

# Dark Showers from Sneaky Dark Matter

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Beyond WIMPs

March 25th, 2026

*JHEP* 06 (2025) 198, arXiv: 2411.15073

In collaboration with Adrián Carmona,  
Christiane Scherb, and Pedro Schwaller



Cluster of Excellence  
**PRISMA<sup>++</sup>**



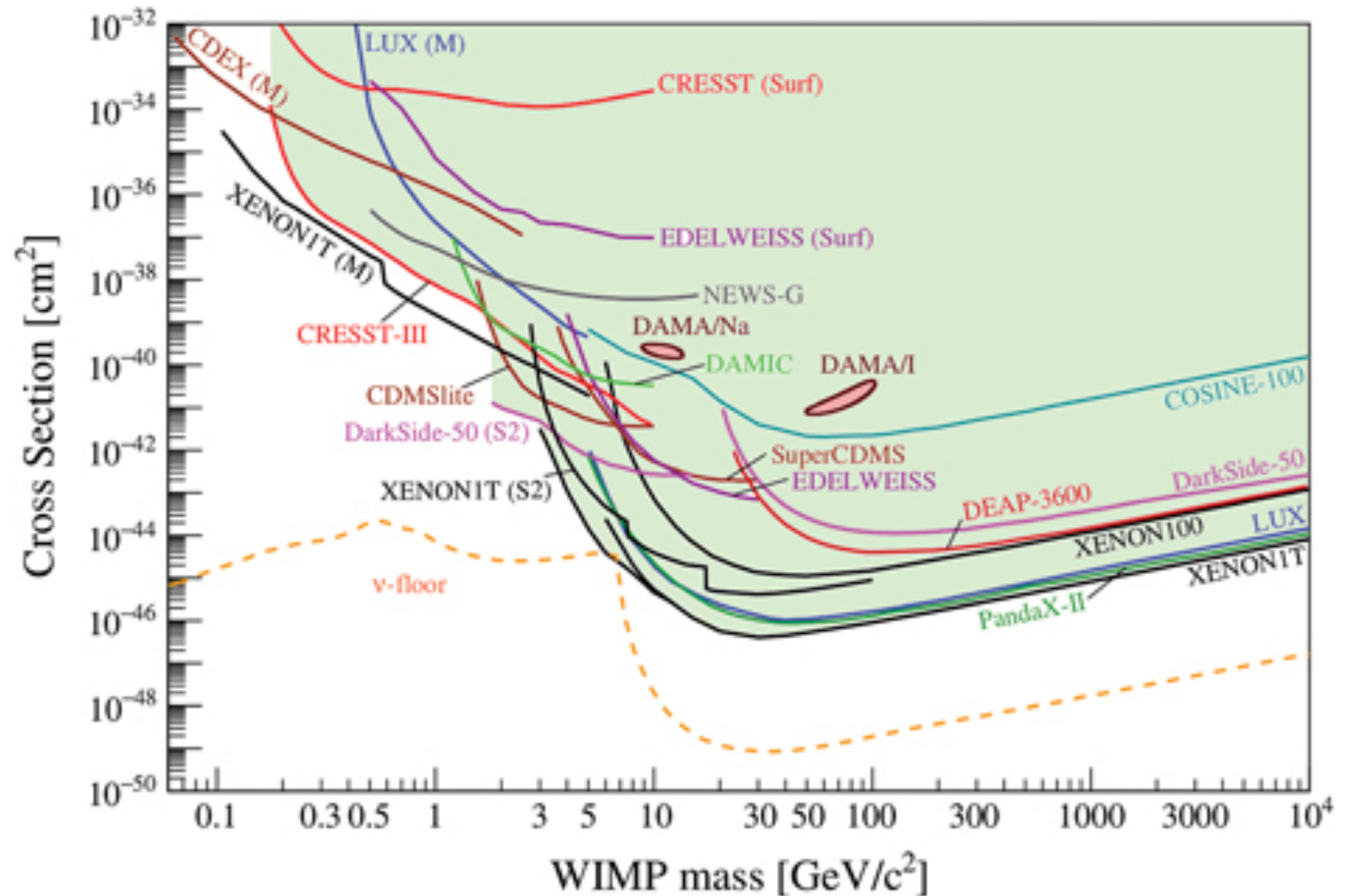
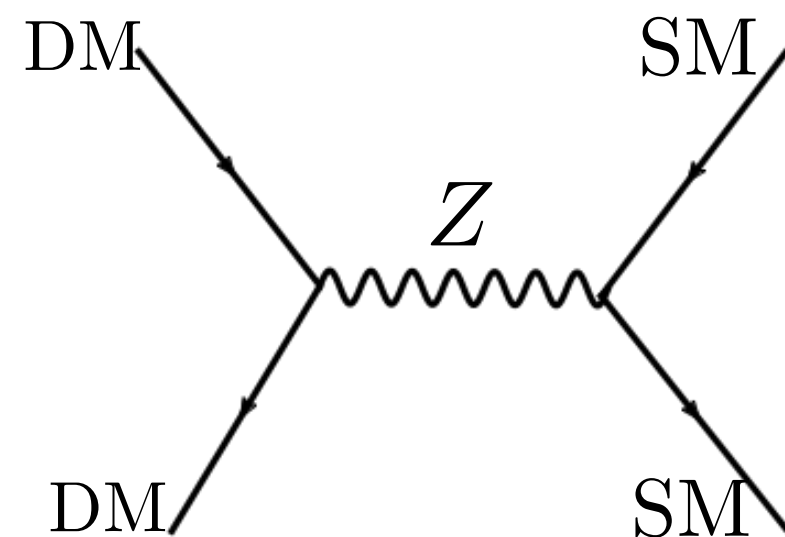
# Weakly Interacting Massive Particle

A particle charged under  $SU(2)_W$ , with weak scale mass could have the right relic abundance to be DM.

However, this vanilla picture is excluded by many orders of magnitude.

$$\Omega_{\text{DM}} \equiv \frac{\rho_{\text{DM}}}{\rho_{\text{crit}}} \sim 0.23 \times \left( \frac{10^{-26} \text{cm}^3/\text{s}}{\langle \sigma v \rangle} \right)$$

$$\langle \sigma v \rangle \propto \frac{\alpha^2}{m_{\text{DM}}^2}$$

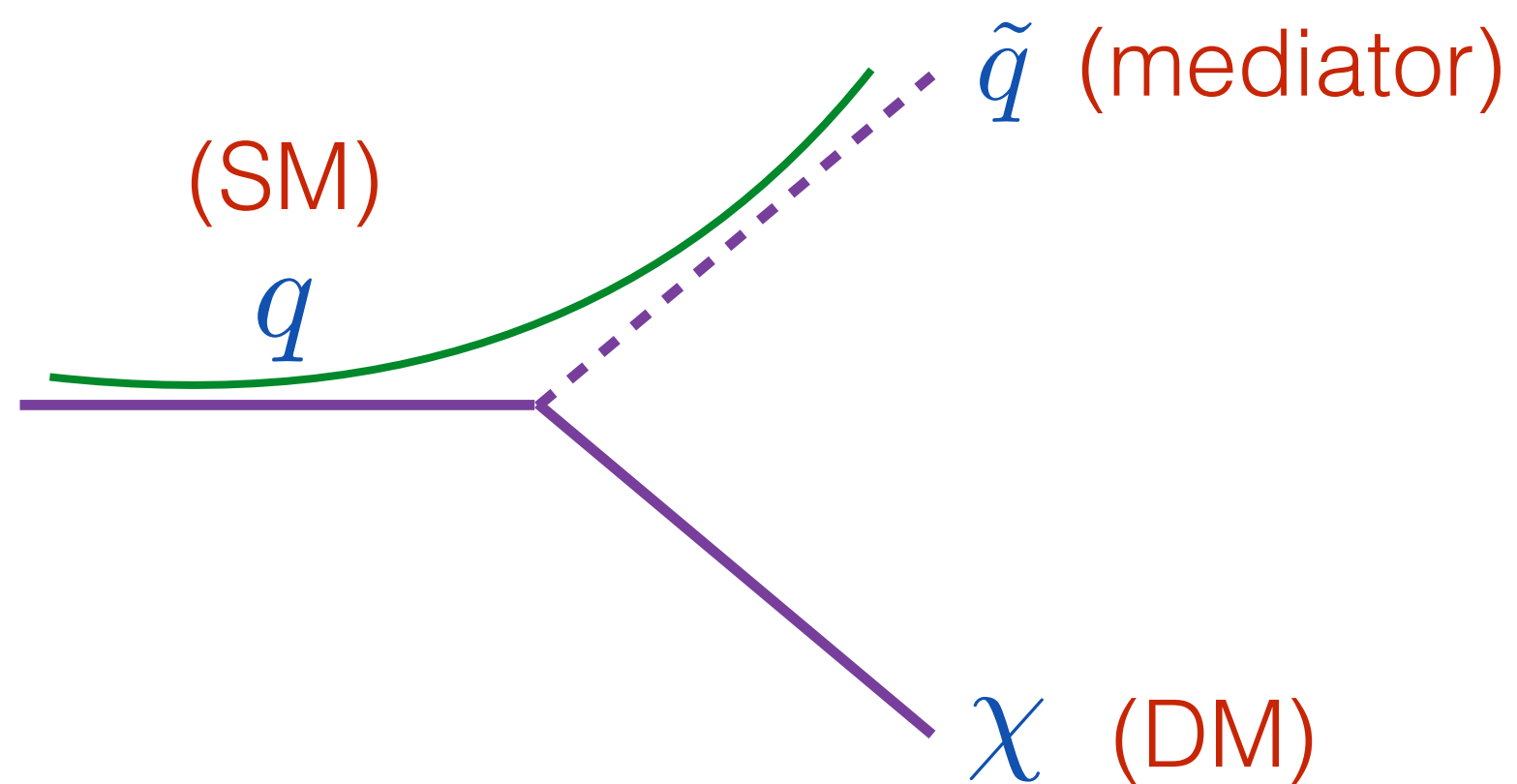


# How to move beyond WIMP?

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WIMP DM inherits SM charge.

Moving beyond: we need to have DM neutral under SM. In this case, the only way to see dark sector is to have a mediator that is charged under both SM and dark sector.



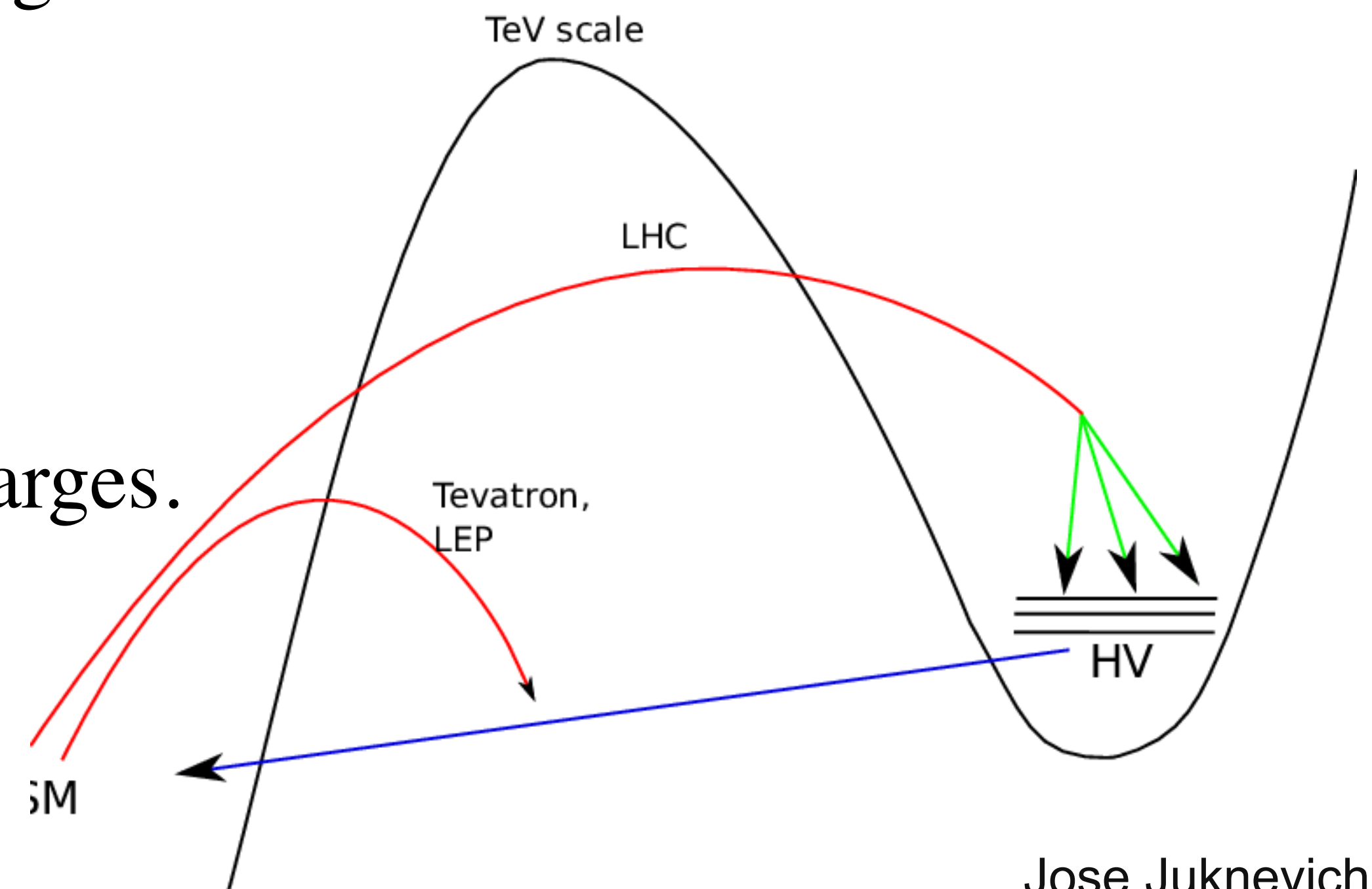
# Hidden Valley models

Once we introduce a new sector, nothing forces it to be simple.

Extending SM gauge groups by a non-abelian dark gauge group,  $G_V$ .

SM particles neutral under  $G_V$ .

Heavy mediators carrying both SM charges and  $G_V$  charges.



# Exploring the landscape of Hidden Valley models

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Assume  $G_V = SU(3)_D$ , with  $n_f$  dark quarks  $Q_\alpha$ .

$$\mathcal{L}_D \supset -\frac{1}{4}G_D^{a,\mu\nu}G_{D,\mu\nu}^a + \bar{Q}_\alpha i \not{D} Q_\alpha - m_{Q_{\alpha\beta}} \bar{Q}_\alpha Q_\beta$$

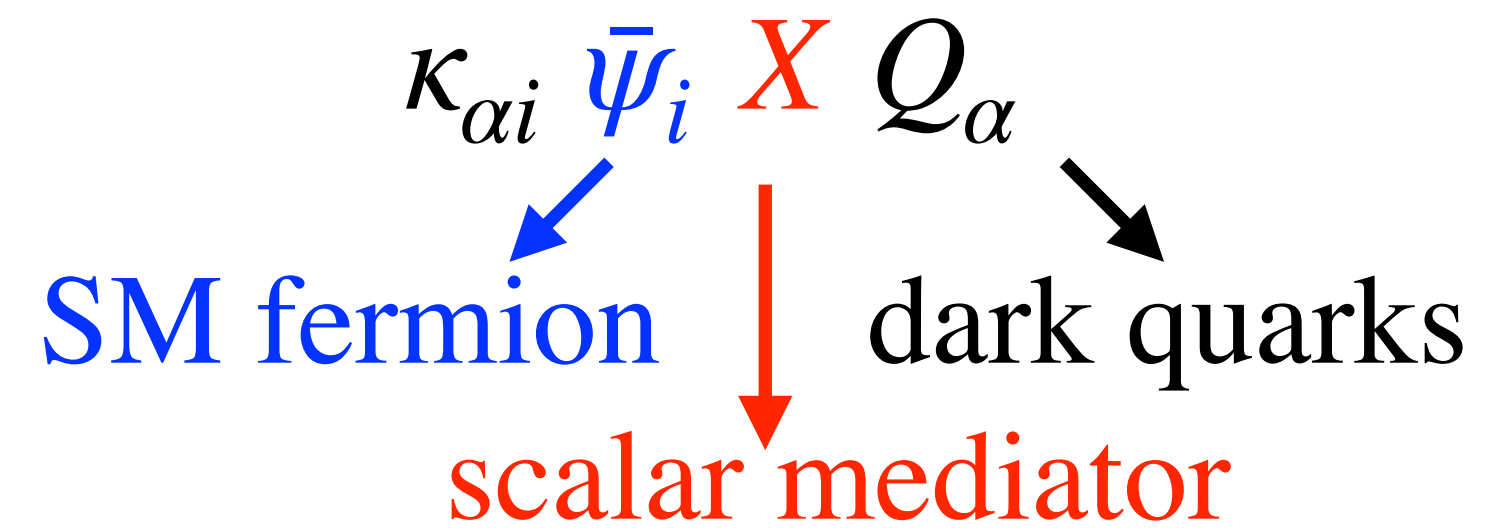
$$m_{Q_{\alpha\beta}} = m_Q \delta_{\alpha\beta}$$

Global  $SU(n_f)_L \times SU(n_f)_R$  in the dark sector is spontaneously broken to  $SU(n_f)_V$ , after confinement, resulting in  $n_f^2 - 1$  goldstone bosons.

# Exploring the landscape of Hidden Valley models

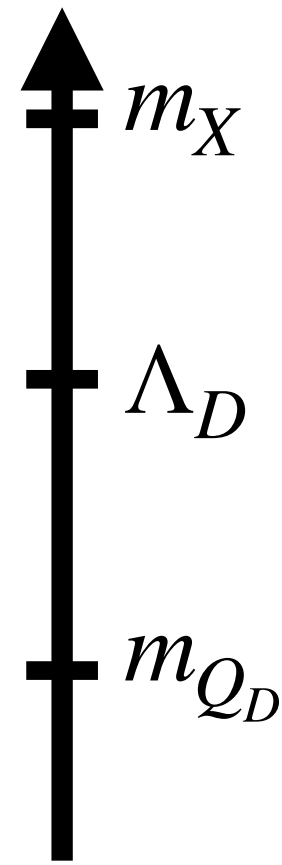
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The  $SU(n_f)_V$  is broken via the interaction of dark quarks with the SM particles:



Depending on  $X$  quantum numbers, it can only couple to either up type quark or down type quark.

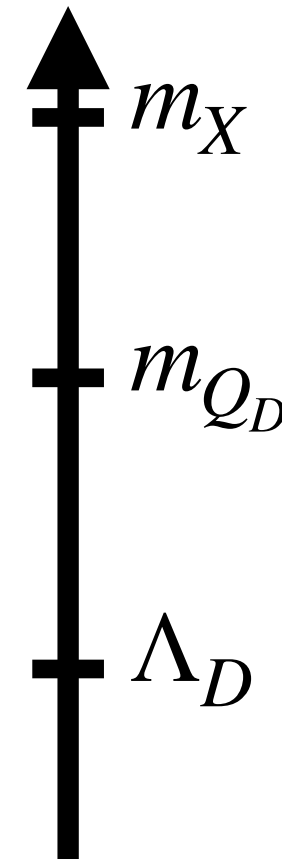
## Light quarks



### Chiral EFT of mesons

Kilic, Okui, Sundrum [0906.0577]  
Bai, Hill [1005.0008]  
Buckley, Neil [1209.6054]  
Hochberg et al [1402.5143, 1512.07917]  
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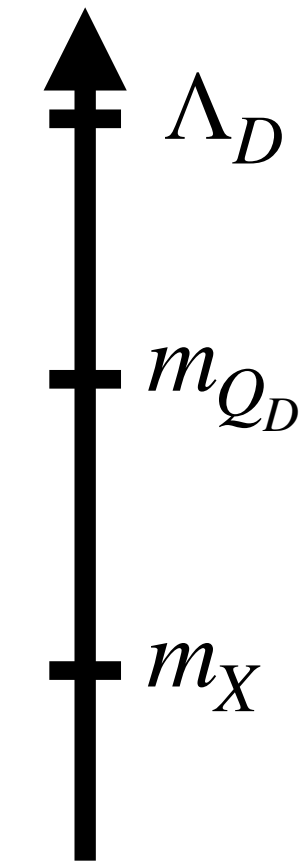
## Heavy quarks



### Long lived glue balls

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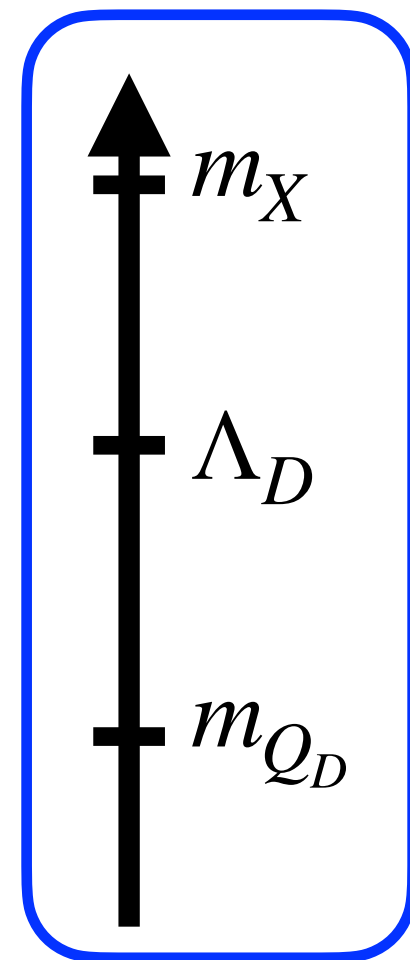
## Light mediator



### Partial compositeness

Kaplan [9111035]  
Contino, Da Rold, Pomarol [0612048]  
Agashe, Contino, Pomarol [0412089]  
Contino [1005.4269]  
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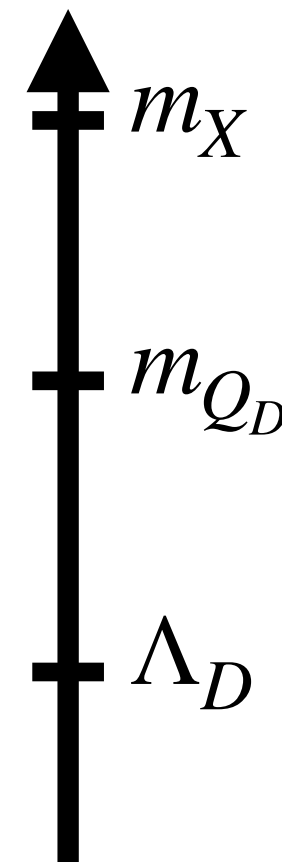


Focus of this talk!

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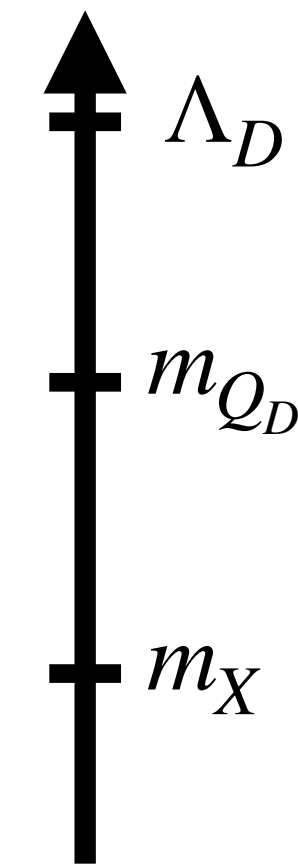
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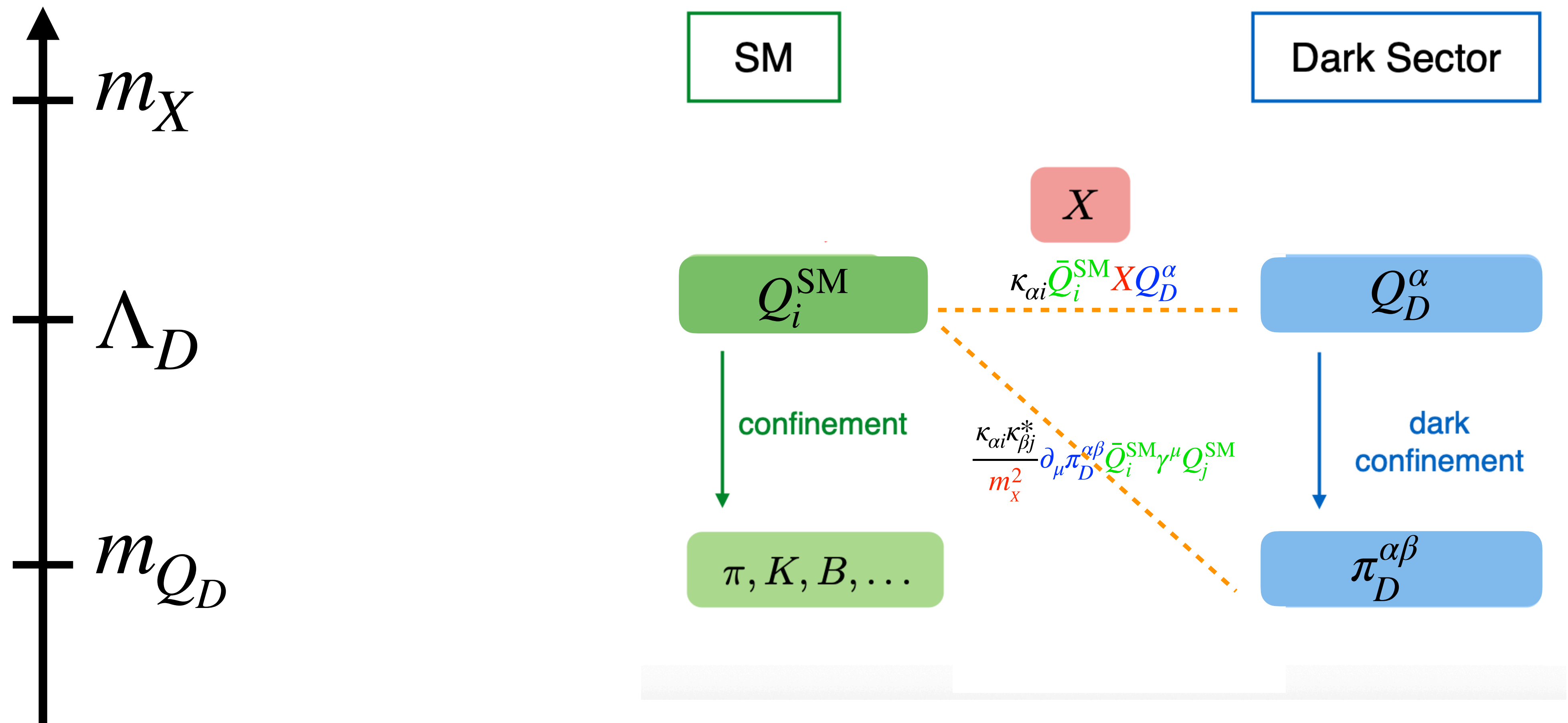
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# Portal after dark confinement



# Structure of the portal coupling $\kappa$

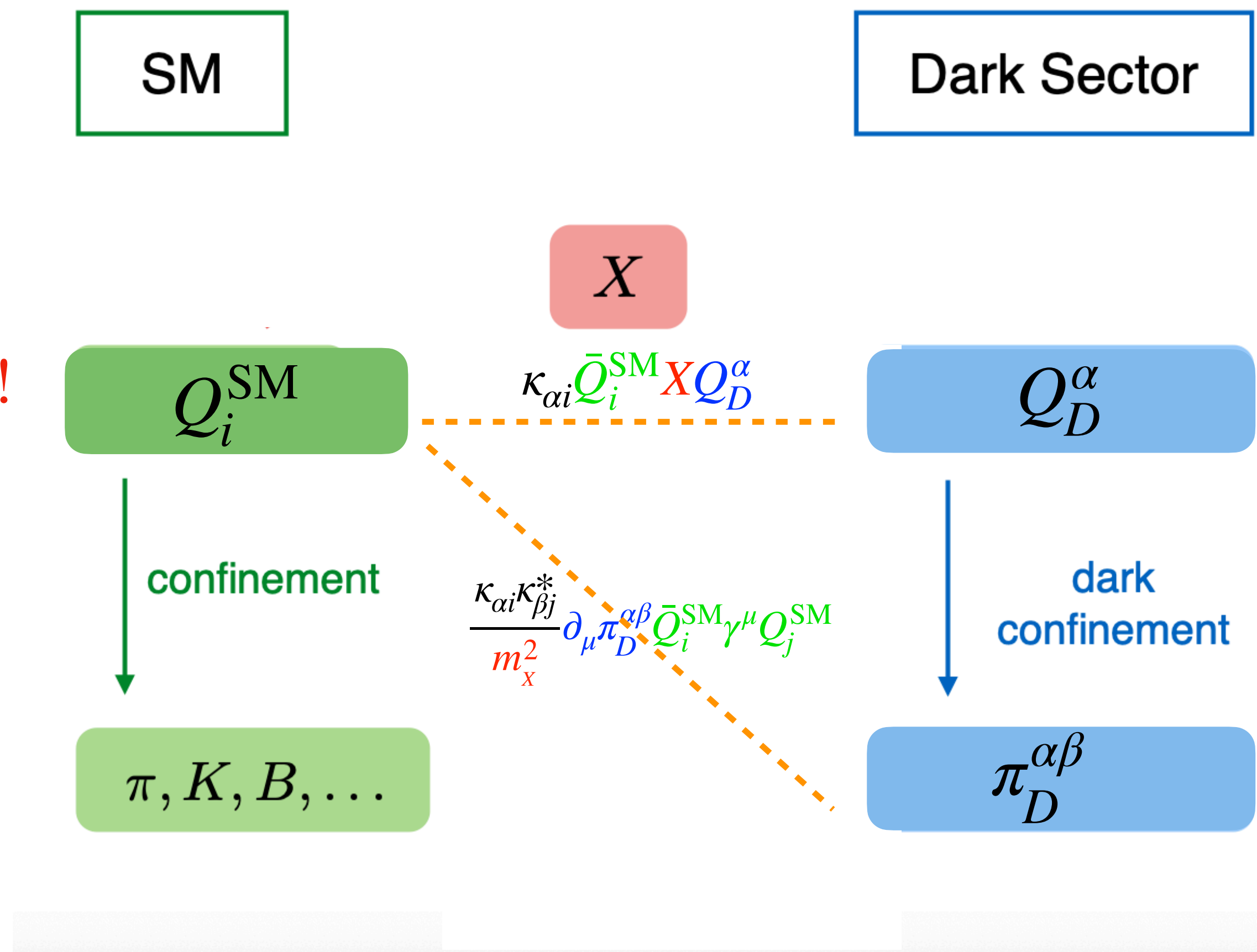
$$\kappa_{n_f \times 3} = V_{n_F \times n_F} D_{n_F \times 3} U_{3 \times 3}$$

V: unitary matrix.

Can be rotated away using the flavor symmetry!

D: diagonal matrix

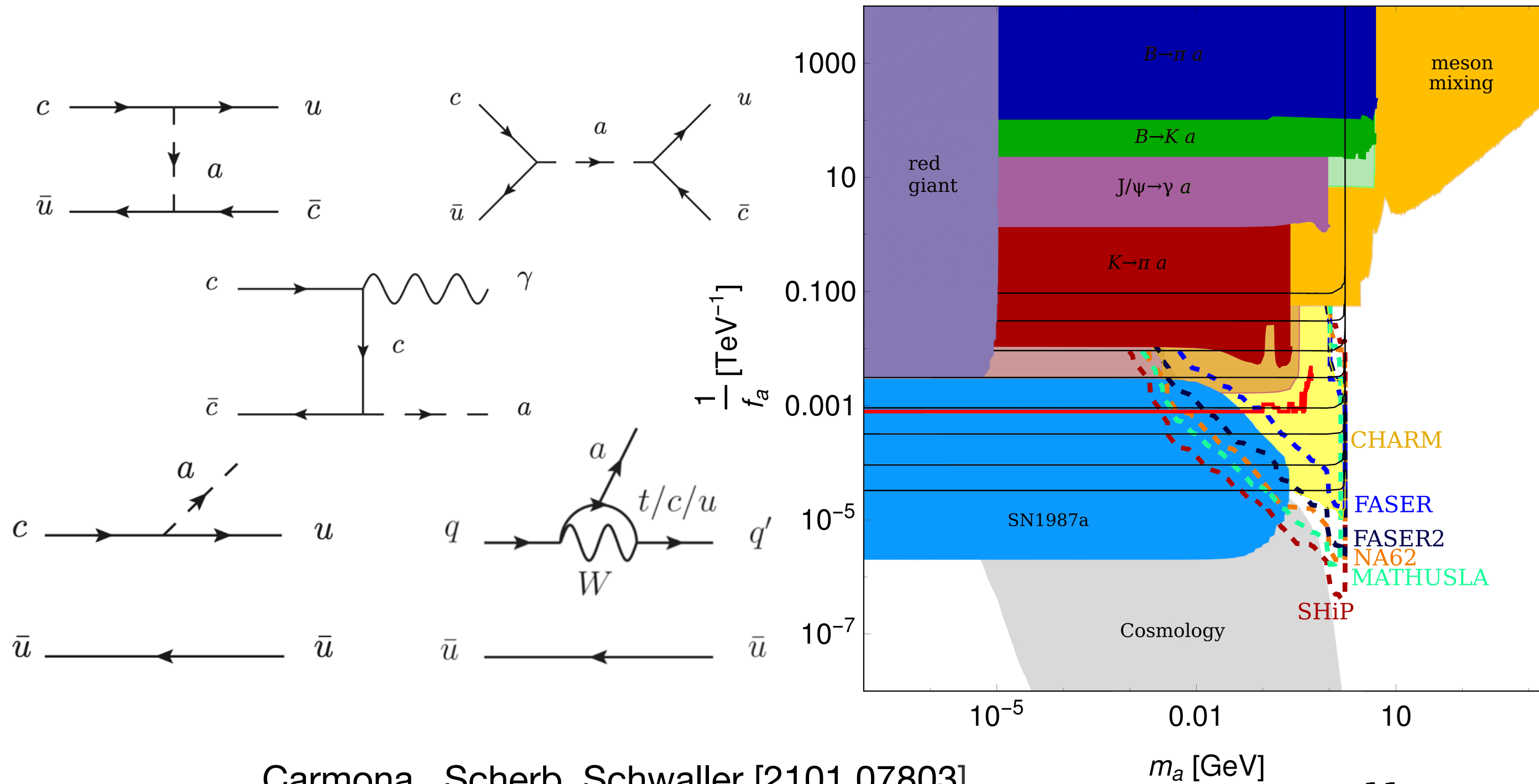
U: unitary matrix



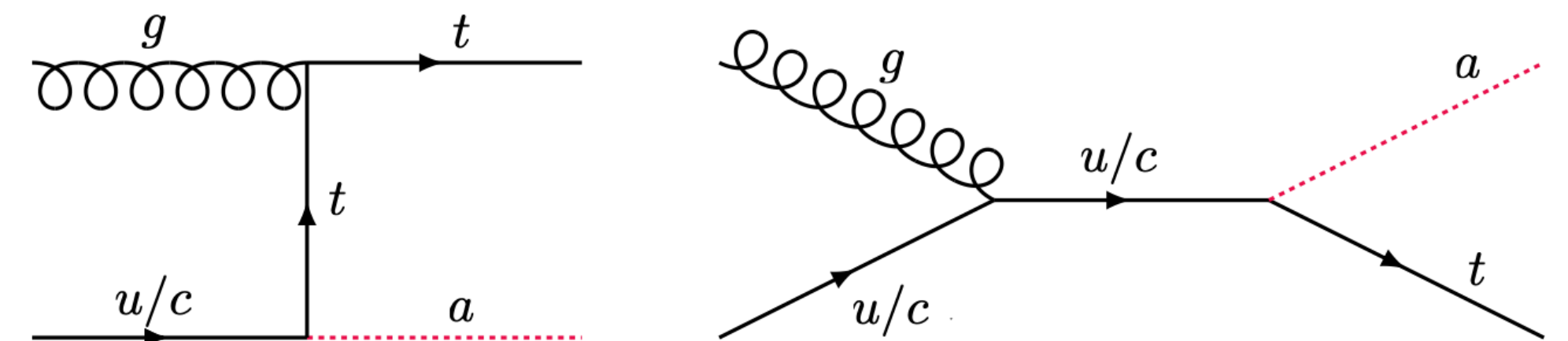
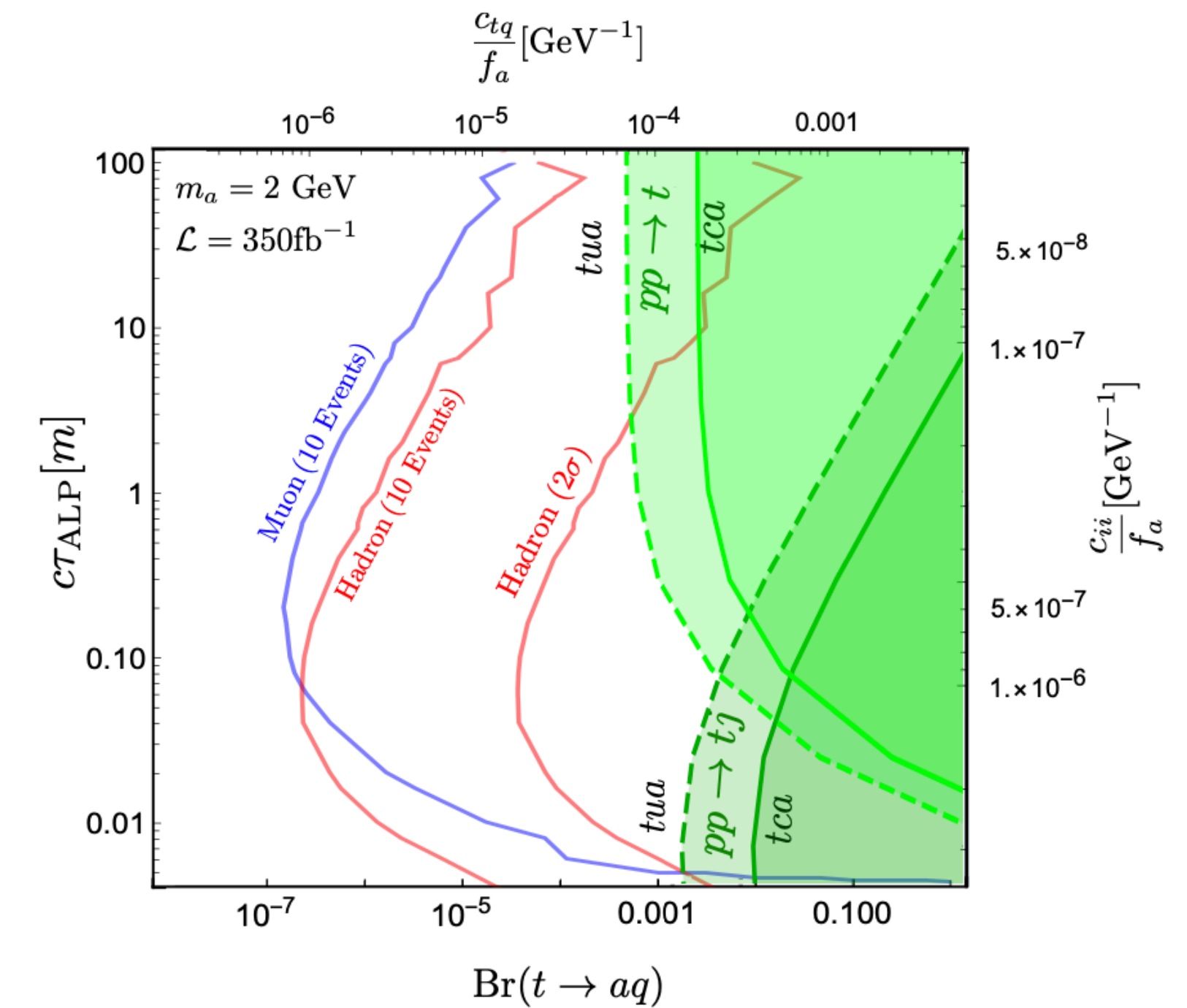
# Dynamics with $n_f \leq 3$ : interesting phenomenology

$$\mathcal{K}_{n_f \times 3} = V_{n_f \times n_f} D_{n_f \times 3} U_{3 \times 3}$$

If  $n_f \leq 3$ , all dark pions decay into SM.



Carmona, Scherb, Schwaller [2101.07803]



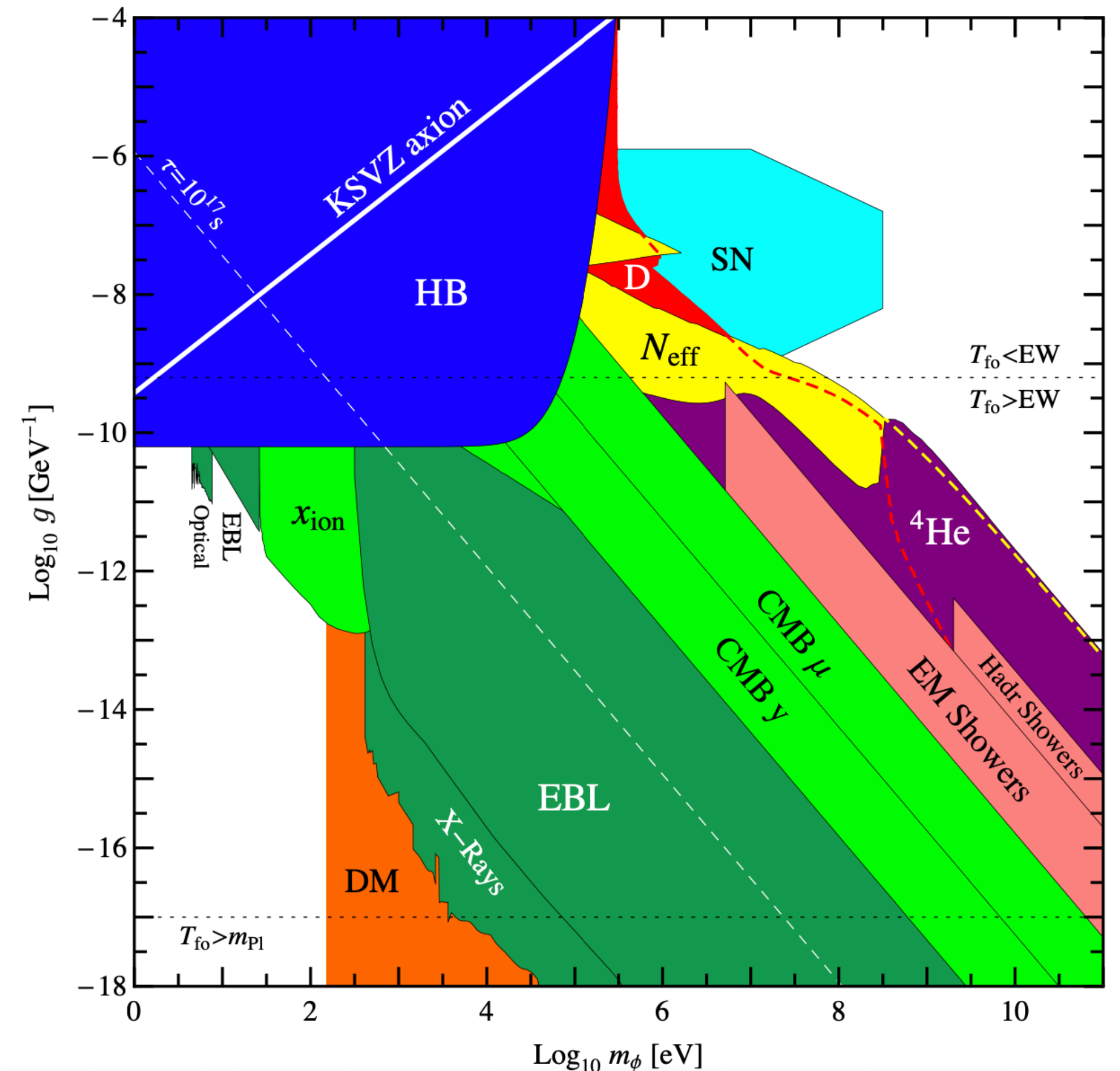
Carmona, FE, Scherb, Schwaller [2202.09371]

# Dynamics with $n_f \leq 3$ : who is DM?

All dark pions decay into SM.  
 They could still be long lived DM.  
 Even if they are short lived, they could have important cosmological implications.

If dark pions are not DM, then DM must be dark baryons...

$\rho_D \rho_D \rightarrow \pi_D \pi_D$  is too efficient and produces too little DM. Therefore, one has to assume an asymmetry in dark baryons to get the right relic abundance.



Cadamuro, Redondo [1110.2895]

# What happens if $n_f > 3$ ?

If  $n_f > 3$ , we have stable dark pions that are dark matter.

For example for the case of  $n_f = 4$  :

$$\kappa_{4 \times 3} = V_{4 \times 4} D_{4 \times 3} U_{3 \times 3}$$

$$D_{4 \times 3} = \begin{pmatrix} \kappa_1 & 0 & 0 \\ 0 & \kappa_2 & 0 \\ 0 & 0 & \kappa_3 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\pi_{\alpha\beta} : \bar{Q}_\alpha Q_\beta$$

$\alpha \in \{1,2,3\}, \beta = 4$

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$$\alpha \in \{1,2,3\}, \beta = 4$$

More rigorously, we have  $SU(3) \times U(1) \subset SU(4)$

$$\mathbf{15} = \mathbf{8}_0 \oplus \mathbf{1}_0 \oplus (\mathbf{3}_{\sqrt{2/3}} + h.c.)$$

$\pi_{\text{tran}}$

Decay into SM

$\pi_{\text{DM}}$

Stable

$$\Pi_D = \pi_D^a T^a$$

$$\Pi_D = \left[ \begin{array}{c|c} \mathbf{8} & \mathbf{3} \\ \hline \mathbf{3}^\dagger & \mathbf{1} \end{array} \right]$$

# Cosmology of dark pions: setup + assumptions

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The relevant degrees of freedom, assuming  $\kappa_{ij} = \kappa$ , for  $i, j \leq 3$  :

$$\kappa_{4 \times 3} = \kappa \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \\ 0 & 0 & 0 \end{pmatrix}$$

$$n_f, \quad N_d = 3, \quad m_{\pi_D}, \quad f_D/m_{\pi_D}, \quad m_X, \quad \kappa$$

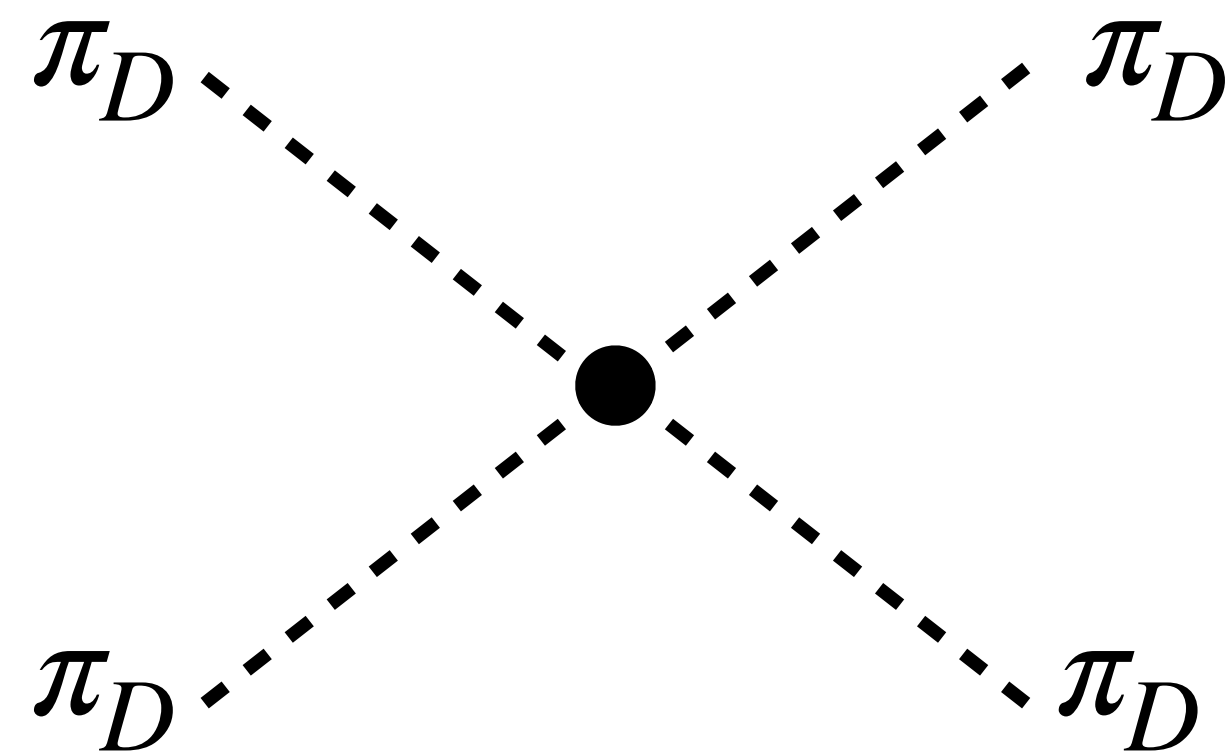
Note that in this case, all dark pions have the same mass, up to loop corrections!

Sometimes, it is useful to talk about lifetime of transient pions instead of  $m_X$  or  $\kappa$ .

$$c\tau_{\pi_{\text{tran}}}^{\text{off-diag}} = 3/4 c\tau_{\pi_{\text{tran}}}^{\text{diag}} \dots \text{So, we can use } c\tau \equiv c\tau_{\pi_{\text{tran}}}^{\text{diag}}.$$

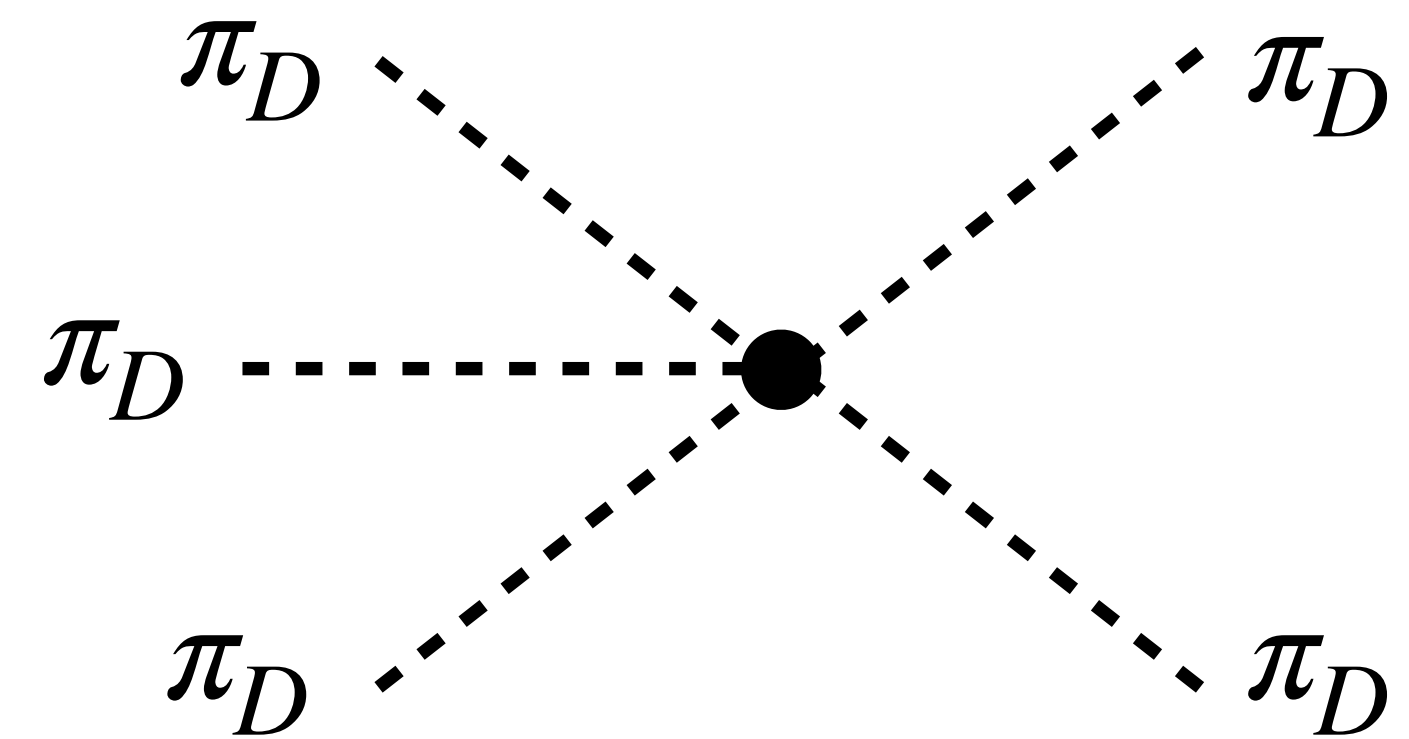
# How is the relic abundance set?

Self-interaction between dark pions:



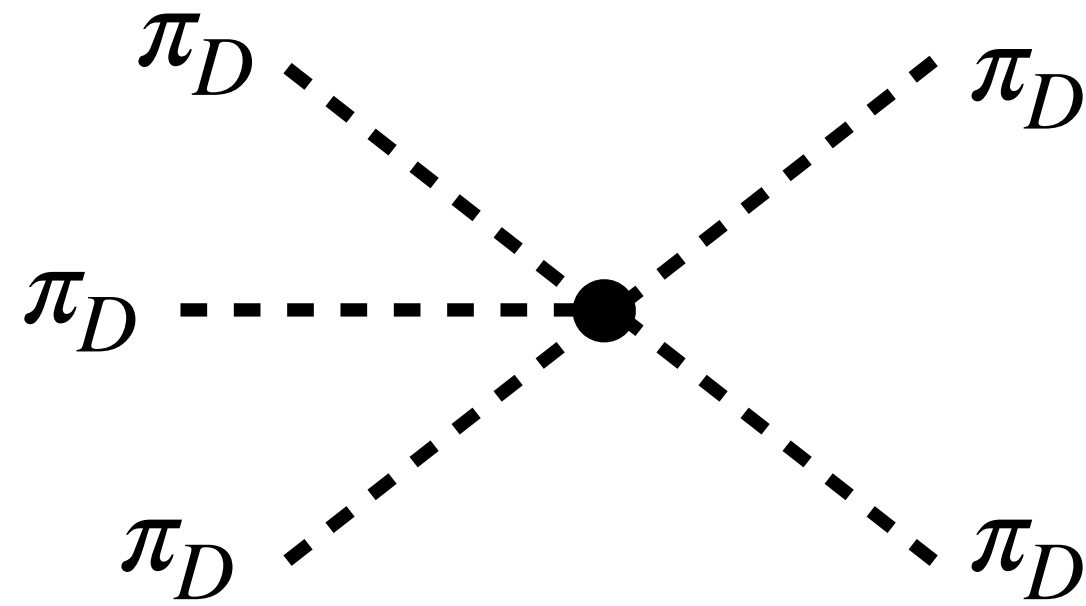
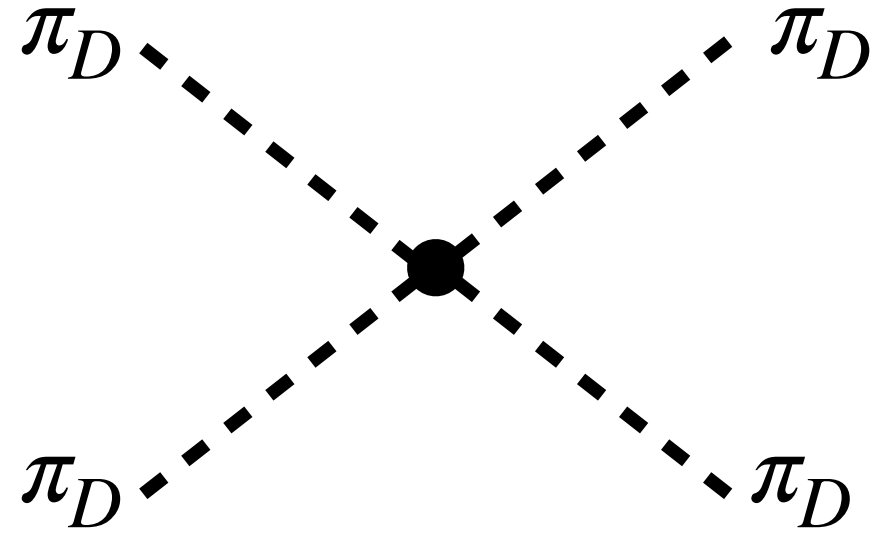
$$\pi_D = \pi_{\text{tran}} \text{ OR } \pi_{\text{DM}}$$

A function of  $SU(n_f)$   
structure constant.



For the case of  $n_f = 4$ , there seem to be an accidental symmetry that forces  $\pi_{\text{DM}}$  to always appear in **pairs**.

# Cosmology of dark pions



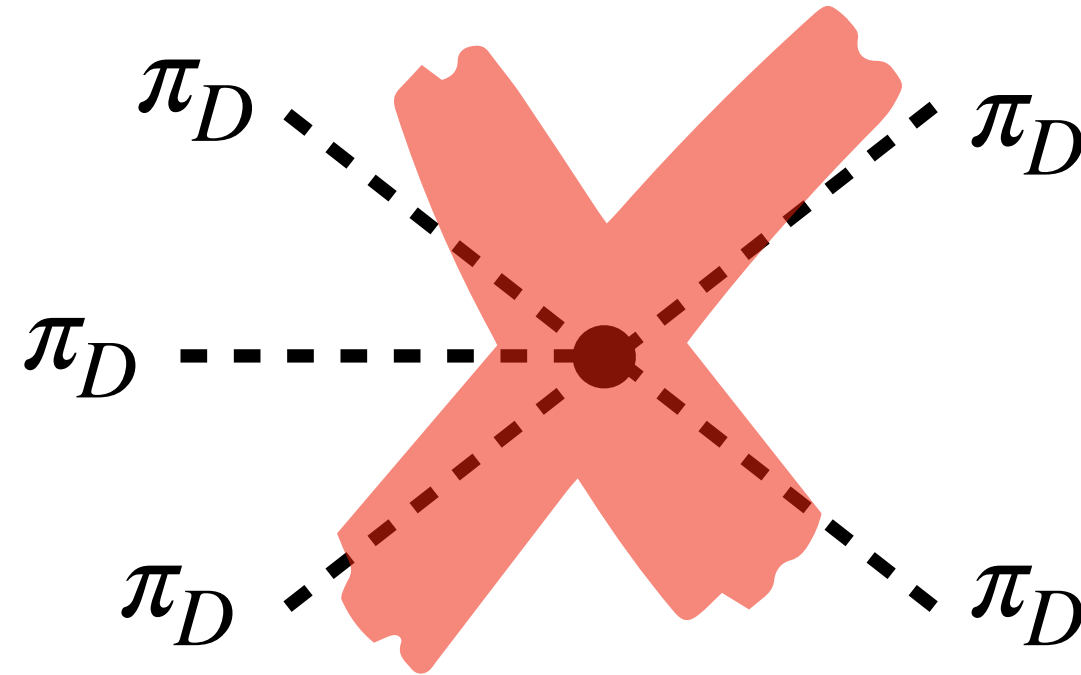
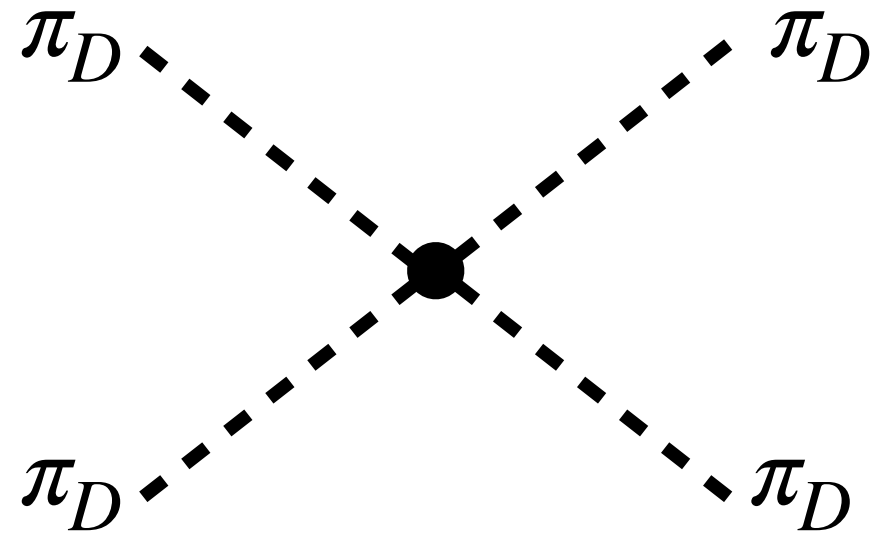
$$\langle \sigma v \rangle_{2\text{DM} \rightarrow 2\text{tran}} = \frac{2m_{\pi_D}^2}{\pi^{3/2} f_D^4 \sqrt{x}}$$

$$\langle \sigma v^2 \rangle_{ijk \rightarrow lm} = O(1) \frac{25m_{\pi}^5 N_d^2}{32\sqrt{5}\pi^5 f_D^{10} x^2}$$

$$\begin{aligned} \frac{1}{a^3} \frac{d}{dt} (n_{\text{DM}} a^3) = & - \langle \sigma v \rangle_{2\text{DM} \rightarrow 2\text{tran}} [n_{\text{DM}}^2 - (n_{\text{DM}}^2)_{\text{eq}}] \\ & - 2 \langle \sigma v^2 \rangle_{3\text{DM} \rightarrow 1\text{DM} 1\text{tran}} \left[ n_{\text{DM}}^3 - \left( \frac{n_{\text{DM}}^2}{n_{\text{tran}}} \right)_{\text{eq}} n_{\text{DM}} n_{\text{tran}} \right] \\ & - 2 \langle \sigma v^2 \rangle_{2\text{DM} 1\text{tran} \rightarrow 2\text{tran}} \left[ n_{\text{DM}}^2 n_{\text{tran}} - \left( \frac{n_{\text{DM}}^2}{n_{\text{tran}}} \right)_{\text{eq}} n_{\text{tran}}^2 \right] \\ & + 2 \langle \sigma v^2 \rangle_{3\text{tran} \rightarrow 2\text{DM}} \left[ n_{\text{tran}}^3 - \left( \frac{n_{\text{tran}}^3}{n_{\text{DM}}^2} \right)_{\text{eq}} n_{\text{DM}}^2 \right], \end{aligned}$$

$$\begin{aligned} \frac{1}{a^3} \frac{d}{dt} (n_{\text{tran}} a^3) = & + \langle \sigma v \rangle_{2\text{DM} \rightarrow 2\text{tran}} [n_{\text{DM}}^2 - (n_{\text{DM}}^2)_{\text{eq}}] \\ & - \langle \sigma v^2 \rangle_{3\text{tran} \rightarrow 2\text{tran}} [n_{\text{tran}}^3 - (n_{\text{tran}})_{\text{eq}} n_{\text{tran}}^2] \\ & - 3 \langle \sigma v^2 \rangle_{3\text{tran} \rightarrow 2\text{DM}} \left[ n_{\text{tran}}^3 - \left( \frac{n_{\text{tran}}^3}{n_{\text{DM}}^2} \right)_{\text{eq}} n_{\text{DM}}^2 \right] \\ & - \langle \sigma v^2 \rangle_{1\text{DM} 2\text{tran} \rightarrow 1\text{DM} 1\text{tran}} [n_{\text{tran}}^2 n_{\text{DM}} - (n_{\text{tran}})_{\text{eq}} n_{\text{tran}} n_{\text{DM}}] \\ & + \langle \sigma v^2 \rangle_{2\text{DM} 1\text{tran} \rightarrow 2\text{tran}} \left[ n_{\text{tran}} n_{\text{DM}}^2 - \left( \frac{n_{\text{DM}}}{n_{\text{tran}}} \right)_{\text{eq}} n_{\text{tran}}^2 \right] \\ & - \langle \sigma v^2 \rangle_{2\text{DM} 1\text{tran} \rightarrow 2\text{DM}} [n_{\text{DM}}^2 n_{\text{tran}} - (n_{\text{tran}})_{\text{eq}} n_{\text{DM}}^2] \\ & + \langle \sigma v^2 \rangle_{3\text{DM} \rightarrow 1\text{DM} 1\text{tran}} \left[ n_{\text{DM}}^3 - \left( \frac{n_{\text{DM}}^2}{n_{\text{tran}}} \right)_{\text{eq}} n_{\text{DM}} n_{\text{tran}} \right] - \Gamma(\pi_{\text{tran}}) n_{\text{tran}}. \end{aligned}$$

# Cosmology of dark pions



$$\langle \sigma v \rangle_{2_{\text{DM}} \rightarrow 2_{\text{tran}}} = \frac{2m_{\pi_D}^2}{\pi^{3/2} f_D^4 \sqrt{x}}$$

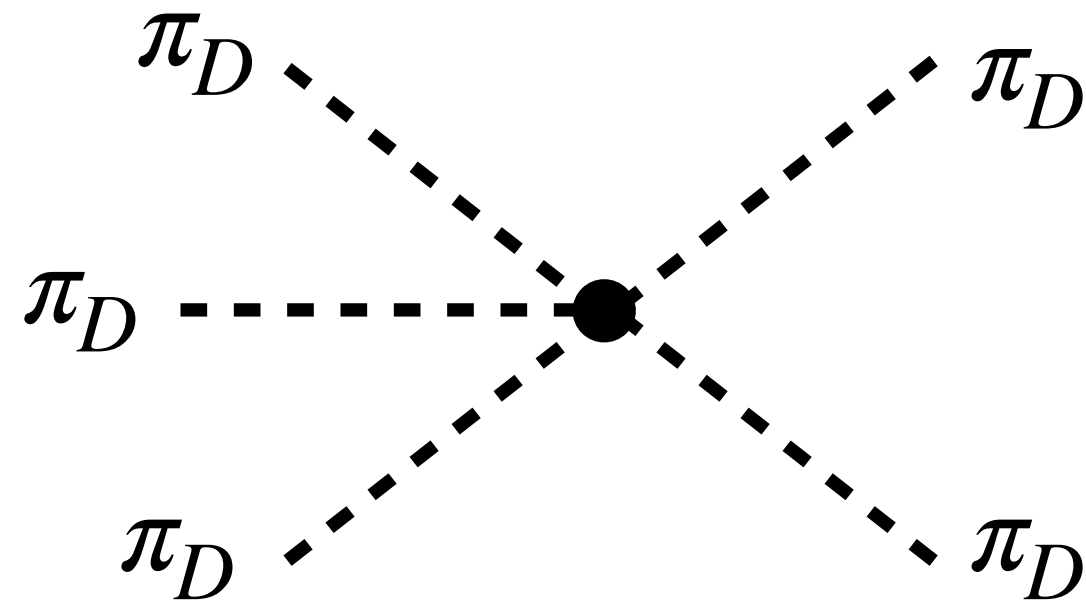
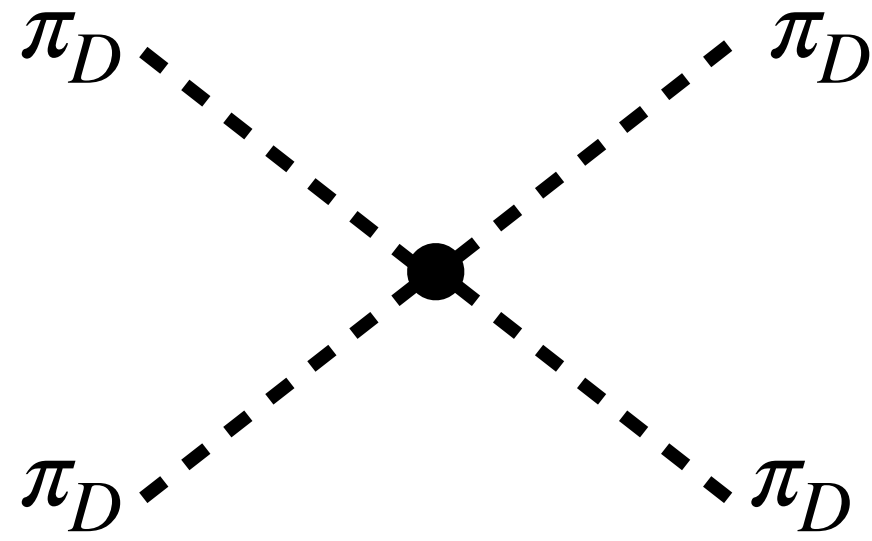
$$\langle \sigma v^2 \rangle_{ijk \rightarrow lm} = O(1) \frac{25m_{\pi}^5 N_d^2}{32\sqrt{5}\pi^5 f_D^{10} x^2}$$

Dominant for  
 $m_{\pi_D} \lesssim 10^6 \text{ GeV}$

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$$\langle \sigma v^2 \rangle_{ijk \rightarrow lm} = O(1) \frac{25m_{\pi}^5 N_d^2}{32\sqrt{5}\pi^5 f_D^{10} x^2}$$

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$$\begin{aligned} \frac{1}{a^3} \frac{d}{dt} (n_{\text{tran}} a^3) = & + \langle \sigma v \rangle_{2_{\text{DM}} \rightarrow 2_{\text{tran}}} [n_{\text{DM}}^2 - (n_{\text{DM}}^2)_{\text{eq}}] \\ & - \langle \sigma v^2 \rangle_{3_{\text{tran}} \rightarrow 2_{\text{tran}}} [n_{\text{tran}}^3 - (n_{\text{tran}})_{\text{eq}} n_{\text{tran}}^2] \\ & - 3\langle \sigma v^2 \rangle_{3_{\text{tran}} \rightarrow 2_{\text{DM}}} \left[ n_{\text{tran}}^3 - \left( \frac{n_{\text{tran}}^3}{n_{\text{DM}}^2} \right)_{\text{eq}} n_{\text{DM}}^2 \right] \\ & - \langle \sigma v^2 \rangle_{1_{\text{DM}} 2_{\text{tran}} \rightarrow 1_{\text{DM}} 1_{\text{tran}}} [n_{\text{tran}}^2 n_{\text{DM}} - (n_{\text{tran}})_{\text{eq}} n_{\text{tran}} n_{\text{DM}}] \\ & + \langle \sigma v^2 \rangle_{2_{\text{DM}} 1_{\text{tran}} \rightarrow 2_{\text{tran}}} \left[ n_{\text{tran}} n_{\text{DM}}^2 - \left( \frac{n_{\text{DM}}}{n_{\text{tran}}} \right)_{\text{eq}} n_{\text{tran}}^2 \right] \\ & - \langle \sigma v^2 \rangle_{2_{\text{DM}} 1_{\text{tran}} \rightarrow 2_{\text{DM}}} [n_{\text{DM}}^2 n_{\text{tran}} - (n_{\text{tran}})_{\text{eq}} n_{\text{DM}}^2] \\ & + \langle \sigma v^2 \rangle_{3_{\text{DM}} \rightarrow 1_{\text{DM}} 1_{\text{tran}}} \left[ n_{\text{DM}}^3 - \left( \frac{n_{\text{DM}}^2}{n_{\text{tran}}} \right)_{\text{eq}} n_{\text{DM}} n_{\text{tran}} \right] - \Gamma(\pi_{\text{tran}}) n_{\text{tran}}. \end{aligned}$$

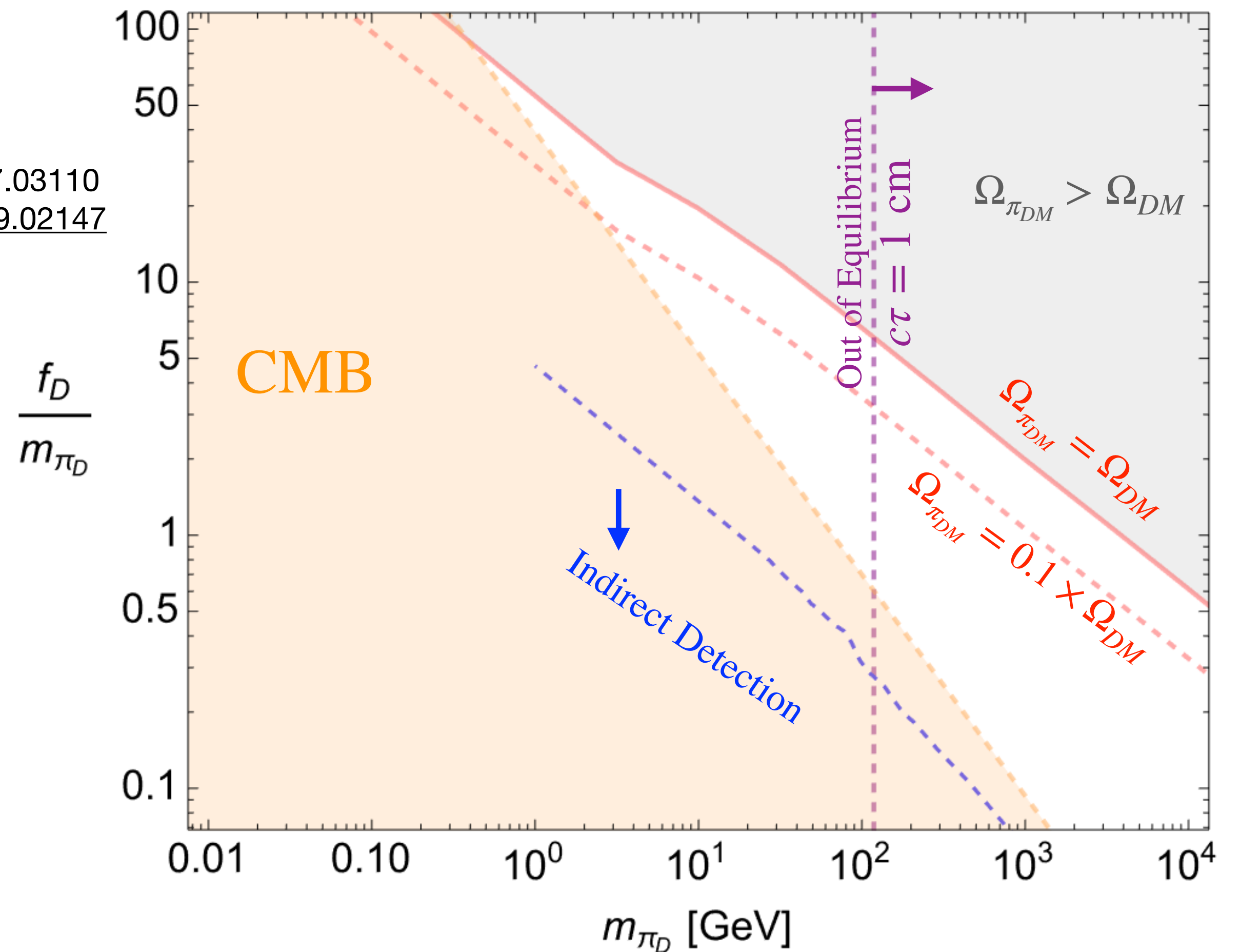
$$c\tau(m_{\pi_D}/\text{GeV})^2 \ll 100 \text{ m}$$

# Cosmological and astrophysical constraints

Relic abundance is set by the co-decaying annihilation of DM pions to degenerate transient pions:

$$\langle \sigma v \rangle_{2_{DM} \rightarrow 2_{tran}} = \frac{2m_{\pi_D}^2}{\sqrt{3}\pi^{3/2}f_D^4} v \leftarrow \text{Sneaky!}$$

J. Dror et al. 1607.03110  
J.Kopp et al. 1609.02147



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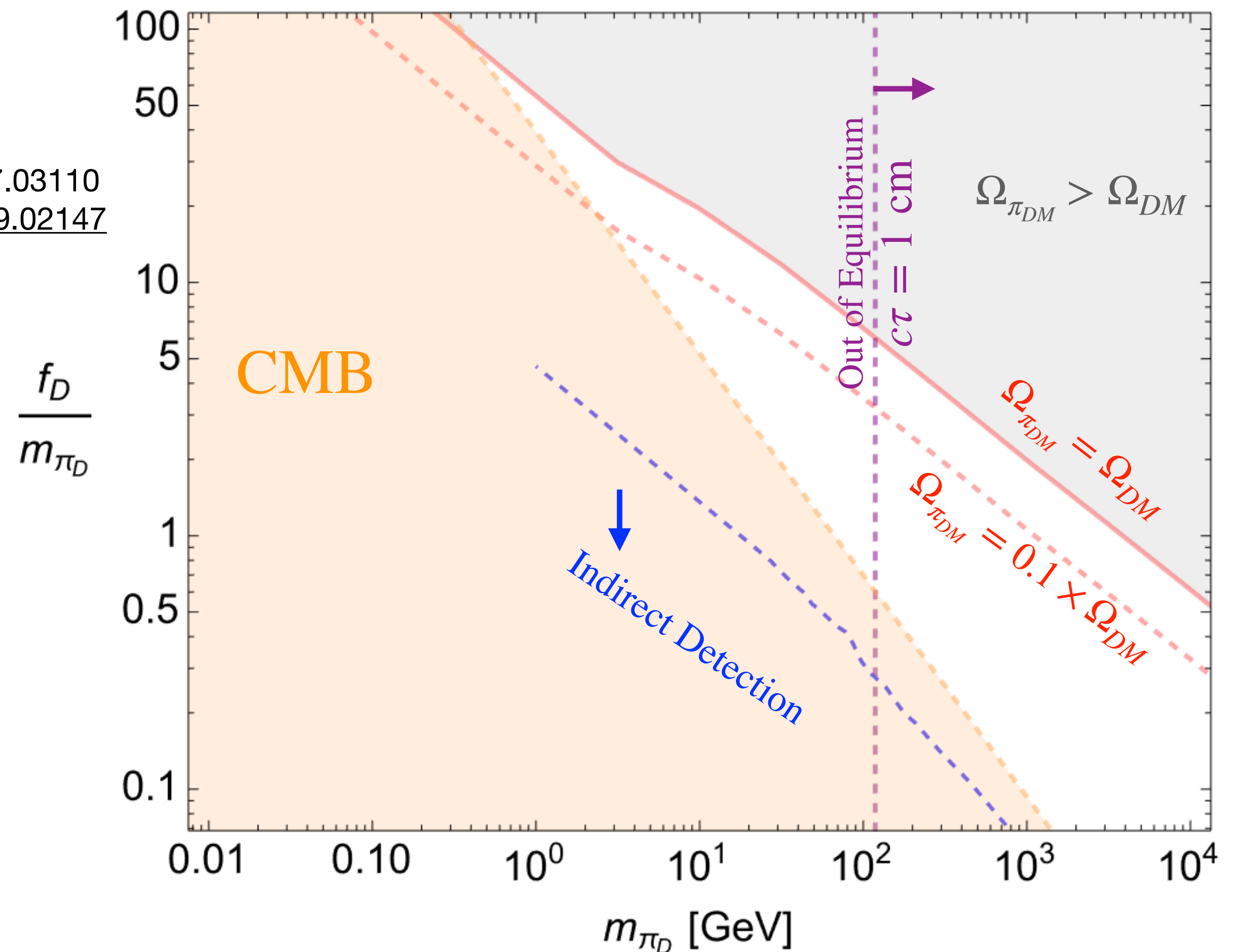
J. Dror et al. 1607.03110  
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CMB: the energy injection as a result of DM annihilation:

$$p_{ann} = f_{eff} \frac{\langle \sigma v \rangle}{m_{\pi_D}}$$

Indirect Detection: cascade annihilation to SM particles.

Dark sector is no longer in equilibrium with SM, and the relic abundance calculation requires more careful calculation.

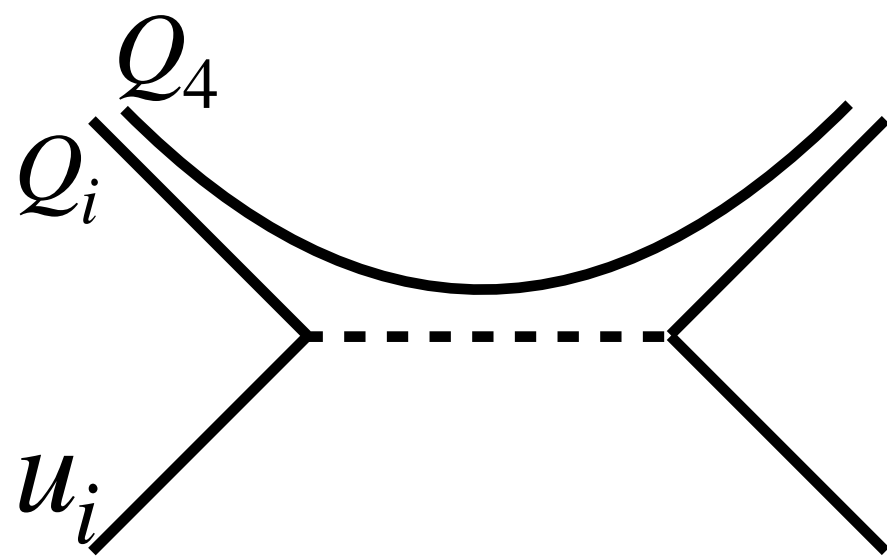


# Direct Detection constraints

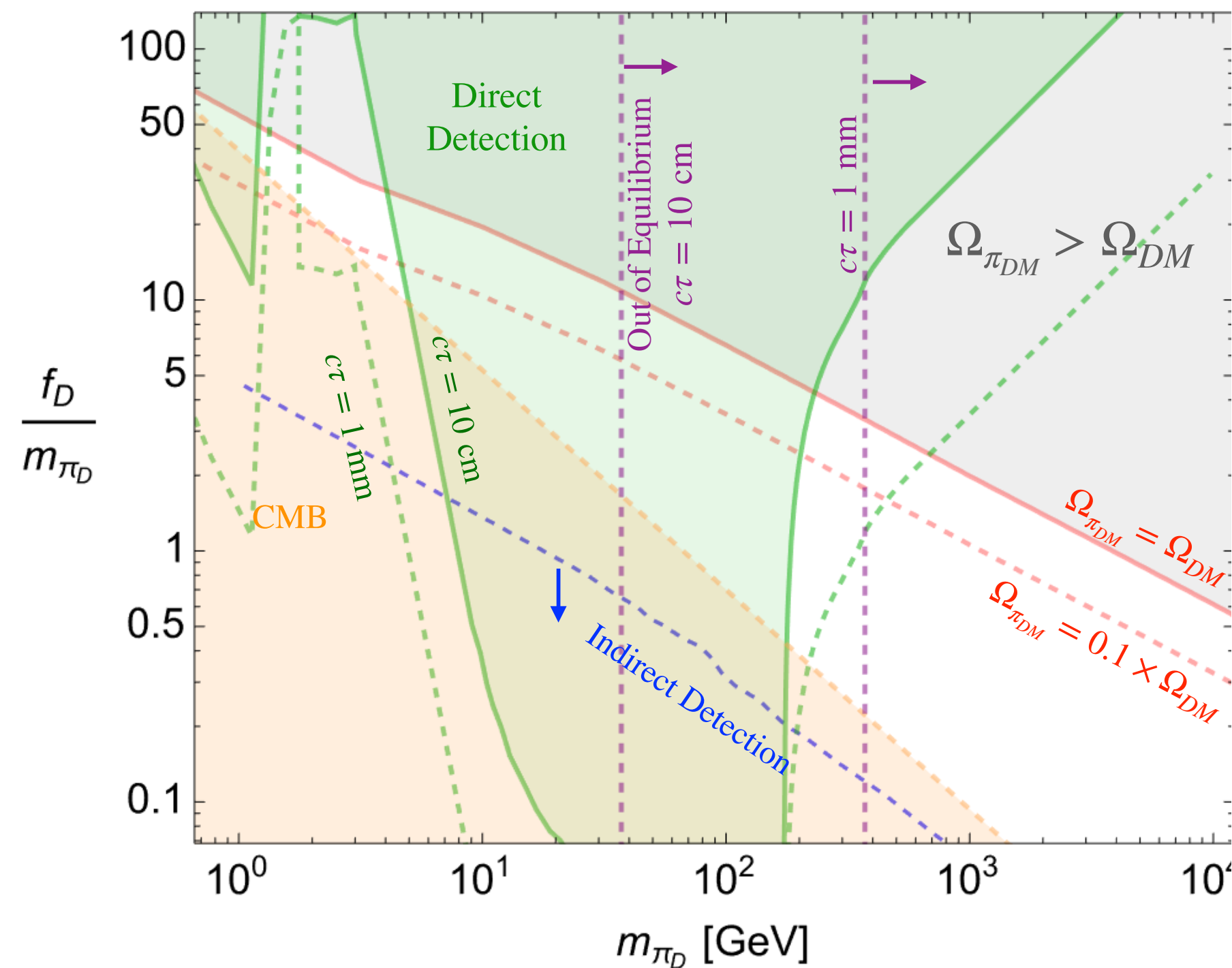
Scattering rate off of nucleus (LZ, SENSEI):

$$\sigma_{SI} \sim \frac{\kappa^4}{m_X^4} u^2 A^2$$

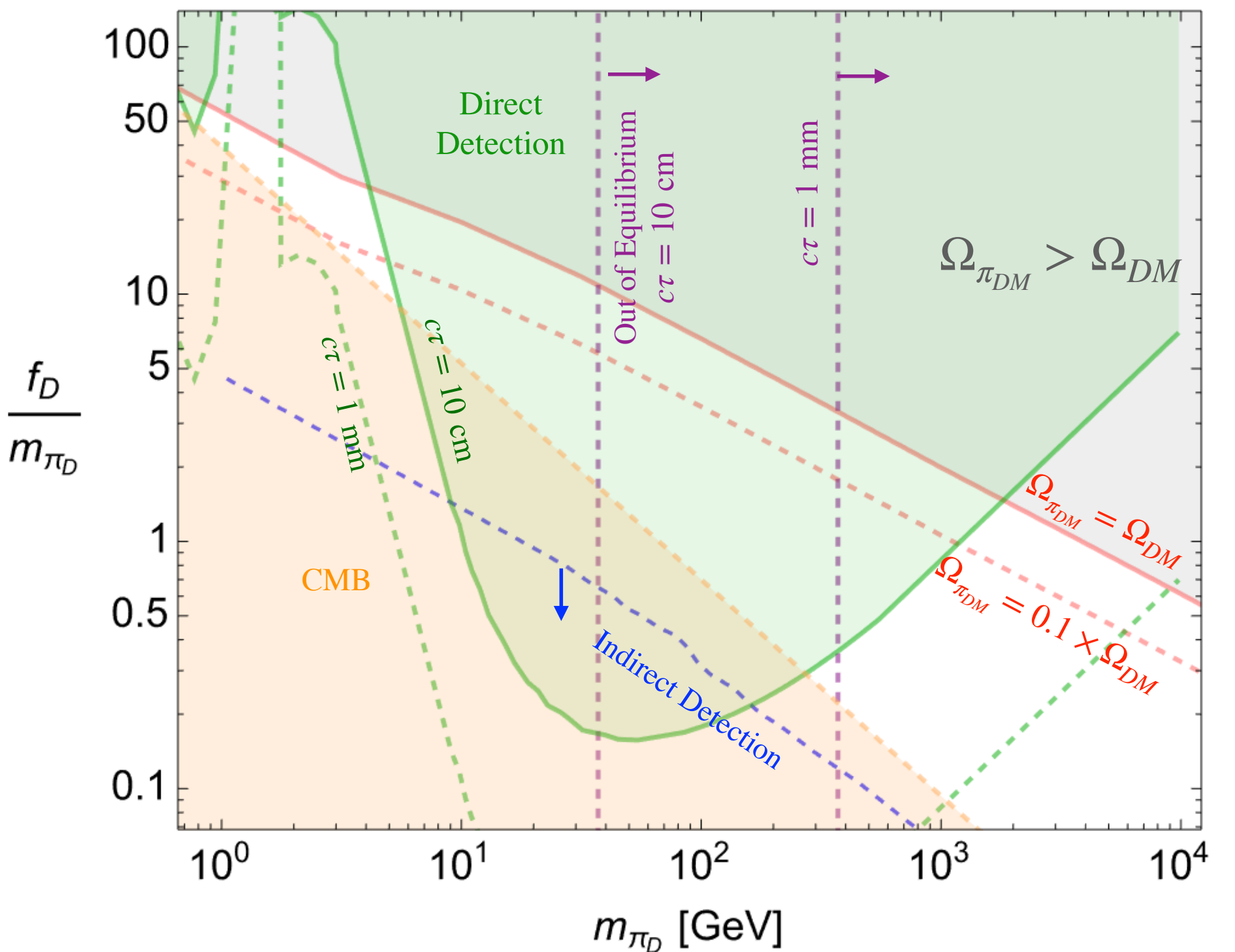
The constraints can be translated to  $c\tau$



Up type quark

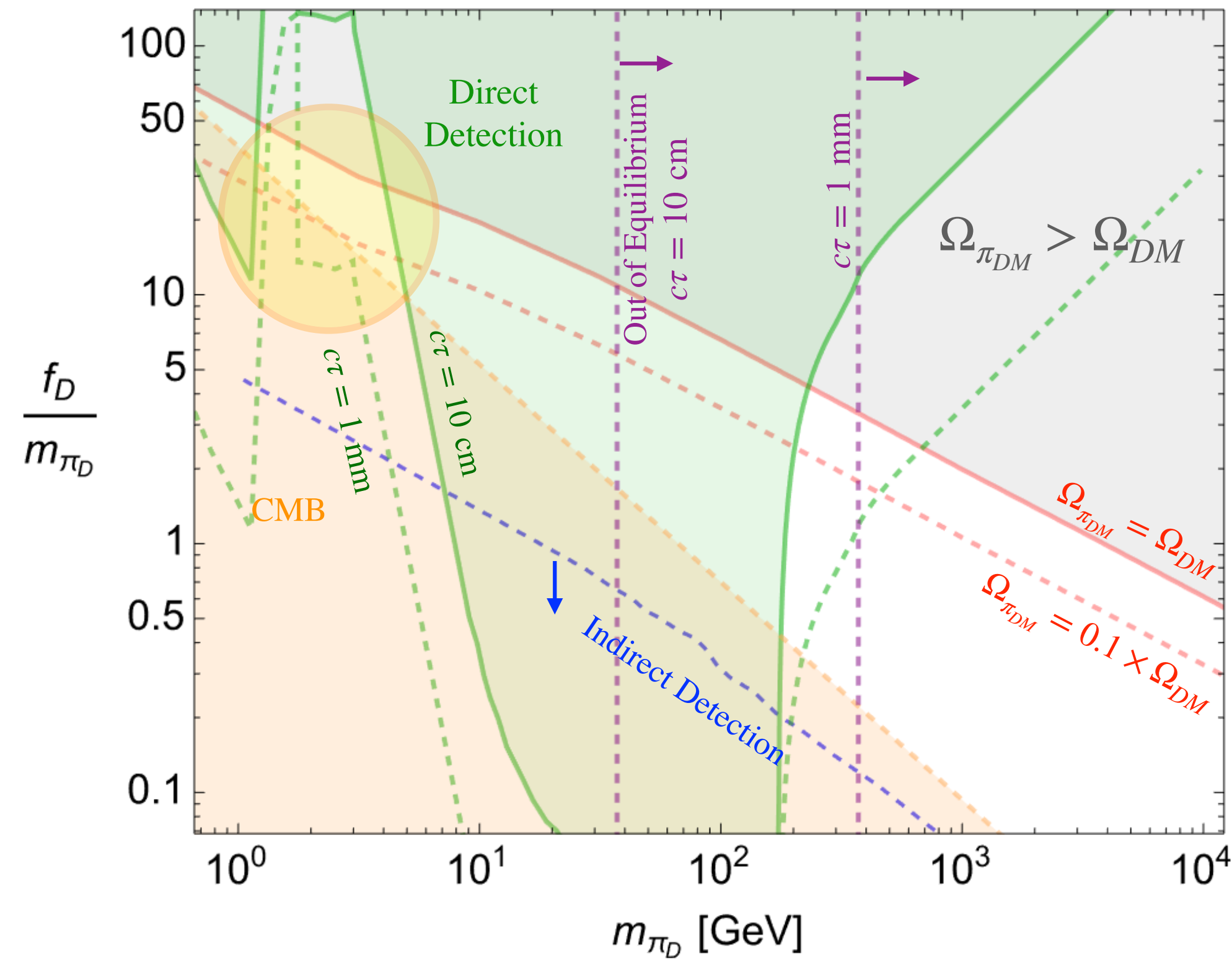


Down type quark

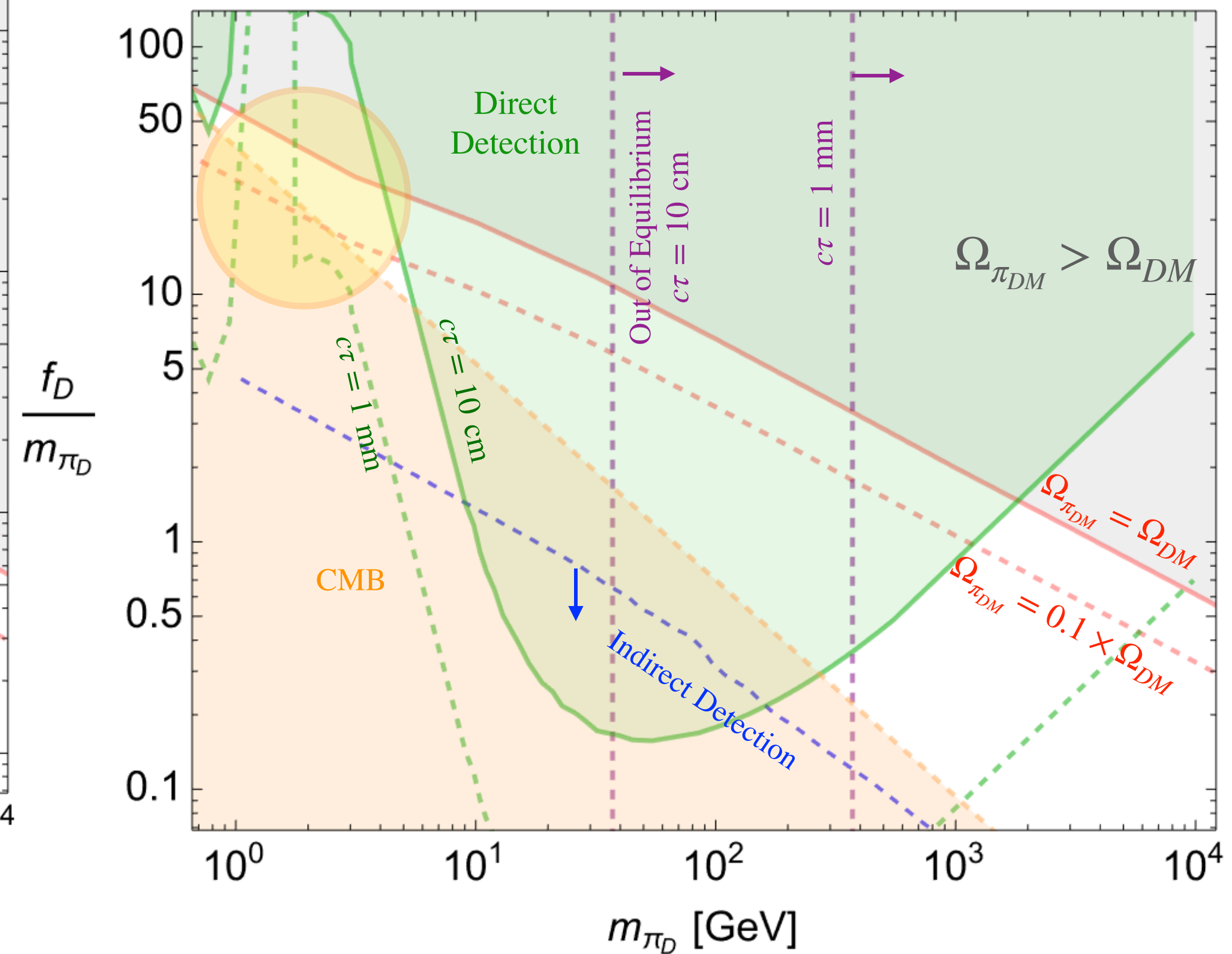


# Available and Ideal Parameter Space

Up type quark



Down type quark



Nice motivation to study cm-m lifetimes!

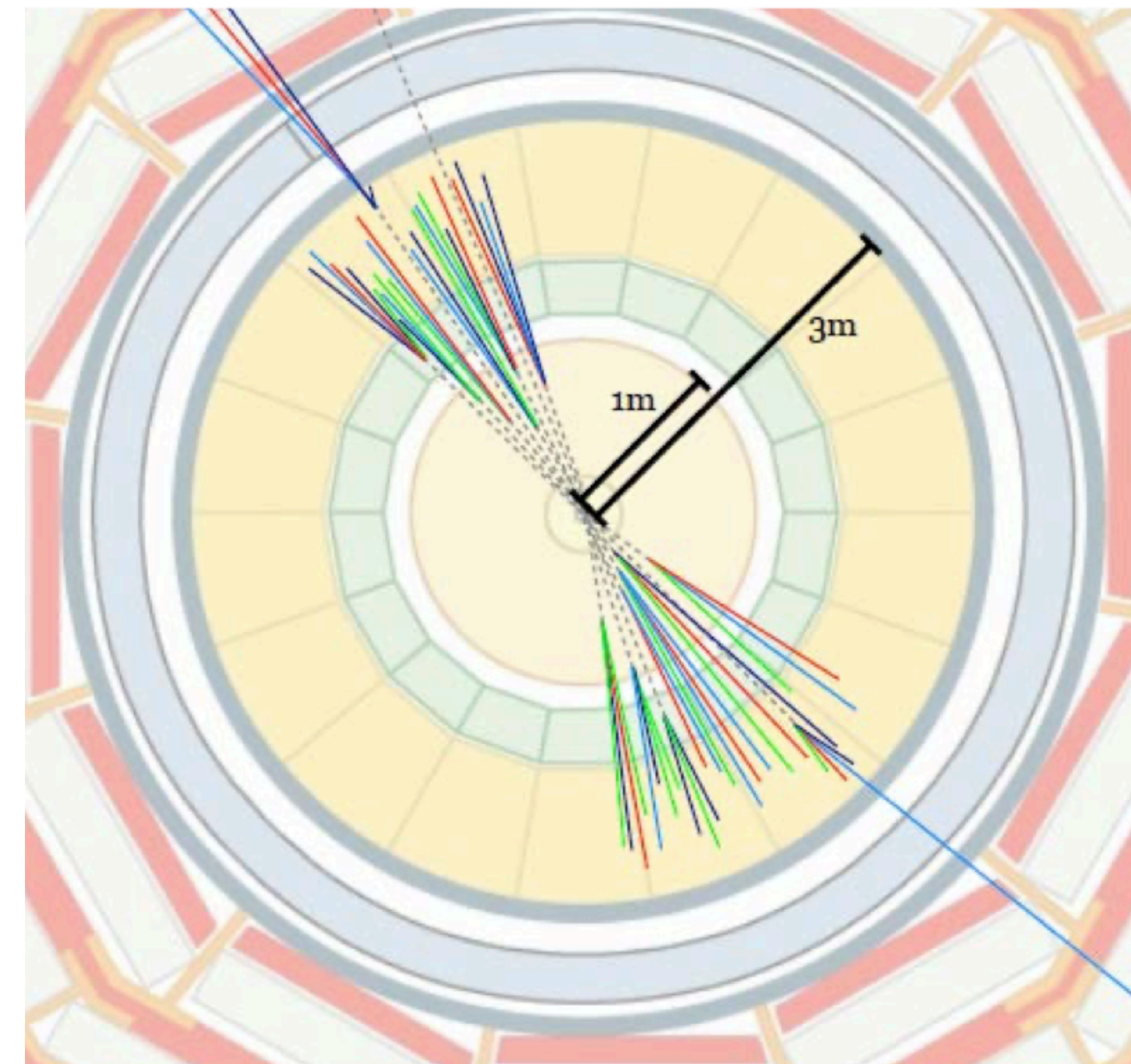
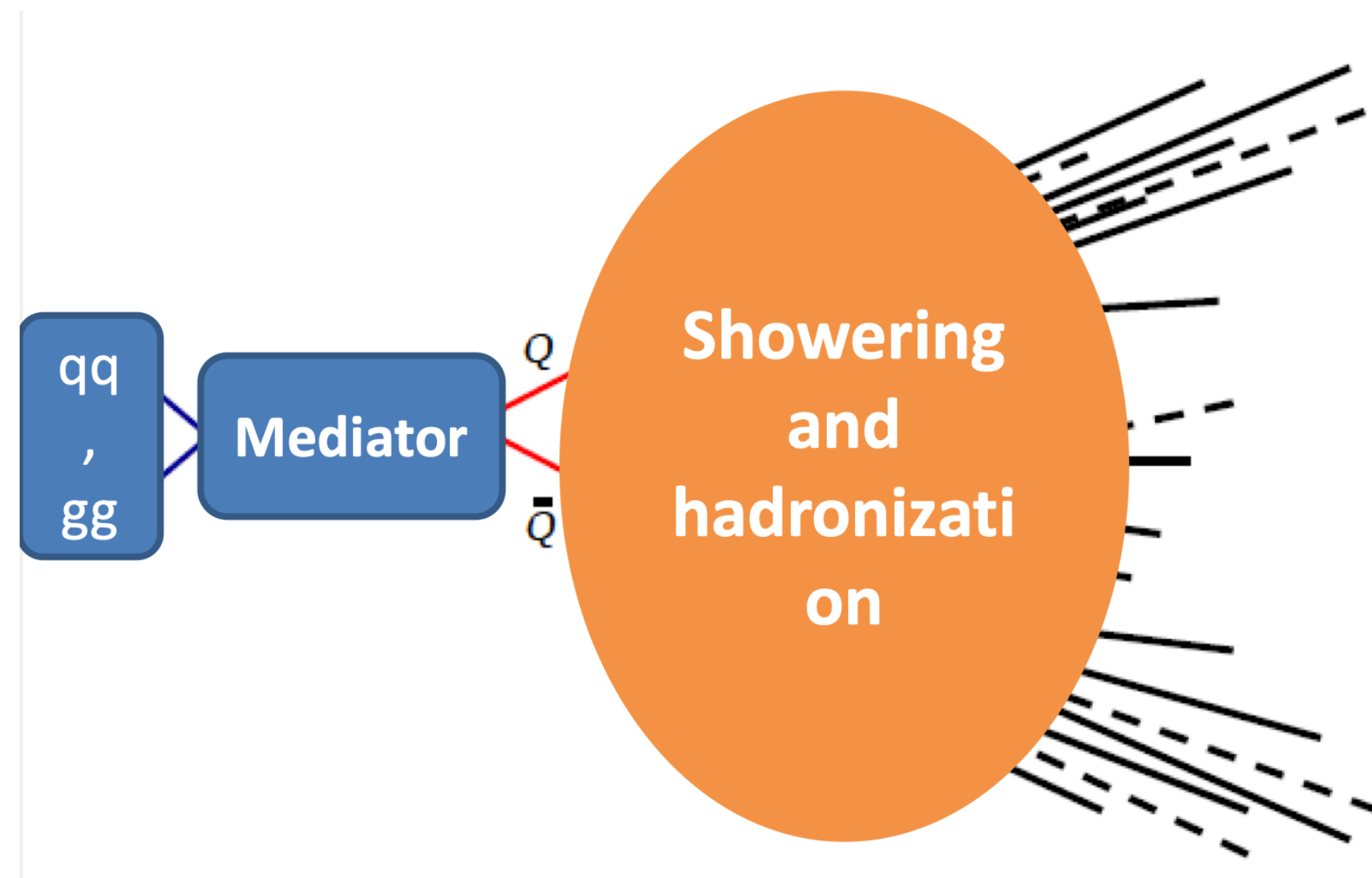
# Dark Showers at the LHC!



Now, there are a lot of dedicated searches/independent workshops at the LHC for dark shower!

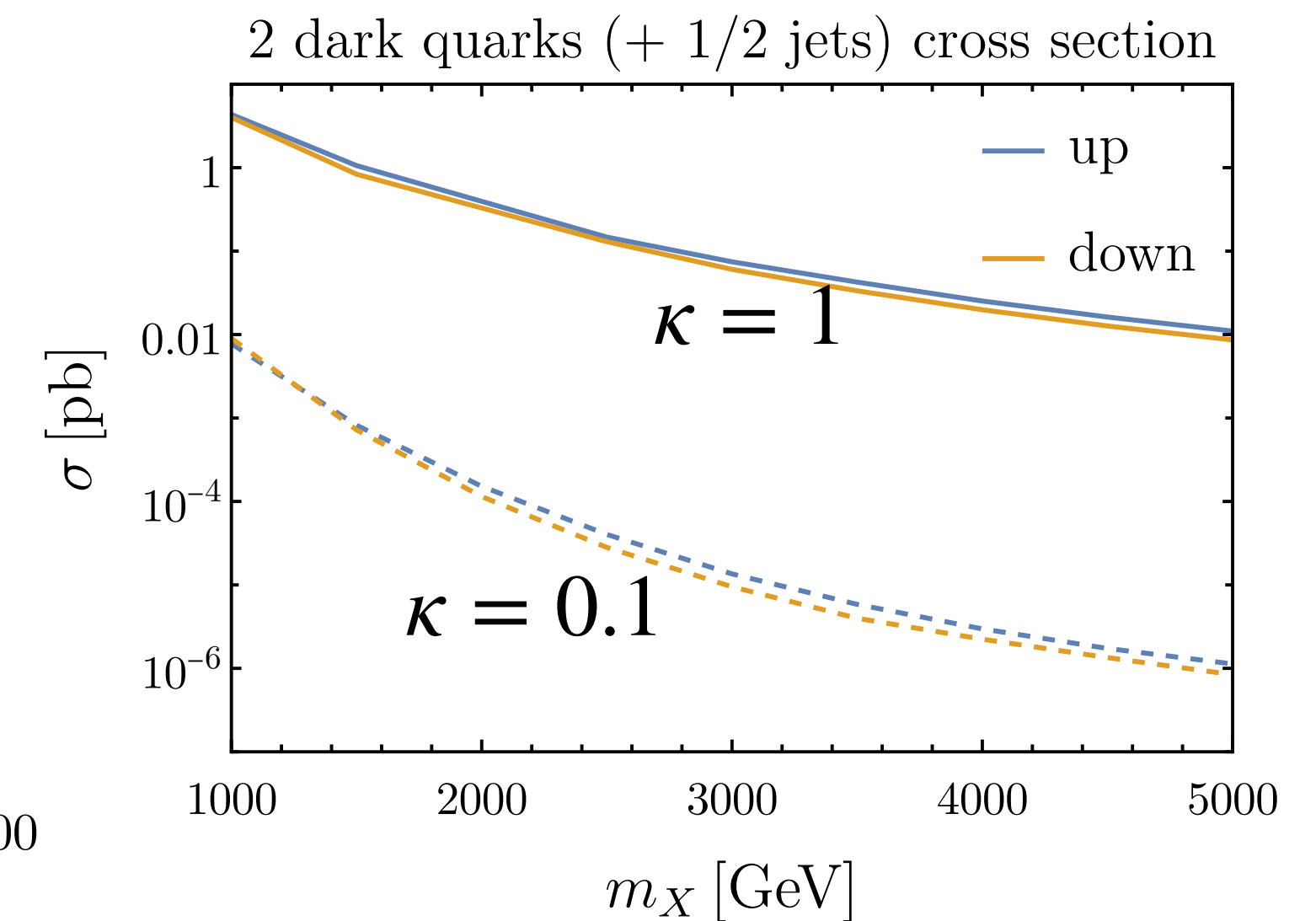
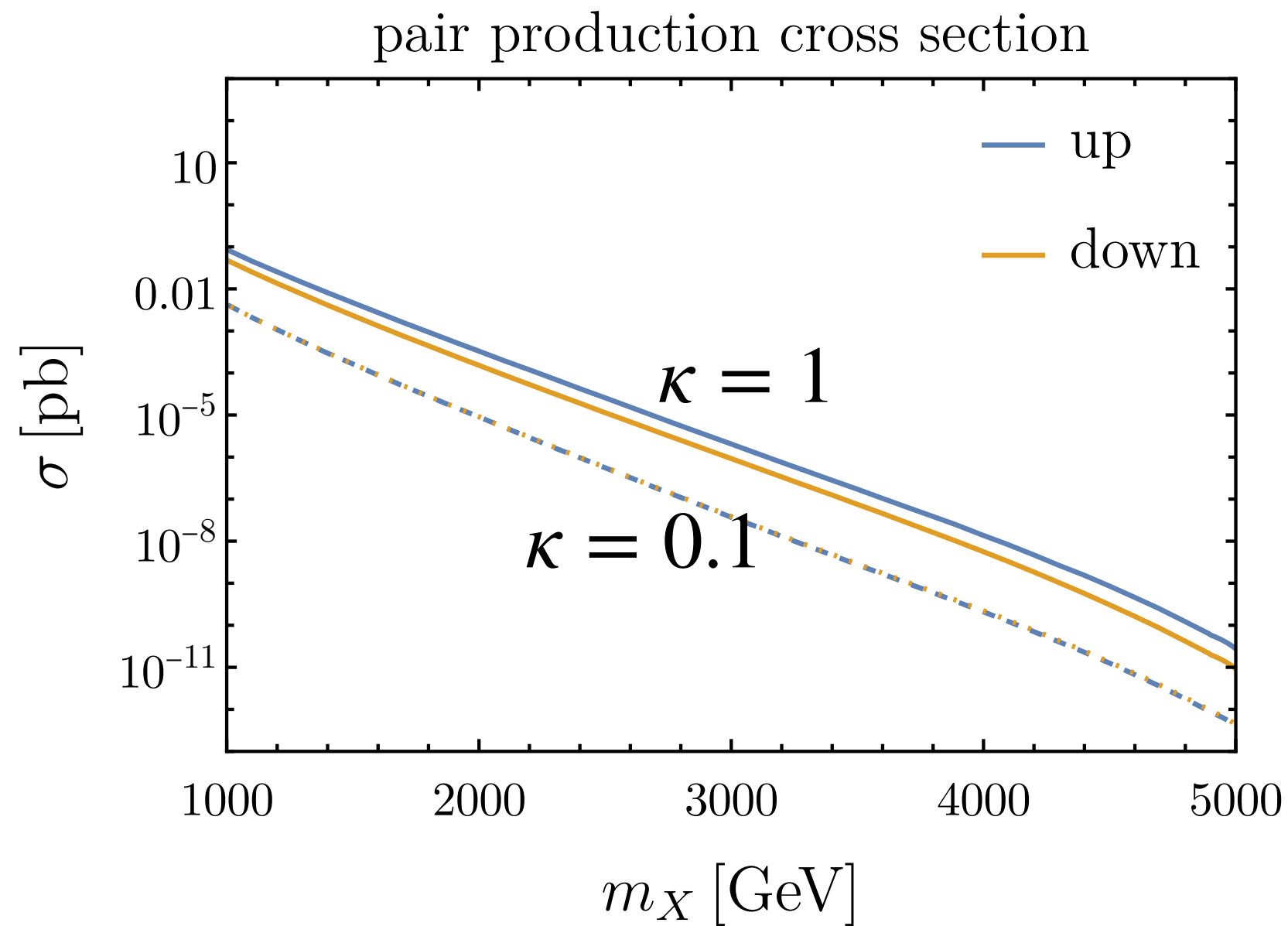
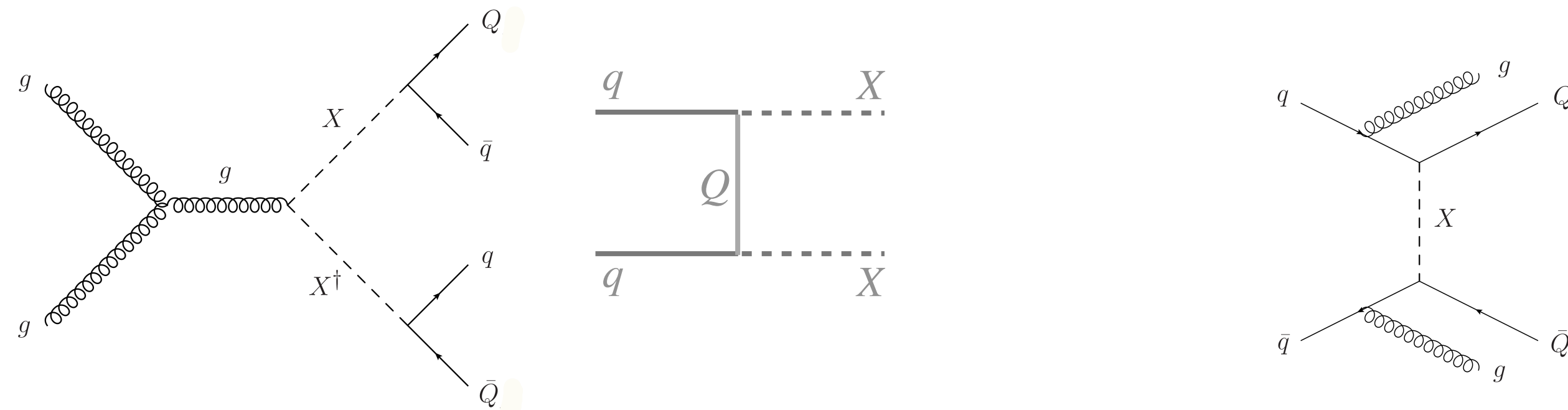
2017

Now



# Production cross section

Depending on the choice of  $\kappa$  and  $m_X$ , certain diagrams and topology might dominate. We can no longer just talk about lifetimes.



# Lifetime of $\pi_{\text{tran}}$ plays a crucial role!

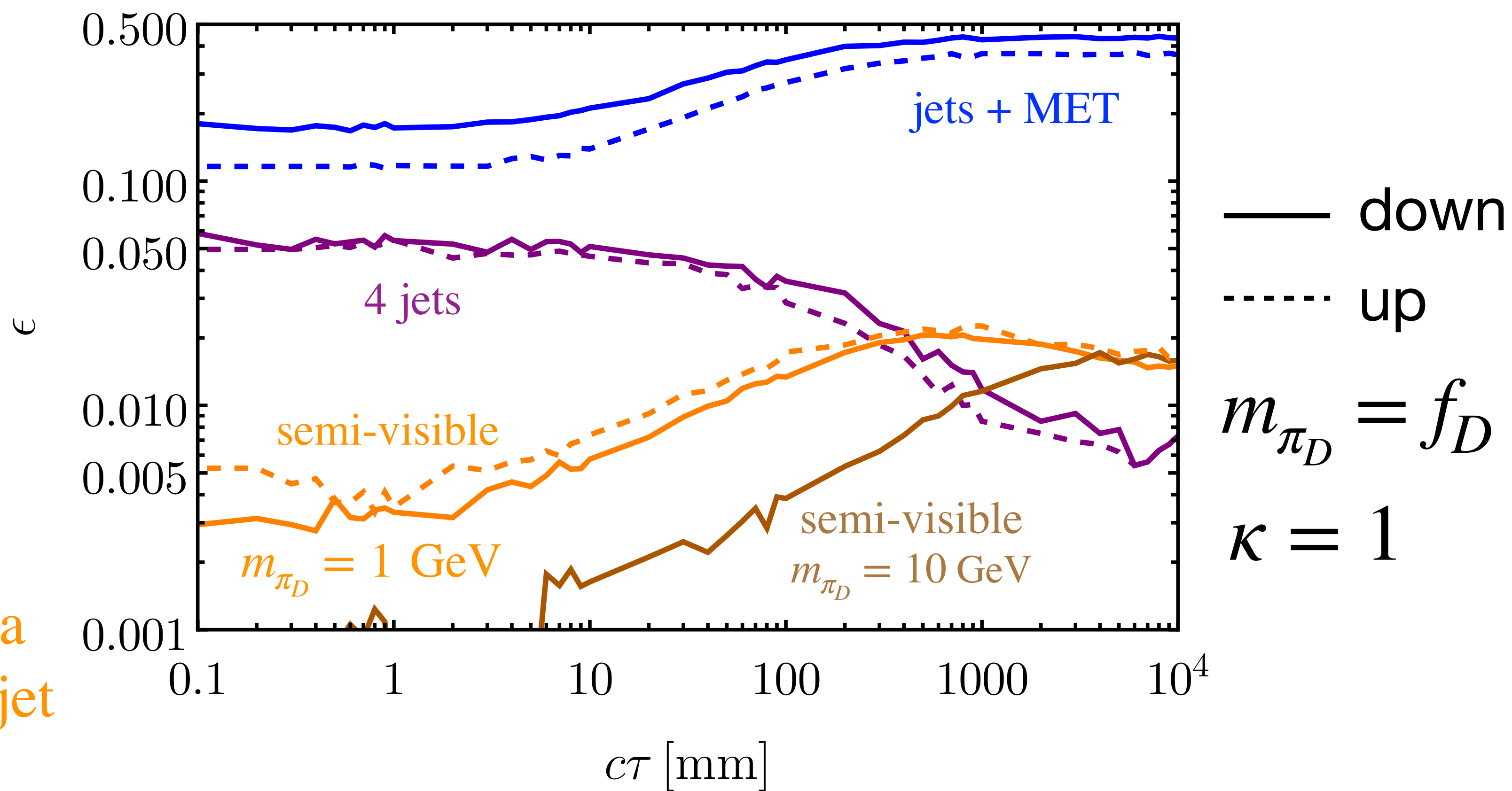
$$\sigma = \epsilon_{\text{eff}}(m_{\pi_D}, c\tau) \times \sigma_{\text{prod}}$$

Another key player is  $c\tau$  of transient pions.

4 jets:  $\pi_{\text{tran}}$  decays instantly

jets+ MET:  $\pi_{\text{tran}}$  is stable in collider scale.

Semi-visible: prompt decay with a large fraction of invisibles in the jet

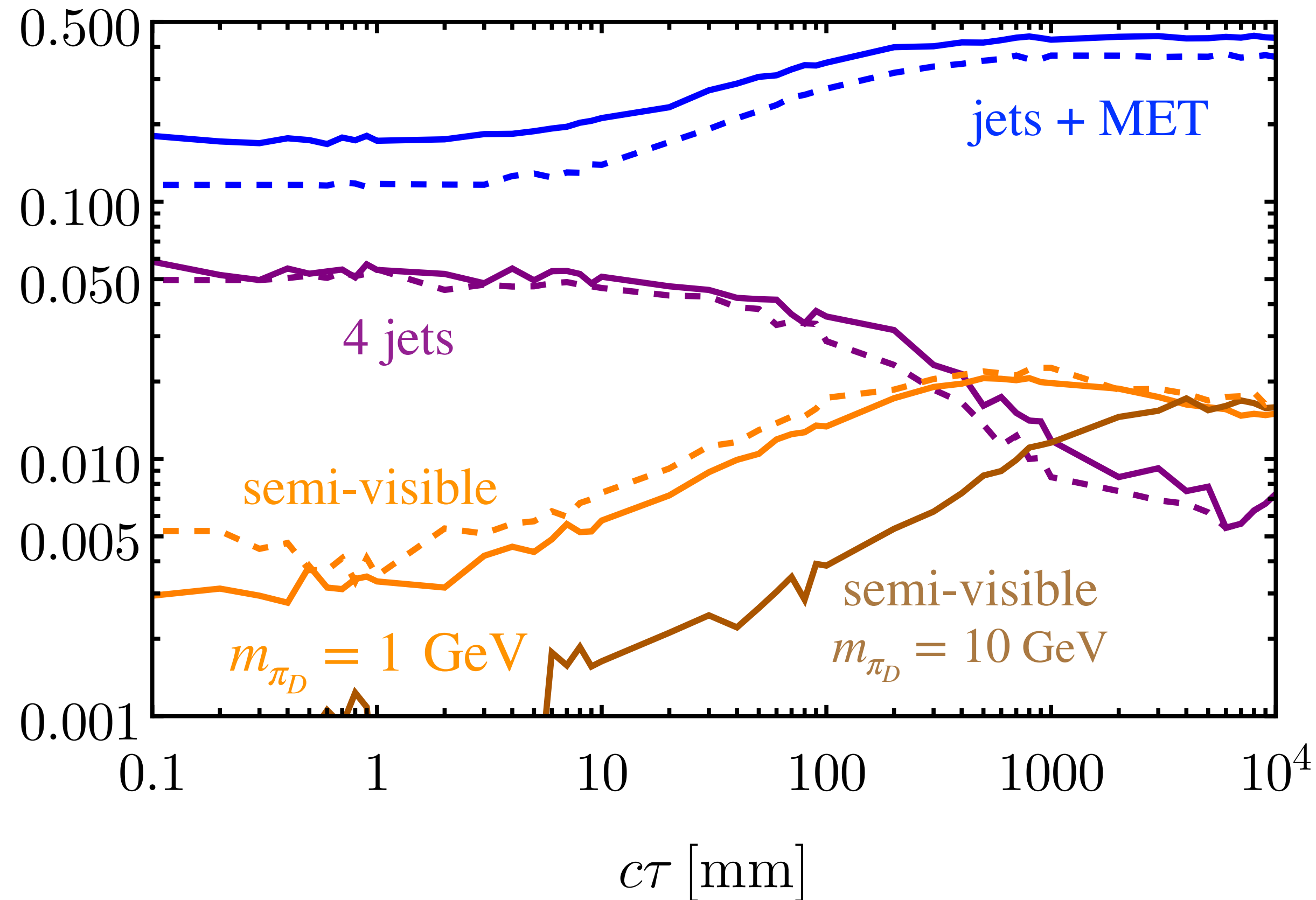


# Lifetime of $\pi_{\text{tran}}$ plays a crucial role!

Only the first 3 generation of dark quarks get produced in the hard process.

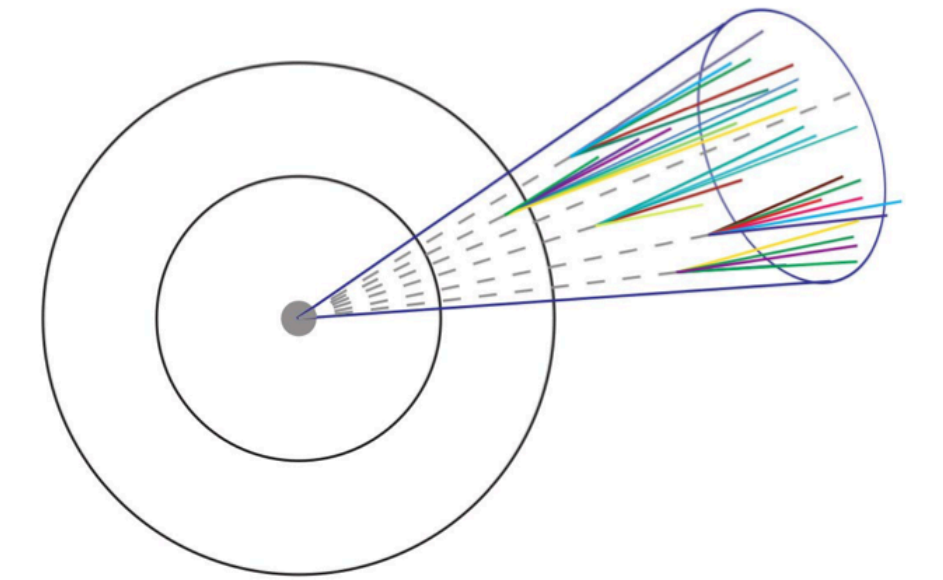
$Q_\alpha \bar{Q}_\alpha$  pair produce with equal probability for all 4 generations, so we have an even number of  $\pi_{DM}$ .

DM fraction is determined by  $n_f$ .

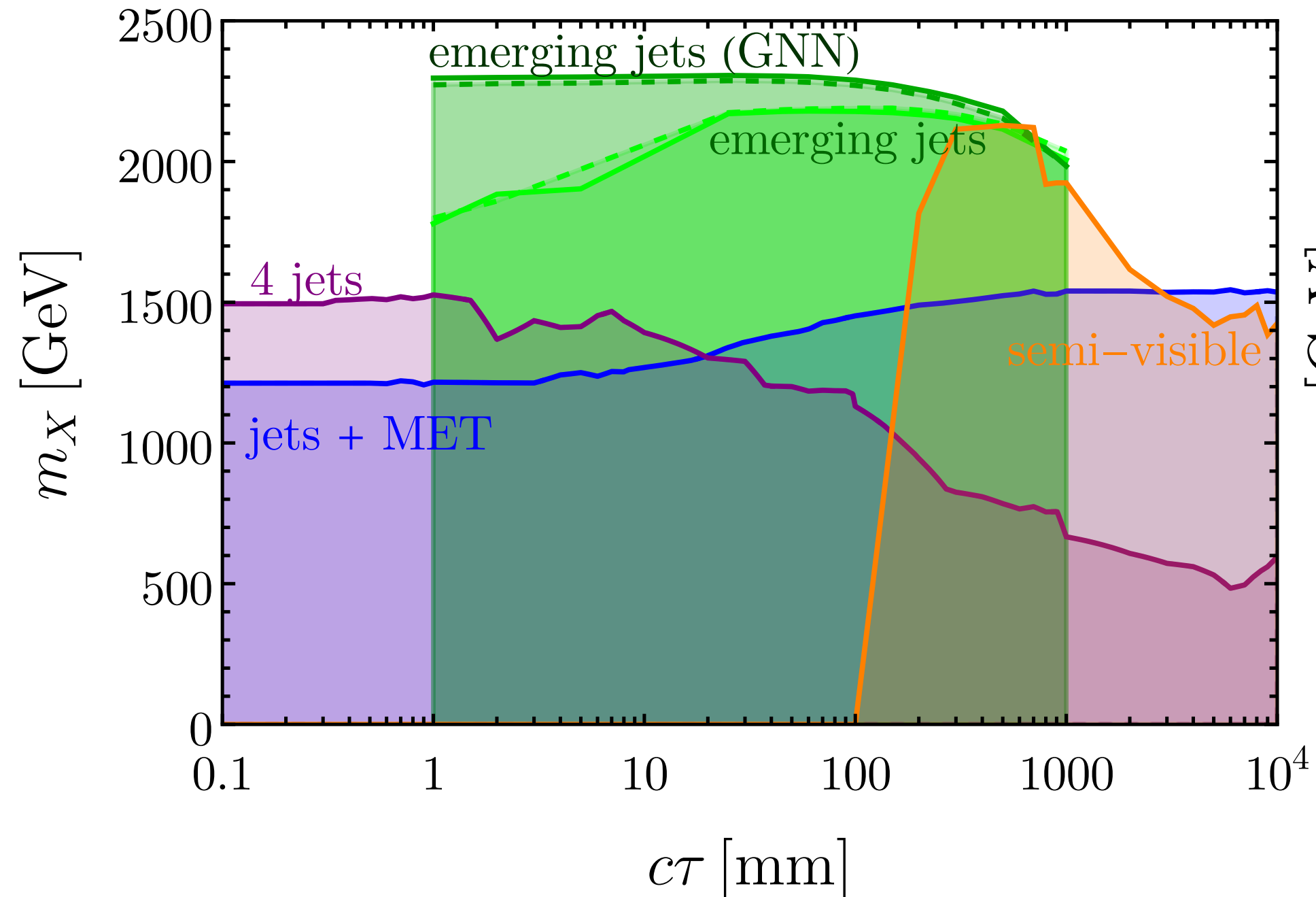


# Emerging jets

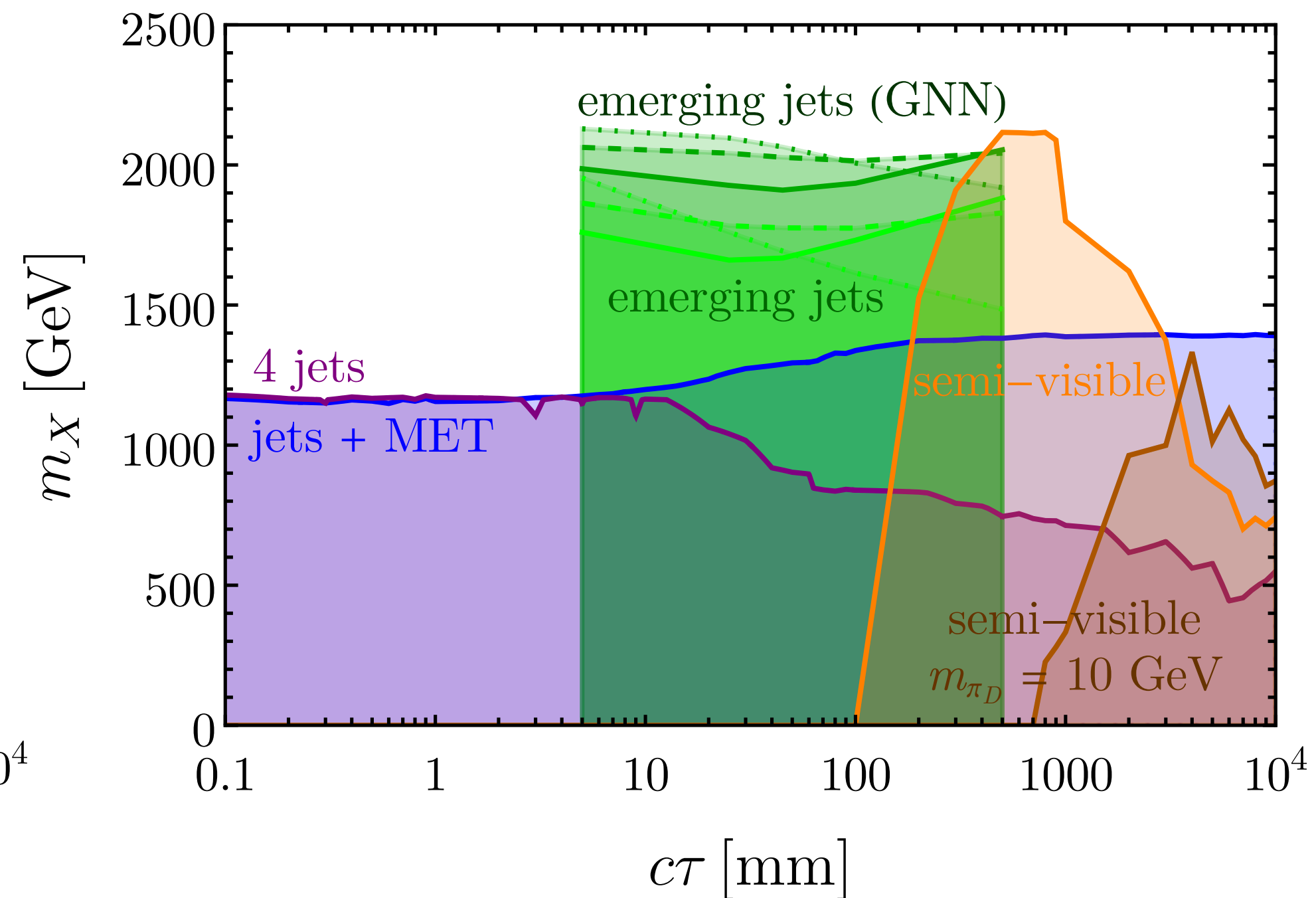
Yet, another possibility is if transient pions are long lived, but not stable.



Up type quark



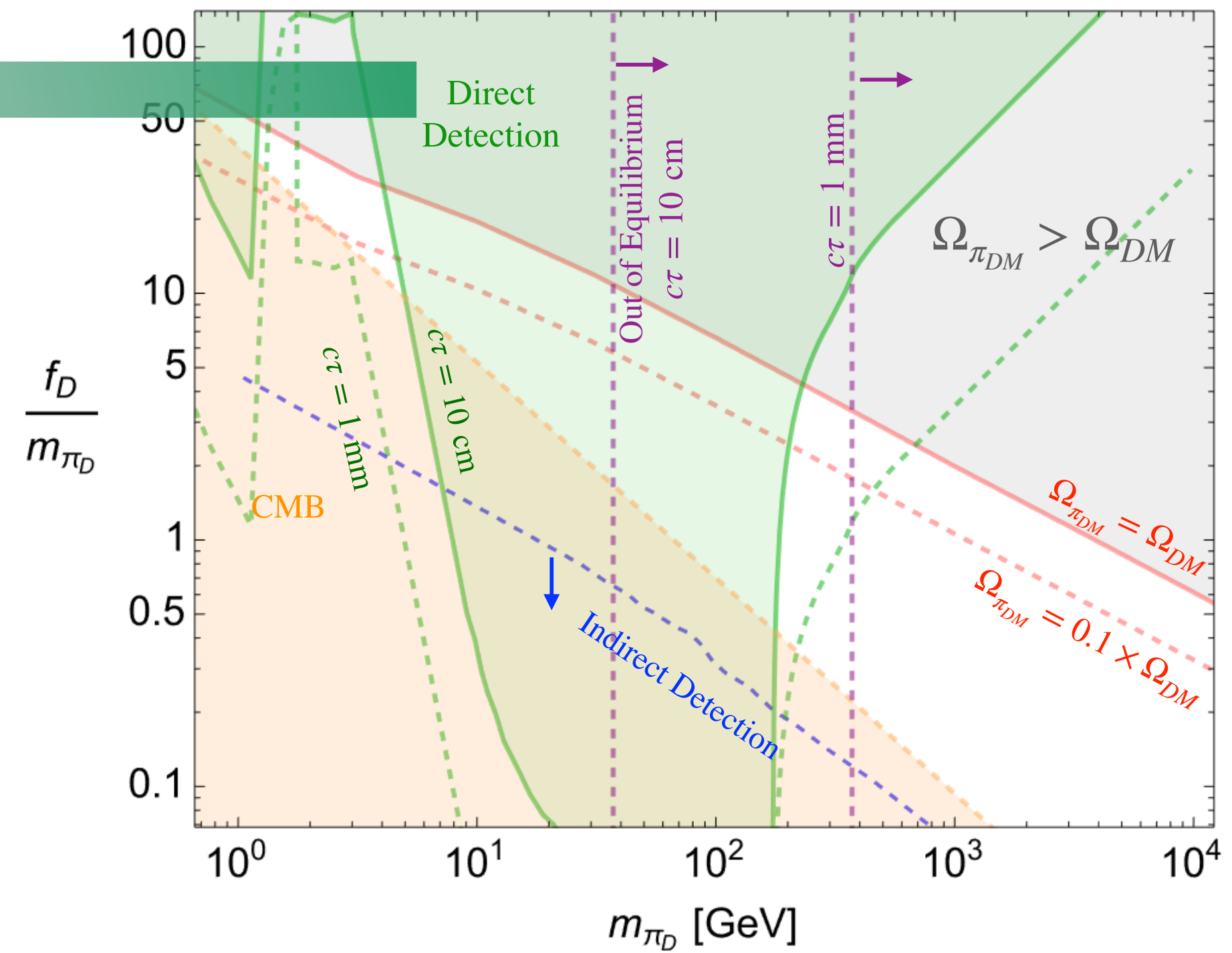
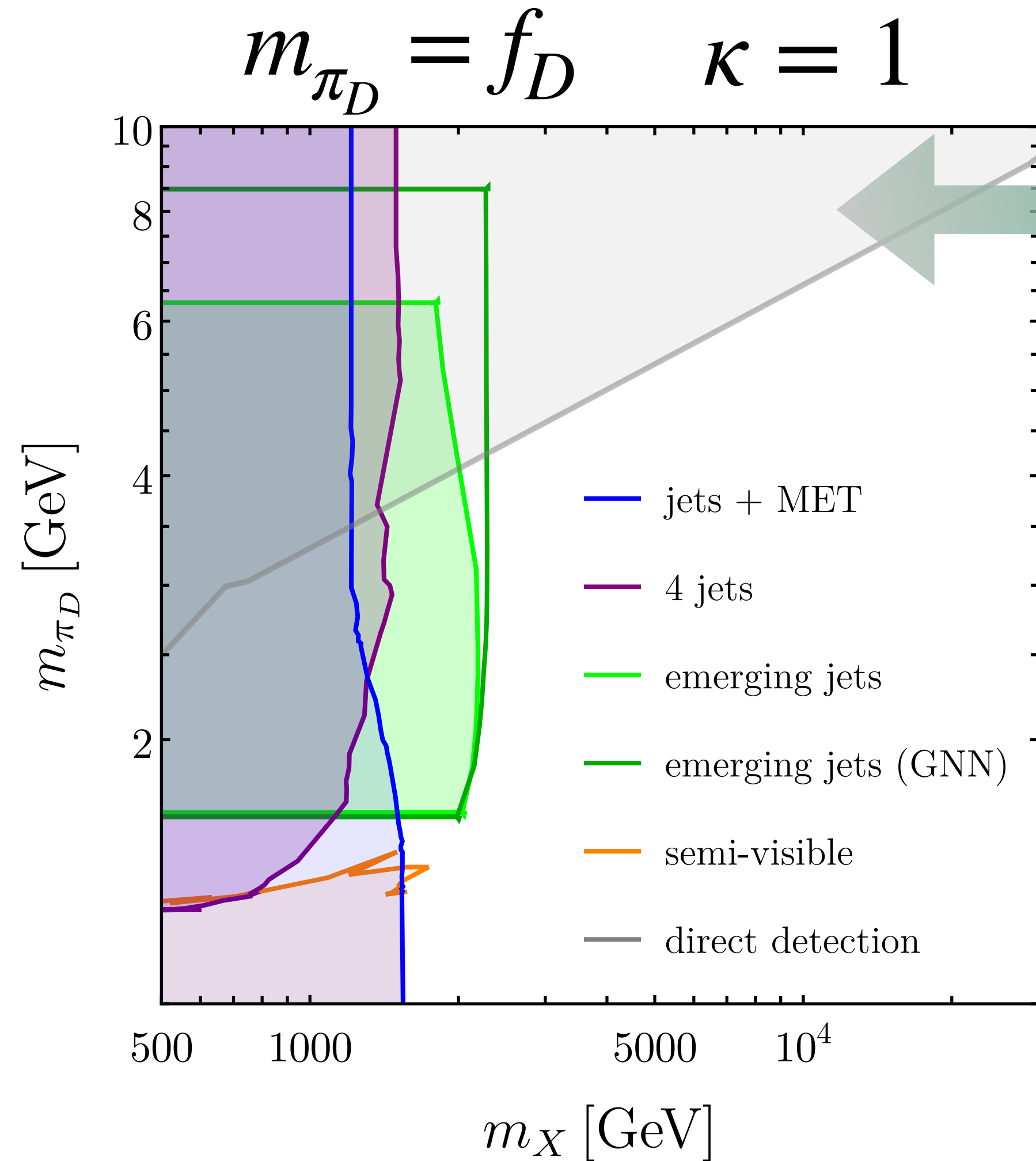
Down type quark



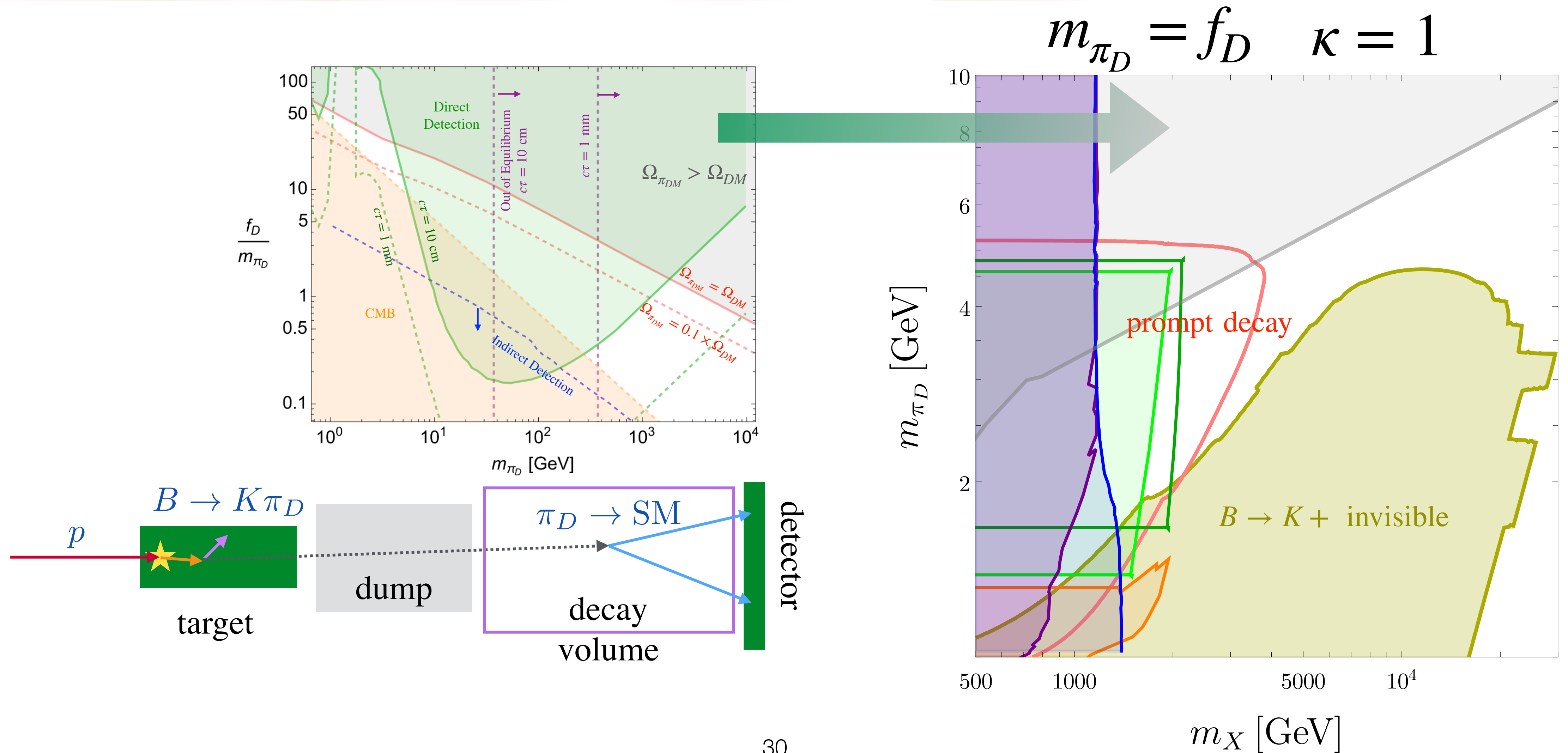
$$m_{\pi_D} = f_D$$

$$m_{\pi_D} = 1 \text{ GeV}$$

# Collider vs. Direct Detection

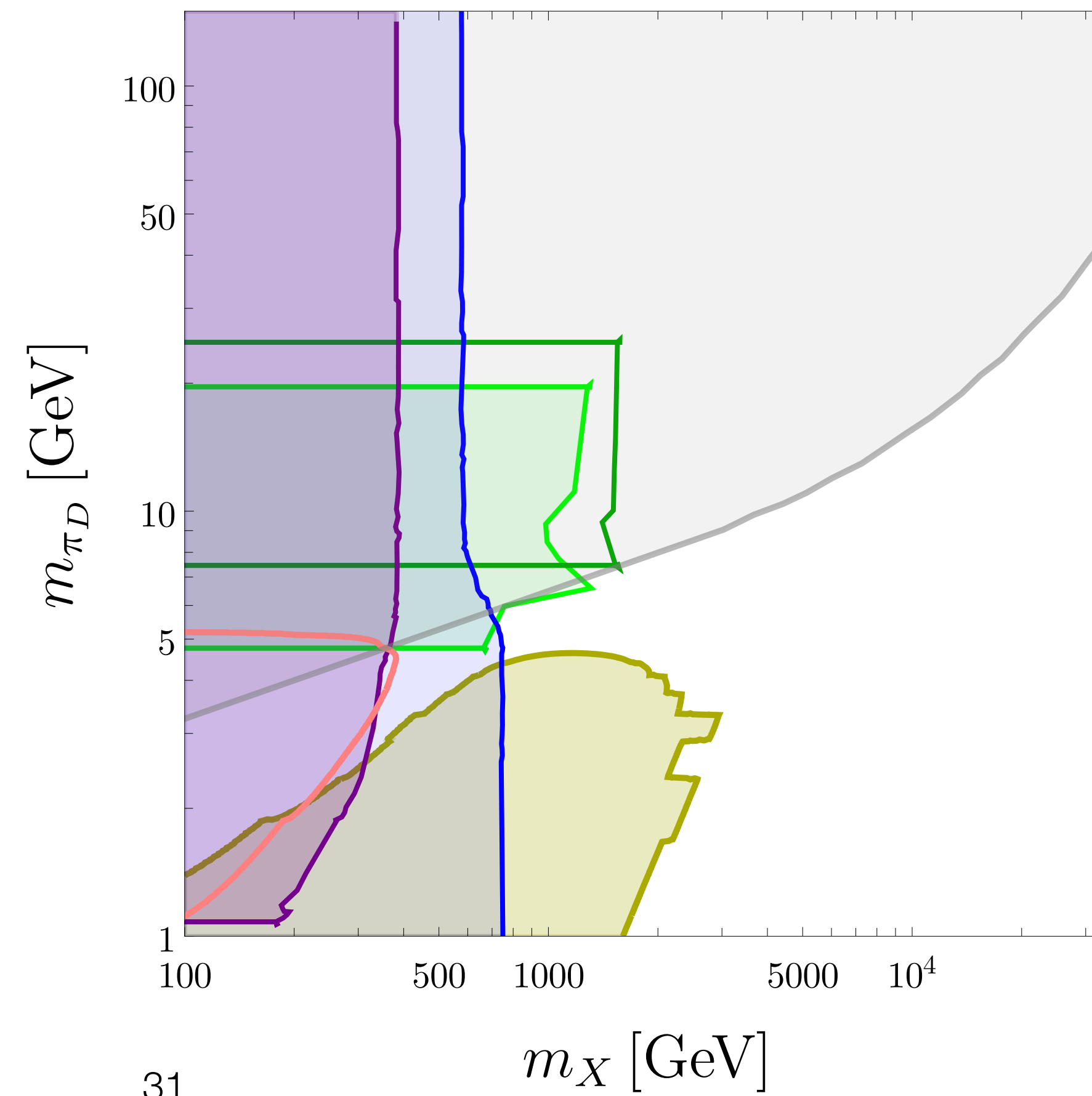
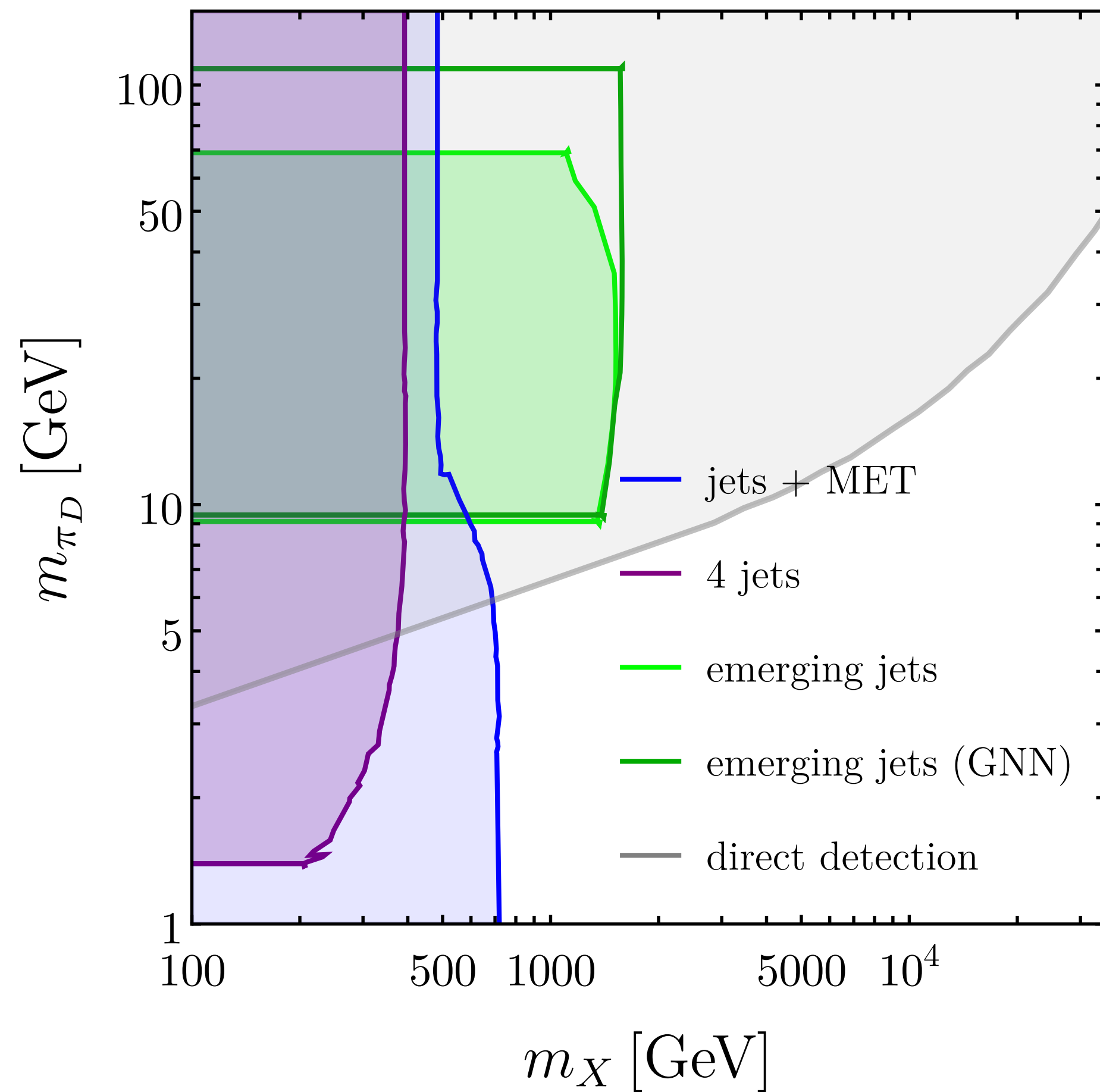


# Collider vs. Direct Detection vs. Flavor



# Terrestrial Constraints

$$m_{\pi_D} = 15 f_D \quad \kappa = 0.1$$



# Summary

---

Sneaky DM is a minimal scenario in dark QCD theories (no need for asymmetry)!

Dark matter annihilation to degenerate transient pions is velocity suppressed.

As a result, indirect detection constraints today are naturally weak, while still allowing the correct relic abundance — this is what makes the scenario ‘sneaky’

Existing constraints motivates a few GeV mass window and macroscopic dark pion life-time.

Semi-visible jets and emerging jets are complementary searches to cover otherwise inaccessible regions of parameter space.

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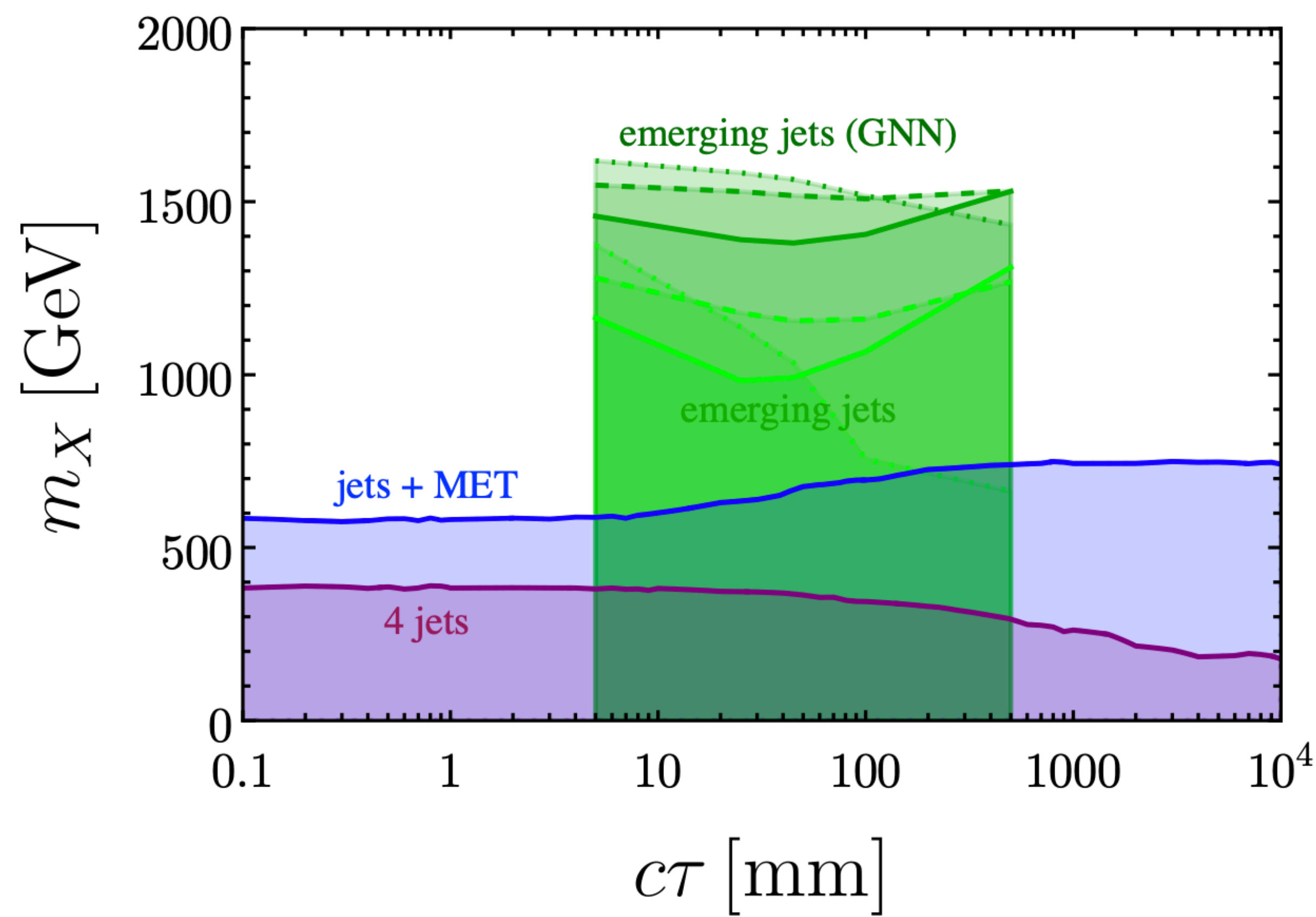
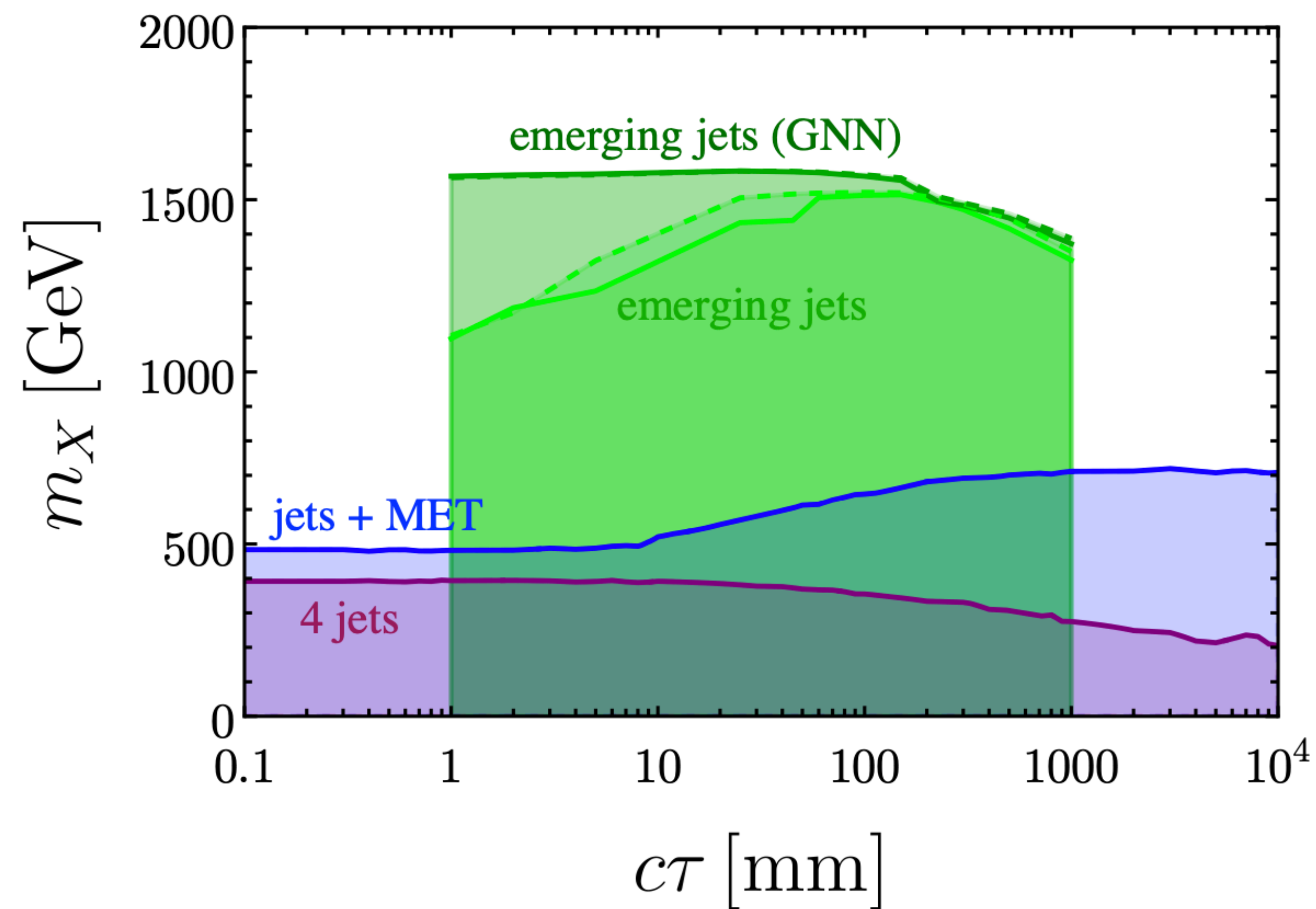
*Thank you for your attention!*

# Back up: change if efficiency w.r.t $\kappa$

Up type quark

$\kappa = 0.1$

Down type quark

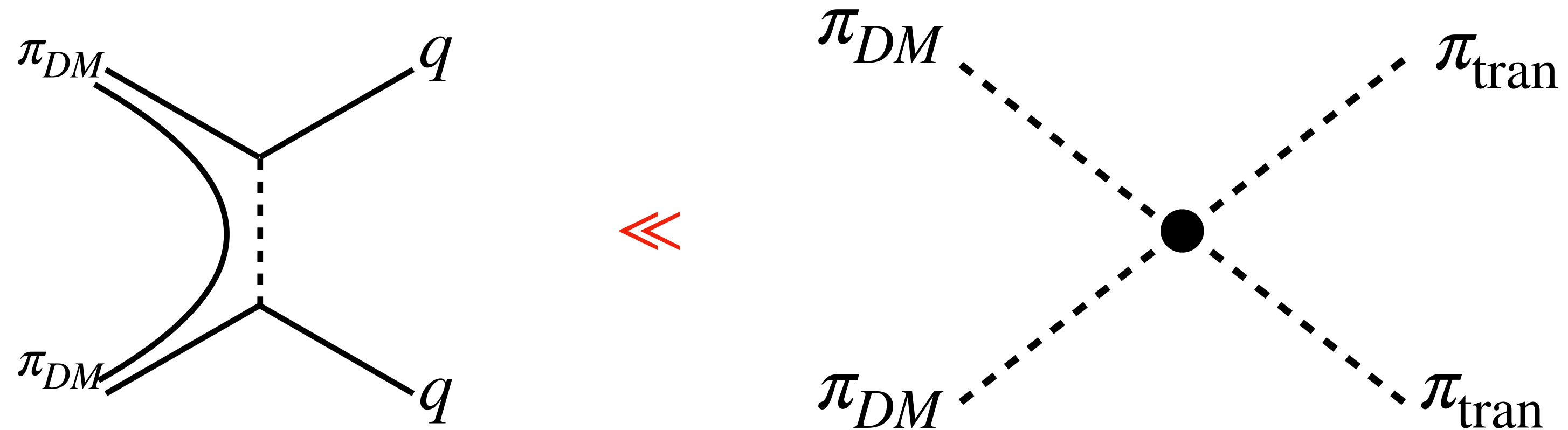


# Back up: details of collider searches

four jets	two jets plus MET	semi-visible
$N_j \geq 4$ with $p_T > 80$ GeV, $ \eta  < 2.5$	$N_{jet} \geq 2$ with $p_T > 30$ GeV, $ \eta  < 2.4$	$N_{jet} \geq 2$ with $p_T > 30$ GeV, $ \eta  < 2.8$
$H_T < 1050$ GeV or $\geq 1$ jet with $p_T > 550$ GeV	$H_T > 300$ GeV in $ \eta  < 2.4$ and $H_T^{miss} > H_T$	$H_T > 600$ GeV and leading jet $p_T > 250$ GeV
	$H_T^{miss} > 300$ GeV in $ \eta  < 5$	$H_T^{miss} > 600$ GeV
	no isolated leptons with $p_T > 10$ GeV	no leptons with $p_T > 7$ GeV
		$\leq 1$ b-jet
	$\Delta\phi(\vec{H}_T^{miss}, j_{1,2}) > 0.5$ and $p_T$ jets $\Delta\phi(\vec{H}_T^{miss}, j_{>2}) > 0.3$	as least one jet with $\Delta\phi(\vec{H}_T^{miss}, j) = 2$
$\Delta R_{1,2} < 2$ , $\Delta\eta < 1.1$ and asymmetry $< 0.1$		

# Back up: another diagram for relic abundance

How does  $\pi_{DM}\pi_{DM} \rightarrow q\bar{q}$  compare with  $\pi_{DM}\pi_{DM} \rightarrow \pi_{tran}\pi_{tran}$ :



$$m_X \sim O(1) \text{ TeV}, \kappa \sim 1$$
$$f_D/m_{\pi_D} \sim 50, m_\pi \sim O(1) \text{ GeV}$$