Beyond $3 \to 2$: towards realistic SIMP dark matter

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Identification of Dark Matter, Zaragoza, 01.06.2026

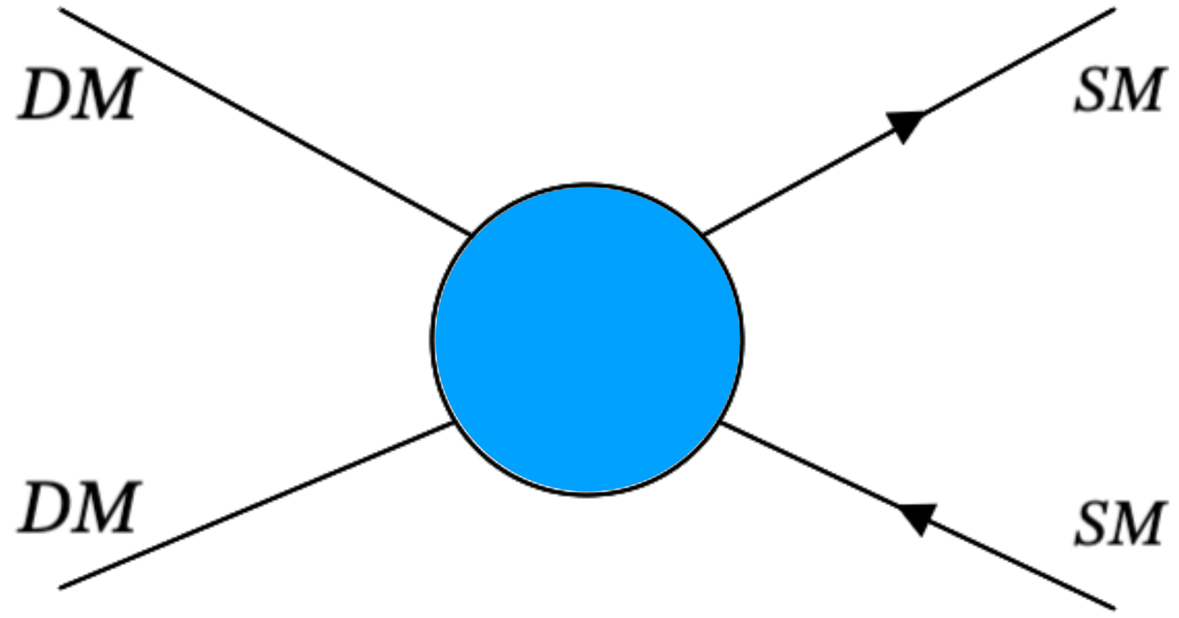
Content

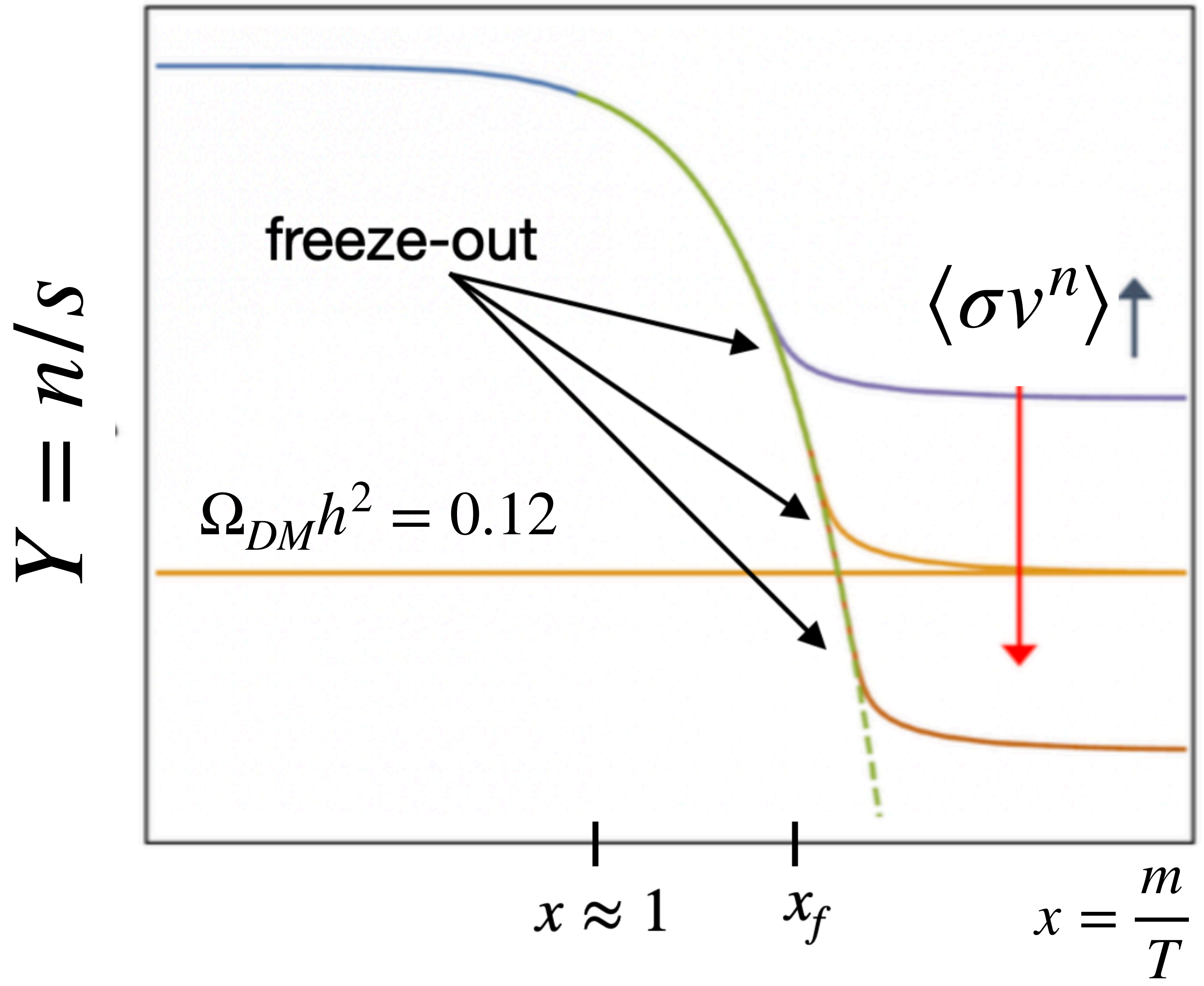
- What are SIMPs?
- Problems with SIMPs
- QCD-like theories
- Hidden Local Symmetry approach to “realistic SIMPs”
- Phenomenology of “realistic SIMPs”

WIMP

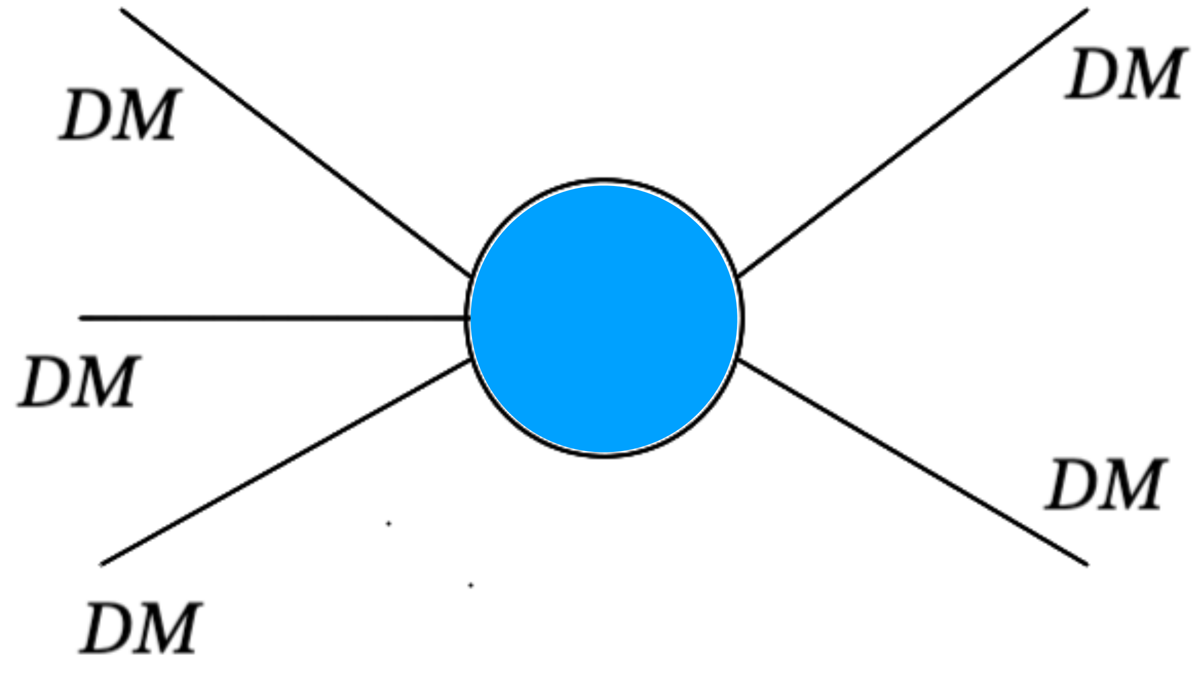
SIMP

$2 \to 2$





$3 \to 2$



$$\Gamma_{2\to 2} \sim n(T_f)\langle \sigma v \rangle \sim H(T_f)$$

$$m_{WIMP} \sim \alpha \sqrt{T_{eq}\, M_P} \overset{\alpha \sim 10^{-2}}{\sim} 100 \text{ GeV}$$

Weak scale mass!

$$\Gamma_{3\to 2} \sim n^2(T_f)\left\langle \sigma v^2 \right\rangle \sim H(T_f)$$

$$m_{SIMP} \sim \alpha (T_{eq}^2\, M_P)^{1/3} \overset{\alpha \sim 1}{\sim} 0.1 \text{ GeV}$$

Sub-GeV DM with strong self-interactions

Adapted from SciPost Phys.Lect.Notes 59 (2022)

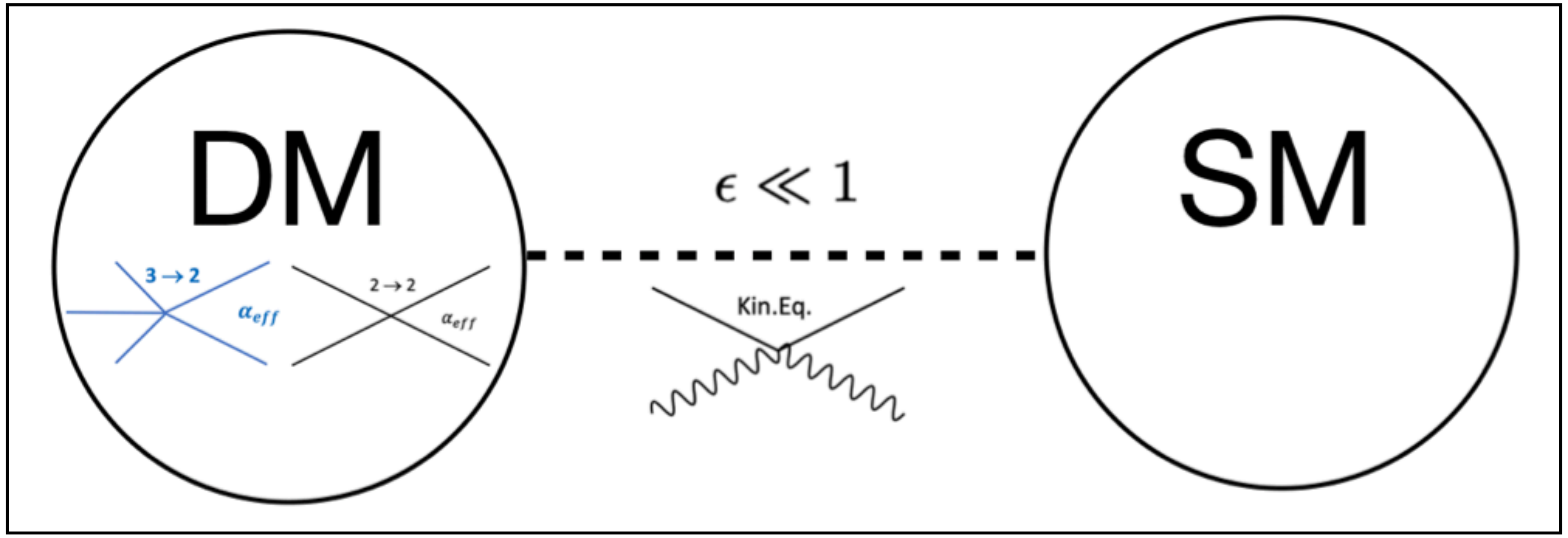
SIMPlest scenario

Dark QCD-like sector provides an appealing realisation of SIMP!

Dark pions have 5-point interactions due to the anomalous WZW term in ChPT:

$$\mathscr{L}_{WZW} \supset \frac{N_c}{240\pi^2 F_\pi^5}\epsilon^{\mu\nu\rho\sigma}\left\langle \pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi\right\rangle \;\Rightarrow\; \text{freeze-out fixes } \frac{M_\pi}{F_\pi}$$

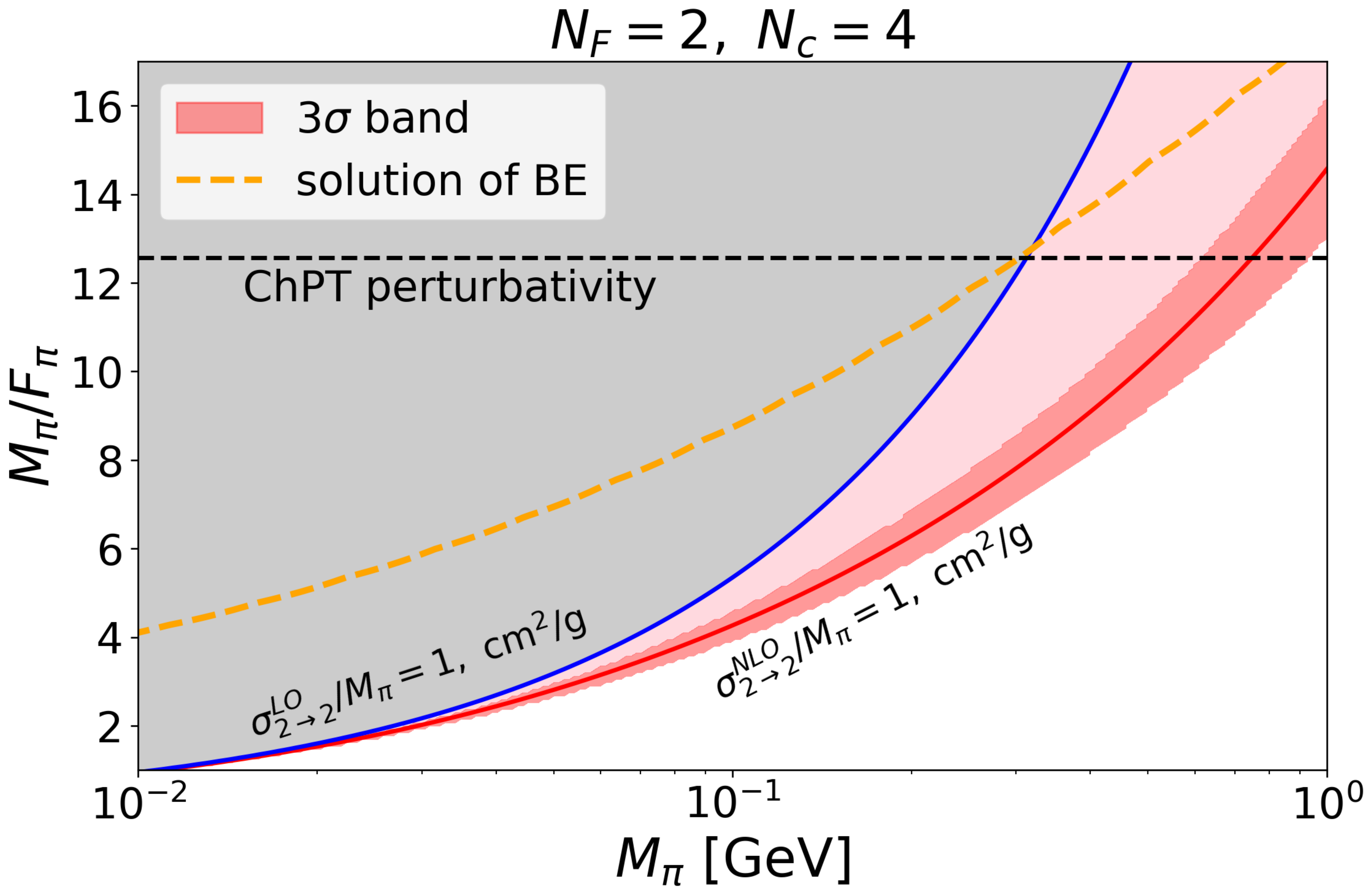
In "real-world" QCD this allows $K^+K^- \to \pi^+\pi^-\pi^0$.



Reproduced from 1402.5143

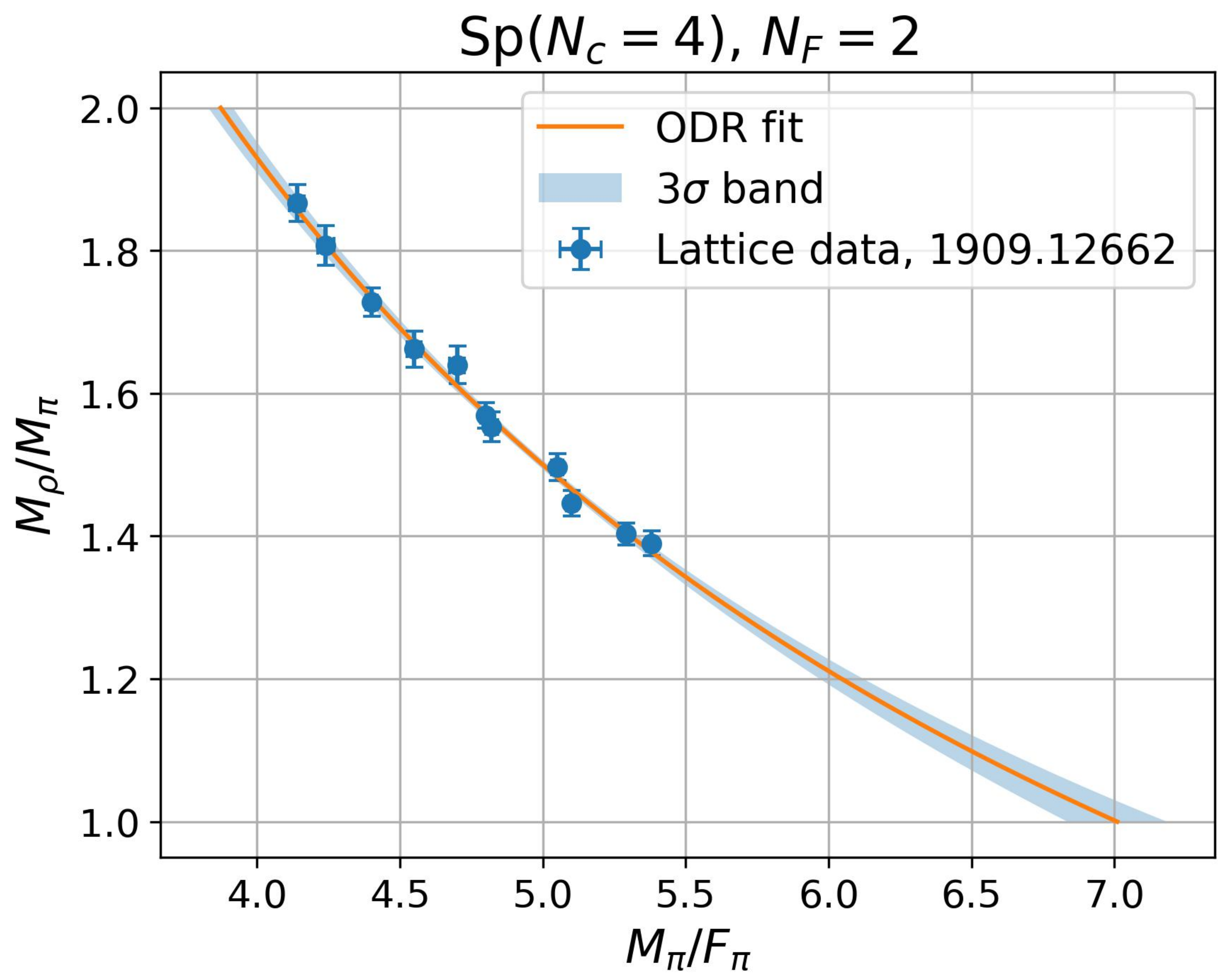
Breakdown of the SIMPlest scenario

NLO correction close the parameter space



Reproduced from Kolešová, Krichevskiy, Kulkarni JHEP 05 (2026) 042

Vector mesons are light for high $\dfrac{M_\pi}{F_\pi}$



QCD - like sectors

$$G \xrightarrow{\langle \bar{q} q \rangle \neq 0} H$$

Representation of the fermions	Complex	Pseudoreal	Real
Example: fundamental of	$SU(N_c)$	$Sp(N_c)$	$O(N_c)$
Chiral symmetry breaking pattern	$SU(N_F) \times SU(N_F)/SU(N_F)$	$SU(2N_F)/Sp(2N_F)$	$SU(2N_F)/SO(2N_F)$
Number of pions	$N_F^2 - 1$	$(2N_F + 1)(N_F - 1)$	$N_F(2N_F + 1) - 1$

Minimal scenario:

$Sp(N_c)$ theory with $N_F = 2$ dark pseudoreal quarks

- anomalous interaction is present
- pions with equal masses at leading order
- lattice data exists, e.g. for $N_c = 4$

$$G = SU(4)$$
$$\downarrow \qquad \Rightarrow N_\pi = 5$$
$$H = Sp(4)$$

Hidden Local Symmetry (HLS)

We have to include the vector mesons!

nonlinear σ - model on manifold G/H

$$\Updownarrow$$

gauge theory with $G_{\text{global}} \times H_{\text{local}}$

Gauge a subgroup to introduce

the external field

e.g. dark photon Z

Vector mesons as gauge bosons

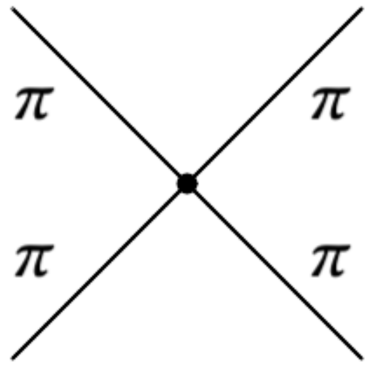
For $H = Sp(4)$, $N_\rho = 10$ fields V_μ^A ("ρ" - mesons)

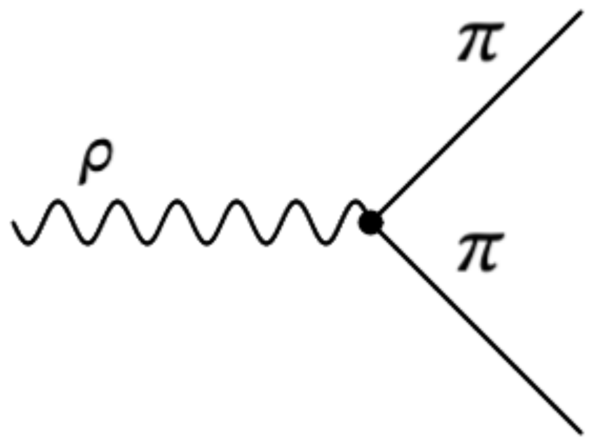
HLS would-be Goldstones are absorbed $\Rightarrow M_\rho \neq 0$

HLS Lagrangian

HLS provides consistent power counting rules for $M_\pi < M_\rho < 4\pi F_\pi$.

LO Lagrangian:





$$
\begin{aligned}
\mathcal{L}_{\mathrm{HLS}}^{\mathrm{IR};(2)} = {} & \beta \langle \bar{X} \rangle + \frac{1}{2}\partial_\mu \pi^a \partial_\mu \pi^a - \frac{2\beta}{f_\pi^2}\pi^a\pi^b \langle \bar{X} T^a T^b \rangle \\
& + \frac{3\alpha_0 - 4}{6 f_\pi^2} k_1^{abcd} \pi^a \pi^b \partial_\mu \pi^c \partial^\mu \pi^d + \frac{2\beta}{3 f_\pi^4} k_2^{abcd} \pi^a \pi^b \pi^c \pi^d \\
& + \frac{\alpha_0 f_\pi^2 g_V^2}{2} V_\mu^A V^{\mu,A} + \frac{\alpha_0 f_\pi^2 e_D^2 q^2}{2} Z_\mu Z^\mu - q e_D g_V \alpha_0 f_\pi^2 V_\mu^{A_Q} Z^\mu \\
& + \frac{g_V \alpha_0}{2} f^{Abc} V_\mu^A \pi^b \partial^\mu \pi^c + e_D \left(1 - \frac{\alpha_0}{2}\right) q f^{A_Q bc} Z_\mu \pi^b \partial^\mu \pi^c \\
& + 2i(\alpha_0 - 1) e_D^2 q^2 f^{A_Q bc} k_3^{ac} Z_\mu Z^\mu \pi^a \pi^b + i q e_D g_V \alpha_0 k_4^{Aab} V_\mu^A Z^\mu \pi^a \pi^b \\
& + \left(2 - \frac{7}{4}\alpha_0\right) \frac{i e_D q}{3 f_\pi^2} k_5^{abcd} Z^\mu \pi^a \pi^b \pi^c \partial_\mu \pi^d \\
& + \frac{i g_V \alpha_0}{12 f_\pi^2} k_6^{Aabcd} V_\mu^A \pi^a \pi^b \pi^c \partial^\mu \pi^d + \mathcal{O}(6\ \text{fields}).
\end{aligned}
$$

Mass mixing between a vector meson and dark photon
$\Rightarrow$ diagonalization is required,

$$\frac{e_D}{g_V} \ll 1$$

dark photon

dark vector meson

dark pions

$$\mathcal{L}_{\mathrm{kin}} \supset -\frac{1}{4} V_{\mu\nu}^A V^{A,\mu\nu} - \frac{1}{4} Z_{\mu\nu} Z^{\mu\nu}$$

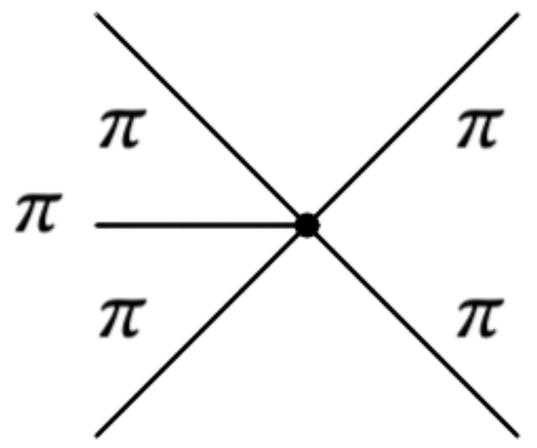
$$\mathcal{L}_{\mathrm{mass}} \supset \frac{M_{Z,\mathrm{UV}}^2}{2} Z_\mu Z^\mu$$

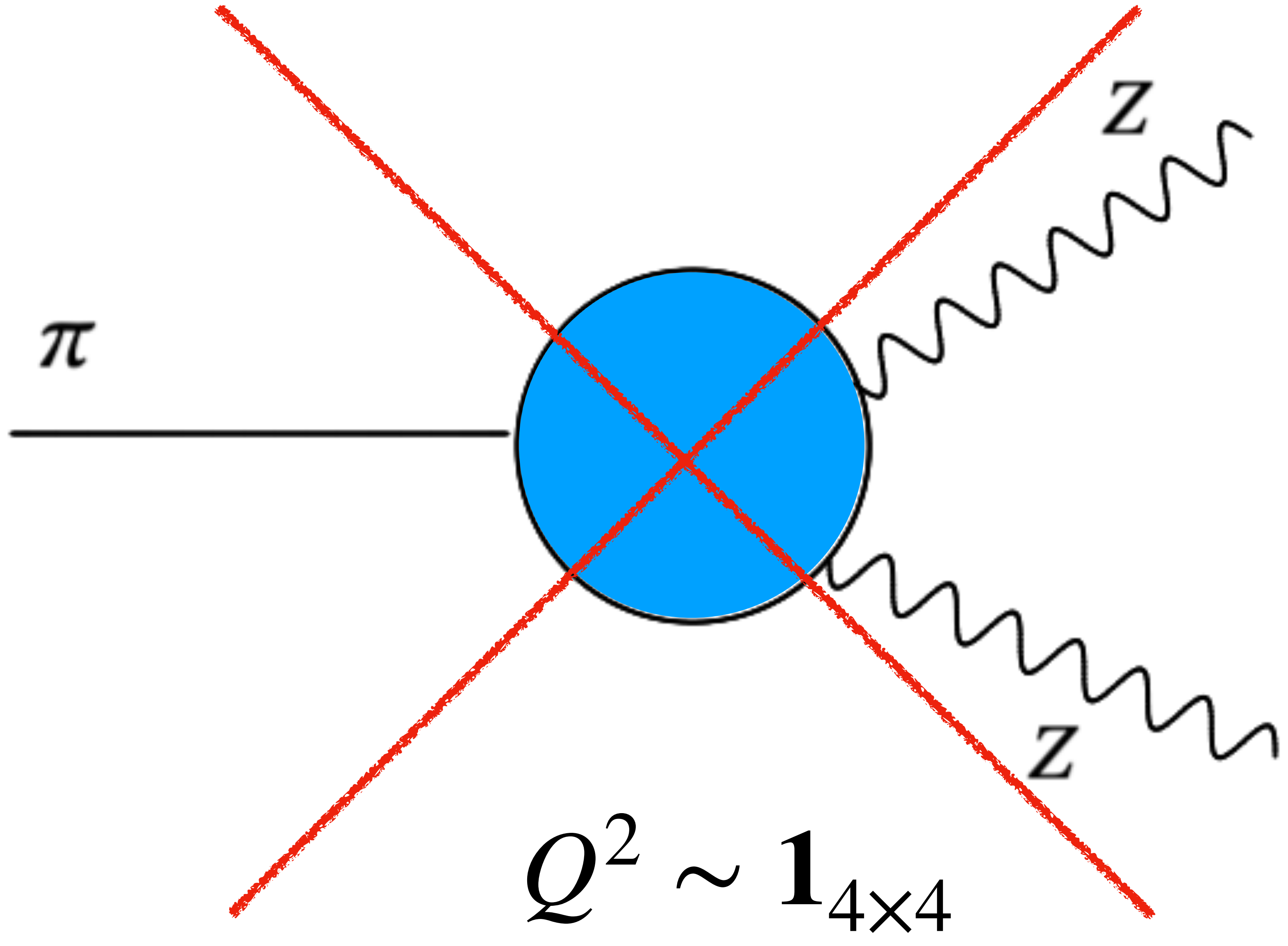
HLS Anomalous Lagrangian

Reproduces the anomalous Ward identities of UV QCD-like theory.

$$
\begin{aligned}
\mathcal{L}^{\mathrm{NLO}}_{V+\pi} = \left(\frac{i d_{\mathcal{R}}}{8\pi^2}\right) \epsilon^{\mu\nu\gamma\delta} \times \\
\Bigg(& \frac{i}{f_\pi^5}\left(-\frac{8}{15} r^{abcde}_{\mathrm{WZW},1} + \frac{\alpha_1}{2} r^{abcde}_{1,1}\right) \pi^a \partial_\mu \pi^b \partial_\nu \pi^c \partial_\gamma \pi^d \partial_\delta \pi^e \\
& + \alpha_3 \frac{g_V}{4 f_\pi^3} r^{Aabc}_{3,2} \mathcal{V}^A_{\mu\nu} \pi^a \partial_\gamma \pi^b \partial_\delta \pi^c \\
& + \alpha_1 \frac{g_V}{f_\pi^3} r^{Aabc}_{1,2} V^A_\mu \partial_\nu \pi^a \partial_\gamma \pi^b \partial_\delta \pi^c \\
& + \alpha_3 \frac{i g_V^2}{2 f_\pi} r^{ABa}_{3,1} \mathcal{V}^A_{\mu\nu} V^B_\gamma \partial_\delta \pi^a \\
& - \alpha_3 i \frac{g_V^2}{12 f_\pi^3} r^{ABabc}_{3,5} \mathcal{V}^A_{\mu\nu} V^B_\gamma \pi^a \pi^b \partial_\delta \pi^c \\
& - i \frac{g_V^2}{2 f_\pi^3} \left(\alpha_2 r^{ABabc}_{2,2} + \alpha_3 r^{ABabc}_{3,4}\right) V^A_\mu V^B_\nu \pi^a \partial_\gamma \pi^b \partial_\delta \pi^c \\
& + (\alpha_2 + \alpha_3) \frac{g_V^3}{f_\pi} r^{ABCa}_{2,1} V^A_\mu V^B_\nu V^C_\gamma \partial_\delta \pi^a \Bigg).
\end{aligned}
$$

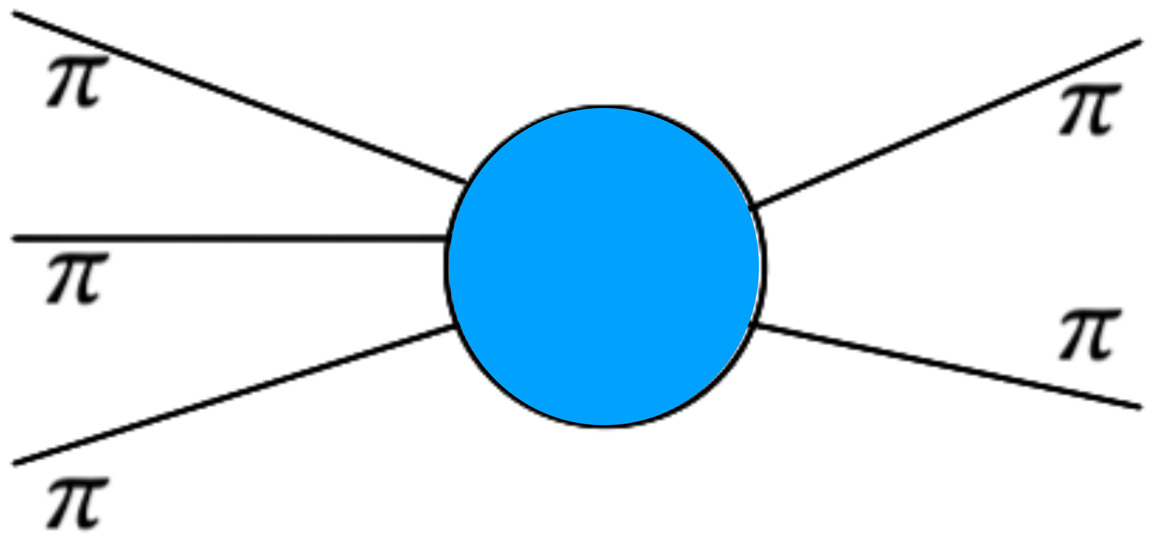
SIMPlest 5-point interaction



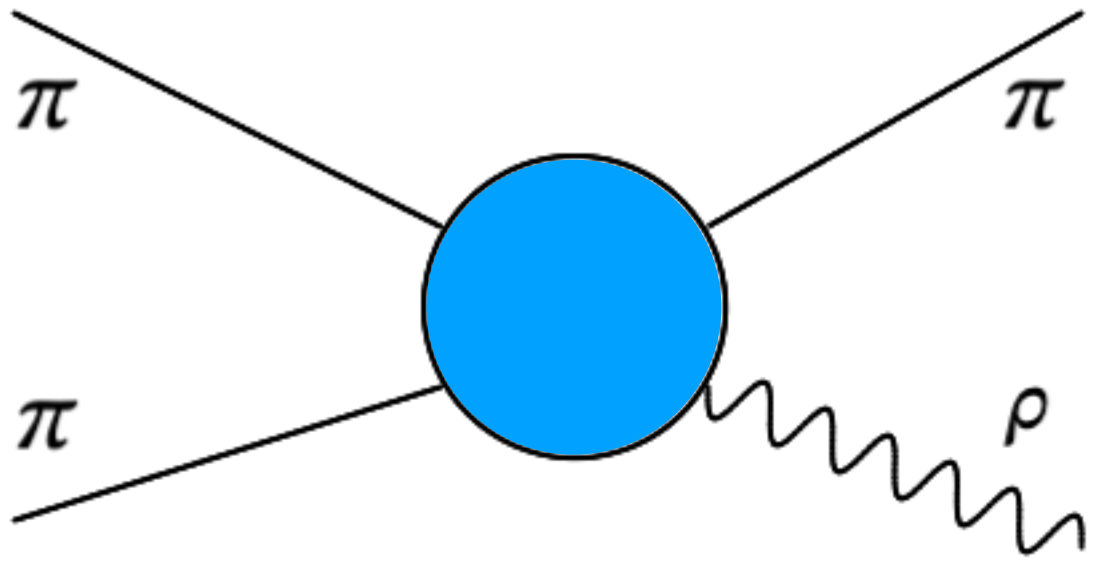


Number changing processes within the dark sector

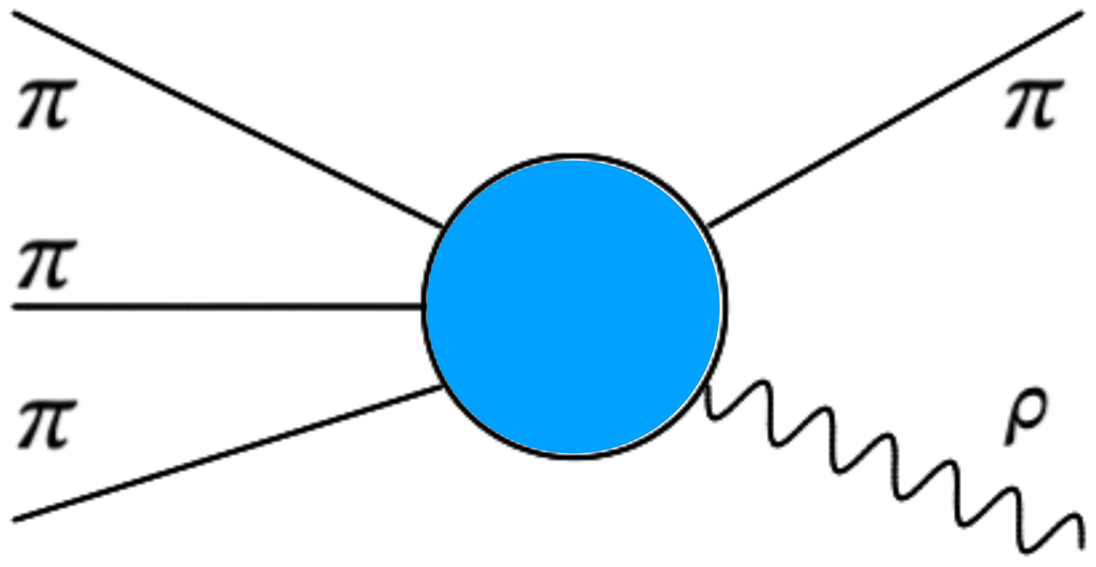
Currently implemented



Hochberg et al, 1411.3727

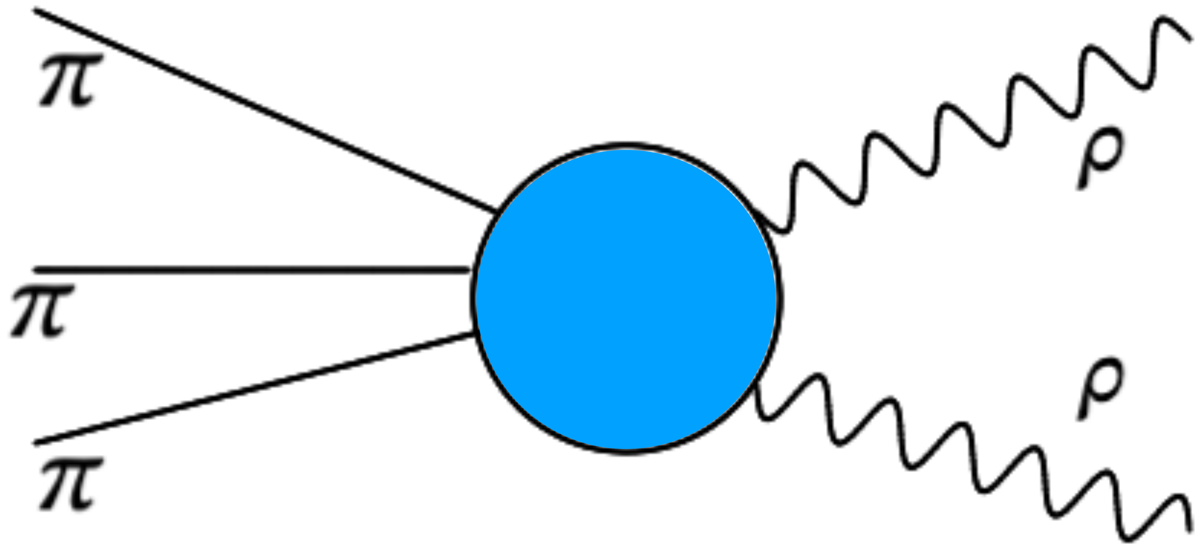


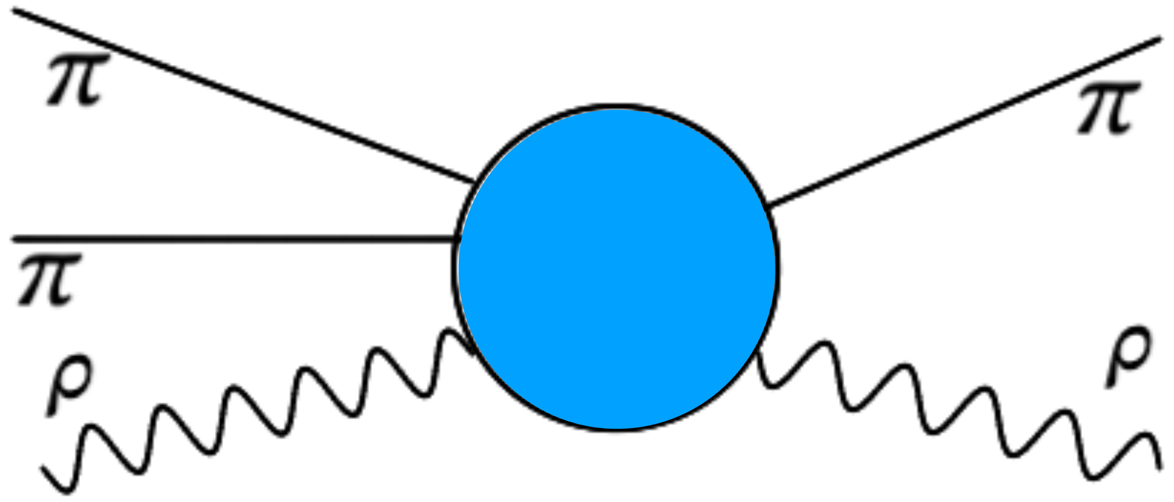
Berlin et al, 1801.05805



Bernreuther et al, 2311.17157

Further processes?





?

Interaction with the visible sector

Kinetic mixing between dark photon and SM photon:

$$\mathscr{L} \supset \frac{\varepsilon}{2} F_{\mu\nu} Z_{\mu\nu} \quad \Rightarrow \quad \mathscr{L} \supset e j^{\mu}_{EM} A_{\mu} - \epsilon e j^{\mu}_{EM} Z_{\mu} + e\epsilon \underbrace{\frac{e_D}{g_V} \frac{M_V^2}{M_{Z,UV}^2 - M_V^2}}_{\text{comes from mass mixing of } Z_\mu \text{ and } V_\mu^{A_Q}} j^{\mu}_{EM} V^{A_Q}_{\mu}$$

SM photon

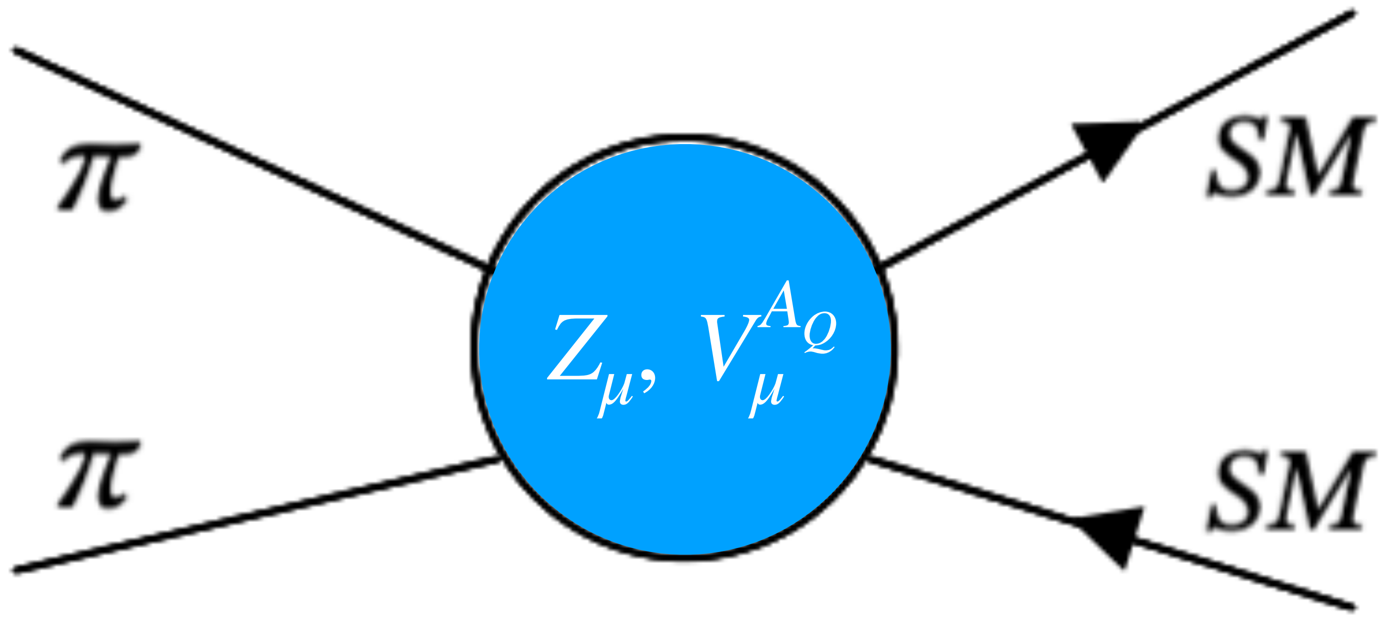
dark photon

SM photon

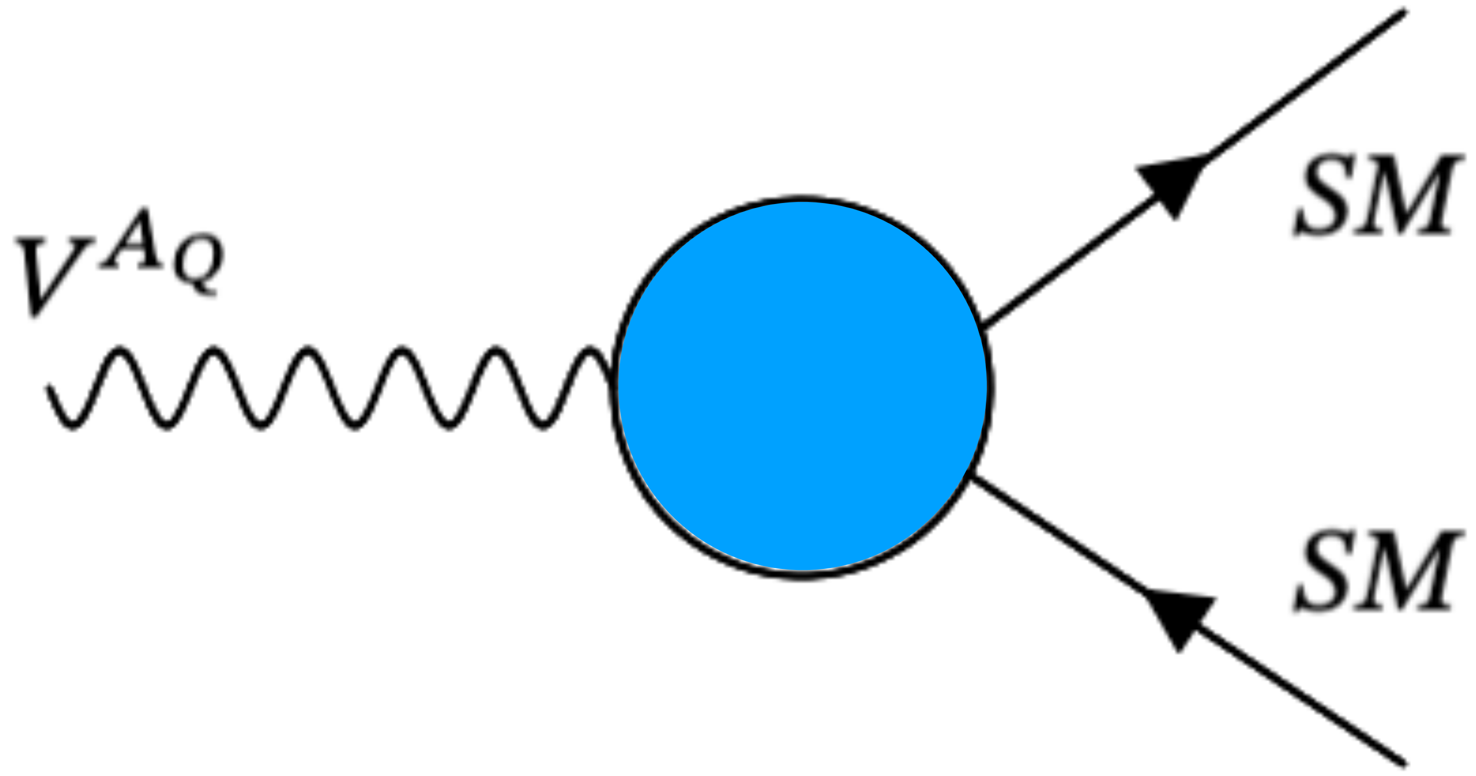
dark photon

comes from mass mixing of Z_μ and $V_\mu^{A_Q}$

dark vector meson



WIMP regime



Boltzmann equations

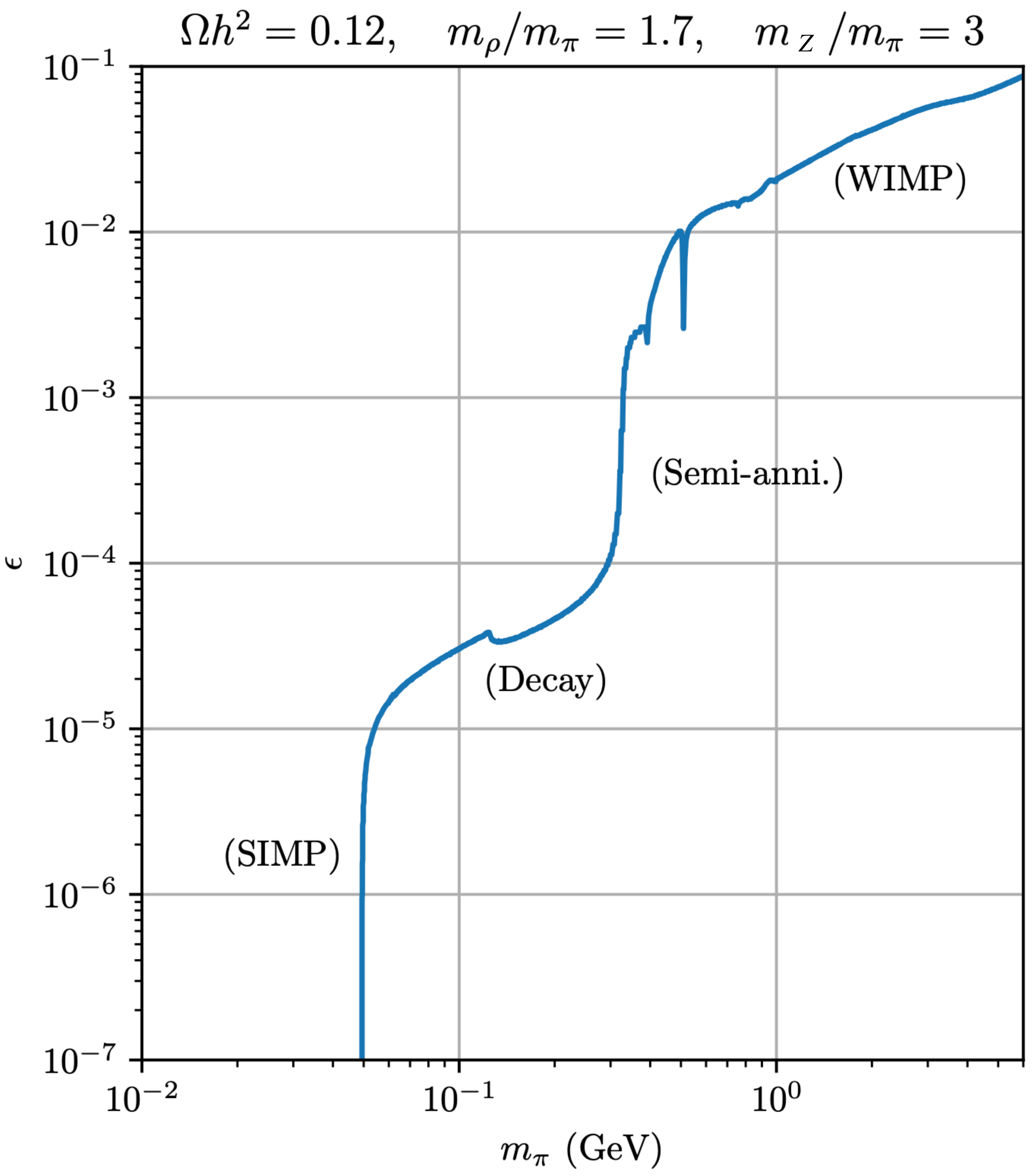
The evolution of total densities: $n_\pi = \sum_{i=1}^{N_\pi=5} n_{\pi_i}, \quad n_\rho = \sum_{i=1}^{N_\rho=10} n_{\rho_i}$

$$\begin{aligned}
&\frac{\mathrm{d}n_\pi}{\mathrm{d}t} + 3Hn_\pi \\
&\quad = -\langle\sigma v(\pi\pi\to \mathrm{SM})\rangle_{\mathrm{eff}}\left(n_\pi^2 - (n_\pi^{\mathrm{eq}})^2\right) \\
&\qquad + \langle\sigma v(\pi\rho\to\pi\pi)\rangle_{\mathrm{eff}}\left(n_\pi n_\rho - n_\pi^2 \frac{n_\rho^{\mathrm{eq}}}{n_\pi^{\mathrm{eq}}}\right) \\
&\qquad - \langle\sigma v^2(3\pi\to 2\pi)\rangle_{\mathrm{eff}}\left(n_\pi^3 - n_\pi^2 n_\pi^{\mathrm{eq}}\right) \\
&\qquad - 2\langle\sigma v^2(3\pi\to \pi\rho)\rangle_{\mathrm{eff}}\left(n_\pi^3 - n_\pi n_\rho \frac{(n_\pi^{\mathrm{eq}})^2}{n_\rho^{\mathrm{eq}}}\right)
\end{aligned}$$

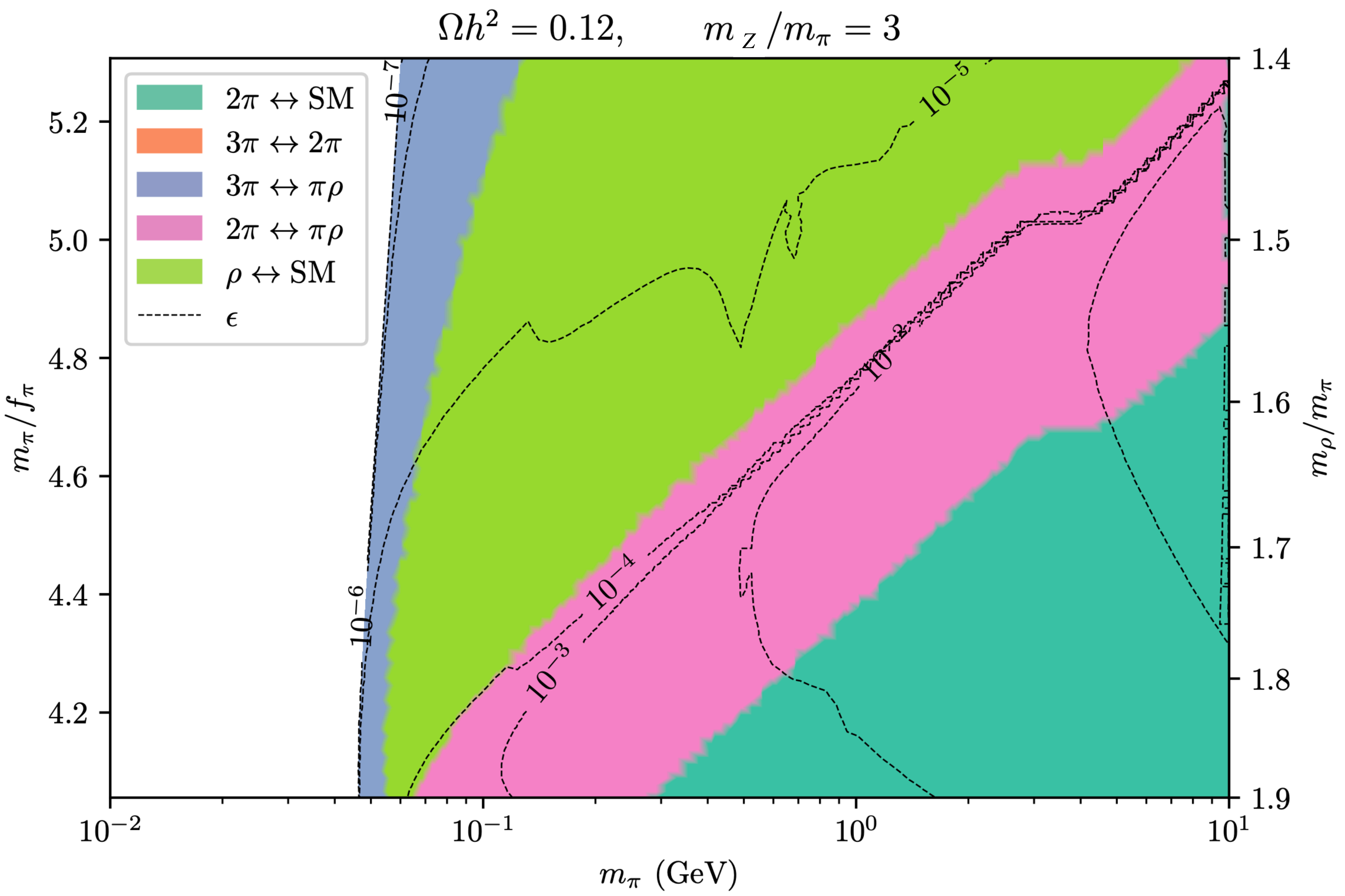
$$\begin{aligned}
&\frac{\mathrm{d}n_\rho}{\mathrm{d}t} + 3Hn_\rho \\
&\quad = -\langle\Gamma(\rho\to \mathrm{SM})\rangle_{\mathrm{eff}}\left(n_\rho - n_\rho^{\mathrm{eq}}\right) \\
&\qquad - \langle\sigma v(\pi\rho\to\pi\pi)\rangle_{\mathrm{eff}}\left(n_\pi n_\rho - n_\pi^2 \frac{n_\rho^{\mathrm{eq}}}{n_\pi^{\mathrm{eq}}}\right) \\
&\qquad + \langle\sigma v^2(3\pi\to \pi\rho)\rangle_{\mathrm{eff}}\left(n_\pi^3 - n_\pi n_\rho \frac{(n_\pi^{\mathrm{eq}})^2}{n_\rho^{\mathrm{eq}}}\right)
\end{aligned}$$

Freeze-out scenarios

- WIMP: $2\pi \leftrightarrow$ SM
- Semi-annihilations to SM:
  - $2\pi \leftrightarrow \pi\rho$ (stops first)
    (decay keeps ρ and SM in equilibrium)
  - Decay: $\rho \leftrightarrow$ SM (stops first)
    (Semi-annihilations keep
    ρ and π in equilibrium)
- SIMP (with ρ): $3\pi \leftrightarrow \pi\rho$

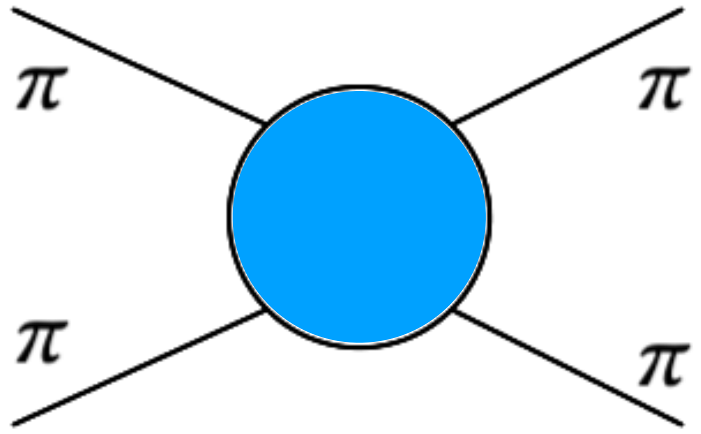


Interactions responsible for freeze-out

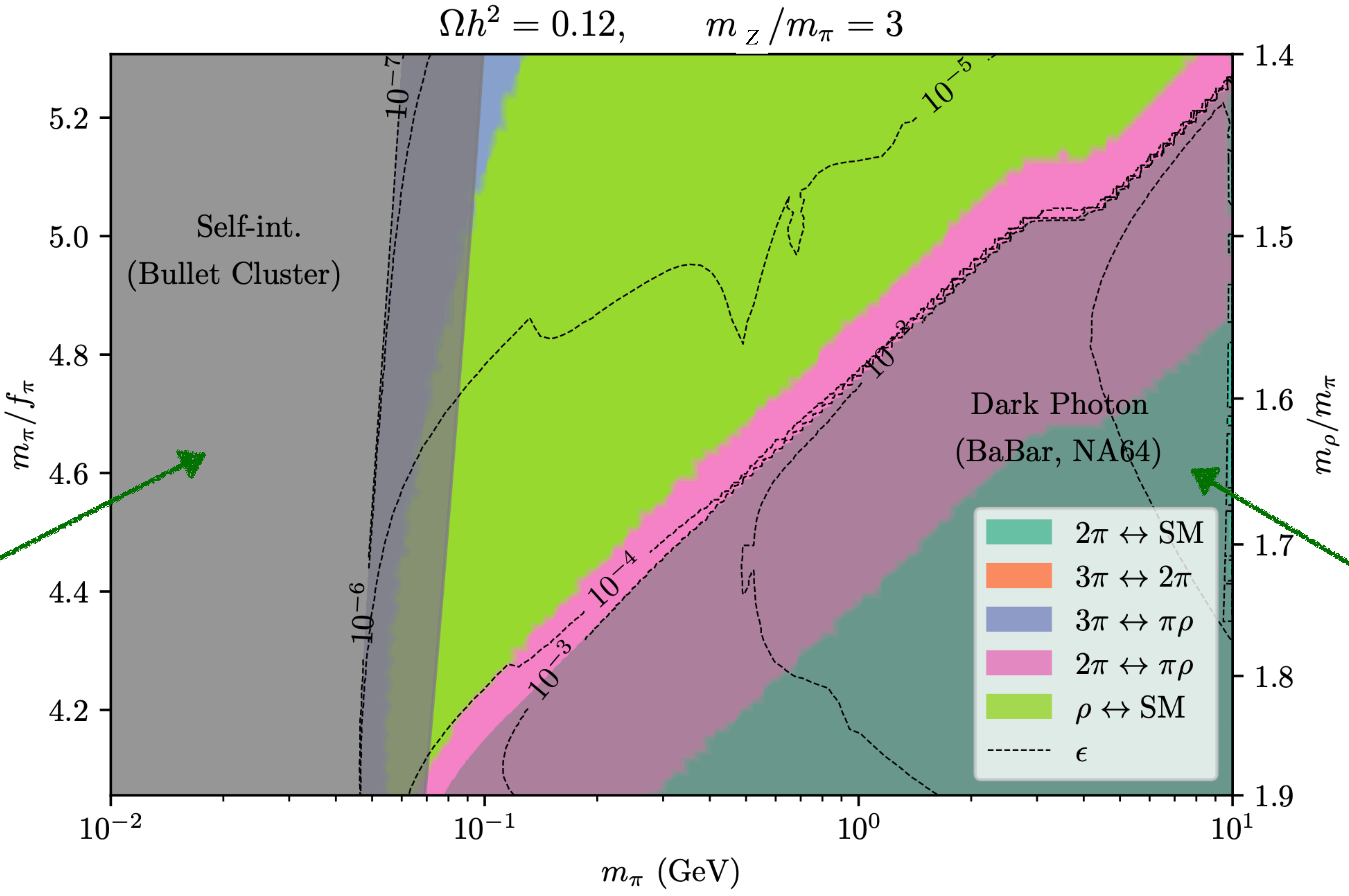


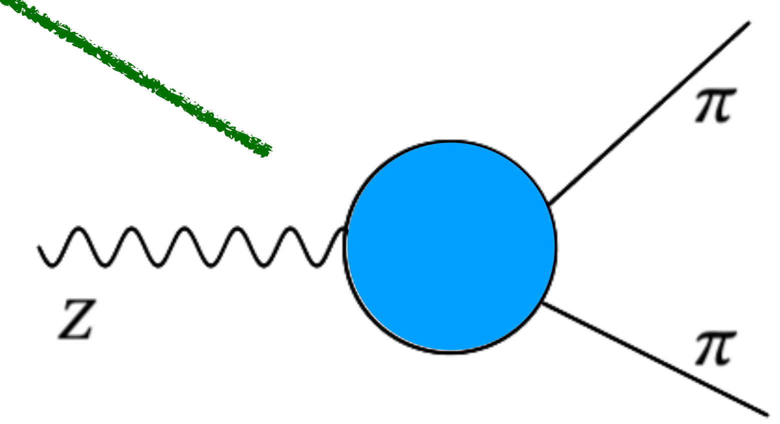
Constraints on freeze-out scenarios

Preliminary



$$\frac{\sigma_{\text{scatter}}}{m_\pi} \lesssim 1\,\text{cm}^2/\text{g}$$





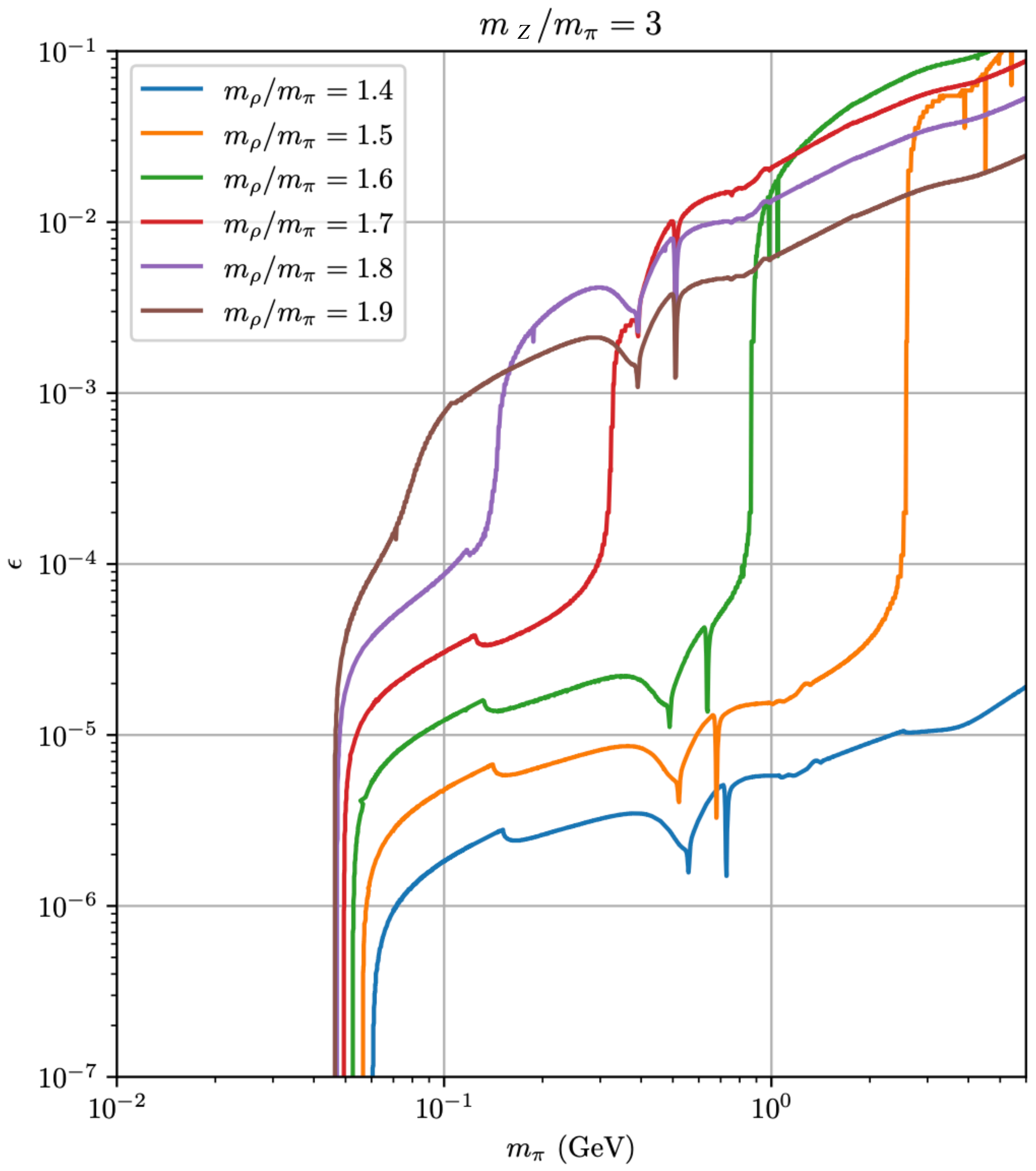
Summary

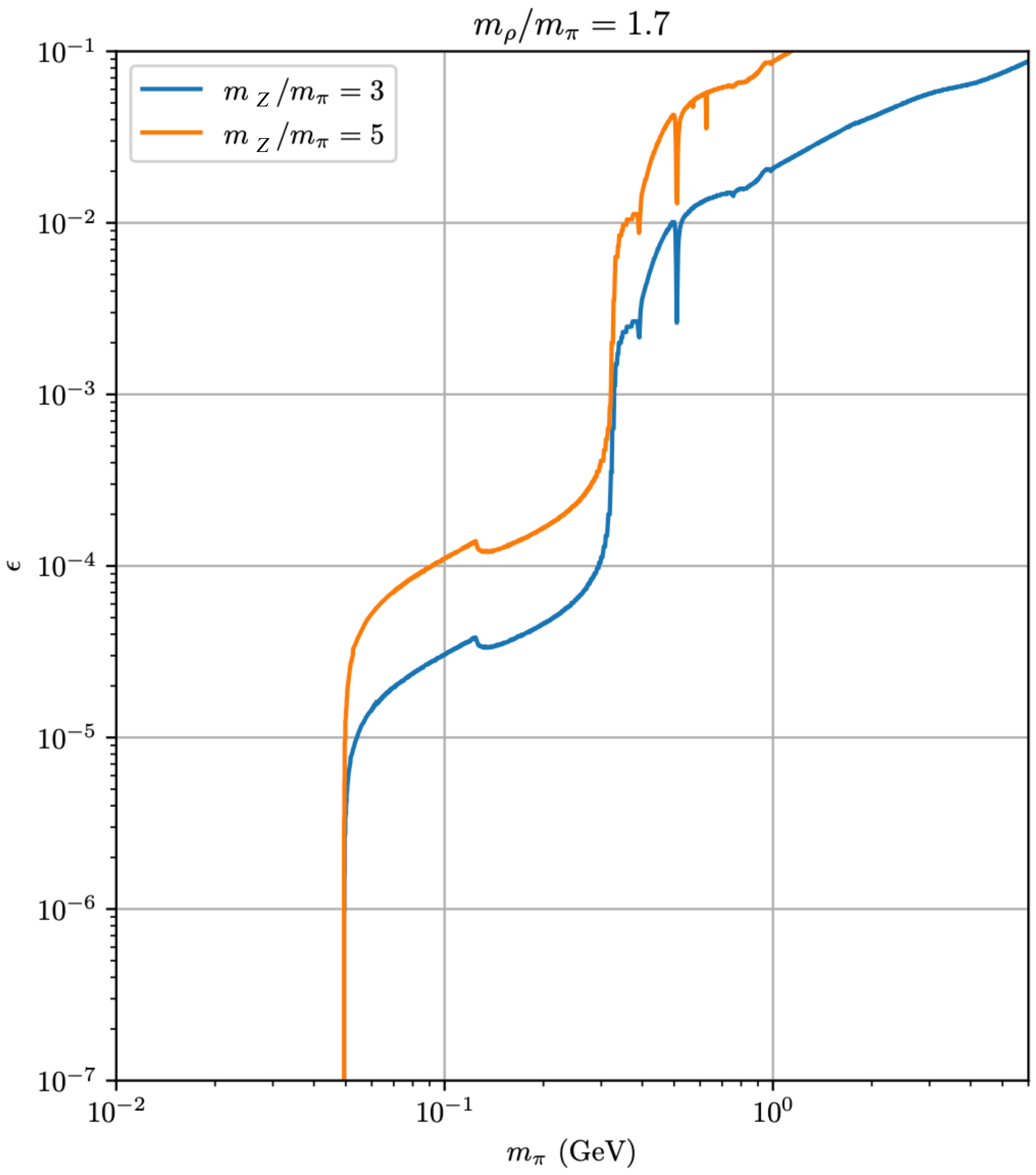
- Realistic dark matter scenarios with QCD-like theories include vector mesons
- HLS theory can be used for a consistent description of dark QCD-like sectors
- QCD-like dark sector have rich phenomenology both in cosmology and beam dump experiments

Thank you for your attention!

Backup

Different freeze-out scenarios





Interactions responsible for freeze-out