Phenomenology and search strategies

Stefania Gori
UC Santa Cruz

Accelerator-based Dark Sector Searches Agora
April 22, 2022

Outline of the talk

1. "Dark sectors at high-intensities". Activities of the RF6 Snowmass topical group

2. **Search strategies** for dark sectors at or below the GeV scale

3. **Big idea solicited white papers.** Phenomenology and present / future experiments

Most of the plots are preliminary
Comments are welcome!

Apologies if I do not mention all the experiments

RF6: dark sectors at high intensities

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

- mailing list (SNOWMASS-RPF-06-DARK-SECTOR@fnal.gov)
- SLACK channel (#rpf-06-dark-sector)
- webpage: https://snowmass21.org/rare/dark

Key questions:

- Why are dark sectors a compelling opportunity for the next decade?

  see talk by Natalia

- What are the needed theoretical developments to guarantee a broad exploration of the dark sector?

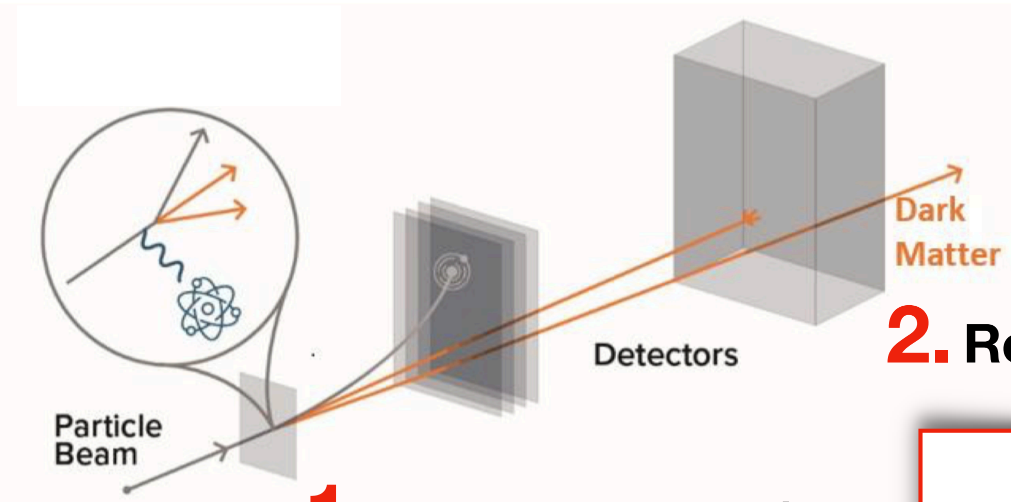
- Which set of benchmark models comprehensively covers the interesting signatures we can look for?

- How will experiments confront the dark sector landscape? (RF6 involves experiments from small to large, both dedicated and multi-purpose).

Goal: **to achieve a broad theoretical and experimental exploration of the physics of dark sectors at or below the GeV scale.**

Search techniques

Production of dark matter

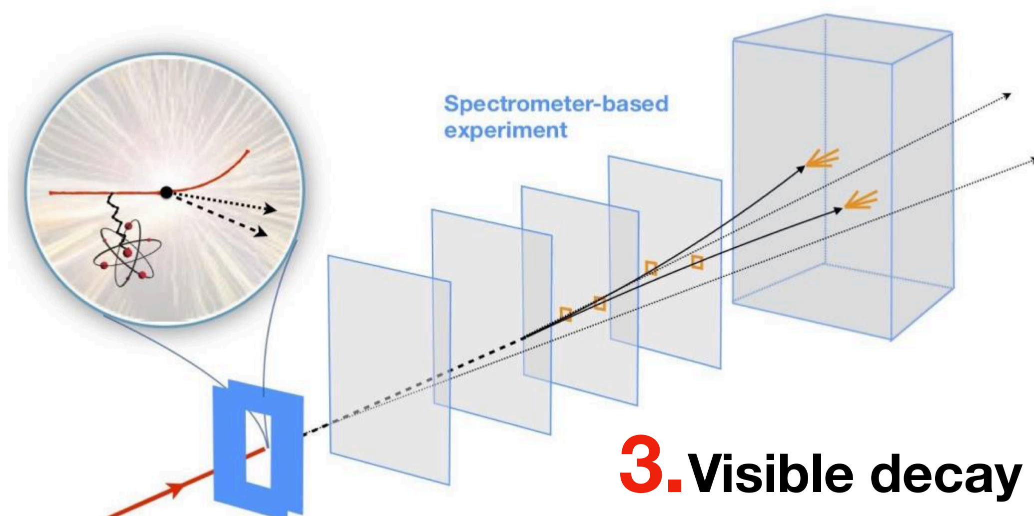


2. Re-scattering

1. Missing energy/ momentum

Several experiments, but the experimental techniques are only 3

Production of unstable dark sector particles

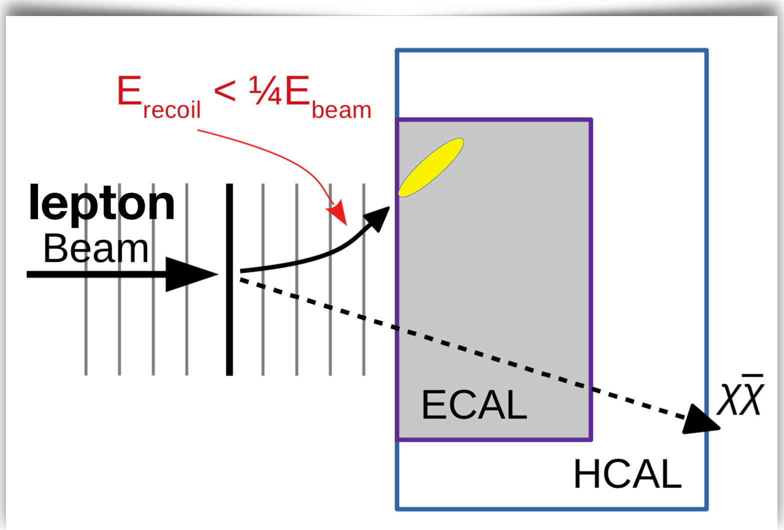


3. Visible decay products

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

1. Missing energy/momentum

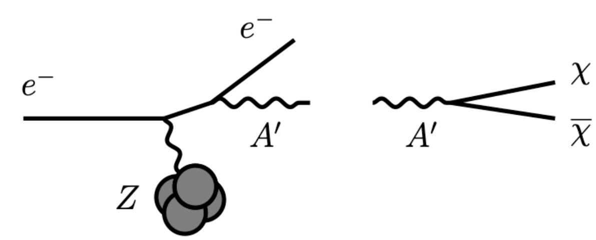


Dark matter events can be kinematically characterized by the calorimetric "disappearance" of a sizable fraction of the beam energy.

Detection strategy

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

For example,



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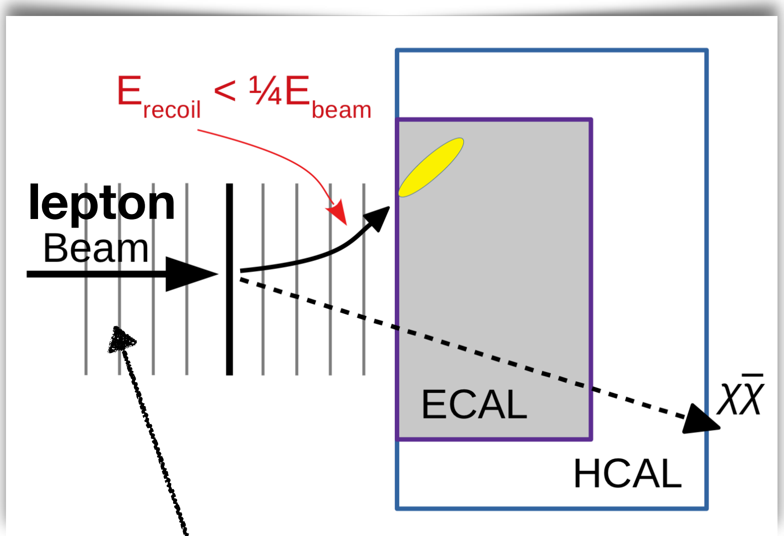

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Detection strategy

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

Running at CERN

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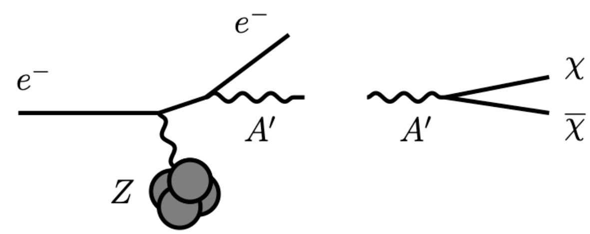


e⁻ beam for the **LDMX** experiment,
Akesson et al., 1808.05219

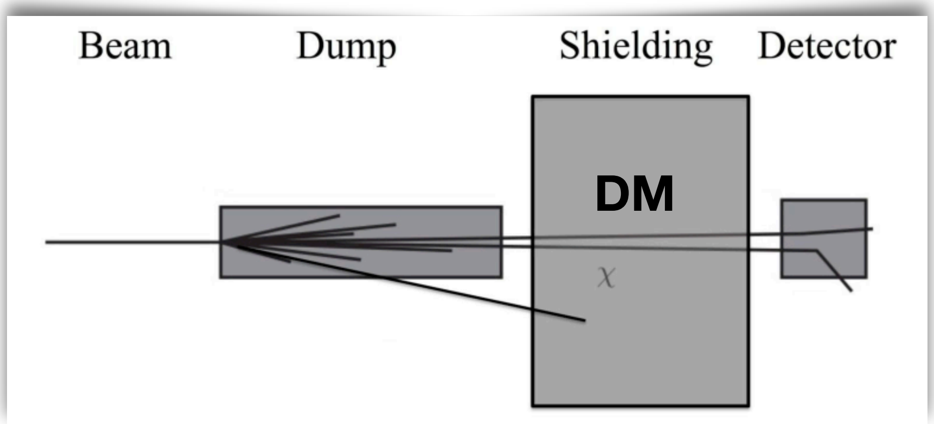
DMNI funding

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

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

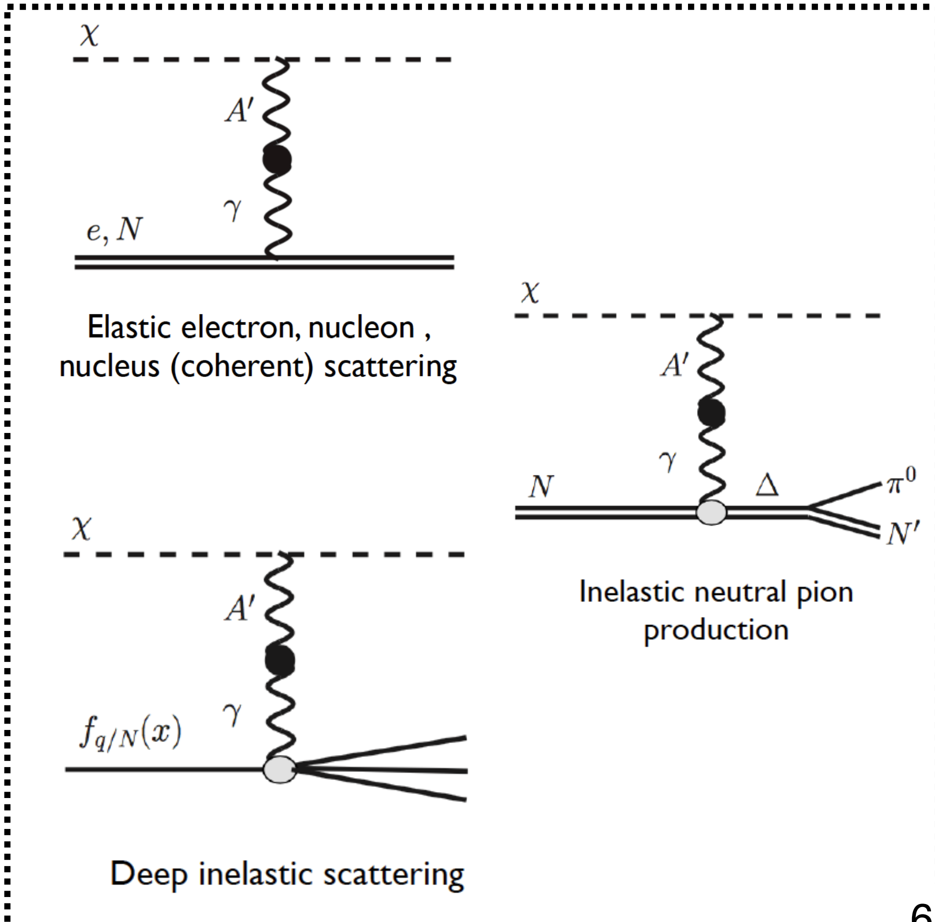
Future experiments

2. Re-scattering



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

Detection strategy



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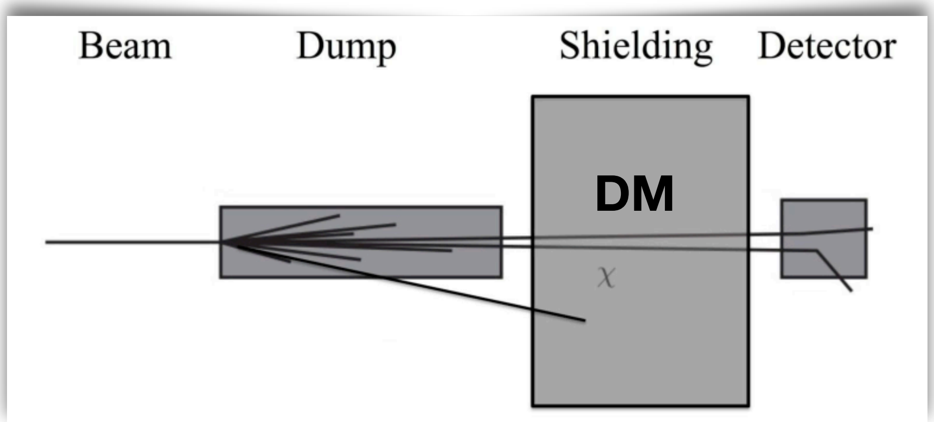


Production of dark matter in the dump and detection of its scattering in forward detectors.

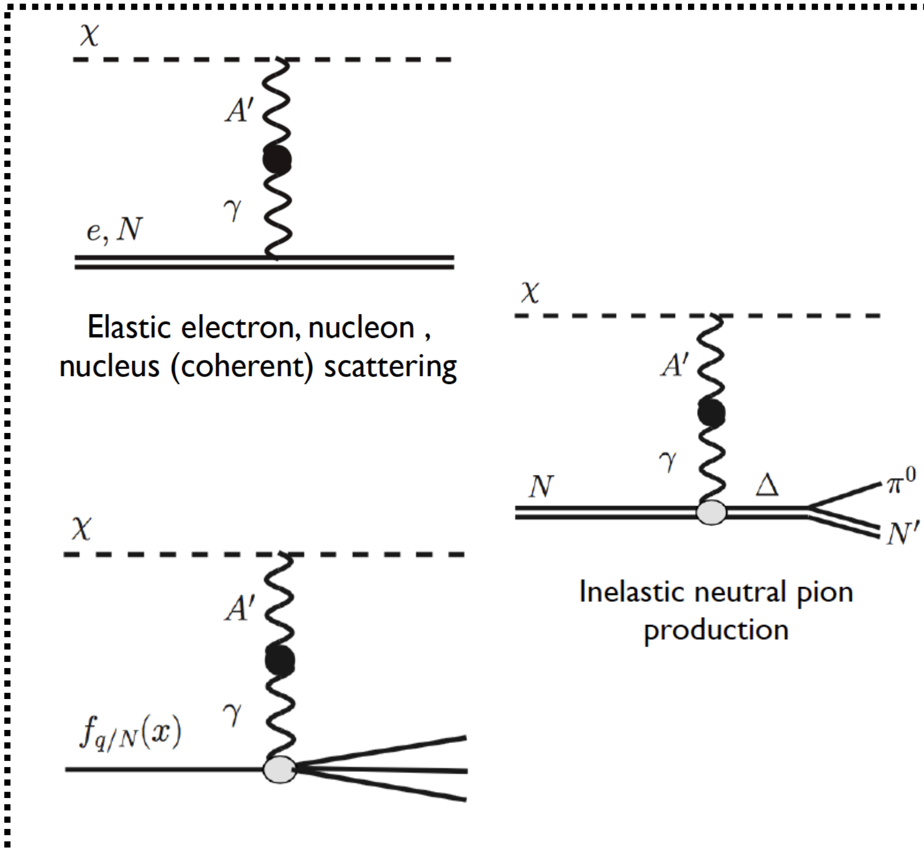
Detection strategy

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

(see Brian's talk) 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 (see Jonathan's talk))



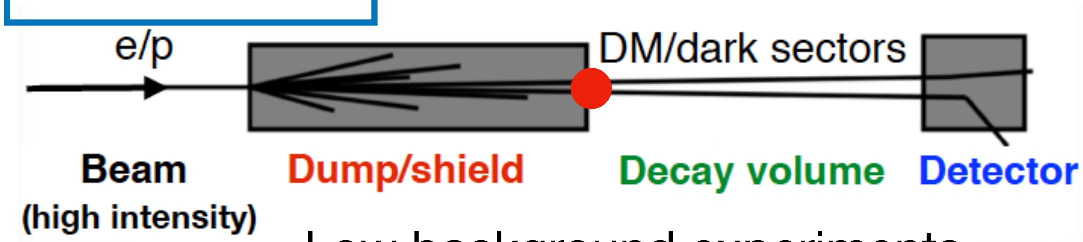
Elastic electron, nucleon , nucleus (coherent) scattering

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

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

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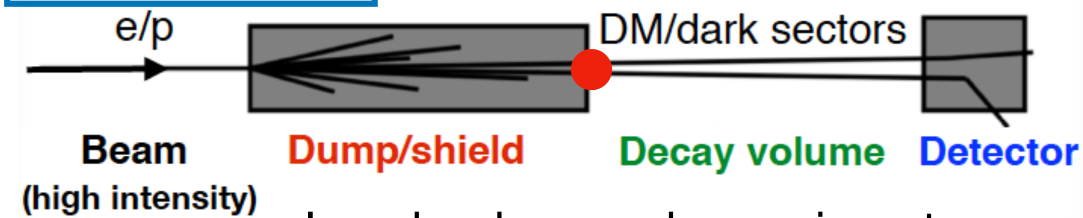

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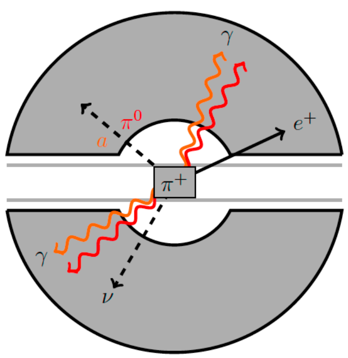

PROMPT

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, …

A broad set of 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 [$m_{A'}/m_\chi=3, \alpha_D=.5$]* **$m_{A'}$ vs. y** [α_D=0.5, 3 m_χ values] <u>m_χ vs. α_D [$m_{A'}/m_\chi=3$, $y=y_{fo}$]</u> m_χ vs. m_A [α_D=0.5, $y=y_{fo}$] *Millicharge m vs. q*	<u>$m_{A'}$ vs. ε [decay-mode agnostic]</u> ***$m_{A'}$ vs. ε [decays]***	**iDM m_χ vs. y [$m_{A'}/m_\chi=3, \alpha_D=.5$] (anom connection)** **SIMP-motivated cascades [slices TBD]** U(1)$_{B-L\ /\ \mu-\tau\ /\ B-3\tau}$ (DM or SM decays)
Scalar	m_χ vs. sinθ [λ=0, fix m_S/m_χ, g_D] (thermal target excluded 1512.04119, should still include) Note secluded DM relevance of S→SM of mediator searches	*m_S vs. sinθ* [λ=0] *m_S vs. sinθ* [λ=s.t. Br(H→ss ~10^{-2})]?	Dark Higgsstrahlung (w/vector) scalar SIMP models Leptophilic/leptophobic dark Higgs
Neutrino	e/μ/τ a la1709.07001 Batell, Han, McKeen, Es Haghi	*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. fq/l [λ=0, fix m_a/m_χ, g_D] (thermal target excluded) What about f_γ, f_G?	*m_a vs. f_γ* *m_a vs. f_G* *m_a vs. $f_q=f_l$* *m_a vs. f_W*	FV axion couplings

<u>Focus:</u> both the DM and the **mediator** are light (O(GeV) or less)

Bold = BRN benchmark, italic = PBC benchmark, others are new suggestions

BRN = basic research needs for DM small projects

RF6 “Big ideas” solicited papers

- Organization around science goals/questions.
- Arrange the breadth of RF6 science so that all the main techniques have a chance to shine.
- Span $\gtrsim$95% of white-paper interests

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1. Detect dark matter particle production (production reaction or through subsequent DM scattering), with a focus on exploring sensitivity to thermal DM interaction strengths.
Editors: Gordan Krnjaic, Natalia Toro

2. Explore the structure of the dark sector by producing and detecting unstable dark particles: Minimal Portal Interactions.
Editors: Brian Batell, Chris Hearty

3. New Flavors and Rich Structures in Dark Sectors.
Editors: Phil Harris, Philip Schuster, Jure Zupan

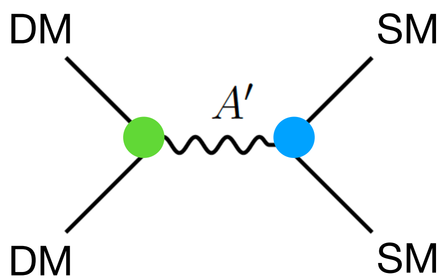
4. Experiments/facilities
Editors: Phil Ilten, Nhan Tran

More details: https://docs.google.com/document/d/1R0O23wjGLxRzsc93a4pJIFn17yW9TCTq
(in our google drive folder, https://drive.google.com/drive/folders/1sMn1cWl2ddqzu46Yi4TcMIX7Cm2GUxO_)

<u>Big idea 1</u> solicited white paper

Detect dark matter particle production (production reaction or through subsequent DM scattering), with a focus on exploring sensitivity to thermal DM interaction strengths. Editors: Gordan Krnjaic, Natalia Toro

Access to DM thermal targets



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

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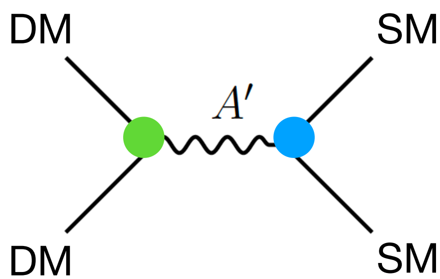


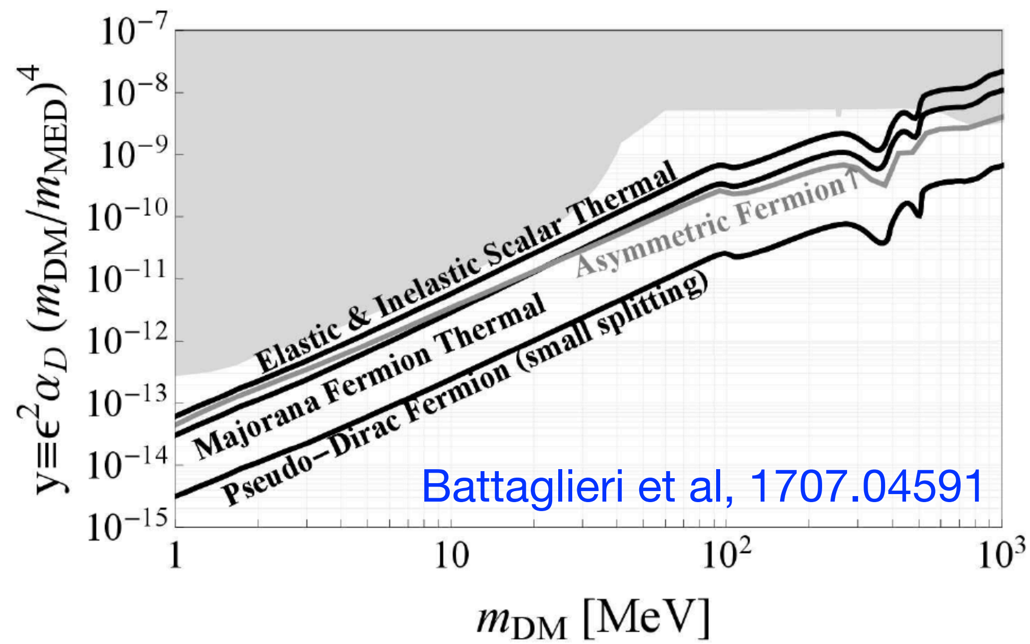
$$\sigma \propto \frac{y}{m_{\rm DM}^2}, \quad y \equiv \epsilon^2 \alpha_D \left(\frac{m_{\rm DM}}{m_{A'}}\right)^4$$

In the case of a dark photon mediator:

$$\text{Majorana}: J_D^\mu = \frac{1}{2}\bar{\chi}\gamma^\mu\gamma_5\chi$$

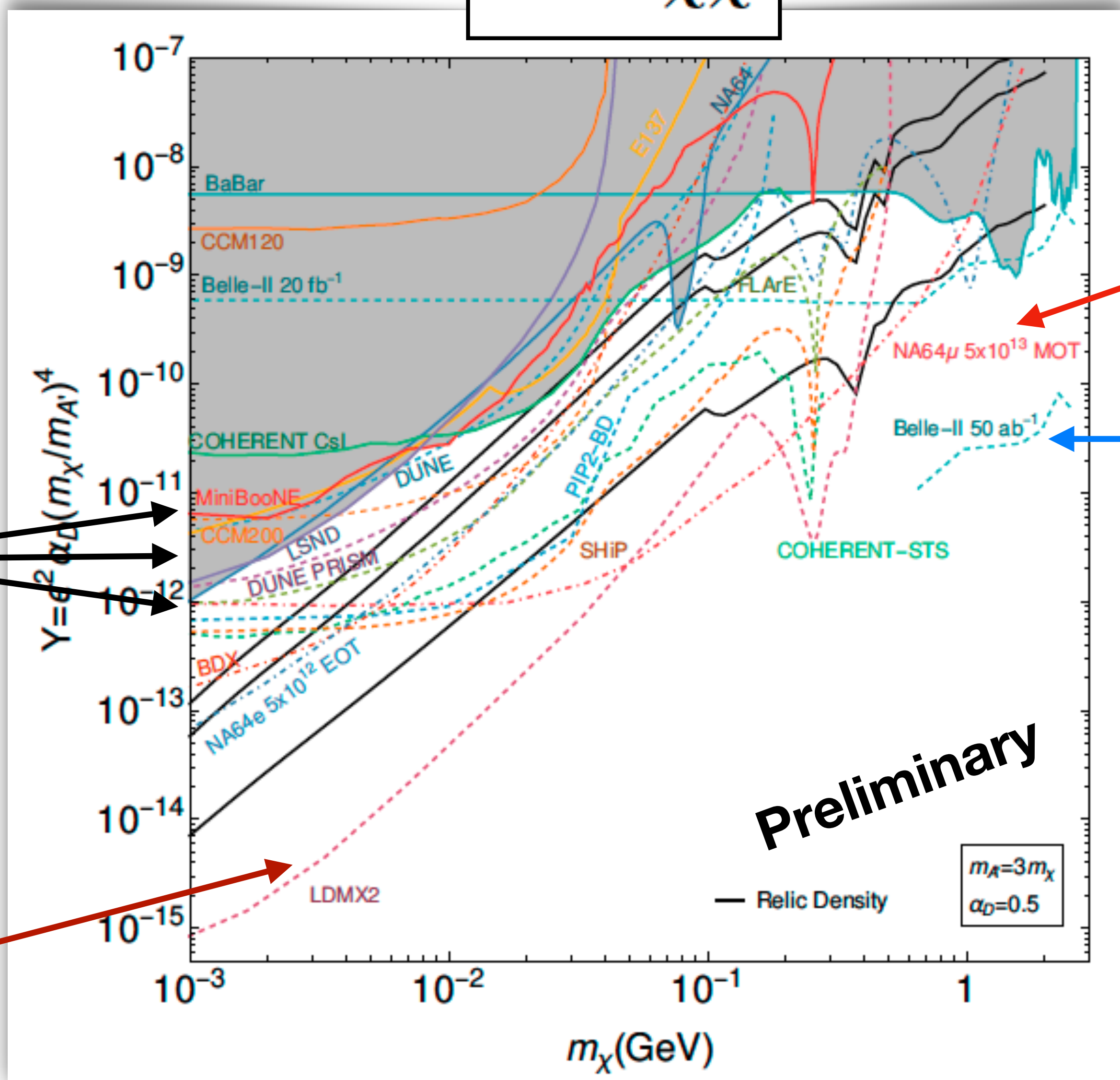
$$\text{PseudoDirac}: J_D^\mu = i\bar{\chi}_1\gamma^\mu\chi_2$$

$$\text{Scalar}: J_D^\mu = i(\chi^*\partial^\mu\chi - \chi\partial^\mu\chi^*)$$



Big idea 1, invisible dark photon

$$A' \to \chi\chi$$



Missing energy

Collider, mono-photon search

Re-scattering

Missing momentum

Big idea 2 solicited white paper

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

Editors: Brian Batell, Chris Hearty

- dark photon $\epsilon B^{\mu\nu} A'_{\mu\nu}$ → $A' \to \ell^+\ell^-, \ldots$
- dark scalar $\kappa|H|^2|S|^2$ → $S \to \mu^+\mu^-,\ \pi^+\pi^-, KK, \ldots$
- sterile neutrino $yHLN$ → $N \to \ell\pi, \ldots$
- ALP $g_{a\gamma} a \tilde{F}_{\mu\nu} F^{\mu\nu}$ → $a \to \gamma\gamma, \ldots$

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How to test these couplings?

Sizable coupling → prompt decay (generically larger backgrounds)

Small coupling → displaced decay (generically small backgrounds)

Experimental targets:

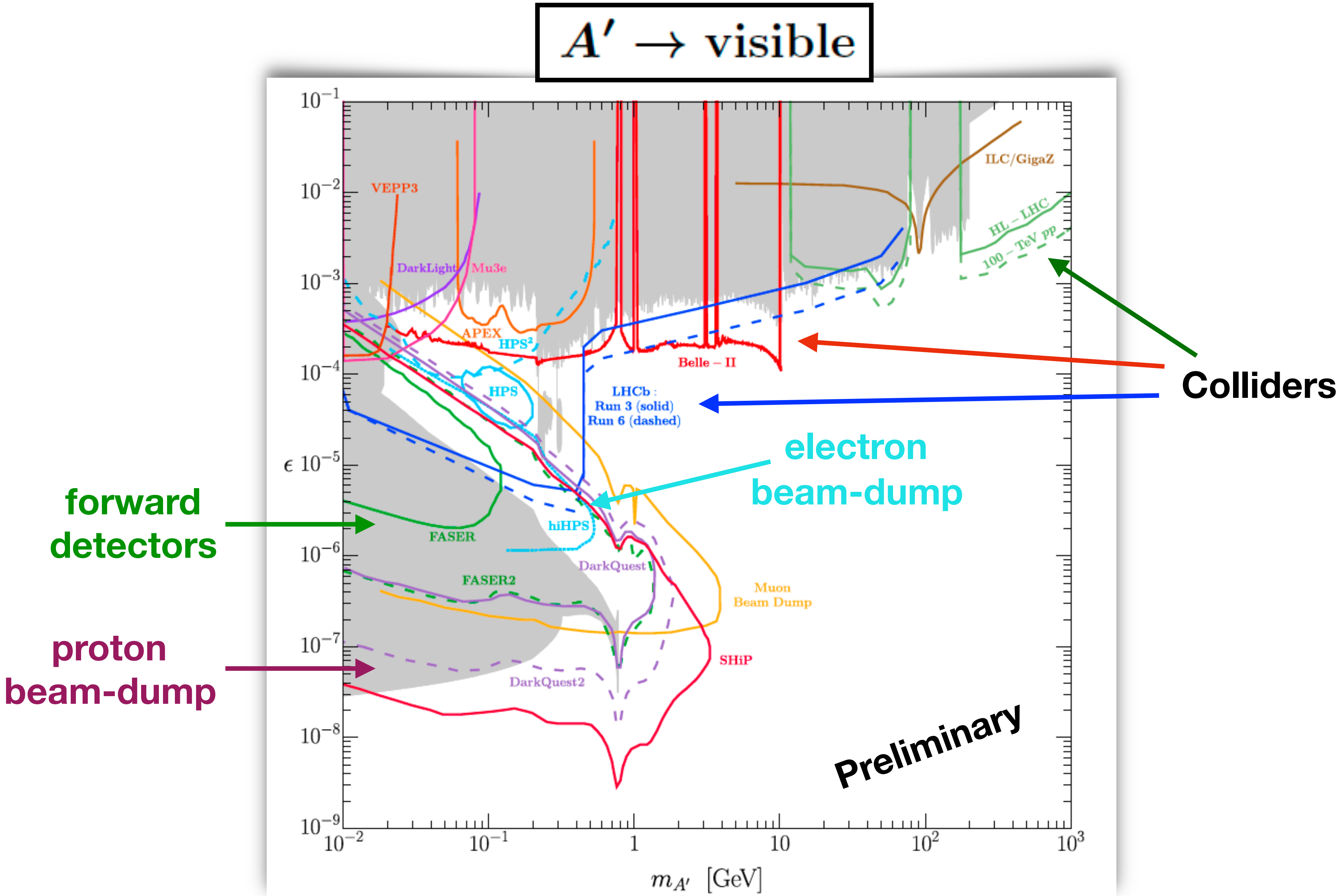
Secluded DM scenarios

(Pospelov, Ritz, Voloshin, 0711.4866)

Forbidden DM scenarios

(D'Agnolo, Ruderman, 1505.07107)

Big idea 2, visible dark photon



Big idea 3 solicited white paper

Beyond Minimal Models: New Flavors and Rich Structures in Dark Sectors.

Editors: Phil Harris, Philip Schuster, Jure Zupan

Richer phenomenology ⇨ rethinking of experimental strategies for achieving optimized sensitivities

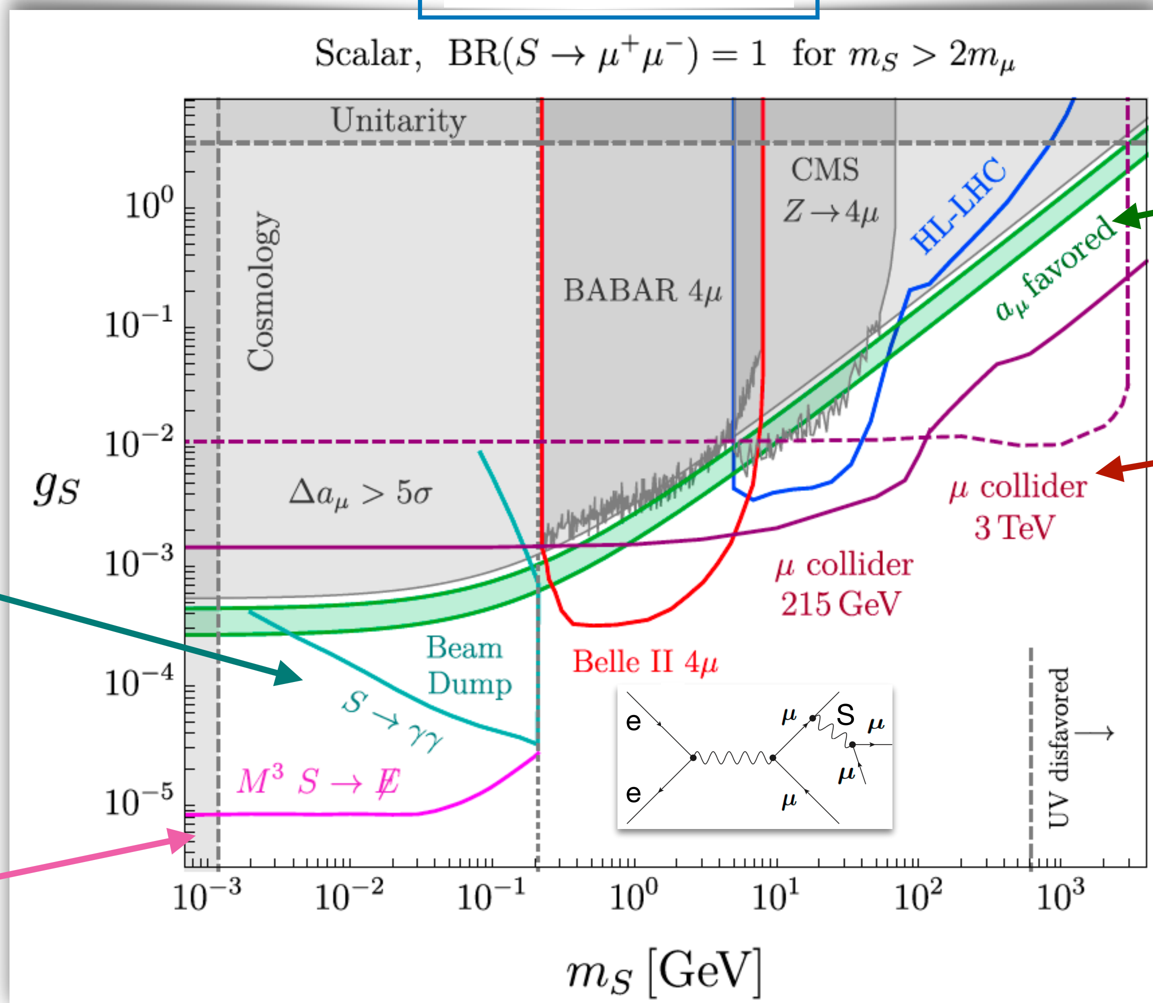
2 themes:

- Dark sector benchmarks for 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. flavor violating ALPs, strongly interactive massive particle DM, inelastic DM, …)

Big idea 3, anomaly motivated scenarios

“flavor-specific” dark sectors

$$\mathcal{L} = -g_S\, S\, \overline{\mu}\mu$$



(g – 2)$_\mu$ favored region

high energy muon colliders

muon beam-dump
Chen, Pospelov, Zhong, 1701.07437

muon missing momentum
Kahn, Krnjaic, Tran, Whitbeck, 1804.03144

Capdevilla, Curtin, Kahn, Krnjaic, 2112.08377

Big idea 3, strongly interacting massive particle DM

Realized in a QCD-like theory SU(N_c) with

$SU(N_f) \times SU(N_f) \to SU(N_f)$ Light pions (some of them can be DM)

$$\mathcal{L}_{\mathrm{WZW}} = \frac{2N_c}{15\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}(\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi)$$

Relic abundance: $3 \to 2$ annihilation

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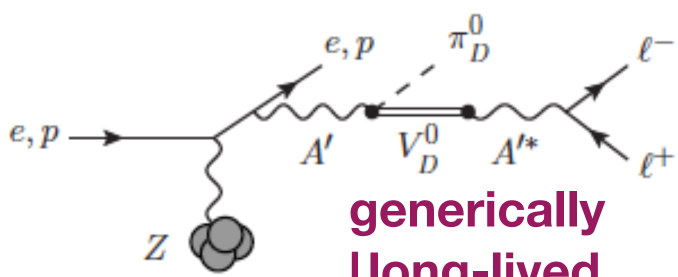
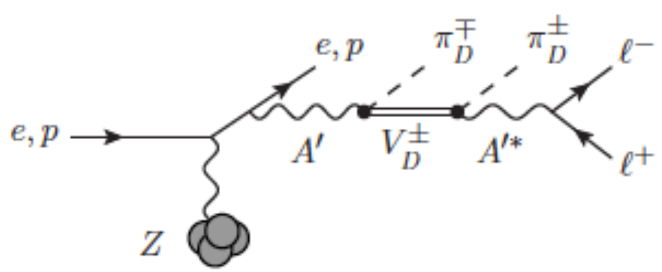
Signatures



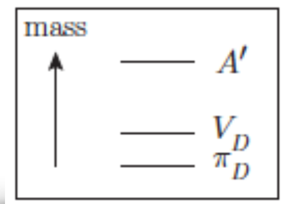
generically long-lived

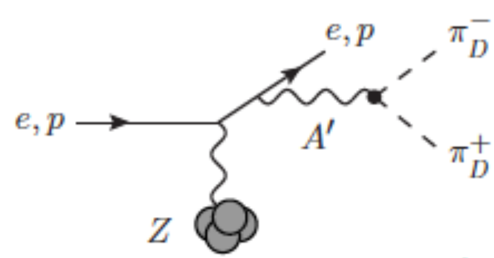
$$A' \to V_D \pi_D,\ V_D \to A'^* \to e^+e^-$$



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

(Semi) Visible A' decay





Invisible A' decay

$$A' \to \pi_D \pi_D$$

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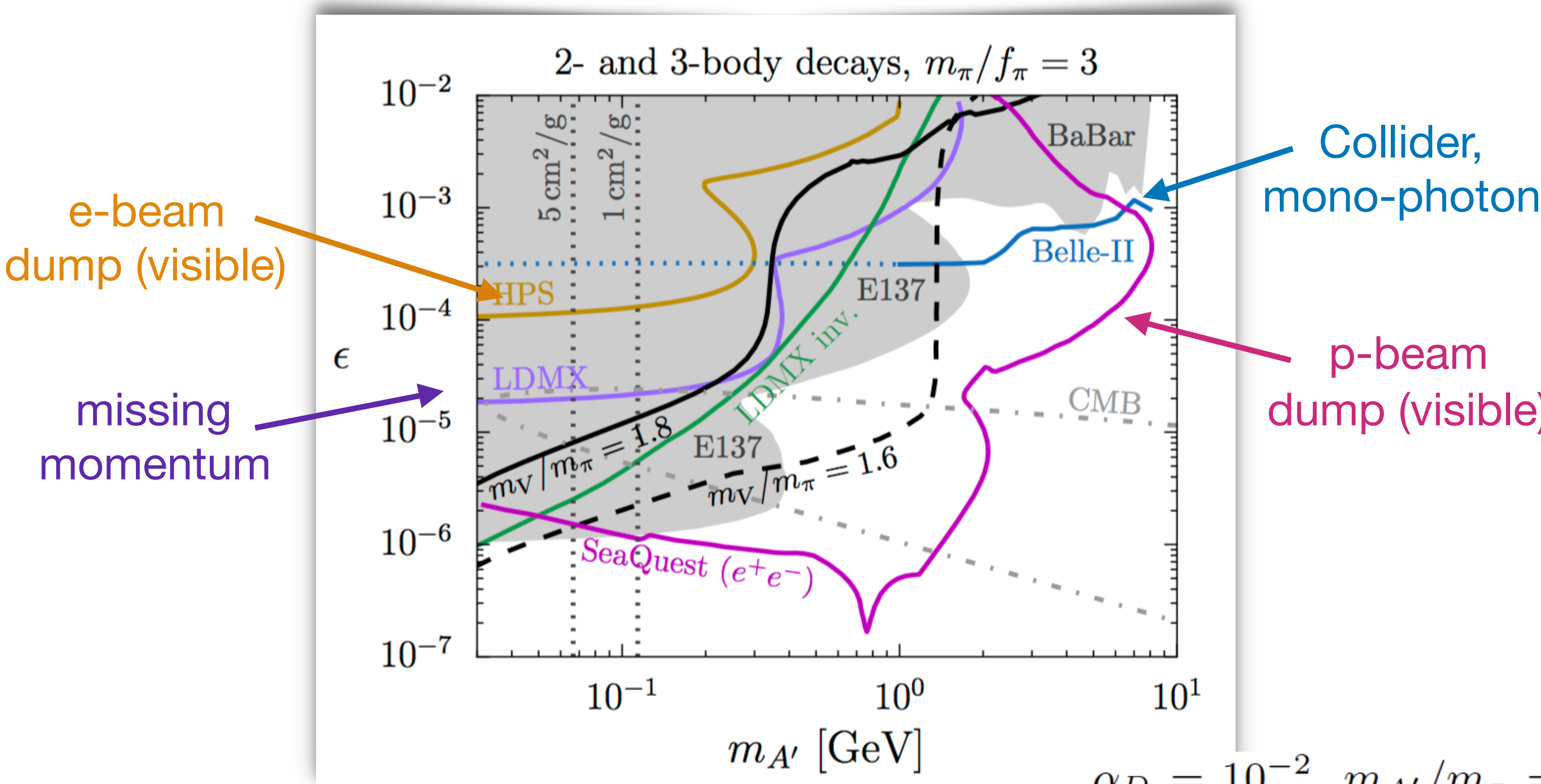
Relic abundance: $3 \to 2$ annihilation

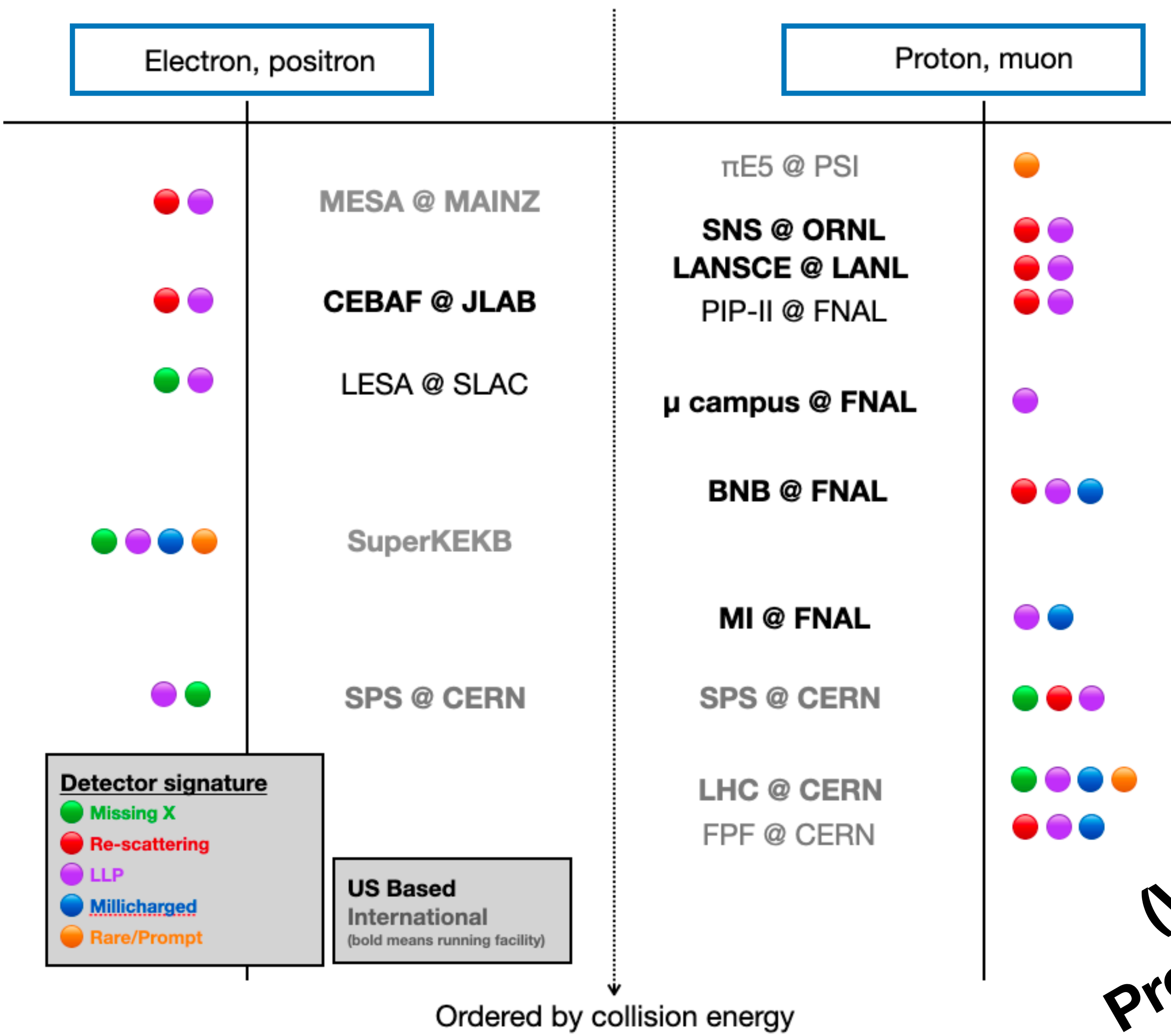


$\alpha_D = 10^{-2}$, $m_{A'}/m_\pi = 3$

Berlin, Blinov, SG, Schuster, Toro, 1801.05805

Experiments and facilities solicited white paper

Editors:
Phil Ilten, Nhan Tran



(Very) Preliminary

Conclusions & Outlook

Dark sector particles naturally appear in many well-motivated extensions of the Standard Model.

High-intensity experiments based on 3 different techniques:
- missing energy/momentum
- re-scattering
- searches for visible decay products

will offer an **unprecedented opportunity to test dark sectors at or below the GeV scale**

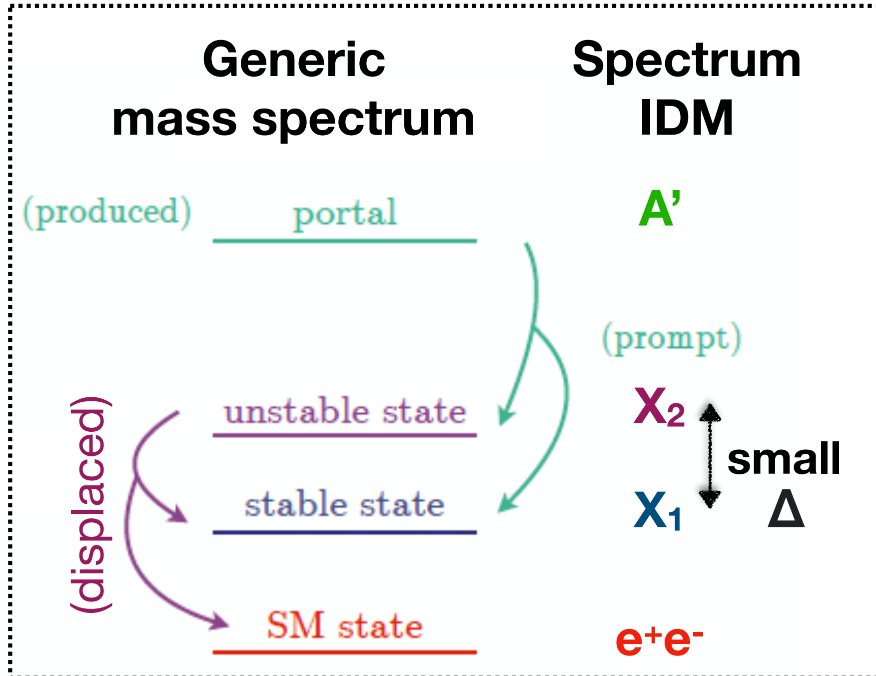
Full exploration of many benchmarks is expected in the coming few years.

Crucial complementarity with
- (high energy) colliders
- auxiliary detectors at colliders
- direct detection experiments

Big idea 3, inelastic dark

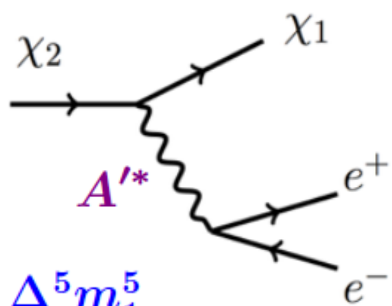
$$-\mathcal{L} \supset m_D\,\eta\,\xi + \frac{1}{2}\,\delta_\eta\,\eta^2 + \frac{1}{2}\,\delta_\xi\,\xi^2 + \text{h.c.}$$

2-component Weyl spinors
with opposite charge under U(1)'



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

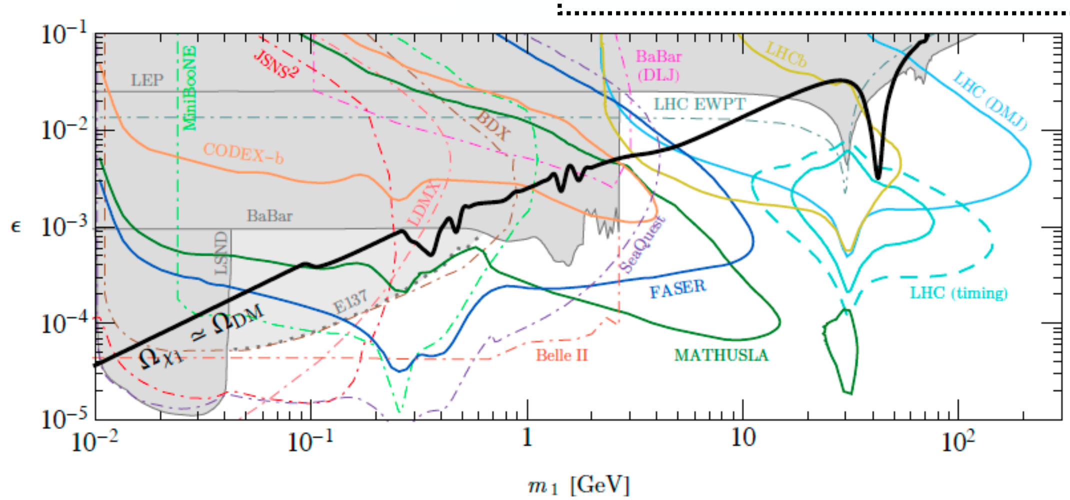
* Freeze-out: $X_1\, X_2 \rightarrow$ SM



* Signatures in our labs:

$$\Gamma(\chi_2 \rightarrow \chi_1 e^+ e^-) \simeq \frac{4\epsilon^2\,\alpha_{\rm em}\,\alpha_D\,\Delta^5 m_1^5}{15\pi m_{A'}^4}$$

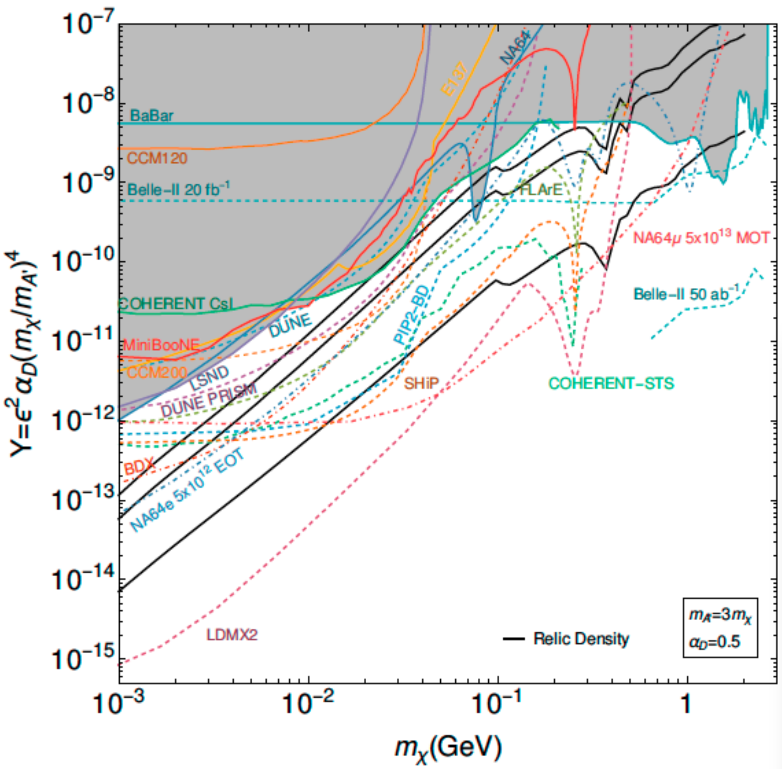
Visible decays if large enough mass splitting.
Invisible component as well



S.Gori

Backup

Invisible dark photon parameter space



Preliminary

$\epsilon, \alpha_D, m_\chi, m_{A'}$