Electroweak and Dark matter scalegenesis from a bilinear scalar condensate

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Based on

J, Kubo and **M. Y.**, arXiv:1505.05971

J, Kubo and **M. Y.**, PTEP **2015** 093B01 (arXiv:1506.06460)

Summary of my talk

- Classically scale invariant model
  - Prohibits the mass term
  - Introduce a new scalar field coupled to a non-abelian gauge field in the hidden sector.
  - The Higgs mass term is generated due to the strong dynamics.
- Dark matter candidate exists.
  - Flavor symmetry makes it stable.
- Strong 1st order EW phase transition

Model

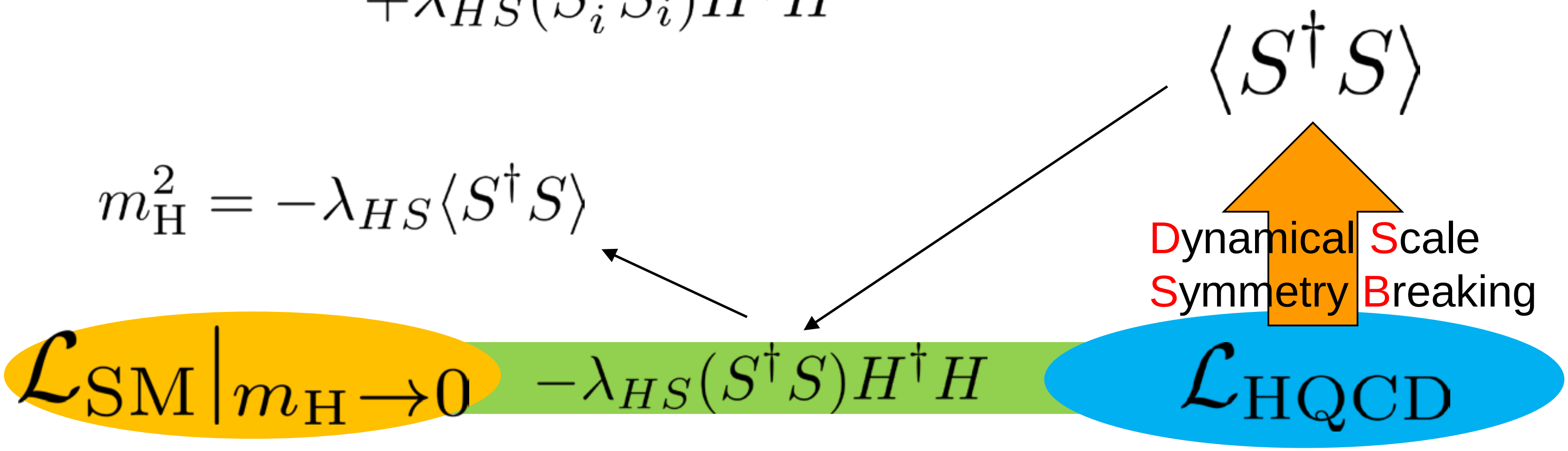
J, Kubo and **M. Y.**, arXiv:1505.05971

cf. J. Kubo, K. S. Lim and M. Lindner Phys. Rev. Lett. 113. 091604

- Strongly interacting Hidden sector
  - $SU(N_c) \times U(N_f)$ invariant + classically scale invariant

$$\mathcal{L}_{\rm HQCD} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + ([D_\mu S_i]^\dagger D^\mu S_i) - \hat{\lambda}_S (S_i^\dagger S_i)(S_j^\dagger S_j) - \hat{\lambda}'_S (S_i^\dagger S_j)(S_j^\dagger S_i) + \hat{\lambda}_{HS} (S_i^\dagger S_i) H^\dagger H$$

$$m_{\rm H}^2 = -\lambda_{HS} \langle S^\dagger S \rangle$$



Effective theory

- Low energy effective Lagrangian

$$\mathcal{L}_{\rm eff} = ([\partial_\mu S_i]^\dagger \partial^\mu S_i) + \lambda_{HS}(S_i^\dagger S_i)H^\dagger H$$
$$-\lambda_S(S_i^\dagger S_i)(S_j^\dagger S_j) - \lambda'_S(S_i^\dagger S_j)(S_j^\dagger S_i)$$

  - Describe the Dynamical Scale Symmetry Breaking.
    - The order parameter is $< S^\dagger S >$
  - Assume that the DSSB is more dominant than the scale anomaly.
  - Scale invariant Lagrangian.
  - λ_S, λ'_S and λ_{HS}: effective coupling constants.
    - which contain the quantum effects of hidden gluon.
  - Renormalizable.
  - Analyzed by the mean-field approx. (non-perturbative method).

Dark matter candidate is ϕ^{α}

- The excitation fields from the vacuum $< S^{\dagger}S >$
  - Assume the unbroken $\mathrm{U}(N_{\mathrm{f}})$ flavor symmetry:

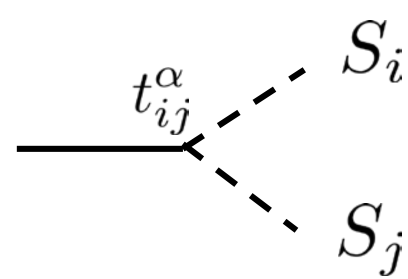
$$\langle\Omega|(S_i^{\dagger}S_j)|\Omega\rangle \ = f_0\delta_{ij} + \delta_{ij}Z_{\sigma}^{\frac{1}{2}}\sigma + t_{ji}^{\alpha}Z_{\phi}^{\frac{1}{2}}\phi^{\alpha}$$

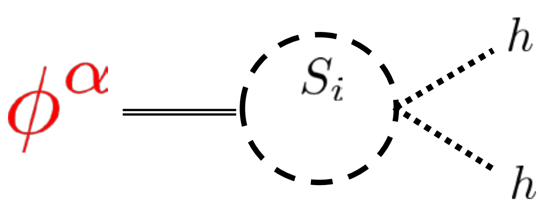
    - c.f. chiral condensate

$$\langle\Omega|\bar{\psi}_i(1-\gamma^5)\psi_j|\Omega\rangle \ = f_0\delta_{ij} + \delta_{ij}Z_{\sigma}^{\frac{1}{2}}\sigma + t_{ji}^{\alpha}Z_{\pi}^{\frac{1}{2}}\pi^{\alpha}$$

- Lagrangian

$$\mathcal{L}'_{\mathrm{MFA}} \supset \ \phi^{\alpha}$$



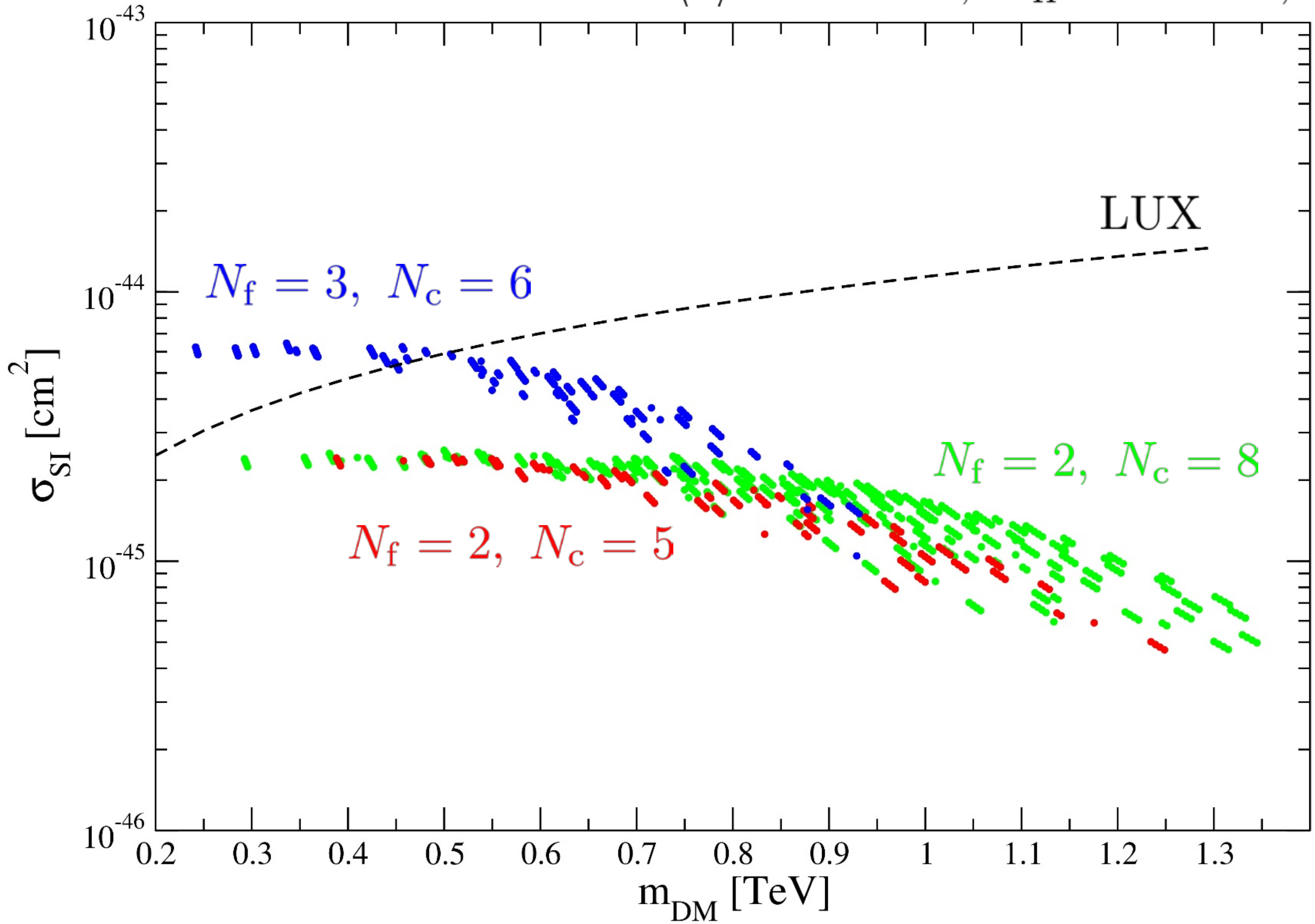


Forbidden by flavor symmetry

ϕ^{α} is stable.

σ_{SI} vs. m_{DM}

$\langle h \rangle = 246$ GeV, $m_H = 126$ GeV, $\Omega \hat{h}^2 \sim 0.12$

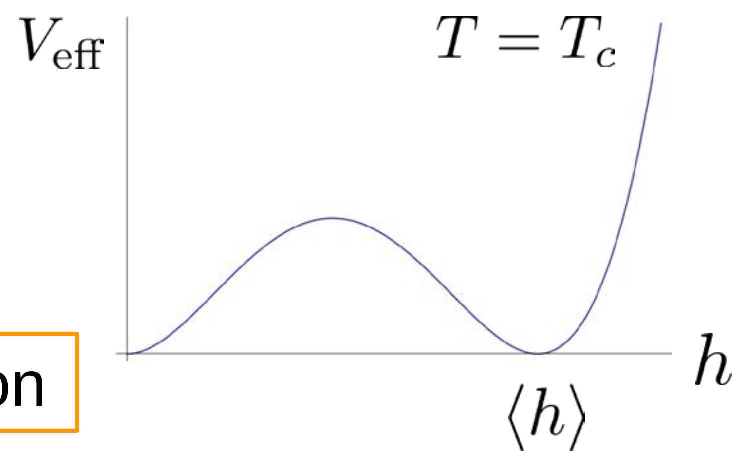


EW Baryogenesis scenario

- Sakharov conditions
  1. Baryon number violation
  2. C-symmetry and CP-symmetry violation
  3. Interactions out of thermal equilibrium.

- Electroweak strong first-order phase transition

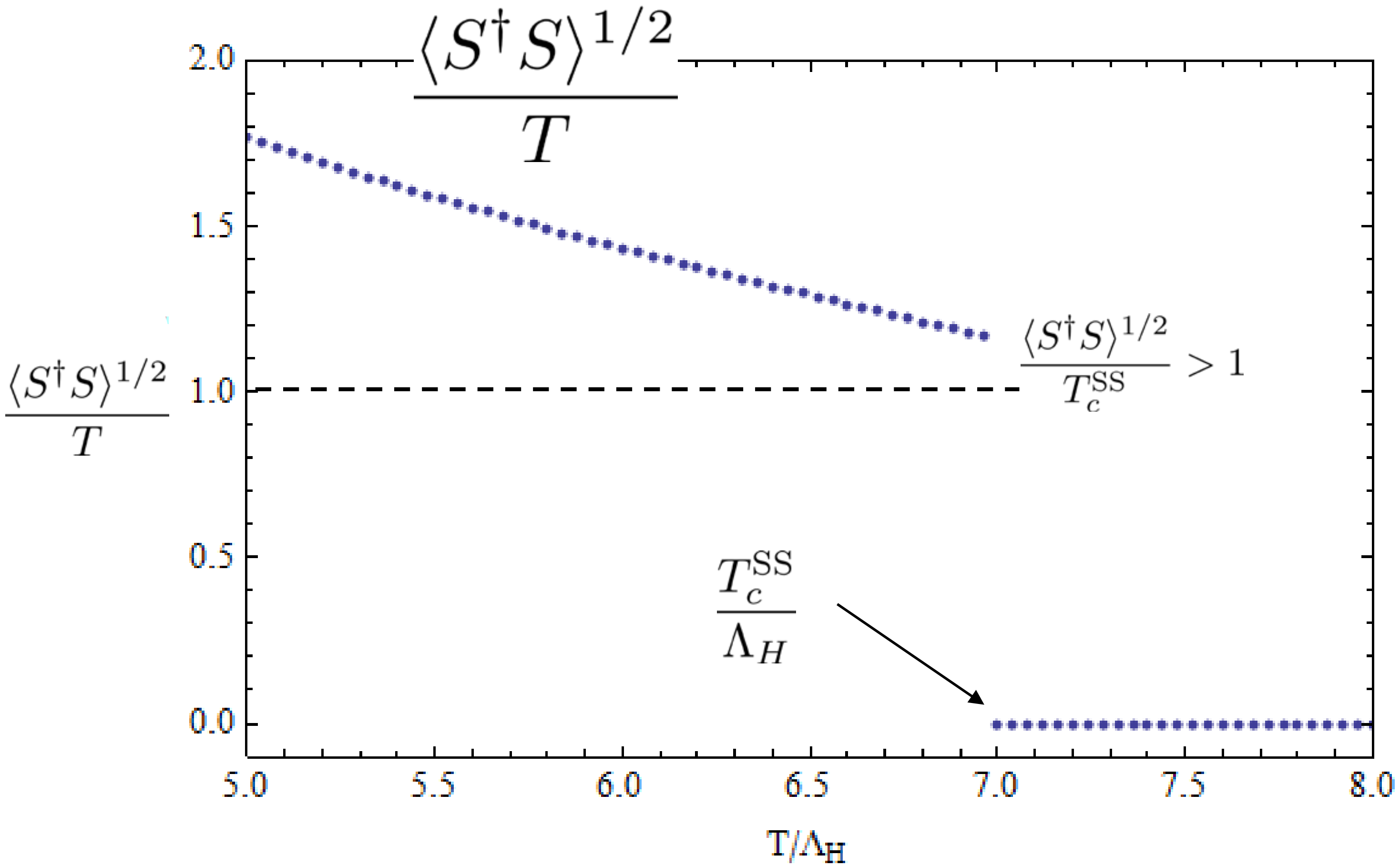
$$\frac{\langle h \rangle}{T_c} \gtrsim 1$$



The SM cannot satisfy this condition

Scale transition is strong 1^{st} order.

J, Kubo and **M. Y.**, PTEP **2015** 093B01 (arXiv:1506.06460)

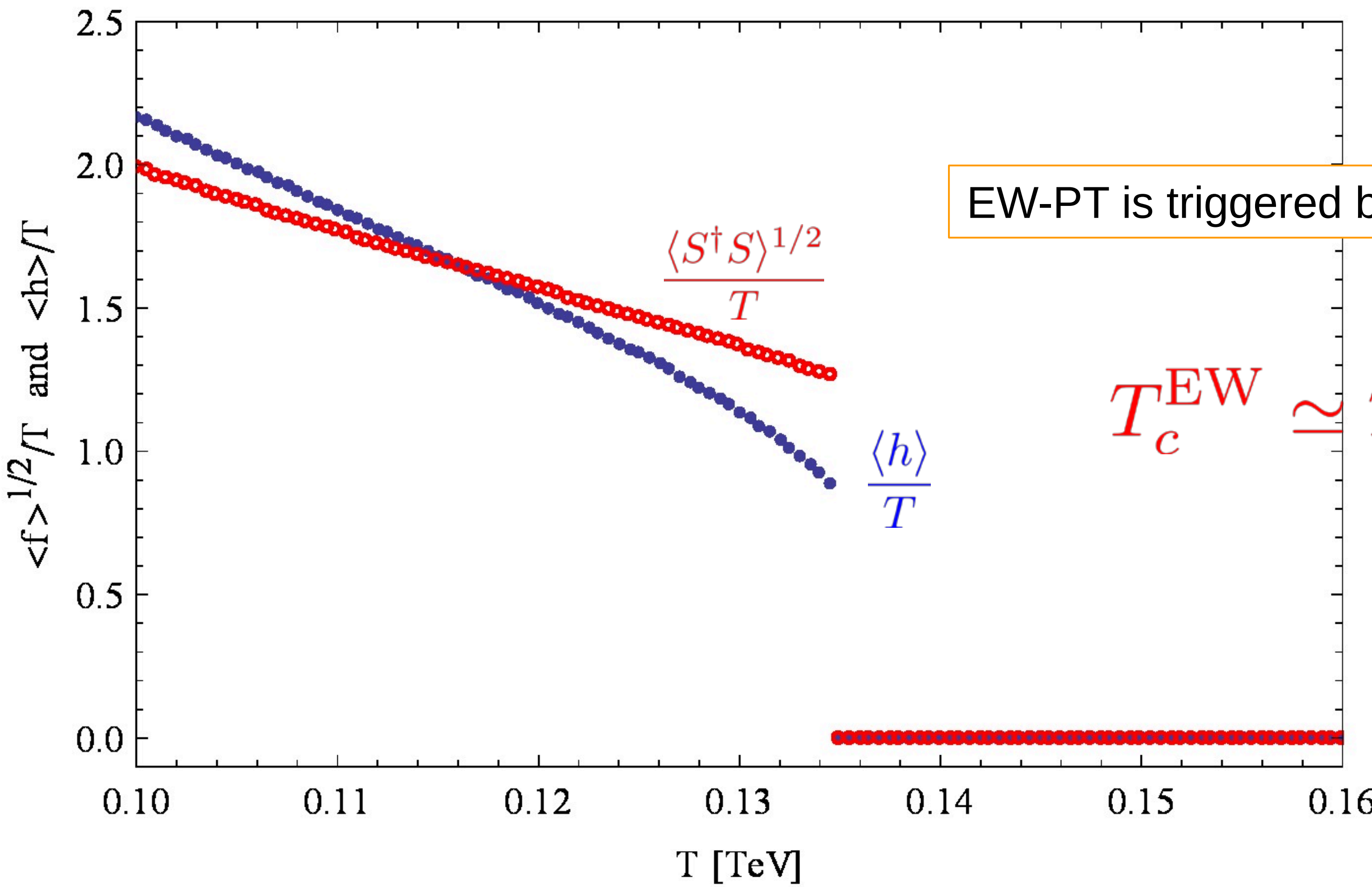


Without dark matter case: $N_f = 1$

EW phase transition becomes strong 1st order

$\langle h \rangle = 246$ GeV, $m_H = 126$ GeV

$N_c = 6$



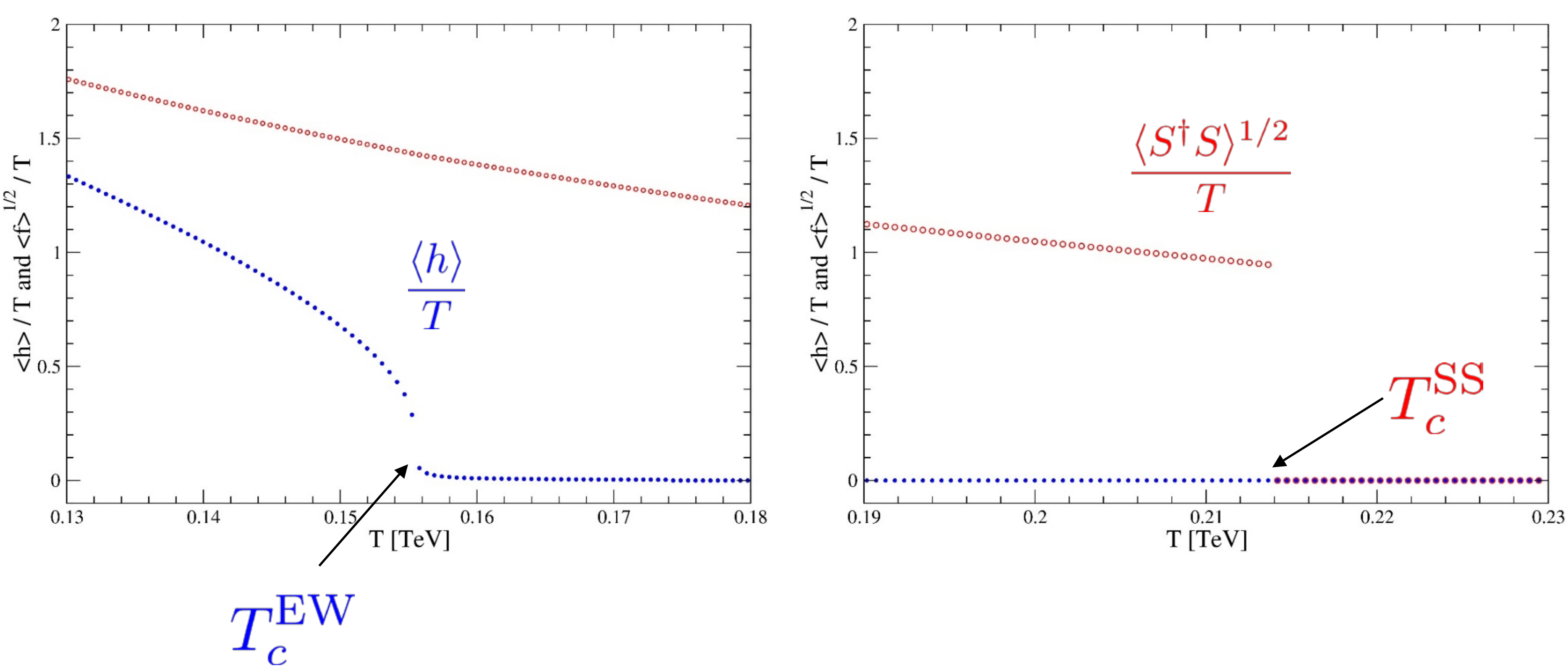
EW-PT is triggered by SS-PT

$T_c^{EW} \simeq T_c^{SS}$

With dark matter case: $N_f = 2$
EW phase transition becomes weak 1st order

$\langle h \rangle = 246$ GeV, $m_H = 126$ GeV, $\Omega \hat{h}^2 \sim 0.12$

$N_c = 6$



Summary

- We suggested a new model based on classically scale invariance.
  - Strongly interacting hidden sector with the scalar field
  - Explain the mechanism of generation of “scale”
  - Dynamical Scale Symmetry Breaking $< S^\dagger S > \neq 0$
  - The EW symmetry breaking $< h > \neq 0$

“Scalegenesis” is realized!

Summary

- We suggested a new model based on classically scale invariance.
  - Strongly interacting hidden sector with the scalar field
  - Explain the mechanism of generation of "scale"
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"Scalegenesis" is realized!

- Dark matter candidate exists.
- The EW 1st order phase transition

Prospects

- The impacts of higher order operators
- More precise analysis is needed.
  - Lattice simulation
- Why is the scale transition 1st order?
- Is the hidden sector UV complete?
  - Working with H. Goto and H. Kawauchi
- C and CP violation

Appendix

Hierarchy problem

- Nothing between Λ_{EW} and Λ_{pl}?
  - $\Lambda_{\mathrm{EW}} \sim \mathcal{O}(10^2)\ \mathrm{GeV} \Leftrightarrow \Lambda_{\mathrm{pl}} \sim \mathcal{O}(10^{19})\ \mathrm{GeV}$
- Fine-tuning problem

$$m_R^2 = m_0^2 - \left(\frac{\lambda}{16\pi^2} + \cdots \right) \Lambda_{\mathrm{pl}}^2$$

$$(10^2\ \mathrm{GeV})^2 \ = \ (10^{19}\ \mathrm{GeV})^2 \ - \ (10^{19}\ \mathrm{GeV})^2$$

- Fermion and gauge field have not the problem.
  - Gauge symmetry: $m_0^2 A_\mu A^\mu$ $\qquad m_Z^2 \propto \langle h \rangle^2 \sim \Lambda_{\mathrm{EW}}^2$
  - Chiral symmetry: $m_0 \bar{\psi}\psi$ $\qquad m_q^2 \propto \langle \bar{\psi}\psi \rangle \sim \Lambda_{\mathrm{QCD}}^2$

Argument by Bardeen

W.A. Bardeen, On naturalness in the standard model, **FERMILAB-CONF-95-391** (1995).

- The quadratic divergences are spurious.
  - Λ always is subtracted by renormalization.
  - The dimensional regularization automatically subtracts the quadratic divergence.

- Only logarithmic terms related to the scale anomaly survive in the perturbation.

→ The non-zero beta function $\beta \neq 0$

Argument by Bardeen

W.A. Bardeen, On naturalness in the standard model, **FERMILAB-CONF-95-391** (1995).

- The RG equation of Higgs mass

$$\frac{dm^2}{d\log\mu} = \frac{m^2}{16\pi^2}\left(12\lambda + 6y_t^2 - \frac{9}{2}g^2 - \frac{3}{2}g_1^2\right)$$

  - If $m(\Lambda_{\mathrm{pl}}) = 0$, the mass dose not run.

- If the Higgs field is coupled to a new particle with mass M,

$$m_R^2 = m_0^2 + \frac{\lambda'}{16\pi^2}M^2\log\left(\frac{\mu^2}{M^2}\right) + \cdots$$

  - If $M \sim \mathcal{O}(\mathrm{TeV})$, fine-tuning is not needed.
    - Even if so, the origin of m_0 with TeV order is unknow.
  - If $M \gg \mathrm{TeV}$, fine-tuning problem appears.

Classical scale invariance

- The classical scale invariance prohibits m_0.
  - Boundary condition: $m_0 = m(\Lambda_{\rm pl}) = 0$
- The origin of observed mass is radiative corrections with TeV scale.

$$m_R^2 = \frac{\lambda'}{16\pi^2} M^2 \log\left(\frac{\mu^2}{M^2}\right)$$

- The classical scale invariance is one of candidates for the solution of fine-tuning problem.

How to generate radiative corrections?

Two ways

- Perturbative way
  - Coleman-Weinberg mechanism
  - Scale anomaly
  - e.g. **CW potential**

- Non-perturbative way
  - Strong dynamics
  - The mass dynamically is generated.
  - e.g. **chiral symmetry breaking**

Advantages of our model

- The number of parameters is less.
- The mediator is the strongly interacting particle.
  - Observing the hidden sector is easier than other models such as the hidden (quark) model.
    - $<\bar{\psi}\psi>\to<S>\to m_H\to<h>$
    - $<S^\dagger S>\to m_H\to<h>$
  - The DM candidate is CP even.
    - c.f. The DM in hidden (quark) QCD is CP odd.
- Strong 1st order of EW phase transition can be realized.(will see later)

Comparison

$\mathcal{L}_{\mathrm{HQCD}}$	Scale invariant	$\mathcal{L}_{\mathrm{QCD}}$	Chiral invariant

Effective model

$$V_{\mathrm{eff}} = \lambda_S (S_i^\dagger S_i)(S_j^\dagger S_j) + \lambda'_S (S_i^\dagger S_j)(S_j^\dagger S_i) - \lambda_{HS}(H^\dagger H)(S^\dagger S)$$

$$V_{\mathrm{eff}} = G[(\bar{\psi}\psi)^2 + (\bar{\psi} i \gamma^5 \tau^\alpha \psi)^2]$$

Order parameter

$$\langle S^\dagger S \rangle \neq 0$$

$$\langle \bar{\psi}\psi \rangle \neq 0$$

meson

σ ϕ^α | σ π^α

Strong interaction is difficult…

- It is hard to analytically solve the strongly interacting system.
- In QCD, effective model approaches are successful.
  - e.g. Nambu—Jona-Lasinio (NJL) model for DχSB

- We formulate an effective theory of our model.

How to formulate?

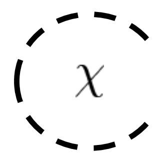
- An effective model describing dynamical scale symmetry breaking (DSSB)
- Scale invariance is broken by scale anomaly.
- The breaking is only logarithmic.
  - The non-perturbative scale breaking due to the condensation $< S^\dagger S > \neq 0$ is dominant.
  - Ignore the breaking by scale anomaly.

Effective potential

- The mean-field approximated effective potential
  - Integrate out χ (Gauss integral) $\quad S_i \to S_i + \chi_i$

$$V_{\rm MFA} = M^2 (S_i^\dagger S_i) + \lambda_{\rm H} (H^\dagger H)^2 \\ - N_{\rm f}(N_{\rm f}\lambda_S + \lambda'_S) f^2 + \frac{N_{\rm f} N_{\rm c}}{32\pi^2} M^4 \ln \frac{M^2}{\Lambda_H^2}$$

$$M^2 = 2(N_{\rm f}\lambda_S + \lambda'_S) f - \lambda_{HS} H^\dagger H$$

Tr log 

$\overline{\rm MS}$ scheme

- Solving the gap equations

$$\langle S \rangle = 0, \quad \langle f \rangle \neq 0, \quad \langle H \rangle \neq 0$$

Input & free parameters

- Input
  - Higgs mass $m_{\rm H} = 126 \text{ GeV}$
  - EW vacuum $\langle h \rangle = 246 \text{ GeV}$
  - DM relic abundance $\Omega \hat{h}^2 \sim 0.12$

- 7 free parameters.

$$\lambda_S \quad \lambda'_S \quad \lambda_{HS} \quad \lambda_H$$

$$N_{\rm f} \quad N_{\rm c} \quad \Lambda_H$$

Where is the vacuum?

- Minimum of $V_{\rm MFA}$; Solving gap equations:

$$\frac{\partial}{\partial S_i^a} V_{\rm MFA} = 0, \quad \frac{\partial}{\partial f} V_{\rm MFA} = 0, \quad \frac{\partial}{\partial H} V_{\rm MFA} = 0$$

- Three solutions:

i. $< S_i^a > \neq 0, < M^2 > = 0, G = 0$

ii. $< S_i^a > = 0, < M^2 > = 0$ → $\langle V_{\rm eff} \rangle = 0$

iii. $< S_i^a > = 0, < M^2 > \neq 0, G > 0$ → $\langle V_{\rm eff} \rangle < 0$

$$M^2 = 2(N_{\rm f}\lambda_S + \lambda'_S) f - \lambda_{HS} H^\dagger H$$

$$G = 4N_{\rm f}\lambda_H\lambda_S - N_{\rm f}\lambda_{HS}^2 + 4\lambda_H\lambda'_S$$

The solution (iii) is suitable.

Solutions

- The vacuum of Higgs

$$\langle h \rangle = \frac{N_{\rm f}\lambda_{HS}}{G}\Lambda_H^2 \exp\left(\frac{32\pi^2\lambda_H}{N_c G} - \frac{1}{2}\right)$$

- The scalar condensate

$$\langle S^\dagger S \rangle = \langle f \rangle = \frac{2\lambda_H}{G}\Lambda_H^2 \exp\left(\frac{32\pi^2\lambda_H}{N_c G} - \frac{1}{2}\right)$$

- Constituent scalar mass

$$M^2 = \Lambda_H^2 \exp\left(\frac{32\pi^2\lambda_H}{N_c G} - \frac{1}{2}\right)$$

$$G = 4N_{\rm f}\lambda_H\lambda_S - N_{\rm f}\lambda_{HS}^2 + 4\lambda_H\lambda_S'$$

Summary so far

Planck — Scale invariant standard model & hidden sector

$$\mathcal{L}_{\mathrm{SM}}\big|_{m_{\mathrm{H}\to 0}} + \mathcal{L}_{\mathrm{HQCD}}$$

Described by the effective model

$$\mathcal{L}_{\mathrm{SM}}\big|_{m_{\mathrm{H}\to 0}} + \mathcal{L}_{\mathrm{eff}}$$

TeV Λ_H — Dynamical scale symmetry breaking

$$\langle S^\dagger S \rangle \neq 0$$

Λ_{EW} — Electroweak symmetry breaking

$$\langle h \rangle \neq 0$$

How to evaluate physical values?

Review: T. Hatsuda and T. Kunihiro, Phys. Rep. 247 221 (1994)

- Mean-field approximation (MFA)
  - Many body system is reduced to 1 body system.
  - Methods:

1. Introduce a "BCS" vacuum $|\Omega\rangle$ and a mean field:

$$f_{ij} \equiv \langle\Omega|S_i^\dagger S_j|\Omega\rangle$$

2. Apply the following replacements to $\mathcal{L}_{\mathrm{eff}}$

$$(S_i^\dagger S_j)(S_j^\dagger S_i) \rightarrow :(S_i^\dagger S_j)(S_j^\dagger S_i): + 2f_{ij}(S_j^\dagger S_i) - |f_{ij}|^2$$

Normal ordering

3. We obtain

$$\langle\Omega| :\mathcal{L}_{\mathrm{Int}}: |\Omega\rangle = 0$$

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{MFA}} + :\mathcal{L}_{\mathrm{Int}}:$$

Mean-field approximation

- Bogoliubov-Valatin vacuum $|\Omega\rangle$

$$\langle\Omega|(S_i^\dagger S_j)|\Omega\rangle = f_0\delta_{ij} + Z_\sigma^{1/2}\delta_{ij}\sigma + Z_\phi^{1/2} t_{ji}^\alpha \phi^\alpha$$

$$\langle S_i S_j\rangle = \left\langle \sum_{a=1}^{N_c} S_i^a S_j^a \right\rangle$$

- Wick contractions

$$\langle\Omega| : \mathcal{O} : |\Omega\rangle = 0$$

$$(S_i^\dagger S_j) =: (S_i^\dagger S_j) : + f_{ij}$$

$$(S_i^\dagger S_j)(S_j S_i) =: (S_i^\dagger S_j)(S_j^\dagger S_i) : + 2 f_{ij}(S_j^\dagger S_i) - |f_{ij}|^2$$

Mean-field approximation

- Lagrangian $\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{MFA}} + \mathcal{L}_I$

$$\langle \Omega | \mathcal{L}_I | \Omega \rangle = 0$$

$$\begin{aligned}\mathcal{L}_{\mathrm{MFA}} = (\partial^\mu S^\dagger \partial_\mu S) - M^2 (S_i^\dagger S_j) \\ + N_f (N_f \lambda_S + \lambda_S') Z_\sigma \sigma^2 + \frac{\lambda_S'}{2} Z_\phi \phi^\alpha \phi^\alpha \\ - 2(N_f \lambda_S + \lambda_S') Z_\sigma^{1/2} \sigma (S_i^\dagger S_i) - 2\lambda_S' Z_\phi^{1/2} (S_i^\dagger t_{ij}^\alpha \phi^\alpha S_j) \\ + \lambda_{HS} (S_i^\dagger S_i) H^\dagger H - \lambda_H (H^\dagger H)^2\end{aligned}$$

- Constituent scalar mass

$$M^2 = 2(N_f \lambda_S + \lambda_S') f - \lambda_{HS} H^\dagger H$$

Effective potential

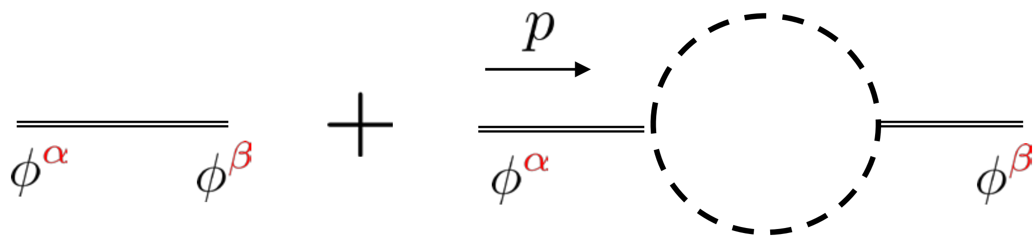
$$V_{\mathrm{MFA}} = M^2(S_i^\dagger S_i) + \lambda_H (H^\dagger H)^2 - N_f(N_f\lambda_S + \lambda'_S) f^2 + \frac{N_c N_f}{32\pi^2} M^4 \log\frac{M^2}{\Lambda_H^2}$$

$$H = \begin{pmatrix} \chi^+ \\ \langle h \rangle + h + i\chi^0 \end{pmatrix}$$

Mass of dark matter

- Mass = a pole of two point function
  - Inverse two point function of ϕ^{α} (dark matter)

$$\Gamma^{\alpha\beta}_{\phi\phi}(p^2) =$$



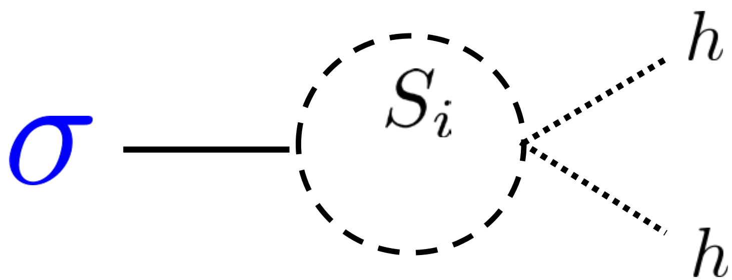
$$= \delta^{\alpha\beta}\left[Z_{\phi}\lambda'_S + Z_{\phi}\lambda'^2_S N_c \Gamma(p^2)\right]$$

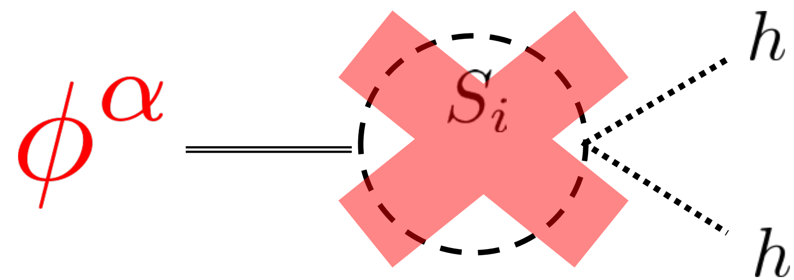
  - Find zero

$$\Gamma^{\alpha\beta}_{\phi\phi}(p^2 = m^2_{\rm DM}) = 0$$

Dark matter candidate is ϕ^{α}

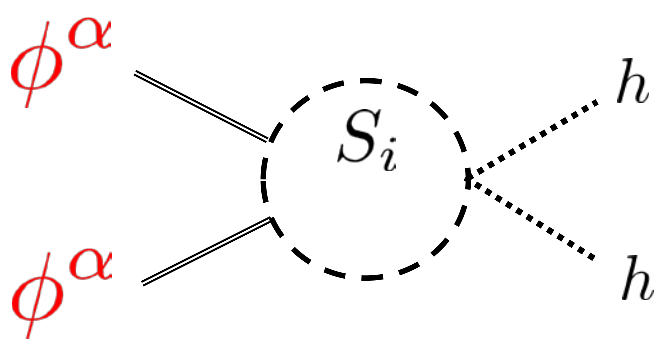
- Decay into Higgs through S loop



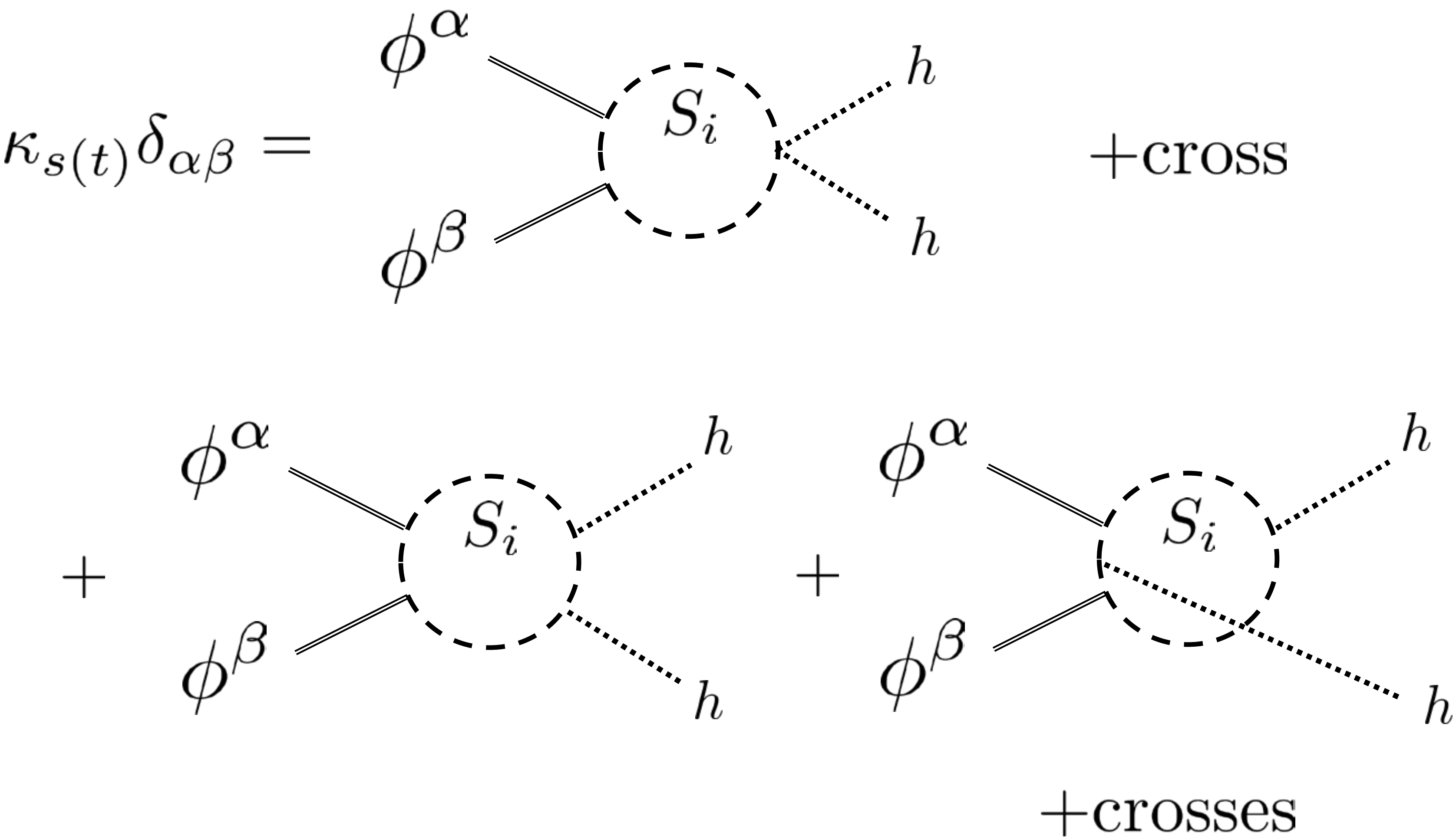


Forbidden by flavor symmetry

- Coannihilation



Coannahilation



Velocity averaged annihilation cross section

$$\langle v\sigma \rangle = \frac{1}{32\pi m_{\rm DM}^3} \sum_{I=W,Z,t,h} (m_{\rm DM}^2 - m_I^2)^{1/2} a_I + \mathcal{O}(v^2)$$

$$a_{W(Z)} = 4(2)[\mathrm{Re}(\kappa_s)]^2 \Delta_h^2 m_{W(Z)}^4 \left(3 + 4\frac{m_{\rm DM}^4}{m_{W(Z)}^4} - 4\frac{m_{\rm DM}^2}{m_{W(Z)}^2}\right)$$

$$a_t = 24[\mathrm{Re}(\kappa_s)]^2 \Delta_h^2 m_t^2 (m_{\rm DM}^2 - m_t^2)$$

$$a_h = [\mathrm{Re}(\kappa_s)]^2 \left(1 + 24\lambda_H \Delta_h \frac{m_W^2}{g^2}\right)^2$$

$$\Delta_h = (4m_{\rm DM}^2 - m_h^2)^{-1}$$

Dark matter candidate is ϕ^α

- The excitation fields from the vacuum $< S^\dagger S >$
  - Assume the unbroken $\mathrm{U}(N_\mathrm{f})$ flavor symmetry:

$$\langle\Omega|(S_i^\dagger S_j)|\Omega\rangle = f_0\delta_{ij} + \delta_{ij}Z_\sigma^{\frac{1}{2}}\sigma + t_{ji}^\alpha Z_\phi^{\frac{1}{2}}\phi^\alpha$$

- Mean-field Lagrangian (before integrating S)

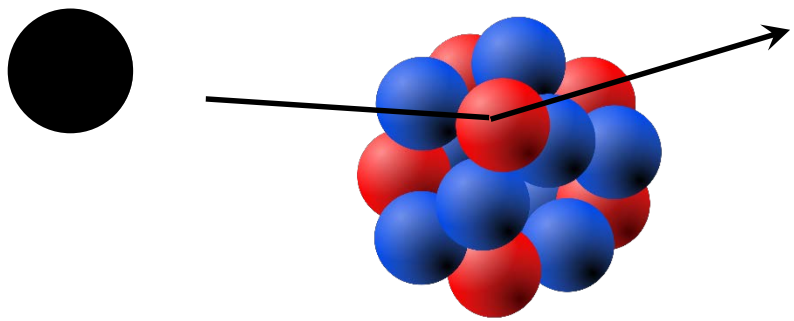
$$\mathcal{L}'_{\mathrm{MFA}} = (\partial_\mu S_i)^2 - M^2(S_i^\dagger S_i) + N_\mathrm{f}(N_\mathrm{f}\lambda_S + \lambda'_S)Z_\sigma\sigma^2 + \frac{\lambda'_S}{2}Z_\phi(\phi^\alpha)^2$$

$$-2(N_\mathrm{f}\lambda_S + \lambda'_S)Z_\sigma^{1/2}\sigma(S_i^\dagger S_i) - 2\lambda'_S Z_\phi^{1/2}(S_i^\dagger t_{ij}^\alpha\phi^\alpha S_j)$$

$$+\lambda_{HS}(S_i^\dagger S_i)H^\dagger H - \lambda_H(H^\dagger H)^2$$

Direct detection

- Scattering off the Nuclei

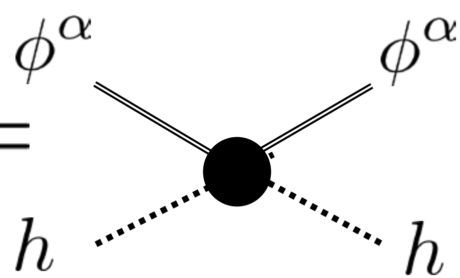


Inverse two-point function

$$\Gamma^{\alpha\beta}_{\phi\phi}(p^2 = m^2_{\rm DM}) = 0$$

  - Spin independent cross section

$$\sigma_{\rm SI} = \frac{1}{4\pi}\left(\frac{\kappa_t \hat{r} m_N^2}{m_{\rm DM} m_h^2}\right)^2 \left(\frac{m_{\rm DM}}{m_N + m_{\rm DM}}\right)^2$$

$\kappa_t =$ 

m_N: nucleon mass

$\hat{r}$: nucleonic matrix element $\hat{r} \sim 0.3$

σ_{SI}

$$\sigma_{\mathrm{SI}} = \frac{1}{4\pi}\left(\frac{\kappa_t \hat{r} m_N^2}{m_{\mathrm{DM}} m_h^2}\right)^2 \left(\frac{m_{\mathrm{DM}}}{m_N + m_{\mathrm{DM}}}\right)^2$$

$$\hat{r} \sim 0.3$$

Dark matter relic abundance

- DM relic abundance

$$\Omega \hat{h}^2 = (N_f^2 - 1)\frac{Y_\infty s_0 m_{\rm DM}}{\rho_c/\hat{h}^2}$$

  - Entropy density

$$s_0 = 2890 \text{ cm}^{-3}$$

  - Critical density/Hubble parameter

$$\rho_c/\hat{h}^2 = 1.05 \times 10^{-5} \text{ GeV cm}^{-3}$$

  - DM number density

$$g_* = 106.75 + N_f^2 - 1$$

$$\frac{dY}{dx} = -0.264 g_*^{1/2} \frac{m_{\rm DM} M_{\rm pl}}{x^2} \langle \sigma v \rangle (Y^2 - \bar{Y}^2)$$

At finite temperature

- Momentum integral

$$\int \frac{d^4p}{(2\pi)^4} f(p_0, \vec{p}) \quad \Rightarrow \quad T \sum_{n=-\infty}^{\infty} \int \frac{d^3p}{(2\pi)^3} f(\omega_n, \vec{p})$$

  - Matsubara frequency

$$\omega_n = \begin{cases} 2n\pi T & \text{(boson loop)} \\ (2n+1)\pi T & \text{(fermion loop)} \end{cases}$$

Effective potential

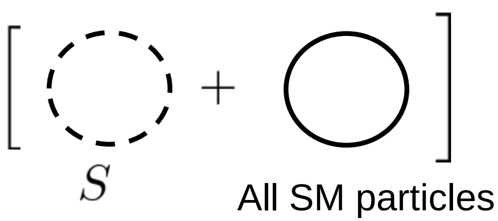
- There are four components.

$$V_{\mathrm{eff}}(f,h;T)=$$

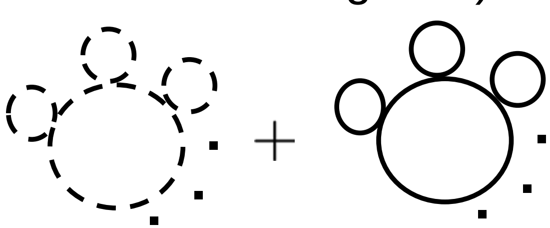
$$V_{\mathrm{MFA}}(f,h)+V_{\mathrm{CW}}(h)$$ ← Zero temp. part

$$+V_{\mathrm{FT}}(f,h;T)+V_{\mathrm{RING}}(h;T)$$ ← Finite temp. part

$$T\sum_{n=-\infty}^{\infty}\int\frac{d^3p}{(2\pi)^3}$$



Summation of thermal mass
(remove the IR divergence)



Phase transition

- V_{eff} at zero temperature

$$V_{\text{eff}}(f,h;T=0) = \quad V_{\text{MFA}}(f,h) + V_{\text{CW}}(h)$$

$$\Rightarrow \langle h \rangle = 246 \text{ GeV} \quad \langle f \rangle \neq 0$$

$$m_{\text{H}} = 126 \text{ GeV}$$

- V_{eff} at critical temperature T_c^{EW}(EWPT)

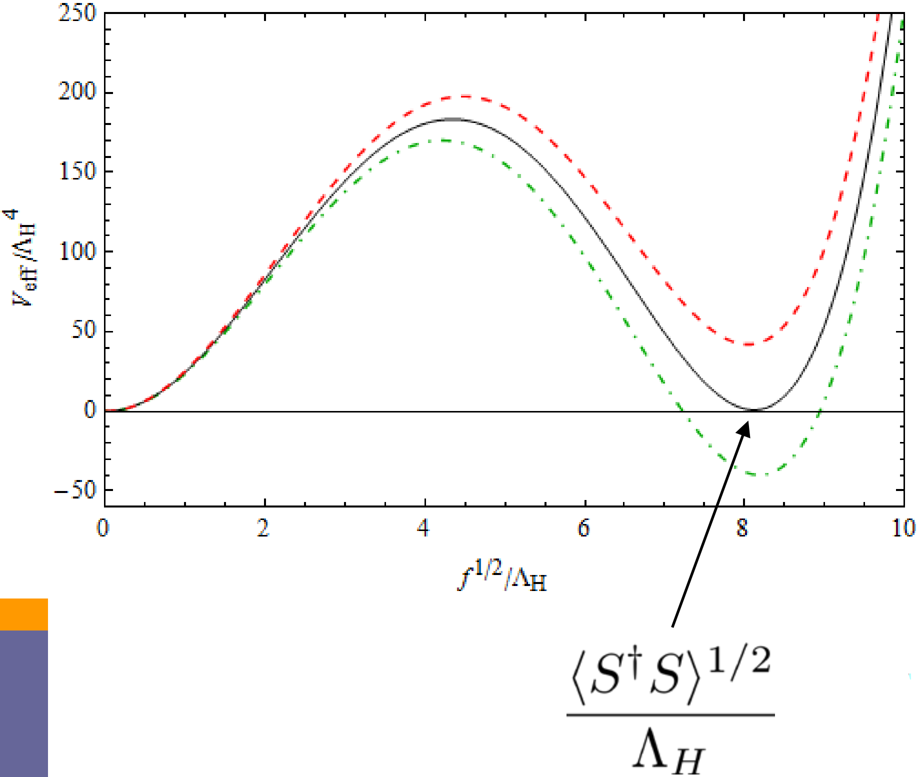
$$V_{\text{eff}}(f,h;T=T_c^{\text{EW}}) \Rightarrow \langle h \rangle = 0$$

- V_{eff} at critical temperature T_c^{SS} (SSPT)

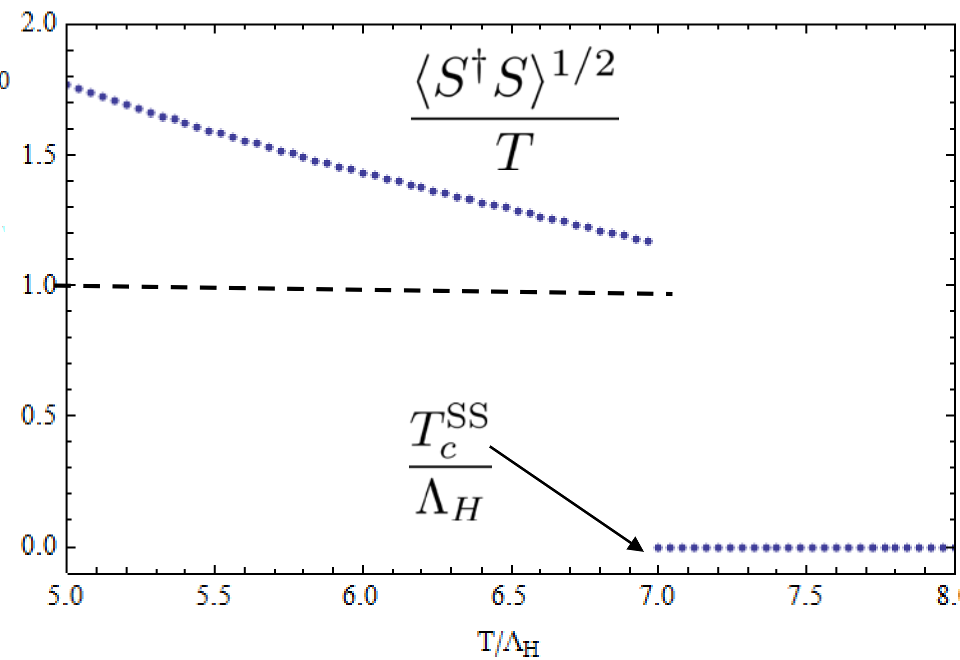
$$V_{\text{eff}}(f,h;T=T_c^{\text{SS}}) \Rightarrow \langle f \rangle = \langle S^\dagger S \rangle = 0$$

Scale transition is strong 1st order.

J, Kubo and **M. Y.**, PTEP **2015** 093B01 (arXiv:1506.06460)



$T_{\rm c}^{\rm SS}/\Lambda_{\rm H} = 7.0$



Difference between two cases

- The Higgs portal is important

$$-\lambda_{HS}(S^\dagger S)H^\dagger H$$

↑ $\lambda_{\rm HS}$ EW-PT is triggered. $\Omega\hat{h}^2 \sim 0.12$ ✗

↓ $\lambda_{\rm HS}$ Not enough to trigger $\Omega\hat{h}^2 \sim 0.12$ ○

- Need more precisely analysis