Title: Scalar gauge theories and Dark Matter

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Abstract: I will consider simple scalar gauge theories with one scalar field in a low-dimensional representation of a gauge group. The renormalizable action often has accidental symmetries that lead to one or more stable states, providing Dark Matter candidates. The gauge group can confine, or be spontaneously broken by the scalar field: I will discuss the spectrum and symmetries in both cases, focusing in particular on possible dualities between the Higgs and confined phases. I will then discuss the Dark Matter phenomenology in a few illustrative cases, showing that the thermal relic abundance can reproduce the cosmological value for masses around 100 TeV.

Scalar gauge theories and Dark Matter

Dario Buttazzo

based on 1907.11228 and 1911.04502
with Di Luzio, Landini, Teresi, Strumia + Ghorbani, Gross, Wang

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Perimeter Institute — 21.01.2020

Outline

Yang-Mills + 1 scalar field

$$\mathscr{L} = -\frac{1}{4}\mathcal{G}^a_{\mu\nu}\mathcal{G}^{\mu\nu,a} + |D_\mu\phi|^2 - m^2|\phi|^2 - V(\phi)$$

- new gauge group G with coupling g
- scalar field ϕ in representation R of G (real or complex)

  $D_\mu = \partial_\mu + i\, g\, \mathcal{G}^a_\mu\, T^a_{(R)}$
- coupling to SM through Higgs portal $|H|^2|\phi|^2$

Motivations

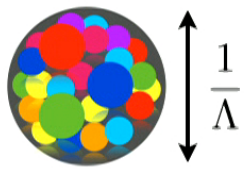
- Why not? A very simple and predictive model.
- Almost as minimal as Minimal DM.
  - Here ϕ is charged under a new gauge group (not SM).
- WIMP more and more challenged by direct/indirect detection:
  thermal freeze-out of DM in early universe & interactions with SM are controlled by the same (gauge) coupling
  - coupling to SM through Higgs portal $\lambda|\phi|^2|H|^2$ can be made small
  - gauge coupling g is free: can have thermal DM with different mass

$$m_{\rm DM} > m_{\rm EW} \quad \Rightarrow \quad g_{\rm DM} > g_{\rm EW}$$

If $g \approx 4\pi \quad \Rightarrow \quad m_\phi \approx 100$ TeV (beyond most experimental bounds)

Motivations

- <u>Composite DM</u>: bound state (baryon, meson, glue-ball, …) of a "dark" strong force confined at $\Lambda \approx$ few GeV — 100 TeV



has already been studied for fermions

Strassler, Zurek 2006
Kribs, Roy, Terning, Zurek 2009
Antipitin, Redi, Strumia, Vigiani 2015
Mitridate, Redi, Smirnov, Strumia 2017
… many more…

➡ do it with scalar constituents!

- \+ scalars can have a potential V(ϕ): can break the gauge group $G \to H$

Study DM candidates and phenomenology, for small representations of simple groups G = SU(N), SO(N), Sp(N), G_2

Trivial examples

- Just a real singlet: $\mathscr{L} = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{m^2}{2}\phi^2 - V(\phi) - \lambda\,|H|^2\phi^2$

  ϕ stable imposing *ad-hoc* parity $\phi \to -\phi$

  Thermal DM now challenged by direct detection (if heavy)

- Dark scalar QED: complex ϕ + U(1) gauge symmetry

  ϕ stable due to charge conservation if $\langle\phi\rangle = 0$

  If $\langle\phi\rangle \neq 0$, charge conjugation is a symmetry *if no kinetic mixing* $F_{\mu\nu}\mathcal{G}^{\mu\nu}$

  massive U(1) gauge boson is stable and DM candidate


ϕ stable due t
If $\langle\phi\rangle \neq 0$, char
massive U(1) g
CAUTION

Non-abelian example: SU(2)

ϕ doublet of SU(2) gauge theory (Hambye 2008)

I. "Higgs" phase: ϕ gets a vev that breaks SU(2) → Ø

$$\langle\phi\rangle = \begin{pmatrix} 0 \\ w \end{pmatrix} \neq 0$$

Spectrum: W_μ^a massive vectors, s "higgs"

$\mathscr{L}$ has custodial symmetry $\mathrm{SO}(4) \to \mathrm{SO}(3)$

i) the W's are stable (they are triplets of the custodial symmetry), *no additional symmetry imposed*

ii) common mass m_W for the vectors W^1, W^2, W^3

Non-abelian example: SU(2)

ϕ doublet of SU(2) gauge theory (Hambye 2008)

II. "Confined" phase: $\langle\phi\rangle = 0$, and SU(2) confines at a scale Λ

(Hambye, Tytgat 2009)

Asymptotic states are singlets of SU(2)

- "mesons"
  - $\phi^\dagger\phi$ spin-0
  - $\phi^\dagger D_\mu \phi$ spin-1
- "baryons"
  - $\phi\epsilon D_\mu\phi$, $\phi^\dagger\epsilon D_\mu\phi^\dagger$ spin-1
- "glue-balls" (in QCD more massive)

Non-abelian example: SU(2)

ϕ doublet of SU(2) gauge theory (Hambye 2008)

II. "Confined" phase: $\langle\phi\rangle = 0$, and SU(2) confines at a scale Λ

$\mathscr{L}$ has custodial symmetry $\mathrm{SO}(4) \equiv \mathrm{SO}(3)_{\mathrm{g}} \times \mathrm{SO}(3)_{\mathrm{c}}$

preserved by the condensate $\langle\phi^*\phi\rangle$

$$\phi^\dagger\phi \sim 1 \text{ of } \mathrm{SO}(3) \longrightarrow s$$

$$\left\{\begin{array}{l} \phi^\dagger D_\mu \phi \\ \phi\,\epsilon\, D_\mu \phi \\ \phi^\dagger \epsilon\, D_\mu \phi^\dagger \end{array}\right. \sim 3 \text{ of } \mathrm{SO}(3) \longrightarrow W_\mu^a$$

Asymptotic states and global symmetries identical in the two phases: *equivalence of "Higgs" and "Confined" phases!*

Equivalence of the two phases

Theorem (Fradkin-Shenker 1979):

If $\langle\phi\rangle$ breaks the gauge group completely, $G \to \emptyset$, then

"Higgs phase" ≡ "Confined phase"

- same global symmetries,
- same asymptotic states,
- all the amplitudes $A(\Lambda, \mathrm{w})$ are analytic functions of the parameters: no phase transition when $\Lambda > \mathrm{w}$

(For SU(2): Banks, Rabinovici 1978)

Equivalent formulation of the theory in terms of composite fields $\phi \cdots \phi$, gauge-invariant iff $G \to \emptyset$ (Fröhlich, Morchio, Strocchi 1981)

Same asymptotic states, all Green functions coincide in the perturbative limit

Equivalence of the two phases

If $G \to H \neq \emptyset$, there is additional gauge dynamics below $\langle \phi \rangle = w$:

the residual group H confines $\Rightarrow$ can have phase transition when $\Lambda_H \sim w$

(For SU(N > 2) Fradkin & Shenker consider many Higgs scalars to get SU(N) $\to \emptyset$)

➡ The complementarity principle seems to be valid more in general, for models with scalars in fundamental representations and $H \neq \emptyset$.

In these cases, it is crucial to take into account the confinement of H

(Dimopoulos, Rabi, Susskind 1980)

Whenever there is only one possible breaking pattern $G \to H$, the Higgs and Confined phases coincide: fundamental of SU(N), SO(N), Sp(N), G_2

SU(N) model

Consider SU(N) with one scalar ϕ in the fundamental rep.

$$\phi(x) = \frac{1}{\sqrt{2}}(0, \cdots, 0, w + s(x))$$ always breaks SU(N) → SU(N – 1)

$$T^a \mathcal{G}^a_\mu = \left(\begin{array}{c|c} \mathcal{A}_\mu & \mathcal{W}_\mu/\sqrt{2} \\ \hline \mathcal{W}^*_\mu/\sqrt{2} & 0 \end{array} \right) - \mathcal{Z}_\mu \sqrt{\frac{\mathcal{N}-1}{2\mathcal{N}}} \left(\begin{array}{c|c} -\mathbb{I}/(\mathcal{N}-1) & 0 \\ \hline 0 & 1 \end{array} \right)$$

Accidental global symmetry: U(1)$_B$ *dark baryon number,* $B_\phi = 1$

$\langle\phi\rangle$ breaks B but leaves a global U(1) unbroken:

$$T_{\mathrm{U}(1)} = \frac{\mathcal{N}}{\mathcal{N}-1}\mathrm{diag}(1, \cdots, 1, 0) = T_{\mathrm{B}} - T^{\mathcal{N}^2-1}\sqrt{2\mathcal{N}/(\mathcal{N}-1)}$$

SU(N) model: Higgs phase

Consider SU(N) with one scalar ϕ in the fundamental rep.

$$\phi(x) = \frac{1}{\sqrt{2}}(0, \cdots, 0, w + s(x))$$ always breaks SU(N) → SU(N – 1)

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Perturbative spectrum:

- s, "Higgs", singlet of SU(N-1)
- A, N(N-2) massless gluons, adjoint of SU(N-1) → *confine*
- W, 2*(N-1) (anti-)fundamentals of SU(N-1), $m_W^2 = g^2 w^2/4$

  charged under unbroken U(1) ⇒ stable DM candidates!
- Z, massive singlet of SU(N-1), $m_Z^2 = g^2 w^2 \frac{\mathcal{N}-1}{2\mathcal{N}}$

  For $N = 2$, $m_W = m_Z$ and Z is stable

  For $N > 2$ no custodial symmetry, $Z \to AAA$

SU(N) model: condensation of SU(N-1)

SU(N-1) confines at a scale $\Lambda = m_W \exp\left(-\frac{6\pi}{11(\mathcal{N}-1)\,\alpha(m_W)}\right)$

Spectrum of bound states:

- Dark glueballs $A_{\mu\nu}A^{\mu\nu}$, have mass ~ 7Λ
- s (spin-0), Z_μ (spin-1) singlets of SU(N-1)
- Dark mesons $W_\mu{}^*W^\mu$ decay through W^*-W annihilations
- Dark baryons $\mathcal{B} = \varepsilon\, W^{N-1}$ have charge N-1 ⇒ stable DM candidates

If $m_W >> \Lambda$, baryons with heavy spin-1 constituents: spectrum from NR-QM

Lightest state minimizes angular momentum: antisymmetric wavefunction

- SU(3) → SU(2): $(3\otimes 3)_a = 3$ spin-1
  $\mathcal{B}^\mu = \epsilon^{\alpha\beta}\epsilon^{\mu\nu\rho\sigma}\mathcal{W}^\alpha_\nu D_\rho \mathcal{W}^\beta_\sigma$
- SU(4) → SU(3): $(3\otimes 3\otimes 3)_a = 1$ spin-0
  $\mathcal{B} = \epsilon^{\alpha\beta\gamma}\epsilon^{\mu\nu\rho\sigma}\mathcal{W}^\alpha_\mu \mathcal{W}^\beta_\nu D_\rho \mathcal{W}^\gamma_\sigma$

…

SU(N) model: confined phase

Other possibility: $\langle\phi\rangle = 0$, and whole SU(N) confines when g(Λ) ≈ 4π

Spectrum of bound states:

- Dark glueballs $G_{\mu\nu}G^{\mu\nu}$, have mass ~ 7Λ
- $\phi^*\phi \equiv s$ spin-0 meson
- $\phi^* D_\mu \phi \equiv Z_\mu$ spin-1 meson
- Dark baryons $\mathcal{B} = \varepsilon\, \phi^N$ are stable due to dark baryon number

$$\mathcal{B} = \phi^{\alpha_1}\epsilon_{\alpha_1\alpha_2\cdots\alpha_\mathcal{N}}(D^{(n)}\phi)^{\alpha_2}(D^{(m)}\phi)^{\alpha_2}\cdots(D^{(k)}\phi)^{\alpha_\mathcal{N}}$$

$\alpha_1 = \mathcal{N},\ \langle\phi^{\alpha_1}\rangle = w \quad \Rightarrow \quad \alpha_2\cdots\alpha_\mathcal{N} \neq \mathcal{N},\ D_\mu\phi^{\alpha_i} \equiv W_\mu^{\alpha_i}$ goldstones

Match with baryons of SU(N-1) when w ≠ 0 *Same phase!*

One caveat!

What if the strong dynamics breaks baryon number? $\langle \mathcal{B} \rangle \neq 0$?

- The operator $\mathcal{B}$ always contains derivatives: $\langle \mathcal{B} \rangle = 0$ in general?
  (in QCD it violates Lorentz symmetry and is exactly 0)

- For (vector-like) fermionic gauge theories, Vafa-Witten theorem
  $\Rightarrow$ vector-like symmetries not broken by the condensates

  This is however not true for scalar theories with a potential;

  effect of $V(\phi)$ important if $|\lambda| >>1$. RGE make λ large and negative in IR

  (but then, we are again in the Higgs phase?)

  Non-perturbative behavior of scalar-gauge theories not well known…

- We *assume* that $\langle \mathcal{B} \rangle = 0$, and $\langle \phi^* \phi \rangle$ is the only condensate.

Phenomenology

$$V(\phi, H) = -m^2|\phi|^2 + \lambda_\phi|\phi|^4 - \lambda_{H\phi}|\phi|^2|H|^2 - \mu^2|H|^2 + \lambda_H|H|^4$$

- 4 BSM parameters: $m,\ \lambda_\phi,\ \lambda_{H\phi},\ g$
- Special case: *scale-invariant* potential $m = \mu = 0$

  All the scales are generated dynamically à la Gildener-Weinberg:

  w defined by $\lambda_\phi(w) < 0$ $\qquad$ $v = w\sqrt{\dfrac{\lambda_{H\phi}}{2\lambda_H}}$

- Determine $m_{DM} \approx w$ from Ω_{DM}, assuming thermal freeze-out

  ⇒ *g only free parameter*

➡ No phase transition between Higgs and confinement:

limit $g \to 4\pi$ smoothly obtained from perturbative case

Relic abundance

At high temperatures, bath of gauge vectors & scalars in thermal eq.

Dark baryon is the stable DM candidate.

1. Freeze-out of elementary W annihilations
   - perturbative: $\sigma v_{\rm rel}(\mathcal{W}^*\mathcal{W} \to \mathcal{A}\mathcal{A}) \approx \# \frac{g^4}{m_{\mathcal{W}}^2}$

     and similar for $WW^* \to As$, $WW^* \to ss$, $WW^* \to Zs$, $WW^* \to ZA$
   - non-perturbative: $\sigma v_{\rm rel}(\mathcal{W}^*\mathcal{W} \to \mathcal{A}\mathcal{A}) \approx 1/\Lambda^2$

Freeze-out when $\Gamma \approx H$. W is heavy $\Rightarrow$ $T_{\rm dec} \approx M_W/25$

Relic abundance of W's: $\frac{\Omega_{\mathcal{W}} h^2}{0.11} \approx \frac{1}{\sigma v_{\rm rel}} 2.2 \times 10^{-26}\,{\rm cm}^3/{\rm s}$

Relic abundance: baryons

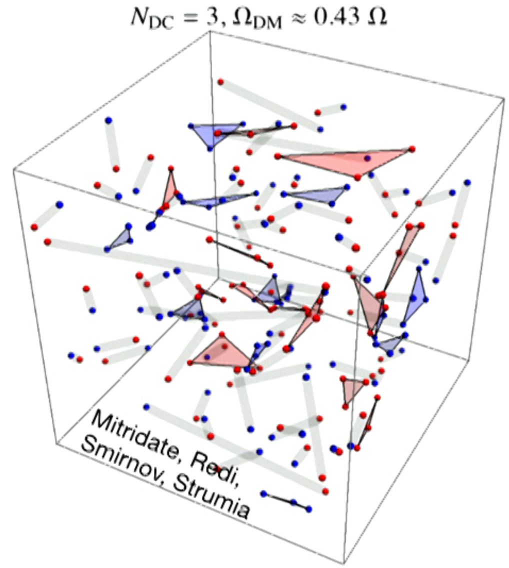
2. At confinement scale, baryons and mesons form.

Mesons decay (WW* → glueballs → SM), Baryons are stable DM

Assuming nearest-neighbor interaction:

- Probability to bind constituents in a meson $p_{\mathcal{M}} \approx 1/2$,
- Probability to bind constituents in a baryon $p_{\mathcal{B}} \approx 1/2^{(N-1)-1}$

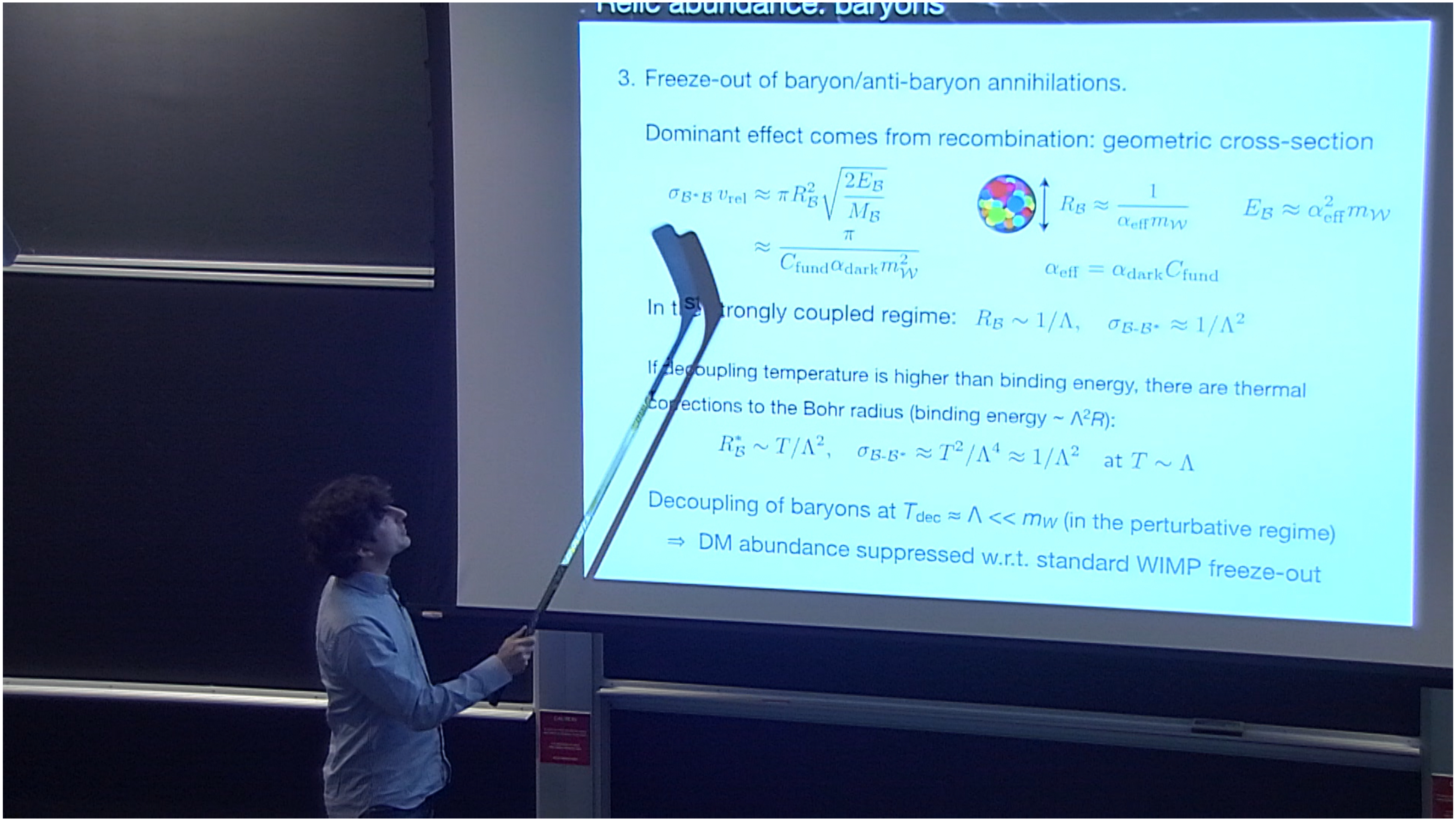
  but $N - 1$ particles vs. 2 particles



Baryon fraction after confinement

$$\wp = \frac{\mathcal{N} p_{\mathcal{B}}}{\mathcal{N} p_{\mathcal{B}} + 2 p_{\mathcal{M}}} = \frac{1}{1 + 2^{\mathcal{N}-2}/(\mathcal{N}-1)}$$

$$\Omega_{\text{baryon}} = \wp\, \Omega_{\mathcal{W}}$$


3. Freeze-out of baryon/anti-baryon annihilations.
Dominant effect comes from recombination: geometric cross-section
$\sigma_{\mathcal{B}^*\mathcal{B}}\, v_{\rm rel} \approx \pi R_{\mathcal{B}}^2 \sqrt{\frac{2E_{\mathcal{B}}}{M_{\mathcal{B}}}}$
$\approx \frac{\pi}{C_{\rm fund}\alpha_{\rm dark} m_{\mathcal{W}}^2}$
$R_{\mathcal{B}} \approx \frac{1}{\alpha_{\rm eff} m_{\mathcal{W}}}$
$E_{\mathcal{B}} \approx \alpha_{\rm eff}^2 m_{\mathcal{W}}$
$\alpha_{\rm eff} = \alpha_{\rm dark} C_{\rm fund}$
trongly coupled regime: $R_{\mathcal{B}} \sim 1/\Lambda, \quad \sigma_{\mathcal{B}\text{-}\mathcal{B}^*} \approx 1/\Lambda^2$
oupling temperature is higher than binding energy, there are thermal
ections to the Bohr radius (binding energy ~ $\Lambda^2 R$):
$R_{\mathcal{B}}^* \sim T/\Lambda^2, \quad \sigma_{\mathcal{B}\text{-}\mathcal{B}^*} \approx T^2/\Lambda^4 \approx 1/\Lambda^2$ at $T \sim \Lambda$
Decoupling of baryons at $T_{\rm dec} \approx \Lambda << m_W$ (in the perturbative regime)
⇒ DM abundance suppressed w.r.t. standard WIMP freeze-out

Relic abundance: baryons

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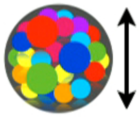
$$\sigma_{\mathcal{B}^*\mathcal{B}}\, v_{\rm rel} \approx \pi R_{\mathcal{B}}^2 \sqrt{\frac{2E_{\mathcal{B}}}{M_{\mathcal{B}}}} \approx \frac{\pi}{C_{\rm fund}\,\alpha_{\rm dark}\, m_{\mathcal{W}}^2}$$



$$R_{\mathcal{B}} \approx \frac{1}{\alpha_{\rm eff}\, m_{\mathcal{W}}} \qquad E_{\mathcal{B}} \approx \alpha_{\rm eff}^2 m_{\mathcal{W}}$$

$$\alpha_{\rm eff} = \alpha_{\rm dark} C_{\rm fund}$$

In the strongly coupled regime: $R_{\mathcal{B}} \sim 1/\Lambda, \quad \sigma_{\mathcal{B}\text{-}\mathcal{B}^*} \approx 1/\Lambda^2$

If decoupling temperature is higher than binding energy, there are thermal corrections to the Bohr radius (binding energy ~ $\Lambda^2 R$):

$$R_{\mathcal{B}}^* \sim T/\Lambda^2, \quad \sigma_{\mathcal{B}\text{-}\mathcal{B}^*} \approx T^2/\Lambda^4 \approx 1/\Lambda^2 \quad \text{at } T \sim \Lambda$$

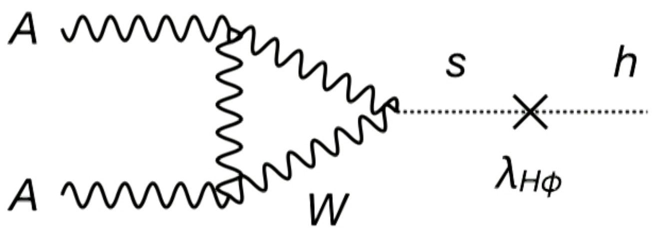
Decoupling of baryons at $T_{\rm dec} \approx \Lambda << m_W$ (in the perturbative regime)

⇒ DM abundance suppressed w.r.t. standard WIMP freeze-out

Dark glueballs

4. Late-time reheating of SM bath can dilute DM abundance

W's annihilate to dark glueballs → decay to SM through Higgs portal



$$\mathscr{L} = \frac{\alpha_{\rm dark}}{8\pi}\beta_{0,\mathcal{W}}\mathcal{A}_{\mu\nu}\mathcal{A}^{\mu\nu}\left(\frac{s}{w}+\cdots\right)$$

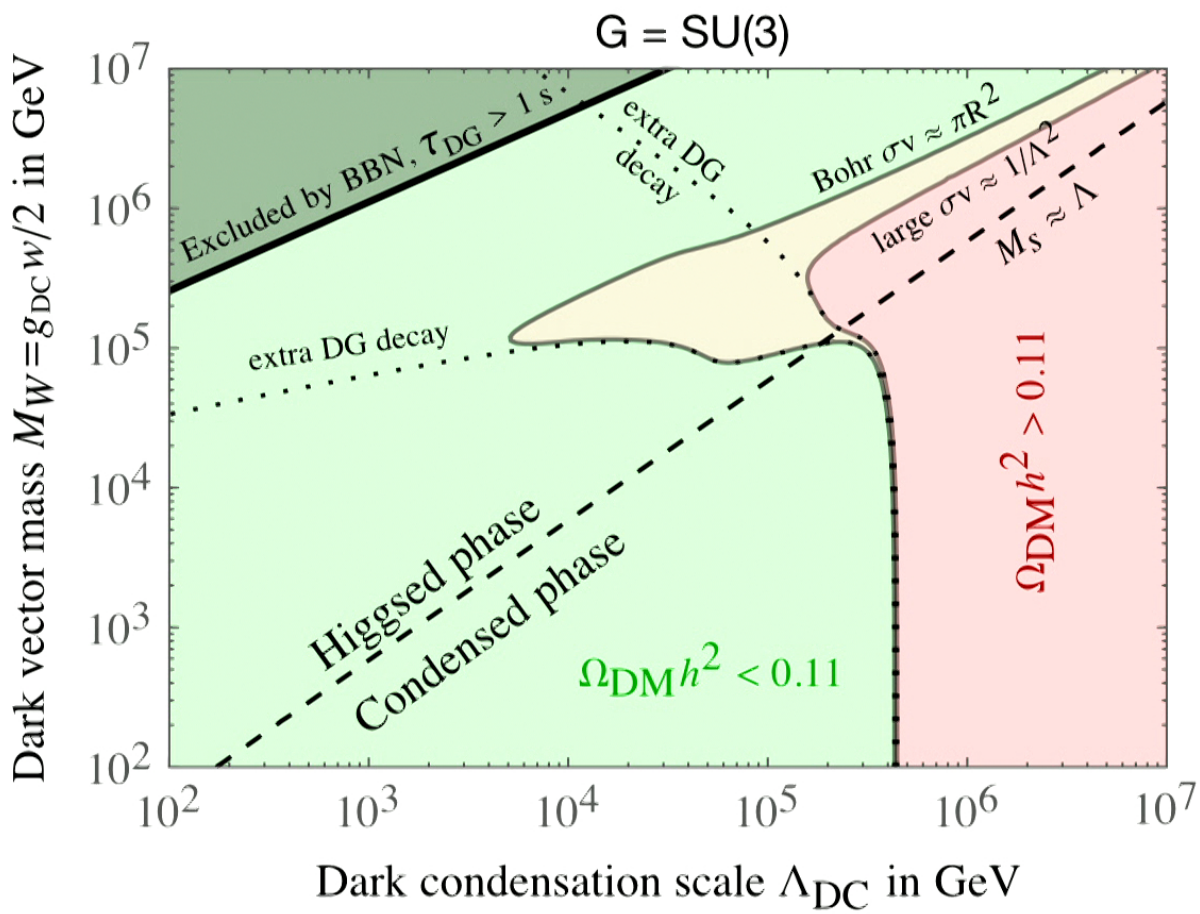
coefficient of W contribution to β-function of g (≡ Higgs soft theorems)

Decay rate depends on $\lambda_{H\phi}$.

In scale invariant case $v = w\sqrt{\frac{\lambda_{H\phi}}{2\lambda_H}}$ $\lambda_{H\phi}$ is small if w >> v:

- If glueballs are long-lived & decay after baryon freeze-out
  ⇒ dilution of DM density
- If very long-lived, $\tau_{DG} > 1$ s ⇒ bounds from BBN

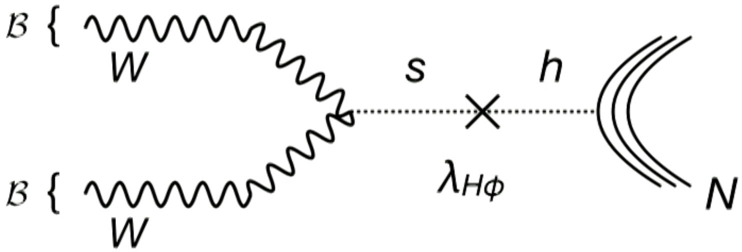
SU(N) model: phenomenology



Bounds from DM searches

- Direct detection: $\mathscr{L} \approx \frac{M_{\mathcal{B}}^2}{w} \overline{\mathcal{B}}\mathcal{B}s$

coupling to nucleons through Higgs-scalon mixing



$$\sigma_{\rm SI} \approx g^2 \frac{m_N^4}{m_h^2 M_s^4} \lambda_{H\phi}$$

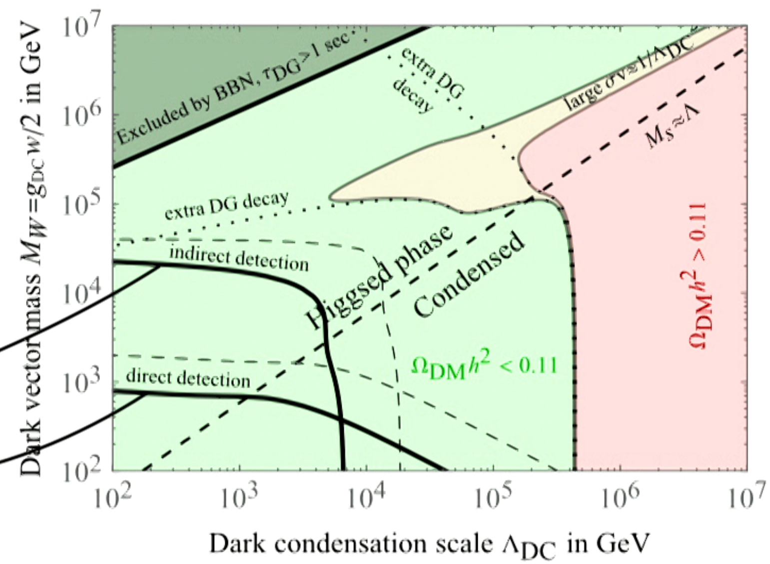
- Indirect detection:

enhanced by recombination

$$\sigma_{\mathcal{B}^*\mathcal{B}}\, v_{\rm rel} \approx \frac{\pi}{C_{\rm fund}\alpha_{\rm dark} m_{\mathcal{W}}^2}$$

bounds assume $\Omega_B = \Omega_{DM}$

thermal region not probed



A fundamental of SO(N)

$\langle \phi \rangle$ always breaks SO(N) → SO(N – 1)

- The group is real ⇒ no conserved U(1) charge, no Z_μ in the spectrum
- Theory accidentally invariant under O(N); O(N)/SO(N) ≡ Z_2 parity

$$s \to s, \quad A_\mu \to A_\mu, \quad W_\mu \to -W_\mu \quad \text{not broken by } \langle \phi \rangle \quad \Rightarrow \text{ W stable}$$

Baryons

Higgs phase:

$$\mathcal{B} = \epsilon_{\alpha_1 \cdots \alpha_{\mathcal{N}-1}} \mathcal{W}^{\alpha_1} \mathcal{A}^{\alpha_2 \alpha_3} \ldots \mathcal{A}^{\alpha_{\mathcal{N}-2} \alpha_{\mathcal{N}-1}} \quad \text{N even}$$

$$\mathcal{B} = \epsilon_{\alpha_1 \cdots \alpha_{\mathcal{N}-1}} \mathcal{A}^{\alpha_1 \alpha_2} \ldots \mathcal{A}^{\alpha_{\mathcal{N}-2} \alpha_{\mathcal{N}-1}} \quad \text{N odd}$$

gluons can be valence constituents: □ x □ ~ Adj

the states match: two phases equal

Confined phase:

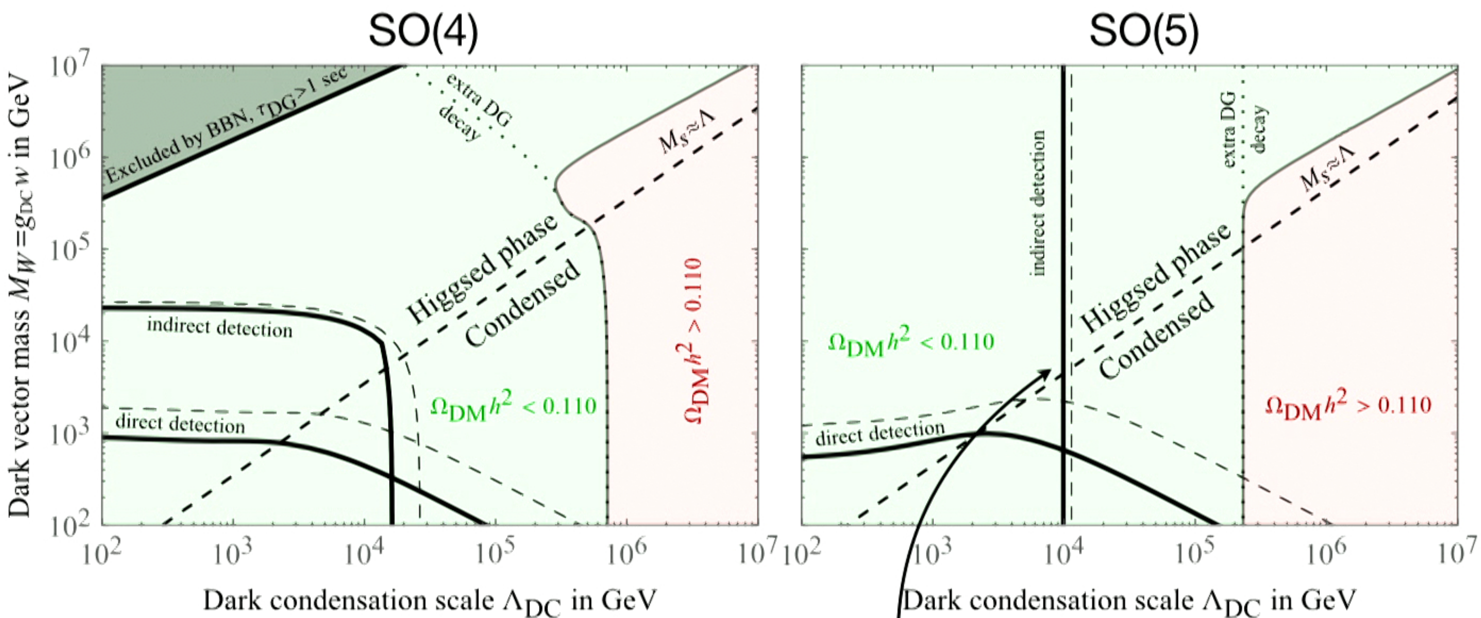
$$\mathcal{B} = \epsilon_{\alpha_1 \cdots \alpha_{\mathcal{N}}} \mathcal{G}^{\alpha_1 \alpha_2} \ldots \mathcal{G}^{\alpha_{\mathcal{N}-1} \alpha_{\mathcal{N}}} \quad \text{N even}$$

$$\mathcal{B} = \epsilon_{\alpha_1 \cdots \alpha_{\mathcal{N}}} \phi^{\alpha_1} \mathcal{G}^{\alpha_2 \alpha_3} \ldots \mathcal{G}^{\alpha_{\mathcal{N}-1} \alpha_{\mathcal{N}}} \quad \text{N odd}$$

A fundamental of SO(N): phenomenology

The lightest baryon always contains massless constituents: relativistic

$\Rightarrow$ annihilation cross-section ~ $1/\Lambda^2$



Baryon = $A^{(N-1)/2}$: DM mass does not depend on w

A fundamental of Sp(N)

ϕ is complex: baryon number stabilizes DM

$\langle\phi\rangle$ breaks Sp(N) → Sp($N-2$),

a global U(1) is preserved

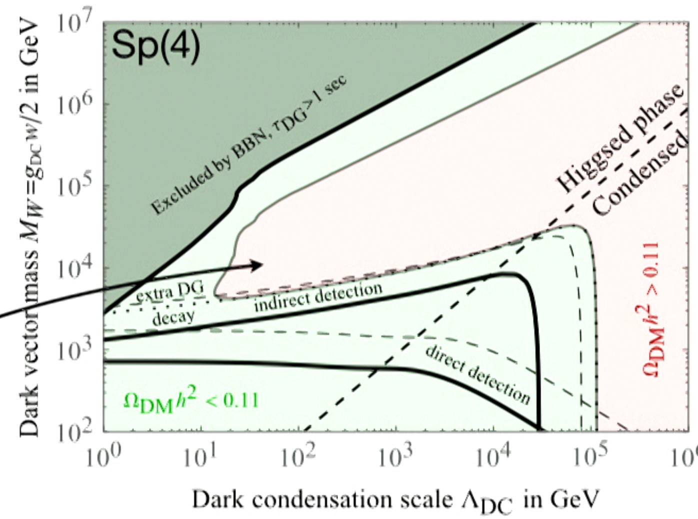
$$\mathcal{G}_\mu = \left(\begin{array}{c|cc} \mathcal{A}_\mu & \mathcal{X}^*_\mu/2 & \gamma_{N-2}\mathcal{X}_\mu/2 \\ \hline \mathcal{X}_\mu/2 & \mathcal{Z}_\mu/2 & \mathcal{W}_\mu/\sqrt{2} \\ \gamma_{N-2}\mathcal{X}^*/2 & -\mathcal{W}^*_\mu/\sqrt{2} & -\mathcal{Z}_\mu/2 \end{array}\right)$$

- ✦ Baryons are <u>not stable</u>: $\epsilon = \gamma \otimes \cdots \otimes \gamma$ decay to N/2 mesons

(Witten 1983)

- ✦ States with charge +2 <u>are stable</u>:
  - the elementary W
  - mesons $\mathcal{M} = \chi^T \cdot \gamma \cdot \chi$

    (equivalent to $\phi^T \cdot \gamma \cdot D_\mu \phi$)



perturbative annihilations:
the elementary W is DM

A fundamental of G_2

Group of octonion multiplications: $e_i \cdot e_j = -\delta_{ij} + O_{ijk} e_k$

The only exceptional group with unique breaking $G_2 \to SU(3)$ by $\phi \sim \square$

dim($\square$) = 7,

dim(G_2) = 14

- Spectrum: similar to SU(4) → SU(3)
  - s ~ singlet, A ~ Adj
  - complex W in 3 + $\bar{3}$, $m_W = g^2 w^2/3$; no Z_μ
- G_2 is real: no baryon number.

  Charge conjugation: $\mathcal{A}_{\rm real} \to -\mathcal{A}_{\rm real}, \quad \mathcal{A}_{\rm imag} \to \mathcal{A}_{\rm imag}, \quad \mathcal{W} \to -\overline{\mathcal{W}}$

  is preserved by $\langle \phi \rangle$ and becomes C of SU(3)
- There are cubic interactions $\epsilon_{\alpha\beta\gamma} \mathcal{W}^\alpha_\mu \mathcal{W}^\beta_\nu \mathcal{W}^\gamma_\rho$

  $\Im(\mathcal{WWW}) = \mathcal{WWW} - \overline{\mathcal{WWW}}$ is C-even, decays.

  $\Re(\mathcal{WWW}) = \mathcal{WWW} + \overline{\mathcal{WWW}}$ is C-odd, stable DM.

  Similar to K-$\bar{\text{K}}$ system: K_L with infinite lifetime

Summary: fundamental representations

Group	Global symmetry	DM candidate	DM Annihilation
$\mathrm{SU}(\mathcal{N})$	Dark baryon number	Baryon $\epsilon S^{\mathcal{N}} \cong \mathcal{W}^n$	Bohr-like – $1/\Lambda^2_{\mathrm{DC}}$
$\mathrm{SO}(\mathcal{N}_{\mathrm{even}})$	O-parity	1-ball $\epsilon \mathcal{G}^{\mathcal{N}/2} \cong \mathcal{W}\mathcal{A}^{(n-1)/2}$	$1/\Lambda^2_{\mathrm{DC}}$
$\mathrm{SO}(\mathcal{N}_{\mathrm{odd}})$	O-parity	0-ball $\epsilon \mathcal{S}\mathcal{G}^{(\mathcal{N}-1)/2} \cong \mathcal{A}^{n/2}$	$1/\Lambda^2_{\mathrm{DC}}$
$\mathrm{Sp}(\mathcal{N})$	Dark baryon number	Meson $\mathcal{S}\gamma\mathcal{S} \cong \mathcal{W}, \mathcal{X}\mathcal{X}$	Perturbative
G_2	Inner automorphism	Baryon $\epsilon \mathcal{S}\mathcal{G}^3, O\mathcal{S}^3 \cong \mathrm{Re}\,\mathcal{W}^3$	Bohr-like – $1/\Lambda^2_{\mathrm{DC}}$

- Many different models with different DM candidates
- DM is stabilized by accidental symmetries: different origin for each model

- For all these models there is a single phase, smooth limit $g \to 4\pi$
- General feature: strong DM annihilation $\to$ mass ~ 100 TeV

A symmetric of SU(N) → SU(N – 1)

Higgs phase:

- A, W, W*, Z, s as before
- $\tilde{\phi}$ ~ symmetric of SU(N – 1): additional scalars, play a crucial role!

Confinement of SU(N – 1):

- Baryons $\mathcal{B} = \epsilon \cdot \mathcal{W}^{\mathcal{N}-1}$ stable
- Di-baryons $\mathcal{D} = \epsilon_{\alpha_1 \cdots \alpha_{\mathcal{N}-1}} \epsilon_{\beta_1 \cdots \beta_{\mathcal{N}-1}} \tilde{\phi}^{\alpha_1 \beta_1} \ldots \tilde{\phi}^{\alpha_{\mathcal{N}-1} \beta_{\mathcal{N}-1}}$

  can be stable if light, otherwise $\mathcal{D} \to \mathcal{B}\mathcal{B}$

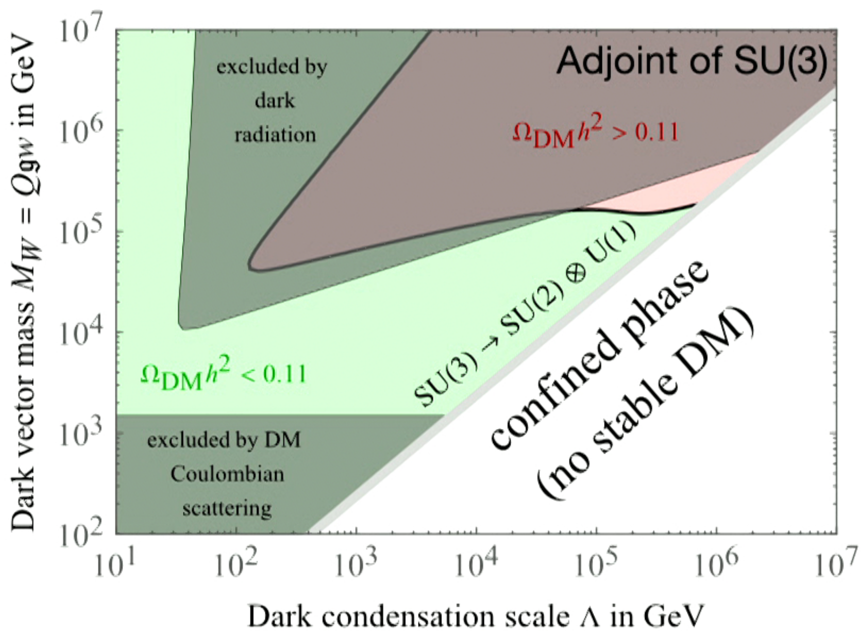
Confined phase:

- Di-baryons $\mathcal{D} = \epsilon_{\alpha_1 \cdots \alpha_{\mathcal{N}}} \epsilon_{\beta_1 \cdots \beta_{\mathcal{N}}} \Phi^{\alpha_1 \beta_1} \ldots \Phi^{\alpha_{\mathcal{N}} \beta_{\mathcal{N}}}$
- Baryons exist only for even N! (Φ has even number of indices)

  $\mathcal{B} = \epsilon_{\alpha_1 \cdots \alpha_{\mathcal{N}}} (\mathcal{G}\Phi)^{\alpha_1 \alpha_2} \cdots (\mathcal{G}\Phi)^{\alpha_{\mathcal{N}-1} \alpha_{\mathcal{N}}}$ No duality between phases!

An adjoint of SU(N)

- Higgs phase has an unbroken U(1): dark photon
  - Bounds on dark radiation from N_{eff}
  - Massless dark photon mediates Coulomb scattering of DM: various observations imply $m_{\text{DM}} \gtrsim \text{TeV} \times g_{\text{dark}}^{4/3}$
  - DM free-streaming during structure formation (weaker bound)



- Confined phase:

$$\mathscr{L} \supset f^{abc}\Phi^a\Phi^b\Phi^c$$

no stable DM candidate (unless cubic interaction forbidden by ad-hoc parity)

Summary

Low Battery
Your Mac will sleep soon unless plugged into a power outlet.
Close

- Scalar gauge theories can have a very rich phenomenology

Heavy DM Mesons Glue-balls Dark radiation
Freeze-out C-parity
Baryons Goldstone bosons
Recombination U(1) charge O-parity

- We performed an (almost) complete study of **SU(N)**, **SO(N)**, **Sp(N)**, and some exceptional groups
  with scalars in fundamental, symmetric, antisymmetric, adjoint

- Almost always, for reasons specific to each model,
  DM candidates stabilized by accidental symmetries

- Usually thermal DM at around 100 TeV, very few experimental bounds