Light (MeV-GeV) dark matter: the Snowmass approach

Stefania Gori
UC Santa Cruz

FIPs 2022 workshop

CERN

October 20, 2022

MeV-GeV Dark Matter living in a dark sector

The DM mass scale

MeV GeV TeV

Dark sectors

Thermal DM

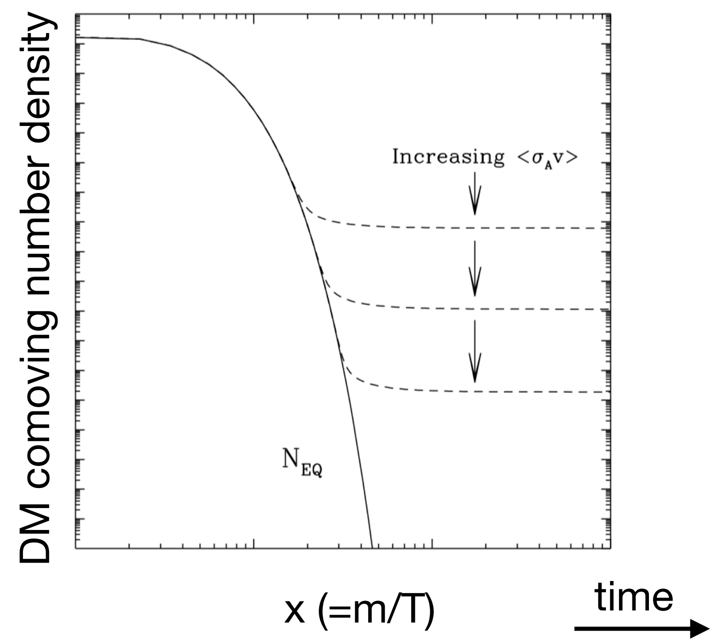
WIMPs

Simple production mechanism works here

Lee-Weinberg bound (~ few GeV)

Dark sectors are needed

freeze-out



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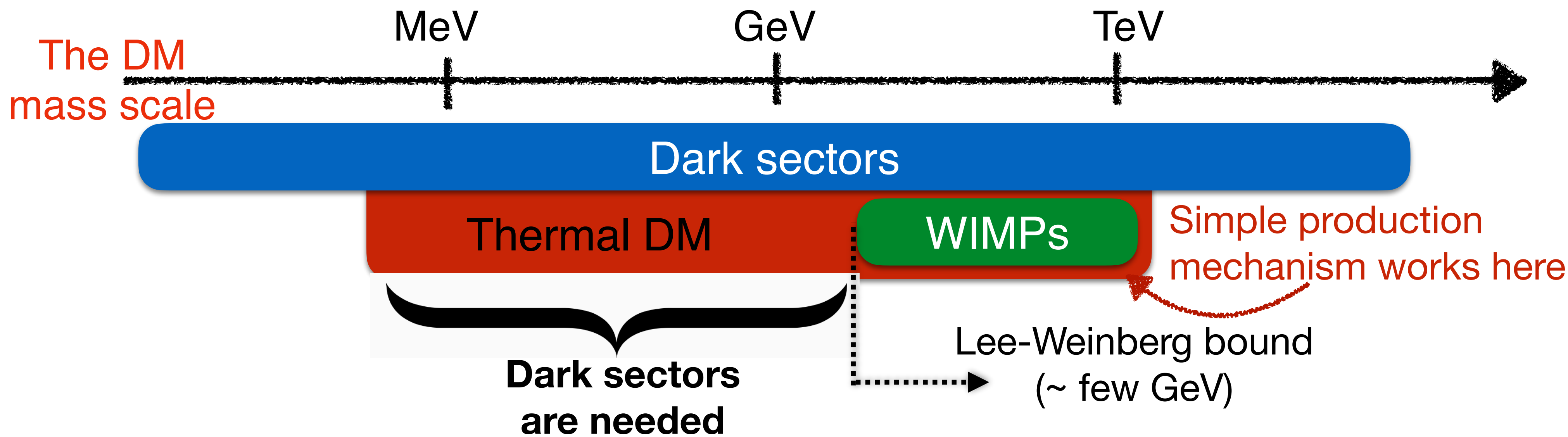
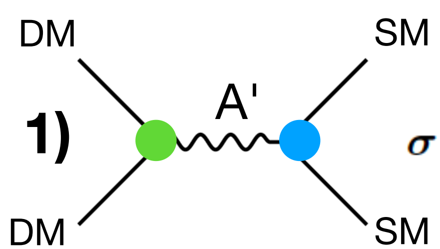


DM thermal freeze-out targets

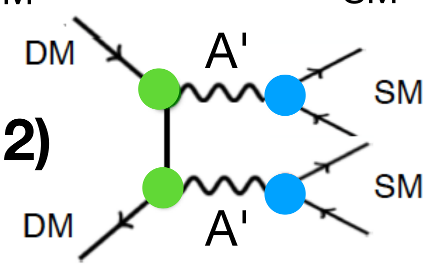
1)



if $m_{A'} > 2m_{DM}$ → **Invisible signatures**

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

2)



if $m_{A'} < m_{DM}$ → **Visible signatures**

ε is lower bounded

Signatures motivated by several other open problems in particle physics

(strong CP problem, neutrino mass generation, hierarchy problem, …)

see also talk by N. Toro yesterday

Snowmas effort on the study of MeV-GeV DM

The Snowmass community effort (April 2020-now): https://snowmass21.org/start

- Energy Frontier
- Neutrino Physics Frontier
- Rare Processes and Precision
- Cosmic Frontier
- Theory Frontier
- Accelerator Frontier
- Instrumentation Frontier
- Computational Frontier
- Underground Facilities
- Community Engagement

Topical groups

EF09: BSM: More general explorations
EF10: BSM: Dark Matter at colliders
https://arxiv.org/pdf/2209.13128.pdf

NF3: BSM
https://arxiv.org/pdf/2209.10362.pdf

RF6: Dark Sector Studies at High Intensities
https://arxiv.org/pdf/2209.04671.pdf

CF1: Dark Matter: particle-like
https://www.overleaf.com/project/6230f6d17d45434260f05329

CF3: Dark Matter: cosmic probes
https://arxiv.org/pdf/2209.08215.pdf

Topical groups that participated to the Dark Matter complementarity white paper:
Boveia et al, 2210.01770

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RF6, Dark Sectors at High Intensity

Conveners: SG, Mike Williams

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

We defined **three Big Ideas** each with associated goals for the next decade

Report: https://arxiv.org/pdf/2209.04671.pdf

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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, N. Blinov, C. Hearty, R. McGehee (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://arxiv.org/pdf/2207.08990.pdf)

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

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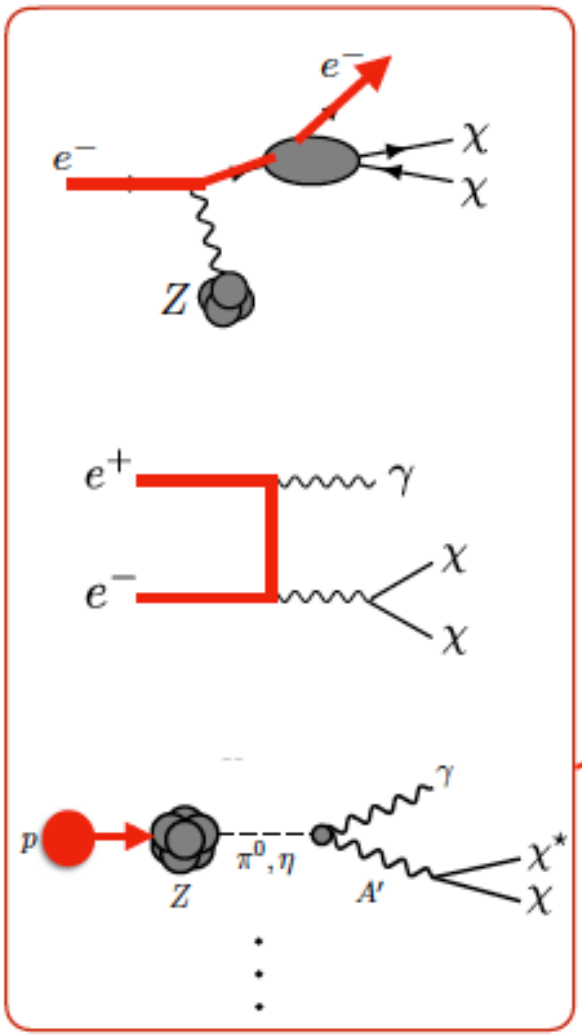
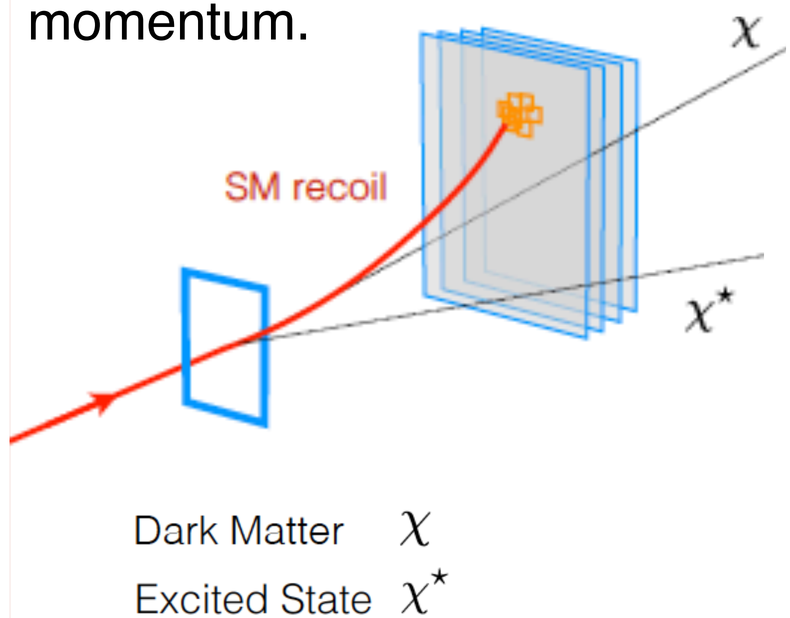
Big idea 1: DM production at high intensities

https://arxiv.org/abs/2207.00597



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



Synergy with auxiliary detectors at collider experiments

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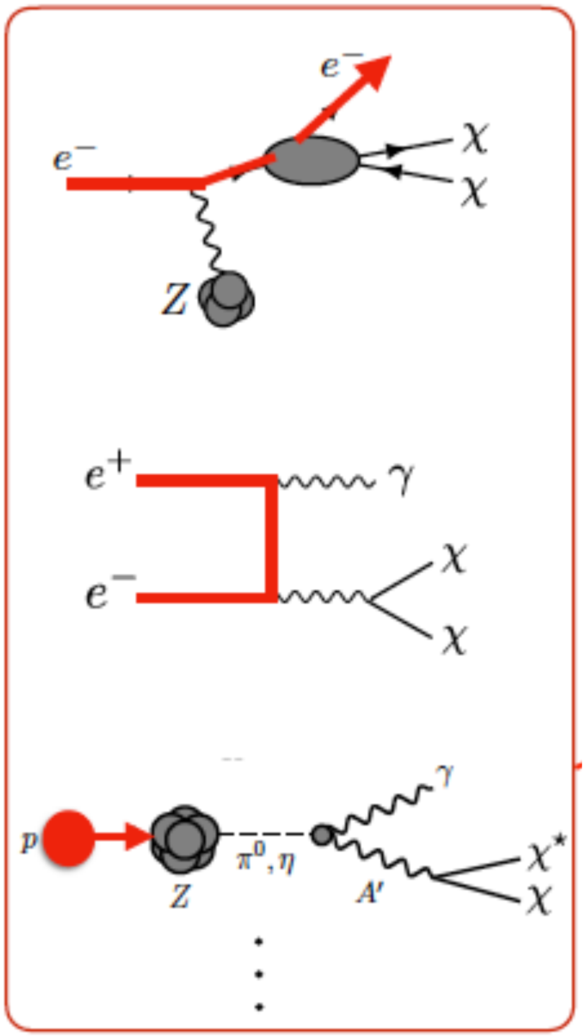

(proton beam: synergistic with the accelerator-based **neutrino physics program**)

Detection of DM scattering in forward detectors. **(2)**

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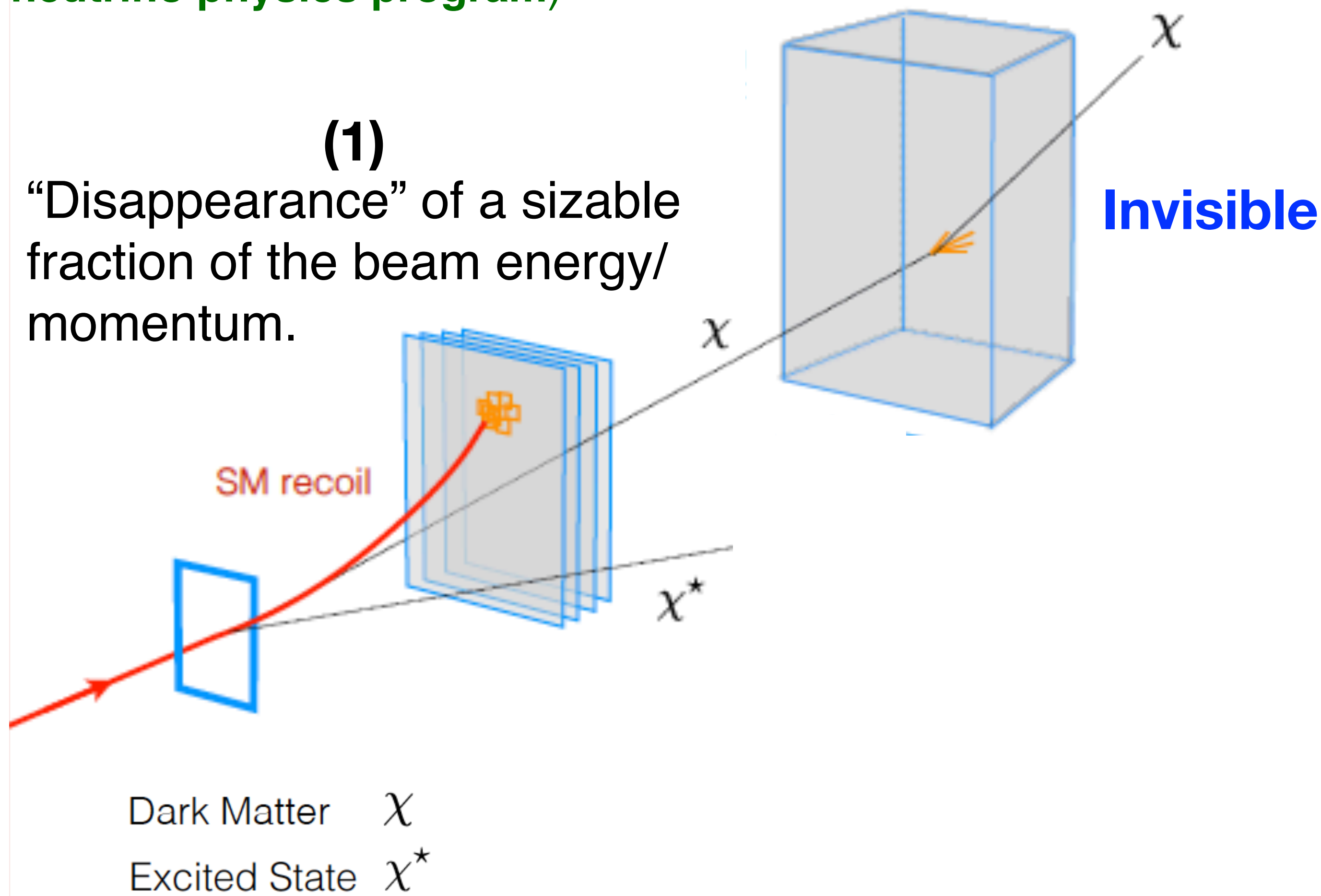
Invisible



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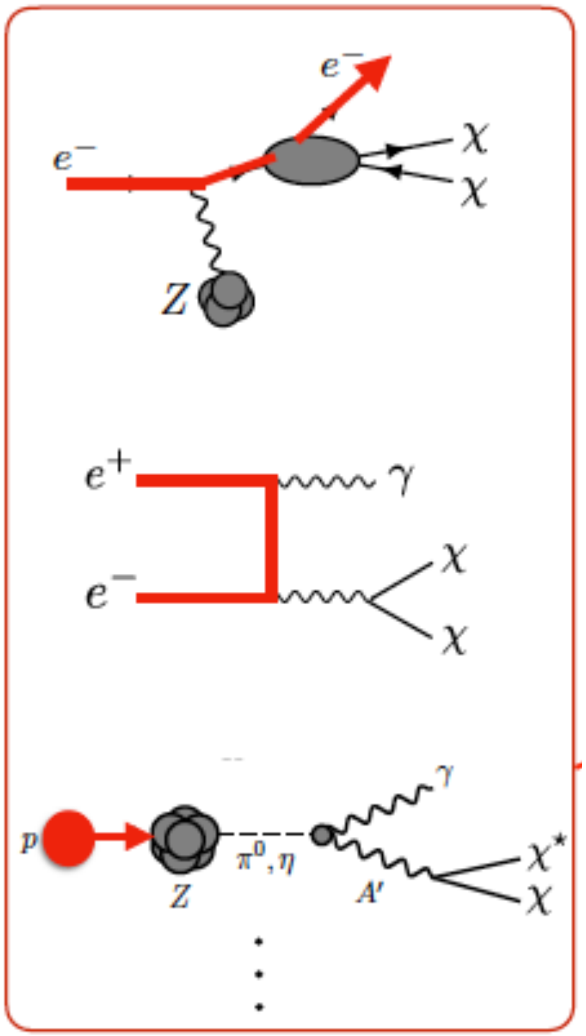

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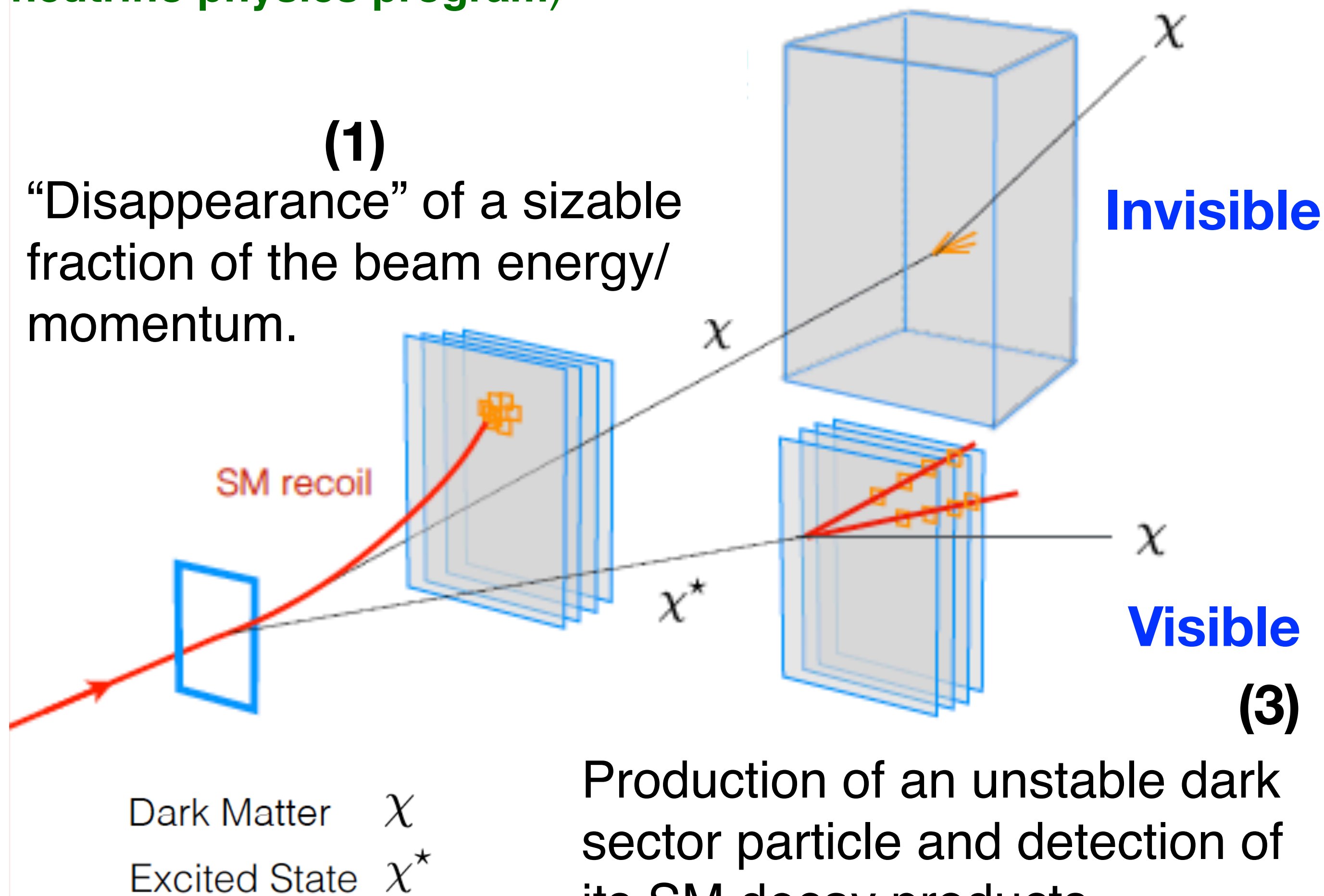


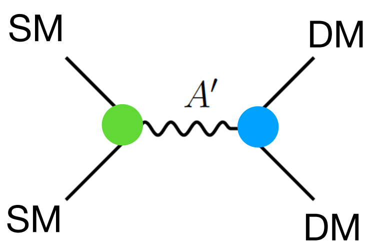
(3)
Production of an unstable dark sector particle and detection of its SM decay products.

Synergy with auxiliary detectors at collider experiments

DM thermal milestones

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

A'→XX



Dark photon mediated DM

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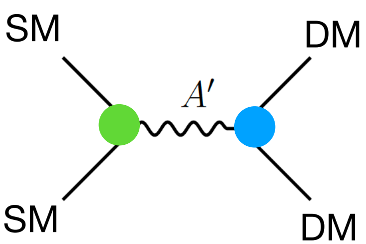

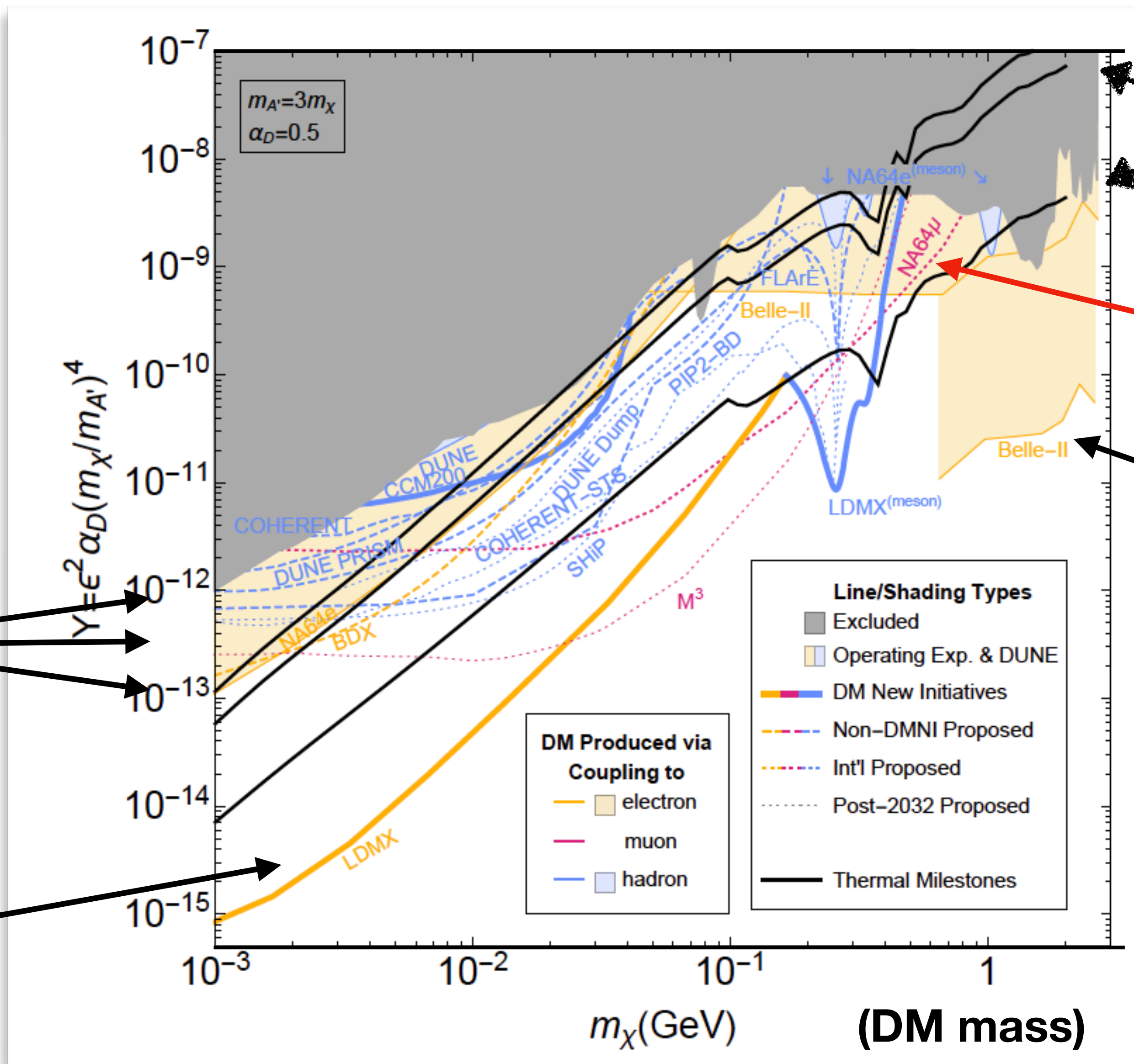

(DM mass)

benchmarks for thermal DM

(1) Missing energy

(1) Collider, mono-photon search

(2) Re-scattering

(1) Missing momentum

Krnjaic, Toro et al, 2207.00597

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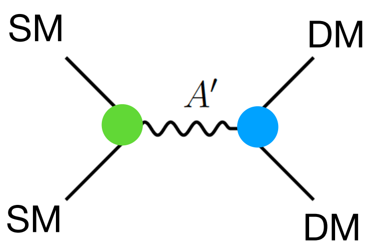
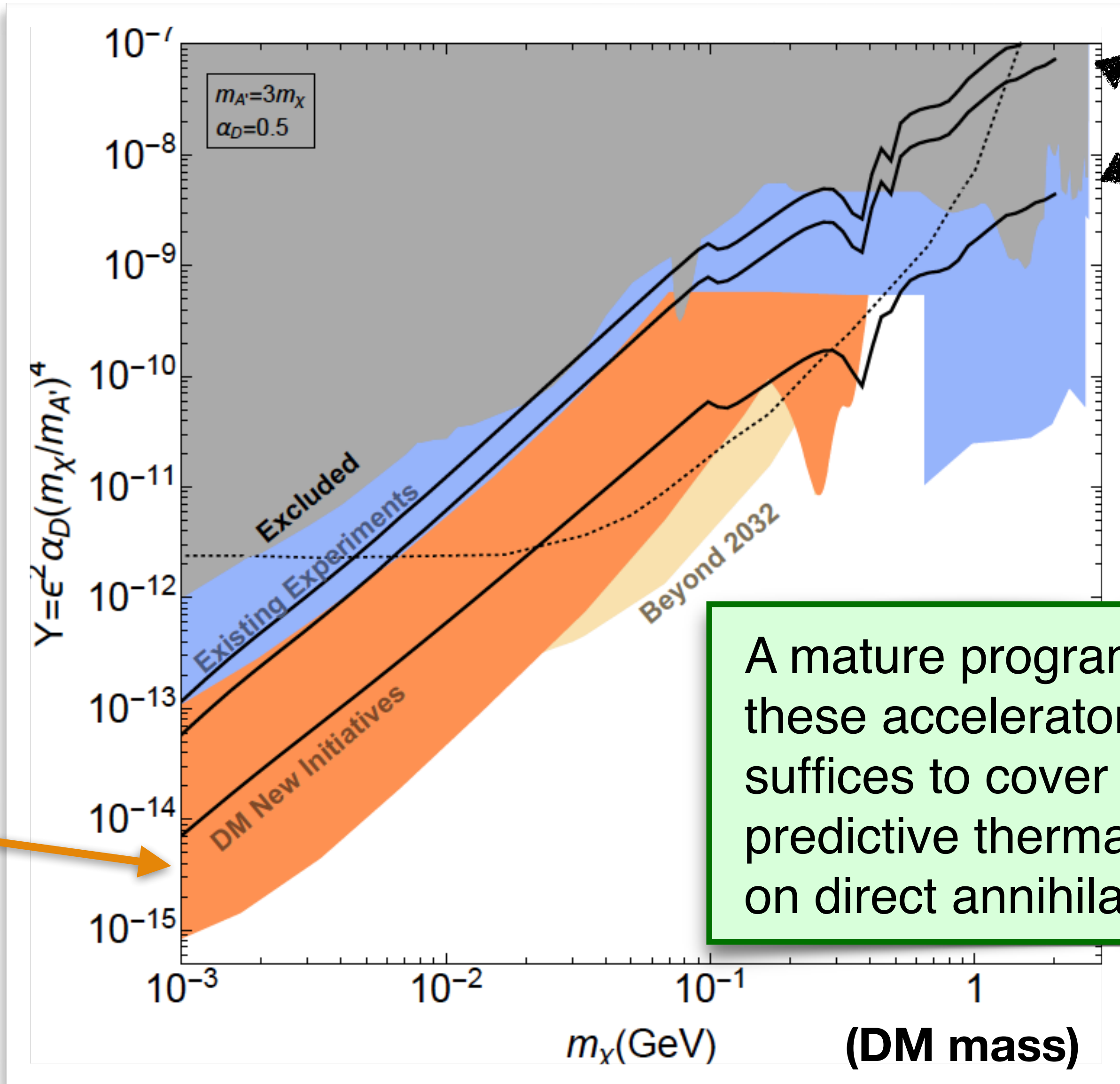




benchmarks for thermal DM

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

DOE supported DM Small projects New Initiatives (DMNI)

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

Krnjaic, Toro et al, 2207.00597

Dark photon mediated DM

Additional DM production benchmarks & messages

* $L_\mu - L_\tau$ mediated
* $B\text{-}3L_\tau$ mediated
* B mediated

* Higgs-mixed scalar mediated
* Muon-philic scalar mediated
* Neutrino-philic scalar mediated

* Sterile neutrino mediated (t-channel and s-channel)

* Inelastic Dark Matter
* Strongly interacting massive particle Dark matter (SIMP)

* Millicharged particles

PBC/FIP benchmark

Benchmarks

The breadth of ideas for experiments 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

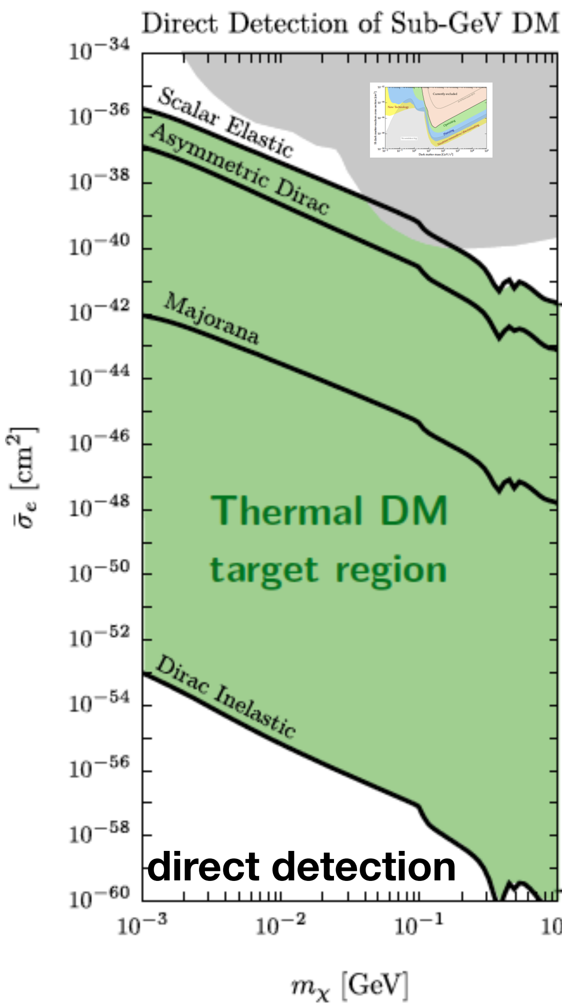
- those where a mediator does not couple to electrons but preferentially to μ and/or τ leptons or baryons.

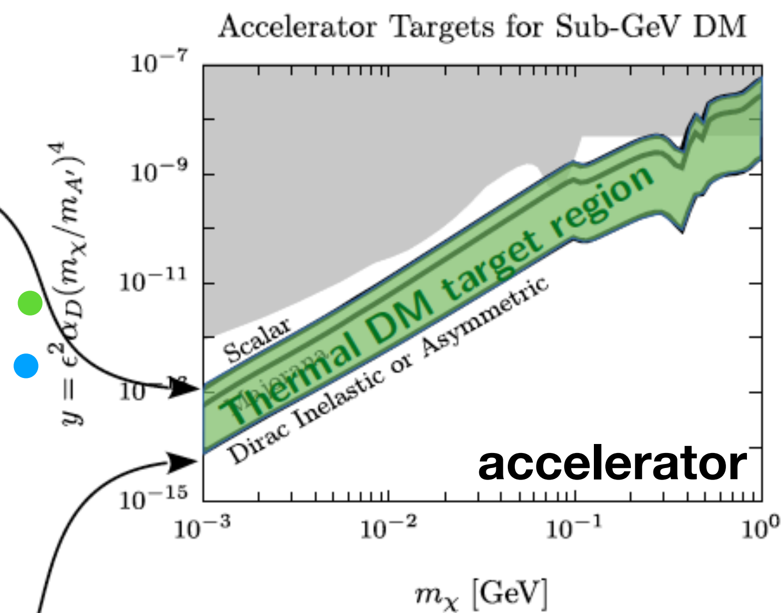
- Models where meta-stable particles in the dark sector play important roles in DM cosmology and enable new discovery techniques

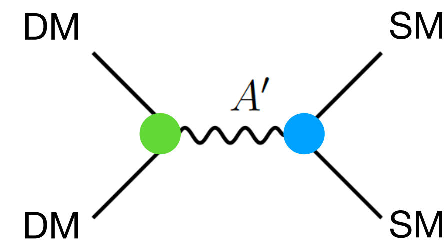
Messages

Complementarity with DM direct detection

To connect these two probes,
one need to make
model assumptions







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

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

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

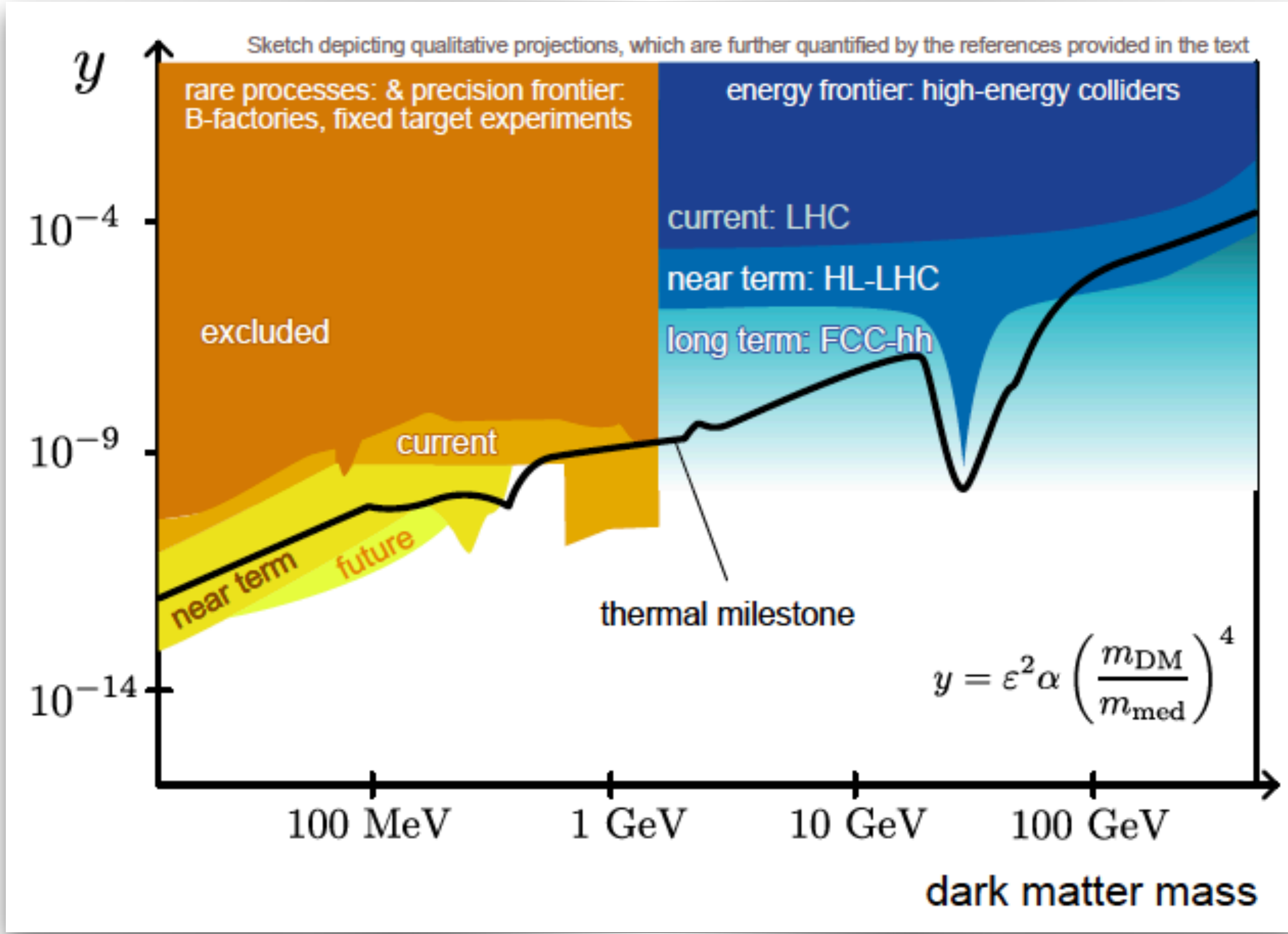
Accelerator production recreates the kinematic conditions of the early universe.

It is ~ unaffected by the nature of DM

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

See, CF1:
https://www.overleaf.com/project/6230f6d17d45434260f05329

Complementarity with high energy colliders



Dark Matter complementarity white paper:
Boveia et al, 2210.01770

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

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"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

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

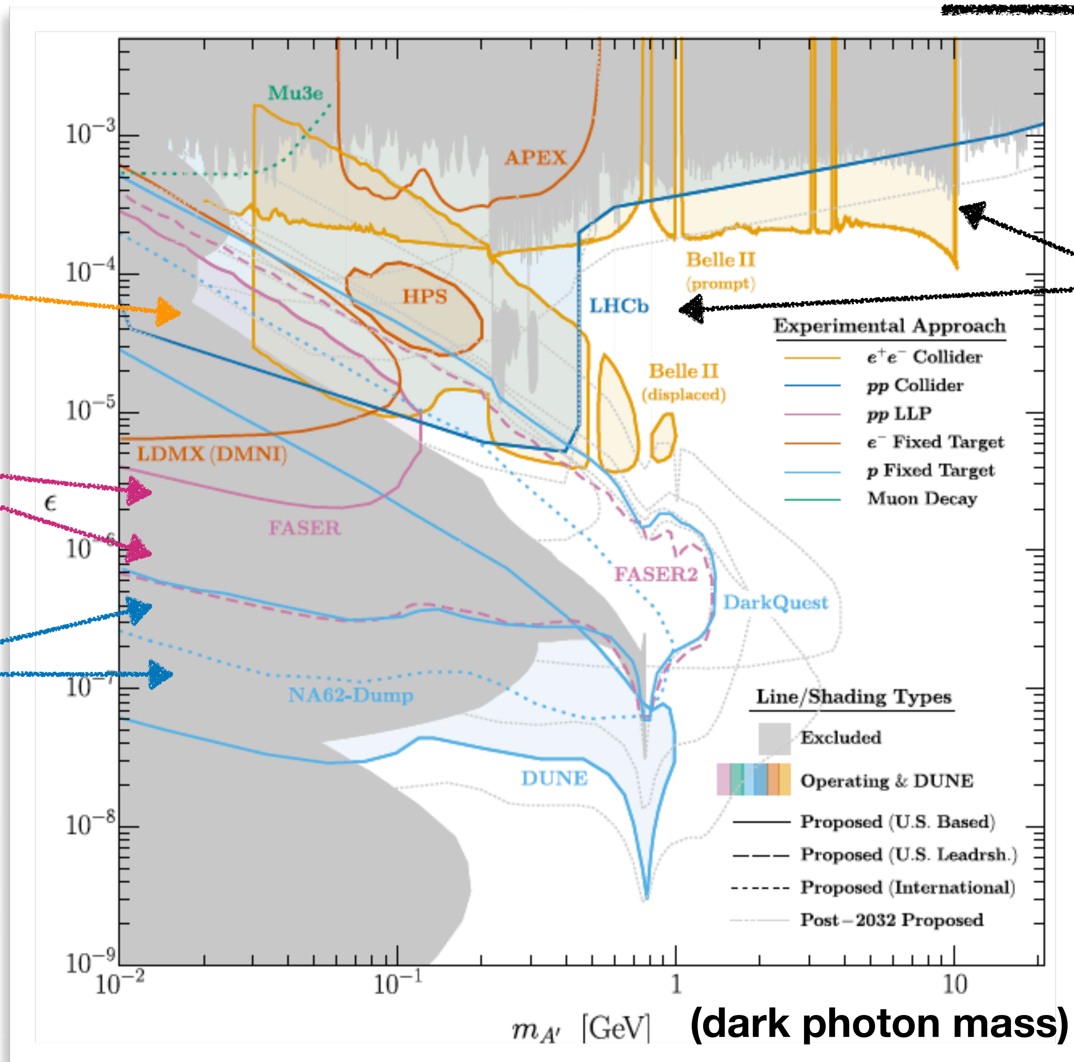
energy frontier

electron fixed target

forward detectors

proton beam-dump

Colliders



(dark photon mass)

Batell et al., 2207.06905

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

Exploring visible dark photons

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electron fixed target

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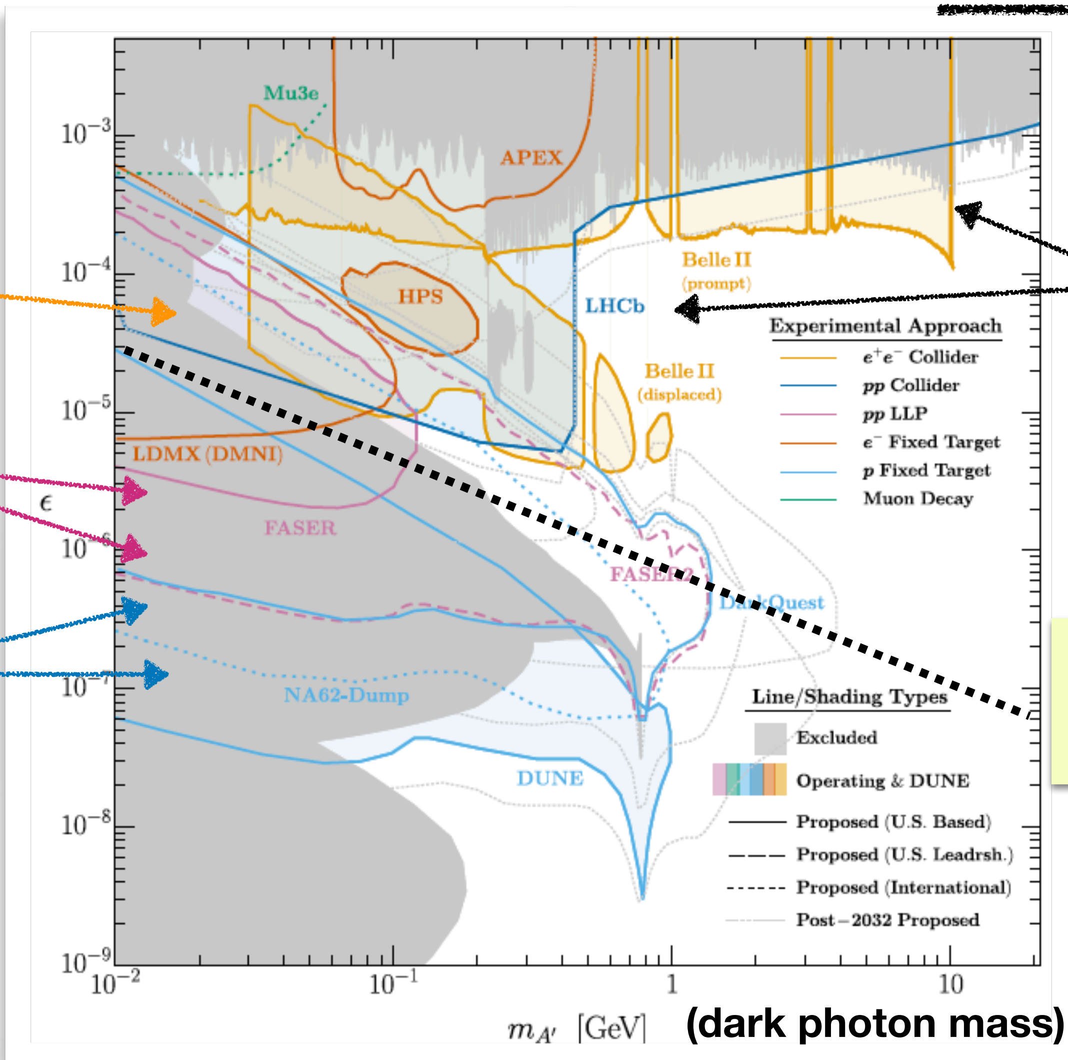

(dark photon mass)

energy frontier

Colliders

roughly: life time ~ cm

long-lived regime

Batell et al., 2207.06905

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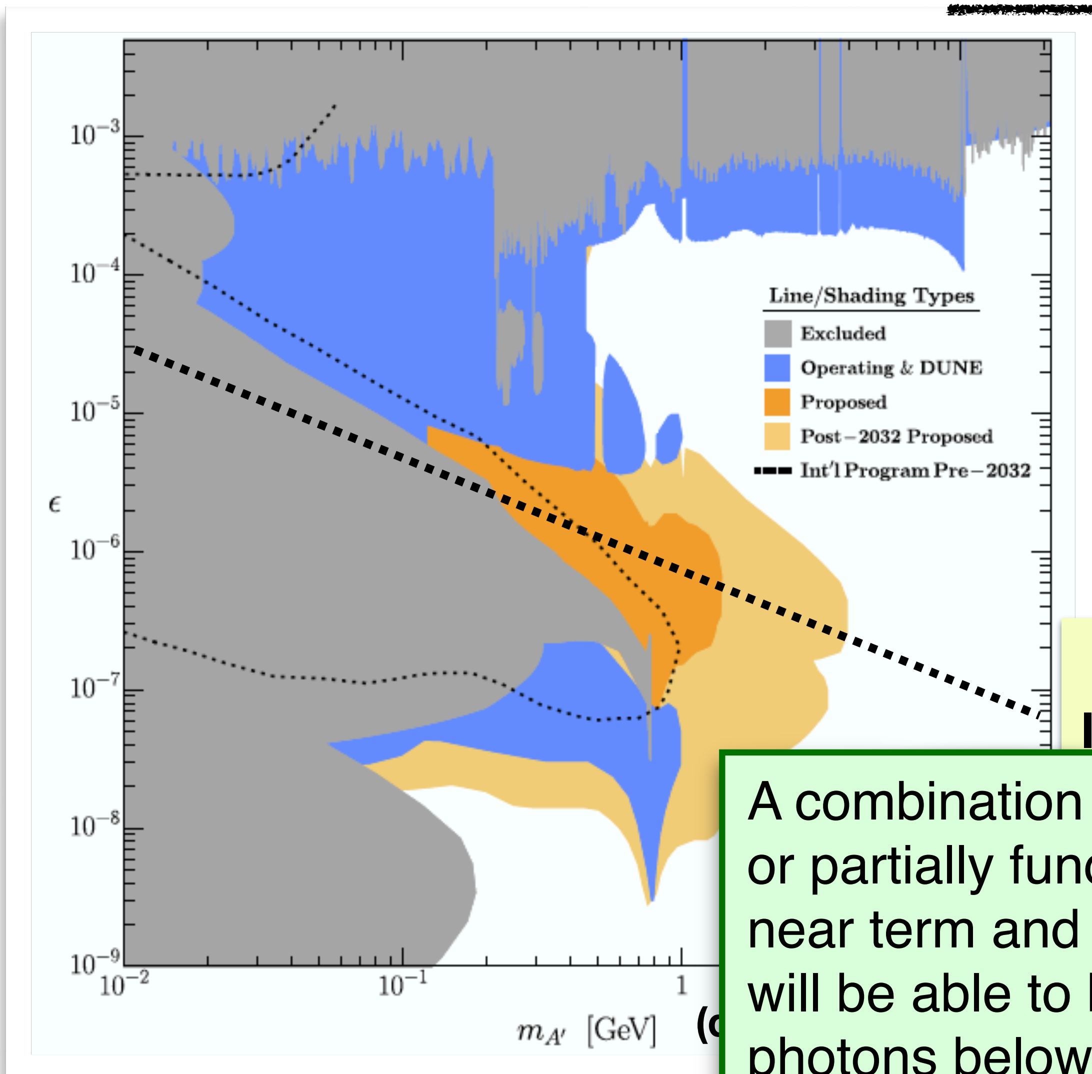
S.Gori

Exploring visible dark photons

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



energy frontier

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

Batell et al., 2207.06905

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

Big idea 3: richer dark sectors

https://arxiv.org/pdf/2207.08990.pdf

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

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Richer phenomenology ⇒ rethinking of experimental strategies for achieving optimized sensitivities

2 themes:

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

2. 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, …))

1. 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?

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Example

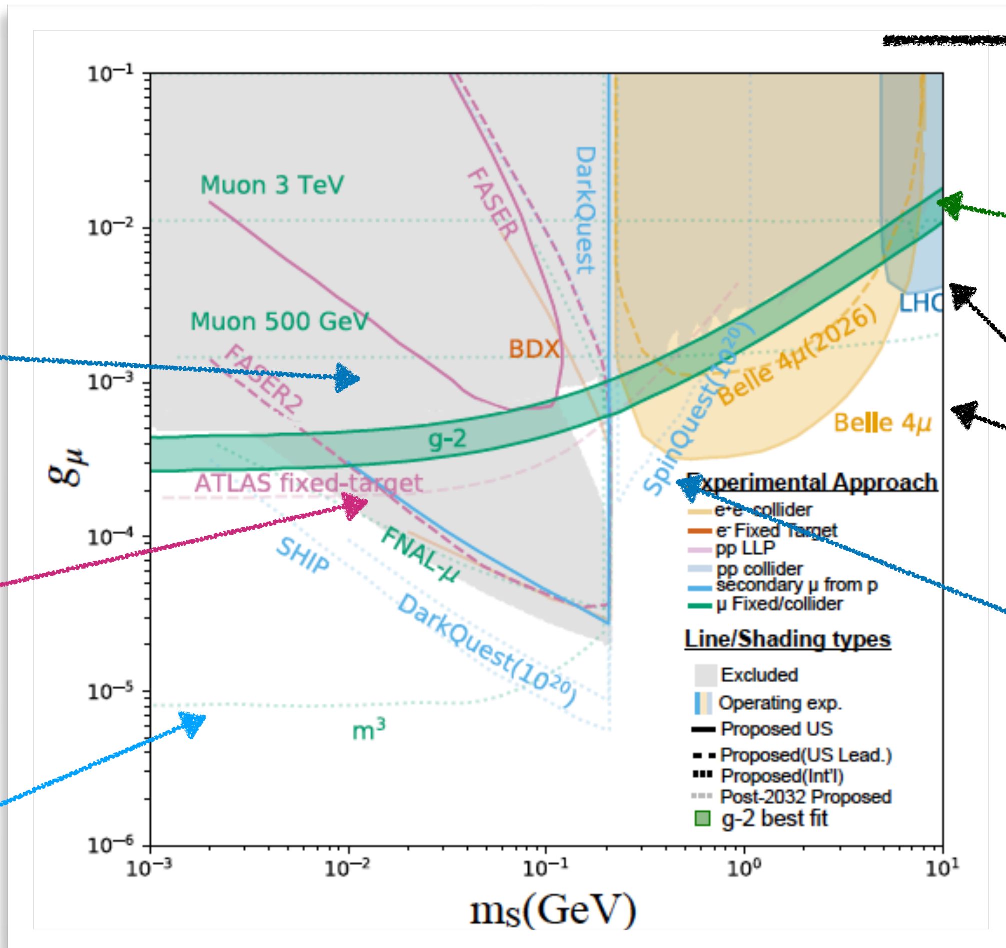
$$g_\mu S \bar{\mu} \mu + \text{h.c.}$$

flavor specific dark sectors

proton beam-dump

LHC auxiliary detectors

Missing momentum



energy frontier

$(g-2)_\mu$ region

Colliders

proton beam-dump

Harris et al, 2207.08990.pdf

see also talk by N. Tran yesterday

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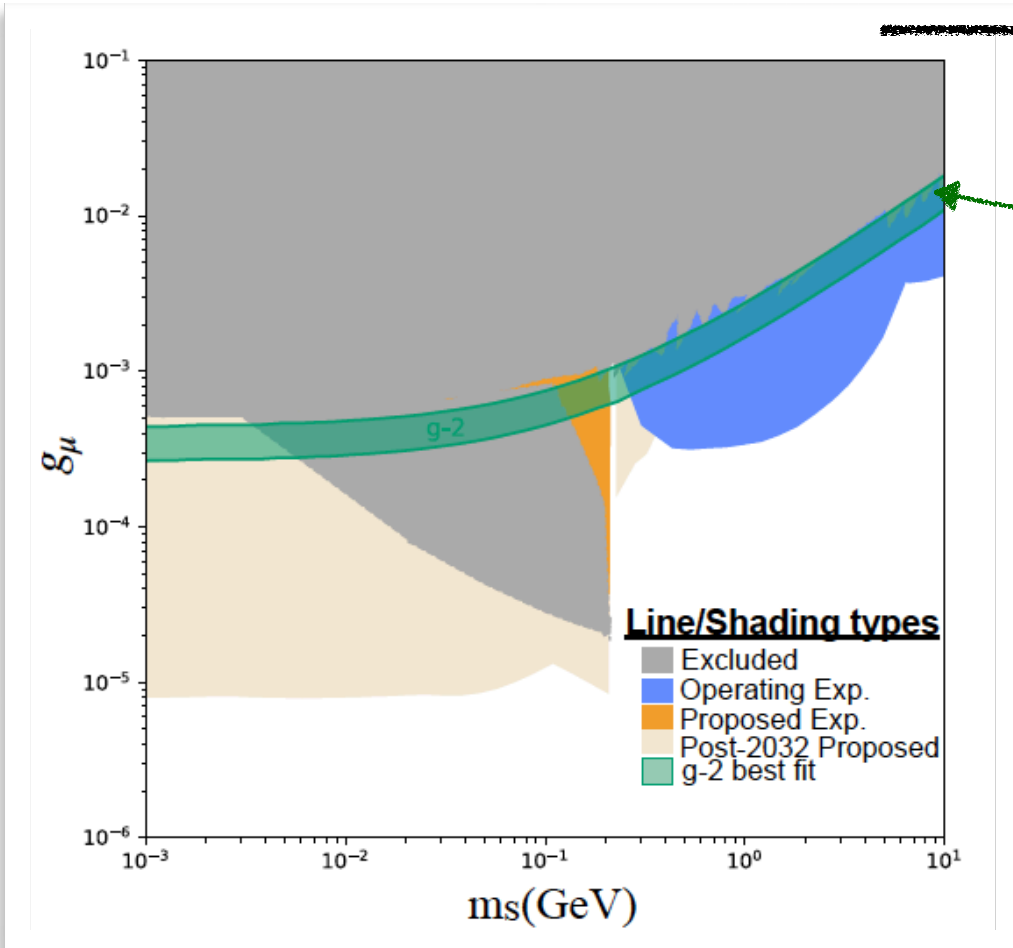


energy frontier

$(g-2)_\mu$ region

Harris et al, 2207.08990.pdf

see also talk by N. Tran yesterday

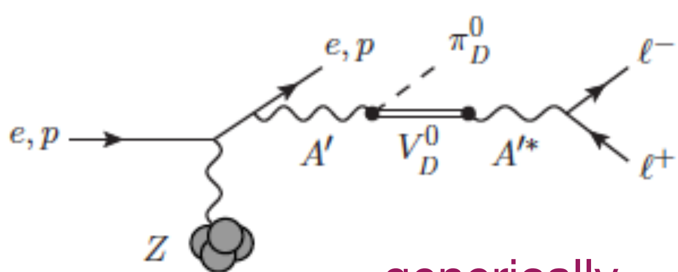
2. DM in a strongly interacting dark sector

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

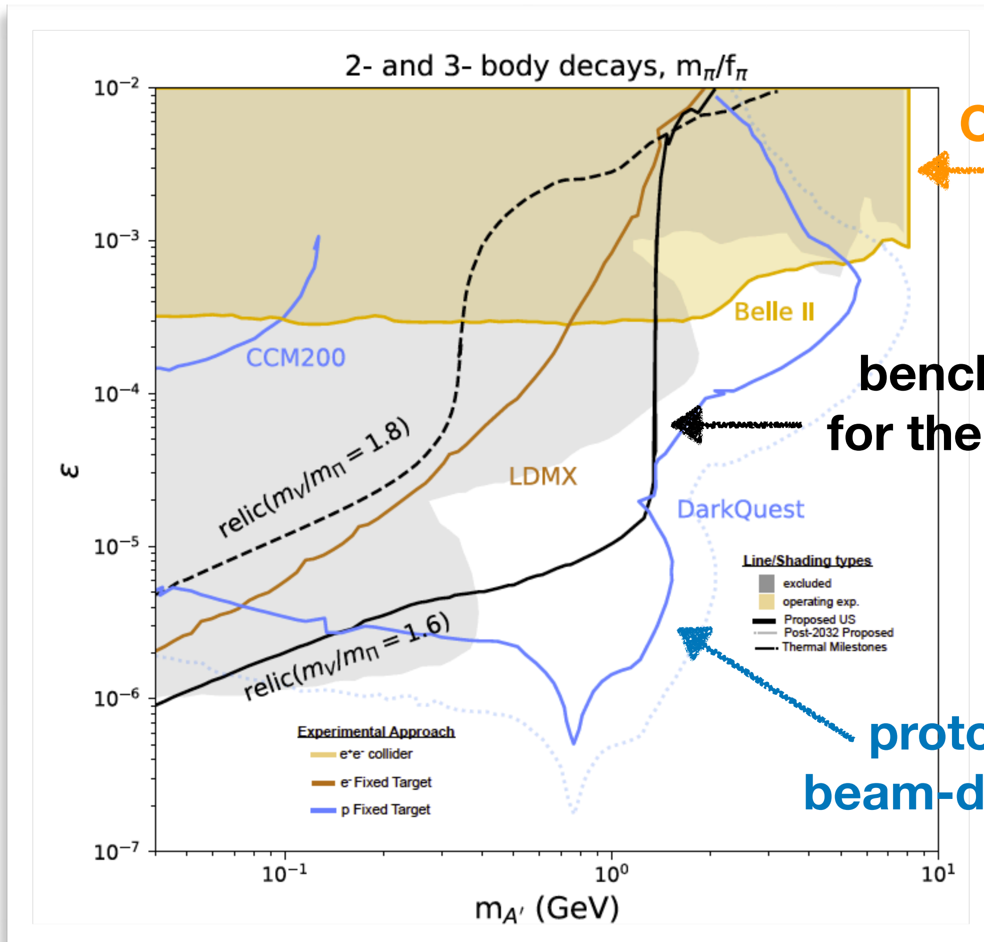
For example:



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

Additional visible benchmarks & messages

- ✱ Dark scalar
- ✱ Electron-mixed sterile neutrino
- ✱ Tau-mixed sterile neutrino
- ✱ ALP coupled to photons
- ✱ ALP coupled to gluons

Big idea 2

- ✱ $L_\mu - L_\tau$ visible gauge boson
- ✱ Inelastic Dark Matter (dark photon mediated)

Big idea 3

- ✱ Strongly interacting massive particle Dark Matter (dark photon mediated)
- ✱ Flavor violating QCD axion (s-d-ALP coupling)
- ✱ ALP coupled to gluons
- ✱ ALP coupled to SU(2) gauge bosons
- ✱ ALP coupled to up quarks
- ✱ ALP coupled to down quarks

PBC/FIP benchmark

Benchmarks

Searching for visible signatures offers a unique access to dark sector physics (minimal mediator, non-minimal mediator, excited DM states).

Sizable gain in sensitivity for all minimal portal models.

Planned and proposal experimental program will remain robust to unexpected final states from non-minimal models.

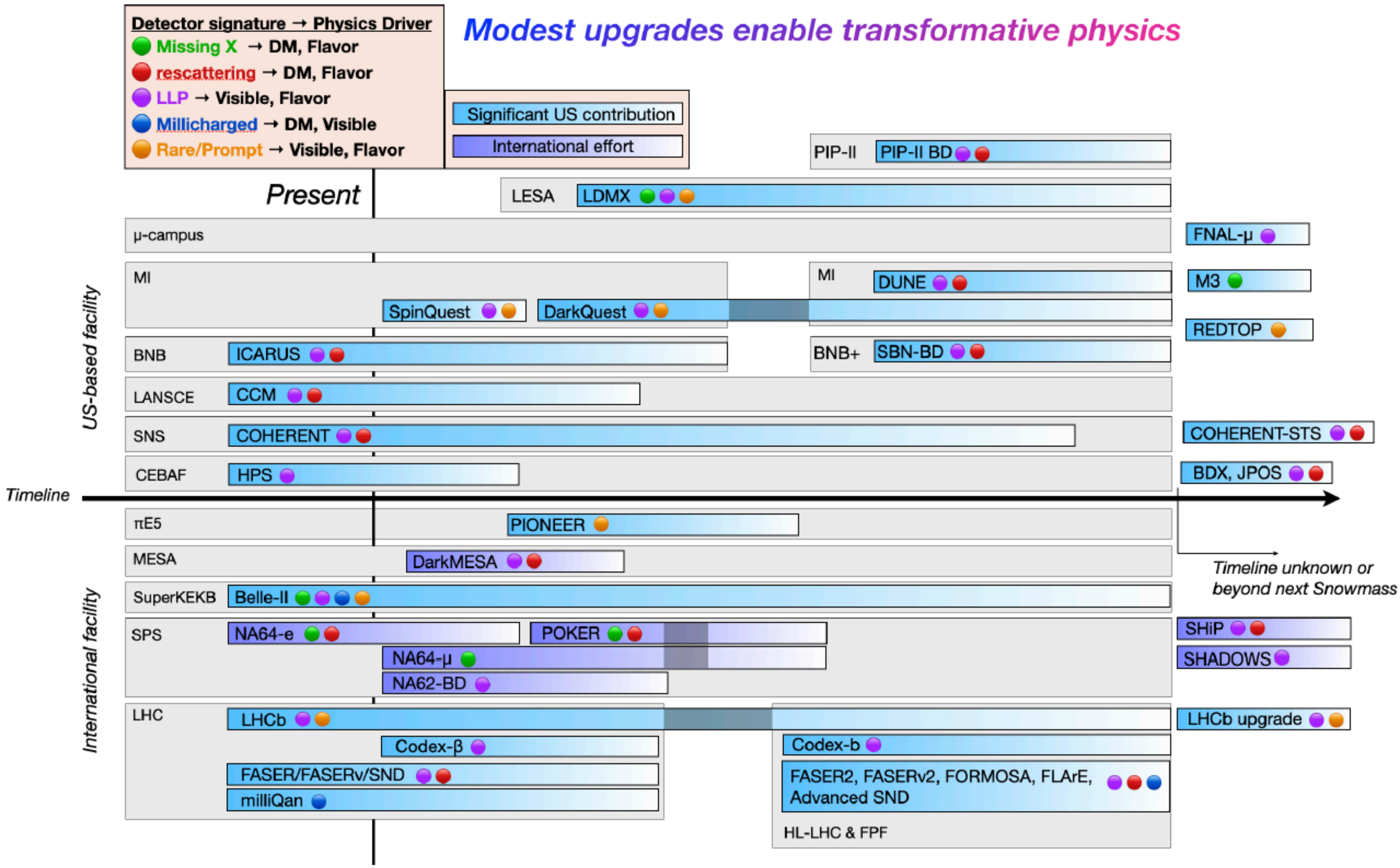
Interplay between prompt and displaced signatures.

Important complementarity of flavor factories (pion, Kaon, B mesons) and beam dump experiments / auxiliary detectors at colliders

Messages

Experiments/facilities

Ilten, Tran et al, 2206.04220



Theory

1. **Theory**: Better understand which dark-sector scenarios can address 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

Take home messages

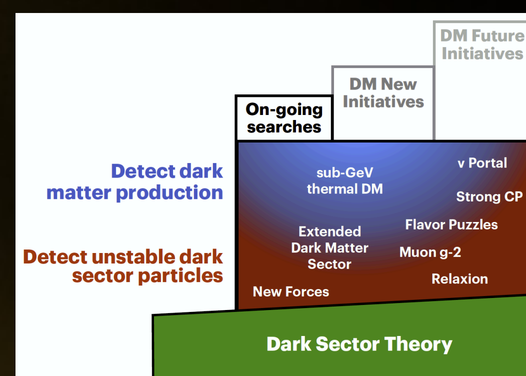
Dark sector particles in the MeV-GeV range naturally appear in DM models, as well as many well-motivated extensions of the Standard Model.

Unique role of **high-intensity experiments**

Important complementarity:

- dark-sector analyses at multi-purpose experiments (Belle II, LHCb);
- 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

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

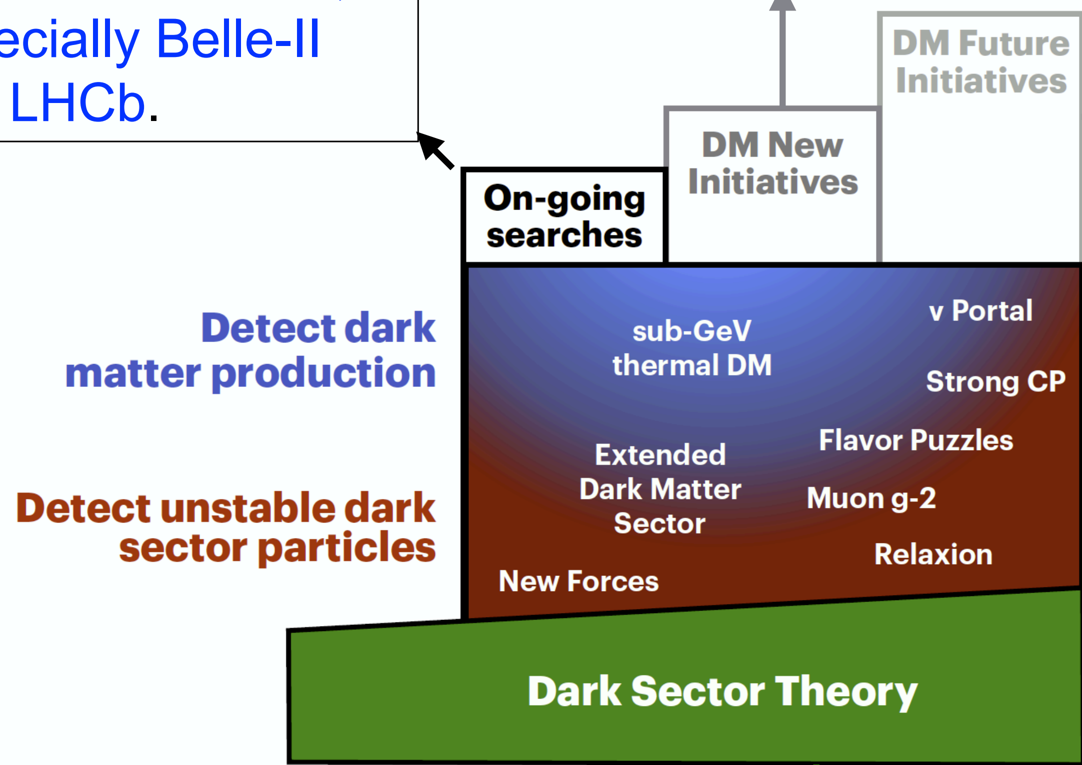


Backup

A 4-pronged approach for accelerator-based dark sector searches

* 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

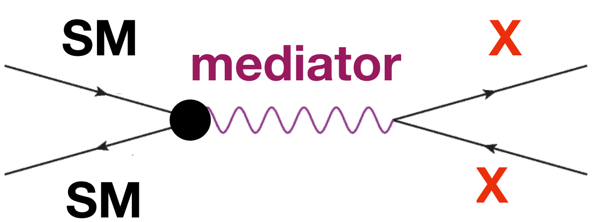
* Support theory efforts to explore dark sector models and collaborate in dark-sector experiments – this has been at the foundation of essentially all ongoing and planned experimental activities in this growing field.

Final states to look for

a. **Invisible, non-SM**

Dark Matter production

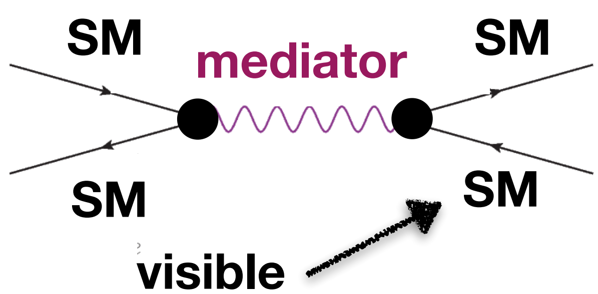
Producing stable particles that could be (all or part of) Dark Matter



b. **Visible, SM**

Production of portal-mediators that decay to SM particles

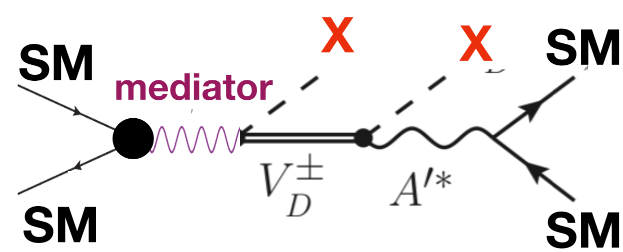
Systematically exploring the portal coupling to SM particles



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**

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

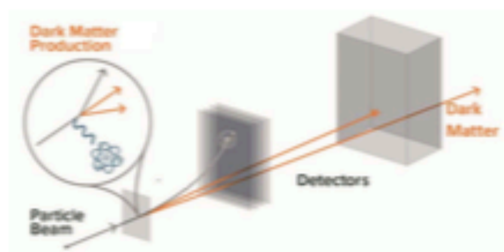
DM New Initiatives (DMNI)

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

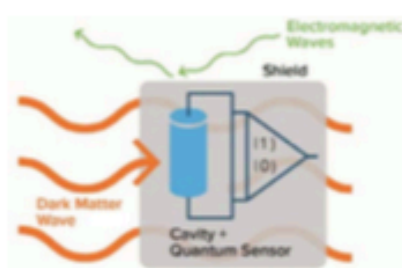


PRD 2

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.

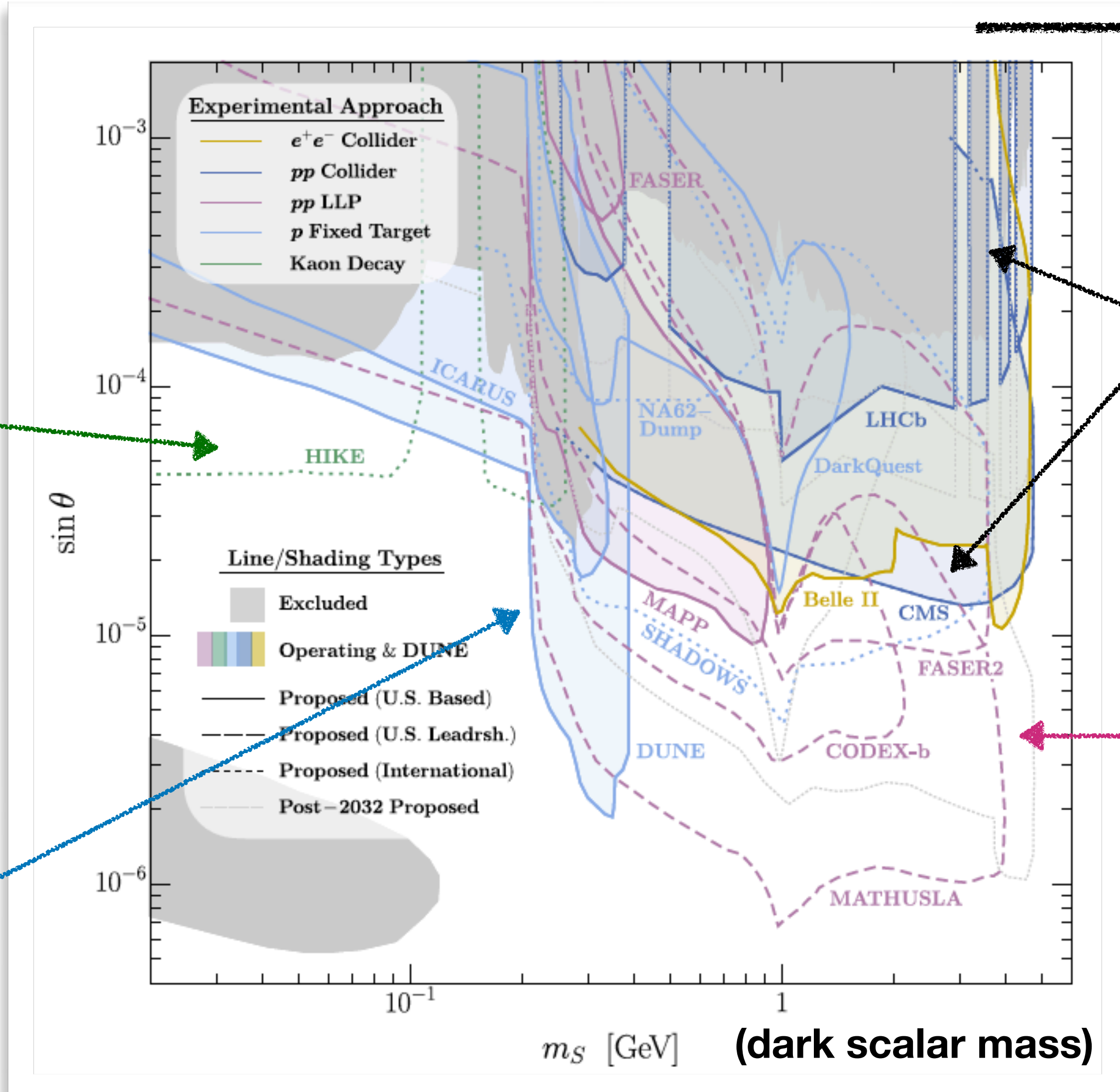
Exploring visible dark scalars

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

Kaon factories

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

proton beam-dump



energy frontier

Colliders

LHC auxiliary detectors

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

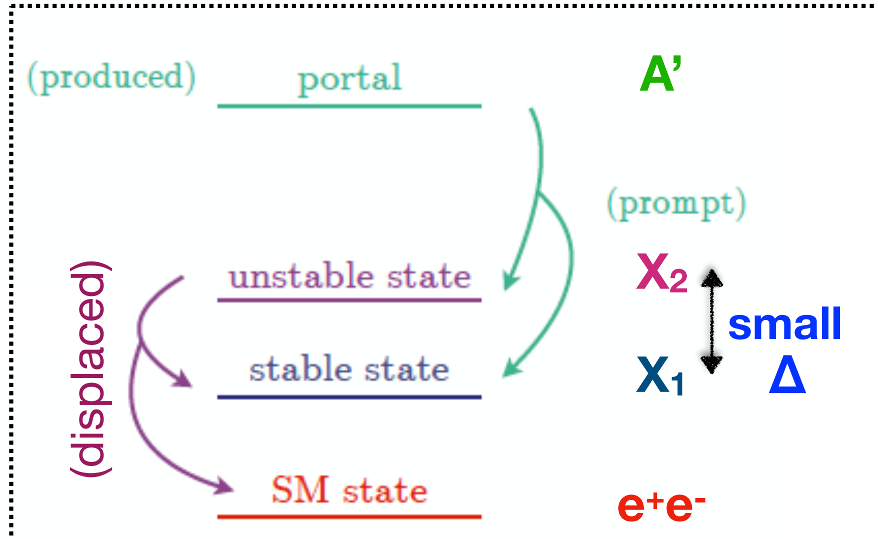
This entire parameter space predicts a **dark sector in thermal equilibrium** with the SM

DM models with metastable particles

Inelastic Dark Matter

Tucker-Smith, **Weiner**, 0101138

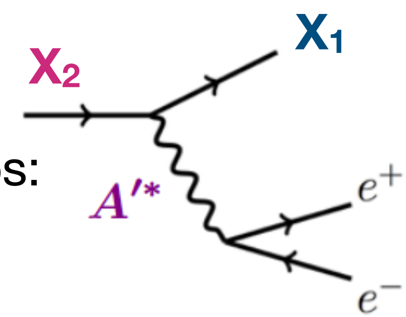
$$\mathcal{L} \supset \frac{i e_D\, m_D}{\sqrt{m_D^2 + (\delta_\xi - \delta_\eta)^2/4}} A'_\mu \left(\bar{\chi}_1 \gamma^\mu \chi_2 - \bar{\chi}_2 \gamma^\mu \chi_1\right)$$



* <u>A non-minimal freeze-out</u> mechanism:

$X_1\ X_2 \rightarrow$ SM

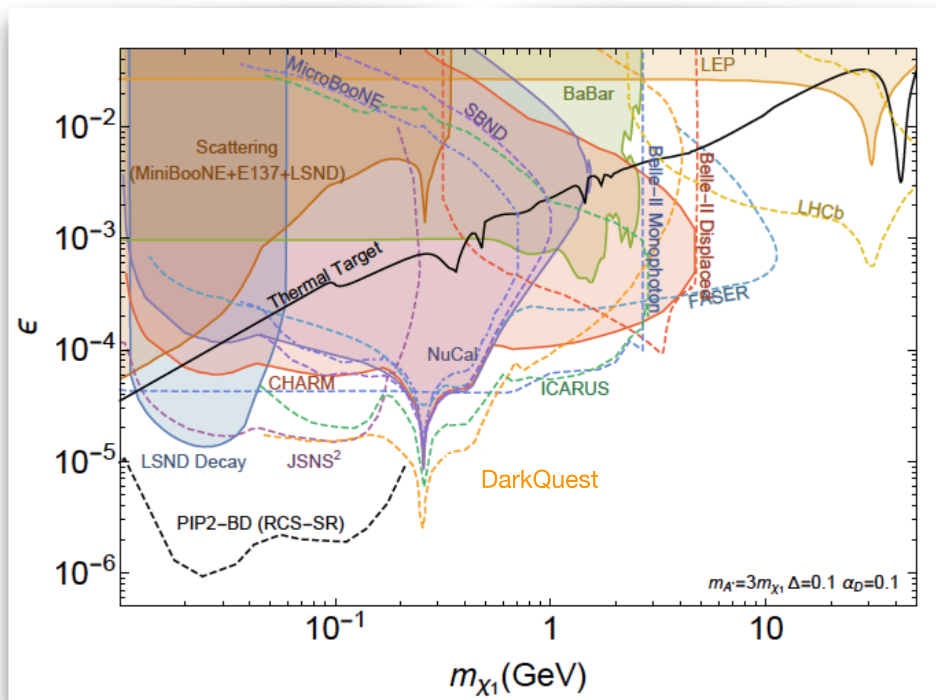
DM **DM excited state**



* <u>Signatures</u> in our labs:

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

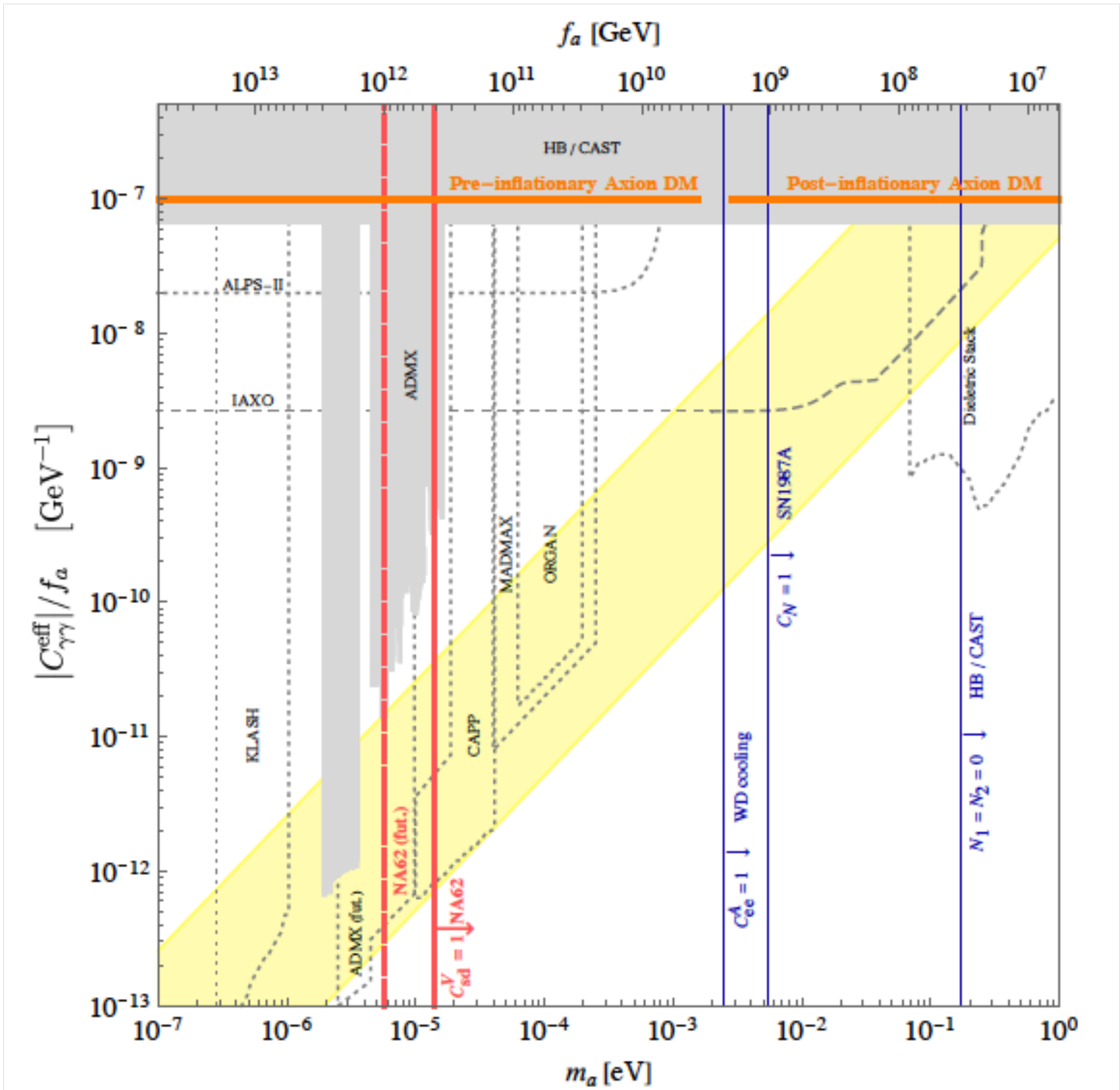
- Prompt visible decays
- Long lived particles
- Invisible component



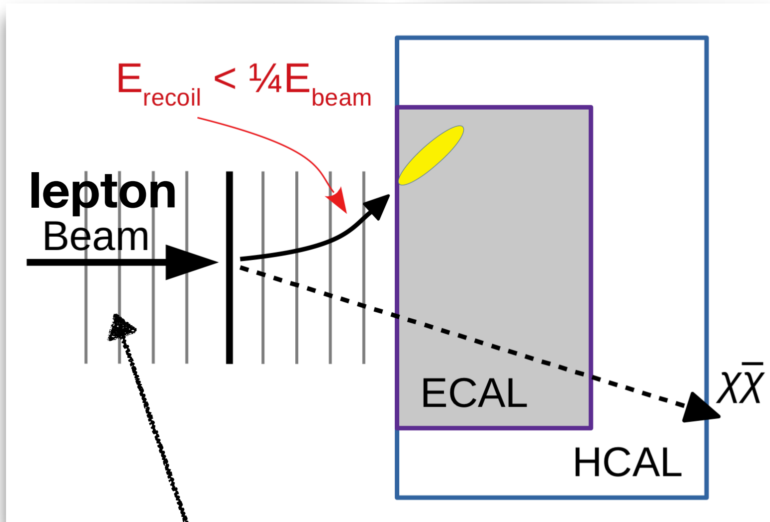
S.Gori

Backup

Flavor violating ALPs



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

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

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

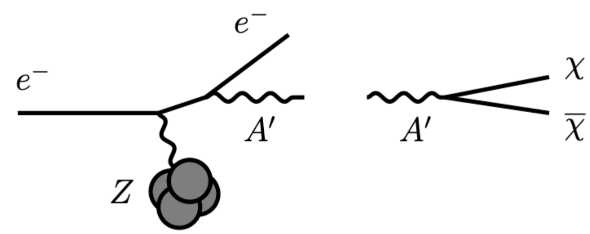
μ^- beam for the **M³** experiment,
Kahn et al., 1804.03144

Future experiments

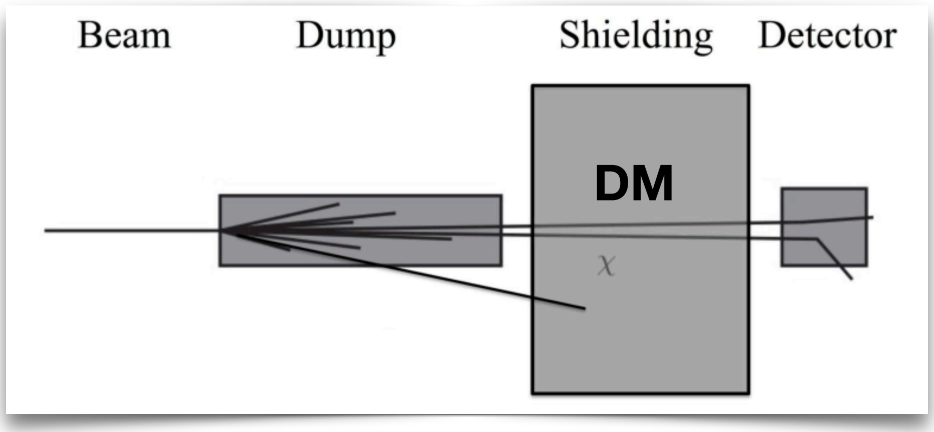
DMNI funding

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

For example,



2. Re-scattering



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

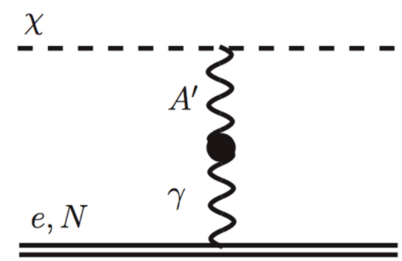
DMNI funding

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

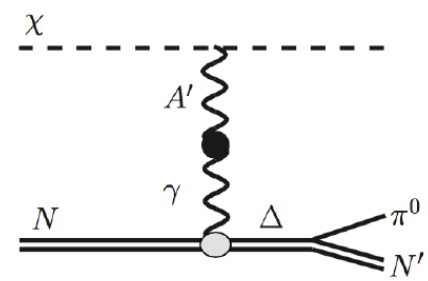
Synergy with beam dump-experiments that utilize high energy beams (forward facility, future colliders)

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

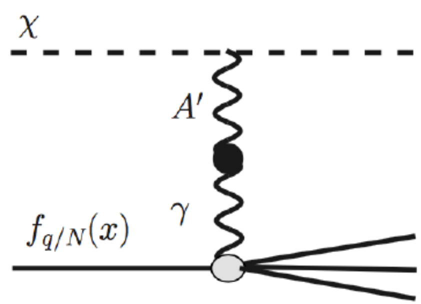
Detection strategy



Elastic electron, nucleon , nucleus (coherent) scattering



Inelastic neutral pion production

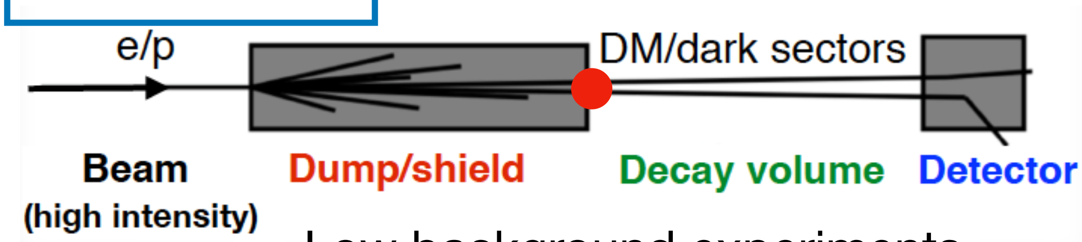


Deep inelastic scattering

Backup

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

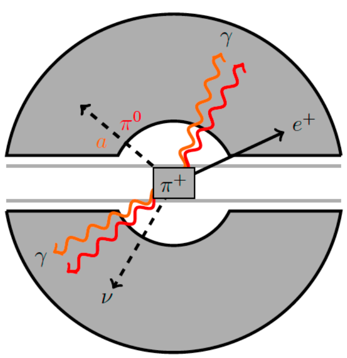
p beam for the NA62, KLEVER experiments at CERN

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