Low energy effective description of dark $Sp(4)$ theory with matter in non fundamental representation

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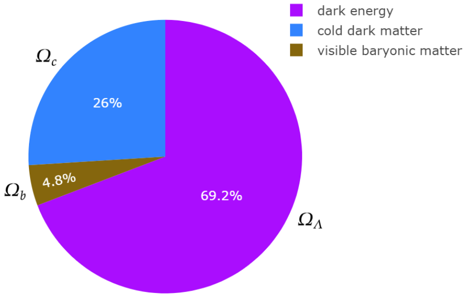
Let's start with the usual story

There is a non-negligible non-visible matter component in the universe



No experimentally verified description on the fundamental level so far

Cusp vs. Core problem

Data from the DDO 154 dwarf galaxy

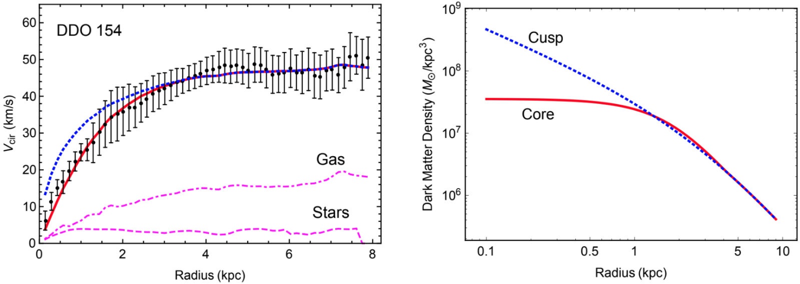


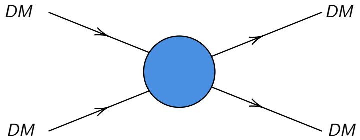
Figure: Taken from the talk on Dark QCD of [Murayama (2022)]

Self interacting dark matter

Introduction of self interactions within the dark sector may solve these problems as shown by N-body simulations. [arXiv:astro-ph/9909386v2]

- Required self interaction cross section:

$$\frac{\sigma}{m} = 0.1 - 1.0 \ \frac{\mathrm{cm}^2}{g}$$

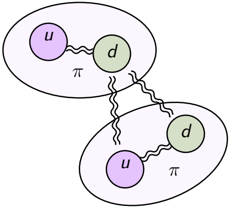


Constraints:

- Bullet cluster constraint: $\frac{\sigma}{m} \lesssim 0.7 \ \frac{\mathrm{cm}^2}{g}$ [arXiv:astro-ph/0704.0261]

Dark matter as composite states

Cold dark matter may consist of composite states of an additional confining, non-abelian gauge sector in a chiraly broken phase.



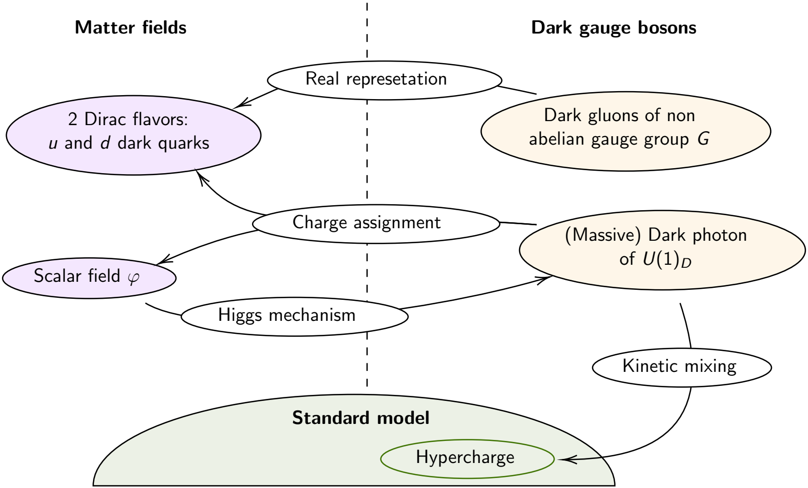
- Natural implementation of dark matter self interactions.
- Potential velocity dependence of self interaction may relate problems at different scales.
- Accidental flavor symmetry may stabilize dark matter.

Technical aspect:
Low energy effective description of the relevant parts of the spectrum.

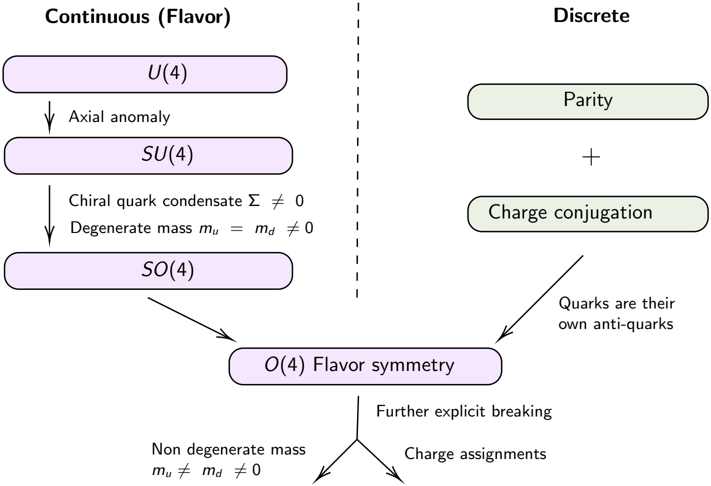
Dark matter model in the UV

arXiv:hep-ph/1512.07917

arXiv:hep-ph/2005.01515



Symmetries and breaking patterns of fermion sector



Lightest states - pion dark matter

Spontaneous symmetry breaking:

$SU(4) \rightarrow SO(4)$

Order parameter:

$\Sigma = \langle \bar{u}u + \bar{d}d \rangle \neq 0$

The **lightest states** are given by the **9** pseudo Nambo-Goldstone bosons

Regular 2-Flavor **QCD** only has **3 pions**

pseudo scalar

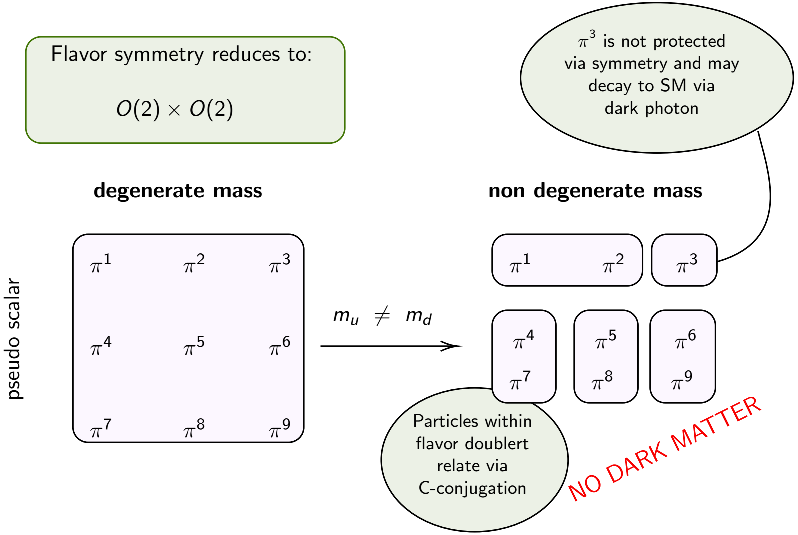
π^1	π^2	π^3
π^4	π^5	π^6
π^7	π^8	π^9

Chiral effective theory based on $\boldsymbol{SU(4) \,/\, SO(4)}$ coset space

Explicit breaking via non degenerate mass

Flavor symmetry reduces to:

$O(2) \times O(2)$



$U(1)_D$ charge assignments in mass degenerate scenario

Guidance principles:

Charge fermions under $U(1)_D$ gauge group $\rightarrow$ Consistency (no gauge anomalies)

Charge fermions under $U(1)_D$ gauge group $\rightarrow$ Pions stability

Pions stability $\rightarrow$ maintain global symmetry

Pions stability $\rightarrow$ no anomalous pion currents

Charge assignments of quarks and pions :

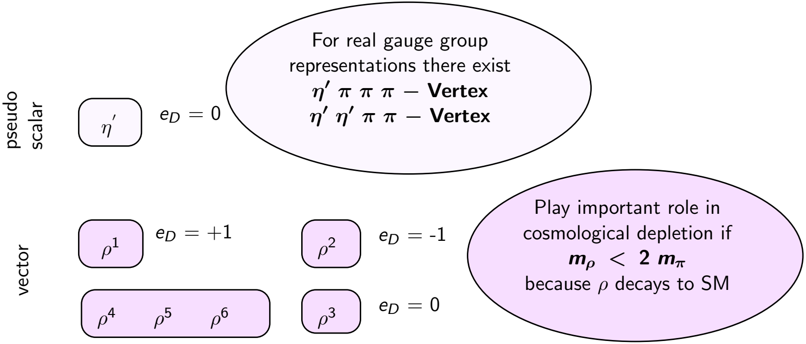
There is only one physically distinct charge assignment in the UV that provides stable dark pions

$u \quad d$	$e_D = +1/2$
$\pi^1 \quad \pi^2 \quad \pi^3$	$e_D = 0$
$\pi^4 \quad \pi^5 \quad \pi^6$	$e_D = +1$
$\pi^7 \quad \pi^8 \quad \pi^9$	$e_D = -1$

Flavor symmetry $SU(2)$ remains

Further particles to be considered

Dependent on the mass-spectrum further particles will take part in the cosmological depletion of dark matter.



SIMP-Mechanism

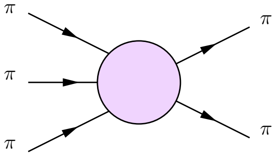
arXiv:hep-ph/1411.3727

arXiv:hep-ph/1402.5143

Dark matter depletion via self-cannibalizing $3 \to 2$ process.

$$\frac{N_C}{f_\pi^5}\epsilon^{\mu\nu\rho\sigma}\,\mathrm{Tr}\{\pi\;\partial_\mu\pi\;\partial_\nu\pi\;\partial_\rho\pi\;\partial_\sigma\pi\;\}$$

Results from topological Wess-Zumino-Witten terms.



Standard construction of these terms not possible since

$$\pi_4(SU(4)/SO(4)) \neq 0$$

What was done so far

- Investigation of UV-theory
  - Identification of relevant structures
  - Investigation of symmetries and flavor structure
  - Construction of gauge invariant interpolating operators.
- Modelling the effective description
  - First order chiral effective Lagrangian for pions under $U(1)_D$.
  - Inclusion of the η'-meson in the effective description.

Further steps in this work

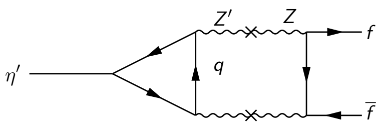
- Construction of topological terms.
- Investigation of the freeze out process and the competing processes:
  - Pion annihilation decay via Z'
  - Pion depletion via η-decay
  - Pion depletion via ρ's
  - $3 \to 2$ self-cannibalizing of pions
- Investigation of self interaction strength.

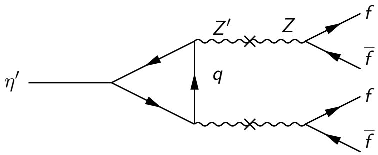
Bonus content

η-decay to standard model

arXiv:hep-ph/1805.09345v1

Dependent on the mass $m_{\eta'}$ and lifetime $\tau_{\eta'}$ of the η' the dark matter scenario might be sufficiently altered or spoiled.





η'-decay may lower the relic abundance of dark matter significantly and may render the model invalid.

Limiting cases:

- η' decays almost instantly
  $\Rightarrow$ NO DARK MATTER
- $\tau_{\eta'} \approx$ age of universe.
  $\Rightarrow$ Pion abundance not affected.
  BBN or CMB constraints on $m_{\eta'}$.

Interpolating operators for pions

	$\overline{\Psi_{\mathcal{C}}}\ T_n^{\Psi}\Psi + \left(\overline{\Psi_{\mathcal{C}}}\ T_n^{\Psi}\Psi\right)^*$	J^D		$\overline{\Psi_{\mathcal{C}}}\ T_N^{\pi}\Psi + \left(\overline{\Psi_{\mathcal{C}}}\ T_N^{\pi\top}\Psi\right)^*$	I_3	B
π_1	$\frac{1}{\sqrt{2}}\left(\overline{u}\gamma^5 d + \overline{d}\gamma^5 u\right)$	1^-	π^A	$\overline{u}\gamma^5 d$	1	0
π_2	$\frac{1}{\sqrt{2}}\left(\overline{u}\gamma^5 d - \overline{d}\gamma^5 u\right)$	1^-	π^B	$\overline{d}\gamma^5 u$	-1	0
π_3	$\frac{1}{\sqrt{2}}\left(\overline{u}\gamma^5 u - \overline{d}\gamma^5 d\right)$	1^-	π^C	$\frac{1}{\sqrt{2}}\left(\overline{u}\gamma^5 u - \overline{d}\gamma^5 d\right)$	0	0
π_4	$\frac{1}{2}\left(\overline{u_{\mathcal{C}}}\gamma^5 u + \overline{u}\gamma^5 u_{\mathcal{C}}\right)$	1^-	π^D	$\frac{1}{\sqrt{2}}\overline{u_{\mathcal{C}}}\gamma^5 u$	-1	-1
π_5	$\frac{1}{2}\left(\overline{d_{\mathcal{C}}}\gamma^5 d + \overline{d}\gamma^5 d_{\mathcal{C}}\right)$	1^-	π^E	$\frac{1}{\sqrt{2}}\overline{d}\gamma^5 d_{\mathcal{C}}$	1	-1
π_6	$\frac{1}{\sqrt{2}}\left(\overline{u}\gamma^5 d_{\mathcal{C}} + \overline{u_{\mathcal{C}}}\gamma^5 d\right)$	1^-	π^F	$\overline{u}\gamma^5 d_{\mathcal{C}}$	0	-1
π_7	$\frac{1}{2}\left(\overline{u_{\mathcal{C}}}\gamma^5 u - \overline{u}\gamma^5 u_{\mathcal{C}}\right)$	1^-	π^G	$\frac{1}{\sqrt{2}}\overline{u}\gamma^5 u_{\mathcal{C}}$	1	1
π_8	$\frac{1}{2}\left(\overline{d}\gamma^5 d_{\mathcal{C}} - \overline{d_{\mathcal{C}}}\gamma^5 d\right)$	1^-	π^H	$\frac{1}{\sqrt{2}}\overline{d_{\mathcal{C}}}\gamma^5 d$	-1	1
π_9	$\frac{1}{\sqrt{2}}\left(\overline{u}\gamma^5 d_{\mathcal{C}} - \overline{u_{\mathcal{C}}}\gamma^5 d\right)$	1^-	π^I	$\overline{u_{\mathcal{C}}}\gamma^5 d$	0	1