Can we generate the DM masses of $\mathcal{O}(1)$ GeV from the QCD vacuum?

based on arXiv:2411.18725

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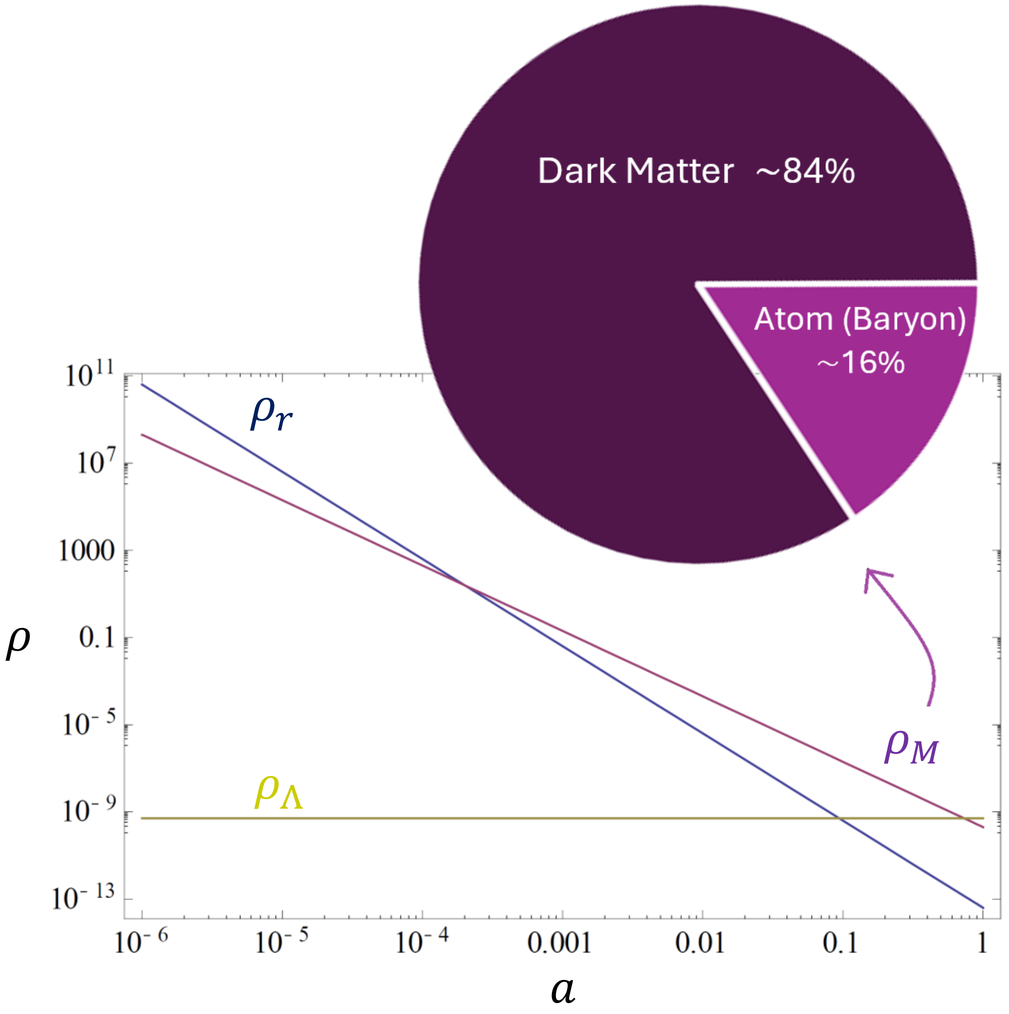
Why?

The Dark Matter-Baryon Coincidence



$\Rightarrow$ Why $\rho_D / \rho_B \approx 5$?

For comparison,

$\rho_{\text{proton}} / \rho_{\text{neutron}} \approx 7$

$\rho_{\text{proton}} / \rho_{\text{electron}} \approx 1800$

More about the DM-Baryon Coincidence

- For non-relativistic particles, the energy density = number density × mass

$$\rho_D/\rho_B = n_D/n_B \times m_D/m_B = 5\ !?$$

from unknown Baryogenesis (n_D/n_B)

from QCD confinement (m_D/m_B)

- For comparison,

$$\rho_p/\rho_n = n_p/n_n \times m_p/m_n = 7$$ (Symmetry!!)

n_p/n_n: $\sim 7 \because SU(2)_F$

m_p/m_n: $\sim 1 \because SU(2)_F$

$$\rho_p/\rho_e = n_p/n_e \times m_p/m_e = 1800$$

n_p/n_e: $\sim 1 \because U(1)_{EM}$

m_p/m_e: ~ 1800

Previous attempts: Asymmetric Dark Matter

- The problem is partly solved in *Asymmetric DM models* [Petraki, Volkas '13; Zurek '13]

$$\rho_D/\rho_B = n_D/n_B \times m_D/m_B = 5\ !?$$

n_D/n_B: $\sim\mathcal{O}(1) \because U(1)_{D-B}$

m_B: from QCD confinement

- For comparison,

$$\rho_p/\rho_n = n_p/n_n \times m_p/m_n = 7 \quad \text{(Symmetry!!)}$$

n_p/n_n: $\sim 7 \because SU(2)_F$; m_p/m_n: $\sim 1 \because SU(2)_F$

$$\rho_p/\rho_e = n_p/n_e \times m_p/m_e = 1800$$

n_p/n_e: $\sim 1 \because U(1)_{EM}$; m_p/m_e: ~ 1800

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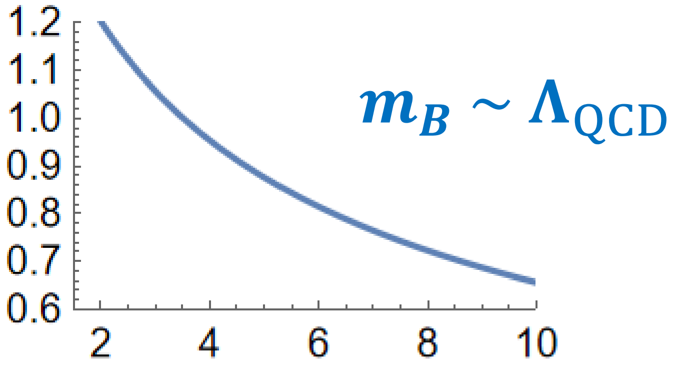
$$\rho_D/\rho_B \;=\; n_D/n_B \;\times\; m_D/m_B \;=\; 5\,!?$$

$\sim\mathcal{O}(1) \because U(1)_{D-B}$



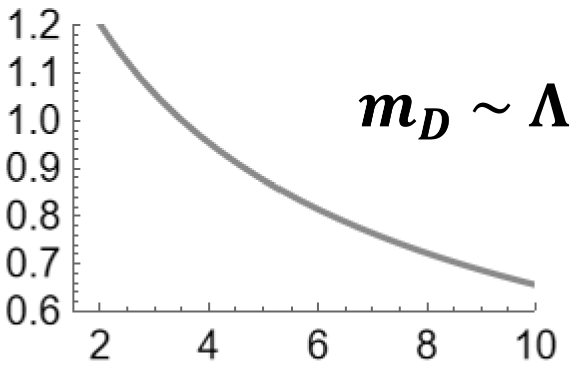
a complete solution should also explain how $m_D \sim \Lambda_{\mathrm{QCD}}$

Previous attempts: Mirror / Unification / IRFT

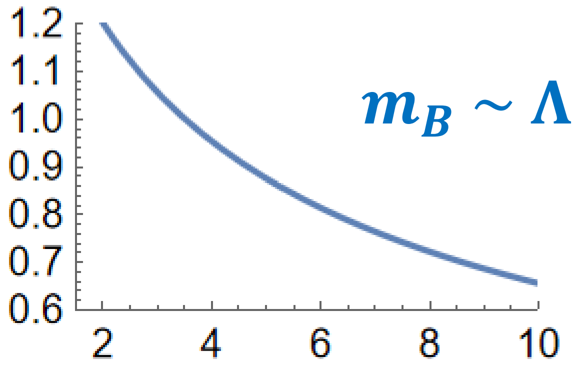
- The problem is partly solved in *Asymmetric DM models* [Petraki, Volkas '13; Zurek '13]

$$\rho_D/\rho_B = n_D/n_B \times m_D/m_B = 5\,!?$$

$\sim\mathcal{O}(1) \because U(1)_{D-B}$



$m_D \sim \Lambda_{\mathrm{DC}}$



$m_B \sim \Lambda_{\mathrm{QCD}}$

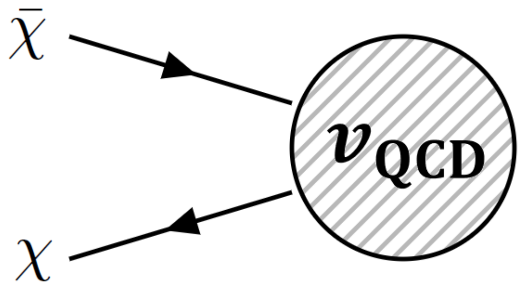
$\sim\mathcal{O}(1) \because \Lambda_{\mathrm{DC}} \sim \Lambda_{\mathrm{QCD}}$ from Symmetry / Dynamics

New attempt: DM masses from QCD vacuum

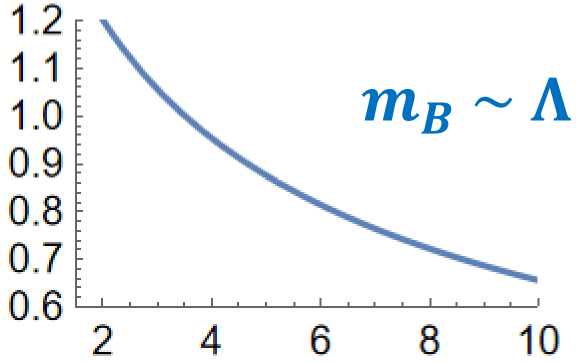
- The problem is partly solved in *Asymmetric DM models* [Petraki, Volkas '13; Zurek '13]

$$\rho_D/\rho_B \;=\; n_D/n_B \;\times\; m_D/m_B \;=\; 5\,!?$$

$\sim\mathcal{O}(1) \because U(1)_{D-B}$



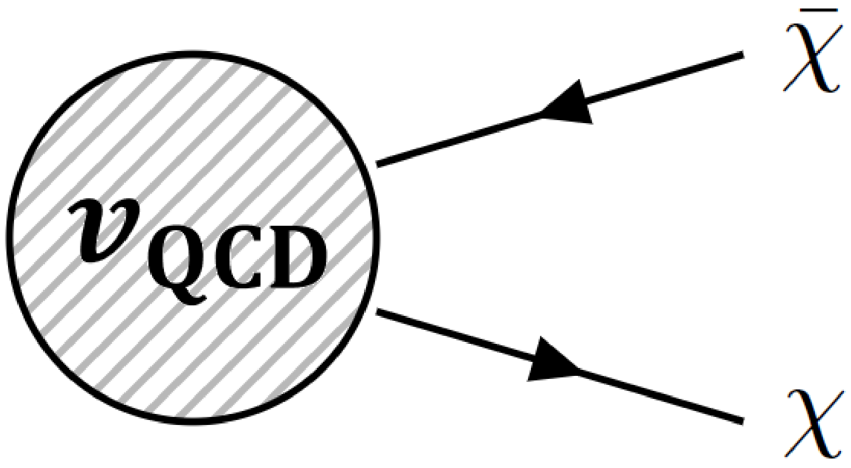
$m_D \sim 4\pi\, v_{\text{QCD}} \sim \Lambda_{\text{QCD}}$



$m_B \sim \Lambda_{\text{QCD}}$

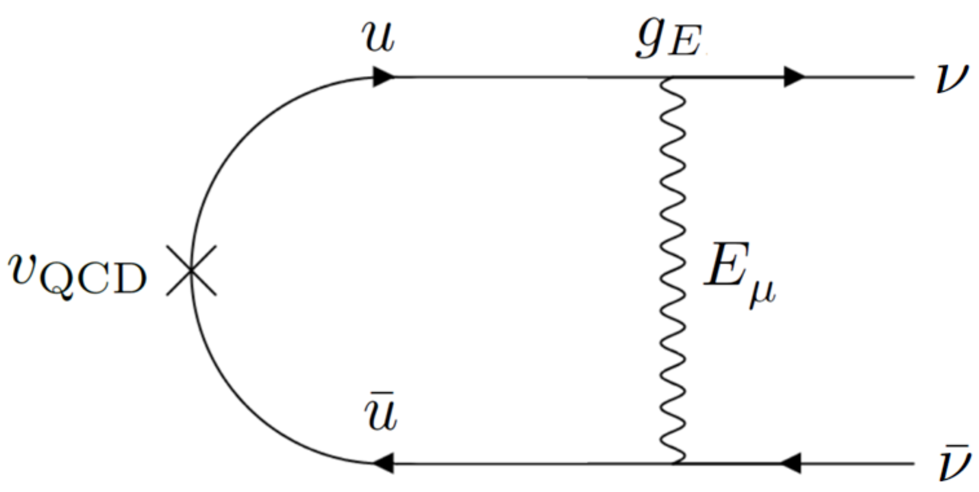
$\sim\mathcal{O}(1) \because$ m_D is also generated from QCD vacuum

How ?

to get  for colorless χ

Neutrino mass from QCD + PS leptoquark

- Example: By including new leptoquark fields from Pati-Salam model, we can mediate quarks and neutrino, which then gets masses from the QCD vacuum



$$\Rightarrow \quad m_\nu \sim \frac{g_E^2}{M_E^2} \langle u\bar{u}\rangle_{\rm QCD} = \frac{\langle u\bar{u}\rangle_{\rm QCD}}{f_E^2}$$

$$\text{with} \quad \langle u\bar{u}\rangle_{\rm QCD} \sim 4\pi\, v_{\rm QCD}^3$$

- DM model: $u \to \psi\,,\ \ v \to \chi$ where ψ is colored and χ is colorless
- For a realistic model, we still need

  (1) ψ to be heavy (2) $\langle \psi\bar{\psi}\rangle \sim 4\pi\, f_E^2\, v_{\rm QCD}$ → **Misalignment in Composite Higgs Models !!**

Misalignment: top mass in CHM with EHC

- Use the $SU(4)/Sp(4)$ Fundamental CHM as an example

  4 Weyl hyperfermions in the fundamental representation of the $Sp(N_{HC})$ hypercolor group

$$(U_L, D_L) = (1,2)_0 \ , \ U_R = (1,1)_{1/2} \ , \ D_R = (1,1)_{-1/2} \Rightarrow F = (U_L, D_L, \tilde{U}_L, \tilde{D}_L)^T$$

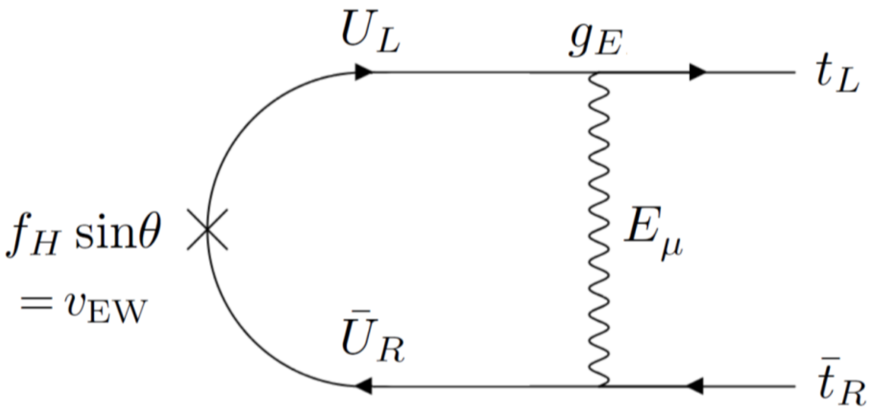
- Two types of condensates can be formed once hypercolor group becomes strongly coupled

$$\langle F\bar{F}\rangle = 4\pi f_H^3 \left(\cos\theta \cdot \Sigma_{EW} + \sin\theta \cdot \Sigma_{E\!\!\!/W}\right) \text{ where } \Sigma_{EW} = f_H \begin{pmatrix} i\sigma_2 & 0 \\ 0 & -i\sigma_2 \end{pmatrix}, \quad \Sigma_{E\!\!\!/W} = f_H \begin{pmatrix} 0 & \mathbb{I} \\ -\mathbb{I} & 0 \end{pmatrix}$$

$$f_H \sin\theta = v_{\text{EW}} = 246 \text{ GeV}$$

the relevant condensate for top quark mass is $\langle U_L \bar{U}_R\rangle = 4\pi f_H^3 \sin\theta = 4\pi f_H^2 v_{\text{EW}}$!!

For hyperfermion: the masses come from condensate $\langle F\bar{F}\rangle = 4\pi f_H^3$ which gives $M_U = M_D \sim 4\pi f_H$



$\Rightarrow$

$$m_t \sim \frac{g_E^2}{M_E^2}\langle U_L \bar{U}_R\rangle = \frac{4\pi f_H^2 v_{\text{EW}}}{f_E^2}$$

$$= y\, v_{\text{EW}} \quad \text{where} \quad y = 4\pi \frac{f_H^2}{f_E^2}$$

Cacciapaglia, Sannino 1508.00016, 2002.04914

DM masses from QCD-triggered misalignment

- Analogous to CHMs, we need similar ingredient in our DM model, including

  Gauge: Hypercolor → Dark Color ; EHC → Pati-Salam , **Fermion:** $U, D \rightarrow \psi, \psi'$; $t \rightarrow \chi$

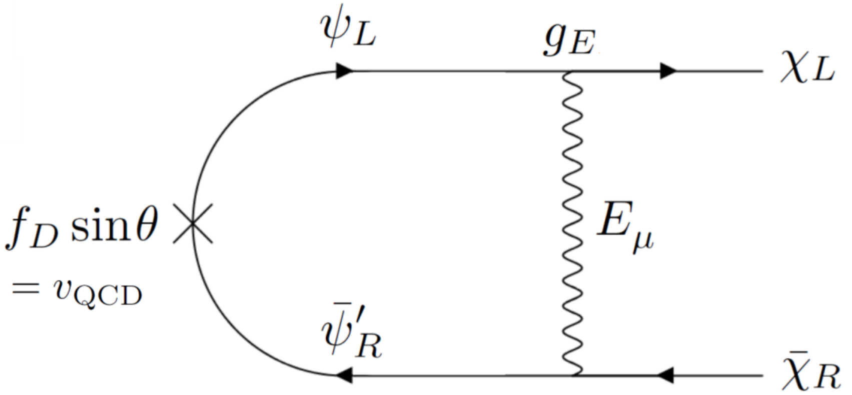
- In minimal setup, we introduce 2 Dirac dark fermions ψ, ψ' in the fundamental representation of both the *SU(N)*$_D$ dark color and *SU(3)*$_C$ color group with $SU(2)_L \times SU(2)_R$ global symmetry

- Again, two types of condensates can be formed once dark color becomes strongly coupled

$$\langle \Psi\bar{\Psi} \rangle = 4\pi\, f_D^3 \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \xrightarrow{\text{QCD}} 4\pi\, f_D^3 \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \quad \text{with} \quad f_D \sin\theta = v_{\text{QCD}} \sim 0.1 \text{ GeV}$$

where the DM χ only couples to the off-diagonal vacuum through PS leptoquarks

For colored DFs: the masses come from condensate $\langle \Psi\bar{\Psi} \rangle = 4\pi f_D^3$ which gives $M_\psi = M_{\psi'} \sim 4\pi f_D$



$$\Rightarrow \quad m_\chi \sim \frac{g_E^2}{M_E^2} \langle \psi_L \bar{\psi}'_R \rangle = \frac{4\pi\, f_D^2\, v_{\text{QCD}}}{f_E^2} = \left(4\pi \frac{f_D^2}{f_E^2} \right) v_{\text{QCD}}$$

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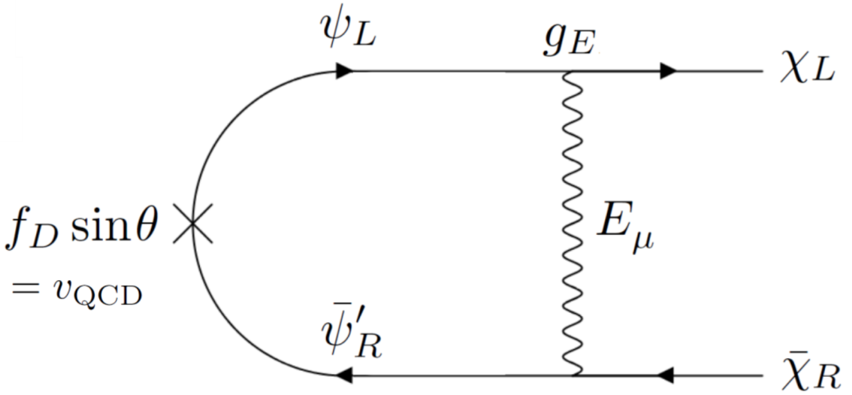

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$$= \left(4\pi \frac{f_D^2}{f_E^2} \right) v_{\text{QCD}} \xrightarrow{f_D = f_E} 4\pi v_{\text{QCD}}$$

Last step: a "Chiral" strongly coupled theory

- What does $f_D = f_E$ mean?

1. The extended gauge group (Patil-Salam) is broken by dark color dynamics
2. The dark matter/fermion χ should be part of dark color sector but remain massless

$\Rightarrow$ A strongly coupled theory with a massless fermion $\Rightarrow$ A chiral gauge theory !!

- Example: SU(5) with anti-symmetric A + anti-fundamental $\bar{F}$

	$SU(5)$	$U(1)_5$
A	A	1
$\bar{F}$	$\bar{\square}$	-3

$\Rightarrow$

	$SU(5)$	$U(1)_5$
$A\bar{F}\bar{F}$	1	-5

d.o.f @ low energy

$U(1)_5$ unbroken (can be $U(1)_D$)

Massless Composite Fermion!!

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- Include QCD: SU(5) with anti-symmetric A + anti-fundamental $\bar{F}$ + three pairs of $F, \bar{F}$

	$SU(5)$	$SU(4)$	$SU(3)$
A	A	1	1
$\bar{F}_S$, $\bar{F}_T$	$\bar{\square}$	$\bar{\square}$	1
F_T	$\square$	1	$\square$

$\Rightarrow$

	$SU(3)_C$	$U(1)_5$
$\chi_L = A\bar{F}_S\bar{F}_S$	1	-5
$\psi_L = A\bar{F}_S\bar{F}_T$	$\bar{\square}$	$-7/3$
$\psi_R = (A\bar{F}_S)^c F_T$	$\square$	$+7/3$

Massless Weyl baryon $m_\chi = 0$!!

Massive Dirac baryon $m_\psi \sim \Lambda_{DC}$ which is charged under $SU(3)_C$

Gauge : $SU(4) \times SU(3) \times U(1)_X \rightarrow SU(3)_C \times U(1)_Y$ with massive leptoquark $U_1(E_\mu)$ + G' + Z'

UV complete theory: "54321 model" !?

- Need to add a copy $SU(5)'$ to (1) cancel anomalies (2) generate DM mass
- Gauge group: $(SU(5) \times SU(5)' \rightarrow \boldsymbol{SU(5)_D}) \times \boldsymbol{SU(4)_h} \times \boldsymbol{SU(3)_\ell} \times \boldsymbol{SU(2)_W} \times \boldsymbol{U(1)_X}$
- Fermion/Baryon content:

	$SU(5)$	$SU(5)'$	$SU(5)_D$	$SU(4)_h$	$SU(3)_\ell$	$U(1)_X$
A	A	1	A	1	1	0
$\bar{F}$	$\bar{\Box}$	1	$\bar{\Box}$	$\bar{\Box}$	1	$-1/2$
F	$\Box$	1	$\Box$	1	$\Box$	$+2/3$
$\bar{A}'$	1	$\bar{A}$	$\bar{A}$	1	1	0
F'	1	$\Box$	$\Box$	$\Box$	1	$+1/2$
$\bar{F}'$	1	$\bar{\Box}$	$\bar{\Box}$	1	$\bar{\Box}$	$-2/3$

$\xrightarrow{\Lambda_{DC}}$ $\Rightarrow$

	$SU(3)_C$	$U(1)_5$	$U(1)_Y$
$\chi_L = A\bar{F}_S\bar{F}_S$	1	-5	0
$\psi_L = A\bar{F}_S\bar{F}_T$	$\bar{\Box}$	$-7/3$	$+2/3$
$\psi_R = (A\bar{F}_S)^c F_T$	$\Box$	$+7/3$	$-2/3$
$\chi_R = \bar{A}' F'_S F'_S$	1	$+5$	0
$\psi'_R = \bar{A}' F'_S F'_T$	$\bar{\Box}$	$+7/3$	$-2/3$
$\psi'_L = (\bar{A}' F'_S)^c \bar{F}'_T$	$\Box$	$-7/3$	$+2/3$

with LQ $U_1(E_\mu)$ + G' +Z' & dark mesons

massless baryon χ couples strongly to π_D

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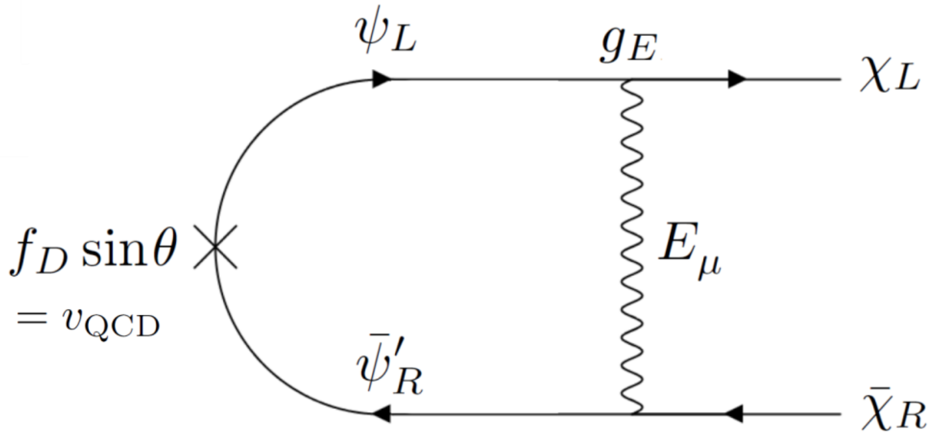
Λ_{QCD} $\Rightarrow$



$$m_\chi \sim 4\pi\, v_{\text{QCD}} \sim \mathcal{O}(1)\ \text{GeV}$$

π_D gets a vev of v_{QCD} and thus χ becomes massive

Summary

- **Why? - Motivation**
  - The **Dark Matter-Baryon Coincidence** is a nontrivial condition
  - The coincidence might be the hint to probe the nature of Dark Matter
  - Previous solutions always have DM masses from the dark color confinement scales Λ_{DC}
- **How? - New attempt**
  - In this study, we try to get **DM masses from QCD vacuum** instead
  - Goal: to propagate QCD vacuum to colorless DM without suppressions
  - Idea: Chiral Dark Color (massless baryon) with QCD-triggered Misalignment ($f^2 v_{\mathrm{QCD}}$)
- **Phenomenology**
  - **Dark pNGBs** – dark pion (ALP) / QCD axion (if anomalous) / dark photon (if gauged)
  - **Self-interaction** – can explain the observed small-scale structure "core-cusp problem"