On the construction of theories of composite Dark Matter

KIAS HEP Seminar

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

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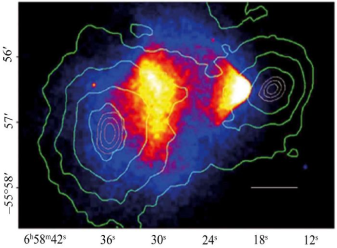
Outline

STRONG-DM group

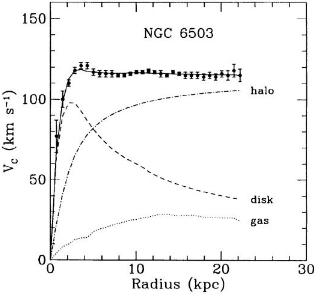
- A focus on strongly interacting theories of dark matter.
- Several approached taken in characterizing SIMP (strongly interacting massive particle) dark matter.
- Close collaboration between lattice theorists, cosmologists, experimentalists and phenomenologists.

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

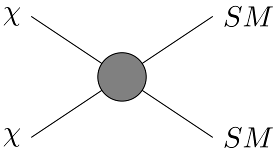


arXiv:1209.0388

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.

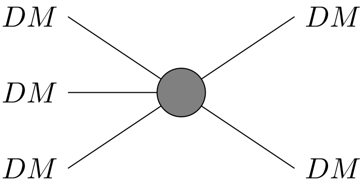
The standard WIMP



$$\Omega_\chi h^2 \approx 0.1 \left(\frac{0.01}{\alpha}\right)^2 \left(\frac{m_\chi}{100 \text{ GeV}}\right)^2$$

- DM is a thermal relic
- Freezes out through an incomplete annihilation process
- Weakly interacting particles at the weak scale reproduce observed relic density (Gondolo, Gelmini, Nucl. Phys. B, 360 145 (1991))

Alternative routes to the relic density



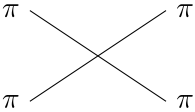
- If this is the primary number changing process, then $m_{DM} \sim \alpha x_F^{-1} \left(x_F^{-1} T_{eq}^2 M_{Pl} \right)^{\frac{1}{3}}$.
- For $x_F \approx 20$ and $\alpha \approx 1$, we have $m_{DM} \approx 100 MeV$ (Hochberg et al. arXiv:1402.5143)

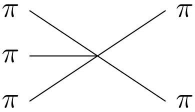
Strong interactions and composite states

- In the SM, exactly these sorts of interactions sourced by the Wess-Zumino-Witten action in QCD.
- New interest in DM as a composite particle in a QCD-like hidden sector.
- In isolation, lightest hidden sector states are completely stable.

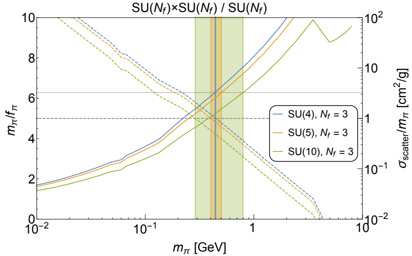
Why strongly interacting DM?

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

Strong Dynamics in the SM

- At the UV level, at a scale Λ_{QCD}, the strong coupling diverges and quarks confine into colour neutral combinations. Pions are sourced by bilinears $q\bar{q}$
- Pions can be characterized as the pseudo Nambu-Goldstone bosons of *chiral symmetry* breaking.
- The condensate
$$\langle\bar{\psi}\psi\rangle = \mu^3 \neq 0$$
breaks the global flavour symmetry $SU(N_f) \times SU(N_f) \to SU(N_f)$.
- $N_f^2 - 1$ pNGBs

How do we study the pNGBs

1. Lattice Field Theory (DeGrand Detar, 2006)
   - Simulates the full theory, nonperturbative.
   - Allows us to access low-energy constants: pion masses and decay constants.
   - Costly, especially if we want to work close to the chiral limit.
2. Chiral Perturbation Theory (χPT) (Georgi, 1984)
   - General and systematic expansion in the small momenta and masses of our pNGBs.
   - Respects all the symmetries of the UV action
   - Heavier flavours integrated out, their influence can be seen in the low-energy constants (LECs) associated with each term.
   - LECs require some extra input (eg. from experimental data or from lattice).

From $SU(3)$ to $Sp(4)$

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 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 $Sp(4)$

Pseudoreality

- Pseudoreal representations have the property that they are isomorphic to their conjugate representation.
- The defining property of the symplectic group is that for $U \in Sp(2N)$,

$$U^* = SUS^\dagger, \qquad S = i\sigma_2 \otimes \mathbb{1}_{N\times N}$$

- At the generator level this implies

$$T^{a*} = -ST^aS^\dagger.$$

$\implies$ symmetry between particle and antiparticle and expanded flavour symmetry

From $SU(3)$ to $Sp(4)$

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

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

Symmetries of $Sp(4)$

- $Sp(4)$ with two fundamental fermions possesses an expanded flavour-symmetry
- $SU(2) \times SU(2)$ expanded to $SU(4)$
- Condensate

$$\langle \psi_i^T \psi_j \rangle = \mu^3 E_{ij}, \qquad E = \begin{pmatrix} 0 & \mathbb{I}_2 \\ -\mathbb{I}_2 & 0 \end{pmatrix}$$

  breaks $SU(4) \to Sp(4)$
- $15 - 10 = 5$ pNGBs

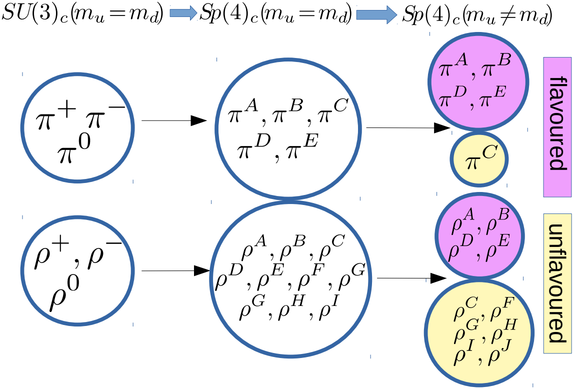
Spectrum of the low-energy theory

- Theory contains all the standard meson states of QCD.
- Contains also extra states, due to the expanded symmetry.
- Theory contains no baryons $\implies$ single component dark. matter.
- In what follows, we will consider first the case of degenerate fermions.

Di-quarks

- $Sp(4)$ theories allow the construction of colour neutral states of quark pairs.
- Due to pseudoreality, these form part of our Goldstone multiplet.
- Along with standard $\bar{u}d$ states, we have also $u^T d$ states, totally degenerate with the others.

The complete spectrum



The chiral Lagrangian

- The dynamics of the pNGBs can be described through fluctuations in the orientation of the vacuum condensate
- The chiral EFT is built out of the field

$$\Sigma = e^{i\pi/f_\pi} E e^{i\pi^T/f_\pi}.$$

- At leading order it takes the familiar form

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

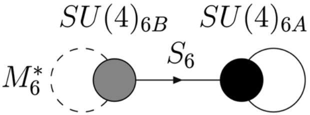
Minimal extensions of the EFT

- While χPT should describe our Goldstones well, other states in the hidden sector may also be interesting.
- The spin-1 multiplet, analogous to the ρ multiplet in QCD can play an important role at colliders.
- We make use of the idea of *hidden local symmetry* in order to couple them to the EFT.

Hidden Local Symmetry

- The hidden local symmetry framework allows us to describe the effective interactions between pNGBs and the lightest spin-1 states.
- We gauge a copy of our global $Sp(4)$ which is completely broken by the condensate.
- 15 real Nambu-Goldstones $\sigma^a T^a$ appear in our theory and provide mass to all spin-1 states.

Hidden Local Symmetry



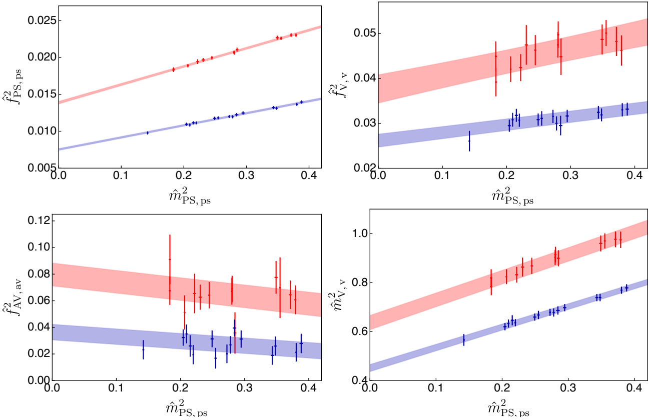
From (Bennett et al. arXiv:1912.06505)

- 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.

What characterizes the low-energy states?

- Scales of the full UV theory $\rightarrow \mu$, m_Q, Λ
- Encoded in the low-energy constants of the EFT $\rightarrow m_\pi$, m_ρ, f_π, f_ρ
- Lattice computations of these already available for degenerate fermions.

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



Minimal coupling to the SM

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

Dark photon

- $U(1)$ symmetry under which dark quarks are charged.
- Broken by a dark Higgs mechanism.
- Weak Hypercharge portal:

$$\mathcal{L}_{int} \sim \frac{\varepsilon}{2\cos\theta_W} B_{\mu\nu} V^{\mu\nu}.$$

- *Millicharged* dark matter under SM group.

Explicit symmetry breaking

- $U(1)$ couplings can break part of our remaining flavour symmetry.
- Symmetry breaking in effective theory should match that of UV Lagrangian.
- Important implications for stability of the DM.

Global Symmetries and Goldstone stability

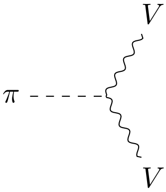
- The symmetry breaking term in the UV is of the form

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

with $\mathcal{Q}$ a charge matrix in flavour space.
- Can perform flavour rotation to work out conserved symmetry.

Goldstone Decay

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



- Decay can only occur if the particle is no longer protected by symmetry $\implies$ falls into a *trivial* representation of the flavour group.

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), $(\pi^{A,B})$, $(\pi^{D,E})$

Unique properties

- Unlike for a standard $SU(3)$ gauge symmetry, nontrivial assignments can *completely* stabilize the DM.
- No need for external stabilizing symmetry.
- Contact still made with the standard model.

Decay of the ρ

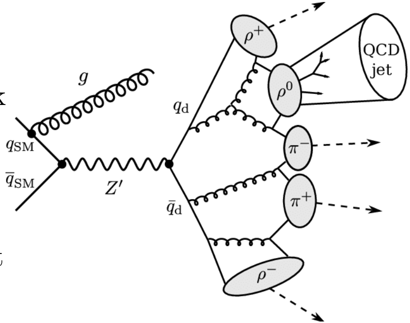
- A singlet ρ can mix with our $U(1)$ field through interactions of the form

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

- 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_π is below threshold, then the ρ will decay dominantly back into the hidden sector.

Dark Showers

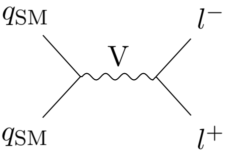
- In general, can lead to dark showers at colliders.
- Characterized by semi-visible jets.
- Searches limited by current event generators.



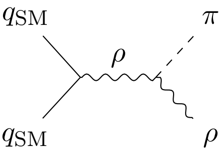
Bernreuther et al. arXiv:1907.04346

Other searches

- Bump searches in dilepton production cross section



- More distinctive signatures from e.g.

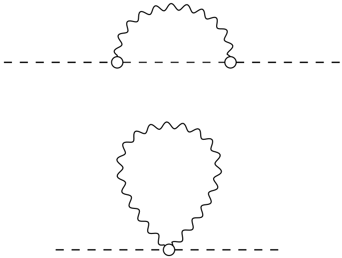


Symmetry breaking in the EFT

- 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.

Other sources of explicit breaking

- Another source of symmetry breaking is introduced by fermion mass-splitting.
- The global $Sp(4)$ breaks to $SU(2) \times SU(2)$.
- The pNGBs always transform in a 4-plet and a singlet of of the remaining symmetry $\implies$ mass-splitting between flavour singlet and off-diagonal 4-plet.

Non-degenerate fermions

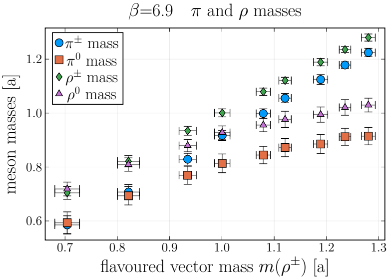
- GMOR relation predicts a degenerate spectrum.$\mathcal{O}(m_Q^2)$ corrections break the degeneracy $\implies$ NLO chiral Lagrangian

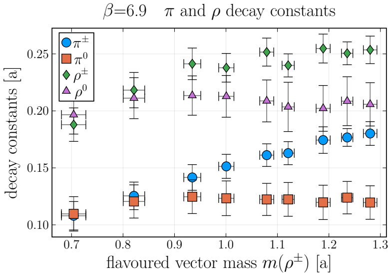
$$\begin{aligned}\mathcal{L}_{4,mass} = {} & a_4 \mathrm{Tr}\left[\partial_\mu \Sigma \partial^\mu \Sigma^\dagger\right] \mathrm{Tr}\left[M\Sigma + \Sigma^\dagger M^\dagger\right] + a_5 \mathrm{Tr}\left[\partial_\mu \Sigma \partial^\mu \Sigma^\dagger \left(\Sigma M + M^\dagger \Sigma^\dagger\right)\right]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

- 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)





Outlook and Conclusions

- Dark matter remains one of the most important unanswered questions in physics today.
- Strongly interacting theories can naturally explain some of the properties we expect of particle dark matter.
- As a minimal realisation of the SIMP scenario, we have constructed the low-energy theory of pNGBs of $SU(4)/Sp(4)$ symmetry breaking.

Outlook and Conclusions

- Through the use of hidden local symmetry we have coupled the pNGBs to the lightest spin-1 states in the hidden sector
- We've coupled the hidden sector to a simple $U(1)$ mediator and completely described the associated symmetry breaking patterns.
- We've described the decays of hidden sector particles and the associated phenomenological consequences.
- Moving forward: FeynRules implementation of our model $\rightarrow$ decay widths and cross-sections, constraining our parameter space.