Accidental Composite Dark Matter and Grand Unification

by

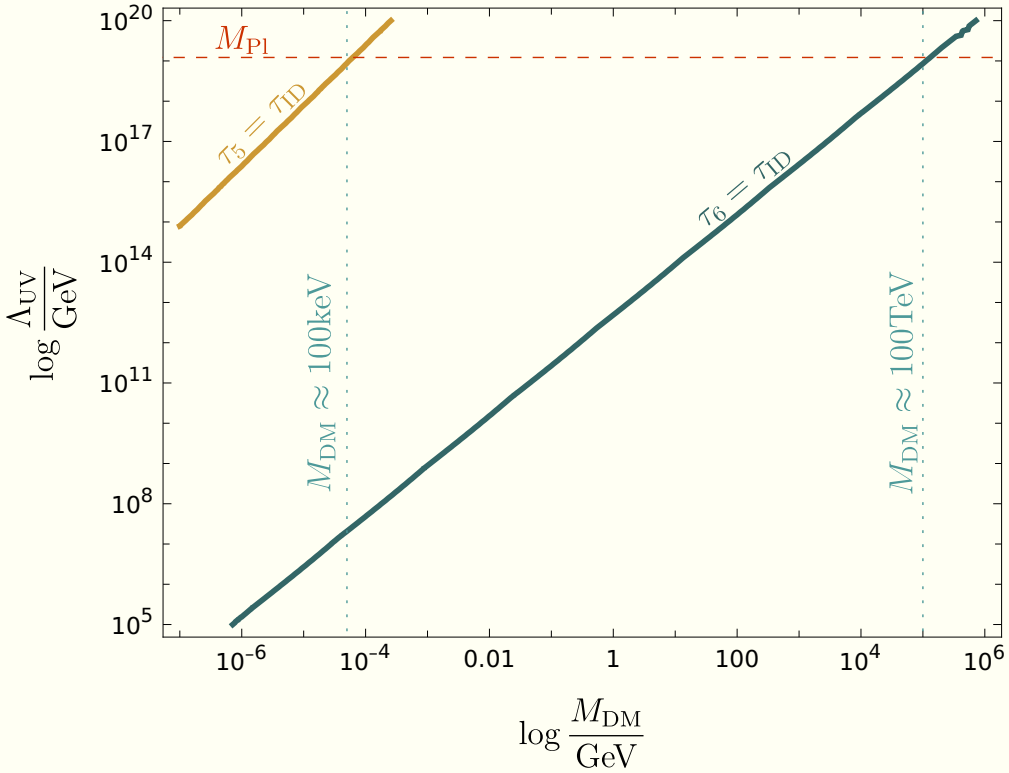
Stefano Palmisano

Dark Matter

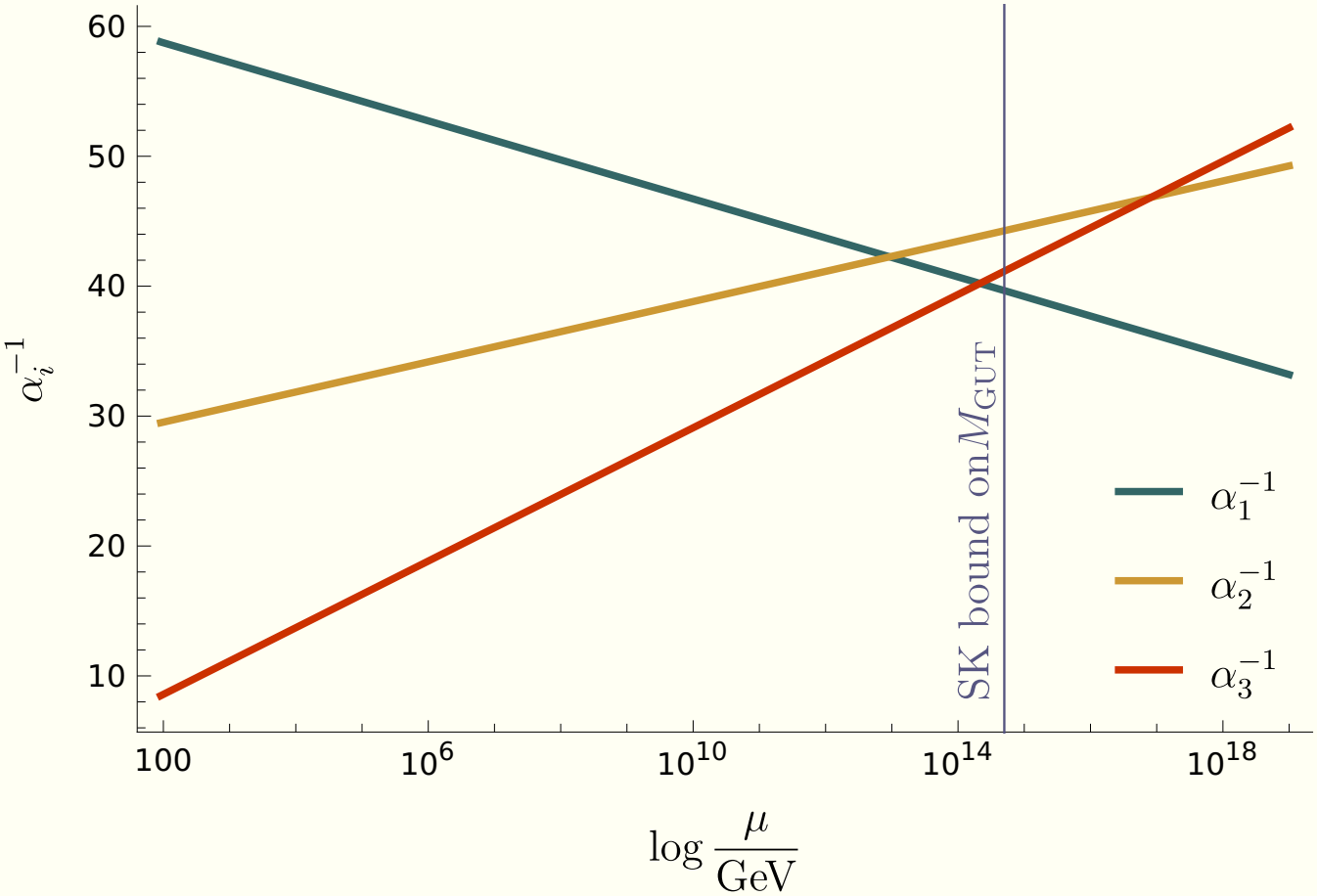
- Must be neutral
  - no electric charge
  - uncolored
  - hypercharge also constrained
- Must be stable:
  - Bound depends on mass and decay products
  - $\tau_{\mathrm{DM}} \gtrsim 10^{28}$ s

Accidentally Stable Particles

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



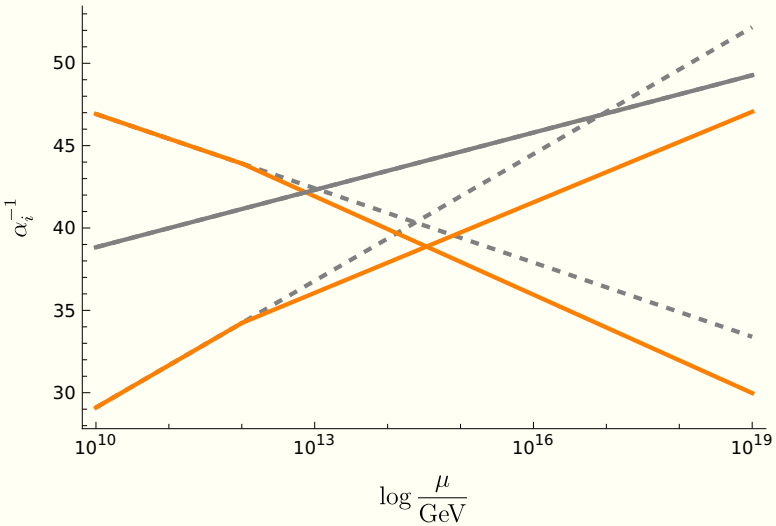
Grand Unification in the SM



GUT scale bounded by proton lifetime*

*10.1103/PhysRevD.102.112011

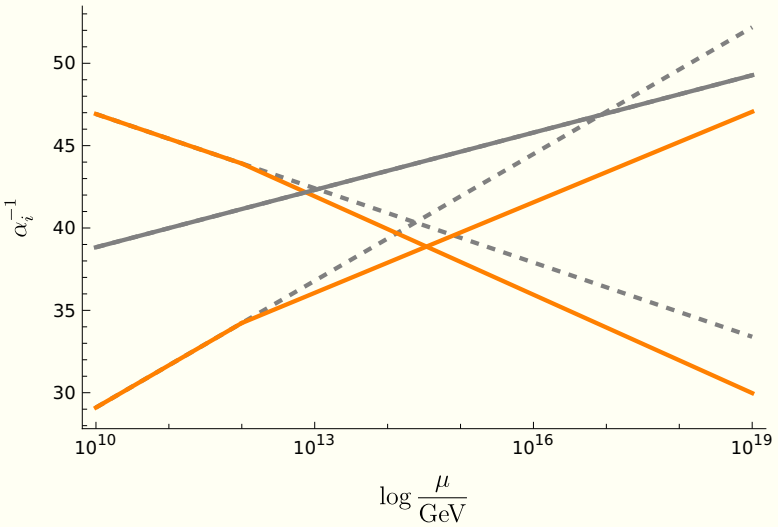
Grand Unification with New Physics



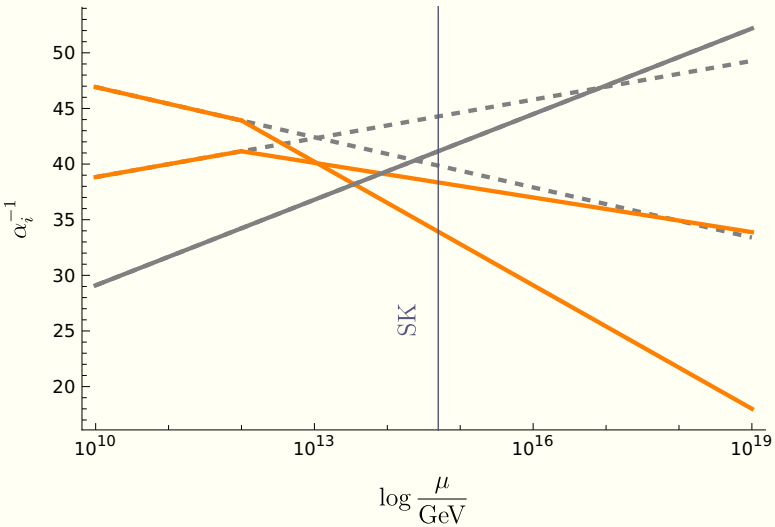
No $SU(2)$ charged particles

*10.1007/jhep09(2016)014

Grand Unification with New Physics



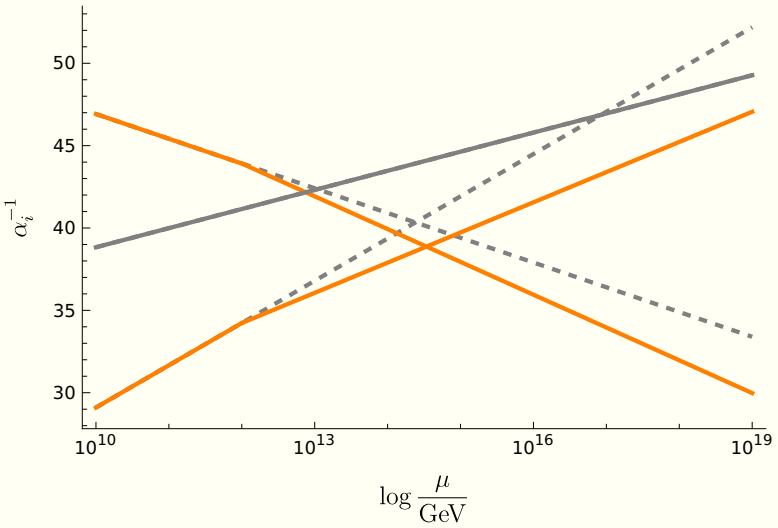
No $SU(2)$ charged particles



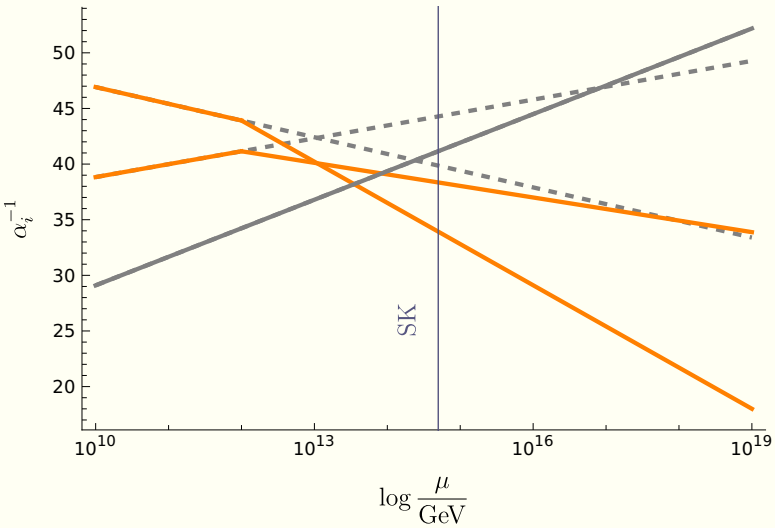
No colored particles

*10.1007/jhep09(2016)014

Grand Unification with New Physics



No $SU(2)$ charged particles



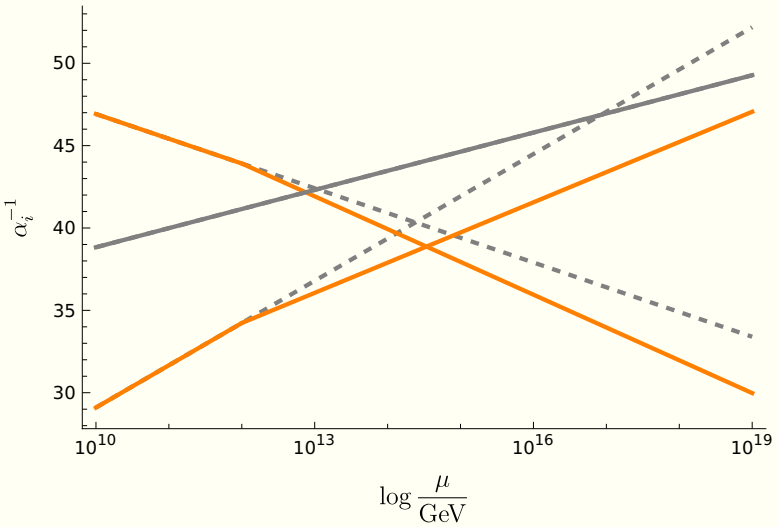
No colored particles

Grand-Unifying New Physics

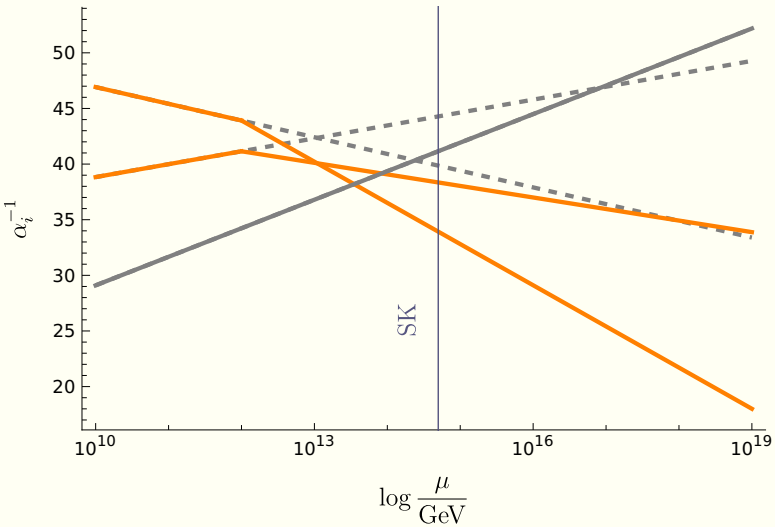
- Must be charged under $SU(2)_L$

*10.1007/jhep09(2016)014

Grand Unification with New Physics



No $SU(2)$ charged particles



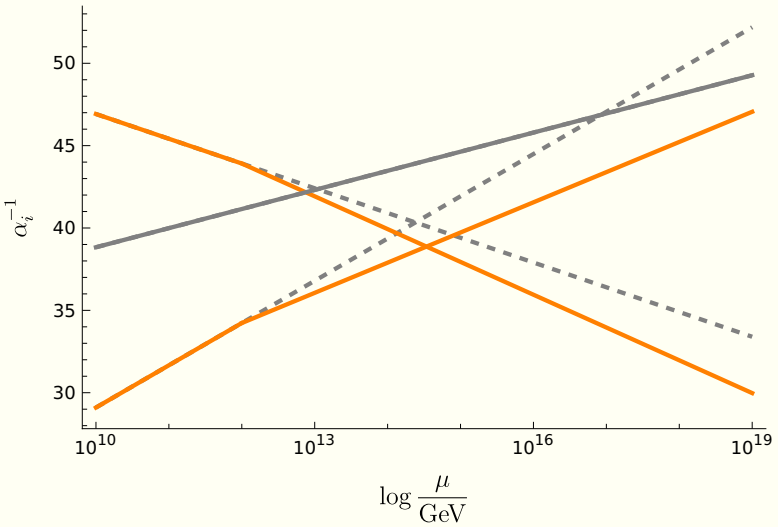
No colored particles

Grand-Unifying New Physics

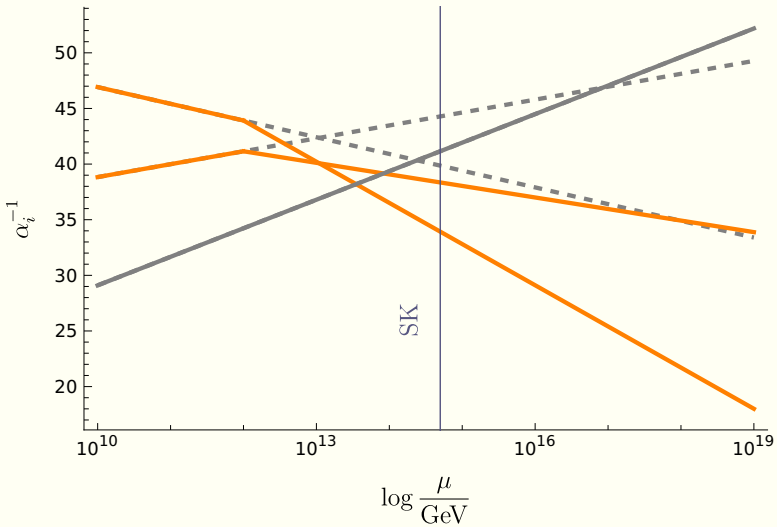
- Must be charged under $SU(2)_L$ and colored*.

*10.1007/jhep09(2016)014

Grand Unification with New Physics



No $SU(2)$ charged particles



No colored particles

Grand-Unifying New Physics

- Must be charged under $SU(2)_L$ and colored*.
- How can it be dark matter?

*10.1007/jhep09(2016)014

Accidental Composite Dark Matter

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

- Color of dark quarks confined in color-neutral dark hadrons
- Dark baryon number keeps the lightest dark baryon stable, no need of ad-hoc symmetries

*10.1007/JHEP07(2015)039

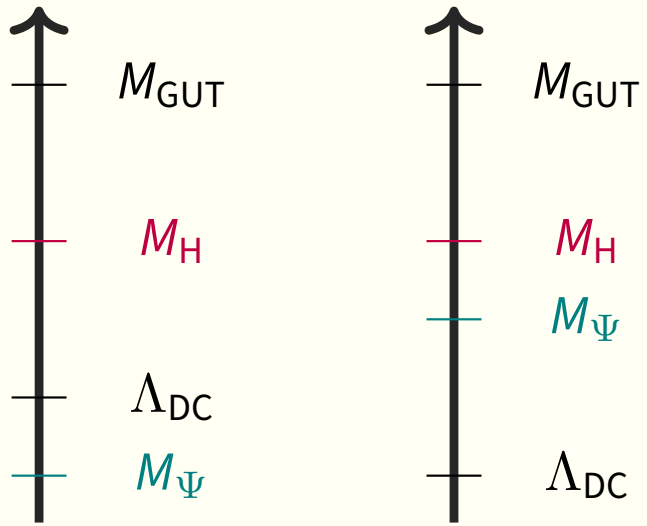
†https://doi.org/10.1007/JHEP10%282017%29210

Accidental Composite Dark Matter

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

- Color of dark quarks confined in color-neutral dark hadrons
- Dark baryon number keeps the lightest dark baryon stable, no need of ad-hoc symmetries

- Strongly-coupled, or QCD-like*
- Weakly-coupled, or "Coulomb-like"†



*10.1007/JHEP07(2015)039

†https://doi.org/10.1007/JHEP10%282017%29210

Régimes

Strongly coupled

- Dark baryons with mass $\sim N_{\mathrm{DC}} \Lambda_{\mathrm{DC}}$
- Cross section at unitarity limit
  $\langle \sigma v \rangle \sim \frac{\pi}{\Lambda_{\mathrm{DC}}} \longrightarrow M_{\mathrm{DM}} \sim 100\,\mathrm{TeV}$
- Lightest dark hadrons $\rightarrow$ dark pions
  (pseudo-Nambu-Goldstone bosons)

Régimes

Strongly coupled

- Dark baryons with mass $\sim N_{\mathrm{DC}} \Lambda_{\mathrm{DC}}$
- Cross section at unitarity limit
  $\langle \sigma v \rangle \sim \frac{\pi}{\Lambda_{\mathrm{DC}}} \longrightarrow M_{\mathrm{DM}} \sim 100\,\mathrm{TeV}$
- Lightest dark hadrons $\rightarrow$ dark pions
  (pseudo-Nambu-Goldstone bosons)

Weakly coupled

- Dark baryons with mass $\sim N_{\mathrm{DC}} M_{\Psi}$
- Lightest dark hadrons $\rightarrow$ dark glueballs
- Cosmology more subtle

Lightest Dark Baryon

Strongly-coupled

- $\Delta_{\text{spin}} M \sim \Lambda_{\text{DC}}$
- $\Delta_{\text{SM}} M \sim \alpha_{\text{SM}} \Lambda_{\text{DC}} \ll \Lambda_{\text{DC}}$

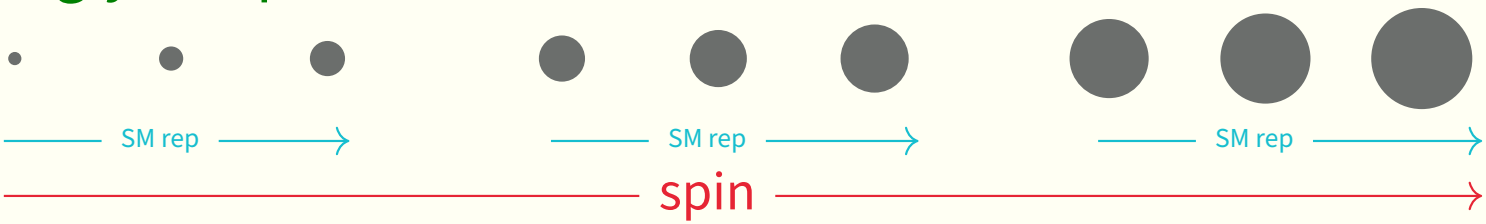
Weakly-coupled*

- $\Delta_{\text{SM}} M \sim \alpha_{\text{DC}} \alpha_{\text{SM}} M_{\Psi}$
- $\Delta_{\text{spin}} M \sim \alpha_{\text{DC}}^4 M_{\Psi} \ll \Delta_{\text{SM}} M$

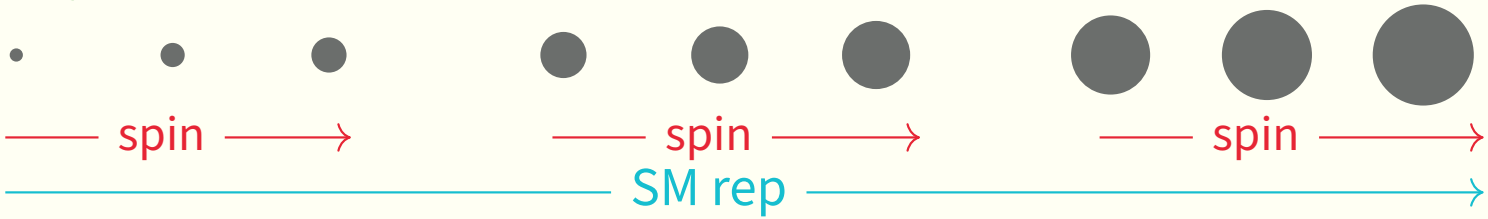
*Davide Barbini - Tesi Magistrale

Lightest Dark Baryon

Strongly-coupled



Weakly-coupled*



*Davide Barbini - Tesi Magistrale

Model Selection

- Dark quark from $SU(5)$ fragments, e.g.
  - $Q \sim (\mathbf{3}, \mathbf{2})_{\frac{1}{6}} \subset \mathbf{10}$ of $SU(5)$
  - $\widetilde{D} \sim (\mathbf{3}, \mathbf{1})_{-\frac{1}{3}} \subset \mathbf{5}$ of $SU(5)$

*10.1007/JHEP07(2015)039

Model Selection

- Dark quark from $SU(5)$ fragments, e.g.
  - $Q \sim (\mathbf{3}, \mathbf{2})_{\frac{1}{6}} \subset \mathbf{10}$ of $SU(5)$
  - $\widetilde{D} \sim (\mathbf{3}, \mathbf{1})_{-\frac{1}{3}} \subset \mathbf{5}$ of $SU(5)$
- Interactions with Higgs determine accidental symmetries
  - $Q^c H \widetilde{D}$
  - $U(1)_Q \otimes U(1)_{\widetilde{D}} \to U(1)_{\text{dark baryon}}$

*10.1007/JHEP07(2015)039

Model Selection

- Dark quark from $SU(5)$ fragments, e.g.
  - $Q \sim (\mathbf{3}, \mathbf{2})_{\frac{1}{6}} \subset \mathbf{10}$ of $SU(5)$
  - $\widetilde{D} \sim (\mathbf{3}, \mathbf{1})_{-\frac{1}{3}} \subset \mathbf{5}$ of $SU(5)$
- Interactions with Higgs determine accidental symmetries
  - $Q^c H \widetilde{D}$
  - $U(1)_Q \otimes U(1)_{\widetilde{D}} \to U(1)_{\text{dark baryon}}$
- N.B. Accidental symmetries keeping charged particles stable must be broken explicitly, or the model discarded

*10.1007/JHEP07(2015)039

Model Selection

- Dark quark from $SU(5)$ fragments, e.g.
  - $Q \sim (\mathbf{3}, \mathbf{2})_{\frac{1}{6}} \subset \mathbf{10}$ of $SU(5)$
  - $\widetilde{D} \sim (\mathbf{3}, \mathbf{1})_{-\frac{1}{3}} \subset \mathbf{5}$ of $SU(5)$
- Interactions with Higgs determine accidental symmetries
  - $Q^c H \widetilde{D}$
  - $U(1)_Q \otimes U(1)_{\widetilde{D}} \to U(1)_{\text{dark baryon}}$
- N.B. Accidental symmetries keeping charged particles stable must be broken explicitly, or the model discarded
- $Q \oplus \widetilde{D}$ essentially only viable model*

*10.1007/JHEP07(2015)039

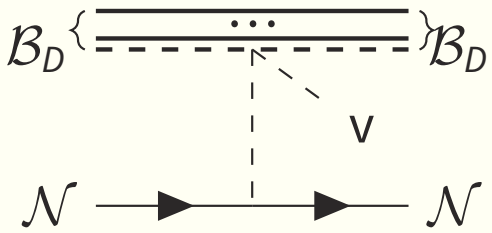
Adding a Scalar Dark Quark

- Singlet scalar dark quark* $\phi \sim (\mathbf{1}, \mathbf{1})_0$ allows new interactions
  - $\Psi_D^c \phi \psi_{\text{SM}}$
    - Breaks unwanted accidental symmetries
    - Transfer SM baryon and lepton number to dark quarks
  - $|\phi|^2 |H|^2$
    - Portal for hybrid dark hadrons
- Several more models (but all extensions of $Q \oplus \widetilde{D}$!)
- Peculiar phenomenology

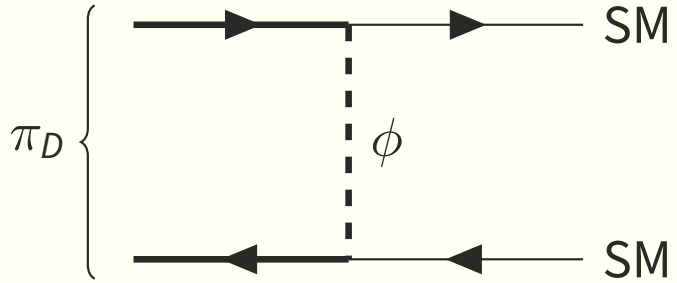
*10.1007/JHEP09(2024)025

Phenomenology with Dark Scalar

Direct Detection



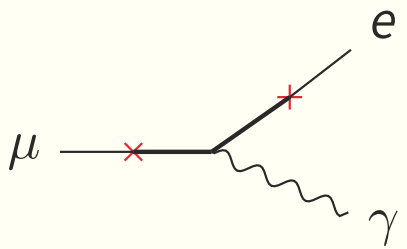
Dπs at colliders



Dark leptoquarks

$$\text{"}\bar{Q}L\text{"} \sim (\mathbf{3}, \mathbf{1} \oplus \mathbf{3})_{-\frac{2}{3}} \sim S_1 \oplus S_3$$

Lepton Flavor and CP Violation



e.g.

GUTzilla

- Direct detection bounds* $M_{\mathrm{DM}}/(2Y)^2 > 2 \times 10^{10}$ GeV

*arXiv:2410.17036

†10.1007/jhep09(2016)014

GUTzilla

- Direct detection bounds* $M_{\mathrm{DM}}/(2Y)^2 > 2 \times 10^{10}$ GeV
- Minimal extension of SM for unification†

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

which needs an ultraheavy scenario

*arXiv:2410.17036

†10.1007/jhep09(2016)014

GUTzilla

- Direct detection bounds* $M_{\mathrm{DM}}/(2Y)^2 > 2 \times 10^{10}$ GeV
- Minimal extension of SM for unification†

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

  which needs an ultraheavy scenario
- Symmetry broken at dimension 6

$$\frac{QQQ\ell}{M^2}$$

  not enough for accidental stability with masses so large

*arXiv:2410.17036

†10.1007/jhep09(2016)014

Accident-zilla?

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	$(\mathbf{1}, \mathbf{2})_{\frac{1}{2}}$

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	$(\mathbf{1}, \mathbf{2})_{\frac{3}{2}}$

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 $\mathbf{10}$ of $SU(5)$ always yields charged lightest dark baryon

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 $\mathbf{10}$ of $SU(5)$ always yields charged lightest dark baryon
- Must look at $\mathbf{15}$ of $SU(5)$ or beyond

Thank you for the attention