MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

Cartography of gauge-fermion dynamics

1. Confinement

2. DχSB

3. Conformality

Work in collaboration with
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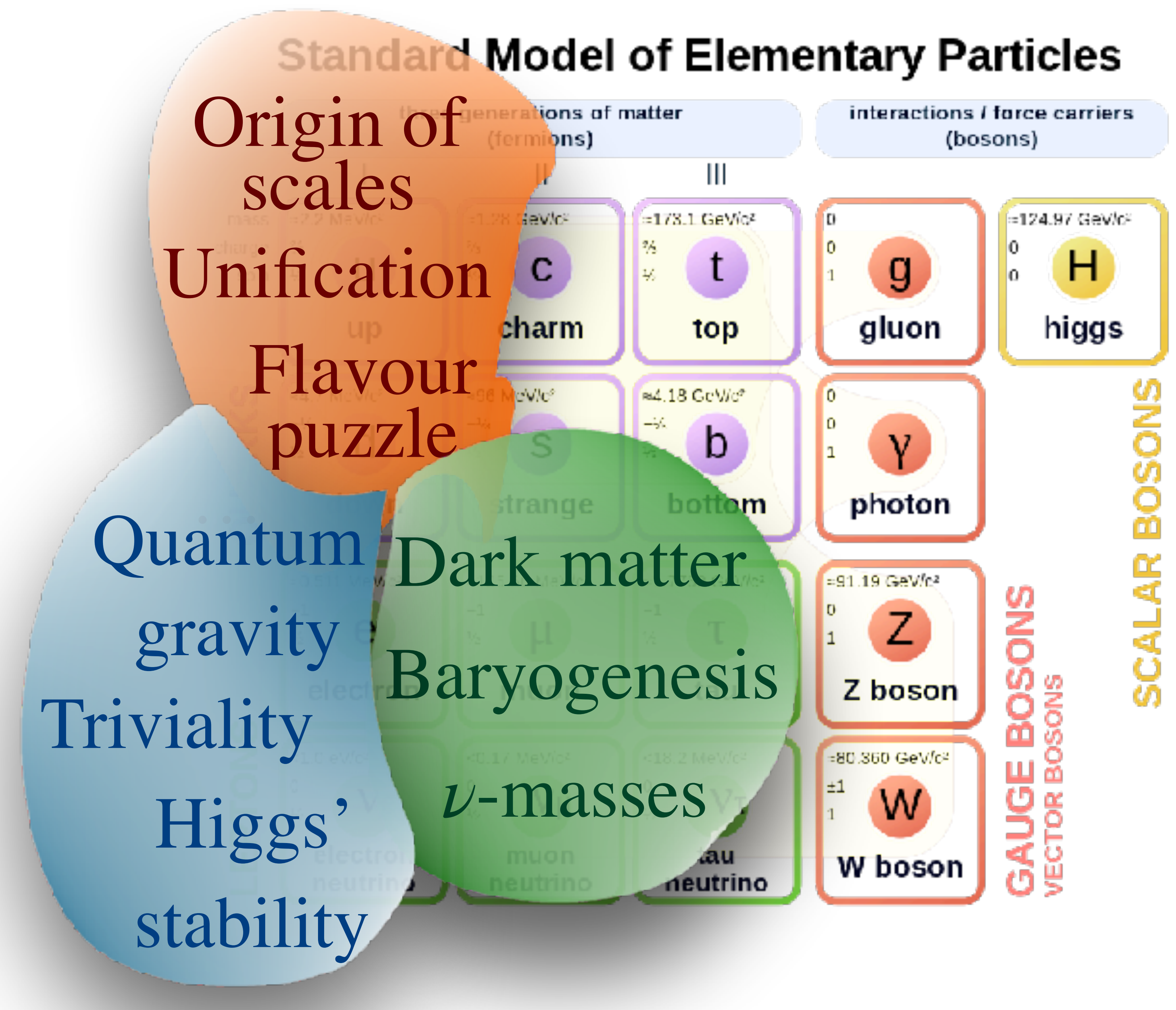
ERG2024, Les Diablerets

Gauge-fermion theories

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

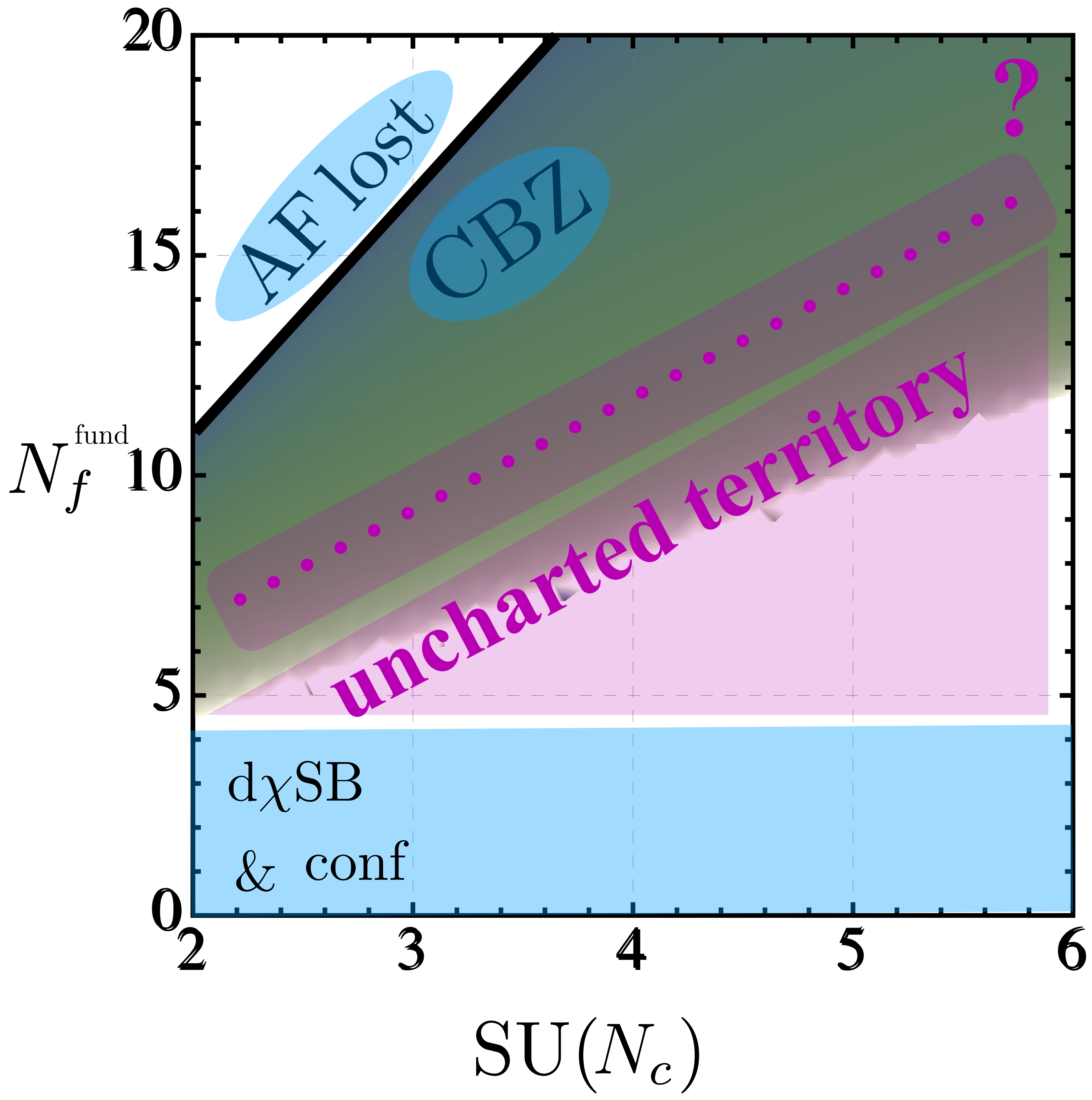
- ✦ Importance in the **natural world:** ~QCD, ~EW sector
- ✦ Non-trivial **dynamics** and **features**:
  - Confinement
  - Dynamical chiral symmetry breaking (dχSB)
  - Walking dynamics



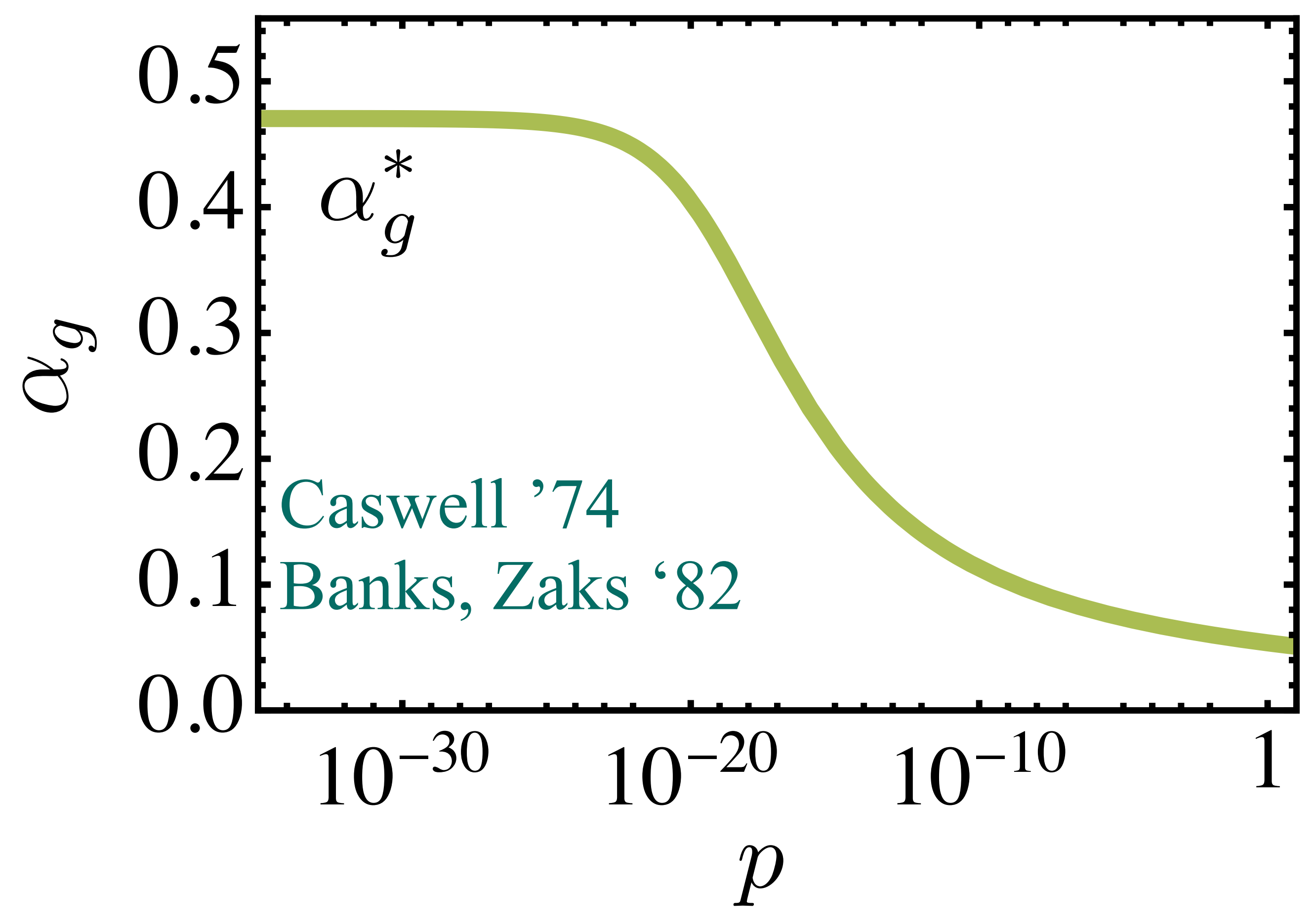
- ✦ Answer to fundamental puzzles of nature:
  - Strong dark sectors responsible for Dark Matter
  - Composite Higgs and Technicolour models
  - Cosmological phase transitions and gravitational wave signatures

What we know so far from first-principles?

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



- Where **asymptotic freedom** is lost
- **Few flavours**: QCD-like theories
- **CBZ IR fixed-point** (perturbative)



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

- **Tailor-made task** for the **functional Renormalisation Group:** $\Gamma_k[\phi]$
  - Quantitative Ihssen,Pawlowski,Sattler,Wink[2408.08413]
  - Versatile: easily study large range of parameter and theory space
  - Chiral limit with no difficulties

Colour confinement and the gluon mass gap

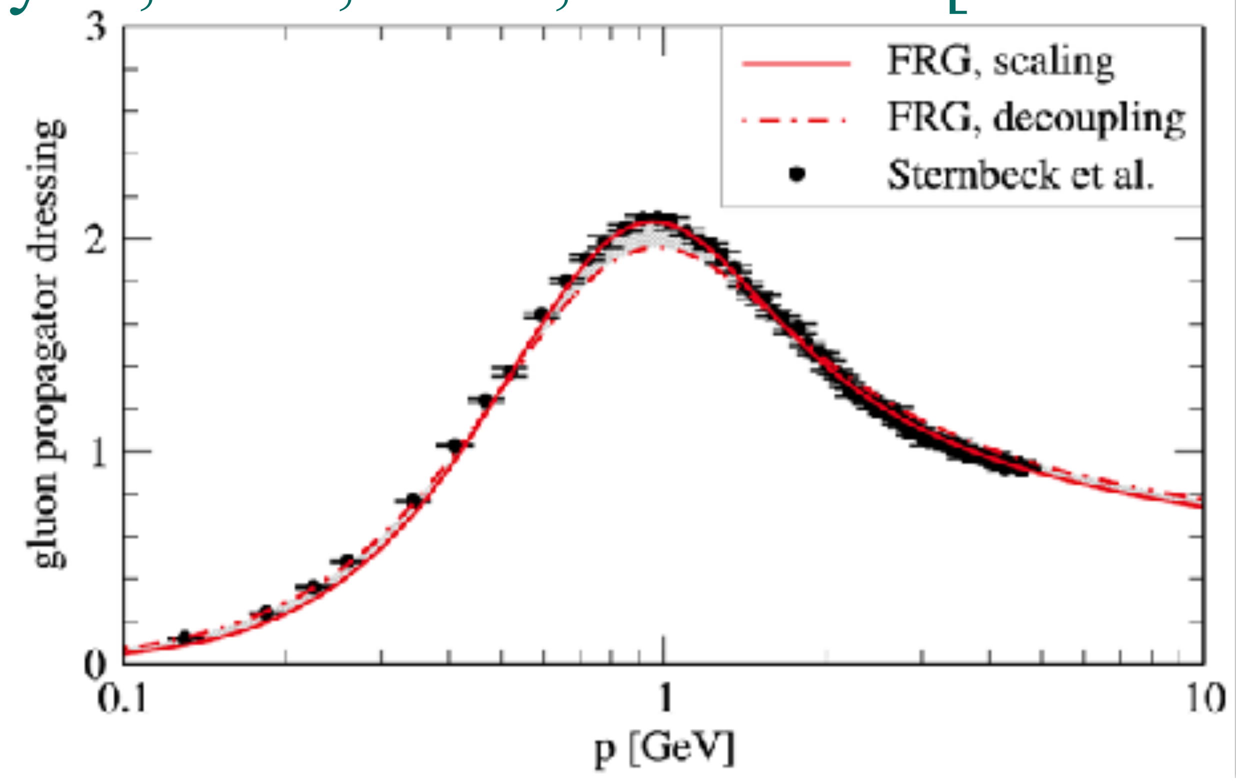
✦ **Absence** of **coloured asymptotic states**

✦ **Massive spectrum** of bound states (glueballs)

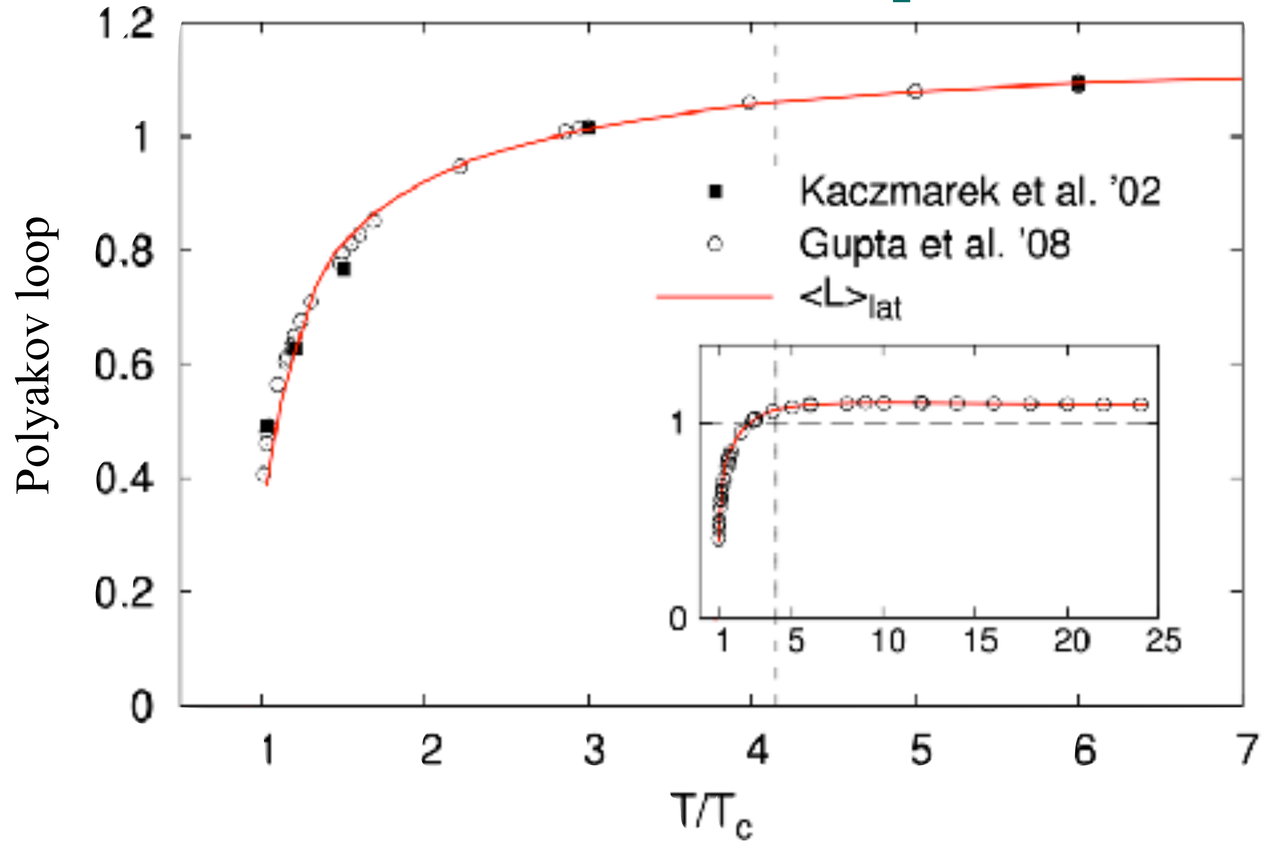
✦ Existence of a gluon **mass gap:**

- Wilson area law
- Kugo-Ojima conditions
- Confinement-deconfinement phase transition

Cyrol,Fister,Mitter,Pawlowski [1605.01856]



Herbst,Luecker,Pawlowski[1510.03830]



✦ **fRG bootstrap approach** to confinement:

- **Mass gap** generated by **quantum fluctuations**

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

- **Uniquely defined** confinement condition

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

✦ New: "*easy*" confinement

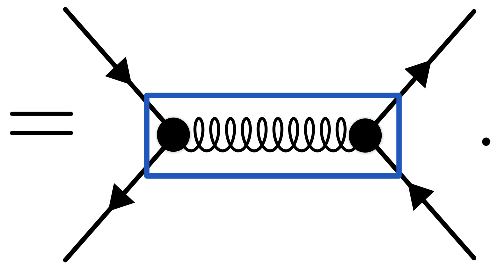
- **Cutoff dependences suffice**
- Semi-analytical
- Facilitate study beyond QCD-limit

Confinement in correlation functions

$N_c = 3 \;\; N_f = 2$

- Flows computed: $\{g_{A\bar\psi\psi}, g_{A\bar c c}, g_{A^3}, g_{A^4}, \bar m_A, Z_A, Z_c\}$
- **Exchange couplings**:

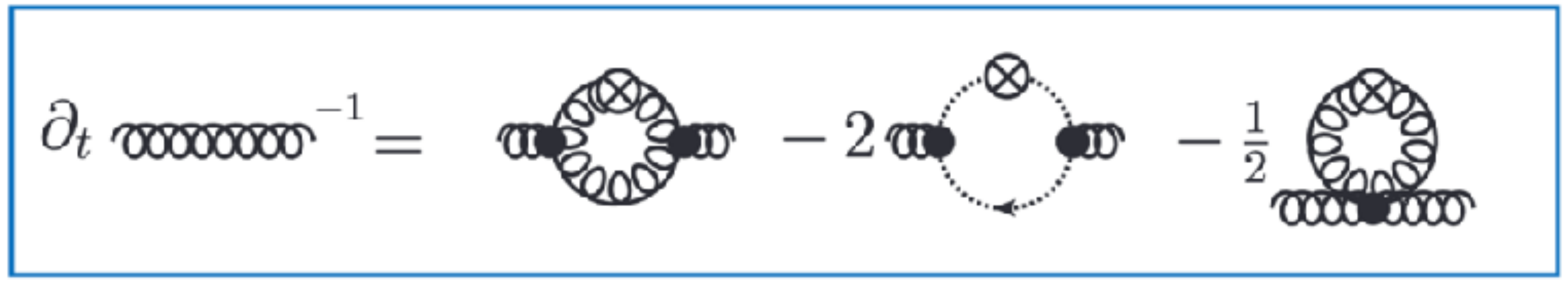
$$\alpha_{A\psi\bar\psi} = \frac{\left[\Gamma_k^{(A\psi\bar\psi)}\right]^2_{\mathcal{T}=1}}{4\pi\, Z_A Z_\psi^2} = \frac{g^2_{A\psi\bar\psi}}{4\pi\,(1+\bar m^2_{\text{gap}})}$$

$\alpha_{A\psi\bar\psi} =$  $\cdot\, p^2$

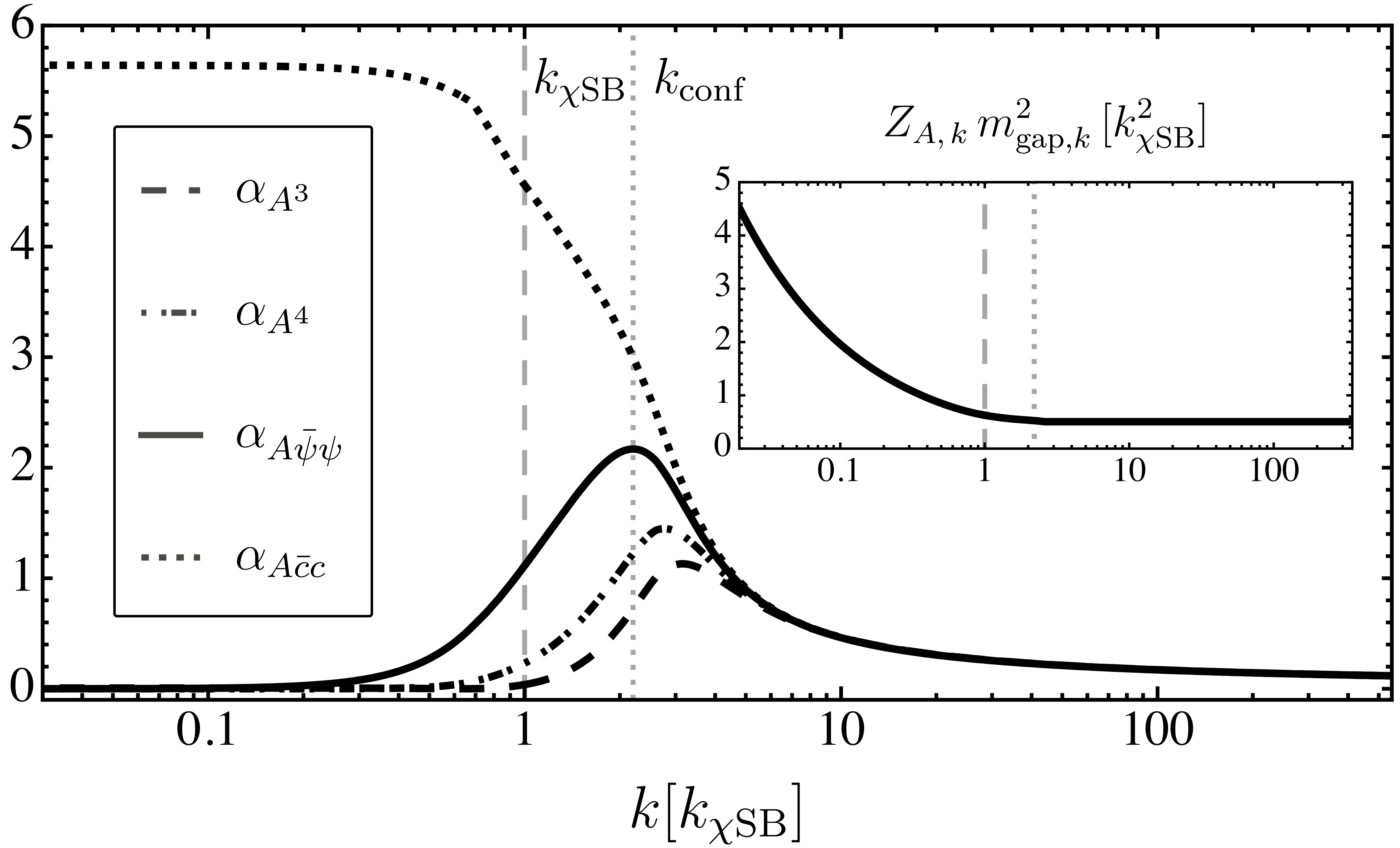
- **Decay** of correlation functions below the **mass gap scale**

$$k_{\text{conf}} \sim m_{\text{gap}} \sim T_{\text{conf}} \sim \Lambda_{\text{QCD}}$$

- The **interplay** of **gapped gauge** and **ghost** contributions

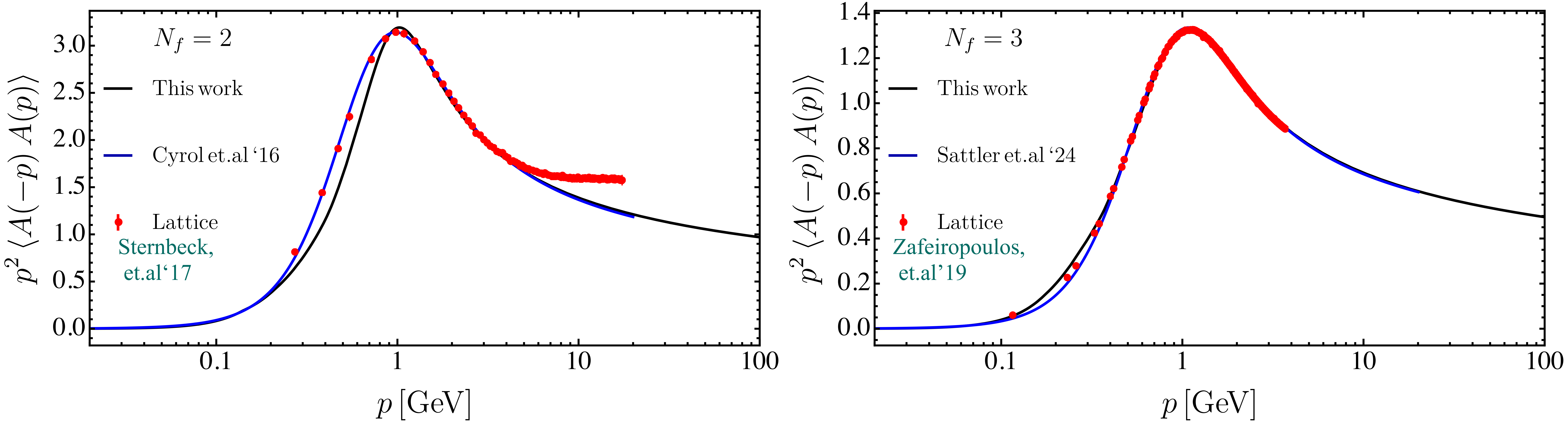


Cyrol,Fister,Mitter,Pawlowski [1605.01856]



"Easy" confinement

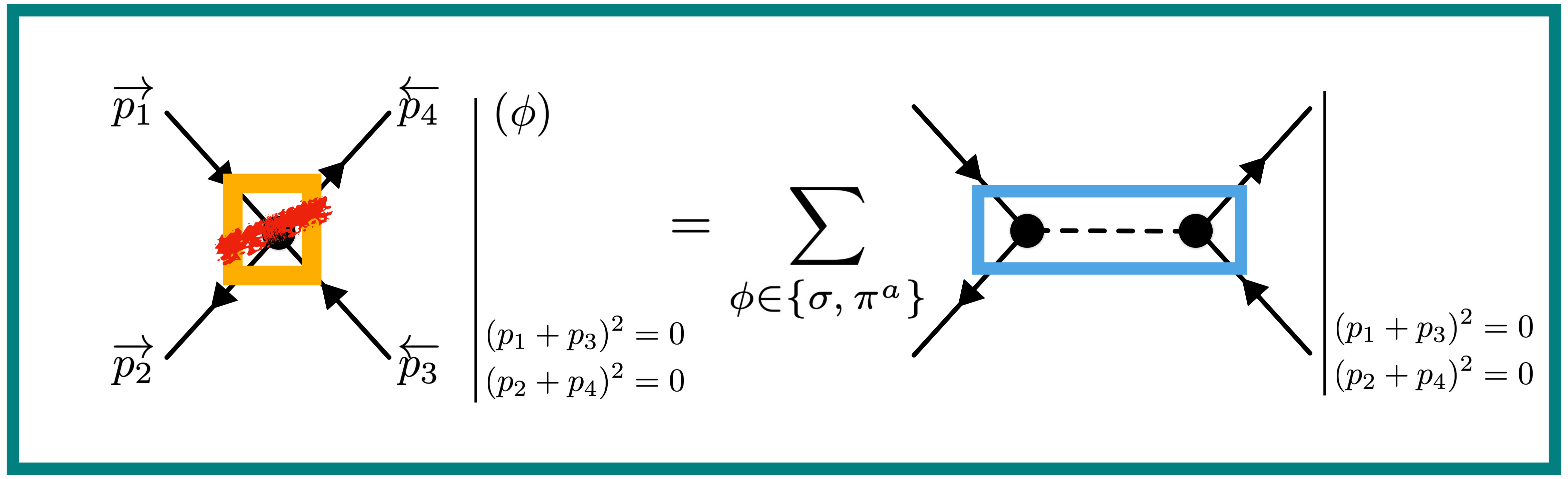
Gluon propagator dressing: $$p^2 \langle A(-p) A(p) \rangle = p^2 \left[\Gamma_k^{(AA)}(p^2 = 0) \right]^{-1}_{k=c\,p}$$



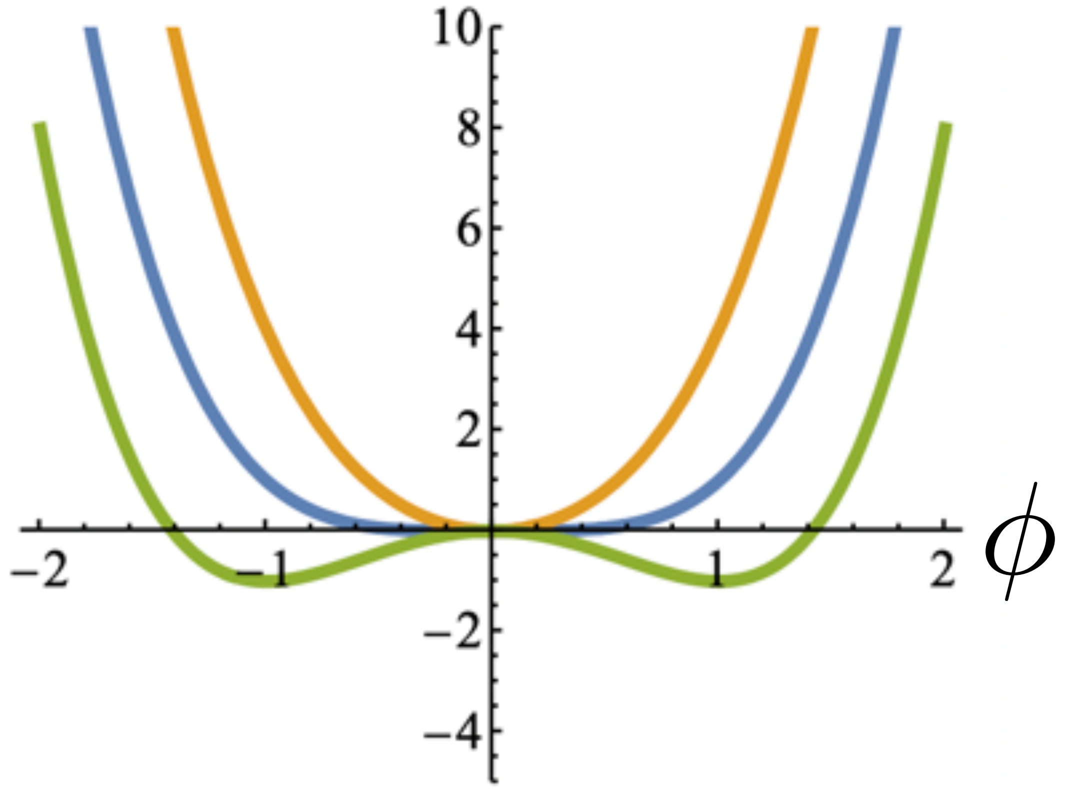
Emergent composites

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

Stratonovich’57 Hubbard’59 Gies, Wetterich ’01



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



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

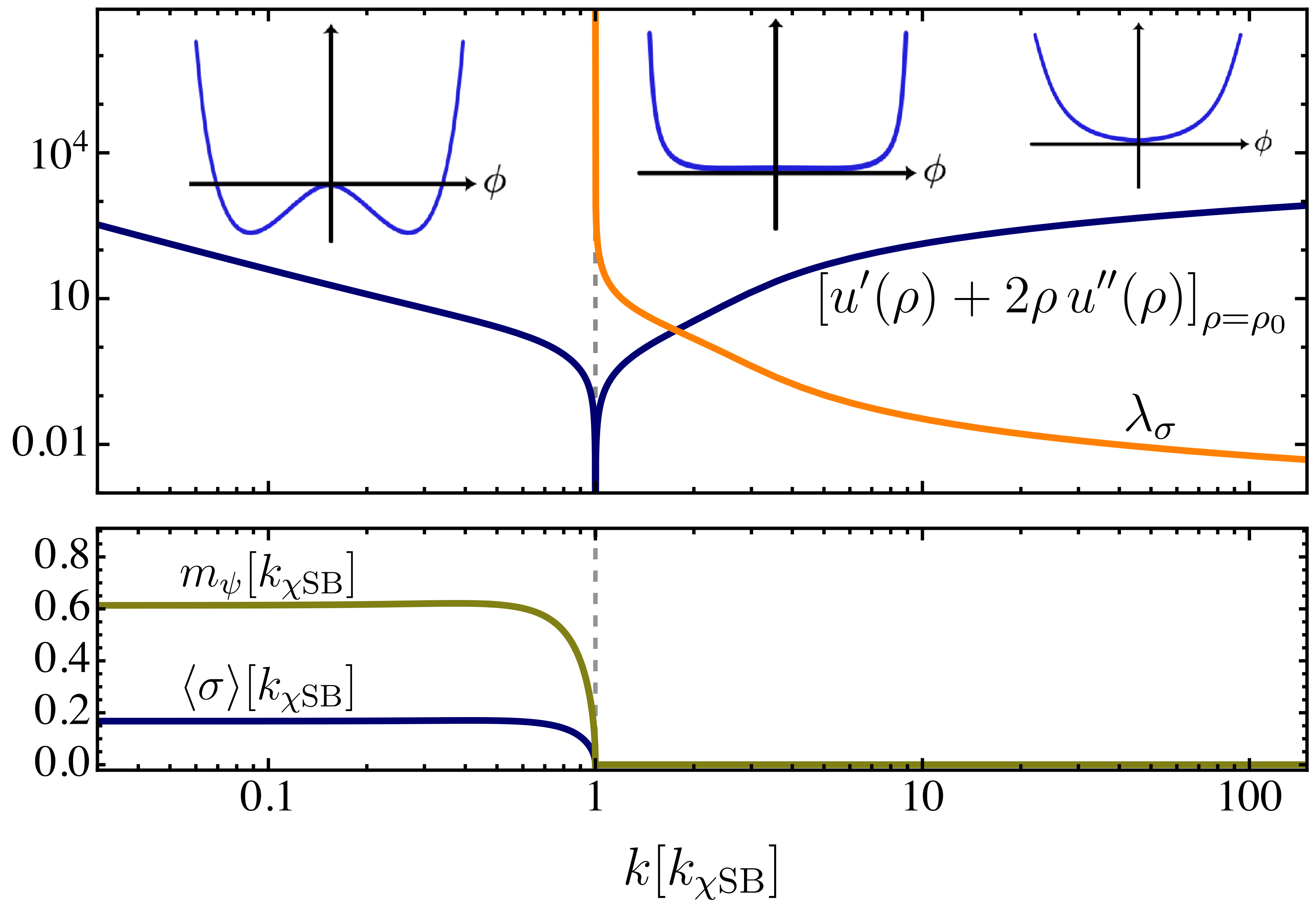
$$+ h\, \bar{\psi}\, \left(T^0_f \sigma + \mathrm{i}\gamma_5\, T^a_f \pi^a \right)\, \psi + \frac{1}{2} (\partial_\mu \phi)^2 + V(\phi^2) + \ldots$$

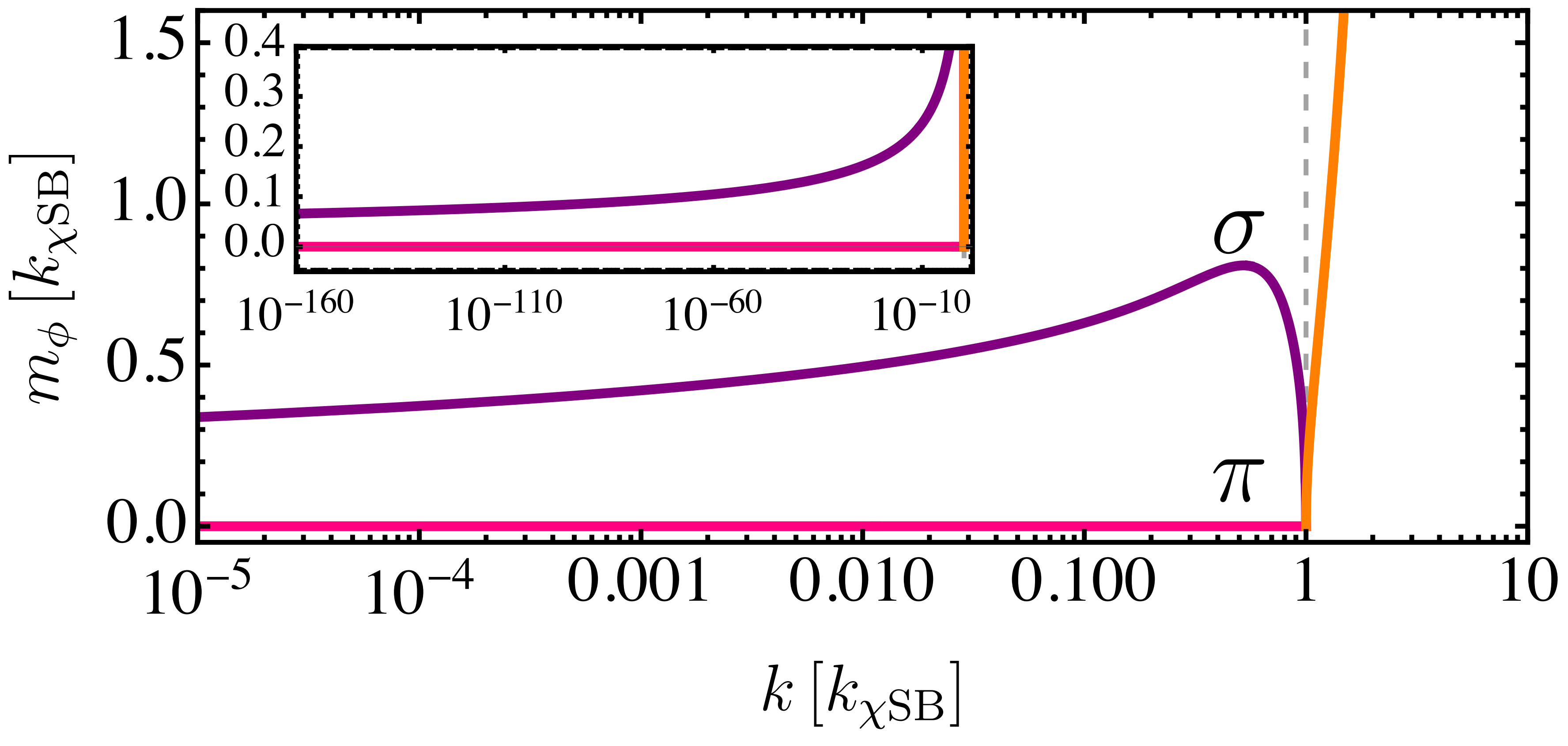
$$\phi = (\sigma, \mathrm{i}\gamma_5 \pi^a)$$

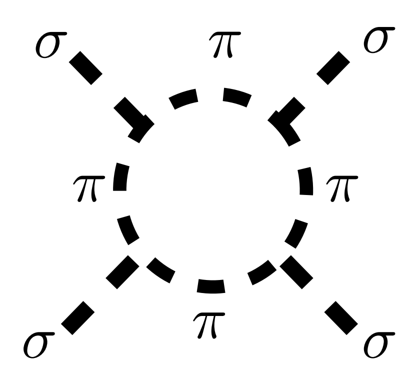
$$V(\phi^2) = \sum_{n=1}^{N_{\max}} \frac{\lambda_n}{n!} \left(\frac{\phi^2}{2} \right)^n$$

Dynamical χSB

$N_c = 3 \;\; N_f = 2$



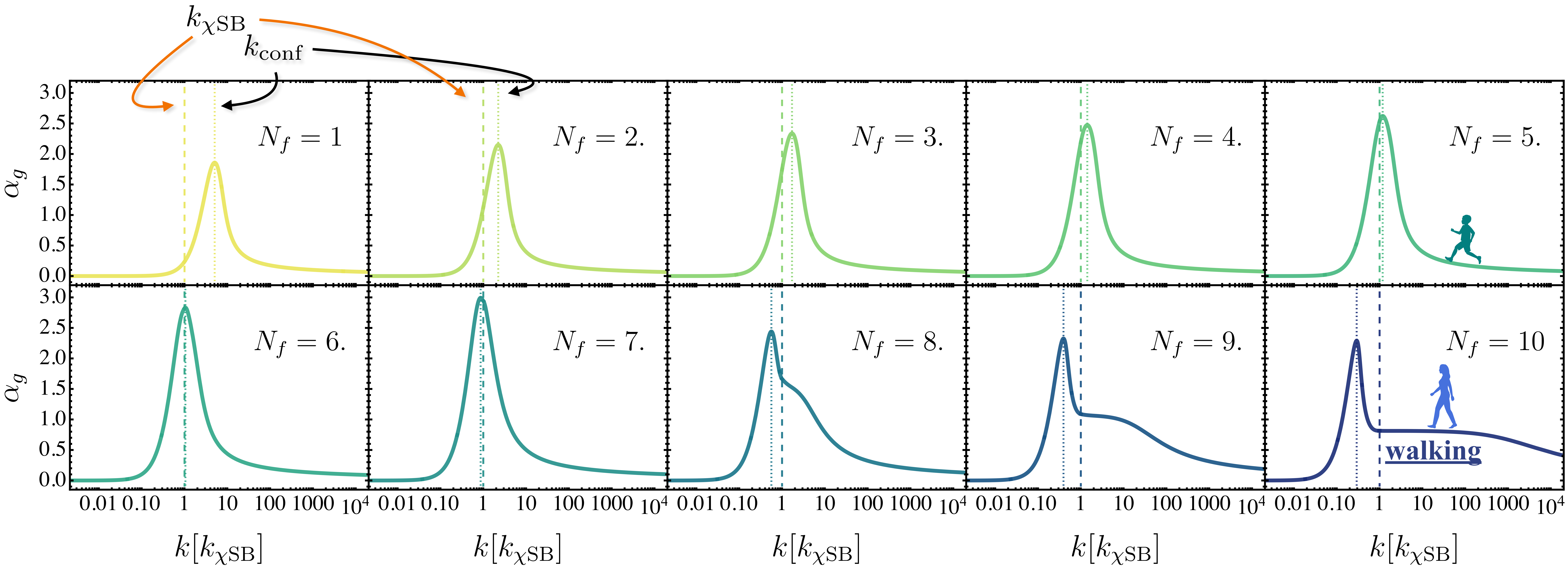




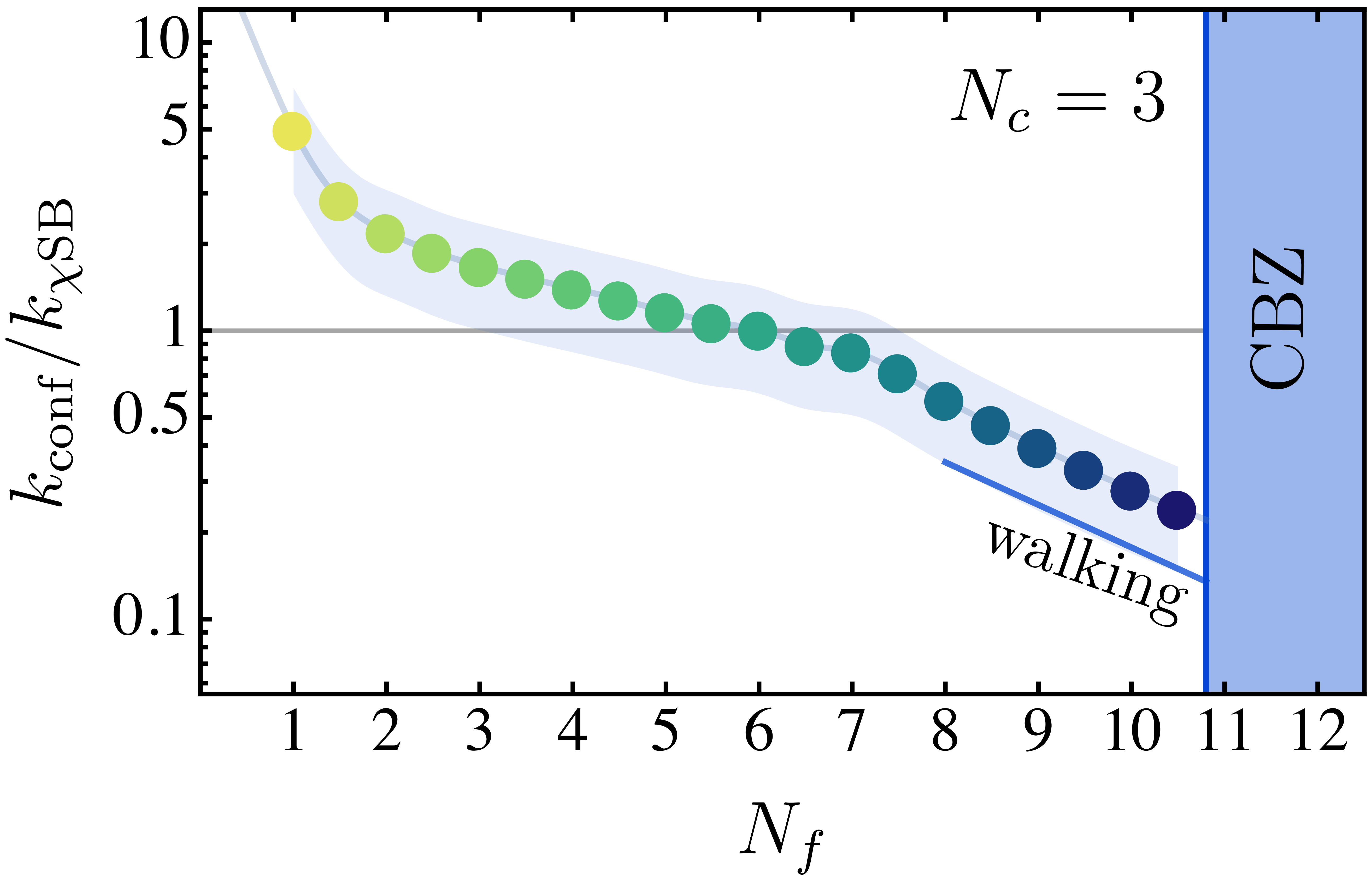
- ✦ Flows computed: $\{h, V(\phi), Z_\psi, Z_\phi, \lambda_i\}$
- ✦ **Continuous** interpolation between chirally **symmetric** and **broken** regimes
- ✦ A **clear** and **precise** way to **diagnose** χ**SB**

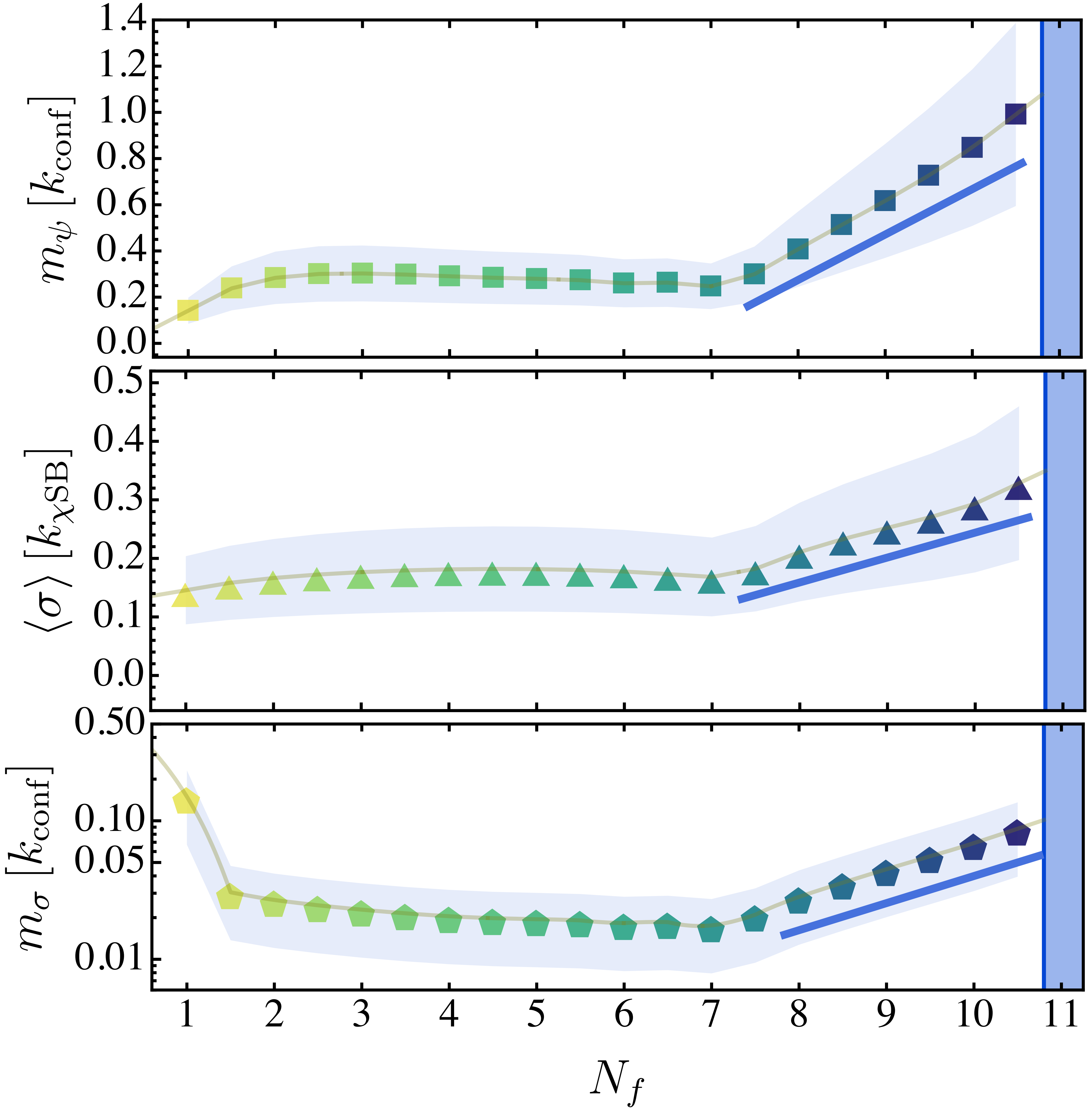
- ✦ Obtaining **fundamental parameters**
  - Constituent fermion masses: m_ψ (within 10% error)
  - Chiral condensate: $\langle\sigma\rangle \sim f_\pi$
  - Composite masses of bosonised channels: m_σ, m_π
- ✦ Account for **higher dimensional fermionic** operators via higher-order scalar potential

Many flavour dynamics

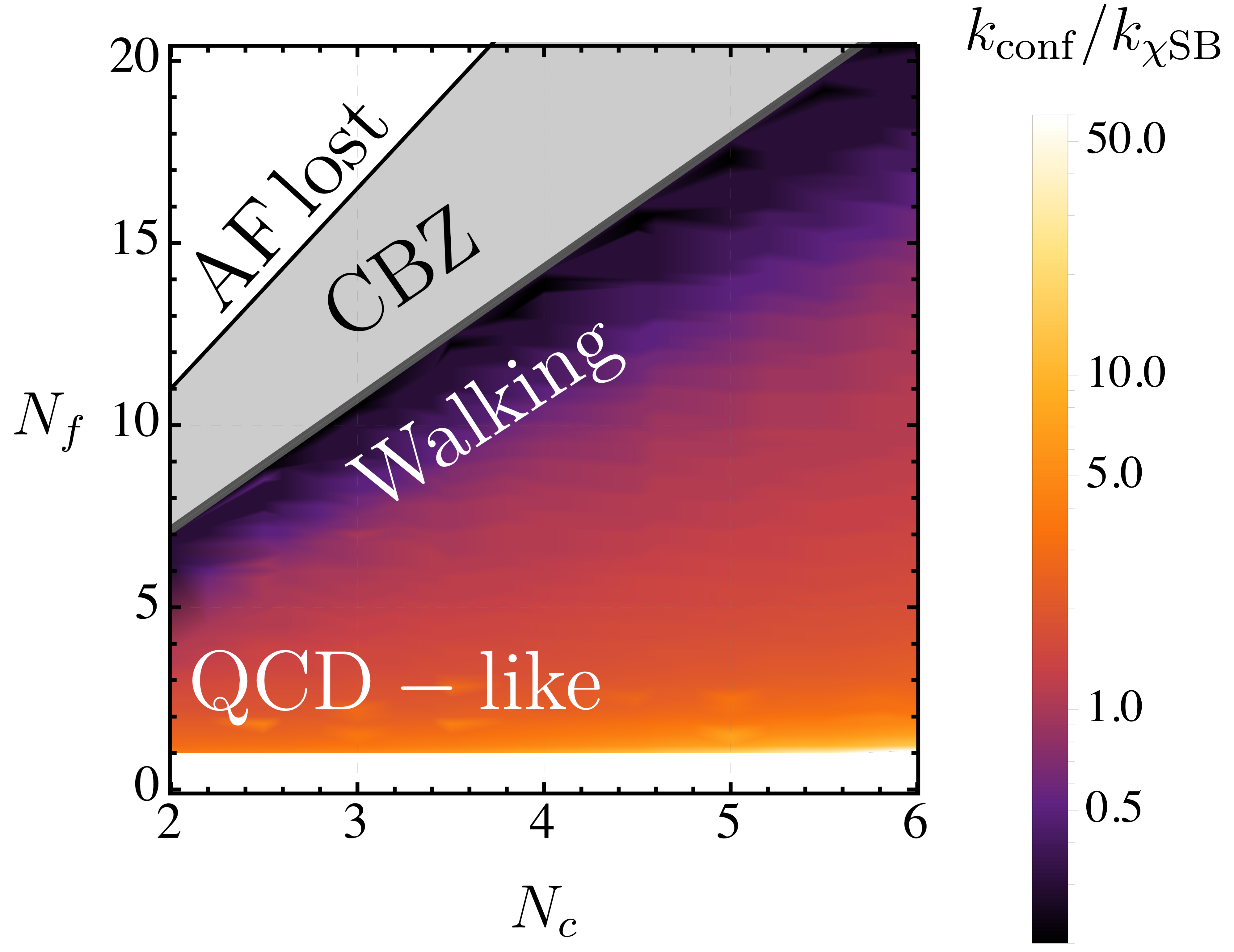


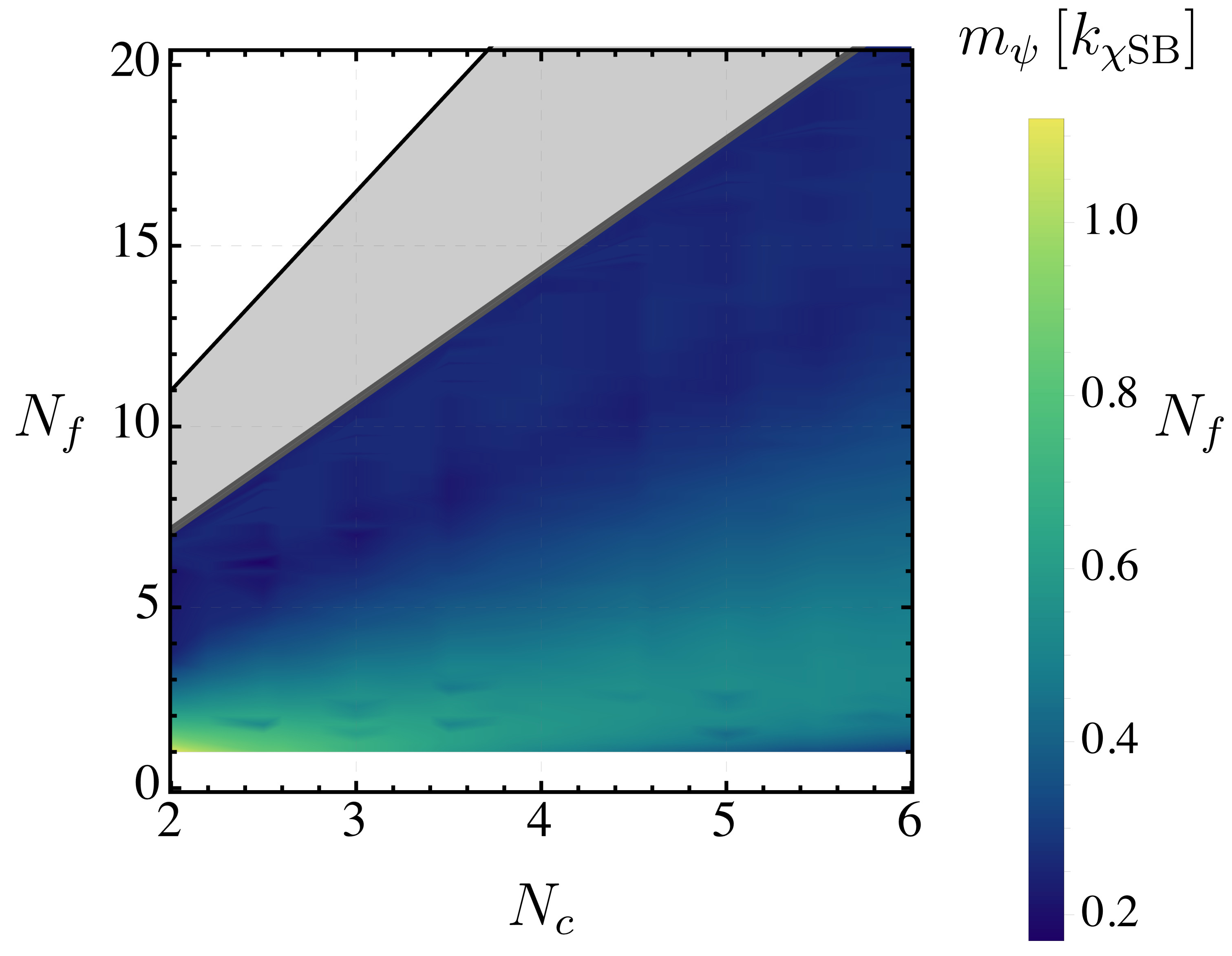
Interplay of scales and fundamental parameters

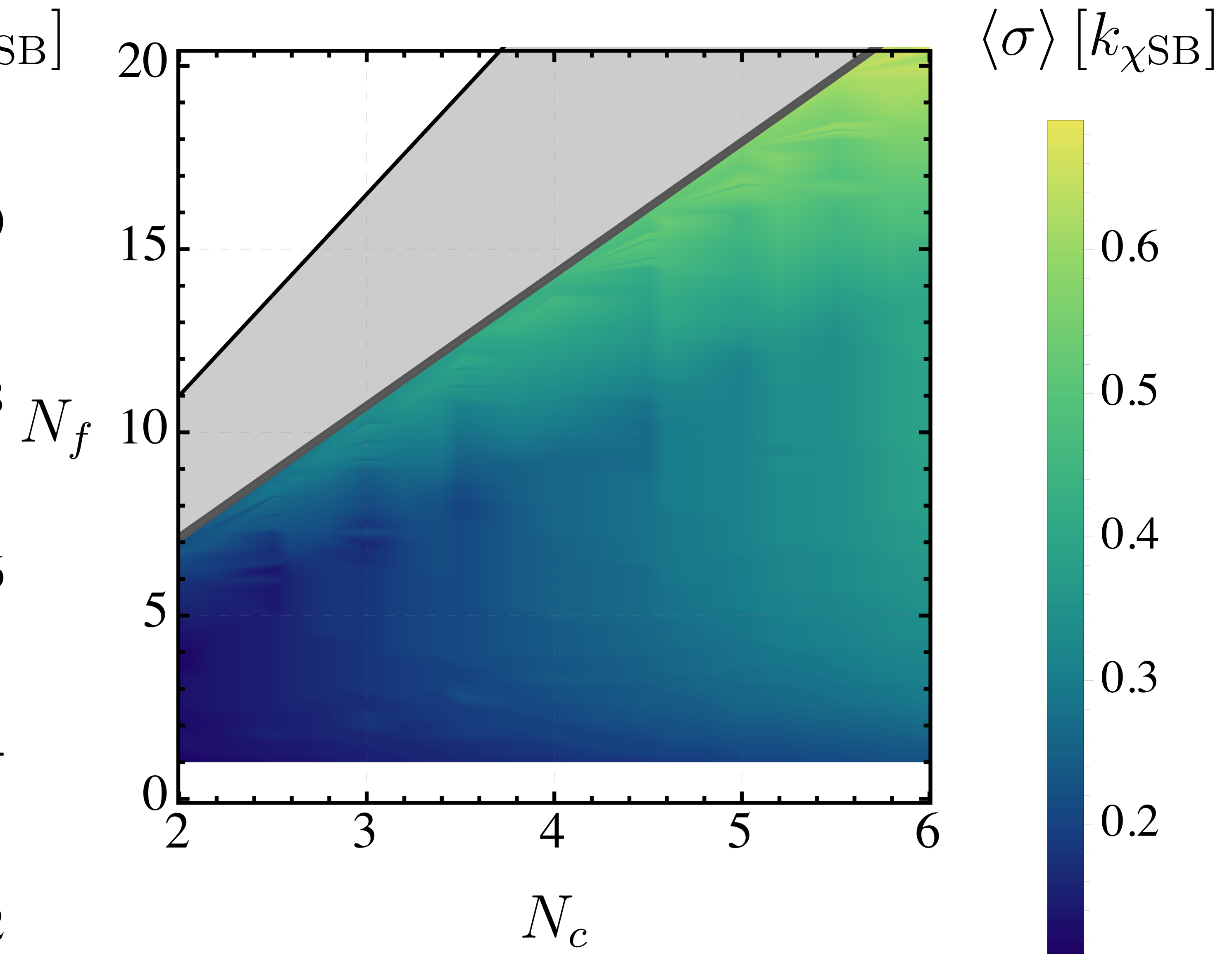


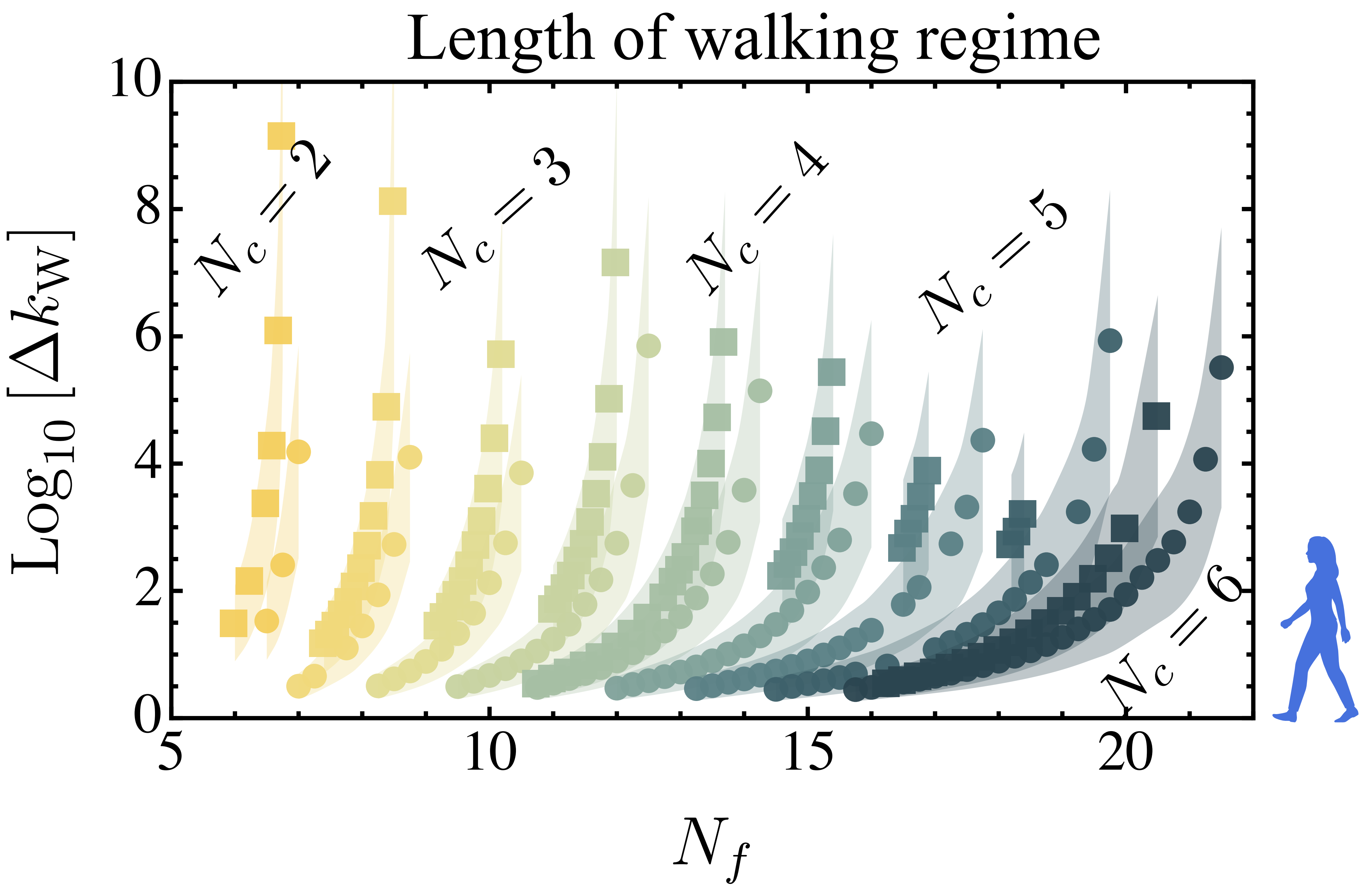


Cartography and walking distance





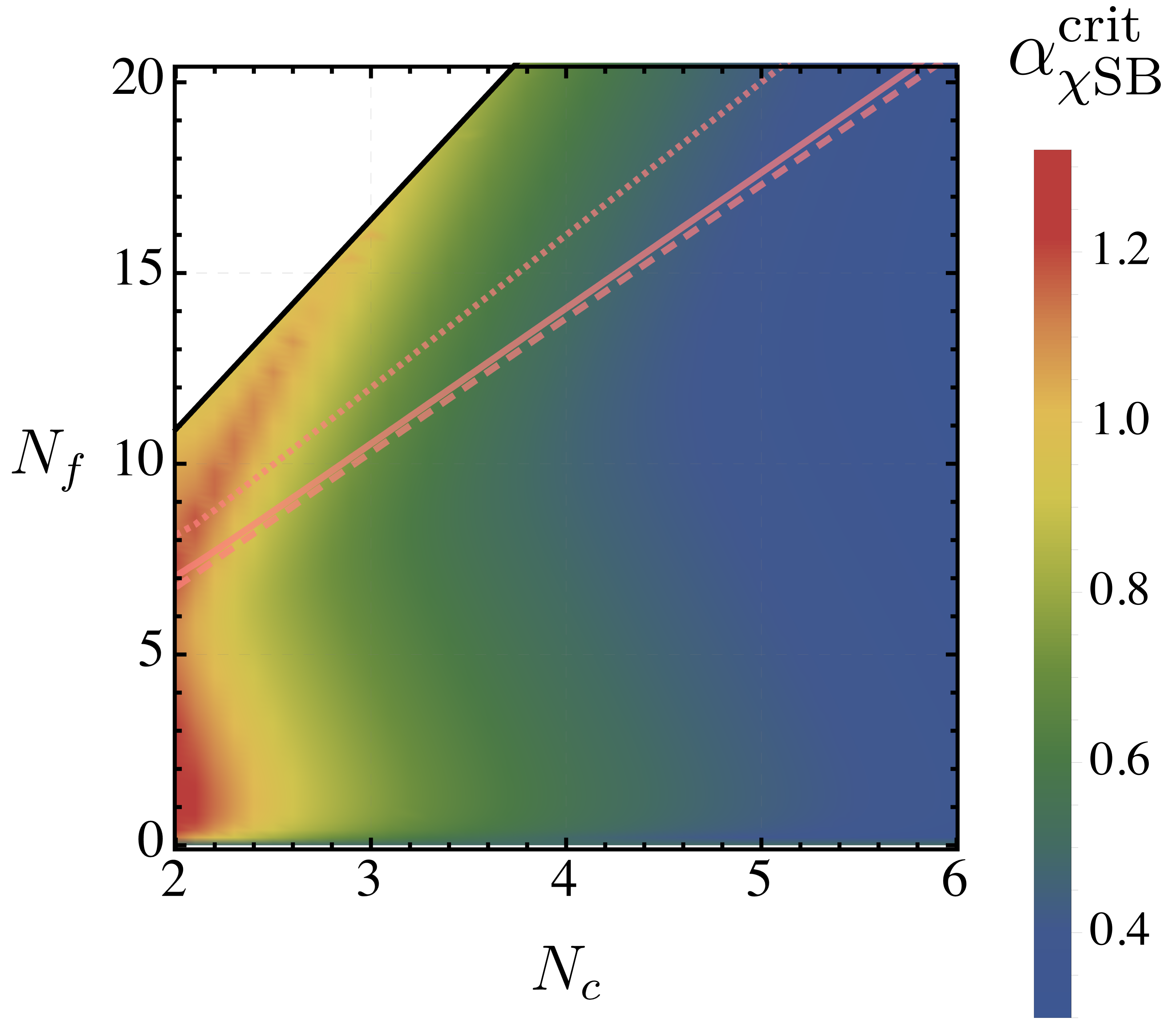


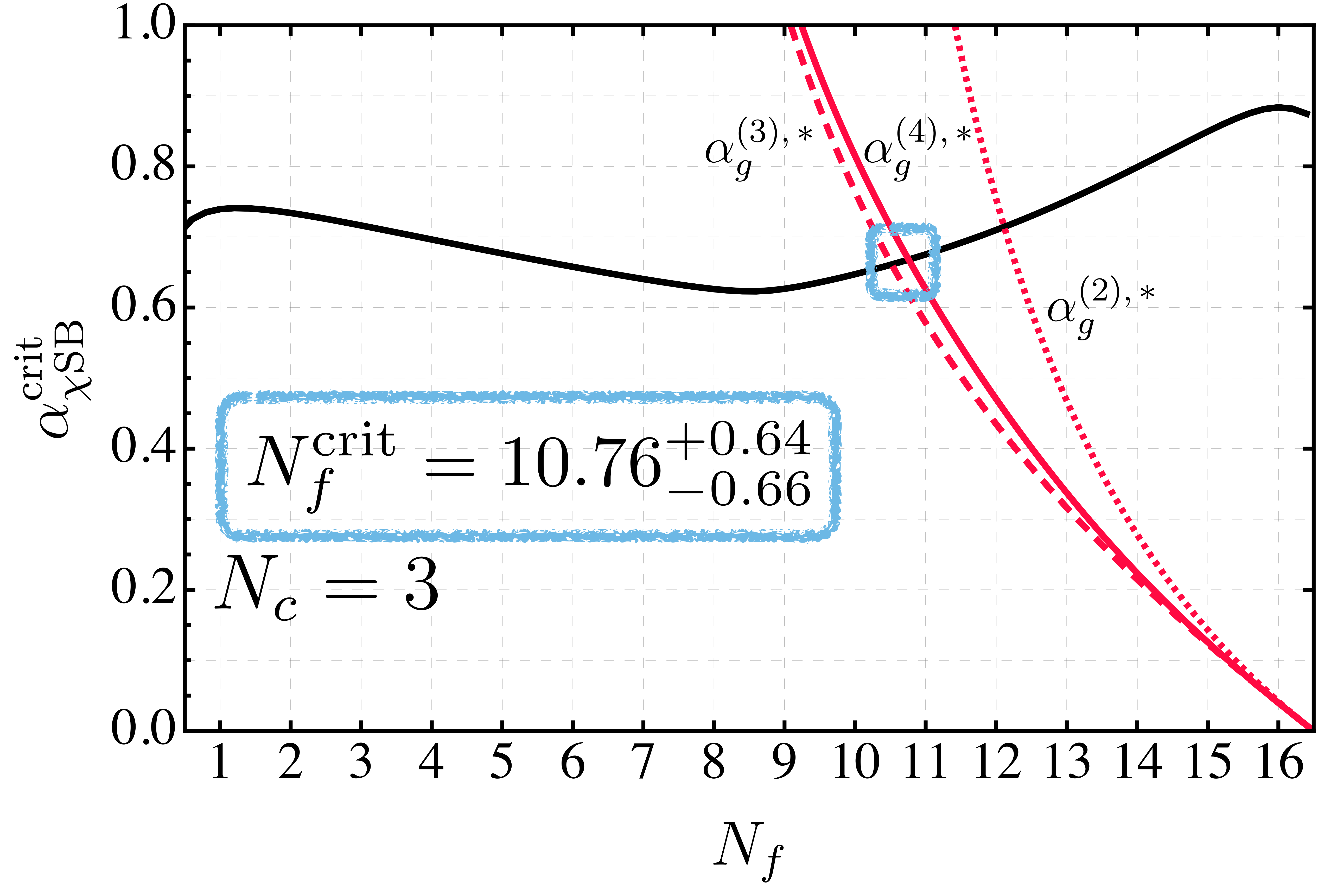


Boundary of the conformal window

$\alpha_{\chi\mathrm{SB}}^{\mathrm{crit}}$: Critical strength of **gauge dynamics** necessary to trigger dynamically χSB

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



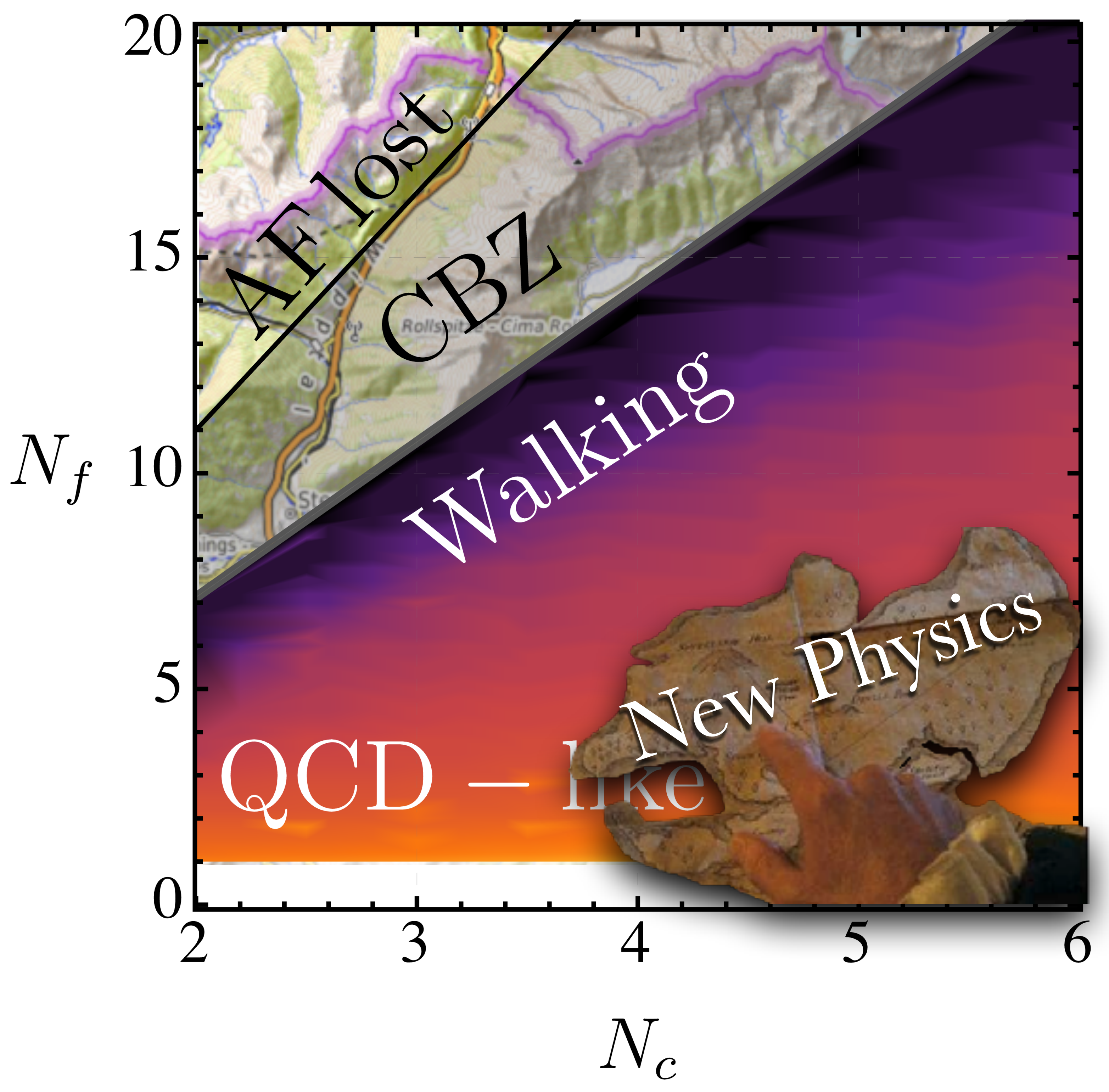


Summary and conclusions

✦ **Comprehensive first-principles study** of the **landscape of gauge-fermion theories**:

- *"Easy"* new **treatment** of **confinement**
- Determination of **fundamental parameters**:
  ➡ m_ψ , $\langle\sigma\rangle$, m_σ , <u>size of walking regime</u>, …
- **Lower boundary** of the **CBZ window** $N_f^{\rm crit} = 10.76^{+0.64}_{-0.66}$
- Flow over Effective Field Theories
- Scalings of strongly coupled CFTs

} ask me!



Thank you for your attention!