

UNIVERSITY OF OSLO

The SIMP and the Vector Meson

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Outline

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



Team



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Dark Matter

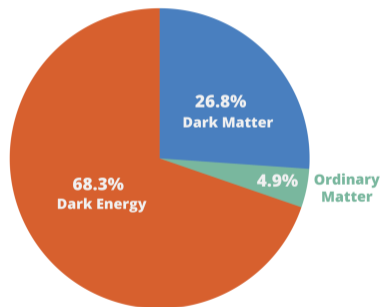
Evidence:

- Rotation curves
- Structure formation

Properties:

- Gravitates
- Non-relativistic
- 5x as much as ordinary matter

Estimated matter-energy content of the Universe



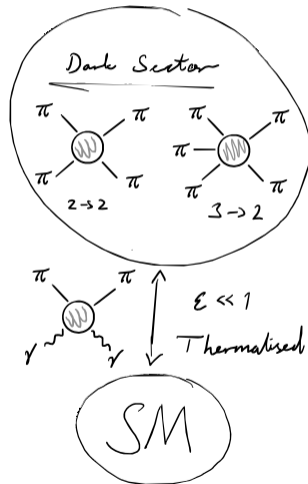
Strongly Interacting Massive Particles (SIMP)

Idea:

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

Consequences:

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



Hochberg et al. [1402.5143]

QCD-like SIMP Models

Underlying confining interaction

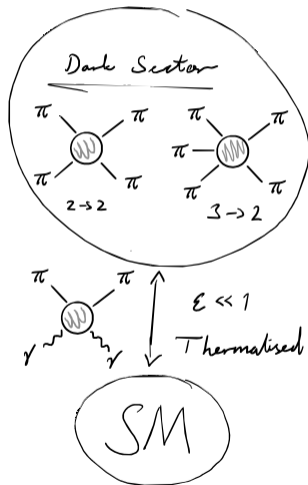
- E.g., $SU(N)$, $Sp(N)$, $SO(N)$

Spontaneously broken flavour symmetry

Stable pNGB \Rightarrow Dark pions

Wess-Zumino-Witten term $\Rightarrow 3\pi \rightarrow 2\pi$

Hochberg et al. [1411.3727]



Relic abundance for SIMPlEst model

Wess-Zumino-Witten term:

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

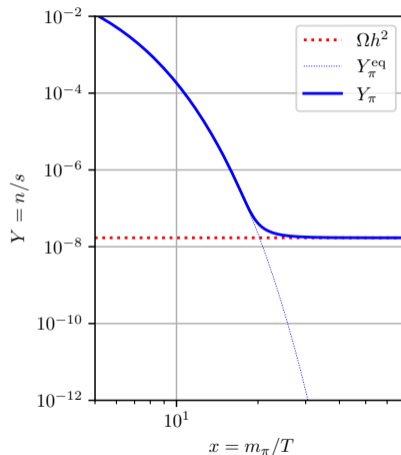
Boltzmann equation:

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v^2 \rangle (n^3 - n_{\text{eq}} n^2)$$

Freeze-out condition:

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

Hochberg et al. [1411.3727]



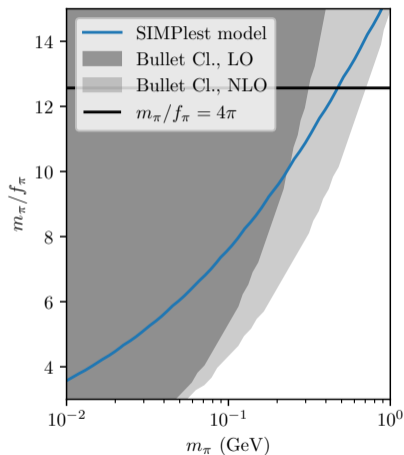
Limitations of SIMPlest model

Perturbativity bound:

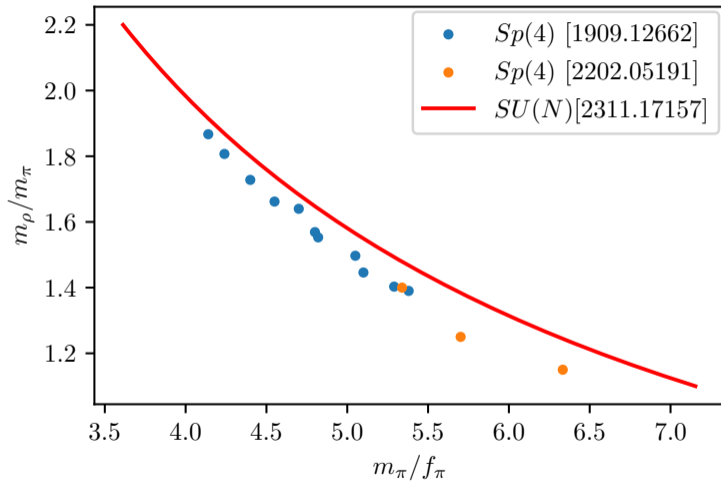
$$\frac{m_\pi}{f_\pi} \lesssim 4\pi$$

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

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

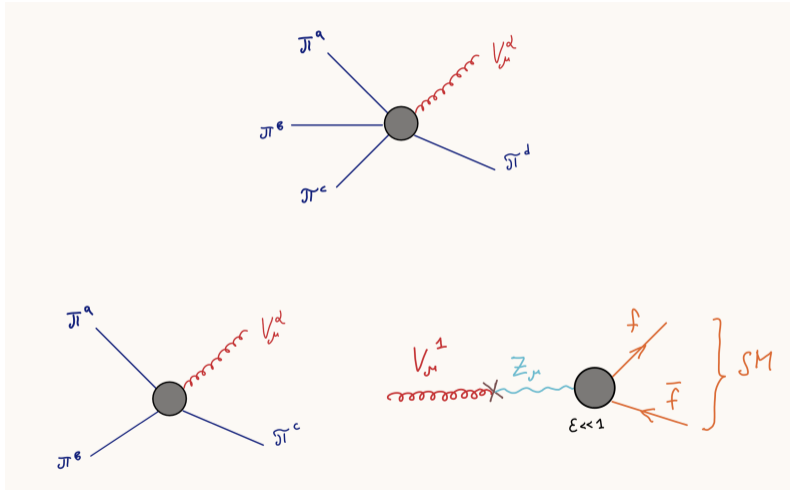


Vector meson masses from lattice



SIMPs with Vector Mesons

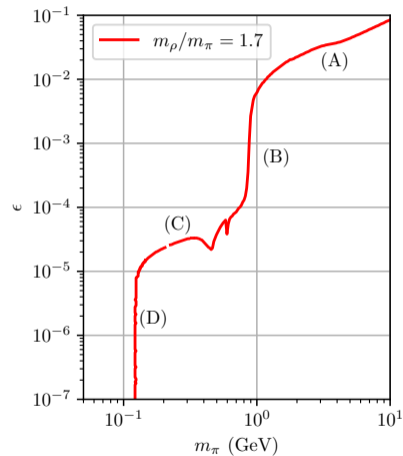
Interactions with vector mesons



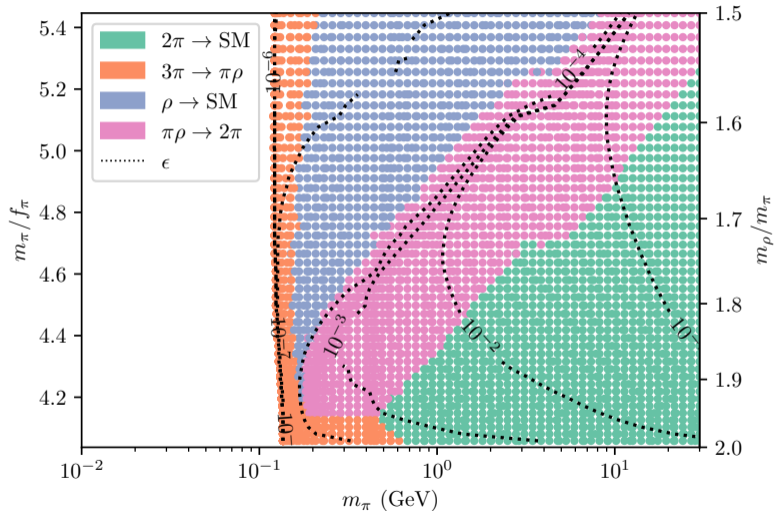
Freeze-out with vector mesons

- A) WIMP: $2\pi \leftrightarrow \text{SM}$
- B) Semi-annihilation: $2\pi \leftrightarrow \pi\rho$
Decay keeps ρ in equil. with SM.
- C) Decay: $\rho \leftrightarrow \text{SM}$
Semi-annih. keeps ρ and π in equil.
- D) SIMP with ρ : $3\pi \leftrightarrow \pi\rho$

Combining [1801.05805] and [2311.17157]



Freeze-out with vector mesons



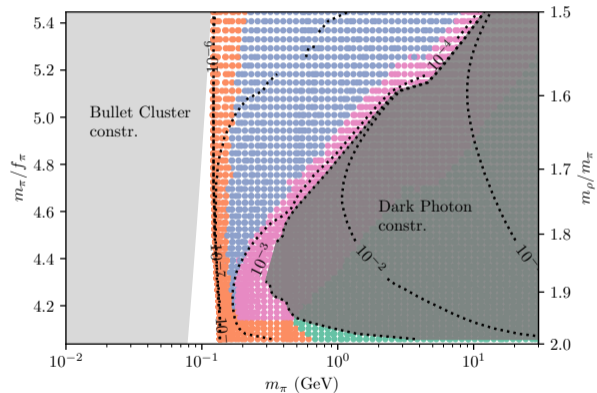
Constraints

Bullet cluster limits self-coupling:

$$\frac{\sigma(2\pi \rightarrow 2\pi)}{m_\pi} \lesssim 2 \frac{\text{cm}^2}{\text{g}}$$

Dark photon \rightarrow Upper limit on ϵ

Thermalisation \rightarrow Lower limit on ϵ



Towards realistic SIMPs

SIMP models

Representation of the fermions	Complex	Pseudoreal	Real
Example: Fundamental rep.	$SU(N_c)$	$Sp(N_c)$	$O(N_c)$
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

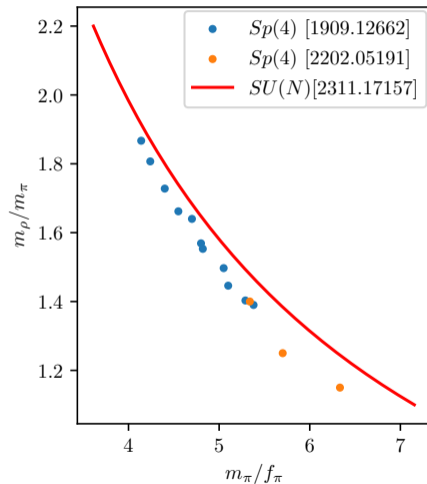
Consider scenario with stable pions

- $Sp(N)$

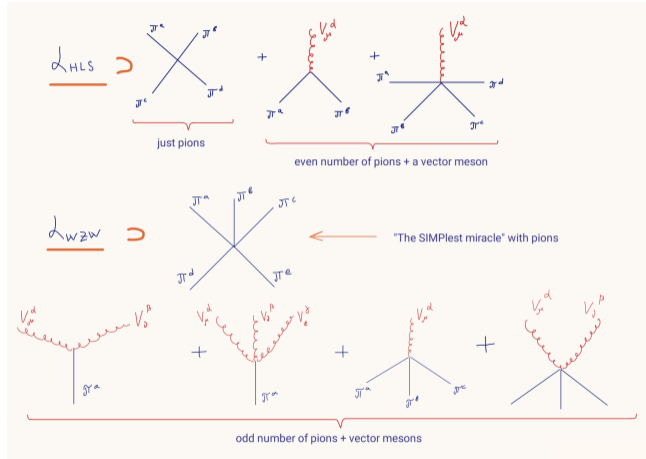
Use recent lattice data for m_ρ/m_π

Consistent treatment of vector mesons

- Hidden Local Symmetry



Hidden Local Symmetry Lagrangian

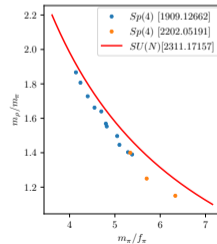
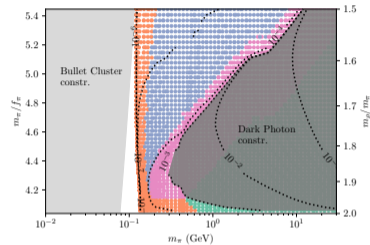


Credit: Pomper, Krichevskiy

Summary

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

Work in progress!



Thank you for the attention!

Backup

HLS Lagrangian

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

NLO Lagrangian

$$\begin{aligned}
\mathcal{L}^{\text{NLO}} = & \frac{i d_{\mathcal{R}}}{8\pi^2} \varepsilon^{\mu\nu\gamma\delta} \left[i e_D \frac{\alpha_1}{f_\pi^3} r_7^{abc} Z_\mu \partial_\nu \pi^a \partial_\gamma \pi^b \partial_\delta \pi^c + i g_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 \right. \\
& - i e_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 - i g_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}}{2 f_\pi} \bar{V}_{\mu\nu}^\alpha Z_\gamma \partial_\delta \pi^a + g_V^2 \frac{\alpha_3 r_{15}^{\alpha\beta a}}{2 f_\pi} \bar{V}_{\mu\nu}^\alpha V_\gamma^\beta \partial_\delta \pi^a + e_D g_V \frac{\alpha_4 r_{26}^{\alpha a}}{2 f_\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 + i e_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 + i g_V \frac{\alpha_3}{4 f_\pi^3} r_{19}^{\alpha abc} \bar{V}_{\mu\nu}^\alpha \pi^a \partial_\gamma \pi^b \partial_\delta \pi^c \\
& - i e_D g_V^2 \frac{\alpha_3}{2 f_\pi} r_{16}^{\alpha\beta a} \bar{V}_{\mu\nu}^\alpha V_\gamma^\beta A_\delta \pi^a - i e_D^2 g_V \frac{\alpha_4}{2 f_\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 \\
& \left. - e_D^2 \frac{r_2^{abc}}{36 f_\pi^3} F_{\mu\nu} F_{\gamma\delta} \pi^a \pi^b \pi^c \right] + \mathcal{O}(6 \text{ fields})
\end{aligned}$$

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