pseudo-Nambu-Goldstone-boson

pNGB DM inspired by Grand Unification

Dark Matter

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The 2nd Workshop on Grand Unified Theories: Phenomenology and Cosmology at HIAS, UCAS, Xihu District, Hangzhou, April 17-22, 2025

Pseudo-Nambu-Goldstone dark matter from gauged $U(1)_{B-L}$ symmetry [Prototype]
Y. Abe, T. Toma, K. Tsumura
JHEP 05 (2020) 057 arXiv:2001.03954 [hep-ph]

Pseudo-Nambu-Goldstone Dark Matter Model Inspired by Grand Unification [GUT extension of $U(1)_{B-L}$]
Y. Abe, T. Toma, K. Tsumura, N. Yamatsu
Phys. Rev. D104, 035011 (2021) arXiv:2104.13523 [hep-ph]

Pseudo-Nambu-Goldstone Dark Matter from Non-Abelian Gauge Symmetry
H. Otsuka, T. Shimomura, K. Tsumura, Y. Uchida, N. Yamatsu
Phys. Rev. D106, 115033 (2022) arXiv:2210.08696 [hep-ph]

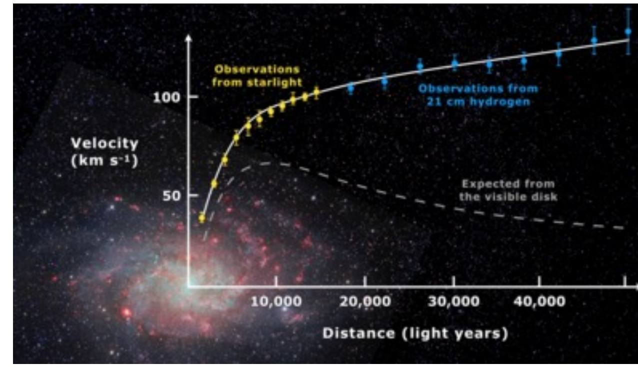
Pseudo-Nambu-Goldstone Dark Matter in SU(7) Grand Unification [GUT extension of $SU(2)_D$]
C.-W. Chiang, K. Tsumura, Y. Uchida, N. Yamatsu
Phys. Rev. D109, 055040 (2024) arXiv:2311.13753 [hep-ph]

Contents

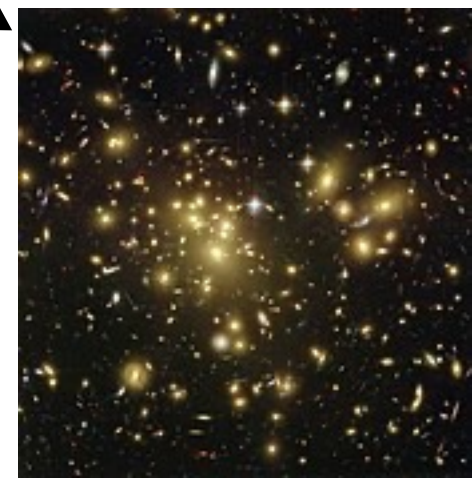
- Introduction of pNGB DM
- pNGB DM from U(1)$_{B-L}$
- pNGB DM from SO(10) Grand Unification
- pNGB DM from Dark SU(2)
- pNGB DM from SU(7) Grand Unification
- Summary

Evidences for DM

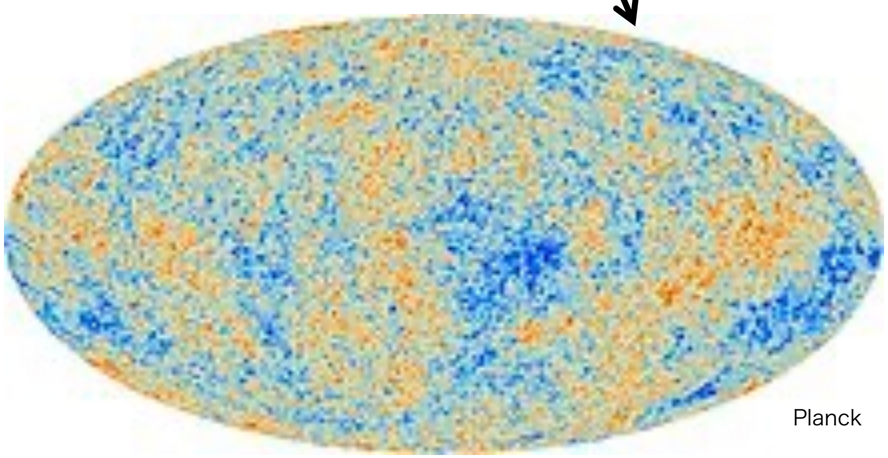
- Galaxy Rotation Curve
- Velocity Dispersion of Galaxies
- Galaxy Clusters and Gravitational Lensing
- Sky surveys and baryon acoustic oscillations
- Cosmic Microwave Background (CMB)
- Type Ia supernovae distance measurements
- Lyman-Alpha Forest
- Structure Formation



https://en.wikipedia.org/wiki/Galaxy_rotation_curve



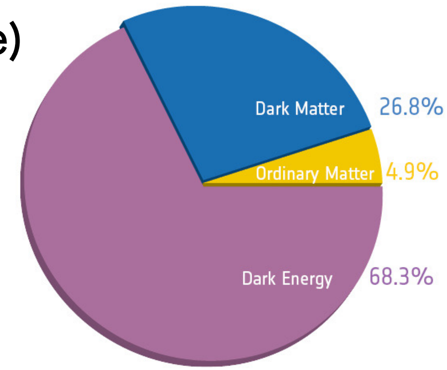
https://en.wikipedia.org/wiki/Dark_matter

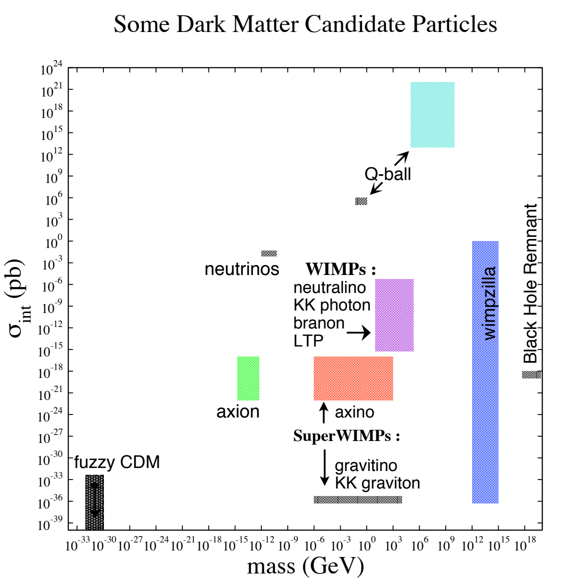


Planck

Nature of DM

- Stable (longer lifetime than the age of our universe)
- Electrically neutral
- 27% of energy density of our universe
- Non-relativistic (cold)





Many Candidates for DM

- ✓ Primordial Black Hole
- ✓ WIMP [Weakly Interacting Massive Particle]
- ✓ SIMP
- ✓ Axion, Axion cluster
- ✓ Soliton (EW-skyrmion, Q-ball, B-ball, …)
- ✓ Super Massive Relic (WIMPzilla, …)
- ✓ …

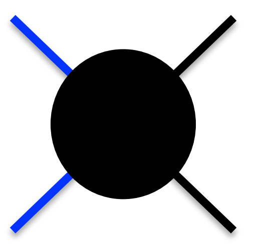
WIMP Dark Matter

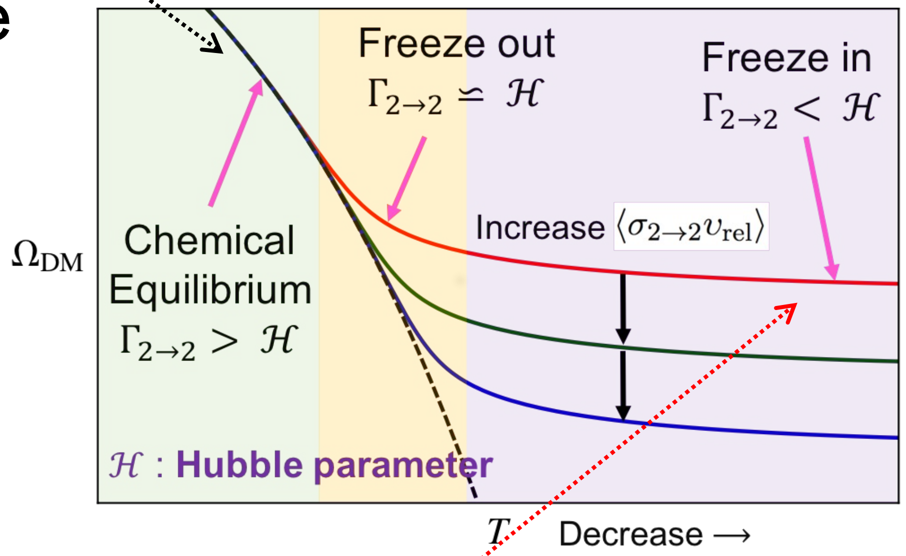
- DM Produced Thermally in Chemical Equilibrium

$$\dot{n} + 3Hn = -(n - n_{eq})\langle\sigma_{2\to2}v_{rel}\rangle$$

$$\Gamma_{2\to2} = n_{DM}\langle\sigma_{2\to2}v_{rel}\rangle$$

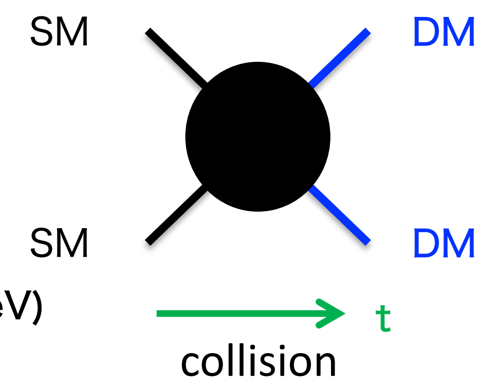
- Freeze out abundance





$$\langle\sigma_{2\to2}v_{rel}\rangle \equiv \frac{\alpha_{2\to2}^2}{M_{DM}^2} \Rightarrow \Omega_{DM} \simeq \frac{0.1\,\mathrm{pb}}{\langle\sigma_{2\to2}v_{rel}\rangle}$$

DM search

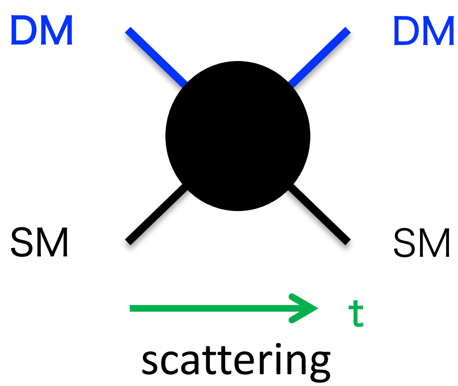


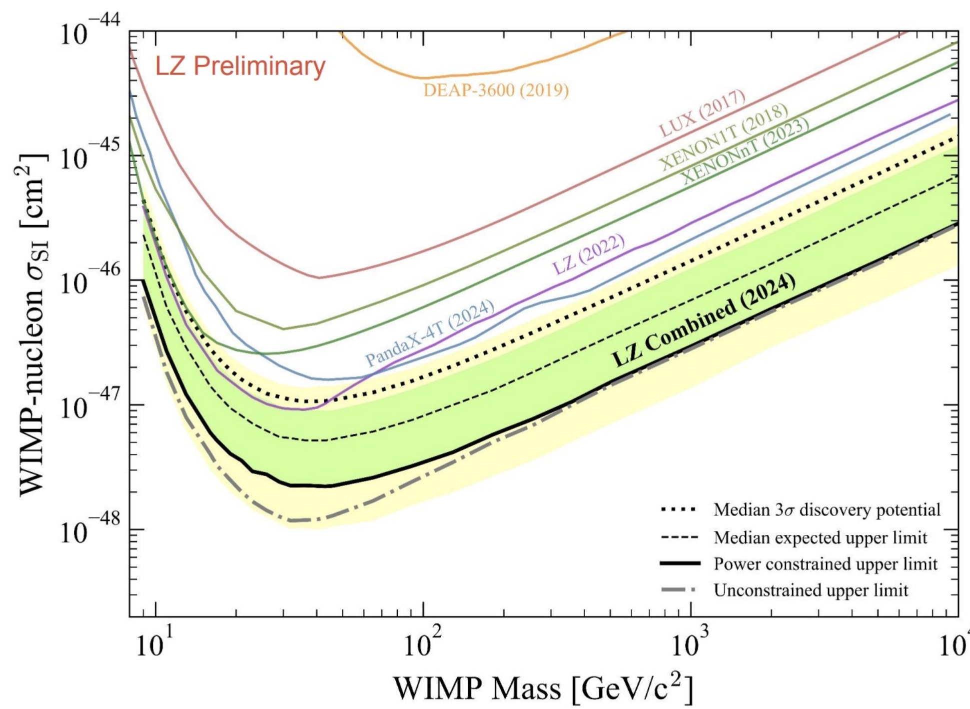
- **Collider Search of DM**

  SM particles collide and produce DMs (cf. LHC Energy 14TeV)

- **DM Direct Detection**

  DMs hit SM particles



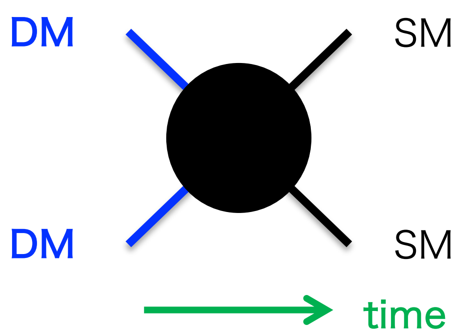


Cross sections bounds is getting severer,
while Freeze out cross section must be kept !!

pNGB DM

- SSB & soft breaking of Global Symmetry
- Derivative Interaction

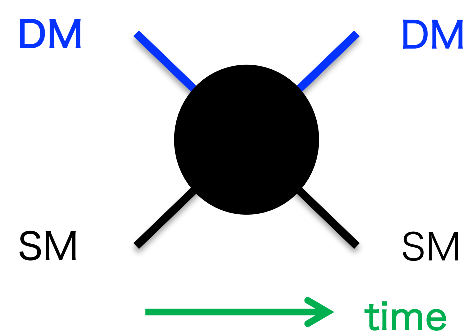
Freeze out



annihilation

$$E_{\rm ann} \sim 2M_{\rm DM}\, c^2$$

Direct Detection



scattering

$$E_{\rm recoil} \sim \frac{1}{2} M_{\rm DM} \underline{v_{\rm DM}^2} \left(\frac{4M_{\rm DM}M_N}{M_{\rm DM}^2 + M_N^2} \right)$$

velocity suppression

Natural suppression for DD while keeping annihilation

DM-DM-Higgs int. in NL rep.

Soft U(1)$_S$ breaking

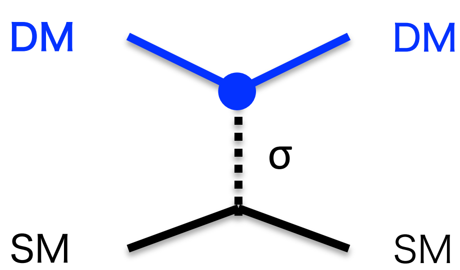
- Original Model : $V(H,S) = -m_H^2|H|^2 - m_S^2|S|^2 - \left(m_{\rm DM}^2 S^2 + {\rm h.c.}\right) + \lambda_H|H|^4 + \frac{\lambda_S}{2}|S|^4 + \lambda_{HS}|H|^2|S|^2$

- Non-linear rep. $S = \frac{v_S + \sigma}{\sqrt{2}}\, e^{i\pi_{\rm DM}/v_S}$

- DM-DM-Higgs interaction in NL rep.

$$\mathcal{L} = +\frac{1}{2}\left(1 + \frac{\sigma}{v_S}\right)^2 \left(\partial_\mu \pi_{\rm DM}\, \partial^\mu \pi_{\rm DM} - m_{\rm DM}^2 \pi_{\rm DM}^2\right) + \mathcal{O}(\pi^4)$$

from Kinetic term   from potential



No interaction if DM satisfies EOM (On-shell condition)

Cons of Original model

C. Gross, O. Lebedev, T. Toma, *Phys.Rev.Lett. 119 (2017) 19, 191801, Cancellation Mechanism for Dark-Matter–Nucleon Interaction*

- pNGB Mass is introduced by hand!!

  In general, there are more U(1) breaking terms

$$
\begin{aligned}
V(S) = &- \mu_S^2 (S^* S) + \lambda_S (S^* S)^2 \\
&+ \{ m_S^2 S^2 + \kappa S^3 + \kappa' (S^* S) S + \lambda S^4 + \lambda' (S^* S) S^2 + \mathrm{H.c.} \}
\end{aligned}
$$

Mass — Forbidden by Z_2 — Hard breaking of U(1)

= Z_2 symmetric model with softly broken U(1) symmetry

- Domain Wall problem (Z_2 sym. should not be broken spontaneously)

pNGB DM from $U(1)_{B\text{-}L}$

A Model

Pseudo-Nambu-Goldstone dark matter from gauged $U(1)_{B-L}$ symmetry
Y. Abe, T. Toma, K. Tsumura JHEP 05 (2020) 057 arXiv:2001.03954 [hep-ph]
Pseudo-Goldstone dark matter in a gauged B-L extended standard model
N. Okada, D. Raut, Q. Shafi PRD 103, 055024 (2021) arXiv:2001.05910 [hep-ph]

● Gauged $U(1)_{B-L}$

(motivated by neutrino mass a la seesaw mechanism)

	Q_L	L	u^c_R	d^c_R	e^c_R	ν^c_R	H	S_1	S_2
$SU(3)_c$	$\mathbf{3}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$SU(2)_W$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)_Y$	$+1/6$	$-1/2$	$-2/3$	$+1/3$	$+1$	0	$+1/2$	0	0
$U(1)_{B-L}$	$+1/3$	-1	$-1/3$	$-1/3$	$+1$	$+1$	0	$+1$	$+2$

● Key idea of the model building

$$V_{\rm sym} = V_1(S_1^* S_1) + V_2(S_2^* S_2)$$

$U(1)_1 \times U(1)_2 \ \rightarrow \ \text{None}$ one is absorbed by Z_{B-L} & the other is exact massless NGB

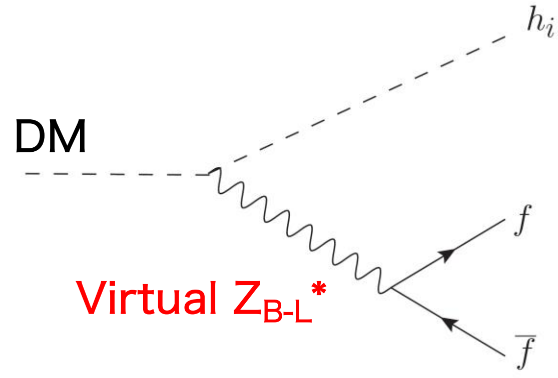
$\Downarrow \ \kappa$

$U(1)_{\rm B-L} \ \rightarrow \ \text{None}$ with κ → one is absorbed by Z_{B-L} & the other is massive pNGB

$$V_{\text{soft-breaking}} = \kappa\, S_2^* S_1^2 + \text{H.c.} \quad \rightarrow \quad \frac{1}{2} m_{\rm DM}^2 \pi_{\rm DM}^2 \quad (m_{\rm DM}^2 \propto \kappa)$$

Through κ, $U(1)_1$ and $U(1)_2$ are identified as a (global) subgroup of $U(1)_{B-L}$

Long-Lived DM



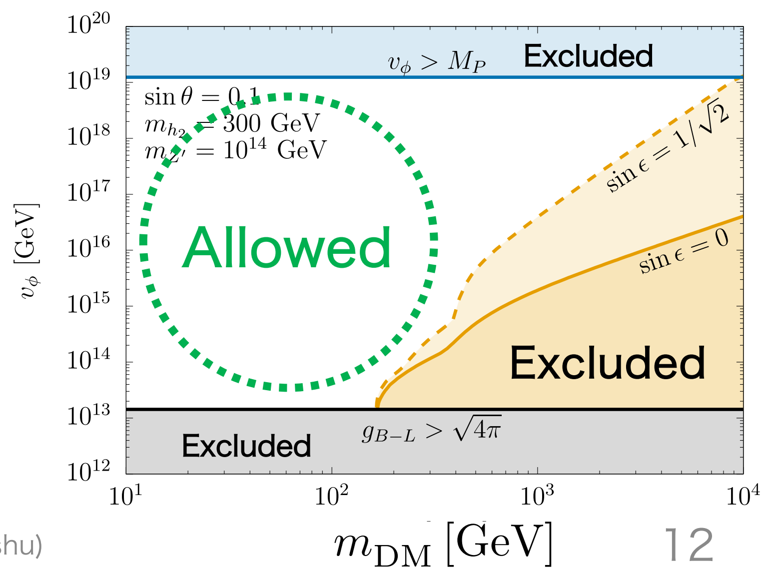
- pNGB DM decays to SM particles
  via super-heavy Z_{B-L}

- DM lifetime $\simeq \dfrac{1}{M_{Z_{\text{B-L}}}^4} > 10^{27}\,\text{sec}$

  Stability (Longevity) constraint

⇨ $M_{Z_{\text{B-L}}} > 10^{13}\,\text{GeV}$ for $M_{\text{DM}} < 1\,\text{TeV}$

Imply Very High New Physics Scale

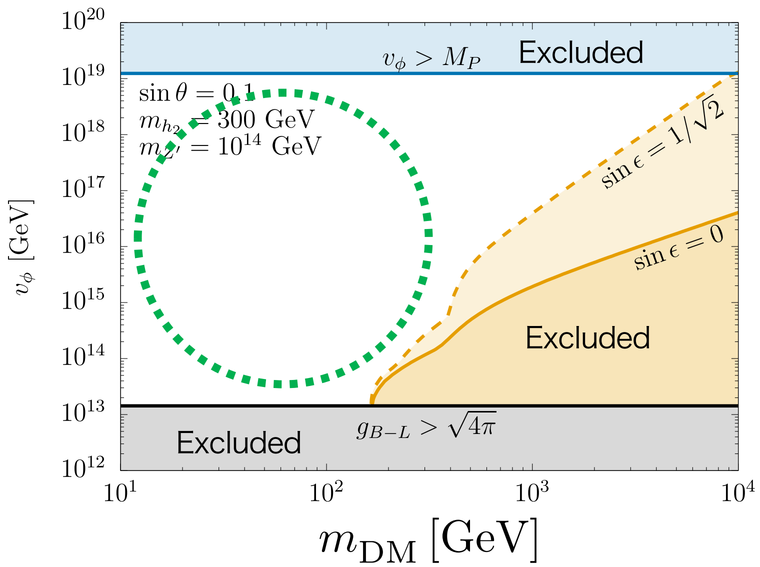


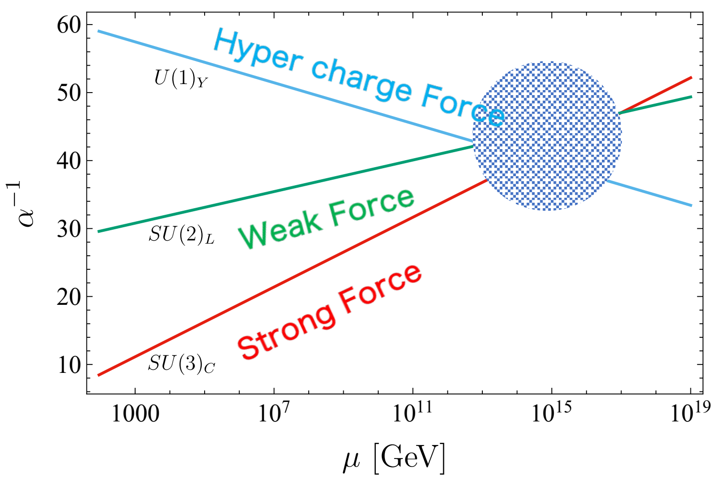
pNGB DM from SO(10) GUT

Does pNGB DM imply GUT?

- High Energy Scale is needed for DM Longevity

$$M_{Z_{\text{B-L}}} > 10^{13}\,\text{GeV} \quad \text{for} \quad M_{\text{DM}} < 1\,\text{TeV}$$





- GUT naturally predict Ultra High Energy Scale

pNGB DM in SO(10) GUT

- Model

Pseudo-Nambu-Goldstone Dark Matter Model Inspired by Grand Unification
Y. Abe, T. Toma, K. Tsumura, N. Yamatsu
Phys. Rev. D104, 035011 (2021) hep-ph/2104.13523

	$\Psi_{\mathbf{16}}$						$\Phi_{\mathbf{10}}$	$\Phi_{\mathbf{16}}$	$\Phi_{\overline{\mathbf{126}}}$
$SO(10)$	$\mathbf{16}$						$\mathbf{10}$	$\mathbf{16}$	$\overline{\mathbf{126}}$
	$\psi_{(\mathbf{4},\mathbf{2},\mathbf{1})}$		$\psi_{(\overline{\mathbf{4}},\mathbf{1},\mathbf{2})}$				$\phi_{(\mathbf{1},\mathbf{2},\mathbf{2})}$	$\phi_{(\overline{\mathbf{4}},\mathbf{1},\mathbf{2})}$	$\phi_{(\overline{\mathbf{10}},\mathbf{1},\mathbf{3})}$
$G_{\rm PS}$	$(\mathbf{4},\mathbf{2},\mathbf{1})$		$(\overline{\mathbf{4}},\mathbf{1},\mathbf{2})$				$(\mathbf{1},\mathbf{2},\mathbf{2})$	$(\overline{\mathbf{4}},\mathbf{1},\mathbf{2})$	$(\overline{\mathbf{10}},\mathbf{1},\mathbf{3})$
	Q_L	L	u_R^c	d_R^c	e_R^c	ν_R^c	H	S	Φ
$SU(3)_c$	$\mathbf{3}$	$\mathbf{1}$	$\overline{\mathbf{3}}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$SU(2)_L$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)_Y$	$+1/6$	$-1/2$	$-2/3$	$+1/3$	$+1$	0	$+1/2$	0	0
$U(1)_{B-L}$	$+1/3$	-1	$-1/3$	$-1/3$	$+1$	$+1$	0	$+1$	$+2$

$G_{\rm PS} = SU(4)_C \times SU(2)_L \times SU(2)_R \supset G_{\rm SM} \times U(1)_{\rm B-L}$

✓ Symmetry breaking

$$SO(10) \longrightarrow G_{\rm PS} \longrightarrow G_{\rm SM} \longrightarrow SU(3)_C \times U(1)_{\rm EM}$$

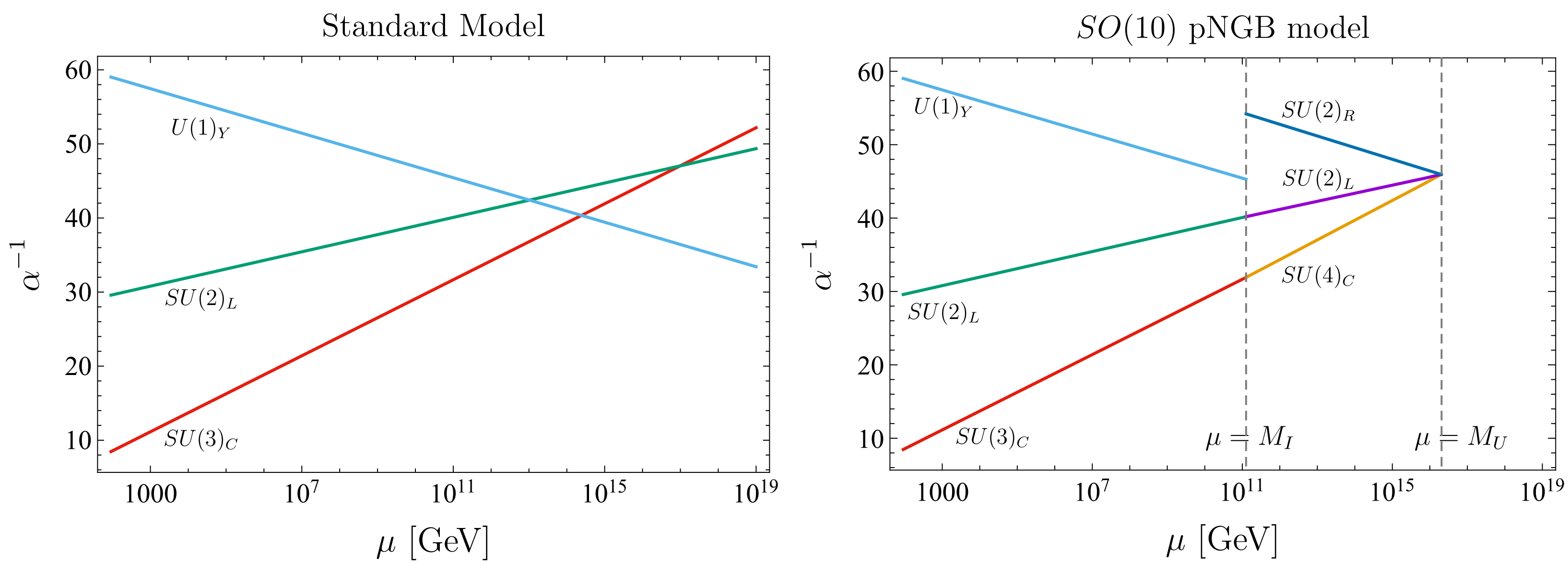
$\langle \Phi_{\mathbf{210}} \rangle \sim M_{\rm GUT}$ — Proton stability

$\langle \Phi_{\overline{\mathbf{126}}} \rangle \sim M_{\rm I}$ — DM longevity

$\langle \Phi_{\mathbf{10}} \rangle \sim M_{\rm EW}$ EW sym. breaking

Predictions of SO(10) pNGB DM

- Unification of Interaction Strength

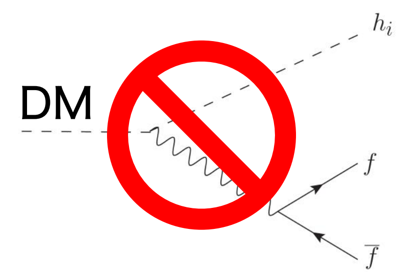


In SO(10) pNGB DM model, Unification is Requirement !!

→ predictions : $M_I = 1.3 \times 10^{11}\,\text{GeV}, M_U = 2.1 \times 10^{16}\,\text{GeV}, g = 0.38\,\text{at}\,M_I$

DM longevity   Proton stability   DM abundance

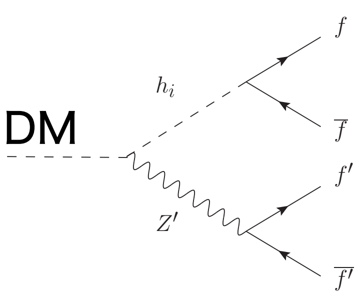
Decay of SO(10) pNGB DM

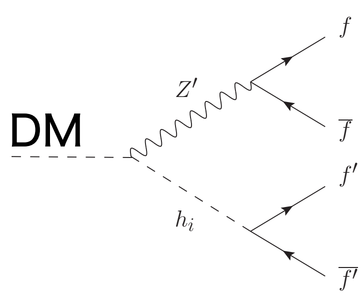


- Low Intermediate scale M_I
  → 3 body decay must be forbidden by kinematics

$$M_{\rm DM} < \sum_{n=1}^{3} M_{\rm final,n}$$

- 4 body decays

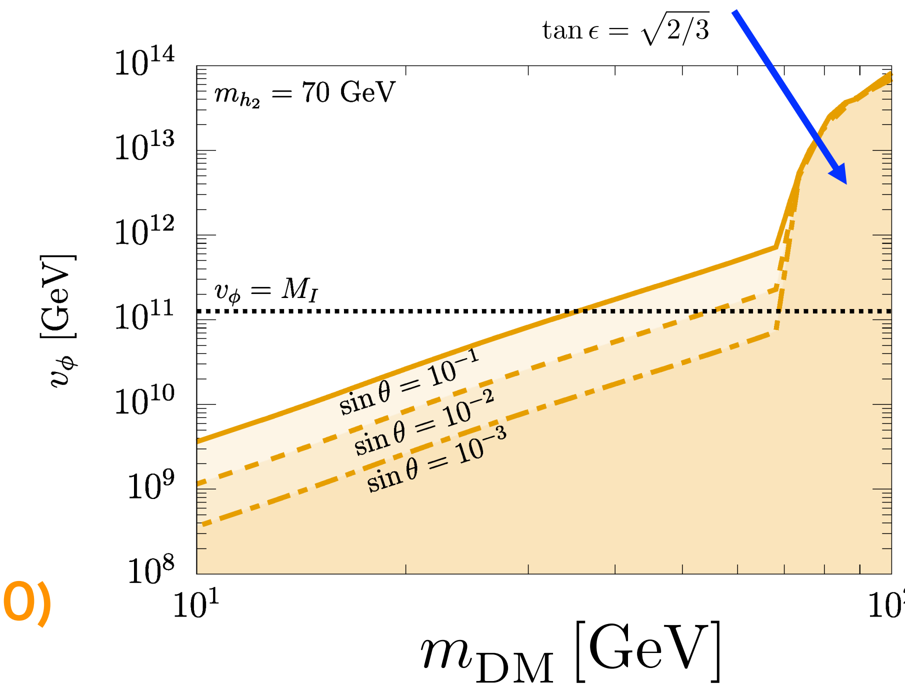




$$M_{\rm DM} \lesssim 70\,{\rm GeV}$$

Light DM is implied from SO(10)

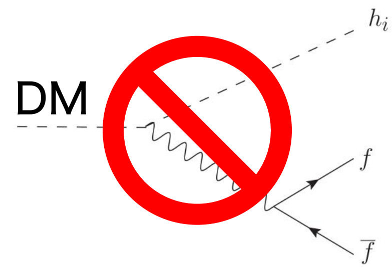
Kinetic mixing is predicted by SO(10)



Decay of SO(10) pNGB DM

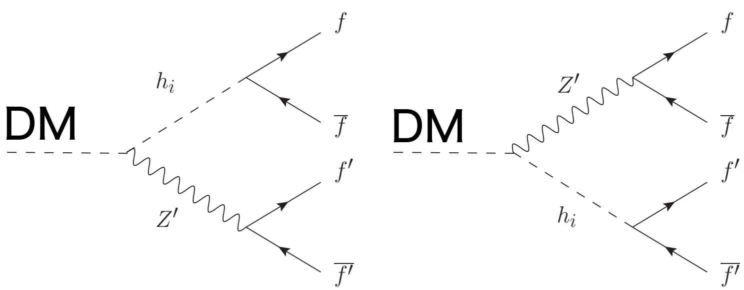
- Low Intermediate scale M_I

  → 3 body decay must be forbidden by kinematics



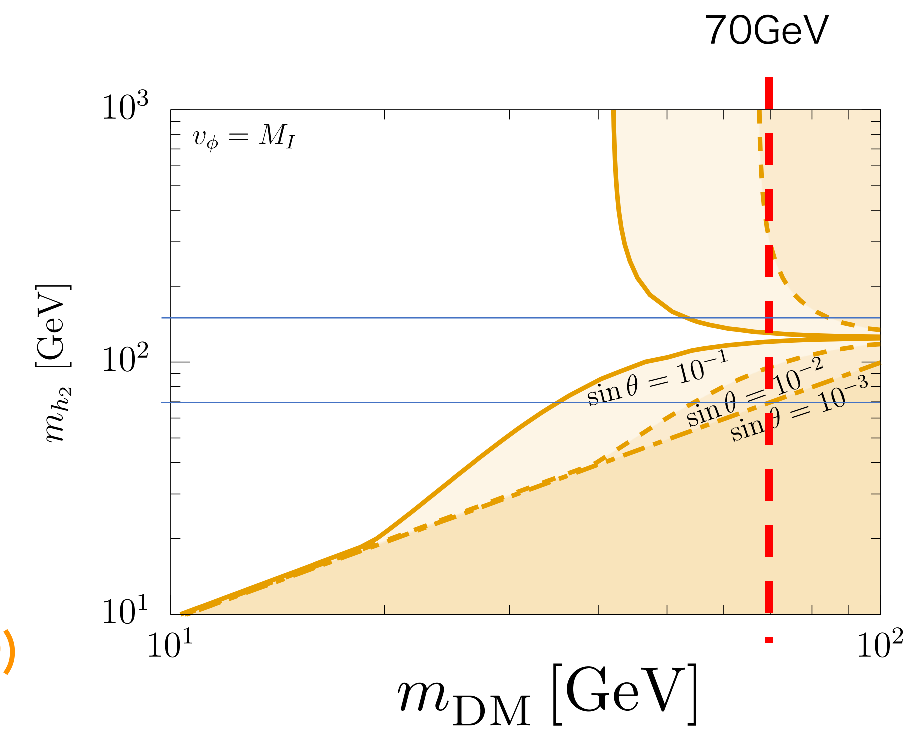
$$M_{\rm DM} < \sum_{n=1}^{3} M_{\rm final,n}$$

- 4 body decays



$$M_{\rm DM} \lesssim 70\,{\rm GeV}$$

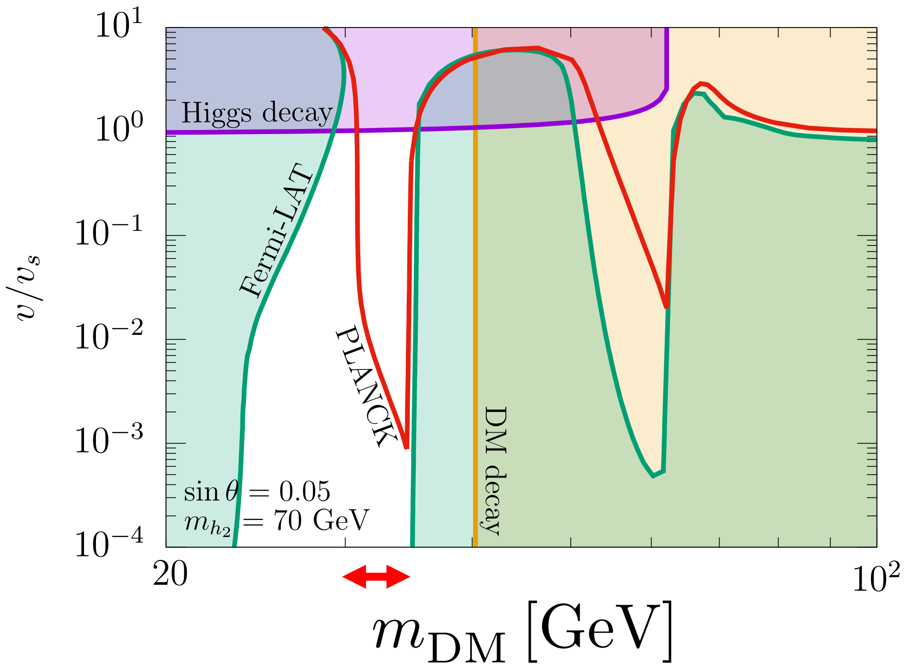
Light DM is implied from SO(10)



Relic Abundance & Constraints

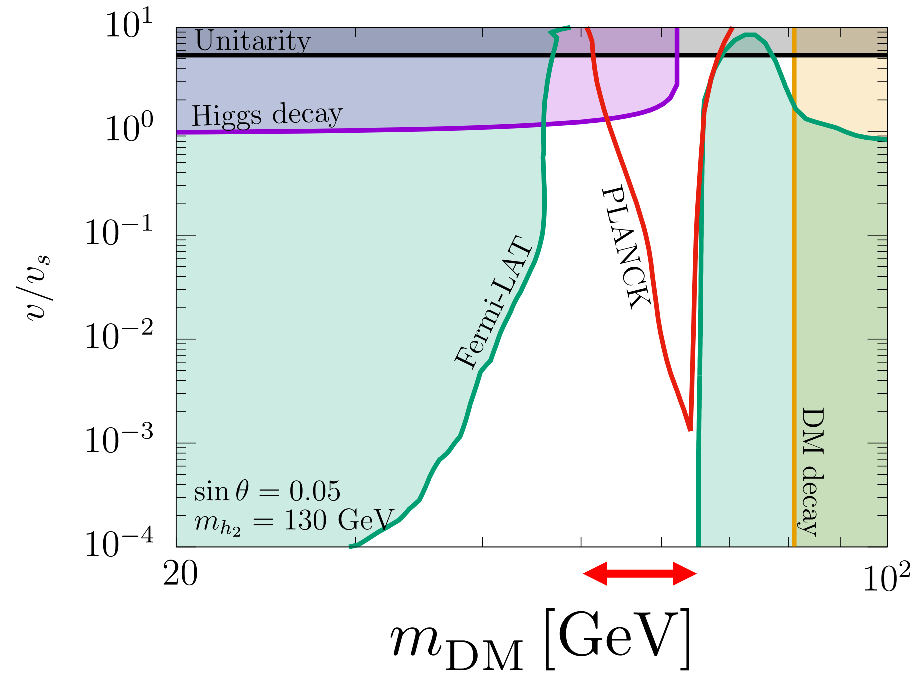
- Narrow DM mass window

M_{h2}=70GeV



30-35GeV

M_{h2}=130GeV



50-65GeV

Other sym breaking patterns

- $G_{GUT} \to G_I \to G_{SM}$

$$G_{\rm PS} = SU(4)_C \times SU(2)_L \times SU(2)_R \supset G_{\rm SM} \times U(1)_{\rm B-L}$$

$$G_{\rm LR} = SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \supset G_{\rm SM} \times U(1)_{\rm B-L}$$

Group G_I	Scalars at $\mu = M_I$	b_j	$\log_{10}(M/1[\mathrm{GeV}])$ M_I	$\log_{10}(M/1[\mathrm{GeV}])$ M_U	α_U^{-1}	
$G_{\rm PS}$ <210>	$(\mathbf{1},\mathbf{2},\mathbf{2})_{\mathbf{10}}$, $(\overline{\mathbf{4}},\mathbf{1},\mathbf{2})_{\mathbf{16}}$, $(\overline{\mathbf{10}},\mathbf{1},\mathbf{3})_{\overline{\mathbf{126}}}$	$\begin{pmatrix} b_{4C} \\ b'_{2L} \\ b_{2R} \end{pmatrix} = \begin{pmatrix} -\frac{22}{3} \\ -3 \\ +\frac{13}{3} \end{pmatrix}$	11.10 ± 0.08	16.31 ± 0.15	45.92 ± 0.50	◎
$G_{\rm PS} \times \underline{D}$ (= Z_2) <54>	$(\mathbf{1},\mathbf{2},\mathbf{2})_{\mathbf{10}}$, $(\mathbf{4},\mathbf{2},\mathbf{1})_{\mathbf{16}}$, $(\overline{\mathbf{4}},\mathbf{1},\mathbf{2})_{\mathbf{16}}$, $(\overline{\mathbf{10}},\mathbf{1},\mathbf{3})_{\overline{\mathbf{126}}}$, $(\mathbf{10},\mathbf{3},\mathbf{1})_{\overline{\mathbf{126}}}$	$\begin{pmatrix} b_{4C} \\ b'_{2L} \\ b_{2R} \end{pmatrix} = \begin{pmatrix} -4 \\ +\frac{13}{3} \\ +\frac{13}{3} \end{pmatrix}$	13.71 ± 0.03	$\underline{15.22 \pm 0.04}$ Rapid proton decay	40.82 ± 0.13	×
$G_{\rm LR}$ <45>	$(\mathbf{1},\mathbf{2},\mathbf{2},0)_{\mathbf{10}}$, $(\mathbf{1},\mathbf{1},\mathbf{2},1)_{\mathbf{16}}$, $(\mathbf{1},\mathbf{1},\mathbf{3},2)_{\overline{\mathbf{126}}}$	$\begin{pmatrix} b'_{3C} \\ b'_{2L} \\ b_{2R} \\ b_{B-L} \end{pmatrix} = \begin{pmatrix} -7 \\ -3 \\ -\frac{13}{6} \\ +\frac{23}{4} \end{pmatrix}$	$\underline{8.57 \pm 0.06}$ Rapid DM decay	16.64 ± 0.13	46.13 ± 0.41	×
$G_{\rm LR} \times \underline{D}$ <210>	$(\mathbf{1},\mathbf{2},\mathbf{2},0)_{\mathbf{10}}$, $(\mathbf{1},\mathbf{1},\mathbf{2},1)_{\mathbf{16}}$, $(\mathbf{1},\mathbf{2},\mathbf{1},1)_{\mathbf{16}}$, $(\mathbf{1},\mathbf{1},\mathbf{3},2)_{\overline{\mathbf{126}}}$, $(\mathbf{1},\mathbf{3},\mathbf{1},-2)_{\overline{\mathbf{126}}}$	$\begin{pmatrix} b'_{3C} \\ b'_{2L} \\ b_{2R} \\ b_{B-L} \end{pmatrix} = \begin{pmatrix} -7 \\ -\frac{13}{6} \\ -\frac{13}{6} \\ +\frac{15}{2} \end{pmatrix}$	$\underline{10.11 \pm 0.04}$ Rapid DM decay	15.57 ± 0.09	43.38 ± 0.30	×

If DM is stable, M_I can be lower.

pNGB DM from dark SU(2)

SU(2)$_D$ Model

- Can UV-complete pNGB DM be stable?
- Idea : Replace U(1)$_{B\text{-}L}$ by SU(2)$_D$
  → Exact (Dark) Custodial symmetry
- Straightforward extension of U(1)$_{B\text{-}L}$ model

S$_1$ S$_2$

	Q_L	L	u_R^c	d_R^c	e_R^c	ν_R^c	H	Σ_2	Σ_3
$SU(3)_c$	$\mathbf{3}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$SU(2)_W$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)_Y$	$+1/6$	$-1/2$	$-2/3$	$+1/3$	$+1$	0	$+1/2$	0	0
$SU(2)_D$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{3}$

SU(2)$_D$ gauge symmetry

$$\begin{cases} H \rightarrow H \\ \Sigma_2 \rightarrow U_D \Sigma_2 \\ \Sigma_3 \rightarrow U_D \Sigma_3 U_D^\dagger \end{cases}$$

Trivial rep. (SM Higgs does not transform)

Fundamental rep.

Adjoint rep.

Dark custodial symmetry

- Without "κ term" (no coupling btw Σ_2 & Σ_3)

$$V(\Sigma_2,\Sigma_3) = -\frac{\mu_2^2}{2}\mathrm{Tr}\left(\Sigma_2^\dagger\Sigma_2\right) - \frac{1}{2}\mu_3^2\mathrm{Tr}\left(\Sigma_3^2\right) + \frac{\lambda_2}{4}\left(\mathrm{Tr}\left(\Sigma_2^\dagger\Sigma_2\right)\right)^2 + \frac{1}{4}\lambda_3\mathrm{Tr}\left(\Sigma_3^2\right)^2 + \frac{1}{2}\lambda_{23}\mathrm{Tr}\left(\Sigma_2^\dagger\Sigma_2\right)\mathrm{Tr}\left(\Sigma_3^2\right)$$

$SU(2)_{2L}$ x $SU(2)_{2R}$ x $SU(2)_3$ global symmetries
$$\begin{cases} \Sigma_2 \to U_{L2}\,\Sigma_2\,U_{R2}{}^\dagger \\ \Sigma_3 \to U_3\,\Sigma_3\,U_3{}^\dagger \end{cases}$$

Enhanced global symmetry → unbroken global $SU(2)_V$ after SSB

gauged

with "κ term" $\quad \kappa\, S_2^* S_1^2 \quad \Rightarrow \quad \kappa\,\mathrm{Tr}(\sigma_3\,\Sigma_2^\dagger\Sigma_3\Sigma_2)$

$SU(2)_L$ x $U(1)_R$ → unbroken global $U(1)_V$ [DM is stable]

pNGB DM from SU(7) GUT

Symmetry breaking patterns

- Embedding G_{SM} x **SU(2)$_D$** into GUT

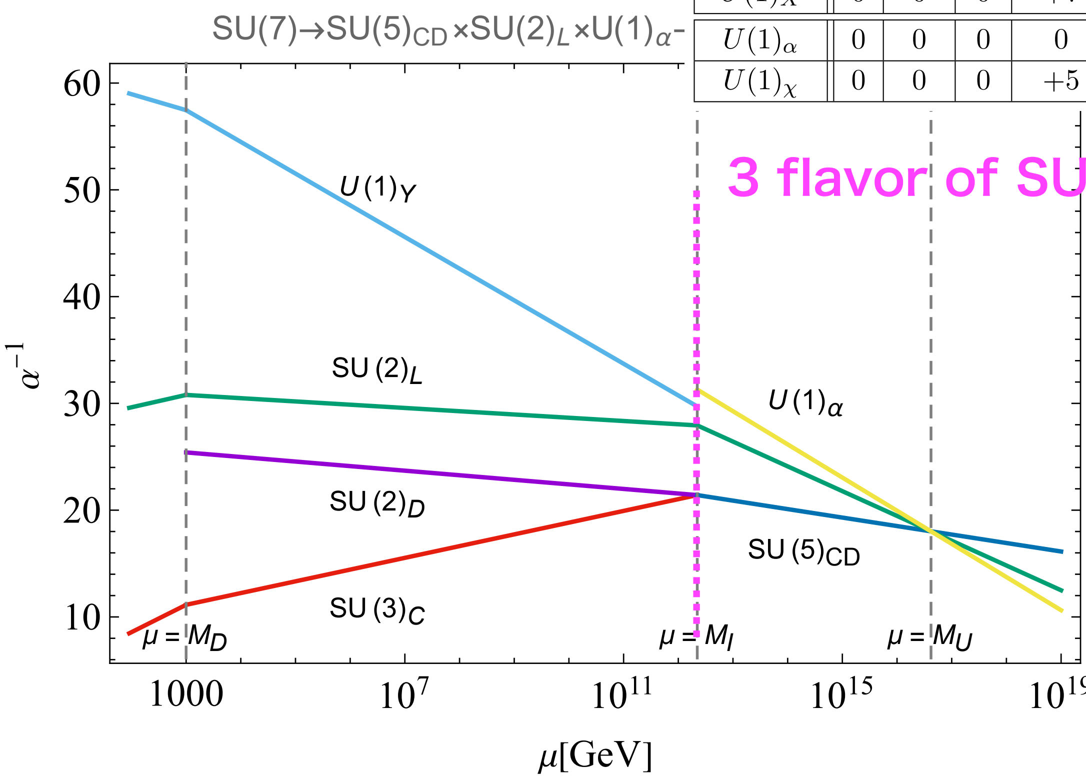
$$SU(7) \xrightarrow[M_{GUT}]{} \begin{cases} G_{521} := SU(5)_{GG} \times SU(2)_D \times U(1)_X \\ G_{341} := SU(3)_C \times SU(4)_{LD} \times U(1)_a \\ G'_{521} := SU(5)_{CD} \times SU(2)_L \times U(1)_\alpha \end{cases}$$

$$\xrightarrow[M_I]{} \begin{cases} \underbrace{SU(3)_C \times SU(2)_L \times U(1)_Y}_{\text{subgroups of } SU(5)_{GG}} \times SU(2)_D \times U(1)_X \\ SU(3)_C \times \underbrace{SU(2)_L \times SU(2)_D \times U(1)_b}_{\text{subgroups of } SU(4)_{LD}} \times U(1)_a \\ \underbrace{SU(3)_C \times SU(2)_D \times U(1)_\chi}_{\text{subgroups of } SU(5)_{CD}} \times SU(2)_L \times U(1)_\alpha \end{cases}$$

$$= SU(3)_C \times SU(2)_L \times U(1)_Y \times \underline{SU(2)_D} \times U(1)_X,$$

Extra matter

	$\Psi^{(m)}_{\mathbf{48}}$										
$SU(7)$	$\mathbf{48}$										
	$\psi_{(\mathbf{24},\mathbf{1})(0)}$					$\psi_{(\mathbf{1},\mathbf{3})(0)}$	$\psi_{(\mathbf{1},\mathbf{1})(0)}$	$\psi_{(\mathbf{5},\mathbf{2})(7)}$		$\psi_{(\overline{\mathbf{5}},\mathbf{2})(-7)}$	
G'_{521}	$(\mathbf{24},\mathbf{1})(0)$					$(\mathbf{1},\mathbf{3})(0)$	$(\mathbf{1},\mathbf{1})(0)$	$(\mathbf{5},\mathbf{2})(7)$		$(\overline{\mathbf{5}},\mathbf{2})(-7)$	
	$\tilde{g}$	$\tilde{W}'$	$\tilde{B}$	d'_D	d'^c_D	$\tilde{W}$	$\tilde{B}'$	$\tilde{X}$	L'_D	$\tilde{X}^c$	L'^c_D
$SU(3)_C$	$\mathbf{8}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$\overline{\mathbf{3}}$	$\mathbf{1}$
$SU(2)_L$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$
$U(1)_Y$	0	0	0	$-1/3$	$+1/3$	0	0	$-5/6$	$+1/2$	$+5/6$	$-1/2$
$SU(2)_D$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$
$U(1)_X$	0	0	0	$+7$	-7	0	0	0	-7	0	$+7$
$U(1)_\alpha$	0	0	0	0	0	0	0	$+7$	$+7$	-7	-7
$U(1)_\chi$	0	0	0	$+5$	-5	0	0	$+2$	-3	-2	$+3$



3 flavor of $SU(5)_{CD}$ adjoint matter @ M_I

→ Successful GCU

& ν mass generation

& p stability

$$\begin{cases} M_I & = 2 \times 10^{12}\ \mathrm{GeV} \\ M_U & = 4 \times 10^{16}\ \mathrm{GeV} \\ \alpha_U^{-1} & = 18.0 \end{cases}$$

DM (in)stablility

- **U(1)$_V$ violation** caused by <u>Yukawa int</u>

  Similarly to the SM

- U(1)$_V$ can be restored by appropriate **Z_2 parity**

  Eliminate unwanted Yukawa

Gauge

	A_μ		
$SU(7)$	$\mathbf{48}$		
	G'_μ	W_μ	B'_μ
G'_{521}	$(\mathbf{24},\mathbf{1})(0)$	$(\mathbf{1},\mathbf{3})(0)$	$(\mathbf{1},\mathbf{1})(0)$

Higgs (odd: Φ_{48})

	$\Phi_{\mathbf{7}}$	$\Phi_{\mathbf{21}}$	$\Phi_{\mathbf{35}}$	Φ_{48}	
$SU(7)$	$\mathbf{7}$	$\mathbf{21}$	$\mathbf{35}$	$\mathbf{48}$	
	$\phi_{(\mathbf{5},\mathbf{1})(+2)}$	$\phi_{(\mathbf{10},\mathbf{1})(+4)}$	$\phi_{(\mathbf{10},\mathbf{2})(-1)}$	$\phi_{(\mathbf{1},\mathbf{1})(0)}$	$\phi_{(\mathbf{24},\mathbf{1})(0)}$
G'_{521}	$(\mathbf{5},\mathbf{1})(+2)$	$(\mathbf{10},\mathbf{1})(+4)$	$(\mathbf{10},\mathbf{2})(-1)$	$(\mathbf{1},\mathbf{1})(0)$	$(\mathbf{24},\mathbf{1})(0)$

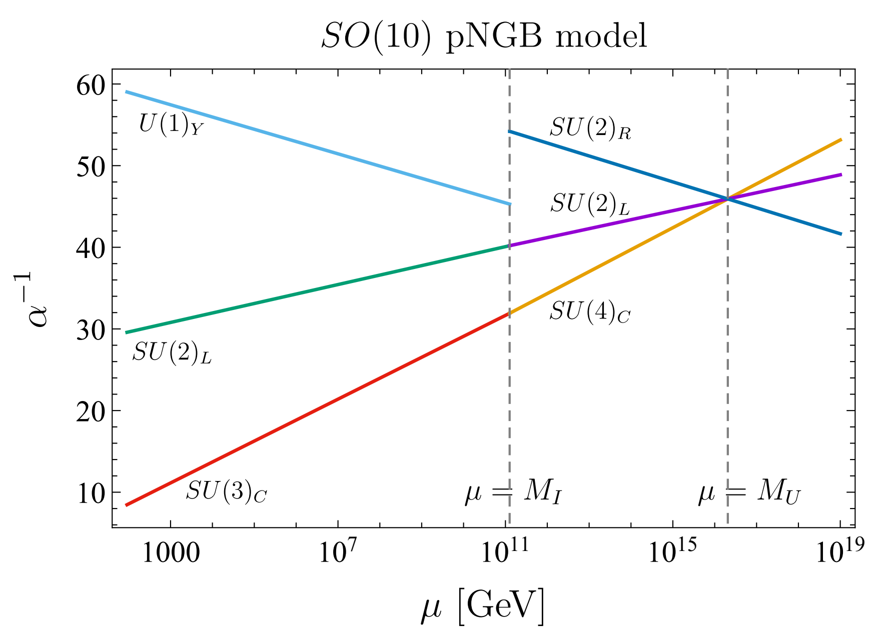
Fermion (odd: $\Psi^{(m)}_{\mathbf{48}}$)

	$\Psi^{(m)}_{\mathbf{21}}$			$\Psi^{(n)}_{\bar{\mathbf{7}}}$		$\Psi^{(m)}_{\mathbf{48}}$				
$SU(7)$	$\mathbf{21}$			$\bar{\mathbf{7}}$		$\mathbf{48}$				
	$\psi_{(\mathbf{5},\mathbf{2})(-3)}$	$\psi_{(\mathbf{10},\mathbf{1})(4)}$	$\psi_{(\mathbf{1},\mathbf{1})(-10)}$	$\psi_{(\bar{\mathbf{5}},\mathbf{1})(-2)}$	$\psi_{(\mathbf{1},\mathbf{2})(5)}$	$\psi_{(\mathbf{24},\mathbf{1})(0)}$	$\psi_{(\mathbf{1},\mathbf{3})(0)}$	$\psi_{(\mathbf{1},\mathbf{1})(0)}$	$\psi_{(\mathbf{5},\mathbf{2})(7)}$	$\psi_{(\bar{\mathbf{5}},\mathbf{2})(-7)}$
G'_{521}	$(\mathbf{5},\mathbf{2})(-3)$	$(\mathbf{10},\mathbf{1})(4)$	$(\mathbf{1},\mathbf{1})(-10)$	$(\bar{\mathbf{5}},\mathbf{1})(-2)$	$(\mathbf{1},\mathbf{2})(5)$	$(\mathbf{24},\mathbf{1})(0)$	$(\mathbf{1},\mathbf{3})(0)$	$(\mathbf{1},\mathbf{1})(0)$	$(\mathbf{5},\mathbf{2})(7)$	$(\bar{\mathbf{5}},\mathbf{2})(-7)$

Summary

Summary

- pNGB DM naturally avoid DM direct detection constraint
- pNGB DM is derived from UV complete theories
  - $U(1)_{B\text{-}L}$ [long lived pNGB DM]
    - ➔ large scale (GUT scale?)
  - $SU(2)_D$ [stable pNGB DM]
- These models are embedded in GUT theories
  - $U(1)_{B\text{-}L}$ → SO(10)
    - ➔ low mass DM
  - $SU(2)_D$ → SU(7)



Backup

SSB and Explicit breaking

- Yukawa interactions

$$
\begin{aligned}
&y_u \overline{Q}_L \widetilde{H} u_R + y_d \overline{Q}_L H d_R \\
&= \frac{y_u + y_d}{2} \overline{Q}_L \begin{pmatrix} \widetilde{H} & H \end{pmatrix} \begin{pmatrix} u_R & d_R \end{pmatrix} + \frac{y_u - y_d}{2} \overline{Q}_L \begin{pmatrix} \widetilde{H} & H \end{pmatrix} \begin{pmatrix} u_R & -d_R \end{pmatrix} \\
&= \frac{y_u + y_d}{2} \overline{Q}_L \Sigma Q_R + \frac{y_u - y_d}{2} \overline{Q}_L \Sigma \tau^3 Q_R
\end{aligned}
$$

$SU(2)_L$ x $SU(2)_R$ invariant

$$\overline{Q}_L \Sigma Q_R \to (\overline{Q}_L U_L^\dagger)(U_L \Sigma U_R^\dagger)(U_R Q_R)$$

SSB : $\langle \Sigma \rangle = \frac{v}{\sqrt{2}} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$

➔ $SU(2)_V$

Explicit $SU(2)_R$ violation

$$\overline{Q}_L \Sigma \tau^3 Q_R \to (\overline{Q}_L U_L^\dagger)(U_L \Sigma U_R^\dagger) \tau^3 (U_R Q_R)$$

$U(1)_{R3}$ [of $SU(2)_R$] is kept unbroken since VEV and τ^3 commute

➔ $U(1)_{V3}$ (Exact symmetry)

This is the fate of $SU(2)_V$ breaking in SM