Accidental Composite Dark Matter and Grand Unification

Based on [JHEP 25 (2024)] with Francesco Rescigno and Federica Troni
and on work in progress with Davide Barbini and Roberto Contino

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22 May 2025

New Frontiers in Theoretical Physics 2025
CONVEGNO NAZIONALE DI FISICA TEORICA

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Outlook

Motivation and Framework
- Dark Matter
- Accidental Stability
- Grand Unification

Accidental Composite Dark Matter

Scalar Dark Quark
- Phenomenology

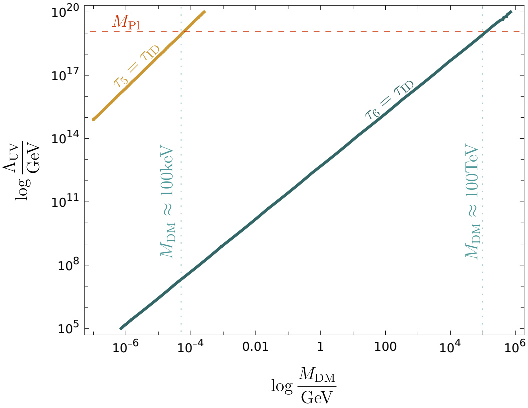
Dark Matter

- Must be dark:
  - no electric charge
  - uncolored
  - hypercharge constrained
- (Must be matter)
- Must be there:
  - $\tau_{\mathsf{DM}} \gtrsim 10^{25} \div 10^{28}$s depends on model and mass

Accidentally Stable Particles

No symmetries should be imposed $\rightarrow$ only accidental symmetries

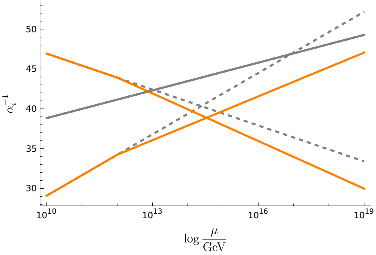
$$\tau_n \sim \frac{8\pi}{m}\left(\frac{\Lambda}{m}\right)^{2n-8}$$



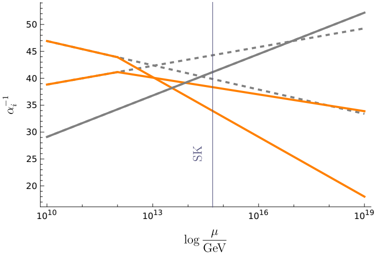
Example: protons! stable thanks to baryon number, broken at dim. 6

Grand Unification with New Physics

Can dark matter be embedded in a GUT framework?



No $SU(2)$ charged particles



No colored particles

Grand-Unifying New Physics

- Must be charged under $SU(2)_L$ and colored [Harigaya, et al. JHEP 14 (2016)]
- How can it be dark matter?

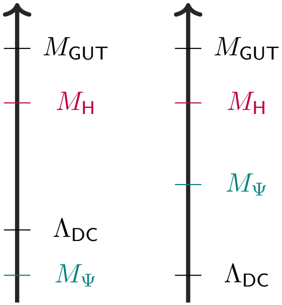
Accidental Composite Dark Matter

$SU(N_{\mathsf{DC}}) \otimes SU(5)_{\mathsf{GUT}}$ theories

- Color of dark quarks confined in color-neutral dark hadrons
- Dark baryon number keeps the lightest dark baryon stable

Strongly-coupled

[Antipin, et al. JHEP 39 (2015)]

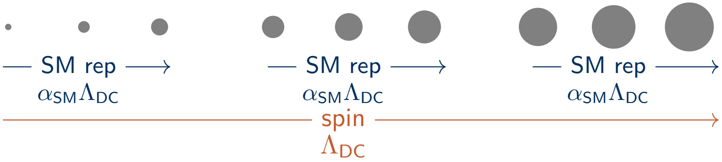


Weakly-coupled

[Mitridate, et al. JHEP 210 (2017)]

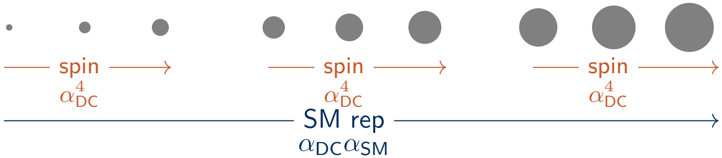
Strongly-Coupled Régime

- Dark baryons with mass $\sim N_{\mathsf{DC}} \Lambda_{\mathsf{DC}}$
- $\langle \sigma \, v \rangle \sim \frac{\pi}{\Lambda_{\mathsf{DC}}} \longrightarrow M_{\mathsf{DM}} \sim 100\,\mathsf{TeV}$
    - Coincidence of unitarity limit and dark matter lifetime bound



Weakly-Coupled Régime

- Somewhat smaller masses for dark baryons
- Mass orderings are the way around in the Coulombic régime



[work in progress with Davide Barbini (master thesis, now at IFAE) and Roberto Contino]

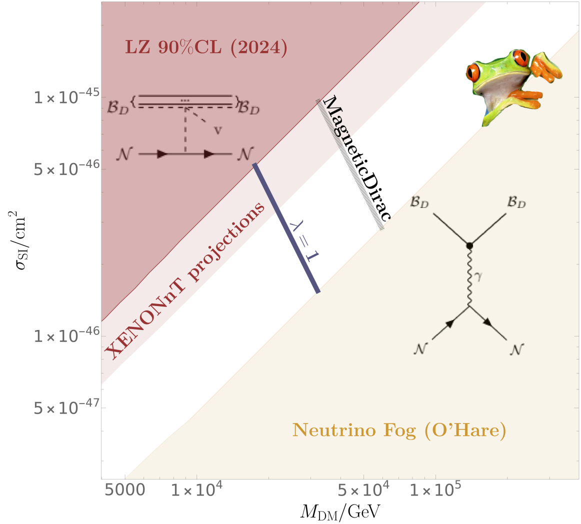
Adding a Scalar Dark Quark

- Dark quarks from $SU(5)$ fragments
- Interactions with Higgs determine accidental symmetries
- $U(1)^n_{\text{species}} \to U(1)_{\text{dark baryon}}$, otherwise stable charged relics

Scalar dark quark

- Introduce $\phi \sim$ total singlet under SM [SP, F. Rescigno, F. Troni JHEP 25 (2024)]
- New interactions:
  - y (dark fermion)$^c \times \phi \times$ (SM fermion)
  - $\lambda\, |\phi|^2 \times$ (SM Higgs)^2
- Hybrid dark hadrons: both fermion and scalar constituents

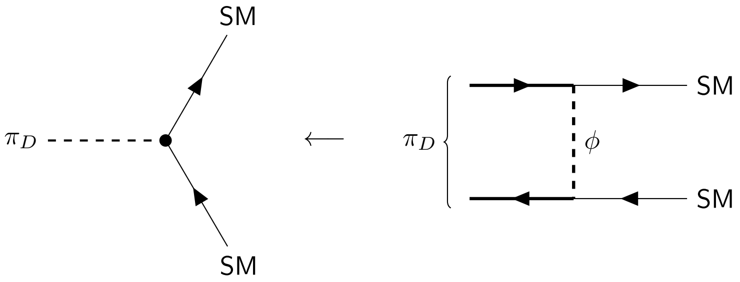
Direct Detection of Hybrid Dark Baryons



[LZ collaboration, arXiv:2410.17036]

[O'Hare, Phys.Rev.Lett. 127 (2021)]

Dark Pions: Decay and Production at Colliders



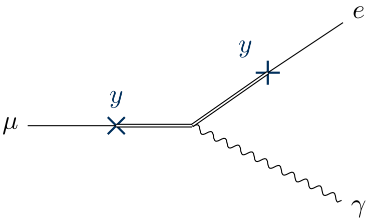
Chiral suppression: $\langle 0|J^{\mu}_{5,D}|\pi_D\rangle \propto f_D p^{\mu} \longrightarrow \Gamma \propto \left(\frac{m_{\mathsf{SM}}}{m_{\pi_D}}\right)^2 \ll 1$

In some models: $\langle 0|J_{5,D}|\pi_D\rangle \propto f_D^2 \longrightarrow \Gamma$ unsuppressed

Lepton Flavor and CP Violation

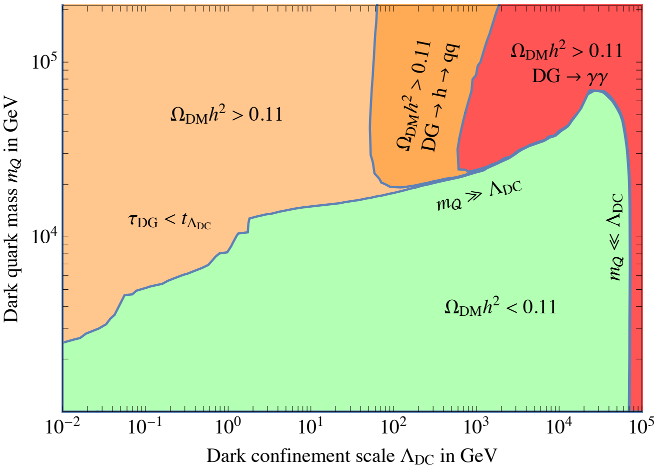
- Hybrid dark "mesons" $\to$ share the quantum n. of SM fermions
- Bounds on BR($\mu \to$ eγ), d_e, etc. $\longrightarrow y \lesssim 10^{-1} \div 10^{-2}$

  [Frigerio, et al. JHEP 17 (2018)]
- Consistent with decay of charged dark pions before BBN



Thank you for the attention

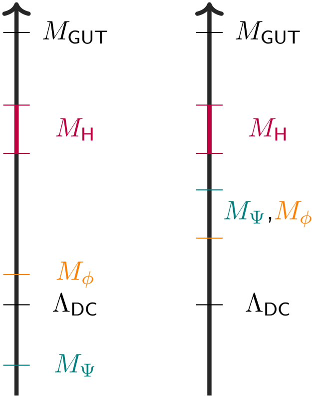
Weakly-Coupled Dark Baryon Abundance



[Mitridate, et al., JHEP 210 (2017)]

Two Régimes (feel old yet?)

Fermion constituents



Hybrid?

Hybrid Dark Baryons

Fermion Constituents

$$\underbrace{(\text{dark color})}_{\text{anti-symmetric}} \otimes \underbrace{(\text{spin}) \otimes (\text{dark flavor} \sim \text{SM})} = (\text{anti-symmetric})$$

- $N_F = 1/2$ (odd), 0 (even)

Scalar Constituents

- No spin, no flavour $\longrightarrow \underbrace{(\text{dark color})}_{\text{anti-symmetric}} \otimes \underbrace{(\text{spatial})}_{\text{anti-symmetric}} = (\text{symmetric})$
- e.g. $N_S = 2 \longrightarrow J_S = 1$ by virtue of $P = (-1)^\ell$

Hybrid Dark Matter

- Odd N_F, i.e. even $N_{\text{DC}} \rightarrow \ J_{N_F+1} = \frac{1}{2}$
- Even N_F, i.e. odd $N_{\text{DC}} \rightarrow \ J_{N_F+1} = 0$
- If $N_{\text{DC}} = \cancel{3}, 5, 7, \ldots$ the dark matter may have 1 scalar constituent

Coulombic Régime

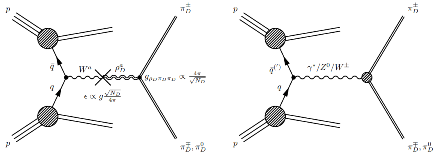
- Assume $\alpha_{\mathsf{SM}} \ll \alpha_{\mathsf{DC}} \ll 1$
- One-gluon exchange approximation:

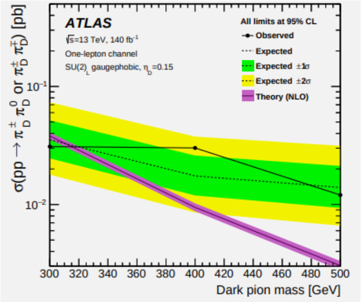
$$V \sim -\frac{\alpha}{r} \longrightarrow \mathcal{E}_B \sim \alpha_{\mathsf{DC}}^2 M_\Psi$$

- Also for SM interacitons $\longrightarrow \Delta\mathcal{E} \sim \alpha_{\mathsf{SM}}\alpha_{\mathsf{DC}} M_\Psi + \mathcal{O}\left(\alpha_{\mathsf{SM}}^2\right)$
- Spin-spin interacitons

$$V \sim \vec{S}_1 \cdot \vec{S}_2 \, \delta^{(3)}(\vec{r}) \longrightarrow \Delta\mathcal{E} \sim \alpha_{\mathsf{DC}}^4 M_\Psi$$

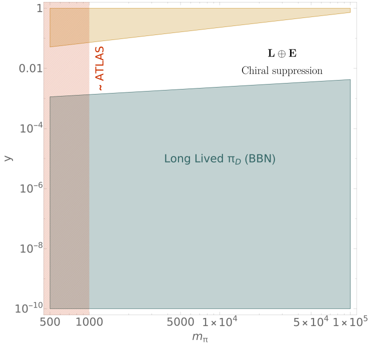
Production of Dark Pions at LHC

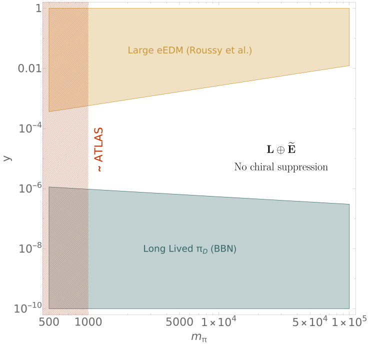




[ATLAS Collaboartion, JHEP 5 (2024)]

Constraints on Yukawas





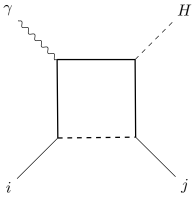
[ATLAS collaboration, JHEP 5 (2024)]

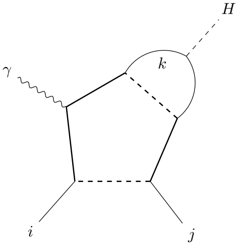
[Roussy, et al., Science 381 (2023)]

Lepton Flavor and CP violation

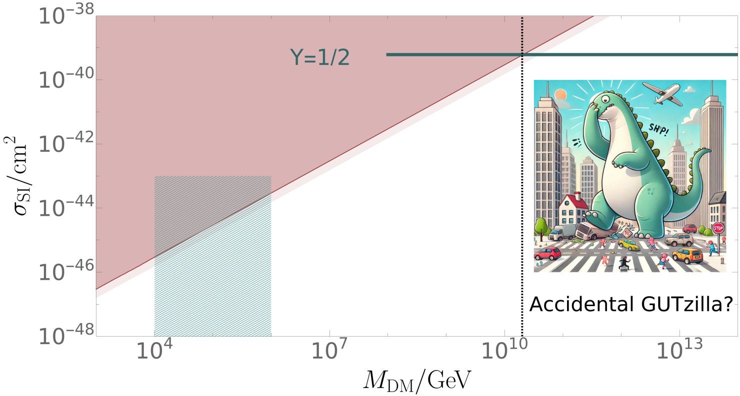
$$\mu\to \mathsf{e}\gamma,\ d_e, \ldots \ \longleftarrow\ \mathcal{Q}^{ij}_{e\gamma} = (\ell_i \sigma^{\mu\nu} e^c_j) H^\dagger F \mu\nu$$

$$\frac{C^{e\gamma}_{ij}}{\Lambda^2} = \underbrace{\frac{\overbrace{c^{e\gamma}_{ij}}^{\text{order one}}}{16\pi^2 m^{*2}} e y^{i*}_L y^j_{\tilde{E}} y_{L\tilde{E}}}_{\text{one loop}} \quad \text{or} \quad \frac{C^{e\gamma}_{ij}}{\Lambda^2} = \underbrace{\frac{c^{e\gamma}_{ij}}{256\pi^4 m^{*2}} e Y^{k\,k}_{\mathsf{SM}} y^{i\,*}_L y^k_L y^{k\,*}_E y^j_E}_{\text{two loops}}$$





Accident-zilla?



- Minimal extension of SM for unification

$$Q \sim (\mathbf{3},\mathbf{2})_{\frac{1}{6}} \quad \text{with } N_{\mathrm{DC}} = 3 \;\longrightarrow\; \mathrm{DM} \sim (\mathbf{1},\mathbf{2})_{\frac{1}{2}} \;,$$

- Symmetry broken at dimension 6: $\frac{QQQ\ell}{M^2}$ not enough for accidental stability with masses so large

Accident-zilla?

Raise Number of Dark Colors

N_{DC}	Operator	Dimension	Bound on M_{DM}	Lightest DB
3	$QQQ\ell$	6	$2 \cdot 10^5$ GeV	$(\mathbf{1}, \mathbf{2})_{\frac{1}{2}}$
6	$Q^6 H^\dagger H^\dagger$	11	$3 \cdot 10^{14}$ GeV	$(\mathbf{1}, \mathbf{1})_1$
9	$Q^9 e^c H$	16	$2 \cdot 10^{16}$ GeV	$(\mathbf{1}, \mathbf{2})_{\frac{3}{2}}$

Extend Model with other Dark Quarks

- Extending with dark quarks from the **10** of $SU(5)$ always yields charged lightest dark baryon
- Must look at **15** of $SU(5)$ or beyond