Dark sectors at accelerator experiments

Stefania Gori
UC Santa Cruz

Baryon and Lepton Number Violation (**BLV2019**) workshop

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Introduction

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Does it interact with us (with the Standard Model (SM) of particle physics)?

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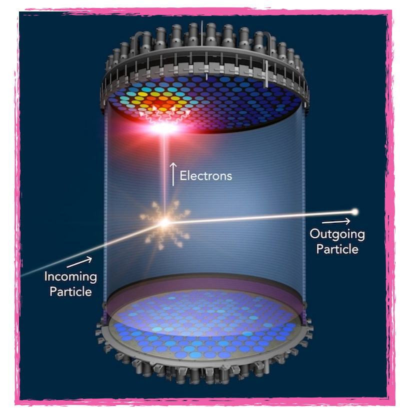
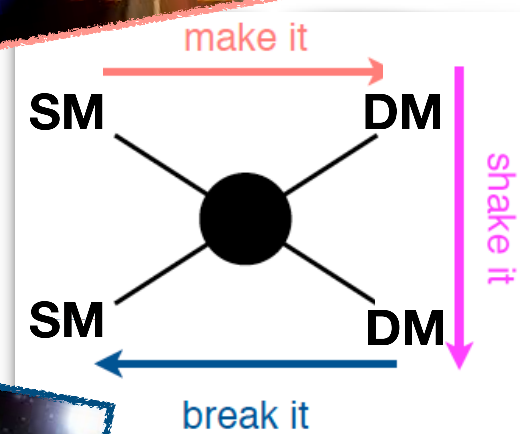
Collider searches

talk by V. Sharma

Direct detection



talk by J. R. Monroe



Astrophysical probes

talk by P. Serpico

Introduction

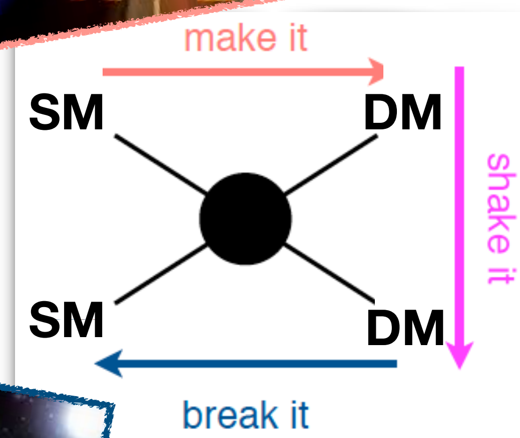
What is Dark Matter (DM)?
Does it interact with us (with the Standard Model (SM) of particle physics)?

For this talk:

- DM models to test @ the LHC & beyond.
- Invisible & visible signatures.

Collider searches

talk by V. Sharma



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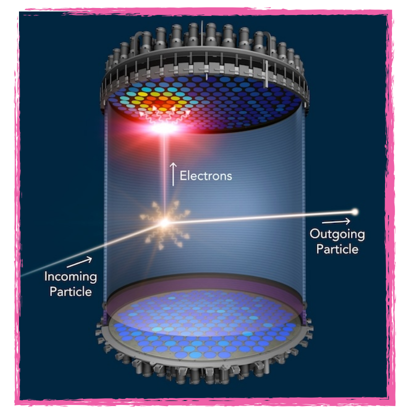

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Astrophysical probes

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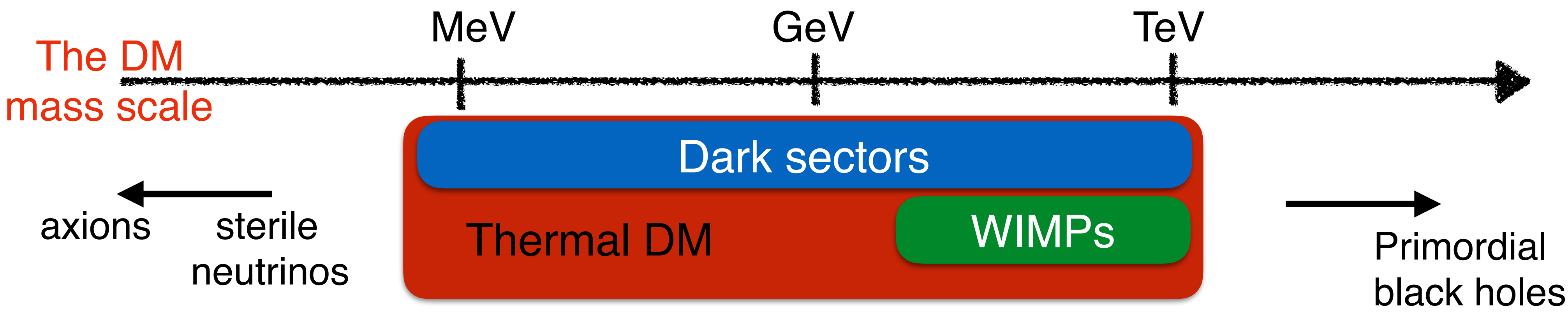
Thermal dark matter



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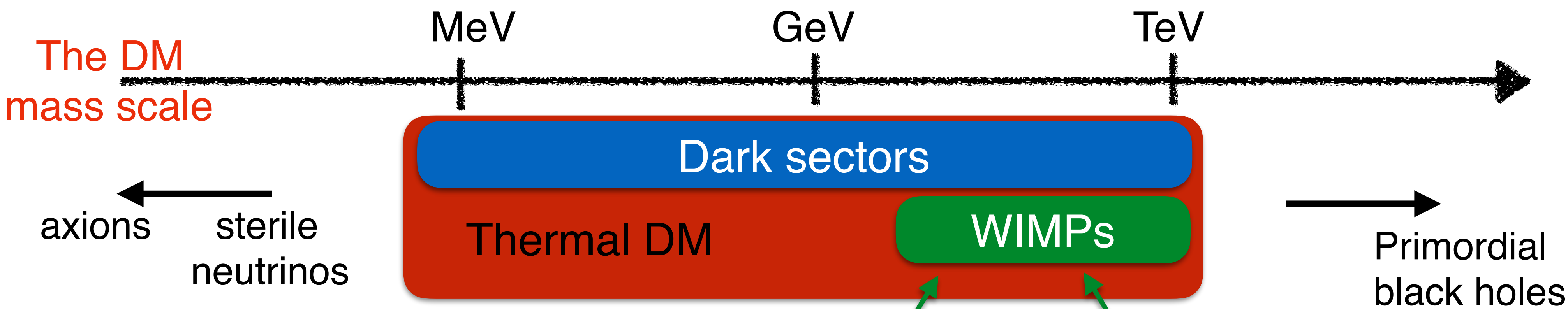
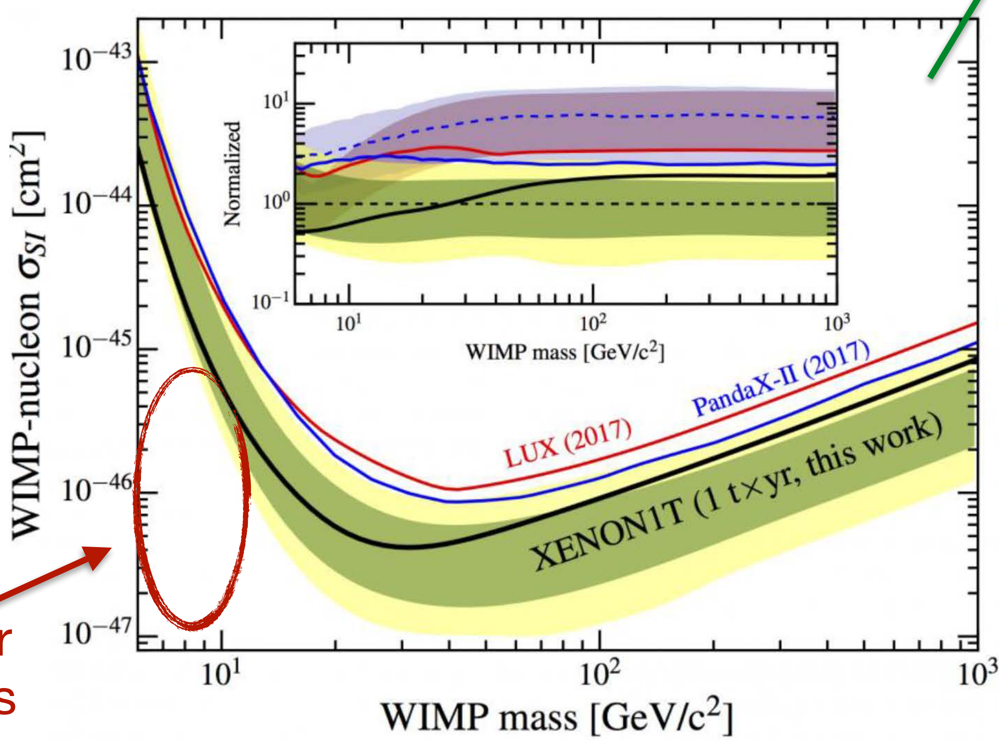
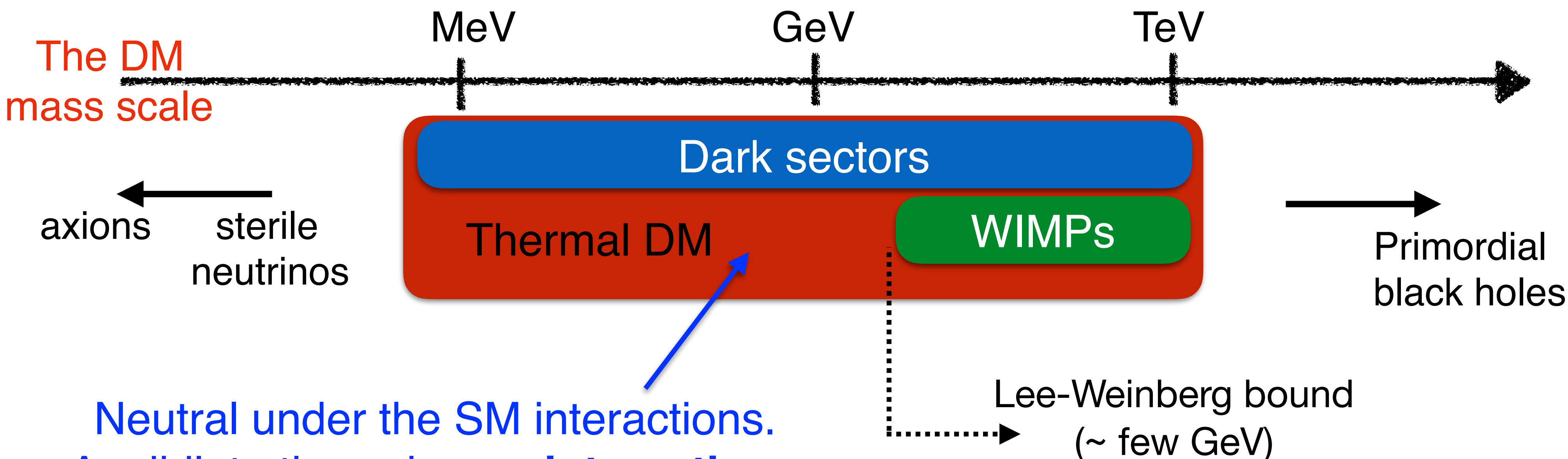




Annihilate through **weak interactions**

weaker bounds

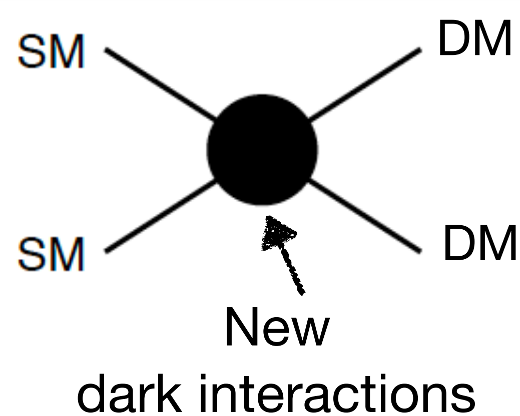
Thermal dark matter



Neutral under the SM interactions.
Annihilate through **new interactions**

Need for new particles in addition to DM

dark sector



Dark sectors beyond Dark Matter

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

Dark sectors beyond Dark Matter

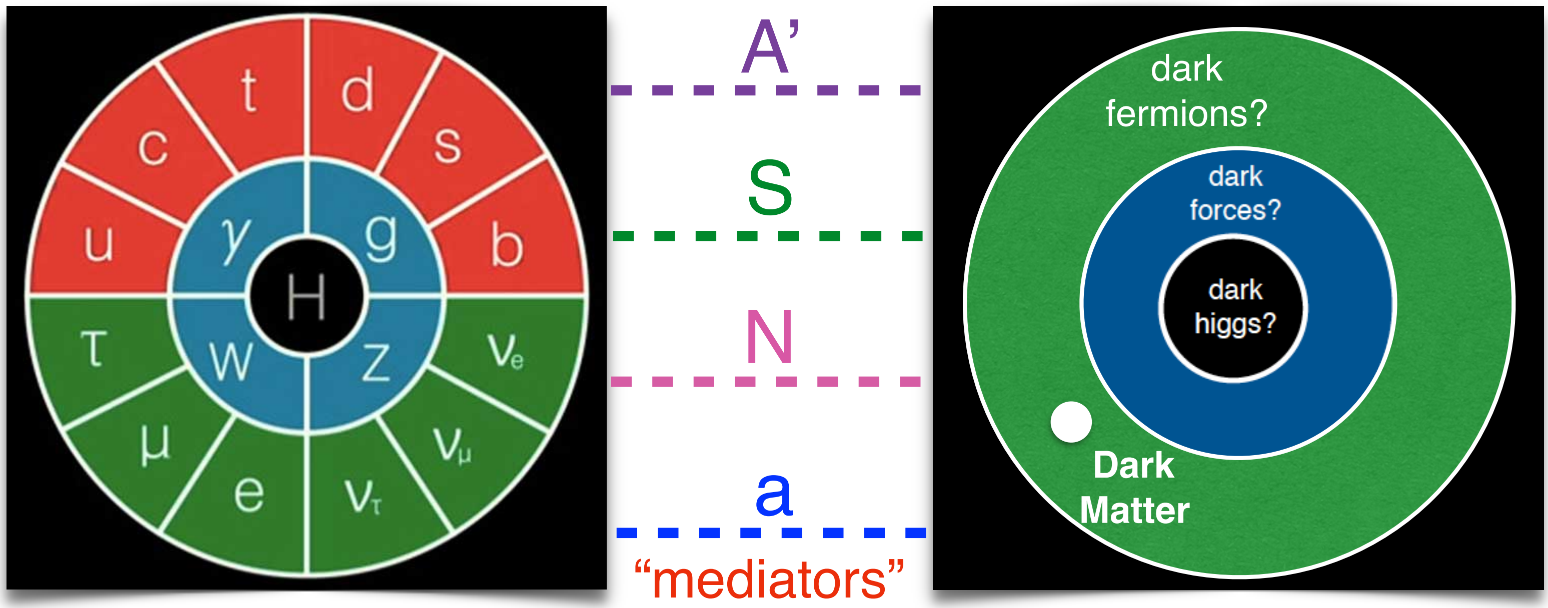
Beyond the DM motivation, many other open problems in particle physics let us think about dark particles.

- 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.

How to have access to the dark sector?



Only a few interactions exist that are allowed by Standard Model symmetries:

Opportunity of testing light dark matter through its interactions with the mediator (that interacts with the SM)

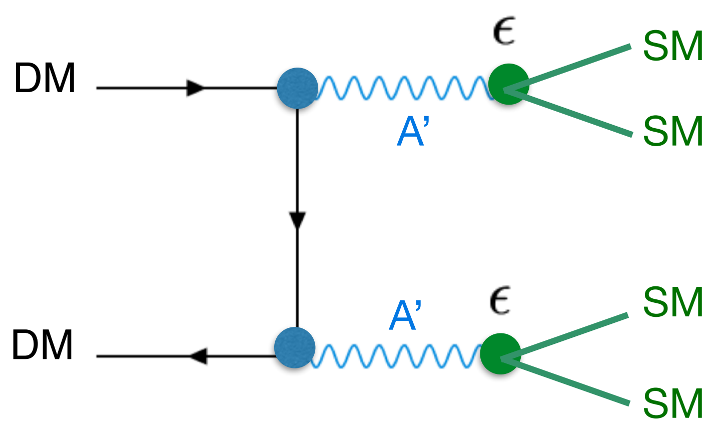
"mediators"	"portal interactions"
Dark photon	$\epsilon B^{\mu\nu} A'_{\mu\nu}$
Higgs	$\kappa \lvert H\rvert^2 \lvert S\rvert^2$
Neutrino	$y H L N$
Axion	$g_{a\gamma} a \tilde{F}_{\mu\nu} F^{\mu\nu}$

Several classes of thermal DM models

1. **The mediator is the lightest state of the dark sector**

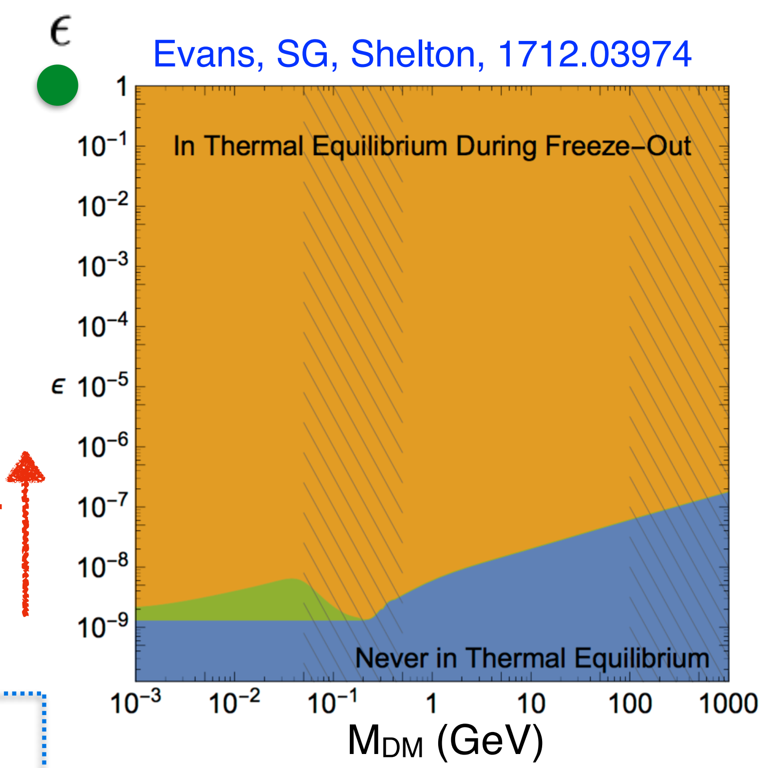
("secluded" case)

Pospelov, Ritz, Voloshin, 0711.4866



Thermalization regulated by

Evans, SG, Shelton, 1712.03974



Lower bound

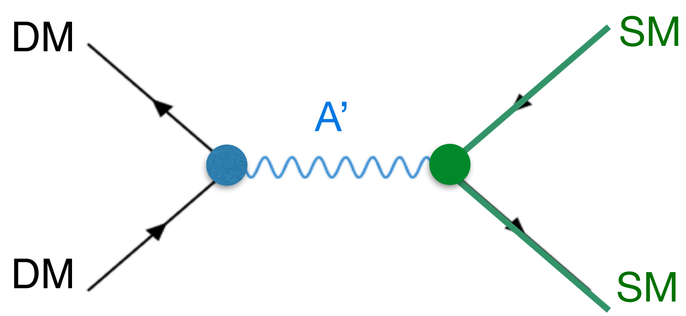
The mediator (A') decays back to the SM particles (**visible decays**)

Several classes of "thermal" DM models

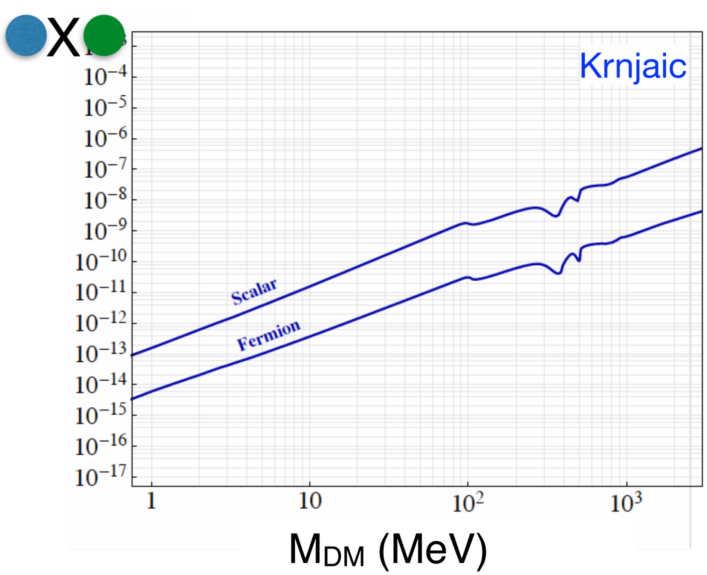
2.

The mediator is the heavier than some other state of the dark sector

2.1. $m_{A'} > m_{DM}$



The mediator (A') decays to DM particles (**invisible decays**)



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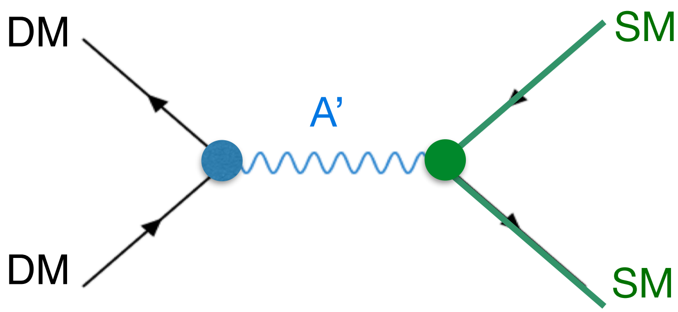
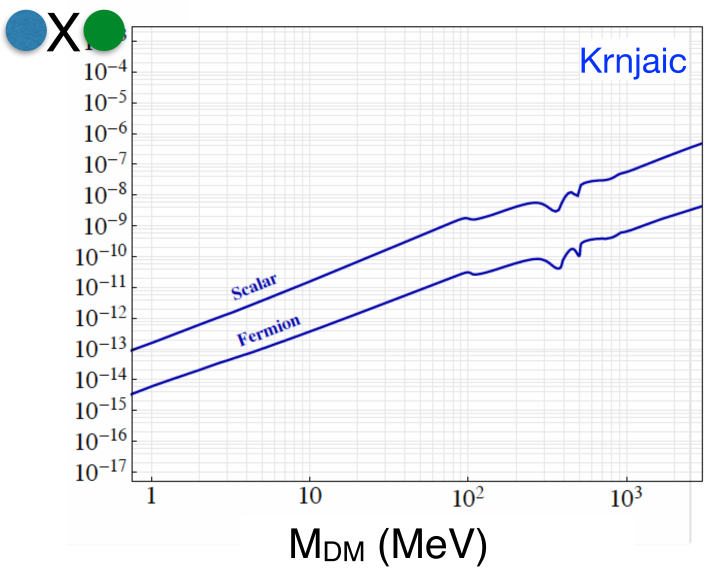
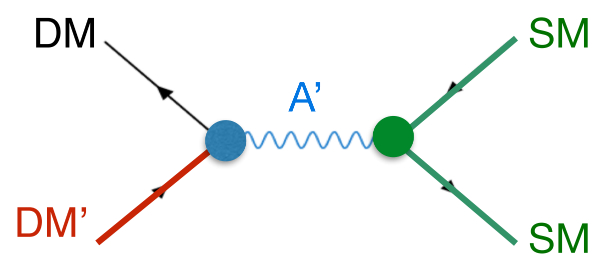




2.2. $m_{A'} > m_{DM'} > m_{DM}$

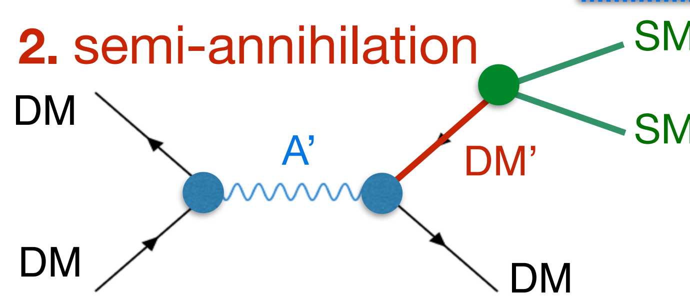
Several interesting models:

1. co-annihilation



The mediator (A') decays to DM + SM particles (**visible+invisible decays**)

2. semi-annihilation

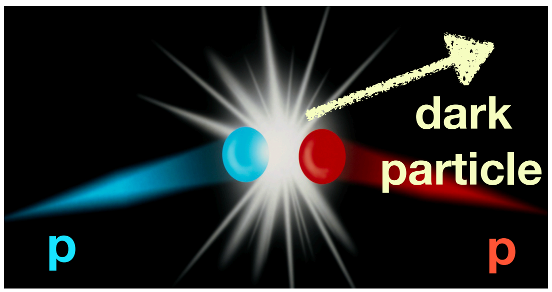


In all cases, the relic abundance is regulated by ●, ●

A broad program of searches

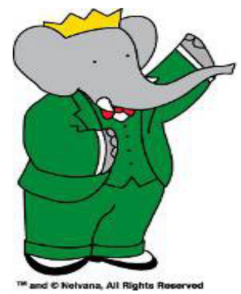
… of light (< 10 GeV) dark-sector particles

The LHC



Novel search strategies are needed!

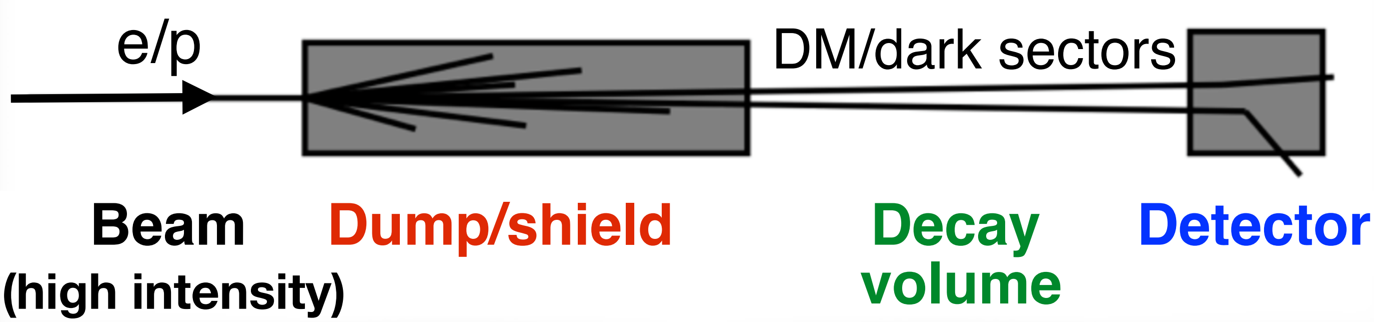
B-factories



Unique access to dark sectors!

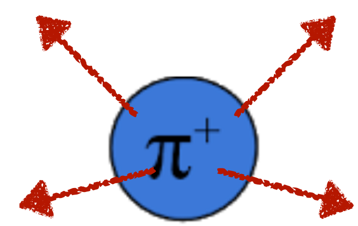
high energy

Fixed target / neutrino experiments



Precision light flavor experiments

Example:



Search techniques for visible dark sectors

At the LHC, the search for light resonances can be challenging (triggers, background level, particle id.) → Needs for specific strategies!

Searches for:

- 125 GeV **Higgs exotic decays**. Example: $h \to ss$, $s \to ff$ thanks to $\kappa|H|^2|S|^2$
- Light resonances (di-muons, …). Crucial role covered by **LHCb**
- **Boosted objects** (resonance production + jet)

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Many visible dark particles can be produced and detected at B-factories

- "Direct" production. Example: $e^+e^- \to \gamma A'$, $A' \to$ mu mu
- B meson decays. Example: B → K s, s → mu mu
- Upsilon decays. Example: Y → γs, s → tau tau

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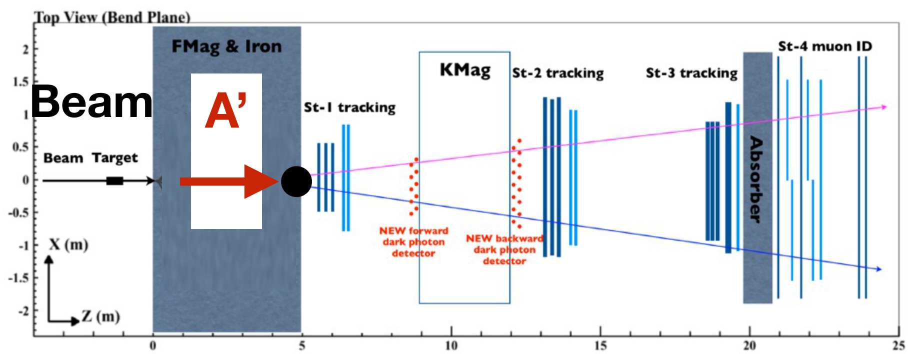
Fixed target - beam dump experiments can search for long-lived visible dark particles

Example:
SeaQuest experiment
@ Fermilab



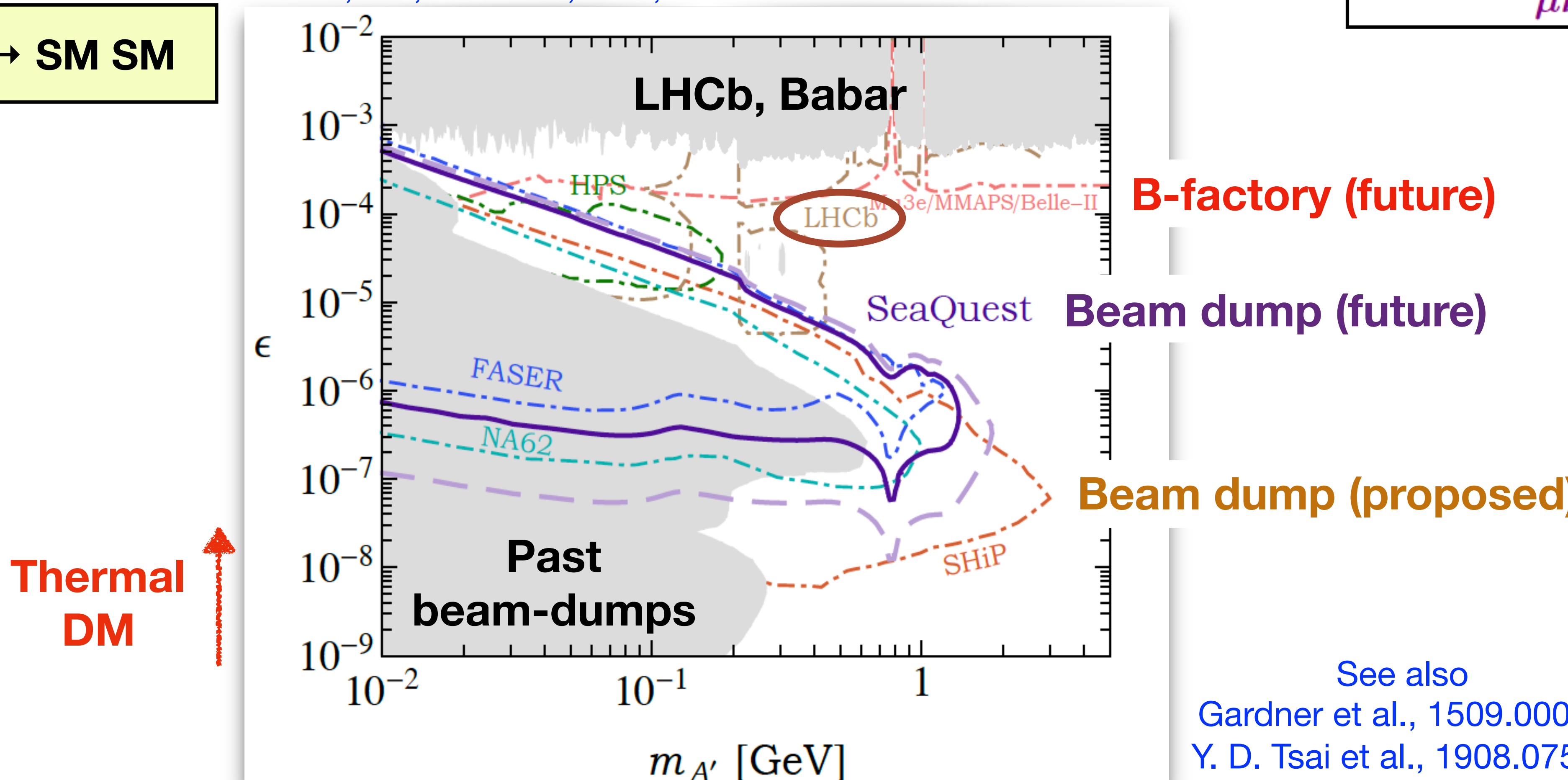
Reach on visible dark sectors

A large part of the thermal dark photon parameter space is probed or will be probed in the coming years.

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

A' → SM SM

Berlin, SG, Schuster, Toro, 1804.00661



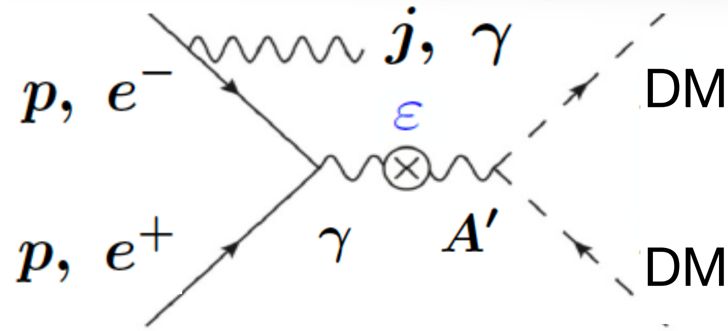
See also
Gardner et al., 1509.00050
Y. D. Tsai et al., 1908.07525

Search techniques for invisible dark sectors

* Mono-X searches at high energy colliders

mono-jet at the LHC

mono-photon at Babar/Belle(II)



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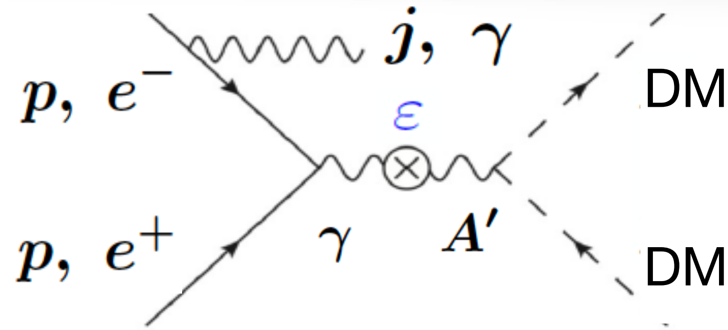
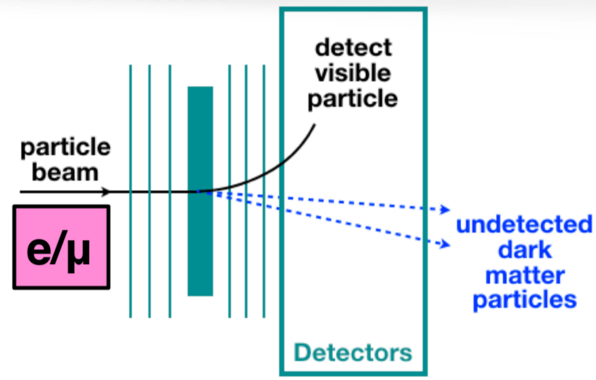


* Missing mass/energy measurements at electron (muon) fixed target experiments (e.g. NA64)



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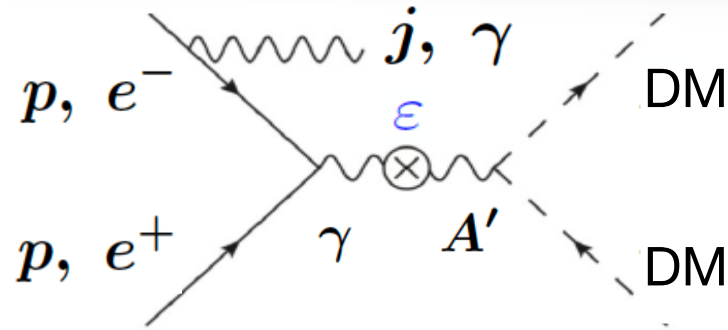

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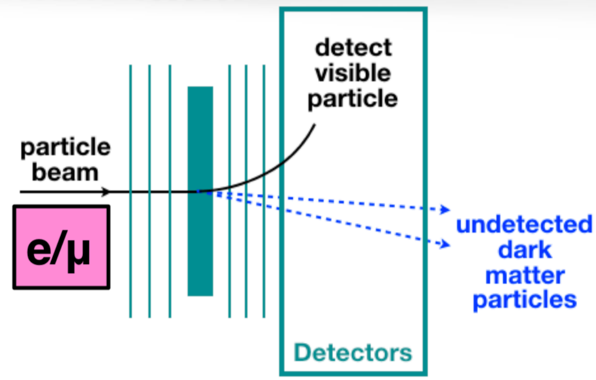
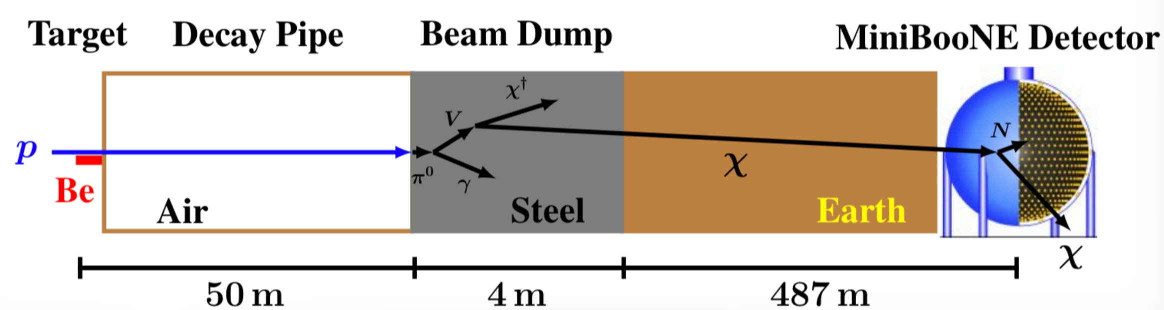


✱ Search for DM scattering in the detector of neutrino experiments (e.g. MiniBooNE)



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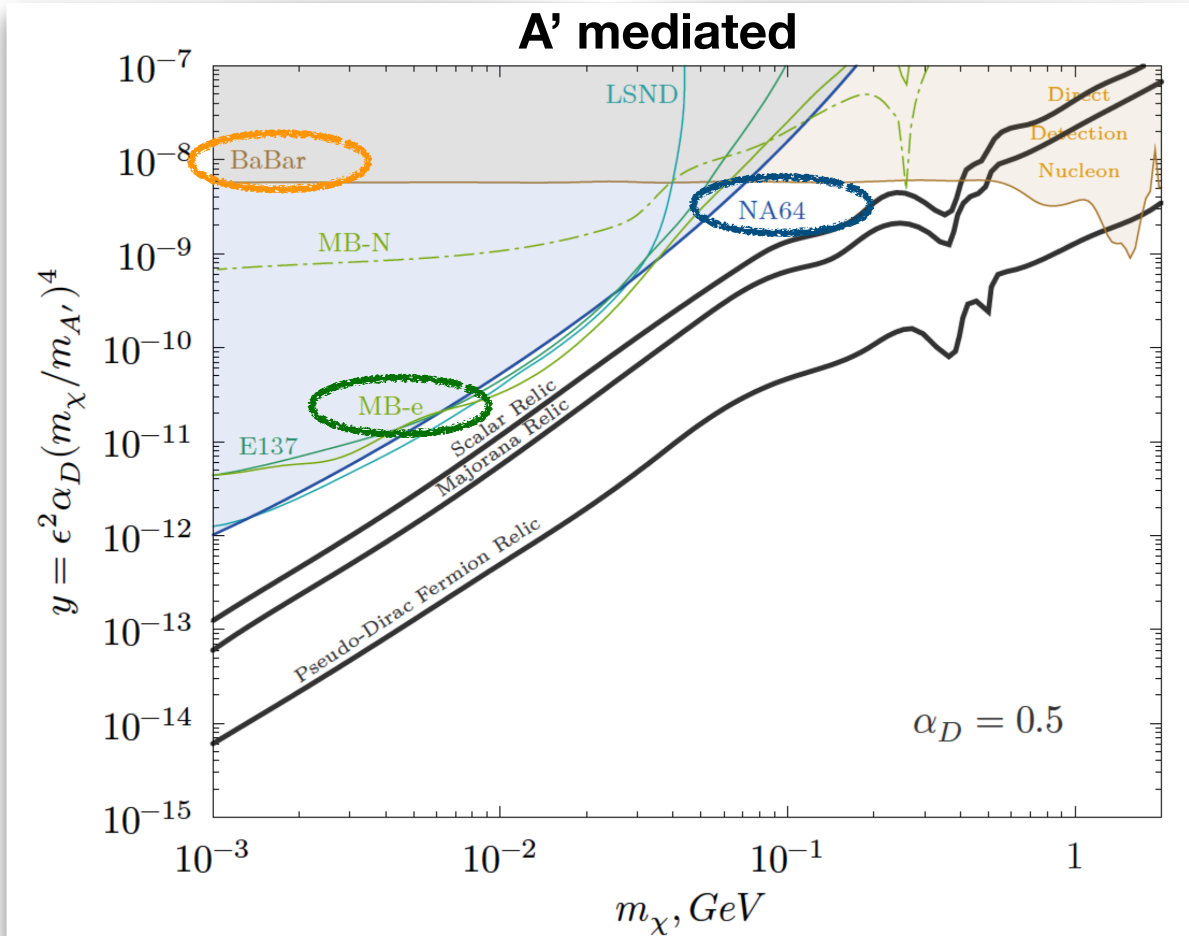
NA64 collaboration, 1906.00176



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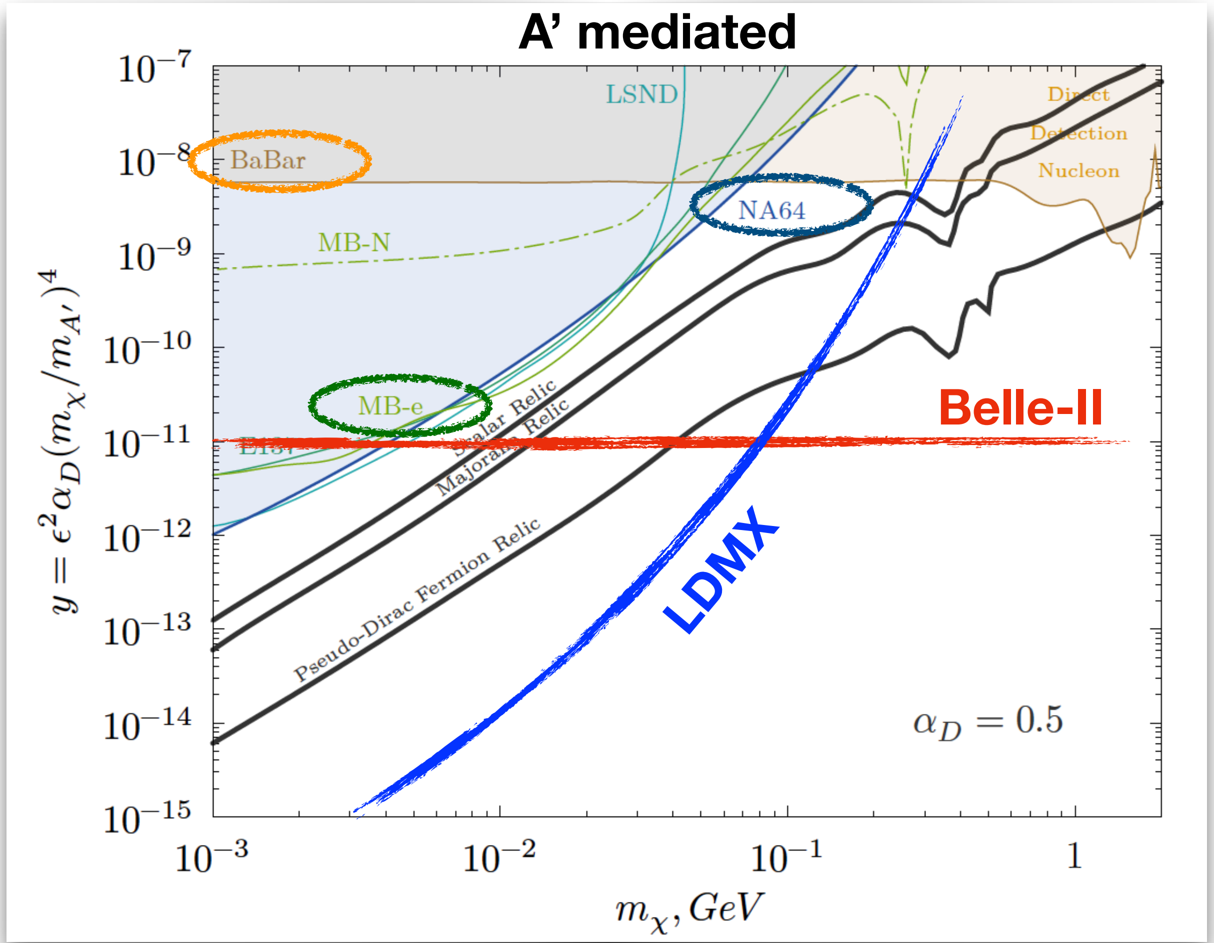

Future experiments will probe broader regions of parameter space:
Belle-II Kou et al.,1808.10567, LDMX (proposed) Akesson et al., 1808.05219

Richer dark sectors

Beyond minimal dark sector models, one can search for a variety of light DM models where DM is only one of the many components of the dark sector.

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Let us mention an example:

Hochberg, Kuflik, Volansky, Wacker, 1402.5143,

Strongly-Interacting-Massive-Particle (SIMP)

Measured relic abundance achieved via a 3 → 2 process

dark pions, mesons, ...

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

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

Light pions

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

The lightest dark pion can be a DM candidate.

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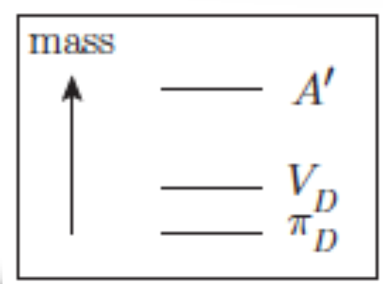
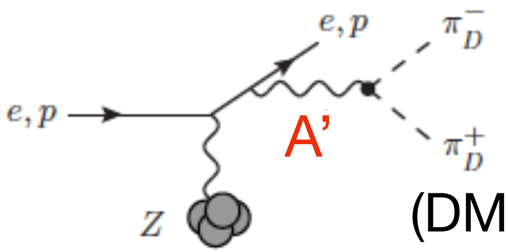
The lightest dark pion can be a DM candidate.

The cosmology and the phenomenology of the model will depend on the rest of the dark spectrum (and not only on the mediator)



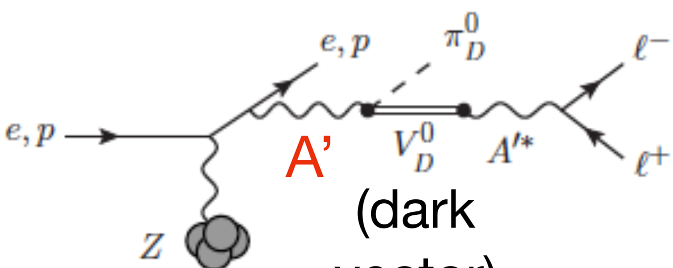
Berlin, Blinov, SG, Schuster, Toro, 1801.05805

Searching for SIMPs



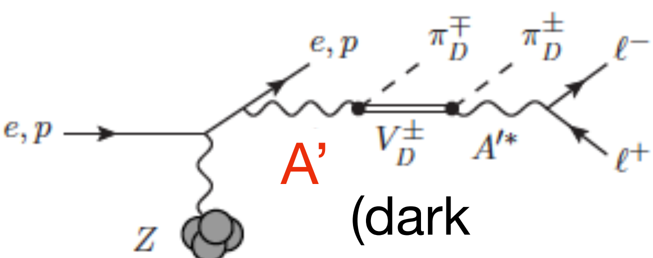
invisible

(DM)



(dark vector)

“semi”-visible



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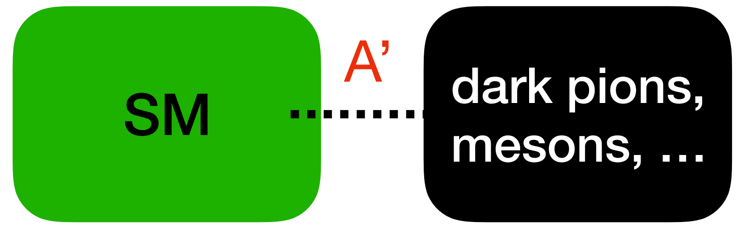

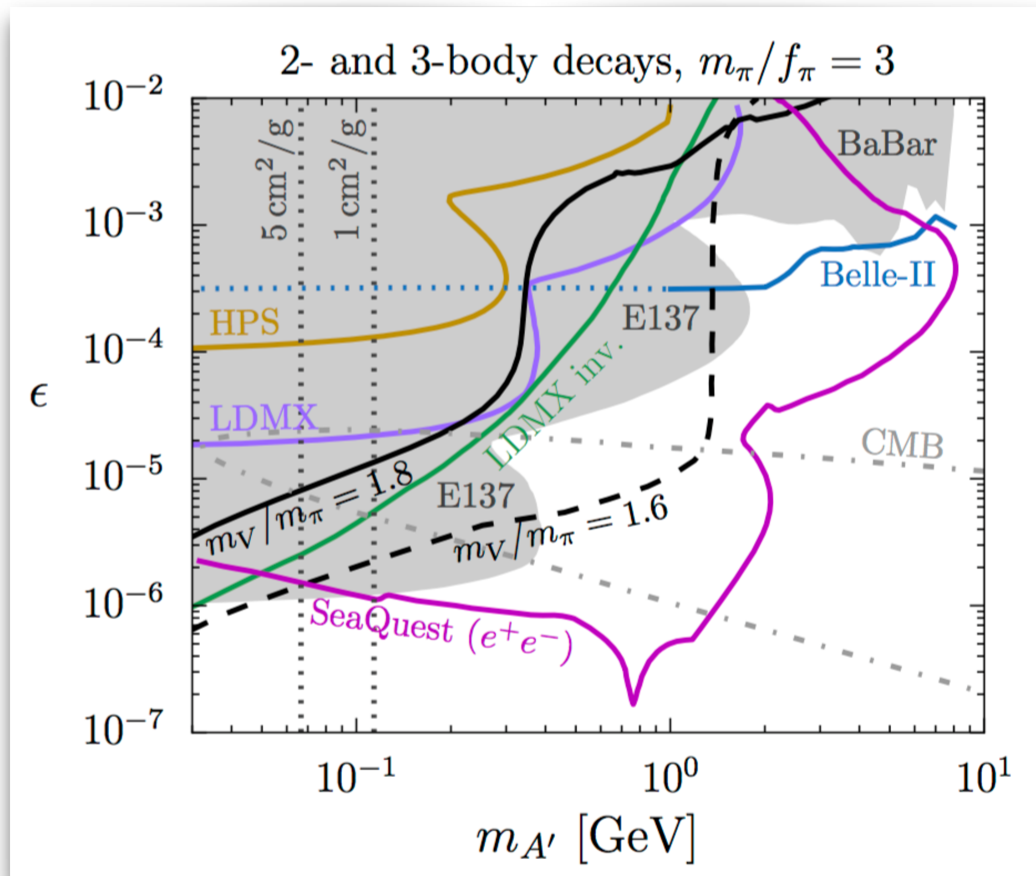

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What about axion-like-particles?

We can do a similar analysis for ALPs exploiting the axion-portal, $g_{a\gamma} a \tilde{F}_{\mu\nu} F^{\mu\nu}$

Are there additional opportunities?

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We can do a similar analysis for ALPs exploiting the axion-portal, $g_{a\gamma} a \tilde{F}_{\mu\nu} F^{\mu\nu}$
Are there additional opportunities?

ALPs will mix with light hadrons with the right quantum and CP properties…
They will mix with neutral SM pions (π^0)!

$$\varepsilon\, \partial_\mu a\, \partial^\mu \pi^0$$

The nature of the mixing will depend on the UV theory:

Examples:

gluon coupling: $C_{ag} a G^b_{\mu\nu} \tilde{G}^{b,\mu\nu}$ $\Rightarrow$ $\varepsilon \sim \frac{f_\pi}{\alpha_s} c_{ag} \frac{m_d - m_u}{m_d + m_u}$

fermion coupling: $c_{ff} \partial^\mu a \bar{f} \gamma_\mu \gamma_5 f$ $\Rightarrow$ $\varepsilon \sim f_\pi (c_{uu} - c_{dd})$

Production of ALPs through their mixing with pions?
Can we use pion experiments for this purpose?

$$|a^{\text{phys}}\rangle = (\cos\vartheta + \ldots)|a_0\rangle + \sin\vartheta\, |\pi^0\rangle + \ldots$$

Mixing with heavier hadrons

Precision pion experiments

Several (past and present) small-scale experiments have been built to accurately measure π^+ rare decays

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1. $\boxed{\pi^+ \to e^+ \nu}$

$$\mathrm{BR} \sim \frac{m_e^2}{m_\mu^2} \frac{(m_\pi^2 - m_e^2)^2}{(m_\pi^2 - m_\mu^2)^2}$$

Helicity suppressed decay

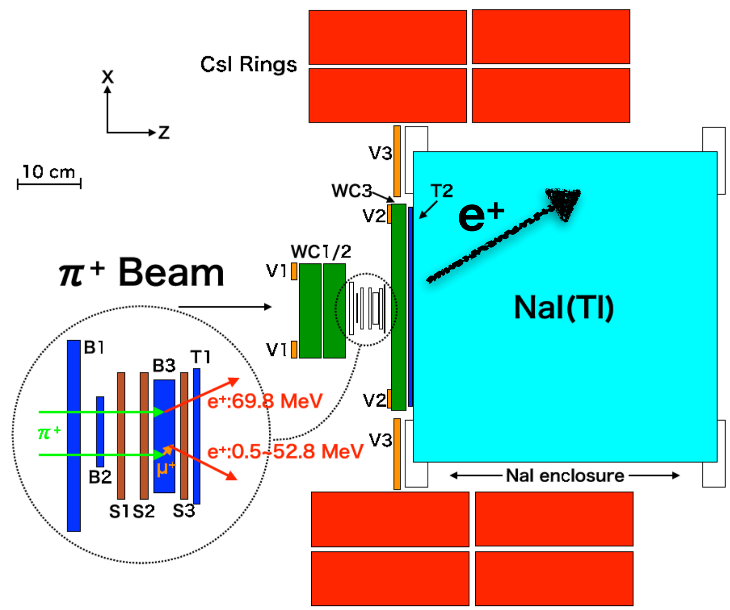
Most precise measurement:
PIENU experiment @ TRIUMF

$$\mathrm{BR}^{\mathrm{exp}} = (1.234 \pm 0.004) \times 10^{-4}$$

Mainly stat. uncertainty

Theoretical uncertainty
~1 order of magnitude smaller!

Pion decay at rest.



Courtesy of D.Bryman

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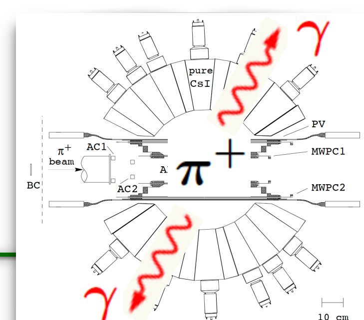
$$\mathrm{BR} \sim \frac{(m_{\pi^\pm} - m_{\pi^0})^5 \, m_{\pi^\pm}^3}{f_\pi^2 m_\mu^2 (m_{\pi^\pm}^2 - m_\mu^2)^2}$$

Phase space suppressed decay

Most precise measurement:
PIBETA experiment @ PSI

$$\mathrm{BR}^{\mathrm{exp}} = (1.036 \pm 0.006) \times 10^{-8}$$



Novel bounds on ALPs

One can recast this existing pion rare decay data, to set constraints on ALPs

$$\boxed{\pi^+ \to a e^+ \nu}$$

No helicity suppression, nor phase space suppression!

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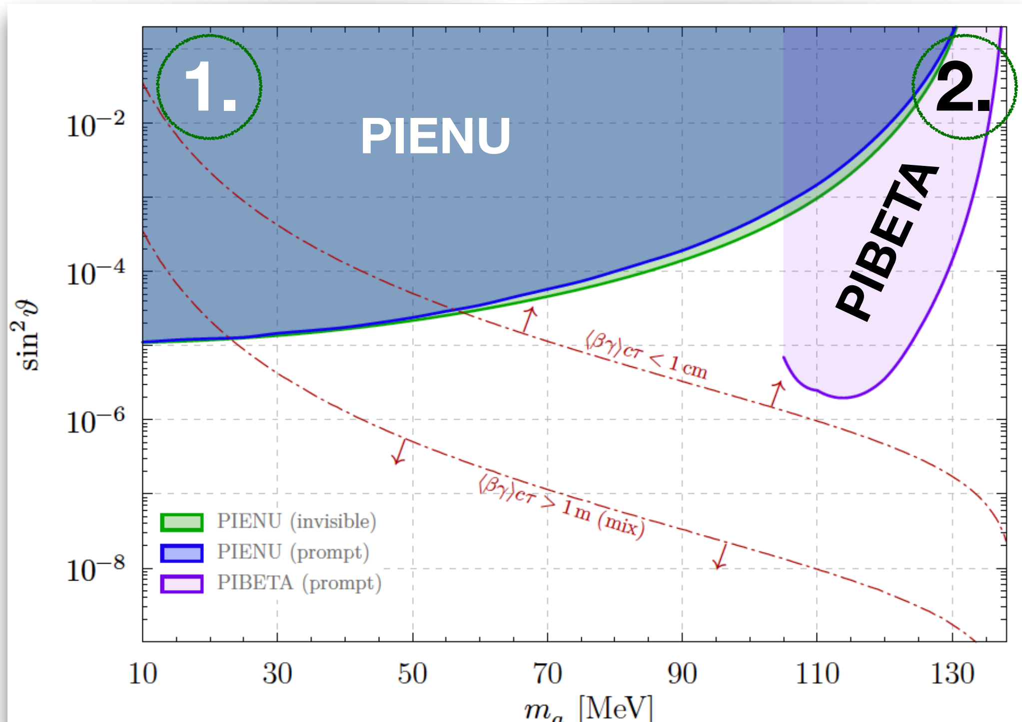
No helicity suppression, nor phase space suppression!

Altmannshofer, SG, Robinson, 1909.00005

1. The energy spectrum of e^+ will be different than the one from $\pi^+ \to e^+ \nu$ (independent on the ALP decay mode)

2. If the ALP decays to photons, the photon spectrum will be different than the one from $\pi^+ \to \pi^0 e^+ \nu$



~Model independent bounds on the mixing

$$|a^{\rm phys}\rangle \simeq \sin\vartheta\,|\pi^0\rangle + |a^0\rangle$$

Novel bounds on ALPs

One can recast this existing pion rare decay data, to set constraints on ALPs

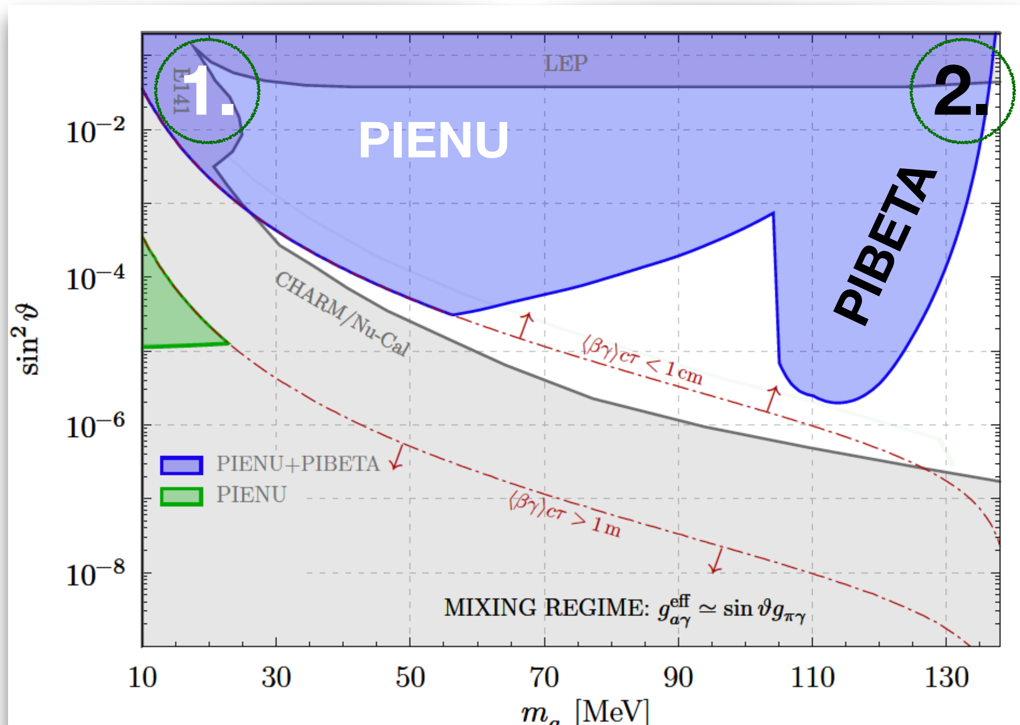
$$\boxed{\pi^+ \to a e^+ \nu}$$

No helicity suppression, nor phase space suppression!

Altmannshofer, SG, Robinson, 1909.00005

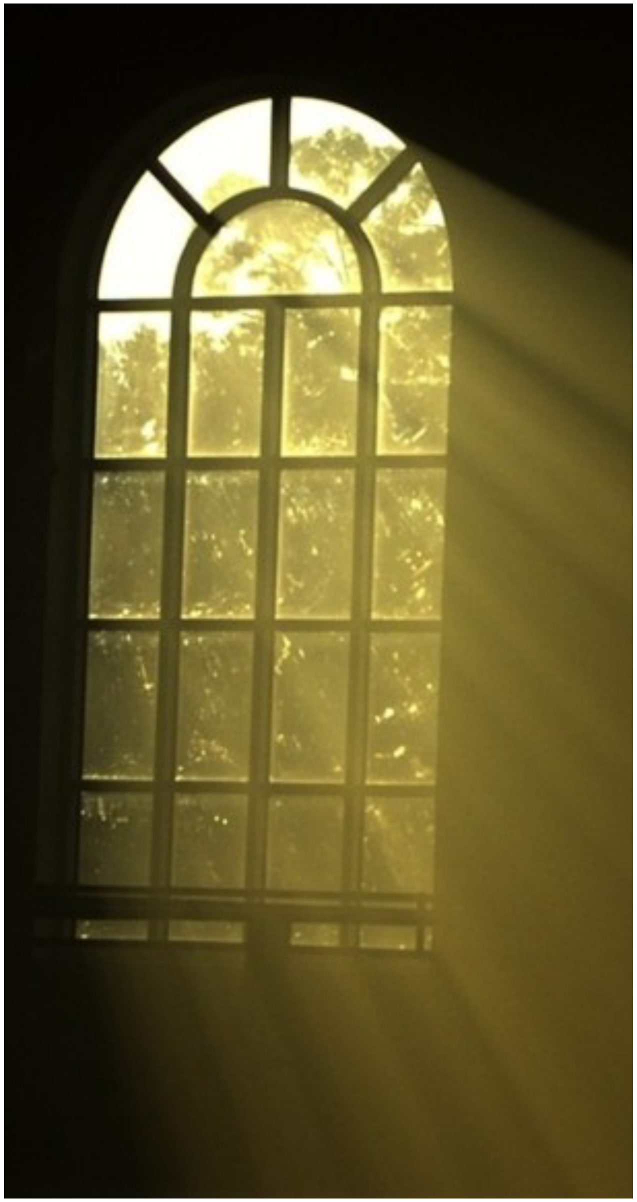
1. The energy spectrum of e+ will be different than the one from $\pi^+ \to e^+\nu$ (independent on the ALP decay mode)

2. If the ALP decays to photons, the photon spectrum will be different than the one from $\pi^+ \to \pi^0 e^+ \nu$



Complementarity with other experiments for models with $g_{a\gamma} a \tilde{F}^{\mu\nu} F_{\mu\nu}$, $g_{a\gamma} = \sin\vartheta \dfrac{\sqrt{2}\alpha}{8\pi f_\pi}$

Conclusions & final messages



Light thermal dark sector models are our next lamp-post in the search for Dark Matter.

* Interesting model building aspects.
* Many possible searches are possible at a plethora of complementary collider experiments (high energy vs. high intensity).
* Complementarity with astrophysical and cosmological measurements.

More and more opportunities to exploit existing experiments to search for light dark particles.

Good discovery potential!

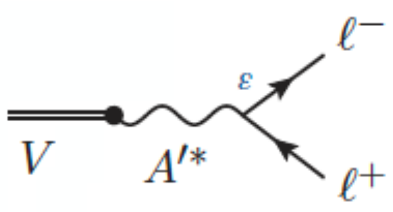
The dark pion relic abundance

Berlin, Blinov, SG, Schuster, Toro, 1801.05805

Several processes can contribute to the dark pion annihilation:

1. $3\pi_D \to 2\pi_D$ annihilation $\Gamma(3\to 2) = n_\pi^2 \langle \sigma v^2 \rangle\ ,\ \langle \sigma v^2 \rangle \sim \left(\frac{m_\pi}{f_\pi}\right)^{10} \frac{1}{m_\pi^5}$

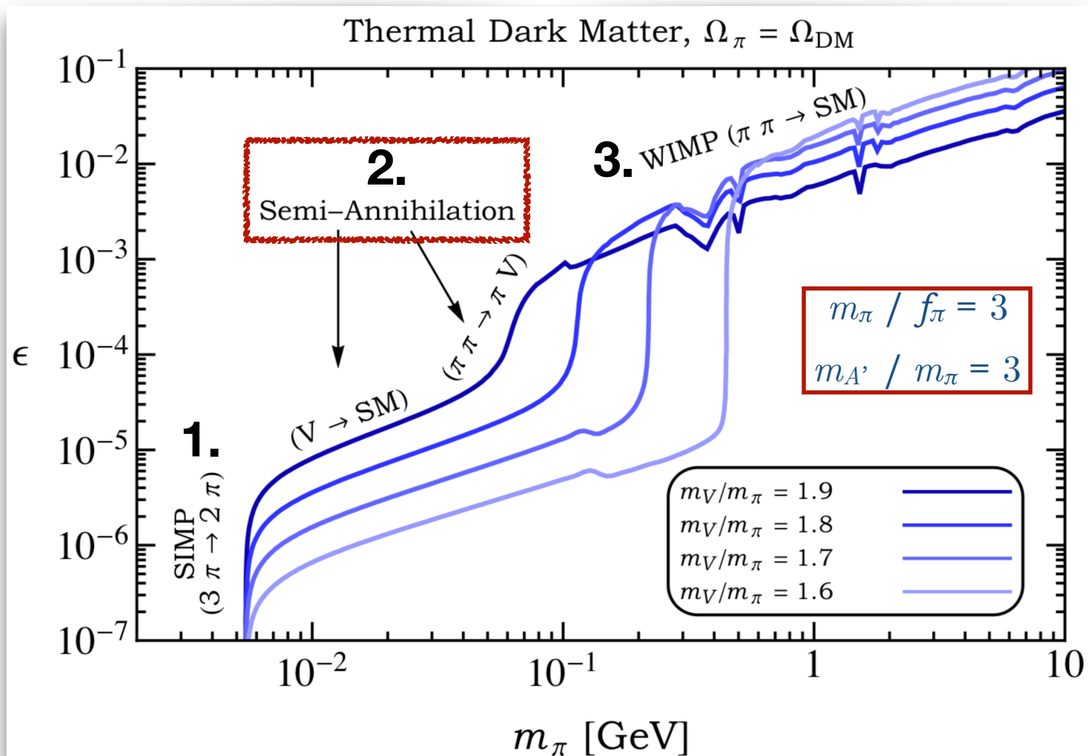
2. $\pi_D \pi_D \to V_D \pi_D$ semi-annihilation



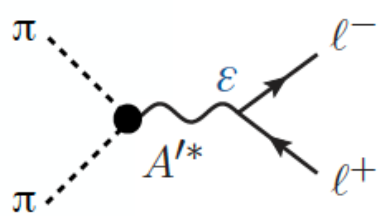
$m_V < 2m_\pi$

(If the dark vectors (V) have a mass close to the mass of the dark pions)

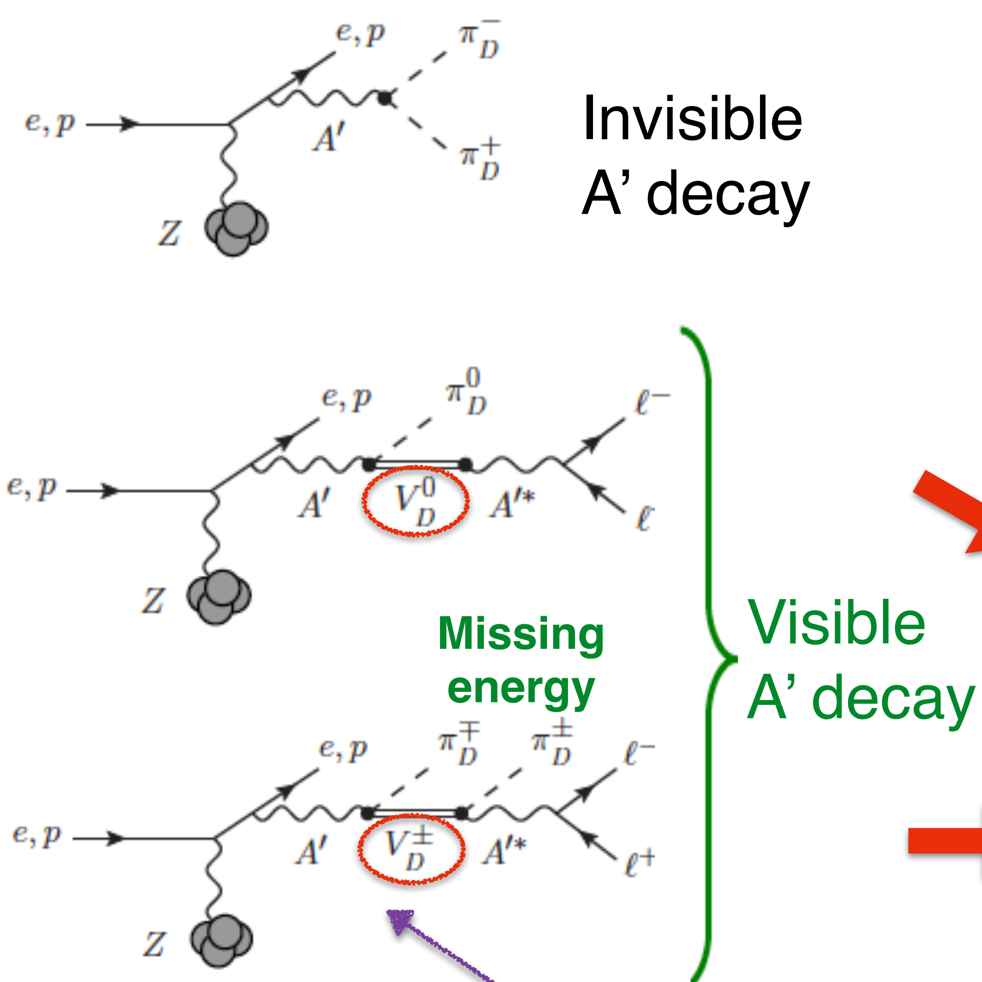
$$\langle \sigma v \rangle \sim \frac{e^{-(m_V - m_\pi)/T}}{m_\pi^2} \gtrsim \frac{e^{-m_\pi/T}}{m_\pi^2}$$

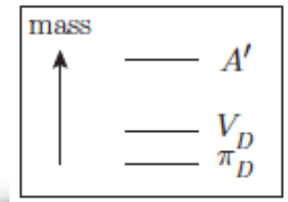


3. $\pi_D \pi_D \to \ell^+ \ell^-$

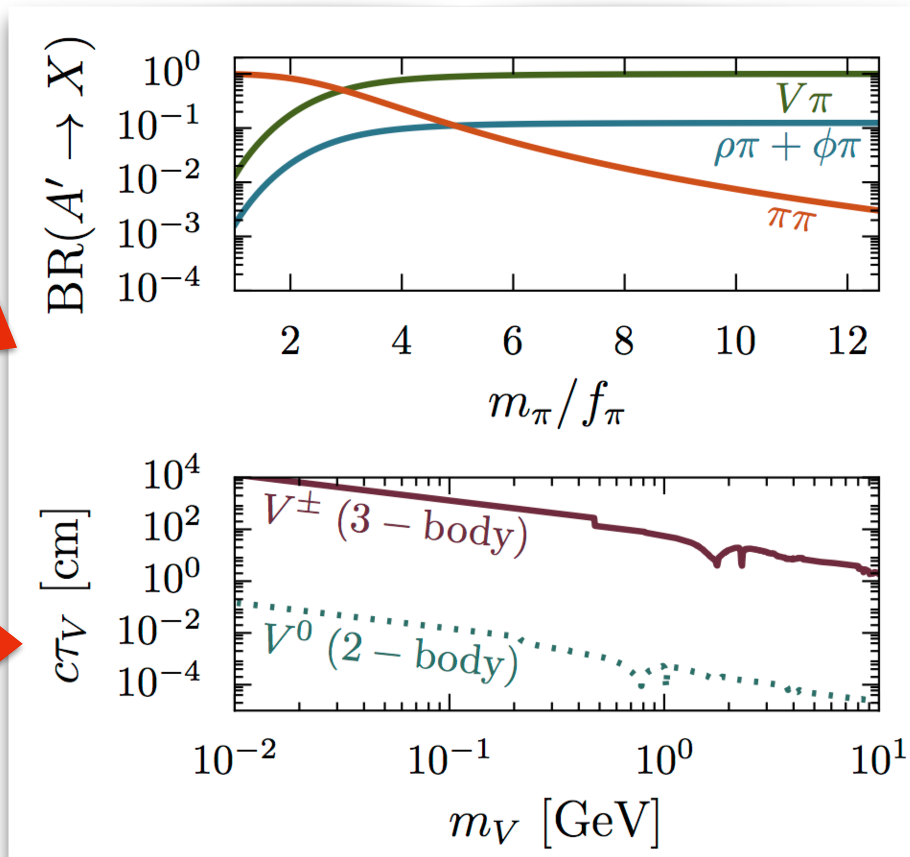


SIMPs & displaced decays





Berlin, Blinov, SG, Schuster, Toro, 1801.05805



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

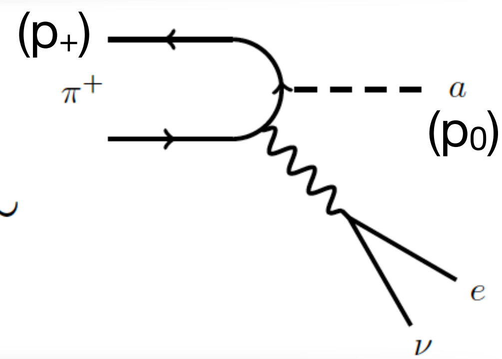
Displaced decays

Producing ALPs in pion decays

$$\boxed{\pi^+ \to a e^+ \nu}$$

Altmannshofer, SG, Robinson, 1909.00005

$$\mathcal{A}[\pi^+ \to a e \nu] \sim$$



$$\mathcal{A}^\mu \simeq \langle a|\pi^{*0}\rangle\langle\pi^{*0}|\bar{d}\gamma^\mu u|\pi^+\rangle \equiv \sin\vartheta\langle\pi^{*0}|\bar{d}\gamma^\mu u|\pi^+\rangle$$

ALP mass

$$\langle\pi^{*0}|\bar{d}\gamma^\mu u|\pi^+\rangle = c_\pi\Big[f_+(p_+^\mu + p_0^\mu) + (f_0 - f_+)\frac{m_+^2 - m_0^2}{q^2}\underbrace{(p_+^\mu - p_0^\mu)}_{q^\mu}\Big]$$

form factors

$f_+(q^2) \simeq 1$ as long as q^2 is small ➡ m_0>~10 MeV

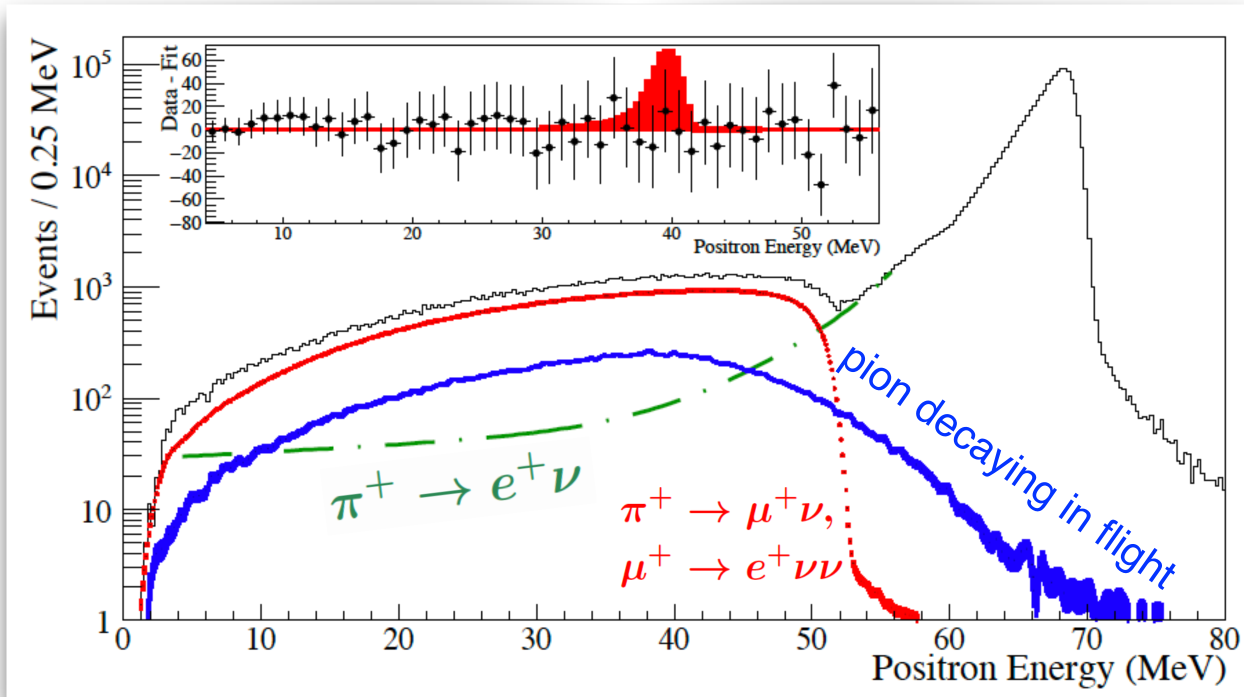
Theory: more understanding of form factors is needed to probe lighter ALPs!

$$\frac{\mathrm{BR}[\pi^+ \to a e^+\nu]}{\mathrm{BR}[\pi^+ \to e^+\nu]} \sim \frac{m_0^4 \sin^2\vartheta}{f_\pi^2 m_\mu^2(1 - m_e^2/m_+^2)^2} \times \int_1^{\frac{(m_0^2+m_+^2)}{2m_0 m_+}} (w^2-1)^{3/2} dw$$

PIENU measurement

Effectively they test lepton flavor universality: $R_{e,\mu} = \dfrac{\Gamma(\pi^+ \to e^+\nu(\gamma))}{\Gamma(\pi^+ \to \mu^+\nu(\gamma))}$

Residuals!



PIENU collaboration, 1712.03275

Multi-component fit with floating normalizations

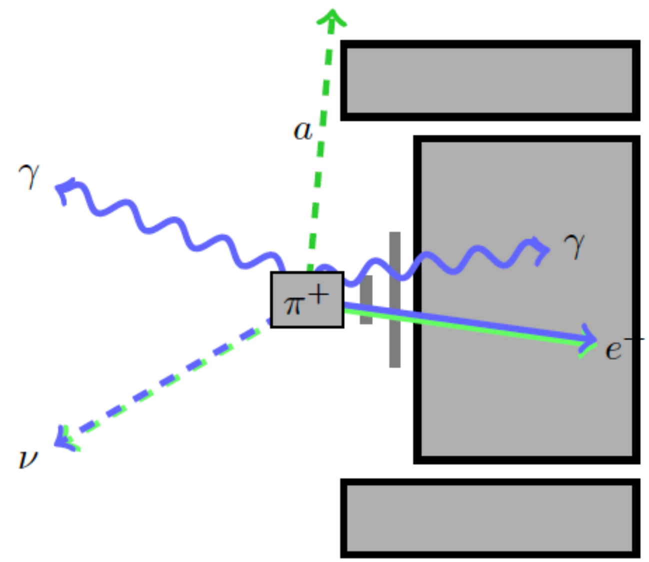
ALPs at PIENU

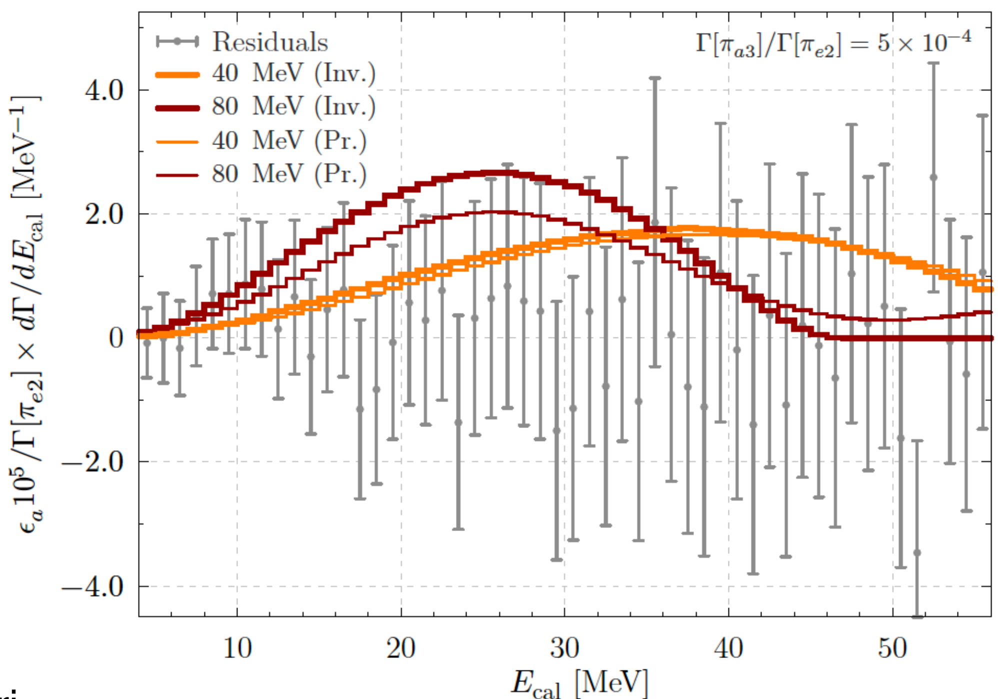
The production of the ALP will affect
the energy spectrum measured by the calorimeter

2. Invisible regime: the energy spectrum of the positron depends on the ALP mass.

1. Prompt regime: the energy measured by the calorimeter can get a contribution from the photons produced from the ALP decay.

$$\boxed{\pi^+ \to a e^+ \nu}$$





Altmannshofer, SG, Robinson, 1909.00005