BSM searches at intensity-frontier experiments

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UC Santa Cruz

28th IFT Xmas Workshop

December 14, 2022

Outline of the talk

0. Introduction

- High intensity & high energy experiments
- Light (< electroweak scale) Beyond the Standard Model (BSM) particles

1. (Thermal) Dark Matter (DM) models

2. Axion-like-particles (ALPs)

3. Off-shell probes of light BSM particles

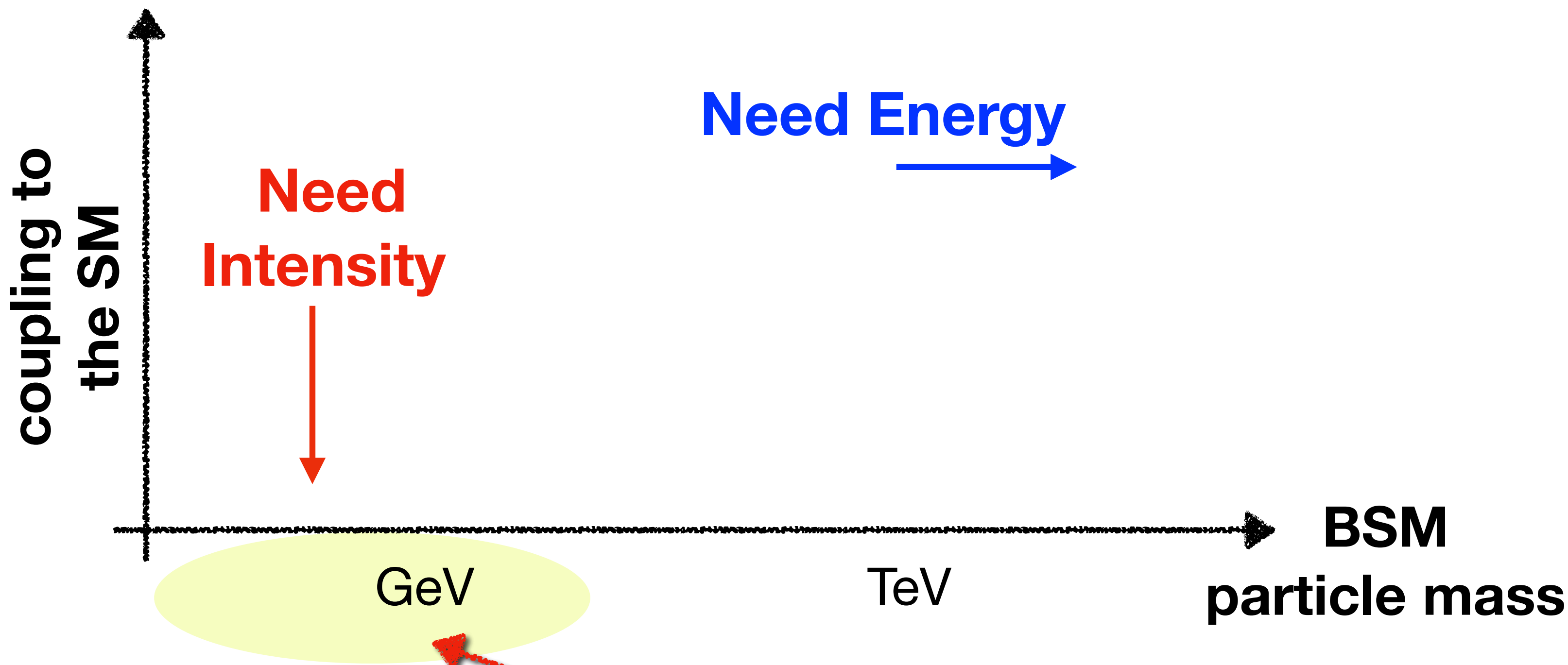
Fixed target / beam dump experiments

Flavor factories

Goal: discuss opportunities to test light BSM particles at high-intensity experiments

Neutrino experiments

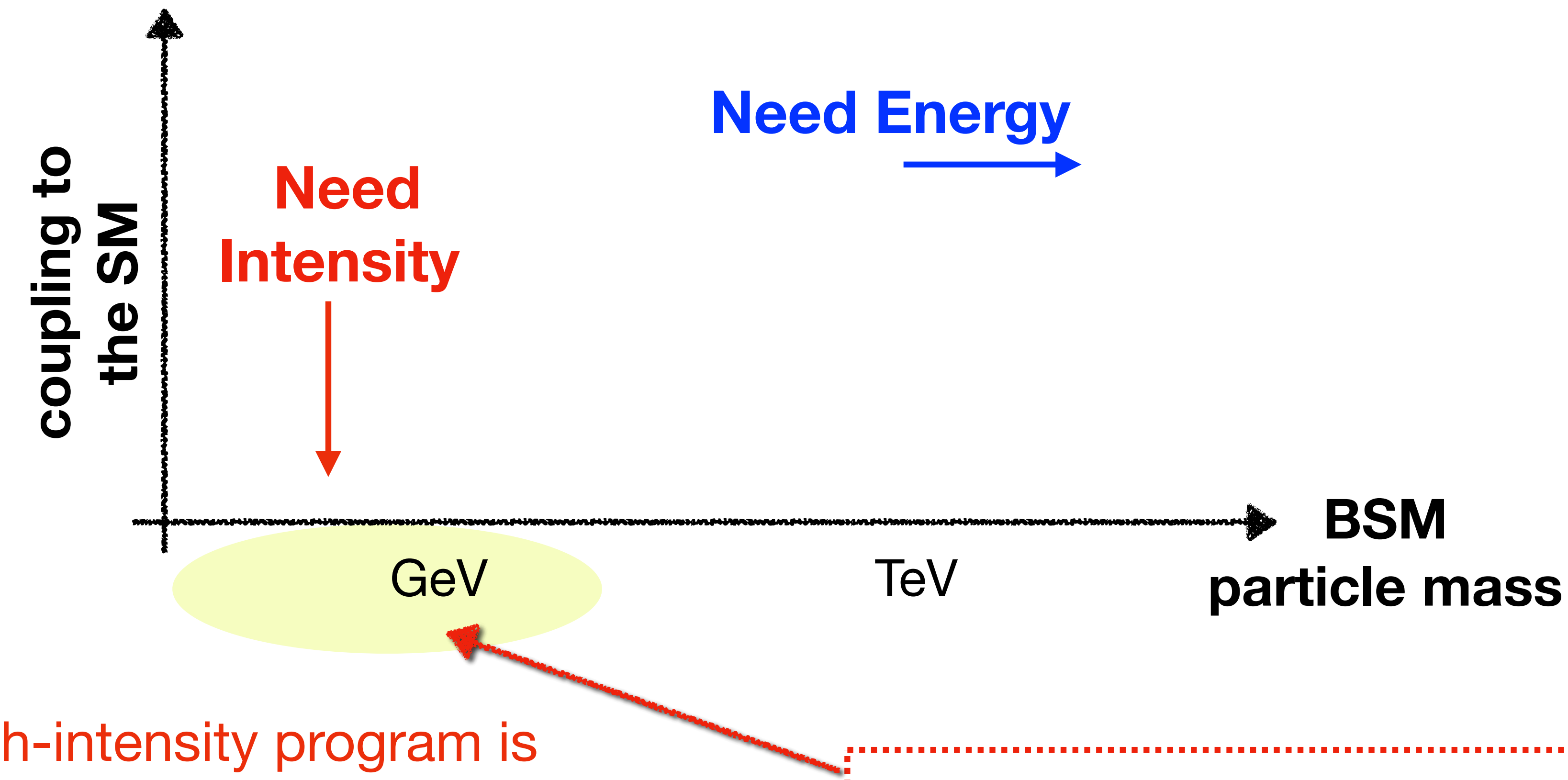
High-intensity & high-energy experiments



It is very difficult to charge these particles under the electroweak interactions

⇒ **dark sector**

High-intensity & high-energy experiments



The high-intensity program is particularly interesting, since

* many experiments are starting to run
* many will collect a much larger luminosity in the next coming years
* many are proposed for the future

It is very difficult to charge these particles under the electroweak interactions

➡ **dark sector**

Flavor factories

A big jump in luminosity is expected in the coming years

	Past/Present	Future
B-factories	**LHCb:** more than ~ 10^{12} b quarks produced so far; **Belle** (running until 2010): ~10^9 BB-pairs were produced.	**LHCb:** ~40 times more b quarks will be produced by the end of the LHC; **Belle-II:** ~50 times more BB-pairs will be produced.

Flavor factories

A big jump in luminosity is expected in the coming years

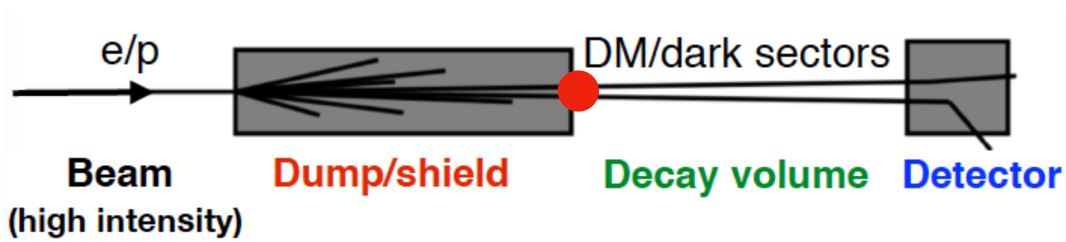
	Past/Present	Future
Pion-factories	**PIENU experiment** at TRIUMF: ~10^{11} pi$^+$	**PIONEER experiment** at PSI (phase 1 approved. Data in ~2028(?)): ~10^{12} pi$^+$
Kaon-factories	**E949** at BNL: ~10^{12} K^+ (decay at rest experiment); **E391** at KEK: ~10^{12} K_L	**NA62** at CERN: ~10^{13} K^+ by the end of its run (decay in flight experiment); **KOTO** at JPARC: ~10^{14} K_L by the end of its run
B-factories	**LHCb:** more than ~ 10^{12} b quarks produced so far; **Belle** (running until 2010): ~10^9 BB-pairs were produced.	**LHCb:** ~40 times more b quarks will be produced by the end of the LHC; **Belle-II:** ~50 times more BB-pairs will be produced.

Fixed target, neutrino experiments, LHC auxiliary detectors

Fixed target (beam dump) experiments

Several running now:
e^- beam for the **NA64** experiment (CERN), **HPS** (JLab)

Several proposed for the coming years:
e^- beam for the **LDMX** experiment (SLAC),
e^+ beam for the **POKER** experiment (CERN)
μ^- beam for the **M^3** experiment (Fermilab)
p beam for the **DarkQuest** experiment (Fermilab)
p beam for the **SHADOWS** experiment (CERN)



Neutrino experiments

Several running now:
Microboone, **Coherent, T2K**, …

DUNE planned for the future

LHC auxiliary detectors

They use the primary interactions of the LHC to produce new particles.
Several proposals: **FASER, Codex-b, MATHUSLA**, …

Dark Matter at high-intensity experiments

Dark Matter & the “WIMP” paradigm

Weakly Interacting Massive Particles (WIMP) models:
One of the dominant models for more than 3 decades

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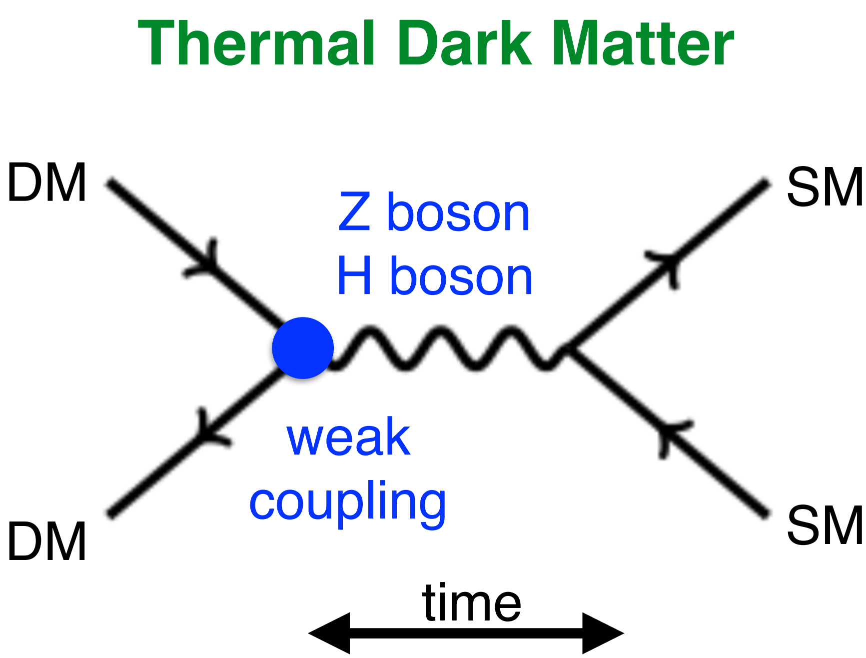
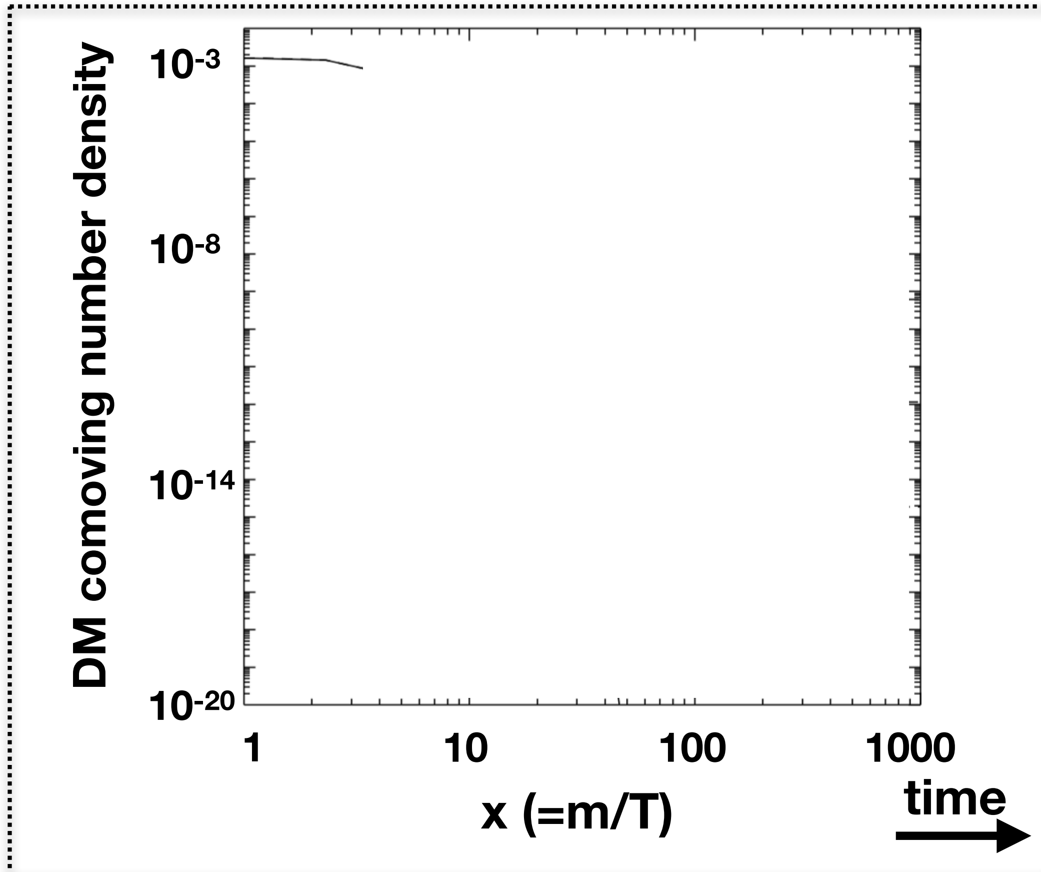
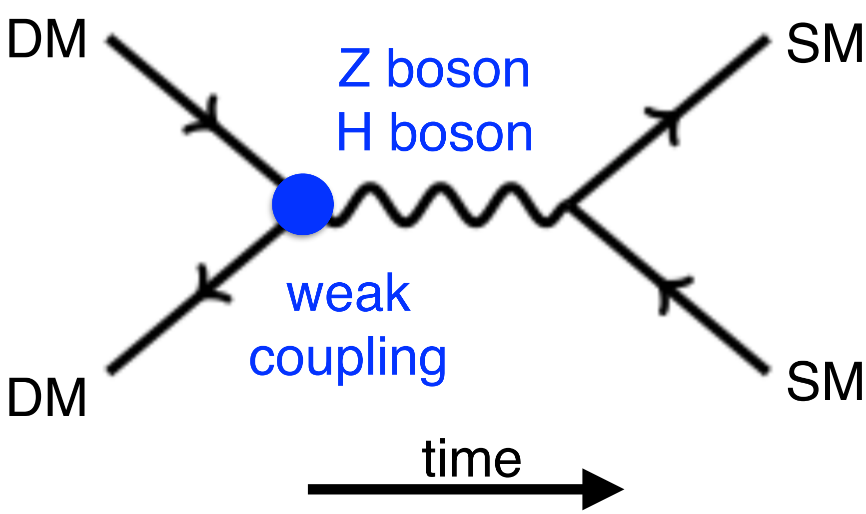


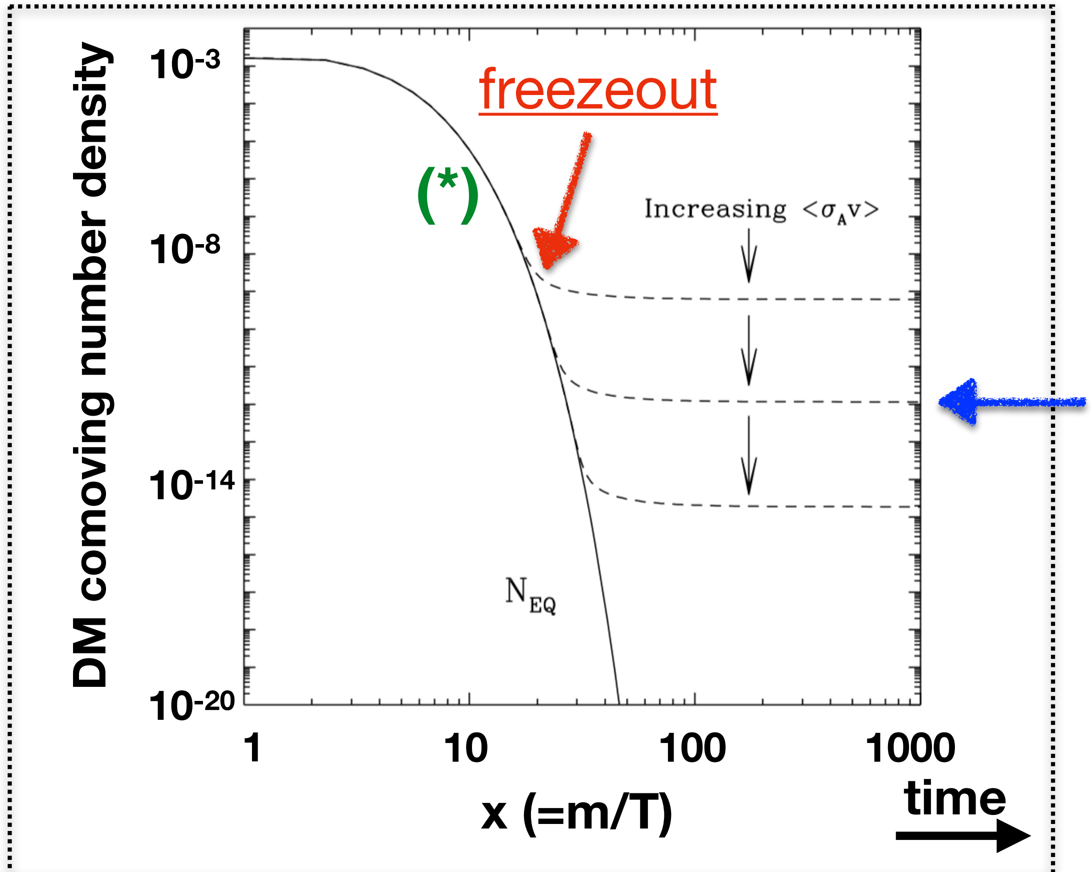


Dark Matter & the "WIMP" paradigm

Weakly Interacting Massive Particles (WIMP) models:
One of the dominant models for more than 3 decades

DM annihilation to SM (*):





Thanks to these interactions, DM with a mass O(100 GeV) can "freeze out" and obtain the measured relic abundance

WIMP "miracle"? … or "coincidence"

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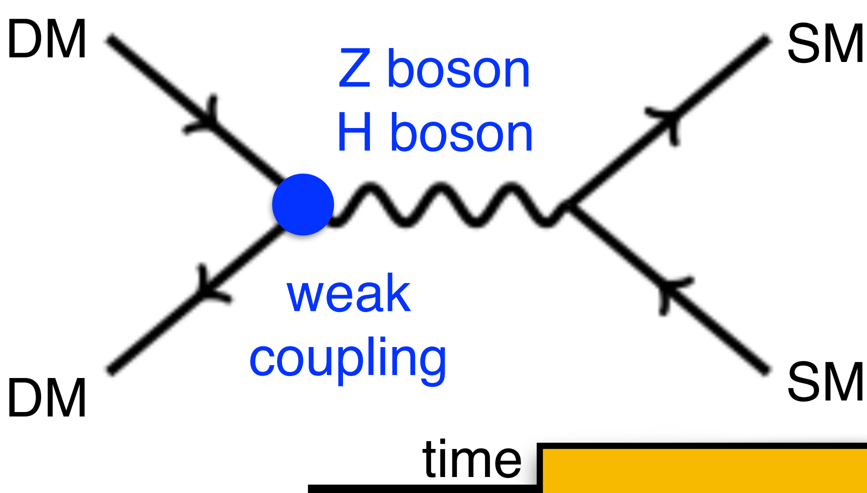

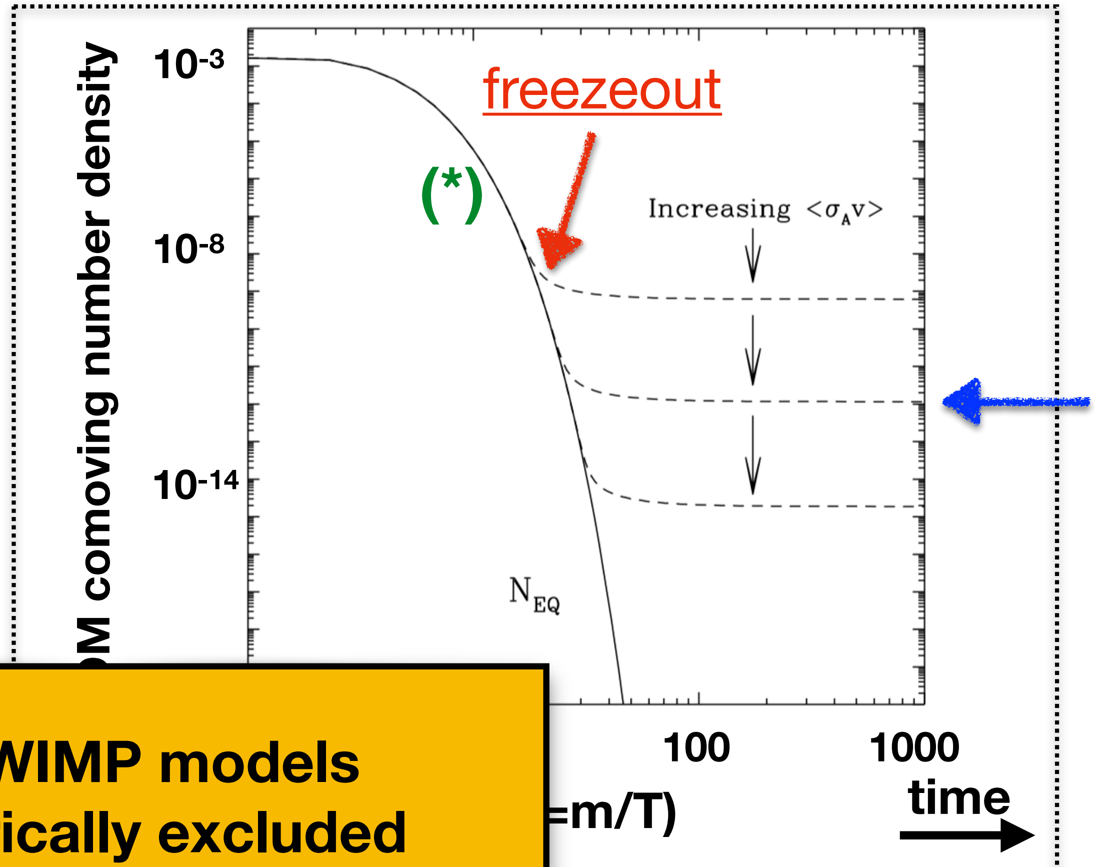

Vanilla WIMP models are generically excluded

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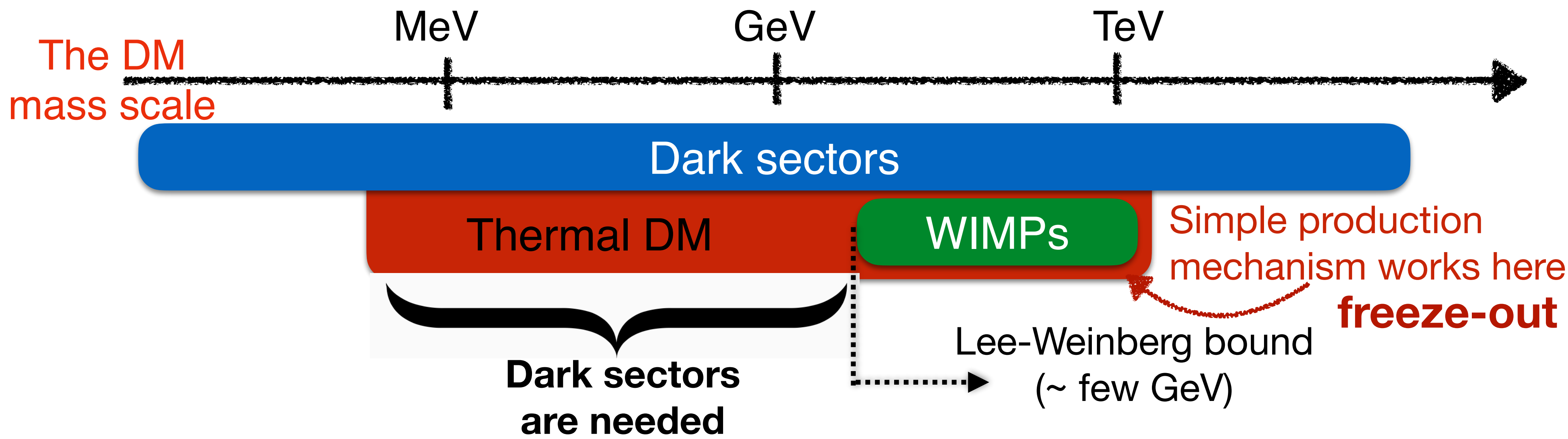
Dark Matter living in a dark sector



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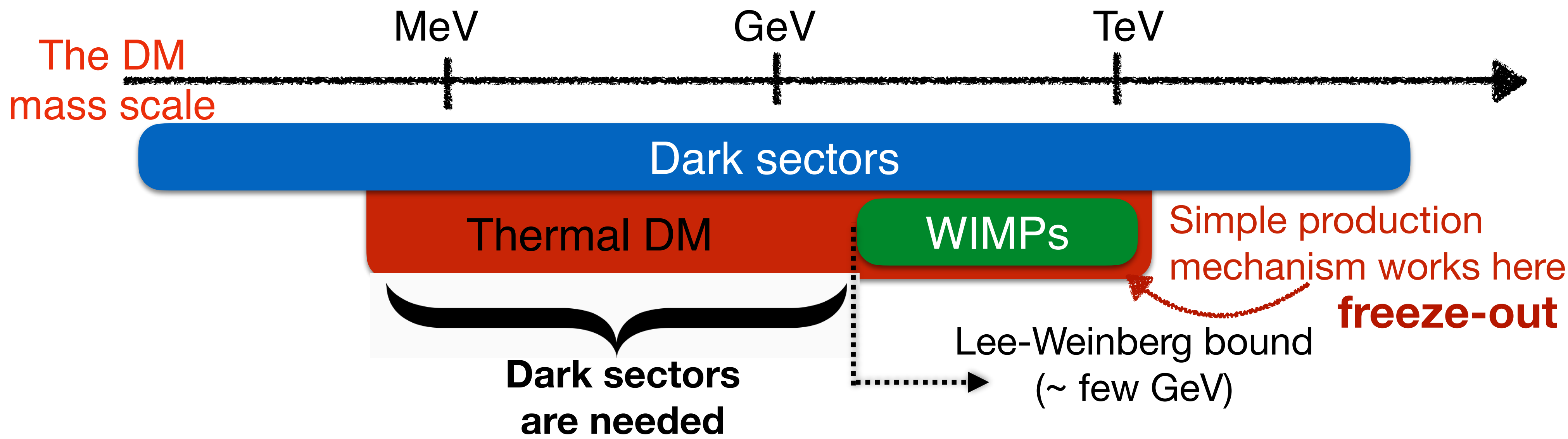
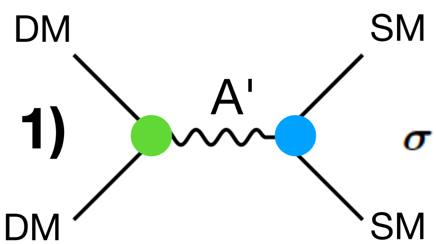
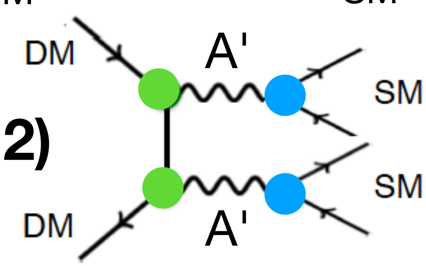


DM thermal freeze-out targets



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

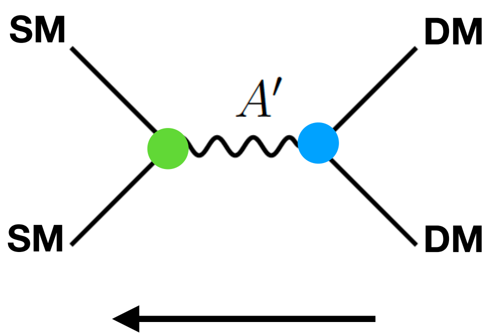
DM freeze-out thermal targets

Dark photon mediated DM:

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

A'→XX

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



DM annihilation

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This combination of couplings is fixed to a certain value.
The value depends on the nature of DM
(Dirac fermion, Majorana fermion, scalar, …)

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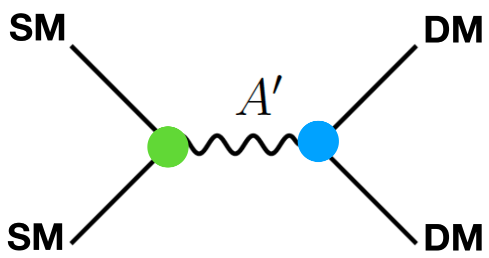

Signals at **direct detection** experiments can be velocity suppressed
(e.g., if DM is a Majorana fermion)

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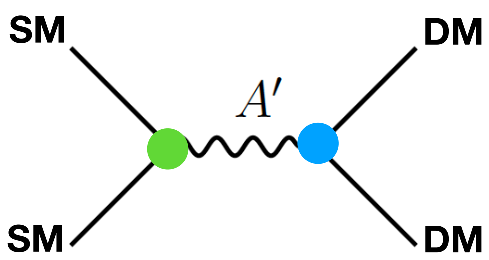

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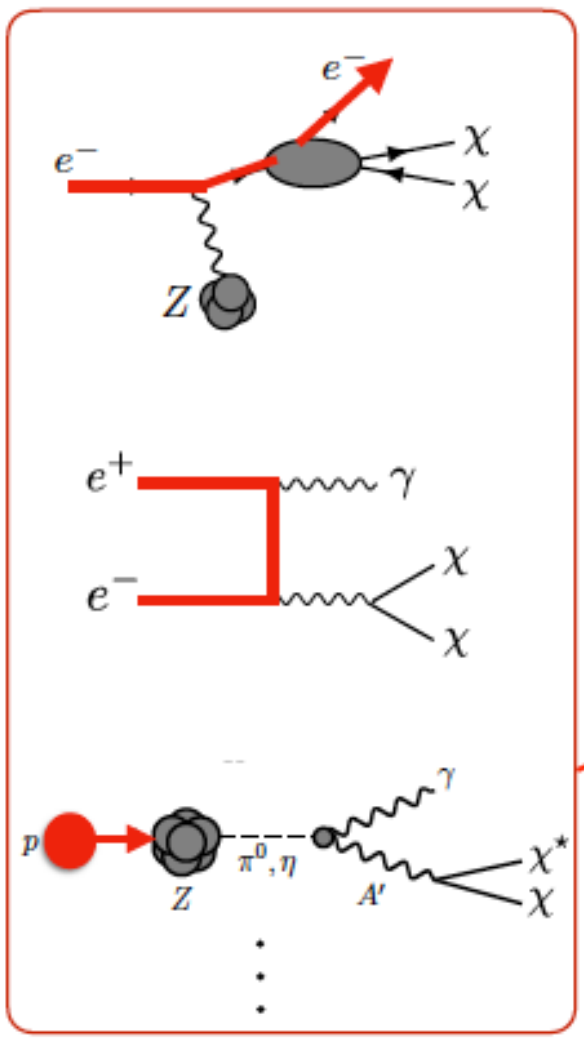
Accelerator experiments and direct detection experiments test different DM regimes (relativistic vs. non-relativistic DM)

This combination of couplings is fixed to a certain value.
The value depends on the nature of DM
(Dirac fermion, Majorana fermion, scalar, …)

Signature at accelerator experiments:
invisible decays of the dark photon

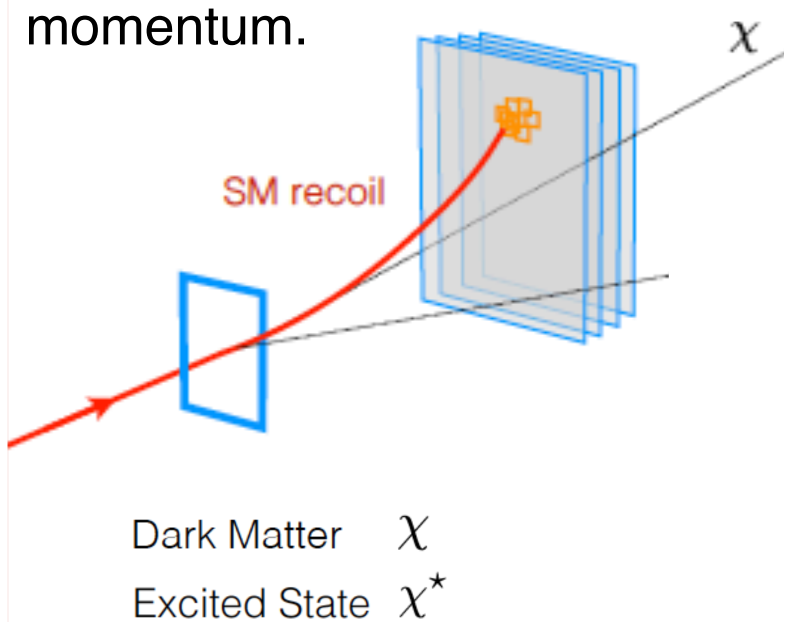
DM production and detection at high intensities

https://arxiv.org/abs/2207.00597



(1)

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



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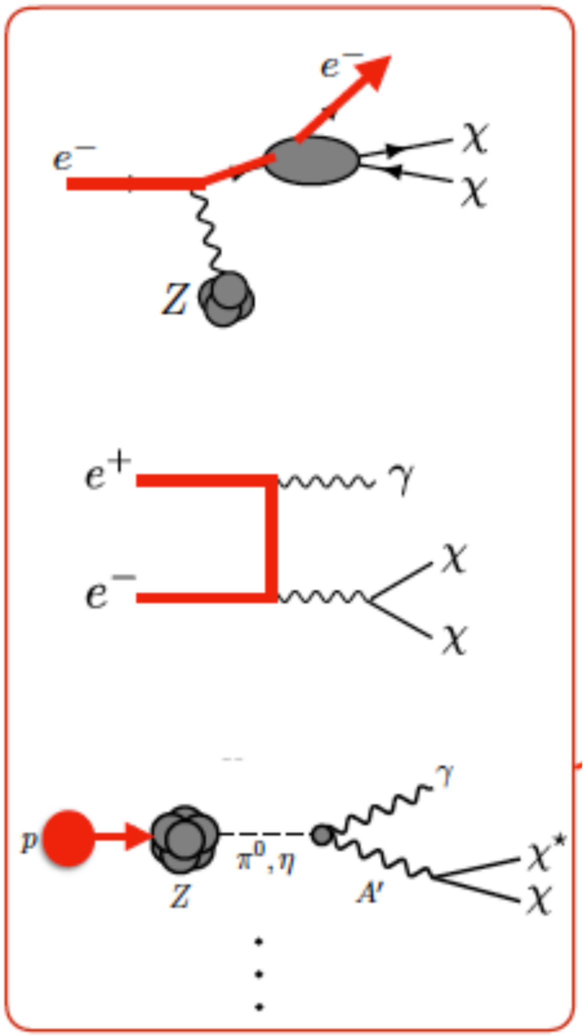

(proton beam: synergistic with the accelerator-based **neutrino physics program**)

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

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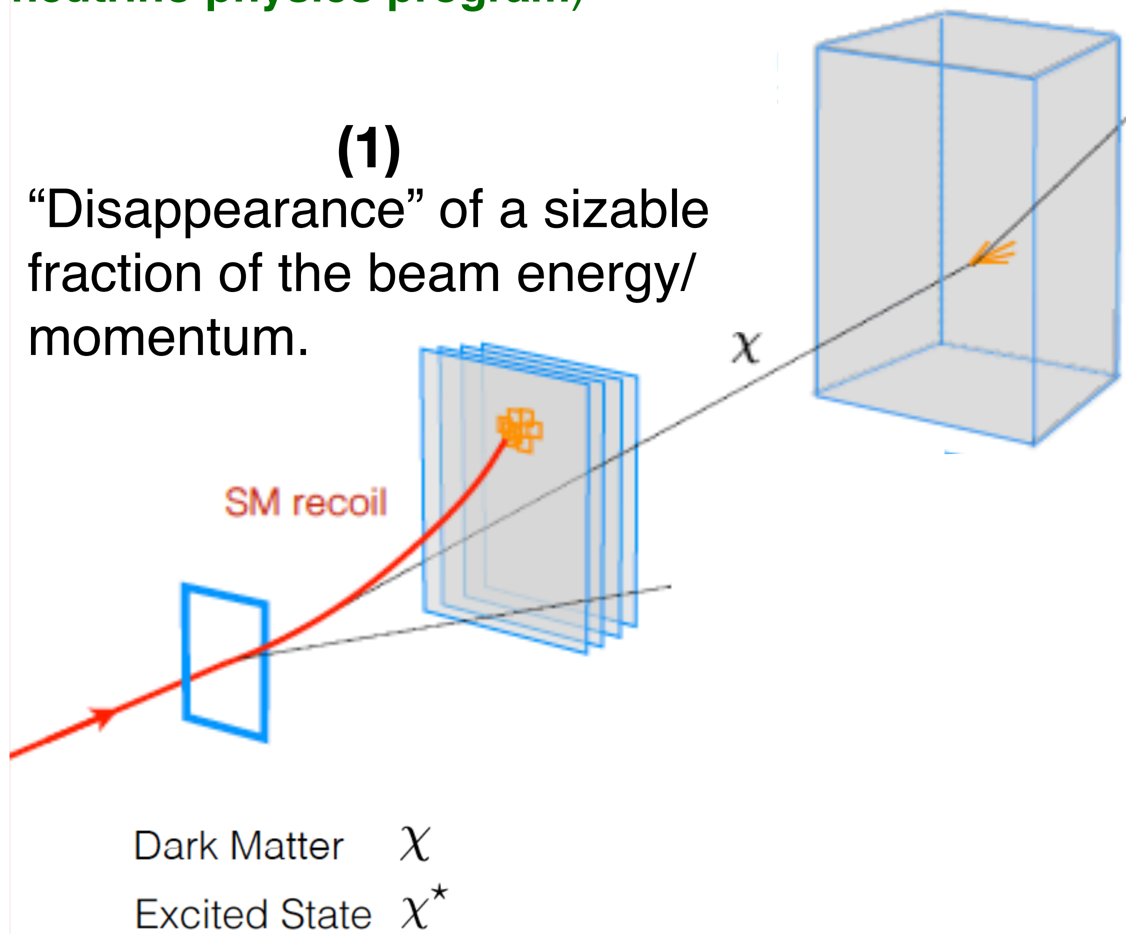

Invisible

DM production and detection at high intensities

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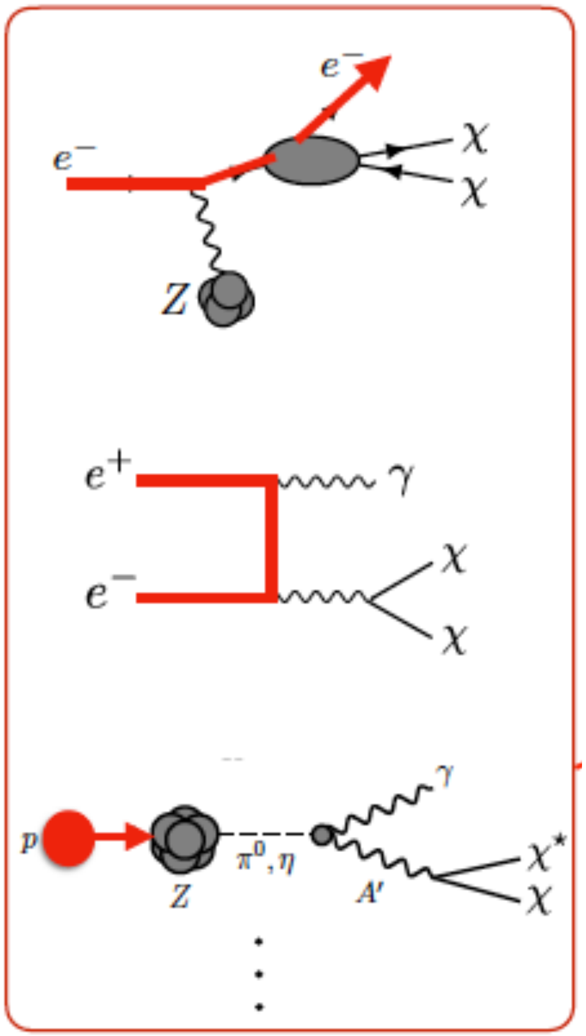

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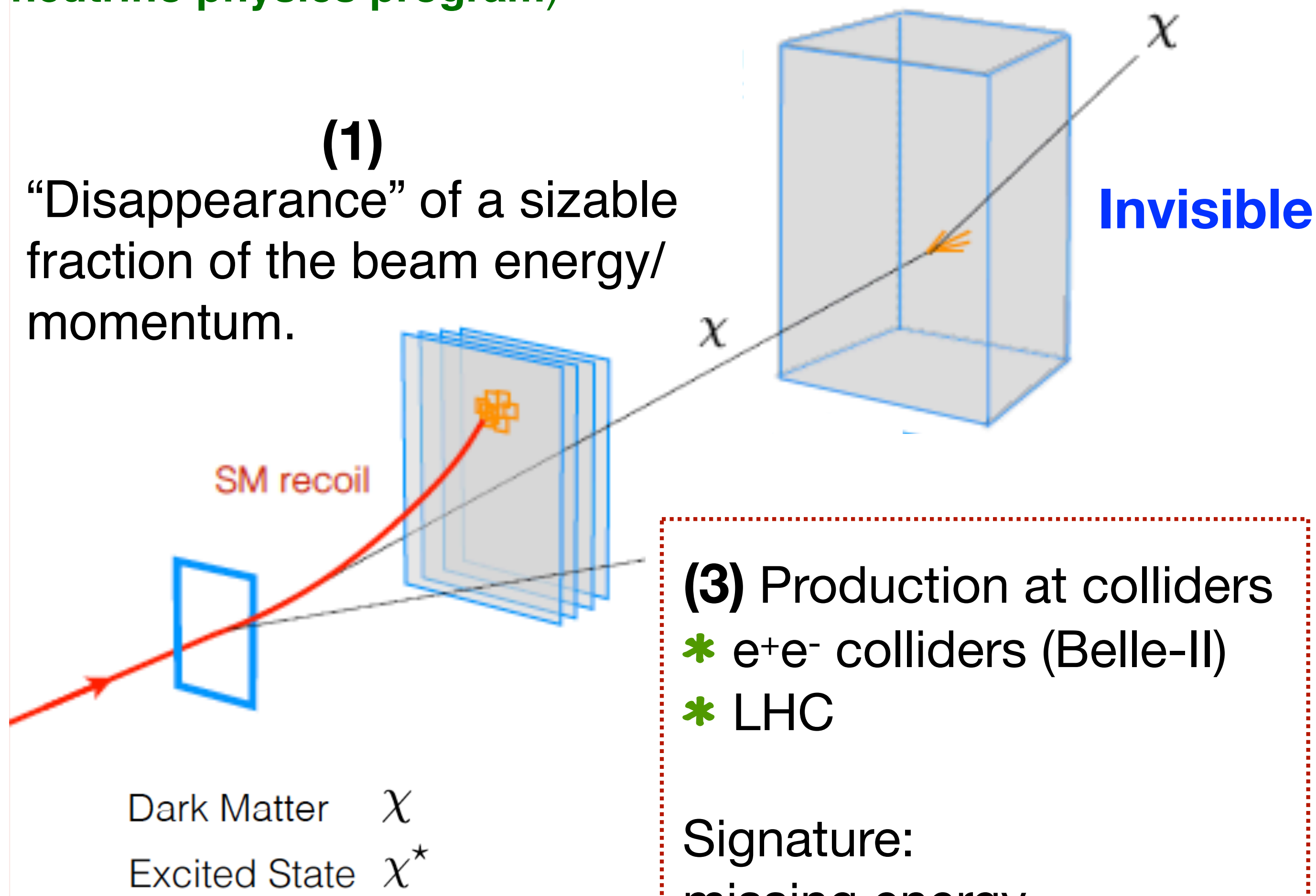


(3) Production at colliders
- e^+e^- colliders (Belle-II)
- LHC

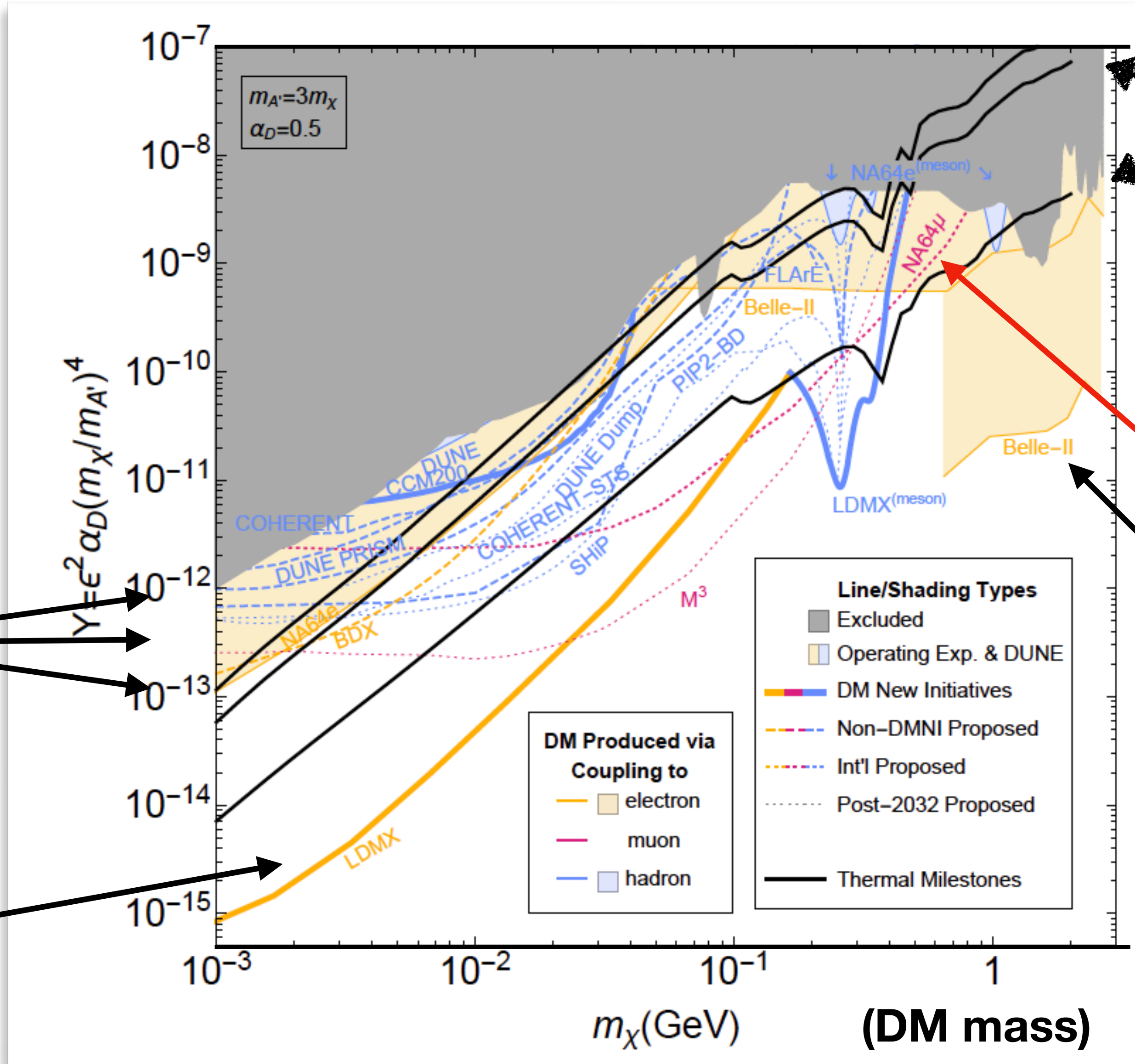
Signature:
missing energy
mono-X searches

Exploring the invisible dark photon

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

A'→XX

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



(DM mass)

benchmarks for thermal DM
(scalar, Majorana fermion, Pseudo-Dirac, respectively)

(1) Missing energy

(3) Collider, mono-photon search

(2) Re-scattering

(1) Missing momentum

Krnjaic, Toro et al, 2207.00597

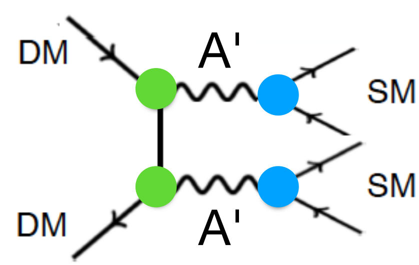
DM secluded / forbidden scenarios

$m_{A'} < 2m_{DM}$

Experimental targets:

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

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



ε is lower bounded

DM secluded / forbidden scenarios

- 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, $L_\mu - L_\tau$, …

$A' \to \ell^+\ell^-, \ldots$

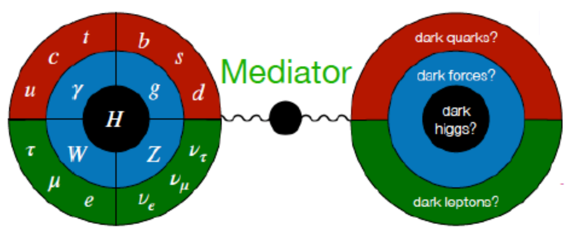
$S \to \mu^+\mu^-,\ \pi^+\pi^-, KK, \ldots$

$N \to \ell\pi, \ldots$

$a \to \gamma\gamma,$

$Z' \to \mu^+\mu^-, \ldots$

"visible" signatures



How to test these couplings?

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

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

$m_{A'} < 2m_{DM}$

Experimental targets:

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

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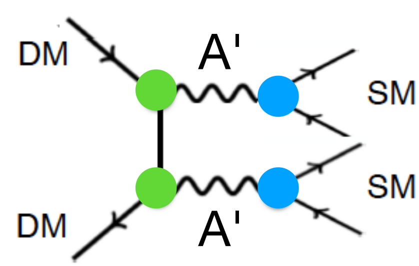
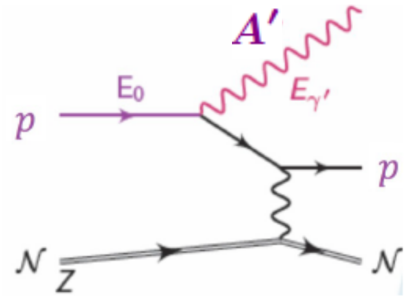


ε is lower bounded

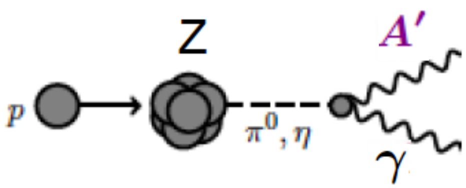
The visible dark photon

Production

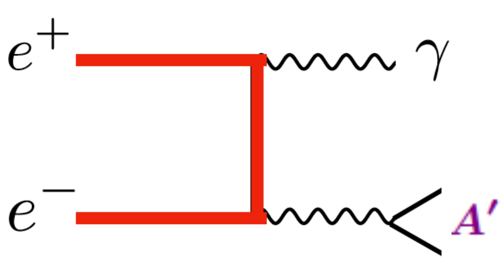


brems-
strahlung

Fixed targets



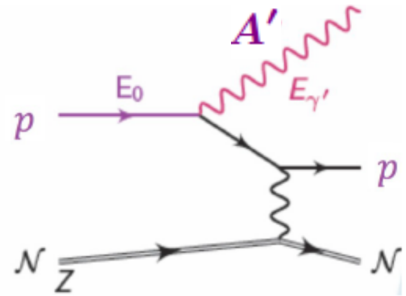
meson
decay



e^+e^- colliders

The visible dark photon

Production



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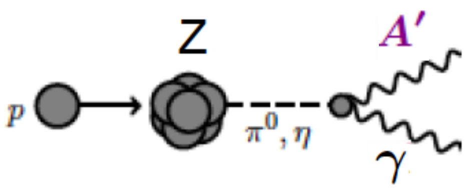

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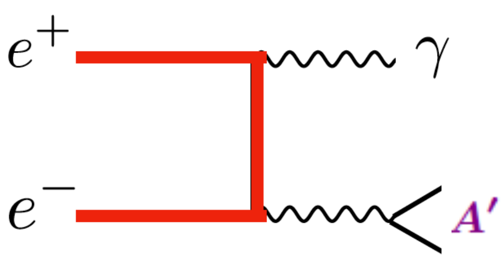
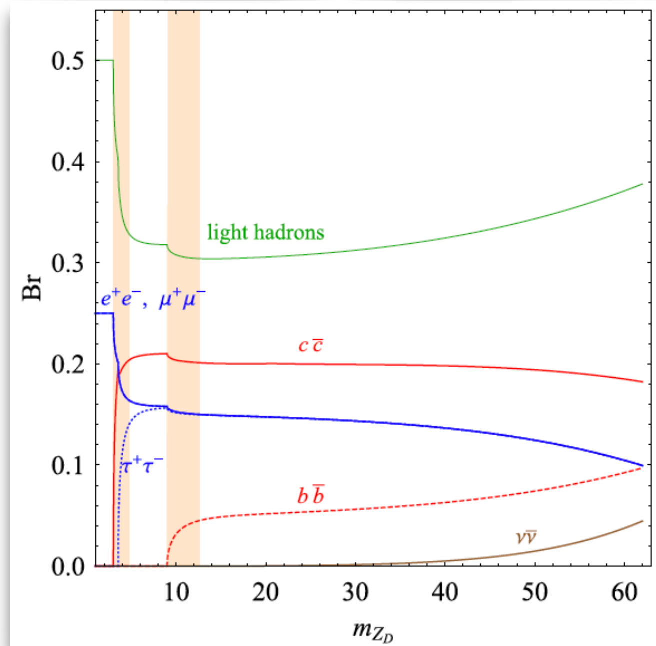
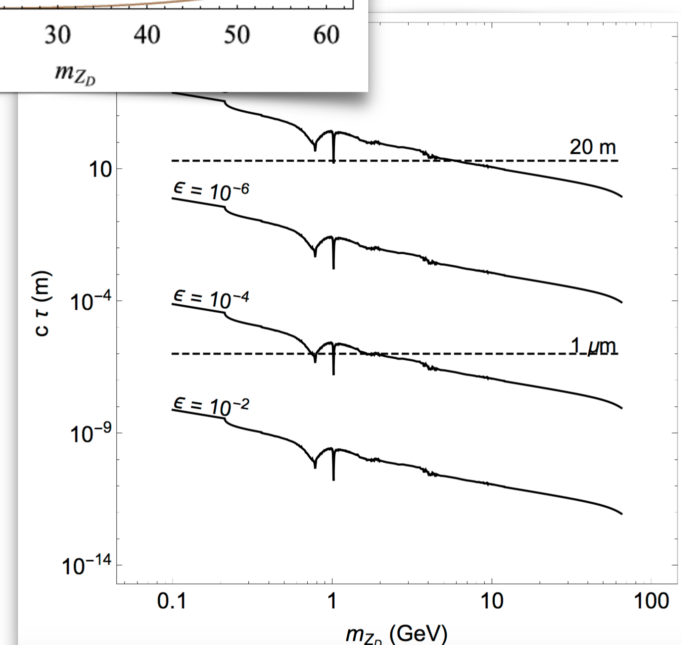


e+e- colliders

Decay





it can be long-lived

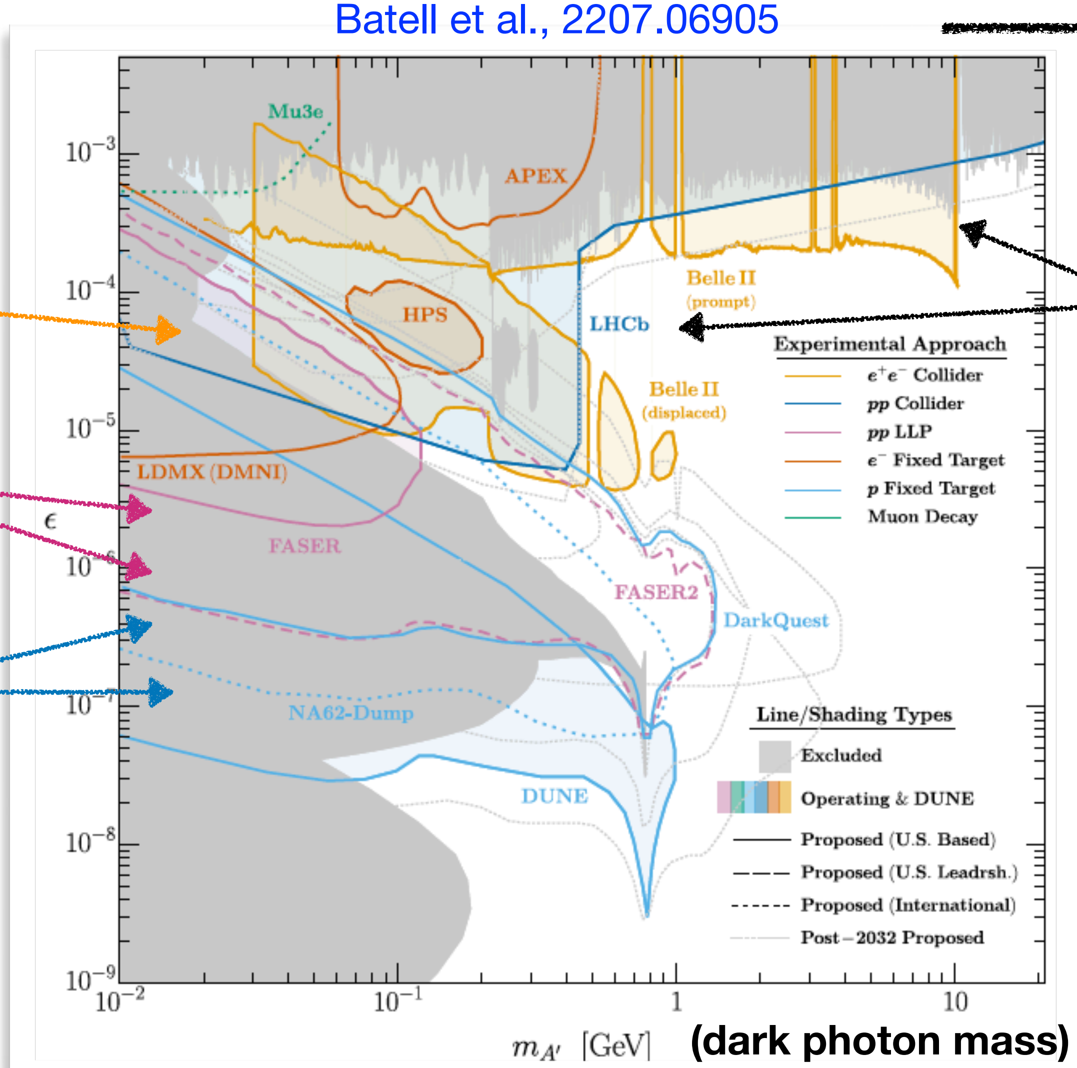
$$\epsilon B^{\mu\nu} A'_{\mu\nu}$$

Curtin, Essig, SG, Shelton, 1412.0018

Exploring visible dark photons

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

Batell et al., 2207.06905



energy frontier

Colliders

electron fixed target

forward detectors

proton beam-dump

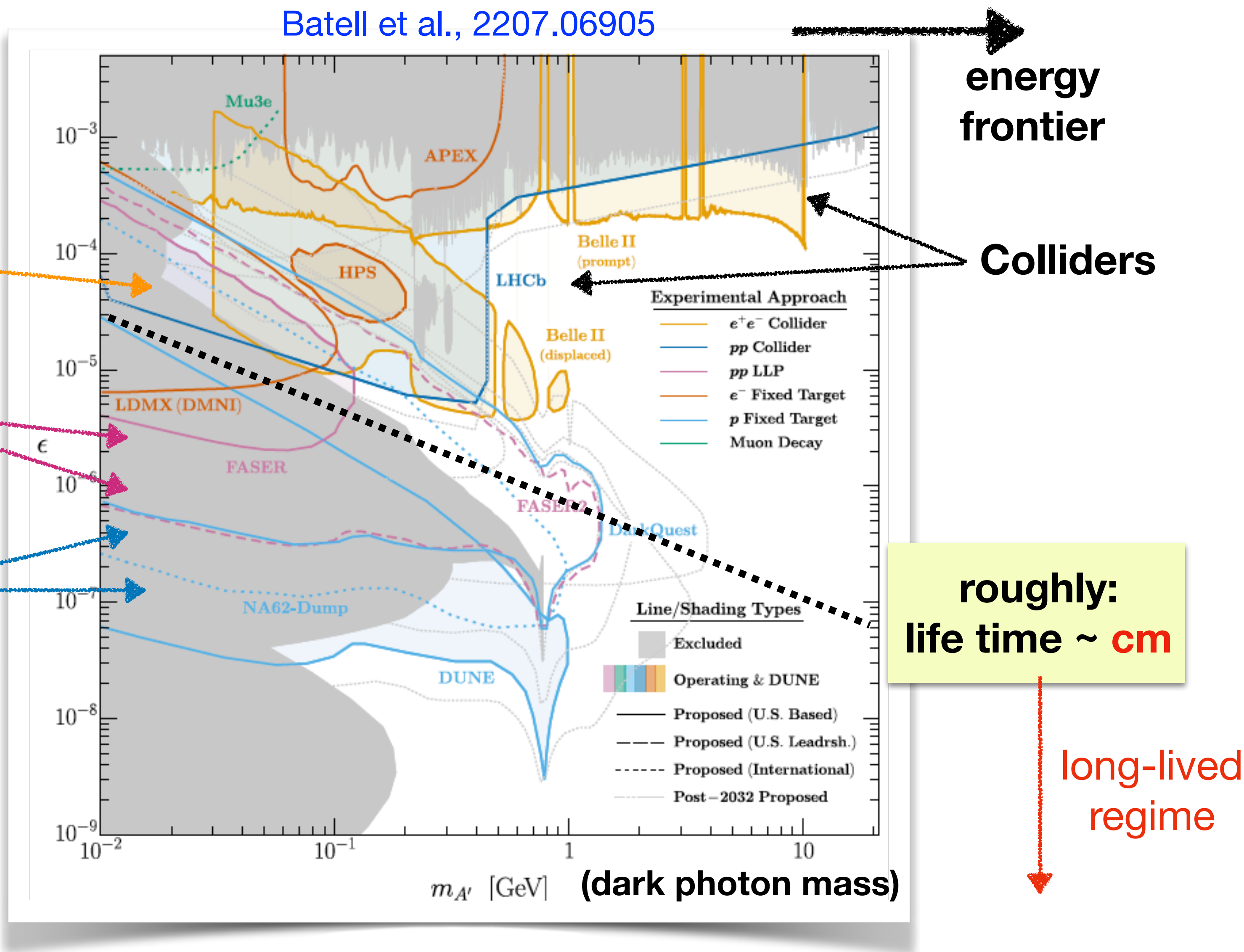
(dark photon mass)

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

Exploring visible dark photons

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

Batell et al., 2207.06905



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DM models can be more complex

Many models contain more particles (than the DM candidate + the mediator)

Examples:

- Inelastic Dark Matter (IDM)
- Strongly interacting massive particles (SIMPs)

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SIMP

Hochberg, Kuflik, Volansky, Wacker, 1402.5143,

Hochberg, Kuflik, Murayama, Volansky, Wacker, 1411.3727

freeze-out through the annihilation

$$3 \to 2$$

$$m_{\rm DM} \sim \alpha_{\rm ann}(T_{\rm eq}^2 M_{\rm pl})^{1/3} \sim 100 \text{ MeV}$$

Possibly realized in a QCD-like theory SU(N_c) with

$$SU(N_f) \times SU(N_f) \to SU(N_f)$$

N_f^2-1 Light pions

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

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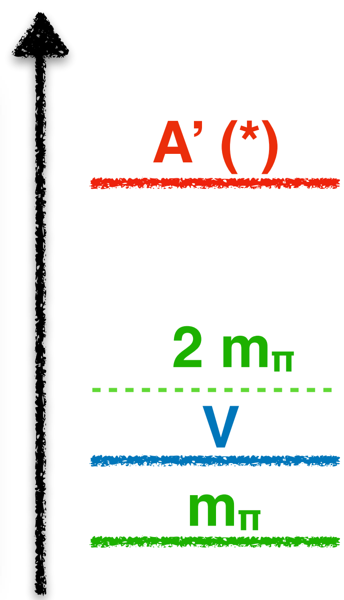


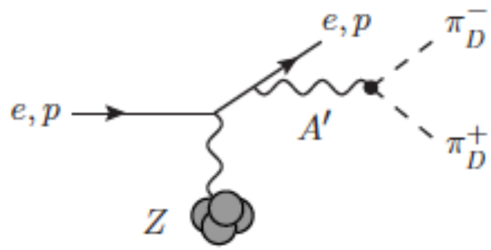
prevent $\pi\pi \to A'A'$ (CMB)

additional resonances of the dark QCD sector

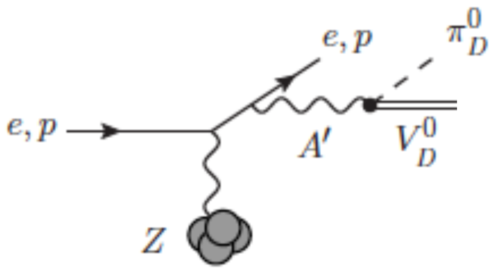
(*) Needed to maintain thermalization between the two sectors

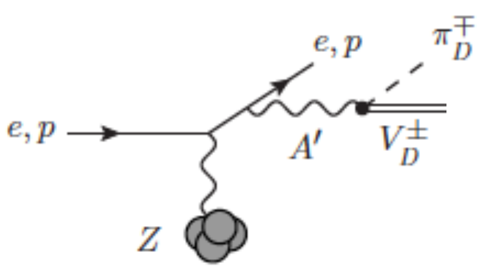
SIMP decays of the dark photon

$A' \to \pi_D^+ \pi_D^-$ (DM)



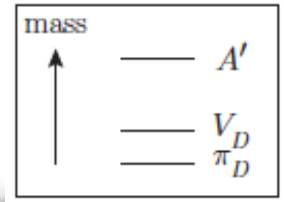
$\Gamma \propto \alpha_D m_{A'}$



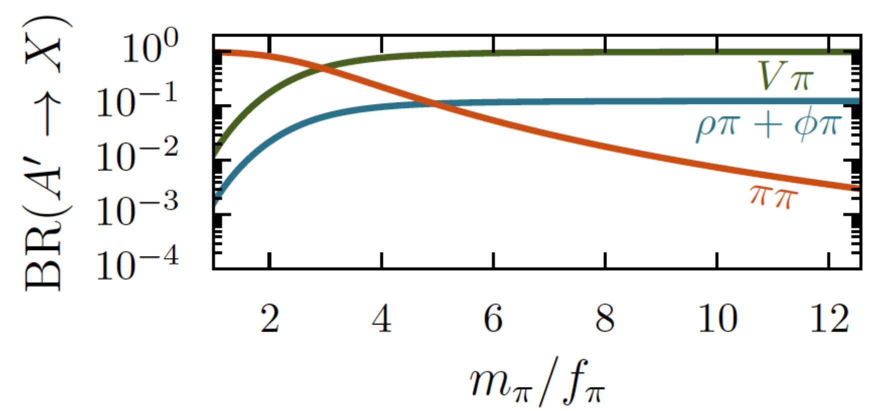


$$\Gamma \propto \alpha_D \frac{m_{A'}^3 m_V^2}{f_\pi^4}$$

$A' \to \pi_D V_D$



Berlin, Blinov, SG, Schuster, Toro, 1801.05805



$\alpha_D = 10^{-2}, \quad \epsilon = 10^{-3}$

SIMP decays of the dark photon

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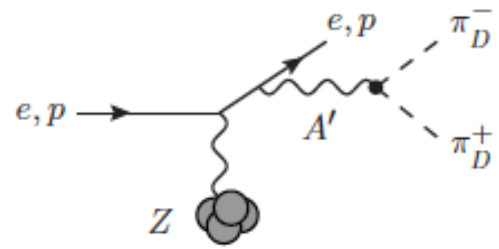
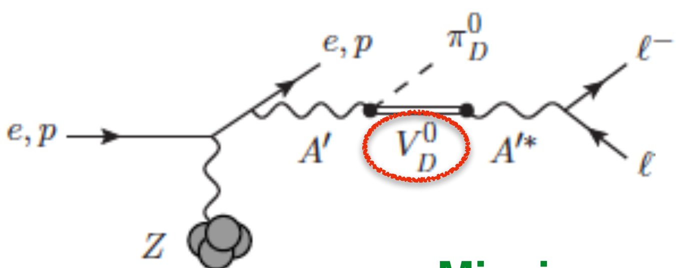
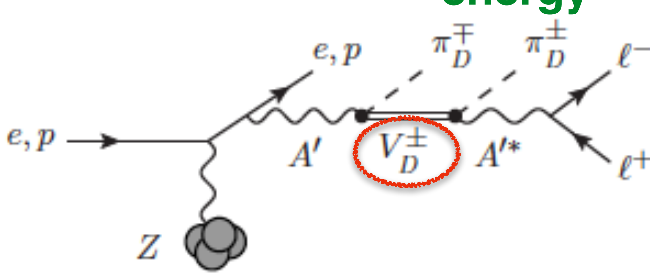


Invisible
A' decay

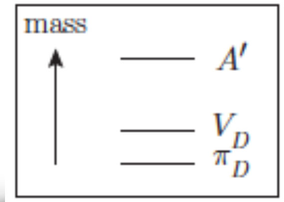


Missing energy

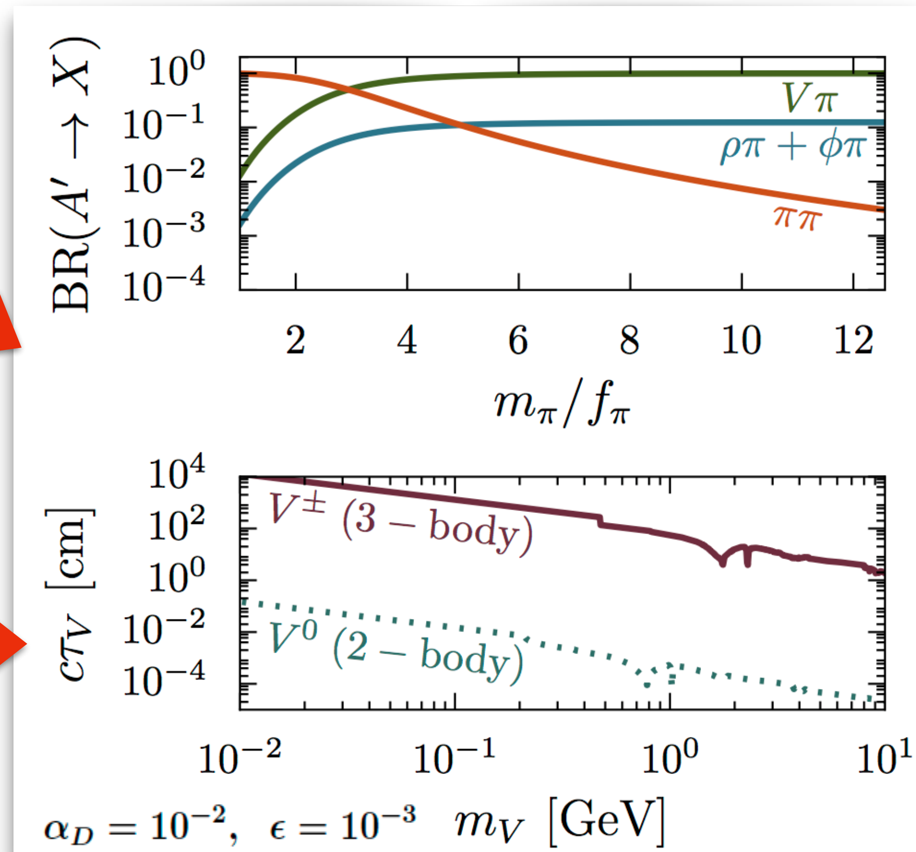


Visible
A' decay

$A' \rightarrow \pi_D V_D$



Berlin, Blinov, SG, Schuster, Toro, 1801.05805

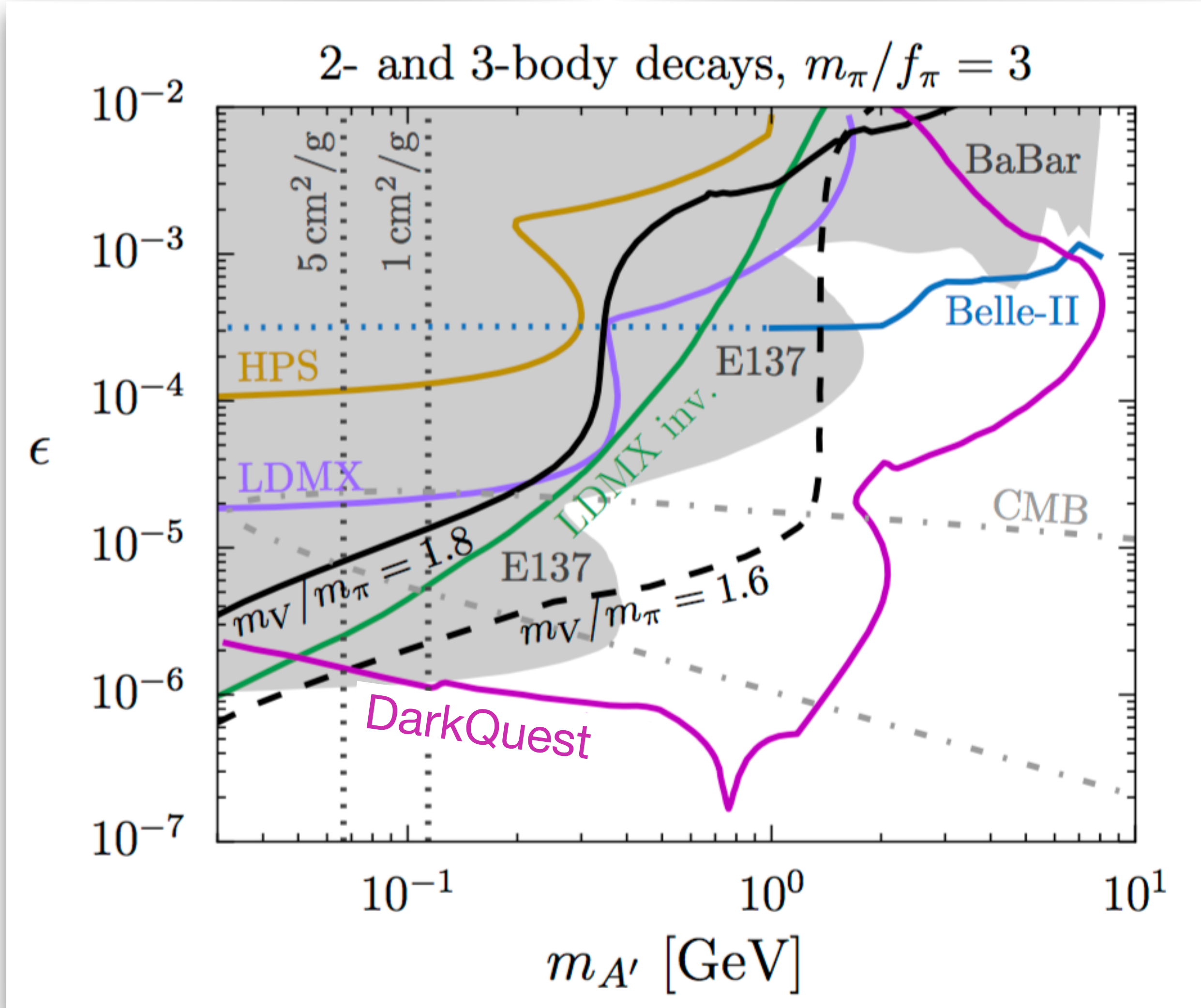


Displaced decays of the dark vector

⇨ Good for beam dump experiments

The reach for SIMPs

Berlin, Blinov, SG, Schuster, Toro, 1801.05805



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

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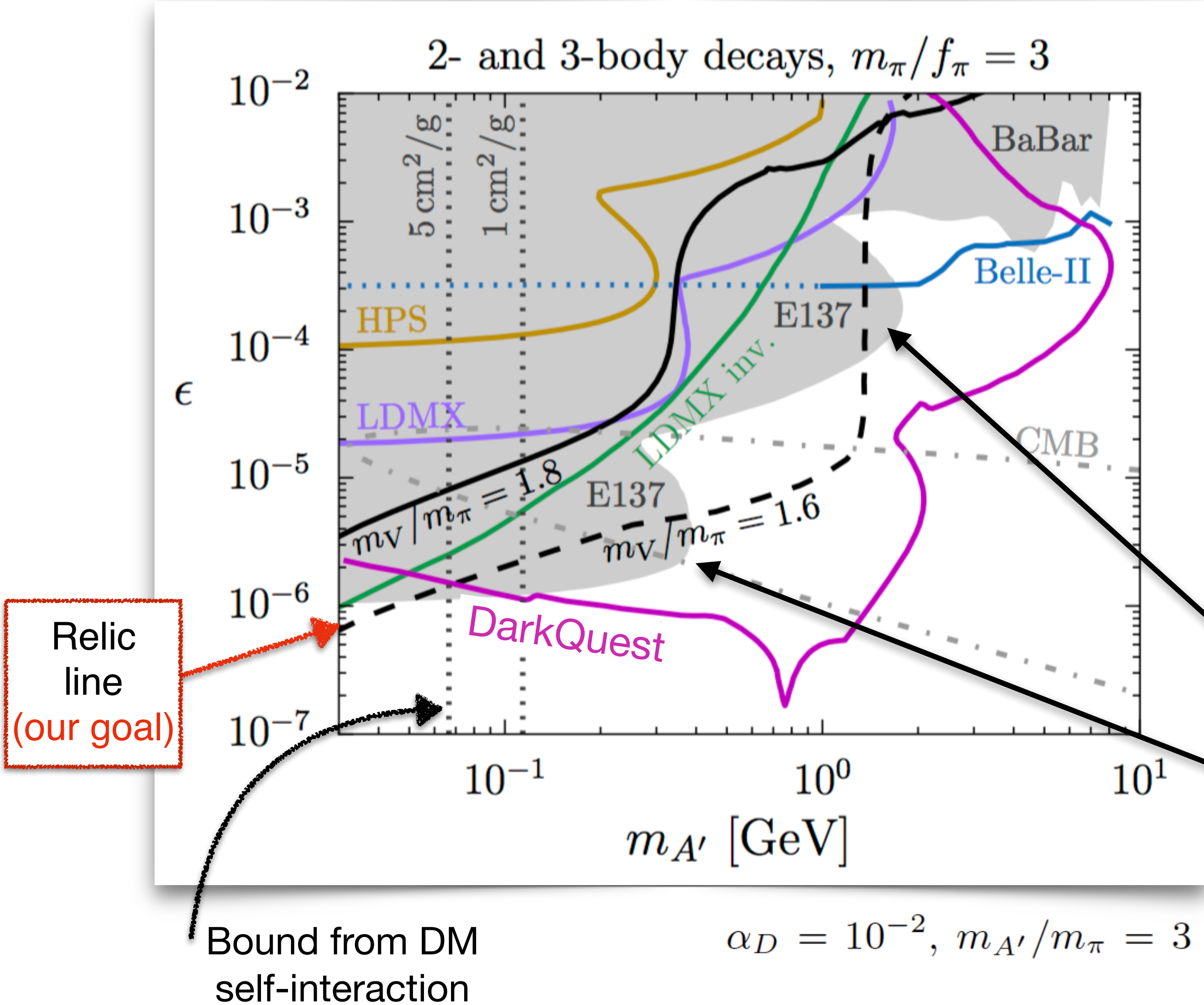

Gray:

reach of past experiments:

- Babar:

$e^+e^- \to \gamma A', \quad A' \to \text{inv}$

- E137:

past electron beam dump experiment. Search for visibly decaying A'

$A' \to \pi_D V_D$

$V_D^0 \to \ell^+\ell^-$

$V_D^\pm \to \pi_D^\pm \ell^+\ell^-$

The reach for SIMPs

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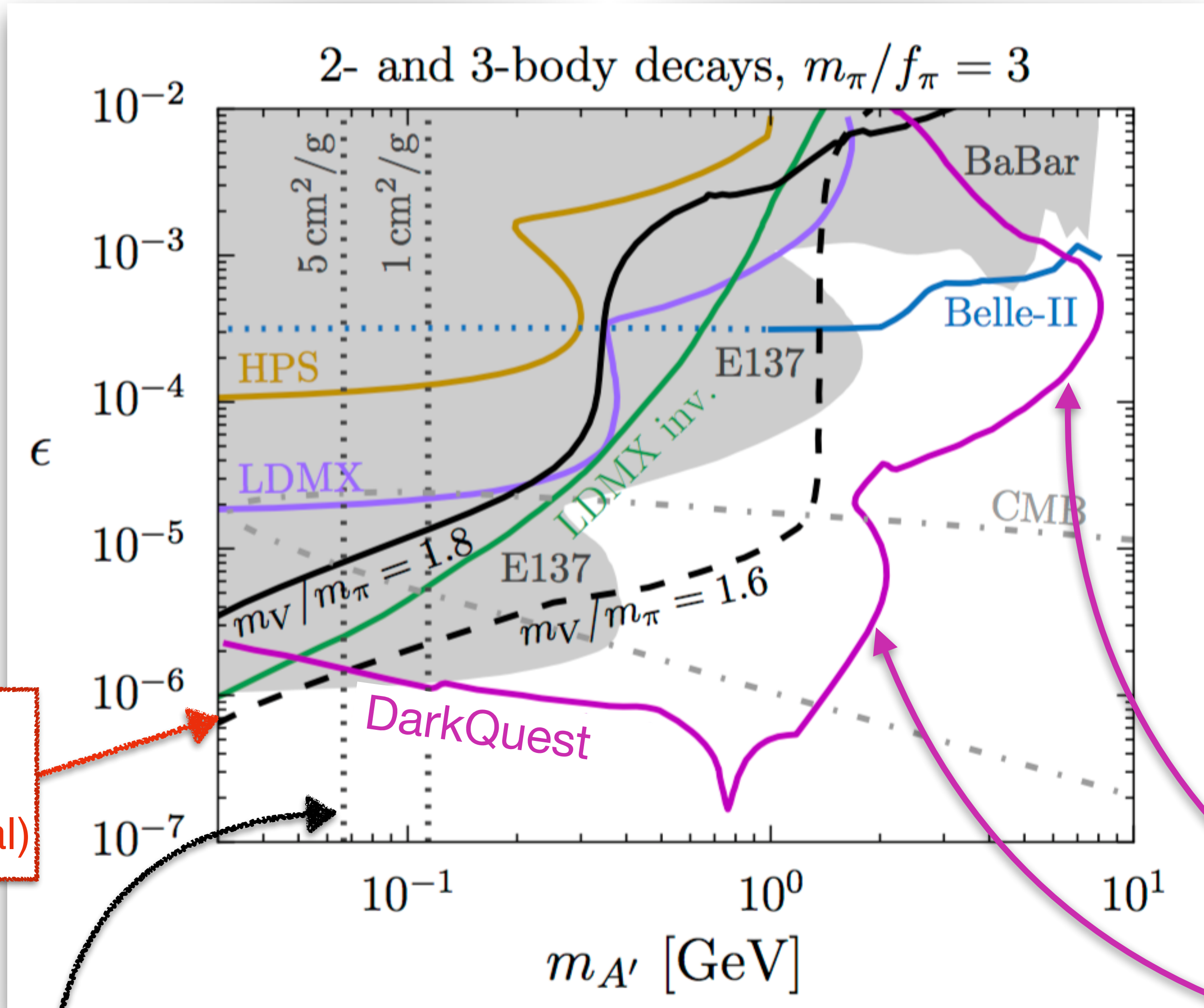

Relic line (our goal)

Bound from DM self-interaction

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

In color:

reach of future experiments:

- Belle II: (same Babar signature)

$$e^+e^- \to \gamma A', \quad A' \to \mathrm{inv}$$

- LDMX: invisible A’
- LDMX: visible A’
- HPS: visible A’
- DarkQuest: visible A’

$$A' \to \pi_D V_D$$

$$V_D^0 \to \ell^+\ell^-$$

$$V_D^\pm \to \pi_D^\pm \ell^+\ell^-$$

Beyond Dark Matter:
dark sector particles at high-intensity experiments

Dark sectors beyond Dark Matter

Beyond the DM motivation, many other open problems in particle physics let us think about dark particles.

- Models to address the strong CP problem. Axions and axion-like particles;
- Models to address the gauge hierarchy problem (relaxion);
- SUSY extended models (Next-to-Minimal-Supersymmetric-Standard-Model);
- Models for baryogengesis;
- Models for neutrino mass generation;
- Models addressing anomalies in data;

($(g-2)_\mu$, galactic center excess for Dark Matter, B-physics anomalies, …).

Some of these particles are naturally light thanks to approximate global symmetries.

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

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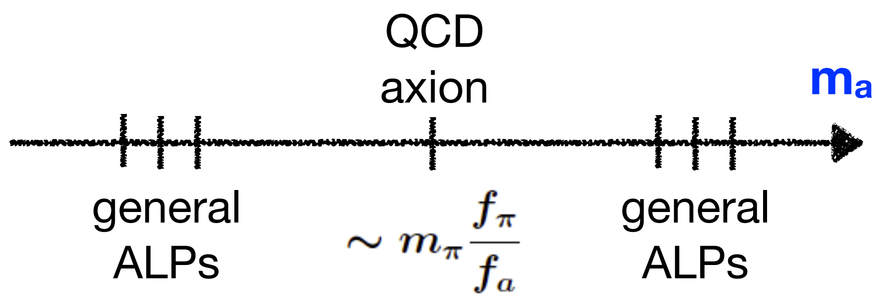
Axion-like-particles (ALPs)

Scalar with an approximate shift symmetry

(Possibly) connected to the Strong CP problem:
why is the QCD θ parameter so small?

$$\mathcal{L}_{\rm QCD} \supset \bar{\theta}\frac{g^2}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

Mass can be protected by
a Peccei-Quinn symmetry
→ ALPs below the EW scale?



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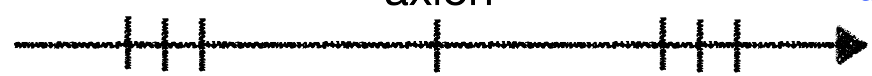
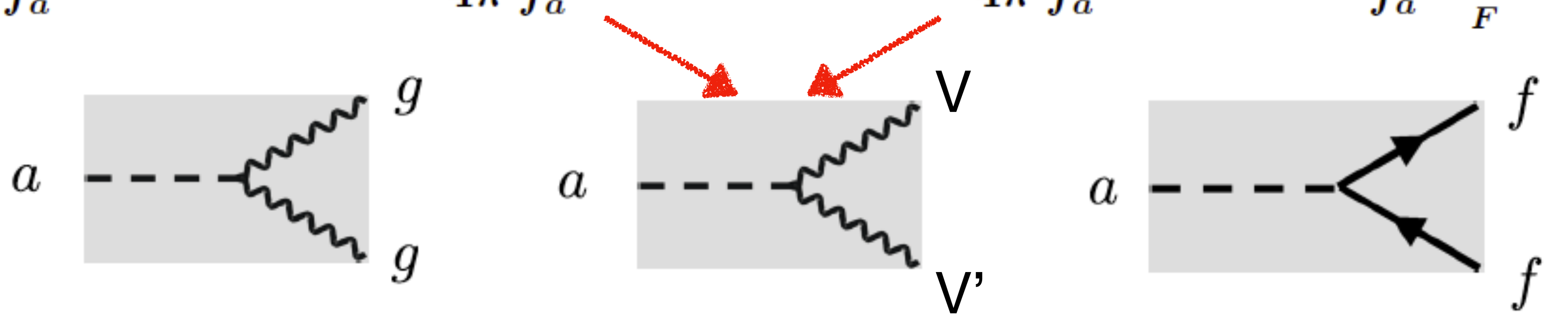


$$\mathcal{L} \supset c_{GG} \frac{\alpha_s}{4\pi} \frac{a}{f_a} G^a_{\mu\nu} \tilde{G}^{\mu\nu,a} + c_{WW} \frac{\alpha_2}{4\pi} \frac{a}{f_a} W^A_{\mu\nu} \tilde{W}^{\mu\nu,A} + c_{BB} \frac{\alpha_1}{4\pi} \frac{a}{f_a} B_{\mu\nu} \tilde{B}^{\mu\nu} + \frac{\partial_\mu a}{f_a} \sum_F \bar{\psi}_F C_F \gamma_\mu \psi_F$$



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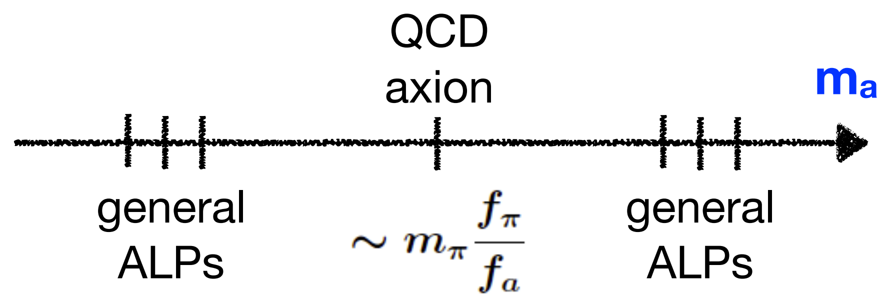

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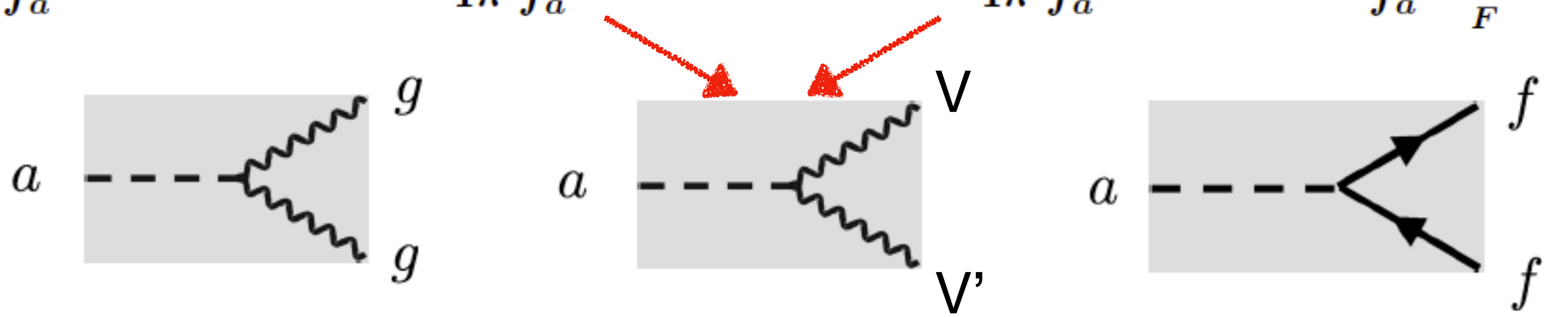


In particular, a ALP-photon coupling
is generated in the broken phase

by far the most studied

Broad program of ALP searches at high-intensity experiments?

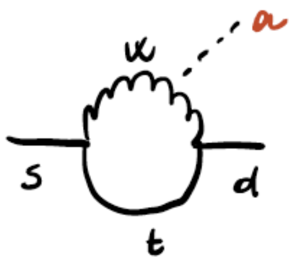
Neutral & charged current meson decays to ALPs

Flavor changing neutral current

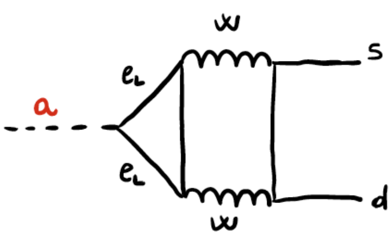
They arise in models with

* ALPs mixed with SM neutral pions
  (e.g. $K^+ \to \pi^+ \pi^0 \;\Rightarrow\; K^+ \to \pi^+ a$)

* ALPs coupling to W or tops



* ALPs coupling to leptons
  (higher loop)



$$
\begin{aligned}
K_L &\to \pi^0 a \\
K^+ &\to \pi^+ a \\
B &\to K a
\end{aligned}
$$

* Flavor violating ALPs

see e.g. Gavela et al., 1901.02031

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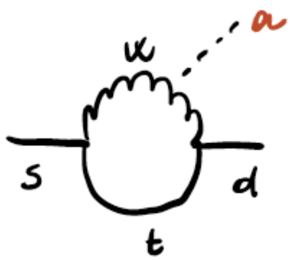
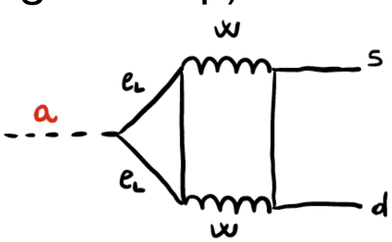


* ALPs coupling to leptons (higher loop)



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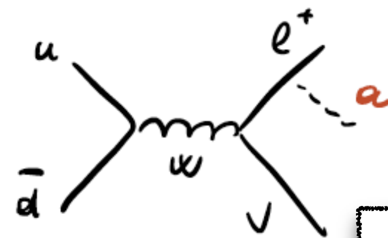

$$\pi^+ \to a \ell^+ \nu$$
$$K^+ \to a \ell^+ \nu$$
$$B^+ \to a \ell^+ \nu$$

Altmannshofer, Dror, SG, 2209.00665

Neutral & charged current meson decays to ALPs

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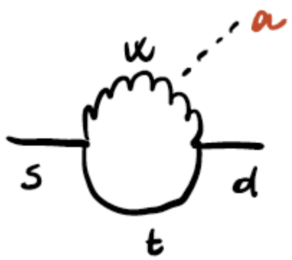

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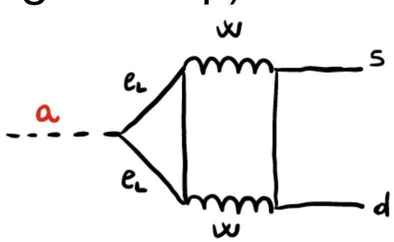

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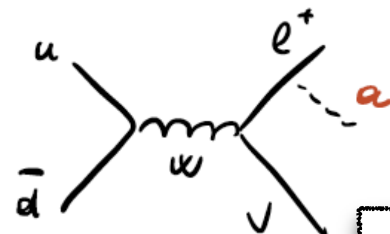

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$$K^+ \to a\ell^+\nu$$
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Altmannshofer, Dror, SG, 2209.00665

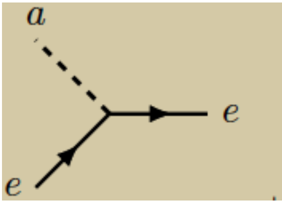
see e.g. Gavela et al., 1901.02031

Lepton-coupled ALP scenario

$$\frac{(\partial_\mu a)}{m_e}\left[\bar{e}\gamma^\mu\left(\bar{g}_{ee}+g_{ee}\gamma_5\right)e+g_\nu\bar{\nu}\gamma^\mu P_L\nu\right]$$

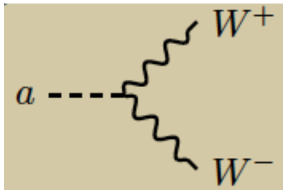
$$\mathcal{L}=-a\partial_\mu j^\mu_{PQ}$$

"Standard" vertex

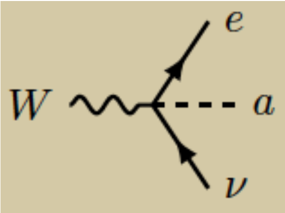


$$\partial_\mu j^\mu_{\rm PQ}=g_{\ell\ell}(\bar{\ell}i\gamma_5\ell)$$
$$+\frac{e^2}{16\pi^2 m_\ell}\frac{\bar{g}_{\ell\ell}-g_{\ell\ell}+g_{\nu_\ell}}{4s_W^2}W^+_{\mu\nu}\tilde{W}^{-,\mu\nu}$$
$$+\frac{e^2}{16\pi^2 m_\ell}\frac{\bar{g}_{\ell\ell}-g_{\ell\ell}(1-4s_W^2)}{2c_W s_W}F_{\mu\nu}\tilde{Z}^{\mu\nu}-g_{\ell\ell}F_{\mu\nu}\tilde{F}^{\mu\nu}+$$
$$+\frac{e^2}{16\pi^2 m_\ell}\frac{\bar{g}_{\ell\ell}(1-4s_W^2)-g_{\ell\ell}(1-4s_W^2+8s_W^4)+g_\nu}{8s_W^2 c_W^2}Z_{\mu\nu}\tilde{Z}^{\mu\nu}$$
$$+\frac{ig}{2\sqrt{2}m_\ell}(g_{\ell\ell}-\bar{g}_{\ell\ell}+g_{\nu_\ell})(\bar{\ell}\gamma^\mu P_L\nu)W^-_\mu$$

Anomaly terms



Weak vertex



(only present for **weak-violating** models)

$$\bar{g}_{ee}-g_{ee}-g_\nu\neq 0$$

ALPs from charged current interactions

Weak-preserving

$$2g_{ee}\frac{(\partial_\mu a)}{m_e}\bar{e}\gamma^\mu P_R e$$

- $\Gamma_{\pi^+\to e^+\nu a} \propto g_{ee}^2 \frac{m_\pi^3 f_\pi^2}{m_W^4}$
- $\Gamma(K^+ \to e^+\nu a) \propto g_{ee}^2 \frac{m_K^2 f_K^2}{m_W^2}$
- Does not happen

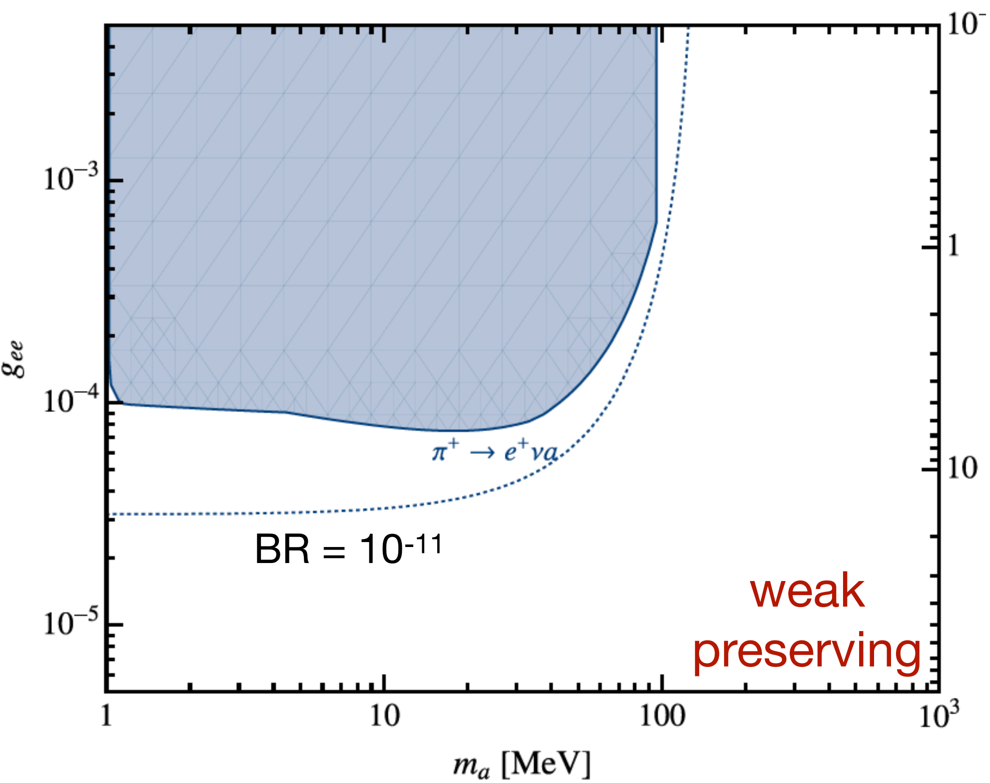
Weak-violating

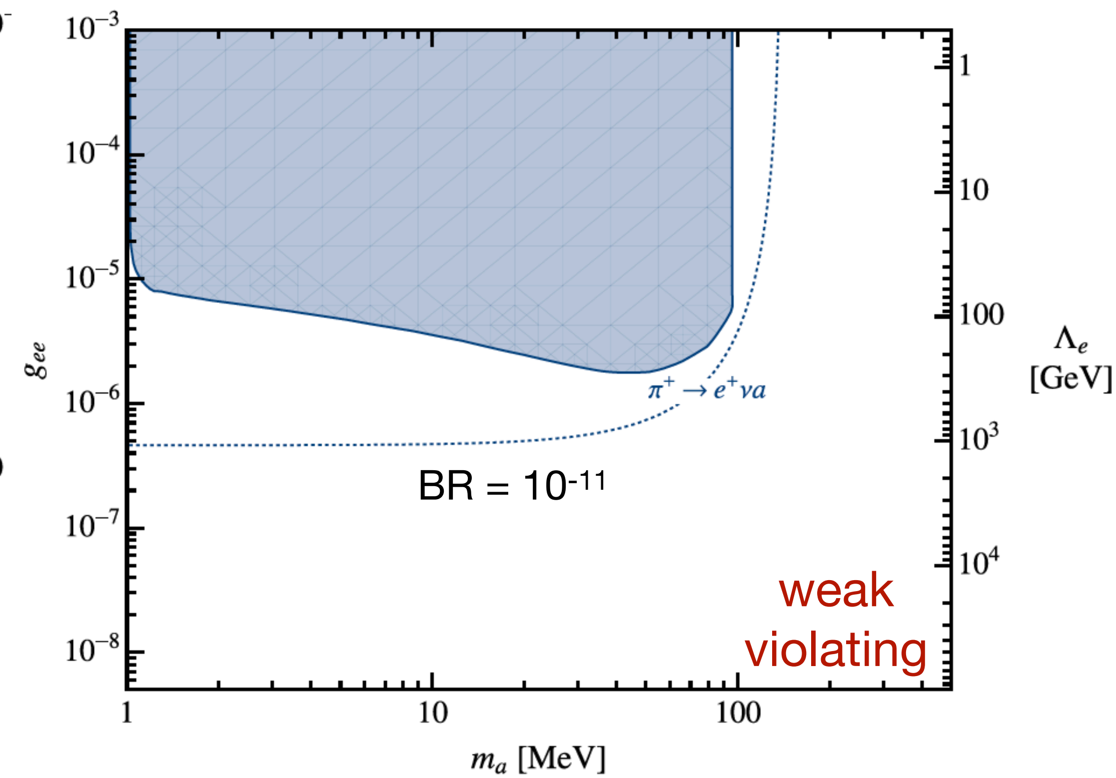
$$g_{ee}\frac{(\partial_\mu a)}{m_e}\bar{e}\gamma^\mu \gamma_5 e$$

- $\Gamma_{\pi^+\to e^+\nu a} \propto \frac{m_\pi^2}{m_e^2} g_{ee}^2 \frac{m_\pi^3 f_\pi^2}{m_W^4}$
- $\Gamma(K^+ \to e^+\nu a) \propto \frac{m_K^2}{m_e^2} g_{ee}^2 \frac{m_K^2 f_K^2}{m_W^2}$
- $\Gamma(W^+ \to e^+\nu a) \propto \frac{m_W^2}{m_e^2} g_{ee}^2$

The reach on the ALP-lepton parameter space

Altmannshofer, Dror, SG, 2209.00665

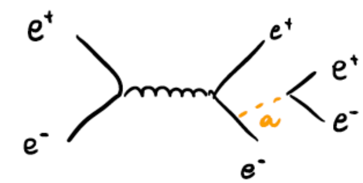


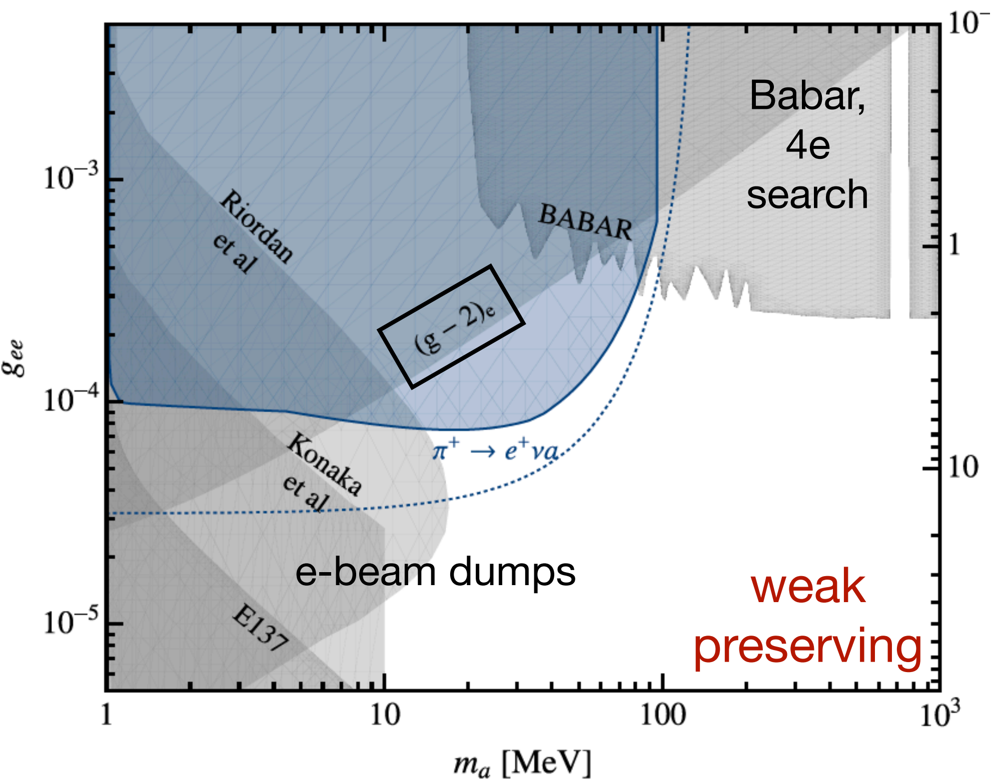


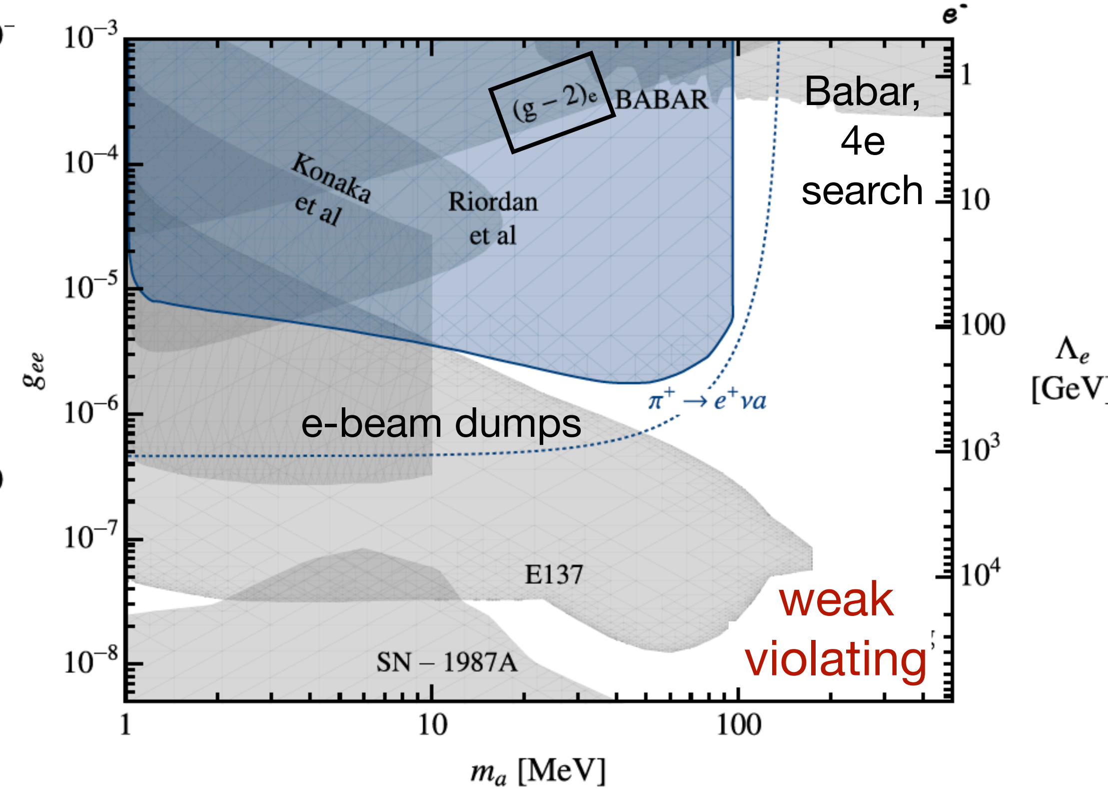
SINDRUM experiment, ’80s
(pion decays)

The reach on the ALP-lepton parameter space

Altmannshofer, Dror, SG, 2209.00665







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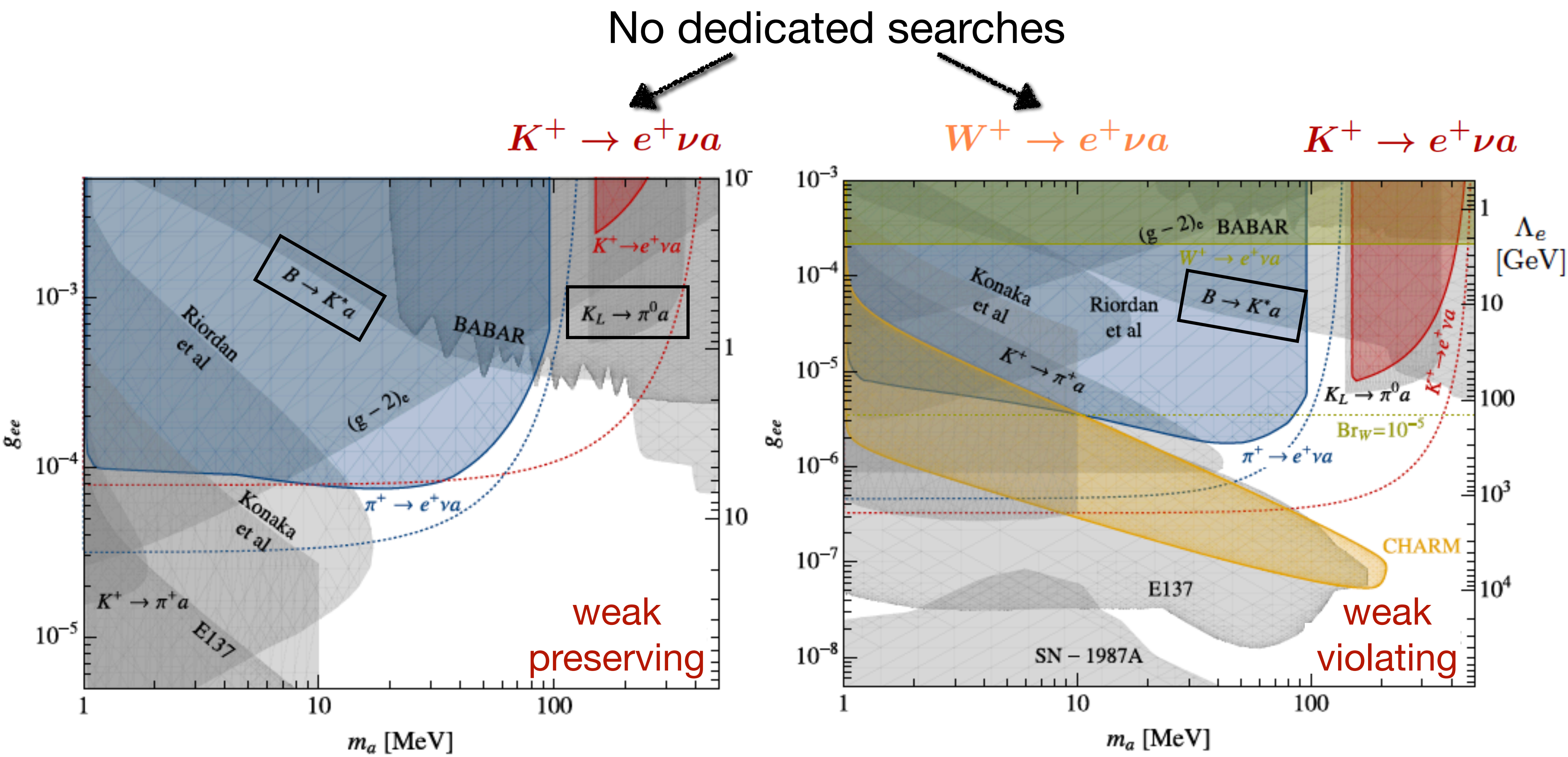

Chapter 3

Testing off-shell dark sectors

Trident scattering processes

If neutrinos interact through new forces beyond the Standard Model,
the scattering of a neutrino beam on target (heavy) nuclei will be modified.

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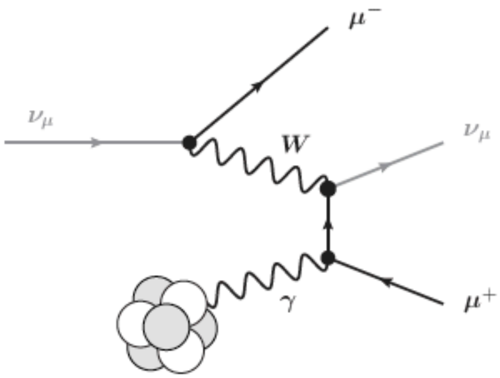
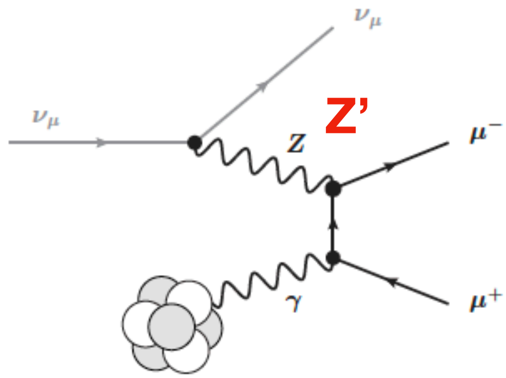
the scattering of a neutrino beam on target (heavy) nuclei will be modified.

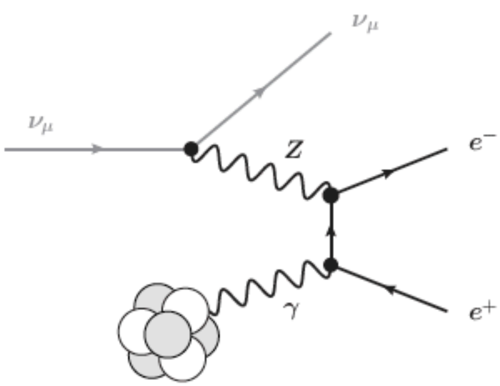
For example:



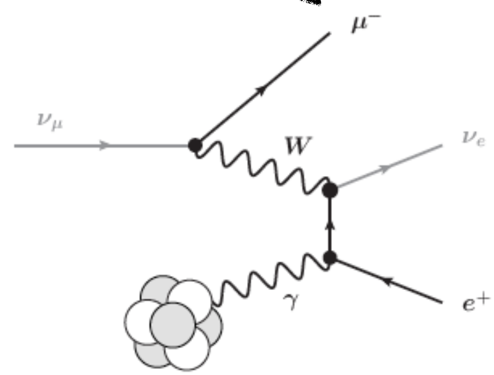


$\nu_\mu \to \nu_\mu \mu^+ \mu^-$

"Trident processes"



$\nu_\mu \to \nu_\mu e^+ e^-$

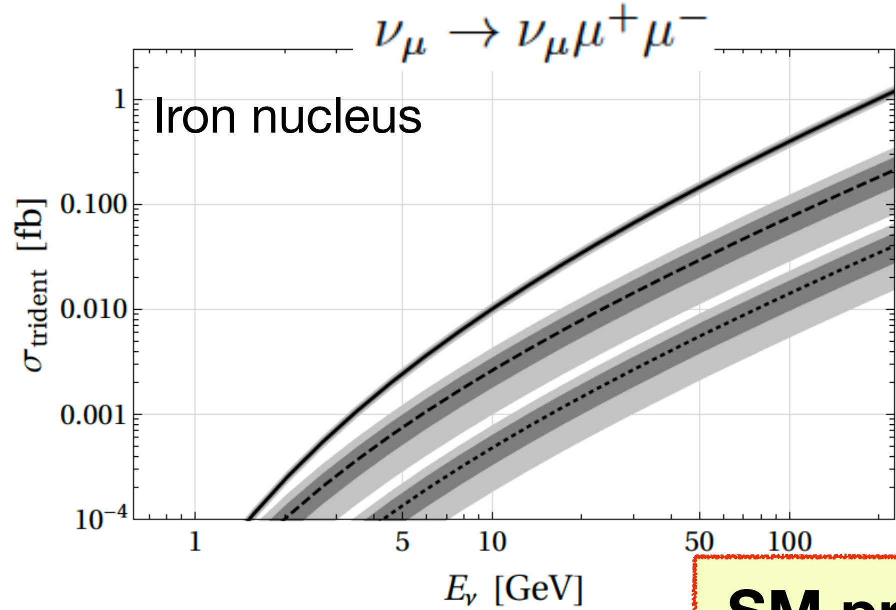


$\nu_\mu \to \nu_e e^+ \mu^-$

- Probe of electroweak interactions.
- Small cross sections (~ 5-6 orders of magnitude smaller than the inclusive neutrino-nucleus cross section) need high intensity!

A strong energy dependence

Altmannshofer, SG, Martin-Albo, Sousa, Wallbank 1902.06765



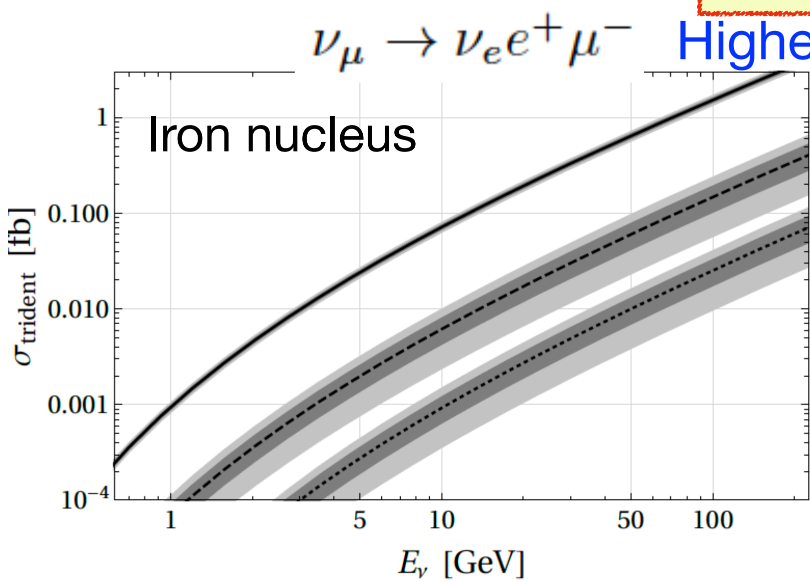
Coherent

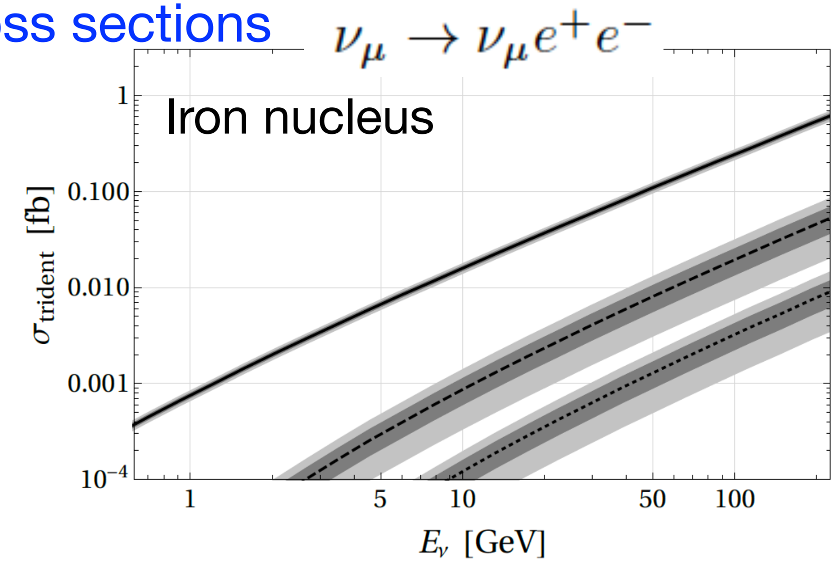
Incoherent, proton

Incoherent, neutron

SM predictions

Higher cross sections





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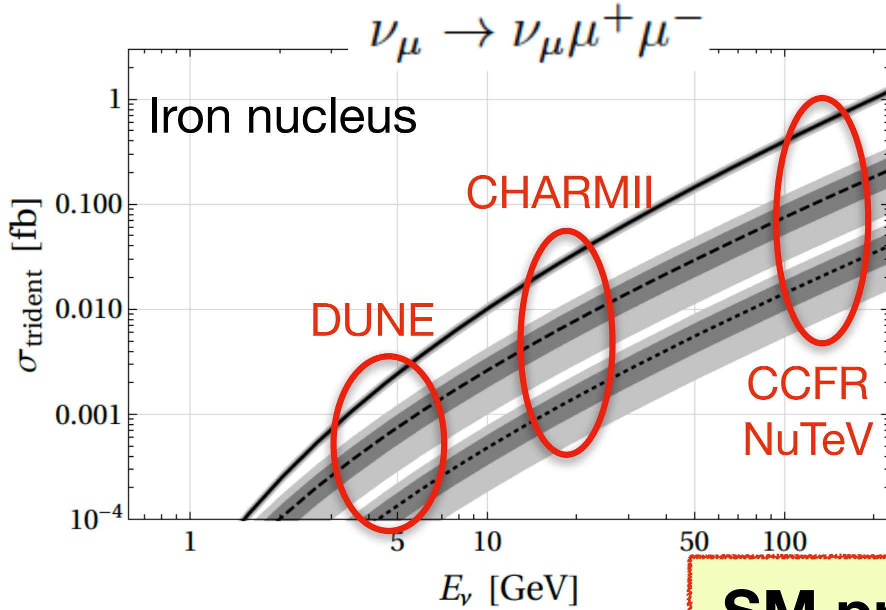


Coherent

Incoherent, proton

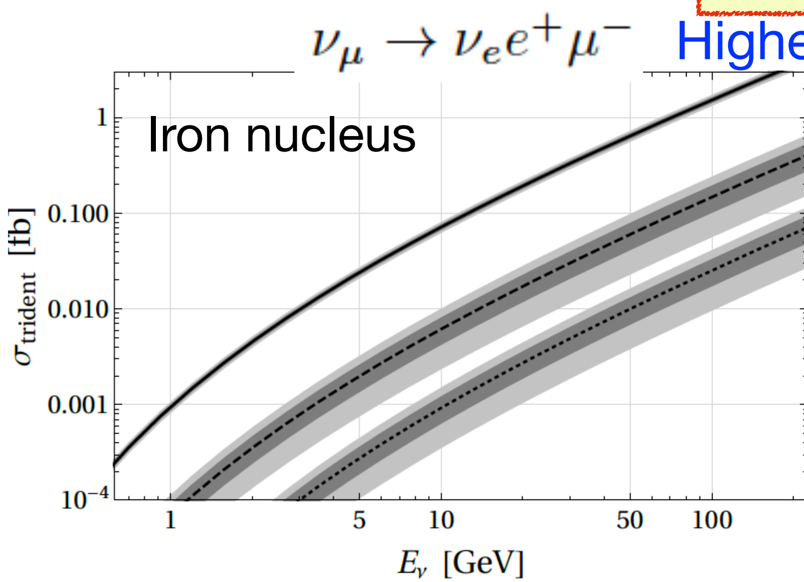
Incoherent, neutron

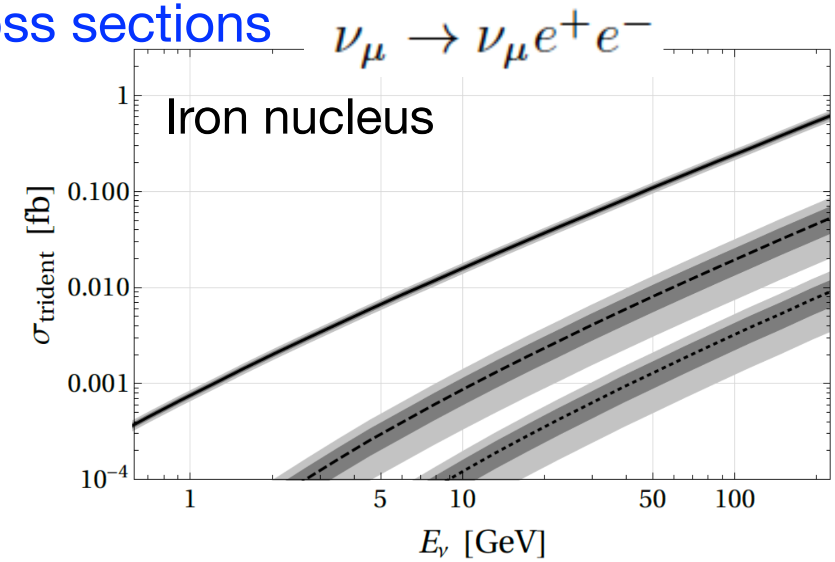
Past experimental results:

$$\sigma_{\text{CHARMII}}/\sigma_{\text{SM}} = 1.58 \pm 0.57\ ,$$
$$\sigma_{\text{CCFR}}/\sigma_{\text{SM}} = 0.82 \pm 0.28\ .$$

SM predictions

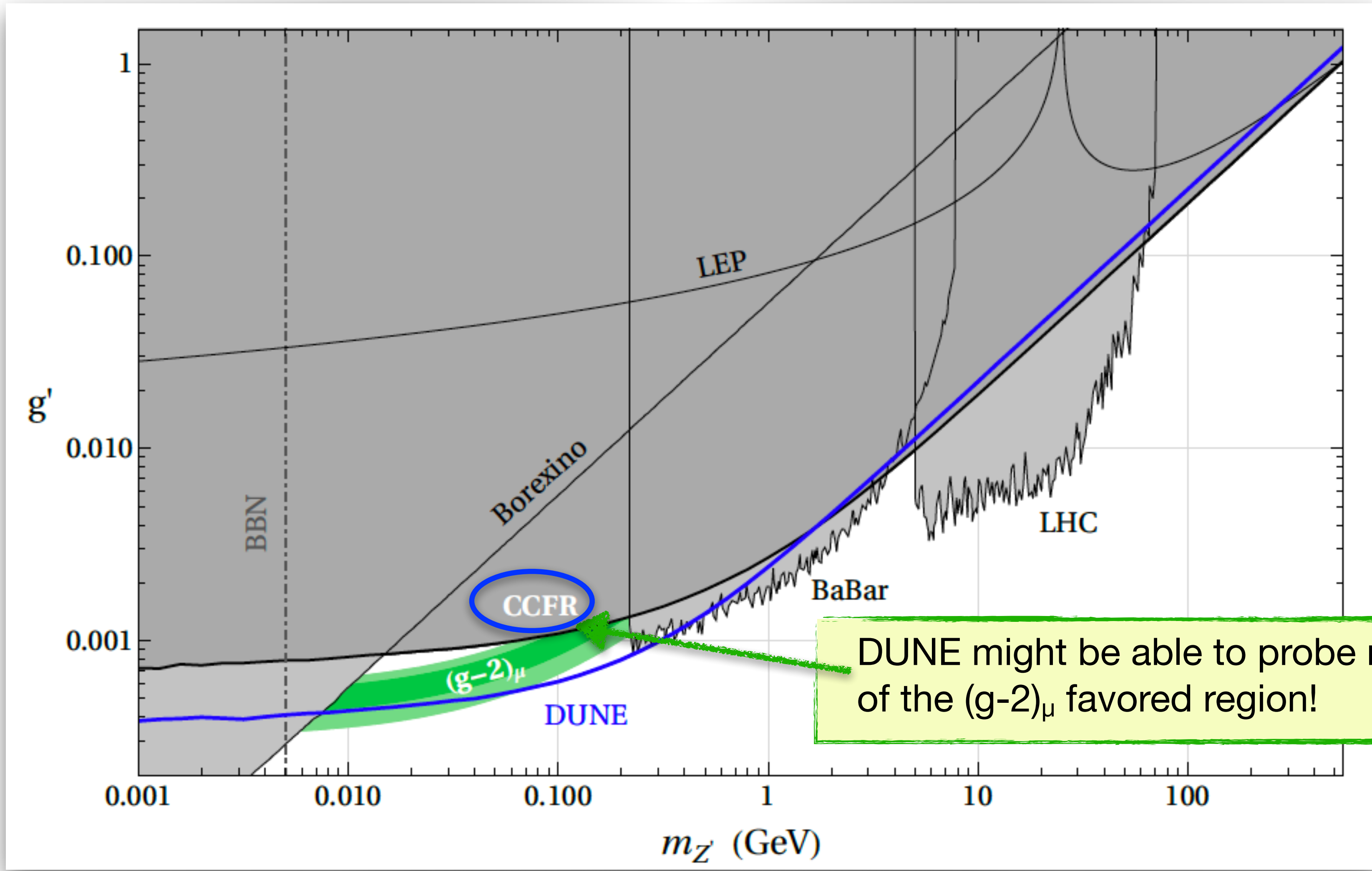
Higher cross sections





Probing new neutrino forces

Z' from gauging L_μ - L_τ



DUNE might be able to probe most of the $(g\text{-}2)_\mu$ favored region!

Altmannshofer, SG, Martin-Albo, Sousa, Wallbank 1902.06765

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**

- Minimal and non-minimal Thermal DM models
- Light New Physics dark particles (e.g. axion-like-particles)

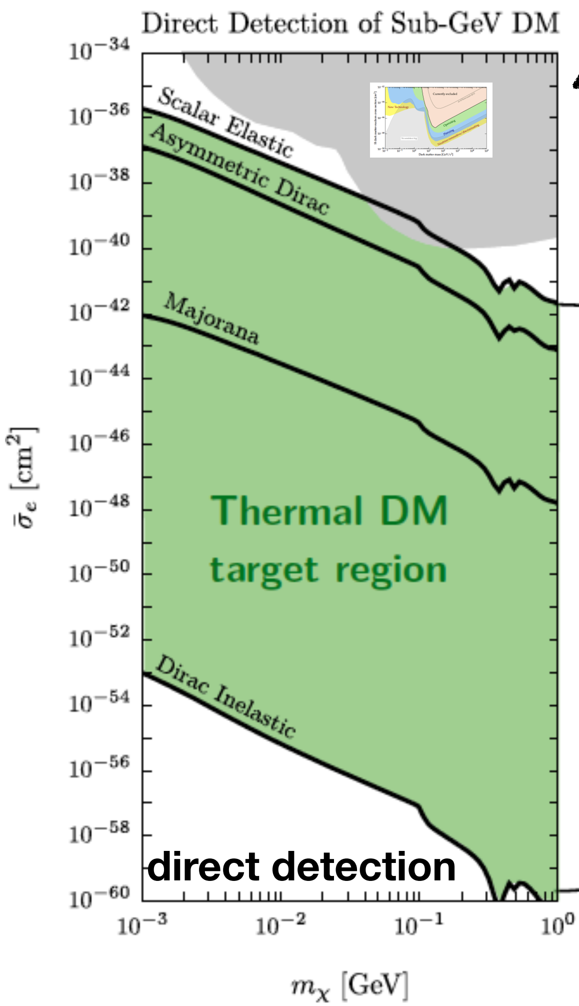
Important complementarity:

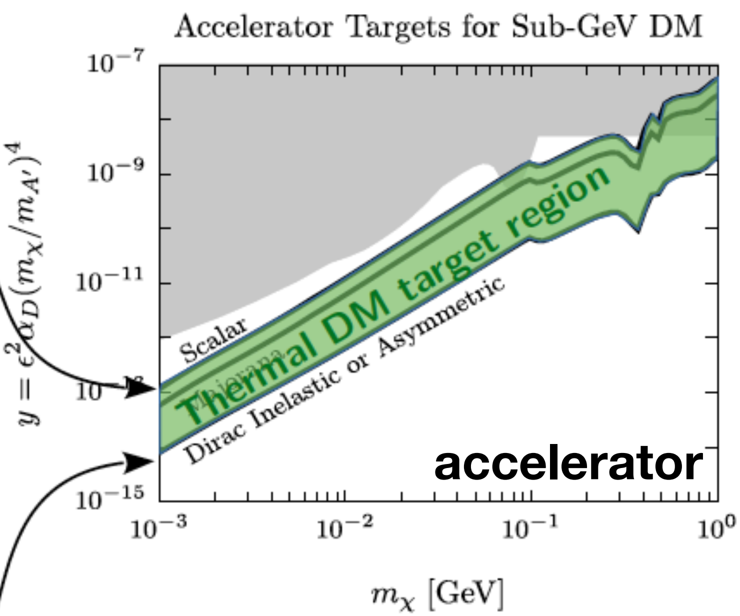
- Flavor factories (pions, Kaons, B-mesons)
- Fixed target experiments
- Neutrino experiments

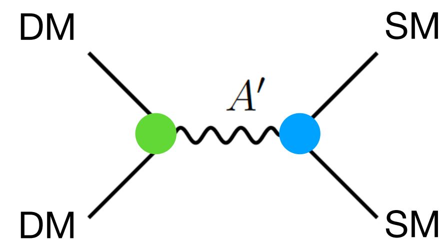
Backup

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

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

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)

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

Additional DM production benchmarks & messages

- $L_\mu - L_\tau$ mediated
- B-3L_τ 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

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

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

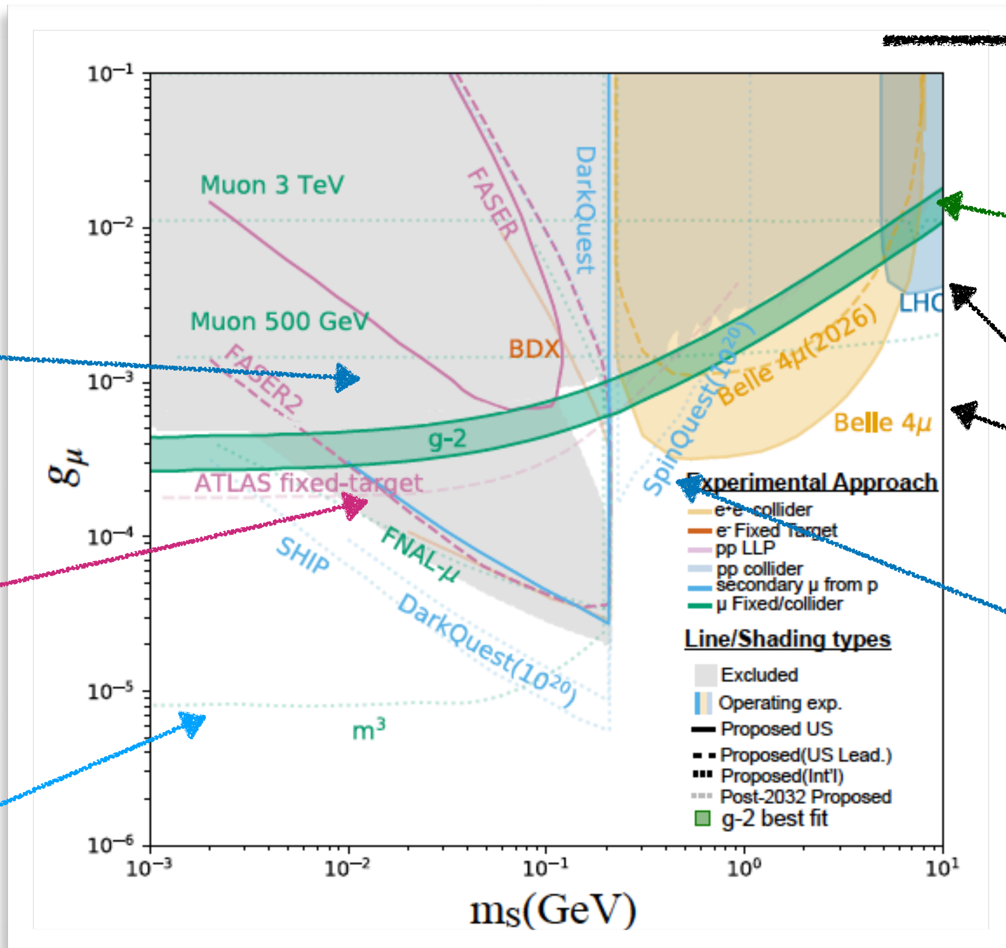
After the last Snowmass, our community was able to probe minimal dark sector models addressing the $(g-2)_\mu$ anomaly.

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

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

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

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.

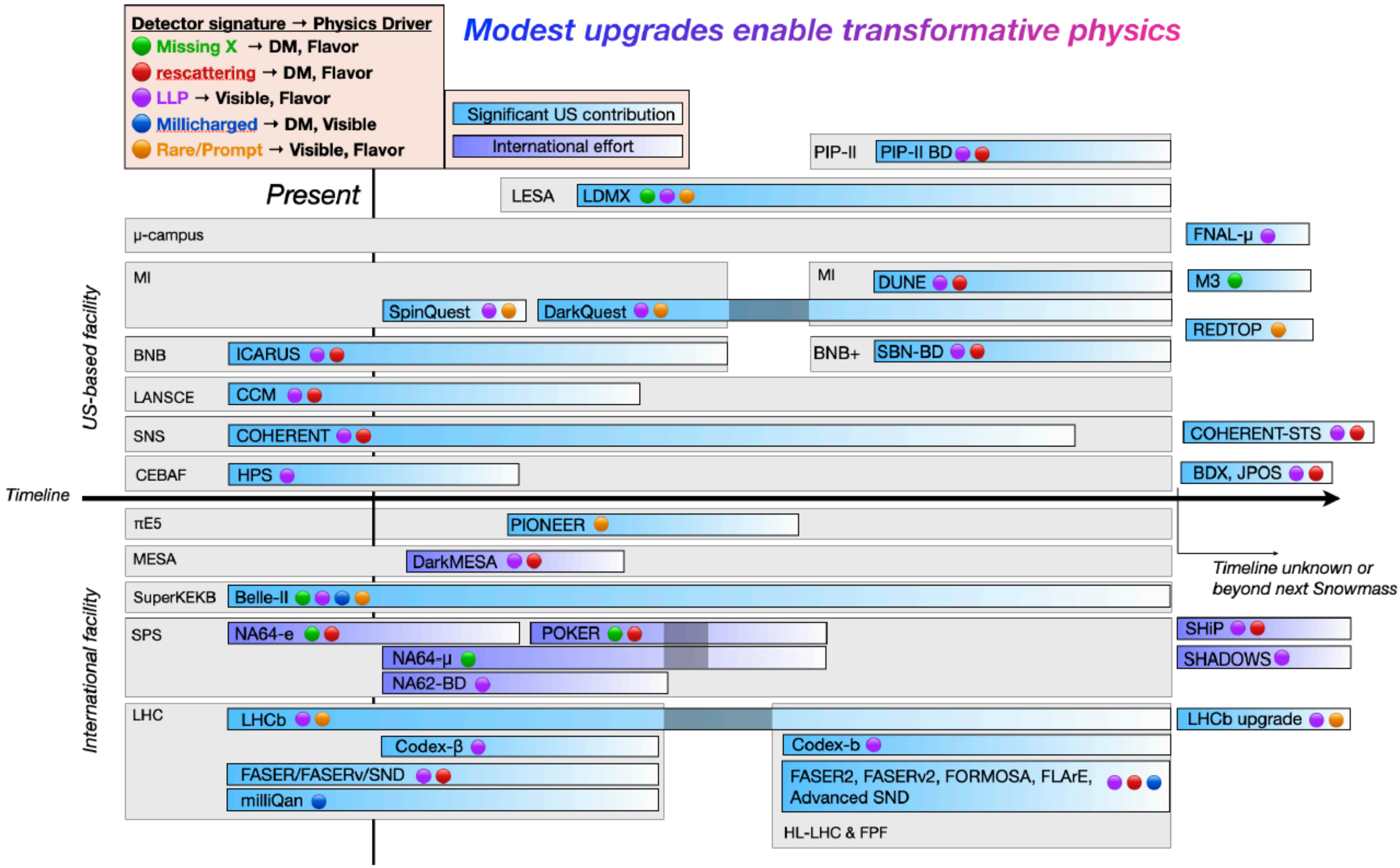
Interplay between prompt and displaced signatures.

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

Messages

Experiments/facilities

Ilten, Tran et al, 2206.04220

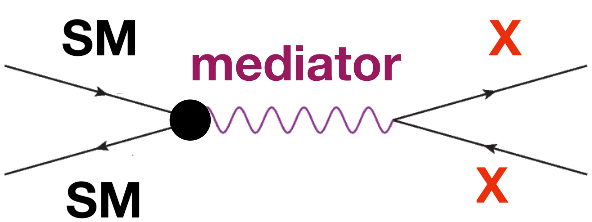


Final states to look for

a. Invisible, non-SM

Dark Matter production

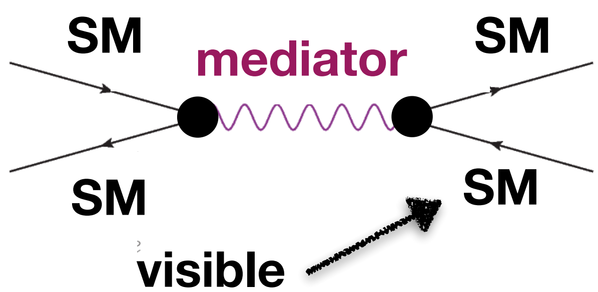
Producing stable particles that could be (all or part of) Dark Matter



b. Visible, SM

Production of portal-mediators that decay to SM particles

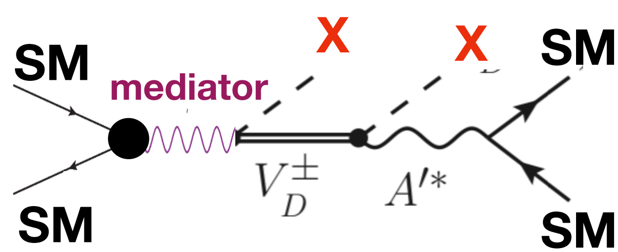
Systematically exploring the portal coupling to SM particles



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

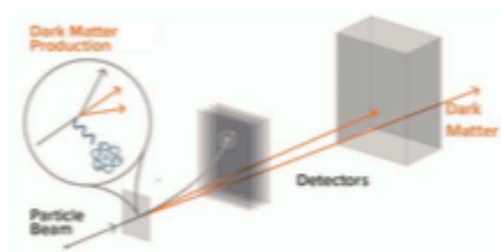
1. **Missing energy/ momentum**
2. **Scattering**
3. **Visible decay products**

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

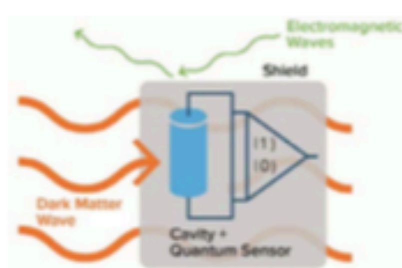


PRD 2

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.

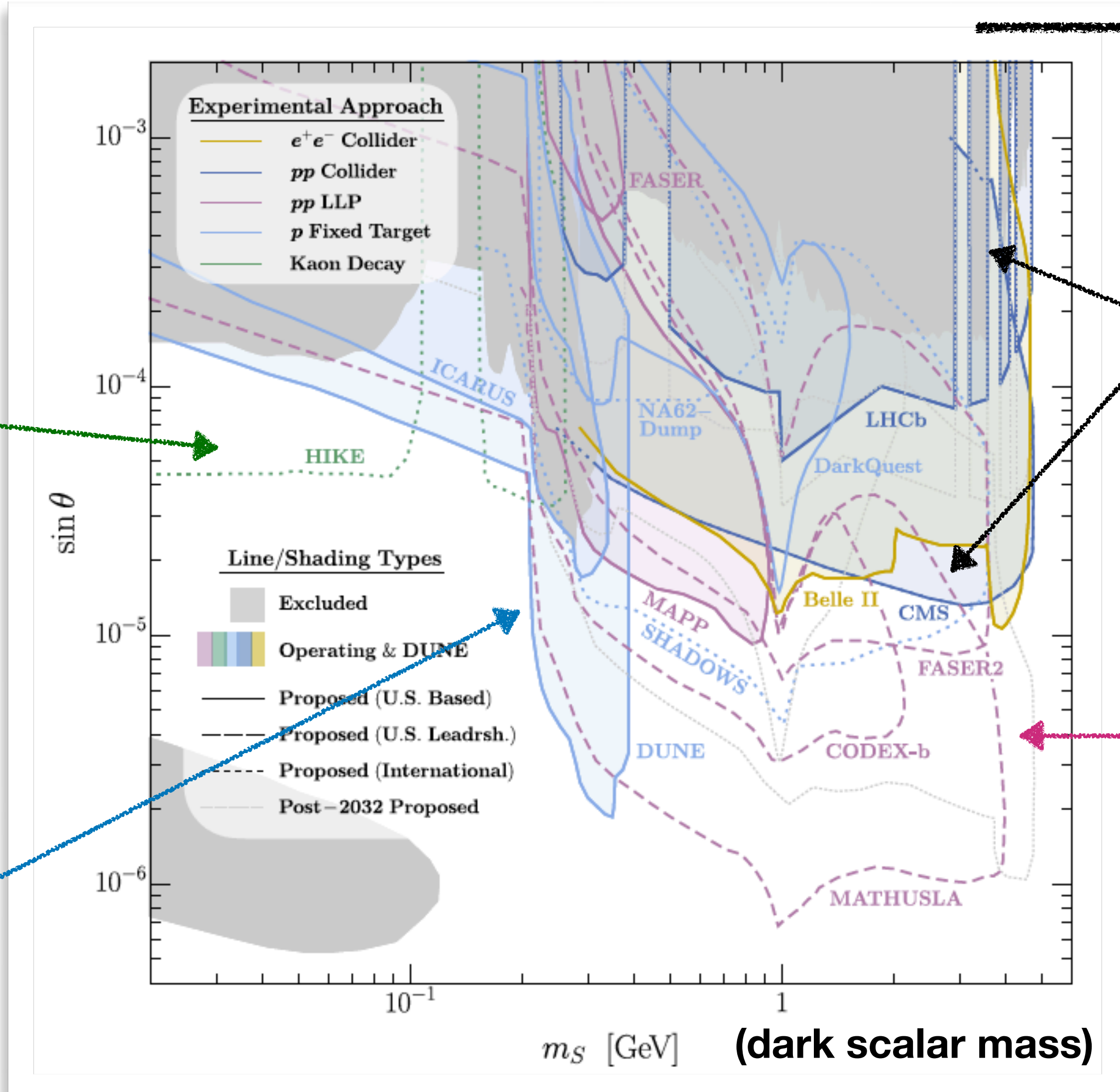
Exploring visible dark scalars

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

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)

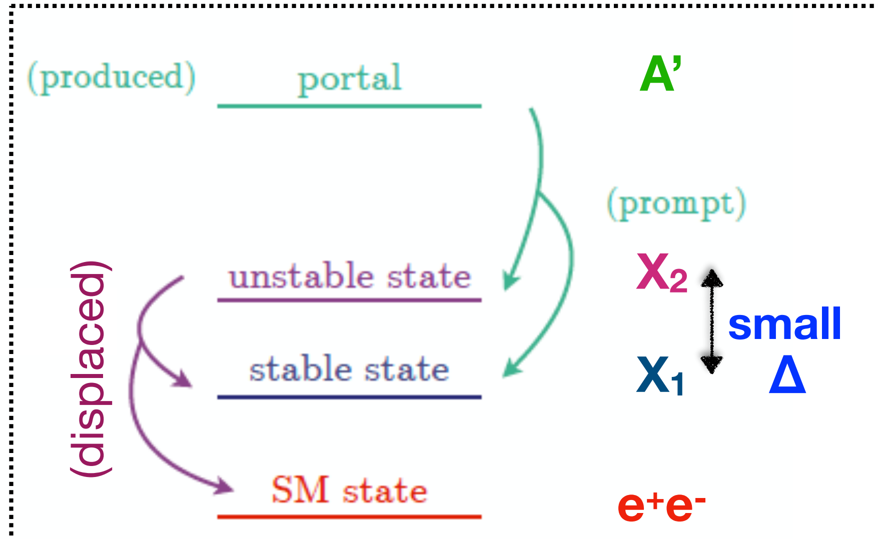
This entire parameter space predicts a **dark sector in thermal equilibrium** with the SM

DM models with metastable particles

Inelastic Dark Matter

Tucker-Smith, Weiner, 0101138

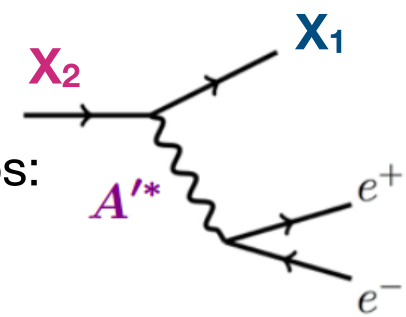
$$\mathcal{L} \supset \frac{i e_D\, m_D}{\sqrt{m_D^2 + (\delta_\xi - \delta_\eta)^2/4}} A'_\mu \left(\bar{\chi}_1 \gamma^\mu \chi_2 - \bar{\chi}_2 \gamma^\mu \chi_1\right)$$



* A non-minimal freeze-out mechanism:

$X_1\, X_2 \to$ SM

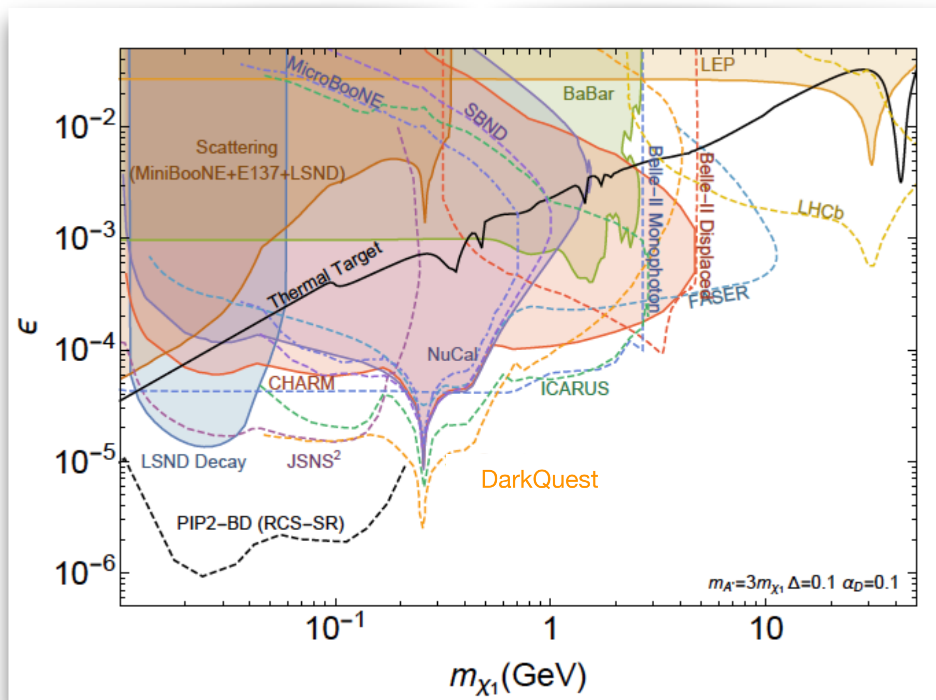
DM **DM excited state**



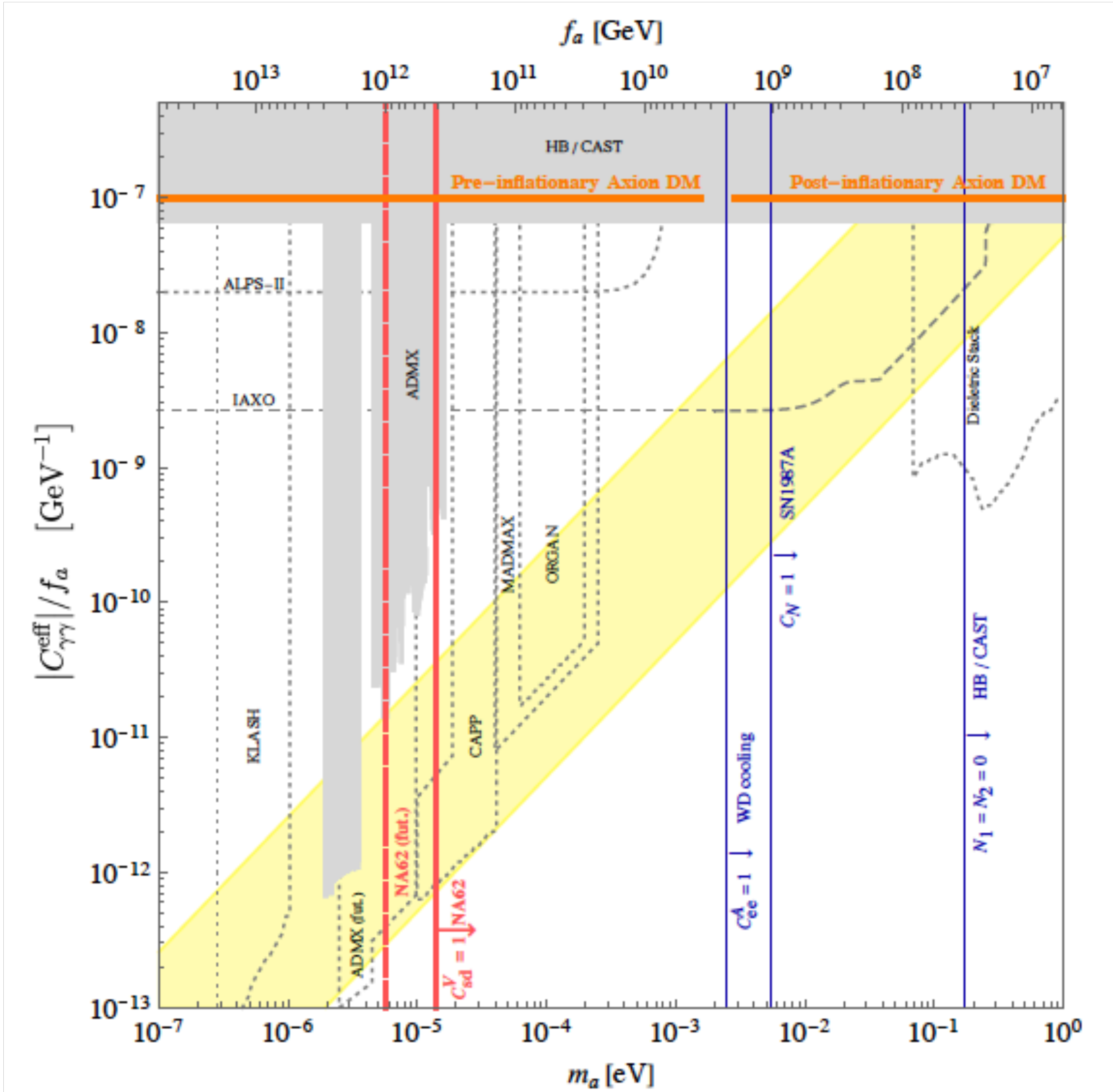
* Signatures in our labs:

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

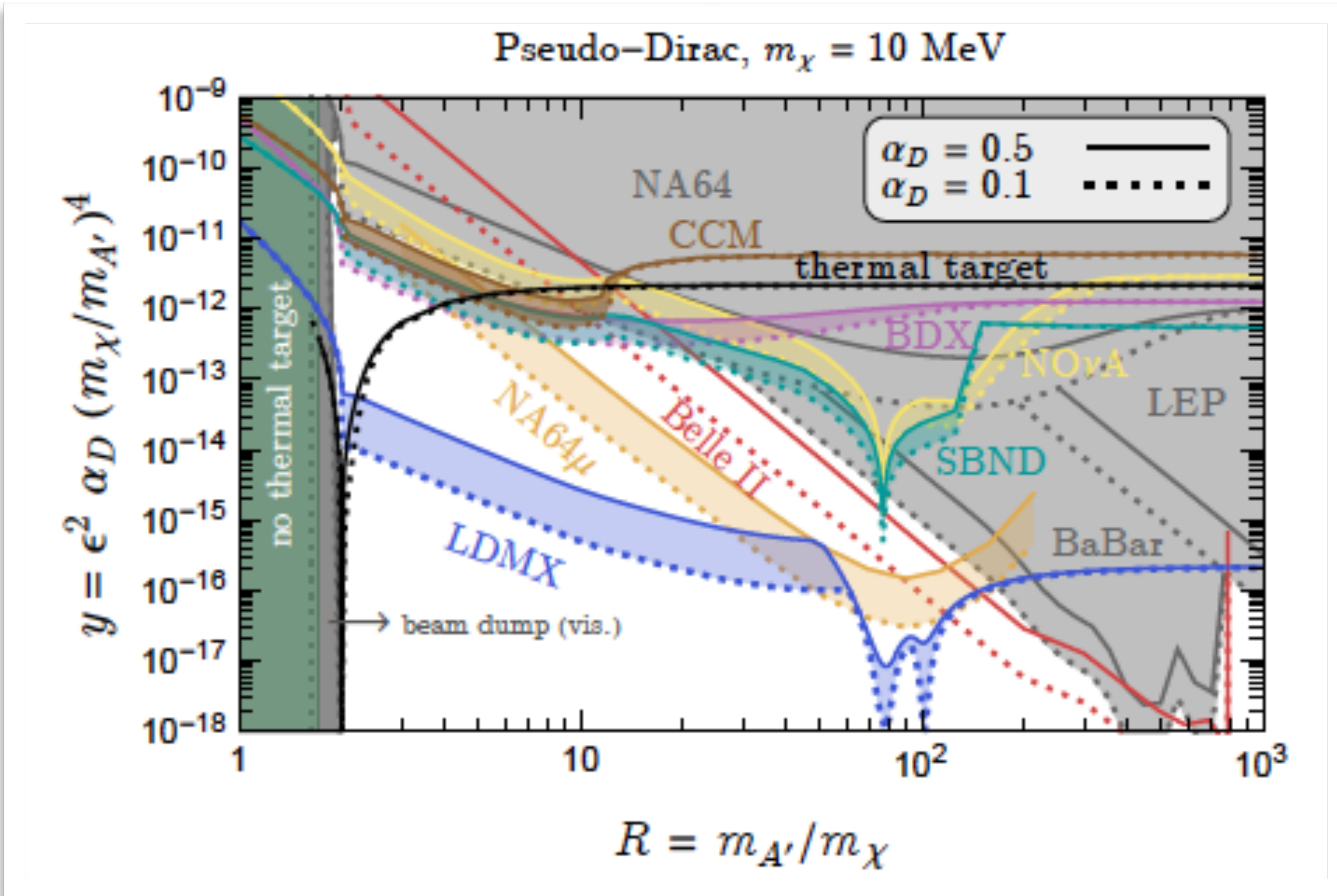
- Prompt visible decays
- Long lived particles
- Invisible component



Flavor violating ALPs



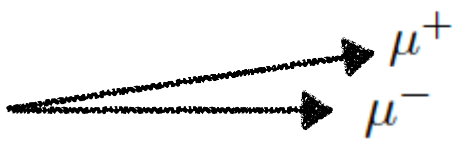
Variations of the invisible dark photon scenario



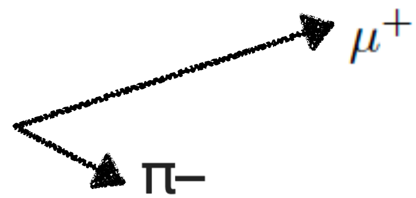
Trident Montecarlo analysis

Starting point: $N_{\rm coherent} \simeq 103.9, \;\; N_{\rm proton} \simeq 39.4, \;\; N_{\rm neutron} \simeq 7.5, \;\; N_{\rm background} \simeq 1.5 \times 10^8$
(optimized beam)
per year

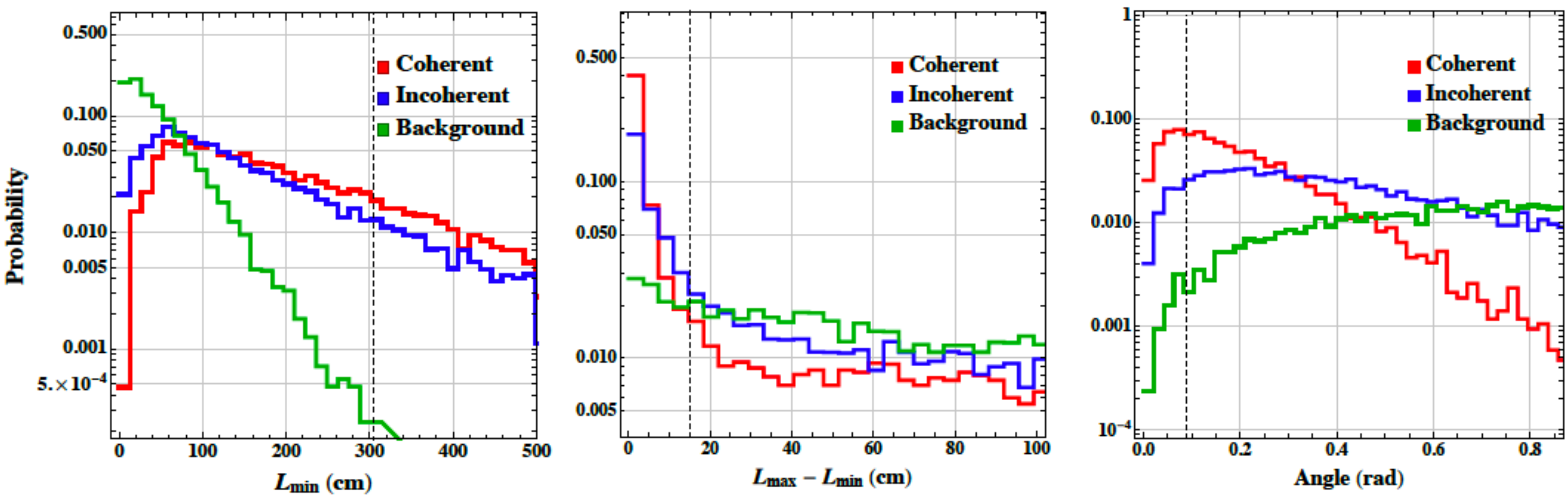
Signal:



Background:



We ask for 2 and only 2 tracks and we optimize the cuts on the following variables:



simulated with the official DUNE Geant 4-based simulation

We also ask for:
small energy deposited in the first 10 cm from the neutrino interaction vertex