Caltech

Dark(Color)Unification

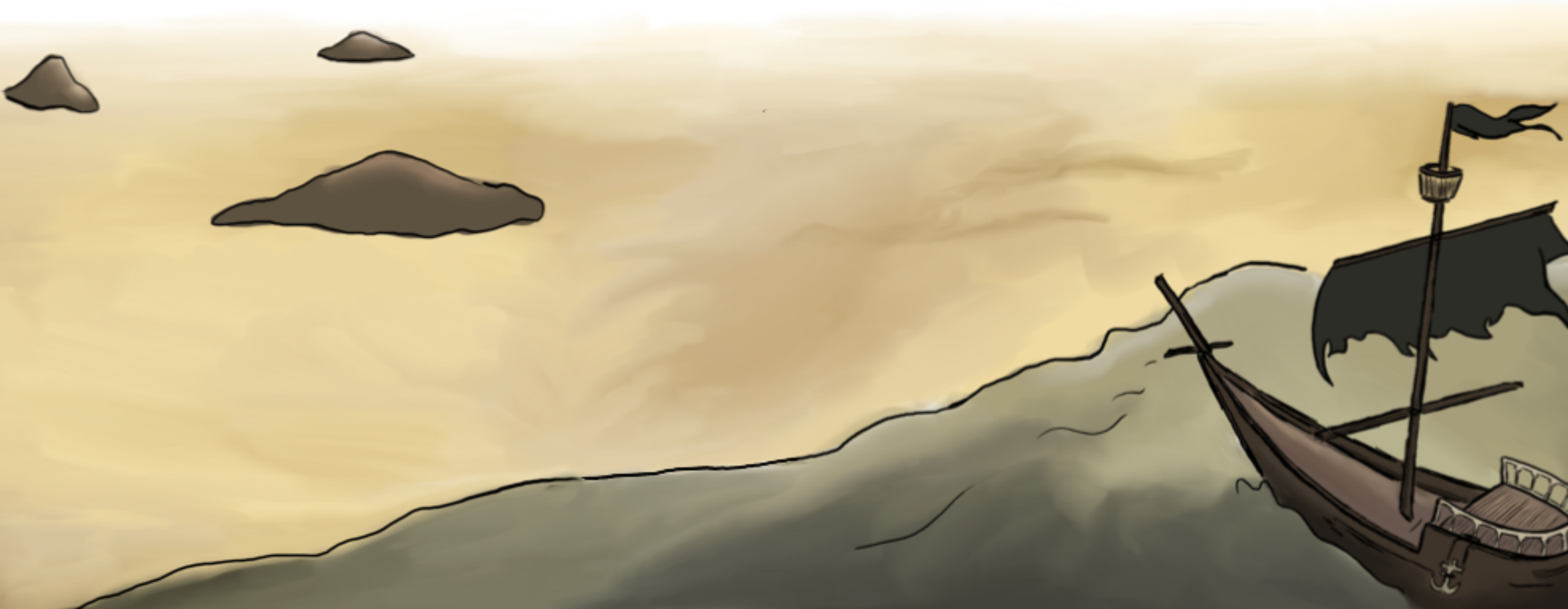
A UV-complete theory for Asymmetric Dark Matter

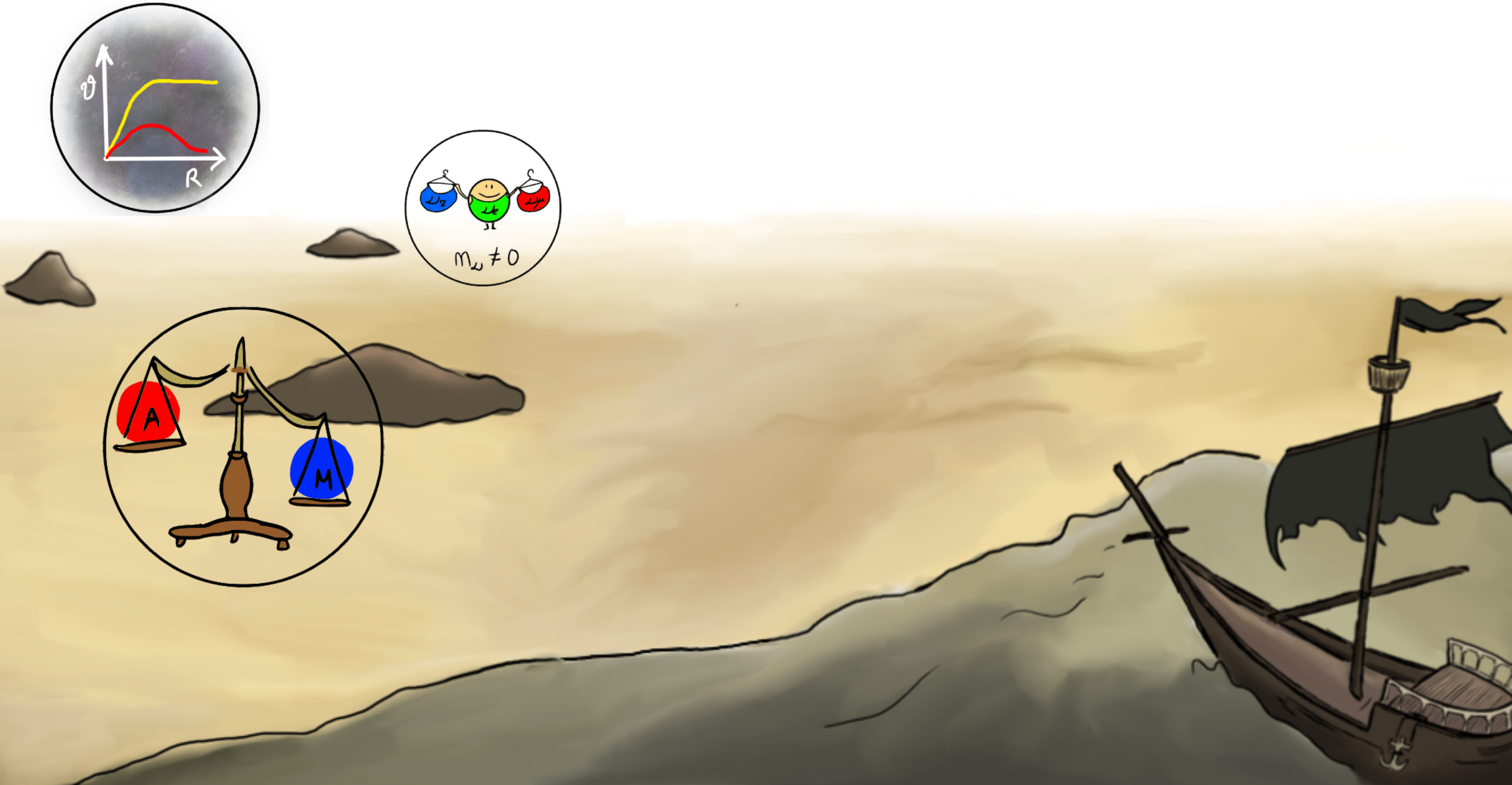
Clara Murgui

In collaboration with Kathryn M. Zurek (Caltech)

June 9th 2022

PPC St. Louis





v
R
ν_τ
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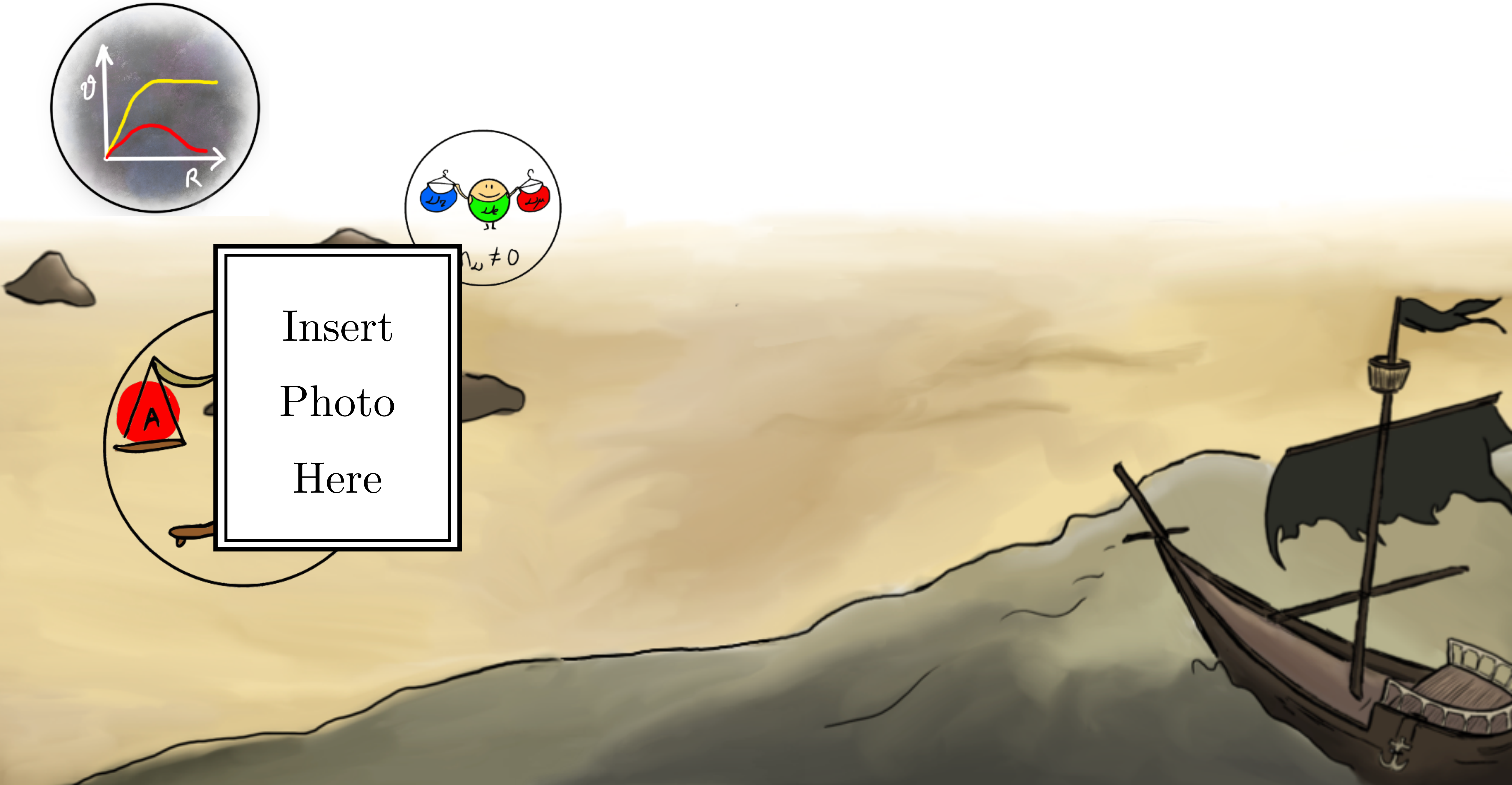
ν_μ
$m_\nu \neq 0$
A
M

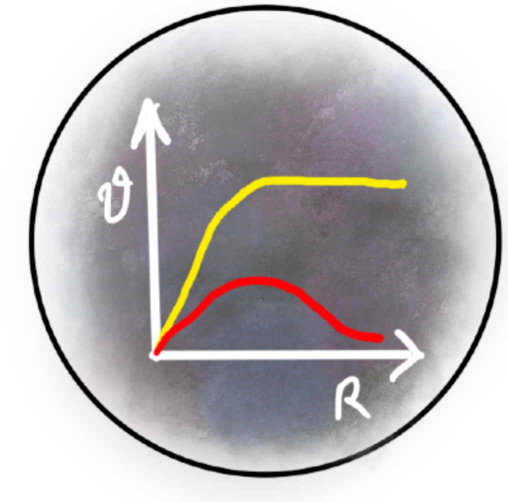


Insert

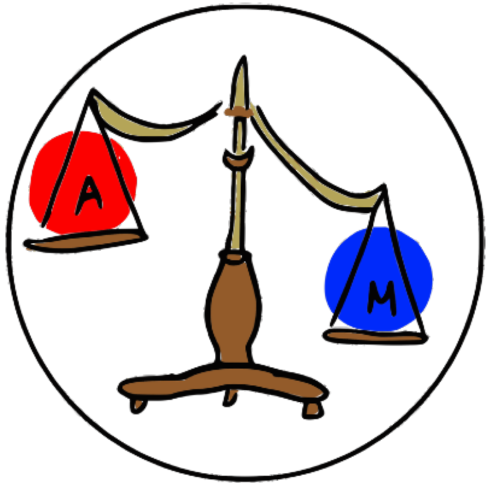
Photo

Here

Just a coincidence?



$$\frac{\Omega_{\rm DM}}{\Omega_B} = \frac{m_{\rm DM} Y_{\rm DM}}{m_p Y_B} \sim 5$$



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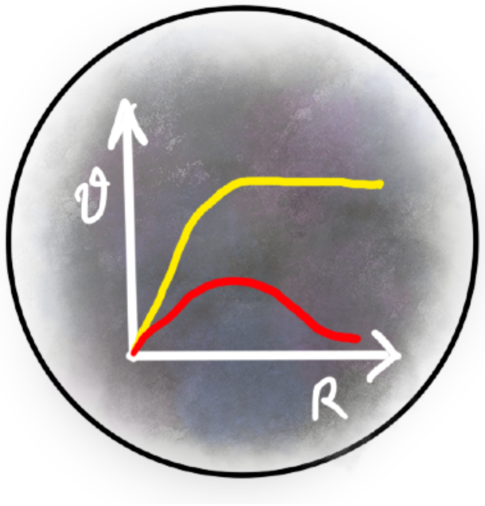

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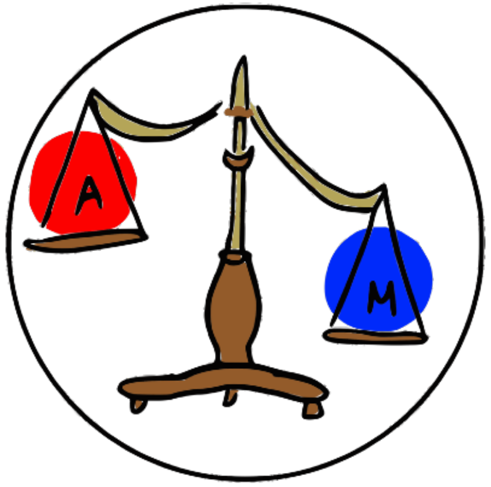
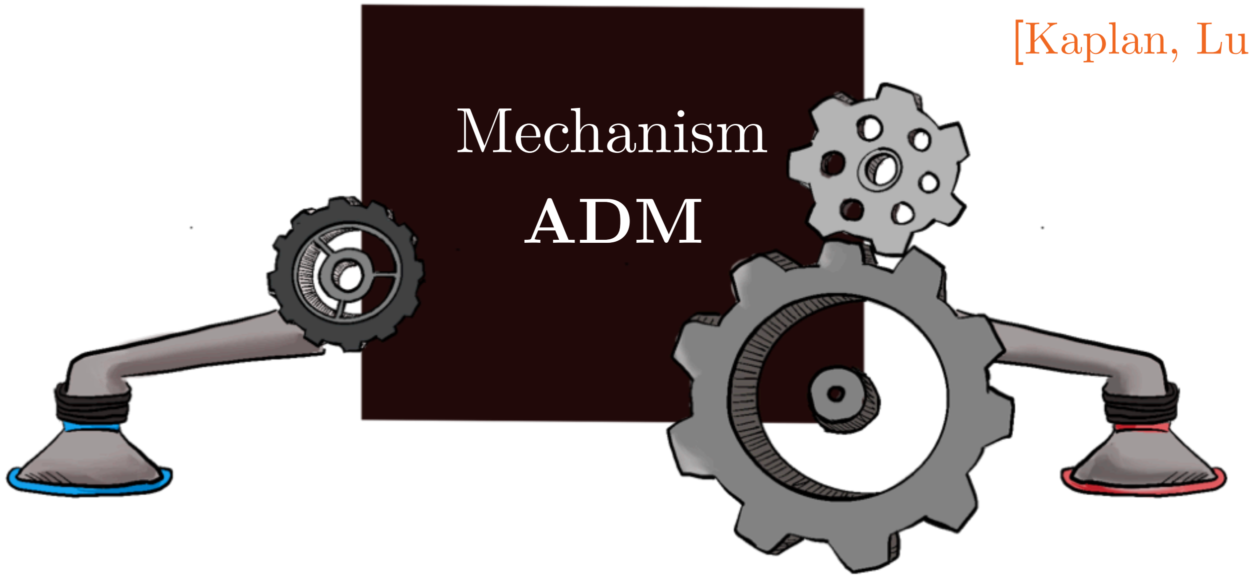


[Kaplan, Luty, Zurek, 2009]

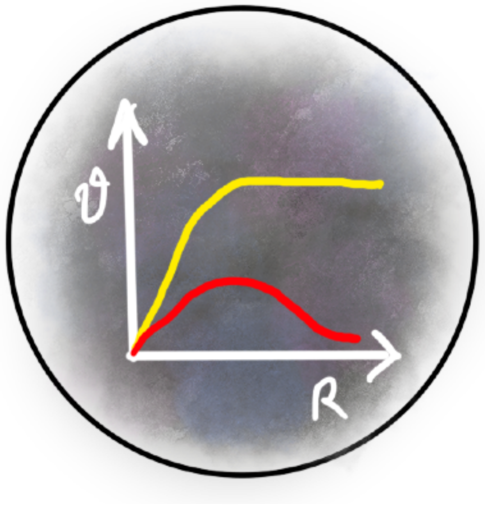


Mechanism

ADM

$$Y_{\Delta B} \sim Y_{\Delta D}$$

Just a coincidence?



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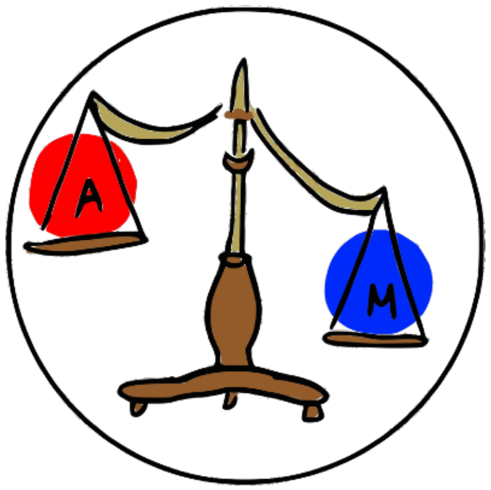

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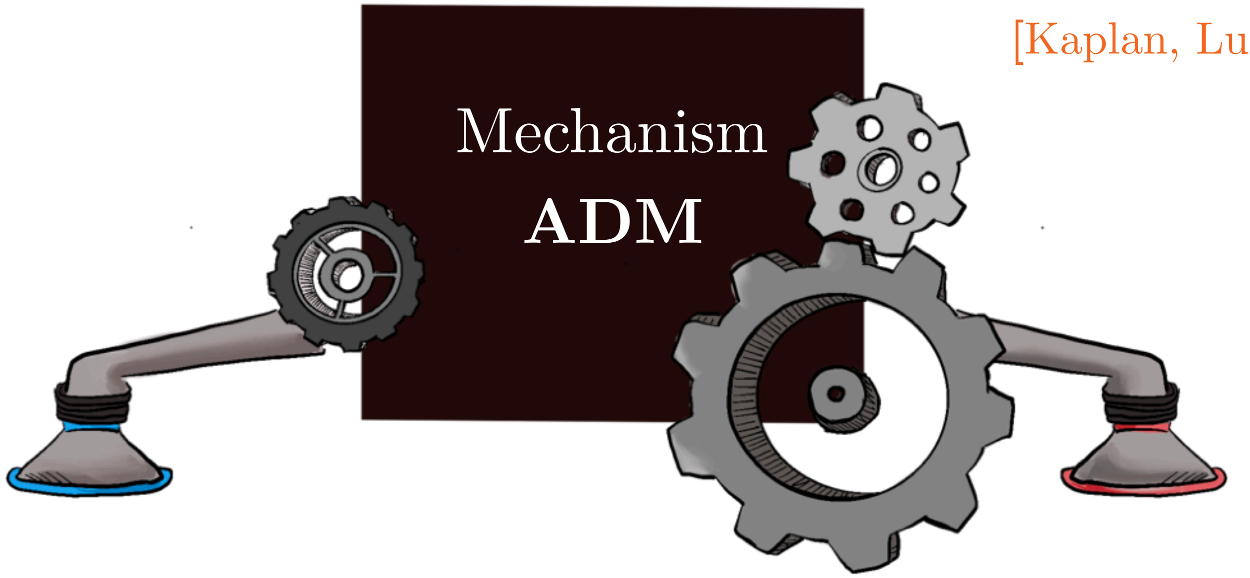
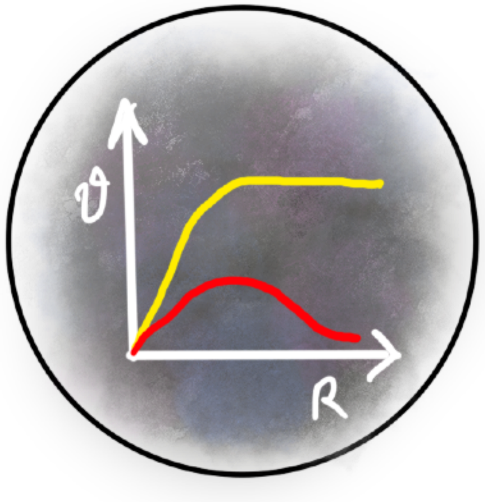


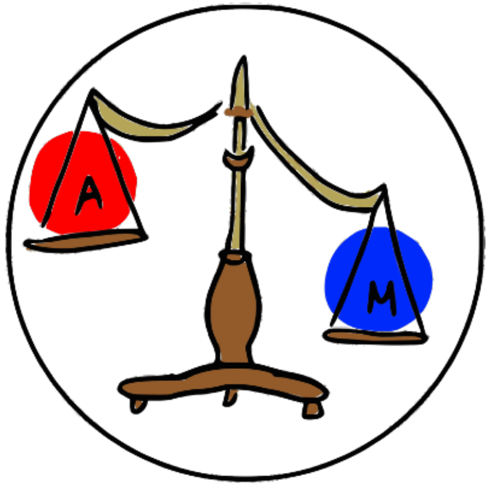
$$Y_{\Delta B} \sim Y_{\Delta D}$$

⇨ $m_{\rm DM} \sim \mathcal{O}(1)\, m_p$?

Just a coincidence?



$$\frac{\Omega_{\mathrm{DM}}}{\Omega_B} = \frac{m_{\mathrm{DM}} Y_{\mathrm{DM}}}{m_p Y_B} \sim 5$$



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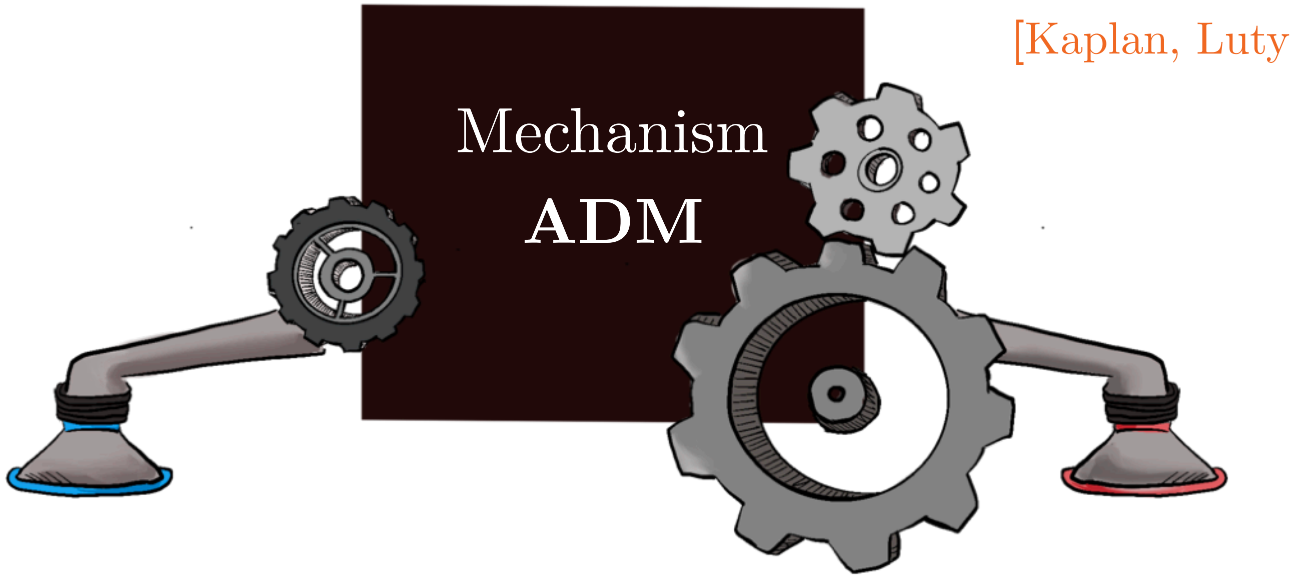
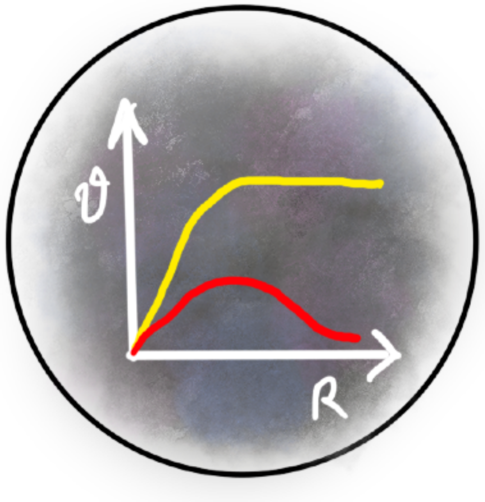


$$Y_{\Delta B} \sim Y_{\Delta D}$$

$$\Rightarrow m_{\mathrm{DM}} \sim \mathcal{O}(1)\, m_p$$

[Foot, Volkas, 2003]
[Foot, Volkas, 2004]
[Lonsdale, Volkas, 2014]
[Lonsdale, 2015]
[Lonsdale, Volkas, 2019]

Just a coincidence?



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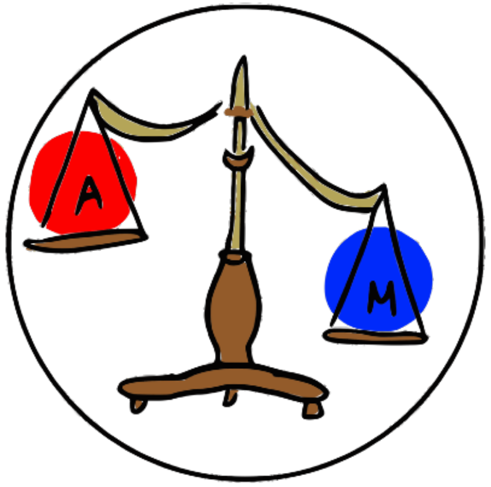

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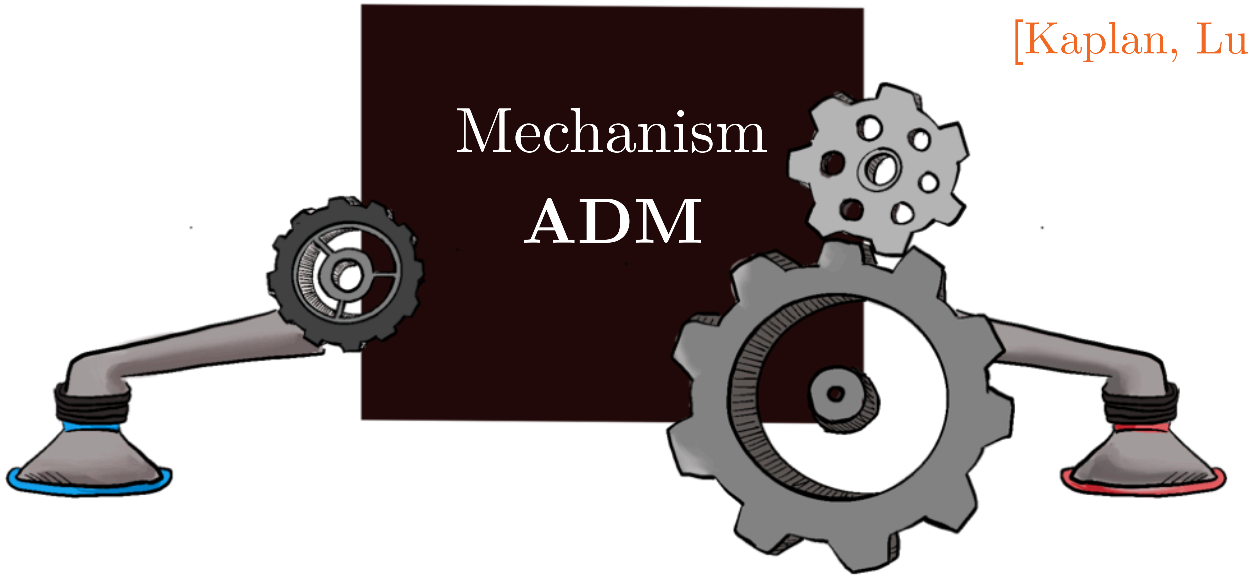

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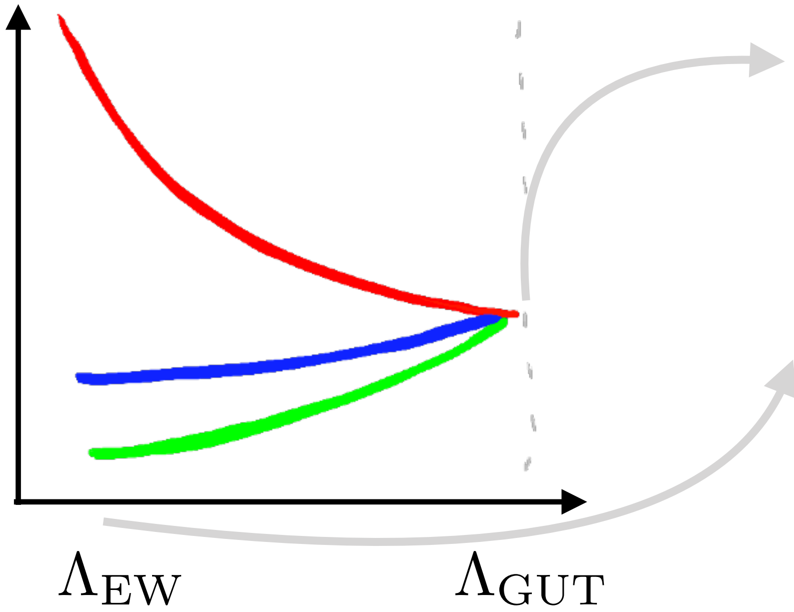
$$Y_{\Delta B} \sim Y_{\Delta D}$$

[Cohen, Phalen, Pierce, Zurek, 2010]

⇨ $m_{\rm DM} \sim \mathcal{O}(1)\, m_p$

The idea: DarkUnification

SU(5)



[Georgi, Glashow, 1974]

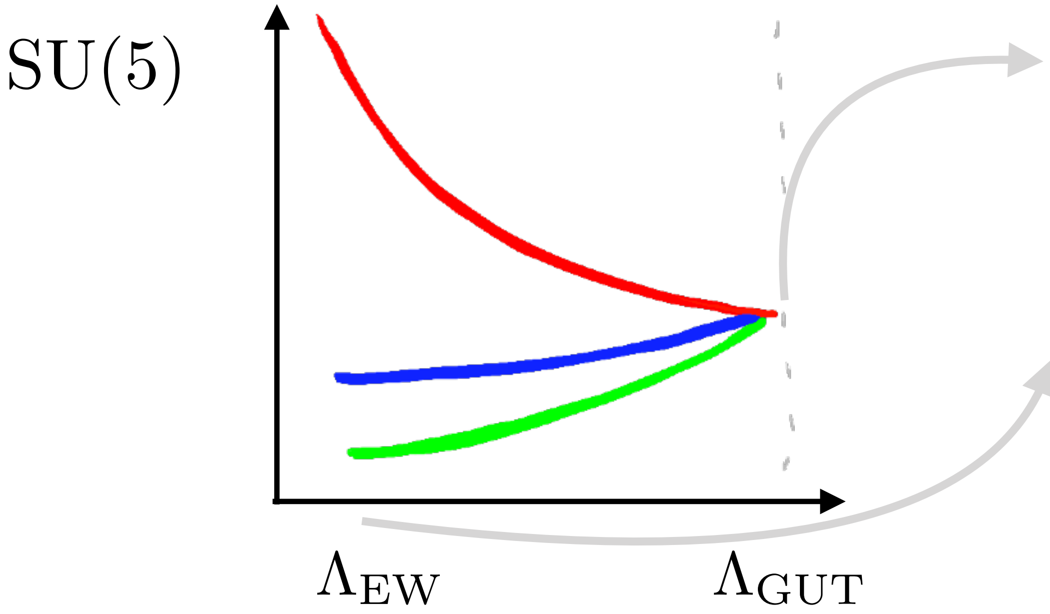
$$\sin^2\theta_{\mathrm{W}}[\Lambda_{\mathrm{GUT}}] = \frac{\alpha_Y}{\alpha_2+\alpha_Y} = \frac{\frac{3}{5}\alpha_1}{\alpha_2+\frac{3}{5}\alpha_1} = \frac{3}{8}$$

$$\downarrow \ll E$$

$$\sin^2\theta_W[\Lambda_{\mathrm{EW}}] = 0.21$$

$$[= 0.231]$$

The idea: DarkUnification



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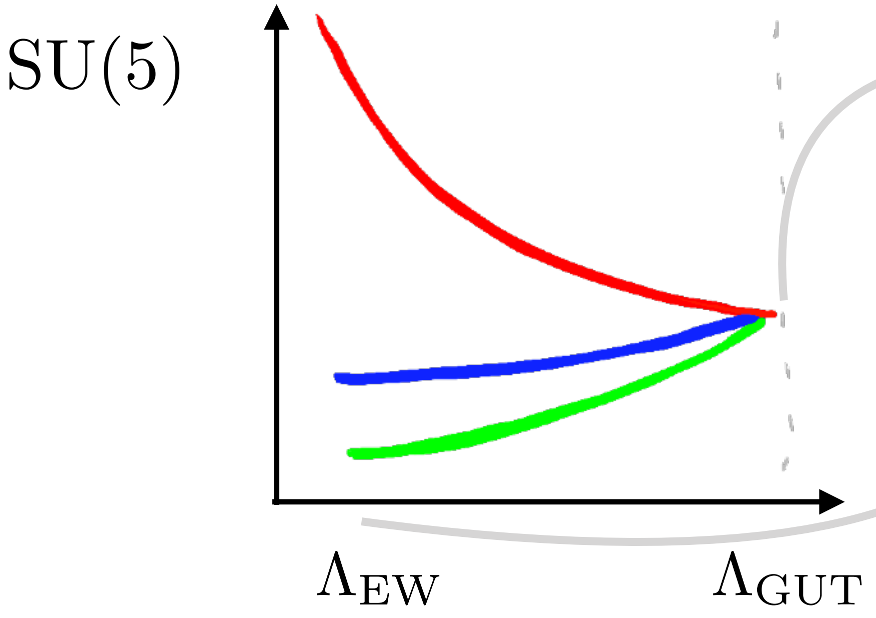
The idea: DarkUnification



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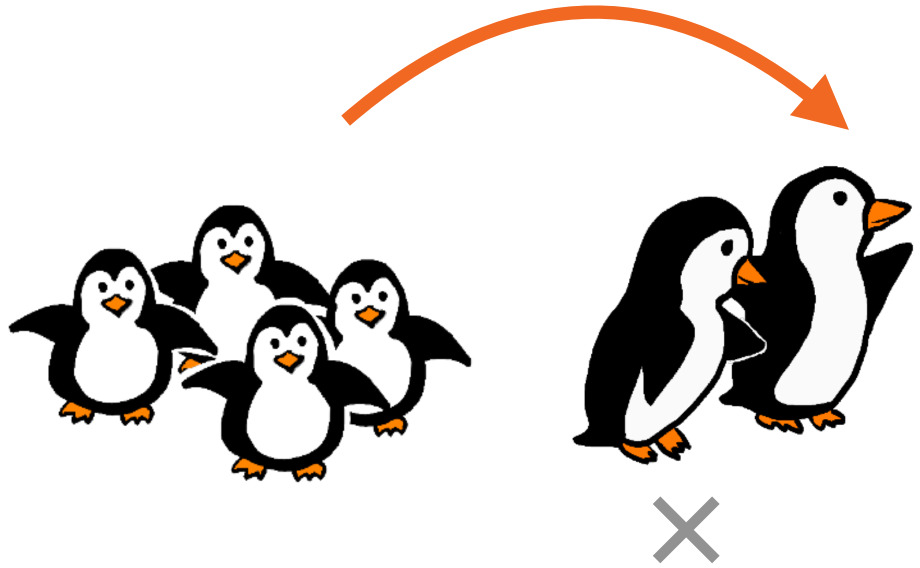
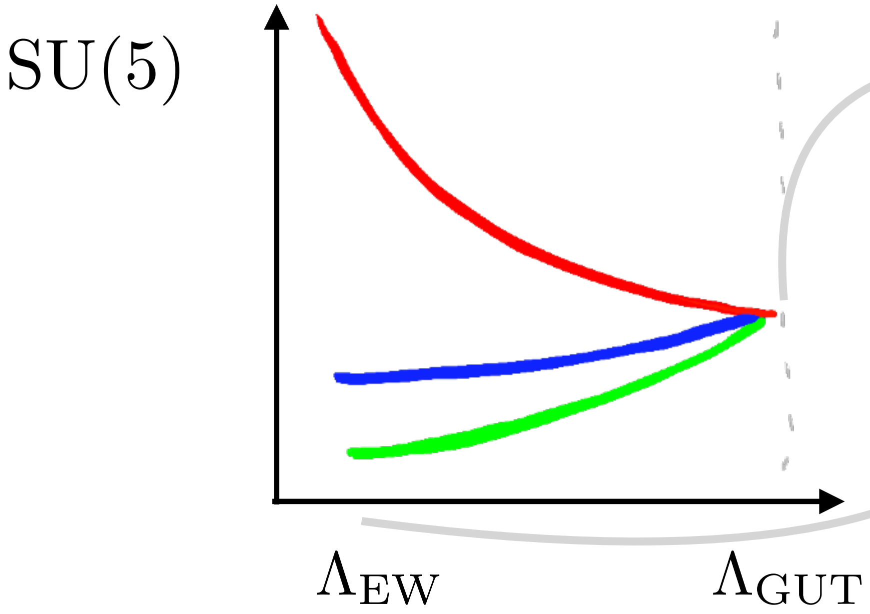


1 Pick subjects of similar nature

2 Common starting point

The idea: DarkUnification



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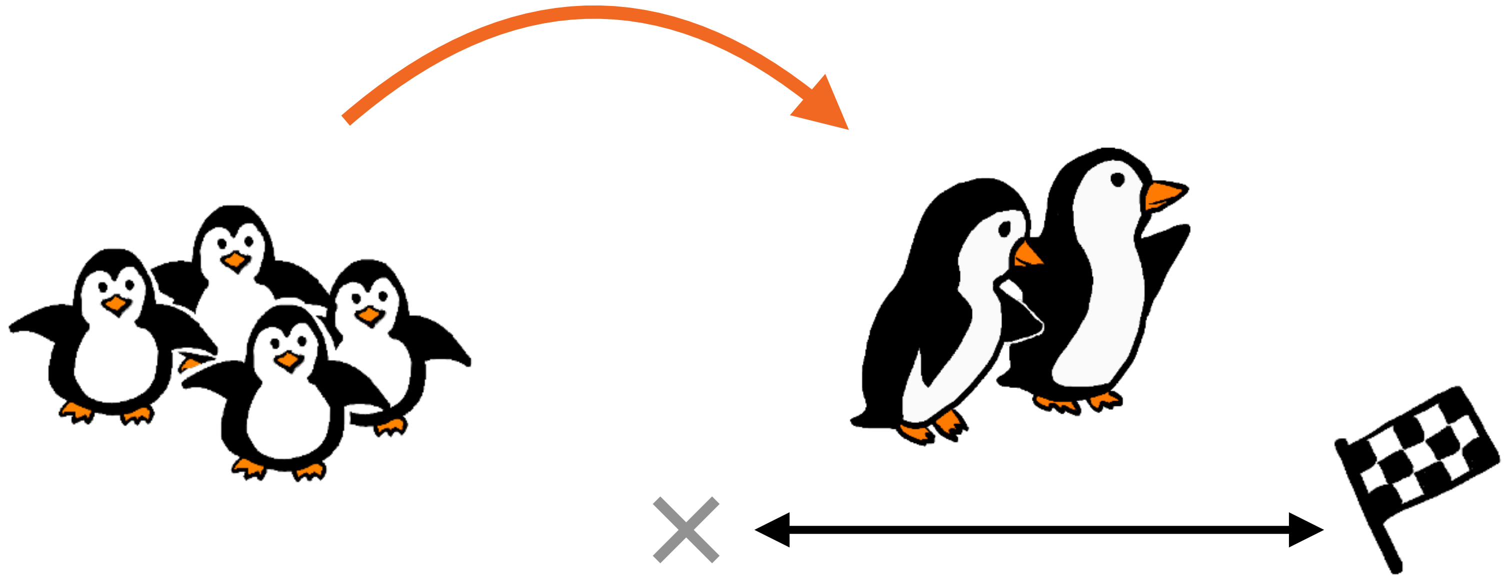
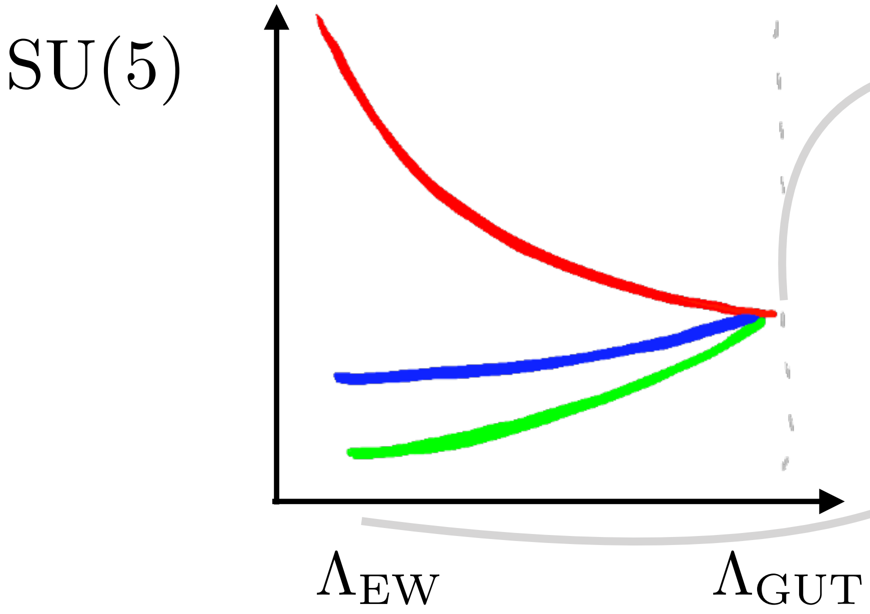


1 Pick subjects of similar nature

2 Common starting point

3 Don’t let them run too much and...

The idea: DarkUnification



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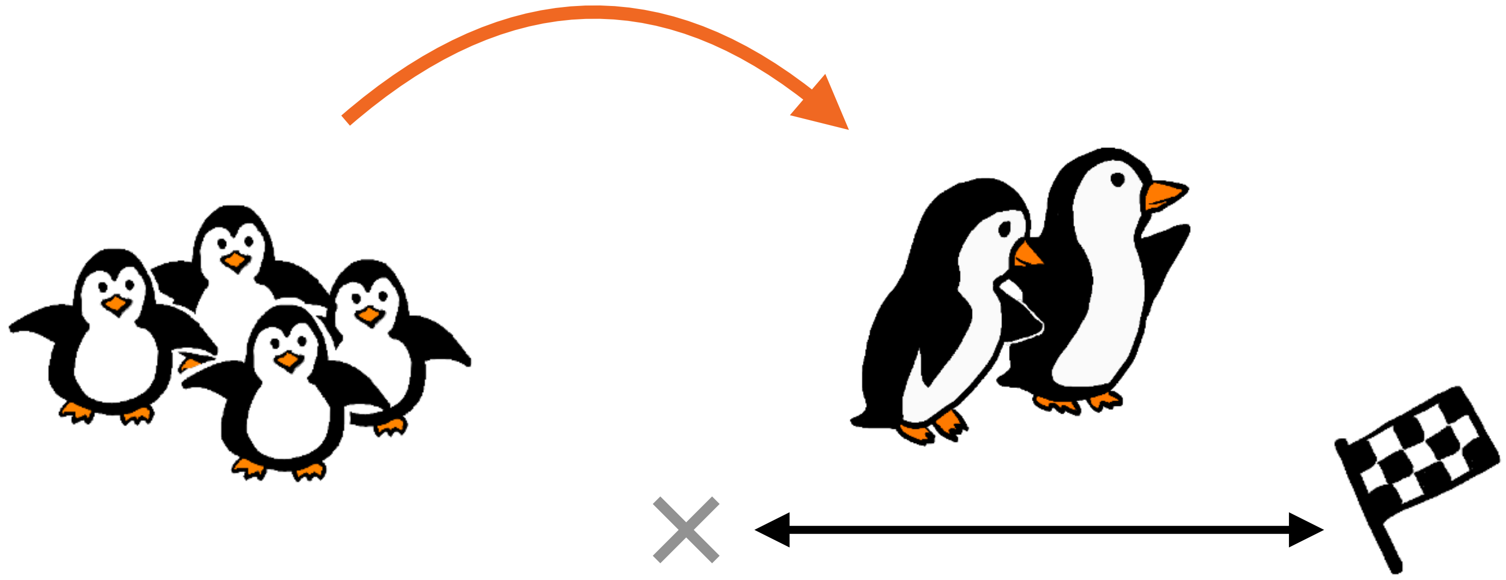

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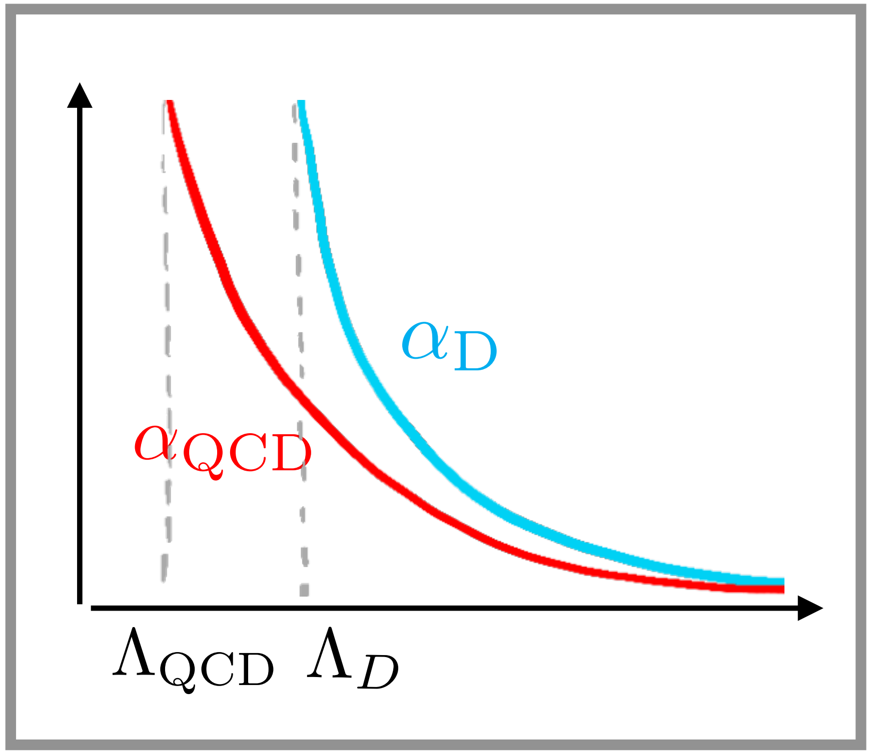
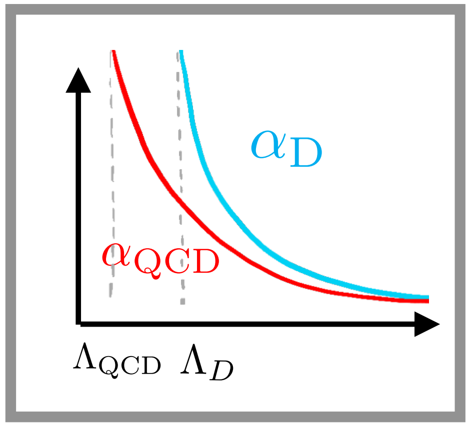


The framework

Hyper-Color

$$\mathrm{SU}(N) \to \mathrm{SU}(3)_C \otimes \mathrm{SU}(N-3)_D \otimes U(1)_N$$



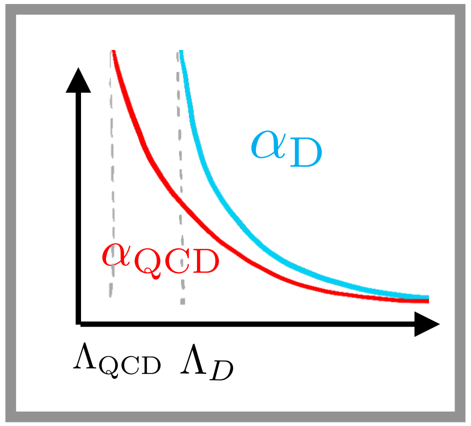
Gauge group:

$$\mathrm{SU}(N) \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_X$$

Hyper-Color

$$\mathrm{SU}(N) \to \mathrm{SU}(3)_C \otimes \mathrm{SU}(N-3)_D \otimes U(1)_N$$

N odd (Witten anomaly)



$$N_Q \sim (N, 2, \#_Q)$$

$$\bar{N}_{u^c} \sim (\bar{N}, 1, \#_{u^c})$$

$$\bar{N}_{d^c} \sim (\bar{N}, 1, \#_{d^c})$$

$$L \sim (1, 2, \tfrac{1}{2})$$

$$e^c \sim (1, 1, 1)$$

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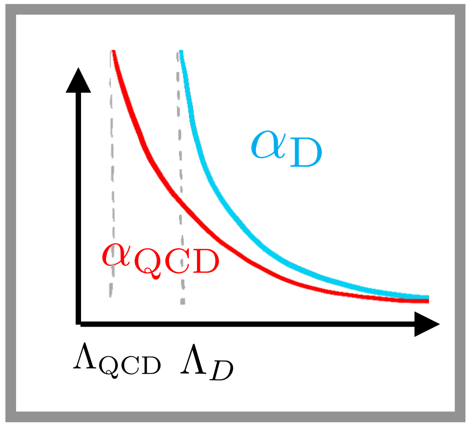

$$N_Q \sim (N, 2, \tfrac{1}{2N})$$

$$\bar{N}_{u^c} \sim (\bar{N}, 1, -\tfrac{N+1}{2N})$$

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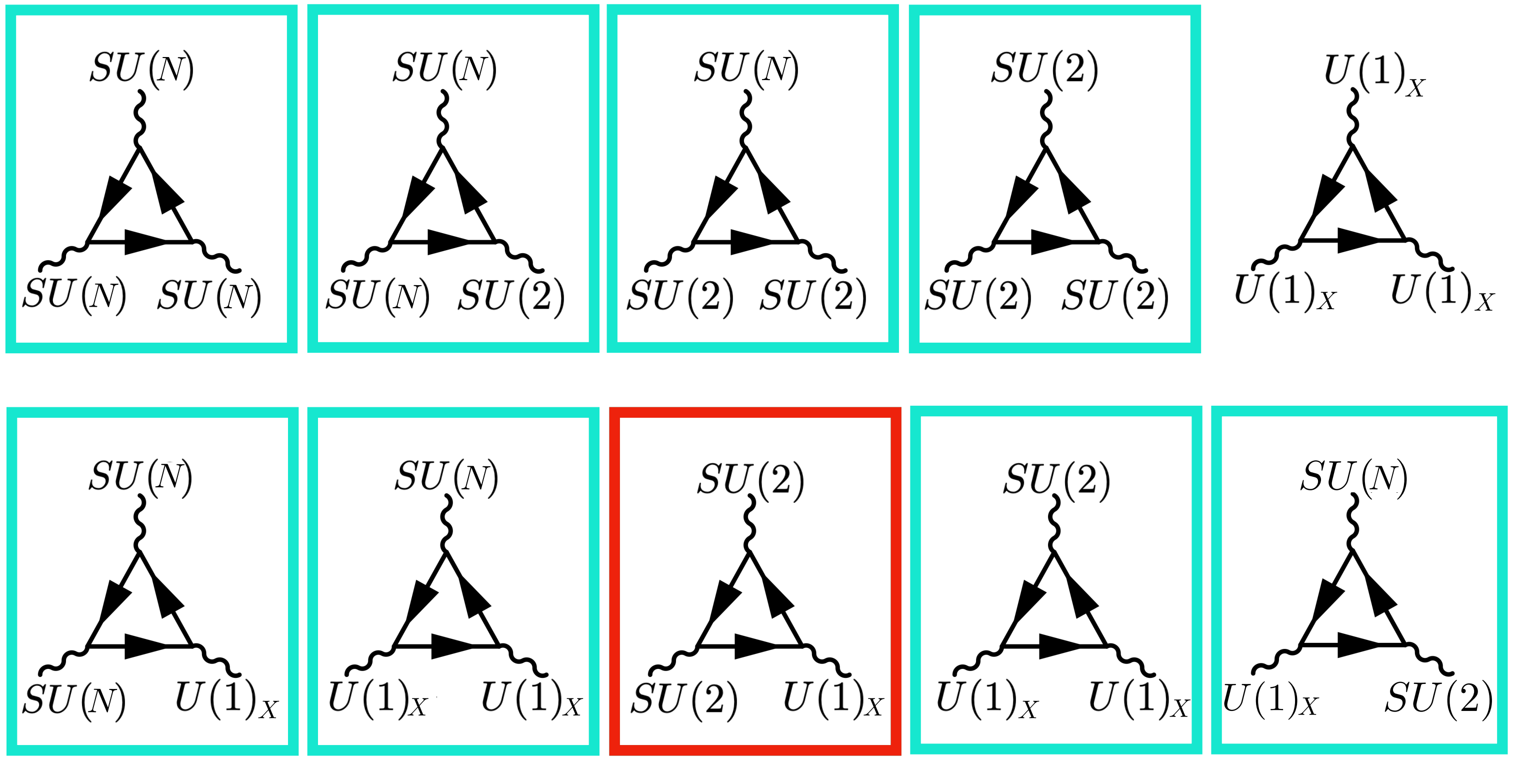
$$L \sim (1, 2, \tfrac{1}{2})$$

$$e^c \sim (1, 1, 1)$$

$$T_{N^2-1} = \frac{1}{\#}\mathrm{diag}(1, 1, 1, -3/N, .., -3/N)$$

gravity anomaly



$$\propto \underbrace{N\#_Q}_{Q} + \underbrace{\frac{1}{2}}_{L}$$

$$\Rightarrow \boxed{\#_Q = 1/(2N)}$$

Hyper-Color

$$\mathrm{SU}(N) \to \mathrm{SU}(3)_C \otimes \mathrm{SU}(N-3)_D \otimes U(1)_N$$

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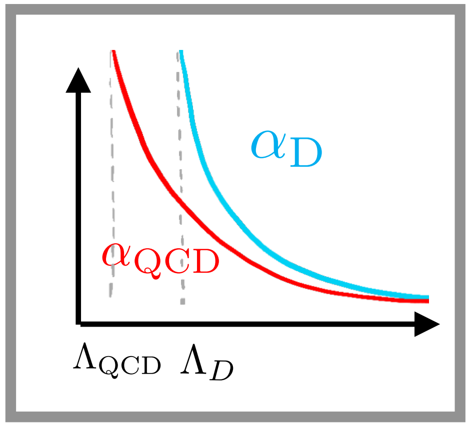

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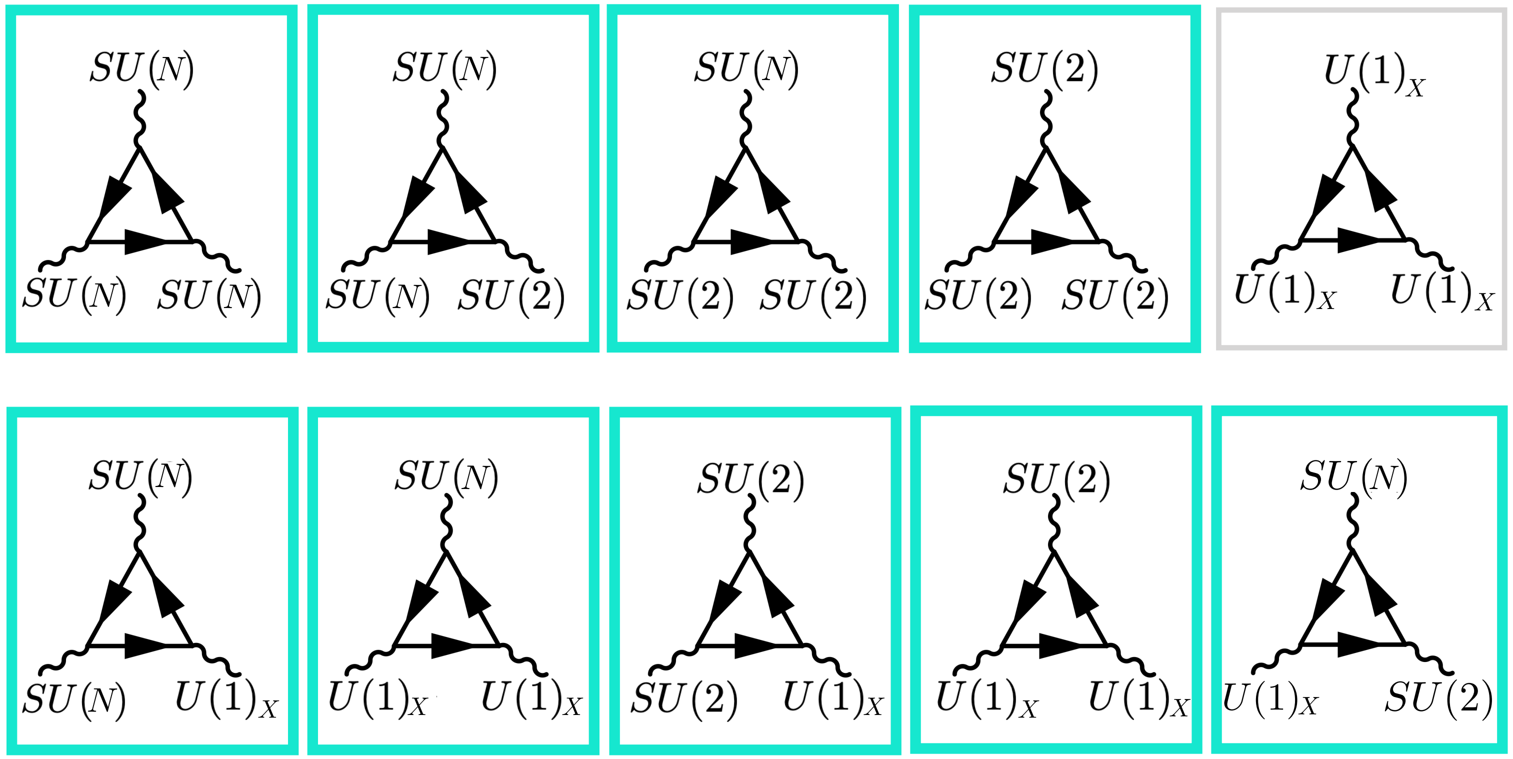
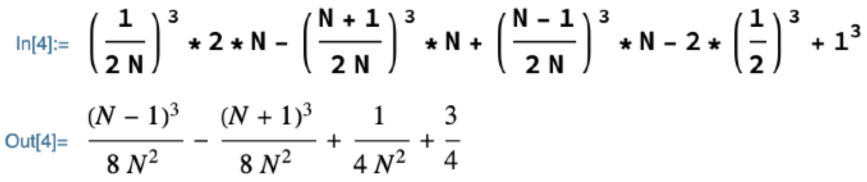




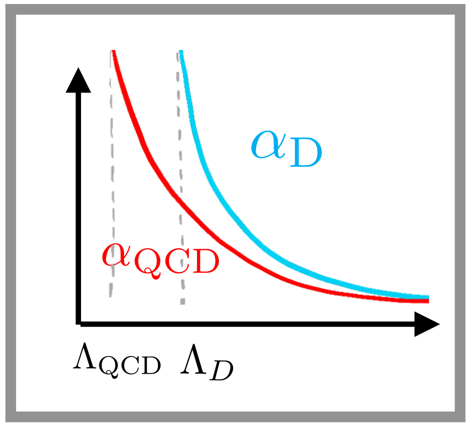
In[4]:= $\left(\frac{1}{2N}\right)^3 * 2 * N - \left(\frac{N+1}{2N}\right)^3 * N + \left(\frac{N-1}{2N}\right)^3 * N - 2 * \left(\frac{1}{2}\right)^3 + 1^3$

Out[4]= $\frac{(N-1)^3}{8N^2} - \frac{(N+1)^3}{8N^2} + \frac{1}{4N^2} + \frac{3}{4}$

Hyper-Color

$$\mathrm{SU}(N) \to \mathrm{SU}(3)_C \otimes \mathrm{SU}(N-3)_D \otimes U(1)_N$$

N odd (Witten anomaly)



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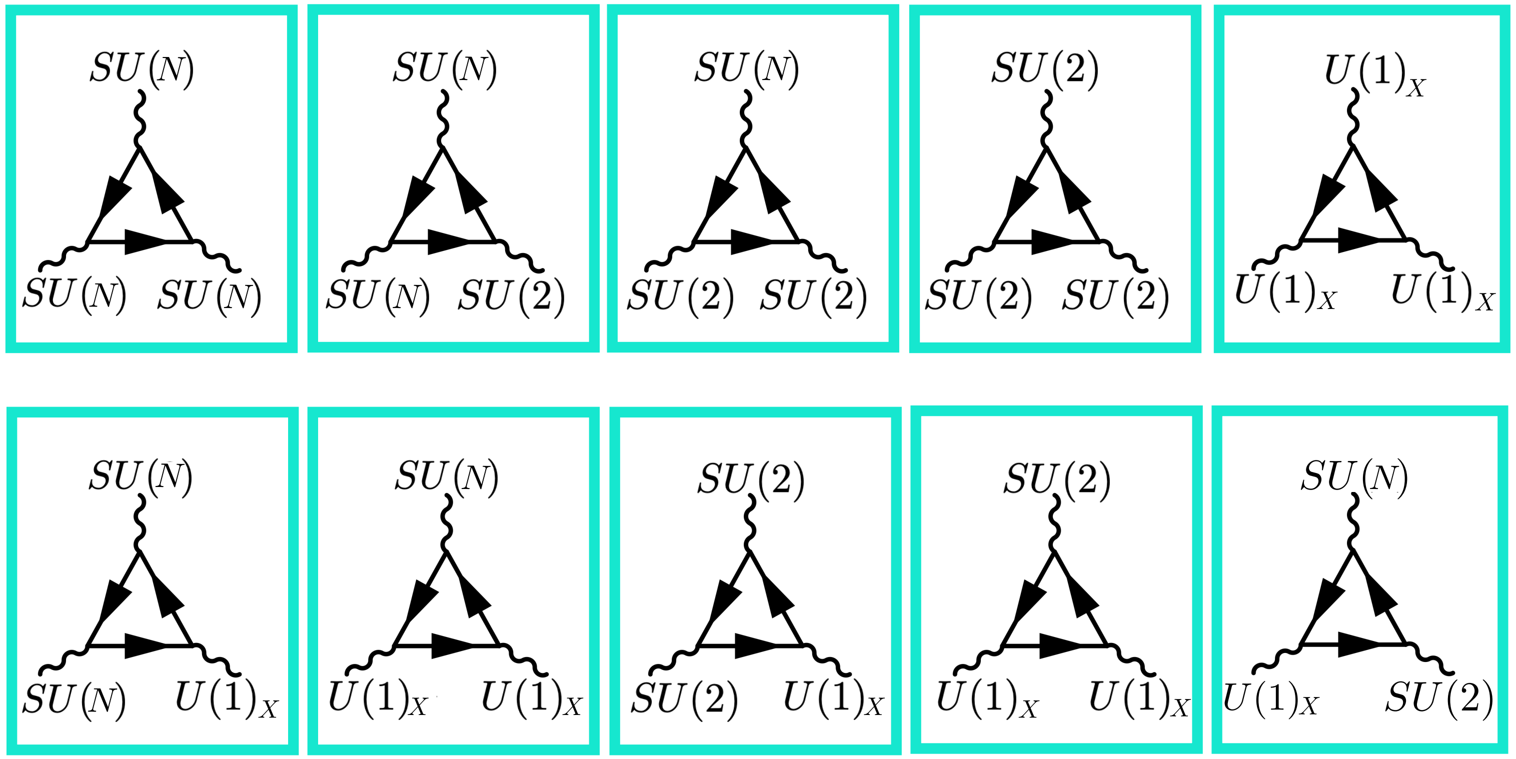

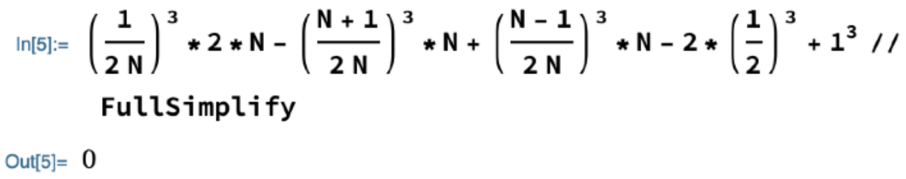

```
In[5]:= (1/(2 N))^3 * 2 * N - ((N + 1)/(2 N))^3 * N + ((N - 1)/(2 N))^3 * N - 2 * (1/2)^3 + 1^3 //
         FullSimplify
Out[5]= 0
```

Hyper-Color

$$\mathrm{SU}(N) \to \mathrm{SU}(3)_C \otimes \mathrm{SU}(N-3)_D \otimes U(1)_N$$

N odd (Witten anomaly)

$$N_q \sim (N, 2, \tfrac{1}{2N})_{\mathcal{G}_N} \sim \begin{pmatrix} q \\ \Psi \end{pmatrix}$$

$$\bar{N}_u \sim (\bar{N}, 1, -\tfrac{N+1}{2N})_{\mathcal{G}_N} \sim \begin{pmatrix} u^c \\ \eta_u \end{pmatrix}$$

$$\bar{N}_d \sim (\bar{N}, 1, \tfrac{N+1}{2N})_{\mathcal{G}_N} \sim \begin{pmatrix} d^c \\ \eta_d \end{pmatrix}$$

$$\begin{pmatrix} \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \end{pmatrix} \begin{matrix} \left.\begin{matrix} \\ \\ \end{matrix}\right\} \mathrm{SU(3)}_c \\ \left.\begin{matrix} \\ \end{matrix}\right\} \mathrm{SU(N\text{-}3)}_D \end{matrix}$$

Quarks

Quirks

[Kang, Luty, 2008],
[Kribs, Roy, Terning, Zurek, 2009]

just SM leptons

$$\begin{pmatrix} \ell \sim (1, 2, \tfrac{1}{2}) \\ e^c \sim (1, 1, 1) \end{pmatrix}$$

$$N \sim (1, 1, 0)$$

type-I seesaw

Hyper-Color

$$\mathrm{SU}(N) \to \mathrm{SU}(3)_C \otimes \mathrm{SU}(N-3)_D \otimes U(1)_N$$

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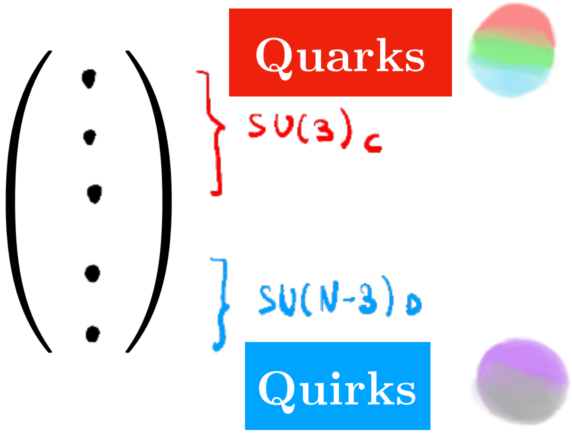

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type-I seesaw

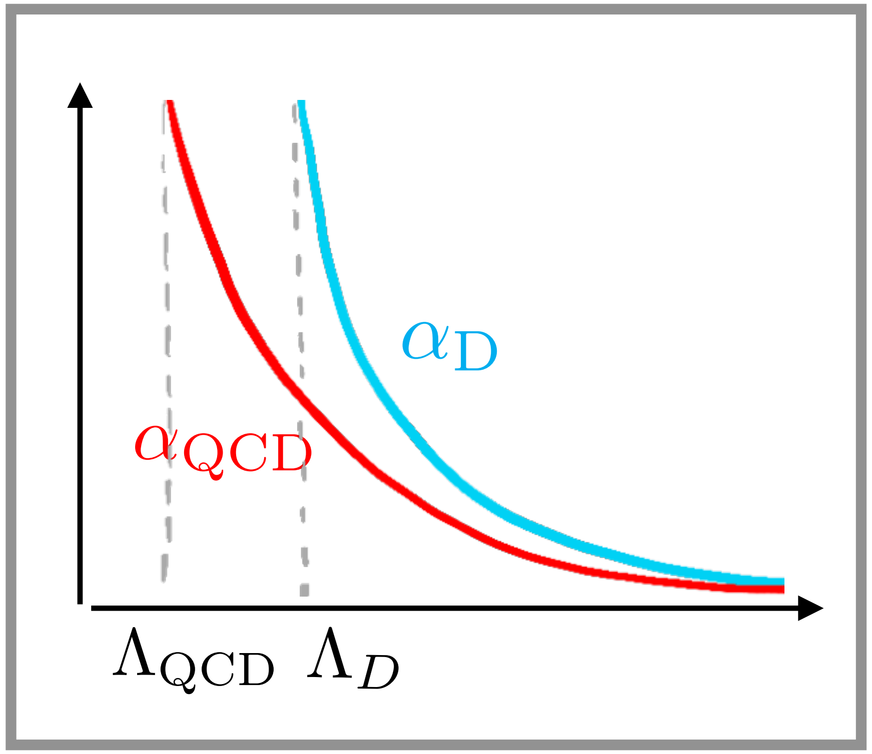
$$\mathcal{L}_{\text{Yuk}} \supset Y_u N_q H \bar{N}_{u^c} + Y_d N_q H^\dagger \bar{N}_{d^c} + \text{h.c.}$$

$$\xrightarrow{\langle H \rangle} M_u \left(1 + \frac{h}{v}\right) [\boxed{u\, u^c} + \boxed{\Psi_u\, \eta_{u^c}}] + M_d \left(1 + \frac{h}{v}\right) [\boxed{d\, d^c} + \boxed{\Psi_d\, \eta_{d^c}}]$$

[See Suchita's talk on Tuesday]

SU(5) Hyper-Color

$$\mathrm{SU}(5) \to \mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_D \otimes \mathrm{U}(1)_5$$



The simplest gauge group

- Gauge group: $\mathrm{SU}(5) \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_X$

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$$q \sim \begin{pmatrix} u \\ d \end{pmatrix} \qquad \Psi \sim \begin{pmatrix} \Psi_u \\ \Psi_d \end{pmatrix}$$

- Minimal matter content:

$$5_q \sim (5, 2, \tfrac{1}{10})_{\mathcal{G}_5} \sim \begin{pmatrix} q \\ \Psi \end{pmatrix}$$

$$\bar{5}_u \sim (\bar{5}, 1, -\tfrac{3}{5})_{\mathcal{G}_5} \sim \begin{pmatrix} u^c \\ \eta_u \end{pmatrix}$$

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- Minimal matter content:

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$$\bar{5}_d \sim (\bar{5}, 1, \tfrac{2}{5})_{\mathcal{G}_5} \sim \begin{pmatrix} d^c \\ \eta_d \end{pmatrix}$$

- Breaking pattern:

$$\mathrm{SU}(5) \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_X \overset{\langle 24_H \rangle}{\to} \mathrm{SU}(2)_D \otimes \mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_5 \otimes \mathrm{U}(1)_X$$

$$24_V \sim (24, 1, 0)_{\mathcal{G}_5} \sim \begin{pmatrix} G^\mu & V^\mu_{\mathrm{DQ}} \sim (3, 1, \tfrac{1}{6}, 2) \\ \dagger & G^\mu_D \sim (1, 1, 0, 3) \end{pmatrix}$$

The simplest gauge group

- Gauge group: $\mathrm{SU}(5) \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_X$

$$q \sim \begin{pmatrix} u \\ d \end{pmatrix} \qquad \Psi \sim \begin{pmatrix} \Psi_u \\ \Psi_d \end{pmatrix}$$

- Minimal matter content:

$$5_q \sim (5, 2, \tfrac{1}{10})_{\mathcal{G}_5} \sim \begin{pmatrix} q \\ \Psi \end{pmatrix}$$

$$\bar{5}_u \sim (\bar{5}, 1, -\tfrac{3}{5})_{\mathcal{G}_5} \sim \begin{pmatrix} u^c \\ \eta_u \end{pmatrix}$$

$$\bar{5}_d \sim (\bar{5}, 1, \tfrac{2}{5})_{\mathcal{G}_5} \sim \begin{pmatrix} d^c \\ \eta_d \end{pmatrix}$$

- Breaking pattern:

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$$\overset{\langle 10_H \rangle}{\to} \mathrm{SU}(2)_D \otimes \mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$$

$$10_H \sim (10, 1, \tfrac{1}{5})_{\mathcal{G}_5}$$

$$\sim \begin{pmatrix} S_1 \sim (\bar{3}, 1, \tfrac{1}{3}, 1) & R_D \sim (3, 1, \tfrac{1}{6}, 2) \\ \text{-T} & \delta_0 \sim (1, 1, 0, 1) \end{pmatrix}$$

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Mass splitting

$$\mathcal{L}_Y \supset Y_u \, 5_q H \bar{5}_u + Y_d \, 5_q H^\dagger \bar{5}_d$$

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$$\mathcal{L}_Y \supset Y_u\, 5_q H \bar{5}_u + Y_d\, 5_q H^\dagger \bar{5}_d$$

$$+ Y_\eta\, \bar{5}_u \bar{5}_d 10_H + Y_\Psi\, 5_q 5_q 10_H^* + \text{h.c.}$$

- Breaking pattern:

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$$\xrightarrow{\langle 10_H \rangle} \mathrm{SU}(2)_D \otimes \mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$$

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Mass splitting

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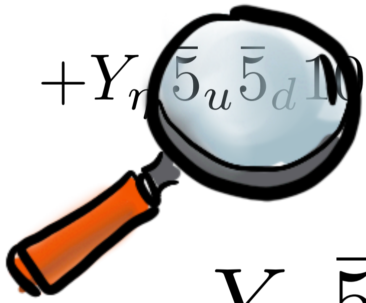
$$+ Y_\eta\, \bar{5}_u \bar{5}_d 10_H + Y_\Psi\, 5_q 5_q 10^*_H + \text{h.c.}$$



$$Y_\eta\, \bar{5}_{ui} \bar{5}_{dj} 10^{ij}_H$$

- Breaking pattern:

$$\mathrm{SU}(5) \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_X \overset{\langle 24_H \rangle}{\rightarrow} \mathrm{SU}(2)_D \otimes \mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_5 \otimes \mathrm{U}(1)_X$$

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The simplest gauge group

- Gauge group: $\mathrm{SU}(5) \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_X$

$\cancel{\mathrm{U}(1)}_Q$

Quirk number violation!

- Minimal matter content:

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Mass splitting

$$\mathcal{L}_Y \supset Y_u\, 5_q H \bar{5}_u + Y_d\, 5_q H^\dagger \bar{5}_d$$

$$+ \boxed{Y_\eta\, \bar{5}_u \bar{5}_d 10_H + Y_\Psi\, 5_q 5_q 10_H^*} + \text{h.c.}$$

$$\begin{pmatrix} \Psi_u & \eta_d \end{pmatrix} \begin{pmatrix} Y_\Psi\, v_{10} & Y_u\, v_{\rm EW} \\ Y_d^T\, v_{\rm EW} & Y_\eta^T\, v_{10} \end{pmatrix} \begin{pmatrix} \Psi_d \\ \eta_u \end{pmatrix} + \text{h.c.}$$

- Breaking pattern:

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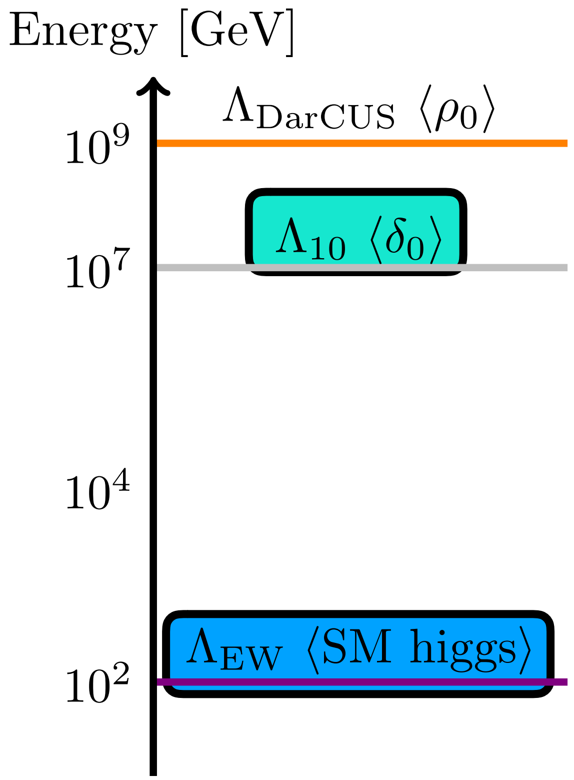
The simplest gauge group

Gauge group: $\mathrm{SU}(5)\otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_X$

$\cancel{\mathrm{U}(1)}_Q$

Quirk number violation!



Mass splitting

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$$+\boxed{Y_\eta\, \bar{5}_u \bar{5}_d 10_H + Y_\Psi\, 5_q 5_q 10^*_H} + \text{h.c.}$$

$$\begin{pmatrix}\Psi_u & \eta_d\end{pmatrix}\begin{pmatrix}\boxed{\mathbf{10}} & \boxed{\mathbf{EW}} \\ \boxed{\mathbf{EW}} & \boxed{\mathbf{10}}\end{pmatrix}\begin{pmatrix}\Psi_d \\ \eta_u\end{pmatrix} + \text{h.c.}$$

$$10_H \sim (10, 1, \tfrac{1}{5})_{\mathcal{G}_5}$$

$$\sim \begin{pmatrix} S_1 \sim (\bar{3}, 1, \frac{1}{3}, 1) & R_D \sim (3, 1, \frac{1}{6}, 2) \\ \text{-T} & \delta_0 \sim (1, 1, 0, 1) \end{pmatrix}$$

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The simplest gauge group

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$$\bar{5}_d \sim (\bar{5},1,\tfrac{2}{5})_{\mathcal{G}_5} \sim \begin{pmatrix} d^c \\ \eta_d \end{pmatrix}$$

MINIMAL CONTENT

MINIMAL MINIMAL MINIMAL MINIMAL MINIMAL MINIMAL MINIMAL MINIMAL

$$\ell \sim (1,2,\tfrac{1}{2})$$

$$e^c \sim (1,1,1)$$

$$N \sim (1,1,0)$$

$$\mathrm{SU}(5)\otimes\mathrm{SU}(2)_L\otimes\mathrm{U}(1)_X \overset{\langle 24_H\rangle}{\rightarrow} \mathrm{SU}(2)_D\otimes\mathrm{SU}(3)_c\otimes\mathrm{SU}(2)_L\otimes\mathrm{U}(1)_5\otimes\mathrm{U}(1)_X$$

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The Dark Sector

- **3** representations of SU(5) -

The Dark Sector

- $5_\chi \sim (5, 1, \frac{1}{10})_{\mathcal{G}_5} \sim \begin{pmatrix} \boxed{q_N^{\alpha}} \\ \chi \end{pmatrix}, \ \bar{5}_\chi$

$$\chi \sim (1, 1, 0, 2)$$

Dark quark

The Dark Sector

- $5_\chi \sim (5, 1, \frac{1}{10})_{\mathcal{G}_5} \sim \begin{pmatrix} \boxed{q_N^{\alpha}} \\ \chi \end{pmatrix}, \; \bar{5}_\chi$

$\chi \sim (1, 1, 0, 2)$

Dark quark

- $10 \sim (10, 1, -\frac{3}{10})_{\mathcal{G}_5} \sim \begin{pmatrix} \boxed{Q_N^{c\beta\gamma}} & M \\ & \xi \end{pmatrix}, \overline{10}$

$$\mathcal{L}_{\rm DS} \supset \; Y_q \, 5_\chi 10 \, 10_H \epsilon_5 + Y_{\bar{q}} \, \bar{5}_\chi \overline{10} \, 10^*_H \epsilon_5 + \text{h.c.}$$

The Dark Sector

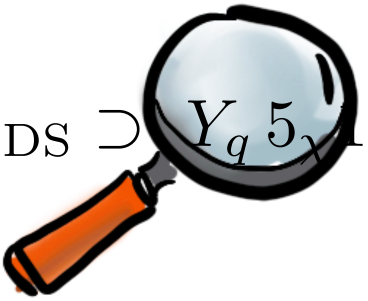
- $5_\chi \sim (5,1,\frac{1}{10})_{\mathcal{G}_5} \sim \begin{pmatrix} \boxed{q_N^{\alpha}} \\ \chi \end{pmatrix},\ \bar{5}_\chi$

$\chi \sim (1,1,0,2)$

Dark quark

- $10 \sim (10,1,-\frac{3}{10})_{\mathcal{G}_5} \sim \begin{pmatrix} \boxed{Q_N^{c\beta\gamma}} & M \\ & \xi \end{pmatrix},\ \overline{10}$

$Y_q\, 5_\chi^{\alpha}\, 10^{\beta\gamma}\, 10_H^{ij}\, \epsilon_{\alpha\beta\gamma}\, \epsilon_{ij}$ ☺



$$\mathcal{L}_{\mathrm{DS}} \supset Y_q\, 5_\chi\, 10\, 10_H \epsilon_5 + Y_{\bar{q}}\, \bar{5}_\chi \overline{10}\, 10_H^* \epsilon_5 + \mathrm{h.c.}$$

$$10_H \sim \begin{pmatrix} S_1 & R_D \\ & \boxed{\delta_0^{ij}} \end{pmatrix}$$

The Dark Sector

- $5_\chi \sim (5, 1, \frac{1}{10})_{\mathcal{G}_5} \sim \begin{pmatrix} \boxed{q_N^\alpha} \\ \chi \end{pmatrix}, \ \bar{5}_\chi$

$\chi \sim (1, 1, 0, 2)$

Dark quark

- $10 \sim (10, 1, -\frac{3}{10})_{\mathcal{G}_5} \sim \begin{pmatrix} \boxed{Q_N^{c\beta\gamma}} & M \\ & \xi \end{pmatrix}, \overline{10}$

- $5_H \sim (5, 1, \frac{1}{10})_{\mathcal{G}_5} \sim \begin{pmatrix} \Omega \\ \Delta_0 \end{pmatrix} \sim (1, 1, 0, 2)$

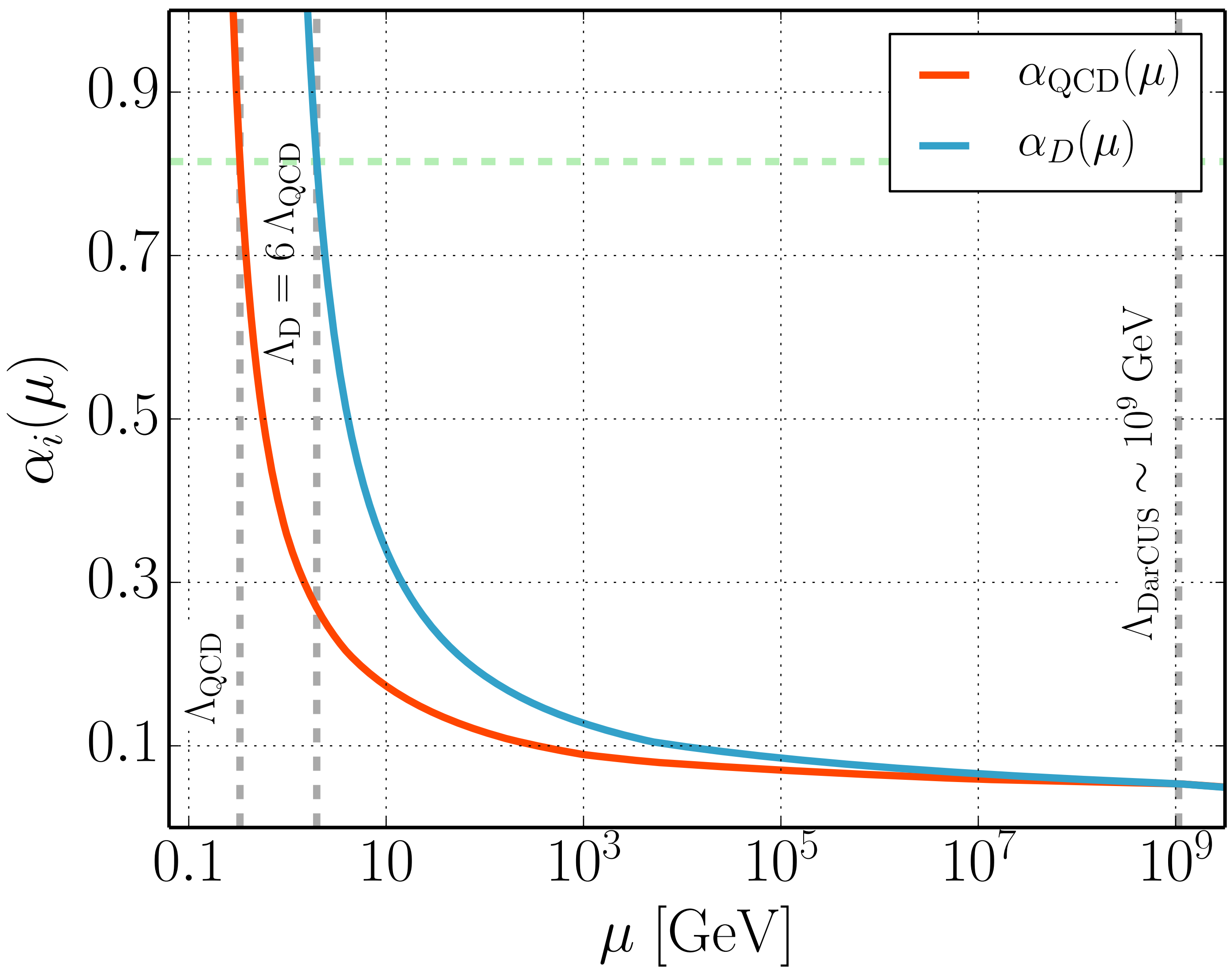
Splitting DM – new quarks

$$\mathcal{L}_{\text{DS}} \supset \boxed{Y_q\, 5_\chi 10\, 10_H \epsilon_5 + Y_{\bar{q}}\, \bar{5}_\chi \overline{10}\, 10_H^* \epsilon_5} + \boxed{Y_{\Delta_0}\, \bar{5}_d\, 10\, 5_H^*} + \boxed{Y_{\bar{\chi}}\, \bar{5}_\chi\, 5_H N + Y_\chi\, 5_\chi\, 5_H^* N} + \text{h.c.}$$

Running

$$\boxed{\alpha_{\mathrm{S}}^{-1}(\mu) = \alpha_{\mathrm{S}}^{-1}(\Lambda_{\mathrm{S}}) - \frac{1}{2\pi}\left(\sum_{i,m_i<\Lambda_S} b_i \ln\left(\frac{\mu}{\Lambda_S}\right) + \sum_{i,m_i>\Lambda_S} b_i \ln\left(\frac{\mu}{M_i}\right)\right)}$$

$$b_i = \frac{1}{3}\sum_R S(R)T_i(R)\prod_{j\neq i}\mathrm{dim}_j(R)$$



Running

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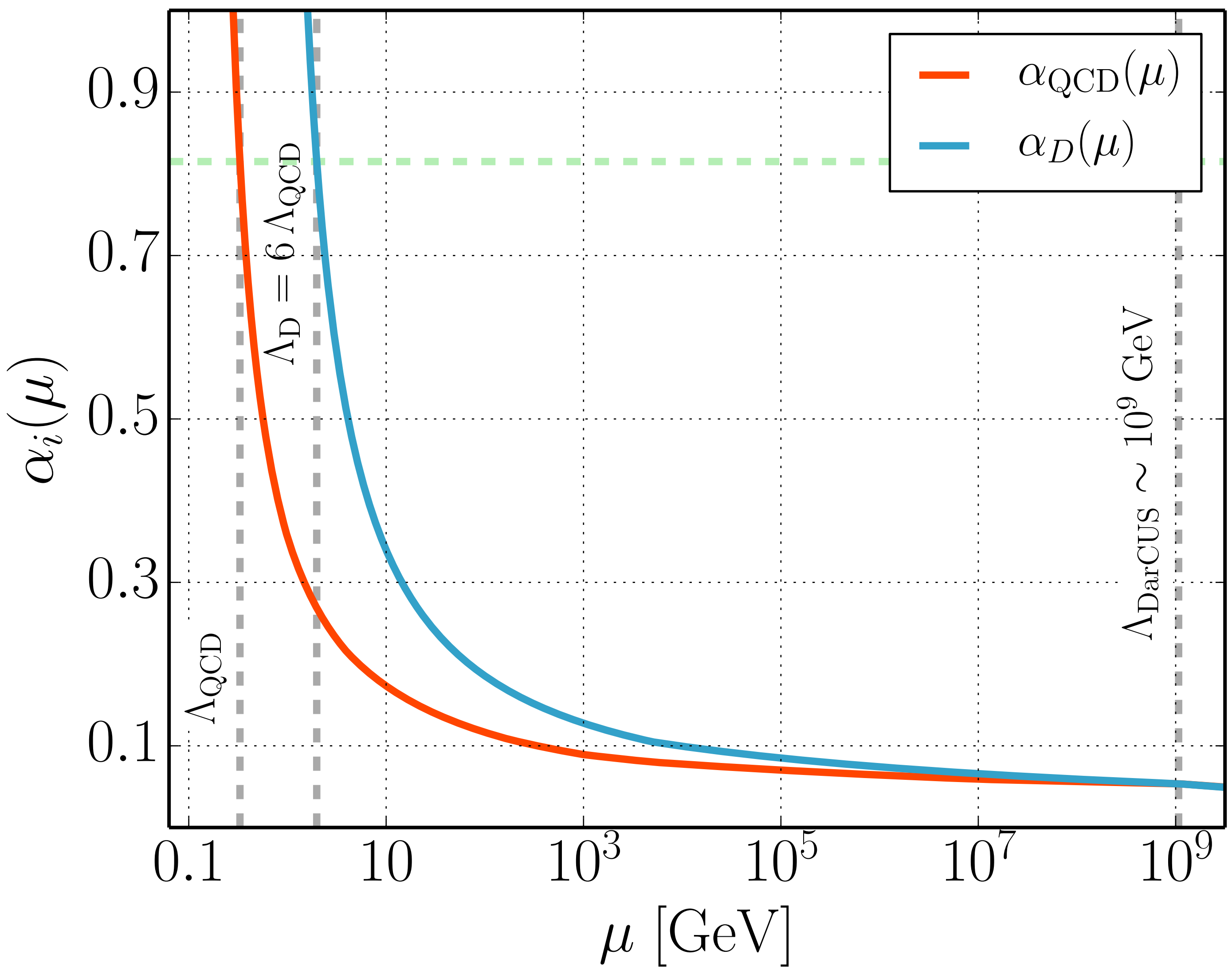

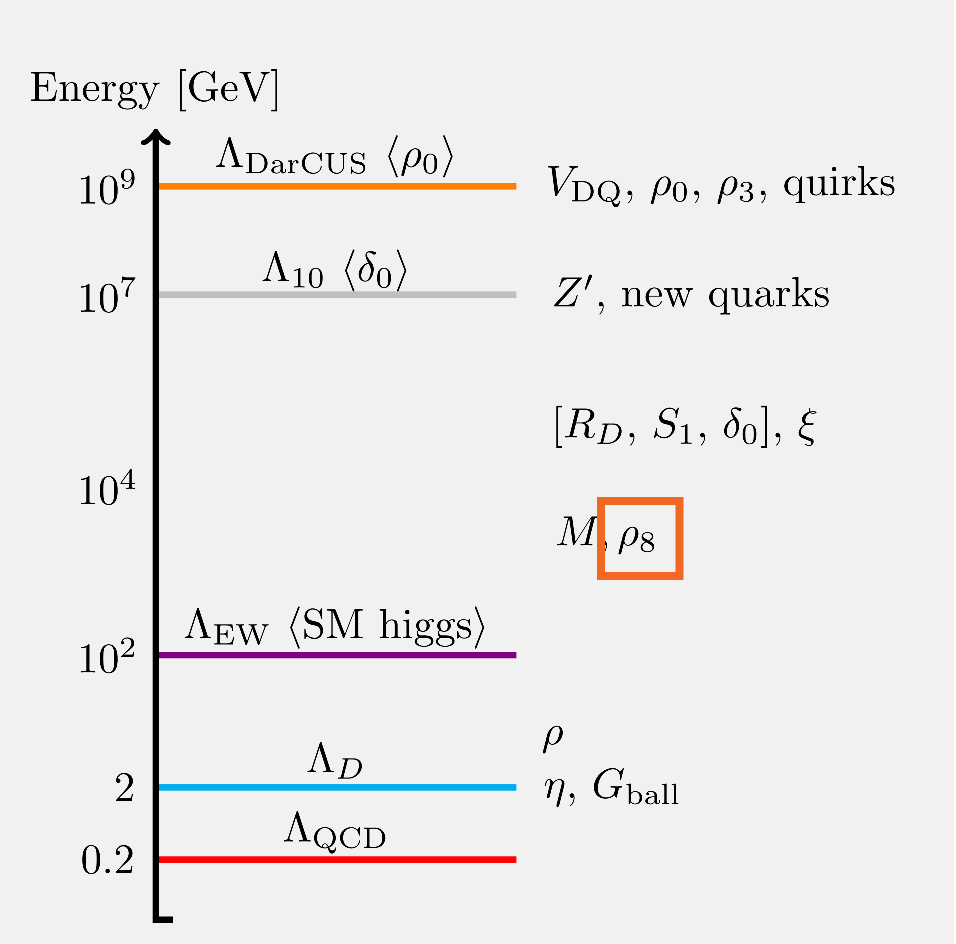

Energy [GeV]

10^9 — $\Lambda_{\mathrm{DarCUS}}$ $\langle\rho_0\rangle$ — V_{DQ}, ρ_0, ρ_3, quirks

10^7 — Λ_{10} $\langle\delta_0\rangle$ — Z', new quarks

$[R_D,\ S_1,\ \delta_0]$, ξ

10^4 — M, $\boxed{\rho_8}$

10^2 — Λ_{EW} $\langle$SM higgs$\rangle$

2 — Λ_D — ρ, η, G_{ball}

0.2 — Λ_{QCD}

Dark Spectrum

- One (light) flavor $\overset{(-)}{\chi} + \ \mathrm{SU}(2)_D$

$$\boxed{2 \equiv \Box \equiv \bar{2} \qquad \text{enlarged symmetry!}} \qquad \mathrm{U}(1)_L \otimes \mathrm{U}(1)_R \overset{\text{enlarged}}{\longrightarrow} \mathrm{U}(2) = \mathrm{U}(1)_A \otimes \mathrm{SU}(2)$$

Dark Spectrum

[Francis, Hudspith, Lewis, Tulin, 2008]

- One (light) flavor $\overset{(-)}{\chi}$ + $\mathrm{SU}(2)_D$

$2 \equiv \square \equiv \bar{2}$ enlarged symmetry!

$$\begin{tikzcd}
\mathrm{U}(1)_L \otimes \mathrm{U}(1)_R \arrow[r, "\text{enlarged}"] & \mathrm{U}(2) = \mathrm{U}(1)_A \otimes \mathrm{SU}(2) \arrow[d, "\chi\mathrm{SB}\quad \langle\bar{\chi}\chi\rangle"] \\
 & \mathrm{Sp}(2)
\end{tikzcd}$$

No Goldstones! (No dark pions)

Dark Spectrum

- One (light) flavor $\overset{(-)}{\chi}$ + $\mathrm{SU}(2)_D$

$\boxed{2 \equiv \square \equiv \bar{2} \quad \text{enlarged symmetry!}}$

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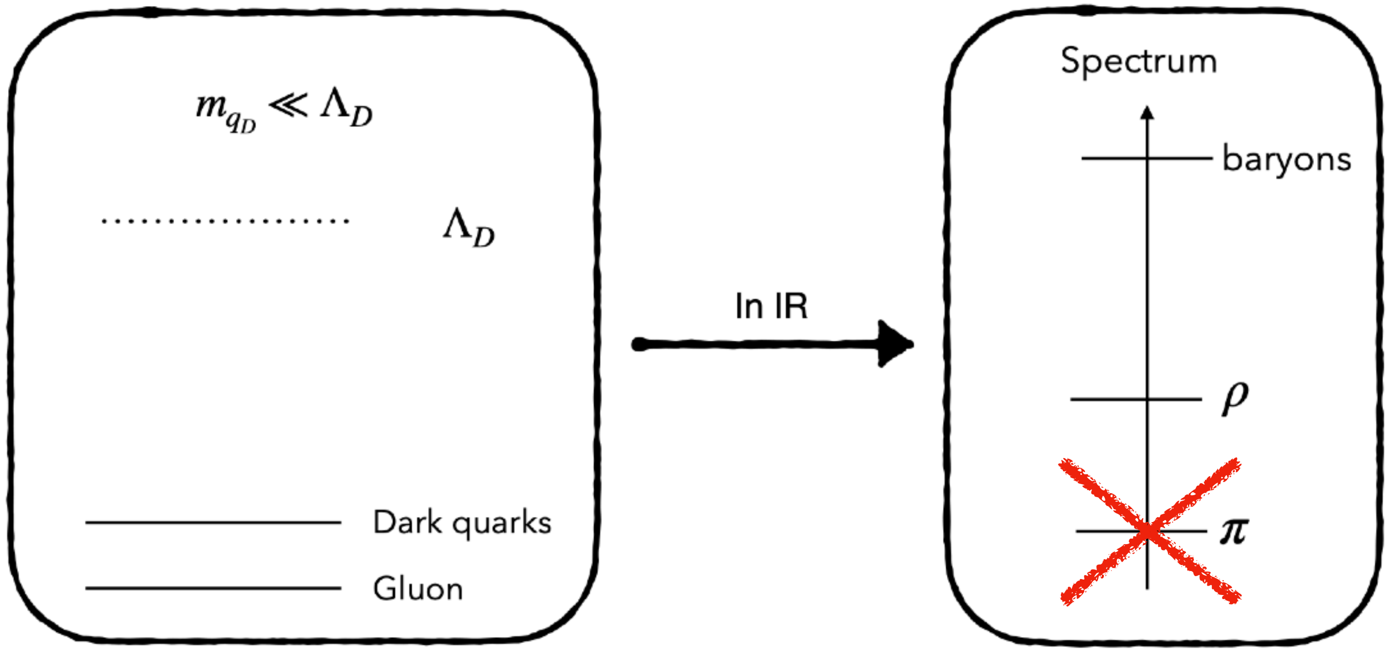

[Borrowed from talk Suchita on Tuesday]

- $N_{c_D} = 2$ and/or $N_{f_D} = 1$ special cases

Dark Spectrum

[Francis, Hudspith, Lewis, Tulin, 2008]

- One (light) flavor $\overset{(-)}{\chi}$ + $SU(2)_D$

$2 \equiv \square \equiv \bar{2}$ enlarged symmetry!

$$\begin{tikzcd} U(1)_L \otimes U(1)_R \arrow[r, "\text{enlarged}"] & U(2) = U(1)_A \otimes SU(2) \arrow[d, "\chi\text{SB}"', "\langle\bar{\chi}\chi\rangle"] \\ & Sp(2) \end{tikzcd}$$

No Goldstones! (No dark pions)

Dark (matter) baryon

vector (1^-)

$$\rho = \begin{pmatrix} \rho^+ \\ \rho^0 \\ \rho^- \end{pmatrix} \sim \begin{pmatrix} \chi\chi \\ \frac{1}{\sqrt{2}}(\chi\bar{\chi} + \bar{\chi}\chi) \\ \bar{\chi}\bar{\chi} \end{pmatrix}$$

Dark Spectrum

[Francis, Hudspith, Lewis, Tulin, 2008]

- One (light) flavor $\overset{(-)}{\chi}$ + $\mathrm{SU}(2)_D$

$2 \equiv \Box \equiv \bar{2}$ enlarged symmetry!

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\end{tikzcd}$$

No Goldstones! (No dark pions)

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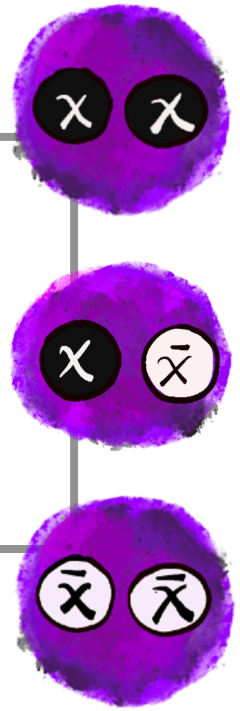

$$Q_D\left(\chi\right) = \frac{1}{2}$$

Dark Baryon Number $\mathrm{U}(1)_D$

Dark Spectrum

[Francis, Hudspith, Lewis, Tulin, 2008]

- One (light) flavor $\overset{(-)}{\chi}$ + $\mathrm{SU}(2)_D$

$$\boxed{2 \equiv \square \equiv \bar{2} \quad \text{enlarged symmetry!}}$$

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\end{tikzcd}$$

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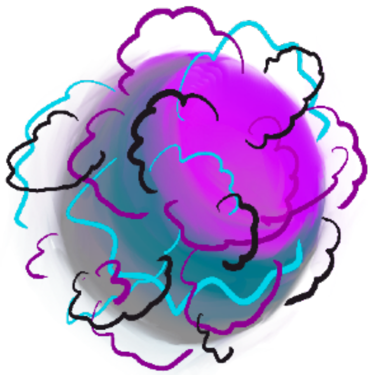
Glueballs



$$G_{\text{ball}} \equiv \langle G_D G_D \rangle$$

$$m_{G_{\text{ball}}} \sim \mathcal{O}(1)\Lambda_D$$

Dark Spectrum

[Francis, Hudspith, Lewis, Tulin, 2008]

- One (light) flavor $\overset{(-)}{\chi}$ + $\mathrm{SU}(2)_D$

$\boxed{2 \equiv \square \equiv \bar{2} \quad \text{enlarged symmetry!}}$

$$\mathrm{U}(1)_L \otimes \mathrm{U}(1)_R \xrightarrow{\text{enlarged}} \mathrm{U}(2) = \mathrm{U}(1)_A \otimes \mathrm{SU}(2)$$

$$\chi\mathrm{SB} \quad \langle \bar{\chi}\chi \rangle$$

$$\downarrow$$

$$\mathrm{Sp}(2)$$

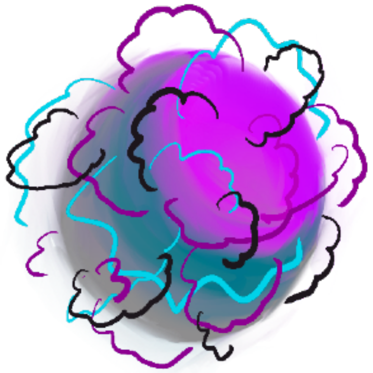
No Goldstones! (No dark pions)

Dark (matter) baryon

vector (1^-)

$$\rho = \begin{pmatrix} \rho^+ \\ \rho^0 \\ \rho^- \end{pmatrix} \sim \begin{pmatrix} \chi\chi \\ \frac{1}{\sqrt{2}}(\chi\bar{\chi} + \bar{\chi}\chi) \\ \bar{\chi}\bar{\chi} \end{pmatrix}$$

Glueballs



$$G_{\text{ball}} \equiv \langle G_D G_D \rangle$$

$$m_{G_{\text{ball}}} \sim \mathcal{O}(1)\Lambda_D$$

Eta meson

pseudoscalar (0^-)

$$\eta \equiv \bar{\chi}\gamma_5\chi$$

$m_\rho > m_\eta$ (in QCD $m_\rho < m_{\eta'}$)

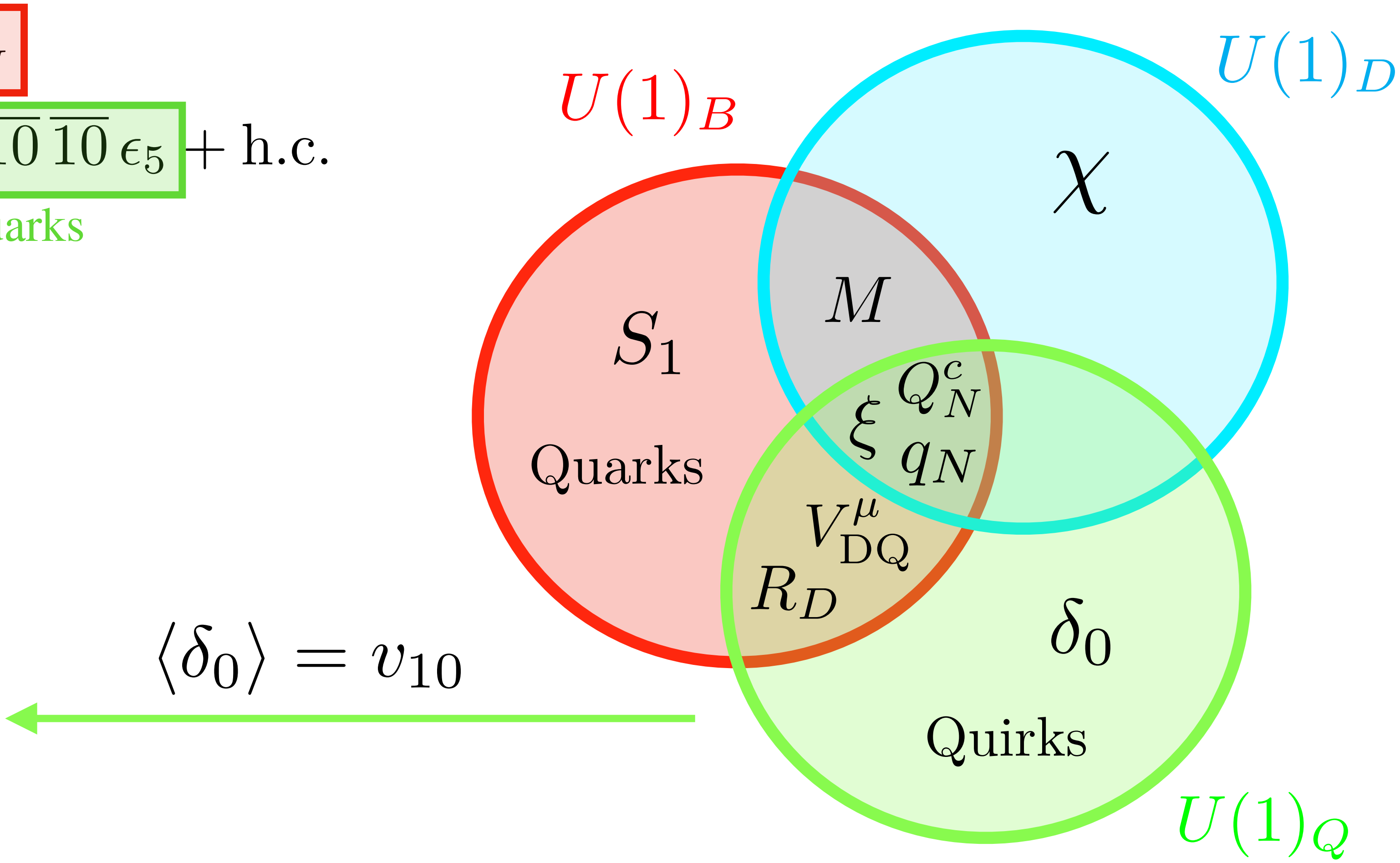
Symmetries

	5_q		$\bar{5}_u$		$\bar{5}_d$		5_χ		10			10_H		
Sym	Ψ	q	u^c	η_u	d^c	η_d	χ	q_N	Q^c_N	M	ξ	S_1	R_D	δ_0
$U(1)_B$	-	$1/3$	$-1/3$	-	$-1/3$	-	-	$1/3$	$-1/3$	$-2/3$	-1	$2/3$	$1/3$	-
$U(1)_D$	-	-	-	-	-	-	$1/2$	$1/2$	$-1/2$	$-1/2$	$-1/2$	-	-	-
$U(1)_Q$	$1/2$	-	-	$-1/2$	-	$-1/2$	-	$-1/2$	$-1/2$	-	$1/2$	-	$1/2$	1

Splitting quarks – quirks

$$\mathcal{L} \supset \boxed{Y_\Psi 5_\Psi 5_\Psi 10^*_H + Y_\eta \bar{5}_d \bar{5}_u 10_H}$$
$$+ \boxed{Y_q 5_\chi\, 10\, 10_H\, \epsilon_5 + Y_{\bar{q}} \bar{5}_\chi\, \overline{10}\, \overline{10}\, \epsilon_5} + \text{h.c.}$$

Splitting DM – new quarks



The (unwanted) $\mathcal{Z}_2$ group

Quirks $V^\mu_{\rm DQ}$ ξ

New quarks R_D

Cosmology

Darko-Baryo-Genesis

- Asymmetry generation ingredients (Sakharov):

  1. Violation of $U(1)_B$ and $U(1)_D$

Wait...

Symmetries

	5_q		$\bar{5}_u$		$\bar{5}_d$		5_χ		10			10_H		
Sym	Ψ	q	u^c	η_u	d^c	η_d	χ	q_N	Q_N^c	M	ξ	S_1	R_D	δ_0
$U(1)_B$	-	$1/3$	$-1/3$	-	$-1/3$	-	-	$1/3$	$-1/3$	$-2/3$	-1	$2/3$	$1/3$	-
$U(1)_D$	-	-	-	-	-	-	$1/2$	$1/2$	$-1/2$	$-1/2$	$-1/2$	-	-	-
$U(1)_Q$	$1/2$	-	-	$-1/2$	-	$-1/2$	-	$-1/2$	$-1/2$	-	$1/2$	-	$1/2$	1

Splitting quarks – quirks

Splitting DM – new quarks

$$\mathcal{L} \supset \boxed{Y_\Psi 5_\Psi 5_\Psi 10_H^* + Y_\eta \bar{5}_d \bar{5}_u 10_H} + \boxed{Y_q 5_\chi\, 10\, 10_H\, \epsilon_5 + Y_{\bar{q}} \bar{5}_\chi\, \overline{10}\, \overline{10}\, \epsilon_5} + \boxed{Y_{\Delta_0}\, \bar{5}_d\, 10\, 5_H^*} + \boxed{Y_{\bar{\chi}}\, \bar{5}_\chi\, 5_H N + Y_\chi\, 5_\chi\, 5_H^* N} + \text{h.c.}$$

$$\boxed{5_H \sim \begin{pmatrix} \Omega \\ \Delta_0 \end{pmatrix}}$$

Symmetries

	5_q		$\bar{5}_u$		$\bar{5}_d$		5_χ		10			10_H		
Sym	Ψ	q	u^c	η_u	d^c	η_d	χ	q_N	Q_N^c	M	ξ	S_1	R_D	δ_0
$U(1)_B$	-	$1/3$	$-1/3$	-	$-1/3$	-	-	$1/3$	$-1/3$	$-2/3$	-1	$2/3$	$1/3$	-
$U(1)_D$	-	-	-	-	-	-	$1/2$	$1/2$	$-1/2$	$-1/2$	$-1/2$	-	-	-
$U(1)_Q$	$1/2$	-	-	$-1/2$	-	$-1/2$	-	$-1/2$	$-1/2$	-	$1/2$	-	$1/2$	1

Splitting quarks – quirks

Splitting DM – new quarks

$$\mathcal{L} \supset \boxed{Y_\Psi 5_\Psi 5_\Psi 10_H^* + Y_\eta \bar{5}_d \bar{5}_u 10_H}$$
$$+ \boxed{Y_q 5_\chi\, 10\, 10_H\, \epsilon_5 + Y_{\bar{q}} \bar{5}_\chi\, \overline{10}\, \overline{10}\, \epsilon_5}$$
$$+ \boxed{Y_{\Delta_0}\, \bar{5}_d\, 10\, 5_H^*} + \boxed{Y_{\bar{\chi}}\, \bar{5}_\chi\, 5_H N + Y_\chi\, 5_\chi\, 5_H^* N} + \text{h.c.}$$

$$\boxed{5_H \sim \begin{pmatrix} \Omega \\ \Delta_0 \end{pmatrix}}$$

⇨ $$\mathcal{L} \supset Y_{\Delta_0}\,(d^c\, Q_N^c\, \Omega^* + \eta_d\, M\, \Omega^* + \boxed{d^c\, M\, \Delta_0^*} + \eta_d\, \xi\, \Delta_0^*)$$
$$+ Y_\chi \boxed{(\chi\, \Delta_0^*} + q_N\, \Omega^*)\, N + Y_{\bar{\chi}}\,(q_N^c\, \Omega + \chi^c\, \Delta_0)\, N + \text{h.c.}$$

$$\boxed{\begin{aligned} Q_B(\Delta_0) &= -1 \\ Q_D(\Delta_0) &= -1/2 \end{aligned}}$$

$$\boxed{\begin{aligned} Q_B(\chi \Delta_0^* N) &= 1 \\ Q_D(\chi \Delta_0^* N) &= 1 \end{aligned}}$$

Symmetries

	5_q		$\bar{5}_u$		$\bar{5}_d$		5_χ		10			10_H		
Sym	Ψ	q	u^c	η_u	d^c	η_d	χ	q_N	Q_N^c	M	ξ	S_1	R_D	δ_0
$U(1)_B$	-	$1/3$	$-1/3$	-	$-1/3$	-	-	$1/3$	$-1/3$	$-2/3$	-1	$2/3$	$1/3$	-
$U(1)_D$	-	-	-	-	-	-	$1/2$	$1/2$	$-1/2$	$-1/2$	$-1/2$	-	-	-
$U(1)_Q$	$1/2$	-	-	$-1/2$	-	$-1/2$	-	$-1/2$	$-1/2$	-	$1/2$	-	$1/2$	1

Splitting quarks – quirks

Splitting DM – new quarks

$$\mathcal{L} \supset \boxed{Y_\Psi 5_\Psi 5_\Psi 10_H^* + Y_\eta \bar{5}_d \bar{5}_u 10_H} + \boxed{Y_q 5_\chi\, 10\, 10_H\, \epsilon_5 + Y_{\bar{q}} \bar{5}_\chi\, \overline{10}\, \overline{10}\, \epsilon_5} + \boxed{Y_{\Delta_0}\, \bar{5}_d\, 10\, 5_H^*} + \boxed{Y_{\bar{\chi}}\, \bar{5}_\chi\, 5_H N + Y_\chi\, 5_\chi\, 5_H^* N} + \text{h.c.}$$

$$\boxed{5_H \sim \begin{pmatrix} \Omega \\ \Delta_0 \end{pmatrix}}$$

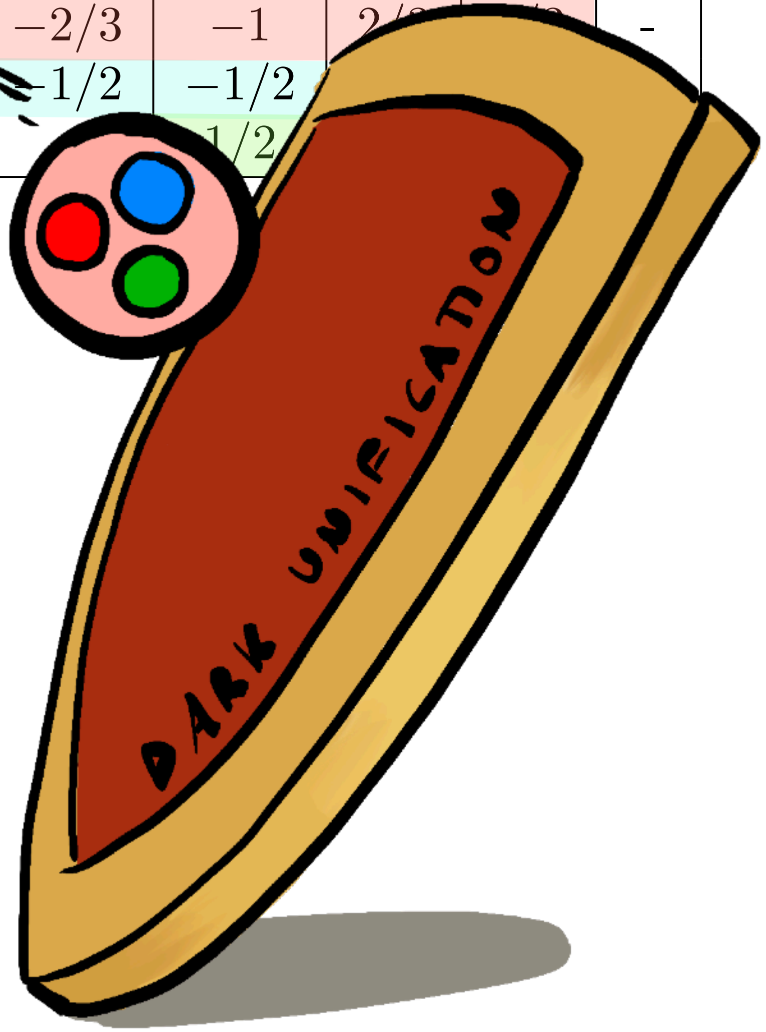
⇨ $$\mathcal{L} \supset Y_{\Delta_0} (d^c\, Q_N^c\, \Omega^* + \eta_d\, M\, \Omega^* + \boxed{d^c\, M\, \Delta_0^*} + \eta_d\, \xi\, \Delta_0^*) + Y_\chi \left(\boxed{\chi\, \Delta_0^*} + q_N\, \Omega^*\right) N + Y_{\bar{\chi}} \left(q_N^c\, \Omega + \chi^c\, \Delta_0\right) N + \text{h.c.}$$

$$\boxed{\begin{aligned} \mathcal{Q}_B(\Delta_0) &= -1 \\ \mathcal{Q}_D(\Delta_0) &= -1/2 \end{aligned}} \qquad \boxed{\begin{aligned} Q_B(\chi\Delta_0^* N) &= 1 \\ Q_D(\chi\Delta_0^* N) &= 1 \end{aligned}}$$

⇨ $\mathrm{U}(1)_{B-D}$

Symmetries

	5_q		$\bar{5}_u$		$\bar{5}_d$		5_χ		10			10_H		
Sym	Ψ	q	u^c	η_u	d^c	η_d	χ	q_N	Q_N^c	M	ξ	S_1	R_D	δ_0
$U(1)_B$	-	$1/3$	$-1/3$	-	$-1/3$	-	-	$1/3$	$-1/3$	$-2/3$	-1	$2/$		-
$U(1)_D$	-	-	-	-	-	-	$1/2$	$1/2$	$-1/2$	$-1/2$	$-1/2$			
$U(1)_Q$	$1/2$	-	-	$-1/2$	-	$-1/2$	-	$-1/2$	$-1/2$		$1/2$			



Splitting quarks – quirks

Splitting DM – new quarks

$$\mathcal{L} \supset \boxed{Y_\Psi 5_\Psi 5_\Psi 10_H^* + Y_\eta \bar{5}_d \bar{5}_u 10_H} + \boxed{Y_q 5_\chi\, 10\, 10_H\, \epsilon_5 + Y_{\bar{q}} \bar{5}_\chi\, \overline{10}\, \overline{10}\, \epsilon_5} + \boxed{Y_{\Delta_0}\, \bar{5}_d\, 10\, 5_H^*} + \boxed{Y_{\bar{\chi}}\, \bar{5}_\chi\, 5_H N + Y_\chi\, 5_\chi\, 5_H^* N} + \text{h.c.}$$

$$\mathcal{L} \supset Y_{\Delta_0} (d^c\, Q_N^c\, \Omega^* + \eta_d\, M\, \Omega^* + \boxed{d^c\, M\, \Delta_0^*} + \eta_d\, \xi\, \Delta_0^*) + Y_\chi \boxed{(\chi\, \Delta_0^*} + q_N\, \Omega^*)\, N + Y_{\bar{\chi}}\, (q_N^c\, \Omega + \chi^c\, \Delta_0)\, N + \text{h.c.}$$

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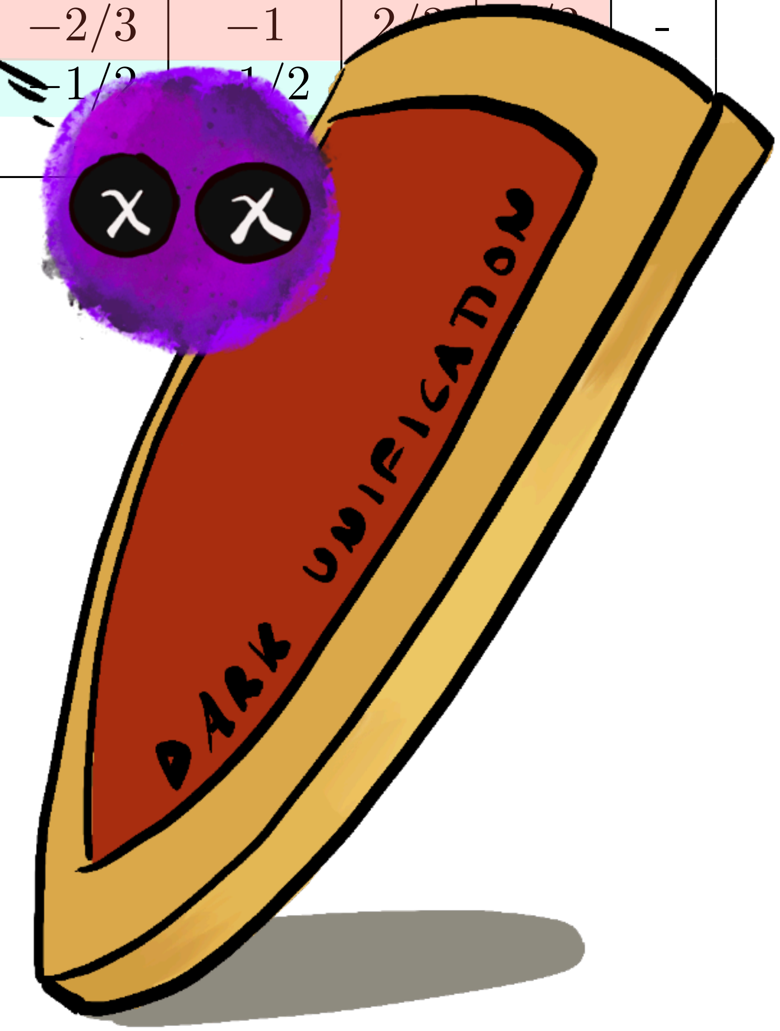
$\Rightarrow$ $\mathrm{U}(1)_{B-D}$

Symmetries

	5_q		$\bar{5}_u$		$\bar{5}_d$		5_χ		10			10_H		
Sym	Ψ	q	u^c	η_u	d^c	η_d	χ	q_N	Q_N^c	M	ξ	S_1	R_D	δ_0
$U(1)_B$	-	$1/3$	$-1/3$	-	$-1/3$	-	-	$1/3$	$-1/3$	$-2/3$	-1	$2/$		-
$U(1)_D$	-	-	-	-	-	-	$1/2$	$1/2$	$-1/2$	$-1/2$	$1/2$			
$U(1)_Q$	$1/2$	-	-	$-1/2$	-	$-1/2$	-	$-1/2$	$-1/2$					



Splitting quarks – quirks

Splitting DM – new quarks

$$\mathcal{L} \supset \boxed{Y_\Psi 5_\Psi 5_\Psi 10_H^* + Y_\eta \bar{5}_d \bar{5}_u 10_H} + \boxed{Y_q 5_\chi \, 10 \, 10_H \, \epsilon_5 + Y_{\bar{q}} \bar{5}_\chi \, \overline{10} \, \overline{10} \, \epsilon_5} + \boxed{Y_{\Delta_0} \, \bar{5}_d \, 10 \, 5_H^*} + \boxed{Y_{\bar{\chi}} \, \bar{5}_\chi \, 5_H N + Y_\chi \, 5_\chi \, 5_H^* N} + \text{h.c.}$$

$$\mathcal{L} \supset Y_{\Delta_0} \left(d^c \, Q_N^c \, \Omega^* + \eta_d \, M \, \Omega^* + \boxed{d^c \, M \, \Delta_0^*} + \eta_d \, \xi \, \Delta_0^* \right) + Y_\chi \left(\boxed{\chi \, \Delta_0^*} + q_N \, \Omega^* \right) N + Y_{\bar{\chi}} \left(q_N^c \, \Omega + \chi^c \, \Delta_0 \right) N + \text{h.c.}$$

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$$\mathcal{Q}_D(\Delta_0) = -1/2$$

$$Q_B(\chi \Delta_0^* N) = 1$$
$$Q_D(\chi \Delta_0^* N) = 1$$

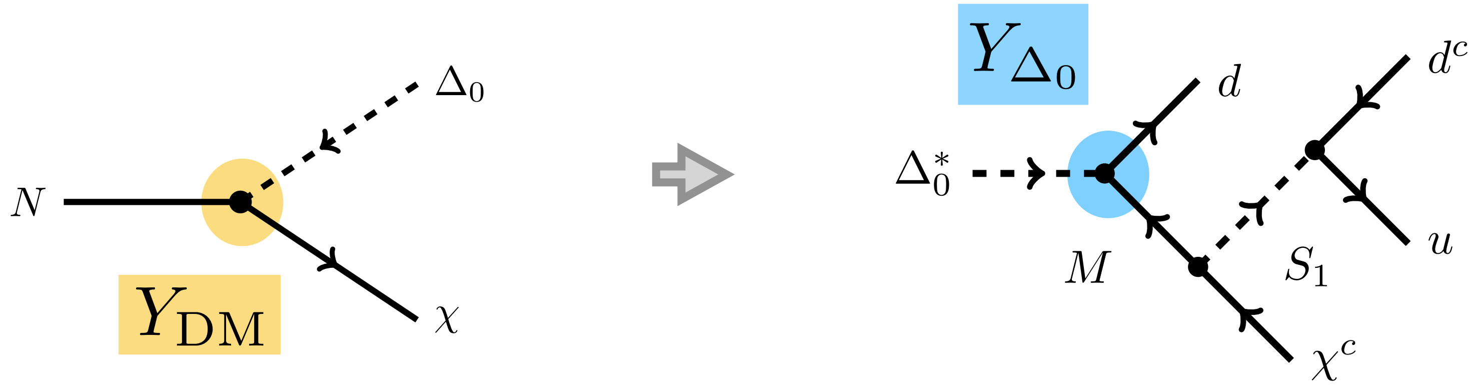
$\text{U}(1)_{B-D}$

Darko-Baryo-Genesis

- Asymmetry generation ingredients: [Sakharov, 1967]

1. Violation of $\mathrm{U}(1)_B$ and $\mathrm{U}(1)_D$

$$\boxed{(Y_{\Delta B} =)\, Y_{\Delta D} \simeq \mathrm{Br}(N \to \Delta_0^* \chi)\, \epsilon_{\mathrm{CP}}^{N} \frac{T_{\mathrm{RH}}^{N}}{M_N}}$$



- $\mathrm{U}(1)_{B-D}$

Darko-Baryo-Genesis

N lifetime (i.e. reheat temperature)

$$T_{\rm RH}^{N} \sim \left(\frac{45}{16\pi^3 g_*}\right)^{1/4} \sqrt{\Gamma_N M_{\rm Pl}}$$

$$\Gamma_N \simeq \; 6\times 10^7 \; {\rm s}^{-1} \left(\frac{|Y_{\rm DN}|}{10^{-9}}\right)^2 \left(\frac{M_N}{1\ {\rm TeV}}\right)$$

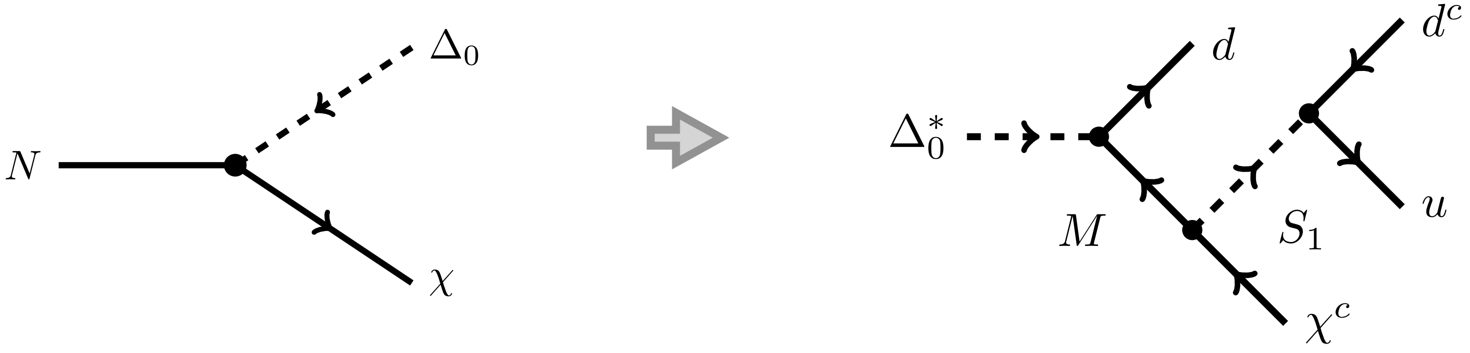
- Asymmetry generation ingredients:

1 Violation of $\mathrm{U}(1)_B$ and $\mathrm{U}(1)_D$

2 Out-of-equilibrium $\Gamma_N[T=M_N] < 3H[T=M_N]$

$$\boxed{(Y_{\Delta B} =)\, Y_{\Delta D} \simeq {\rm Br}(N\to \Delta_0^*\chi)\, \epsilon_{\rm CP}^{N} \frac{T_{\rm RH}^{N}}{M_N}}$$

N mass



Darko-Baryo-Genesis

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Asymmetry generation ingredients:

1 Violation of $U(1)_B$ and $U(1)_D$

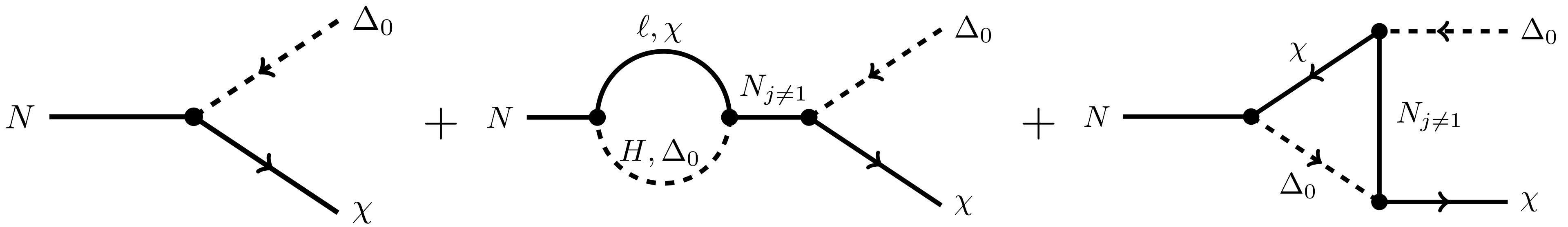
2 Out-of-equilibrium $\Gamma_N[T = M_N] < 3H[T = M_N]$

$$(Y_{\Delta B} =)\, Y_{\Delta D} \simeq {\rm Br}(N \to \Delta_0^* \chi)\, \epsilon_{\rm CP}^N \frac{T_{\rm RH}^N}{M_N}$$

N mass

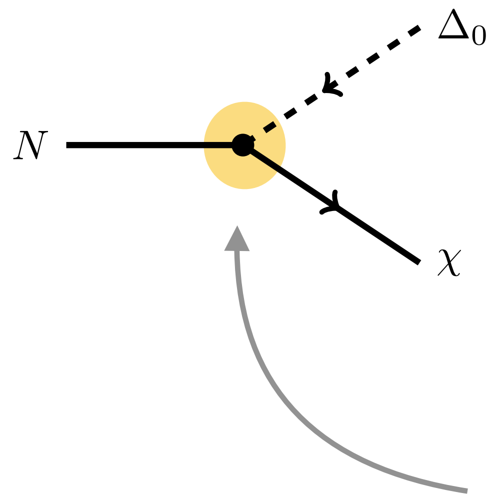
CP asymmetry

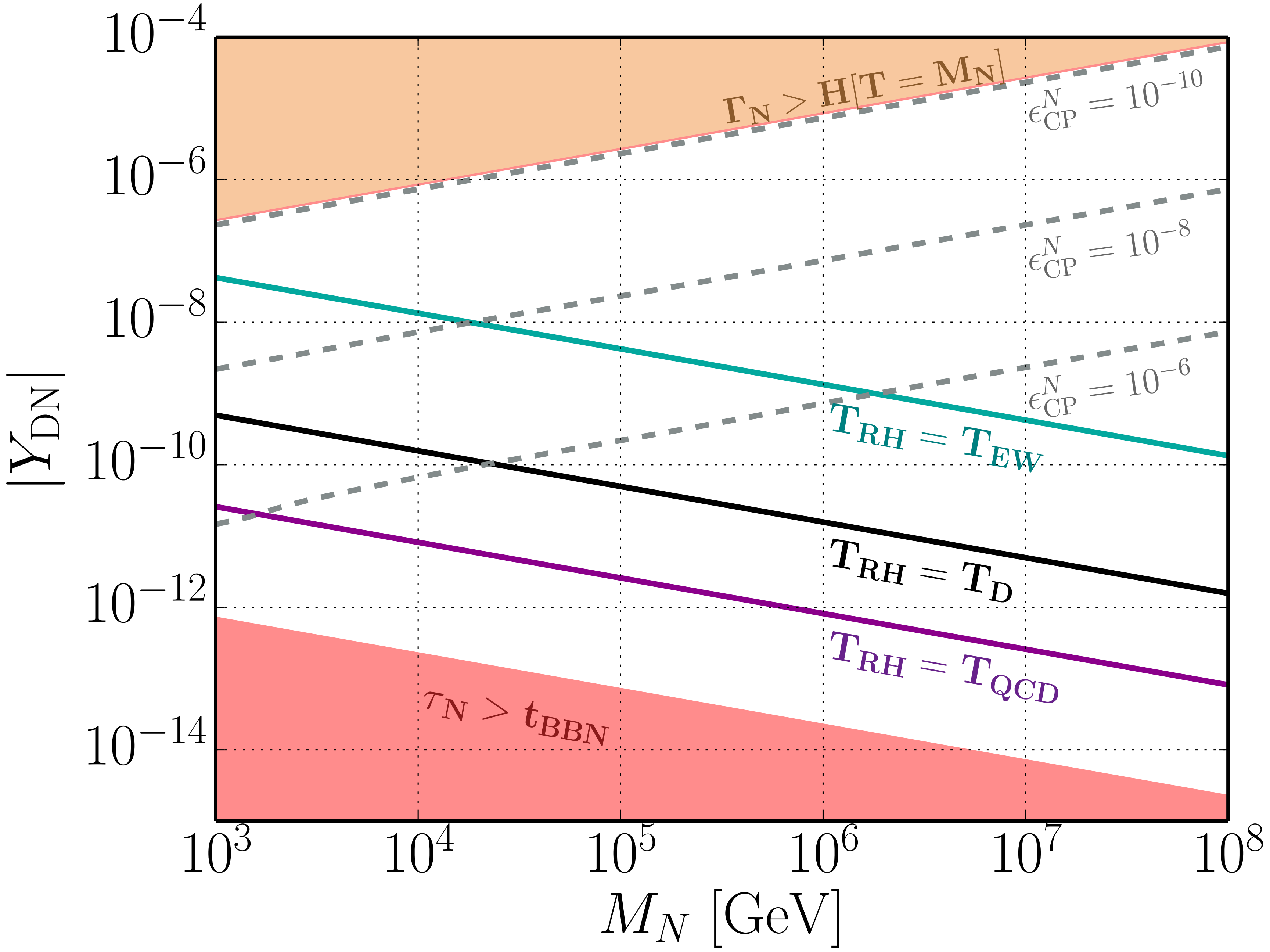
[Falkowski, Ruderman, Volansky, 2011]



3 Violation of C and CP (*à la* usual leptogenesis)

Darko-Baryo-Genesis





Darko-Baryo-Genesis

- Relevant parameters:

$$\boxed{(Y_{\Delta B} =)\, Y_{\Delta D} \simeq \mathrm{Br}(N \to \Delta_0^* \chi)\, \epsilon_{\mathrm{CP}}^{N} \frac{T_{\mathrm{RH}}^{N}}{M_N}}$$

- Cosmology tells us: $\frac{\Omega_D}{\Omega_B} = \overset{\mathrm{U}(1)_{B-D}}{\boxed{\frac{Y_{\Delta D}}{Y_{\Delta B}}}} \frac{m_\rho}{m_p} \sim 5$

[Francis, Hudspith, Lewis, Tulin, 2008]

$m_\rho \sim 2.5\, \Lambda_D$

$m_p \sim 3\, \Lambda_{\mathrm{QCD}}$

Darko-Baryo-Genesis

- Relevant parameters

$$\boxed{(Y_{\Delta B} =)\, Y_{\Delta D} \simeq \mathrm{Br}(N \to \Delta_0^* \chi)\, \epsilon_{\mathrm{CP}}^N \frac{T_{\mathrm{RH}}^N}{M_N}}$$

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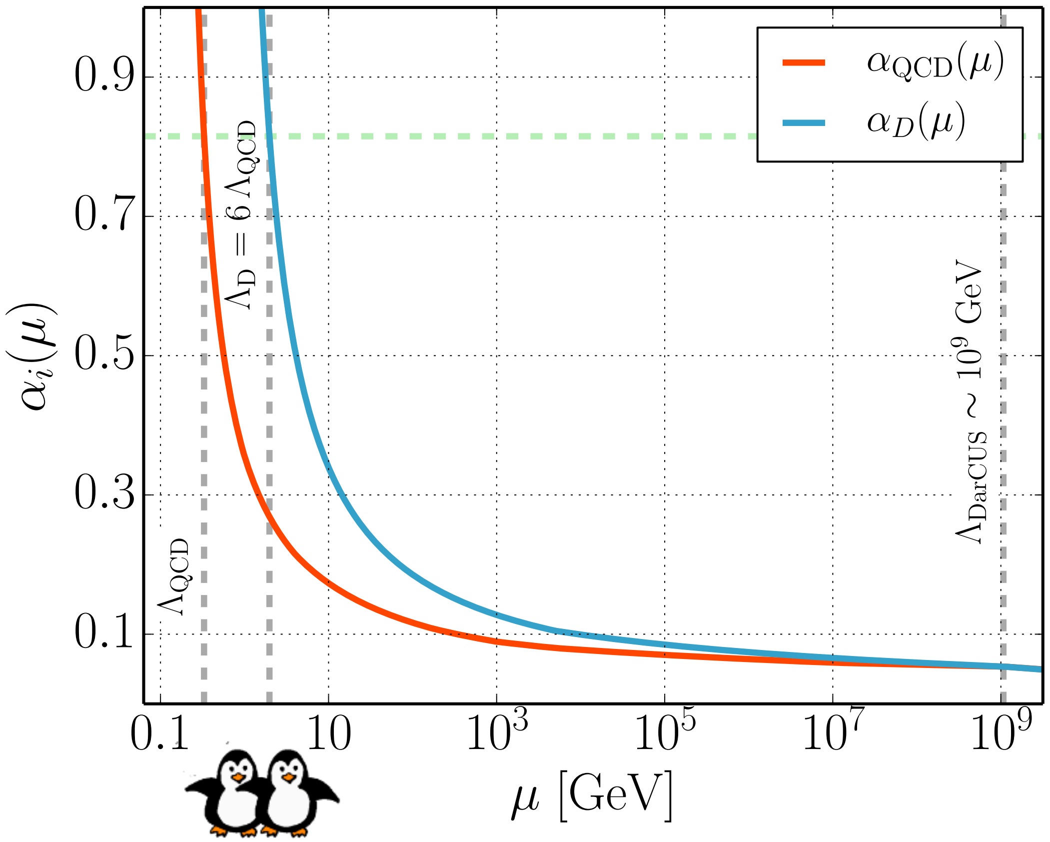
[Francis, Hudspith, Lewis, Tulin, 2008]
$m_\rho \sim 2.5\, \Lambda_D$

$m_p \sim 3\, \Lambda_{\mathrm{QCD}}$

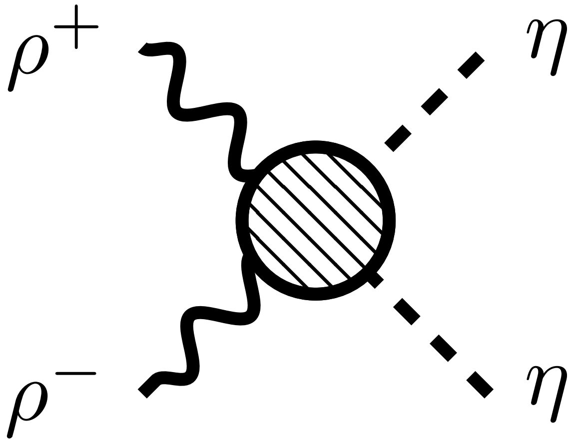
$$\boxed{\Rightarrow\ \Lambda_D \sim 6\, \Lambda_{\mathrm{QCD}}}$$



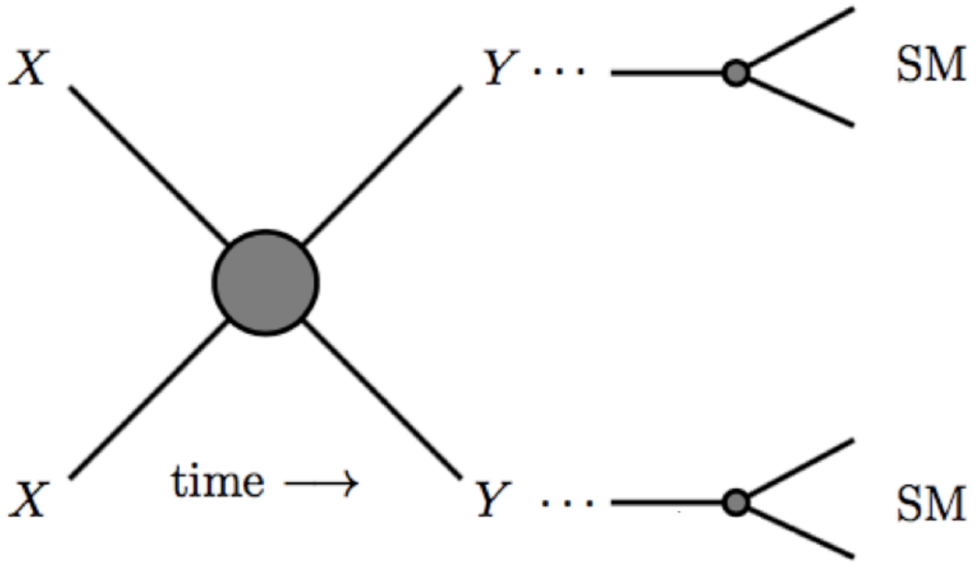
Annihilation symmetric abundance

[Francis, Hudspith, Lewis, Tulin, 2008]

$$m_\eta < m_\rho \quad (\forall m_\chi < \Lambda_{\rm D})$$



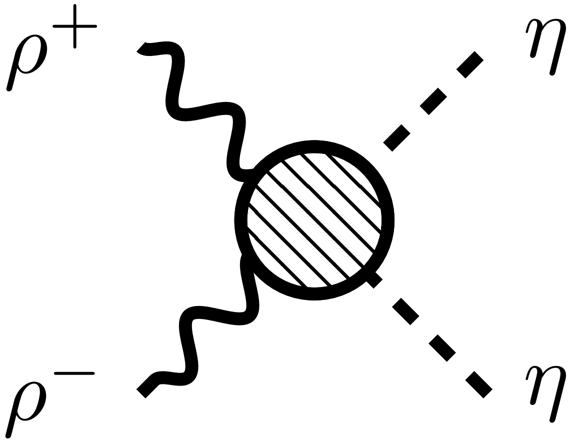
[Case “6” in Dan’s talk on Tuesday]

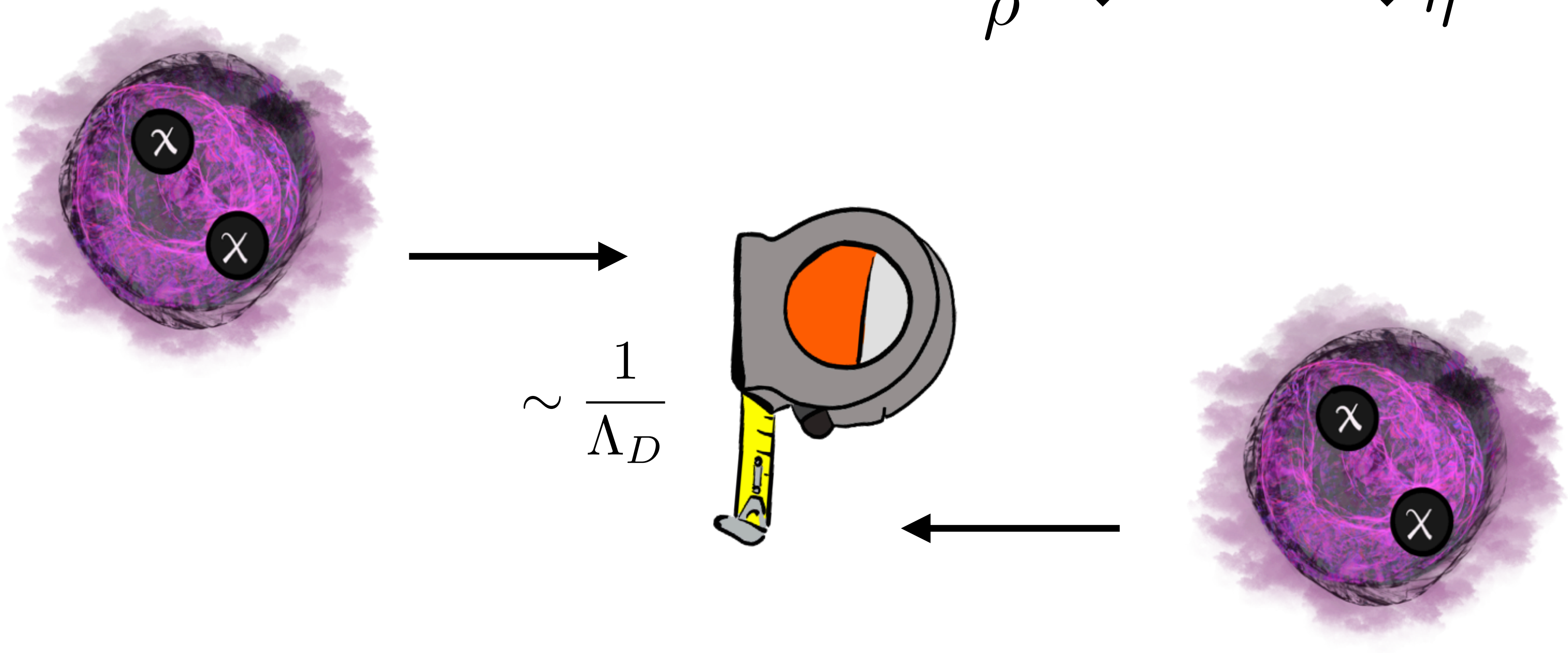


Annihilation symmetric abundance

[Francis, Hudspith, Lewis, Tulin, 2008]

$$m_\eta < m_\rho \quad (\forall m_\chi < \Lambda_\mathrm{D})$$

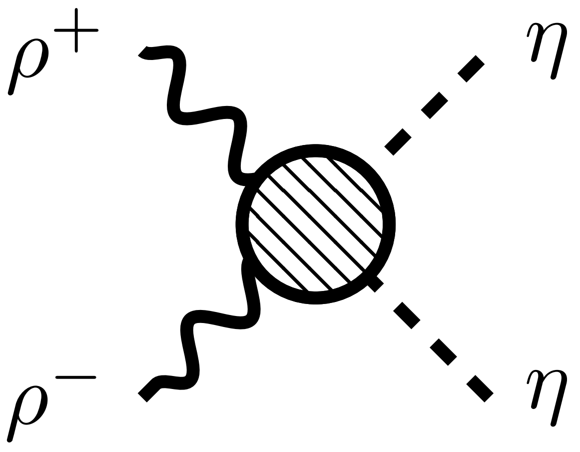


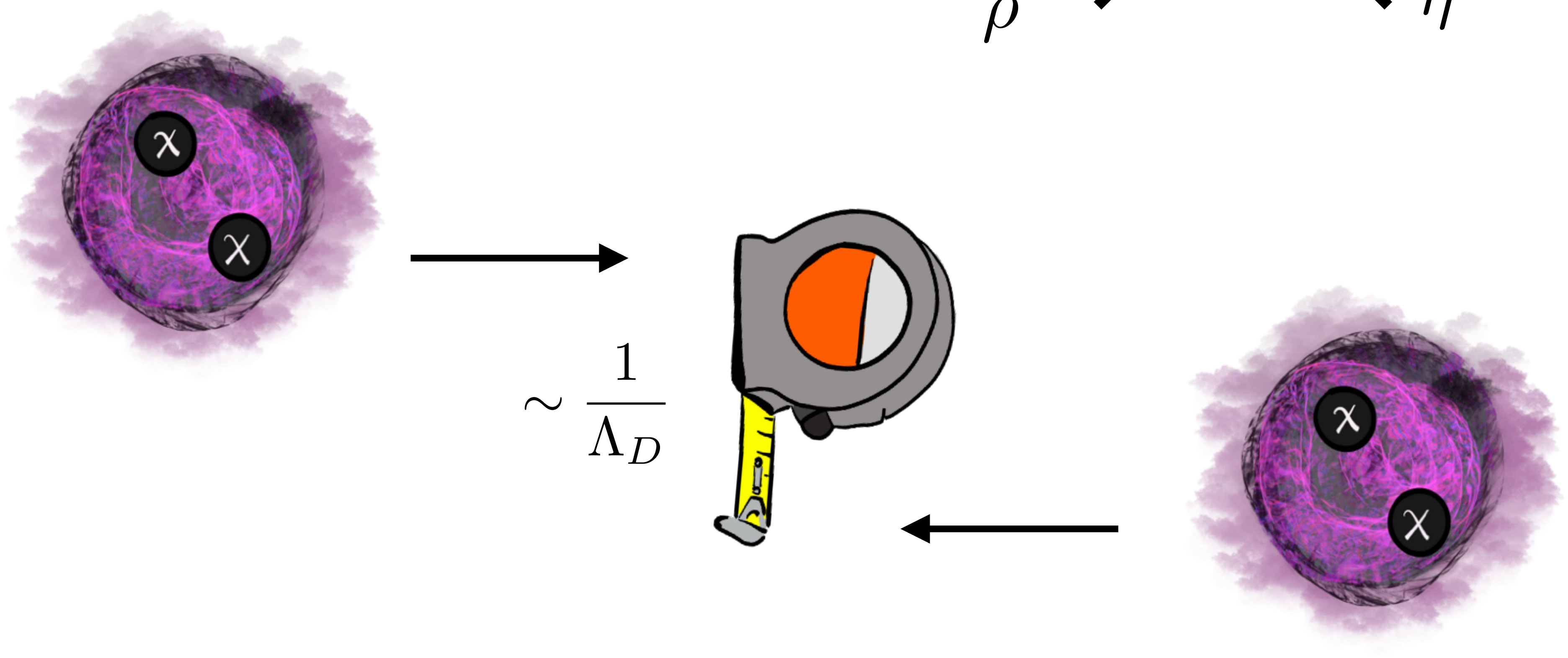


Annihilation symmetric abundance

[Francis, Hudspith, Lewis, Tulin, 2008]

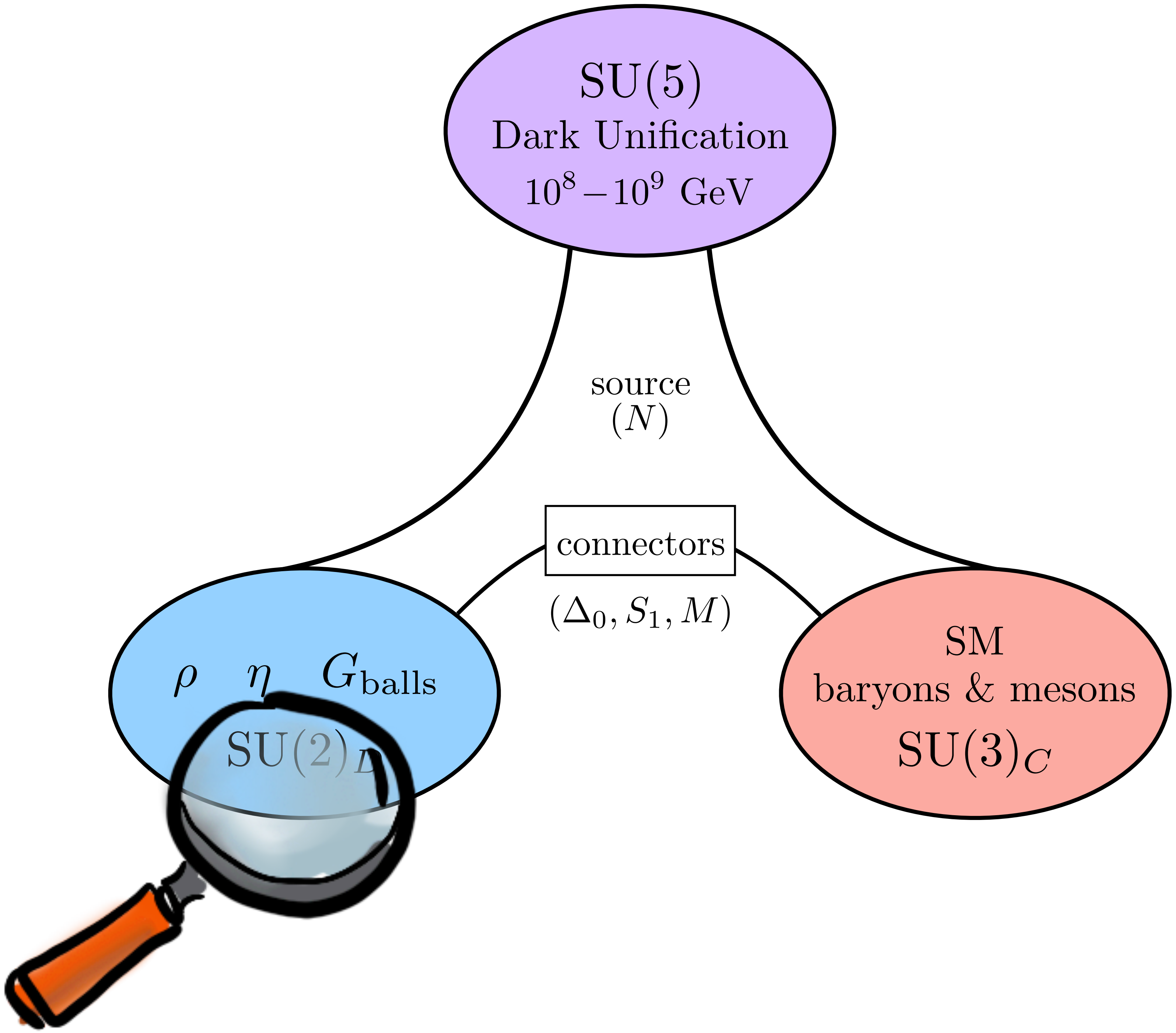
$$m_\eta < m_\rho \quad (\forall m_\chi < \Lambda_{\rm D})$$





$$\langle\sigma_{\rm ann}v\rangle \sim \left(\frac{4\pi}{\Lambda_D^2}\right)\left(\frac{3}{2}\frac{\Lambda_D}{m_\rho}\right)^{1/2} \sim 4\times10^{-17}{\rm cm}^3\ {\rm s}^{-1}\left(\frac{2\ {\rm GeV}}{\Lambda_D}\right)^2$$

Dark hadrons



SU(5)
Dark Unification
$10^8 - 10^9$ GeV

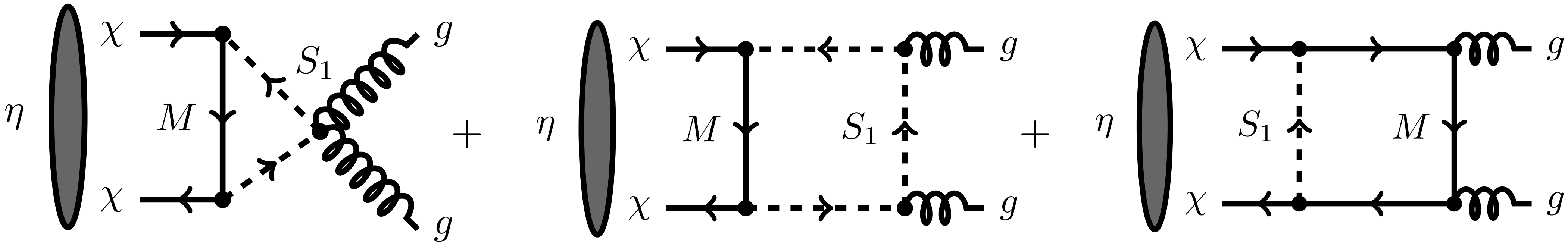
source
(N)

connectors
(Δ_0, S_1, M)

ρ η G_{balls}
$SU(2)_D$

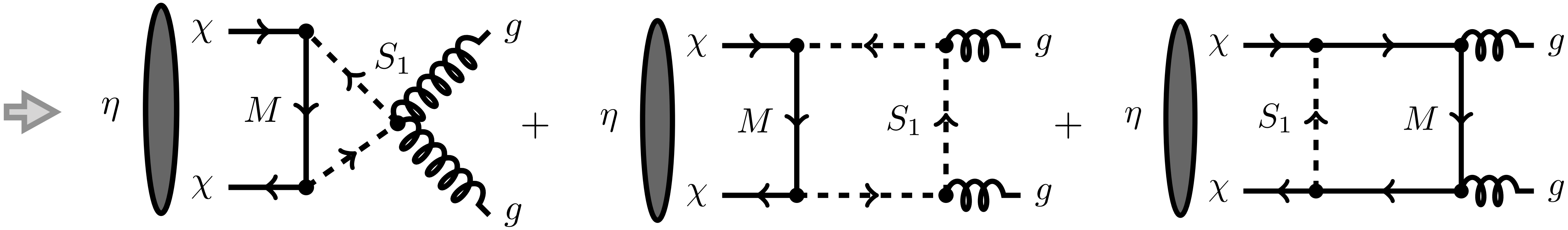
SM
baryons & mesons
$SU(3)_C$

Dark hadrons



$$\tau_\eta^{-1} \sim \quad 8\ \mathrm{s}^{-1} \left(\frac{\alpha_{\rm QCD}}{0.8}\right)^2 \left(\frac{|Y_{\rm NewQ}|}{1}\right)^4 \left(\frac{10\ \mathrm{TeV}}{M_{S_1/M}}\right)^6 \left(\frac{m_\eta}{4\ \mathrm{GeV}}\right)^7$$

Dark hadrons



$$\tau_\eta^{-1} \sim \; 8\ \mathrm{s}^{-1} \left(\frac{\alpha_{\rm QCD}}{0.8}\right)^2 \left(\frac{|Y_{\rm NewQ}|}{1}\right)^4 \left(\frac{10\ \mathrm{TeV}}{M_{S_1/M}}\right)^6 \left(\frac{m_\eta}{4\ \mathrm{GeV}}\right)^7$$

Light connectors M or S_1

Early Matter Domination!

Charged Relics

The (unwanted) $\mathscr{Z}_2$ group

Quirks V^{μ}_{DQ} ξ

New quarks R_D

$R_D \sim (3, 1, \frac{1}{6}, 2)$

Charged Relics

The (unwanted) $\mathscr{Z}_2$ group

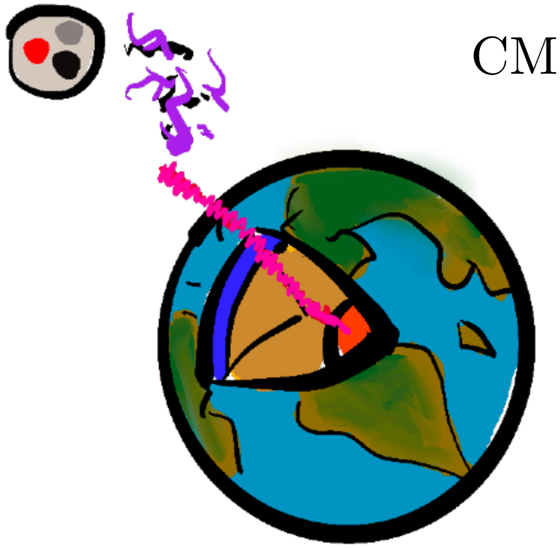
Quirks $V^{\mu}_{\rm DQ}$ ξ

New quarks R_D

$R_D \sim (3, 1, \frac{1}{6}, 2)$

Annihilation [De Luca, **Mitridate**, Redi, Smirnov, Strumia, 2018]

$$\Omega^{\rm hybrid}_{R_D} h^2 \sim \; 3 \times 10^{-7} \left(\frac{M_{R_D}}{3 \text{ TeV}}\right)^{3/2} \left(\frac{g_*}{10}\right)^{1/2}$$



CMB: $\Omega^{\rm hybrids}_{R_D} h^2 < 0.0044$

[Perl, Lee, Loomba, 2019]

Charged Relics

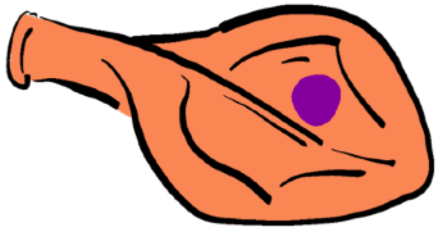
The (unwanted) $\mathscr{Z}_2$ group

Quirks $V^{\mu}_{\rm DQ}$ ξ

New quarks R_D

$R_D \sim (3, 1, \frac{1}{6}, 2)$

Inflation



E

Lightest $\mathcal{Z}_2$ field

$T_{\rm inf}$

Annihilation

[De Luca, **Mitridate**, Redi, Smirnov, Strumia, 2018]

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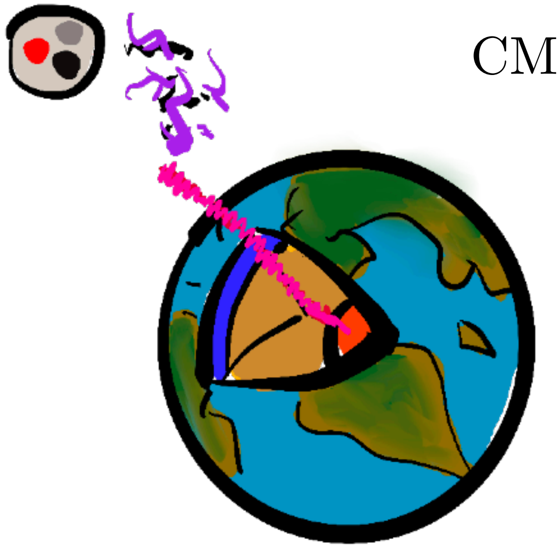

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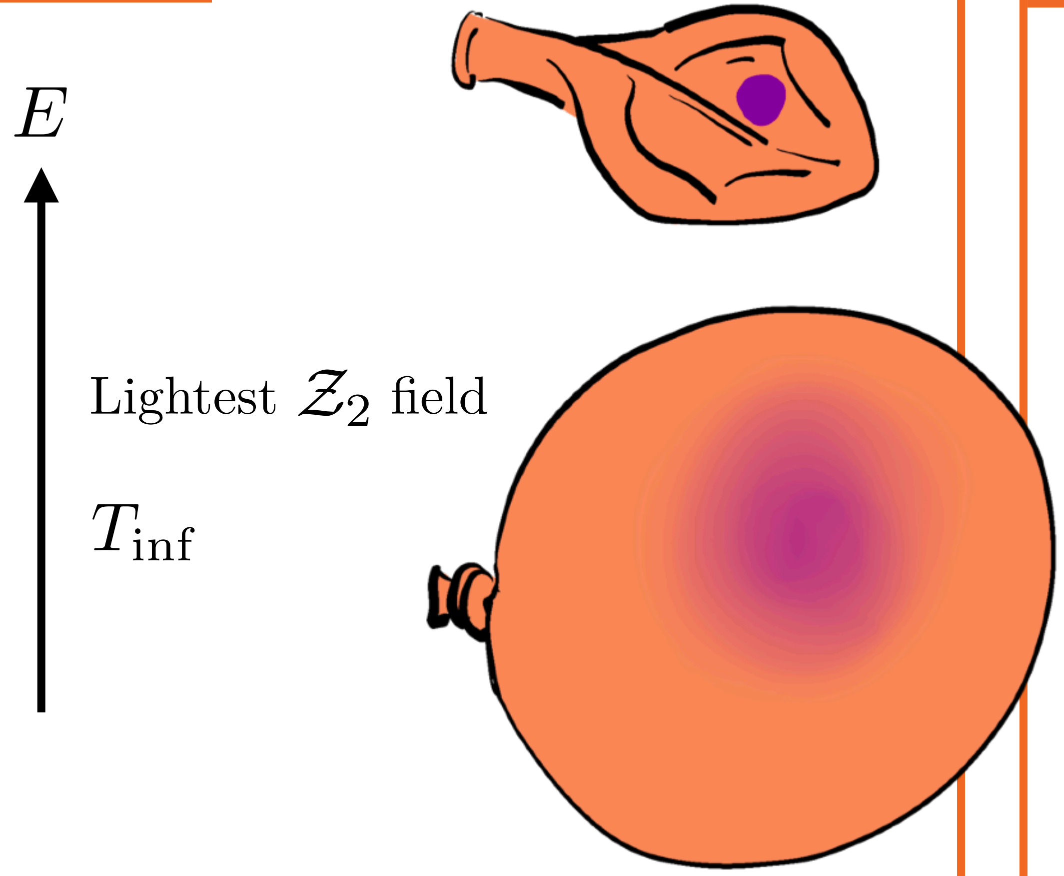

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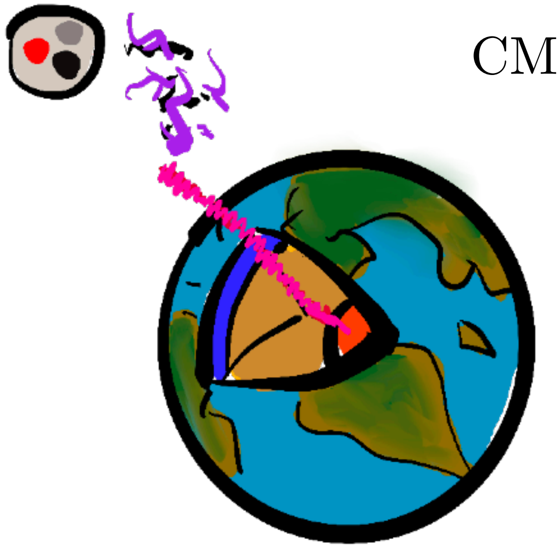

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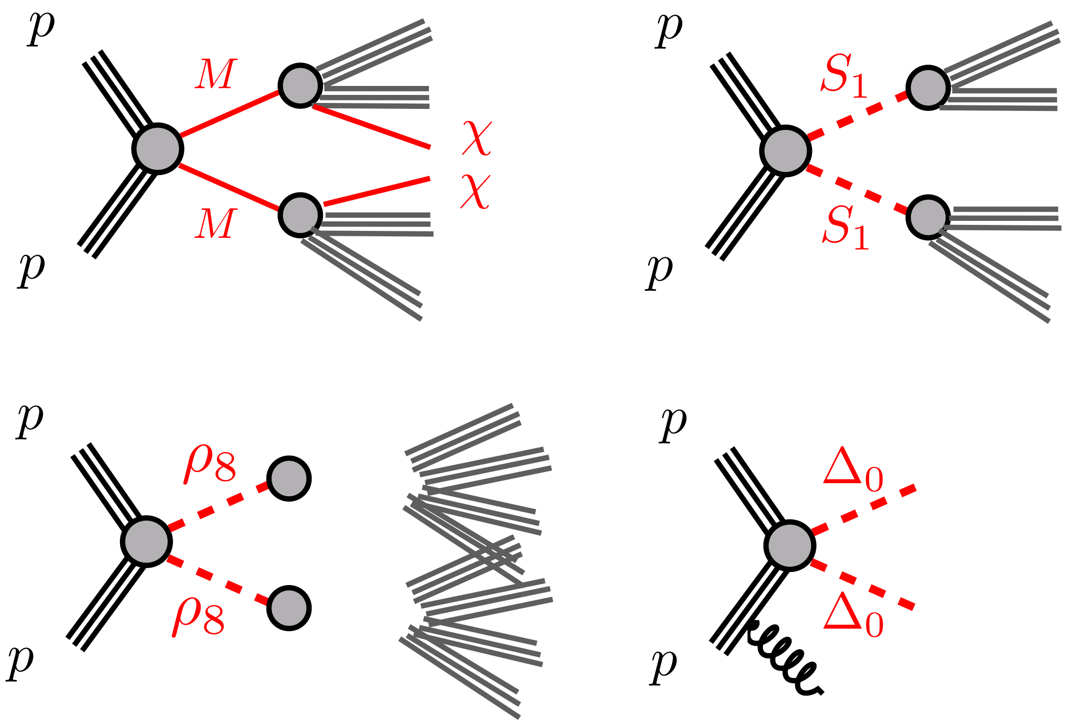
[Perl, Lee, Loomba, 2019]

Signatures

Phenomenological signatures

- Potential light fields $S_1 \quad M \quad (\rho_8) < 10\ \text{TeV}$

@ colliders



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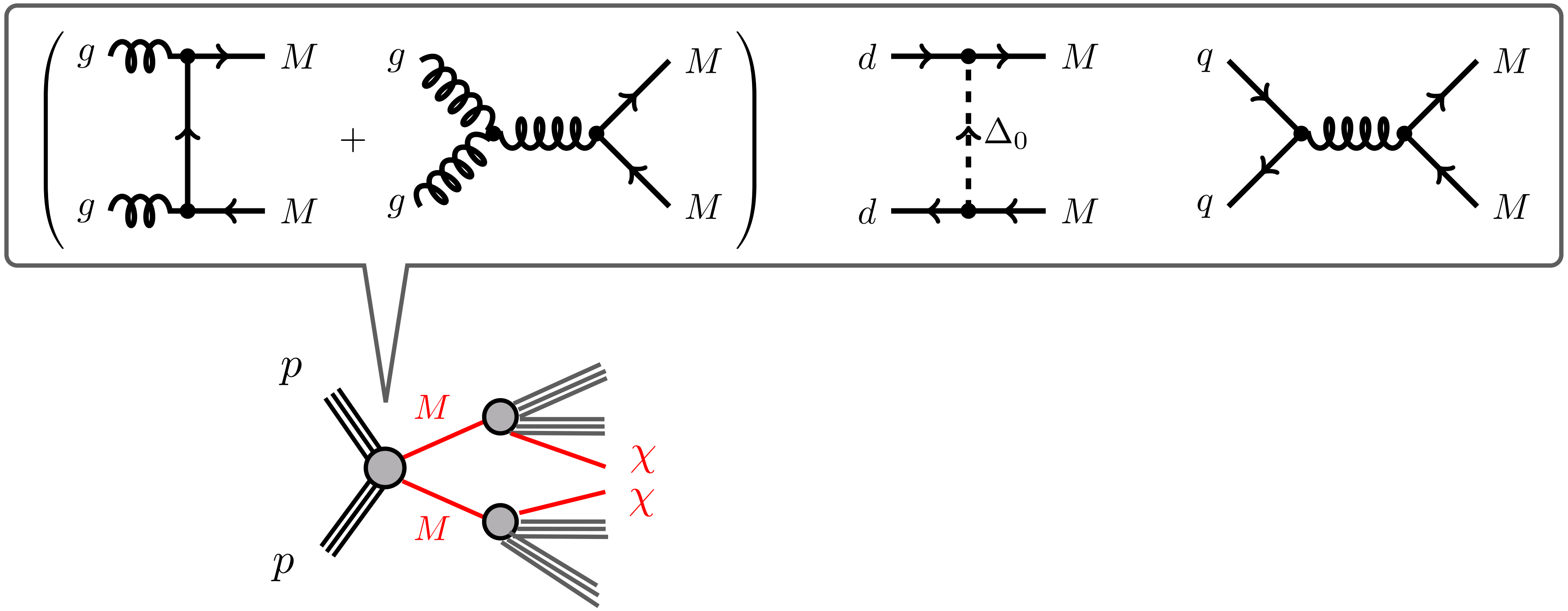

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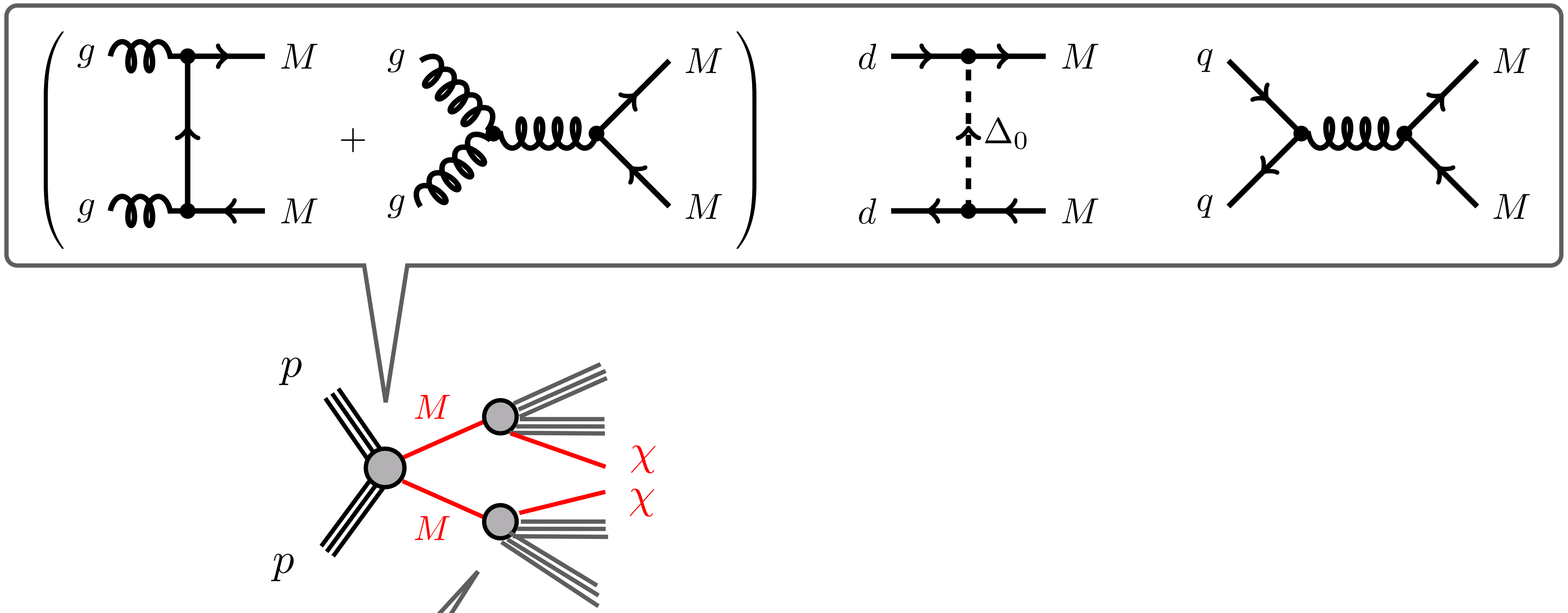

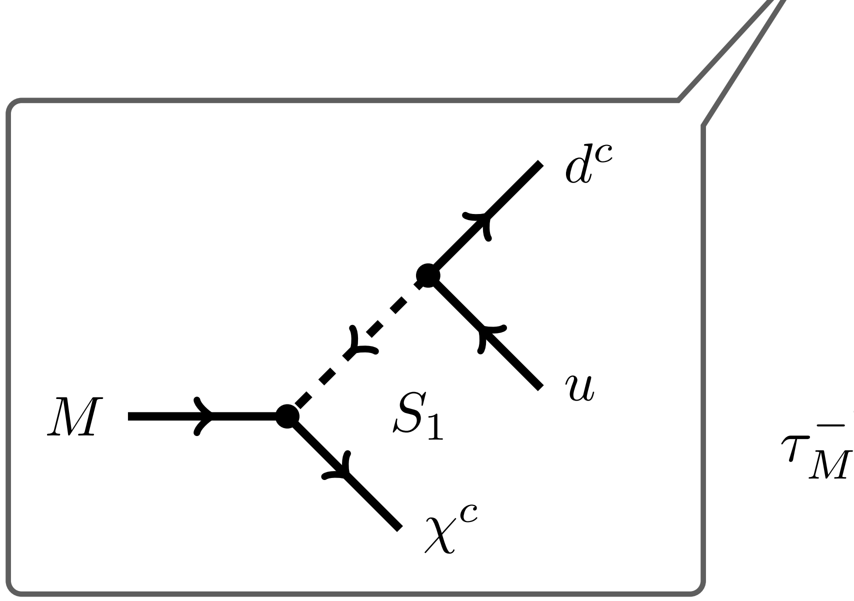

$M \to 2$ JETs + MET

$$\tau_M^{-1} \simeq 9.3 \times 10^{21}\ \mathrm{s}^{-1} \left|\frac{Y_{\mathrm{NewQ}}}{1}\right|^2 \left|\frac{Y_{\mathrm{quirks}}}{1}\right|^2 \left(\frac{M_M}{3\ \mathrm{TeV}}\right)^5 \left(\frac{10\ \mathrm{TeV}}{M_{S_1}}\right)^4$$

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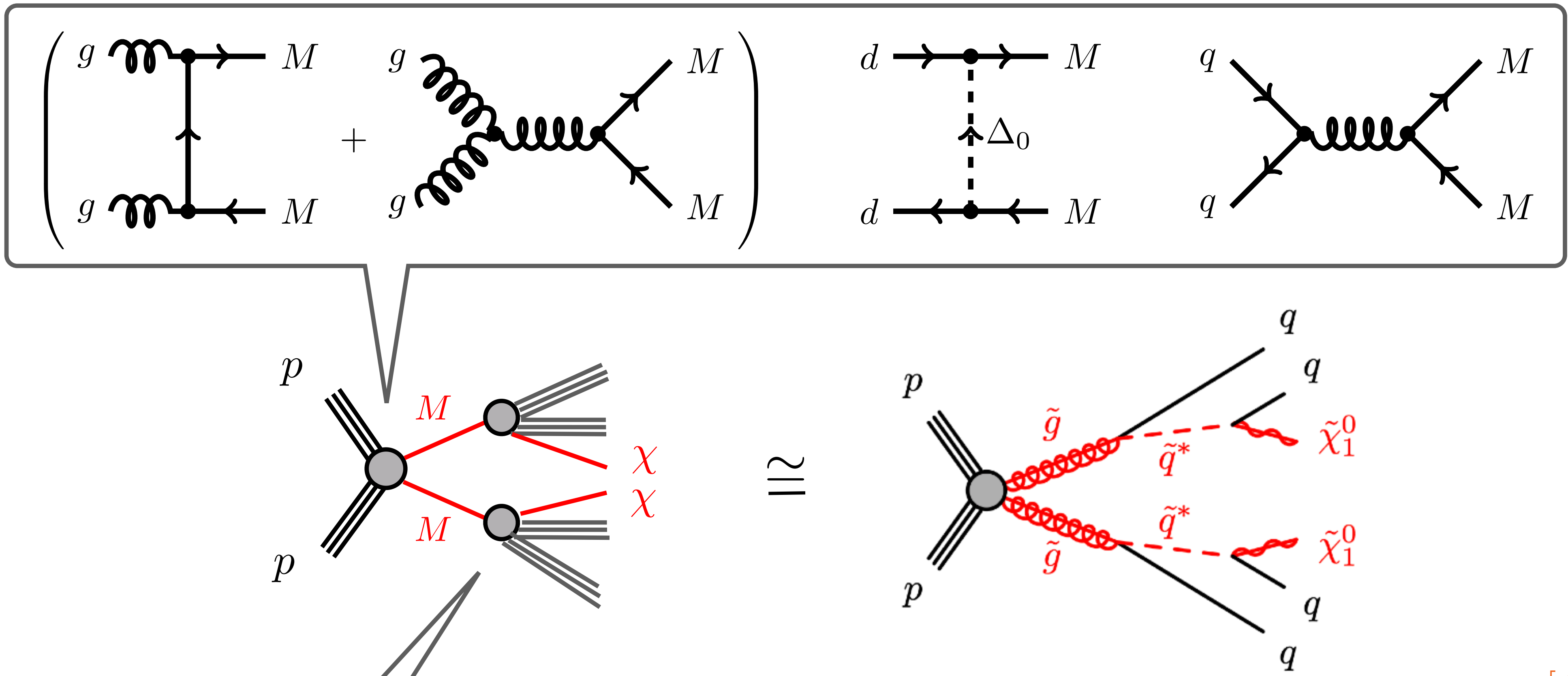

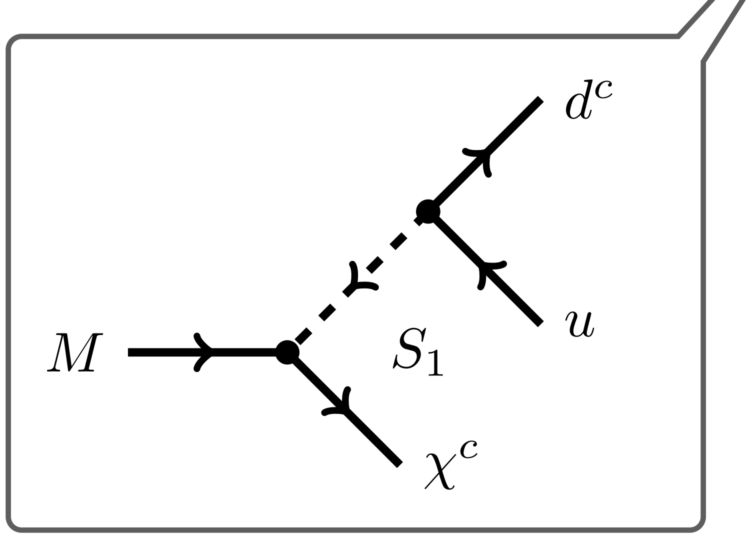

[ATLAS, CMS]

$M \to 2$ JETs + MET

$m_{\rm gluino} > 2 - 2.4$ TeV

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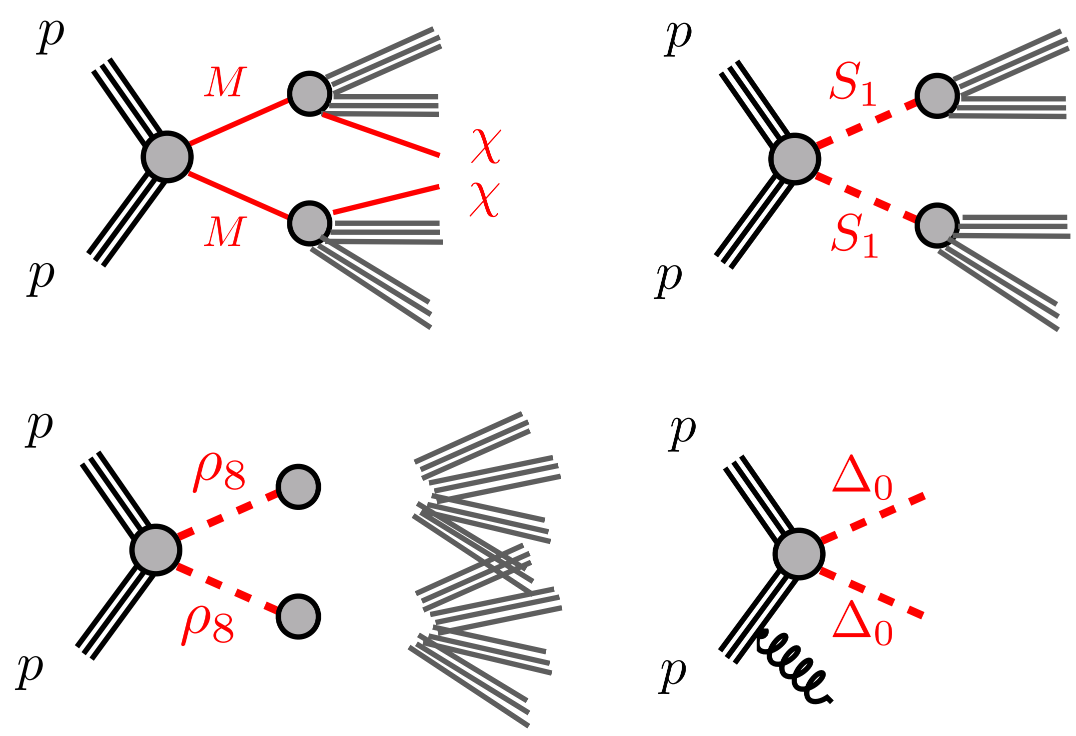
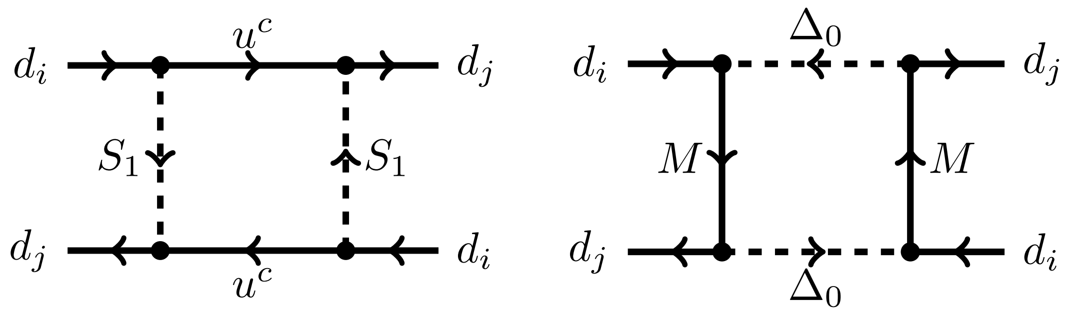
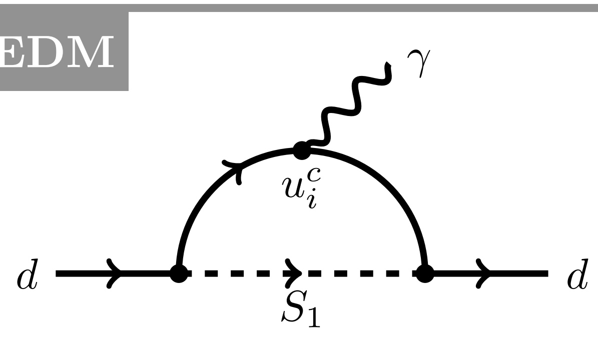


Flavor observables

Meson mixing

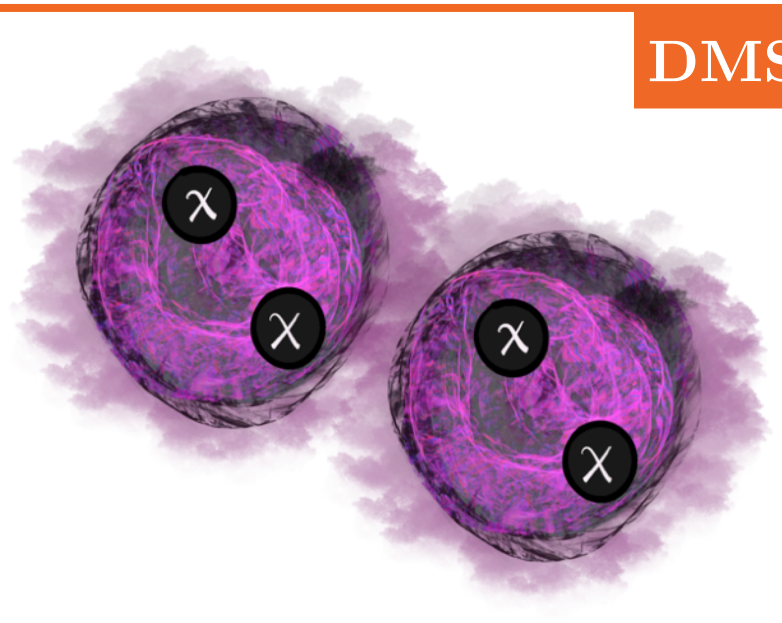


Neutron EDM



Astrophysical signatures

DMSI

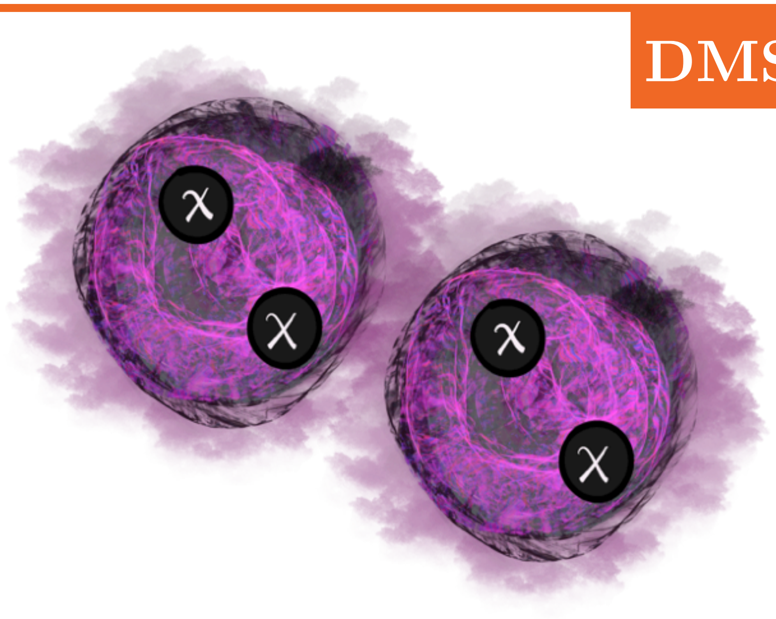


$$\sigma/m_\rho \sim 16\pi/m_\rho^3 \lesssim 1\ \mathrm{cm}^2/\mathrm{g}$$

⇨ $m_\rho \gtrsim 500$ MeV ☺

Astrophysical signatures

DMSI



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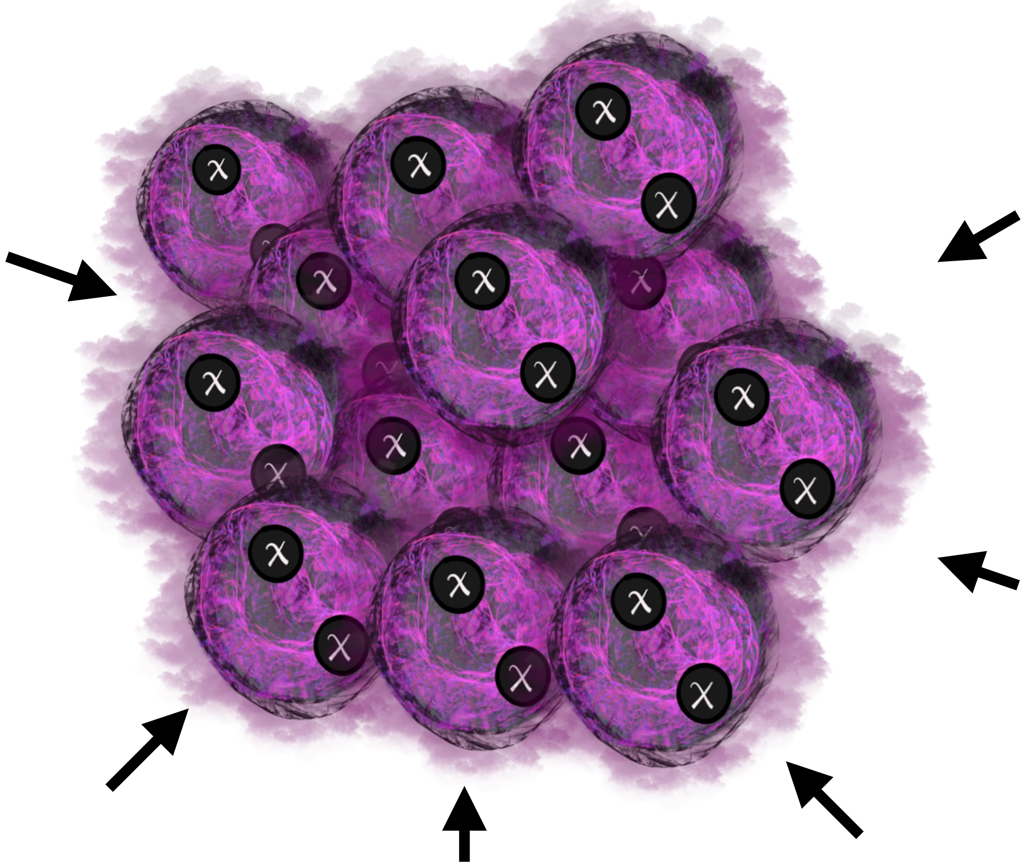
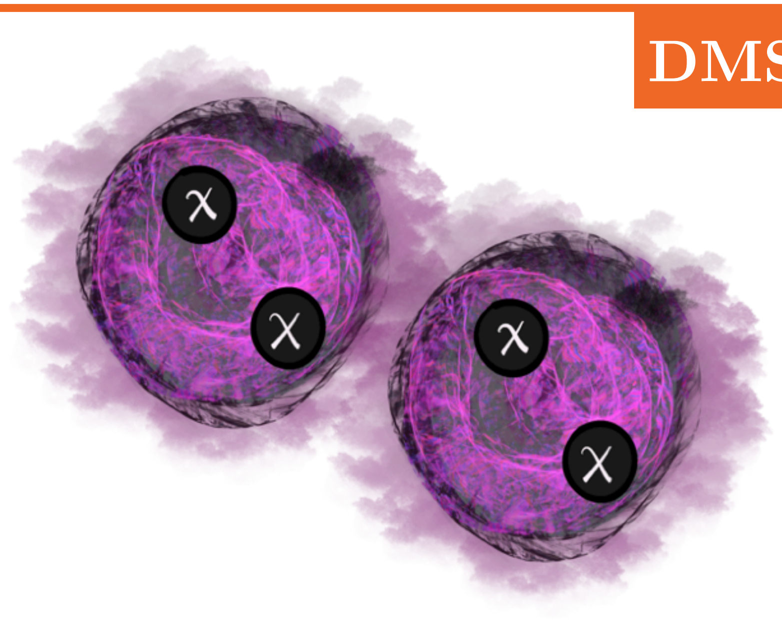
Nuggets



Astrophysical signatures

DMSI



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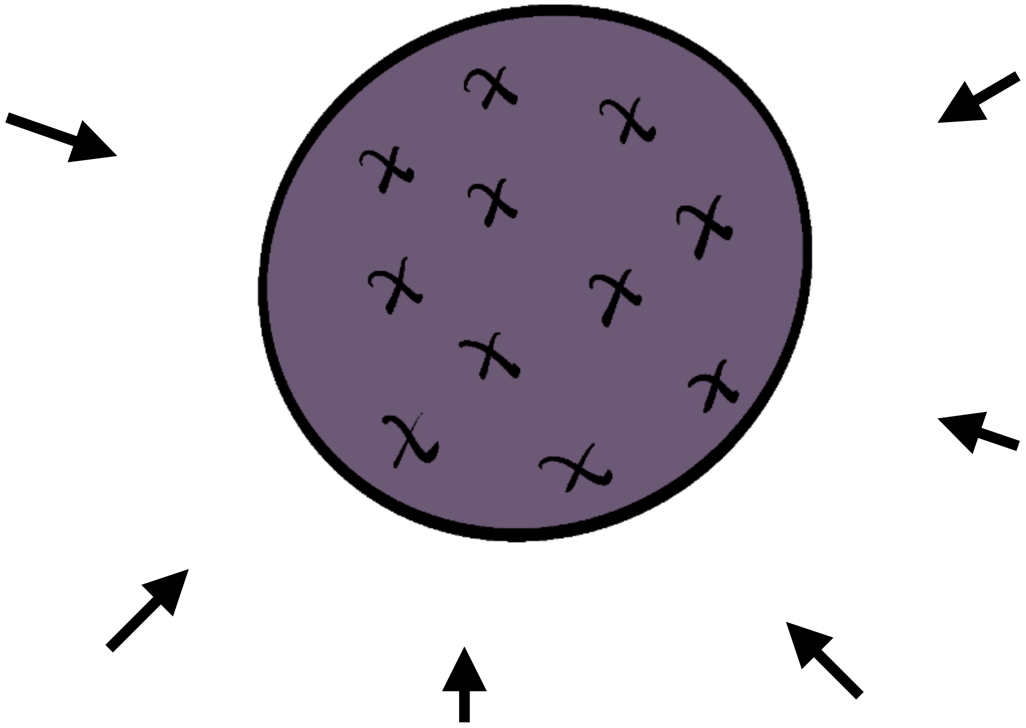
Nuggets

[Wise, Zhang, 2014]
[Gresham, Lou, Zurek, 2018]



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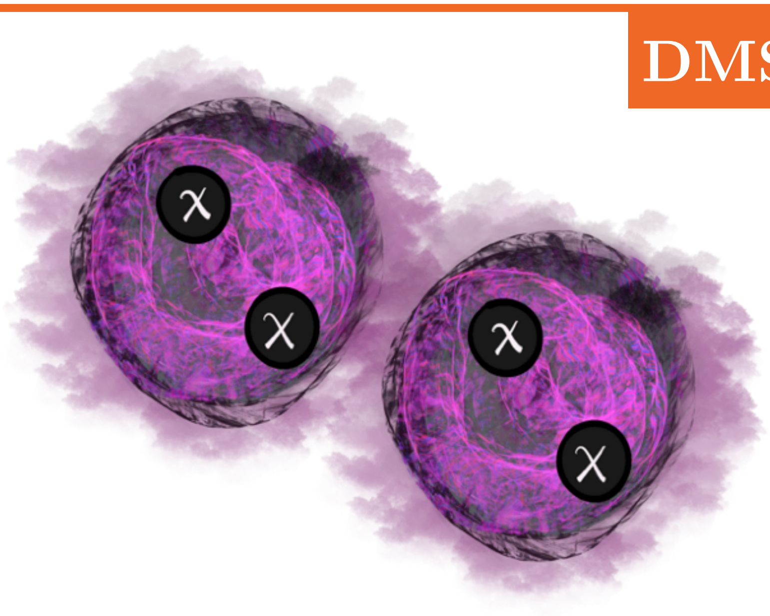

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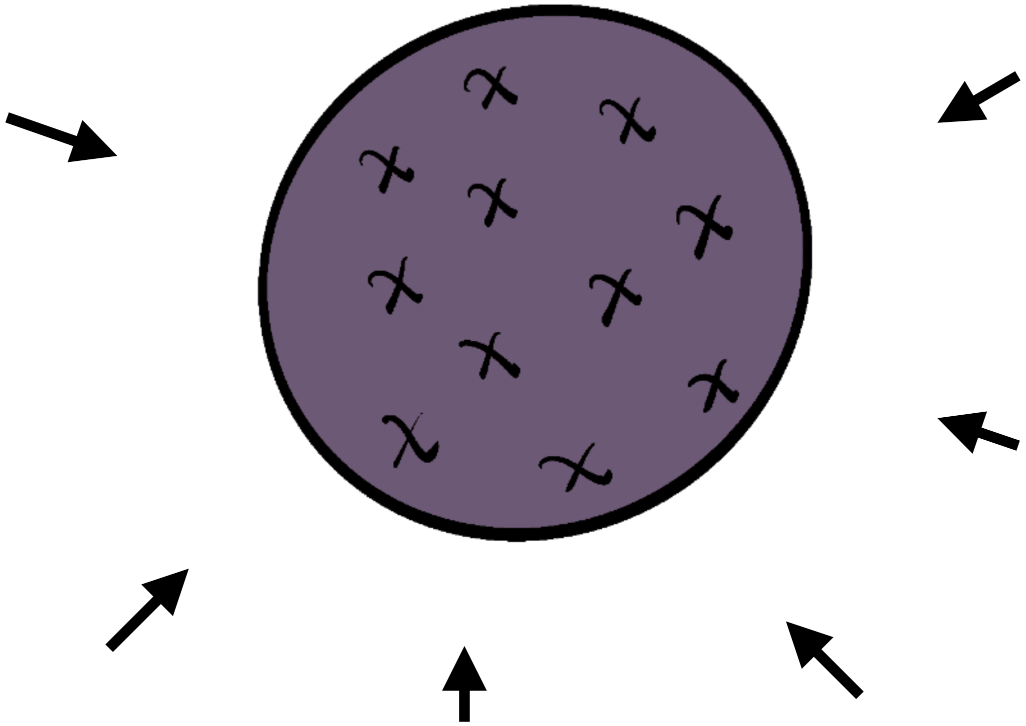


GW

FOPT??

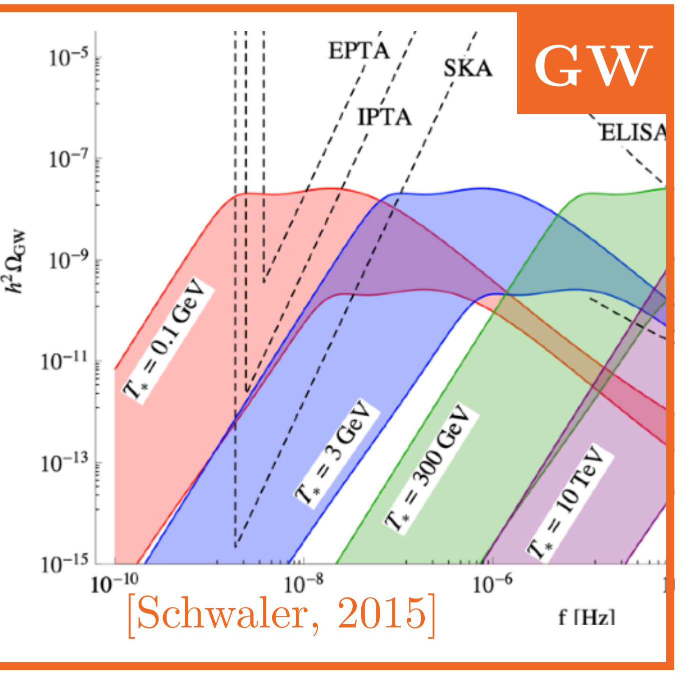
$\mathrm{SU}(2)_D$

+ 1 light flavor

Cosmic strings

$\mathrm{U}(1)_Q \to \mathcal{Z}_2$

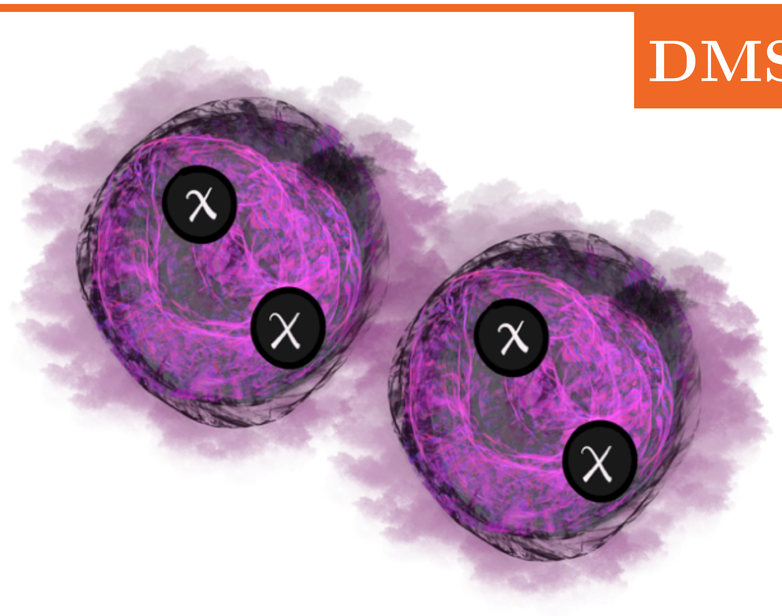
$\mathrm{U}(1)_5 \otimes \mathrm{U}(1)_X \to \mathrm{U}(1)_Y$



[Schwaler, 2015]

Astrophysical signatures

DMSI



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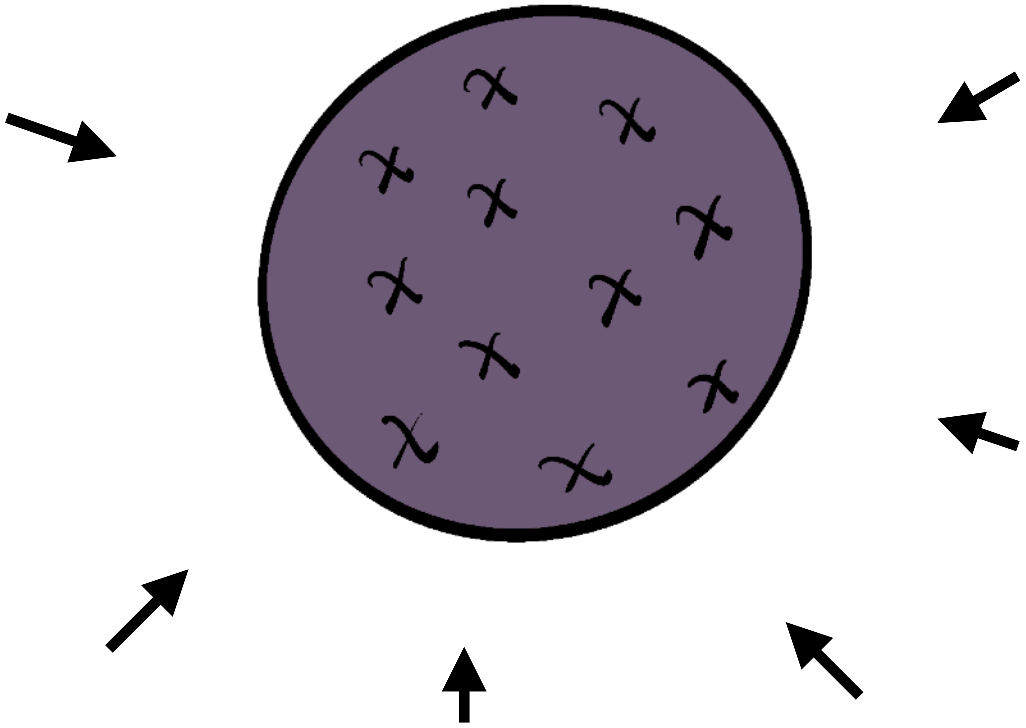

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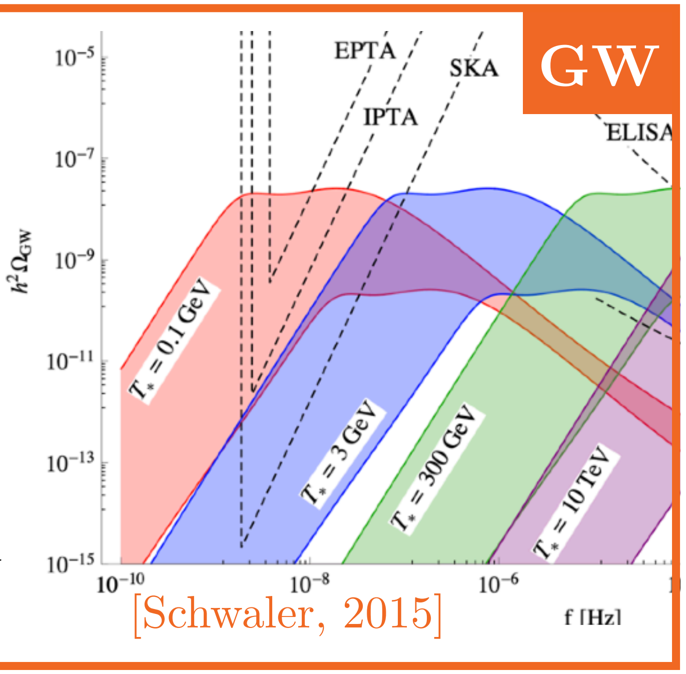
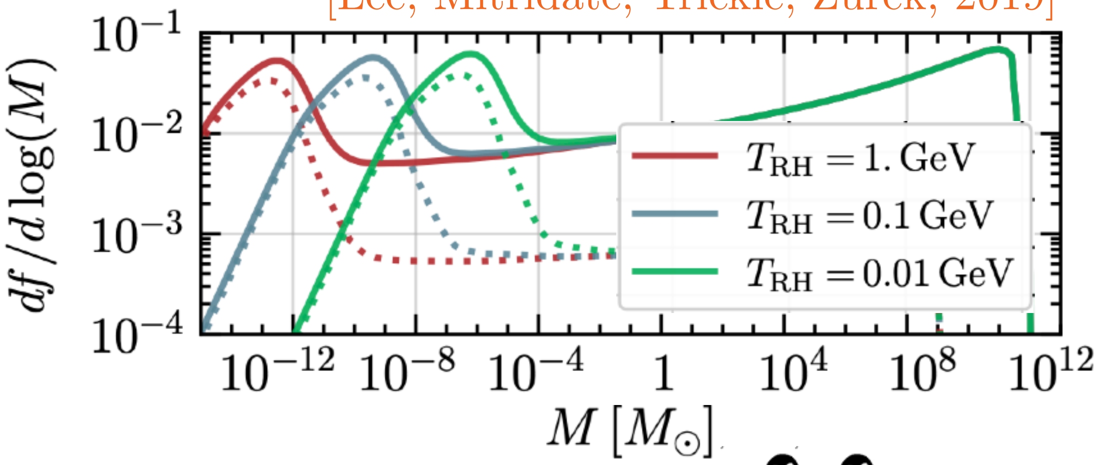


[Schwaler, 2015]

EMD

The lightest dark hadron $(\eta, G_{\mathrm{ball}})$

[Lee, Mitridate, Trickle, Zurek, 2019]

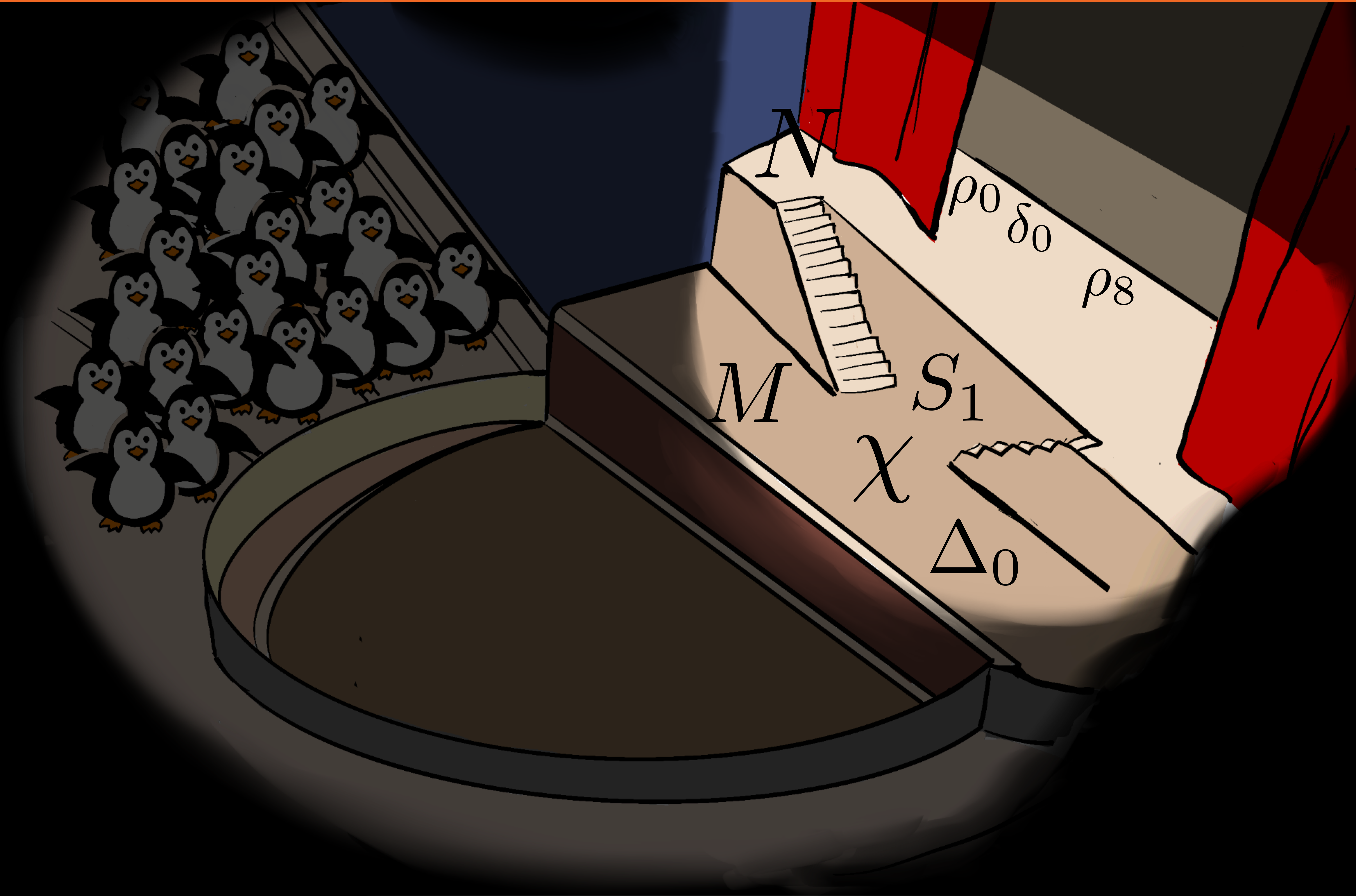


Cast of Characters

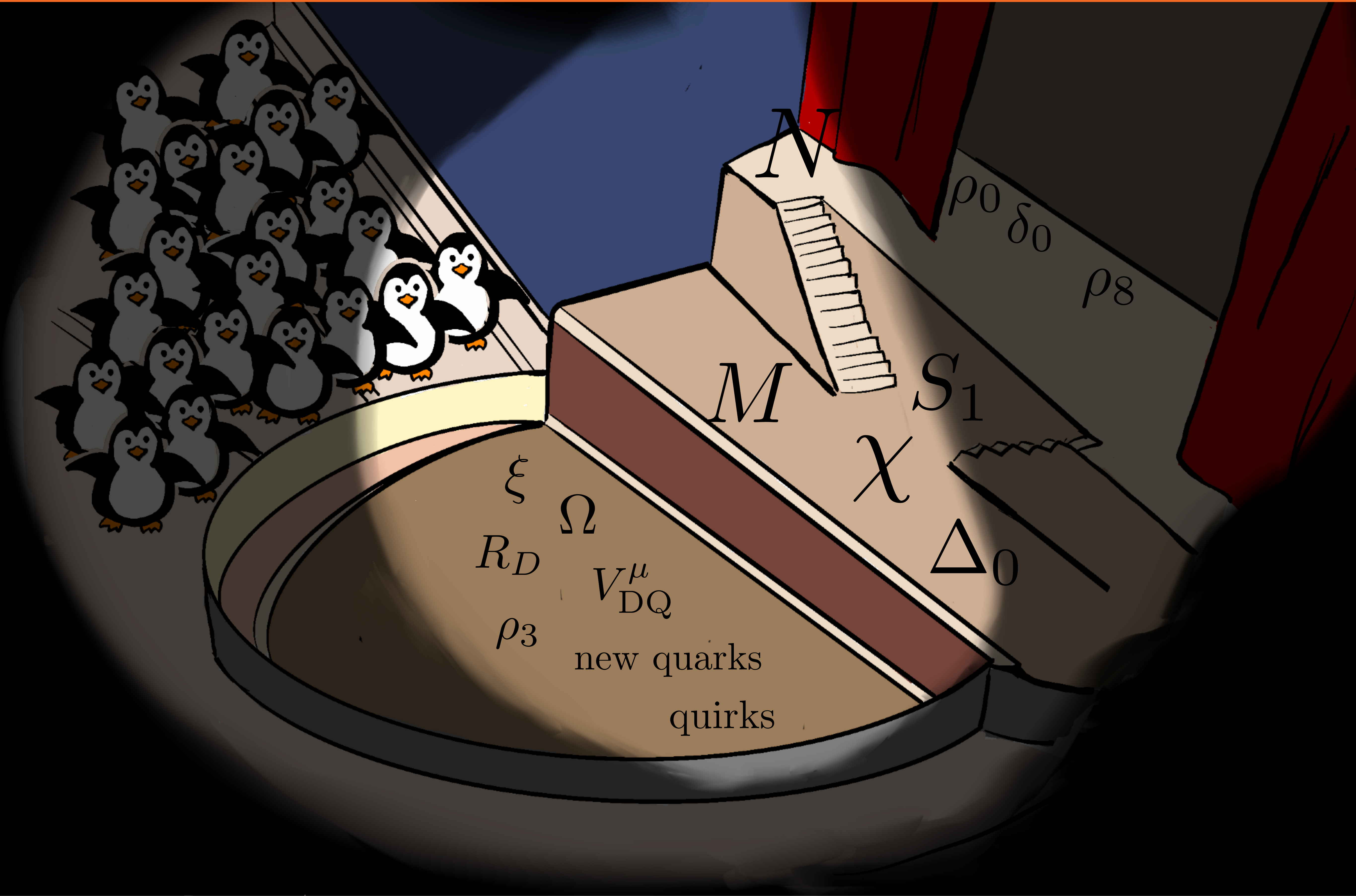
Main Characters

Main Characters

Supporting Cast

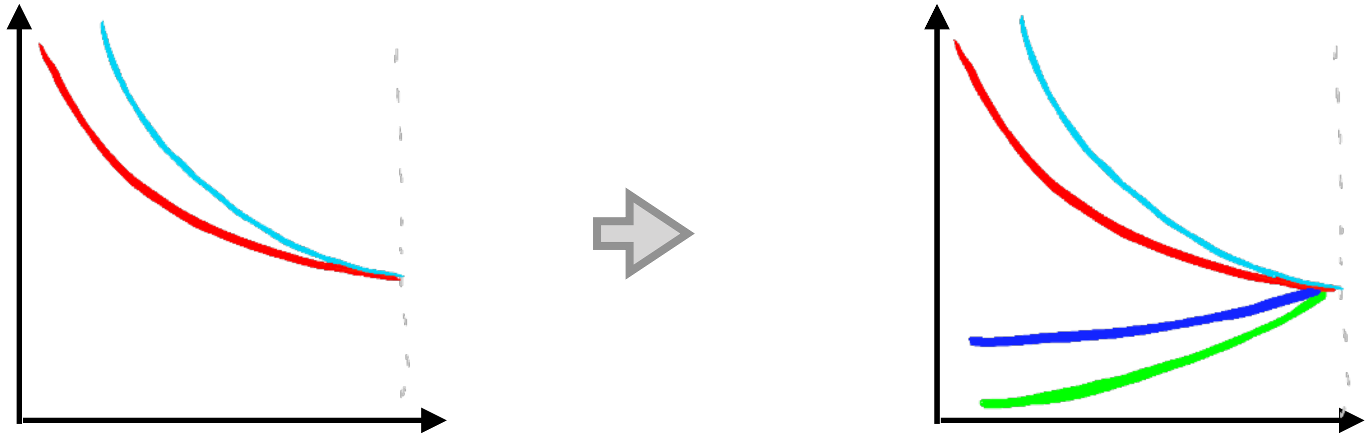


Chorus


N
ρ_0
δ_0
ρ_8
M
S_1
χ
Δ_0
ξ
Ω
R_D
V^{μ}_{DQ}
ρ_3
new quarks
quirks

Towards Grand Unification

$$\mathrm{SU}(7) \supset \mathrm{SU}(5) \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_7 \supset \mathcal{G}_{\mathrm{SM}} \otimes \mathrm{SU}(2)_D$$



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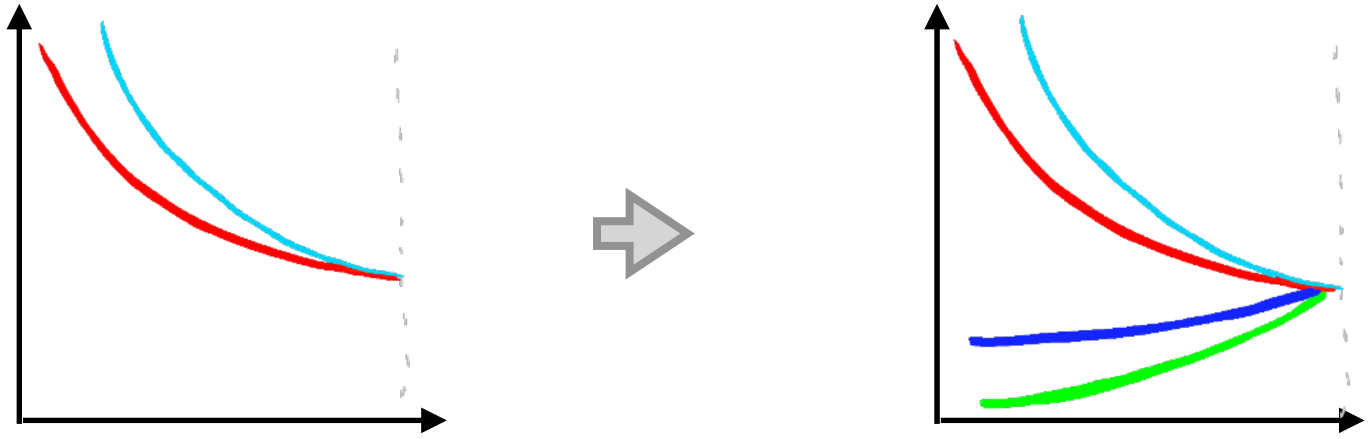

$$\mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y \to \mathrm{U}(1)_{\mathrm{em}} \qquad \Rightarrow \qquad 7_H \sim \begin{pmatrix} S_1^* \\ \Delta_0 \\ -- \\ H \end{pmatrix}$$

➡ Minimal matter content (Embedding of the SM):

$$\bar{7} = \begin{pmatrix} d^c \\ \chi \\ -- \\ \ell \end{pmatrix} \qquad \text{and} \qquad 21 = \left(\begin{array}{cc|c} u^c & M & q \\ -M^T & N & \Psi_2 \\ --- & --- & -- \\ -q^T & -\Psi_2^T & e^c \end{array}\right)$$

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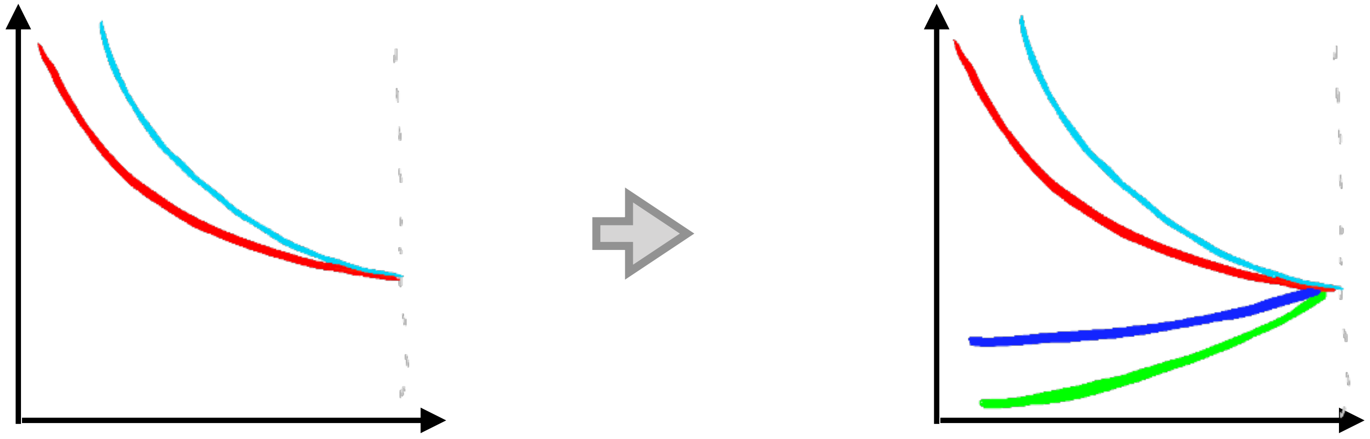

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- Simplest Yukawa interaction:

$$\boxed{Y_e\, \bar{7}\, 21\, 7^*_H}$$

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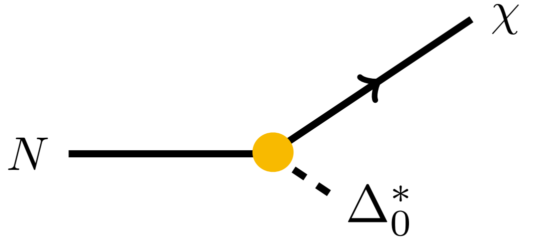
- Simplest Yukawa interaction:

$$Y_e\, \bar{7}\, 21\, 7_H^*$$

$$\Big\downarrow \text{Expand}$$

$$\supset Y_e \left(d^c u^c S_1 + d^c M \Delta_0^* + \chi M S_1 + \boxed{\chi N \Delta_0^*} \right)$$

Darko-Baryo-Genesis



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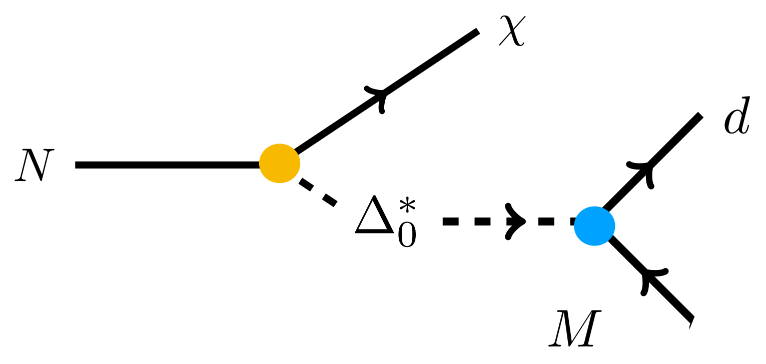
Darko-Baryo-Genesis



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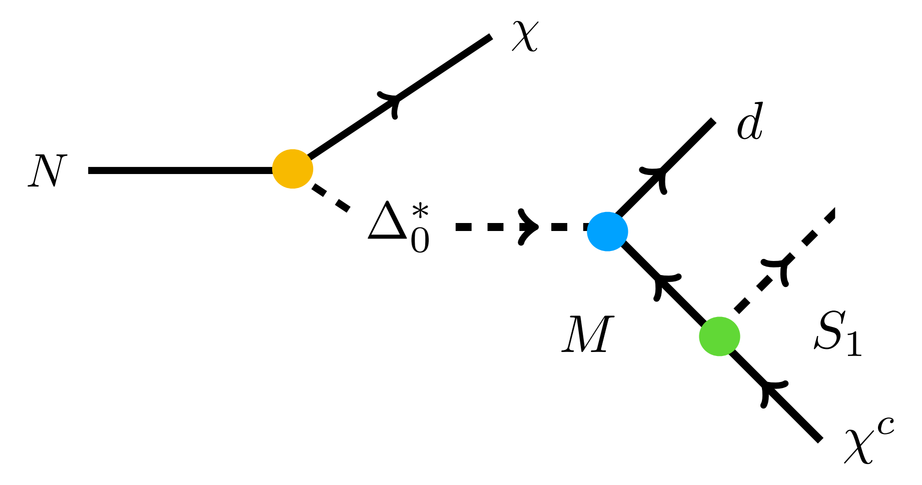

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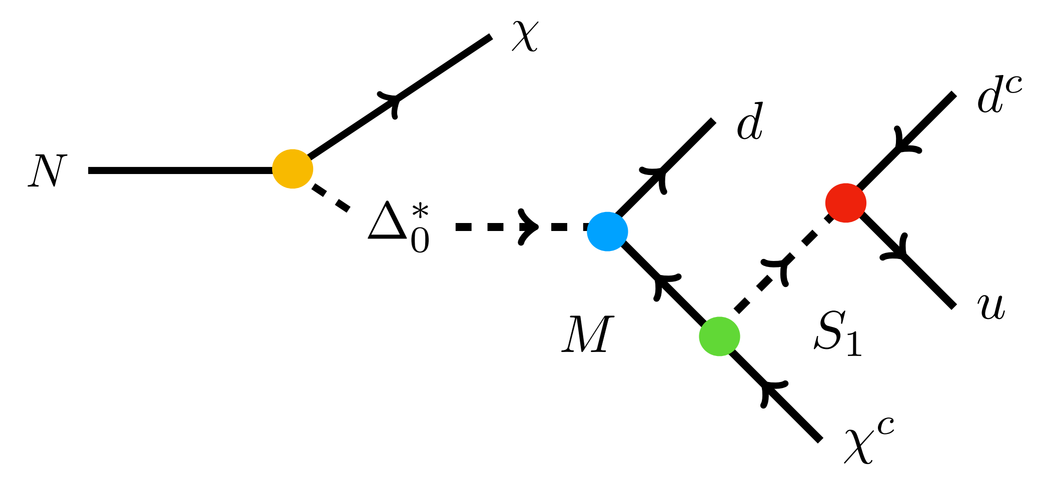
Darko-Baryo-Genesis



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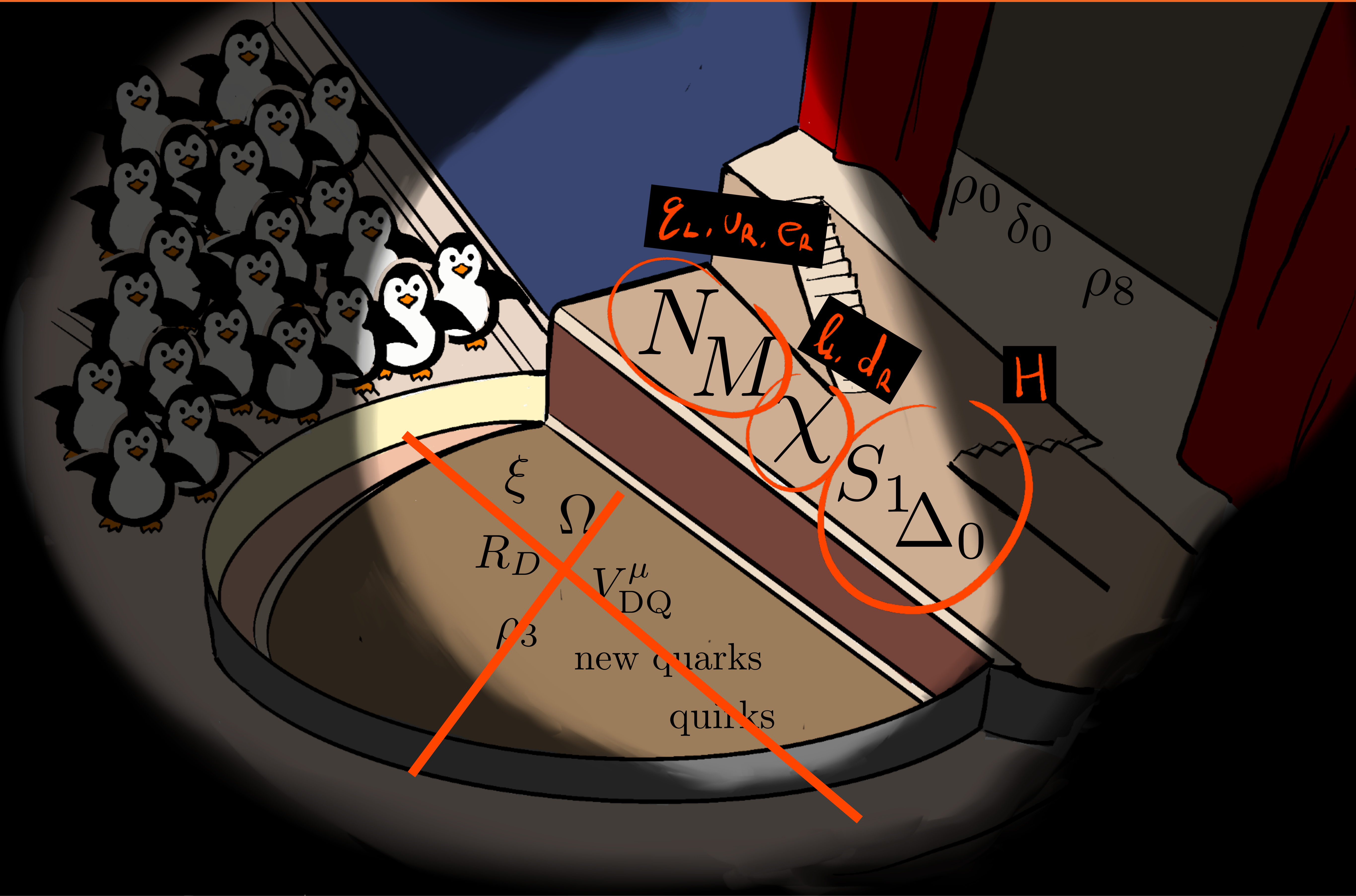
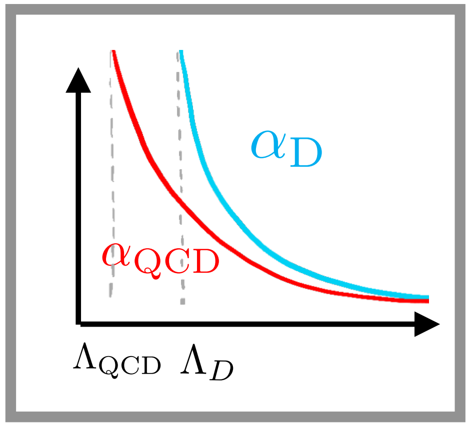
Dark Unification in SU(7)



Conclusions



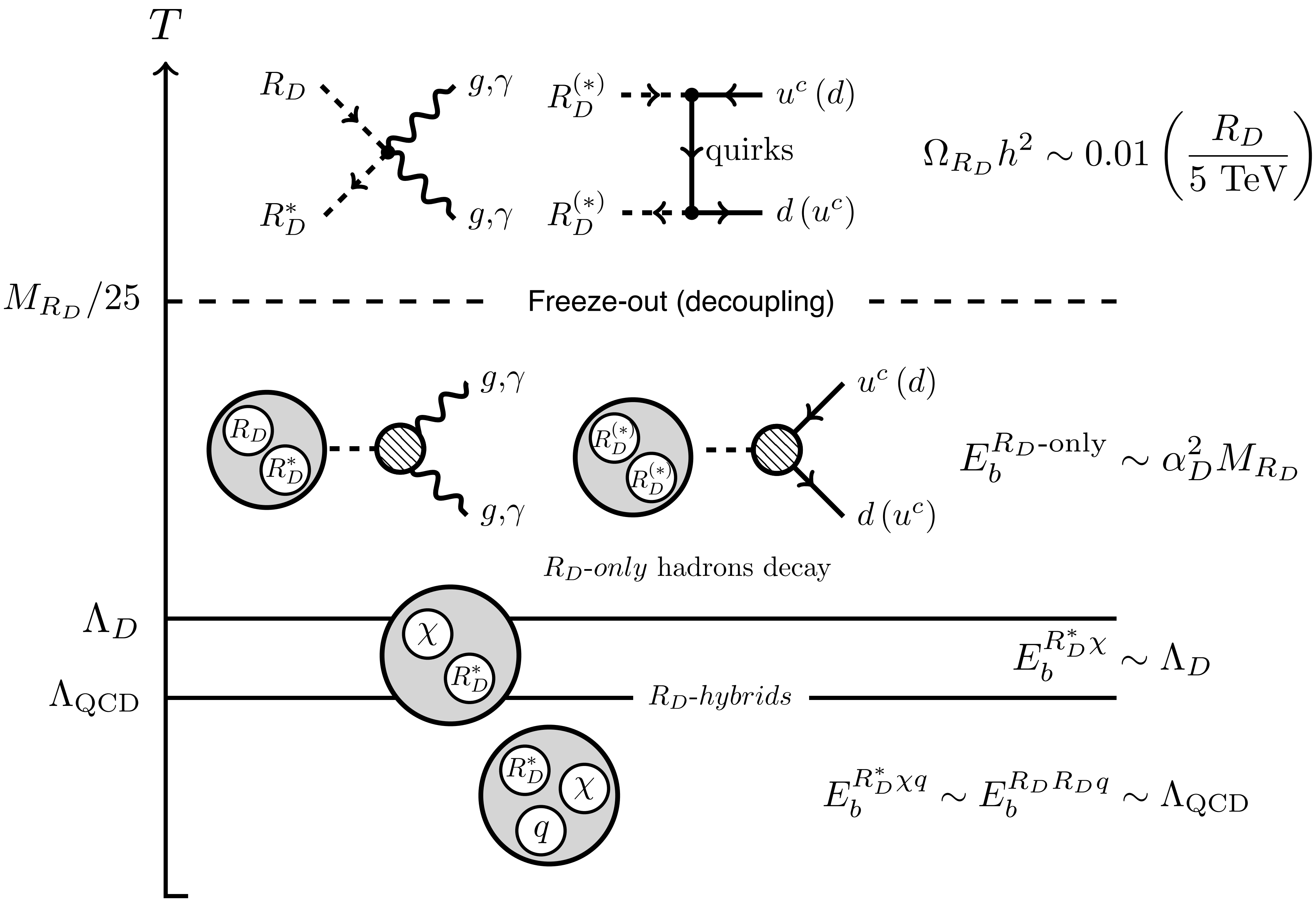
- Idea of Dark-Color Unification.
- Simplest gauge group to achieve it: SU(5) hypercolor
    - Anomaly-free within SM representations
    - Naturally provides a mechanism for splitting quarks & quirks
    - Can host an hadronic DM candidate (spin 1 baryon) and Darko-Baryo-genesis.
- An (equal) asymmetry in the baryon and dark baryon sector ($\mathrm{U}(1)_{B-D} \Rightarrow Y_{\Delta B} = Y_{\Delta D}$) + nearby confinement scales ($\Lambda_{\rm D} \sim 6\Lambda_{\rm QCD}$) justify same order relic densities ($\Omega_D \sim 5\Omega_B$).
- Colored fermions and scalars are predicted to be at the TeV scale.
- DM self-interactions, Early Matter Domination, GW (amongst others) are expected.
- The main drivers for darko-baryo-genesis and its required interactions appear (unavoidably) with the SM fields when unifying the strong and electroweak sectors in SU(7).

Thank you!

Back-up slides

Charged Relics

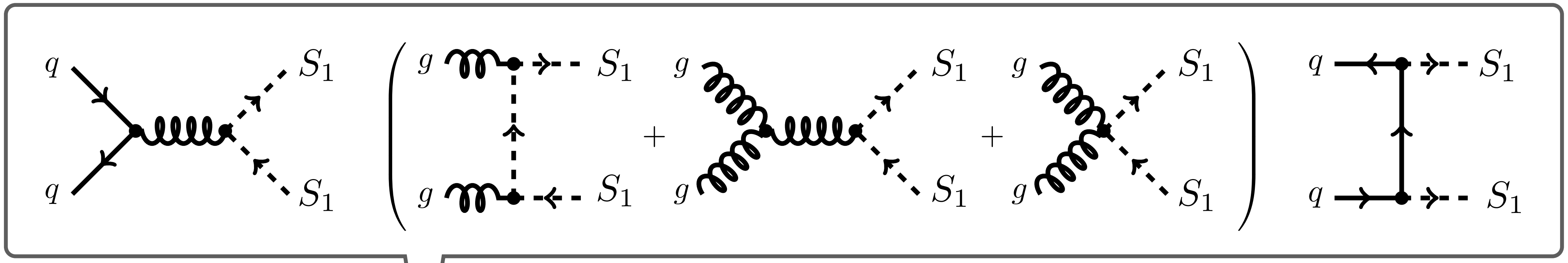
[De Luca, **Mitridate**, Redi, Smirnov, Strumia, 2019]

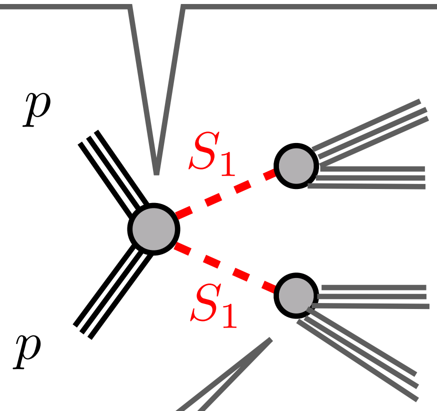


Phenomenological signatures

- Potential light fields S_1 M R_D ρ_8

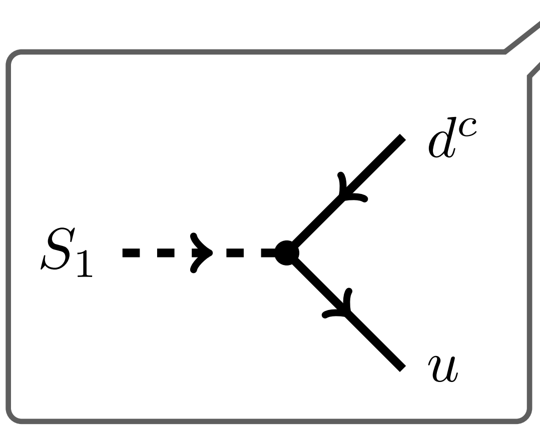
At colliders





Scalar diquark constraints
[CMS, 2019]

$$(M_{S_1} > 7.5 \text{ TeV})$$



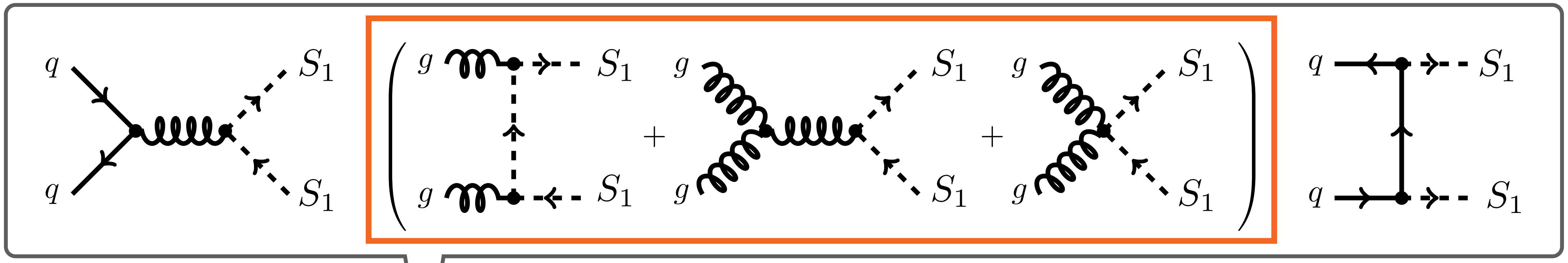
$S_1 \to 2$ JETs

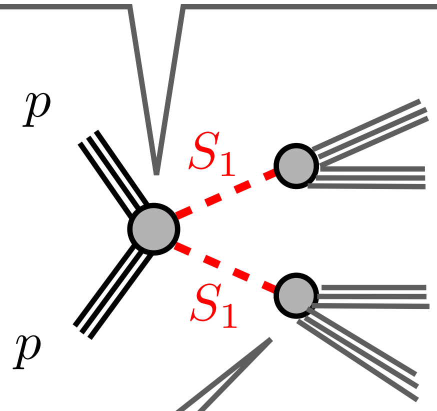
$$\tau_{S_1}^{-1} \simeq \frac{M_{S_1}}{4\pi} |Y_{\text{quirks}}|^2 \simeq 1.2 \times 10^{27} \text{ s}^{-1} \left(\frac{M_{S_1}}{10 \text{ TeV}} \right) \left(\frac{|Y_{\text{quirks}}|}{1} \right)^2$$

Phenomenological signatures

Potential light fields S_1 M R_D ρ_8

At colliders

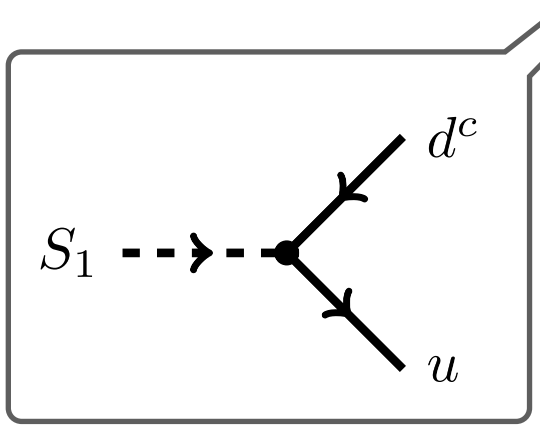




Scalar diquark constraints

[CMS, 2019]

$(M_{S_1} > 7.5 \text{ TeV})$ $\boxed{M_{S_1} \gtrsim 1 \text{ TeV}}$



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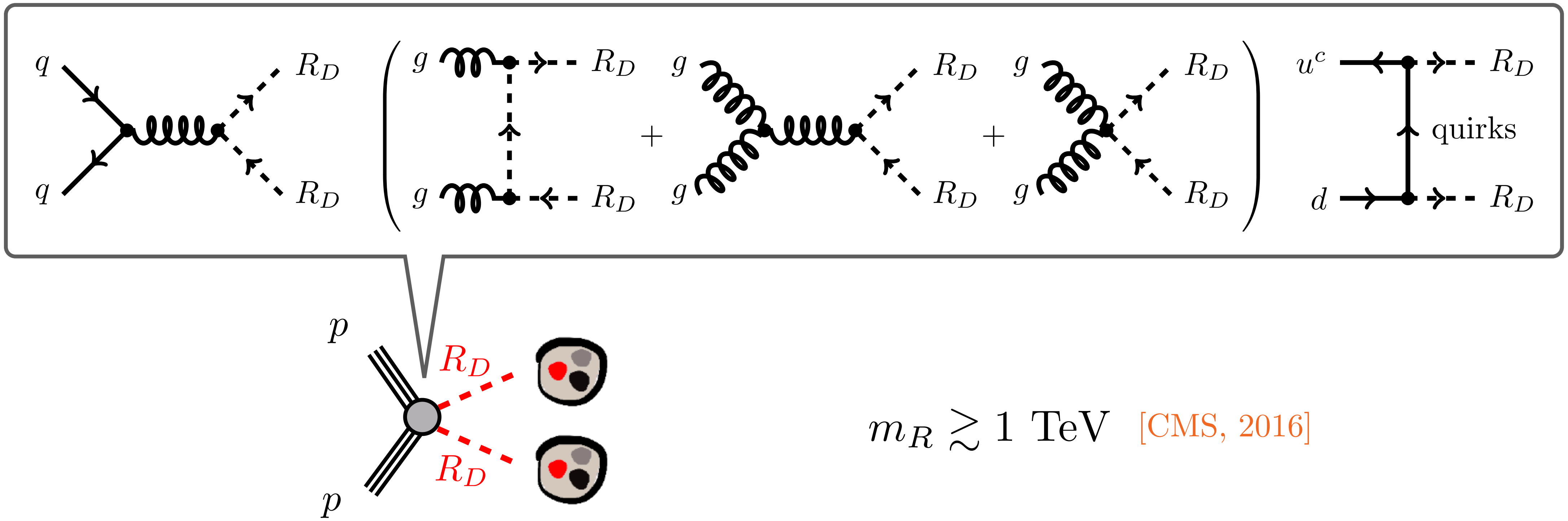
Phenomenological signatures

Potential light fields S_1 M R_D ρ_8

At colliders

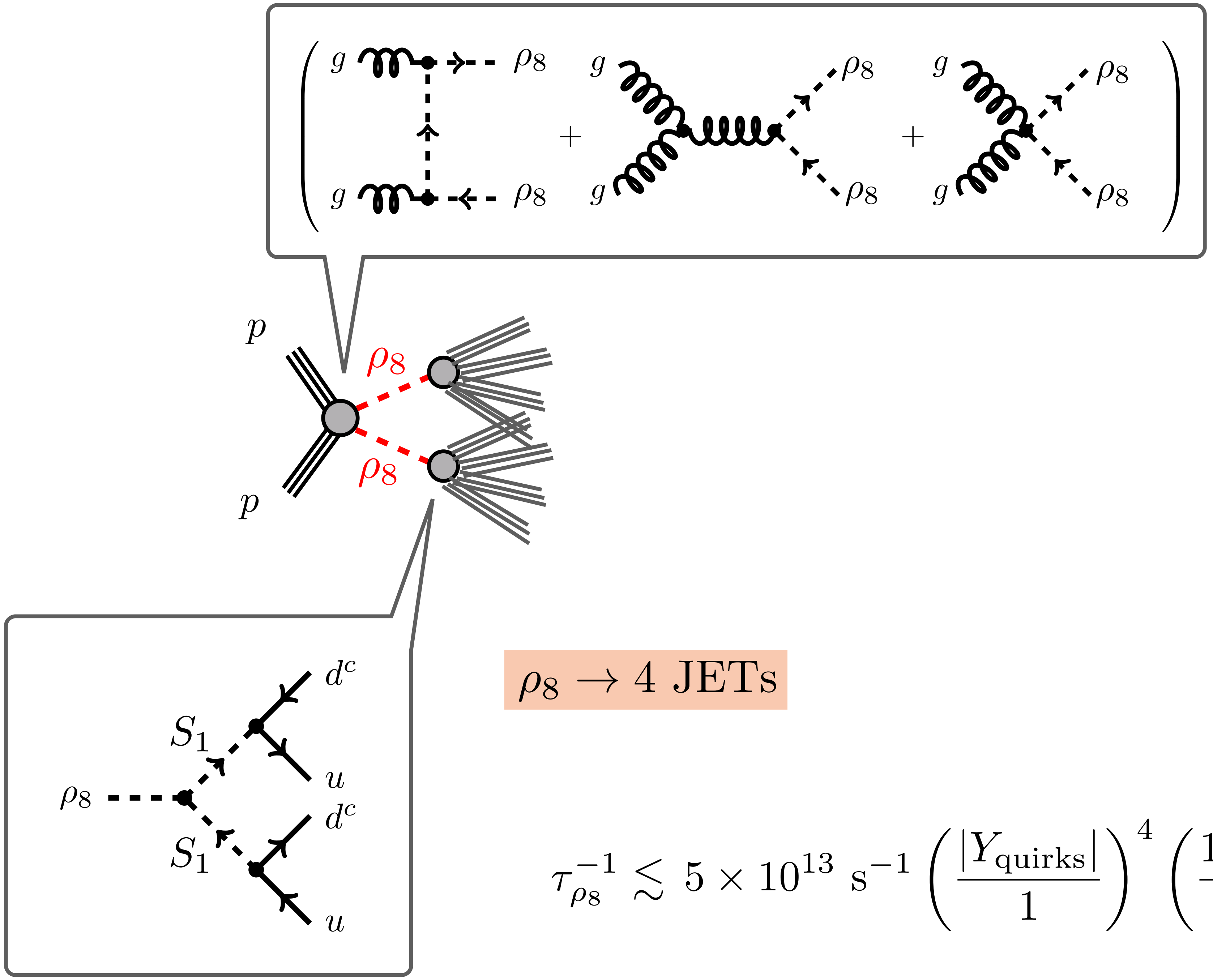


$m_R \gtrsim 1$ TeV [CMS, 2016]

Phenomenological signatures

- Potential light fields S_1 M R_D ρ_8

At colliders



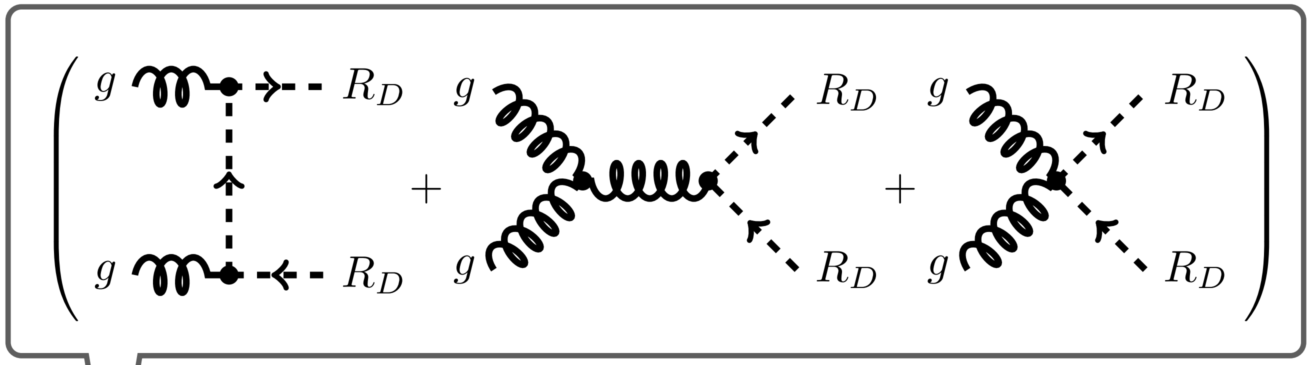
$\rho_8 \to 4$ JETs

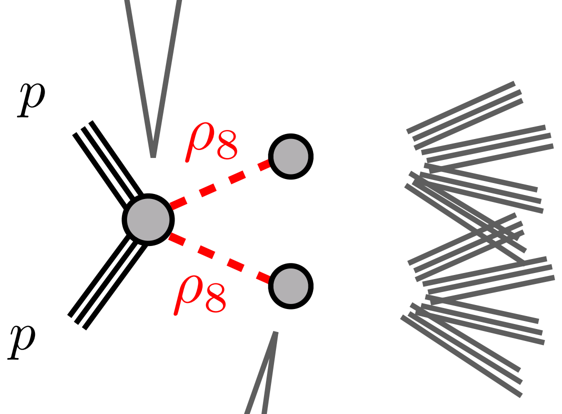
$$\tau_{\rho_8}^{-1} \lesssim 5 \times 10^{13}\ \mathrm{s}^{-1} \left(\frac{|Y_{\mathrm{quirks}}|}{1}\right)^4 \left(\frac{10\ \mathrm{TeV}}{M_{S_1}}\right)^8 \left(\frac{M_{\rho_8}}{1\ \mathrm{TeV}}\right)^9$$

Phenomenological signatures

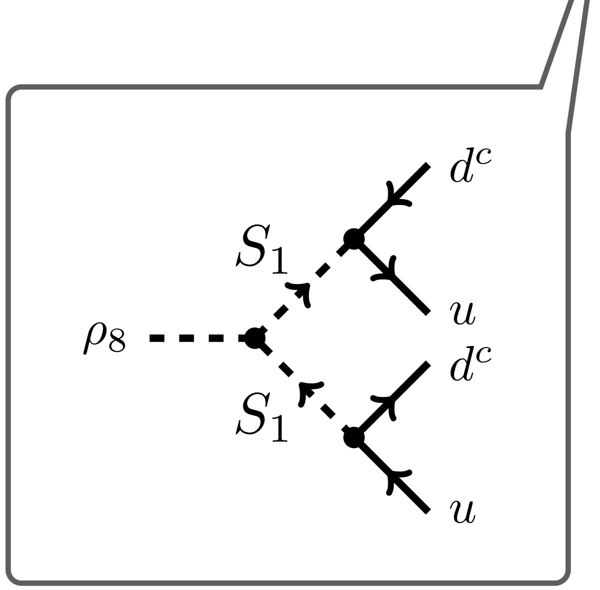
- Potential light fields S_1 M R_D ρ_8

At colliders





- Potential displaced vertices of 4 jets



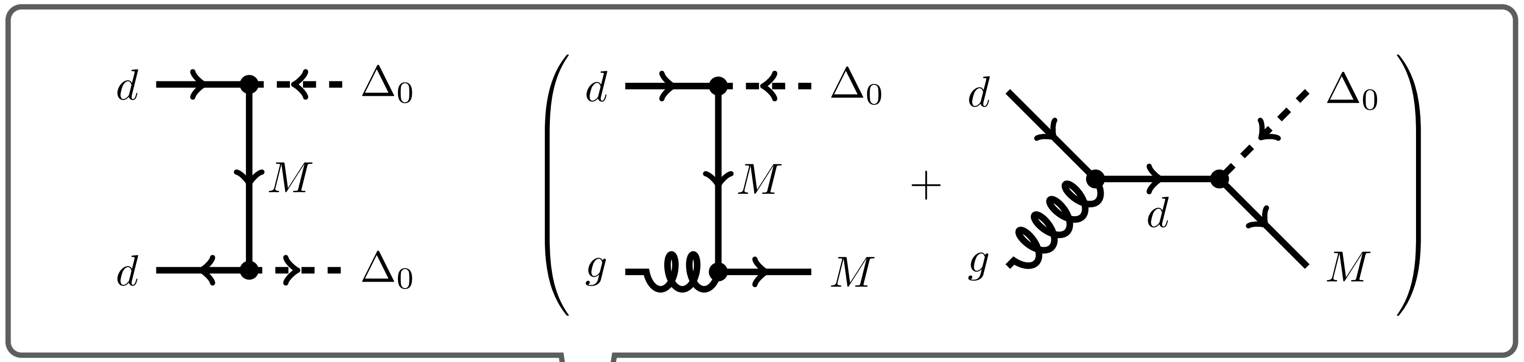
$\rho_8 \to 4$ JETs

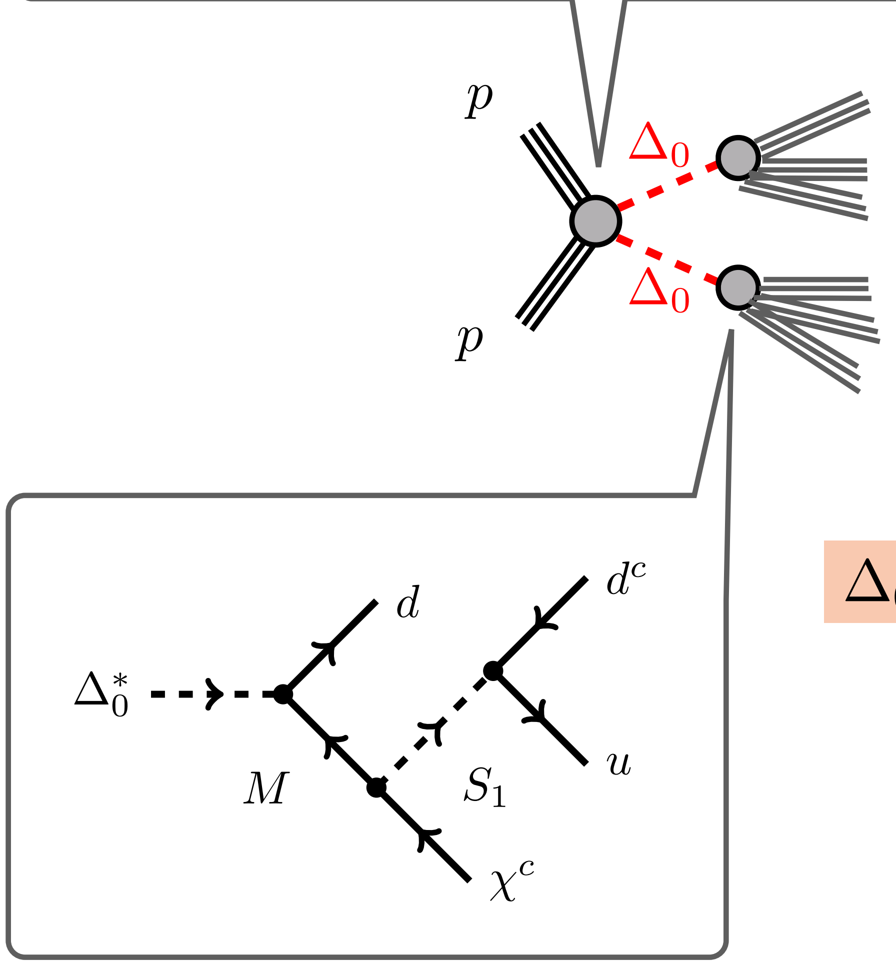
$$\tau_{\rho_8}^{-1} \lesssim 5 \times 10^{13}\ \mathrm{s}^{-1} \left(\frac{|Y_{\text{quirks}}|}{1}\right)^4 \left(\frac{10\ \text{TeV}}{M_{S_1}}\right)^8 \left(\frac{M_{\rho_8}}{1\ \text{TeV}}\right)^9$$

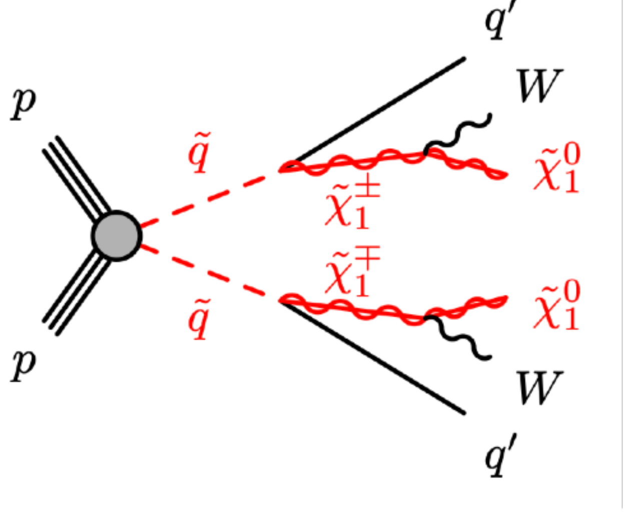
Pheno signatures

Potential light fields S_1 M R_D ρ_8 Δ_0

At colliders







Stop searches
[ATLAS, 2021]

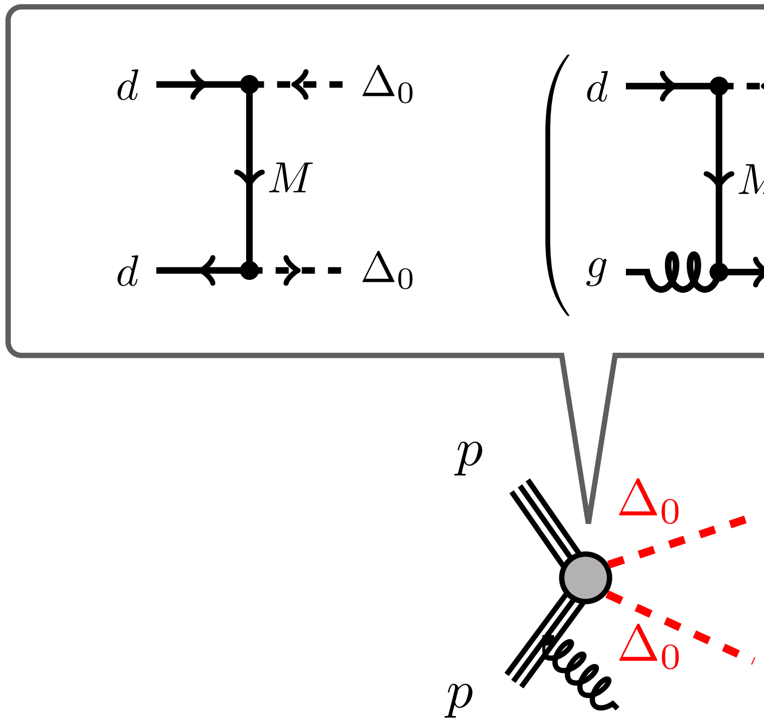
$m_{\tilde{q}} > 1.3$ TeV

$\Delta_0 \to 3$ JETs + MET

Pheno signatures

Potential light fields S_1 M R_D ρ_8 Δ_0

At colliders



Monojet searches
[ATLAS, 2021]

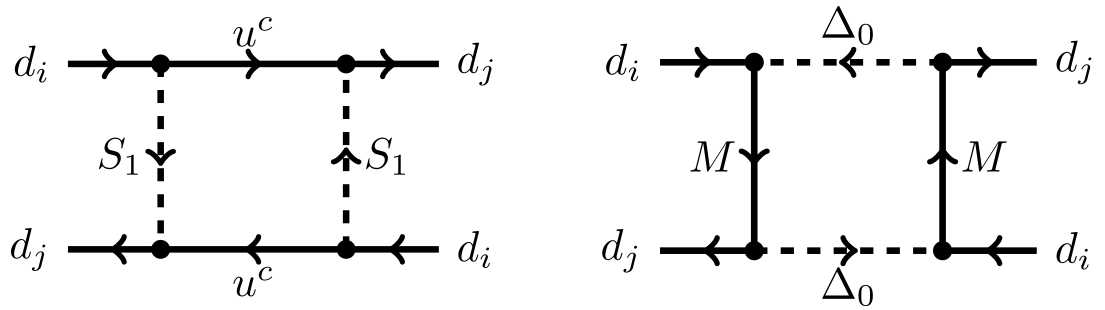
$\Delta_0 \rightarrow$ 3 ~~JETs~~ + MET

Phenomenological signatures

Flavor observables

Meson mixing

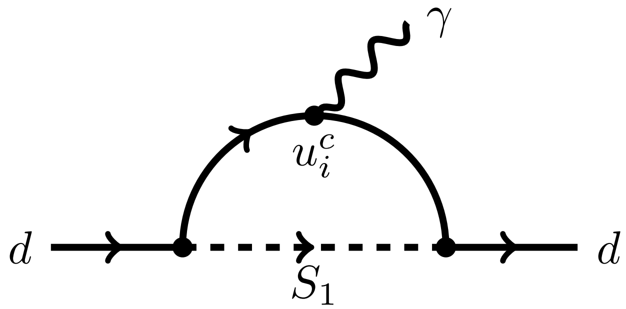
[Pich, Mandal, 2019]



$$\sqrt{\left|\mathrm{Re}\{(Y^1_{\Delta_0}(Y^2_{\Delta_0})^*)^2\}\right|}\left(\frac{\mathrm{TeV}}{M_{M/\Delta_0}}\right) \lesssim 0.01$$

$$\sqrt{\left|\mathrm{Im}\{(Y^1_{\Delta_0}(Y^2_{\Delta_0})^*)^2\}\right|}\left(\frac{\mathrm{TeV}}{M_{M/\Delta_0}}\right) \lesssim 8 \times 10^{-4}$$

Neutron EDM



$$|d_d| \simeq \sum_j \frac{e}{6\pi^2}\frac{m_{q_j}}{M^2_{S_1}} \mathrm{Im}\{Y_\eta^{1j}(Y_\Psi^{1j})^*\} \ln\left(\frac{M_{S_1}}{m_{q_j}}\right)$$

$$\frac{\mathrm{Im}\{Y_{\mathrm{quirks}}\}}{M_{S_1}/\mathrm{TeV}} \lesssim 4 \times 10^{-4}$$

Is the DM stable enough?

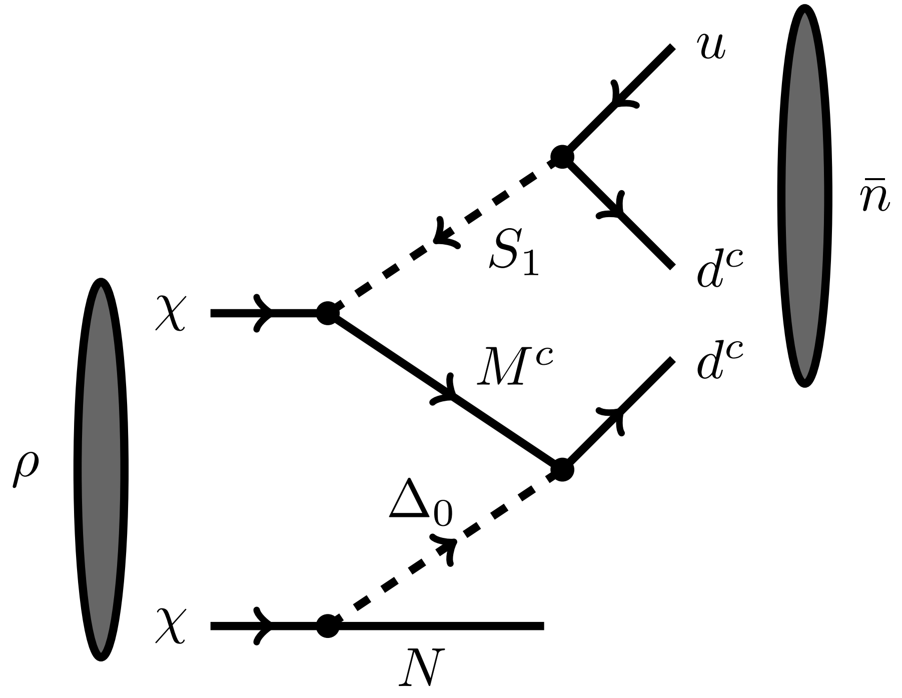
$$\frac{1}{\Lambda^{3.5}} \chi \, \chi \, q \, q \, q$$

$$\begin{aligned}\mathcal{L} \supset\ & Y_{\Delta_0} \left(d^c \, Q_N^c \, \Omega^* + \eta_d \, M \, \Omega^* + \boxed{d^c \, M \, \Delta_0^*} + \eta_d \, \xi \, \Delta_0^* \right) \\ & + Y_\chi \left(\boxed{\chi \, \Delta_0^*} + q_N \, \Omega^* \right) N + Y_{\bar{\chi}} \left(q_N^c \, \Omega + \chi^c \, \Delta_0 \right) N + \text{h.c.}\end{aligned}$$

⇨ $\mathrm{U}(1)_{B-D}$

Is the DM stable enough?

$$\frac{1}{\Lambda^5}\chi\,\chi\,q\,q\,q\,N$$

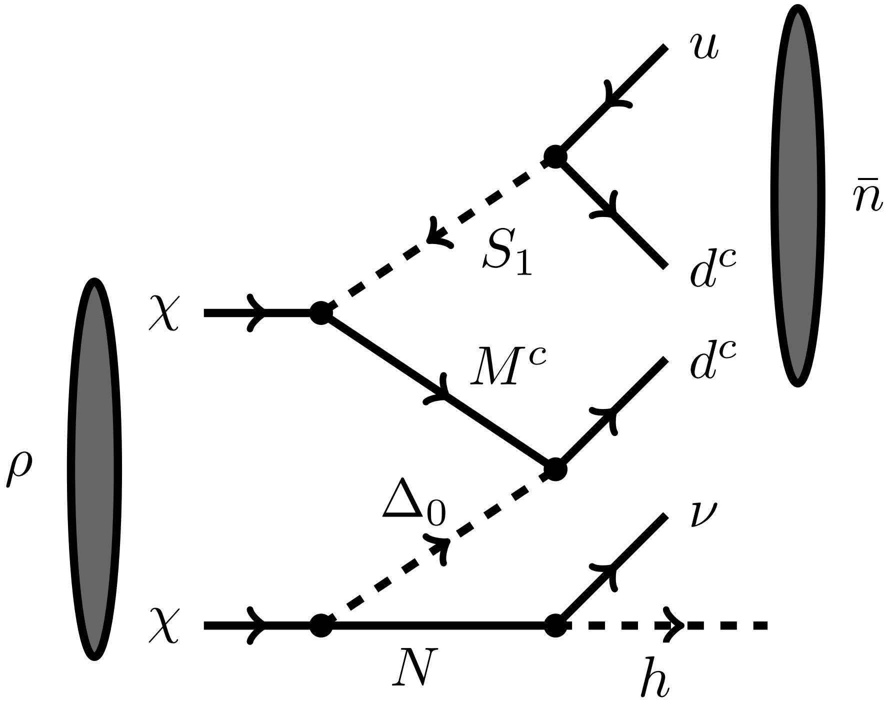


$$\mathcal{L} \supset Y_{\Delta_0}\,(d^c\,Q_N^c\,\Omega^* + \eta_d\,M\,\Omega^* + \boxed{d^c\,M\,\Delta_0^*} + \eta_d\,\xi\,\Delta_0^*) \\ + Y_\chi\,\boxed{(\chi\,\Delta_0^*} + q_N\,\Omega^*)\,N + Y_{\bar{\chi}}\,(q_N^c\,\Omega + \chi^c\,\Delta_0)\,N + \text{h.c.}$$

⇨ $\mathrm{U}(1)_{B-D}$

Is the DM stable enough?

$$\frac{1}{\Lambda^6} \chi\, \chi\, q\, q\, q\, \nu\, h$$

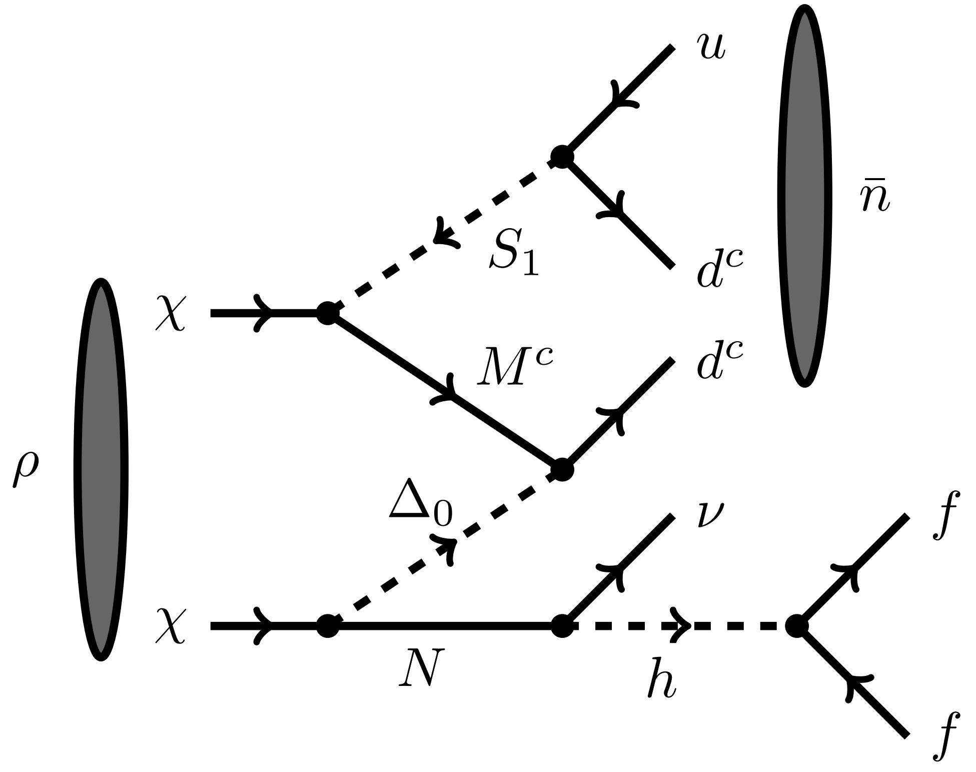


$$\begin{aligned}\mathcal{L} \supset\ & Y_{\Delta_0} \left(d^c\, Q_N^c\, \Omega^* + \eta_d\, M\, \Omega^* + \boxed{d^c\, M\, \Delta_0^*} + \eta_d\, \xi\, \Delta_0^*\right) \\ & + Y_\chi \left(\boxed{\chi\, \Delta_0^*} + q_N\, \Omega^*\right) N + Y_{\bar{\chi}} \left(q_N^c\, \Omega + \chi^c\, \Delta_0\right) N + \text{h.c.}\end{aligned}$$

⇨ $\mathrm{U}(1)_{B-D}$

Is the DM stable enough?

$$\frac{1}{\Lambda^8}\chi\,\chi\,q\,q\,q\,\nu\,\bar{f}\,f$$

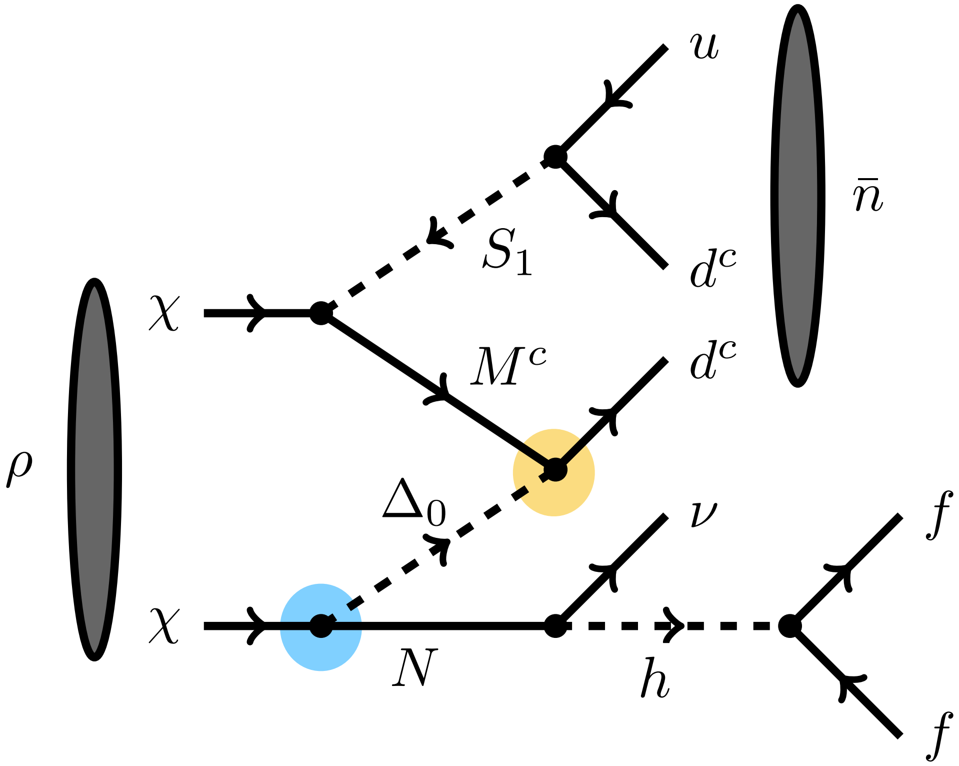


$$\mathcal{L} \supset Y_{\Delta_0}\,(d^c\,Q_N^c\,\Omega^* + \eta_d\,M\,\Omega^* + \boxed{d^c\,M\,\Delta_0^*} + \eta_d\,\xi\,\Delta_0^*) + Y_\chi\,\boxed{(\chi\,\Delta_0^*} + q_N\,\Omega^*)\,N + Y_{\bar{\chi}}\,(q_N^c\,\Omega + \chi^c\,\Delta_0)\,N + \text{h.c.}$$

⇨ $\mathrm{U}(1)_{B-D}$

Is the DM stable enough?

$$\mathcal{O}_{B-D} \sim \frac{Y_f Y_{\text{quirks}} Y_\nu Y_{\Delta_0} Y_{\text{DN}} Y_{\text{NewQ}}}{m_H^2 M_M M_{S_1}^2 M_N M_{\Delta_0}^2} (\bar{d}^c \chi)(\bar{\nu}\, \chi)(\bar{d}^c u)(\bar{f} f)$$



⇨ $$\mathcal{L} \supset Y_{\Delta_0} (d^c\, Q_N^c\, \Omega^* + \eta_d\, M\, \Omega^* + \boxed{d^c\, M\, \Delta_0^*} + \eta_d\, \xi\, \Delta_0^*)$$
$$+ Y_\chi \boxed{(\chi\, \Delta_0^*} + q_N\, \Omega^*)\, N + Y_{\bar{\chi}}\, (q_N^c\, \Omega + \chi^c\, \Delta_0)\, N + \text{h.c.}$$

⇨ $\mathrm{U}(1)_{B-D}$

Dark Spectrum

⇨ $$\rho = \begin{pmatrix} \rho^+ \\ \rho^0 \\ \rho^- \end{pmatrix} \sim \begin{pmatrix} \chi_D \chi_D \\ \chi_D^c \chi_D \\ \chi_D^c \chi_D^c \end{pmatrix}$$

$$\rho_\mu^a = \bar{X}\,\gamma_\mu \tau^a X, \qquad \text{where} \qquad X = \begin{pmatrix} \chi_L \\ -i\sigma_2 C \bar{\chi}_R^T \end{pmatrix}$$

$$\boxed{\begin{aligned} \rho_\mu^0 &= \bar{X}\gamma_\mu \tau^3 X &&= \overline{\chi_D}\,\gamma_\mu \chi_D, \\ \sqrt{2}\rho_\mu^+ &= \bar{X}\gamma_\mu(\tau^1 - i\tau^2)X &&= \overline{\chi_D^c}\,\gamma_\mu\, i\sigma_2\, \chi_D, \\ \sqrt{2}\rho_\mu^- &= \bar{X}\gamma_\mu(\tau^1 + i\tau^2)X &&= \overline{\chi_D}\,\gamma_\mu\, i\sigma_2^T\, \chi_D^c. \end{aligned}}$$

Symmetries

	5_q		$\bar{5}_u$		$\bar{5}_d$		5_χ		10			10_H			24^μ
Sym	Ψ	q	u^c	η_u	d^c	η_d	χ	q_N	Q^c_N	M	ξ	S_1	R_D	δ_0	$V^\mu_{\rm DQ}$
$U(1)_B$	-	$1/3$	$-1/3$	-	$-1/3$	-	-	$1/3$	$-1/3$	$-2/3$	-1	$2/3$	$1/3$	-	$1/3$
$U(1)_D$	-	-	-	-	-	-	$1/2$	$1/2$	$-1/2$	$-1/2$	$-1/2$	-	-	-	-
$U(1)_Q$	$1/2$	-	-	$-1/2$	-	$-1/2$	-	$-1/2$	$-1/2$	-	$1/2$	-	$1/2$	1	$-1/2$

Interactions at the $\mathrm{SU(5)} \otimes \mathrm{SU(2)}_L \otimes \mathrm{U(1)}_X$ level

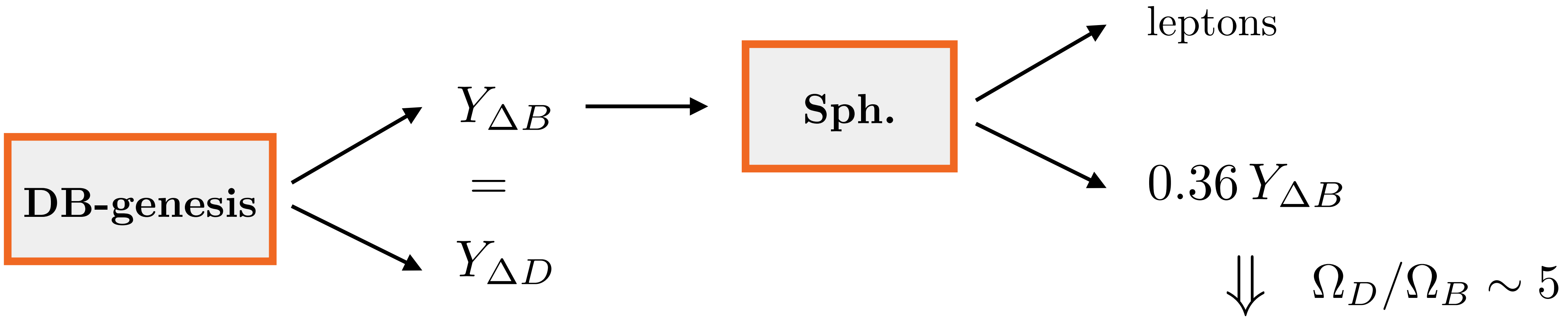
$$\mathcal{L} \supset Y_\Psi 5_\Psi 5_\Psi 10^*_H + Y_\eta \bar{5}_d \bar{5}_u 10_H + Y_q 5_\chi \, 10 \, 10_H \, \epsilon_5 + Y_{\bar{q}} \bar{5}_\chi \, \overline{10} \, \overline{10} \, \epsilon_5 + \text{h.c.}$$

Interactions at the $\mathrm{SM} \otimes \mathrm{SU(2)}_D$ level

$$-\mathcal{L} \supset Y_\Psi \left(\Psi \, \Psi \, \delta^*_0 + Q \, Q \, S^*_1 + \psi \, Q \, R^*_D\right) + Y_\eta \left(\eta_u \, \eta_d \, \delta_0 + u^c d^c S_1 + \eta_u \, d^c R_D + \eta_d \, u^c R_D\right) + Y_q \left(q_N \, Q^c_N \, \delta_0 + q_N \, M \, R_D + q_N \, \xi \, S_1 + \chi \, Q^c_N \, R_D + \chi \, M \, S_1\right) + Y_{\bar{q}} \left(q^c_N \, Q_N \, \delta^*_0 + q^c_N \, M^c \, R^*_D + q^c_N \, \xi^c \, S^*_1 + \chi^c \, Q_N \, R^*_D + \chi^c \, M^c \, S^*_1\right) + \text{h.c.}$$

Other sources of B violation

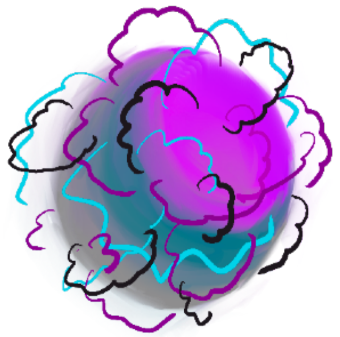
- Sphalerons

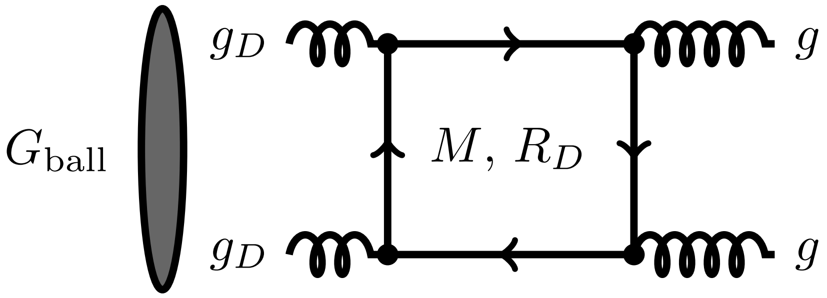


$$\Lambda_{\mathrm{DarCUS}} \sim 6 \times 10^7 \text{ GeV}$$

- $V \supset \lambda\, 10^*_H 5_H 24_H 5_H + \text{h.c.}$

Annihilation symmetric abundance

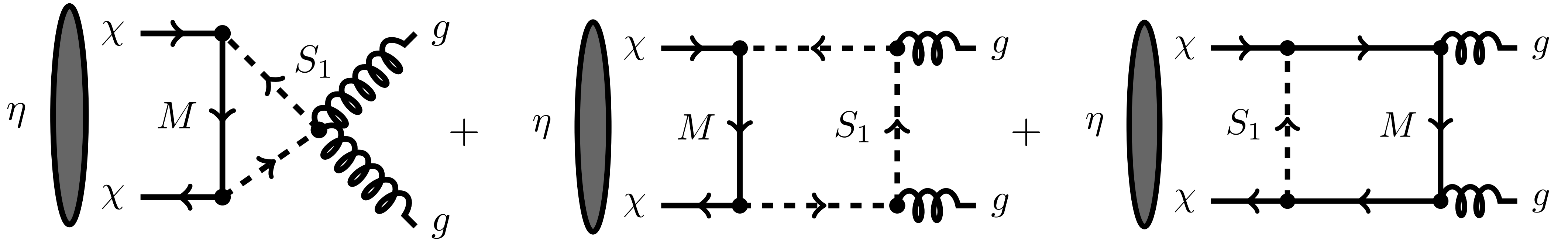




$$m_{G_\text{ball}} \sim n\,\Lambda_D$$

$$\tau_{G_\text{ball}} \overset{n=1}{\simeq} 0.5\text{ s}\left(\frac{0.8}{\alpha_\text{QCD}}\right)^2\left(\frac{0.8}{\alpha_D}\right)^2\left(\frac{M_M}{1\text{ TeV}}\right)^8\left(\frac{2\text{ GeV}}{\Lambda_D}\right)^9$$

Light connectors M or R_D



$$\tau_\eta^{-1} \sim \ 8\text{ s}^{-1}\left(\frac{\alpha_\text{QCD}}{0.8}\right)^2\left(\frac{|Y_\text{NewQ}|}{1}\right)^4\left(\frac{10\text{ TeV}}{M_{S_1/M}}\right)^6\left(\frac{m_\eta}{4\text{ GeV}}\right)^7$$

Light connectors M or S_1

Early Matter Domination!

Dark Spectrum

- N_f (light) flavors + $\mathrm{SU}(2)_D$

$\boxed{2 \equiv \square \equiv \bar{2} \quad \text{enlarged symmetry!}}$

$$\begin{tikzcd}
\mathrm{U}(N_f)_L \otimes \mathrm{U}(N_f)_R \arrow[r, "\text{enlarged}"] & U(2N_f) = U(1)_A \otimes \mathrm{SU}(2N_f) \arrow[d, "\chi\text{SB}"'] \\
& \mathrm{Sp}(2N_f)
\end{tikzcd}$$

$\langle \bar{\chi}\chi \rangle$

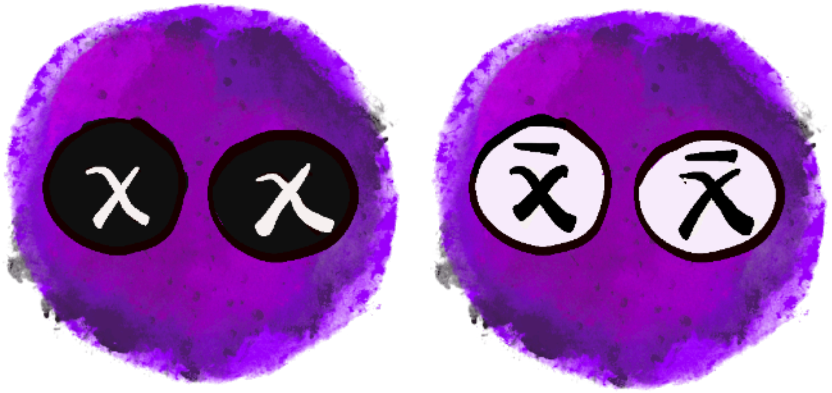
$$\#_{\text{broken gen}} = (2N_f + 1)(N_f - 1)$$

$N_f = 1$! No Goldstones! (No dark pions)

Q_D () $= \frac{1}{2}$

Dark Baryon Number (D)

Meson



Baryons

Dark Spectrum

[Francis, Hudspith, Lewis, Tulin, 2008]

- One (light) flavor + $SU(2)_D$

$$\chi_D = \chi_L + (\chi_L^c)^c = \chi_L + \chi_R$$

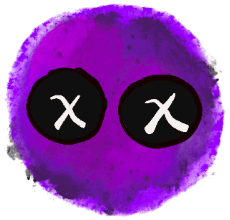
$$\mathcal{L}^{\text{eff}}_{\text{SU}(2)_D} = -\frac{1}{2}\text{Tr}\{G_{D\mu\nu}G_D^{\mu\nu}\} + \overline{\chi_D}(iD_\mu\gamma^\mu - m_\chi)\chi_D + \cdots$$

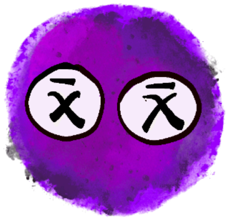
$$X = \begin{pmatrix} \chi_L \\ -i\sigma_2 C\bar{\chi}_R^T \end{pmatrix} \Rightarrow \mathcal{L}^{\text{eff}}_{\text{SU}(2)_D} = \bar{X}iD_\mu\gamma^\mu X - \frac{m_\chi}{2}\left(X^T i\sigma_2 CEX + \bar{X}i\sigma_2 CE\bar{X}^T\right) + \cdots$$

Dark (matter) baryon

vector (1^-)

$$\rho = \begin{pmatrix} \rho^+ \\ \rho^0 \\ \rho^- \end{pmatrix} \sim \begin{pmatrix} \chi\chi \\ \frac{1}{\sqrt{2}}(\chi\bar{\chi} + \bar{\chi}\chi) \\ \bar{\chi}\bar{\chi} \end{pmatrix}$$





Towards Grand Unification

$$\mathrm{SU}(7) \supset \mathrm{SU}(5) \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_7 \supset \mathcal{G}_{\mathrm{SM}} \otimes \mathrm{SU}(2)_D$$

4 $\mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y \to \mathrm{U}(1)_{\mathrm{em}} \quad \Rightarrow \quad 7_H \sim \begin{pmatrix} S_1^* \\ \Delta_0 \\ -- \\ H \end{pmatrix}$

⇨ Breaking patterns:

1 $\mathrm{SU}(7) \xrightarrow{\langle 48_H \rangle} \mathrm{SU}(5) \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_7$

3 $\mathrm{U}(1)_7 \otimes \mathrm{U}(1)_5 \xrightarrow{\langle 21_H \rangle} \mathrm{U}(1)_Y$

2 $\mathrm{SU}(5) \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_7 \xrightarrow{\langle 24_H \rangle} \mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_7 \otimes \mathrm{U}(1)_5 \otimes \mathrm{SU}(2)_D$

⇨ Minimal matter content (Embedding of the SM):

$$\bar{7} = \begin{pmatrix} d^c \\ \chi \\ -- \\ \ell \end{pmatrix} \quad \text{and} \quad 21 = \left(\begin{array}{cc|c} u^c & M & q \\ -M^T & N & \Psi_2 \\ --- & --- & -- \\ -q^T & -\Psi_2^T & e^c \end{array}\right)$$

Towards an anomaly-free SU(7)

- Anomay-free theory

1. $\bar{7} \ + \ 21 \ + \overline{35}$
2. $5 \times \bar{7} \ + \ 21 \ + \ 35$

$$\overline{35} = (10, 1, -6) \oplus (\overline{10}, 2, 1) \oplus (\bar{5}, 1, 8)$$

$$\begin{array}{lll}
(\bar{3}, 1, \frac{1}{3}, 1) & (\bar{3}, 2, \frac{1}{6}, 1) & (\bar{3}, 1, \frac{2}{3}, 1) \\
(3, 1, -\frac{2}{3}, 2) & (\bar{3}, 2, \frac{1}{6}, 2) & (1, 1, -1, 2) \\
(1, 1, 1, 1) & (1, 2, -\frac{1}{2}, 1) &
\end{array}$$