Skyrmion Dark Matter inside the Standard Model

Koichi Yamawaki
@Giessen

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Based on

H.Ohki-S.Matsuzaki-KY, **arXiv:1608.03691**

``Dark Side of the Standard Model:Dormant New Physics Awaken''
See also, KY, arXiv:1609.03715

Dark Side of the Standard Model: Dormant New Physics Awaken

Shinya Matsuzaki,[1,2,*] Hiroshi Ohki,[3,†] and Koichi Yamawaki[4,‡]

[1] *Institute for Advanced Research, Nagoya University, Nagoya 464-8602, Japan.*
[2] *Department of Physics, Nagoya University, Nagoya 464-8602, Japan.*
[3] *RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973, USA*
[4] *Kobayashi-Maskawa Institute for the Origin of Particles and the Universe (KMI), Nagoya University, Nagoya 464-8602, Japan.*

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We find that the nonperturbative physics of the standard-model Higgs Lagrangian provides a dark matter candidate, "dormant skyrmion in the standard model", the same type of the skyrmion, a soliton, as in the hadron physics. It is stabilized by another nonperturbative object in the standard model, the dynamical gauge boson of the hidden local symmetry, which is also an analogue of the rho meson.

Main Message

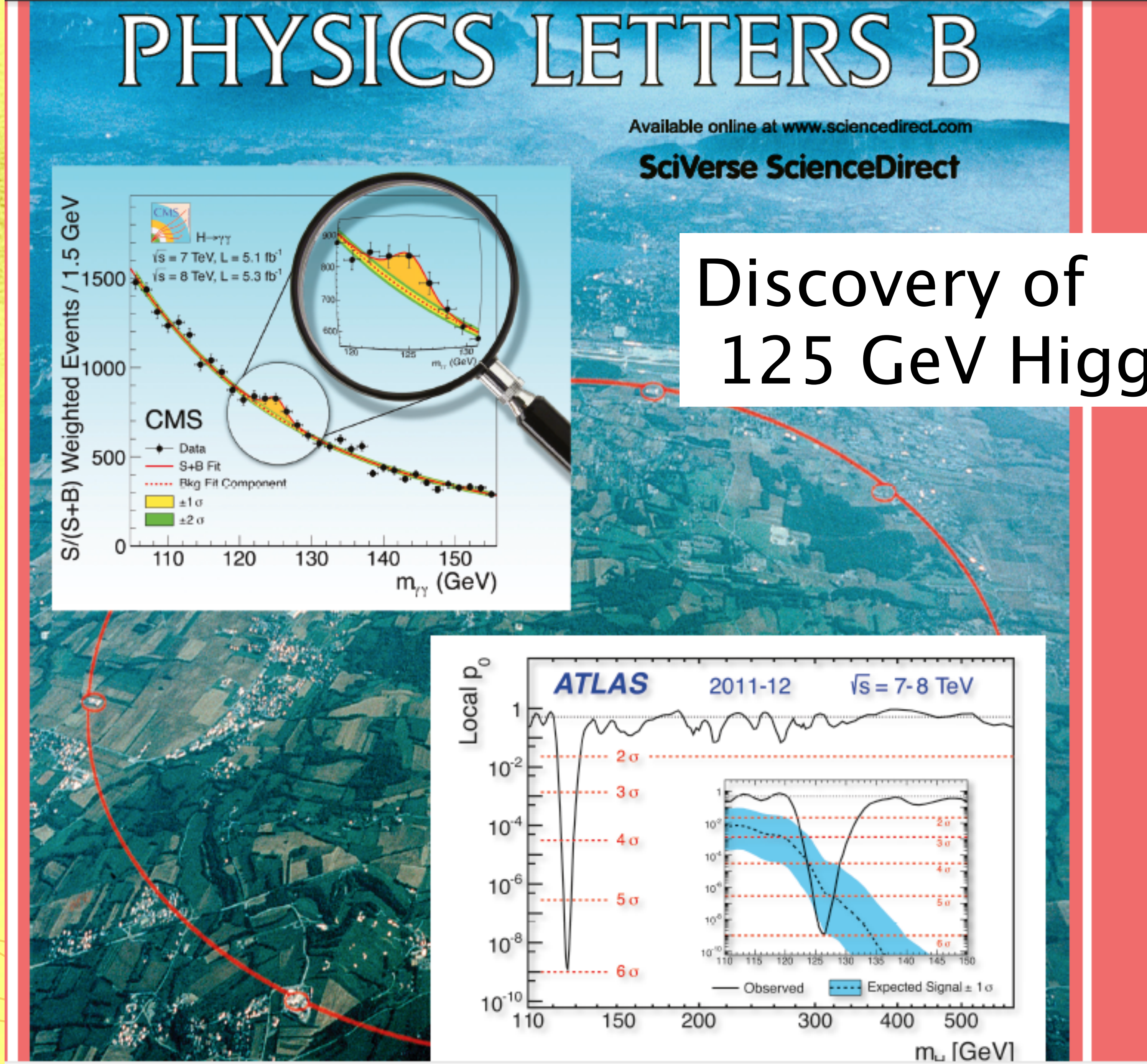
Dark Matter = SM Skyrmion:
I=J=0 Bound State of NG modes
of SM Higgs Field (W_L,Z_L)

SM Higgs = (Pseudo) Dilaton; NG Boson of
Scale Sym

Contents

- Standard Model Higgs as a Pseudo-dilaton
- Composite “Rho” as Dynamical Gauge Boson of Hidden Local Symmetry in the Standard Model
- Skyrmion as a Composite Dark Matter in the Standard Model

Discovery of 125 GeV Higgs



The Nobel Prize in Physics 2013
François Englert, Peter Higgs

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The Nobel Prize in Physics 2013

Photo: A. Mahmoud

François Englert

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Peter W. Higgs

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Standard Model is incomplete (besides Origin of Mass)

- No Dark matter candidate
- Baryogenesis: KM CP violation not enough,

No 1st order phase transition

- Strong CP Problem: neutron EDM
- Landau Pole (at least theoretically for Higgs)
- Naturalness Problem

Beyond the SM ?

Our Ignorance of the Nonperturbative Physics of SM ?

Dark Matter ← Nonperturbative SM

Nonperturbative in SM? Perturbative SM so successful

Weak coupling does not imply that perturbation is a whole story

- Sphaleron exists for both electroweak/Higgs coupling weak
- Instanton exists for even small gauge coupling - theta vacuum
- ’t Hooft-Polyakov monopole in the Georgi-Glashow model exists even in the vanishing scalar coupling (BPS limit)
- Skyrmion exists in the chiral Lagrangian with the Skyme term generated at one-loop for the derivative coupling weak in the low energy
- $\Lambda_{\rm QCD} \sim \mu \exp(-\frac{1}{b_0 \alpha(\mu)})$ is not Taylor expandable in coupling no matter how small at high energy: scale of nonperturbative dynamics

SM Higgs = Pseudo- Dilaton

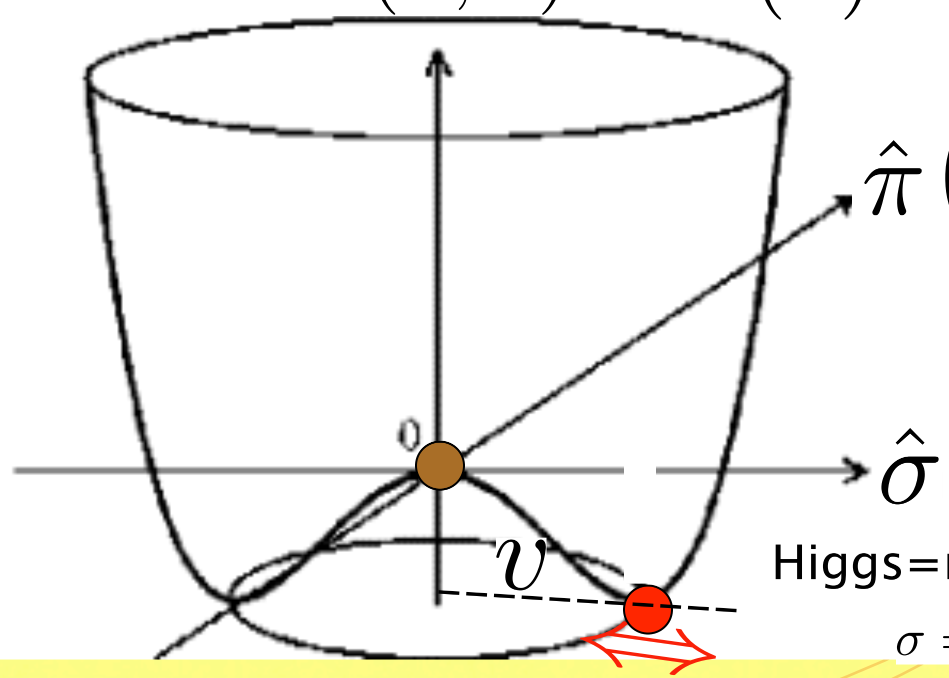
$$\mathcal{L}_{\rm Higgs} = |\partial_\mu h|^2 - \mu_0^2 |h|^2 - \lambda |h|^4$$

$$= \frac{1}{2}\left[(\partial_\mu \hat{\sigma})^2 + (\partial_\mu \hat{\pi}_a)^2\right] - \frac{1}{2}\mu_0^2\left[\hat{\sigma}^2 + \hat{\pi}_a^2\right] - \frac{\lambda}{4}\left[\hat{\sigma}^2 + \hat{\pi}_a^2\right]^2$$

$$\simeq SU(2)_L \times SU(2)_R \to SU(2)_V$$

$$h = \frac{1}{\sqrt{2}}\begin{pmatrix} i\hat{\pi}_1 + \hat{\pi}_2 \\ \hat{\sigma} - i\hat{\pi}_3 \end{pmatrix}$$

$$V(\hat{\sigma}, \hat{\pi}) = V(\sigma)$$



Higgs=radial oscillation

$$\sigma = \sqrt{\hat{\sigma}^2 + \hat{\pi}^2}$$

$$v^2 = -\frac{\mu_0^2}{\lambda} = \frac{M_\phi^2}{2\lambda} = (246\,\text{GeV})^2$$

$$M_\phi^2 = \frac{\partial^2 V}{\partial \sigma^2}\Big|_{\sigma=v} = -2\frac{\partial^2 V}{\partial \sigma^2}\Big|_{\sigma=0} = -2\mu_0^2$$

SM Higgs = (Pseudo) Dilaton

Fukano-Matsuzaki-Terashi-KY, NPB904(2016) 400

Polar decomposition

$$M=(i\tau_2 h^*, h)=\frac{1}{\sqrt{2}}\left(\hat\sigma\cdot 1_{2\times 2}+2i\hat\pi\right)$$

$$\sigma^2=\hat\sigma^2+\hat\pi_a^2$$

chiral non-singlet

$$=H\cdot U$$

scale tr. chiral tr.

$$U=\exp\left(\frac{2i\pi}{v}\right)\longrightarrow g_L U g_R^\dagger$$

Higgs=radial oscillation

$$H=\frac{1}{\sqrt{2}}\sigma\cdot 1_{2\times 2}$$

chiral singlet

$$\sigma=v\cdot\chi$$

$$\chi=\exp\left(\frac{\phi}{v}\right)$$

$$\delta_D\chi=(1+x^\mu\partial_\mu)\chi$$

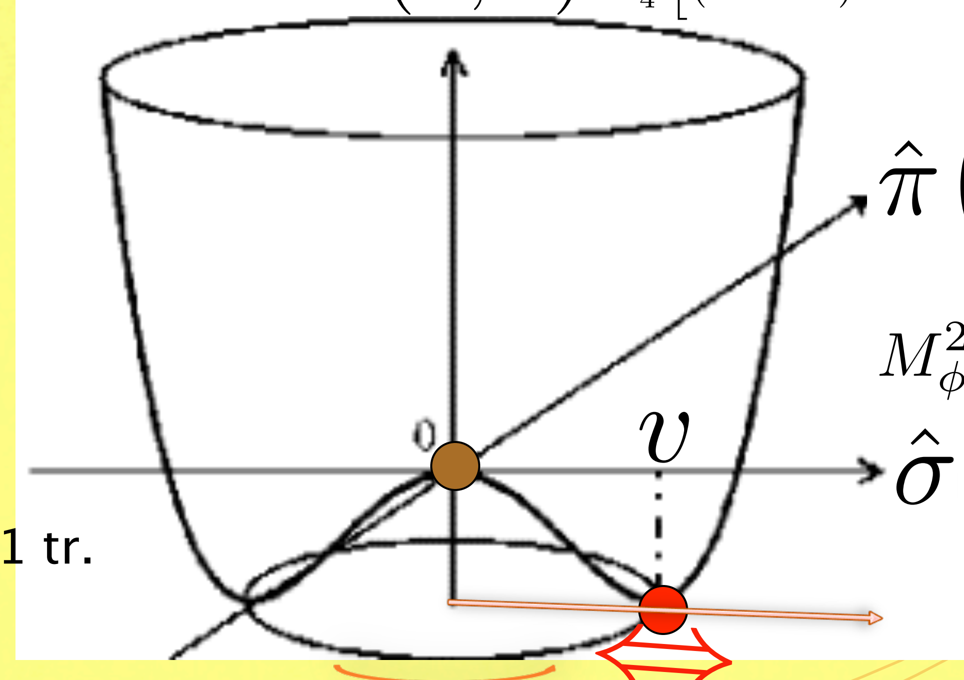
dimensionless, dim=1 tr.

$$\delta_D\phi=v+x^\mu\partial_\mu\phi$$

dimensionful, dim=0 tr.

: Higgs=dilaton

$$V(\hat\sigma,\hat\pi)=\frac{\lambda}{4}\left[\left(\sigma^2-v^2\right)^2-v^4\right]=\frac{(2\lambda v^2)}{2}\phi^2+\cdots$$



$$\hat\pi\ \left(\hat\pi\equiv\hat\pi_a\frac{\tau_a}{2}\right)$$

$$M_\phi^2=\left.\frac{\partial^2 V}{\partial\sigma^2}\right|_{\sigma=v}=\left.\frac{\partial^2 V}{\partial\phi^2}\right|_{\phi=0}$$

π phase σ radial

SM Higgs= (Pseudo) Dilaton

$$\mathcal{L}_{\rm Higgs} = \frac{1}{2}{\rm tr}\left(\partial_\mu M \partial^\mu M^\dagger\right) - \left[\frac{\mu_0^2}{2}{\rm tr}\left(MM^\dagger\right) + \frac{\lambda}{4}\left({\rm tr}\left(MM^\dagger\right)\right)^2\right]$$

$$= \chi^2 \cdot \left[\frac{1}{2}\left(\partial_\mu \phi\right)^2 + \frac{v^2}{4}{\rm tr}\left(\partial_\mu U \partial^\mu U^\dagger\right)\right] - \frac{\lambda}{4} v^4 \left[\left(\chi^2 - 1\right)^2 - 1\right]$$

scale-inv. (dim=4)

scale-br. (dim=2) only ϕ

$$\lambda \to 0 \quad (v = {\rm const.} \neq 0)$$

$M_\phi \to 0$

BPS limit

$$= \chi^2 \cdot \left[\frac{1}{2}\left(\partial_\mu \phi\right)^2 + \frac{v^2}{4}{\rm tr}\left(\partial_\mu U \partial^\mu U^\dagger\right)\right]$$

interacting !

Higgs=dilaton

$$\lambda \to \infty \, (v = {\rm const.} \neq 0) \qquad \chi(x) \to 1$$

$$= \left[\frac{1}{2} \cdots{}^2 + \frac{v^2}{4}{\rm tr}\left(\partial_\mu U \partial^\mu U^\dagger\right)\right]$$

nonliner chiral Lagrangia

dim=2

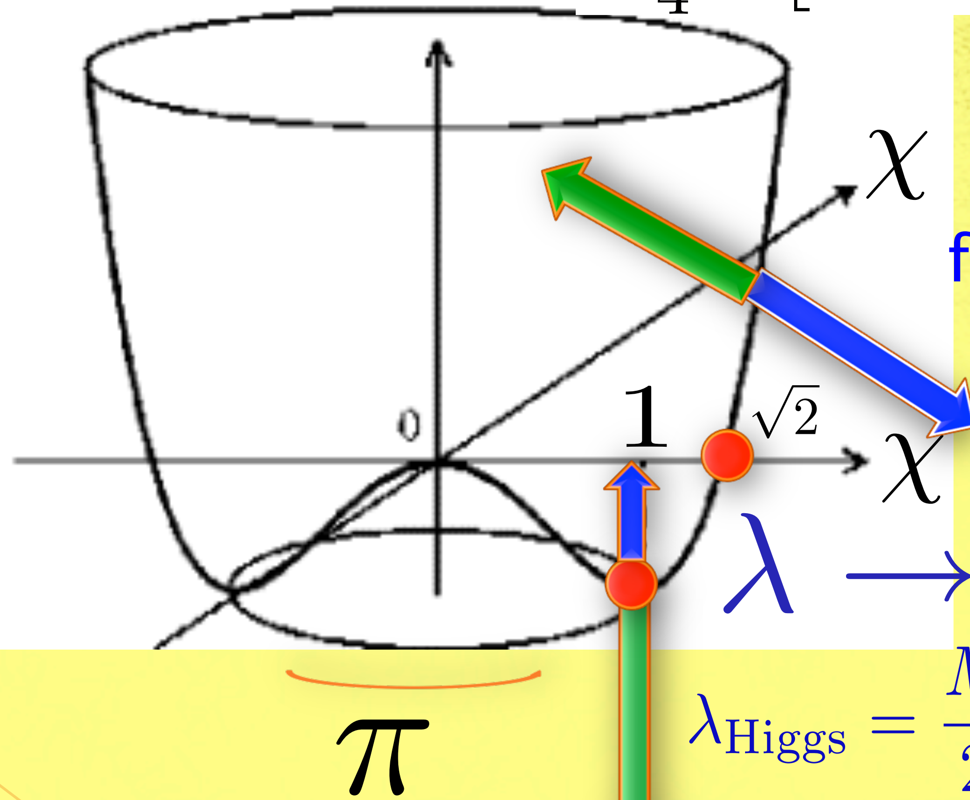
~~scale inv~~

QCD

$$G/H = SU(2)_L \times SU(2)_R / SU(2)_V$$

$V(\chi(x)) \to 0 \;\; (\lambda \to 0, \infty)$

$$V(\chi) = \frac{\lambda}{4} v^4 \left[\left(\chi^2(x) - 1\right)^2 - 1 \right]$$



flat direction BPS limit

$$\lambda \to 0$$

$$\lambda_{\mathrm{Higgs}} = \frac{{M_\phi}^2}{2v^2} \simeq \frac{1}{2}\left(\frac{125\,\mathrm{GeV}}{246\,\mathrm{GeV}}\right)^2 \sim \frac{1}{8} \ll 1$$

$$\lambda \to \infty \qquad (\chi(x) \to \chi(x) \equiv 1)$$

$$\lambda_{\mathrm{QCD}} = \frac{1}{2}\left(\frac{600\,\mathrm{MeV}}{93\,\mathrm{MeV}}\right)^2 \sim 20 \gg 1$$

Low Energy Theorem for Scale Sym.

Dim=4

$$M_X^2 \cdot \chi^2 X^\dagger X = M_X^2 X^\dagger X + \frac{2M_X^2}{v}\phi X^\dagger X + \cdots ,$$

$$M_X \cdot \chi \bar{X} X = M_X \bar{X} X + \frac{M_X}{v}\phi \bar{X} X + \cdots .$$

$$g_{\phi X^\dagger X} = \frac{2M_X^2}{F_\phi}, \quad g_{\phi \bar{X} X} = \frac{M_X}{F_\phi} \quad (F_\phi = v) ,$$

Ex.

Couplings to SM particles $g_{\phi \bar{f} f} = \frac{m_f}{v}$ $g_{\phi WW} = \frac{2m_W^2}{v}$

(also from low energy theorem for G/H)

$$\sqrt{2} g_Y \bar{f} h f = g_Y v(\chi \bar{f} f) = m_f \bar{f} f + \frac{m_f}{v}\phi \bar{f} f \cdots$$

No dilaton in QCD

f_0 (500) is dilaton?

$$g_{\phi X^\dagger X} = \frac{M_X^2}{F_\phi}, \quad g_{\phi \bar{X} X} = \frac{M_X}{F_\phi} \quad (F_\phi = v) \ ,$$

$g_{\sigma\pi\pi}/g_{\sigma NN} = m_\pi/m_N$ for $\mathcal{L} = m_\pi g_{\sigma\pi\pi} \cdot \sigma \pi^a \pi_a, \, g_{\sigma NN} \cdot \bar{N} \sigma N$,

$g_{\sigma\pi\pi}^2 \simeq (m_\pi/m_N)^2 g_{\sigma NN}^2 \simeq 2$ for the observed value $g_{\sigma NN} \simeq 10$

$$\Gamma_\sigma \simeq 3 \times \frac{m_\pi^2 g_{\sigma\pi\pi}^2}{8\pi m_\sigma} \left(1 - \frac{4m_\pi^2}{m_\sigma^2}\right)^{1/2} \sim 7 - 8 \text{ MeV } (m_\sigma = 500 - 600 \, \text{MeV})$$

$\Gamma_{f_0} = 400 - 700 \, \text{MeV},$

Hidden Local Symmetry in SM

Hidden Local Symmetry

Bando-Kugo-Uehara-KY-Yanagida PRL,54(1985) 12
Bando-Kugo-KY, NP B259 (1985);493
Phys. Rep. 164 (1988) 217

Gauge boson : auxiliary field

Gauge equivalence

$$G/H \simeq G_{\rm global} \times H_{\rm local}$$

Gauge fixing

$$H = H_{\rm global} + H_{\rm local} \subset G$$

$$\subset G_{\rm global}$$

$$\mathcal{L} = \frac{F_\pi^2}{4} \mathrm{tr}\left(\partial_\mu U \partial^\mu U^\dagger\right)$$

$$F_\pi = v$$

$$U(x) = \xi_L^\dagger(x) \cdot \xi_R(x)$$

$$\xi_{R,L}(x) \to h(x) \cdot \xi_{R,L}(x) \cdot {g'}^\dagger_{R,L}$$

$$\left(h(x) \in H_{\text{local}},\ {g'}_{R,L} \in G_{\text{global}}\right)$$

$$D_\mu \xi_{R,L}(x) = \partial_\mu \xi_{R,L}(x) - i\rho_\mu(x)\xi_{R,L}(x)$$

$$\{\hat{\alpha}_{\mu,R,L}, \hat{\alpha}_{\mu,||,\perp}\} \to h(x) \cdot \{\hat{\alpha}_{\mu,R,L}, \hat{\alpha}_{\mu,||,\perp}\} \cdot h^\dagger(x)\,,$$

$$\hat{\alpha}_{\mu,R,L} \equiv \frac{1}{i} D_\mu \xi_{R,L} \cdot \xi_{R,L}^\dagger = \frac{1}{i} \partial_\mu \xi_{R,L} \cdot \xi_{R,L}^\dagger - \rho_\mu\,,$$

$$\hat{\alpha}_{\mu,||,\perp} \equiv \frac{1}{2}\left(\hat{\alpha}_{\mu,R} \pm \hat{\alpha}_{\mu,L}\right) = \begin{cases} \alpha_{\mu||} - \rho_\mu \\ \alpha_{\mu\perp} \end{cases},,$$

$$\alpha_{\mu||} = \frac{1}{2i}\left(\partial_\mu \xi_R \cdot \xi_R^\dagger + \partial_\mu \xi_L \cdot \xi_L^\dagger\right) = \frac{1}{F_\rho}\partial_\mu \check{\rho} - \frac{i}{2F_\pi^2}[\partial_\mu \pi, \pi] + \cdots$$

$$\alpha_{\mu\perp} = \frac{1}{2i}\left(\partial_\mu \xi_R \cdot \xi_R^\dagger - \partial_\mu \xi_L \cdot \xi_L^\dagger\right)$$

$$= \frac{1}{2i}\xi_L \cdot \partial_\mu U \cdot \xi_R^\dagger = \frac{1}{2i}\xi_R \partial_\mu U^\dagger \cdot \xi_L^\dagger\,, \qquad F_\rho^2 = aF_\pi^2 = av^2.$$

$$\xi_{R,L} = e^{i\check{\rho}/F_\rho} \cdot e^{\pm i\pi/v}$$

2 independent invariants under $G_{\mathrm{global}} \times H_{\mathrm{local}}$

$$\mathcal{L}_A = v^2 \cdot \mathrm{tr}\hat{\alpha}_\perp^2(x) = v^2 \cdot \mathrm{tr}\alpha_{\mu\perp}^2(x) = \frac{v^2}{4} \cdot \mathrm{tr}\left(\partial_\mu U \partial^\mu U^\dagger\right)\,,$$

$$\mathcal{L}_V = v^2 \cdot \mathrm{tr}\,\hat{\alpha}_{\mu||}^2(x) = v^2 \cdot \mathrm{tr}\,\left(\rho_\mu(x) - \alpha_{\mu||}(x)\right)^2\,,$$

$$= v^2 \cdot \mathrm{tr}\left(\left(\rho_\mu(x) - \frac{1}{F_\rho}\partial_\mu \check{\rho}\right) - \frac{i}{2F_\pi^2}[\partial_\mu \pi, \pi] + \cdots\right)^2$$

$$\mathcal{L}_{\mathrm{s-HLS}} = \chi^2(x) \cdot \left(\frac{1}{2}(\partial_\mu \phi)^2 + \mathcal{L}_A + a\mathcal{L}_V\right)$$

Gauge fixing (unitary gauge)

$$\xi_{R,L} = e^{i\check{\rho}/F_\rho} \cdot e^{\pm i\pi/v}$$

$$\xi_L^\dagger = \xi_R = \xi = e^{i\pi/v} \qquad \check{\rho} = 0$$

$$G_{\text{global}} \times H_{\text{local}} \Rightarrow G/H$$ (Higgs Mechanism)

$$\mathcal{L}_{\text{Higgs-HLS}} = \chi^2(x) \cdot \left(\frac{1}{2} (\partial_\mu \phi)^2 + \frac{v^2}{4} \cdot \text{tr} \left(\partial_\mu U \partial^\mu U^\dagger \right) \right) - V(\phi) + \chi^2(x) \cdot F_\rho^2 \cdot \text{tr} \left(\rho_\mu(x) - \alpha_{\mu||}(x) \right)^2 , \quad (F_\rho^2 = a v^2)$$

$$\rho_\mu = \alpha_{\mu||}$$ Eq. Motion

0

$$\mathcal{L}^{\rho} = -\frac{1}{2g^2}\mathrm{tr}\rho_{\mu\nu}^2$$

$$\rho_\mu(x) \mapsto g\,\rho_\mu(x)$$

$$\chi^2\, a\mathcal{L}_V = \chi^2 F_\rho^2 \cdot \mathrm{tr}\,\left(g\rho_\mu - \alpha_{\mu,||}\right)^2 = M_\rho^2\,\mathrm{tr}(\rho_\mu)^2 + g_{\rho\pi\pi}\cdot 2i\mathrm{tr}\left(\rho^\mu\left[\partial_\mu\pi,\pi\right]\right) +$$

$$M_\rho^2 = g^2 F_\rho^2 = a(g\,v)^2\,, \quad g_{\rho\pi\pi} = \frac{F_\rho^2}{2v^2}g = \frac{a}{2}g\,,$$

Dynamical Generation of HLS

$$\mathcal{L}_{\rm NJL} = \bar\psi i\gamma^\mu\partial_\mu\psi + \frac{G}{2}\left[(\bar\psi\psi)^2 + (\bar\psi i\gamma_5\tau^a\psi)^2\right]$$

Auxiliary fields $\hat\sigma = -G\bar\psi\psi/\sqrt{2}$ $\hat\pi^a = -G\bar\psi i\gamma_5\tau^a\psi/\sqrt{2}$

$$= \bar\psi\left(i\gamma^\mu\partial_\mu - \frac{1}{\sqrt{2}}[\hat\sigma + i\gamma_5\tau^q\hat\pi_a]\right)\psi - \frac{1}{2}\frac{1}{G}(\hat\sigma^2 + \hat\pi_a^2)$$

Large N leading $Z_\phi^{1/2}\hat\sigma \to \hat\sigma$ $Z_\phi = \frac{N_C}{8\pi^2}\ln\frac{\Lambda^2}{m_F^2}$ $m_F = v\,Z_\phi^{-1/2}/\sqrt{2}$

$$\mathcal{L}_{1/N} = \bar\psi\left(i\gamma^\mu\partial_\mu - \frac{Z_\phi^{-1/2}}{\sqrt{2}}[\hat\sigma + i\gamma_5\tau^a\hat\pi_a]\right)\psi + \mathcal{L}_\phi$$

$$\mathcal{L}_{\rm Higgs} = \frac{1}{2}\left[(\partial_\mu\hat\sigma)^2 + (\partial_\mu\hat\pi_a)^2\right] - \frac{1}{2}\mu_0^2\left[\hat\sigma^2 + \hat\pi_a^2\right] - \frac{\lambda}{4}\left[\hat\sigma^2 + \hat\pi_a^2\right]^2$$

$$\mu_0^2 = \left(\frac{1}{G} - \frac{1}{G_{\rm cr}}\right)Z_\phi^{-1} = -2m_F^2 = -v^2 Z_\phi^{-1} = -\lambda v^2$$

$$\lambda = \tilde\lambda Z_\phi^{-2} = Z_\phi^{-1} = \left[\frac{N_c}{8\pi^2}\ln\frac{\Lambda^2}{m_F^2}\right]^{-1}$$

$$\hat\sigma, \hat\pi = \text{bound states of } \bar\psi . \psi$$

Dynamical Generation of HLS Gauge Boson

$$\mathcal{L}_{\rm tree}(\pi) = \mathcal{L}_{\rm tree}(\pi, \rho_\mu)$$

$\mu = \Lambda$

Large Nf — Quantum loop — $\mu < \Lambda$

$$-\frac{1}{2g^2}{\rm tr}[\rho_{\mu\nu}^2]\,, \qquad \frac{1}{g^2} = \frac{C_2(G)}{(4\pi)^2}\left(\frac{a^2}{24} + \left(-\frac{11}{3} + \frac{1}{24}\right)\right)\ln\frac{\Lambda^2}{\mu^2}\,,$$

$C_2(G) = N_f$ =2

$\mathcal{L}_{\rm kinetic} \to 0\,(\mu \to \Lambda)$ ⇒ $a > \sqrt{87}$

$$\rho_\mu \sim \pi\partial_\mu\pi + \cdots$$

$\rho =$ bound state of π

Skyrmion in SM

I=J=0,1/2,1,…

$U(1)_{X_s}$

$$J^{\mu}_{X_s} = \frac{1}{24\pi^2}\epsilon^{\mu\nu\rho\sigma}\mathrm{tr}\left(U^\dagger\partial_\nu U\cdot U^\dagger\partial_\rho U\cdot U^\dagger\partial_\sigma U\right)$$

$$I = J = 0,\ Q_{X_s} = 1$$

$$M_\rho^2 = ag^2v^2 \gg v^2,$$

$$\rho_\mu \to \alpha_{\mu||} = \frac{1}{2i}\left(\partial_\mu\xi_R(x)\cdot\xi_R^\dagger(x) + \partial_\mu\xi_L(x)\cdot\xi_L^\dagger(x)\right)$$

$$(a\to\infty,\ g = \text{constant})$$

$$\rho_{\mu\nu} \to \rho_{\mu\nu}|_{\rho_\mu=\alpha_{\mu||}} = i[\hat{\alpha}_{\mu\perp},\hat{\alpha}_{\nu\perp}],\quad \hat{\alpha}_{\mu\perp} = \frac{\xi_L(\partial_\mu U)\xi_R^\dagger}{2i},$$

$$\mathcal{L}^{(\rho)}_{\text{kinetic}}(\rho_\mu) \to -\frac{1}{2g^2}\mathrm{tr}\left(i[\hat{\alpha}_{\mu\perp},\hat{\alpha}_{\nu\perp}]\right)^2 = \frac{1}{32g^2}\mathrm{tr}[[\partial_\mu UU^\dagger,\partial_\nu UU^\dagger]^2],$$

Stabilizes Skyrmion

Simplest case $a \to \infty,\ g = \text{const.}(> \sqrt{87})$

$$\mathcal{L}_{\text{Higgs-Skyrme}} = \chi^2(x) \cdot \left(\frac{1}{2} (\partial_\mu \phi)^2 + \frac{v^2}{4} \cdot \text{tr} \left(\partial_\mu U \partial^\mu U^\dagger \right) \right) - V(\phi) + \frac{1}{32 g^2} \text{tr}[[\partial_\mu U U^\dagger, \partial_\nu U U^\dagger]^2],$$

Scale-invariant Skyrme Model

Skyrmion = Bound State of π

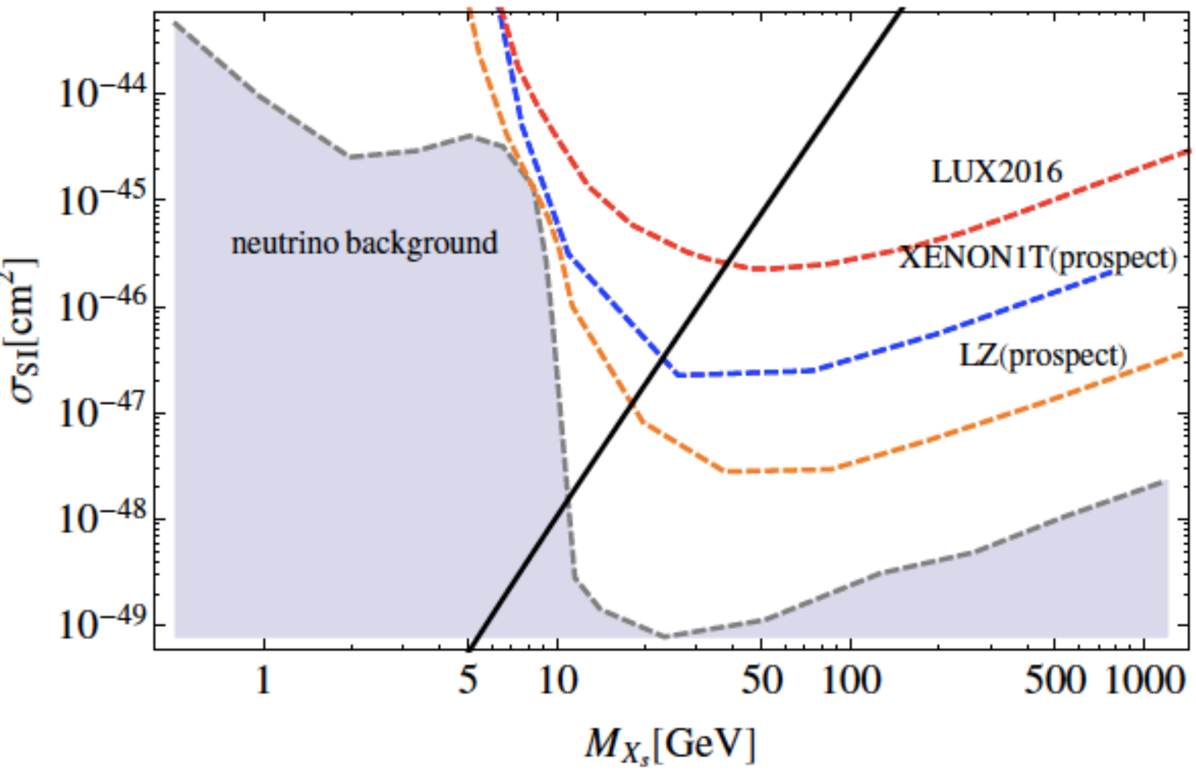
Higgs coupling to Dark matter Uniquely determinedby Low Energy Theorem

$$g_{\phi X_s X_s} = \frac{2M_{X_s}^2}{v} = 2v\lambda_{X_s}, \quad \lambda_{X_s} = \frac{M_{X_s}^2}{v^2}$$

⇓

Direct detection Experiment LUX, PANDAX-II

Direct Detection



$$M_{X_s} \lesssim 38\,\mathrm{GeV}\,.$$

$$\sigma_{\mathrm{SI}}^{\mathrm{elastic/nucleon}}(X_s N \to X_s N) = \frac{\lambda_{X_s}^2}{\pi M_\phi^4}$$

$$\times \left[\frac{Z \cdot m_*(p, X_s) g_{\phi pp} + (A - Z) \cdot m_*(n, X_s) g_{\phi nn}}{A}\right]^2$$

$$m_*(N, X_s) \quad = \quad \frac{M_{X_s} m_N}{M_{X_s} + m_N}$$

Xe: $(Z = 54,\ A = 131.293,\ u = 0.931\ \mathrm{GeV})$,

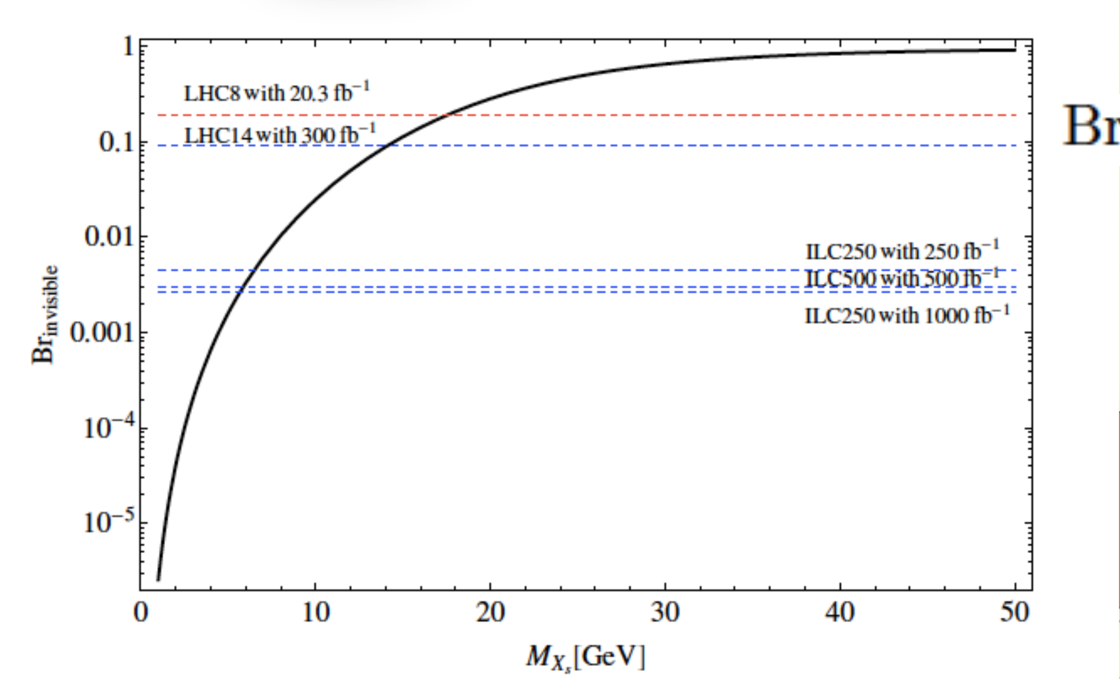
$$g_{\phi pp(nn)} \quad = \quad \sum_q \sigma_q^{(p(n))}/v \quad \simeq 0.248(0.254)\,\mathrm{GeV}/v.$$

Indirect Search Limit (Higgs invisible decay

$$M_{X_s} \lesssim 38\,\mathrm{GeV}\,. \qquad M_{X_s} < M_\phi/2$$

$$\Gamma(\phi \to X_s \bar{X}_s) = \frac{\lambda_{X_s}^2 v^2}{4\pi m_\phi}\sqrt{1 - \frac{4M_{X_s}^2}{m_\phi^2}}\,.$$

$$\mathrm{Br}[\phi \to X_s\bar{X}_s] = \Gamma(\phi \to X_s\bar{X}_s)/\Gamma_\phi^{\mathrm{tot}} = \Gamma(\phi \to X_s\bar{X}_s)/[\Gamma_\phi^{\mathrm{SM}} + \Gamma(\phi \to X_s\bar{X}_s)]$$



$$\mathrm{Br}_{\mathrm{invisible}} \lesssim 0.2$$

$$M_{X_s} \lesssim 18\,\mathrm{GeV}\,,$$

Relic Abundance in Thermal History

Thermal Relic Abundance

$$\Omega_{X_s} h^2 = \frac{2\times(1.07\times10^9)x_f}{g_*(T_f)^{1/2} M_{\rm Pl}{\rm GeV}\langle\sigma_{\rm ann}v_{\rm rel}\rangle}$$

Freeze out temperature $x_f = M_{X_s}/T_f(\sim 20).$

Effective d.o.f/ at Tf $g_*(T_f) = 100$

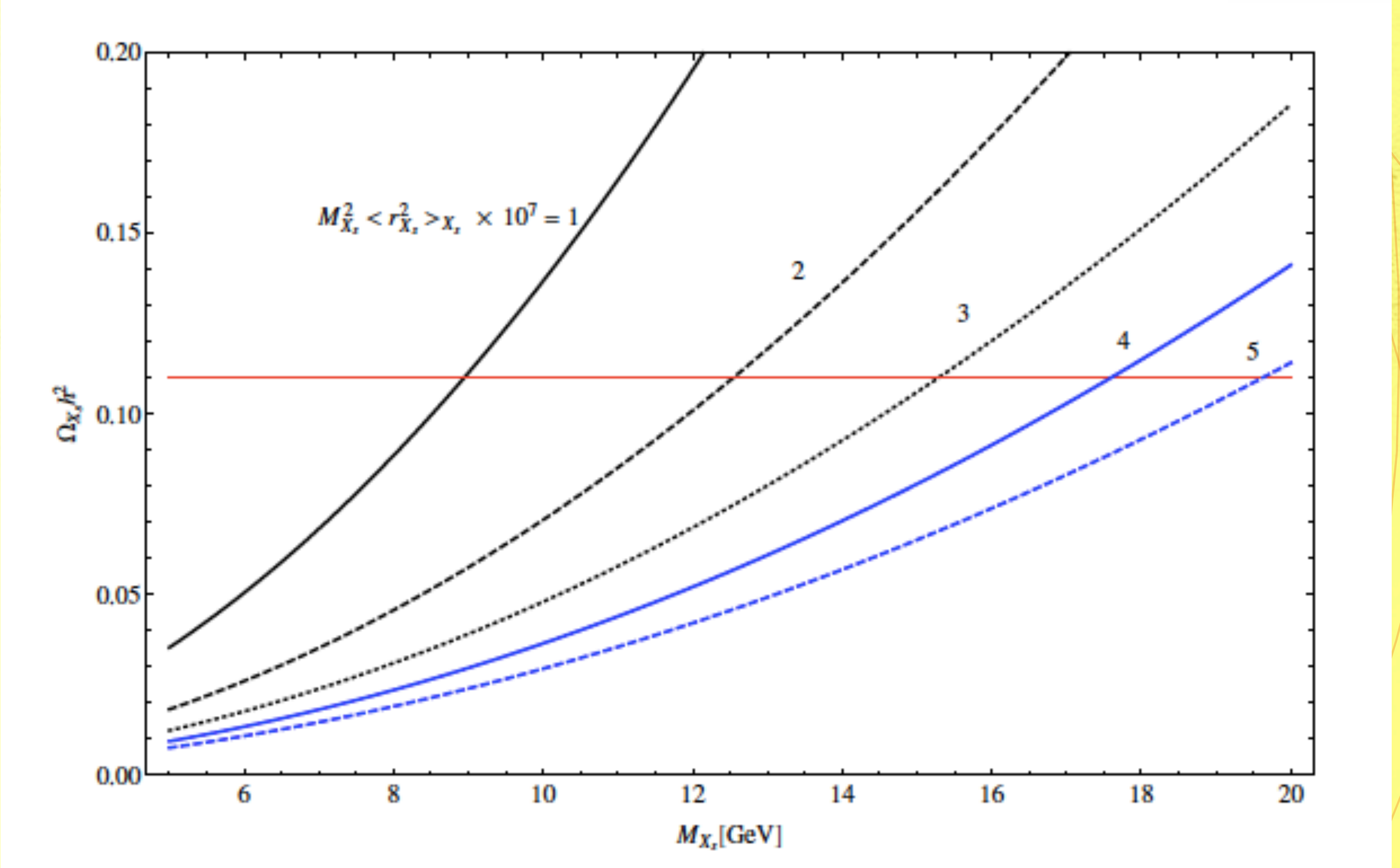
Skyrmion = soliton (extended object)

$$\langle\sigma_{\rm ann}v_{\rm rel}\rangle_{\rm radius} = \mathcal{O}(\pi\cdot\langle r^2_{X_s}\rangle_{X_s})$$

$$\langle r^2_{X_s}\rangle_{X_s} \simeq \frac{(2.2)^2}{g^2v^2}, \qquad M_{X_s} \simeq \frac{35v}{g}$$

$$\text{or} \qquad M^2_{X_s}\langle r^2_{X_s}\rangle_{X_s} \simeq 10^{-7}\left(\frac{500}{g}\right)^4,$$

g=500 for $M_{X_s} \simeq 18\,{\rm GeV}$



$\Omega_{X_s} h^2 = \mathcal{O}(0.1)$ ⟸ $M_{X_s} = \mathcal{O}(10\,\mathrm{GeV})$

Conclusion

SM is richer than ever considered

- Standard Model Higgs as a Pseudo-dilaton
- Composite "Rho" as Dynamical Gauge Boson of Hidden Local Symmetry in the Standard Model
- Skyrmion as a Composite Dark Matter in the Standard Model

Skyrmion $U(1)_{X_s}$ Charge Radius

$$M_{X_s} = \frac{2\pi v}{g}\int_0^\infty dr \Big[\chi^2(r)\left(r^2F'(r)^2 + 2\sin^2(F(r))\right) + \sin^2(F(r))\left(\frac{\sin^2(F(r))}{r^2} + 2F'(r)^2\right) + \chi^2(r)r^2\phi'(r)^2 + \frac{M_\phi^2}{4g^2v^2}r^2\left(\chi(r)^4 - 2\chi(r)^2 + 1\right)\Big]$$

$$\simeq 35\,\frac{v}{g}\,,$$

$$\langle r^2_{X_s}\rangle_{X_s} = \int_0^\infty dr\, r^2\left(4\pi r^2\right) J^0_{X_s} = \frac{2}{\pi}\int_0^\infty dr\, r^2 \sin^2(F(r))F'(r)$$

$$\simeq (2.2)^2\frac{1}{g^2v^2}\,,$$

$$U(\vec{x}) = \exp(i\vec{\tau}\vec{\hat{r}}F(\vec{r})),$$

$$\tilde{r} = gvr$$

$$\tilde{r} \longrightarrow r$$