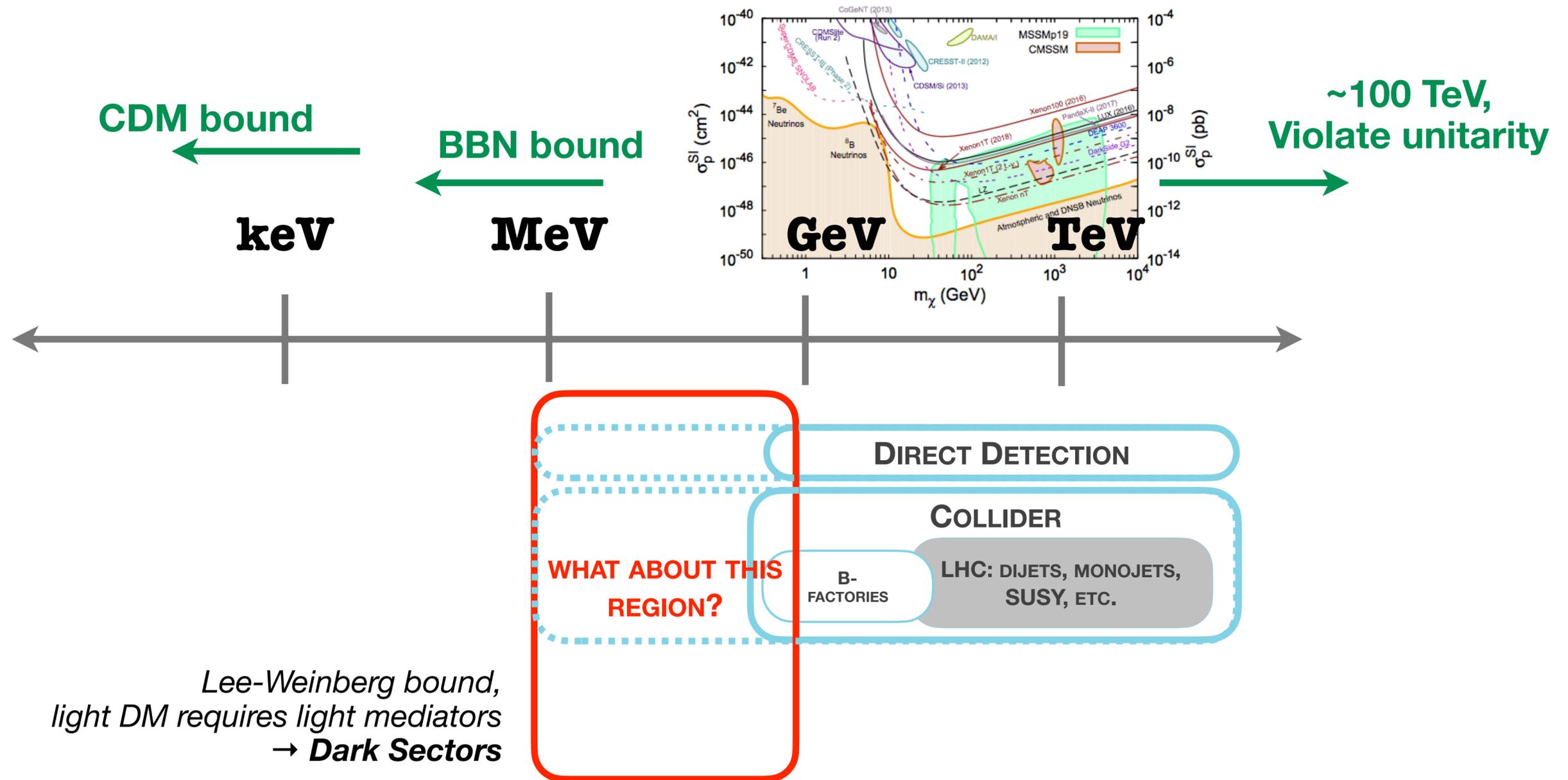
- We know how much DM there is
- **Thermal freeze-out** is a nice origin story for dark matter
- **Easily realized, predictive, UV insensitive**



Thermal, but not WIMP



Thermal, but not WIMP



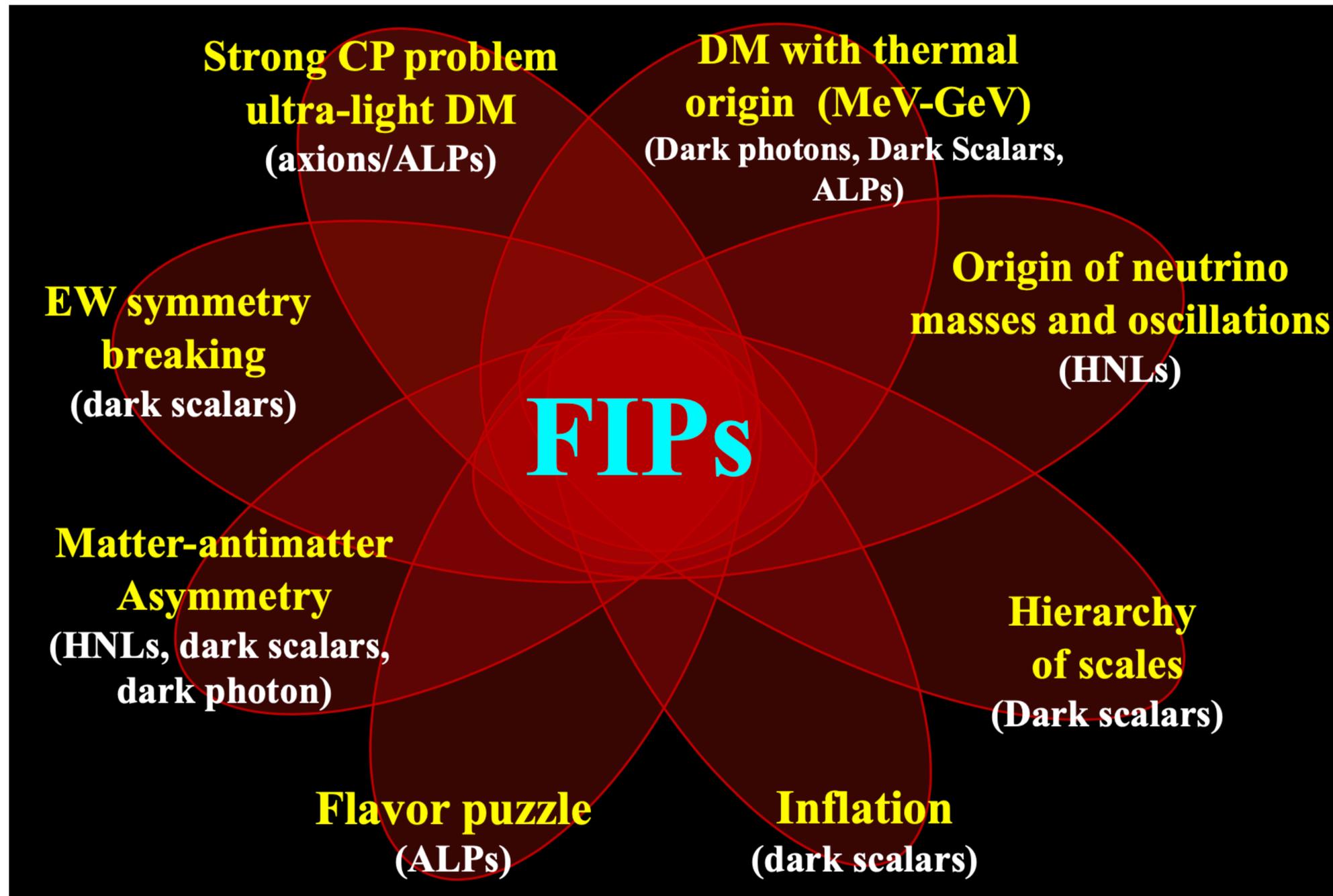
Lee-Weinberg bound,
light DM requires light mediators
→ **Dark Sectors**

**NORMAL MATTER LIVES
HERE. WHY NOT DM?**

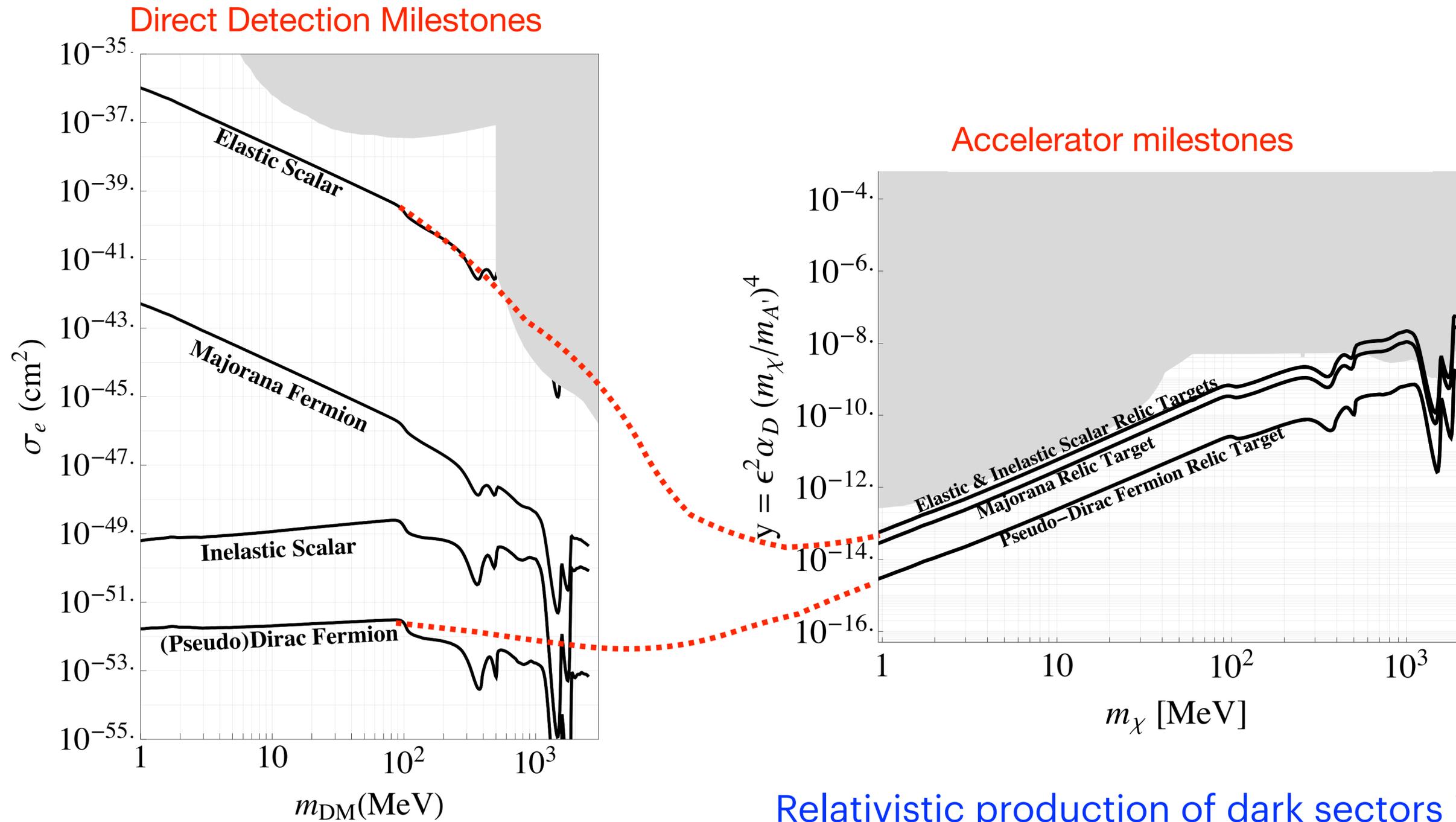
+ Curious results...
muon $g-2$, proton radius puzzle, KOTO anomaly,
MiniBooNE/MicroBooNE excess, Xenon-1T excess, flavor
anomalies, neutron lifetime anomaly

Dark Sectors

CERN physics beyond colliders



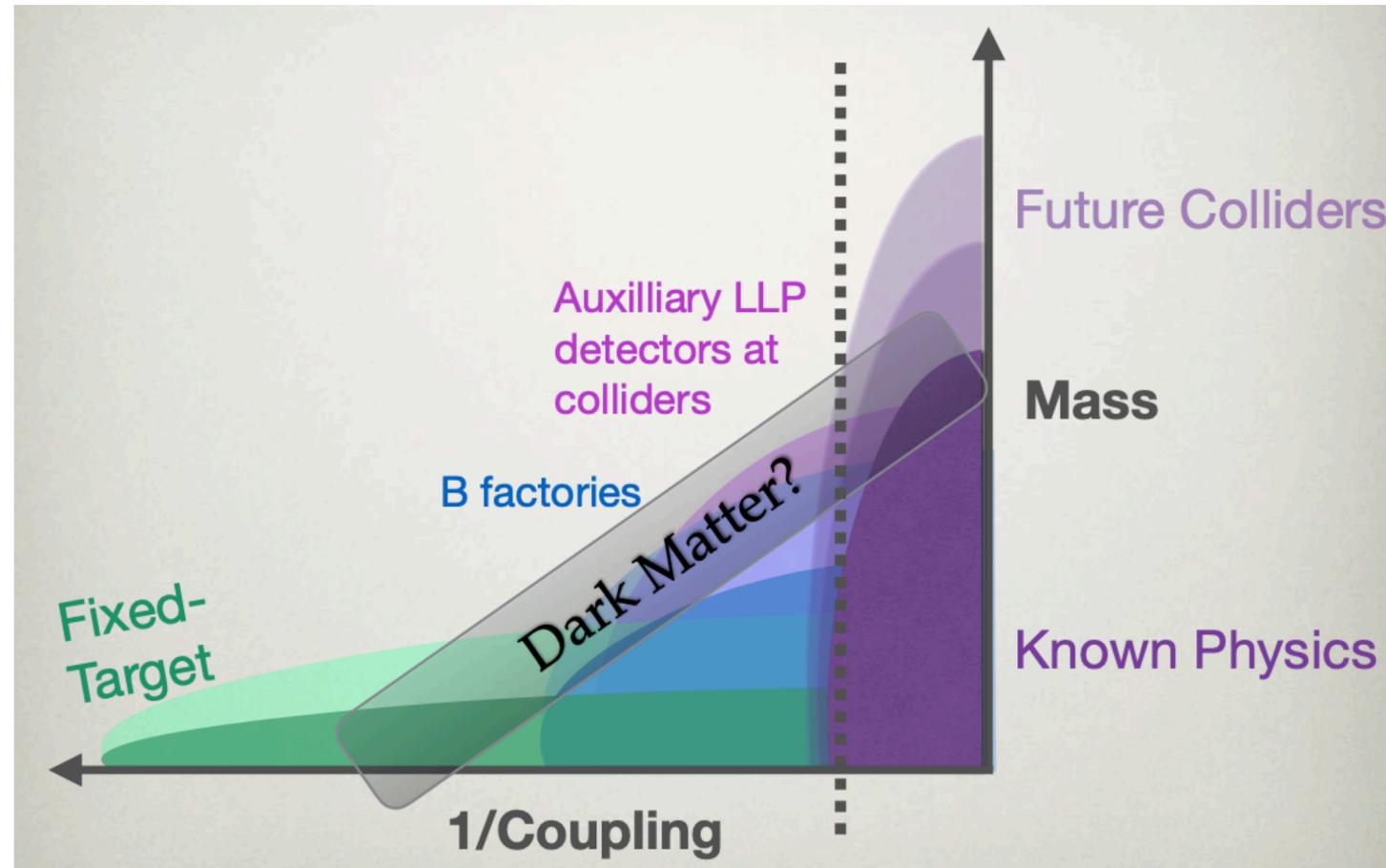
Why accelerators?



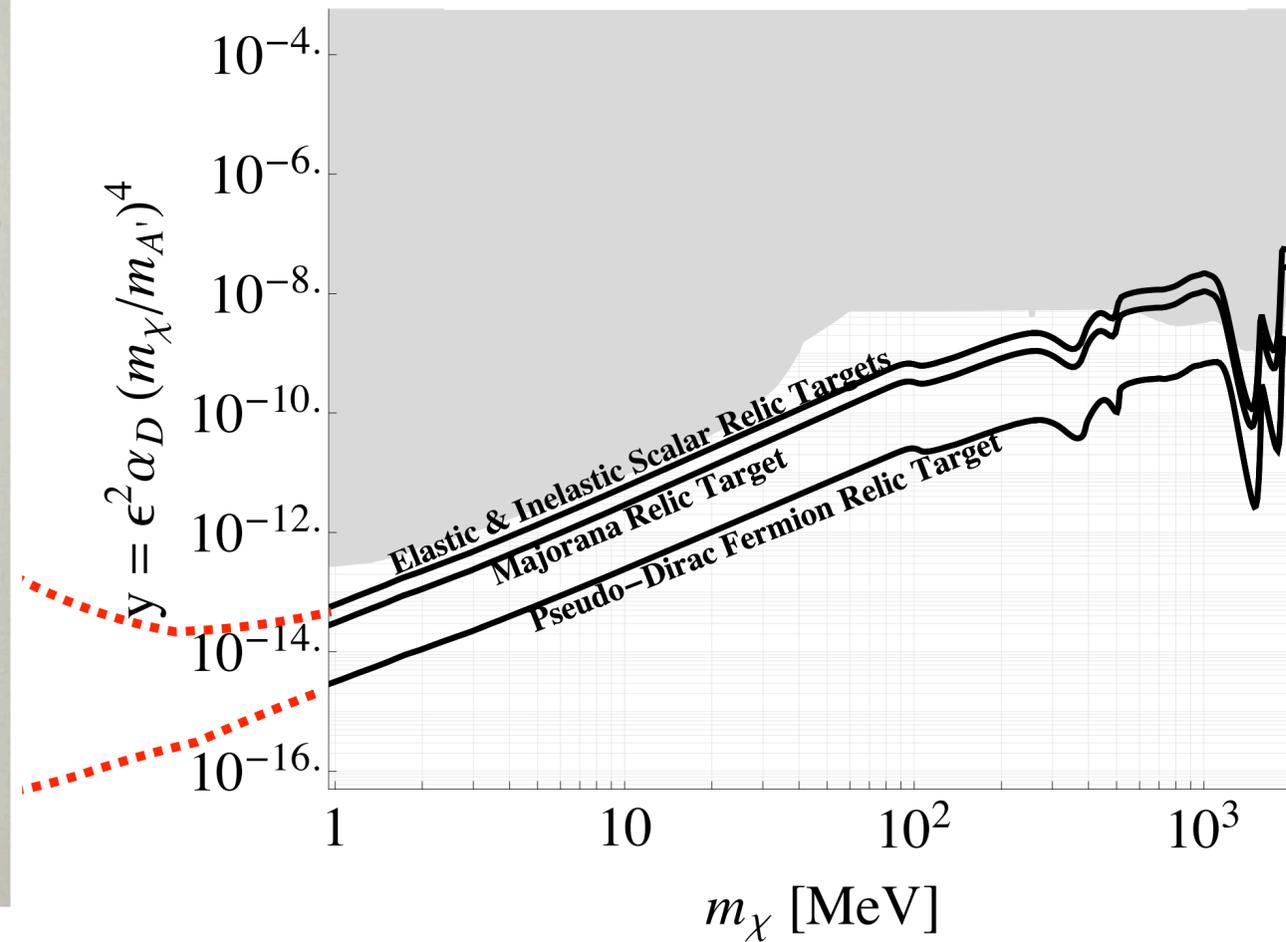
Relativistic production of dark sectors is less sensitive to loop- or velocity-suppression

What accelerators?

Natalia Toro

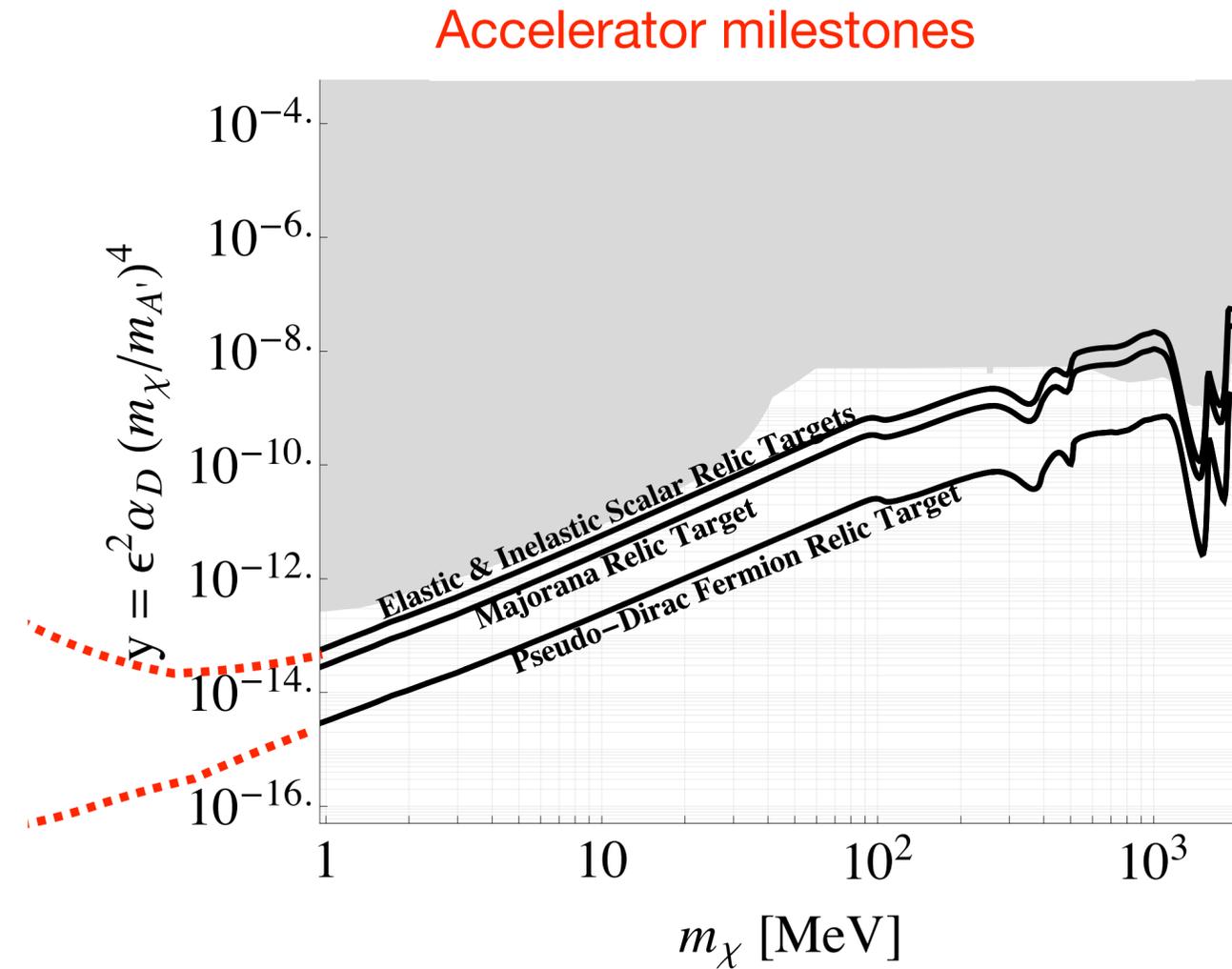
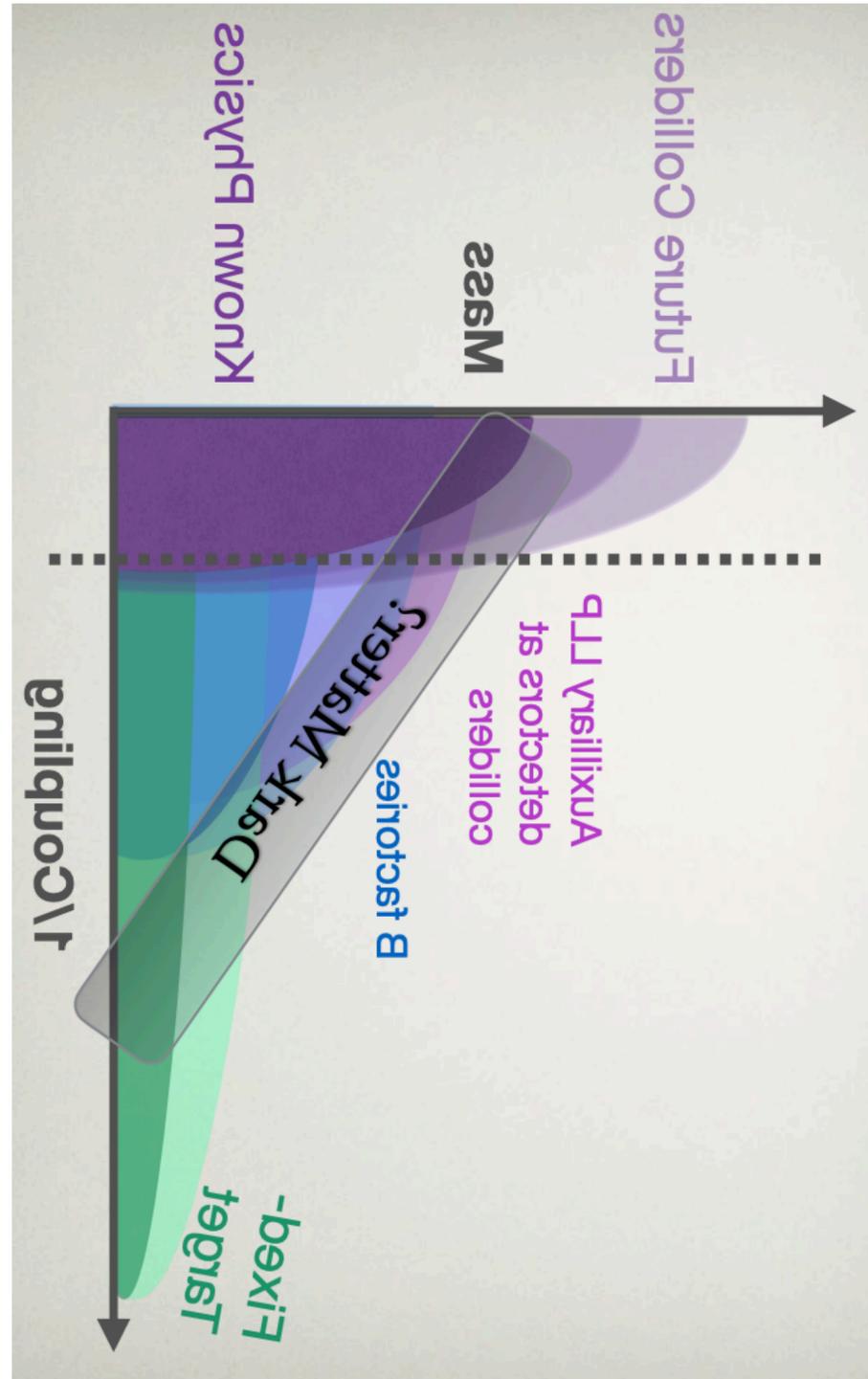


Accelerator milestones



Relativistic production of dark sectors is less sensitive to loop- or velocity-suppression

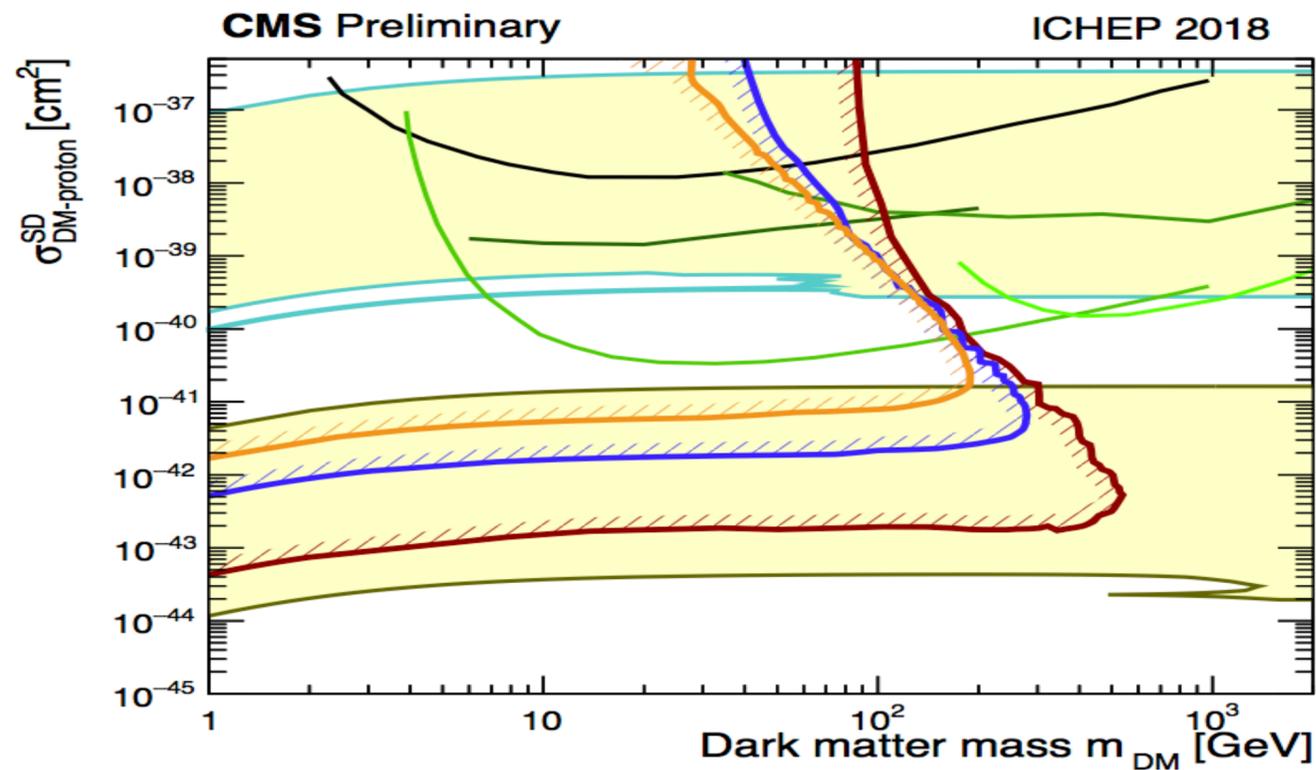
What accelerators?



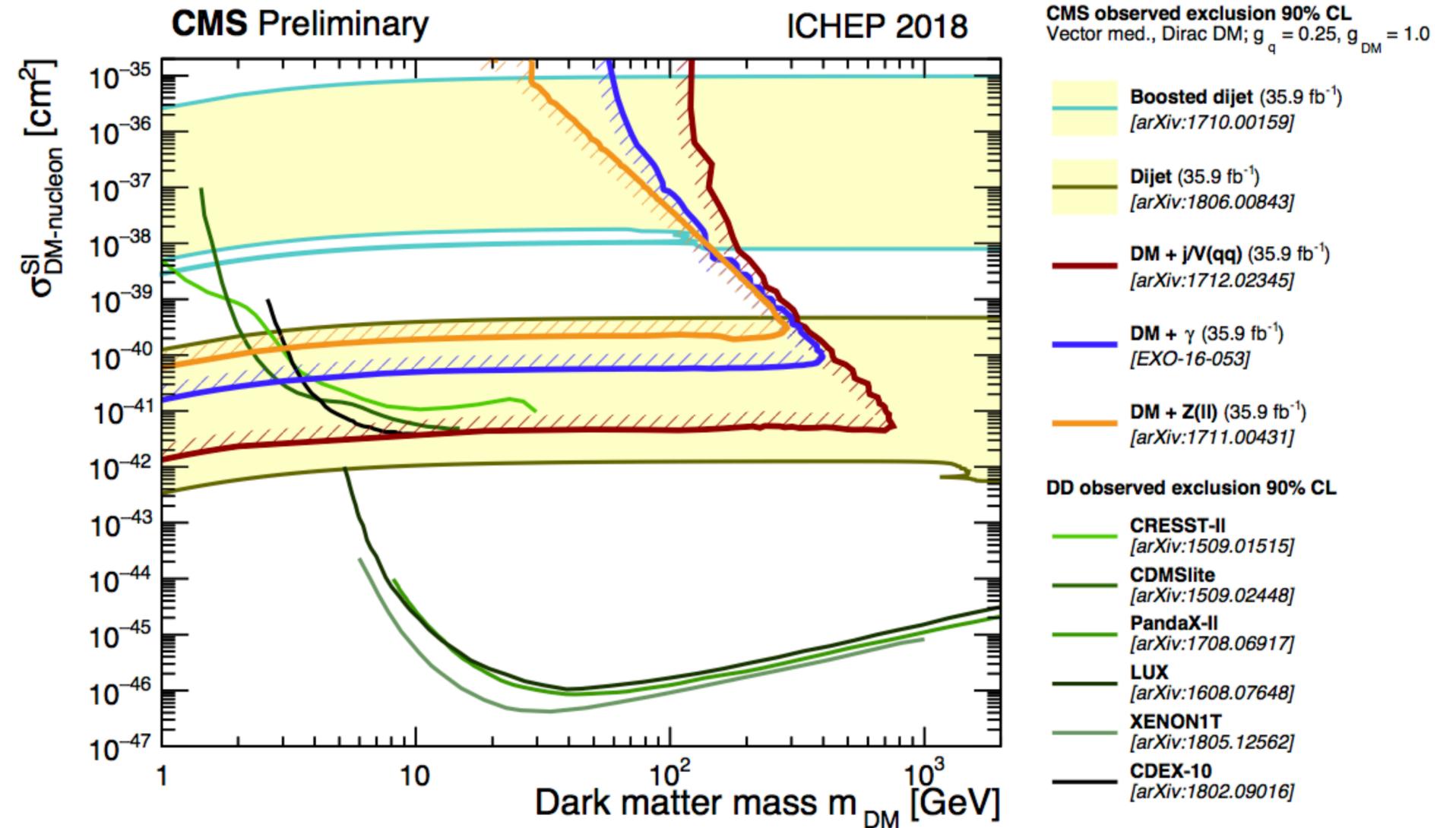
Relativistic production of dark sectors is less sensitive to loop- or velocity-suppression

Accelerators and direct detection

Spin-dependent



Spin-independent

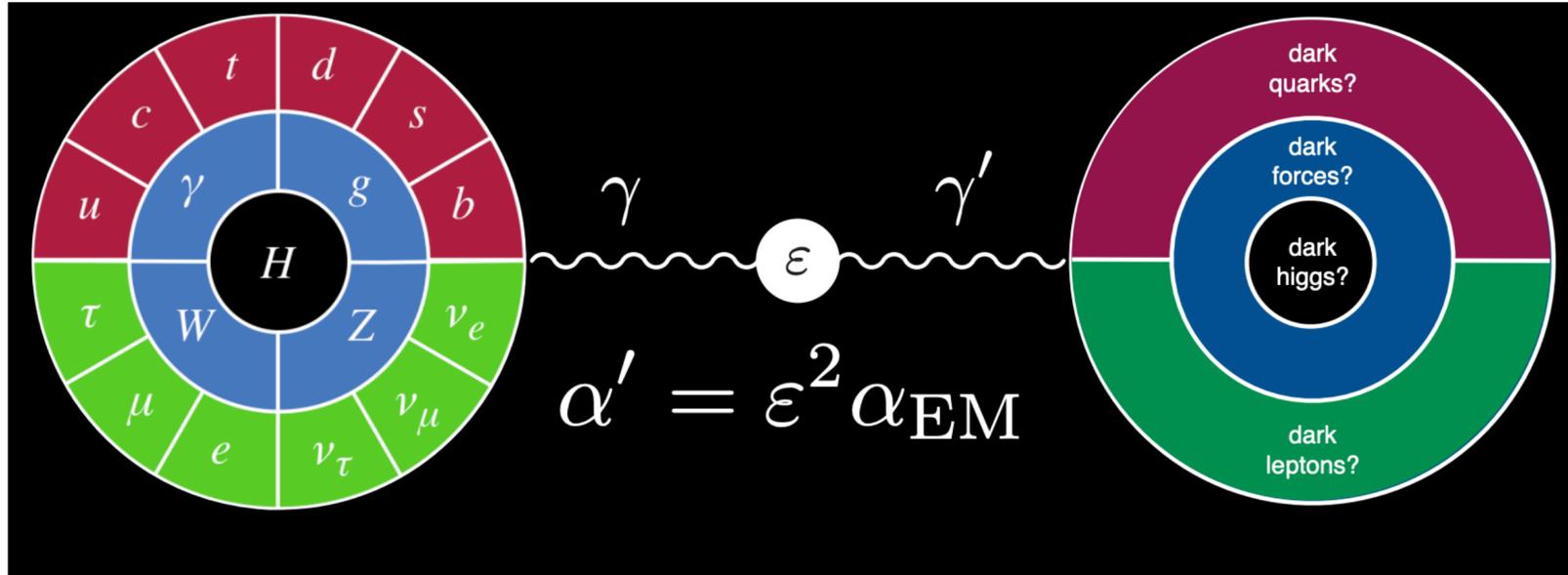


Experimental signatures and techniques

Asterisk 1

Many of the plots you will see, we've been discussing for the last few days and thus are not final

Portal benchmarks



initiated by N.Toro

Benchmarks in Final State x Portal Organization

	DM Production	Mediator Decay Via Portal	Structure of Dark Sector
Vector	m_χ vs. y [$m_A/m_\chi=3, \alpha_0=.5$] m_A vs. y [$\alpha_0=0.5, 3 m_\chi$ values] m_χ vs. Q_D [$m_A/m_\chi=3, y=y_0$] m_χ vs. m_A [$\alpha_0=0.5, y=y_0$] Millicharge m vs. q	m_A vs. ϵ [decay-mode agnostic] m_A vs. e [decays]	iDM m_χ vs. y [$m_A/m_\chi=3, \alpha_0=.5$] (anom connection) SIMP-motivated cascades [slices TBD] $U(1)_{B-L/\mu-\tau/B-3\tau}$ (DM or SM decays)
Scalar	m_χ vs. $\sin\theta$ [$\lambda=0$, fix $m_S/m_\chi, g_D$] (thermal target excluded 1512.04119, should still include) Note secluded DM relevance of $S \rightarrow SM$ of mediator searches	m_S vs. $\sin\theta$ [$\lambda=0$] m_S vs. $\sin\theta$ [$\lambda=s.t. Br(H \rightarrow \phi\phi \sim 10^{-2})$?]	Dark Higgsstrahlung (w/vector) scalar SIMP models? Leptophilic/leptophobic dark Higgs?
Neutrino	$e/\mu/\tau$ a la 1709.07001? Batell, Han, McKeen, Es Haggi	m_N vs. U_e m_N vs. U_μ m_N vs. U_τ Think more about reasonable flavor structures	Sterile neutrinos with new forces?
ALP	m_χ vs. f_q/l [$\lambda=0$, fix $m_a/m_\chi, g_D$] (thermal target excluded) What about f_y, f_g ?	m_a vs. f_y m_a vs. f_g m_a vs. $f_q=f_l$ (separate?) Think more about reasonable coupling relations including $f_{W/Z}$	FV axion couplings

How to make the dark sector 101

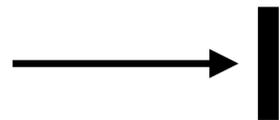
Particle beams
 e^\pm, p, μ

+

Collider



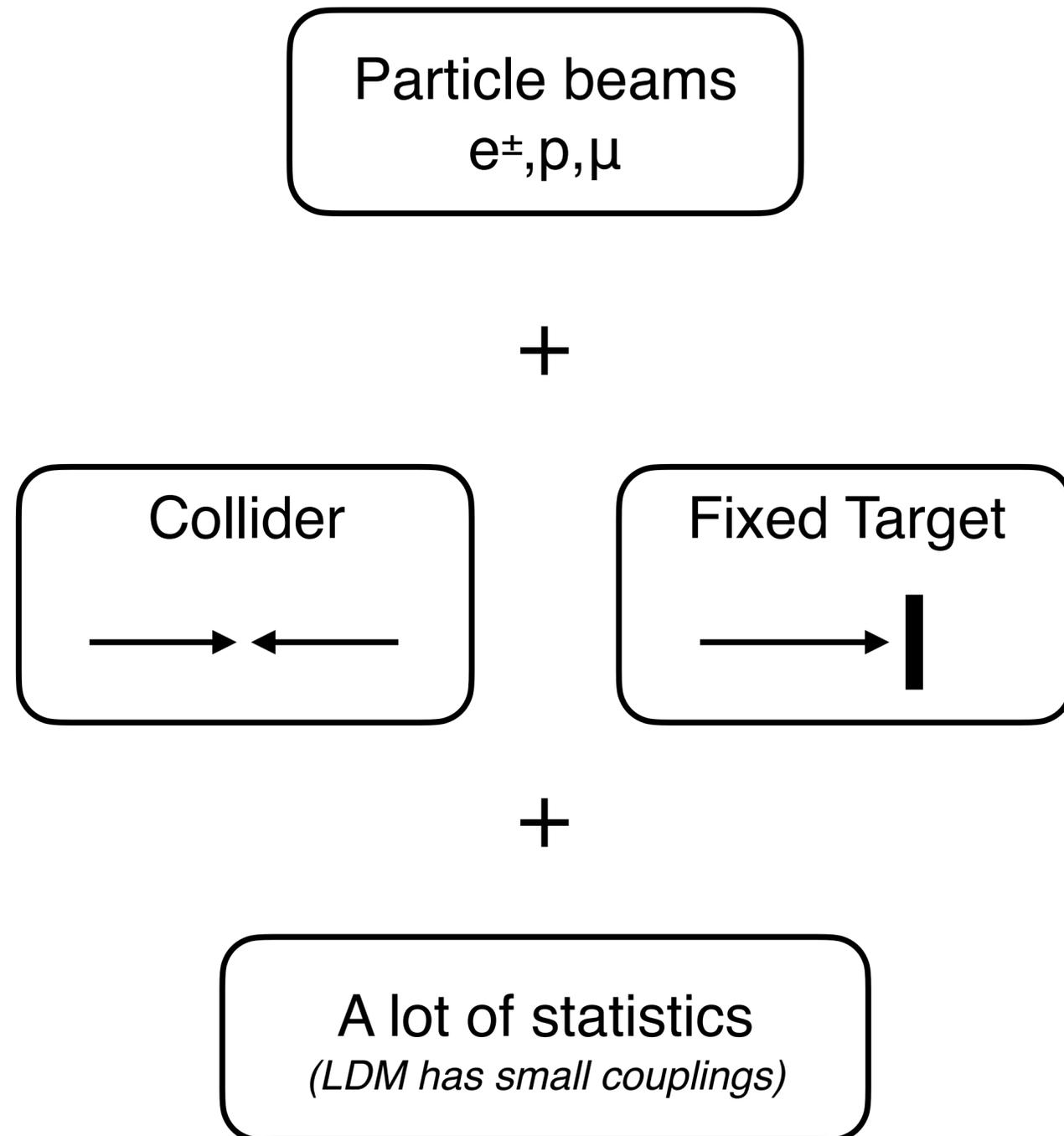
Fixed Target



+

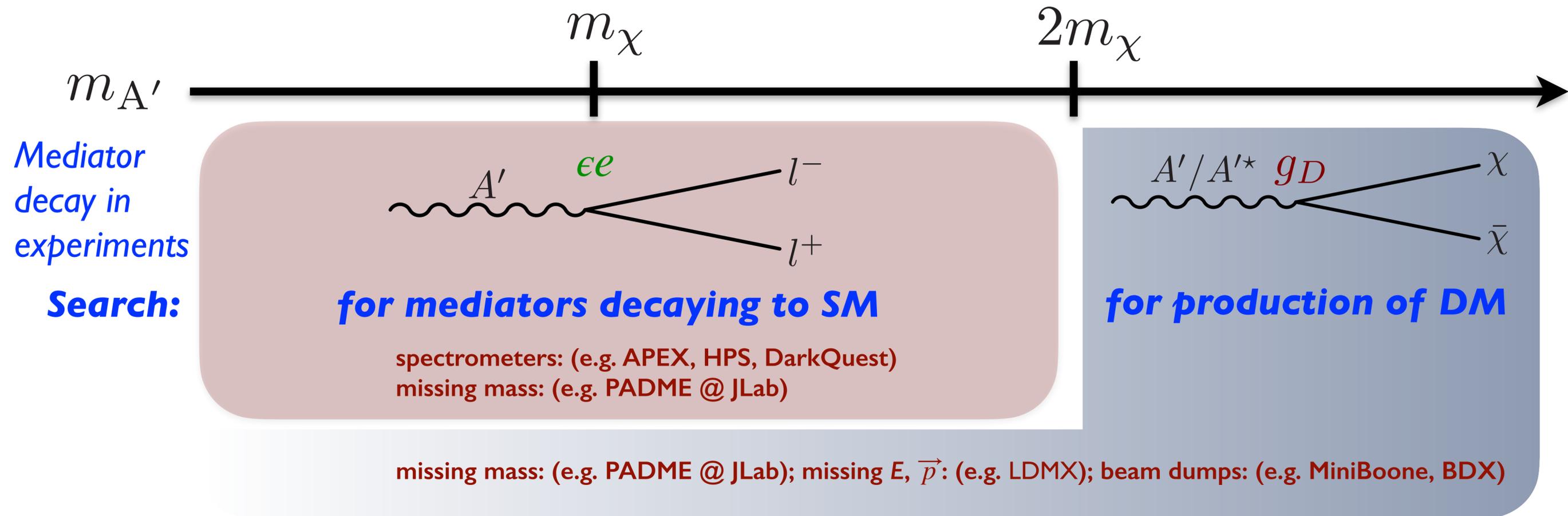
A lot of statistics
(LDM has small couplings)

How to make the dark sector 101



- **Electrons/positrons** are easy to make and very **precise**
 - You can make a lot of them and control them very well
- **Protons** make all kinds of stuff, **versatile** production mechanism
 - e.g. mesons, muons, taus, heavy quarks,...
 - Cons: protons make all kinds of stuff, including neutrinos
- **Muons** are **unique window** to 2nd generation
 - Heavy (than electrons), clean (minimum ionizing)
 - Cons: muon beams are harder to come by and control

Visible and invisible



T Nelson

Snowmass and dark sectors

**Invisible,
non-SM**

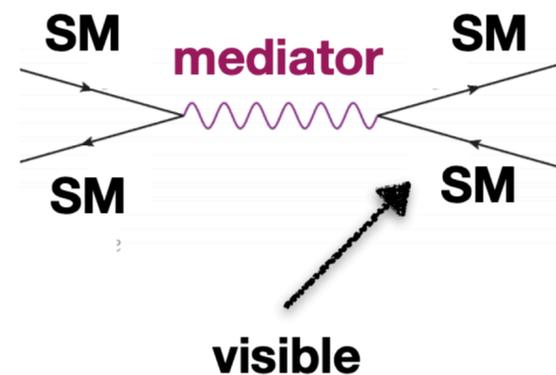
Dark Matter production
Producing stable particles that could be (all or part of) Dark Matter



**Visible,
SM**

Production of portal-mediators that decay to SM particles

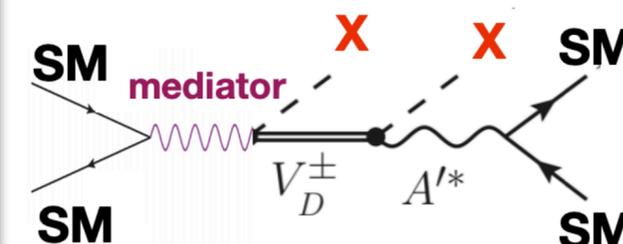
Systematically exploring the portal coupling to SM particles



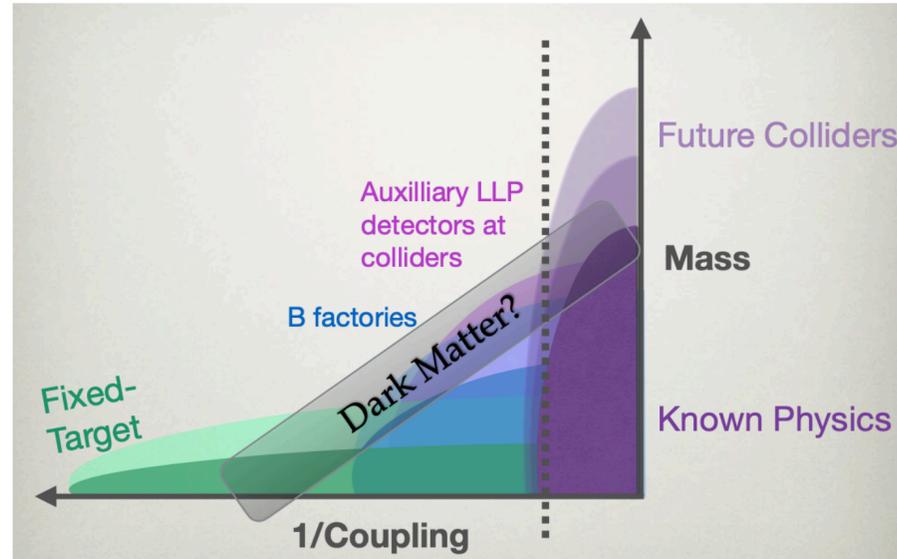
**Mixed
visible-invisible**

Production of “rich” dark sectors

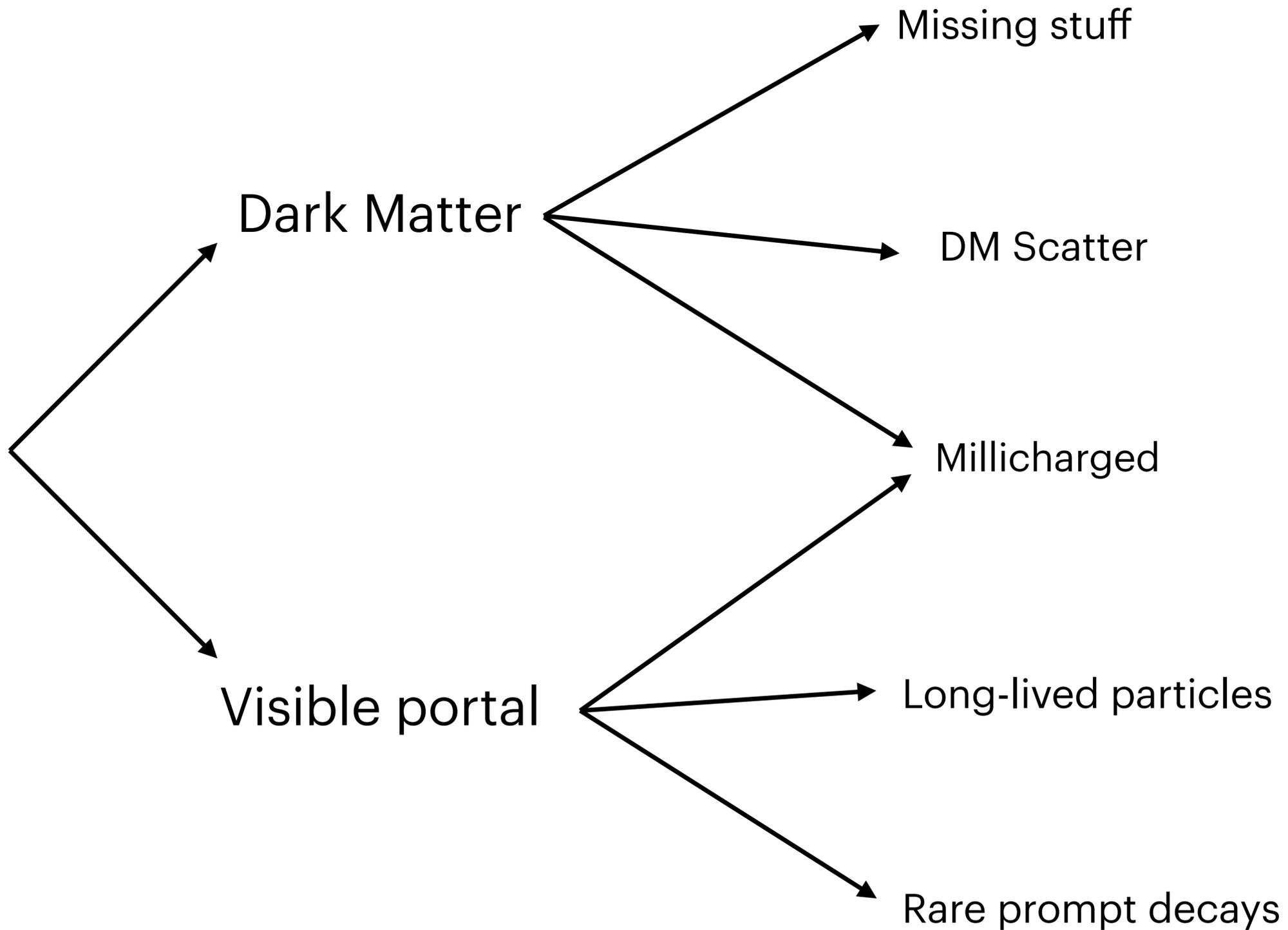
Testing the structure of the dark sector



Stefania Gori, Mike Williams



Particle beams
 e^\pm, p, μ



How to “see” the dark sector 101

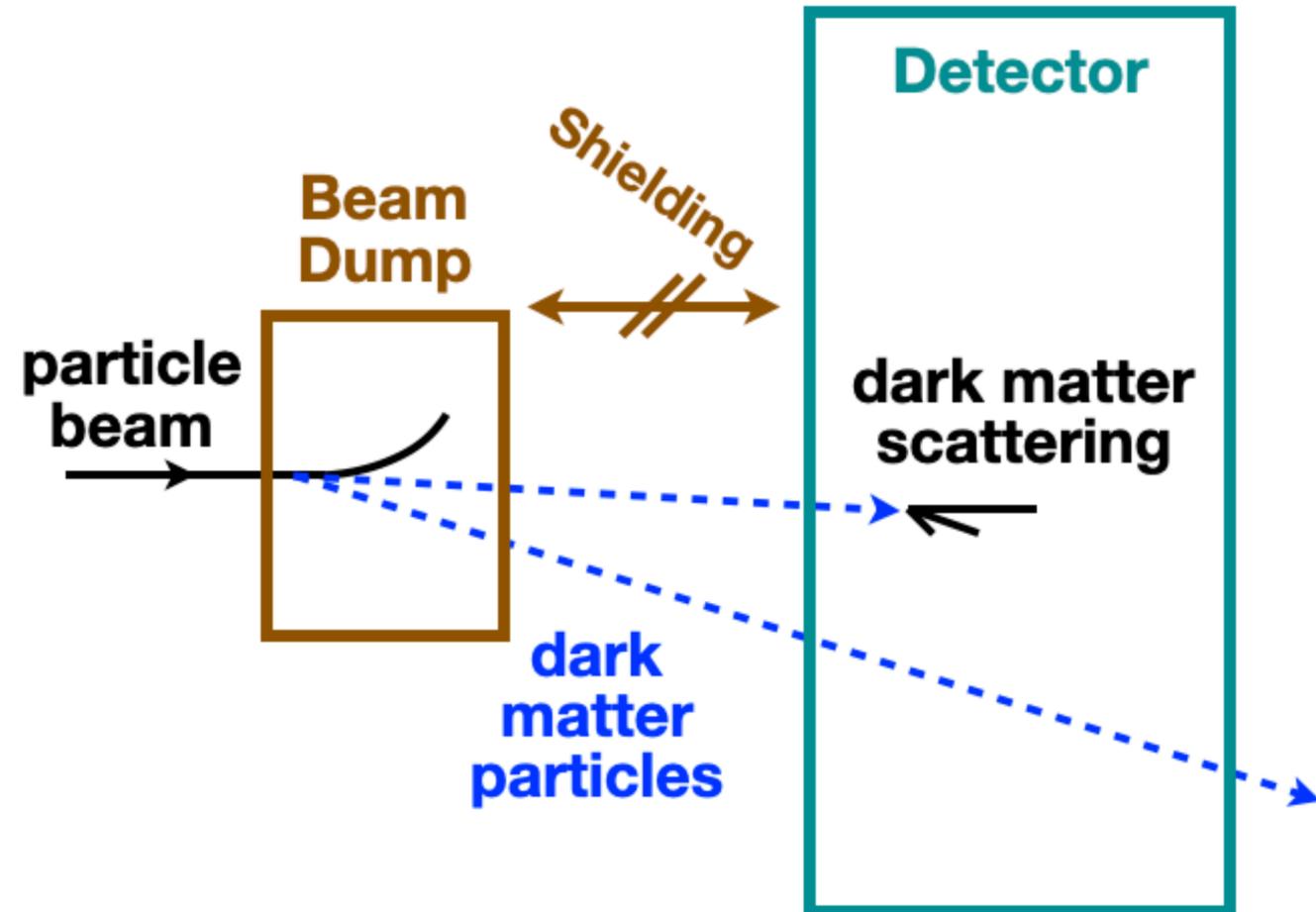
Disclaimer

- For simplicity, I have schematic representations of experiments as fixed target experiments.
- If you instead want to imagine a collider, change your reference frame

How to “see” the dark sector 101

DM rescattering

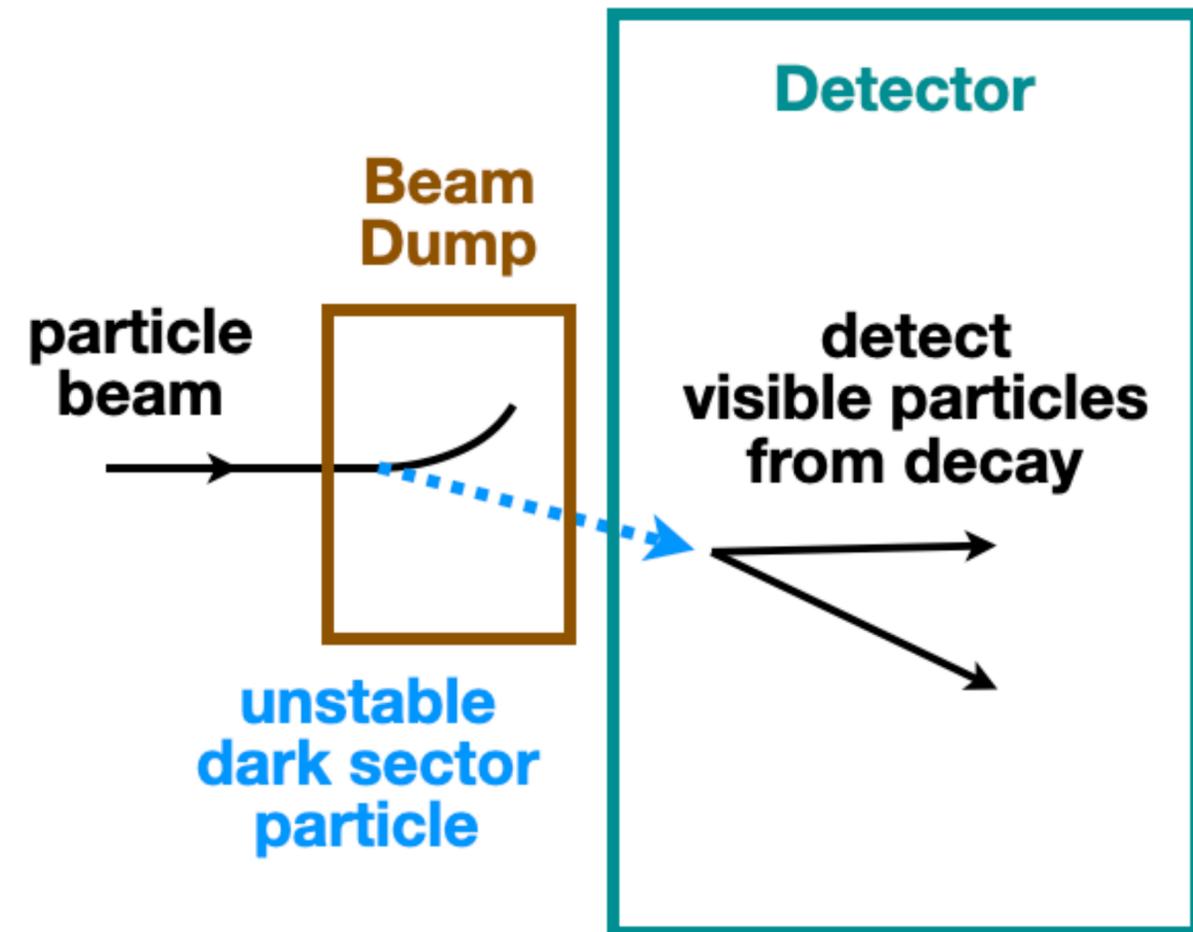
- Detector density helps
 - Fighting ε^4 because you need to both produce and scatter the DM
 - Synergy with neutrino detectors, for example
- But detection measures both production and scattering processes (complementary to Missing X)



How to “see” the dark sector 101

Long-lived particles

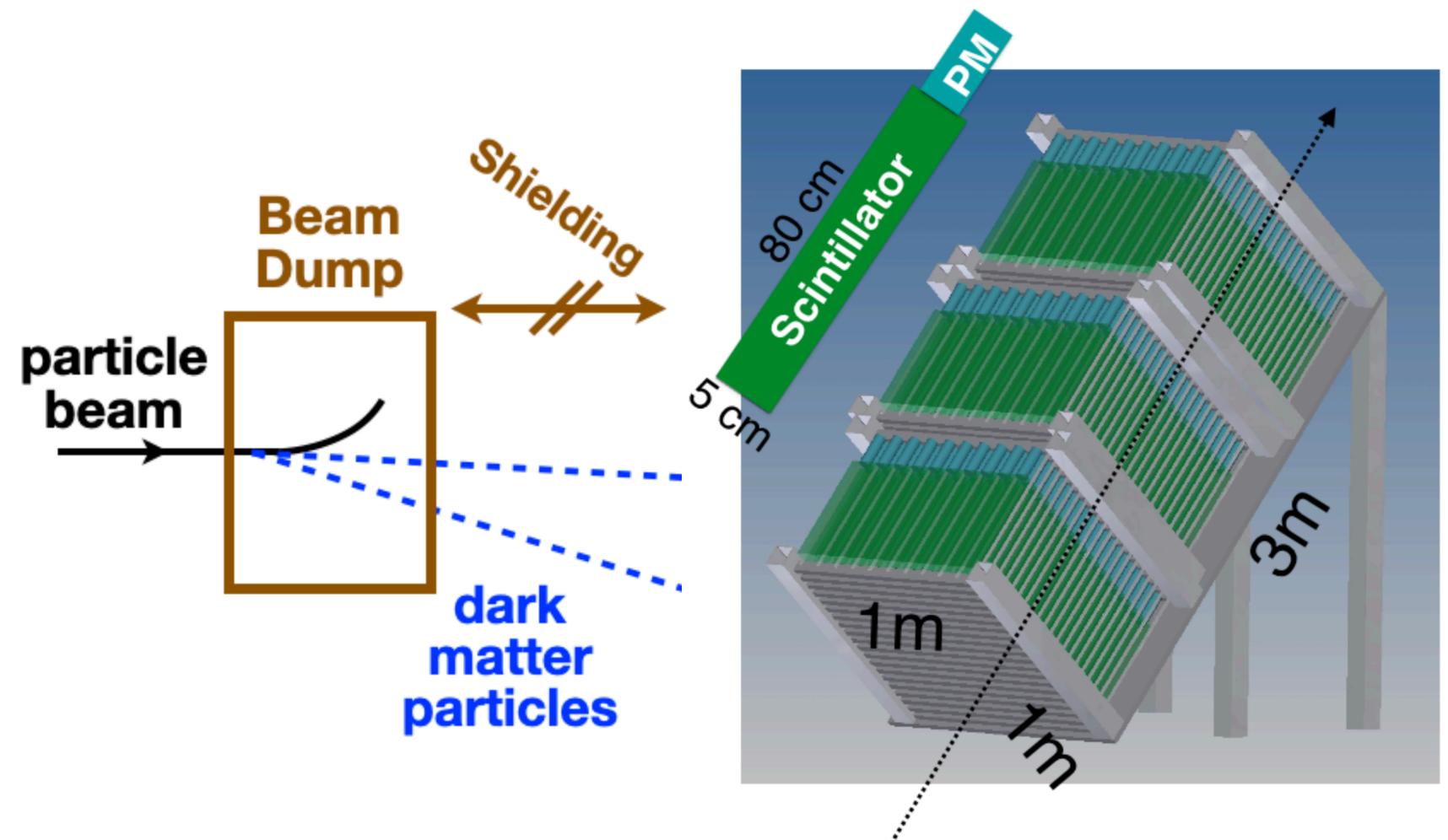
- A cousin of DM scatter experiments so often you will see fixed-target experiments doing both
- But in the LLP case, precision and low detector mass can be important to cover open parameter space



How to “see” the dark sector 101

Millicharged

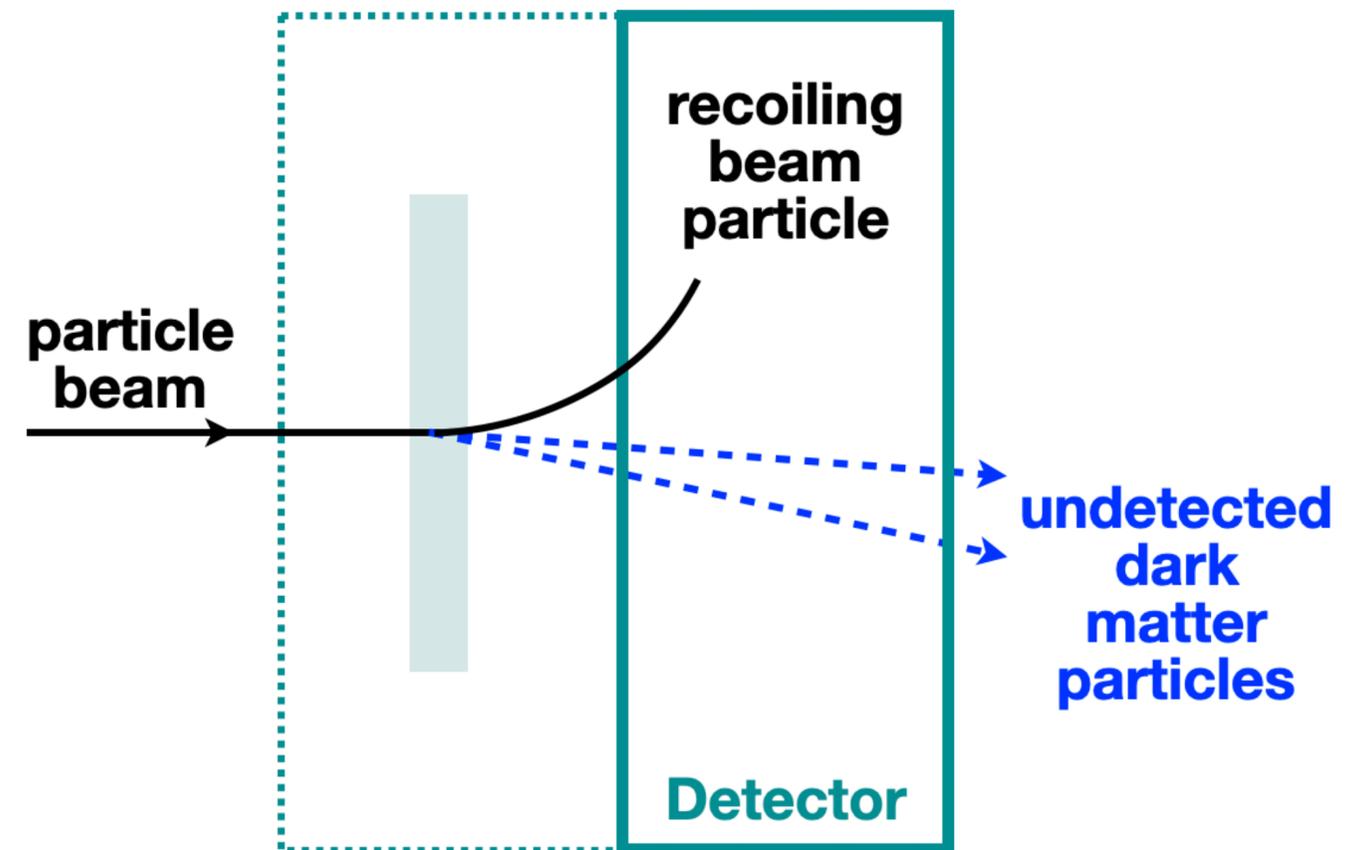
- Kind of like DM rescattering, but with special detector configurations to detect fractionally charged particles



How to “see” the dark sector 101

Missing X

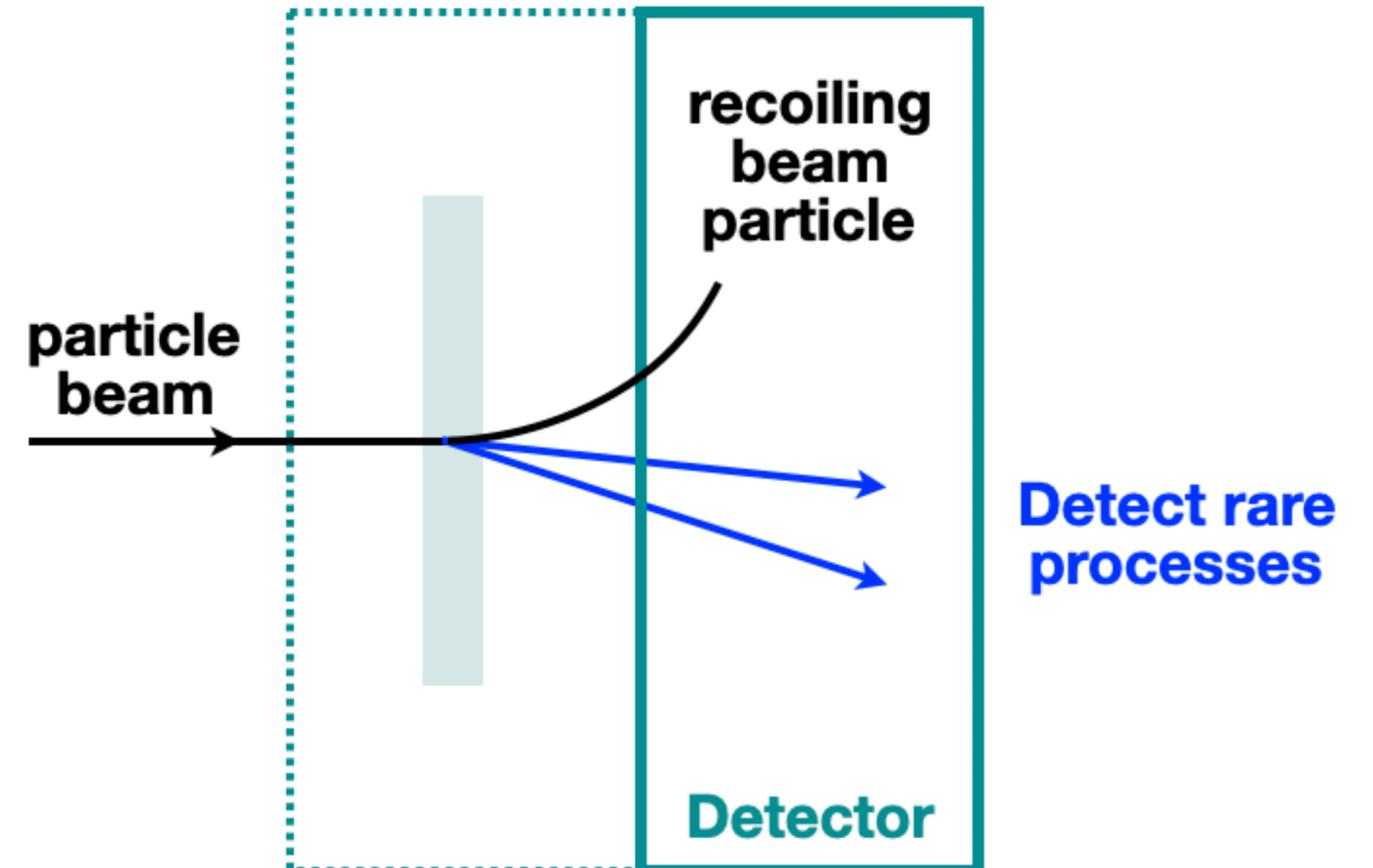
- “See” missing mass, momentum, or energy by detecting nothing
 - Experimental challenge to measure rare missing stuff
 - Scales as ε^2
- Showing missing momentum here
 - Missing energy: target and detector are the same
 - Can also include millicharge as invisible



How to “see” the dark sector 101

Rare prompt decays

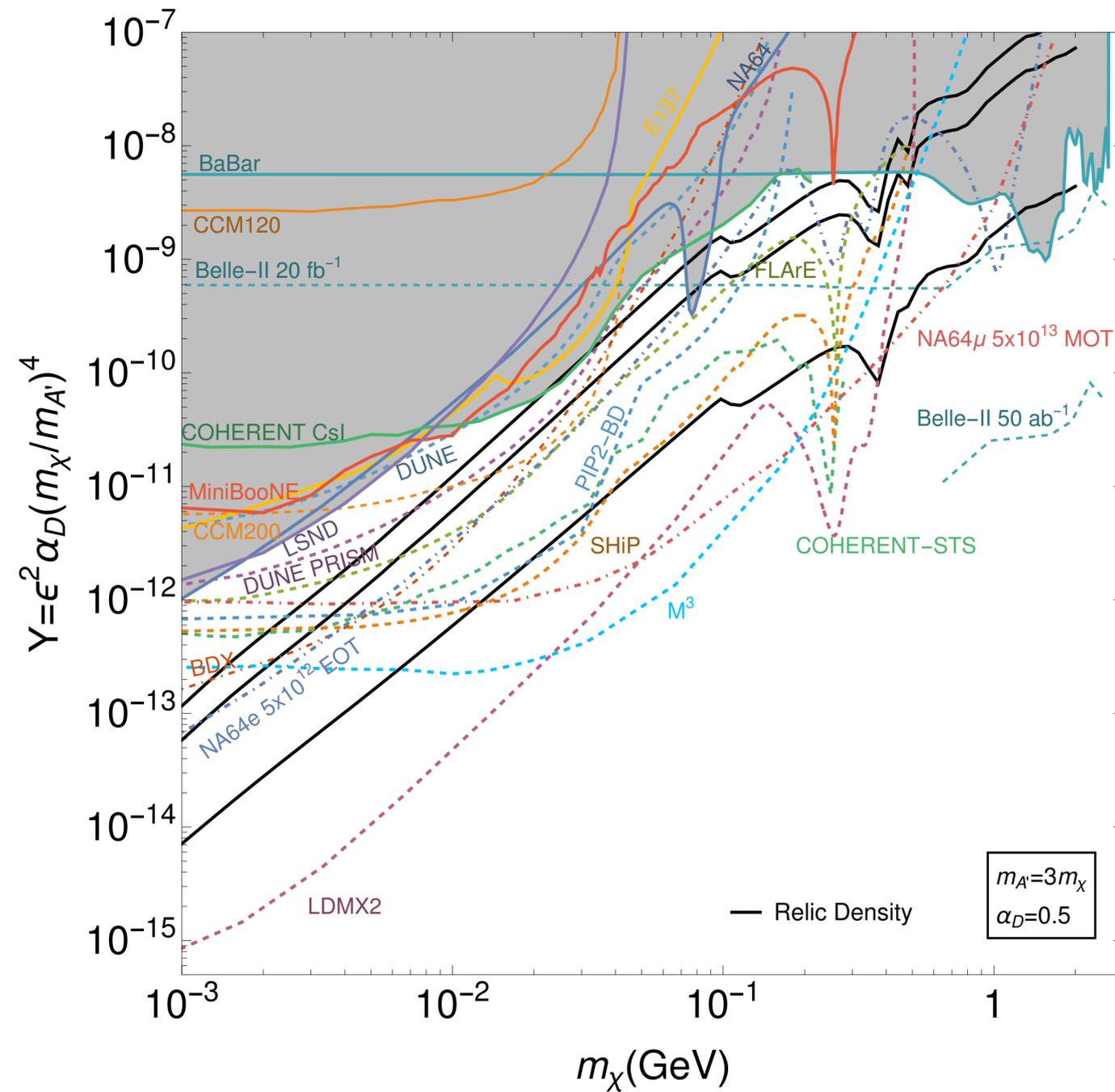
- Needs lots of intensity
- “Traditional” detection but precision important to sort out from SM backgrounds



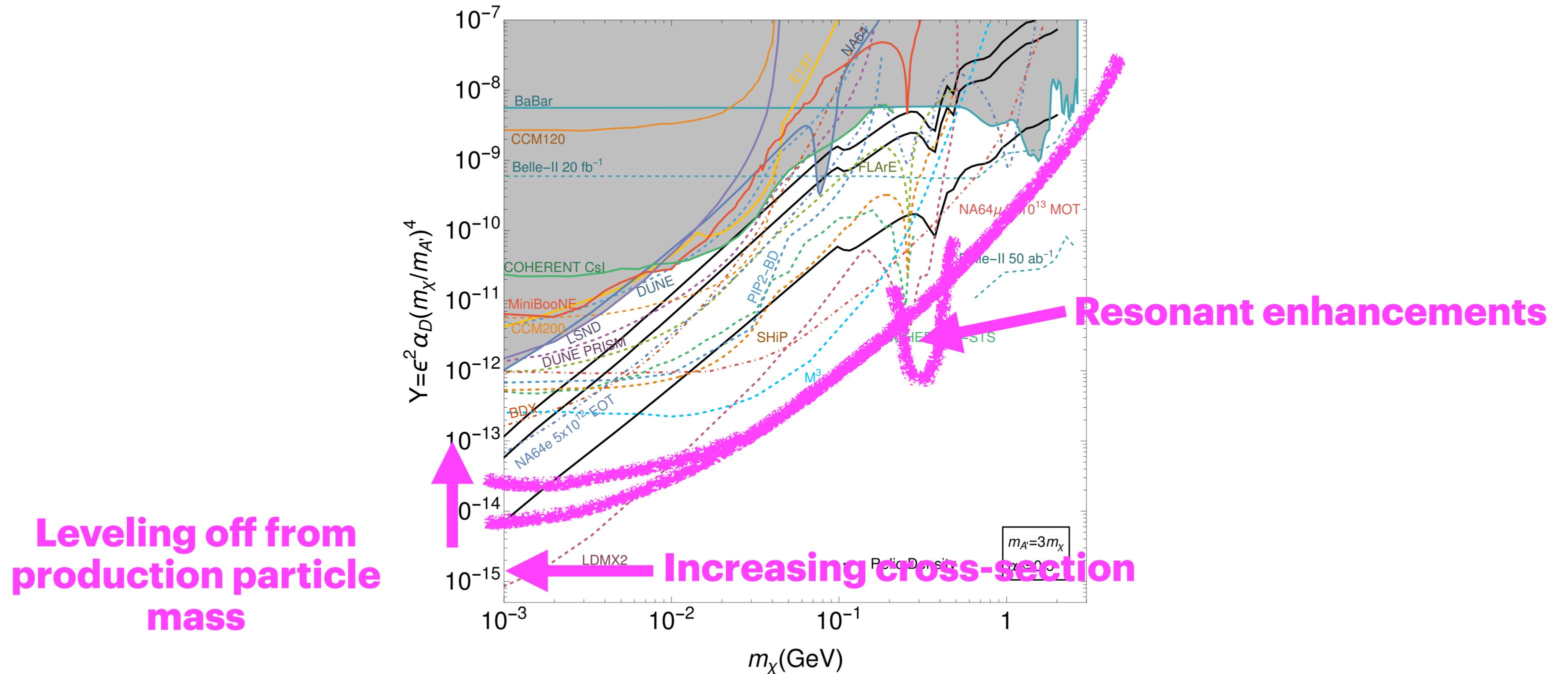
Physics drivers & experiments



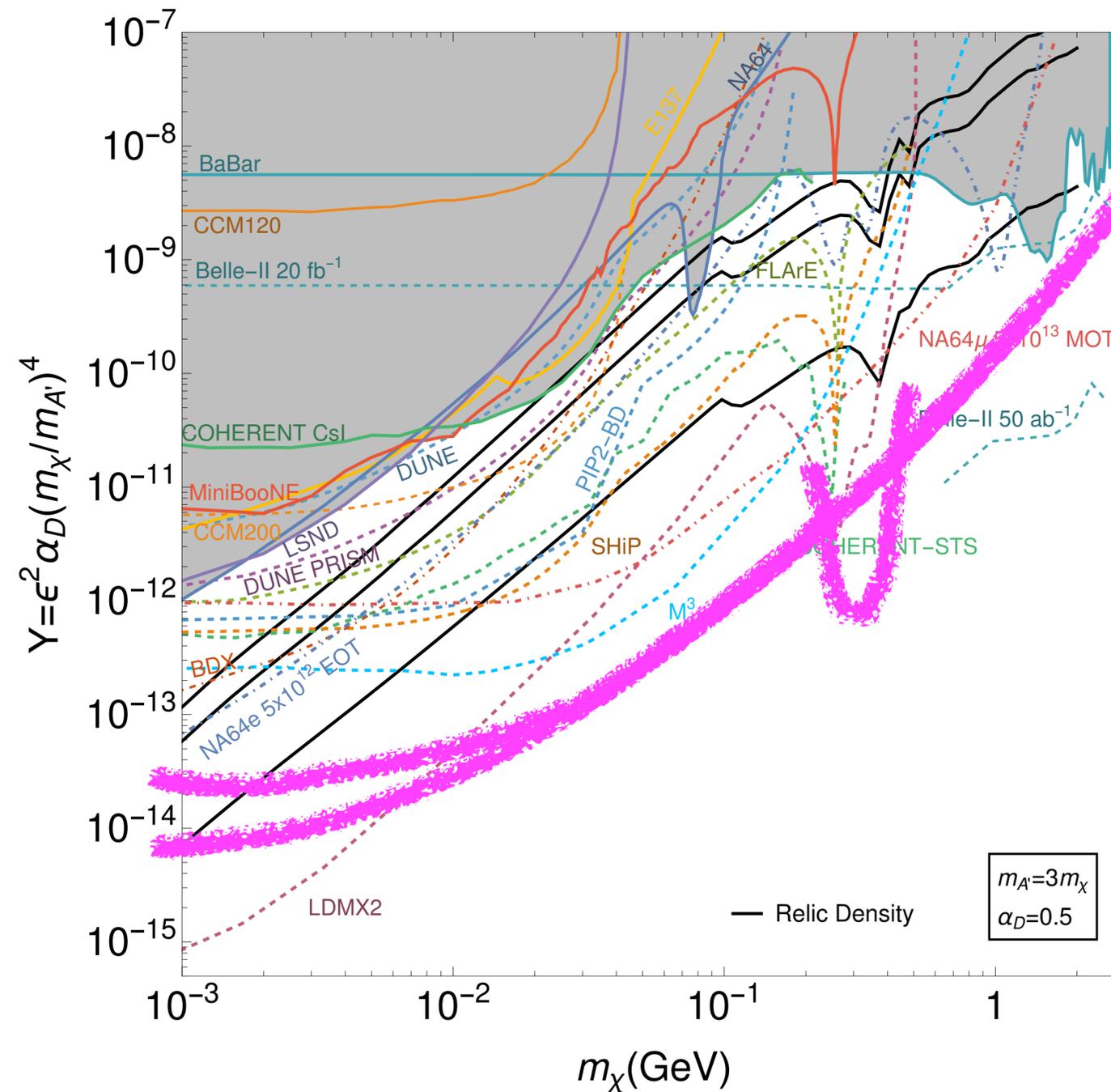
DM production physics driver



DM production physics driver

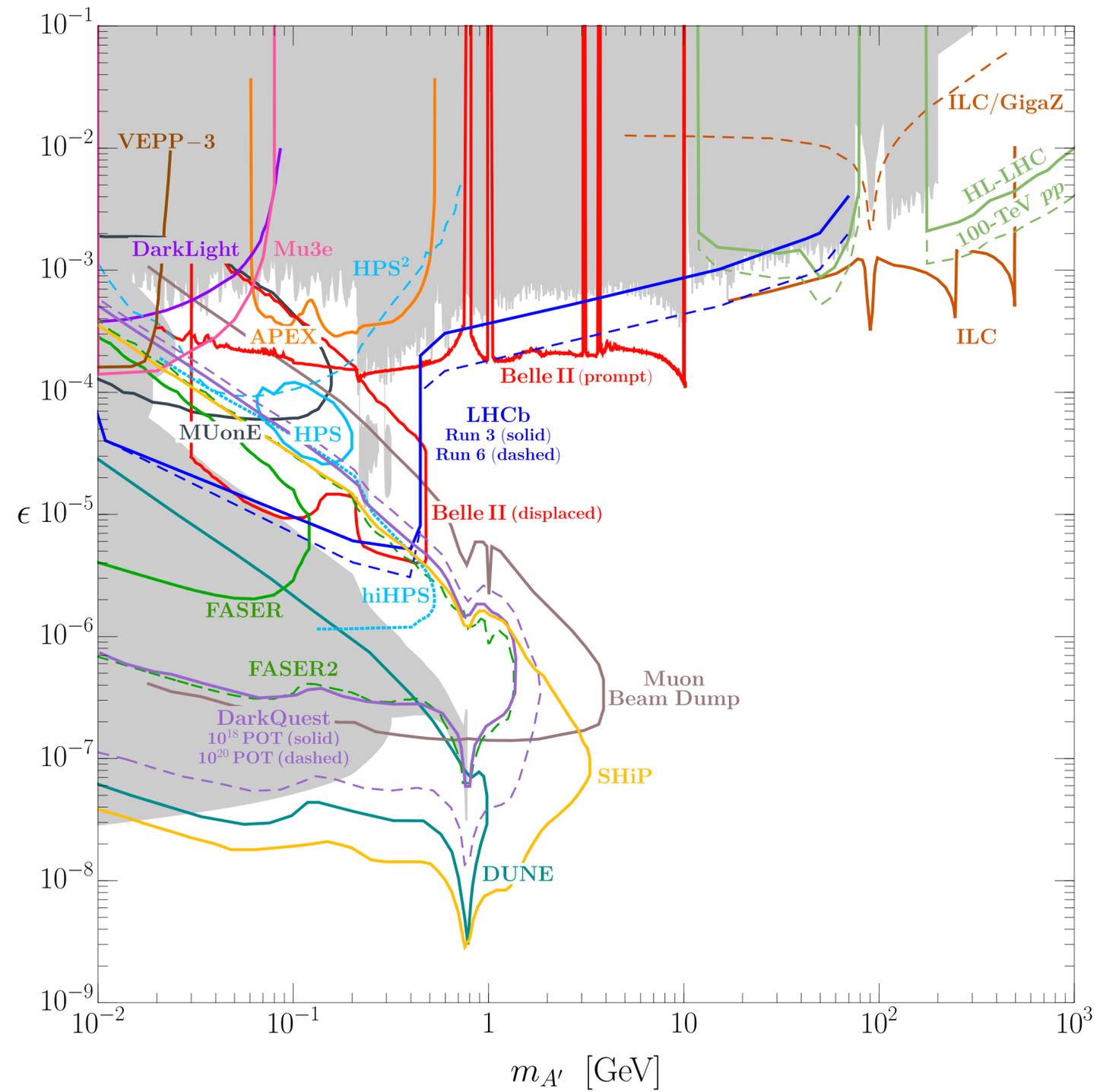


DM production physics driver

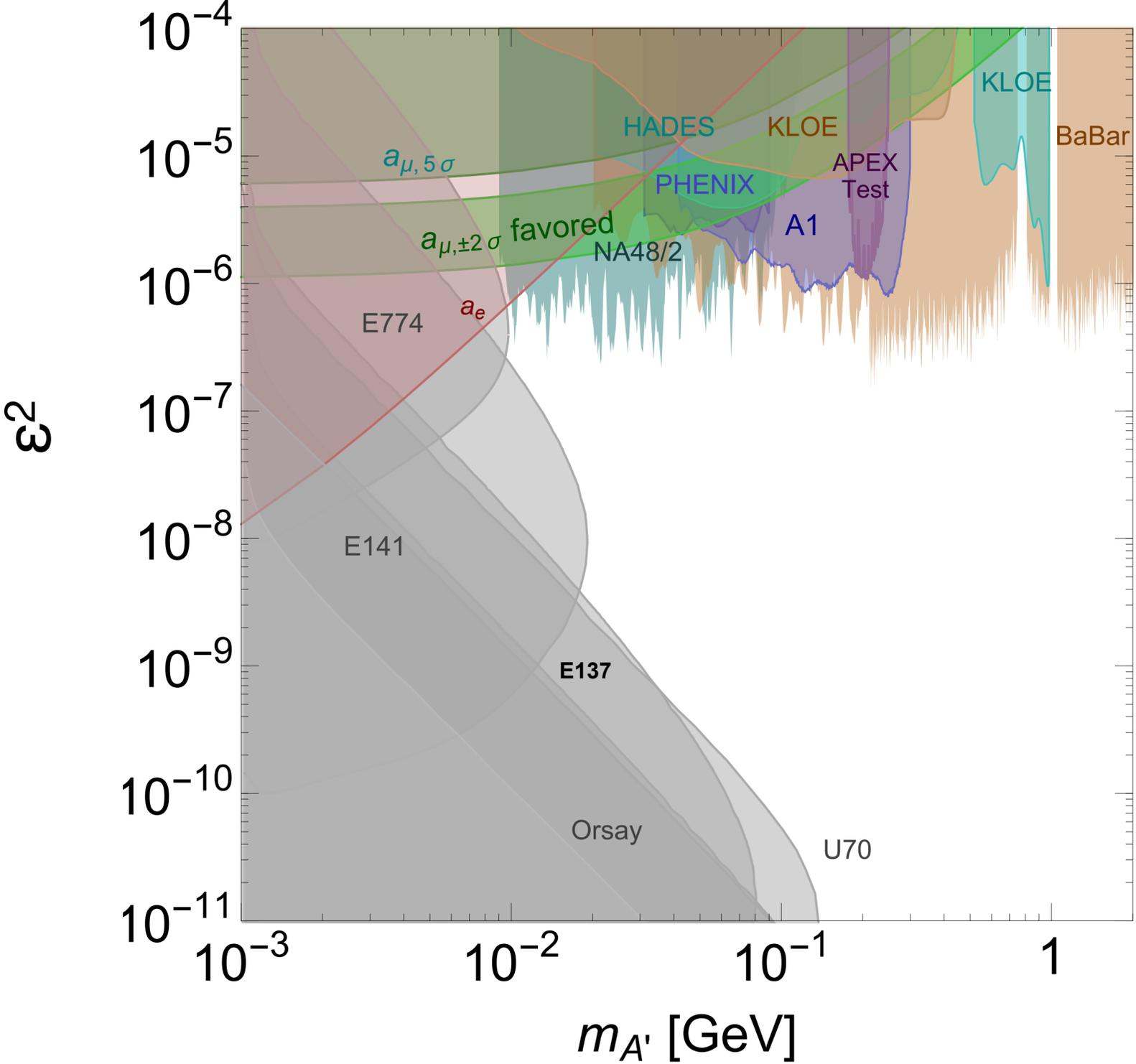


Complementarity in hadronic, electron and muon couplings exploration with rescattering and missing X

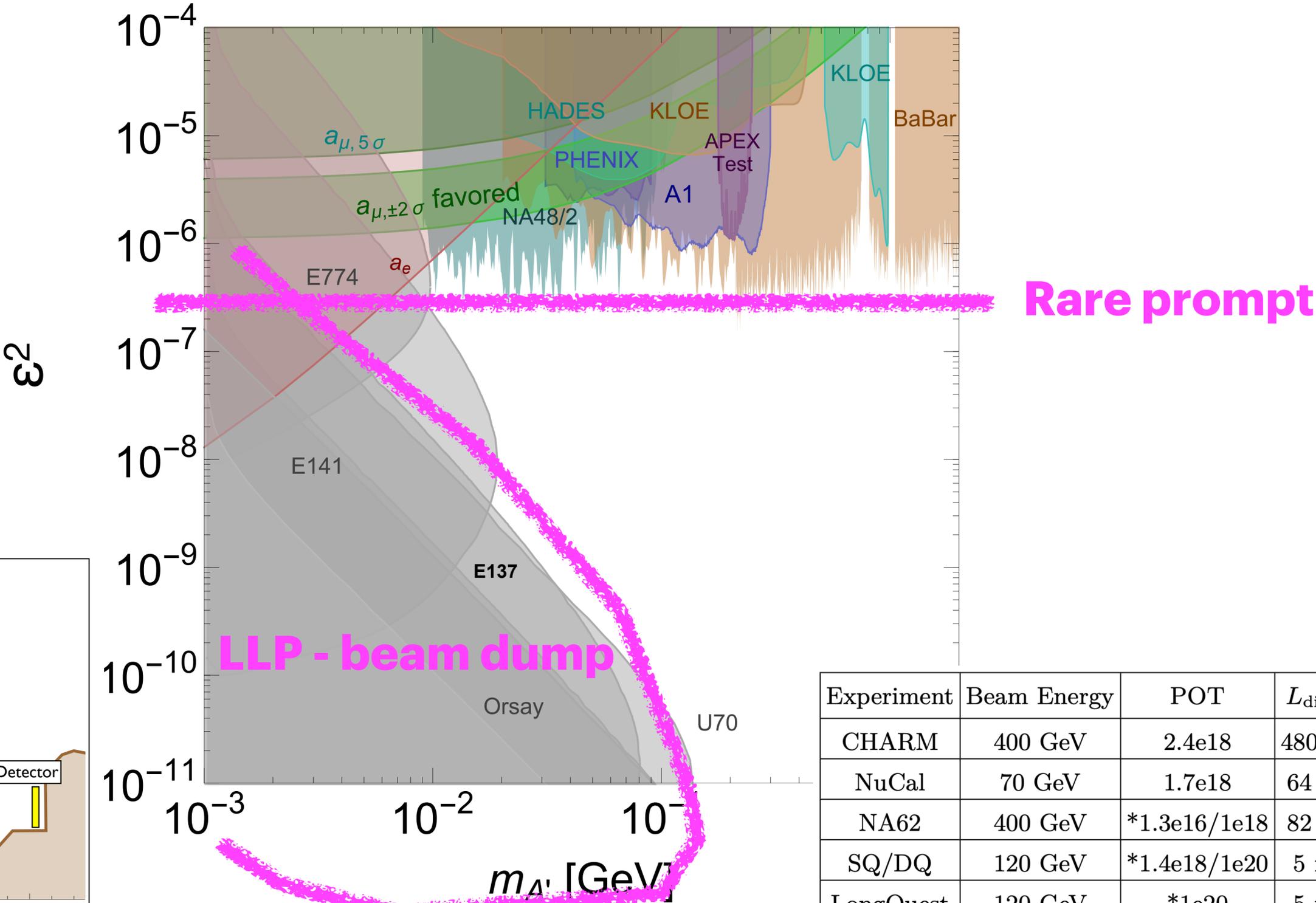
Visible portals



Dark photon schematic



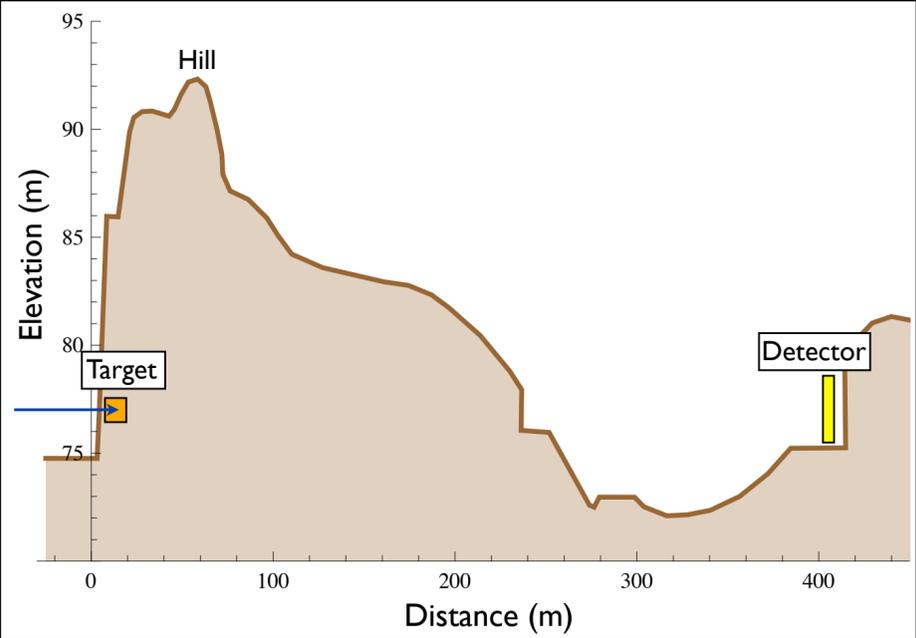
Dark photon schematic



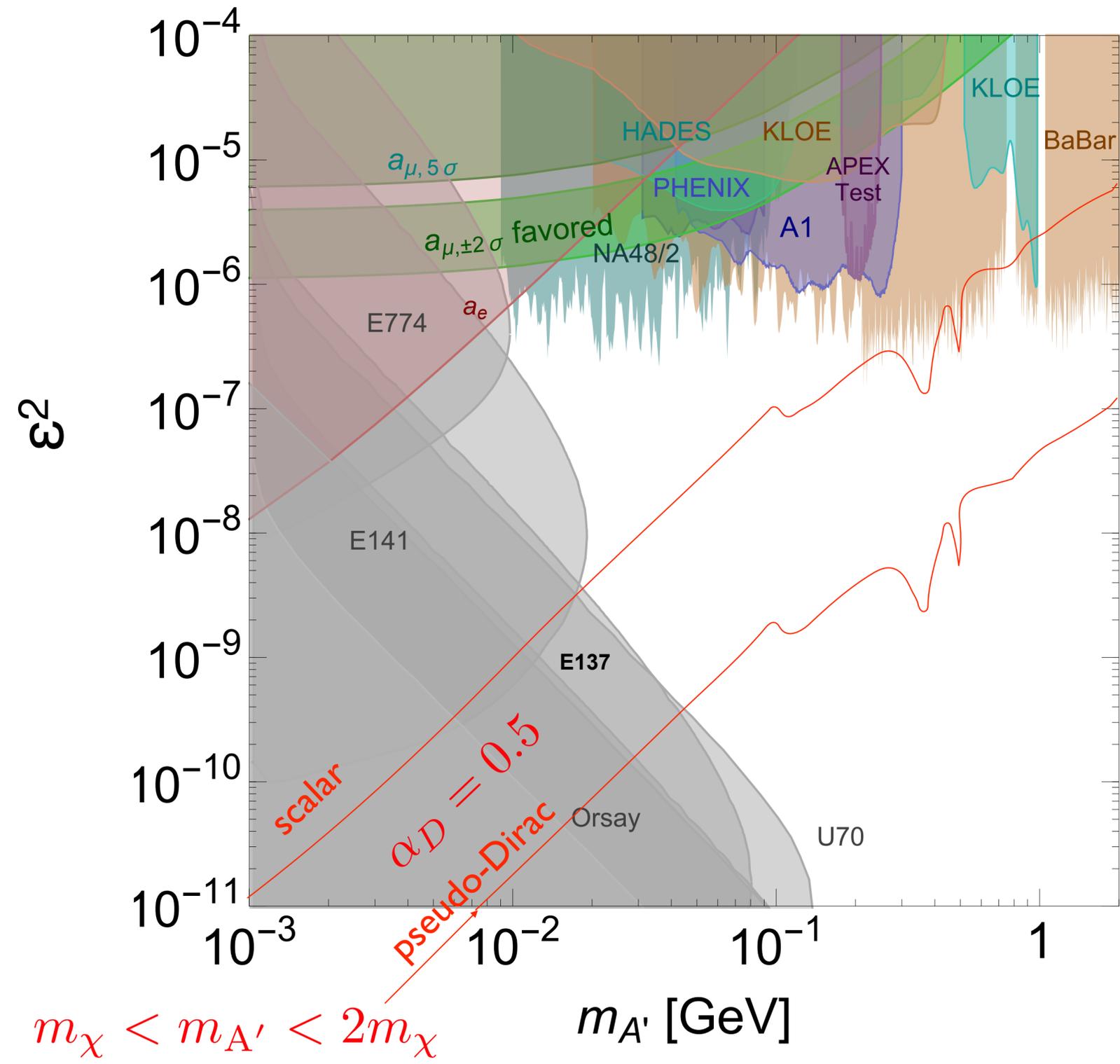
Rare prompt

LLP - beam dump

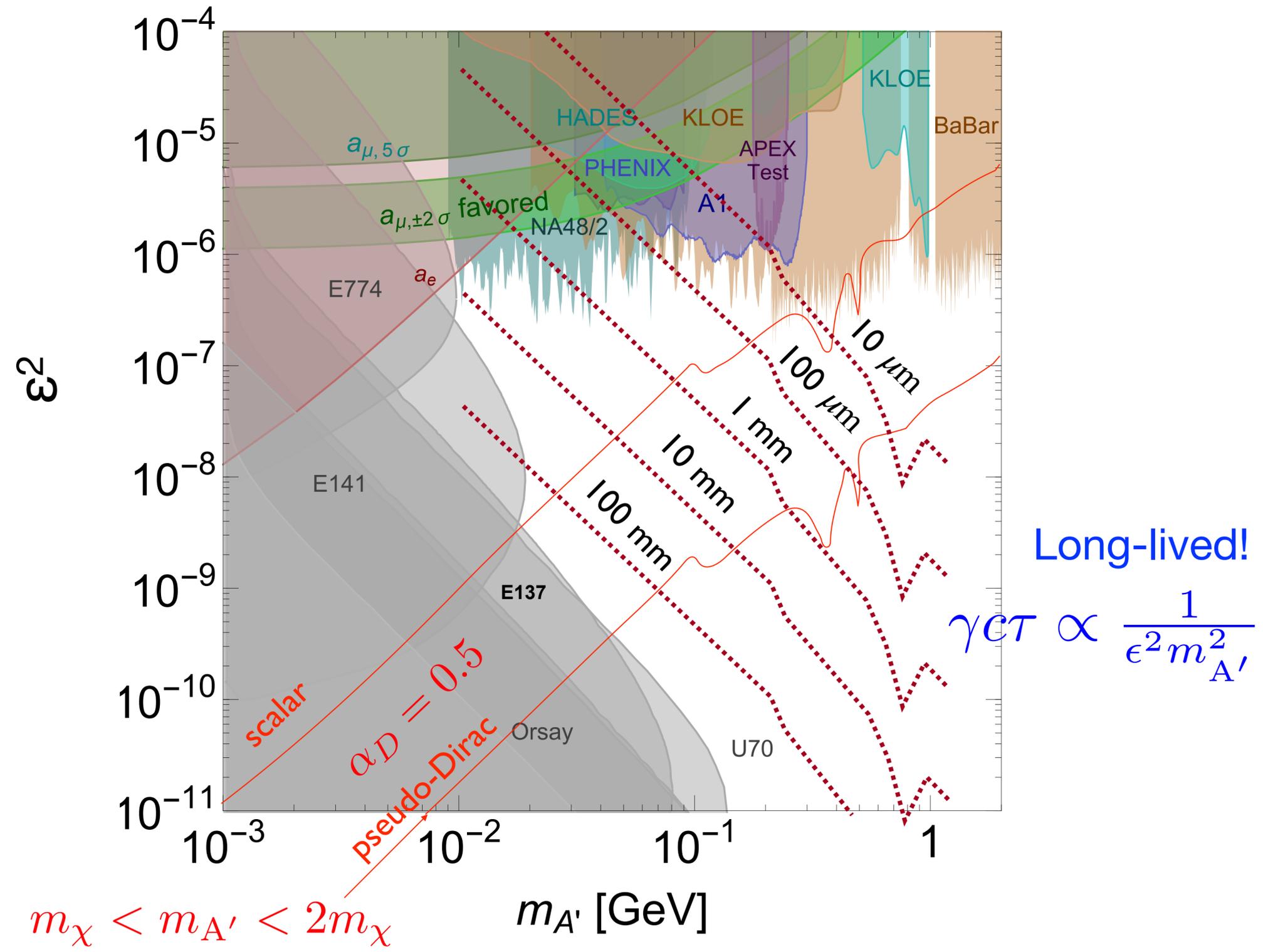
Experiment	Beam Energy	POT	$L_{\text{dist.}}$	L_{dec}
CHARM	400 GeV	2.4e18	480 m	35 m
NuCal	70 GeV	1.7e18	64 m	23 m
NA62	400 GeV	*1.3e16/1e18	82 m	75 m
SQ/DQ	120 GeV	*1.4e18/1e20	5 m	*7 m
LongQuest	120 GeV	*1e20	5 m	*7/13 m



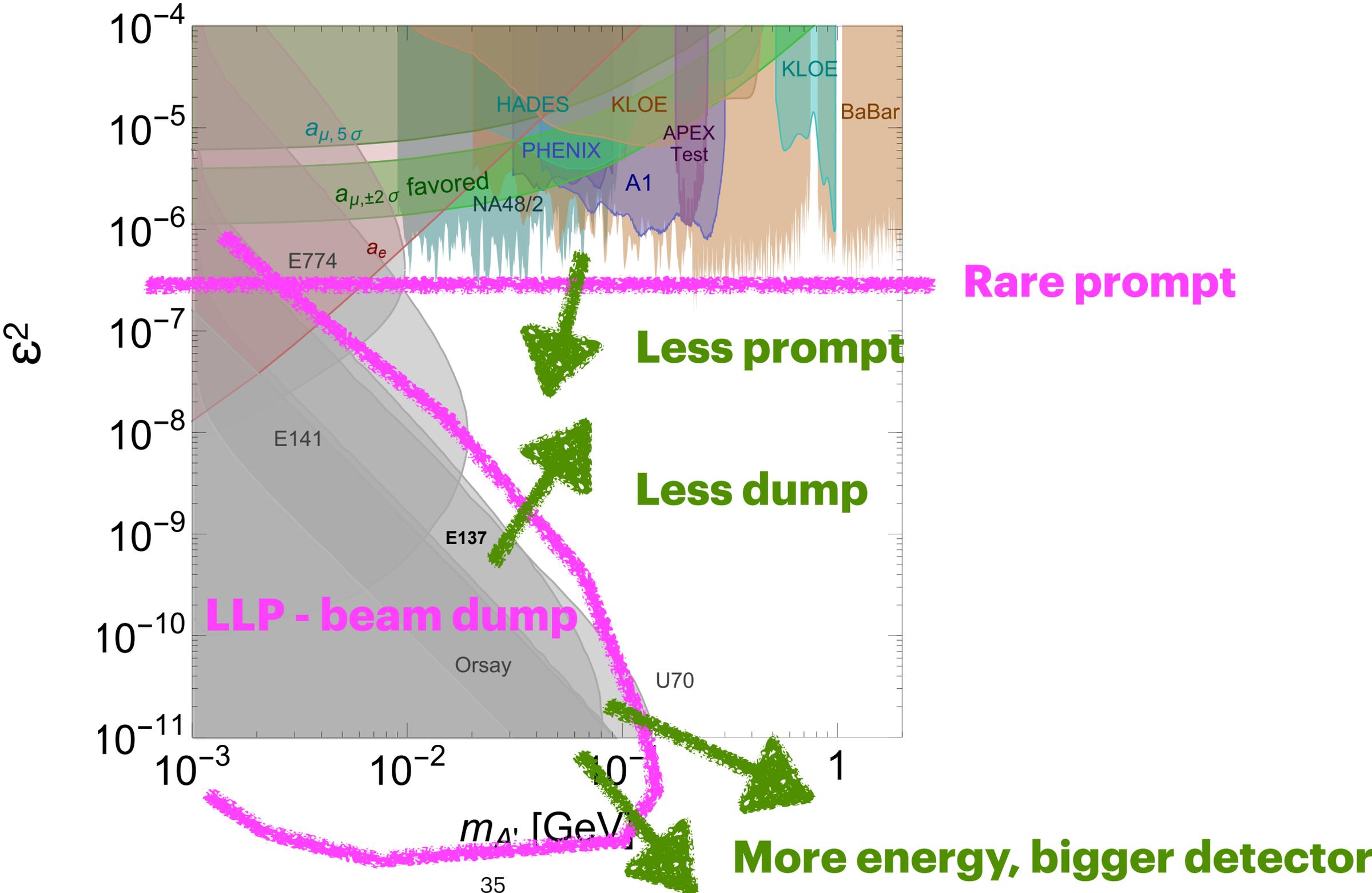
Dark photon schematic



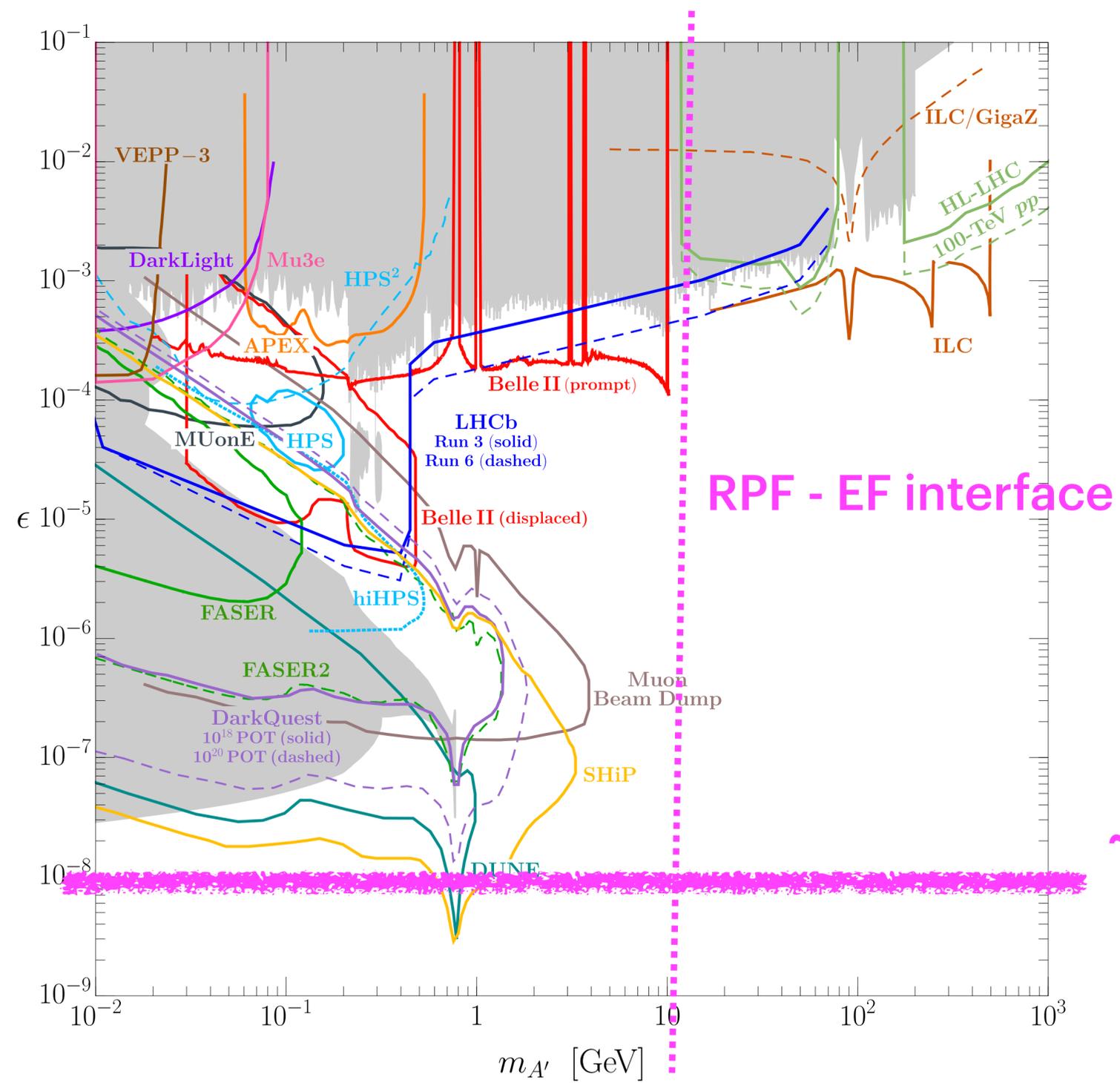
Dark photon schematic



Dark photon schematic



Visible portals

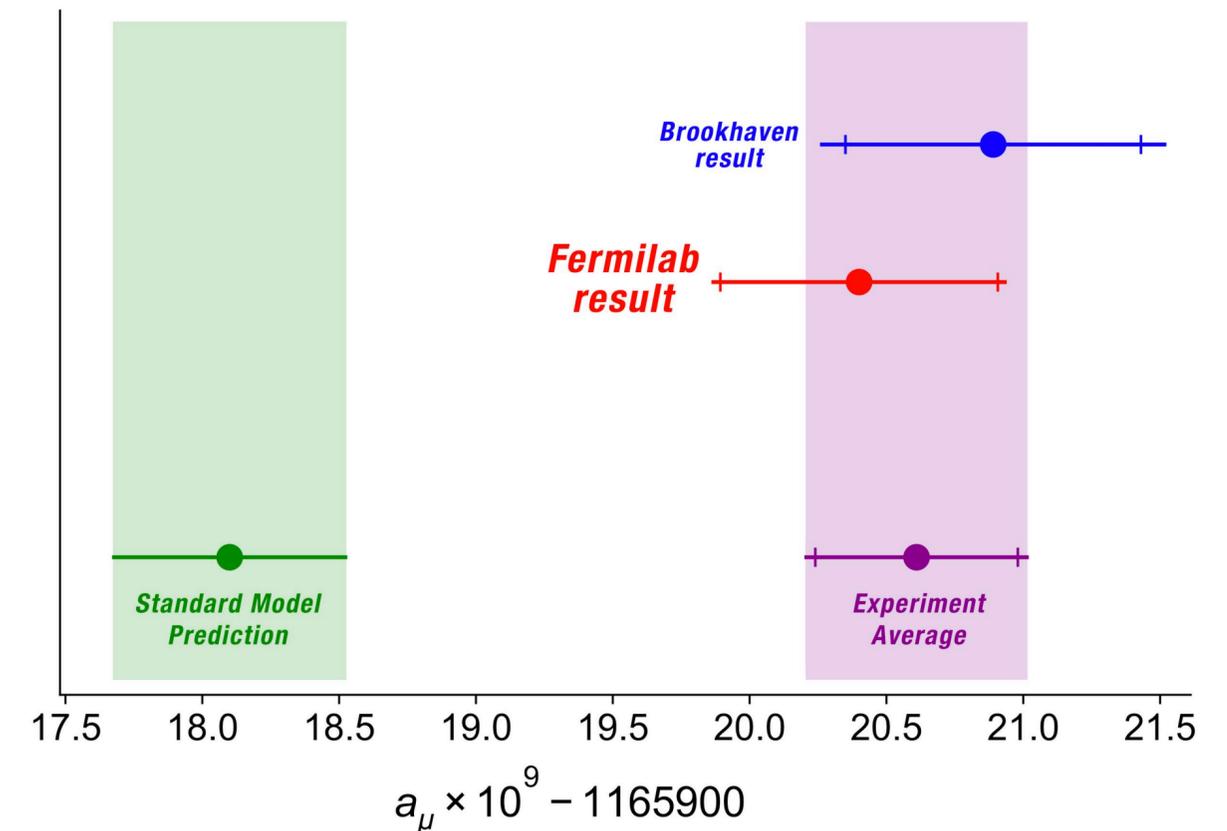


~ thermalization and SN constraints down here

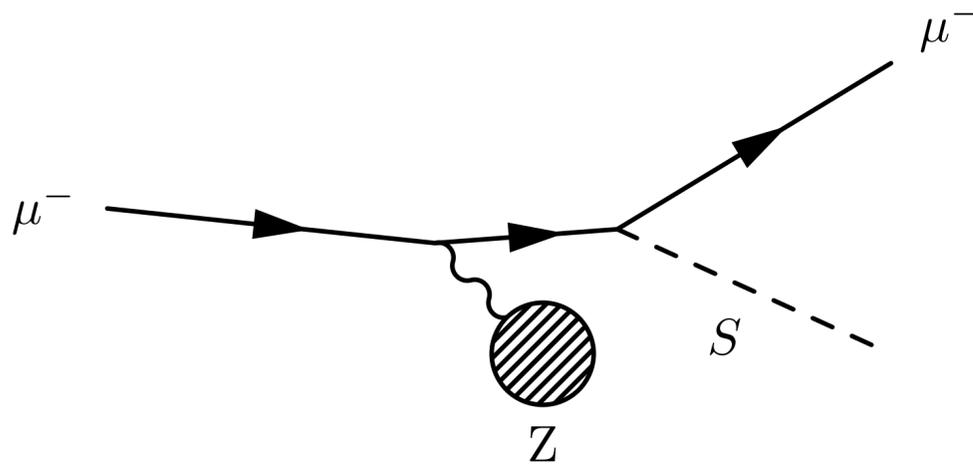
New flavors and rich structures

Benchmark models

- Models explaining $(g-2)_\mu$
- Inelastic dark matter - sector structure from mass splittings χ_1, χ_2
- SIMPs - structure from dark QCD
- Axions with non-minimal couplings



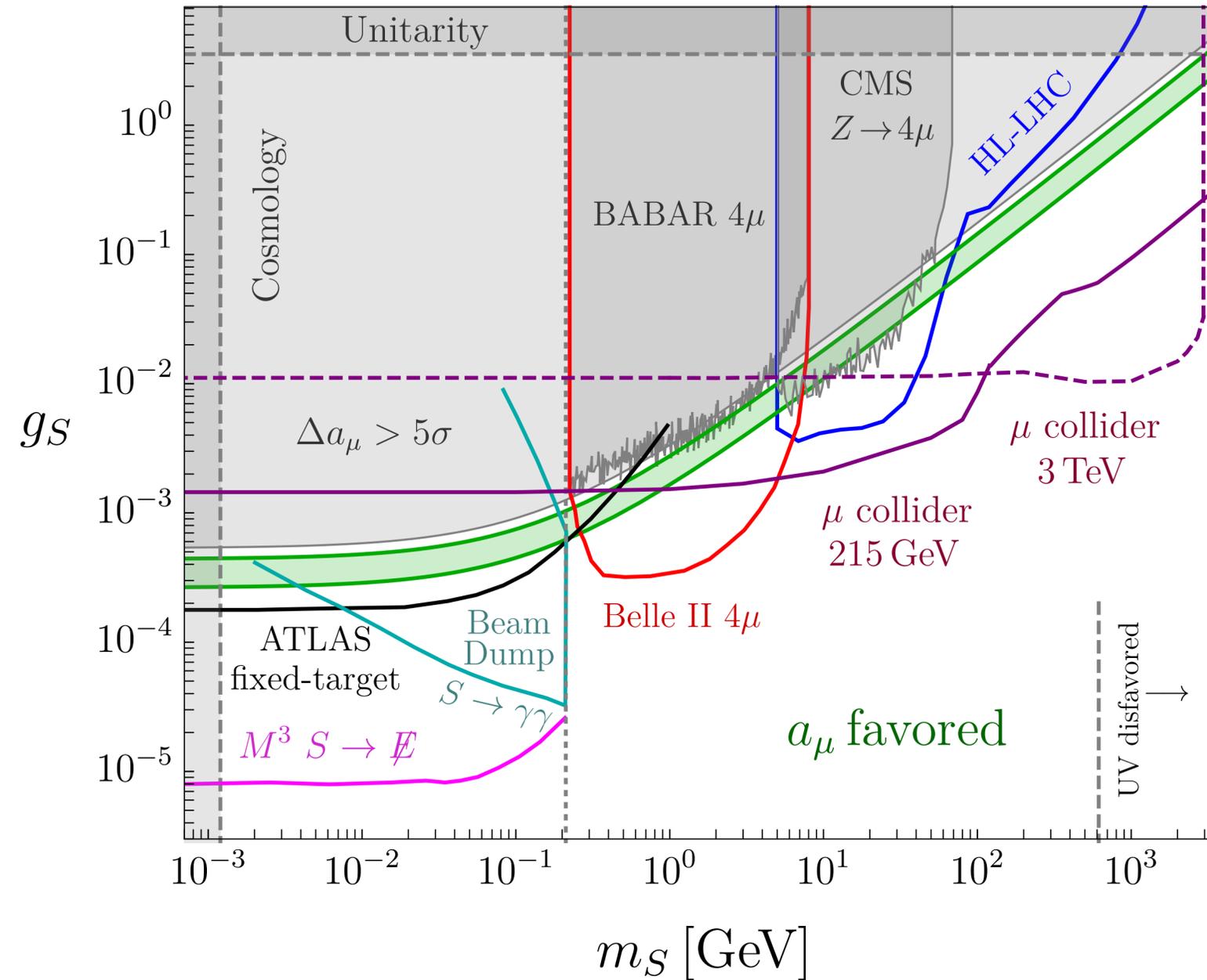
New flavors and rich structures



	Invisible			Visible			
final state/ mediator	Long-lived	neutrinos $\nu\nu$	DM $\chi\chi$	photons $\gamma\gamma$	electrons e^+e^-	muons $\mu^+\mu^-$	hadrons $\pi\pi, \dots$
	no(?)	yes	yes	no	no(?)	yes* ($m_V > 2m_\mu$)	no(?)
vector	<ul style="list-style-type: none"> $L_\mu - L_\tau$ gauge boson: UV complete, automatic coupling to neutrinos, easy to couple to DM. (* $m_V > 2m_\mu$ constrained by dedicated BABAR search) Challenging to build viable models with sizable couplings of vector mediator to electrons or hadrons (gauge anomalies, constraints from neutrino physics) 						
	yes ($m_S < 2m_\mu$)	yes	yes	yes ($m_S < 2m_\mu$)	yes ($m_S < 2m_\mu$)	yes ($m_S > 2m_\mu$)	yes ($m_S > 2m_\pi$)
scalar	<ul style="list-style-type: none"> All minimal signatures can be realized in scalar simplified models. UV complete models require new SM-charged states above weak scale with special flavor structure (such states can in principle affect $(g-2)$) More phenomenological studies needed to chart the parameter space 						
signature	missing momentum			prompt or displaced resonance			

New flavors and rich structures

Scalar, $\text{BR}(S \rightarrow \mu^+ \mu^-) = 1$ for $m_S > 2m_\mu$



Asterisk 2

I have glossed over some benchmarks for the sake of time and simplicity. There are unrepresented parts of parameter space missing from these slides, but there are also significant overlaps with the benchmarks that have been shown.

Takeaway messages & discussion

Takeaway messages & discussion

RPF:

***Modest upgrades enable near-term
transformative dark sector physics***

Experiments/facilities summary

Table 1. Summary of experimental initiatives, facilities, and key features. **To discuss: how to include connection to physics drivers.**

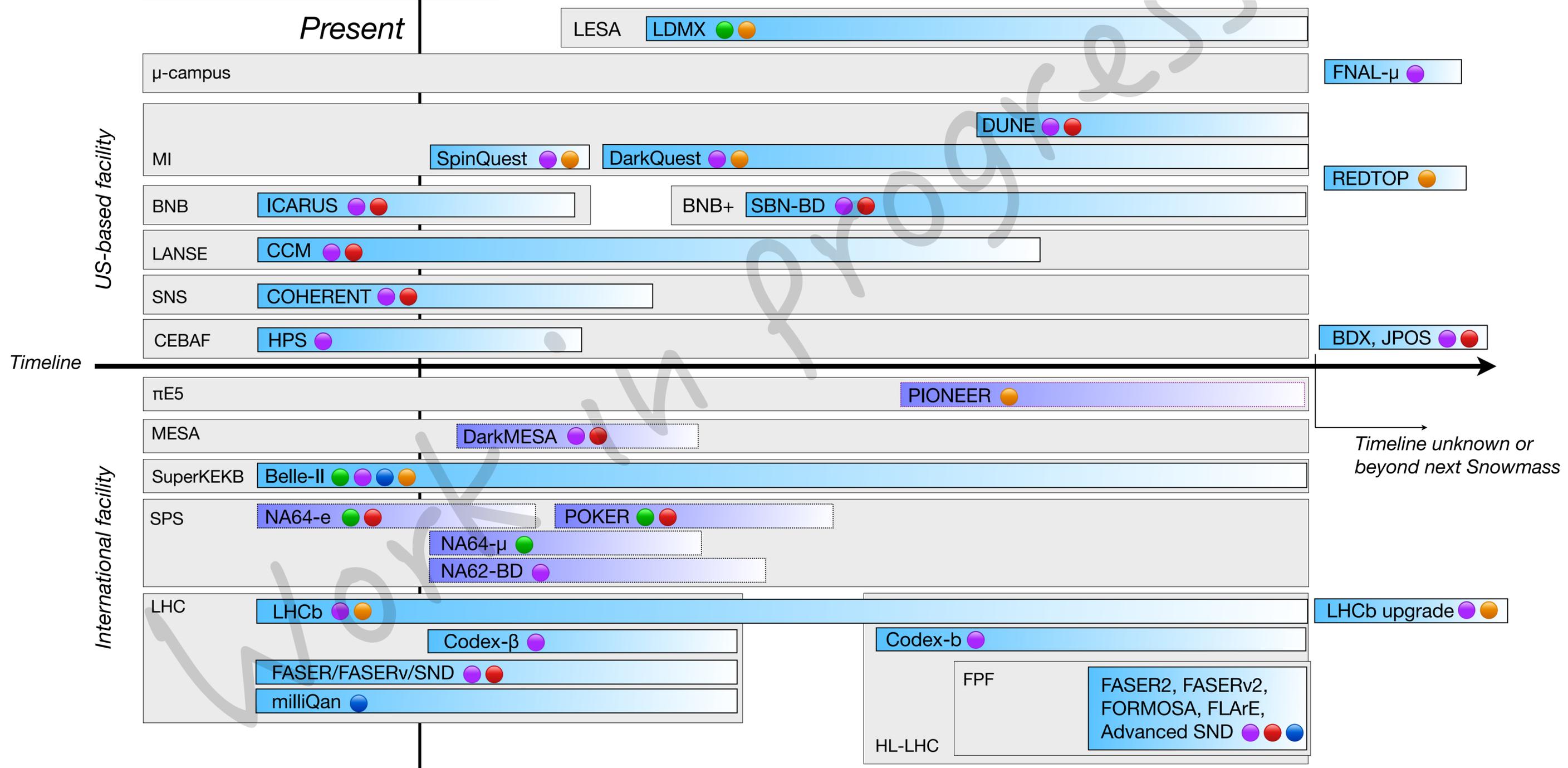
Experiment	Facility	Beam Config	Beam Energy	Det Signature	Physics Driver Priorities			Timeline	Refs.
					DM	Visible	Flavor		
US-based									
HPS	CEBAF @ JLab	electron FT	1-6 GeV	LLP	-	-	-	running	section 3.15, [13]
COHERENT	SNS @ ORNL	proton FT	1 GeV	DM Scatter	-	-	-	running	section 4.5, [14]
CCM	LANSE @ LANL	proton FT	0.8 GeV	DM Scatter	-	-	-	running	[15]
SpinQuest/DarkQuest	MI @ FNAL	proton FT	120 GeV	LLP	-	-	-	construction, proposed upgrade	section 3.5, [16]
LDMX	LESA @ SLAC	electron FT	4-8 GeV	Missing X	-	-	-	R&D funding, 2024	section 3.17, [17]
BDX	CEBAF @ JLab	electron BD	11 GeV	DM Scatter, Millicharged	-	-	-	proposed	section 3.1, [18]
JPOS	CEBAF @ JLab	positron FT	11 GeV	Missing X	-	-	-	proposed	section 3.16, [19]
PIP-II BD	PIP-II @ FNAL	proton FT	1 GeV	DM Scatter, LLP	-	-	-	proposed (2029)	section 3.23, [20]
SBN-BD	Booster @ FNAL	proton BD	8 GeV	DM Scatter	-	-	-	proposed (2029)	[21]
REDTOP	TBD	proton FT	1-5 GeV	Missing X, LLP, Prompt	-	-	-	proposed	section 3.25, [22]
M ³	MI @ FNAL	muon FT	15 GeV muons	Missing X	-	-	-	proposed	[23]
FNAL- μ	muon campus @ FNAL	muon FT	3 GeV	LLP	-	-	-	proposed	section 3.13, [24]
International									
Belle-II	SuperKEKB @ KEK	e+e- collider	150 MeV	Missing X, LLP, Prompt	-	-	-	running	section 3.2, [25]
CODEX- β	LHC @ CERN	pp collider	6.5-7 TeV	LLP	-	-	-	construction (2023)	section 3.4, [26]
CODEX-b	LHC @ CERN	pp collider	6.5-7 TeV	LLP	-	-	-	proposed (2026)	section 3.3, [27]
LHCb	LHC @ CERN	pp collider	6.5-7 TeV	LLP, Prompt	-	-	-	running, future upgrade planned	section 3.18, [28]
NA62	SPS-H4 @ CERN	proton BD	400 GeV	LLP	-	-	-	dedicated running planned	[29]
FASERnu	LHC @ CERN	pp collider	6.5-7 TeV	DM Scatter	-	-	-	running	section 3.9, [30]
milliQAN	LHC @ CERN	pp collider	6.5-7 TeV	Millicharged	-	-	-	running	section 3.19, [31]
DarkMESA	MESA @ Mainz	Electron FT	150 MeV	DM Scatter, LLP	-	-	-	construction (2023)	section 3.6
NA64-e	SPS-M2 @ CERN	electron FT	100-150 GeV	Missing X, Prompt	-	-	-	running	section 3.20, [32]
NA64-mu	SPS-H4 @ CERN	muon FT	100-160 GeV	Missing X	-	-	-	commissioning	section 3.21
NA64/POKER	SPS-M2 @ CERN	positron FT	100 GeV	Missing X	-	-	-	planned (2024)	section 3.24, [32]
PIONEER	π E5 @ PSI	proton FT	10-20 MeV pions	Prompt	-	-	-	planned (2028)	section 3.22, [33]
FASER2	FPF @ CERN	pp collider	6.5-7 TeV	LLP	-	-	-	proposed (2029)	section 3.8 [34]
FORMOSA	FPF @ CERN	pp collider	6.5-7 TeV	Millicharged	-	-	-	proposed (2029)	section 3.14, [35]
FASERnu2	FPF @ CERN	pp collider	6.5-7 TeV	DM Scatter	-	-	-	proposed (2029)	section 3.10, [30]
FLArE	FPF @ CERN	pp collider	6.5-7 TeV	DM Scatter	-	-	-	proposed (2029)	section 3.12, [36]
SND@LHC	LHC @ CERN	pp collider	6.5-7 TeV	DM Scatter	-	-	-	running	section 3.27, [37]
Advanced SND@LHC	FPF	pp collider	6.5-7 TeV	DM Scatter	-	-	-	proposed (2029)	section 3.27, [37]

Modest upgrades enable transformative physics

Detector signature → Physics Driver

- **Missing X** → DM, Flavor
- **rescattering** → DM, Flavor
- **LLP** → Visible, Flavor
- **Millicharged** → DM, Visible
- **Rare/Prompt** → Visible, Flavor

- Significant US contribution
- International effort



Considerations for the summary figure

- Start with your favorite physics drivers
- Look for experiments that are currently running and forecast how limits could evolve in the next couple years
- Discuss what opportunities for progress remain considering:
 - “ Δ physics” - what new space would it cover for a given physics drivers
 - how US can contribute either at US-based facilities or US-driven international experiments
 - how mature the concept is and its timeline

n.b. we are working to simplify our physics driver summary figures and take into account above considerations

Outlook

- We have an excellent opportunity in front of us to make significant impact in dark sector physics real-estate of high interest by the next Snowmass
- Strong connections and complementarity with other frontiers
 - Accelerator, Cosmic, Energy, Neutrino
- **No shortage of ideas and enthusiasm!**
 - Different folks driven by different physics
 - Work in progress to provide organizing principles for these exciting efforts
 - Your input is welcome — are we converging on the practically useful summary of the information?