



Ana Luisa Foguel

based on [arXiv:2510.26765](https://arxiv.org/abs/2510.26765) [accepted at JHEP]

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Vector dark matter with non-abelian kinetic mixing

60th Rencontres de Moriond - EW+U 2026

18 March 2026

Introduction and Motivations

The Standard Model

DM ??

three generations of matter (fermions)			interactions / force carriers (bosons)	
I	II	III		
u (2.2 MeV/c ²) up	c (1.28 GeV/c ²) charm	t (172.1 GeV/c ²) top	g (0) gluon	H (124.97 GeV/c ²) higgs
d (-4.7 MeV/c ²) down	s (-96 MeV/c ²) strange	b (-4.18 GeV/c ²) bottom	γ (0) photon	
e (-0.511 MeV/c ²) electron	μ (-105.66 MeV/c ²) muon	τ (-1.7768 GeV/c ²) tau	Z (91.1876 GeV/c ²) Z boson	
ν _e (0) electron neutrino	ν _μ (0) muon neutrino	ν _τ (0) tau neutrino	W (80.379 GeV/c ²) W boson	



Gravity = (Gauge)² ?

new Higgs resonance, now for real...

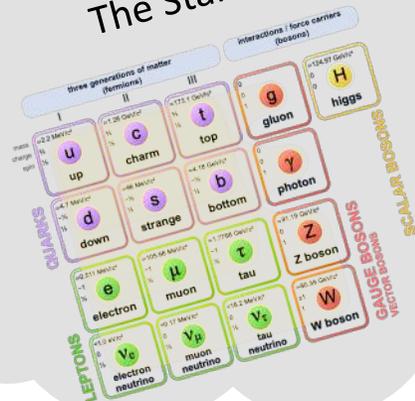
π = 3?

negative neutrino masses... humm

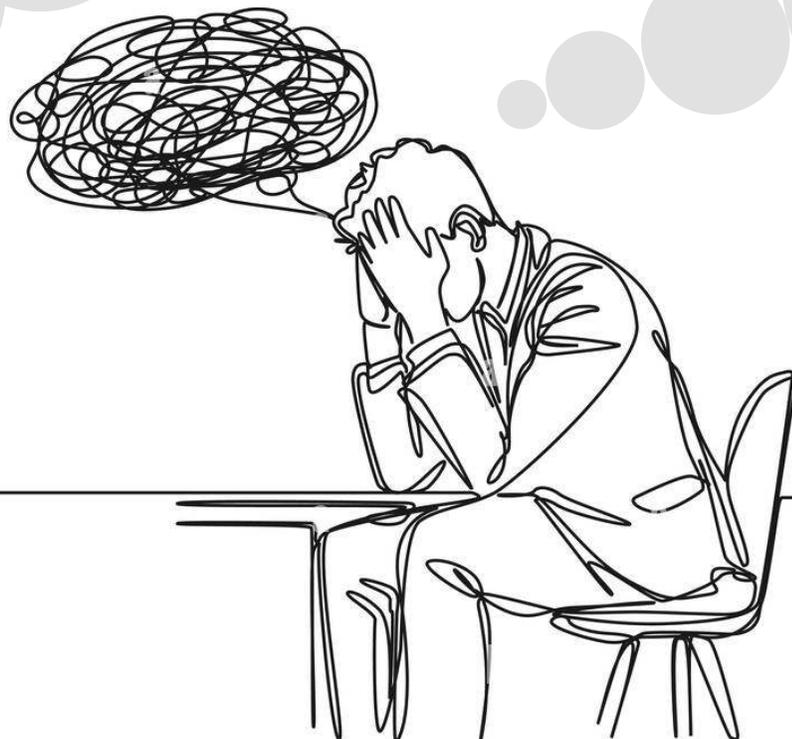
pizza places:
+34 68767942
+34 67524012

Introduction and Motivations

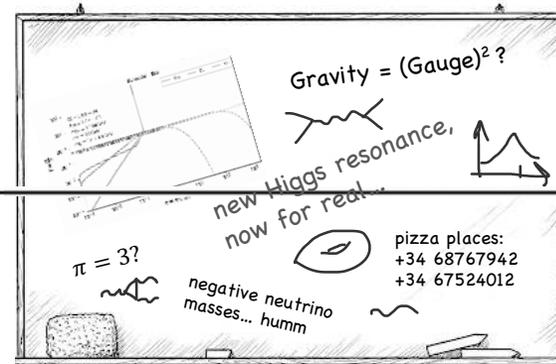
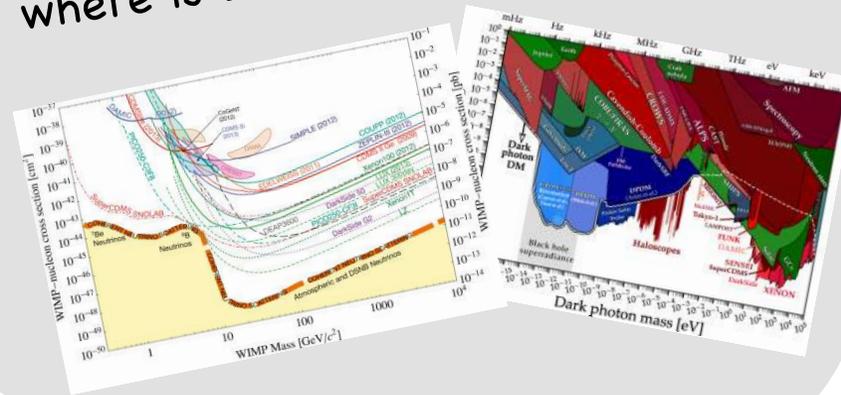
The Standard Model



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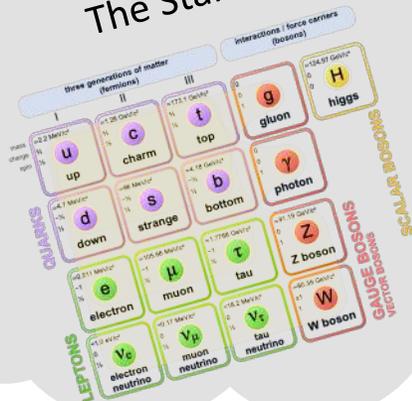


where is New Physics?
where is DM???



Introduction and Motivations

The Standard Model

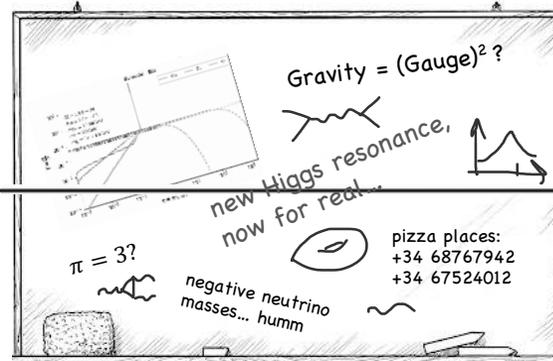
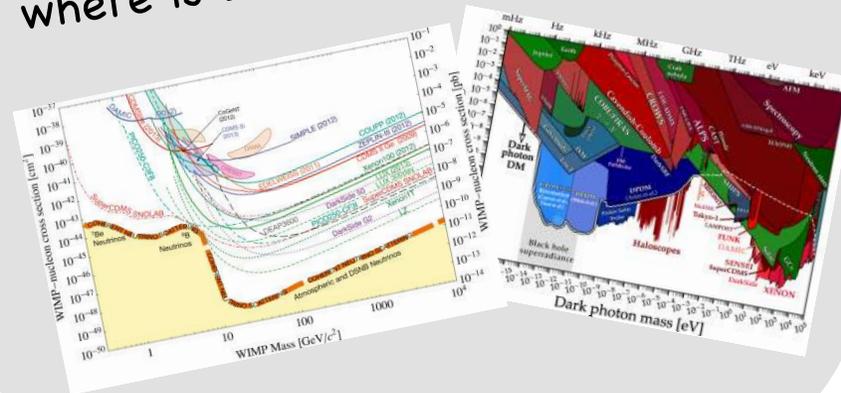


DM ??

and what about...
neutrino masses?
BAU? Hierarchy problem?
Strong CP?

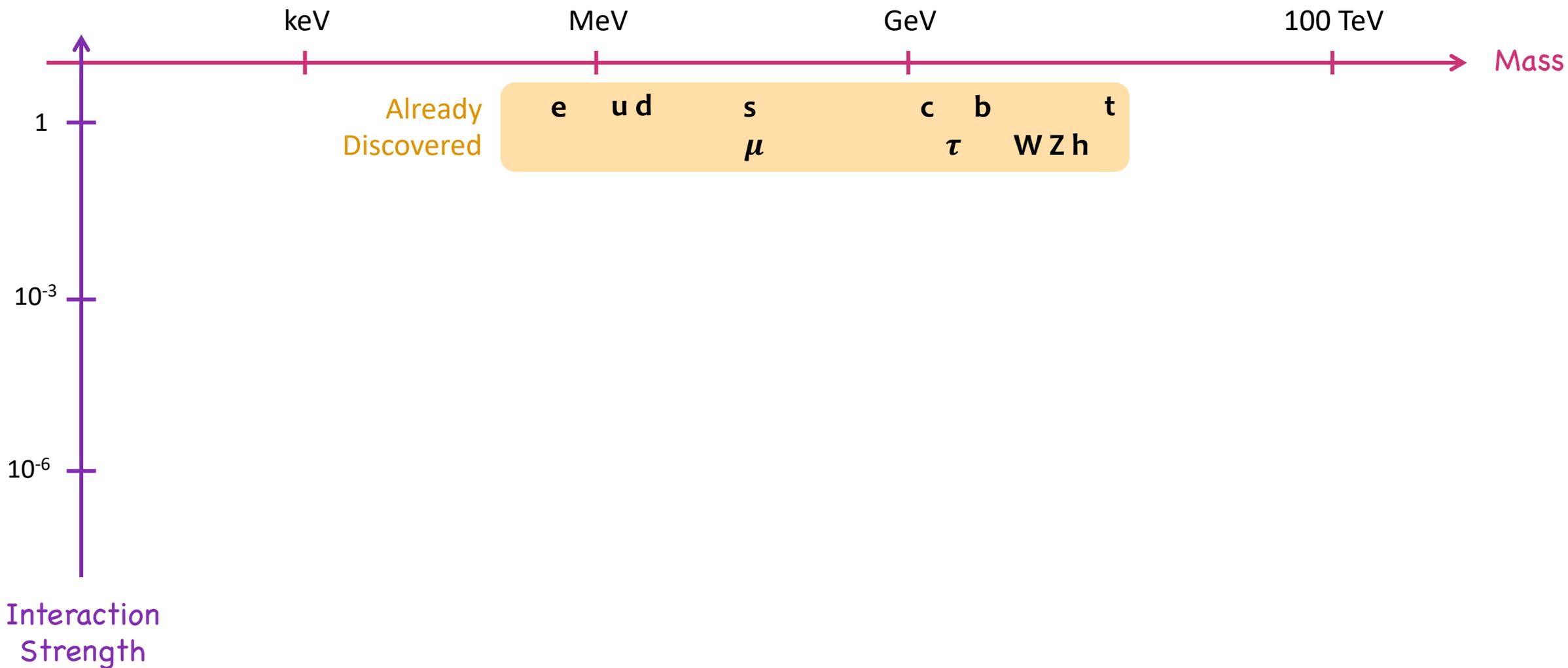


where is New Physics?
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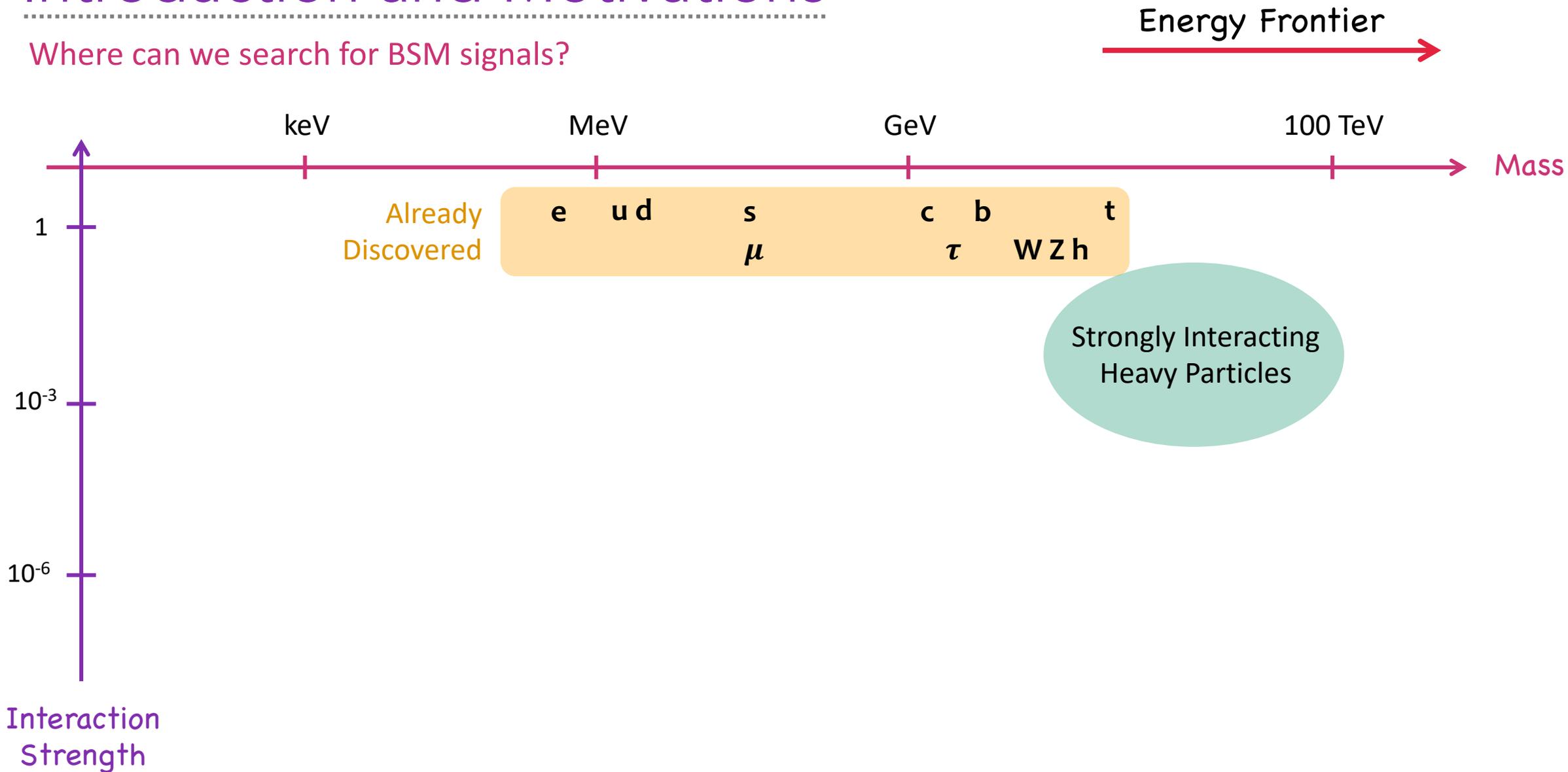
Introduction and Motivations

Where can we search for BSM signals?



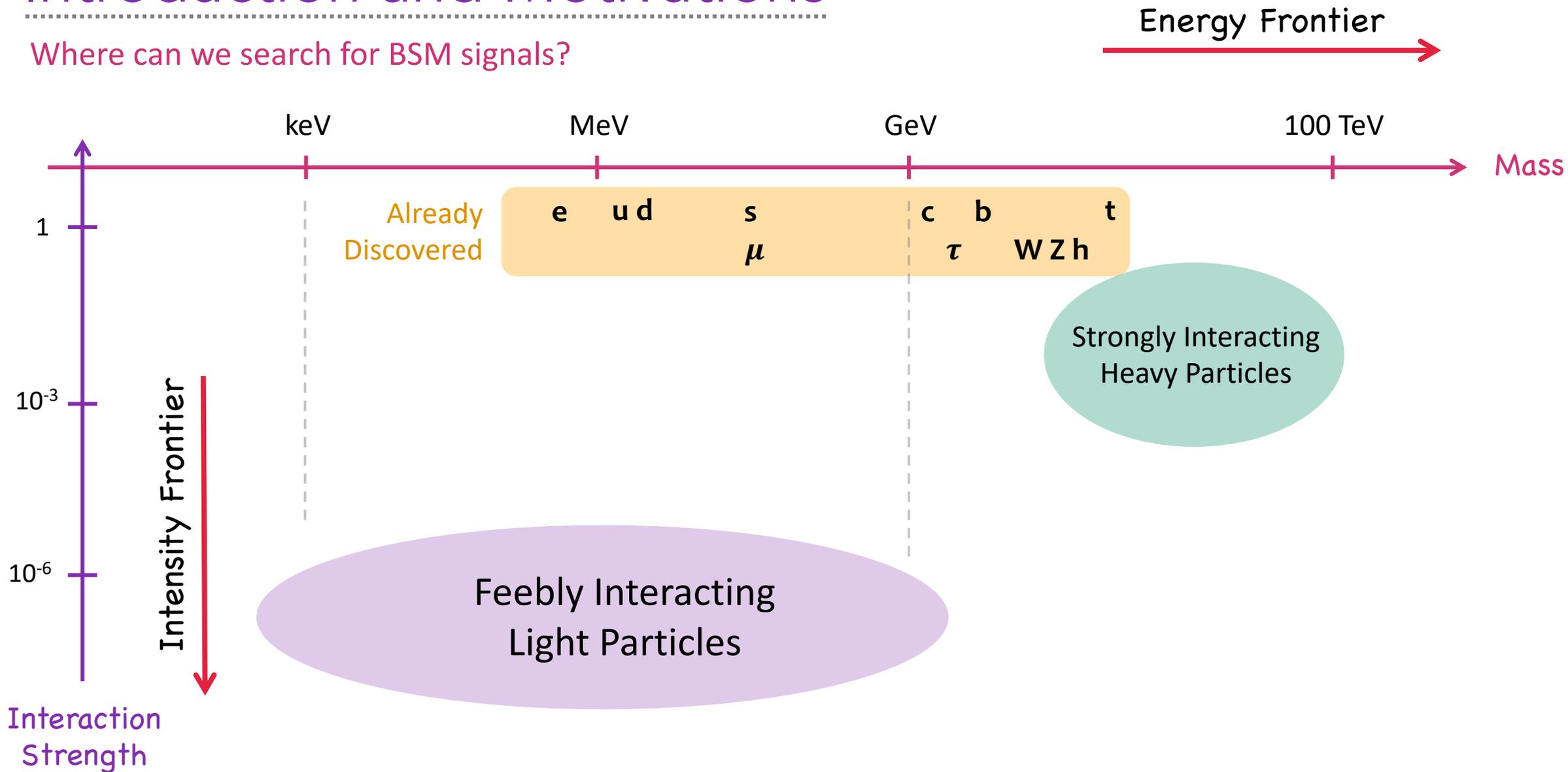
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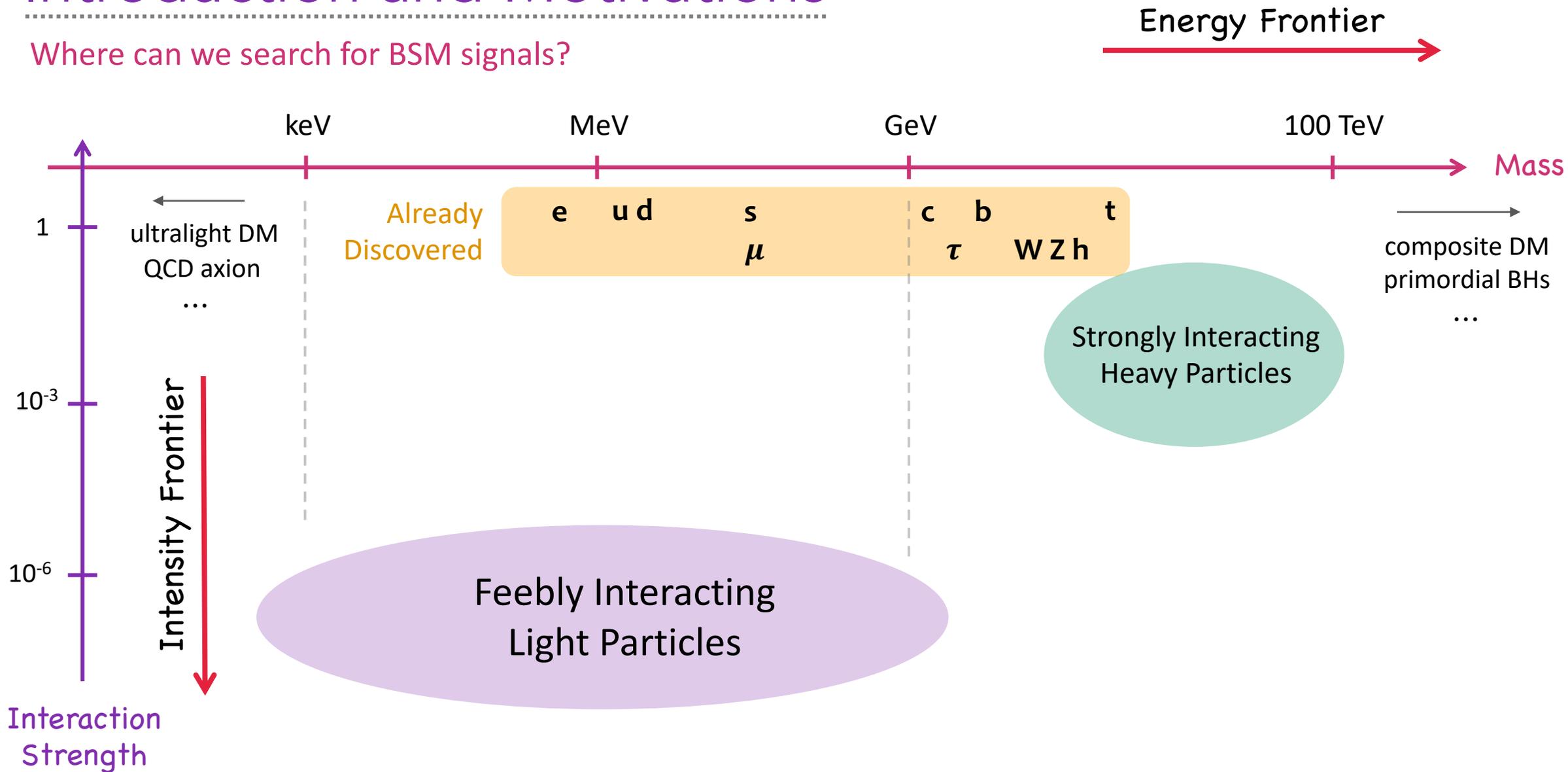
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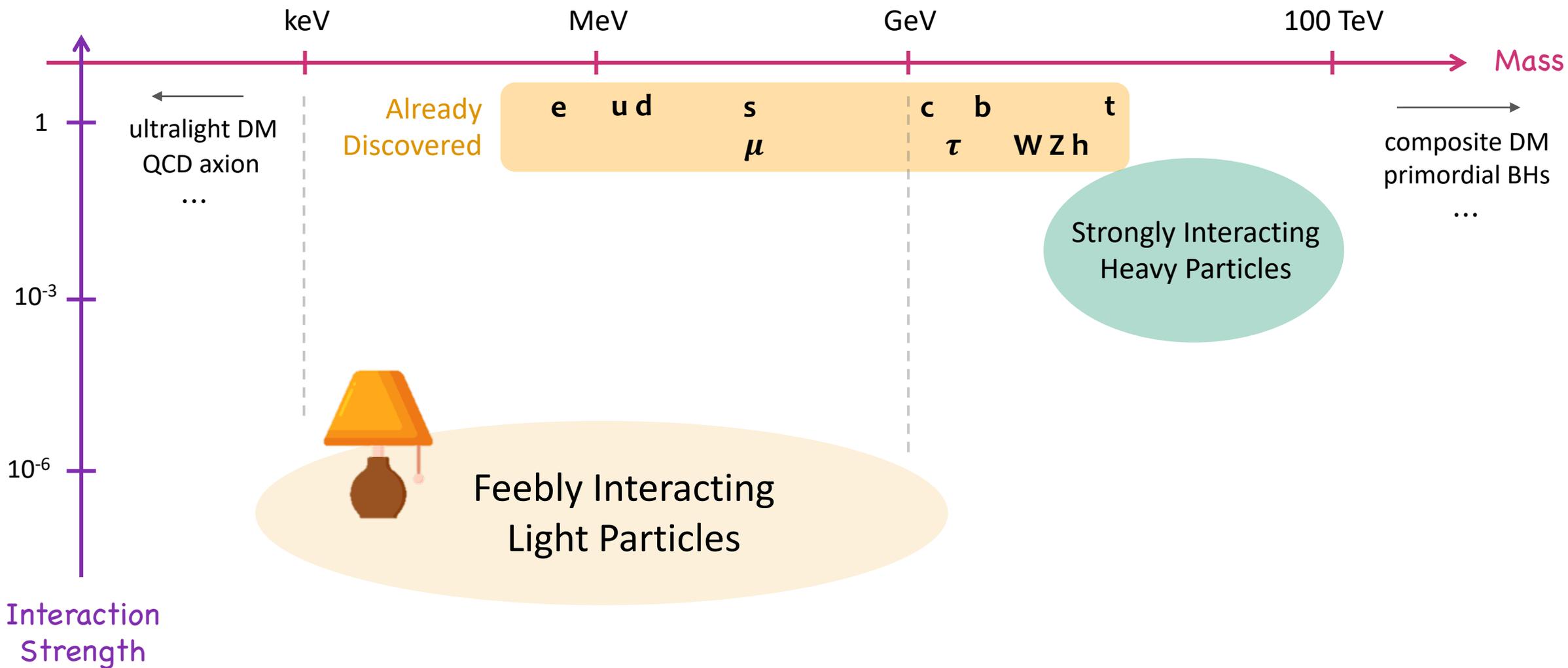
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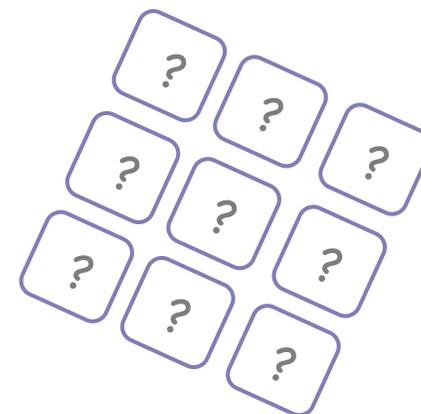
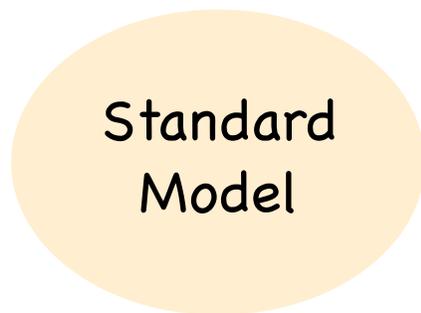
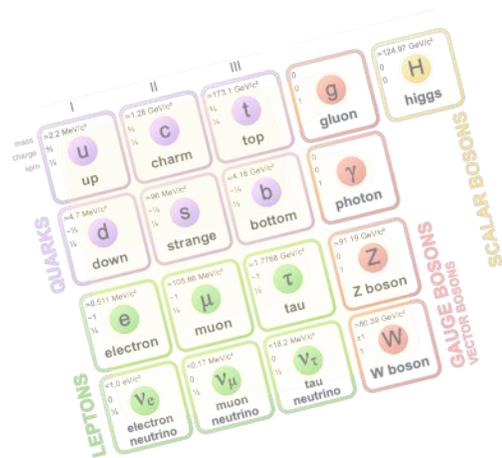
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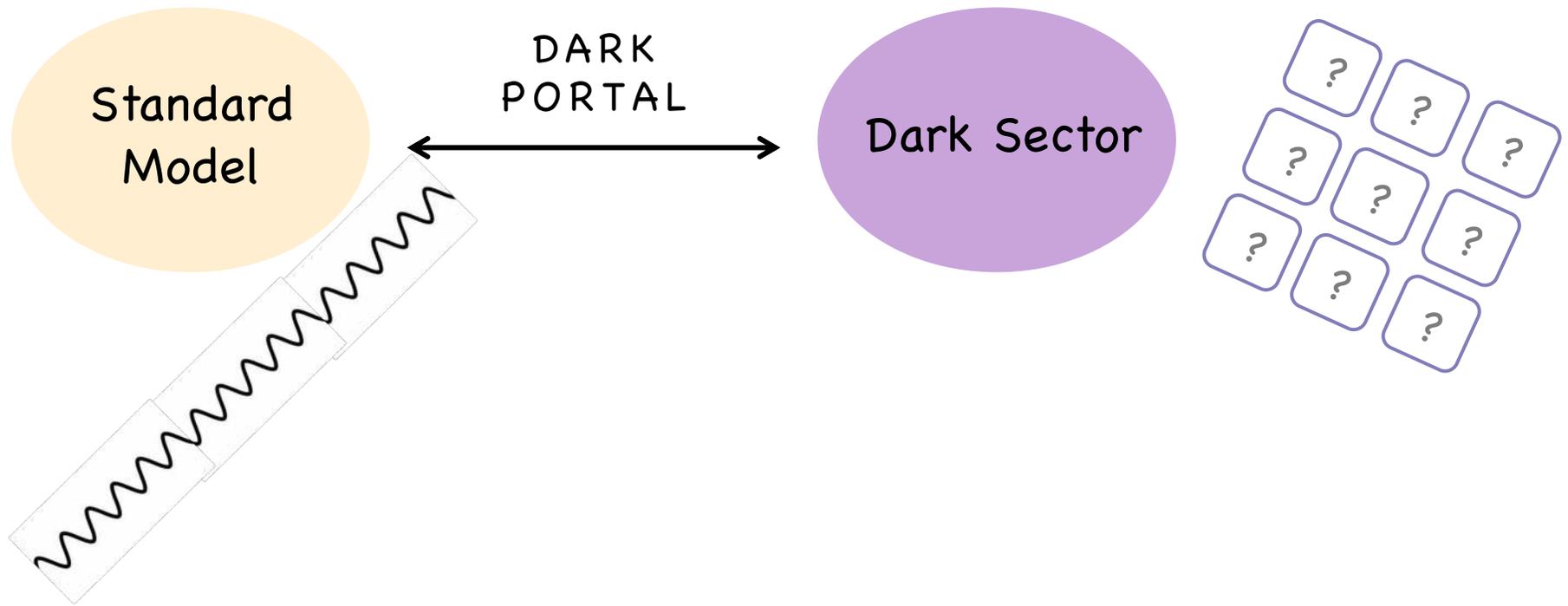
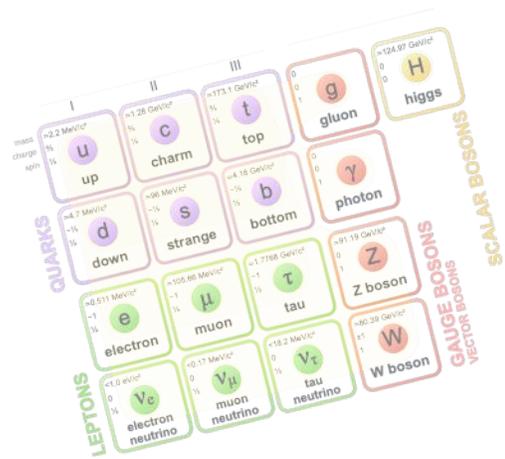
Introduction and Motivations · Hidden Portals

How can we search for light particle BSM signals?



Introduction and Motivations · Hidden Portals

How can we search for light particle BSM signals?



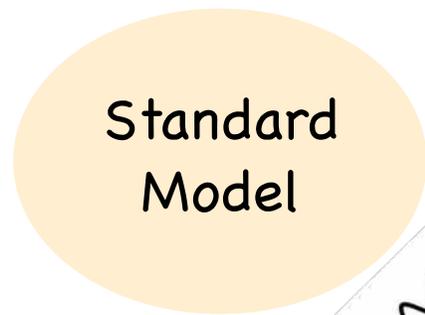
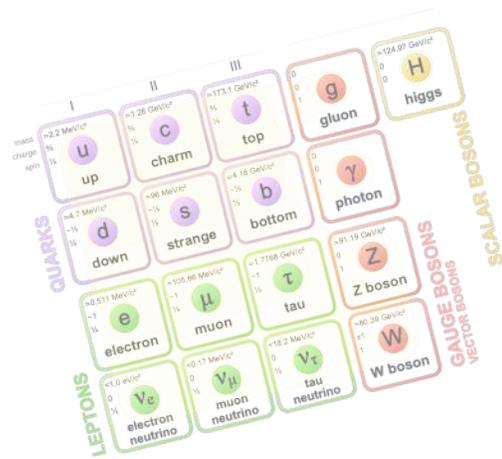
Vector Portal

$$\mathcal{L}_{\text{KM}} = \epsilon \hat{Z}_{Q\mu\nu} \hat{B}^{\mu\nu}$$

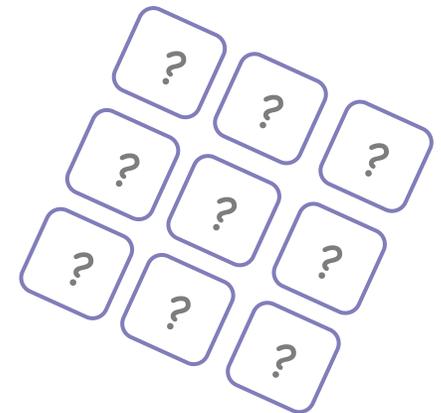
dark boson

Introduction and Motivations · Hidden Portals

How can we search for light particle BSM signals?



DARK PORTAL



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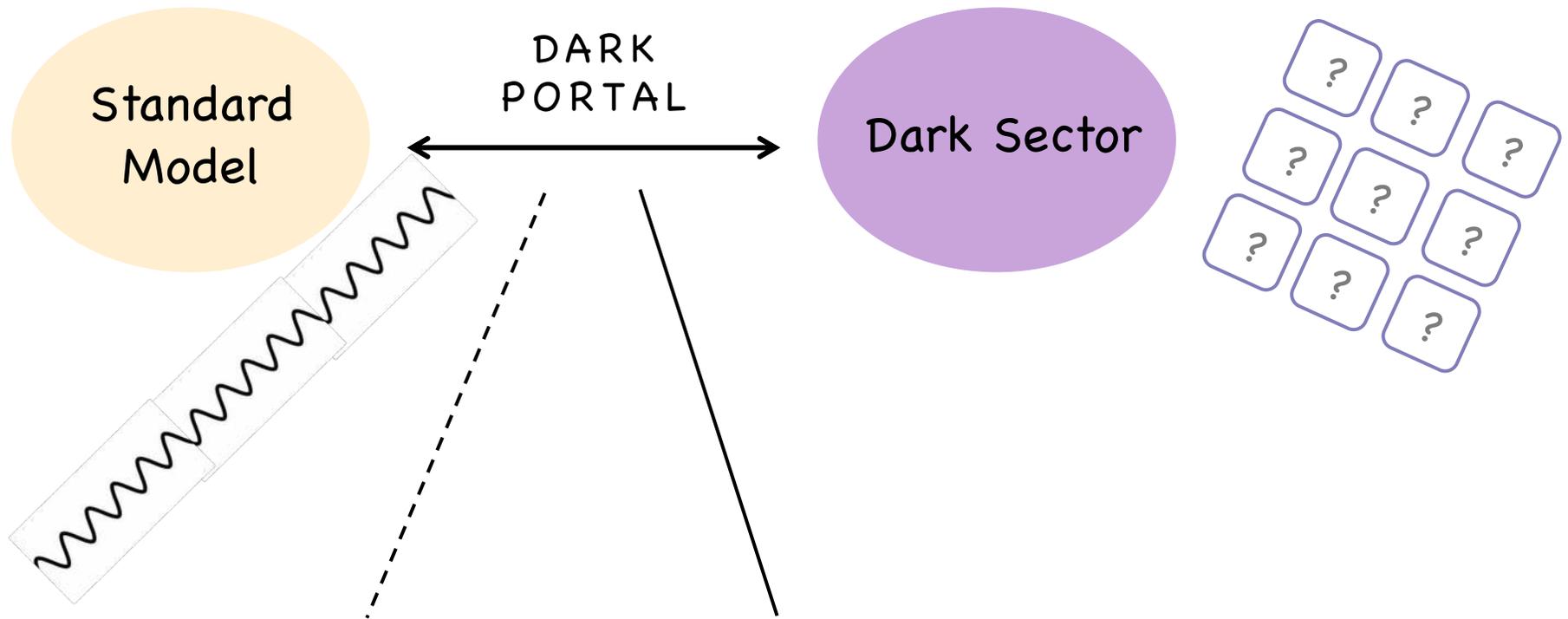
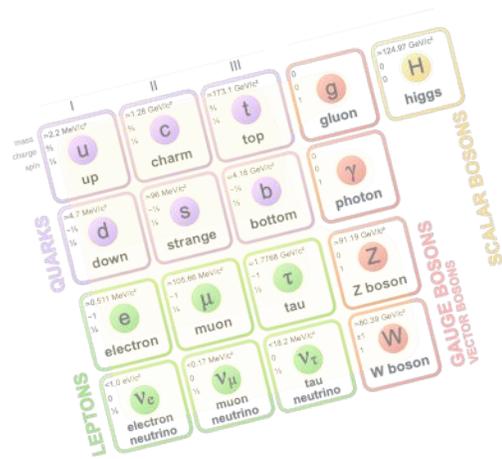
Scalar Portal

$$V(H, S) \supset \kappa |H|^2 |S|^2$$

dark Higgs

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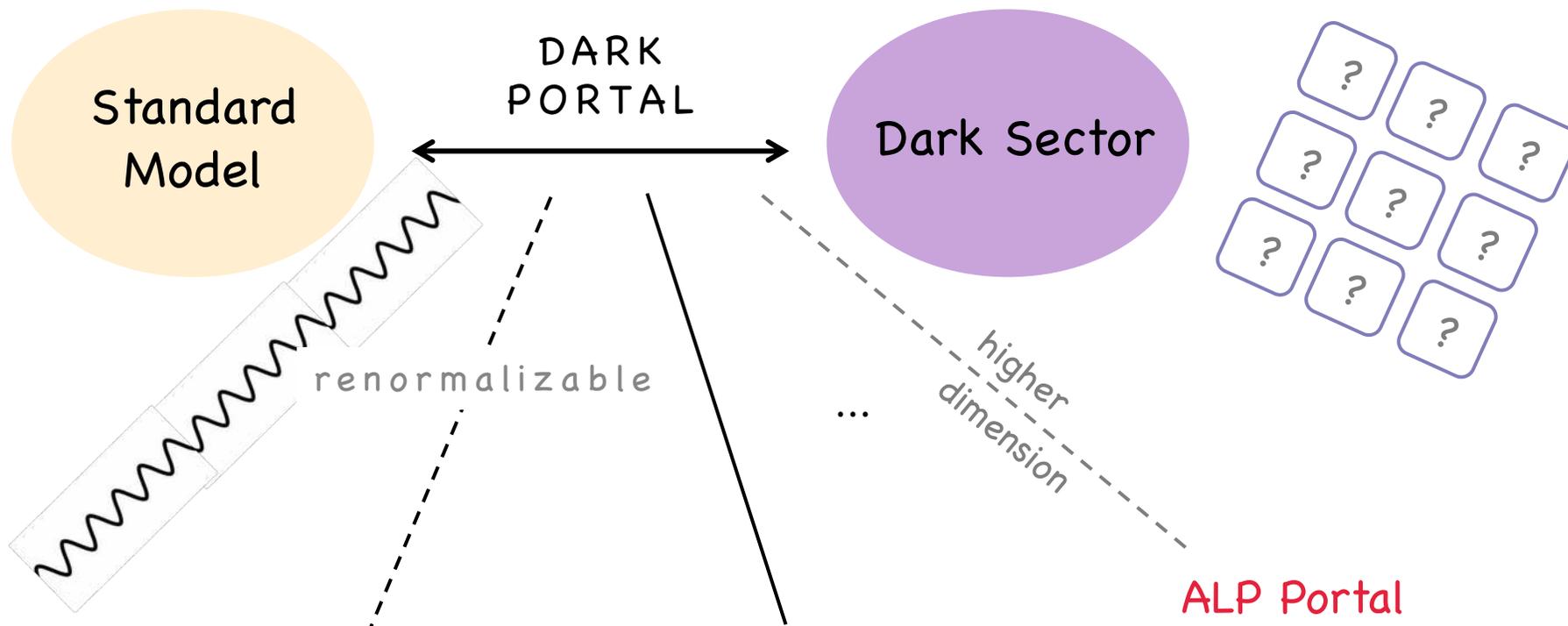
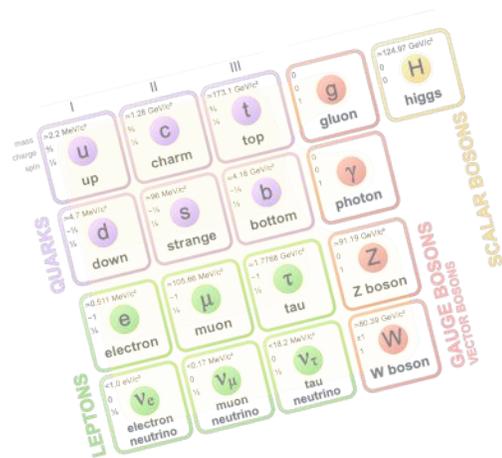
Neutrino Portal

$$\mathcal{L} \supset -y^\alpha L_\alpha H N + \text{h.c.}$$

Heavy Neutral Lepton

Introduction and Motivations · Hidden Portals

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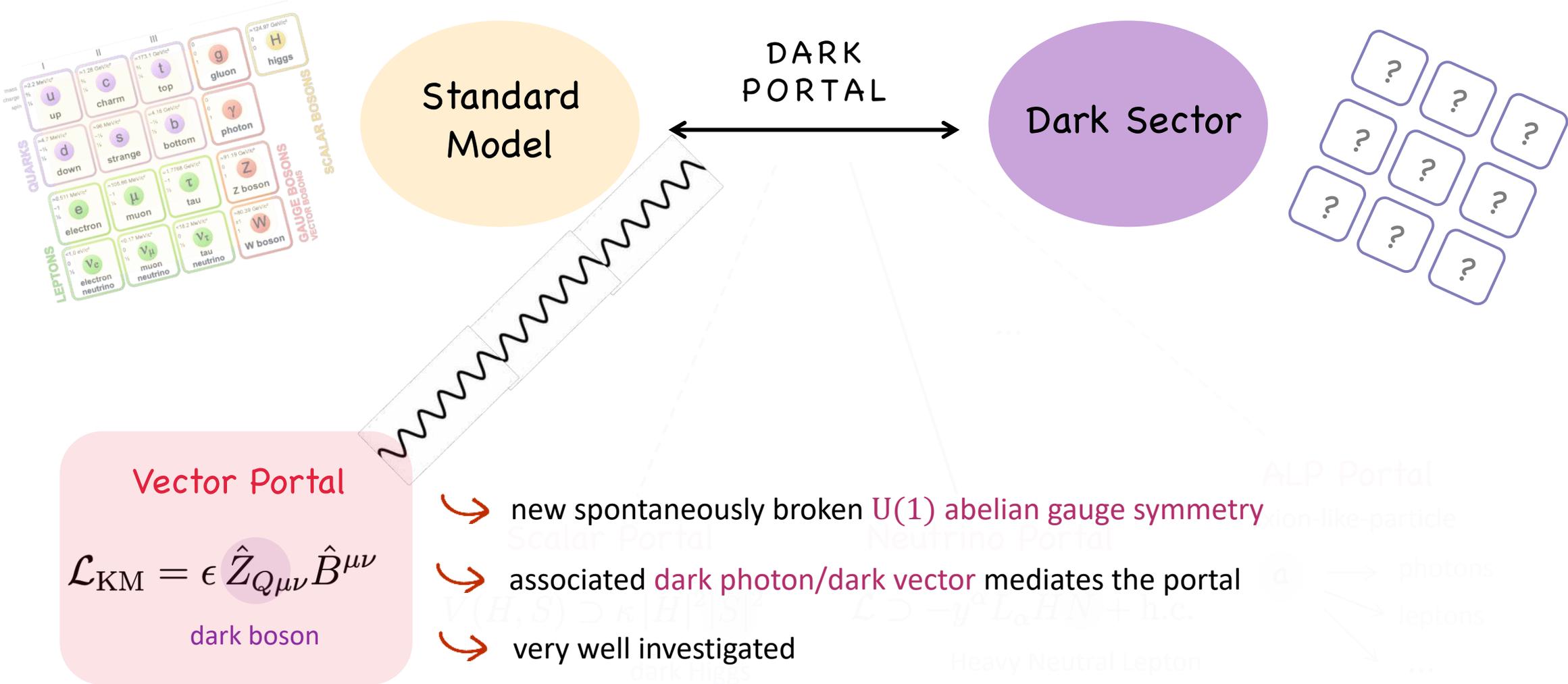
Heavy Neutral Lepton

ALP Portal
axion-like-particle



Introduction and Motivations · Hidden Portals

How can we search for light particle BSM signals?



	I	II	III	
mass charge spin	2.2 MeV/c² 2/3 1/2	1.28 GeV/c² 2/3 1/2	173.1 GeV/c² 2/3 1/2	124.97 GeV/c² 0 0
QUARKS	u up	c charm	t top	H higgs
	4.7 MeV/c² -1/3 1/2	96 MeV/c² -1/3 1/2	4.18 GeV/c² -1/3 1/2	
	d down	s strange	b bottom	γ photon
	0.511 MeV/c² -1 1/2	105.66 MeV/c² -1 1/2	1.7768 GeV/c² -1 1/2	Z boson
LEPTONS	e electron	μ muon	τ tau	W boson
	0.511 MeV/c² 0 1/2	105.66 MeV/c² 0 1/2	1.7768 GeV/c² 0 1/2	
	ν _e electron neutrino	ν _μ muon neutrino	ν _τ tau neutrino	
	0 0 1/2	0 0 1/2	0 0 1/2	
				SCALAR BOSONS
				GAUGE BOSONS VECTOR BOSONS

Vector Portal

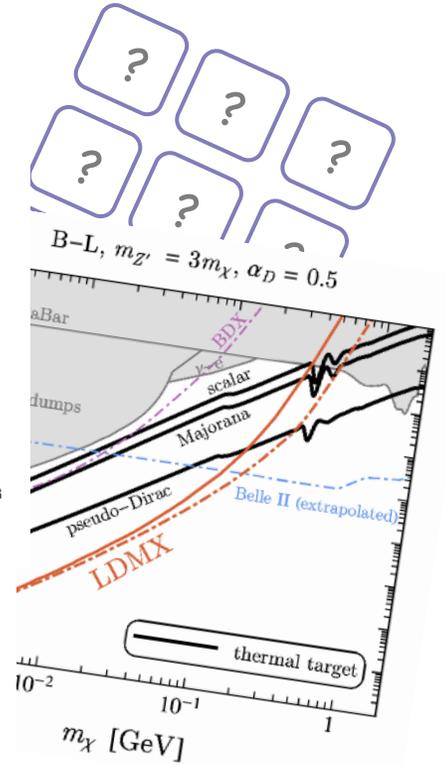
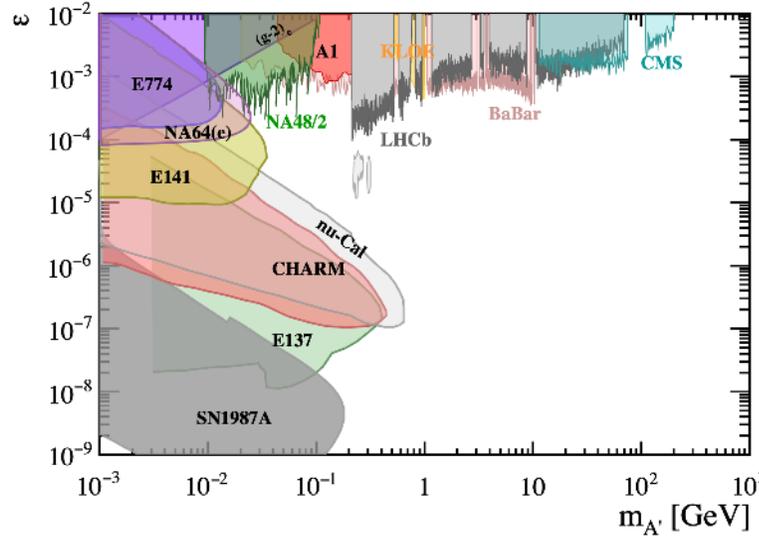
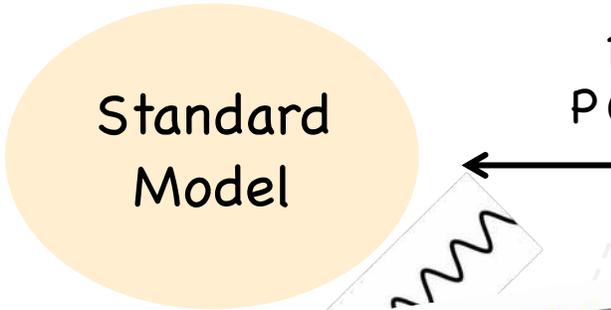
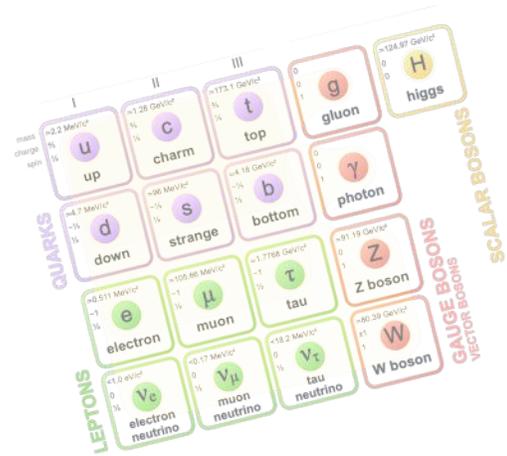
$$\mathcal{L}_{\text{KM}} = \epsilon \hat{Z}_{Q\mu\nu} \hat{B}^{\mu\nu}$$

dark boson

- new spontaneously broken U(1) abelian gauge symmetry
- associated dark photon/dark vector mediates the portal
- very well investigated

Introduction and Motivations • Hidden Portals

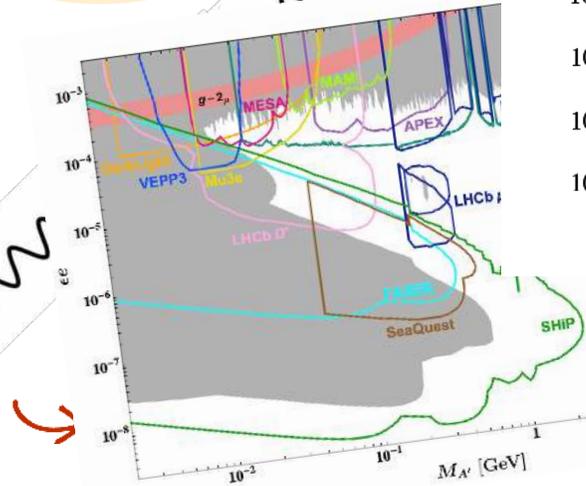
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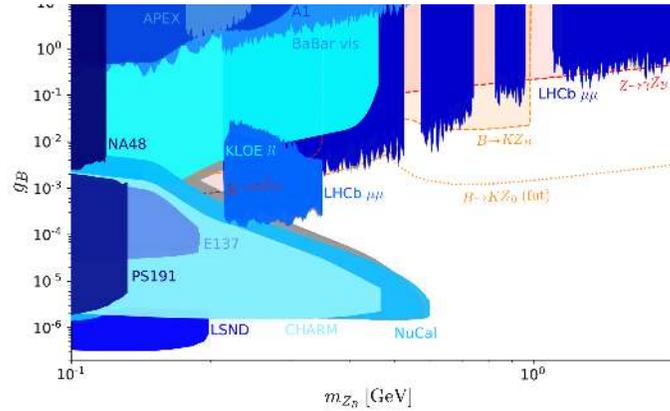
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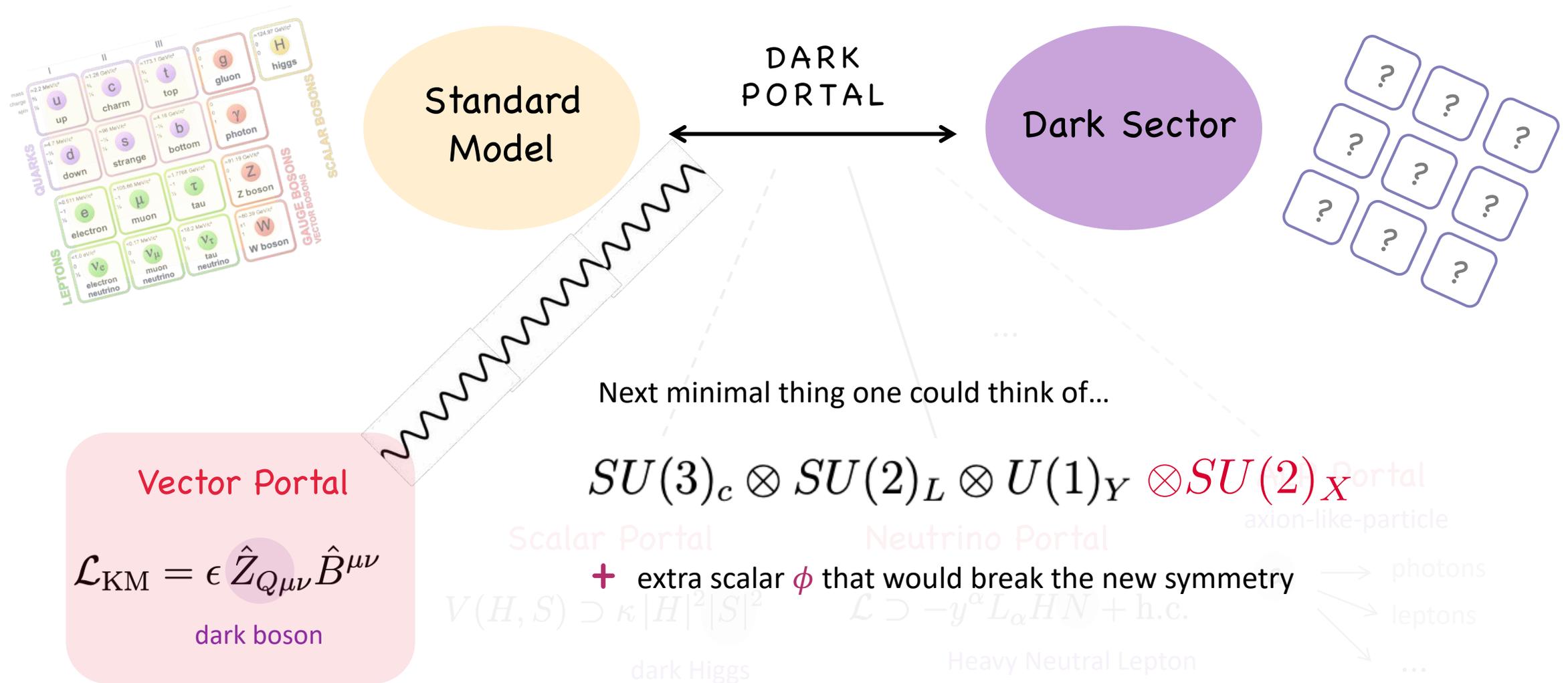


associated dark photon/
dark Higgs
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Introduction and Motivations · Hidden Portals

How can we search for light particle BSM signals?



Vector Dark Matter

Next minimal thing one could think of...

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes SU(2)_X$$

+ extra scalar ϕ that would break the new symmetry

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In the literature...

→ Studied in combination with the Higgs portal

Scalar Portal

$$V(H, S) \supset \kappa |H|^2 |S|^2$$

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→ or together with another extra abelian symmetry that mixes kinematically

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes SU(2)_X \otimes U(1)_D$$

[arXiv:1904.04109](https://arxiv.org/abs/1904.04109)

[arXiv:2307.02207](https://arxiv.org/abs/2307.02207)

Vector Dark Matter

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Here...

Let's consider the minimal case and suppress the Higgs portal

Besides...

We introduce a dim-6 operator that induce kinetic mixing

In the literature...

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In summary

- After the SSB of the new group, we are left with a custodial global symmetry
- ⇒ The **three gauge bosons** form a triplet representation with **degenerate mass**

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$$m_X^2 = \frac{g_X^2 v_X^2}{4}$$

Vector Dark Matter

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In summary

- After the SSB of the new group, we are left with a custodial global symmetry
⇒ The **three gauge bosons** form a triplet representation with **degenerate mass**
- The neutral gauge boson will act as the **dark photon mediator**

$$m_X^2 = \frac{g_X^2 v_X^2}{4}$$

$$\mathcal{L}_{KM} = \frac{1}{\Lambda^2} (\phi^\dagger \sigma^a \phi) X_{\mu\nu}^a B^{\mu\nu} \supset -\frac{\epsilon}{2c_w} X_{\mu\nu}^3 B^{\mu\nu}, \quad \epsilon \equiv \frac{c_w v_X^2}{\Lambda^2},$$

Vector Dark Matter

Next minimal thing one could think of...

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In summary

→ The charged states $X_\mu^\pm \equiv (X_\mu^1 \mp iX_\mu^2)/\sqrt{2}$ are stable and represent the **Vector Dark Matter candidates**

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Vector Dark Matter

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In summary

→ The charged states $X_\mu^\pm \equiv (X_\mu^1 \mp iX_\mu^2)/\sqrt{2}$ are stable and represent the **Vector Dark Matter candidates**

→ From the dim-6 operator we also get a direct **coupling to the photon**

$$\mathcal{L}_{KM} = \frac{1}{\Lambda^2} (\phi^\dagger \sigma^a \phi) X_{\mu\nu}^a B^{\mu\nu} \supset \frac{\epsilon g_X}{c_w} B_\mu \partial_\nu (X_\mu^- X_\nu^+ - X_\mu^+ X_\nu^-)$$

derivative coupling
vector DM with a photon portal

Relic Density Computation

To compute the relic density, one needs to solve the **Boltzmann equation** considering all relevant number-changing processes

$$\dot{n}_X + 3Hn_X = 2 \left(\gamma_{XX}^{\text{kinetic}} + \gamma_{XX}^{\text{dark}} + 2 \frac{n_X}{n_X^{\text{eq}}} \gamma_{XXX} + \gamma_{XXZ_D} + \gamma_{Z_D Z_D Z_D} \right) \left[1 - \frac{n_X^2}{(n_X^{\text{eq}})^2} \right]$$

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where

$$\hookrightarrow n_X \equiv n_{X^+} + n_{X^-} \quad \text{total DM component}$$

Reaction densities

$$\hookrightarrow \gamma_{\{i\} \leftrightarrow \{j\}} \equiv \int \prod_{i \in \{i\}} d\Pi_i f_i \prod_{j \in \{j\}} d\Pi_j (2\pi)^4 \delta^4(p_{\{i\}} - p_{\{j\}}) |\mathcal{M}_{\{i\} \leftrightarrow \{j\}}|^2$$

- 2 – 2 processes: $\gamma_{12 \rightarrow \{j\}} = \langle \sigma v \rangle_{12 \rightarrow \{j\}} n_1^{\text{eq}} n_2^{\text{eq}} \Rightarrow = \frac{T}{64\pi^2} \int_{s_{\text{min}}}^{\infty} ds \sqrt{s} K_1 \left(\frac{\sqrt{s}}{T} \right) \hat{\sigma}_{12 \leftrightarrow ab}(s)$

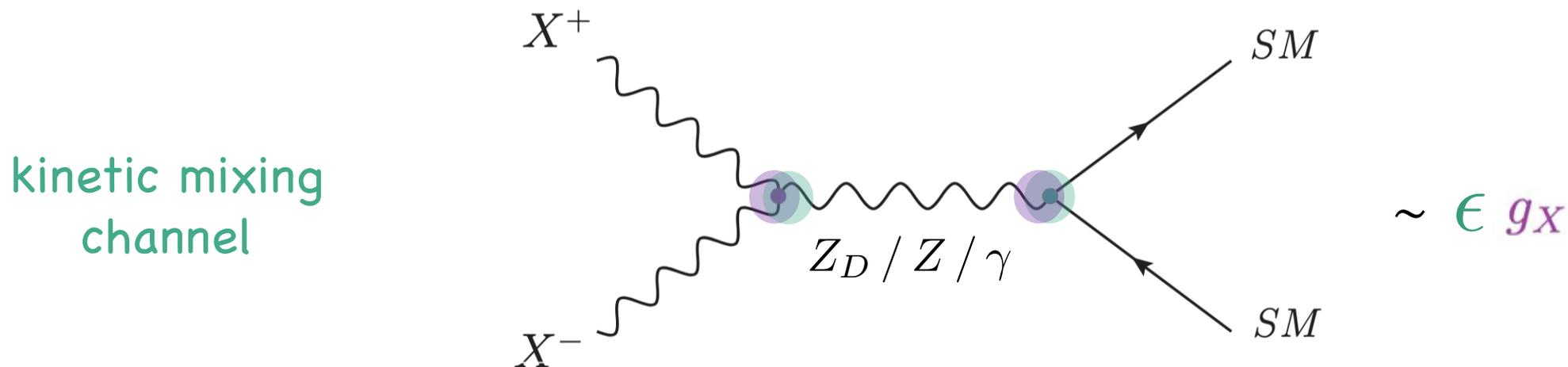
- 3 – 2 processes: $\gamma_{123 \rightarrow \{j\}} = \langle \sigma v^2 \rangle_{123 \rightarrow \{j\}} n_1^{\text{eq}} n_2^{\text{eq}} n_3^{\text{eq}} \Rightarrow$ non-relativistic approximation

Relic Density Computation

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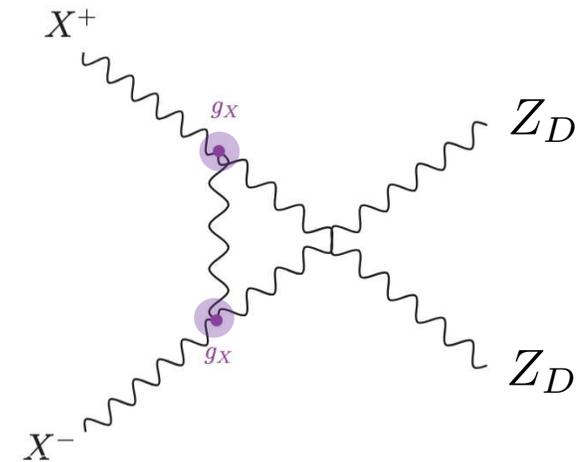
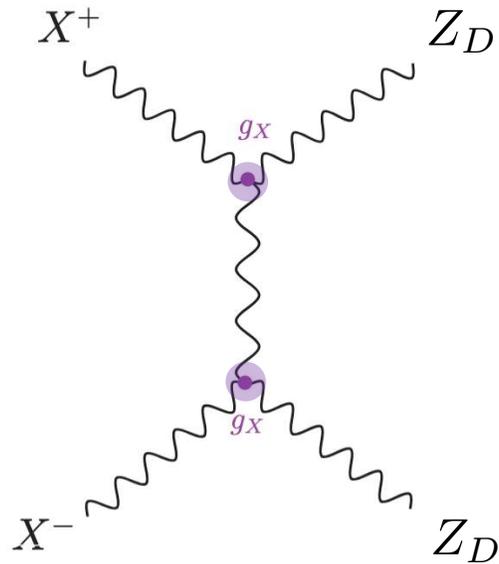
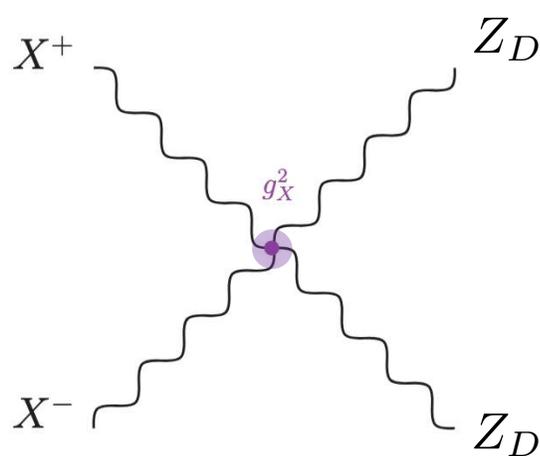
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where

dark sector
annihilation



Relic Density Computation

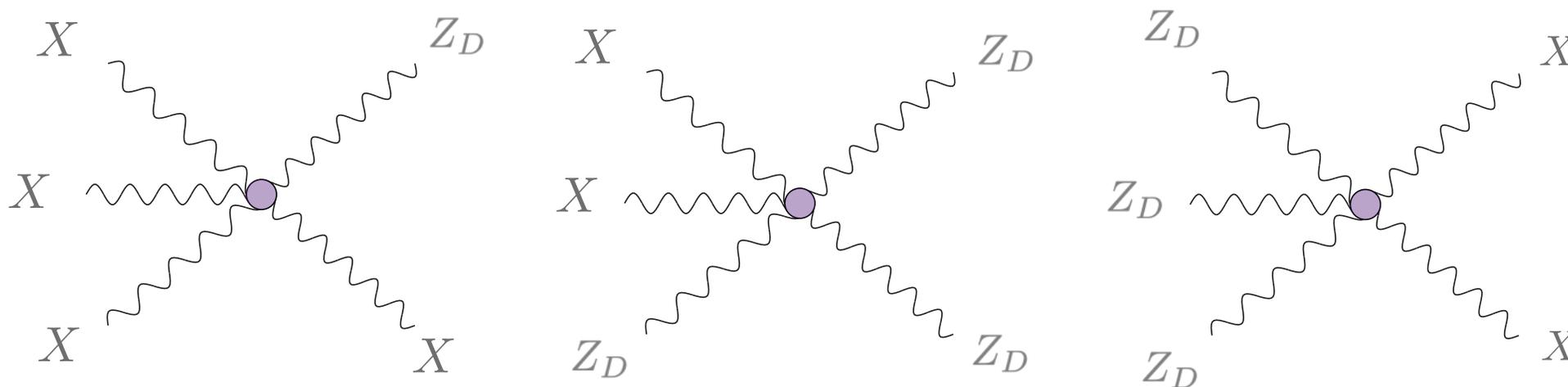
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where

3 → 2 SIMP
channels

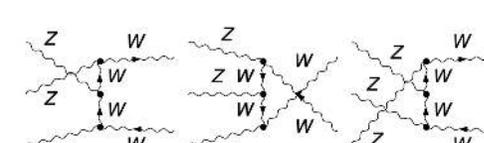
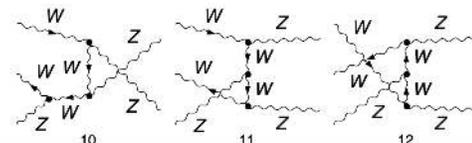
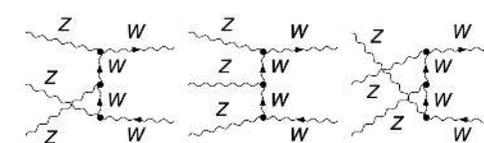
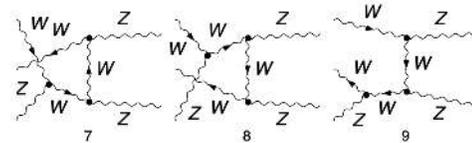
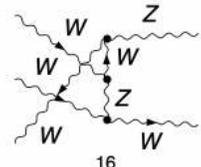
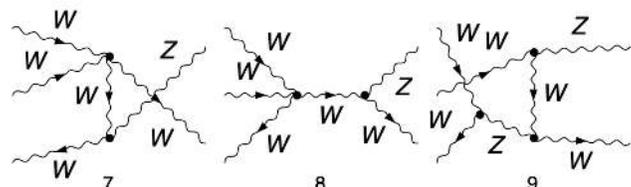
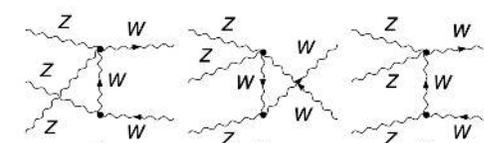
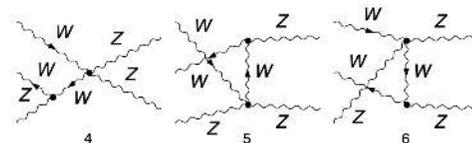
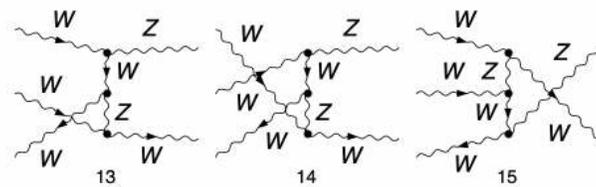
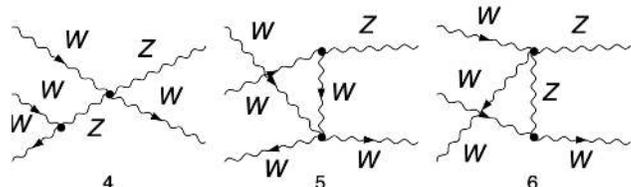
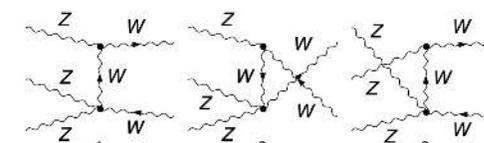
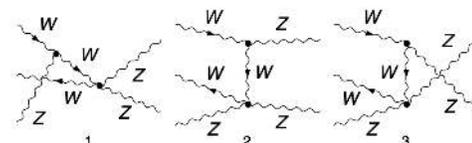
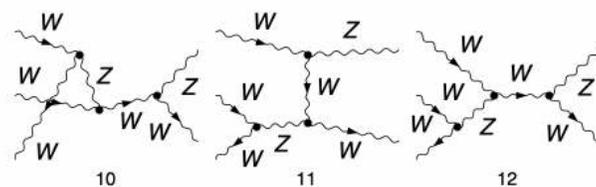
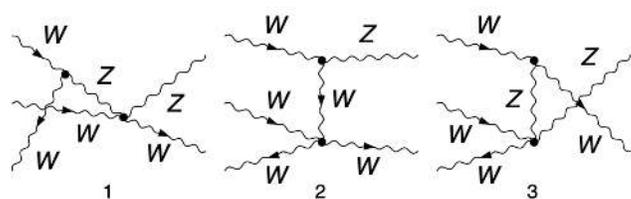
(Strongly Interacting
Massive Particle)



Relic Density Computation

To compute the relic density, one needs to solve the **Boltzmann equation** considering all relevant number-changing processes

$$\dot{n}_X + 3Hn_X = 2 \left(\gamma_{XX}^{\text{kinetic}} + \gamma_{XX}^{\text{dark}} + 2 \frac{n_X}{n_X^{\text{eq}}} \gamma_{XXX} + \gamma_{XXZ_D} + \gamma_{Z_D Z_D Z_D} \right) \left[1 - \frac{n_X^2}{(n_X^{\text{eq}})^2} \right]$$

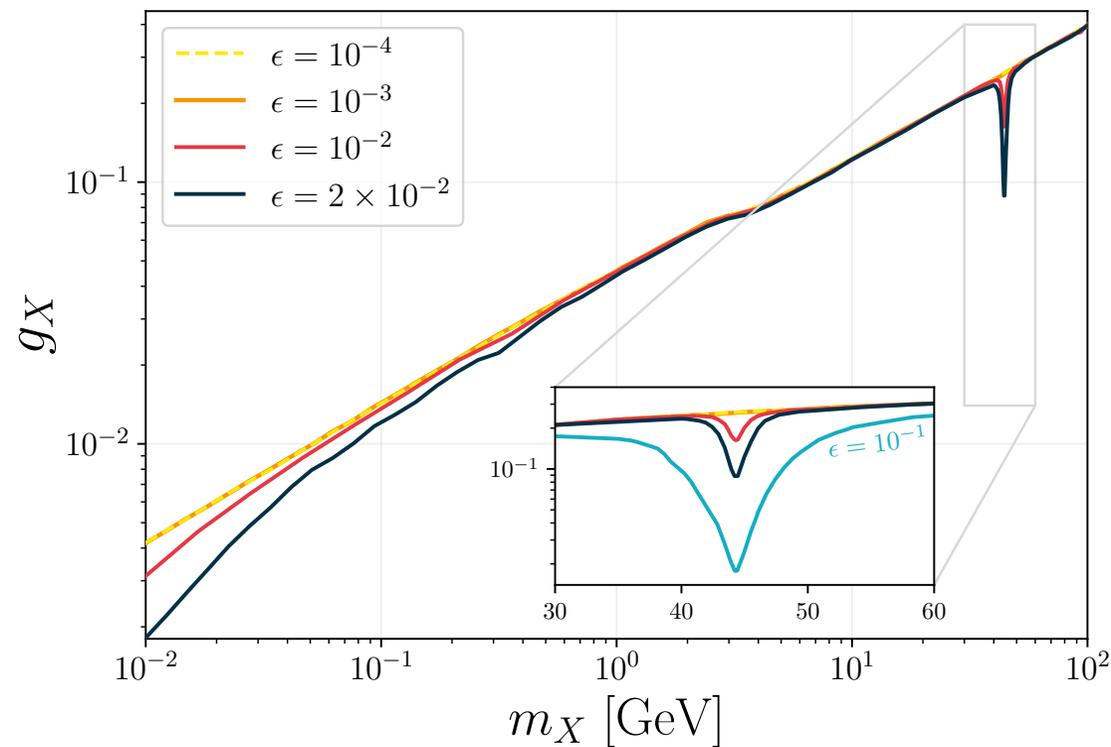
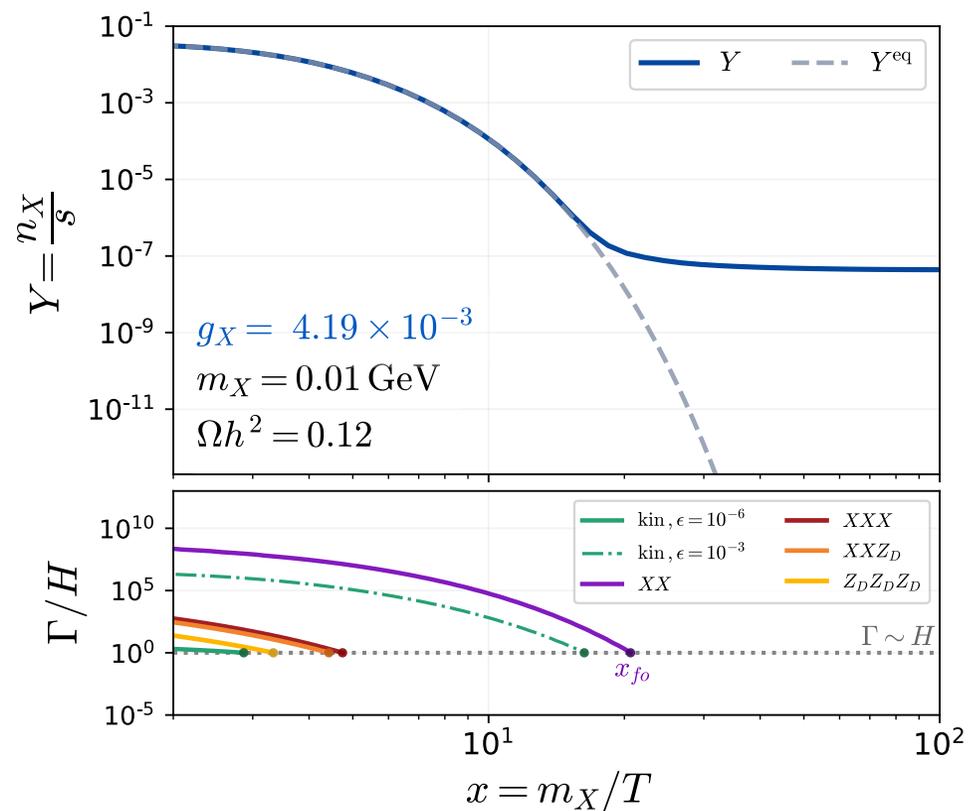


Dark Matter Production Mechanisms

ALF, R.Z. Funchal, M. Frigerio

[arXiv:2510.26765](https://arxiv.org/abs/2510.26765)

1 Freeze-out

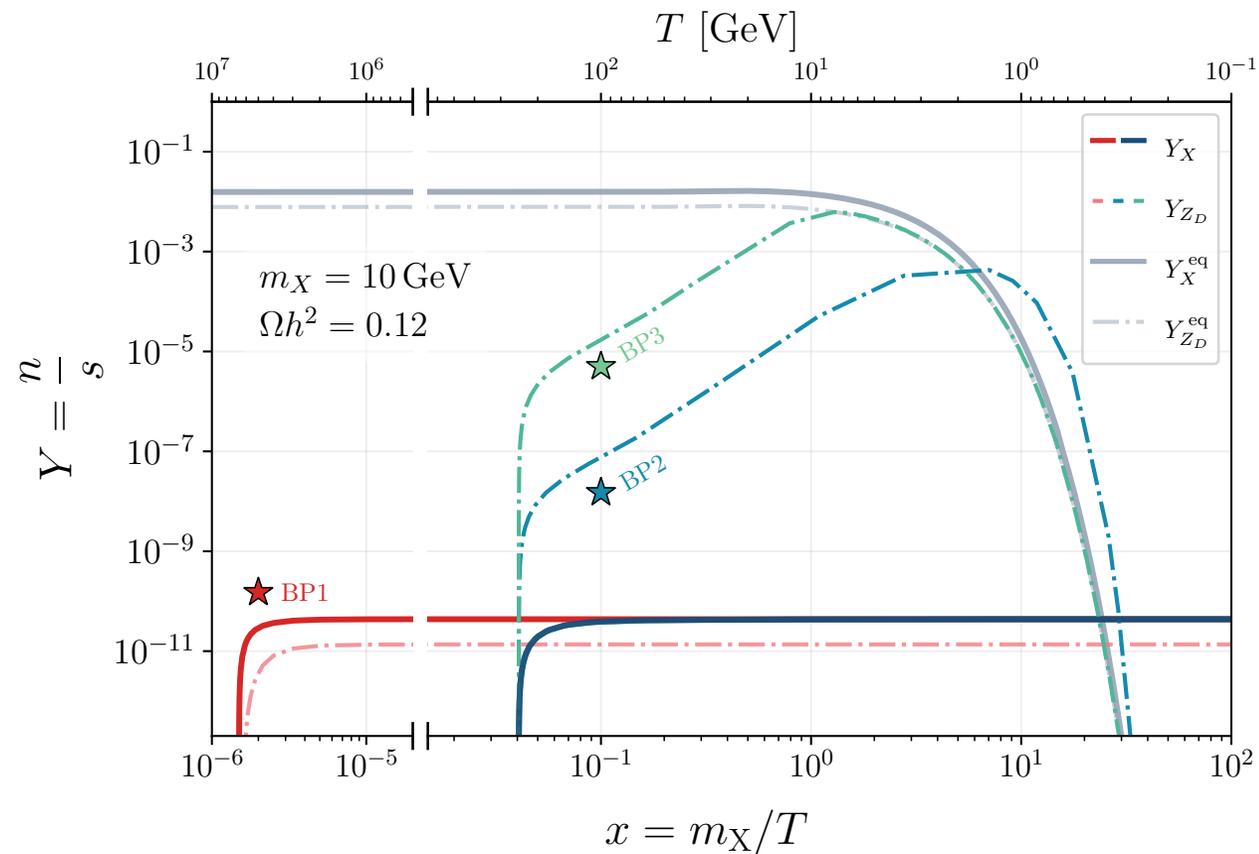
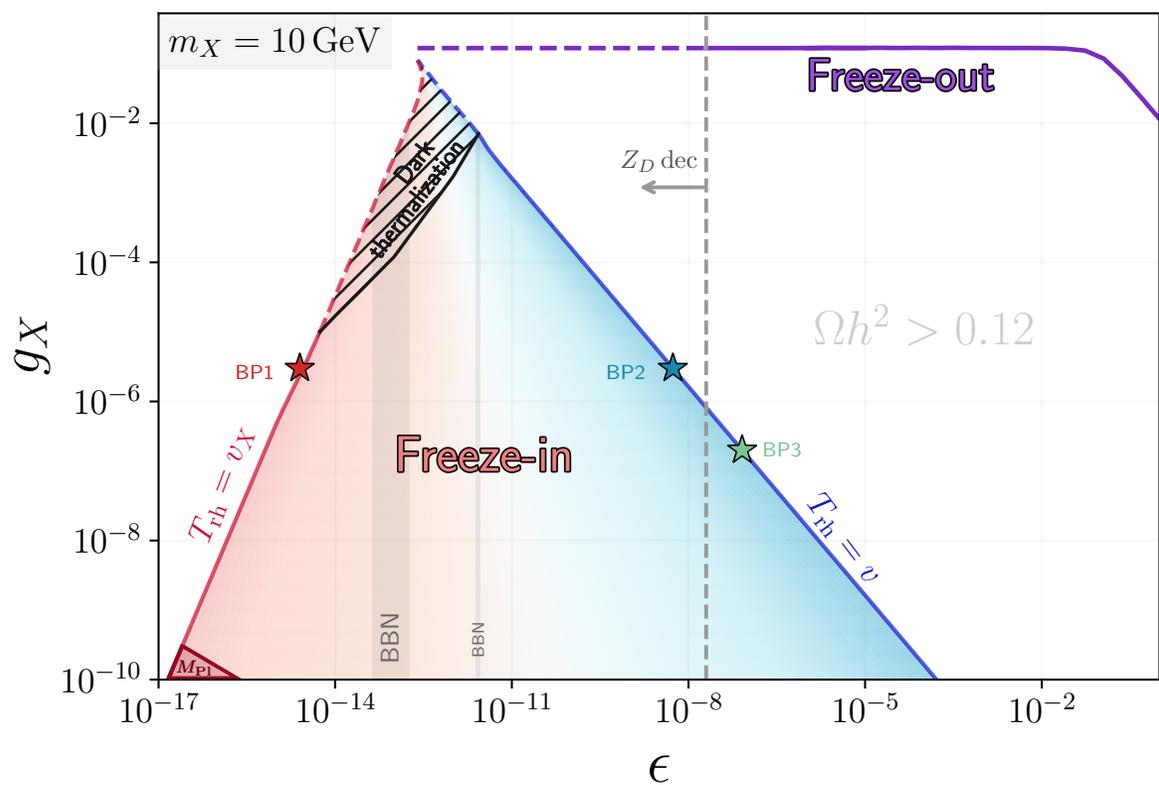


Dark Matter Production Mechanisms

ALF, R.Z. Funchal, M. Frigerio

[arXiv:2510.26765](https://arxiv.org/abs/2510.26765)

2 Freeze-in

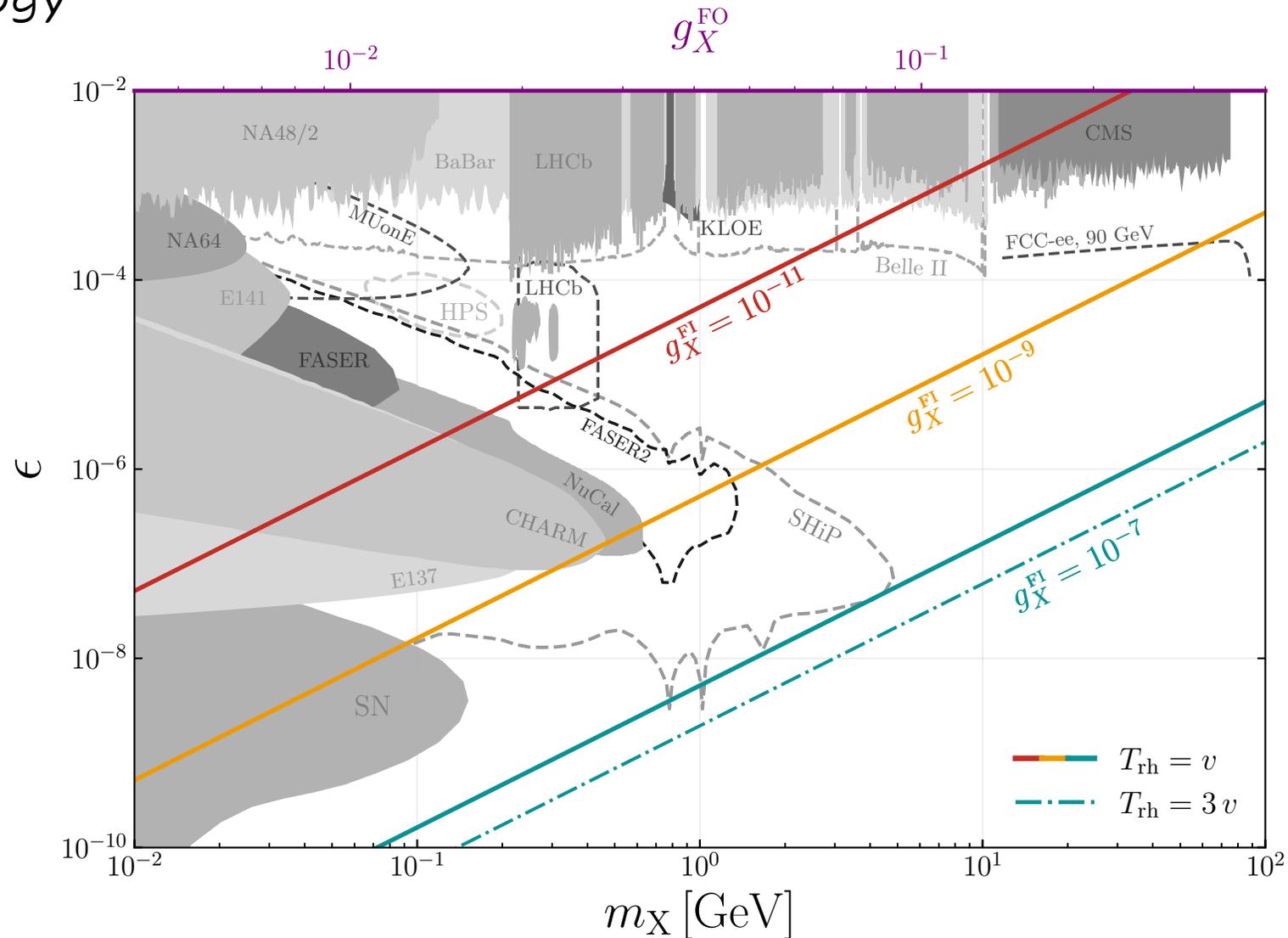


Vector DM with non-abelian Kinetic Mixing

ALF, R.Z. Funchal, M. Frigerio

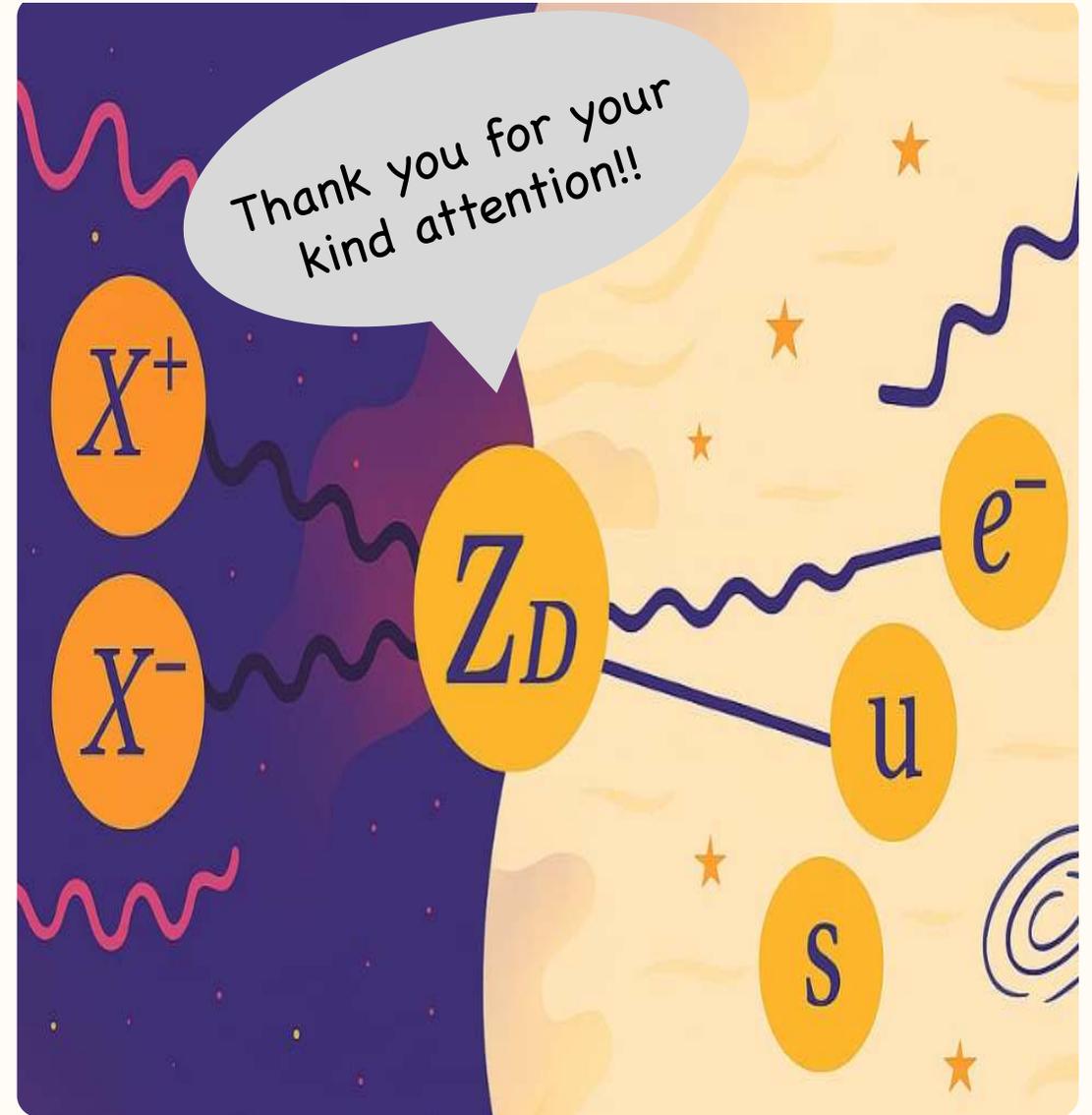
[arXiv:2510.26765](https://arxiv.org/abs/2510.26765)

Phenomenology



Conclusions

- We consider a scenario with **Vector Dark Matter candidates** by
 - ➔ extending the SM by extra gauge $SU(2)_X$
 - ➔ including dim-6 operator that induces **Kinetic Mixing**
- The correct relic density can be obtained via:
 - ➔ **Freeze-out**: dark sector annihilations dominate
 - ➔ **Freeze-in**: UV-dependent scenario
 - ➔ **Mass splitting case**: larger mediator-to-DM mass ratio shifts the channels dominance
- Dark photon phenomenology probes the DM states!



BACKUP

Introduction and Motivations

How can we search for light particle BSM signals?



→ we cannot reproduce the correct thermal abundance if we couple directly to the Weak interactions....

Lee-Weinberg bound

$$m_\chi \gtrsim 2 \text{ GeV}$$

→ So, how can we explore **sub-GeV dark sectors**?

- including **new light dark sector mediator states** that will act as **portals** between the dark sector and the SM!

Relic Density Computation · Propaganda Interlude

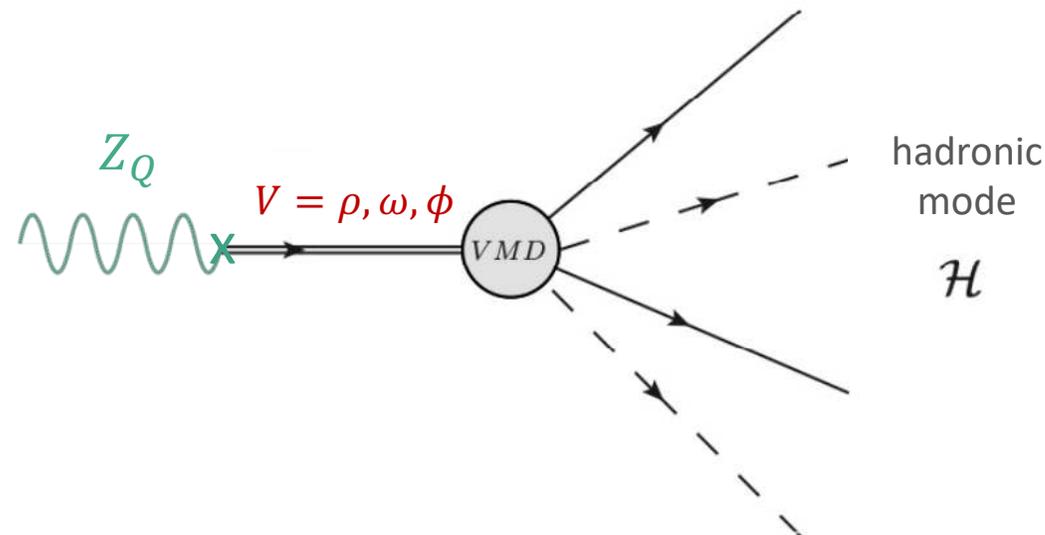
ReD-DeLiVeR (Relic Density with DeLiVeR)

- update of the previous python package **DELIVER** (**Decays of Light Vectors Revised**), which can be used to compute decay rates and branching ratios for **user-defined $U(1)_Q$ charges**,
- **key feature**: includes a complete set of **hadronic decays** (20 channels)

channel	resonances
$\pi\gamma$	$\rho, \omega, \omega', \omega'', \phi$
$\pi\pi$	ρ, ρ', \dots
3π	$\rho, \rho'', \omega, \omega', \omega'', \phi$
4π	$\rho, \rho', \rho'', \rho'''$
KK	$\rho, \dots, \omega, \dots, \phi, \dots$
$KK\pi$	$\rho, \rho', \rho'', \phi, \phi', \phi''$

channel	resonances
$\eta\gamma$	$\rho, \rho', \omega, \phi$
$\eta\pi\pi$	ρ, ρ', ρ''
$\omega\pi \rightarrow \pi\pi\gamma$	ρ, ρ', ρ''
$\omega\pi\pi$	ω''
$\phi\pi$	ρ, ρ'
$\eta'\pi\pi$	ρ'''
$\eta\omega$	ω', ω''
$\eta\phi$	ϕ', ϕ''
$p\bar{p}/n\bar{n}$	$\rho, \rho', \dots, \omega, \omega', \dots$
$\phi\pi\pi$	ϕ', ϕ''
$K^*(892)K\pi$	ρ'', ϕ'
6π	ρ'''

ALF, P. Reimitz, R.Z. Funchal [JHEP 04 (2022)119]



Relic Density Computation · Propaganda Interlude

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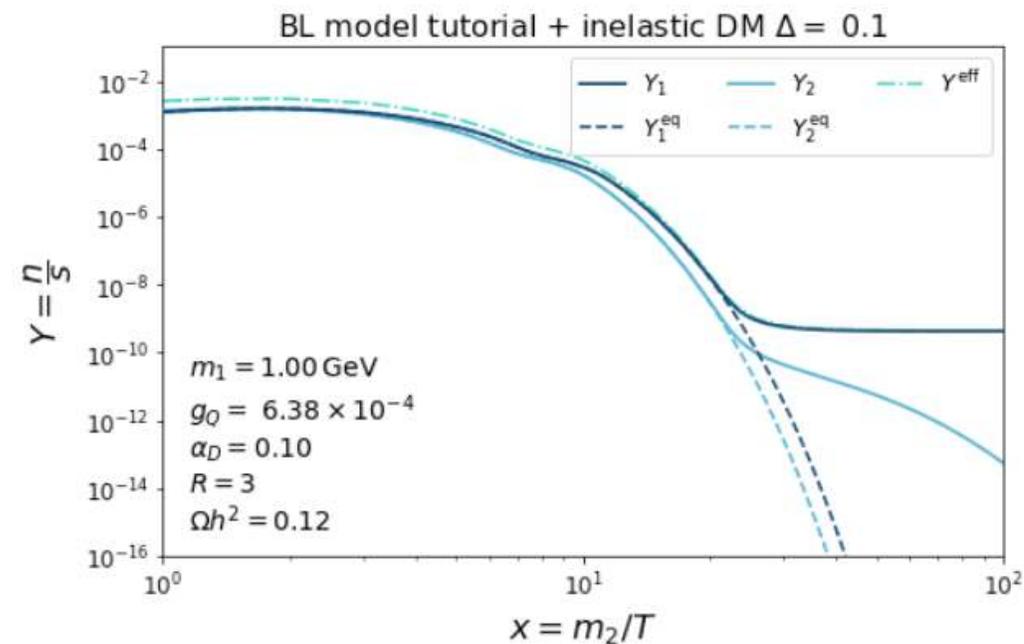
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→ **new version**:

- inclusion of DM candidates

} simplified DM models
inelastic DM

- computation of **relic density** and **rates**



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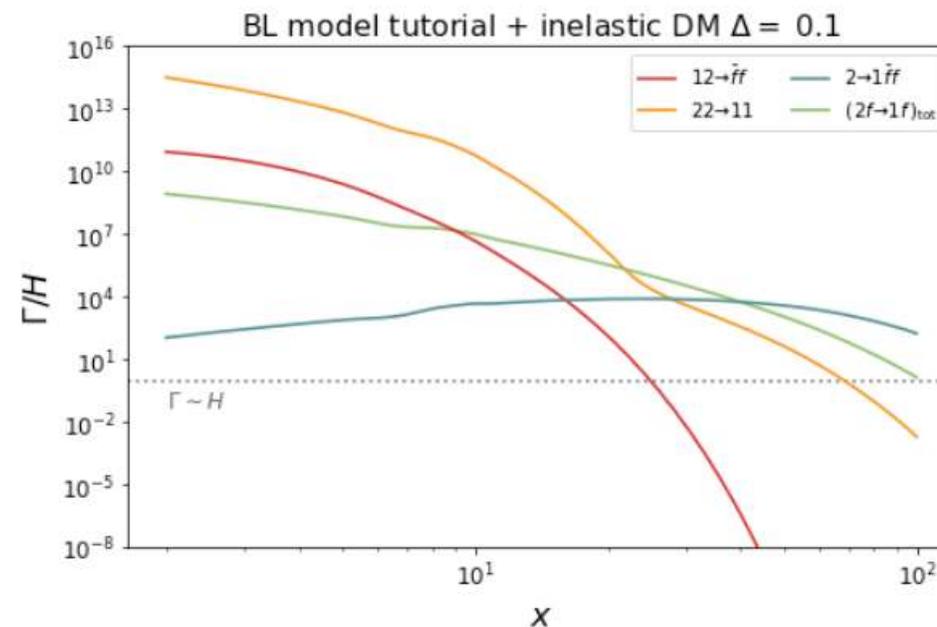
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Relic Density Computation · Propaganda Interlude

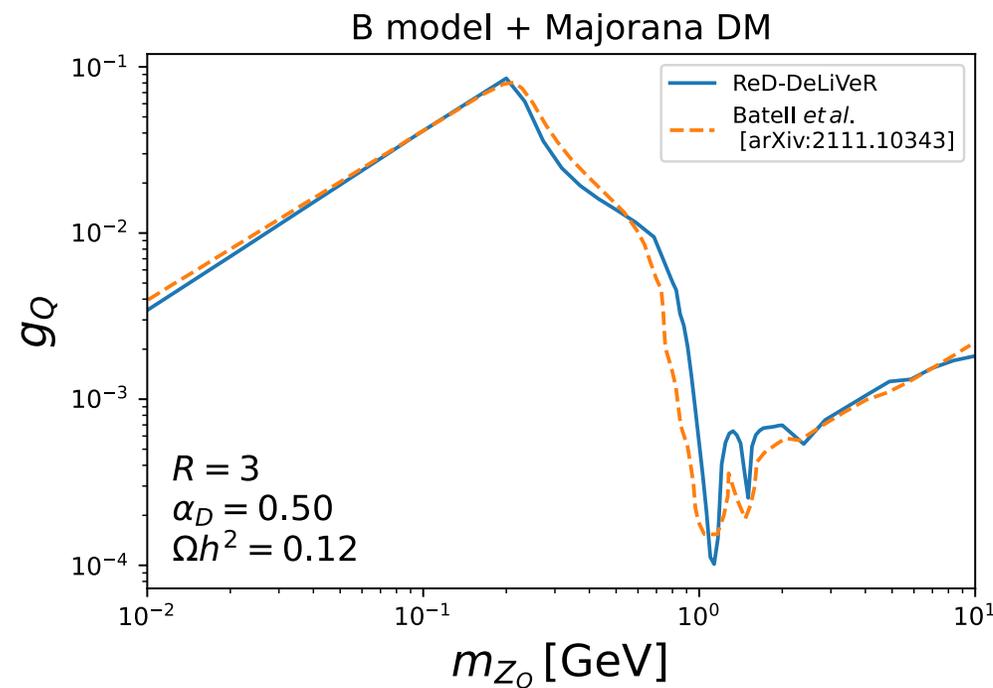
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inelastic DM



specially for B-coupled models, it is very important to compute correctly the hadronic contributions

Relic Density Computation · Propaganda Interlude

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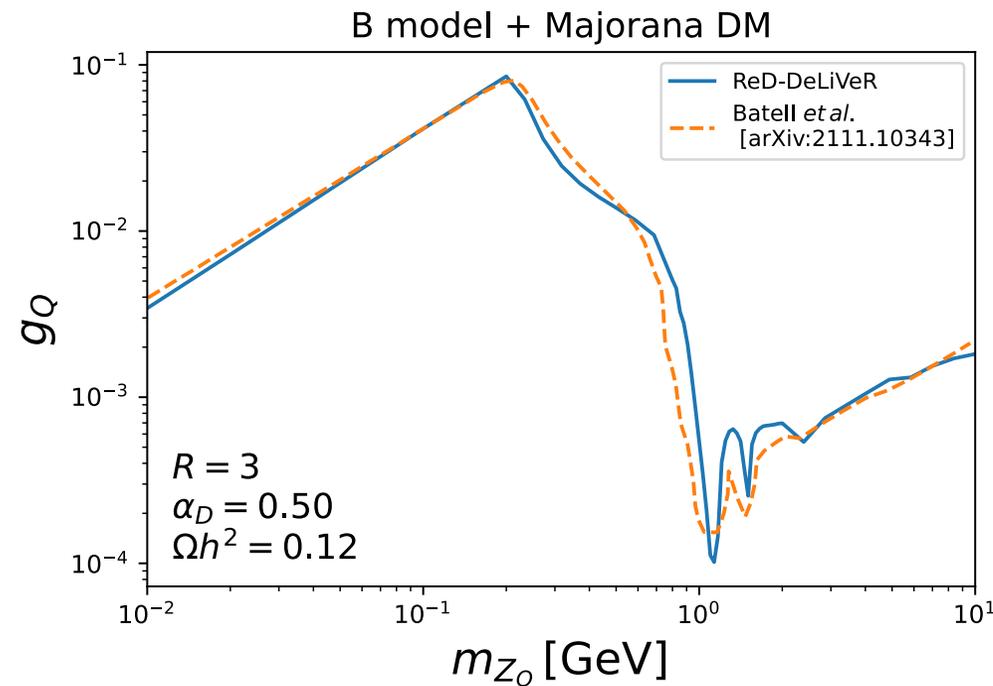
→ **publicly available** on GitHub together with a **Tutorial!**

<https://github.com/anafoguel/ReD-DeLiVeR>

ReD-DeLiVeR

by Ana Luisa Foguel, Peter Reimitz, and Renata Zukanovich Funchal

arXiv: 2410.00881



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Dark Matter Production Mechanisms

ALF, R.Z. Funchal, M. Frigerio

[arXiv:2510.26765](https://arxiv.org/abs/2510.26765)

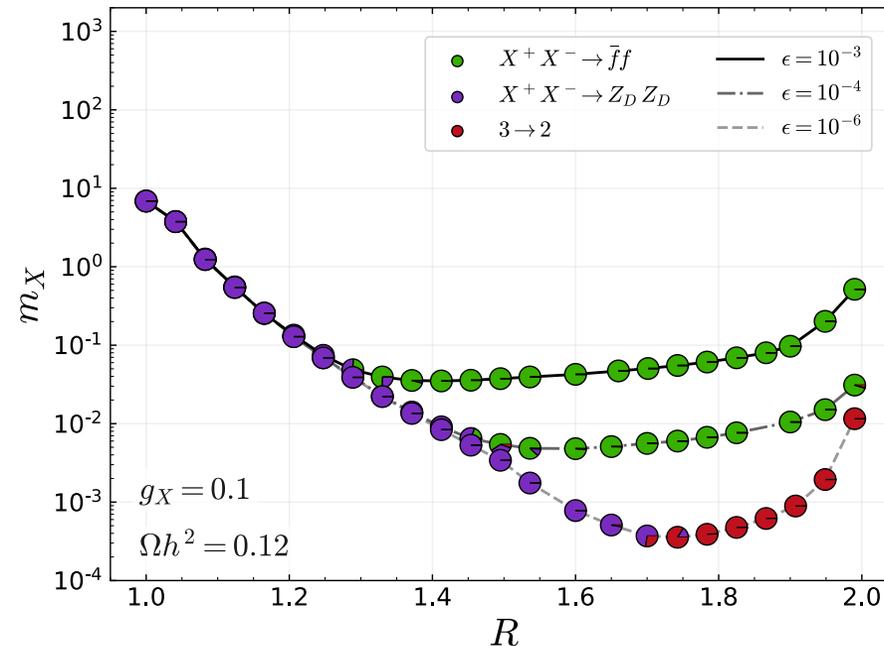
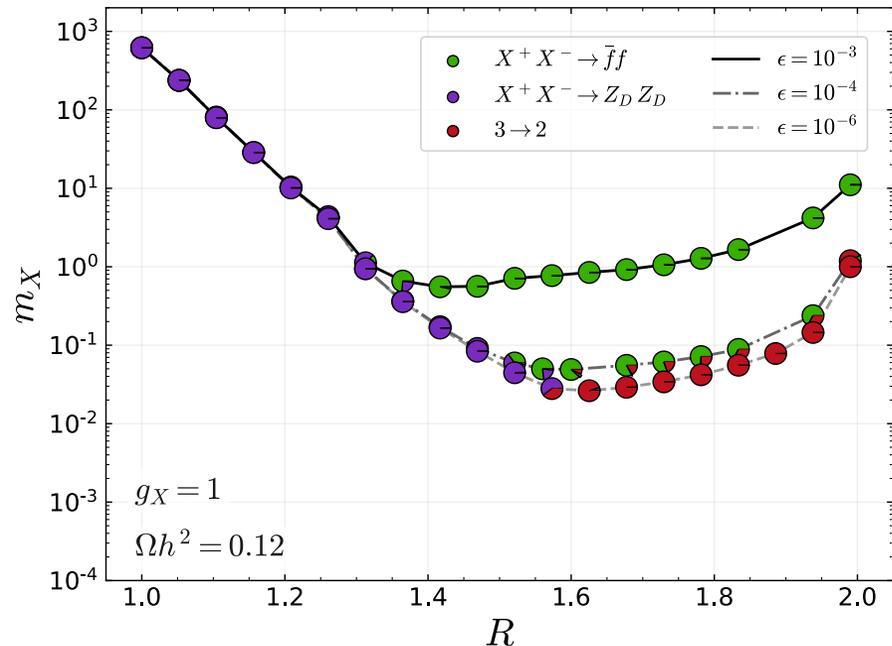
3 Alternative scenario: Mass splitting

→ To check the effects of different channels we allow for a **mass splitting** between the mediator and the DM states

$$R = \frac{m_{Z_D}}{m_X}$$

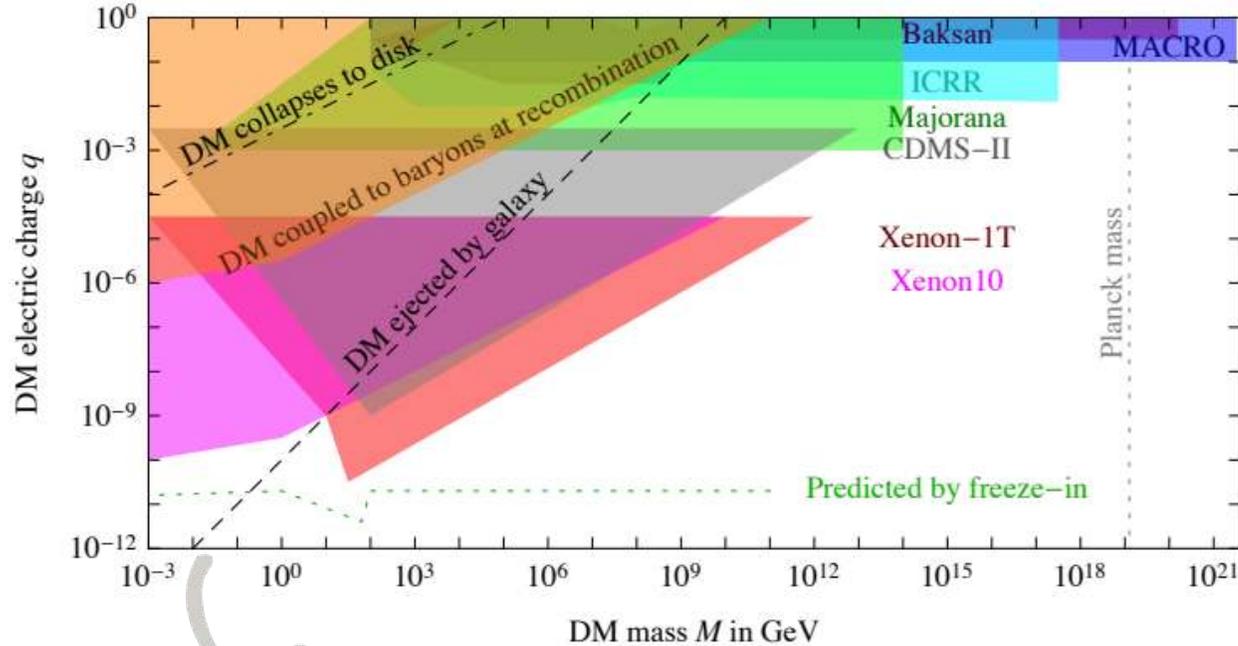
→ This scenario can be achieved if, for example, the dark scalar belongs to a higher multiplet representation

Check: [arXiv:2012.11377](https://arxiv.org/abs/2012.11377)



Bounds

[arXiv:2406.01705](https://arxiv.org/abs/2406.01705)



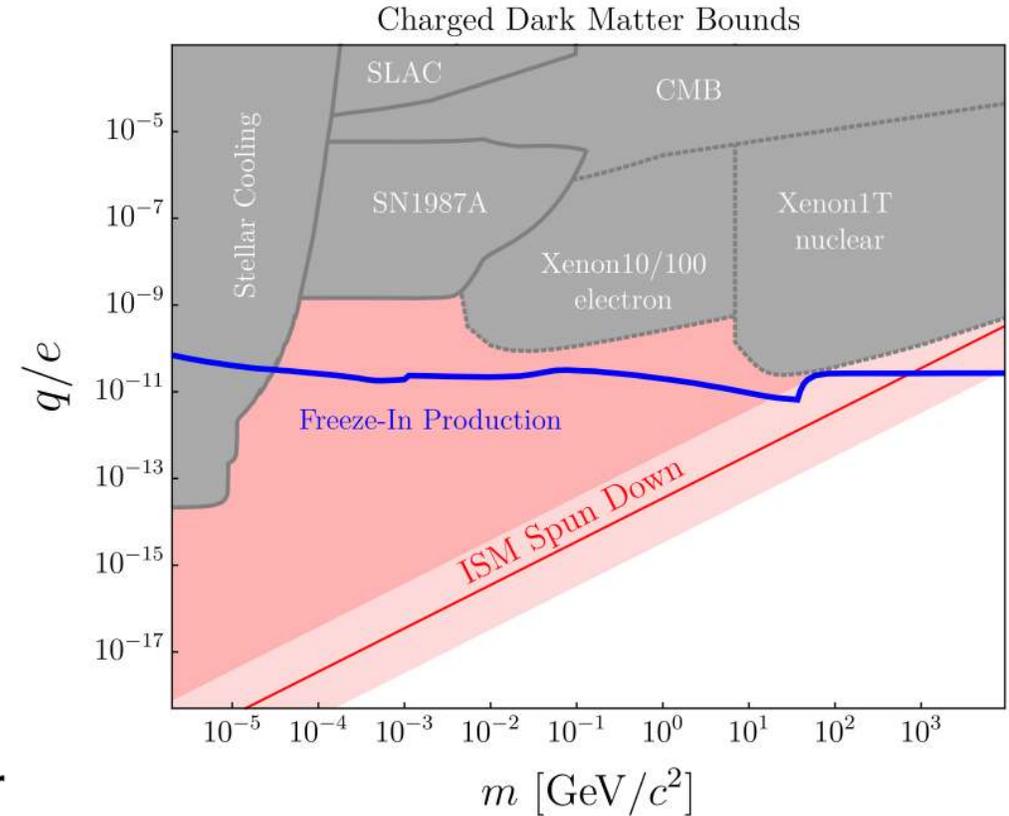
Reopening the window on charged dark matter

Leonid Chuzhoy, Edward W. Kolb

[arXiv:0809.0436](https://arxiv.org/abs/0809.0436)

ABSTRACT: We reexamine the limits on charged dark matter particles. We show that if their mass and charge fall in the range $100(q_X/e)^2 \lesssim m_X \lesssim 10^8(q_X/e)$ TeV, then magnetic fields prevent particles in the halo from entering the galactic disk, while those initially trapped inside are accelerated through the Fermi mechanism and ejected within about 0.1 – 1 Gyrs. Consequently, previous constraints on charged dark matter based on

[arXiv:1908.05275](https://arxiv.org/abs/1908.05275)



DM-ISM interactions change disk angular momentum ?

apparently, only for “true” milli-charges...

[arXiv:2112.11476](https://arxiv.org/abs/2112.11476)

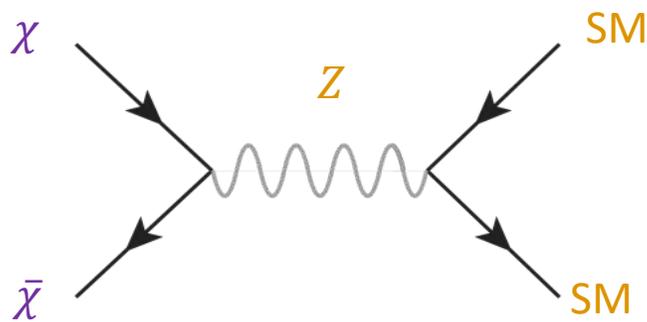
Introduction and Motivations

How can we search for light particle BSM signals?



Suppose we have particles χ and $\bar{\chi}$ in the dark sector

→ natural possibility: couple to the gauge bosons of **weak interactions**



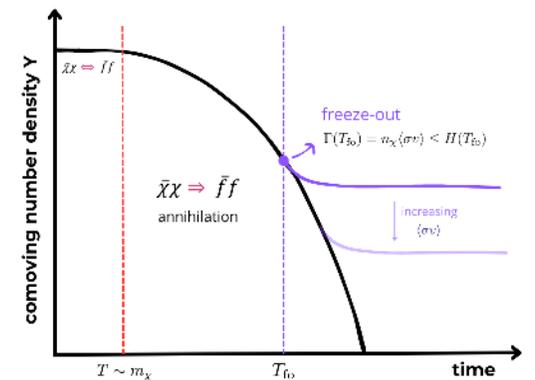
However...

$$\langle \sigma v \rangle \sim \frac{m_\chi^2}{m_Z^4}$$

which means that lowering the DM mass decreases the thermal-average cross section

→ **DM is overproduced!**

Remember!



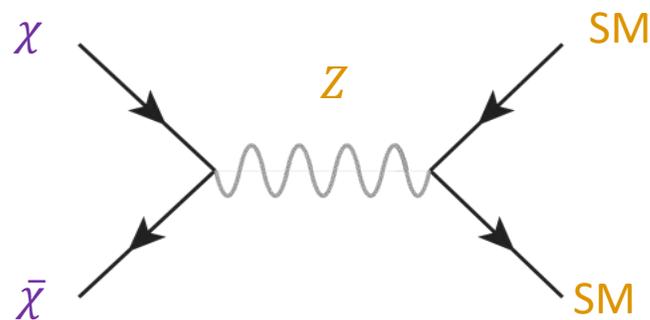
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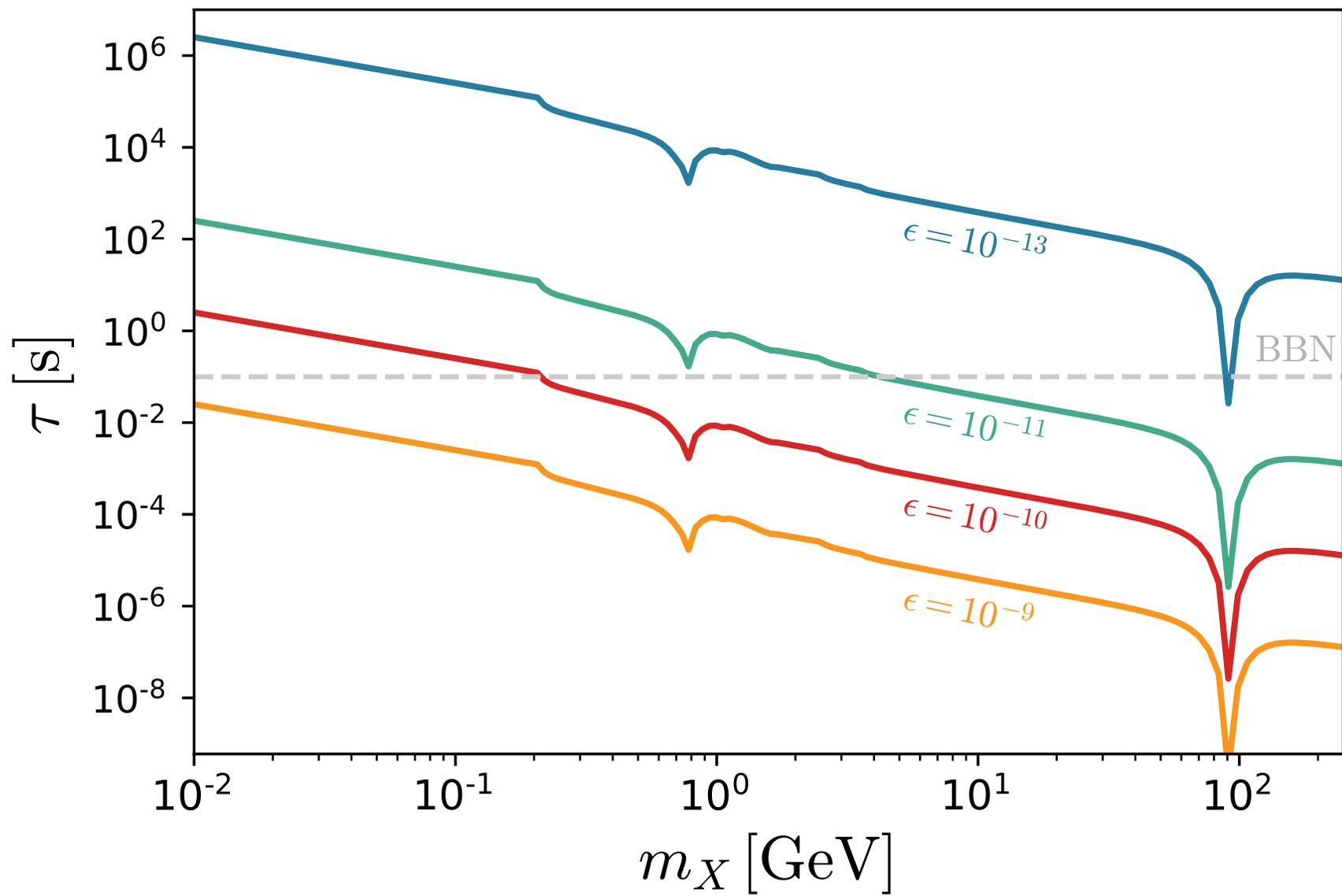
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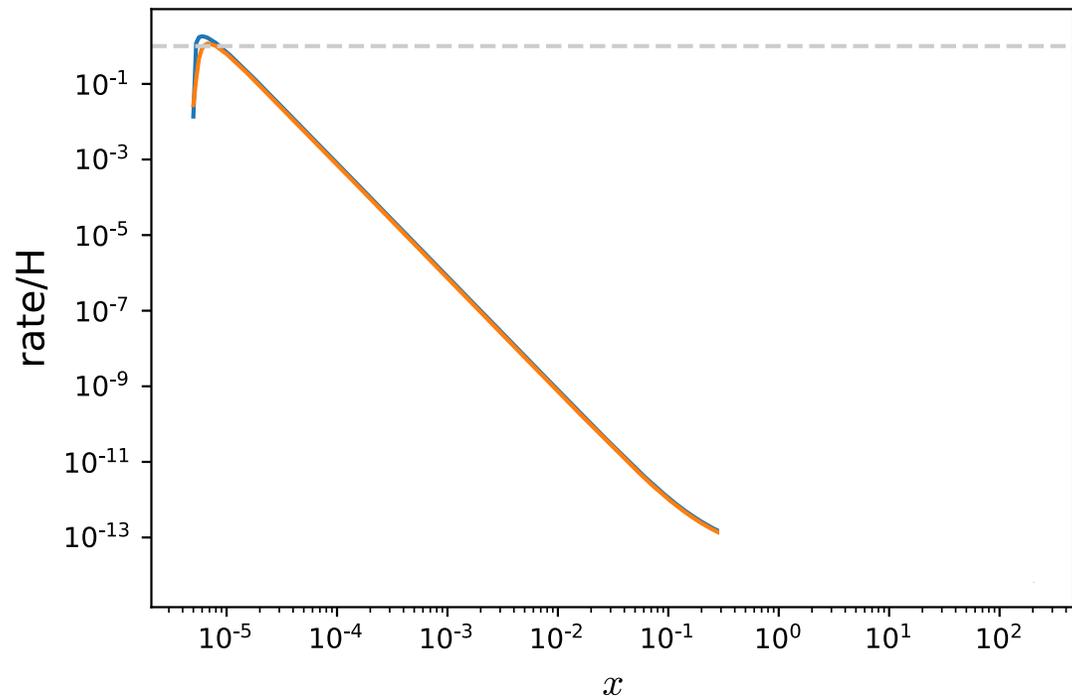
→ **DM is overproduced!**

Lee-Weinberg bound

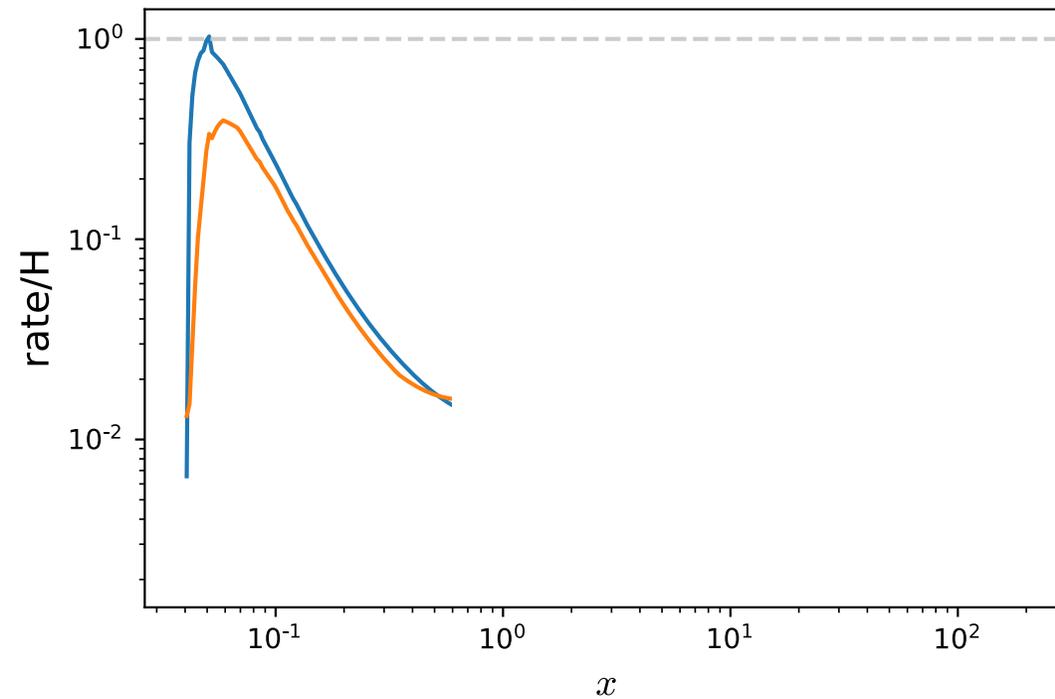
$$m_\chi \gtrsim 2 \text{ GeV}$$



mDM=10 GeV , eps= 5.5e-15 , gDM= 1e-05, R= 1 , Trh = 1999999 GeV



mDM=10 GeV , eps= 2.7e-12 , gDM= 0.007, R= 1 , Trh = 246.0 GeV



UV-completion

More details will be given shortly.

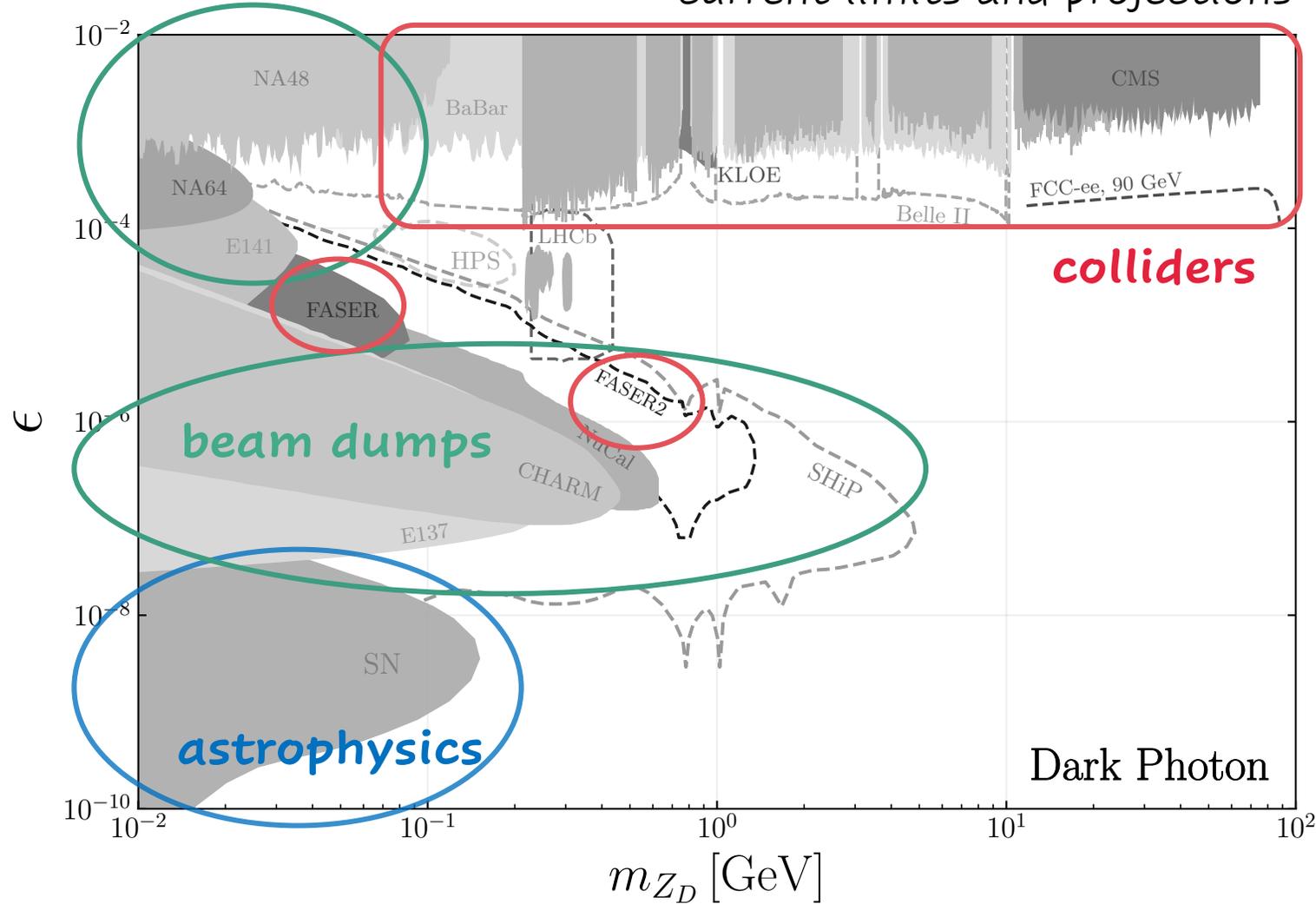
The effective operators in Eq. (6) can be induced by integrating out certain scalar(s) crossing the dark and SM sectors. For example, an $[SU(2)_X]$ -doublet scalar with $U(1)_Y$ charge can mediate the $SU(2)_X \times U(1)_Y$ mixing, an $[SU(2)_X]$ -doublet and $[SU(2)_L]$ -triplet scalar without $U(1)_Y$ charge can mediate the $SU(2)_X \times SU(2)_L$ mixing, while an $[SU(2)_X \times SU(2)_L]$ -bidoublet scalar with $U(1)_Y$ charge or an $[SU(2)_X]$ -doublet and $[SU(2)_L]$ -triplet with $U(1)_Y$ charge can mediate both of the $SU(2)_X \times U(1)_Y$ and $SU(2)_X \times SU(2)_L$ mixing. It should be noted these crossing scalars are also non-trivial under the $U(1)_D$ global symmetry to forbid some unexpected couplings.

[arXiv:2209.08843](https://arxiv.org/abs/2209.08843)

Vector Portal

- Hunting for the Dark Photon

current limits and projections



strategy

1. Dark Vector production

→ Meson Decays

$$M \rightarrow \gamma Z_D \quad (M = \pi^0, \eta, K, D, \dots)$$

$$\omega \rightarrow \pi^0 Z_D, \quad \phi \rightarrow \eta Z_D$$

→ Bremsstrahlung

$$e^- N \rightarrow e^- N Z_D$$

$$p N \rightarrow p N Z_D$$

→ Drell-Yan

$$q \bar{q} \rightarrow Z_D$$

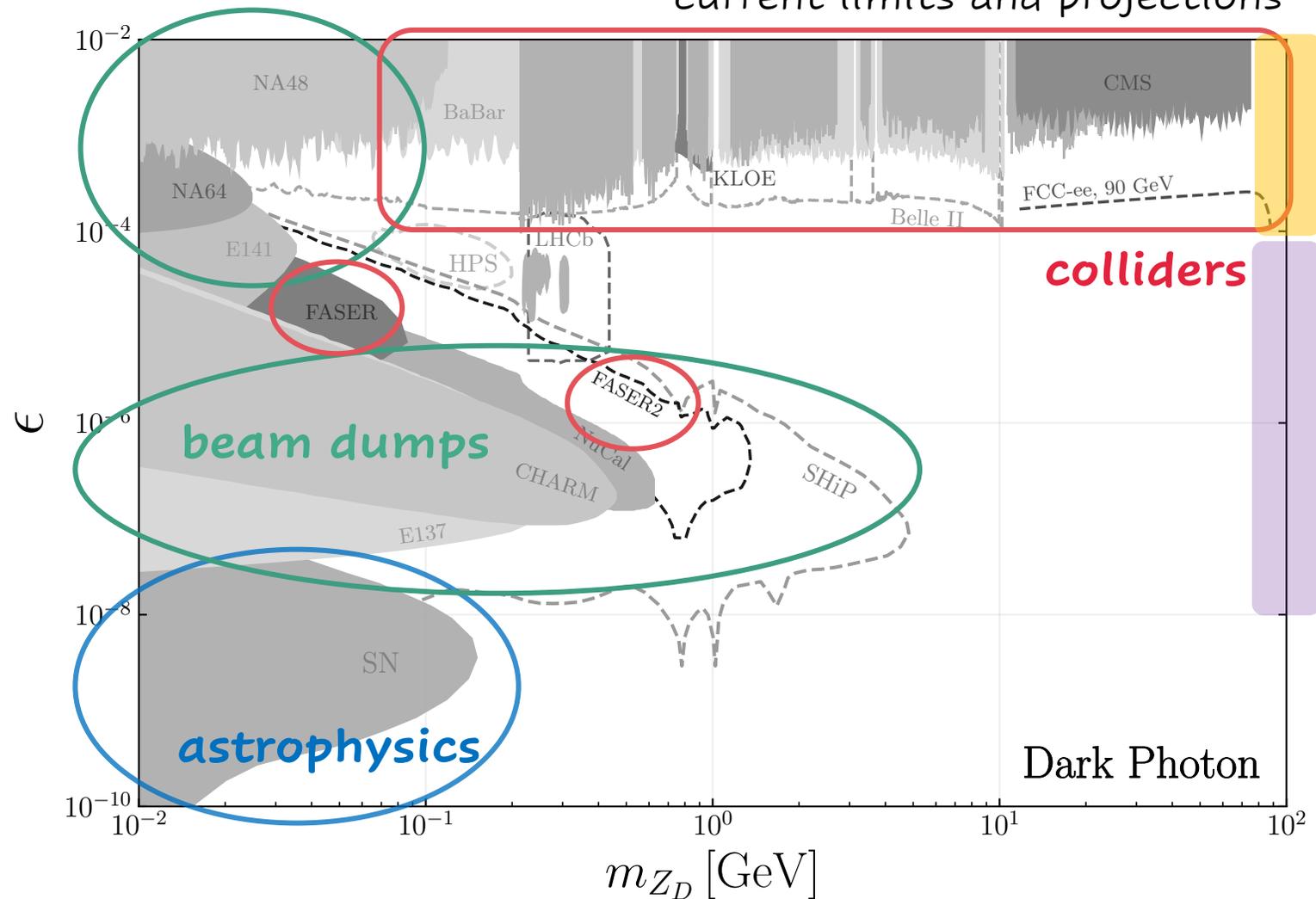
→ $e^+ e^-$ annihilation

$$e^+ e^- \rightarrow \gamma Z_D$$

Vector Portal

- Hunting for the Dark Photon

current limits and projections



strategy

1. Dark Vector production
2. Dark Vector propagates and...

→ prompt

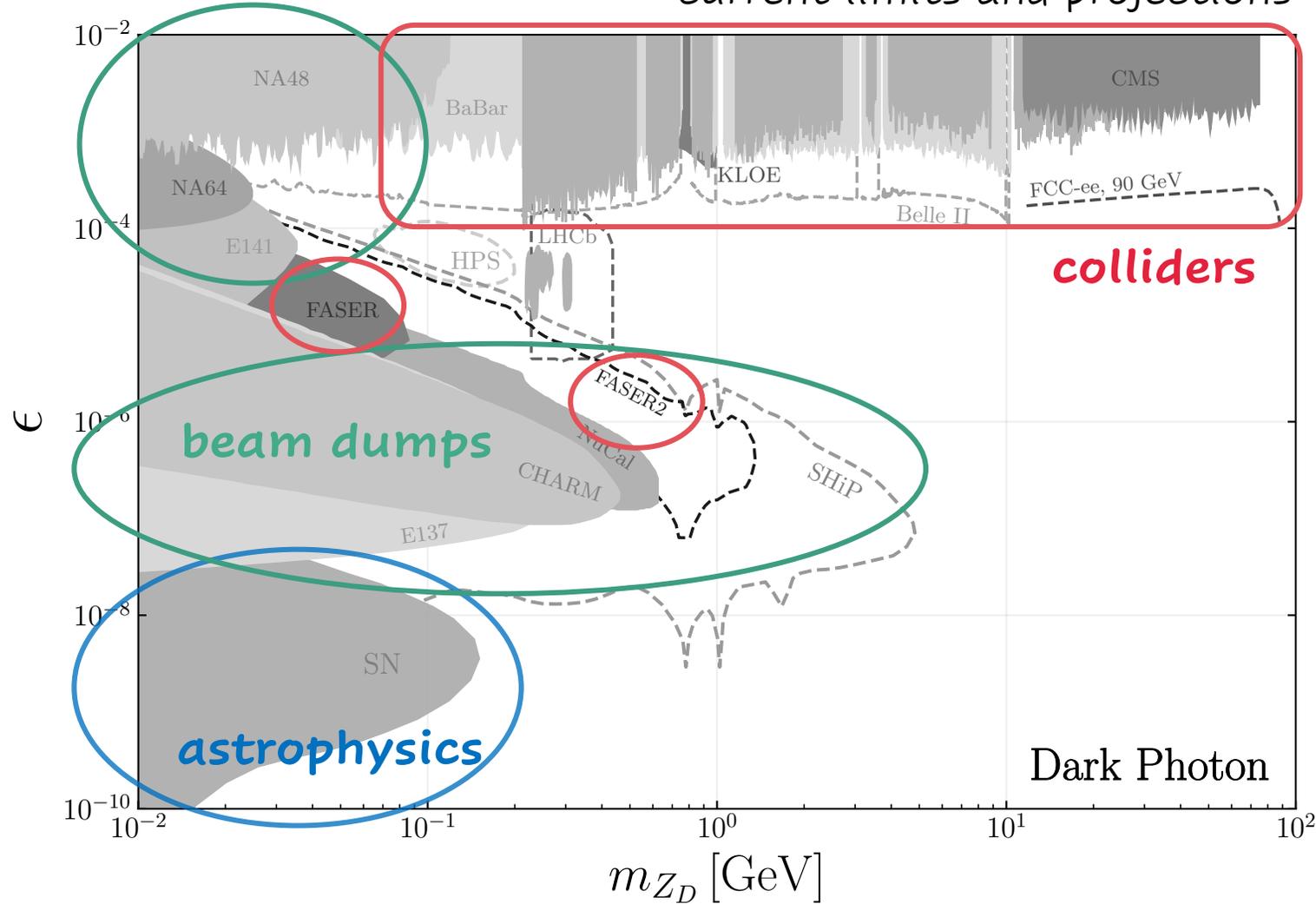
→ displaced

(long-lived particle)

Vector Portal

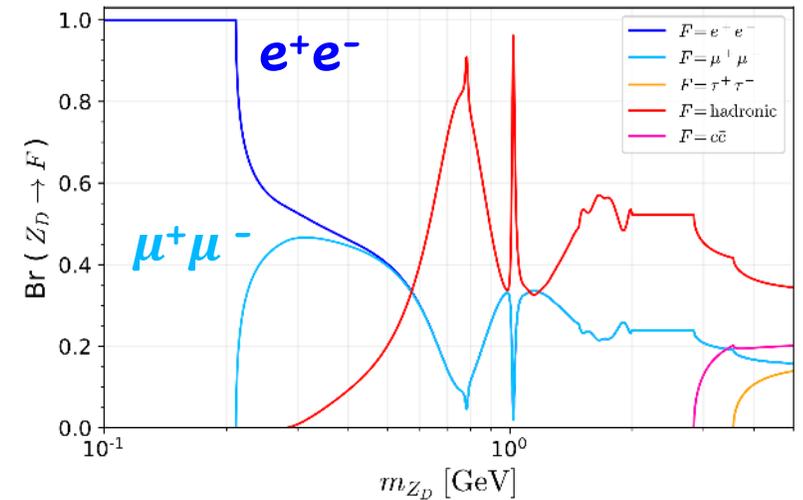
- Hunting for the Dark Photon

current limits and projections



strategy

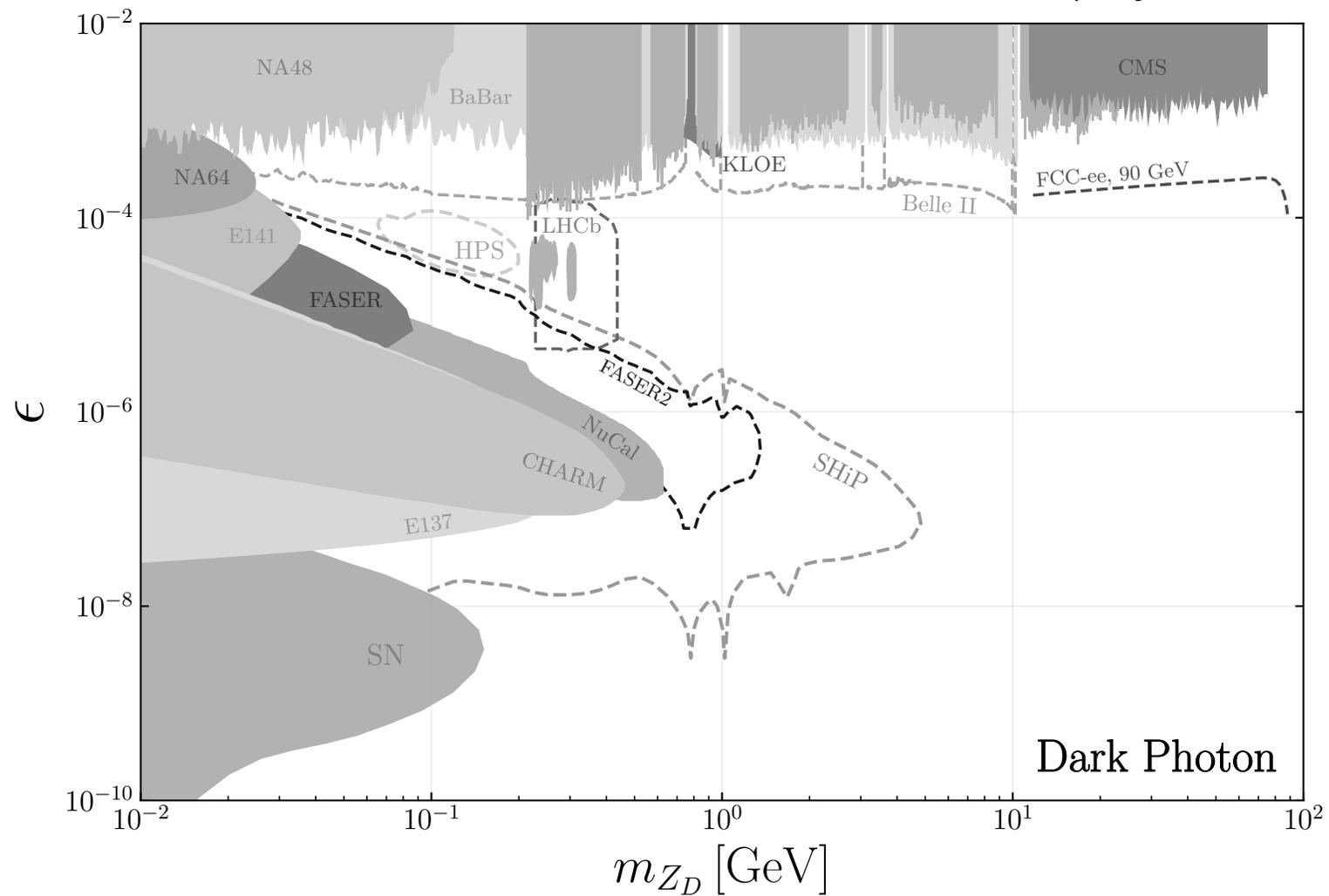
1. Dark Vector production
2. Dark Vector propagates and...
3. Decay to SM states



Vector Portal

- Hunting for the Dark Photon

current limits and projections



[Fradette *et al.*, arXiv:1407.0993]

