Phases of Chiral Gauge Theories

In collaboration with A. Pastor Gutiérrez, Haolin Li, Ling-Xiao Xu

Motivations

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- Compelling mechanism for the EWSB
- Mass NP >> Higgs Mass

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- QFT has still not shown us all of its tricks ?
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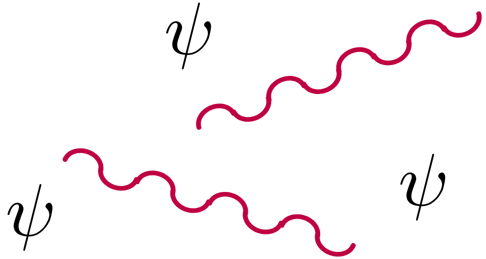

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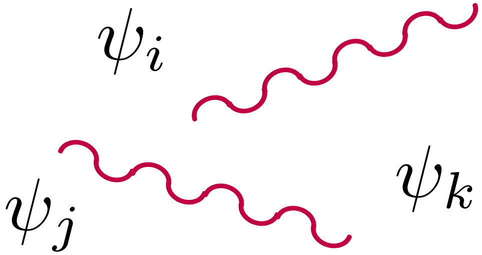

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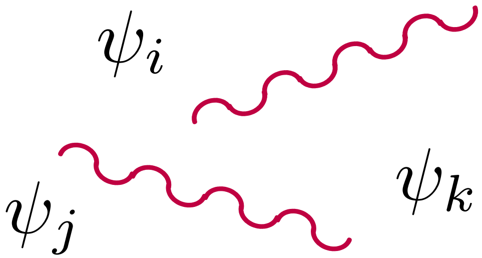
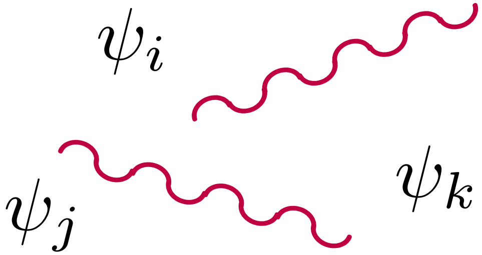


- 4D Gauge Theory

Motivations

Chiral Gauge Dynamics :



- 4D Gauge Theory $\quad SU(N_c)\,,\ Sp(N_c)\,,\ SO(N_c)\ldots$

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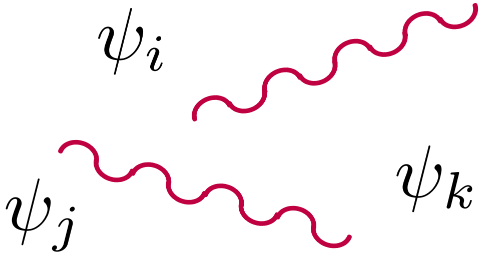

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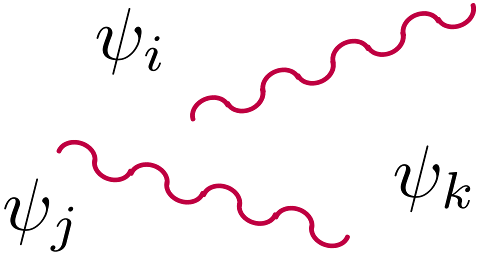

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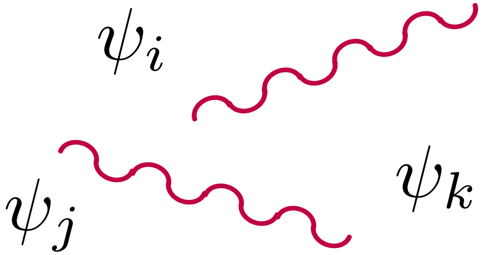

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- Asymptotically Free setup

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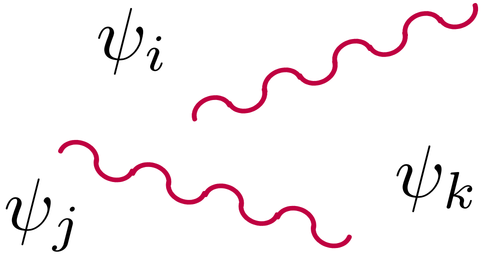

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  ⋯ Strong Coupling⋯

- 1) QCD VS Chiral Dynamic

- 2) Functional Methods

- 3) Results !

QCD VS Chiral Dynamic

QCD !

QCD !

- Vafa-Witten Theorems (Weingarten inequalities)

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- Vafa-Witten Theorems (Weingarten inequalities)
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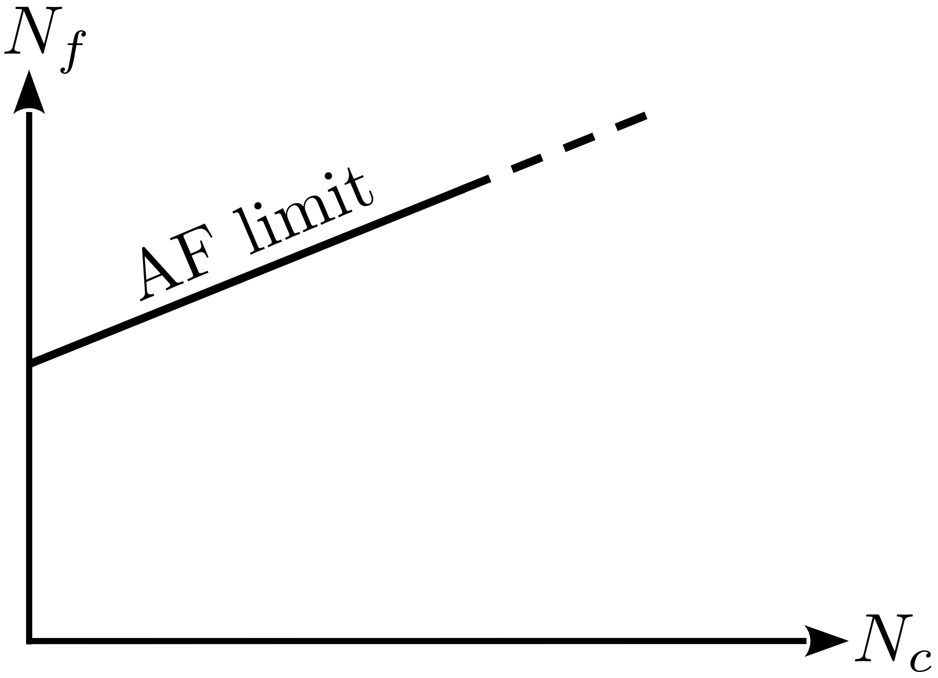
- Lattice

QCD !



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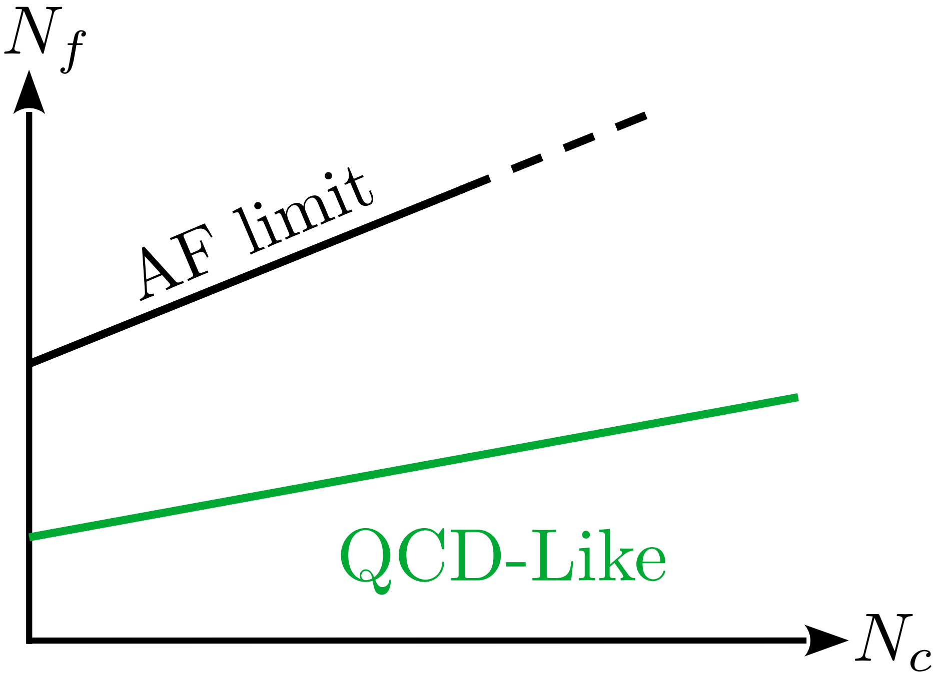

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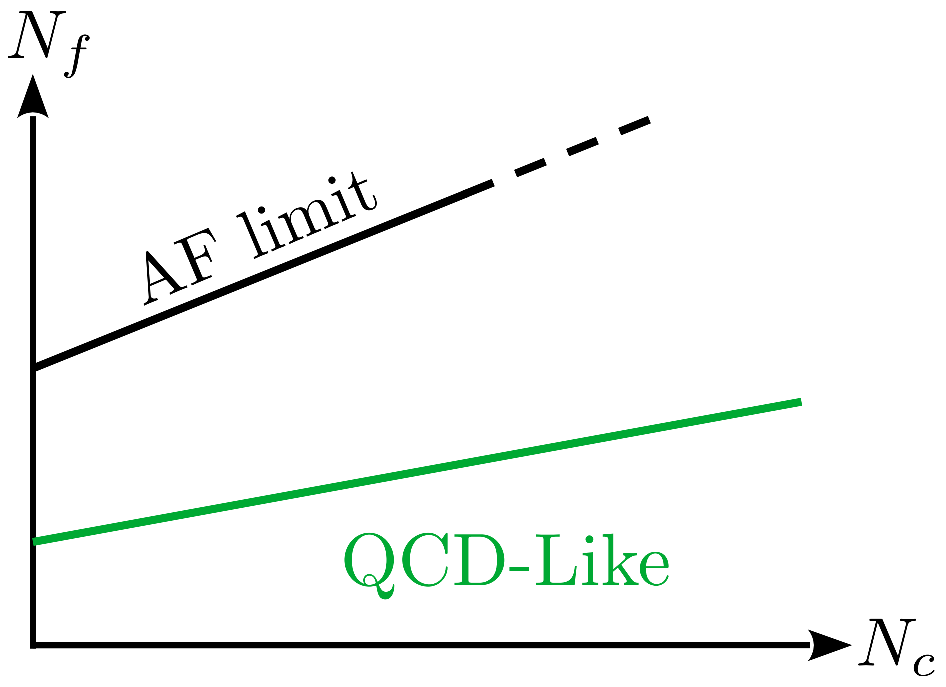
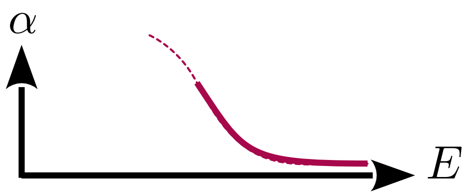
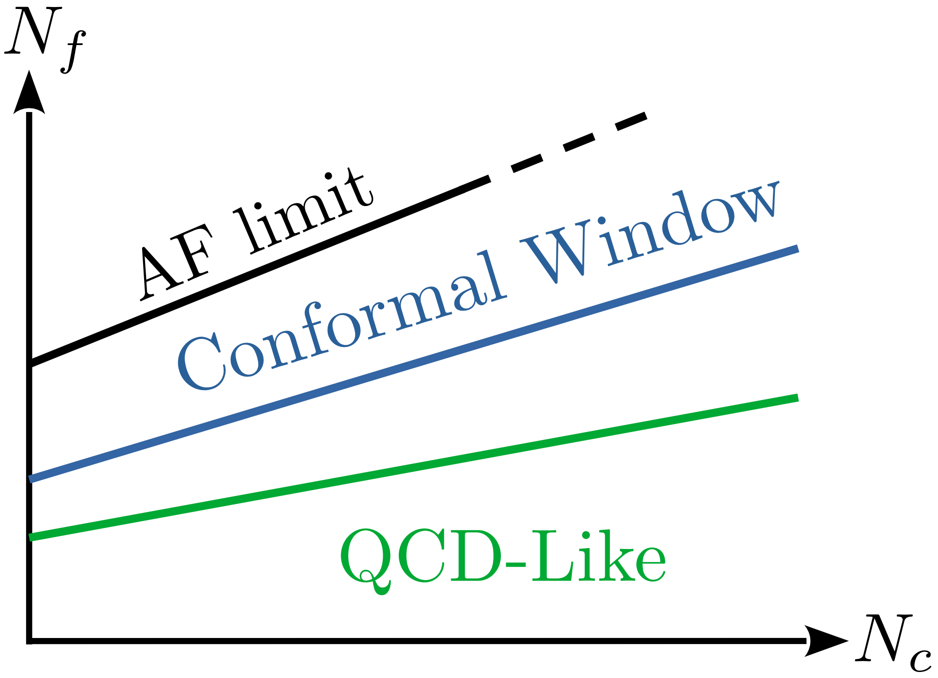


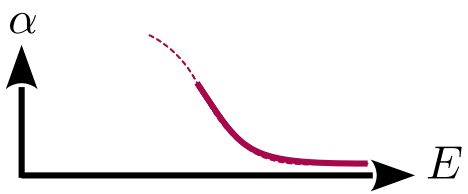


Confinement & Condensation

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

QCD !





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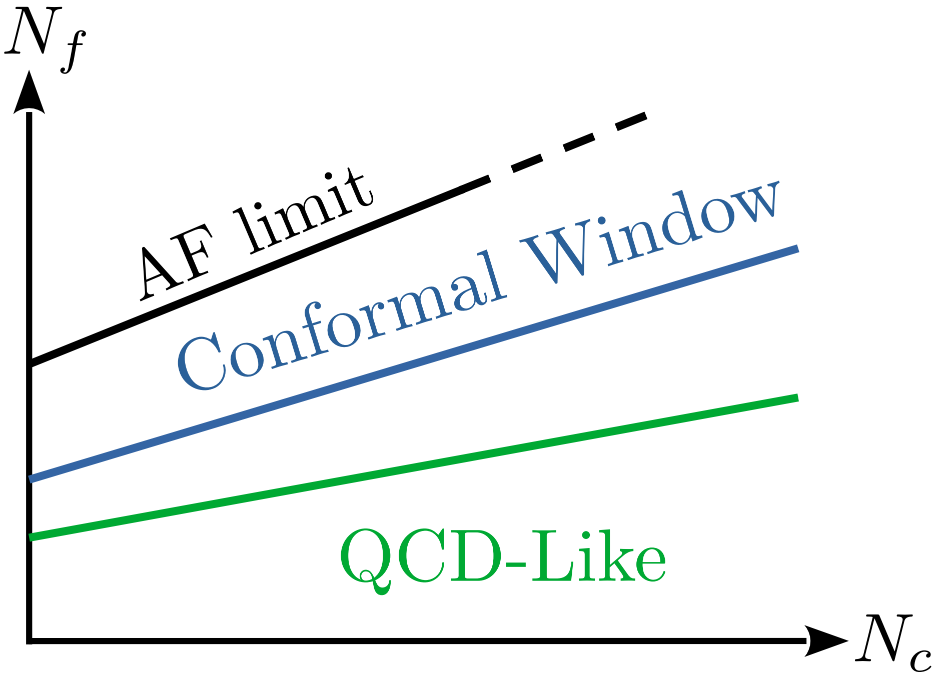
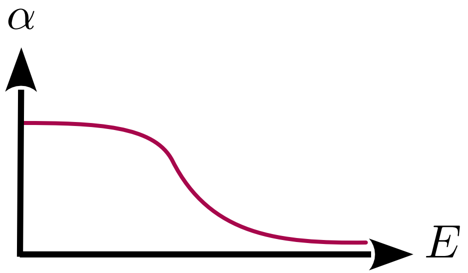
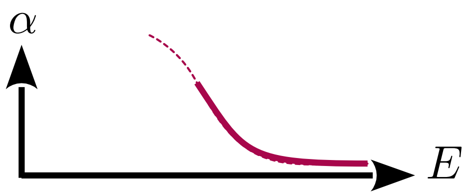




No Confinement & No Condensation



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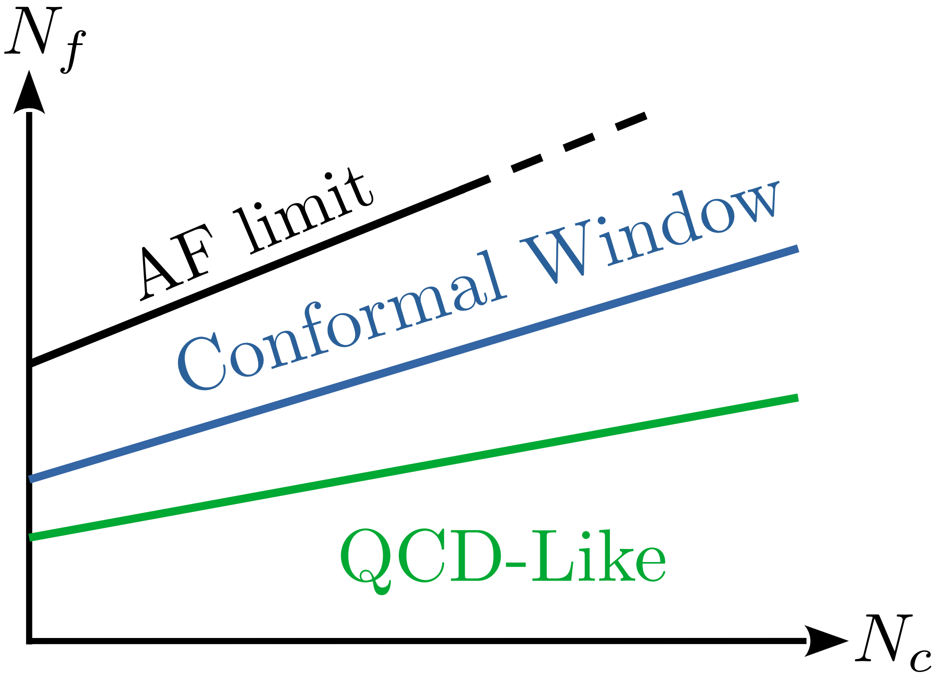
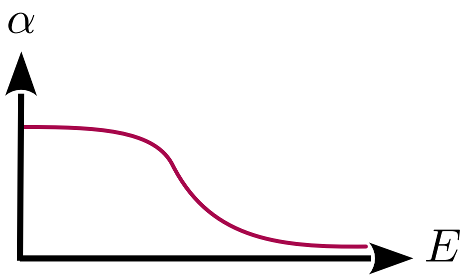
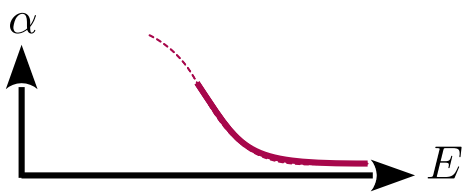




No Confinement & No Condensation
But a Conformal phase



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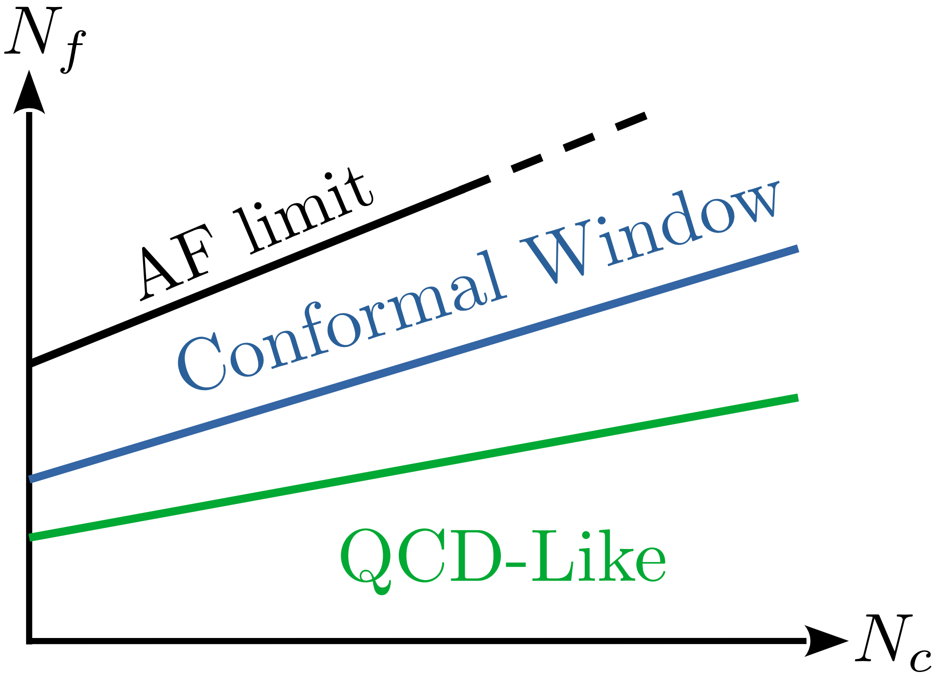

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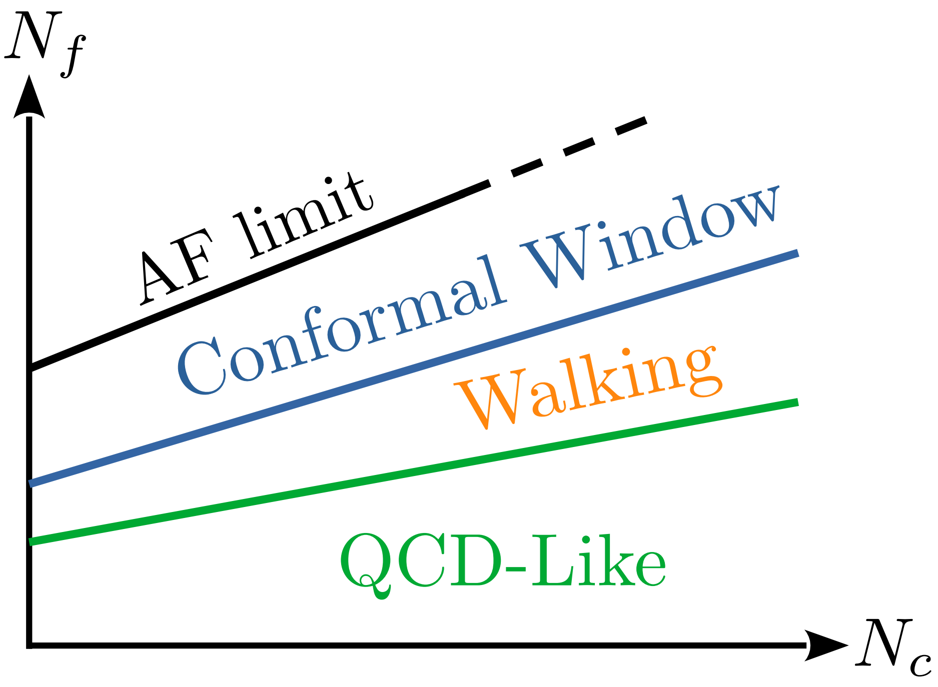

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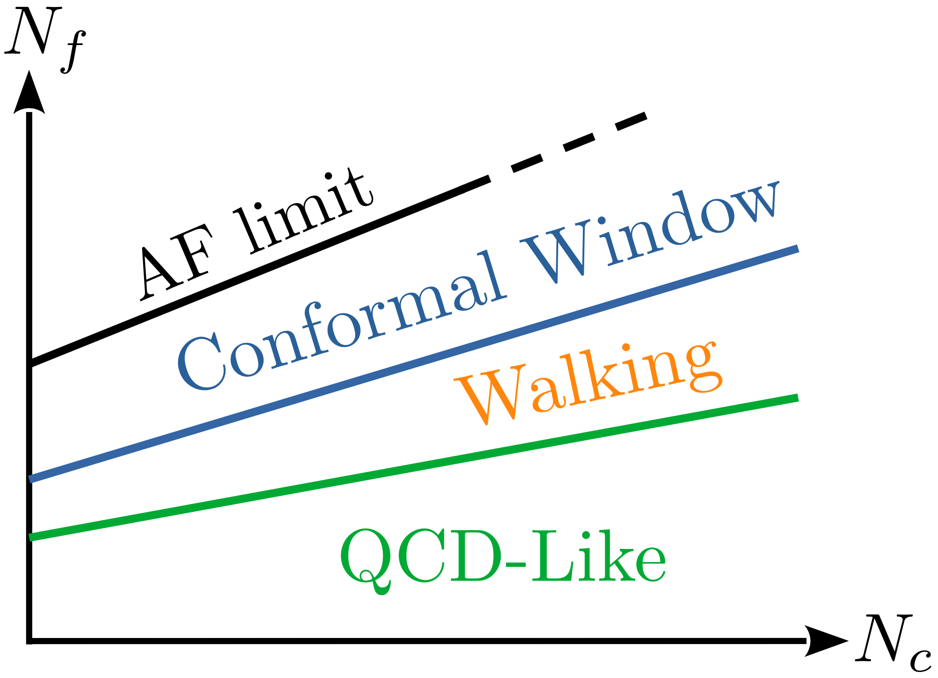

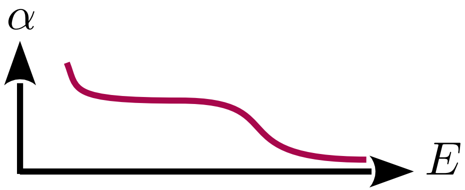

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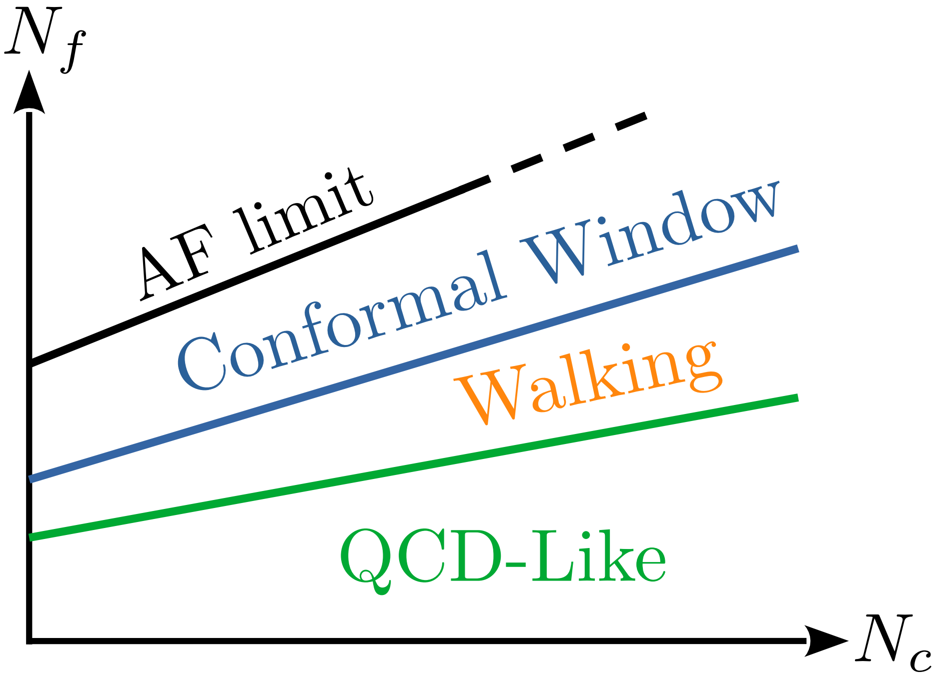

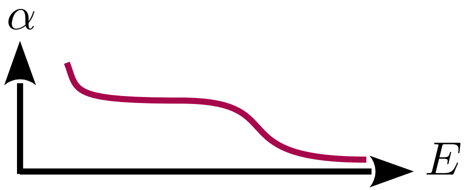

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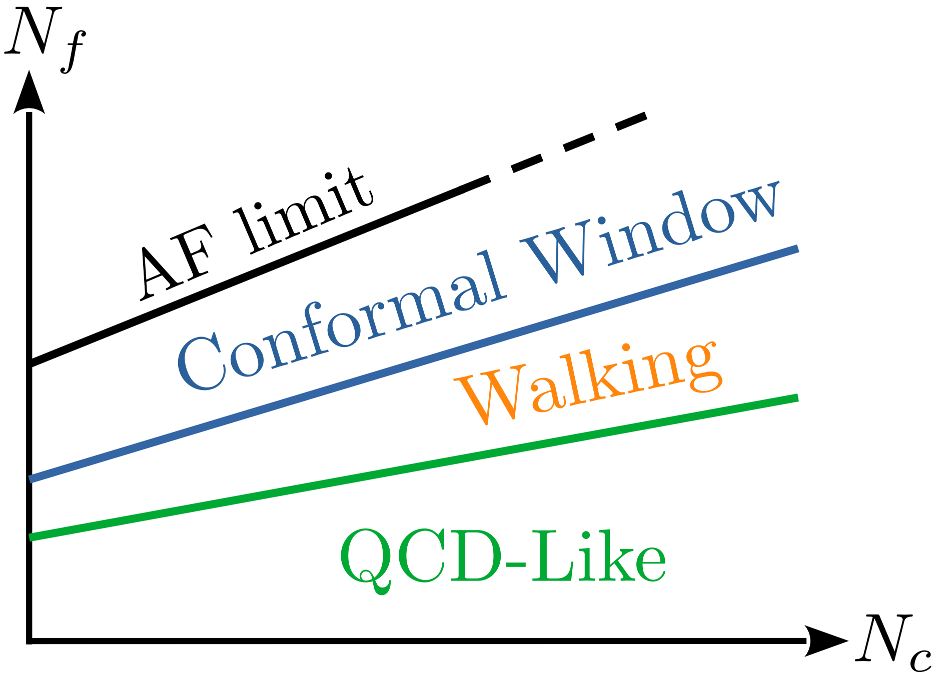

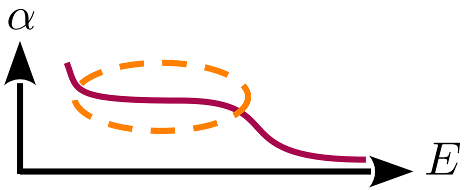

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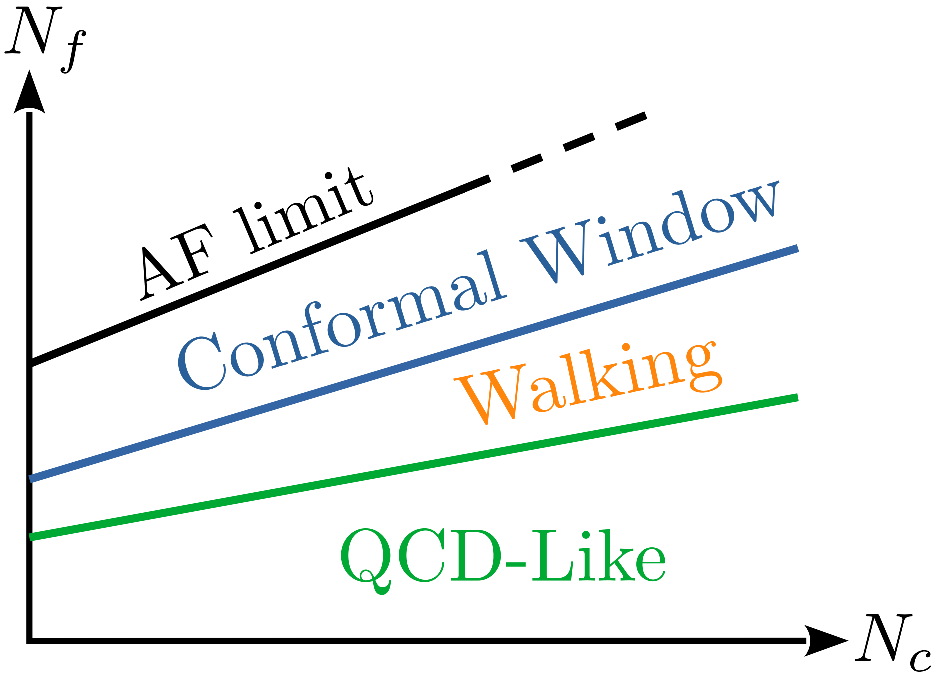
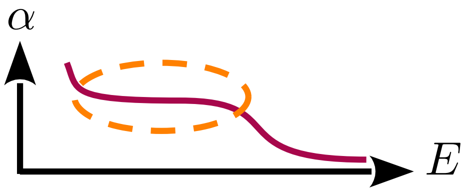
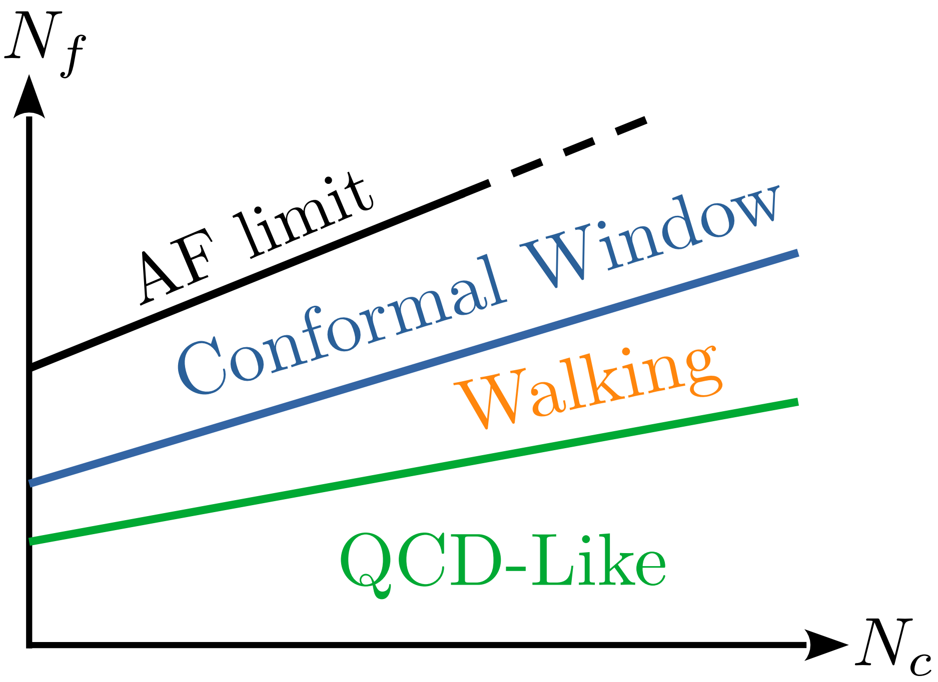




Confinement & Condensation

And near Conformal phase !

QCD !



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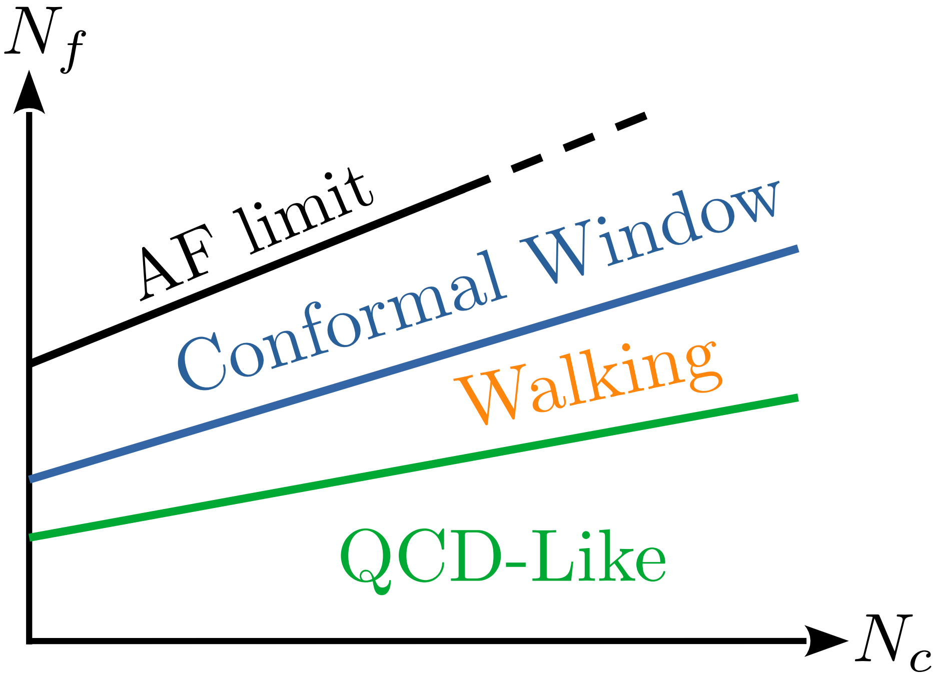

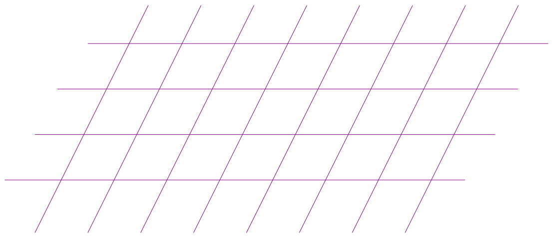

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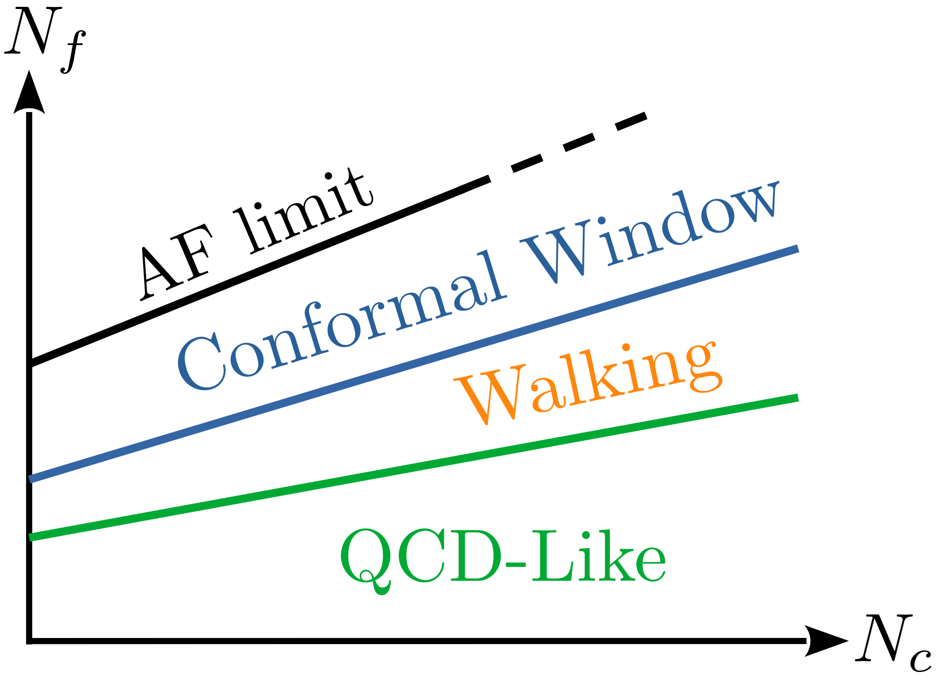

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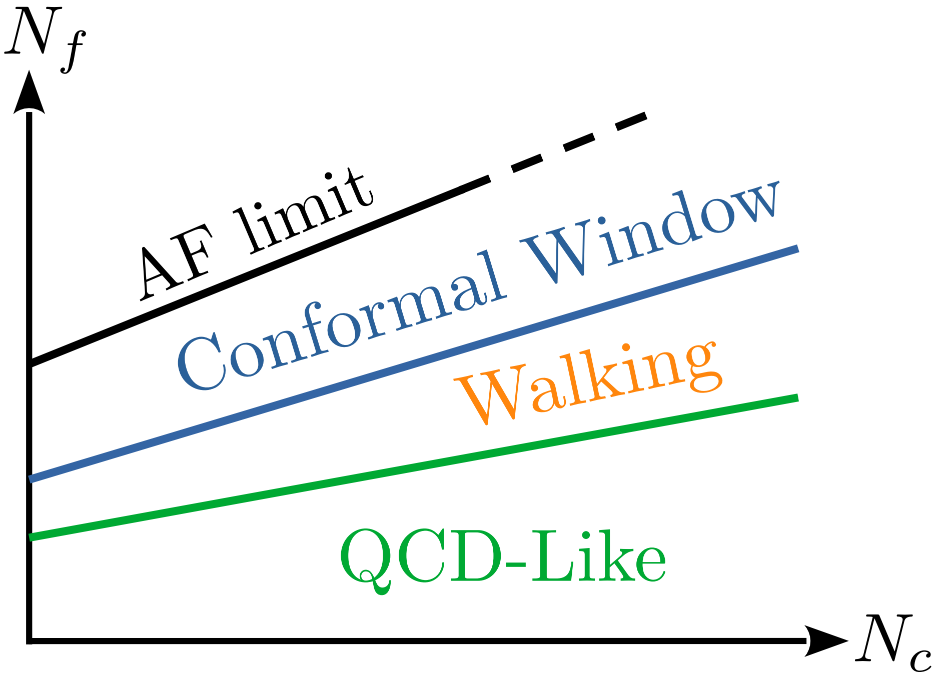
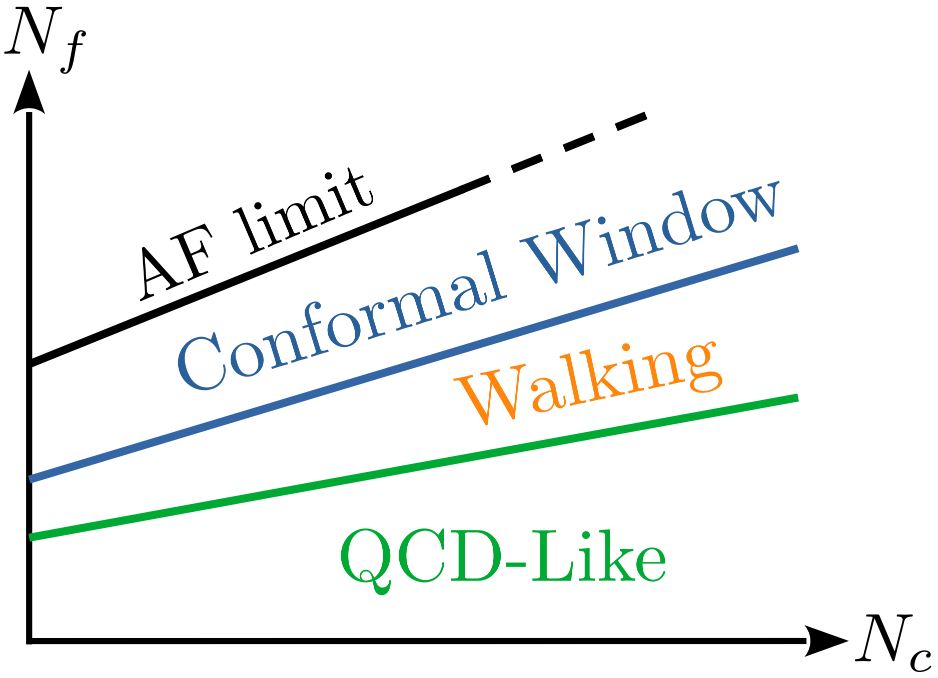


The Landscape is not fully explored

QCD !



The Landscape is not fully explored

- $m_{\text{proton}} \quad f_\pi \quad f_\rho$?

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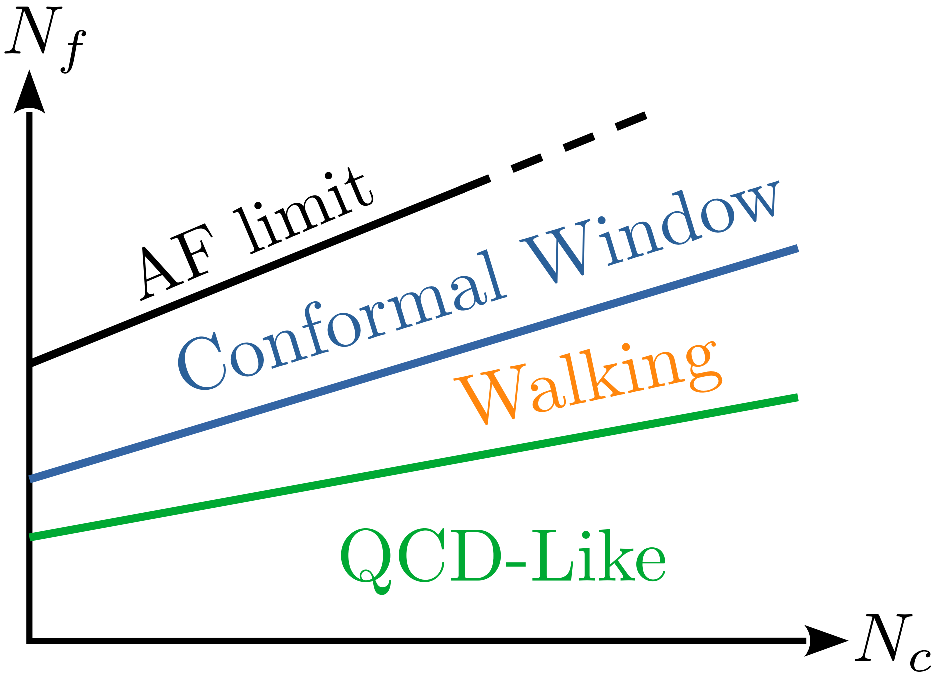

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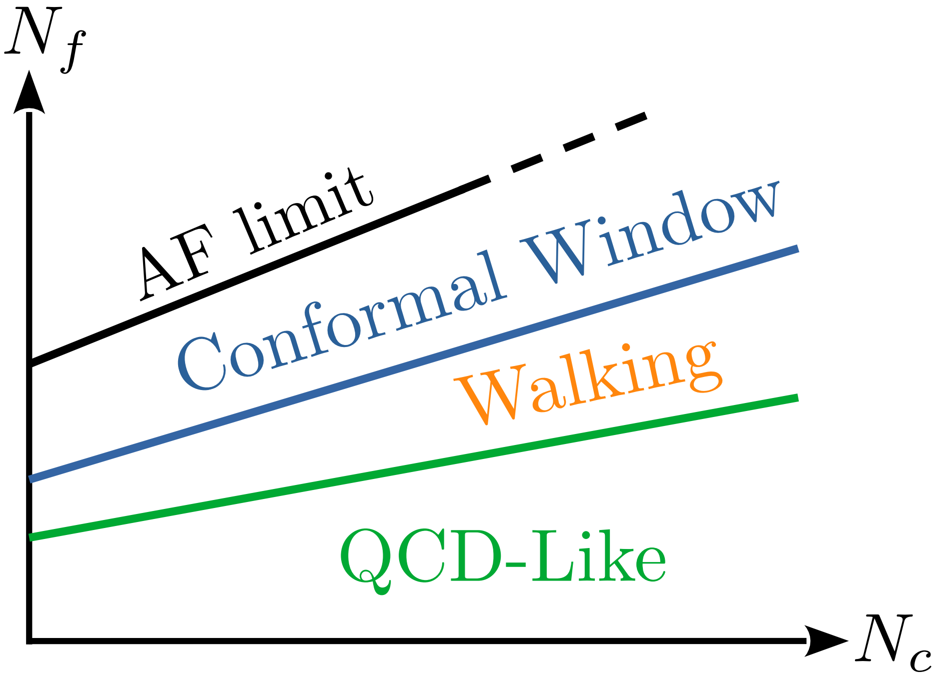
- EWSB from $\langle \bar{\psi}\psi \rangle \neq 0$

QCD !



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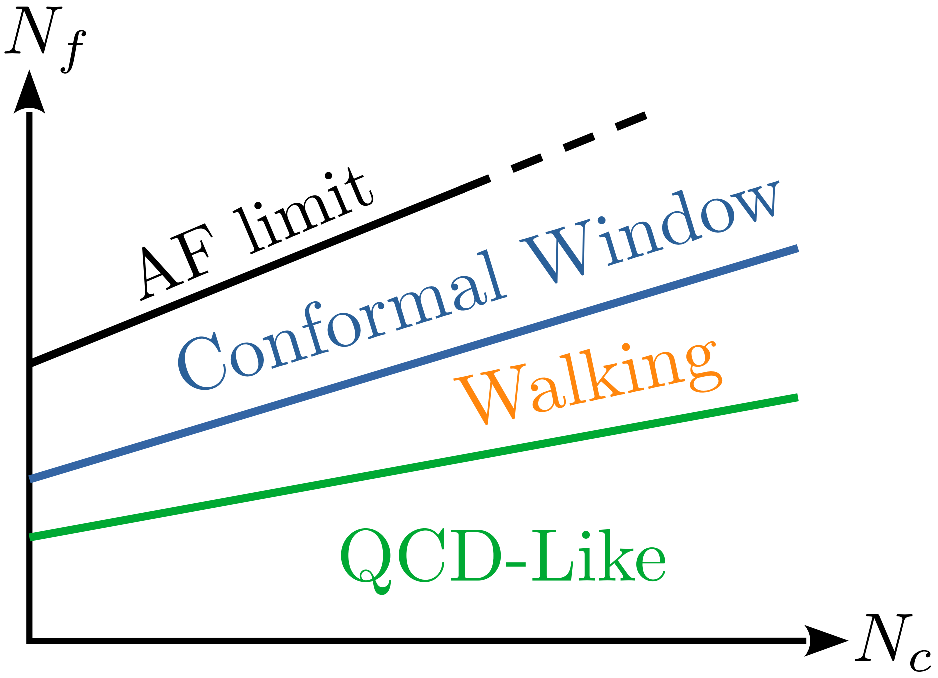

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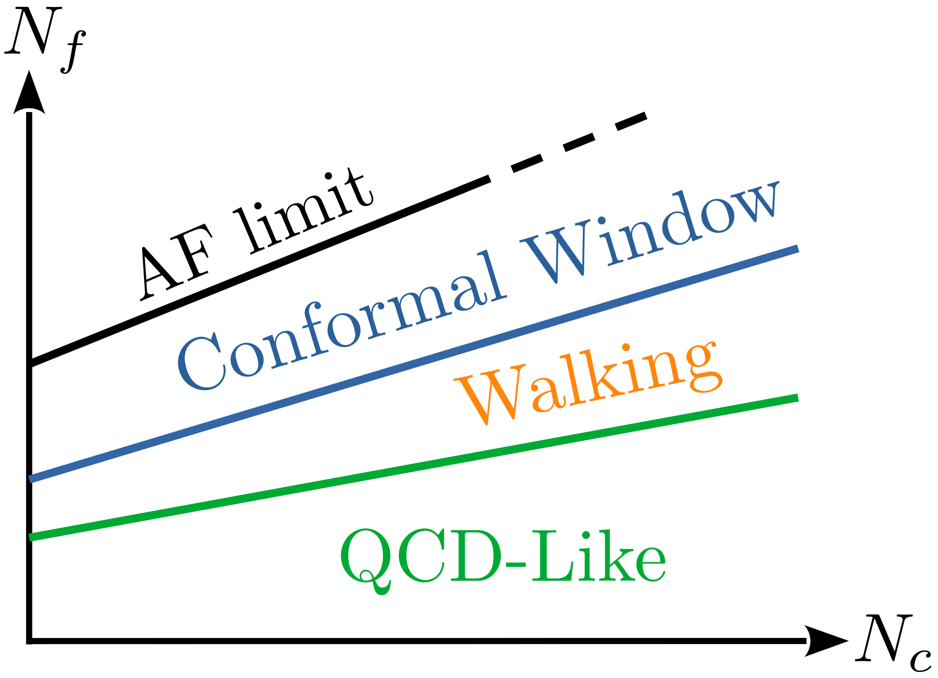

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- EWSB from $\langle \bar{\psi}\psi \rangle \neq 0$
- $g_\rho \; [\pi \partial_\mu \pi] \; \rho^\mu$?

Chiral Dynamic

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- Vafa-Witten Theorems

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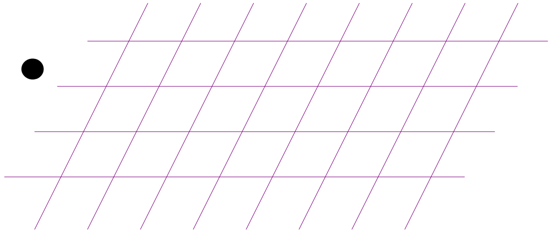
- 

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Spectrum ?

Chiral Dynamic

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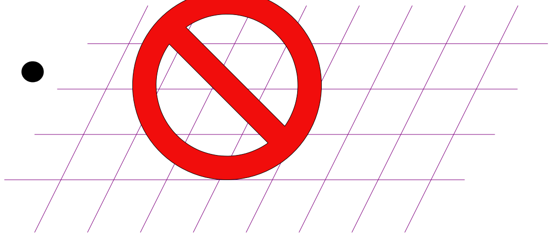
- 

Spectrum ? Coupling ?

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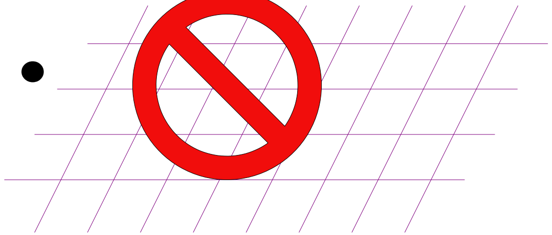
- 

Spectrum ? Coupling ? Conformality ?

Chiral Dynamic

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- 

Spectrum ? Coupling ? Conformality ? Breaking Pattern ?

Chiral Dynamic

Chiral Dynamic

Georgi-Glashow model $\quad (\mathrm{GG})$:

Chiral Dynamic

Georgi-Glashow model (GG) :

$SU(N_c)$	Flavor
A	
$\bar{F}$	

Chiral Dynamic

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→ Global Symmetry : $SU\left(N_c - 4\right) \times U\left(1\right)$

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→ $\mathcal{B} = A\left\{\bar{F}\bar{F}\right\}$

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What is the IR ?

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- Generalized Symmetries (1-form 't Hooft Anomaly) $\longrightarrow$ $\langle A\bar{F}\rangle \neq 0$
- Anomaly Mediated SuSy Breaking $\longrightarrow$ $\langle A\bar{F}\rangle \neq 0\,, \quad \langle \bar{F}\bar{F}\rangle \neq 0$

Toy Model

Georgi-Glashow (GG):

$SU(N_c)$	Flavor
A	1
$\bar{F}$	$N_c - 4$

Toy Model

General Georgi-Glashow (GG) :

$SU(N_c)$	Flavor
A	1
$\bar{F}$	$N_c - 4$

Toy Model

General Georgi-Glashow (GG) :

→ $N_g \times$ Georgi-Glashow

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Toy Model

General Georgi-Glashow (GG) :

$\longrightarrow$ $N_g \times$ Georgi-Glashow

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Toy Model

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Toy Model

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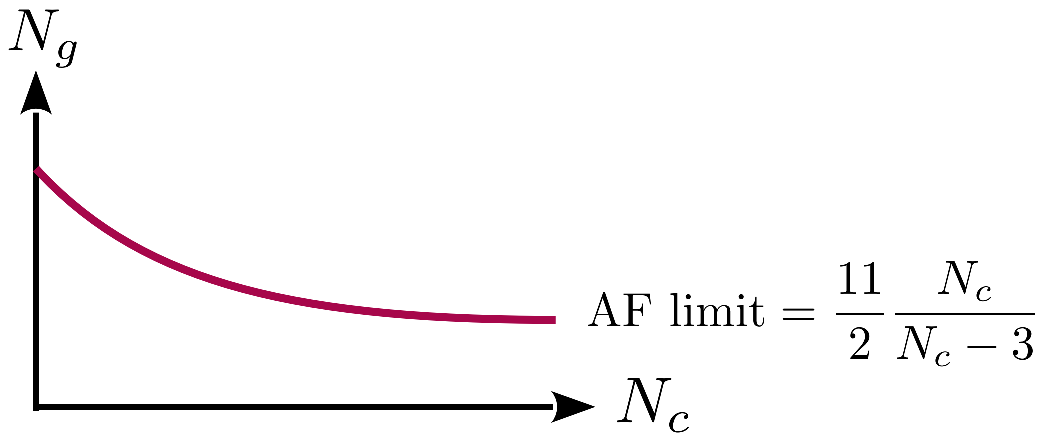
→



Functional Methods

How To Diagnose $\chi\mathrm{SB}$?

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→ $$\mathcal{Z}[J] = \int \mathcal{D}\varphi \;\; e^{-S[\varphi]+J\varphi}$$

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How To Diagnose $\chi\mathrm{SB}$?

- $\mathcal{Z}[J] = \int \mathcal{D}\varphi \;\; e^{-S[\varphi]+J\varphi}$

- $\mathcal{W}[J] = \ln \mathcal{Z}[J]$

$$\langle \phi(x_1) \ldots \phi(x_n) \rangle_c = \frac{\partial^n}{\partial J(x_1) \ldots \partial J(x_n)} \mathcal{W}[J]$$

How To Diagnose $\chi\mathrm{SB}$?

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1-PI Effective Action : $\Gamma[\phi] = \sup_J \left\{ \int J\phi - \mathcal{W}[J] \right\}$

$$\Gamma[\phi] = \sum_n \frac{1}{n!} \int_{x_1 \dots \, x_n} \Gamma^{(n)}[\phi = 0]\, \phi(x_1) \dots \phi(x_n)$$

How To Diagnose $\chi\mathrm{SB}$?

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How To Diagnose χSB?

$$\rightarrow \qquad \Gamma\left[\bar{\psi}, \psi, A_\mu\right] \supset \int \lambda_{\mathrm{4F}}\, \bar{\psi}\psi\bar{\psi}\psi$$

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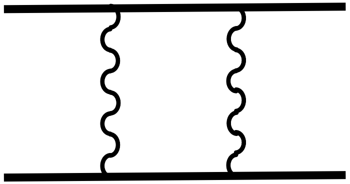

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$\boxed{\text{Divergent 4F flow signal } \chi\mathrm{SB}}$

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Divergent 4F flow signal $\chi\mathrm{SB}$

$$(\psi_1\psi_2)\,(\psi_1\psi_2) \Longrightarrow \langle\psi_1\psi_2\rangle \neq 0$$

How To Diagnose $\chi\mathrm{SB}$?

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Integro-Differential Equation HARD

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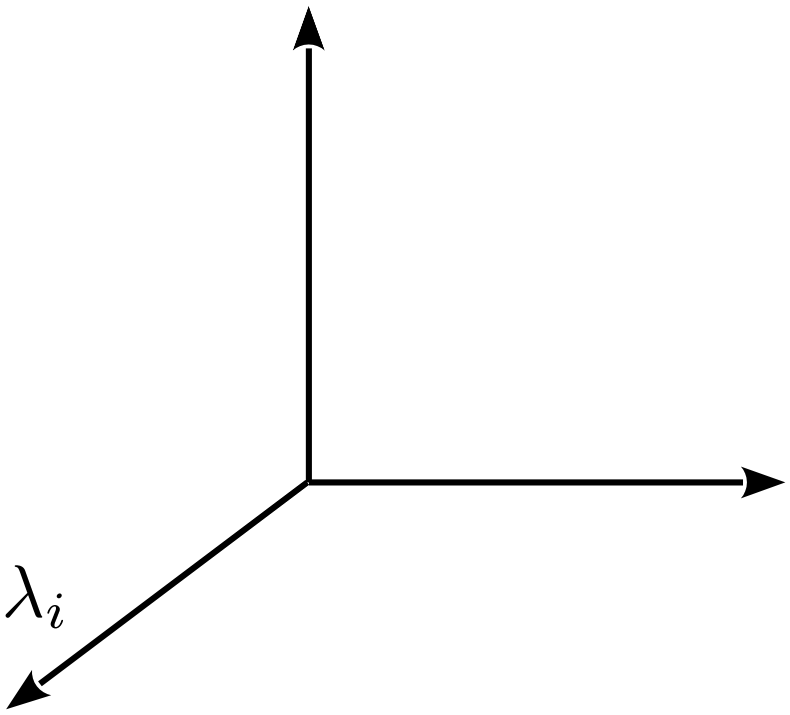

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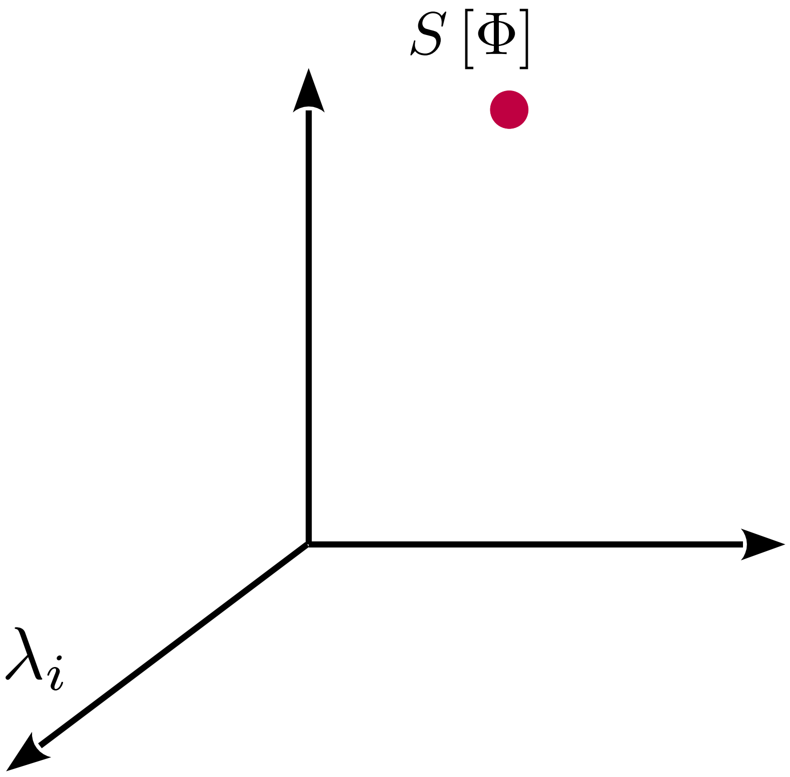

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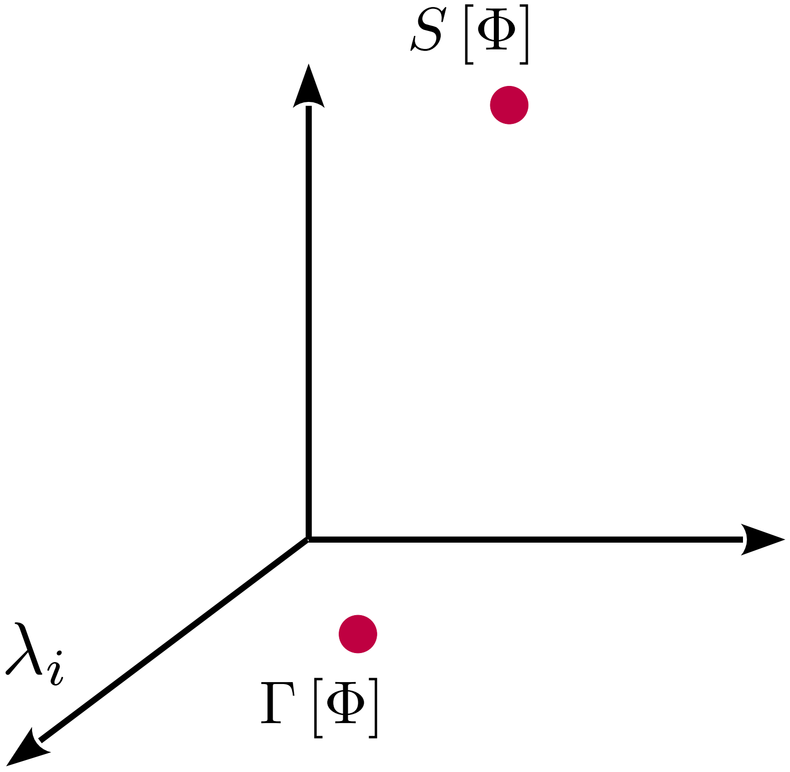

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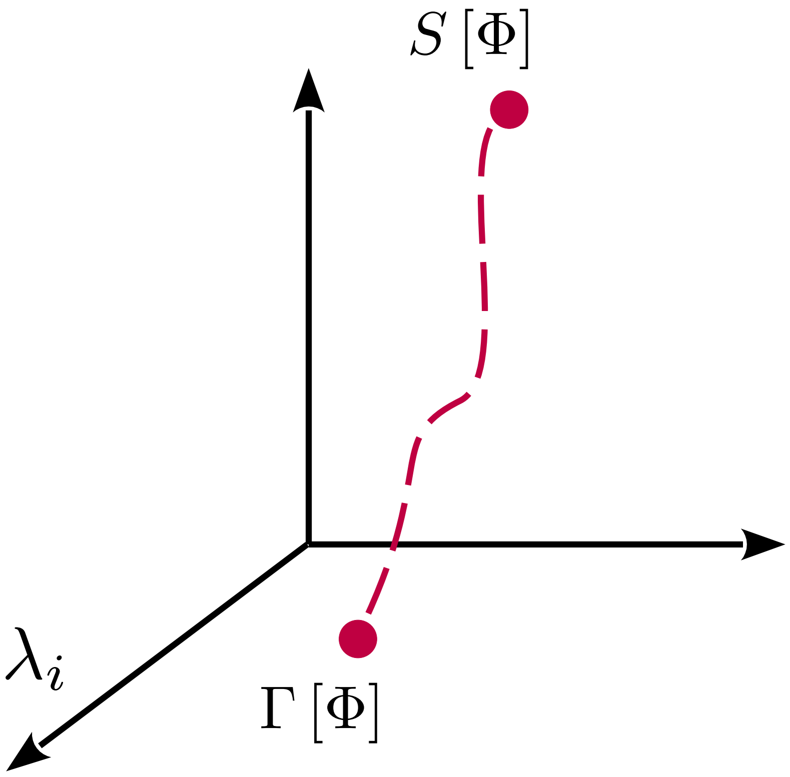

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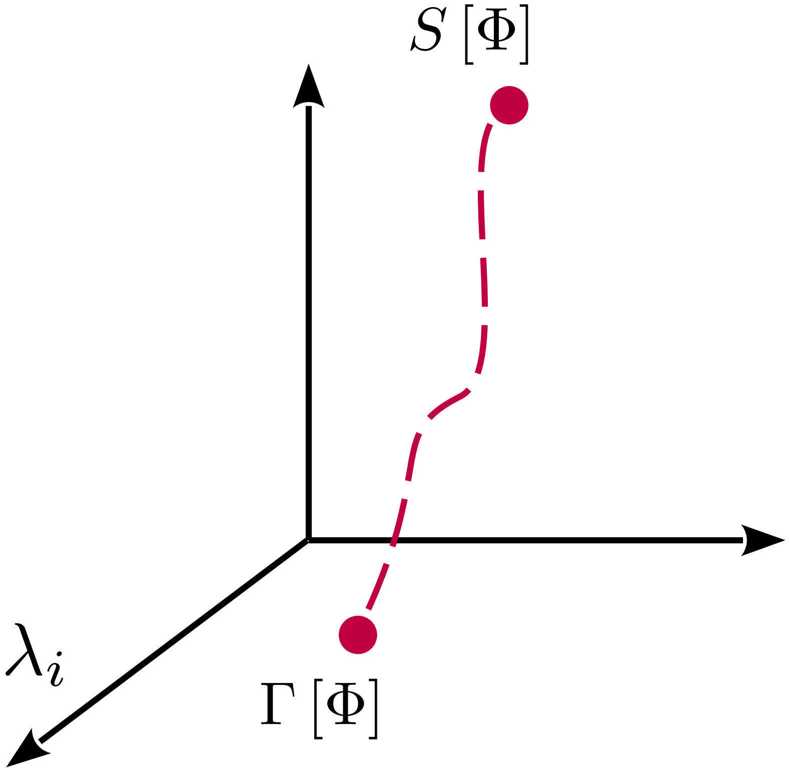

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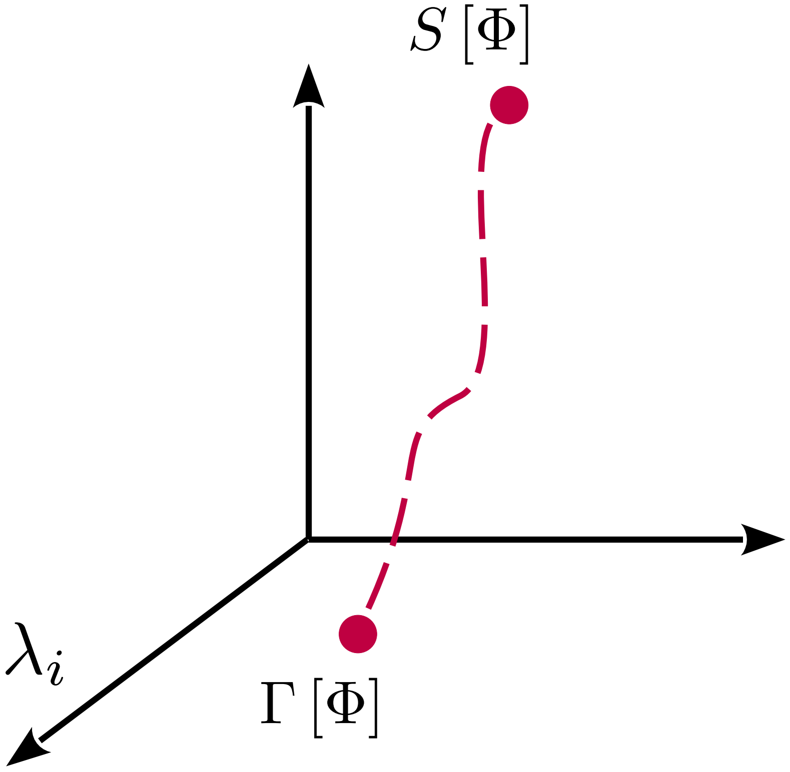

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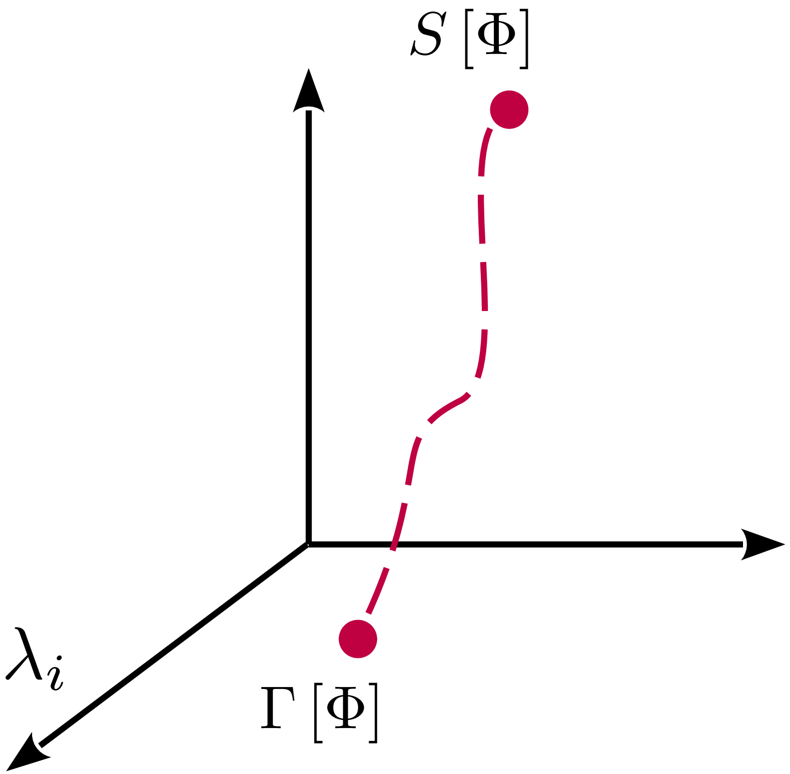

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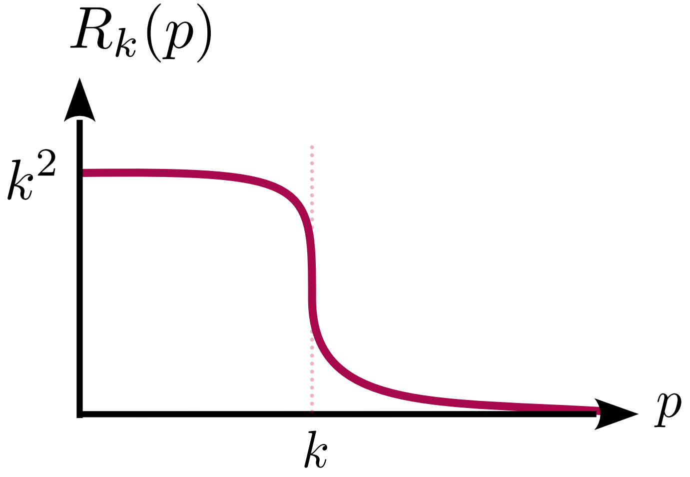

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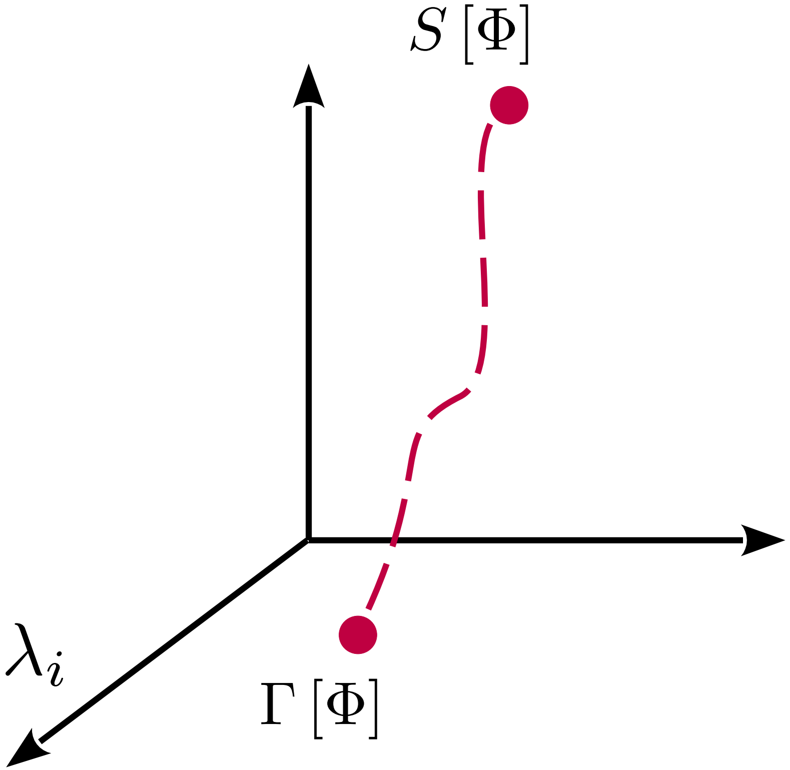

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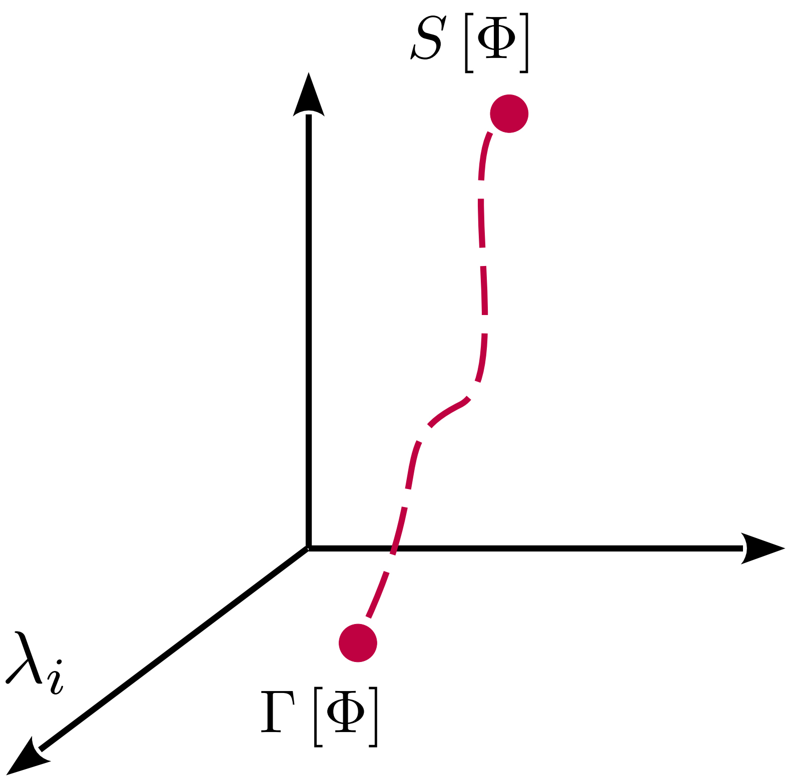

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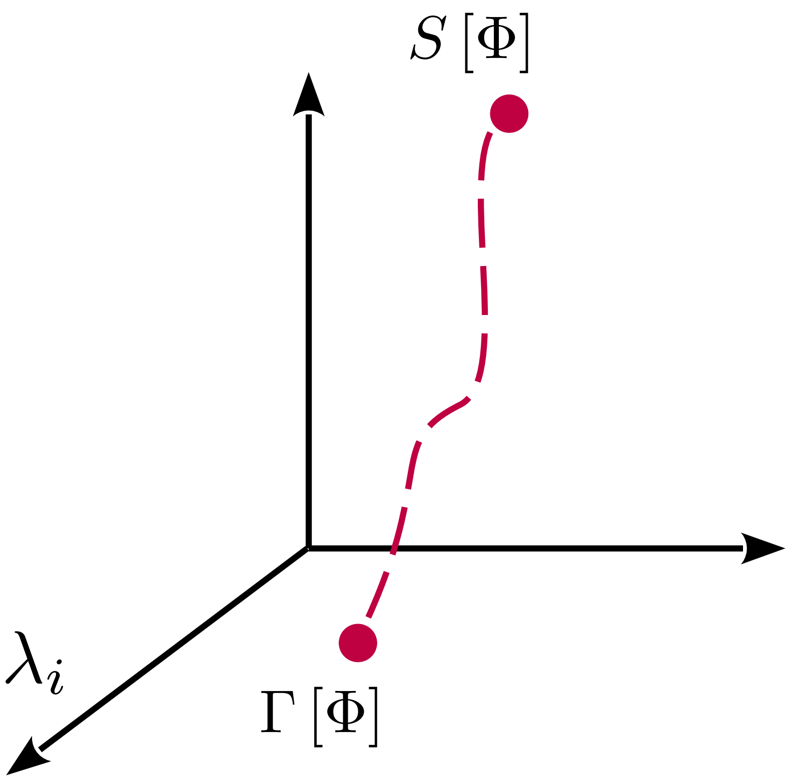

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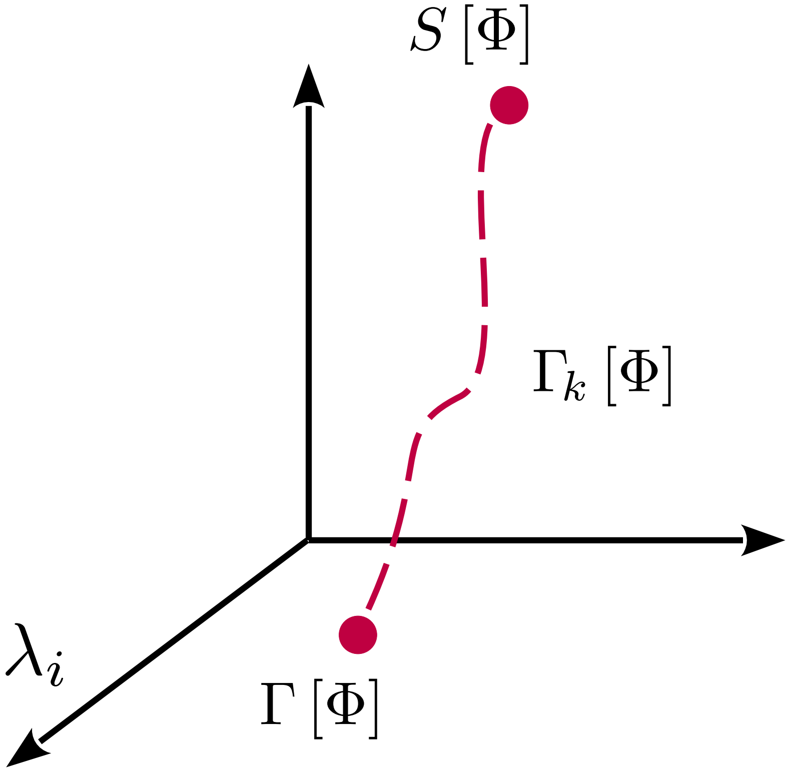

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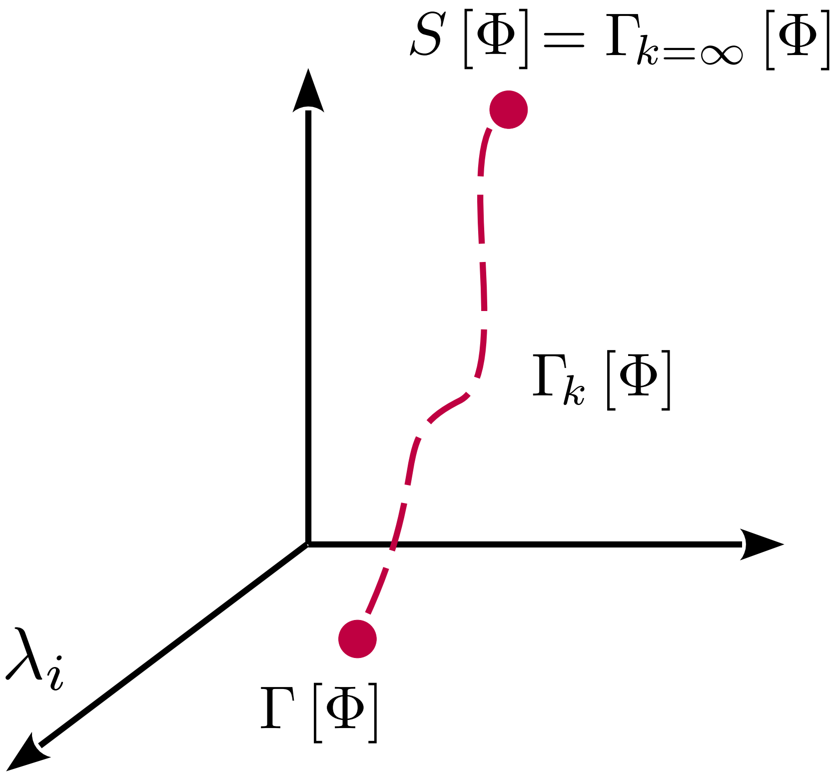

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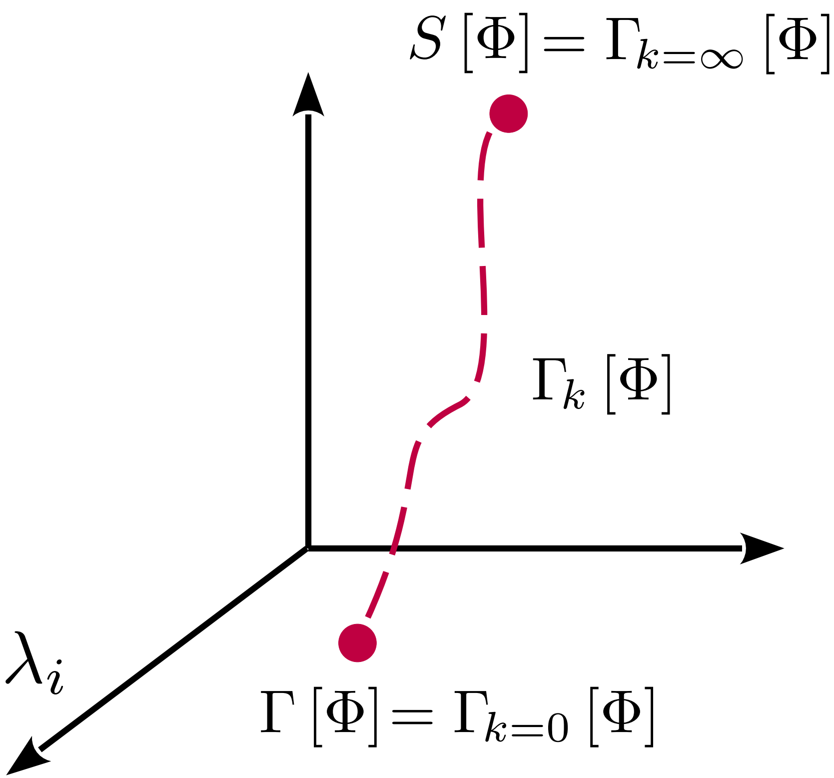

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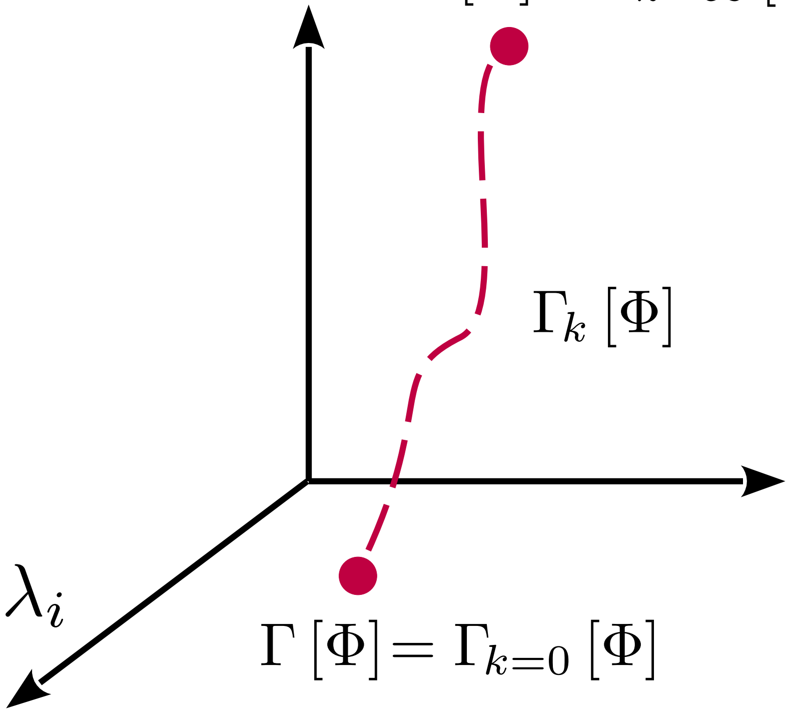

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$$t = \ln\frac{k}{\Lambda_{\mathrm{UV}}}$$

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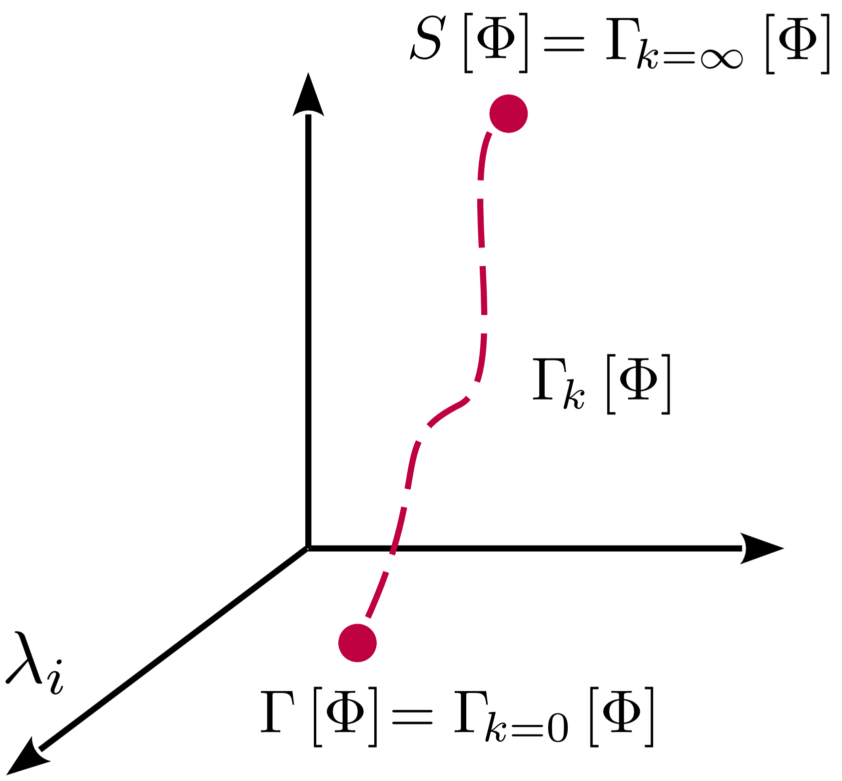

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« Simple » Differential Equation

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Infinite tower of differential equations ! In practice, $\Gamma^{(n)} = 0, \quad \forall n > N_{\max}$

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→ Does one of the λ_i diverge ?

Results

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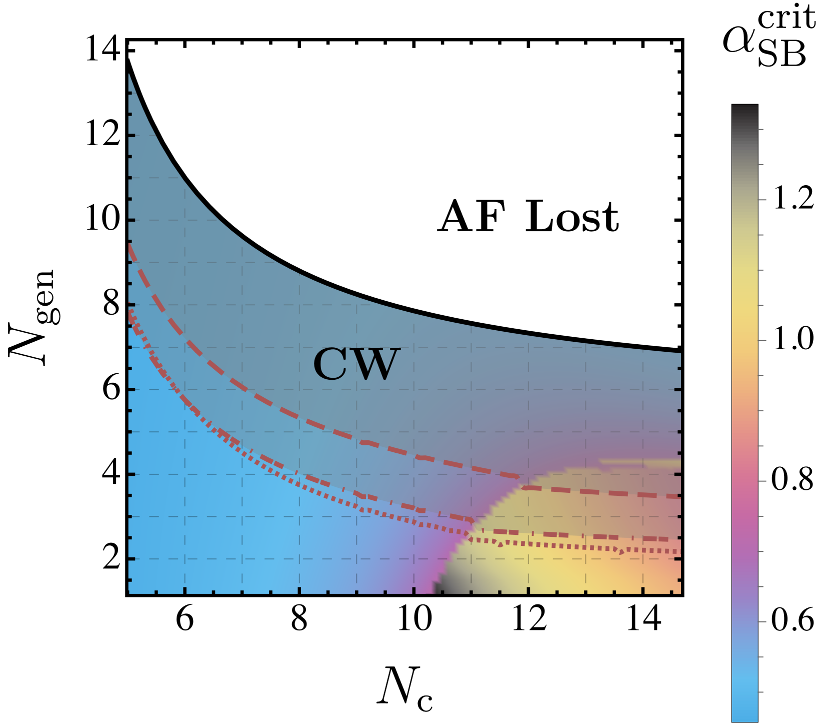
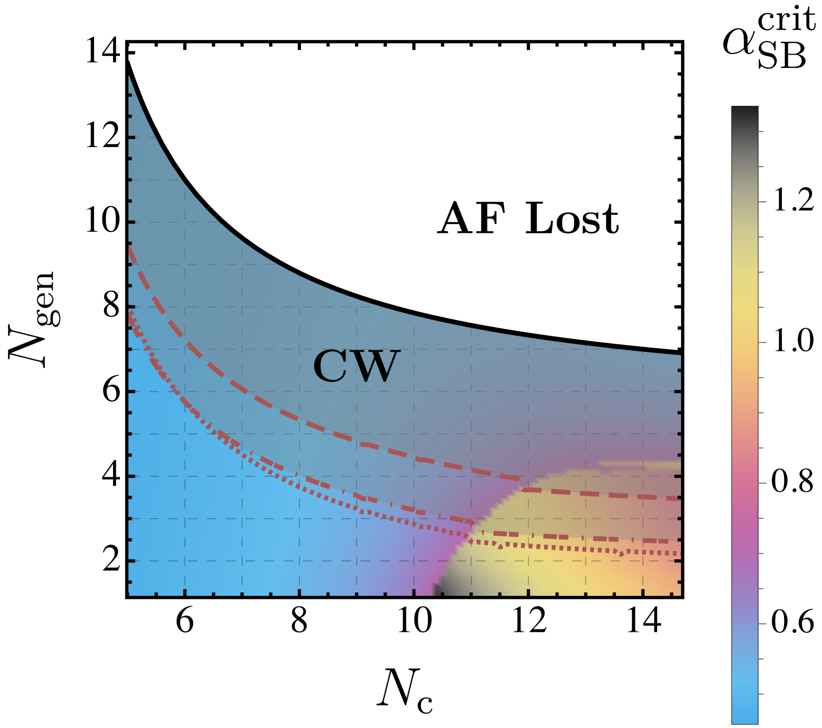


AF Lost
CW
$N_{\rm gen}$
$N_{\rm c}$
$\alpha_{\rm SB}^{\rm crit}$
14
12
10
8
6
4
2
6
8
10
12
14
1.2
1.0
0.8
0.6

Results



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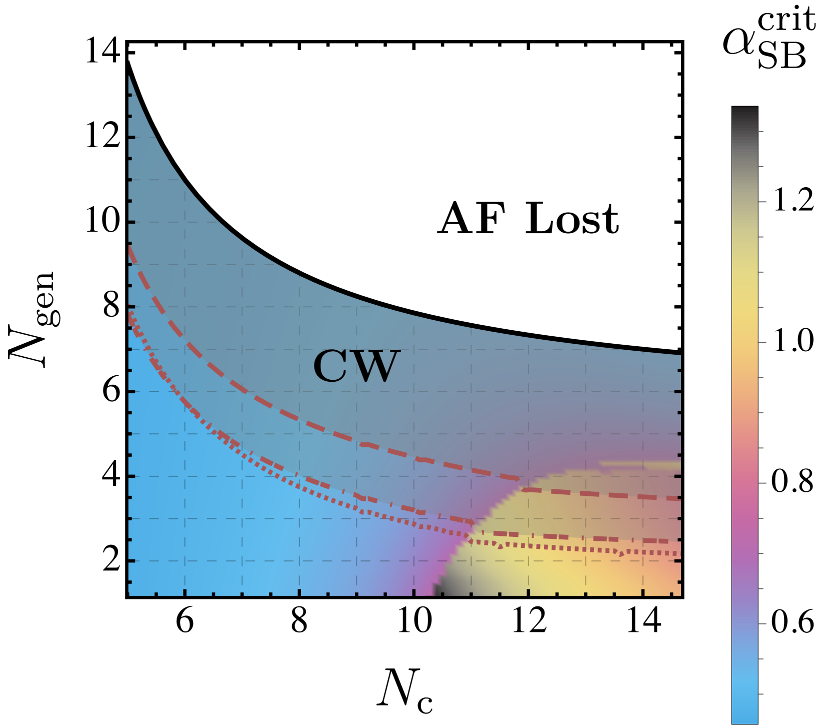
Results



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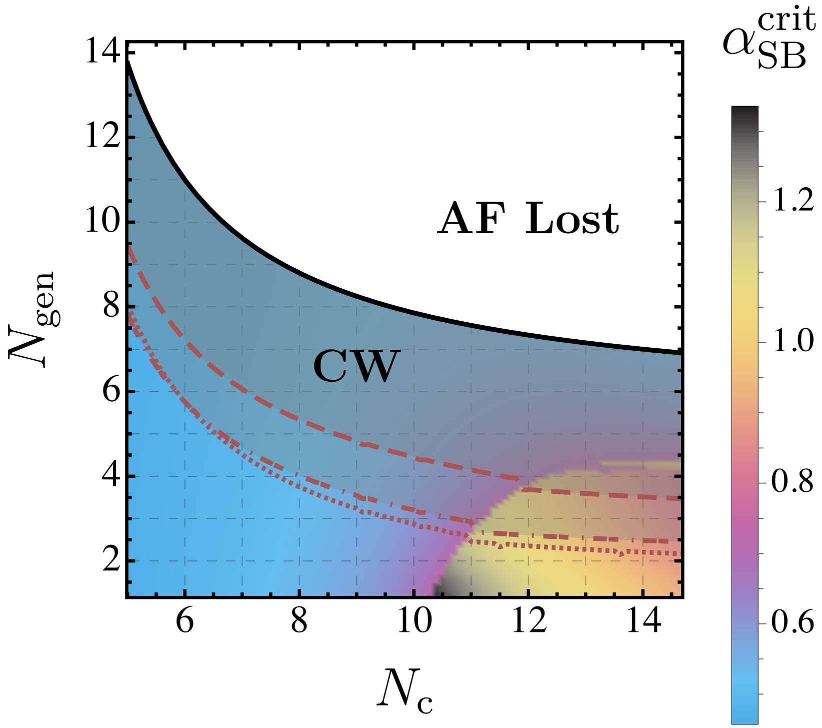

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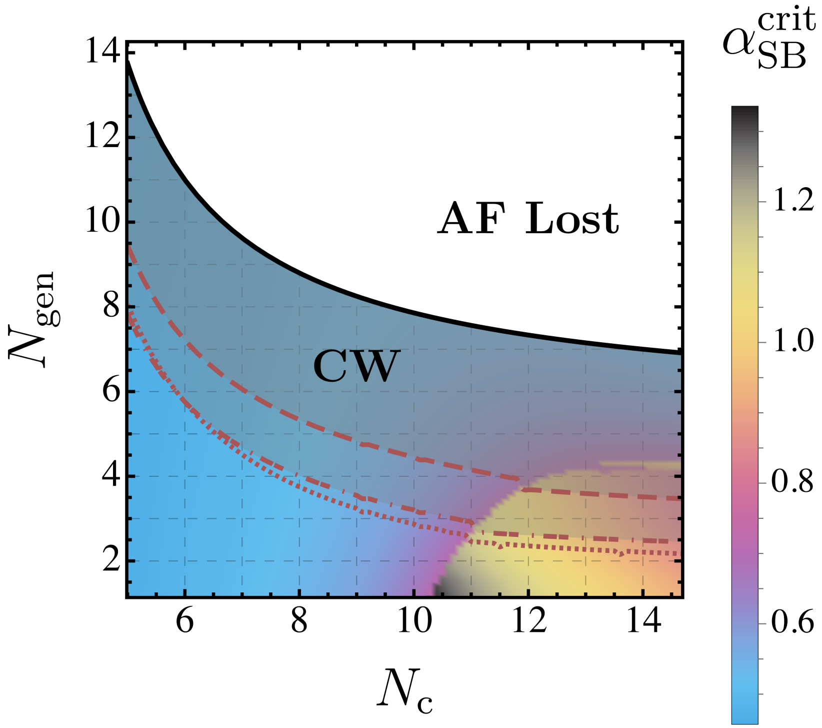

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- We used the 2-, 3- and 4-loop β

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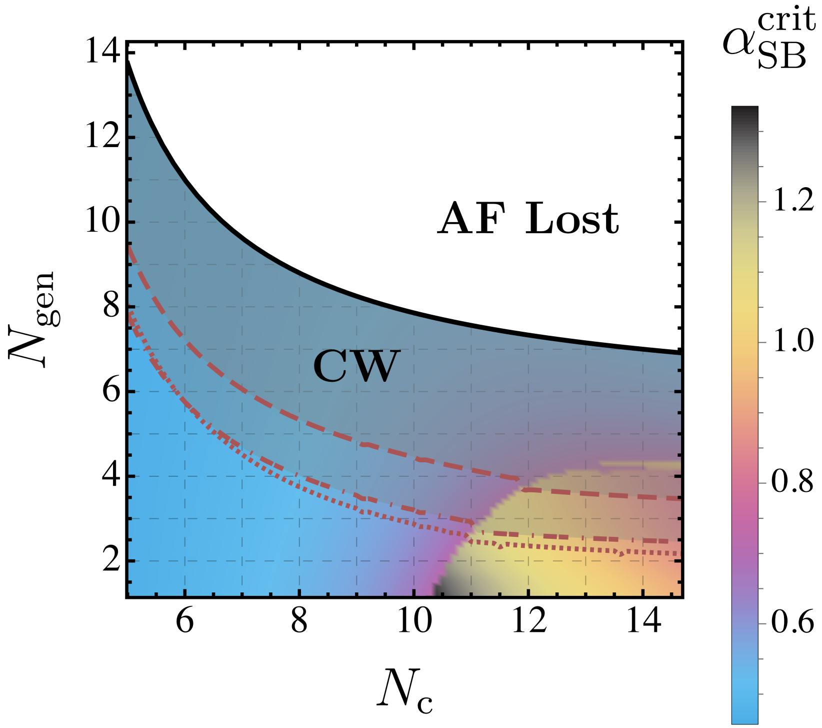

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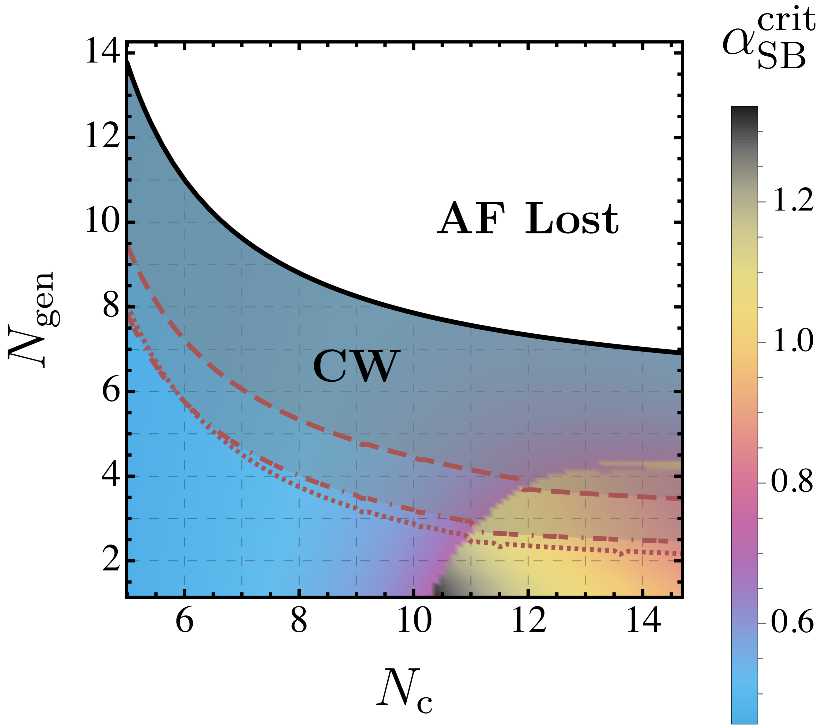
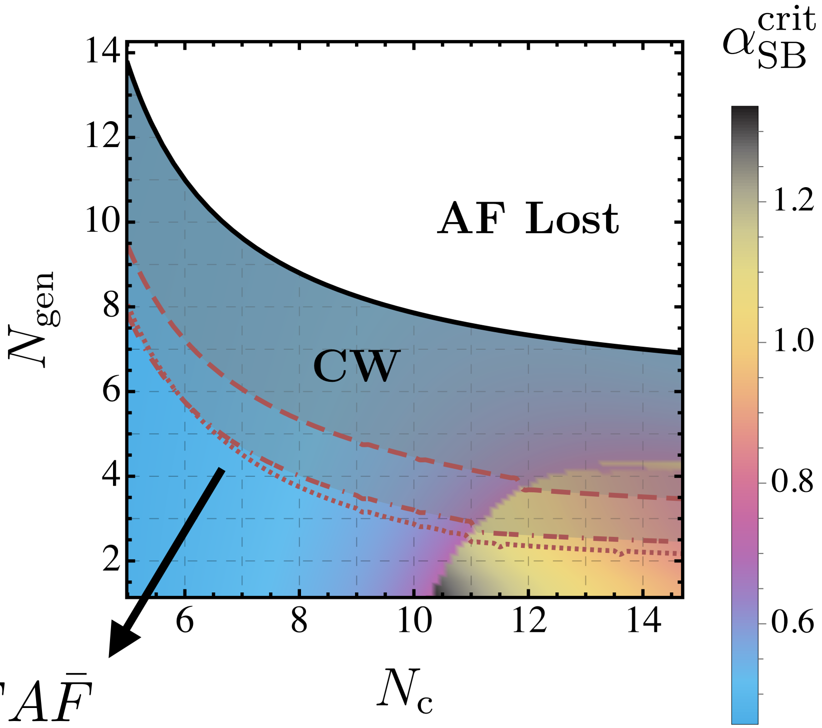
Results



→ IR Conformal !

Results



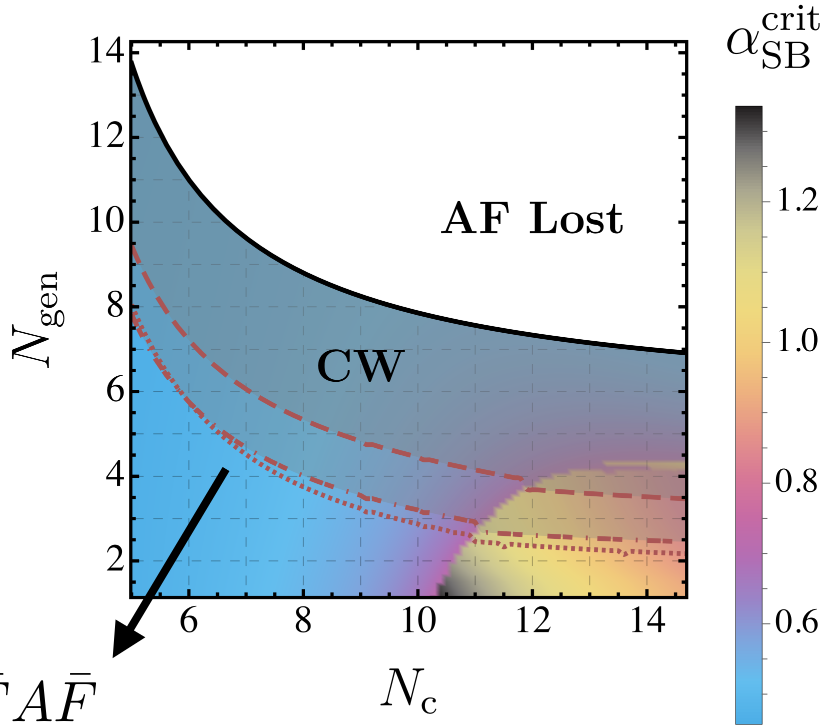
$A\bar{F}A\bar{F}$

$\langle A\bar{F}\rangle \neq 0$

→ IR Conformal !

→ Clear signal for $\chi\mathrm{SB}$

Results



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- 2nd region for $\chi\mathrm{SB}$

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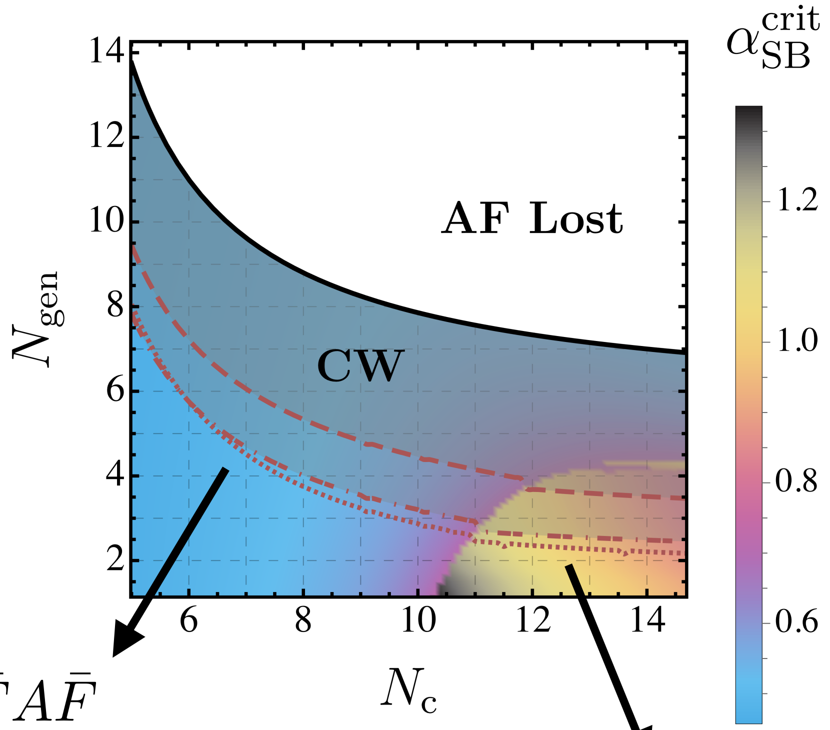

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All 4F diverge !

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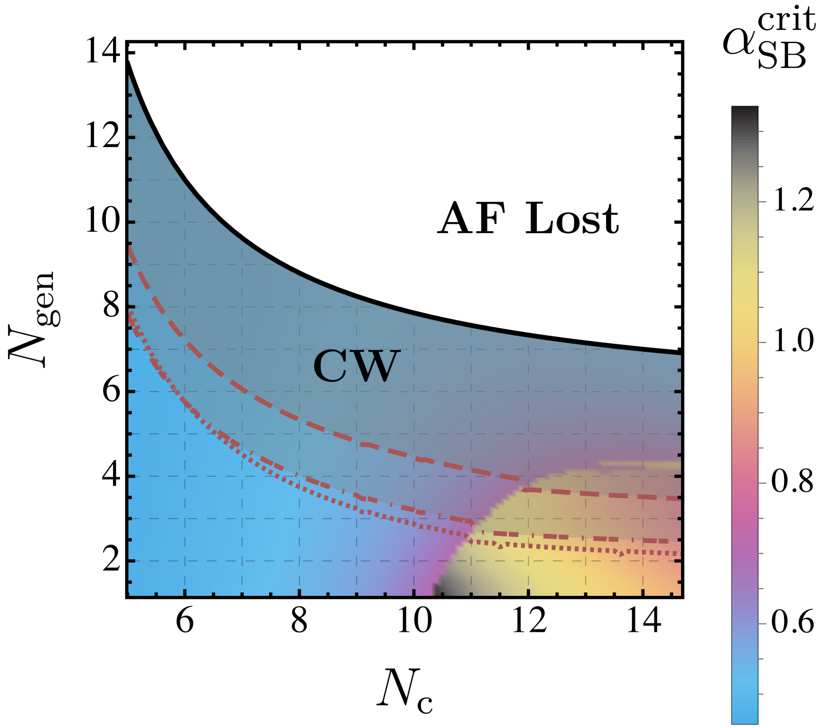
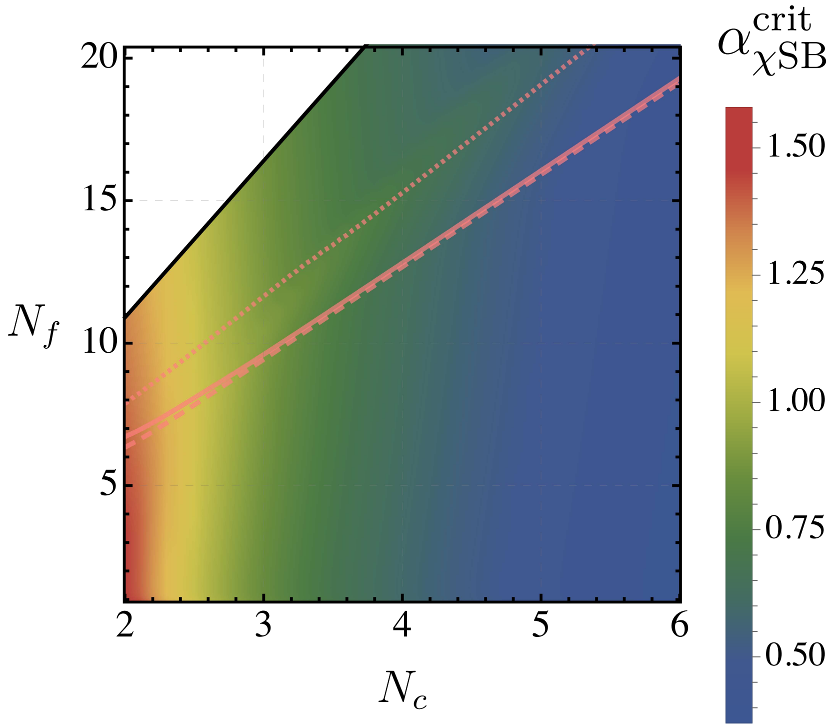
Results



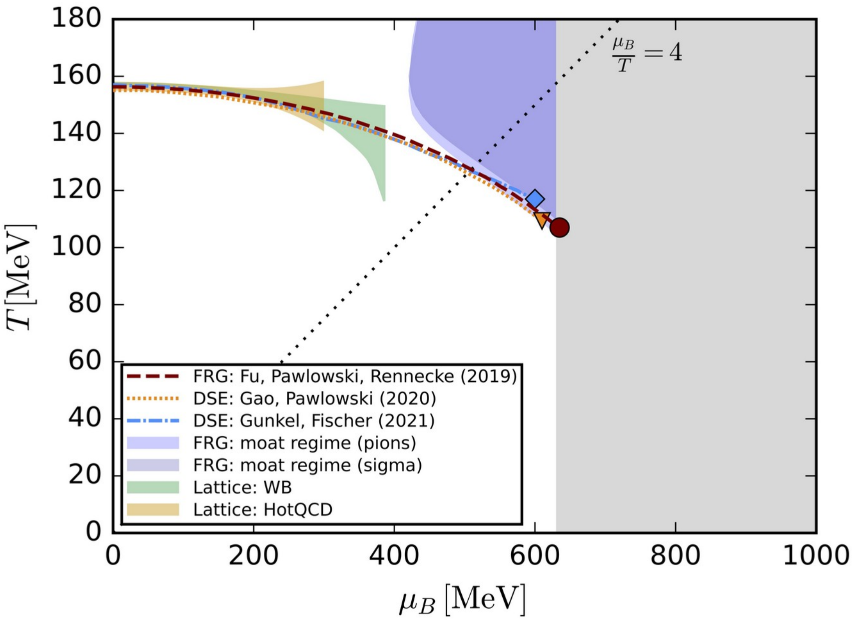


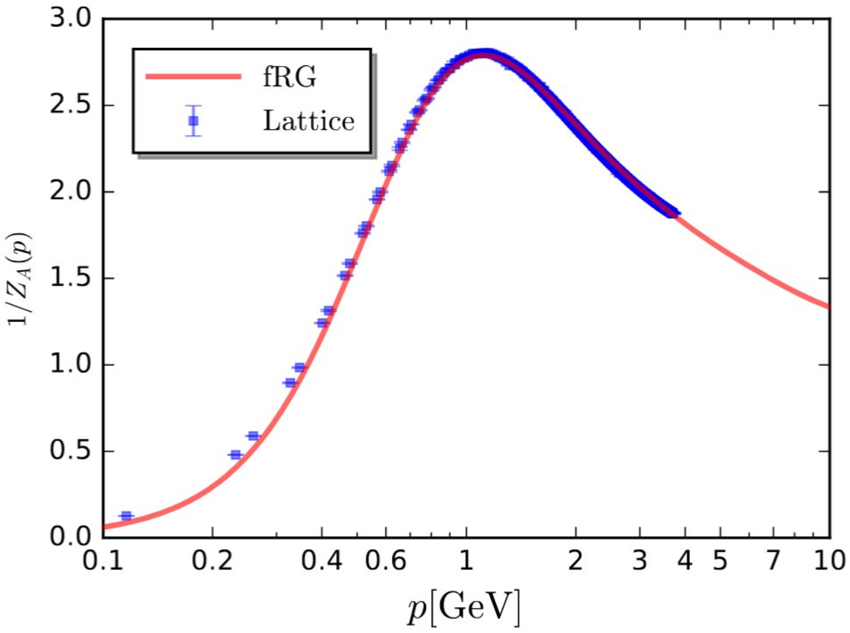
2412.12254 [hep-th] Pastor-Gutiérrez, Pawlowski, Goertz

Conclusion

- Strong evidence for conformal phase
- Color-dependent IR
- Deep IR exploration (Confinement, Spectrum, $\cdots$)

Power of Functional Methods





Results

$$\mathcal{O}^1 = \left(\overline{\psi}^{f_1 i_1}\gamma^\mu P_L \psi_{f_1 i_1}\right)\left(\overline{\psi}^{f_2 i_2}\gamma^\mu P_L \psi_{f_2 i_2}\right),$$

$$\mathcal{O}^2 = \left(\overline{\psi}^{f_1 i_1}\gamma^\mu P_L \psi_{f_2 i_1}\right)\left(\overline{\psi}^{f_2 i_2}\gamma^\mu P_L \psi_{f_1 i_2}\right),$$

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$$\mathcal{O}^4 = \left(\overline{\chi}^{f_1 a_1}\gamma^\mu P_L \chi_{f_1 a_1}\right)\left(\overline{\chi}^{f_2 a_2}\gamma^\mu P_L \chi_{f_2 a_2}\right),$$

$$\mathcal{O}^5 = \left(\overline{\chi}^{f_1 a_1}\gamma^\mu P_L T^{a_2}_{a_1} \chi_{f_1 a_2}\right)\left(\overline{\chi}^{f_2 a_3}\gamma^\mu P_L T^{a_4}_{a_3} \chi_{f_2 a_4}\right),$$

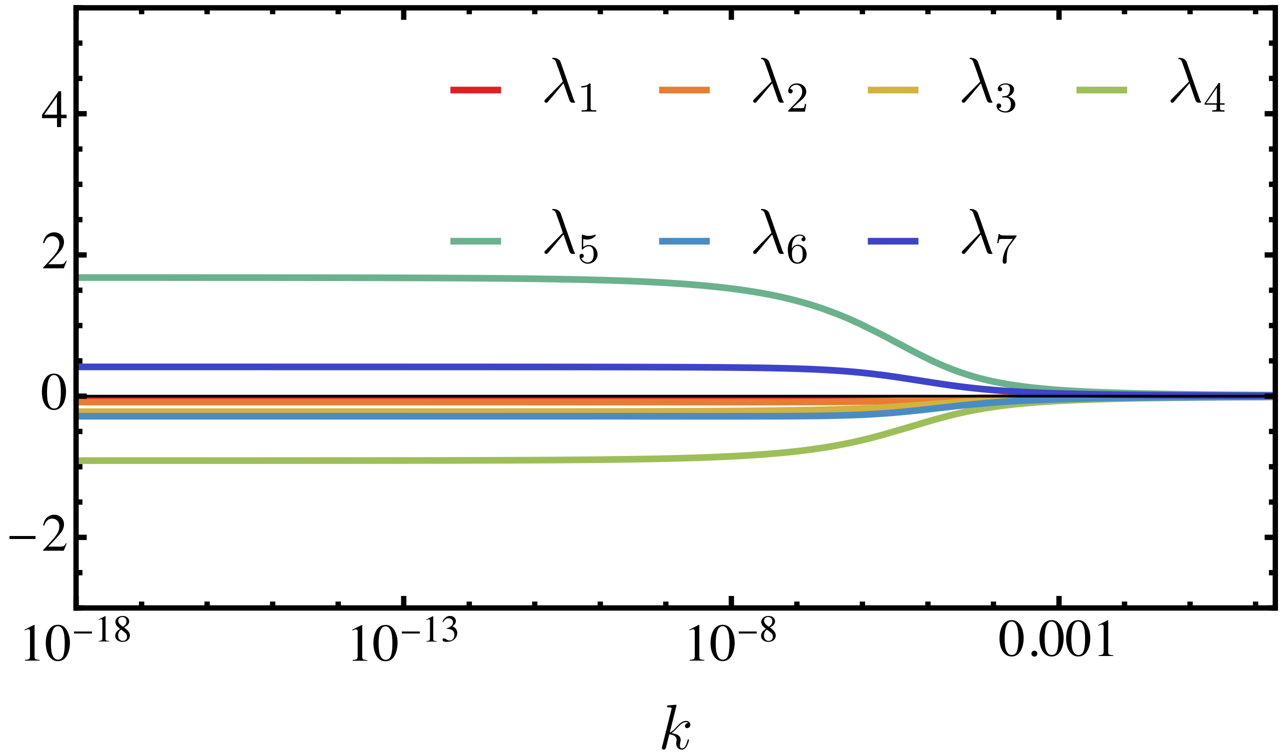
$$\mathcal{O}^6 = \left(\overline{\psi}^{f_1 i_1}\gamma^\mu P_L \psi_{f_1 i_1}\right)\left(\overline{\chi}^{f_2 a_2}\gamma^\mu P_L \chi_{f_2 a_2}\right),$$

$$\mathcal{O}^7 = \left(\overline{\psi}^{f_1 i_1}\gamma^\mu P_L T^{i_2}_{i_1} \psi_{f_1 i_2}\right)\left(\overline{\chi}^{f_2 a_3}\gamma^\mu P_L T^{a_4}_{a_3} \chi_{f_2 a_4}\right).$$

$$\psi \longleftrightarrow \bar{F}$$

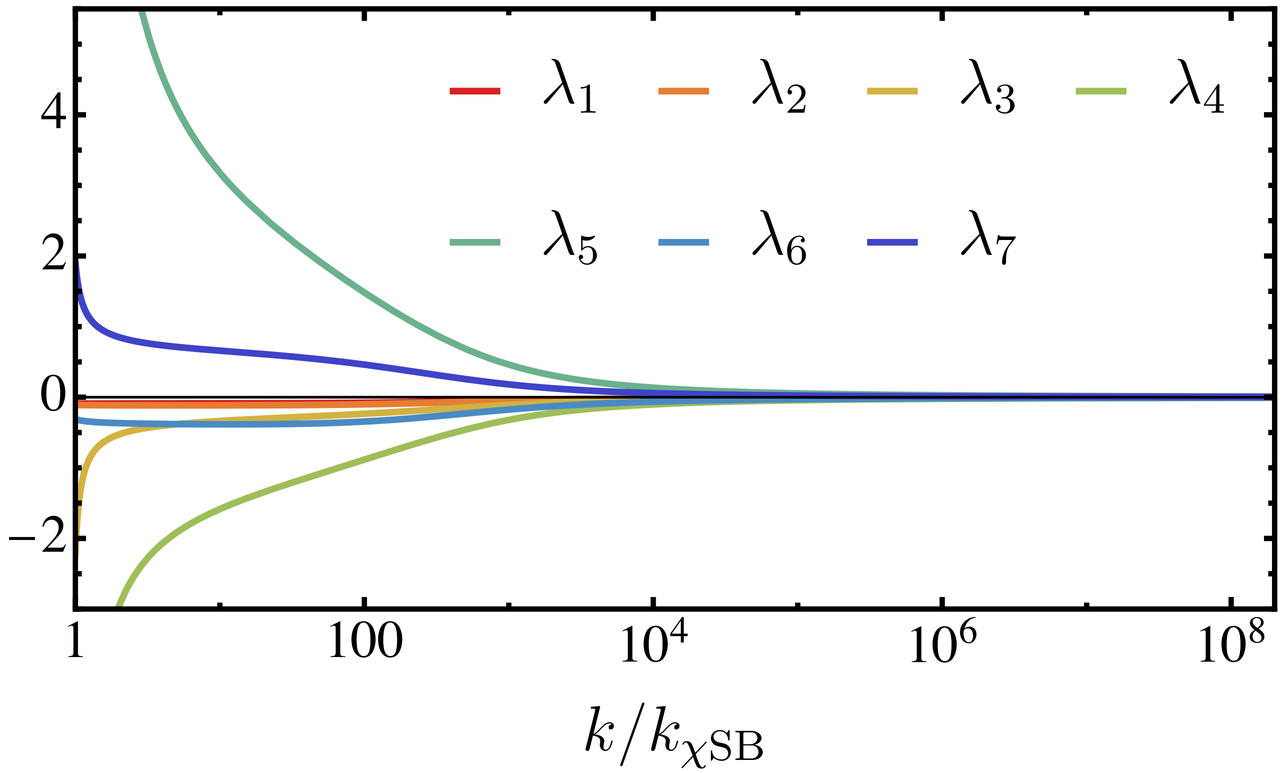
$$\chi \longleftrightarrow A$$

Results



λ_1
λ_2
λ_3
λ_4
λ_5
λ_6
λ_7
4
2
0
−2
10^{-18}
10^{-13}
10^{-8}
0.001
k

Results



λ_1
λ_2
λ_3
λ_4
λ_5
λ_6
λ_7
4
2
0
−2
1
100
10^4
10^6
10^8
$k/k_{\chi\mathrm{SB}}$

How To Diagnose $\chi\mathrm{SB}$?

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→ Nambu-Jona-Lasino Model

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

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- $U(1)_V \times U(1)_A$

How To Diagnose $\chi\mathrm{SB}$?

→ $Z \propto \int \mathcal{D}\bar{\psi}\mathcal{D}\psi e^{S}$

How To Diagnose $\chi\mathrm{SB}$?

$$\rightarrow \quad Z \propto \int \mathcal{D}\bar{\psi}\mathcal{D}\psi e^{S} = \mathcal{N} \int \mathcal{D}\bar{\psi}\mathcal{D}\psi\mathcal{D}\phi \; e^{\frac{m^2}{2}\phi^2} \; e^{S} \qquad \phi = (\sigma, \pi)$$

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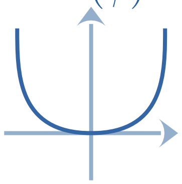

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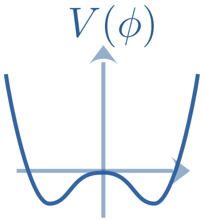

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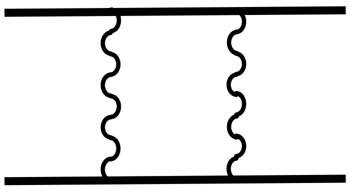

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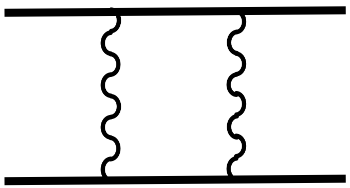

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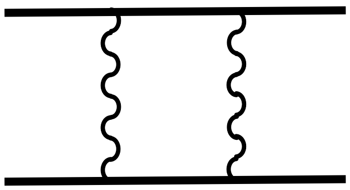

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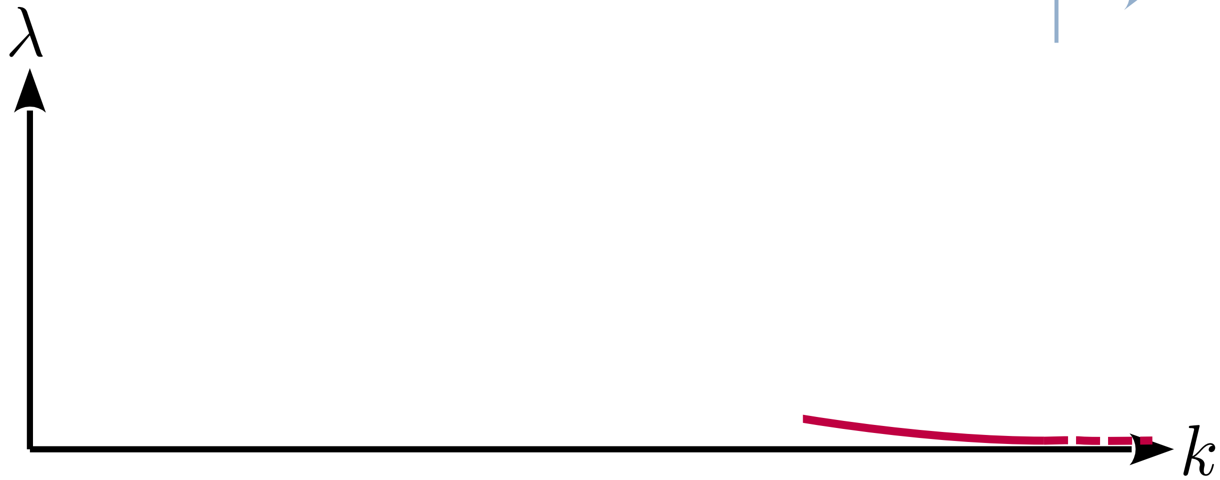

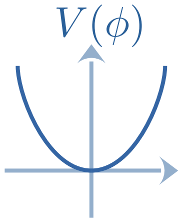

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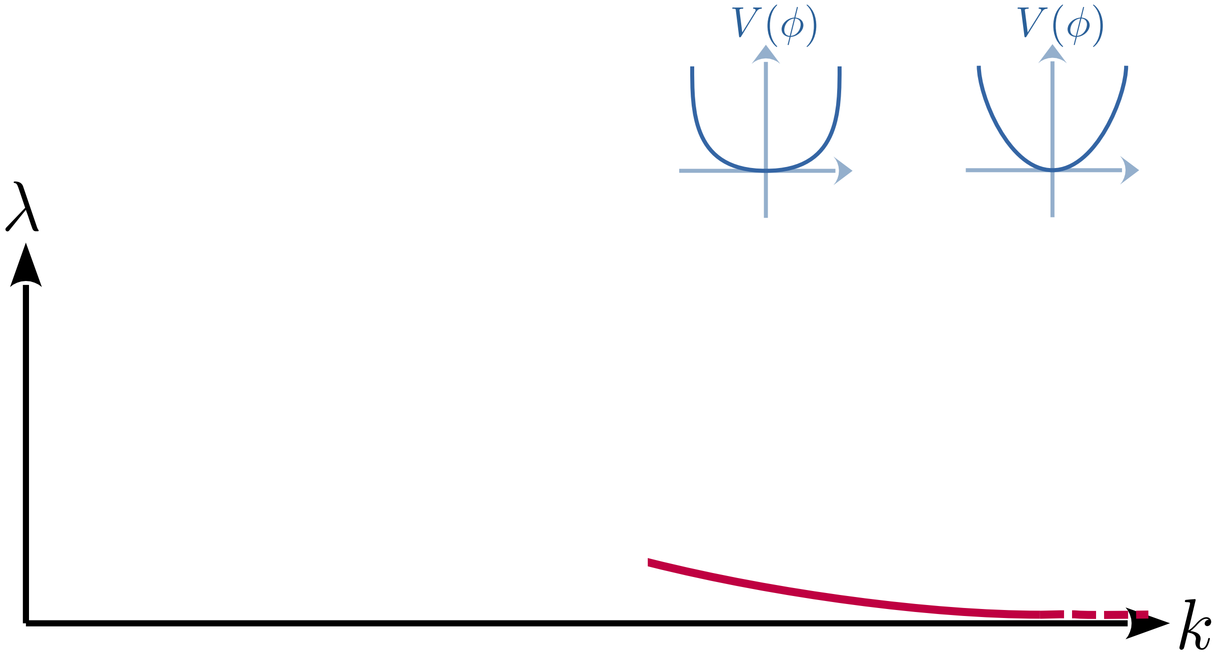

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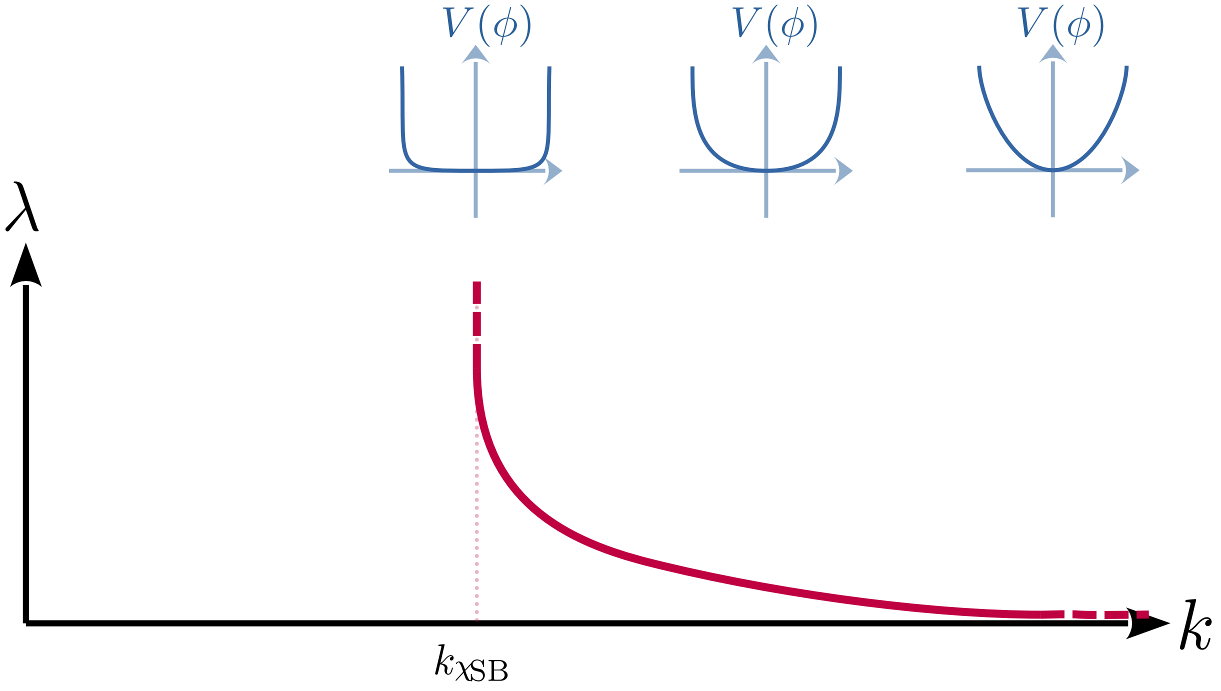

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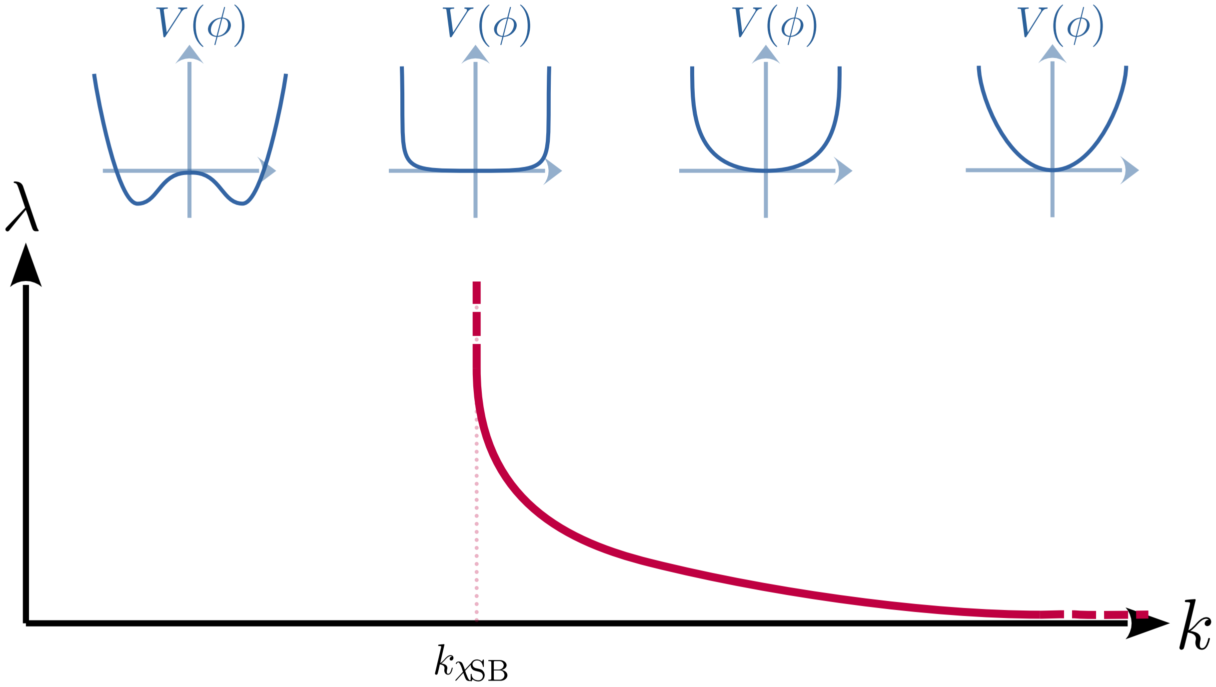

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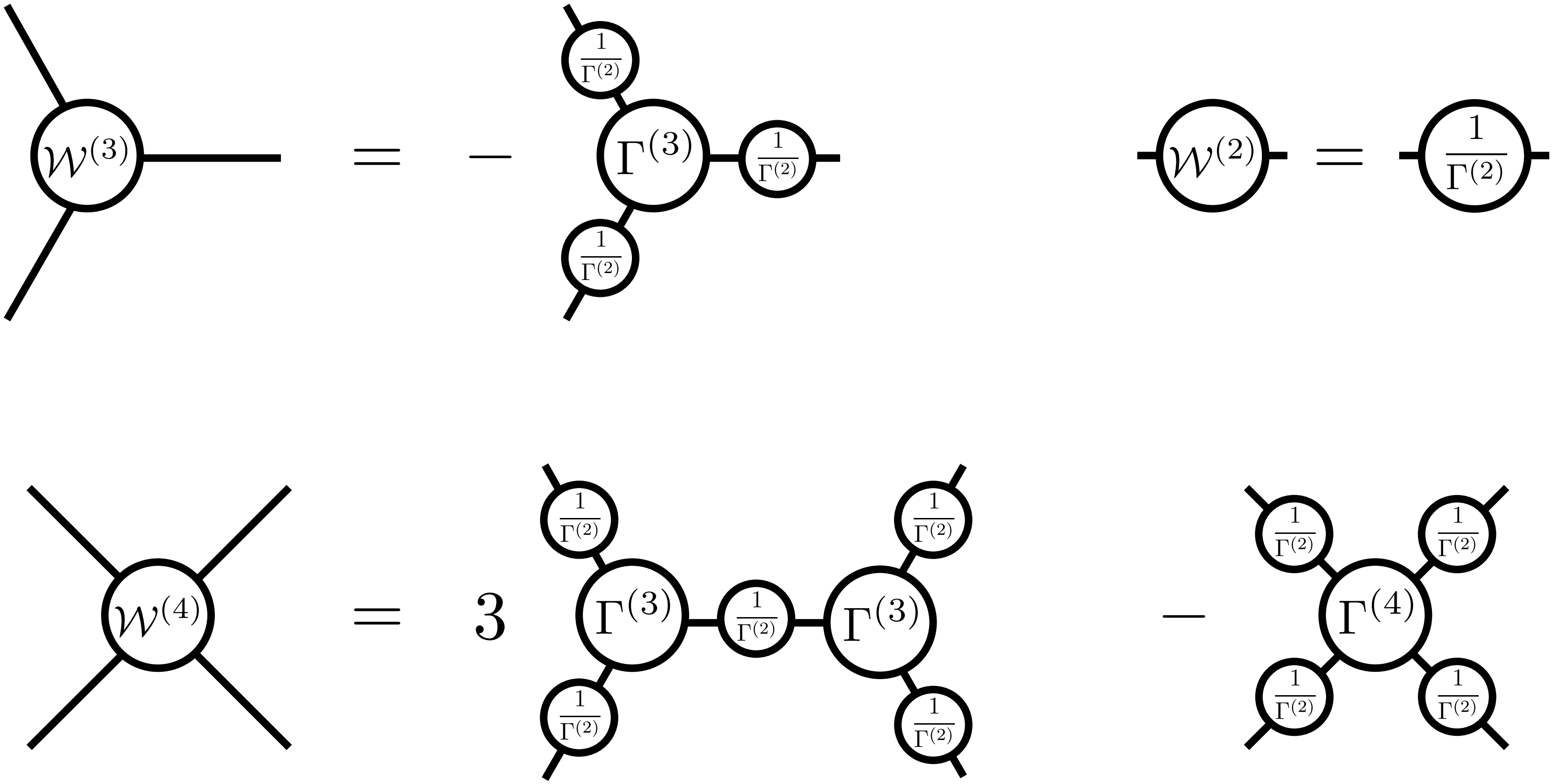

Chiral Dynamic

- Vacuum $\Rightarrow G/H$

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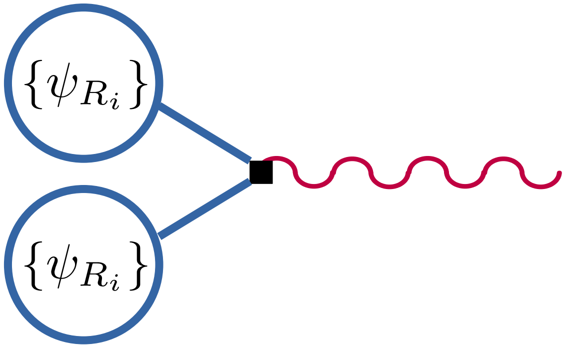
$\rightarrow$ 

$\rho_\mu = \bar{\psi}\sigma_\mu\psi$

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