Unlocking the Inelastic Dark Matter window with Vector Mediators

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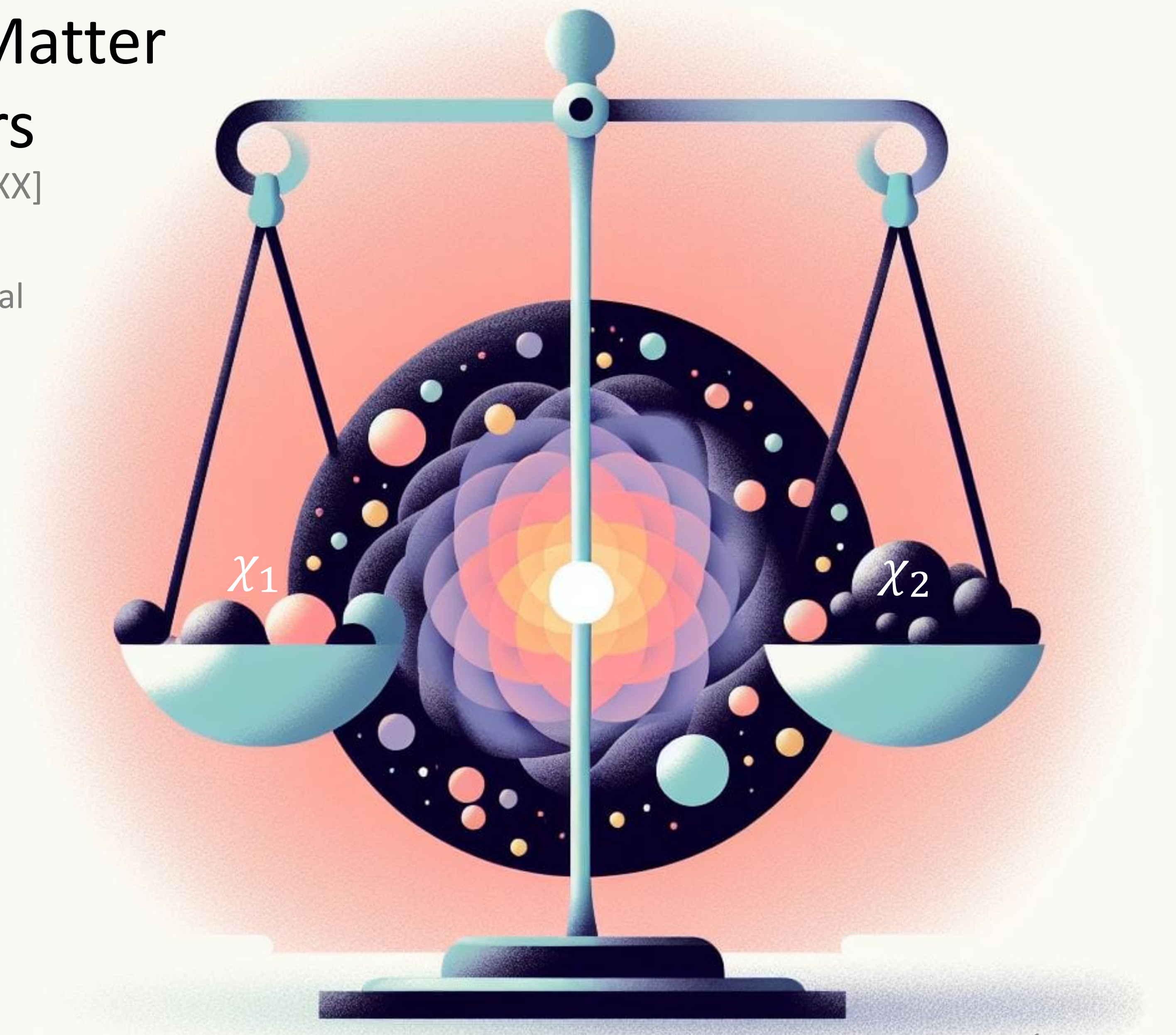
26 September 2024



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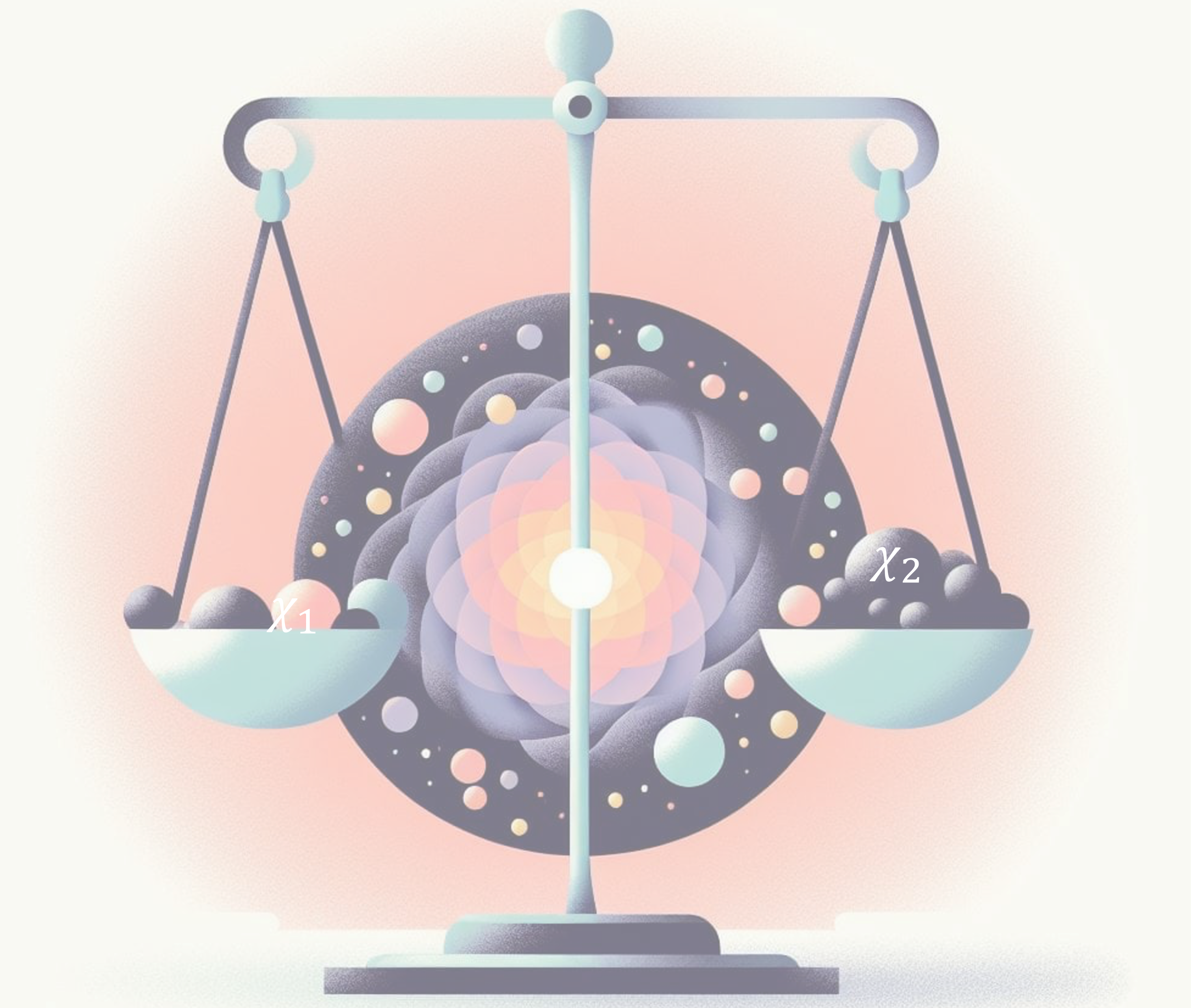
Outline

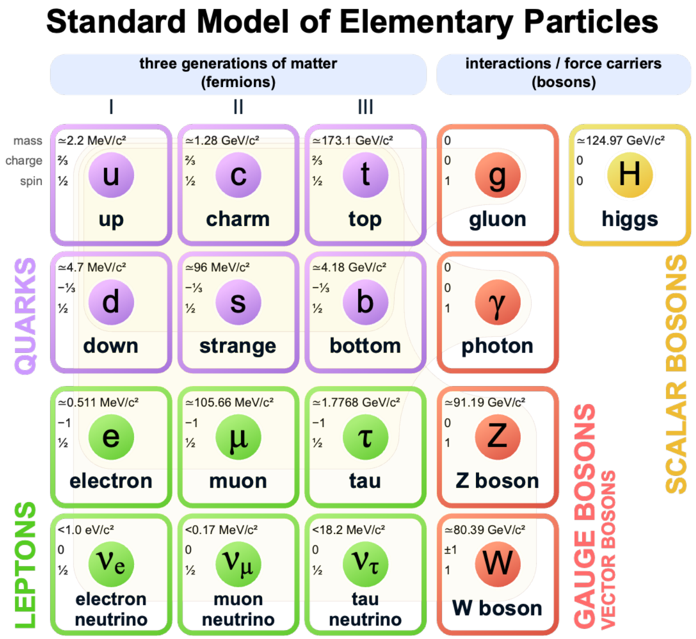
1. Introduction and Motivations
2. Inelastic Dark Matter
   - Theoretical framework
   - Decay Rates
3. Relic Density Computation
4. ReD-DeLiVeR code
5. Bounds
6. Conclusions



Introduction and Motivations

Standard Model (SM)

- → most successful description of the fundamental interactions between elementary particles (up to this date!)
- → several confirmed experimental predictions



SM gauge group

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

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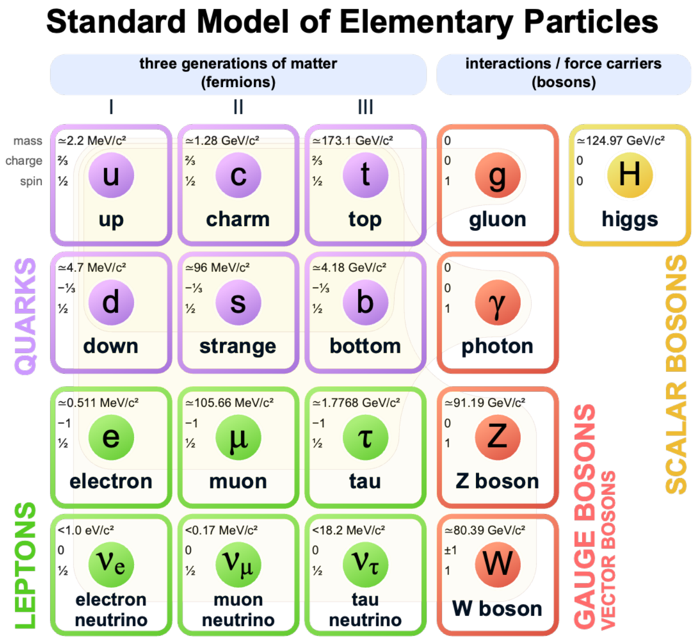

However... it cannot be the final theory of Nature!

There are several problems and unanswered questions

- Hierarchy Problem
- Neutrino Masses
- Dark Matter candidates + ⋯

?

How can we find a solution?

We need to rely on Beyond the Standard Model (BSM) theories

SM gauge group

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

Introduction and Motivations

Where can we search for BSM signals?

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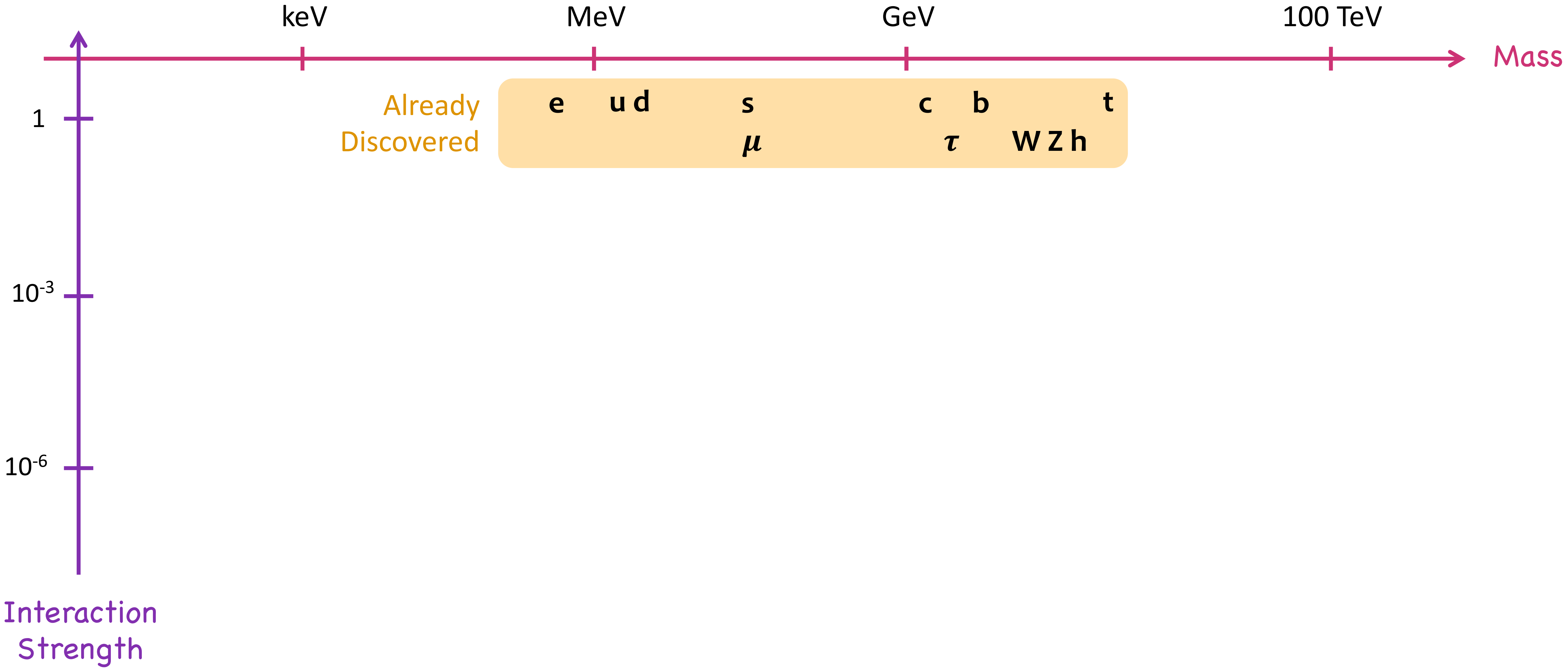

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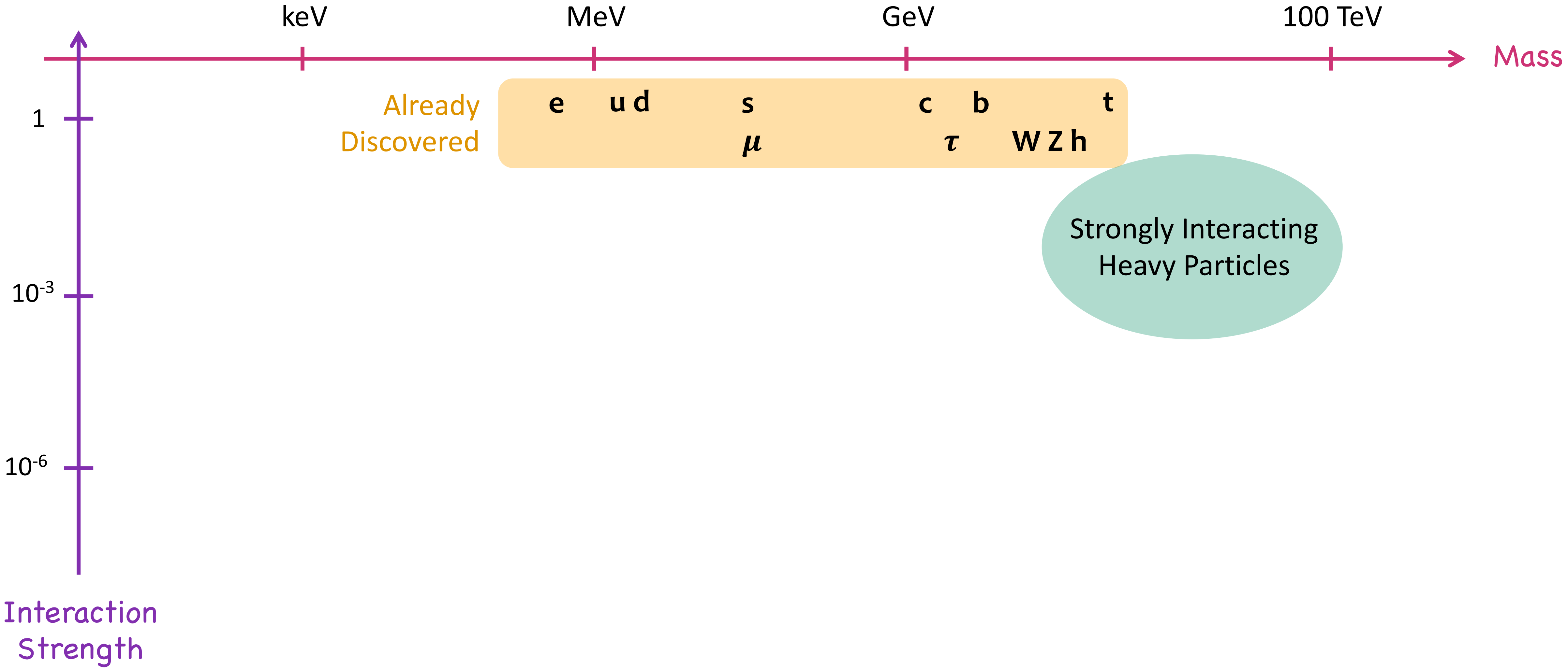

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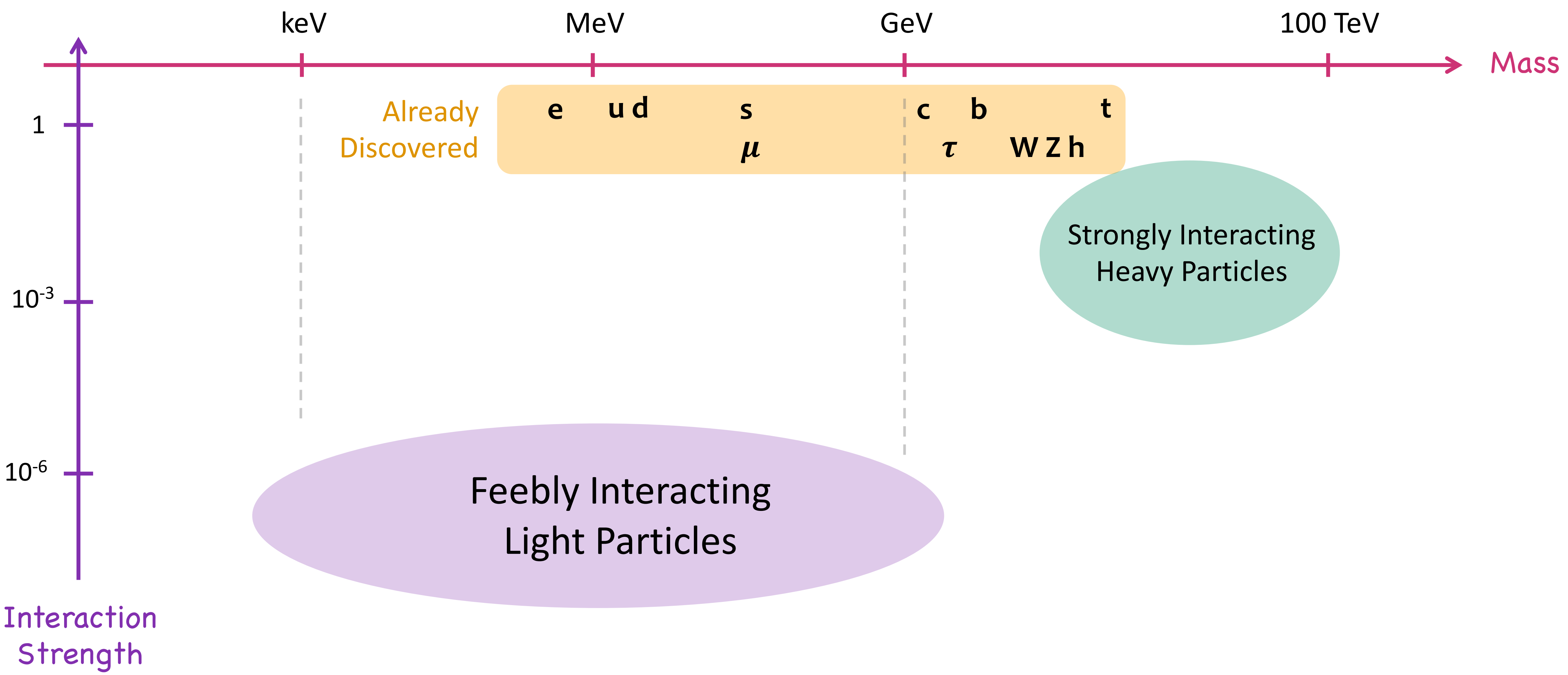

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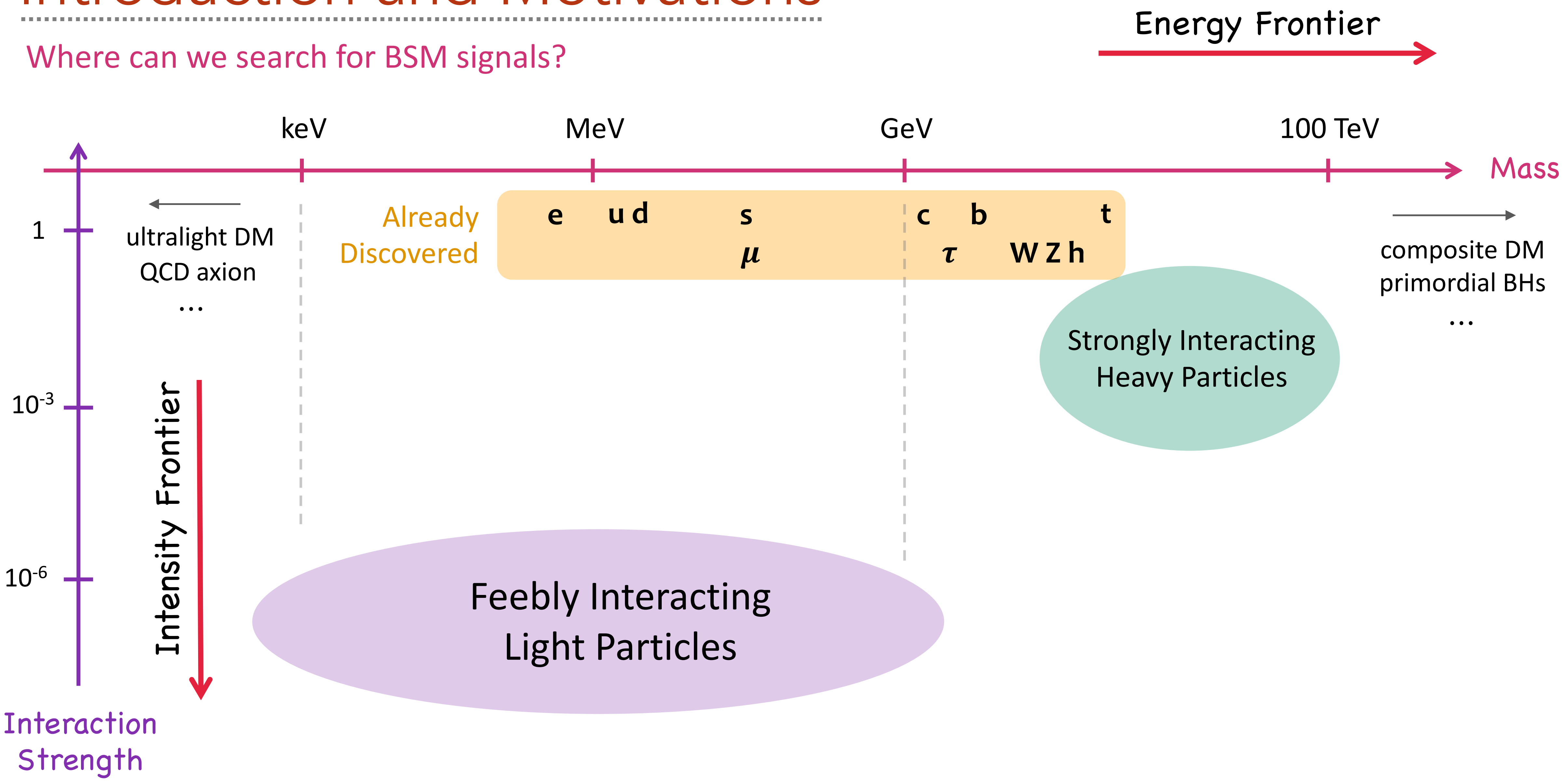

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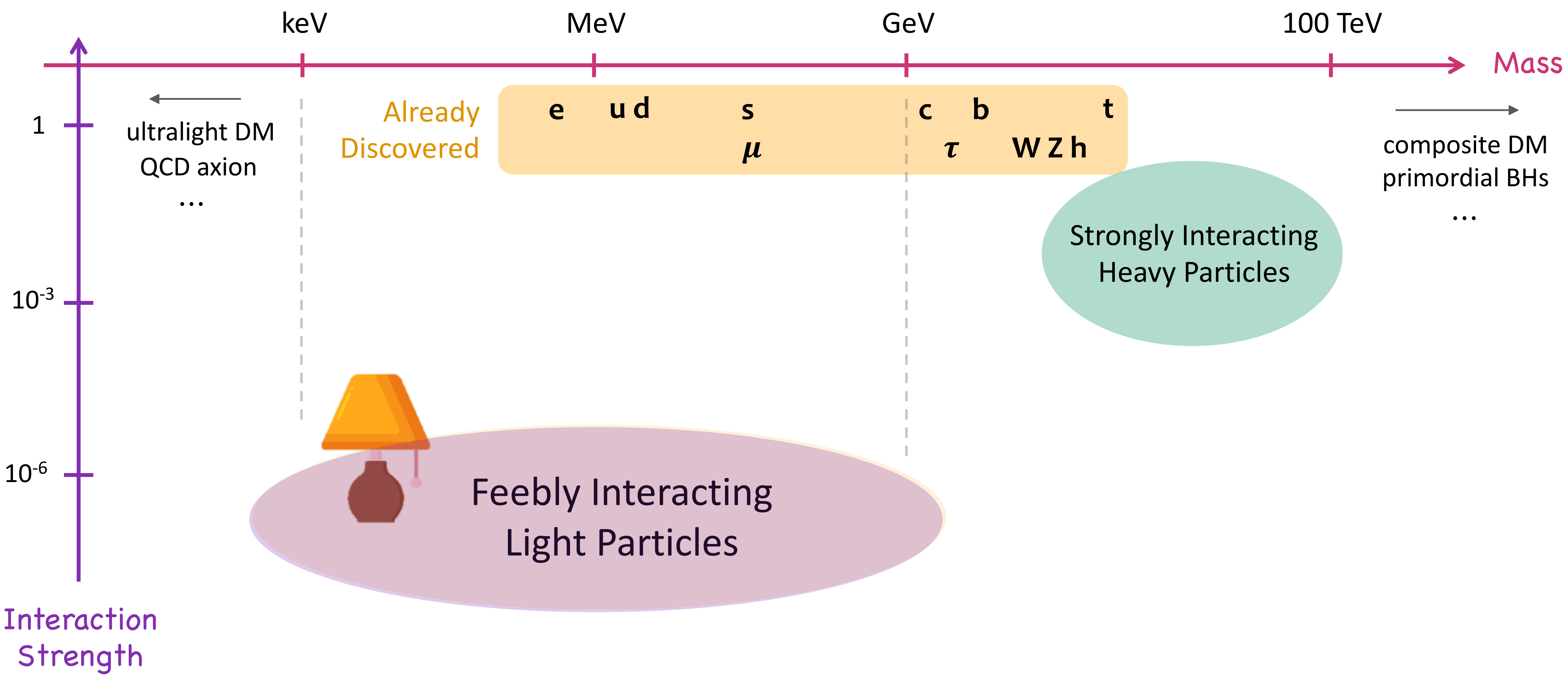

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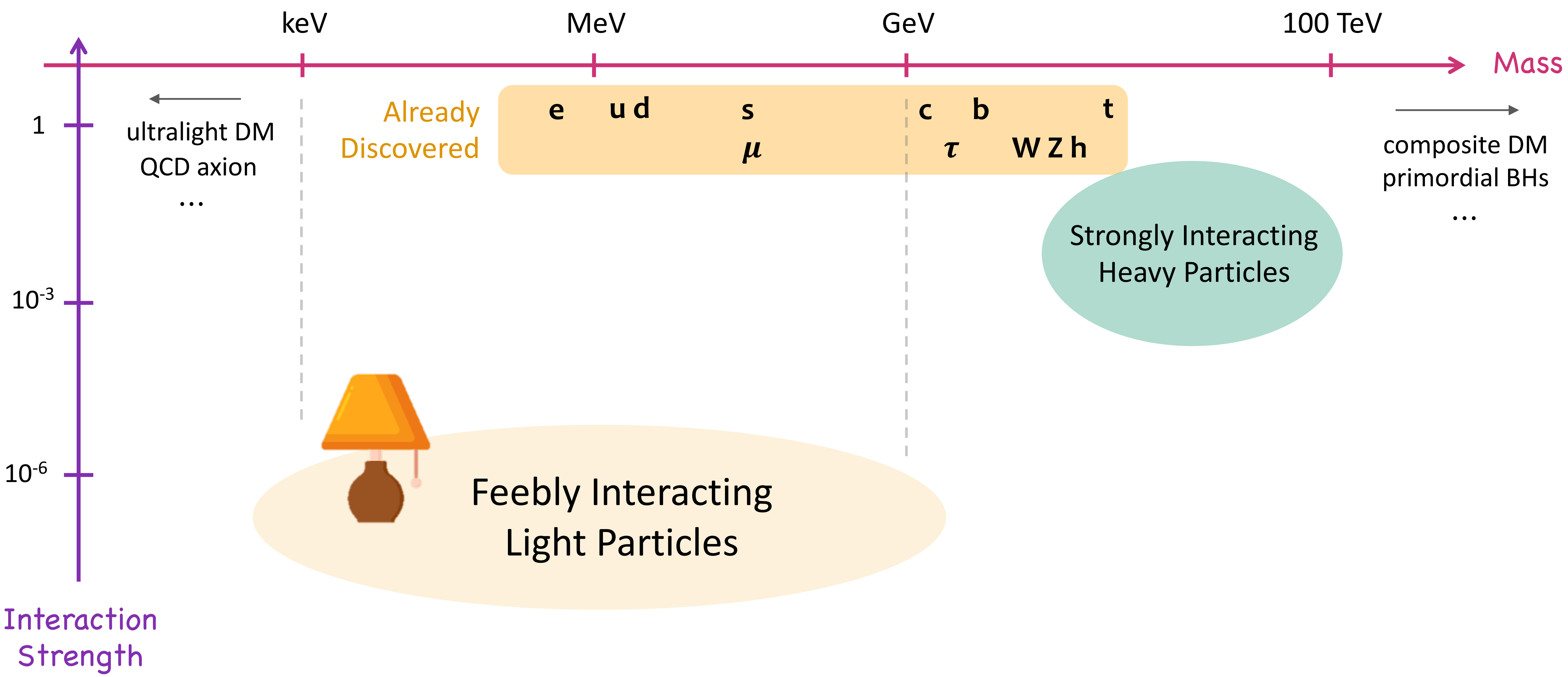

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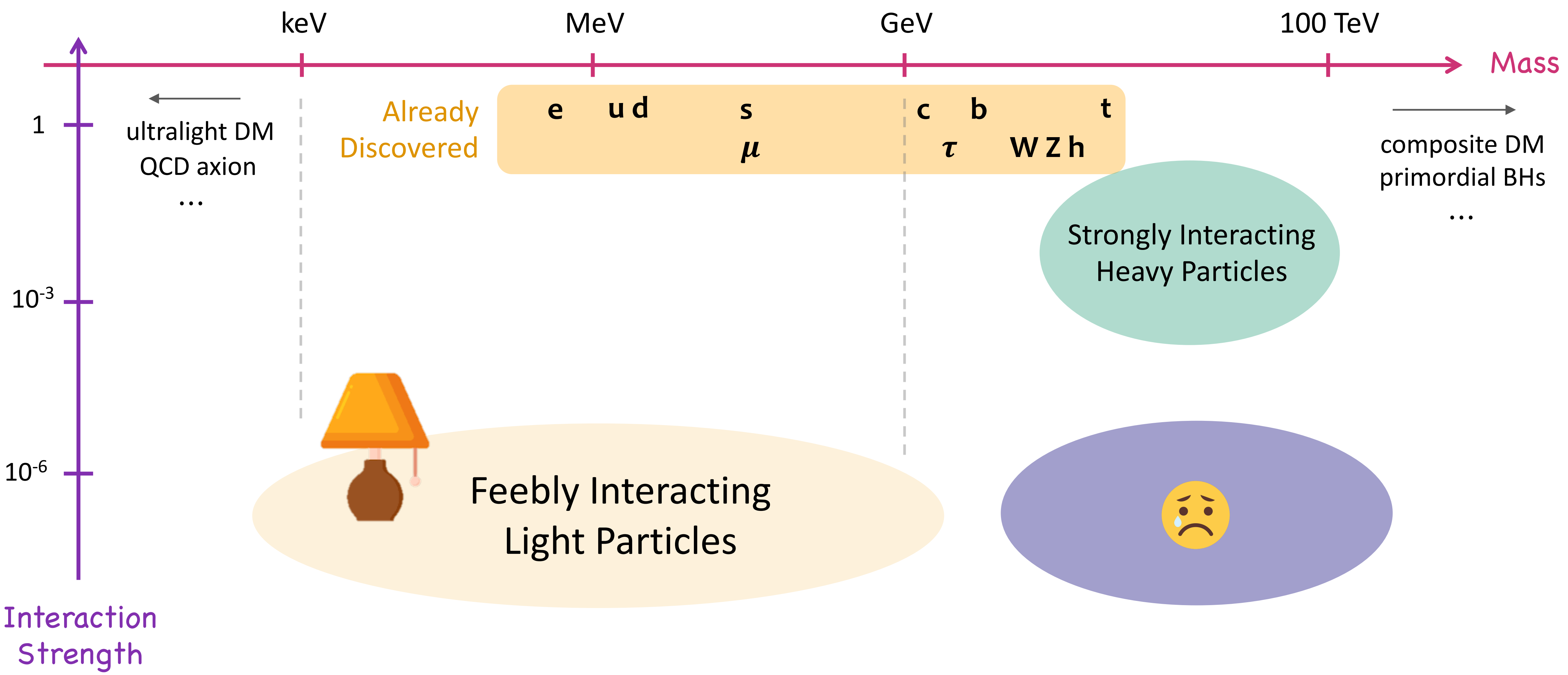
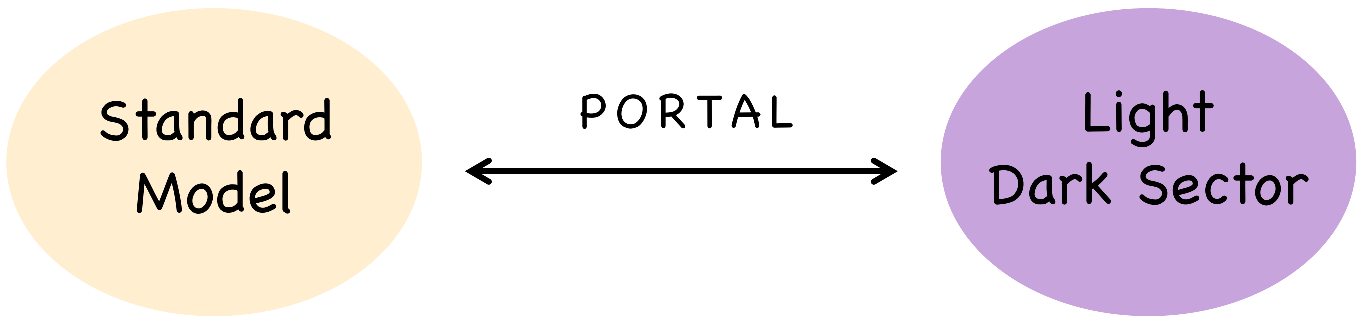


Introduction and Motivations

How can we search for light particle BSM signals?



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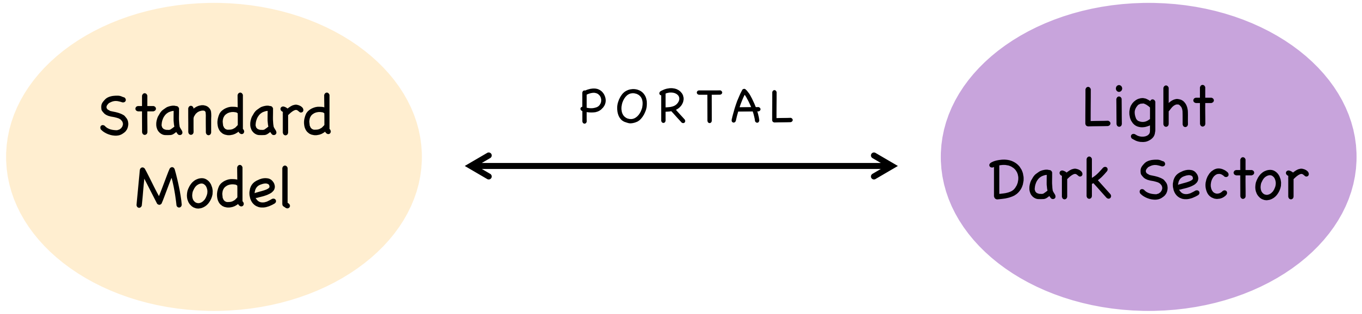
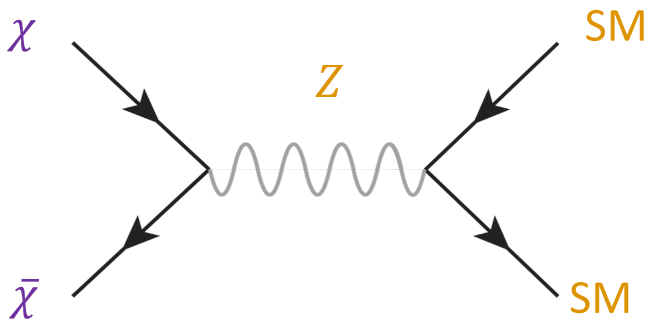


Suppose we have particles χ and $\bar{\chi}$ in the dark sector

↪ 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!

Lee-Weinberg bound

$$m_\chi \gtrsim 2\,\mathrm{GeV}$$

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Lee-Weinberg bound

$$m_\chi \gtrsim 2\,\mathrm{GeV}$$

$\Rightarrow$ So, how can we explore sub-GeV dark sectors?

solution: inclusion of new light dark sector mediator states!

These light mediators will act as portals between the dark sector and the SM.

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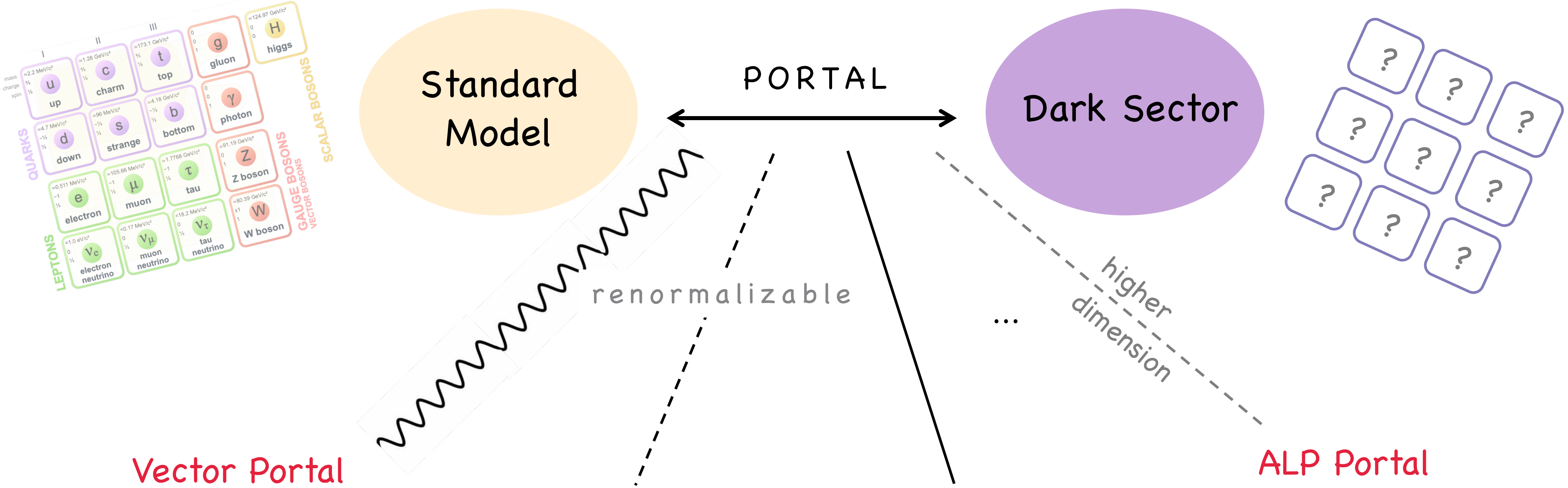

Vector Portal

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

dark boson

Scalar Portal

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

dark Higgs

Neutrino Portal

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

Heavy Neutral Lepton

ALP Portal

axion-like-particle

a → photons

a → leptons

a → ...

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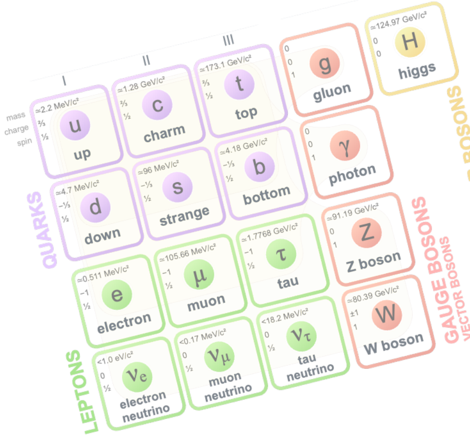
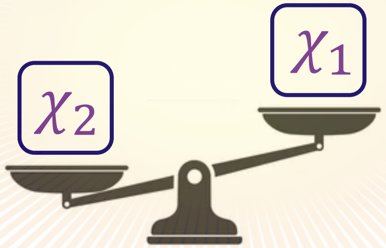


Standard Model

PORTAL

Dark Sector

Inelastic Dark Matter



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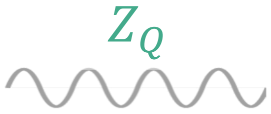
Inelastic Dark Matter

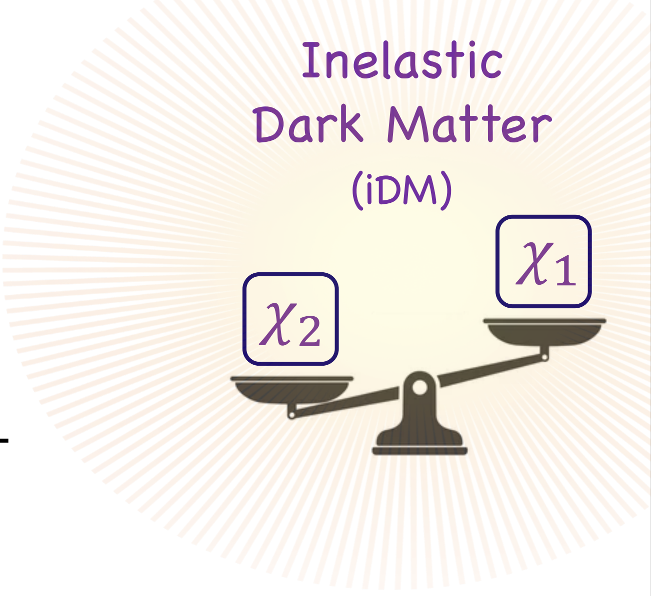
Theoretical Framework

Dark Sector

- two-component Weyl fermions forming a Dirac pair ⇒ pseudo-Dirac pair

- new vector mediator coming from a spontaneously broken $\mathrm{U}(1)_\mathrm{Q}$ abelian gauge symmetry





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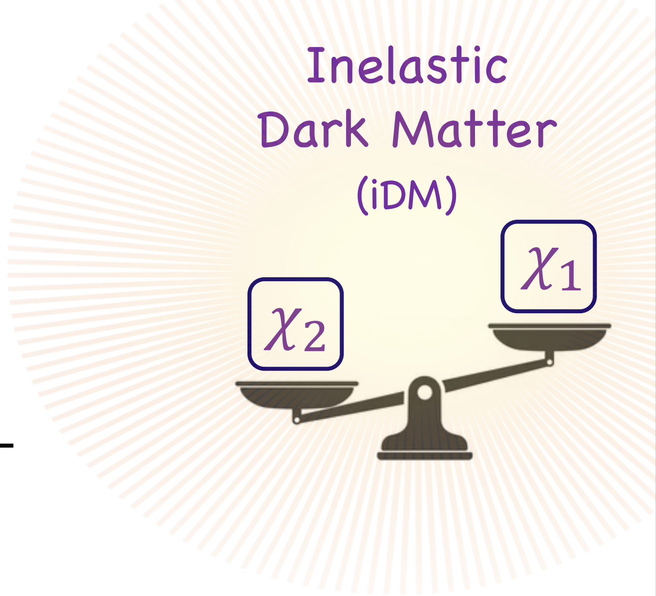

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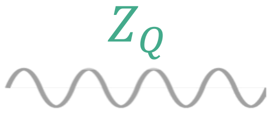

From the diagonalization of the fermion mass terms

Dirac / Majorana

$$\mathcal{L} \supset -m_D \psi_1 \psi_2 - \frac{1}{2}(\delta_1\, \psi_1^2 + \delta_2\, \psi_2^2) + \text{h.c.}\,, \qquad \text{with} \qquad \delta_{1,2} \ll m_D$$

⇒ mass eigenstates

$$\chi_1 \simeq \frac{i}{\sqrt{2}}(\psi_1 - \psi_2),$$

pseudo-Dirac pair with nearly degenerate masses

$$\chi_2 \simeq \frac{1}{\sqrt{2}}(\psi_1 + \psi_2)\,,$$

$$m_{1,2} \simeq m_D \mp \frac{1}{2}(\delta_1 + \delta_2) \quad \Rightarrow \quad \Delta := \frac{m_2 - m_1}{m_1} = \frac{\delta_1 + \delta_2}{m_1} < 1$$

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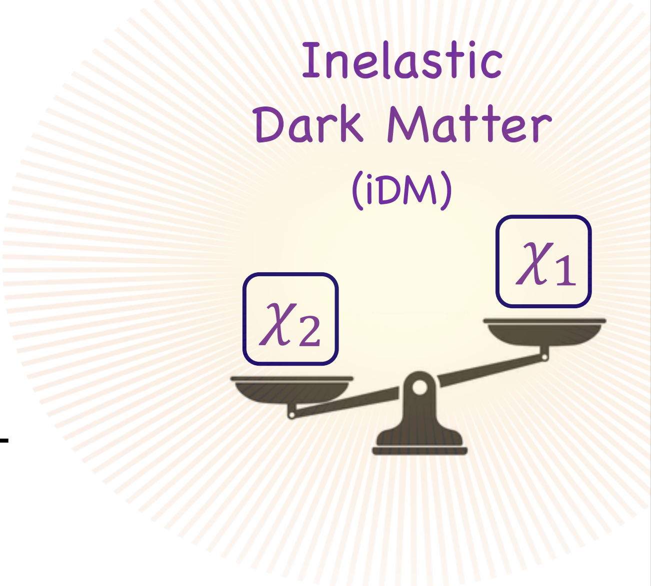

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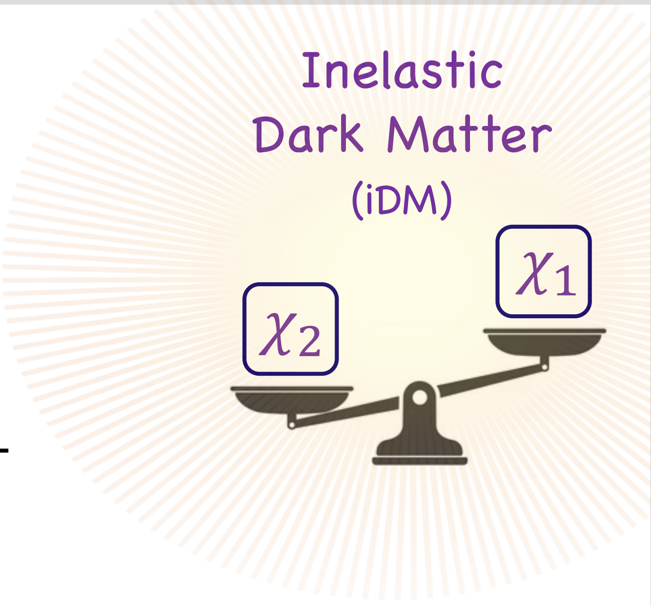

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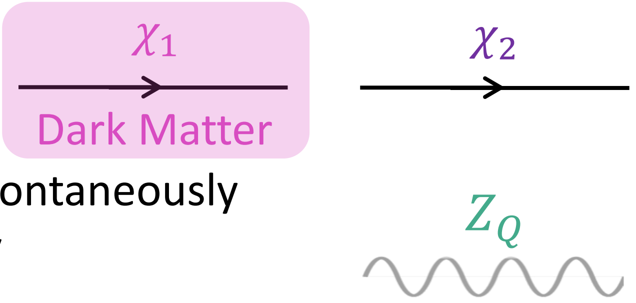

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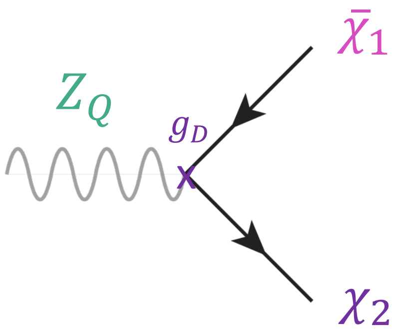

The interaction term with the mediator turns to be off-diagonal

$$\mathcal{L} \supset g_D Z_{Q\mu}(\psi_1^\dagger \bar{\sigma}^\mu \psi_1 - \psi_2^\dagger \bar{\sigma}^\mu \psi_2) \longrightarrow \mathcal{L}_{\text{int}}^{\text{D}} = \frac{i}{2} g_D Z_{Q\mu} \bar{\chi}_2 \gamma^\mu \chi_1 + \text{h.c.}$$

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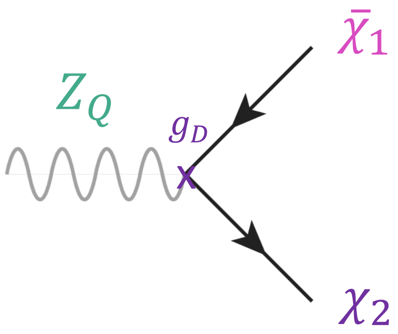

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Motivations

↪ **Thermal relics:** DM abundance can be computed via thermal freeze-out.

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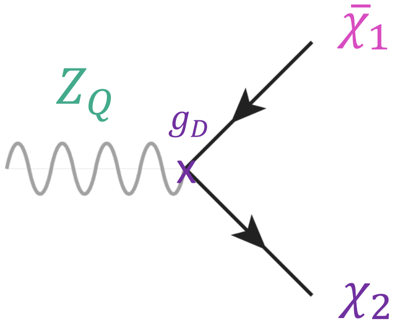

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- **Thermal relics:** DM abundance can be computed via thermal freeze-out.
- **Evades indirect and direct detection experimental limits**

The heavier state χ_2 can decay into the DM candidate χ_1, depleting its abundance

$\Rightarrow$ no present-day population of heavier states to co-annihilate with the DM $\rightarrow$ avoid indirect detection signals

$\Rightarrow$ similarly, direct detection signals depend on up-scatter of the light state, which is kinematically suppressed

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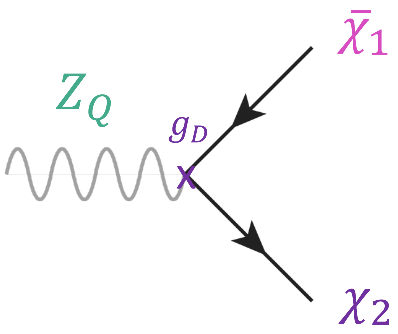

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  $\Rightarrow$ similarly, direct detection signals depend on up-scatter of the light state, which is kinematically suppressed

- **Evades stringent CMB limits**

  Since the abundance of χ_2 is already reduced during recombination era, coannihilations that would inject energy into the plasma are suppressed.

Inelastic Dark Matter

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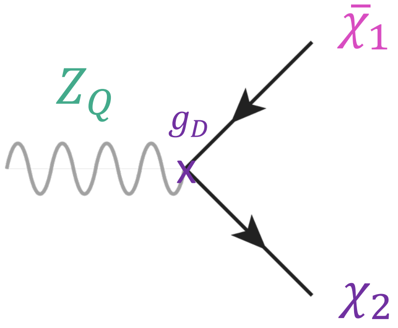

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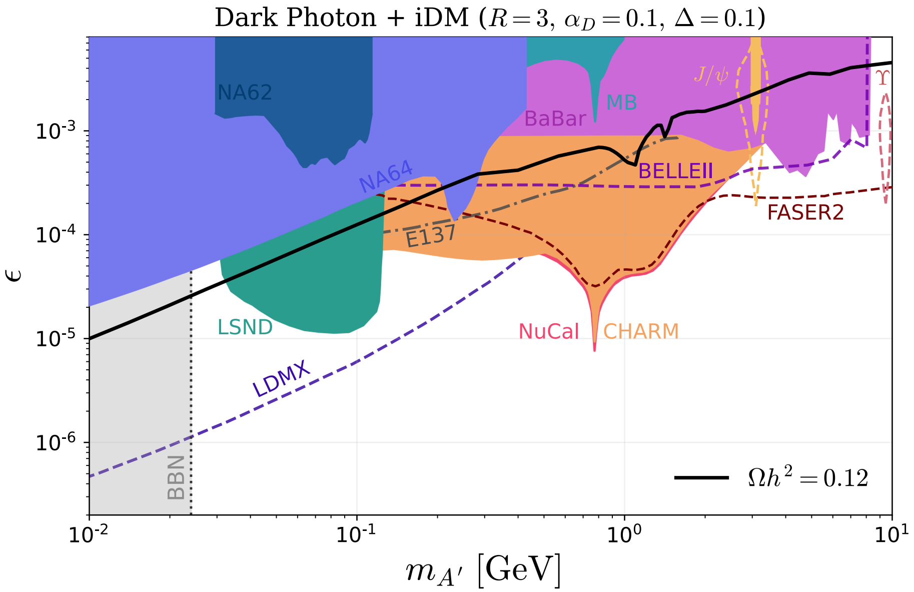
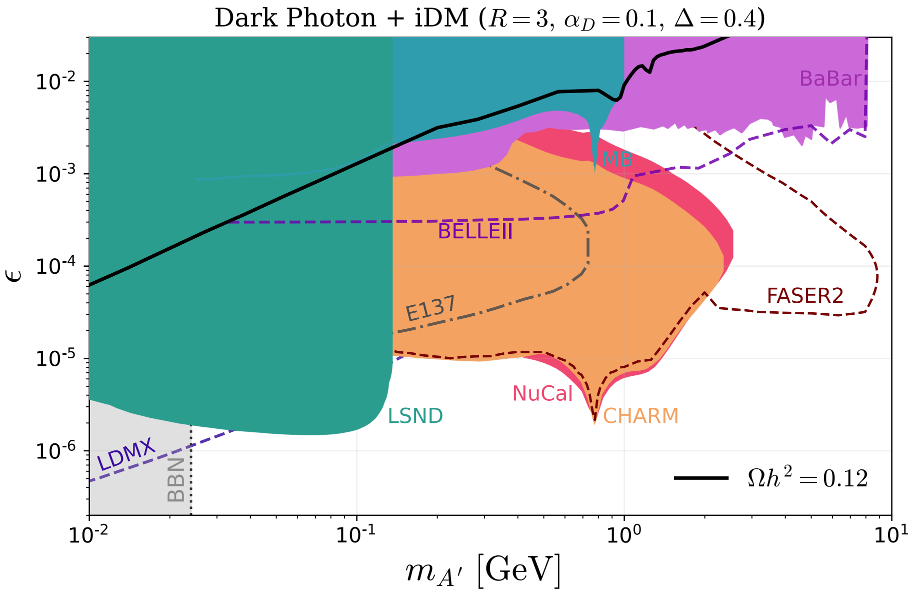
What's new?

- In the literature: only considered the minimal scenario with a secluded dark photon portal Z_D

However… this case has been nearly completely ruled out by experimental limits…





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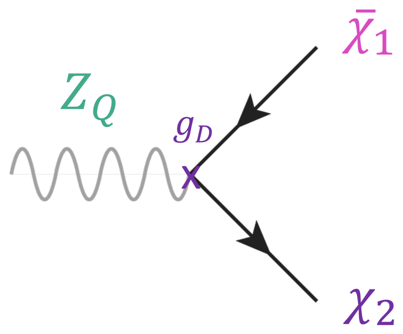

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What's new?

- This work: we consider the case of generic charges for the $\mathrm{U}(1)_{\mathrm{Q}}$ group

⇓

vector mediator also couples to the SM via direct terms depending on the choice of charge

$$\mathcal{L}_{\rm int}^{\rm SM} = e\epsilon J^\mu_{\rm em} Z_{Q\mu} - g_Q J^\mu_Q Z_{Q\mu}$$

$$J^\mu_Q = \sum_f q_Q^f \, \bar{f}\gamma^\mu f + \sum_{\ell=e,\mu,\tau} q_Q^{\nu_\ell} \, \bar{\nu}_\ell \gamma^\mu P_L \nu_\ell,$$

$$Q = x_B B - x_e L_e - x_\mu L_\mu - x_\tau L_\tau$$

x_B	x_e	x_μ	x_τ	Q	q_Q^f quarks	e/ν_e	μ/ν_μ	τ/ν_τ
1	1	1	1	$B-L$	$\frac{1}{3}$	-1	-1	-1
1	0	0	3	$B-3L_\tau$	$\frac{1}{3}$	0	0	-3
1	0	0	0	B	$\frac{1}{3}$	0	0	0
0	0	-1	1	$L_\mu - L_\tau$	0	0	1	-1

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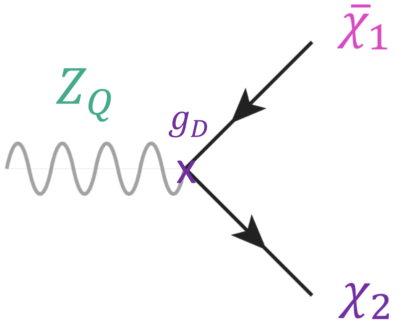

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iDM$_Q$ models

free parameters: $m_{Z_Q}, \; R, \; \Delta, \; g_Q, \; \alpha_D$

$$Q = x_B B - x_e L_e - x_\mu L_\mu - x_\tau L_\tau$$

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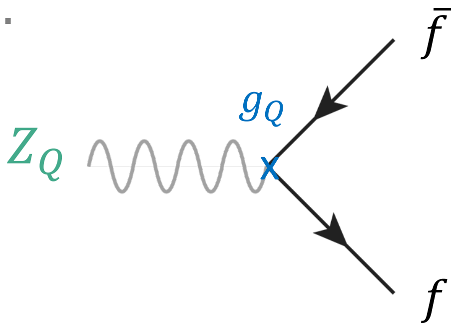
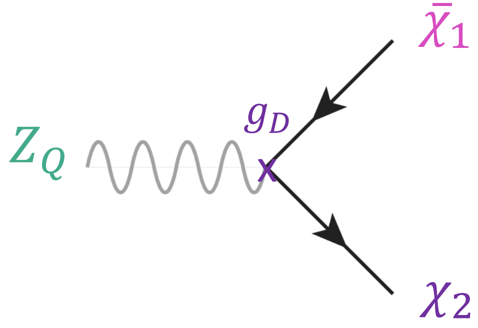
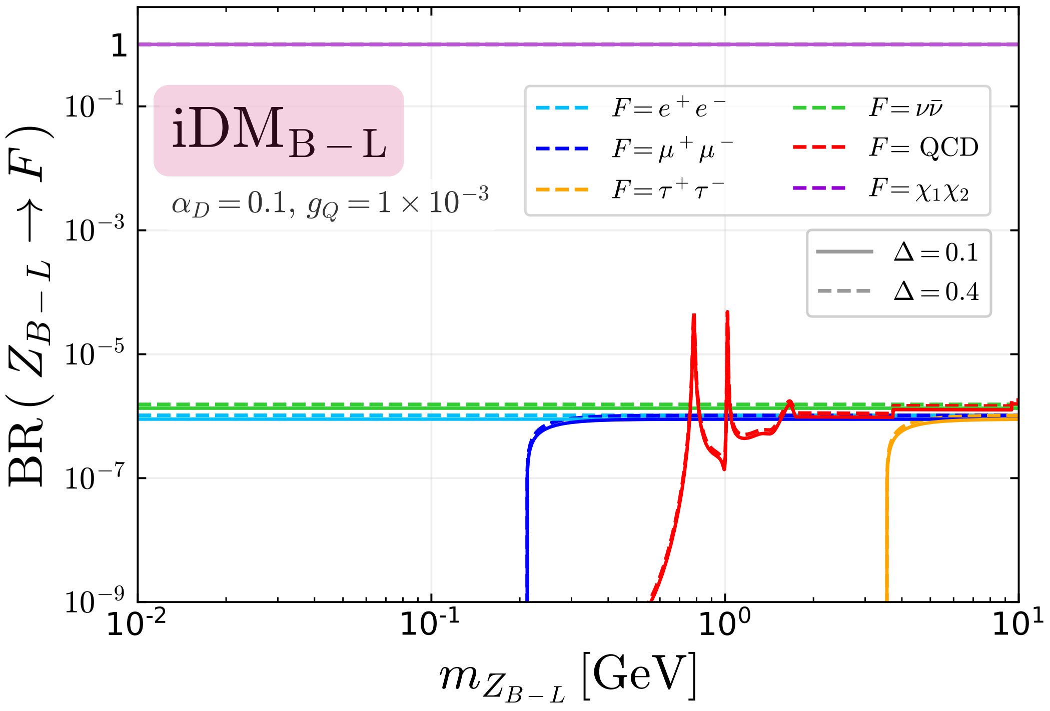
Inelastic Dark Matter · Decay Rates

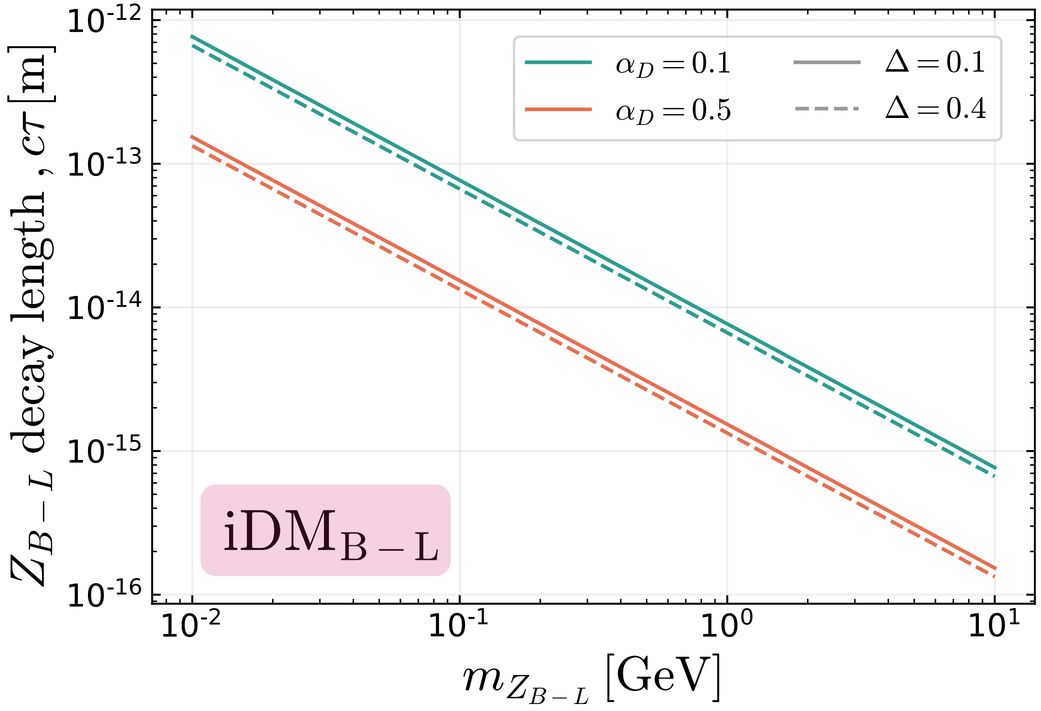
Decay rates · Mediator

- Hierarchy $m_{Z_Q} > m_1 + m_2$
- Limit $g_D \gg g_Q$





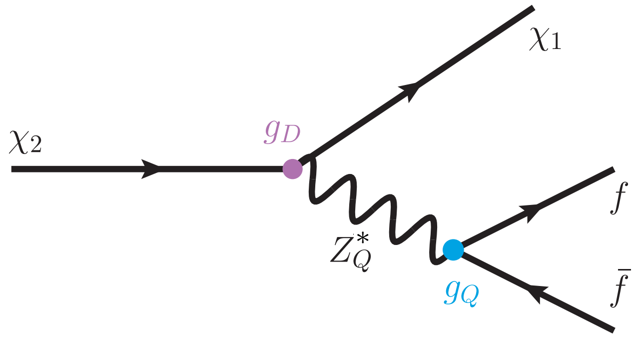




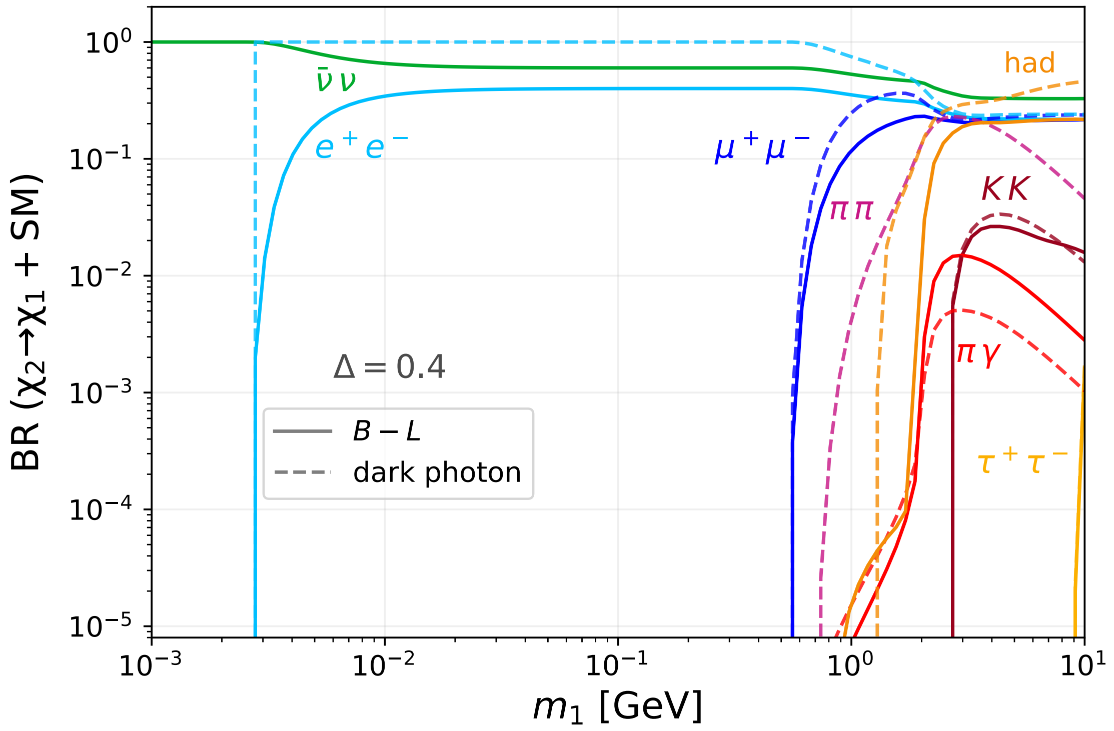
prompt-decay

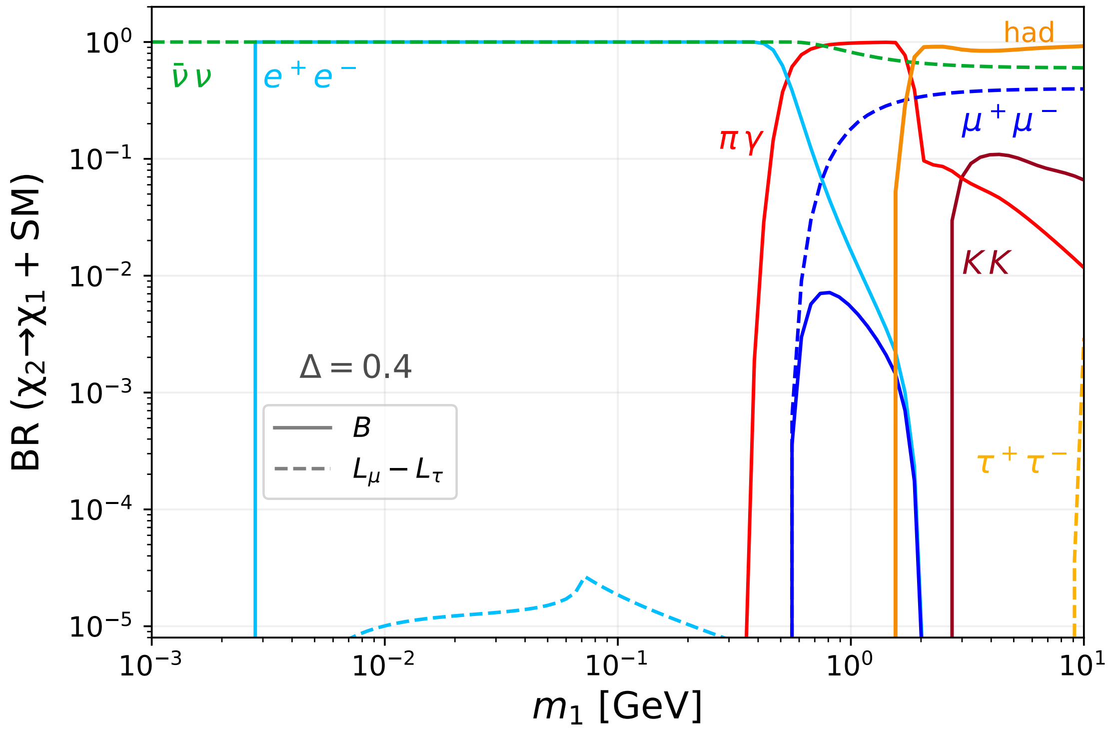
Inelastic Dark Matter · Decay Rates

Decay rates · Dark fermion χ_2



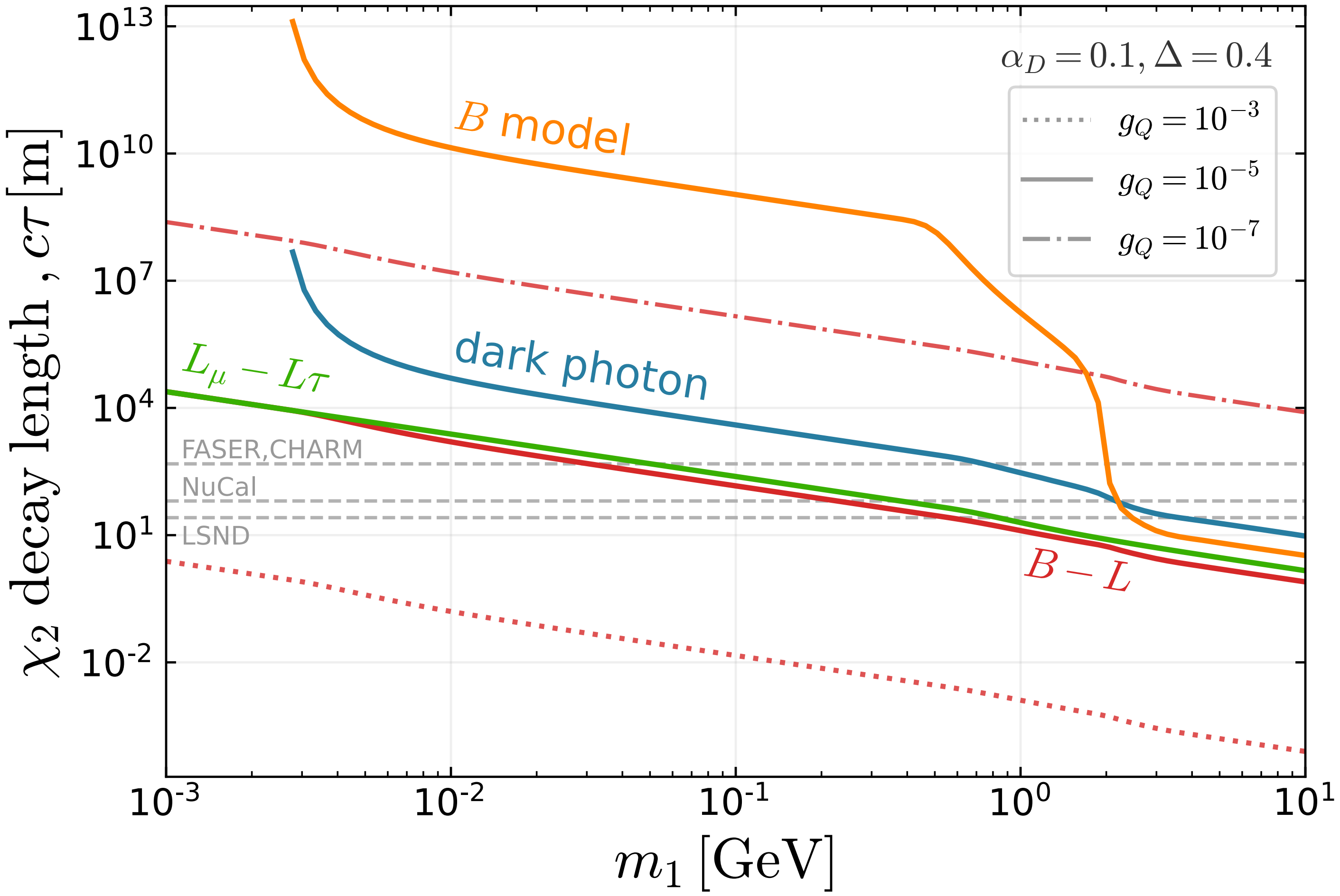
$$\Gamma(\chi_2 \to \chi_1 \bar{f} f) \simeq \frac{4\,\alpha_Q\,\alpha_D\,\Delta^5\,m_{Z_Q}}{15\pi R^5}$$





Inelastic Dark Matter · Decay Rates

Decay rates · Dark fermion χ_2



Boltzmann Equation

$$\frac{\mathrm{d}Y_{1,2}}{\mathrm{d}x} = \frac{s}{Hx}\left[-\langle\sigma v\rangle_{12\to ff}\left(Y_1Y_2 - Y_1^{\mathrm{eq}}Y_2^{\mathrm{eq}}\right) \pm 2\langle\sigma v\rangle_{22\to 11}\left((Y_2)^2 - \left(Y_1\frac{Y_2^{\mathrm{eq}}}{Y_1^{\mathrm{eq}}}\right)^2\right)\right.$$
$$\left.\pm\left(\langle\sigma v\rangle_{2f\to 1f}Y_f^{\mathrm{eq}} + \frac{1}{s}\langle\Gamma\rangle_{2\to 1ff}\right)\left(Y_2 - Y_1\frac{Y_2^{\mathrm{eq}}}{Y_1^{\mathrm{eq}}}\right)\right],$$

Inelastic Dark Matter · Relic Density Computation

Boltzmann Equation

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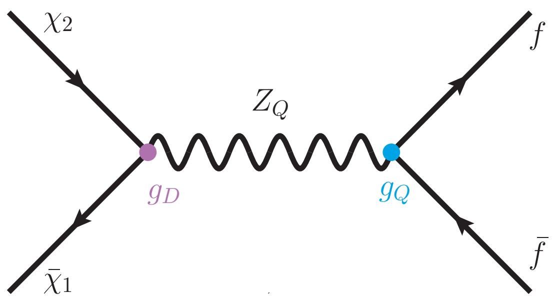

a) $\chi_1\,\chi_2 \to$ SM

Inelastic Dark Matter · Relic Density Computation

Boltzmann Equation

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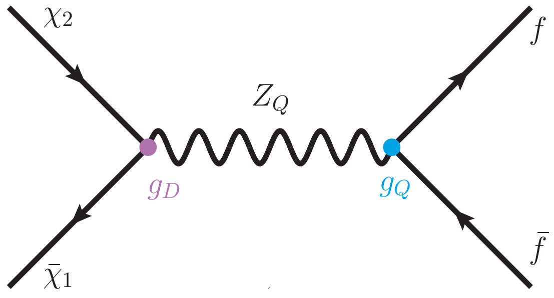

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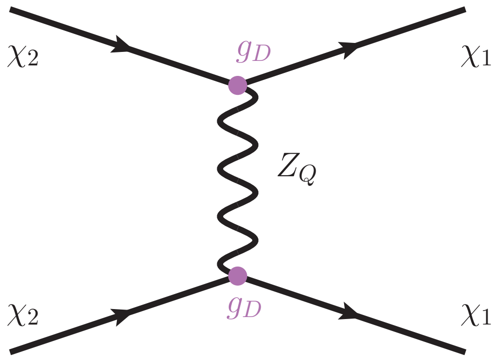

b) $\chi_2\,\chi_2 \to \chi_1\,\chi_1$

Inelastic Dark Matter · Relic Density Computation

Boltzmann Equation

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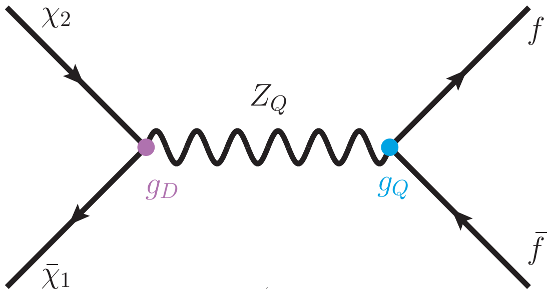

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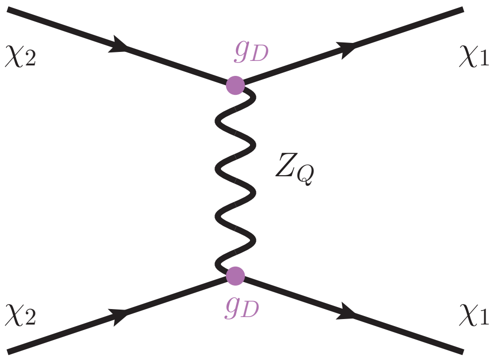
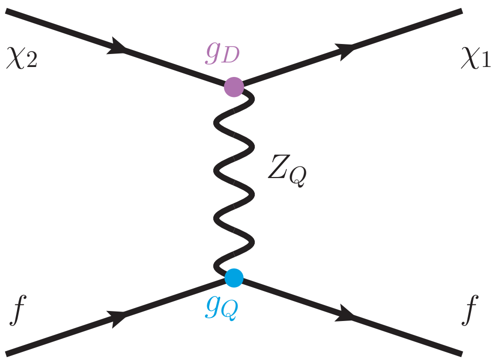


b) $\chi_2\,\chi_2 \to \chi_1\,\chi_1$



c) $\chi_2\,f \to \chi_1\,f$

Inelastic Dark Matter · Relic Density Computation

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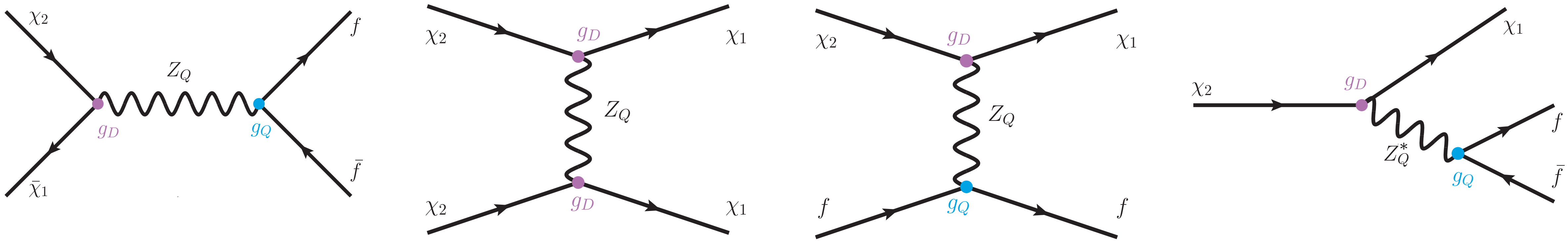


a) $\chi_1\,\chi_2 \to \mathrm{SM}$

b) $\chi_2\,\chi_2 \to \chi_1\,\chi_1$

c) $\chi_2\,f \to \chi_1\,f$

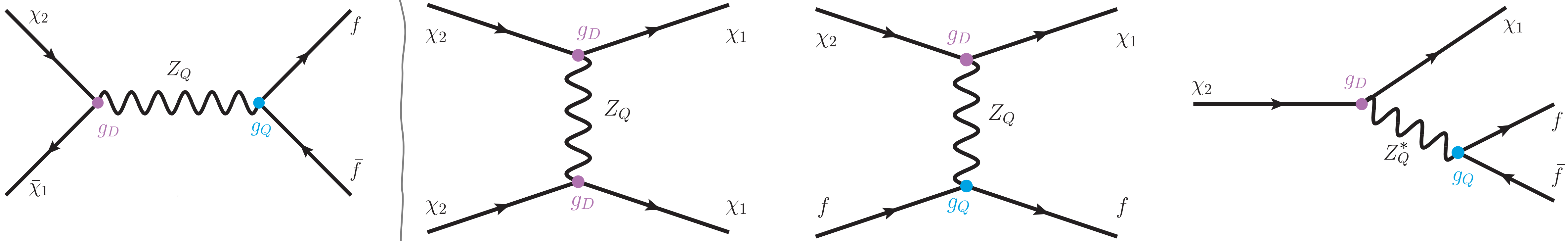
d) $\chi_2 \to \chi_1 + \mathrm{SM}$

Inelastic Dark Matter · Relic Density Computation

Boltzmann Equation

$$\frac{\mathrm{d}Y_{1,2}}{\mathrm{d}x} = \frac{s}{Hx}\left[-\langle\sigma v\rangle_{12\to ff}\left(Y_1 Y_2 - Y_1^{\mathrm{eq}} Y_2^{\mathrm{eq}}\right) \pm 2\langle\sigma v\rangle_{22\to 11}\left((Y_2)^2 - \left(Y_1 \frac{Y_2^{\mathrm{eq}}}{Y_1^{\mathrm{eq}}}\right)^2\right) \pm \left(\langle\sigma v\rangle_{2f\to 1f} Y_f^{\mathrm{eq}} + \frac{1}{s}\langle\Gamma\rangle_{2\to 1ff}\right)\left(Y_2 - Y_1 \frac{Y_2^{\mathrm{eq}}}{Y_1^{\mathrm{eq}}}\right)\right],$$

coannihilations dominate!



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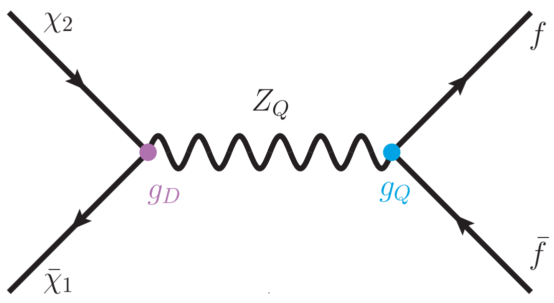


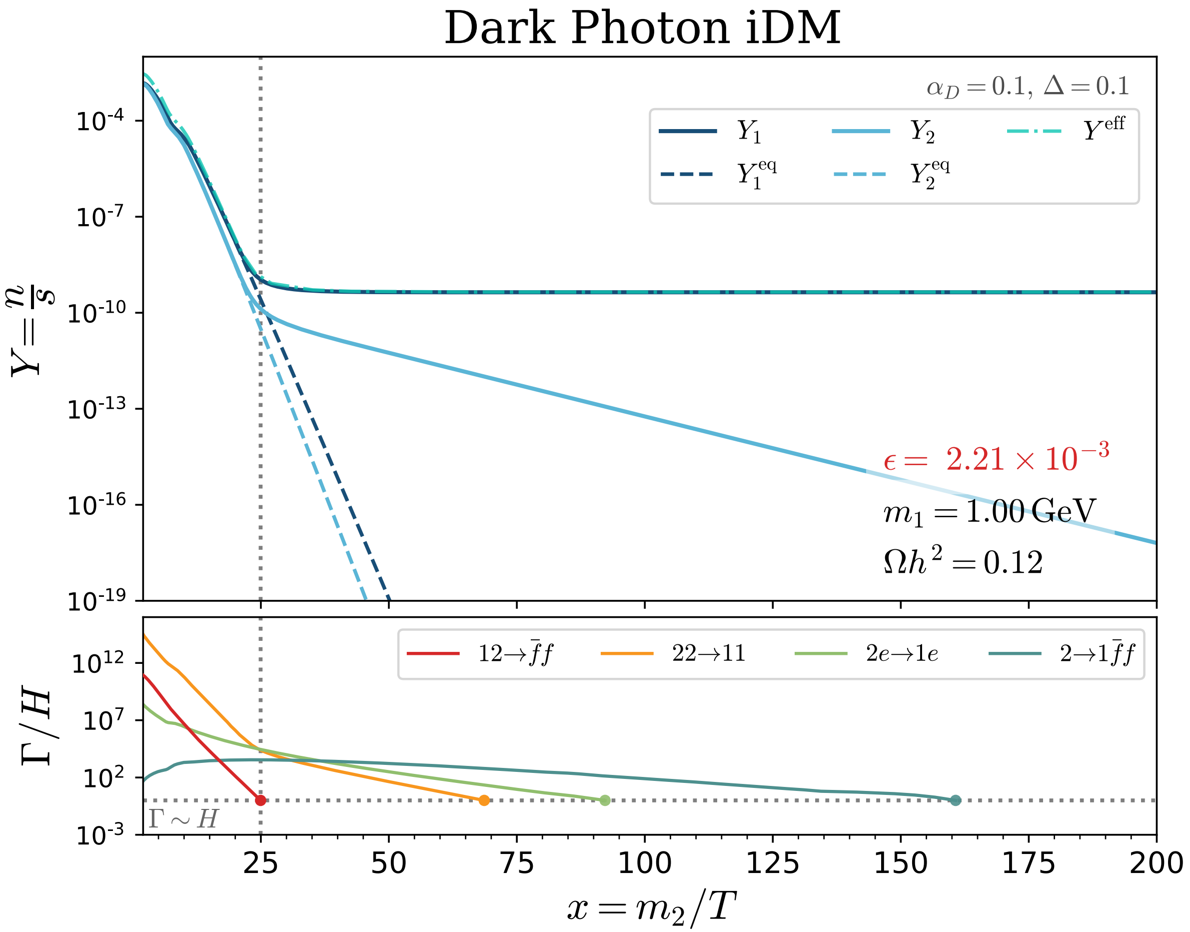
a) $\chi_1\,\chi_2 \to \mathrm{SM}$

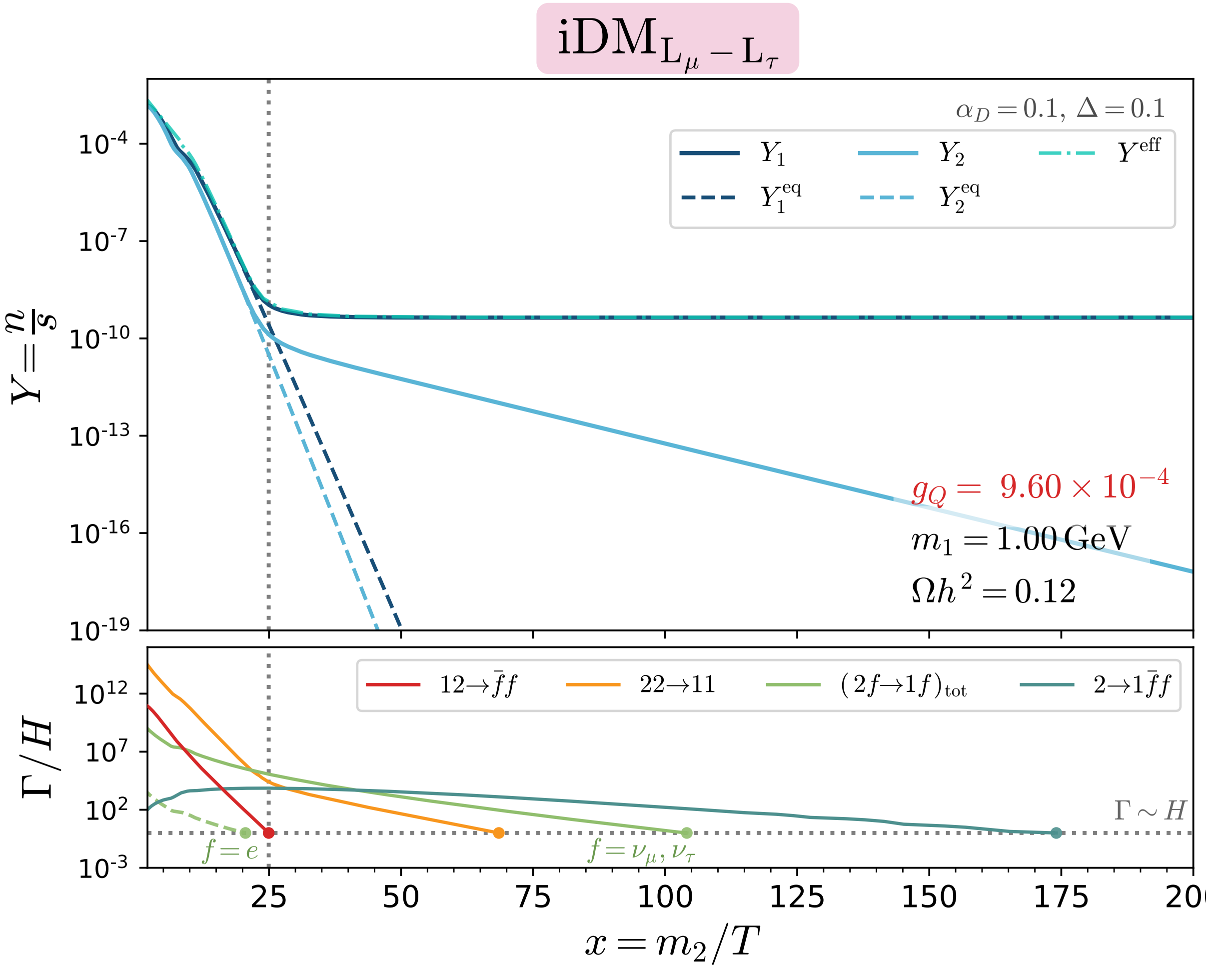
we can simplify by considering $n = n_1 + n_2$

$$\frac{dY}{dx} = -2\frac{s}{xH}\langle\sigma v\rangle_{\mathrm{eff}}\left(Y^2 - Y_{\mathrm{eq}}^2\right)$$

$$\langle\sigma v\rangle_{\mathrm{eff}} = \langle\sigma v\rangle_{12\to ff}\frac{n_1^{\mathrm{eq}}n_2^{\mathrm{eq}}}{(n^{\mathrm{eq}})^2}$$

Inelastic Dark Matter · Relic Density Computation





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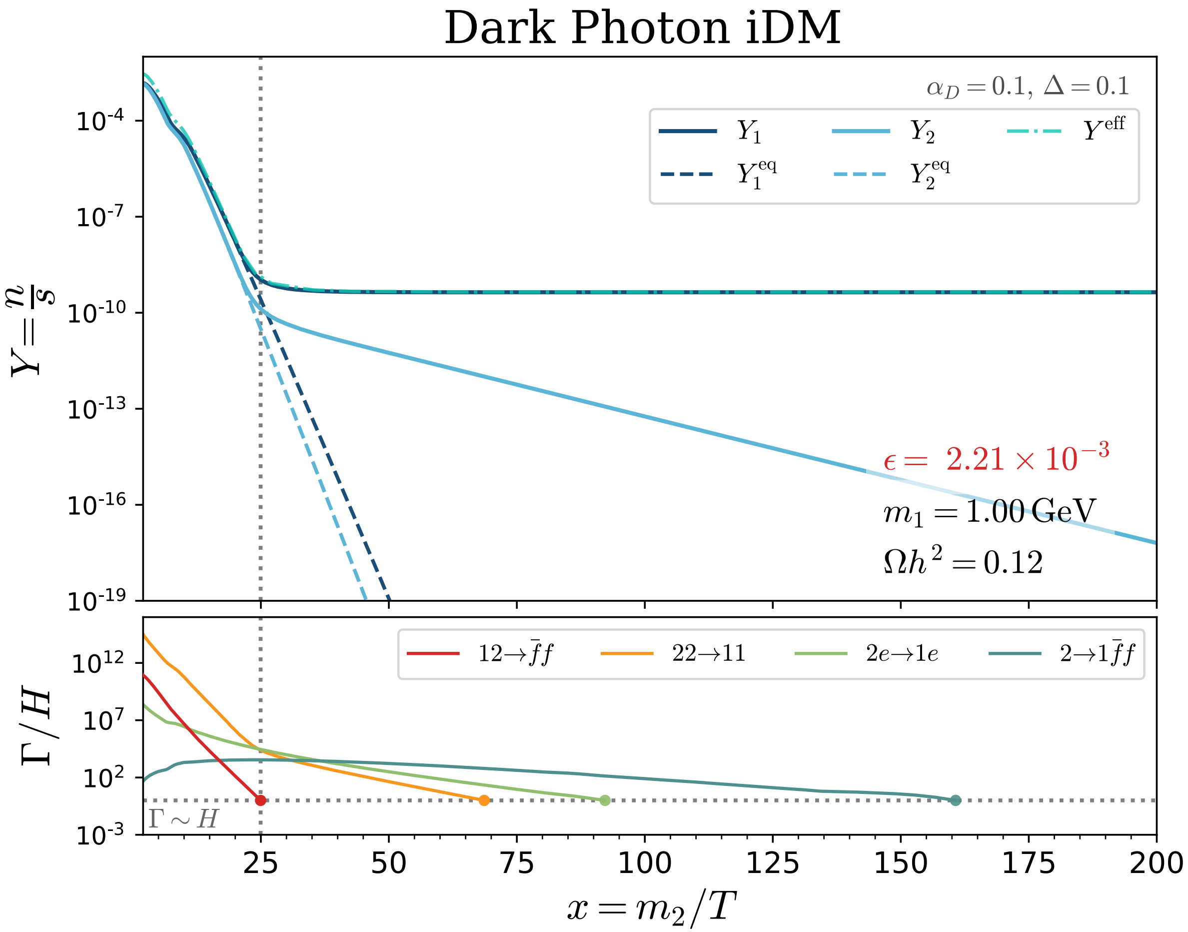
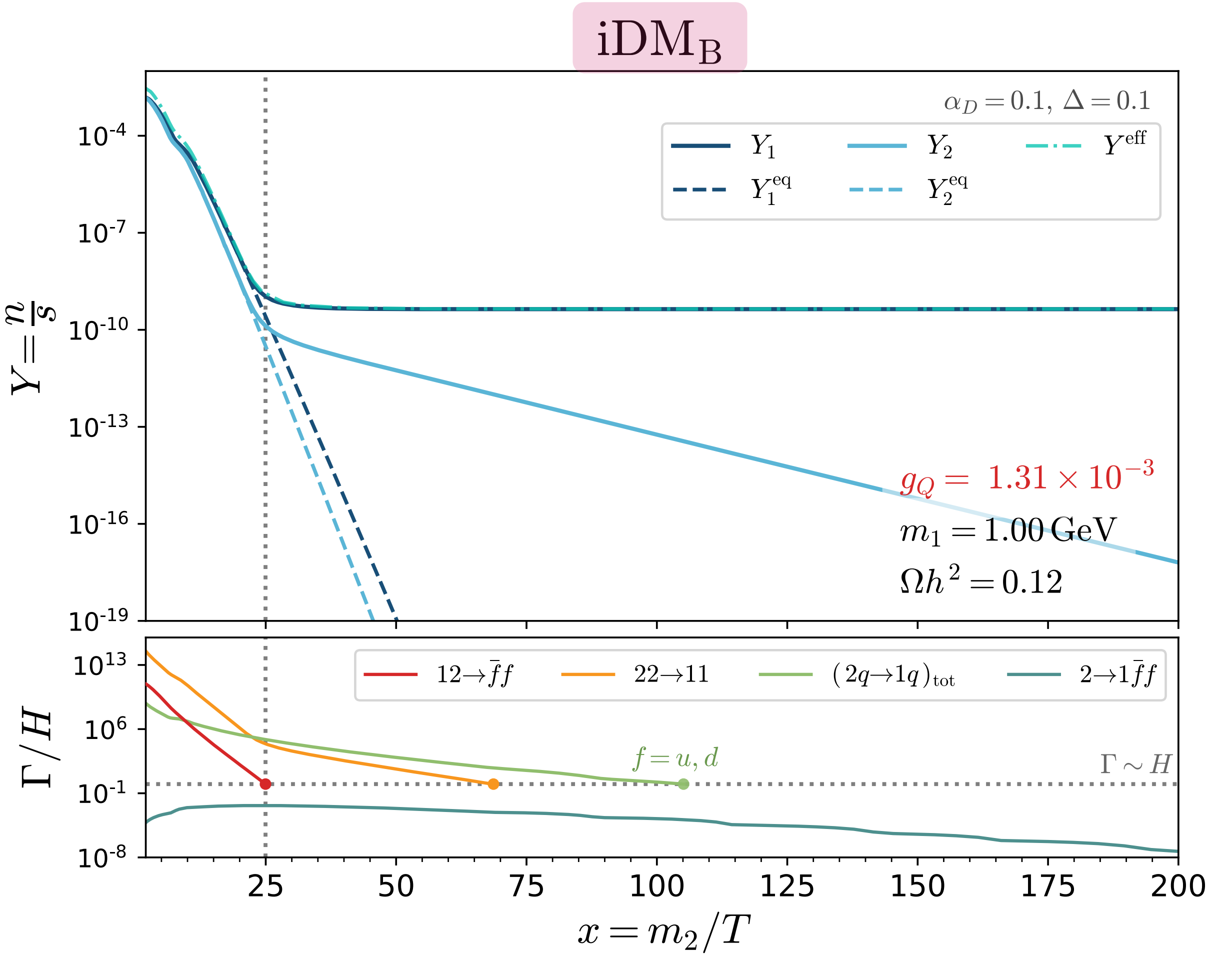




Inelastic Dark Matter · ReD-DeLiVeR code

- python package DELIVER (**De**cays of **Li**ght **Ve**ctors **R**evised) is publicly available on GitHub
  - compute decay rates and branching ratios for user-defined $U(1)_Q$ charges
  - complete set of hadronic decays (20 channels)

https://github.com/preimitz/DeLiVeR

README.md

DeLiVeR: Decays of Light Vectors Revised

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

arXiv 2201.01788

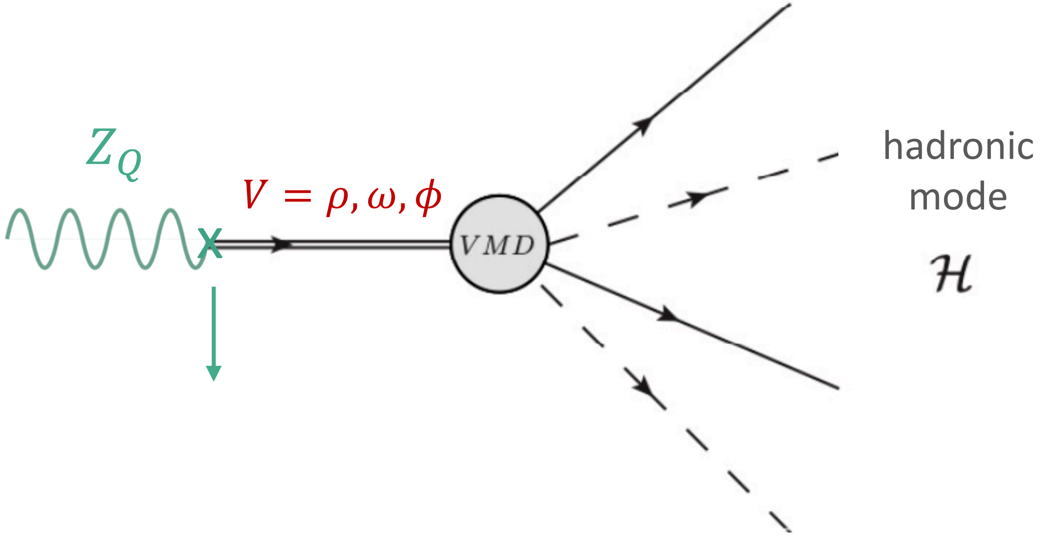
Introduction

We provide a numerical package to calculate decay quantities of light vector particles. It includes the calcualtion of decay widths, and branching ratios for all leptonic and almost all hadronic decays as well as decays to some exemplary dark matter models. Those quantities are needed to set constraints on vector mediator models in the GeV and sub-GeV range.

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

channel	resonances
$\pi\gamma$	$\boldsymbol{\rho}, \omega, \boldsymbol{\omega'}, \boldsymbol{\omega''}, \boldsymbol{\phi}$
$\pi\pi$	$\rho, \rho', \ldots$
3π	$\boldsymbol{\rho}, \boldsymbol{\rho''}, \omega, \omega', \omega'', \phi$
4π	$\rho, \rho', \rho'', \rho'''$
KK	$\boldsymbol{\rho}, \ldots, \boldsymbol{\omega}, \ldots, \phi, \ldots$
$KK\pi$	$\boldsymbol{\rho}, \boldsymbol{\rho'}, \boldsymbol{\rho''}, \phi, \phi', \phi''$

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



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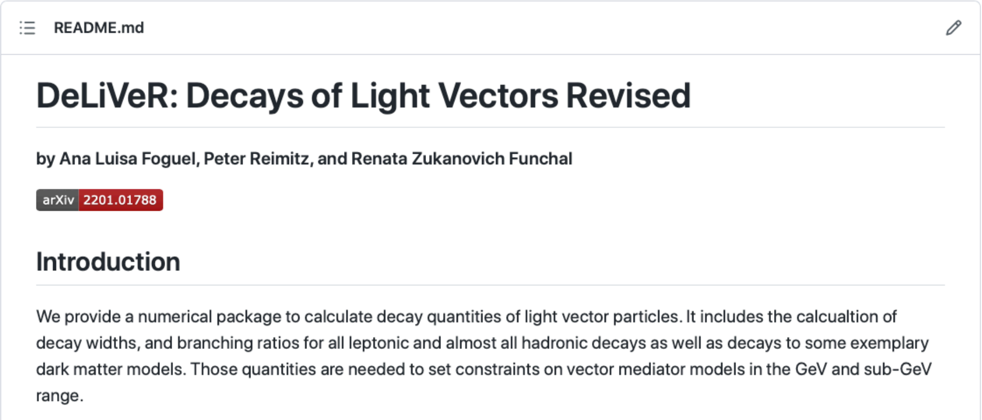
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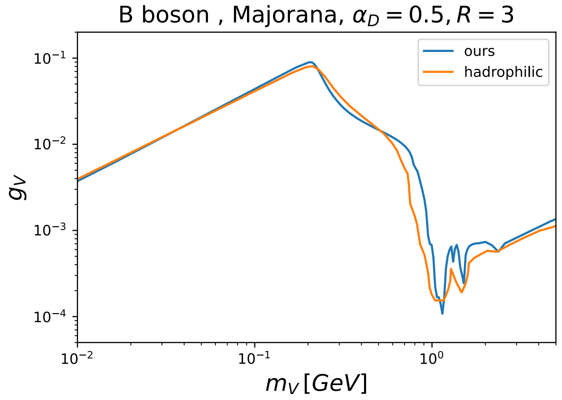
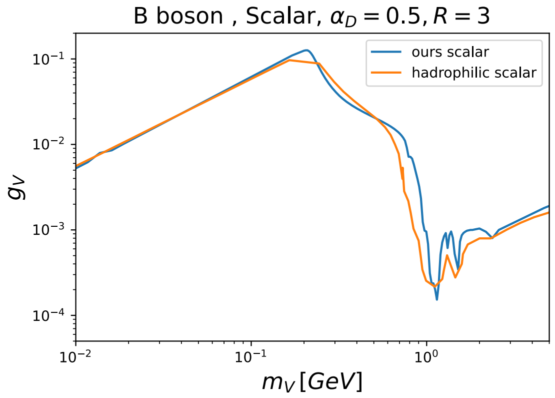
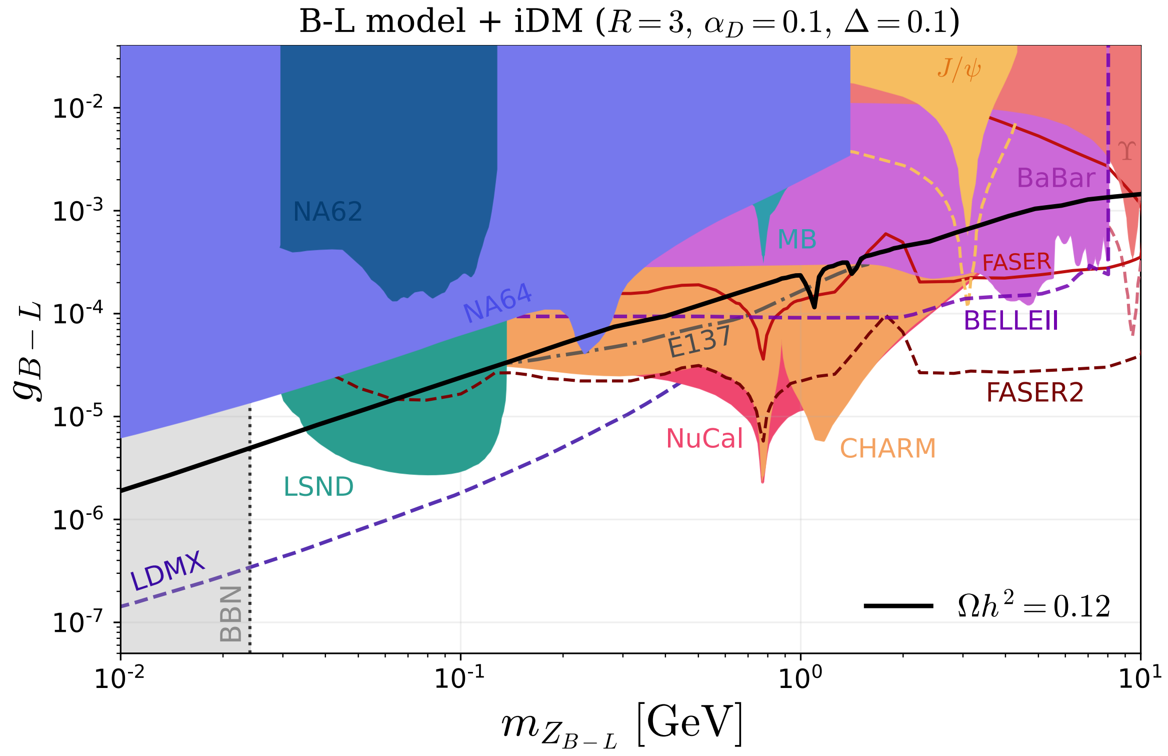
- ReD-DeLiVeR (Relic Density with DeLiVeR)
  - designed to solve numerically the Boltzmann equations and evaluate the relic density curves and thermal targets for both simplified DM models and the iDM scenario.

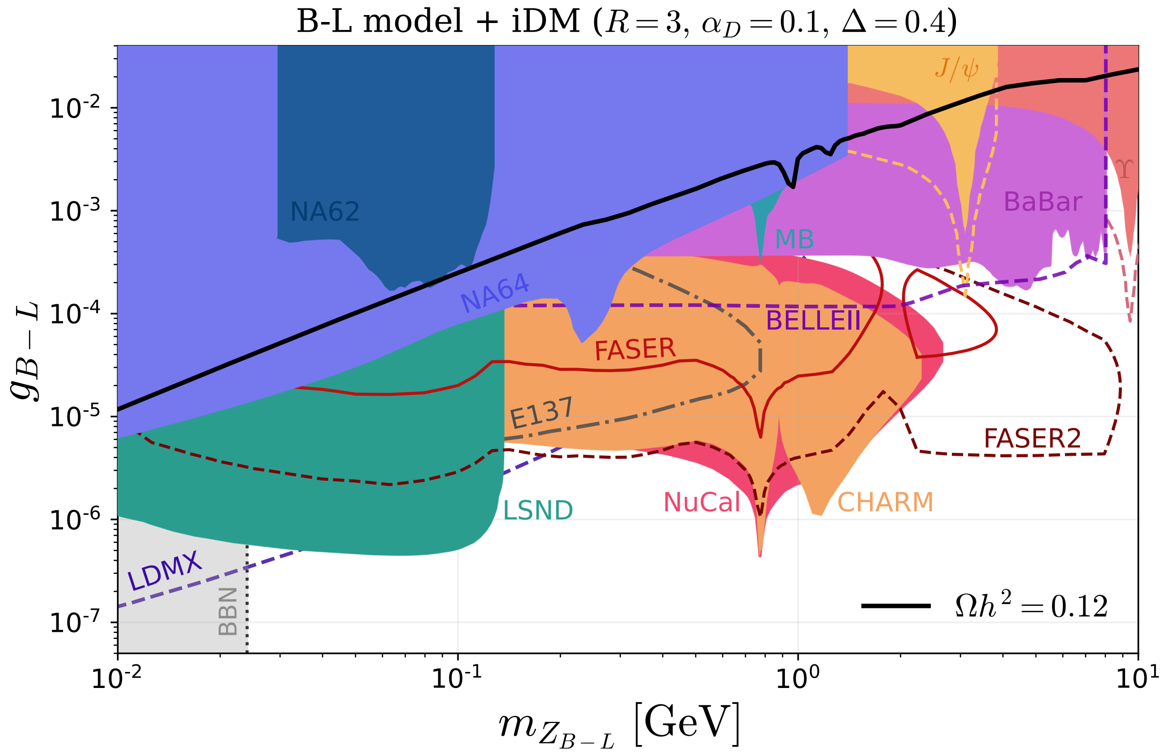




Inelastic Dark Matter · Bounds

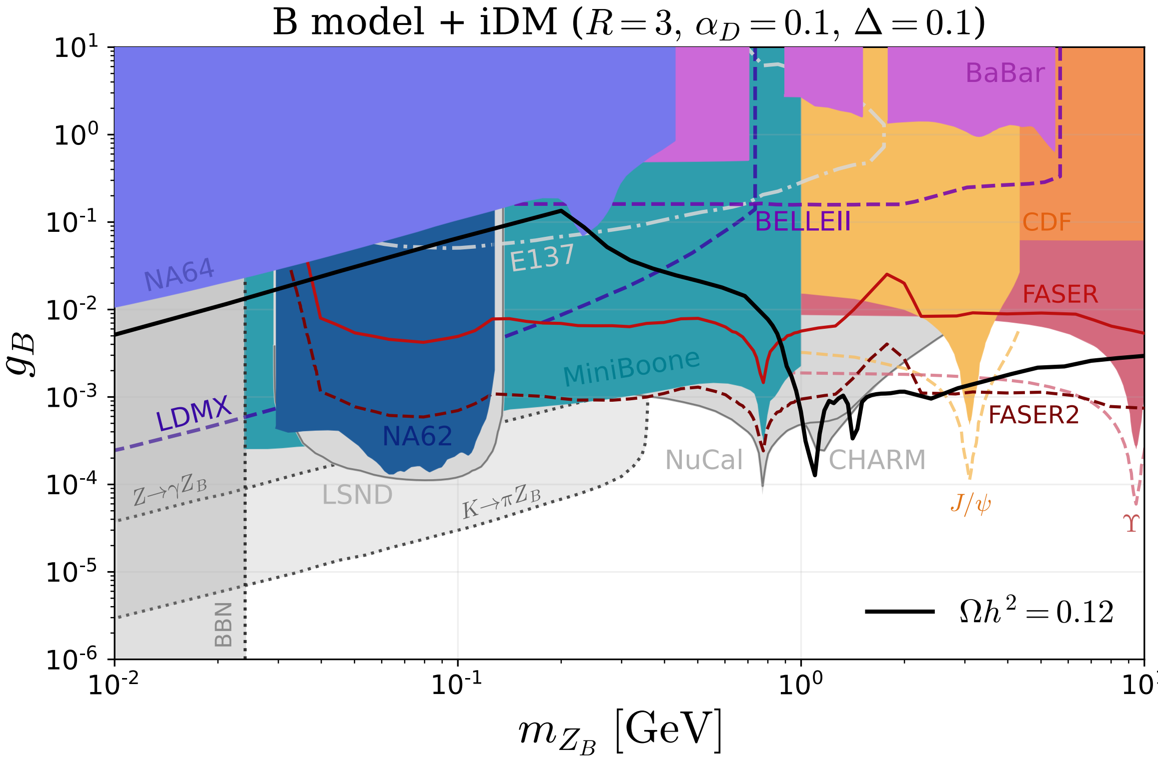
iDM_{B-L}

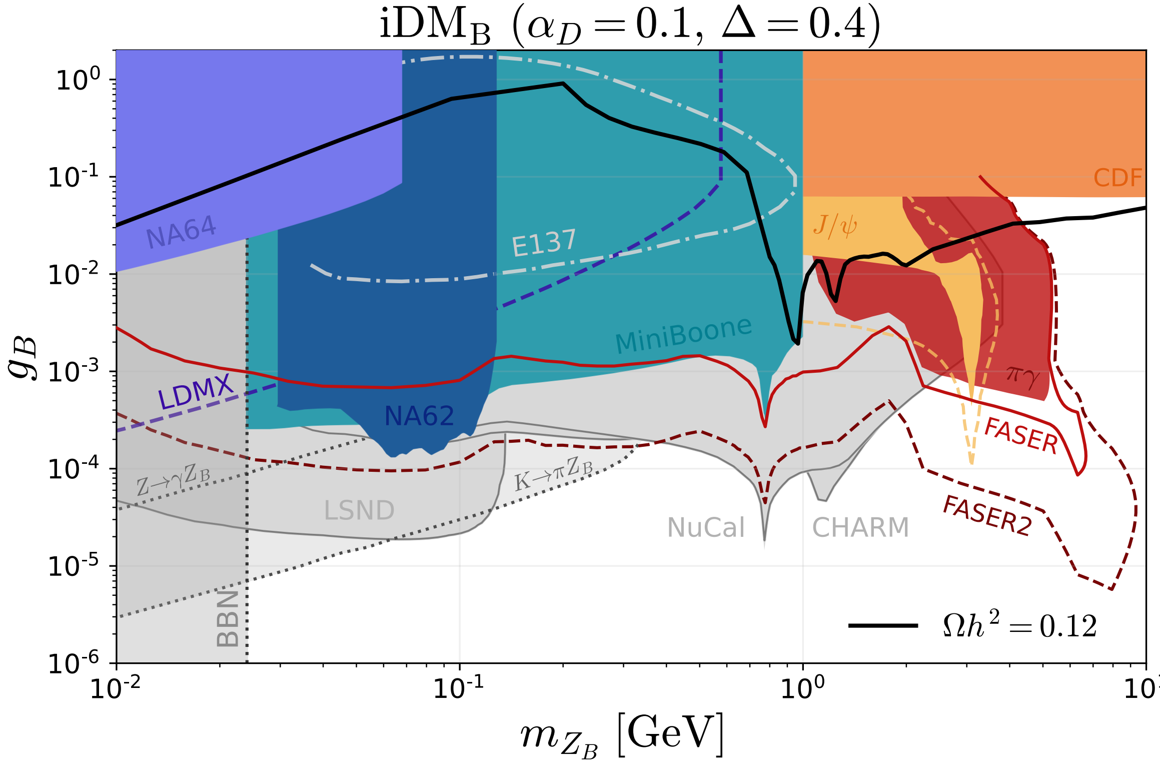




Inelastic Dark Matter · Bounds

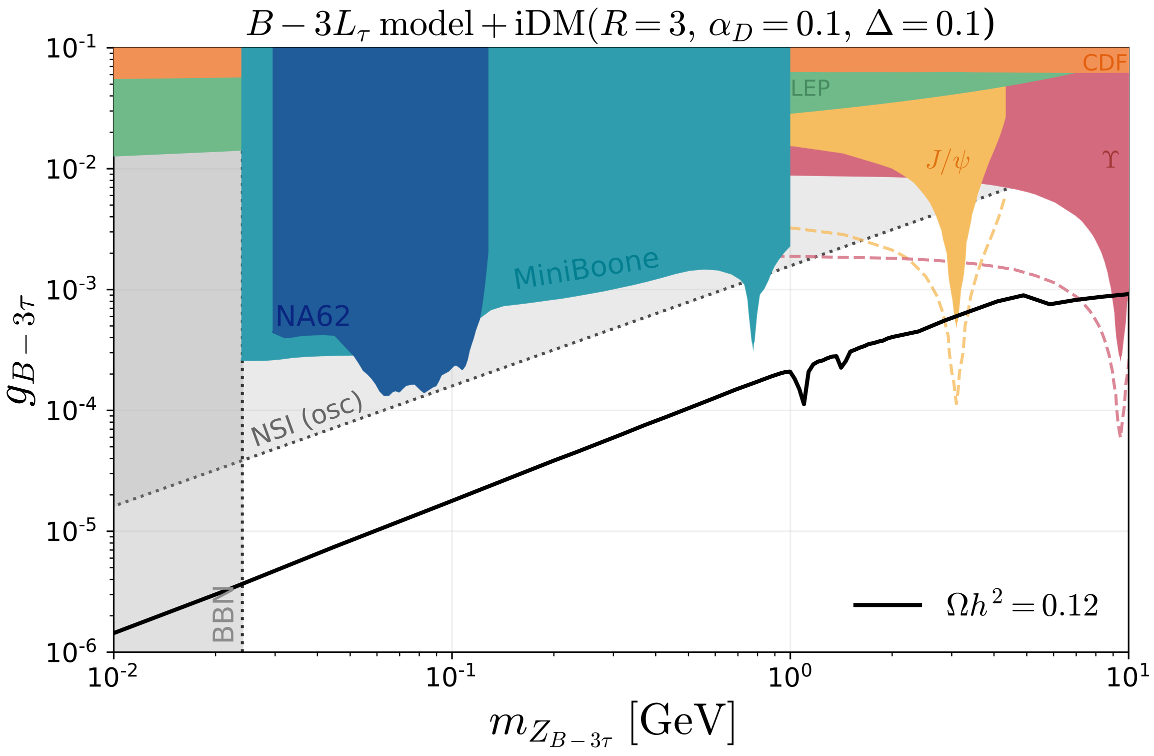
iDM_B

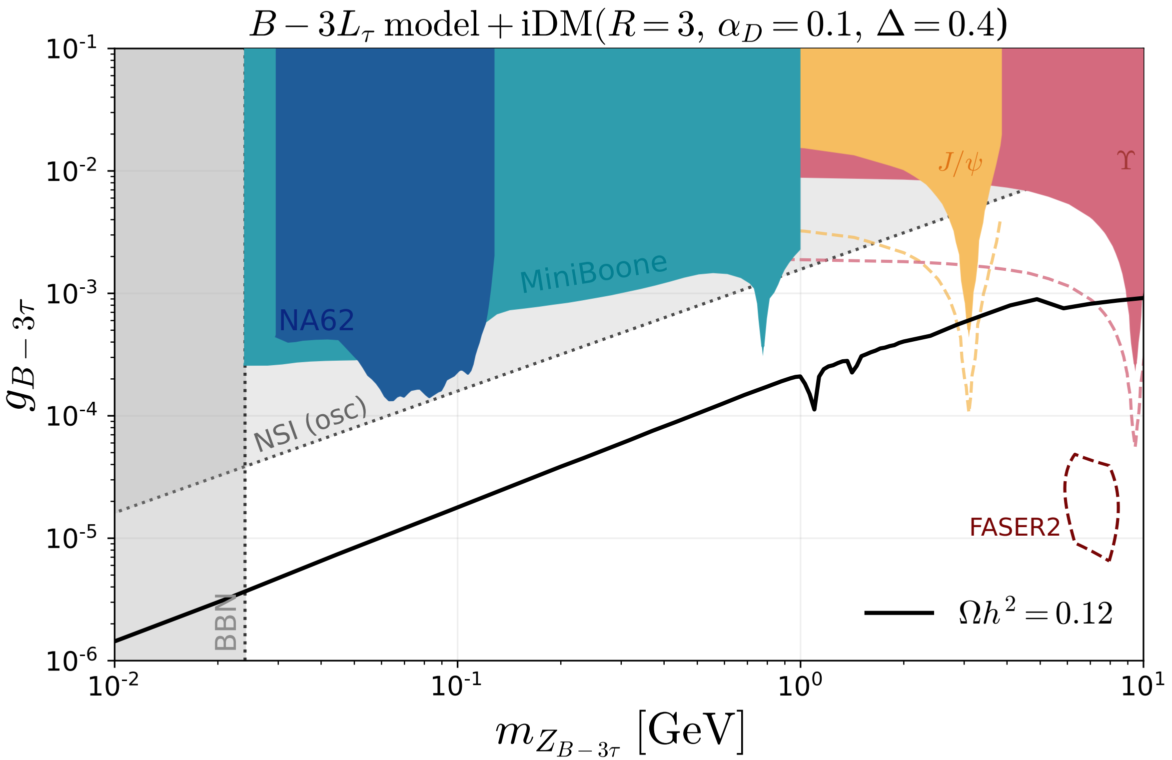




Inelastic Dark Matter · Bounds

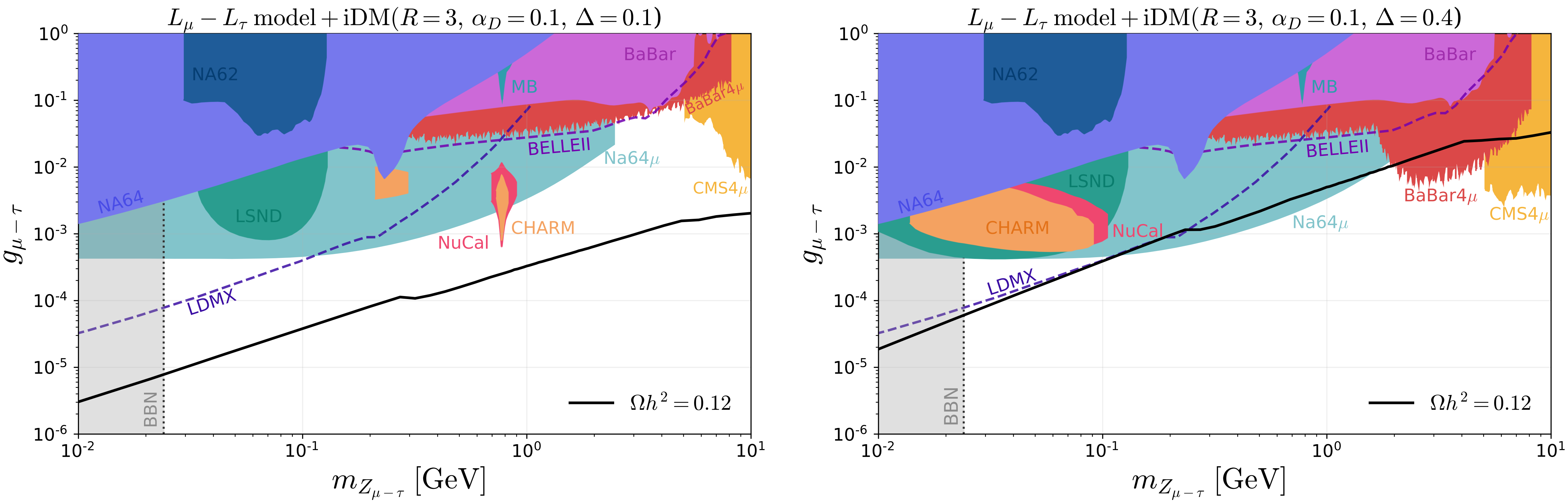
iDM_{B-3L_τ}





Inelastic Dark Matter · Bounds

$\mathrm{iDM}_{L_\mu - L_\tau}$



Conclusions

- Light Feebly Interacting Particles can shed light in several unanswered questions of the SM
- As experiments increase their luminosities, and we enter the intensity frontier era of particle physics, we increase the capabilities to probe new light sectors.
- As a guiding principle, we consider different portals between the Dark Sector and the SM
- In this work we considered a **vector portal** to a fermionic **inelastic Dark Matter** sector

thermal relics

evade indirect and direct detection

evade CMB bounds

general vector mediators

iDM_Q

- We developed a code that computes the relic density ReD-DeLiVeR
- With general mediators, we showed that we can unlock new regions of the parameter space of the vanilla dark photon model

$$B - 3L_\tau \qquad L_\mu - L_\tau$$

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Thank you for your kind attention!

BACKUP

Inelastic Dark Matter

DM Thermal Freeze-out · WIMP miracle

We know that freeze-out happens when $\Gamma \sim H$

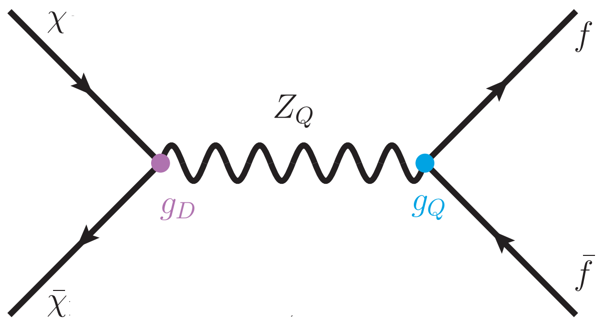
$$m_\chi \sim \alpha_{\rm eff}\sqrt{T_{\rm eq}M_{\rm Pl}} \sim \alpha_{\rm eff} \times 30\,{\rm TeV}$$

WIMP miracle

↪ For couplings similar to the electroweak coupling $(\alpha_{\rm eff} \sim 10^{-2}) \Rightarrow$ EW scale emerges naturally

However, this also implies that

$$m_{\rm DM} \gtrsim \frac{m_Z^2}{(T_{\rm eq}\, m_{\rm Pl})^{1/2}} \sim {\rm GeV}.$$



Hence, sub-GeV DM motivates the presence of new light mediators

Inelastic Dark Matter

CMB Bounds

Even after DM freezes-out, annihilations processes (that continue to occur out-of-equilibrium) can continue to inject energy in the plasma.

↳ if annihilations into EM charged particles can persist between recombination and reionization this can distort the CMB (Cosmic Microwave Background)

In terms of the thermally averaged cross-section we have the following limit

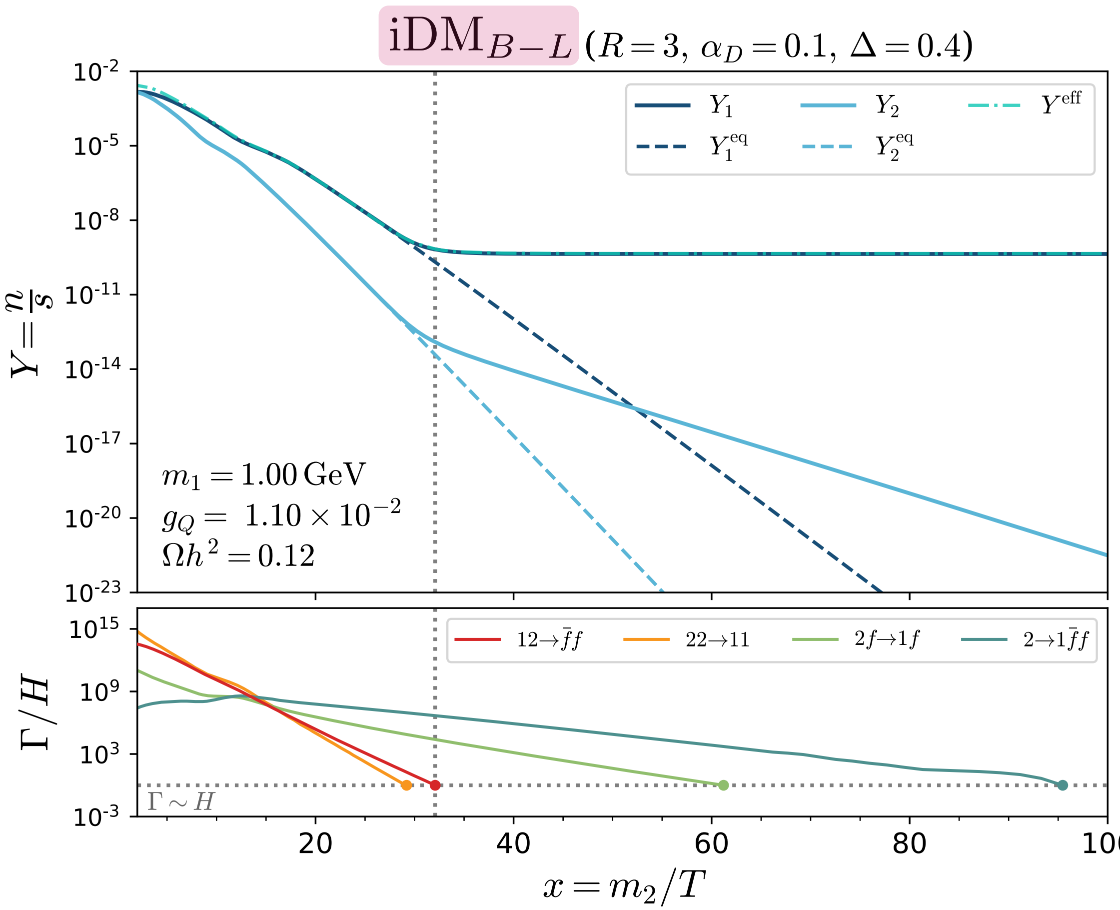
$$\langle \sigma v \rangle_{\rm cmb} \lesssim 3 \times 10^{-26}\ {\rm cm^3\, s^{-1}} \left(\frac{m_{\rm DM}}{10\ {\rm GeV}} \right)$$

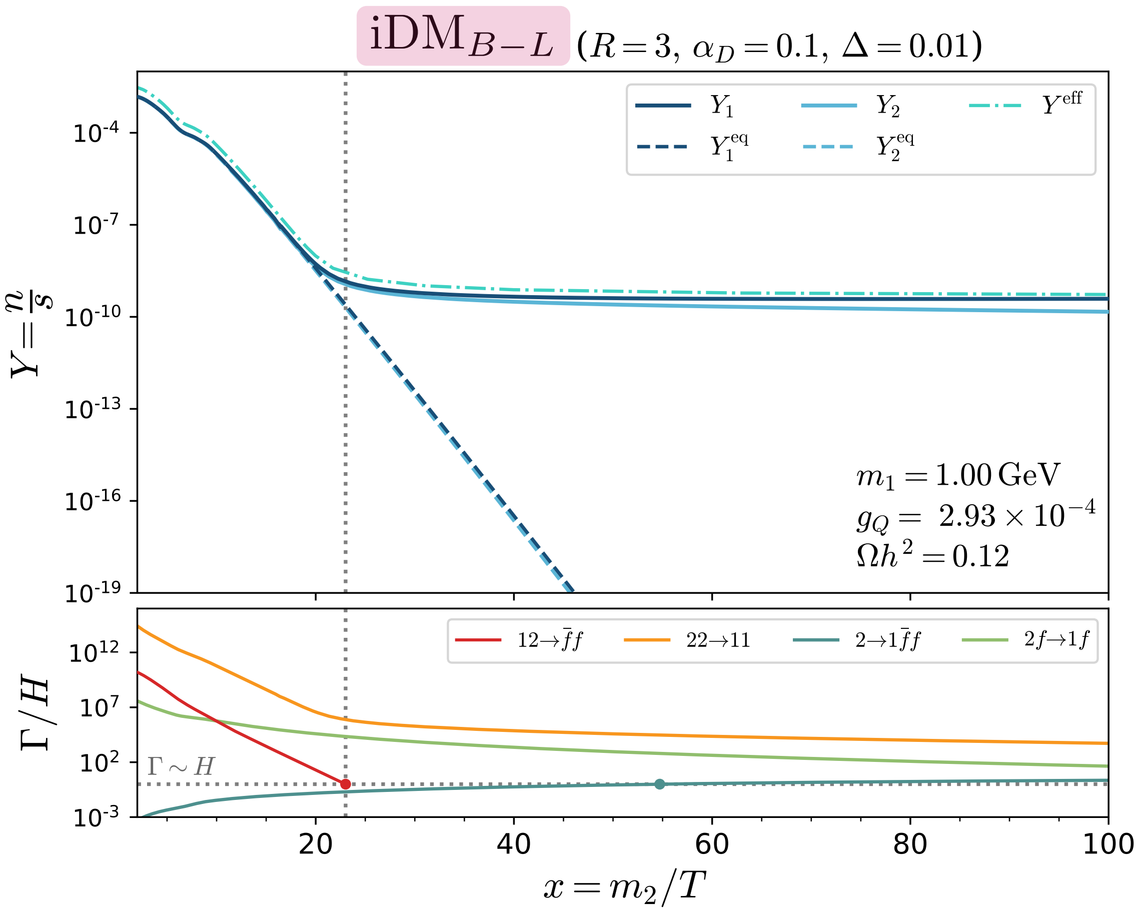
since standard thermal DM predicts $\langle \sigma v \rangle \sim 10^{-26}\ {\rm cm^3\, s^{-1}}$ we have the bound $m_{\rm DM} \gtrsim 10\,{\rm GeV}$

for models involving annihilations to visible final states with velocity independent (s-wave) cross sections.

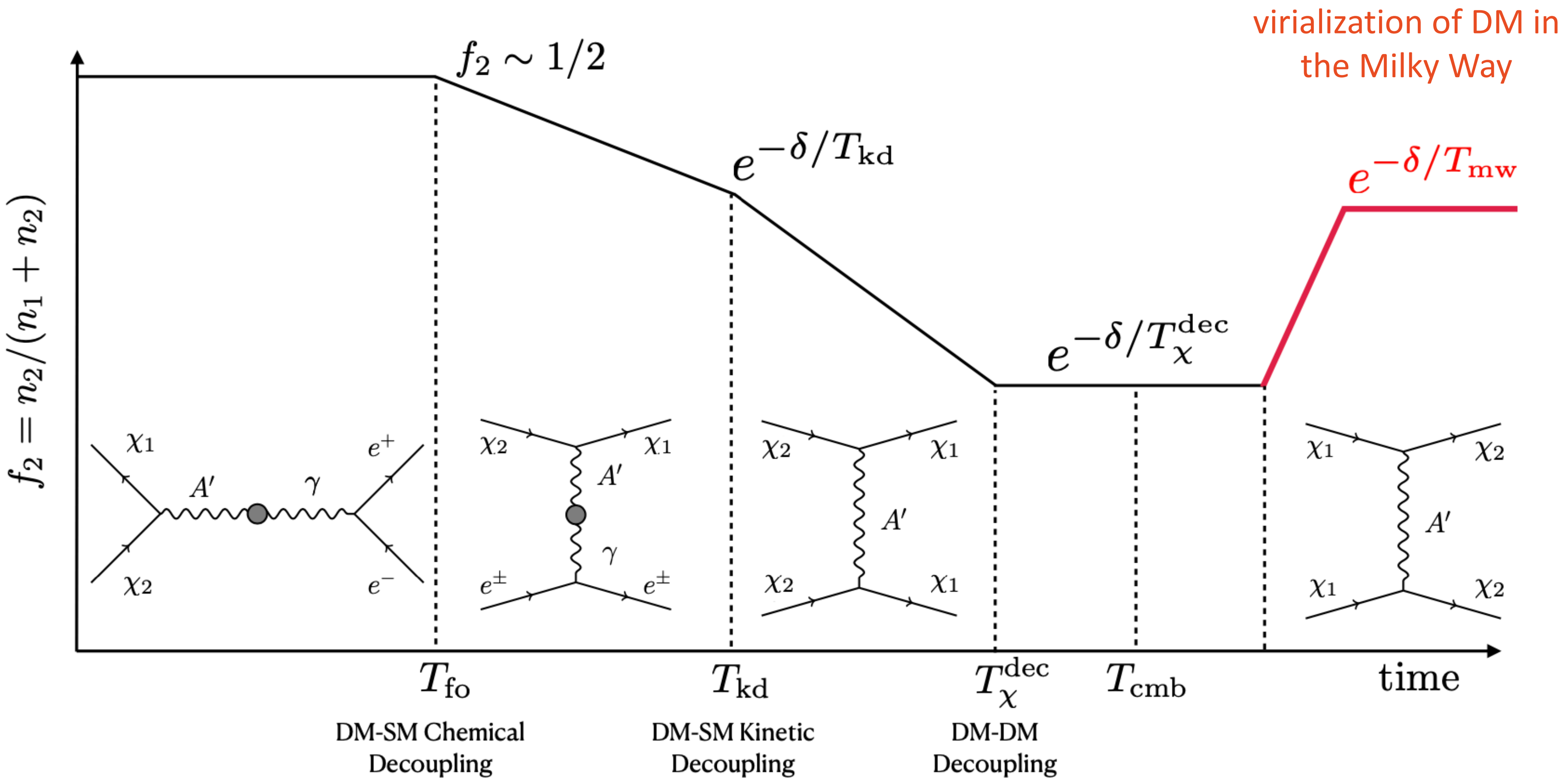
Inelastic DM scenarios can avoid this bound!

Inelastic Dark Matter · Relic Density Computation





Inelastic Dark Matter



arXiv:2311.00032v1 [hep-ph]