The Fate of Chiral Gauge Theories

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Why Chiral Gauge theories (CGTs)

- High Energy Physics:

  -- Asymptotic free, no mass scale, one parameter in the theory

  -- Original SU(5) GUT is a strongly coupled chiral gauge theory

  -- Composite Higgs models for solving the Hierachy problem

- Condense Matter Physics:

  -- Quantum Hall Effects, Chiral Magnetic effects, Luttinger liquid…

  -- Symmetric Mass generation → Helps put chiral guage theory on lattice by gapping the fermion-doubler [D. Tong 2104.03997], and see [Wang, You, 2204.14271] for a review

- Crucial to study the phase of CGTs:

  Conformal? Confinement? Dynamical Symmetry Breaking?

Tools for vector-like theories

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  -- vector-like symmetry cannot be broken

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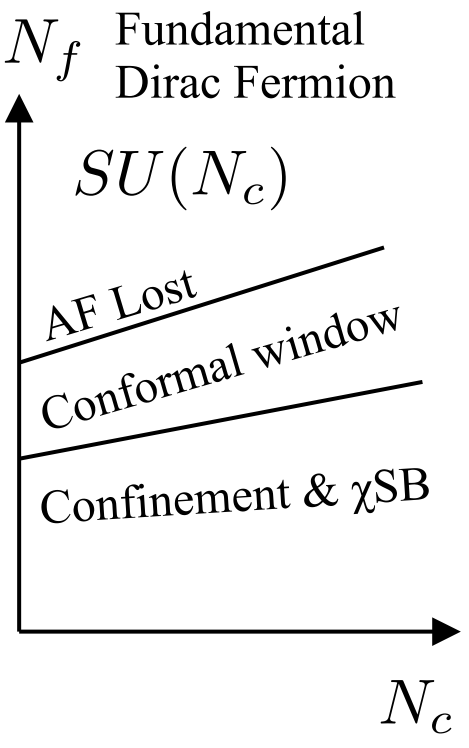

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  -- Different gauge representations, different Nc dependence

- Lattice Experiment

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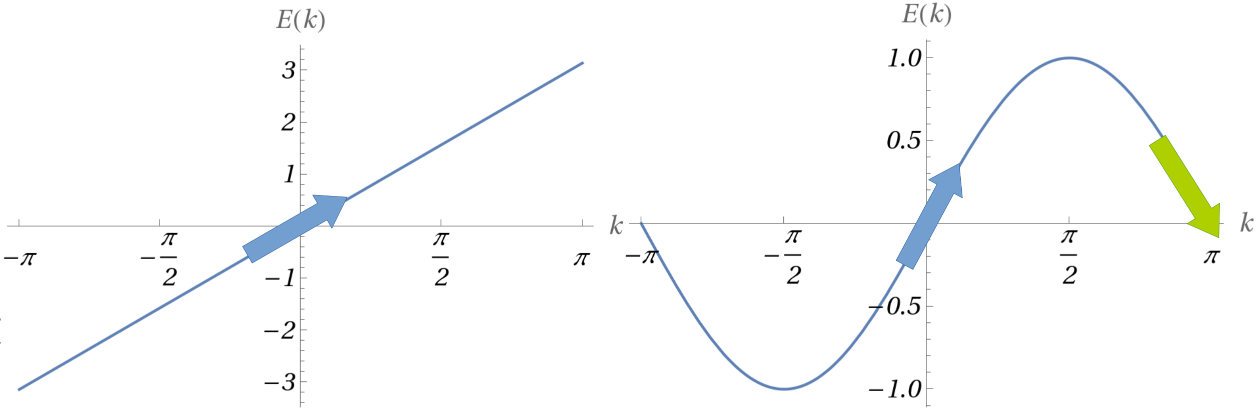

- Lattice Experiment fermion-doubler, Nielsen-Ninomiya theorem

The toy model

Georgi-Glashow model:

	$SU(N_c)$	Flavor
χ	$\begin{array}{c}\square\\[-2pt]\square\end{array}$	1
ψ	$\overline{\square}$	$N_c - 4$

The Global symmetry: $SU\left(N_c - 4\right) \times U\left(1\right)$

Baryon: $\mathcal{B} = A\left\{\bar{F}\bar{F}\right\}$ Match the t'Hooft anomaly

The toy model

General Georgi-Glashow model:

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$\times N_g$

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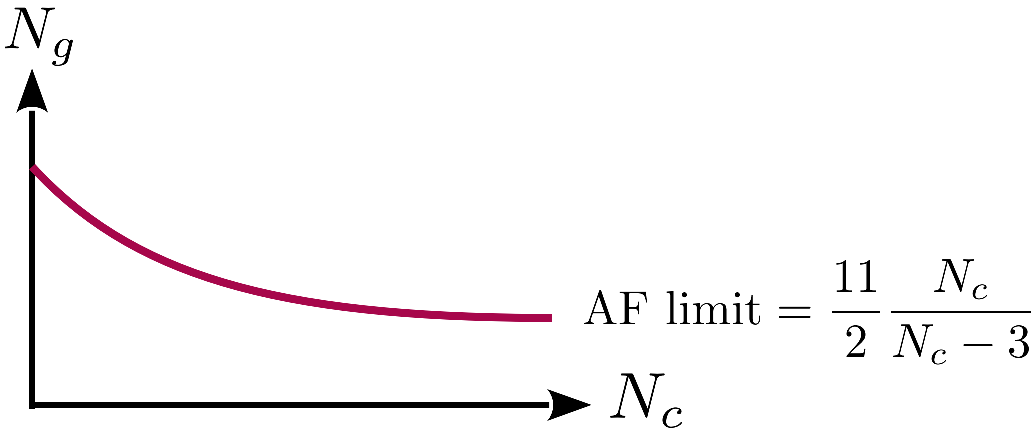


The tool: Functional renormalization group method

- Functional Renormalization Group:
  a non-perturbative method widely used in QCD

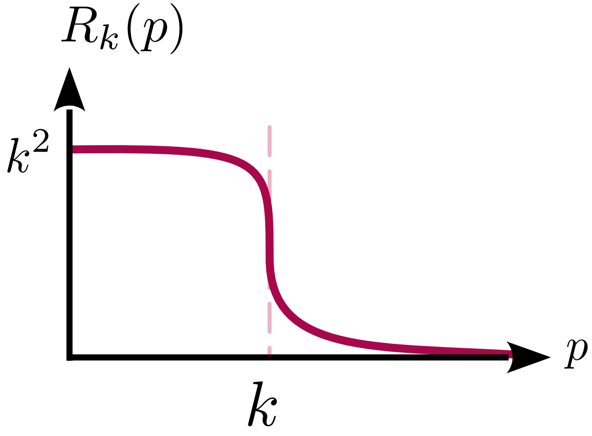
See Dupuis,et.al [2006.04853] for a reivew

- Basic idea: effective average action: $\Gamma_k[\phi]$

$$\int [\mathcal{D}\phi]_{p>k} = \int \mathcal{D}\phi \, \exp\left(-\Delta S_k[\phi]\right) \qquad \Delta S_k[\phi] = \int_p \phi(p) R_k \phi(-p)$$

$$\Gamma_k[\phi] = \int_x J(x)\phi(x) - \mathcal{W}_k[J] - \Delta S_k[\phi]$$

IR cutoff scale: $k \sim T \sim \langle p \rangle$



The tool: Functional renormalization group method

Master formula:

Wetterich '93

$$\partial_t \Gamma_k[\phi] = \frac{1}{2}\mathrm{Tr}\left[\frac{1}{\Gamma_k^{(2)} + R_k}\partial_t R_k\right]$$

$\partial_t \equiv k\partial_k$

$$\partial_t \Gamma^{(1)}{}_k = -\frac{1}{2}\mathrm{STr}\ \Gamma^{(3)}{}_k \quad \frac{\partial_t R_k}{\Gamma^{(2)} + R_k}$$

Both UV and IR finite

$$\partial_t \Gamma^{(2)}{}_k = -\frac{1}{2}\mathrm{STr}\ \left[\Gamma^{(4)}{}_k - 2\Gamma^{(3)}{}_k\Gamma^{(2)}{}_k\Gamma^{(3)}{}_k\right] \frac{\partial_t R_k}{\Gamma^{(2)} + R_k}$$

⋮

Infinite tower of flow equation, needs to truncate $\Gamma_k^{(i>n_{\max})} = 0$

We choose $n_{\max} = 4$, enough to capture the fermion condensates

The tool: Functional renormalization group method

Truncated effactive action:

$$\Gamma_k = \int \mathcal{L}_{kin} + \mathcal{L}_{gh} + \mathcal{L}_{gf} + Z_\psi^2 \sum_{i=1}^{2} \lambda_i \mathcal{O}_i + Z_\chi^2 \sum_{i=3}^{5} \lambda_i \mathcal{O}_i + Z_\psi Z_\chi \sum_{i=6}^{7} \lambda_i \mathcal{O}_i$$

$$\lambda_i = \lambda_i(p_m)|_{p_m \to 0}$$

$$\mathcal{O}_1 = (\psi^\dagger \bar{\sigma}^\mu \psi)(\psi^\dagger \bar{\sigma}^\mu \psi)$$

$$\mathcal{O}_2 = (\psi^{\dagger f_1} \bar{\sigma}^\mu \psi_{f_2})(\psi^{\dagger f_2} \bar{\sigma}^\mu \psi_{f_1})$$

$$\mathcal{O}_3 = (\chi^{\dagger f_1} \bar{\sigma}^\mu \chi_{f_2})(\chi^{\dagger f_2} \bar{\sigma}^\mu \chi_{f_1})$$

$$\mathcal{O}_4 = (\chi^\dagger \bar{\sigma}^\mu \chi)(\chi^\dagger \bar{\sigma}^\mu \chi)$$

$$\mathcal{O}_5 = (\chi^\dagger \bar{\sigma}^\mu T_{\mathrm{anti}}\, \chi)(\chi^\dagger \bar{\sigma}^\mu T_{\mathrm{anti}}\, \chi)$$

$$\mathcal{O}_6 = (\psi^\dagger \bar{\sigma}^\mu \psi)(\chi^\dagger \bar{\sigma}^\mu \chi)$$

$$\mathcal{O}_7 = (\psi^\dagger \bar{\sigma}^\mu T_{\mathrm{a-fund}}\, \psi)(\chi^\dagger \bar{\sigma}^\mu T_{\mathrm{anti}}\, \chi)$$

Complete four fermion basis is derived for arbitrary *Ng* and *Nc*. Constructed with Young Tensor Method [**HLL**, et.al. 2005.00008, 2201.04639]

Except for *Ng*=1 and *Nc*=5, where one additional operator is needed:

$$\mathcal{O}_8 = \epsilon_{i_1 i_2 i_3 i_4 i_5} (\chi^{i_1 i_2} \chi^{i_3 i_4})(\chi^{i_5 j} \psi_j)$$

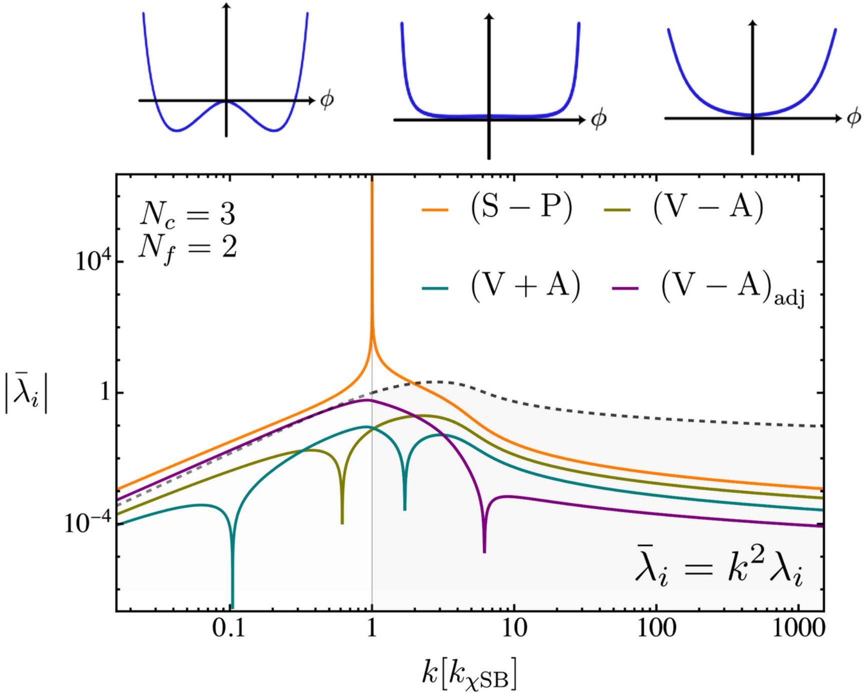
The tool: Functional renormalization group method

How to diagnose Symmetry breaking?

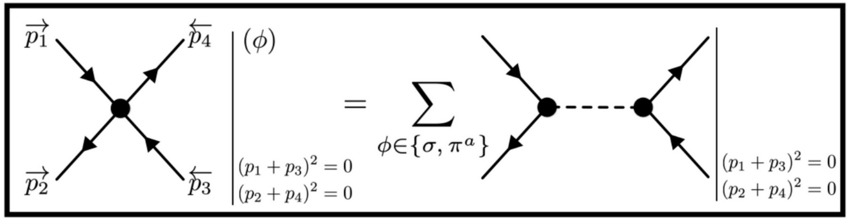
Divergent 4-fermi flow
$(\psi_1\psi_2)(\psi_1\psi_2)$

→

Fermion condensate
$\langle\psi_1\psi_2\rangle \neq 0$



Exact field redefinition Stratonovich'57 Hubbard'59



$\lambda_i \propto 1/m^2_{\phi_i}$ $\qquad m^2_{\phi_i} = \partial_{\phi_i^2} V(\phi_1)$

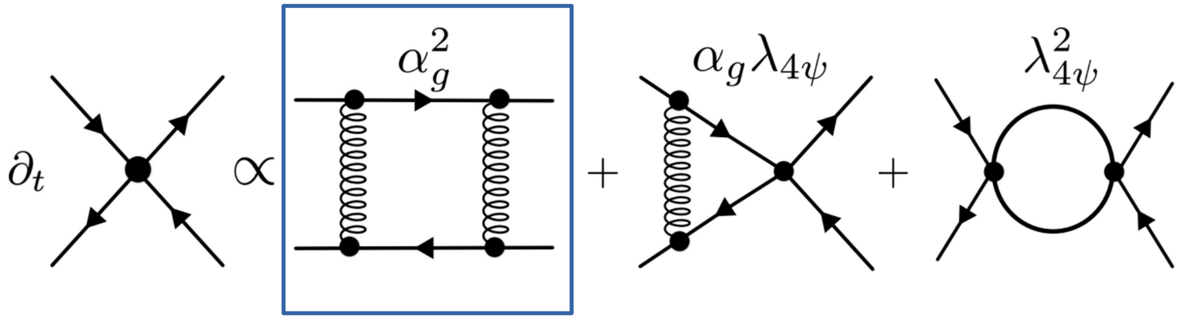
$\lambda_i \to \infty \qquad m^2_{\phi_i} \to 0 \qquad \xi \to \infty$

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

See [2006.04853] for detailed discussion

The tool: Functional renormalization group method

4-fermion flows:



$$\bar{\lambda} = k^2 \lambda$$

$$\partial_t \bar{\lambda}_i \propto 2\,\bar{\lambda}_i + \boldsymbol{c}_{\mathrm{A},i} \cdot \alpha_g^2 + \boldsymbol{c}_{\mathrm{B},ij} \cdot \alpha_g\,\bar{\lambda}_j + \boldsymbol{c}_{\mathrm{C},ijk} \cdot \bar{\lambda}_j \bar{\lambda}_k + \ldots$$

Canonical scaling

The tool: Functional renormalization group method

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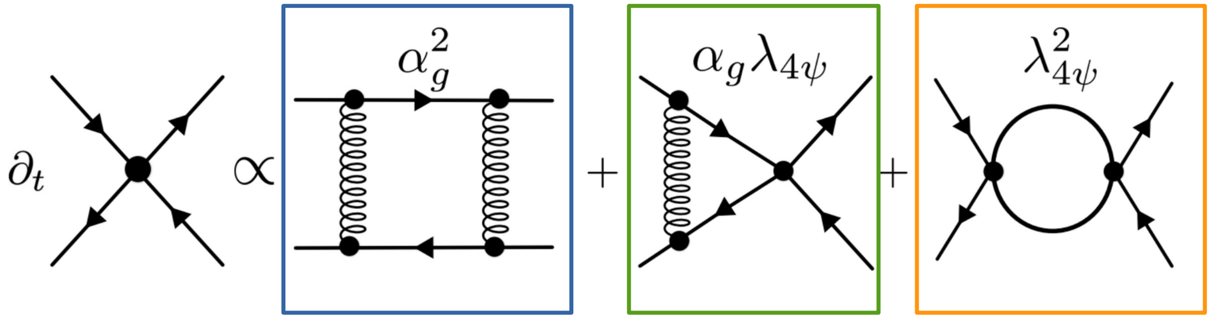

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The tool: Functional renormalization group method

Focus on a $\bar{\lambda}_i$, the flow is a qudratic function of $\bar{\lambda}_i$:

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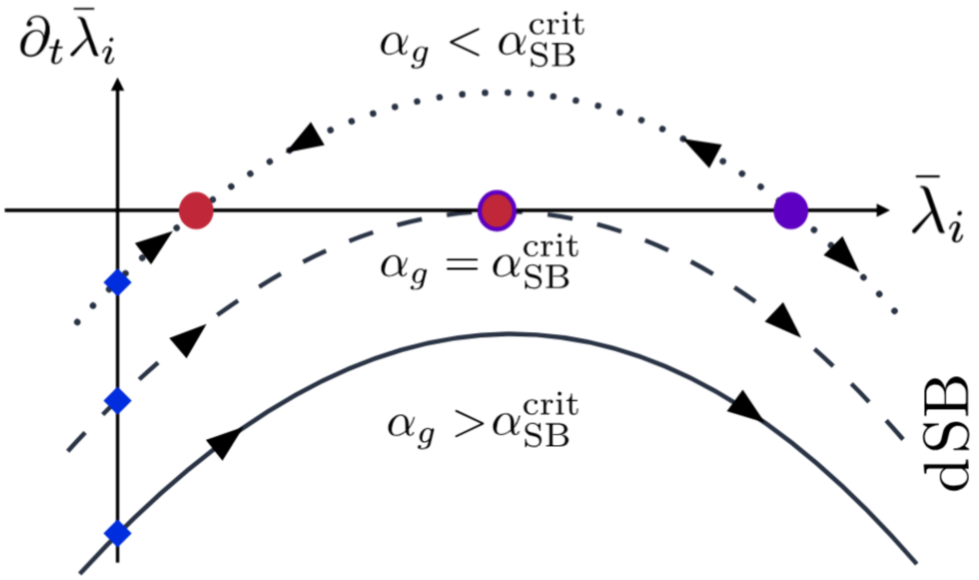

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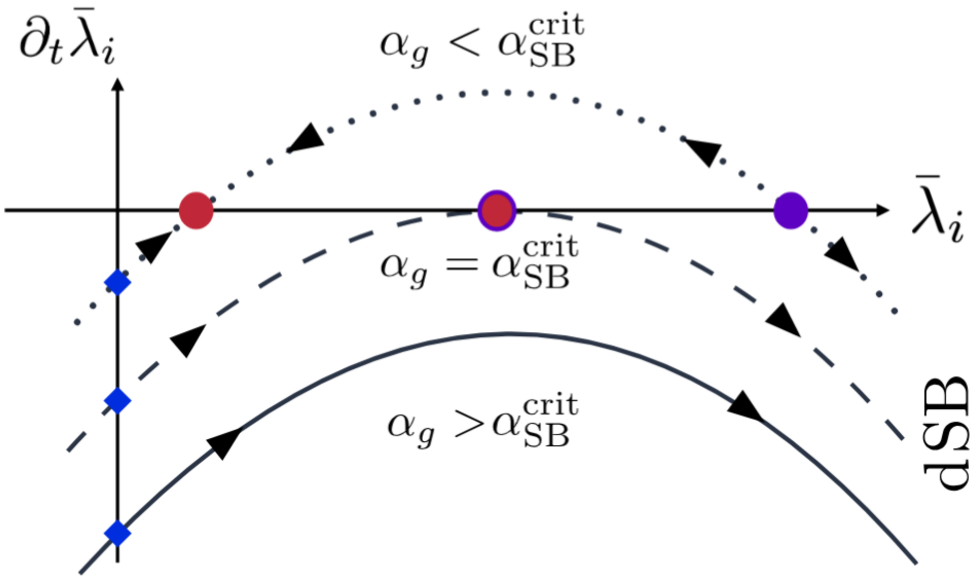

Necessary condition for dSB:

1. reosnant structure (naive)

$$\frac{\boldsymbol{c}_{A,i}}{\boldsymbol{c}_{C,iii}} > 0$$

2. $\alpha_{\mathrm{SB}}^{\mathrm{crit}}$ is reached

The tool: Functional renormalization group method

Technical side

FeynRules:
4-fermion
Feynman Rules

DoFun:
Generate Diagram and
Flow equation

FormTracer
& adapted to:
SU(N) trace algebra
for anti-sym rep

4ψ For example

$$\partial_t \bar{\lambda}_1 = (2 + 2\eta_\psi)\bar{\lambda}_1 + \frac{k^2}{Z_\psi^2} \frac{\partial_t \left[\mathcal{P}_{1,R}^{abcd} \Gamma_k^{(\bar{\psi}_a \psi_b \bar{\psi}_c \psi_d)}\right](N_c N_\psi + 1) - \partial_t \left[\mathcal{P}_{2,R}^{abcd} \Gamma_k^{(\bar{\psi}_a \psi_b \bar{\psi}_c \psi_d)}\right](N_c + N_\psi)}{128 N_c (N_c^2 - 1) N_\psi (N_\psi^2 - 1)},$$

$$\partial_t \bar{\lambda}_2 = (2 + 2\eta_\psi)\bar{\lambda}_2 + \frac{k^2}{Z_\psi^2} \frac{\partial_t \left[\mathcal{P}_{2,R}^{abcd} \Gamma_k^{(\bar{\psi}_a \psi_b \bar{\psi}_c \psi_d)}\right](N_c N_\psi + 1) - \partial_t \left[\mathcal{P}_{1,R}^{abcd} \Gamma_k^{(\bar{\psi}_a \psi_b \bar{\psi}_c \psi_d)}\right](N_c + N_\psi)}{128 N_c (N_c^2 - 1) N_\psi (N_\psi^2 - 1)}.$$

The tool: Functional renormalization group method

$$\partial_t \bar{\lambda}_i \propto 2\,\bar{\lambda}_i + \boldsymbol{c}_{\mathrm{A},i} \cdot \alpha_g^2 + \boldsymbol{c}_{\mathrm{B},ij} \cdot \alpha_g\, \bar{\lambda}_j + \boldsymbol{c}_{\mathrm{C},ijk} \cdot \bar{\lambda}_j \bar{\lambda}_k + \ldots$$

In General GG model: $\boldsymbol{c}_{C,iii} > 0 \quad \forall i$

$$\boldsymbol{c}_{\mathrm{A},\,i} = \frac{9}{2}\Bigg\{ -\frac{1}{4N_c^2} - \frac{3}{16},\ -\frac{N_c^2-8}{16N_c},\ -1,\ \boxed{-1+\frac{4+2N_c}{N_c^2},}\ 1-\frac{N_c}{8}+\frac{4}{N_c},\ \boxed{-1+\frac{N_c+2}{N_c^2},}\ 1-\frac{N_c}{4}+\frac{4}{N_c}\Bigg\}\,.$$

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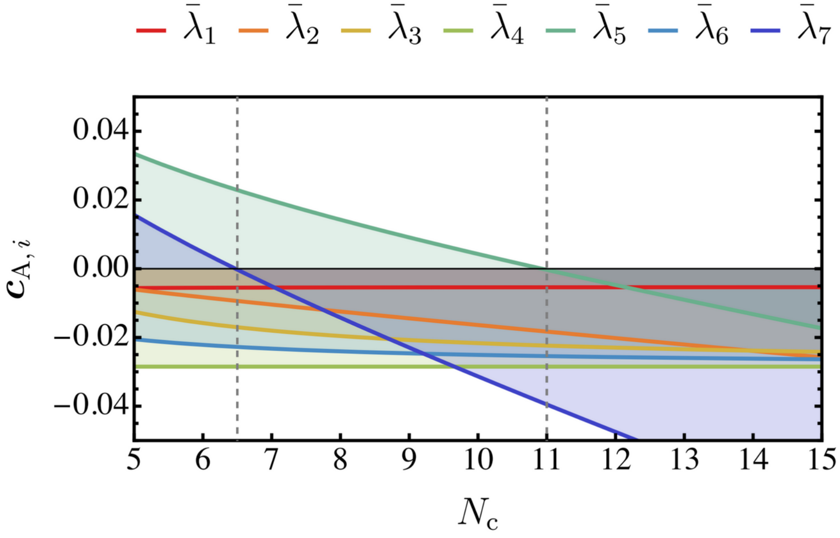
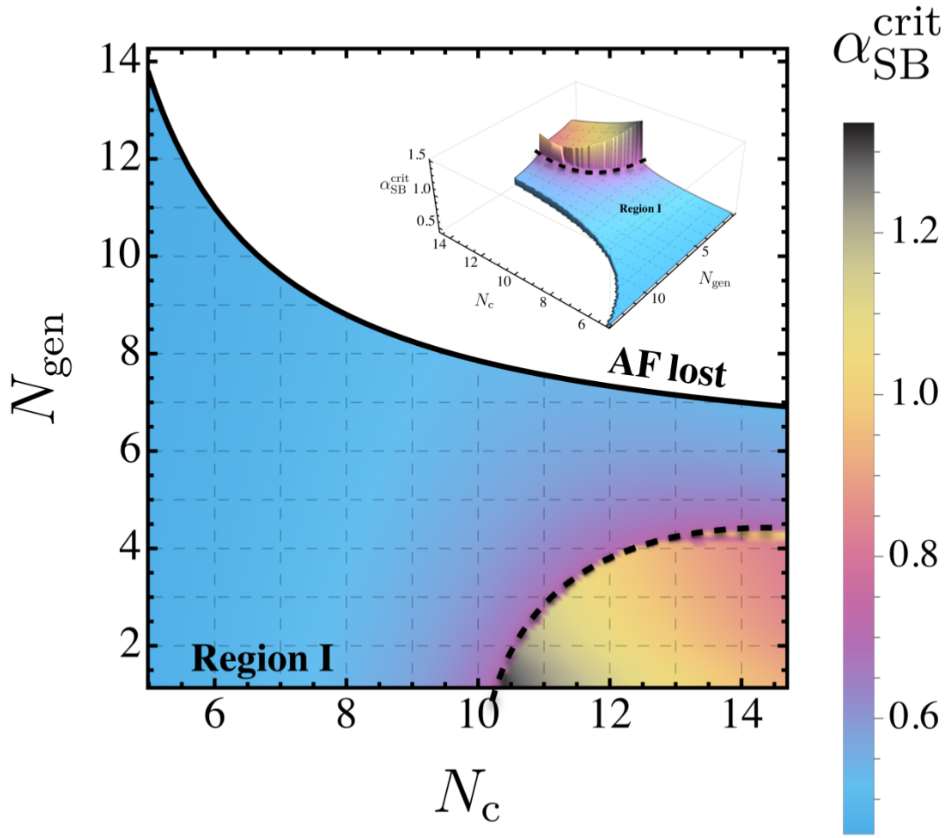


Results



- **Region I:**
  - Weak $\alpha_g^{\rm crit}$: dynamics derivable within perturbation theory
  - Clear dominance of $\mathcal{O}_5 = (\chi^\dagger \bar\sigma^\mu T_{\rm anti}\,\chi)(\chi^\dagger \bar\sigma^\mu T_{\rm anti}\,\chi)$
  - Condensate $\langle \chi\chi \rangle \neq 0$

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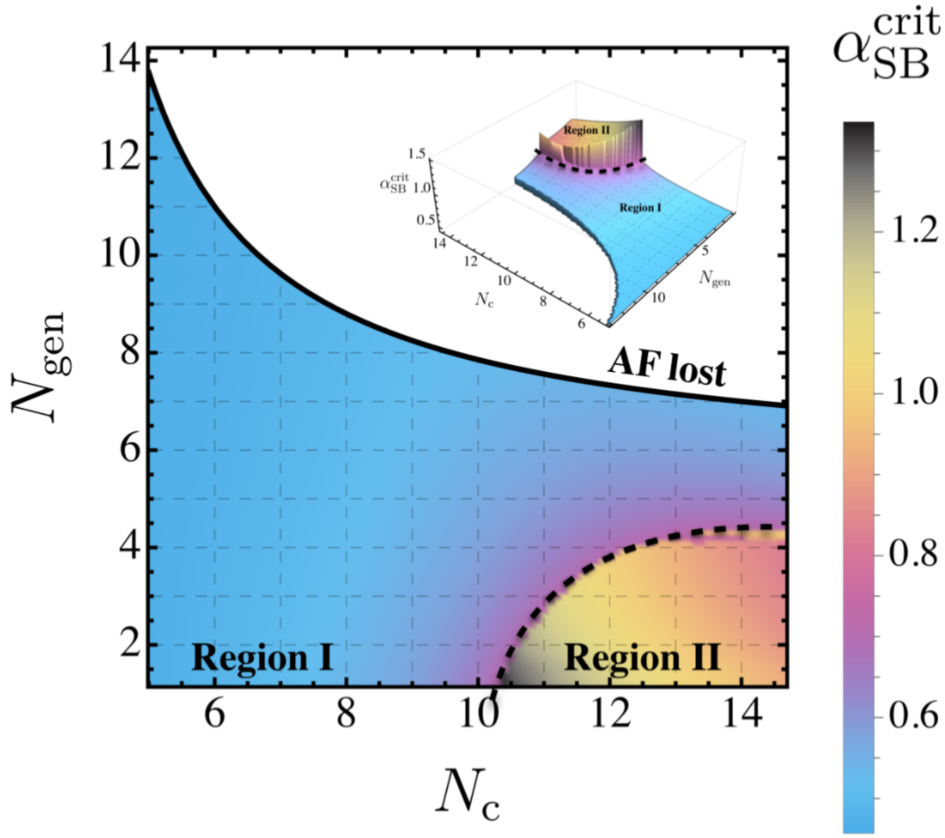

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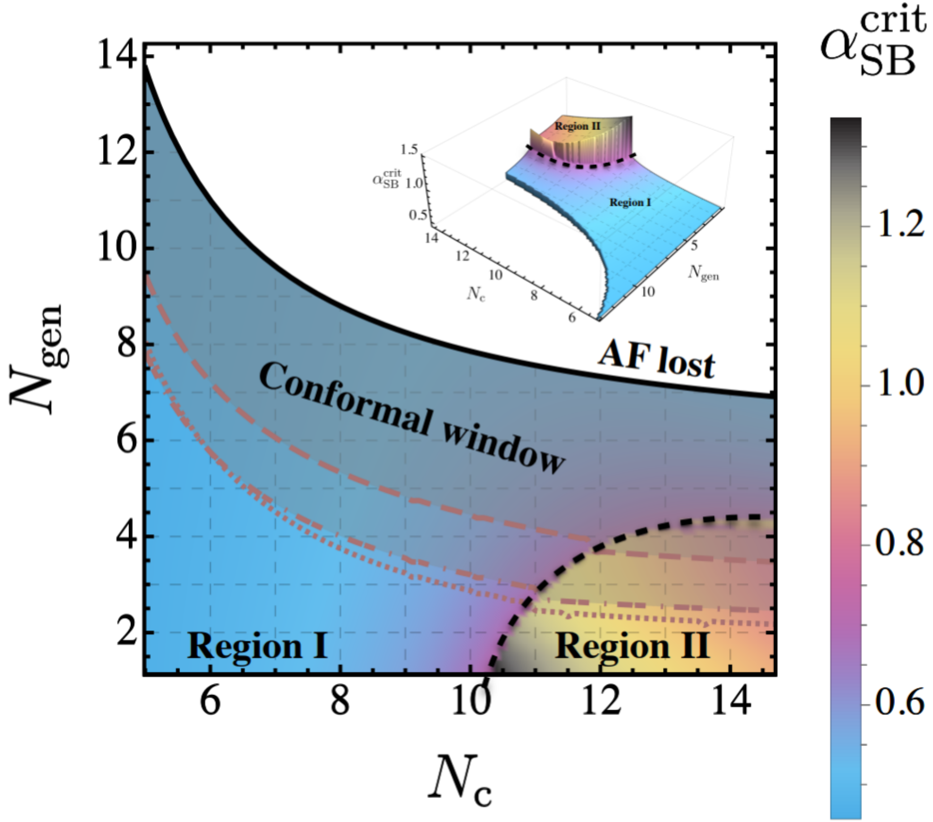

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- **Conformal window:**
  $\alpha_g^{crit} = \alpha_g^*$

$$\begin{cases} \alpha_g^*|_{\overline{\text{MS}}\ 2-\text{loop}} \\ \alpha_g^*|_{\overline{\text{MS}}\ 3-\text{loop}} \\ \alpha_g^*|_{\overline{\text{MS}}\ 4-\text{loop}} \end{cases}$$

New!

Summary

- We find strong evidence for the dSB in General Georgi-Glashow models
- In particular, for $N_c \leq 10$, naive resonance with fixed point merging occurs indicates condensate in the anti-symmetric fermion.
- For $N_c > 10$, α^{crit} is large so might need higher order effects.

Outlook

- Bosonize the theory to find the exact direction of the condensate, i.e. finding the residual symmetry.
- Needs to study the confinement effects, which may suppress the gauge fermion coupling after photon developed a mass gap.

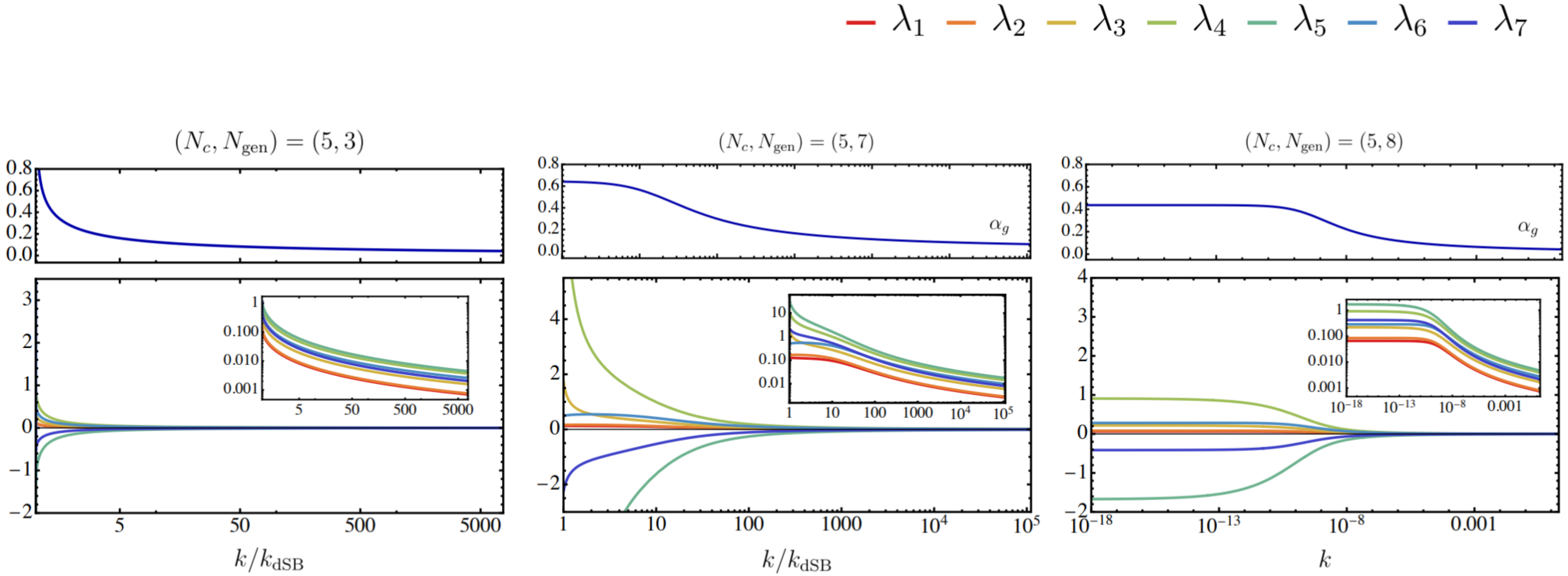
Comparison Ngen=1

MAC: $\langle \chi\psi \rangle$ $N = 5, N \geq 7$ $\langle \chi\chi \rangle$ $\langle \chi\psi \rangle$ $N = 6$

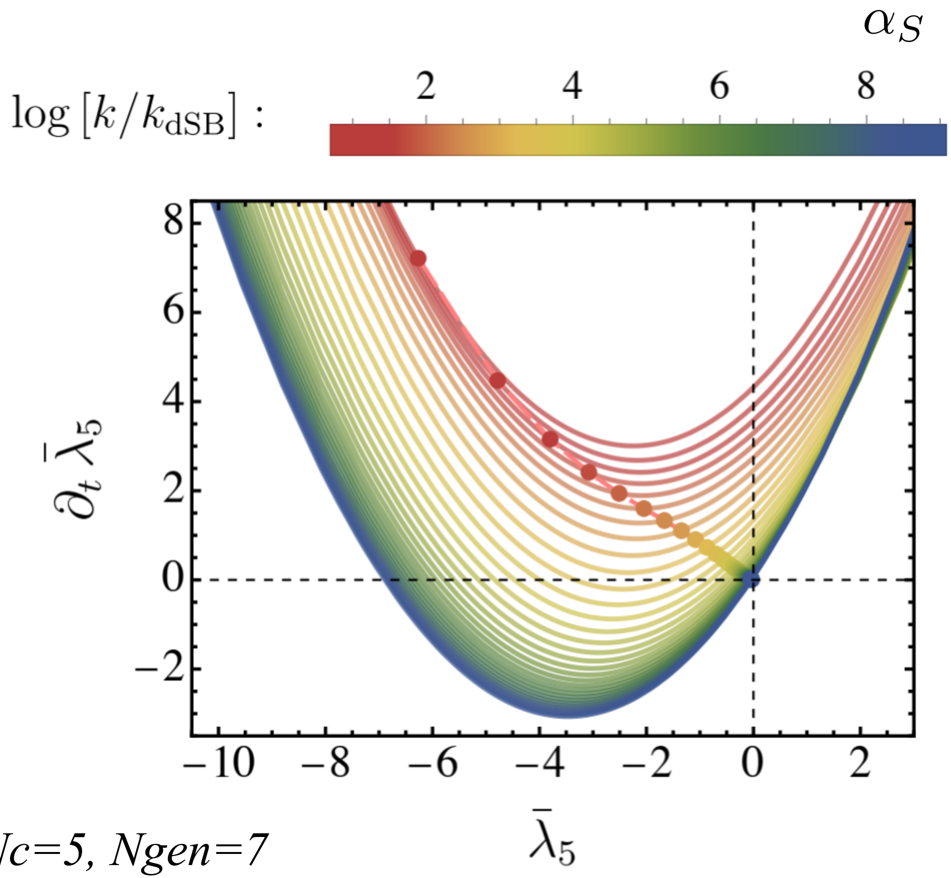
Anomaly matching: $\langle \chi\chi \rangle$ $\langle \chi\psi \rangle$

Anomaly mediated SUSY breaking $\langle \chi\psi \rangle$ $\langle \psi\psi \rangle$

Some result



λ_1 λ_2 λ_3 λ_4 λ_5 λ_6 λ_7
$(N_c, N_{gen}) = (5,3)$
$(N_c, N_{gen}) = (5,7)$
$(N_c, N_{gen}) = (5,8)$
α_g
k/k_{dSB}
k



Nc=5, Ngen=7

$$R_{A,c}(p^2) = Z_\varphi p^2 r_{A,c}(x),$$

$$R_\psi(p^2) = \mathrm{i} Z_\psi \gamma_\mu p_\mu r_\psi(x),$$

$$x = p^2/k^2$$

$$r_{A,c}(x) = (1/x - 1)\theta(1-x),$$

$$r_\psi(x) = (1/\sqrt{x} - 1)\theta(1-x),$$

$$S = \int \bar{\psi} \partial\!\!\!/ \psi - \frac{\lambda}{2}\left(\left(\bar{\psi}\psi\right)^2 - \left(\bar{\psi}\gamma^5\psi\right)^2 \right)$$

$$Z \propto \int \mathcal{D}\bar{\psi}\mathcal{D}\psi e^{S} = \mathcal{N} \int \mathcal{D}\bar{\psi}\mathcal{D}\psi\mathcal{D}\phi \;\; e^{\frac{m^2}{2}\phi^2} \; e^{S}$$

$$\phi = (\sigma, \pi)$$

$$\sigma \to \sigma + y\frac{\bar{\psi}\psi}{\sqrt{2}m^2} \qquad \pi \to \pi + i\, y\frac{\bar{\psi}\gamma^5\psi}{\sqrt{2}m^2}$$

$$Z \propto \mathcal{N} \int \mathcal{D}\bar{\psi}\mathcal{D}\psi\mathcal{D}\phi e^{S_{BF}}$$

$$S_{FB} = \int \bar{\psi}\partial\psi + \frac{y}{\sqrt{2}}\bar{\psi}\left(\sigma + i\pi\gamma^5\right)\psi + \frac{m^2}{2}\left(\sigma^2 + \pi^2\right) \qquad \lambda \equiv \frac{y^2}{2m^2}$$

$$\sigma = \frac{-y}{\sqrt{2}m^2}\bar{\psi}\psi \qquad \pi = \frac{-iy}{\sqrt{2}m^2}\bar{\psi}\gamma^5\psi$$

$$S_{\mathrm{B}} = \int \mathrm{d}^4x \left\{ m^2\phi^*\phi - \ln\det\left[\mathrm{i}\partial\!\!\!/ + h\left(P_{\mathrm{L}}\phi - P_{\mathrm{R}}\phi^*\right)\right]\right\}$$

$$U(1)_A \qquad \begin{pmatrix} \sigma \\ \pi \end{pmatrix} = \begin{pmatrix} \cos 2\alpha & \sin 2\alpha \\ -\sin 2\alpha & \cos 2\alpha \end{pmatrix} \begin{pmatrix} \sigma \\ \pi \end{pmatrix}$$

$$\partial_t \Gamma[\bar{\phi}] = \frac{1}{2} \mathrm{Tr}\, G_k\, \partial_t R_k \,,$$

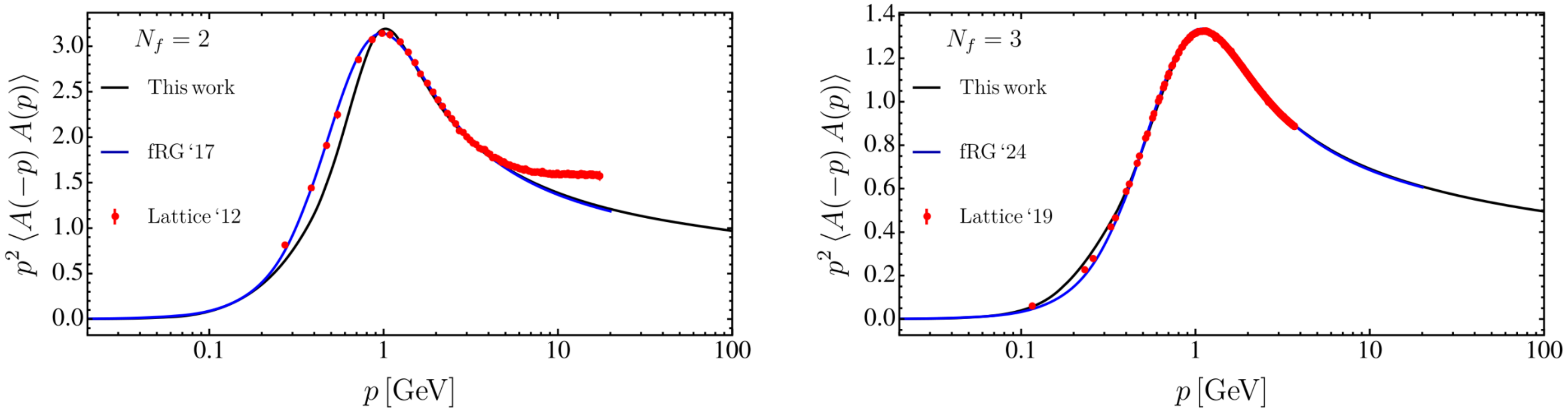
$$\partial_t \Gamma^{(1)}[\bar{\phi}] = -\frac{1}{2} \mathrm{Tr}\, \Gamma_k^{(3)} \left(G_k\, \partial_t R_k\, G_k \right),$$

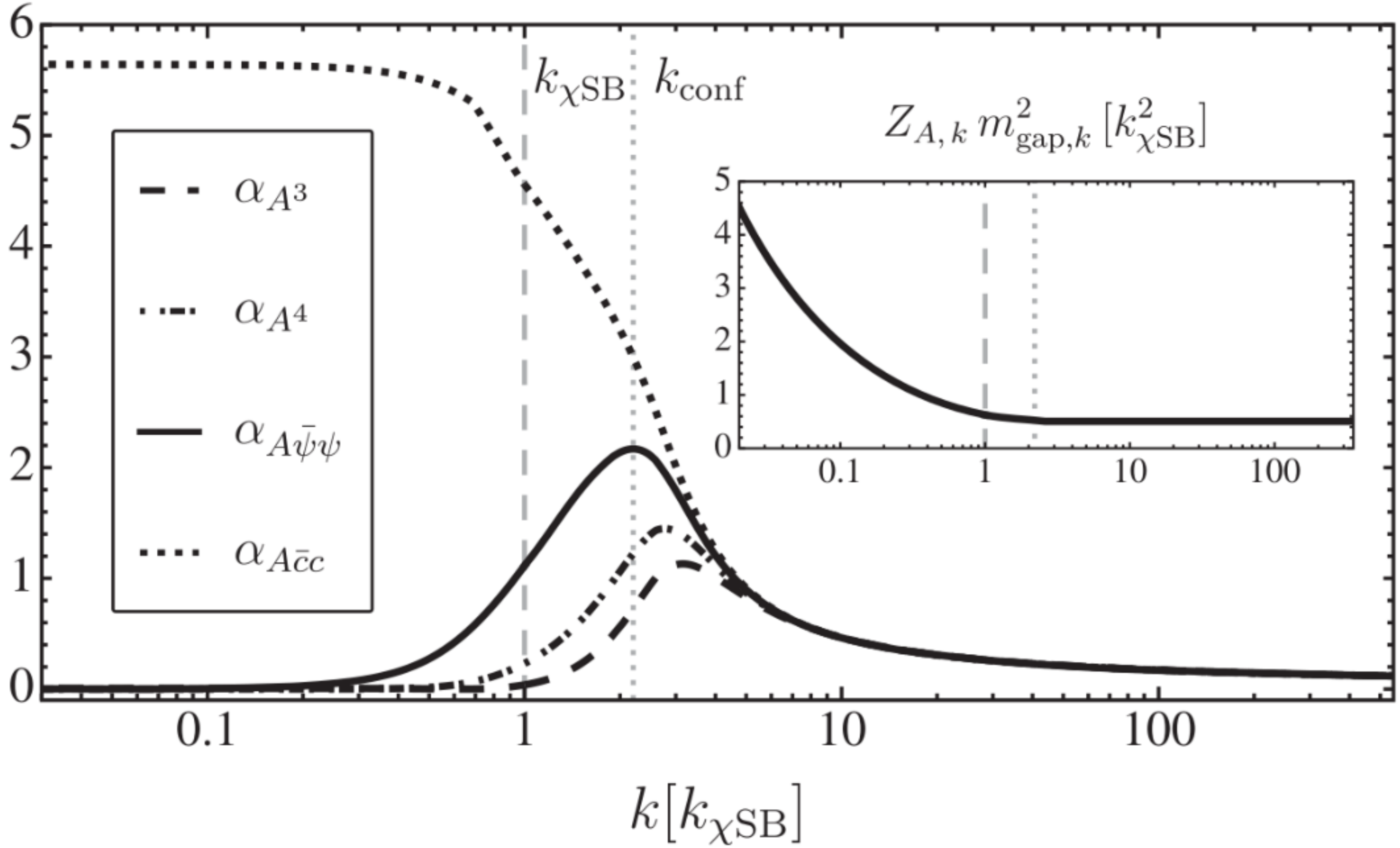
$$\partial_t \Gamma^{(2)}[\bar{\phi}] = -\frac{1}{2} \mathrm{Tr} \left[\Gamma_k^{(4)} - 2\, \Gamma_k^{(3)}\, G_k\, \Gamma_k^{(3)} \right] \left(G_k\, \partial_t R_k\, G_k \right),$$

$$\partial_t \Gamma^{(3)}[\bar{\phi}] = -\frac{1}{2} \mathrm{Tr} \left[\Gamma_k^{(5)} - 6\, \Gamma_k^{(4)}\, G_k\, \Gamma_k^{(3)} + 6\, \Gamma_k^{(3)}\, G_k\, \Gamma_k^{(3)}\, G_k\, \Gamma_k^{(3)} \right] \left(G_k\, \partial_t R_k\, G_k \right),$$

$$\begin{aligned} \partial_t \Gamma^{(4)}[\bar{\phi}] = -\frac{1}{2} \mathrm{Tr} \Big[& \Gamma_k^{(6)} - 8\, \Gamma_k^{(5)}\, G_k\, \Gamma_k^{(3)} - 6\, \Gamma_k^{(4)}\, G_k\, \Gamma_k^{(4)} + 18\, \Gamma_k^{(4)}\, G_k\, \Gamma_k^{(3)}\, G_k\, \Gamma_k^{(3)} \\ & + 12\, \Gamma_k^{(3)}\, G_k\, \Gamma_k^{(4)}\, G_k\, \Gamma_k^{(3)} - 24\, G_k\, \Gamma_k^{(3)}\, G_k\, \Gamma_k^{(3)}\, G_k\, \Gamma_k^{(3)} \cdot G_k\, \Gamma_k^{(3)} \Big] \left(G_k\, \partial_t R_k\, G_k \right), \end{aligned}$$

$$\Gamma_{\text{glue},k}[A,c,\bar{c}] = \frac{1}{2}\int_p A^a_\mu(p)\left[Z_{A,k}(p^2+m^2_{\text{gap},k})\Pi^\perp_{\mu\nu}(p) + \frac{1}{\xi}Z^{\parallel}_{A,k}(p^2+m^2_{\text{mSTI},k})\frac{p_\mu p_\nu}{p^2}\right]A^a_\nu(-p)$$
$$+\frac{1}{3!}\int_{p_1,p_2} Z^{3/2}_{A,k}\lambda_{A^3,k}\left[\mathcal{T}^{(1)}_{A^3}(p_1,p_2)\right]^{a_1a_2a_3}_{\mu_1\mu_2\mu_3}\prod_{i=1}^{3}A^{a_i}_{\mu_i}(p_i)$$
$$+\frac{1}{4!}\int_{p_1,p_2,p_3} Z^{2}_{A,k}\lambda_{A^4,k}\left[\mathcal{T}^{(1)}_{A^4}(p_1,p_2,p_3)\right]^{a_1a_2a_3a_4}_{\mu_1\mu_2\mu_3\mu_4}\prod_{i=1}^{4}A^{a_i}_{\mu_i}(p_i) + \int_p Z_{c,k}\bar{c}^a(p)p^2\delta^{ab}c^b(-p)$$
$$+\int_{p_1,p_2} Z_{c,k}Z^{1/2}_{A,k}\lambda_{c\bar{c}A,k}\left[\mathcal{T}^{(1)}_{c\bar{c}A}(p_1,p_2)\right]^{a_1a_2a_3}_{\mu}\bar{c}^{a_2}(p_2)c^{a_1}(p_1)A^{a_3}_\mu(-p_1-p_2).$$





6
5
4
3
2
1
0
0.1
1
10
100
$k[k_{\chi\mathrm{SB}}]$
$k_{\chi\mathrm{SB}}$
k_{conf}
α_{A^3}
α_{A^4}
$\alpha_{A\bar{\psi}\psi}$
$\alpha_{A\bar{c}c}$
$Z_{A,k}\, m^2_{\mathrm{gap},k}\, [k^2_{\chi\mathrm{SB}}]$
5
4
3
2
1
0
0.1
1
10
100