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Towards Realistic SIMP Dark Matter

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Outline

- What are SIMPs?
- SIMP models with vector mesons
- Towards realistic SIMP Dark Matter

Team

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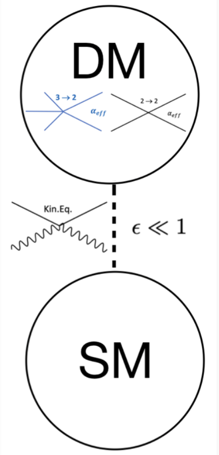
Strongly Interacting Massive Particles (SIMP)

Idea:

- Number changing processes in the Dark Sector
- $3 \longrightarrow 2$ process fix relic abundance of DM

Consequences:

- SIMP Miracle
  - Strong coupling
  - Sub-GeV Dark Matter
- Small coupling to Standard Model
- Sizable self-interactions



Hochberg et al. [1402.5143]

QCD-like SIMP Models

Underlying confining interaction

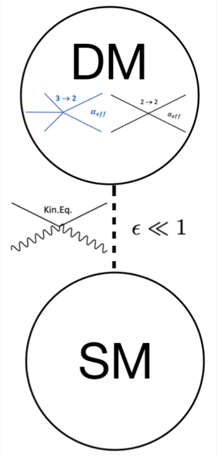
- E.g., $SU(N)$, $Sp(N)$, $SO(N)$

Spontaneously broken flavour symmetry

Stable pNGB $\longrightarrow$ Dark pions

Wess-Zumino-Witten term $\Longrightarrow 3\pi \longrightarrow 2\pi$

Hochberg et al. [1411.3727]



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Relic abundance for SIMPlest model

Wess-Zumino-Witten term:

$$\langle \sigma v^2 \rangle \propto \left(\frac{m_\pi}{f_\pi}\right)^{10} \frac{1}{m_\pi^5}$$

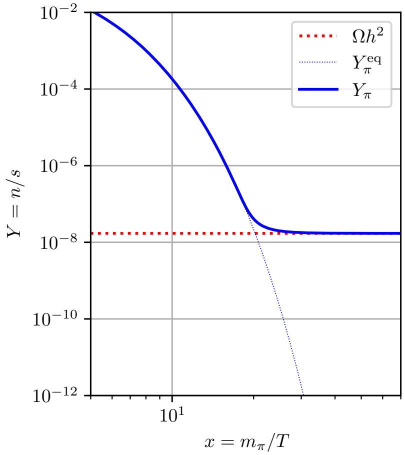
Boltzmann equation:

$$\frac{\mathrm{d}n}{\mathrm{d}t} + 3Hn = -\langle \sigma v^2 \rangle (n^3 - n_{\mathrm{eq}} n^2)$$

Freeze-out condition:

$$\langle \sigma v^2 \rangle n_{\mathrm{eq}}^2 \sim H$$

Hochberg et al. [1411.3727]



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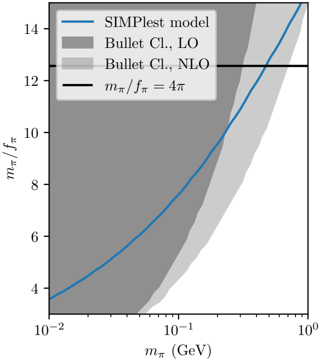
Limitations of SIMPlest model

Perturbativity bound:

$$\frac{m_\pi}{f_\pi} \lesssim 4\pi$$

NLO corrections closes parameter space Hansen et al. [1507.01590]

Vector mesons should NOT be ignored [1801.07726, 1801.05805, 2311.17157]



Kolesova, Krichevskiy, Kulkarni [to appear]

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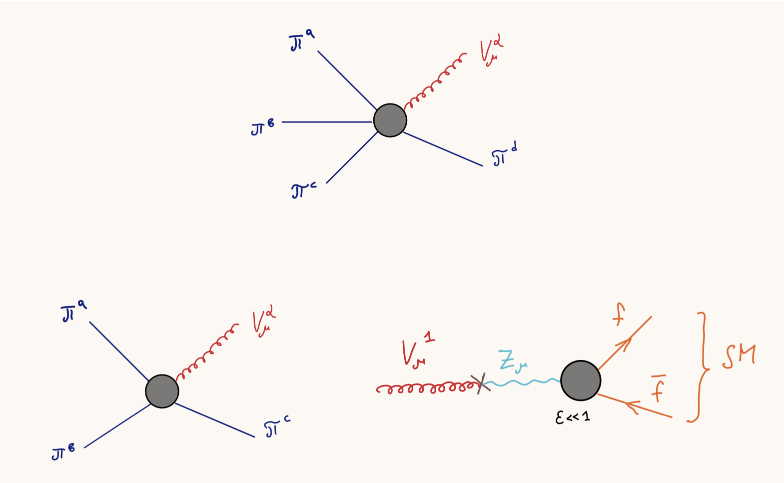
Freeze-out with vector mesons



Freeze-out with vector mesons

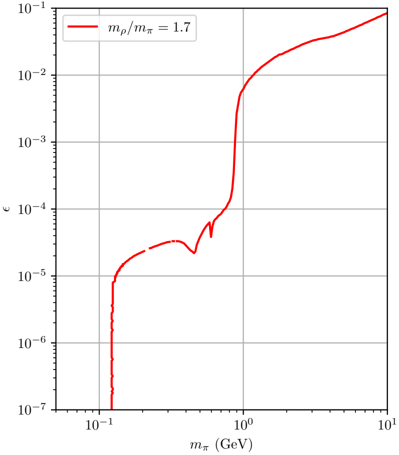
A) WIMP: $2\pi \leftrightarrow \mathrm{SM}$

B) Semi-annihilation: $2\pi \leftrightarrow \pi\rho$
Decay keeps ρ in equil. with SM.

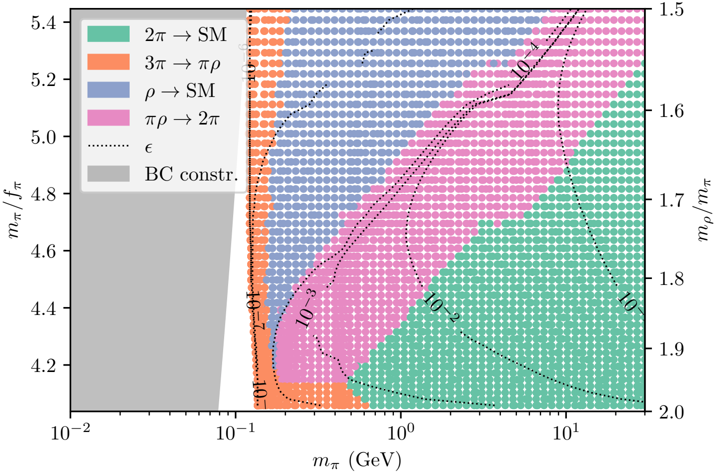
C) Decay: $\rho \leftrightarrow \mathrm{SM}$
Semi-annih. keeps ρ and π in equil.

D) SIMP with ρ: $3\pi \leftrightarrow \pi\rho$

Combining [1801.05805, 2311.17157]



Freeze-out with vector mesons



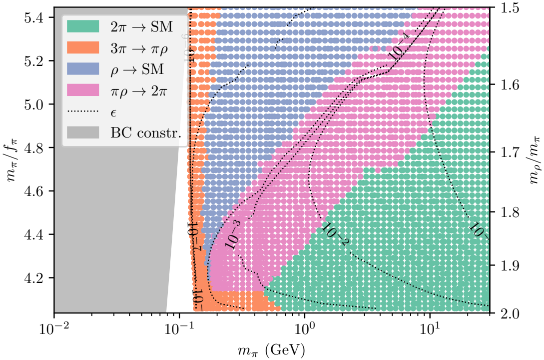
Constraints

Bullet cluster limits self-coupling:

$$\frac{\sigma(2\pi \to 2\pi)}{m_\pi} \lesssim 2\,\frac{\mathrm{cm}^2}{\mathrm{g}}$$

Dark photon $\to$ Upper limit on ϵ

Thermalisation $\to$ Lower limit on ϵ



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Towards realistic SIMP

SIMP models

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	$N_F^2 - 1$	$(2N_F + 1)(N_F - 1)$	$N_F(2N_F + 1) - 1$

Towards realistic SIMPs

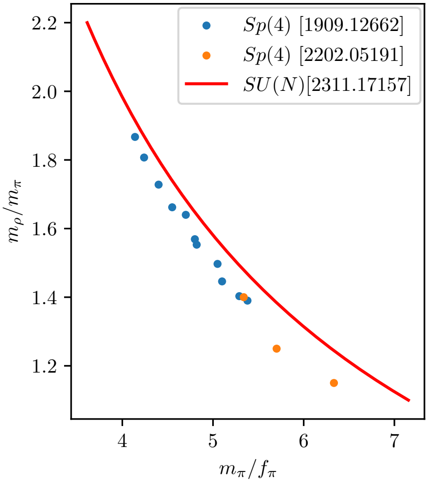
Consider scenario with stable pions

- $Sp(N)$

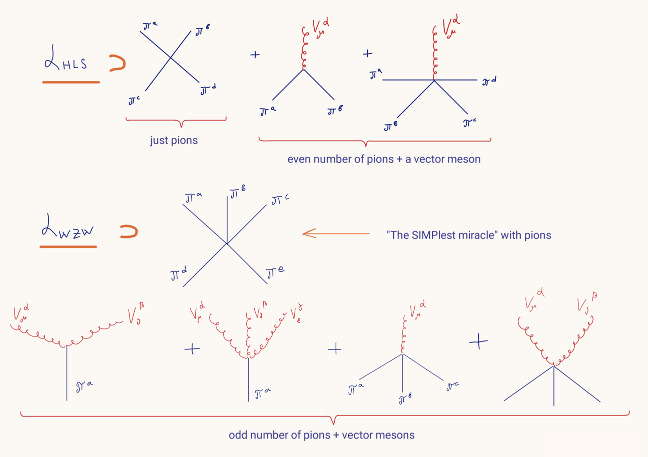
Use recent lattice data for m_ρ/m_π

Consistent treatment of vector mesons

- Hidden Local Symmetry



Hidden Local Symmetry Lagrangian

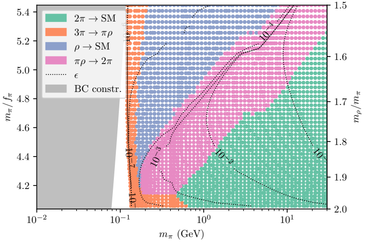


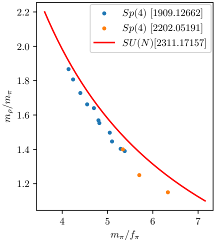
Credit: Pomper, Krichevskiy

Summary

1. Relic abundance can be fixed by Dark Sector interactions
2. Lattice results $\longrightarrow$ Realistic models

Work in progress!





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Thank you for the attention!

Backup

HLS Lagrangian

$$
\begin{aligned}
\mathcal{L}_{\mathrm{HLS}}^{\mathrm{IR};(2)} = & -2\beta\left(m_u+m_d\right)+\frac{1}{2}\partial_\mu\pi^a\partial_\mu\pi^a-\frac{2\beta}{f_\pi^2}\pi^a\pi^b\left\langle\bar{X}T^aT^b\right\rangle \\
& +\frac{3\alpha_0-4}{6f_\pi^2}\pi^a\pi^b\partial_\mu\pi^c\partial^\mu\pi^d\left\langle T^a\left[T^b,T^c\right]T^d\right\rangle+\frac{2\beta}{3f_\pi^4}\pi^a\pi^b\pi^c\pi^d\left\langle\bar{X}T^aT^bT^cT^d\right\rangle \\
& +\frac{\alpha_0f_\pi^2g_V^2}{2}V_\mu^\alpha V^{\mu,\alpha}+\frac{\alpha_0f_\pi^2e_D^2q^2}{2}Z_\mu Z^\mu-qe_Dg_V\alpha_0f_\pi^2Z^\mu V_\mu^1 \\
& -\frac{g_V\alpha_0}{2}f^{\alpha bc}V_\mu^\alpha\partial^\mu\pi^b\pi^c+e_D\left(\frac{\alpha_0}{2}-1\right)qf^{\hat{1}bc}Z_\mu\partial^\mu\pi^b\pi^c \\
& +\frac{1-\alpha_0}{2\sqrt{2}}e_D^2q^2f^{\hat{1}bc}Z_\mu Z^\mu\pi^a\pi^b\left(\delta_{a,5}\delta_{c,4}-\delta_{c,5}\delta_{a,4}\right) \\
& +iqe_Dg_V\alpha_0\pi^a\pi^bV_\mu^\alpha Z^\mu\left(-f^{\hat{1}bc}\left\langle X^\alpha T^aT^c\right\rangle+f^{\hat{1}ac}\left\langle X^\alpha T^cT^b\right\rangle\right) \\
& +\left(2-\frac{7}{4}\alpha_0\right)\frac{ie_Dq}{3f_\pi^2}Z^\mu\pi^a\pi^b\pi^c\partial_\mu\pi^d\left\langle\left(3T^a\left[T^d,T^c\right]T^b+\left[T^aT^bT^c,T^d\right]\right)X^1\right\rangle \\
& +\frac{ig_V\alpha_0}{12f_\pi^2}V_\mu^\alpha\pi^a\pi^b\pi^c\partial^\mu\pi^d\left\langle\left(3T^a\left[T^d,T^c\right]T^b+\left[T^cT^aT^b,T^d\right]\right)X^\alpha\right\rangle+\mathcal{O}(6\text{ fields}),
\end{aligned}
$$

NLO Lagrangian

$$
\begin{aligned}
\mathcal{L}^{\rm NLO} = \frac{id_{\mathcal{R}}}{8\pi^2}\varepsilon^{\mu\nu\gamma\delta}\Bigg[& ie_D\frac{\alpha_1}{f_\pi^3} r_7^{abc} Z_\mu \partial_\nu\pi^a\partial_\gamma\pi^b\partial_\delta\pi^c + ig_V\frac{\alpha_1}{f_\pi^3} r_6^{\alpha abc} V_\mu^\alpha \partial_\nu\pi^a\partial_\gamma\pi^b\partial_\delta\pi^c \\
& - ie_D g_V^2 \frac{1}{f_\pi}\left(\alpha_2 r_9^{\alpha\beta a} + \alpha_3 r_{22}^{\alpha\beta a}\right) V_\mu^\alpha V_\nu^\beta Z_\gamma \partial_\delta\pi^a - ig_V^3\frac{1}{f_\pi}\left(\alpha_2 r_{10}^{\alpha\beta\omega a}+\alpha_3 r_{23}^{\alpha\beta\omega a}\right) V_\mu^\alpha V_\nu^\beta V_\gamma^\omega \partial_\delta\pi^a \\
& + e_D g_V \frac{\alpha_3 r_{14}^{\alpha a}}{2f_\pi}\bar V_{\mu\nu}^{\ \ \alpha} Z_\gamma\partial_\delta\pi^a + g_V^2\frac{\alpha_3 r_{15}^{\alpha\beta a}}{2f_\pi}\bar V_{\mu\nu}^{\ \ \alpha} V_\gamma^\beta \partial_\delta\pi^a + e_D g_V \frac{\alpha_4 r_{26}^{\alpha a}}{2f_\pi} V_\mu^\alpha Z_{\nu\gamma}\partial_\delta\pi^a \\
& - \frac{1}{f_\pi^5}\left(-\frac{8}{15} r_1^{abcde} + \frac{\alpha_1}{2} r_5^{abcde}\right) \pi^a\partial_\mu\pi^b\partial_\nu\pi^c\partial_\gamma\pi^d\partial_\delta\pi^e + ie_D\frac{1}{f_\pi^3}\left(-\frac{2}{9} r_4^{abc} + \frac{\alpha_4}{4} r_{30}^{abc}\right) Z_{\mu\nu}\pi^a\partial_\gamma\pi^b\partial_\delta\pi^c \\
& + e_D g_V \frac{1}{f_\pi^3}\left(\alpha_1 r_8^{\alpha abc} + \frac{\alpha_2}{2} r_{13}^{\alpha abc}\right) V_\mu^\alpha Z_\nu \pi^a\partial_\gamma\pi^b\partial_\delta\pi^c + g_V^2\frac{1}{f_\pi^3}\left(\frac{\alpha_2}{2} r_{12}^{\alpha\beta abc} + \frac{\alpha_3}{2} r_{25}^{\alpha\beta abc}\right) V_\mu^\alpha V_\nu^\beta \pi^a\partial_\gamma\pi^b\partial_\delta\pi^c \\
& - e_D g_V^3 \frac{1}{f_\pi}\left(\alpha_2 r_{11}^{\alpha\beta\omega a} + \alpha_3 r_{24}^{\alpha\beta\omega a}\right) V_\mu^\alpha V_\nu^\beta V_\gamma^\omega A_\delta \pi^a + ig_V\frac{\alpha_3}{4f_\pi^3} r_{19}^{\alpha abc}\bar V_{\mu\nu}^{\ \ \alpha}\pi^a\partial_\gamma\pi^b\partial_\delta\pi^c \\
& - ie_D g_V^2 \frac{\alpha_3}{2f_\pi} r_{16}^{\alpha\beta a}\bar V_{\mu\nu}^{\ \ \alpha} V_\gamma^\beta A_\delta\pi^a - ie_D^2 g_V\frac{\alpha_4}{2f_\pi} r_{27}^{\alpha a} V_\mu^\alpha F_{\nu\gamma} A_\delta \pi^a \\
& + e_D^2\frac{1}{f_\pi^3}\left(\frac{\alpha_4}{4} r_{31}^{abc} + \frac{\alpha_4}{4} r_{33}^{abc} - \frac{2}{9} r_3^{abc} + \frac{\alpha_4}{4} r_{29}^{abc}\right) F_{\mu\nu} A_\gamma \pi^a\pi^b\partial_\delta\pi^c \\
& + e_D g_V\frac{1}{f_\pi^3}\left(\frac{\alpha_3}{12} r_{17}^{\alpha abc} + \frac{\alpha_3}{4} r_{20}^{\alpha abc} + \frac{\alpha_3}{4} r_{21}^{\alpha abc}\right) \bar V_{\mu\nu}^{\alpha} A_\gamma \pi^a\pi^b\partial_\delta\pi^c \\
& + g_V^2\frac{\alpha_3}{12 f_\pi^3} r_{18}^{\alpha\beta abc}\bar V_{\mu\nu}^{\ \ \alpha} V_\gamma^\beta\pi^a\pi^b\partial_\delta\pi^c + e_D g_V \frac{1}{f_\pi^3}\left(\frac{\alpha_4}{12} r_{28}^{\alpha abc} + \frac{\alpha_4}{4} r_{32}^{\alpha abc}\right) V_\mu^\alpha F_{\nu\gamma}\pi^a\pi^b\partial_\delta\pi^c \\
& - e_D^2\frac{r_2^{abc}}{36 f_\pi^3} F_{\mu\nu}F_{\gamma\delta}\pi^a\pi^b\pi^c\Bigg] + \mathcal{O}(6\text{ fields})
\end{aligned}
$$

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