Unlocking the Inelastic Dark Matter window with Vector Mediators

Ana Luisa Foguel

in collaboration with Peter Reimitz and Renata Z. Funchal

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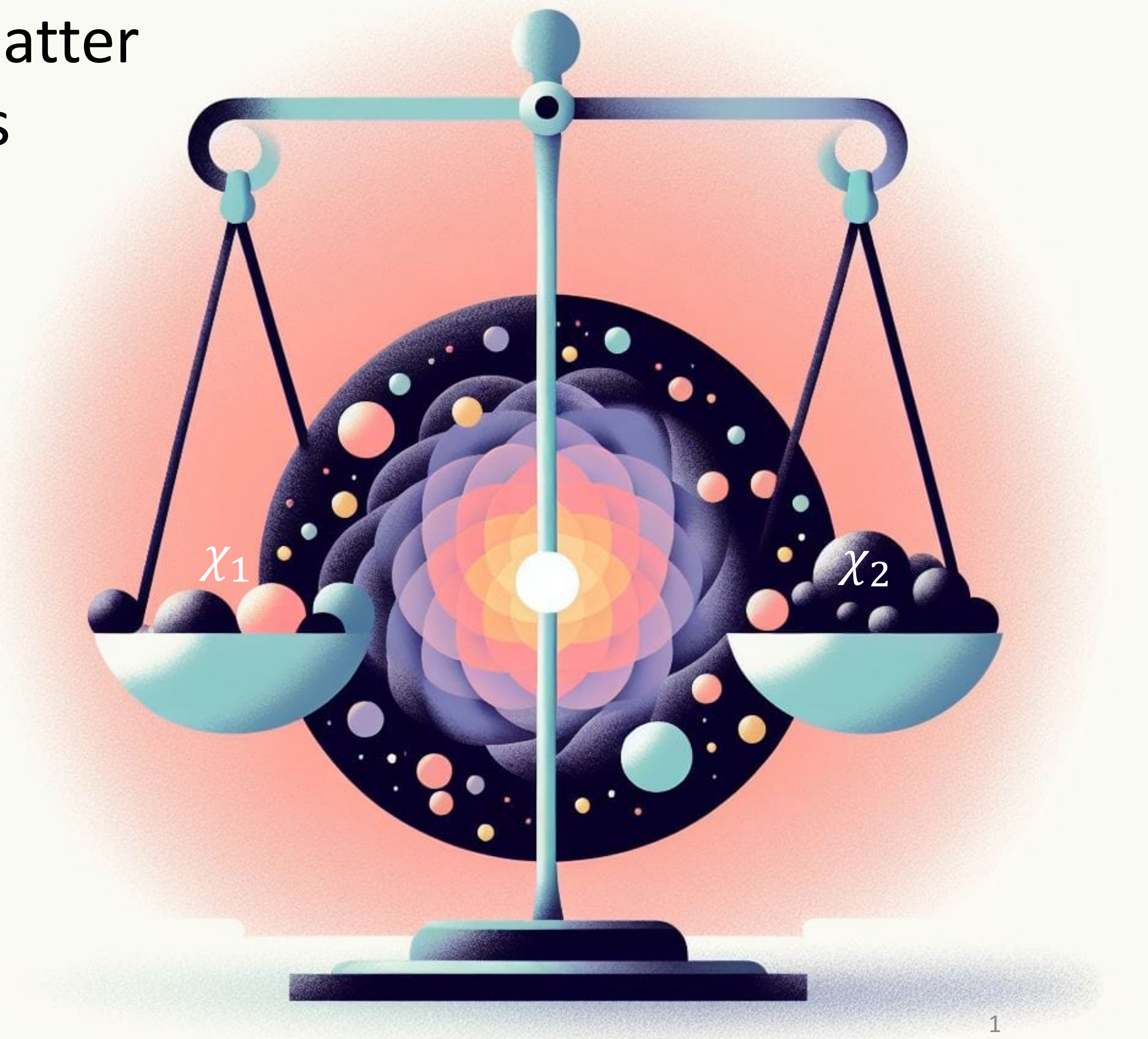
NBI Neutrino School

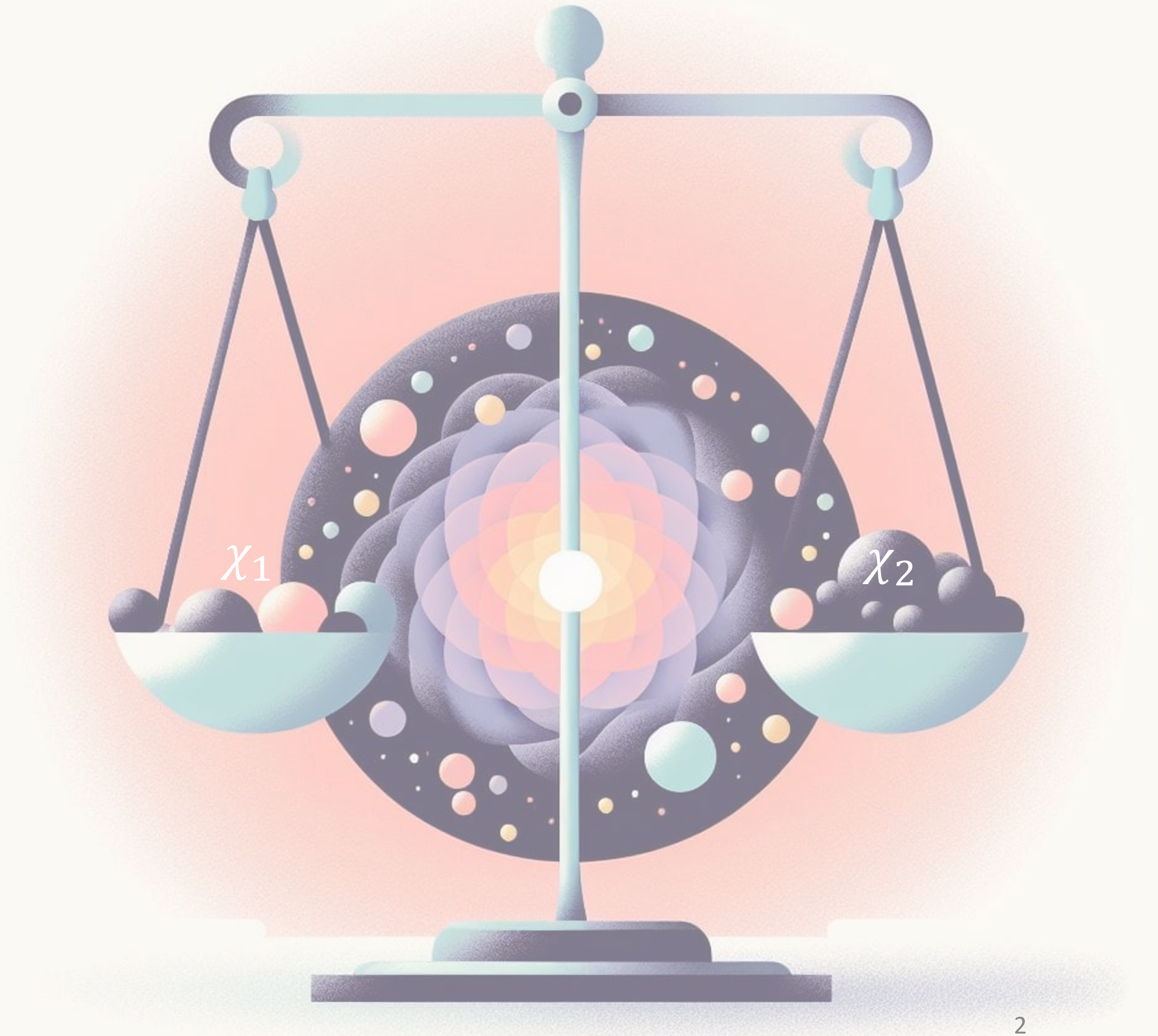
9 July 2025

IFUSP Instituto de Física da USP

FAPESP



Outline



Introduction and Motivations

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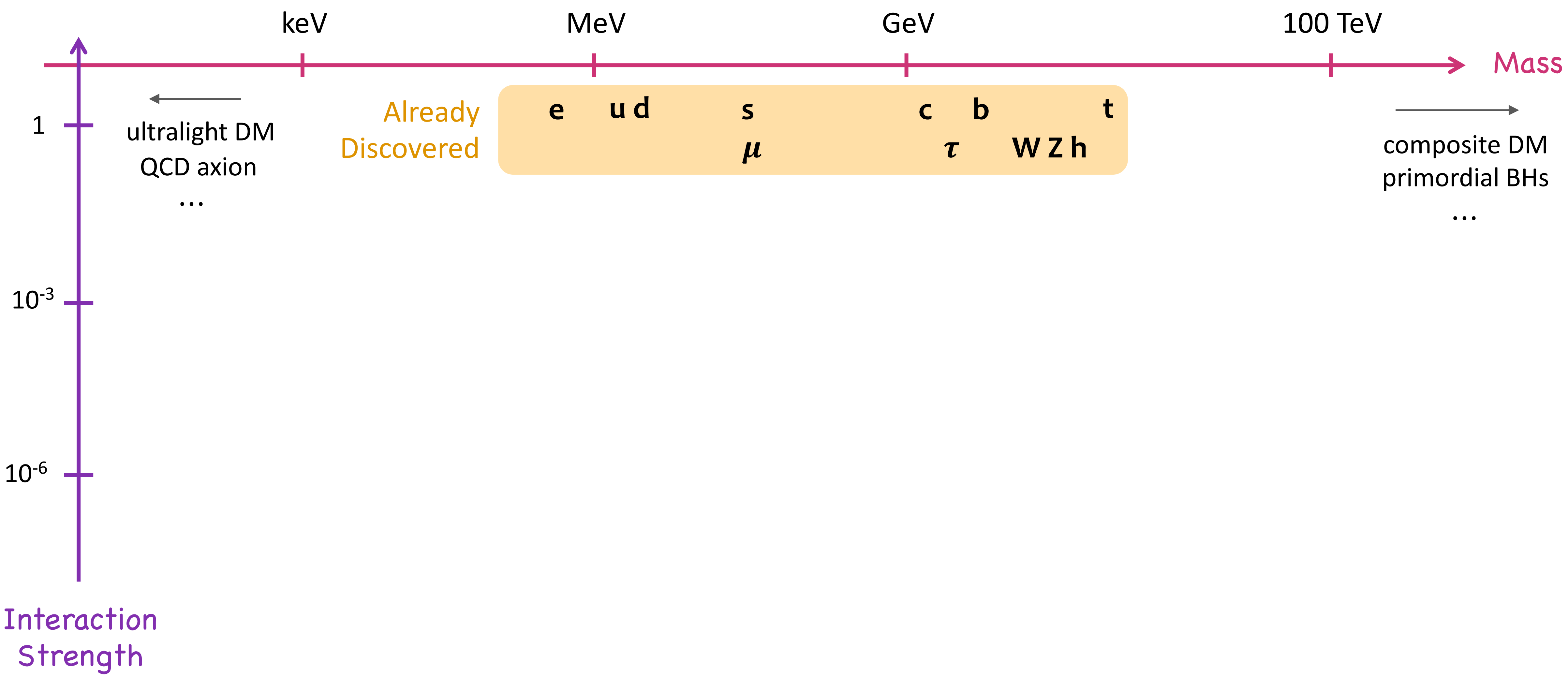
Where can we search for BSM signals?



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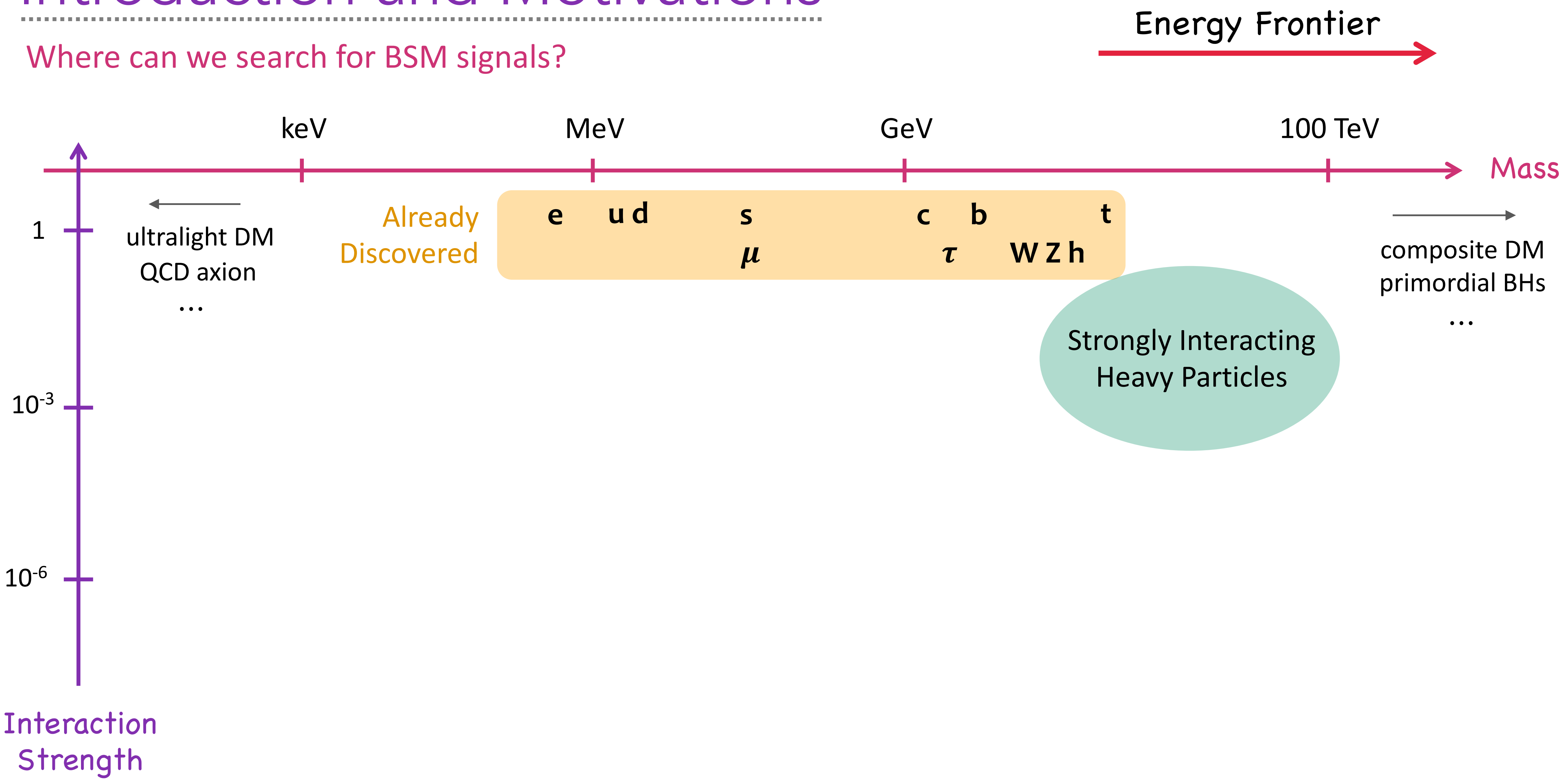

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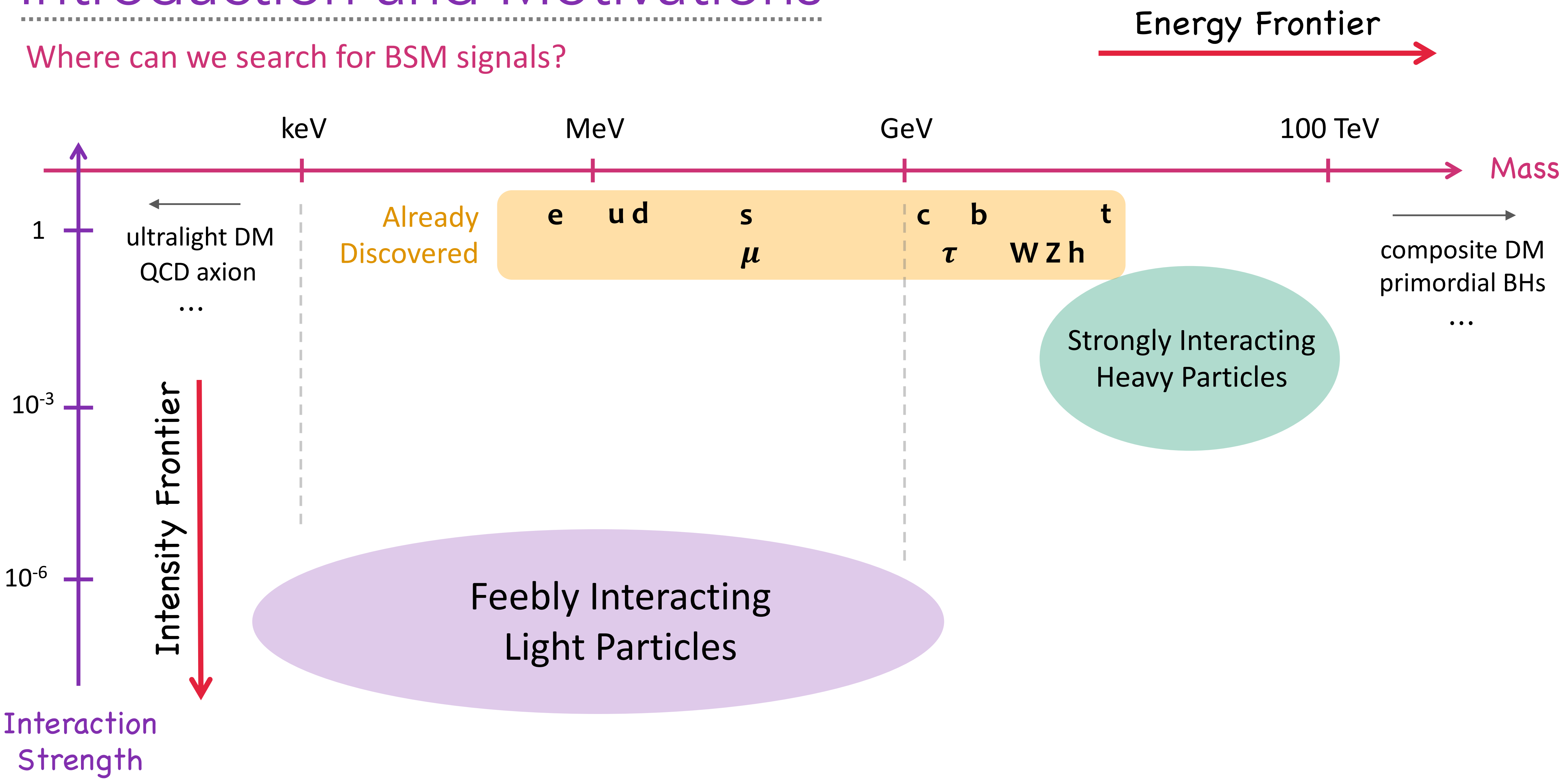

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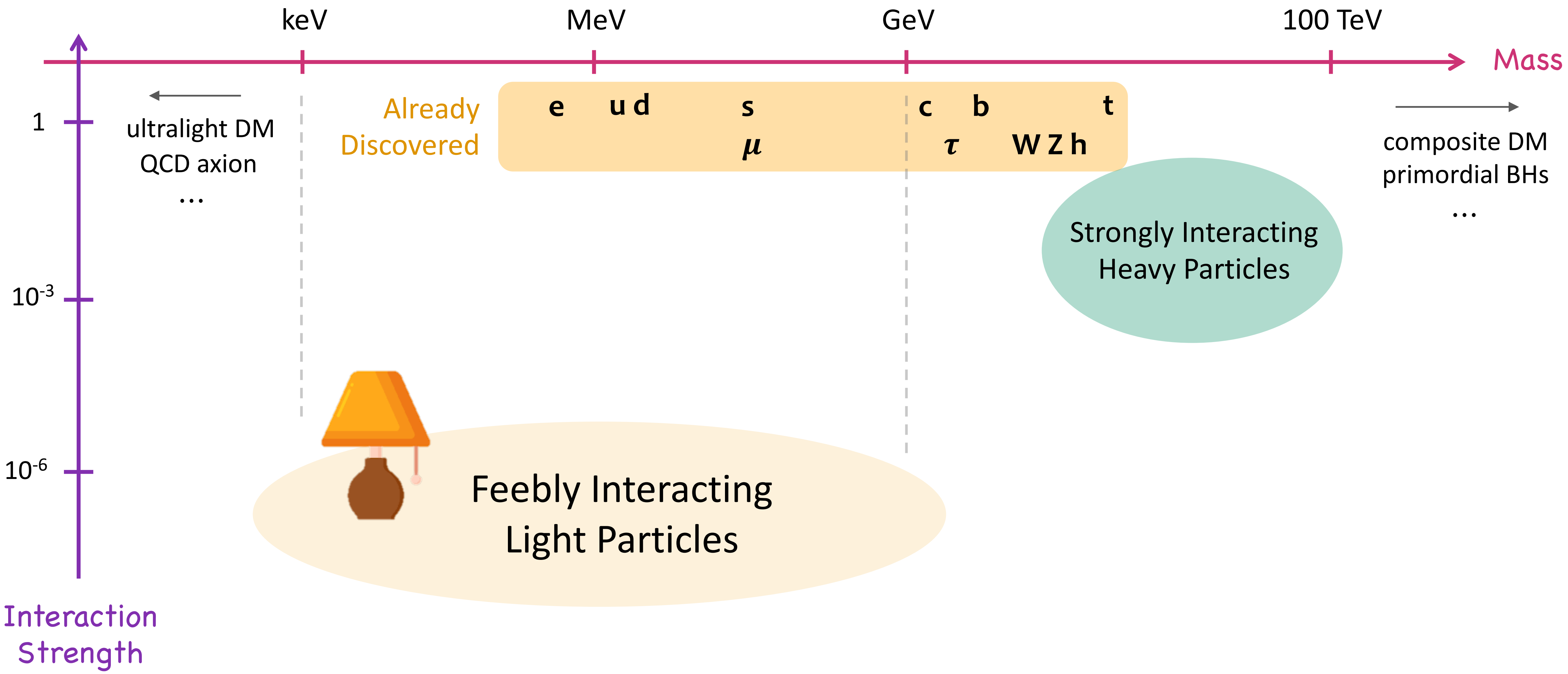

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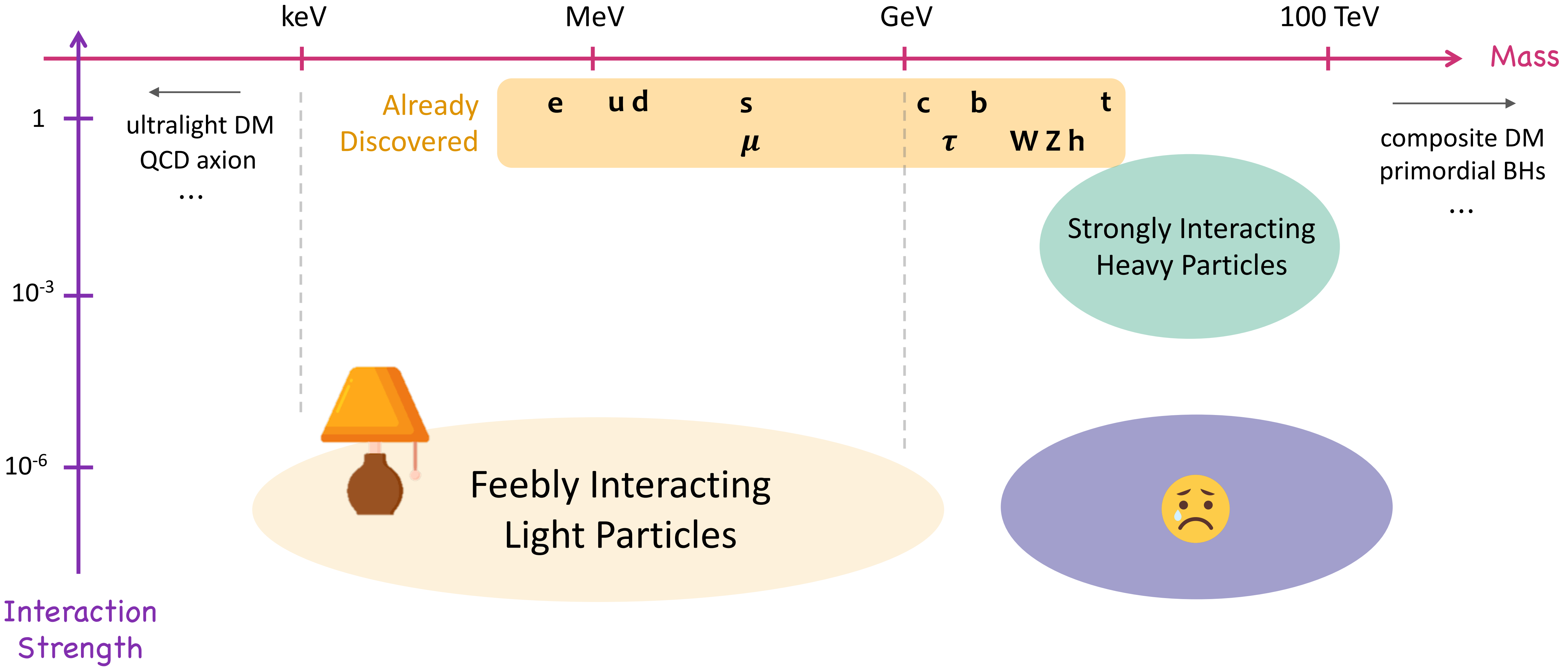

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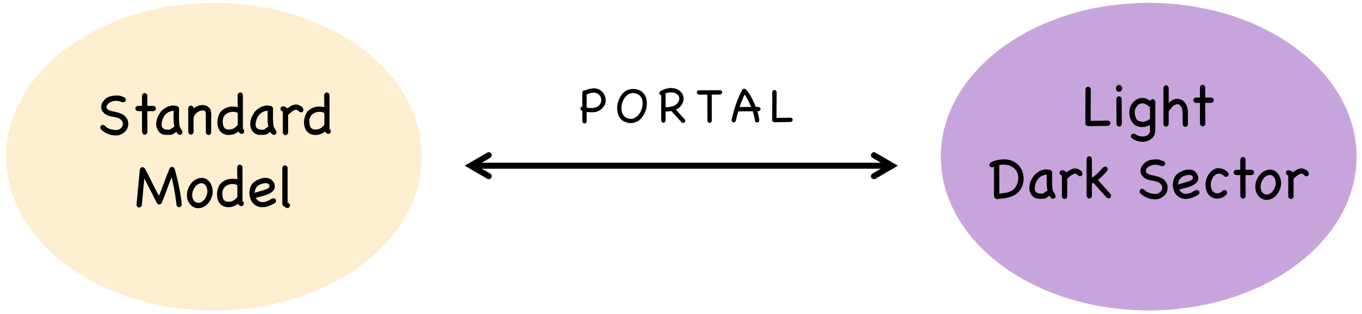
How can we search for light particle BSM signals?



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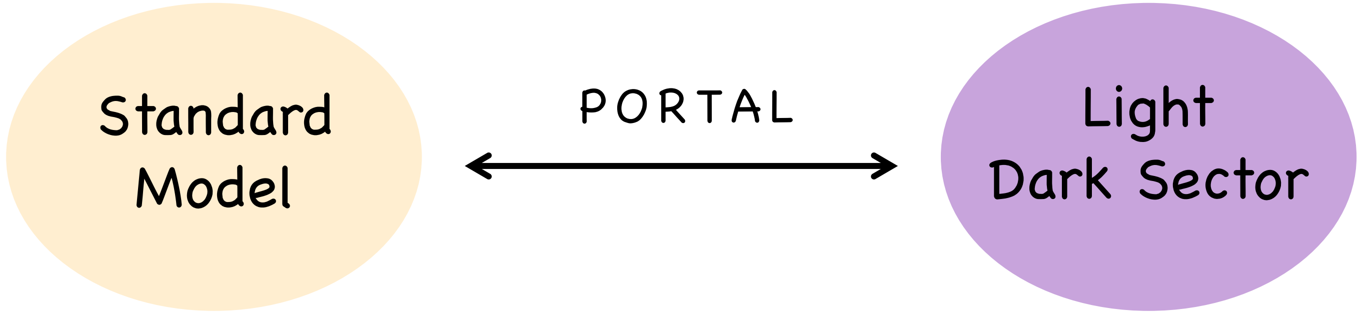
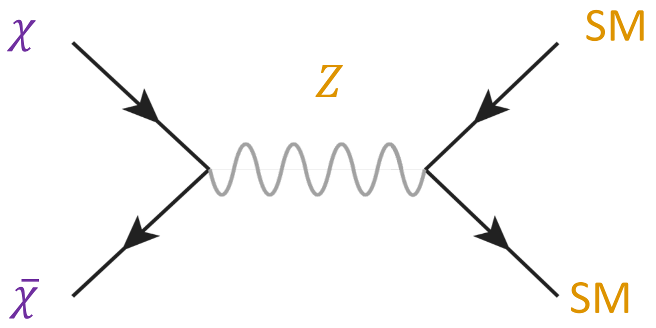


Suppose we have particles χ and $\bar{\chi}$ in the dark sector

natural possibility: couple to the gauge bosons of weak interactions



Introduction and Motivations

How can we search for light particle BSM signals?

Standard Model ⟷ PORTAL ⟷ Light Dark Sector

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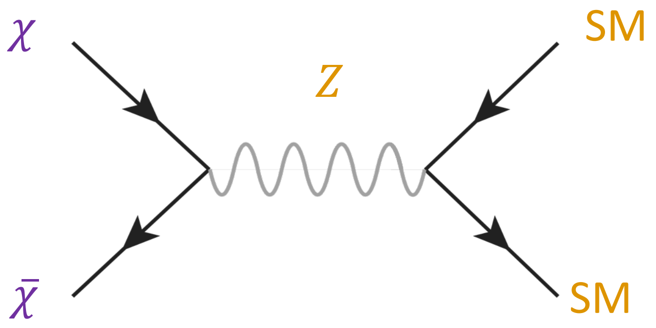
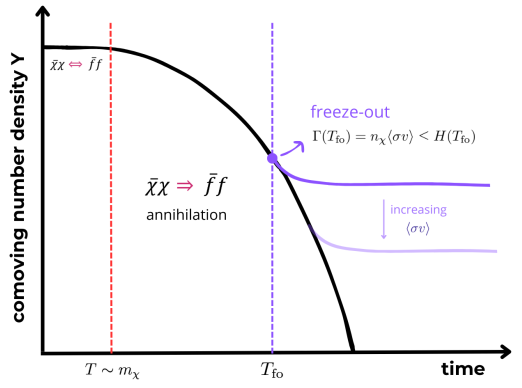


However… $\langle \sigma v \rangle \sim \frac{m_\chi^2}{m_Z^4}$

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

→ DM is overproduced!

Remember!



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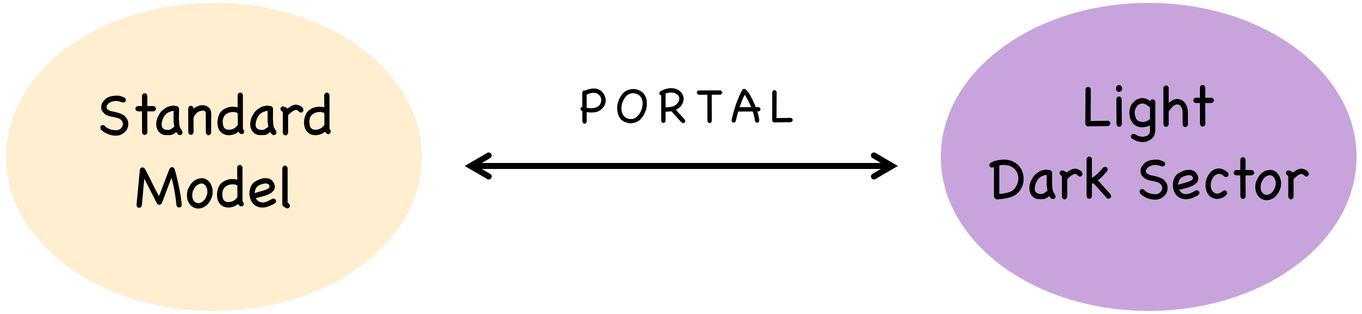

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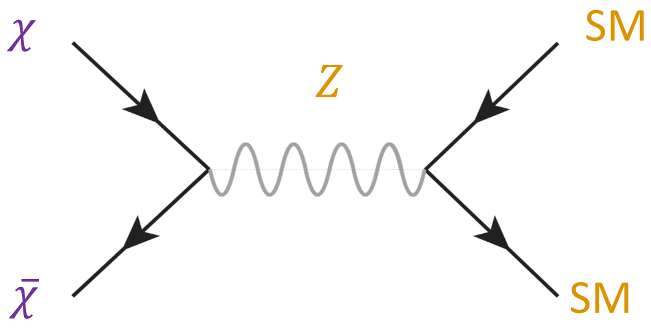

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Lee-Weinberg bound

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

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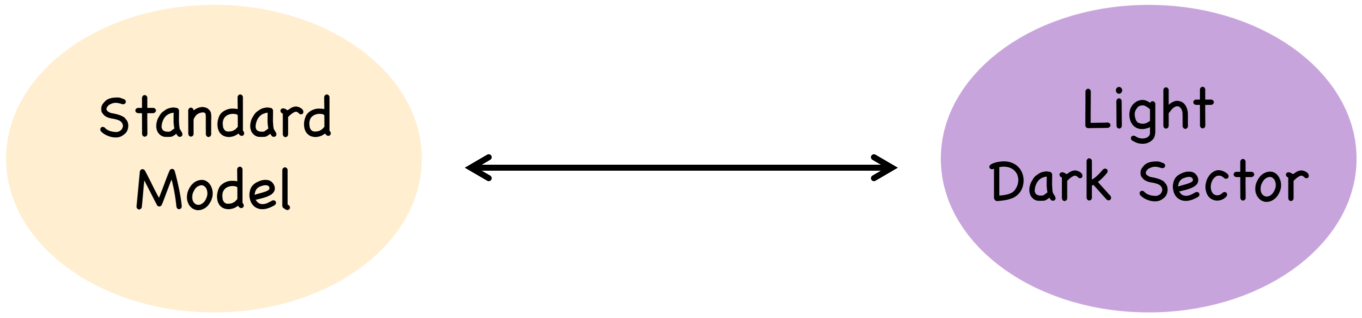

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solution: inclusion of new light dark sector mediator states!

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

Introduction and Motivations · Hidden Portals

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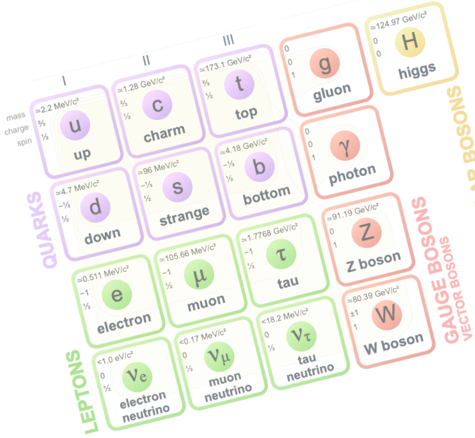
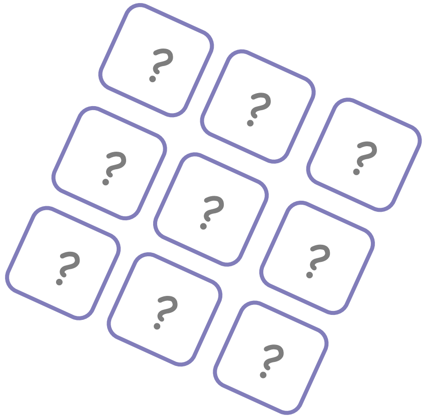


Standard Model

PORTAL

Dark Sector



renormalizable

...

higher dimension

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

→ leptons

→ ...

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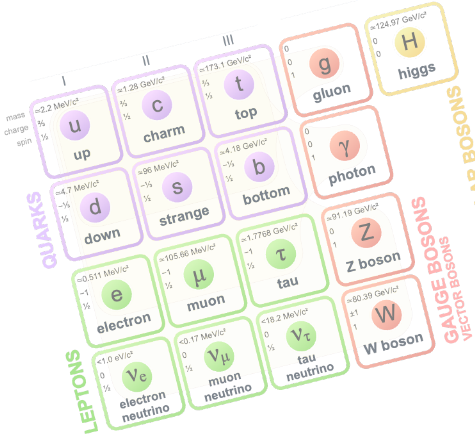
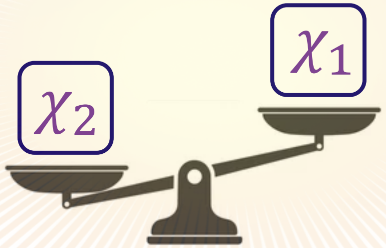


Standard Model ⟵ PORTAL ⟶ Dark Sector

Inelastic Dark Matter



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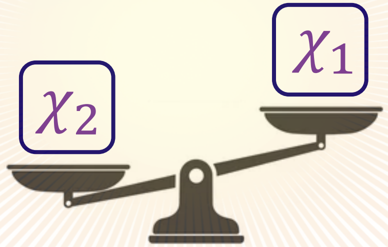
Inelastic Dark Matter (iDM)



Theoretical Framework

Dark Sector

- two-component Weyl fermions forming a Dirac pair $\Rightarrow$ pseudo-Dirac pair
- new vector mediator coming from a spontaneously broken $\mathrm{U}(1)_Q$ abelian gauge symmetry

From the diagonalization of the fermion mass terms

Dirac — Majorana

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

$\Rightarrow$ mass eigenstates

$$\chi_1 \simeq \frac{i}{\sqrt{2}}(\psi_1 - \psi_2), \qquad \chi_2 \simeq \frac{1}{\sqrt{2}}(\psi_1 + \psi_2)\,,$$

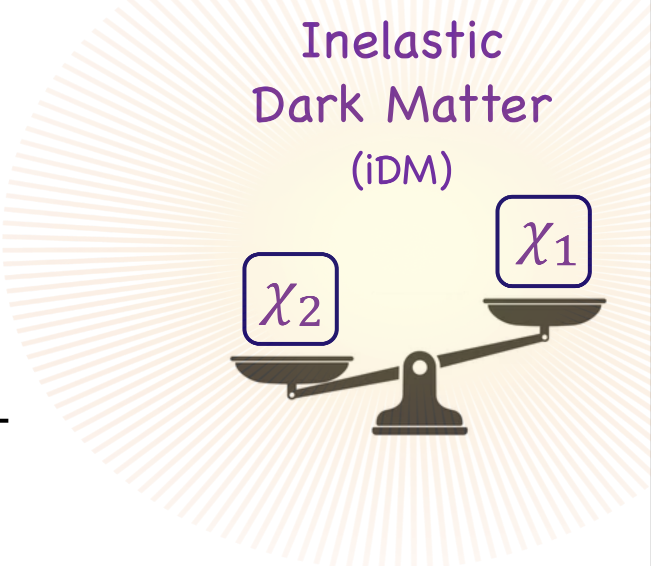
pseudo-Dirac pair with nearly degenerate masses

$$m_{1,2} \simeq m_D \mp \frac{1}{2}(\delta_1 + \delta_2) \quad \Rightarrow$$

Mass splitting

$$\Delta := \frac{m_2 - m_1}{m_1} = \frac{\delta_1 + \delta_2}{m_1} < 1$$

Inelastic Dark Matter



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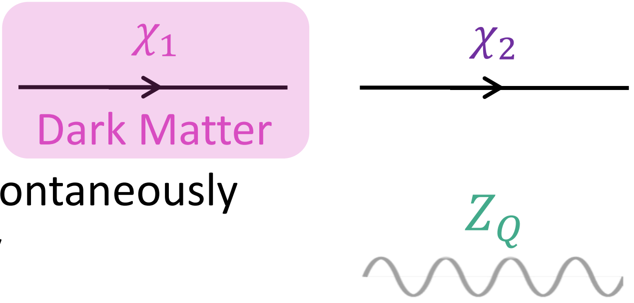

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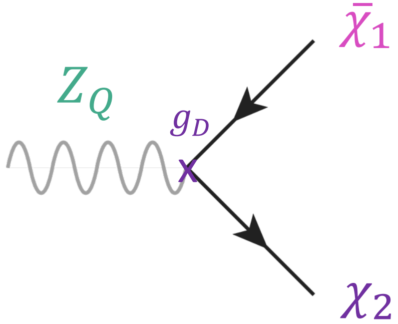

The interaction term with the mediator turns to be off-diagonal

$$\mathcal{L} \supset g_D Z_{Q\mu}(\psi_1^\dagger \bar{\sigma}^\mu \psi_1 - \psi_2^\dagger \bar{\sigma}^\mu \psi_2) \longrightarrow \mathcal{L}_{\text{int}}^{\text{D}} = \frac{i}{2} g_D Z_{Q\mu} \bar{\chi_2} \gamma^\mu \chi_1 + \text{h.c.}$$

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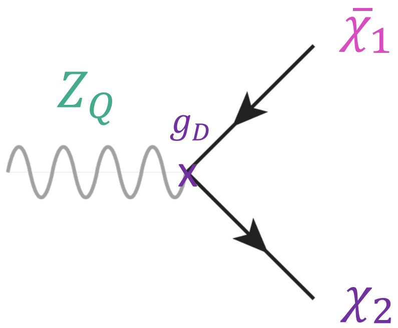

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→ **Thermal relics:** DM abundance can be computed via thermal freeze-out.

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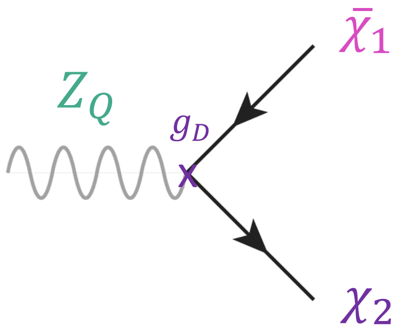

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- **Thermal relics:** DM abundance can be computed via thermal freeze-out.
- **Evades indirect and direct detection experimental limits**

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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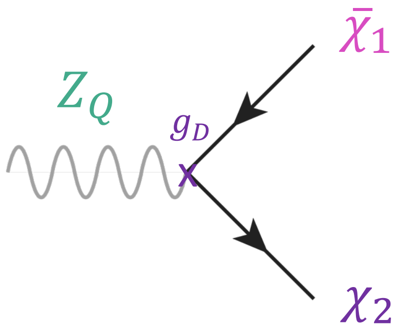

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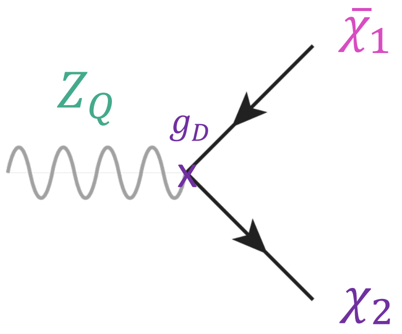
- **Evades stringent CMB limits**

  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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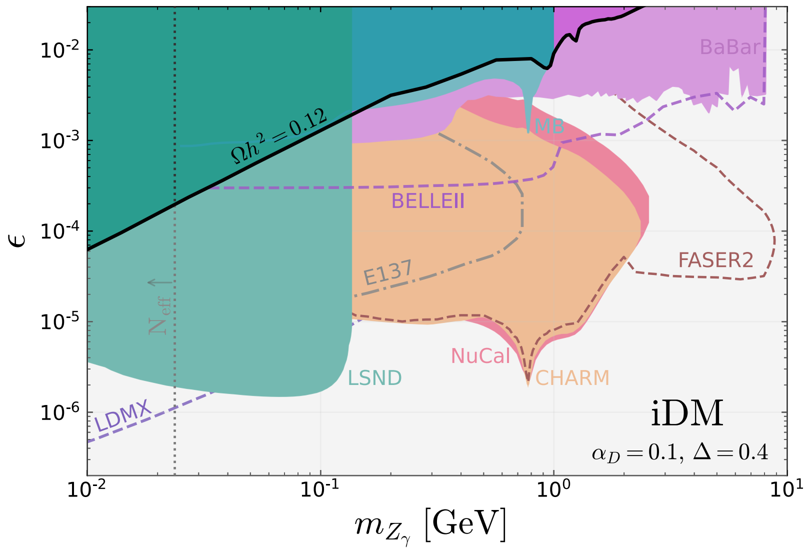
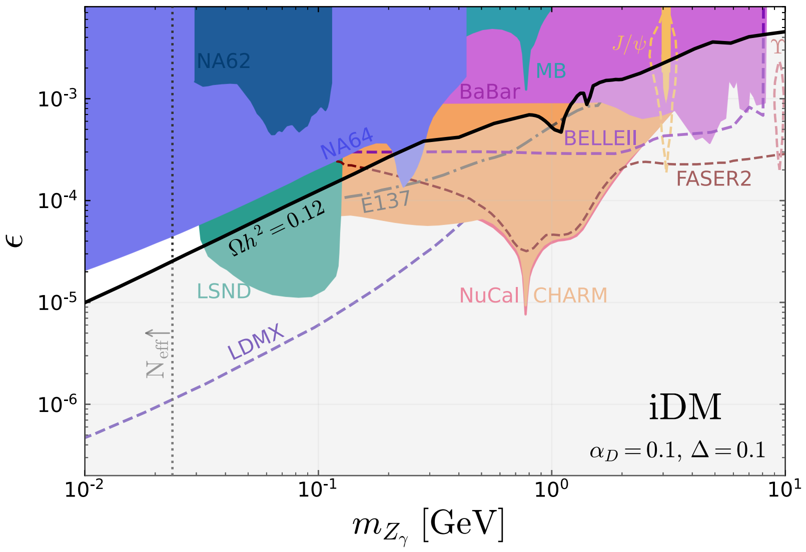
What's new?

- 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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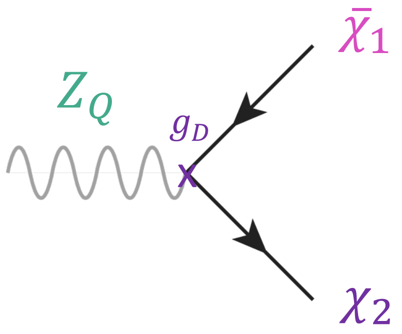

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What's new?

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

$\Downarrow$

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

$$\mathcal{L}_{\text{int}}^{\text{SM}} = e\epsilon J_{\text{em}}^\mu Z_{Q\mu} - g_Q J_Q^\mu Z_{Q\mu}$$

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

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

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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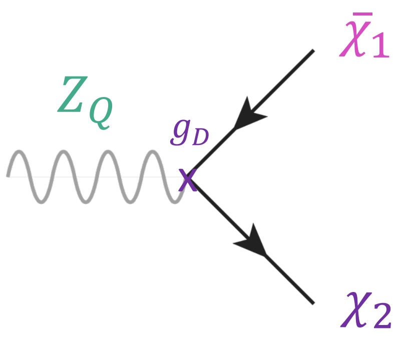

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ALF, P. Reimitz, R.Z. Funchal
arXiv:2410.00881 **[hep-ph]**

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iDM_Q models

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

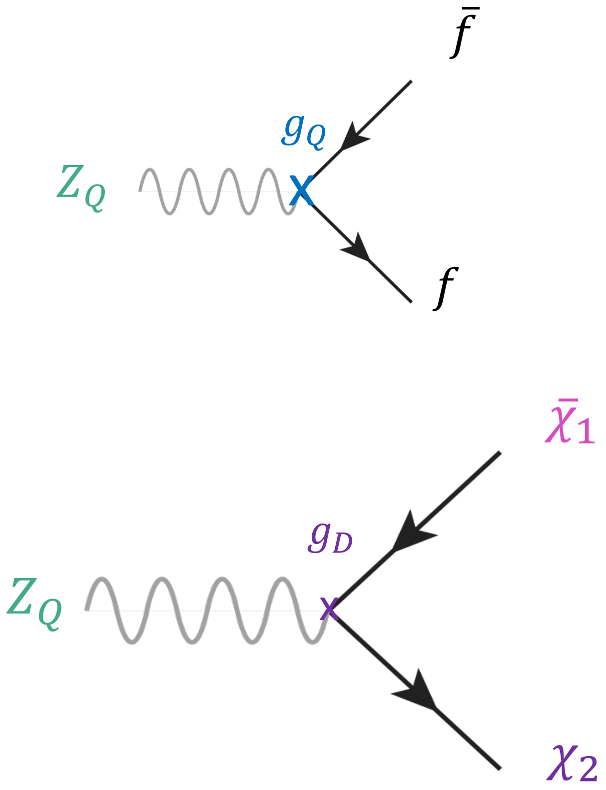
$$Q = x_B B - x_e L_e - x_\mu L_\mu - x_\tau L_\tau$$

x_B	x_e	x_μ	x_τ	Q	q^f_Q 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

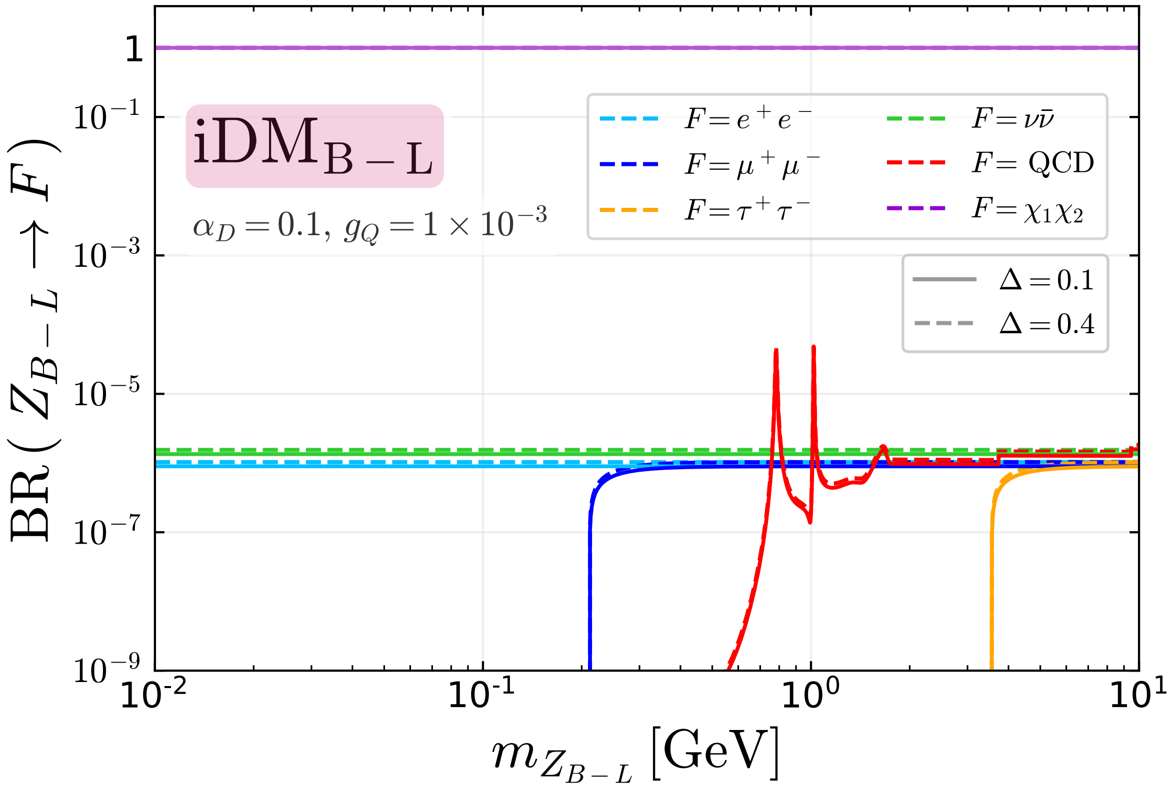
Inelastic Dark Matter · Decay Rates

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

Mediator



prompt-decay



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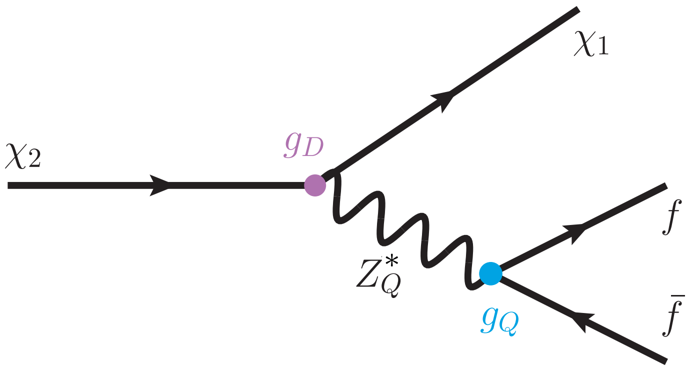
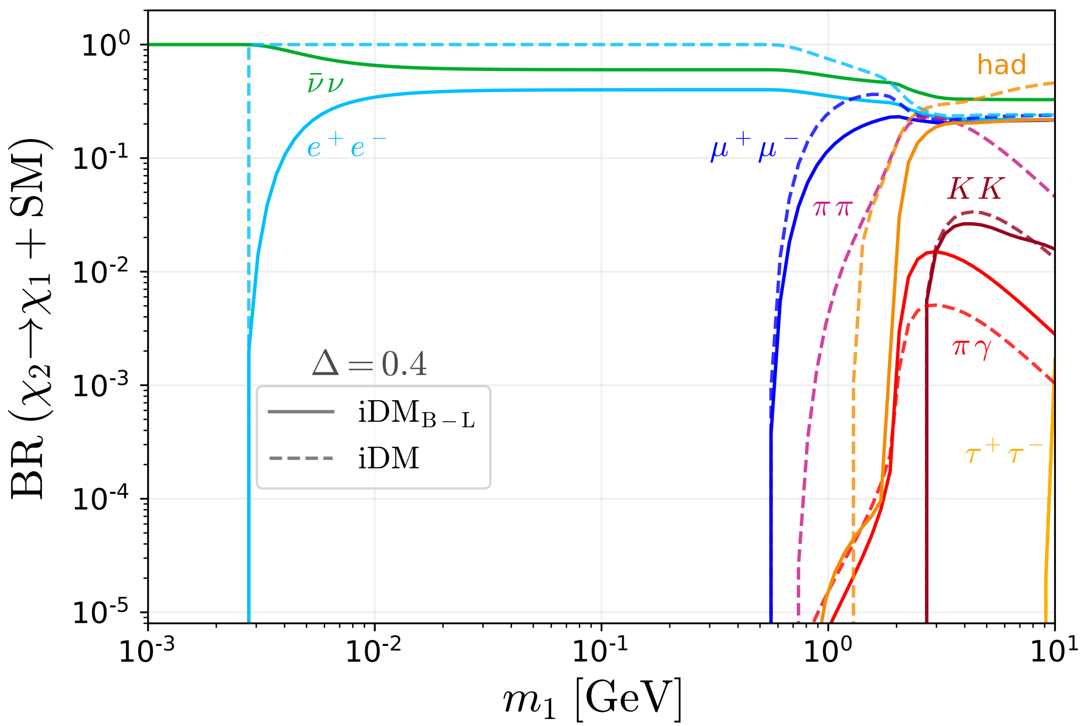
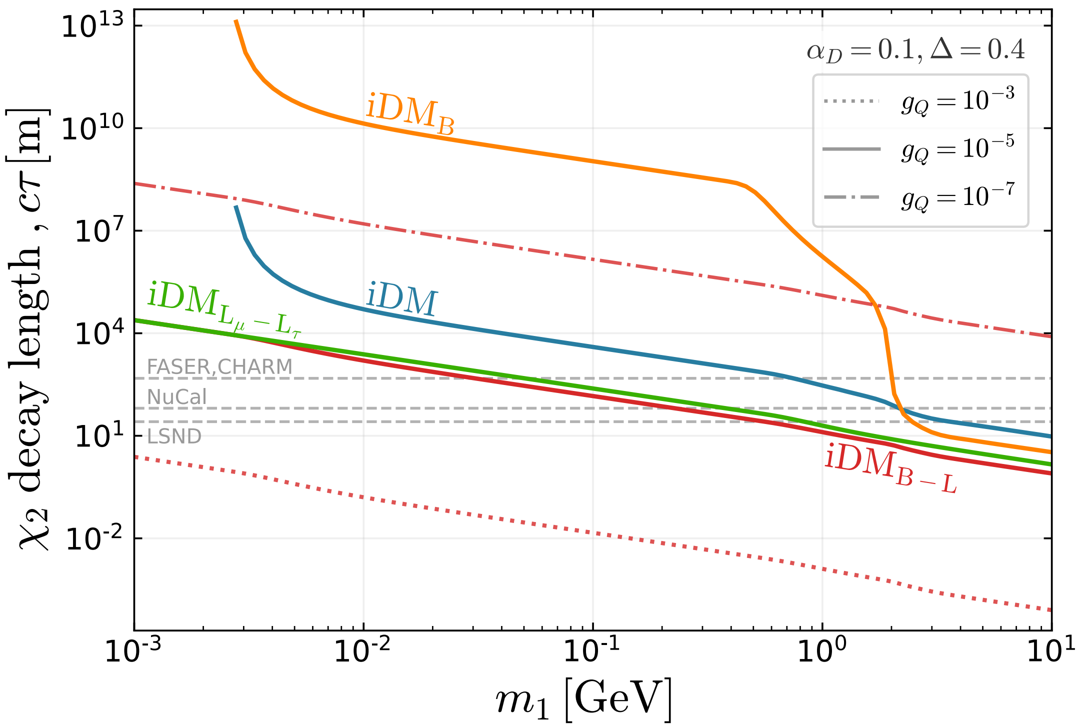


Dark fermion

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





Inelastic Dark Matter · Relic Density Computation

Boltzmann Equation

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

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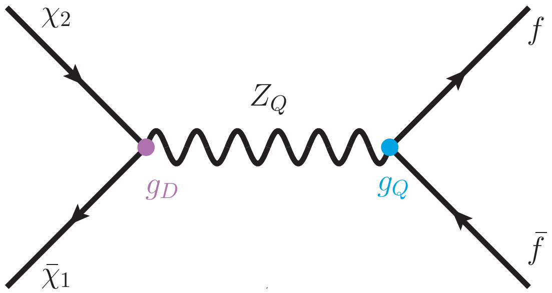
$$\left. \pm \left(\langle\sigma v\rangle_{2f\to 1f} Y_f^{\mathrm{eq}} + \frac{1}{s}\langle\Gamma\rangle_{2\to 1ff}\right)\left(Y_2 - Y_1 \frac{Y_2^{\mathrm{eq}}}{Y_1^{\mathrm{eq}}}\right)\right],$$



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

Inelastic Dark Matter · Relic Density Computation

Boltzmann Equation

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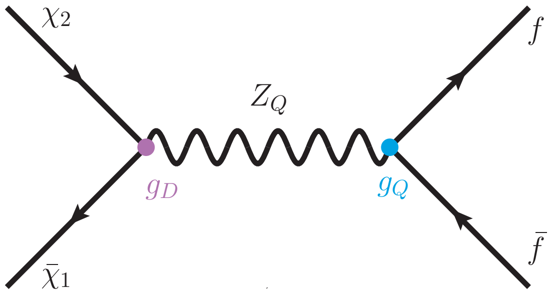
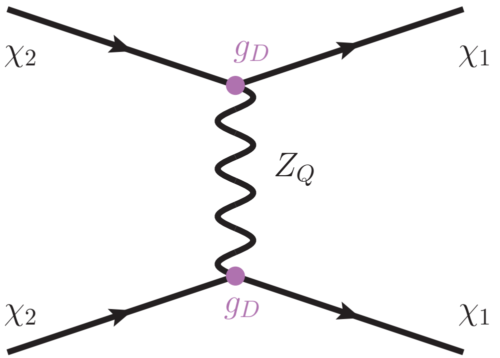


a) $\chi_1\,\chi_2 \to \mathrm{SM}$



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

Inelastic Dark Matter · Relic Density Computation

Boltzmann Equation

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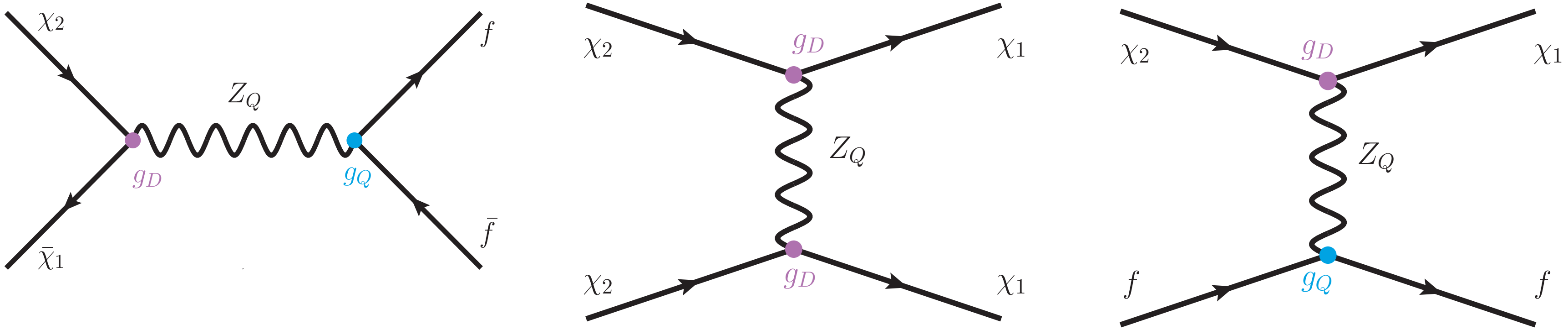

a) $\chi_1\,\chi_2 \to \mathrm{SM}$

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

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

Inelastic Dark Matter · Relic Density Computation

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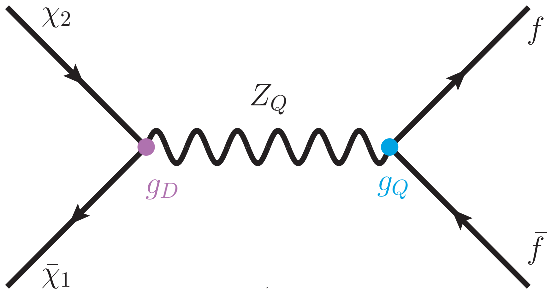

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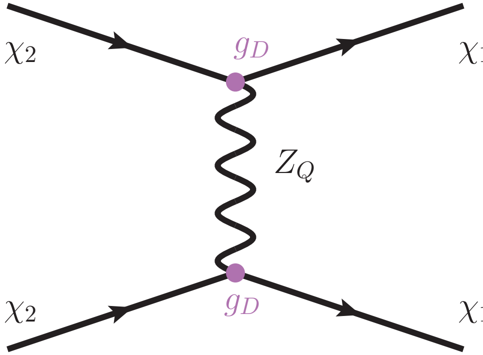
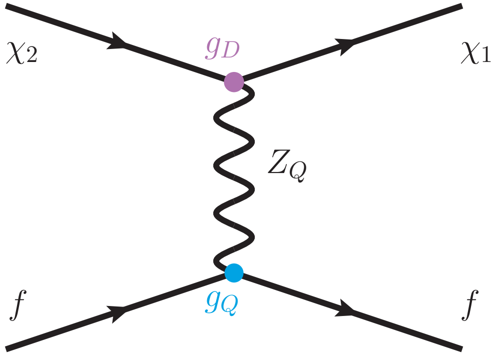
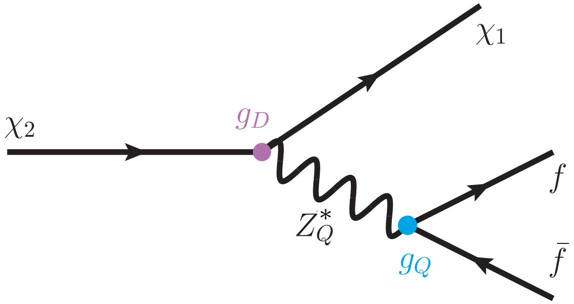


b) $\chi_2\,\chi_2 \to \chi_1\,\chi_1$



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



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

Inelastic Dark Matter · Relic Density Computation

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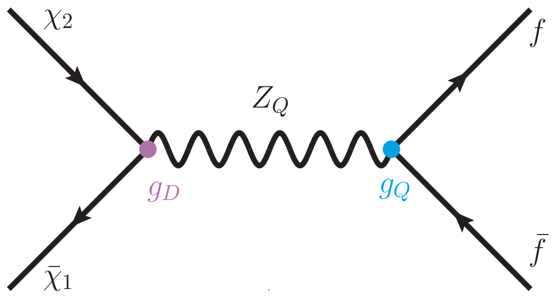
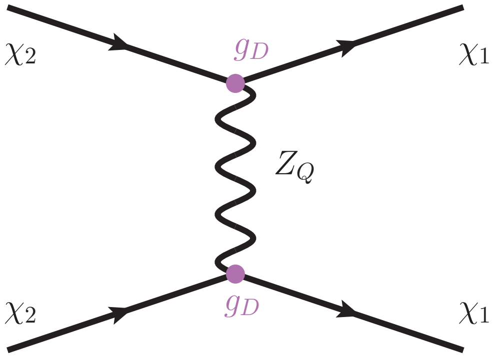
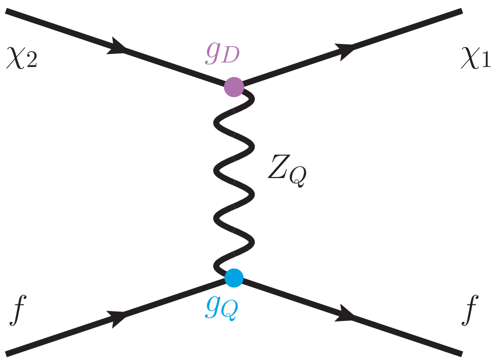
coannihilations dominate!



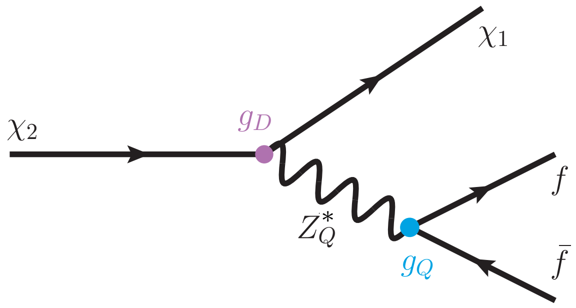
a) $\chi_1\,\chi_2 \to \mathrm{SM}$



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



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



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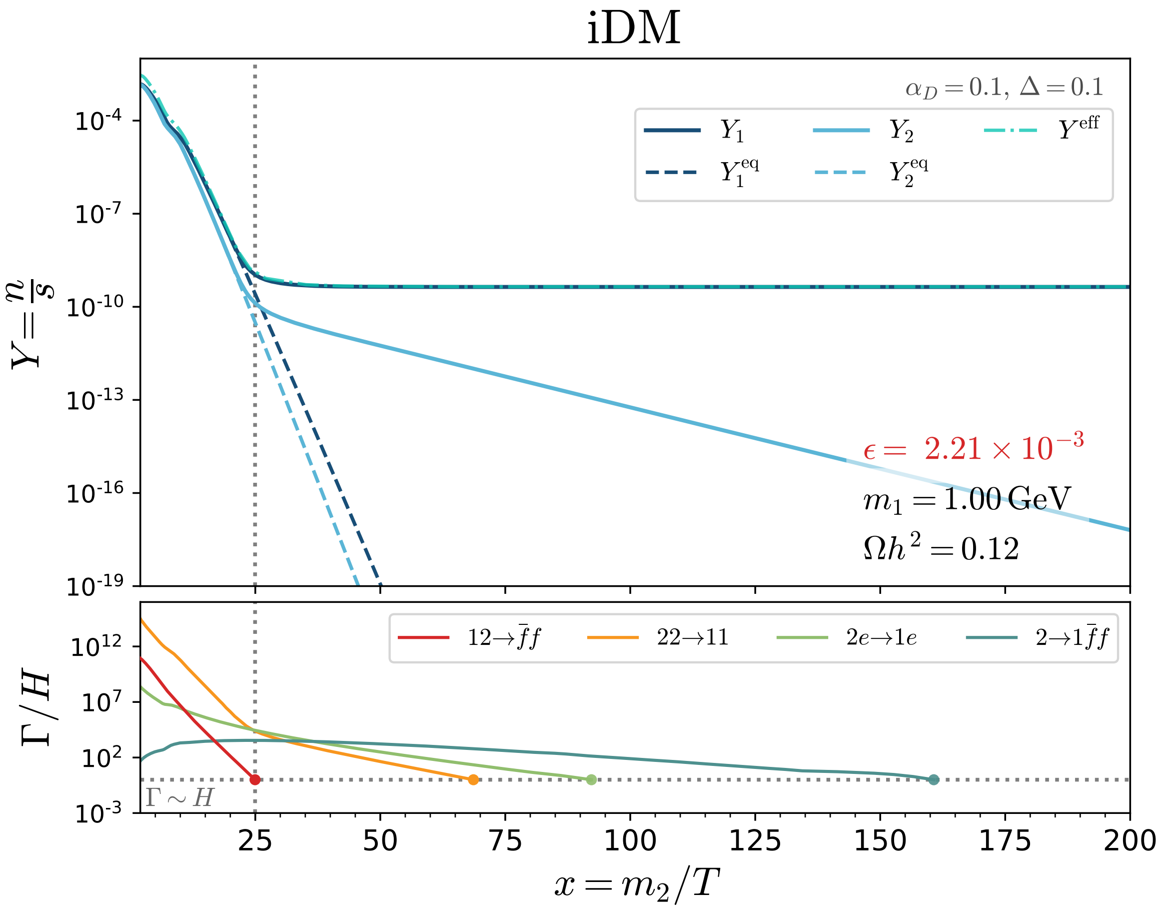
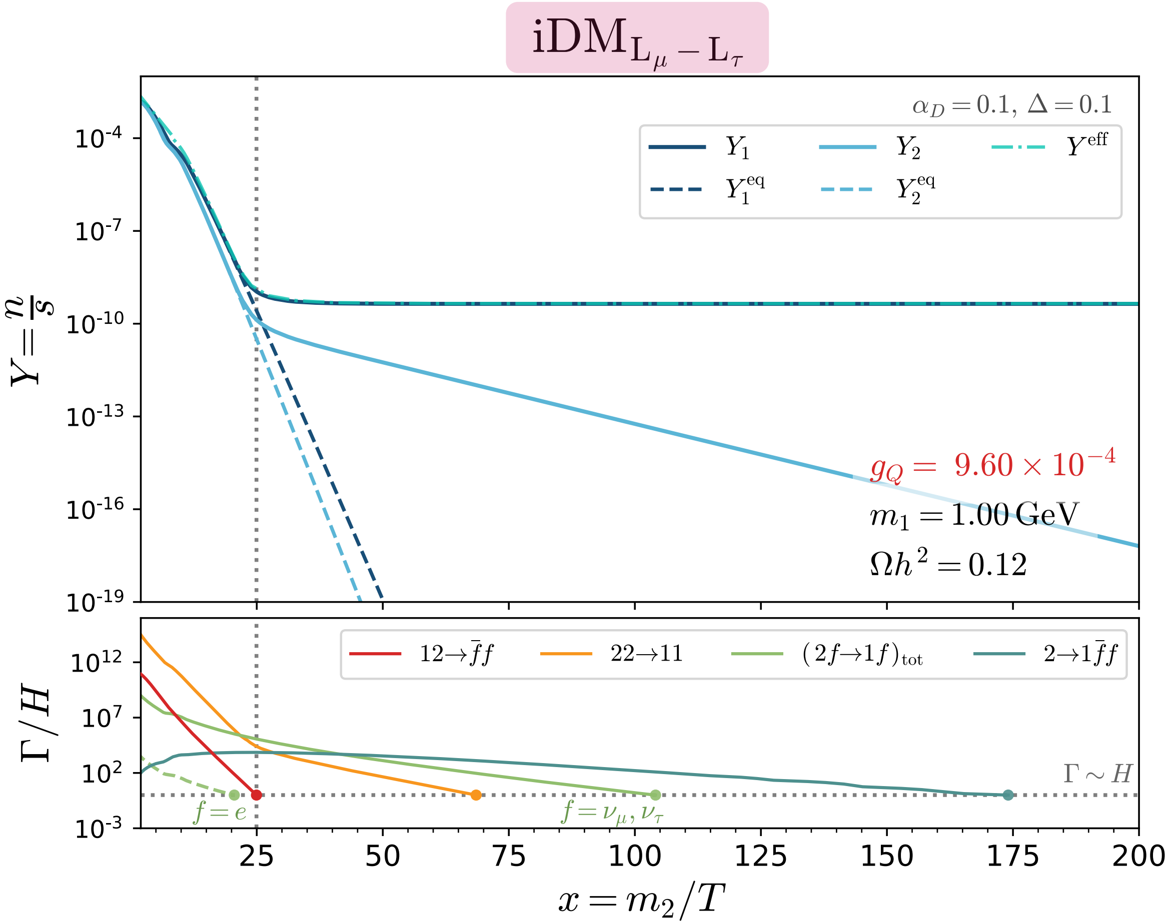
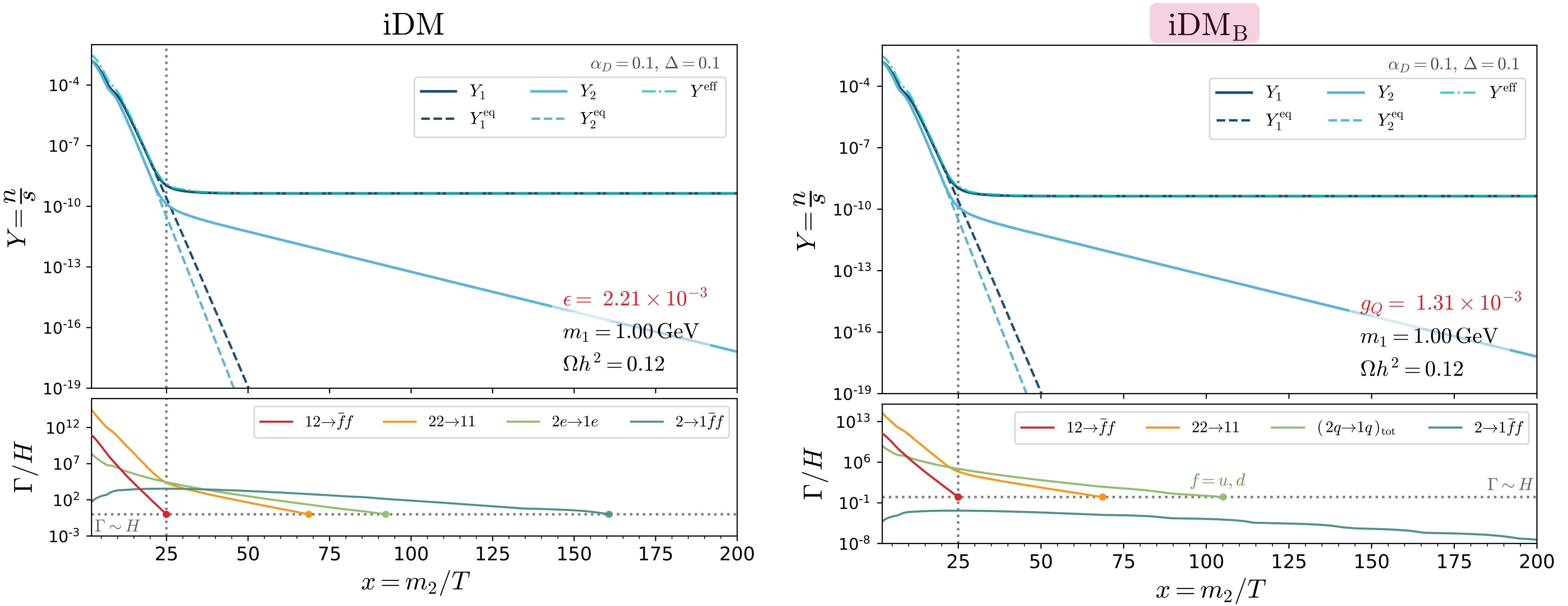
Inelastic Dark Matter · Relic Density Computation





Inelastic Dark Matter · Relic Density Computation



Inelastic Dark Matter · ReD-DeLiVeR code

ReD-DeLiVeR (Relic Density with DeLiVeR)

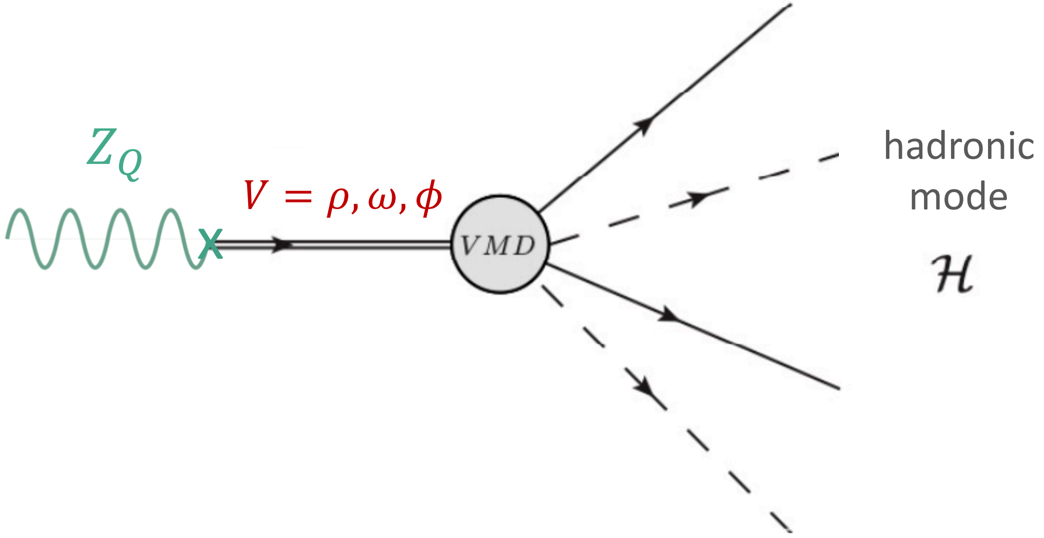
- update of the previous python package DELIVER (**De**cays of **Li**ght **Ve**ctors **R**evised), which can be used to compute decay rates and branching ratios for user-defined $U(1)_Q$ charges,

- **key feature**: includes a complete set of hadronic decays (20 channels)

channel	resonances
$\pi\gamma$	$\boldsymbol{\rho}, \omega, \boldsymbol{\omega'}, \boldsymbol{\omega''}, \boldsymbol{\phi}$
$\pi\pi$	$\rho, \rho', \ldots$
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'''

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



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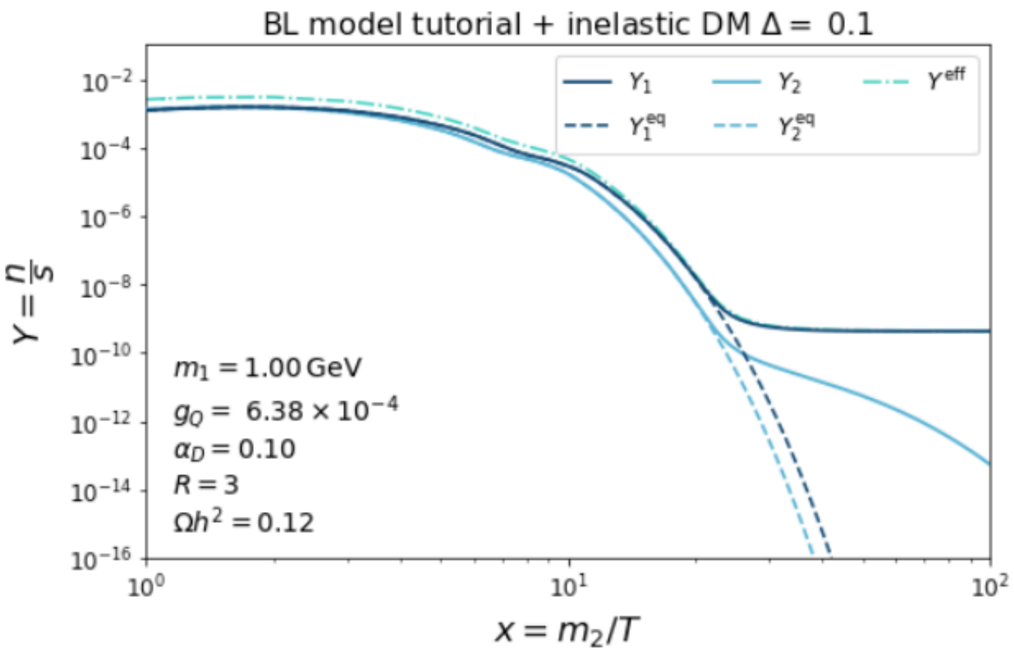
- **new version**:
  - inclusion of DM candidates { simplified DM models; inelastic DM }
  - computation of relic density and rates



Inelastic Dark Matter · ReD-DeLiVeR code

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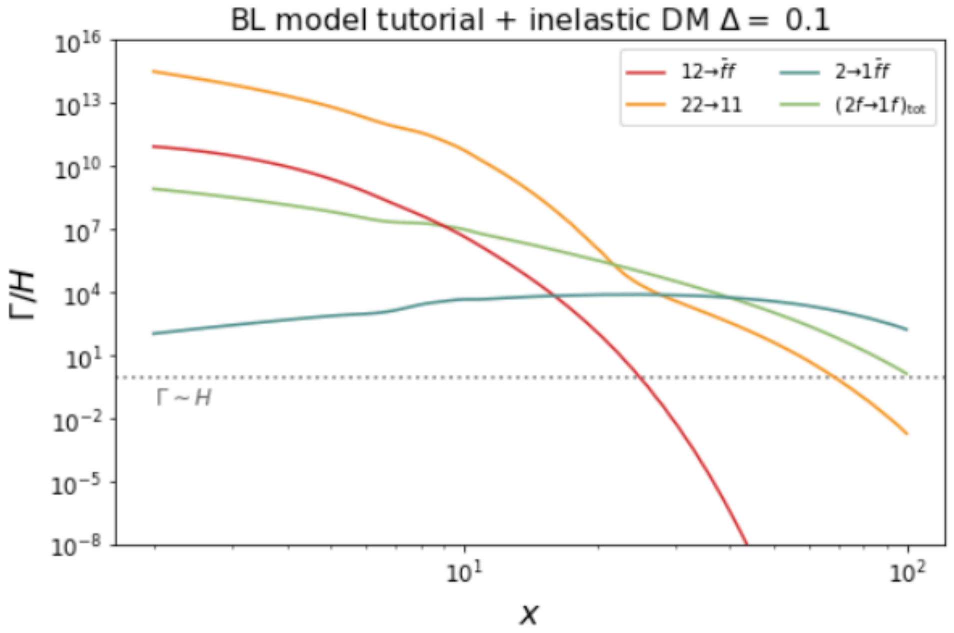

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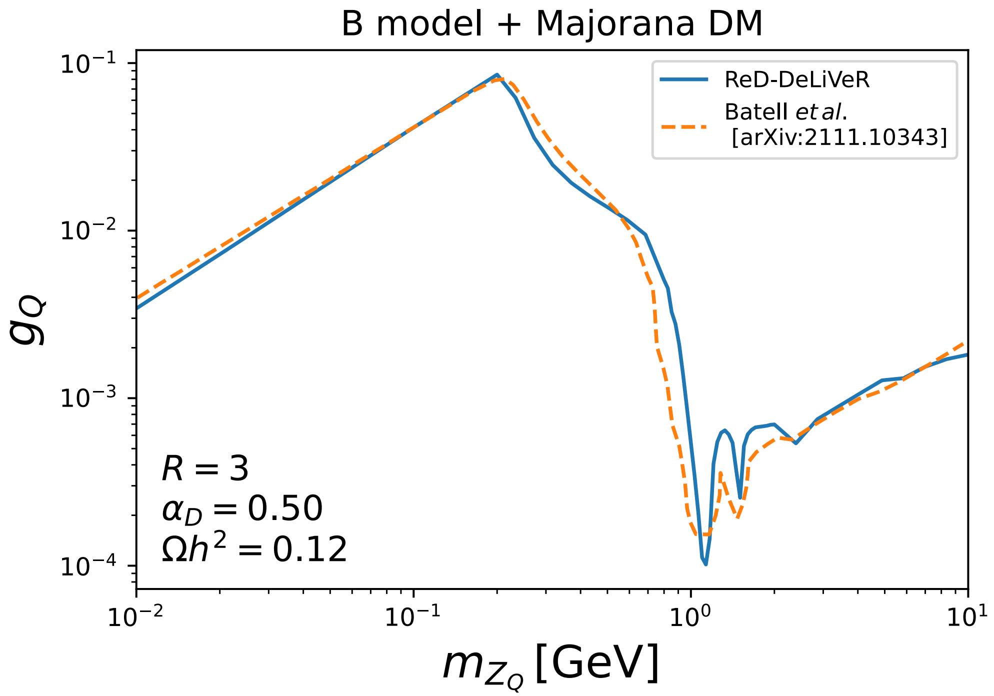

specially for B-coupled models, it is very important to compute correctly the hadronic contributions

Inelastic Dark Matter · ReD-DeLiVeR code

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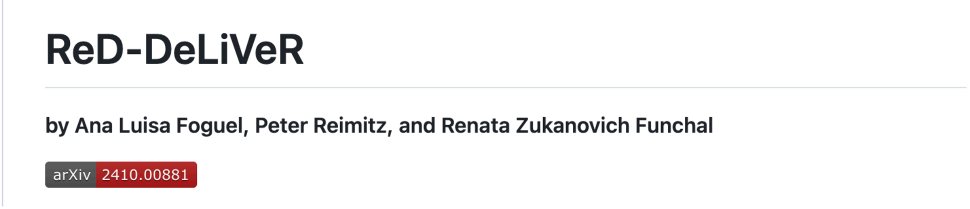
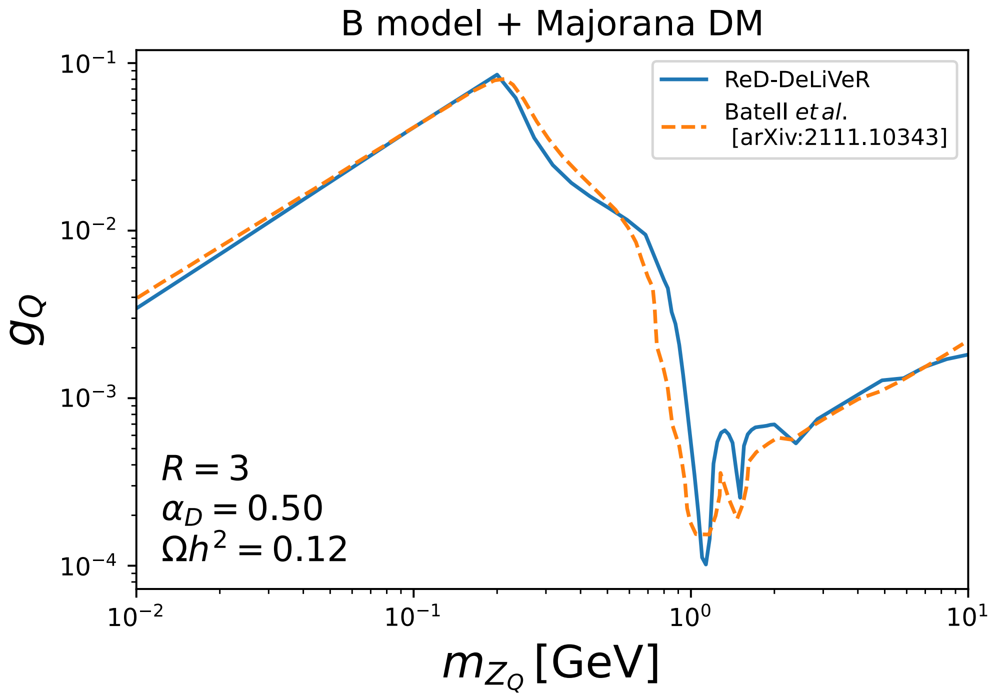
  - computation of thermal targets
- publicly available on GitHub together with a **Tutorial**!

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





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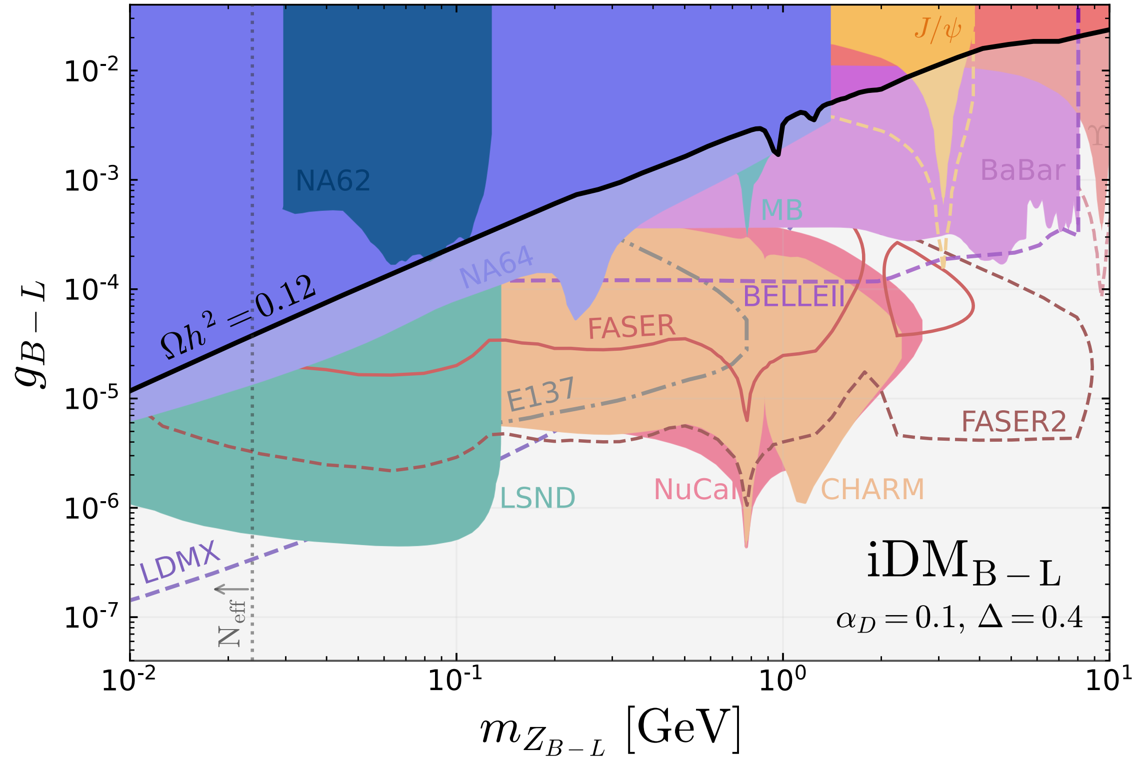
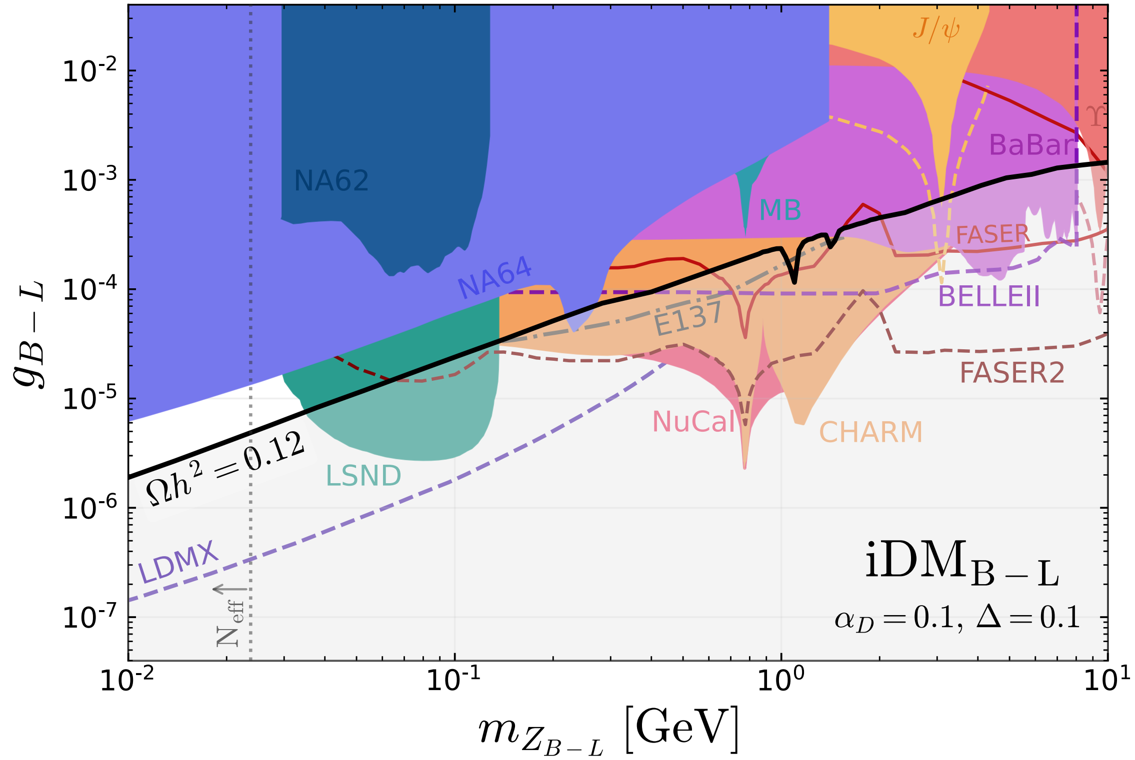
Inelastic Dark Matter · Bounds

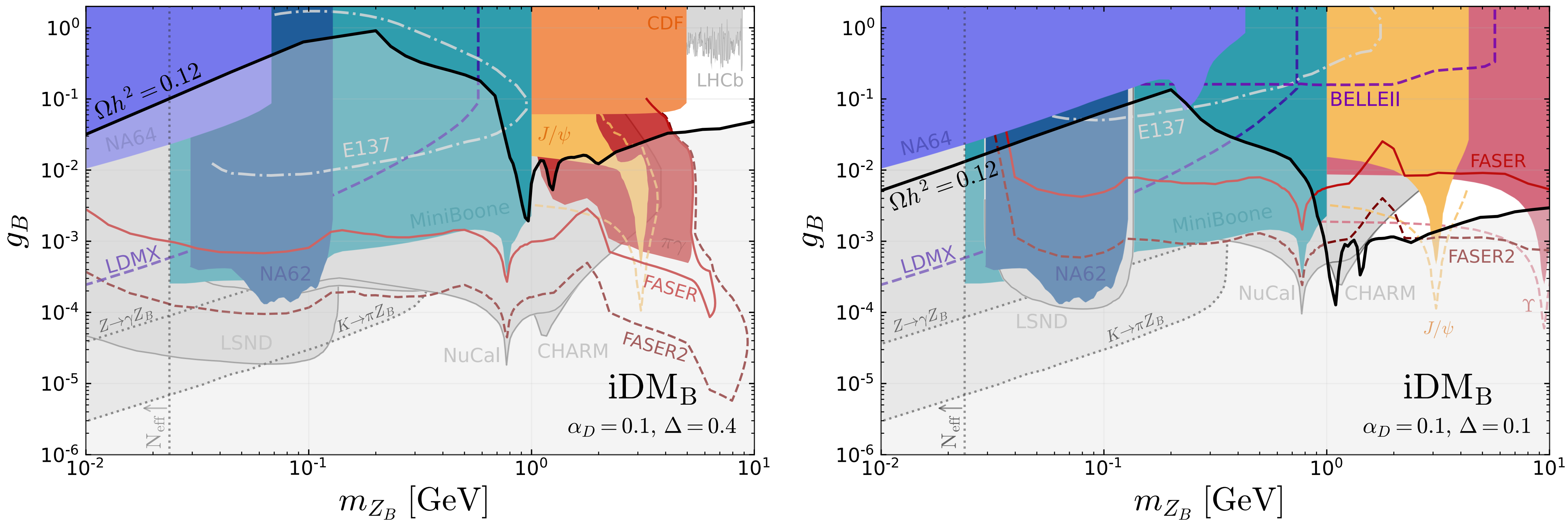
iDM_{B-L}





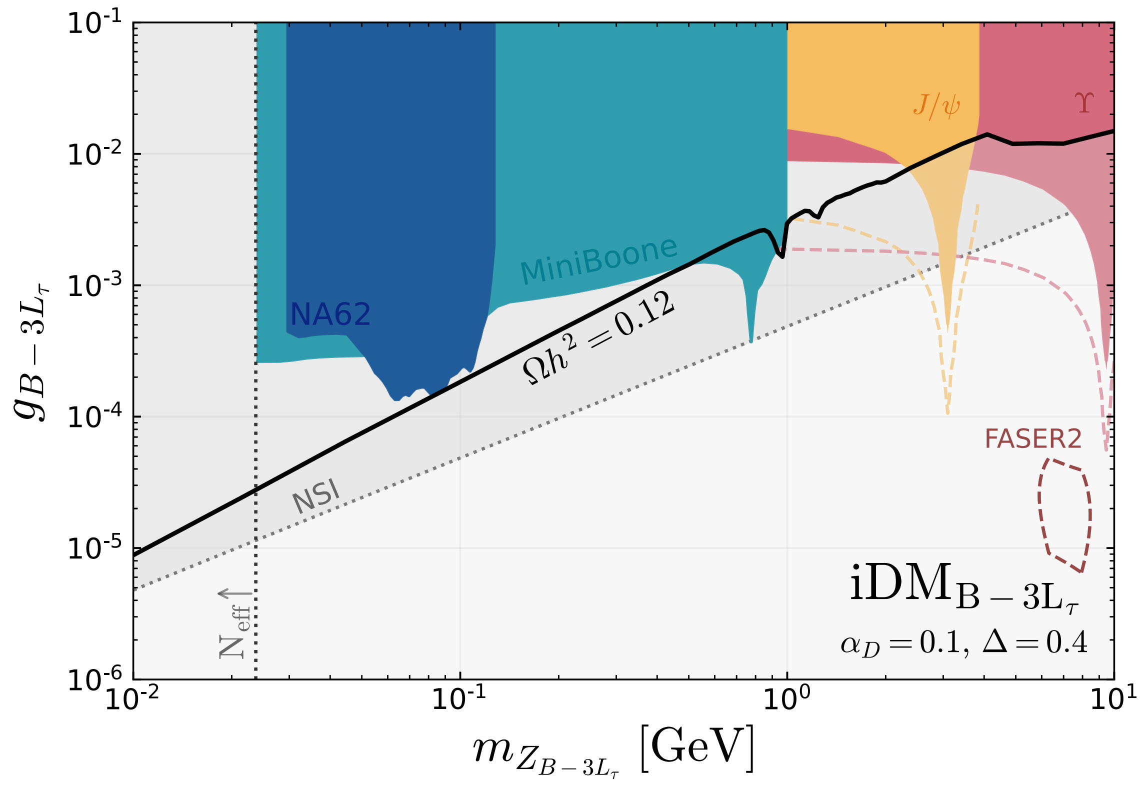
Inelastic Dark Matter · Bounds

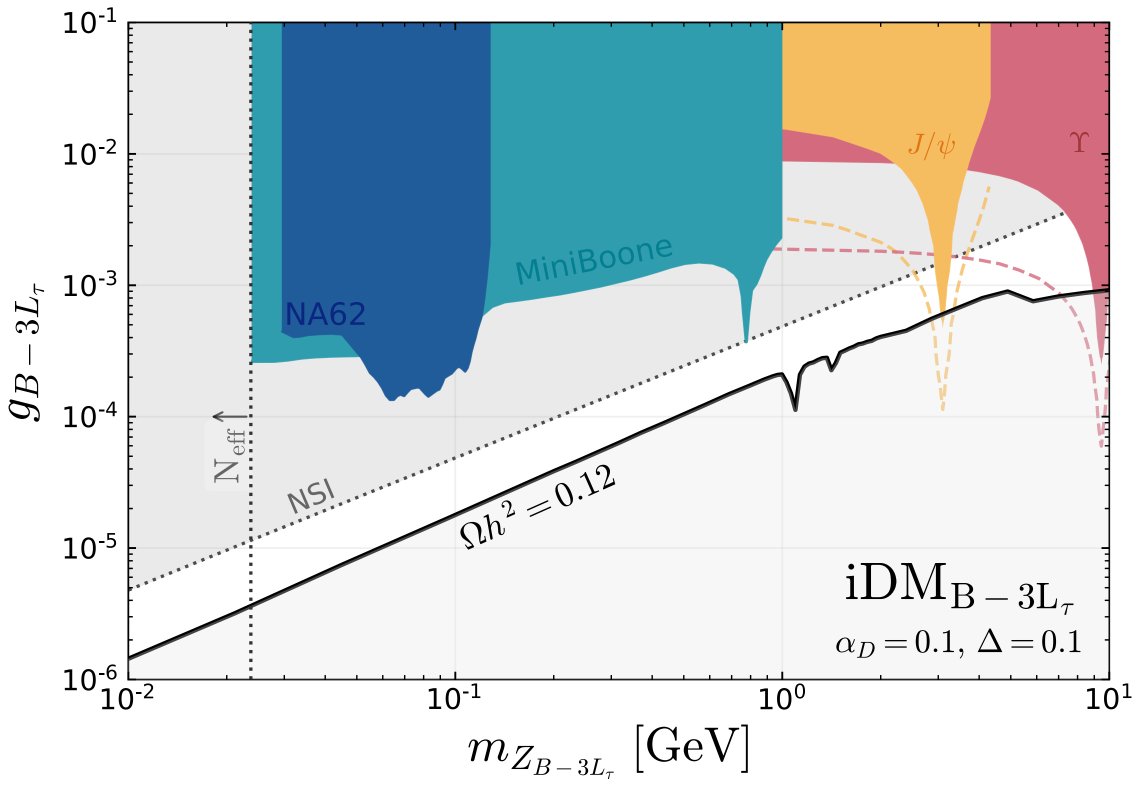
iDM_B



Inelastic Dark Matter · Bounds

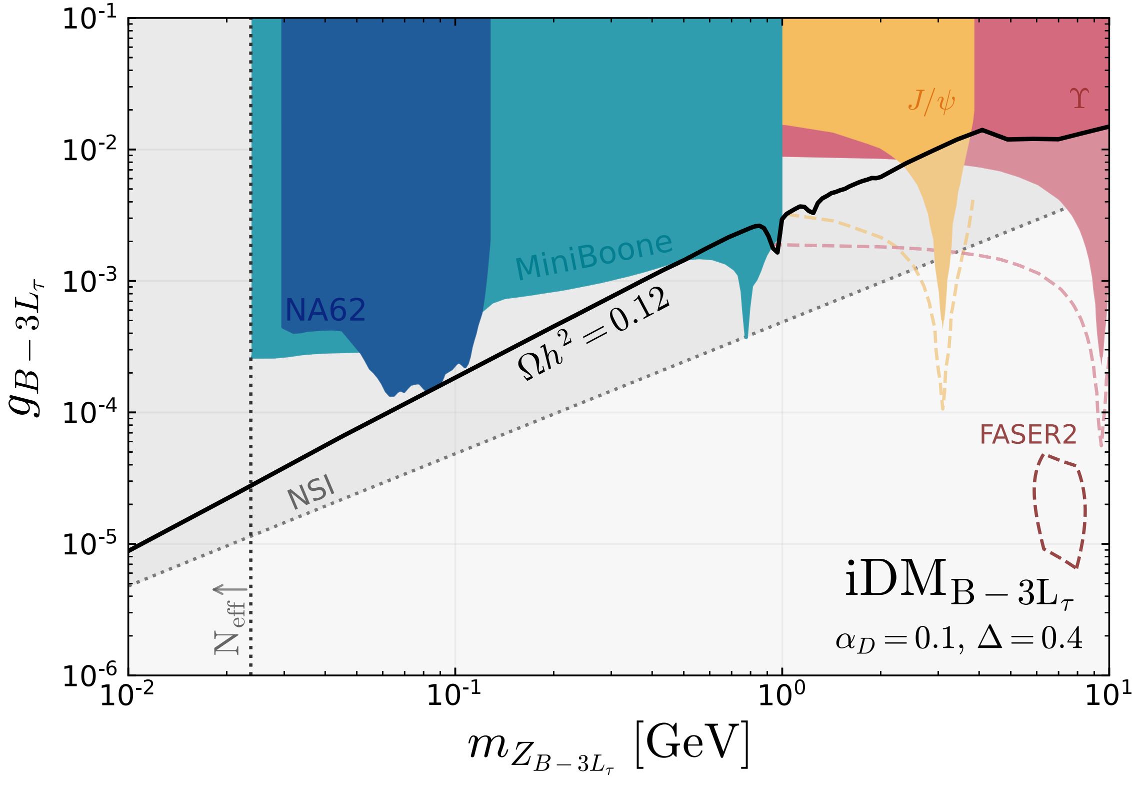
iDM_{B-3L_τ}

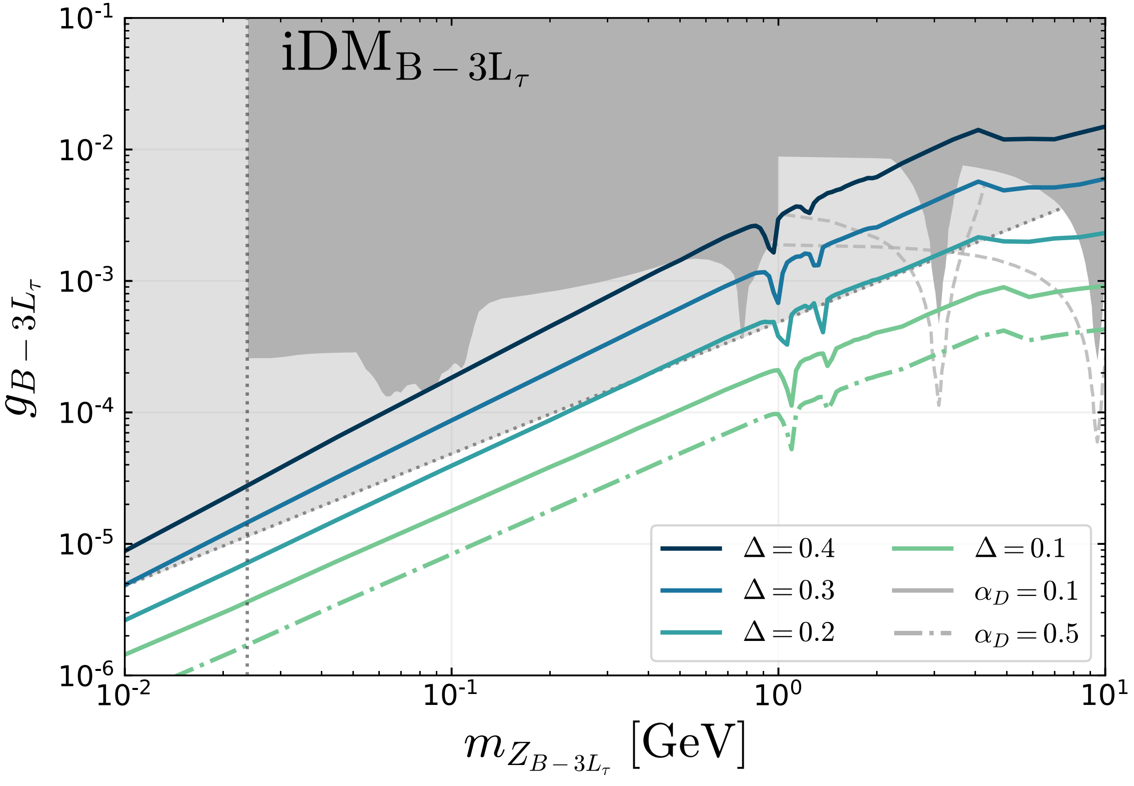




Inelastic Dark Matter · Bounds

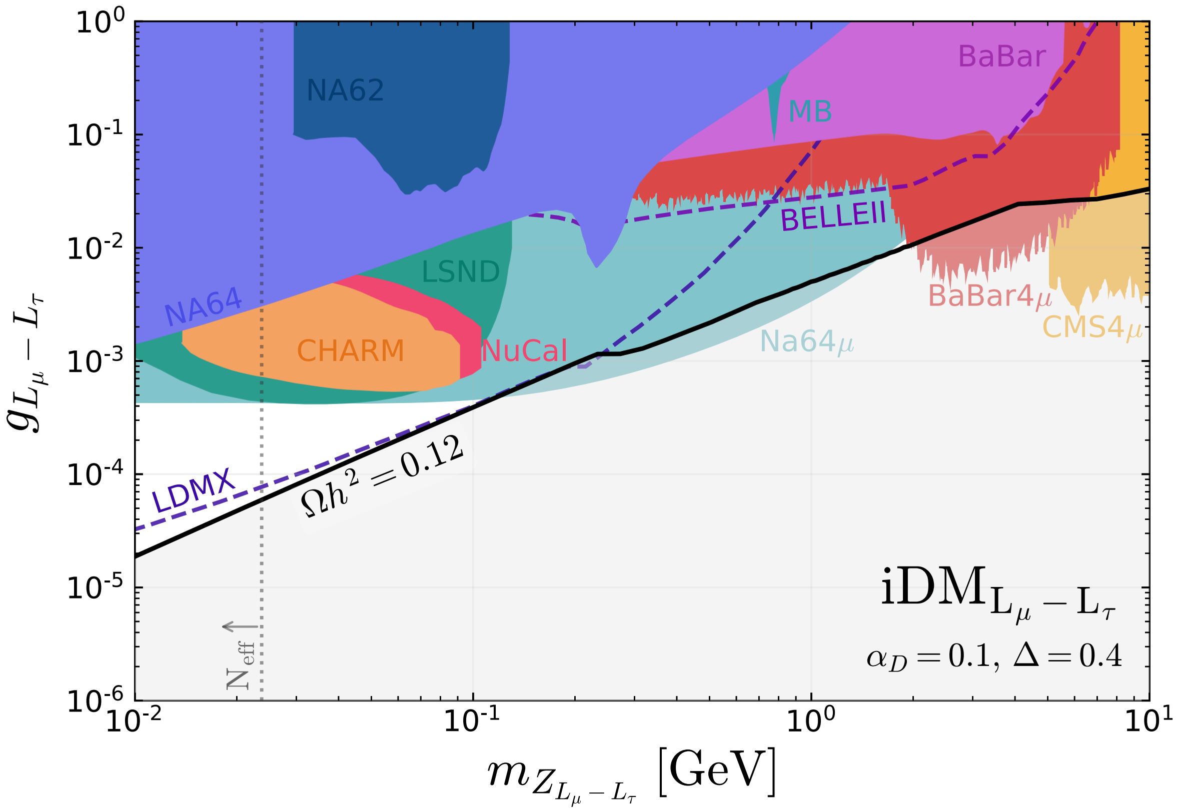
iDM_{B-3L_τ}

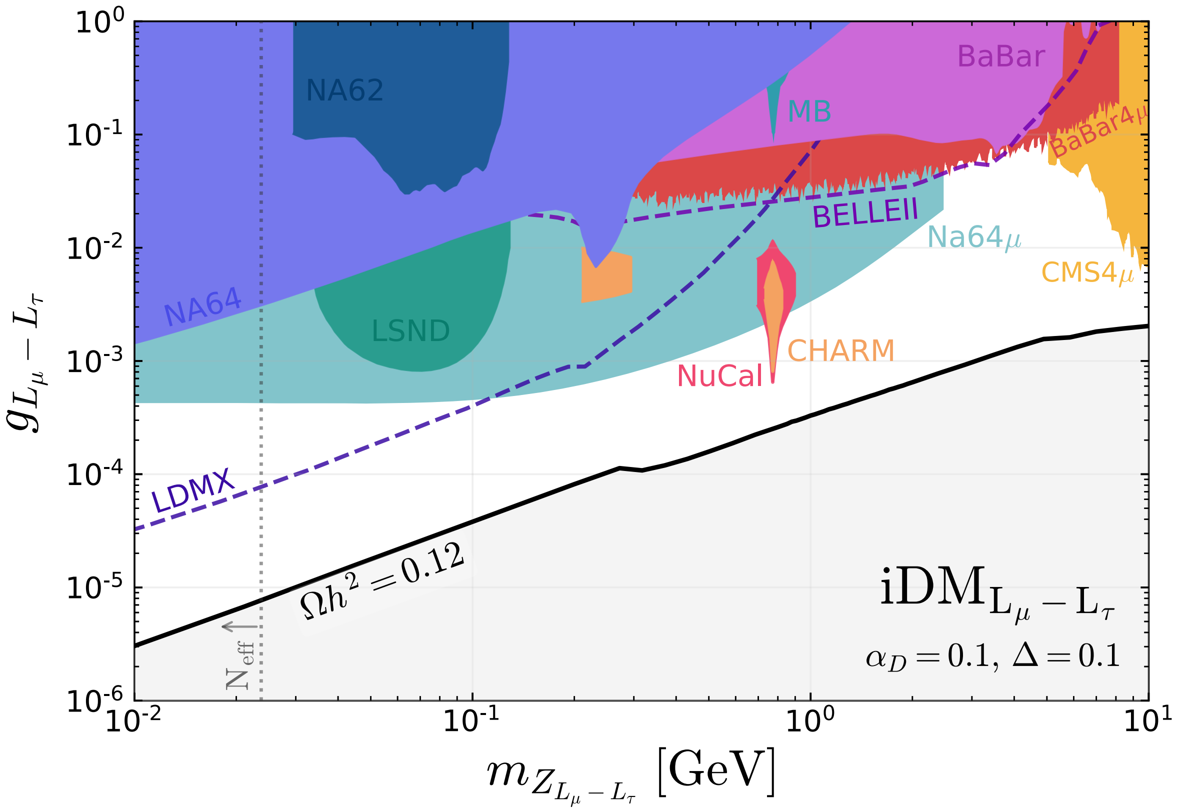




Inelastic Dark Matter · Bounds

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





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

Thank you for your kind attention!

Thank you for your attention!!

BACKUP

Inelastic Dark Matter

DM Thermal Freeze-out · WIMP miracle

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

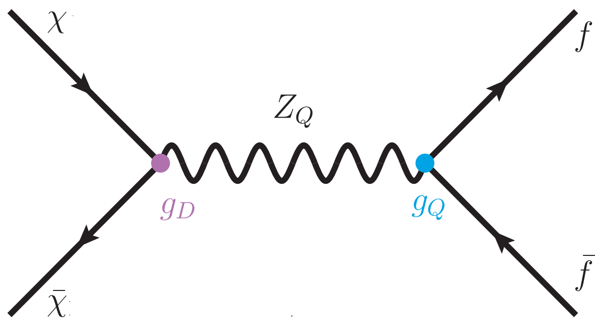
$$m_\chi \sim \alpha_{\rm eff} \sqrt{T_{\rm eq} M_{\rm Pl}} \sim \alpha_{\rm eff} \times 30\,{\rm TeV}$$

WIMP miracle

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

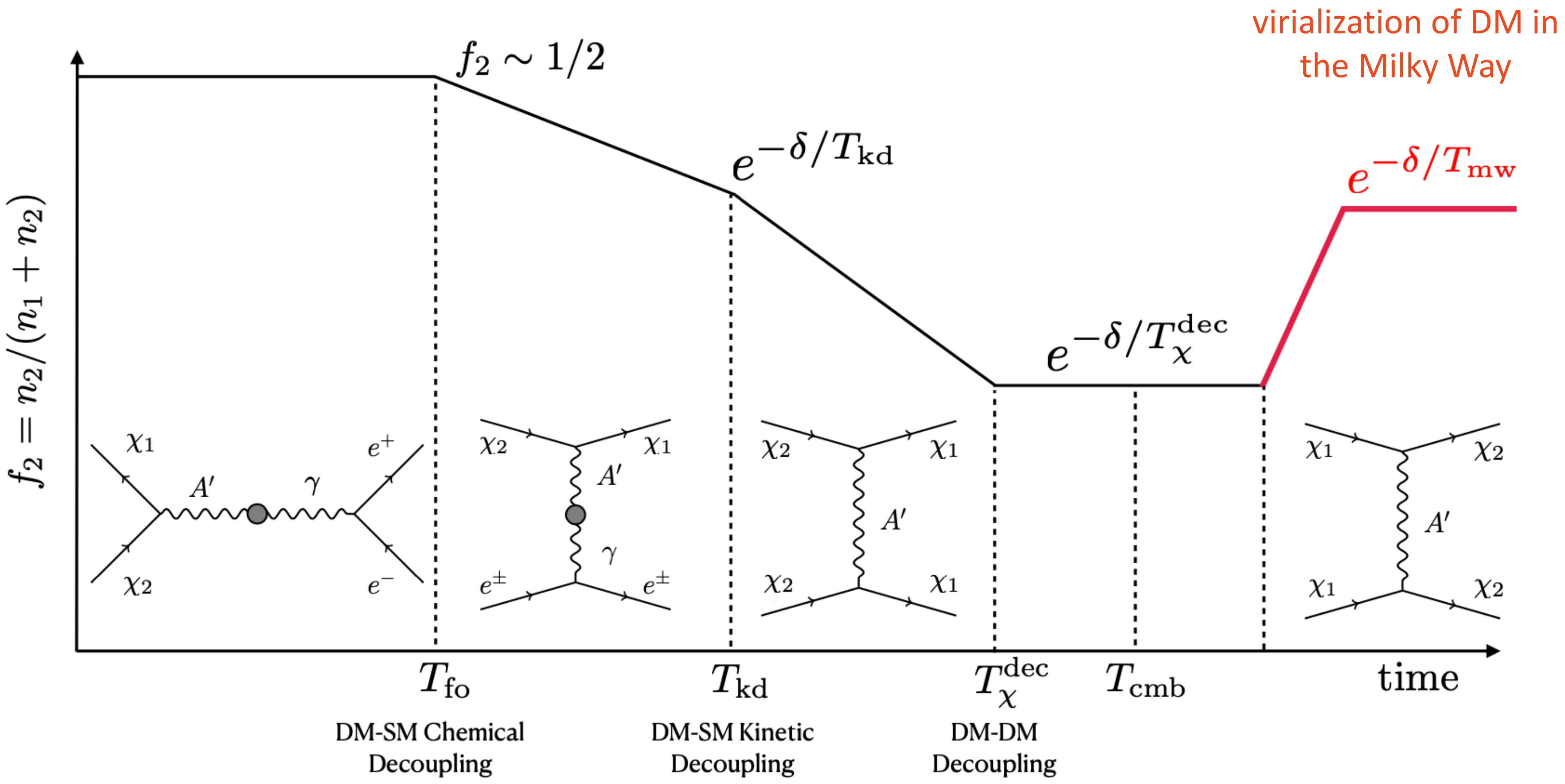
However, this also implies that

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



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

Inelastic Dark Matter

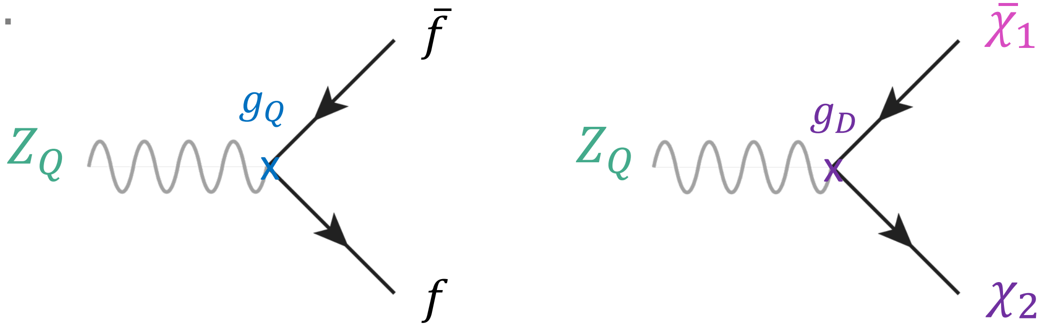


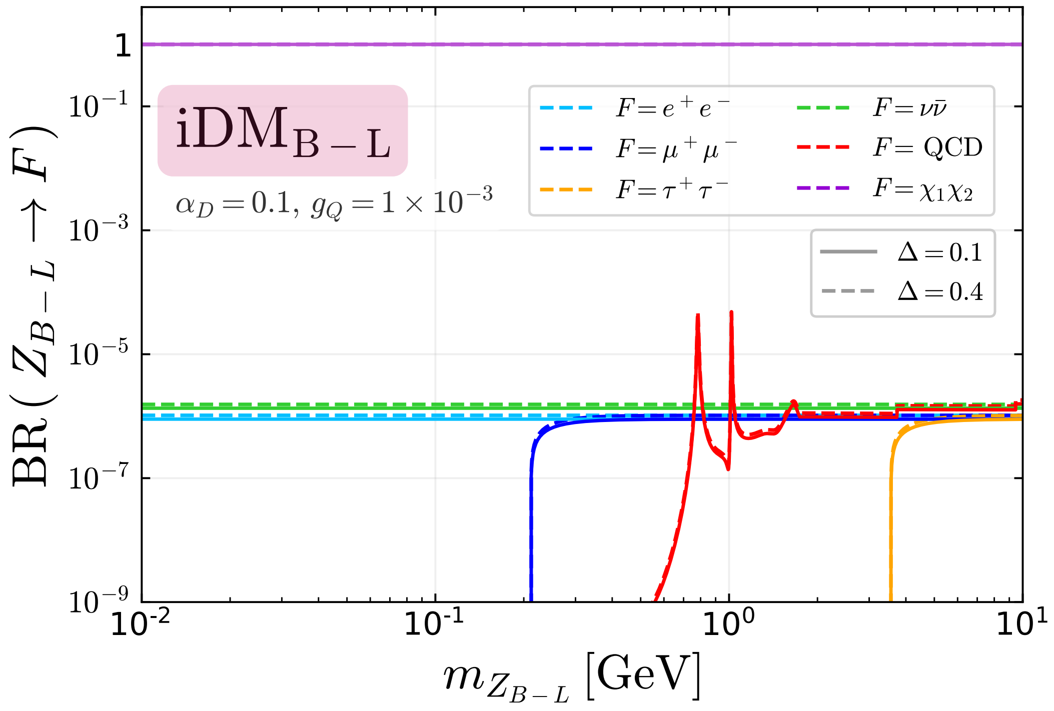
arXiv:2311.00032v1 [hep-ph]

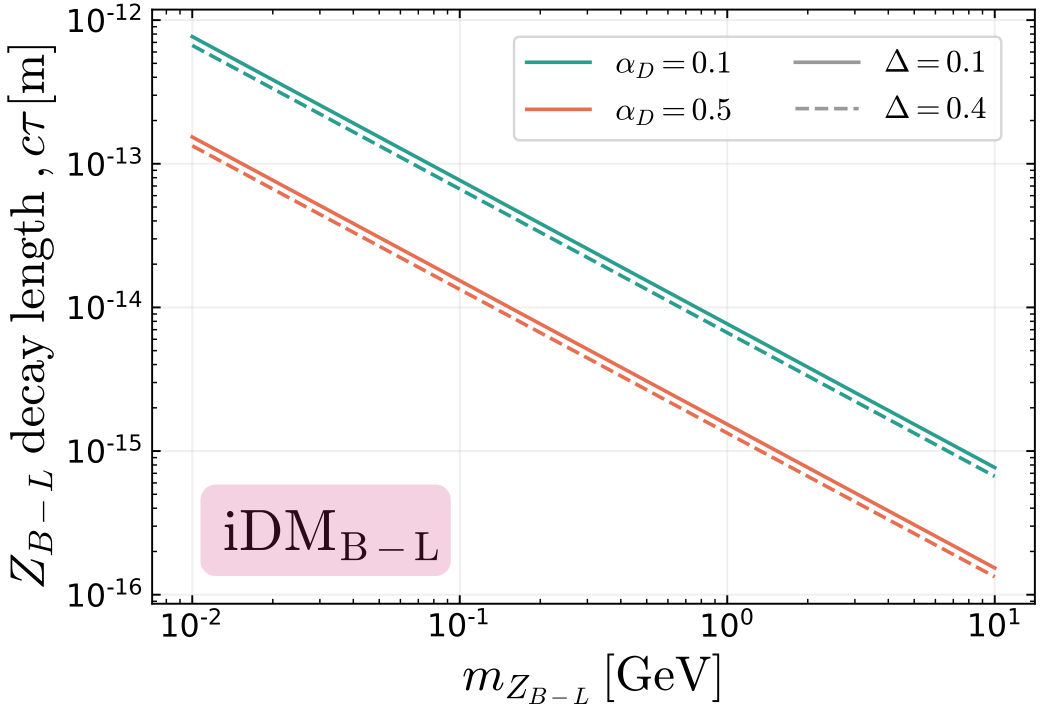
Inelastic Dark Matter · Decay Rates

Decay rates · Mediator

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



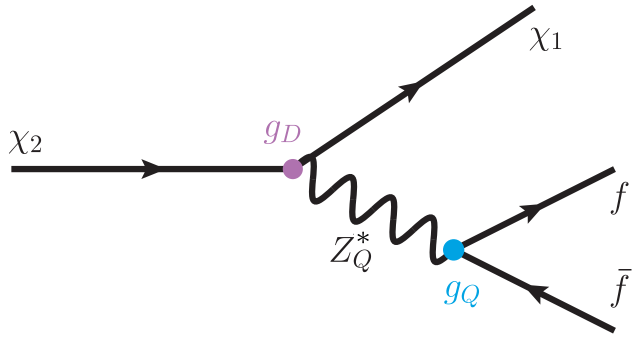




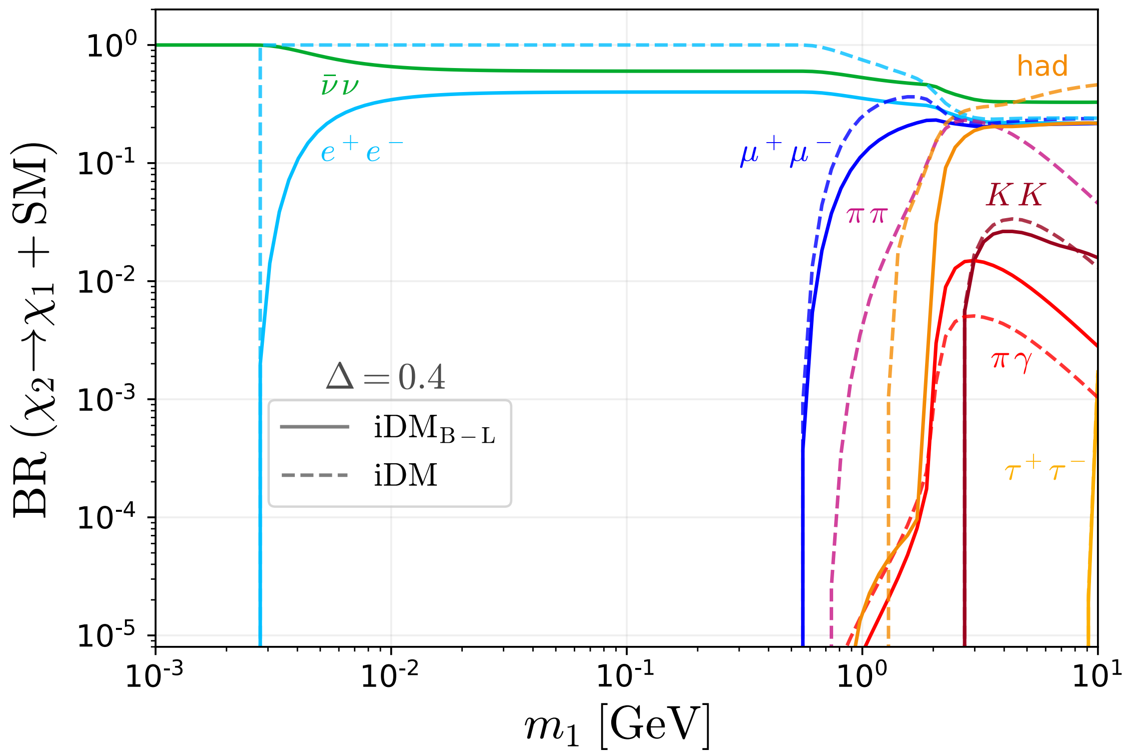
prompt-decay

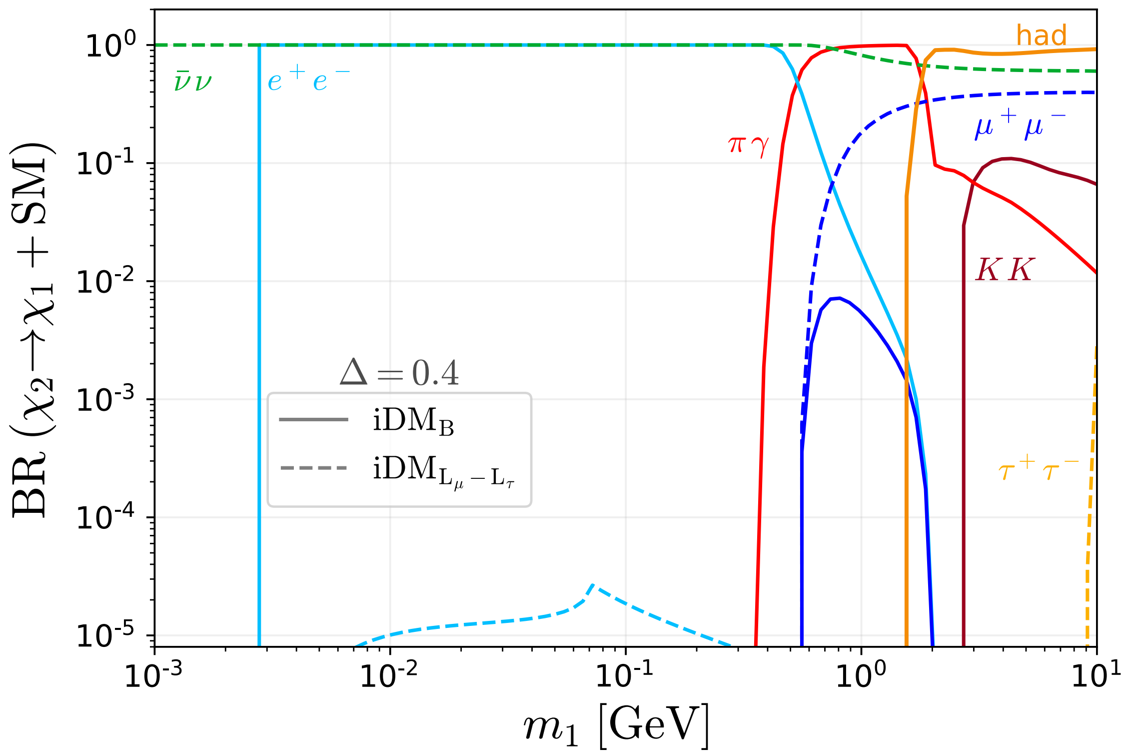
Inelastic Dark Matter · Decay Rates

Decay rates · Dark fermion χ_2



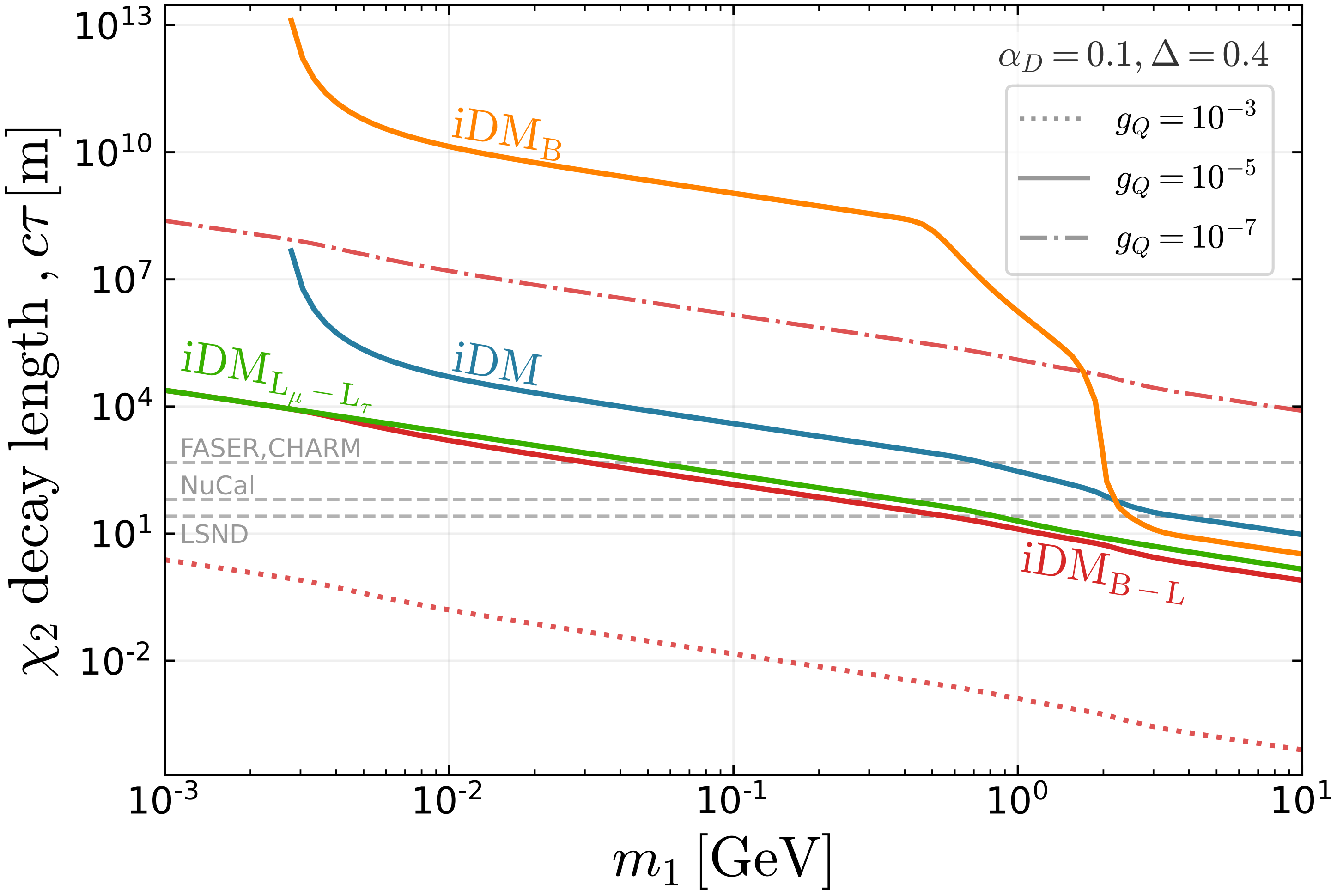
$$\Gamma(\chi_2 \to \chi_1 \bar{f} f) \simeq \frac{4\,\alpha_Q\,\alpha_D\,\Delta^5\,m_{Z_Q}}{15\pi R^5}$$





Inelastic Dark Matter · Decay Rates

Decay rates · Dark fermion χ_2



Inelastic Dark Matter · Relic Density Computation

Boltzmann Equation

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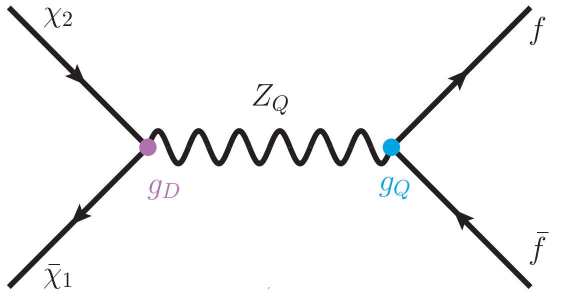
$$\left.\pm\left(\langle\sigma v\rangle_{2f\to 1f}Y_f^{\rm eq} + \frac{1}{s}\langle\Gamma\rangle_{2\to 1ff}\right)\left(Y_2 - Y_1\frac{Y_2^{\rm eq}}{Y_1^{\rm eq}}\right)\right],$$

coannihilations dominate!

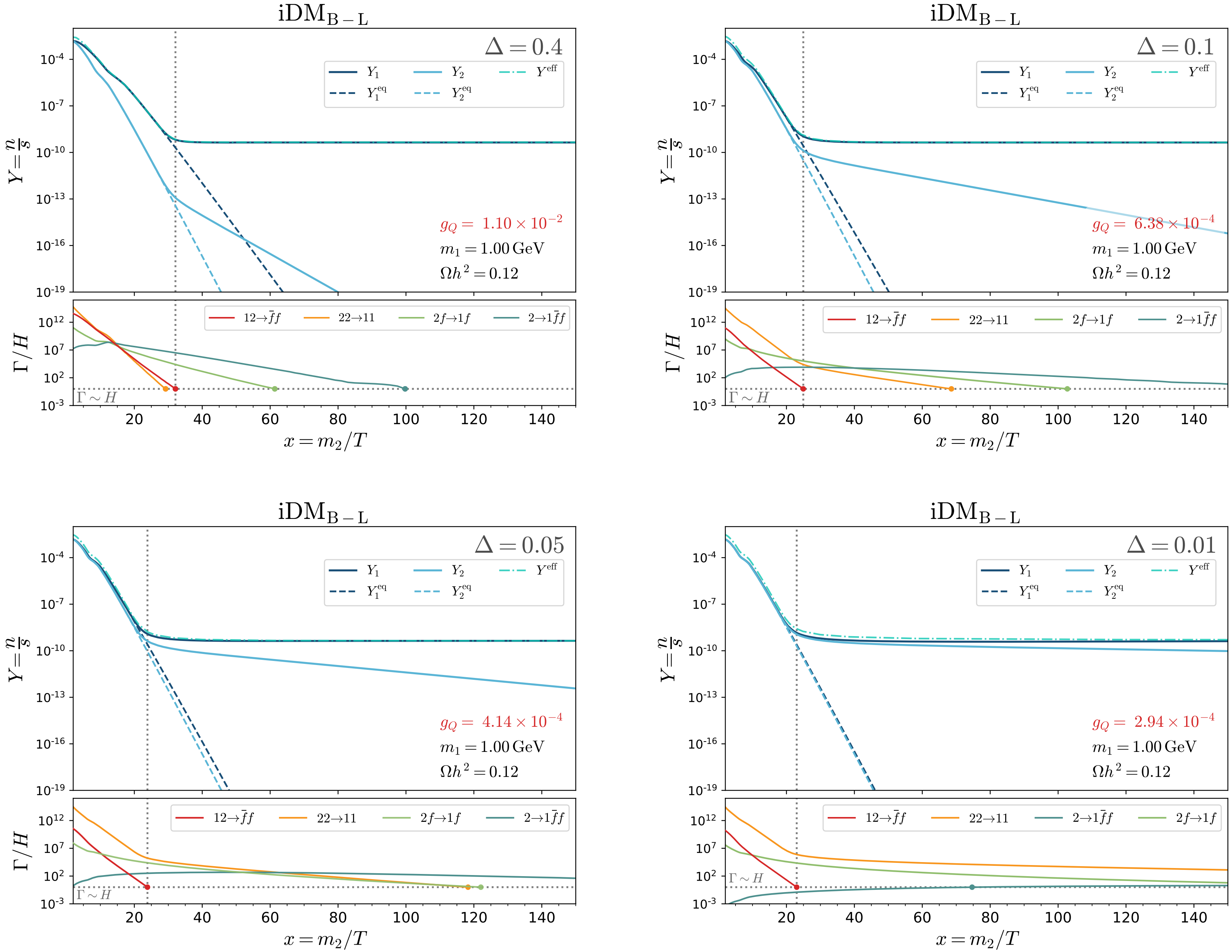


a) $\chi_1\,\chi_2 \to$ SM

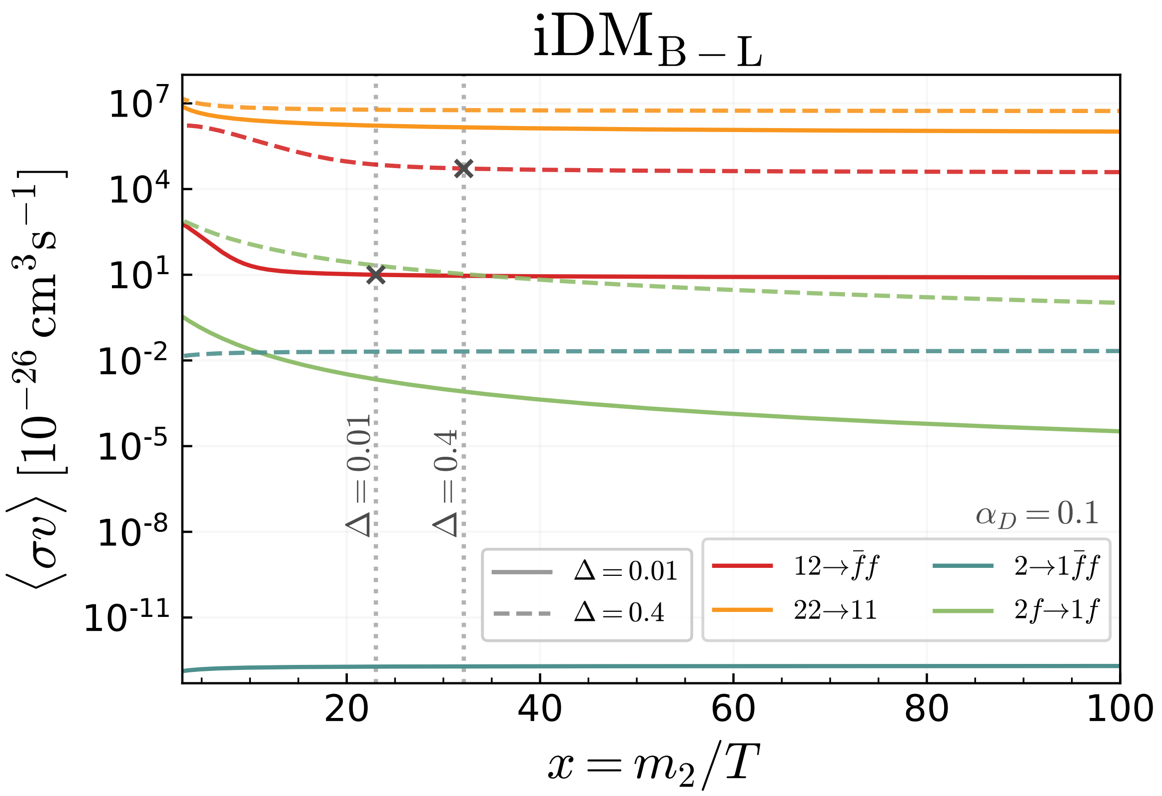
we can simplify by considering $n = n_1 + n_2$

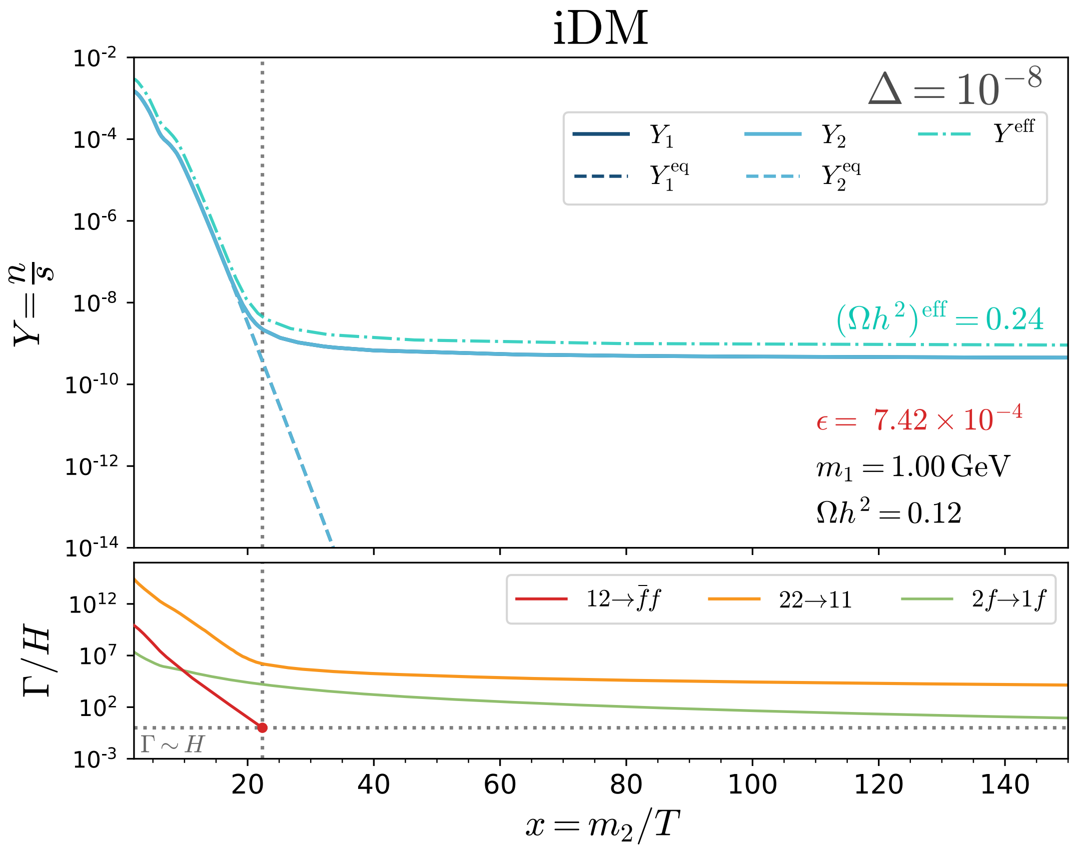
$$\frac{dY}{dx} = -2\frac{s}{xH}\langle\sigma v\rangle_{\rm eff}\left(Y^2 - Y_{\rm eq}^2\right)$$

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

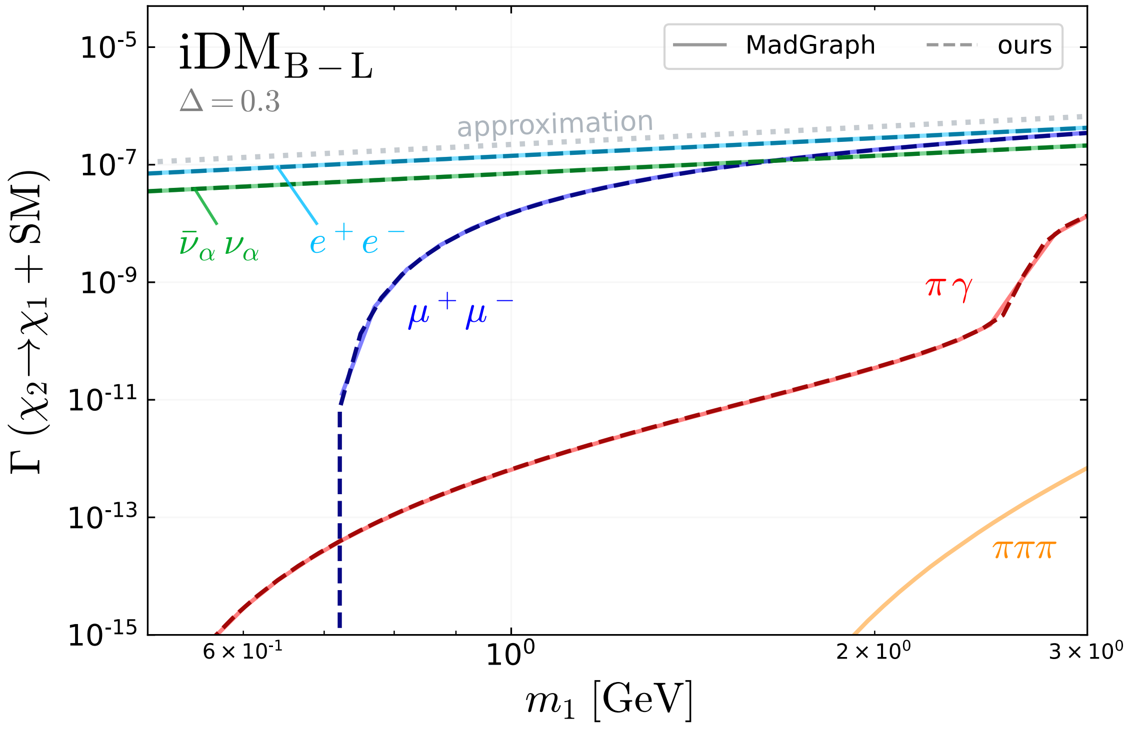


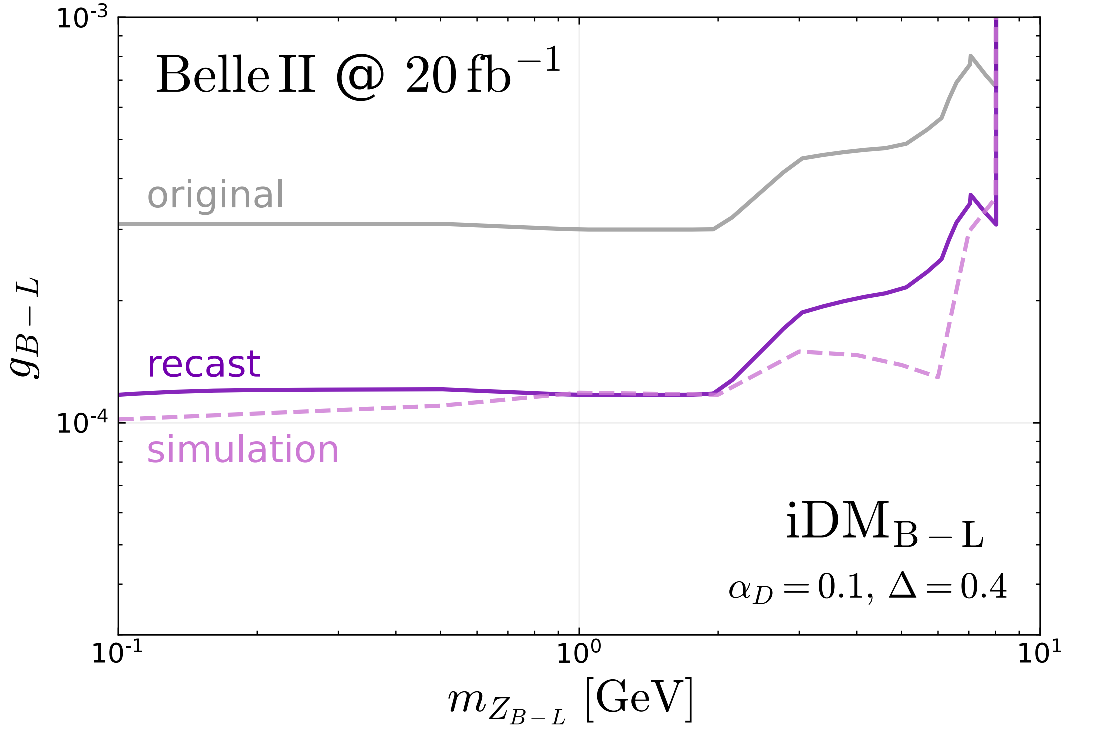
iDM$_{B-L}$
$\Delta = 0.4$
Y_1 Y_2 Y^{eff} Y_1^{eq} Y_2^{eq}
$g_Q = 1.10 \times 10^{-2}$
$m_1 = 1.00\,\mathrm{GeV}$
$\Omega h^2 = 0.12$
$12 \to \bar{f}f$ $22 \to 11$ $2f \to 1f$ $2 \to 1\bar{f}f$
$\Gamma \sim H$
iDM$_{B-L}$
$\Delta = 0.1$
$g_Q = 6.38 \times 10^{-4}$
$m_1 = 1.00\,\mathrm{GeV}$
$\Omega h^2 = 0.12$
iDM$_{B-L}$
$\Delta = 0.05$
$g_Q = 4.14 \times 10^{-4}$
$m_1 = 1.00\,\mathrm{GeV}$
$\Omega h^2 = 0.12$
iDM$_{B-L}$
$\Delta = 0.01$
$g_Q = 2.94 \times 10^{-4}$
$m_1 = 1.00\,\mathrm{GeV}$
$\Omega h^2 = 0.12$
$Y = \frac{n}{s}$
Γ/H
$x = m_2/T$


iDM$_{B-L}$
$\langle \sigma v \rangle \, [10^{-26} \, cm^3 s^{-1}]$
$x = m_2/T$
$\Delta = 0.01$
$\Delta = 0.4$
$\alpha_D = 0.1$
$12 \to \bar{f}f$
$22 \to 11$
$2 \to 1\bar{f}f$
$2f \to 1f$

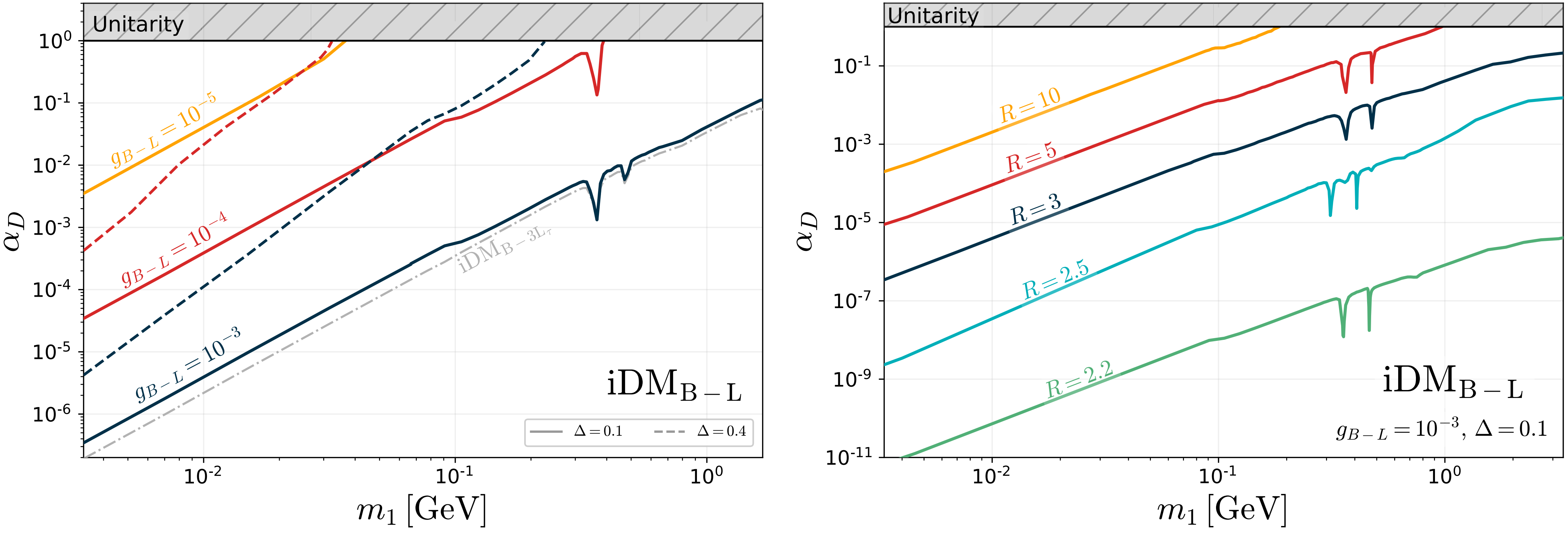

iDM
$\Delta = 10^{-8}$
Y_1
Y_2
Y^{eff}
Y_1^{eq}
Y_2^{eq}
$Y = \frac{n}{s}$
$(\Omega h^2)^{eff} = 0.24$
$\epsilon = 7.42 \times 10^{-4}$
$m_1 = 1.00\,GeV$
$\Omega h^2 = 0.12$
Γ/H
$12 \to \bar{f}f$
$22 \to 11$
$2f \to 1f$
$\Gamma \sim H$
$x = m_2/T$

Simulation Checks



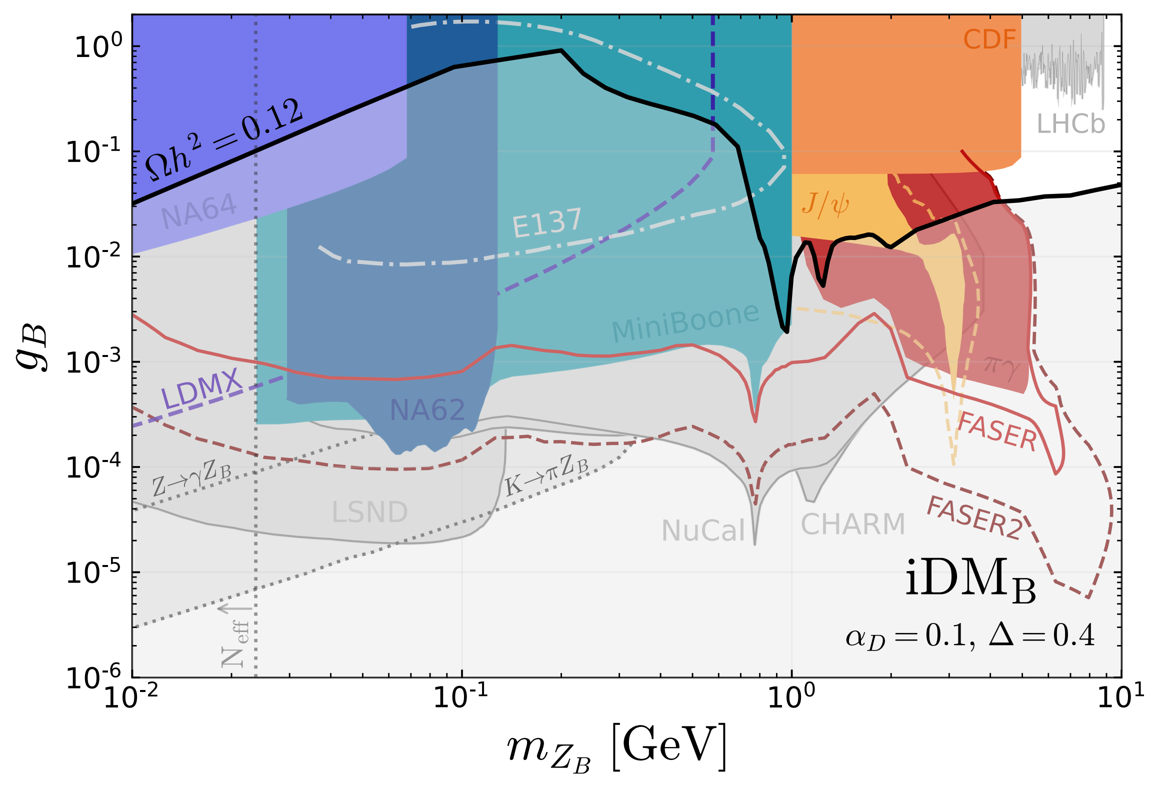


Different thermal targets

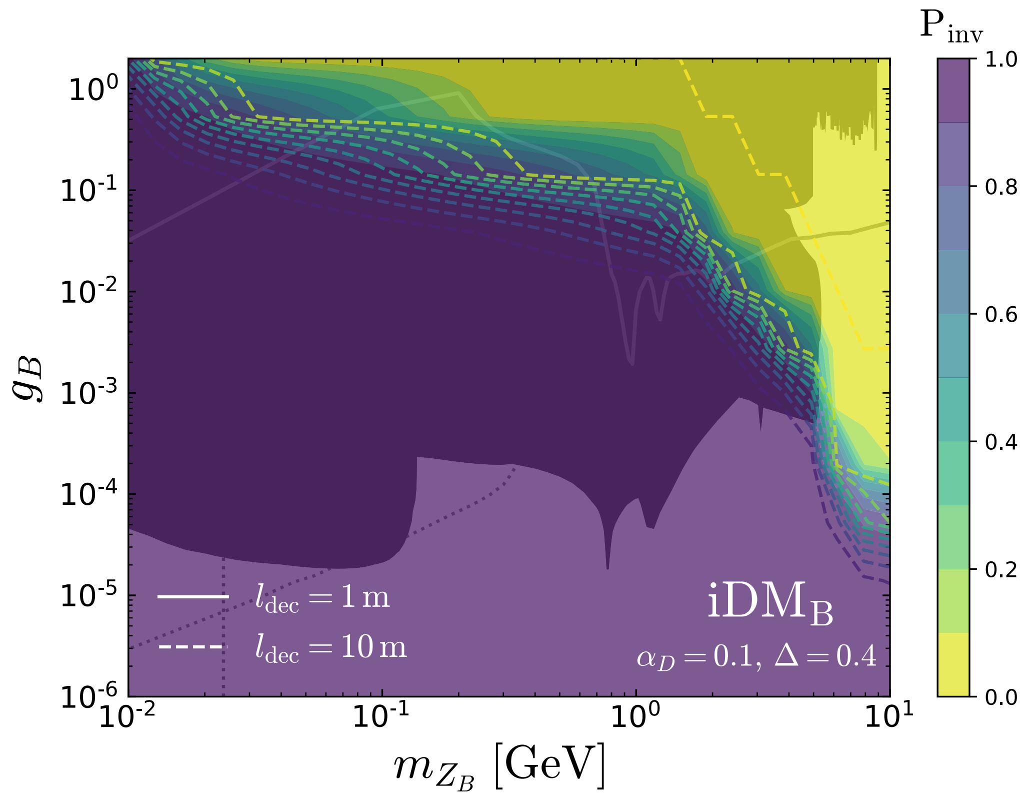


Inelastic Dark Matter · Bounds

iDM_B



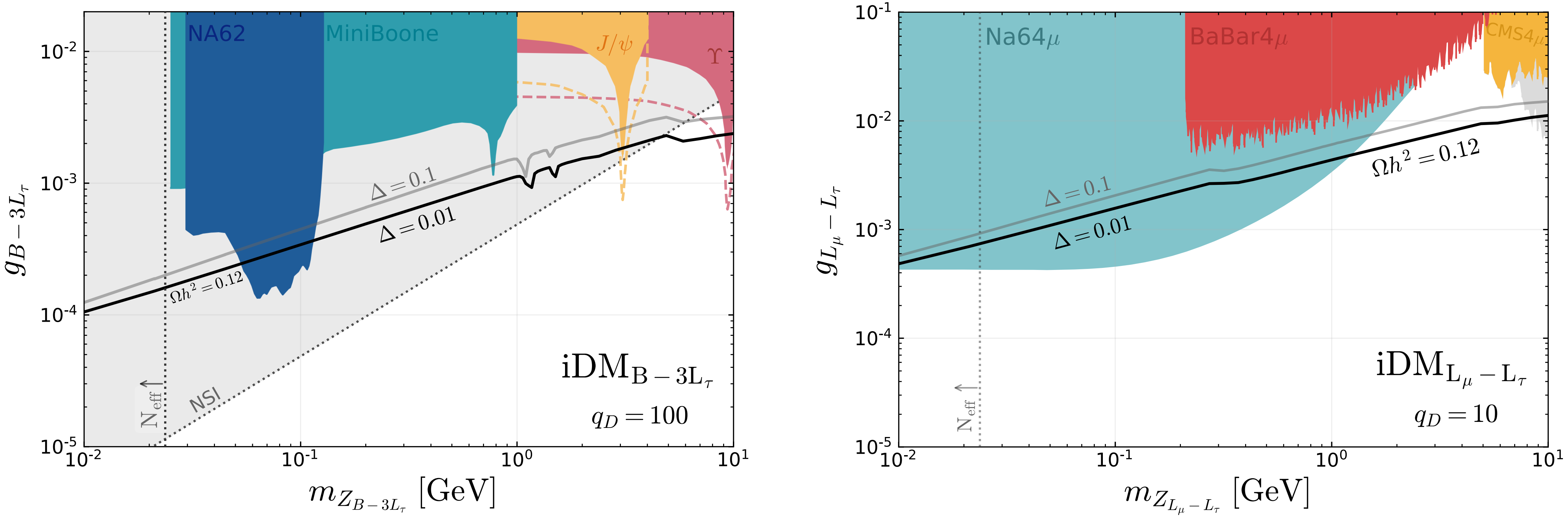
⇒



Fixed Dark Charges

$$\mathcal{L}_{\text{int}}^{\text{D}} = i g_D Z_{Q\mu} \bar{\chi}_2 \gamma^\mu \chi_1 + \text{h.c.}$$

$$g_D \equiv g_Q \, q_D$$



Details on the Experimental Limits

- Invisible searches

BaBar, Belle II, LDMX, NA62 and NA64-e

$$\frac{\sigma_{Z_Q}}{\sigma_{Z_\gamma}}\{\mathrm{BR}(\mathrm{Z_Q} \to \chi_1\chi_2)[\mathrm{BR}(\chi_2 \to \chi_1\bar{\nu}\nu) + \mathrm{P}_{\mathrm{out}}^{\chi_2}\,\mathrm{BR}(\chi_2 \to \chi_1 + \mathrm{vis})] + \mathrm{BR}(\mathrm{Z_Q} \to \bar{\nu}\nu)\}-1 = 0$$

$$\mathrm{P}_{\mathrm{out}}^{\chi_2} = \mathrm{e}^{-\mathrm{L_{out}}/\lambda_{\chi_2}}$$

recast from invisible Dark photon limits

- Semi-visible searches

E137, CHARM, NuCal and LSND

$$\frac{\sigma_{Z_Q}}{\sigma_{Z_\gamma}}\left(\frac{\mathrm{BR}(\mathrm{Z_Q} \to \chi_1\chi_2)}{\mathrm{BR}(\mathrm{Z_\gamma} \to \chi_1\chi_2)}\right)\left(\frac{\mathrm{BR}(\chi_2 \to \mathrm{Z_Q^*} \to \chi_1\mathrm{e^+e^-})}{\mathrm{BR}(\chi_2 \to \mathrm{Z_\gamma^*} \to \chi_1\mathrm{e^+e^-})}\right)\left(\frac{\varepsilon_Q(\tau_{\chi_2})}{\varepsilon_\gamma(\tau_{\chi_2})}\right) - 1 = 0$$

recast from the original iDM limits

Details on the Experimental Limits

- 4μ searches from BaBar and CMS

↳ constrained $L_\mu - L_\tau$ mediators,

$$\frac{g_Q}{g^{\text{exp}}_{L_\mu - L_\tau}}\left[\frac{\mathrm{BR}(\mathrm{Z_Q}\to\mu^+\mu^-)+\mathrm{BR}(\mathrm{Z_Q}\to\chi_1\chi_2)\mathrm{BR}(\chi_2\to\chi_1\mu^+\mu^-)\mathrm{P}^{\chi_2}_{\text{in}}}{\mathrm{BR}(\mathrm{Z_{L_\mu-L_\tau}}\to\mu^+\mu^-)}\right]-1=0$$

$$\mathrm{P}^{\chi_2}_{\text{in}} = \mathrm{e}^{-\mathrm{L_{in}}/\lambda_{\chi_2}} - \mathrm{e}^{-\mathrm{L_{out}}/\lambda_{\chi_2}}$$

- Meson decays

J/Ψ and Υ invisible decay searches

$$\frac{\mathrm{BR}(J/\Psi\to\chi_1\chi_2)}{\mathrm{BR}(J/\Psi\to e^+e^-)} = \frac{\alpha_D}{\alpha_e}\left(\frac{q^c_Q g_Q}{q^c_{\text{em}} e}\right)^2 \frac{m_V^4}{(m^2_{Z_Q}-m^2_V)^2+m^2_{Z_Q}\Gamma^2_{Z_Q}}$$
$$\times\left(1-\frac{\Delta^2}{R^2}m_r^2\right)^{3/2}\left(1+\frac{m_r^2(\Delta+2)^2}{2R^2}\right)\sqrt{1-\frac{m_r^2(\Delta+2)^2}{R^2}}$$

$$\mathrm{BR}(V\to\text{inv})|_{\mathrm{iDM_Q}} = \mathrm{BR}(V\to\chi_1\chi_2)\left[\mathrm{BR}(\chi_2\to\chi_1\bar\nu\nu)+\mathrm{P}^{\chi_2}_{\text{out}}\,\mathrm{BR}(\chi_2\to\chi_1+\text{vis})\right] + \mathrm{BR}(V\to Z_Q^*\to\bar\nu\nu)\,.$$

$\Rightarrow$ $\mathrm{BR}(V\to\text{inv})|_{\mathrm{iDM_Q}} < \mathrm{BR}(V\to\text{inv})|_{\text{exp}}$