Sneaky dark matter from dark flavour symmetries

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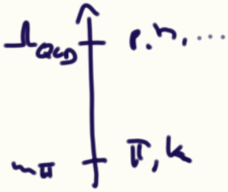
24XX.XXXX

no direct evidence of new physics
→ either heavy, or light & feebly coupled
↳ can still lead to light degrees of freedom e.g. through Goldstone theorem

SM example: QCD

$SU(3)_L \times SU(3)_R \rightarrow SU(3)_V$

$m_q \ll \Lambda_{QCD}$



→ **QCD-like dark sector** (aka Hidden Valley, dark QCD, confining dark sector, etc.)

- $SU(N)_D$ dark flavour symmetry (here: $N=3$)
- α_D strong coupling
- n_F dark quarks Q_D, charged under $SU(N)_D$, singlets under SM gauge group
- dark confinement scale Λ_D
- scalar mediator X, $X \sim (3, \bar{3})$ under $SU(3) \times SU(3)_D$

L $\bar{Q}_a Q_b$

$$\mathcal{L} \supset \frac{1}{4}\left(G_D^{a,\mu\nu}\right)^2 + \bar{Q}_\alpha i \not{D} Q_\alpha - m_{Q\alpha\beta}$$

$$- \left(\kappa_{\alpha i}\, \bar{q}_{R i} X Q_\alpha + \text{h.c.}\right) + \left(D_\mu X\right)^2 + m_X^2 X X^\dagger$$

for m_{Q_D} small : $SU(n_F)_L \times SU(n_F)_R \underset{\substack{\uparrow \\ \text{by } \langle \bar{Q}_\alpha Q_\beta \rangle}}{\longrightarrow} SU(n_F)_V$

$\rightarrow n_F^2 - 1$ light degrees of freedom, call them „dark pions" π_D

$$\begin{tikzcd}
\begin{array}{l}\text{SM quarks} \\ u,c,t \ (Y_X = \frac{2}{3}) \\ \text{or } d,s,b \ (Y_X = -\frac{1}{3})\end{array} \arrow[r, leftrightarrow, bend left, "X", "\kappa_{\alpha i}\bar{q}_i X Q_\alpha"'] \arrow[d, "\Lambda_{QCD}"] & \text{dark quarks} \arrow[d, "\Lambda_D"] \\
K, \pi, D, B, \ldots \arrow[r, leftrightarrow, bend right, "\frac{\kappa_{\alpha i}\kappa^*_{\beta j}}{m_X^2} f_D \partial_\mu \pi^{\alpha\beta} (\bar{q}_i \gamma^\mu q_j)"'] & \pi_D
\end{tikzcd}$$

$\uparrow$ „dark pion decay constant"

$n_F = 2 \rightarrow 3$ dark pions

$n_F = 3 \rightarrow 8$ dark pions

$\boxed{n_F = 4} \rightarrow 15$ dark pions

} all dark pions decay to SM → dark baryon is DM

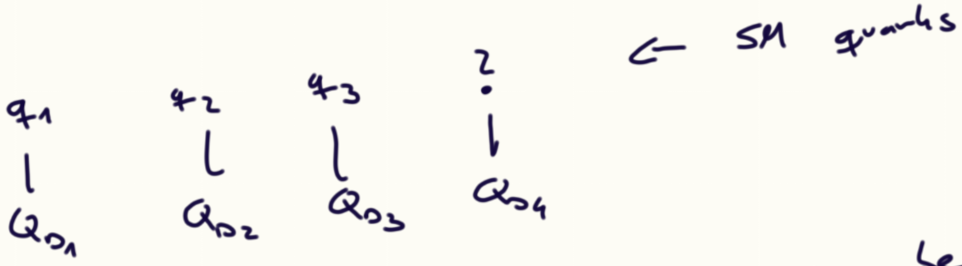
$SU(4)_V \supseteq SU(3) \otimes U(1)$

$15 = 8_0 \oplus 3_0 \oplus \boxed{3_4} \oplus 1_0$ under $SU(3) \otimes U(1)$

↳ charged under dark U(1)

-> can't decay to SM

-> stable -> dark pion DM π_{DM}



intuitiv way to see dark pions can be stable:

decompose coupling as $\kappa = V D U$

$V = 4 \times 4$ hermitian matrix

-> can be rotated away due to dark flavour symmetry if $m_{\alpha\beta} = \delta_{\alpha\beta} m_{Q\alpha\beta}$

$D = 3 \times 4$ diagonal matrix

$U = 3 \times 3$ hermitian matrix

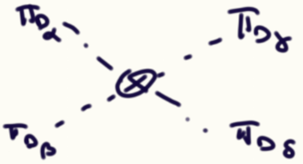
$$\Rightarrow \kappa = \begin{pmatrix} * & * & * \\ * & * & * \\ * & * & * \\ 0 & 0 & 0 \end{pmatrix}$$ -> off-diagonal π_D that contain Q_4 can't decay to SM

-> 3 decaying diagonal π_D

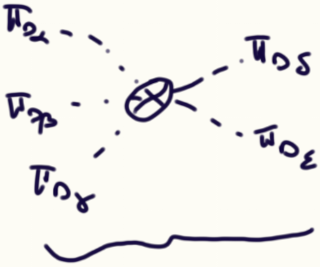
6 decaying off-diagonal π_D

6 stable off-diagonal π_{DM}

2 possible freeze-out processes:



↑
dominant



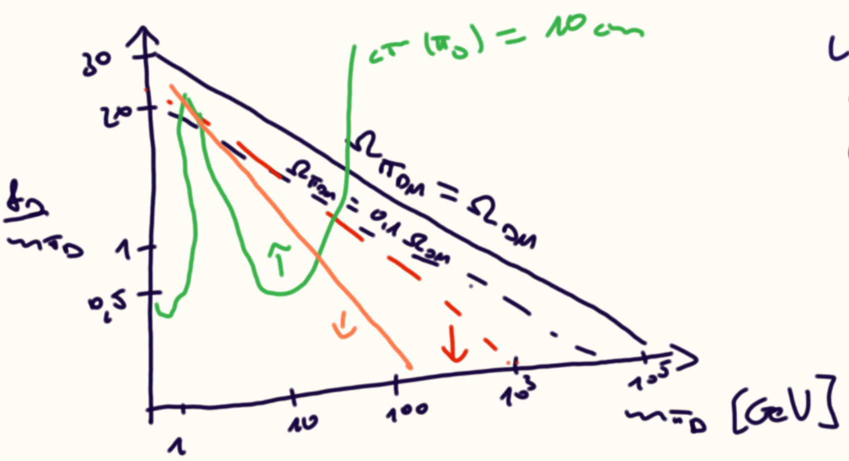
from Wess-Zumino-Witten term

3 assumptions:

1) kinematic equilibrium between π_D & π_{DM}
2) thermal equilibrium between π_D, π_{DM} & SM
3) π_D decay instantly ($\Gamma_{\pi_D} > H$)

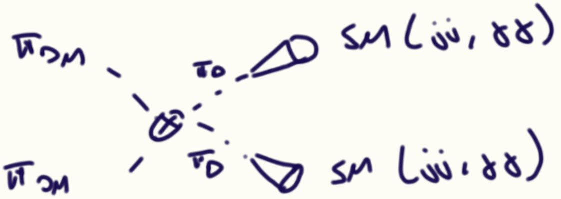
$$\Rightarrow \dot{n}_{DM} + 3 H n_{DM} = - \langle \sigma v^2 \rangle_{2DM \to 2decay} \left[n_{DM}^2 - (n_{DM})_{eq}^2 \right]$$

$$\langle \sigma v^2 \rangle_{2DM \to 2decay} \sim \frac{2 m_{\pi_D}^2}{\pi^{3/2} f_D^4 \sqrt{x}} \qquad x = \frac{m_{\pi_D}}{T}$$

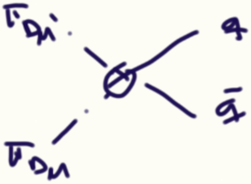


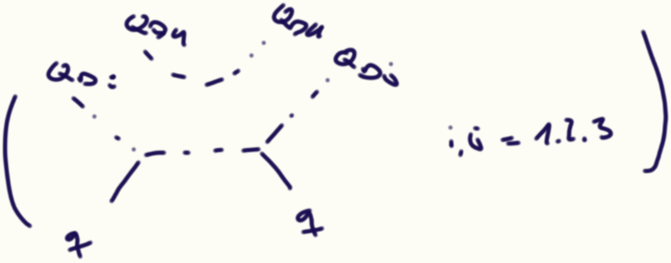
(arrows mark direction of exclusion regions)

indirect detection (Fermi-LAT)



direct detection (XENONnT, LZ, PandaX-4)

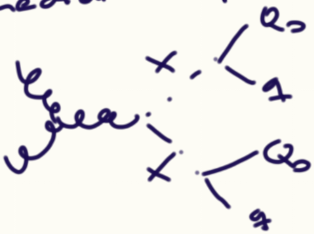


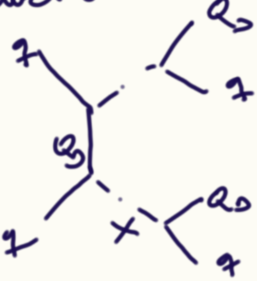


DM self-interactions (CMB Planck Pam)

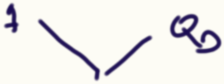
at LHC:

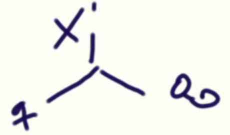
mediator pair-production:





dark quark production





Q_D doesn't couple to SM → only produced in showers → π_{DM} can only be produced in even numbers

signatures:

(— jets + dark jets) (there is always MET from π_{DM}) $m_X \gtrsim 1.5$ TeV

— semi-visible jets (π_D decay prompt) $m_X \gtrsim 2$ TeV

— emerging jets ($c\tau(\pi_D) \sim 1\text{mm} - 1\text{m}$) $m_X \gtrsim 2.5$ TeV

— jets + MET (π_D long-lived/stable on collider scales)

$m_X \gtrsim 1.2 - 1.5$ TeV

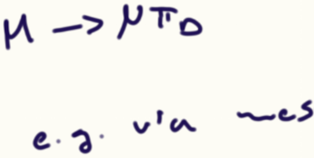
prompt ↗ ↖ long-lived/stable

— semi-visible emerging jets?

— displaced vertices?

other probes

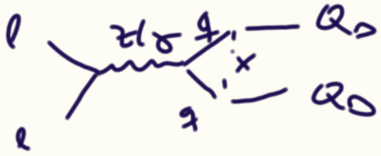
— meson mixing:



— meson decays: $M \to \mu \pi_D$

— fixed target exp. e.g. via meson decays

— FASER, SHiP etc. e.g. via meson decays

— future collider?