Introduction to dark sector physics

Stefania Gori
UC Santa Cruz

2021 Belle II Physics Week

December 2, 2021

Overview

Symmetry magazine

Chapter 1:

Introduction: Why dark sectors are interesting

Chapter 2:

Minimal dark sector models and how to test them

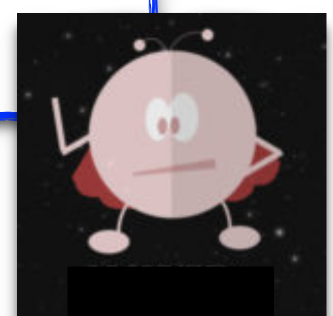
Chapter 3:

Beyond minimal models. Rich dark sector structures

Chapter 1

Introduction

Why dark sectors?



Dark Matter (DM) is there!

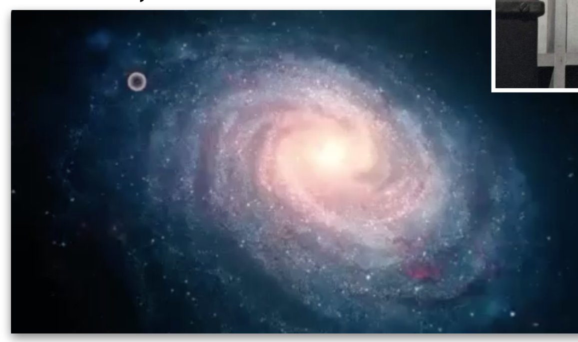
What do we know about it? Not much

1. It gravitates

1933 Fritz Zwicky

Coma cluster (of galaxies)

1970, Vera Rubin



Andromeda Galaxy

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

3. It is stable on cosmological scales

Dark Matter (DM) is there!

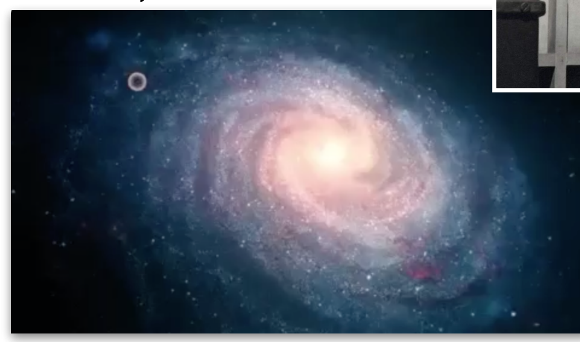
What do we know about it? Not much

1. It gravitates

1933 Fritz Zwicky

Coma cluster (of galaxies)

1970, Vera Rubin



Andromeda Galaxy

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

Dark Matter (DM) is there!

What do we know about it? Not much

1. It gravitates

1933 Fritz Zwicky

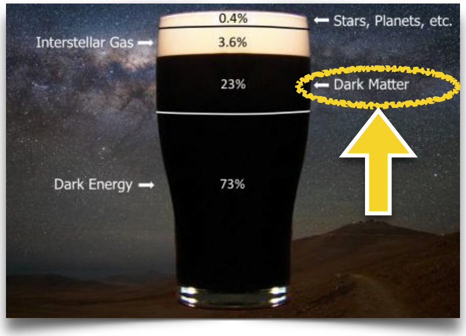
Coma cluster (of galaxies)

1970, Vera Rubin

Andromeda Galaxy

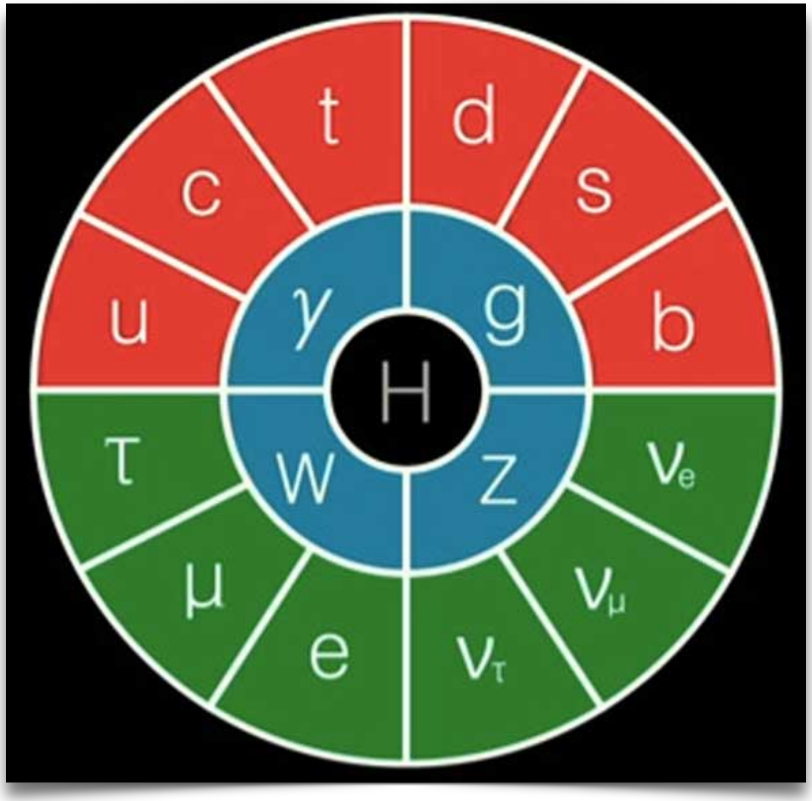
2. It is dark (i.e. it does not interact with photons)

3. It is stable on cosmological scales



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?**

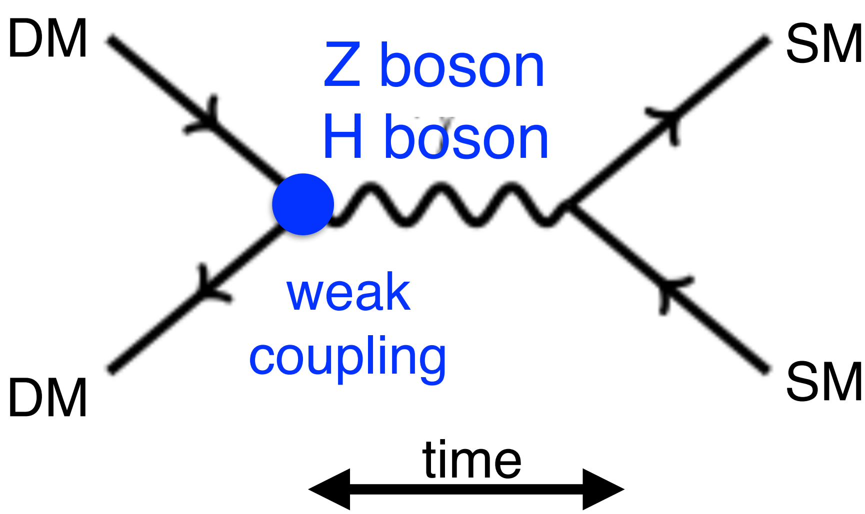
The “WIMP” paradigm

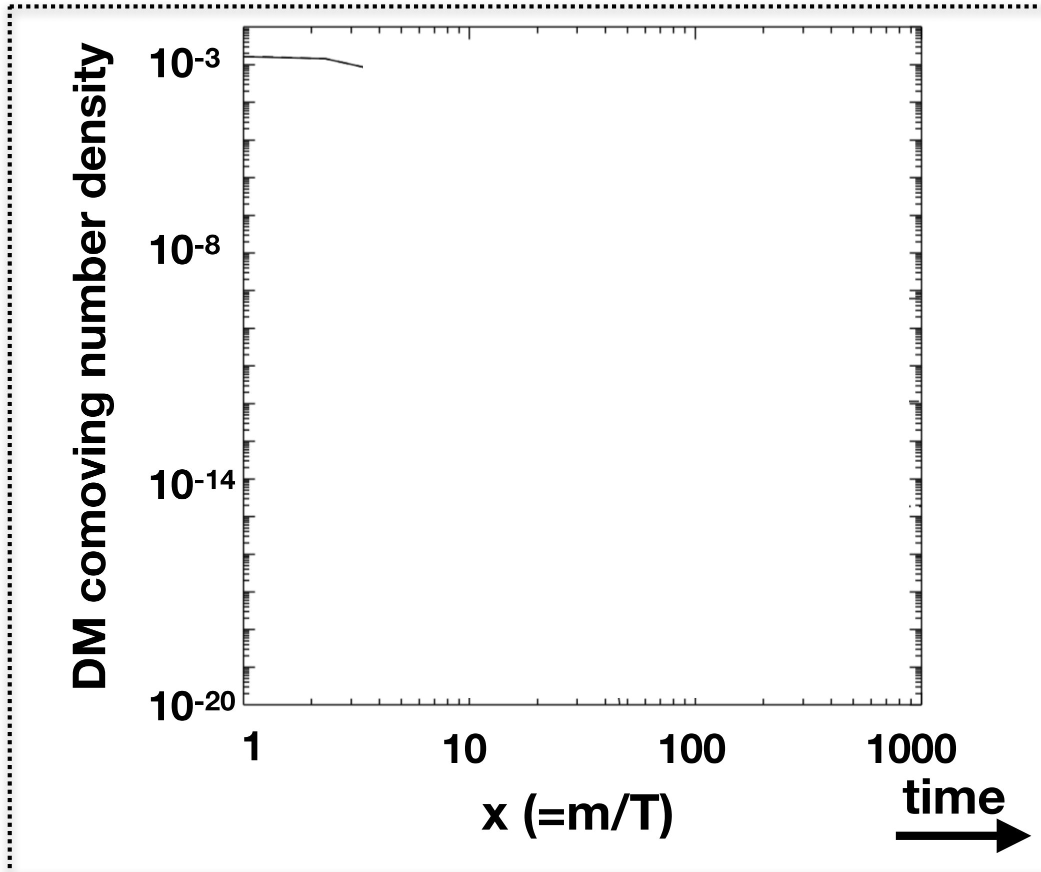
Weakly Interacting Massive Particles (WIMP) models:
One of the dominant models for more than 3 decades

The "WIMP" paradigm

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

Thermal Dark Matter

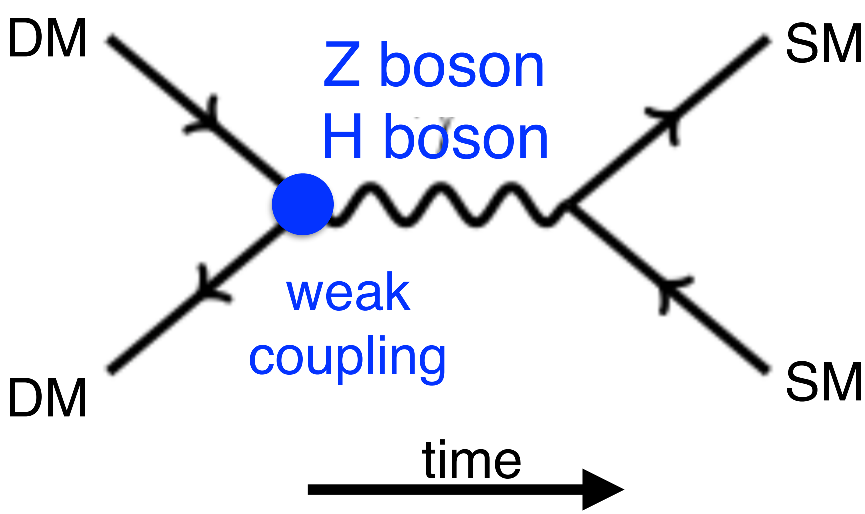


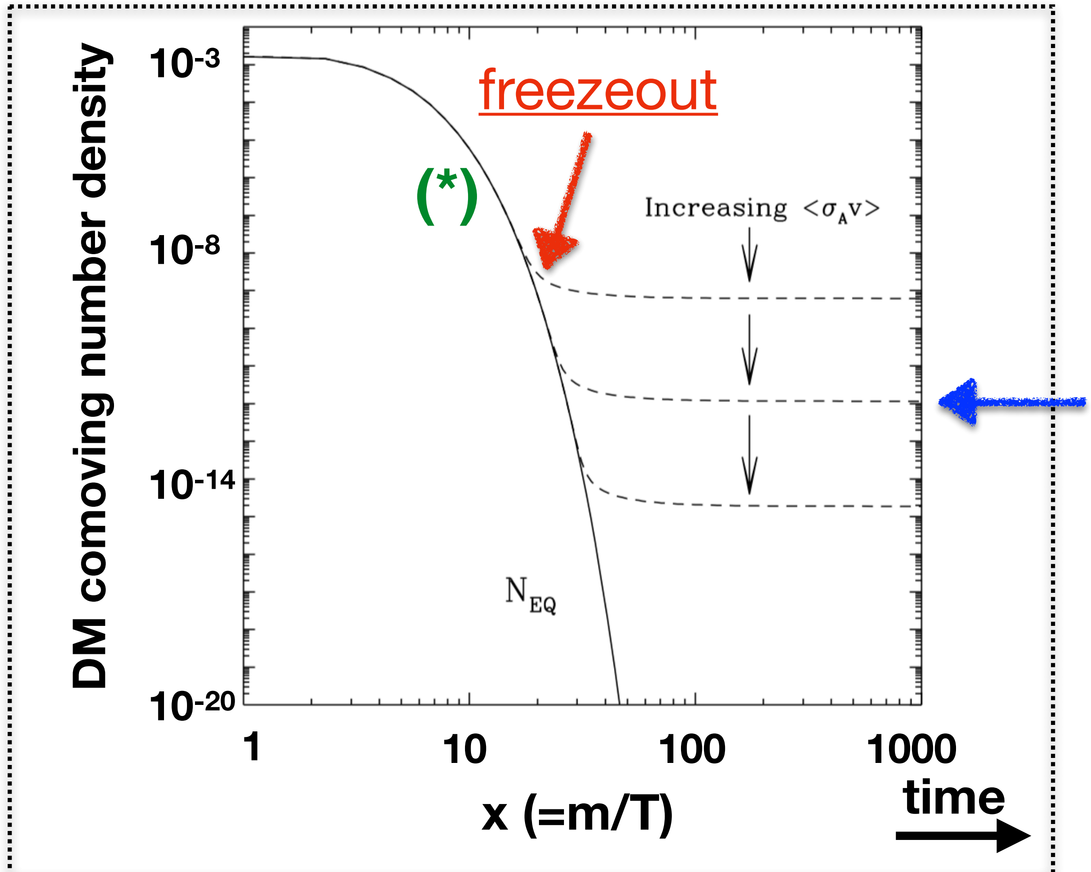


The "WIMP" paradigm

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

DM annihilation to SM (*):





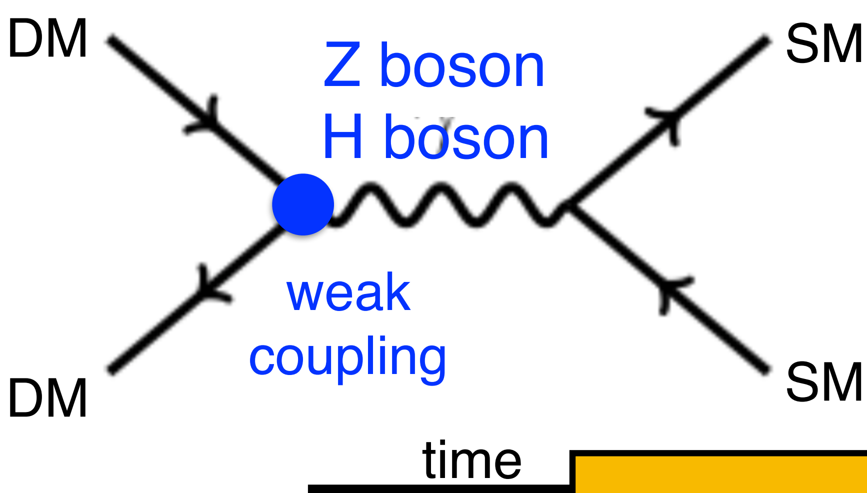
Thanks to these interactions, DM with a mass O(100 GeV) can "freeze out" and obtain the measured relic abundance

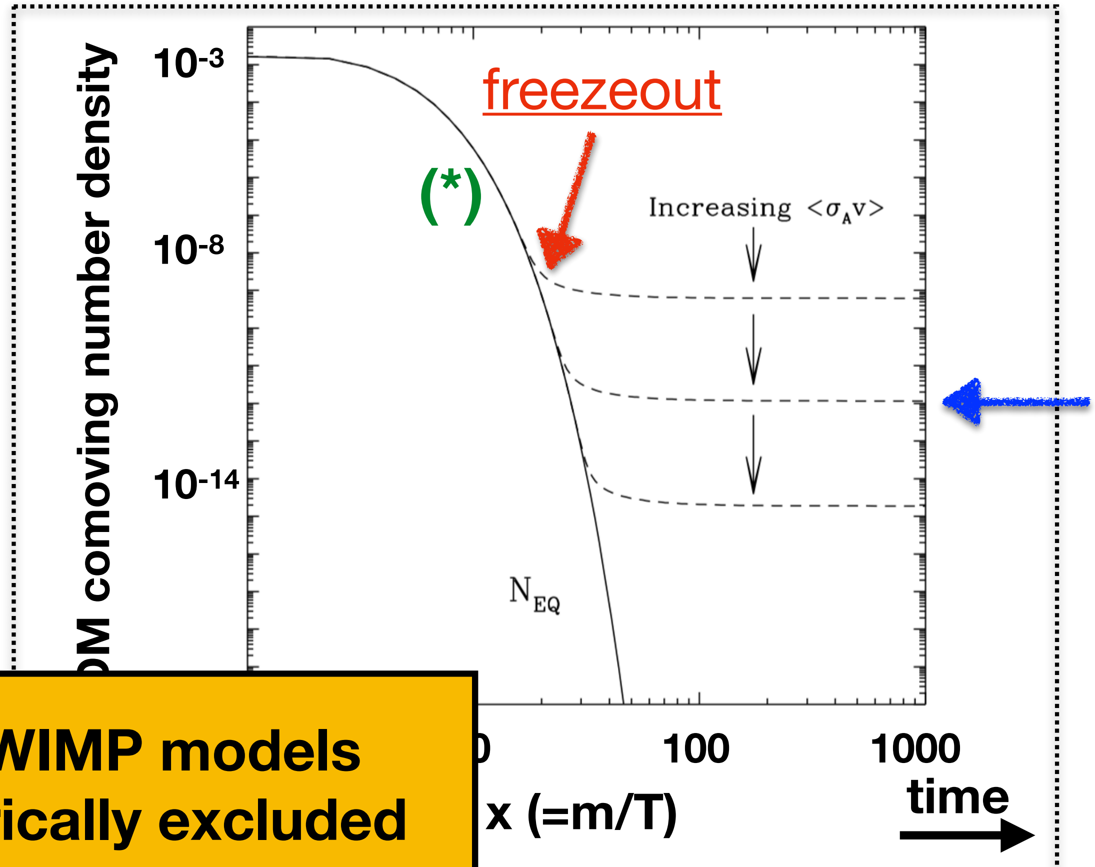
WIMP "miracle"? … or "coincidence"

The "WIMP" paradigm

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

DM annihilation to SM (*):



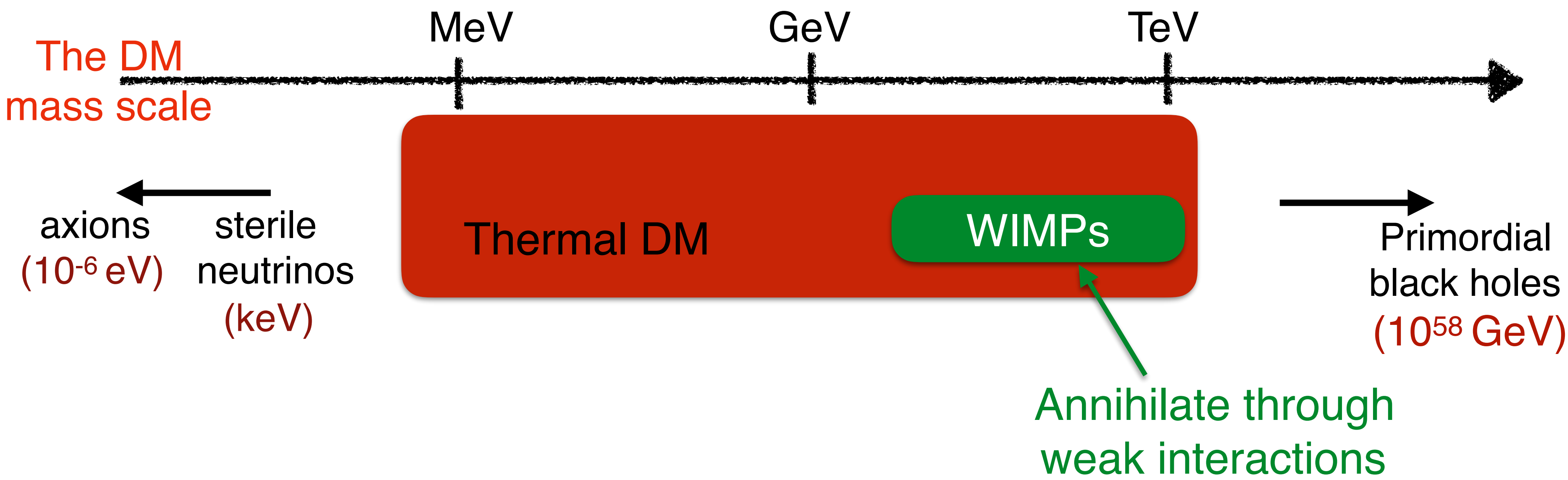


Vanilla WIMP models are generically excluded

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

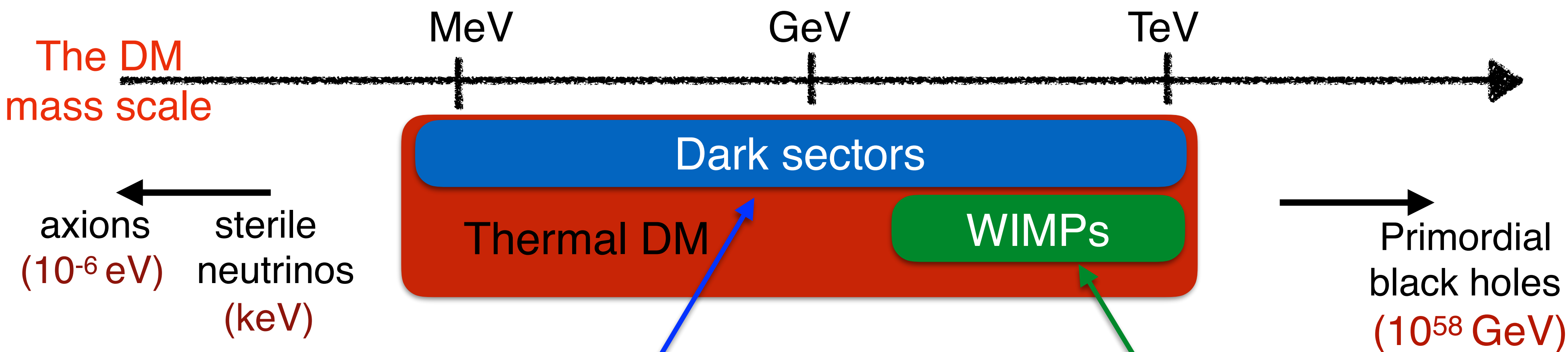
WIMP "miracle"? … or "coincidence"

Dark Matter & dark sectors



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

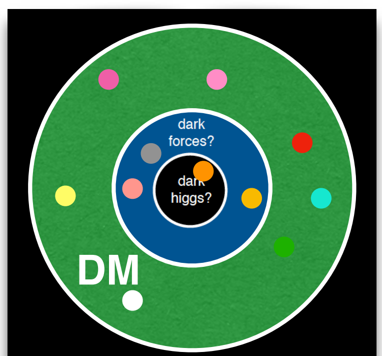
Dark Matter & dark sectors

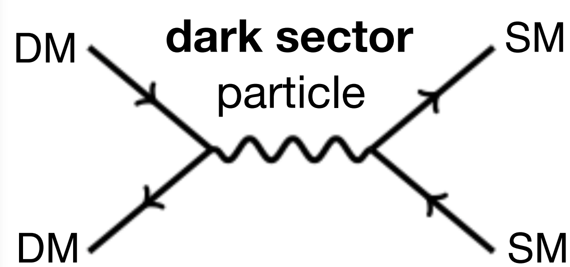


Neutral under the SM interactions.
If thermal, Dark Matter **generically** **<u>needs</u> additional particles** to annihilate with

Annihilate through weak interactions

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





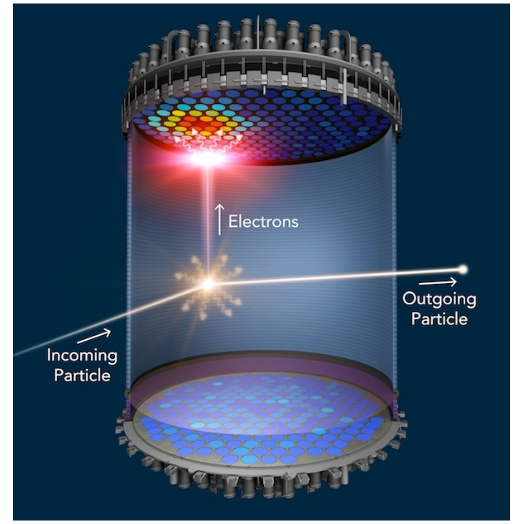
The dark matter scale is **<u>unknown</u>**.
Completely <u>different search strategies</u> depending on the mass of dark matter

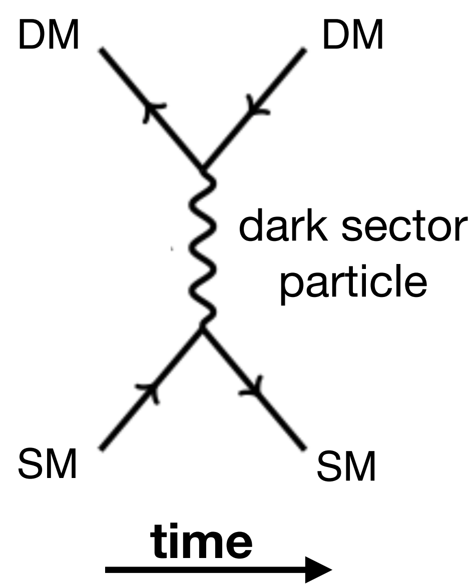
(relatively) Weak direct detection bounds

Large detectors search for DM scattering against nuclei/electrons.

Lower energy thresholds for the scattering recoil

→ access to masses above ~few GeV



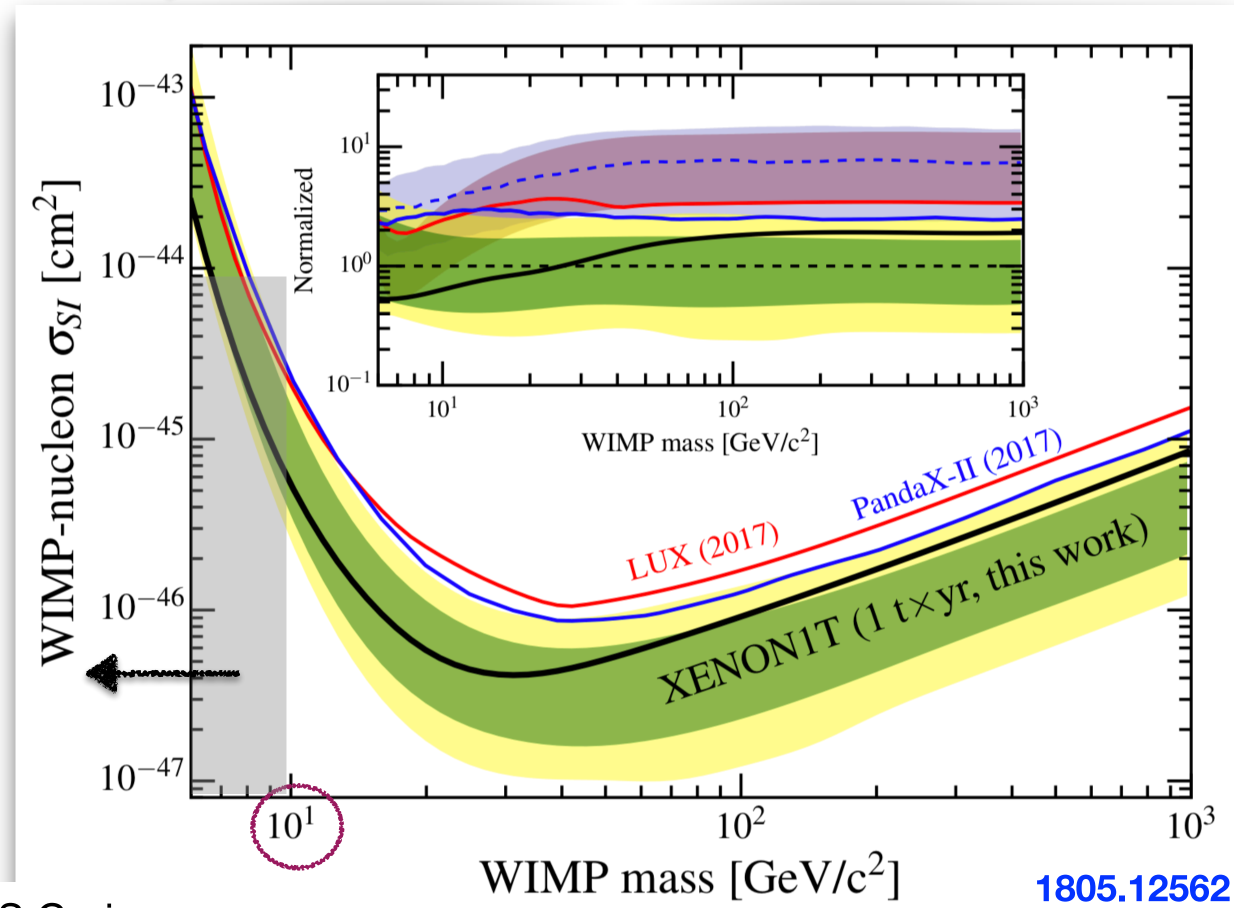


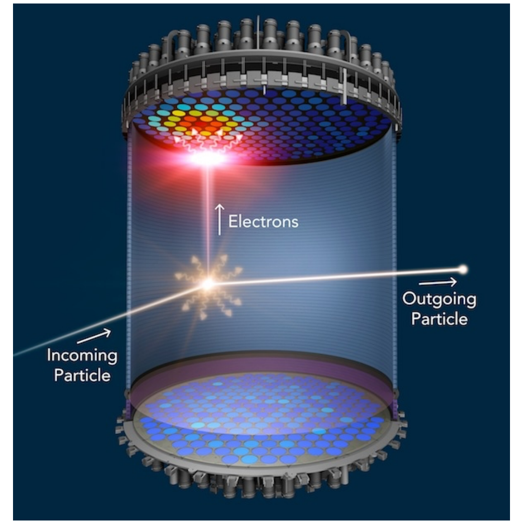
(relatively) Weak direct detection bounds

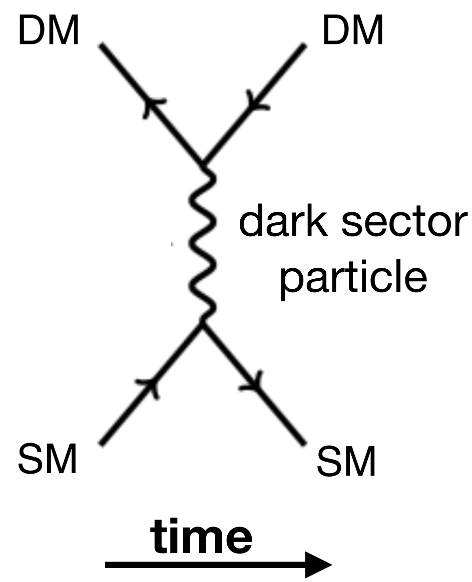
Large detectors search for DM scattering against nuclei/electrons.

Lower energy thresholds for the scattering recoil

→ access to masses above ~few GeV







Dark sectors … beyond Dark Matter

Beyond the Dark Matter motivation,
dark sectors arise in many theories beyond the Standard Model:

- Theories motivated by the hierarchy problem:
  - Supersymmetric theories (Next-to-Minimal-Supersymmetric-Standard-Model)
  - Neutral Naturalness
- Theories to explain the baryon-antibaryon asymmetry
- Theories to address the strong CP problem
- Theories for neutrino masses
- Several anomalies in data can be addressed by dark sectors (eg. $(g-2)_\mu$, B-physics anomalies, …)

Dark sectors … beyond Dark Matter

Beyond the Dark Matter motivation,
dark sectors arise in many theories beyond the Standard Model:

- Theories motivated by the hierarchy problem:
  - Supersymmetric theories (Next-to-Minimal-Supersymmetric-Standard-Model)
  - Neutral Naturalness
- Theories to explain the baryon-antibaryon asymmetry
- Theories to address the strong CP problem
- Theories for neutrino masses
- Several anomalies in data can be addressed by dark sectors (eg. $(g-2)_\mu$, B-physics anomalies, …)

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

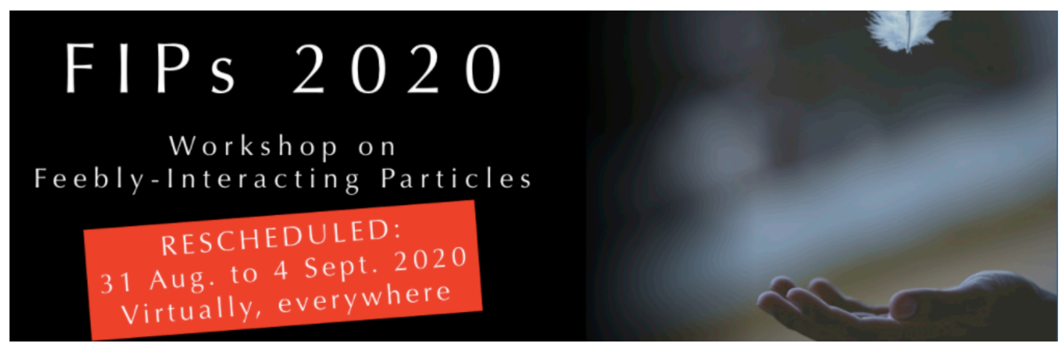
Community effort: the (light) Dark Sector Program

The worldwide search for Dark Sectors has involved hundreds of scientists, new models, dozens of analyses & experiments in last few years


Dark Interactions Workshop, BNL, June 11-13 , 2014


Dark sectors workshop, SLAC, April 28-30, 2016


Light Dark World International Forum 2018
17-21 December 2018
KAIST



Snowmass: dark sectors at high intensities (RF6 group)

Topical conveners: SG (sgori@ucsc.edu), Mike Williams (mwill@mit.edu)

https://snowmass21.org/rare/dark

* To join our **mailing list**: Send an e-mail message to listserv[at]fnal.gov
Leave the subject line blank Type “SUBSCRIBE SNOWMASS-RPF-06-DARK-SECTOR FIRSTNAME LASTNAME”

Or join our **SLACK channel**: #rpf-06-dark-sector

* **We welcome white papers! (by March 15, 2022)**

Snowmass: dark sectors at high intensities (RF6 group)

Topical conveners: SG (sgori@ucsc.edu), Mike Williams (mwill@mit.edu)

https://snowmass21.org/rare/dark

✱ To join our **mailing list**: Send an e-mail message to listserv[at]fnal.gov
Leave the subject line blank Type “SUBSCRIBE SNOWMASS-RPF-06-DARK-SECTOR FIRSTNAME LASTNAME”

Or join our **SLACK channel**: #rpf-06-dark-sector

✱ **We welcome white papers! (by March 15, 2022)**

✱ In addition, we plan **4 solicited white papers focused on “big ideas”:**

1. Detect dark matter particle production (production reaction or through subsequent DM scattering), with a focus on exploring sensitivity to thermal DM interaction strengths.

2. Explore the structure of the dark sector by producing and detecting unstable dark particles: Minimal Portal Interactions.

3. New Flavors and Rich Structures in Dark Sectors.

\+ white paper on experiments/facilities/tools

https://docs.google.com/document/d/1iD2ZZvVoLv3x-RaLtHCo8KGK--2MvSxcn8vrkxtRbWM/edit

Chapter 2

Minimal
dark sector 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?

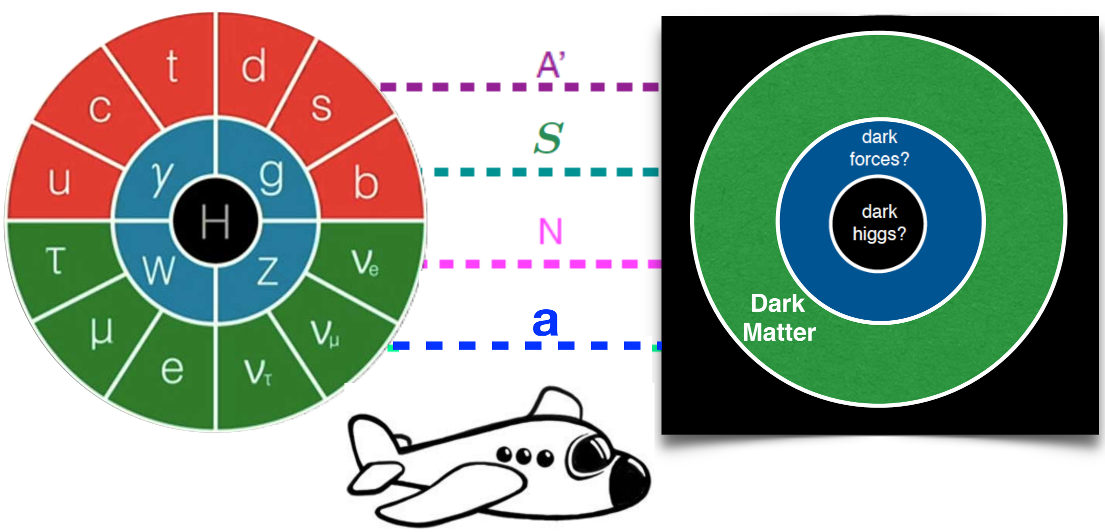
What are the interactions responsible of Dark Matter-SM thermalization?

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?

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



"Portals":

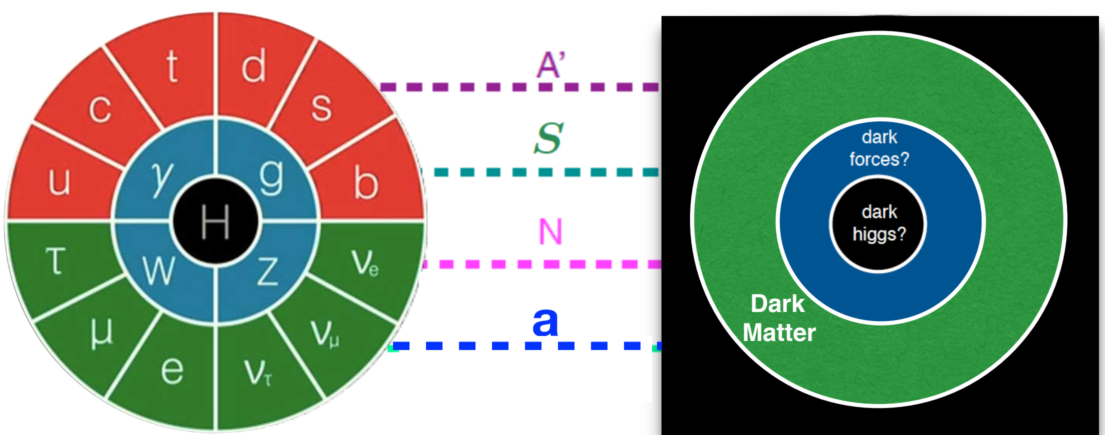
Dark photon	$\epsilon Z^{\mu\nu} A'_{\mu\nu}$
Higgs	$\kappa \lvert H \rvert^2 \lvert S \rvert^2$
Neutrino	$y H L N$
Axion	$\frac{1}{f_s} F_{\mu\nu} \tilde{F}_{\mu\nu} a$

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?

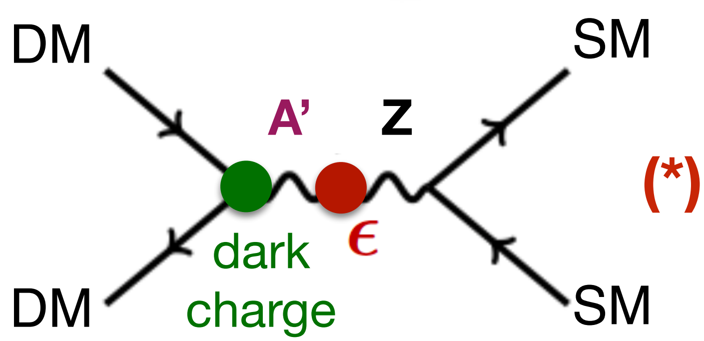
There is only a small set of **"portal"** interactions with the SM



"Portals":

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

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 collider experiments!

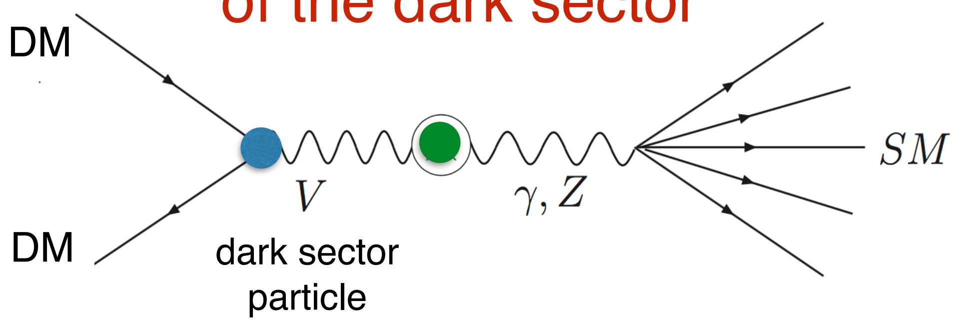
high energy

high intensity

Thermal targets & signatures

Two general classes of thermal DM:

DM is the lightest state
of the dark sector



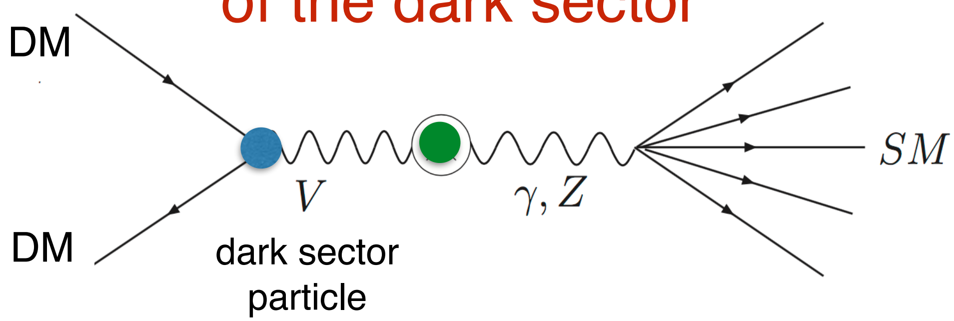
Relic abundance regulated by ●, ●

Thermal targets & signatures

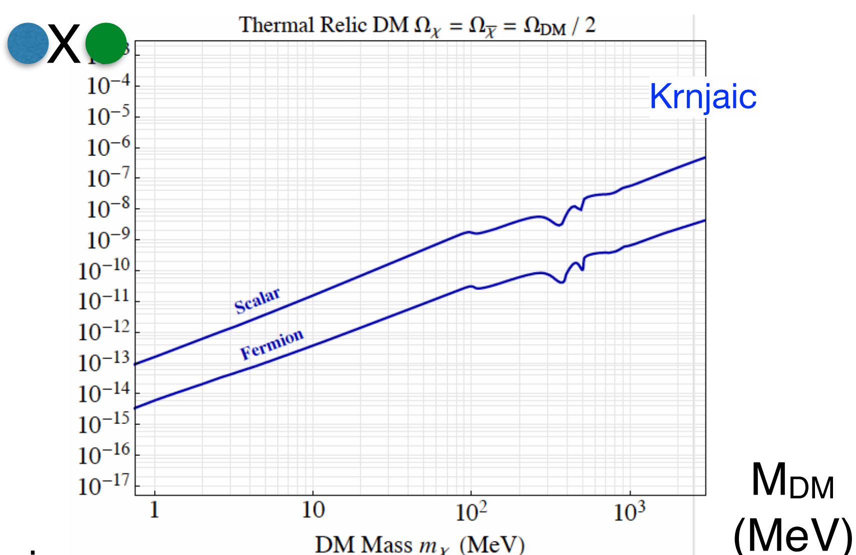
Two general classes of thermal DM:

DM is the lightest state

of the dark sector



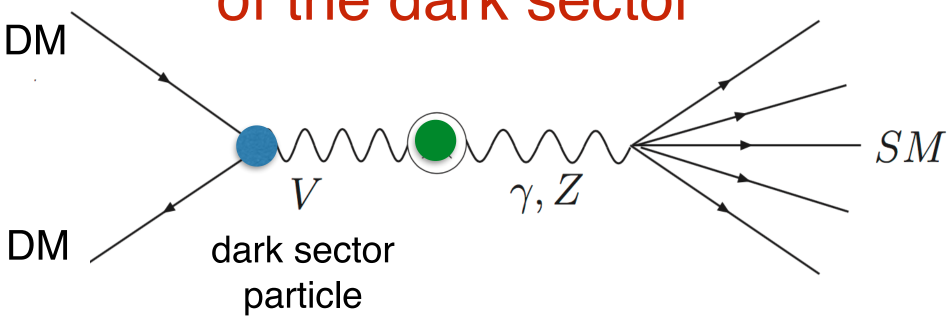
Relic abundance regulated by ●, ●



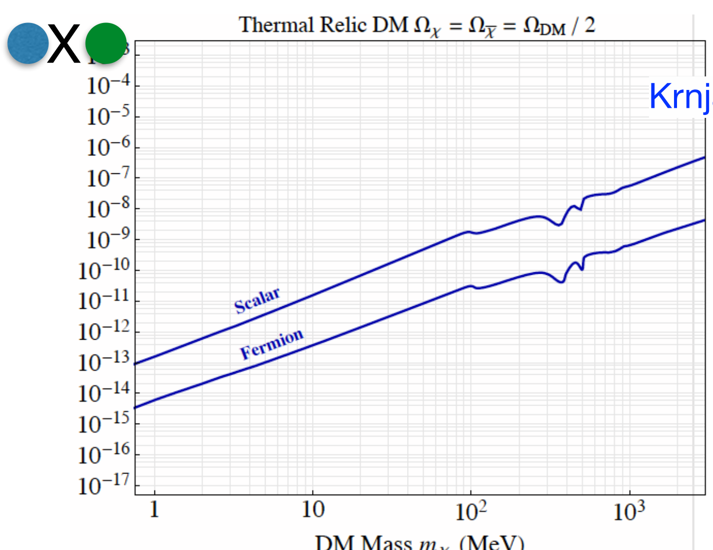
Thermal targets & signatures

Two general classes of thermal DM:

DM is the lightest state of the dark sector



Relic abundance regulated by ●, ●



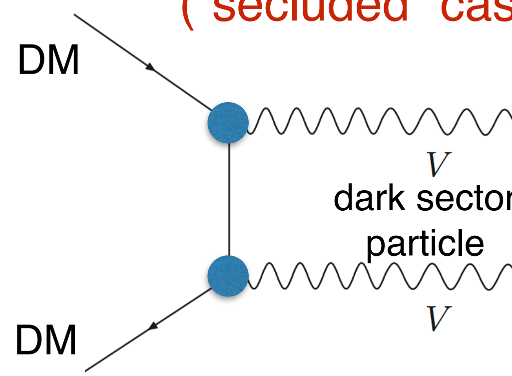
Krnjaic

M_{DM} (MeV)

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

("secluded" case)

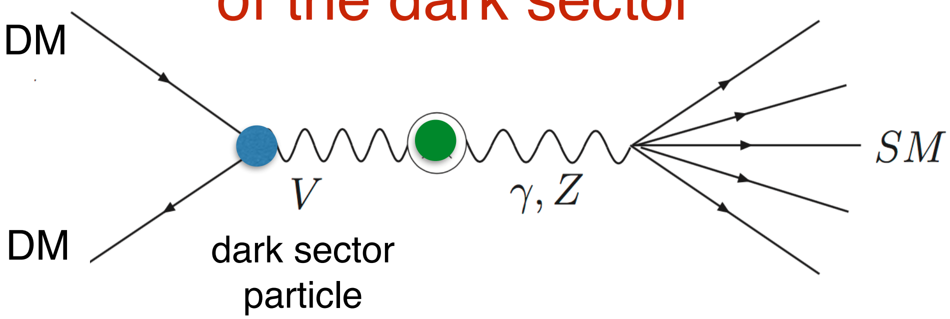
Pospelov, Ritz, Voloshin, 0711.4866



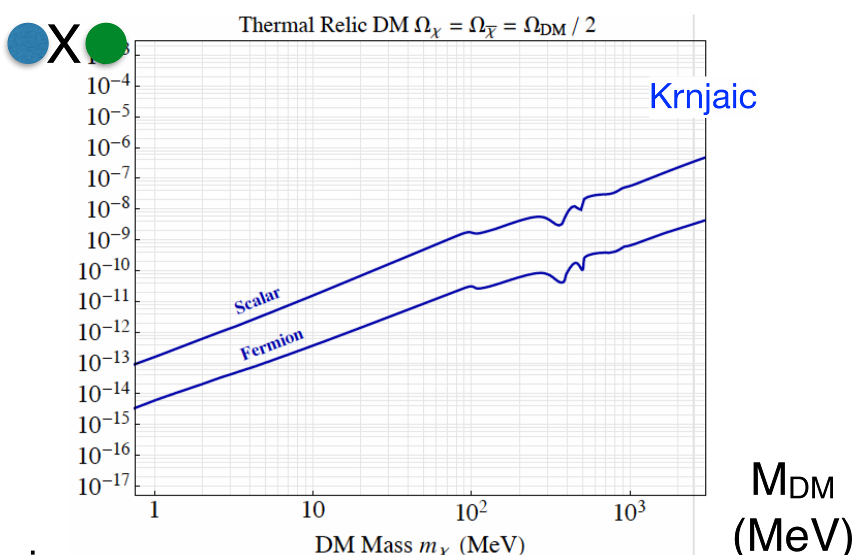
Thermal targets & signatures

Two general classes of thermal DM:

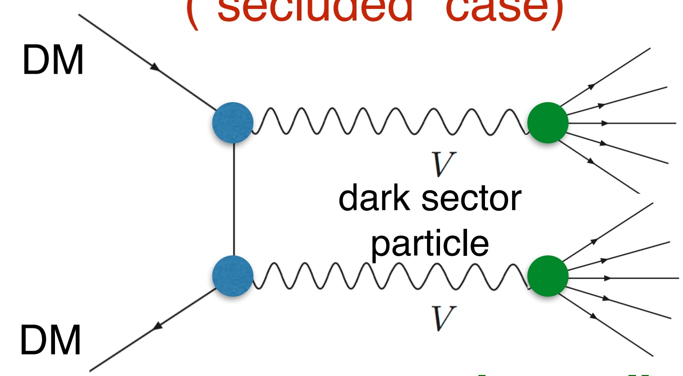
DM is the lightest state
of the dark sector



Relic abundance regulated by ●, ●



One (or more) particles of
the dark sector **are lighter than DM**
("secluded" case)

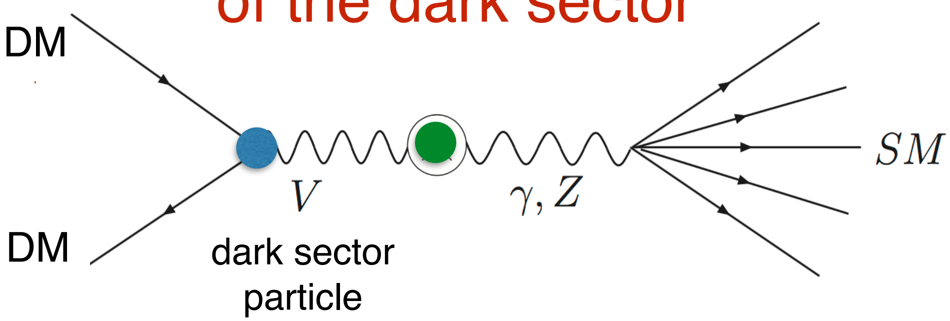


thermalization

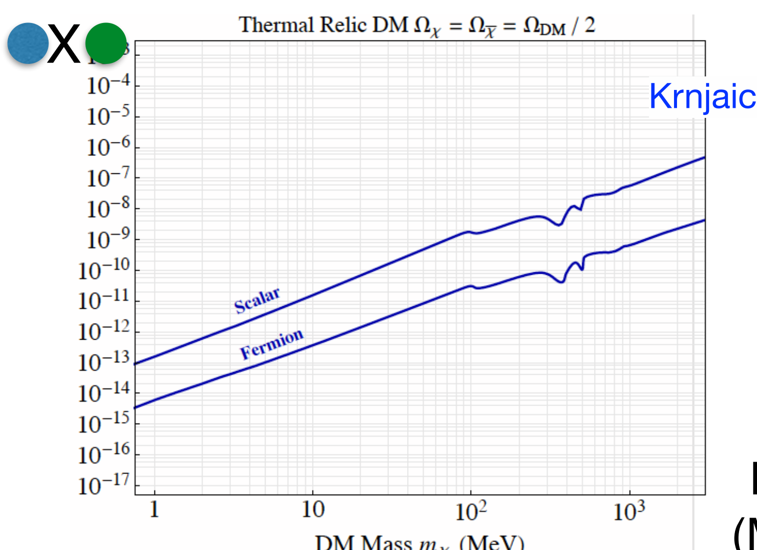
Thermal targets & signatures

Two general classes of thermal DM:

DM is the lightest state of the dark sector



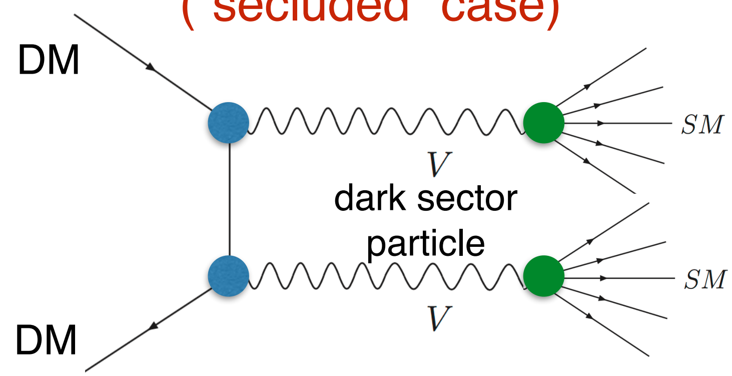
Relic abundance regulated by ●, ●



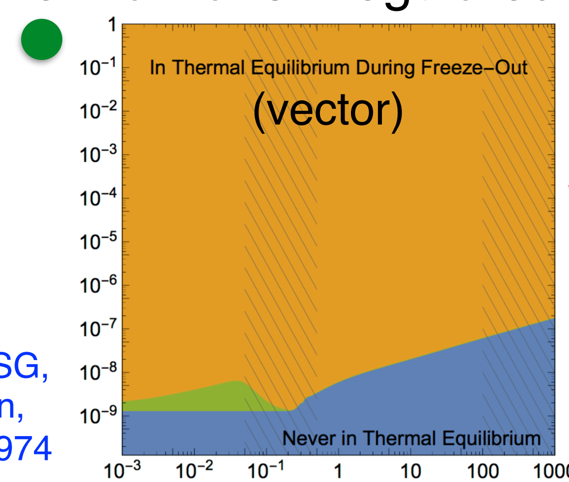
M_{DM} (MeV)

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

("secluded" case)



Thermalization regulated by ●



Lower bound

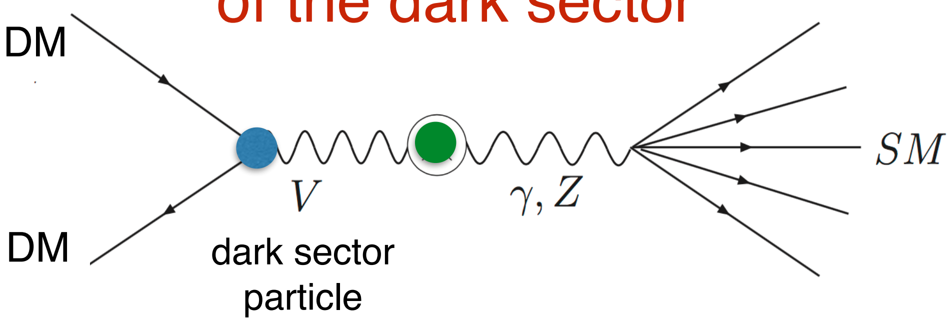
Evans, SG, Shelton, 1712.03974

M_{DM} (GeV)

Thermal targets & signatures

Two general classes of thermal DM:

DM is the lightest state
of the dark sector



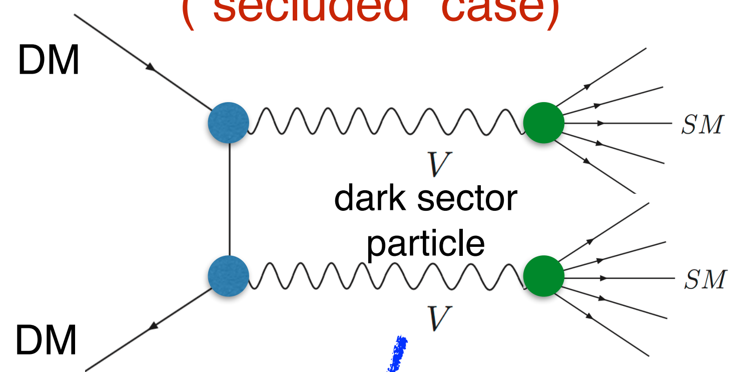
Signatures:

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

V→ DM DM

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

("secluded" case)



Signatures:

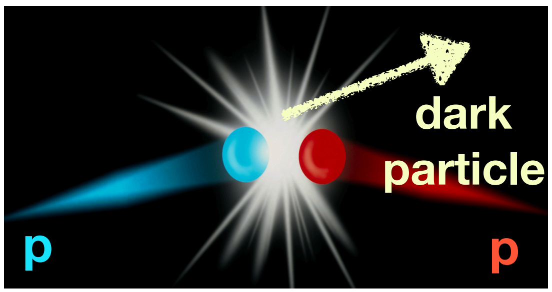
The dark sector particle decays **visible** (to SM particles)

V→ SM SM

A broad program of searches

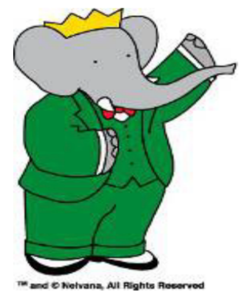
… of light (< few GeV) dark-sector particles

The LHC



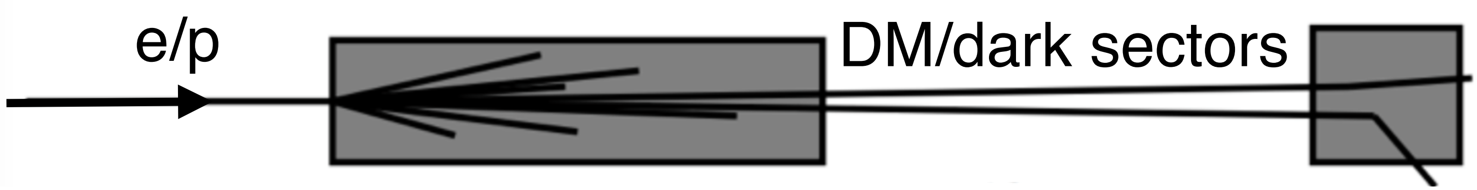
Novel search strategies are needed!

B-factories



Unique access to dark sectors!

Fixed target experiments

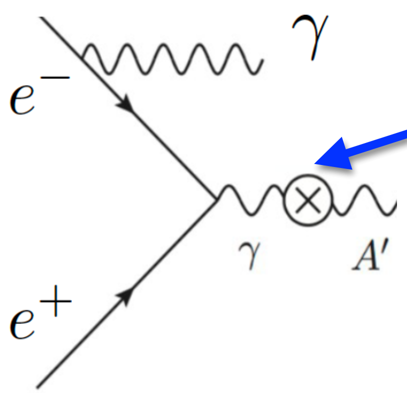


Beam (high intensity) **Dump/shield** **Decay volume** **Detector**

Invisible signatures.

Example scenario: invisible dark photon

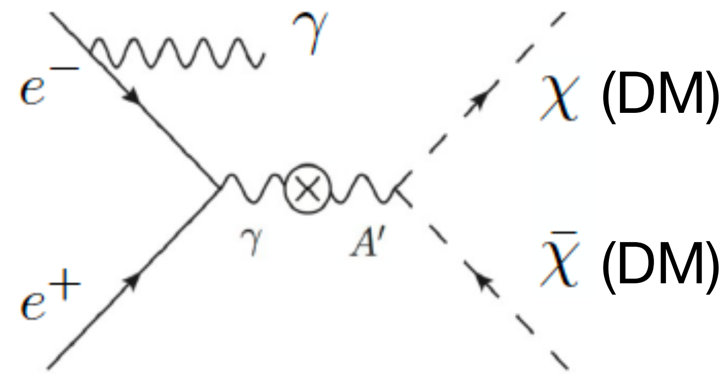
Production of a dark photon at B-factories:



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

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

Decay of the dark photon:

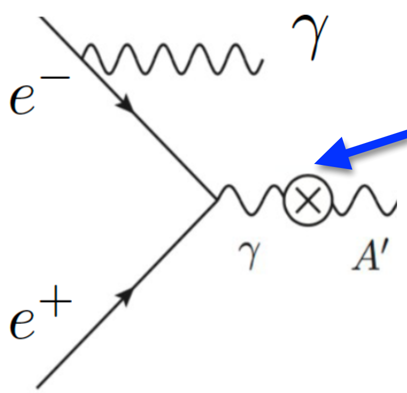


photon + invisible

Invisible signatures.

Example scenario: invisible dark photon

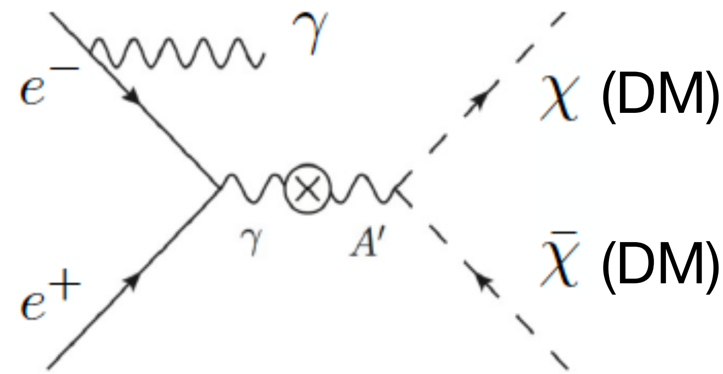
Production of a dark photon at B-factories:



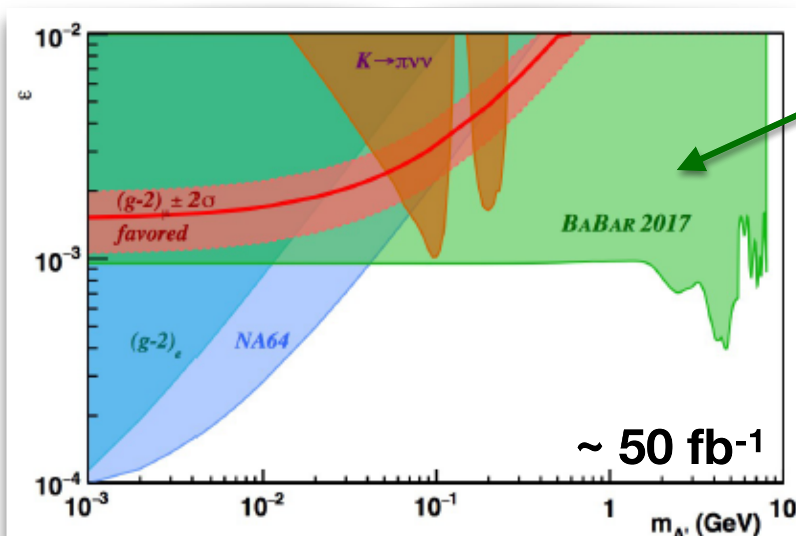
$$\epsilon Z^{\mu\nu} A'_{\mu\nu}$$

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

Decay of the dark photon:



photon + invisible



Babar search

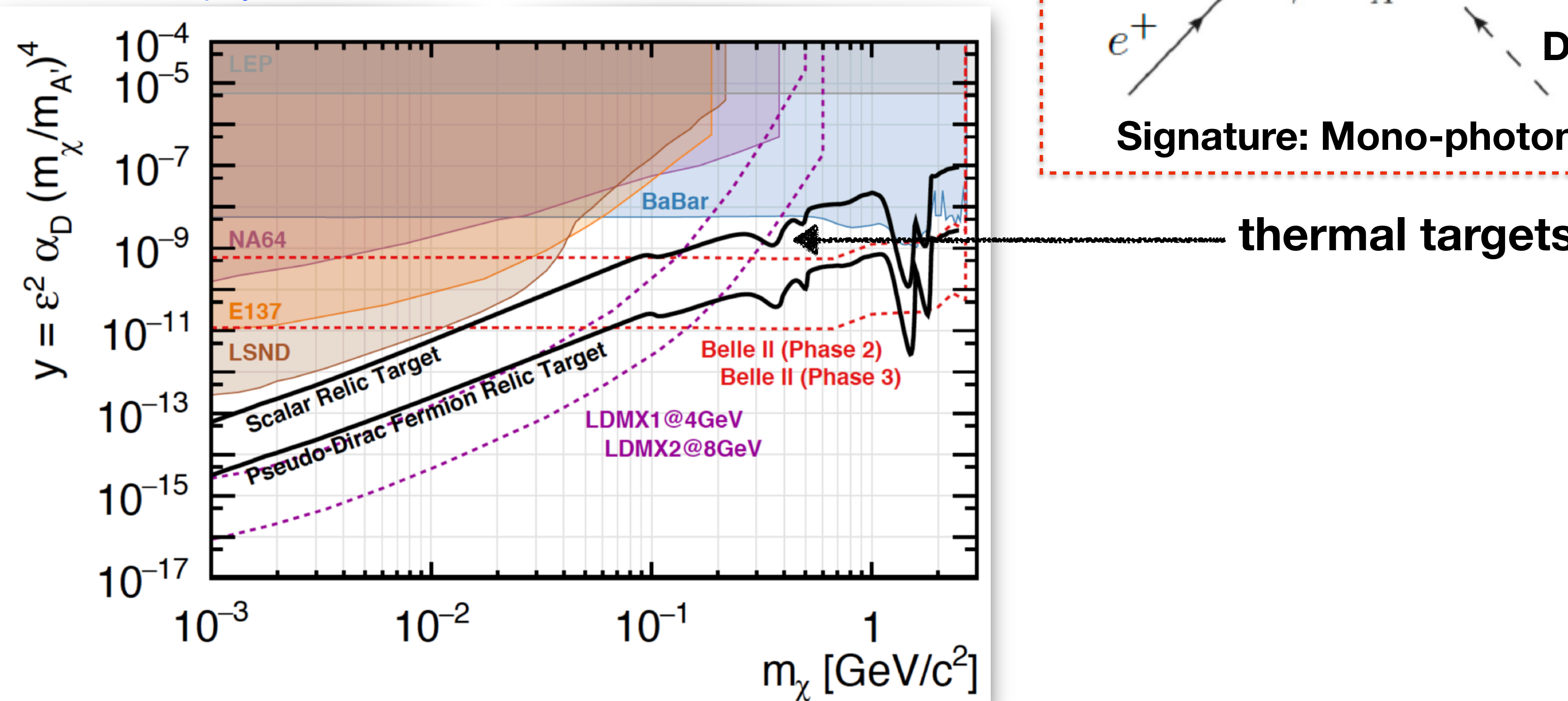
This analysis excludes the entire region favored by $(g\text{-}2)_\mu$!

single-photon trigger

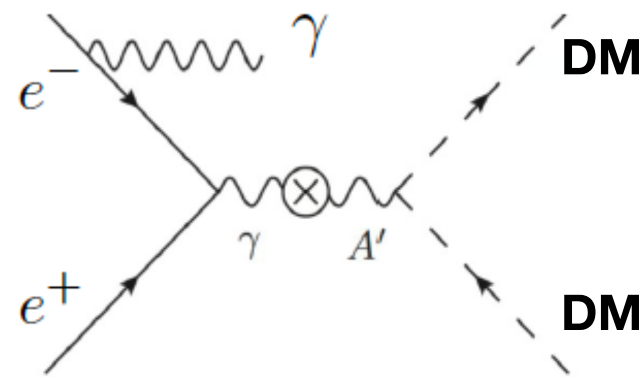
NA64: PRL 118 (2017) 011802

Belle-II reach? & thermal targets

The Belle-II physics book, 1808.10567



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

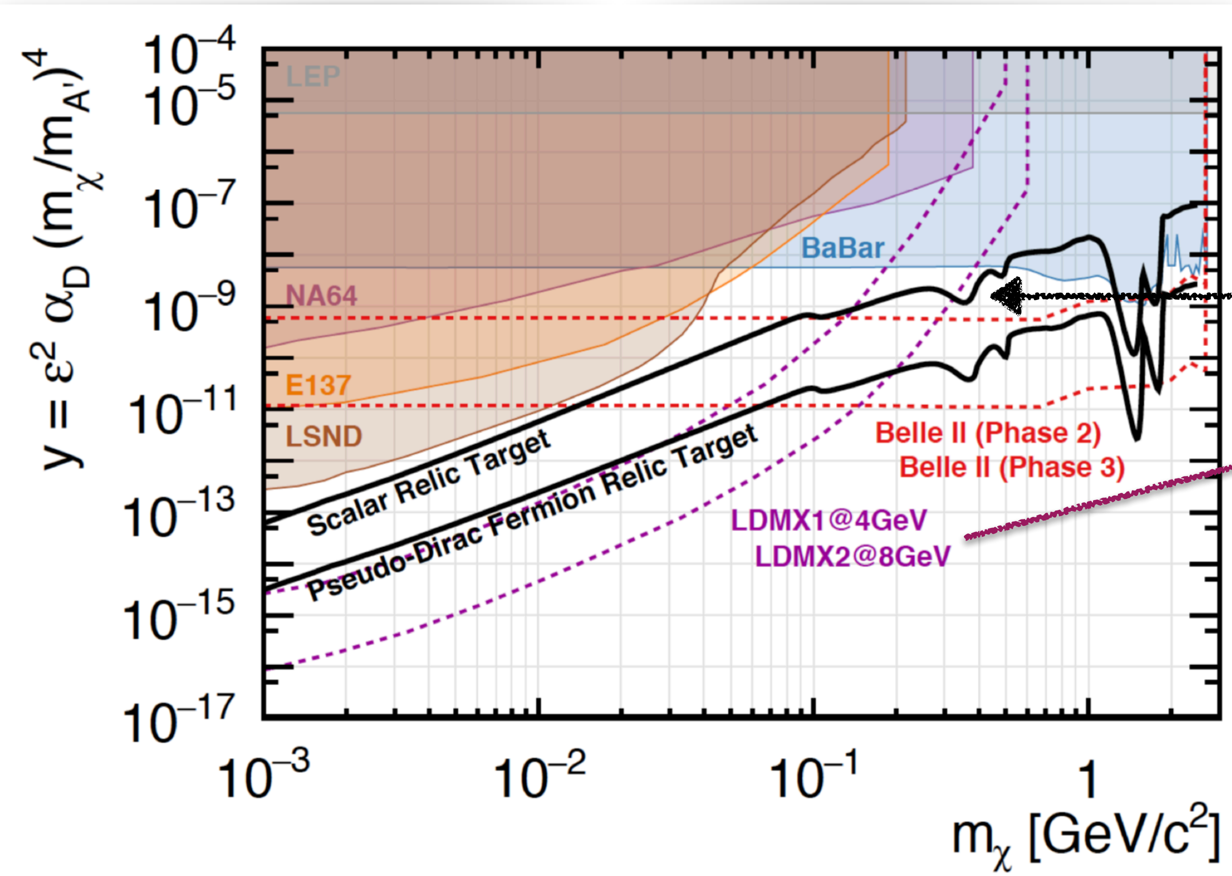


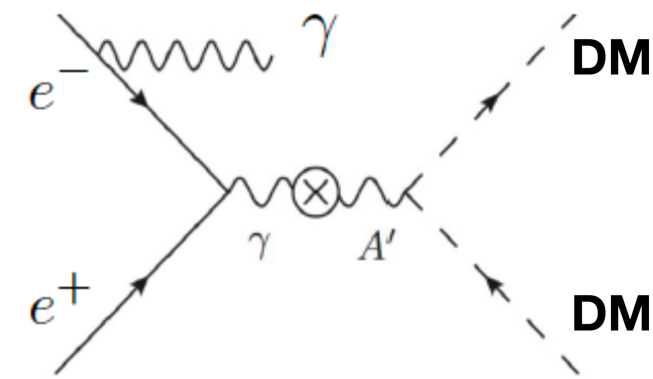
Signature: Mono-photon

Belle-II reach? & thermal targets

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

The Belle-II physics book, 1808.10567

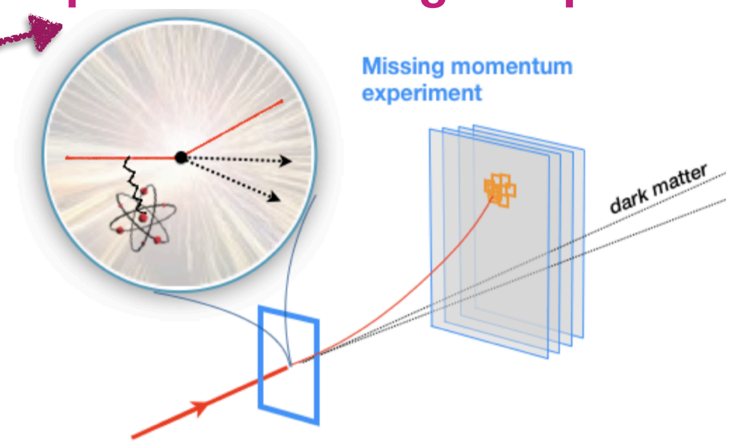




Signature: Mono-photon

thermal targets

Proposed fixed target experiment:

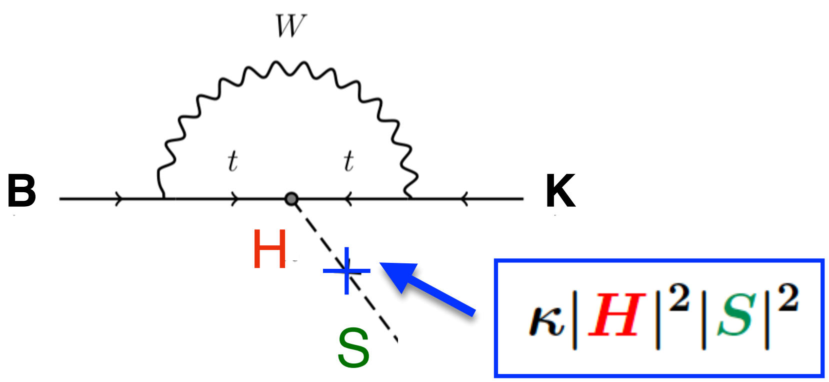


From the DOE "Basic research needs for Dark Matter Small Projects New Initiatives"

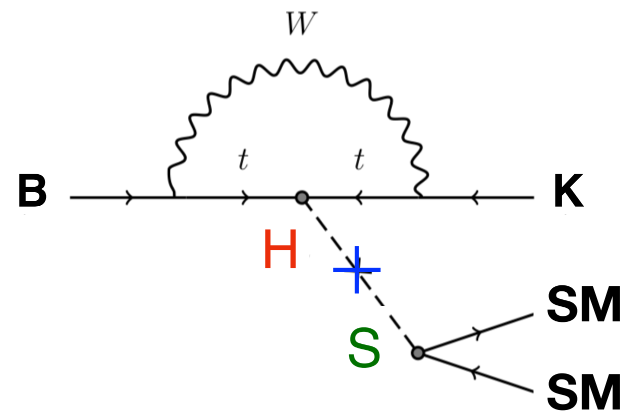
Visible signatures.

Example scenario: visible dark scalar

Production of a dark scalar
at B-factories:



Decay of the dark scalar:

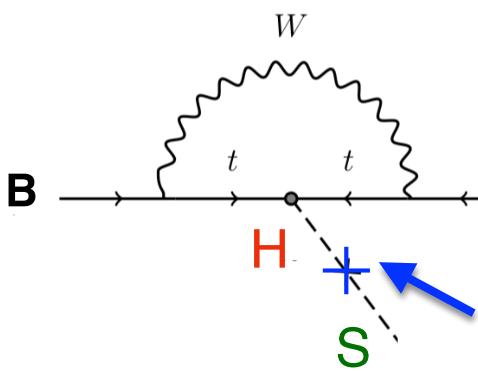


B→KS→Kμμ

Visible signatures.

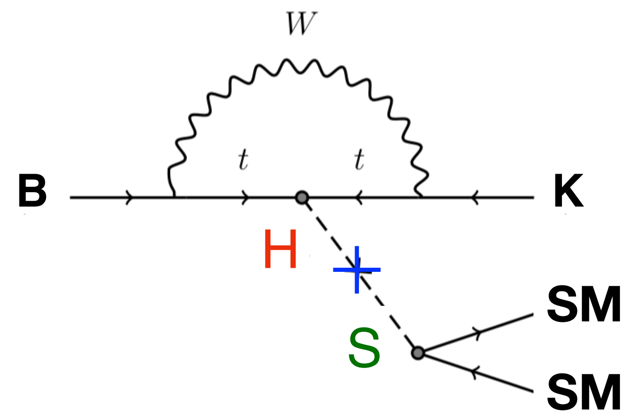
Example scenario: visible dark scalar

Production of a dark scalar
at B-factories:

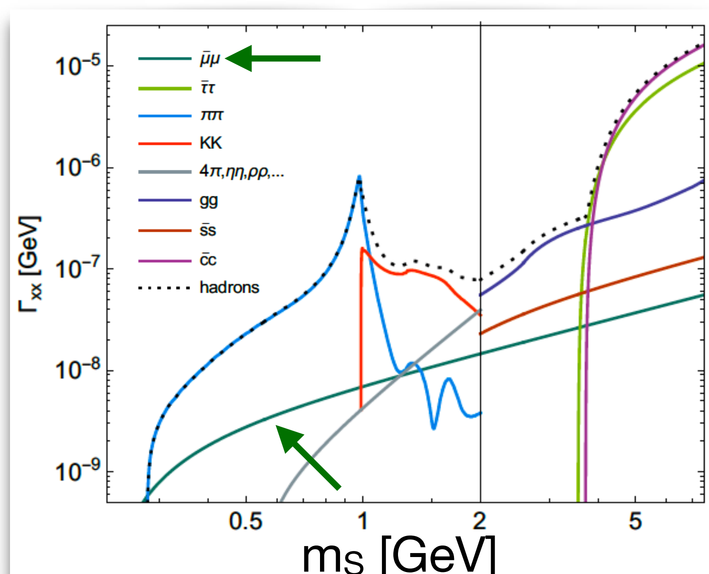


$\boxed{\kappa|H|^2|S|^2}$

Decay of the dark scalar:



B→KS→Kμμ

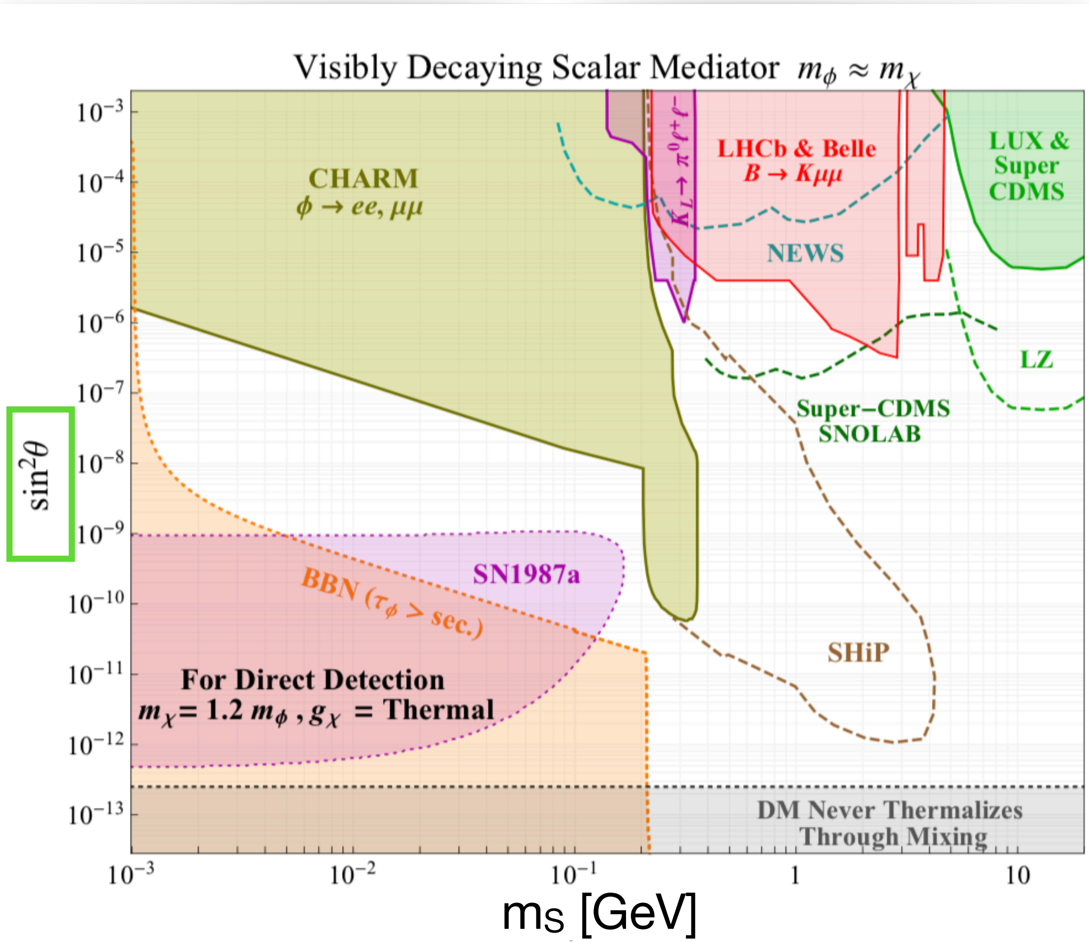


Winkler, 1809.01876

Sizable theoretical uncertainties
in the calculations
of the several scalar widths

Bounds on visible scalars

Krnjaic, 1512.04119



$$\boxed{\kappa |H|^2 |S|^2}$$

$\Downarrow$

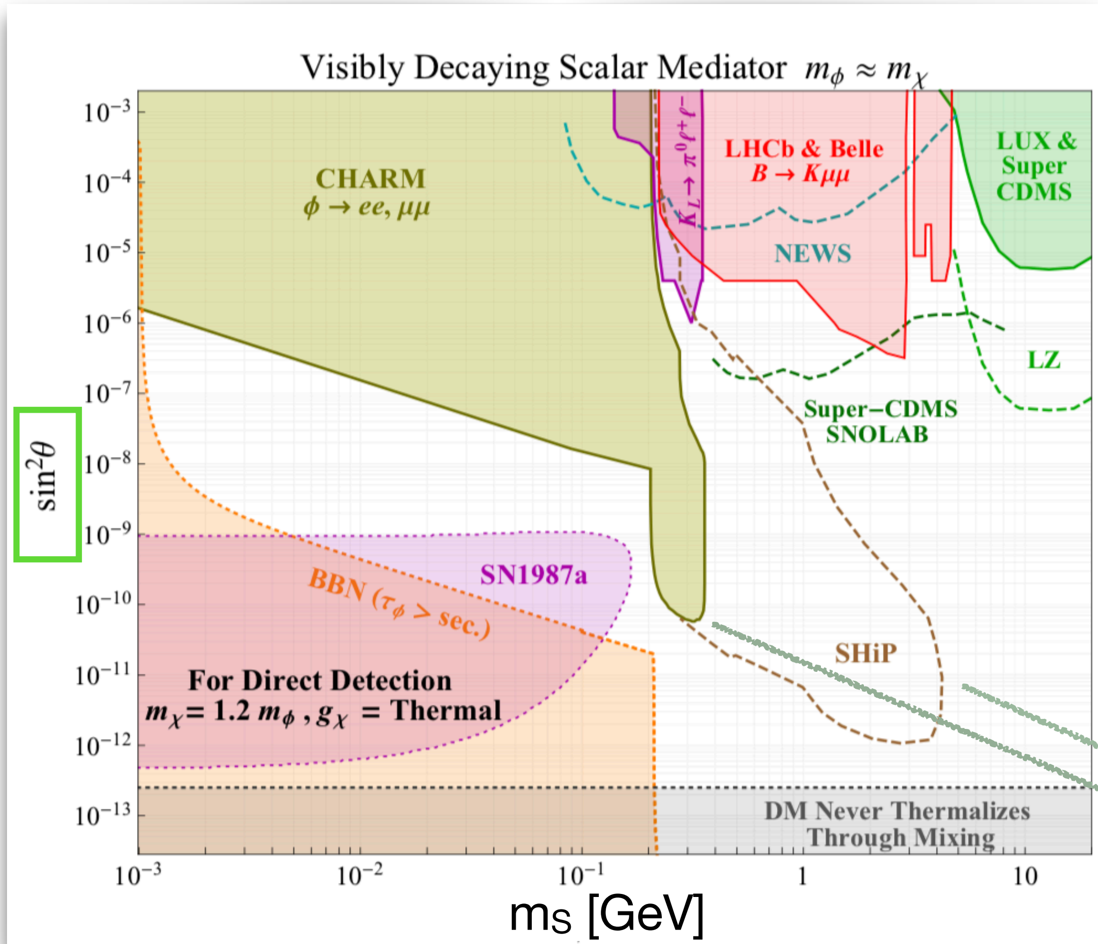
Electroweak symmetry breaking:
If the scalar, S, gets a VEV,
then it will mix with the SM Higgs:

$$\boxed{\tan\theta} \propto \frac{\kappa v_h v_S}{m_h^2 - m_S^2}$$

Belle-II reach?

Bounds on visible scalars

Krnjaic, 1512.04119

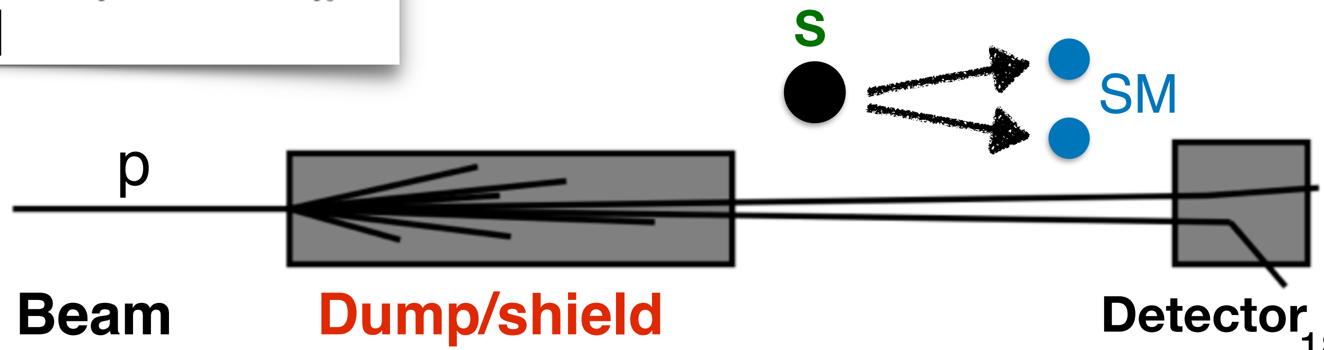


$$\boxed{\kappa |H|^2 |S|^2}$$

Electroweak symmetry breaking:
If the scalar, S, gets a VEV,
then it will mix with the SM Higgs:

$$\boxed{\tan\theta} \propto \frac{\kappa v_h v_S}{m_h^2 - m_S^2}$$

Past and future
(proton) beam dump experiments



Belle-II reach?

Chapter 3

Rich dark sector structures

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

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)

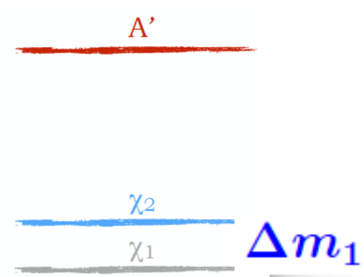
$$-\mathcal{L} \supset m_D\, \eta\, \xi + \frac{1}{2}\, \delta_\eta\, \eta^2 + \frac{1}{2}\, \delta_\xi\, \xi^2 + \mathrm{h.c.}$$

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 ($\delta_{\eta,\xi} \ll m_D$):

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

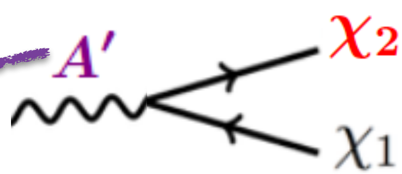
Two states close in mass: $\Delta \equiv \dfrac{m_2 - m_1}{m_1} \sim \dfrac{\delta_\xi + \delta_\eta}{m_D} \ll 1$

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

IDM displaced signatures

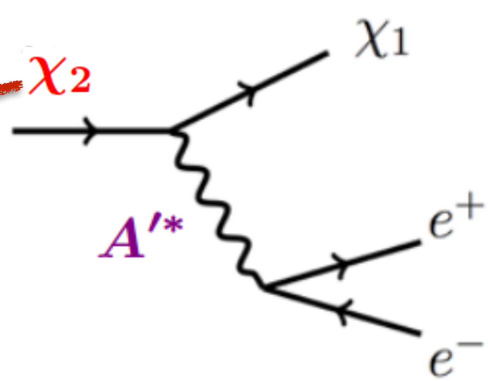
IDMs are rather hidden to direct detection experiments
Also CMB constraints are relaxed
The prime avenue to probe IDM is at high intensity experiments

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



Copiously produced at
high intensity experiments

with



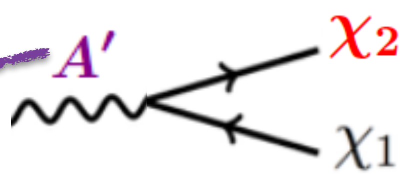
$$\Gamma(\chi_2 \to \chi_1 e^+ e^-) \simeq \frac{4\epsilon^2\, \alpha_{\rm em}\, \alpha_D\, \Delta^5 m_1^5}{15\pi m_{A'}^4}$$

Non-resonant decays

IDM displaced signatures

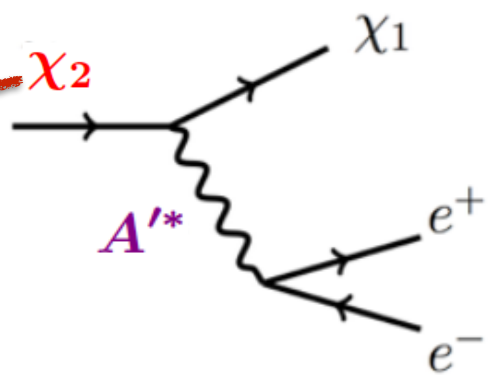
IDMs are rather hidden to <u>direct detection experiments</u>
Also <u>CMB</u> constraints are relaxed
The prime avenue to probe IDM is at high intensity experiments?

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



Copiously produced at high intensity experiments

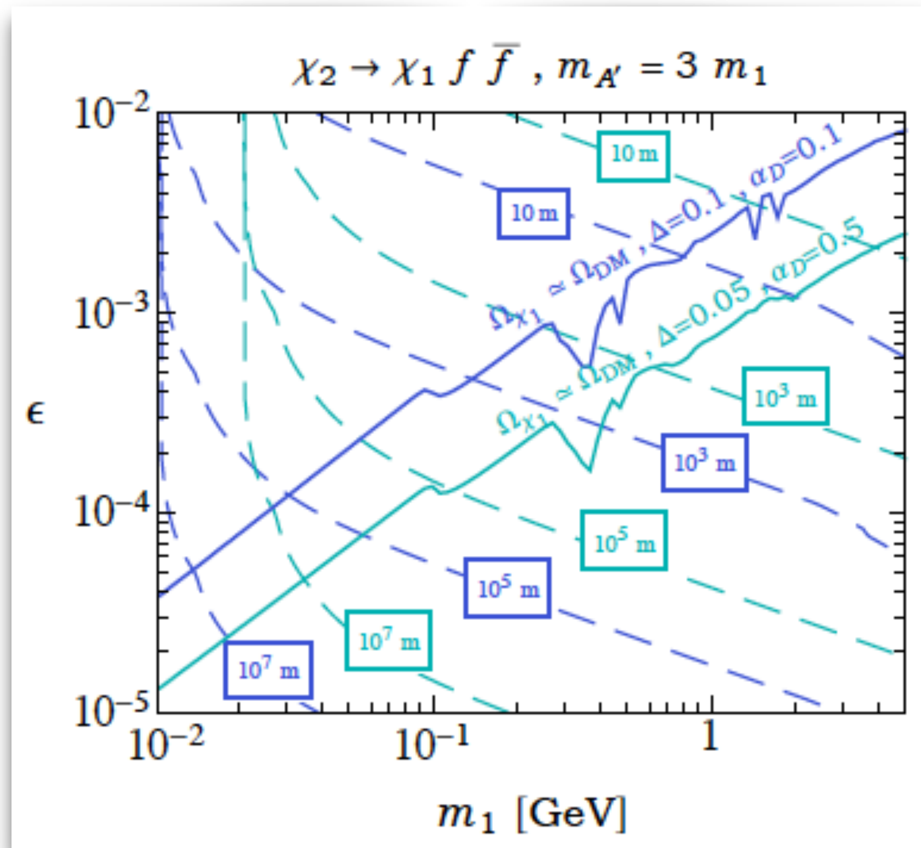
with



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

Non-resonant decays

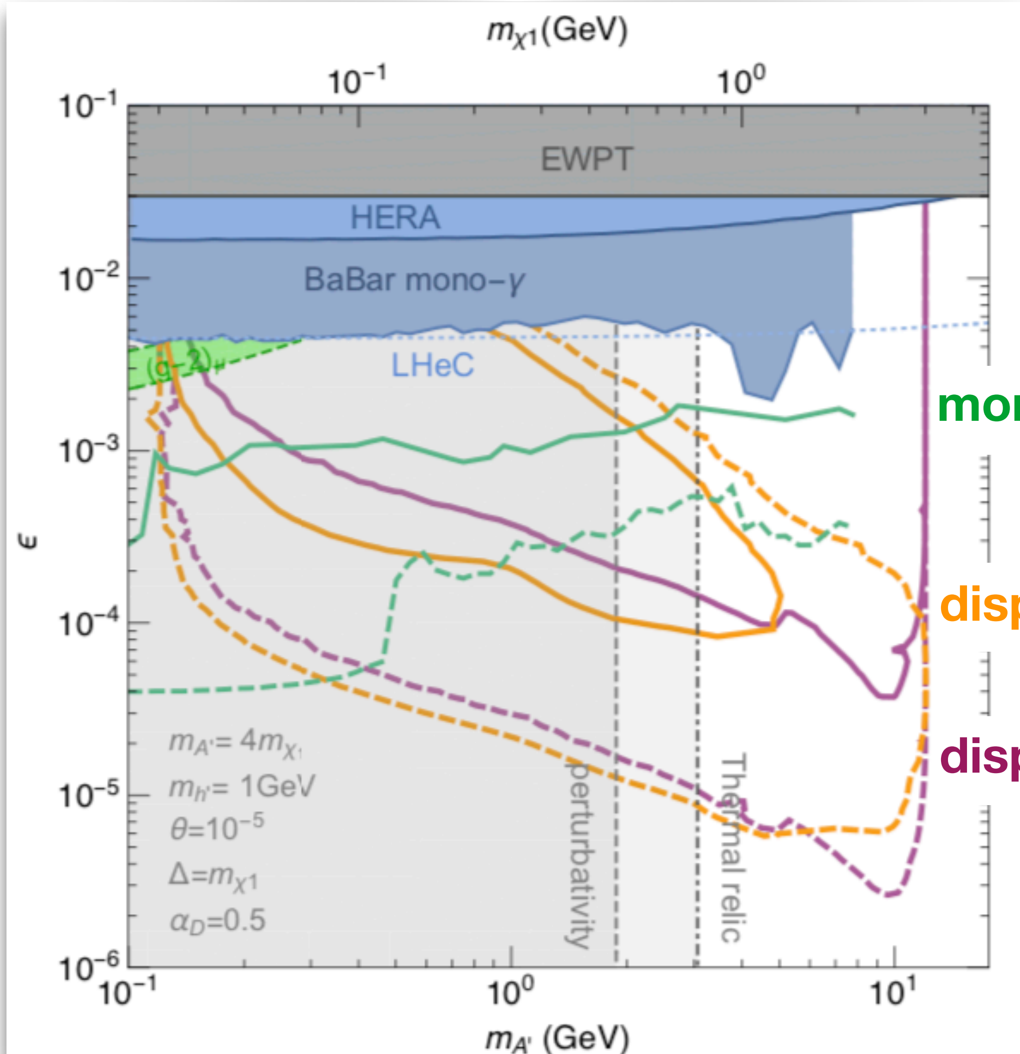
Berlin, SG, Schuster, Toro, 1804.00661



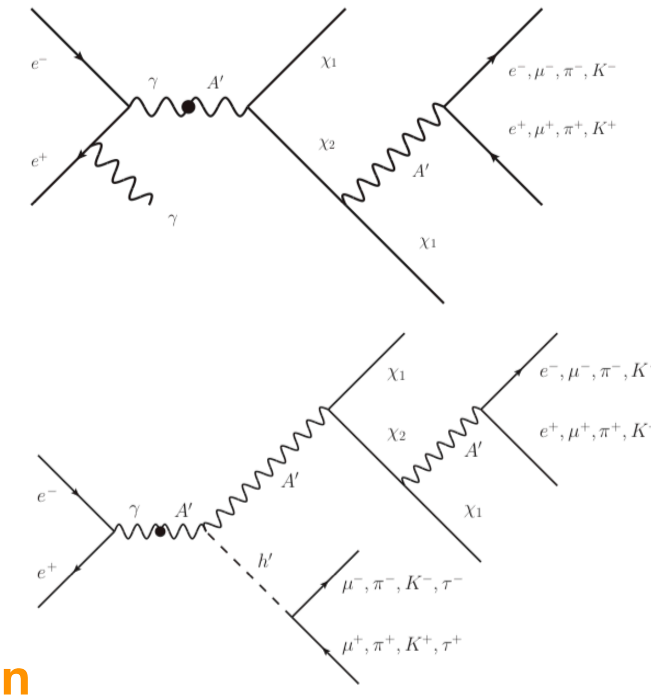
Displaced decays

The Belle II IDM reach

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



— 100/fb
······· 50/ab



mono-photon

displaced+photon

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

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

"0.9 cm < Rxy < 60cm, and a transverse momentum of the corresponding particles of pT > 100 MeV each"

Strongly interacting massive particle DM

Dark Matter can reside in a dark-QCD sector. DM = lightest dark pions

A new annihilation mechanism can lead to the measured relic abundance: $3\pi_D \to 2\pi_D$

These models can address several small scale structure issues (core-cusp problem, too big to fail problem, …) thanks to the DM self-interaction

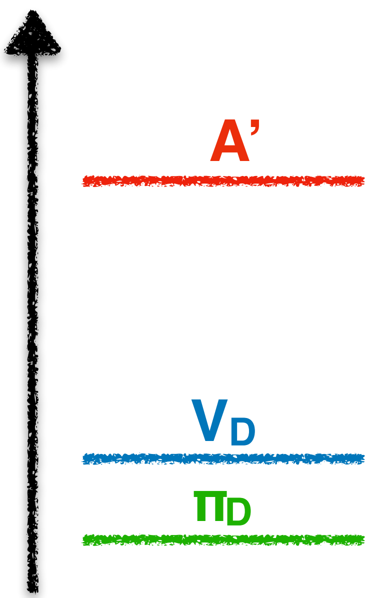
Strongly interacting massive particle DM

Dark Matter can reside in a dark-QCD sector. DM = lightest dark pions

A new annihilation mechanism can lead to the measured relic abundance: $3\pi_D \rightarrow 2\pi_D$

These models can address several small scale structure issues (core-cusp problem, too big to fail problem, …) thanks to the DM self-interaction

Similar signatures as in the IDM models

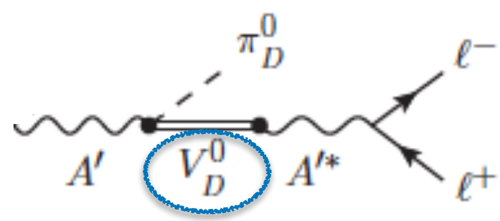


like the rho meson of the SM

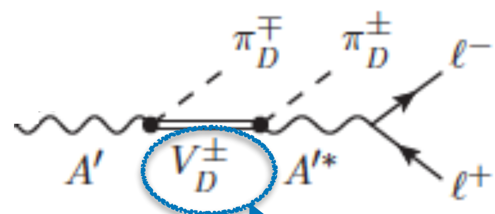
DM

Belle-II reach?

Berlin, Blinov, SG, Schuster, Toro, 1801.05805



Missing energy



V_D has displaced decays

Conclusions

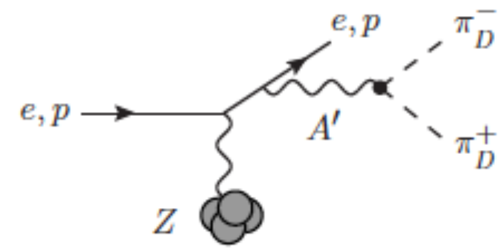
New lamppost for <u>Dark Matter</u> theories:
Thermal dark sectors

Many additional theoretical motivations dark sectors below the electroweak scale

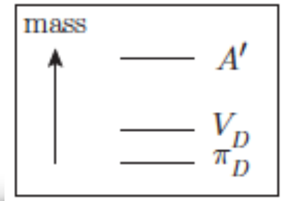
- **Broad range of interesting theoretical models (minimal & non-minimal)**
- **Many new searches can be performed in the future by the <u>Belle II</u> collaboration**
- **Complementarity with present and future <u>fixed target experiments</u>**
- **Importance of targeted triggers**

SIMP decays of the dark photon

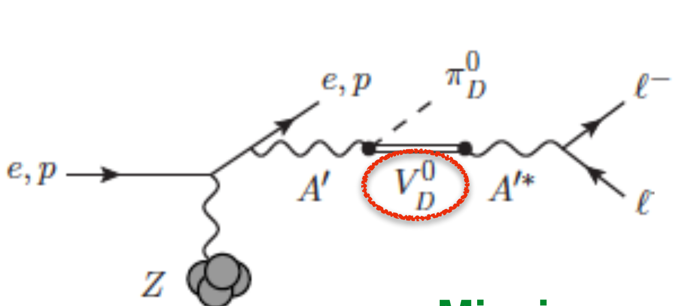
$A' \to \pi_D^+ \pi_D^-$ (DM)



Invisible
A' decay

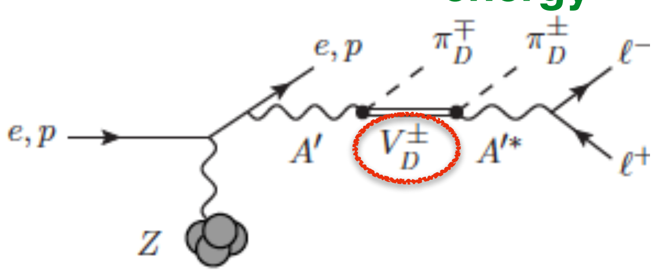


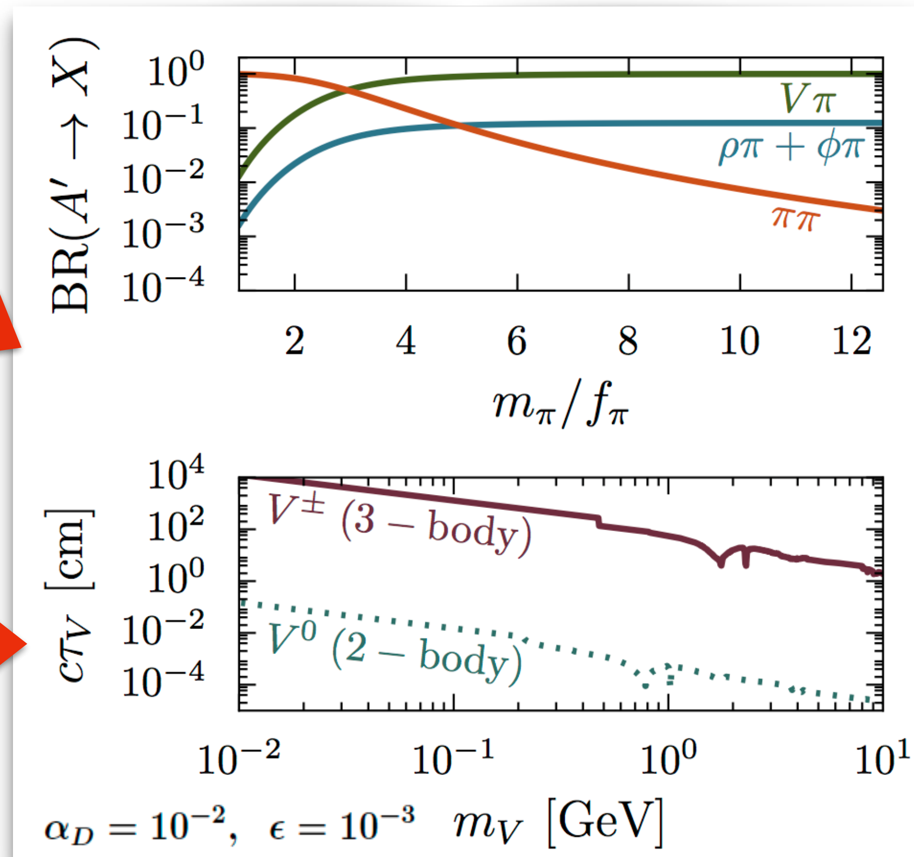
Berlin, Blinov, SG, Schuster, Toro, 1801.05805



Missing
energy

Visible
A' decay





$A' \to \pi_D V_D$

Displaced decays of the dark vector