Theory introduction to the dark sector

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UC Santa Cruz

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KEK

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Overview

Chapter 1: Introduction
Why dark sectors. Theory motivations.
Experimental targets

Chapter 2: Minimal dark sector models
dark photon,
dark scalar, sterile neutrinos

Chapter 3: Axions and axion-like particles
The effective field theory

Chapter 4: Non-minimal theories for dark sectors
Inelastic Dark matter, L_μ - L_τ

TODAY

TOMORROW

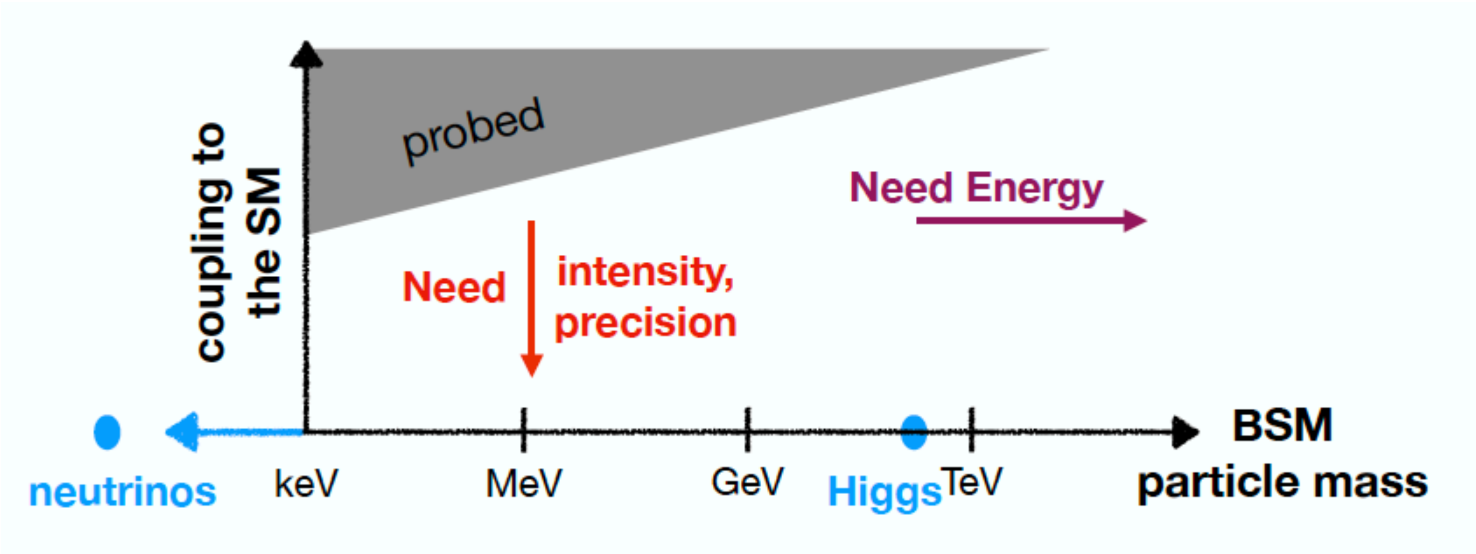
Chapter 1

Introduction

* Why dark sectors.
  Theory motivations (DM & strong CP problem).
* Experimental targets.

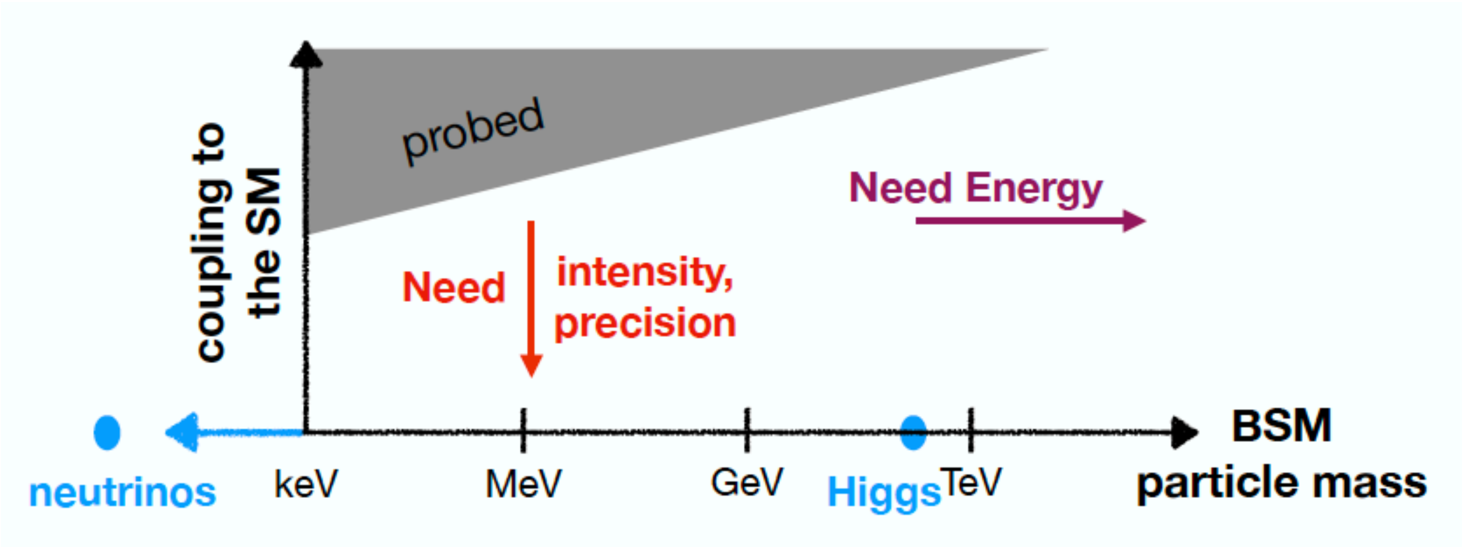
from symmetry magazine

The quest for new physics



We do not know what will be the next New Physics (NP) scale.

The quest for new physics



We do not know what will be the next New Physics (NP) scale.

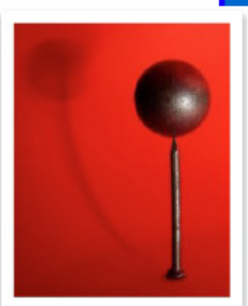
➡ **Search as broadly as possible.**

Accelerator experiments have access to NP scales in the range of few TeV and below.
Enormous progress in the exploration has been made in the past several years. Numerous gaps still to cover.

The most hidden particles are "dark sector particles", i.e. those particles that are not charged under the Standard Model (SM) gauge symmetries.

Because of the LEP bounds, in first approximation only dark sector particles can reside in the ~sub-100 GeV mass range

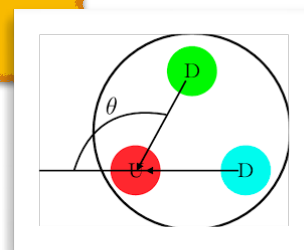
Dark sectors are ubiquitous



Naturalness problem

dark scalars
(twin Higgs, SUSY)

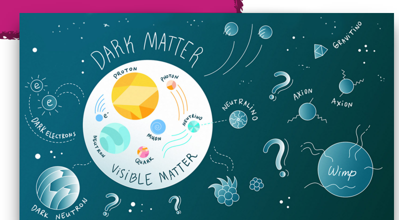
Strong CP problem

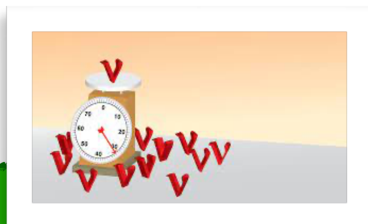


axions

dark photons

Nature of Dark Matter





Neutrino masses

sterile neutrinos

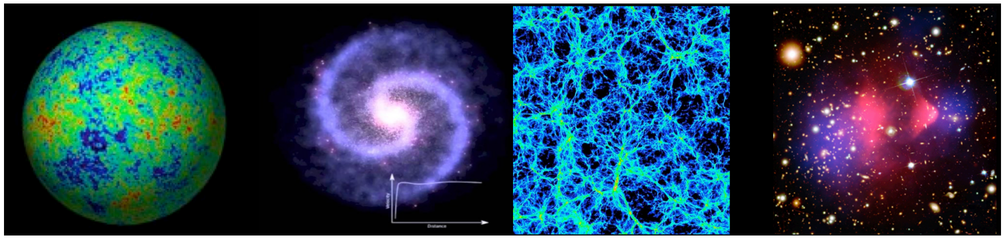
Baryon anti-baryon asymmetry

dark scalars

As we will discuss, **new dark particles could address each of these problems** (focus on DM and strong CP)

The Dark Matter problem

Evidence for dark matter is overwhelming



CMB Rotation curves Structure Lensing

1. It gravitates
2. It is dark (i.e. it does not interact with photons)
3. It is stable on cosmological scales

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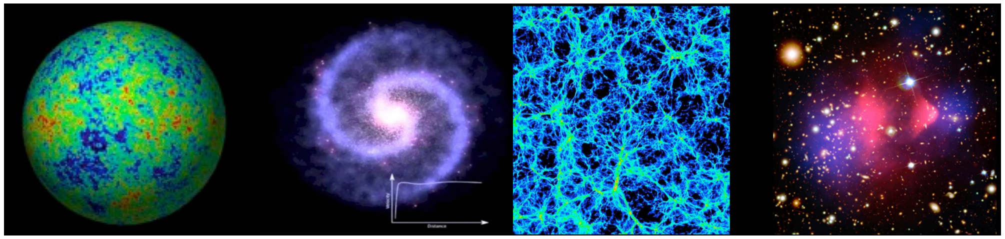

CMB | Rotation curves | Structure | Lensing

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Fun fact:
There is lots of DM in the Universe,
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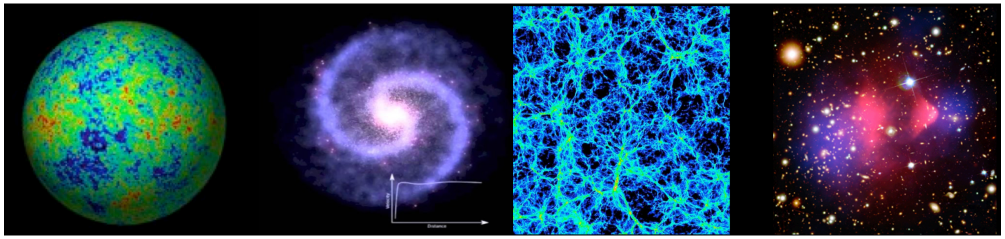

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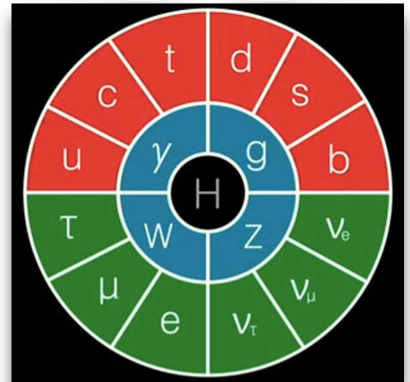

+ ?

We do not know (if and) how DM interacts with the Standard Model

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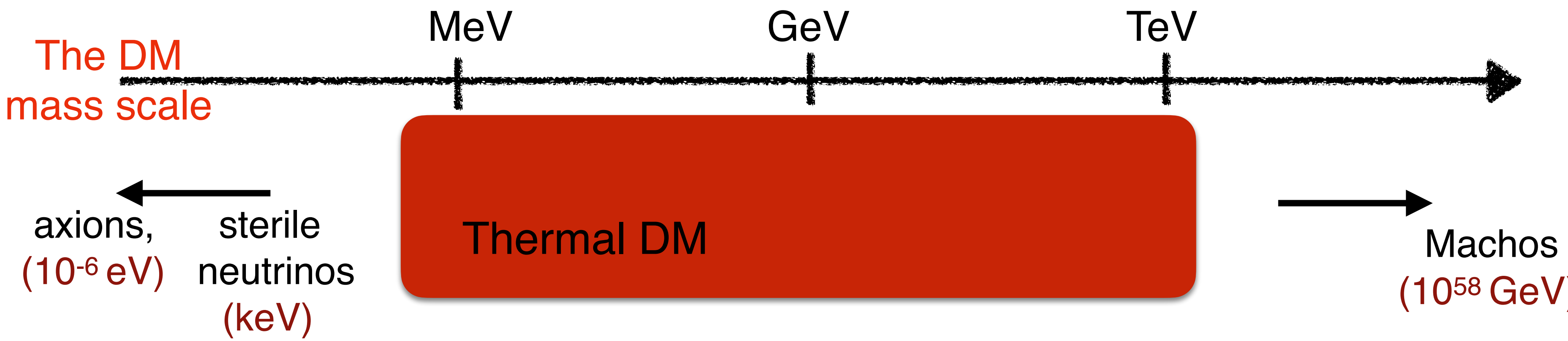
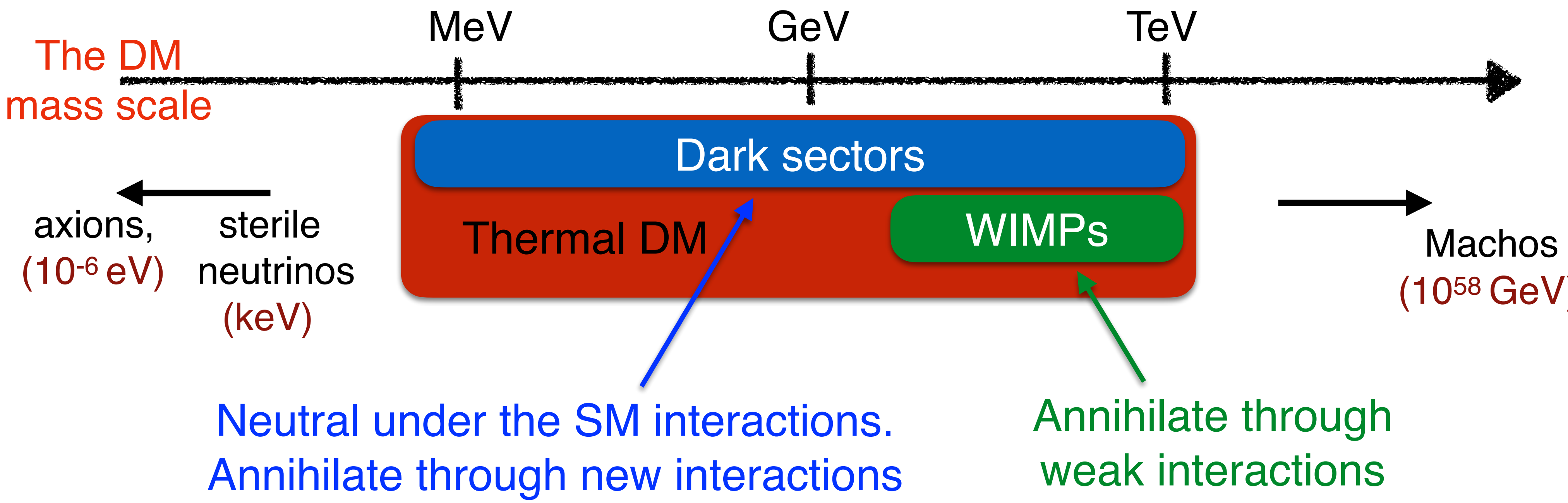
The Dark Matter scale



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

In these lectures, we will focus on dark matter with a mass **below the 10 GeV scale**

The Dark Matter scale



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The “WIMP” paradigm

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

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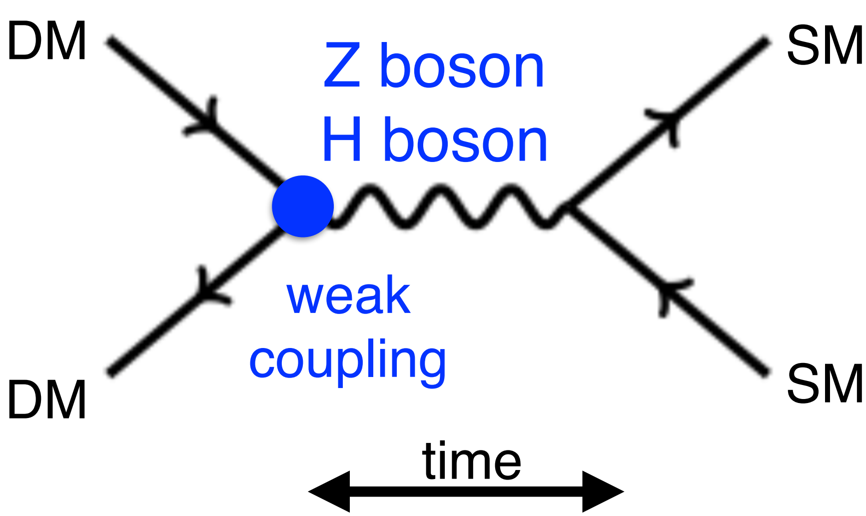
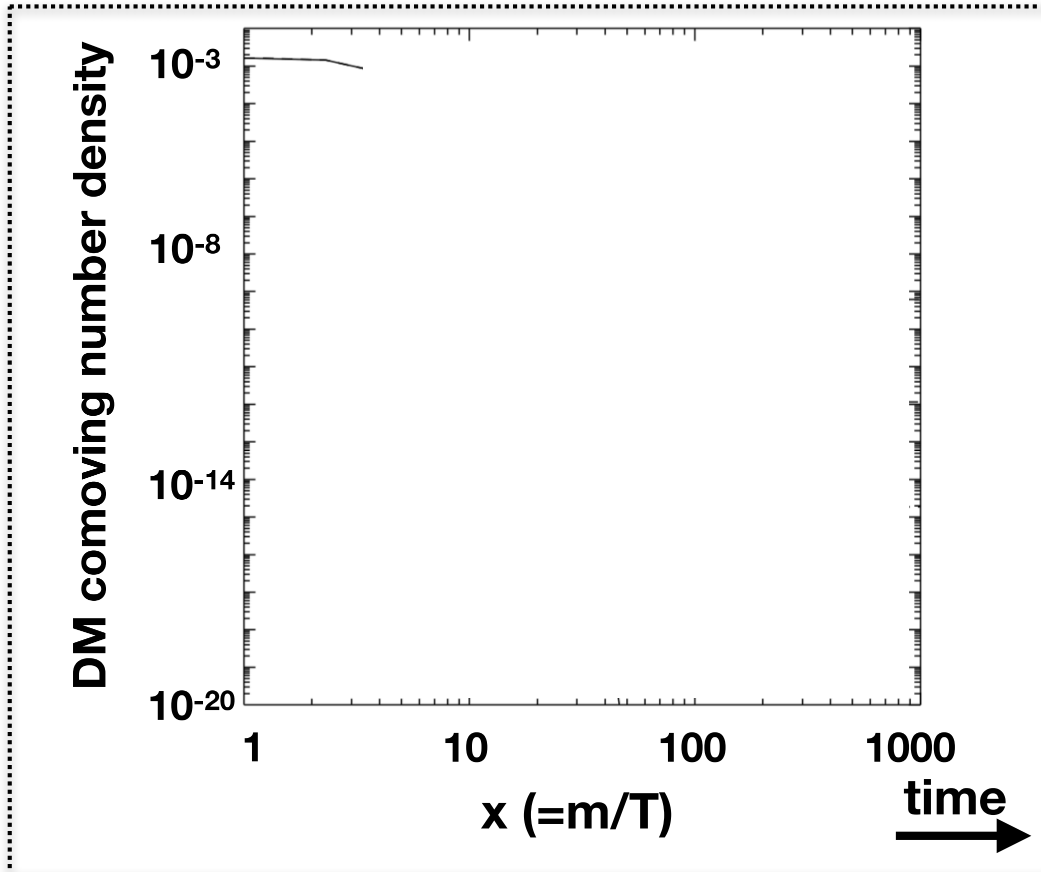
Thermal Dark Matter





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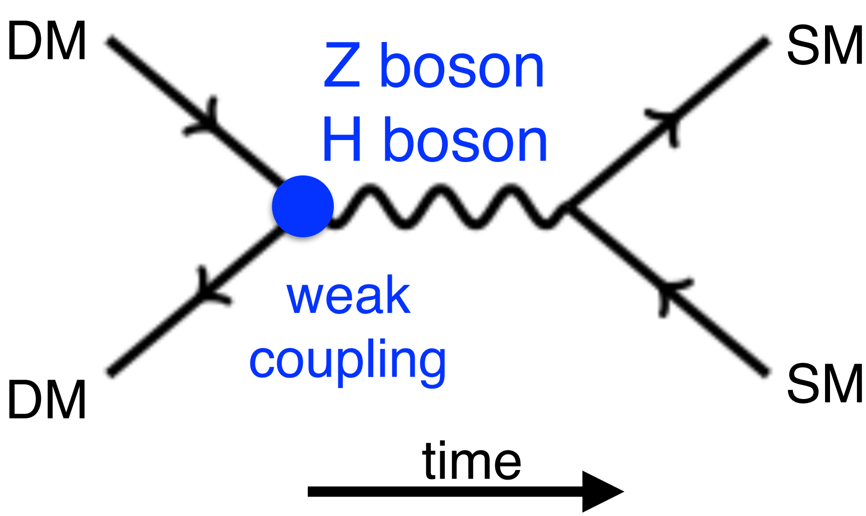
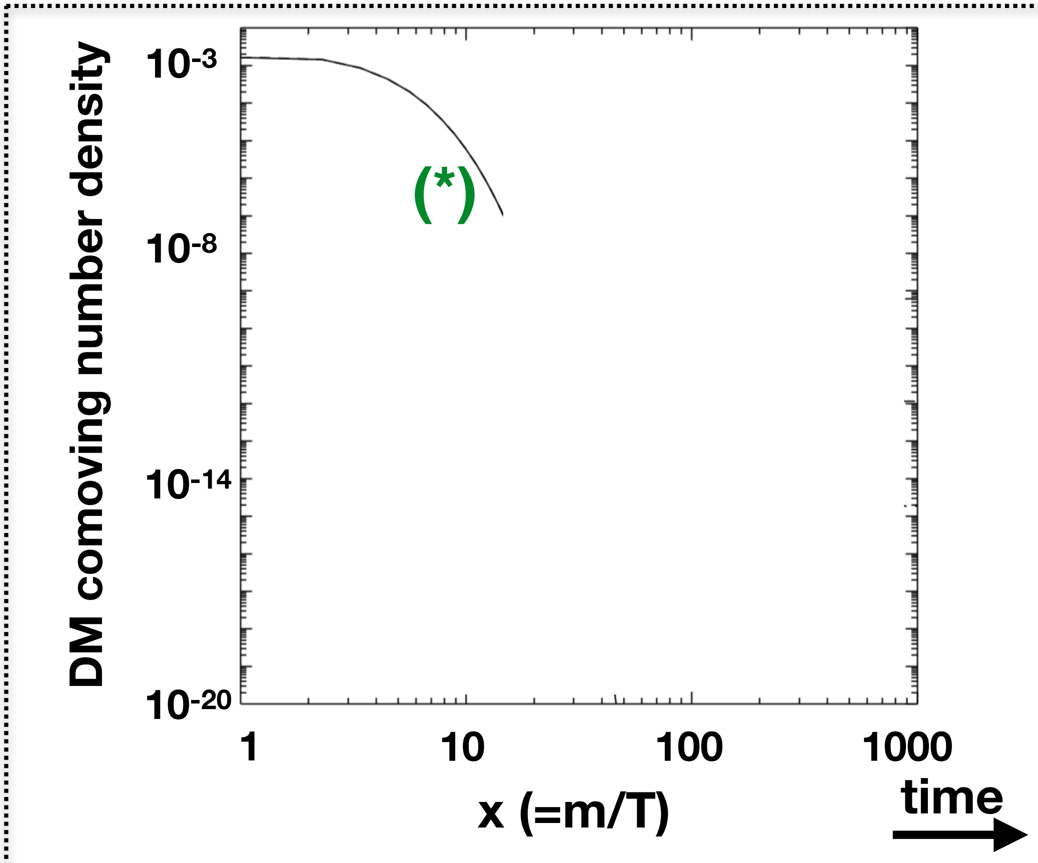
One of the dominant models for more than 3 decades

DM annihilation to SM (*):





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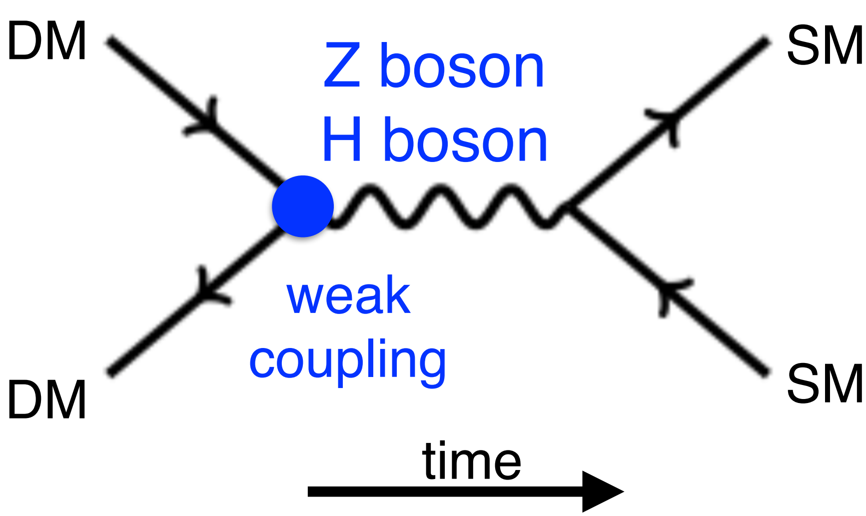
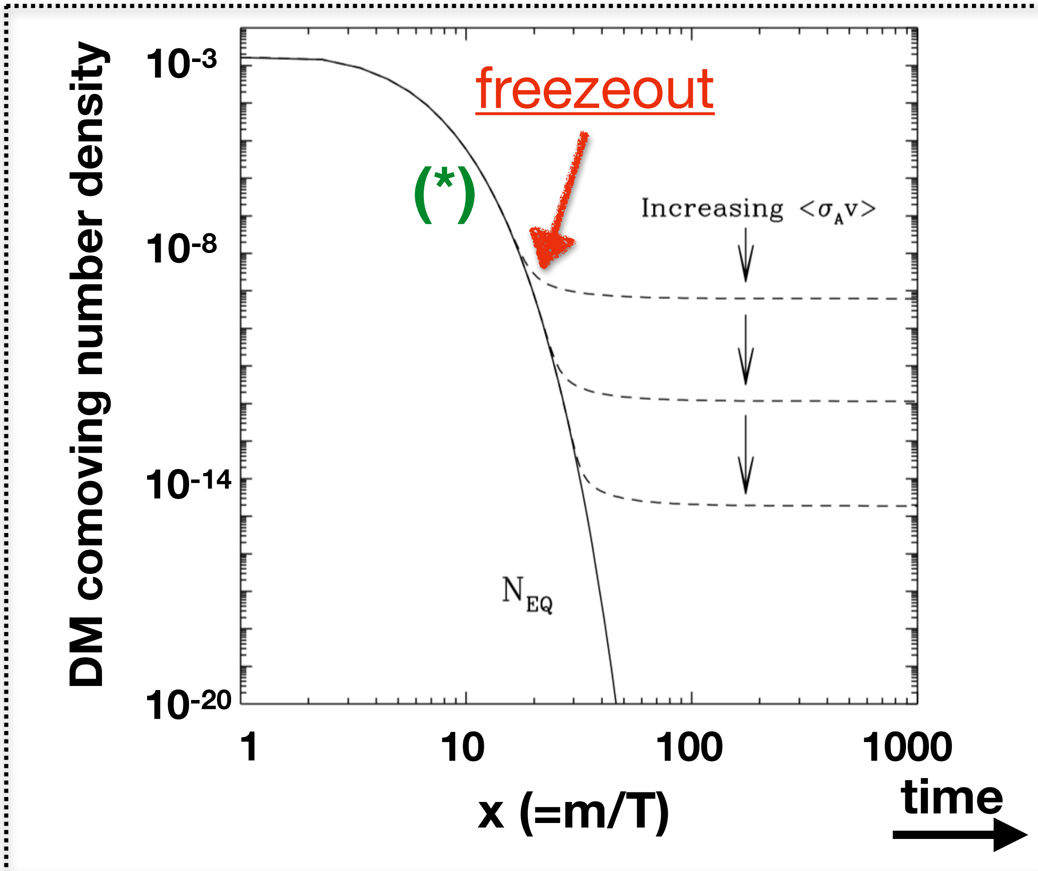


At certain point, annihilation rate becomes smaller than the Hubble rate: DM freezeout



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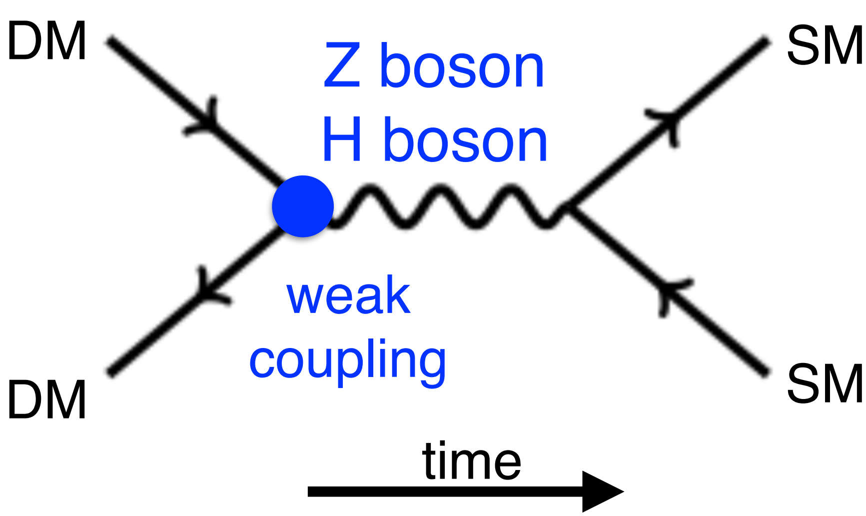

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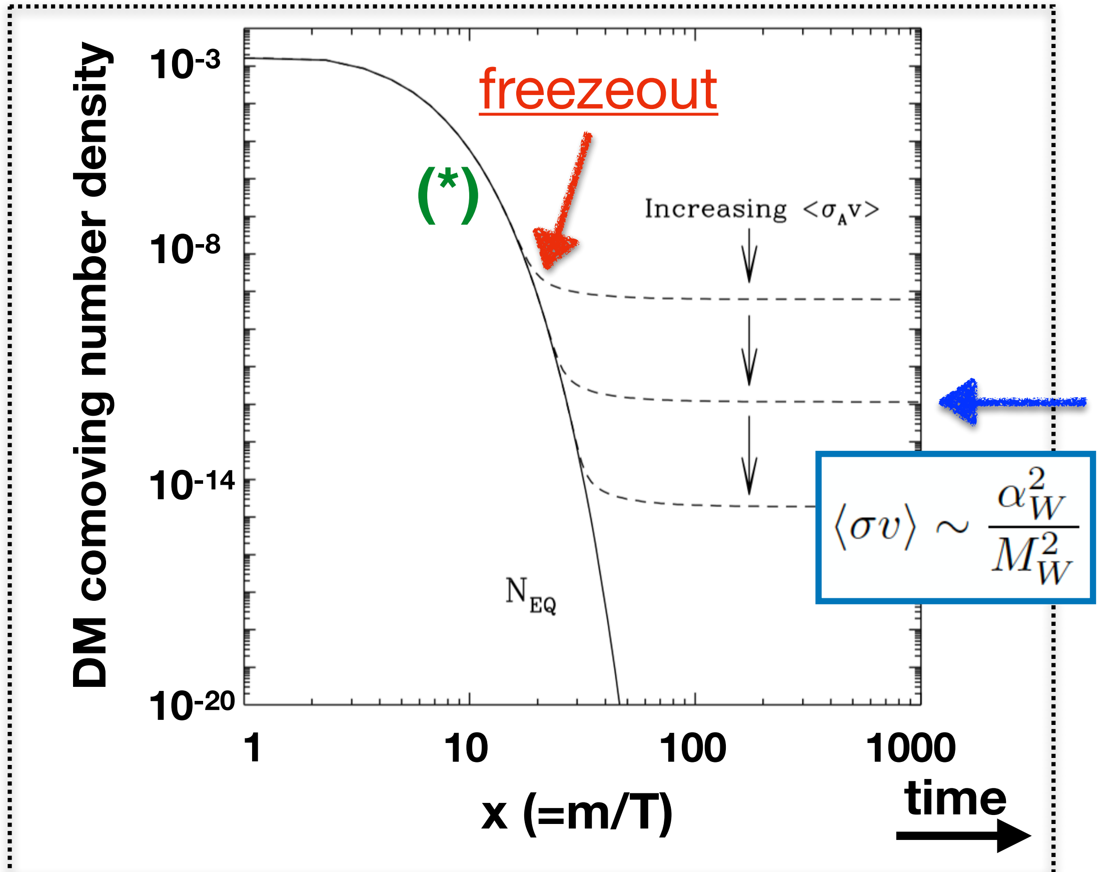
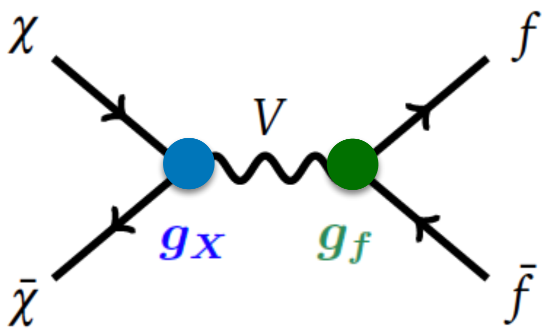


Thanks to these interactions, DM with a mass O(100 GeV) can freezeout and obtain the measured relic abundance

WIMP “miracle”?
… or “coincidence”

Lee-Weinberg bound and DM in a dark sector



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

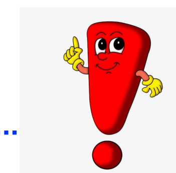
$$\langle \sigma v \rangle^{\min} \simeq \frac{10^{-9}}{\mathrm{GeV}^2}$$

$$\langle \sigma v \rangle \simeq \frac{|\mathcal{M}|^2}{32\pi m_X^2},$$

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

$m_f << m_X$

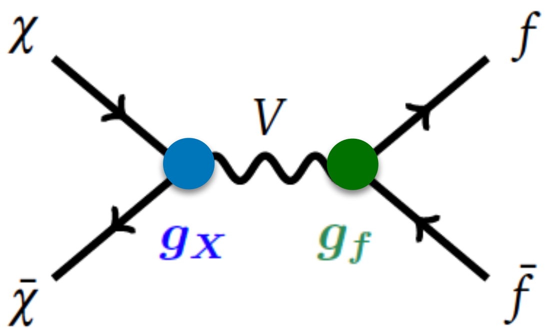
Problem:



$m_V \sim m_Z$,
$\alpha_X \sim \alpha_f \sim \alpha_W$ ⇒ $\langle \sigma v \rangle < \langle \sigma v \rangle^{\min}$ for $m_X \lesssim 1\mathrm{GeV}$

Lee-Weinberg bound

Lee-Weinberg bound and DM in a dark sector



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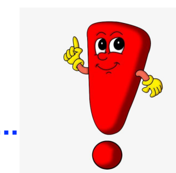

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Lee-Weinberg bound

Need an additional (light) mediator, V, that is not the Z (or Higgs) boson

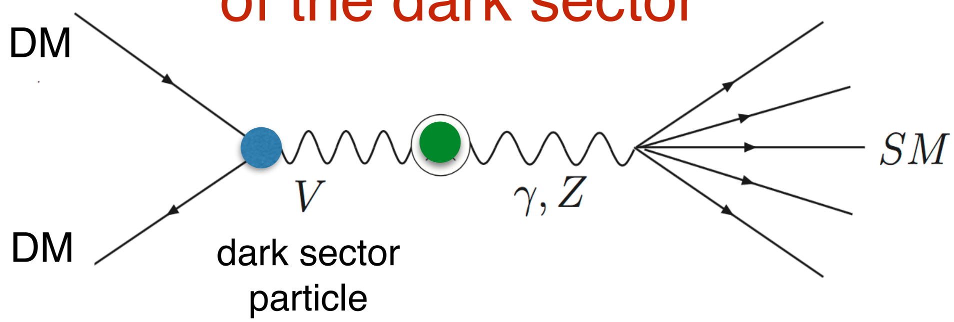
Thermal origin is a simple and compelling idea
for the origin of dark matter.
It can work at low mass as well, if we have **a dark sector**

Thermal targets & signatures @ accelerators

Two general classes of thermal DM:

1.

DM is the lightest state
of the dark sector



Relic abundance regulated by ●, ●

Coupling in the dark sector
Coupling between the dark sector and the SM

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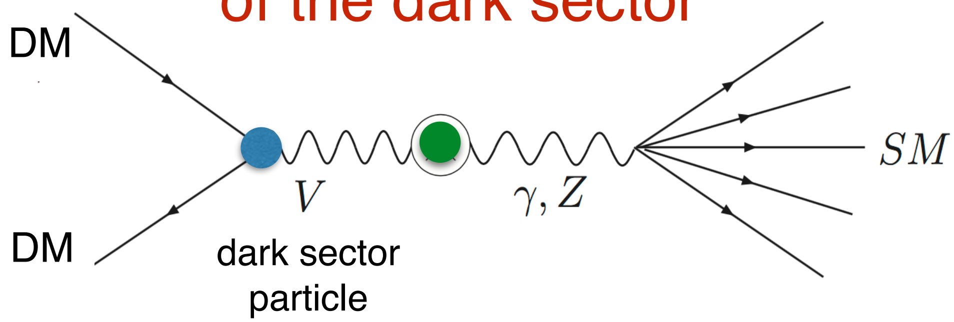

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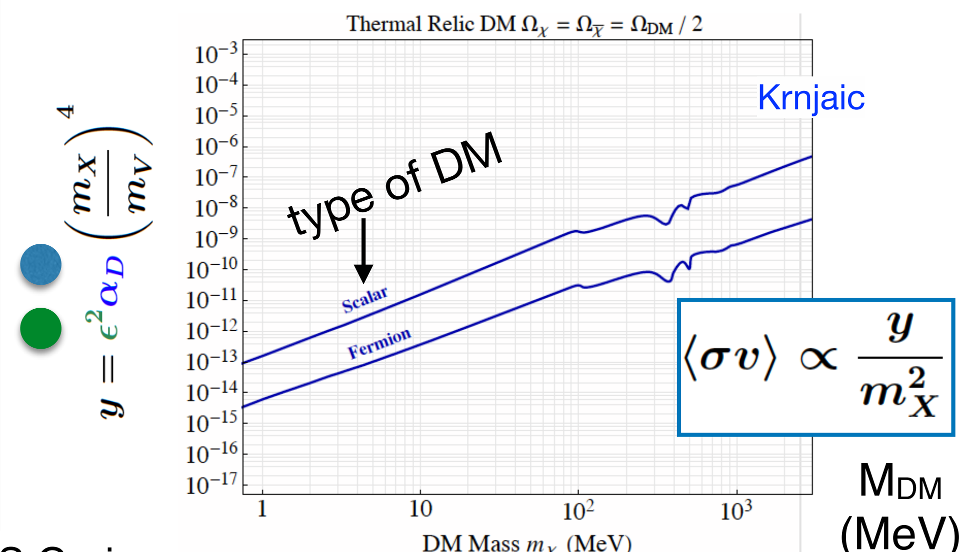

$$\boxed{\langle \sigma v \rangle \propto \frac{y}{m_X^2}}$$

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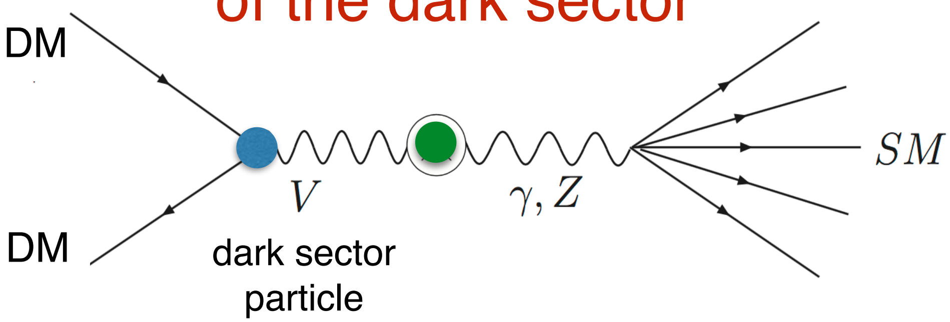
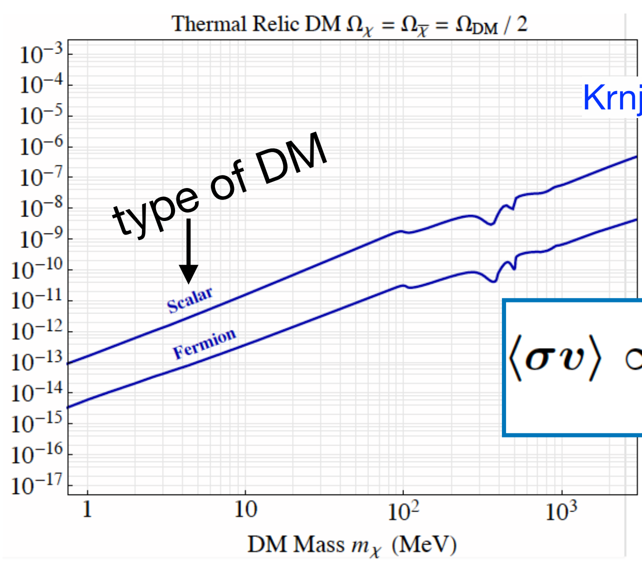


Relic abundance regulated by ●, ●

$y = \epsilon^2 \alpha_D \left(\frac{m_X}{m_V}\right)^4$

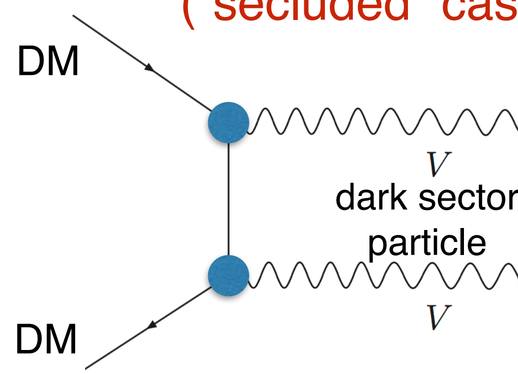


$$\langle \sigma v \rangle \propto \frac{y}{m_X^2}$$

M_{DM} (MeV)

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

("secluded" case)



Pospelov, Ritz, Voloshin, 0711.4866

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

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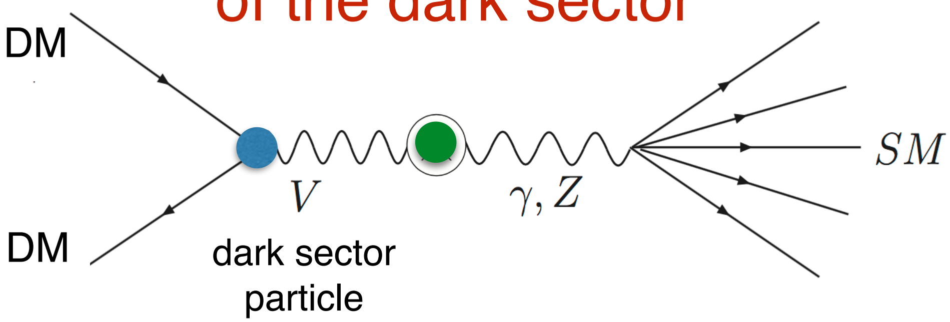

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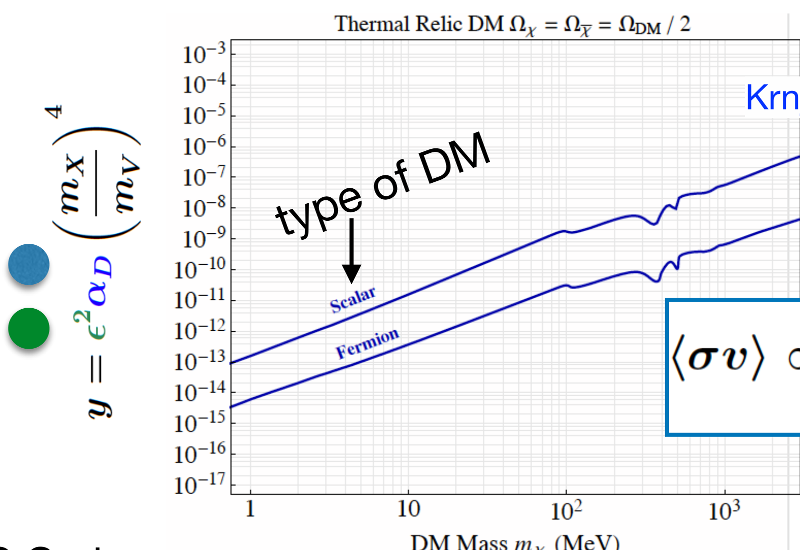

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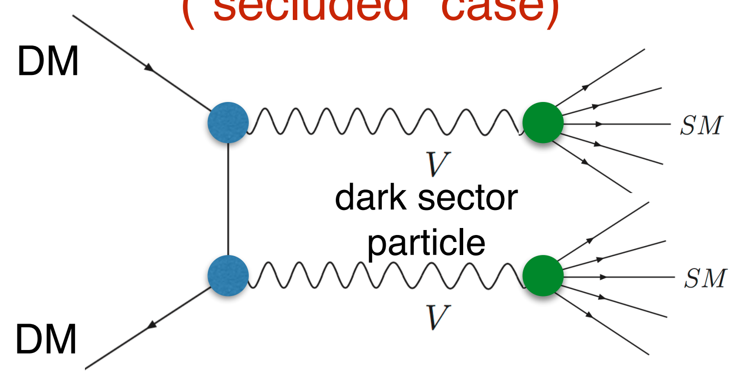

thermalization

Thermal targets & signatures @ accelerators

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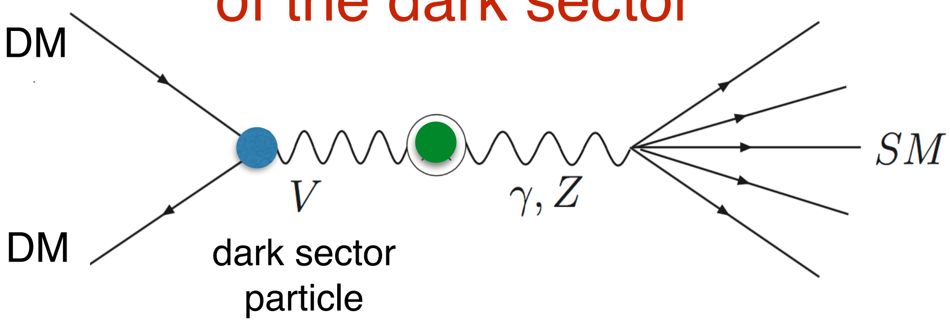

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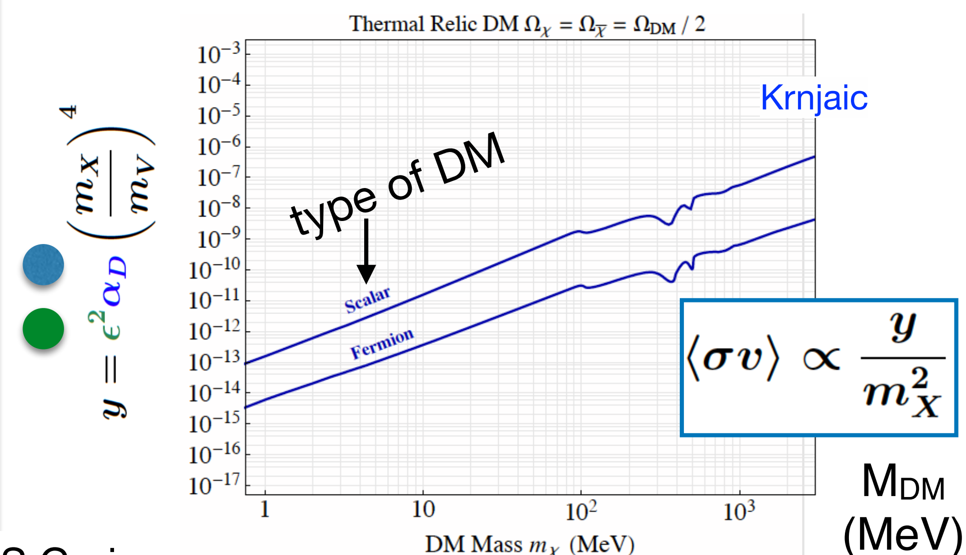

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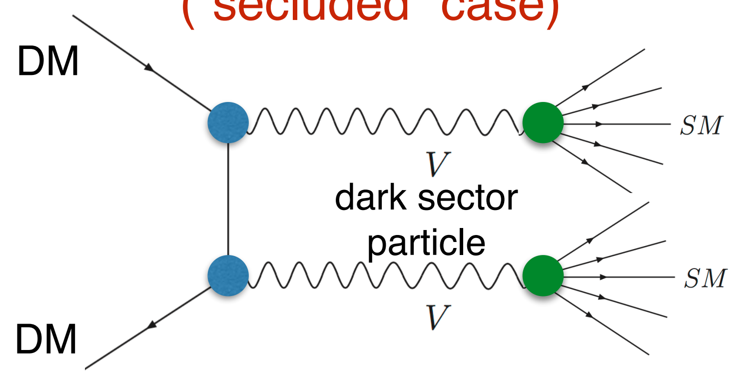

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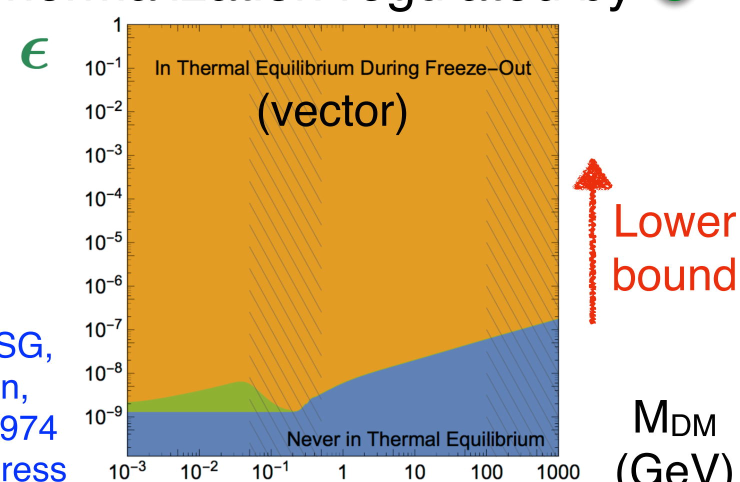

Evans, SG, Shelton, 1712.03974 + in progress

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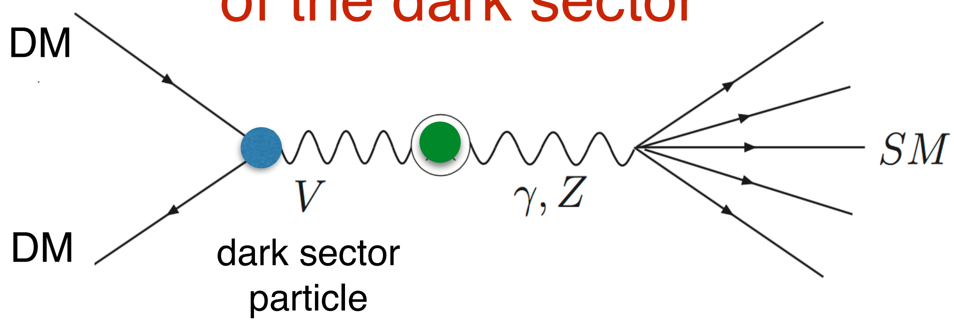

Signatures at accelerator experiments:

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

V→ DM DM

2. **One (or more) particles** of
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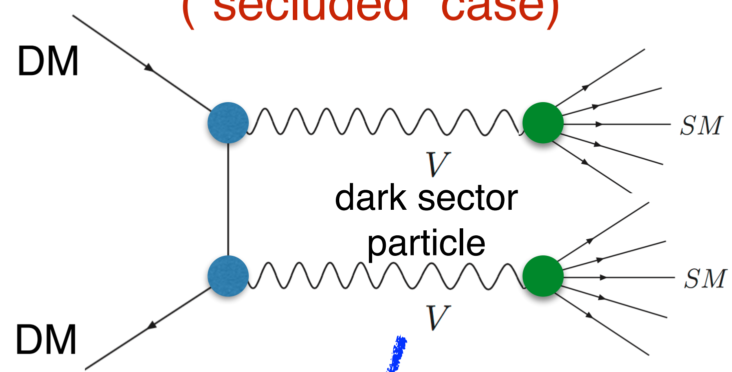

Signatures at accelerator experiments:

The dark sector particle
decays **visible** (to SM particles)

V→ SM SM

Dark sectors beyond Dark Matter: the strong CP problem

The strong interactions have a puzzling problem, which became particularly clear with the development of QCD in the 70s.

Why in QCD is the CP symmetry not very badly broken?

A problem of small numbers

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

Strong experimental bound on the neutron electric dipole moment implies a very small parameter: $|d_n| \leq 10^{-26} e \text{ cm}$ $\Rightarrow$ $\bar{\theta} \leq 10^{-10}$

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Peccei-Quinn solution (Phys.Rev.Lett. 38 (1977) 1440-1443): New spontaneously broken symmetry

Wilczek, Phys.Rev.Lett. 40 (5): 279–282,
Weinberg, Phys.Rev.Lett. 40 (4): 223–226

The SM Lagrangian is augmented by **axion** interactions $\mathcal{L} \supset \frac{a}{f_a}\frac{1}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu}$

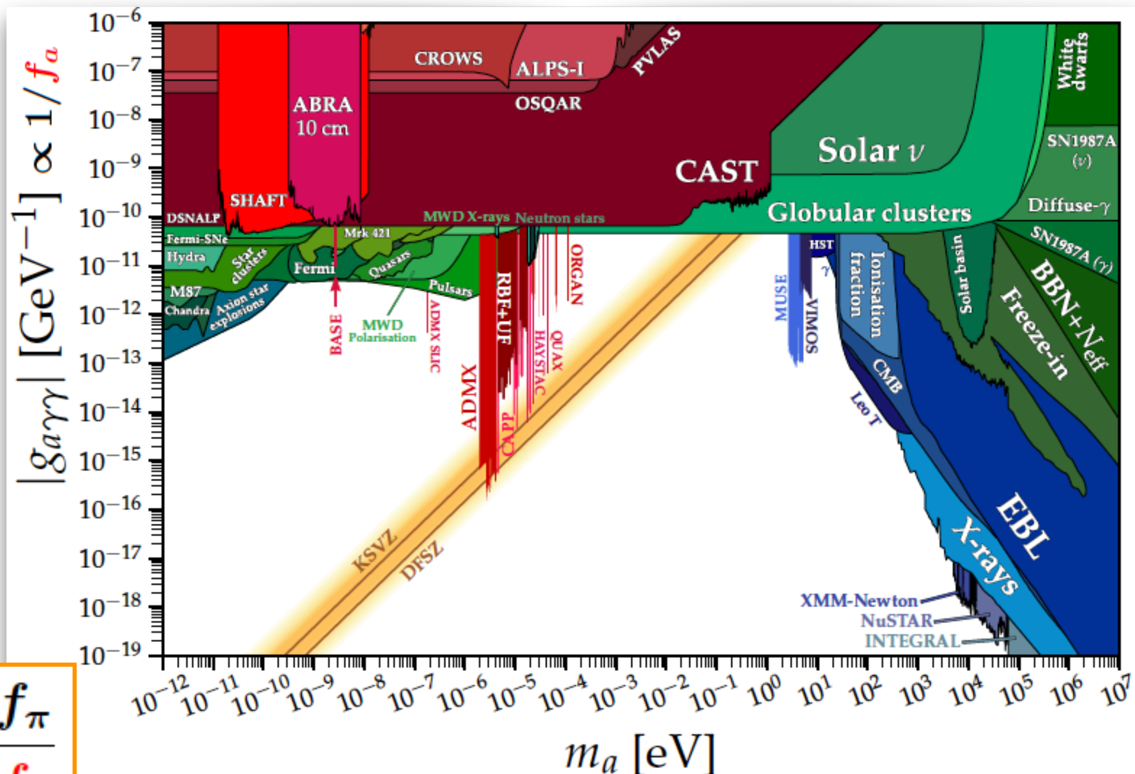
At the minimum of the axion potential $\bar{\theta} = 0$ ✓

<u>Additional interesting property:</u> the QCD axion can be a **DM candidate**!

Probing the QCD axion

Exciting and quickly evolving experimental program.
Complementarity with astrophysical probes.

Adams at al., Snowmass white paper, 2203.14923



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sub-eV New Physics particles

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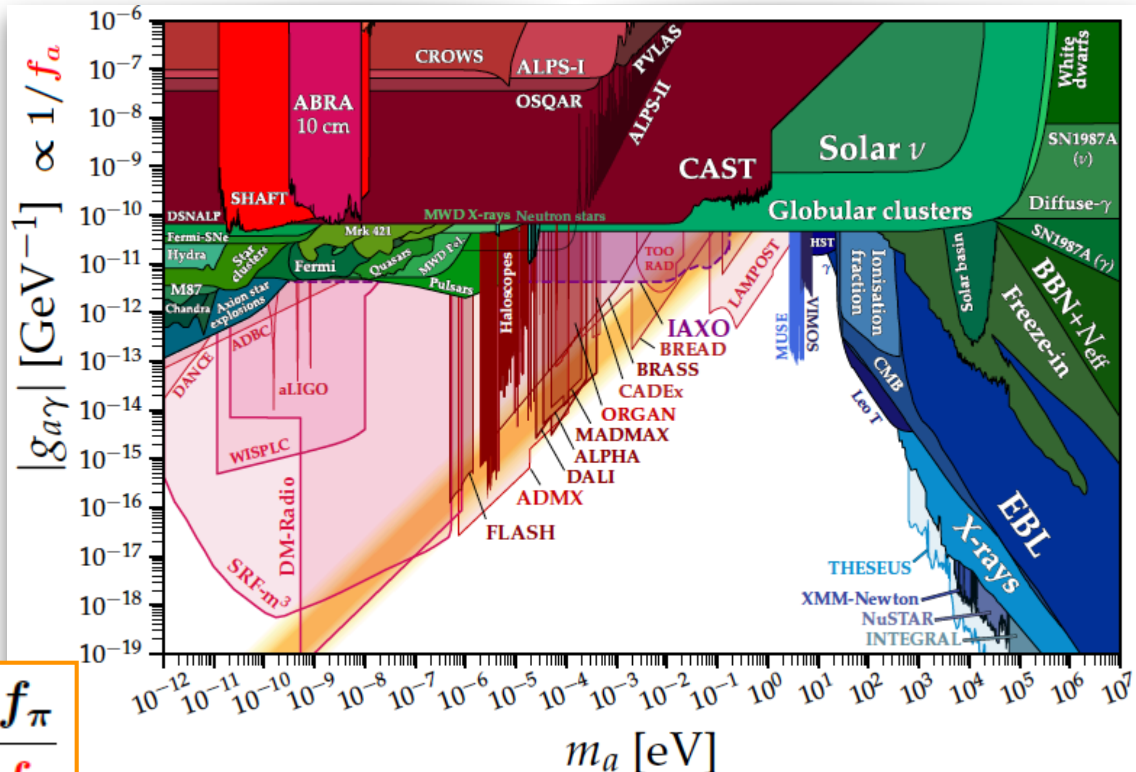

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sub-eV New Physics particles

Heavier axions (or axion-like-particles)

Extended QCD sectors can address the strong CP problem.

➡ Appearance of axions with a mass well above the eV scale.

(e.g., Agrawal, Howe, 1710.04213;
Foster, Kumar, Safdi, Soreq, 2208.10504, …)

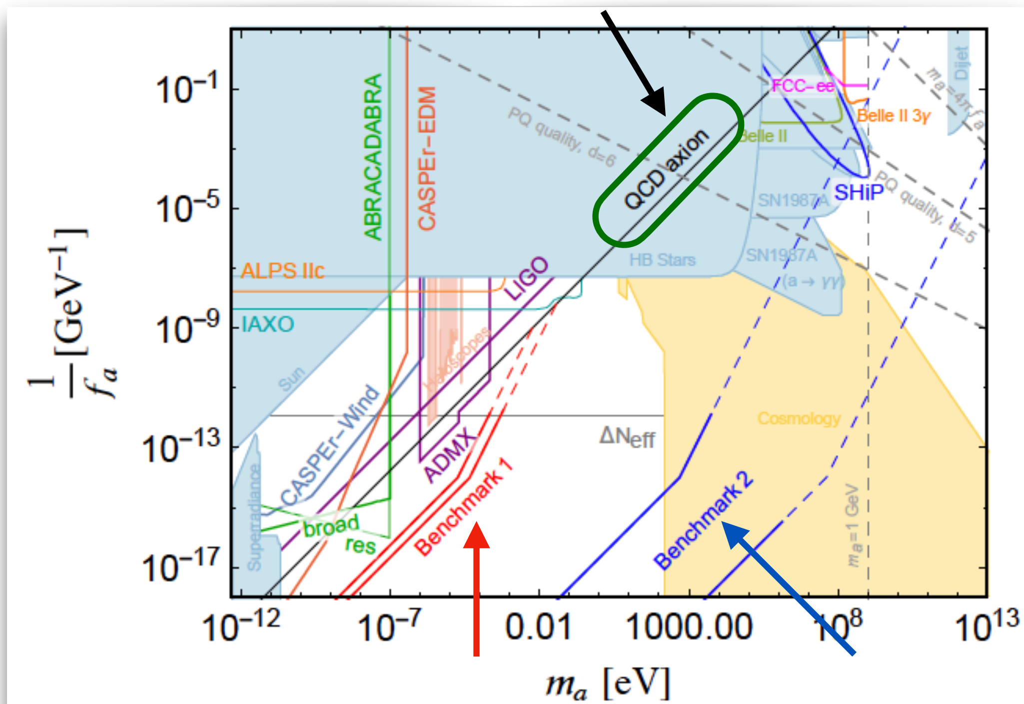
Easier to address the axion quality problem with heavier axions and lower f_a.

Axions coupled to gluons and photons:

$$\frac{g_s^2}{32\pi^2}\frac{a}{f_a}G^a_{\mu\nu}\tilde{G}^{\mu\nu,a}$$

$$\frac{e^2}{32\pi^2}\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Agrawal, Howe, 1710.04213



Chapter 2

Minimal dark sector models

- models
  - dark photons
  - dark scalars
  - sterile neutrinos
- searches at
  - LHC
  - fixed target experiments
  - B-factories

from CHAT AI

Some focus on DM-motivated models

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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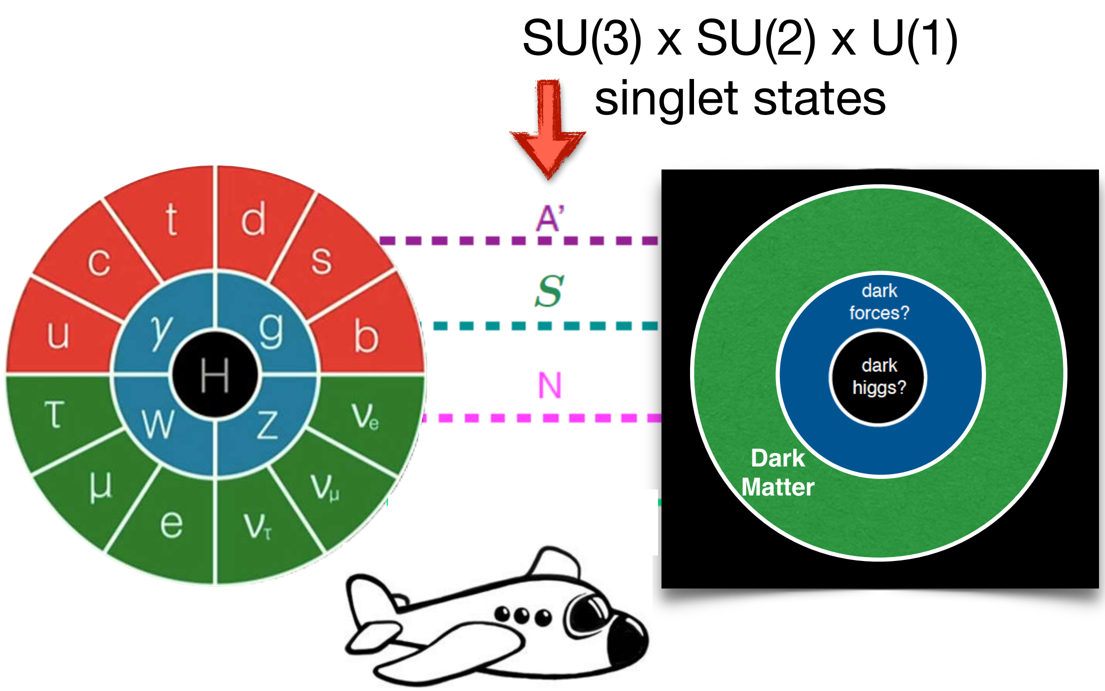

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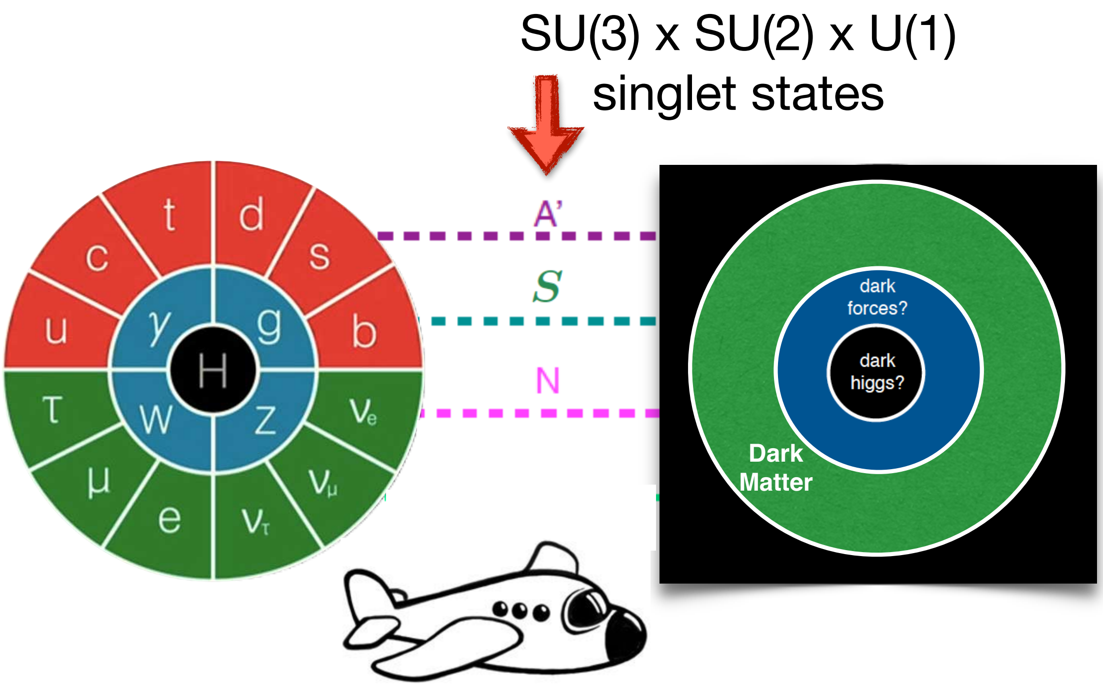
There is only a small set of **“portal”** interactions with the SM



“Portals”:

Dark photon	$\epsilon Z^{\mu\nu} A'_{\mu\nu}$
Higgs	$\kappa \lvert H \rvert^2 \lvert S \rvert^2$
Neutrino	$y H L N$

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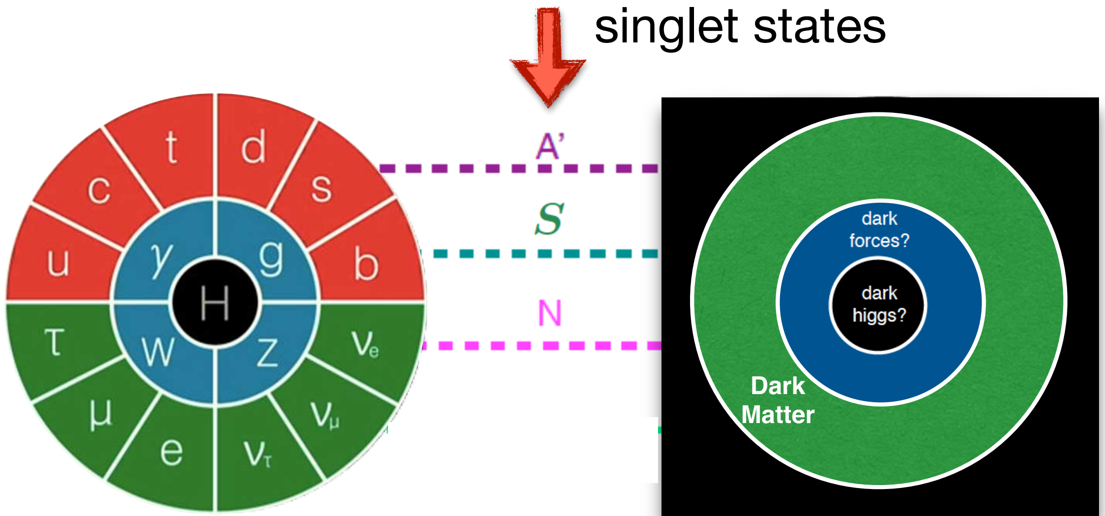
There is only a small set of **"portal"** interactions with the SM

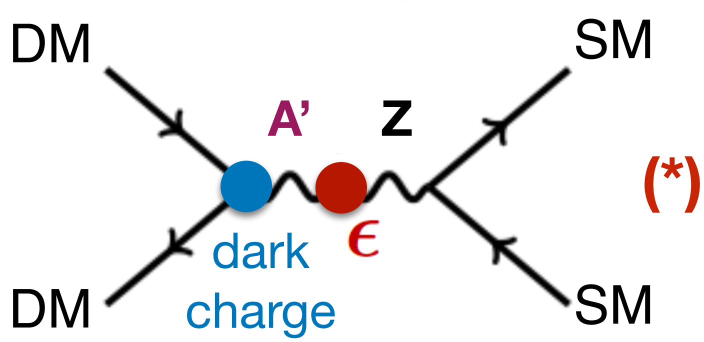
SU(3) x SU(2) x U(1) singlet states



"Portals":

Dark photon	$\epsilon Z^{\mu\nu} A'_{\mu\nu}$ (*)
Higgs	$\kappa \lvert H \rvert^2 \lvert S \rvert^2$
Neutrino	$y H L N$

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	$y H L N$

As we discussed, 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

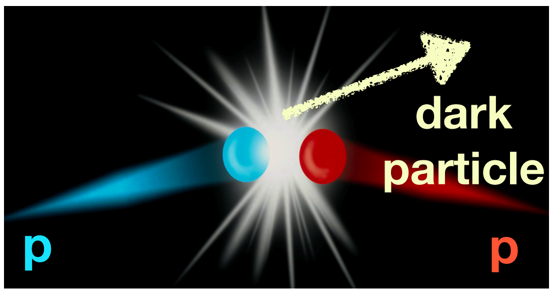
<u>Many opportunities</u> for accelerator experiments!

- high energy
- high intensity

A broad program of searches

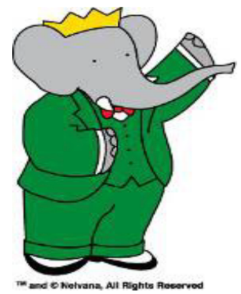
… of light (< few GeV) dark-sector particles

The LHC



Novel search strategies are needed!

B-factories



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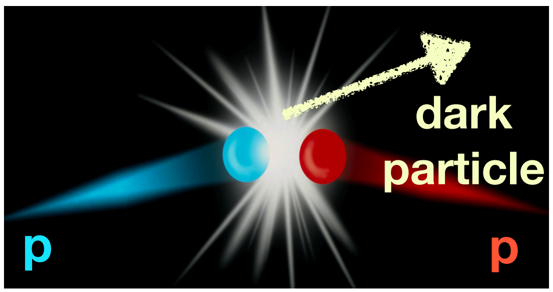

Novel search strategies are needed!

B-factories

Belle II

Unique access to dark sectors!

Fixed target experiments

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

The dark photon portal

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)'?**

Holdom, '86

for a review:
Fabbrichesi, Gabrielli, Lanfranchi, 2005.01515

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Mixing with the SM hyper-charge gauge boson

coupling to DM

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

arising from
* dark Higgs mechanism or
* Stueckelberg mechanism

Massive photon, A'

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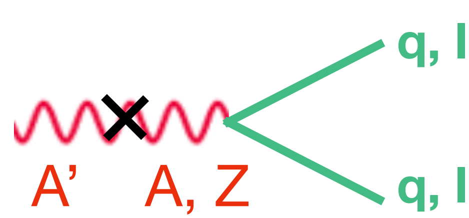
arising from
* dark Higgs mechanism or
* Stueckelberg mechanism

Massive photon, A'

The dark photon (mass eigenstate) has a mixing with the SM photon (A) and the Z.

Thanks to these mixings, the dark photon will acquire couplings to the SM particles (quarks and leptons)



At low mass, A' behaves like the SM photon

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

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

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

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

Model-independent

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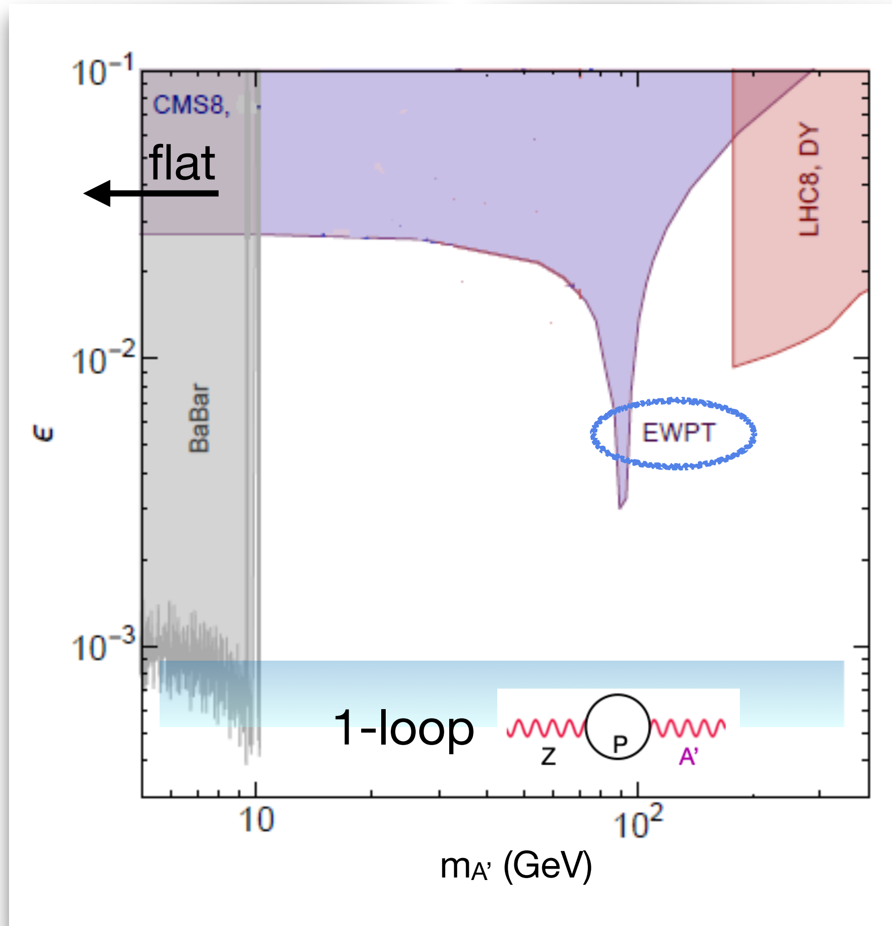
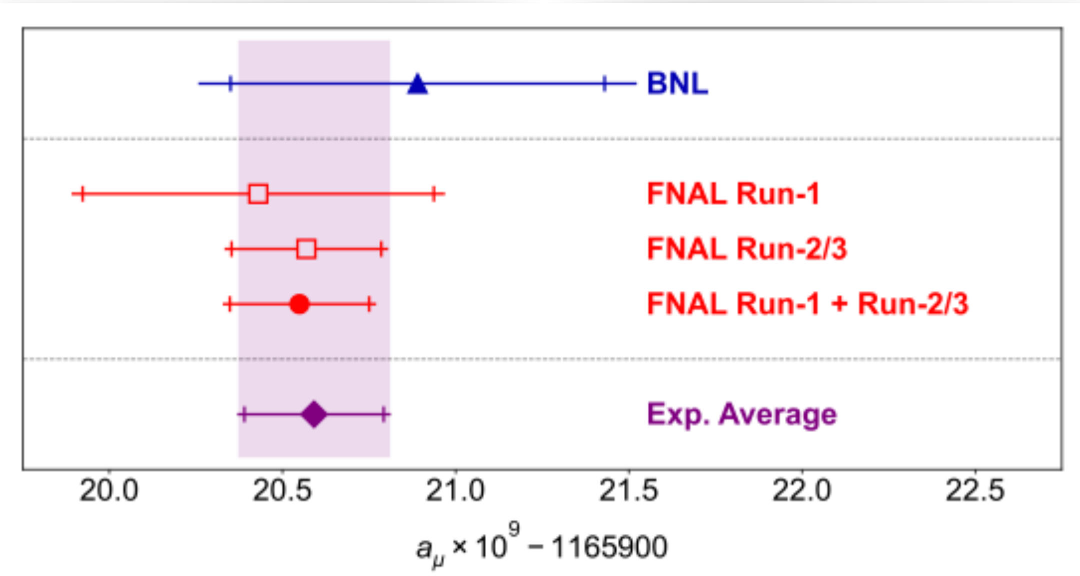


Curtin, Essig, SG, Shelton, 1412.0018
See also Hook, Izaguirre, Wacker, 1006.0973

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

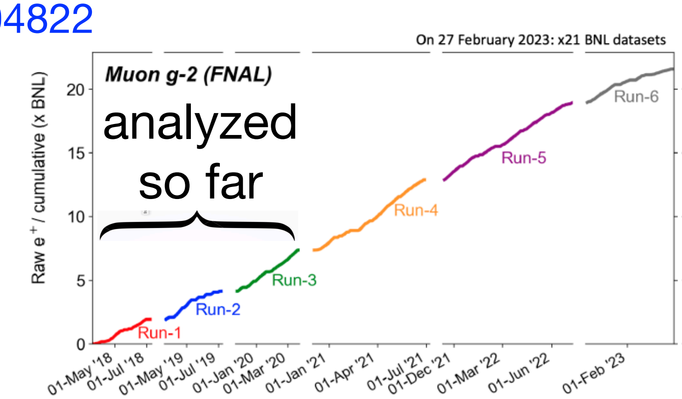
Dark photons and $(g\text{-}2)_\mu$

g-2 collaboration at Fermilab, 2308.06230



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

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



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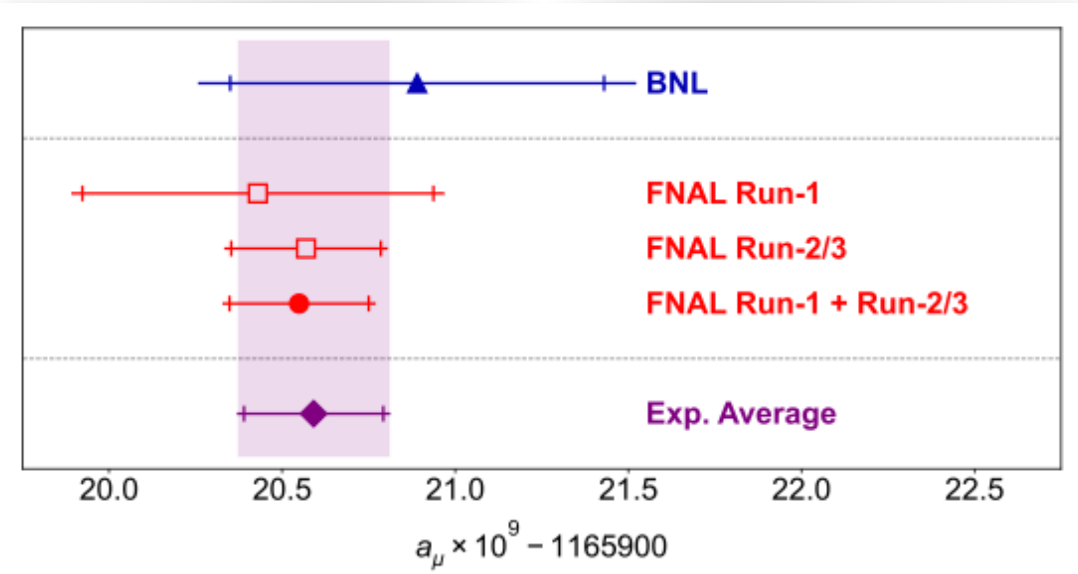

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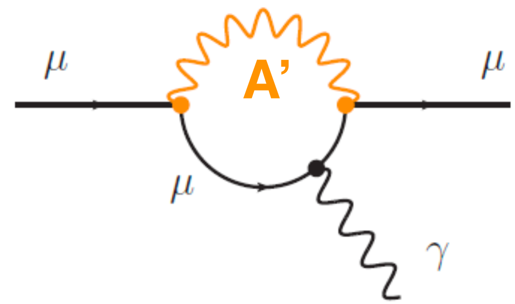

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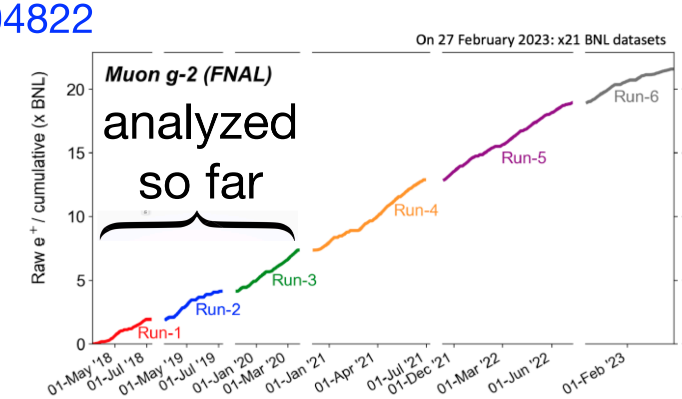
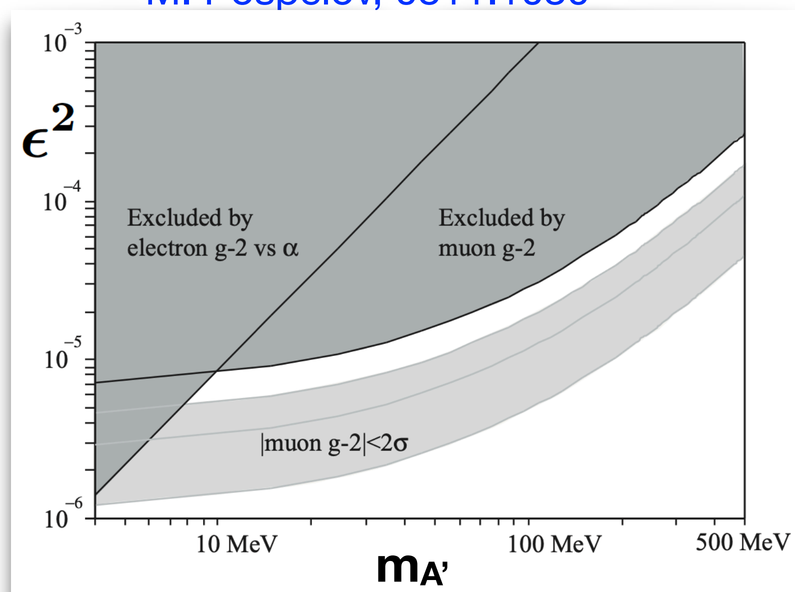


M. Pospelov, 0811.1030



Old result. Numbers should be updated

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 A'

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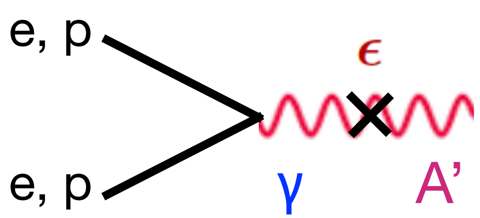
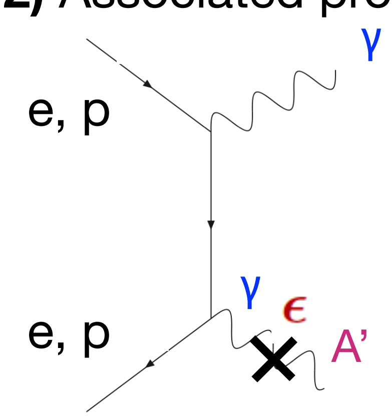
Collider experiments

1) Drell-Yan production:



3) Meson decays:
e.g., $D^* \to D\,A'$

2) Associated production:



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

Good for low energy colliders

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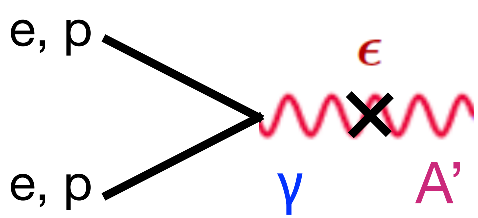

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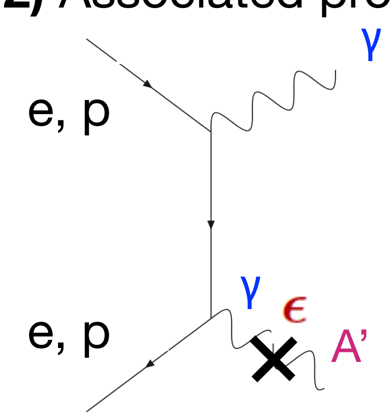

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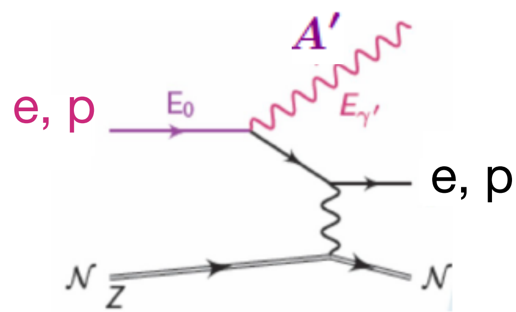
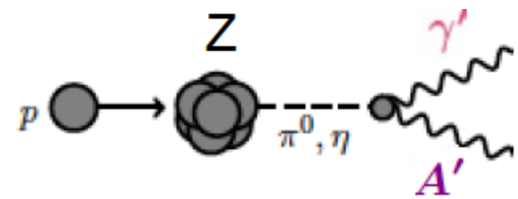
Good for low energy colliders

Fixed target experiments



brems-strahlung



meson decay

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

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

Decays of the dark photon

Generically we have **two cases** with a very different phenomenology:

1. **DM is lighter than A'**

The A' decays promptly into DM (invisible)

2. **DM is heavier than A'**

("secluded" case)

The A' decays either promptly or displaced into SM particles (visible)

Decays of the dark photon

Generically we have **two cases** with a very different phenomenology:

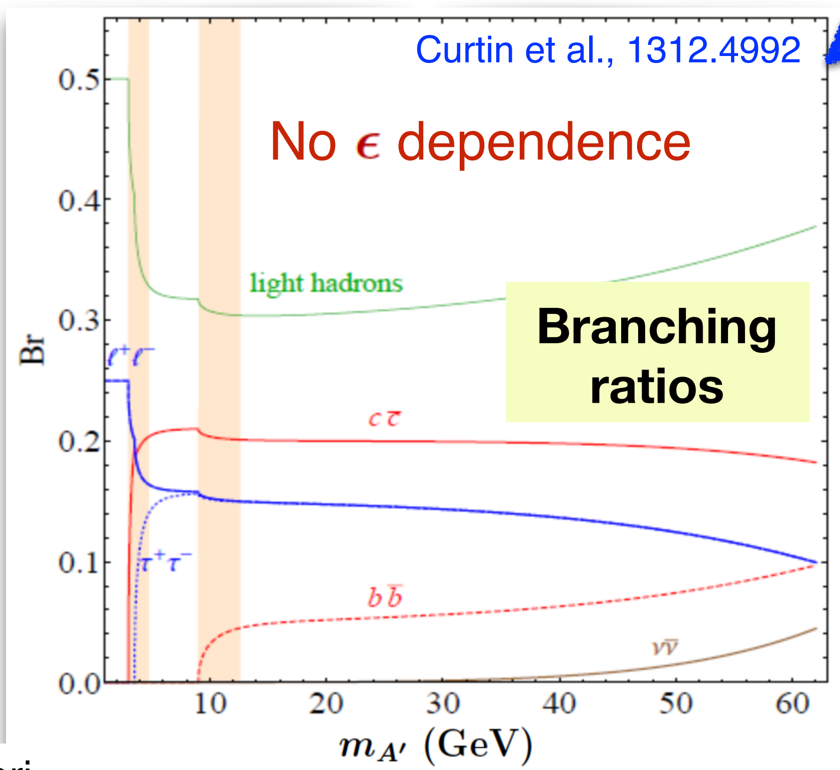
1. **DM is lighter than A'**

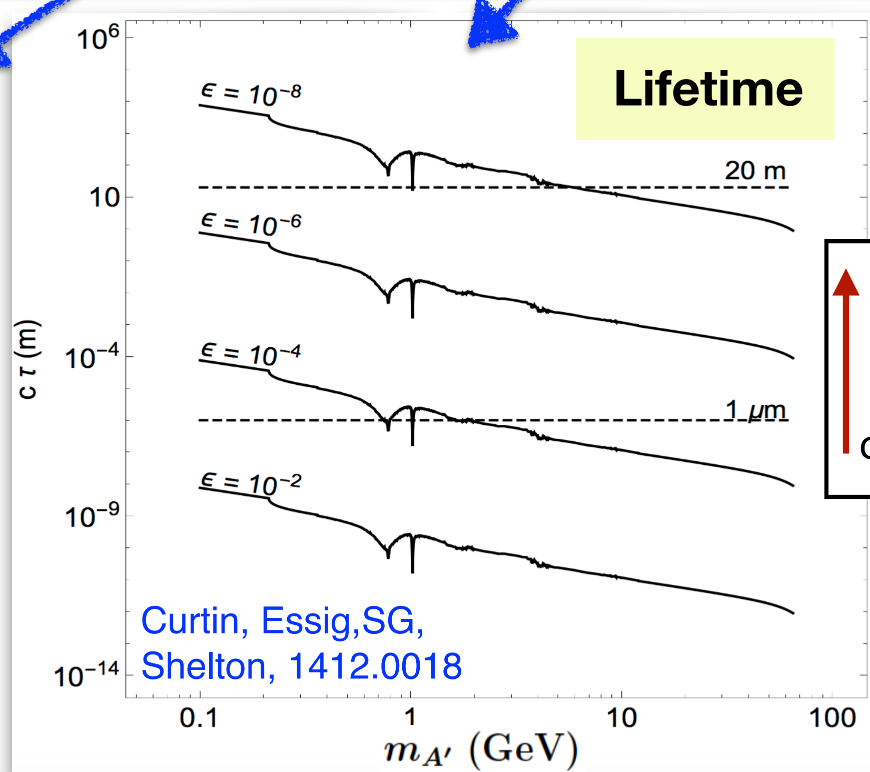
The A' decays promptly into DM (invisible)

DM is heavier than A' **2.**

("secluded" case)

The A' decays either promptly or displaced into SM particles (visible)





Decreasing kinetic mixing coefficient, ε

A couple of details on the visible calculation

2.

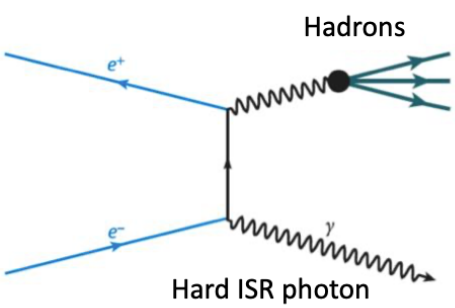
1) For **$m_{A'}$ >> mass of hadronic resonances**, simple calculation of A' → ff

2) For **lighter A'** the ratio: $$R_{A'} \equiv \frac{\Gamma(A' \to \text{hadrons})}{\Gamma(A' \to \mu^+\mu^-)} = R_{A'}(m_{A'})$$

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

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

We can use experimental data to determine $R_{A'}(m_{A'}) = R(m_{A'}^2)$
In this way, we can determine all branching ratios of the dark photon at low mass (where the dark photon has photon-like couplings)



R(s) can be measured at Belle II for different center-of-mass energies, analyzing e^+e^- events with an initial-state radiation photon

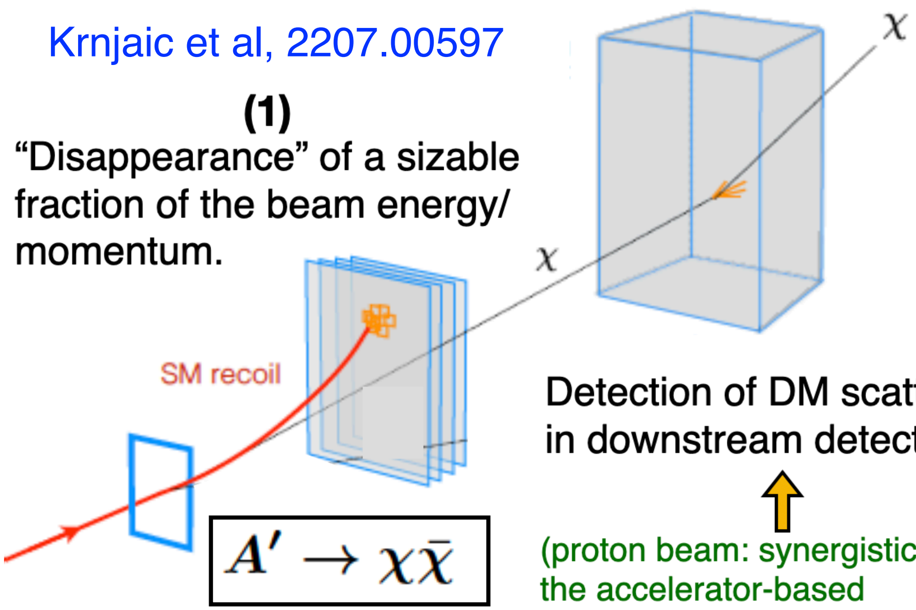
see e.g., 2404.04915, $e^+e^- \to \pi^+\pi^-\pi^0$

Searches for invisible dark photons

Fixed target experiments

Krnjaic et al, 2207.00597

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

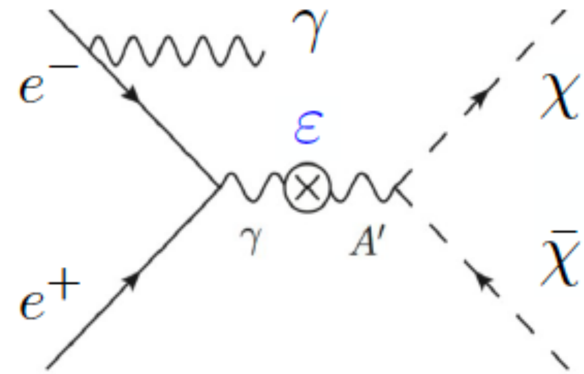


Detection of DM scattering in downstream detectors
(2)

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

NA64 (running), 2307.02404 with ~10^{12} EOT
LDMX (proposed)
M^3 (proposed)

B-factories



mono-photon + invisible

Babar search with ~50/fb, 1702.03327
Two signal regions:

1. Low A’ mass
$E_\gamma > 2$ GeV
2 GeV < $m_{A'}$ < 6 GeV

2. High A’ mass
$E_\gamma > 1$ GeV
4.9 GeV < $m_{A'}$ < 8.3 GeV

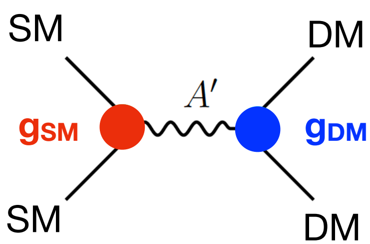
$$E_\gamma = (E^2_{\rm CM} - m^2_{A'})/(2E_{\rm CM})$$

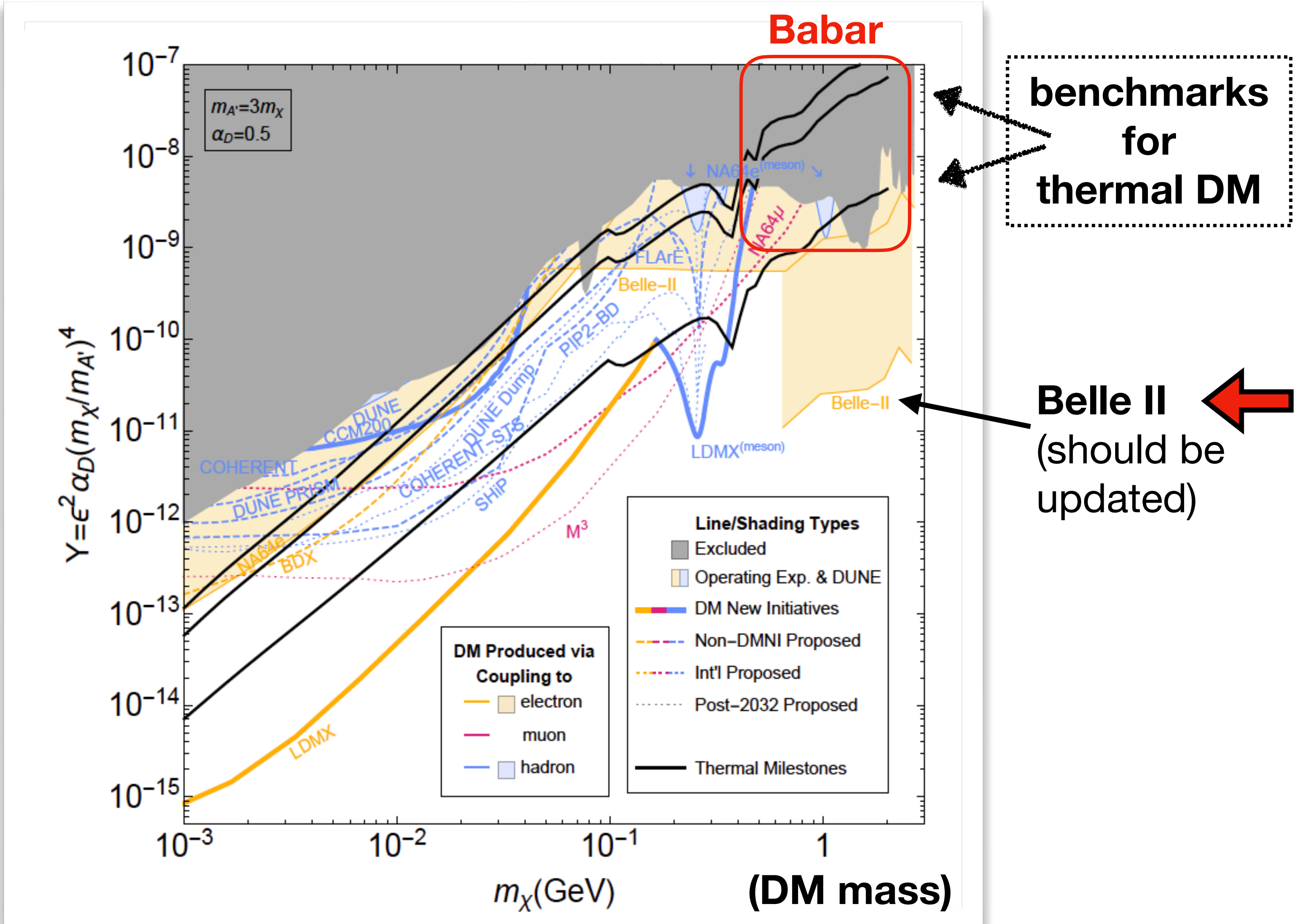
1.

Summary plot: the invisible dark photon

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

A'→DM DM





Krnjaic, Toro et al, 2207.00597

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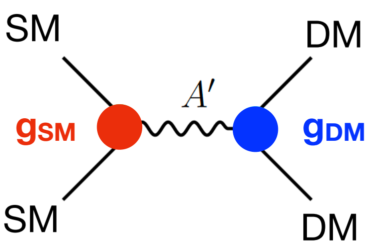
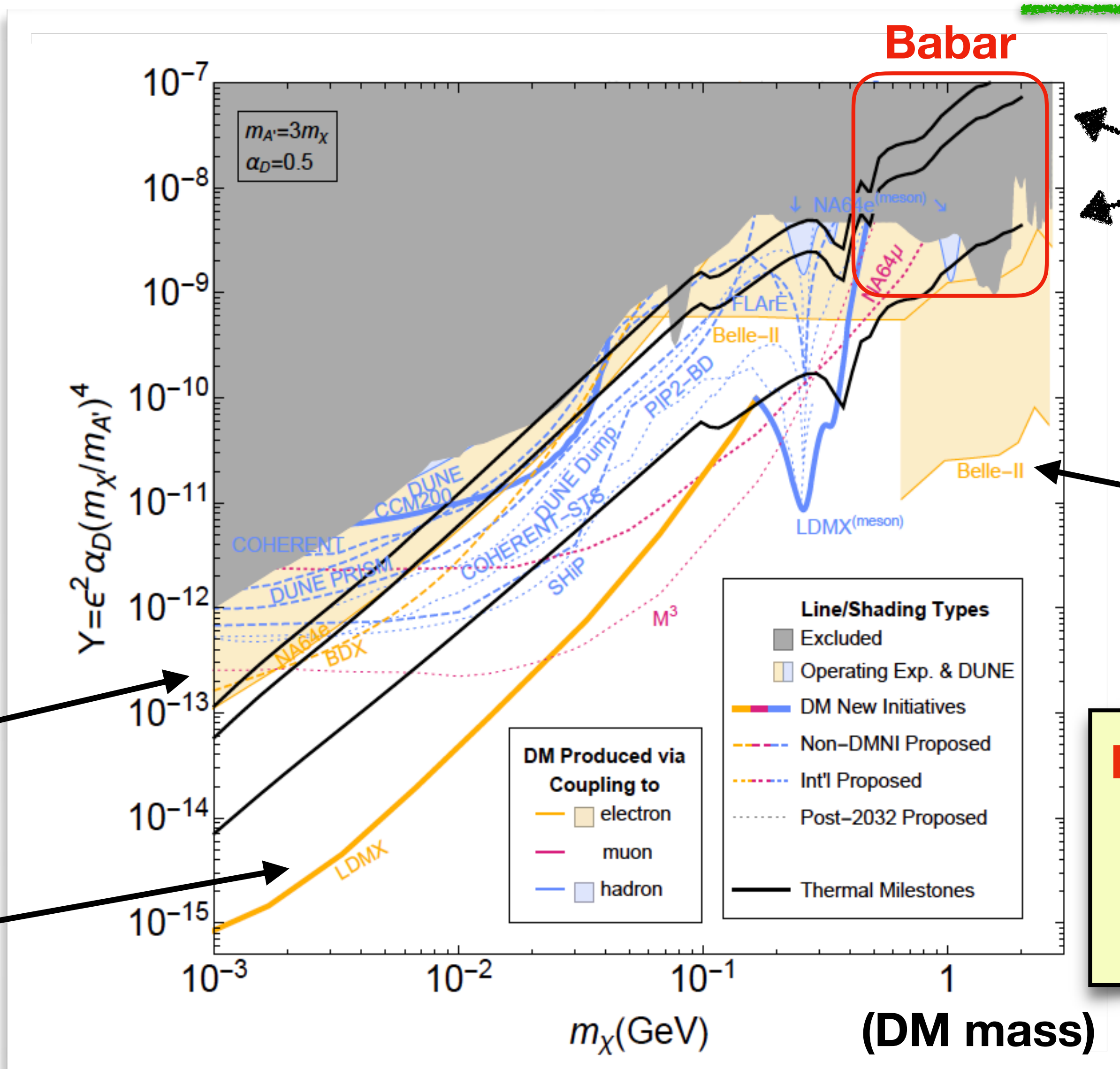




Babar

LHC

benchmarks for thermal DM

Belle II (should be updated)

Scattering experiments

LDMX

(DM mass)

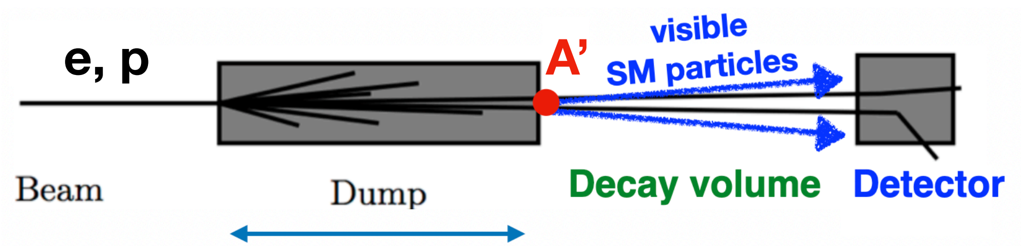
Full coverage of this DM thermal target is possible in the coming years!

Krnjaic, Toro et al, 2207.00597

2.

Searches for visible dark photons

Fixed target experiments



Some example:

p beam, CHARM (CERN) + …

p beam, SeaQuest/DarkQuest (Fermilab)

p beam, NA62 (CERN)

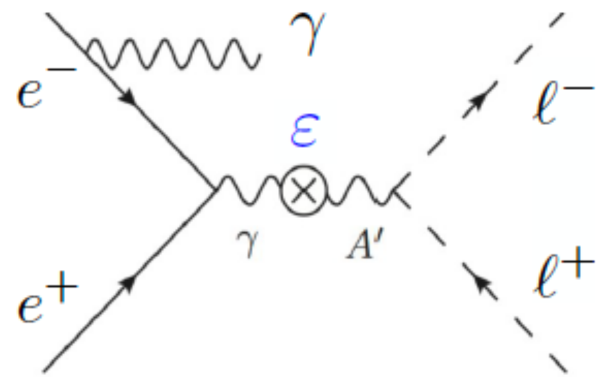
p beam, SHiP(CERN)

e- beam, HPS (JLAB)

e- beam, DarkLight (TRIUMF)

Past experiments | Running experiments | Future experiments

B-factories



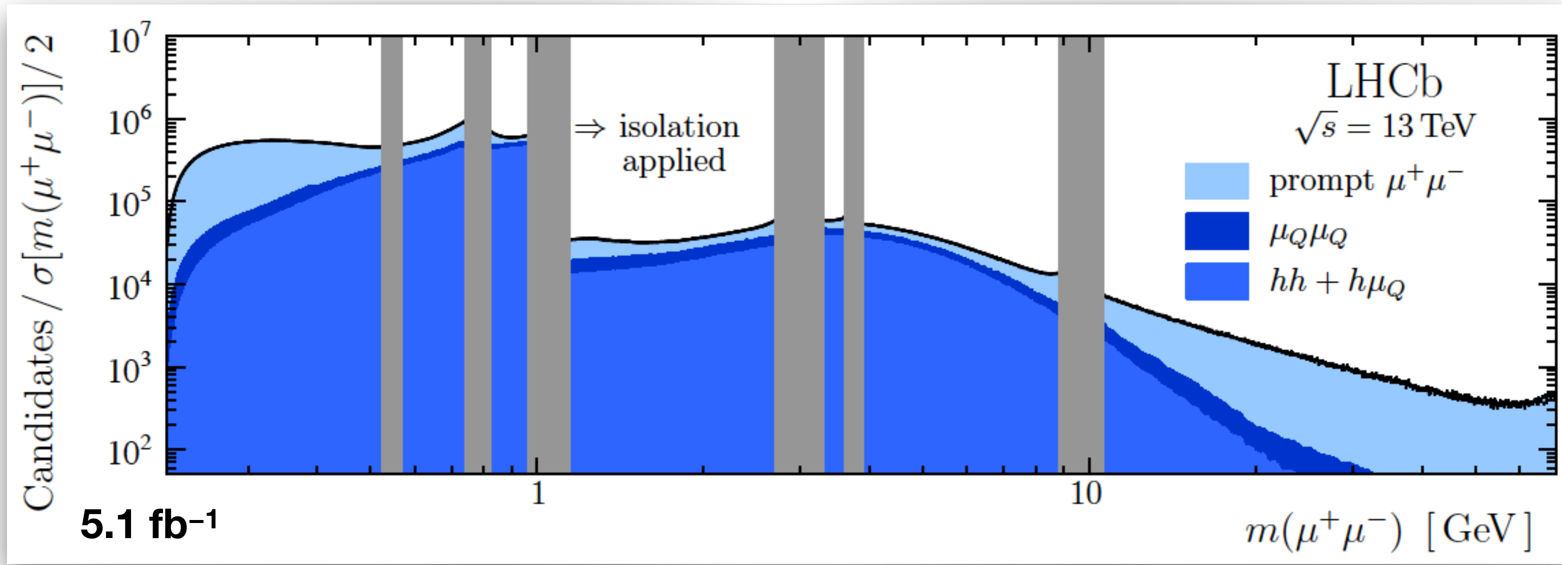
photon + di-lepton resonance

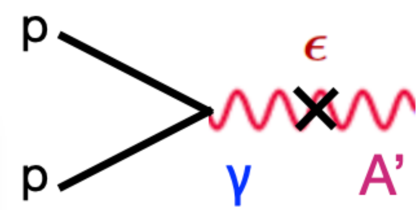
Babar search with 514 fb^{-1}: 1406.2980

2.

Visible dark photons at LHCb

Excellent measurement of the di-muon spectrum:



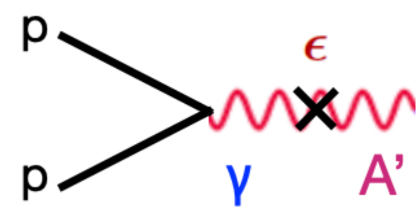


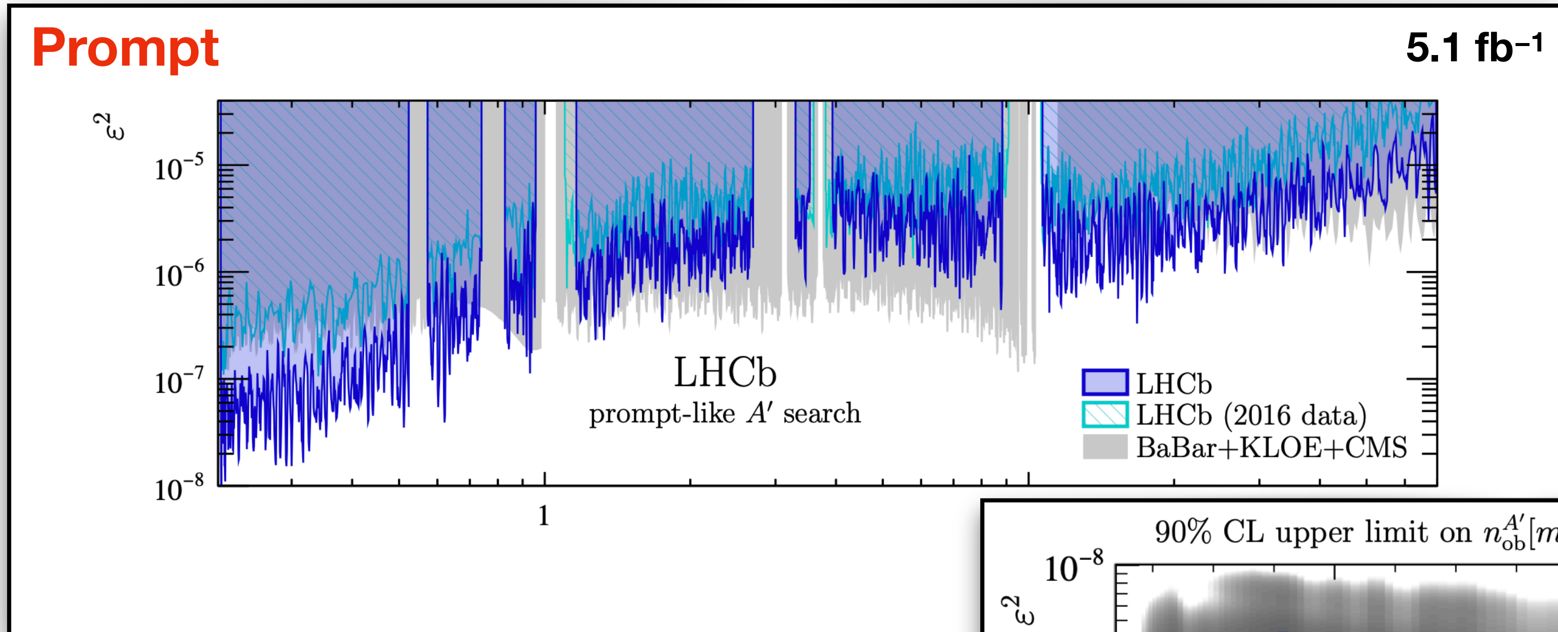
1910.06926

2.

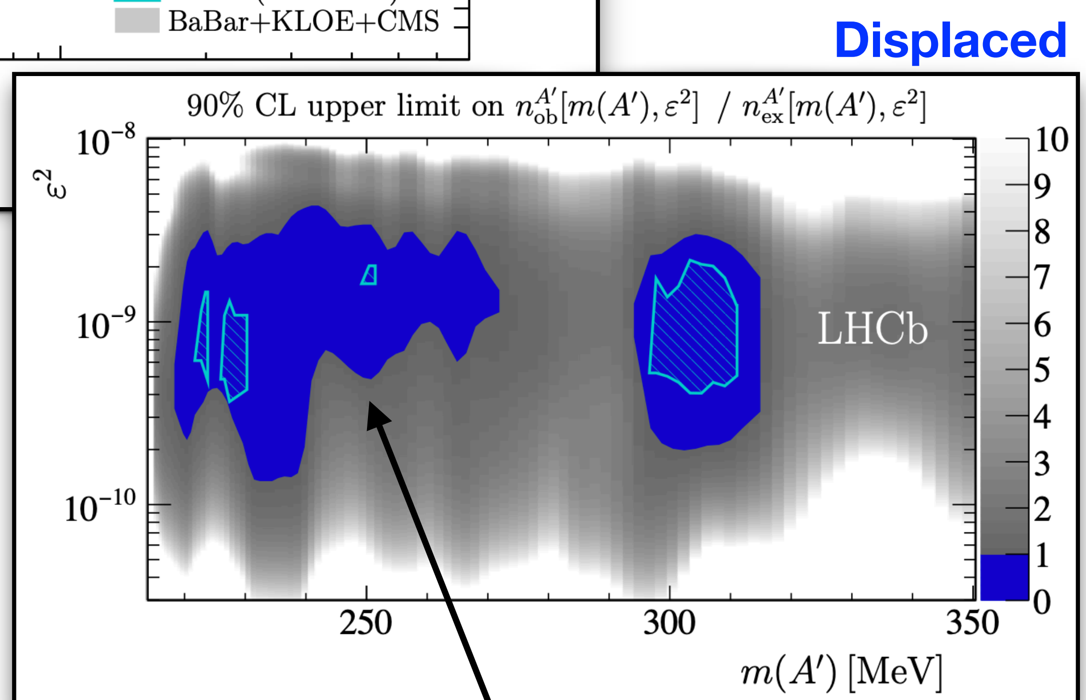
Visible dark photons at LHCb

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





1910.06926



Below the muon threshold: additional opportunities for

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

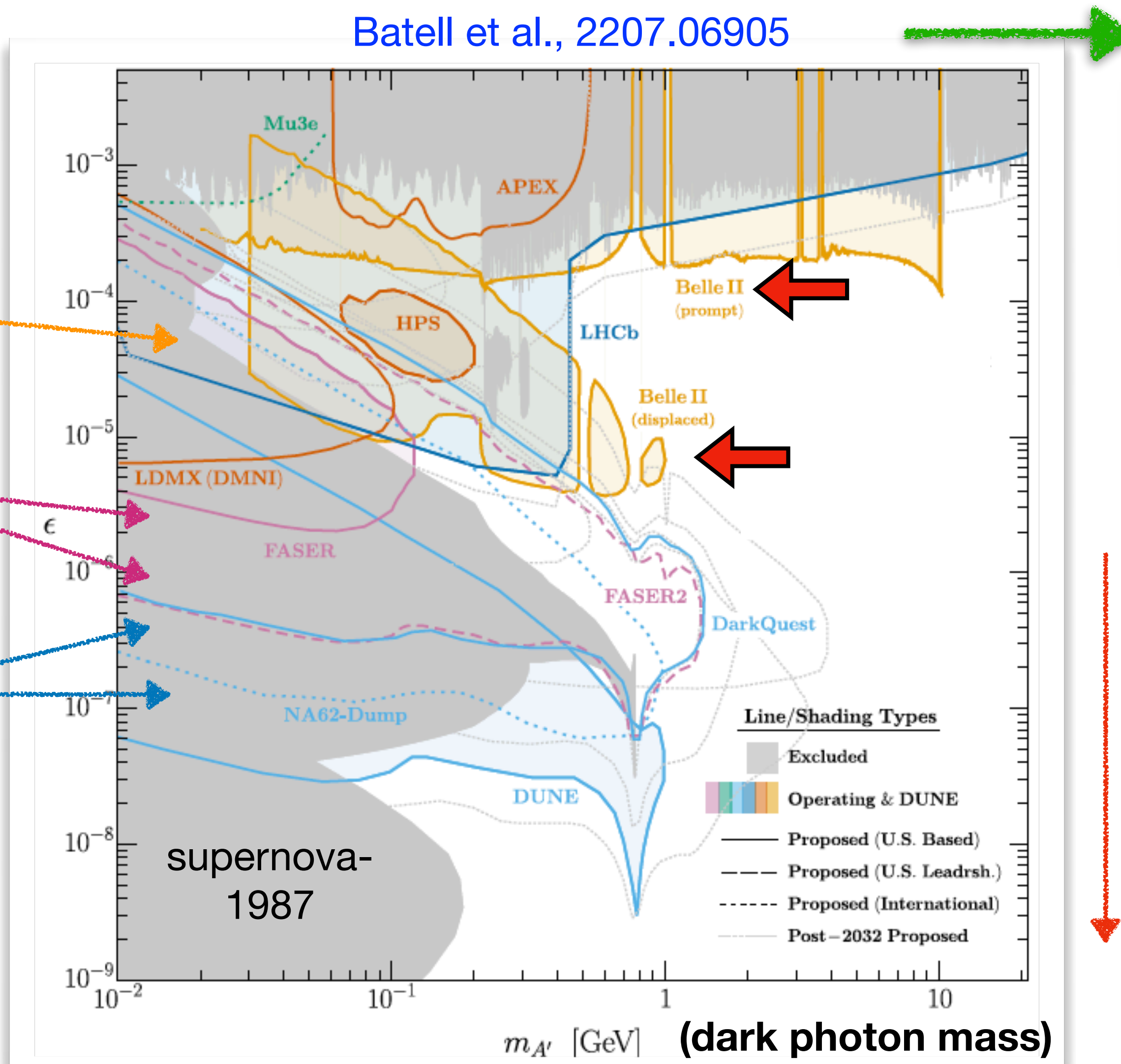
Ilten et al., 1509.06765

lifetimes O(1) ps

2.

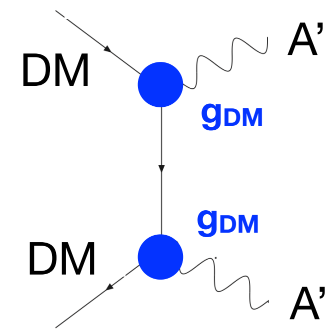
Summary plot: the visible dark photon

Batell et al., 2207.06905



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

A'→SM SM



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

Today's summary

Dark sectors are ubiquitous.

DM and the strong CP problem are two of the many motivations.

DM thermal freeze-out models are highly predictive. They generically require a dark sector if in the sub-GeV mass range.

Minimal portal interactions.

Phenomenology of the minimal dark photon model

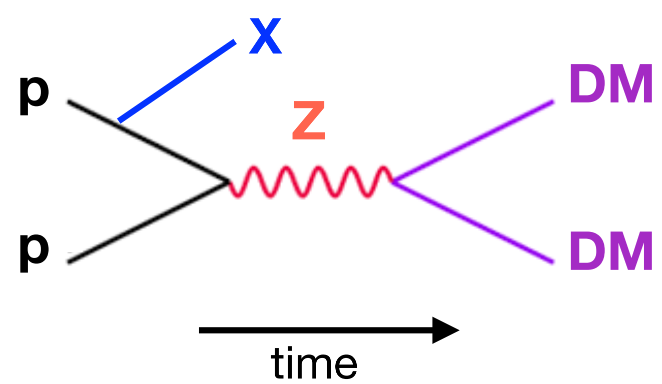
invisible   visible

Backups

LHC production

WIMP Dark Matter can be produced at high energy colliders like the LHC, thanks to its interactions with the Z and Higgs boson:

a. **Drell-Yan production**

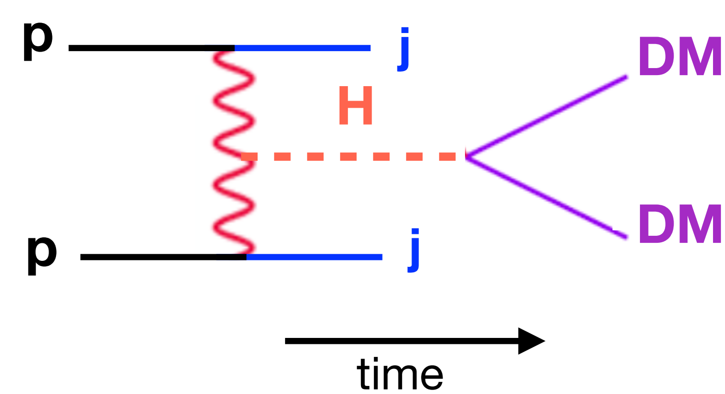


Mono-X searches

(mono-photon, mono-Z, mono-jet, …)

Higgs decays **b.**

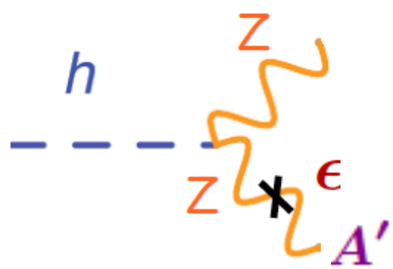
If DM is lighter than the Higgs:



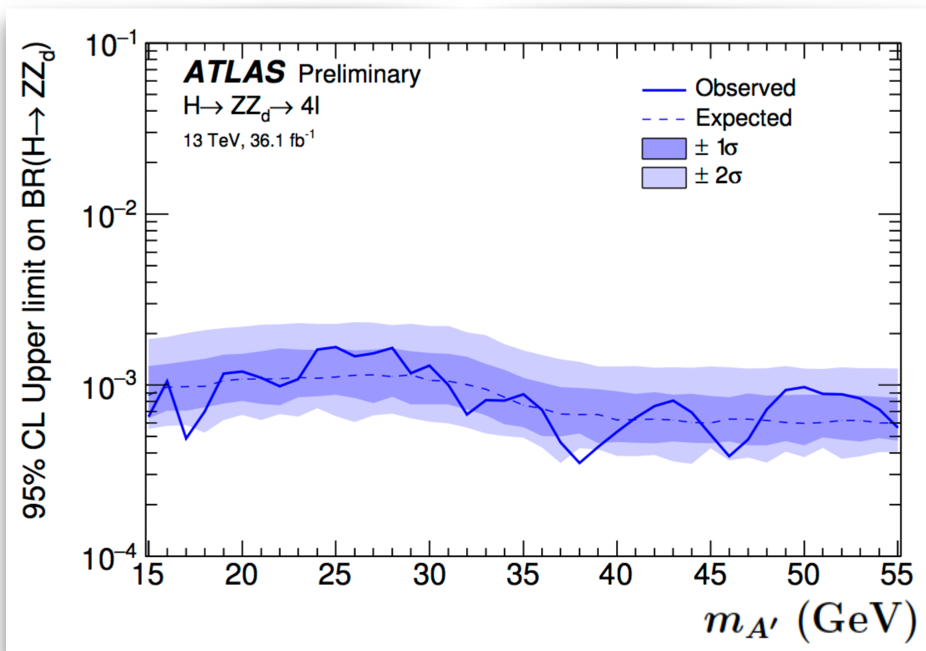
Searches for Higgs invisible decays, with the Higgs produced in association with something

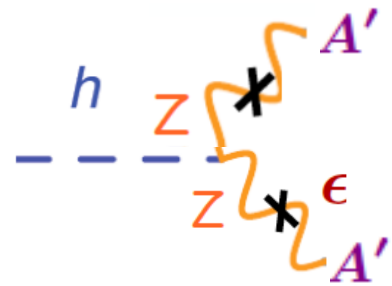
(vector boson fusion, Zh, …)

Dark photon searches at the LHC (2)

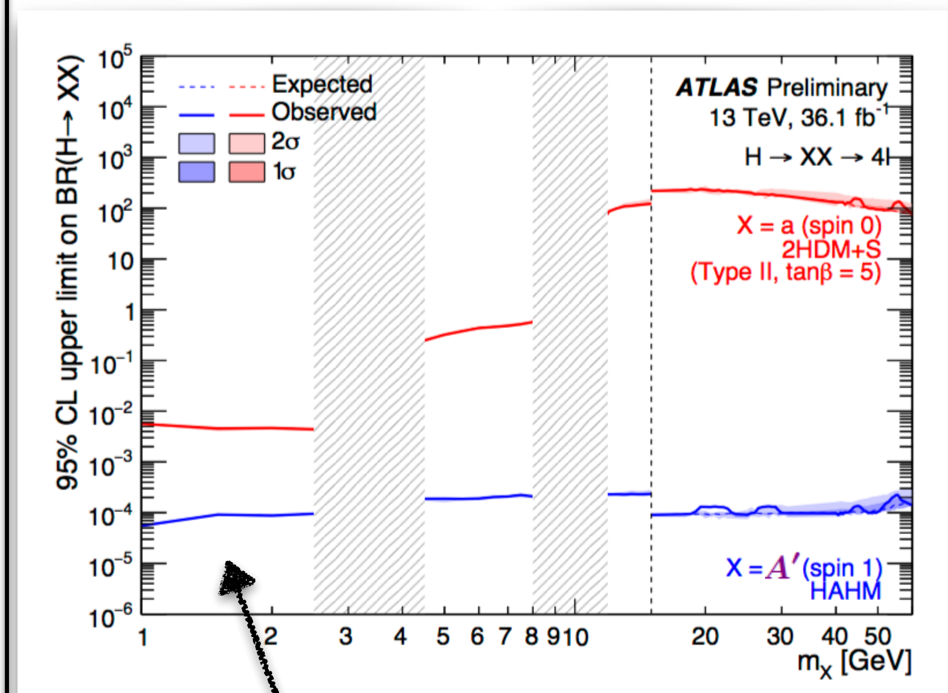


$$h \to Z A' \to 2\ell\, 2\ell'$$





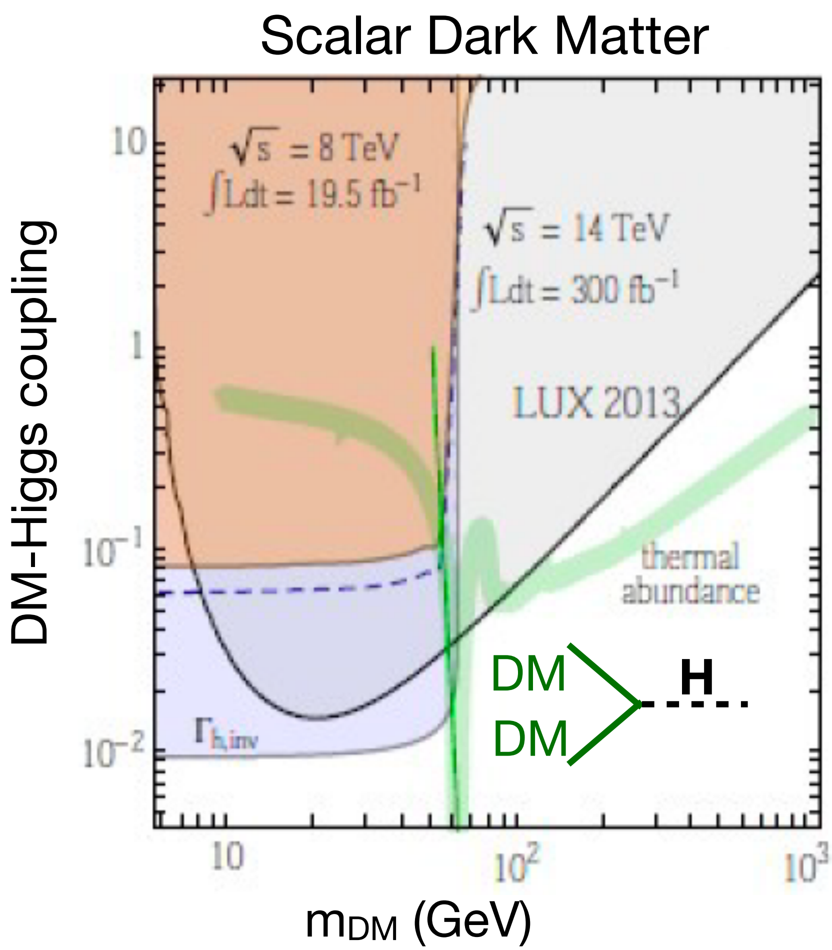
$$h \to A' A' \to 2\ell\, 2\ell'$$

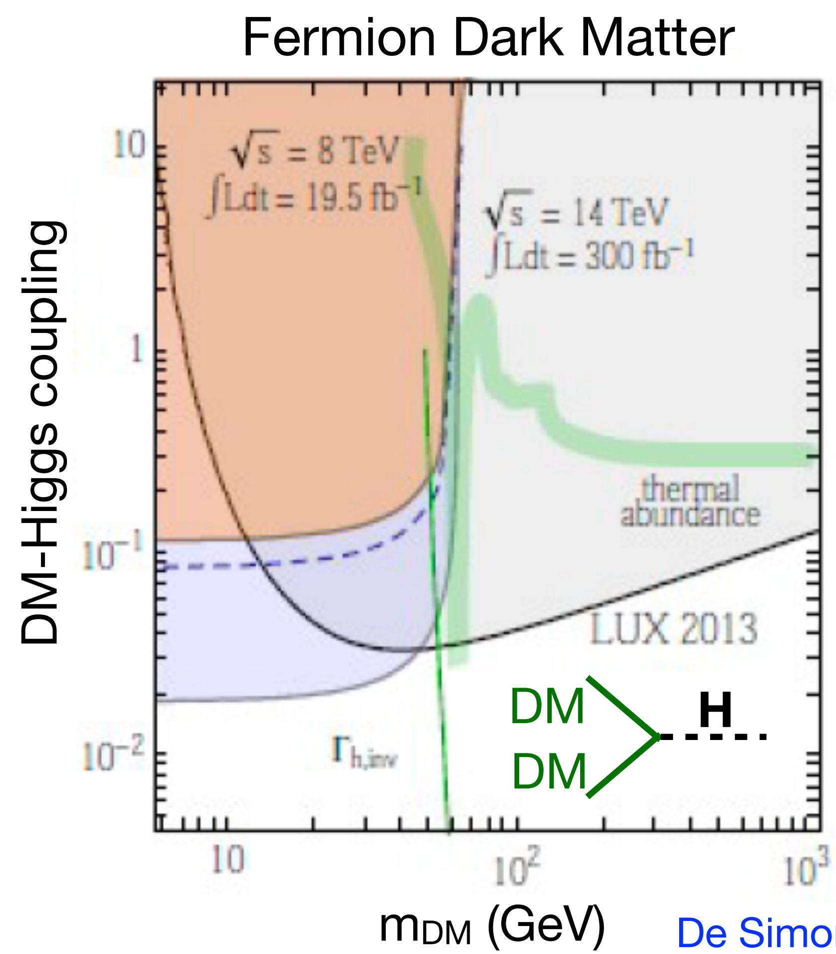


Also lower masses

ATLAS-CONF-2017-042

A full picture for Higgs-mediated DM?





De Simone et al, 1402.6287

<u>Conclusion:</u> in minimal models, if the Higgs is the particle responsible of DM annihilation, then DM cannot be too light