

Conformality, Confinement and Chiral Symmetry Breaking



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Universität Heidelberg & ExtreMe Matter Institute

Cairns, August 22nd 2024



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Based on

Conformality, Confinement & Chiral Symmetry Breaking

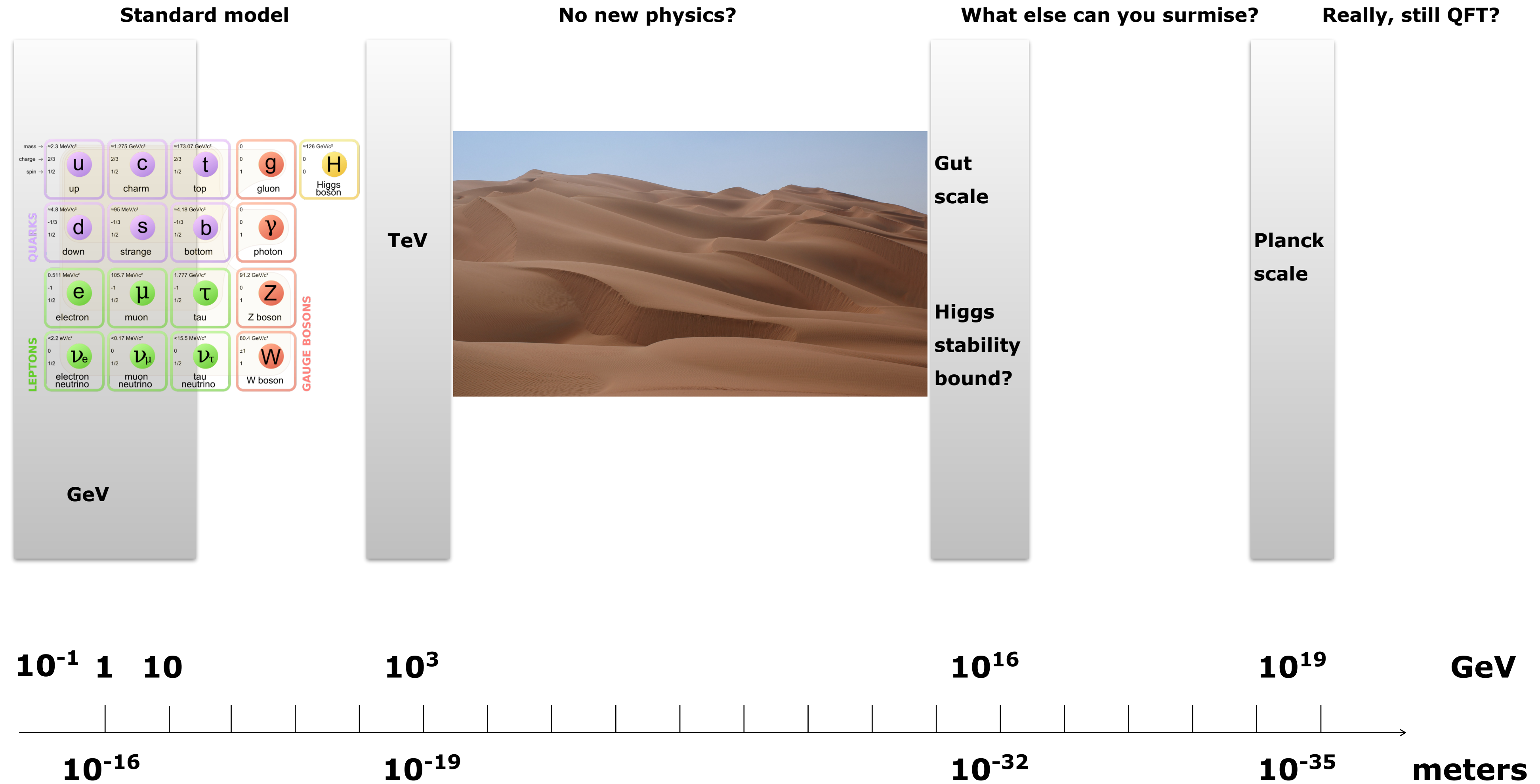
Florian Goertz, *Álvaro Pastor-Gutiérrez*, JMP, in preparation



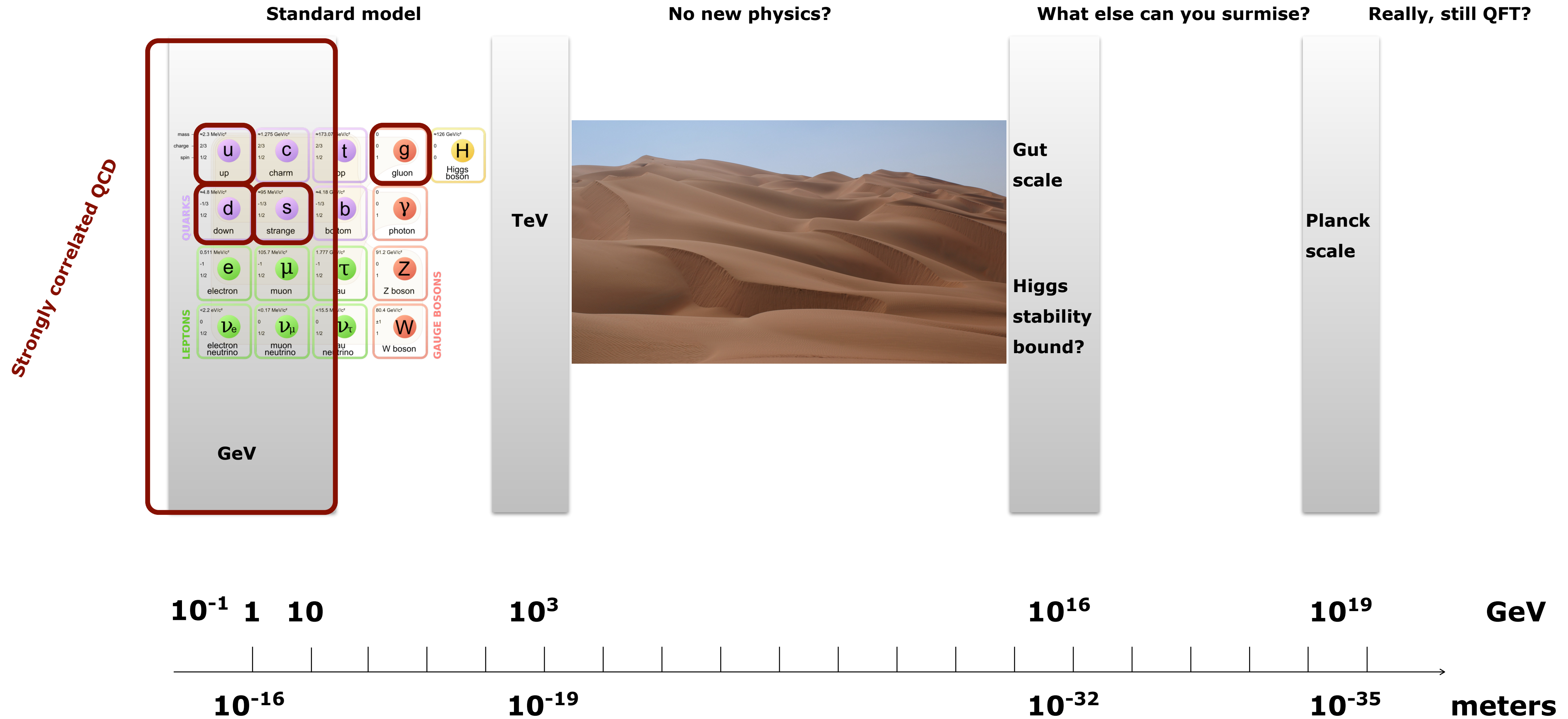
High energy physics in a nutshell

'Never underestimate the joy people derive from hearing something they already know'

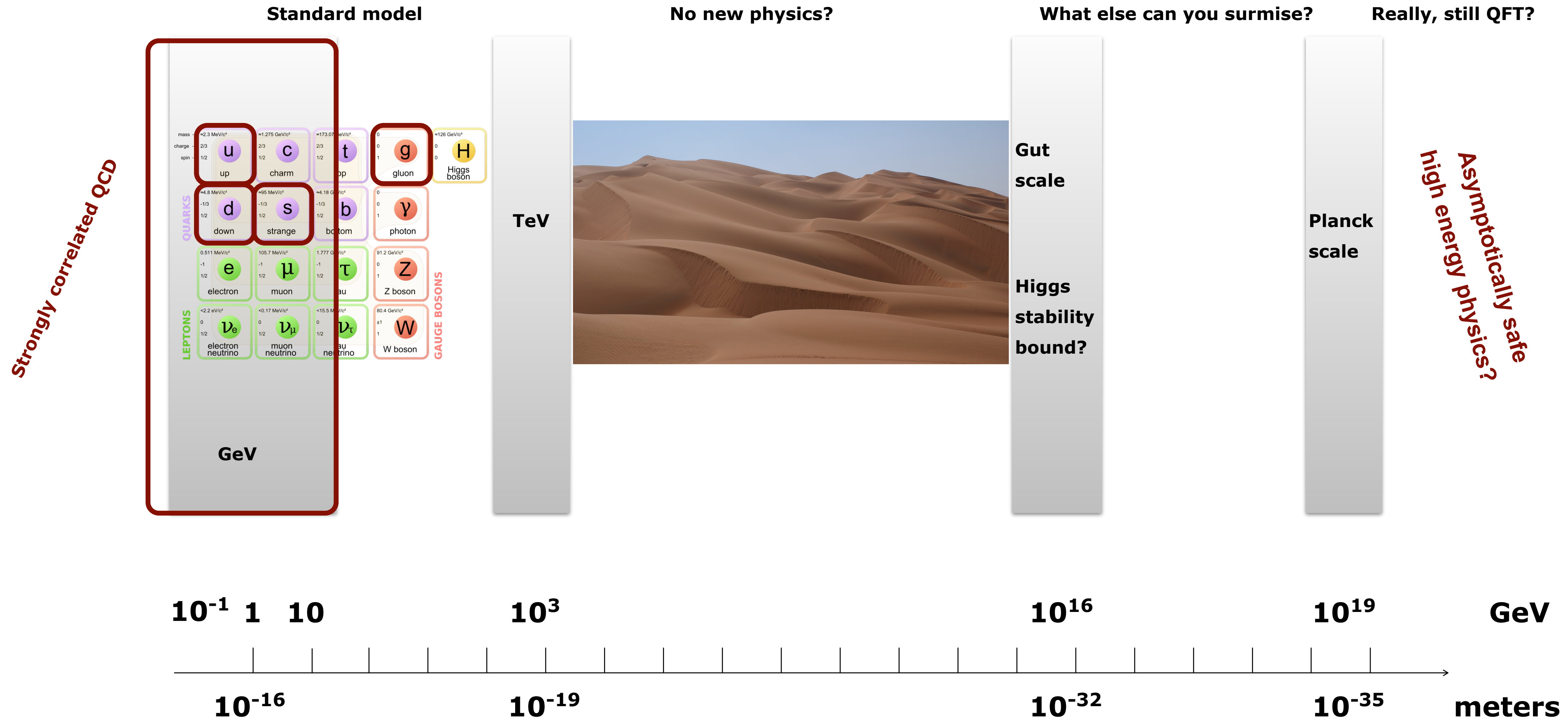
attributed to Fermi



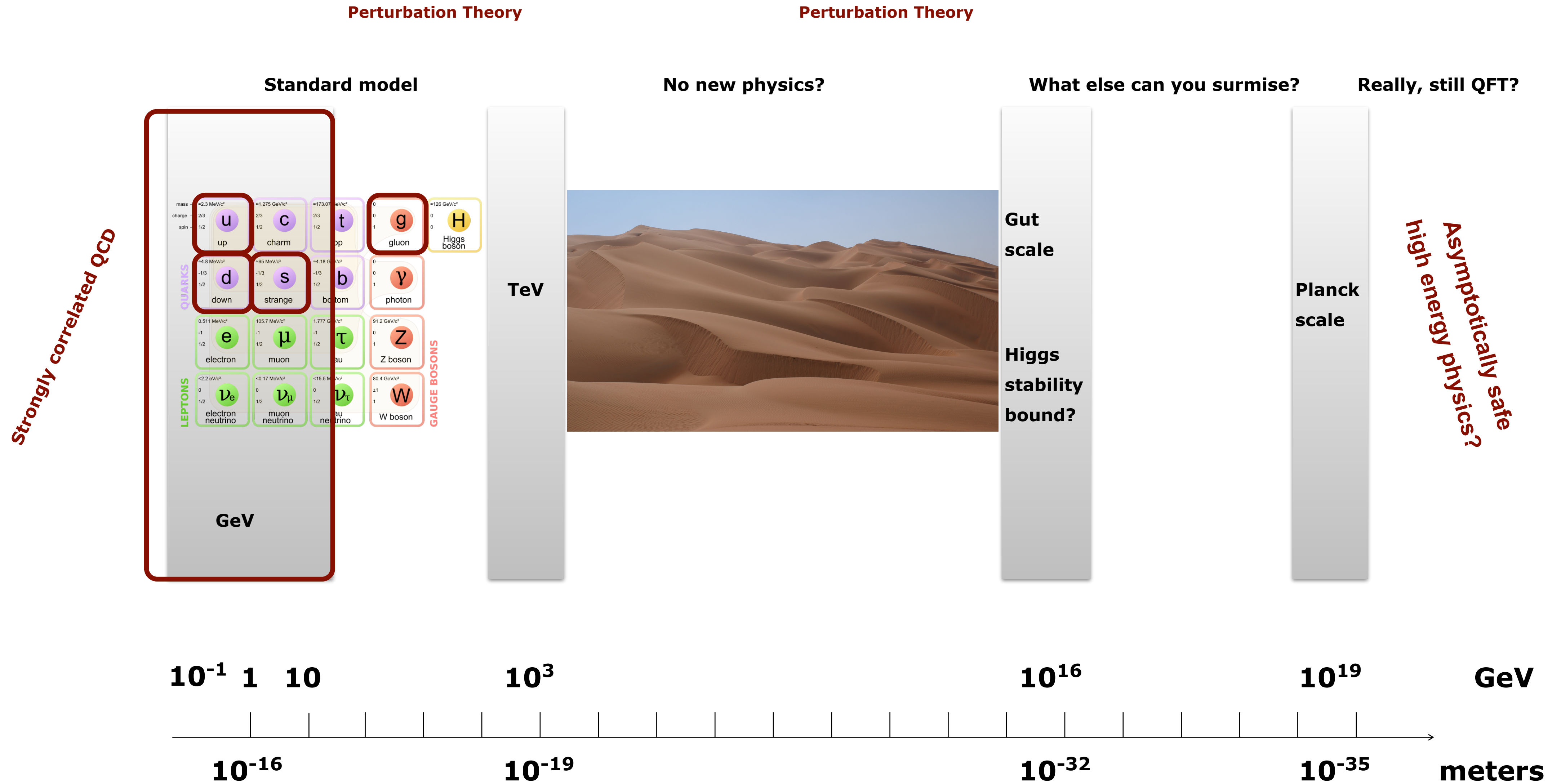
High energy physics in a nutshell



High energy physics in a nutshell

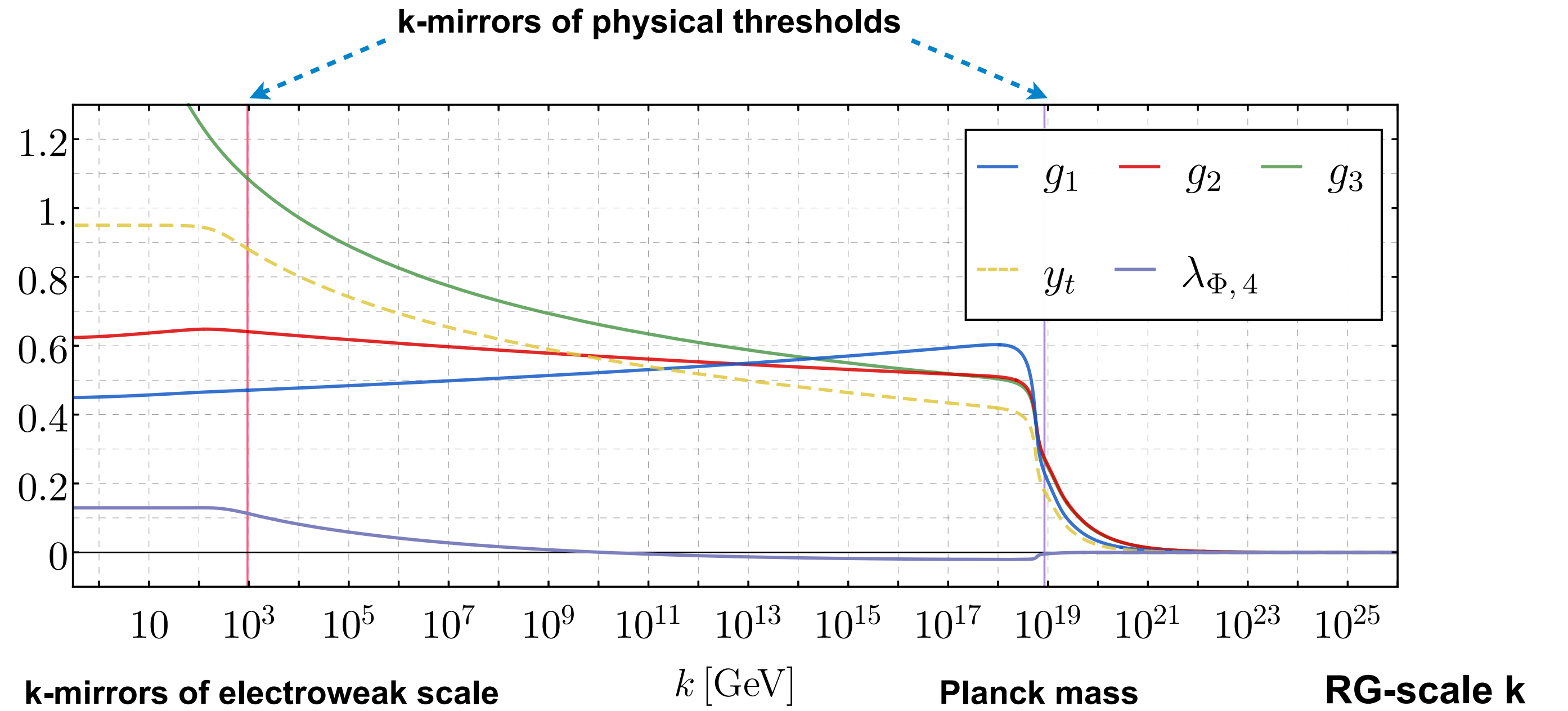
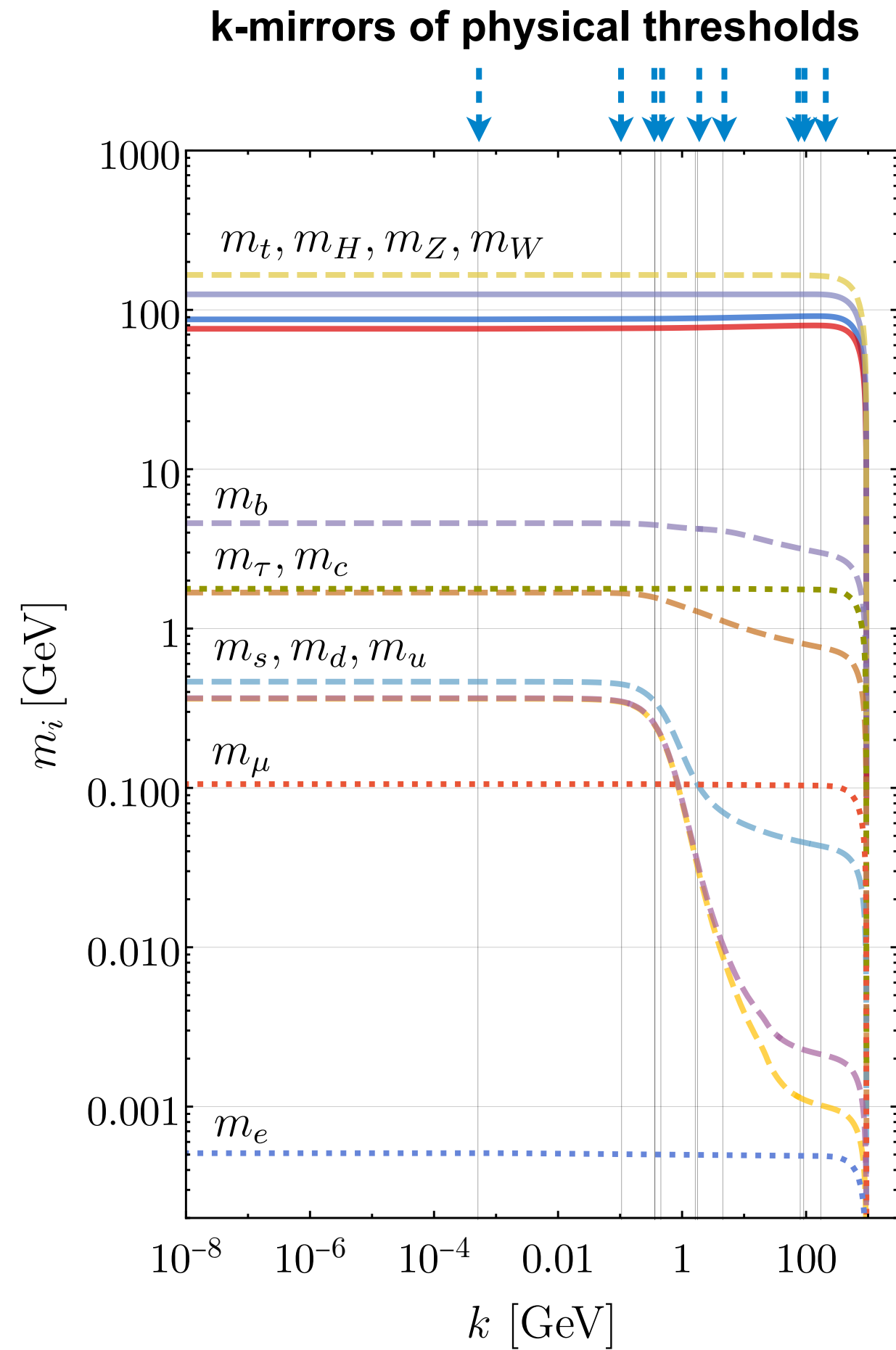


High energy physics in a nutshell



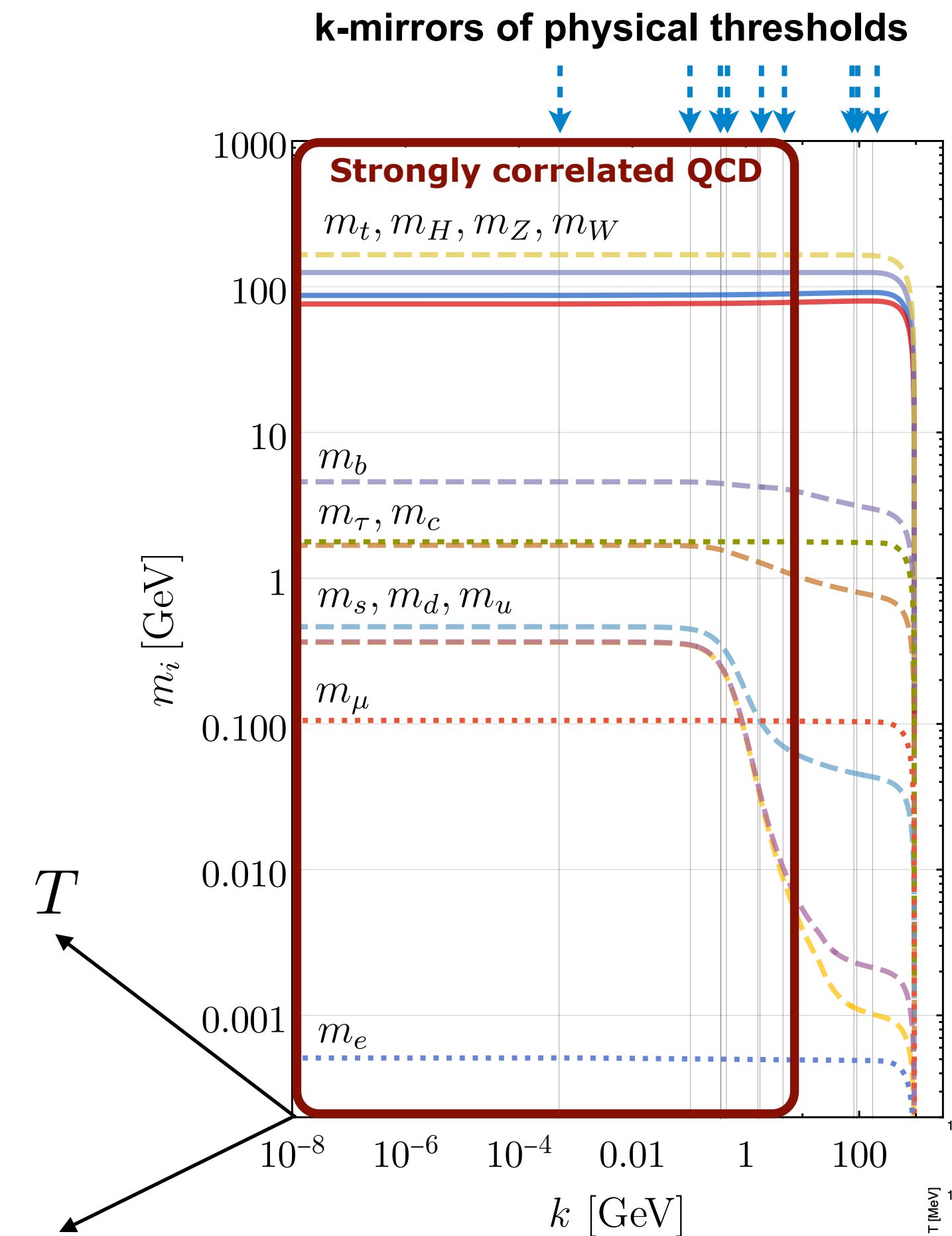
The physics of thresholds

Example: asymptotically safe Standard Model



The physics of thresholds

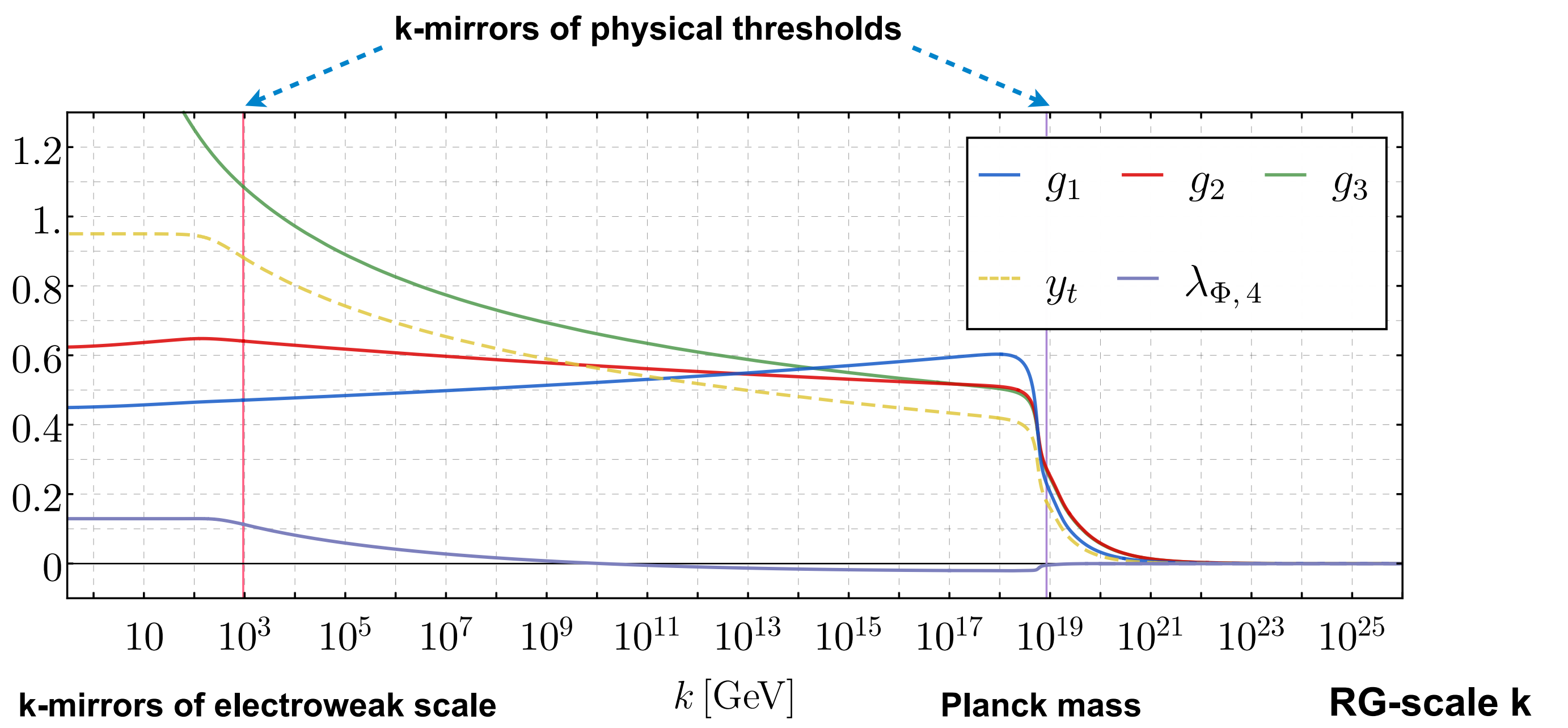
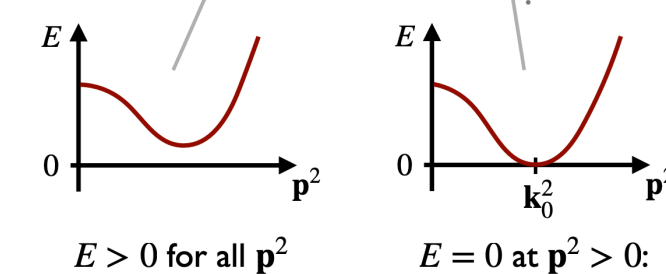
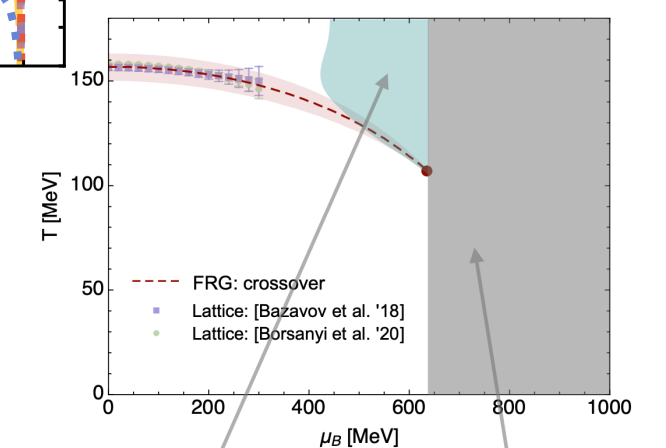
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T

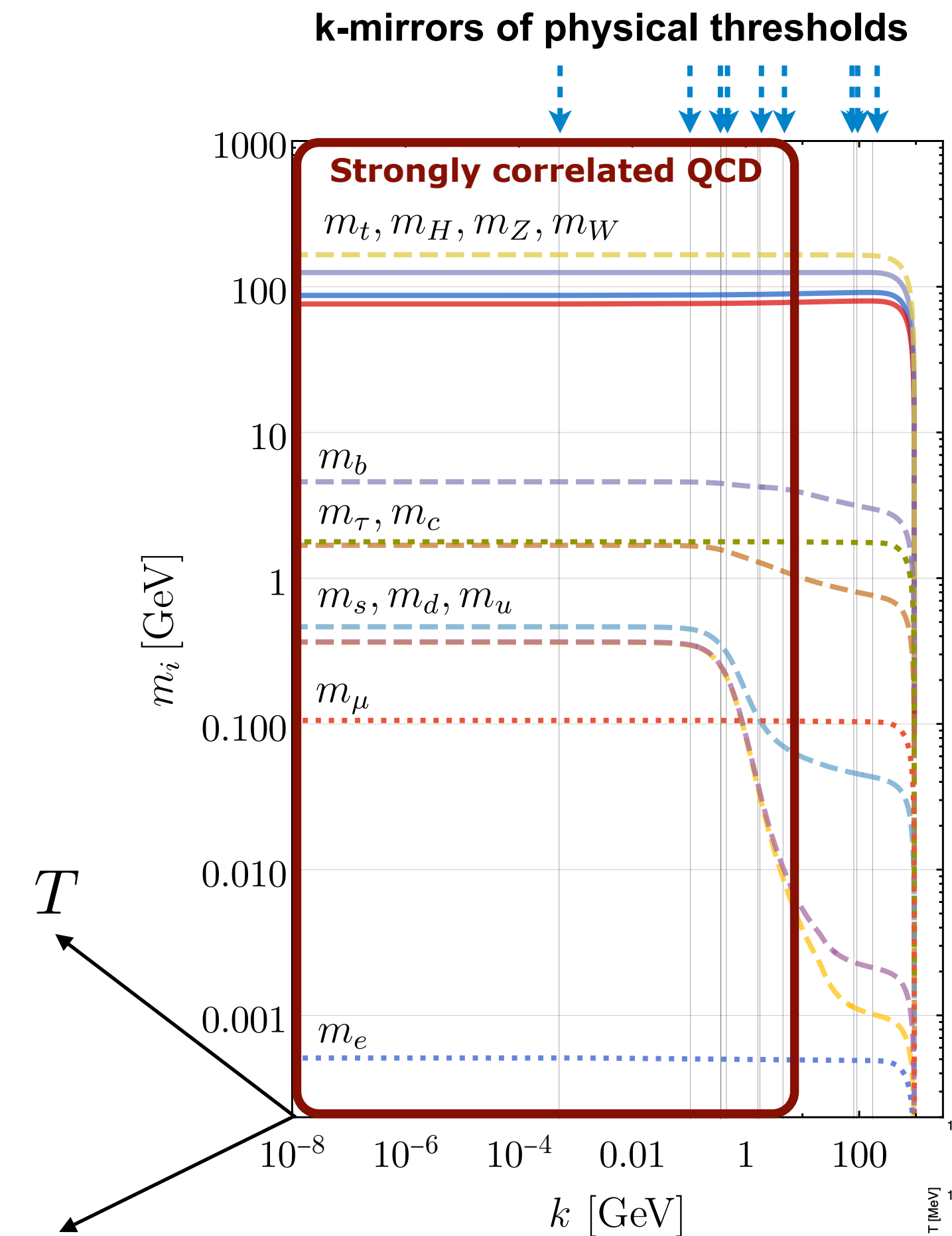
μ_B

see plenary talk of F. Rennecke (Monday)



The physics of thresholds

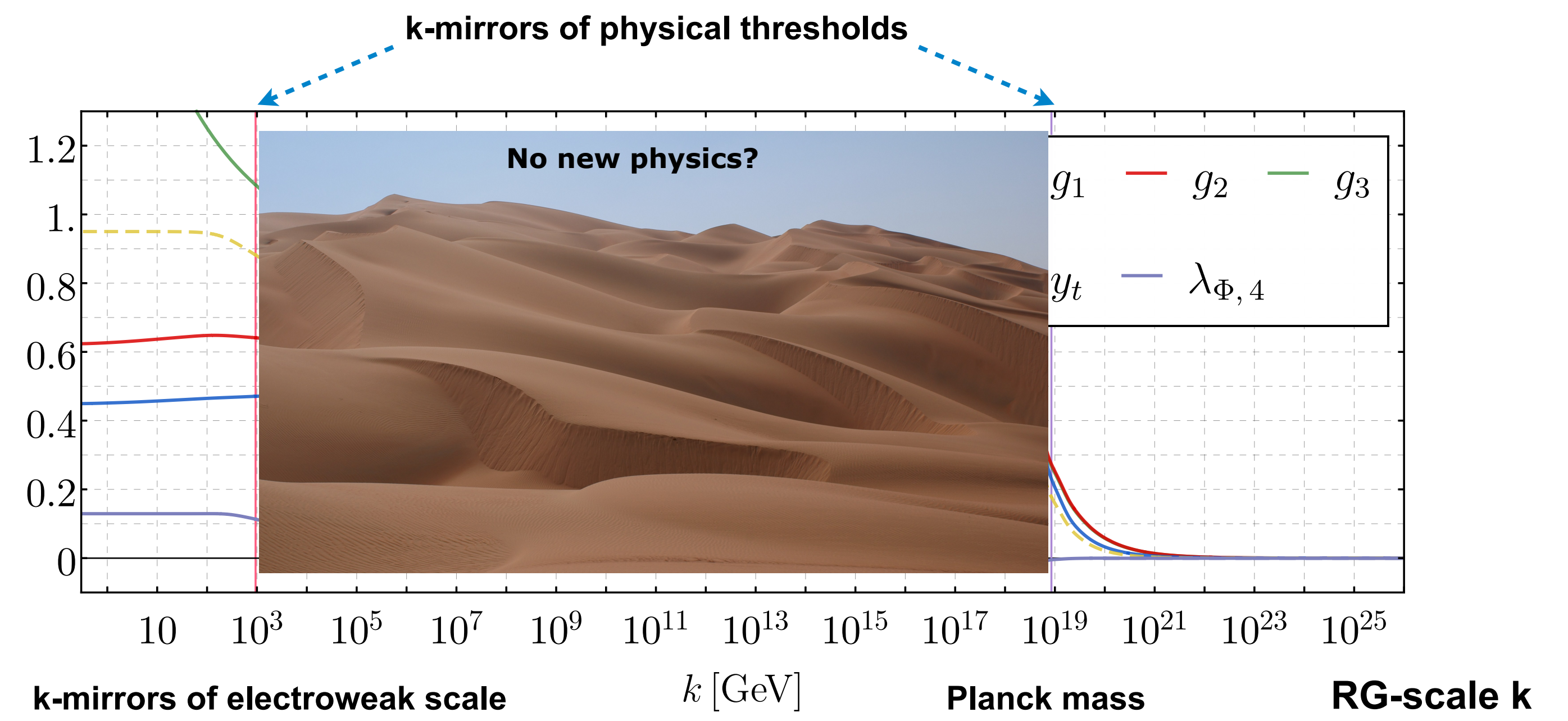
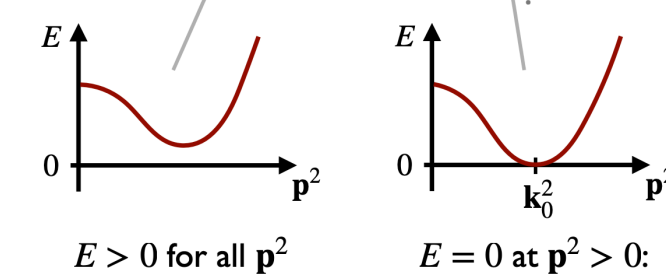
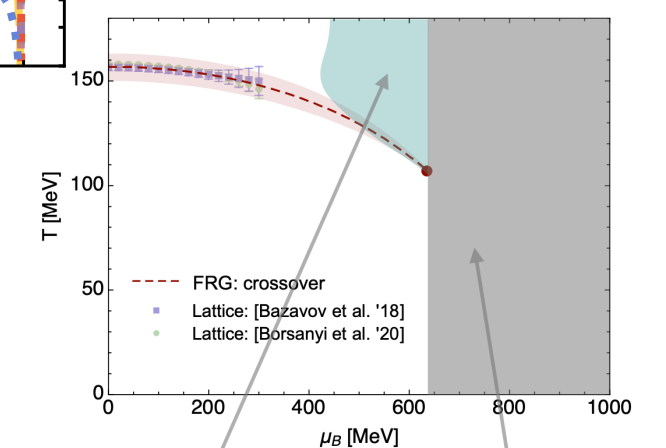
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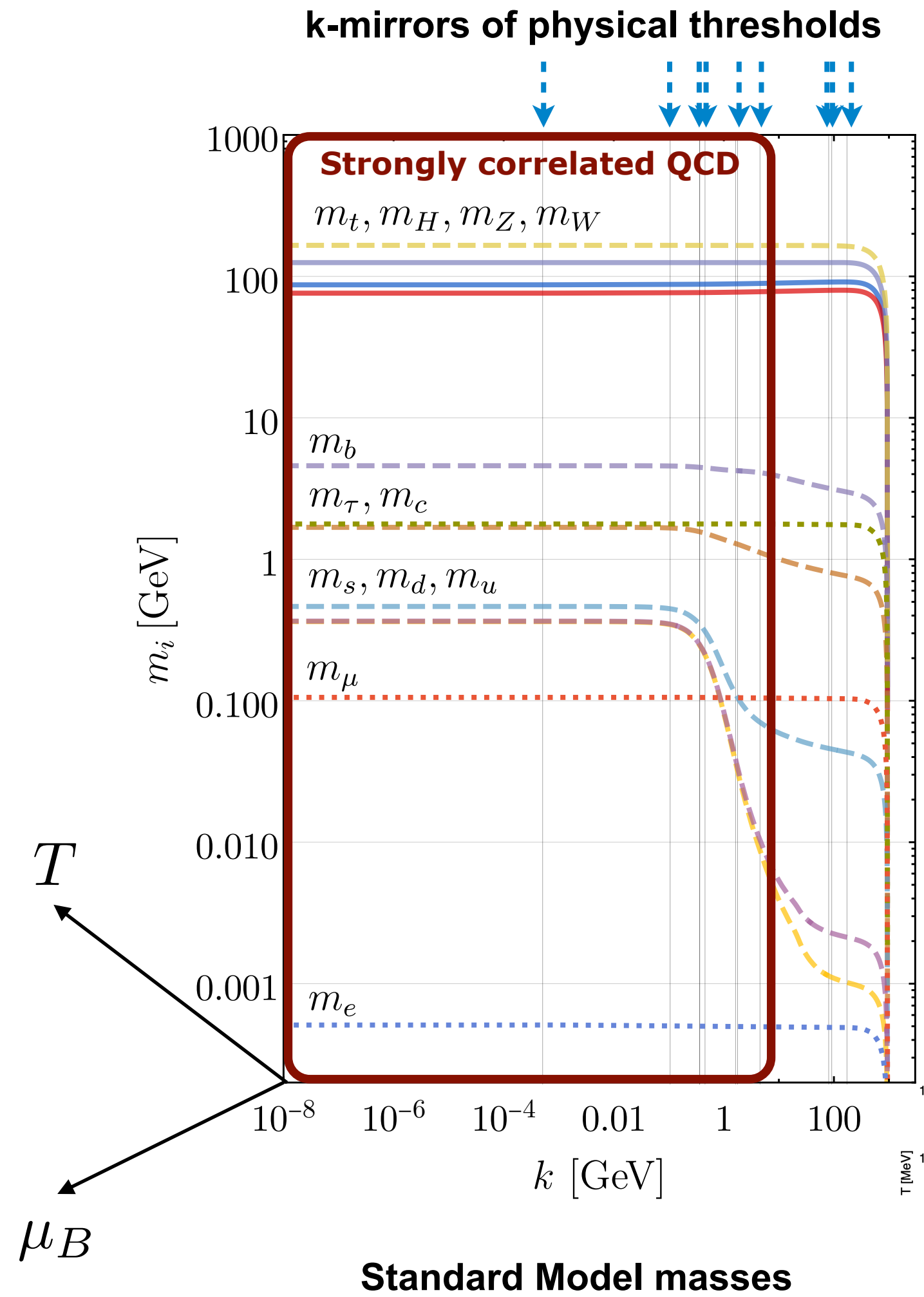
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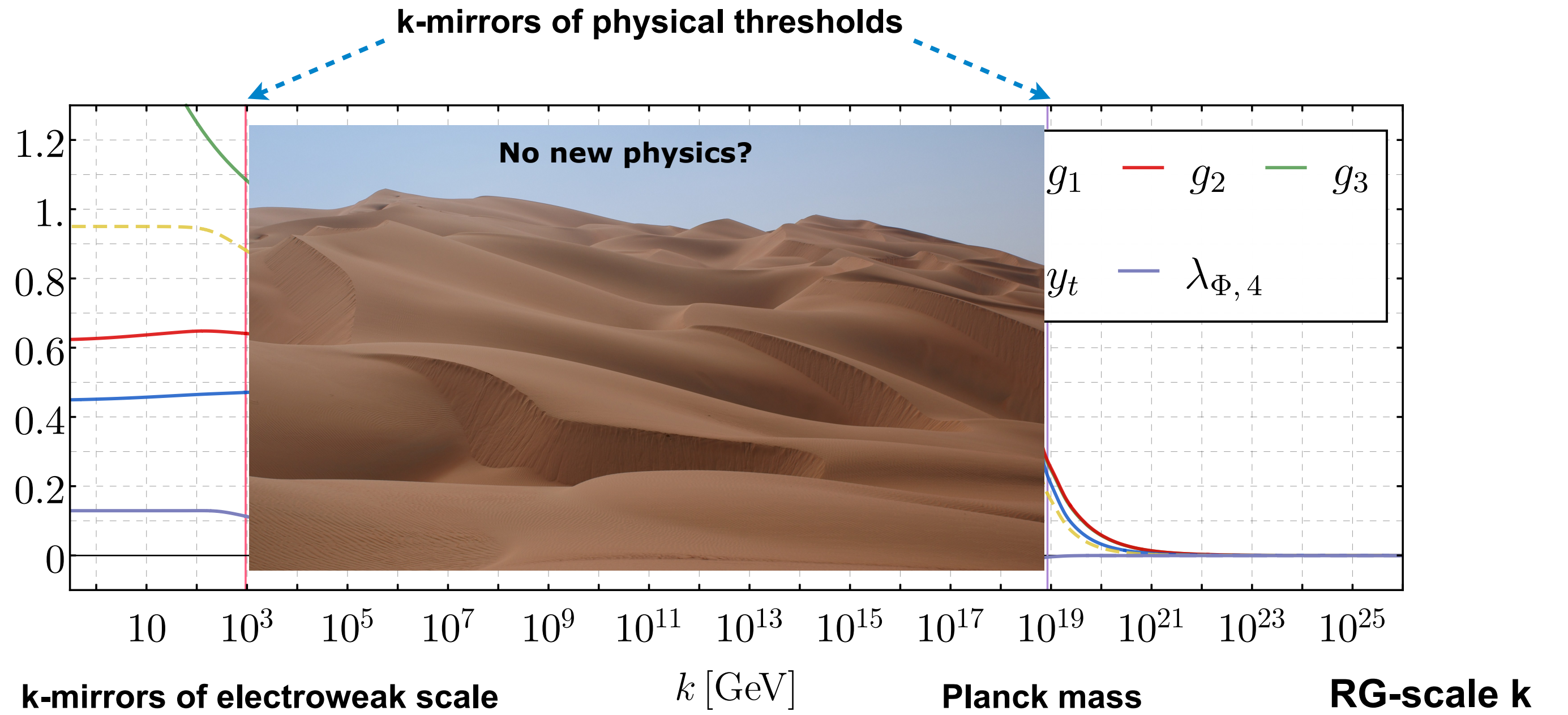
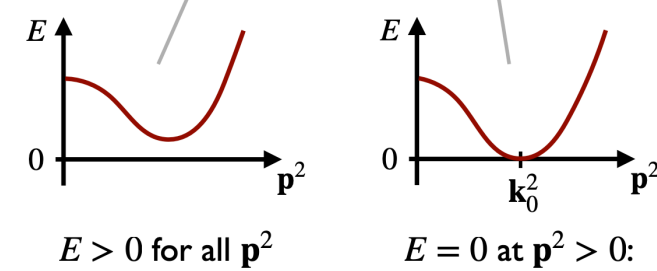
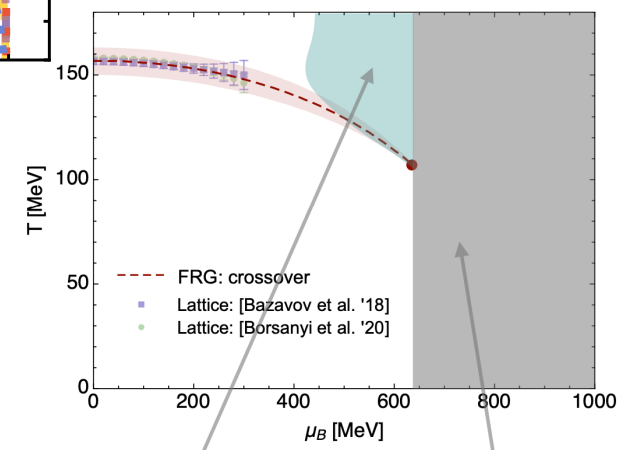


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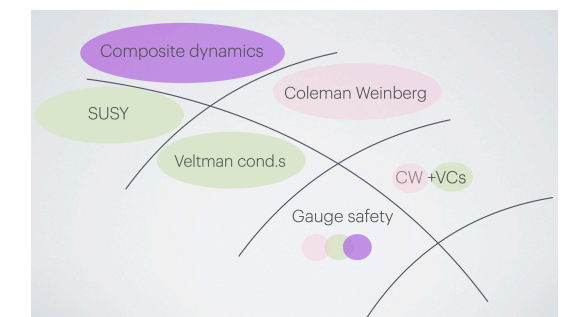
New physics in the desert?

Composite Higgs

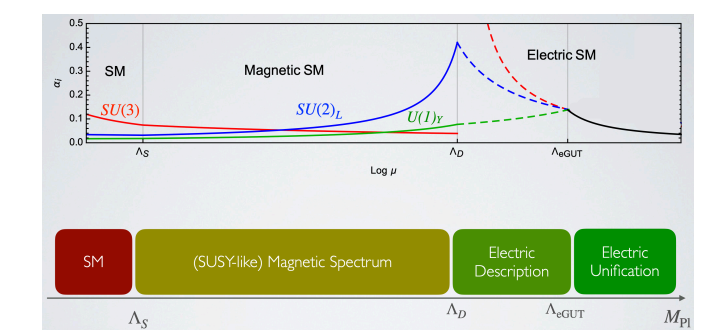
Strongly correlated gauge theories

Conformal, walking regimes

⋮




see plenary of talk F. Sannino (Monday)



Phase structure of many flavour QCD

Two-loop beta-function

$$\beta_g = -\frac{g^3}{(4\pi)^2} \left(\frac{11}{3} C_A - \frac{4}{3} T_F N_f \right) - \frac{g^5}{(4\pi)^4} \left(\frac{34}{3} C_A - 4 C_F T_F N_f - \frac{20}{3} C_A T_F N_f \right) + \dots$$


Casimirs Dynkin index

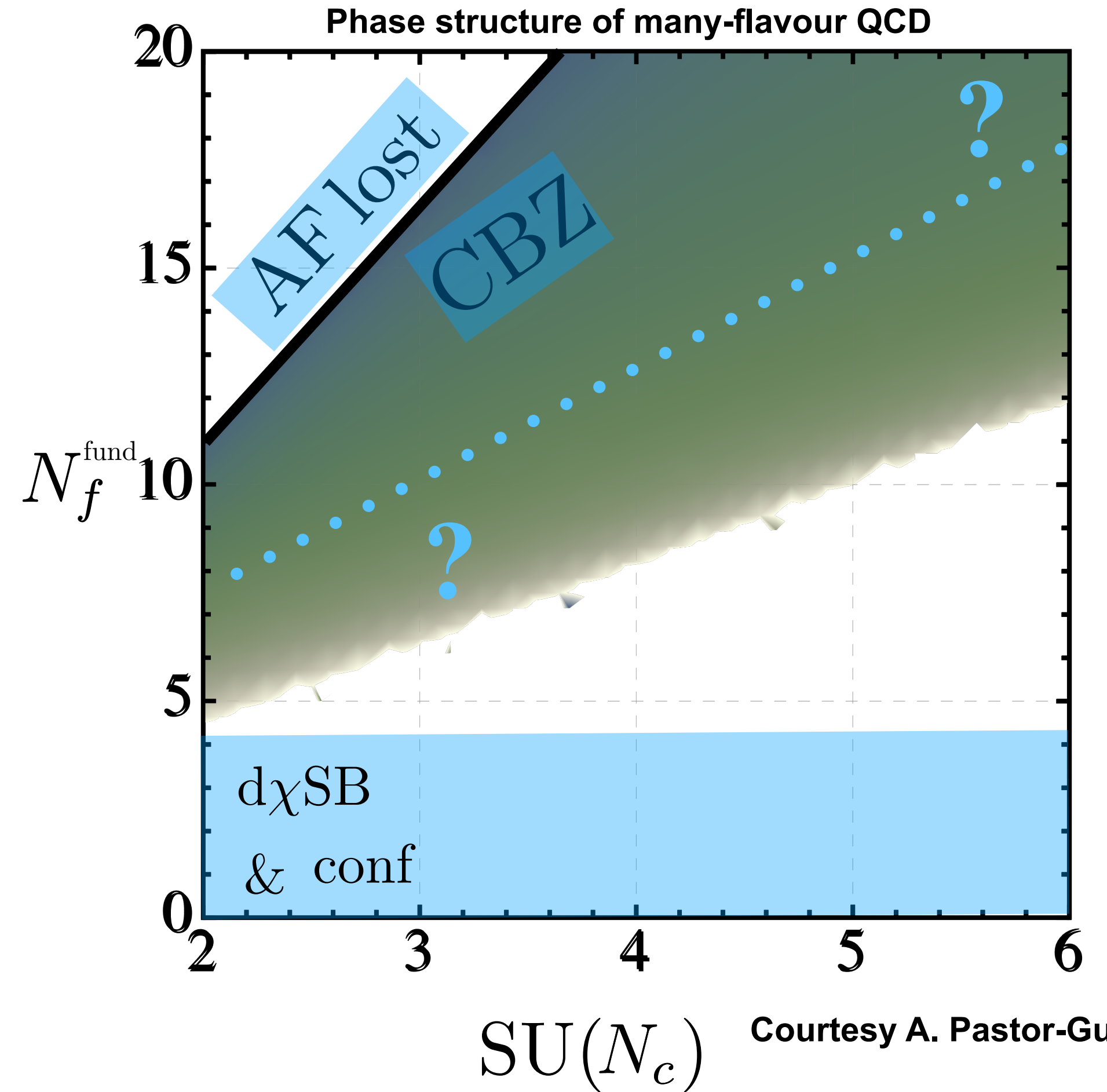
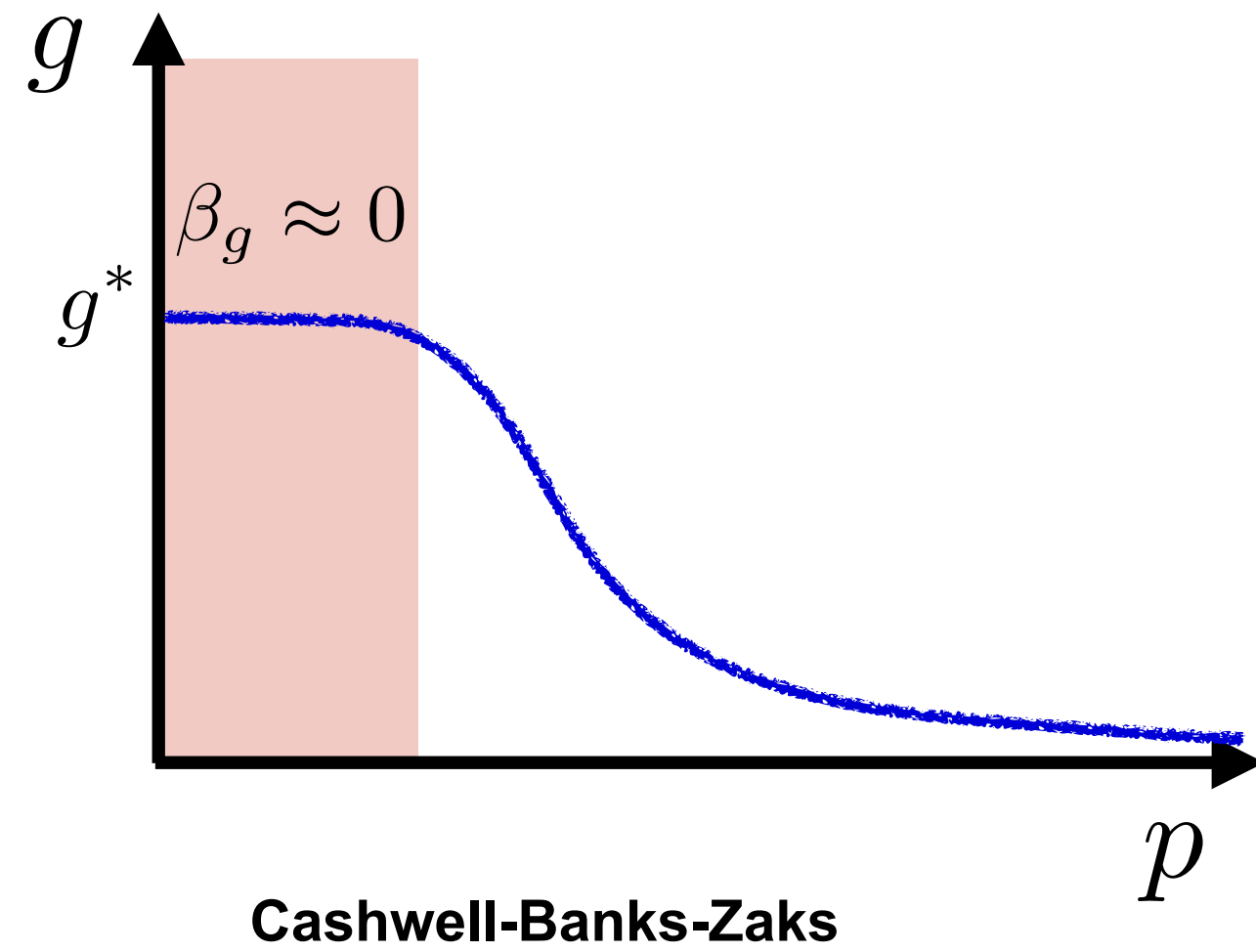
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Casimirs

Dynkin index



Courtesy A. Pastor-Gutierrez

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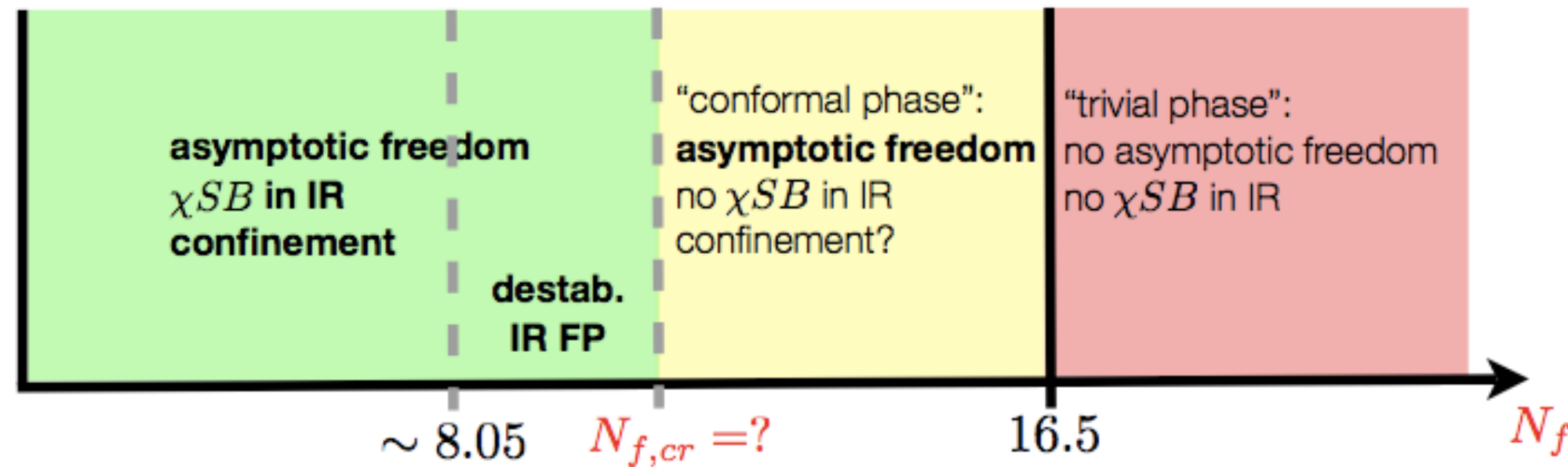
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Casimirs

Dynkin index

Many-flavour QCD with the functional RG



~ 8.05

$N_{f,cr} = ?$

16.5

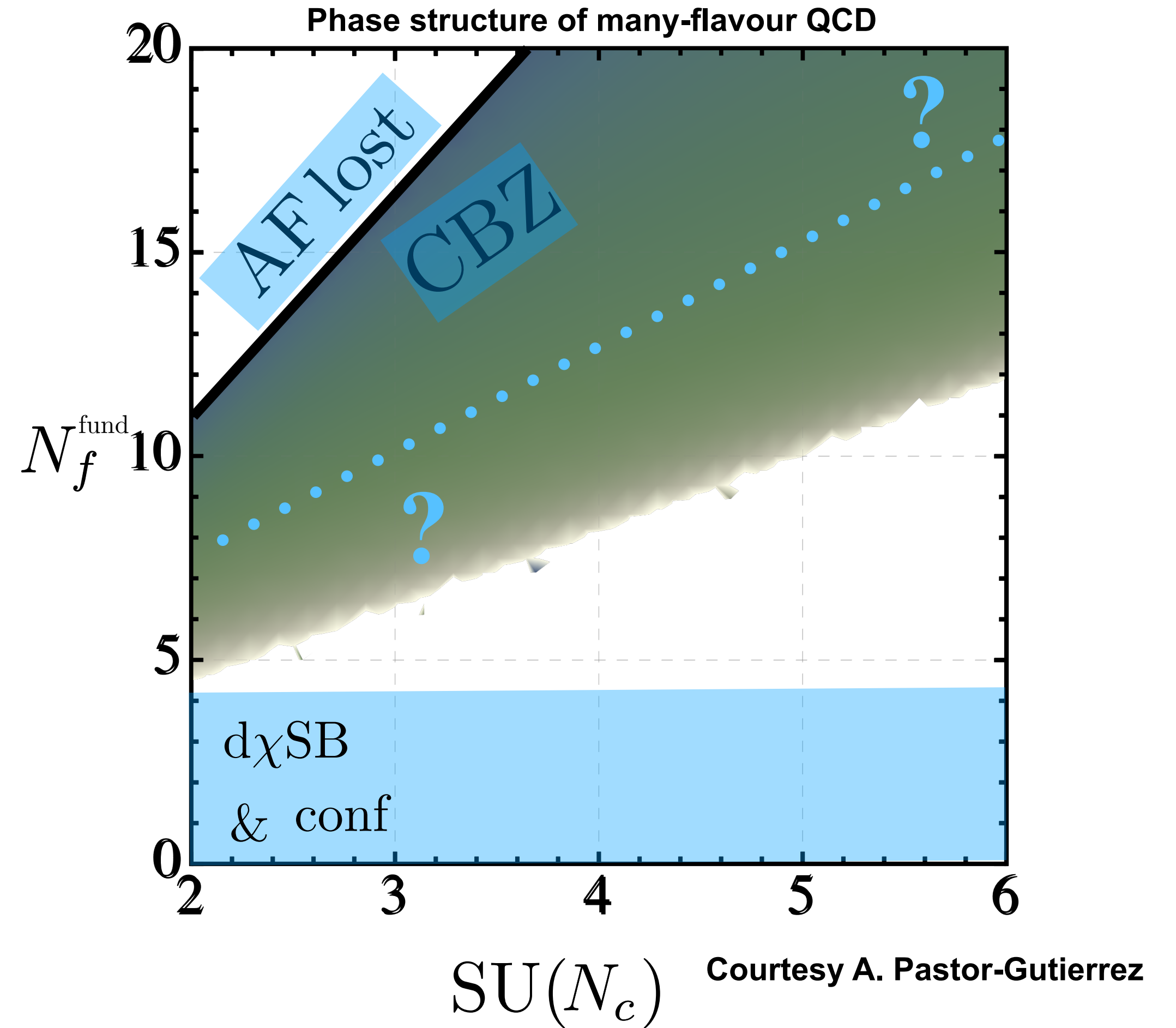
N_f

Non-perturbative infrared
chiral dynamics & confinement

Semi-perturbative
IR beta functions

Perturbative
IR beta functions

fRG schemes converge 'easily'



$SU(N_c)$

Courtesy A. Pastor-Gutierrez

Phase structure of many flavour QCD

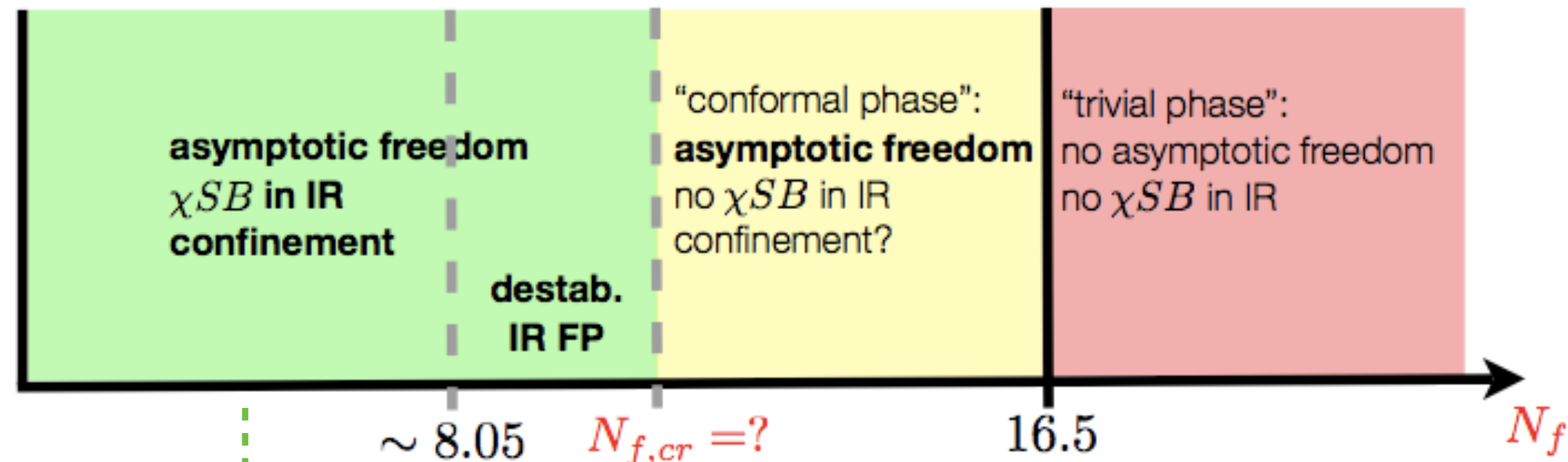
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Casimirs
Dynkin index

Many-flavour QCD with the functional RG

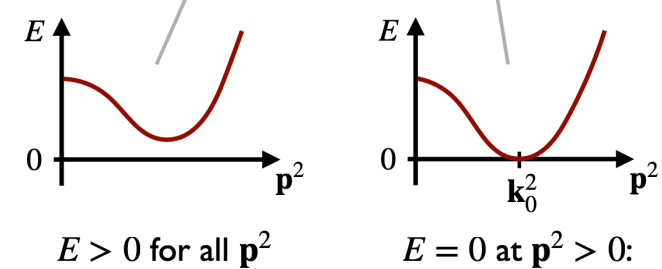
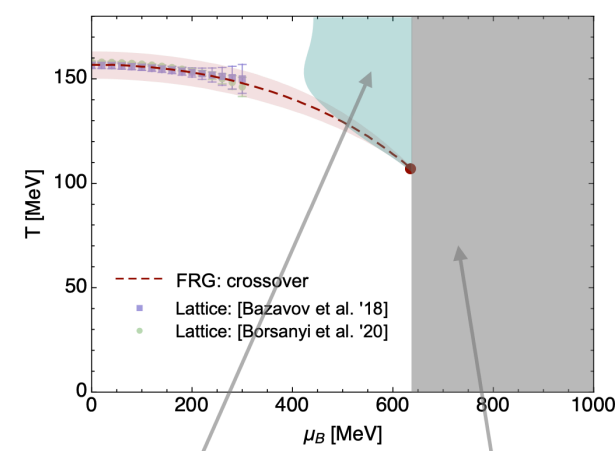


Non-perturbative infrared chiral dynamics & confinement

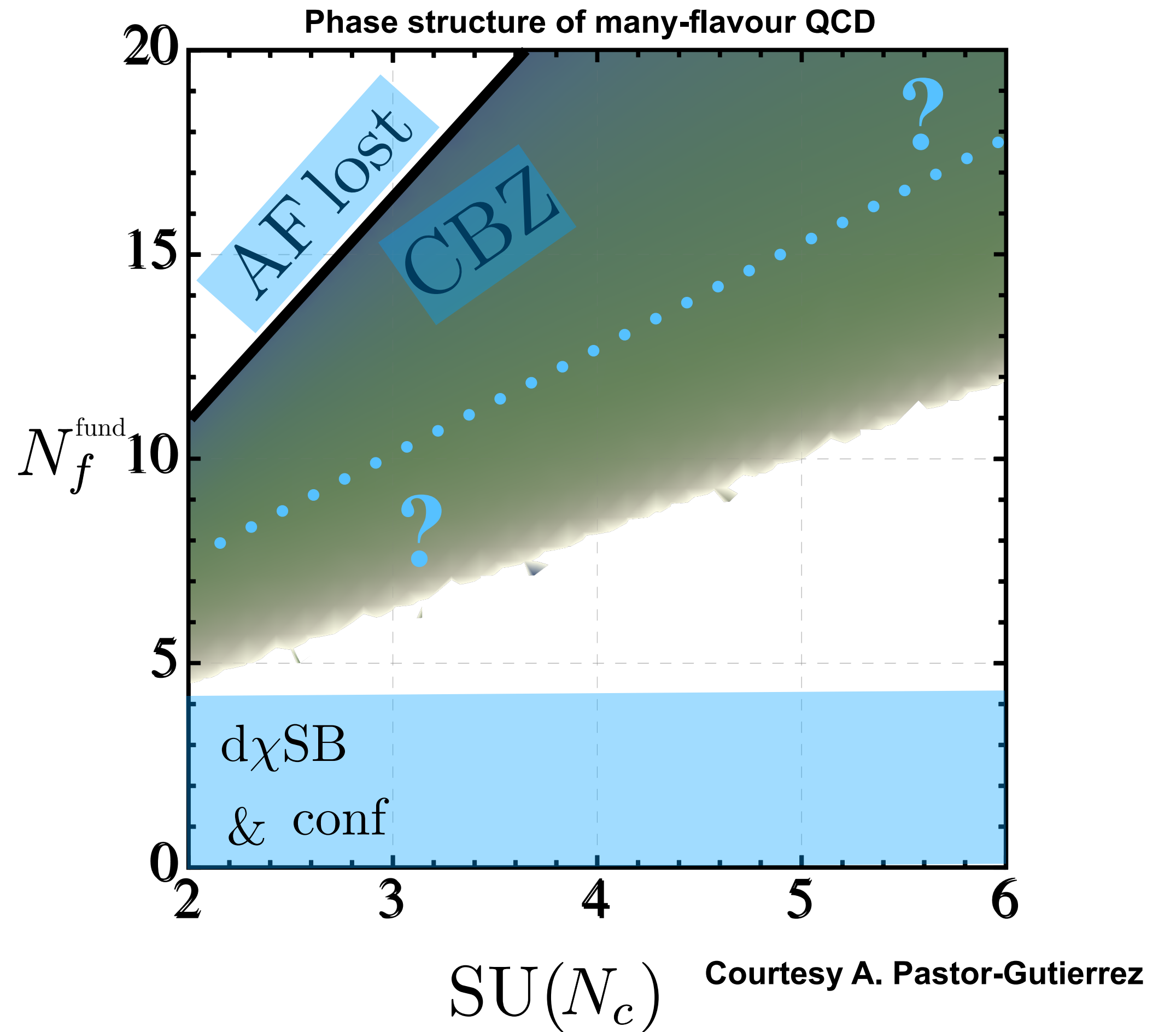
Semi-perturbative IR beta functions

Perturbative IR beta functions

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see plenary talk F. Rennecke (Monday)



Phase structure of many flavour QCD

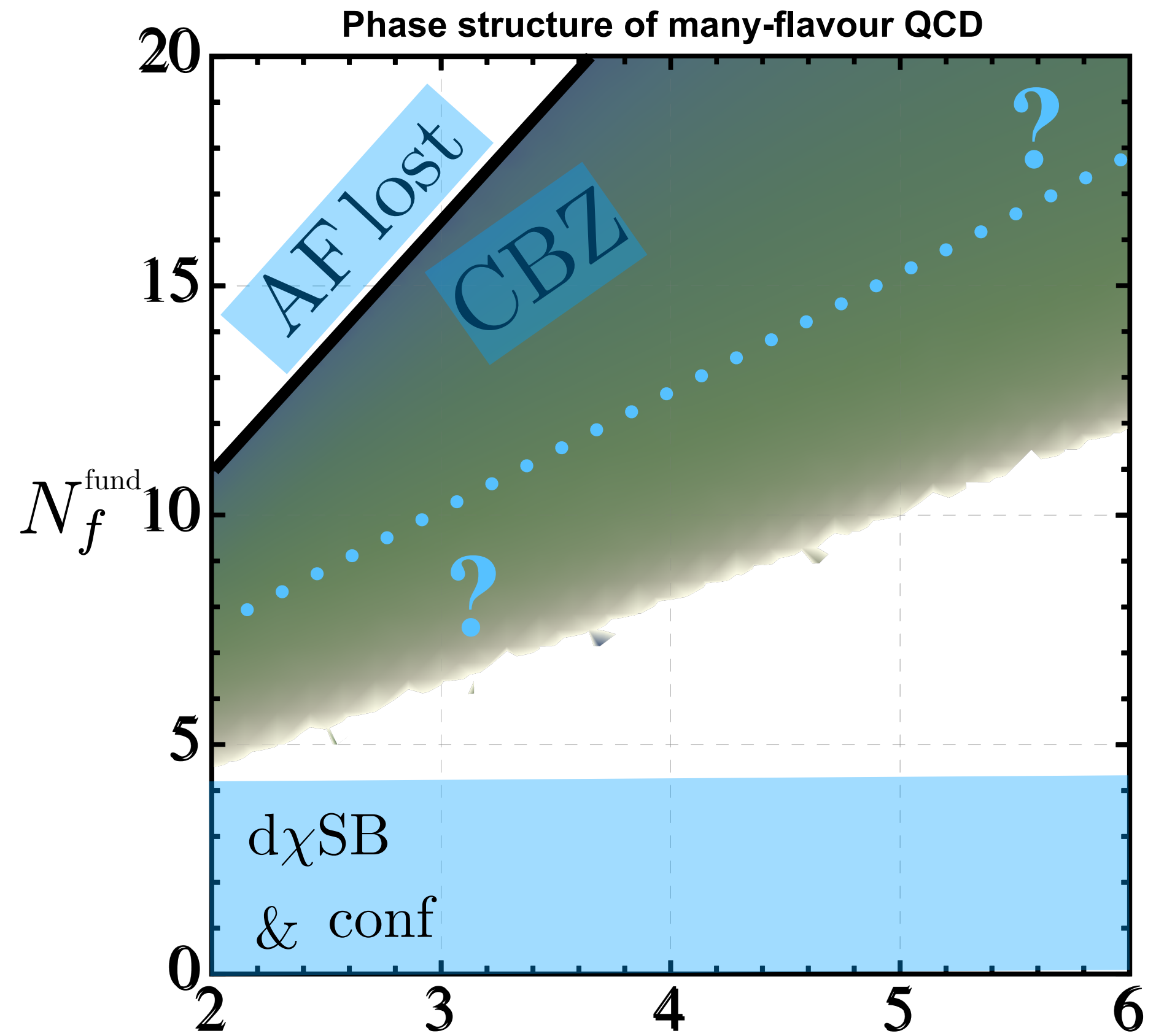
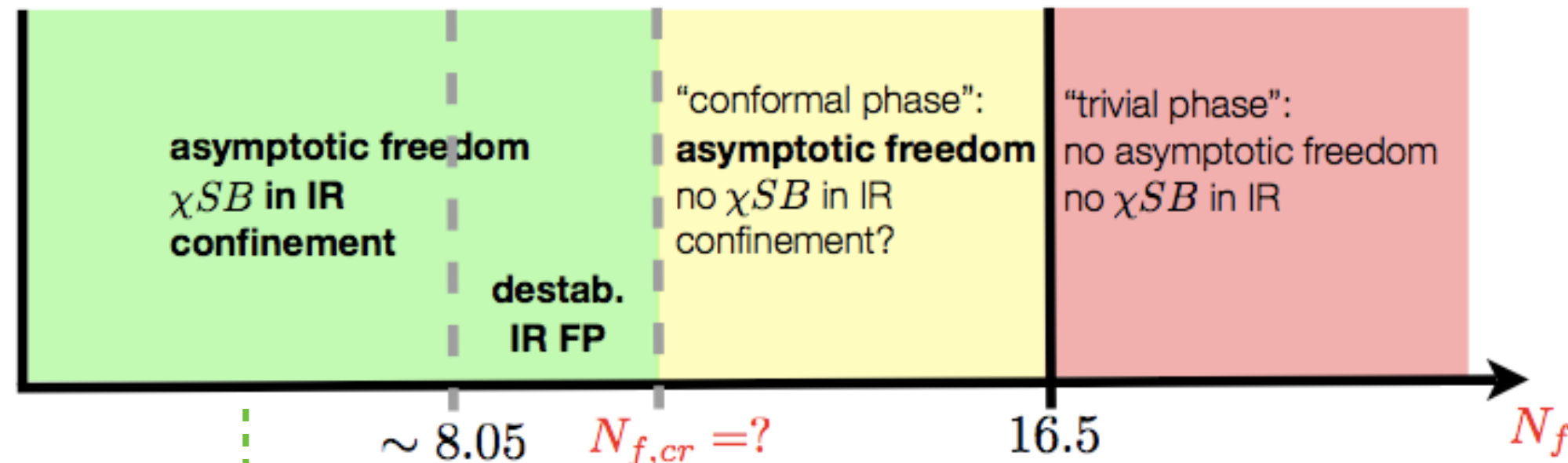
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Casimirs
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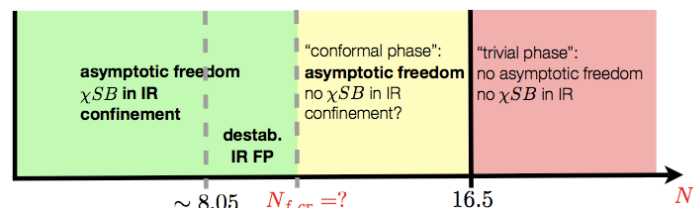
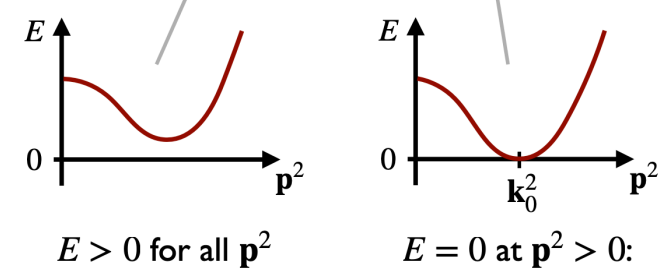
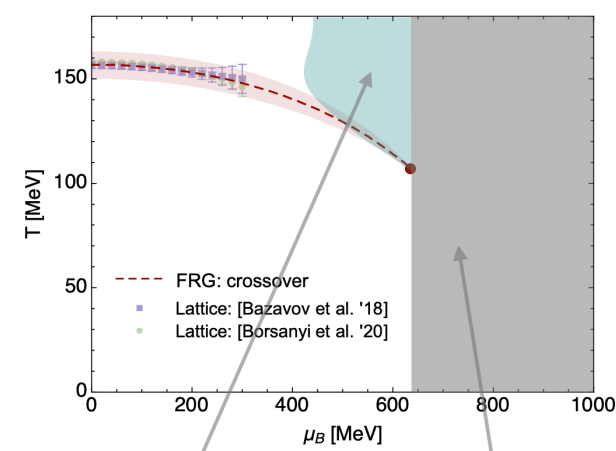
$SU(N_c)$ Courtesy A. Pastor-Gutierrez

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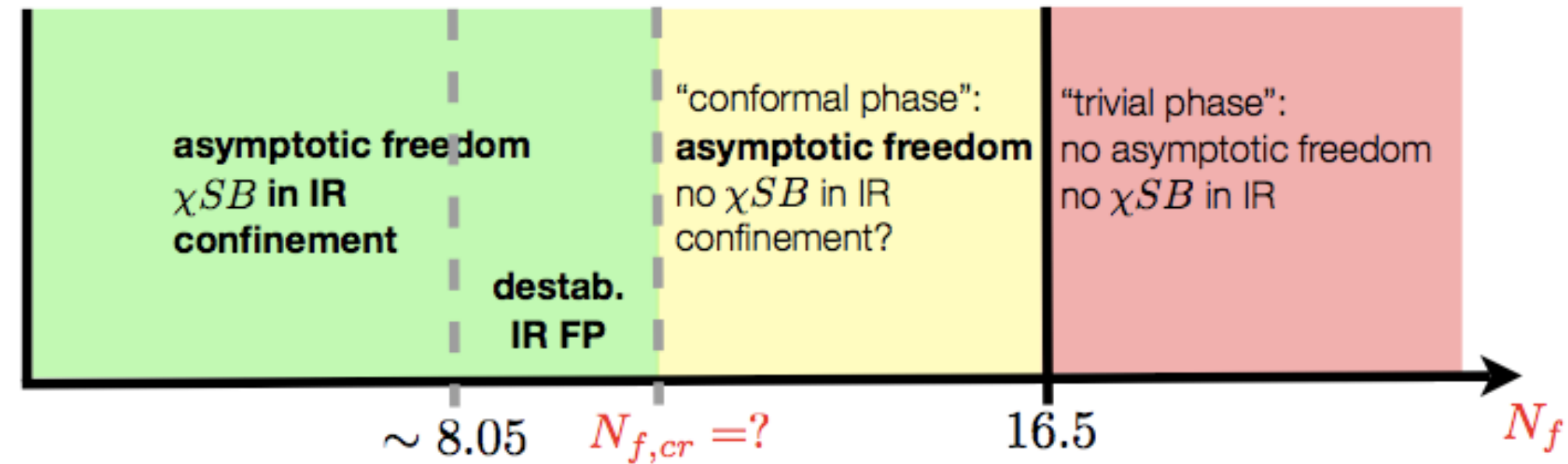


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All N_f : Florian Goertz, **Álvaro Pastor-Gutiérrez**, JMP, in preparation

Phase structure of many flavour QCD

Many-flavour QCD with the functional RG



Non-perturbative infrared
chiral dynamics & confinement



Semi-perturbative
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Perturbative
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fRG schemes converge 'easily'

Critical flavour number

fRG

$$10 \lesssim N_{f,cr} \lesssim 12$$

e.g.

fRG: Gies, Jäckel '05, Braun, Gies '05, 06

Conformal expansion: Lee, 103 (2021) 7, 076006

lattice

$$9 \lesssim N_{f,cr} \lesssim 13$$

Recent works, e.g.

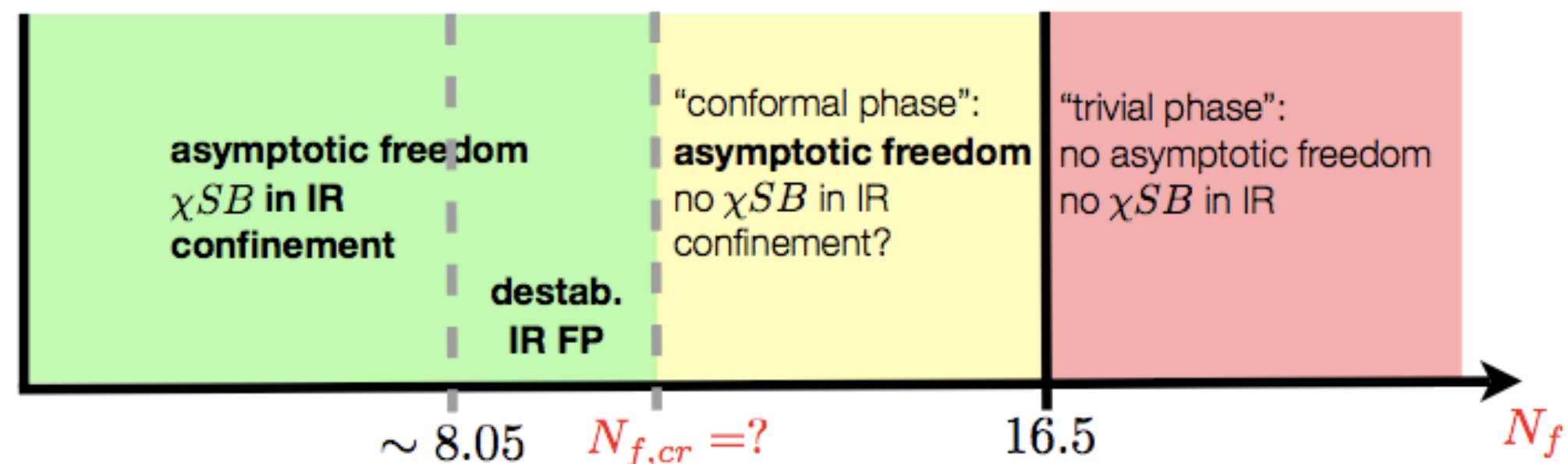
Kotov, Lombardo, Trunin, *Symmetry* 13 (2021) 10, 1833

Kuti, Fodor, Holland, Wong, *PoS LATTICE2021* (2022) 321

Hasenfratz, Neil, Shamir, Svetitsky, Witzel, *PRD* 108 (2023) 7, L071503

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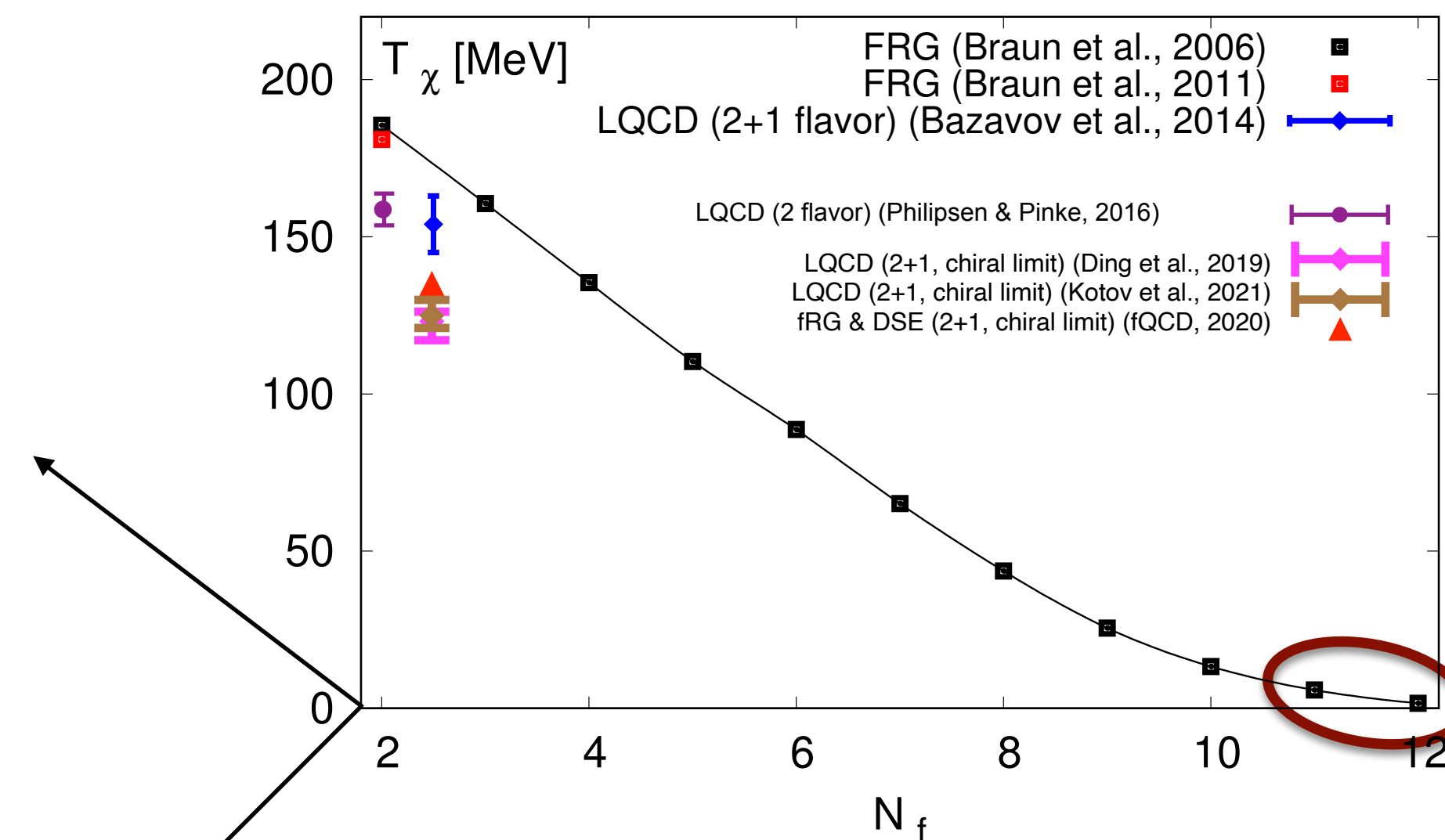
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Hasenfratz, Neil, Shamir, Svetitsky, Witzel, *PRD* 108 (2023) 7, L071503

General phase structure



Scaling: Miransky & beyond

Braun, Gies, Fischer, *PRD* 84 (2011) 034045

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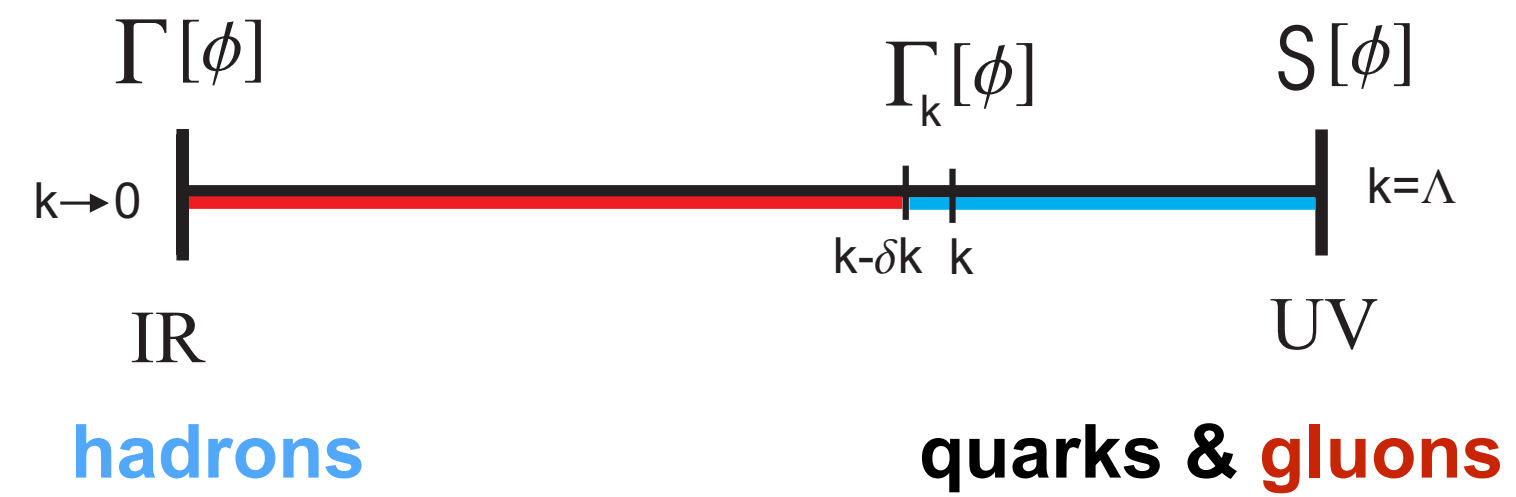
Bersini, D'Alise, Sannino, *PRD* 109 (2024), 125015

Cuteri, Philipsen, Sciarra, *JHEP* 11 (2021) 141

Functional flows for QCD

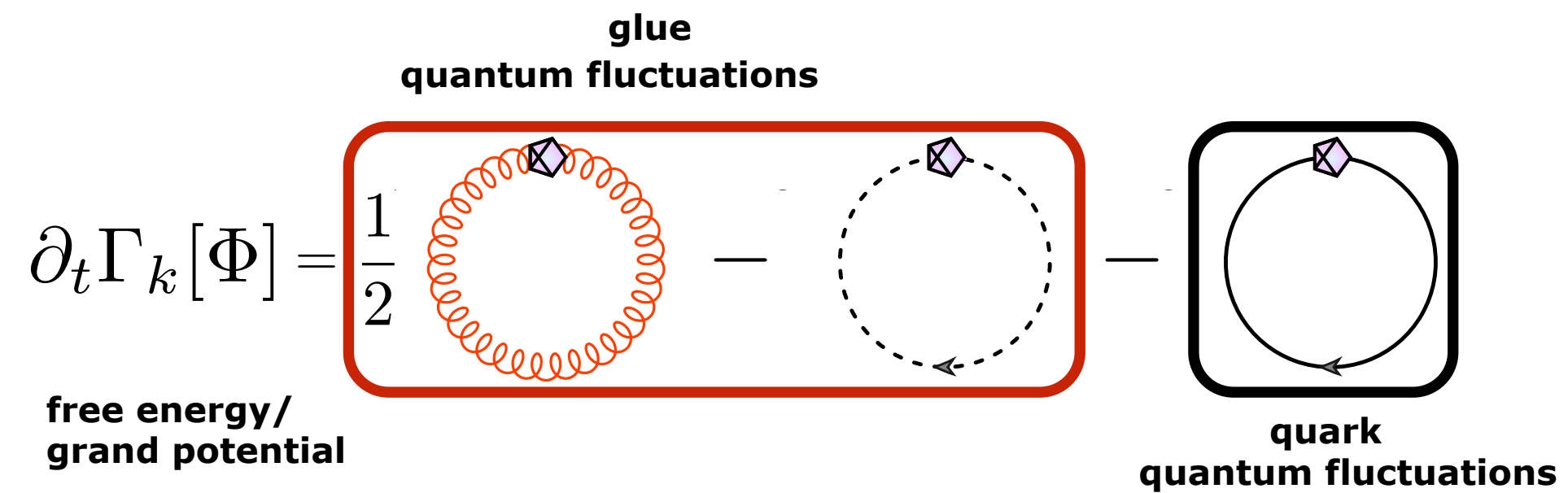
Dupuis et al, Phys.Rept. 910 (2021) 1-114
 Fu, Commun.Theor.Phys. 74 (2022) 9, 097304

free energy at momentum scale



ab initio

functional RG:



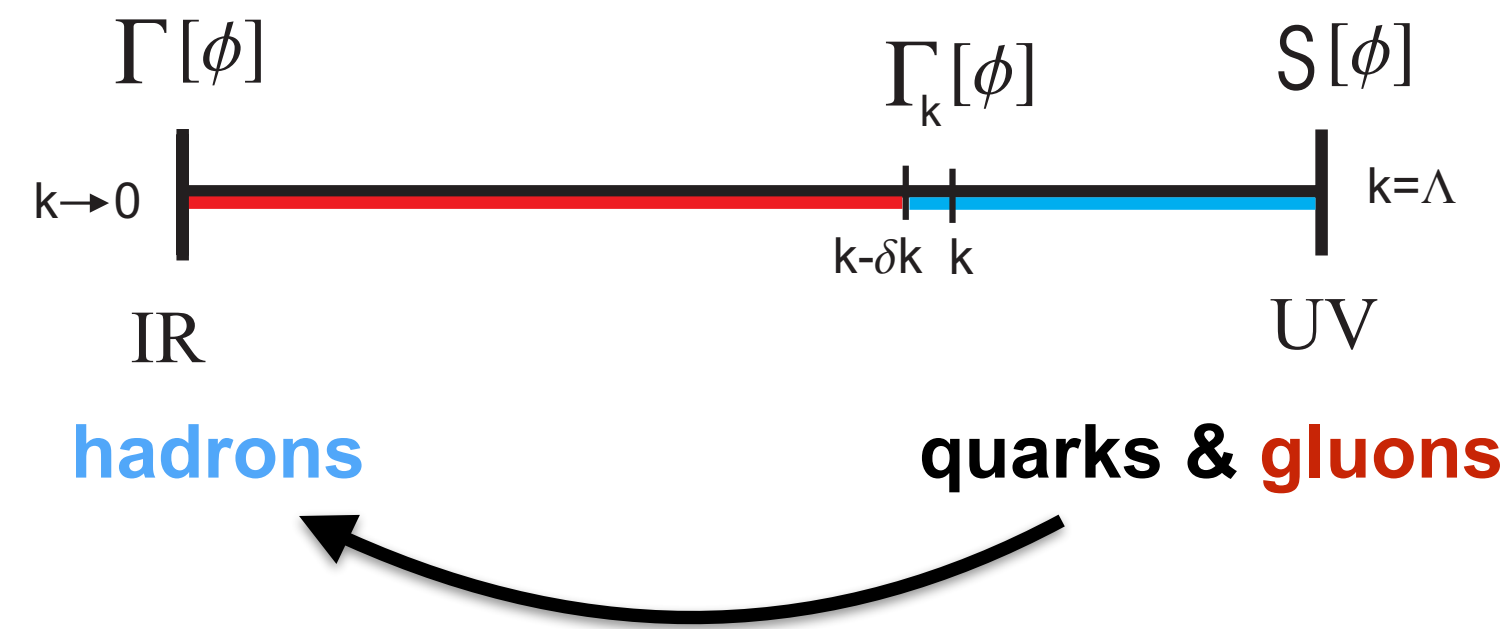
RG-scale k : $t = \ln k$

$$\Phi = (A_\mu, c, \bar{c}, q, \bar{q})$$

Functional flows for QCD

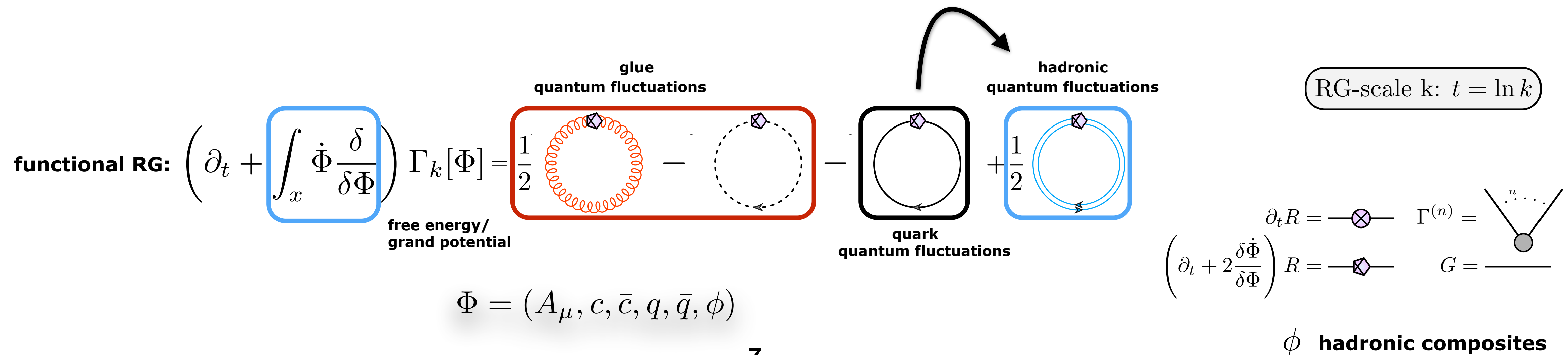
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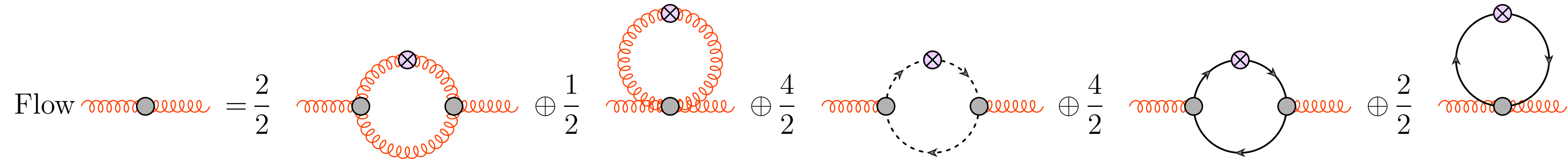


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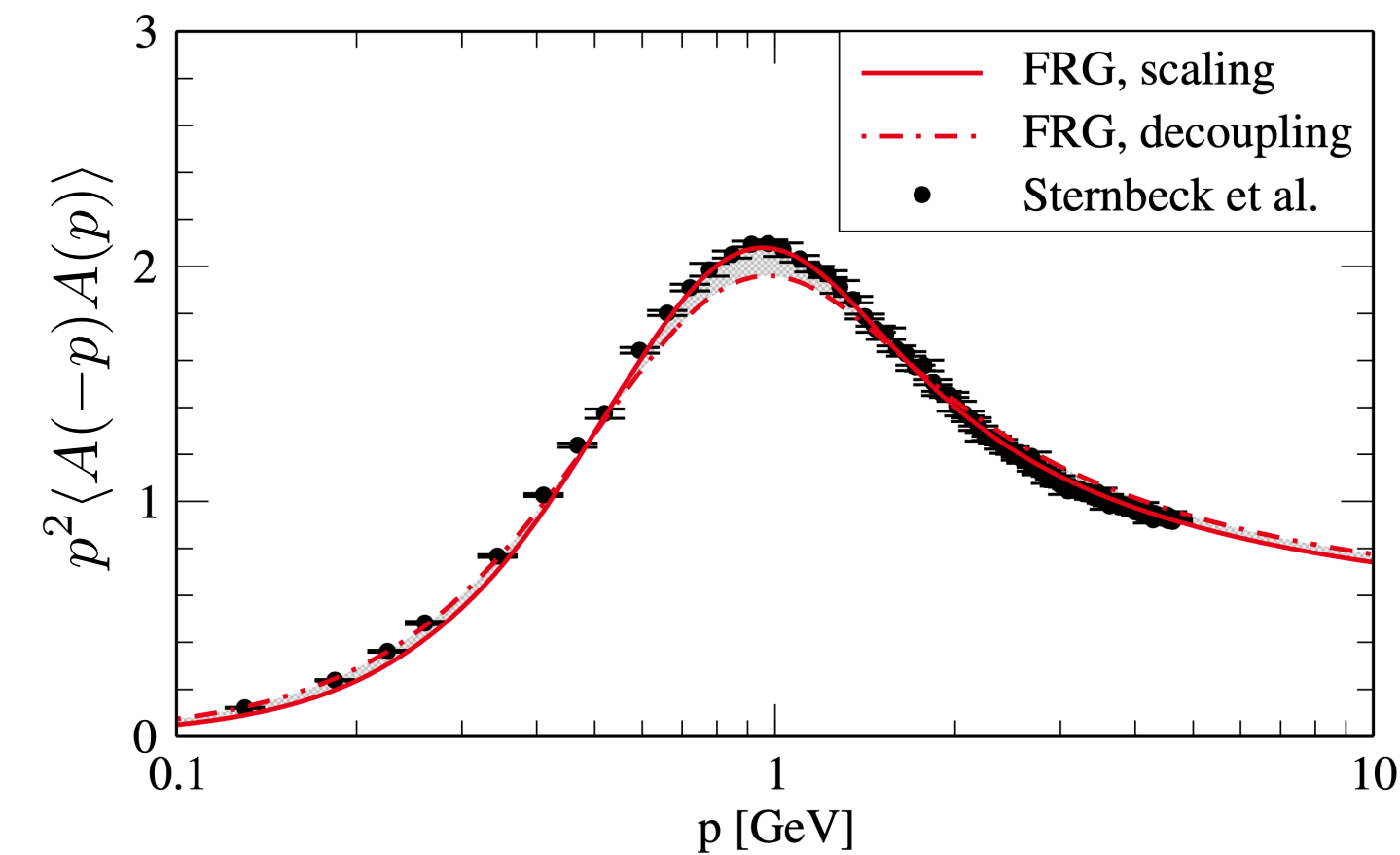
fRG approach with emergent composites/dynamical hadronisation



Getting started: the gluon propagator

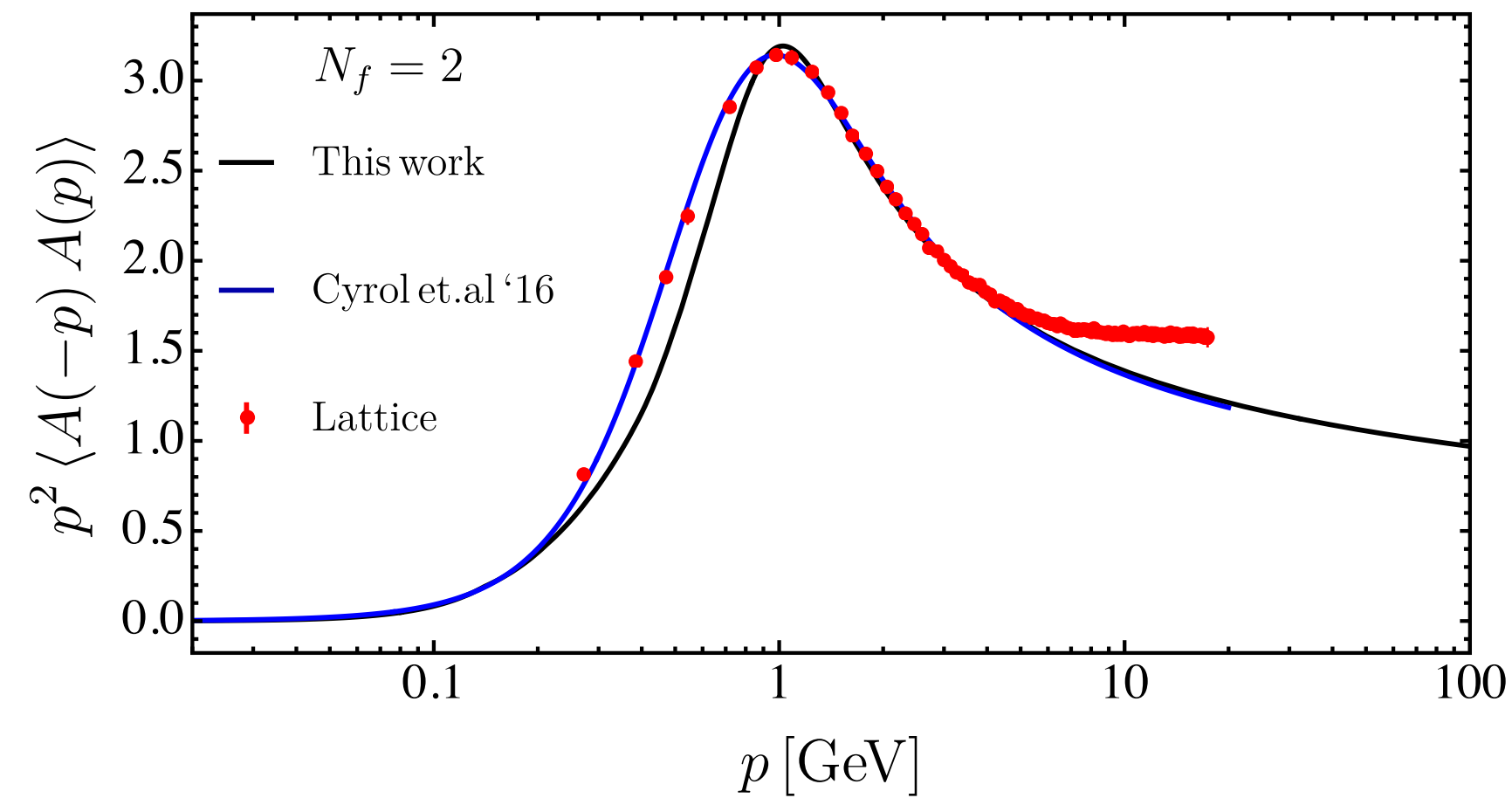


Yang-Mills



Cyrol, Fister, Mitter, JMP, Strodthoff, PRD 94 (2016) 054005

Two flavours (chiral fRG) & physical pion mass (lattice/fRG)

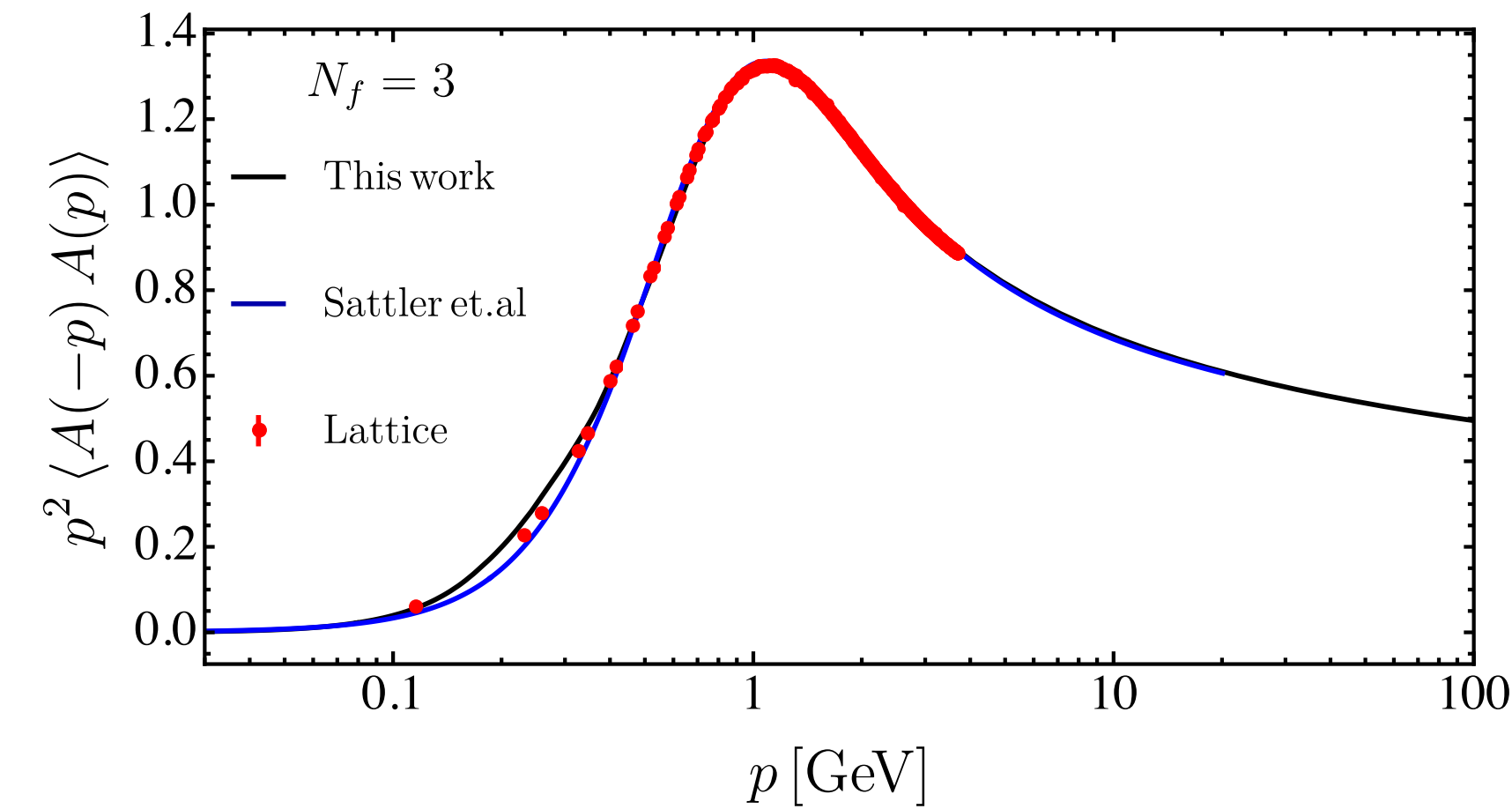


fRG: Cyrol, Mitter, JMP, Strodthoff, PRD 97 (2018) 054006

Ihssen, JMP, Sattler, Wink, arXiv: 2408.08413

Lattice: Sternbeck et al, PoS LATTICE2016 (2017)

Physical 2+1 (lattice/fRG/DSE) & 3 chiral (fRG) flavours



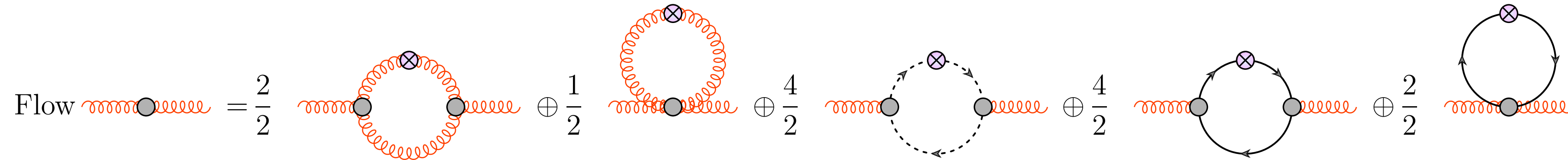
fRG/DSE: Ihssen, JMP, Sattler, Wink, arXiv: 2408.08413

Gao, Papavassiliou, JMP, PRD 103 (2021) 094013

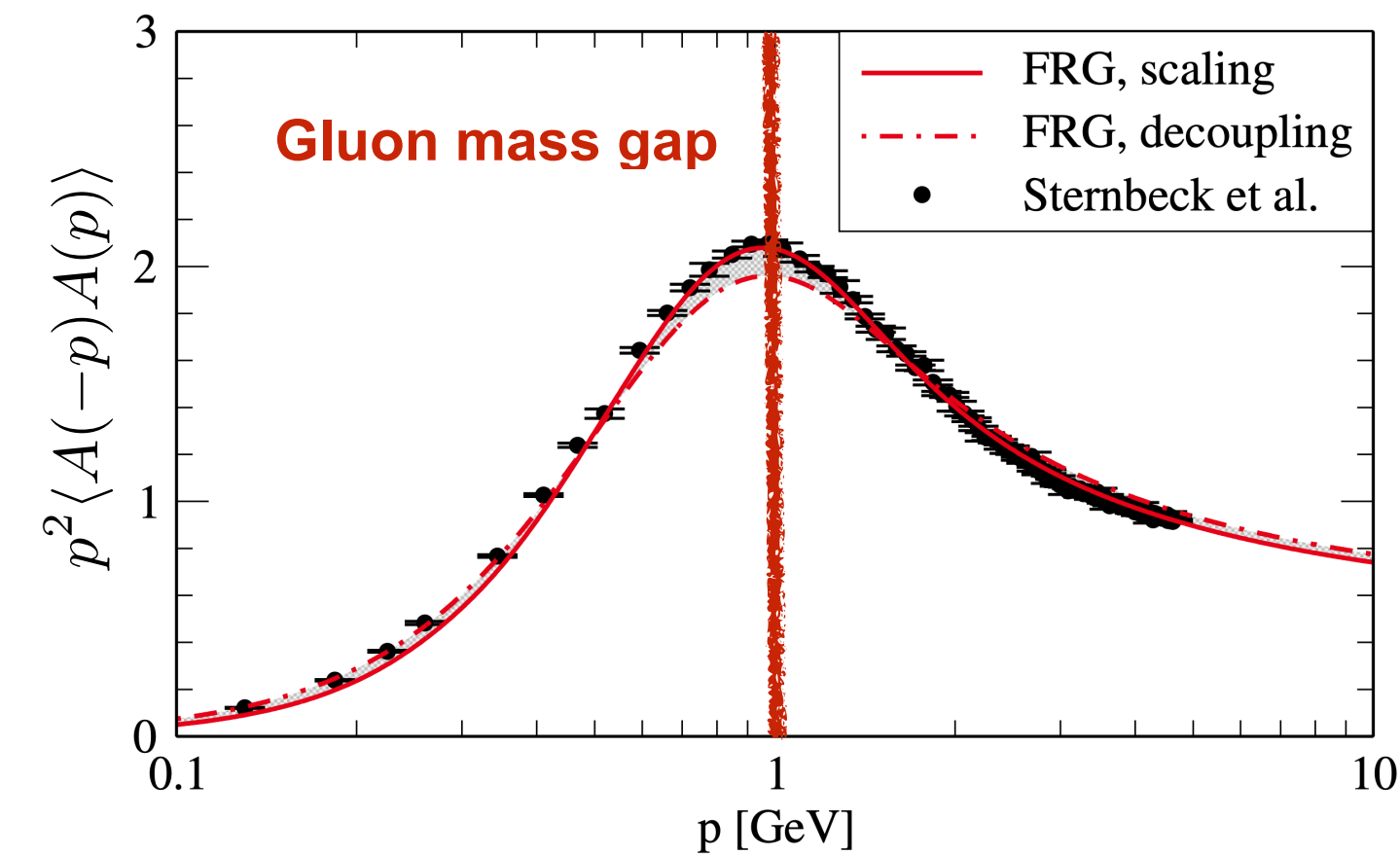
Lattice: Zafeiropoulos et al, PRL 122 (2019) 16, 162002

Cui et al, CPC 44 (2020) 8, 083102

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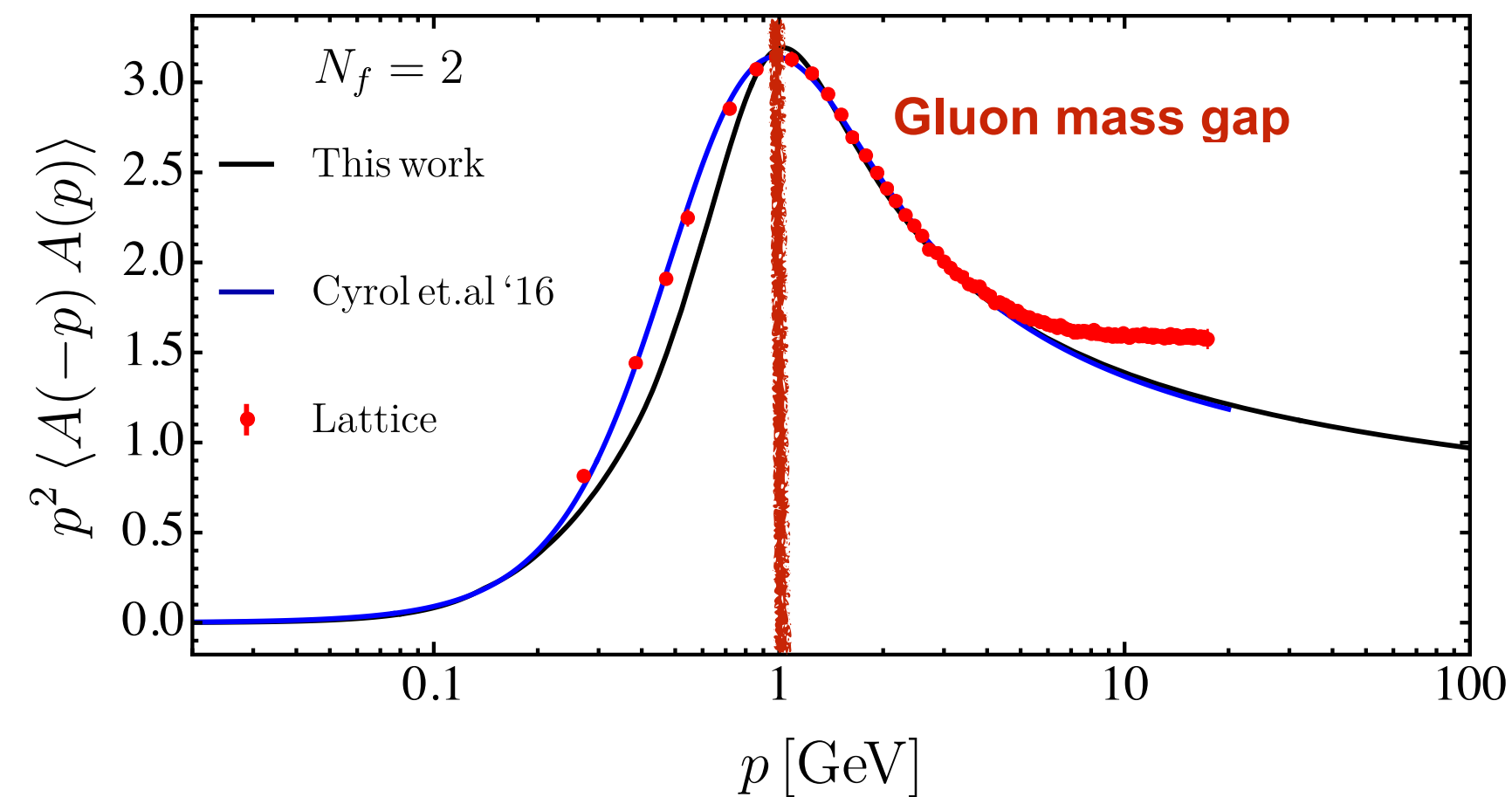


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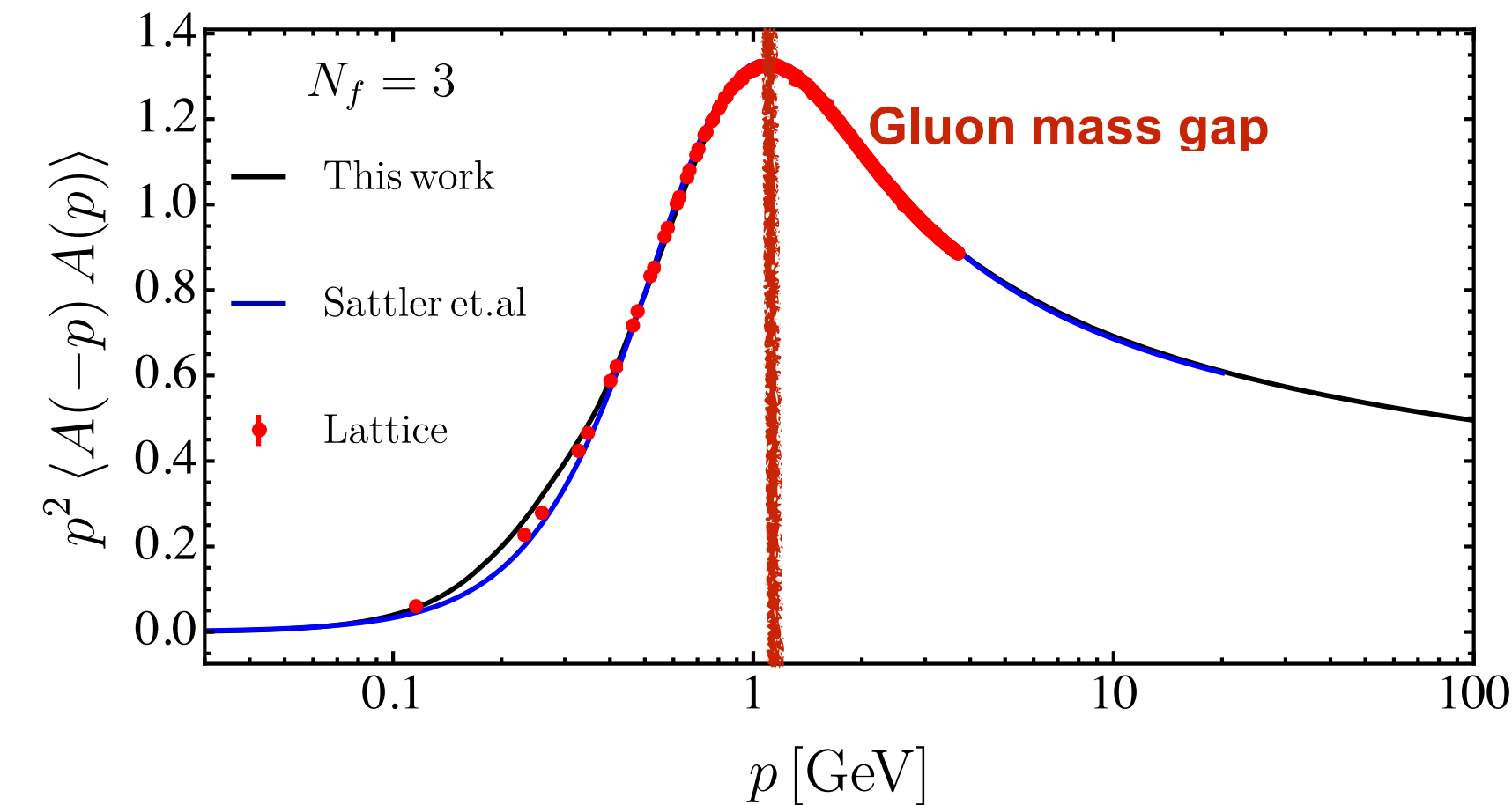


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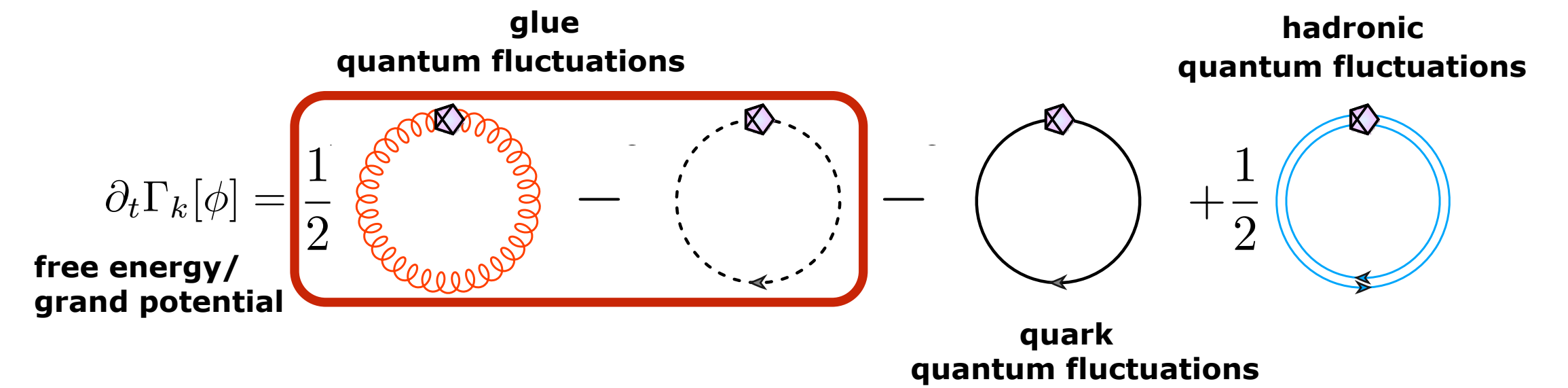
Confinement in Landau gauge QCD

Gluon mass gap confining

FRG: Braun, Gies, JMP, PLB 684 (2010) 262

FRG, DSE, 2PI: Fister, JMP, PRD 88 (2013) 045010

$$L[A_0] = \frac{1}{N_c} \text{tr} \mathcal{P} e^{ig \int_0^\beta A_0(\mathbf{x})}$$



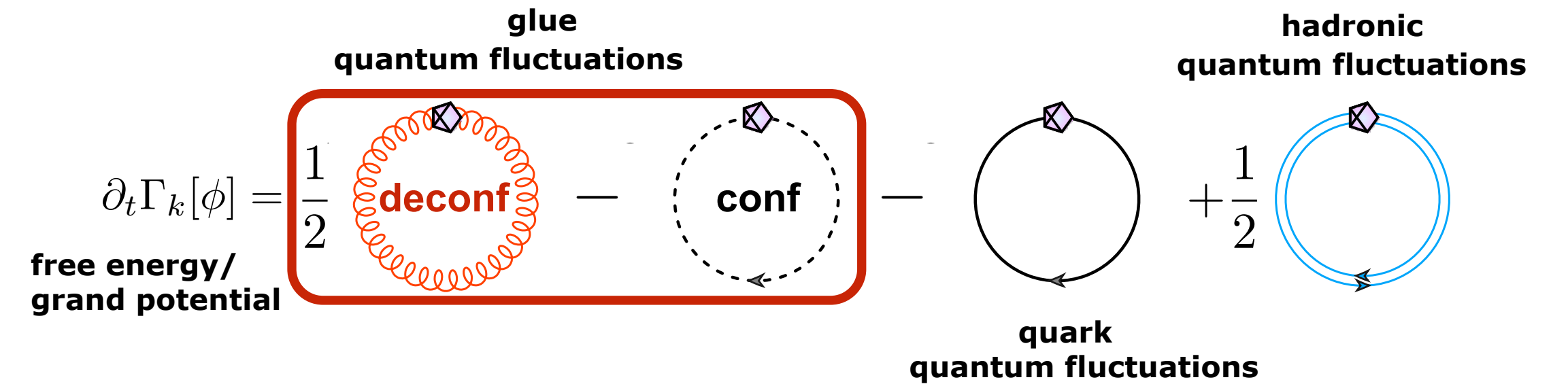
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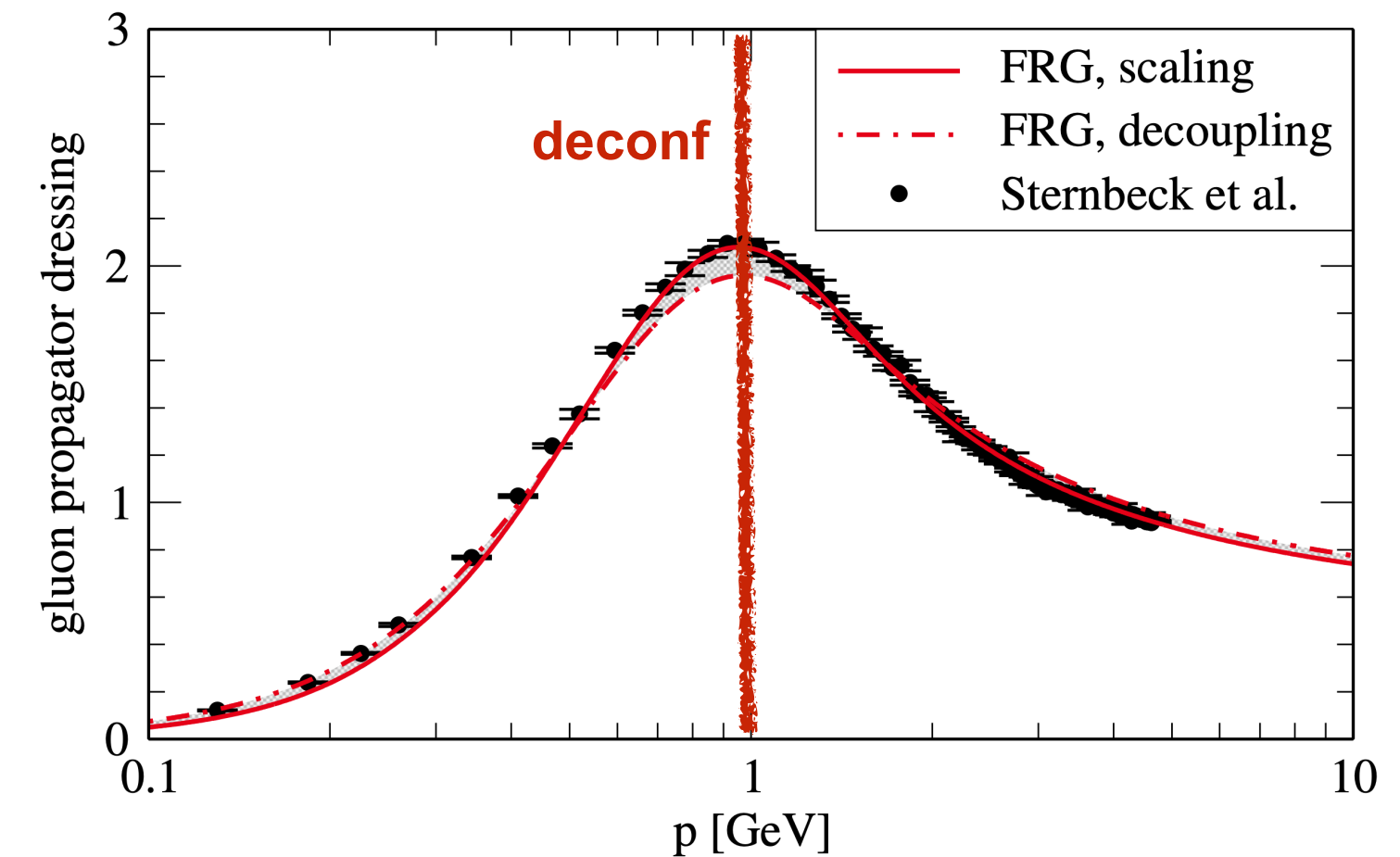
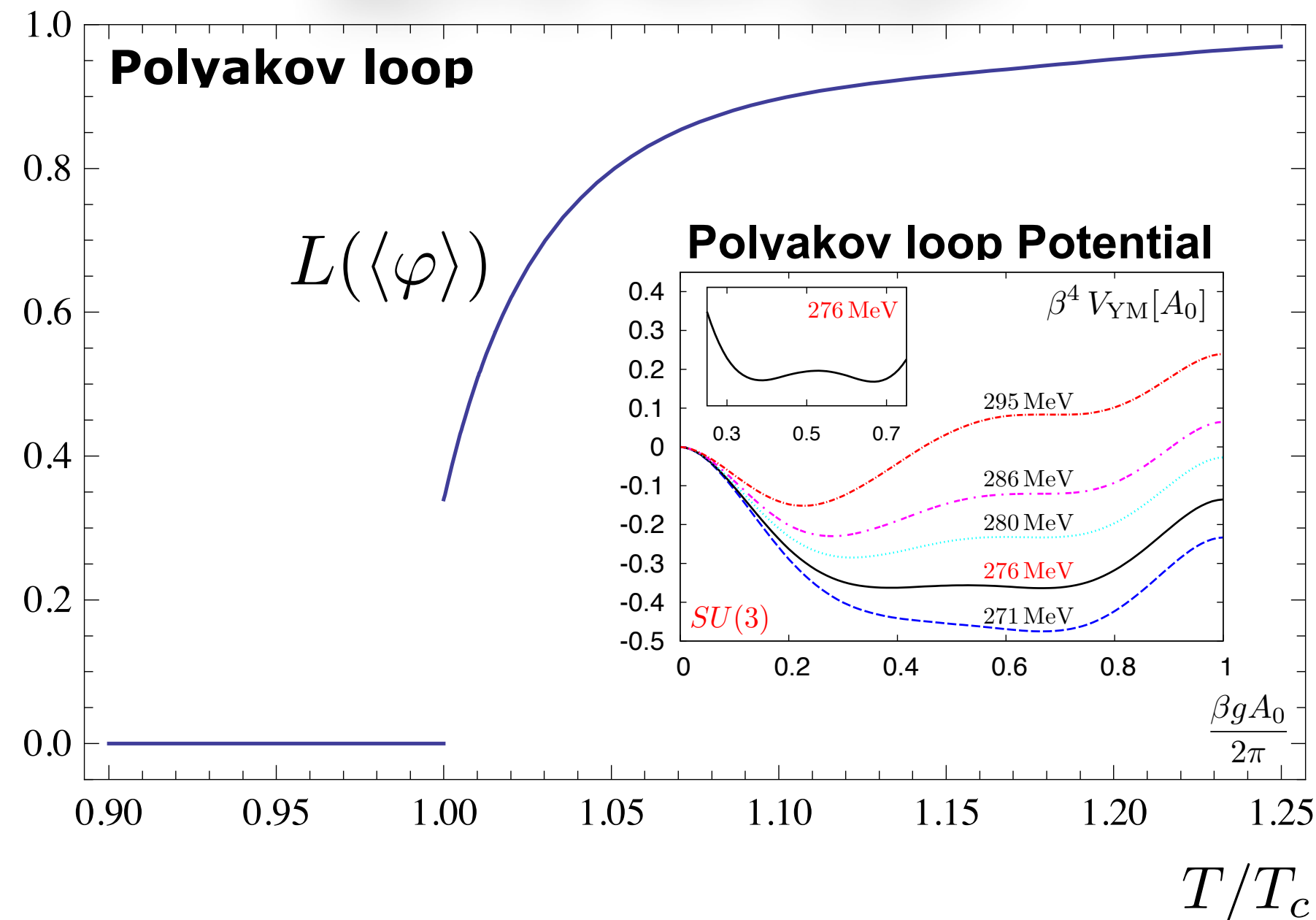
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Polyakov loop Potential: $V_{\text{YM}}[A_0]$

$$\mathcal{P} e^{ig \int_0^\beta A_0(x)} = e^{i\varphi}$$



Cyrol, Fister, Mitter, JMP, Strodthoff, PRD 94 (2016) 054005

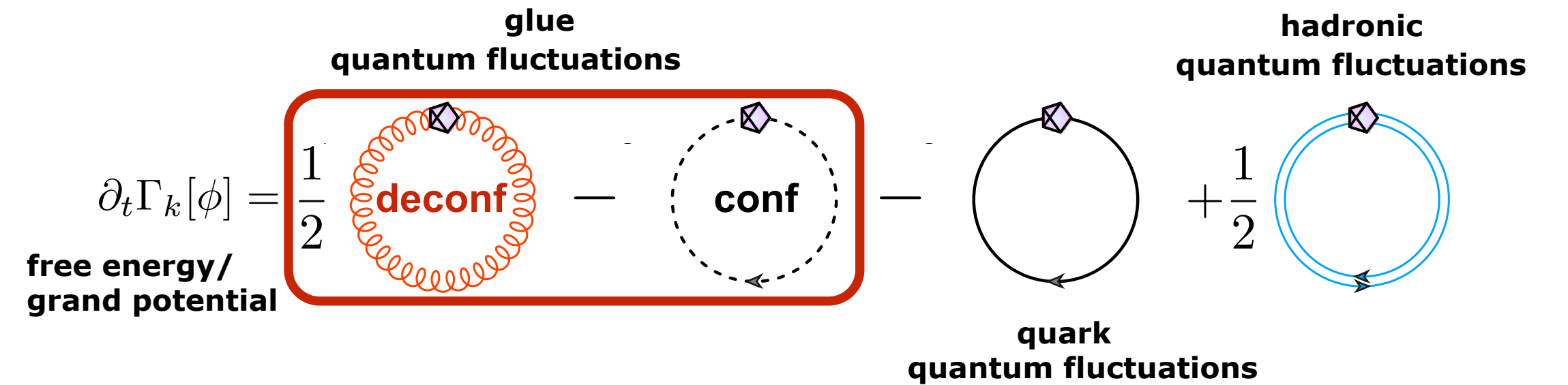
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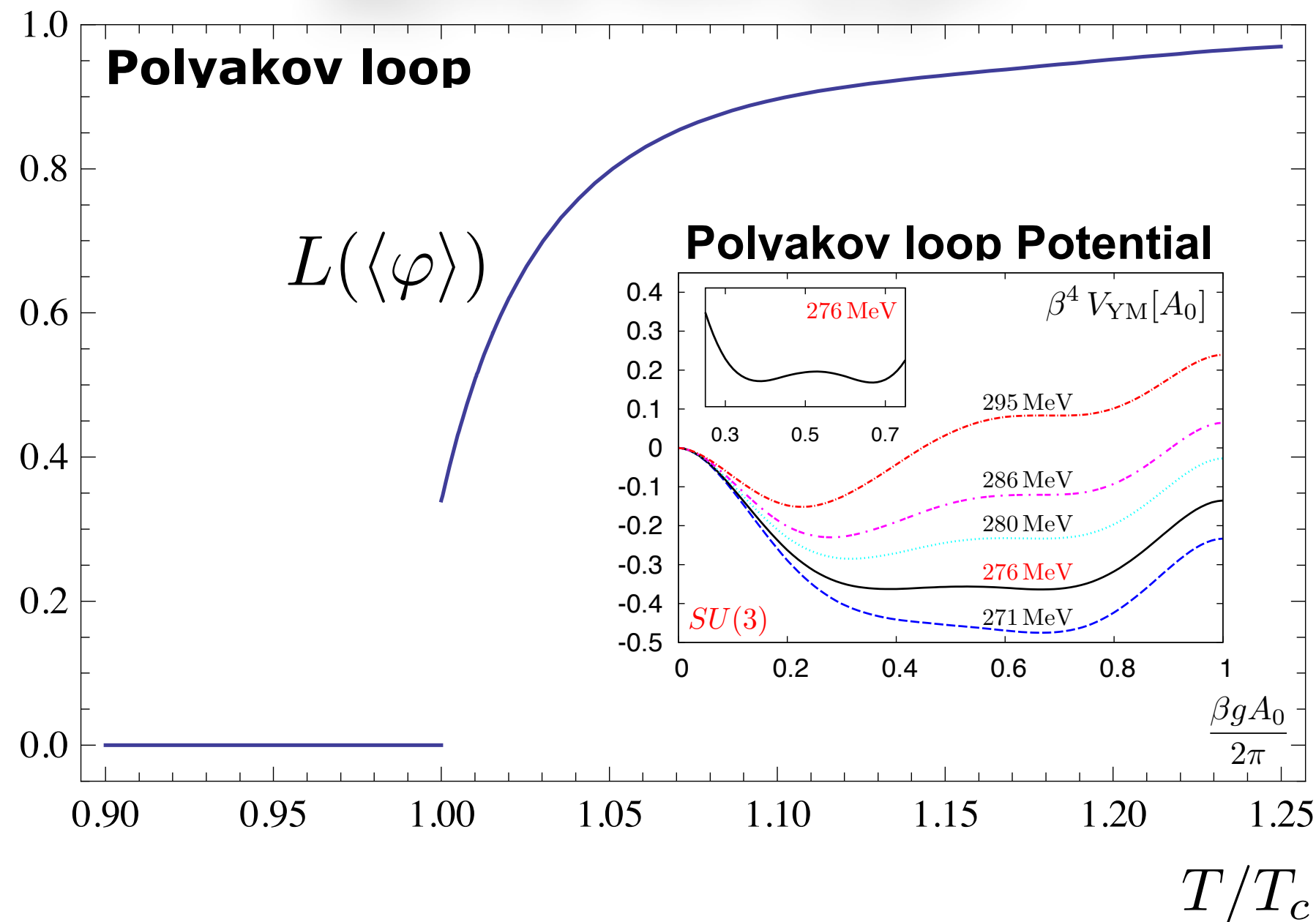
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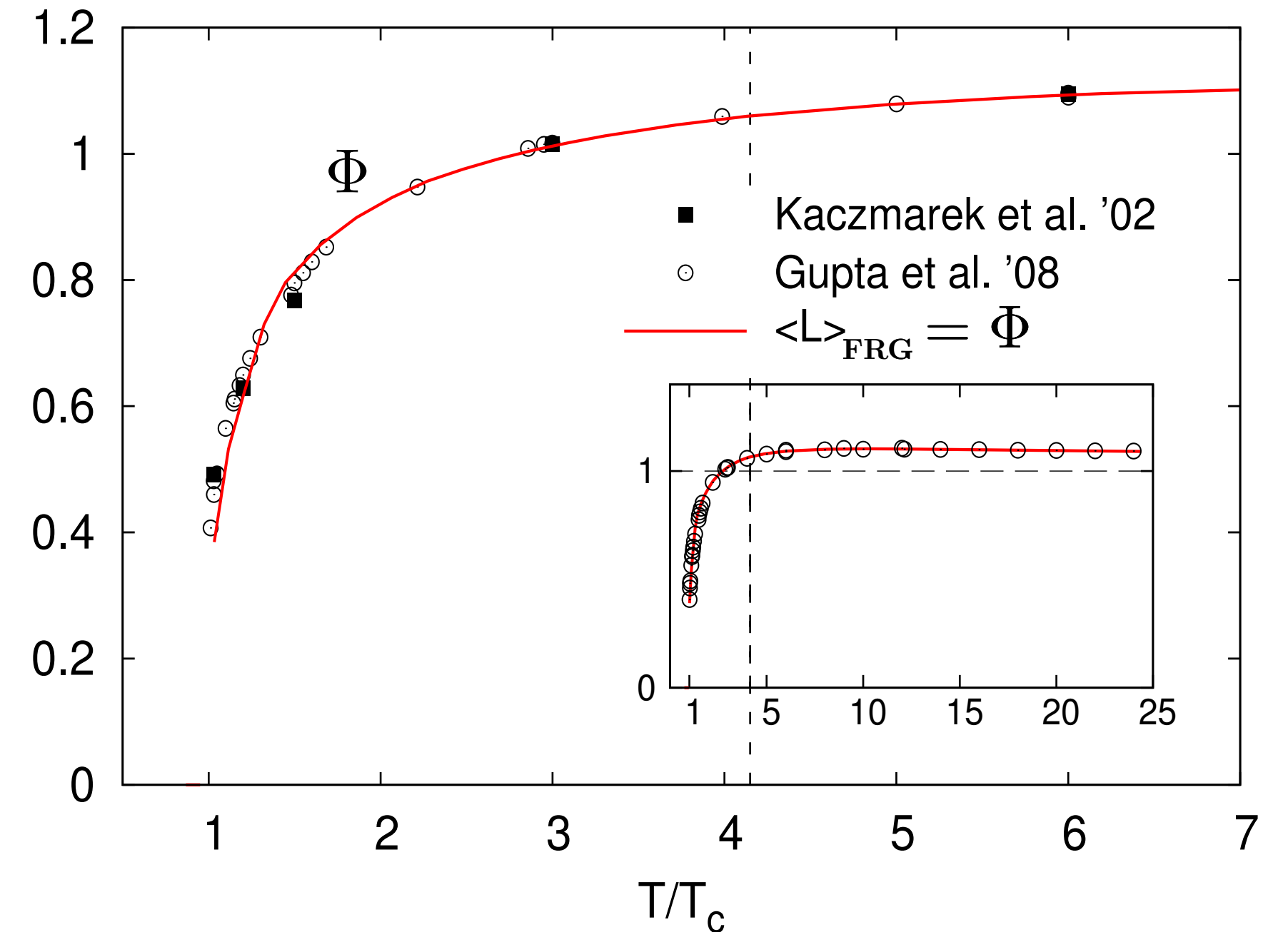


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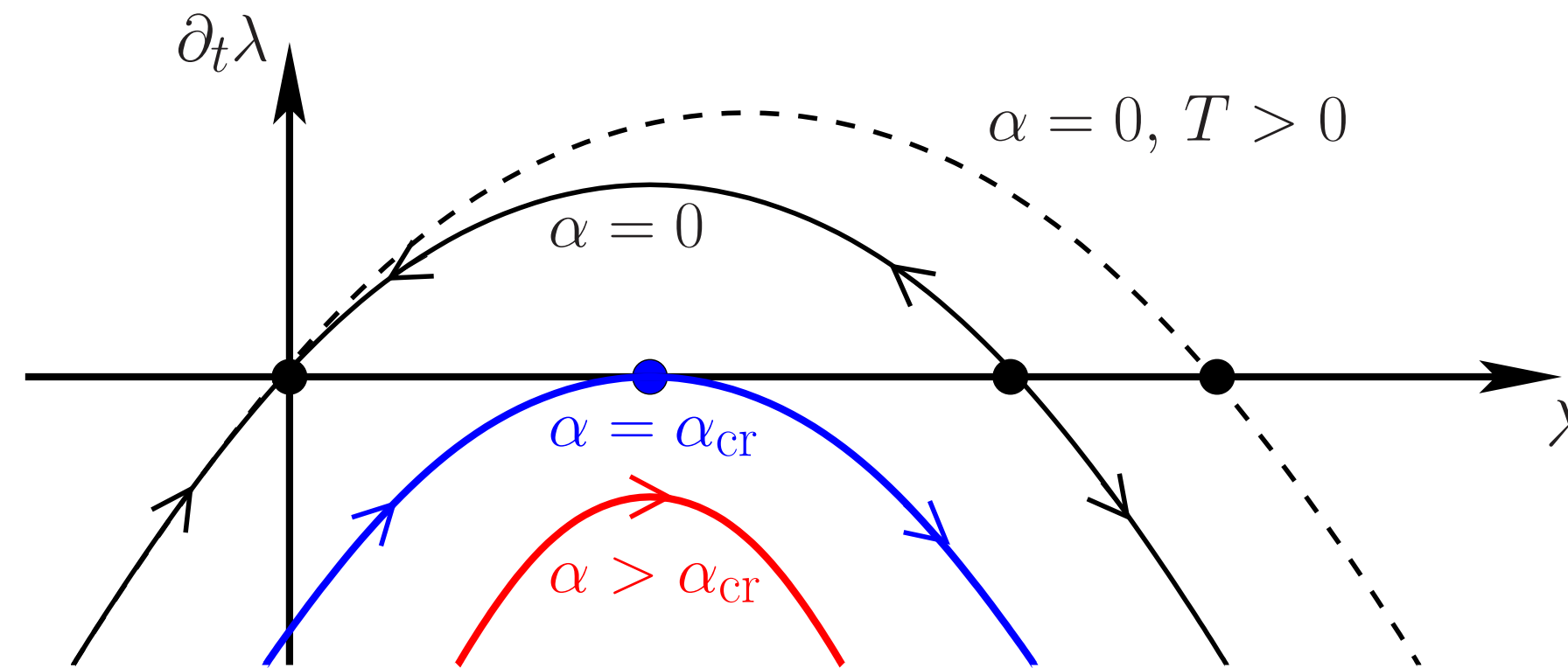
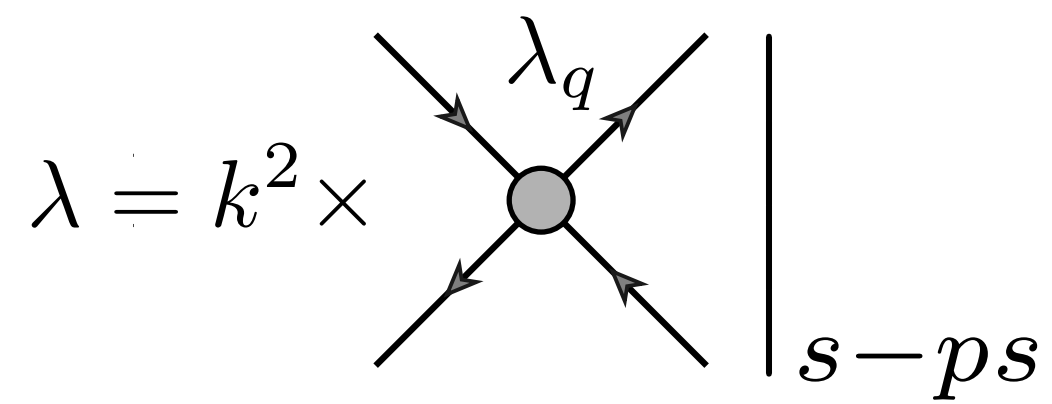
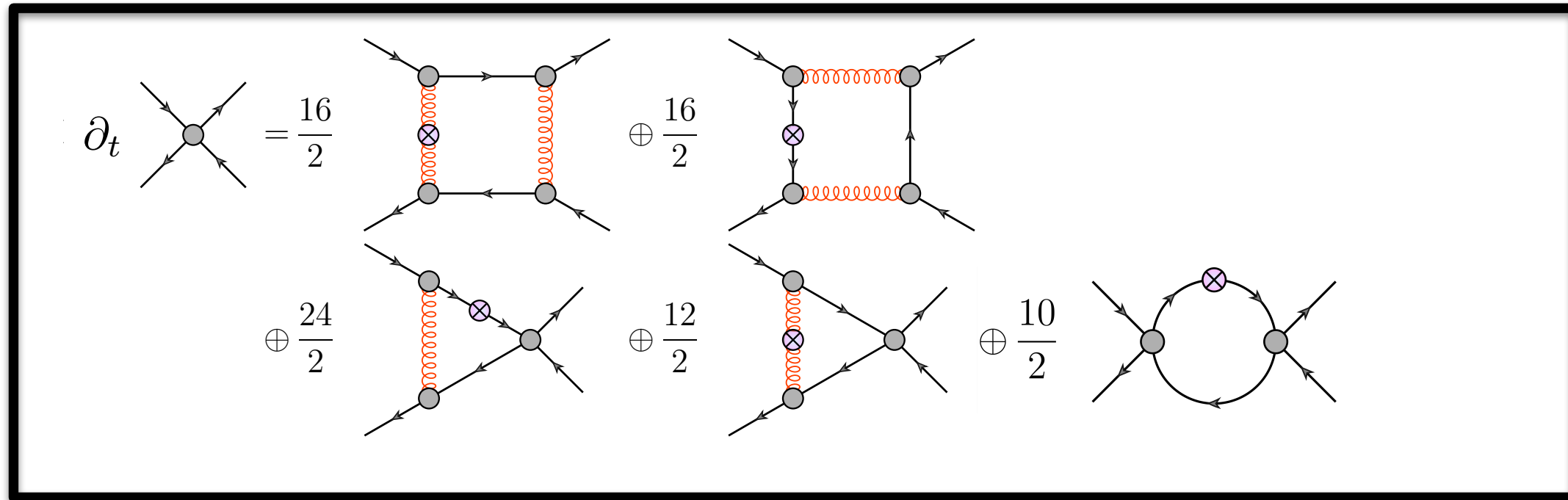


Herbst, Luecker, JMP, arXiv:1510.03830



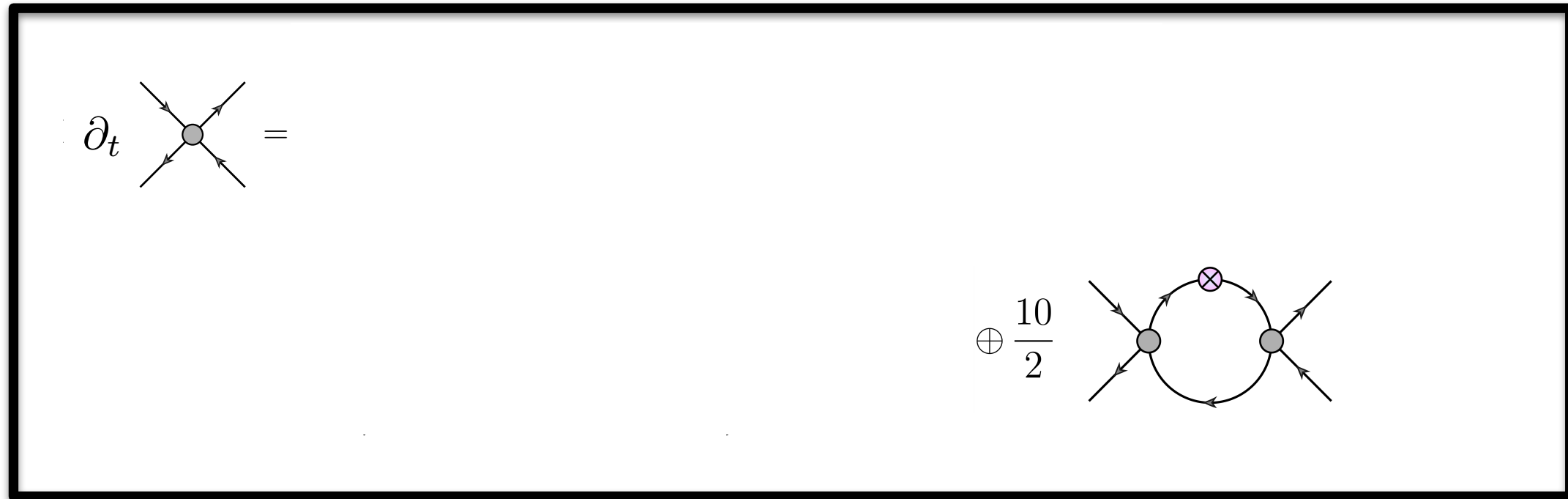
Chiral symmetry breaking

Chiral symmetry breaking in a nutshell



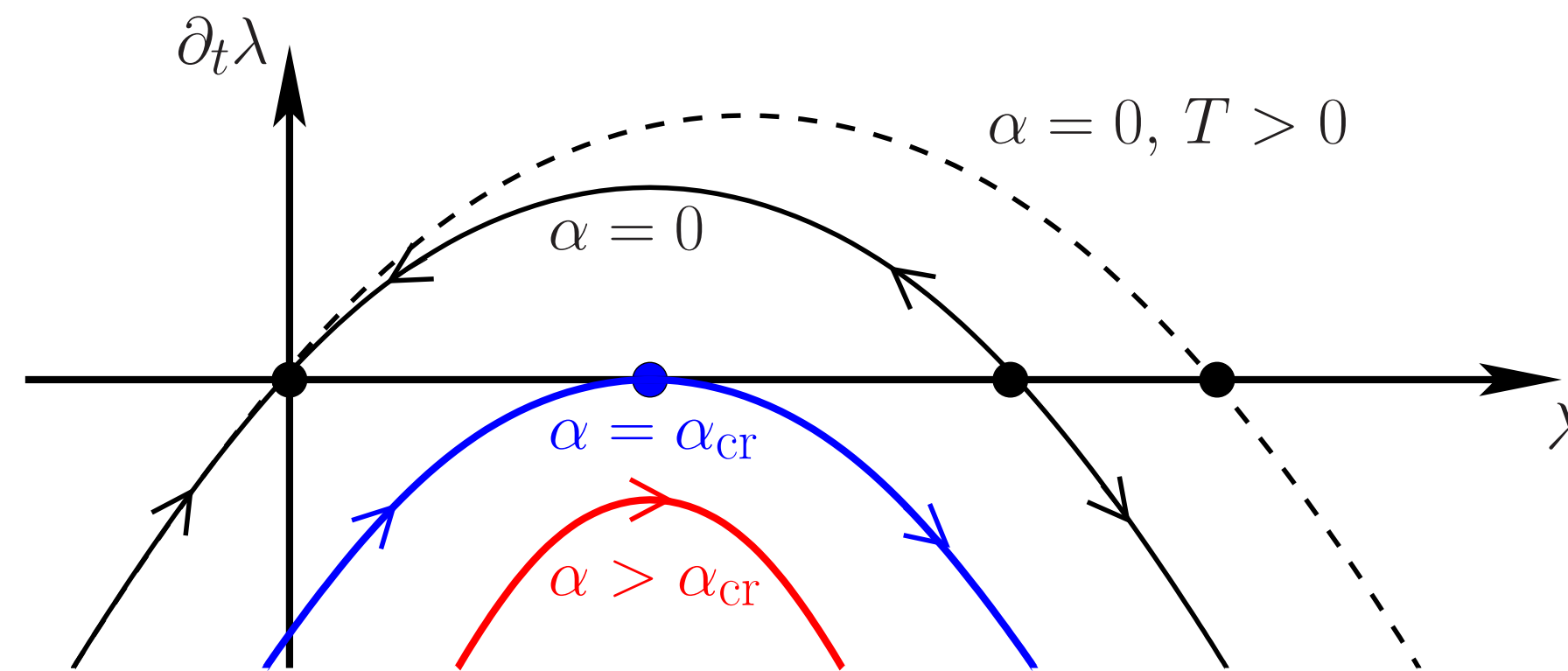
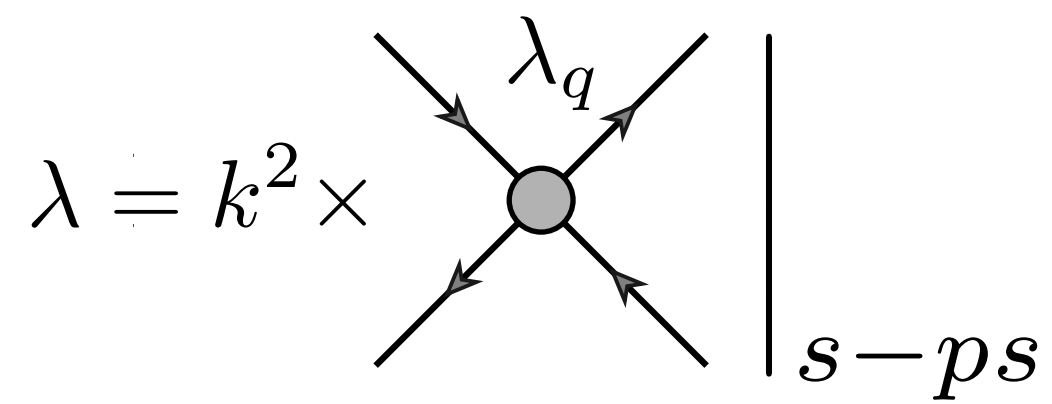
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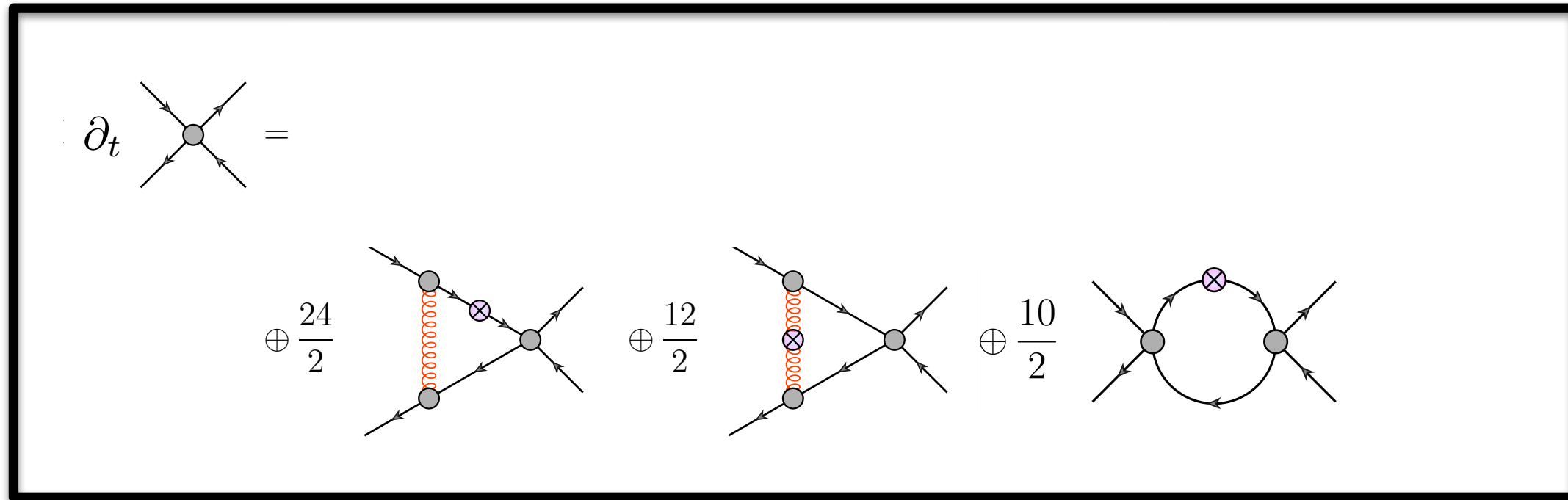
Beta-function of dimensionless scalar-pseudoscalar coupling

$$\partial_t \lambda = 2\lambda - A(k, M_q) \lambda^2$$



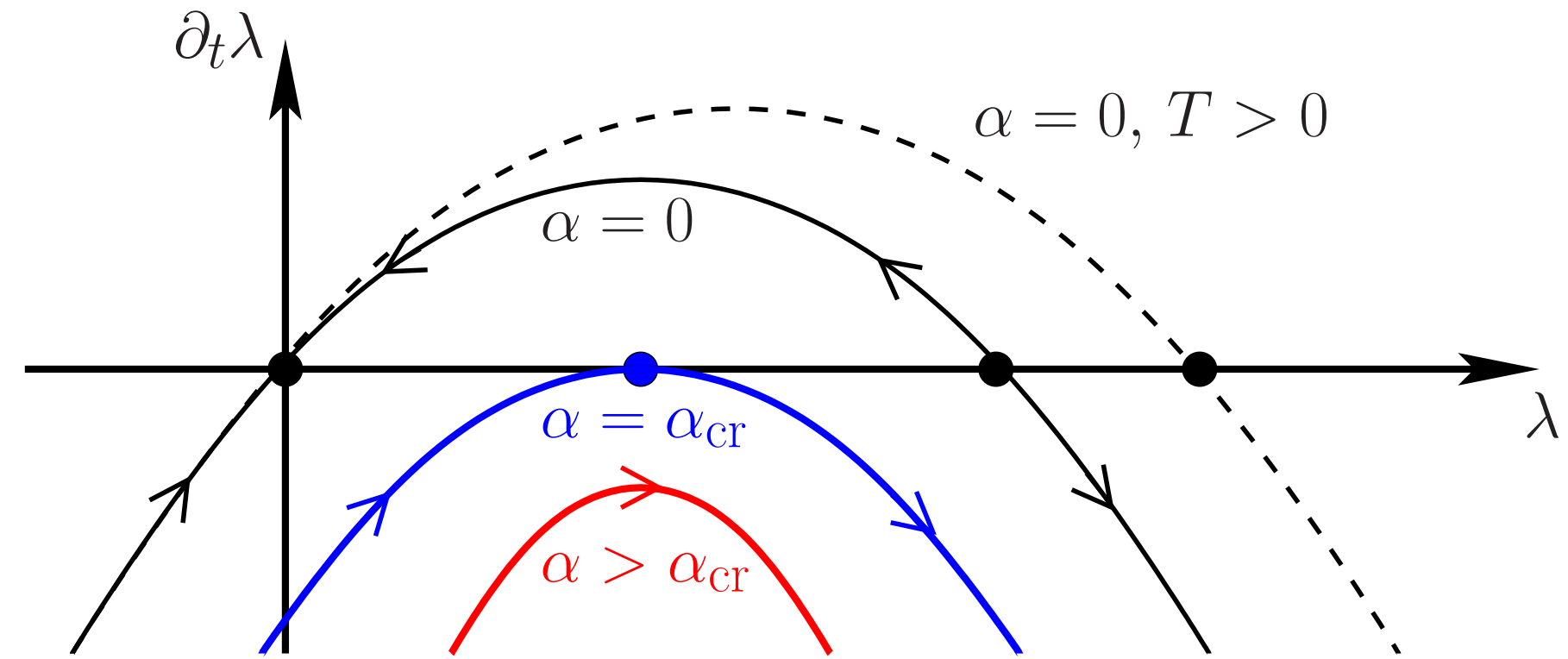
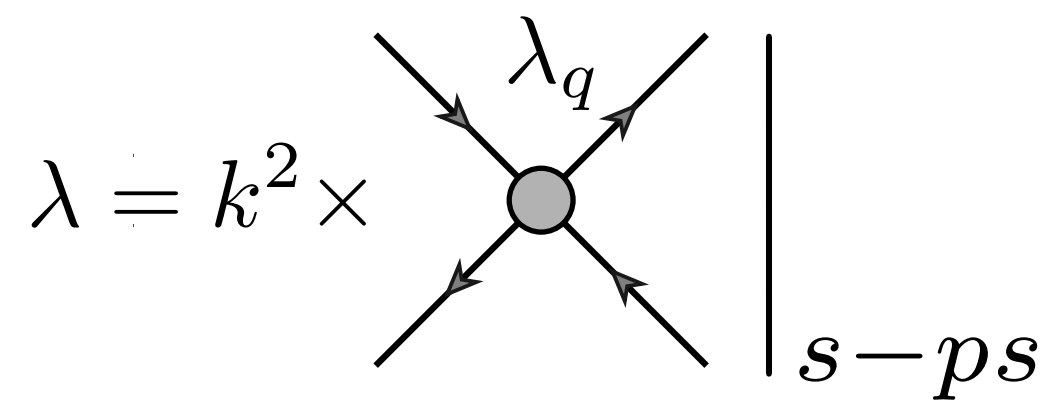
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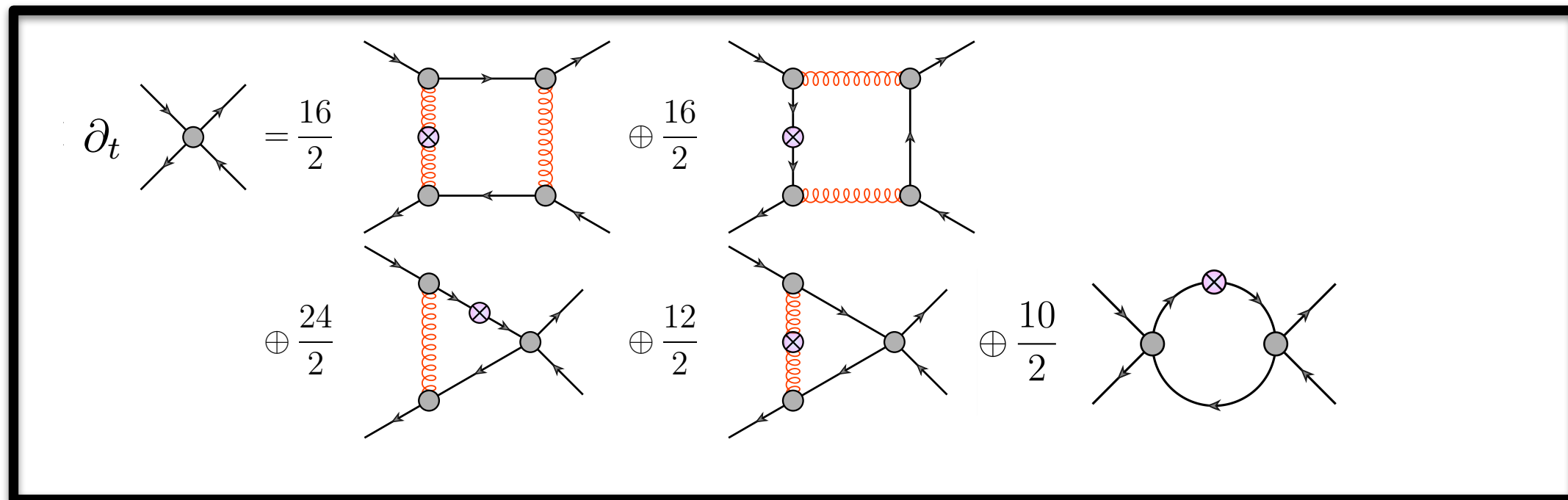
Beta-function of dimensionless scalar-pseudoscalar coupling

$$\partial_t \lambda = 2\lambda - A(k, M_q) \lambda^2 - B(k, M_q, M_{\text{gap}}) \lambda \alpha_s$$



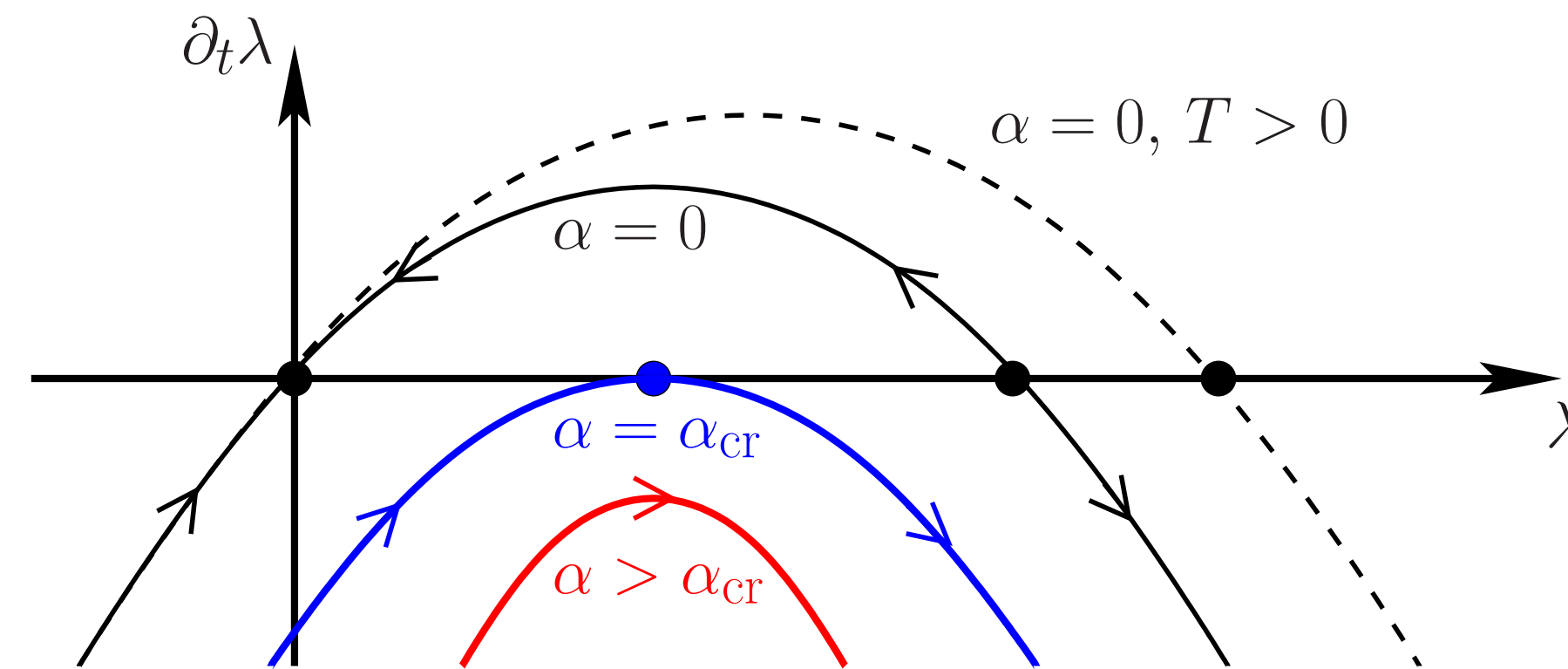
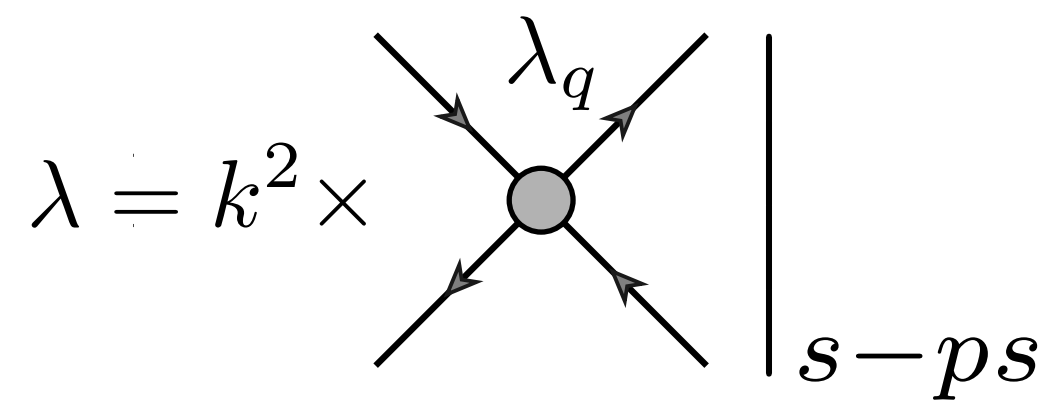
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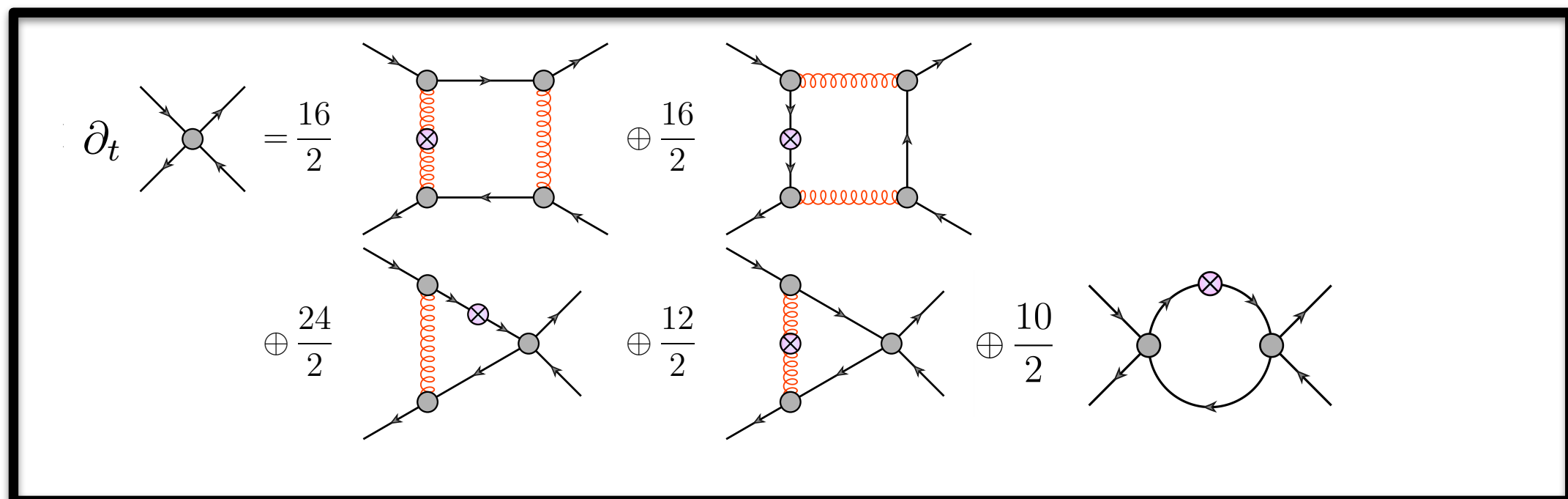
Beta-function of dimensionless scalar-pseudoscalar coupling

$$\partial_t \lambda = \left[2 - B(k, M_q, M_{\text{gap}}) \alpha_s \right] \lambda - A(k, M_q) \lambda^2 - C(k, M_q, M_{\text{gap}}) \alpha_s^2$$



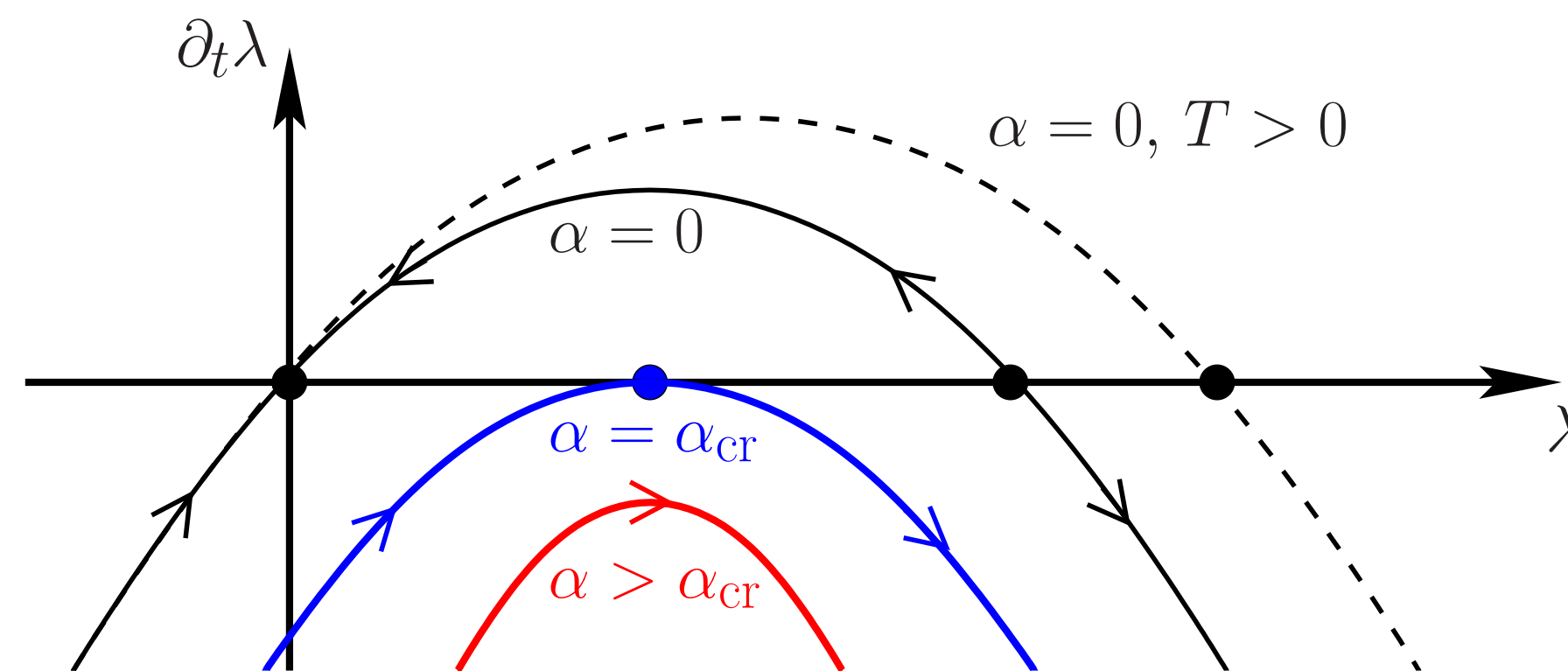
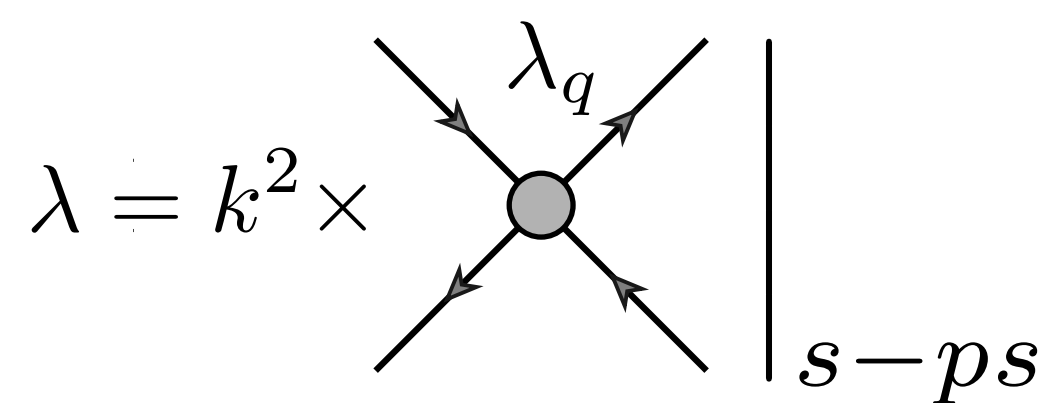
Chiral symmetry breaking

Chiral symmetry breaking in a nutshell



Beta-function of dimensionless scalar-pseudoscalar coupling

$$\partial_t \lambda = \left[2 - B(k, M_q, M_{\text{gap}}) \alpha_s \right] \lambda - A(k, M_q) \lambda^2 - C(k, M_q, M_{\text{gap}}) \alpha_s^2$$



chiral symmetry breaking $\longleftrightarrow \alpha_s > \alpha_{s,cr}$

Chiral symmetry breaking and emergent composites

functional RG: $\left(\partial_t + \int_x \dot{\Phi} \frac{\delta}{\delta \Phi} \right) \Gamma_k[\Phi] =$

glue quantum fluctuations
hadronic quantum fluctuations

$\frac{1}{2}$
quark quantum fluctuations

‘DynHad for mesons & diquarks is BSE-DSE for QCD in a ‘unified’ effective action approach’

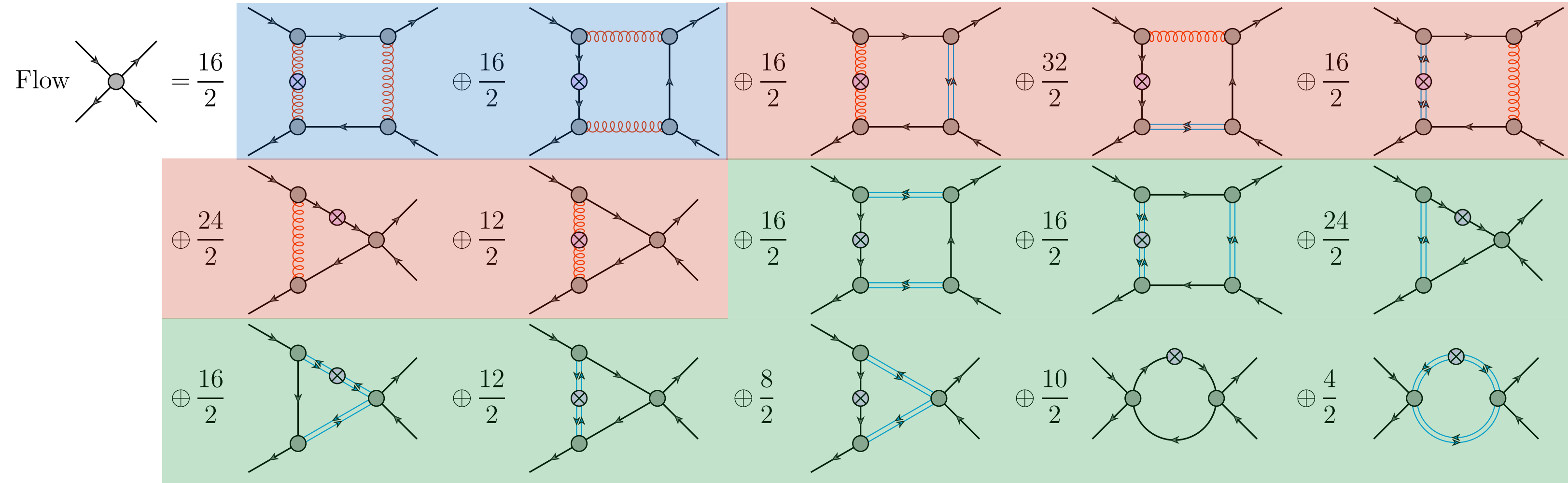
Dynamical hadronisation

where

$$\int_x h_\phi \bar{q} (T_f^0 \sigma + i\gamma_5 T_f^a \pi^a) q$$

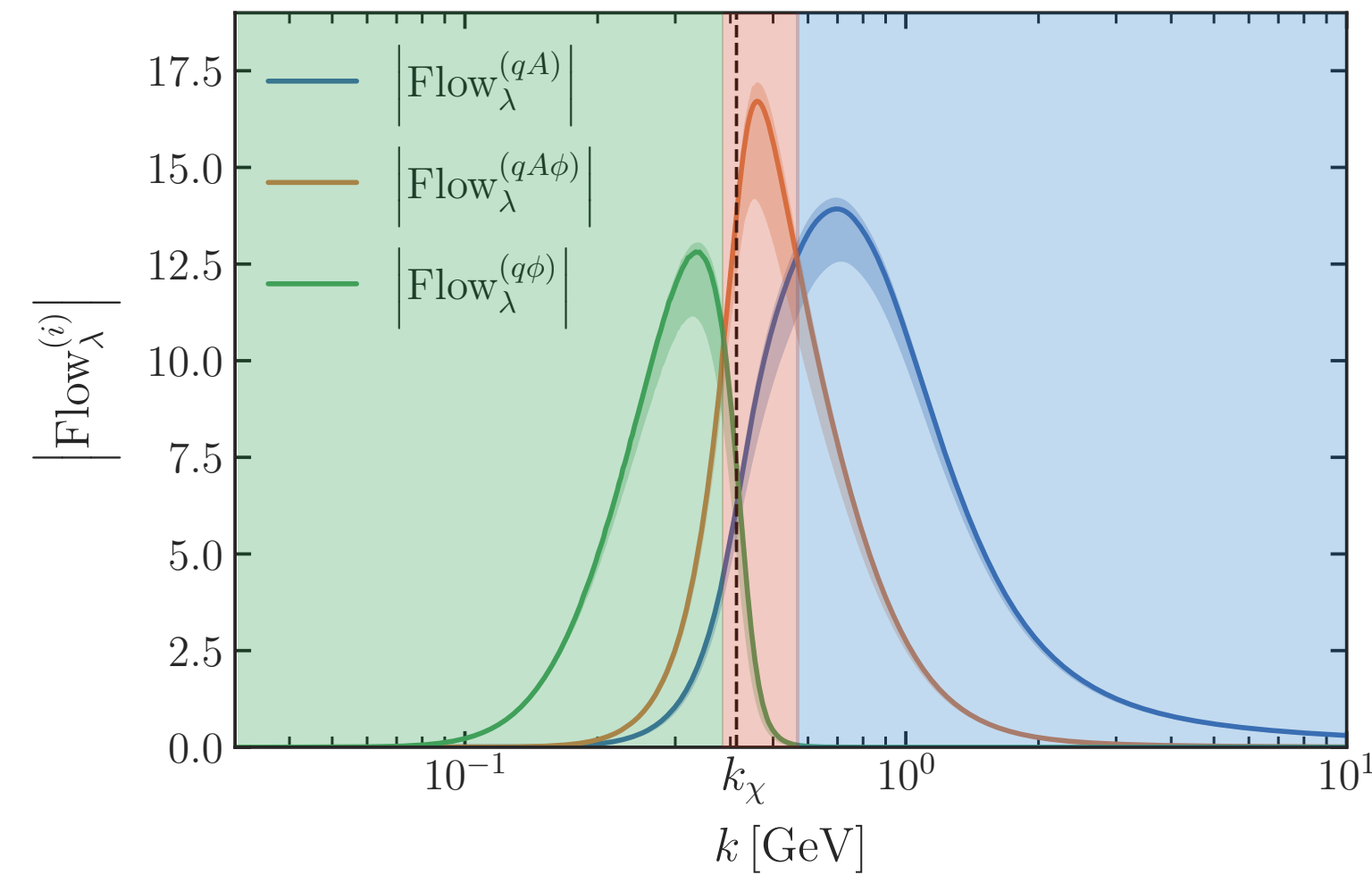
$$\phi = (\sigma, \pi^a)$$

How to: systematic error estimates & the LEGO[®] principle



Rapid convergence in QCD \rightarrow the unreasonable effectiveness of low energy effective theories

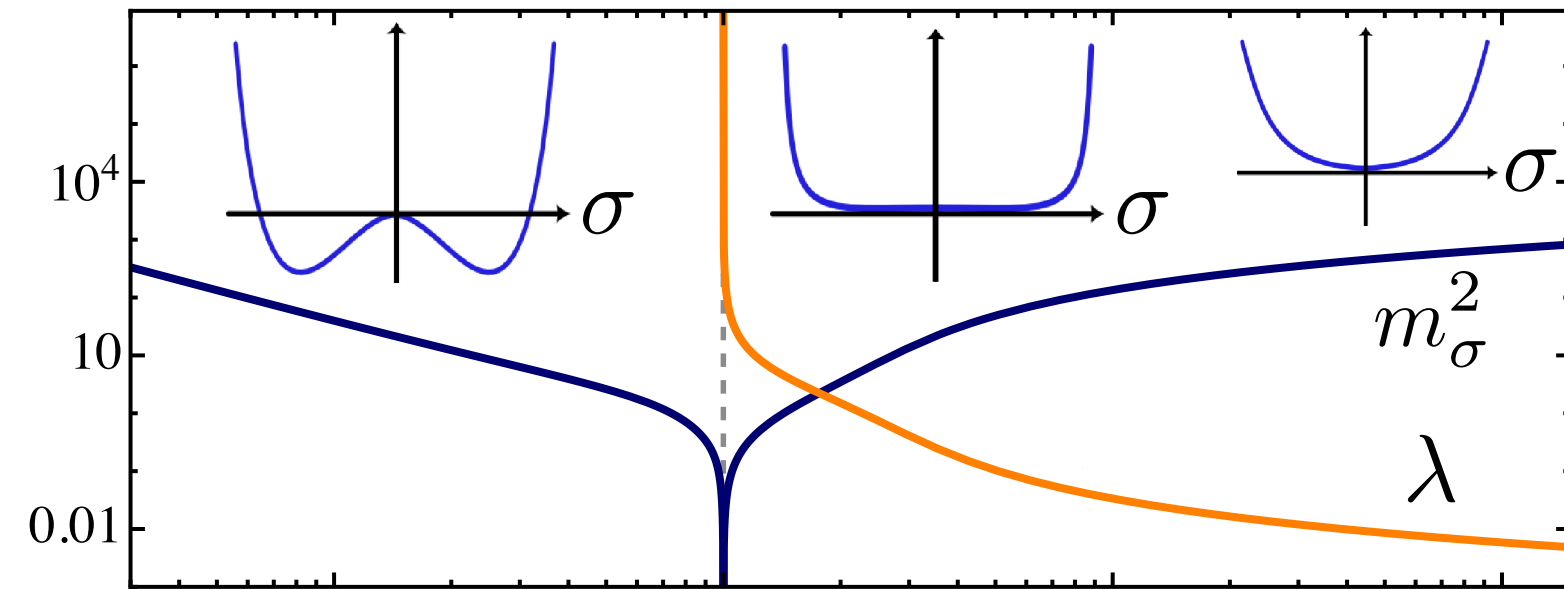
Example: 4-quark scattering vertex



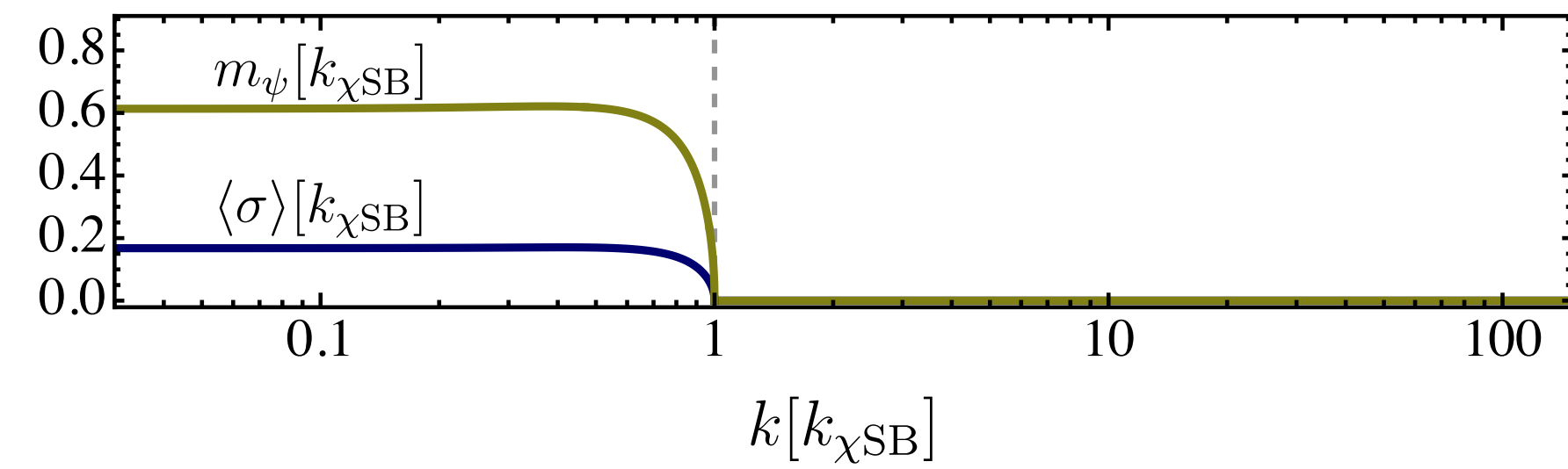
Access and combined use of error estimates from functional QCD & LEFTs

Chiral dynamics

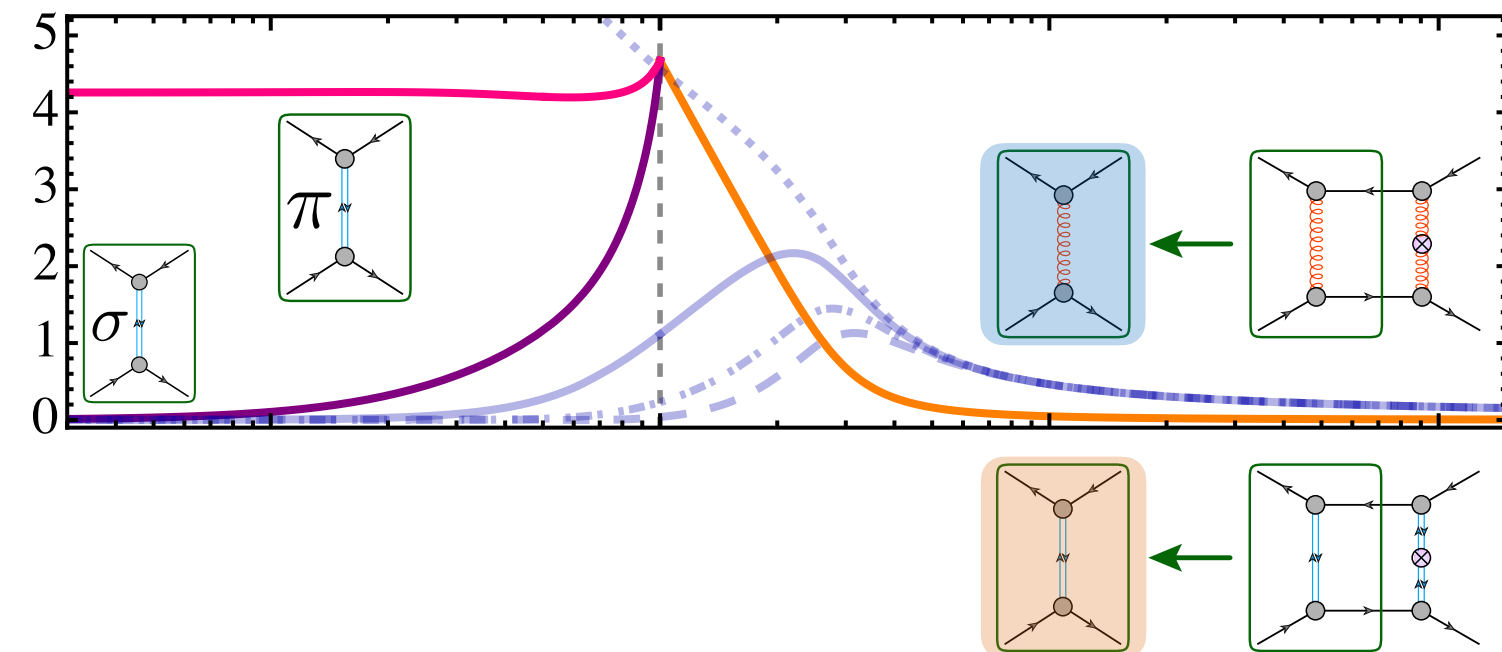
Chiral order parameter potential



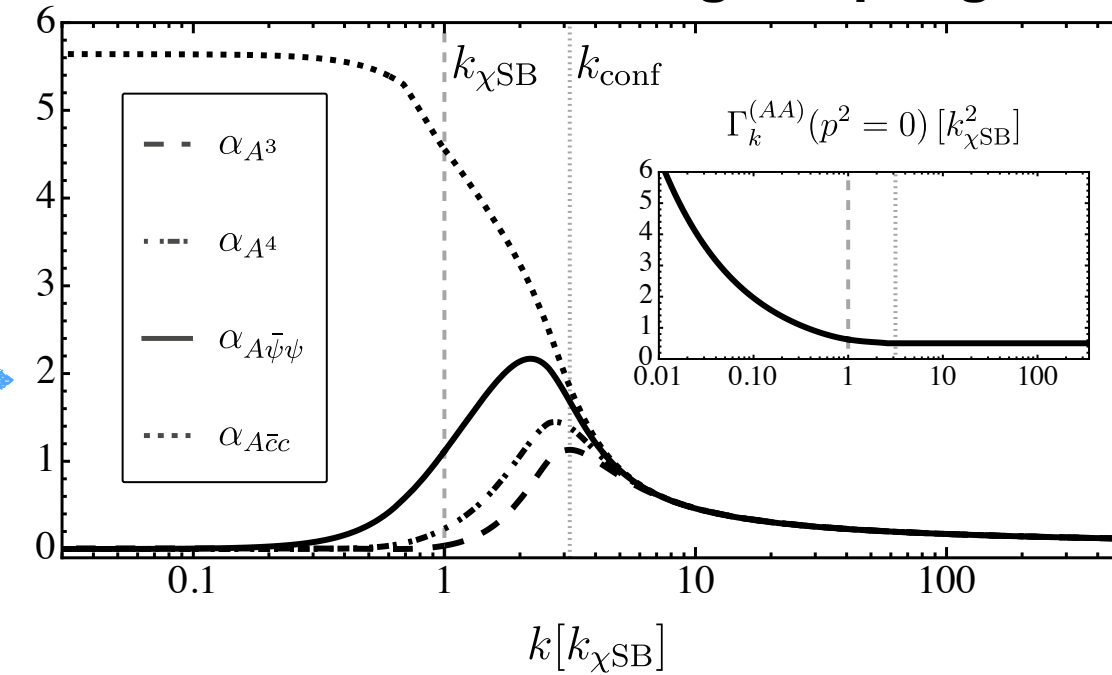
Quark mass function & 'chiral condensate'



Exchange couplings

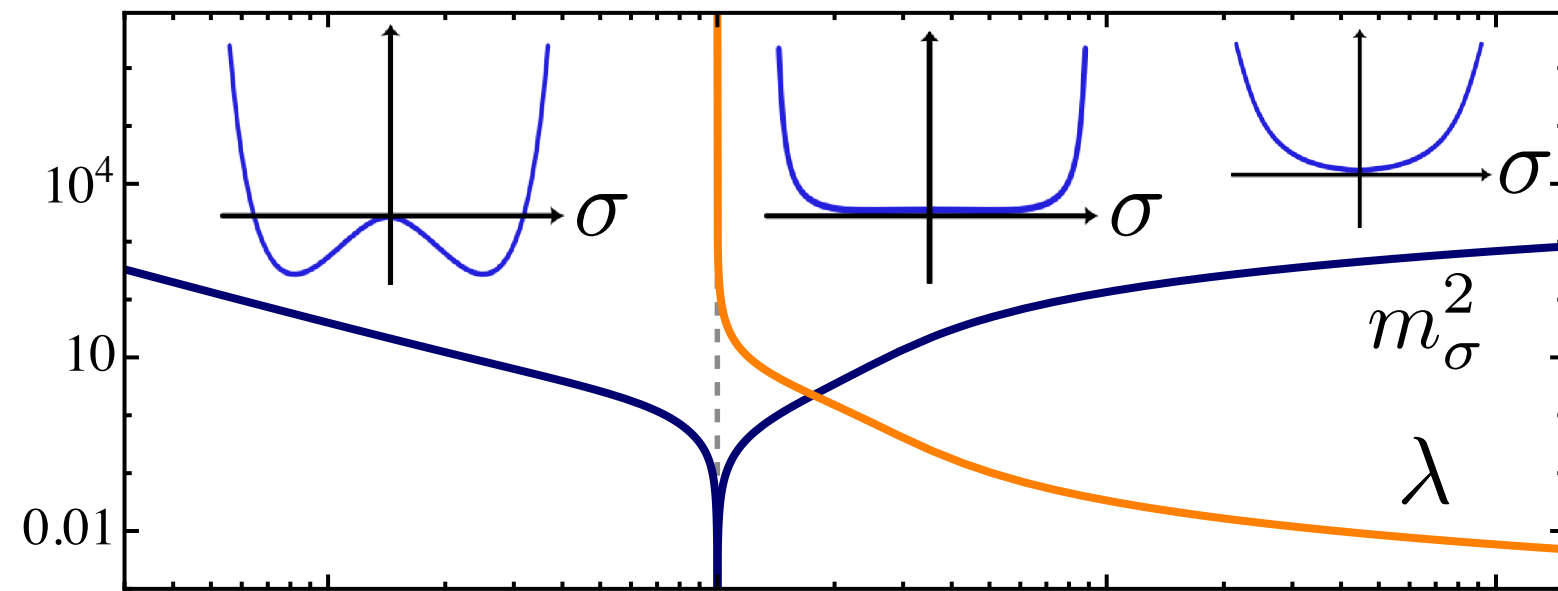


Avatars of the strong coupling

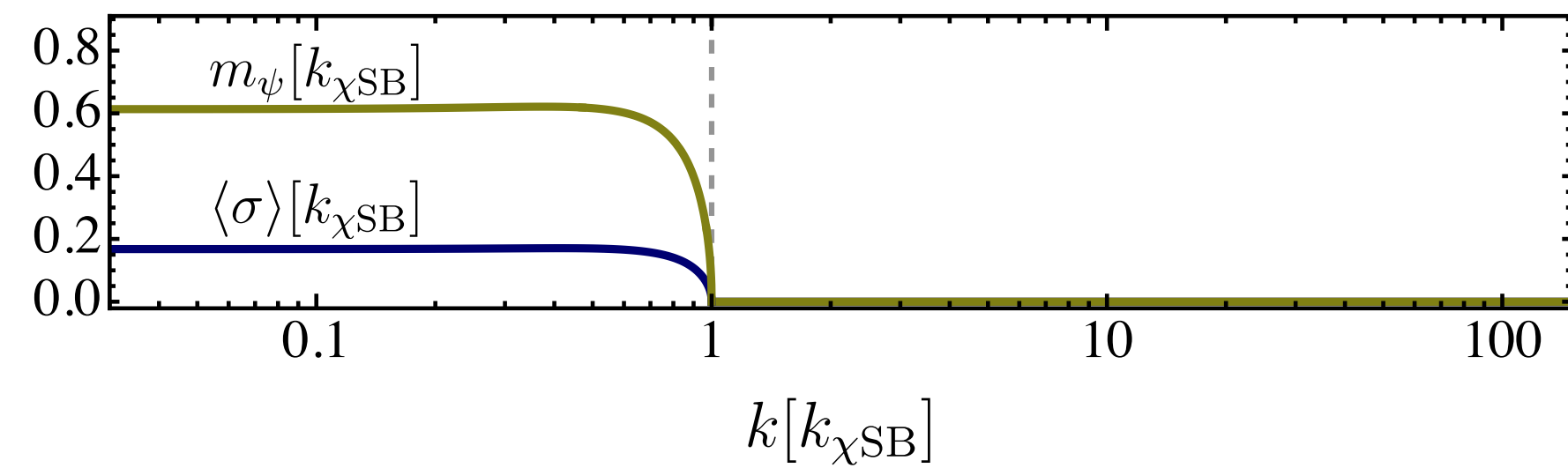


Chiral dynamics

Chiral order parameter potential



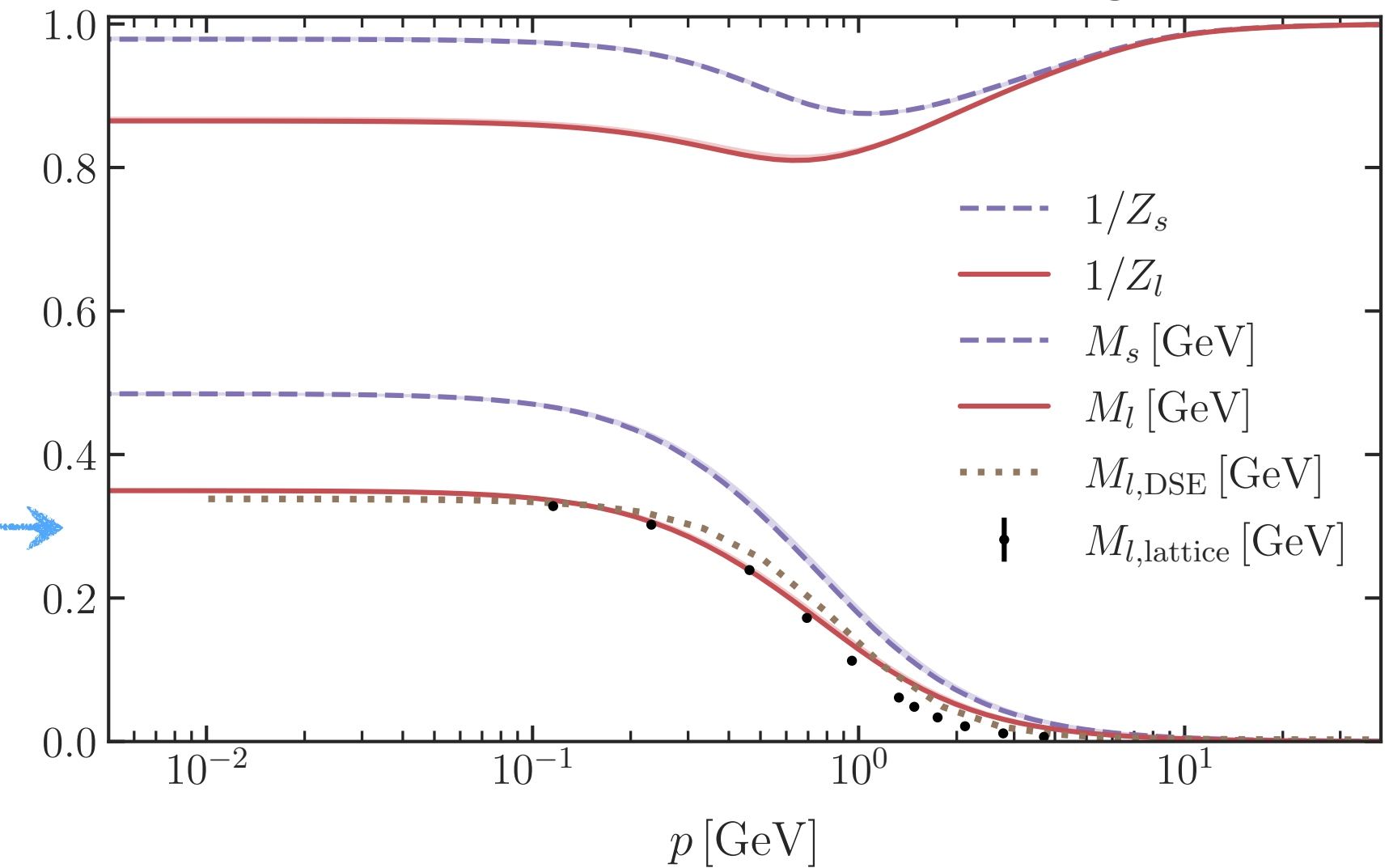
Quark mass function & 'chiral condensate'



k-mirrors of momentum dependences

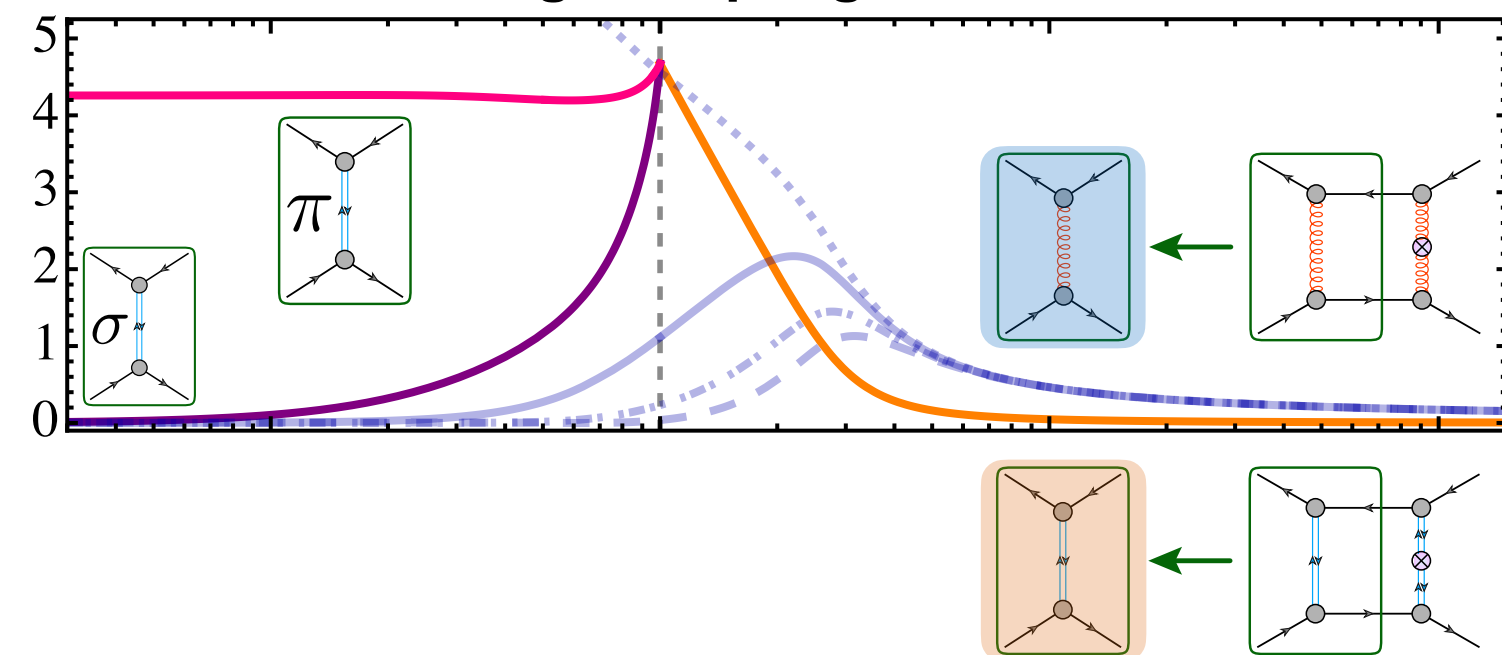
encode

Momentum-dependent quark dressings

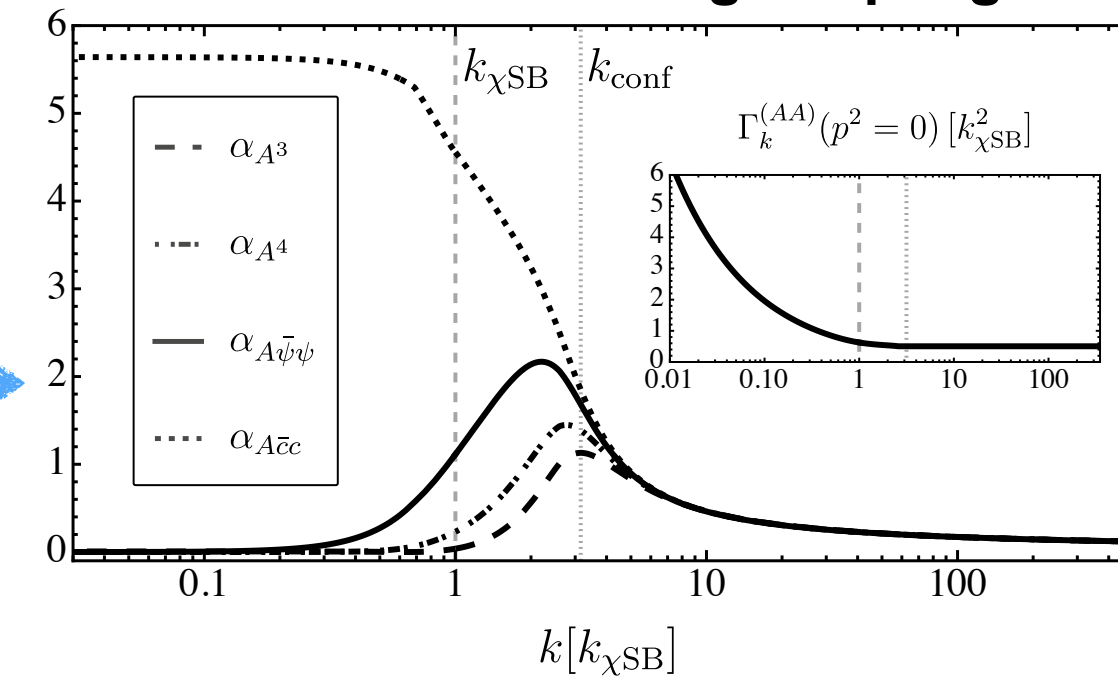


Ihssen, JMP, Sattler, Wink, arXiv: 2408.08413

Exchange couplings



Avatars of the strong coupling



Results on the phase structure of many-flavour QCD

Florian Goertz, **Álvaro Pastor-Gutiérrez**, JMP, in preparation

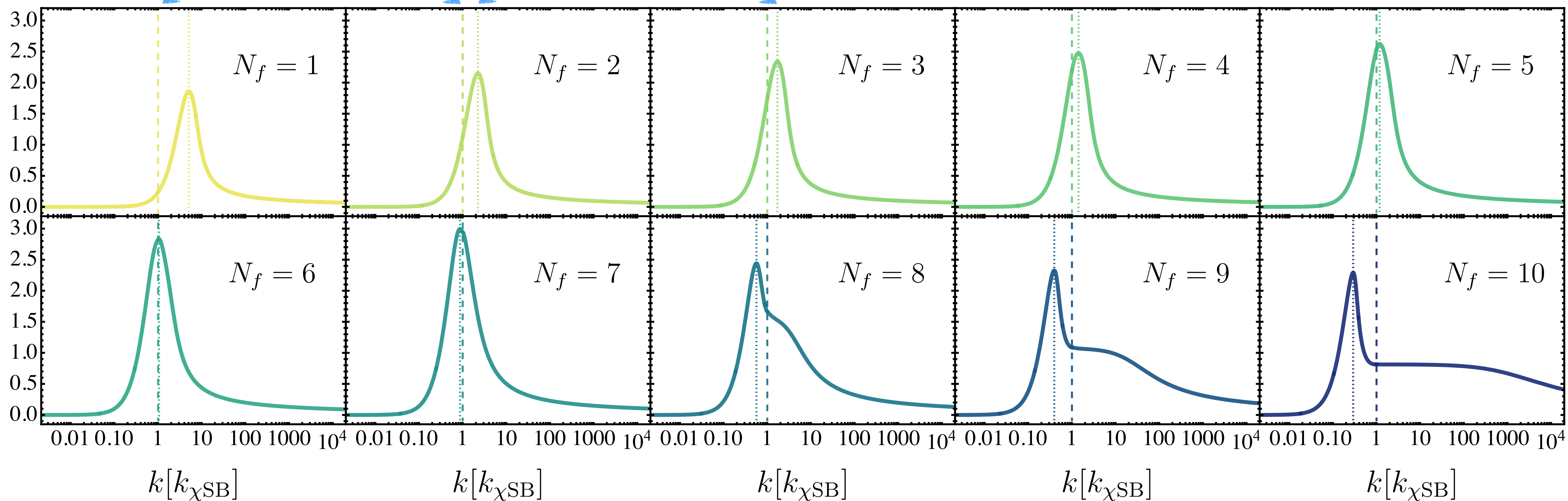
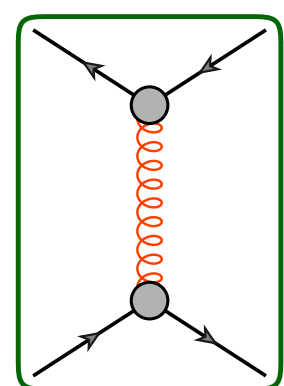
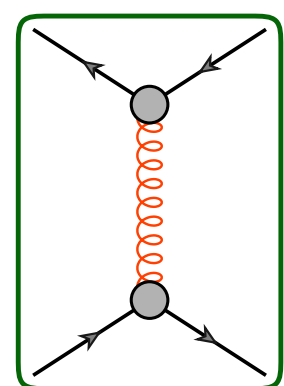
Flavour dependence of gauge dynamics

Getting conformal

RG-scale of chiral symmetry breaking

Confinement RG-scale

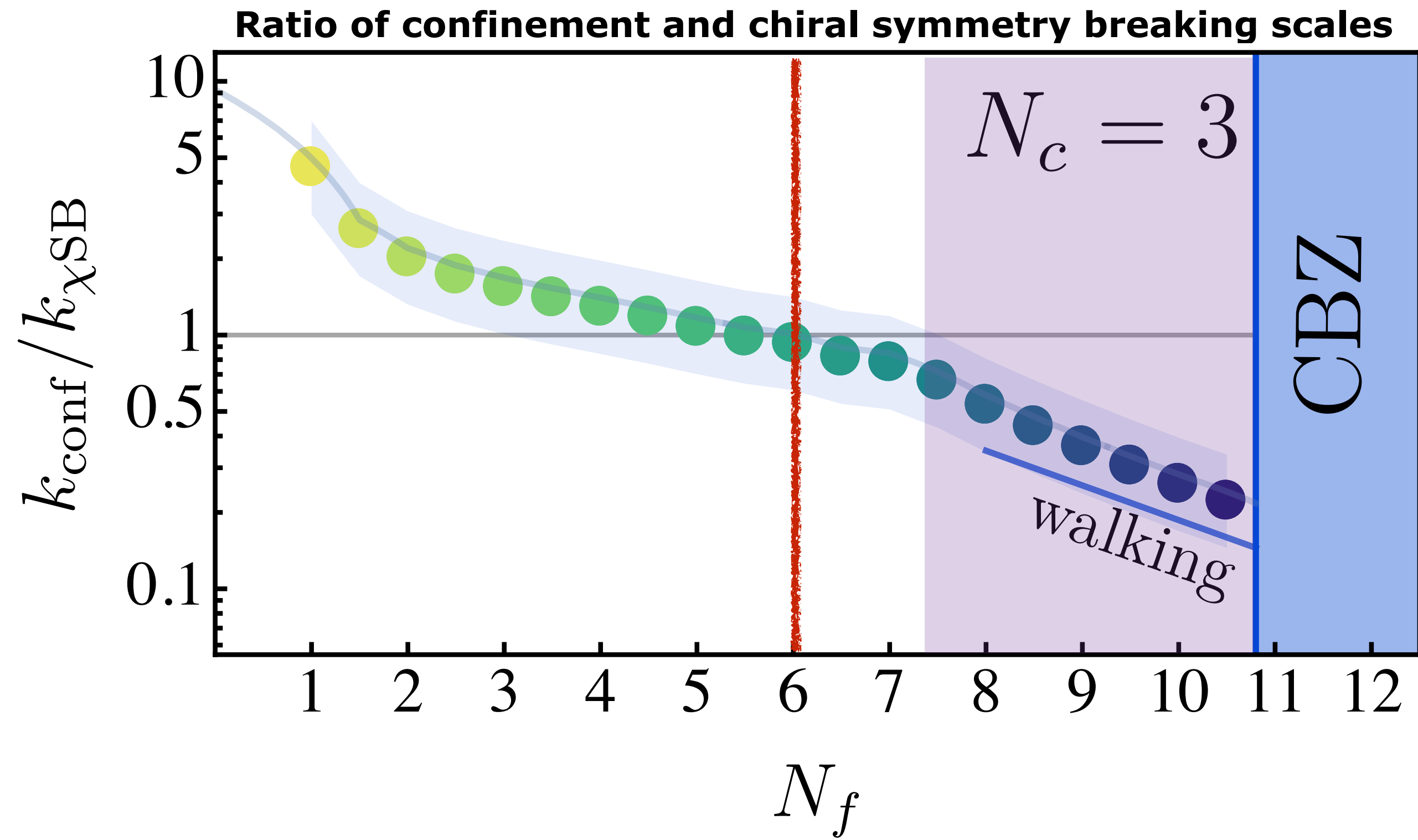
$$N_f \leq 5 : k_{\text{conf}} > k_{\chi}$$



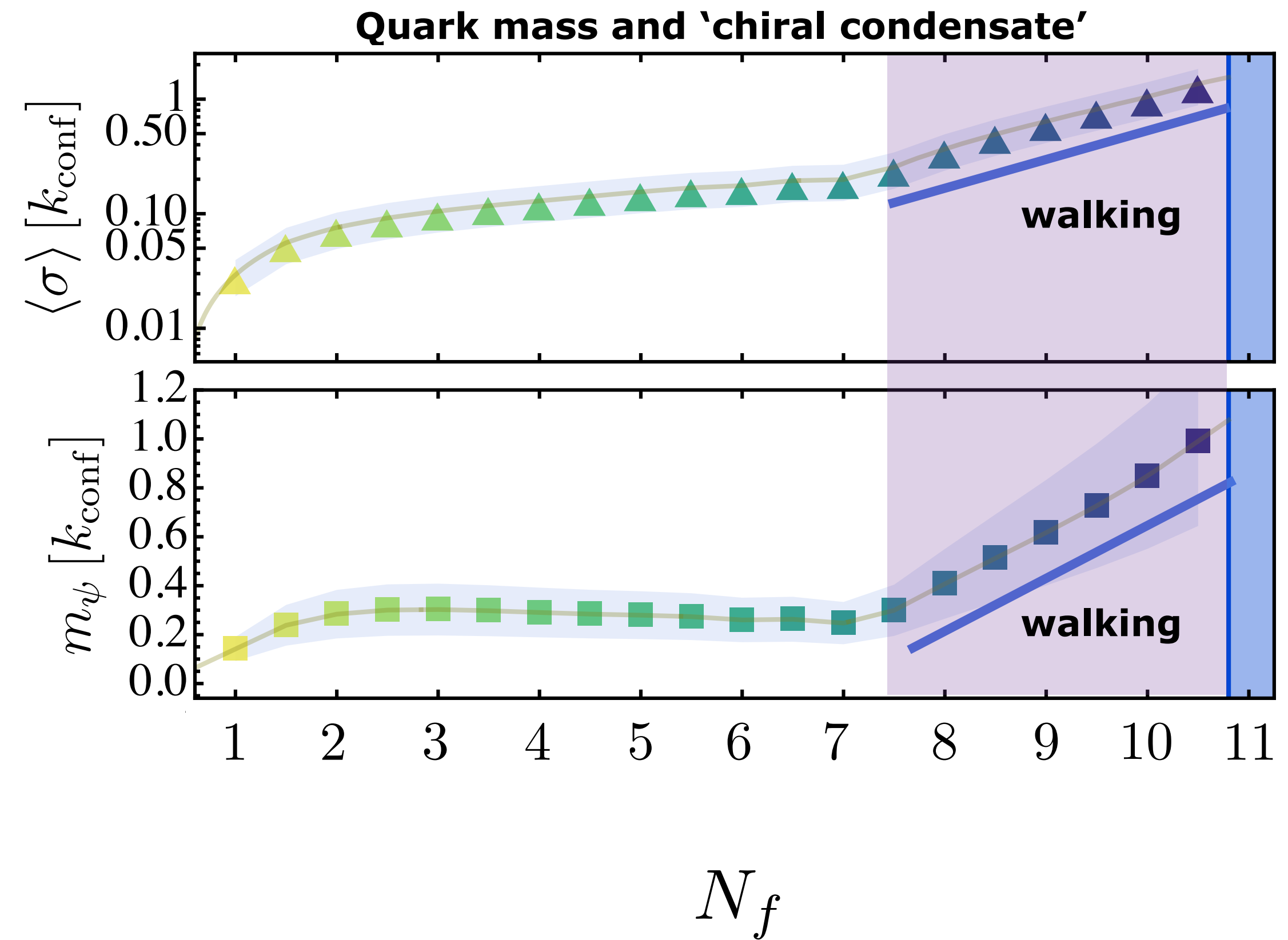
$$N_f = 6 : k_{\text{conf}} \approx k_{\chi\text{SB}}$$

$$N_f > 6 : k_{\text{conf}} < k_{\chi}$$

Interplay of confinement & chiral symmetry breaking scales

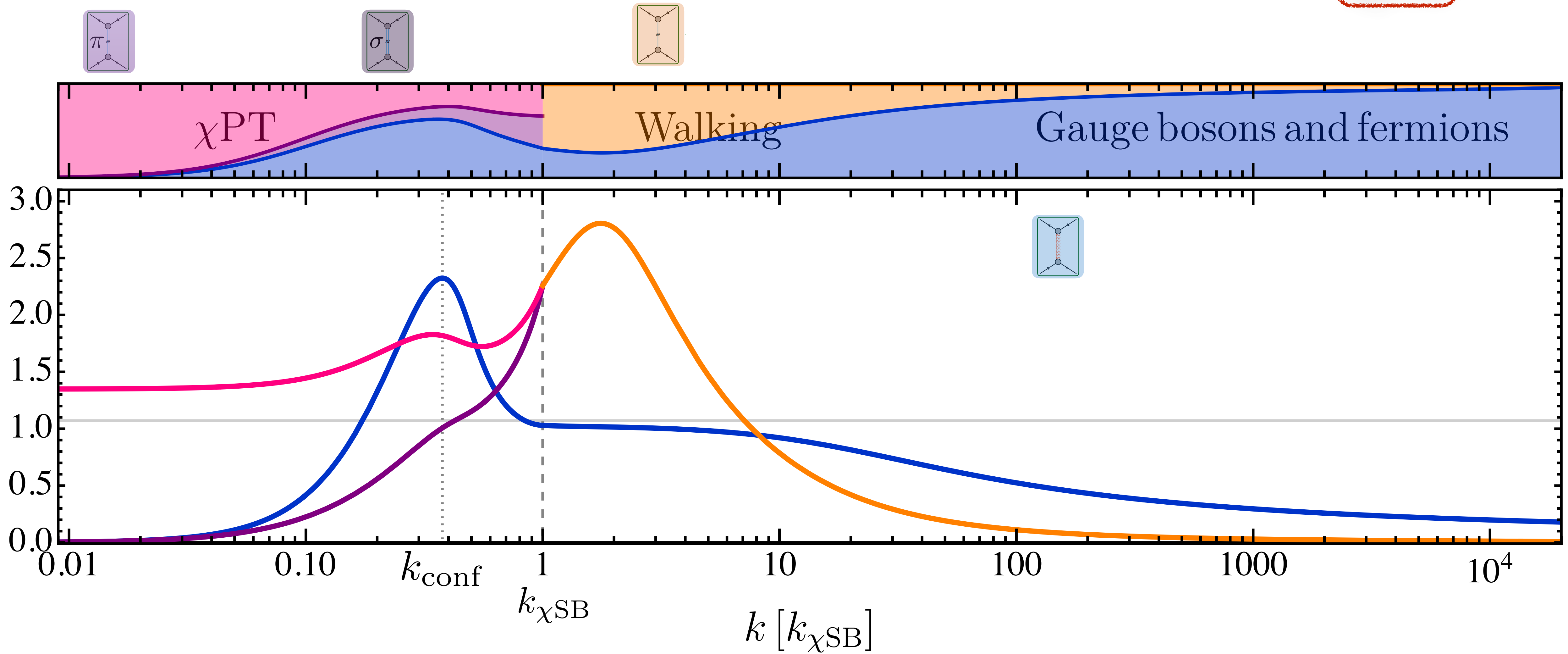


$N_f = 6 : k_{\text{conf}} \approx k_{\chi\text{SB}}$



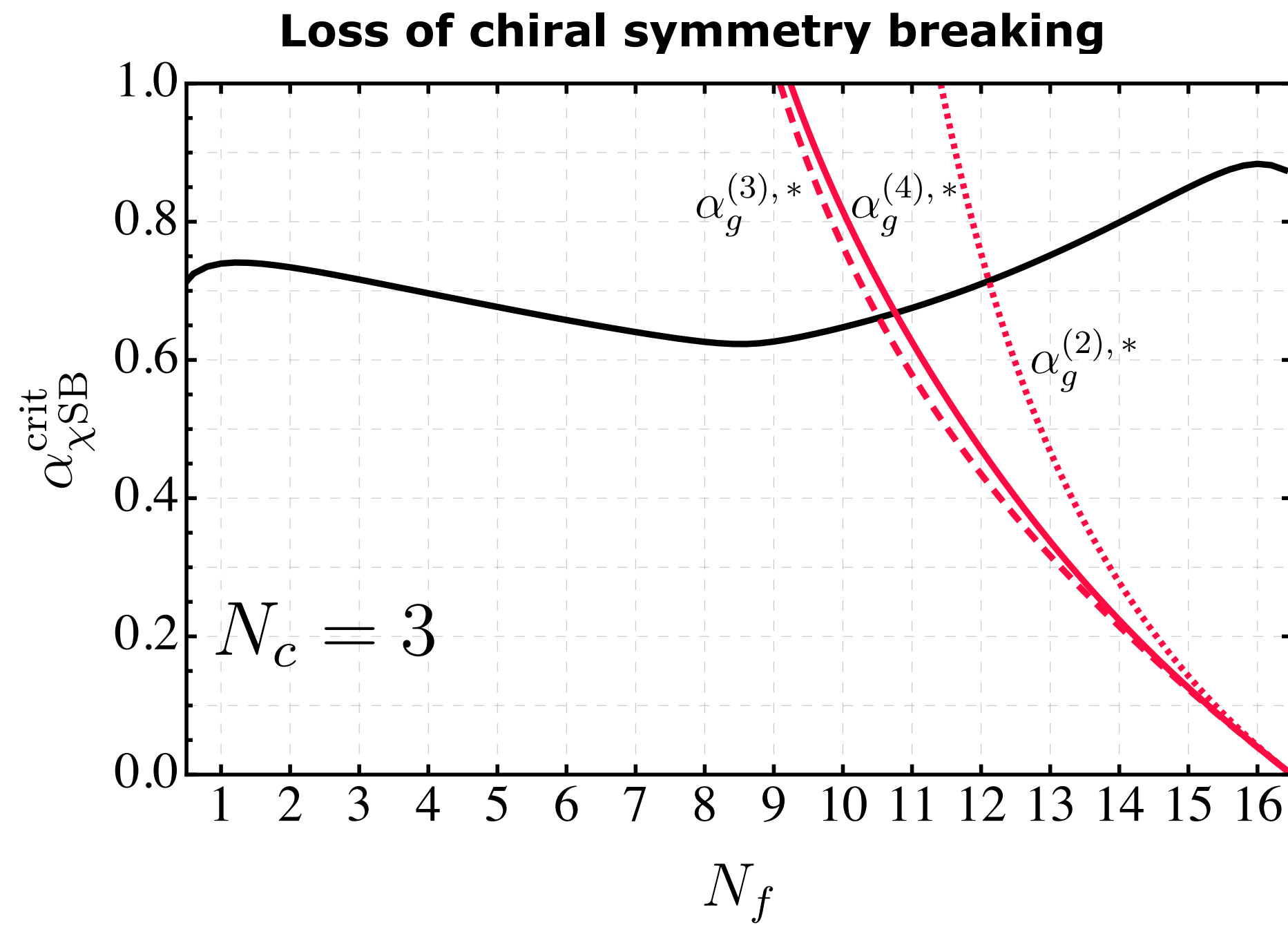
Walking dynamics

$$N_f = 9$$

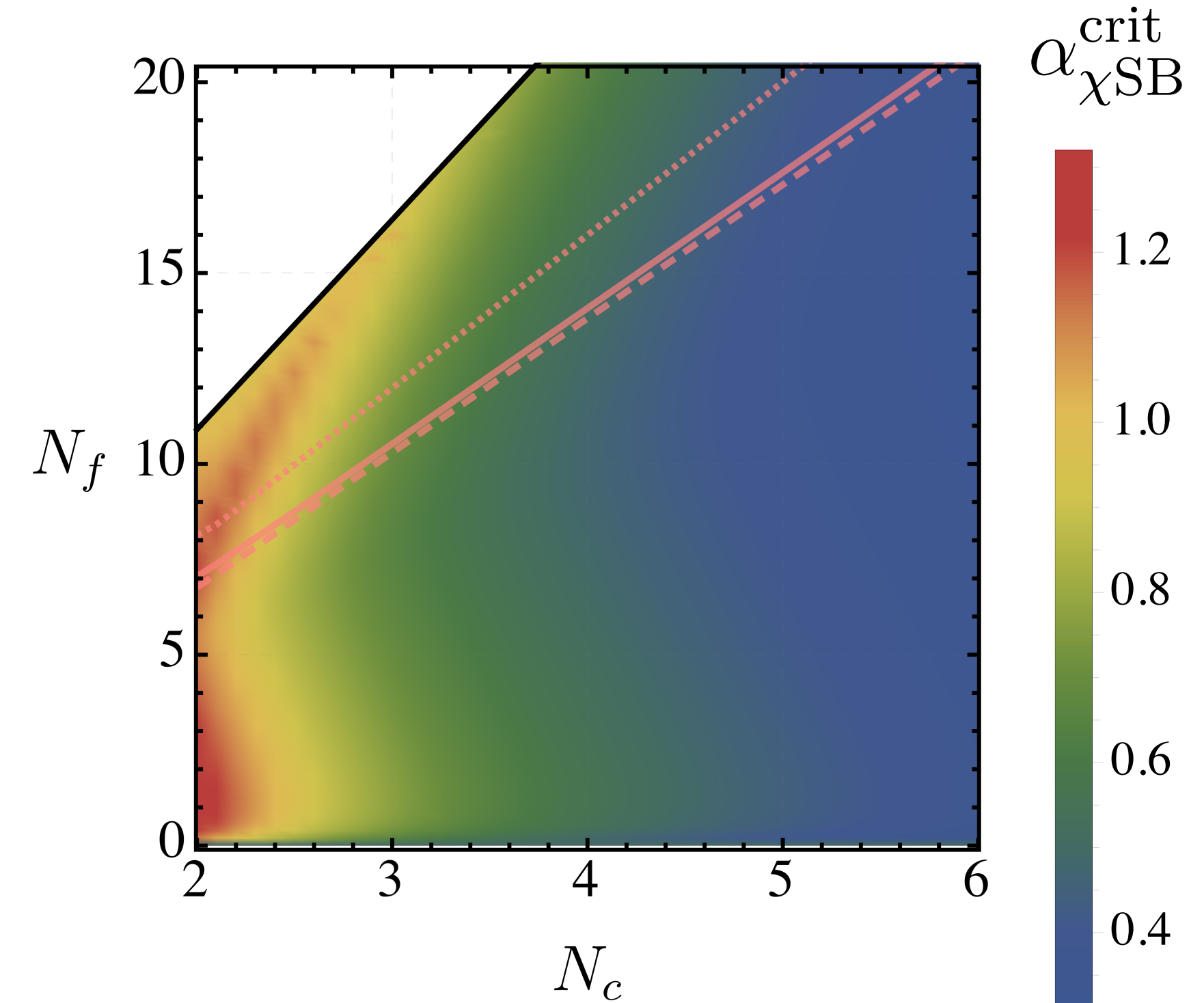


Lower boundary of the CBZ-window

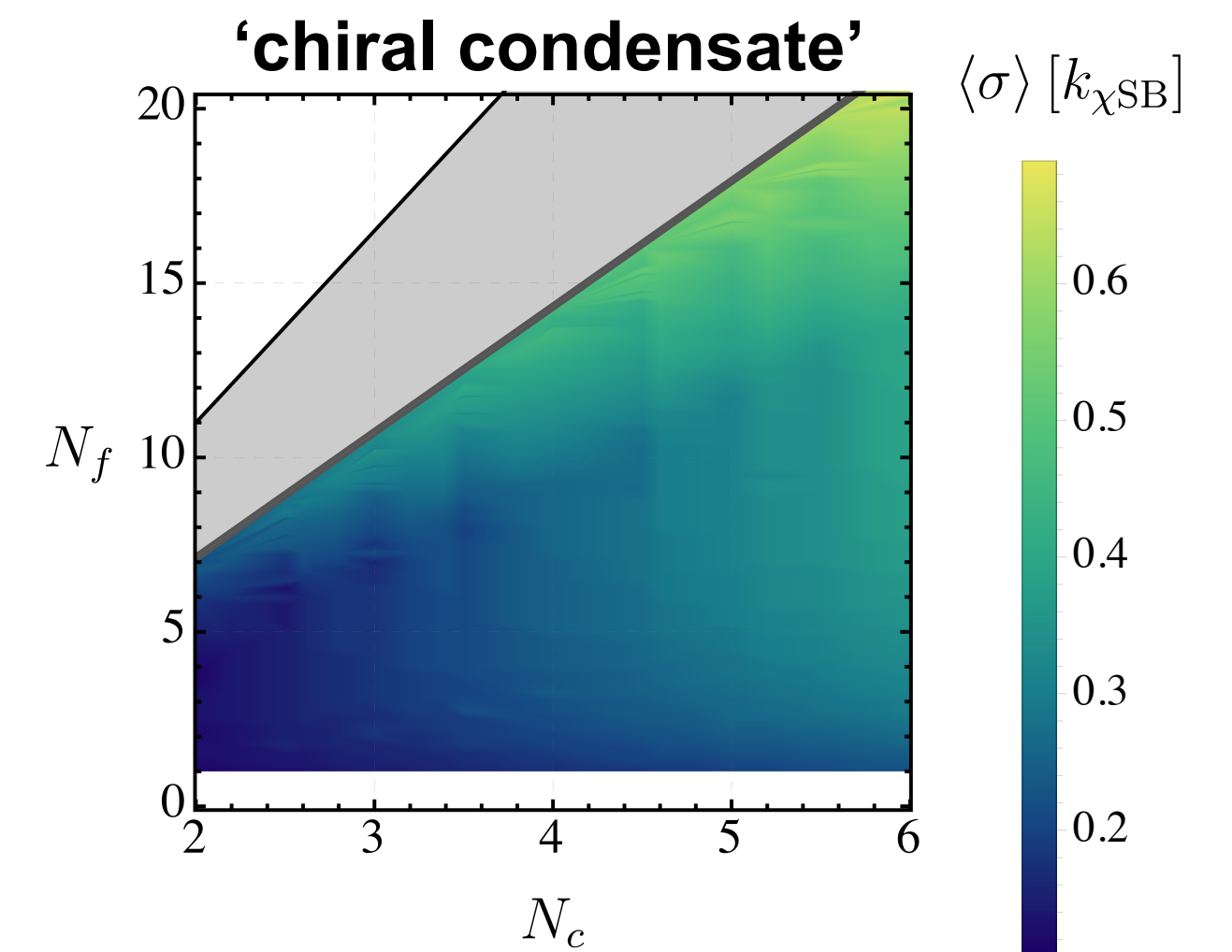
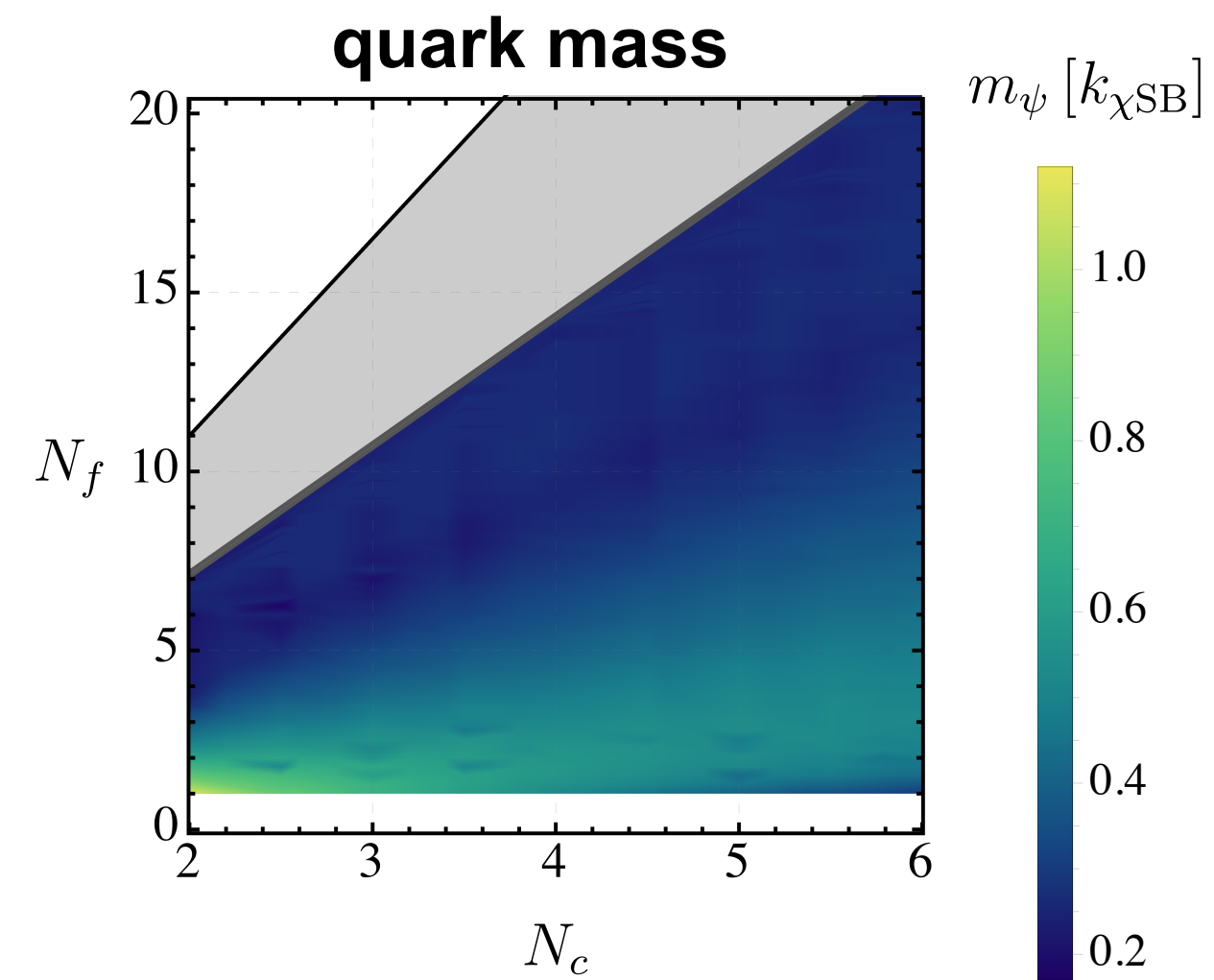
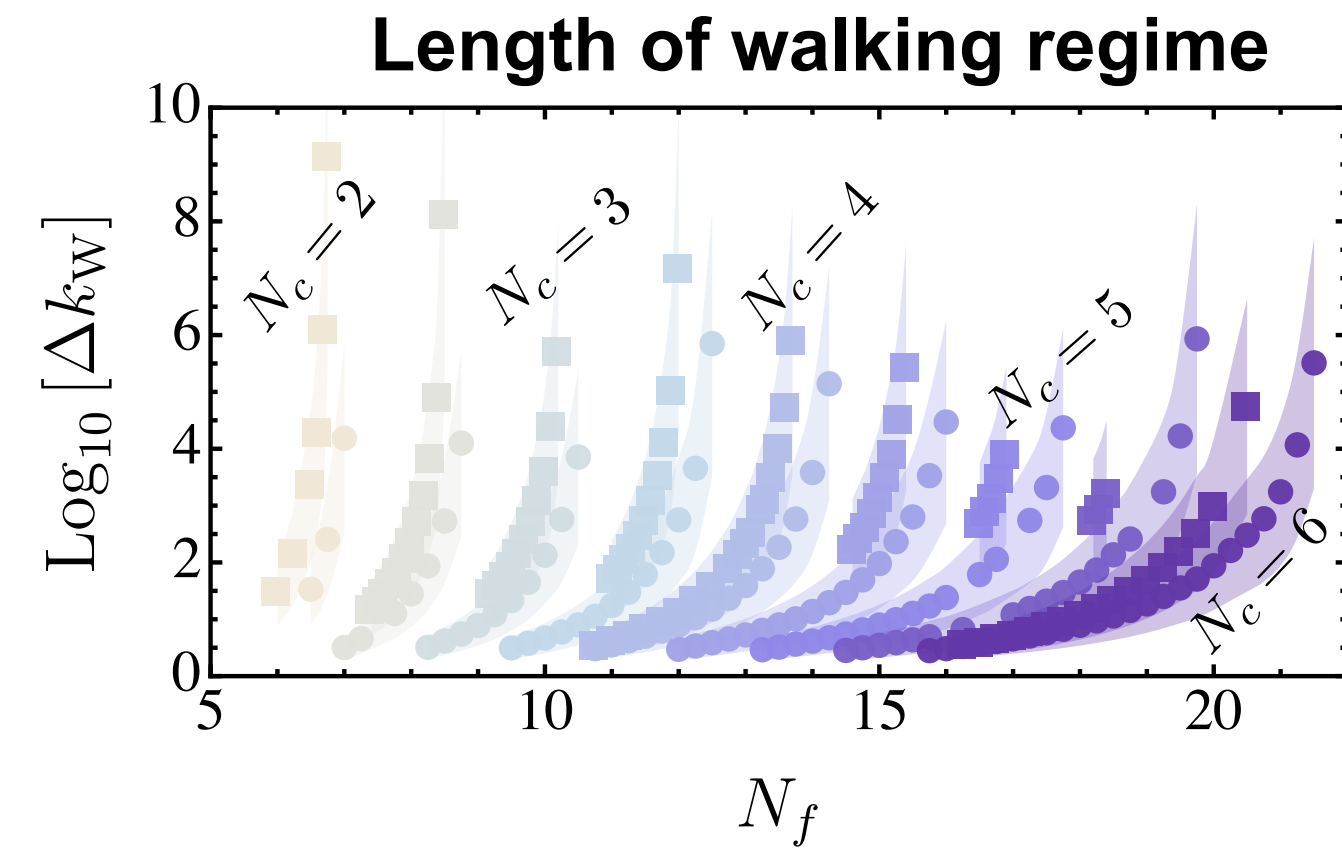
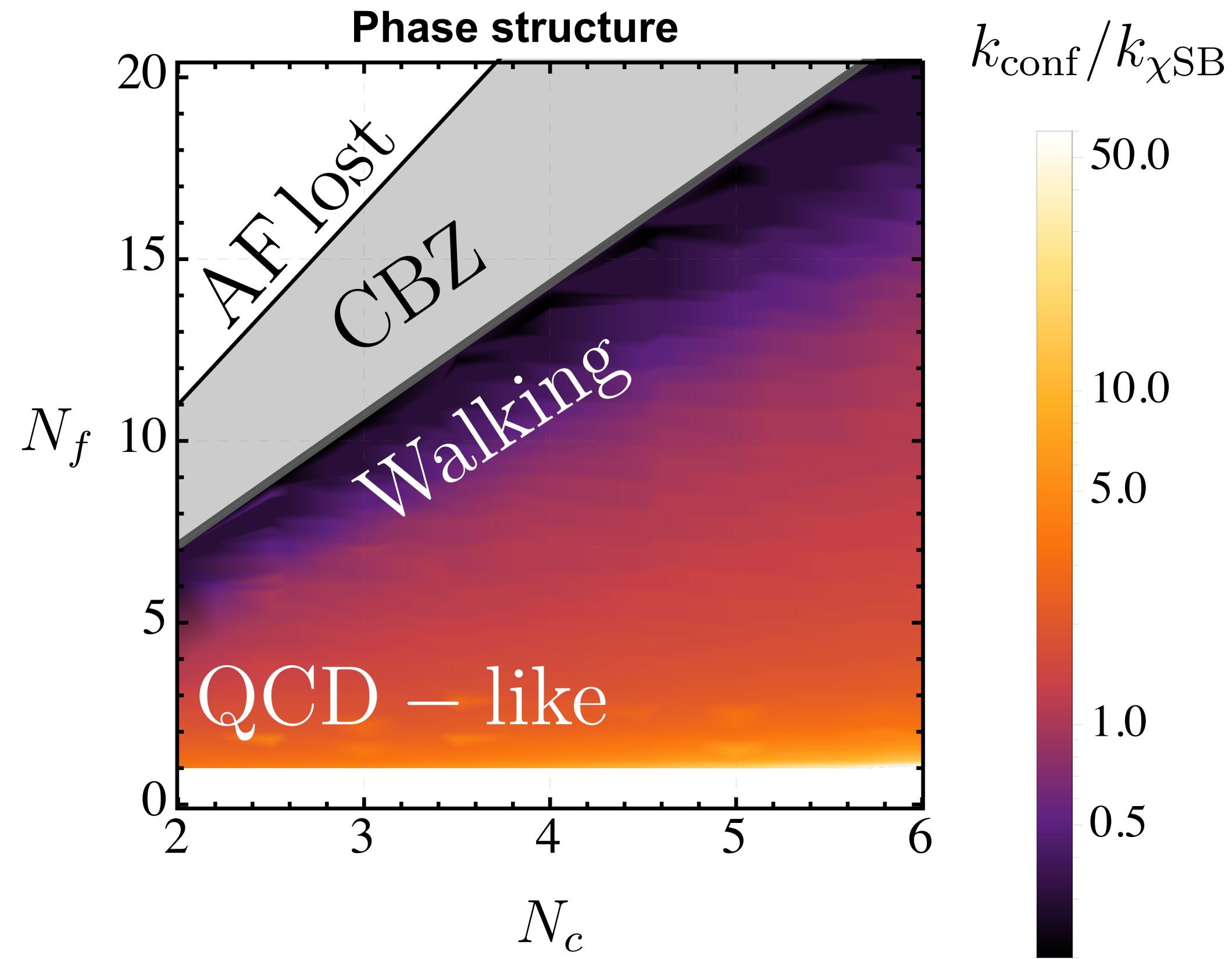
$$\frac{k_{\text{conf}}}{k_{\chi\text{SB}}} \rightarrow 0 \longrightarrow \alpha_{\chi\text{SB}}^{\text{crit}} = \alpha_g^*$$



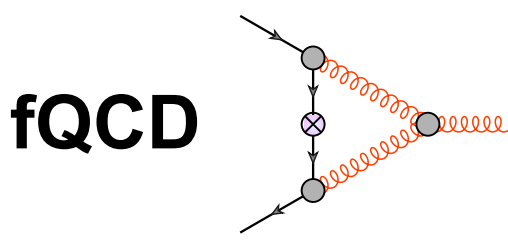
$$N_f^{\text{crit}} \approx 10.8$$



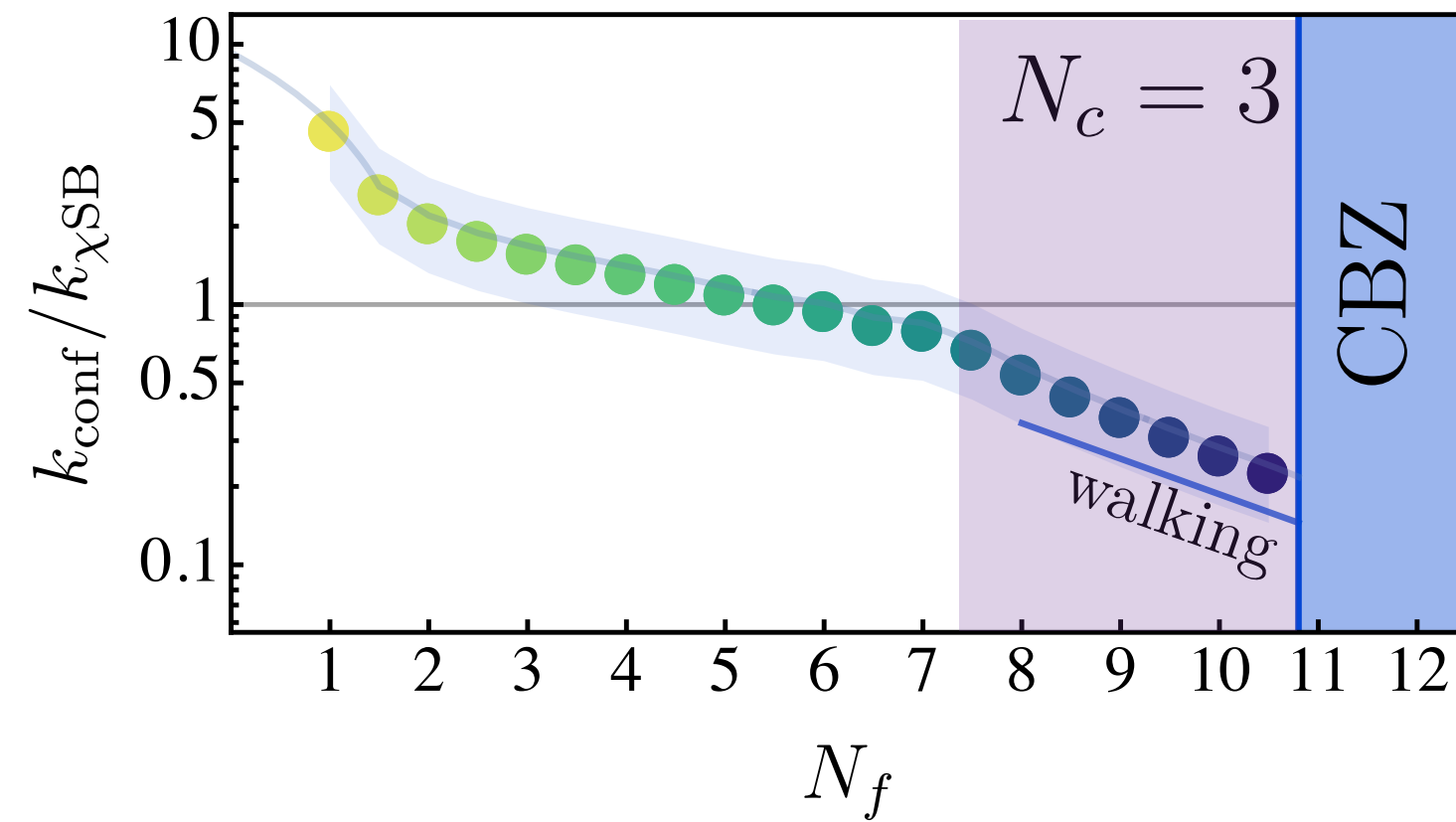
Phase structure of many flavour QCD



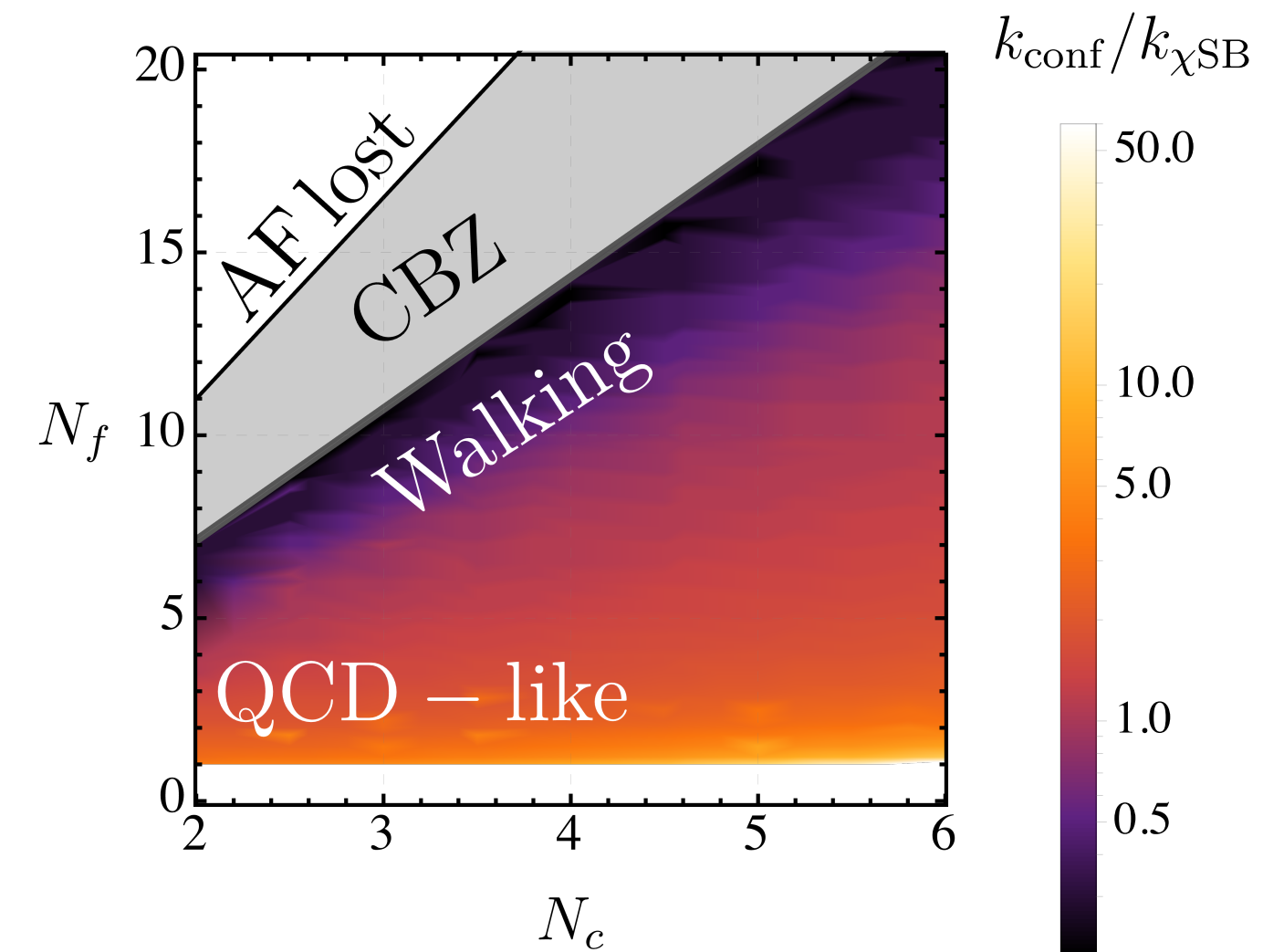
Summary



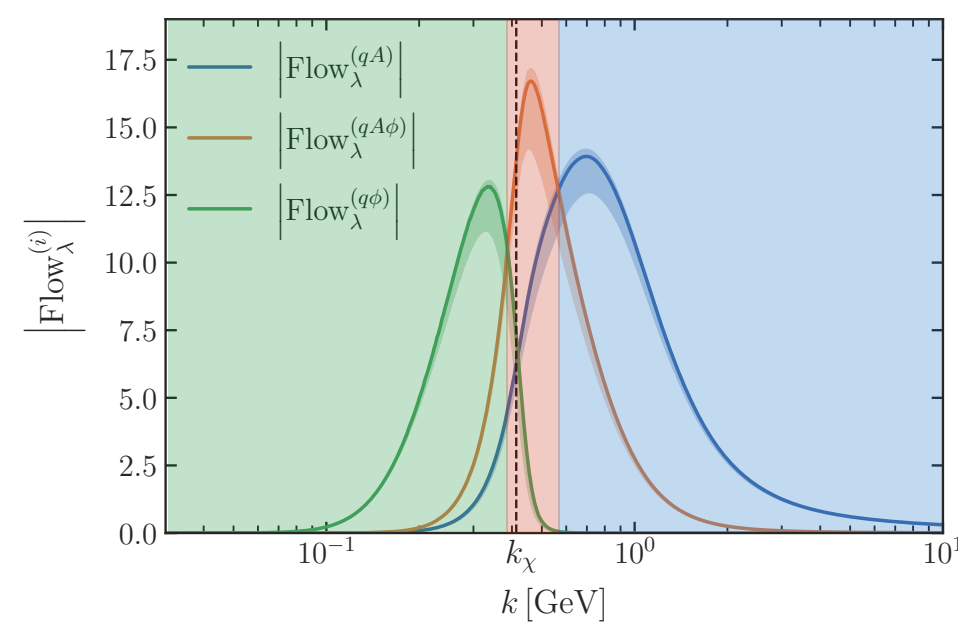
- Functional renormalisation group approach to confining and chiral symmetry breaking dynamics in many-flavour QCD



- Phase structure of many-flavour QCD with full chiral dynamics



- Systematic error estimates with the LEGO[®] principle



Stage is set: Stay tuned!