RF6 Big Idea 1 Organizational Meeting

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Refresher: The Big Picture

- RF6 will have four **Solicited Whitepapers** (level of detail in between Contributed Whitepapers and Topical Group report) organized around “Big Ideas”:
  - **BI1: Detect dark matter particle production (production reaction or through subsequent DM scattering), with a focus on exploring sensitivity to thermal DM interaction strengths.**
  - BI2: Explore the structure of the dark sector by producing and detecting unstable dark particles: *Minimal Portal Interactions*
  - BI3: New Flavors and Rich Structures in Dark Sectors
  - Summary of RF6 Experiments and Facilities
- Contributed WPs are due March 15, and Solicited WPs are due April 15
- The contents of contributed WPs (and other community publications) feed in to the solicited WPs. But we need to coordinate well in advance of the WP submissions.
- **The purpose of this meeting is to share our early thoughts on the framing and scope of the Big Idea 1 Whitepaper, gather your input, and request your involvement.**

Today’s Plan

- The Big Idea: Framing, Motivation, Scope, and Goals of the Document
- List of Related LOIs (What did we miss?)
- Tentative Outline
- More detail on the introduction and motivating models & benchmarks
- Lots of time for discussion
- Timeline for writing
- How to get involved

Framing Big Idea 1

Dark matter particles can be observably produced at intensity-frontier experiments, and opportunities in the next decade will explore important parameter space motivated by thermal DM models, the dark sector paradigm, and anomalies in data.

Discuss motivations, (conceptual) detection strategies, prospects and challenges, and (briefly) connections to other Big Ideas in RF6 and to CF, EF10, and NF probes of dark matter.

Above framing is meant to encompass broad themes and motivate structure, but boundary is not strict.

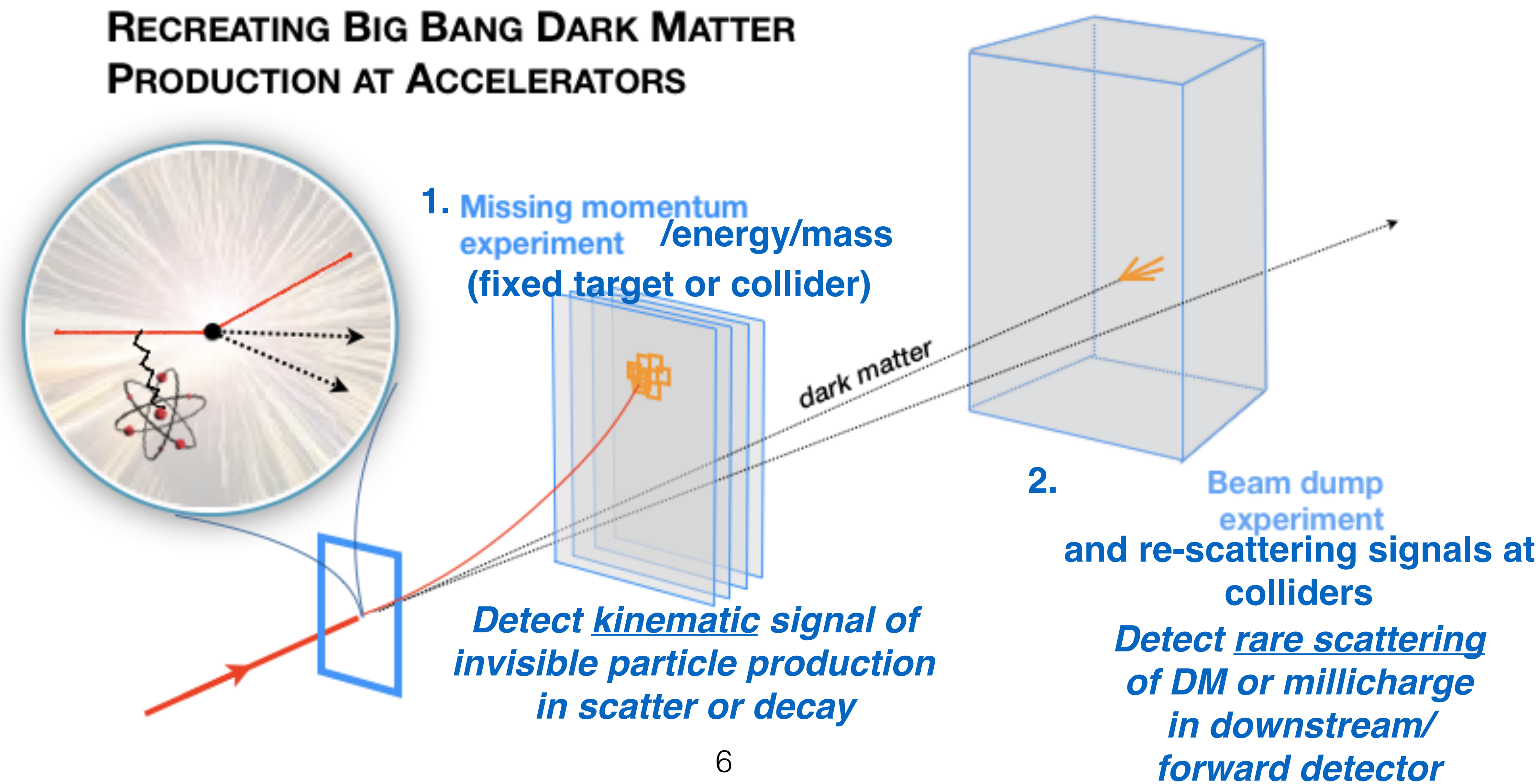
e.g. we will include invisibles that are not DM (unless it makes more sense in another Big Idea paper), low-pT LHC production

Motivations to Highlight

- General picture of **dark matter interacting with new forces**
- **Thermalization and freezeout as a guide**:
  - Thermal origin (broadly construed) is motivated and compelling
  - (Almost) anything sufficiently coupled to be produced could reach thermal equilibrium ➝ needs to freeze out with appropriate abundance – informs thinking about where to look.
- **Finite list of portals, with more breadth in the structure of the dark sector** (one DM particle? More? Relevant self interactions? What process(es) govern freeze-out?)
- **Accelerator-based searches offer a crucial discovery mode for this family of dark matter candidates**:
  - Relative to heavier dark matter, indirect detection is less relevant
  - Direct detection is complementary, while facing its own technical challenges and model-dependence
- Note added following meeting discussion: Why electron-to-proton mass?
  - Electron mass: logical lower bound for thermalized models – most call for annihilation to electrons
  - Proton mass: boundary between WIMP-like and less WIMP-like models, as well as where high-intensity techniques excel (this is a fuzzy boundary)

Conceptual Approaches

Most fall into 3 categories (slightly generalized from DMNI BRN report)

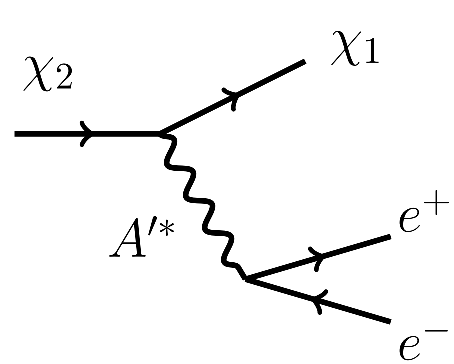


Conceptual Approaches

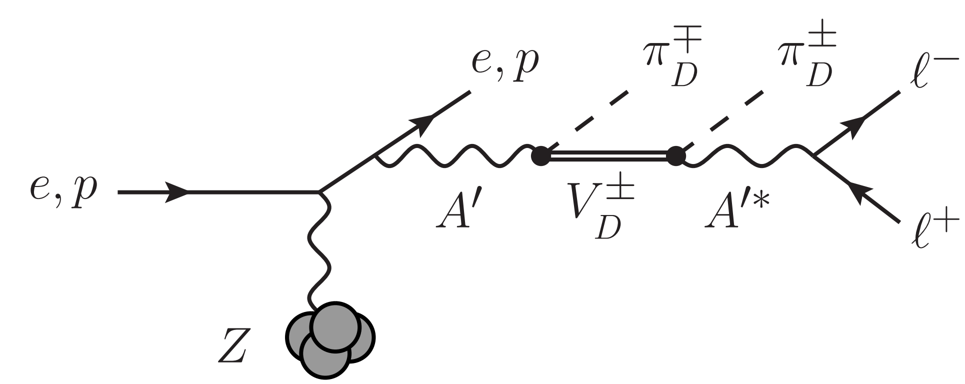
Most fall into 3 categories (slightly generated from DMNI BRN report)

3. Detect semi-visible signals of dark matter production that exploit transitions between dark sector states

e.g. inelastic dark matter: produce excited state that decays in detector



e.g. cascades of dark-sector hadrons in strongly interacting SIMP dark matter



Significant synergy and possible overlap with the other two Big Ideas — we think it makes sense to cover these in multiple places where our focus in BI1 will be on how these signatures enable study of a broader range of DM models….but plan is still evolving.

LOI Survey

- This list is our first attempt to start organizing anticipated community input
  - For some broad LOIs, we have tried to called out the sub-parts relevant to this “Big Idea.”
- If we missed your LOI, DON’T PANIC (but please do let us know)

LOIs: Missing X

- Lepton Fixed Target Missing Energy/Momentum
  - LDMX RF6_RF0-EF10_EF0-CF1_CF0_Andrew_Whitbeck: Missing momentum in *e-* beam
  - Muon missing momentum RF6_RF0-EF10_EF0-CF1_CF0_Andrew_Whitbeck-111
  - DM with positron beams RF6_RF0_Luca_Marsicano-074 (missing energy in beam e+ / atomic e- annihilation)
  - Photon beam experiments RF6_RF0-112 : Missing momentum in Compton
- Missing 4-Momentum in eta decays
  - η-η' factories RF6_RF2_Sean_Tulin (LOI mentions future study of invisible and semi-visible iDM – please let us know what studies are expected for whitepaper)
  - Redtop RF2_RF6-IF6_IF3_REDTOP_Collaboration
  - Did we miss other searches in tagged meson decays?
- Collider
  - Dark sectors at Belle II RF6_RF0-028
  - LHC Large MET signals are out of our scope (EF10)

LOIs: Dark Matter Re-Scattering (Beam Dump or Auxiliary Collider Detector) part 1

- Proton Beams – Light Thermal DM
  - 1GeV proton beam dump at Fermilab (DM scatter on argon detector) RF6_RF0-NF2_NF3-AF2_AF5-099
  - Fixed-Target Searches for New Physics with O(10 GeV) Proton Beams at Fermilab RF6_RF0-NF3_NF0-AF5_AF0-084
  - FNAL booster RF6_RF0_pellico-029
  - LANSCE-PSR Short-Pulse Upgrade for Improved Dark Matter and Sterile Neutrino Searches AF5_AF0-NF2_NF0-RF6_RF0_Vandewater-215
  - Dark Sector Studies With Neutrino Beams (theory) NF3_NF0-RF6_RF0-CF1_CF3-TF9_TF11-148
  - low mass dark matter at ICARUS NF3_NF0-RF6_RF0-CF1_CF0_Animesh_Chatterjee-119
  - Dark Matter Searches at the Next-Generation CEvNS and Neutrino Facilities NF3_NF0-RF6_RF0-TF8_TF9_Doojin_Kim-070
  - (Anti)Neutrinos at LBNF NF5_NF6-EF6_EF4-RF1_RF6-122 (brief mention of DM program — expect studies?)
  - MIvER CEvNS Experiment NF6_NF10-RF6_RF0_Rupak_Mahapatra-104

LOIs: Dark Matter Re-Scattering (Beam Dump or Auxiliary Collider Detector) part 2

- Electron Beams – Light Thermal DM
  - BDX RF6_RF0_BDX-076
- Millicharges (fixed target and/or auxiliary detectors at colliders)
  - Scintillation-based detectors for millicharged particles EF9_EF0-NF3_NF0-RF6_RF0_Matthew_Citron-072
  - Accelerator Probes of Millicharged Particles and Dark Matter EF9_EF10_NF3_NF5_CF1_CF3_CF7_TF7_TF8_TF9_AF5_UF3_Yu-Dai_Tsai-114
- Collider-Based
  - Forward physics facility (auxiliary detector *a la* beam dump but using forward LHC collision products) EF9_EF6_EF10_EF5-NF6_NF3_NF10-RF6_RF0-CF7_CF0-AF5_AF0-UF1_UF2_ForwardPhysicsFacility-193
- Sexaquark Dark Matter Production and Detection in HCAL:
  - Accelerator search for color-flavor-spin singlet uuddss bound state DM CF1_CF0-EF7_EF10-RF3_RF6_Glennys_Farrar-198

LOIs: Semi-Visible Signals

- Spectrometer-based experiments
  - HPS RF6_RF0_Nelson-078
  - DarkQuest RF6_RF0_Nhan_Tran-025
  - Faser 2 EF9_EF6-NF3_NF6-RF6_RF0-CF7_CF0-AF5_AF0_FASER2-038
  - Dark sectors at Belle II RF6_RF0-028
  - I don't know other LHC experiments' plans to address for Snowmass, but 2018 pheno paper (Berlin & Kling) treats ATLAS, CMS, LHCb, CODEX-b, FASER, and MATHUSLA

- Note: some (but not all) beam dump experiments have also studied their sensitivity to iDM decay-in-flight signals

LOIs: Additional Physics Scope and Motivations

- Dark Pion Searches at Colliders and High Intensities EF9_EF0-RF6_RF0-075
- Accelerator search for color-flavor-spin singlet uuddss bound state DM CF1_CF0-EF7_EF10-RF3_RF6_Glennys_Farrar-198
- Stable Mediators
  - Dark sectors at KOTO RF6_RF0_KOTO-050 and Dark sectors at kaon factories (theory) RF6_RF0-034 (production of massless, invisible dark photon in KL0 → $\gamma\bar{\gamma}$ and other meson decays)
  - Passat: A New ALP Detection Strategy (Primakov production of stable ALPs) NF3_NF0-RF6_RF0-CF1_CF0_Doojin_Kim-016
- Heavy Neutral Leptons & Neutrino Portal
  - Neutrino Minimal Standard Model (theory) (includes neutrino portal DM?) NF3_NF1-EF9_EF0-RF4_RF6-CF1_CF3-TF11_TF9-AF5_AF0-195
  - Non minimal HNL models (theory) NF2_NF3-EF9_EF0-RF4_RF6-CF1_CF0-TF8_TF11_Matheus_Hostert-041
  - Heavy Neutral Leptons at Accelerator Neutrino Experiments NF2_NF3-RF6_RF0_Athanasios_Hatzikoutelis-160
  - This is one place where we need to refine the scope.
- Neutron Portal
  - ΔB = 2: A State of the Field, and Looking Forward (RF4, baryon and lepton number violation) RF4_RF6-NF3_NF10-TF2_TF5_Joshua_Barrow-105
  - Sterile neutrons at ORNL and ESS (neutron-sterile neutron oscillation) hRF6_RF3_Joshua_Barrow-115

LOIs: Interfaces to Other Frontiers

- Summarizing experimental sensitivities of collider experiments to Dark Matter models and comparison to other experiments EF9_EF10-RF6_RF0-CF1_CF3_Boyu_Gao-160

- Long Lived Particles at Energy Frontier EF9_EF10-RF6_RF0-TF7_TF8_James_Beacham-201

- Dark matter complementarity CF2_CF7-EF10_EF0-RF6_RF0-TF9_TF0-150

Did we miss your LOI?

- Let us know briefly in the Zoom chat, and email us (in email, please link to LOI and summarize where it fits in Big Idea 1)

- For new ideas since LOI submission deadline, please provide a bit more info on your whitepaper plans and a link to arxiv, if appropriate

Document Skeleton

Executive Summary [3-5p]

Introduce Big Idea [2-3 p]

Search Concepts [3-5 p]

Light DM Models and Frameworks [5-10 p]

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Tentative Framing:

Dark matter particles can be observably produced at intensity-frontier experiments,* and opportunities in the next decade will explore important parameter space motivated by thermal DM models, the dark sector paradigm, and anomalies in data.

* includes: forward LHC searches, LHCb, FASER, etc – focusing on the low-pair-mass, high-intensity region.

Motivation:

Distinguish between RF6 intensity frontier efforts and traditional DM@colliders (high energy mono-X), direct detection, and wavelike DM searches

Highlight strategies/facilities not part of last snowmass DM discussion

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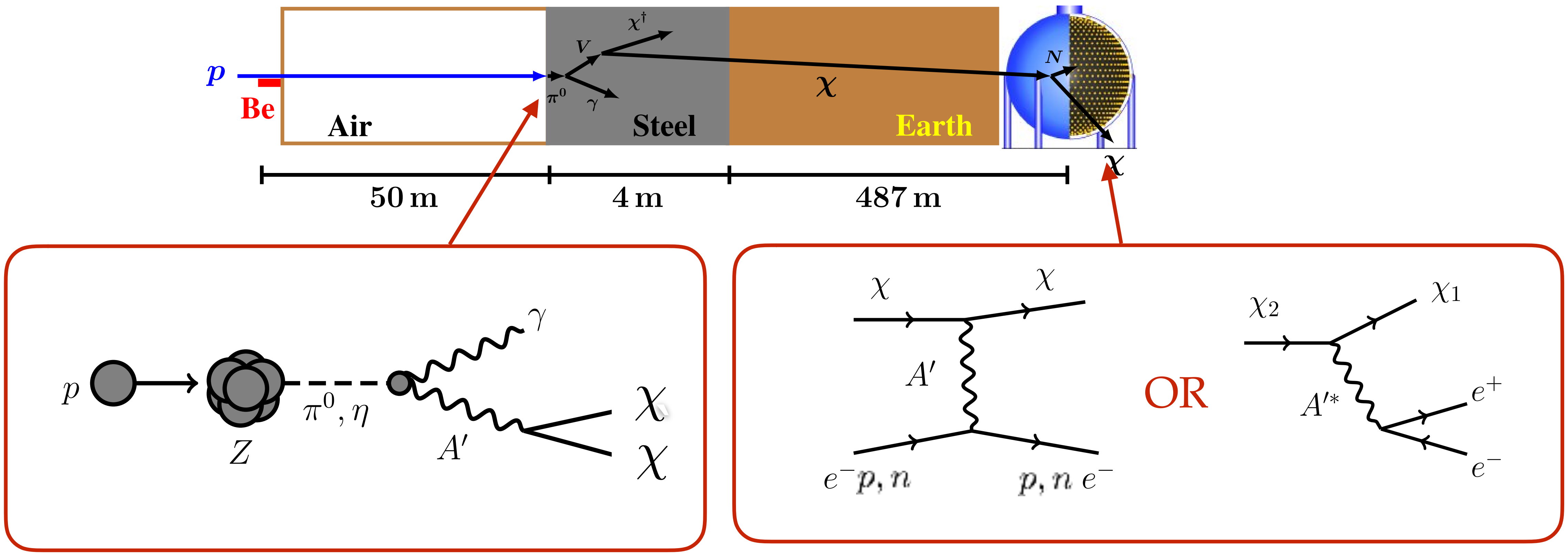
Getting Involved

Proton Beam Dump Production



Production: via proton-dump interactions (e,g, neutrino facilities++)

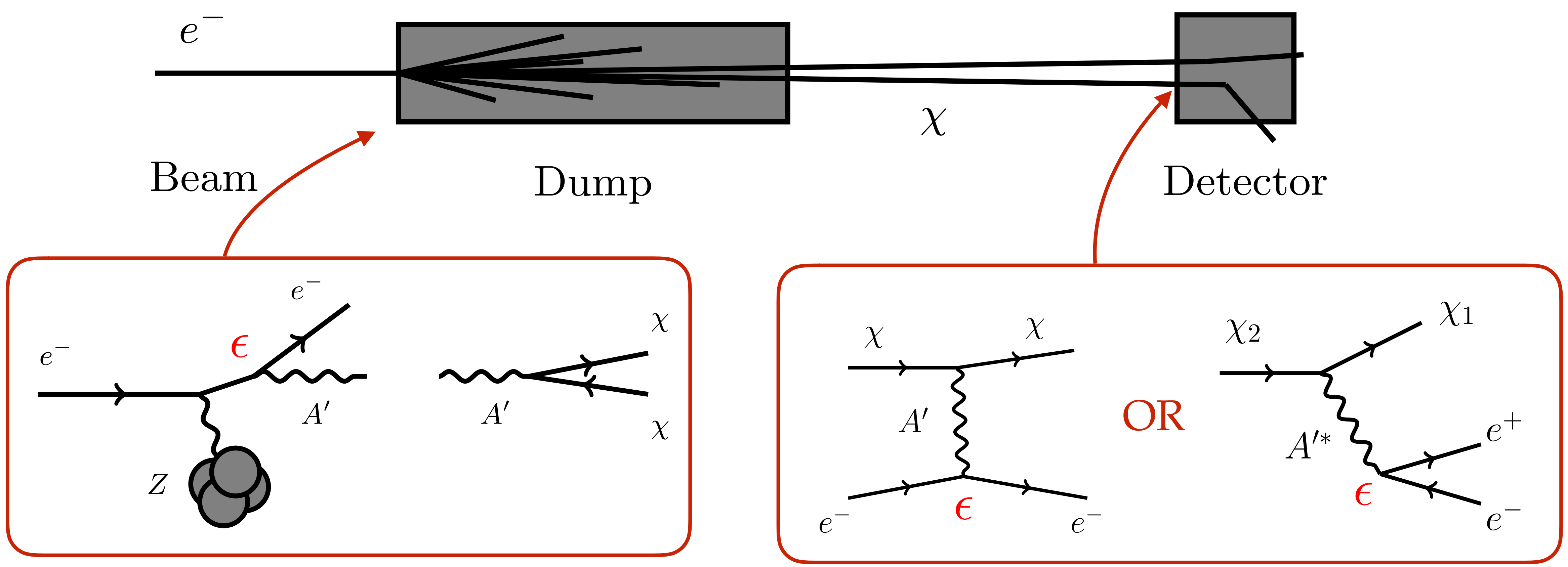
Main production modes via rare meson decays, DIS, bremsstrahlung…

Can produce DM/millicharge, sextet and other BSM — either directly or via on-shell mediator production + decay to DM

Detection: downstream scattering or decays of long lived states

Complementarity: unique sensitivity to hardophilic interactions, parasitic, sensitive to DM thermal targets

Electron Beam Dump Production

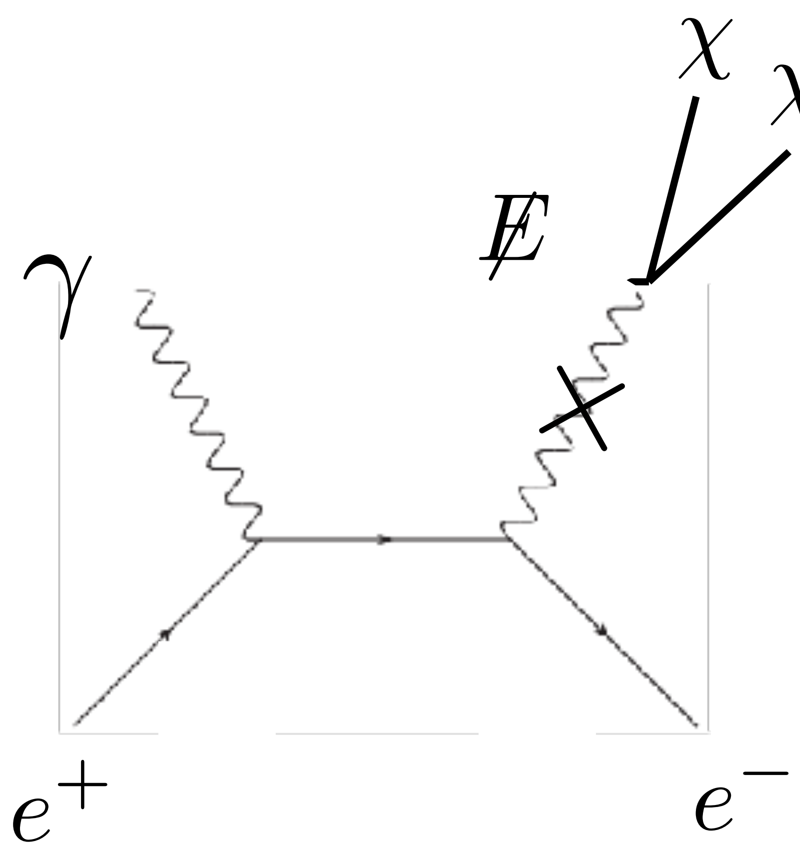


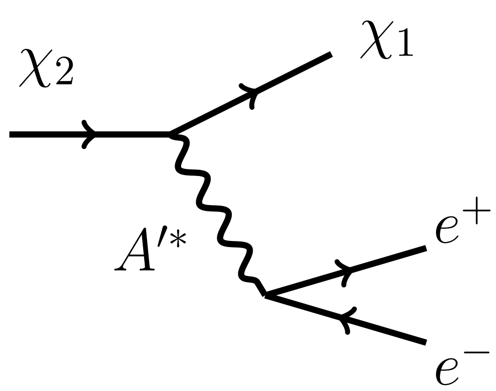
Production: via electron-dump bremsstrahlung and secondary positron interactions. Can produce DM/iDM, millicharge BSM directly or via on-shell mediator production + decay to DM

Detection: downstream scattering or decays of long lived states

Complementarity: leptophilic interactions, parasitic, sensitive to thermal targets

B-Factory Searches





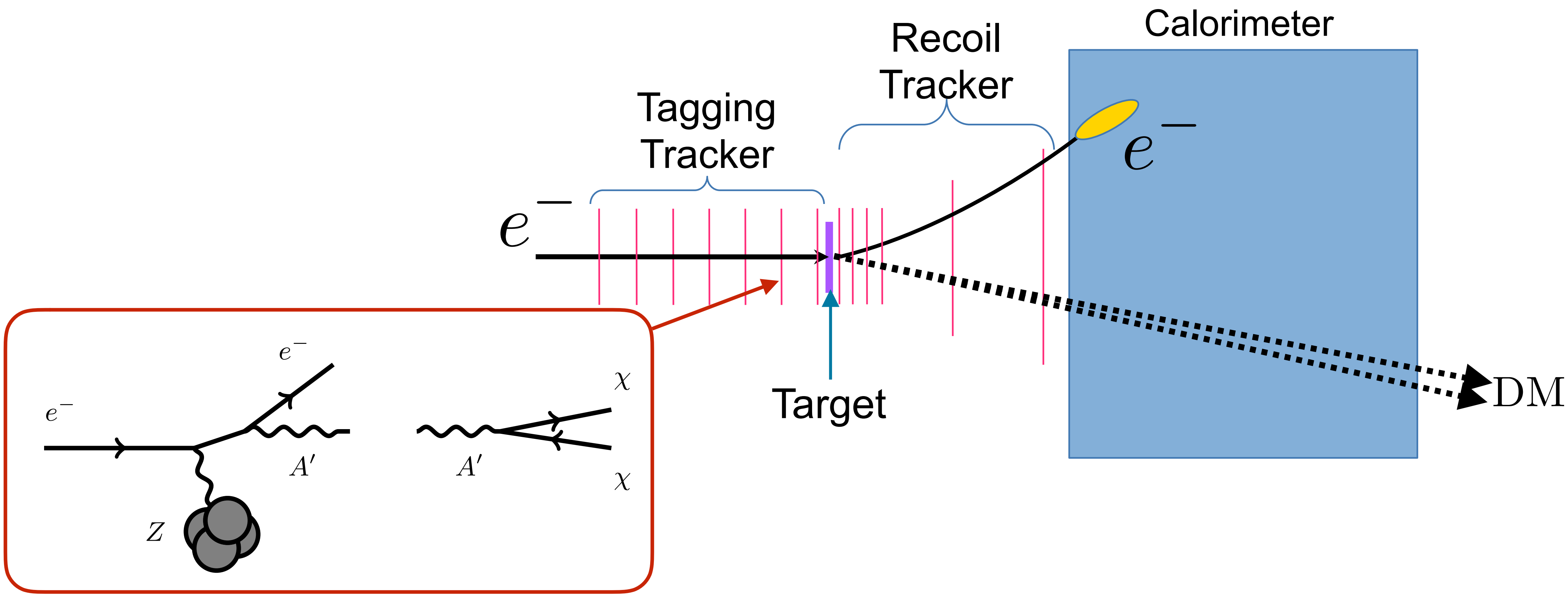
Also probe inelastic DM via displaced vertices

Production: via e-e- annihilation produce DM or mediators with invisible or semi-visible decays. Direct production DM production through contact coupling or mediator decay

Detection: missing energy or semi-visible BSM transition w/ displaced vertex

Complementarity: leptophilic interactions, heavy flavor (mu,tau), currently existing facilities/analysis capability

Electron Beam Missing Energy / Momentum

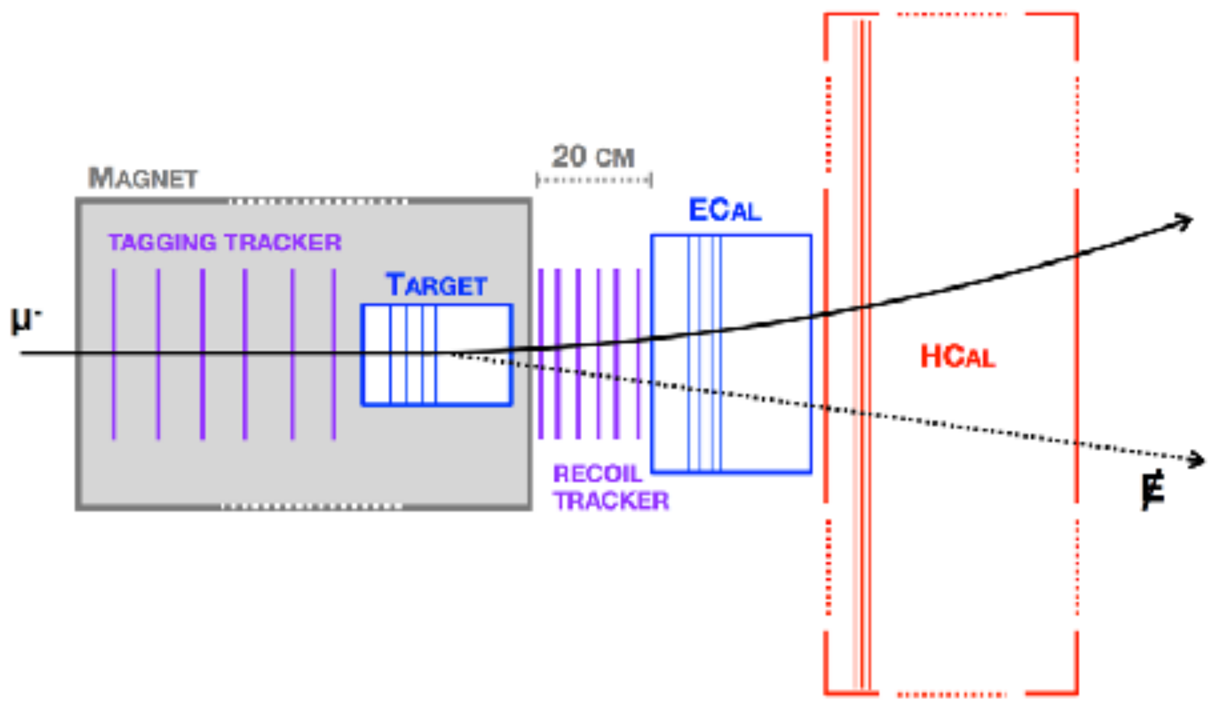


Production: via electro-nuclear bremsstrahlung. Produce DM directly or via on-shell mediator decay. Also reach for ~meter long lived particles

Detection: monitor incoming / outgoing beam kinematics, observe DM production via reduced beam energy / momentum (+no additional activity downstream)s

Complementarity: sensitivity to thermal targets, leptophilic interactions, LLPs

Muon Beam Missing Energy/Momentum

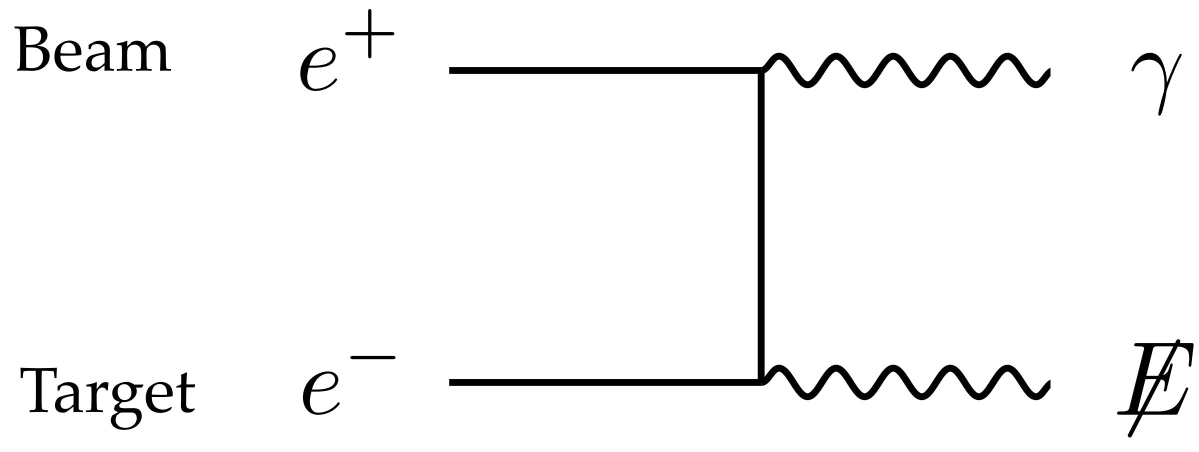


Production: via muon-nucleus bremsstrahlung. Produce DM directly or via on-shell mediator decay.

Detection: monitor incoming/outgoing beam kinematics, observe DM production via reduced beam energy/momentum (+no additional activity downstream)s

Complementarity: muon-philic interactions, heavy flavor, light physics for g-2

Positron Fixed Target Searches

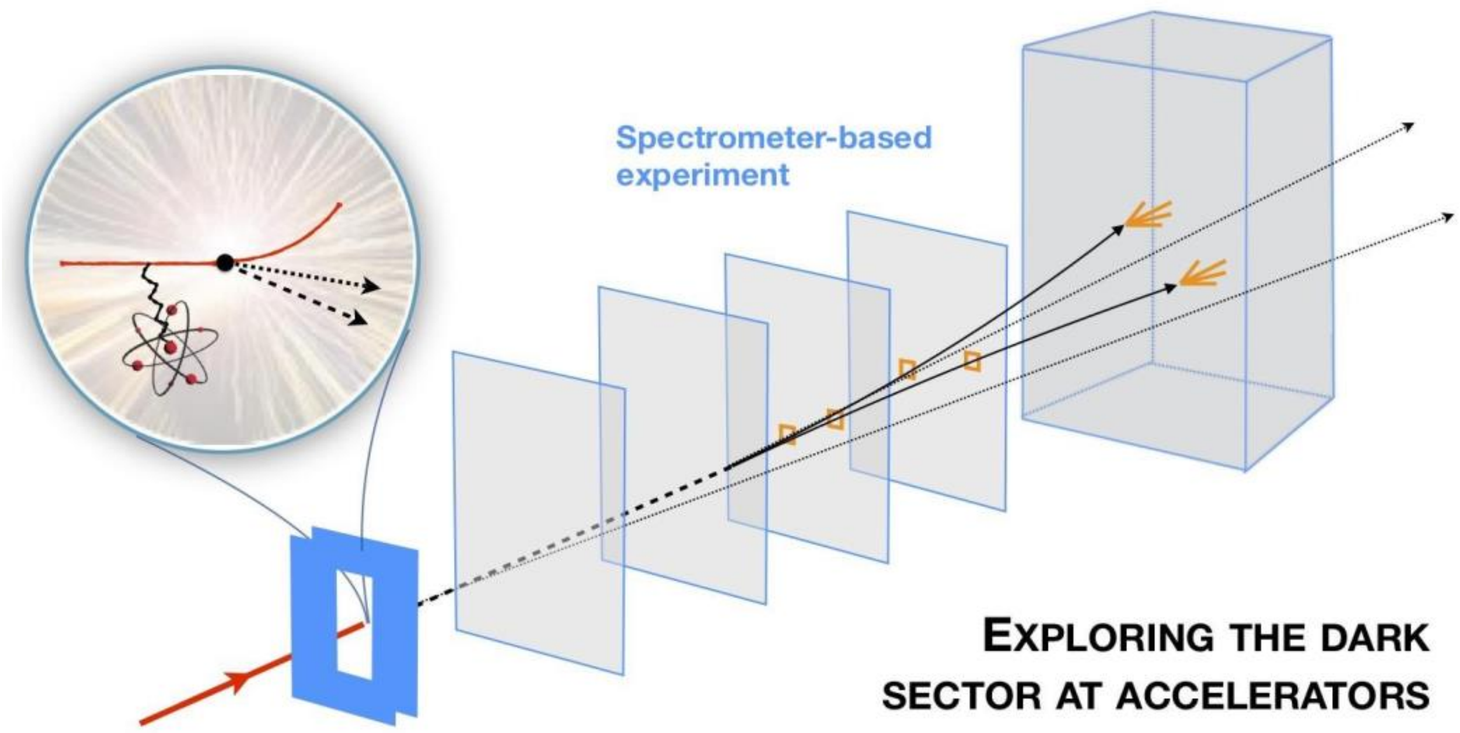


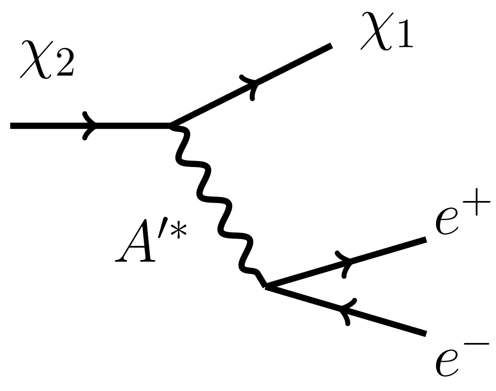
Production: via e+e- annihilation with a positron beam and a fixed electron target. CM energy is known and can be used to reconstruct missing mass.

Detection: a missing invariant mass from known CM energy

Complementarity: enhanced sensitivity near DM pair mass at resonance

Spectrometer Searches





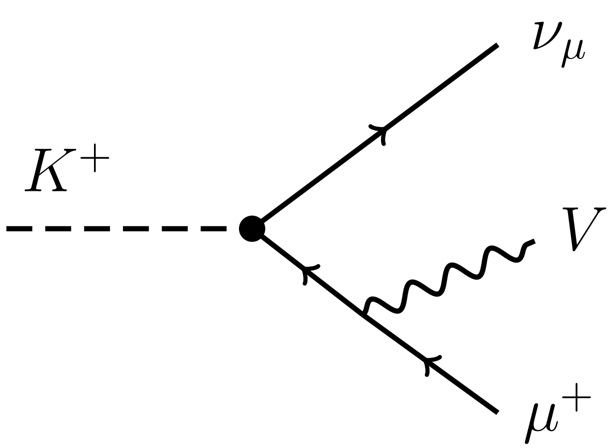
Also probe iDM LLPs

Production: proton-nucleus fixed target scatter produces DM via DIS, bremsstrsahlung, and rare meson decays

Detection: forward produced DM states undergo semi visible transitions downstream in tracker layers and detectors

Complementarity: sensitivity to visibly and semi0visibly decaying BSM states produces in the target. Also sensitive to long lived particles

Tagged Meson Decays



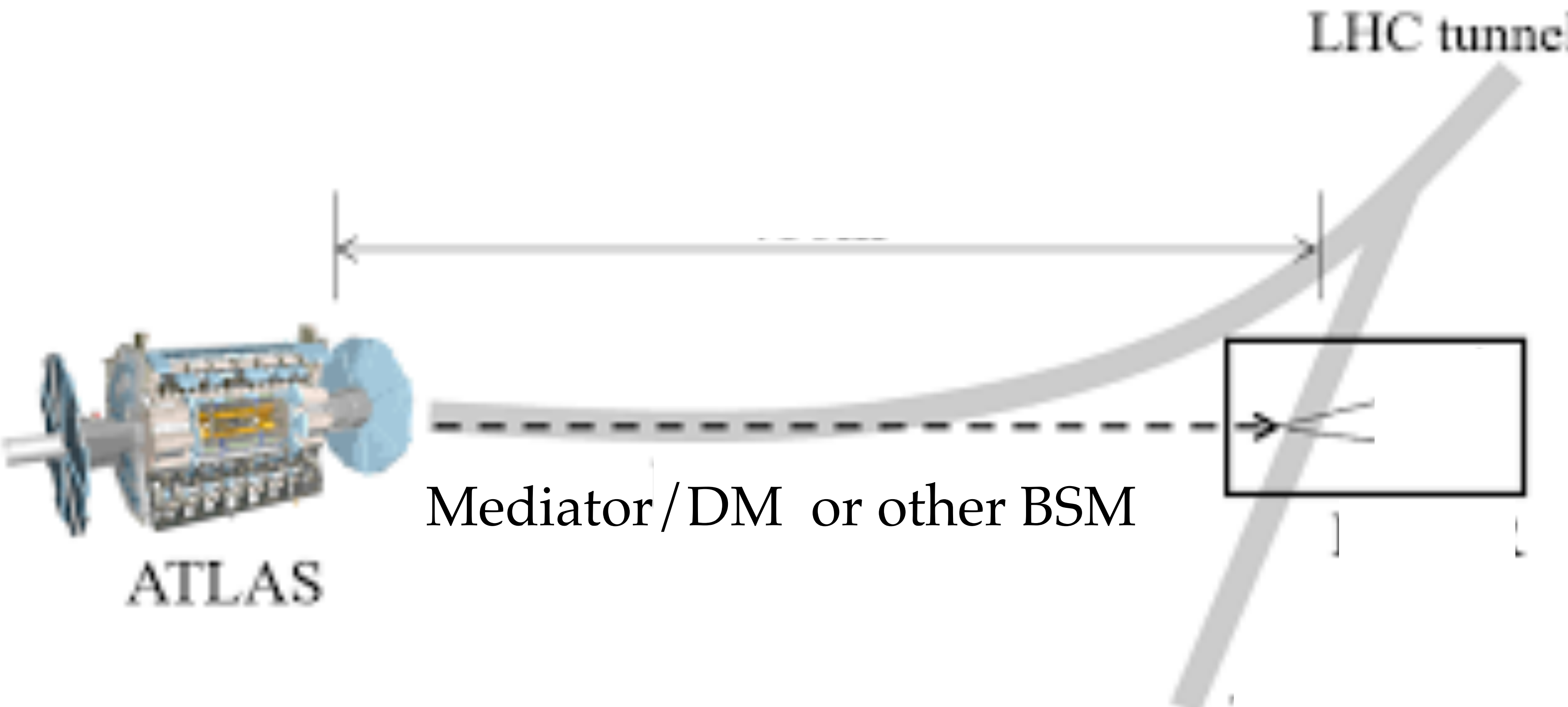
$$K^+ \to \mu^+ \nu_\mu V, \quad V \to \chi\chi$$

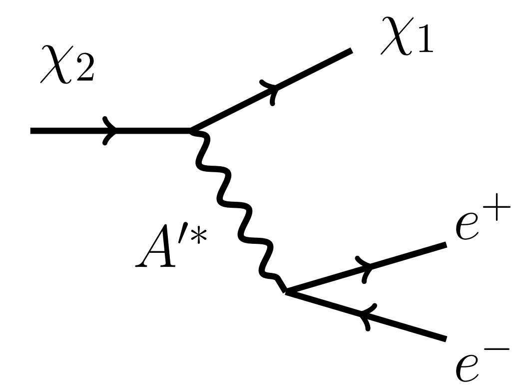
Production: via rare meson decays (kaon, eta, etc.) via invisible signals

Detection: reconstruction of invariant missing mass from known meson kinematics and measured visible energy in final state

Complementarity: muon/hardon-philic interactions, heavy flavor, light physics for g-2, neutrino-philic interactions

Forward LHC Searches





Also probe
Inelastic DM LLP

Production: LHC pp scattering (DIS+bremsstrahlung) produce DM directly or mediators that decay to DM. Can use existing traditional LHC detectors (LHCb) or new additions (FASER/MATHUSLA etc)

Detection: observe DM scattering or semi-visible transition in displaced detector

Complementarity: long lifetime sensitivity to inelastic DM

Discussion …

Document Skeleton

Executive Summary [5p]

Introduce Big Idea [2-3 p]

Search Concepts [2-3 p]

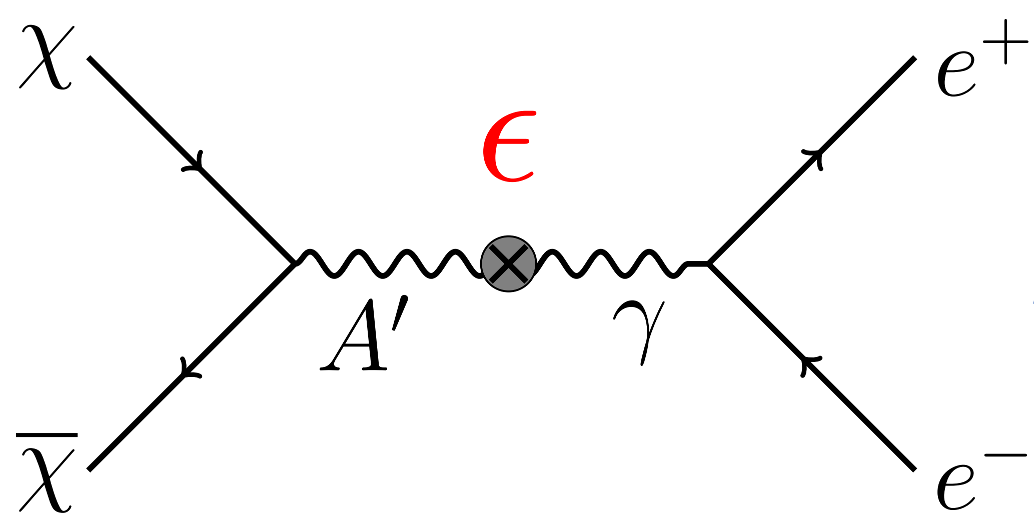
Light DM Models and Frameworks

Getting Involved

DM through Vector Portal

$$\alpha_D \equiv \frac{e_D^2}{4\pi}$$

DM



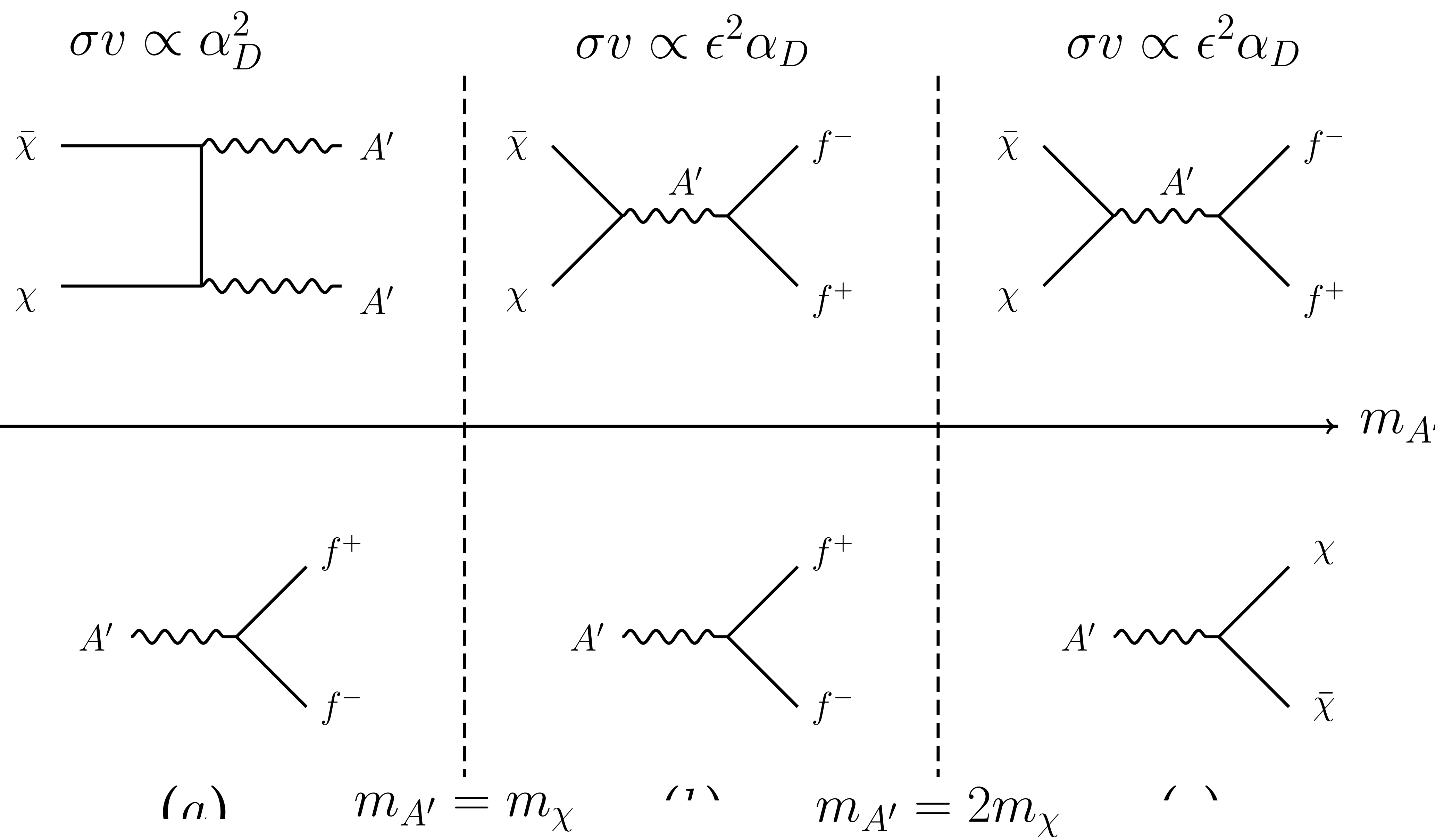
SM

$$\alpha \equiv \frac{e^2}{4\pi}$$

$$\mathcal{L} = -\frac{1}{4} F'_{\mu\nu} F'_{\mu\nu} + \frac{m_{A'}^2}{2} A'_\mu A'^\mu + A'_\mu J^\mu_\chi + \epsilon A'_\mu J^\mu_{\mathrm{EM}}$$

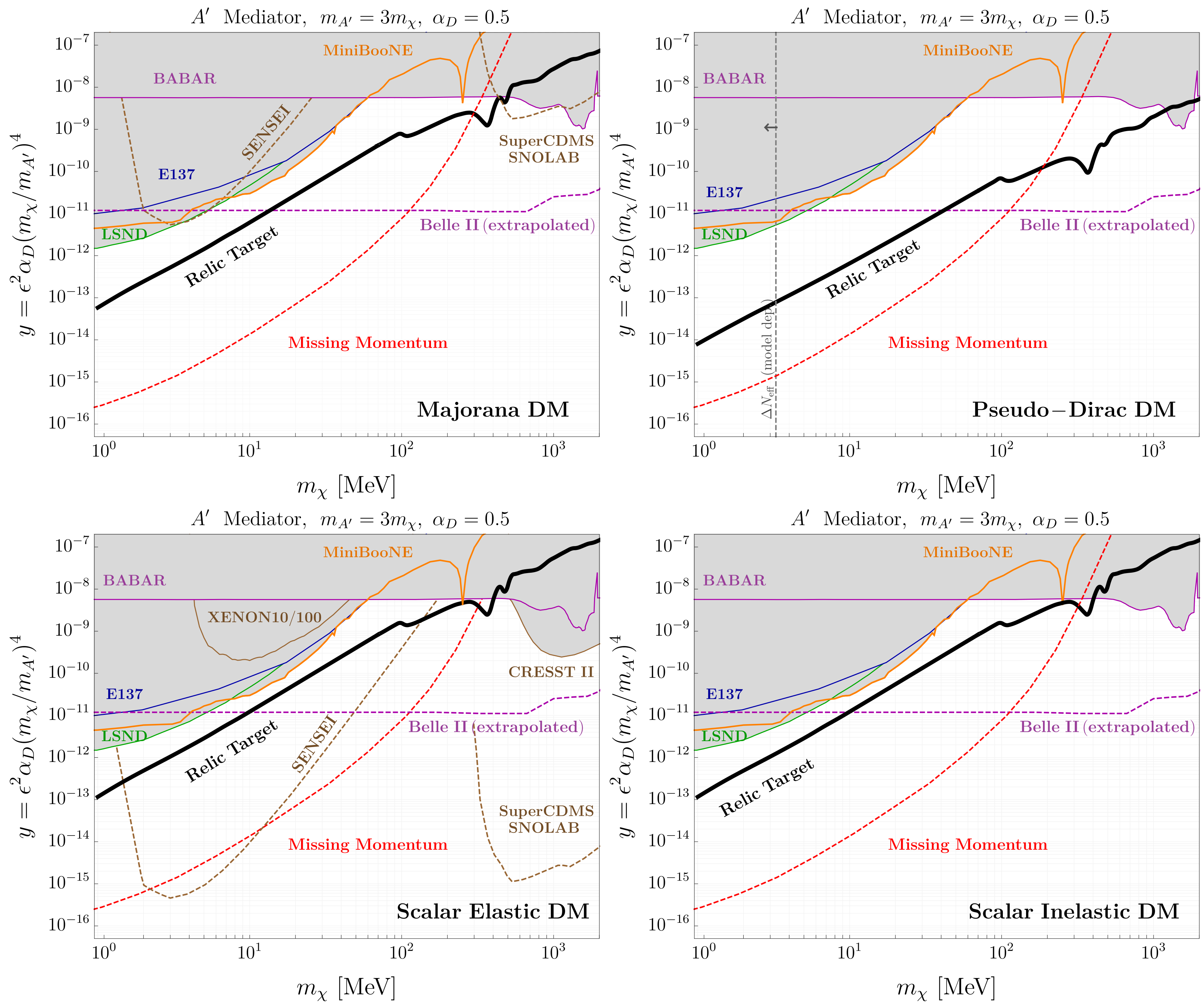
Popular kinetically mixed dark photon mediator coupled to various possible DM candidates

DM through Vector Portal



Multiplicity of signals with different relationship to early universe DM

DM through Vector Portal



Berilin et al 1808.05219

Illustrative **example** of plots with thermal targets — final WP will have more projections

DM through Vector Portal

Connection to other thermal and non-thermal co histories

Strongly Interacting Massive Particle (SIMP) Dark Matter

DM undergoing 3-2 annihilation. Scattering with SM particles via A′ exchange ensures kinetic equilibrium to avoid hot/warm DM

Elastically Decoupling Dark Matter (ELDER)

DM scattering off SM particles decouples before 3-2 annihilation freezes-out

Inverts order of SIMP DM: SM scattering decouples earlier

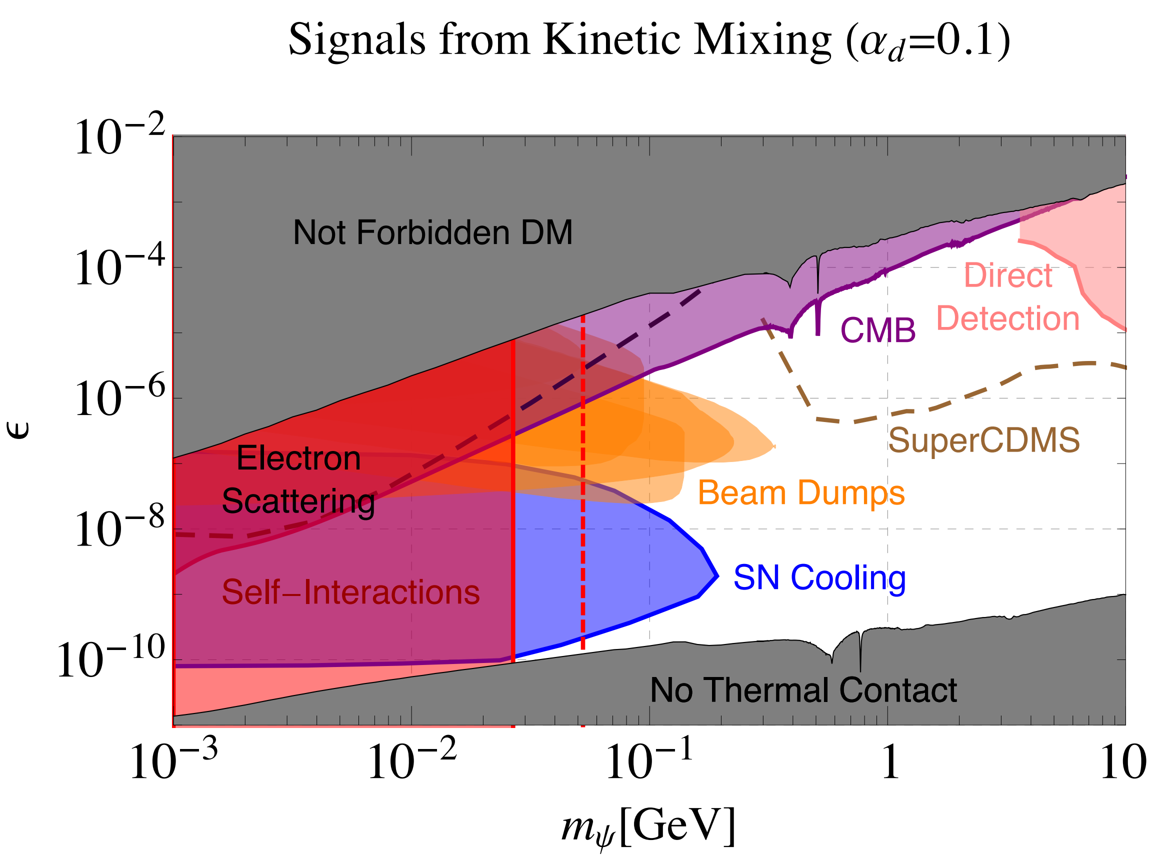
"Forbidden" and "Not-Forbidden" Dark Matter (FDM/NFDM)

DM annihilates to heavier mediators that decay to SM particles

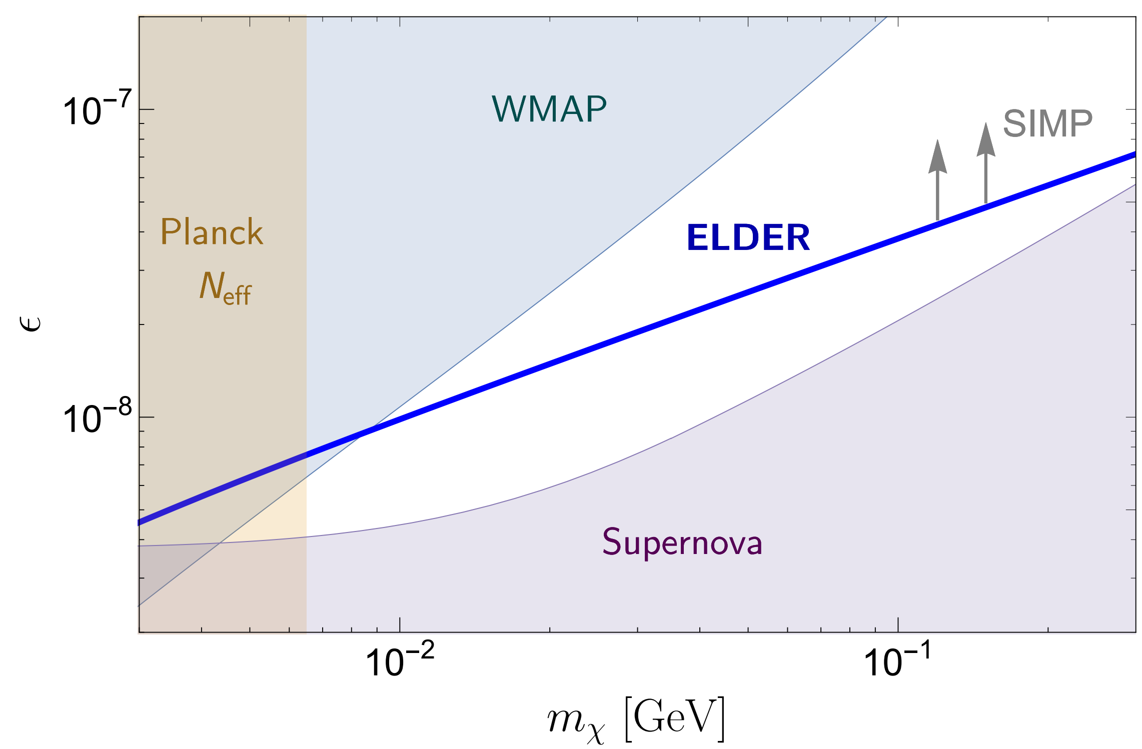
Annihilation shuts off as universe cools — safe from CMB bounds

DM through Vector Portal

Connection to other thermal and non-thermal co histories



Forbidden DM

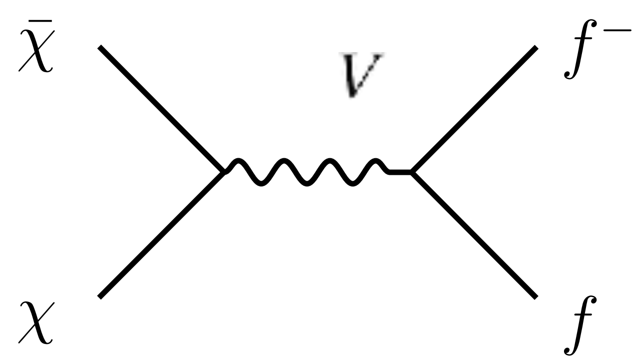


D'Agnolo et al 1505.07107

Kuflik et al 1512.04545

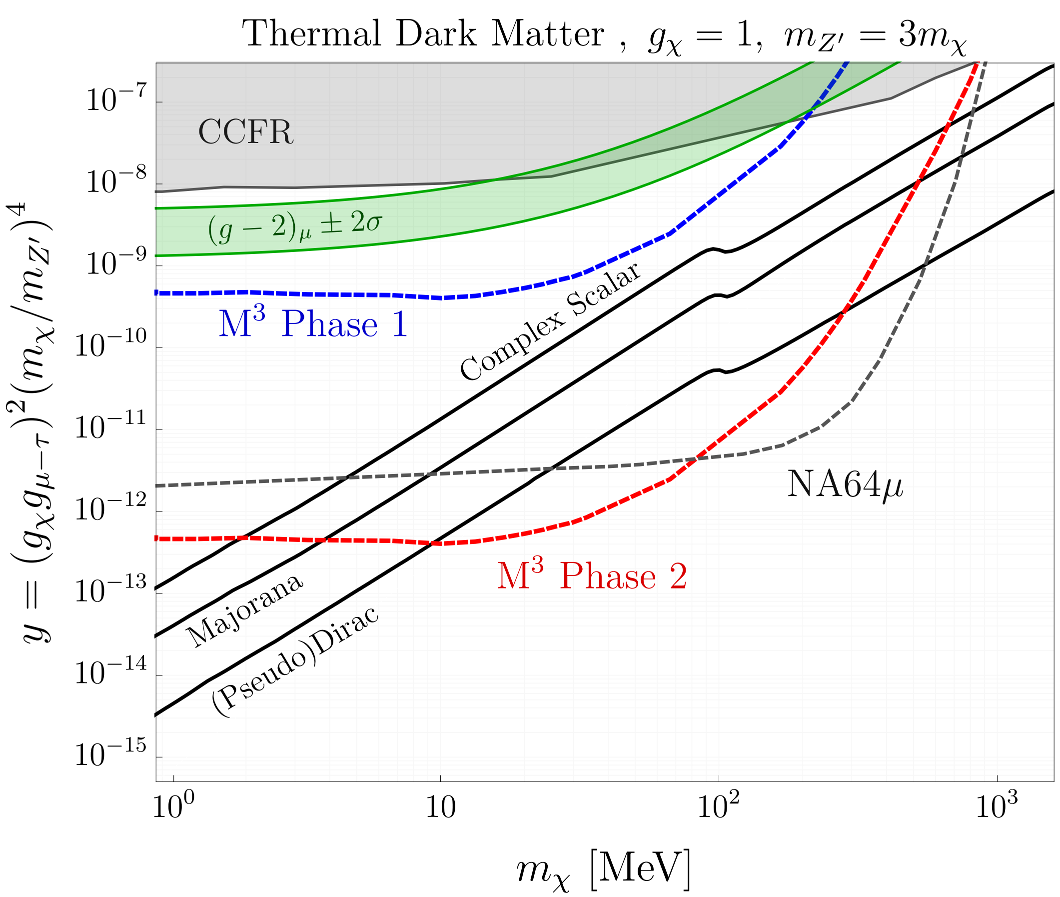
DM via anomaly free U(1) interactions

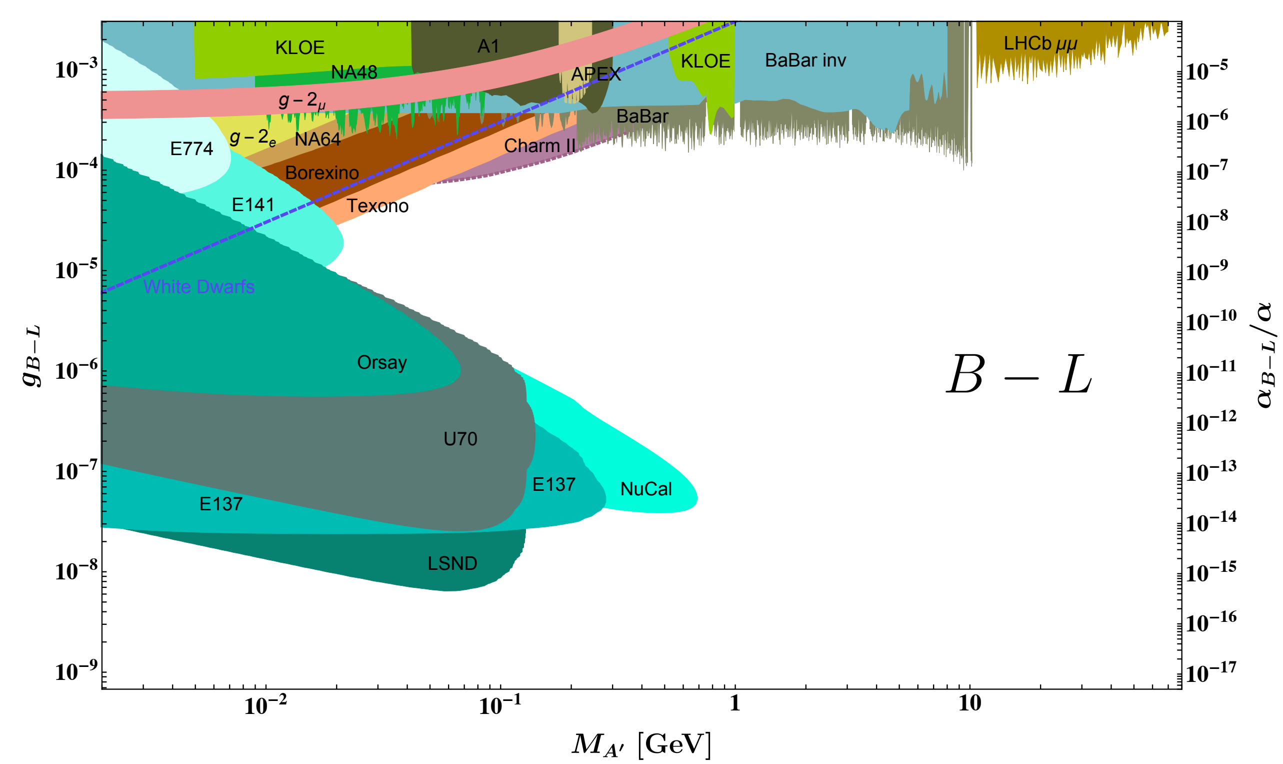
Finite set of simple, anomaly-free abelian extensions $V_\mu J^\mu_{\rm SM}$



$U(1)_{B-L}$ $U(1)_{B-3L_i}$ $U(1)_{L_i-L_j}$

Conceptually similar to kinetic mixing portal but with different flavor structures. Other U(1) with more BSM?





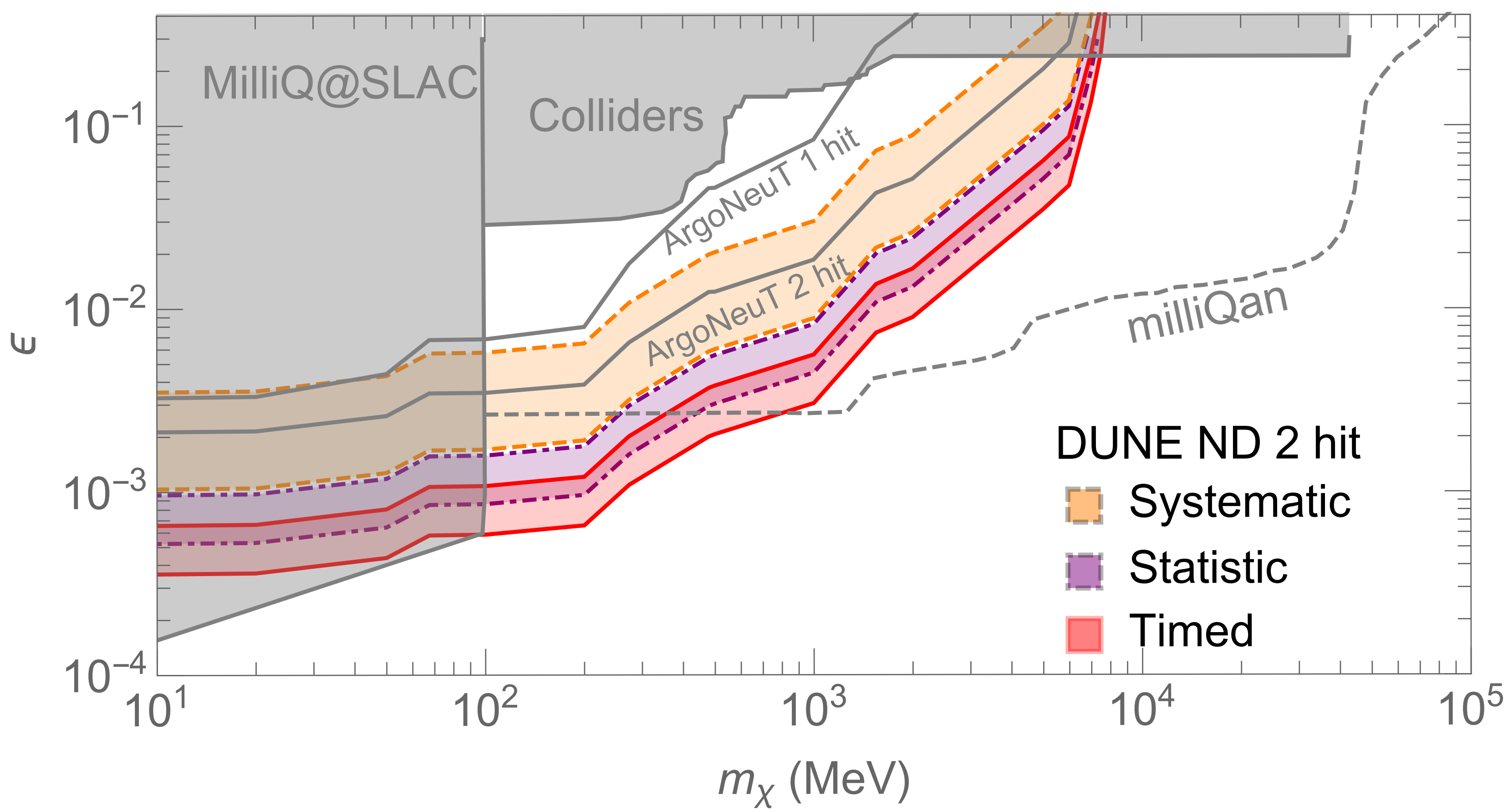
Kahn et al 1804.03144

Illustrative examples

Bauer et al 1803.05466

Millicharged Particles

Can be fundamental QED millicharge particle or massless limit of secluded dark photon mediator to new BSM states



Harnik et al 1902.03246

Illustrative **example** — final WP will have more bounds/projections

Scalar / Pseudoscalar Mediators

Higgs Mixed Scalar

Light new scalars couple to DM and to SM through Higgs portal
Similar for pseudo-scalars (e.g from mixing with 2HDM states)

$$\epsilon\phi\frac{m_f}{v}\bar{f}f$$

Invisible decays enable similar searches at fixed targets

Visible decays through Higgs mixing yield mass weighed branchings

Generalized Flavor Specific (Pseudo)-Scalars $c_i\phi\bar{f}_i f_i$

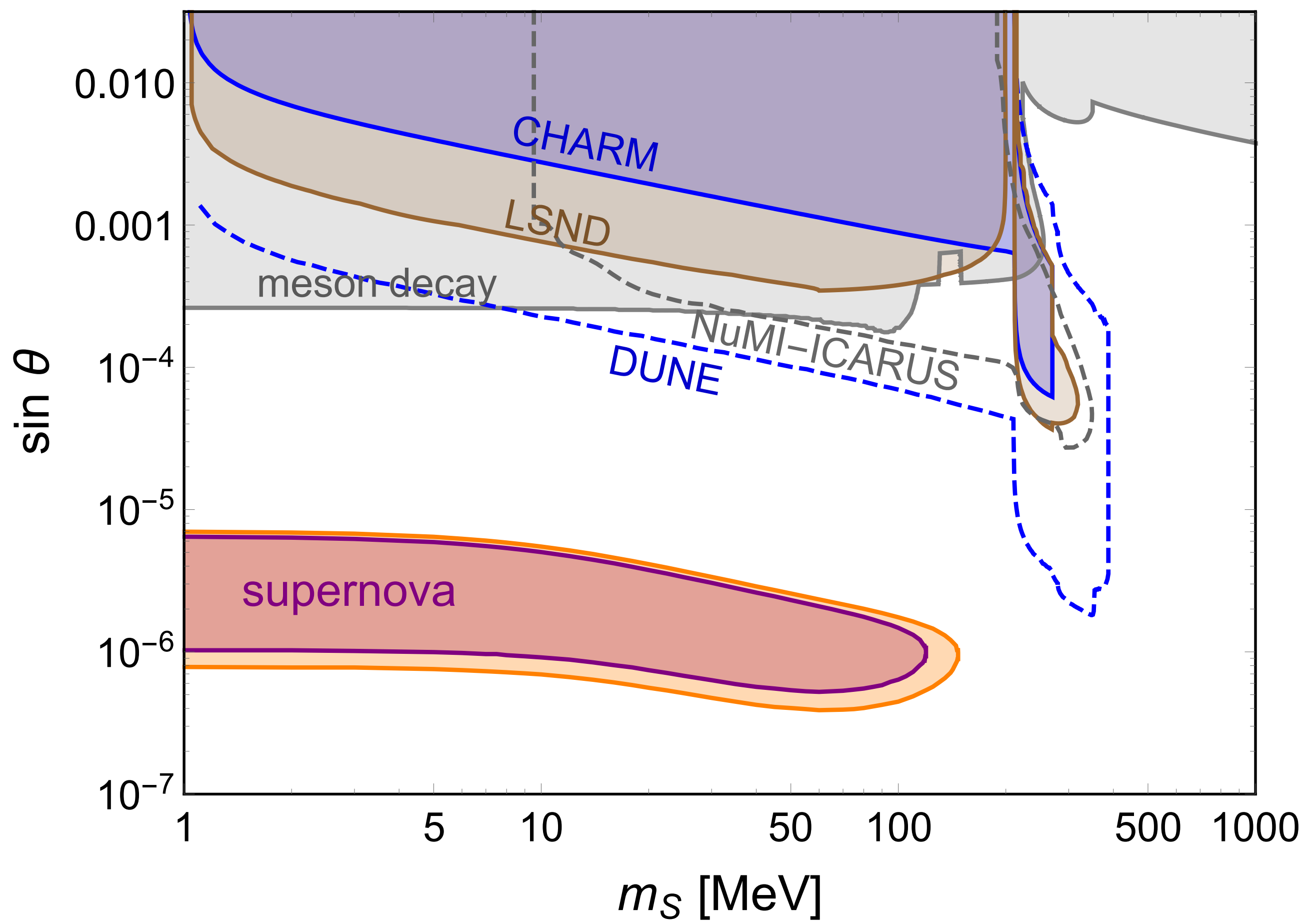
Couple to heavy new BSM states (e.g. vector like quarks). Scalar-SM couplings arise from integrating out the BSM states

Testable thermal targets for first / second generation couplings

Connection to anomalies in g-2, Be17 anomaly

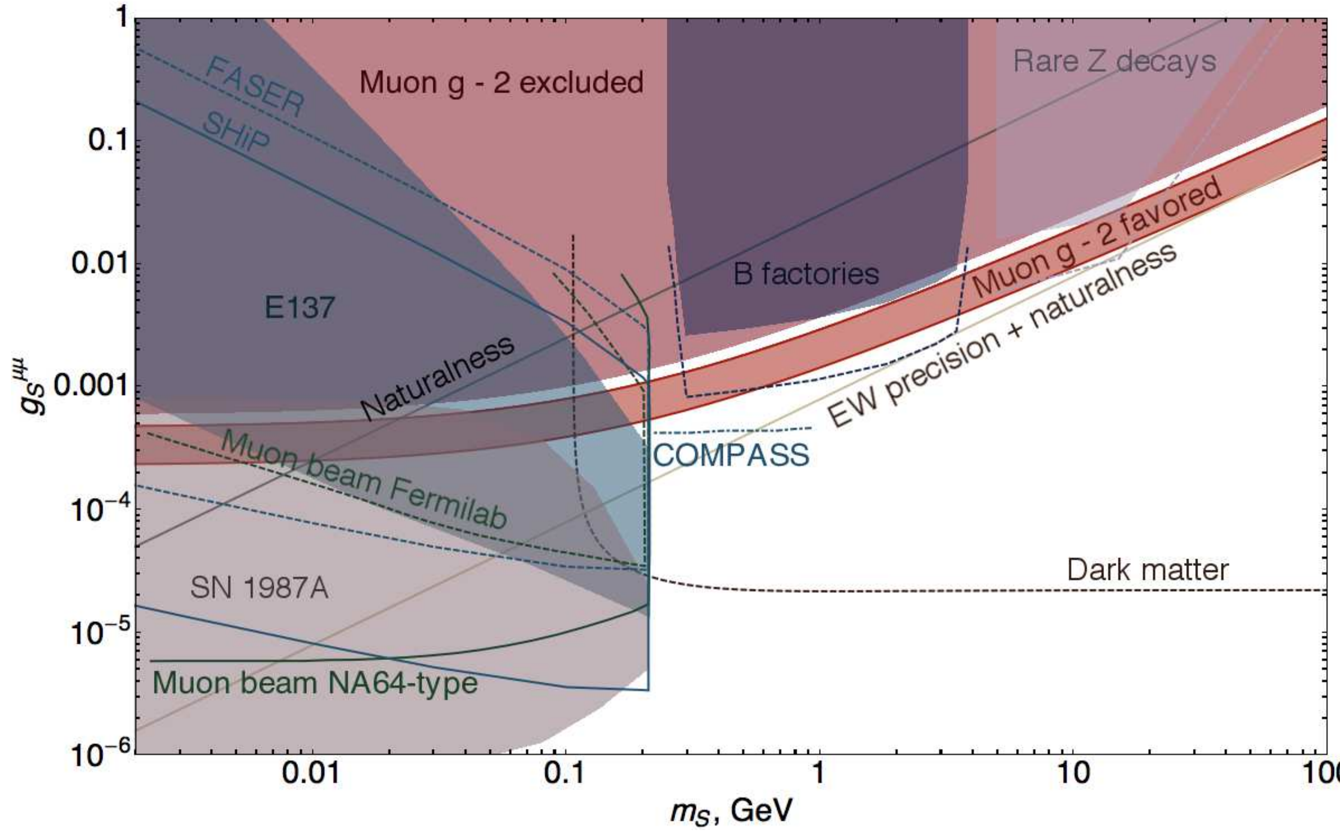
Scalar / Pseudoscalar Mediators

Higgs Mixing



Dev et al 2005.00490

Flavor Specific

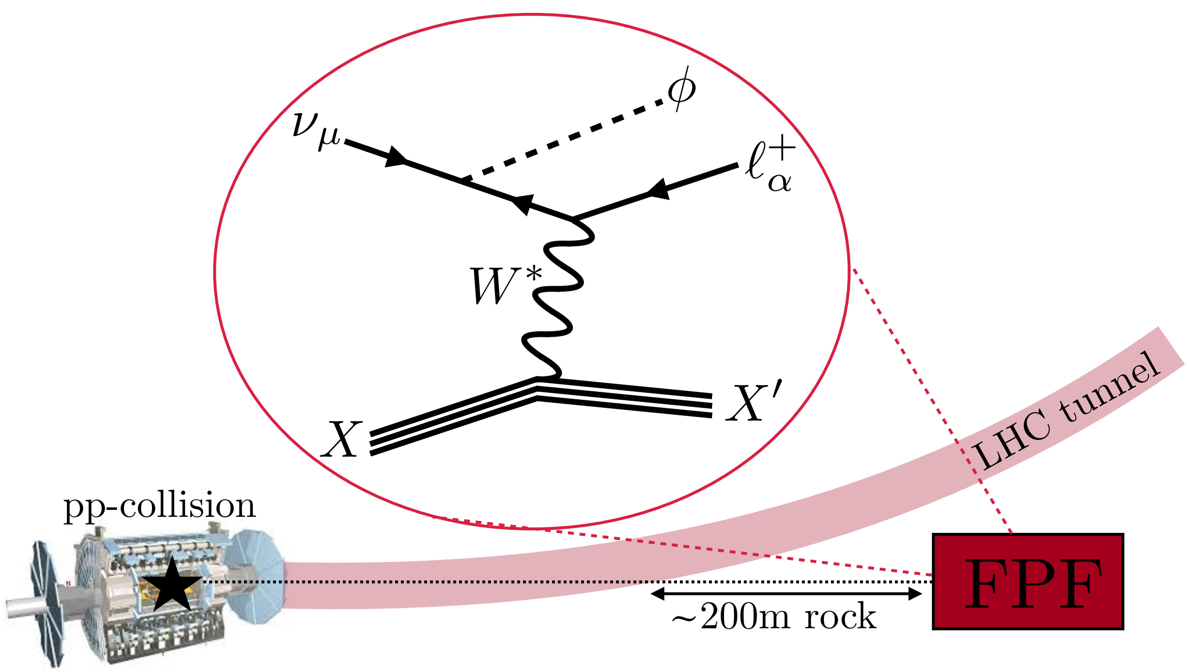


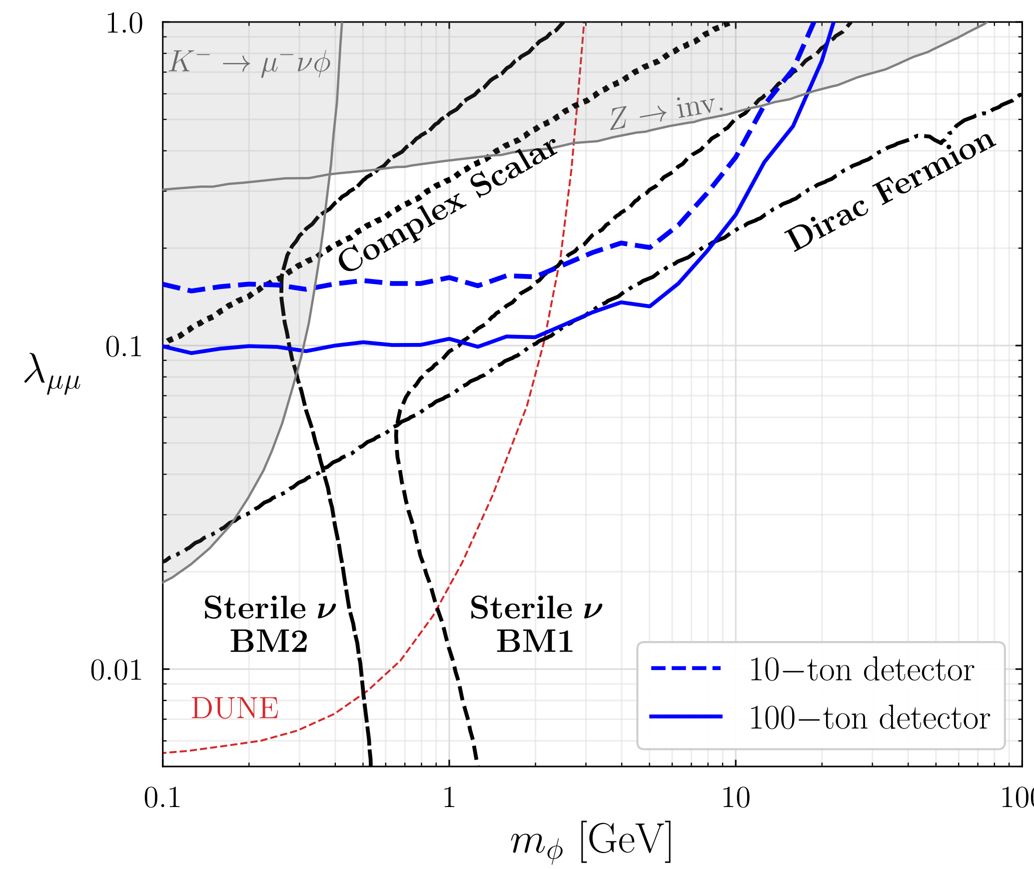
Batell et al 1712.10022

Illustrative **example** — final WP will have more bounds / projections

Neutrino Portal DM

DM thermal relic via neutrino-philic interactions





$$\mathcal{L} \supset \frac{1}{2}\lambda_{\alpha\beta}\nu_\alpha\nu_\beta\phi + \text{h.c.} \,, \quad \mathcal{L}_{\rm DF} = \frac{1}{2}y\overline{\chi}^c\chi\phi + \text{h.c.} \,,$$

Kelly et al 2111.05868

Illustrative **example**

Neutrino Portal DM

Heavy Neutral Lepton

Discussion ...

Document Skeleton

Executive Summary [3-5p]

Introduce Big Idea [2-3 p]

Search Concepts [3-5 p]

Light DM Models and Frameworks [5-10 p]

Getting Involved

Logistics & Getting Involved

If you'd like to help with **writing or plot making**

Please fill out this form **https://tinyurl.com/4yxdfv6j**

Contributed white papers due by **March 15th, 2022**

Goal to write solicited white paper by **mid-April, 2022**

Once we have a list of interested people, we will send out additional information over email and schedule another meeting in the weeks ahead to divide up tasks

Thank You!