Probes of Dark Matter

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Symmetry magazine

Overview

Topic of these lectures:

MeV-GeV Dark Matter (DM) thermal freeze-out (and freeze-in) models.
How they work and how to test them (focus on accelerator based experiments)

Chapter 1:

Introduction: DM freeze-out and freeze-in models.
WIMPs are strongly constrained. Let's go beyond the WIMP paradigm.

Chapter 2:

Generalities of minimal dark sector models for light (< few GeV) DM

Chapter 3:

The minimal dark photon model: how to test it
(model independent, model dependent)

Lecture 1

Some comment on the minimal dark scalar model

Lecture 2

Chapter 4:

Non-minimal models (IDMs, SIMPs)

A few references

(many more throughout the slides)

Reviews and lectures on Dark Matter:

T. Lin, *TASI lectures on DM direct detection*, 1904.07915

M. Lisanti, *TASI lecture notes on DM*, 1603.03797

Reviews on specific models:

Fabbrichesi, Gabrielli, Lanfranchi, *The dark photon*, 2005.01515

Bernal et al., *The Dawn of FIMP Dark Matter: A Review of Models and Constraints,* 1706.07442

Reviews on phenomenological probes:

Kahn, Lin, *Searches for light dark matter using condensed matter systems*, 2108.03239

Beacham et al., *Physics Beyond Colliders at CERN: BSM Working Group Report*, 1901.09966

Battaglieri et al., *U.S. Cosmic Visions: New Ideas in Dark Matter 2017: Community Report*, 1707.04591

Chapter 1

Introduction: DM freeze-out and freeze-in models.

* Vanilla WIMP models
* Stringent constraints from the LHC + direct detection

  ⇨ Freeze-in models **(1)**

  ⇨ Freeze-out models with a lighter DM **(2)**

Dark Matter (DM) is there!

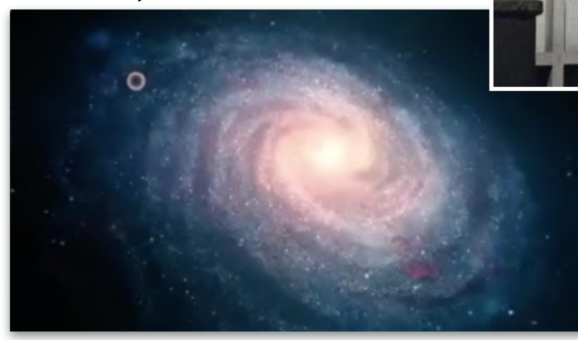
What do we know about it? Not much

1. It gravitates

1933 Fritz Zwicky

Coma cluster (of galaxies)

1970, Vera Rubin



Andromeda Galaxy

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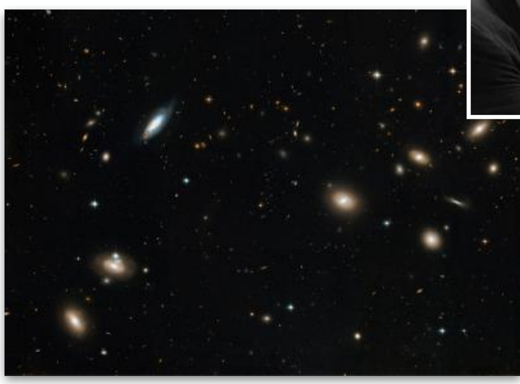

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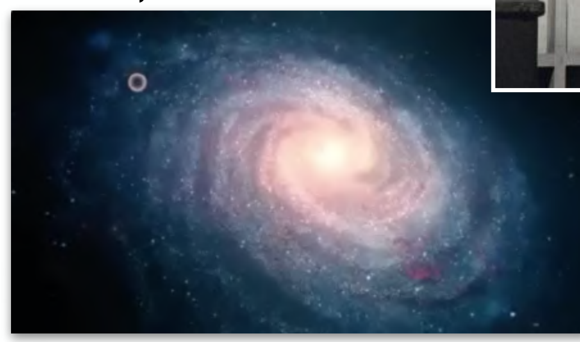

Andromeda Galaxy

2. It is dark (i.e. it does not interact with photons)

3. It is stable on cosmological scales

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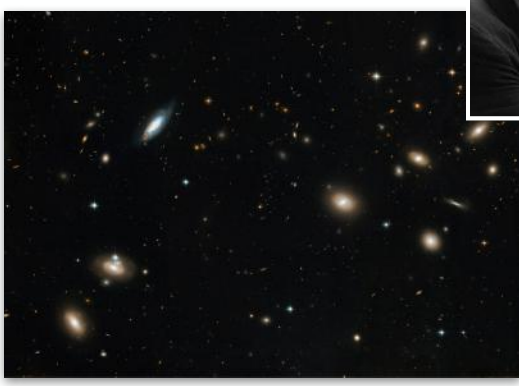

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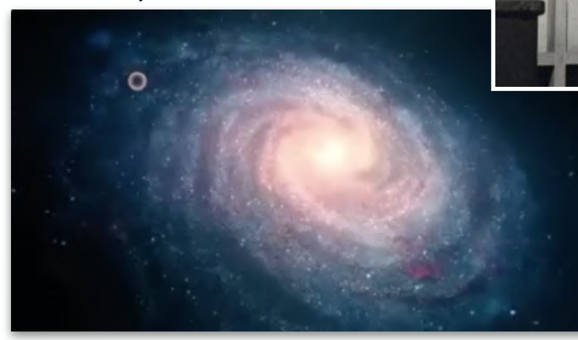

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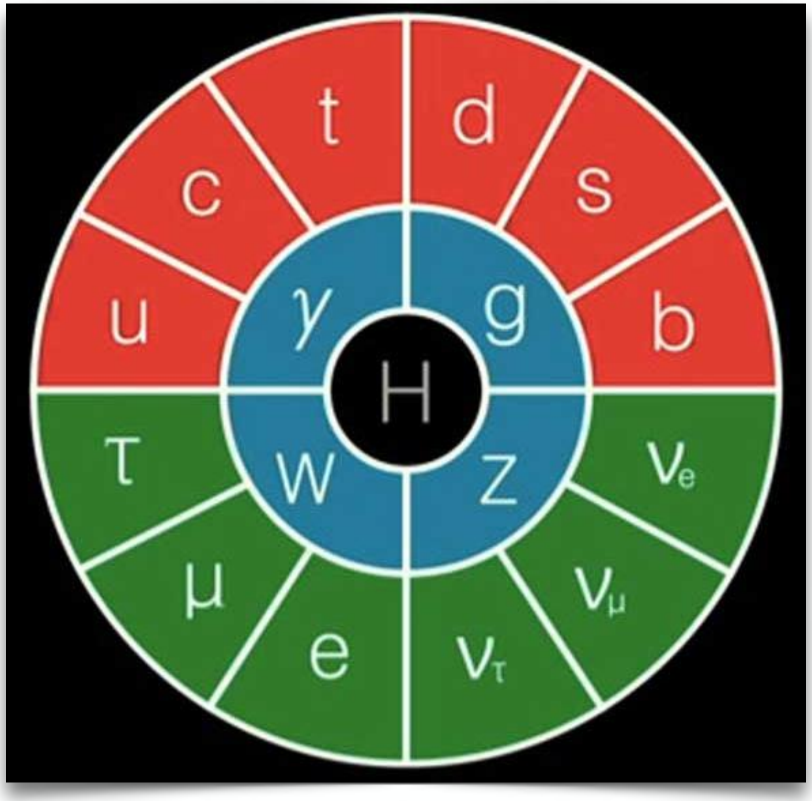
Fun fact: There is lots of DM in the Universe, but
for DM particles weighing several hundred times the mass of the proton,
there should be about one DM particle per coffee-cup-sized volume of space.

The Standard Model (SM) of particle physics



quarks
gauge bosons
leptons

The SM is very successful at describing ordinary matter, but it provides no viable dark matter candidate. **What is the microscopic nature of DM?**

The “WIMP” paradigm

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

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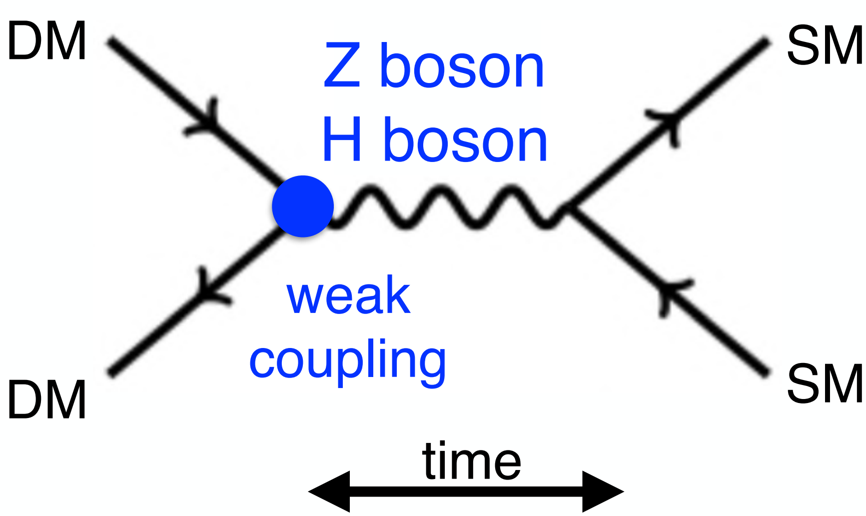
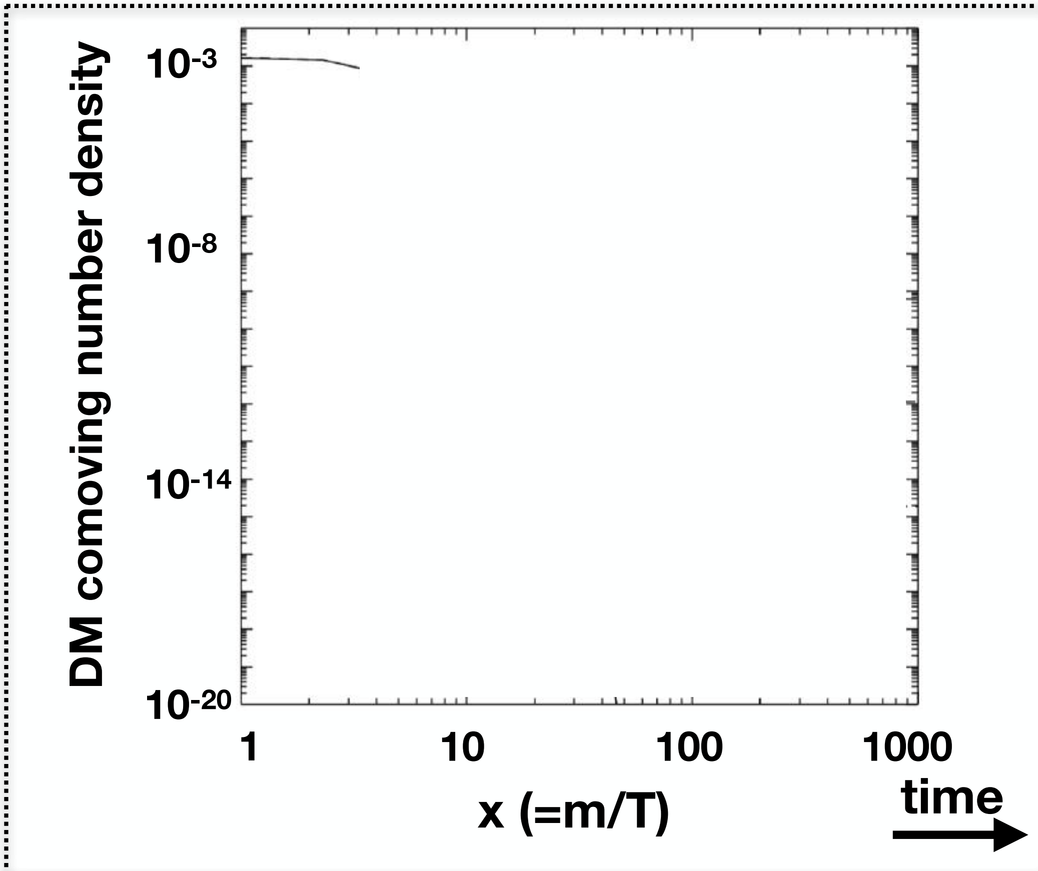
Thermal Dark Matter





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One of the dominant models for more than 3 decades

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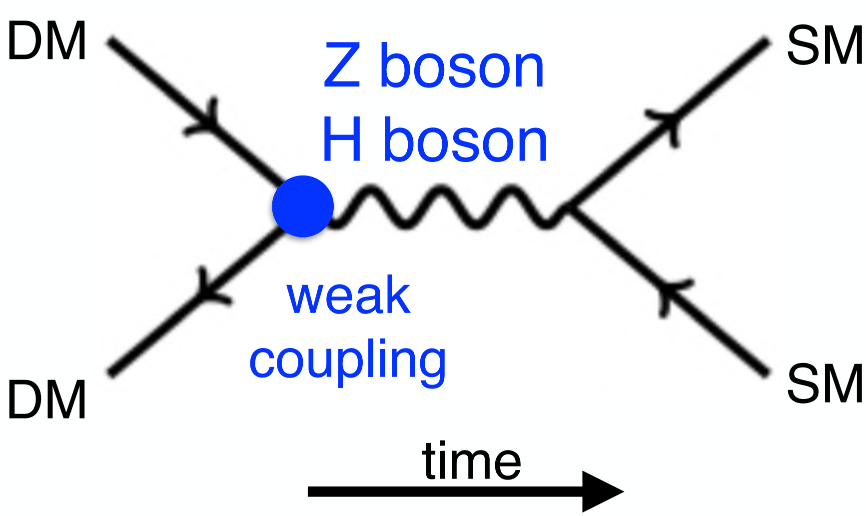

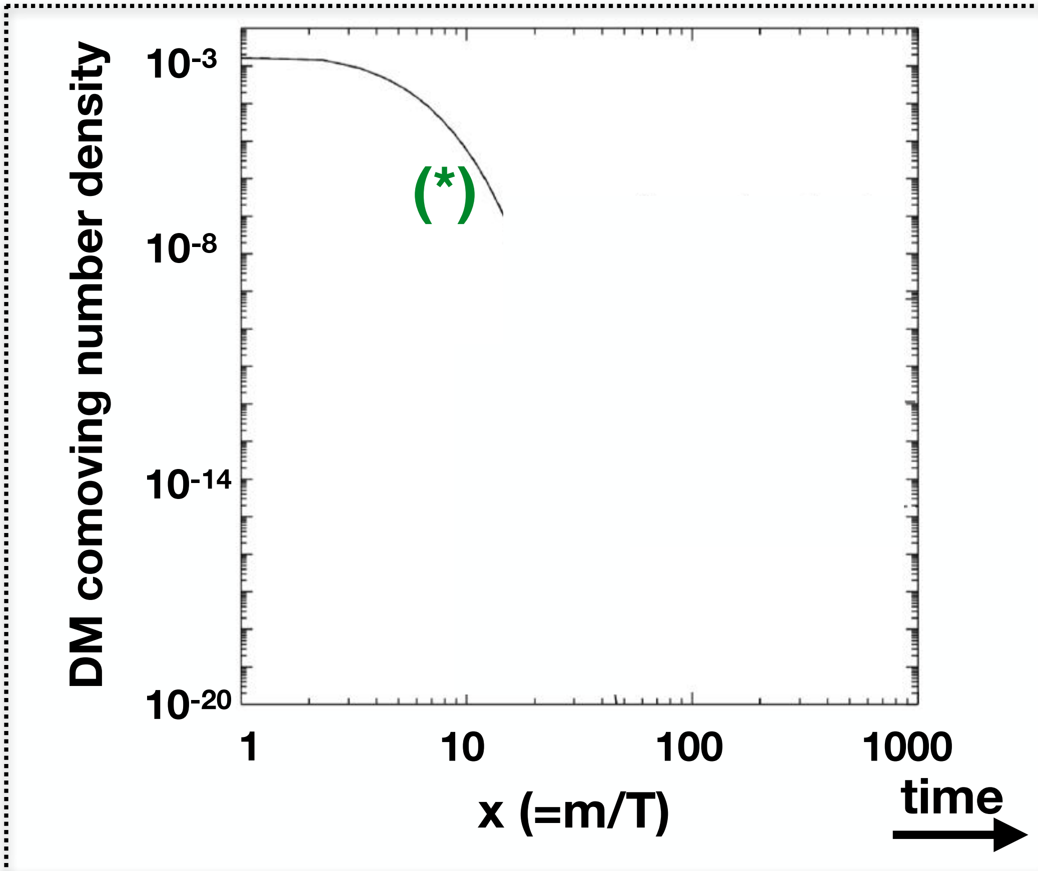

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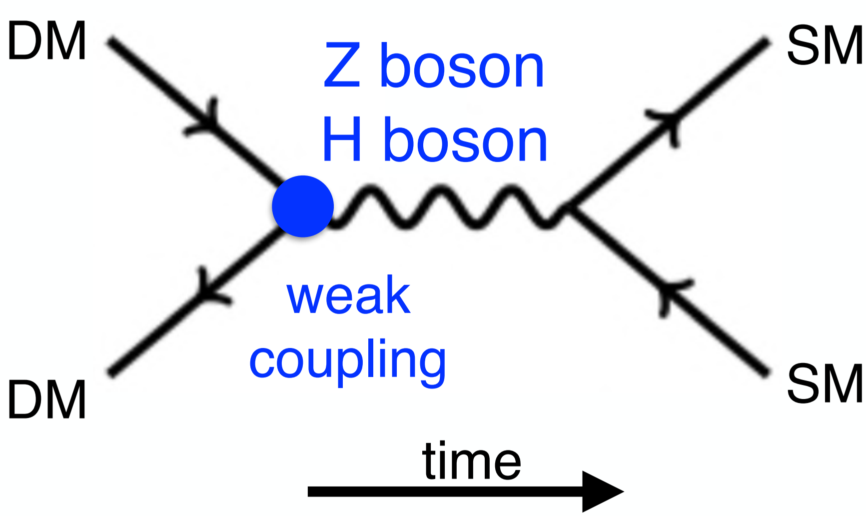
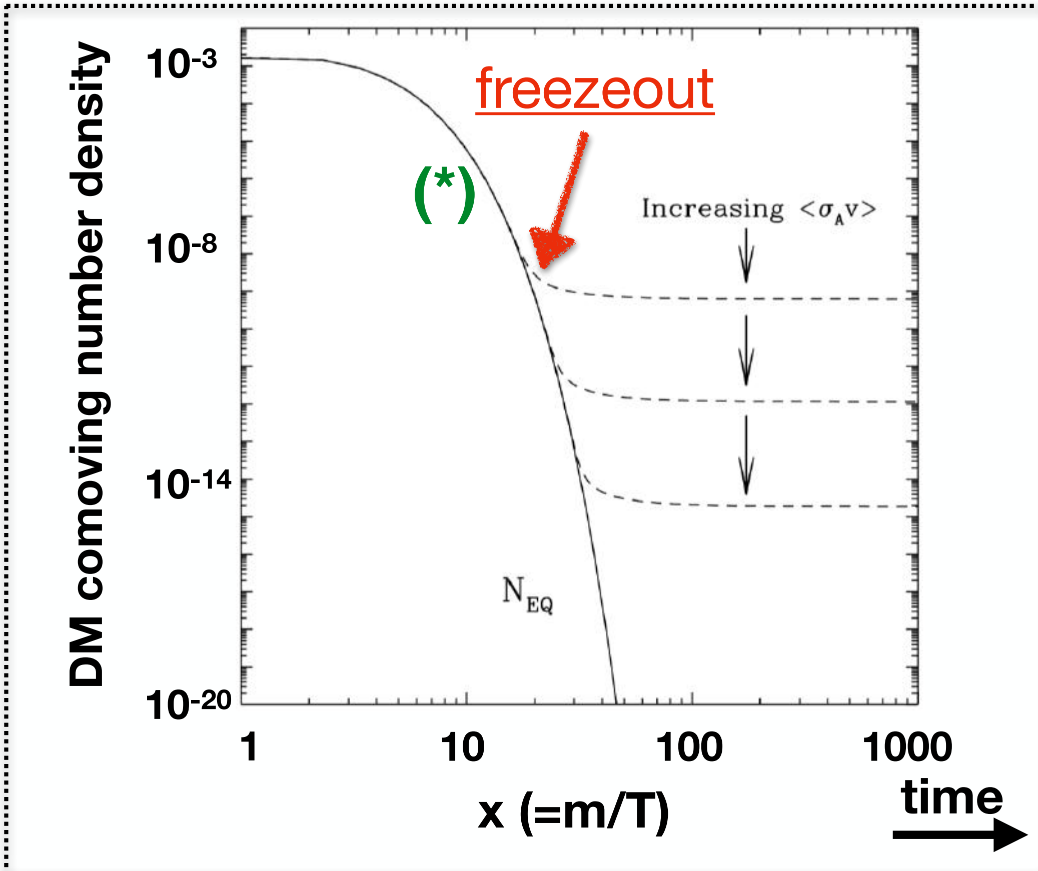


At certain point, annihilation rate becomes smaller than the Hubble rate: DM freezeout



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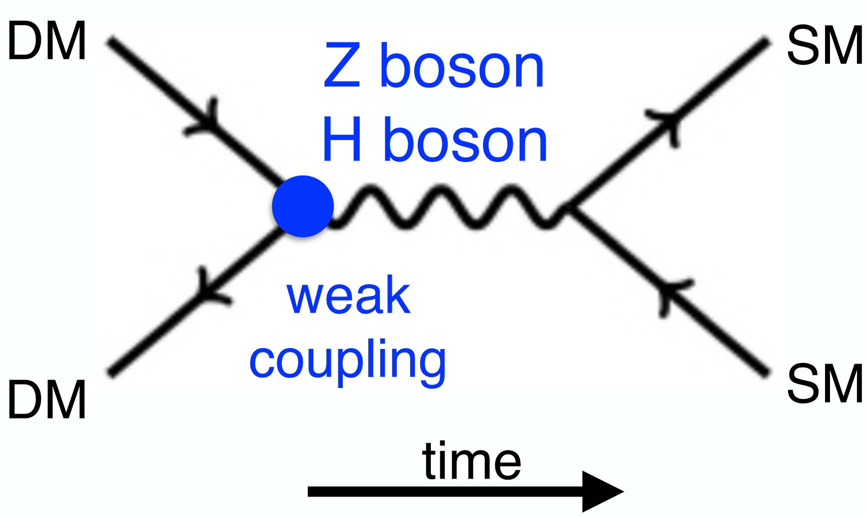

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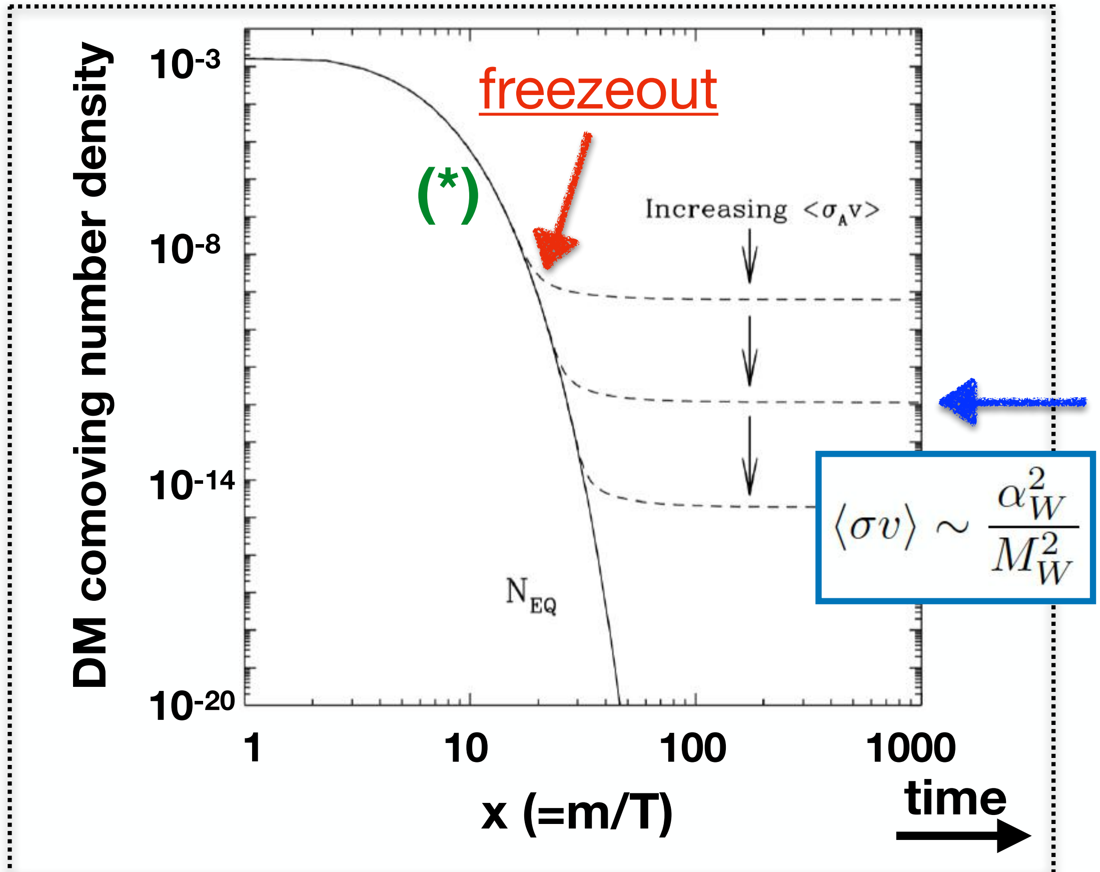

Thanks to these interactions, DM with a mass O(100 GeV) can freezeout and obtain the measured relic abundance

WIMP "miracle"?
… or "coincidence"

Exercise: the DM freeze-out abundance

Boltzmann equation for the DM number density:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle v\sigma_\chi\rangle \left[n_\chi^2 - \underline{(n_\chi^{\rm eq})^2}\right] \Rightarrow \frac{dY_\chi}{dx} = -\frac{xs\langle v\sigma_\chi\rangle}{H(m)}\left[Y_\chi^2 - (Y_\chi^{\rm eq})^2\right]$$

(σ_χ = DM annihilation cross section)

$$\left(Y_\chi \equiv \frac{n_\chi}{s}, \quad x \equiv \frac{m}{T}\right)$$

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After freeze-out:

$$\frac{dY_\chi}{dx} \simeq -\frac{\lambda}{x^{n+2}}Y_\chi^2,\quad \lambda \equiv \frac{\langle v\sigma_\chi\rangle_0 s_0}{H(m)}$$

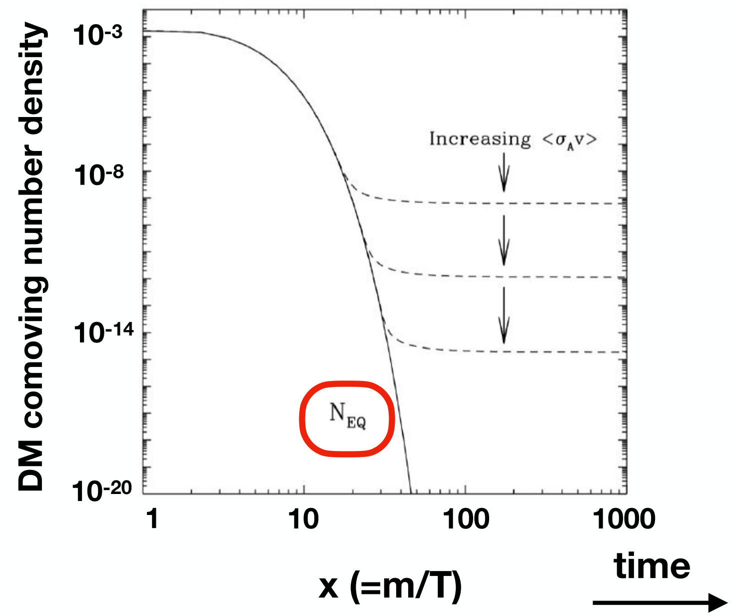
$$(\langle v\sigma_\chi\rangle = \langle v\sigma_\chi\rangle_0 x^{-n},\ s = s_0 x^{-3})$$

For example, for n=0 (corresponds to s-wave):

$$\frac{1}{Y_{\rm today}} - \frac{1}{Y_f} = \frac{\lambda}{x_f} \Rightarrow Y_{\rm today} \simeq \frac{x_f}{\lambda}$$

$n^{eq}\langle v\sigma_\chi\rangle \sim H \Rightarrow x_f = \mathcal{O}(10)$ (freeze-out condition)

$$\Omega_\chi h^2 = \frac{m s_{\rm today} Y_{\rm today}}{\rho_{\rm cr}} \Rightarrow \Omega_\chi h^2 \simeq \frac{10^{-9}}{\langle v\sigma_\chi\rangle {\rm GeV}^2} \sim 0.12$$

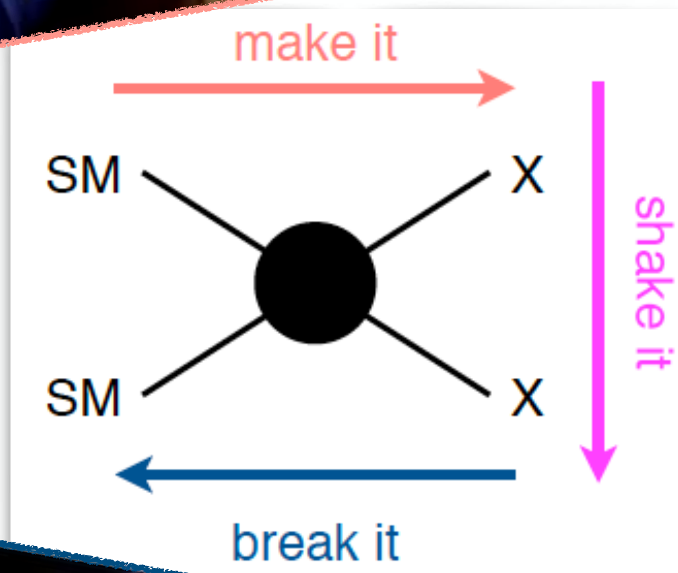


$$\text{if } \langle v\sigma_\chi\rangle = \frac{\alpha^2}{m^2},\quad \alpha \sim 0.01,\ m \simeq 100\ {\rm GeV}$$

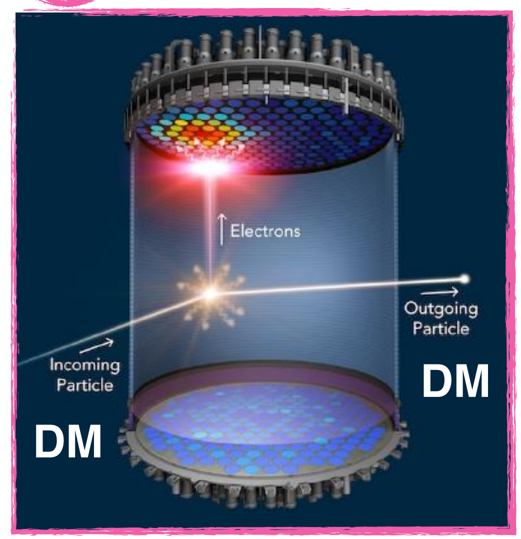
WIMP miracle coincidence

Complementary probes of WIMPs

1. Accelerator searches



2. Direct detection



3. Astrophysical probes

Lectures by R. Leane

Famous example of WIMPs:

lightest neutralino in SUSY models with R-Parity conservation

1.

DM signals at the LHC

At the LHC,

the signature of invisible particles (like DM) is missing (transverse) momentum

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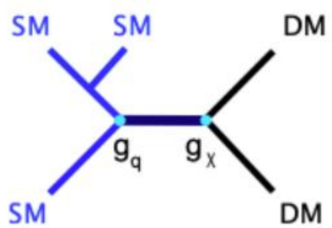
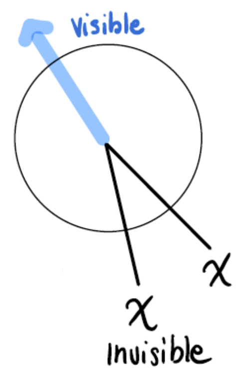
At the LHC,

the signature of invisible particles (like DM) is missing (transverse) momentum

"Mono-X" type of signatures





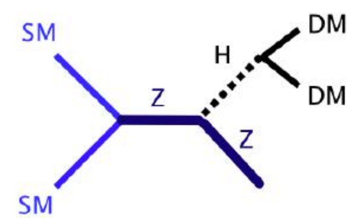
Signature X	
Jet, V (→qq)	+ p_T^{miss}
Z (→ll)	+ p_T^{miss}
VBF	+ p_T^{miss}
WW	+ p_T^{miss}
Displaced μμ	+ p_T^{miss}
Higgs	+ p_T^{miss}
γ	+ p_T^{miss}
tt, t/tW	+ p_T^{miss}

Higgs exotic decays

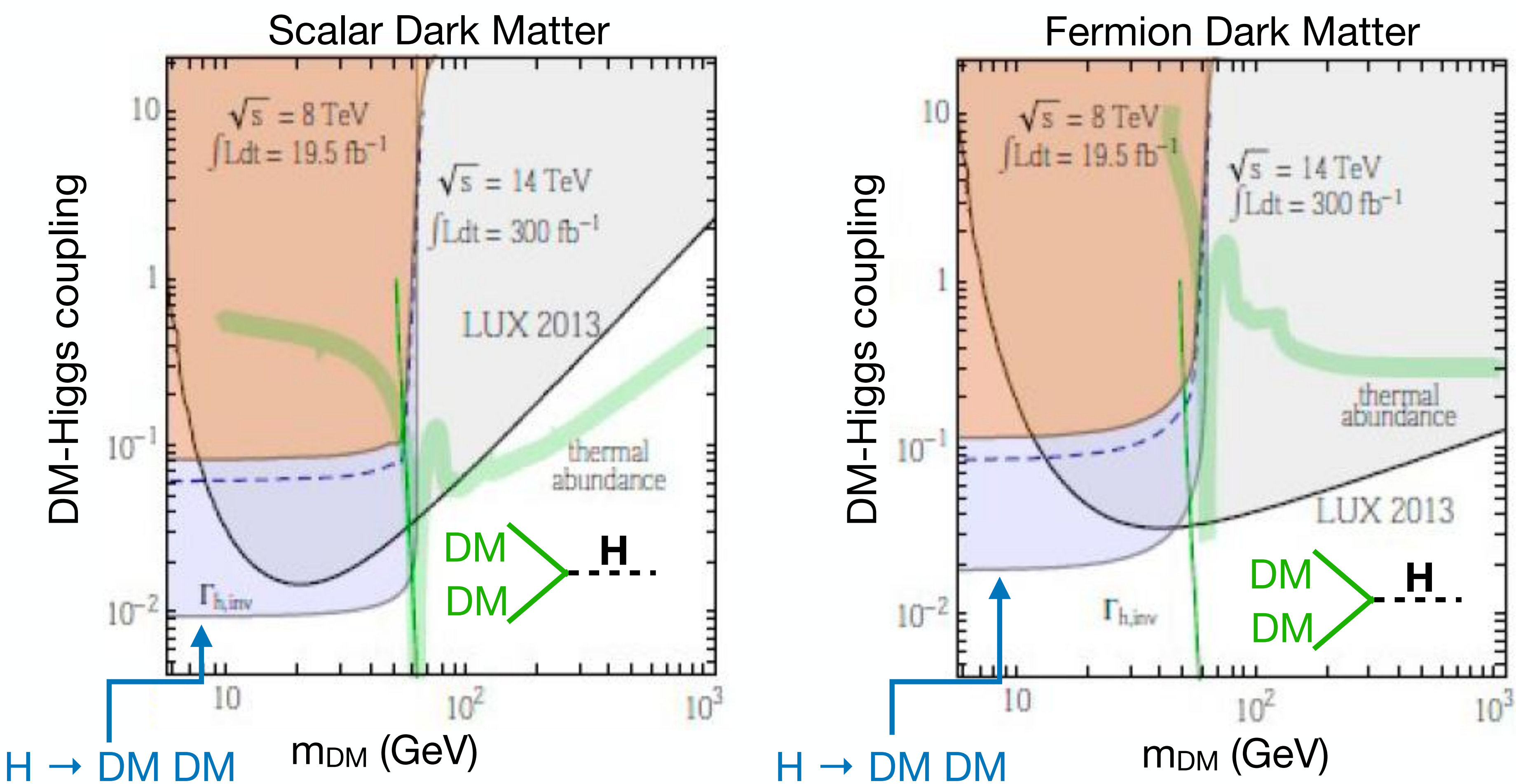
- The SM Higgs width is tiny.
- It is challenging to measure the Higgs width at the LHC (hadron colliders).

→ Generically, models with new particles with M < m_h / 2 predict sizable branching ratios of the Higgs into the new particles (H → NP NP, exotic decay). This includes DM!

Use Higgs productions in association with visible objects. Example,



1. Probing DM with Higgs invisible decays



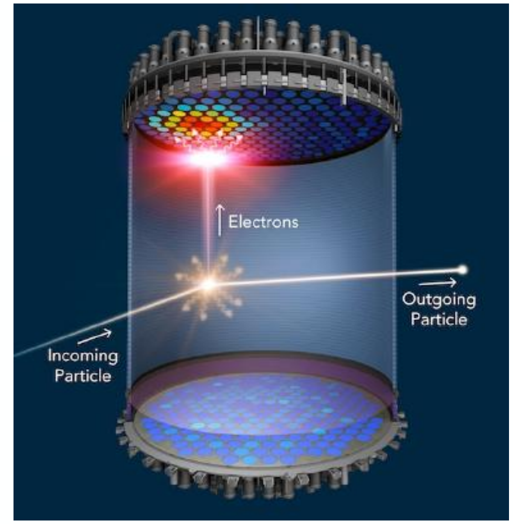
De Simone et al, 1402.6287

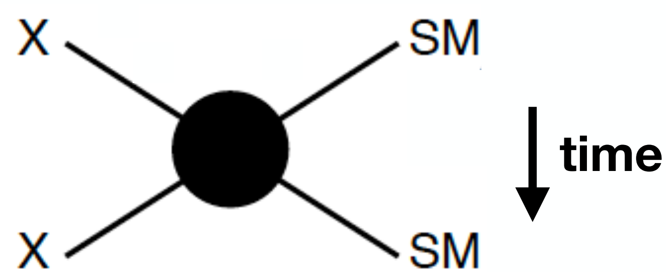
Conclusion: in minimal models, **if** the Higgs is the particle responsible of DM annihilation, then DM cannot be too light, ~~$m_{DM} < m_h/2$~~

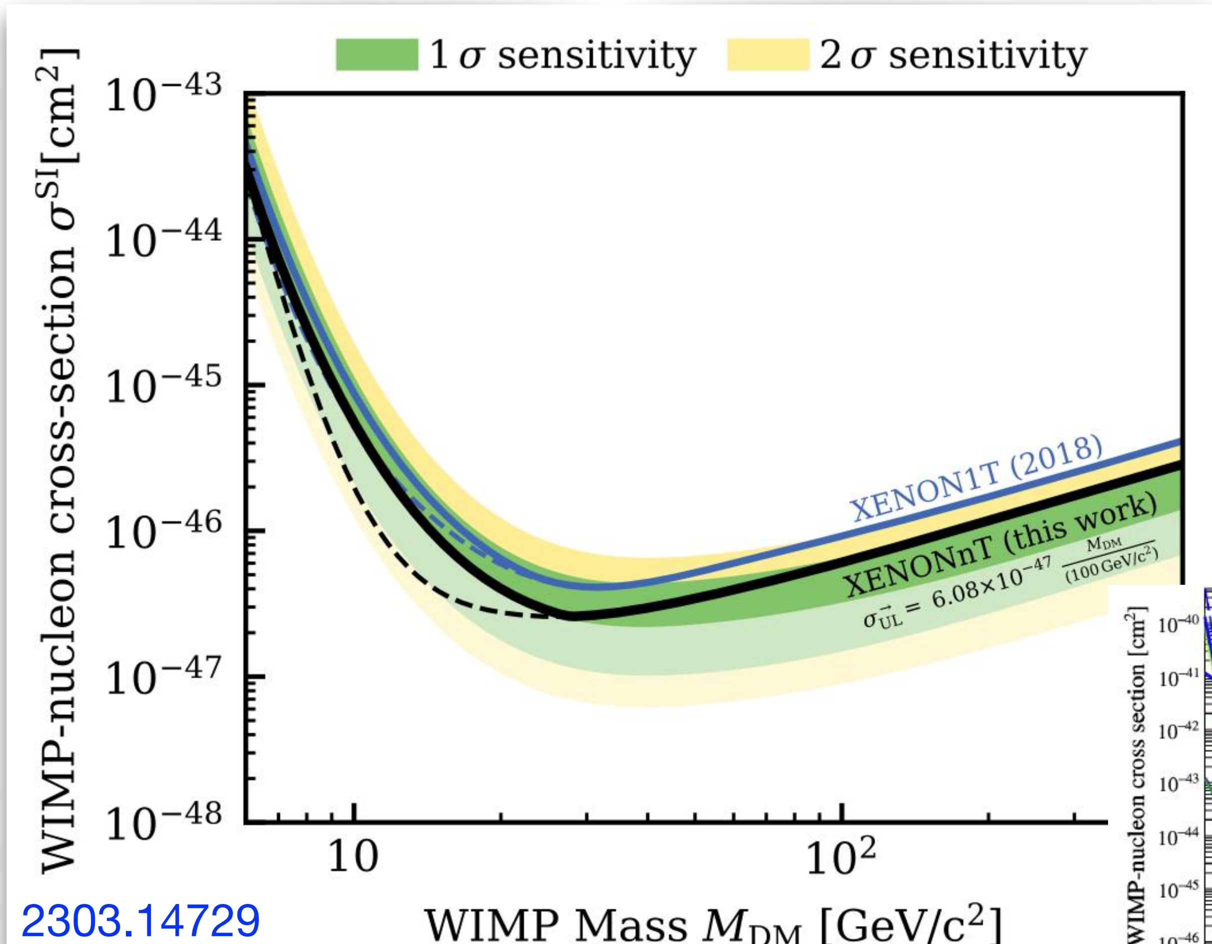
2.

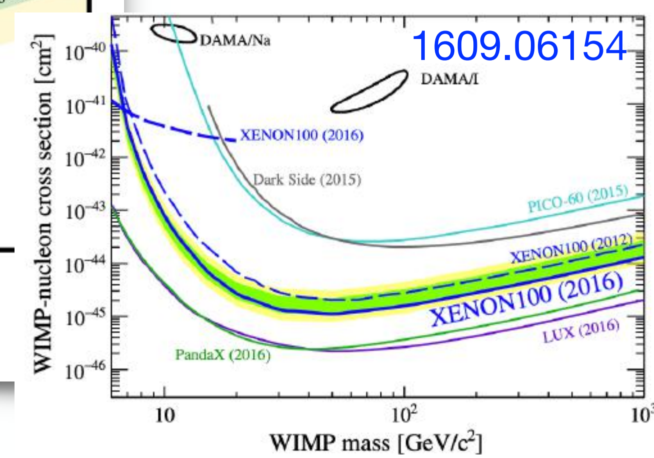
Direct detection

Large detectors that search for DM scattering





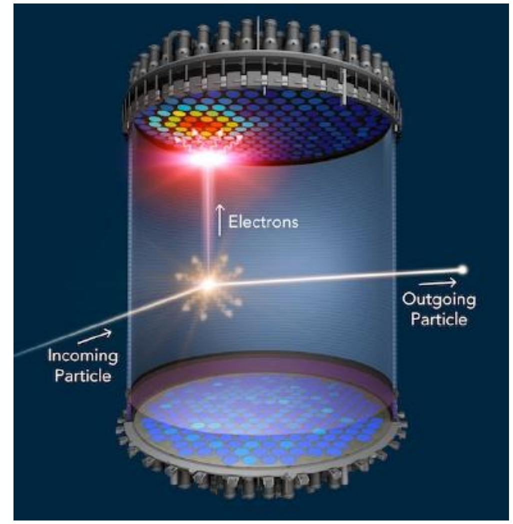


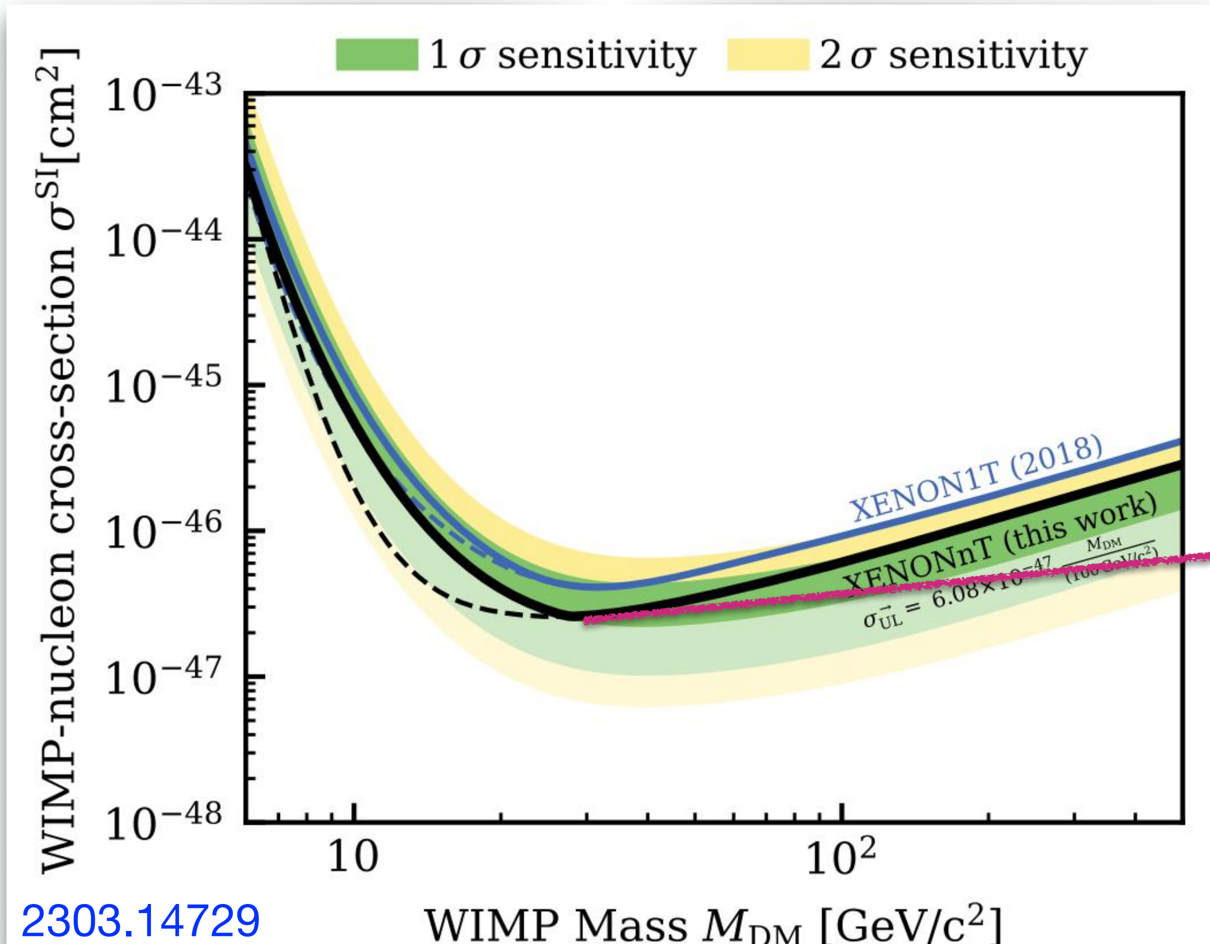


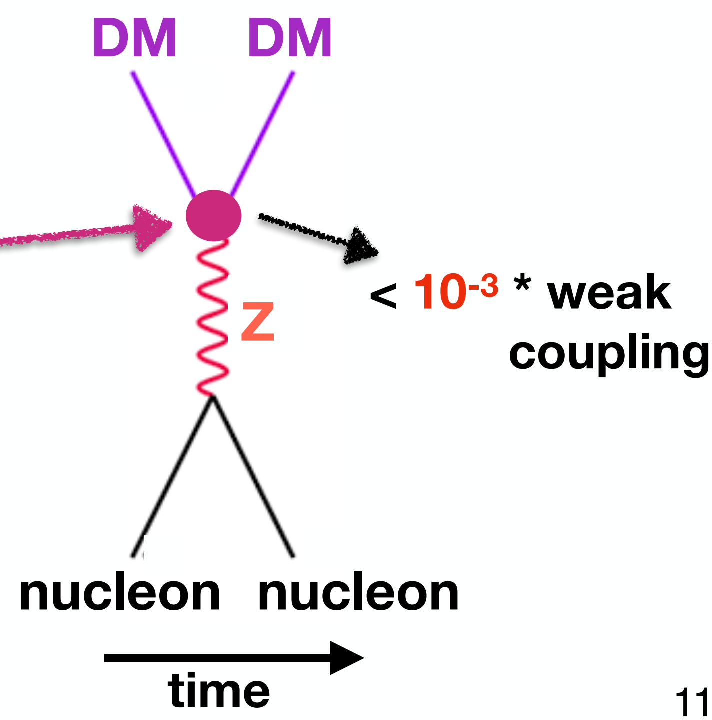
status in 2016

2. Direct detection

Large detectors that search for DM scattering





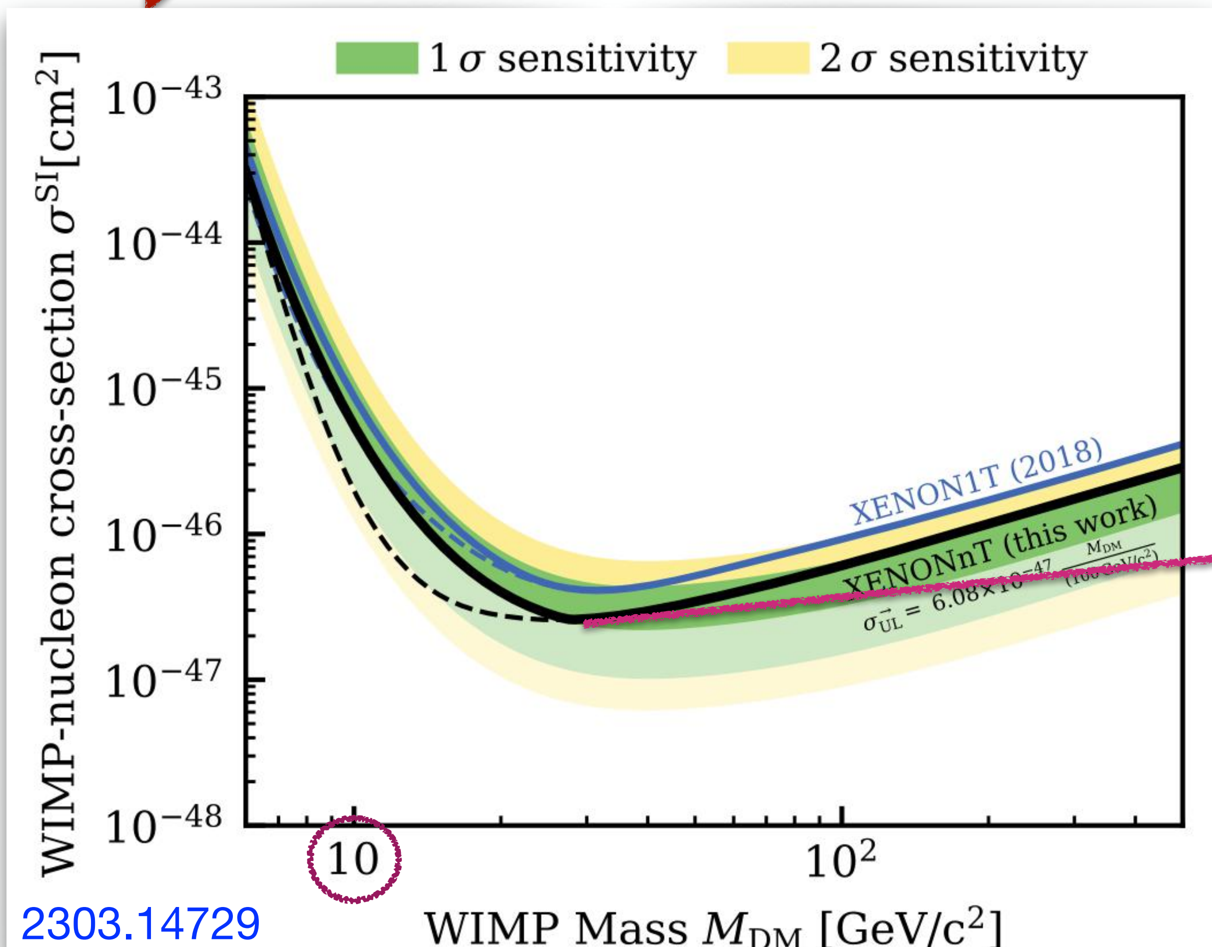


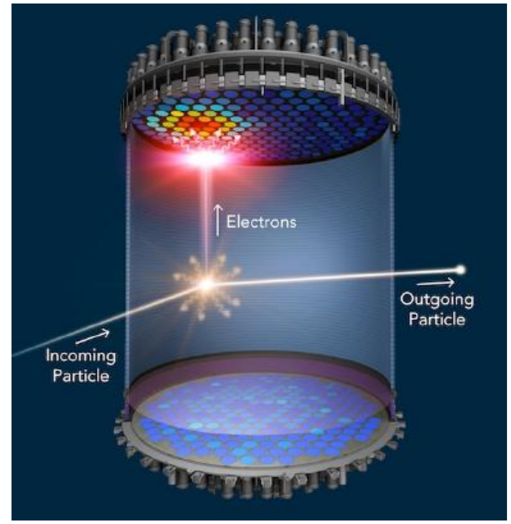
2. Direct detection

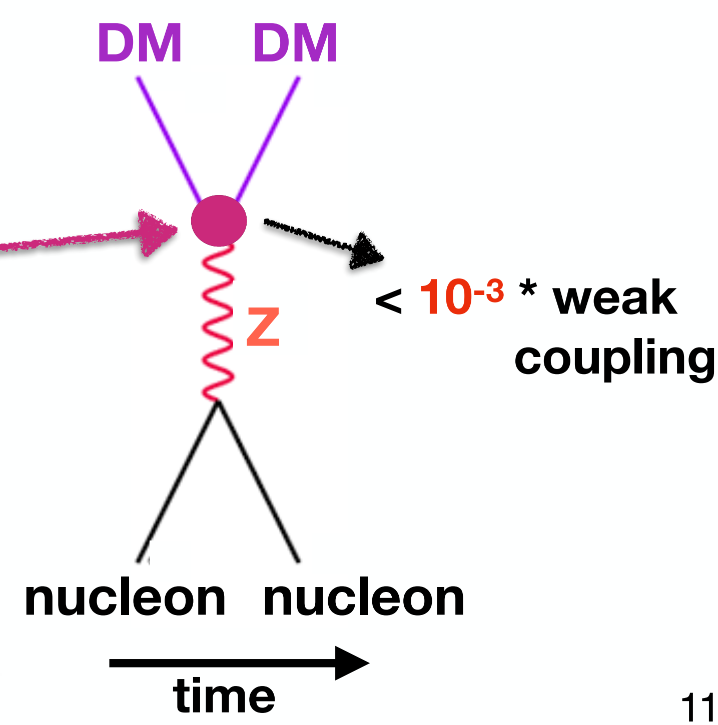
Large detectors that search for DM scattering

Lower energy thresholds for the scattering recoil

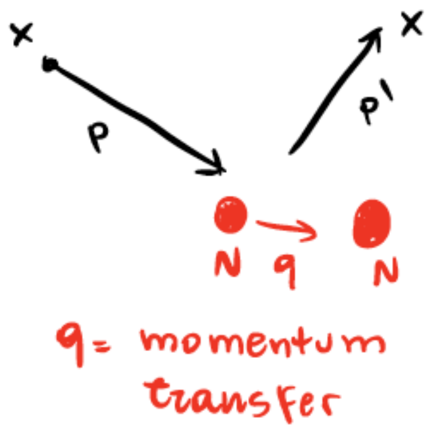
→ access to masses above ~few GeV







Exercise: kinematics of DM-nucleus scattering



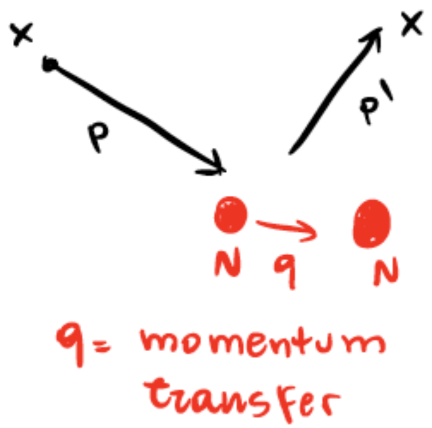
reduced mass of the DM-nucleus system

$$\mu_{\chi N} = \frac{m_\chi m_N}{m_\chi + m_N}$$

$$E_R^{\max} = \frac{q^2_{\max}}{2m_N} = \frac{2\mu^2_{\chi N} v^2}{m_N}$$

DM velocity

Exercise: kinematics of DM-nucleus scattering



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DM velocity

v~10^{-3}

$E_R \geq$ O(keV) to be detected by most experiments

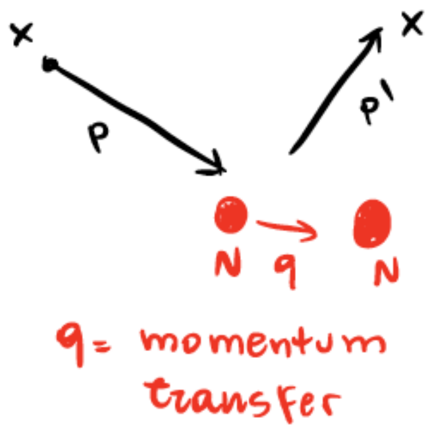
This gives a ~lower bound on the DM masses we can probe.

m_X= 100GeV → E_R^{max} ~ 50 keV

m_X= 1GeV → E_R^{max} ~ **0.02 keV** $\quad m_\chi \ll m_N \Rightarrow E_R^{\max} \simeq 2\frac{m_\chi^2}{m_N} v^2$

scattering on m_N=100GeV (similar to Xenon)

Exercise: kinematics of DM-nucleus scattering



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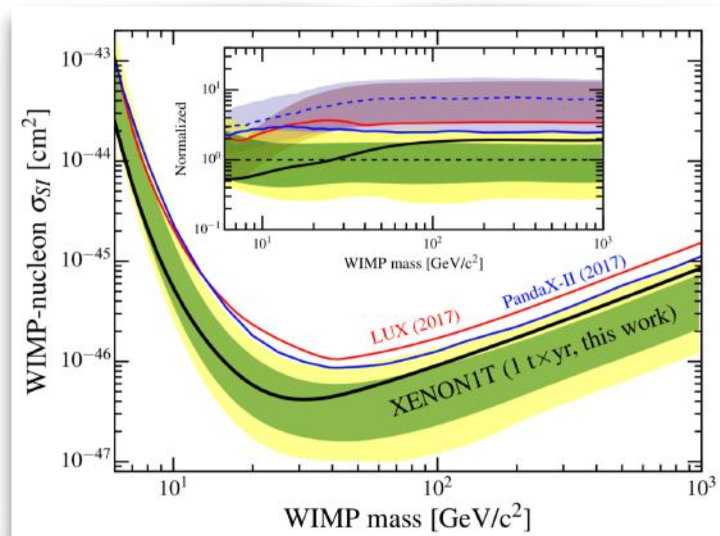
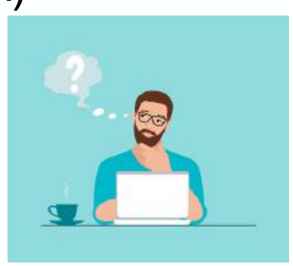


(2) What about considering lower DM masses?



(1) What about different mechanisms to get the measured relic abundance?

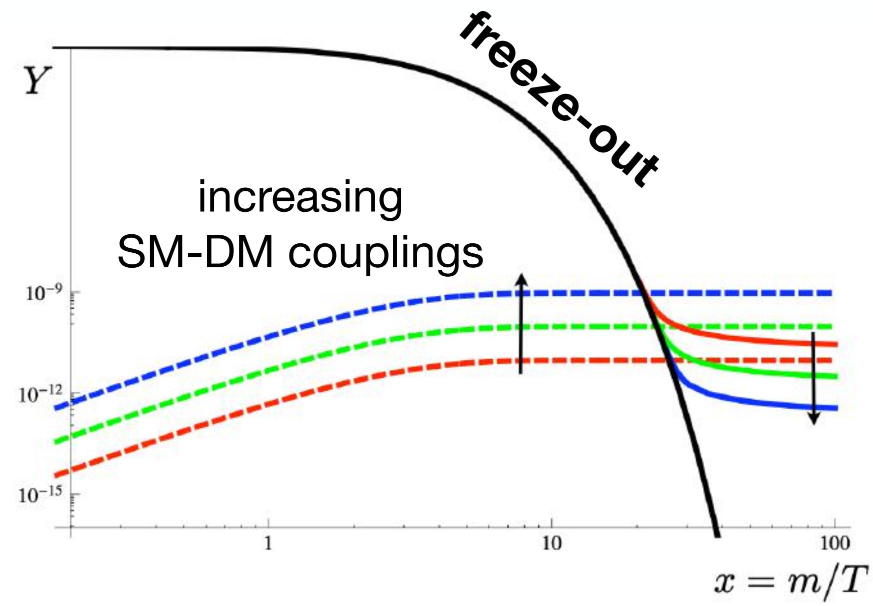
(1) The DM freeze-in mechanism

McDonald, 0106249; Hall, Jedamzik, March-Russell, West, 0911.1120

DM is **not in thermal equilibrium** with the SM thermal bath

Dark matter particles are produced through the decay, scattering, or annihilation of particles in the thermal bath in the early universe.

At certain point the production stops when the rate becomes slower than the expansion rate of the universe.



Only very weakly couplings are needed

→ **More hidden models**

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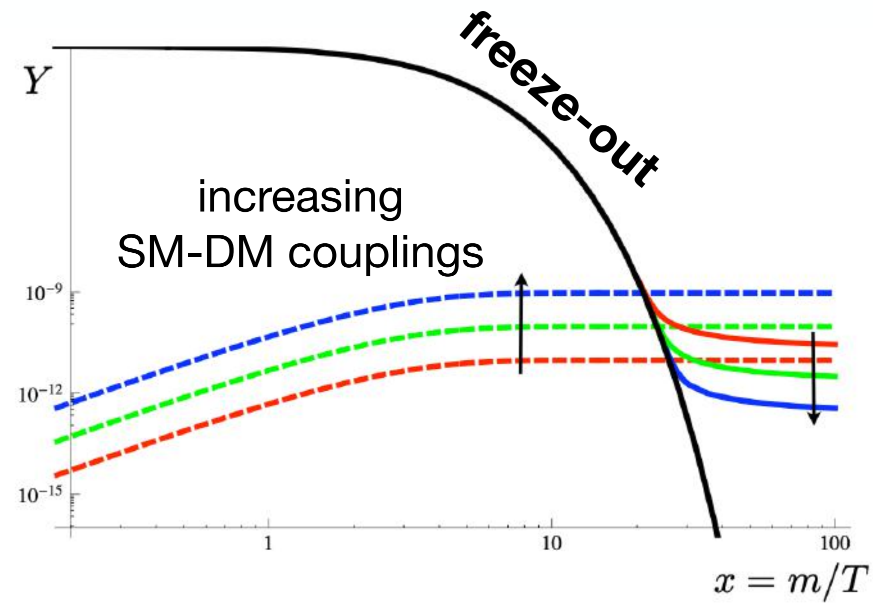


For example, $\mathcal{L} \supset \lambda X B_1 B_2$

in thermal bath $B_1 \to B_2 X$ DM state

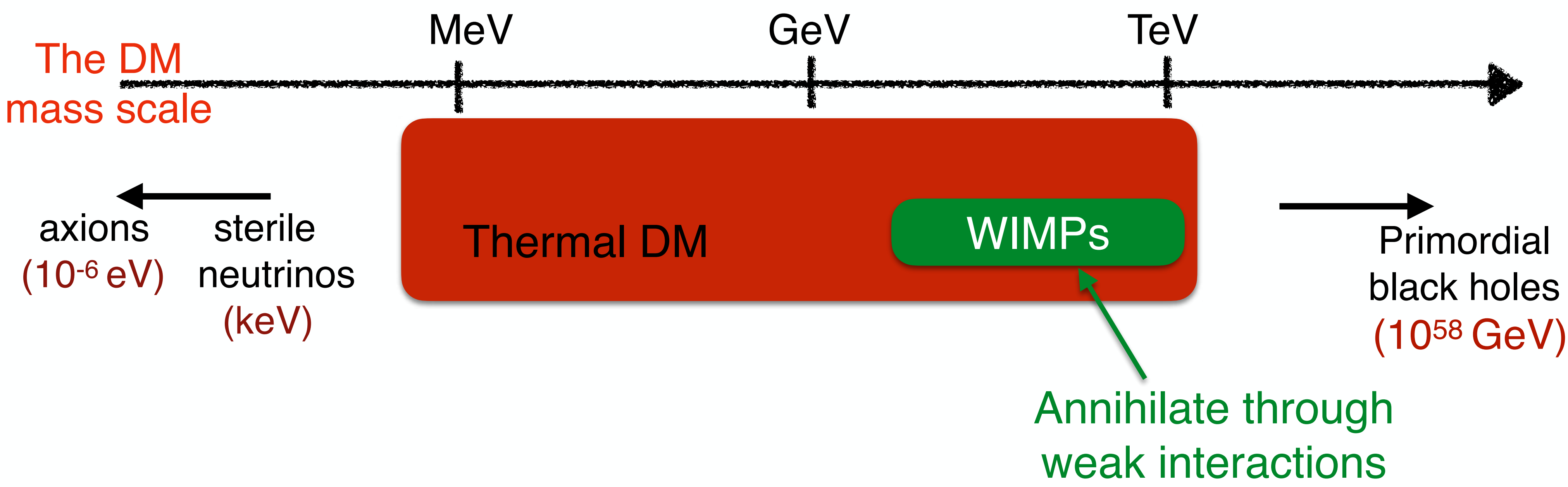
$$\dot{n}_X + 3 n_X H \simeq \int \frac{d^3 p_{B_1}}{(2\pi)^3} \frac{f_{B_1} \Gamma_{B_1}}{\gamma_{B_1}}, \quad \gamma_{B_1} = \frac{E_{B_1}}{m_{B_1}}$$

$$\boxed{\lambda = \mathcal{O}(10^{-12}), \quad \text{if } m_{B_1} = \mathcal{O}(m_X)}$$

Only very weakly couplings are needed

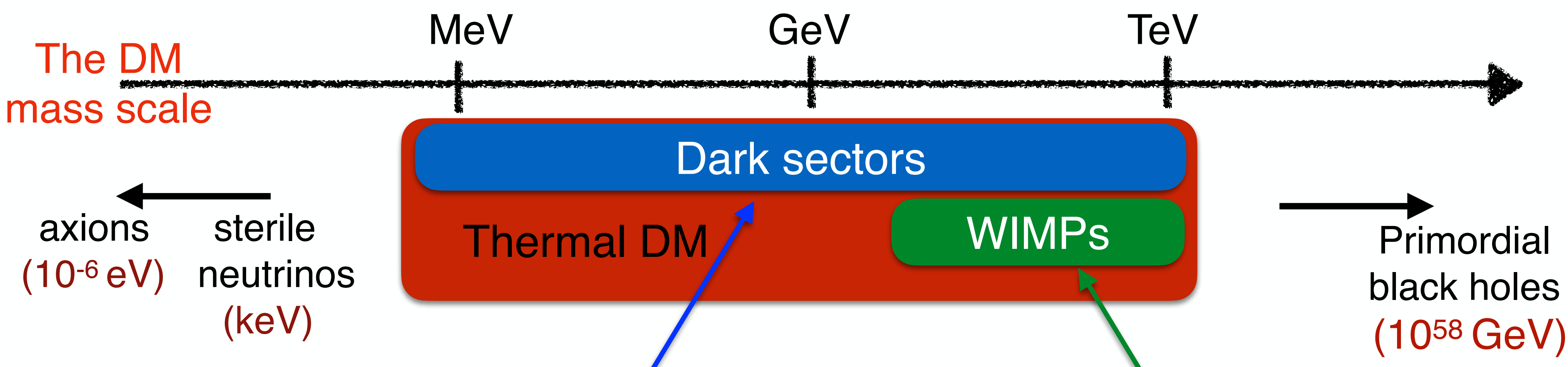
➡ **More hidden models**

(2) Dark Matter & dark sectors



The dark matter scale is **unknown**.
Completely different search strategies depending on the mass of dark matter

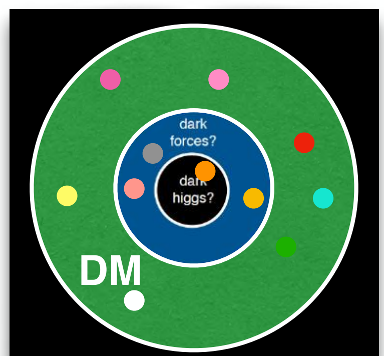
(2) Dark Matter & dark sectors

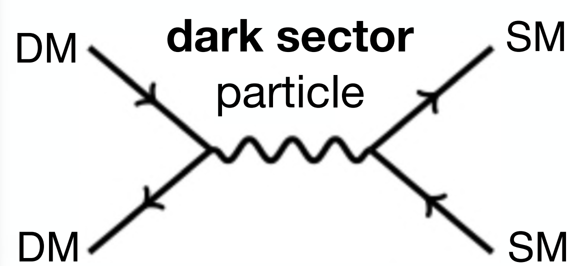


Neutral under the SM interactions.
If thermal, Dark Matter **generically <u>needs</u> additional particles** to annihilate with

Annihilate through weak interactions

dark sector particle = particle not charged under the SM gauge symmetries





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Completely <u>different search strategies</u> depending on the mass of dark matter

(2) Dark Matter & dark sectors

The DM mass scale

MeV GeV TeV

Dark sectors

Thermal DM

WIMPs

axions (10^{-6} eV)

sterile neutrinos (keV)

Primordial black holes (10^{58} GeV)

Neutral under the SM interactions.

Annihilate through weak interactions

Lee-Weinberg bound

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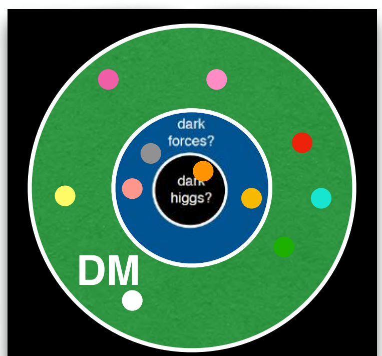

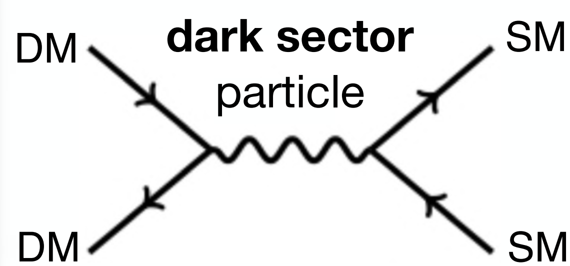

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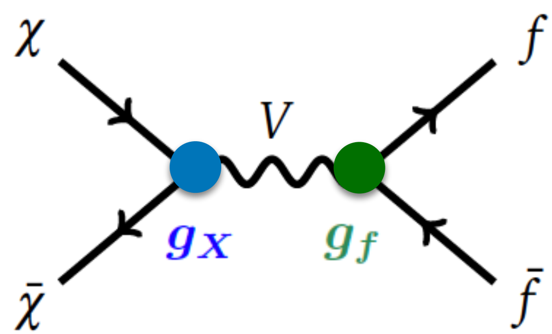
Completely <u>different search strategies</u> depending on the mass of dark matter

Exercise: Lee-Weinberg bound

The thermal freezeout calculation for a (light) DM particle annihilating to light fermions



Minimum annihilation cross section needed for a thermal relic DM candidate (to avoid overabundance):

$$\langle \sigma v \rangle^{\mathrm{min}} \simeq \frac{10^{-9}}{\mathrm{GeV}^2}$$

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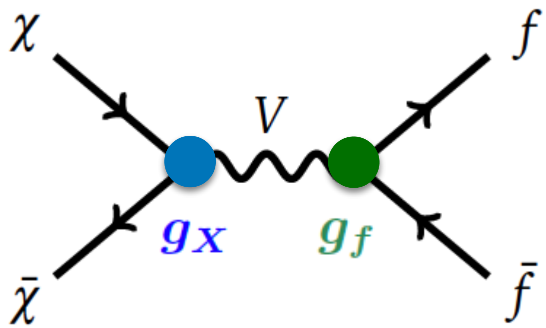

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($m_f << m_X$)

$$m_V > m_X \Rightarrow \langle \sigma v \rangle \simeq \frac{16\pi \alpha_X \alpha_f m_X^2}{m_V^4}$$

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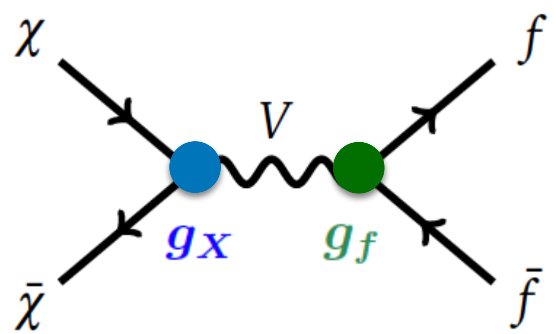

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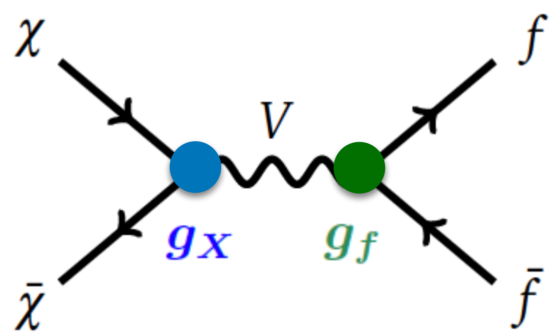

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Thermal origin is a simple and compelling idea for the origin of dark matter.
How does it work at low mass?

Chapter 2

Generalities of <u>minimal freeze-out dark sector models</u>

* Thermal targets (2 different regimes according to the DM mass)
* Complementarity between accelerator experiments and direct / indirect DM searches

Dark sector portals to the Standard Model

Since we live in the Standard Model sector, how can we access (and test) the dark sector?

What are the interactions responsible of Dark Matter-SM thermalization?

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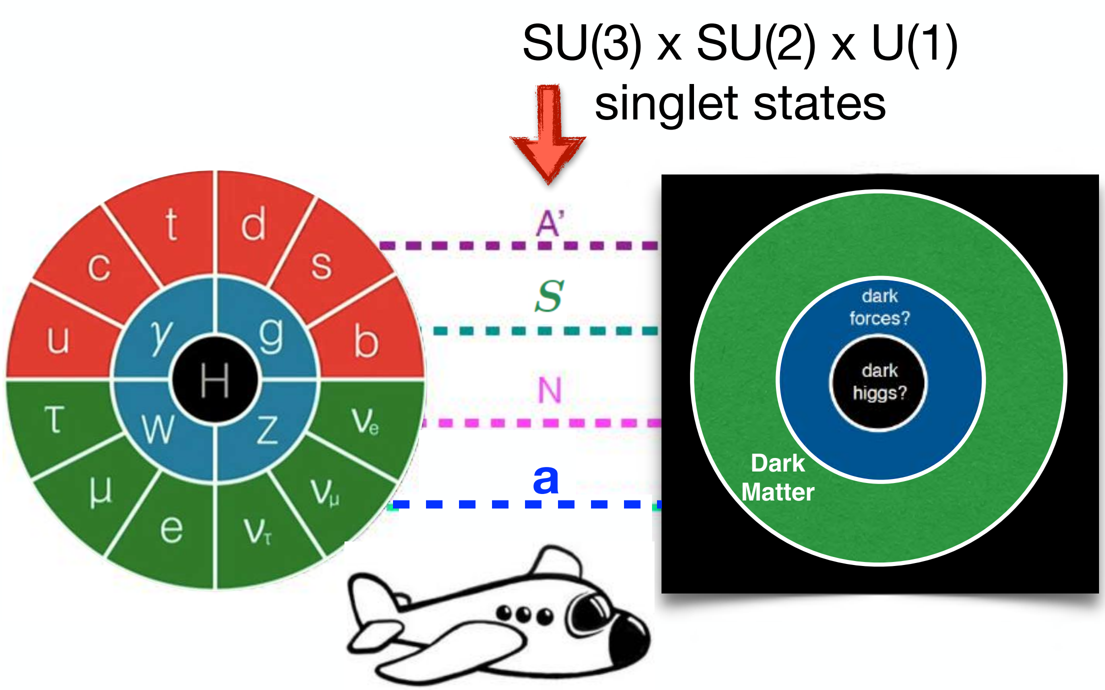

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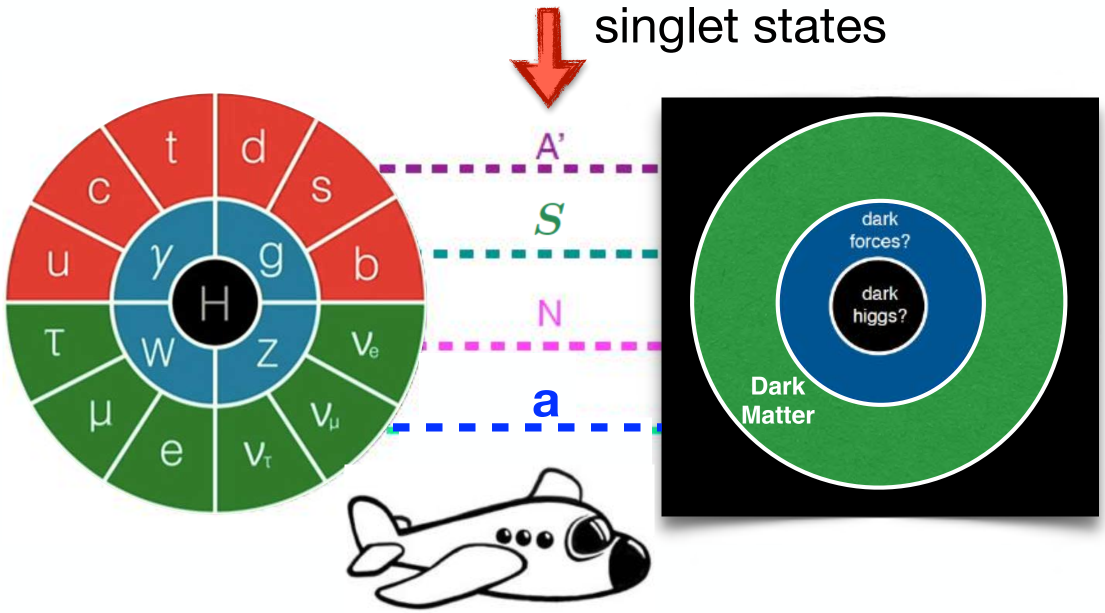
There is only a small set of **“portal”** interactions with the SM

SU(3) x SU(2) x U(1) singlet states



“Portals”:

Dark photon	$\epsilon Z^{\mu\nu} A'_{\mu\nu}$
Higgs	$\kappa \lvert H \rvert^2 \lvert S \rvert^2$
Neutrino	$y H L N$
Axion	$\frac{1}{f_s} F_{\mu\nu} \tilde{F}_{\mu\nu} a$

Only possible couplings at dimension < 6, consistent with SM symmetries

We can also gauge an anomaly-free symmetry of the SM,
$U(1)_{B-L}$, $U(1)_{L\mu - L\tau}$: $(\bar{f}\gamma^\mu f) Z'_\mu$

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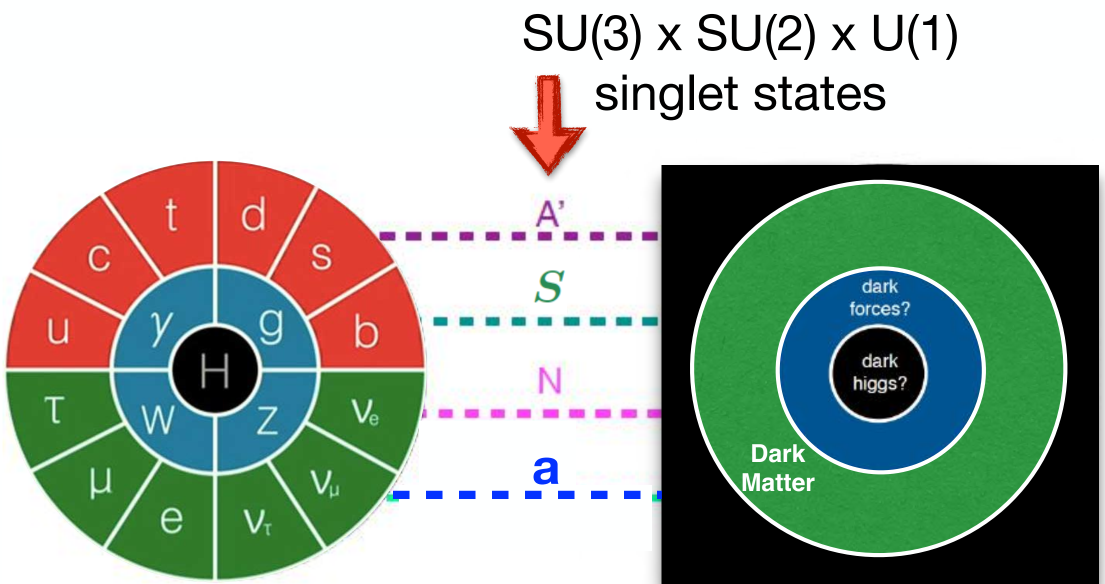

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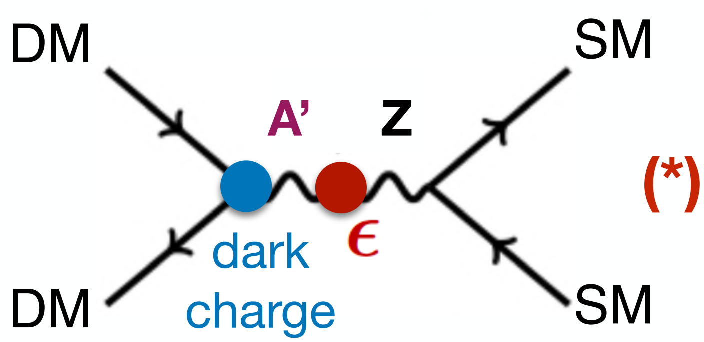
Example:



“Thermal goal” for Dark Matter models

Dark photon	$\epsilon Z^{\mu\nu} A'_{\mu\nu}$
Higgs	$\kappa \lvert H \rvert^2 \lvert S \rvert^2$
Neutrino	$y H L N$
Axion	$\frac{1}{f_s} F_{\mu\nu} \tilde{F}_{\mu\nu} a$

The portal coupling cannot be too small if we want to have a thermal Dark Matter freeze-out scenario

The Standard Model needs to be at least a little coupled to the dark sector

Experimental thermal target

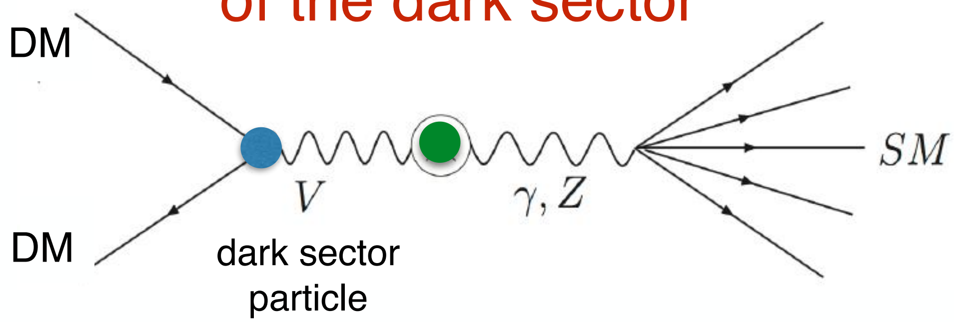
Many opportunities for accelerator experiments!

- high energy
- high intensity

Thermal targets & signatures @ accelerators

Two general classes of thermal DM:

1. **DM is the lightest state** of the dark sector



Relic abundance regulated by ●, ●

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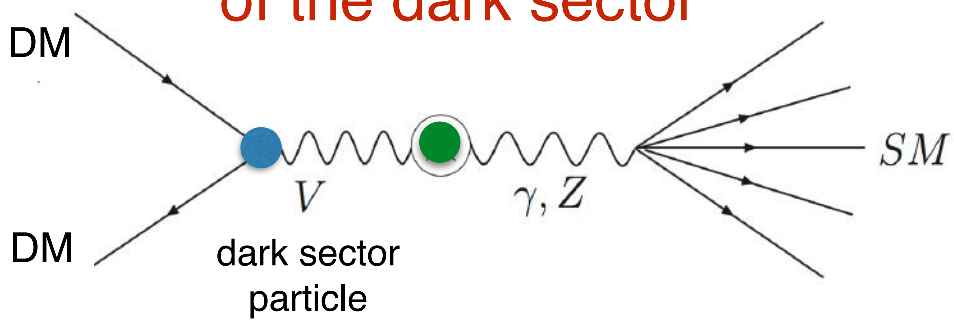

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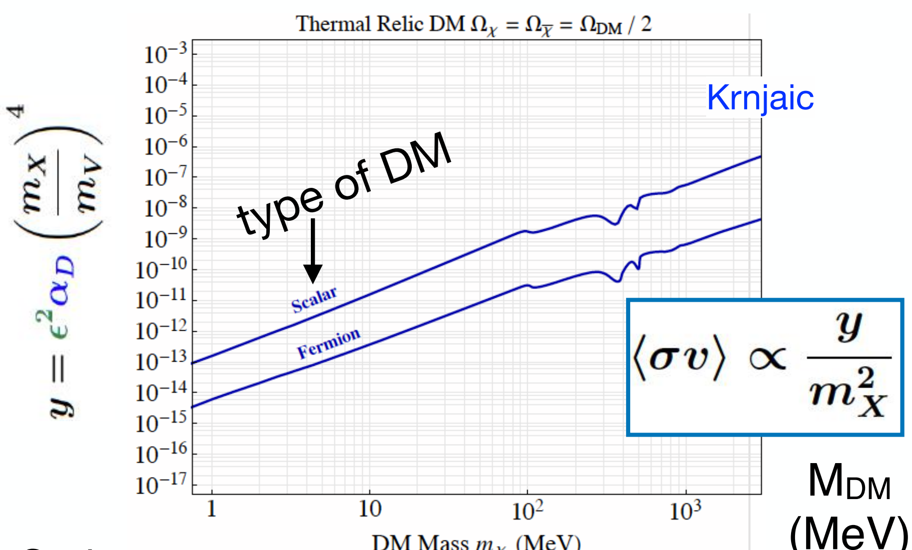

$$\langle \sigma v \rangle \propto \frac{y}{m_X^2}$$

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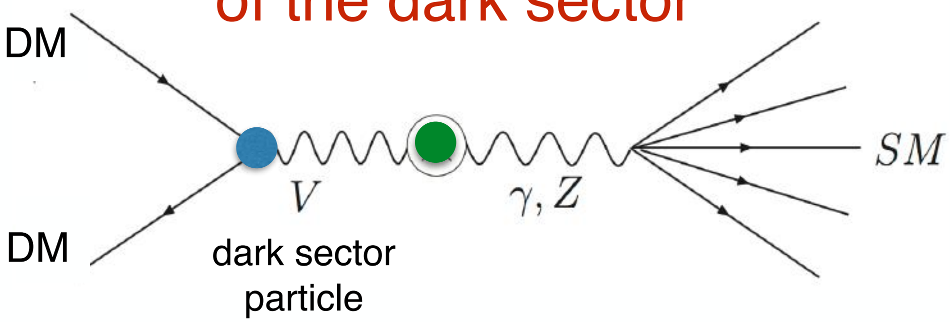

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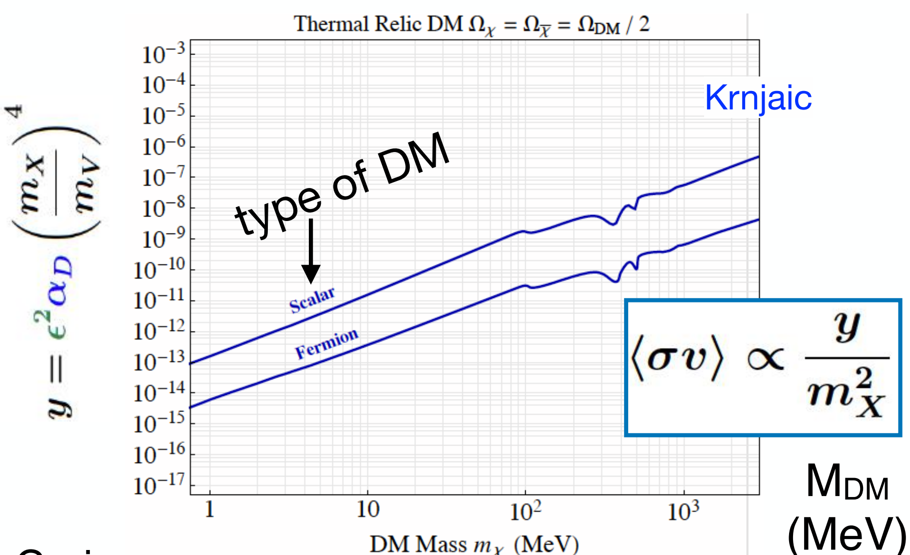
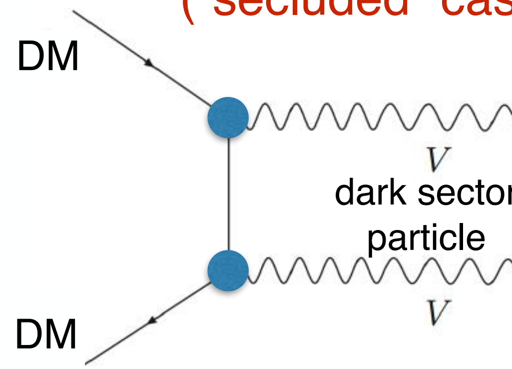


$$\boxed{\langle \sigma v \rangle \propto \frac{y}{m_X^2}}$$

2. **One (or more) particles** of the dark sector **are lighter than DM**

("secluded" case)

Pospelov, Ritz, Voloshin, 0711.4866



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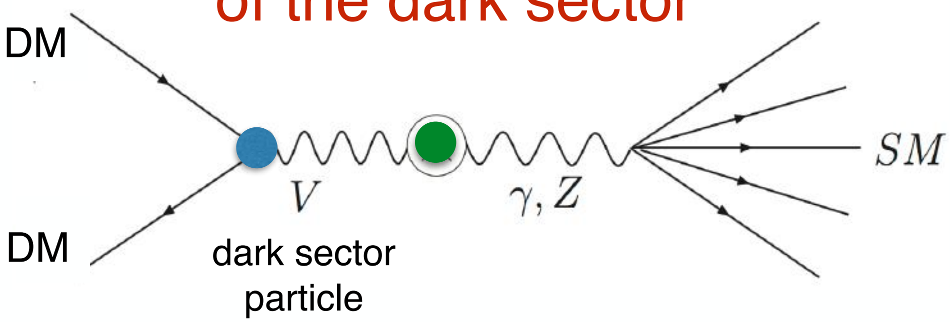

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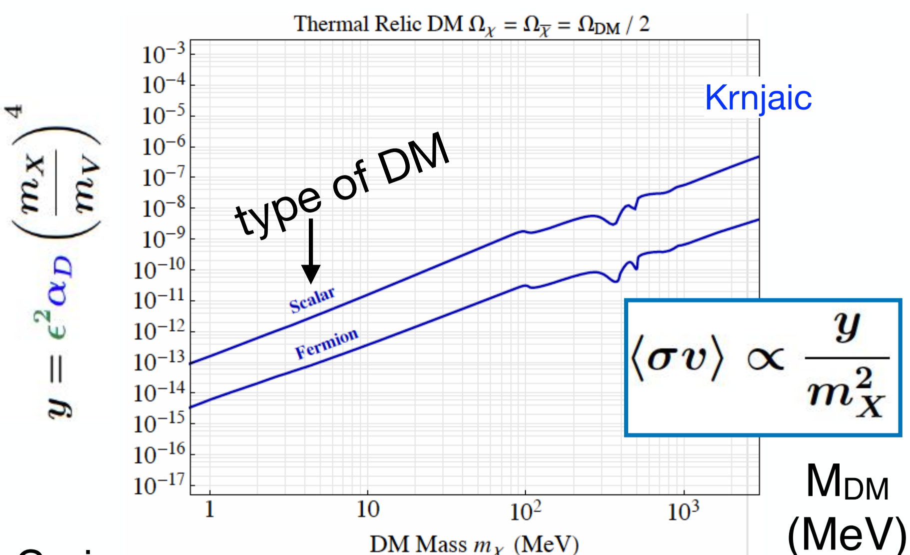

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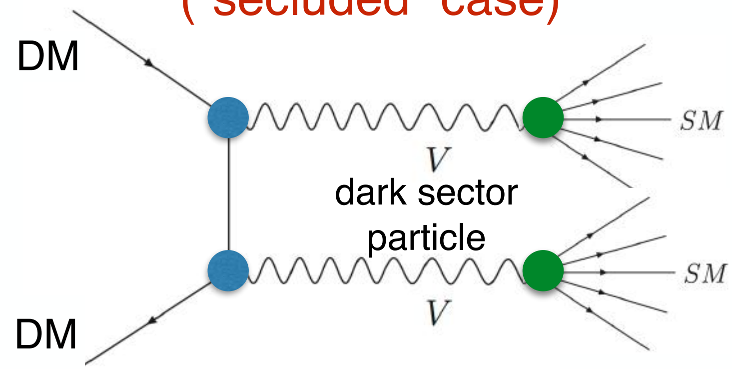

thermalization

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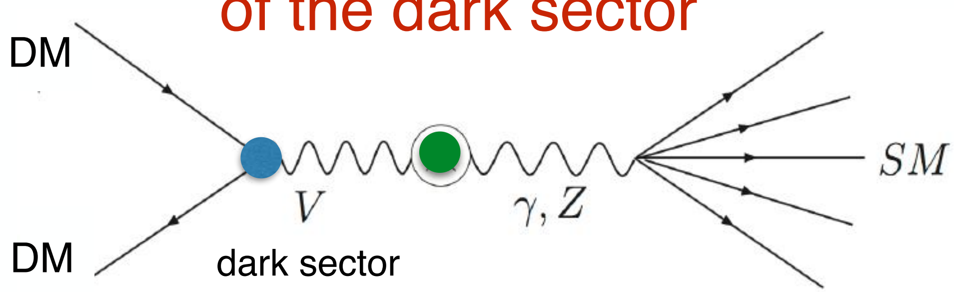

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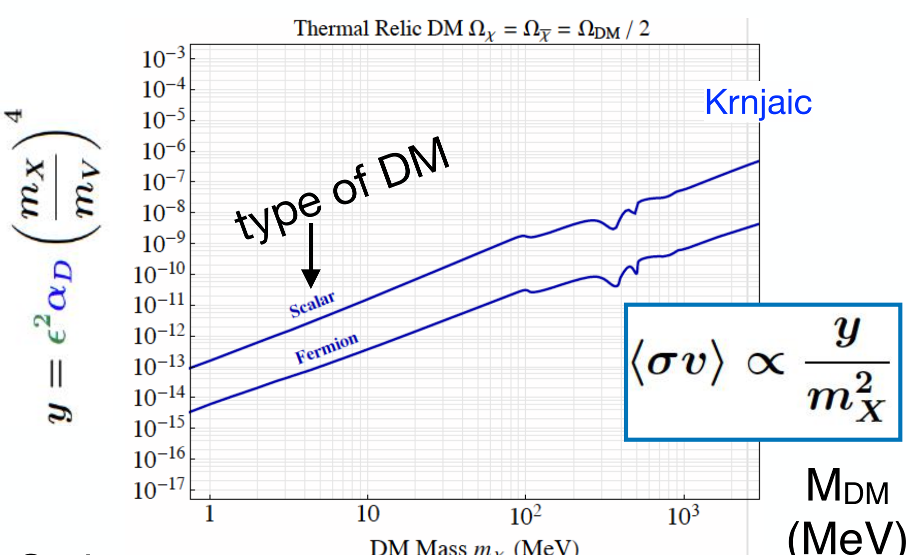

M_{DM} (MeV)

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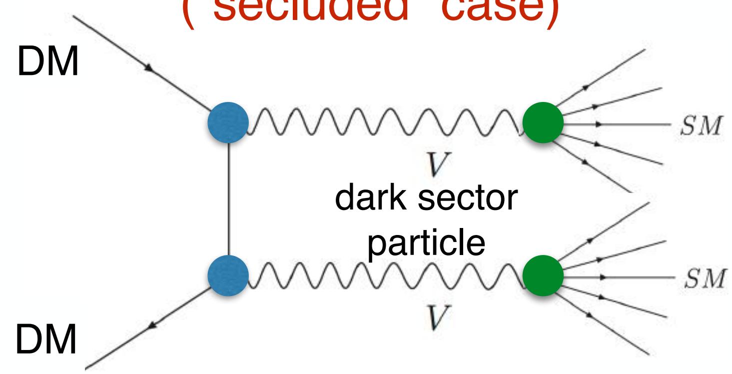
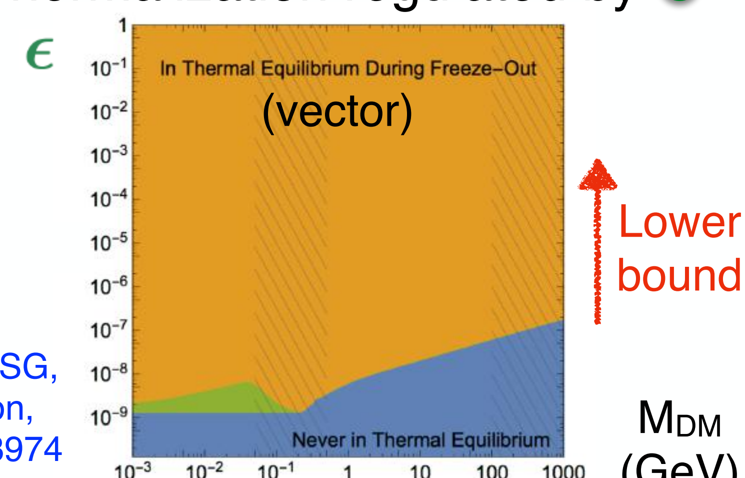


Thermalization regulated by ●



Evans, SG, Shelton, 1712.03974

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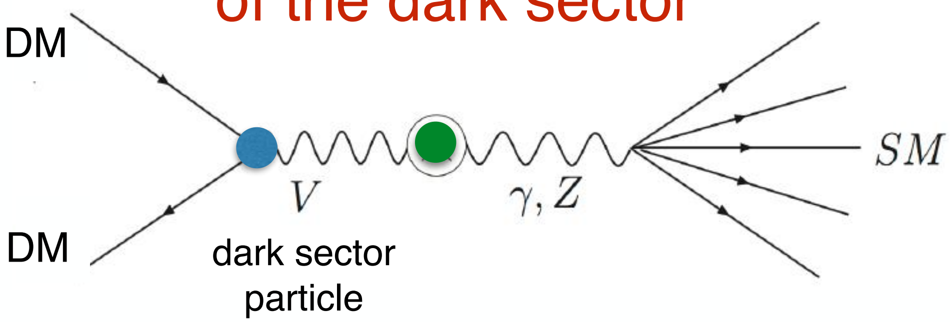

Signatures at accelerator experiments:

The dark sector particle mainly decays **invisible** (to DM)

V→ DM DM

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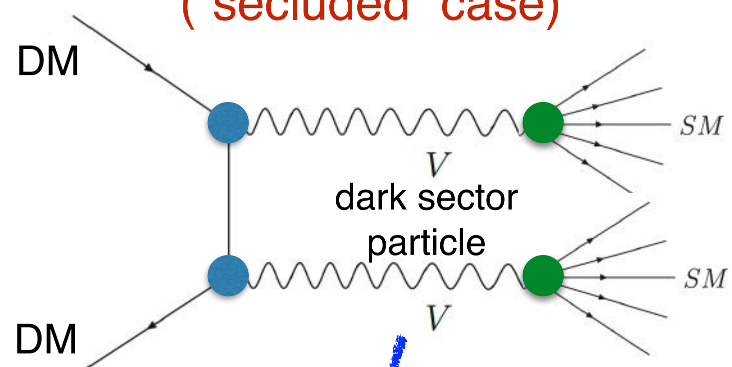

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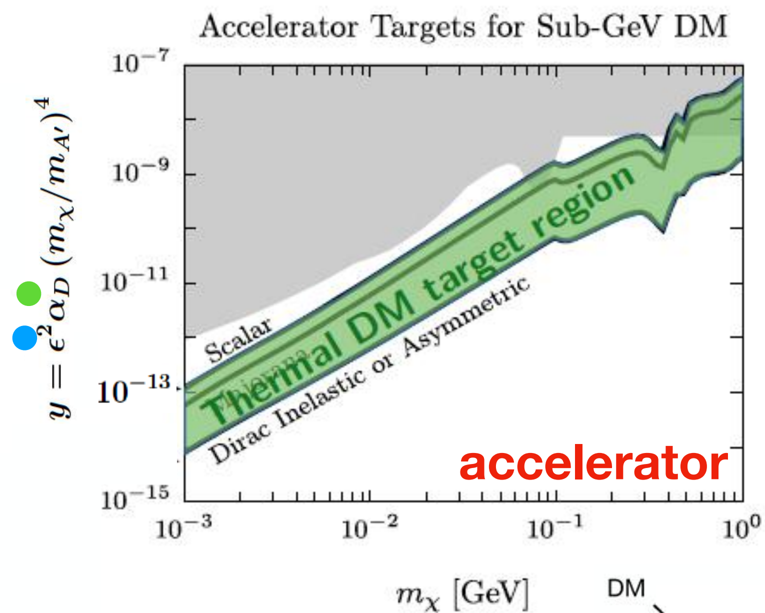
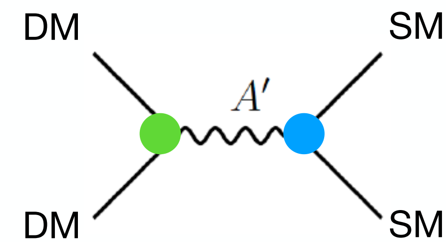
Complementarity with DM direct detection

2.



annihilation



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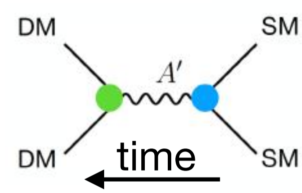

Accelerator production recreates the kinematic conditions of the early universe.

It is ~ unaffected by the nature of DM

Complementarity with DM direct detection

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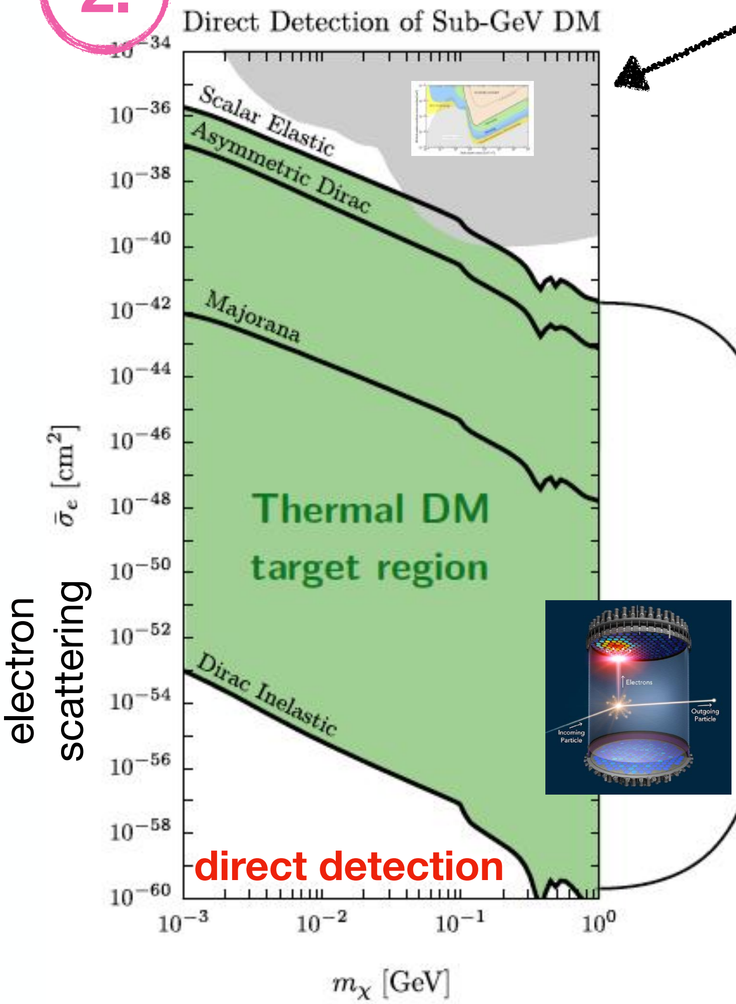
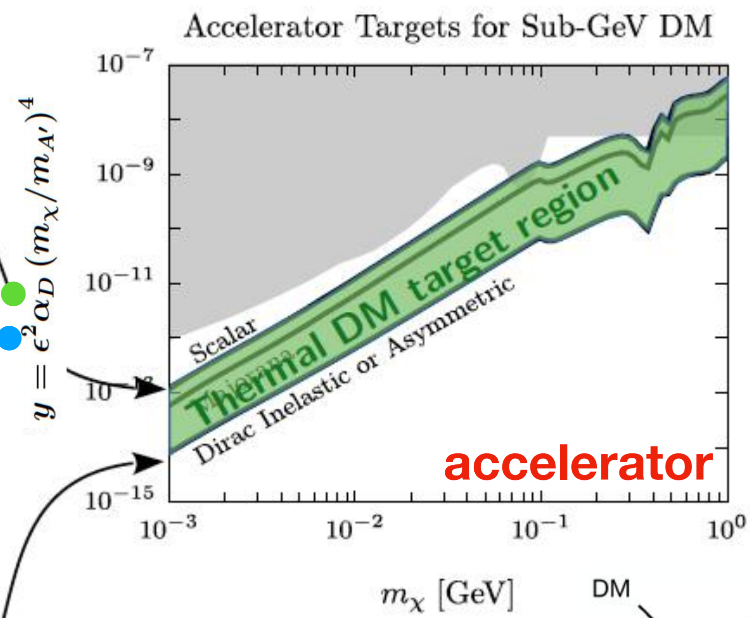
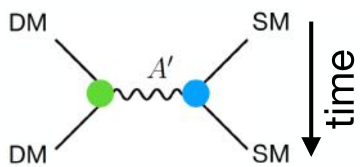
To connect these two probes, one needs to make model assumptions







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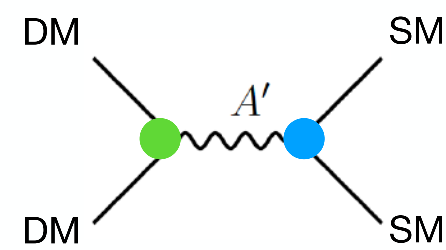

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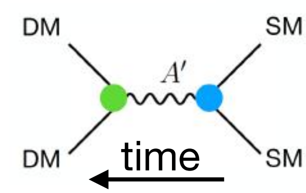

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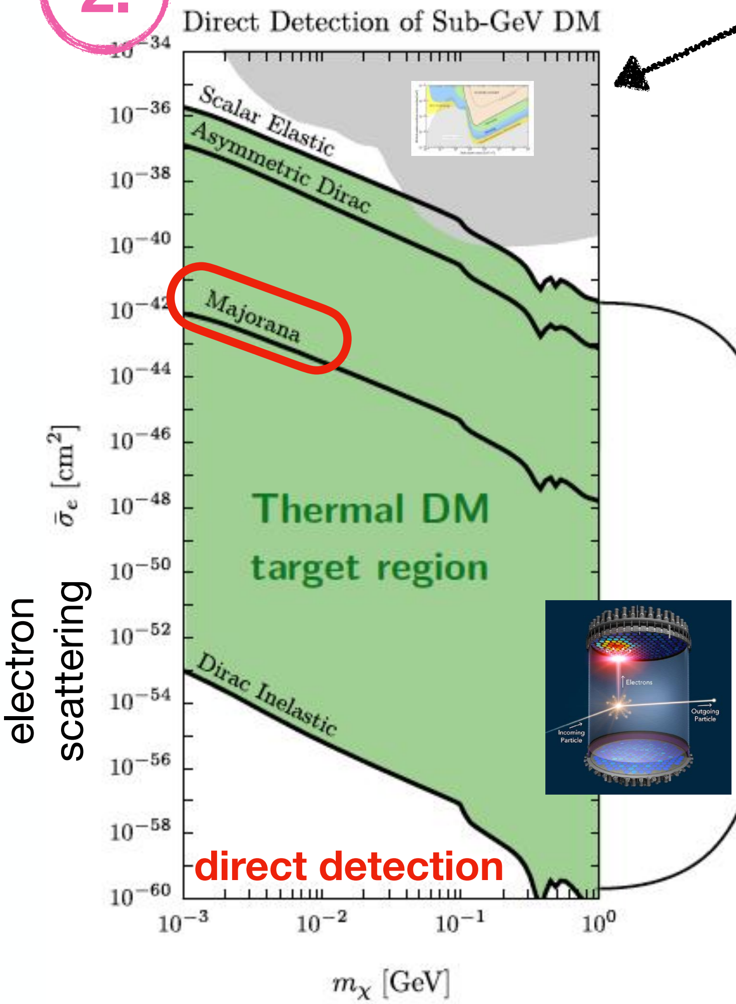

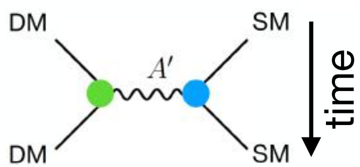

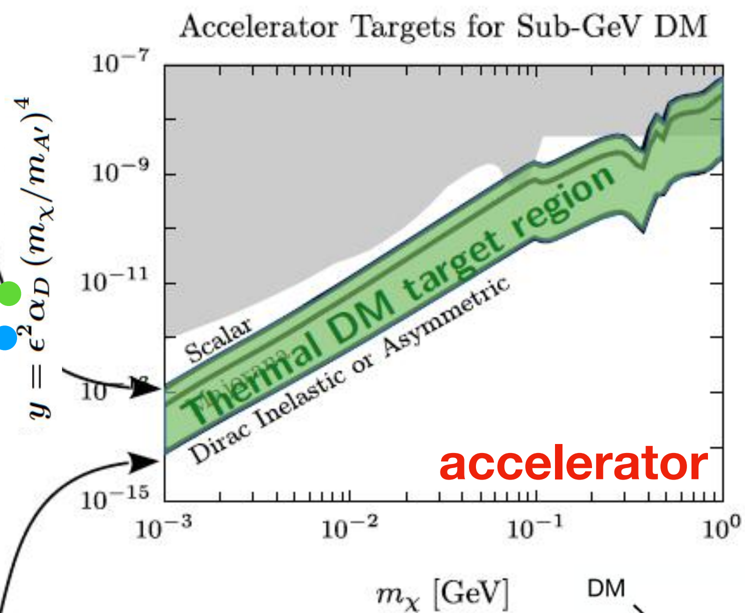

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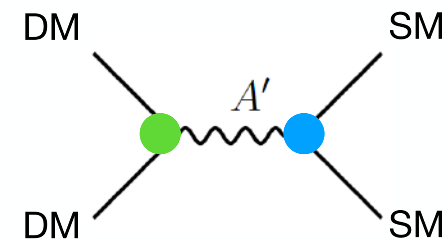

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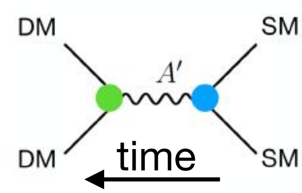

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2. Few comments on direct detection

Rate

Scattering rate:

$$R_\chi = \frac{1}{\rho_T}\frac{\rho_\chi}{m_\chi}\int d^3v f_\chi(v)\frac{V d^3p'_\chi}{(2\pi)^3}\sum_f |\langle f,\bar{p}'_\chi|\mathcal{H}_{\chi T}|i,\bar{p}_\chi\rangle|^2\, 2\pi\delta(E_f - E_i + E'_\chi - E_\chi)$$

$$\langle f,\bar{p}'_\chi|\mathcal{H}_{\chi T}|i,\bar{p}_\chi\rangle = \int \frac{d^3q}{(2\pi)^3}\langle\bar{p}'_\chi|\mathcal{O}_\chi(\bar{q})|\bar{p}_\chi\rangle\langle f|\mathcal{O}_T(\bar{q})|i\rangle$$

Depends on the DM model

Depends on the target response

Dark photon mediated **Majorana** DM model: $(q/m_\chi)^2$ suppressed scattering cross section ⇒ Suppression of the rate at direct detection experiments

2. Few comments on direct detection

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Depends on the DM model
Depends on the target response

Dark photon mediated **Majorana** DM model: $(q/m_\chi)^2$ suppressed scattering cross section ⇨ Suppression of the rate at direct detection experiments

Kinematics

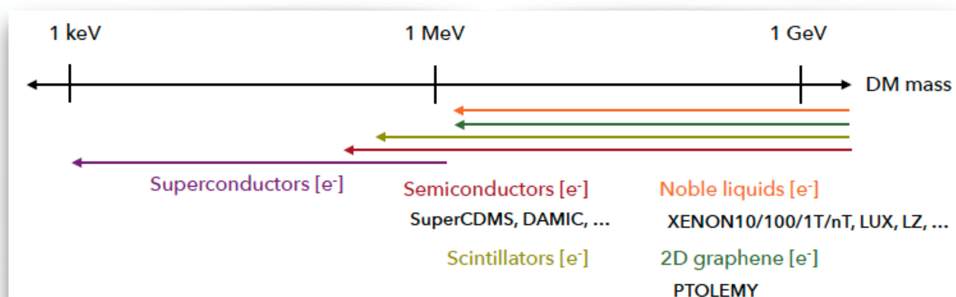
On slide 12: $E_R^{\max} = \frac{q_{\max}^2}{2m_N} = \frac{2\mu_{\chi N}^2 v^2}{m_N}$ with $\mu_{\chi N} = \frac{m_\chi m_N}{m_\chi + m_N}$ (for scattering with nuclei)

Scattering with electrons can give access to lower DM masses ($m_N \to m_e$):

If bound electron with a binding energy E_B: $m_\chi \gtrsim 250\ \mathrm{keV}\ \frac{E_B}{1\mathrm{eV}}$

Alexander et al., 1608.08632

Several materials are under investigation:



+ many studies of new detection strategies using nuclei

For a review: Kahn, Lin, 2108.03239

Complementarity with DM indirect detection

3.

CMB limits are mainly sensitive to the net energy deposited in the ee - photon plasma by DM annihilations near recombination

The CMB bounds can be evaded if annihilation is suppressed at late times or at low dark matter velocities (e.g., in the case of p-wave annihilation), or if the dark matter annihilates entirely to neutrinos or invisible particles.

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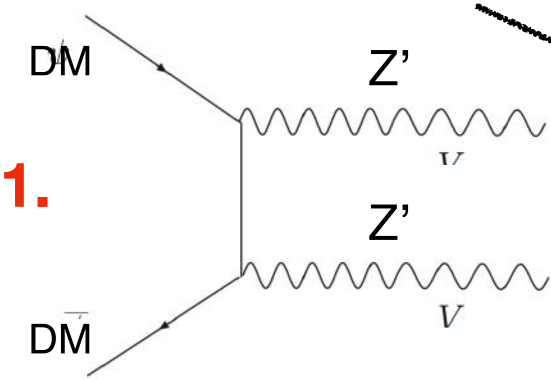
These limits exclude thermal relic dark matter annihilating to SM particles via s-wave processes for dark matter masses below 10 GeV

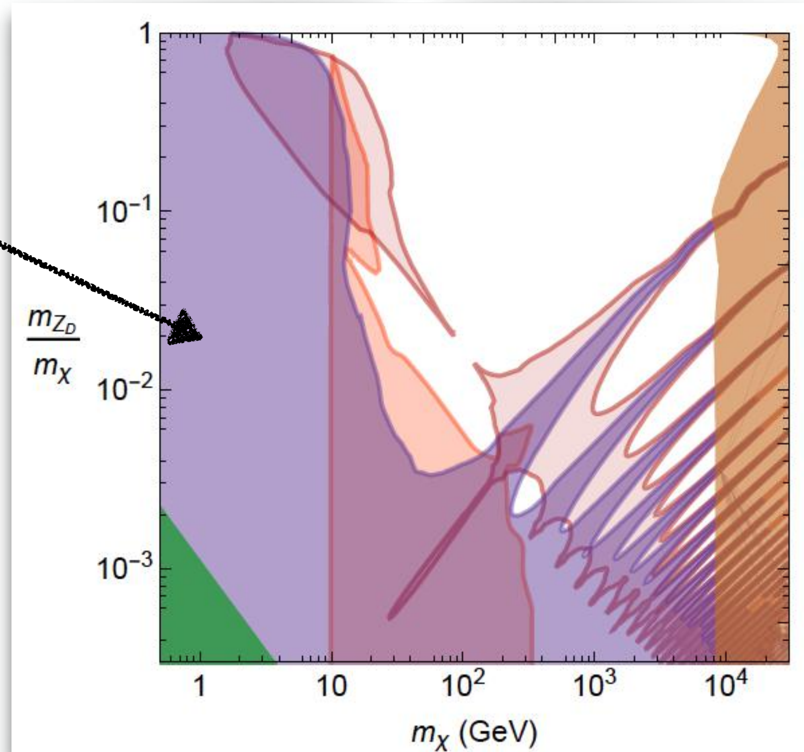
See Berlin et al, 1508.05390 for a classification

See also lectures by R. Leane

1.



Evans, SG, Shelton, 1712.03974



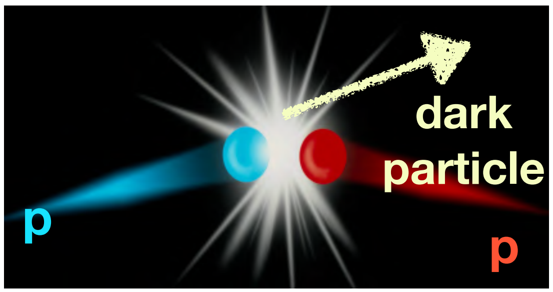
2. s-channel Dirac fermion DM annihilating through a dark vector

A broad program at accelerator experiments

1.

… of light (< few GeV) DM and dark-sector particles

The LHC

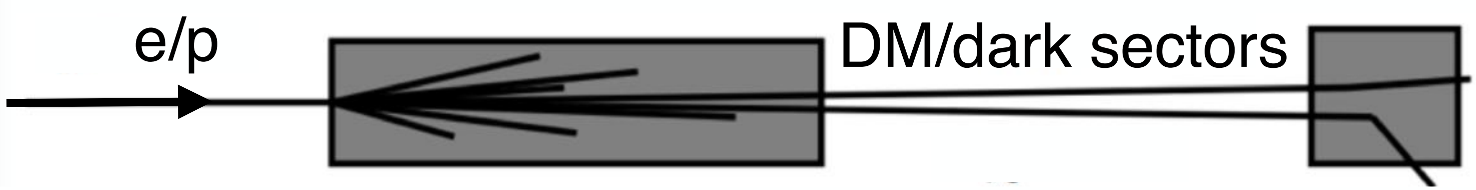


Meson factories

NA62

Belle II

Fixed target experiments



Beam **(high intensity)** | **Dump/shield/ thin target** | **Decay volume** | **Detector**

Chapter 3

The minimal dark photon model: how to test it?

Some comment on the minimal dark scalar model

The dark photon / Z boson

Nature seems well described by a SU(3) x SU(2)$_L$ x U(1)$_{em}$ gauge theory. We need to check this assumption!

Additional gauge symmetries in nature? **U(1)'?**

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for a review:
Fabbrichesi, Gabrielli, Lanfranchi, 2005.01515

Holdom, '86

$$\mathcal{L} \supset -\frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} - \frac{1}{4}\hat{Z}_{D\mu\nu}\hat{Z}_D^{\mu\nu} + \frac{\epsilon}{2\cos\theta}\hat{Z}_{D\mu\nu}\hat{B}_{\mu\nu} + \frac{1}{2}m_{D,0}^2\hat{Z}_D^{\mu}\hat{Z}_{D\mu} - g_D\hat{Z}_D^{\mu}(\bar{X}\gamma_\mu X)$$

The dark photon / Z boson

Nature seems well described by a SU(3) x $SU(2)_L$ x $U(1)_{em}$ gauge theory. We need to check this assumption!

Additional gauge symmetries in nature? **U(1)'?**

for a review:
Fabbrichesi, Gabrielli, Lanfranchi, 2005.01515

Holdom, '86

Mixing with the SM hyper-charge gauge boson

coupling to DM

$$\mathcal{L} \supset -\frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} - \frac{1}{4}\hat{Z}_{D\mu\nu}\hat{Z}_D^{\mu\nu} + \frac{\epsilon}{2\cos\theta}\hat{Z}_{D\mu\nu}\hat{B}_{\mu\nu} + \frac{1}{2}m^2_{D,0}\hat{Z}^\mu_D\hat{Z}_{D\mu} - g_D\hat{Z}^\mu_D(\bar{X}\gamma_\mu X)$$

arising from
* dark Higgs mechanism or
* Stueckelberg mechanism

Massive photon

The dark photon / Z boson

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<u>**Exercise**</u>: after electroweak symmetry breaking, the mass terms are given by:

~SM photon

$$(A^\mu, Z_0^\mu, Z_{D,0}^\mu)\; m_{Z,0}^2 \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & -\epsilon\tan\theta \\ 0 & -\epsilon\tan\theta & \epsilon^2\tan^2\theta + \frac{m_{D,0}^2}{m_{Z,0}^2} \end{pmatrix} \begin{pmatrix} A^\mu \\ Z_0^\mu \\ Z_{D,0}^\mu \end{pmatrix}$$

~dark photon/Z

mixing

having defined

$$\begin{pmatrix} Z_{D,0} \\ B \end{pmatrix} = \begin{pmatrix} \sqrt{1-\frac{\epsilon^2}{\cos^2\theta}} & 0 \\ -\frac{\epsilon}{\cos\theta} & 1 \end{pmatrix} \begin{pmatrix} \widehat{Z}_D \\ \widehat{B} \end{pmatrix}$$

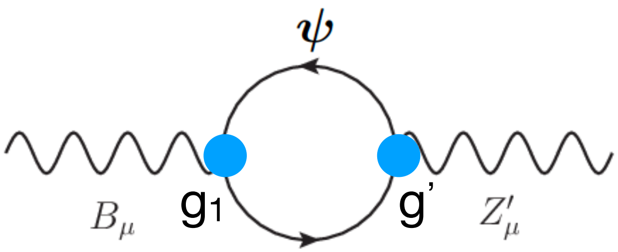
after diagonalization: A, Z, **Z'** (mass eigenstates)

How large is ε?

$$\frac{\epsilon}{2\cos\theta}\widehat{Z}_{D\mu\nu}\widehat{B}_{\mu\nu}$$

This is a dimensionless parameter ⇨ it can be O(1)

If it is absent at the tree level, it can be generated by the loop of heavy New Physics particles charged under both U(1)' and $U(1)_Y$

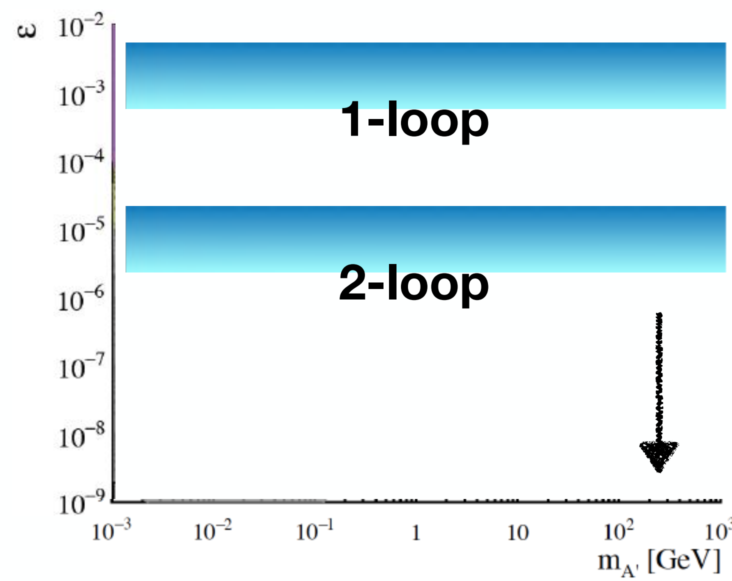


$$\Rightarrow \quad \epsilon = \frac{g' g_1}{16\pi^2}\log\left(\frac{M_\psi}{\Lambda}\right) \simeq 10^{-3}\,\mathcal{O}(1-10)$$

Some theories predict a even smaller kinetic mixing parameter: New Physics particles in doublets of opposite dark charges

⇨ 2-loop contributions, $O(10^{-5})$

Note: as we discussed, for DM freeze-out models, ε cannot be too small. In general, it cannot be smaller than $\sim O(10^{-8})$.



Electro-weak precision tests (EWPTs) and the dark photon

Because of kinetic mixing,
the Z' mixes with the SM Z boson

Effects on the **Z phenomenology**:

1. Tree level shift in the Z mass

(more specifically the Z and W mass get a relative shift)

$$m_Z^2 \sim m_{Z0}^2 (1 + \epsilon^2 \sin^2 \theta)$$

2. Modification of the Z couplings

$$(Z f \bar{f}) \left(1 + \epsilon^2 \sin^2 \theta F(T_3, Q)\right)$$

These observables have been measured very precisely at LEP and SLC!

Model-independent

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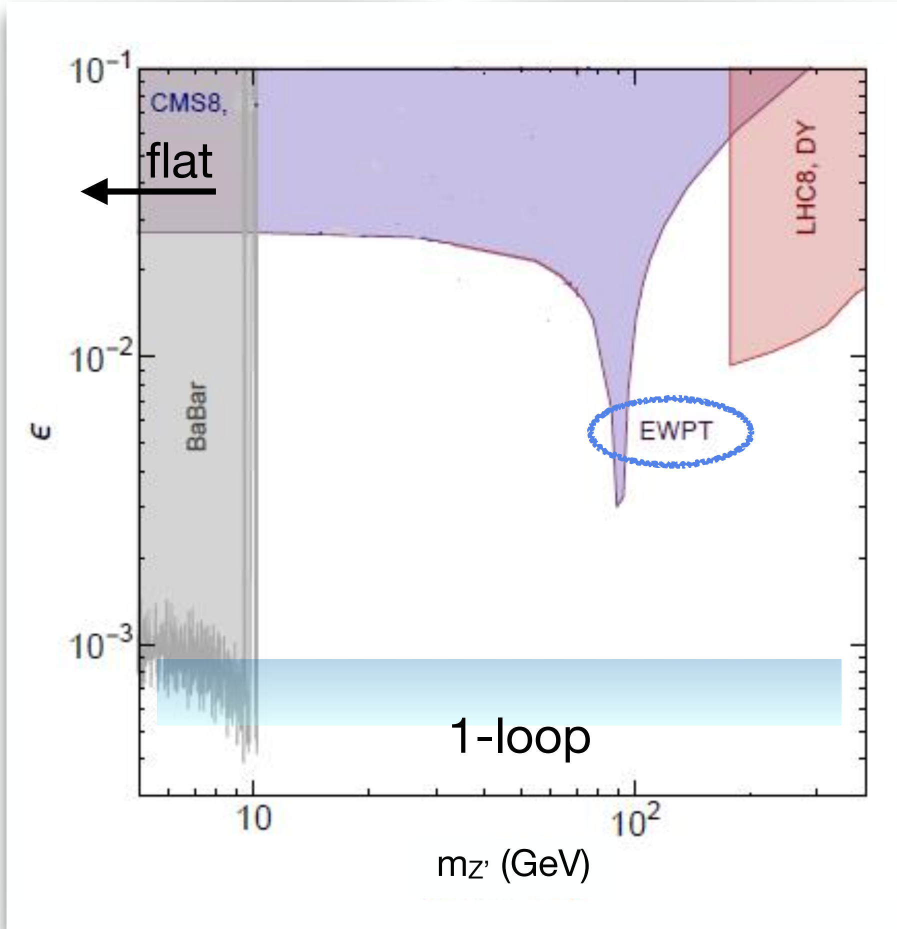


Curtin, Essig, SG, Shelton, 1412.0018
See also Hook, Izaguirre, Wacker, 1006.0973

Large improvements on the bound (by ~an order of magnitude) using future FCC-ee collider measurements (tera-Z)

Couplings of the dark photon

Couplings to SM fermions

$$\mathcal{L}_{Z'\bar{f}f} = g_{Z'f\bar{f}}\, Z'_\mu (\bar{f}\gamma^\mu f)$$

$$g_{Z'f\bar{f}} \equiv \frac{g}{\cos\theta}\left(-\sin\alpha\,(t^3\,\cos^2\theta - Y\,\sin^2\theta) + \epsilon\cos\alpha\,\tan\theta\, Y\right)$$

$g_{Z'f\bar{f}} \simeq eQ\epsilon$ for a light Z' (photon-like couplings)

$\sin\alpha \propto \epsilon$

Coupling to DM

$$\mathcal{L}_{Z'\bar{X}X} = g_{Z'X\bar{X}}\, Z'_\mu (\bar{X}\gamma^\mu X)$$

$$g_{Z'X\bar{X}} \equiv g_D \cos\alpha$$

Coupling to the Higgs

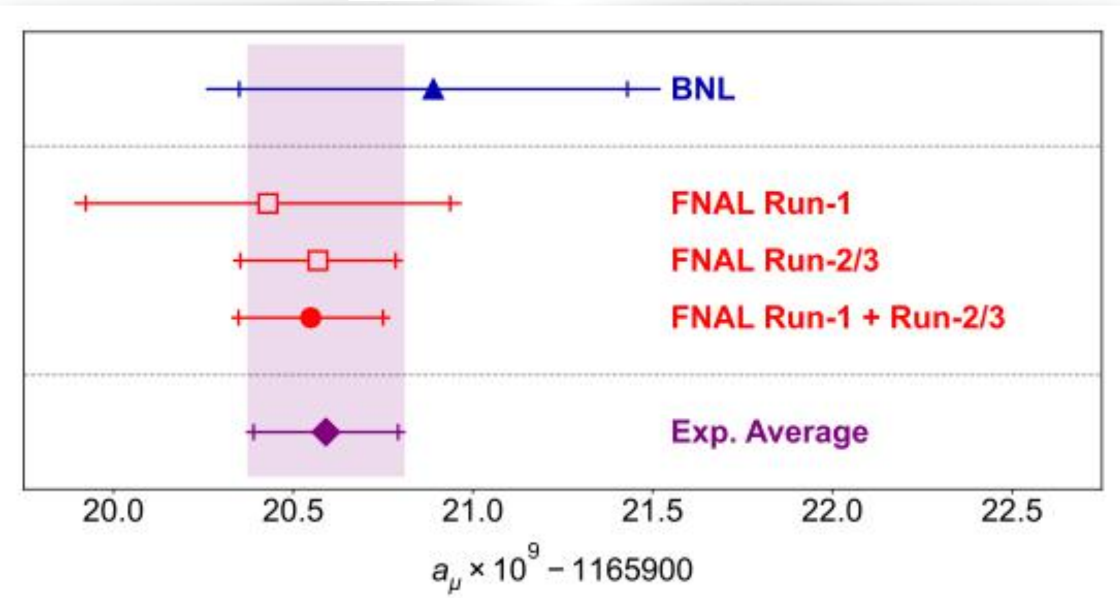
$$\mathcal{L}_{hZZ'} = \left[\frac{2i\epsilon\tan\theta}{v} m^2_{Z_0}\left(2\frac{\epsilon^2\tan^2\theta - 1}{\epsilon\tan\theta}\sin 2\alpha - \cos 2\alpha\right)\right] hZ^\mu Z'_\mu$$

$$\simeq \frac{2i\epsilon\tan\theta}{v}\frac{m^2_{Z'}m^2_Z}{m^2_Z - m^2_{Z'}} hZ^\mu Z'_\mu$$

Exercise: check that these expressions are correct

Dark photons and (g-2)$_\mu$

g-2 collaboration at Fermilab, 2308.06230



$$a_\mu(\text{Exp}) - a_\mu(\text{SM}) = (249 \pm 48) \times 10^{-11}$$ **?**

Evaluated taking this last experimental result and the theory prediction from the g-2 initiative white paper: Aoyama et al., 2006.04822

Dark photons and (g-2)$_\mu$

Model-independent

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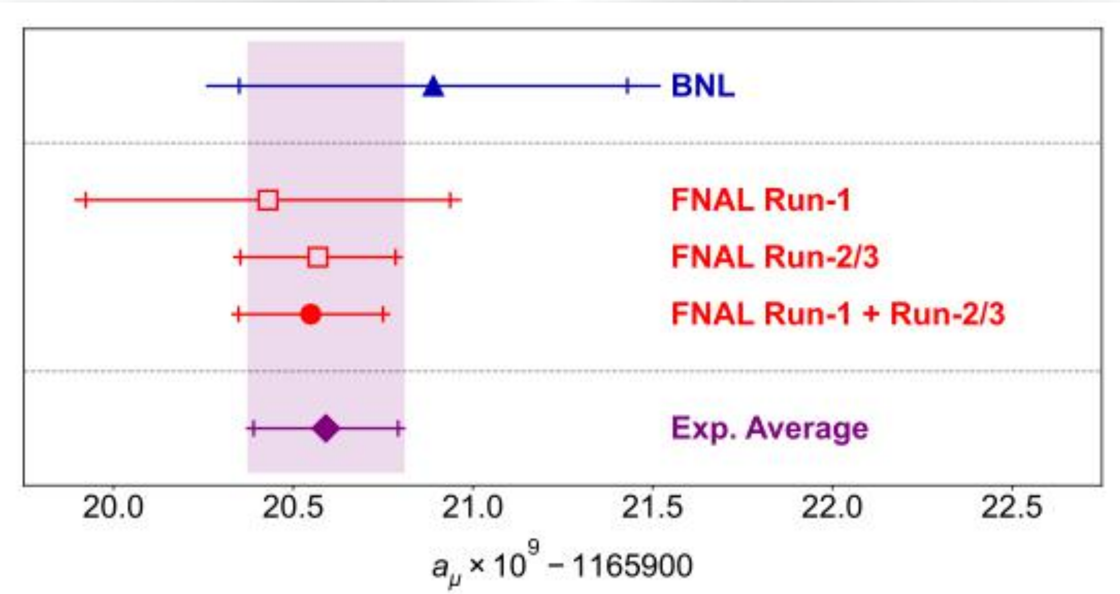

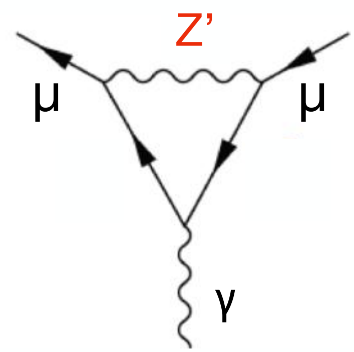

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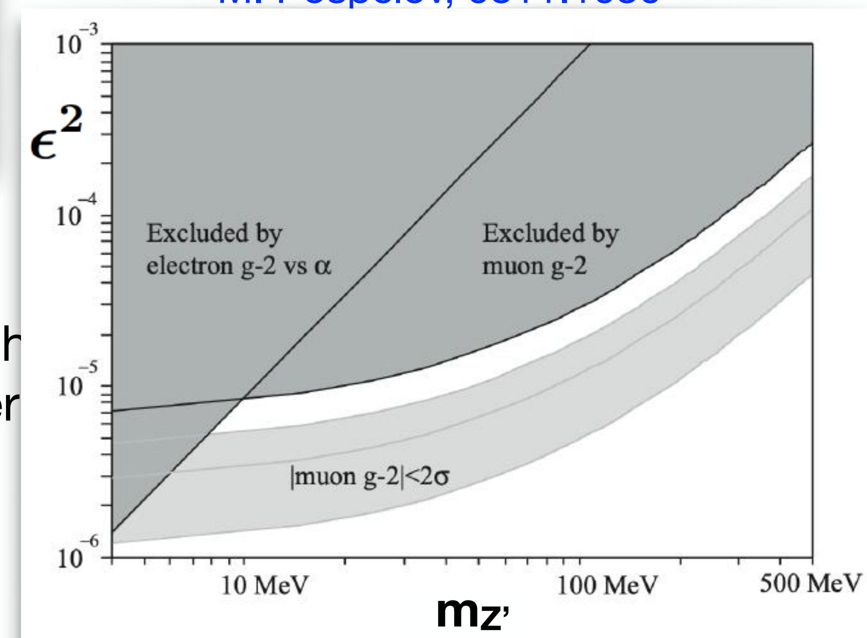
M. Pospelov, 0811.1030



Old result. Numbers should be updated

What did we learn yesterday?

DM thermal freeze-out models are highly predictive.

Vanilla WIMPs have been thoroughly probed by direct detection experiments.

Freeze-in models | Light freeze-out models

Freeze-out models below the few GeV scale:

- need for a dark sector
- less constrained

Minimal portal interactions.

Basics of the dark photon model (model independent bounds).

Does the dark photon decay?

For $\mathbf{m_{Z'} > 2m_X}$, Z' mainly decays to DM particles

1.

(in fact, experimental bounds constrain ε to be small ➡ larger g_D to obtain a DM thermal relic with the measured relic abundance, $\langle \sigma v \rangle \simeq \epsilon^2 \alpha_D \frac{m_X^2}{m_{Z'}^4}$)

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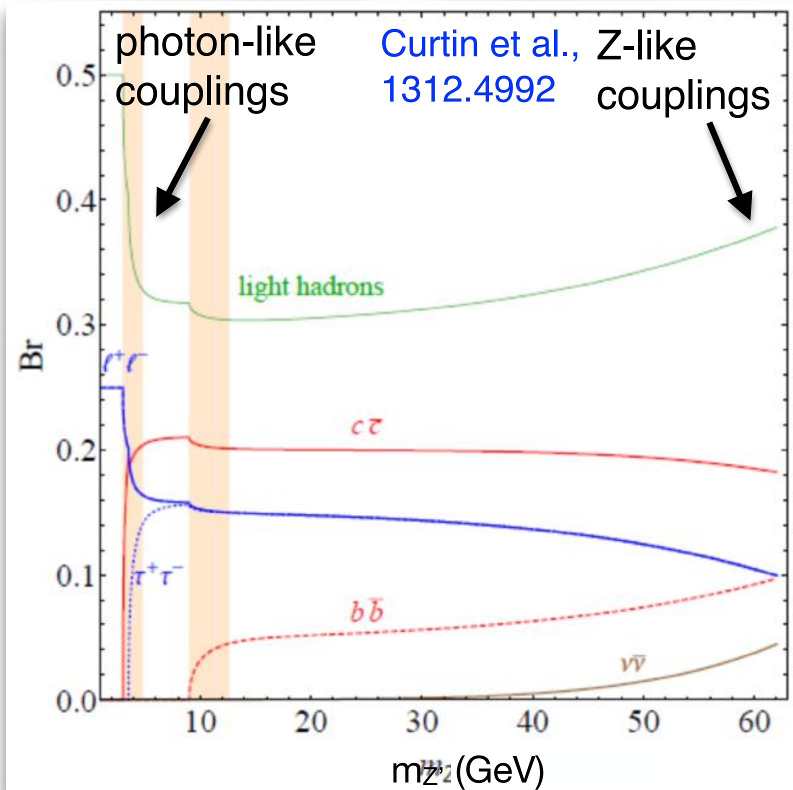
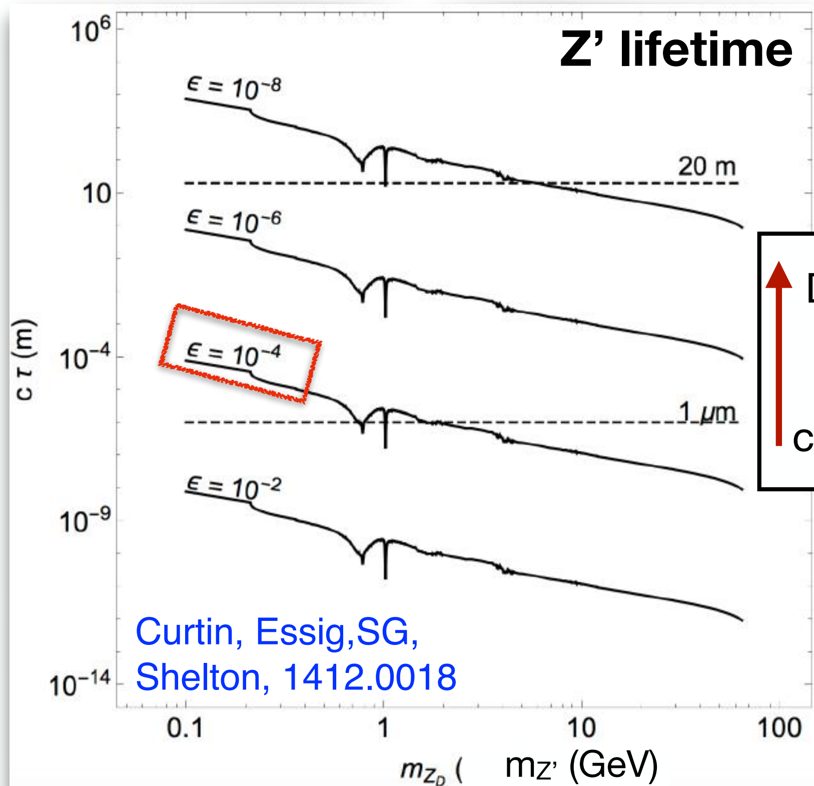
For $\mathbf{m_{Z'} < 2m_X}$, Z' only decays to SM particles

2.





Decreasing kinetic mixing coefficient, ε

No ϵ dependence

Does the dark photon decay?

For $m_{Z'} > 2m_X$, Z' mainly decays to DM particles **1.**

(in fact, experimental bounds constrain ε to be small → larger g_D to obtain a DM thermal relic with the measured relic abundance, $\langle\sigma v\rangle \simeq \epsilon^2\alpha_D \frac{m_X^2}{m_{Z'}^4}$)

For $m_{Z'} < 2m_X$, Z' only decays to SM particles **2.**

Some detail on the calculation:

Define the ratio: $R_{Z_D} \equiv \frac{\Gamma(Z_D \to \text{ hadrons})}{\Gamma(Z_D \to \mu^+\mu^-)} = R_{Z_D}(m_{Z_D})$

then the total width: $\Gamma_{Z_D} = R_{Z_D}\Gamma(Z_D \to \mu^+\mu^-) + \sum_{f=e,\mu,\tau,\nu_{e,\mu,\tau}} \Gamma(Z_D \to f\bar{f})$

$R(s) \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$ is measured accurately and is highly dominated by off-shell $\gamma^* \to$ ff in the s-channel.

→ We can use experimental data to determine $R_{Z_D}(m_{Z_D}) = R(m_{Z_D}^2)$

In this way, we can determine all branching ratios of the dark photon at low mass (where the dark photon has photon-like couplings)

How to produce a dark photon? ("directly")

(At low mass) Z' couples proportionally to the electric charge

⇨ Whenever there is a γ, there will be a Z'

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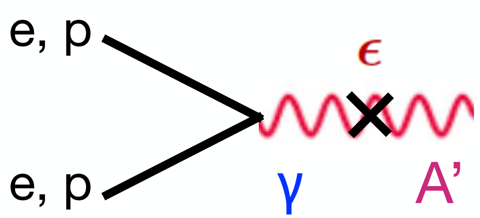
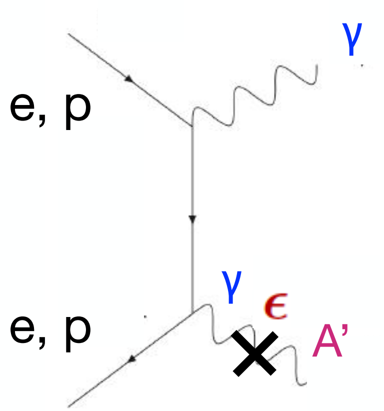
Collider experiments

Drell-Yan production:





$$\sigma \propto \frac{\varepsilon^2 \alpha_{\rm em}^2}{E^2}$$

1/fb at 1GeV (KLOE) competes with 1/ab at 10 GeV (B-factories)

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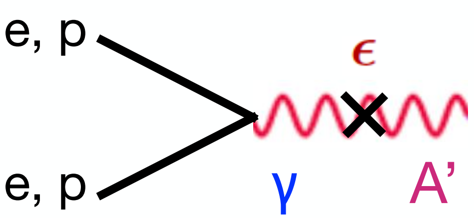

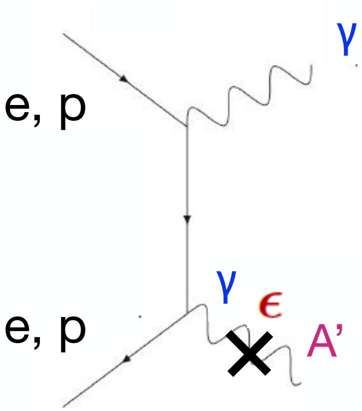

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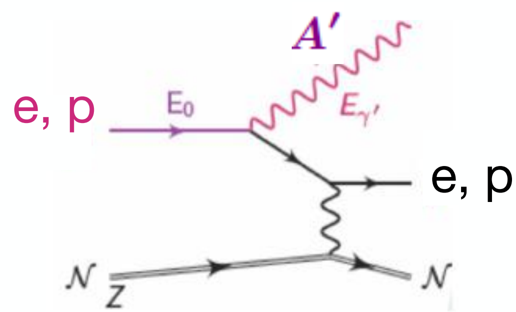
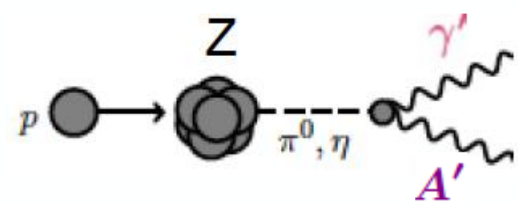
Fixed target experiments



brems-strahlung



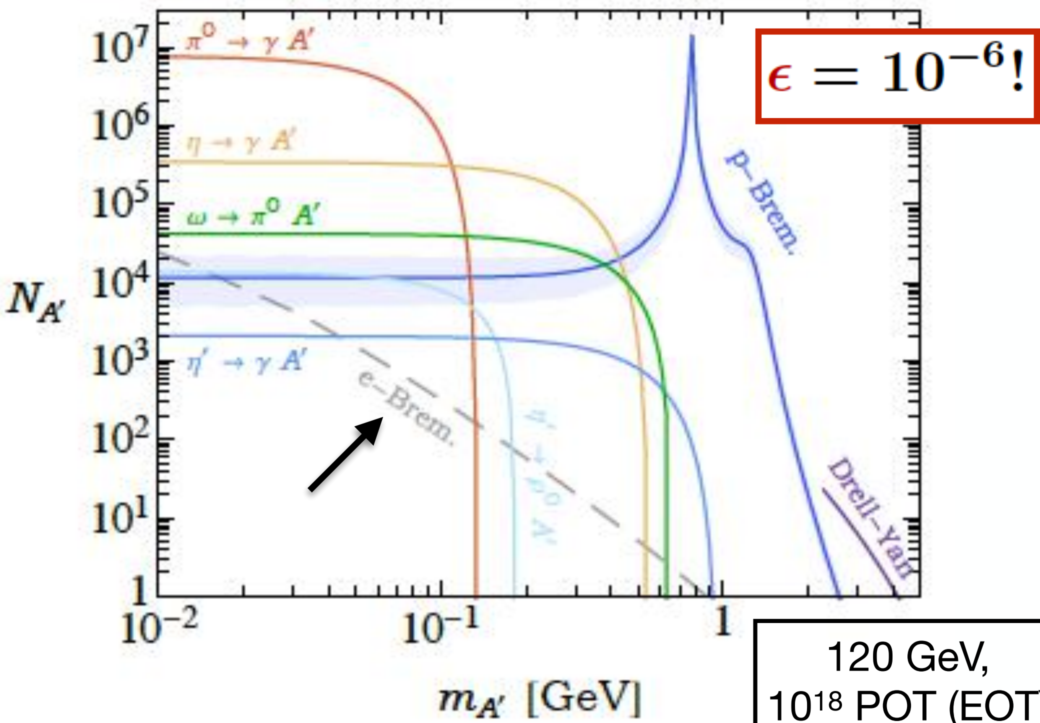
meson decay

$$\sigma \sim \alpha_{\rm em}\, \epsilon^2 \times \sigma_{pp} \quad \text{proton}$$

$$\sigma \sim \frac{\alpha_{\rm em}^3\, \epsilon^2}{m_{A'}^2}\, Z^2 \quad \text{electron}$$

Many dark photons can be produced

Berlin, SG, Schuster, Toro, 1804.00661



120 GeV,
10^{18} POT (EOT)

N. of dark photon @ a proton fixed target experiment like **DarkQuest at Fermilab**

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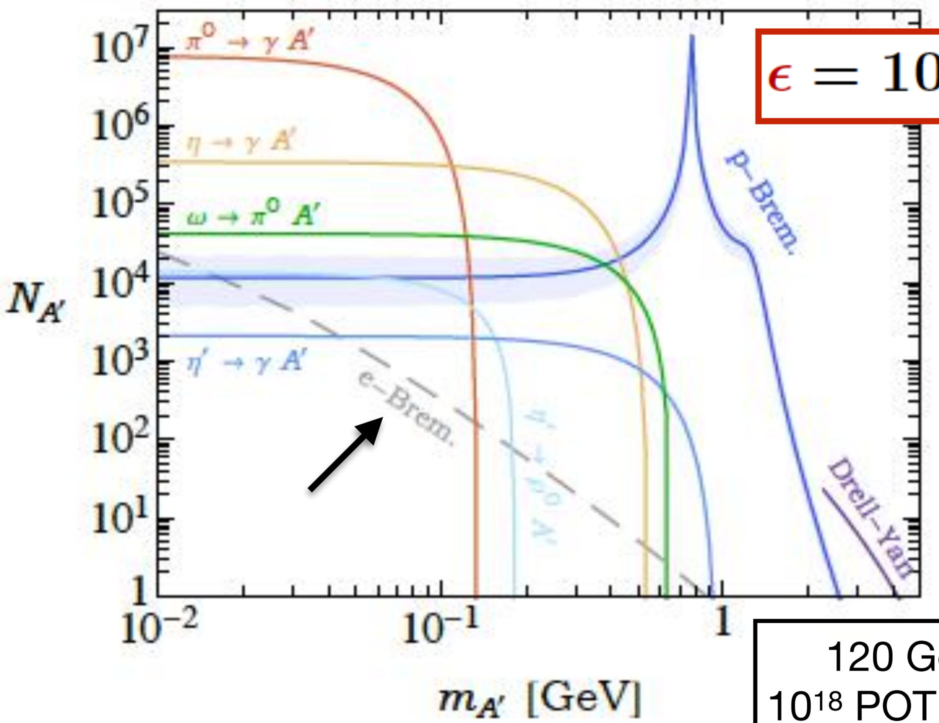
Berlin, SG, Schuster, Toro, 1804.00661



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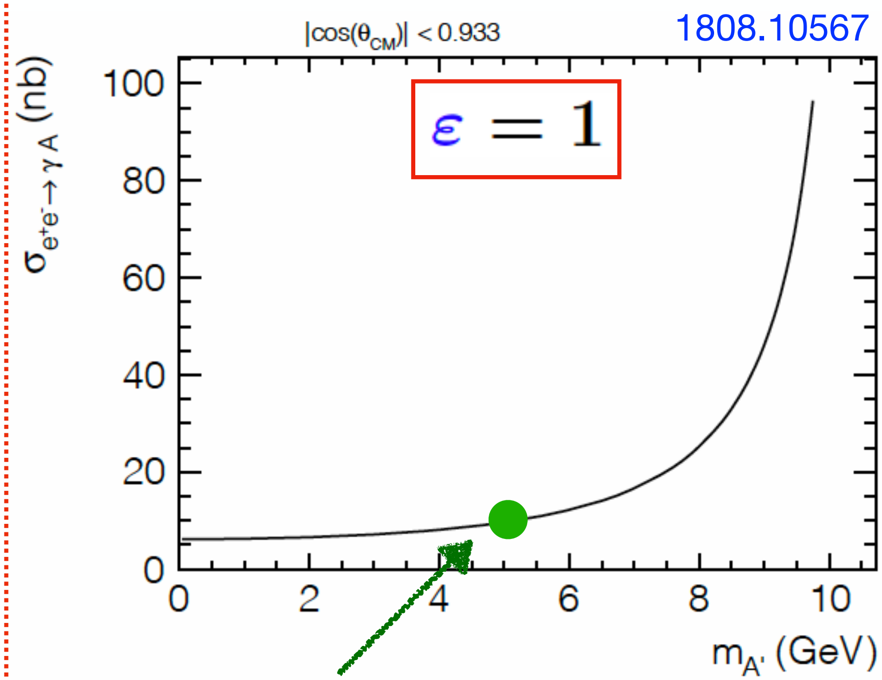
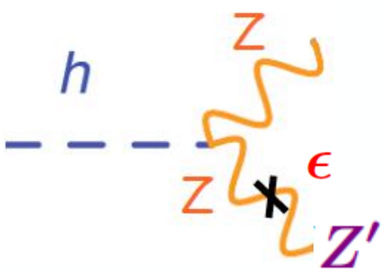
N. of dark photon @ a proton fixed target experiment like **DarkQuest at Fermilab**

production cross section @ Belle II

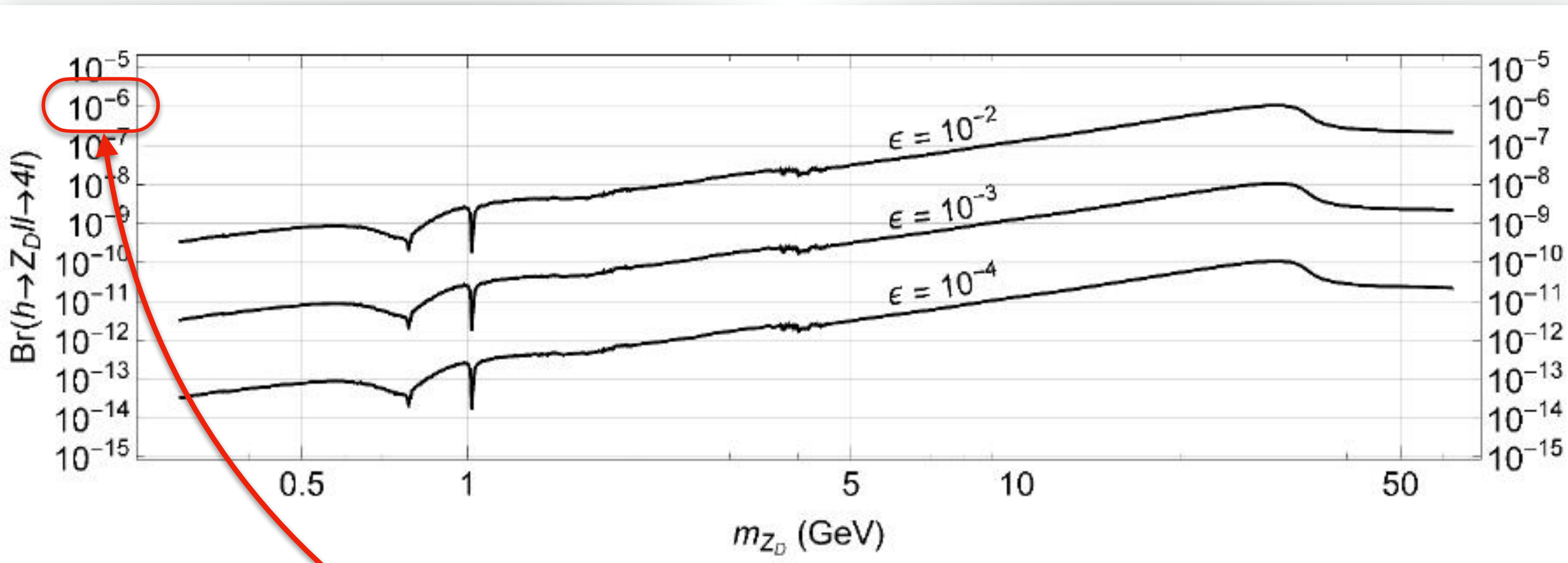


$N_{A'} \sim 10^{10}$ for 50/ab luminosity

How to produce a dark photon? (Higgs decays)

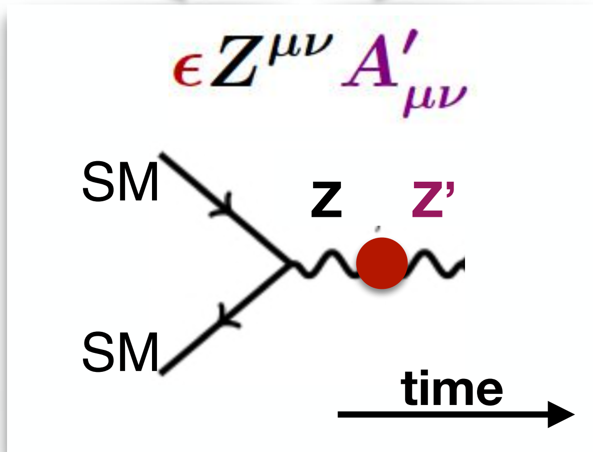


Curtin, Essig,SG, Shelton, 1412.0018



Roughly 100 event at the HL-LHC

What to look for at accelerator experiments?



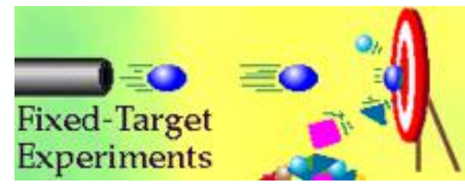
(Typically) high energy

Colliding beam experiments

- B-factories (Belle-II)
  e^+e^- collider
- The LHC (pp collider)

(Typically) high intensity

Fixed target experiments



- Kaon exp.
- proton beam dump exp.
- electron beam dump exp.
- electron fixed target exp.
- neutrino exp.
- light meson (e.g. pion) exp.

Two different types of accelerator experiments

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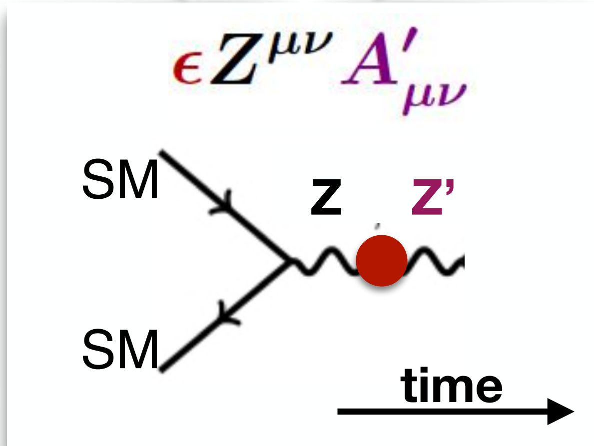

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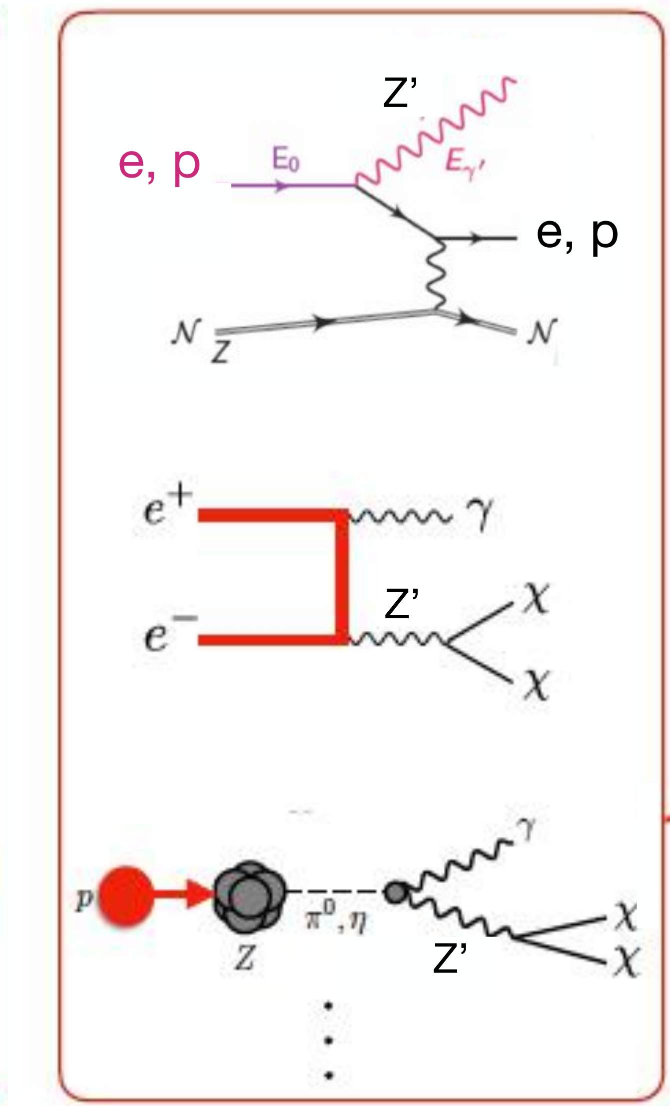
Two different types of accelerator experiments

We will focus on the dark photon, but (broadly speaking) similar studies hold for the other portals

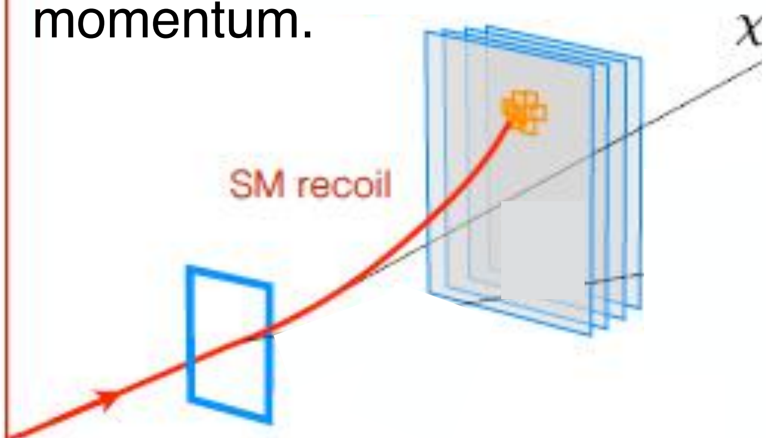
$$\epsilon Z^{\mu\nu} A'_{\mu\nu} \qquad \kappa |H|^2 |S|^2$$
$$y H L N \qquad \frac{1}{f_s} F_{\mu\nu} \tilde{F}_{\mu\nu} a$$

Invisible dark photons. DM production

$m_{Z'} > 2m_X$



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



https://arxiv.org/abs/2207.00597

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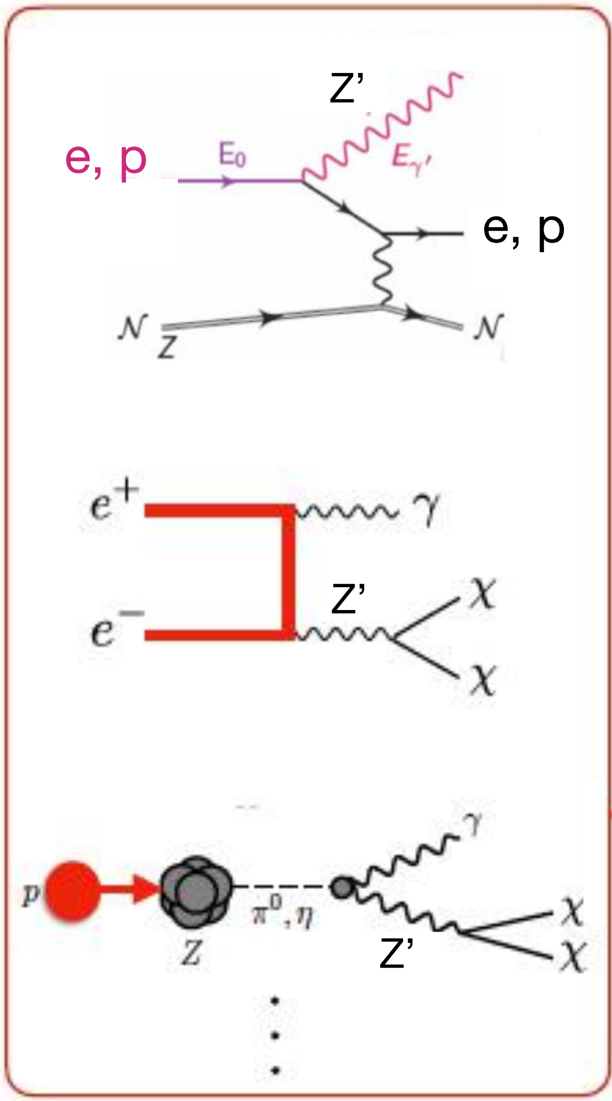

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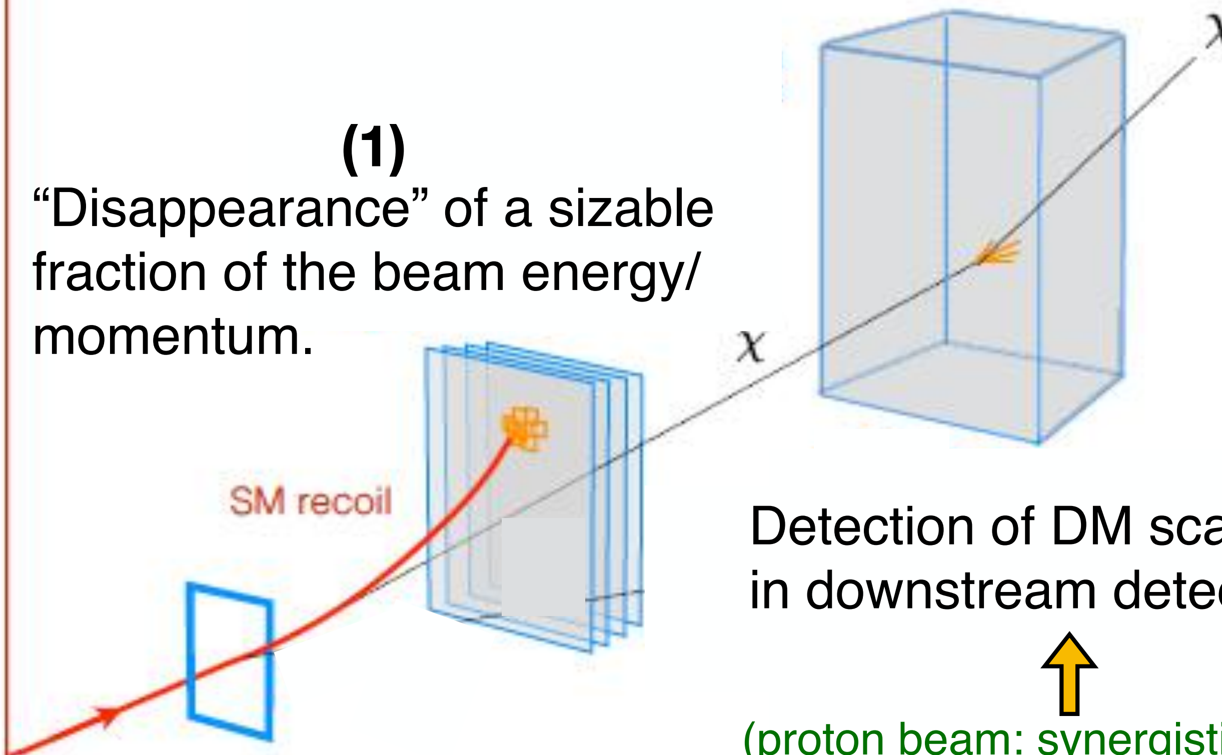


Detection of DM scattering in downstream detectors

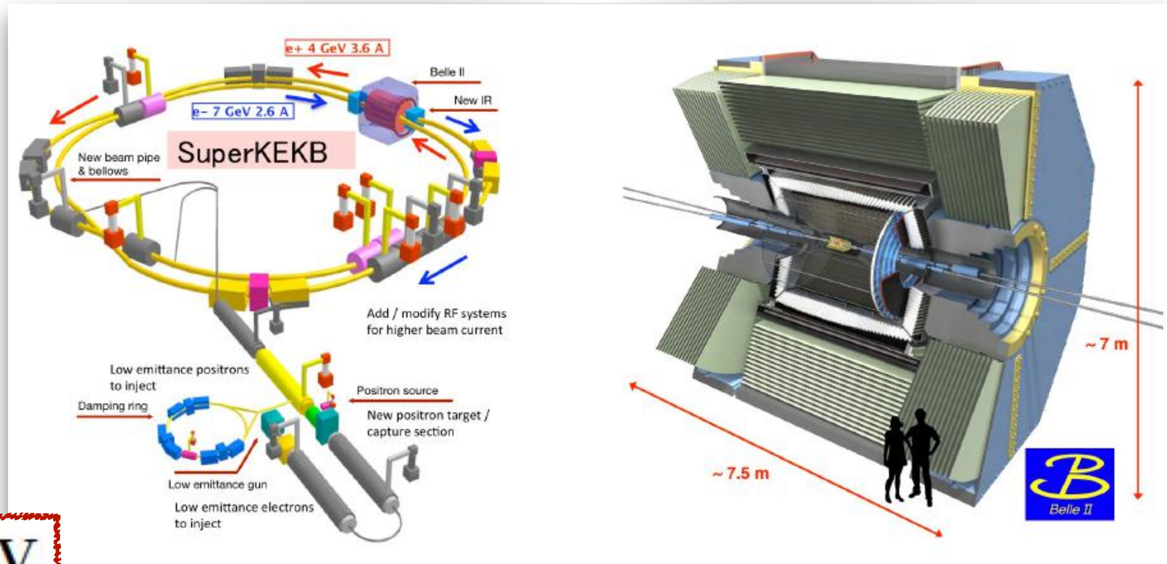
(2)

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

https://arxiv.org/abs/2207.00597

The Belle II experiment

$e^+ e^-$
high-intensity
collider
at KEK, Japan



$$\boxed{\sqrt{s} \sim 10.6 \text{ GeV}}$$

1000 smaller than the LHC

The Belle-II detector started taking physics data in 2019

We are only at the beginning! ~100 times more data to be collected

Main physics goal: study the physics associated to B mesons

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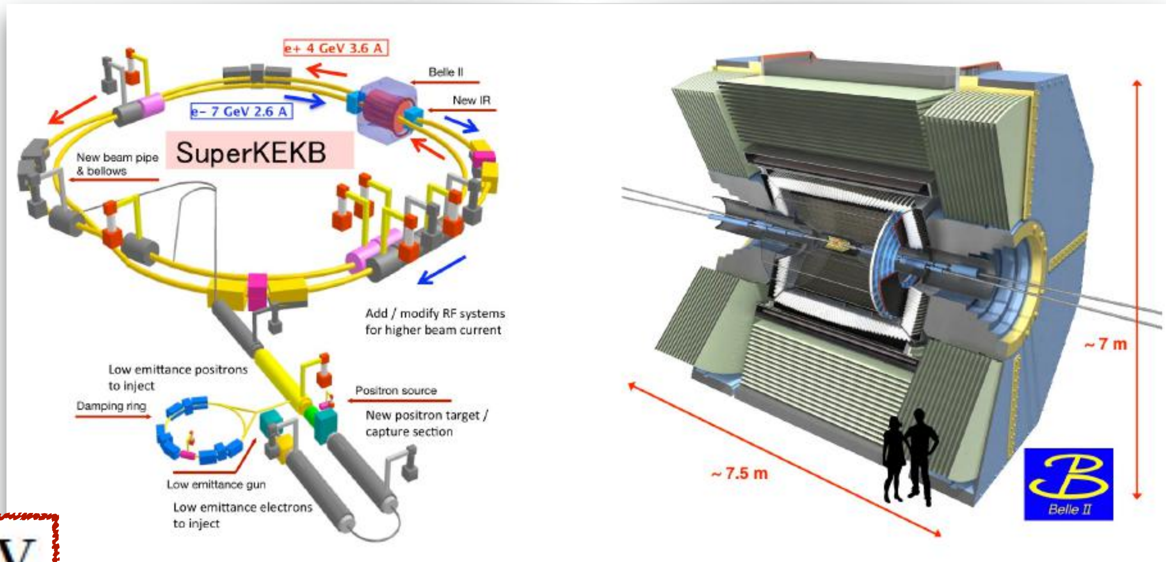

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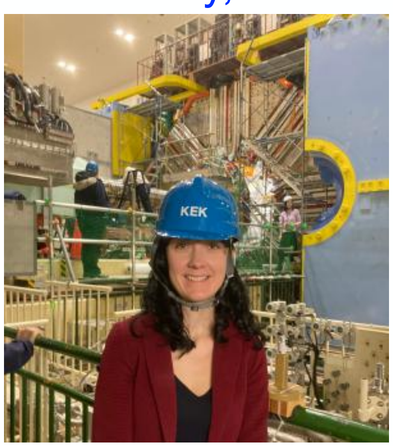
February, 2023



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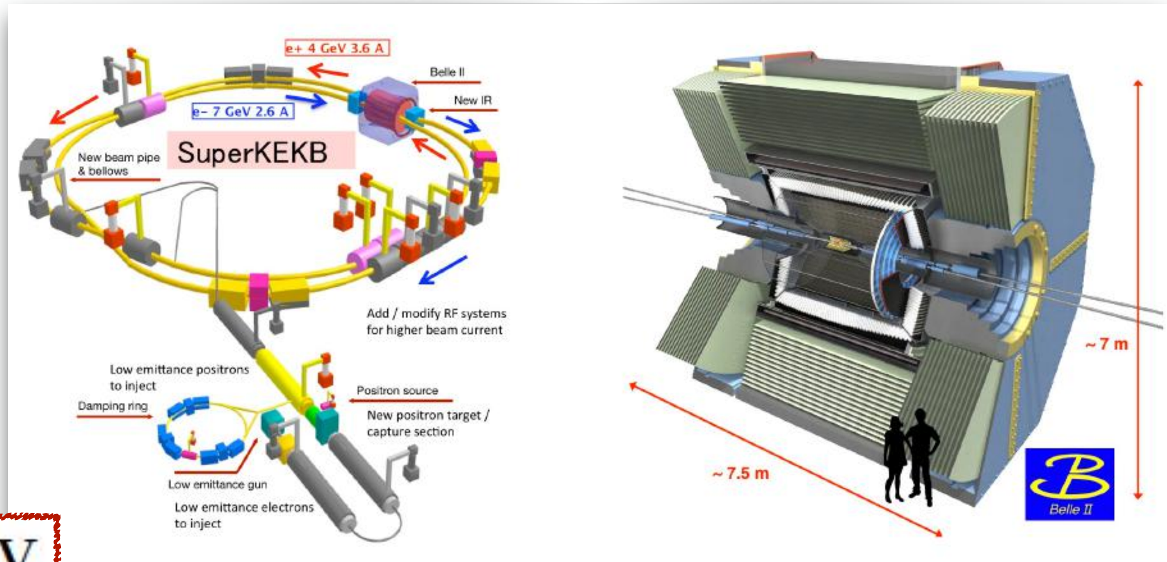

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1000 smaller than the LHC

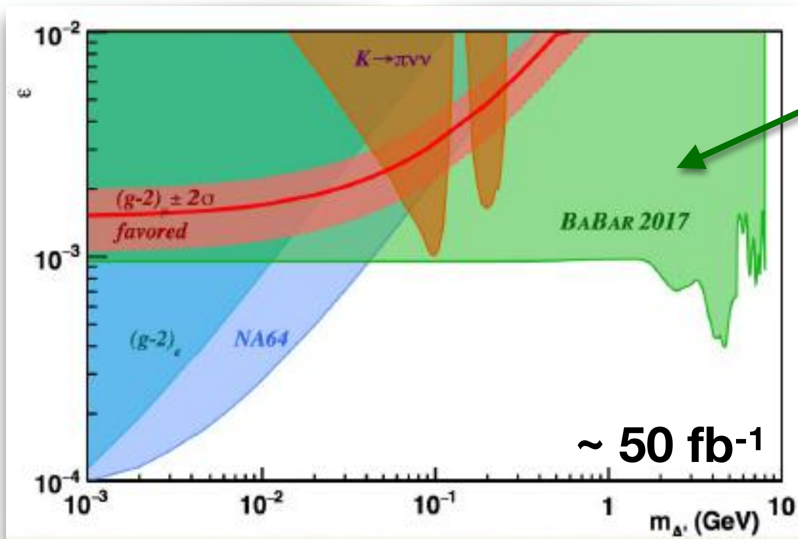
Main physics goal: study the physics associated to B mesons
Many opportunities for dark sectors as well!

B mesons can decay to **dark particles**.

Dark particles can be produced from e^+e^- collisions.

Invisible dark photon at Belle II

1702.03327



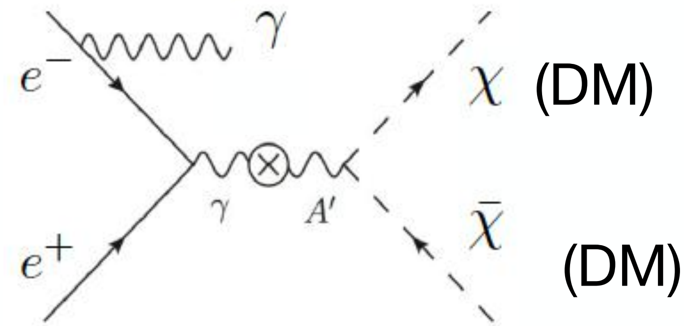
Babar search

single-photon trigger

This analysis excludes the entire region favored by $(g\text{-}2)_\mu$!

(1) Missing energy search

mono-photon + invisible



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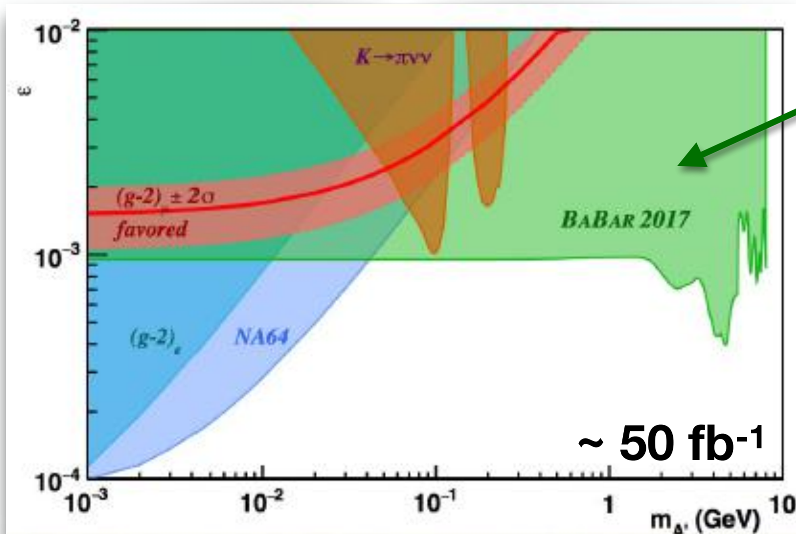

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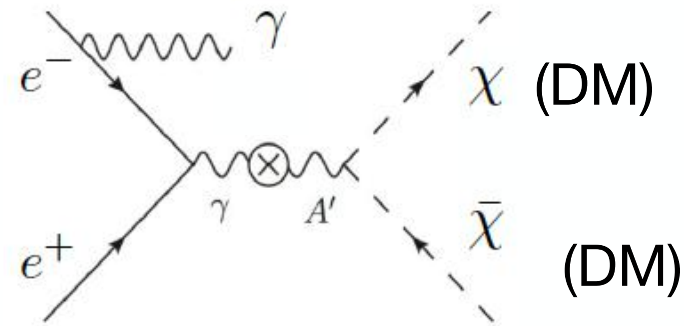
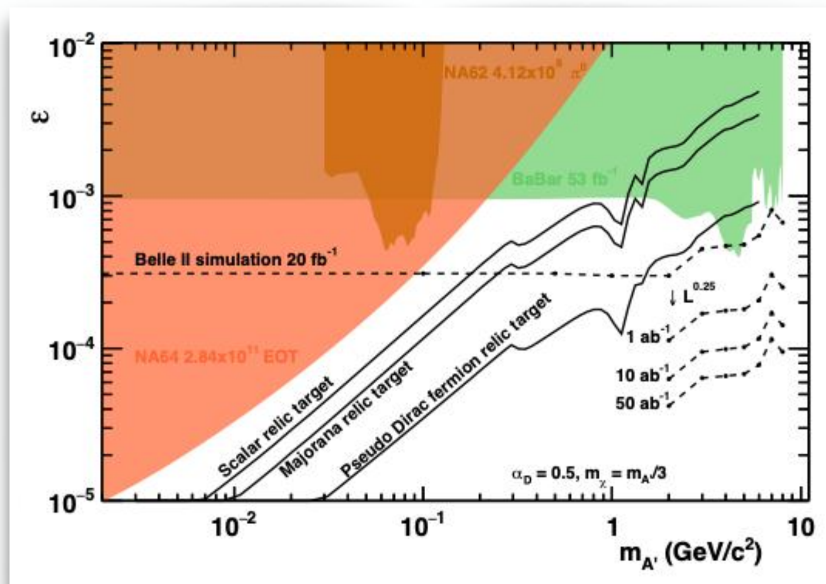
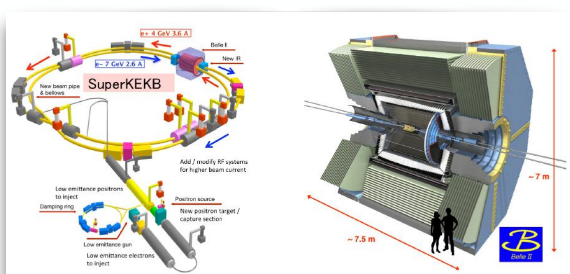




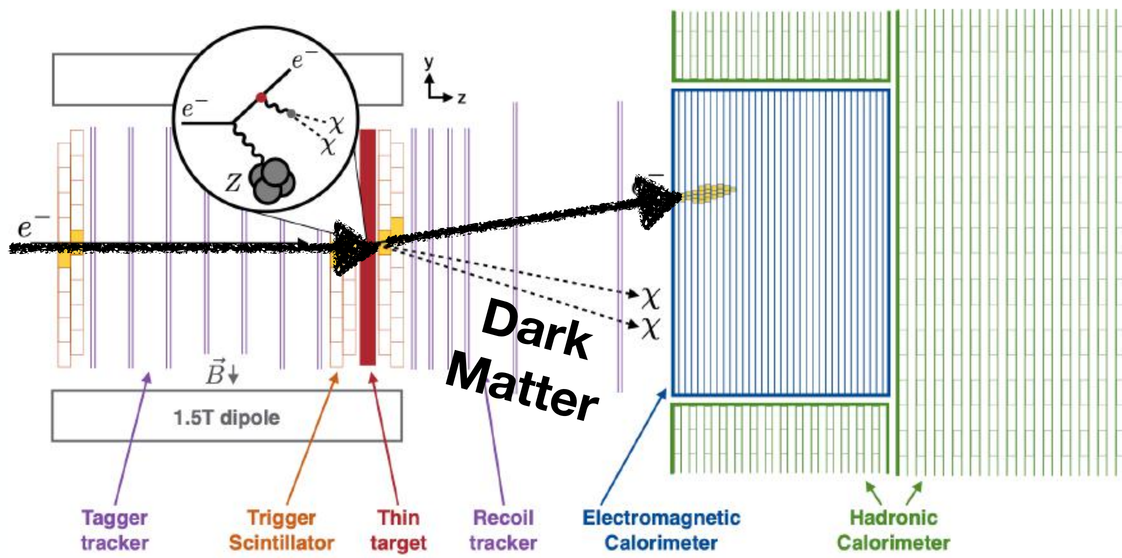


Belle II Snowmass white paper, 2207.06307

Invisible dark photon at LDMX

Akesson et al., 2203.08192

High intensity electron beam (4 and 8 GeV)

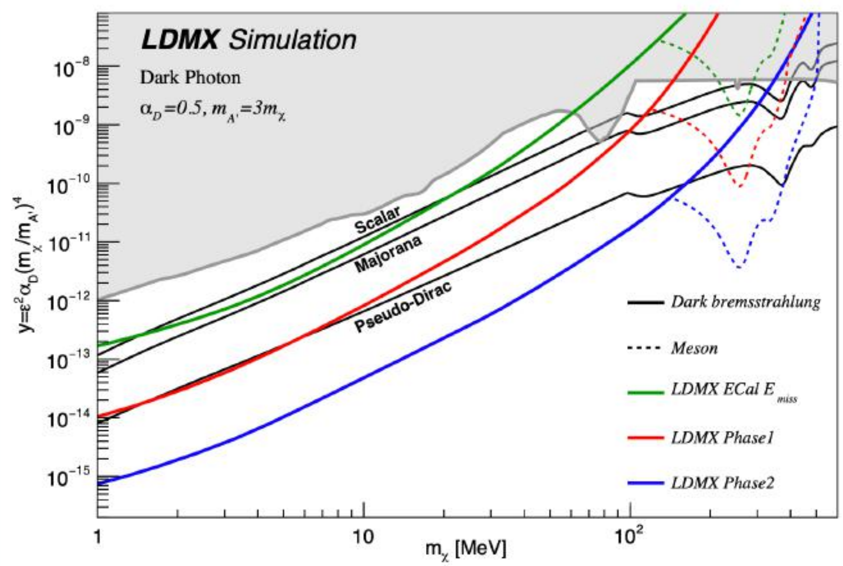


See Izaguirre, Krnjaic, Schuster, Toro, 1411.1404 for the initial proposal

Proposed experiment for SLAC

(1) Missing momentum experiment

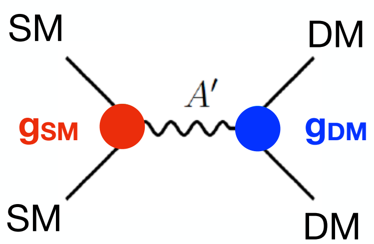
(accurate measurement of the momentum of the deflected electron beam)



Summary: the invisible dark photon

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

A'→DM DM



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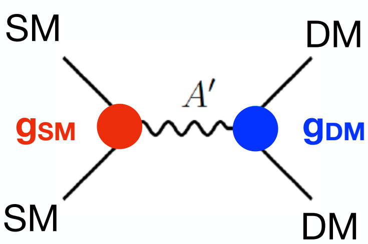
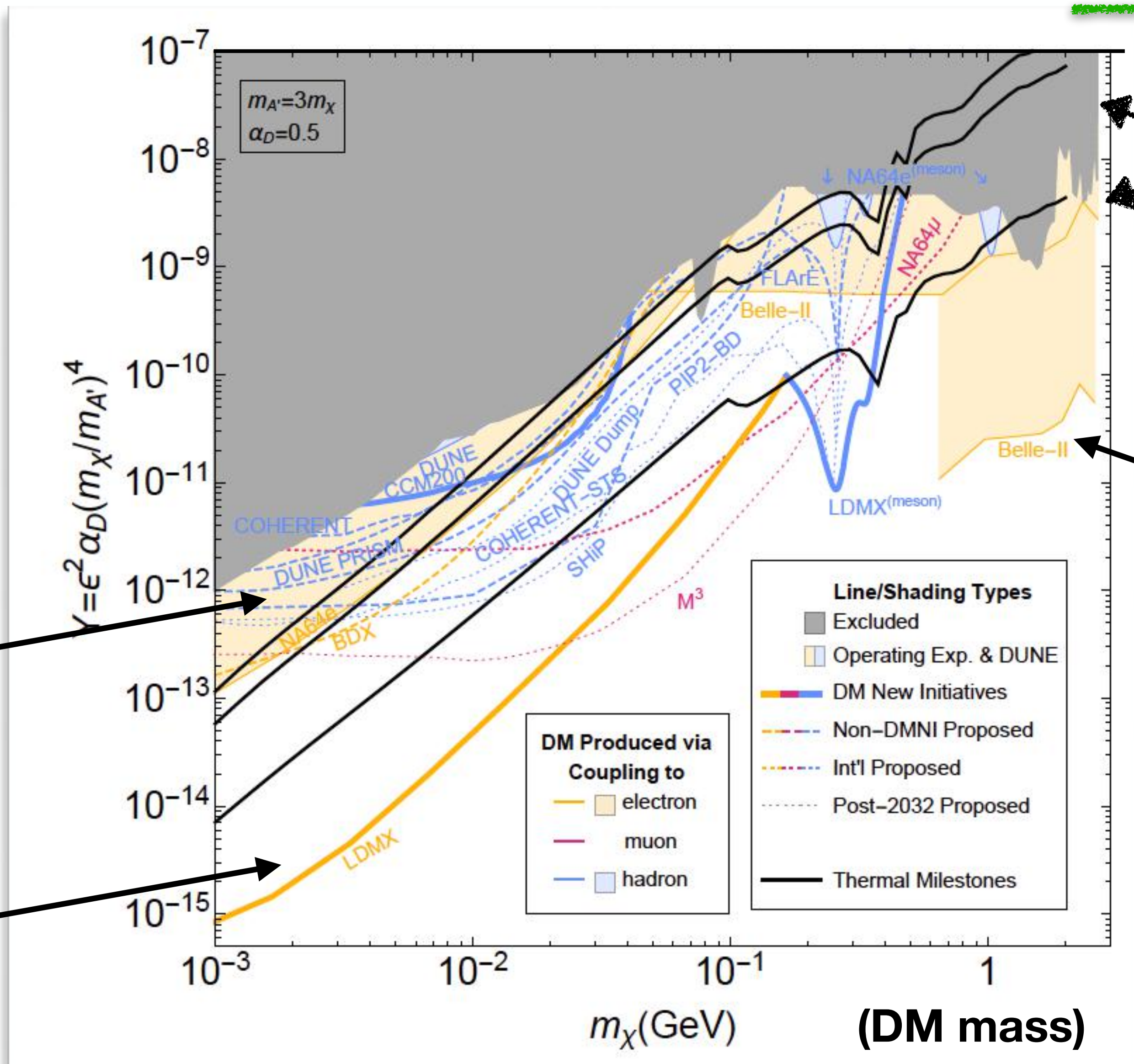


LHC



benchmarks for thermal DM

Belle II

(2) scattering experiments

LDMX

(DM mass)

Krnjaic, Toro et al, 2207.00597

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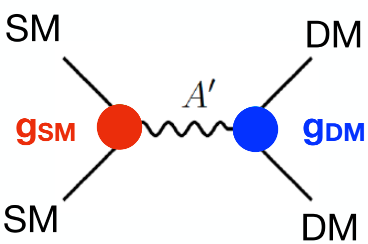

N. of events scales like ε^4

WHY?

N. of events scales like ε^2

LDMX

LHC

benchmarks for thermal DM

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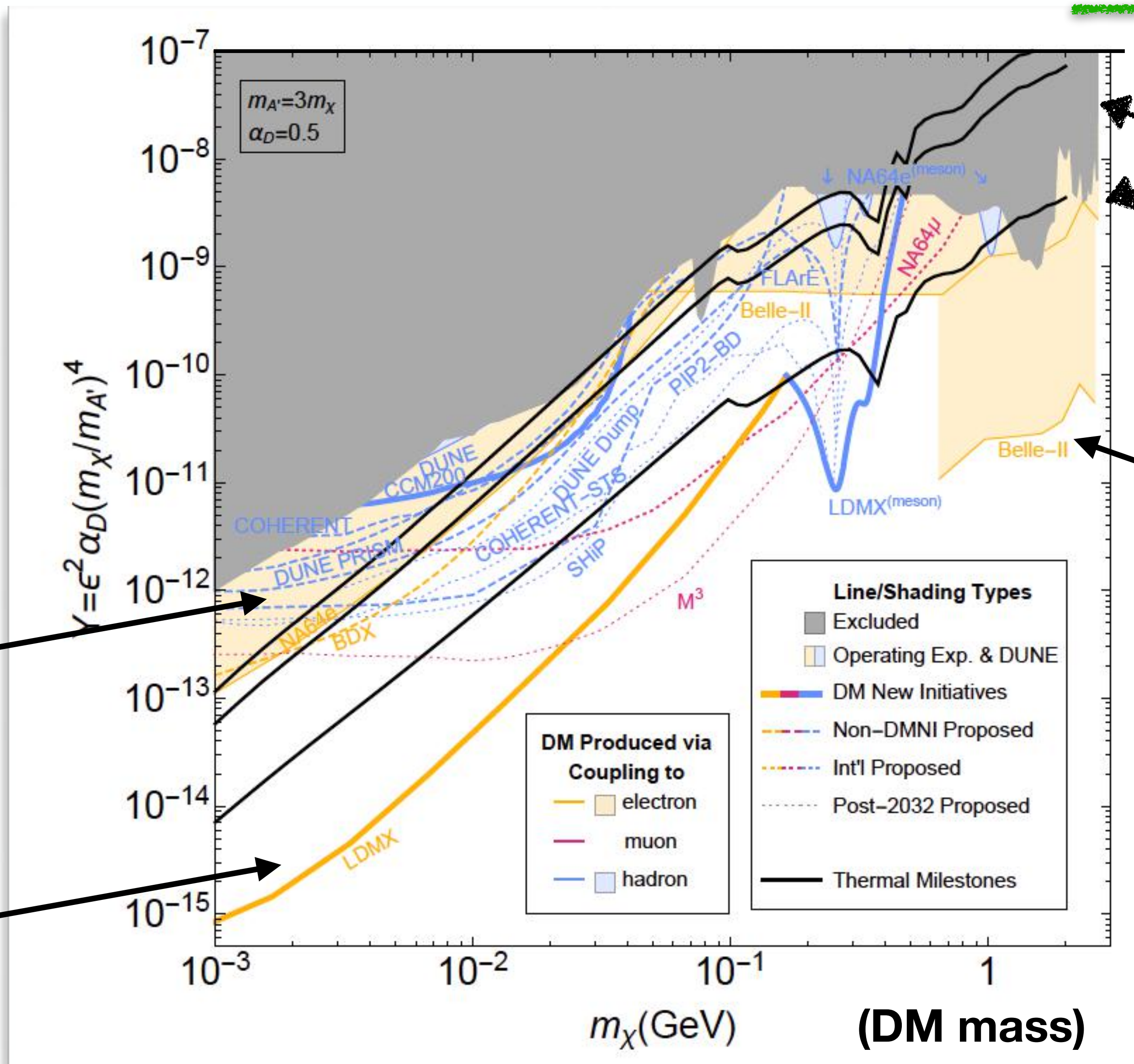

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Krnjaic, Toro et al, 2207.00597

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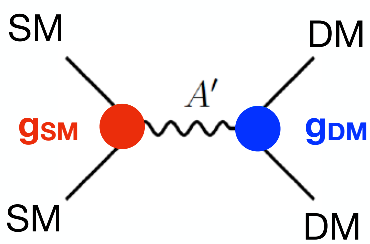

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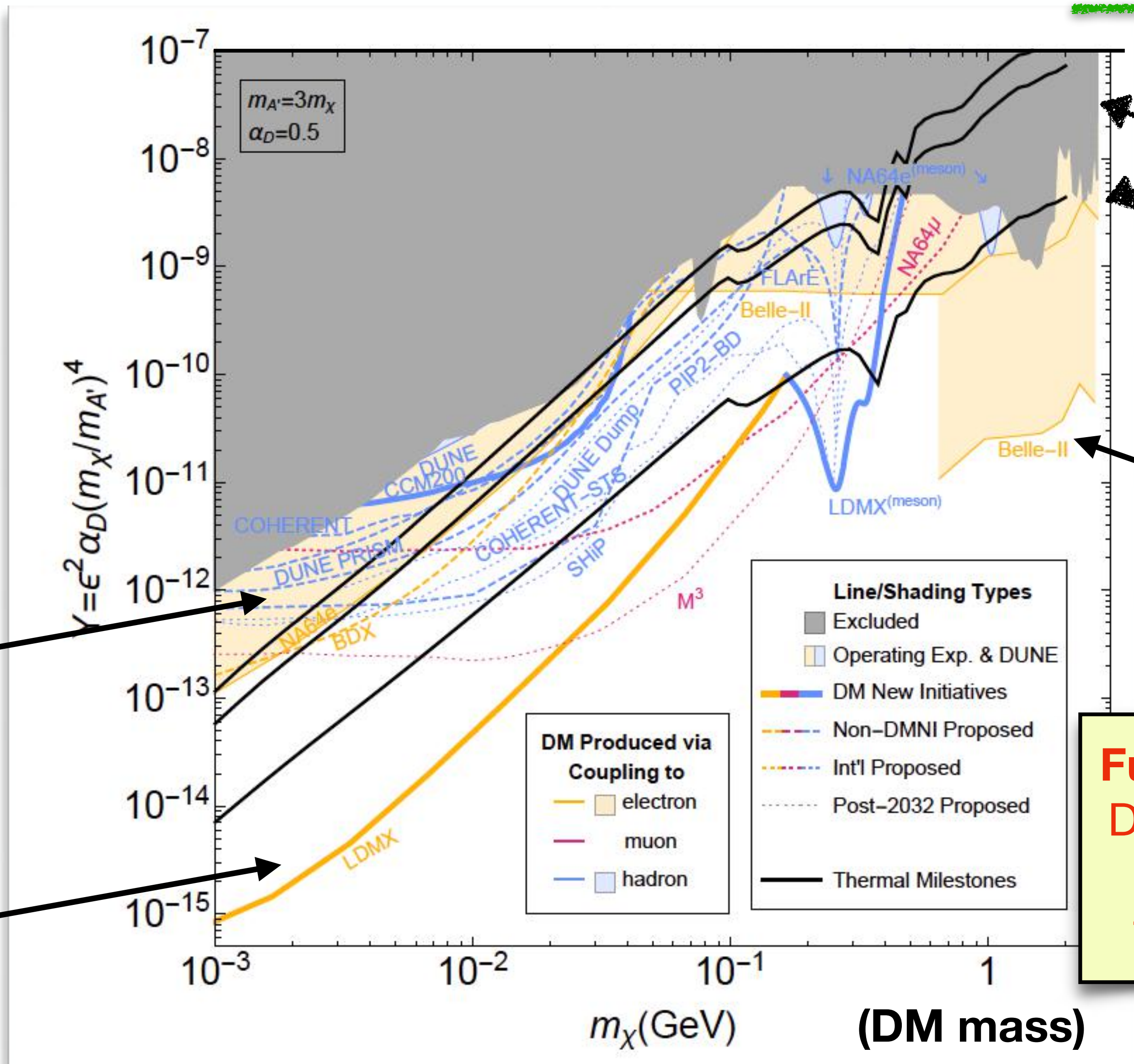


LHC

benchmarks for thermal DM

Belle II

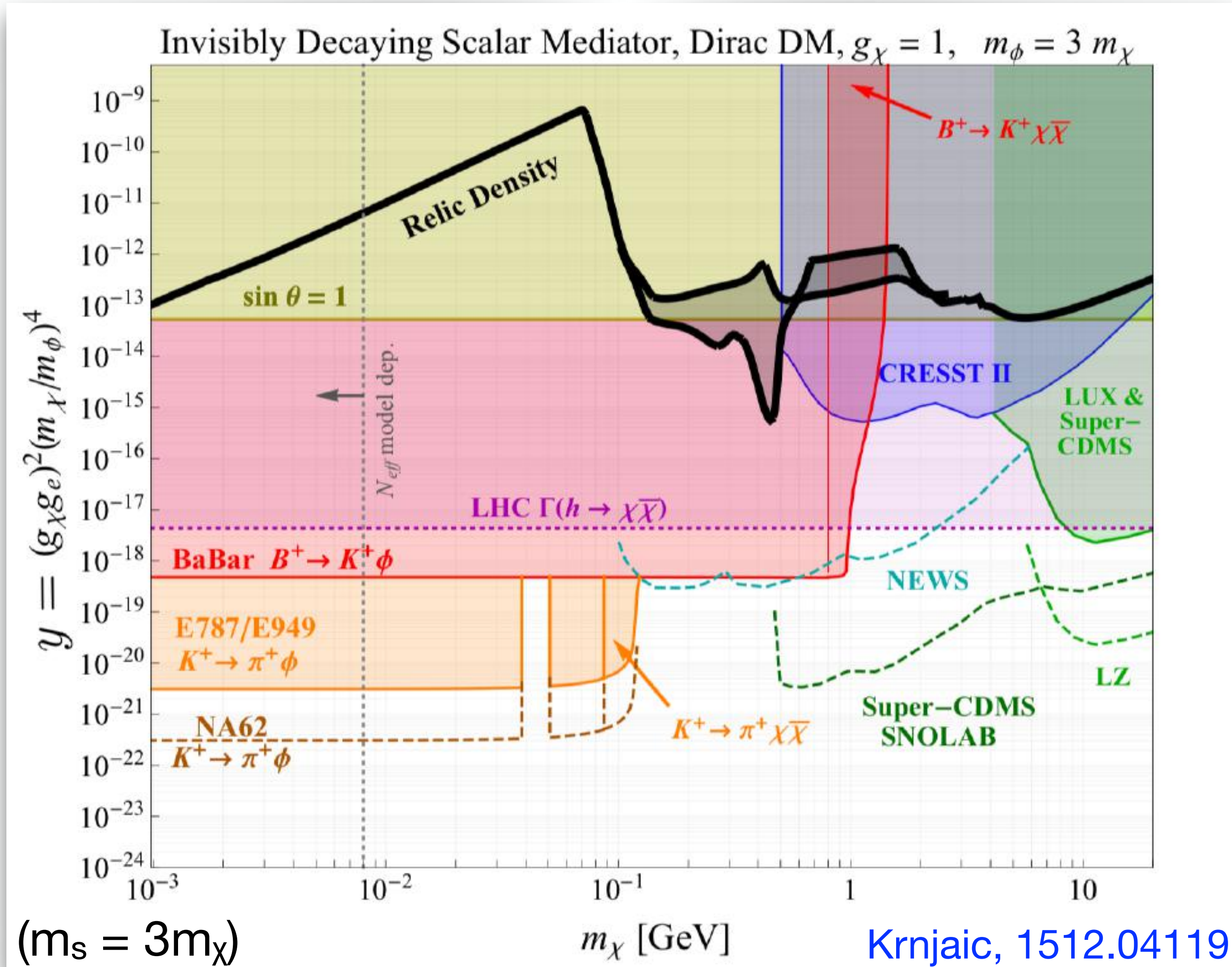
(DM mass)

Full coverage of this DM thermal target is possible in the coming years!

Krnjaic, Toro et al, 2207.00597

(Side note: the invisible dark scalar

We can do the same exercise for a Dirac fermion DM with a dark scalar singlet mediator, s:



($m_s = 3m_\chi$) Krnjaic, 1512.04119

It is **fully probed** by a combination of LHC Higgs invisible decays, DM direct detection, and meson decays!

How does it work?

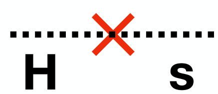
$$\mathcal{L} \supset -\underbrace{\frac{\xi}{2}|H|^2 s^2}_{\text{Higgs portal operator}} + \frac{\mu_s^2}{2}s^2 - \frac{\lambda_s}{4!}s^4 + \mu^2|H|^2 - \lambda|H|^4 + g_\chi s\bar{\chi}\chi$$

X, Dirac DM state

Electroweak symmetry breaking:

If the scalar, s, gets a VEV, then it will mix with the SM Higgs:

$$\tan\theta_s \sim \frac{\xi v_h v_s}{m_h^2 - m_s^2}$$



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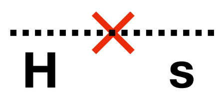
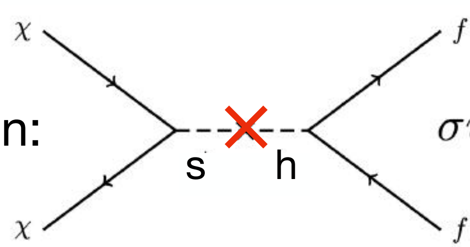
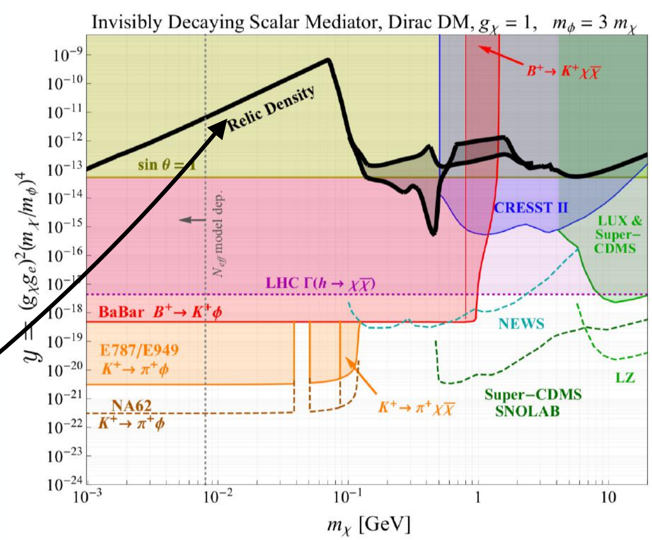


annihilation:



$$\sigma v \propto g_\chi^2 g_f^2$$

$g_f \propto \sin(\theta_s)$



Krnjaic, 1512.04119

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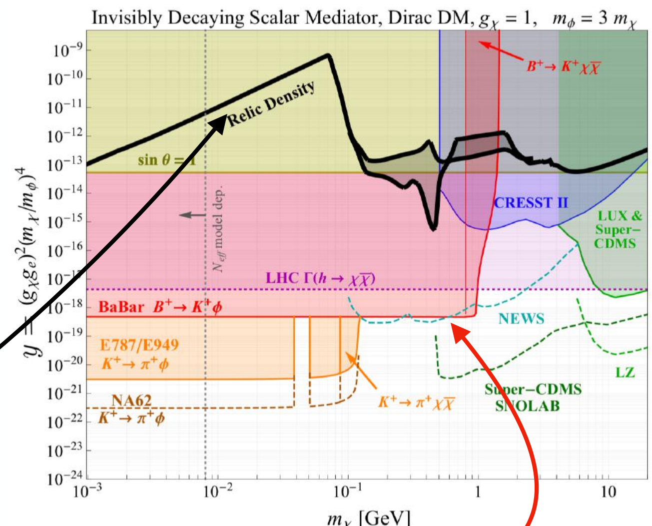
H ✕ s



Krnjaic, 1512.04119

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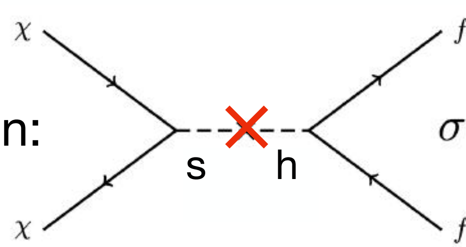

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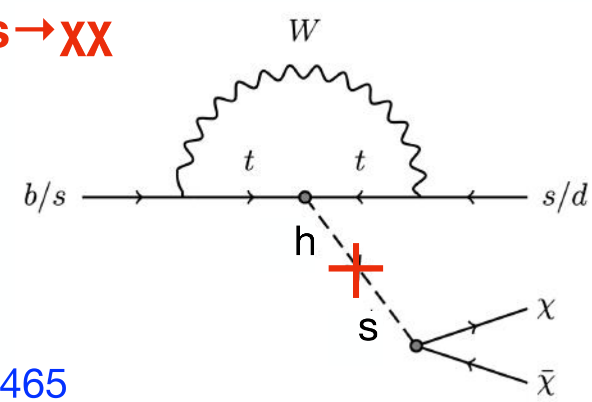
$B^+ \to K^+\, s,\ s \to \chi\chi$



Babar, 1303.7465

$\mathrm{BR}(B^+ \to K^+\nu\bar{\nu}) < 1.6 \times 10^{-5}$

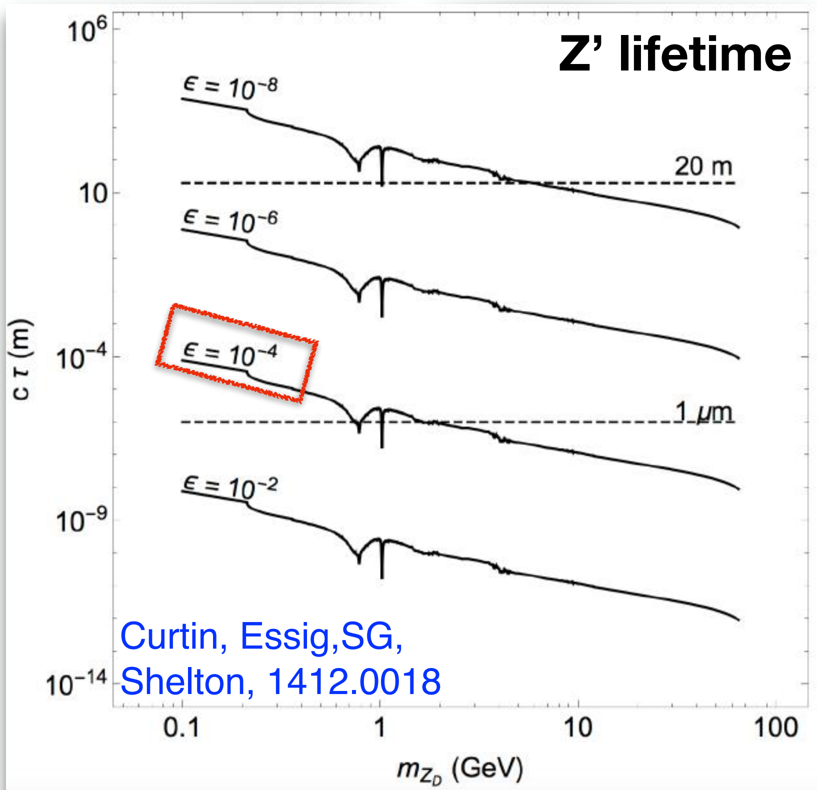
By now, we have evidence for this SM decay (Belle II, 2311.14647)

$\mathrm{BR}(B^+ \to K^+\bar{\nu}\nu) = [2.3 \pm 0.5(\mathrm{stat})\ ^{+0.5}_{-0.4}(\mathrm{syst})] \times 10^{-5}$

Visible dark photons

Several searches can be performed.
Searches target either prompt or displaced dark photons

Reminder:



(for the minimal dark photon model)

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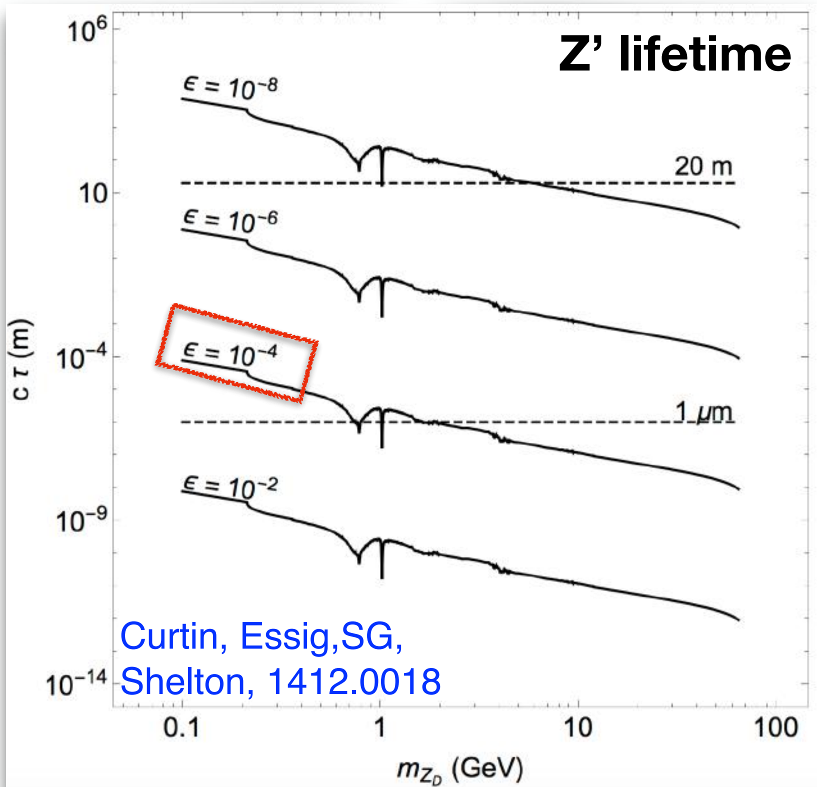


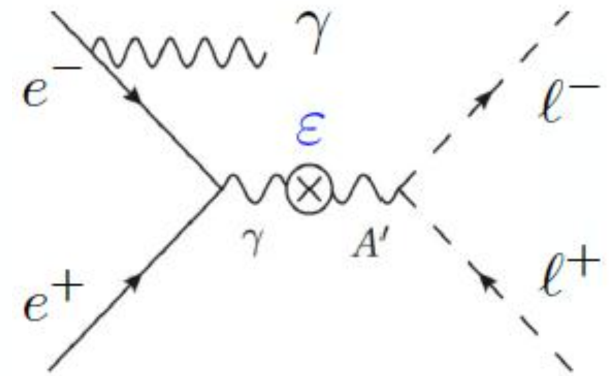
(for the minimal dark photon model)

We will discuss two examples
to show the breadth of possibilities:

1. Belle II (prompt)
2. LHCb (prompt, slightly displaced)
3. Beam dump experiments + forward detectors (displaced)
4. LHC, Higgs decays (prompt + displaced)
5. LHC auxiliary detectors (displaced)
6. Neutrino experiments (displaced)

1. Visible dark photons at B-factories

The $e^+e^- \to \gamma\, e^+e^-$ and $e^+e^- \to \gamma\mu^+\mu^-$ backgrounds are large. ➡ The search for the A' consists of a search for a narrow peak in the di-lepton invariant mass spectrum on top of a large background.



photon +
prompt di-lepton resonance

PRL 113 (2014) no. 20, 201801
arXiv:1406.2980

Babar analysis

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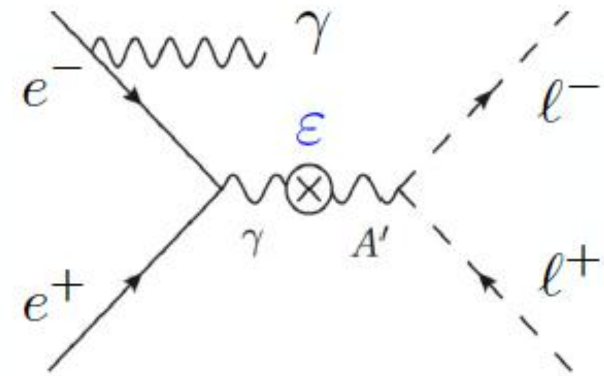

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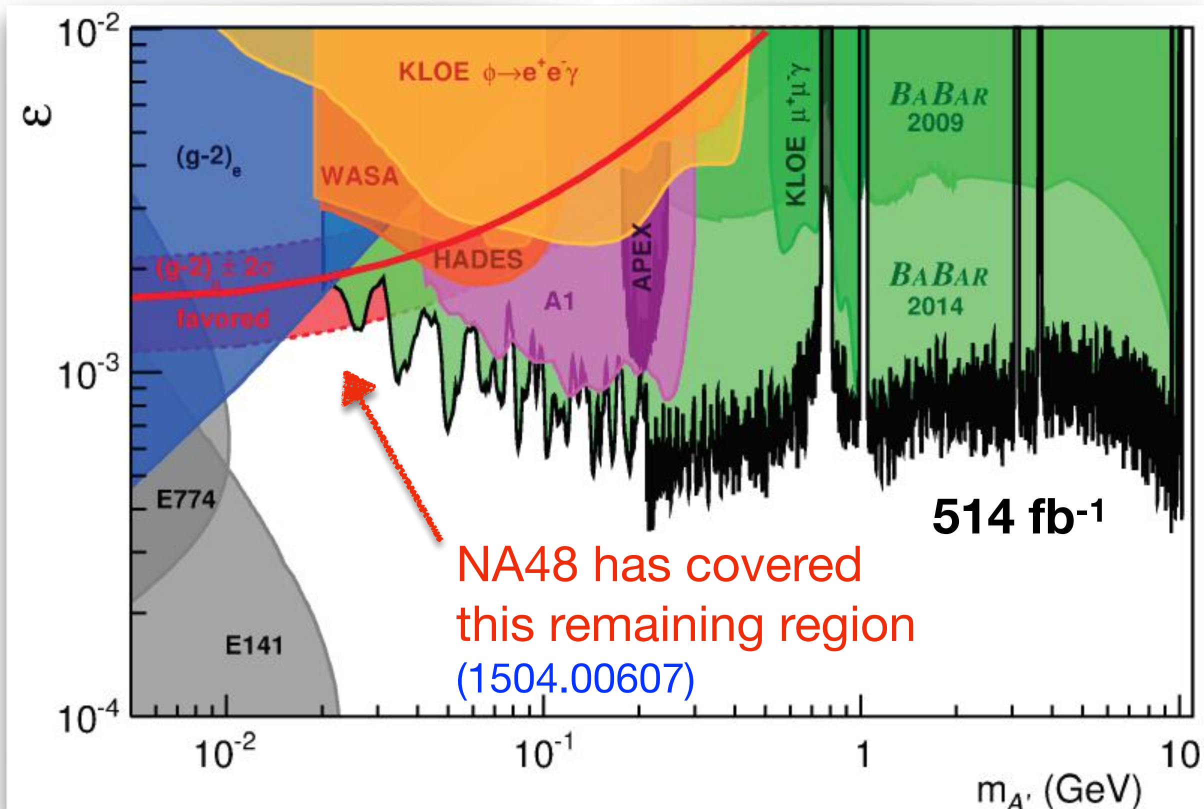
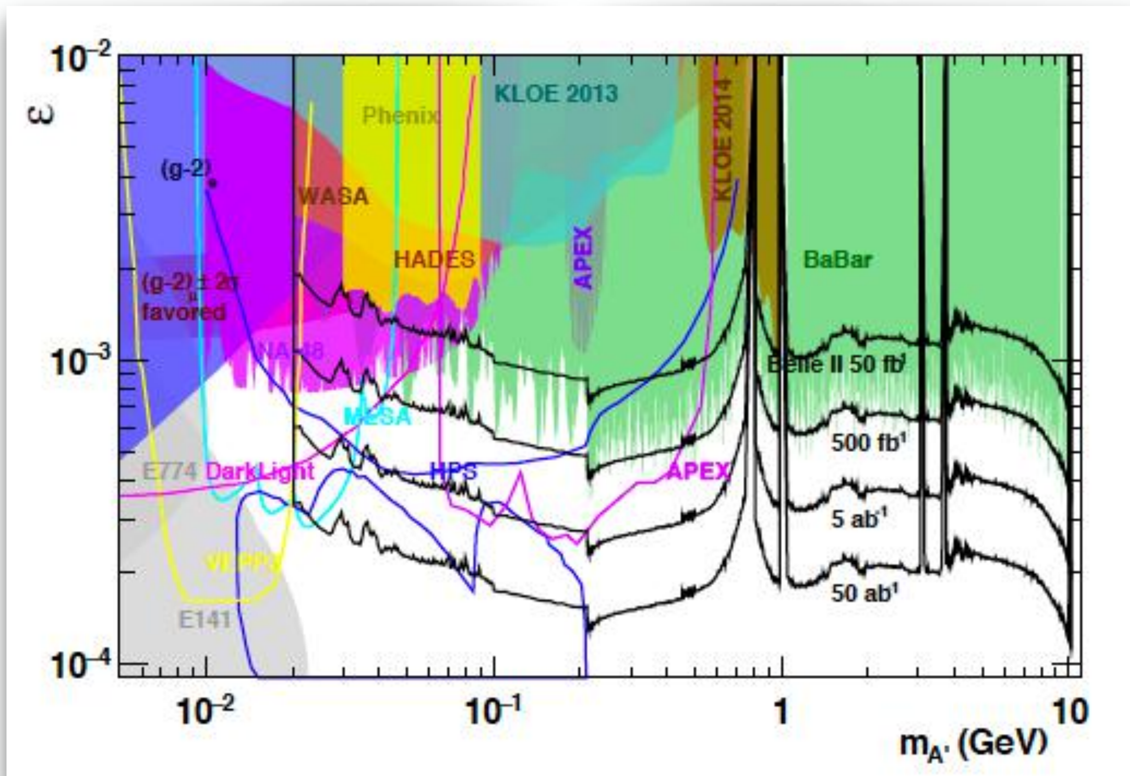


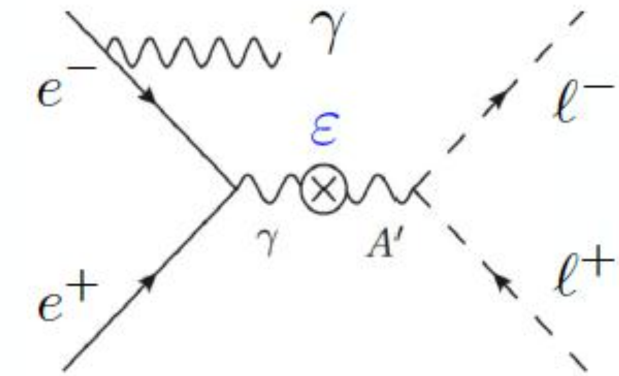
1. Visible dark photons at B-factories

Belle II: Projected limits scaled from BaBar, assuming:

- twice as good mass resolution
- better trigger efficiency for both muons (~ factor 1.1) and electrons (~ factor 2)

The Belle II physics book, 1808.10567





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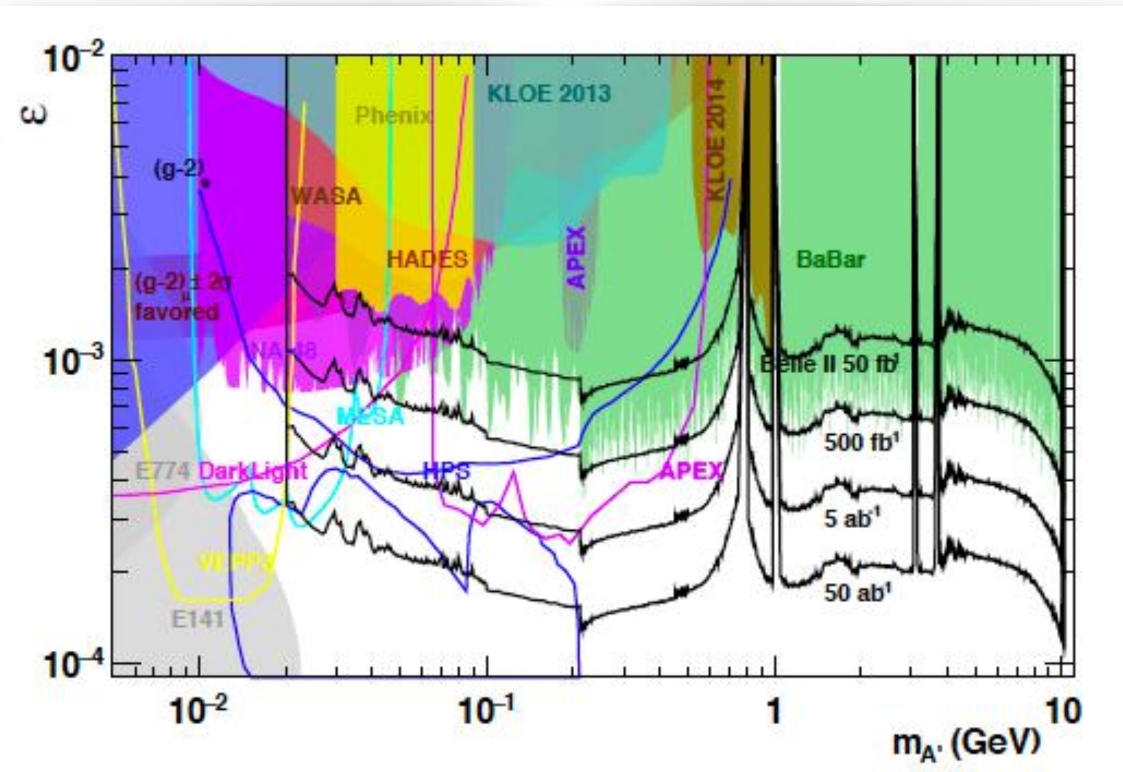
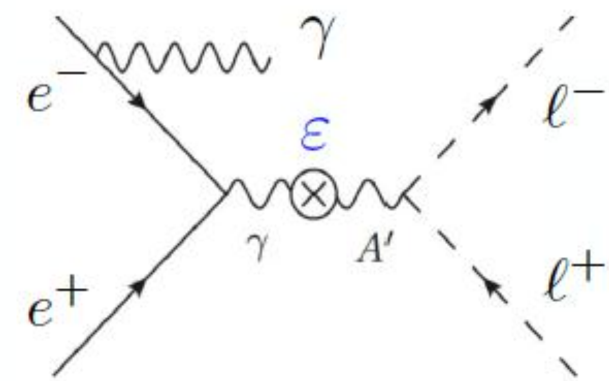
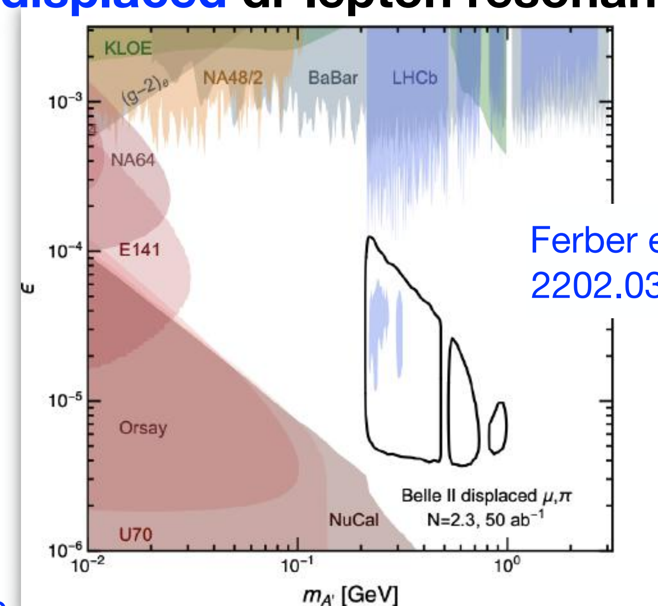




photon + **prompt di-lepton resonance**

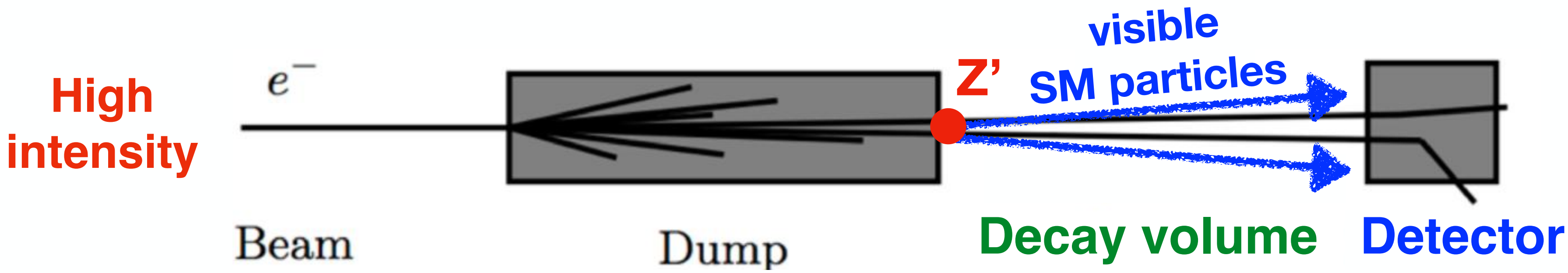
photon + **displaced di-lepton resonance**



Ferber et al, 2202.03452

see also Bandyopadhyay et al, 2203.03280

3. Visible dark photons at beam dump experiments



this length sets the typical lifetime of the dark particle that we can probe

Low background experiments
(depending on the size of the dump)

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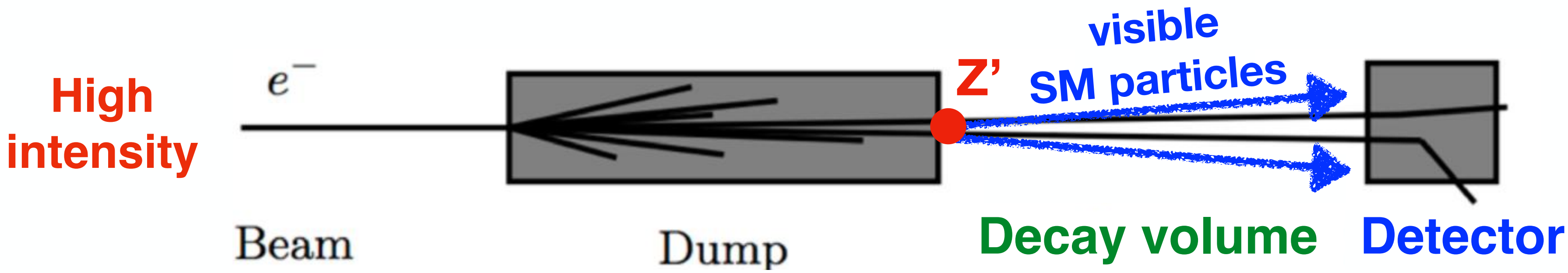

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Low background experiments
(depending on the size of the dump)

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

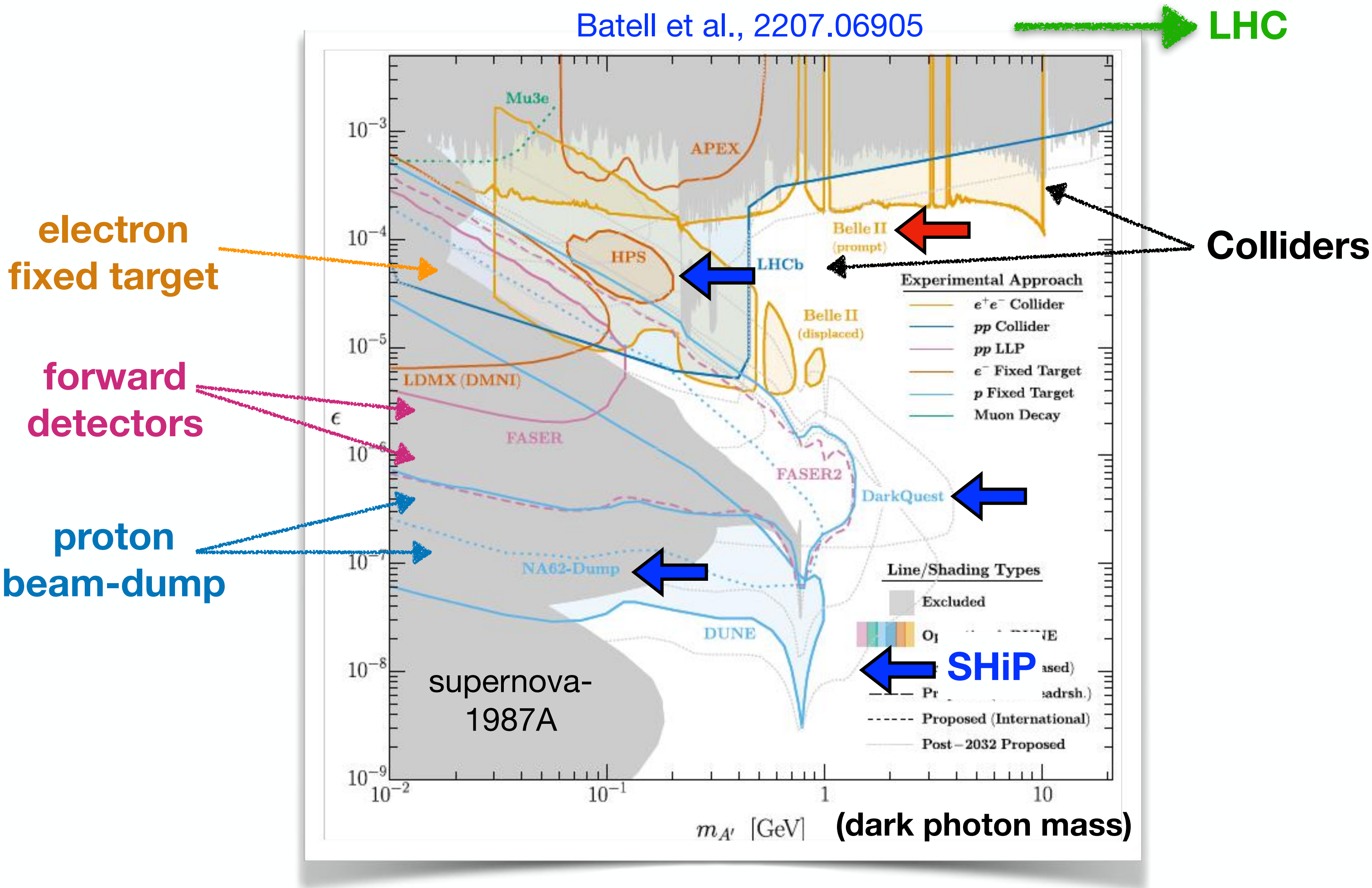
Proton (beam dump) vs. electron fixed target experiments:

Protons: typically higher energies (→ reach towards larger dark sector masses)

but larger backgrounds (needs shielding!)

Summary: the visible dark photon

Batell et al., 2207.06905

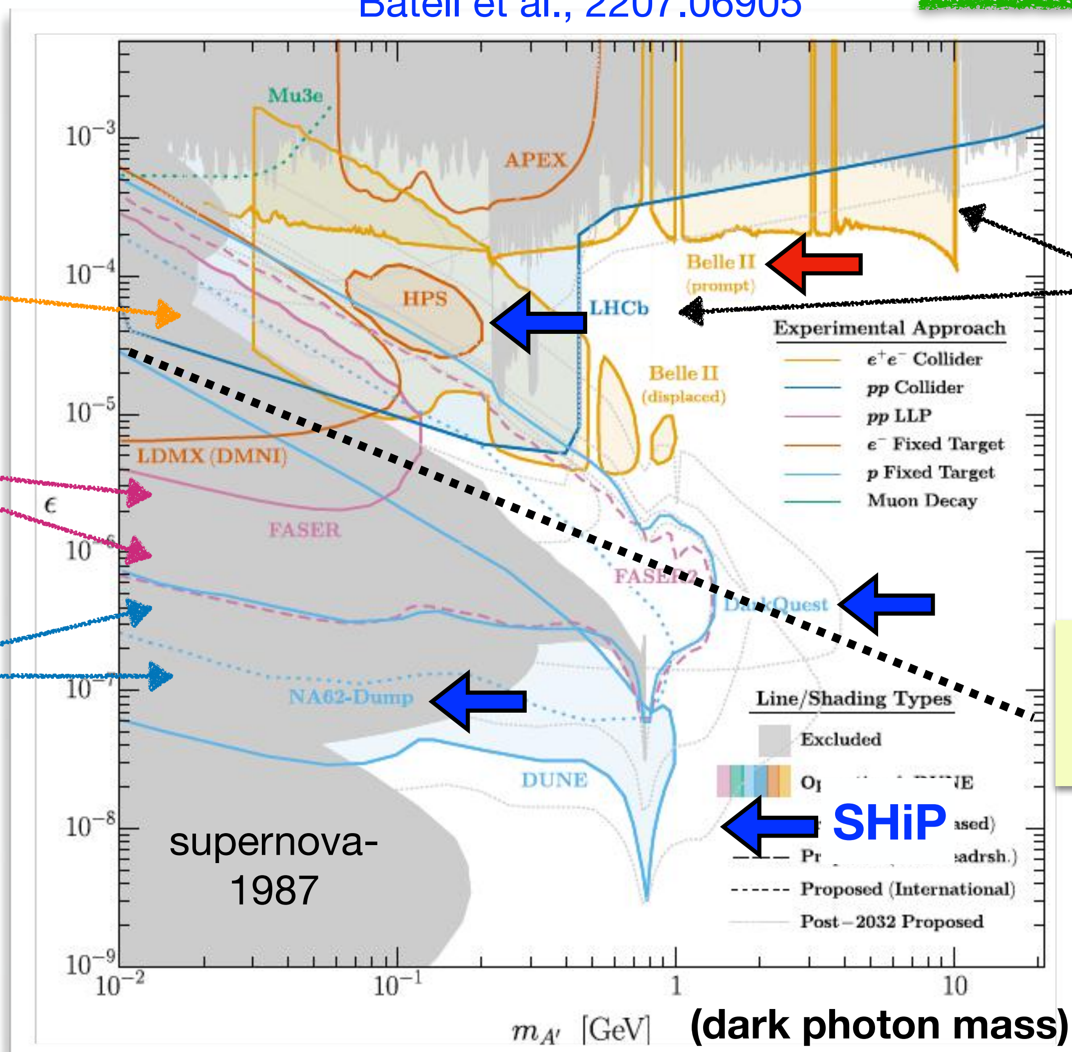


This entire parameter space predicts a **dark sector in thermal equilibrium** with the SM

Summary: the visible dark photon

Batell et al., 2207.06905

LHC



electron fixed target

forward detectors

proton beam-dump

Colliders

roughly:
life time ~ cm

long-lived regime

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

Comparison with other Z' models

L_μ - L_τ is anomaly free with the SM matter content.

Gauging L_μ - L_τ leads to a Z' with vectorial couplings to muons and taus and couplings to the corresponding LH neutrinos.

$$g' Z'_\alpha \left(\bar{\mu}\gamma^\alpha \mu - \bar{\tau}\gamma^\alpha \tau + \bar{\nu}_\mu \gamma^\alpha P_L \nu_\mu - \bar{\nu}_\tau \gamma^\alpha P_L \nu_\tau\right)$$

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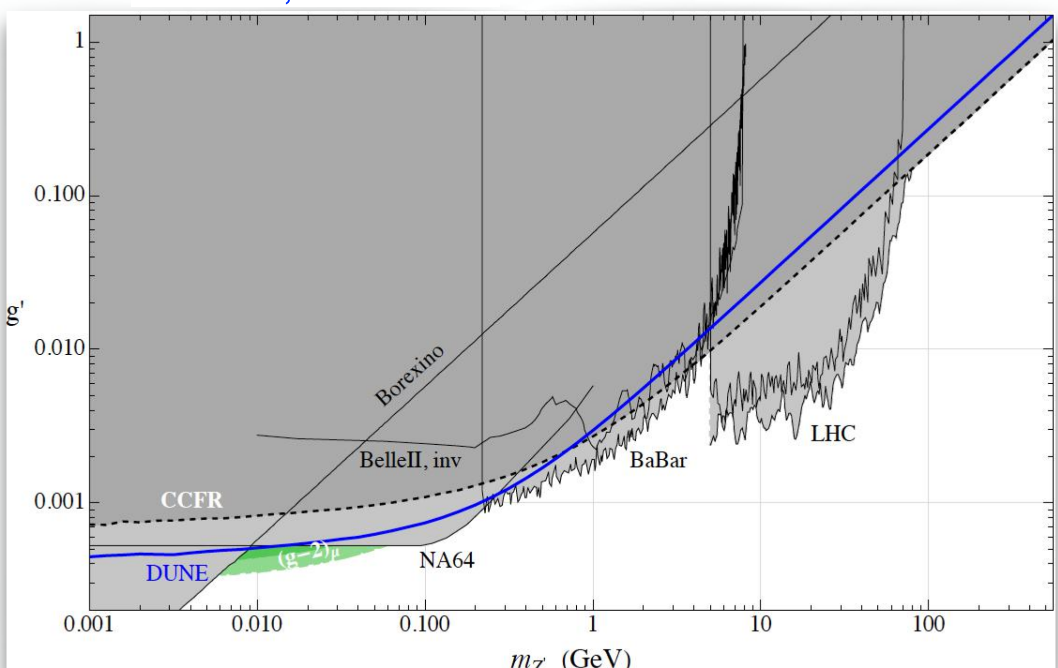
(Updated) Altmannshofer, SG, Martin-Albo, Sousa, Wallbank, 1902.06765



Bounds at the level of ~10^{-3} (as opposed to ~10^{-7})!

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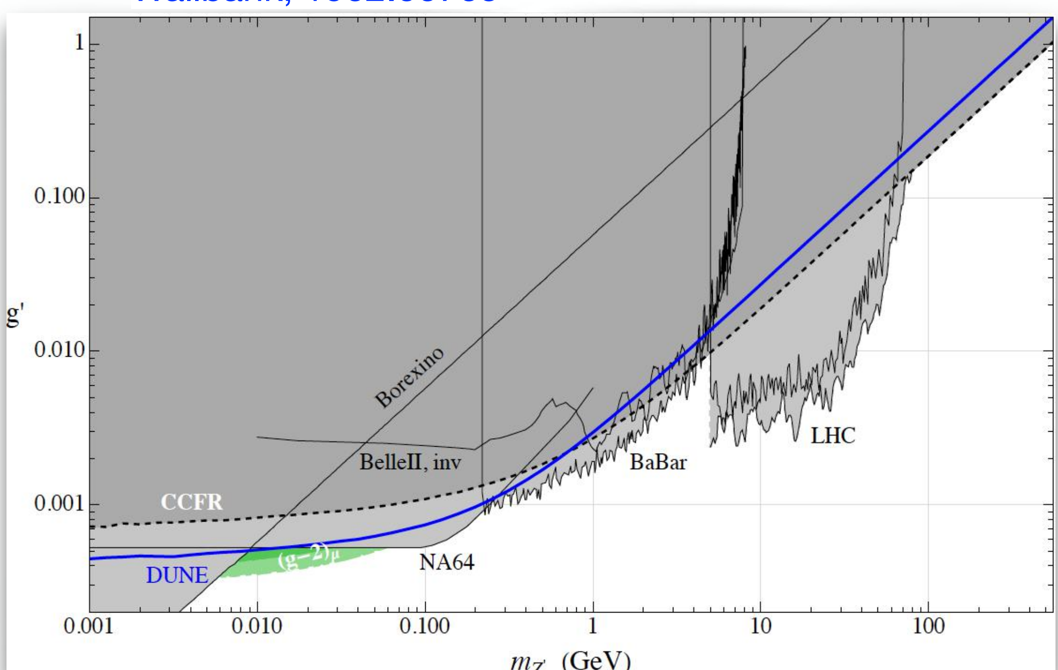
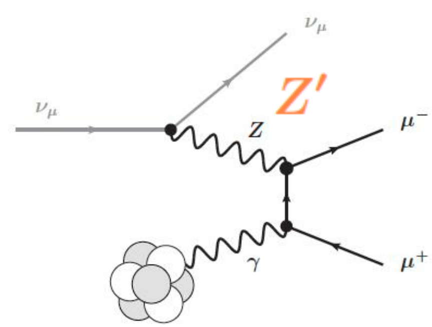


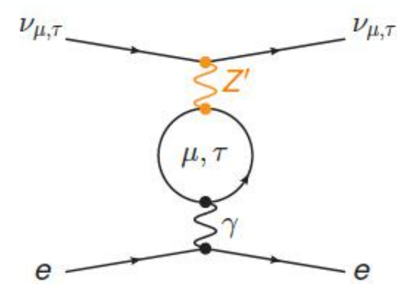
Bounds at the level of ~10^{-3} (as opposed to ~10^{-7})!

Some novel bounds:

1) Trident production @ CCFR / DUNE
$\nu_\mu N \to \mu^+\mu^- N'$



2) Borexino



Chapter 4

Non-minimal models (IDMs, SIMPs)

Inelastic Dark Matter

Dark Matter models often predict the existence of more dark particles, in addition to the DM state and the mediator.

One interesting example: “Inelastic Dark Matter” (IDM)

Inelastic Dark Matter

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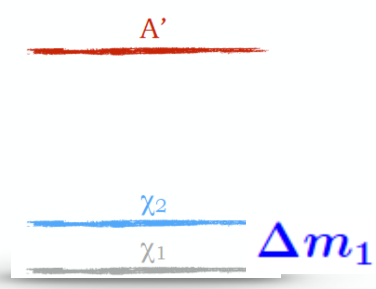
$$-\mathcal{L} \supset m_D\, \eta\xi + \frac{1}{2}\delta_\eta\, \eta^2 + \frac{1}{2}\delta_\xi\, \xi^2 + \text{h.c.}$$

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

$$\chi_1 = i(\eta - \xi)\sqrt{2}\,, \qquad \chi_2 = (\eta + \xi)\sqrt{2}$$

The only relevant interaction is inelastic:

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



The elastic piece is very small $(\delta_{\eta,\xi} \ll m_D)$:

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

Two states close in mass: $\Delta \equiv \frac{m_2 - m_1}{m_1} \sim \frac{\delta_\xi + \delta_\eta}{m_D} \ll 1$

Easy to get it small since it is a U(1)’ breaking effect

Tucker-Smith, Weiner, 0101138

The relic abundance of IDM

Abundance of χ_1 and χ_2 is determined by two coupled Boltzmann equations, that keep into account:

* $\chi_1\ \chi_2$ co-annihilation,
* $\chi_2\ f \to \chi_1\ f$ inelastic scattering,
* $\chi_2 \to \chi_1$ + SM decays

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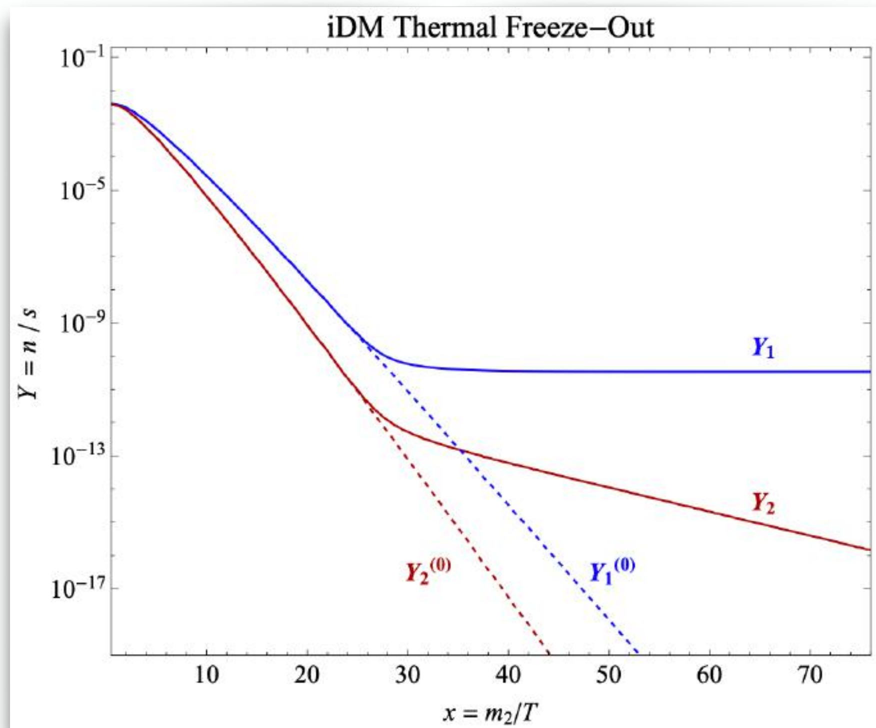
$$\sigma v(\chi_1\chi_2 \to \bar{f} f) \approx \frac{4\pi\epsilon^2\alpha\alpha_D(m_1+m_2)^2}{[(m_1+m_2)^2 - m_{A'}^2]^2}$$

$$\sigma v_{\rm full} = (\sigma v)_{e^+e^-}\theta(s-4m_e^2) + (\sigma v)_{\mu^+\mu^-}\left[\theta(s-4m_\mu^2) + \theta(s-4m_\pi^2)\boxed{R(s)}\right]$$



Izaguirre, Krnjaic, Shuve, 1508.03050

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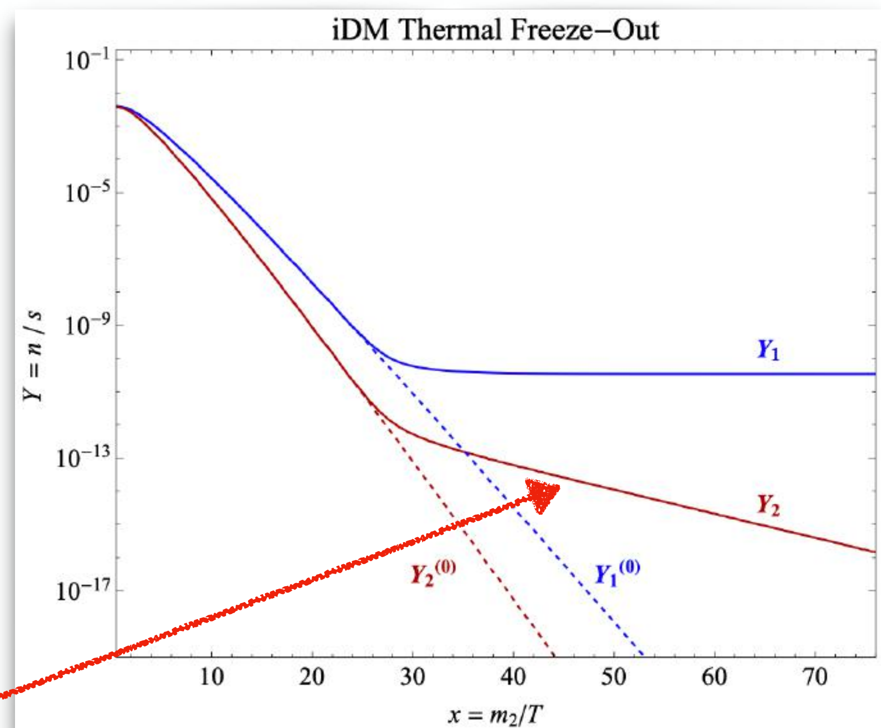


Izaguirre, Krnjaic, Shuve, 1508.03050

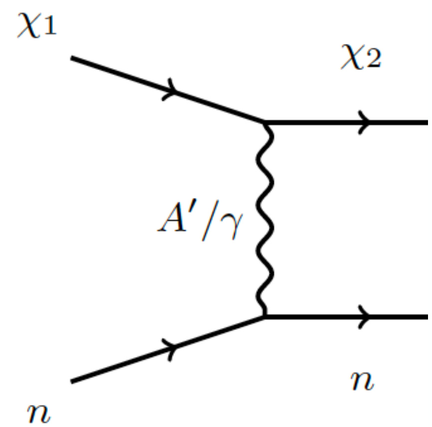
CMB constraints evaded:
χ_2 abundance is depleted today, suppressing indirect detection signals

IDM @ direct detection

χ_1 n → χ_2 n is only allowed
for certain kinematic configurations

When $m_1 \Delta \gg \dfrac{q^2}{2M_N}$

the inelastic process is kinematically
forbidden due to the low DM velocity.



IDM @ direct detection

χ_1 n → χ_2 n is only allowed
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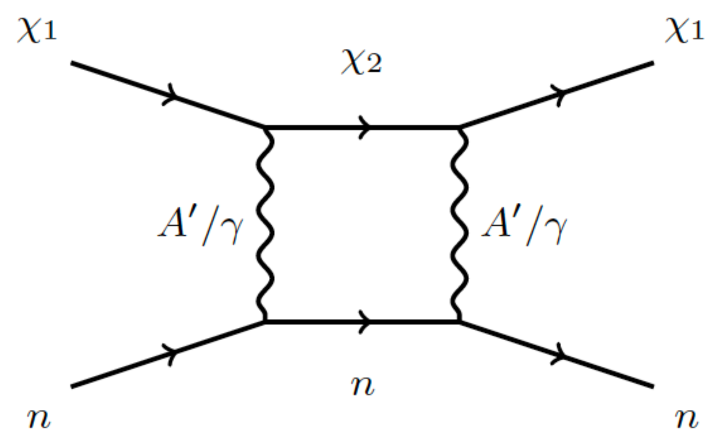

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Other processes can lead to constraints:

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IDM @ direct detection

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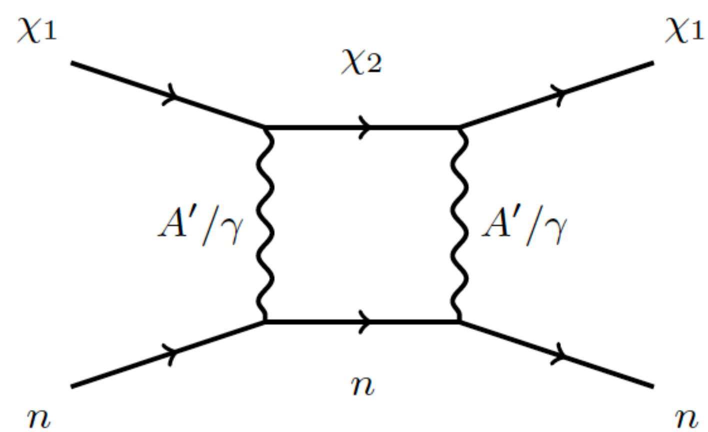


When $m_1\Delta \gg \frac{q^2}{2M_N}$

the inelastic process is kinematically
forbidden due to the low DM velocity.

However, for Δ > 0.1, these
constraints are not relevant
compared to the accelerator
constraints (see next)

Other processes can lead to constraints:

- higher order loop-induced processes
- diagonal interactions suppressed by the mass splitting:

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

if, $\delta_\xi - \delta_\eta = \mathcal{O}(\delta_\xi + \delta_\eta)$ ⇒ $\sigma_{\chi n} \simeq \frac{16\pi\epsilon^2\alpha\alpha_D\Delta^2 Z^2}{m_{A'}^4 A^2}\mu_{\chi n}^2 v^2$

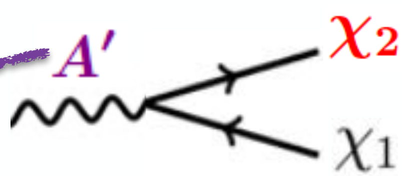
IDM displaced signatures

IDMs are rather hidden to direct and indirect detection experiments
The prime avenue to probe IDM is at high intensity experiments

IDM displaced signatures

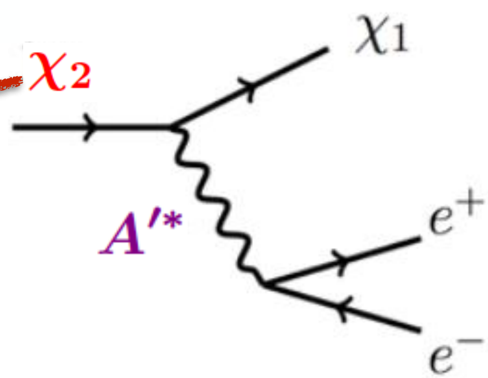
IDMs are rather hidden to <u>direct and indirect detection experiments</u>
The prime avenue to probe IDM is at high intensity experiments

$\boxed{m_X < m_{A'}}$



Copiously produced at
high intensity experiments

with



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

Non-resonant decays

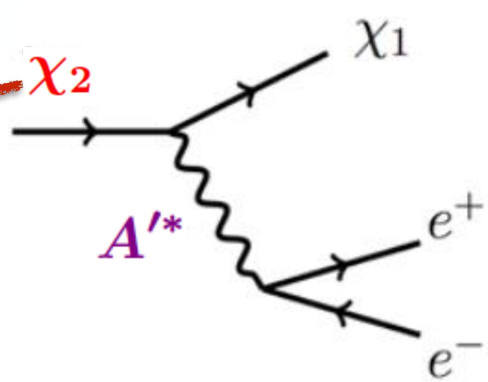
IDM displaced signatures

IDMs are rather hidden to <u>direct and indirect detection experiments</u>
The prime avenue to probe IDM is at high intensity experiments

$\boxed{m_\chi < m_{A'}}$

Copiously produced at high intensity experiments

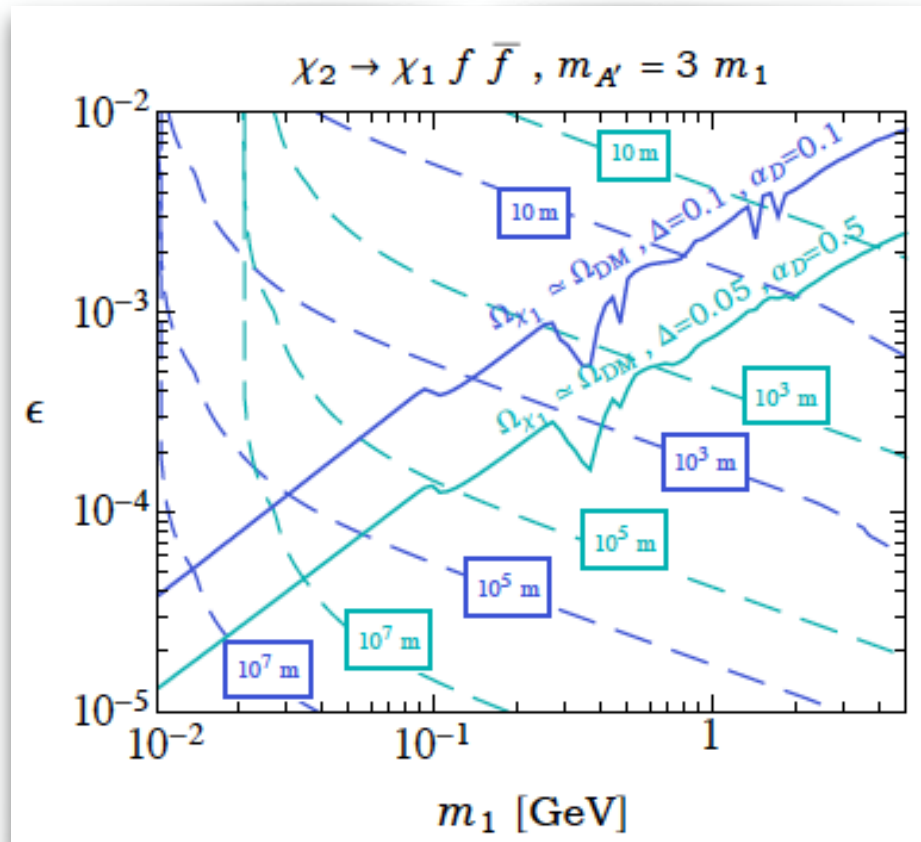
with



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

Non-resonant decays

Berlin, SG, Schuster, Toro, 1804.00661



Displaced decays

The accelerator experiment hunt for IDMs

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

* Depending on the mass splitting, Δ, the A’ decay lead to
- invisible signatures
- visible prompt non-resonant signatures
- displaced signatures

The accelerator experiment hunt for IDMs

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- invisible signatures
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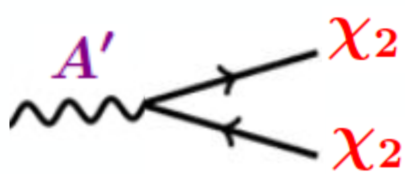
* Depending on the specific Lagrangian parameters, also

and



can be relevant

* Another possibility:
upscattering $\chi_1 N \to \chi_2 N$ where N is a nucleon or a nucleus, followed by χ_2 decay

The accelerator experiment hunt for IDMs

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

✱ Depending on the mass splitting, Δ, the A’ decay lead to
- invisible signatures
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✱ Depending on the specific Lagrangian parameters, also

and

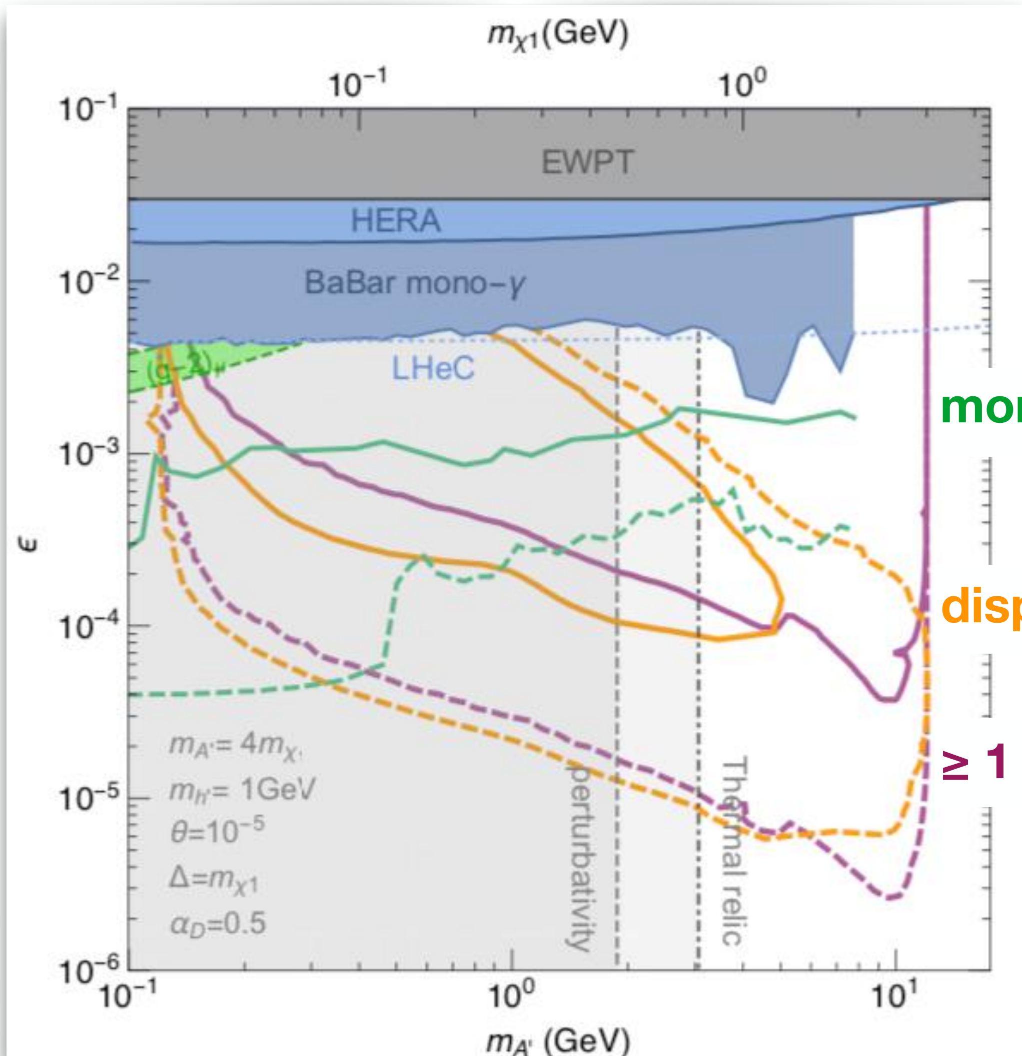
can be relevant

✱ Another possibility:
upscattering $\chi_1 N \to \chi_2 N$ where N is a nucleon or a nucleus, followed by χ_2 decay

Many experiments can target this scenario!
- LHC,
- beam dump experiments
- B-factories
- neutrino experiments (near detectors)

The Belle II IDM reach

Duerr, Ferber, Garcia-Cely, Hearty, Schmidt-Hoberg, 2012.08595



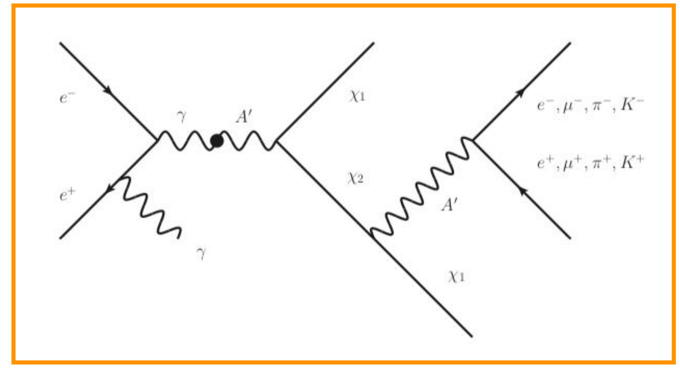
100/fb

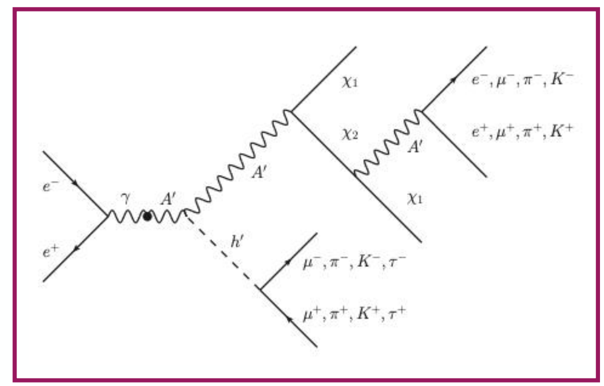
50/ab

mono-photon

displaced+photon

≥ 1 displaced



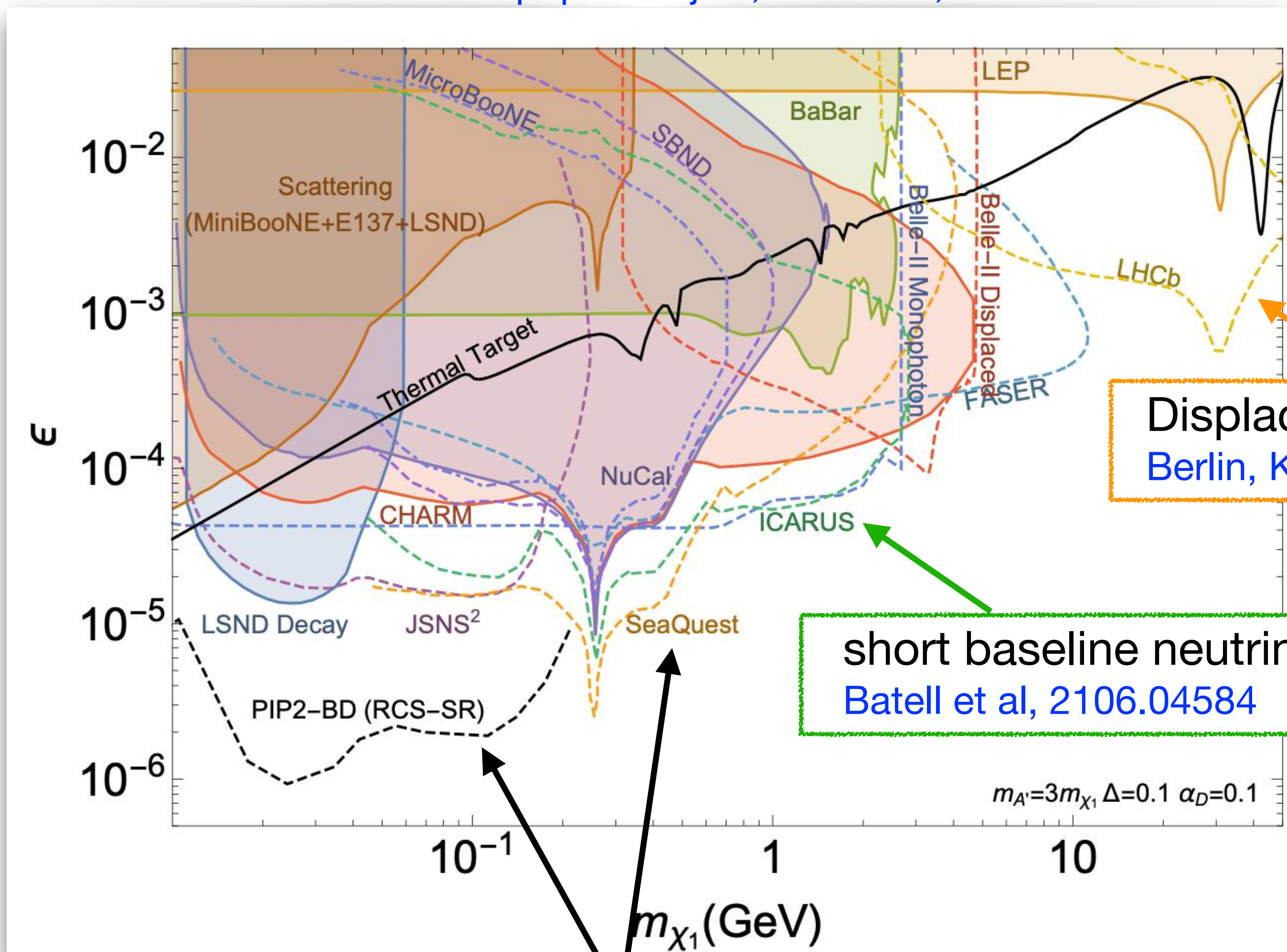


(two pairs of charged particles, at least one pair displaced)

Displaced vertex trigger is very important to obtain a good reach!

Summary: IDMs at accelerator experiments

Snowmass whitepaper Krnjaic, Toro et al, 2207.00597

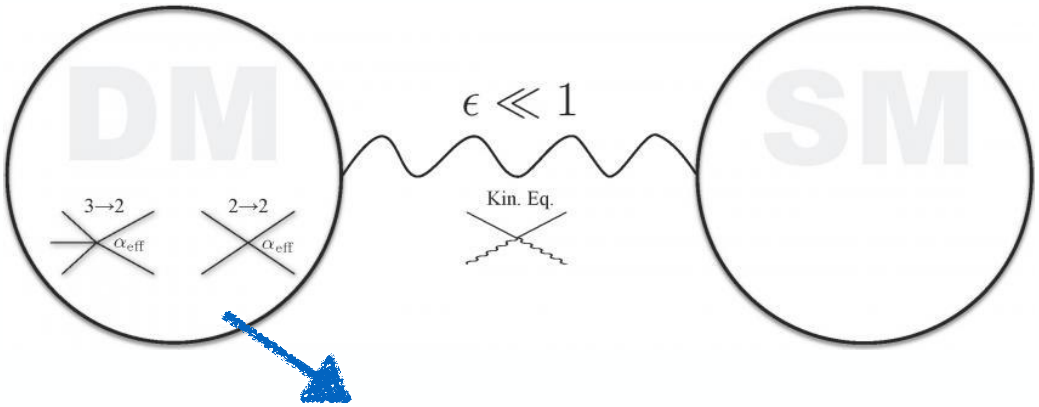


Displaced di-muons
Berlin, Kling, 1810.01879

short baseline neutrino experiment
Batell et al, 2106.04584

proton beam-dumps,
8 GeV, Toups et al, 2203.08079
120 GeV, Berlin, SG, Schuster, Toro, 1804.00661

Strongly interacting massive particles (SIMP) in a nutshell



Hochberg, Kuflik, Volansky, Wacker, 1402.5143,

Hochberg, Kuflik, Murayama, Volansky, Wacker, 1411.3727

A new scale for DM?

(**WIMP**

$$2 \to 2$$

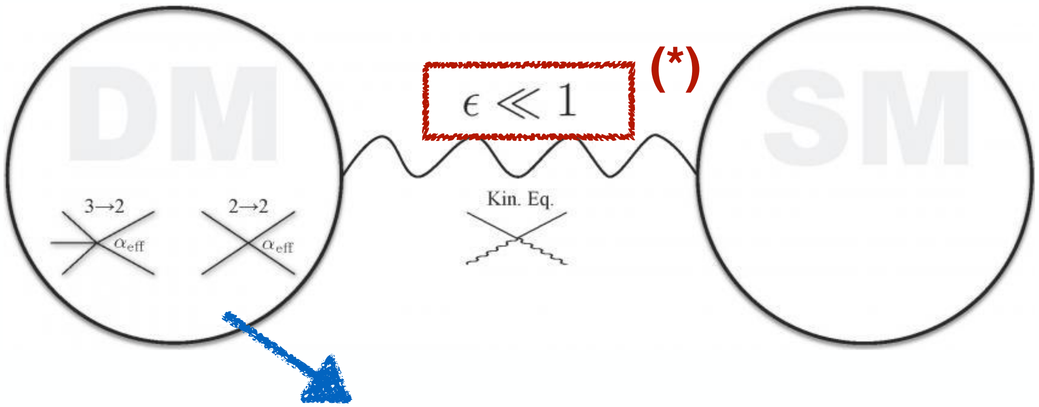
$$m_{\rm DM} \sim \alpha_{\rm ann}(T_{\rm eq} M_{\rm pl})^{1/2} \sim \text{TeV}$$)

SIMP

$$3 \to 2$$

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

Strongly interacting massive particles (SIMP) in a nutshell



Hochberg, Kuflik, Volansky, Wacker, 1402.5143,

Hochberg, Kuflik, Murayama, Volansky, Wacker, 1411.3727

(*) Needed to maintain thermalization between the two sectors

A new scale for DM?

WIMP	**SIMP**
$2 \to 2$	$3 \to 2$
$\left(m_{\rm DM} \sim \alpha_{\rm ann}(T_{\rm eq} M_{\rm pl})^{1/2} \sim \text{TeV} \right)$	$m_{\rm DM} \sim \alpha_{\rm ann}(T_{\rm eq}^2 M_{\rm pl})^{1/3} \sim 100\ \text{MeV}$

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

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

If the portal operator is not too small, the dark pions can be in thermal equilibrium with the SM → **Detection?**

Spectrum and portal to the SM

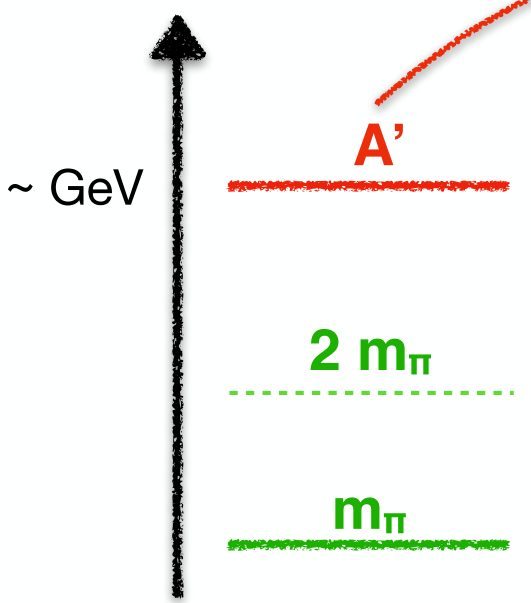
A concrete realization for SIMPs

Berlin, Blinov, SG,
Schuster, Toro, 1801.05805

$$\frac{\epsilon}{2\cos\theta_W} A'_{\mu\nu} B^{\mu\nu}$$

DM is kept in thermal equilibrium

SM



prevent

$\pi\pi \to A'A'$

(CMB)

N_f^2-1 = 8 dark pions:

$$\frac{1}{\sqrt{2}}\begin{pmatrix} \frac{\pi^0}{\sqrt{2}}+\frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}}+\frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \overline{K^0} & -\sqrt{\frac{2}{3}}\,\eta \end{pmatrix}$$

$$SU(3)_L \times SU(3)_R \to SU(3)_D \supset U(1)_D$$

$$N_f = 3$$

Spectrum and portal to the SM

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Berlin, Blinov, SG, Schuster, Toro, 1801.05805

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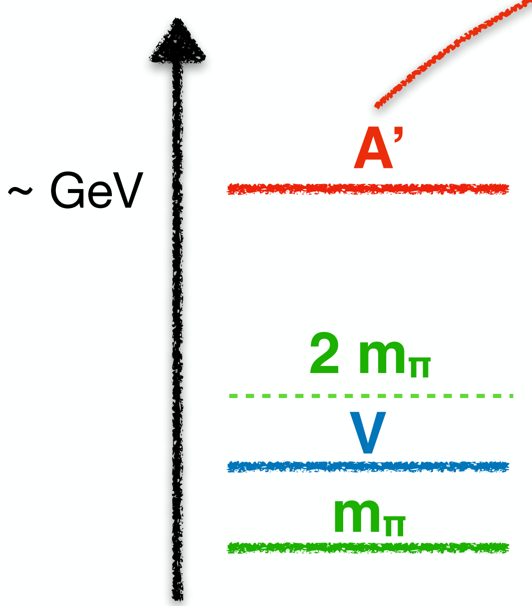

prevent

$$\pi\pi \to A'A'$$

(CMB)

$$\frac{m_\pi}{f_\pi} \gtrsim 3$$

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vector mesons, V:

$$\frac{1}{\sqrt{2}}\begin{pmatrix} \frac{\rho^0}{\sqrt{2}}+\frac{\omega}{\sqrt{2}} & \rho^+_\mu & K^{*+}_\mu \\ \rho^-_\mu & -\frac{\rho^0}{\sqrt{2}}+\frac{\omega}{\sqrt{2}} & K^{*0}_\mu \\ K^{*-}_\mu & \overline{K^{*0}_\mu} & \phi \end{pmatrix}$$

$$SU(3)_L \times SU(3)_R \to SU(3)_D \supset U(1)_D$$

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

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Berlin, Blinov, SG, Schuster, Toro, 1801.05805

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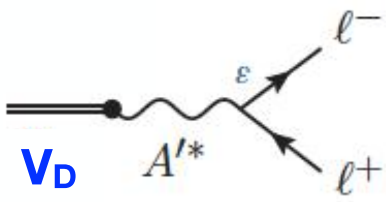
2. $\pi_D \pi_D \to V_D \pi_D$ semi-annihilation



$m_V < 2m_\pi$

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

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

The dark pion relic abundance

Berlin, Blinov, SG, Schuster, Toro, 1801.05805

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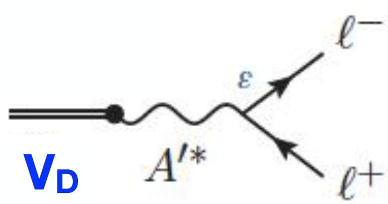

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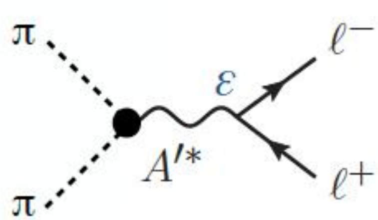

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Berlin, Blinov, SG, Schuster, Toro, 1801.05805

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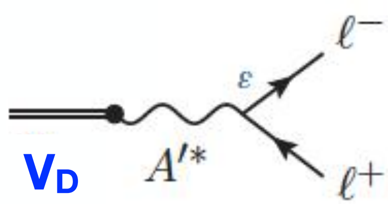

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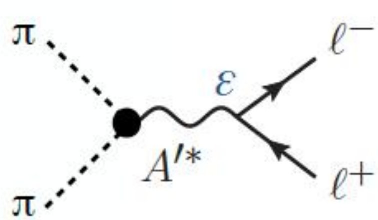
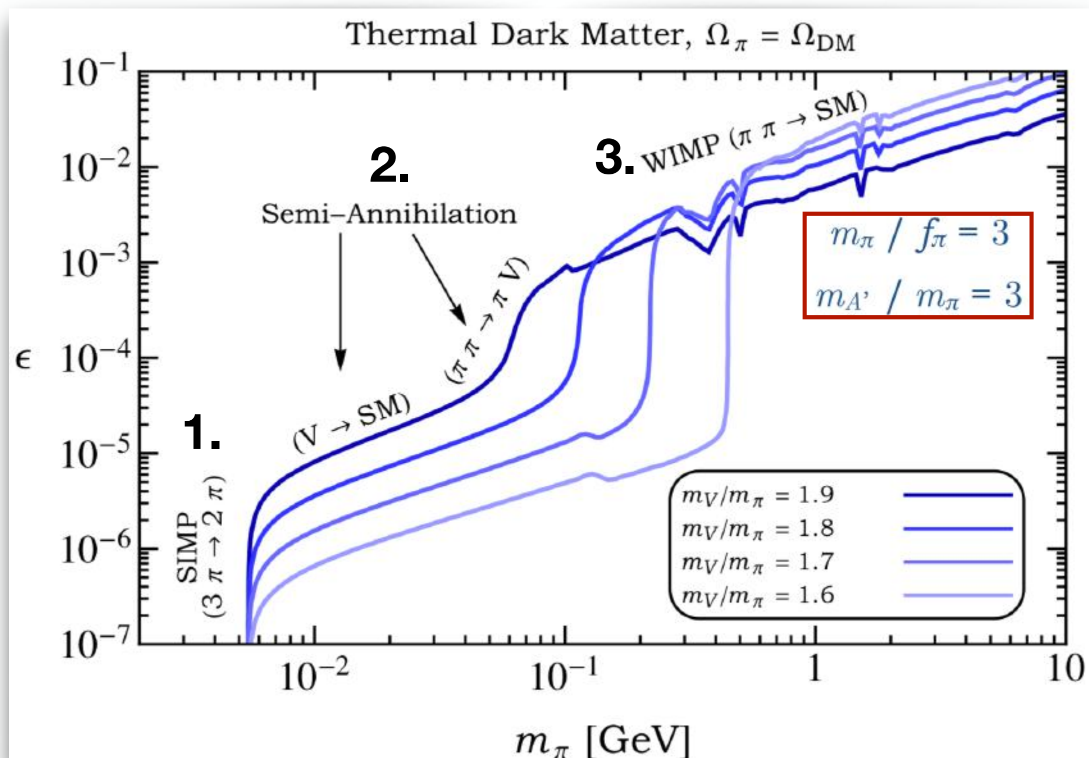
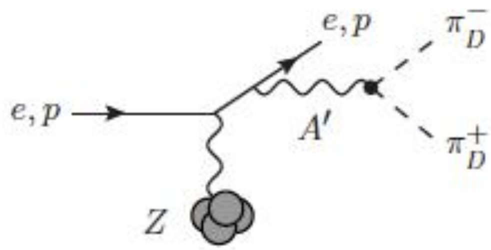


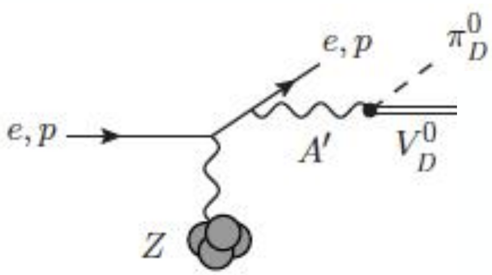


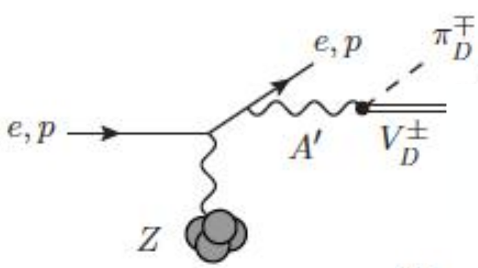
SIMP decays of the dark photon

$$A' \to \pi_D^+ \pi_D^- \quad \text{(DM)}$$



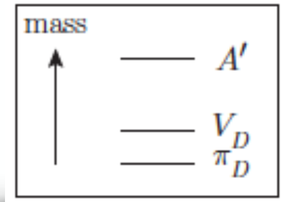
$$\Gamma \propto \alpha_D m_{A'}$$



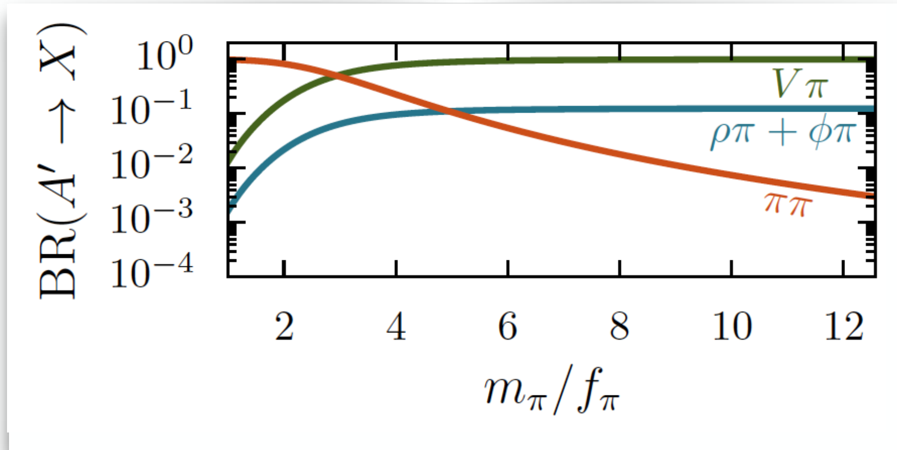


$$\Gamma \propto \alpha_D \frac{m_{A'}^3 m_V^2}{f_\pi^4}$$

$$A' \to \pi_D V_D$$



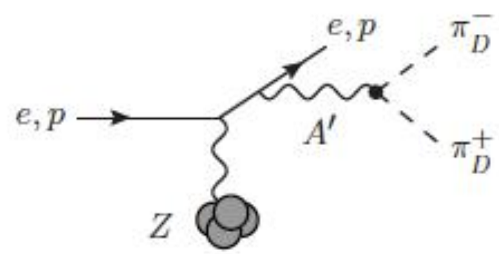
Berlin, Blinov, SG, Schuster, Toro, 1801.05805



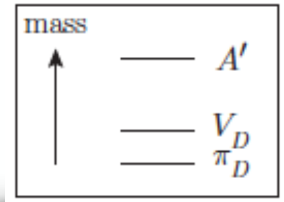
$\alpha_D = 10^{-2}, \quad \epsilon = 10^{-3}$

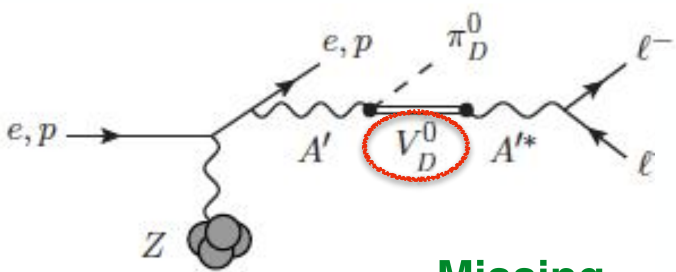
SIMP decays of the dark photon

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

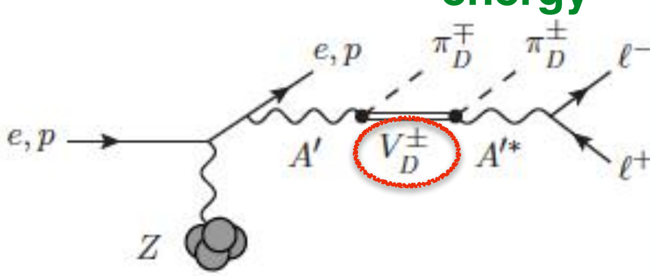


Invisible
A' decay





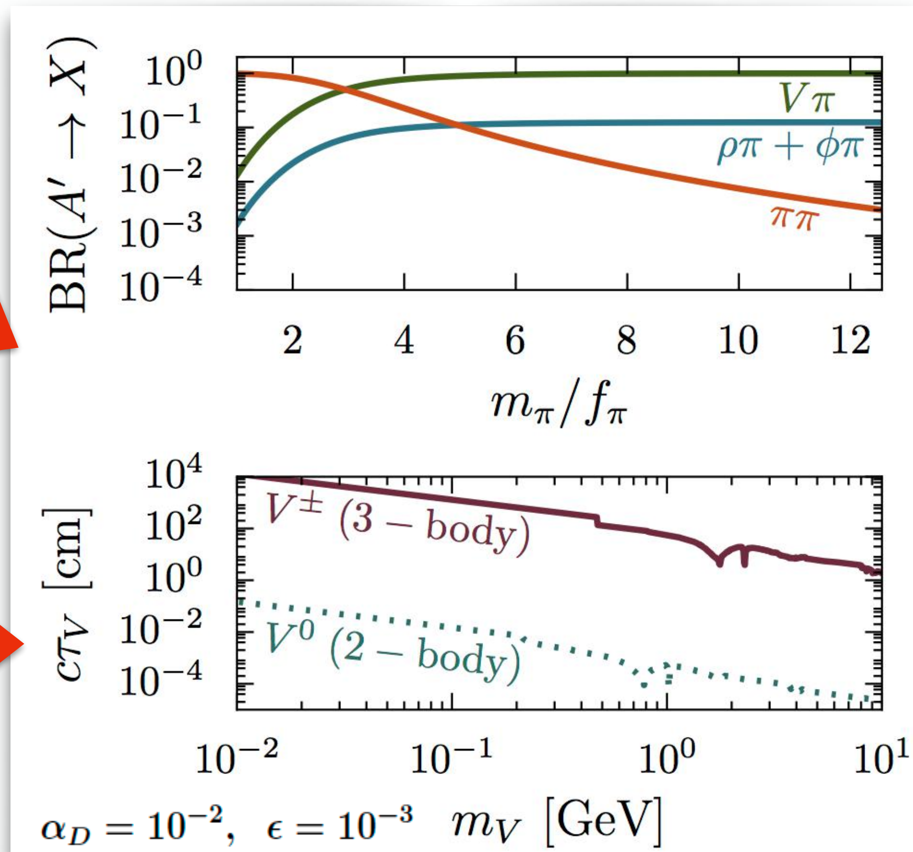
Missing energy



Visible
A' decay

$A' \to \pi_D V_D$

Berlin, Blinov, SG, Schuster, Toro, 1801.05805

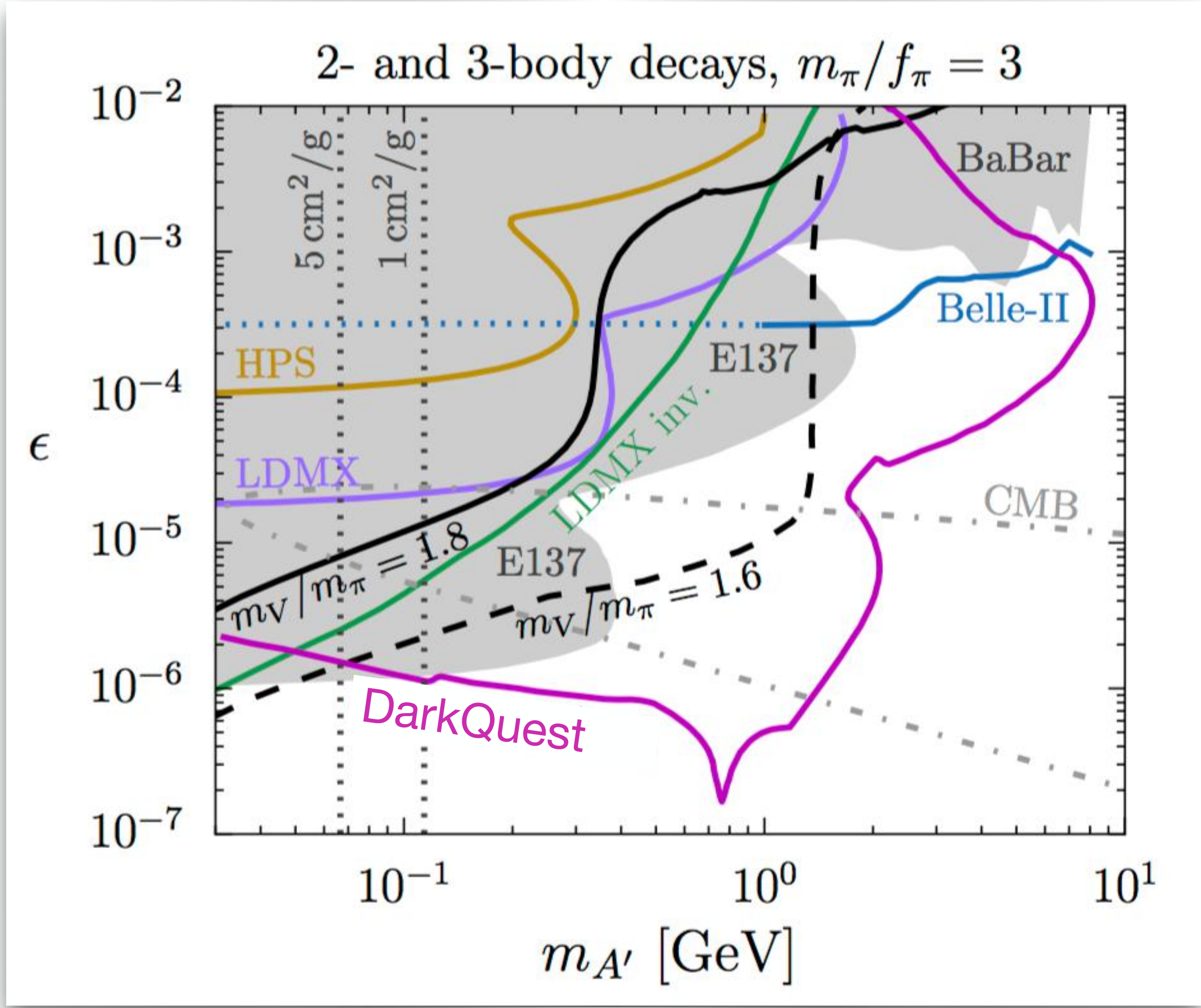


Displaced decays of the dark vector

Summary: SIMPs at accelerator experiments

2+3 body decays

Berlin, Blinov, SG, Schuster, Toro, 1801.05805

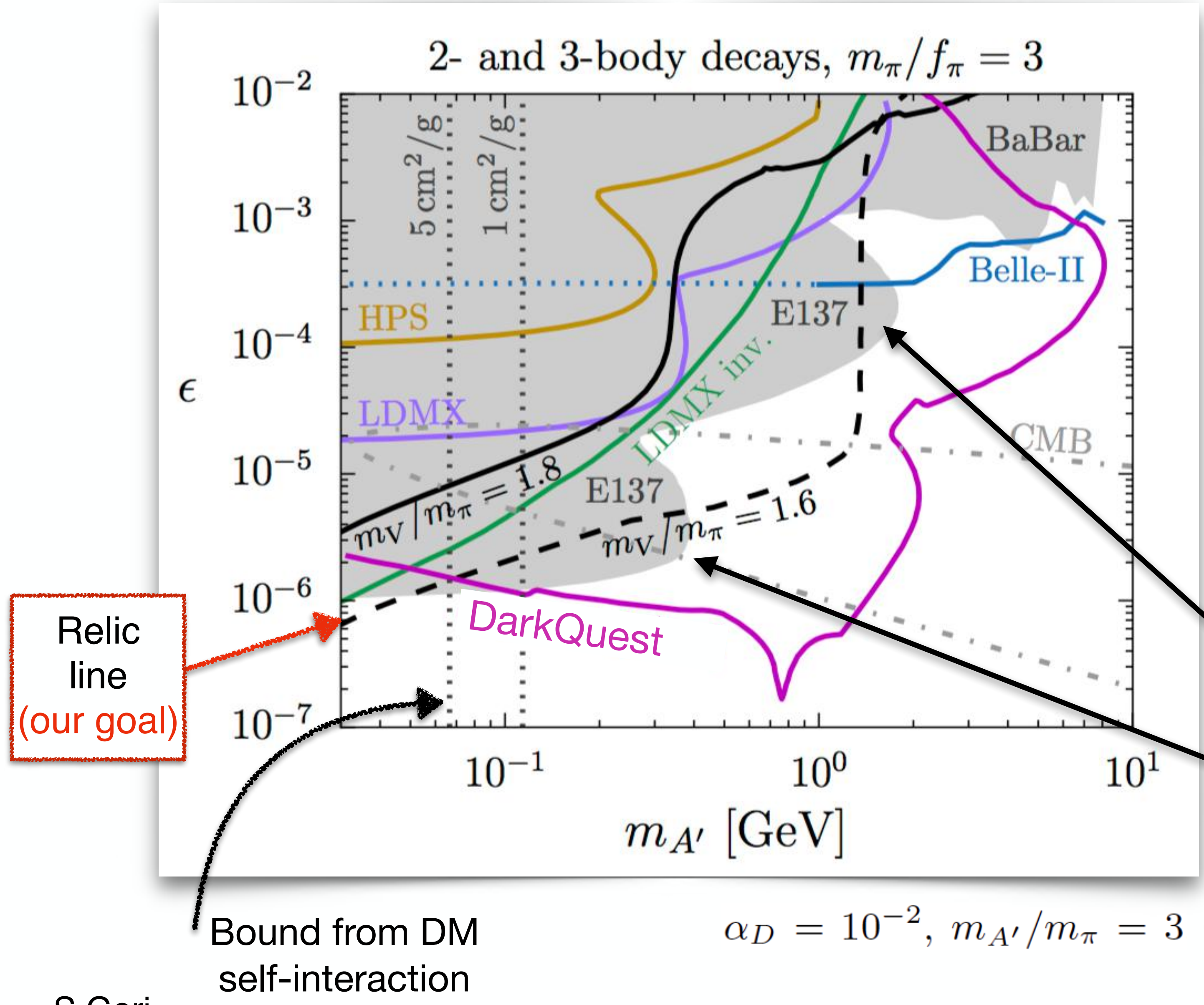


$\alpha_D = 10^{-2}$, $m_{A'}/m_\pi = 3$

Summary: SIMPs at accelerator experiments

2+3 body decays

Berlin, Blinov, SG, Schuster, Toro, 1801.05805



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'

$$A' \to \pi_D V_D$$

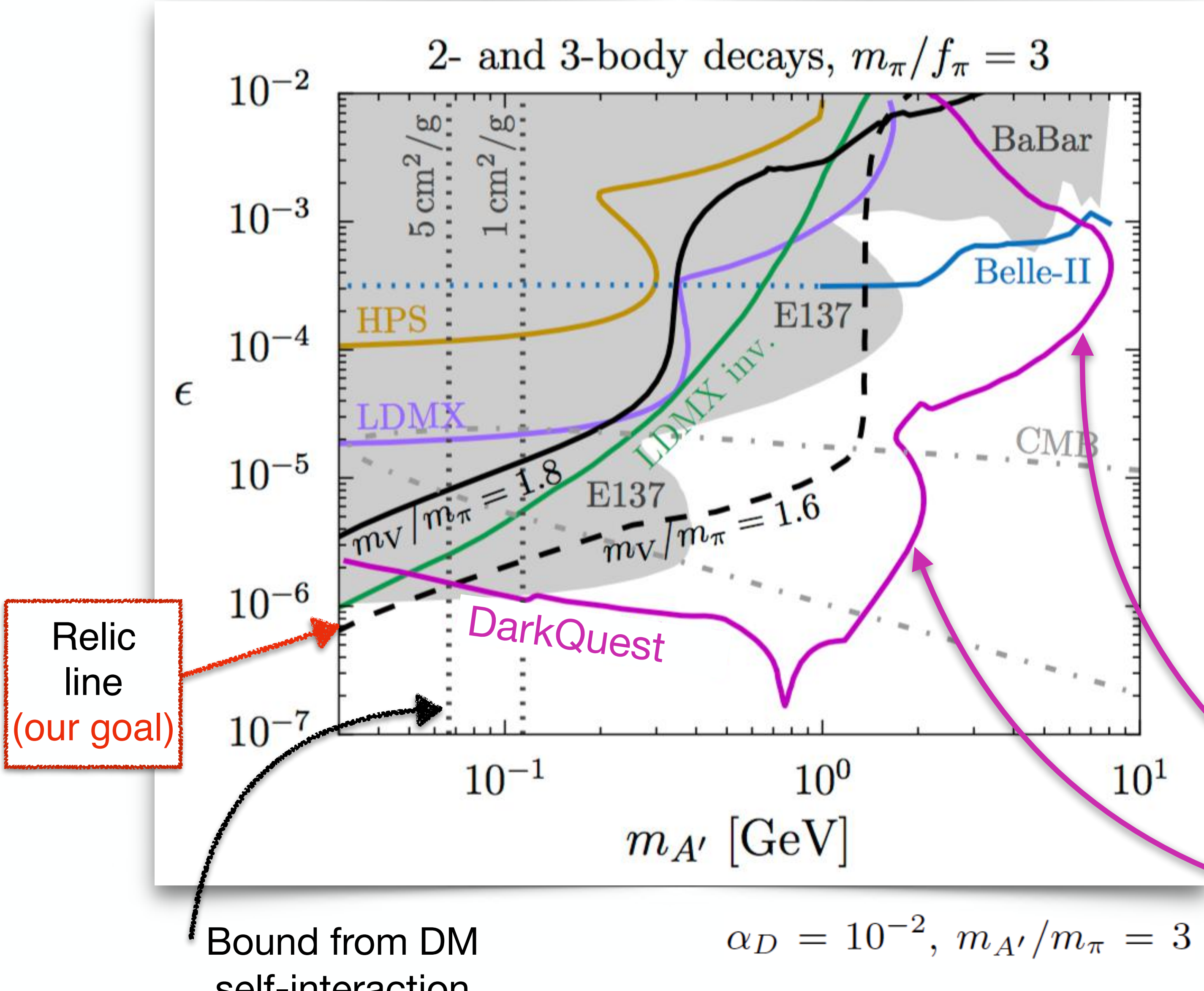
$$V_D^\pm \to \pi_D^\pm \ell^+\ell^-$$

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

Summary: SIMPs at accelerator experiments

2+3 body decays

Berlin, Blinov, SG, Schuster, Toro, 1801.05805



In color:

reach of past experiments:

- Belle II: (same Babar signature)

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

- LDMX: invisible A'
- LDMX: visible A'
- HPS: electron beam dump experiment. Search for visibly decaying A' **(*)**
- DarkQuest

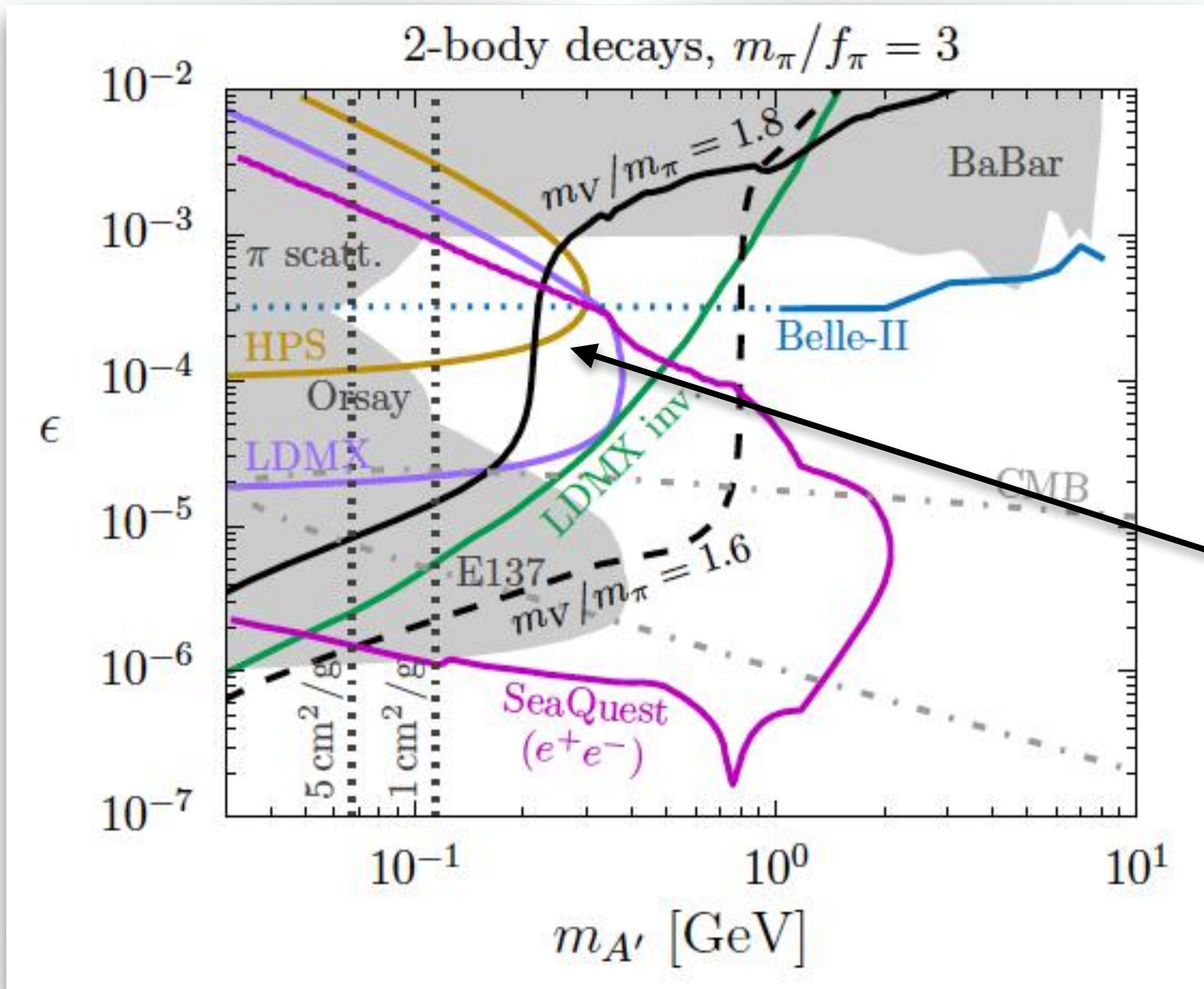
$$A' \to \pi_D V_D$$

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

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

Summary: SIMPs at accelerator experiments

2 body decays



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

If the charged vectors are heavier than $2m_\pi$, then only the neutral vectors will appreciably decay visibly:

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

E137 (past) bounds are relaxed since the experiment had a long baseline (~400 m).

Larger regions of parameter space are open

Take home messages

DM thermal freeze-out models are highly predictive and give us experimental targets.

Complementarity between different accelerator experiments.
Possible complementarity with direct and indirect detection experiments (model dependence).

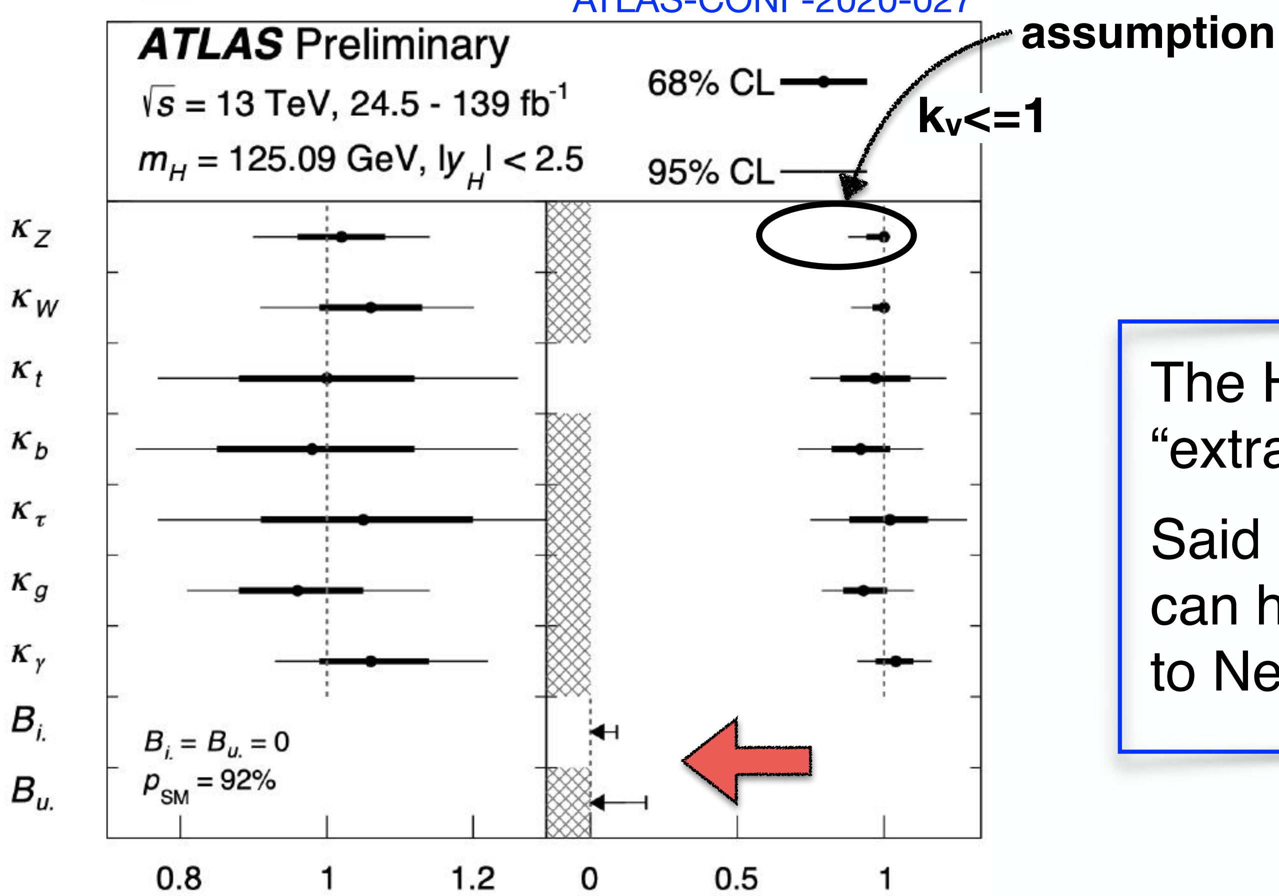
Minimal freeze-out light dark sector models will be extensively probed in the coming few years (if a few new experiments get on-shell)

Rich structure and phenomenology of non-minimal dark sector models (IDM, SIMP)

The importance of Higgs exotic decays

The extraction of info on the Higgs width is hard and has typically some model dependence at the LHC (hadron colliders)

ATLAS-CONF-2020-027



BR_{BSM} < 19%, B_{inv}< 9%

Prospects for the HL-LHC: **~4%,** 2%

The Higgs can have some "extra width".

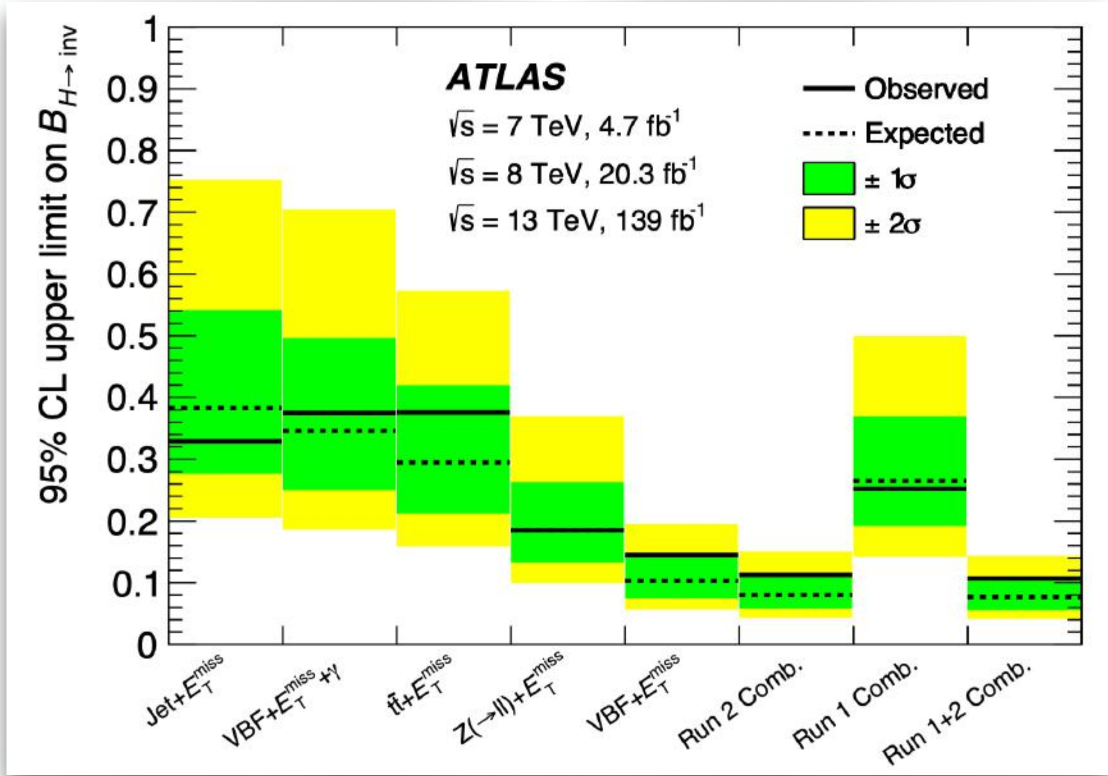
Said in other words: the Higgs can have some exotic decays to New Physics particles

Higgs invisible decays… and beyond

One classic example is the Higgs decaying invisibly

This is realized in e.g. DM theories where the DM particle couples to the Higgs and is light

Several searches for Higgs decaying invisibly:



2301.10731

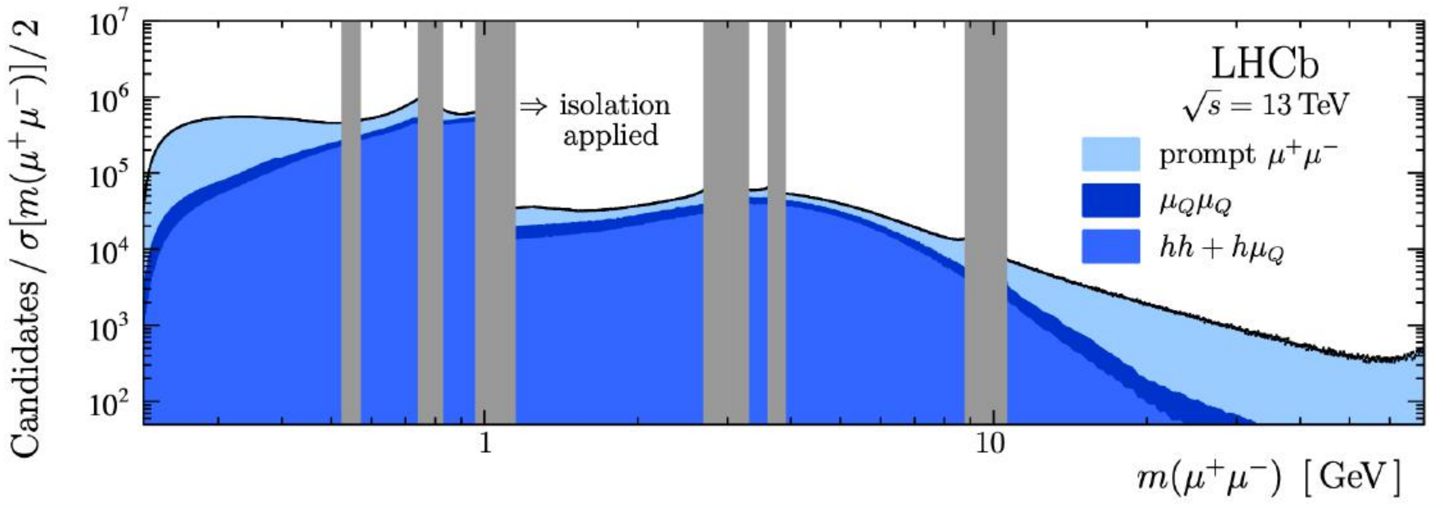
This bound can be interpreted in terms of models that predict the Higgs decaying into DM states

But what about the "extra width" arising from different decay modes that are (at least partially) visible? We have to look for them directly.

2. Visible dark photons at LHCb

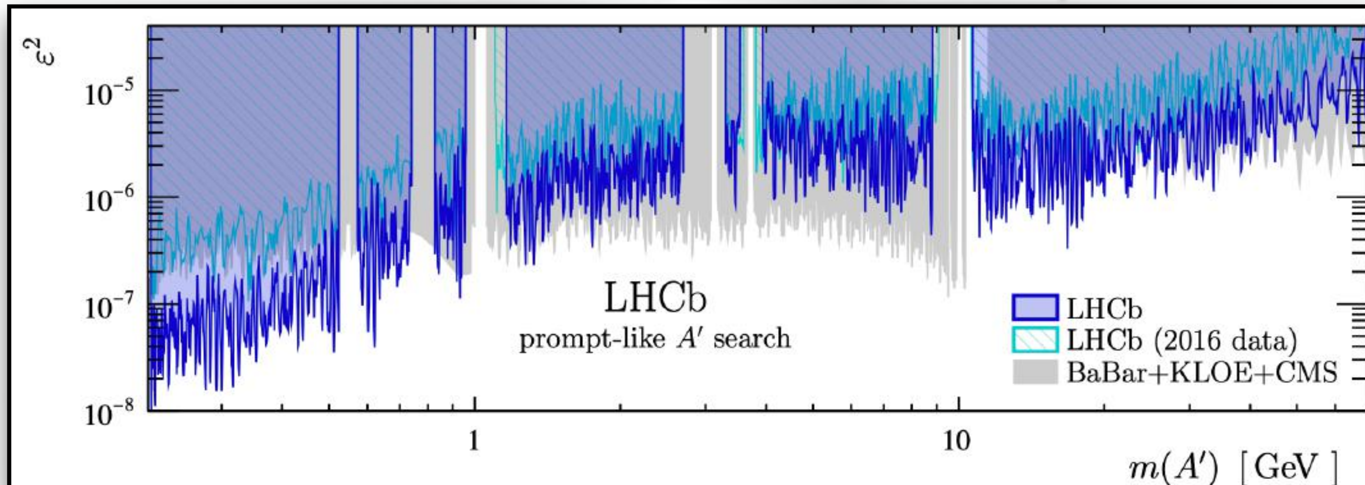
Search for a di-muon resonance: both prompt and displaced

Prompt **5.1 fb^{-1}**



Fantastic di-muon identification in a very broad mass range

1910.06926

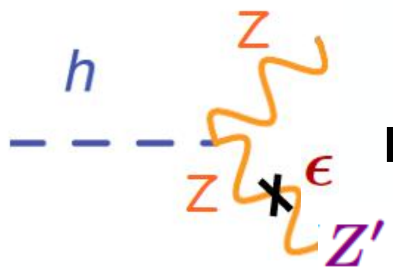


Below the muon threshold: additional opportunities for

$$D^{*0} \to D^0 A', \quad A' \to e^+e^-$$

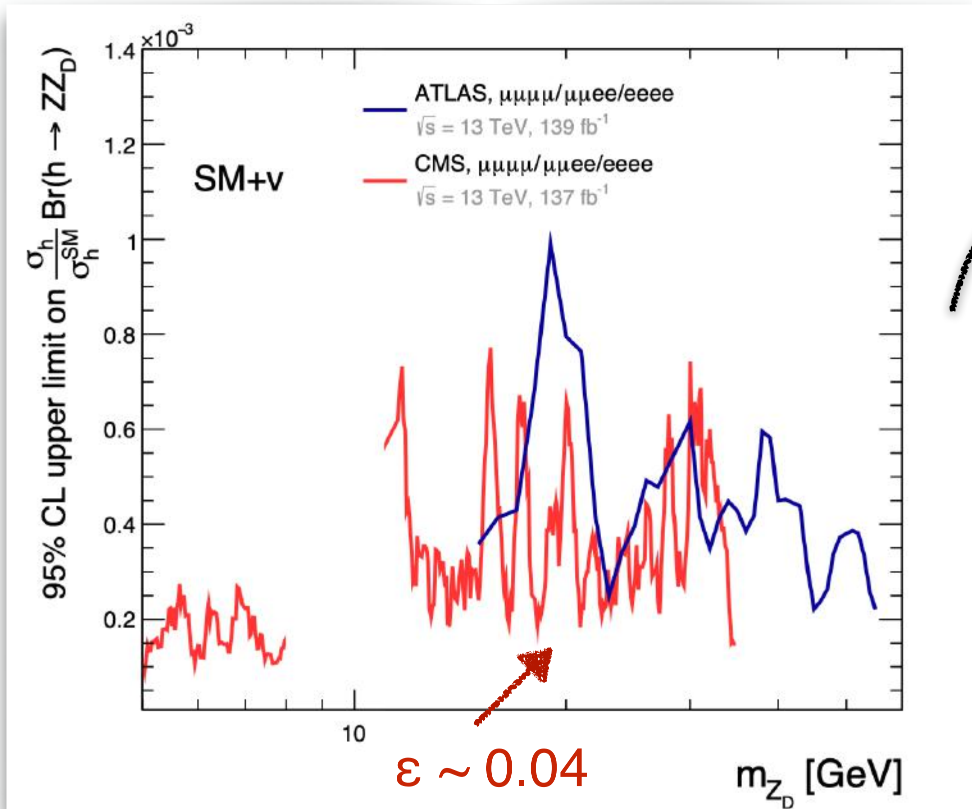
Ilten et al., 1509.06765

4. Visible dark photons from Higgs exotic decays



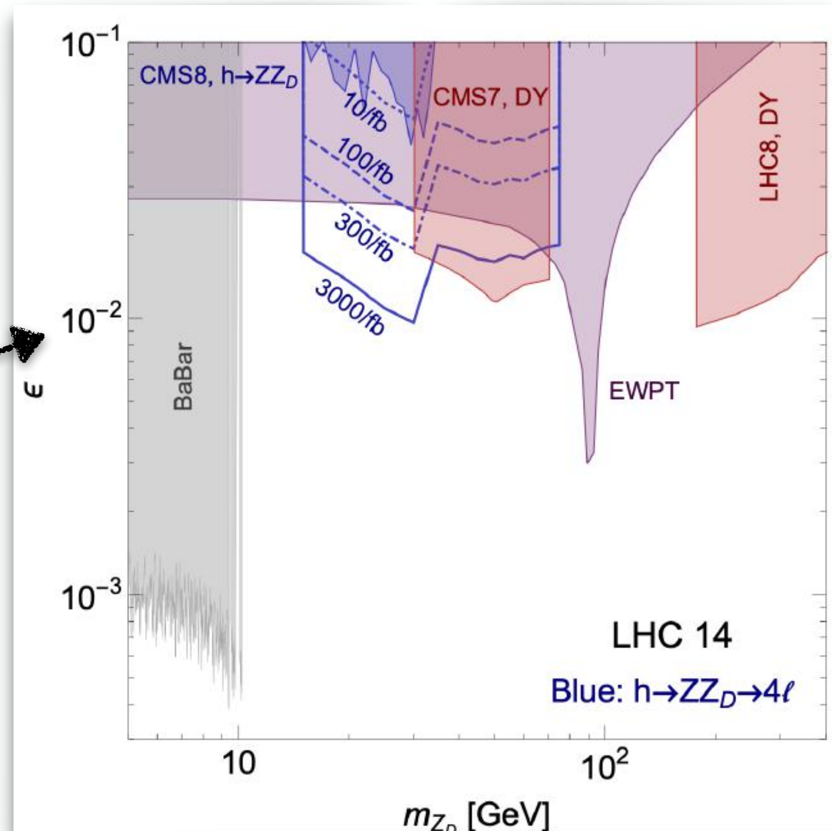
prompt

$$h \to Z Z' \to 2\ell\ 2\ell'$$



ε ~ 0.04

Curtin, Essig, SG, Shelton, 1412.0018

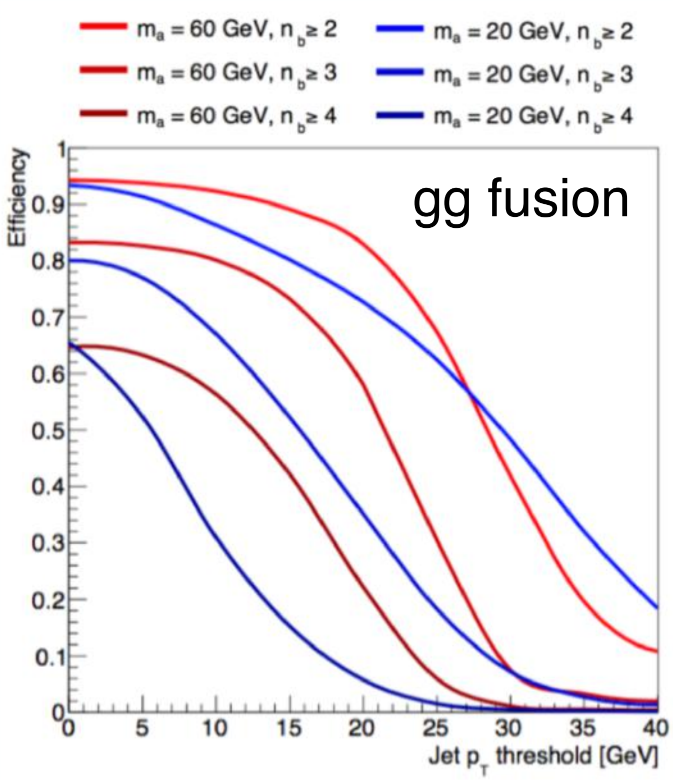


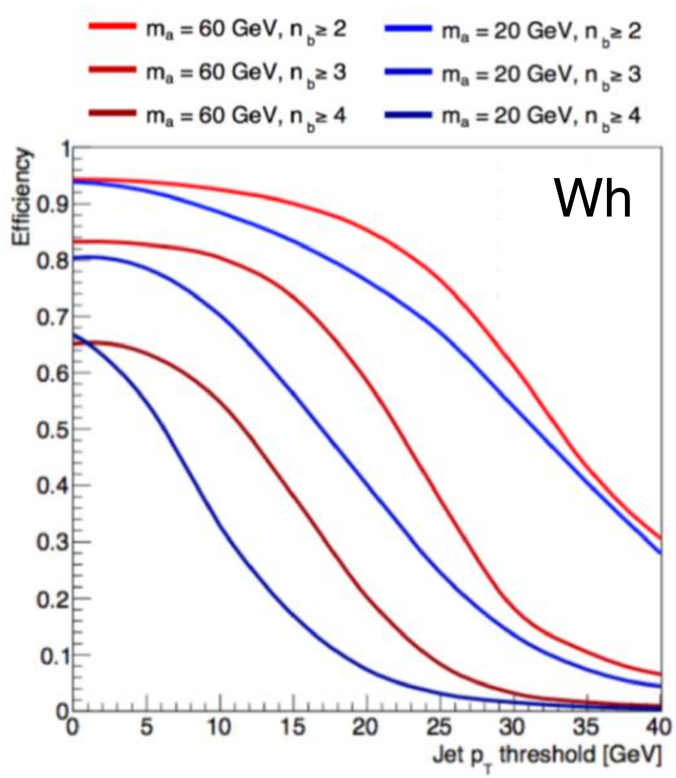
Cepeda, SG, Martínez Outschoorn, Shelton, 2111.12751

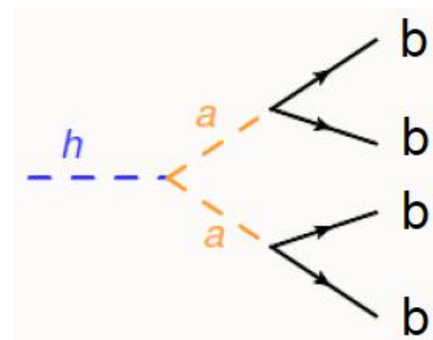
The challenge of Higgs exotic decays: soft objects

To be sensitive to Higgs exotic decays, dedicated studies of trigger strategies are needed

Let us take, for example, the challenging decay mode $h \to 4b$





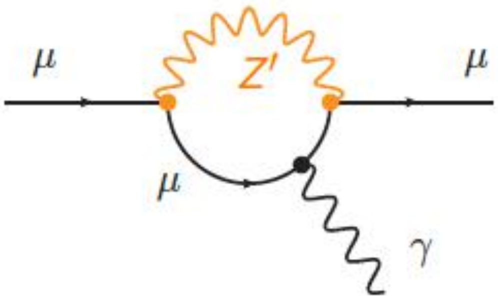


Risk of loosing the signal already at the trigger level

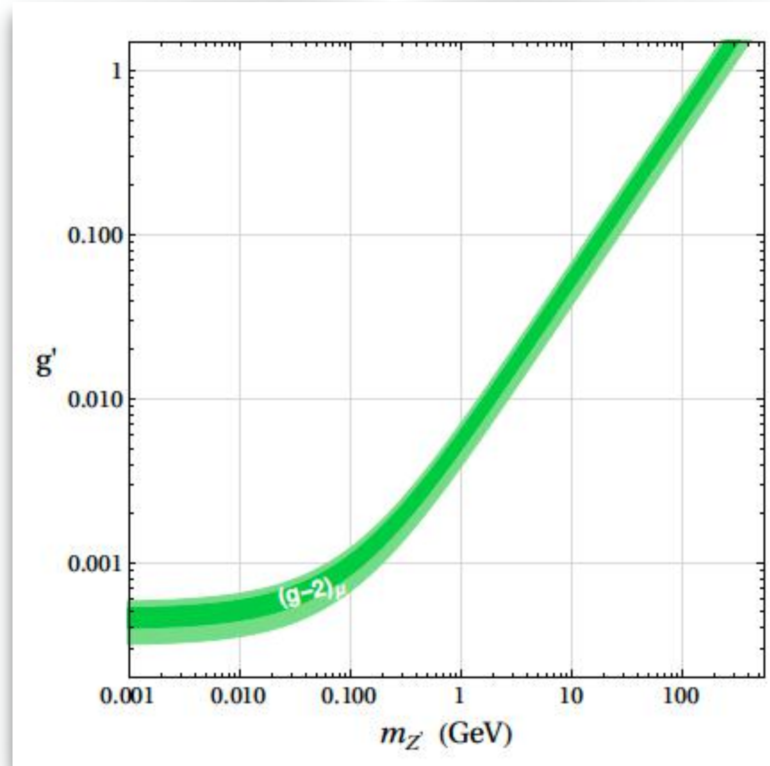
From the LHC Higgs cross section working group, Yellow report 4, 1610.07922

Motivations for this symmetry

- Z' contributes to $(g\text{-}2)_\mu$.
Can it address the anomaly?



$$\Delta a_\mu \simeq \frac{(g')^2}{12\pi^2}\frac{m_\mu^2}{m_{Z'}^2} + \mathcal{O}\left(\frac{m_\mu^4}{m_{Z'}^4}\right)$$



- This symmetry is used in neutrino mass model building to explain why $\theta_{13} << \theta_{23}$

See e.g.Heeck, Rodejohann, 1107.5238

- As we will see later, another motivation is Dark Matter model building

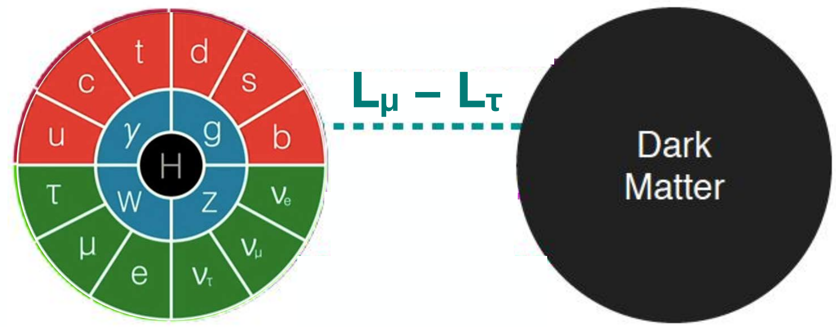
This gauge boson is more hidden than the dark photon since it does not couple to electrons or light quarks at the tree level

A new gauge symmetry for DM?

Dark Matter can be charged under this new gauge symmetry

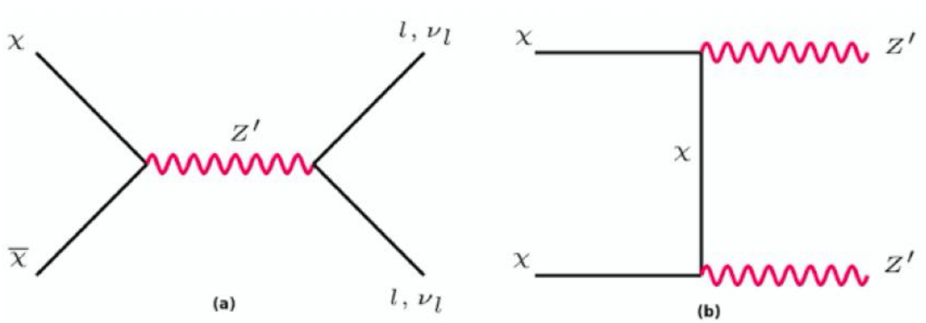
<u>Simple example:</u>
dark matter is a Dirac fermion
charged under $L_\mu - L_\tau$, $q_\chi g' \bar{\chi} \gamma^\mu \chi Z'_\mu$

Altmannshofer, SG, Profumo, Queiroz 1609.04026
(see also Kile et al. 1411.1407; Kim et al. 1505.04620; Baek 1510.02168 ...)



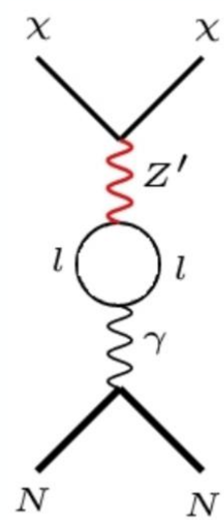
Possible signals at:

1. DM indirect detection experiments



Main constraints from CMB

2. DM direct detection experiments



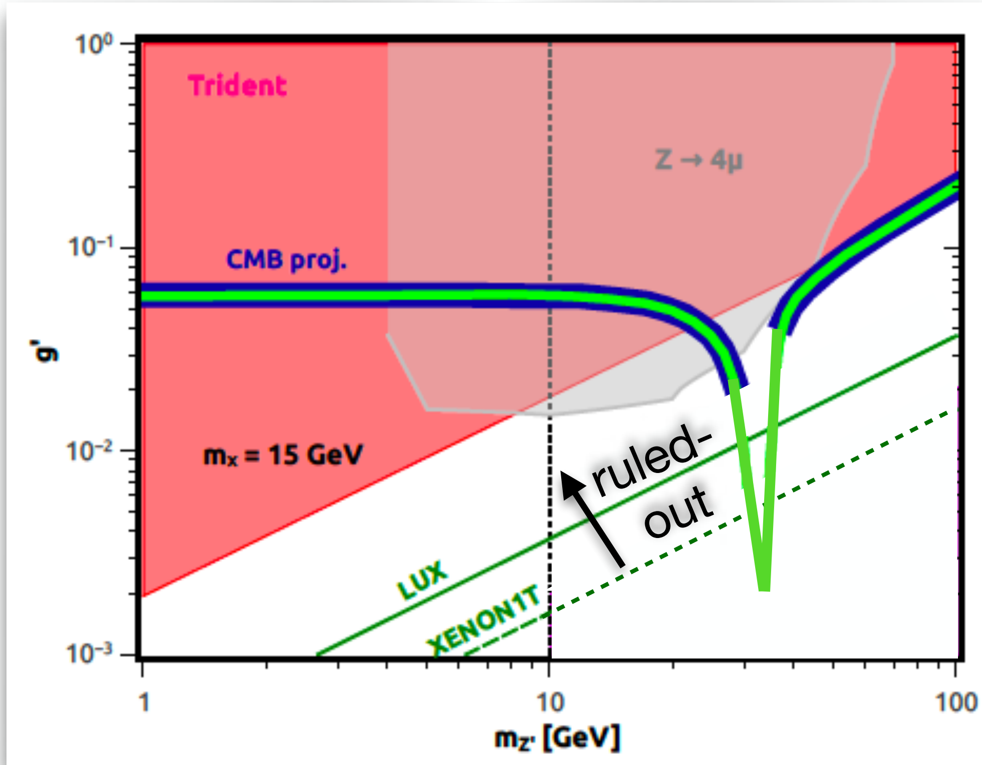
It can be sizable, despite the loop suppression

Constraints from LUX, Xenon, and PandaX

Dark Matter parameter space

Because of constraints from direct detection and CMB, the right relic density can only be obtained close to the resonance $m_{Z'} \simeq 2m_X$

(for light DM)

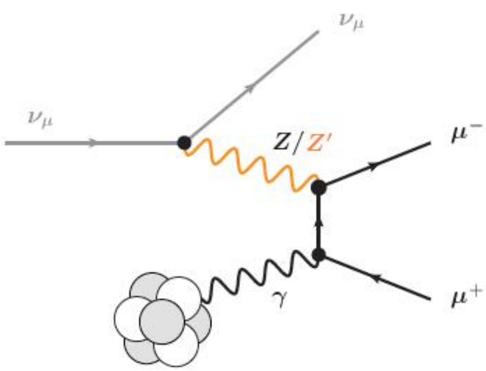


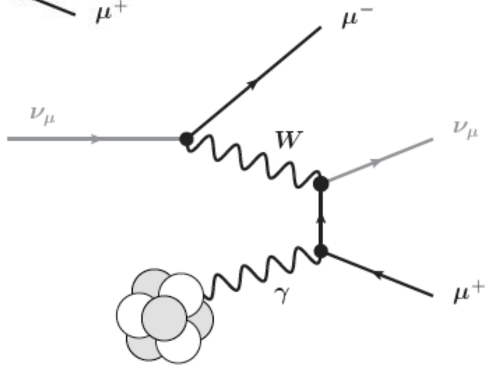
Altmannshofer, SG, Profumo, Queiroz 1609.04026

Tests at neutrino experiments:
CCFR, CHARM experiments

Bounds from the measurement of neutrino trident processes

Neutrino induced $\mu^+\mu^-$ production in the Coulomb field of a heavy nucleus:
"neutrino trident production"





Z' contribution to the cross section:

$$\frac{\sigma}{\sigma_{\rm SM}} \simeq \frac{1+\left(1+4s_W^2+\frac{2v^2(g')^2}{M_{Z'}^2}\right)^2}{1+(1+4s_W^2)^2}$$

(in the approximation of heavy Z')

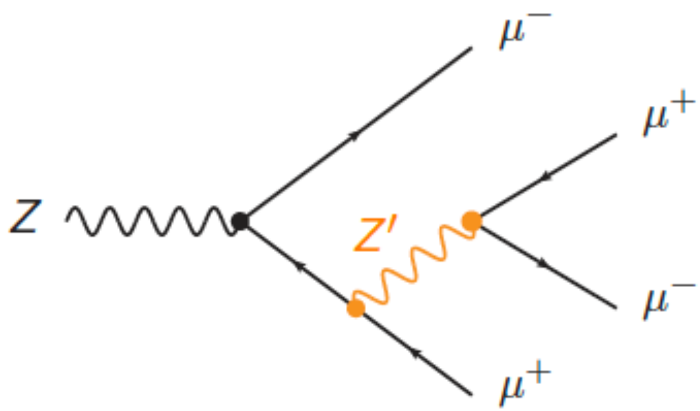
Measurements in the early '90s by CCFR and CHARM:

$\sigma/\sigma_{\rm SM} = 0.82 \pm 0.28$

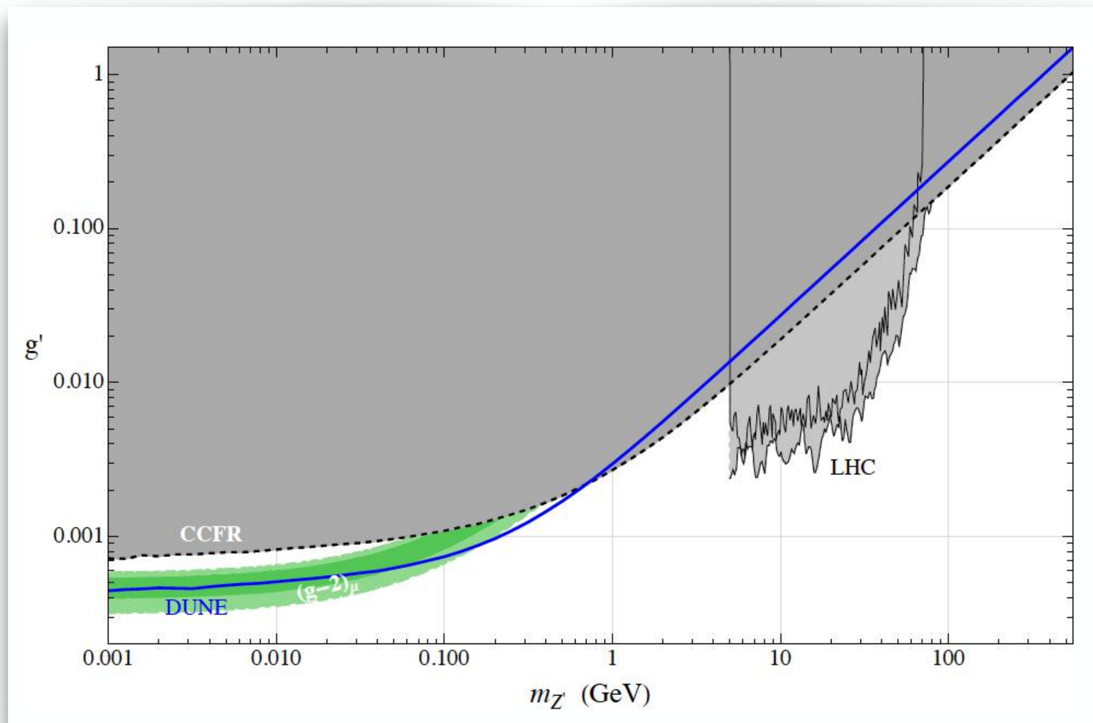
(CCFR, PRL66 (1991) 3117)

LHC searches

Bounds from the measured $Z \to 4\mu$ branching ratio



(Updated) Altmannshofer, SG, Martin-Albo, Sousa, Wallbank, *Phys. Rev. D* 100 (2019) 11, 115029

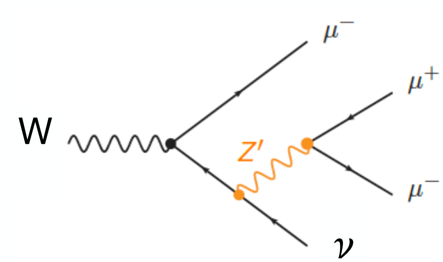


Back then only a ATLAS 7+8 TeV non targeted analysis was available (no bump hunt)

More recent dedicated CMS + ATLAS searches for the L_μ - L_τ gauge boson, (1808.03684, 2402.15212)

NEW

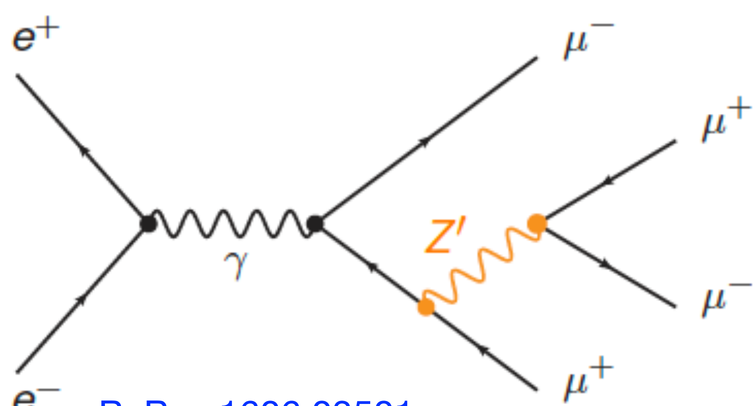
Combination with $W \to Z' \mu \nu \to (\mu \mu) \mu \nu$



Searches at B-factories

B-factories can search for the light Z' produced with muons

$$e^+e^- \to 2\mu Z' \to 4\mu$$

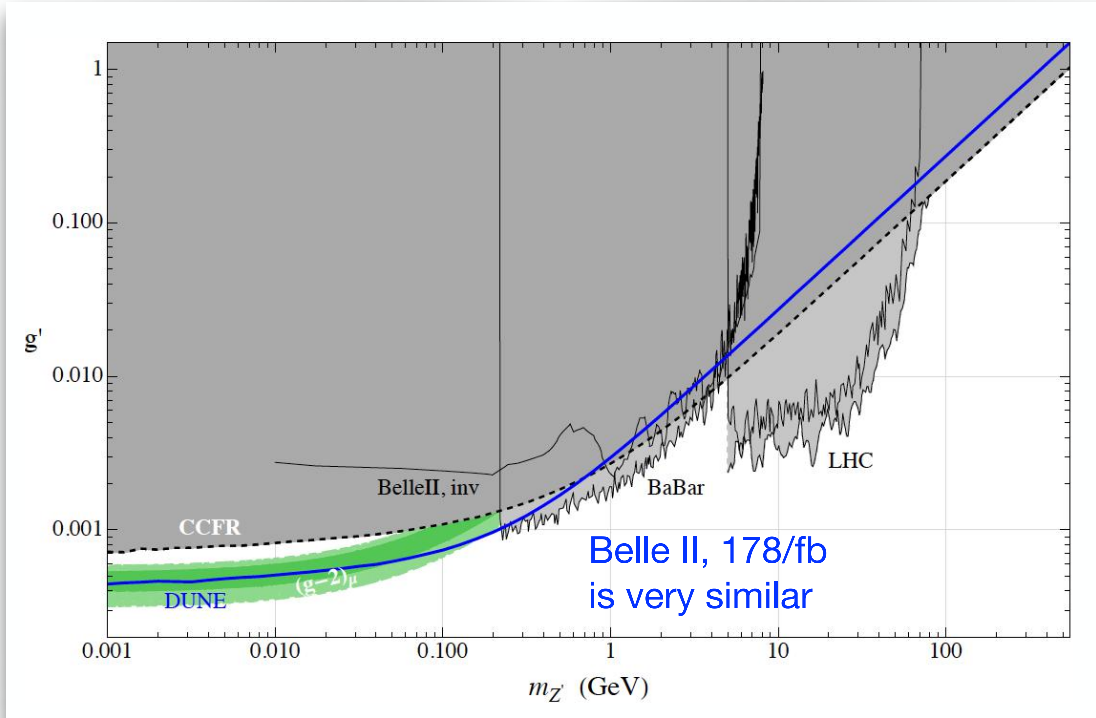


BaBar, 1606.03501
Belle II, 2403.02841

Additional Belle II search 2212.03066 for $e^+e^- \to \mu^+\mu^- + Z'$, $Z' \to \nu\,\nu$ (particularly relevant for $m_{Z'} < 2m_\mu$)

NEW

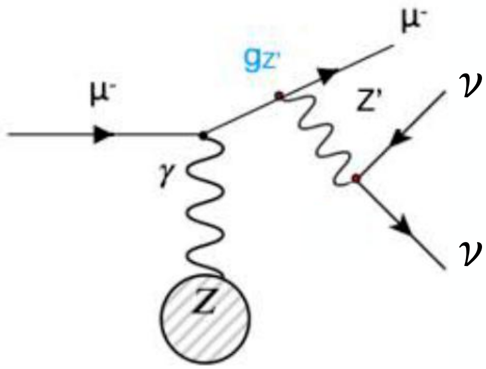
(Updated) Altmannshofer, SG, Martin-Albo, Sousa, Wallbank, *Phys. Rev. D* 100 (2019) 11, 115029

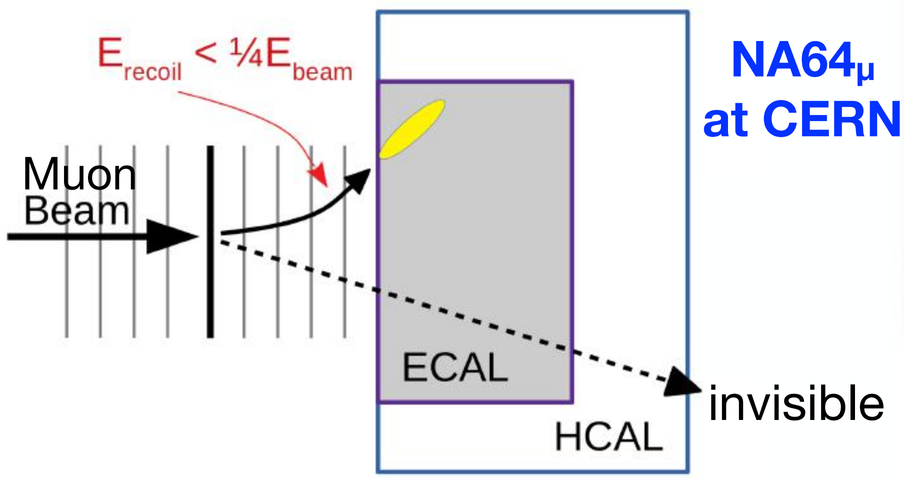


Searches at fixed target experiments

High intensity fixed target experiments can produce an invisible Z'

NEW



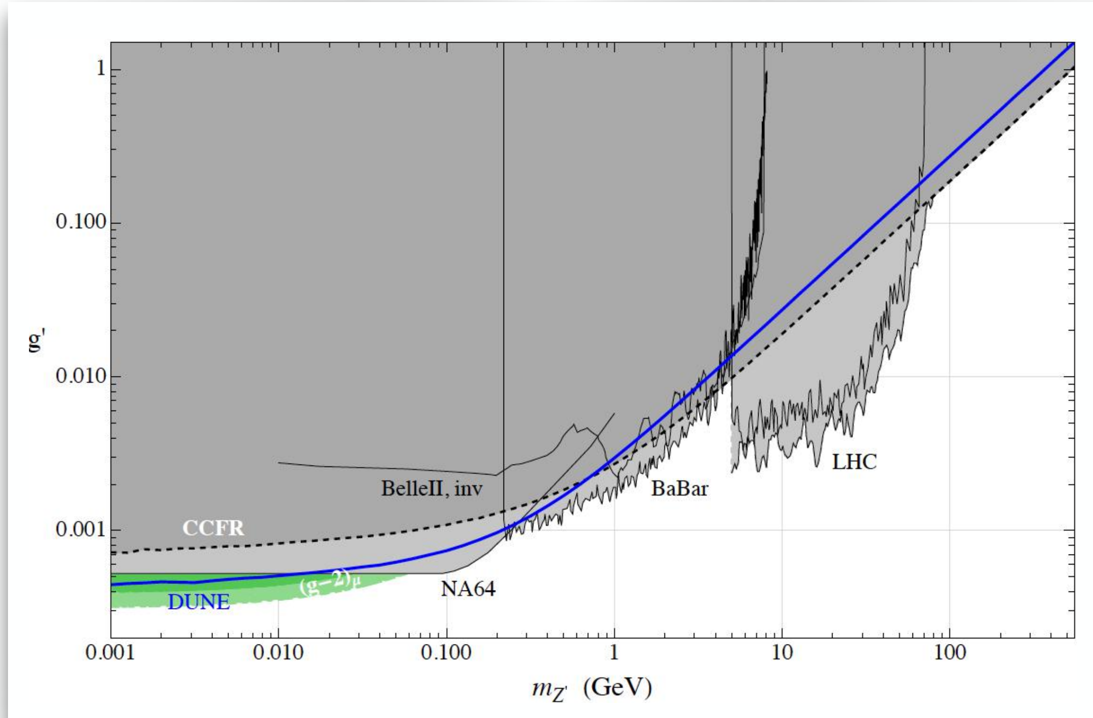


NA64$_\mu$ at CERN

missing energy-momentum search

2401.01708

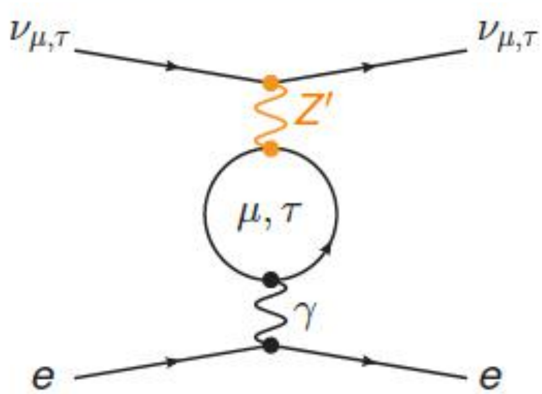
(Updated) Altmannshofer, SG, Martin-Albo, Sousa, Wallbank, *Phys. Rev. D* 100 (2019) 11, 115029



Tests at neutrino experiments

Borexino

Bounds from measurements of neutrino-electron scattering

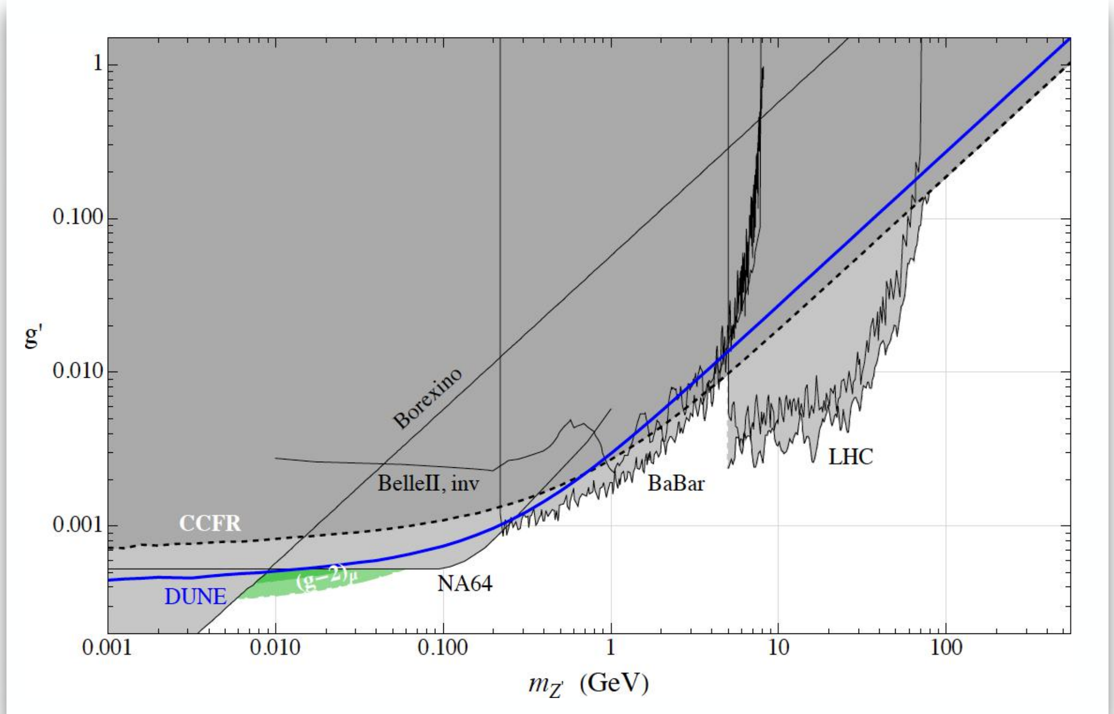


tiny momentum transfer
⇒ Z' can mix with the SM photon

relevant constraint at low masses from the Borexino experiment

Kamada, Yu 1504.00711

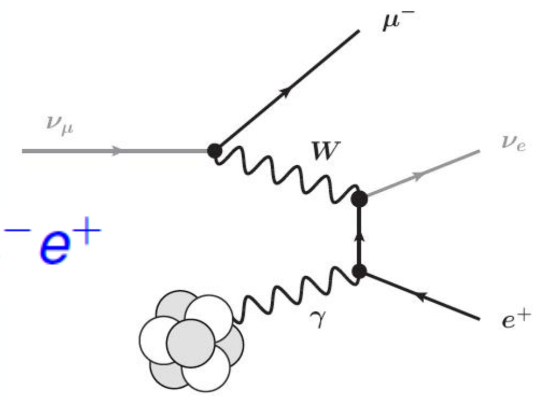
(Updated) Altmannshofer, SG, Martin-Albo, Sousa, Wallbank, *Phys. Rev. D* 100 (2019) 11, 115029

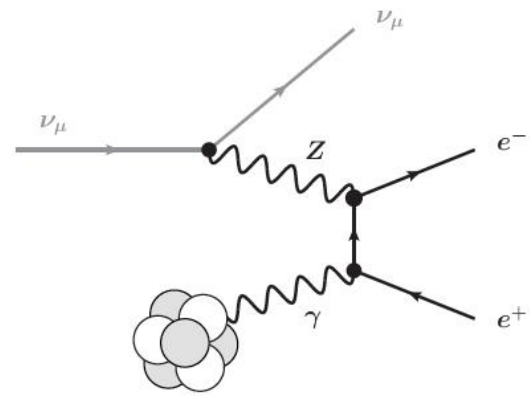


This is a conservative reach for DUNE (magnetized spectrometer)

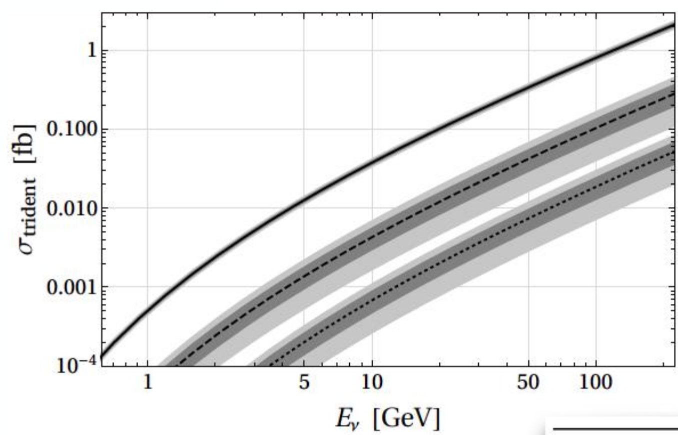
Several new trident processes to search for

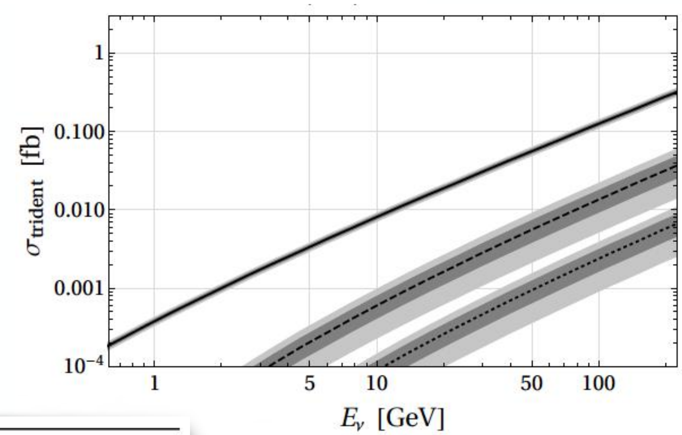
$\nu_\mu \to \nu_e \mu^- e^+$





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





At DUNE:

	Coherent	Incoherent
$\nu_\mu \to \nu_\mu\ \mu^+\mu^-$	1.17 ± 0.07	0.49 ± 0.15
	(516 ± 31)	(216 ± 66)
$\nu_\mu \to \nu_\mu\ e^+e^-$	2.84 ± 0.17	0.18 ± 0.06
	(1252 ± 75)	(79 ± 27)
$\nu_\mu \to \nu_e\ e^+\mu^-$	9.8 ± 0.6	1.2 ± 0.4
	(4322 ± 265)	(529 ± 176)

New processes could be seen at DUNE or Hyper-Kamiokande

Rates are larger than the muon rates

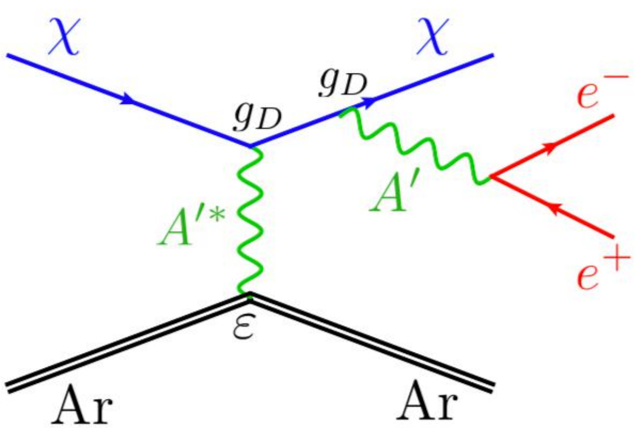
Altmannshofer, SG, Martin-Albo, Sousa, Wallbank, *Phys. Rev. D* 100 (2019) 11, 115029

+ anti-neutrino rates

Dark tridents

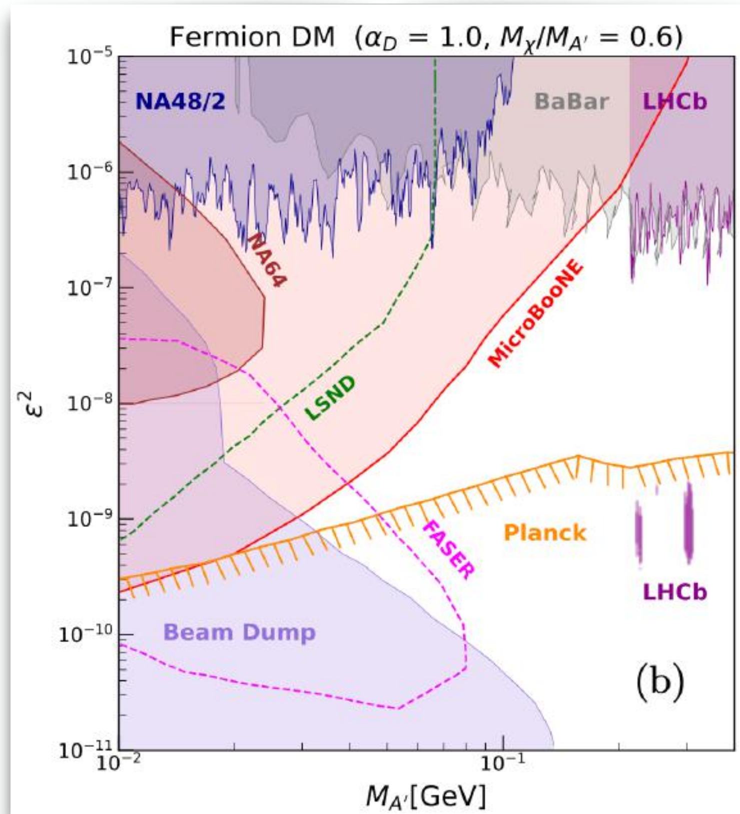
After our paper, several papers studied the opportunities to discover new physics through **“dark trident” production**.

<u>Dark matter</u>, X, production and subsequent scattering with neutrino detectors:



De Gouvea, Fox, Harnik, Kelly, Zhang, 1809.06388.

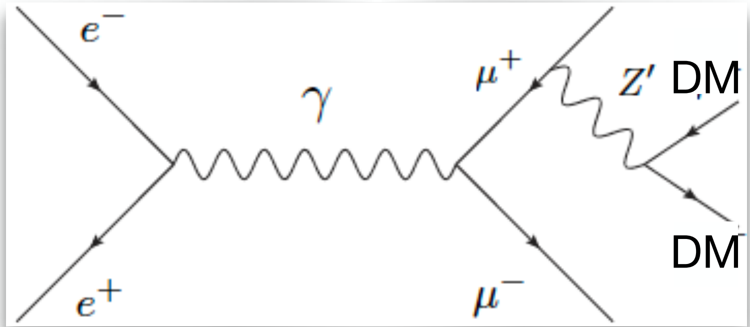
Search at MicroBooNE

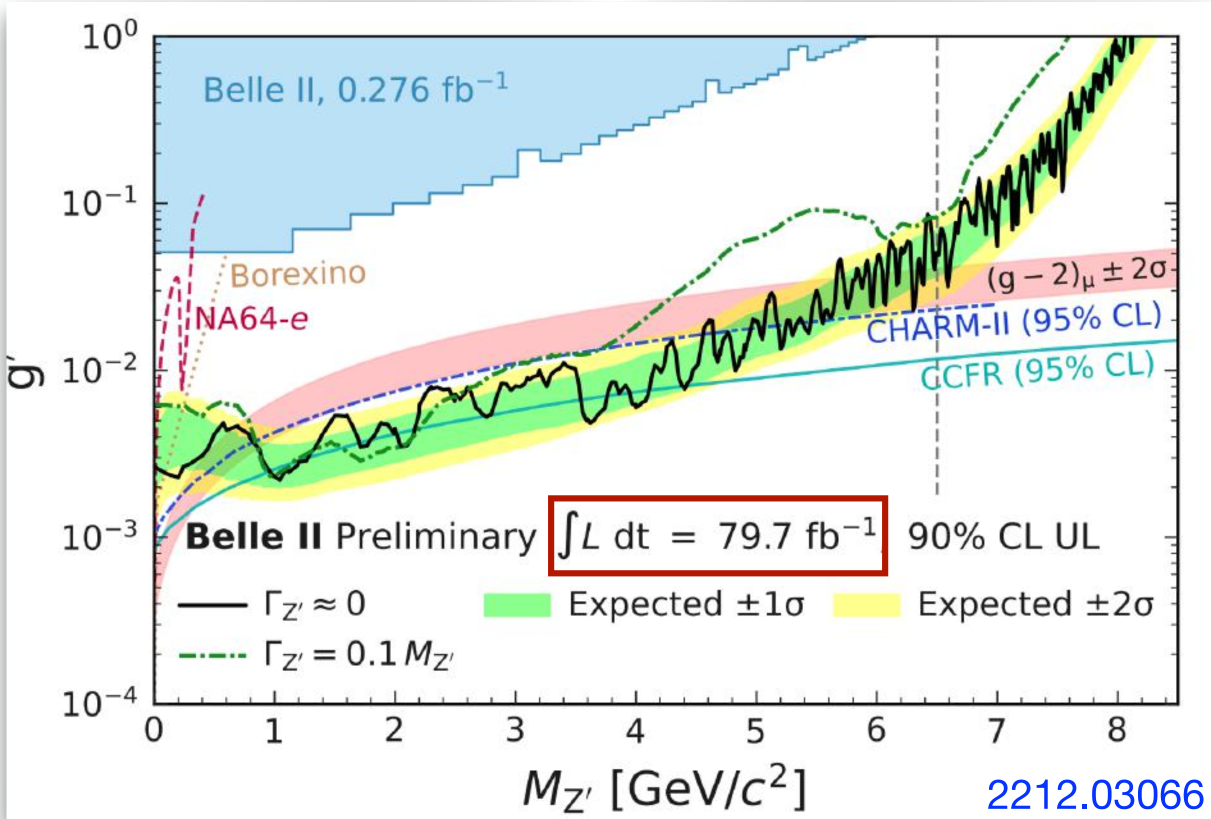


2312.13945

The invisible L_μ - L_τ gauge boson

This was among the very first Belle II analyses





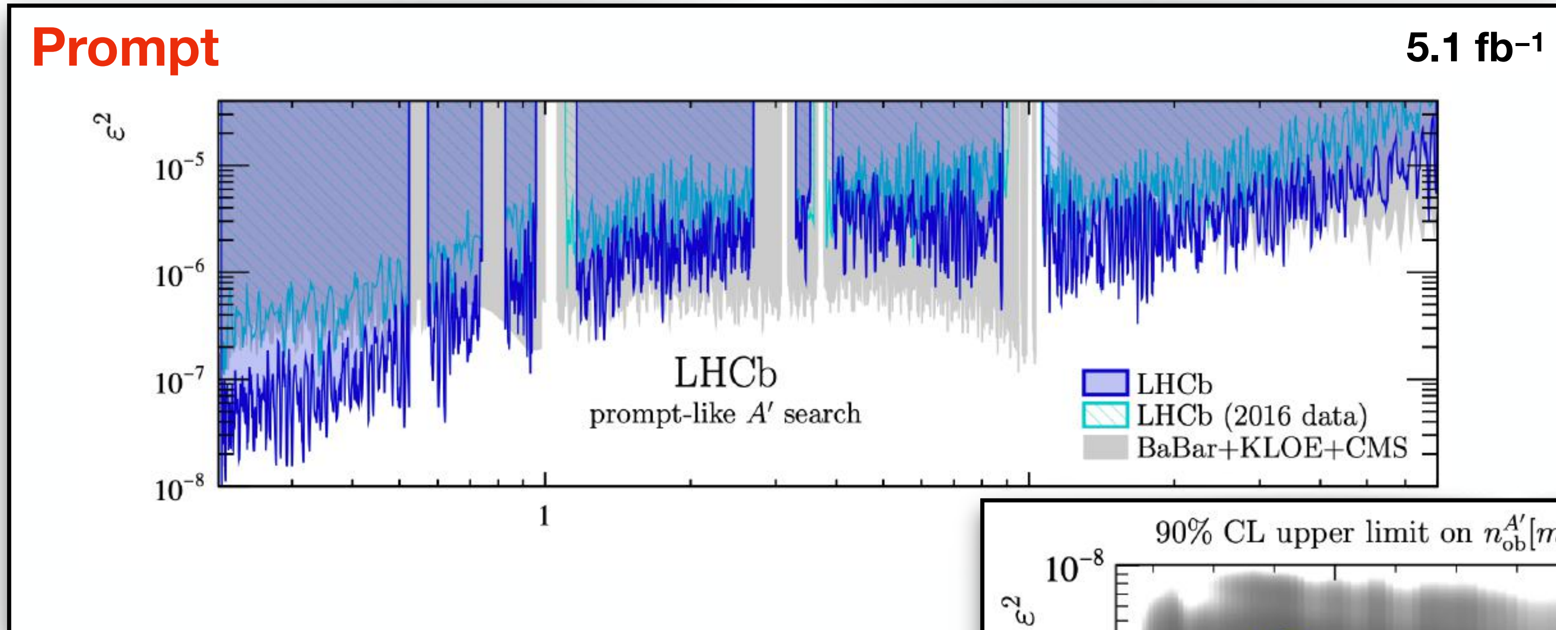
2212.03066

Even with a very limited amount of luminosity
(the total collected luminosity in the future will be 50/ab)
Belle II is competitive with the trident bound in an intermediate range of masses

2. Visible dark photons at LHCb

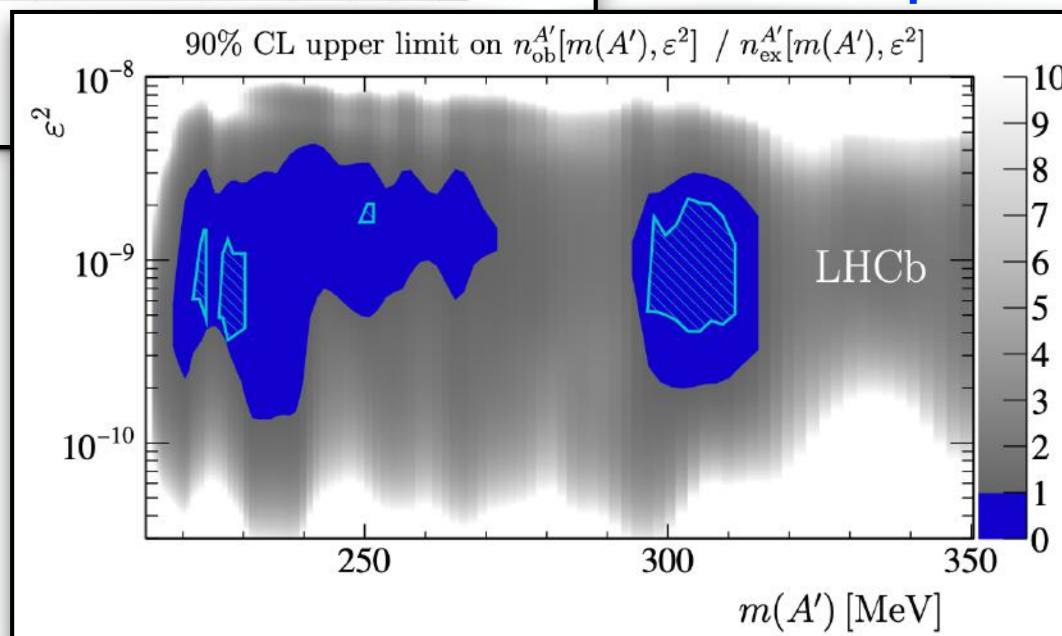
Search for a di-muon resonance: both prompt and displaced

Prompt



1910.06926

Displaced



Below the muon threshold: additional opportunities for

$$D^{*0} \to D^0 A', \quad A' \to e^+ e^-$$

Ilten et al., 1509.06765

lifetimes O(1) ps