On the construction of theories of composite Dark Matter

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Based on arXiv: 2202.05191 with S. Kulkarni, A. Maas, M. Nikolic, J. Pradler, F. Zierler

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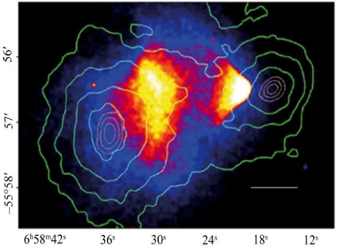
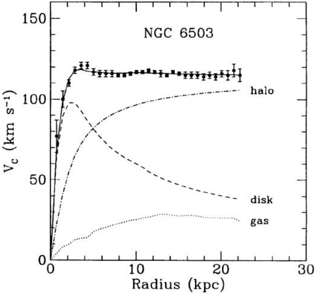
Dark Matter

- One of the biggest unanswered questions in physics today
- Evidence on a variety of scales
- Makes up $\sim 84\%$ of the non-relativistic matter and $\sim 25\%$ of the energy budget of the universe



arXiv:astro-ph/0608407

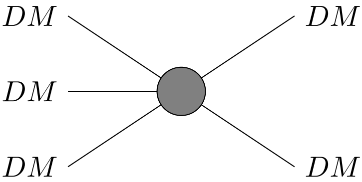


arXiv:1209.0388

DM as a particle

- Stable, or long-lived
- Weakly charged under the standard model group
- Mostly non-relativistic or "cold" at the time of matter-radiation equality
- Probably not an SM particle. Neutrinos were initially seen as a natural candidate but have since been ruled out. (Stable sexaquark?, arXiv:1708.08951)

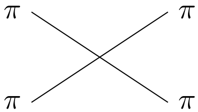
SIMP dark matter

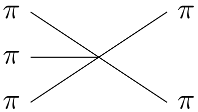


- DM is a thermal relic.
- If this is the primary number changing process, then $m_{DM} \sim \alpha x_F^{-1} \left(x_F^{-1} T_{eq}^2 M_{Pl} \right)^{\frac{1}{3}}$.
- For $x_F \approx 20$ and $\alpha \approx 1$, we have $m_{DM} \approx 100MeV$ (Hochberg et al. arXiv:1402.5143)

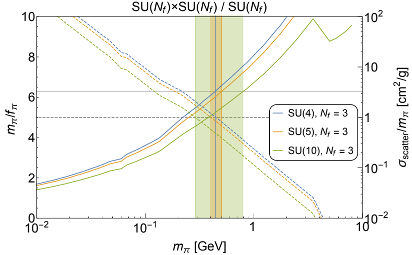
Why strongly interacting DM?

1. Stability of DM in isolation guaranteed.
2. Self-interactions come mostly for free.





3. Dark Matter can freeze out in isolation from the SM.



Hochberg et al. arXiv:1411.3727

Realizing the SIMP mechanism

Gauge Symmetry	Flavour Symmetry	Remaining Symmetry	Number of Goldstones
$SU(N_c), N_c > 2$	$SU(N_f)_L \times SU(N_f)_R$	$SU(N_f)_V$	$N_f^2 - 1$
$Sp(N_c)$	$SU(2N_f)$	$Sp(2N_f)$	$(2N_f + 1)(N_f - 1)$

- For a nonvanishing five-Goldstone vertex, we need at least five pseudo-Nambu Goldstone boson (pNGB) states
- For $SU(3)$ gauge theory, the minimal realization is for $N_f = 3$
- A more minimal realization is possible if we consider fermions in *pseudoreal* representations $\implies$ we consider the fundamental representation of $Sp(4)$

Global Symmetries

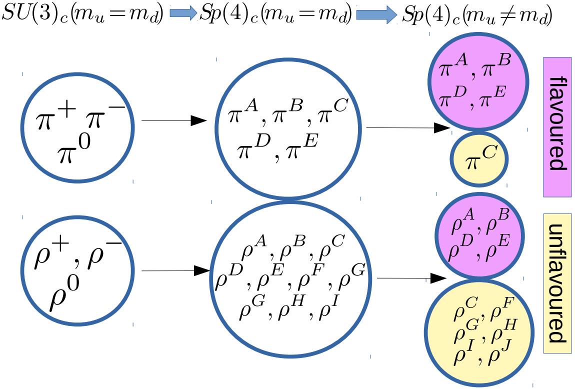
PSEUDOREAL	COMPLEX
$U(4)$	$U(2)\times U(2)$
⇩ axial anomaly	⇩ axial anomaly
$SU(4)$	$SU(2)\times SU(2)\times U(1)$
⇩ chiral symm. breaking $m_u = m_d \neq 0$	⇩ chiral symm. breaking $m_u = m_d \neq 0$
$Sp(4)$	$SU(2)\times U(1)$
⇩ $m_u \neq m_d$	⇩ $m_u \neq m_d$
$SU(2)\times SU(2)$	$U(1)\times U(1)$

Expanded flavour space

- Because of the larger flavour symmetry, we have a four-dimensional flavour space.
- Bound states are built of bilinears of

$$\Psi \equiv \begin{pmatrix} \psi_L \\ \tilde{\psi}_R \end{pmatrix} = \begin{pmatrix} u_L \\ d_L \\ \sigma_2 S u_R^* \\ \sigma_2 S d_R^* \end{pmatrix}$$

The spectrum



Chiral perturbation theory (χPT)

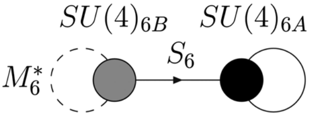
- General and systematic expansion in small momenta and masses
- Goldstones parametrise fluctuations in the orientation of the vacuum:

$$\Sigma = e^{i\pi/f_\pi} E e^{i\pi^T/f_\pi}, \qquad E = \begin{pmatrix} 0 & \mathbb{1}_{N_f} \\ -\mathbb{1}_{N_f} & 0 \end{pmatrix}.$$

- At leading order the aciton is

$$\mathcal{L}_2 = \frac{f_\pi^2}{4} \mathrm{Tr}\left[\partial_\mu \Sigma \partial^\mu \Sigma^\dagger\right] - \frac{\mu^3}{2}\left(\mathrm{Tr}\left[M\Sigma\right] + \mathrm{Tr}\left[\Sigma^\dagger M^\dagger\right]\right),$$

Hidden Local Symmetry



From (Bennett et al. arXiv:1912.06505)

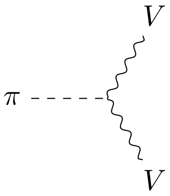
- One symmetry is global, the other is gauged.
- Nonvanishing vev of Σ and S_6 break the symmetry down to global $Sp(4)$.
- Masses of vector states fixed completely in terms of low-energy constants of the full theory with real Goldstones.

Minimal coupling to the SM

- Hidden sector in isolation interacts only gravitationally.
- Simple portals allow the DM to thermalize, as well as talk to the SM
- $U(1)$ extension often discussed because of simplicity and familiarity.

Goldstone Stability

- If a Goldstone can decay, it does so through the AVV anomaly:



- We can realize a theory where this decay is forbidden for all Goldstones, while still having a portal to the SM.
- The symmetry breaking term in the UV is of the form

$$\mathcal{L}_{\text{break}} \sim V^{\mu} \Psi^{\dagger} \mathcal{Q} \partial_{\mu} \Psi,$$

Charge assignment and multiplet structure

$\mathcal{Q}$	Breaking Pattern	Multiplet Structure
$\begin{pmatrix} a & 0 & 0 & 0 \\ 0 & -a & 0 & 0 \\ 0 & 0 & -a & 0 \\ 0 & 0 & 0 & a \end{pmatrix}$	$Sp(4) \to SU(2) \times U(1)$	$\begin{pmatrix} \pi^C \\ \pi^{D,E} \end{pmatrix}$, $(\pi^{A,B})$
$\begin{pmatrix} a & 0 & 0 & 0 \\ 0 & a & 0 & 0 \\ 0 & 0 & -a & 0 \\ 0 & 0 & 0 & -a \end{pmatrix}$	$Sp(4) \to SU(2) \times U(1)$	$\begin{pmatrix} \pi^C \\ \pi^{A,B} \end{pmatrix}$, $(\pi^{D,E})$
$\begin{pmatrix} a & 0 & 0 & 0 \\ 0 & b & 0 & 0 \\ 0 & 0 & -a & 0 \\ 0 & 0 & 0 & -b \end{pmatrix}, \quad a \neq b$	$Sp(4) \to U(1)^2$	(π^C), $(\pi^{A,B})$, $(\pi^{D,E})$
$\begin{pmatrix} 0 & 0 & a & 0 \\ 0 & 0 & 0 & \pm a \\ a & 0 & 0 & 0 \\ 0 & \pm a & 0 & 0 \end{pmatrix},$	$Sp(4) \to SU(2) \times U(1)$	$\begin{pmatrix} \pi^C \\ \pi^{A,B} \\ \pi^{E,D} \end{pmatrix}$, $\begin{pmatrix} \pi^{D,E} \\ \pi^{B,A} \end{pmatrix}$
All other off-diagonal prescriptions	$Sp(4) \to U(1)^2$	(π^C), $(\pi^{A,B})$, $(\pi^{D,E})$

Decay of the ρ

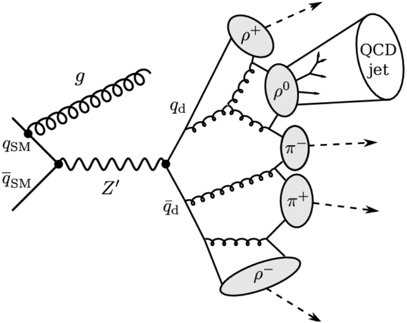
- A singlet ρ can mix with our $U(1)$ field through interactions of the form

$$\mathcal{L}_{V-\rho} \sim -\frac{e_D}{g} V_{\mu\nu} Tr\left(\mathcal{Q}\rho^{\mu\nu}\right).$$

- DM component completely stable $\rightarrow$ heavier states can decay into the SM.
- If $m_\rho < 2m_\pi$, ρ should decay democratically to SM $f\bar{f}$ pairs.
- If m_ρ is above this threshold, then the ρ will decay dominantly back into the hidden sector.

Possible signals: Dark Showers

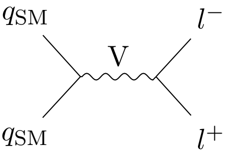
- Vector-gauge boson mixing can in general lead to dark showers.
- Characterized by semi-visible jets.
- Searches limited by current event generators.



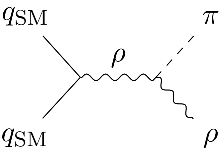
Bernreuther et al. arXiv:1907.04346

Other searches

- Bump searches in dilepton production cross section



- More distinctive signatures from e.g.

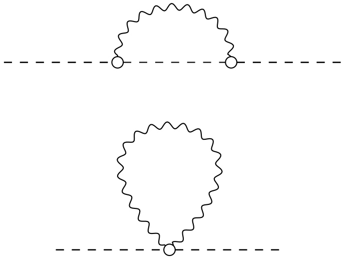


Symmetry breaking in the EFT

- Symmetry breaking amongst Goldstones $\implies$ mass-splitting
- Relevant term in the EFT is

$$\mathcal{L}_{V\text{-split}} = \kappa \, \mathrm{Tr}\left(\mathcal{Q}\Sigma\mathcal{Q}\Sigma^\dagger\right).$$

- We compute the corrections through one-loops contributions to the self-energy given in the figure.



One-loop contributions to renormalized Goldstone masses. Empty dots indicate that all contributions of $\mathcal{O}(e_D^2)$ must be accounted for

Mass-splitting

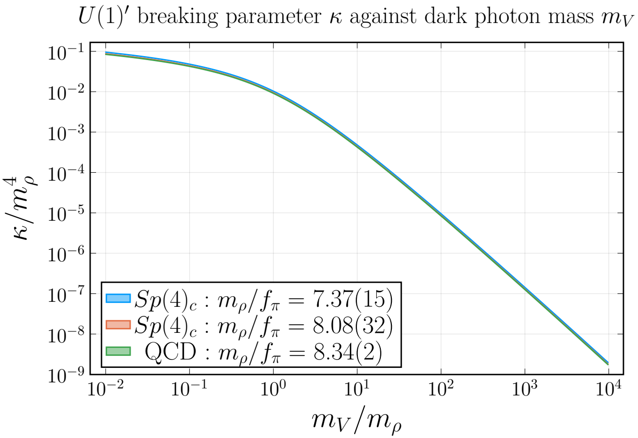
- Ultimately corrections take the form

$$\Delta m_\pi^2 \approx \frac{6e_D^2}{(2\pi)^2}\frac{m_\rho^4}{m_V^2 - m_\rho^2}\log\left(\frac{m_V^2}{m_\rho^2}\right)$$

at leading order in χPT.

- Different symmetry breaking properties than $\mathcal{O}(\Delta m_{ud}^2)$ corrections.
- Can still have fine splitting while preserving DM stability, even when coupled to the SM.

Mass-splitting



Outlook and Conclusions

- Strongly interacting theories can naturally explain some of the properties of DM.
- Symplectic gauge theories with two flavours provide a minimal realization.
- Coupling the EFT to the SM through a simple vector portal can provide novel signatures of such theories.

Non-degenerate fermions

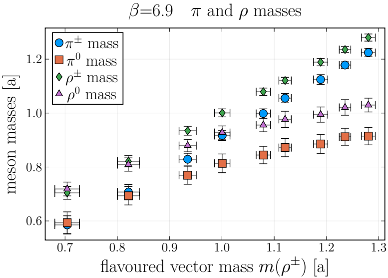
- GMOR relation predicts a degenerate spectrum. $\mathcal{O}(m_Q^2)$ corrections break the degeneracy $\implies$ NLO chiral Lagrangian

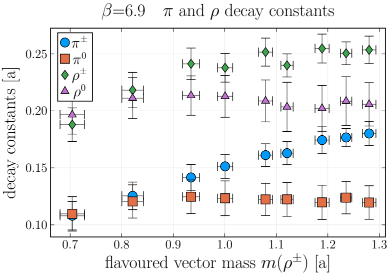
$$
\begin{aligned}
\mathcal{L}_{4,mass} = {} & a_4 \mathrm{Tr}\left[\partial_\mu \Sigma \partial^\mu \Sigma^\dagger\right] \mathrm{Tr}\left[M\Sigma + \Sigma^\dagger M^\dagger\right] + a_5 \mathrm{Tr}\left[\partial_\mu \Sigma \partial^\mu \Sigma^\dagger \left(\Sigma M + M^\dagger \Sigma^\dagger\right)\right] \\
& + a_6 \left(\mathrm{Tr}\left[M\Sigma + \Sigma^\dagger M^\dagger\right]\right)^2 + a_7 \left(\mathrm{Tr}\left[M\Sigma - \Sigma^\dagger M^\dagger\right]\right)^2 \\
& + a_8 \mathrm{Tr}\left[M\Sigma M\Sigma + \Sigma^\dagger M^\dagger \Sigma^\dagger M^\dagger\right].
\end{aligned}
$$

- Corrections to masses and decay constants can be expressed in terms of $\mathcal{O}(p^4)$ LECs.
- In the full theory, masses and decay constants calculable from lattice.

Fits from lattice for non-degenerate fermions

(Maas, Zierler arXiv:2109.14377)





Results for degenerate case (Bennett et al. arXiv:1912.06505)