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Accidental Dark B From Scalar/Gauge Dynamics

based on 1907.11228, 2007.12663 and a bit of 1911.04502
with Ardu, Buttazzo, Di Luzio, Landini, Strumia, Wang, …

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Dark Matter as an accidentally stable particle

- Old-school WIMPs much motivated by non ad-hoc stability (low-scale SUSY)
- Other frameworks where stability arises generically?
- Dark gauge dynamics: stability due to accidental dark baryon number B, analogous to matter stability
- Models with dark fermions: charged under SM for thermal contact, DM neutrality needs to be imposed
- What about dark scalars, singlet under SM?

Dark gauge/scalar dynamics

- Simple model: SM singlet scalar $\mathcal{S}$ charged under dark gauge group $\mathcal{G}$:

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}\mathcal{G}^a_{\mu\nu}\mathcal{G}^{a\,\mu\nu} + |\mathcal{D}_\mu \mathcal{S}|^2 - M^2_{\mathcal{S}}|\mathcal{S}|^2 + \lambda_{\mathcal{S}}|\mathcal{S}|^4 - \lambda_{H\mathcal{S}}|H|^2|\mathcal{S}|^2$$

- SU(2) well-known [Hambye ’08; Hambye, Tytgat ’09; Hambye, Strumia ’13]
- Typically two phases: Higgs and confined
- Naively stability is shaky: symmetries broken by vevs
- Spoiler alert: we will find structural stability, due to a surprising field-theoretic duality

A fundamental of SU(N)

Confined phase

- The Lagrangian is accidentally symmetric under dark B: $\mathscr{S} \to e^{i\alpha}\mathscr{S}$
- Also under dark charge conjugation C: $\mathscr{S} \to \mathscr{S}^*, \quad \mathscr{D}_\mu \to \mathscr{D}_\mu^*$
- Composite states only distinguished by quantum numbers:

$$\mathscr{S}^\dagger\mathscr{S} \qquad \mathscr{S}^\dagger\mathscr{D}_\mu\mathscr{S} \qquad \mathscr{B} \sim \epsilon\mathscr{S}^N \qquad \mathscr{B}^* \qquad \mathscr{G}\mathscr{G}, \mathscr{G}\mathscr{G}\mathscr{G}$$

neutral — B=0, C-odd — B>0 — $\xleftarrow{\quad} C \xrightarrow{\quad}$ — B<0 — B=0, various C

- The dark baryon $\mathscr{B}$ is accidentally stable and thus a dark-matter candidate

A fundamental of SU(*N*)

Higgs phase, perturbative

$$\mathcal{S}(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \vdots \\ 0 \\ w + s(x) \end{pmatrix}$$

- The vev *w* breaks *B*
- It leaves new $B' \sim B + T^{\text{broken}}_{\text{SU(N)}} \propto$ diag$(1,\ldots,1,0)$ unbroken
- The gauge bosons in block form: $T^a \mathcal{G}^a_\mu = \left(\begin{array}{c|c} \mathcal{A}_\mu & \mathcal{W}_\mu/\sqrt{2} \\ \hline \mathcal{W}^*_\mu/\sqrt{2} & 0 \end{array}\right) - \mathcal{Z}_\mu \sqrt{\frac{\mathcal{N}-1}{2\mathcal{N}}} \left(\begin{array}{c|c} -\mathbf{1}/(\mathcal{N}-1) & 0 \\ \hline 0 & 1 \end{array}\right)$
- Spectrum:
  - s : singlet of SU(*N*-1)
  - A_μ : adjoint of SU(*N*-1)
  - W_μ : fundamental of SU(*N*-1), $B' = 1$
  - Z_μ : singlet of SU(*N*-1), $B' = 0$, *C*-odd

A fundamental of SU(*N*)

Higgs phase, after SU(*N*-1) confinement

- Unbroken SU(*N*-1) confines at lower scales
- Composite SU(*N*-1)-singlets must form:
  - Higgs scalar s : neutral
  - vector Z_μ : $B' = 0$, *C*-odd
  - baryon $\mathscr{B} \sim \epsilon W^{N-1}$: $B' > 0$, $\mathscr{B} \to \mathscr{B}^*$ under *C*
  - glueballs AA, AAA : $B' = 0$, various *C*
- Baryon $\mathscr{B}$ is accidentally stable, and thus a dark-matter candidate

surprisingly!

Higgs-confinement duality

- Symmetries in the two phases map into each other: $B \leftrightarrow B', \quad C \leftrightarrow C$
- States too!

$$\mathcal{S}^\dagger \mathcal{S} \leftrightarrow s \qquad \mathcal{S}^\dagger \mathcal{D}_\mu \mathcal{S} \leftrightarrow Z_\mu \qquad \mathcal{B} \sim \epsilon \mathcal{S}^N \leftrightarrow \epsilon W^{N-1} \qquad \mathcal{G}\mathcal{G}, \mathcal{G}\mathcal{G}\mathcal{G} \leftrightarrow AA, AAA$$

- We conjecture that the two phases are the very same, duality in description
- For SU(2) this is the Fradkin-Shenker theorem, proven in the lattice
- This goes through in detail:

$$\mathcal{B} = \mathcal{S}^I [\epsilon_{IJK\dots} (\mathcal{D}^{(n)} \mathcal{S})^J (\mathcal{D}^{(n')} \mathcal{S})^K \cdots]$$

+ vev: $\langle \mathcal{S} \rangle$

+ Goldstone identification: $\mathcal{D}_\mu \mathcal{S}^J \leftrightarrow \mathcal{W}^J_\mu$

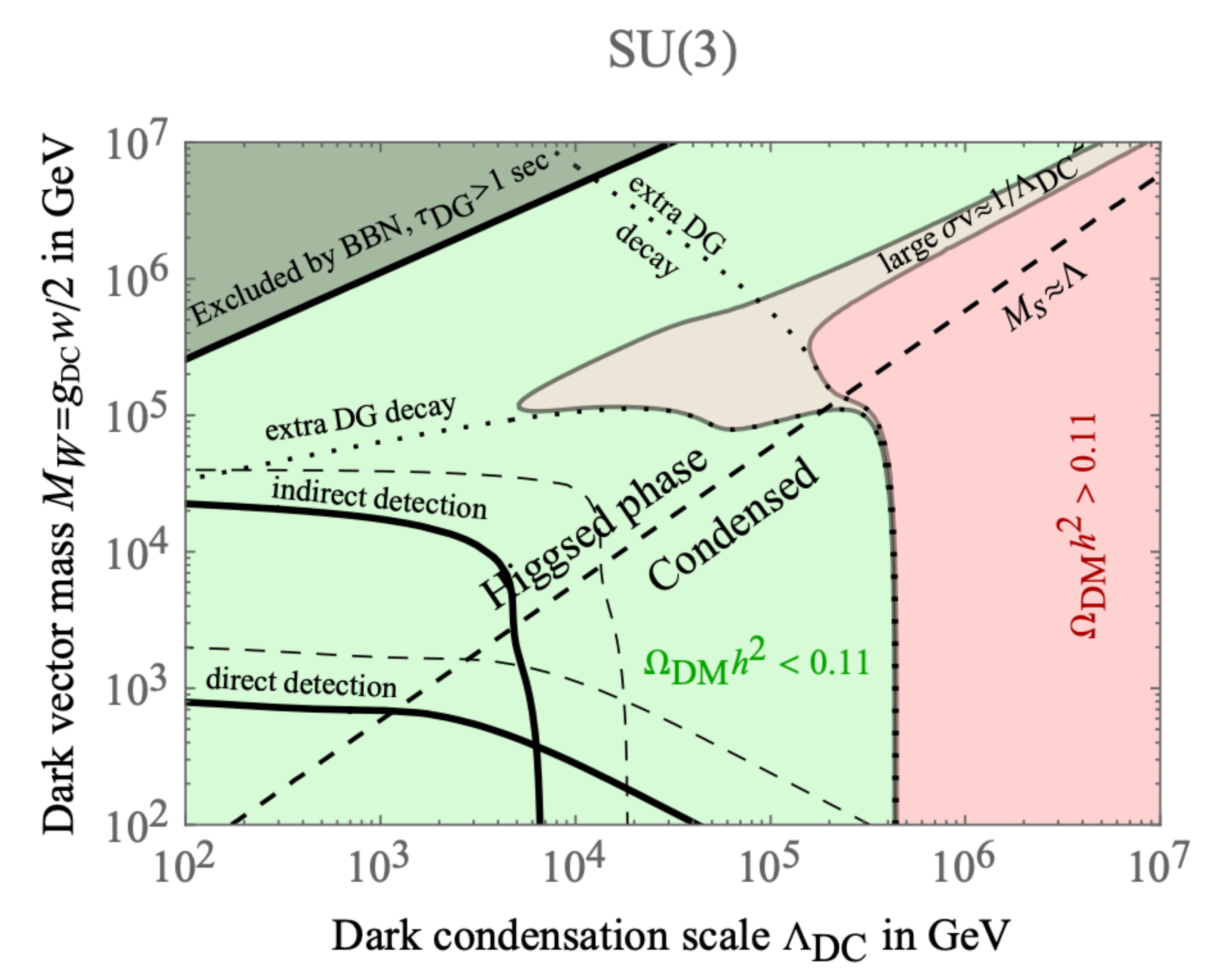
Relic density

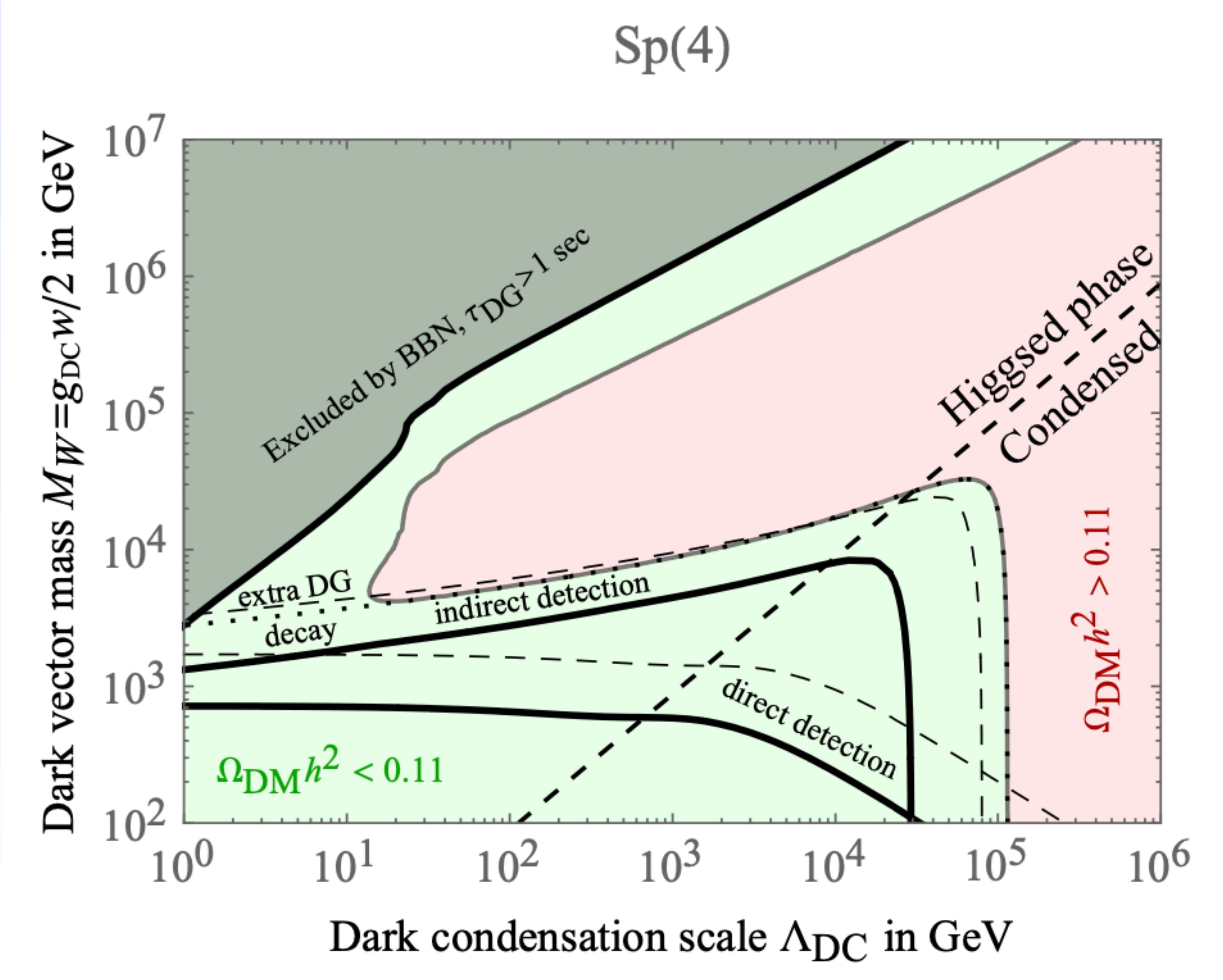
Description in the Higgs phase

- dark baryons $\mathscr{B} \sim \epsilon W^{N-1}$ accidentally stable
- also *C*-odd *AAA* glueball stable, but it never dominates, so focus on $\mathscr{B}$
- relic density determined by rich thermal history:
    1. W_μ vectors perturbatively freeze out ($WW^* \to AA, As, ss, Zs, ZA$)
    2. SU(N-1) later confines, heavy W_μ form unstable mesons and stable $\mathscr{B}$
    3. baryons have large cross-section and re-annihilate
    4. glueballs might decay slowly, and dilute relic density via early matter domination

Parameter space

- Coleman-Weinberg $M_{\mathcal{S}} \simeq 0$ limit for simplicity (or naturalness considerations)
- dimensionless limit also for the Higgs: $\mu_H^2 \simeq \lambda_{HS}\langle \mathcal{S} \rangle^2$ (it increases predictivity)
- two parameters left, can be traded for $M_W \sim g_{\rm dark}\langle \mathcal{S} \rangle$ and strong scale $\Lambda_{\rm DC}$





Other gauge groups with duality

- We identified all Lie groups where the Higgs/confinement duality occurs
- Decisive criterion: only one breaking pattern and so one Higgs phase only
- SO(*N*) with a fundamental: stabilizing symmetry is O-parity (reflection along one group direction, analogous to parity for rotations)
- Sp(*N*) with a fundamental: accidental dark U(1), stable mesons but relic density dominated by neutral *W*, so pheno similar to SU(2).
- G_2 with a fundamental: broken to SU(3) in Higgs phase, $WWW - W^*W^*W^*$ analogous to $K^0 - \overline{K}^0$ system (one combination is stable, the other decays)

Two-index representations

- We studied $\mathcal{S}$ in the symmetric, antisymmetric, adjoint for SU(N), SO(N), Sp(N)
- We found no duality: for each case two Higgs phases, different from confined
- Many possibilities for accidental stabilizing symmetries, complicated pattern of dark-matter candidates
- Additional pheno: dark radiation, self-interaction, monopoles, …
- In some cases SSB of accidental U(1) $\longrightarrow$ Goldstone bosons

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Unbroken phase			Broken phase: perturbative				Broken condensed
gauge $\mathcal{G}$	scalar rep $\mathcal{S}$	accidental global	unbroken gauge $\mathcal{H}$	accidental global $\mathcal{H}$	massive vectors	massive scalars	Dark Matter
$\mathrm{SU}(\mathcal{N})$	fundamental	$\mathrm{U}(1)$, $\mathcal{C}$	$\mathrm{SU}(\mathcal{N}-1)$	$\mathrm{U}(1)$, $\mathcal{C}$	$\mathcal{W}, \mathcal{Z}$	$\mathfrak{s}$	$\mathcal{B} \sim \mathcal{W}^{\mathcal{N}-1}$, $d\mathcal{AAA}$
	symmetric	$\mathrm{U}(1)$, $\mathcal{C}$	$\mathrm{SU}(\mathcal{N}-1)$	$\mathrm{U}(1)$, $\mathcal{C}$	$\mathcal{W}, \mathcal{Z}$	$\mathfrak{s}, \tilde{\mathfrak{s}}$	$\mathcal{B} \sim \mathcal{W}^{\mathcal{N}-1}$, $d\mathcal{AAA}$, $\tilde{\mathfrak{s}}$ can be co-stable
			$\mathrm{SO}(\mathcal{N})$	$\mathcal{P}_{\mathrm{U}}, \mathcal{C}$	$\mathcal{W}$	$\mathfrak{a}, \mathfrak{s}, \tilde{\mathfrak{s}}$	$\mathfrak{a}$ + 0-ball if $\mathcal{N}$ even
	antisymm	$\mathrm{U}(1)$, $\mathcal{C}$	$\mathrm{SU}(\mathcal{N}-2) \otimes \mathrm{SU}(2)$	$\mathrm{U}(1)$,$\mathcal{C}$	$\mathcal{W}, \mathcal{Z}$	$\mathfrak{s}, \tilde{\mathfrak{s}}$	$\mathcal{B} \sim \mathcal{W}^{\mathcal{N}-2}$ if $\mathcal{N}$ even; $\mathcal{W}^{2(\mathcal{N}-2)}$ if odd, $d\mathcal{AAA}$
			$\mathrm{Sp}(\mathcal{N})$	$\mathcal{C}$	$\mathcal{W}$	$\mathfrak{a}, \mathfrak{s}, \tilde{\mathfrak{s}}$	$\mathfrak{a}$
			$\mathrm{Sp}(\mathcal{N}-1)$	$\mathcal{C}$, $\mathrm{U}(1)$	$\mathcal{W}, \mathcal{Z}, \mathcal{X}$	$\mathfrak{s}, \tilde{\mathfrak{s}}$	$\mathcal{Z}, \mathcal{M} \sim \mathcal{X}^T \gamma_{\mathcal{N}-1} \mathcal{X}$
	adjoint	$\mathcal{C}$	$\mathrm{SU}(\mathcal{N}_1) \otimes \mathrm{SU}(\mathcal{N}_2) \otimes \mathrm{U}(1)$	$\mathcal{C}$	$\mathcal{W}^{\pm}$	$\mathfrak{s}, \tilde{\mathfrak{s}}_1, \tilde{\mathfrak{s}}_2$	charged double $\mathcal{B}$, depends on $\mathcal{N}_{1,2}$
			$\mathrm{SU}(\mathcal{N}-1) \otimes \mathrm{U}(1)$	$\mathcal{C}$	$\mathcal{W}^{\pm}$	$\mathfrak{s}, \tilde{\mathfrak{s}}$	charged $\mathcal{B} \sim \mathcal{W}^{\mathcal{N}-1}$
$\mathrm{SO}(\mathcal{N})$	fundamental	$\mathcal{P}_{\mathrm{O}}$	$\mathrm{SO}(\mathcal{N}-1)$	$\mathcal{P}_{\mathrm{O}}$	$\mathcal{W}$	$\mathfrak{s}$	0(1)-ball for $\mathcal{N}$ odd (even)
	symmetric traceless	$\mathcal{P}_{\mathrm{O}}$	$\mathrm{SO}(\mathcal{N}-1)$	$\mathcal{P}_{\mathrm{O}}$	$\mathcal{W}$	$\mathfrak{s}, \tilde{\mathfrak{s}}$	0(1)-ball for $\mathcal{N}$ odd (even)
			$\mathrm{SO}(\mathcal{N}/2) \otimes \mathrm{SO}(\mathcal{N}/2), \mathcal{N}/2$ even	$\mathcal{P}_{\mathrm{O}_1}, \mathcal{P}_{\mathrm{O}_2}$	$\mathcal{W}$	$\mathfrak{s}, \tilde{\mathfrak{s}}_1, \tilde{\mathfrak{s}}_2$	0-ball
			$\mathrm{SO}(\mathcal{N}/2) \otimes \mathrm{SO}(\mathcal{N}/2), \mathcal{N}/2$ odd	$\mathcal{P}_{\mathrm{O}_1}, \mathcal{P}_{\mathrm{O}_2}$	$\mathcal{W}$	$\mathfrak{s}, \tilde{\mathfrak{s}}_1, \tilde{\mathfrak{s}}_2$	1-ball bi-baryon
			$\mathrm{SO}((\mathcal{N}+1)/2) \otimes \mathrm{SO}((\mathcal{N}-1)/2)$	$\mathcal{P}_{\mathrm{O}_1}, \mathcal{P}_{\mathrm{O}_2}$	$\mathcal{W}$	$\mathfrak{s}, \tilde{\mathfrak{s}}_1, \tilde{\mathfrak{s}}_2$	0-ball
	antisymm adjoint	$\mathcal{P}_{\mathrm{O}}, \mathbb{Z}_2$	$\mathrm{SO}(\mathcal{N}-2) \otimes \mathrm{U}(1), \mathcal{N}$ even	$\mathcal{P}_{\mathrm{O}}$	$\mathcal{W}^{\pm}$	$\mathfrak{s}, \tilde{\mathfrak{s}}$	neutral 0-ball + charged 2-ball or $\mathcal{M}^{\pm\pm}$
			$\mathrm{SO}(\mathcal{N}-2) \otimes \mathrm{U}(1), \mathcal{N}$ odd	$\mathcal{P}_{\mathrm{O}}$	$\mathcal{W}^{\pm}$	$\mathfrak{s}, \tilde{\mathfrak{s}}$	charged 1-ball $\mathcal{B}^{\pm}$ + possibly $\mathcal{M}^{\pm\pm}$
			$\mathrm{SU}(\mathcal{N}/2) \otimes \mathrm{U}(1), \mathcal{N}$ even	–	$\mathcal{W}_{ij}^{\pm\pm}$	$\mathfrak{s}, \tilde{\mathfrak{s}}$	charged baryon $\mathcal{W}^{\mathcal{N}/4}$ or dibaryon
			$\mathrm{SU}((\mathcal{N}-1)/2) \otimes \mathrm{U}(1), \mathcal{N}$ odd	–	$\mathcal{W}_{ij}^{\pm\pm}, \mathcal{X}_i^{\pm}$	$\mathfrak{s}, \tilde{\mathfrak{s}}$	charged baryon $\mathcal{X}^{(\mathcal{N}-1)/2}$
$\mathrm{Sp}(\mathcal{N})$	fundamental	$\mathrm{U}(1)$	$\mathrm{Sp}(\mathcal{N}-2)$	$\mathrm{U}(1)$	$\mathcal{W}, \mathcal{X}, \mathcal{Z}$	$\mathfrak{s}$	$\mathcal{W}$ and $\mathcal{M} \sim \mathcal{X}^T \gamma_{\mathcal{N}-2} \mathcal{X}$
	symmetric adjoint	$\mathbb{Z}_2$	$\mathrm{Sp}(\mathcal{N}-2) \otimes \mathrm{U}(1)$	–	$\mathcal{W}^{\pm\pm}, \mathcal{X}_i^{\pm}$	$\mathfrak{s}, \tilde{\mathfrak{s}}$	$\mathcal{W}^{\pm\pm}$ and $\mathcal{M}^{\pm\pm} \sim \mathcal{X}^{\pm T} \gamma_{\mathcal{N}-2} \mathcal{X}^{\pm}$
			$\mathrm{SU}(\mathcal{N}/2) \otimes \mathrm{U}(1)$	$\mathcal{C}$	$\mathcal{W}_{ij}^{\pm}$	$\mathfrak{s}, \tilde{\mathfrak{s}}$	charged baryon $\mathcal{W}^{\mathcal{N}/4}$ or dibaryon, $d_{\mathrm{SU}}\mathcal{AAA}$
	antisymm traceless	$\mathcal{C}_{\mathrm{Sp}}$	$\mathrm{Sp}(\mathcal{N}_1) \otimes \mathrm{Sp}(\mathcal{N}_2)$	$\mathbb{Z}_2, \mathcal{C}_{\mathrm{Sp}}$	$\mathcal{W}_{i_1 i_2}$	$\mathfrak{s}, \tilde{\mathfrak{s}}_1, \tilde{\mathfrak{s}}_2$	DM exists only in special cases
			$\mathrm{Sp}(\mathcal{N}-2) \otimes \mathrm{Sp}(2)$	$\mathbb{Z}_2, \mathcal{C}_{\mathrm{Sp}}$	$\mathcal{W}$	$\mathfrak{s}, \tilde{\mathfrak{s}}$	DM exists only in special cases

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A new phenomenon: high-quality shift symmetry

$\mathcal{S}$ in the symmetric or antisymmetric of SU(N)

- $\langle \mathcal{S}_{ij} \rangle \propto \mathbb{I}_N$ breaks SU$(N) \to$ SO(N)
- Accidental *B* is spontaneously broken: Goldstone $\mathcal{S}_{ij} \supset \mathbb{I}_N \, e^{i\frac{a}{f}}$
- The shift-symmetry of *a* has an extremely high quality: U(1) first broken by det$\mathcal{S}$, at dimension *N*
- Robust phenomenon for general field content, if $\langle \mathcal{S}_{ij} \rangle$ is the only vev:
  - accidental U(1) charge of $\mathcal{O}^{ab\ldots c}_{ij\ldots k}$ is *N*-ality = # lower - # upper indices
  - gauge singlets operators in the EFT $\longrightarrow$ *N*-ality = 0, unless
  - $\mathcal{O} \supset \epsilon_{12\ldots N}$ at dimension $\propto N$

High-quality QCD axion from accidental PQ

- Peccei-Quinn quality problem: the PQ symmetry needs to be protected from operators up to dim ~ 10

- We can use the mechanism with dark SU(N>10) to obtain a high-quality QCD axion, where PQ symmetry is accidental

- Only need to add suitable chiral fermions to generate anomaly under QCD and cancel gauge anomalies

Field	Lorentz	Gauge symmetries				Global accidental symmetries		
name	spin	$\mathrm{U}(1)_Y$	$\mathrm{SU}(2)_L$	$\mathrm{SU}(3)_c$	$\mathrm{SU}(\mathcal{N})$	$\mathrm{U}(1)_{\mathrm{PQ}}$	$\mathrm{U}(1)_{\mathcal{Q}}$	$\mathrm{U}(1)_{\mathcal{L}}$
$\mathcal{S}$	0	0	1	1	$\mathcal{N}\mathcal{N}$	$+1$	0	0
$\mathcal{Q}_L$	1/2	$+Y_{\mathcal{Q}}$	1	3	$\mathcal{N}$	$+1/2$	$+1$	0
$\mathcal{Q}_R$	1/2	$-Y_{\mathcal{Q}}$	1	$\bar{3}$	$\mathcal{N}$	$+1/2$	-1	0
$\mathcal{L}_L^{1,2,3}$	1/2	$+Y_{\mathcal{L}}$	1	1	$\bar{\mathcal{N}}$	$-1/2$	0	$+1$
$\mathcal{L}_R^{1,2,3}$	1/2	$-Y_{\mathcal{L}}$	1	1	$\bar{\mathcal{N}}$	$-1/2$	0	-1

Conclusions

- Dark Matter is generic in models of a dark gauge group with a scalar
- Stability is accidental, not imposed ad hoc
- Stability is present also in Higgs phase, thanks to the gauge/confinement duality
- Rich cosmology, typically heavy dark matter
- Same setup can be instead used to obtain an accidental shift-symmetry protected to arbitrarily high order
- High quality QCD axion with accidental PQ symmetry

Thanks