Cartography of strong new physics:

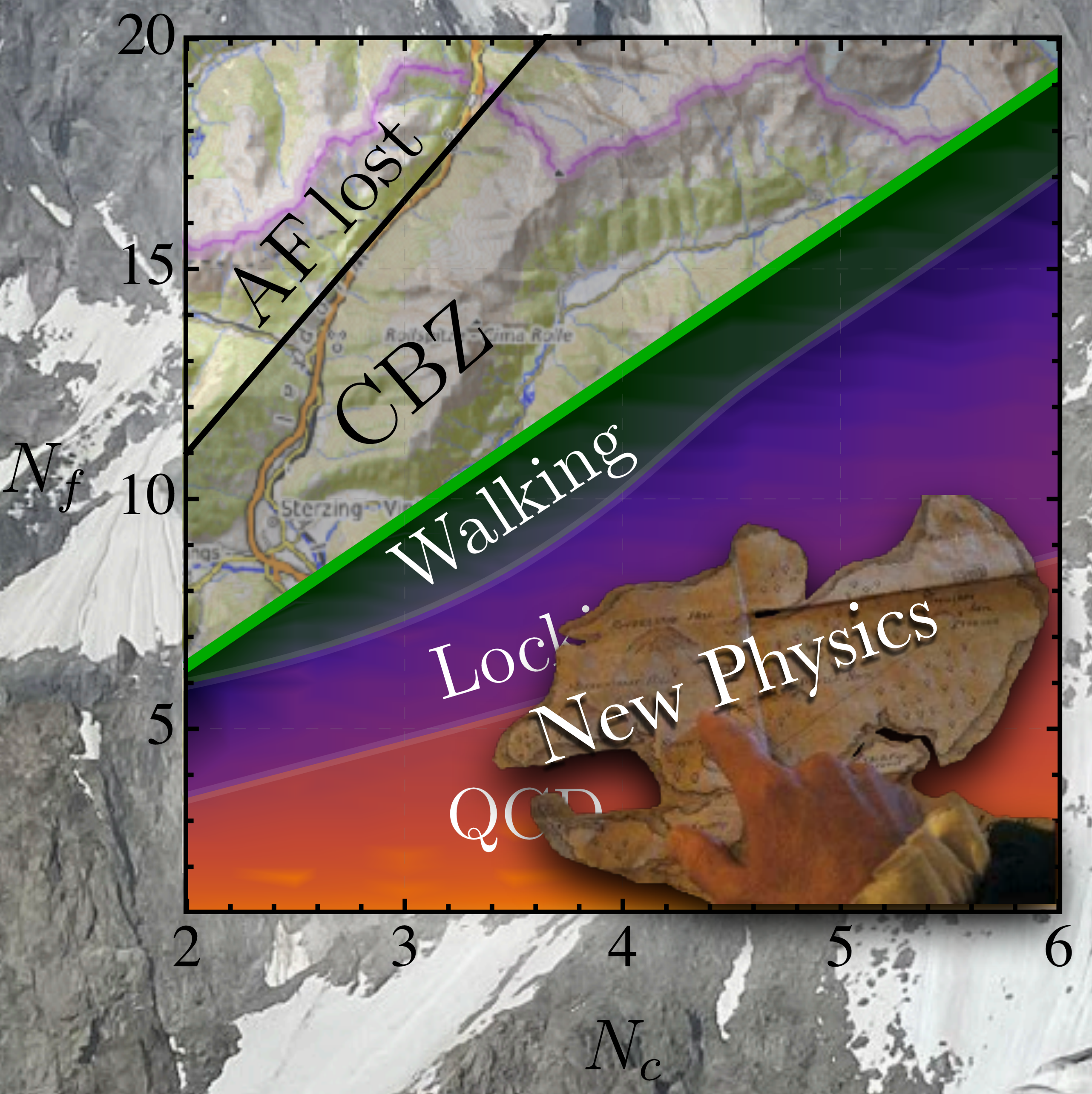
1.confinement

2.dχSB

3.conformality

arXiv: [2412.12254]

Work in collaboration with
Florian Goertz and Jan M. Pawlowski



Álvaro Pastor Gutiérrez

PASCOS 2025, Durham, UK
24th of July 2025

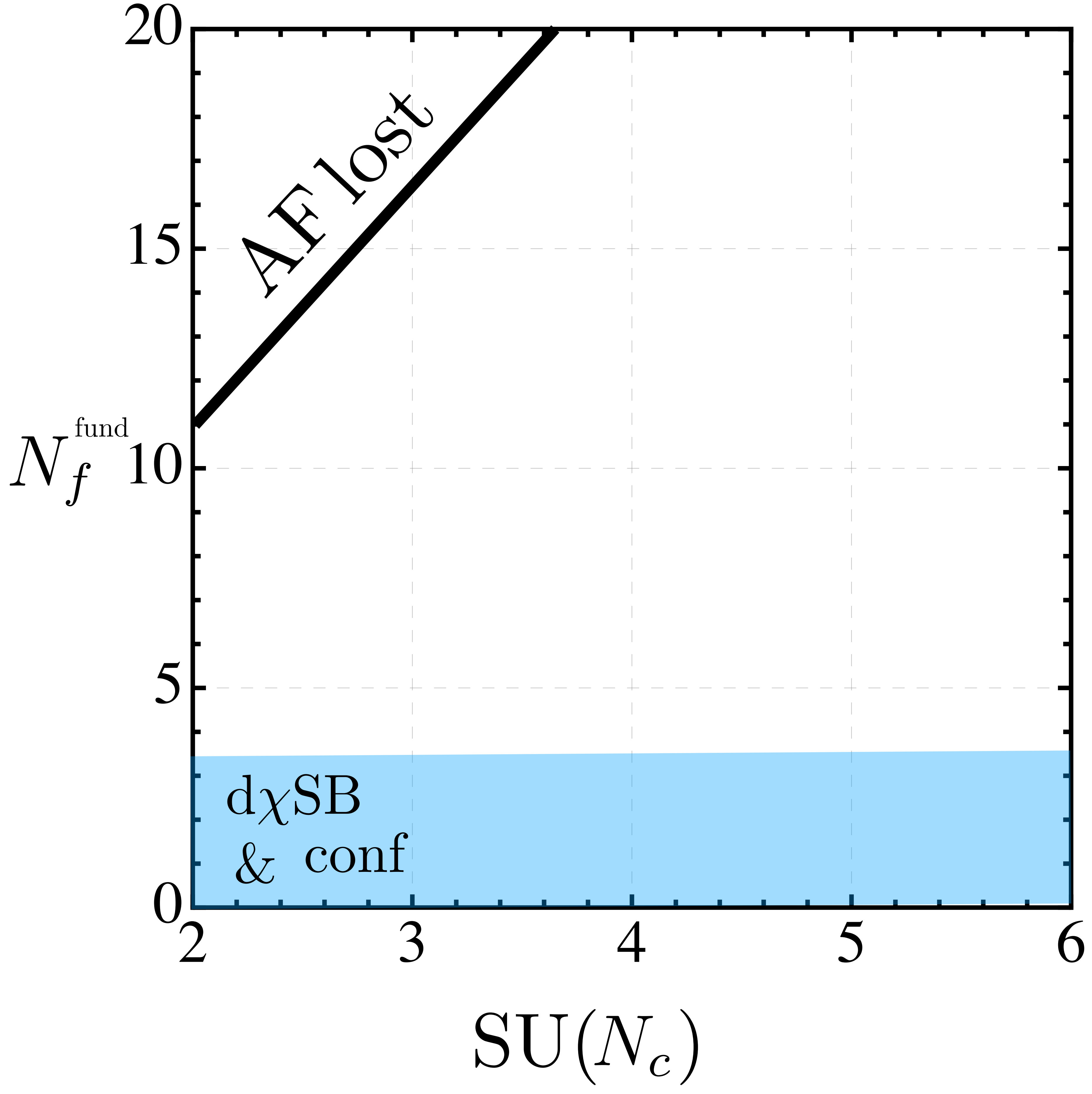
iTHEMS
RIKEN Center for Interdisciplinary Theoretical and Mathematical Sciences

RIKEN's Programs for Junior Scientists

Gauge-fermion QFTs

$$S = \int_x \underbrace{\frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \mathcal{L}_{\rm gf} + \mathcal{L}_{\rm gh}}_{\mathrm{SU}(N_c)} + \underbrace{\bar{\psi} \not{D}\, \psi}_{\mathrm{SU}(N_f)_L \times \mathrm{SU}(N_f)_R}$$

Gauge-fermion QFTs



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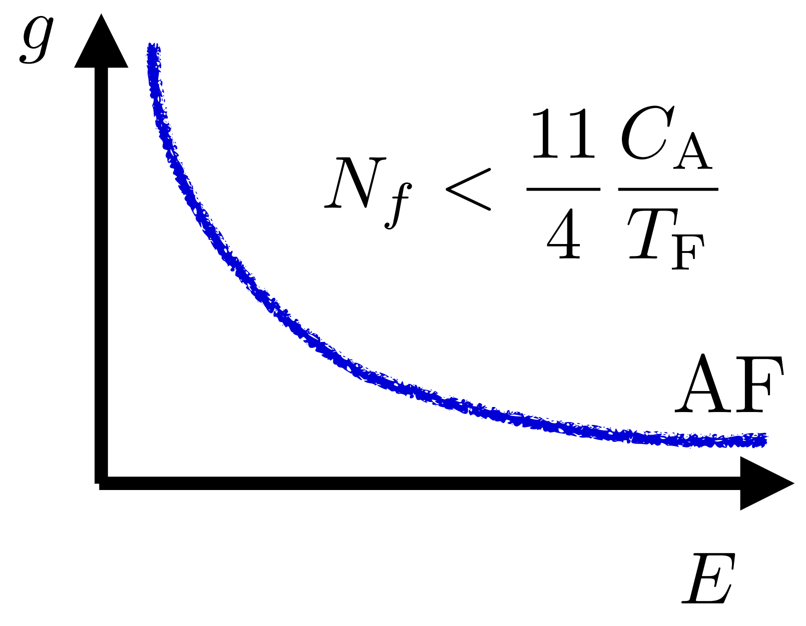
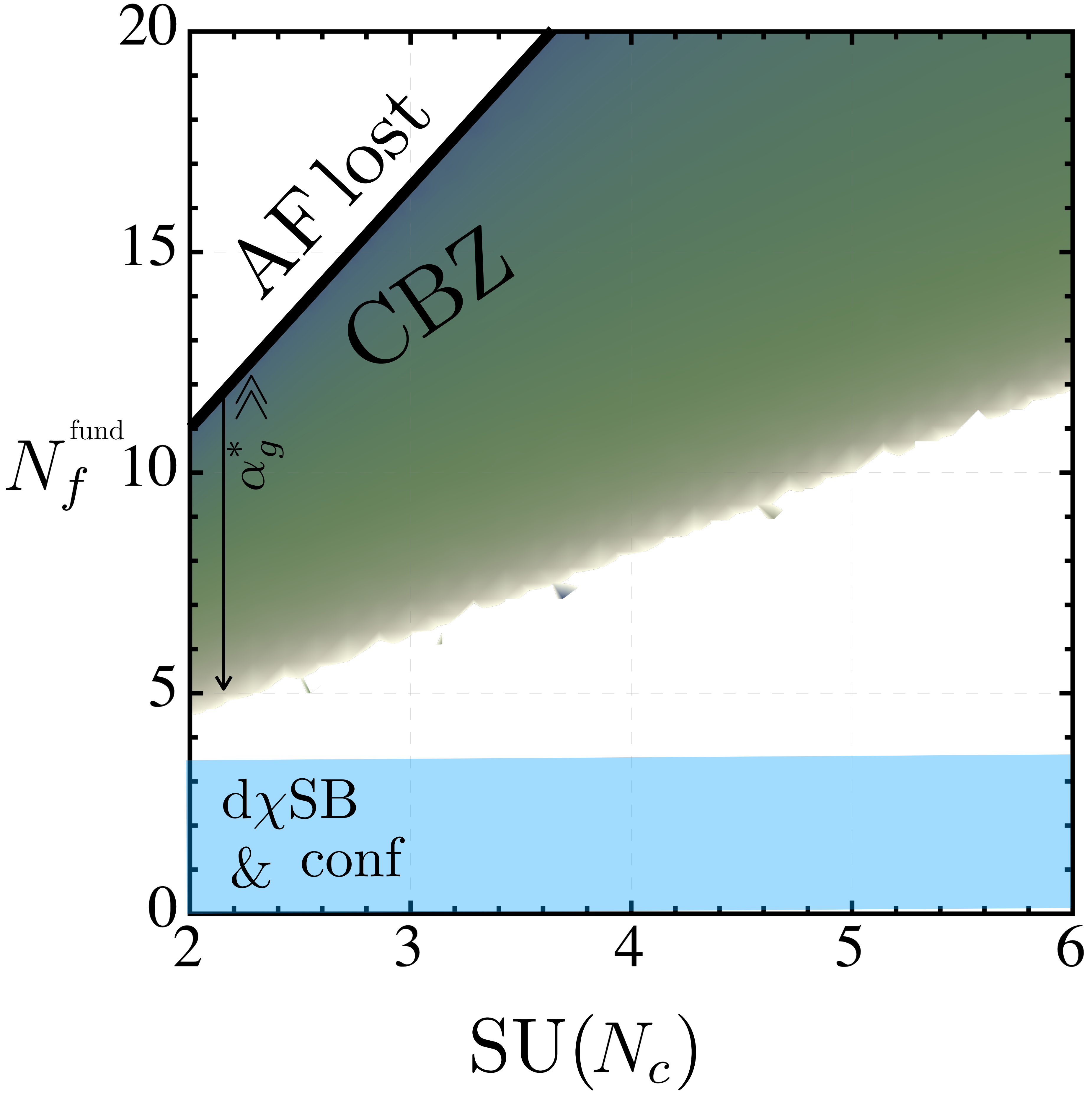
- **Asymptotic freedom**
- **Few flavours**: QCD-like theories

Gross, Wilczek '73
Politzer '73



$$\beta_g = -\frac{g^3}{(4\pi)^2} \left(\frac{11}{3} C_A - \frac{4}{3} T_F N_f \right)$$

Gauge-fermion QFTs



$\mathrm{SU}(N_c)$

$$S = \int_x \boxed{\frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \mathcal{L}_{\mathrm{gf}} + \mathcal{L}_{\mathrm{gh}}} + \boxed{\bar{\psi} \not{D}\, \psi}$$

$\mathrm{SU}(N_f)_L \times \mathrm{SU}(N_f)_R$

- **Asymptotic freedom**
- **Few flavours**: QCD-like theories
- **CBZ IR fixed point** (perturbative)

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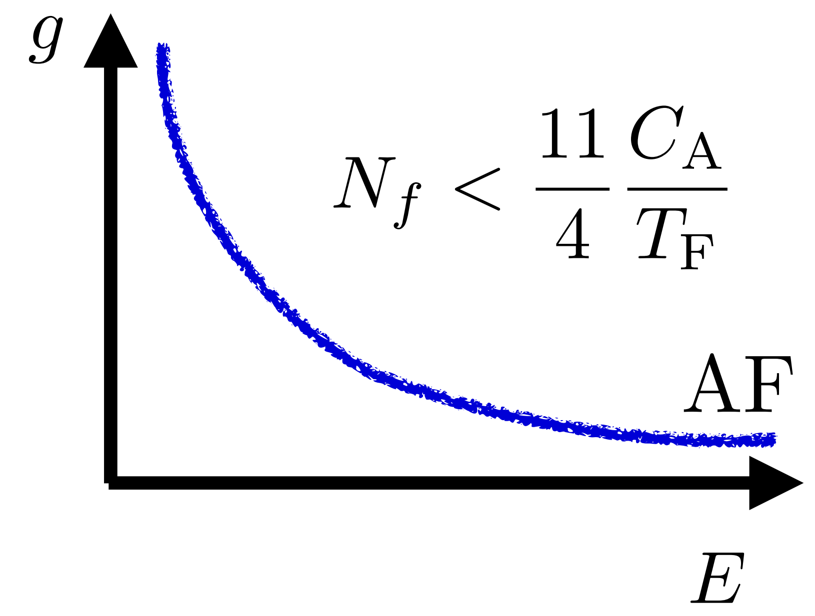
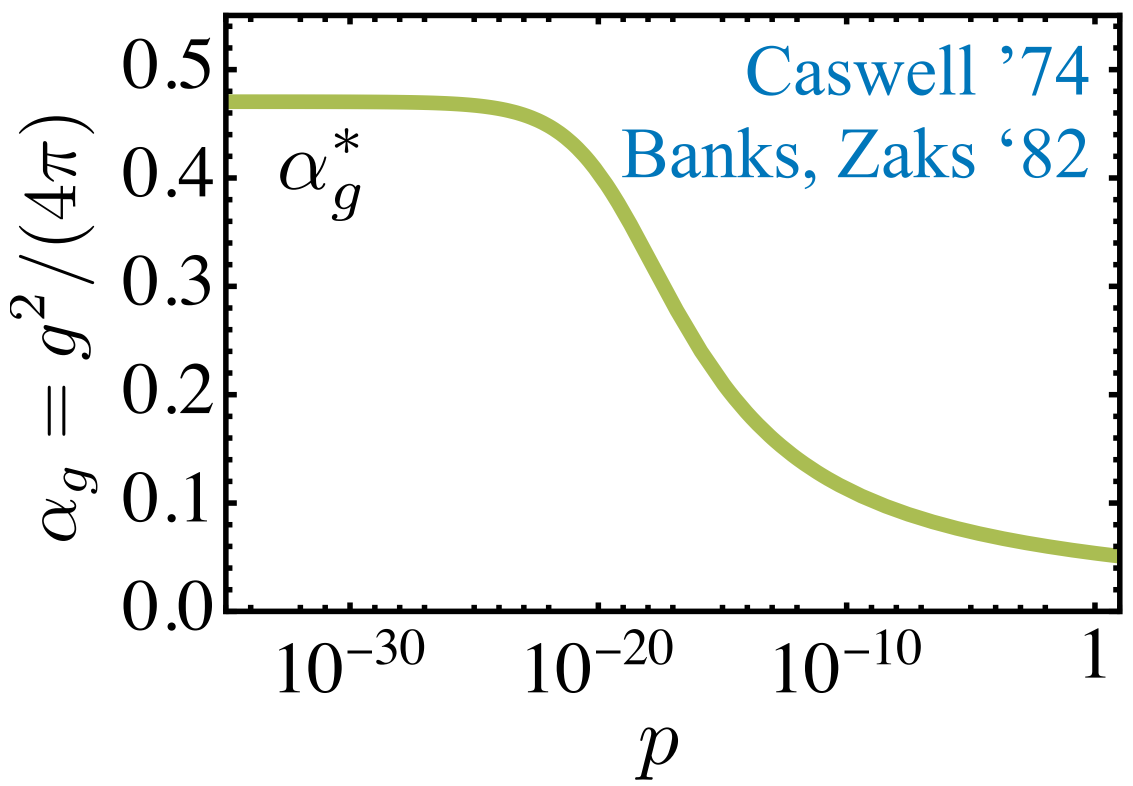


$$\beta_g = -\frac{g^3}{(4\,\pi)^2} \left(\frac{11}{3} C_\mathrm{A} - \frac{4}{3} T_\mathrm{F} N_f \right) - \frac{g^5}{(4\,\pi)^4} \left(\frac{34}{3} C_\mathrm{A} - 4 C_\mathrm{F} T_\mathrm{F} N_f - \frac{20}{3} C_\mathrm{A} T_\mathrm{F} N_f \right) + \cdots$$

$$\beta_g \big|_{g^*} = 0$$

Quantum scale invariance
& **conformality**



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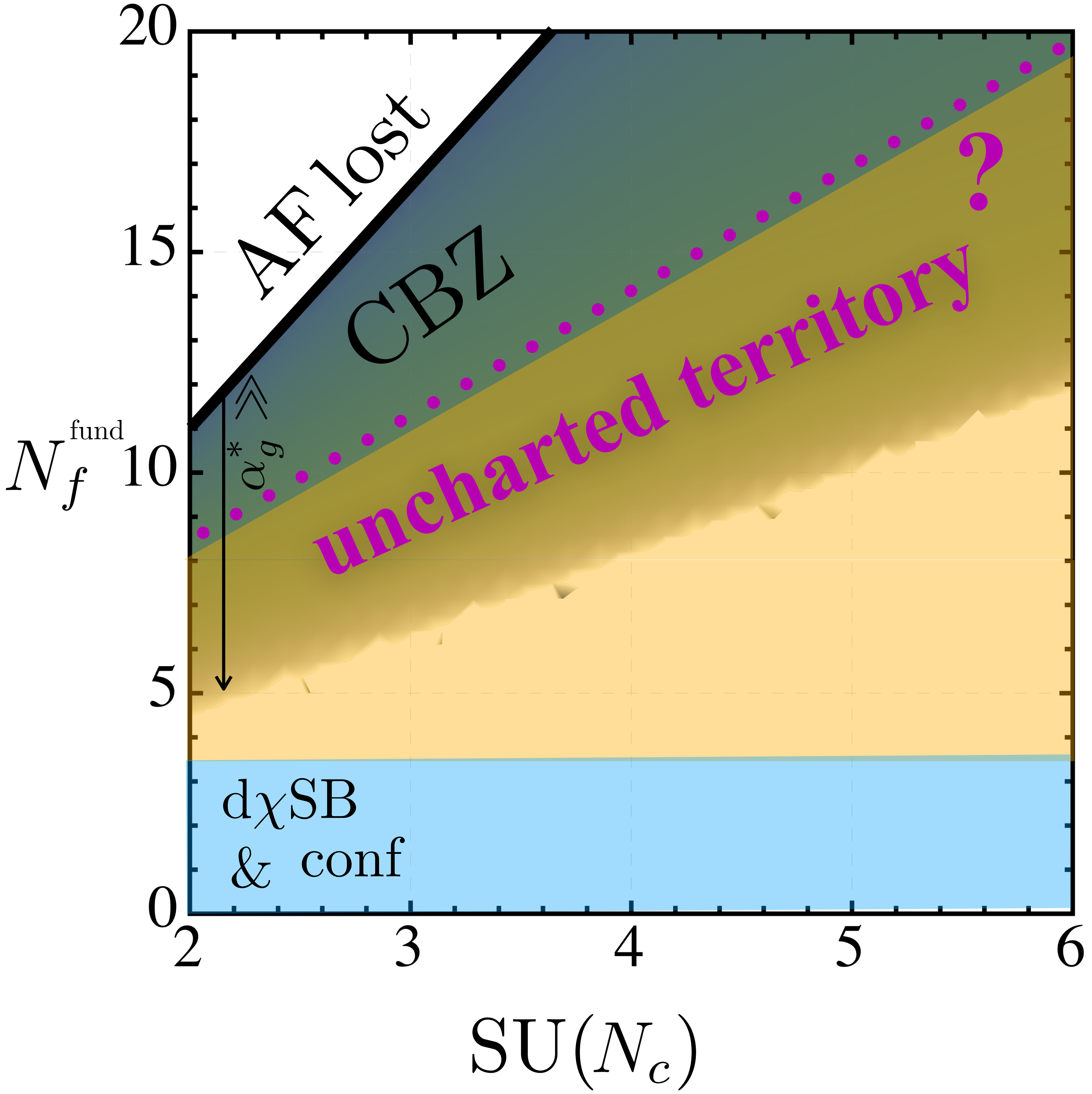

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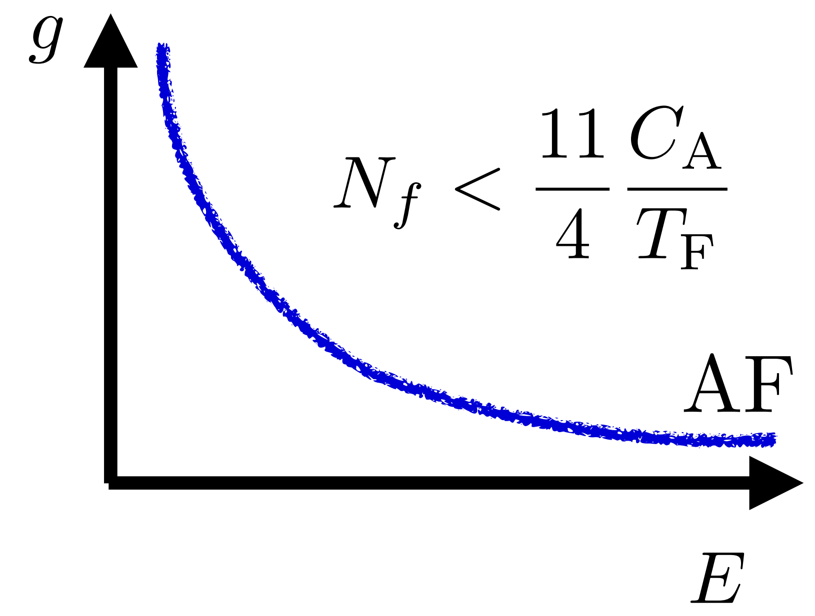

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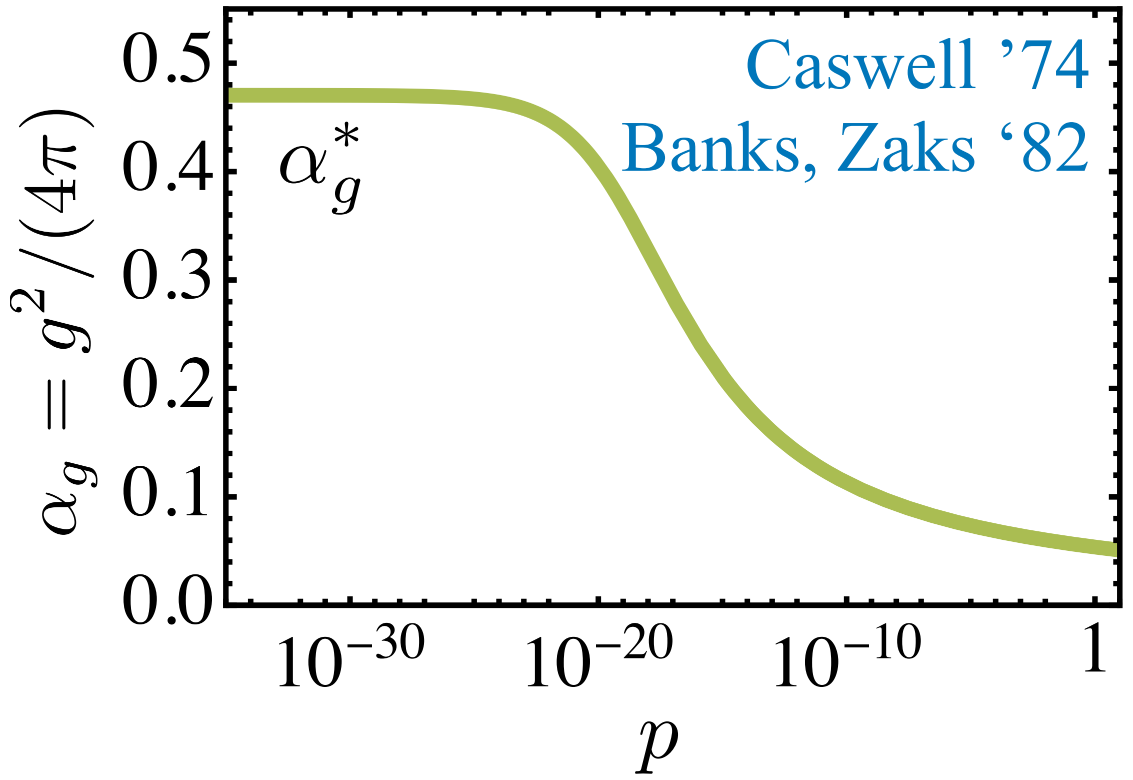
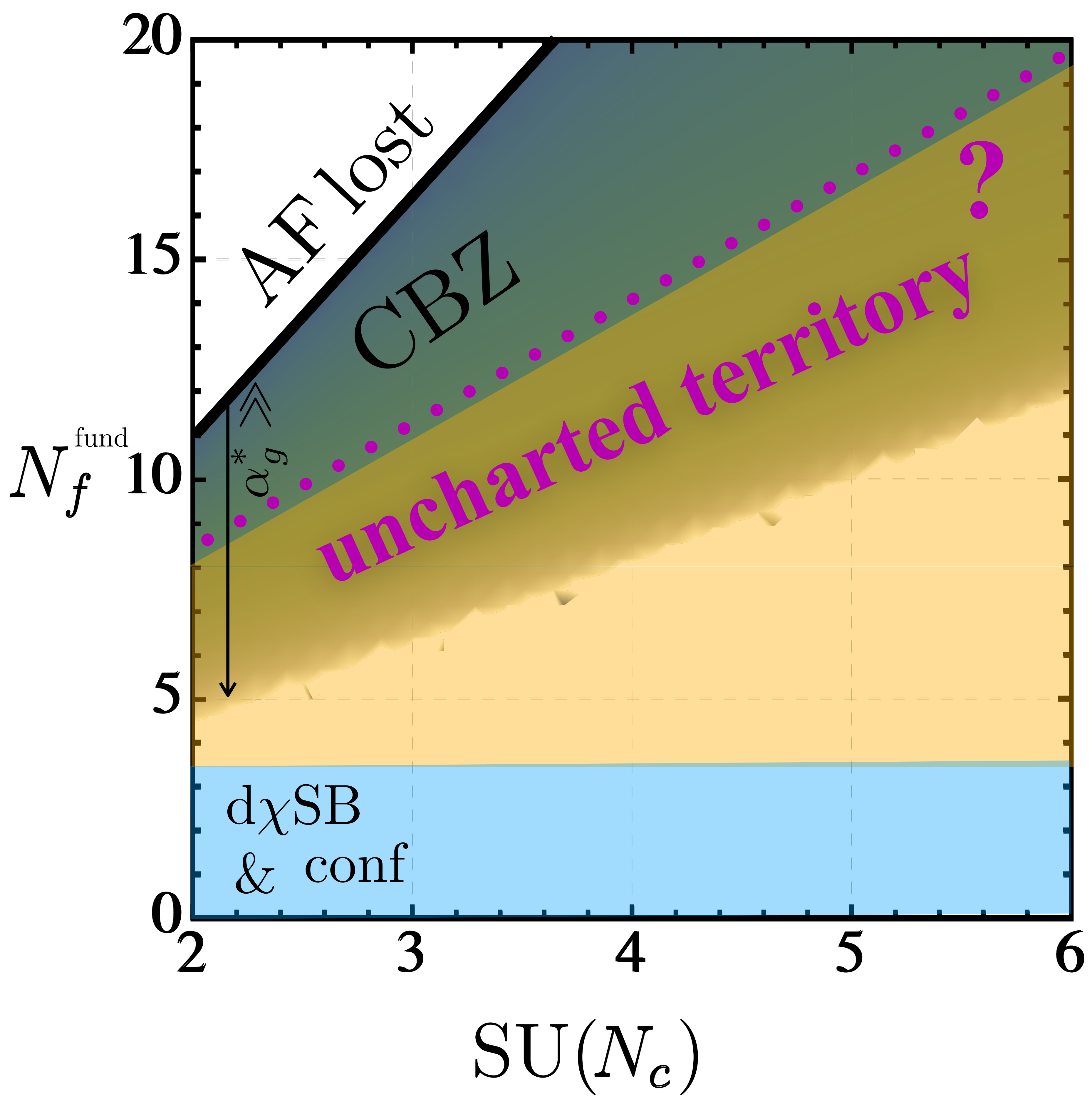


Strong beyond the SM



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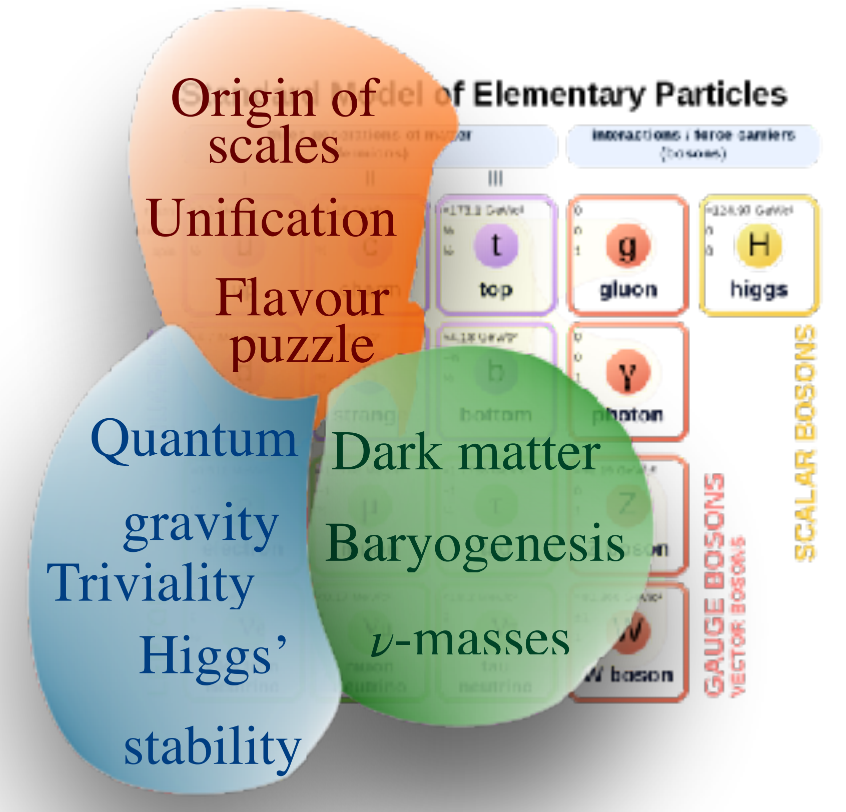


Answer to fundamental problems & puzzles in nature:

- **Strong dark sectors:** Dark Matter, …
- **Composite Higgs** and **Technicolour models**
  - Natural **separation of scales** (*walking regimes*)

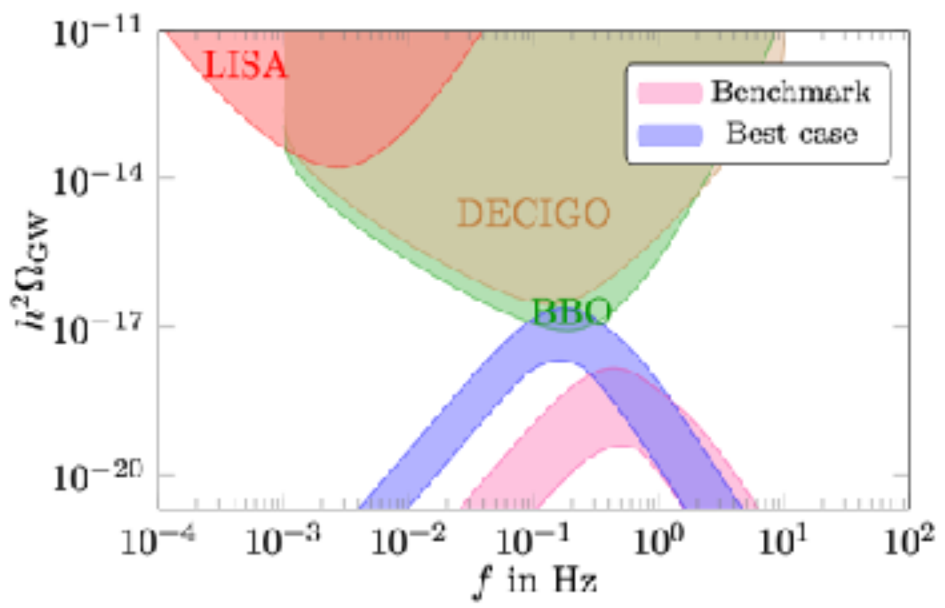
Dietrich,Sannino[0611341]

…

…

Observational prospects:

- **Cosmological phase transitions** (chiral & confining) and **GW** signatures



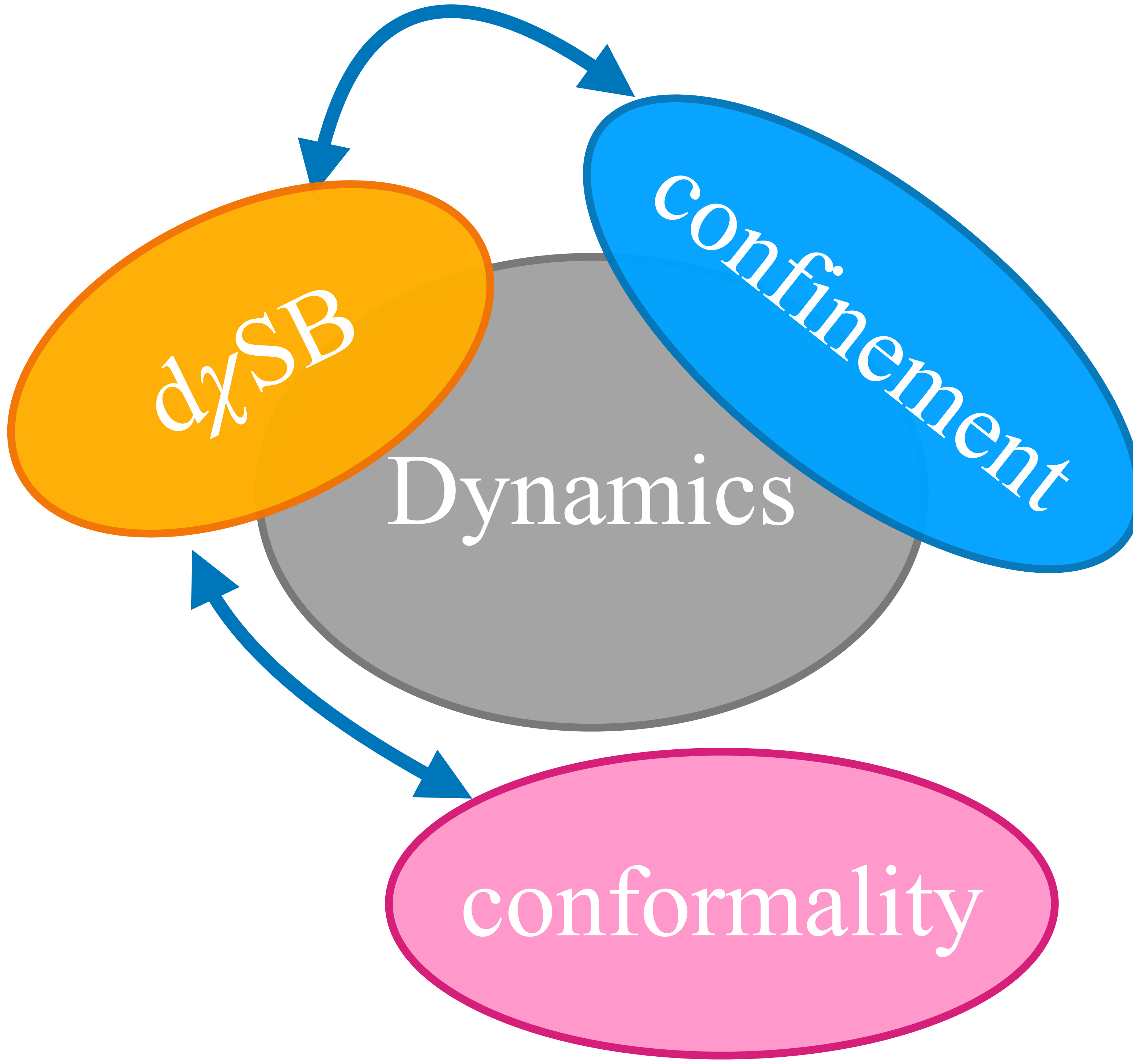
Reichert,Sannino,Wang,Zhang[2109.11552]
Pashechnik,Reichert,Sannino,Wang[2309.16755]
Iso,Okada,Orikasa[0902.4050]
Iso,D.Serpico,Shimada[1704.04955]
…

open the door to **new non-perturbative new physics and dynamics beyond QCD-limit!**

Charting the landscape

$$S = \int_x \frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \mathcal{L}_{\text{gf}} + \mathcal{L}_{\text{gh}} + \bar{\psi} \not{D} \psi$$

1. Understand **interplay of dynamics** & their respective scales ⇝ **phase structure**
2. Extract **fundamental parameters** ⇝ **phenomenology**
3. Precisely determine the **boundary** between conformal & dynamical phases



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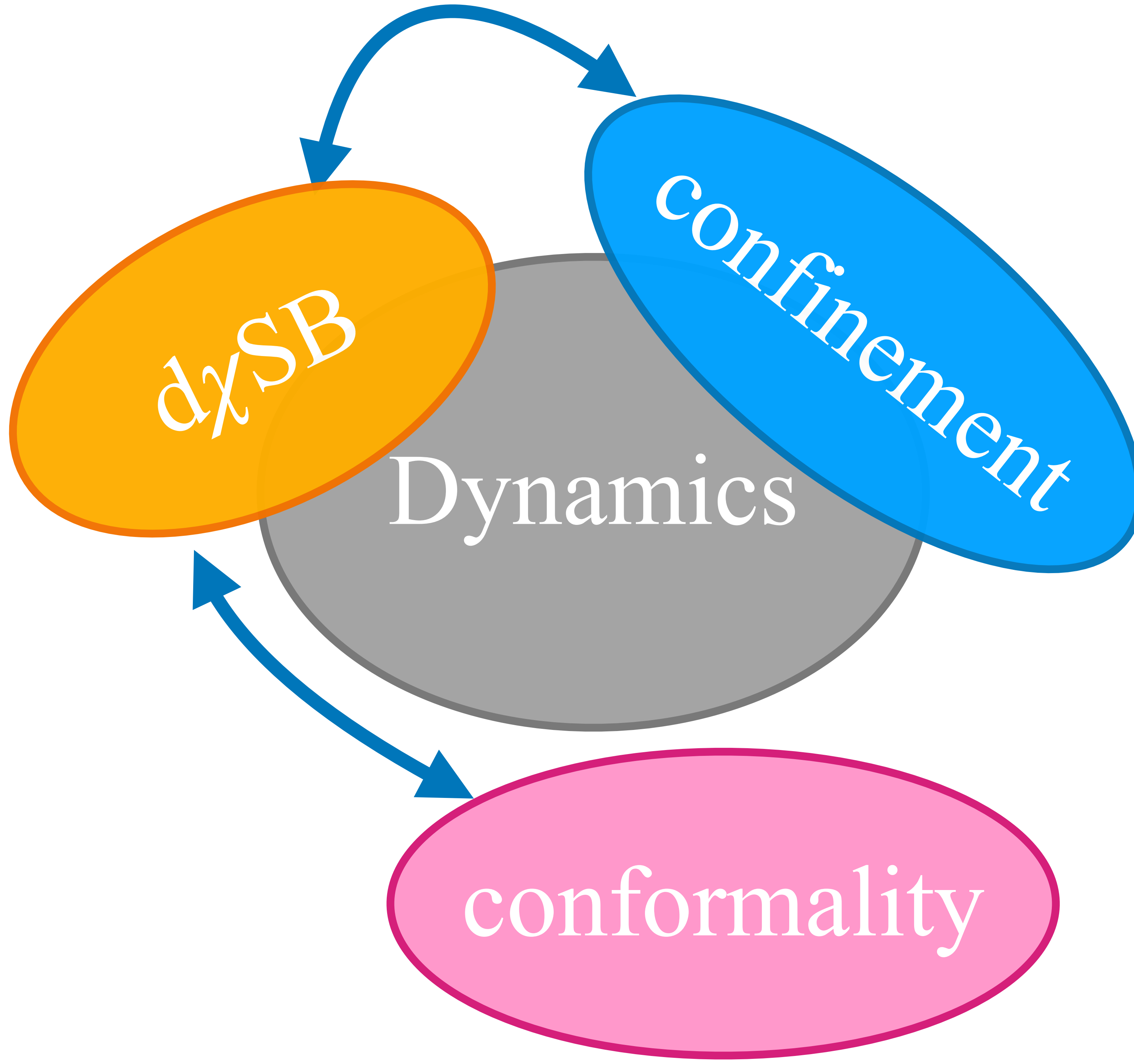


<u>**Tailored-made task**</u> for the **functional Renormalisation Group (fRG):**

- **First principles non-perturbative** approach
- **Quantitative**
- **Versatile**: easily study large range of parameter and theory space
- **Chiral limit** with no difficulties

$$\partial_t \Gamma_k[\phi]$$

Functional Renormalisation Group

✦ **Effective average action**: $\Gamma_k[\phi]$

- Average action of fields over a k^{-d} space-time volume
- Kadanoff's block-spinning idea generalised to the continuum limit

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

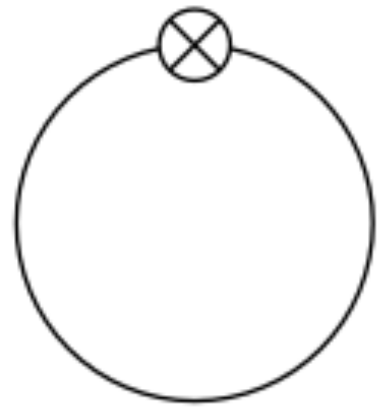
$$\Gamma_k[\phi] = \int_x J(x)\phi(x) - \mathcal{W}_k[J] - \Delta S_k[\phi]$$

Wetterich '89

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

Flow equation:

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



$\partial_t \equiv k \, \partial_k$

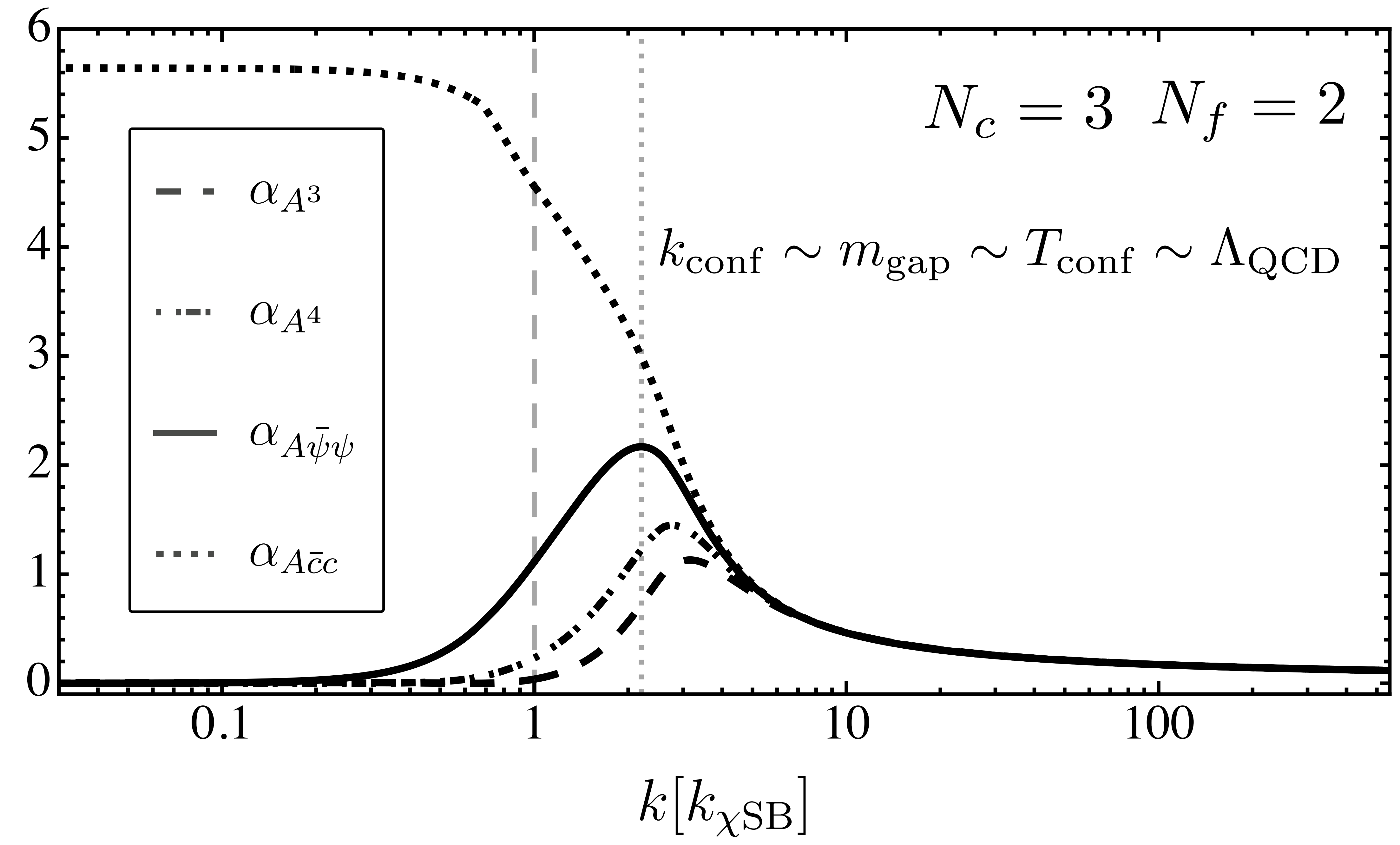
Wetterich '93

- One loop exact
- Non-perturbative
- Mass-dependent
- Analytic regulators
- Versatile
- Systematic schemes
- UV-IR finite
- Diagrammatic
- Real-time formulation
- …

✦ Pedagogical introduction to fRG: Gies [0611146] ✦ Review: Dupuis,et.al [2006.04853]

Colour confinement and the gluon mass gap

- **Absence** of **coloured asymptotic states**
- **Massive spectrum** of bound states (glueballs)



- fRG gauge-fixed approach to confinement:

  Fischer,Maas,Pawlowski [0810.1987] Cyrol,Fister,Mitter,Pawlowski [1605.01856]

  - **Gluon mass gap** generated by **quantum fluctuations**

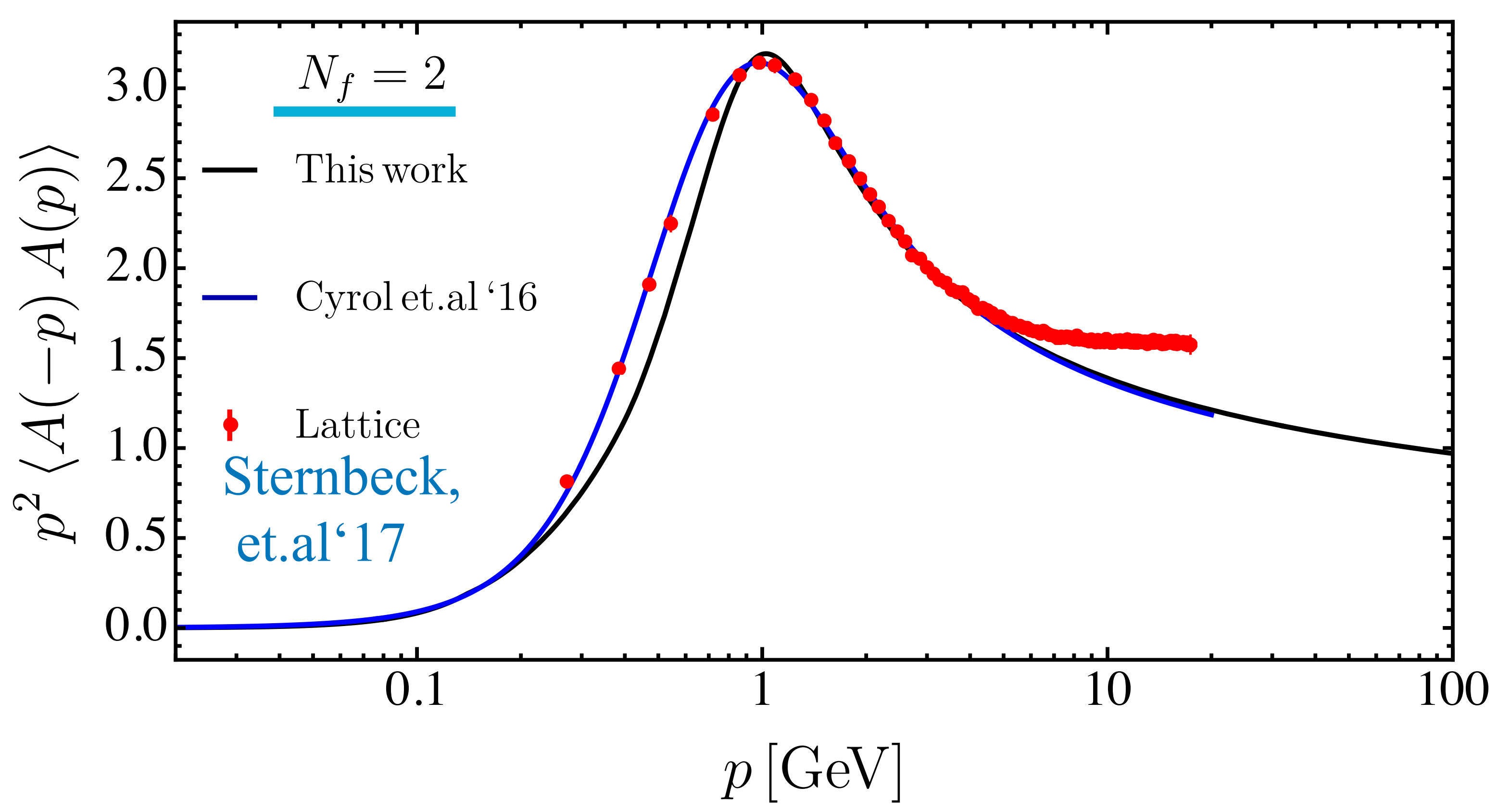
    $$\Gamma_k^{(AA)}(p^2) = Z_{A,k}(p)(p^2 + m^2_{{\rm gap},k}) = \hat{Z}_{A,k}(p)\, p^2$$

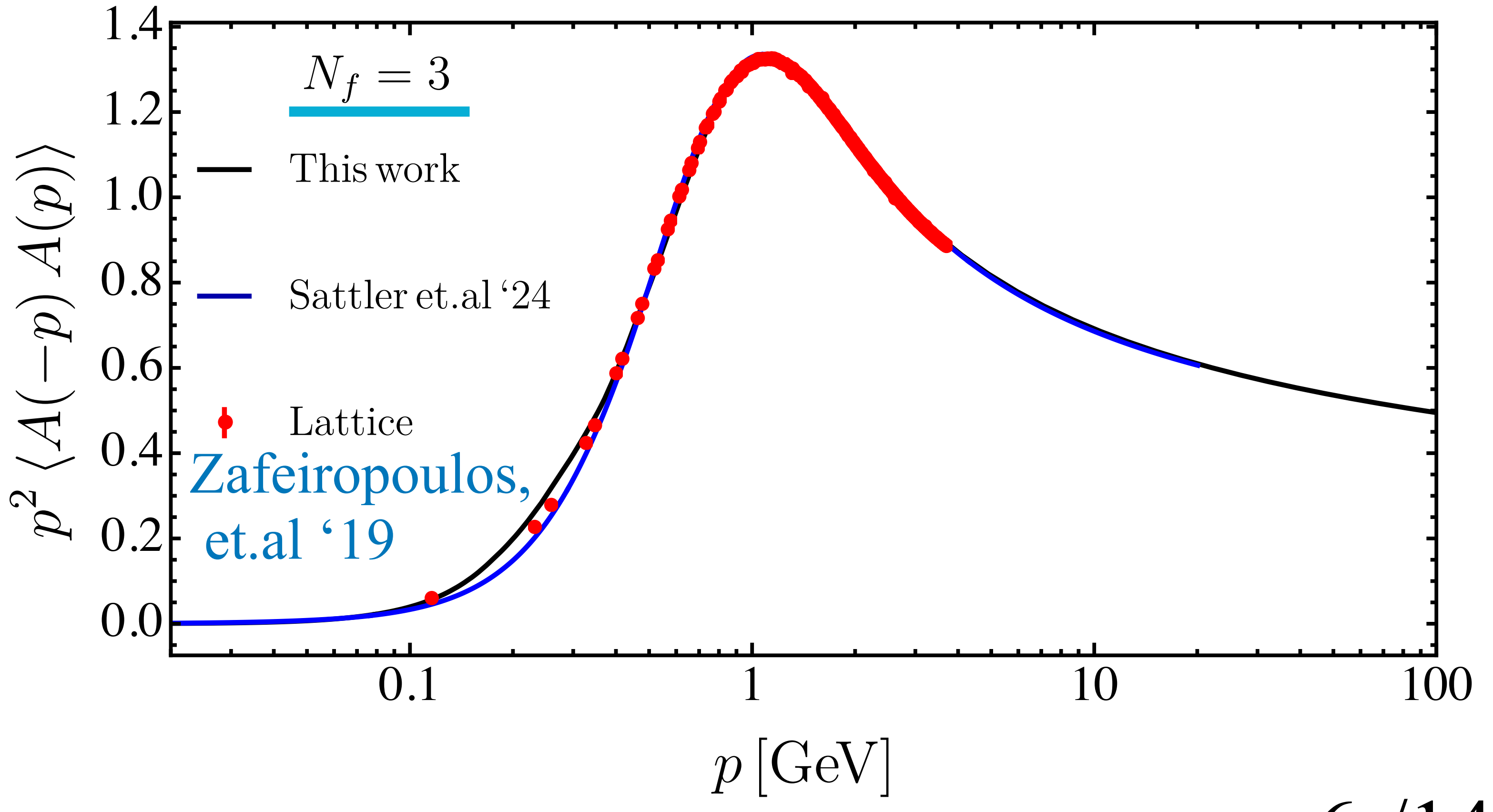
  - **Bootstrap approach**: **uniquely defined** confining solution via existence of a global BRST charge Kugo, Ojima'79

$$\lim_{p\to 0} Z_c(p^2) \propto (p^2)^{\kappa} \qquad \lim_{p\to 0} Z_A(p^2) \propto (p^2)^{-2\kappa}$$

with $\kappa \simeq 0.58$

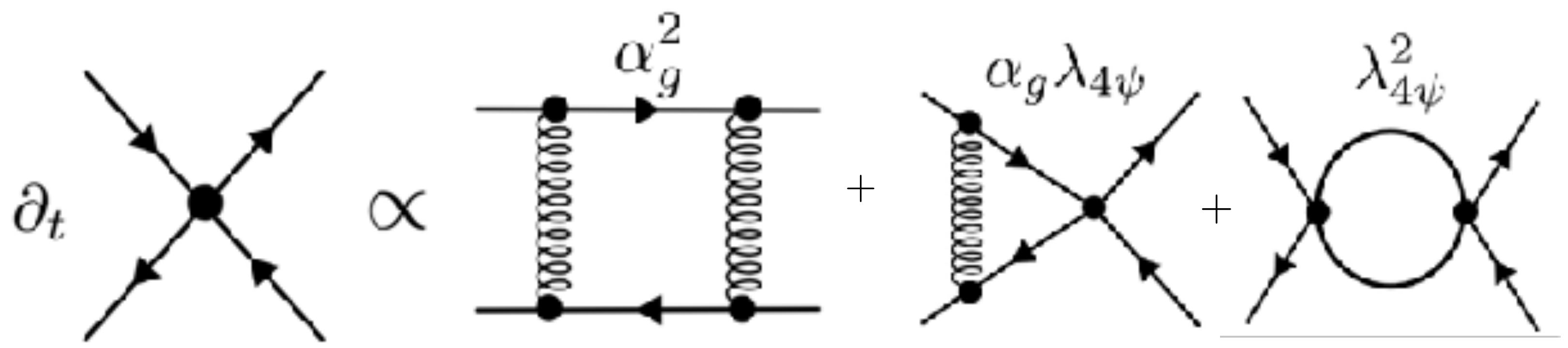
- New: "*easy*" confinement
  - Semi-analytical
  - Facilitate study beyond QCD-limit



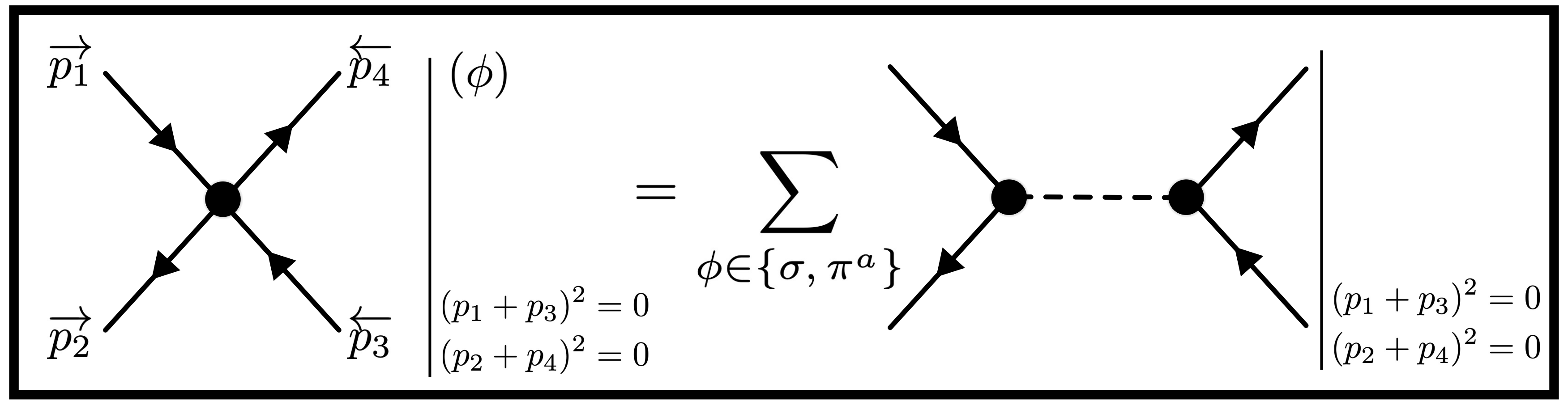


Dynamical chiral symmetry breaking

$$\Gamma_k[\Phi] \supset -\int_x \bar{\lambda}_\sigma \left(\bar{\psi}\,\mathcal{T}_{(\mathrm{S-P})}\psi\right)^2 + \dots$$



Stratonovich'57 Hubbard'59 Gies, Wetterich '01

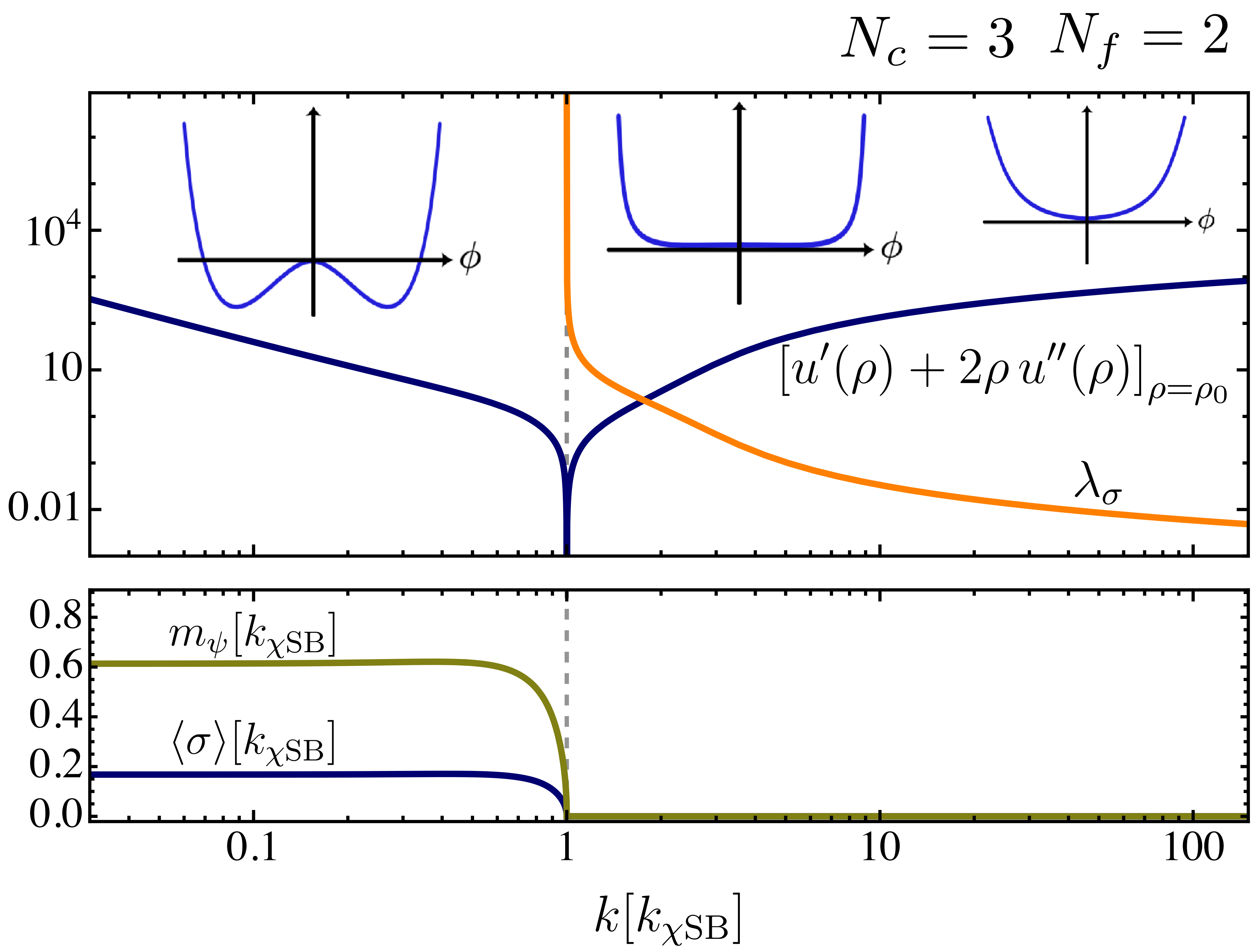


Fukushima,Pawlowski,Strodthoff [2103.01129]

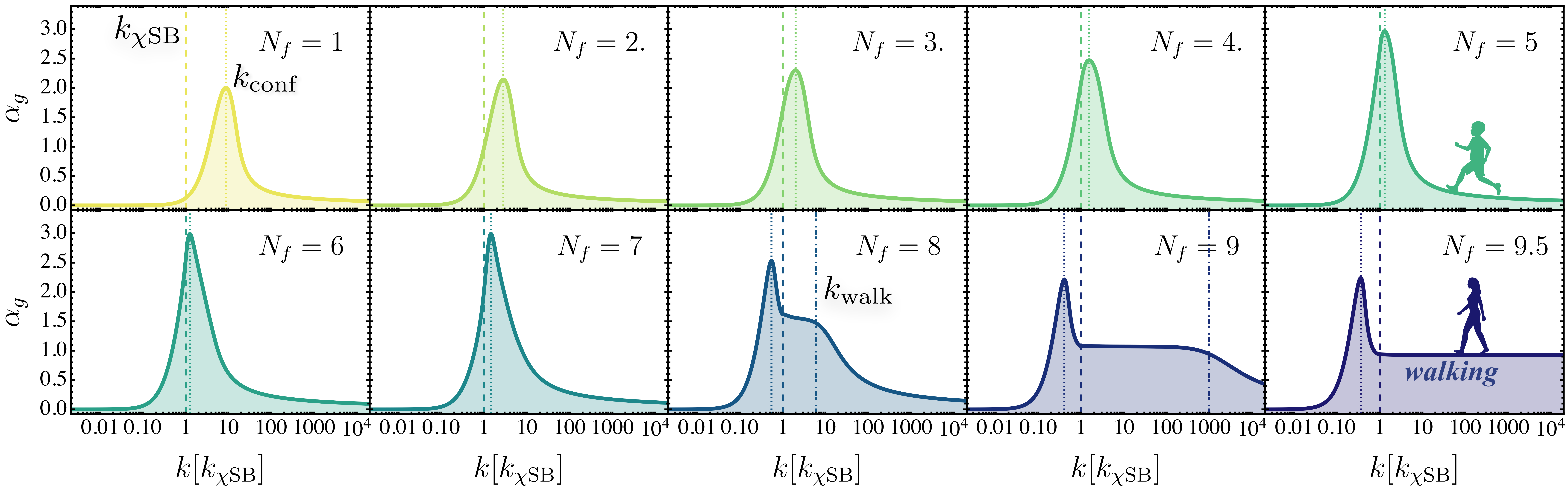
Dynamical bosonisation and generalised flow equation

Pawlowski[hep-th/0512261]

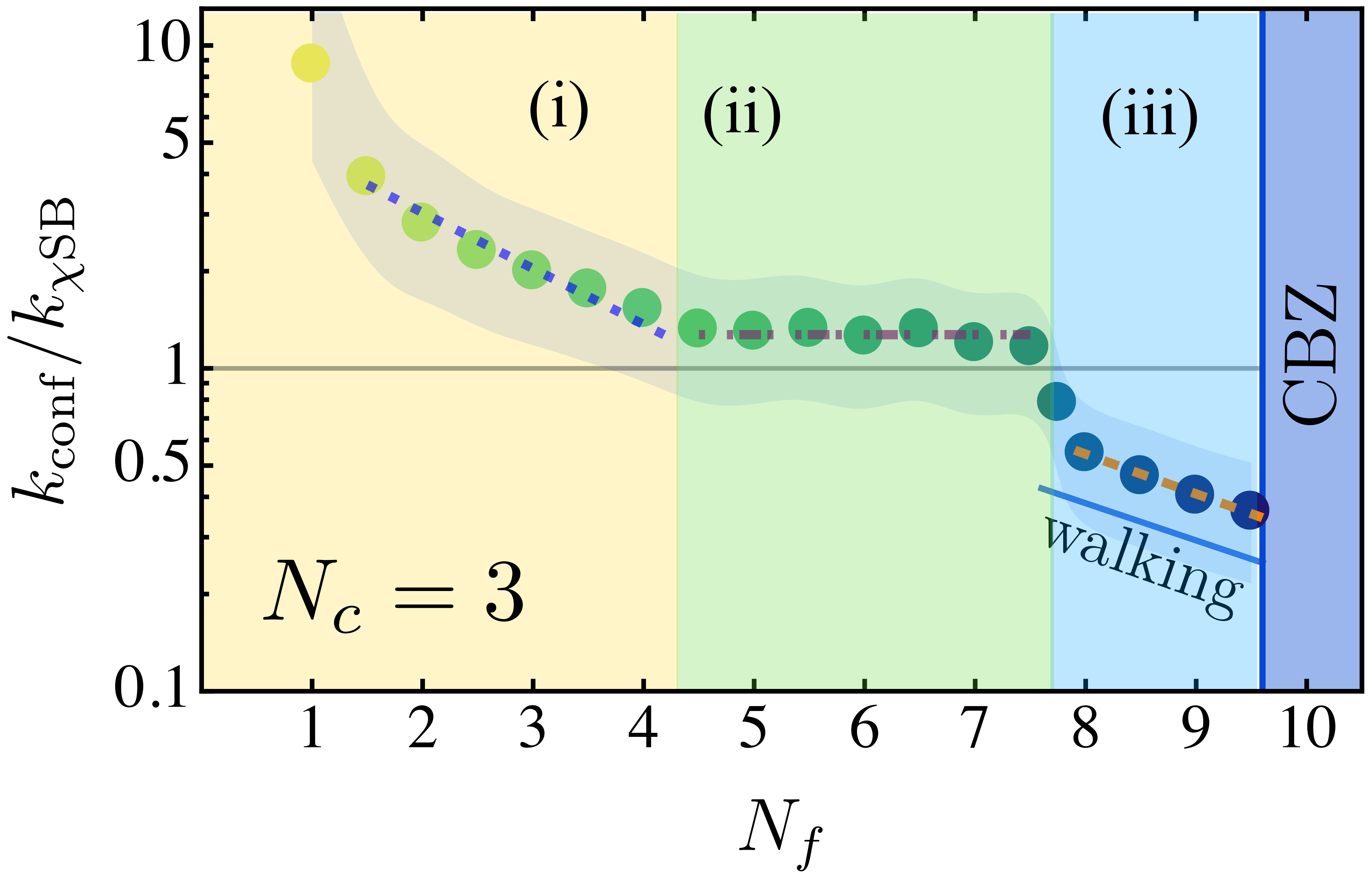
$$\Gamma_k[\Phi] \supset \int_x \bar{h}\,\bar{\psi}\left(T_f^0\sigma + \mathrm{i}\gamma_5 T_f^a\pi^a\right)\psi + Z_\phi\left(\partial_\mu\phi\right)^2 + V(\phi^2) + \dots$$



Many flavour dynamics



Phases of gauge-fermion QFTs



(i) $N_f \lesssim 4$: QCD-like

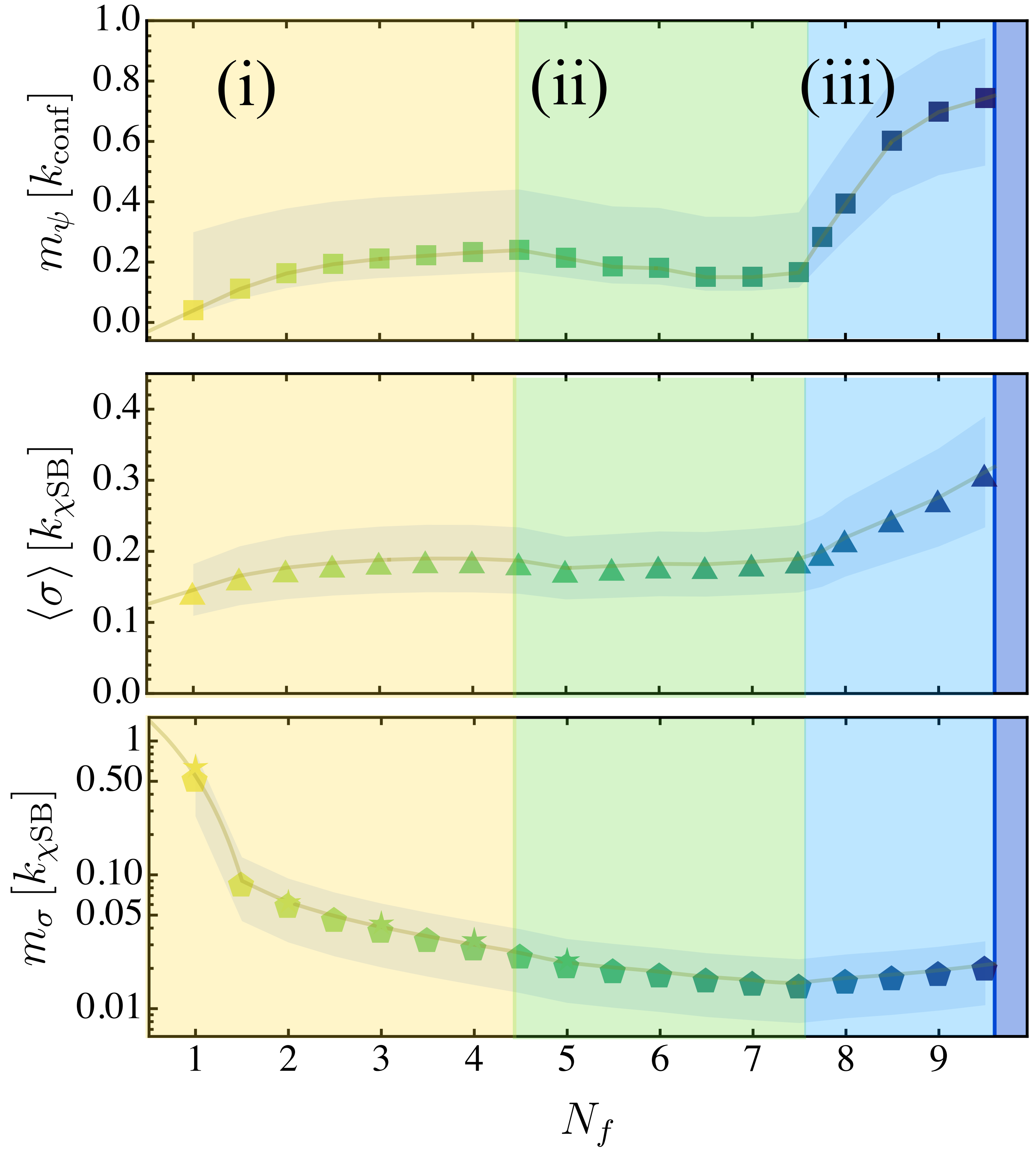
- Criticality for $N_f \lesssim 2$: potential *confinement without dχSB*

(ii) $4 \lesssim N_f \lesssim 7.5$: *Locking*

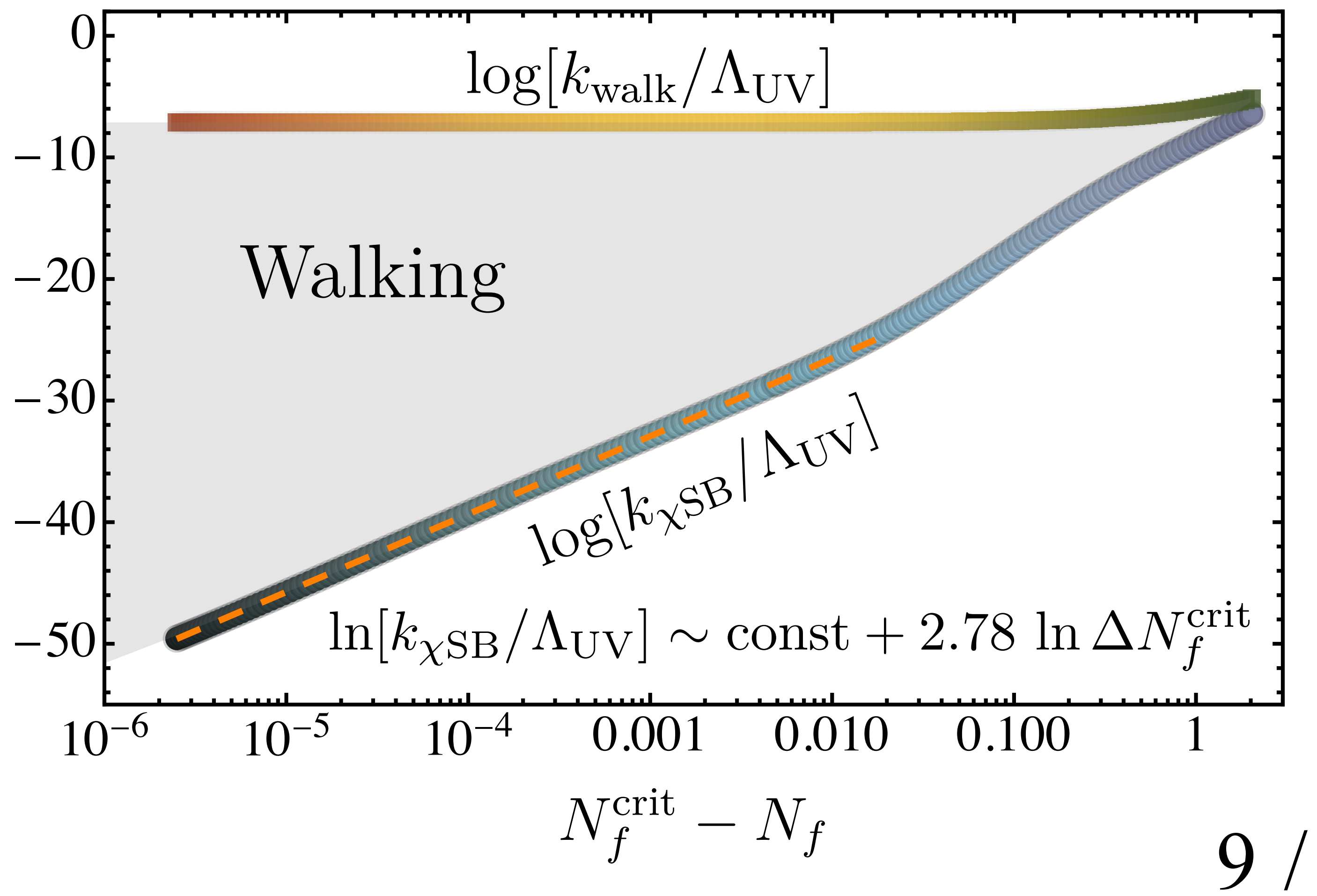
- Very strong dynamics (qualitative)
- ***No** confinement without dχSB*
- Evidence for **new condensates**

(iii) $7.5 \lesssim N_f < N_f^{\rm crit}$: Walking

- Non-NGB bound states heavier than glueballs
- Size of walking regime from first-principles



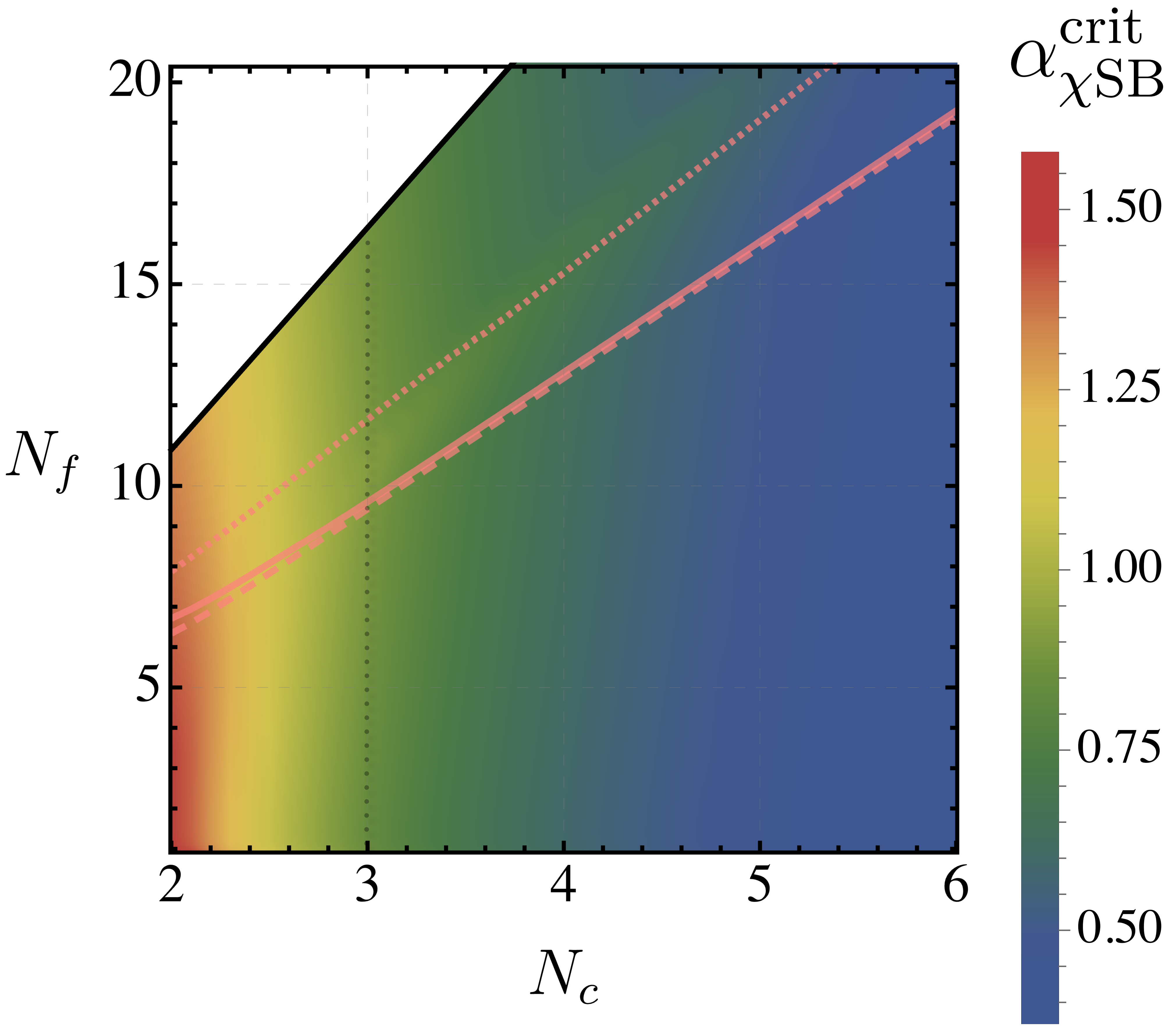
Conformal-dynamical phase transition



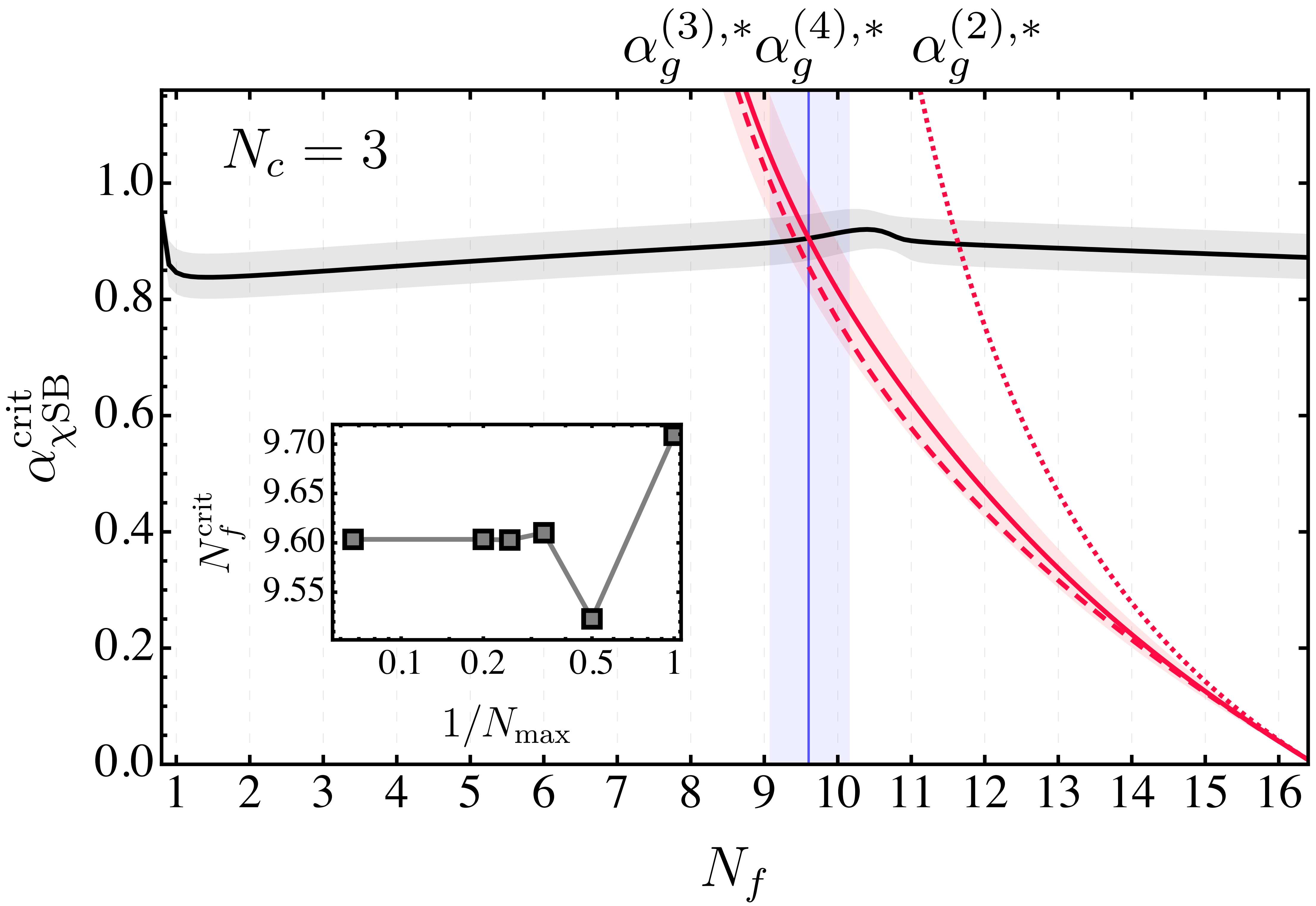
Precise determination of the conformal window

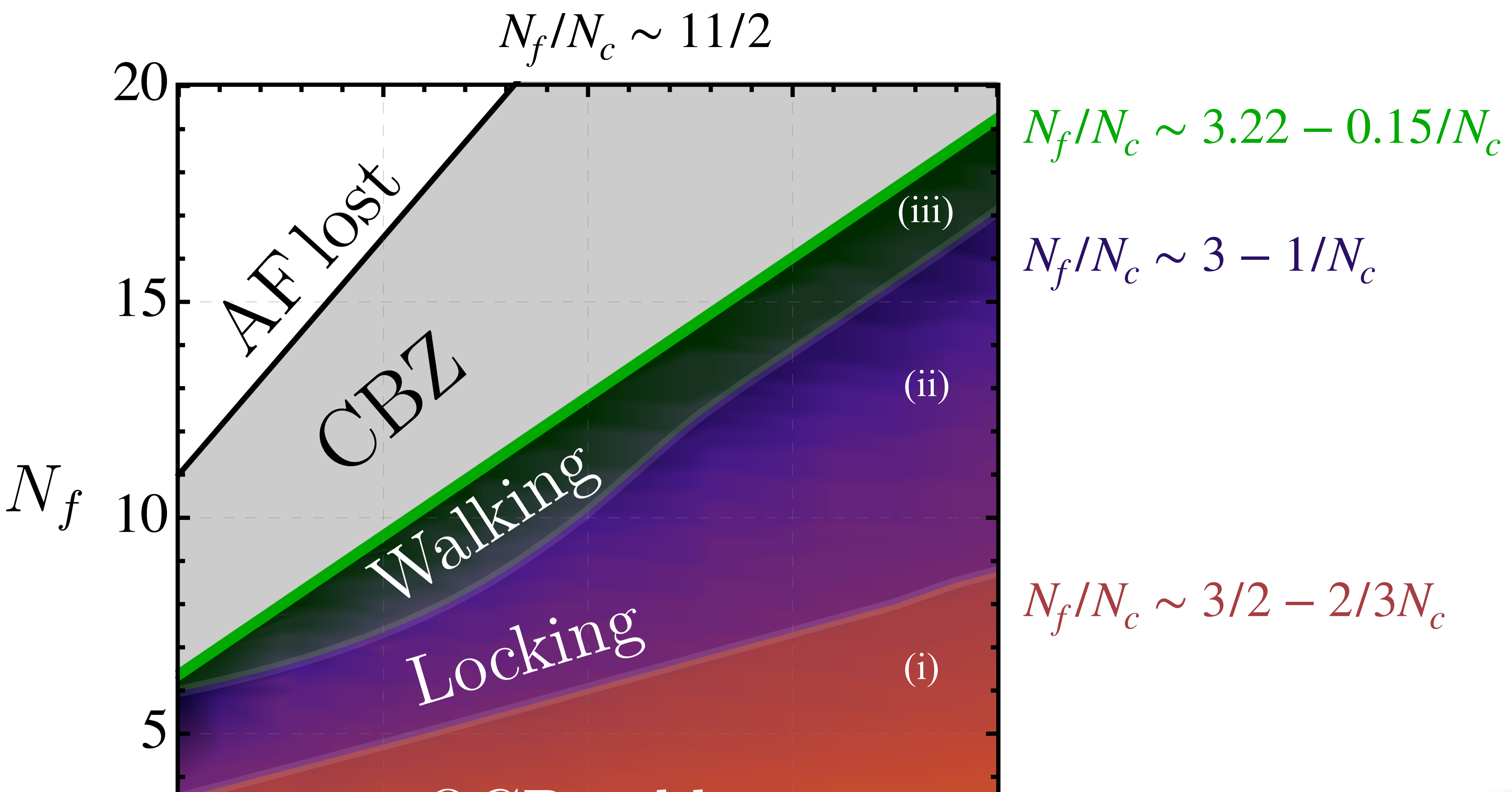
Gies, Jaeckel '05 Braun, Gies'05'06

$\alpha_{\chi\text{SB}}^{\text{crit}}$: Critical strength of **gauge dynamics** necessary to trigger dχSB



$$N_f^{\text{crit}}(N_c = 3) = 9.60^{+0.55}_{-0.53}$$





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Li,ÁPG,Vatani,Xu [to appear early next week]

Dynamics of chiral-gauge theories

Georgi,Glashow'74 Raby,Dimopoulos,Susskind'80
Bolognesi,Konishi[1906.01485]

Generalised Georgi-Glashow theories (purely chiral)

	$SU(N_c)$	$SU(N_{\rm gen}(N_c-4))$	$SU(N_{\rm gen})$	$U(1)$
ψ	$\bar{\square}$	$\square$	1	$-(N_c-2)$
χ	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	1	$\square$	N_c-4

$$\Gamma_{4\mathrm{F},k}[\bar\psi,\psi,\bar\chi,\chi] = -\int_x Z_\psi^2 \sum_{i=1}^{2}\lambda_i\mathcal{O}_i + Z_\chi^2\sum_{i=3}^{5}\lambda_i\mathcal{O}_i + Z_\psi Z_\chi\sum_{i=6}^{7}\lambda_i\mathcal{O}_i$$

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

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

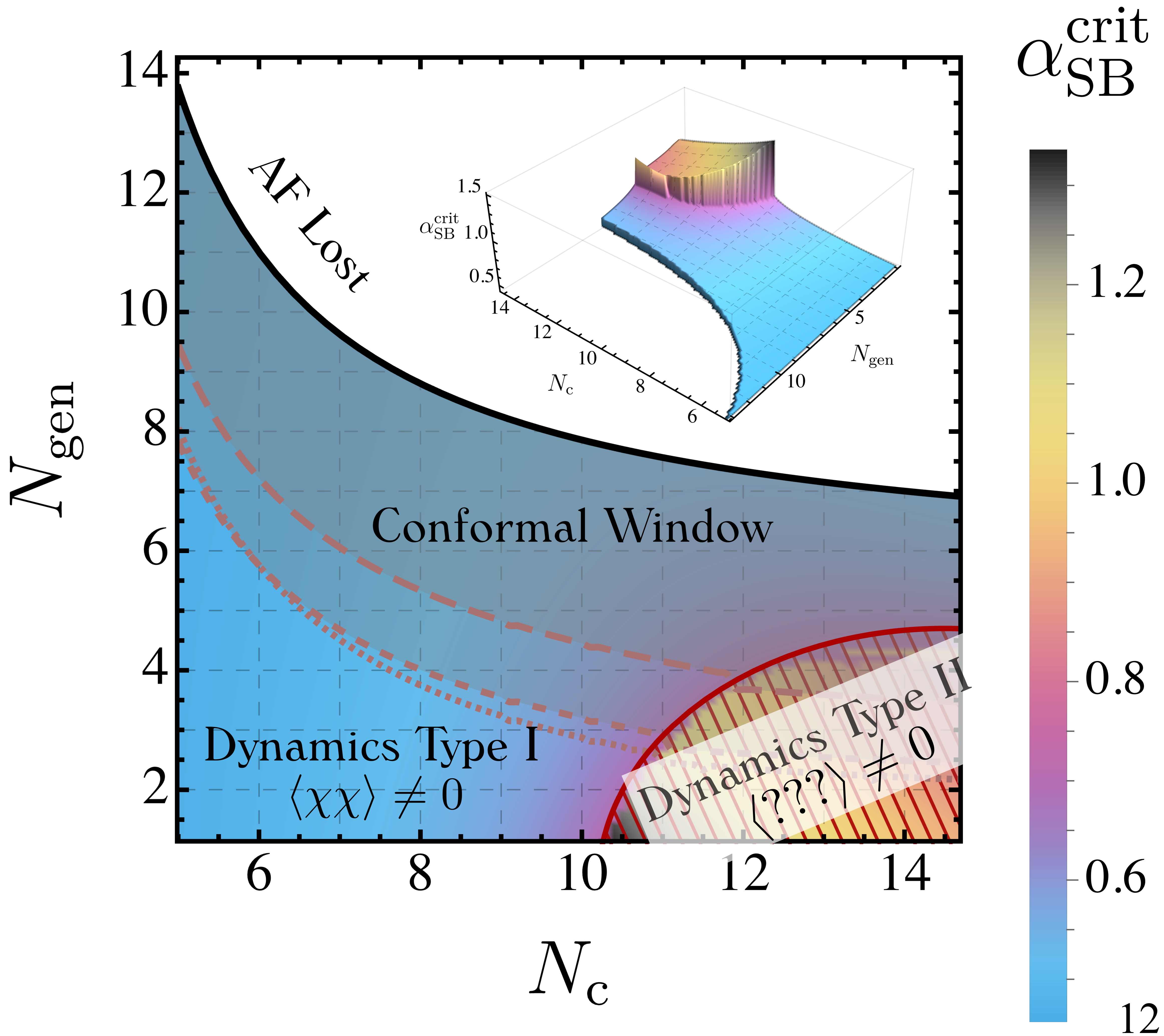
$$\mathcal{O}_3 = \left(\chi^{\dagger f_1}\bar\sigma^\mu\chi_{f_2}\right)\left(\chi^{\dagger f_2}\bar\sigma^\mu\chi_{f_1}\right)$$

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

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

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

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



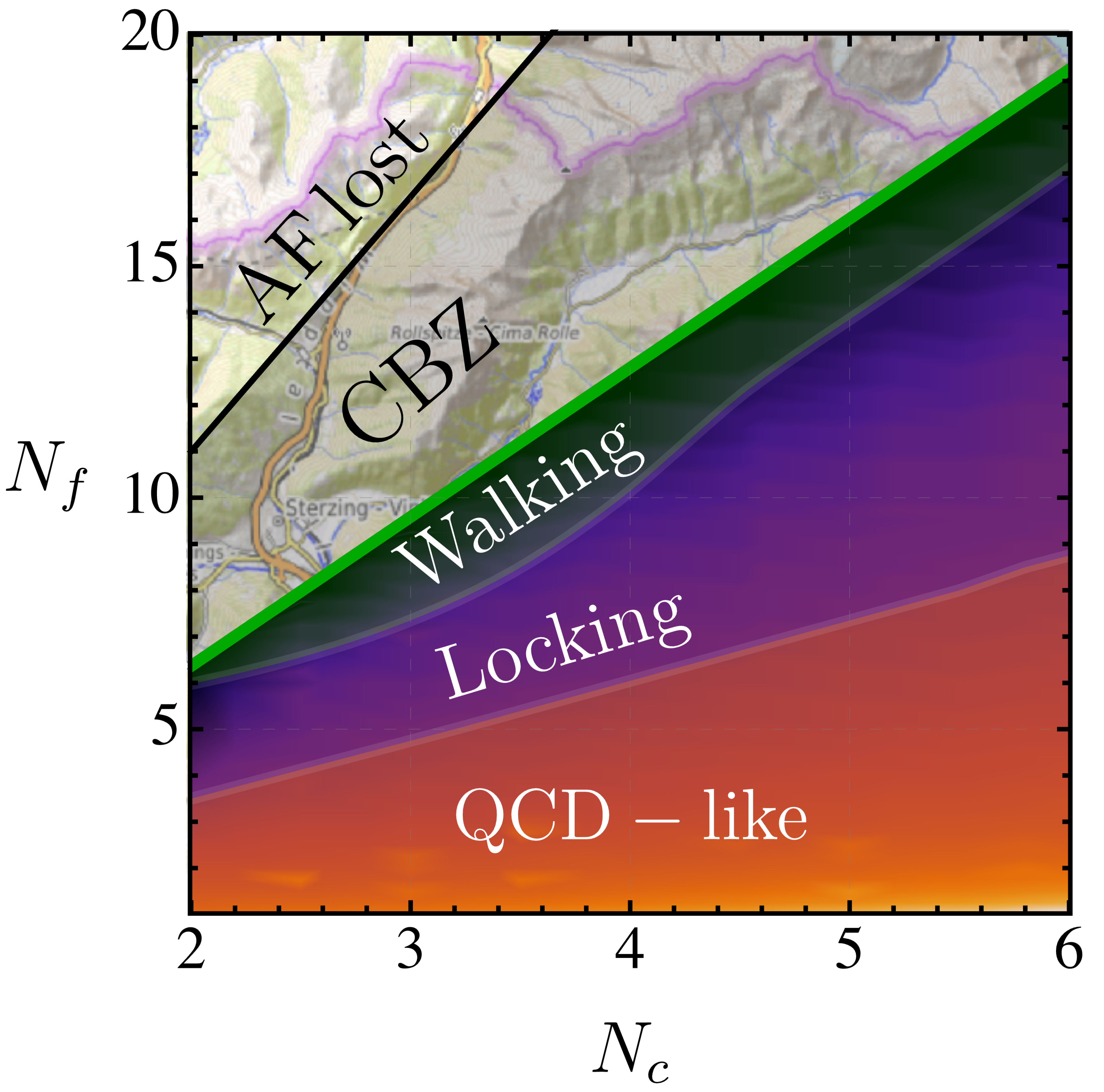
Conclusions

✦ Functional methods are a **powerful** and **versatile non-pertubative** tool to investigate **strong dynamics**

✦ **Charted** the landscape of **gauge-fermion** theories:

- New "easy" treatment of **confinement**
- Determination of **fundamental parameters**:
  - m_ψ , $\langle\sigma\rangle$, m_σ , size of walking regime, …
- Identification of **new phases** and resolution **dynamics**
- **Precise** determination of the lower boundary of the **CBZ window**:

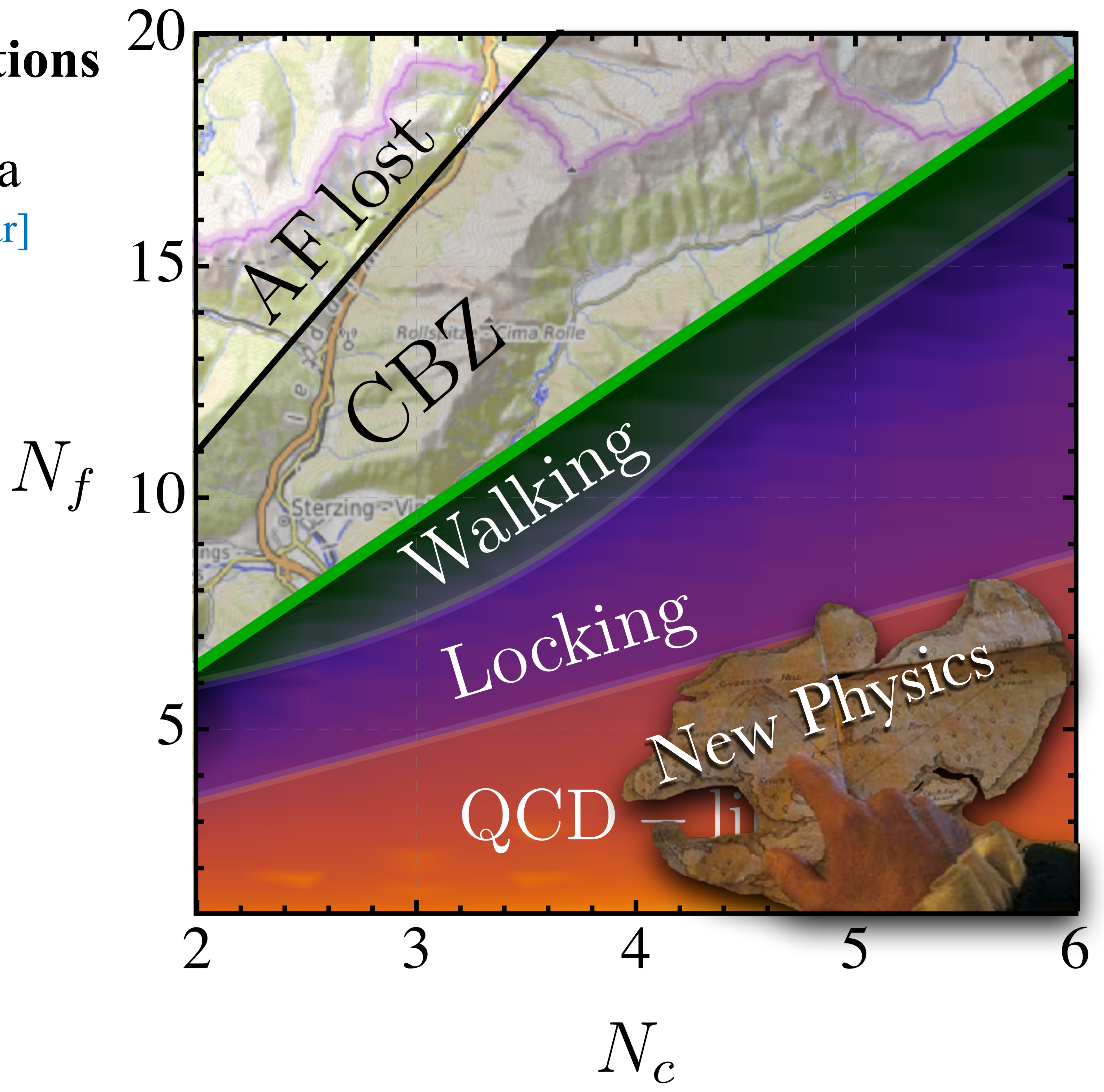
$$N_f^{\text{crit}}(N_c = 3) = 9.60^{+0.55}_{-0.53}$$



And much more in [2412.12254] !

Towards non-perturbative new physics

- Thermal phenomena:
  - **Order** of phase transition at many flavour⇝ **cosmological phase transitions**
  - Inhomogeneous phases in the chiral limit⇝ **precondensation** phenomena
    ÁPG,Pawlowski,Sattler[to appear]
- **Phases** of different classes of **gauge theories**
  - More gauge-fermion: **chiral**, SUSY, … Li,ÁPG,Vatani,Xu[to appear]
  - **Scalar-gauge** QFTs (supercooling, …) Kierkla,ÁPG[to appear]
- SM and beyond with functional methods
  - new features & a framework for **non-perturbative new physics**
    ÁPG,Pawlowski,Reichert [2207.09817] Garces,Goertz,Lindner,ÁPG[2506.15919]
    Goertz,ÁPG [2308.13594]



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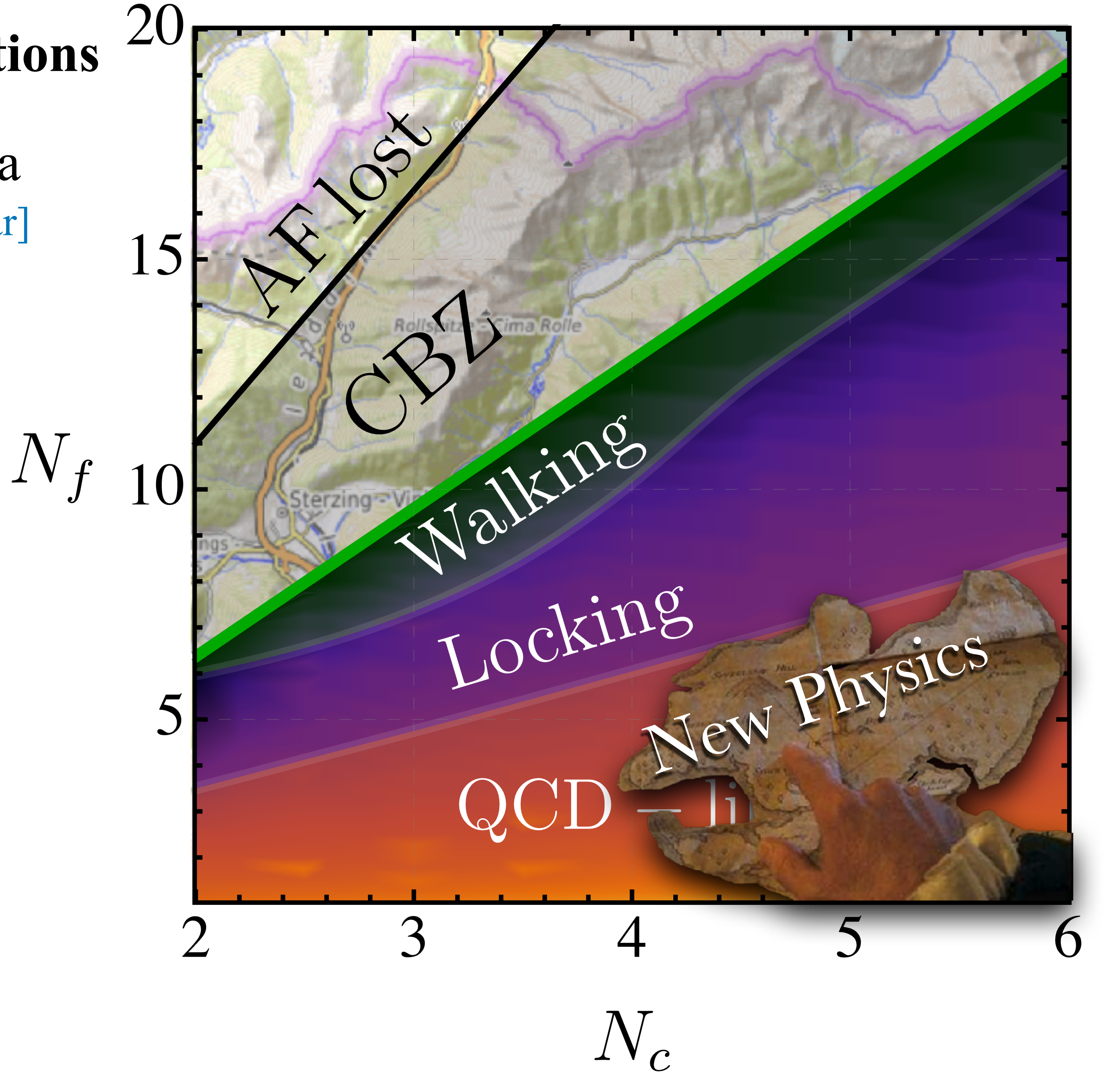
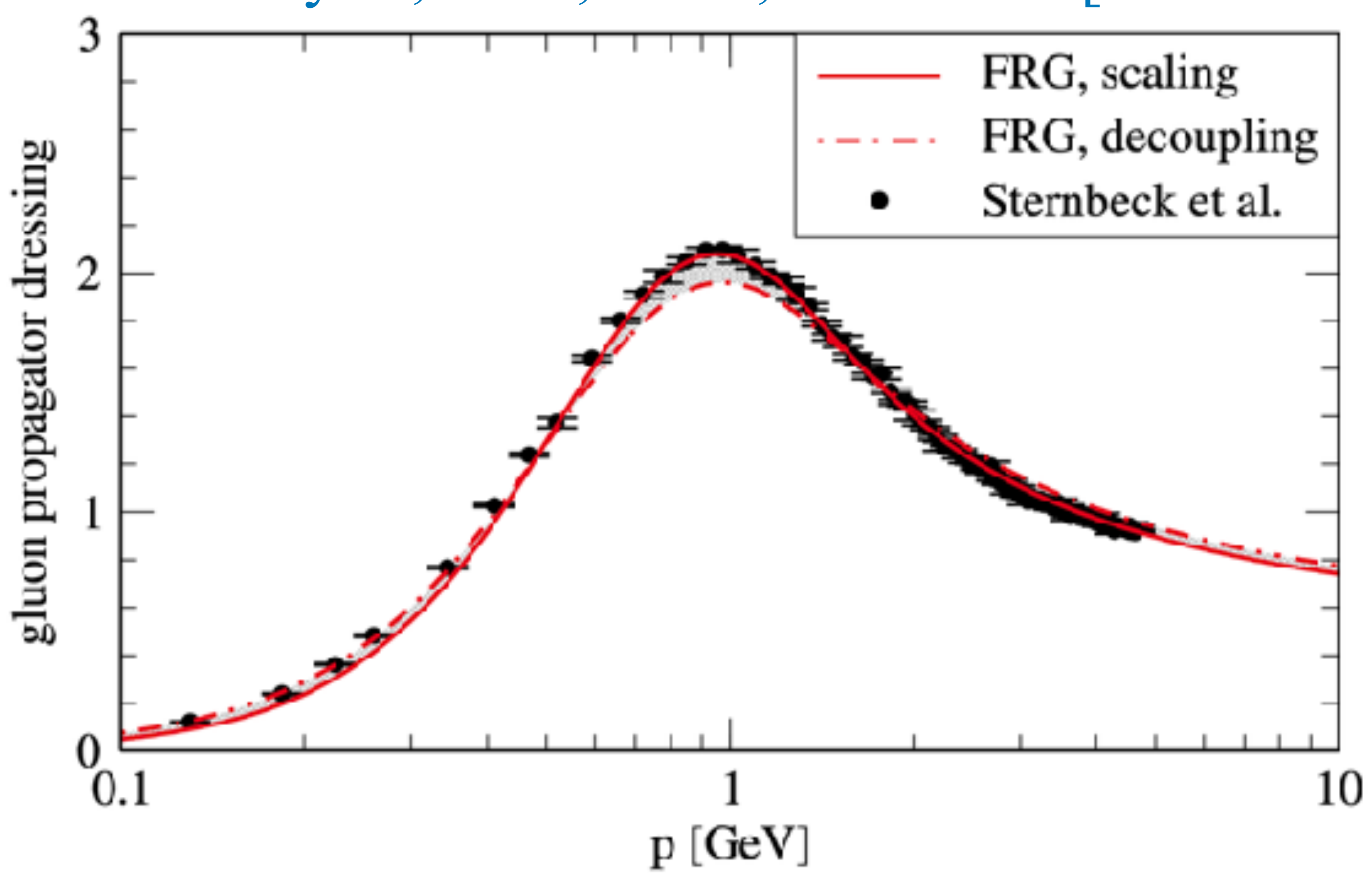


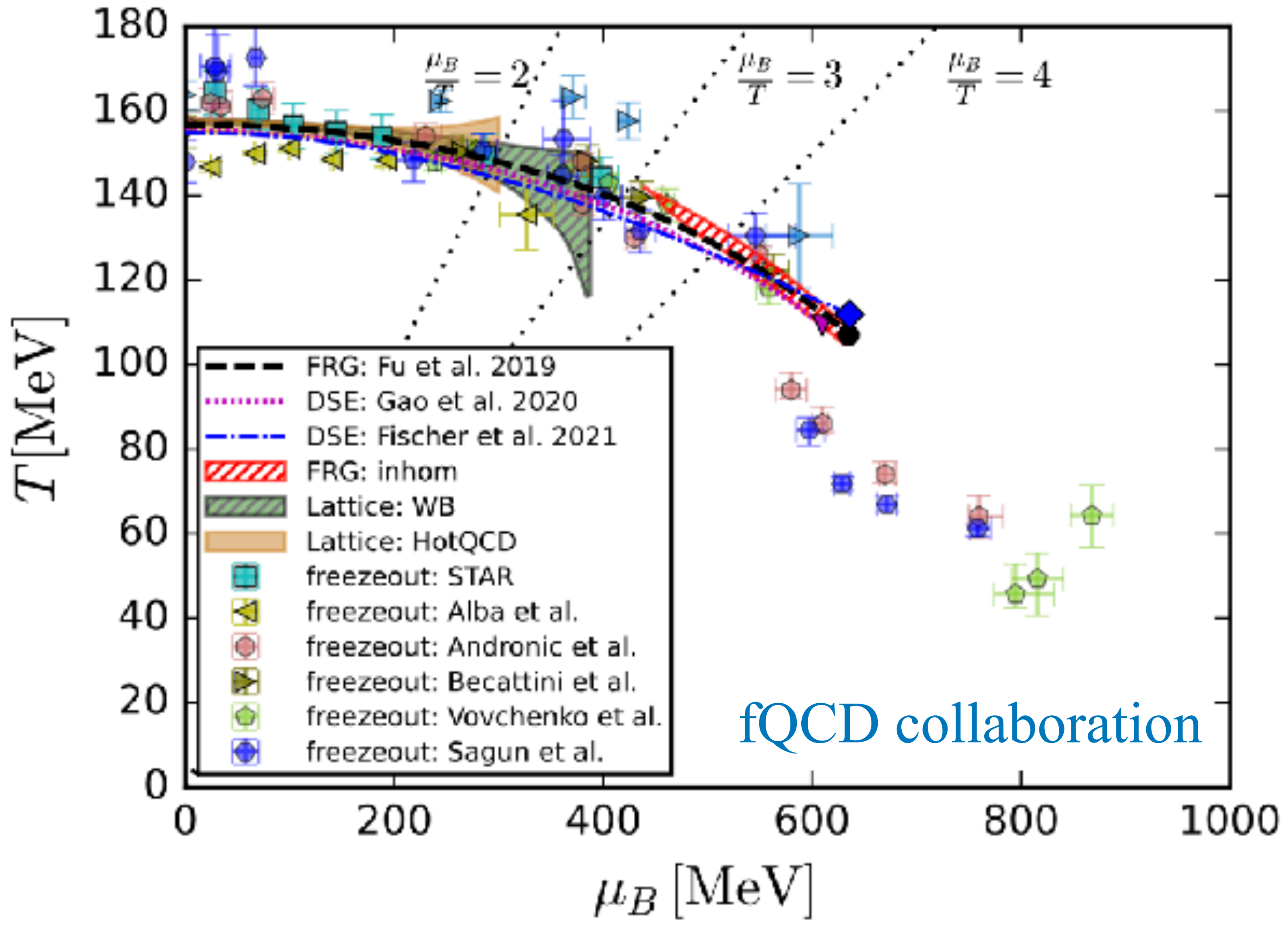
Thanks a lot for your atention!

Additional slides

fRG approach in QCD

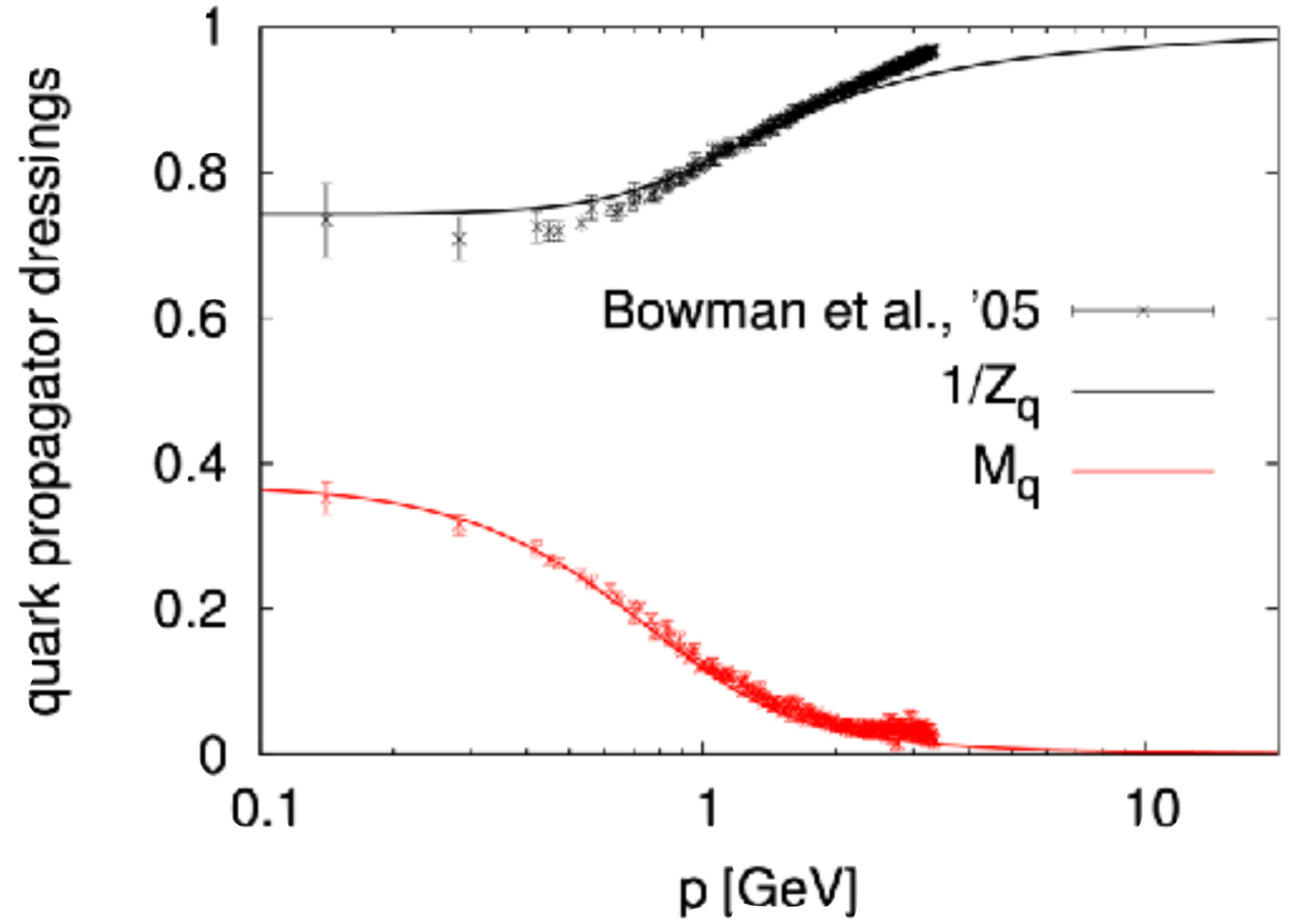
Cyrol,Fister,Mitter,Pawlowski [1605.01856]



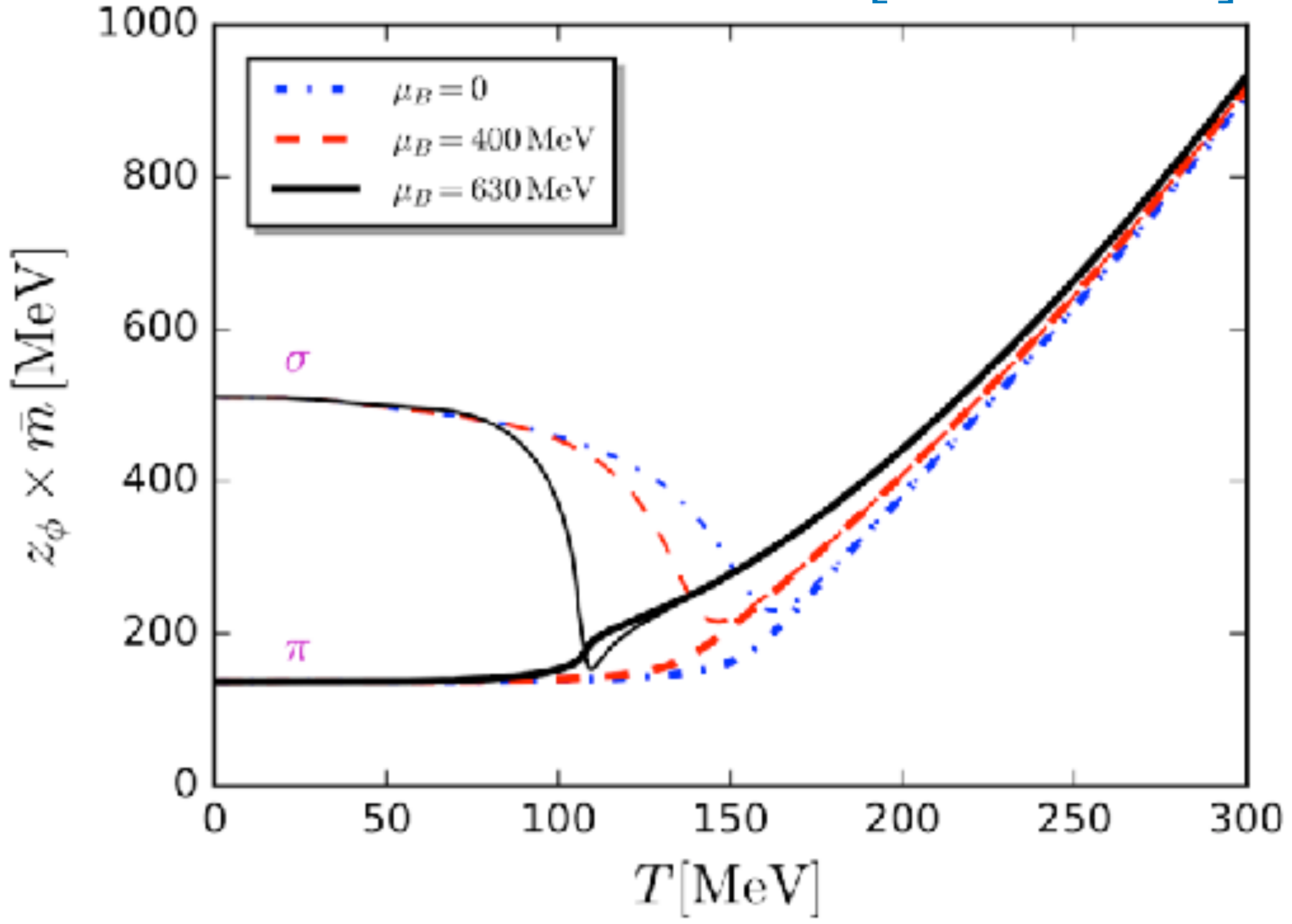


fQCD collaboration

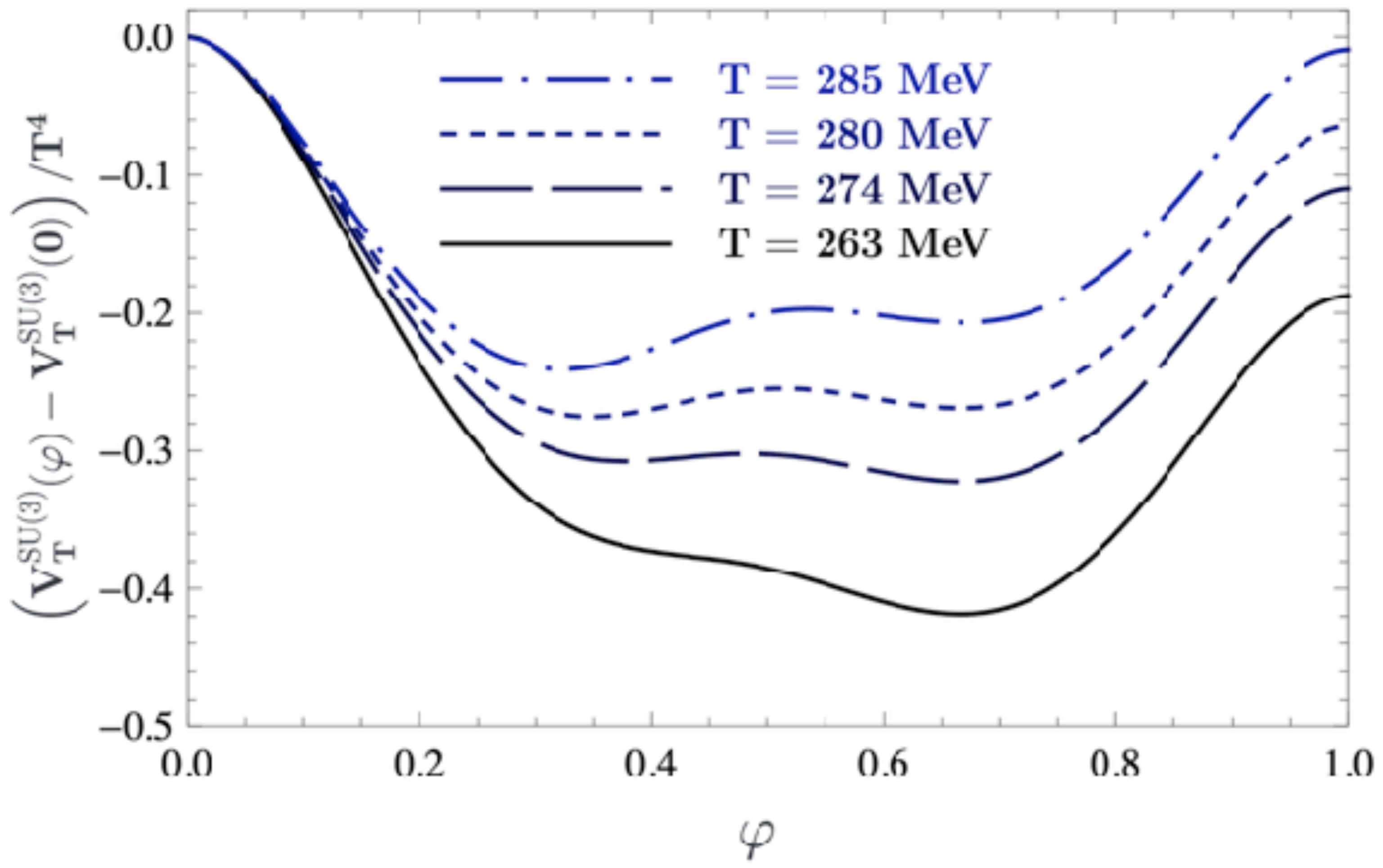
Mitter,Pawlowski, Strodthoff[1411.7978]



Fu,Pawlowski, Rennecke [1909.02991]



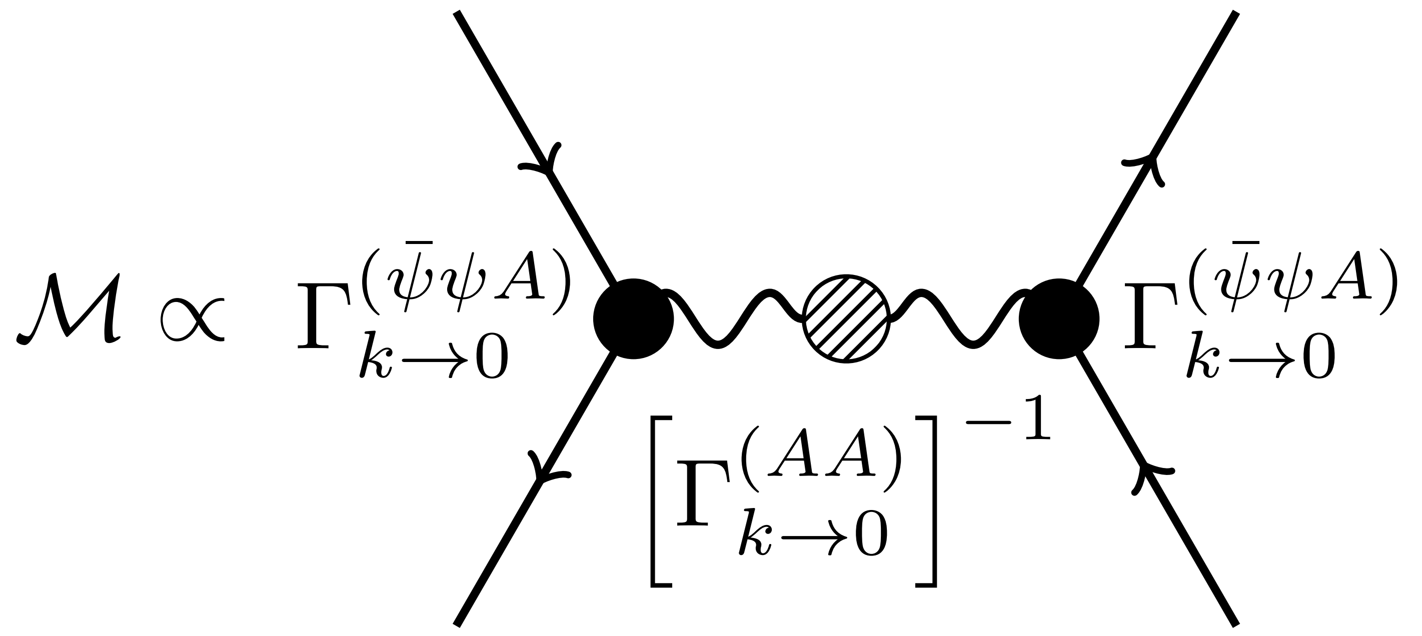
Fister,Pawlowski [1301.4163]



Deriving full correlation functions

$$\Gamma_k[\Phi] = \sum_n^{N_{\rm tr}} \int_{\boldsymbol{p}} \Gamma_k^{(\Phi_{i_1}\cdots\Phi_{i_n})}(\boldsymbol{p})\, \Phi_{i_n}(p_n)\cdots\Phi_{i_1}(p_1)$$

$$\Gamma_k^{(\Phi_{i_1}\cdots\Phi_{i_n})}(p_1,...,p_n) = \frac{\delta}{\delta\Phi_{i_1}(p_1)}\cdots\frac{\delta}{\delta\Phi_{i_n}(p_n)}\Gamma_k[\Phi]$$

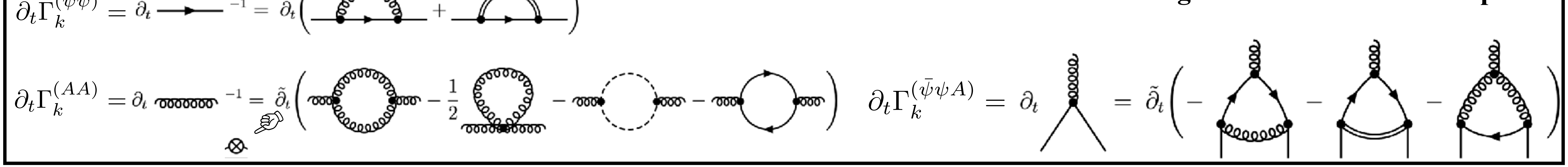


<u>Example:</u> quark-gluon vertex and gauge coupling β-function

$$\partial_t \Gamma_k^{(\bar\psi\psi A)} = \partial_t \left(Z_A^{1/2} Z_\psi\ g_{\bar\psi\psi A}\cdot \mathcal{T}_\mu \right) \quad ☞ \quad \partial_t g_{\bar\psi\psi A} = \frac{\mathrm{Tr}\left[\mathcal{T}_\mu\,\partial_t\Gamma_k^{(\bar\psi\psi A)}\right]}{\mathrm{Tr}\left[\mathcal{T}_\mu^2\right] Z_A^{1/2} Z_\psi} + \left(\frac{1}{2}\eta_A + \eta_\psi\right) g_{\bar\psi\psi A}$$

with anomalous dimensions $\eta_{\phi_i} = -\frac{\partial_t Z_{\phi_i}}{Z_{\phi_i}} = -\frac{\partial_{p^2}\,\partial_t \Gamma_k^{(\phi_i\phi_i)}}{Z_{\phi_i}}$

Diagramatic flows to be computed



Gauge symmetry in the RG flow

$$\Delta S_k[\phi] = \int_p \phi(p) R_k \phi(-p)$$

✦ Gauge symmetry at the quantum level ☞ Slavnov-Taylor identities (STIs) ☞ In the presence of a cutoff derive the modified STIs (mSTIs).

Becchi[9607188],Bonini,D'Attanasio,Marchesini'95 Ellwanger[9402077]

$$\int_x \frac{\delta \Gamma}{\delta \mathcal{Q}_i(x)} \frac{\delta \Gamma}{\delta \Phi_i(x)} = 0 \qquad \int_x \frac{\delta \Gamma_k}{\delta \mathcal{Q}_i(x)} \frac{\delta \Gamma_k}{\delta \Phi_i(x)} = \mathrm{Tr} R^{ij} G_{jl} \frac{\delta^2 \Gamma_k[\Phi, \mathcal{Q}]}{\delta \Phi_l \delta \mathcal{Q}^i}$$

$\Phi_i = \{A_\mu, c, \bar{c}, \ldots\}$

$\mathcal{Q}^i$: BRST sources of the Φ_i fields

- In the physical limit $k \to 0$ and $R_k \to 0$ and mSTI ☞ STI and no gauge symmetry breaking is present.

✦ **Under control:** quantitatively and qualitatively

Pawlowski[0512261] Gies[0611146]

- Deviation from the STI can be checked along the RG-flow — Pawlowski,Schneider,Wink[2202.11123]
- Gauge invariant flow equations and field transformations — Ihssen,Pawlowski[2503.22638]

Morris,Rosten[0606189]
Wetterich[1607.02989]

Yang-Mills phases and confinement

Fischer,Maas,Pawlowski[0810.1987]
Cyrol,Fister,Mitter,Pawlowski [1605.01856]

$$\Gamma_k^{(AA)}(p^2) = Z_{A,\,k}(p)\left(p^2 + m^2_{A,\,k}\right)$$

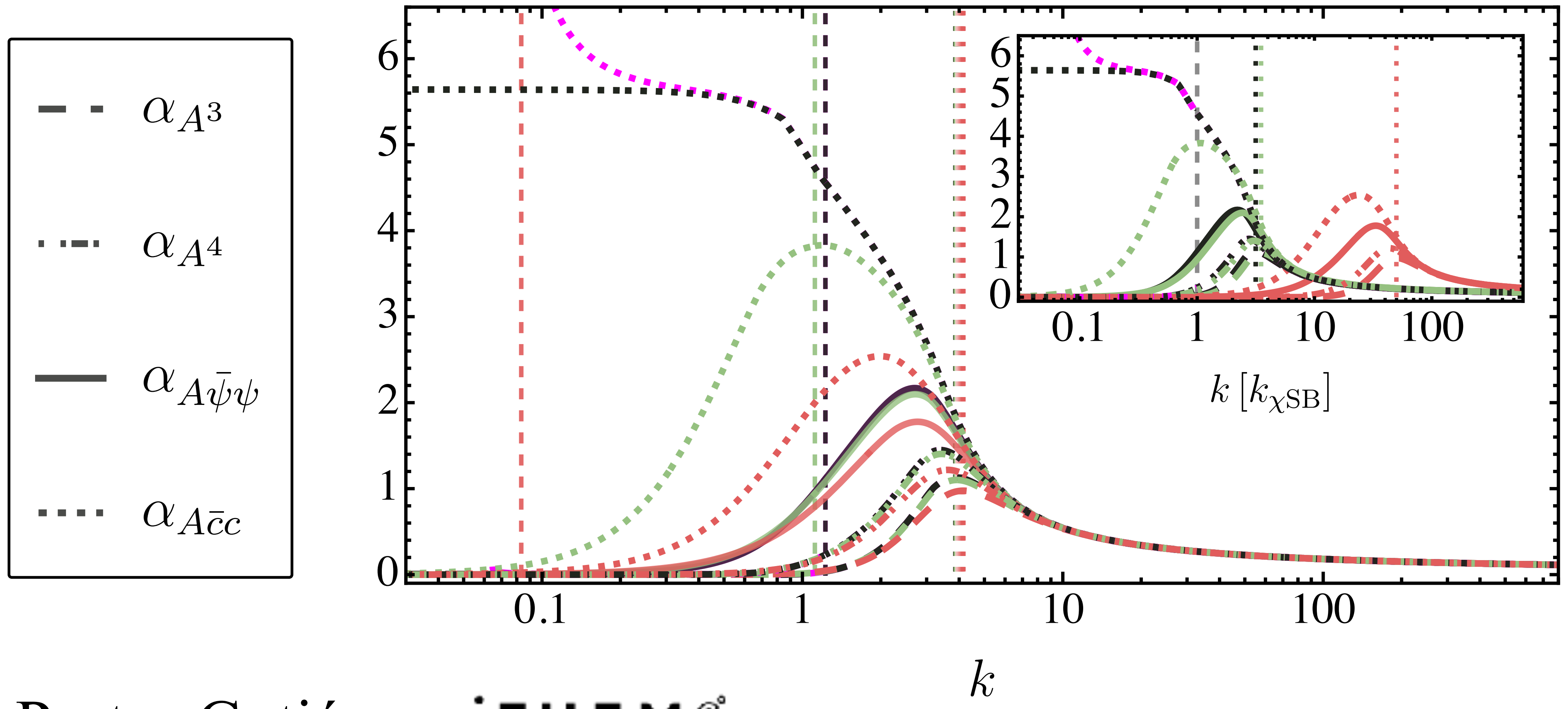
✦ Mass gap as a dialing parameter

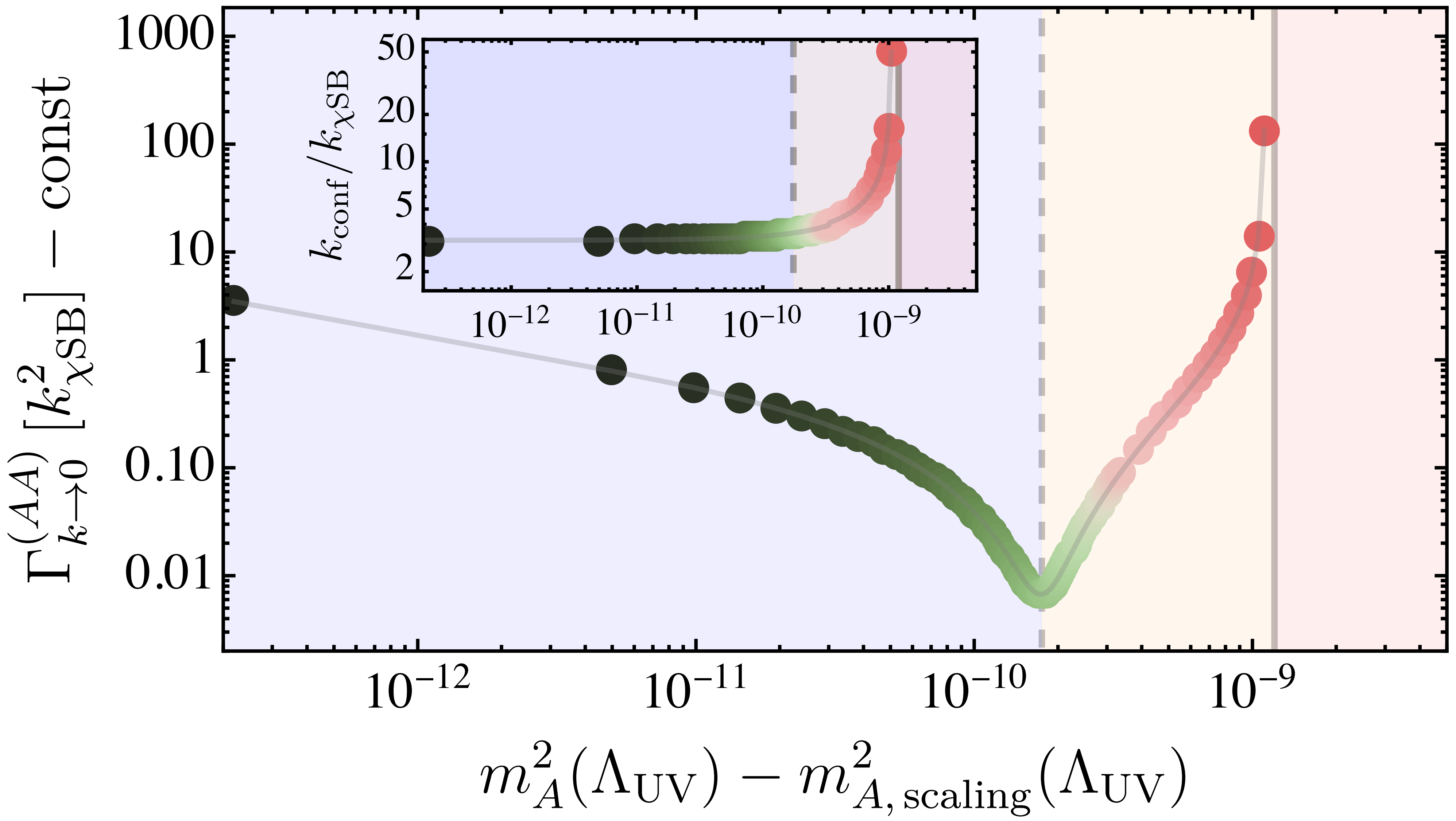
✦ Confining solutions:

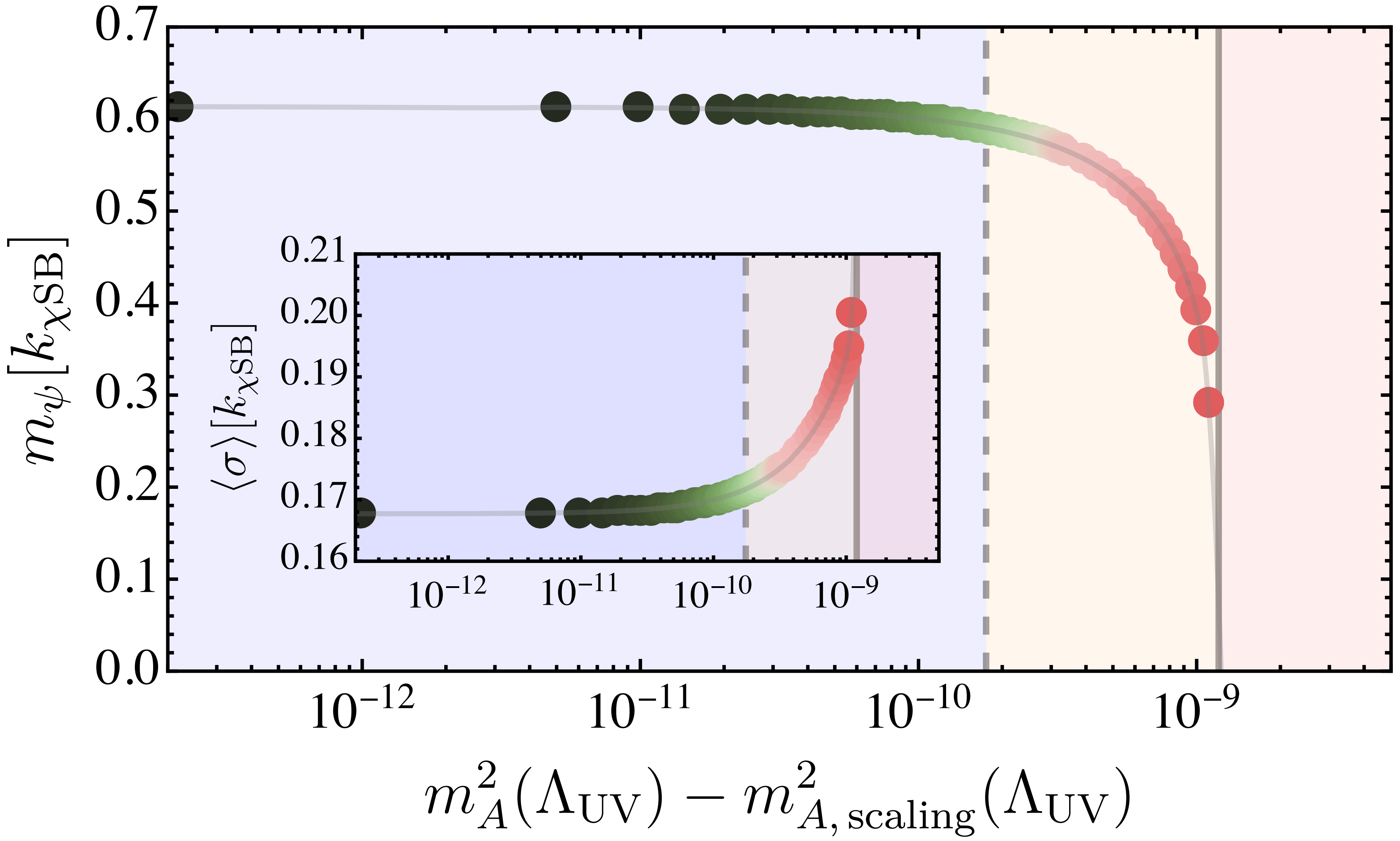
- Scaling
- Decoupling

✦ Non-confining solutions:

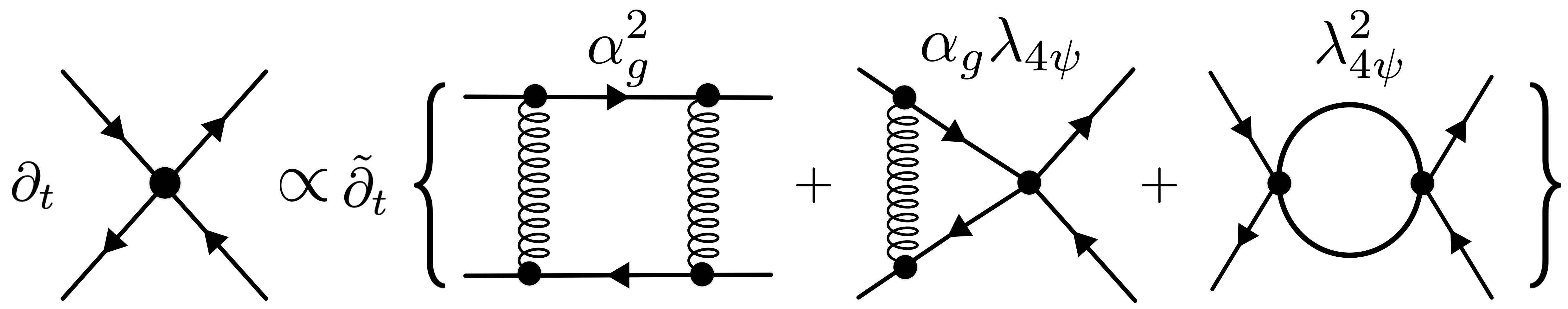
- Coulomb phase
- Massive Yang-Mills







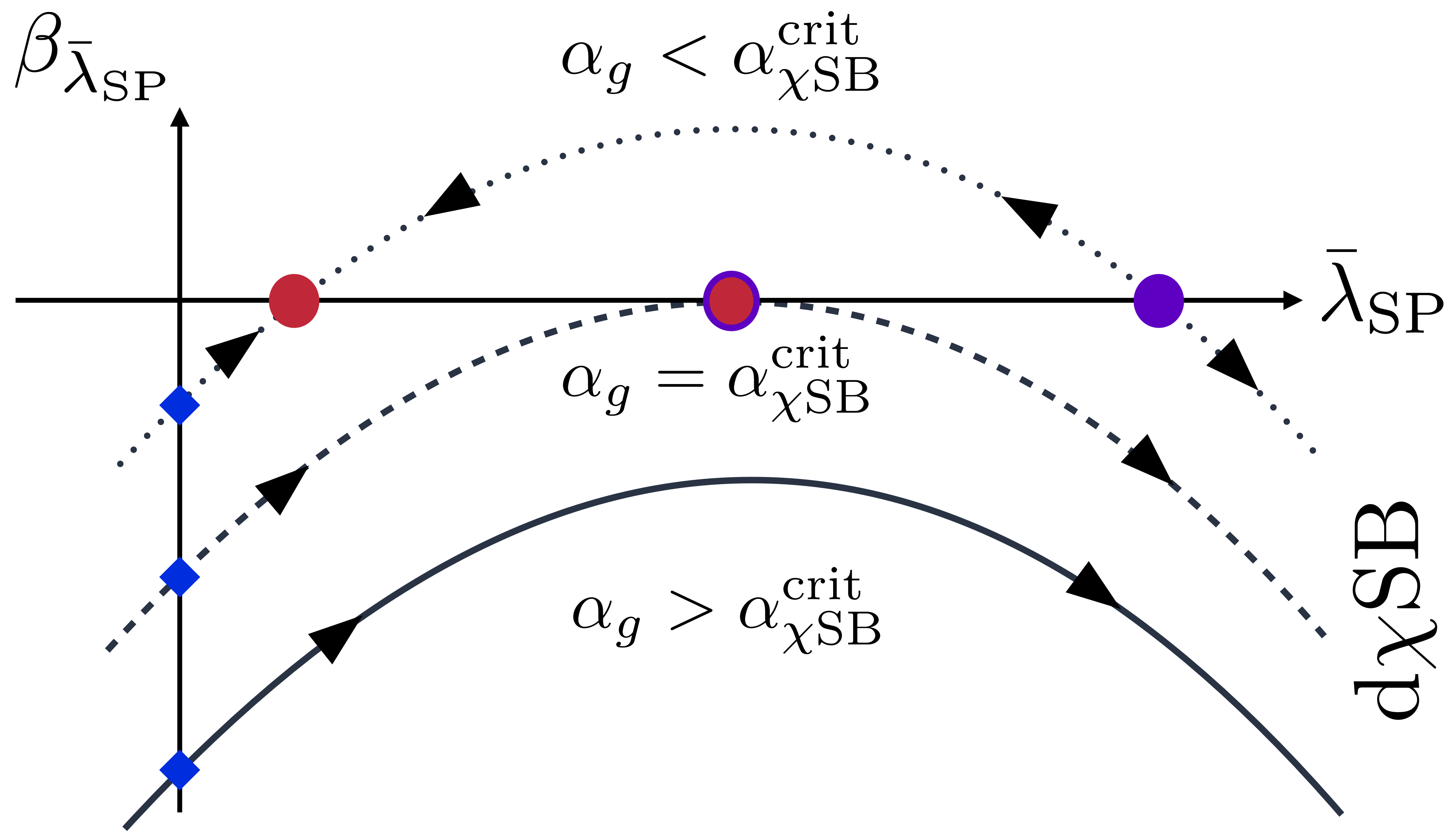
Dynamical chiral symmetry breaking



$$\bar{\lambda}_{\mathrm{SP}} = \lambda_{\mathrm{SP}} k^2\,, \qquad \beta_{\bar{\lambda}_{\mathrm{SP}}} \equiv \partial_t \bar{\lambda}_{\mathrm{SP}} = 2\bar{\lambda}_{\mathrm{SP}} + \text{diagrams}$$

$$\partial_t \lambda_{4\psi} \propto c_1\, \alpha_g^2 + c_2\, \alpha_g \lambda_{4\psi} + c_3\, \lambda_{4\psi}^2$$

$$\alpha_{\chi\mathrm{SB}}^{\mathrm{crit}} = \min\left\{\alpha_g \,|\, \beta_{\bar{\lambda}_{\mathrm{SP}}} \leq 0 \quad \forall \bar{\lambda}_{\mathrm{SP}}\right\}$$

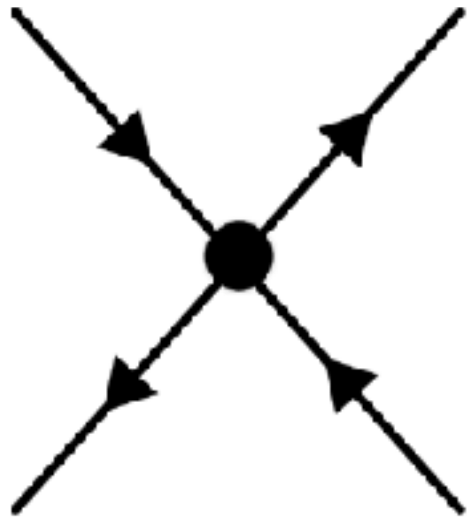


Dynamical chiral symmetry breaking

$$S = \int_x \frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \mathcal{L}_{\mathrm{gf}} + \mathcal{L}_{\mathrm{gh}} + \bar{\psi} \gamma_\mu D_\mu \, \psi$$

Dynamical chiral symmetry breaking

$$\Gamma = \int_x \frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \mathcal{L}_{\rm gf} + \mathcal{L}_{\rm gh} + \bar{\psi}\gamma_\mu D_\mu \psi + \lambda \left(\bar{\psi}\mathcal{T}\psi\right)^2 + \kappa \left(\bar{\psi}\mathcal{T}\psi\right)^3 + \dots$$

∂_t 

Dynamical chiral symmetry breaking

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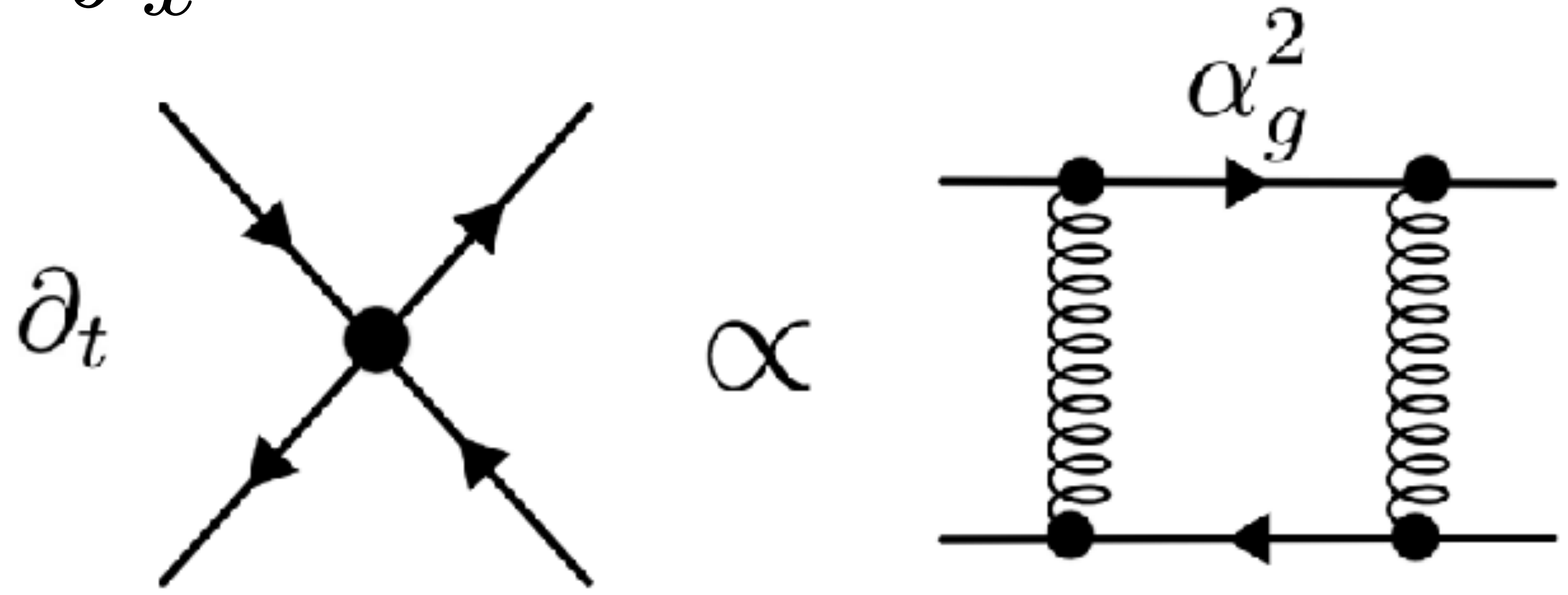

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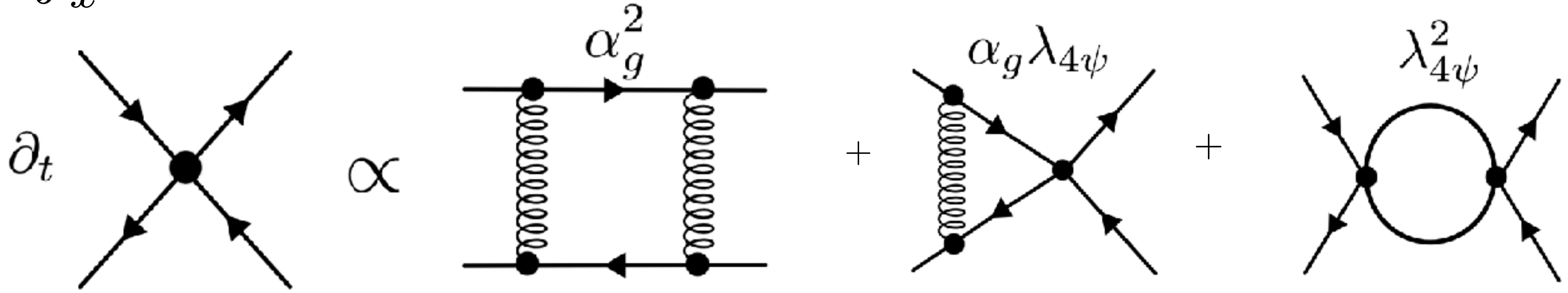

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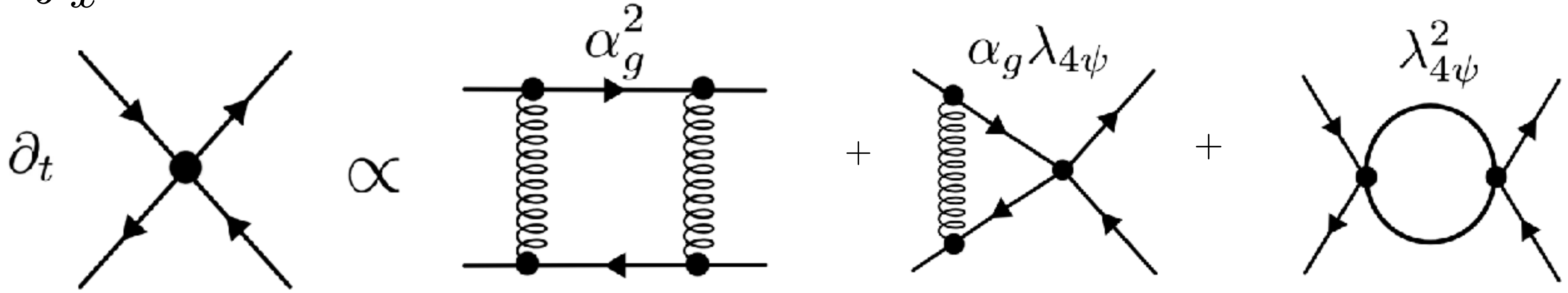

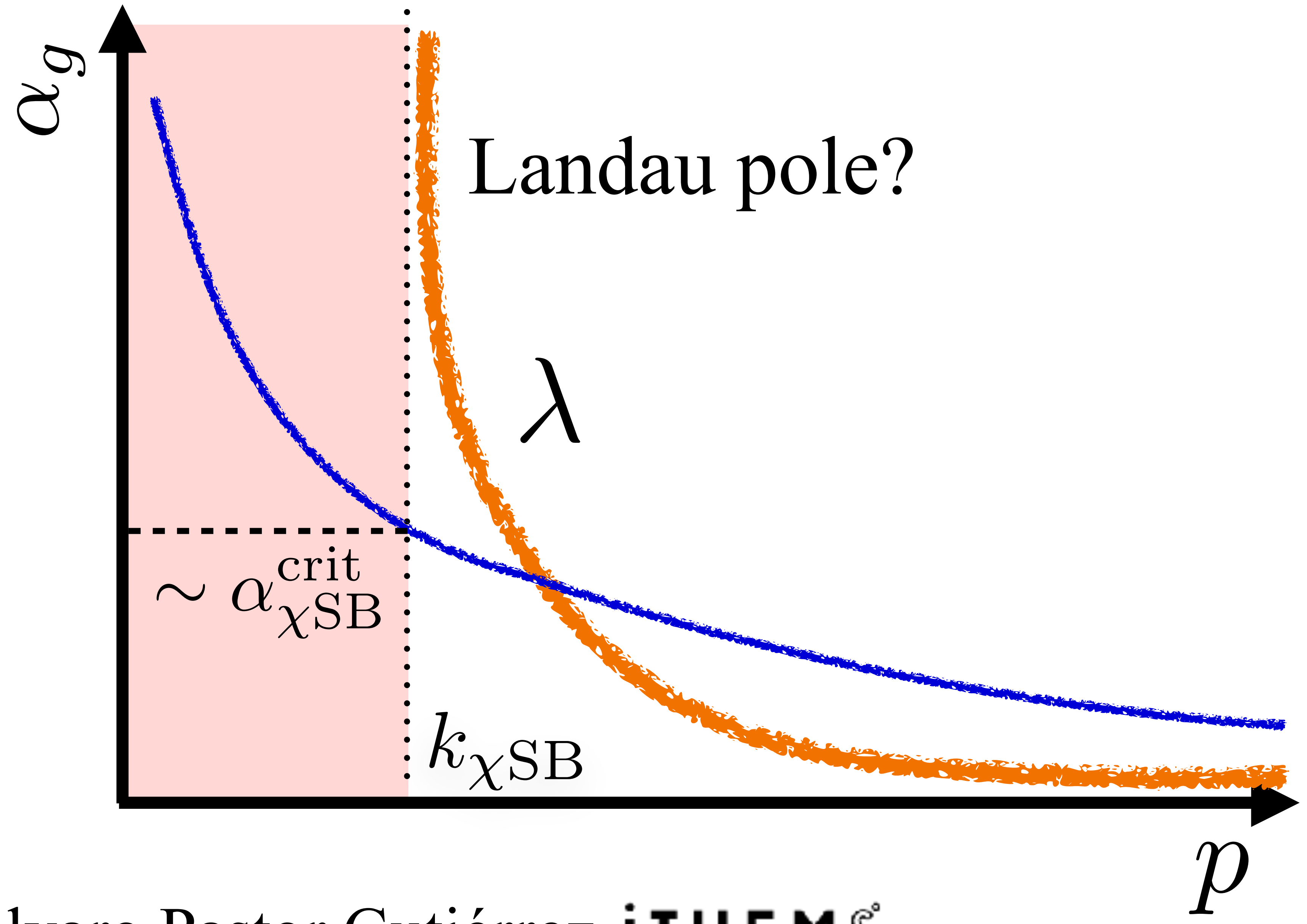

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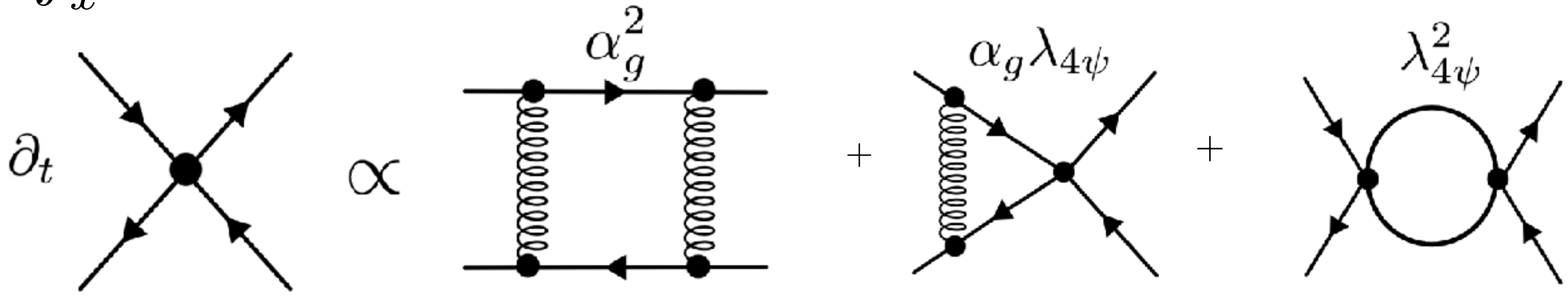
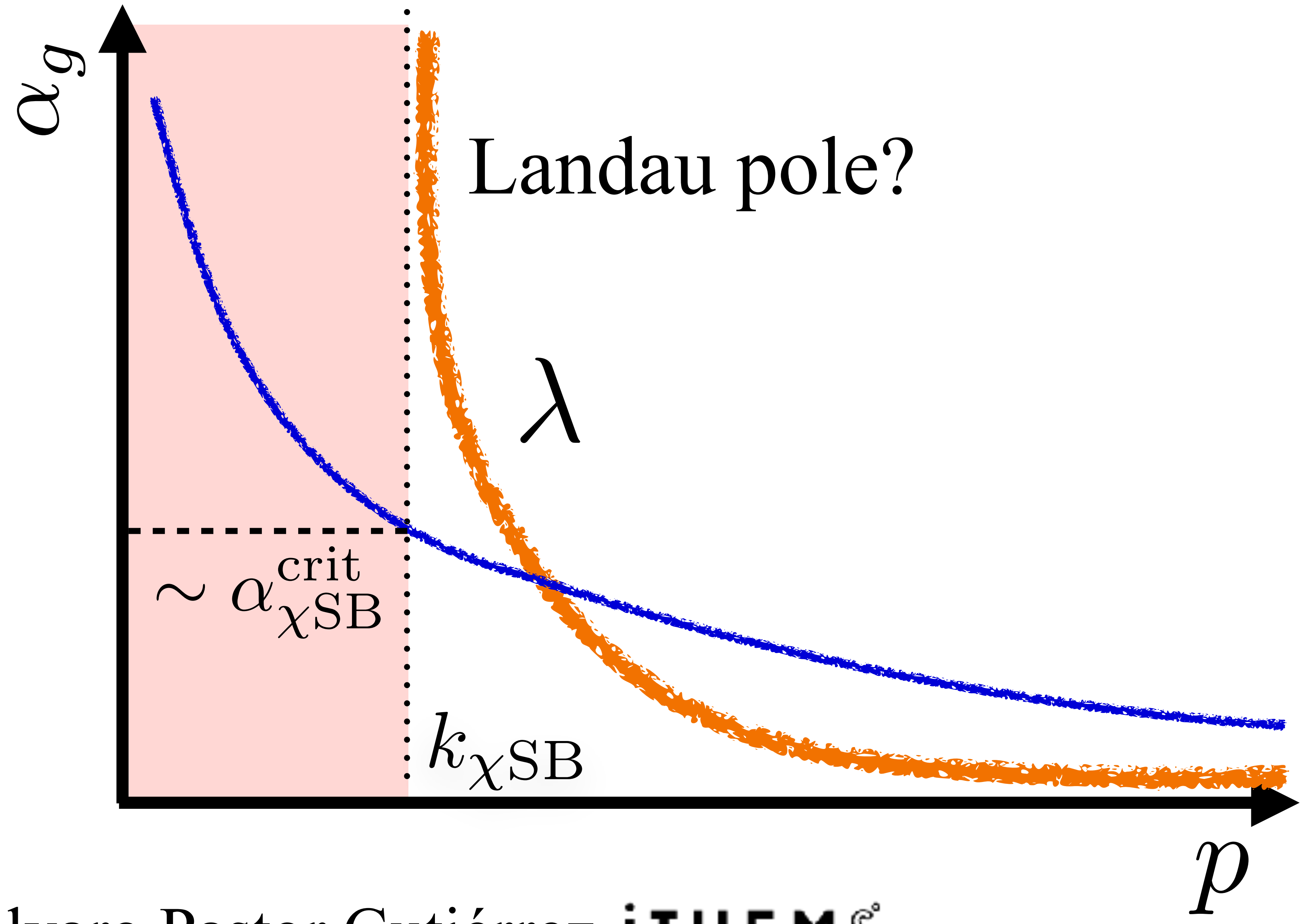


Resonant channel



From bosonisation we learned:

$$\langle(\bar{\psi}\psi)^2\rangle \sim \langle\phi\phi\rangle^{-1} \longrightarrow \lambda \propto 1/m_\phi^2$$

Dynamical chiral symmetry breaking

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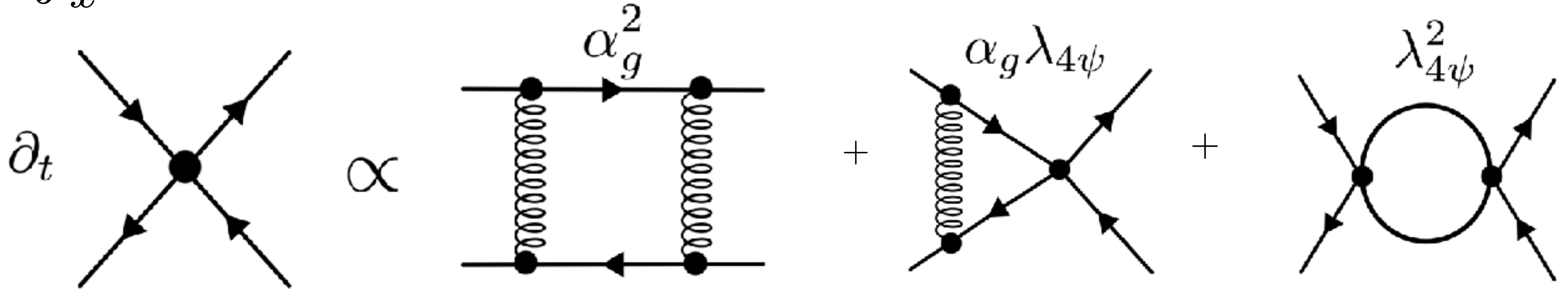
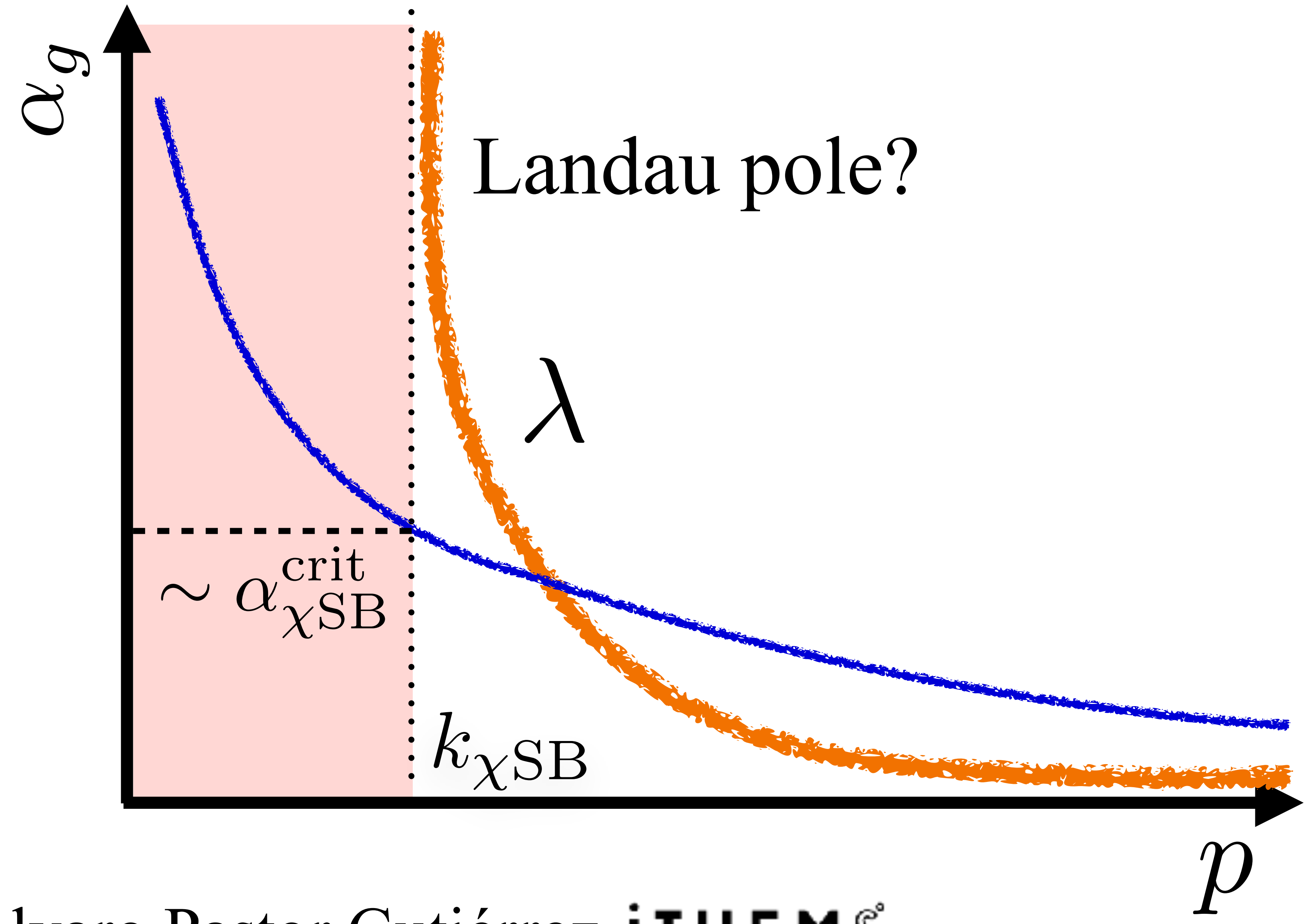


Resonant channel

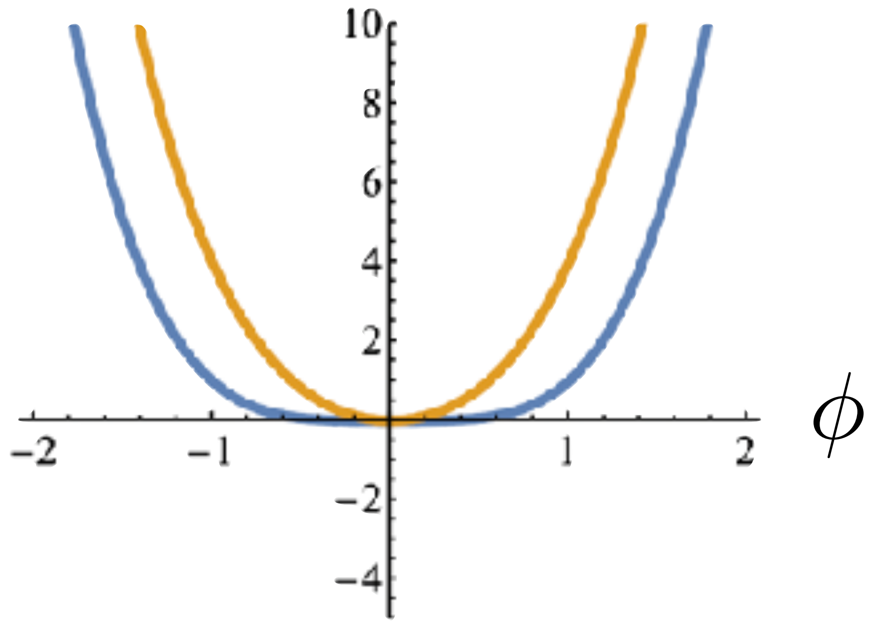


From bosonisation we learned:

$$\langle(\bar{\psi}\psi)^2\rangle \sim \langle\phi\phi\rangle^{-1} \longrightarrow \lambda \propto 1/m_\phi^2$$

$$\chi\text{SB} \longrightarrow (\lambda = \infty) \equiv (m_\phi = 0)$$

Critical point, infinite correlation length

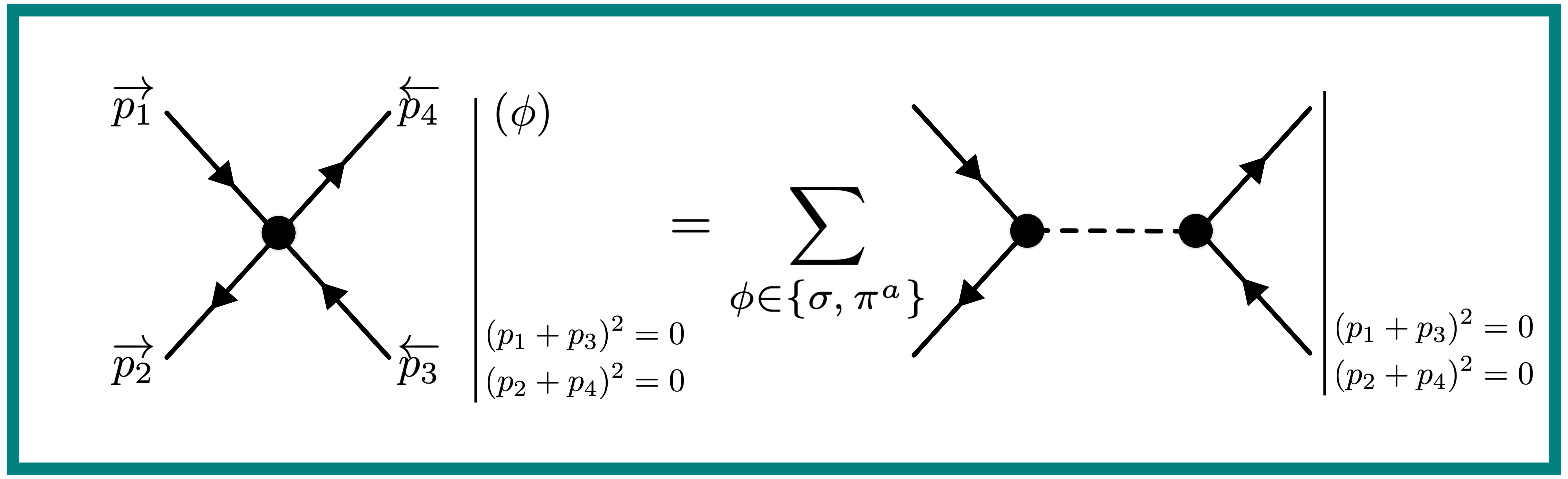


Higher dimensional operators carry information of **bound states formation** and **dχSB**

Emergent composites

$$\bar{\Gamma} = \int_x \frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + (\partial_\mu \bar{c}^a) D^{ab}_\mu c^b + \frac{1}{2\xi} (\partial_\mu A^a_\mu)^2 + \bar{\psi} \left[(\gamma_\mu D_\mu) \right] \psi - \lambda \left[\left(\bar{\psi} \, T^0_f \, \psi \right)^2 + (\bar{\psi} \, \mathrm{i}\gamma_5 \, T^a_f \, \psi)^2 \right] + \dots$$

Stratonovich'57 Hubbard'59 Gies, Wetterich '01



Pawlowski[hep-th/0512261] Fukushima,Pawlowski,Strodthoff [2103.01129]

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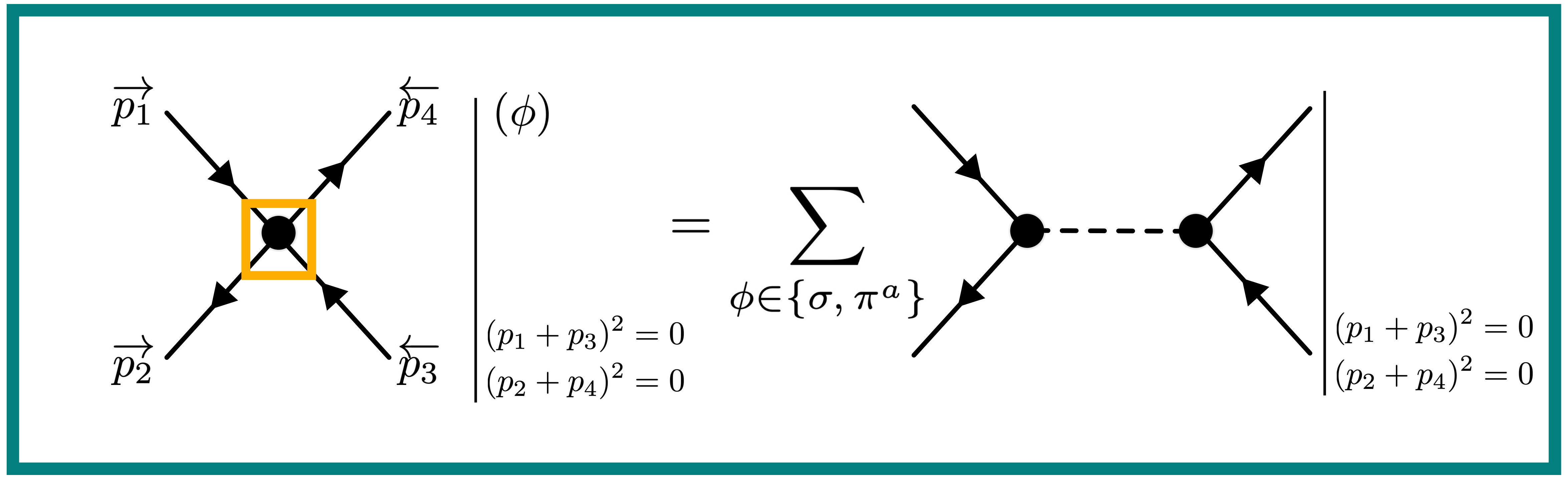
Stratonovich'57 Hubbard'59

Gies, Wetterich '01



Pawlowski[hep-th/0512261]

Fukushima,Pawlowski,Strodthoff [2103.01129]

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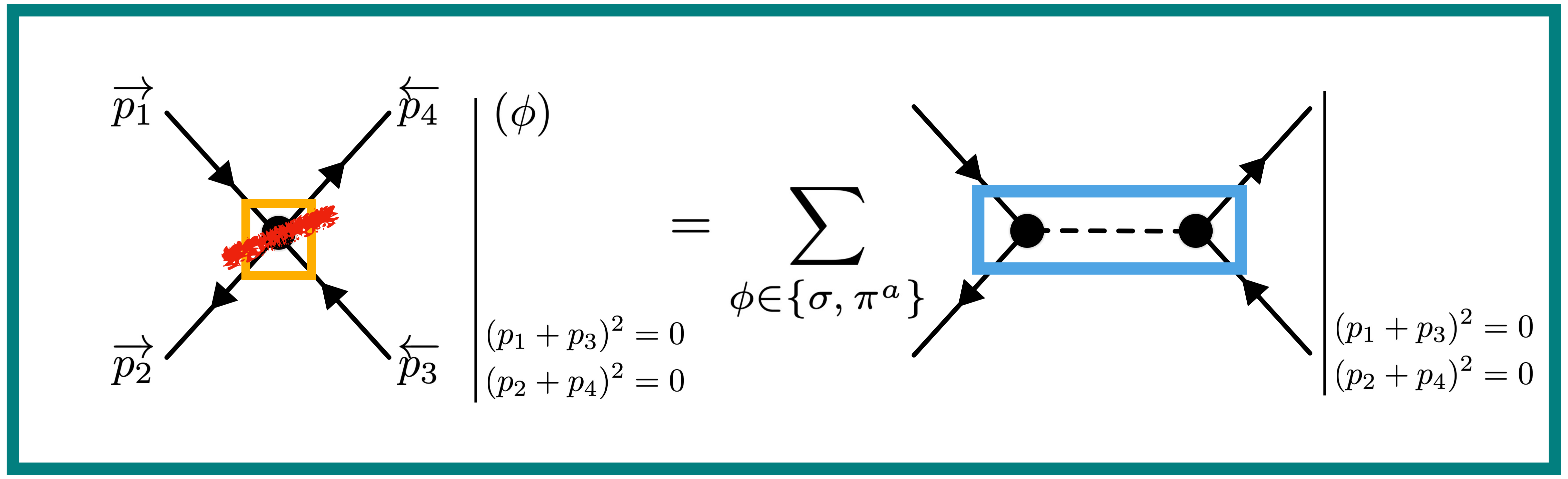
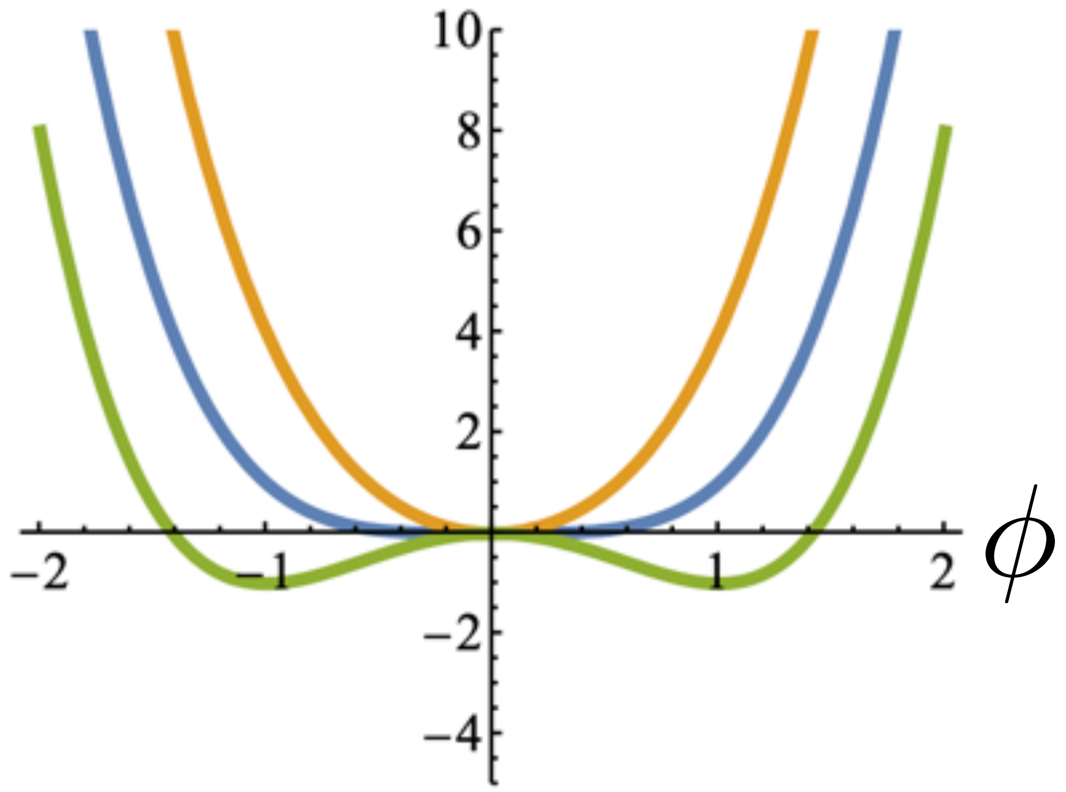
Stratonovich'57 Hubbard'59

Gies, Wetterich '01





Pawlowski[hep-th/0512261]

Fukushima,Pawlowski,Strodthoff [2103.01129]

$$\bar{\Gamma} = \int_x \frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + (\partial_\mu \bar{c}^a) D^{ab}_\mu c^b + \frac{1}{2\xi}(\partial_\mu A^a_\mu)^2 + \bar{\psi}\left[(\gamma_\mu D_\mu) + m(\sigma)\right]\psi$$

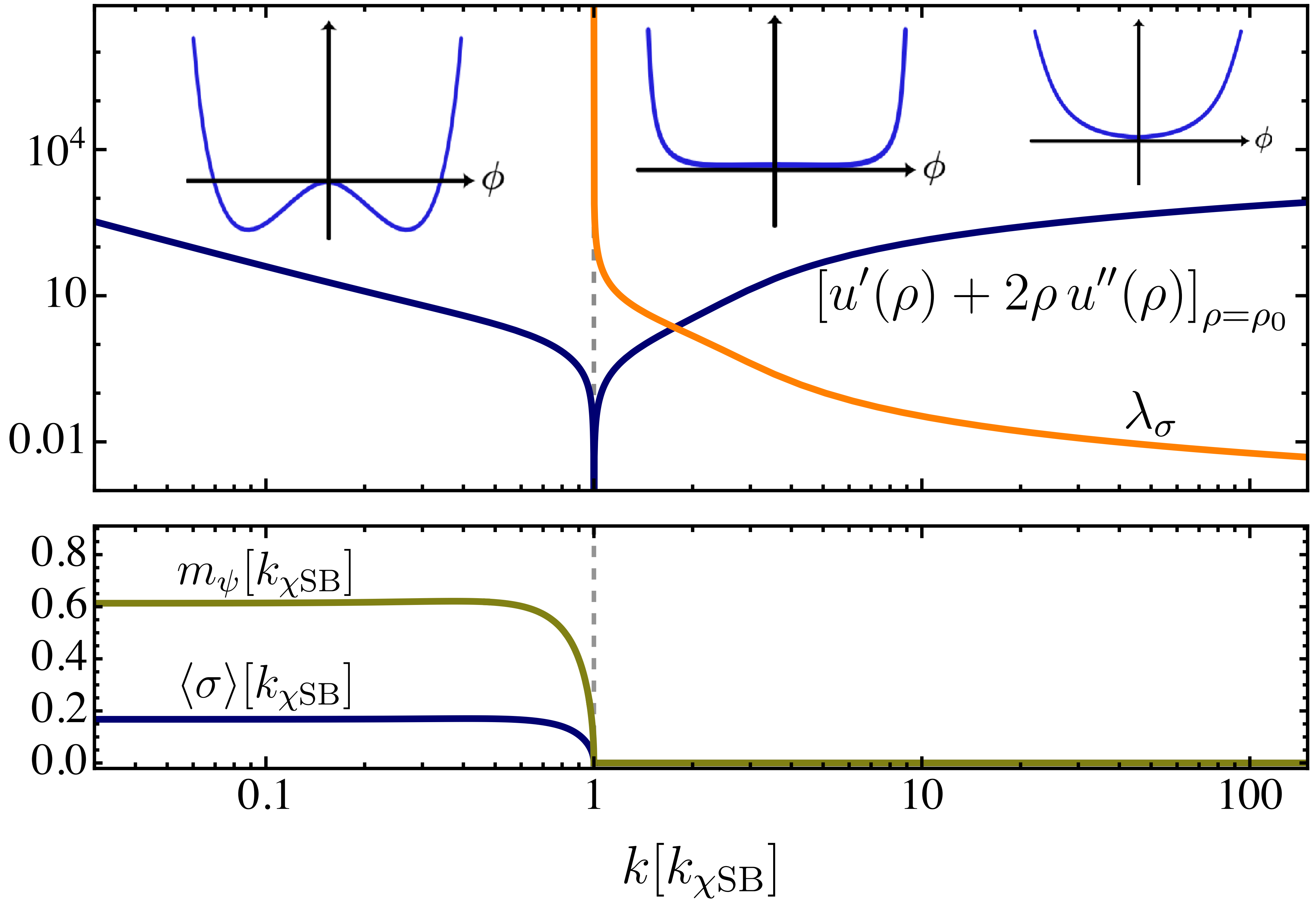
$$\phi = (\sigma, \mathrm{i}\gamma_5 \pi^a)$$

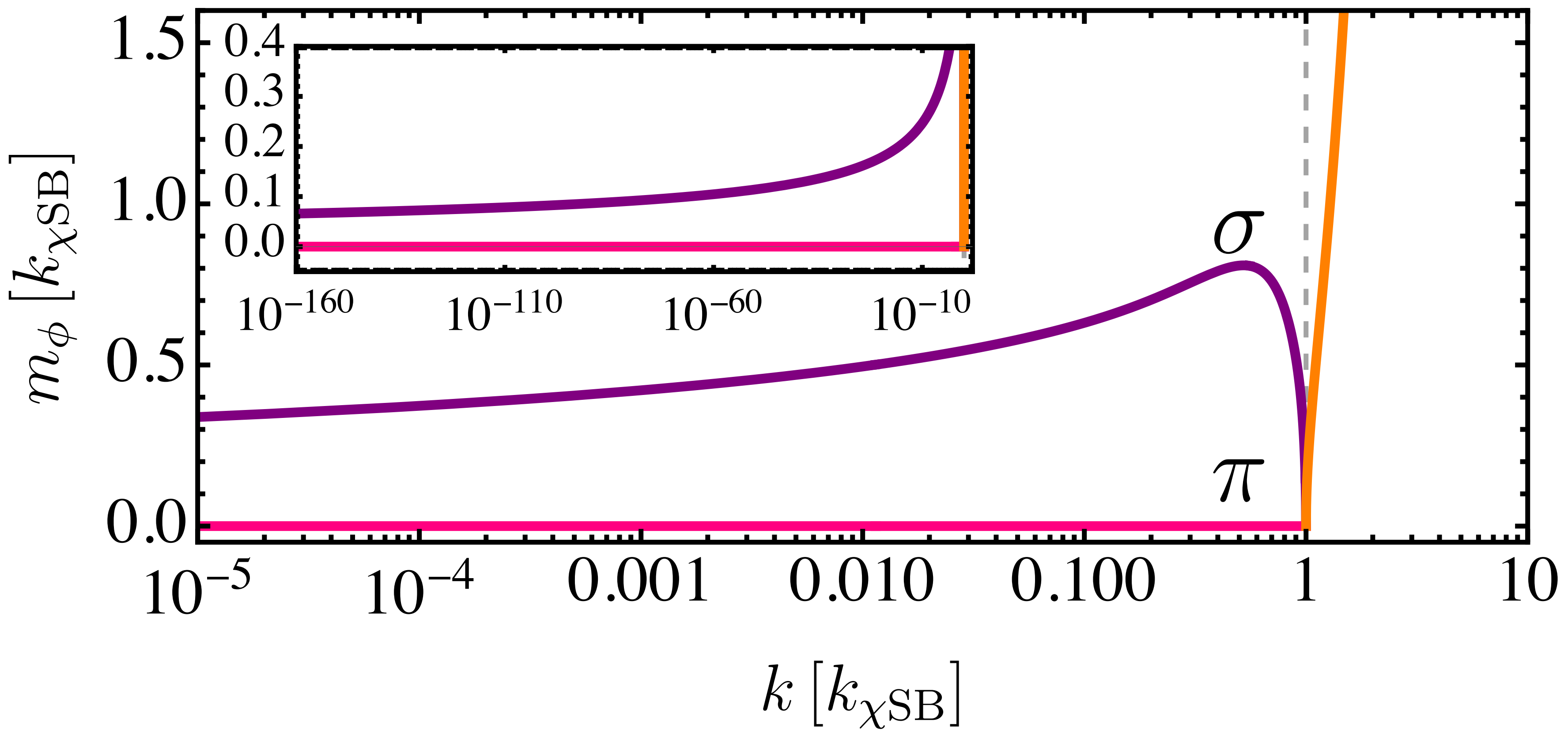
$$+ h\,\bar{\psi}\,(T^0_f \sigma + \mathrm{i}\gamma_5\, T^a_f \pi^a)\,\psi + \frac{1}{2}(\partial_\mu \phi)^2 + V(\phi^2) + \ldots$$

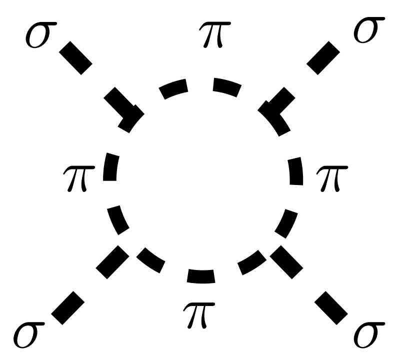
$$V(\phi^2) = \sum_{n=1}^{N_{\max}} \frac{\lambda_n}{n!}\left(\frac{\phi^2}{2}\right)^n$$

Dynamics in the chirally broken phase $N_c = 3 \;\; N_f = 2$

- ✦ Flows computed: $\{h, V(\phi), Z_\psi, Z_\phi, \lambda_i\}$
- ✦ **Continuous** interpolation between chirally **symmetric** and **broken** regimes
- ✦ A **clear** and **precise** way to **diagnose** χSB

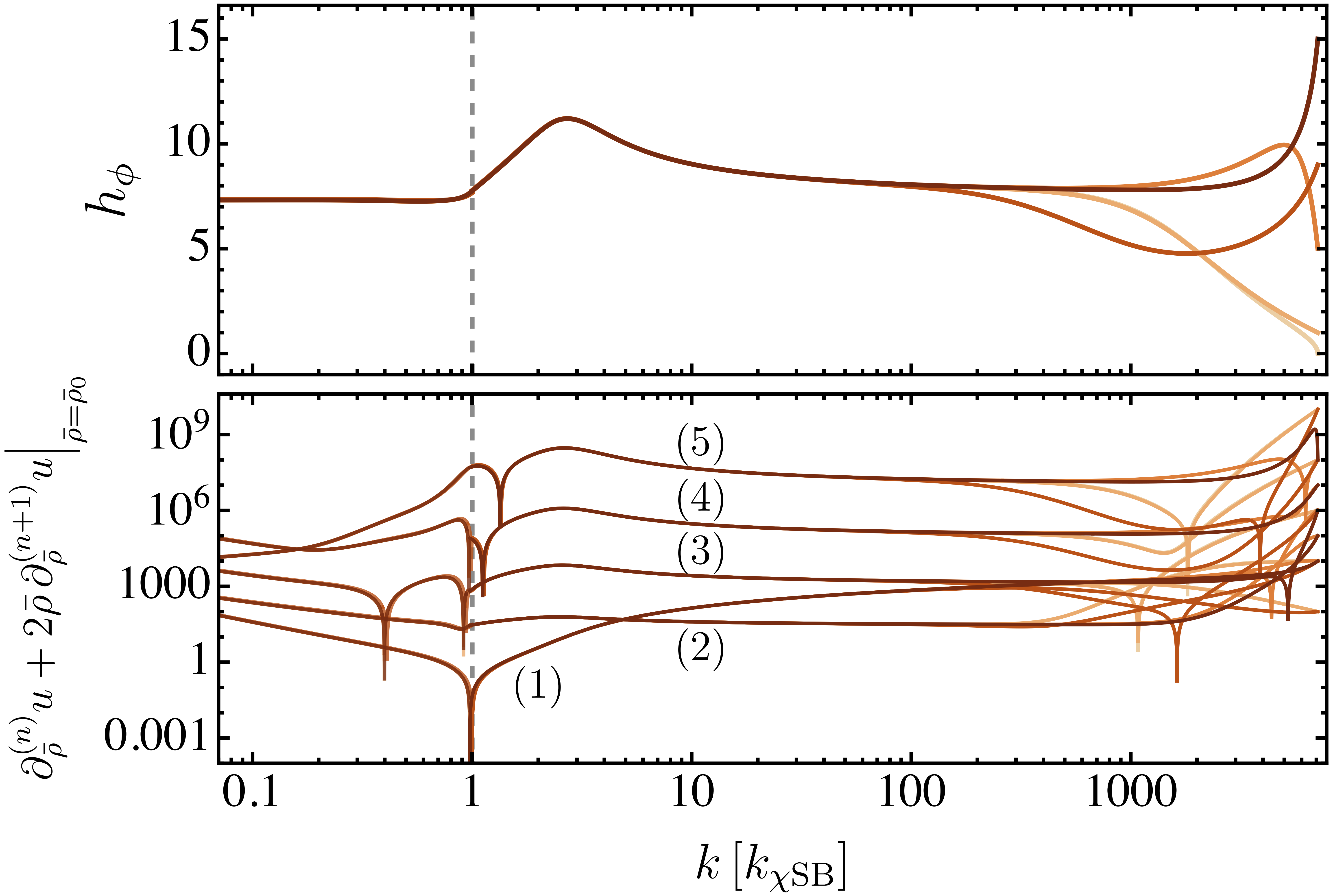




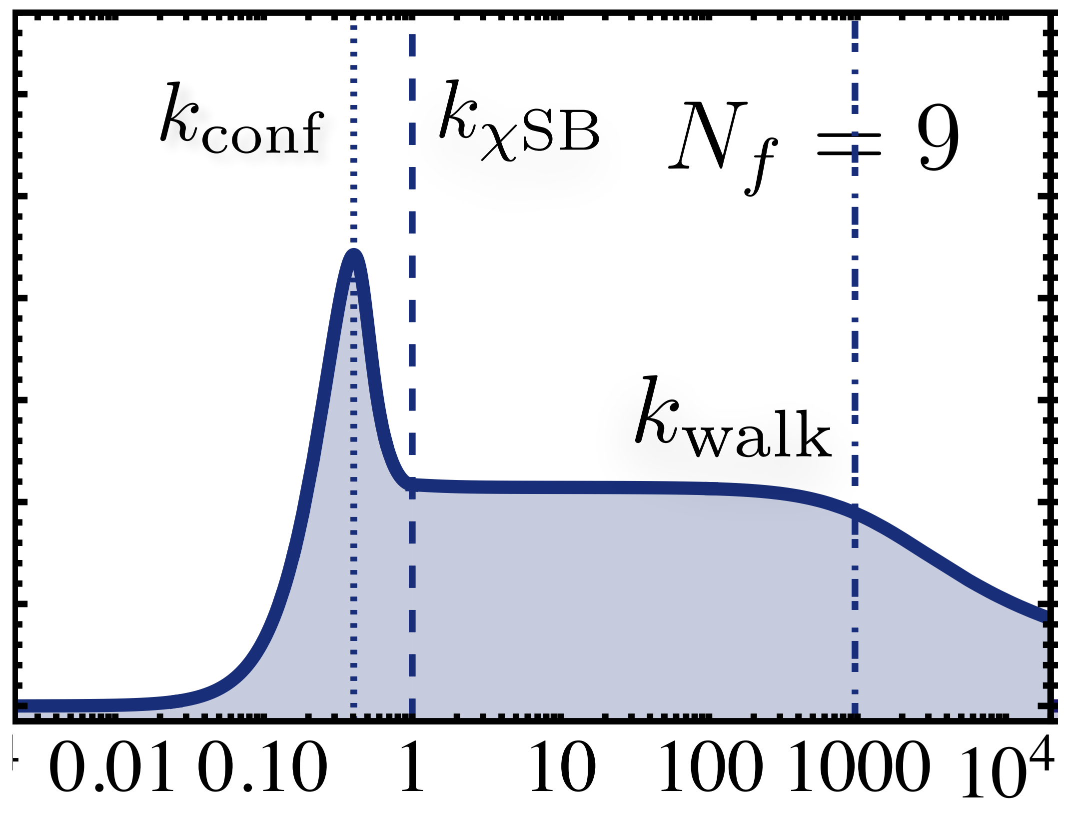


- ✦ Obtaining **fundamental parameters**
  - Constituent fermion masses: m_ψ
  - Chiral condensate: $\langle\sigma\rangle \sim f_\pi$
  - Composite masses of bosonised channels: m_σ, m_π
- ✦ Account for **higher dimensional fermionic** operators via higher-order scalar potential:
  - Non-perturbative effects and higher precision

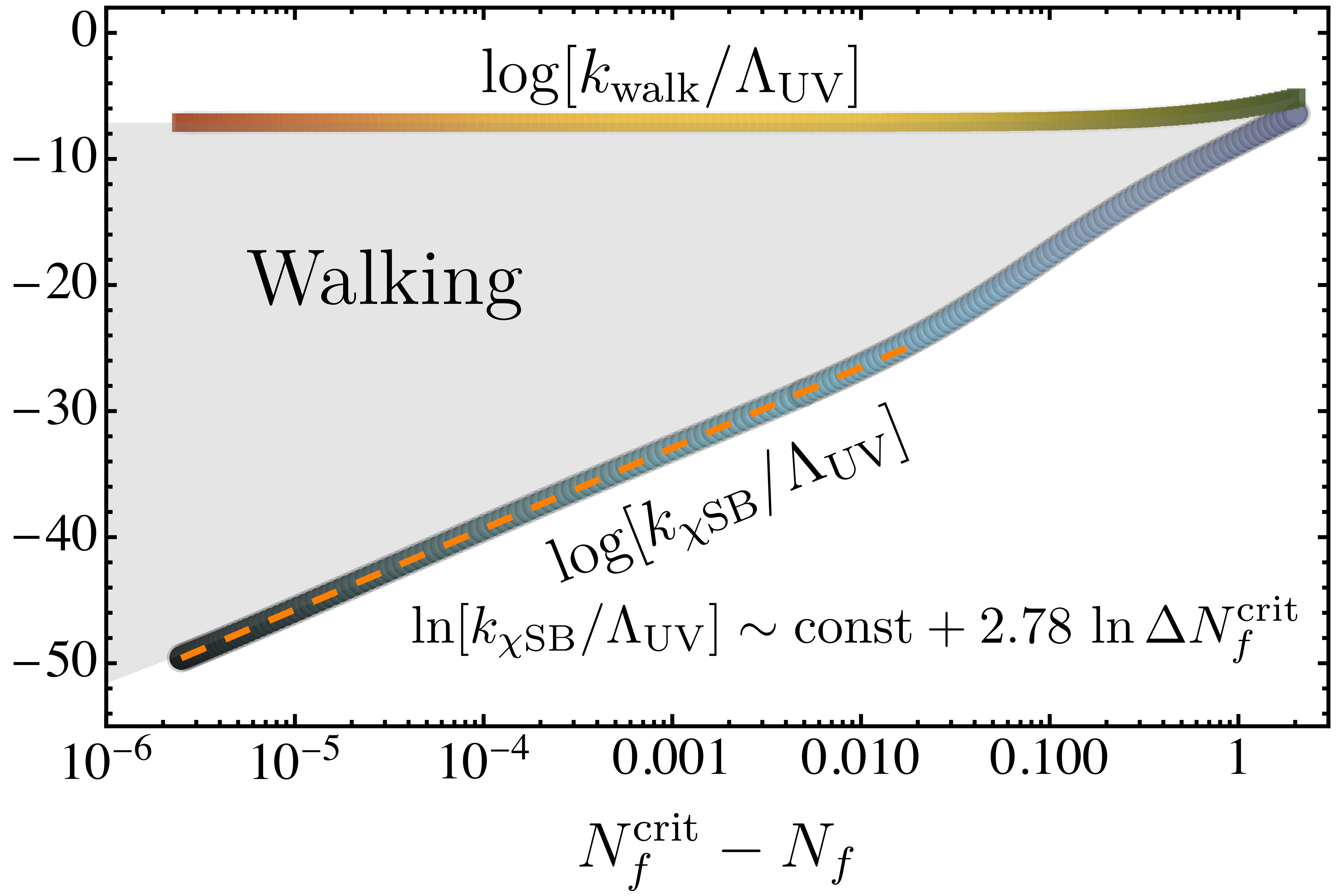
Dynamical bosonisation



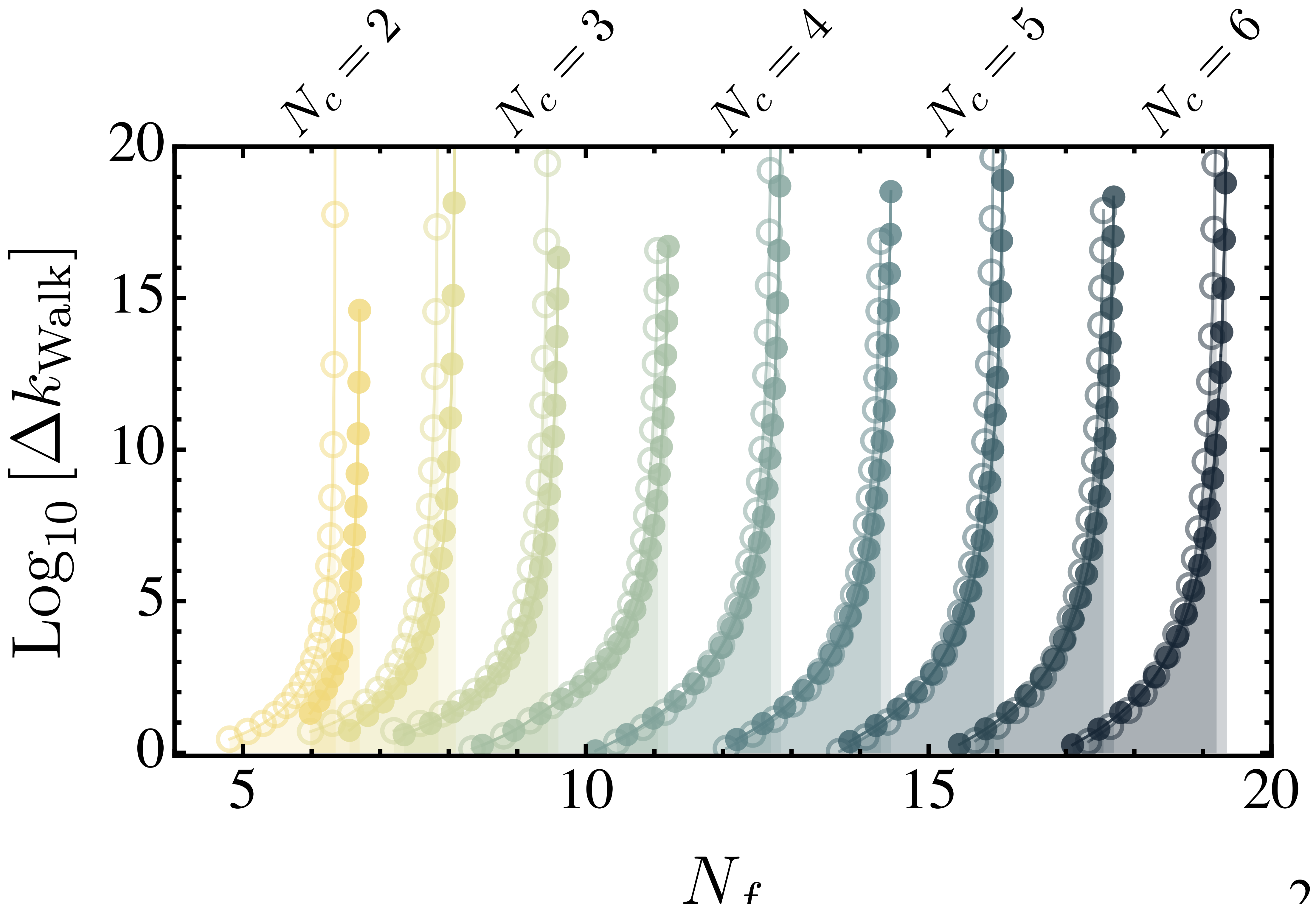
Near-conformal scaling and



Conformal-dynamical phase transition



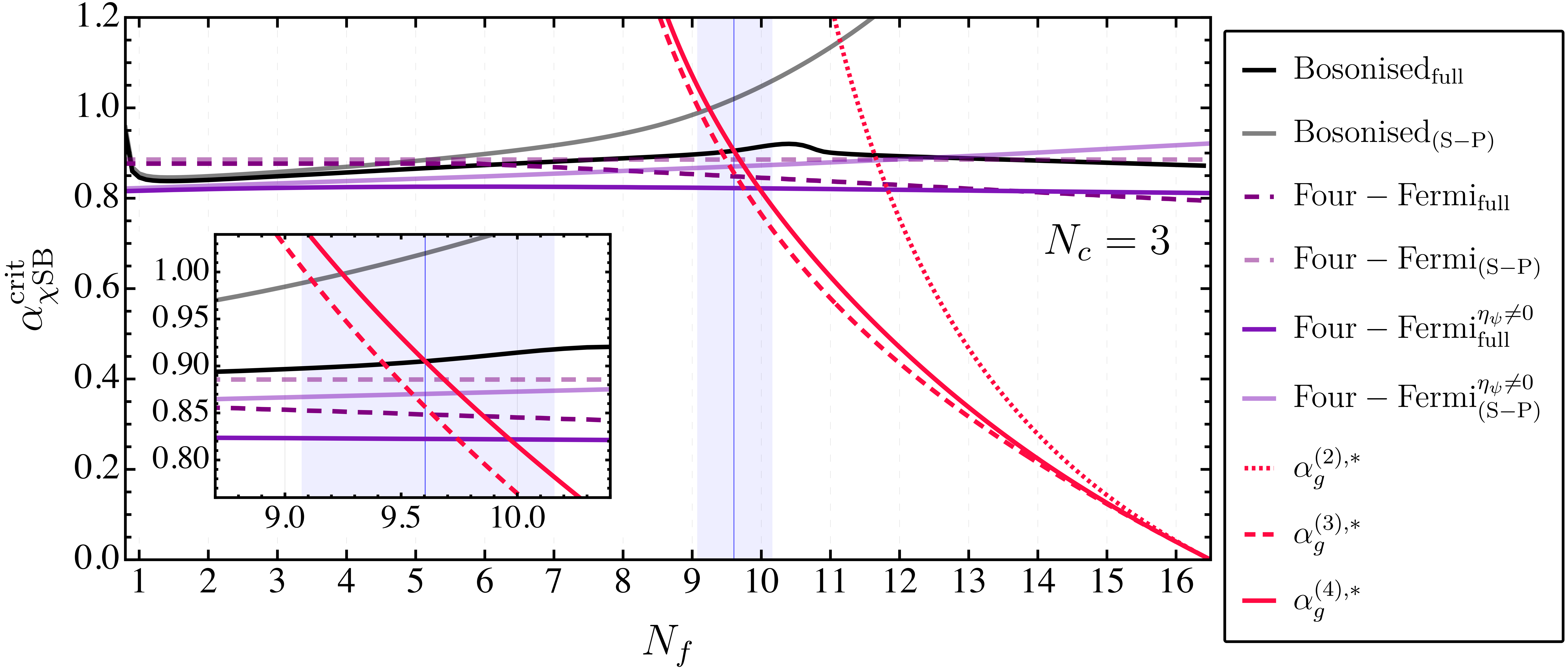
Length of walking regime from first principles:



Miransky,Yamawaki [9611142]
Miransky [9812350]

Braun,Fischer,Gies [1012.4279]
Braun,Gies[0912.4168]

Boundary of the conformal window: systematics



Comparison to perturbative methodology

Lee[2008.12223]
Dietrich,Sannino[0611341]
Ryttov,Shrock[1608.00068]
Appelquist,Terning,Wijewardhana[9602385]
Hasenfratz,Neil,Shamir,Svetitsky,Witzel[2306.07236]
...

$$\gamma_m = \frac{\partial_t \bar{m}_\psi}{\bar{m}_\psi} = \left[\frac{\partial_t \left(T_f^0 \, \Gamma_k^{(\bar\psi\psi)}(p^2=0) \right)}{Z_\psi m_\psi} + \eta_\psi \right]$$

$$= \gamma_m^{(1)} + \gamma_m^{(>1)} = \frac{3\,\alpha_g\, C_{\rm F}}{2\pi} + \dots$$

dχSB when $\left|\gamma_m^{(1)}\right|_{g^*} \gtrsim 1$

- But which exact value?
- And which $\gamma_m^{(i)}$?

} **Imprecise**

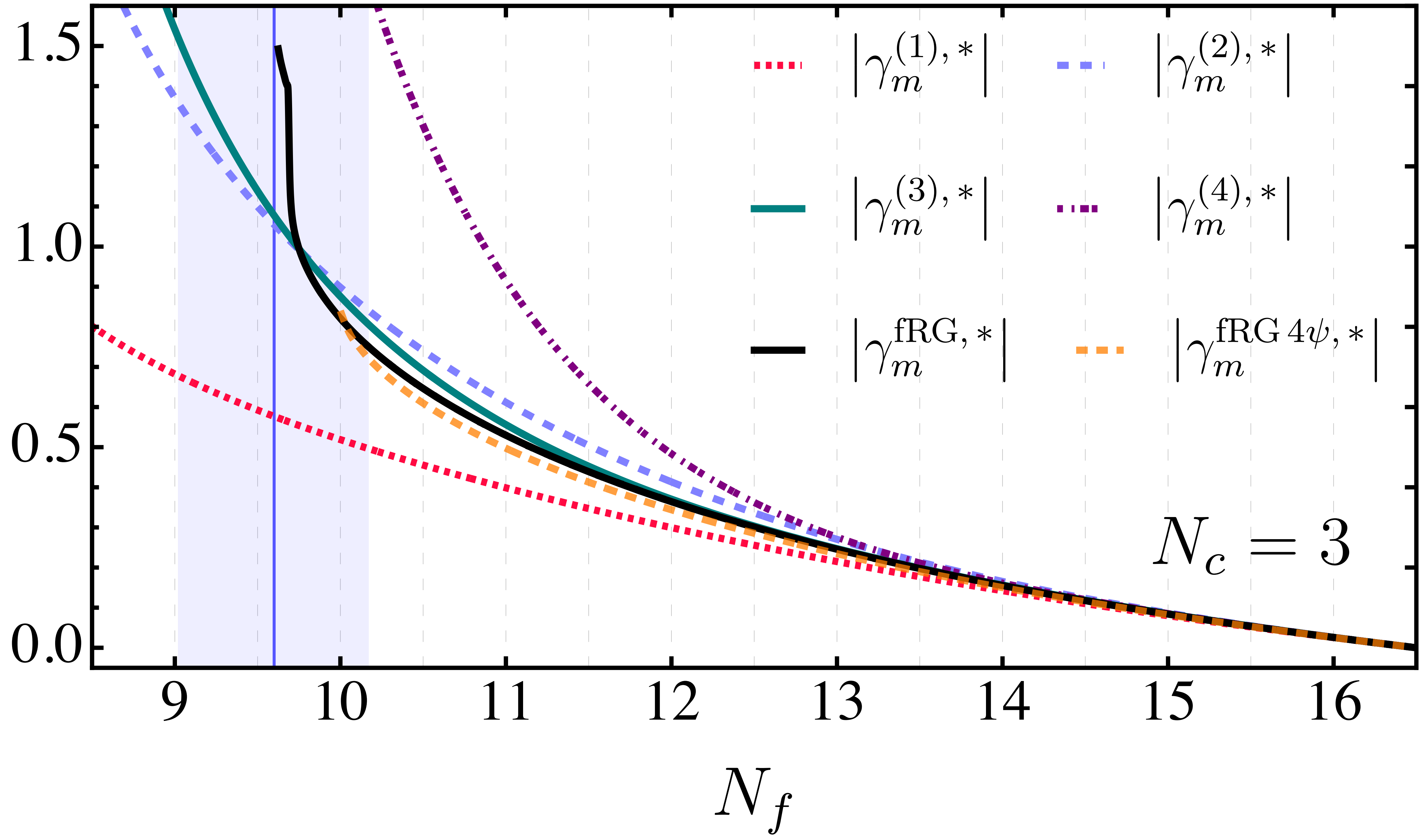
From the fRG prediction:

$\left|\gamma_m^{\rm fRG,\,*}\right| (N_f^{\rm crit}) = 1.49$ **Strongly coupled CFTs?**

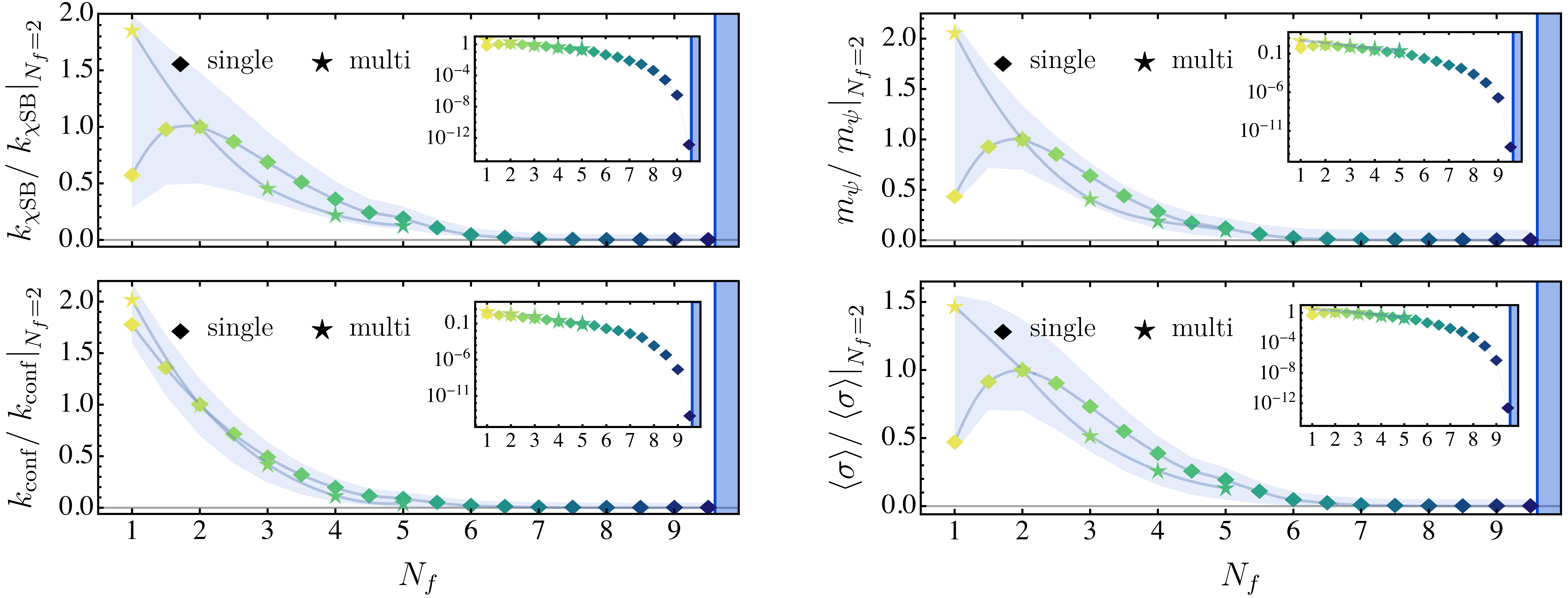
$\left|\gamma_m^{(i),\,*}\right| (N_f^{\rm crit}) = \{0.58,\, \underbrace{1.05,\, 1.08}_{},\, 2.64\}$

2- and 3- loop results should be used

$N_f^{\rm crit}(N_c=3) = 9.60^{+0.55}_{-0.53}$



Large N_f scaling



Different tensor structures