Understanding Dark Matter & Dark Sectors at the RP Frontier

Stefania Gori

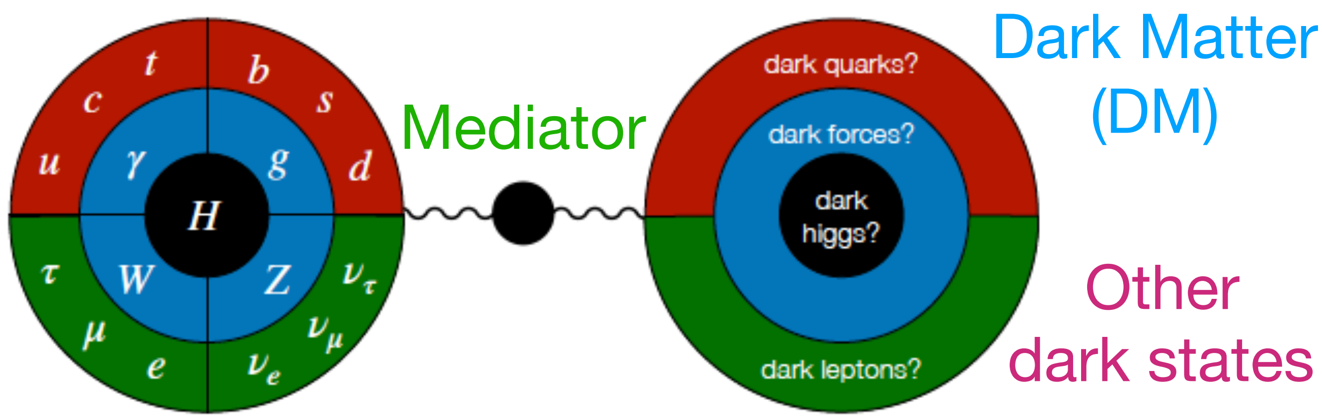
UC Santa Cruz

Community summer study
Snowmass

Seattle

July 20, 2022

What's a dark sector?

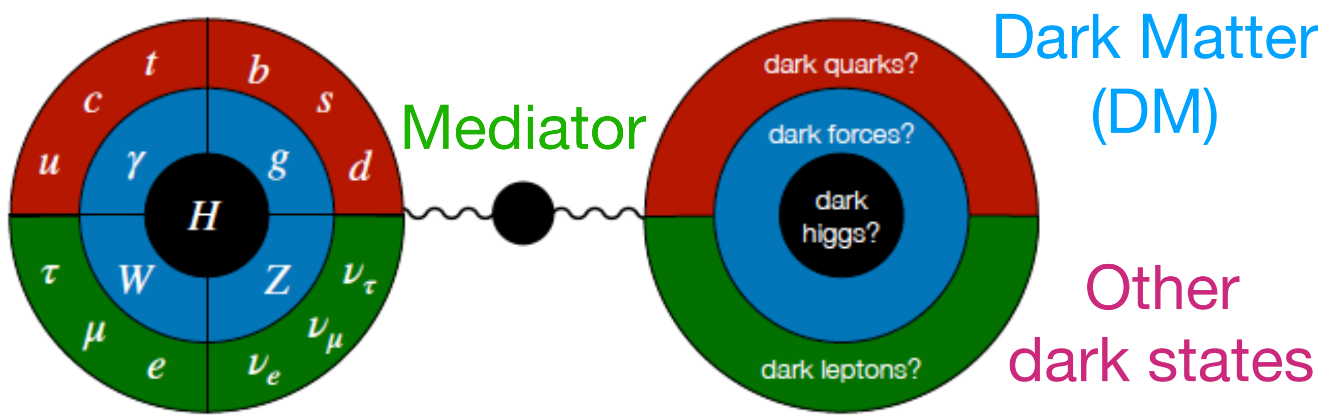


The Standard Model (SM)

The dark sector

Particles neutral under the SM gauge symmetries

What’s a dark sector?



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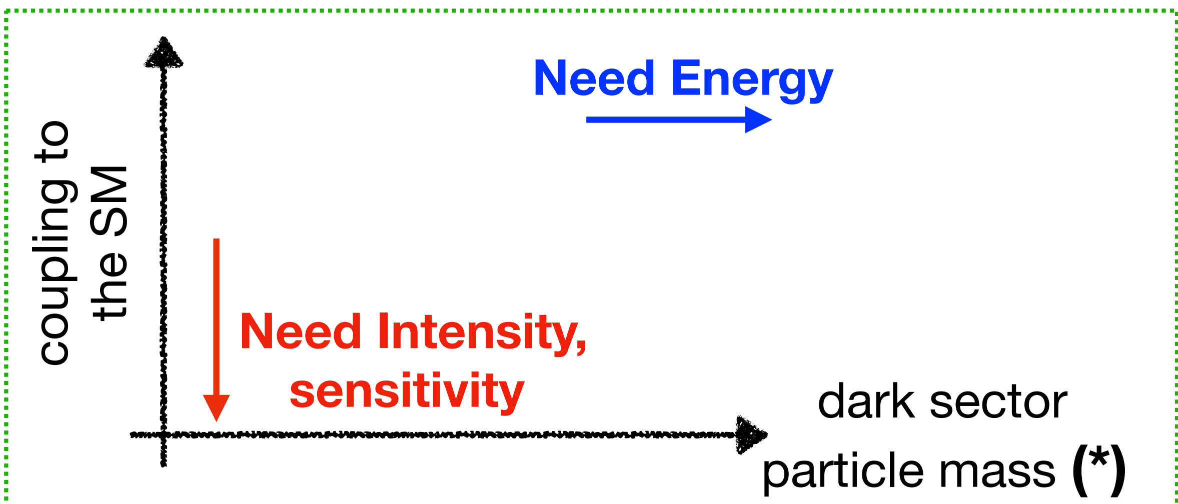
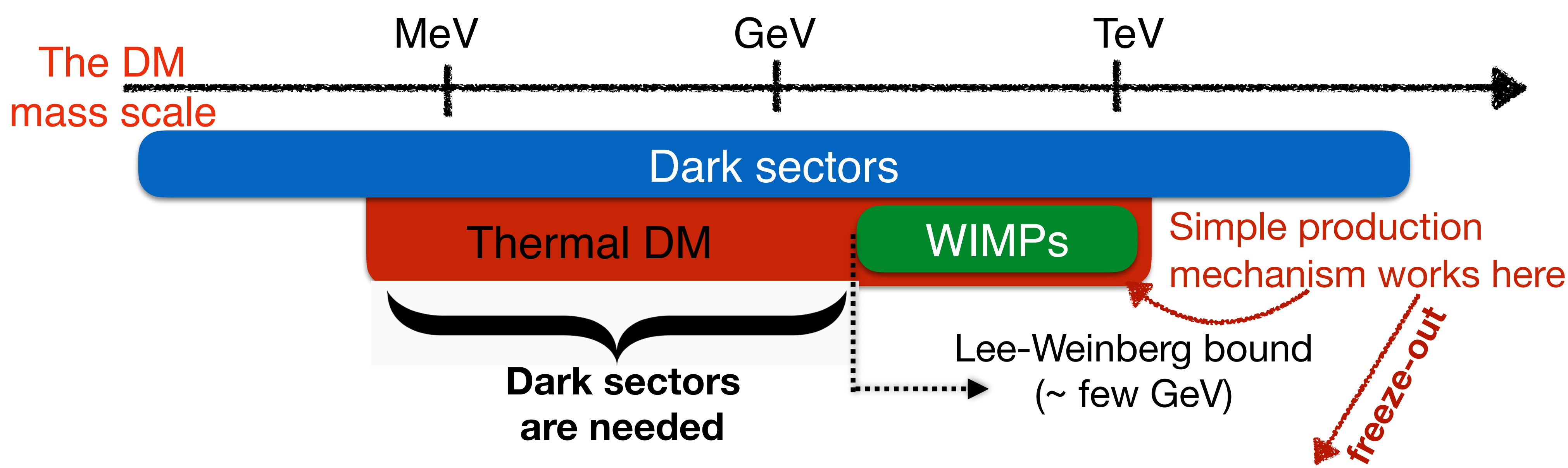
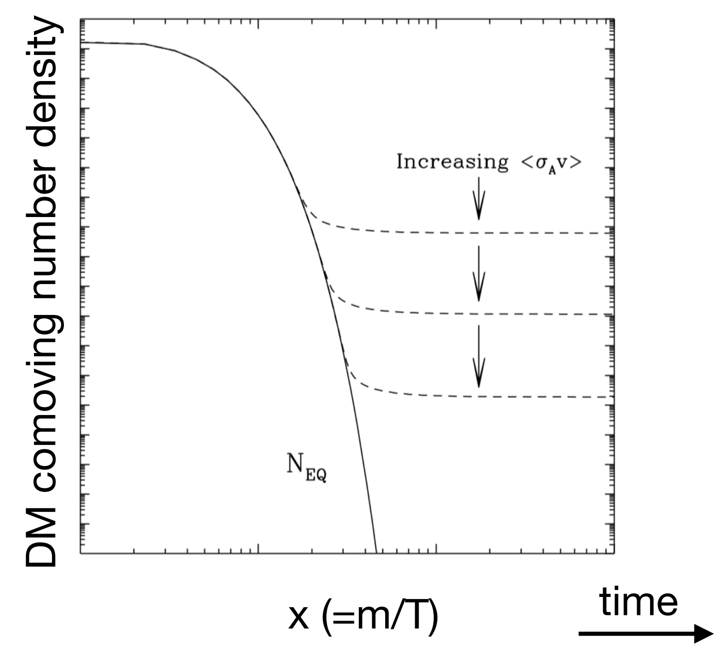


(*) It can be protected by an approximate symmetry

Why a dark sector?…

Dark Matter living in a dark sector





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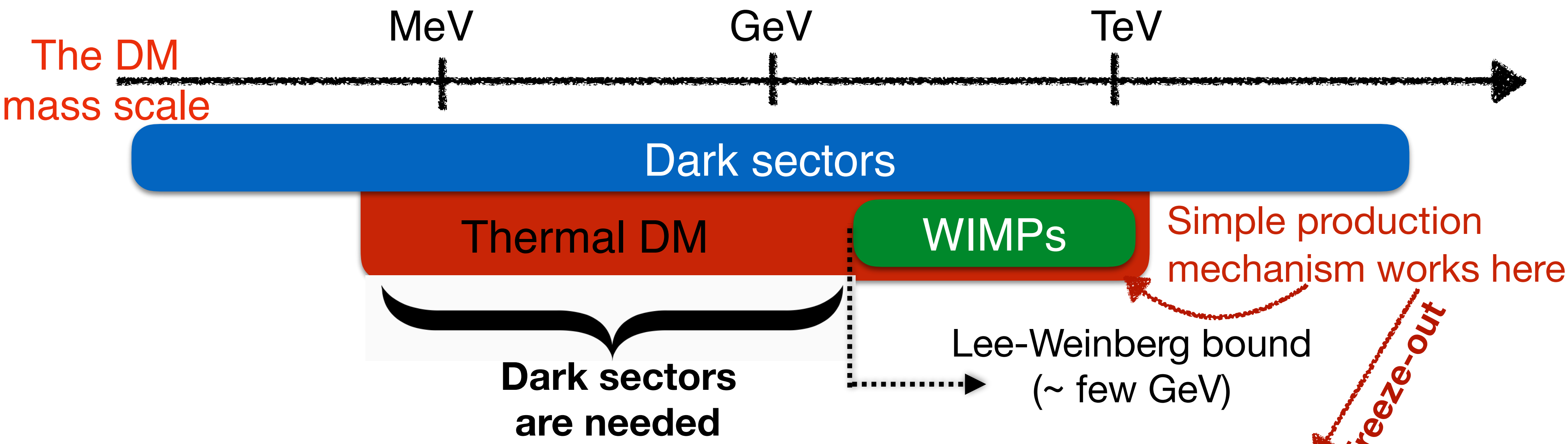
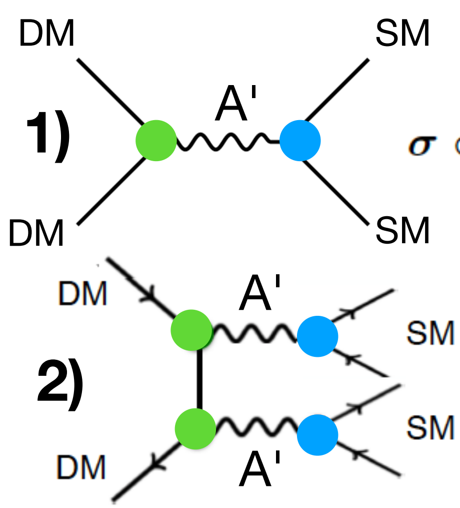


DM thermal freeze-out targets

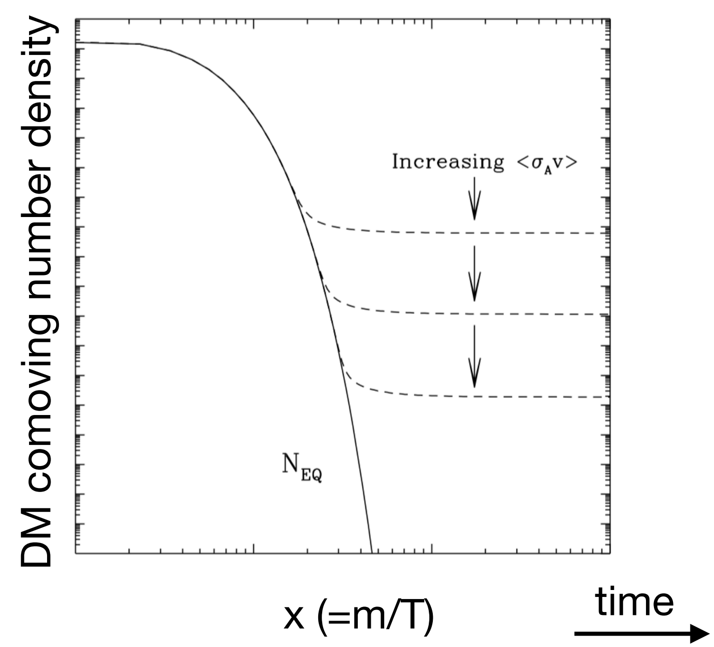


if $m_{A'} > 2m_{DM}$

$$\sigma \propto \frac{y}{m_{DM}^2}, \quad y \equiv \epsilon^2 \alpha_D \left(\frac{m_{DM}}{m_{A'}}\right)^4$$

if $m_{A'} < m_{DM}$

ε is lower bounded



Dark sectors: a generic feature of New Physics models

Beyond the Dark Matter motivation,
dark sectors arise in many theories beyond the Standard Model:

- ✱ Theories motivated by the <u>hierarchy problem</u>:
  - Supersymmetric theories (Next-to-Minimal-Supersymmetric-Standard-Model)
  - Neutral Naturalness
  - Relaxion theories
- ✱ Theories that explain the <u>baryon-antibaryon asymmetry</u>
- ✱ Theories that address the <u>strong CP problem</u>
- ✱ Theories for the generation of <u>neutrino masses</u>

✱ Several anomalies in data can be addressed by dark sectors
(eg. $(g-2)_\mu$, B-physics anomalies, short-baseline neutrino anomalies, …)

From a phenomenological point of view,
the signatures to search for are often similar

Exploring the dark sector

Symmetries of Standard Model provide a framework for the systematic exploration of (weakly-coupled) dark sector physics

- SM gauge-invariant
- Dark sector gauge-invariant
- Lorentz invariant
- Lowest dimensional operator first
- Minimal number of particles first **(*)**
- Flavor invariant operators first **(*)**

simple set of requirements

(*) some studies go beyond this assumption

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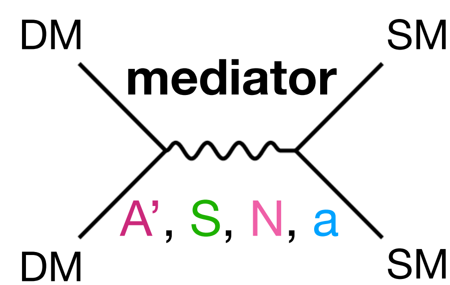
Dark sector portals

Experimental targets

- dark photon $\epsilon B^{\mu\nu} A'_{\mu\nu}$
- dark scalar $\kappa |H|^2 |S|^2$
- sterile neutrino $y H L N$
- ALP $g_{a\gamma} a \tilde{F}_{\mu\nu} F^{\mu\nu}$
- Gauging an anomaly free SM symmetry: B-L, $L_\mu - L_\tau$, …

the couplings are in general small but models do have a lower bound:
e.g., thermal freeze-out; thermalization; anomalies in data, …



The community effort after Snowmass 2013

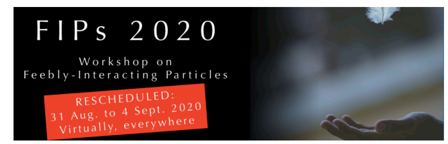
The worldwide search for Dark Sectors has involved hundreds of scientists, new models, many new analyses & experiments in last few years

Vibrant theory + experimental community

Dark Interactions Workshop, BNL, 2014

Dark sectors workshop, SLAC, 2016

Many workshops since 2013:



Cosmic Visions community workshop 2017 (~mini-Snowmass). Community report: Battaglieri et al., 1707.04591

This is also an international effort:
The Physics Beyond Colliders Study Group at CERN, https://pbc.web.cern.ch

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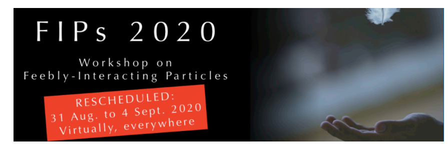

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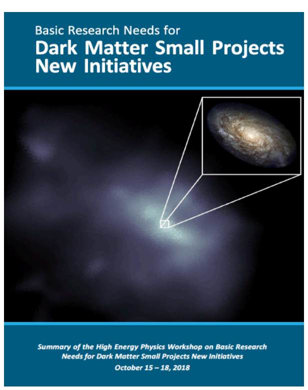


Most recently, Basic Research Needs (BRN) workshop 2018:
DOE-charged panel with the goal of identifying priority science in Dark Matter scope, achievable with small US-based experiments.
DM Small projects New Initiatives (DMNI)

https://science.osti.gov/-/media/hep/pdf/Reports/Dark_Matter_New_Initiatives_rpt.pdf

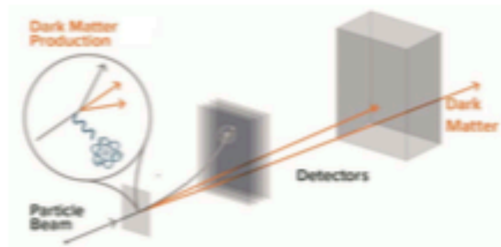
DM New Initiatives (DMNI)

Summary of the High Energy Physics Workshop on Basic Research Needs for Dark Matter Small Projects New Initiatives

October 15 – 18, 2018

PRD 1

Create & Detect Dark-Matter Particles at Accelerators

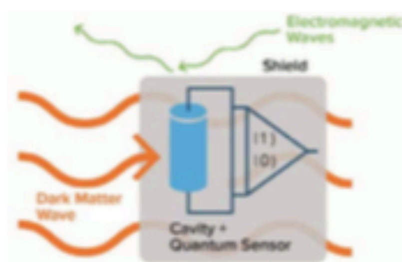


PRD 2

Detect Galactic Particle Dark Matter Underground

PRD 3

Detect Galactic Wave Dark Matter in the Laboratory



Success!

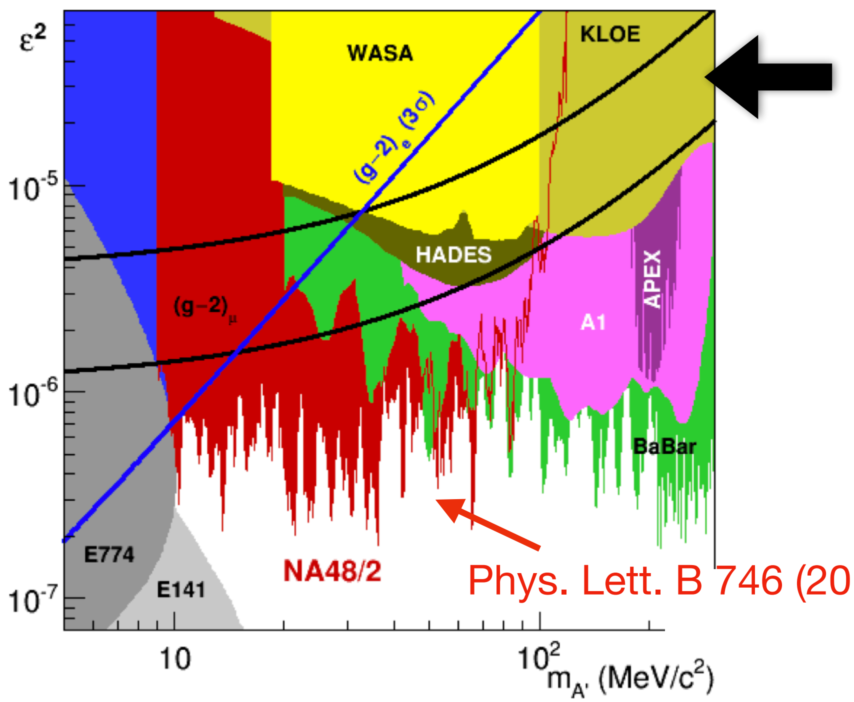
Experiments in all 3 PRDs received planning funds through 2019 FOA 8

high intensities

Thrust 1 (near term):
Through 10- to 1000-fold improvements in sensitivity over current searches, use particle beams to explore interaction strengths singled out by thermal dark matter across the electron-to-proton mass range.
(CCM & LDMX got partial support)

Thrust 2 (near and long term):
Explore the structure of the dark sector by producing and detecting unstable dark particles.

Several milestones were reached after 2013

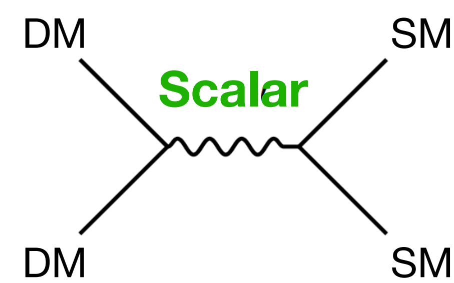


Phys. Lett. B 746 (2015) 178

Dark photon explanation of **$(g-2)_\mu$** is now fully probed

Scalar-mediated thermal DM is now completely probed

Krnjaic, 1512.04119



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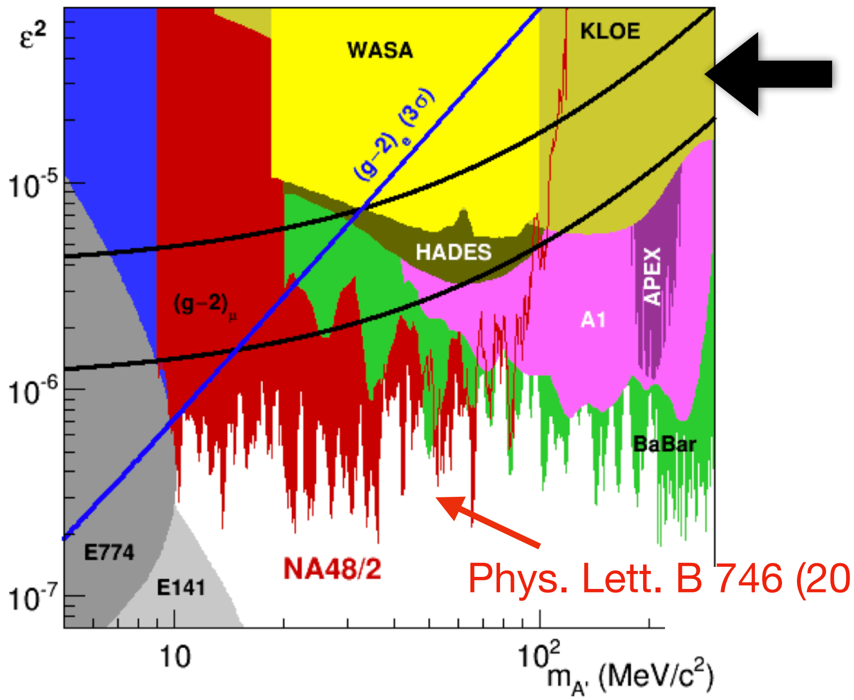

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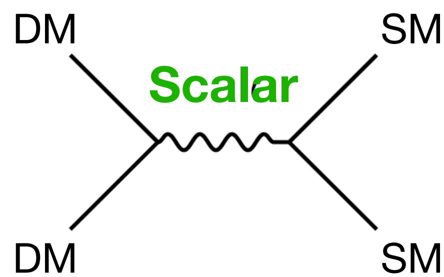
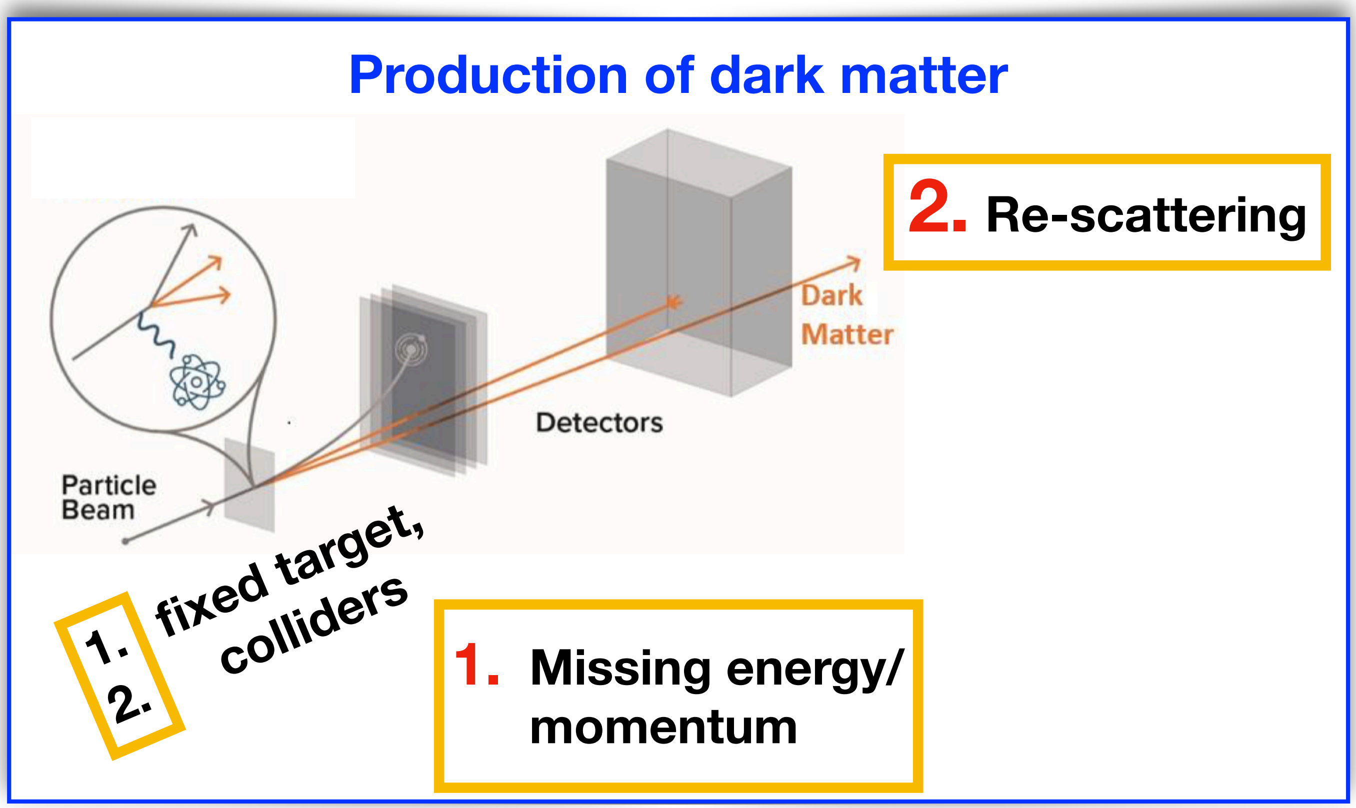


Rapid development of the field.

- New dedicated experiments (e.g. fixed targets, beam dumps, long-lived particle detectors, …);
- Novel analyses of data to discover dark sectors at multi-purpose experiments;

- New theories for DM (e.g. strongly interacting massive particles, Hochberg et al. 1411.3727);
- New theories to address the hierarchy problem (e.g. relaxion models, Graham et al. 1504.07551).
- New theories to address anomalies in data (e.g. $(g-2)_\mu$, MiniBooNE, …)

Search techniques for dark sectors at high intensities



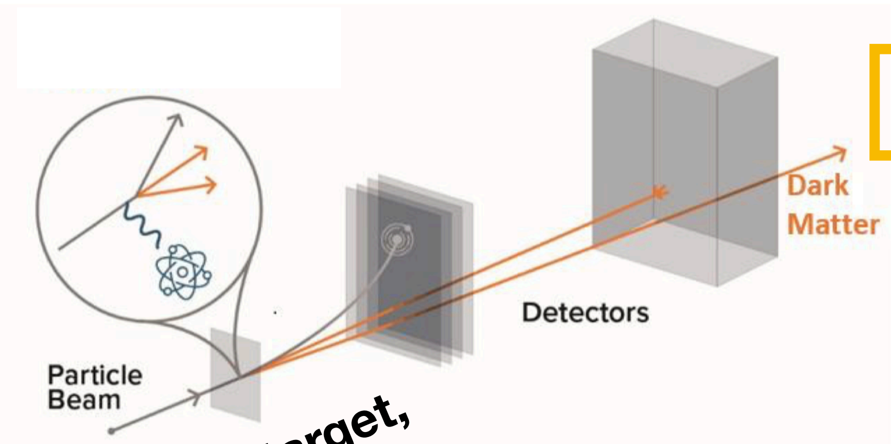
The experimental techniques are only 3

Basic Research Needs for
DM Small projects New Initiatives (DMNI),
2018

https://science.osti.gov/-/media/hep/pdf/Reports/Dark_Matter_New_Initiatives_rpt.pdf

Search techniques for dark sectors at high intensities

Production of dark matter



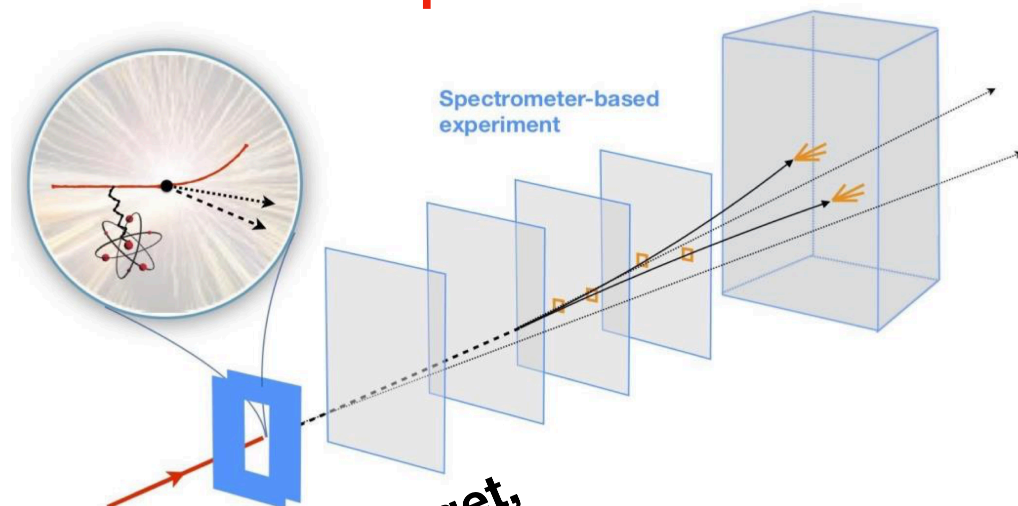
2. Re-scattering

1. 2. fixed target, colliders

1. Missing energy/ momentum

The experimental techniques are only 3

Production of unstable dark sector particles



1. 2. fixed target, colliders

3. Visible decay products

Basic Research Needs for
DM Small projects New Initiatives (DMNI),
2018

https://science.osti.gov/-/media/hep/pdf/Reports/Dark_Matter_New_Initiatives_rpt.pdf

Latest results &
What to do next?

What do we want this field to look like in ~10 years?
What is within reach? What should we focus on?

RF6, Dark Sectors at High Intensity

Conveners: Stefania Gori (sgori@ucsc.edu), Mike Williams (mwill@mit.edu)

Organization around science goals/questions.
We built on what we have learned since 2013.

We defined **three Big Ideas** each with associated ambitious —but achievable—goals for the next decade

The draft of the report: https://www.overleaf.com/read/ggdtjhvnmgjs

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1. Dark matter production at intensity-frontier experiments
(focus on exploring sensitivity to thermal DM interaction strengths).
Editors: G. Krnjaic, N. Toro (https://arxiv.org/abs/2207.00597)

2. Exploring dark sector portals with intensity-frontier experiments
(focus on minimal portal interactions).
Editors: B. Batell, C. Hearty (https://arxiv.org/abs/2207.06905)

3. New flavors and rich structures of the dark sector at intensity-frontier experiments
(focus on beyond minimal models)
Editors: P. Harris, P. Schuster, J. Zupan (https://www.dropbox.com/s/gksd3y43k0vtpyw/Snowmass_RF6_Big_Idea_3.pdf?dl=0)

4. Experiments / facilities.
Editors: P. Ilten, N. Tran (https://arxiv.org/abs/2206.04220)

The draft of the report: https://www.overleaf.com/read/ggdtjhvnmgjs

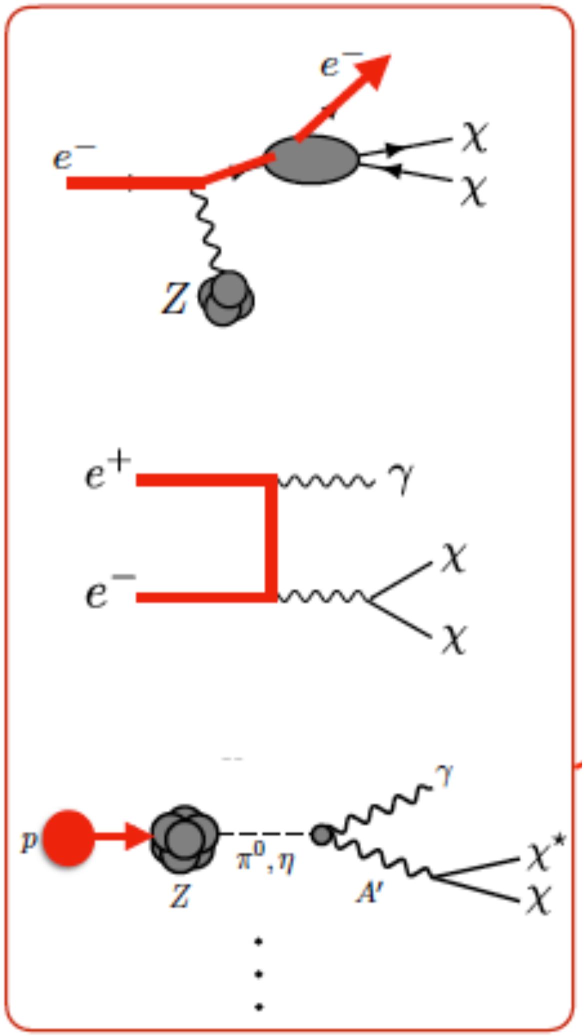
Big idea 1

DM production at high intensities

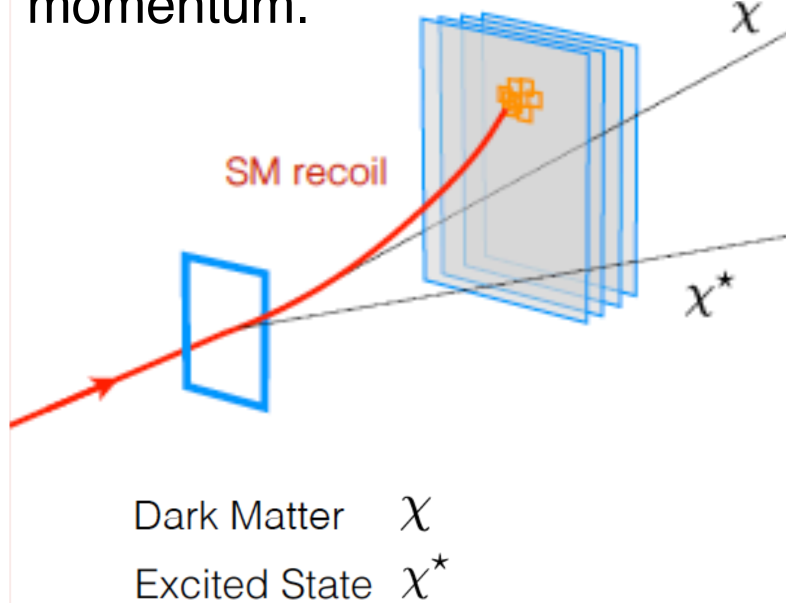
see also N. Toro's talk at the DM cross-frontier session (Tuesday 07/19, 8:25am)

Big idea 1: DM production at high intensities

https://arxiv.org/abs/2207.00597



(1)
"Disappearance" of a sizable fraction of the beam energy/ momentum.



Synergy with auxiliary detectors at collider experiments

Big idea 1: DM production at high intensities

https://arxiv.org/abs/2207.00597

(proton beam: synergistic with the accelerator-based **neutrino physics program**) ⇨ Detection of DM scattering in forward detectors. **(2)**

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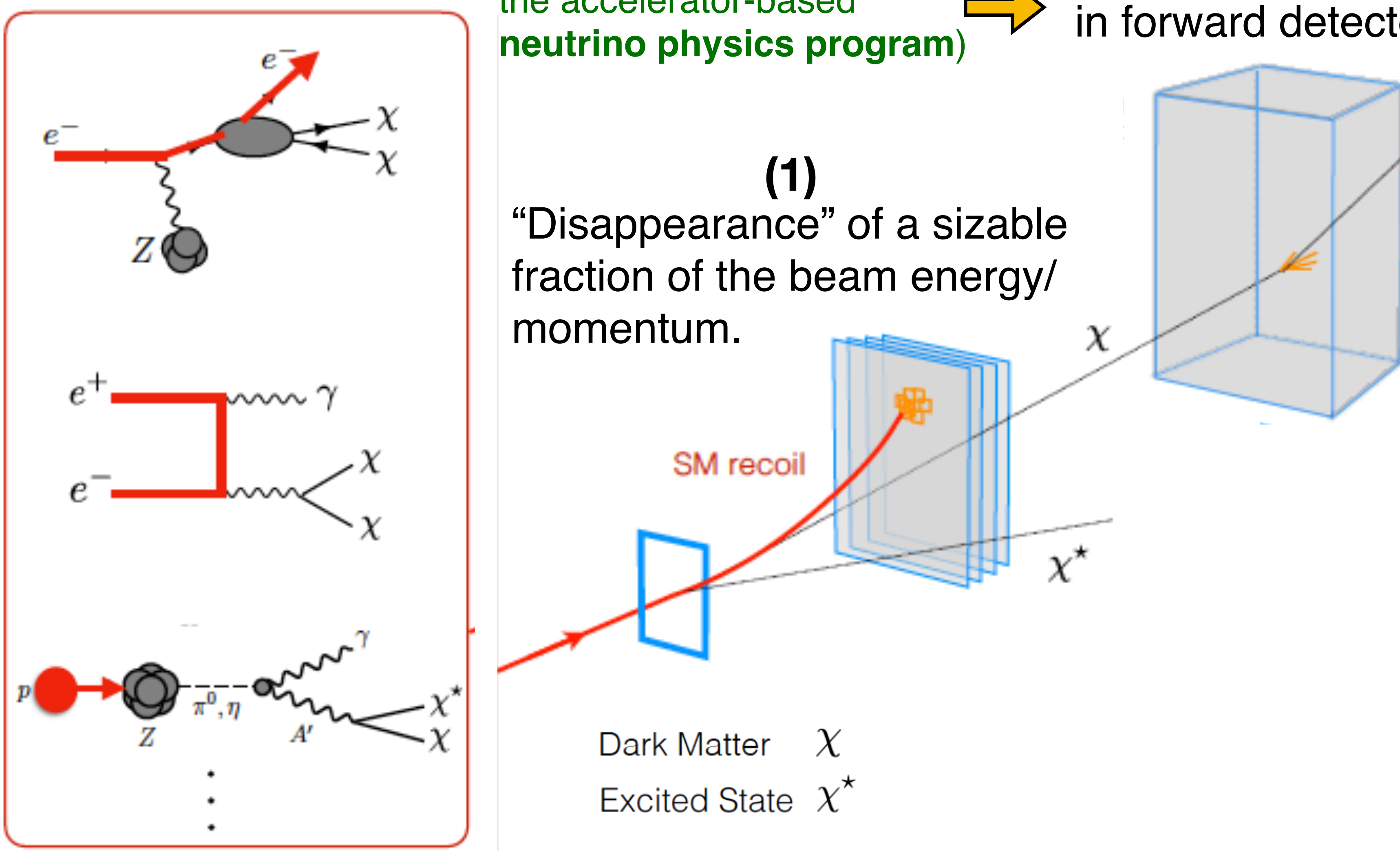

Synergy with auxiliary detectors at collider experiments

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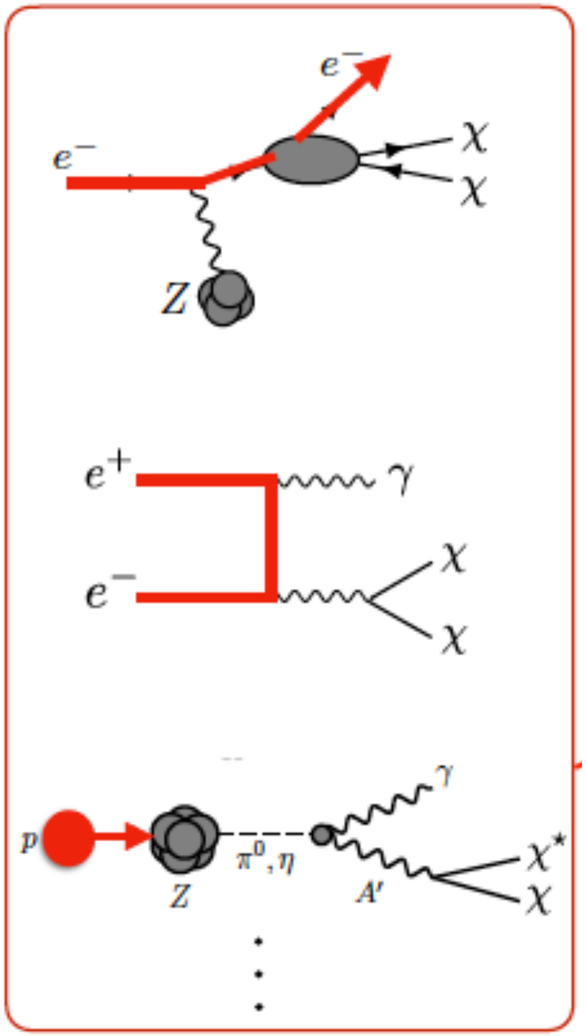

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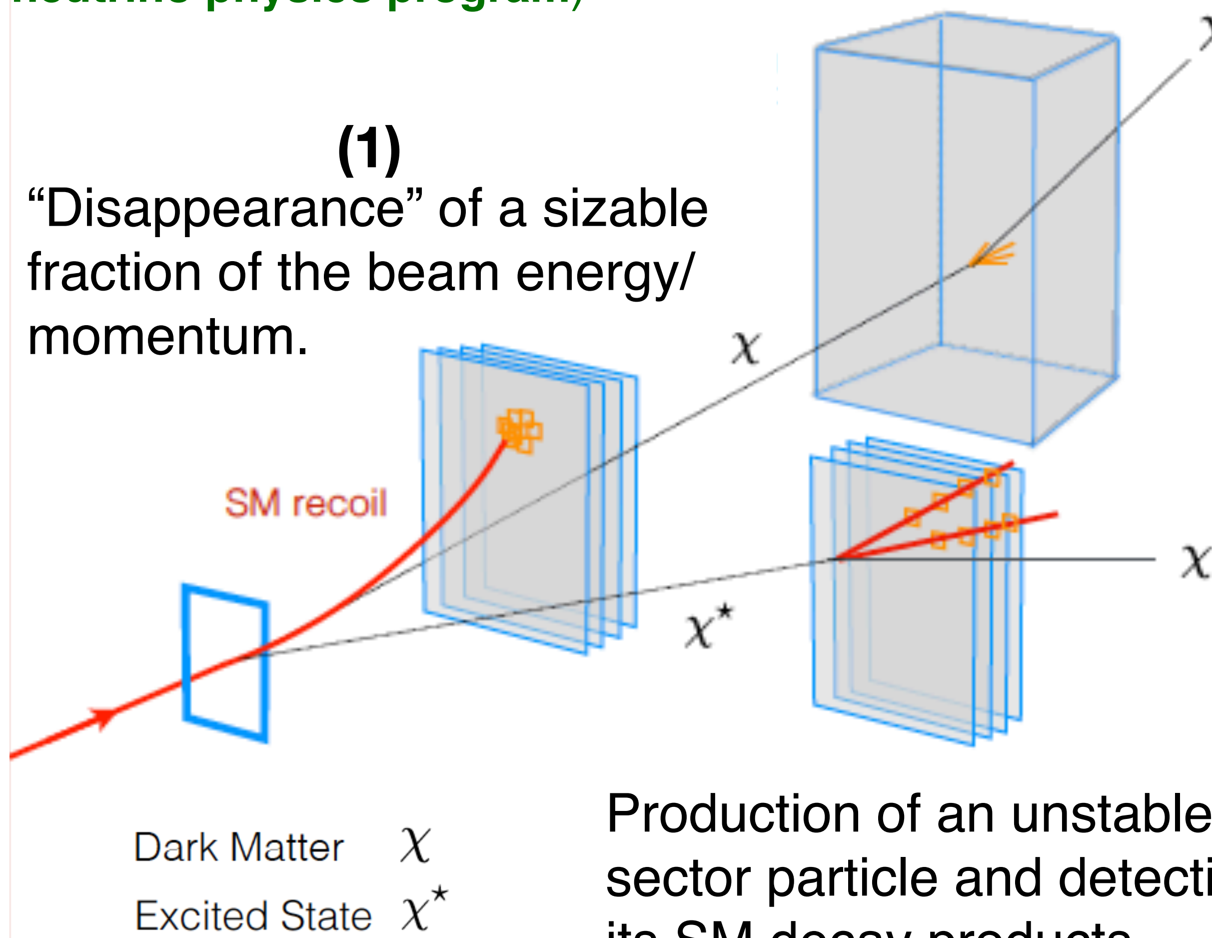
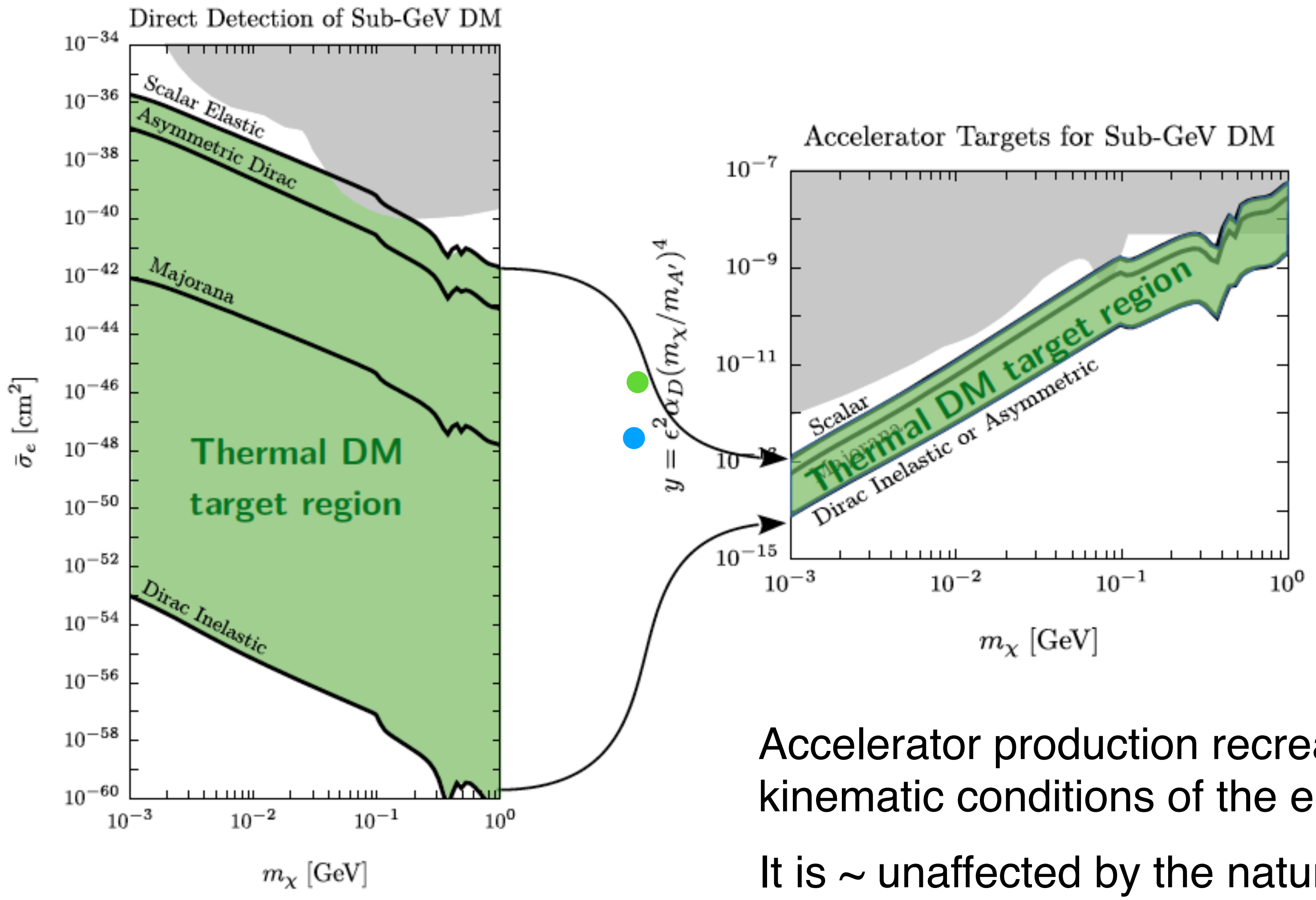
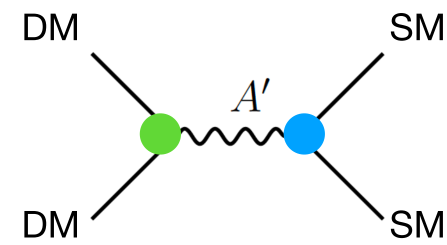


(3)
Production of an unstable dark sector particle and detection of its SM decay products.

Synergy with auxiliary detectors at collider experiments

Complementarity with DM direct detection





if $m_{A'} > 2m_{DM}$

$$\sigma \propto \frac{y}{m_{\rm DM}^2},$$

$$y \equiv \epsilon^2 \alpha_D \left(\frac{m_{\rm DM}}{m_{A'}}\right)^4$$

Accelerator production recreates the kinematic conditions of the early universe.

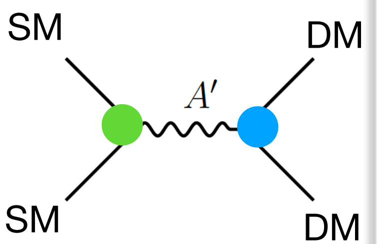
It is ~ unaffected by the nature of DM

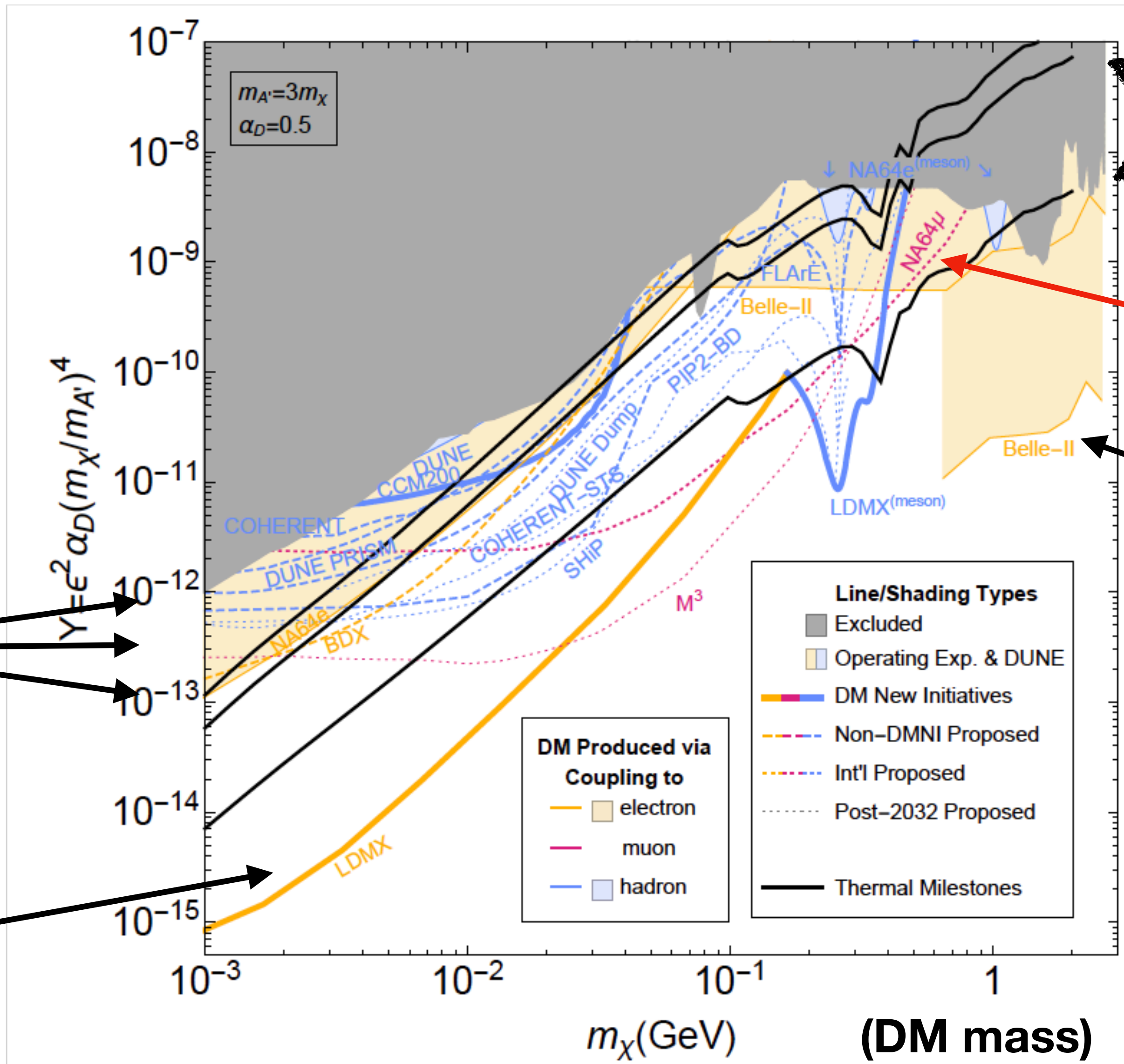
A broad experimental program encompassing both accelerator and direct detection searches is necessary

DM thermal milestones

$\epsilon B^{\mu\nu} A'_{\mu\nu}$

A'→XX





benchmarks for thermal DM

(1) Missing energy

(1) Collider, mono-photon search

(2) Re-scattering

(1) Missing momentum

Dark photon mediated DM

DM thermal milestones

$\epsilon B^{\mu\nu} A'_{\mu\nu}$

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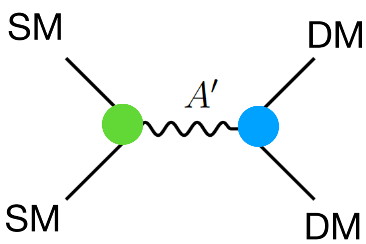
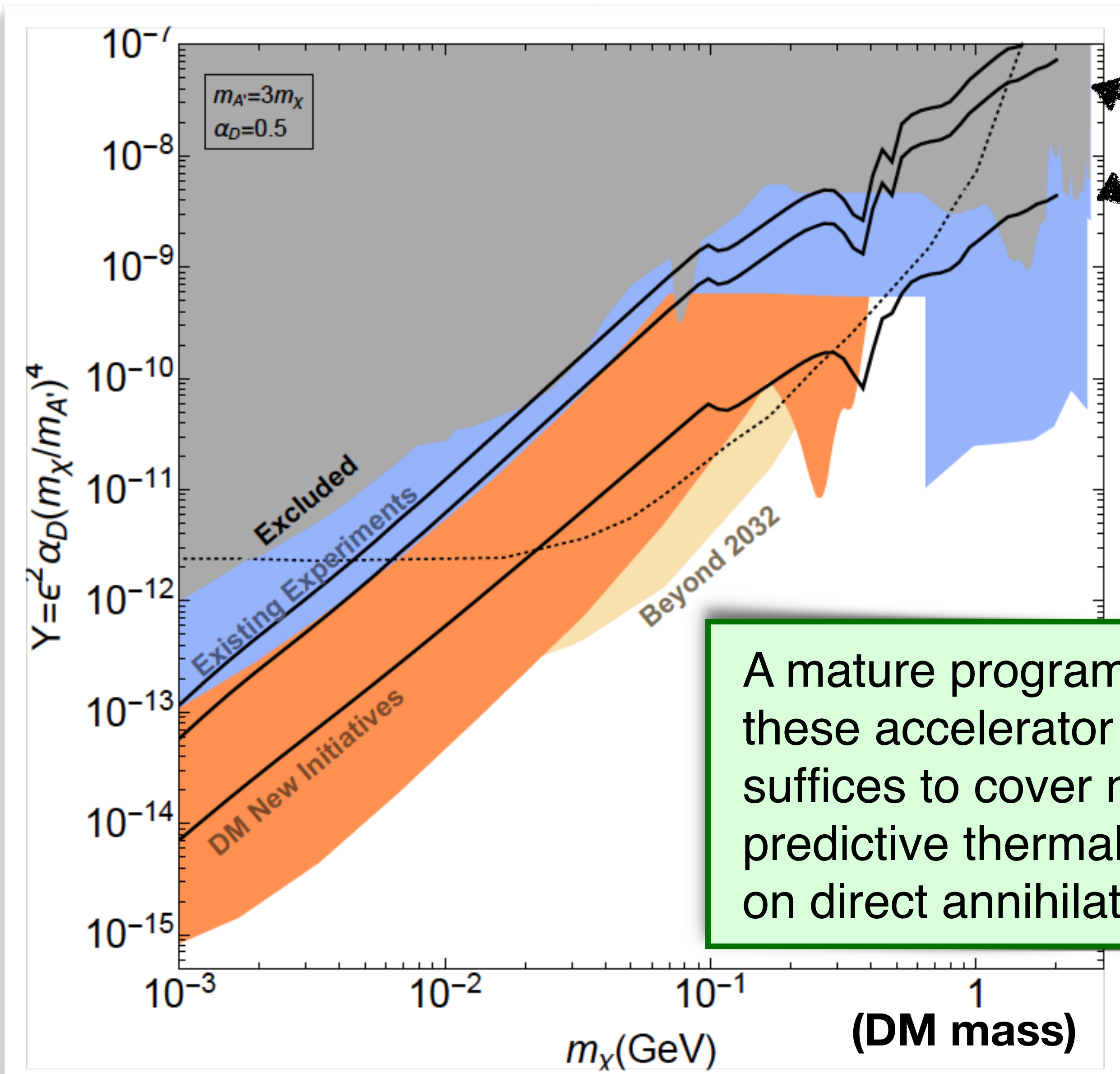


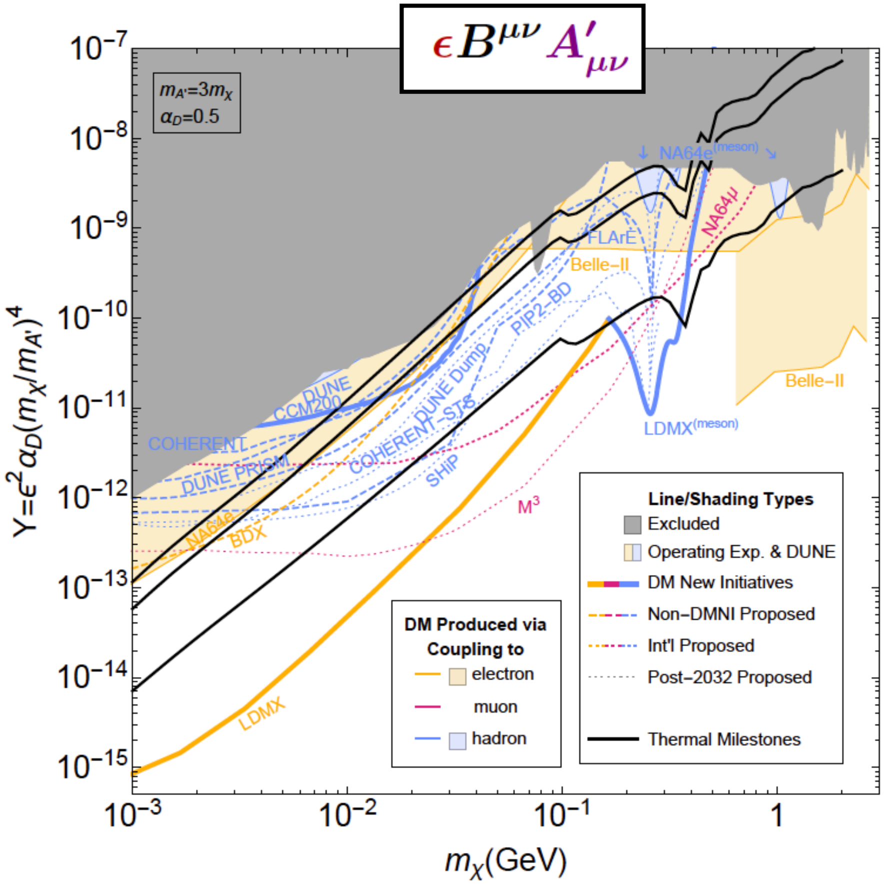


benchmarks for thermal DM

A mature program that combines these accelerator based efforts suffices to cover nearly all of the predictive thermal targets based on direct annihilation

Dark photon mediated DM

Beyond the dark photon scenario

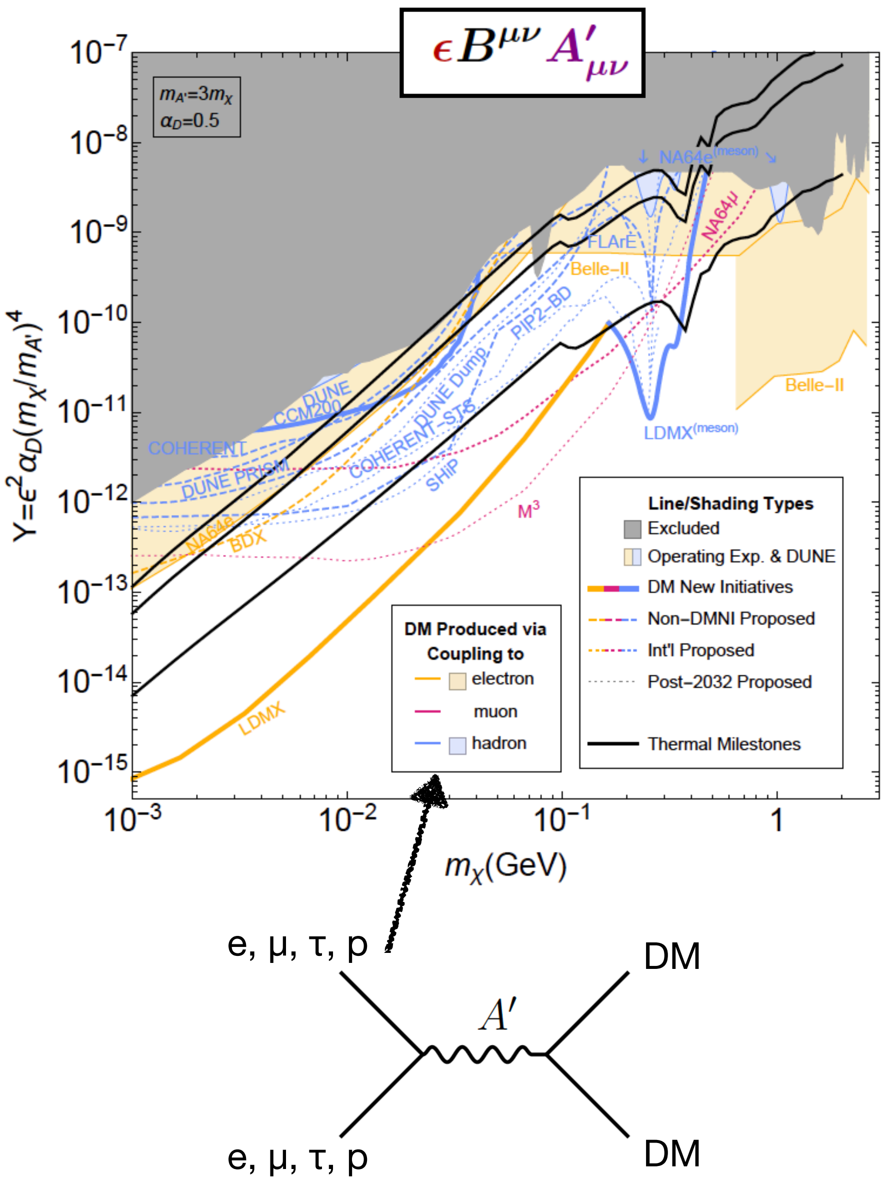


The breadth of ideas within this program is important for several reasons.

- In the case of discovery the ability to measure dark sector masses and interaction strengths

.

Beyond the dark photon scenario



The breadth of ideas within this program is important for several reasons.

- In the case of discovery the ability to measure dark sector masses and interaction strengths

- More in general, probe generalizations of thermal freeze-out, such as

- those where a mediator does not couple to electrons but preferentially to μ and/or τ leptons or baryons. ⟵

- Models where meta-stable particles in the dark sector play important roles in DM cosmology and enable new discovery techniques

.

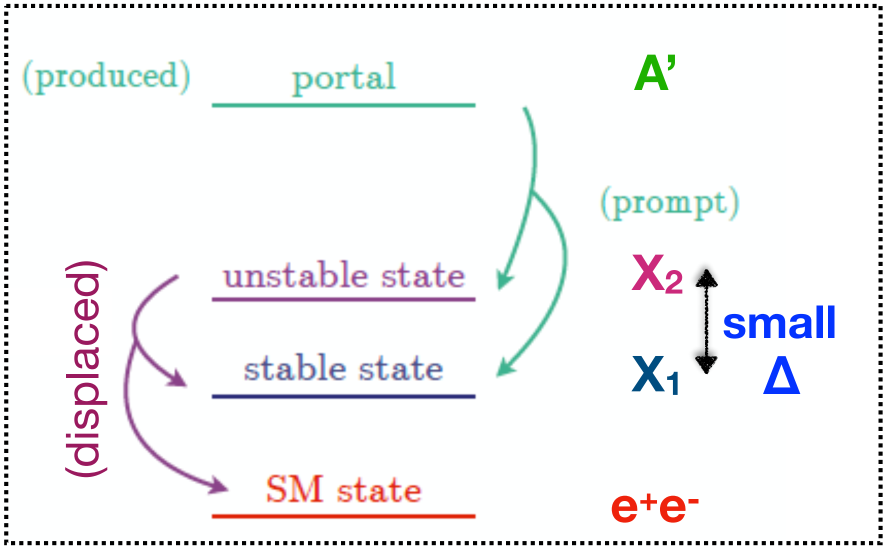
DM models with metastable particles

Inelastic Dark Matter

Tucker-Smith, **Weiner**, 0101138

$$\mathcal{L} \supset \frac{ie_D\, m_D}{\sqrt{m_D^2 + (\delta_\xi - \delta_\eta)^2/4}} A'_\mu \left(\bar{\chi}_1 \gamma^\mu \chi_2 - \bar{\chi}_2 \gamma^\mu \chi_1\right)$$

* A non-minimal freeze-out mechanism:
  $X_1\, X_2 \to$ SM
  DM **DM excited state**



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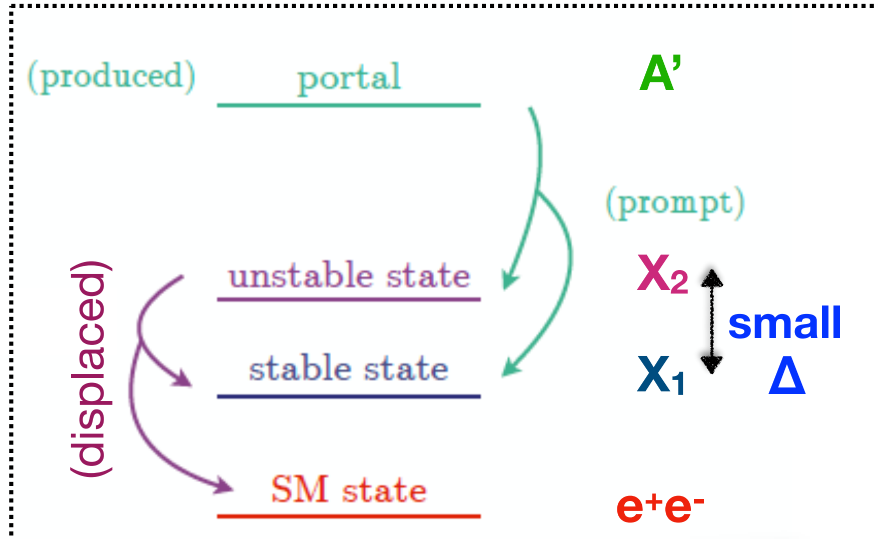


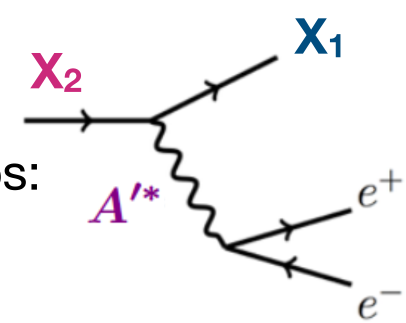
* A non-minimal freeze-out mechanism:

  $X_1\ X_2 \rightarrow$ SM

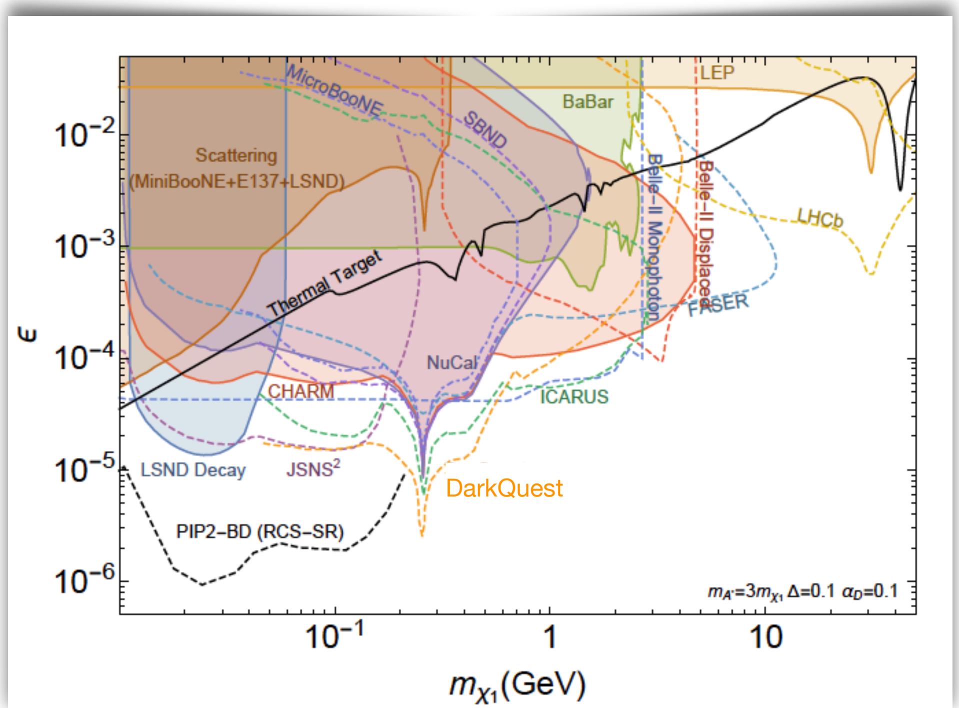
  DM **DM excited state**

* Signatures in our labs:

  $X_2 \rightarrow X_1\, e^+ e^-$



- Prompt visible decays
- Long lived particles
- Invisible component



Big idea 2

Exploring dark sector portals at high intensities

see also B. Batell's talk
at the Long-Lived-Particles cross-frontier session (Wednesday 07/20, 10:50am)

Additional studies done in RF2 "Weak Decays of Strange and Light Quarks"
https://www.overleaf.com/project/624974a61ca81b31df6471da

Big idea 2: dark sector portals at high intensities

https://arxiv.org/abs/2207.06905

Explore the structure of the dark sector by producing and detecting unstable dark particles: Minimal Portal Interactions.

- dark photon $\epsilon B^{\mu\nu} A'_{\mu\nu}$
- dark scalar $\kappa |H|^2 |S|^2$
- sterile neutrino $y H L N$
- ALP $g_{a\gamma} a \tilde{F}_{\mu\nu} F^{\mu\nu}$
- New gauge symmetries: B-L, $L_\mu - L_\tau$, …

$$A' \to \ell^+\ell^-, \ldots$$
$$S \to \mu^+\mu^-,\ \pi^+\pi^-, KK, \ldots$$
$$N \to \ell\pi, \ldots$$
$$a \to \gamma\gamma,$$
$$Z' \to \mu^+\mu^-, \ldots$$

"visible" signatures

How to test these couplings?

Sizable coupling → **prompt** decay (generically larger backgrounds)

Small coupling → **displaced** decay (generically small backgrounds)

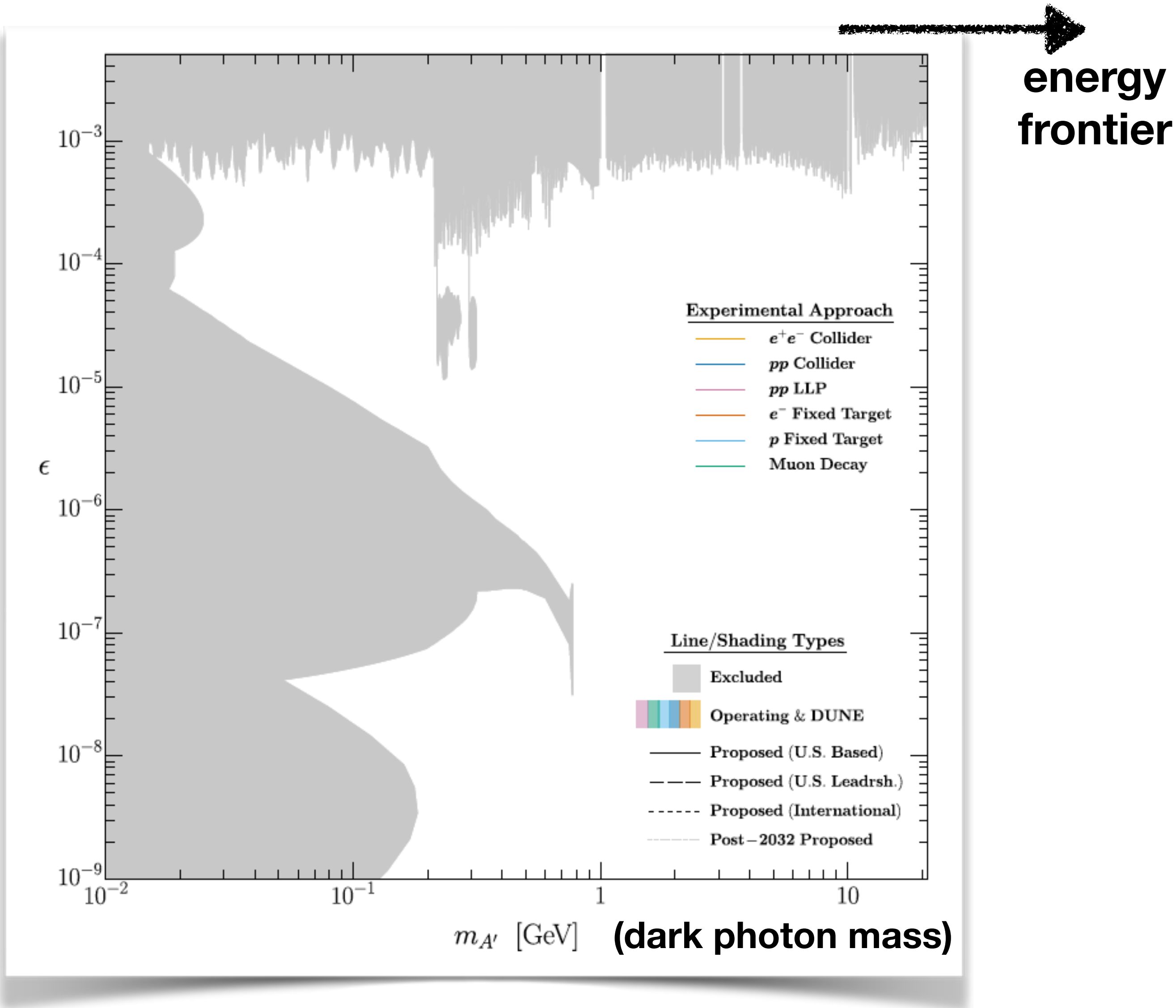
Experimental targets:

Secluded DM scenarios (Pospelov, Ritz, Voloshin, 0711.4866)

Forbidden DM scenarios (D'Agnolo, Ruderman, 1505.07107)

Exploring visible dark photons

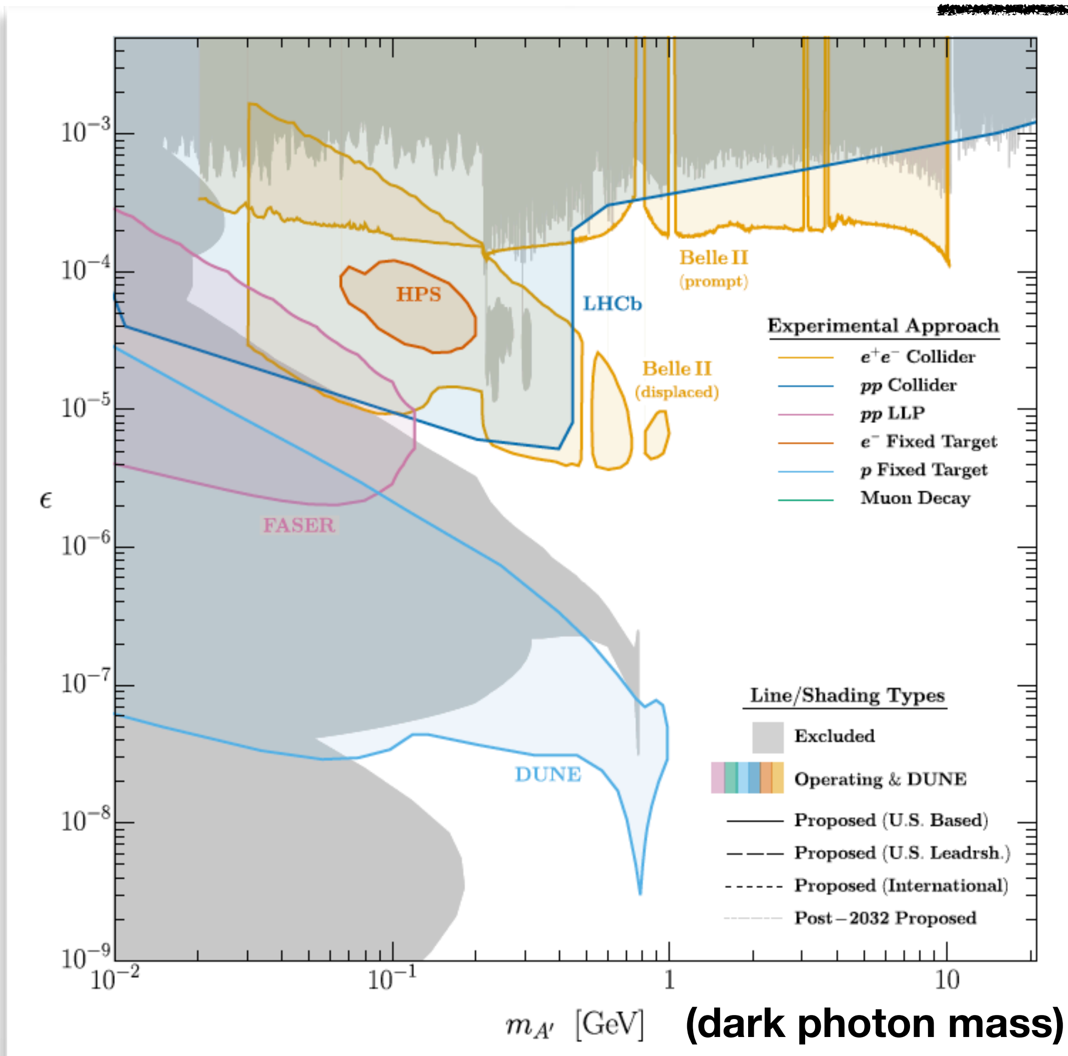
$\epsilon B^{\mu\nu} A'_{\mu\nu}$



This entire parameter space predicts a **dark sector in thermal equilibrium** with the SM

Exploring visible dark photons

$\epsilon B^{\mu\nu} A'_{\mu\nu}$



energy frontier

(dark photon mass)

This entire parameter space predicts a **dark sector in thermal equilibrium** with the SM

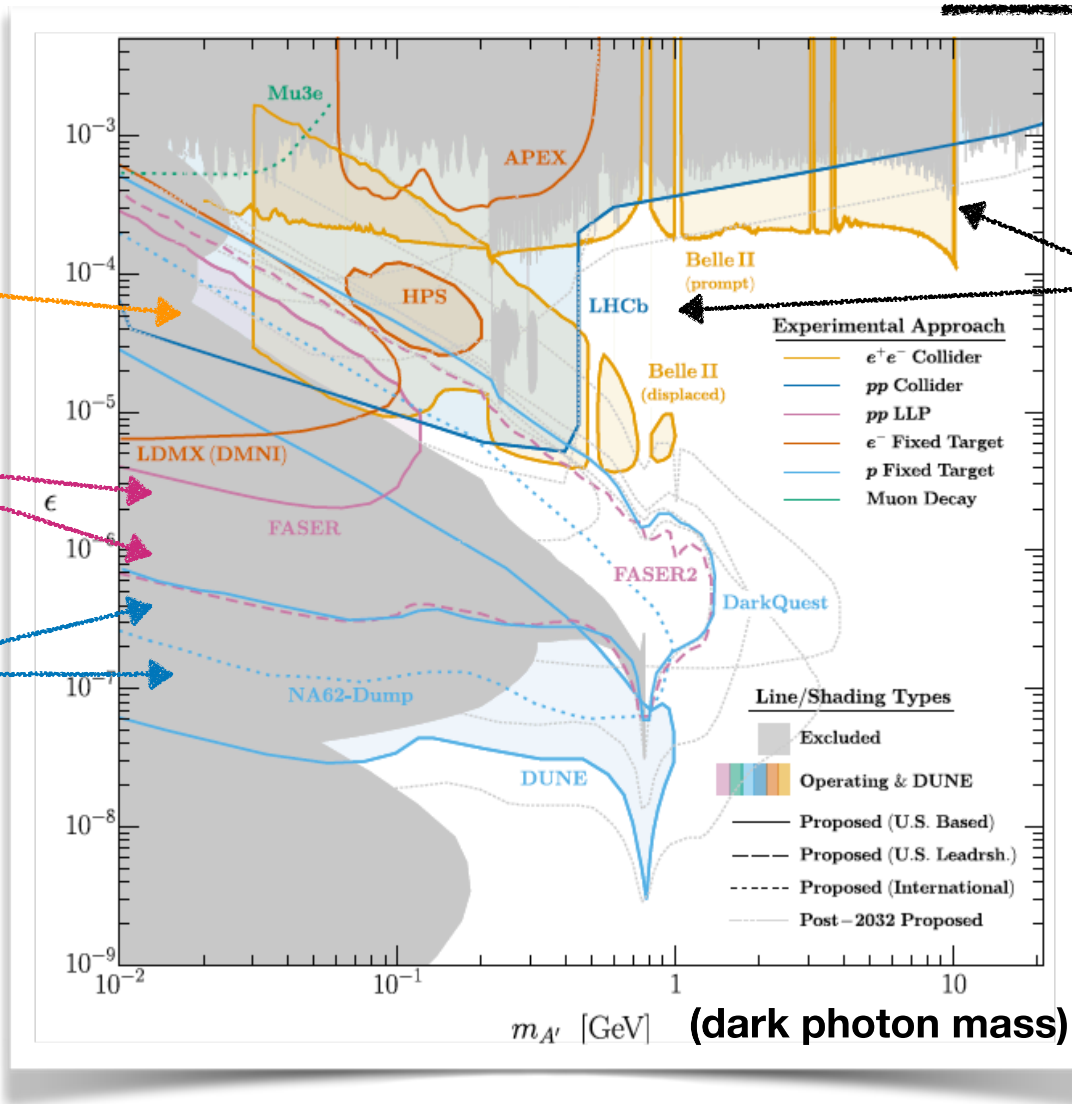
Exploring visible dark photons

$\epsilon B^{\mu\nu} A'_{\mu\nu}$

electron fixed target

forward detectors

proton beam-dump



energy frontier

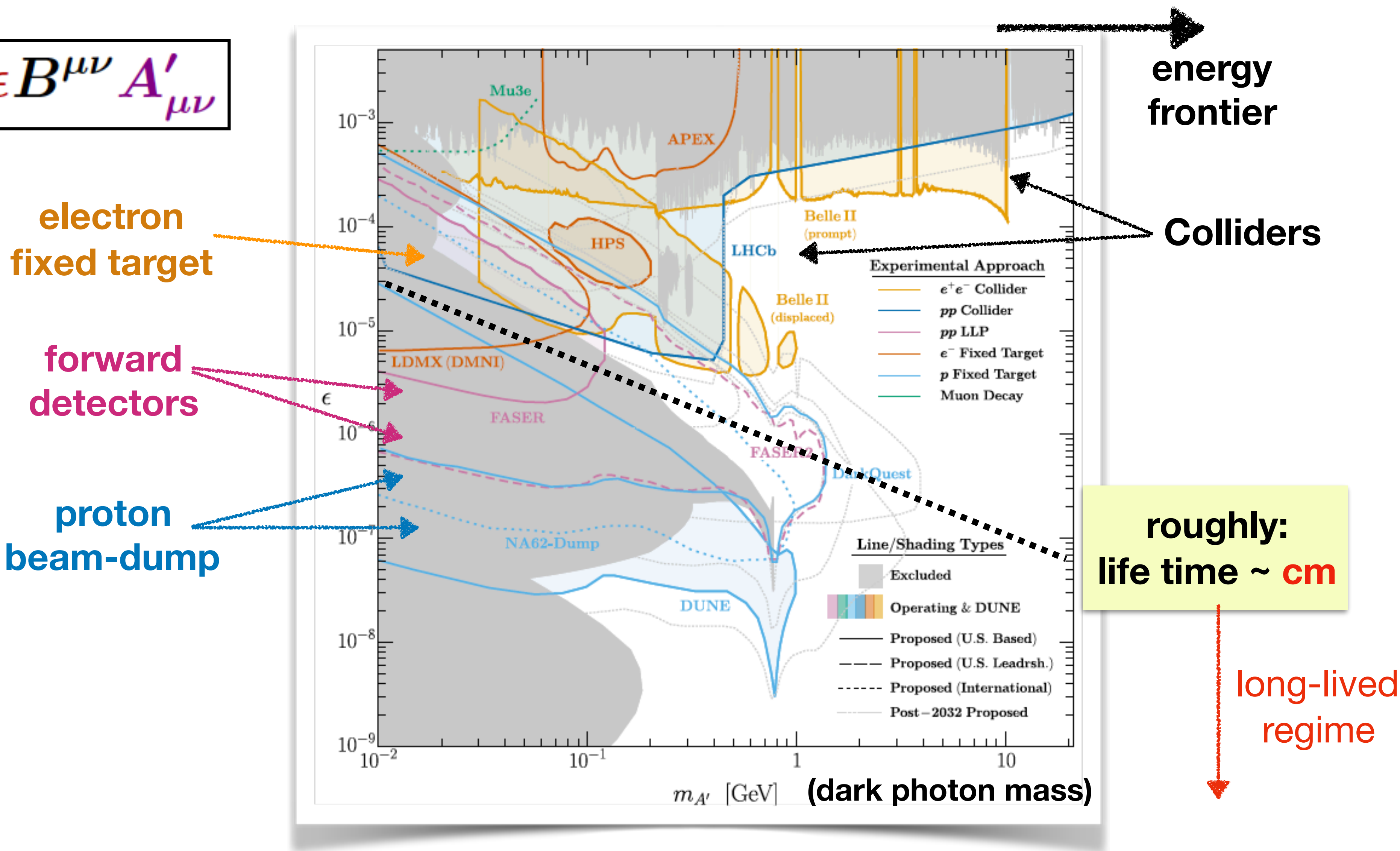
Colliders

(dark photon mass)

This entire parameter space predicts a **dark sector in thermal equilibrium** with the SM

Exploring visible dark photons

$\epsilon B^{\mu\nu} A'_{\mu\nu}$



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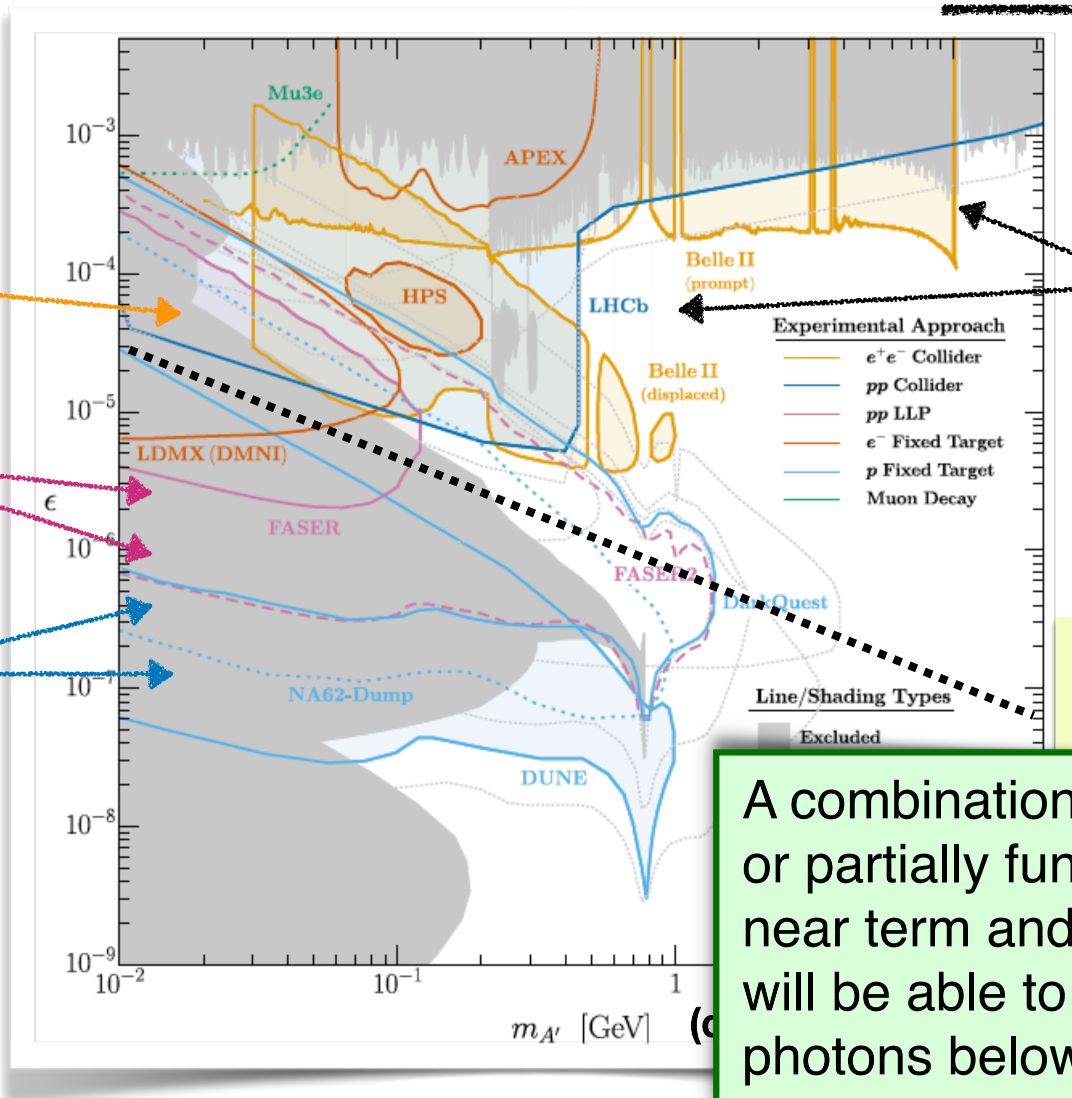
Exploring visible dark photons

$\epsilon B^{\mu\nu} A'_{\mu\nu}$

electron fixed target

forward detectors

proton beam-dump



energy frontier

Colliders

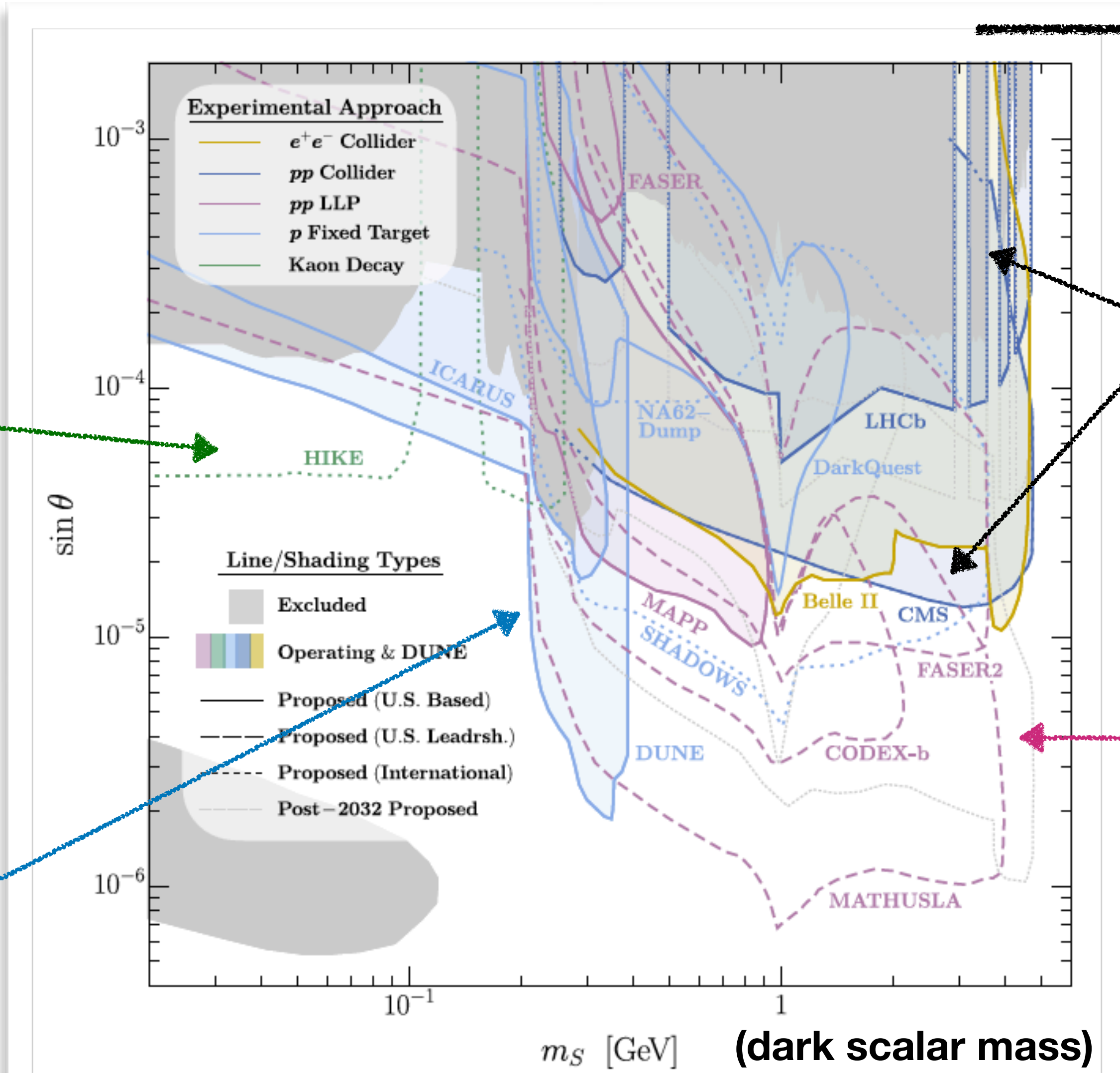
roughly: life time ~ cm

A combination of operating, fully or partially funded, and proposed near term and future experiments will be able to broadly probe dark photons below the GeV scale

This entire parameter space predicts a **dark sector in thermal equilibrium** with the SM

Exploring visible dark scalars

$$\kappa |H|^2 |S|^2$$



energy frontier

Colliders

Kaon factories

Other models (sterile neutrinos) can be probed at next generation pion factories (PIONEER)

proton beam-dump

LHC auxiliary detectors

This parameter space can be predicted in relaxion models (to address the hierarchy problem)

This entire parameter space predicts a **dark sector in thermal equilibrium** with the SM

Big idea 3

New flavors and rich structures of the dark sector at high intensities

Big idea 3: richer dark sectors

https://www.dropbox.com/s/gksd3y43k0vtpyw/Snowmass_RF6_Big_Idea_3.pdf?dl=0

New Flavors and Rich Structures in Dark Sectors.

To-date, much of the emphasis for experimental work on dark sectors has been anchored to minimal models (i.e. minimal number of particles & flavor universality).

New necessary step: more complete coverage of non-minimal dark sector models

Richer phenomenology ⇒ rethinking of experimental strategies for achieving optimized sensitivities

Big idea 3: richer dark sectors

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Richer phenomenology ⇨ rethinking of experimental strategies for achieving optimized sensitivities

2 themes:

- Dark sector benchmarks that address anomalies in data
  E.g. $(g-2)_\mu$, flavor anomalies, Xenon 1T excess, MiniBooNE excess, …

- Commonly used benchmarks going beyond the assumption of minimality
  E.g. (1) flavor violating ALPs, (2) DM models with a DM excited state (inelastic DM, strongly interacting massive particles, …))

Addressing anomalies in data, $(g-2)_\mu$

After the last Snowmass, our community was able to probe minimal dark sector models addressing the $(g-2)_\mu$ anomaly.

Can we fully probe a light explanation of $(g-2)_\mu$ even beyond minimal models?

Addressing anomalies in data, $(g-2)_\mu$

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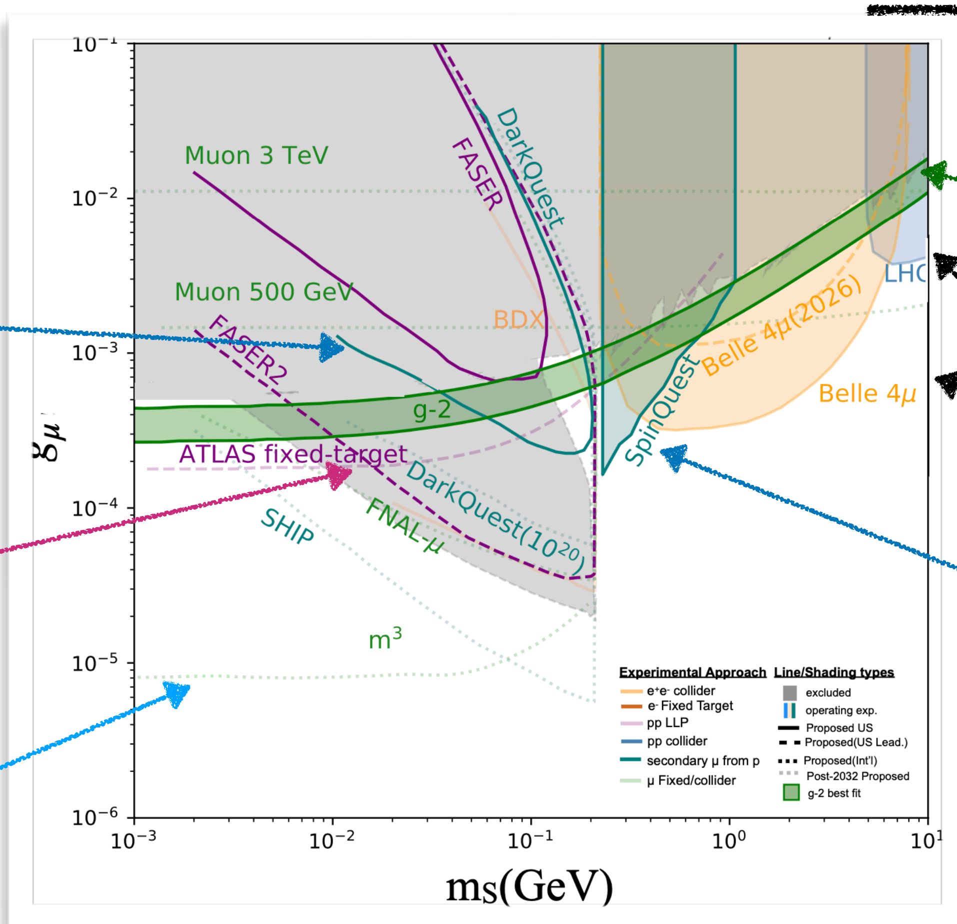
Can we fully probe a light explanation of $(g-2)_\mu$ even beyond minimal models?

Example

$$g_\mu S \bar{\mu} \mu + \text{h.c.}$$

flavor specific dark sectors



proton beam-dump

LHC auxiliary detectors

Missing momentum

energy frontier

$(g-2)_\mu$ region

Colliders

proton beam-dump

DM in a strongly interacting dark sector

Dark Matter can be the lightest state of a dark QCD-like theory (e.g. a dark pion)

Novel process responsible of freeze-out: $3 \to 2$ annihilation ⇦ Motivation to consider MeV-GeV DM!

The additional dark states will lead to a richer phenomenology

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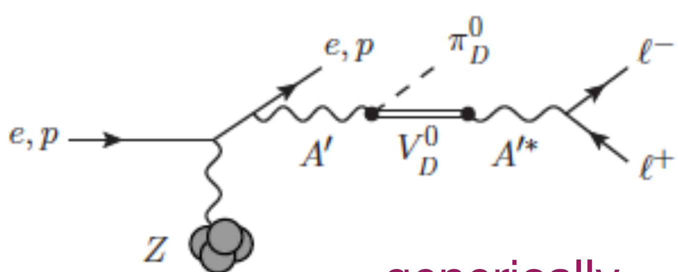
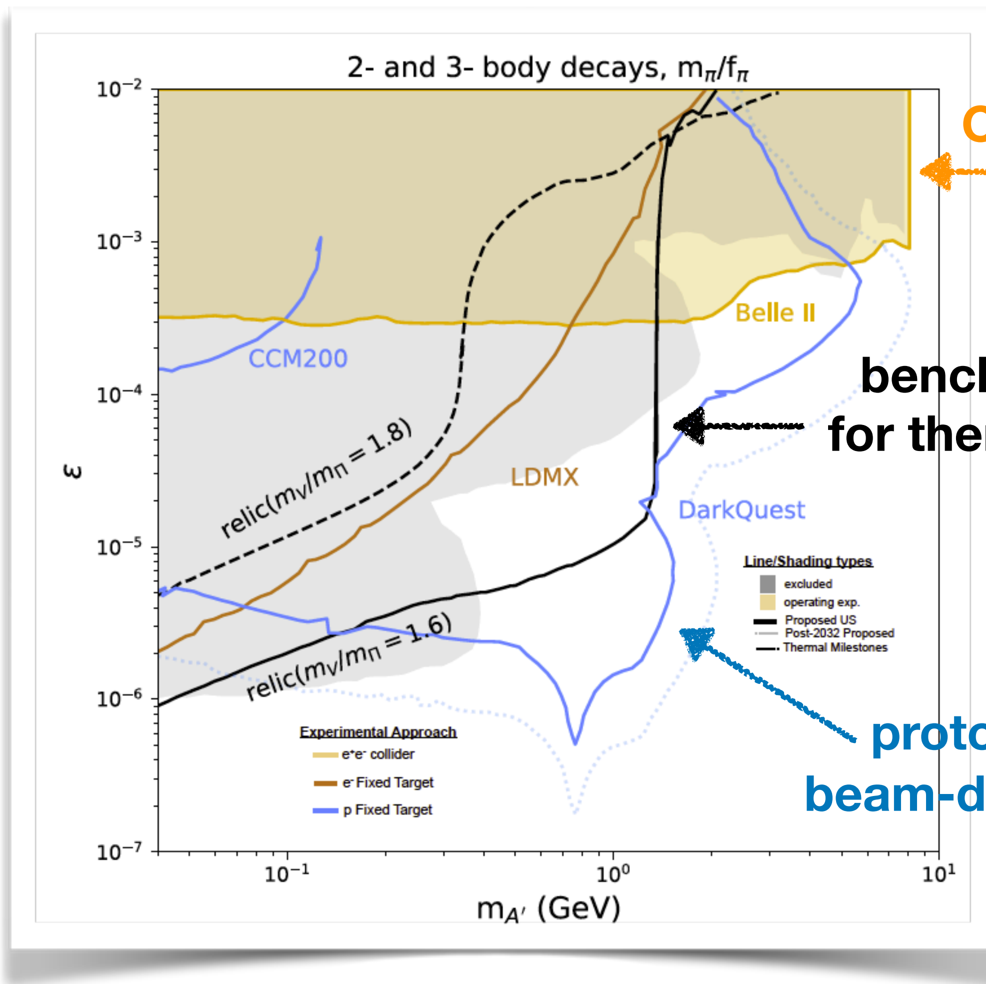
For example:



generically long-lived

$A' \to V_D \pi_D$ ⟵ DM state

$V_D \to A'^* \to e^+ e^-$



Colliders

benchmarks for thermal DM

proton beam-dump

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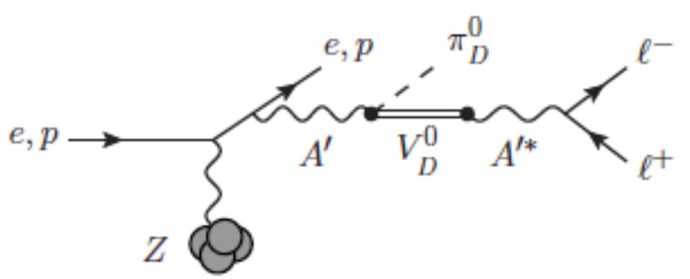
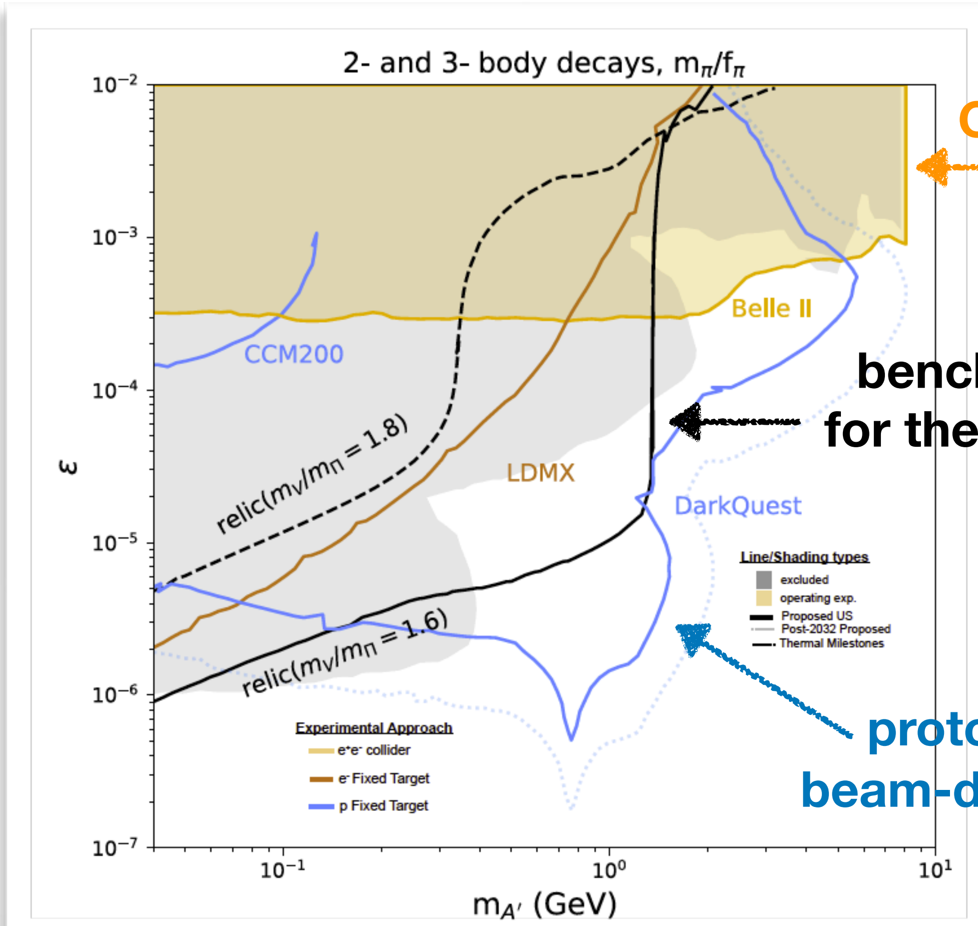
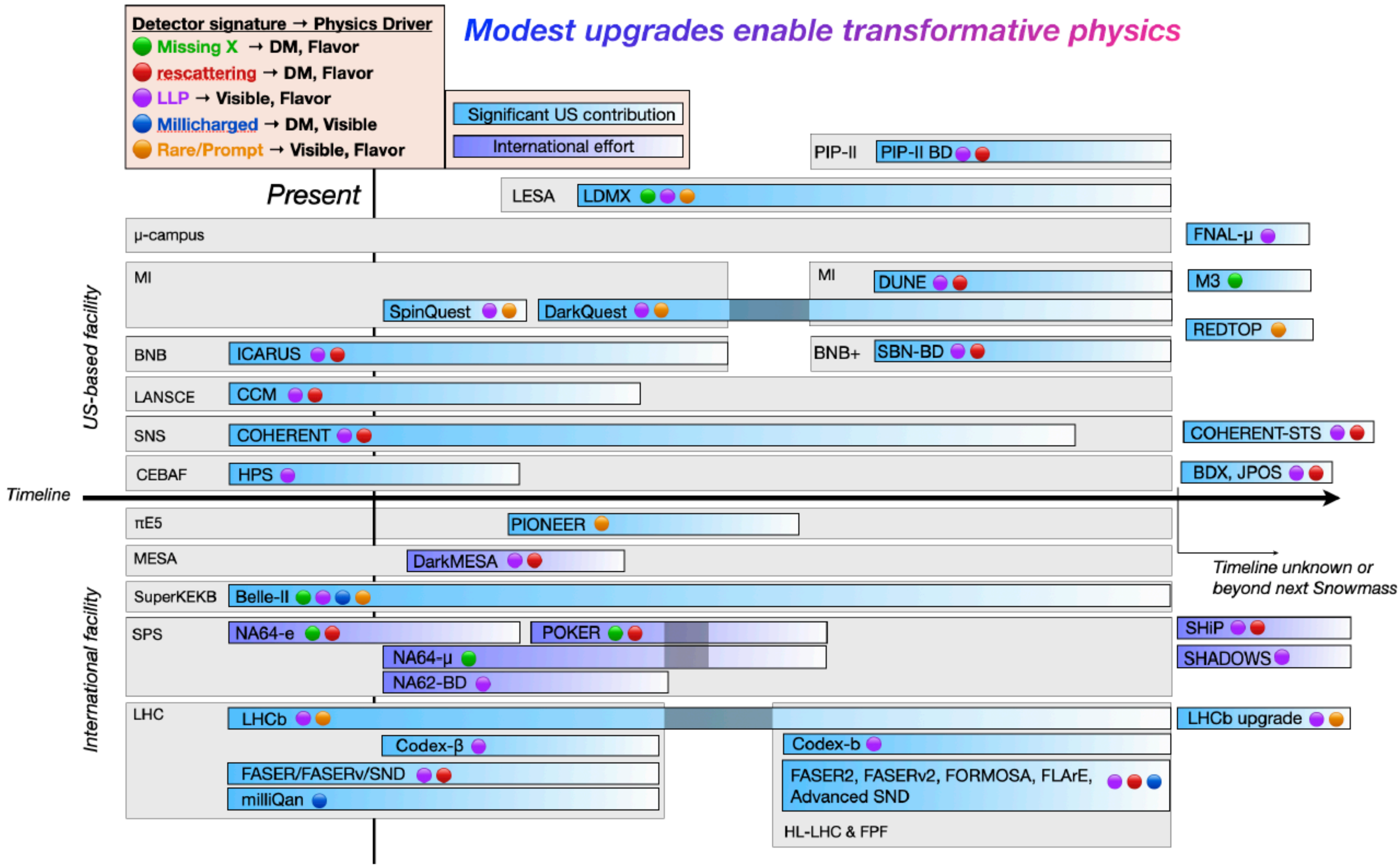


Planned and proposal experimental program will remain robust to unexpected final states



Experiments/facilities

https://arxiv.org/abs/2206.04220



Theory

Theory is **essential** for the development of projects.

Continued support for leadership in dark sector theory will be **critical**.

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Theory is **essential** for the development of projects.

Continued support for leadership in dark sector theory will be **critical**.

1. **Theory**: Better understand which dark-sector scenarios can address (current and future) open problems in particle physics;

2. **Pheno**: Develop new ideas for exploring the phenomenology of dark sectors. Develop simulation / generator tools that can be integrated into experimental analyses

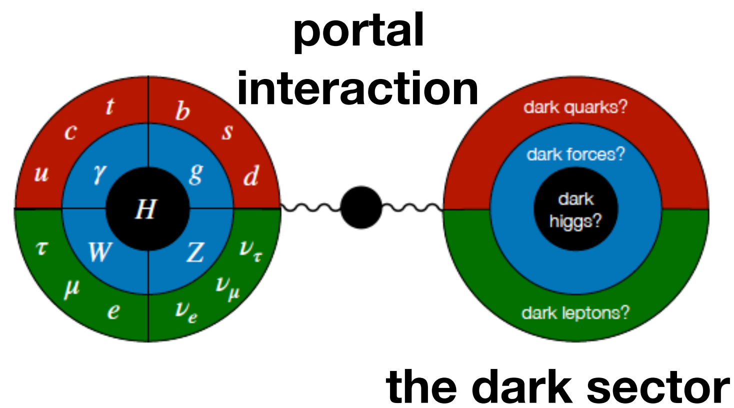
3. **Collaboration**: Collaborate at every stage of new dark-sector experiments, from design through interpretation of the data. This type of theory work has been at the foundation of essentially all ongoing and planned experimental activities in this growing field.

Examples: Proposal for

- LDMX Izaguirre, Krnjaic, Schuster, Toro, 1411.1404
- DarkQuest Berlin, SG, Schuster, Toro, 1804.00661
- M^3 Kahn, Krnjaic, Tran, Whitbeck 1804.03144
- Faser Feng, Galon, Kling, Trojanowski, 1708.09389
- CODEX-b Gligorov, Knapen, Nachman, Papucci, Robinson, 1708.09395
- Mathusla Chou, Curtin, Lubatti, 1606.06298

To conclude...

Dark Sectors at High Intensity



The existence of dark matter motivates a dark sector neutral under the SM forces

Dark sectors are a compelling possibility for new physics, with potential relevance to

lightness of SM neutrinos, baryon-antibaryon asymmetry,
hierarchy problem, strong-CP problem (e.g., axions, axion-like-particles),
anomalies in data

Dark sectors are generically weakly coupled to SM matter (via portal interactions) and can naturally have MeV-to-GeV masses.

➡ Only mild constraints from precision atomic physics & high-energy colliders

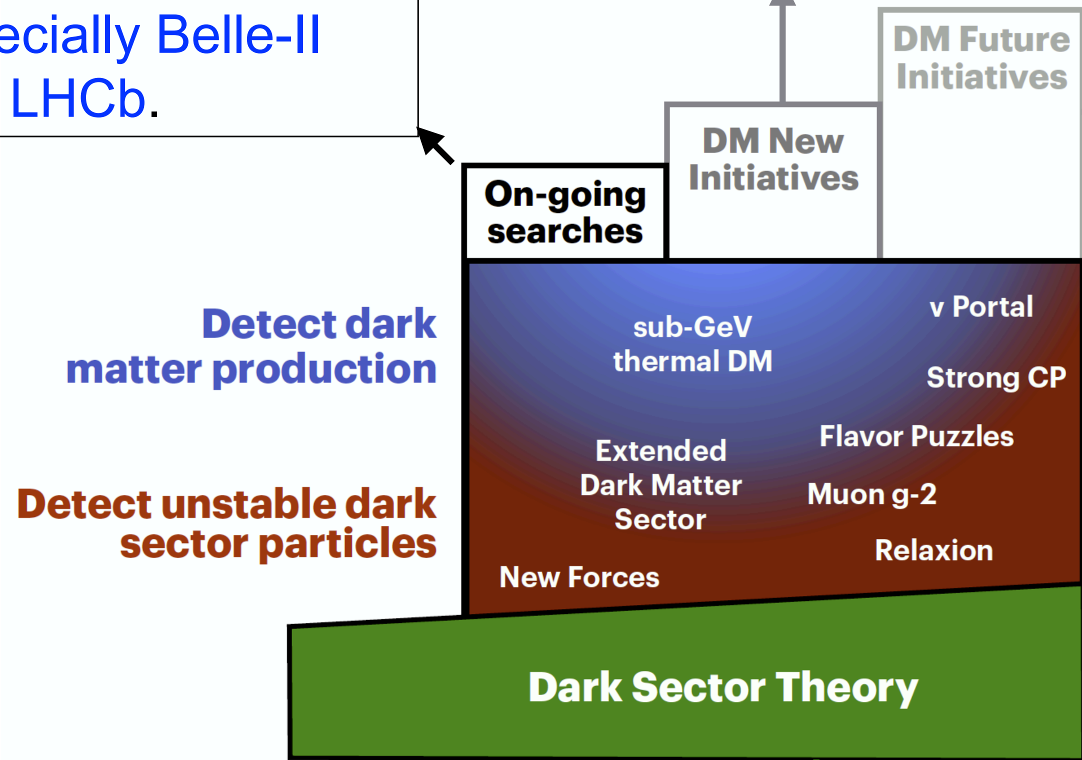
➡ Intensity-frontier experiments offer unique and unprecedented access to:

Big idea 1 • Light dark matter production
Big idea 2 • Systematic exploration of dark sector portals
Big idea 3 • Searches for new flavors and rich structures in dark sectors

To promote US leadership in dark sector studies:

* Exploit the capabilities of existing multi-purpose detectors, especially Belle-II and LHCb.

* Invest in fully funding projects supported by “DM New Initiative”, LDMX and CCM



* Expand DMNI with focus on signals of visible decays of dark sector particles – proposals include proton and lepton beam-dump experiments, long-lived-particle detectors

* Support theory efforts to explore dark sector models and collaborate in dark-sector experiments – this has been at the foundation of essentially all ongoing and planned experimental activities in this growing field.

Take home messages

Dark sector particles in the MeV-GeV range
naturally appear in DM models, as well as many well-motivated extensions of the Standard Model.

Very dynamic community

Unique role of **high-intentity experiments**

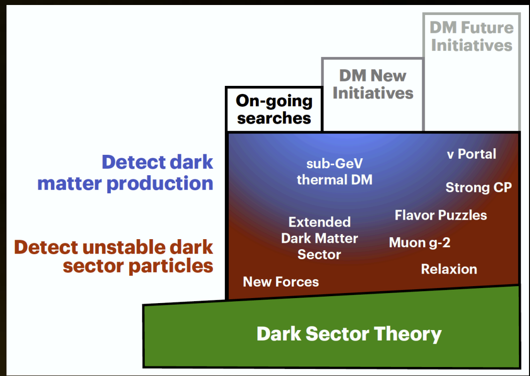
Support for this program:

- dark-sector analyses at multi-purpose experiments;
- completion of the DM New Initiatives (DMNI) program;
- expand DMNI with a focus on complementary signals (focus on visible signals and long-lived particles);
- a robust dark sector theory effort

P5 drivers

- Identify the NP of DM
- Explore the unknown
- Origin of neutrino masses

Well-defined science milestones that can be reached in the next decade (and beyond)



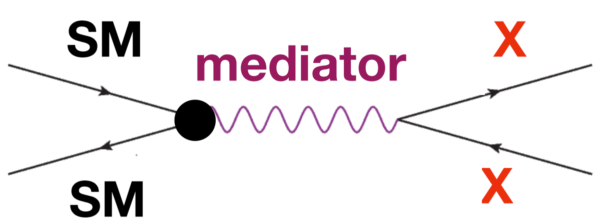
Backup

Final states to look for

a. Invisible, non-SM

Dark Matter production

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

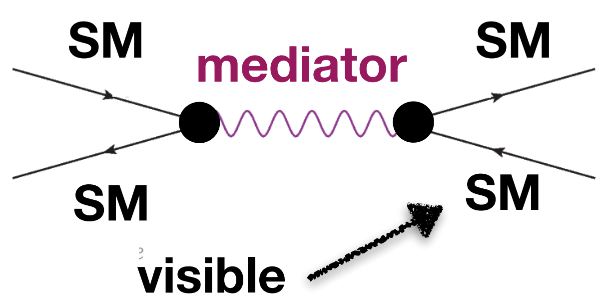


1. **Missing energy/ momentum**
2. **Scattering**

b. Visible, SM

Production of portal-mediators that decay to SM particles

Systematically exploring the portal coupling to SM particles

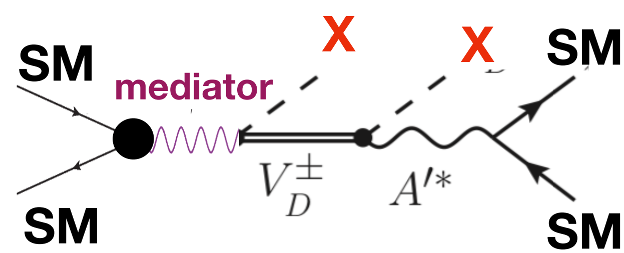


3. **Visible decay products**

c. Mixed visible-invisible

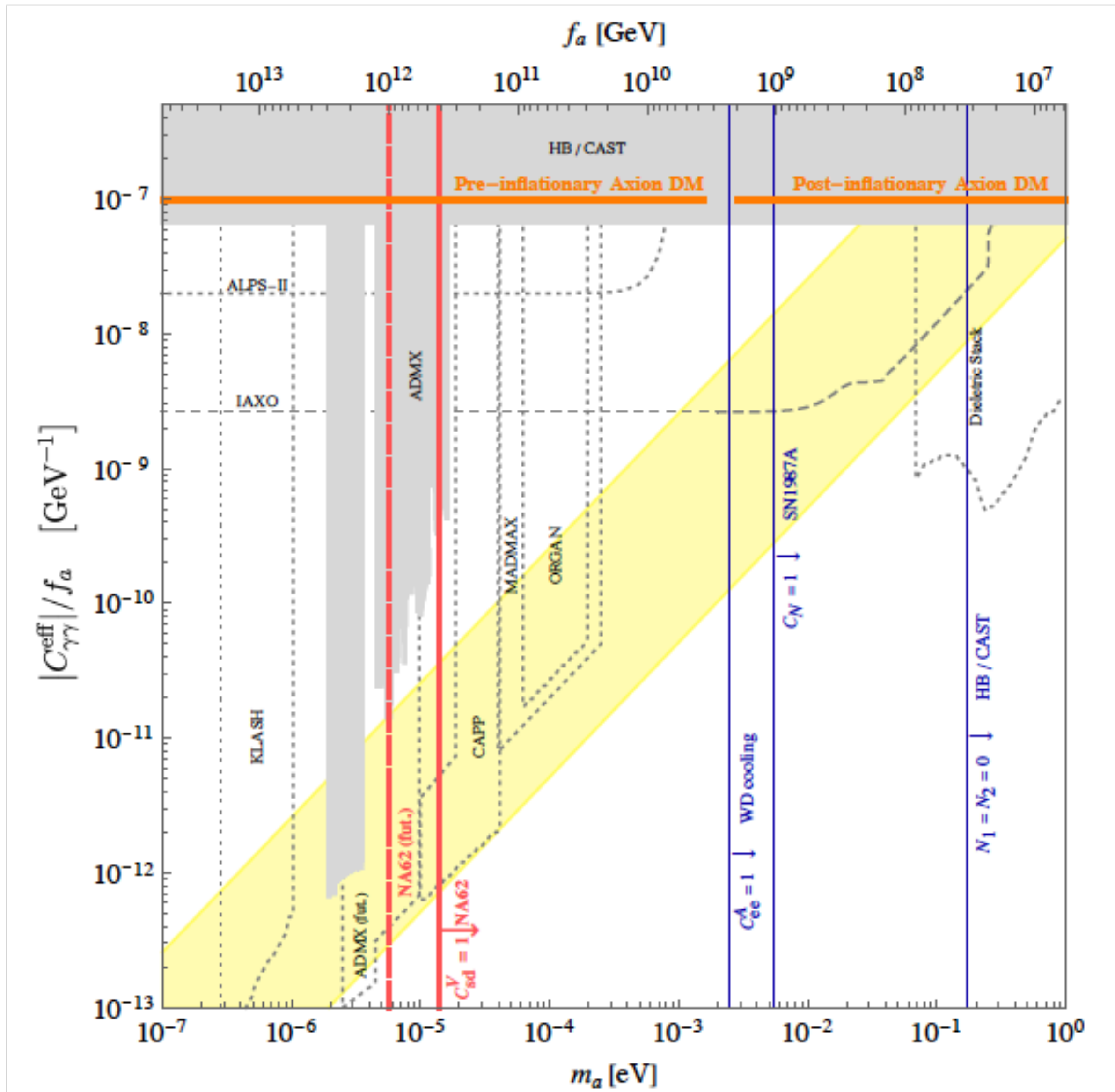
Production of "rich" dark sectors

Testing the structure of the dark sector

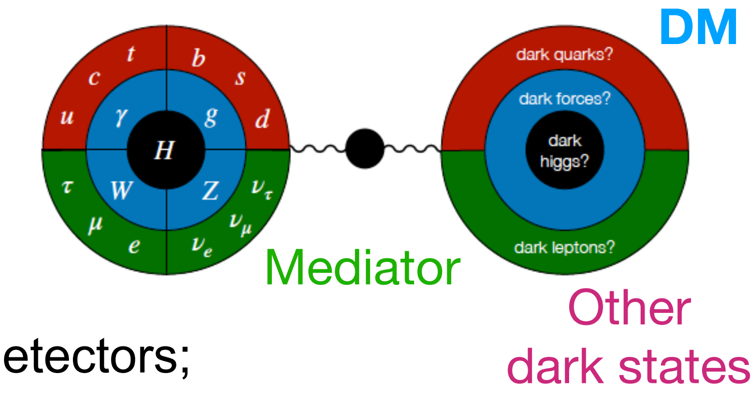


1. **Missing energy/ momentum**
2. **Scattering**
3. **Visible decay products**

Flavor violating ALPs



Experimental techniques



1. Detect dark matter particle production

(i) inferring missing energy, momentum, or mass;

(ii) detecting re-scattering of DM particles in downstream detectors;

(iii) observing semi-visible signatures of metastable dark sector particles.

2. Producing and detecting unstable dark particles: Minimal Portal Interactions

Detect visible decay products of the mediator (prompt or displaced decays).

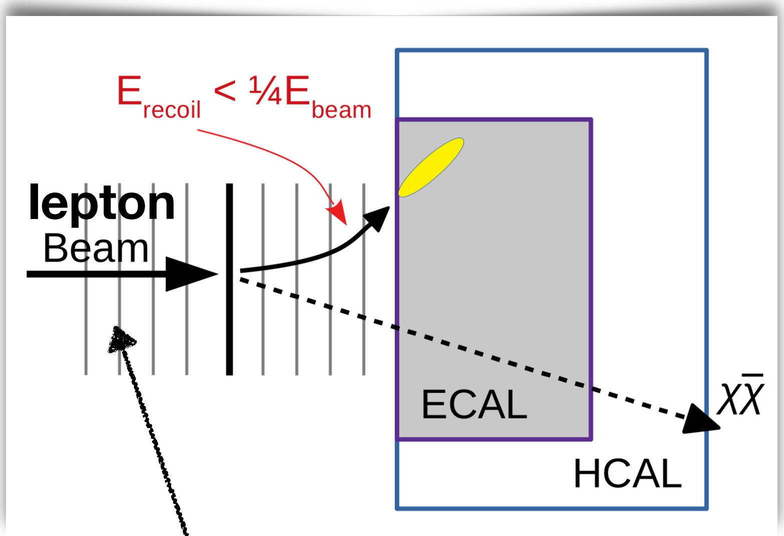
Mediator produced at (e^+e^-, pp) colliders, meson factories, fixed target experiments

3. Beyond minimal models

(i) Detect visible decay products of the mediator in non-minimal models, e.g. flavor specific couplings (prompt or displaced decays);

(ii) Detect visible or invisible signatures of other dark sector states, e.g. DM excited states

1. Missing energy/momentum



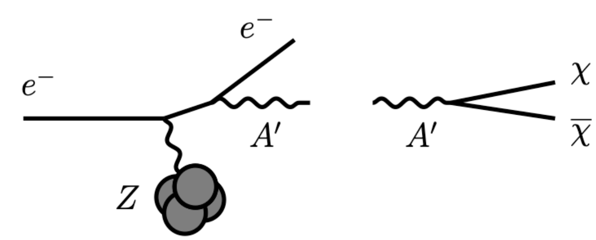
Dark matter events can be kinematically characterized by the calorimetric "disappearance" of a sizable fraction of the beam energy. **Detection strategy**

e⁻ beam for the **NA64** experiment,
Andreas et al., 1312.3309

Running at CERN

Dark Matter can be produced through the mediation of a on-shell or off-shell mediator.

For example,



e^- beam for the **LDMX** experiment,
Akesson et al., 1808.05219

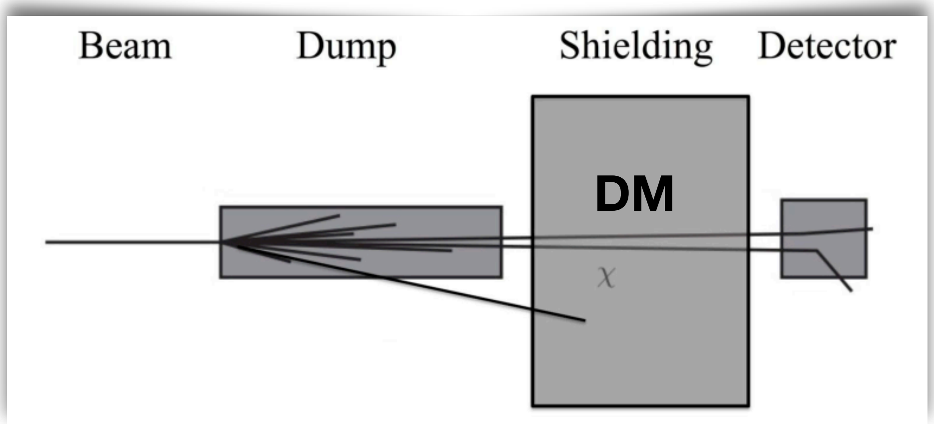
e^+ beam for the **POKER** experiment,
Andreev et al., 2108.04195

μ^- beam for the **M³** experiment,
Kahn et al., 1804.03144

Future experiments

DMNI funding

2. Re-scattering



Production of dark matter in the dump and detection of its scattering in forward detectors.

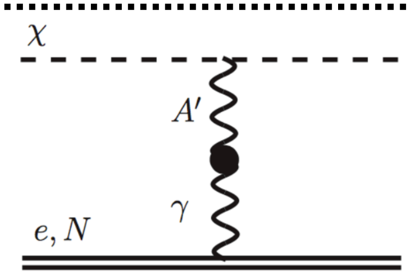
Detection strategy

Proton-beam experiments are highly synergistic with the accelerator-based neutrino physics program. They use the same beamlines and detectors:
LSND, MiniBooNE, COHERENT, CCM

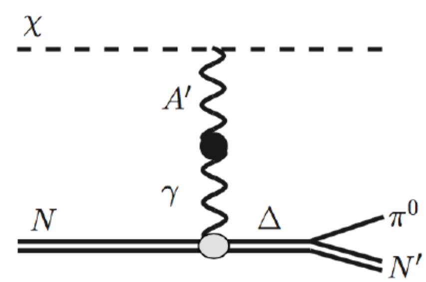
DMNI funding

Electron-beam experiments have the advantage of a more compact secondary DM beam (BDX experiment)

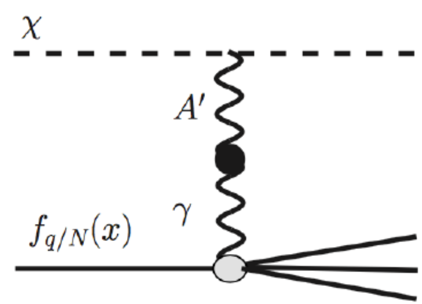
Synergy with beam dump-experiments that utilize high energy beams (forward facility, future colliders)



Elastic electron, nucleon , nucleus (coherent) scattering



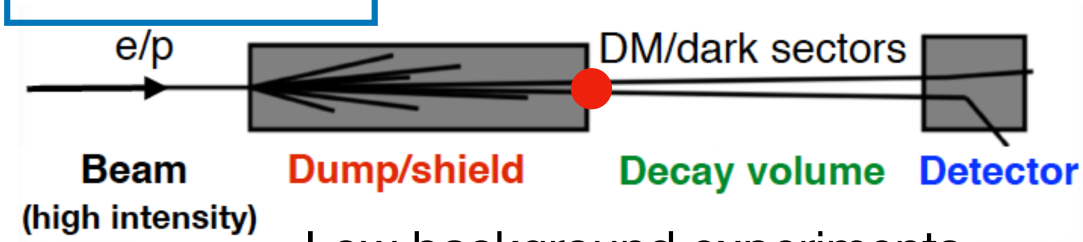
Inelastic neutral pion production



Deep inelastic scattering

3. Visible signatures

DISPLACED



Low background experiments
(depending on the size of the dump)

Production of an unstable dark sector particle in the dump and detection of its SM decay products in forward detectors.
Detection strategy

p beam for the SeaQuest/DarkQuest experiment at Fermilab

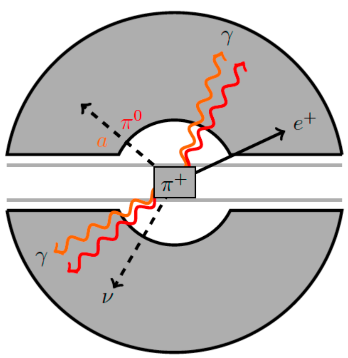
p beam for the NA62, KLEVER experiments at CERN

e- beam for the HPS experiment at JLAB

e- beam for the DarkLight experiment at TRIUMF

Running experiments

Future experiments



PROMPT

Production of an unstable dark sector particle from meson decay and detection of its SM decay products.
Detection strategy

Pion decaying at rest (PIONEER experiment)

Eta/eta' decaying (almost) at rest (REDTOP experiment)

Enormous synergy with collider experiments! Belle II, LHCb, …

Variations of the invisible dark photon scenario