UNIVERSITY OF OSLO

The SIMP and the Vector Meson

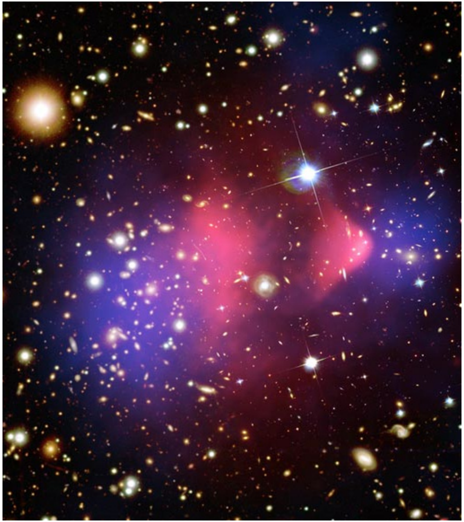
Halvor Melkild
halvor.melkild@fys.uio.no

Les Houches on Dark Universe

11.07.2025

Outline

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



Team

Daniil Krichevskiy
University of Stavanger

Helena Kolešová
University of Stavanger

Joachim Pomper
University of Pisa

Torsten Bringmann
University of Oslo

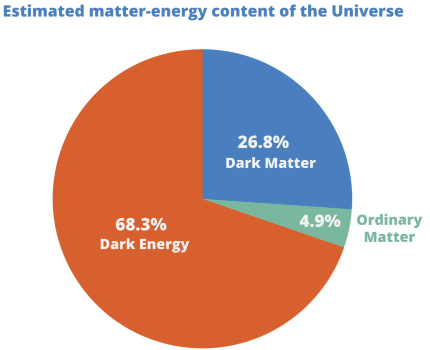
Dark Matter

Evidence:

- Structure formation
- Rotation curves
- $(\cdots)$

Properties:

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



ATLAS EXPERIMENT

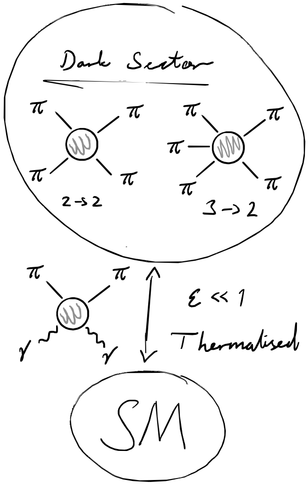
Strongly Interacting Massive Particles (SIMP)

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]

UNIVERSITY
OF OSLO

QCD-like SIMP Models

Underlying confining interaction

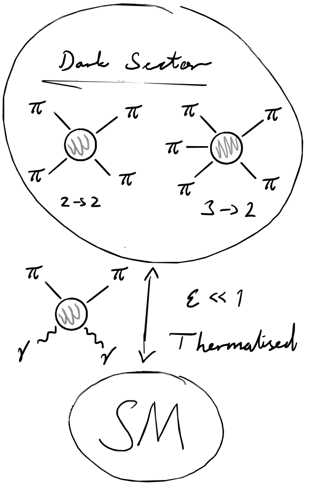
- E.g., $SU(N)$, $Sp(N)$, $SO(N)$

Spontaneously broken flavour symmetry

Stable pNGB $\Rightarrow$ Dark pions

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

Hochberg et al. [1411.3727]



Relic abundance for SIMPlest model

Wess-Zumino-Witten term:

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

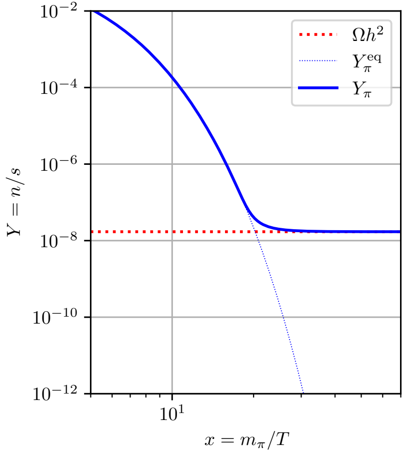
Boltzmann equation:

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

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:

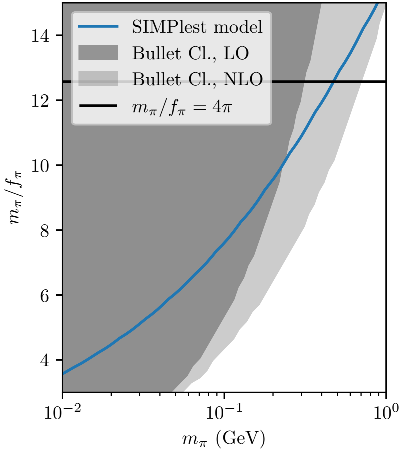
$$\frac{m_\pi}{f_\pi} \lesssim 4\pi$$

NLO corrections closes parameter space

Hansen et al. [1507.01590]

Vector mesons should NOT be ignored

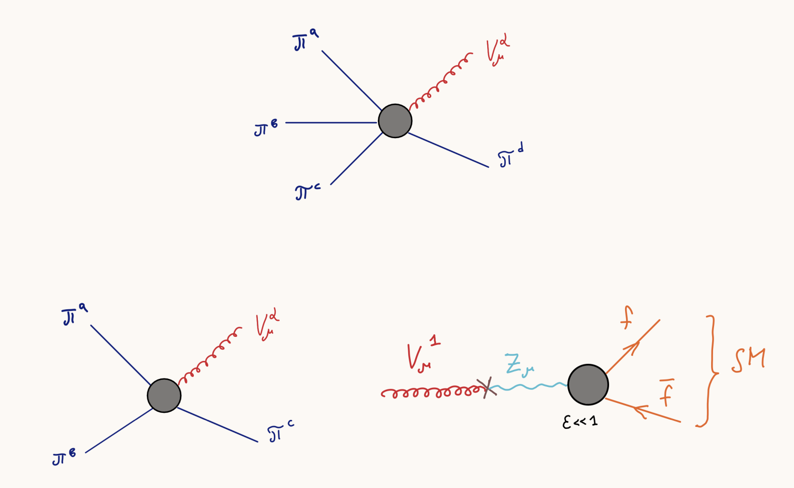
[1801.07726, 1801.05805, 2311.17157]



Kolesova, Krichevskiy, Kulkarni [to appear]

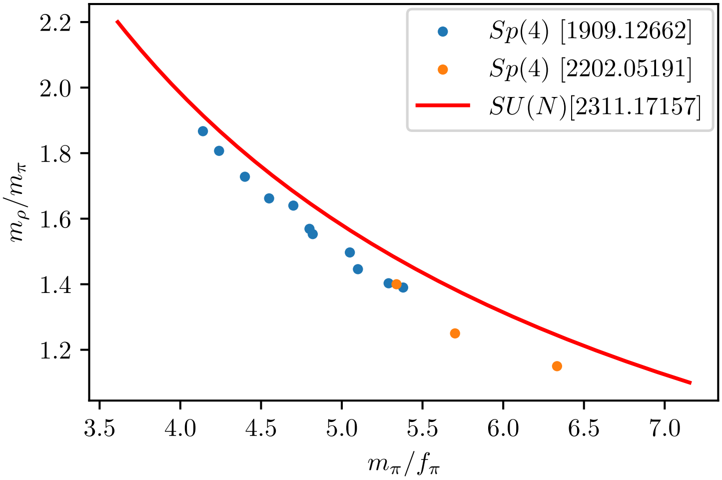
SIMPs with Vector Mesons

Interactions with vector mesons



UNIVERSITY
OF OSLO

Vector meson masses from lattice



UNIVERSITY
OF OSLO

Freeze-out with vector mesons

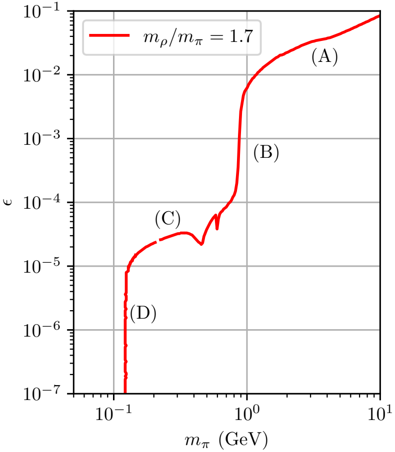
A) WIMP: $2\pi \leftrightarrow \mathrm{SM}$

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

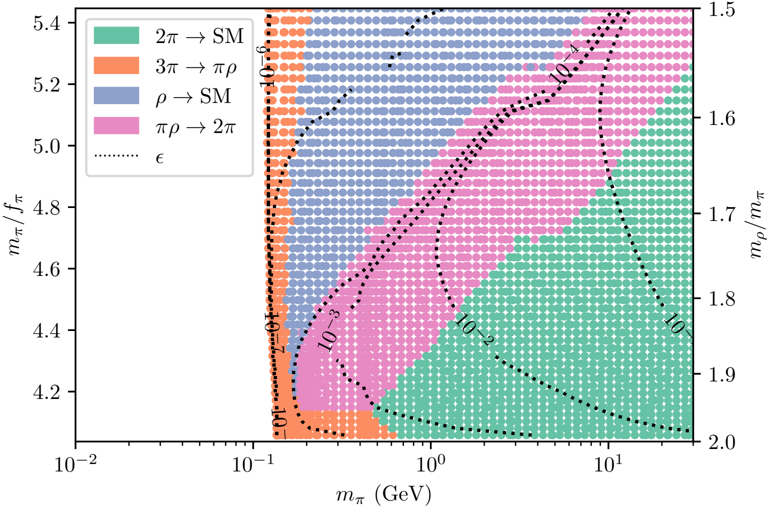
C) Decay: $\rho \leftrightarrow \mathrm{SM}$
Semi-annih. keeps ρ and π in equil.

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

Combining [1801.05805] and [2311.17157]



Freeze-out with vector mesons



UNIVERSITY
OF OSLO

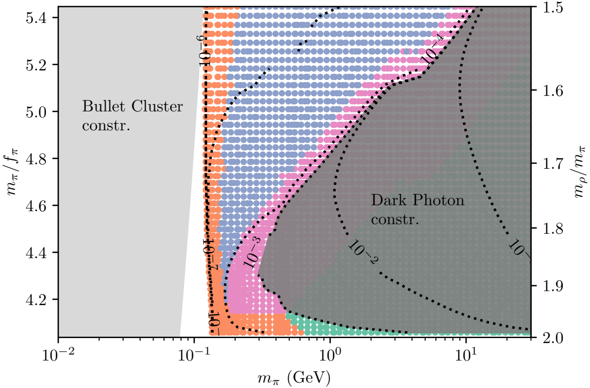
Constraints

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



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

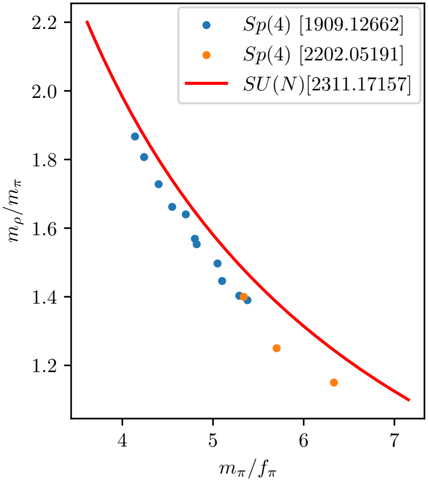
Consider scenario with stable pions

- $Sp(N)$

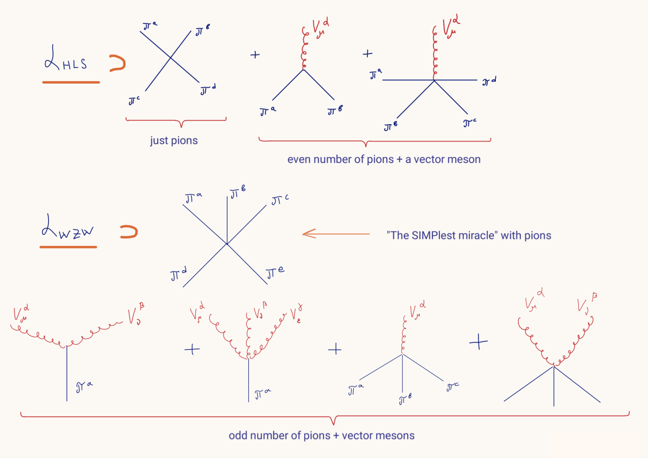
Use recent lattice data for m_ρ/m_π

Consistent treatment of vector mesons

- Hidden Local Symmetry

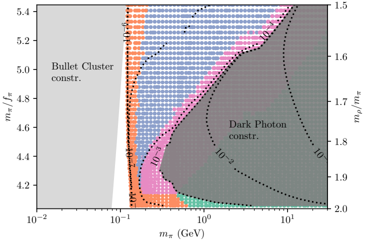


Hidden Local Symmetry Lagrangian



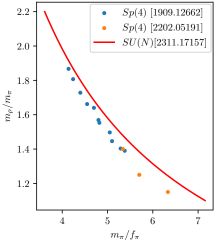
Credit: Pomper, Krichevskiy

Summary



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

Work in progress!



Thank you for the attention!

Backup

HLS Lagrangian

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

NLO Lagrangian

$$
\begin{aligned}
\mathcal{L}^{\mathrm{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_Dg_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_Dg_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_Dg_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_Dg_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_Dg_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_Dg_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^2g_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_Dg_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}{12f_\pi^3}r_{18}^{\alpha\beta abc}\bar{V}_{\mu\nu}^{\ \alpha}V_\gamma^\beta\pi^a\pi^b\partial_\delta\pi^c + e_Dg_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}}{36f_\pi^3}F_{\mu\nu}F_{\gamma\delta}\pi^a\pi^b\pi^c\Bigg] + \mathcal{O}(6\text{ fields})
\end{aligned}
$$

UNIVERSITY
OF OSLO

Image credit

Front page:

- X-ray: NASA/CXC/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

Halvor Melkild
E-mail: halvor.melkild@fys.uio.no
The SIMP and the Vector Meson