Conformal or Confining

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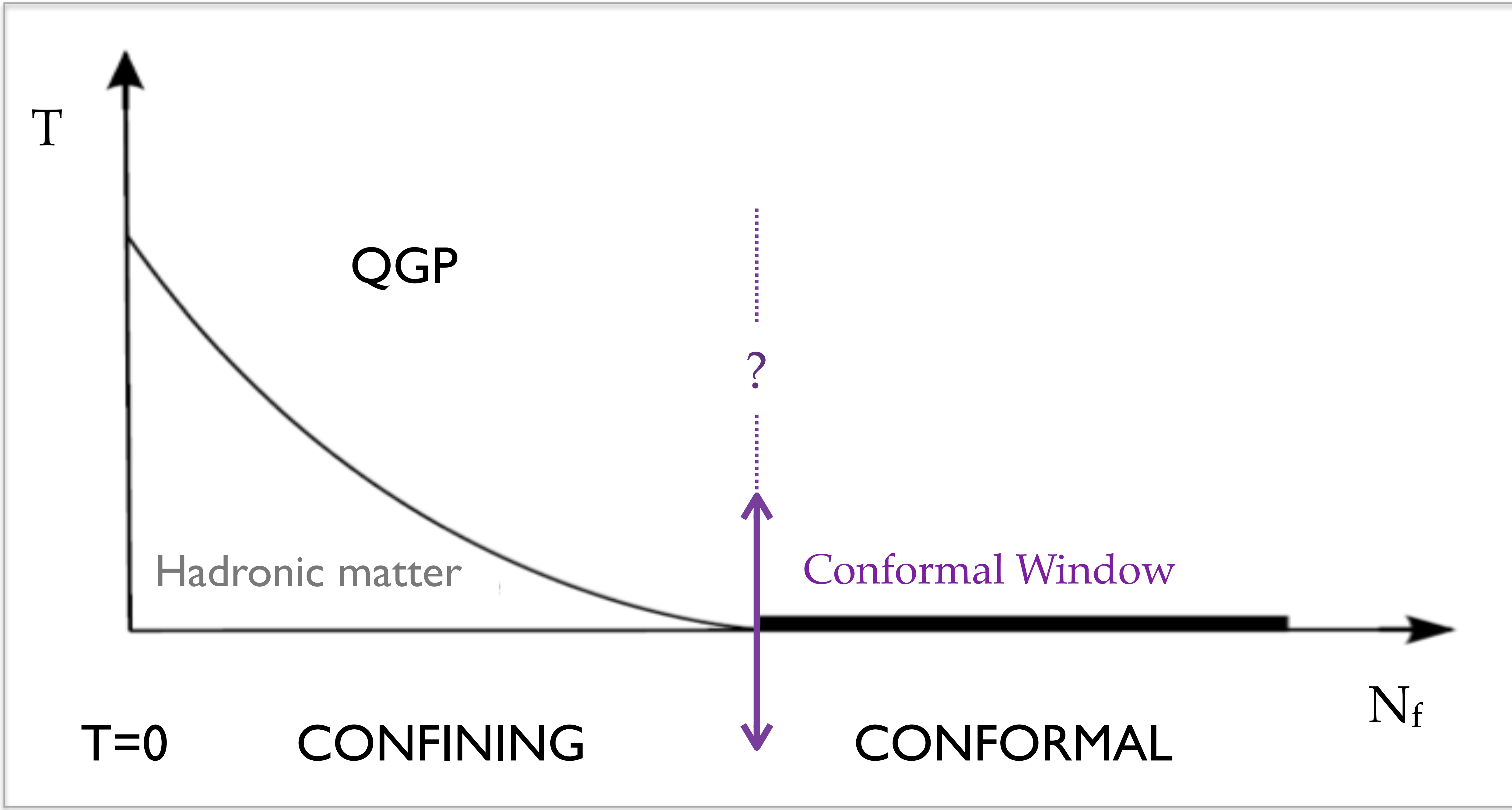
Theory of this seminar:

QCD-N_f = Yang-Mills + N_f massless Dirac fermions in Fund repr.

- Find its phase diagram

References:

- 2009 Nf=12: Evidence for existence of conformal window (CW)
  Theory has IRFP
- 2009-13 Explored possible non-trivial UVFP
  Explored chiral phase boundary below conformal window
  "Exotic" phase in CW found due to improvement of lattice action
  Properties of exotic phase clarified (NB: it applies to e.g. graphene)
- 2014 Spectrum in CW (Nf=12 as prototype); gamma_m $\approx$ 0.12
  Theory in analogy with quantum critical phenomena
- arXiv:1506.06396: Lower edge CW, Scalar glueball anomalous dimension
- arXiv:1509.00733: Topology, U(1) axial anomaly
  Glueballs and Wilson flow
  Breaking of conformal symmetry & spectrum:
    - QCD in isolation (no dilaton)
    - Embedding in complete theory (Planck scale)
      & SSB of global or local conformal symmetry



(Here = Mass-gap of Quenched QCD)

(CFT @ nontrivial IRFP Other FP's ?)

Questions

- How far is the complete theory from perturbation theory or large-N ?

  I) Interplay of confinement and chiral symmetry
  II) Consequences of removing supersymmetry

- Is there a preconformal regime ?
- Is there a non-trivial UVFP ?

Phenomenologically Appealing if:

- Conformal Window @ small Nf
- Large anomalous dimensions
- Exist (parametrically) light scalars

Outline

- The scalar glueball anomalous dimension
- The lower edge of the conformal window

Nunes da Silva, EP, Robroek arXiv:1506.06396

Question

How far is the complete theory from perturbation theory or large-N ?

Trace anomaly of QCD

$$T^{\mu}_{\mu} = \frac{\beta(\alpha)}{16\pi\alpha^2}\,\mathrm{Tr}(G^2) + \text{fermion mass contribution}$$

$$\beta(\alpha) \equiv \frac{d\alpha(\mu)}{d\ln\mu} \qquad \alpha \equiv \frac{g^2}{4\pi}$$

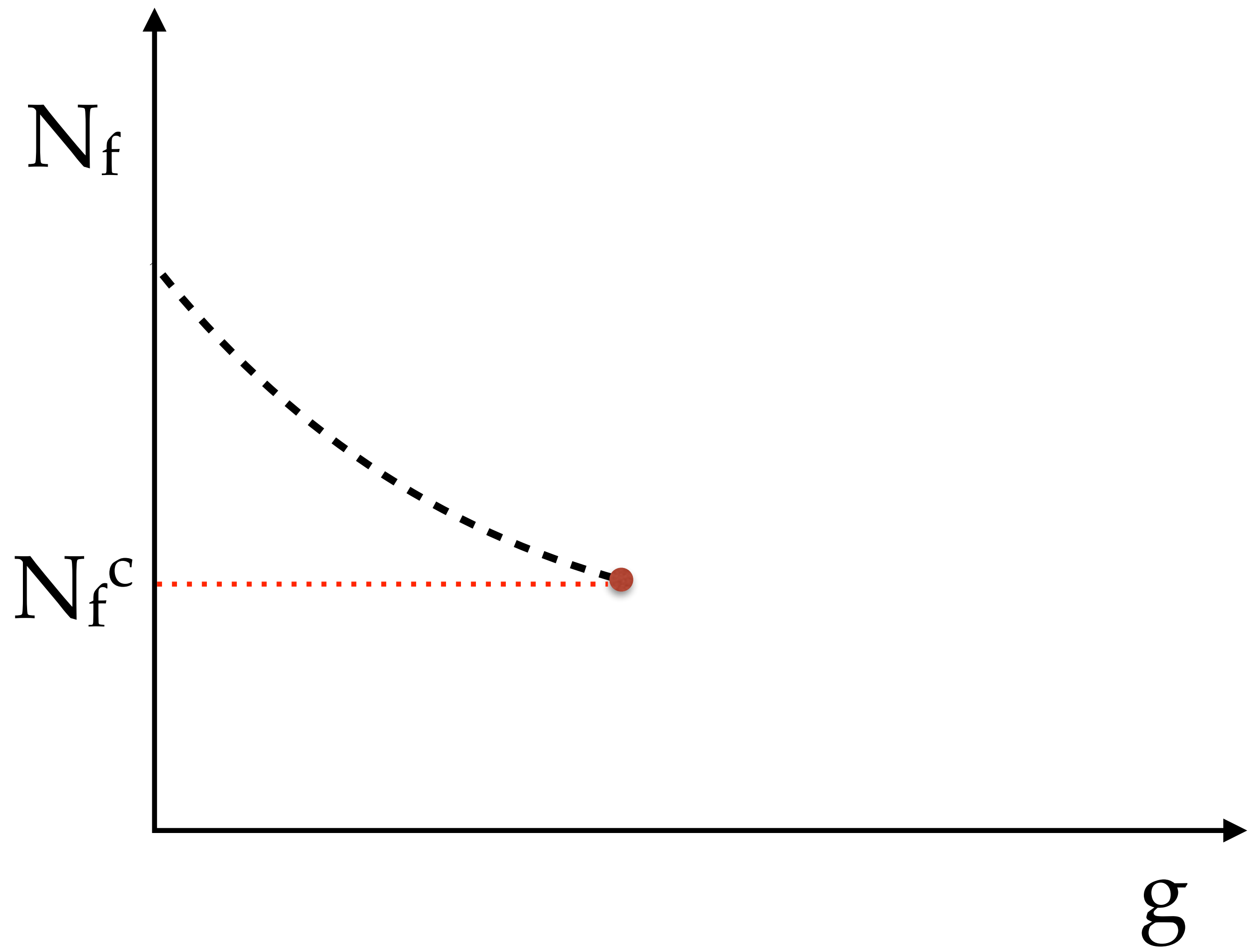
Scaling of a quantum operator

$$\frac{dO}{d\ln\mu} = d_O O \qquad O(\mu) \sim \mu^{d_O} \qquad\qquad d_O = d_c + \gamma_O$$

Non renormalization of T^{μ}_{μ} implies $d_{T^{\mu}_{\mu}} = 4 \text{ in } d = 4$

$$d_G = 4 - \beta'(\alpha) + \frac{2}{\alpha}\beta(\alpha) \qquad \boxed{\gamma_G = -\beta'(\alpha^*) \ \text{IRFP}}$$

Line of IR fixed points



Perturbation Theory: $\beta(\alpha) = -\alpha \sum_{l=1}^{\infty} b_l \alpha^l$

	$n=2$		$n=3$		$n=4$	
N_f	$\alpha_{\mathrm{IR},n}$	$\beta'(\alpha_{\mathrm{IR},n})$	$\alpha_{\mathrm{IR},n}$	$\beta'(\alpha_{\mathrm{IR},n})$	$\alpha_{\mathrm{IR},n}$	$\beta'(\alpha_{\mathrm{IR},n})$
6	-	-	12.992	84.646	-	-
7	-	-	2.453	5.956	-	-
8	-	-	1.464	2.654	1.552	1.784
9	5.237	4.169	1.027	1.472	1.070	1.460
10	2.21	1.522	0.764	0.869	0.815	0.851
11	1.23	0.706	0.578	0.513	0.626	0.496
12	0.754	0.360	0.435	0.296	0.470	0.281

INCREASING $|\gamma_G|$

Two loops: $\alpha_{\mathrm{IR},2} = -b_1/b_2 \qquad \beta'(\alpha_{\mathrm{IR},2}) = -b_1^2/b_2$

Endpoint zero* is where b_2 changes sign, i.e., $\alpha_{\mathrm{IR},2} \to \infty$

* Zero is necessary but not sufficient condition

Compare with exact large-N QCD beta-function in the Veneziano limit

[Bochicchio '13]

$$\boxed{\beta(g) = \frac{g^3\, c(g)}{1 - \frac{4}{(4\pi)^2} g^2} \quad \begin{array}{l} \longrightarrow \text{zero} \\ \longrightarrow \text{pole} \end{array}}$$

c(g) contains an anomalous dimension term not present in SQCD

Lower edge of CW found at $N_f/N = 5/2$ where quantum instability of <u>glueball kinetic term</u> sets in [Bochicchio arXiv:1312:1350]

NB: Condition for zero at the lower edge of CW is (and must be) renormalisation scheme independent

Plausible picture

SQCD	$N_c + 2 \leq N_f \leq 3N_c/2$ free magnetic phase	cusp in RG flow may occur
QCD	no such phase	no cusp (differentiable flow)

The large-N beta-function suggests that the two-loop singularity (b_2=0, $\alpha_{\mathrm{IR},2} \to \infty$) is an artifact of n-loop truncated perturbation theory.

Fate of IRFP coupling

[Luescher Weisz 02
Luescher Weisz 04
Bochicchio 13]

Learn from (large-N) Yang-Mills:
A RG scheme "constructed" where the canonical coupling coincides with the physical coupling that saturates

$$V(r) = \sigma r - \frac{g^2_{phys}(1/r)}{4\pi r}$$

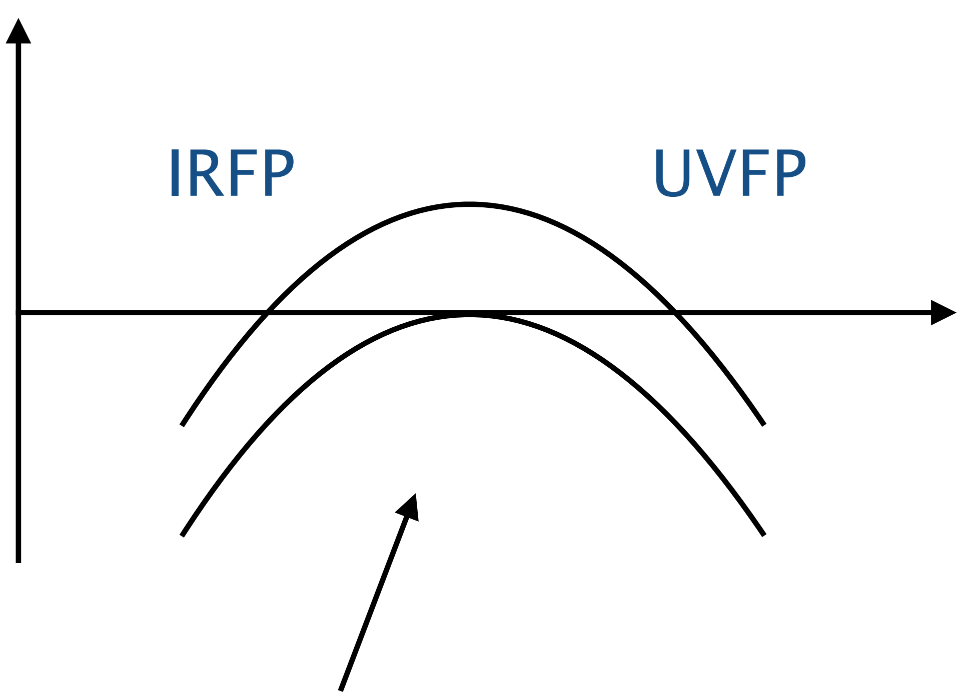
breaks conformal symmetry

If RG transformation exists, it suggests that zeros in the beta-function can occur below the conformal window

Fate of the anomalous dimension for $N_f \searrow N_f^c$

- Perturbation theory predicts an increasing $|\gamma_G|$ $(|\beta'(\alpha_*|)$
- The large-N QCD beta-function in the Veneziano limit reproduces the two-loop result up to O(1/N^2), but plausibly cures singularities.
- What happens for a UV-IR fixed-point merging ?

$$\beta(\alpha, N_f) = (N_f - N_f^c) - (\alpha - \alpha^c)^2$$



$\beta'(\alpha^c) \;=\; 0$, a local maximum at N_f^c

Its magnitude DECREASES for $N_f \searrow N_f^c$

The scalar glueball anomalous dimension can discriminate between the two mechanisms

The lower edge of the conformal window

Identify the lower edge of the CW with a lattice formulation of the theory (Euclidean action for YM+N_f) that preserves chiral symmetry

Strategy:

Use observable(s) that undergo a phase transition — other observables are likely to change smoothly across the endpoint

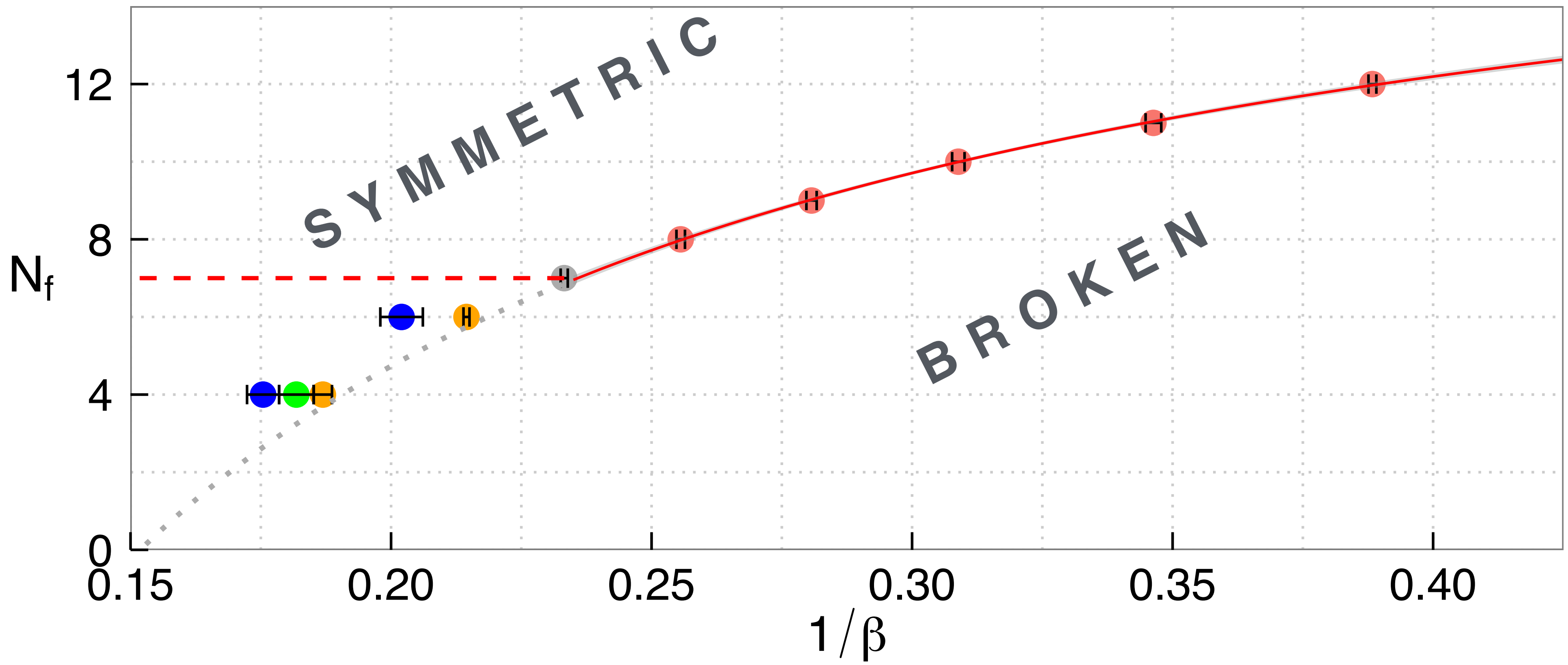
This study:

Order parameter of chiral symmetry breaking (xSB)
(Chiral symmetry restored if conformal symmetry realized)

3 signatures: Nf dependence
Nt dependence
Exotic phase at nonzero fermion mass

Line of bulk (T=0) chiral symmetry breaking phase transitions for $N_f \searrow N_f^c$

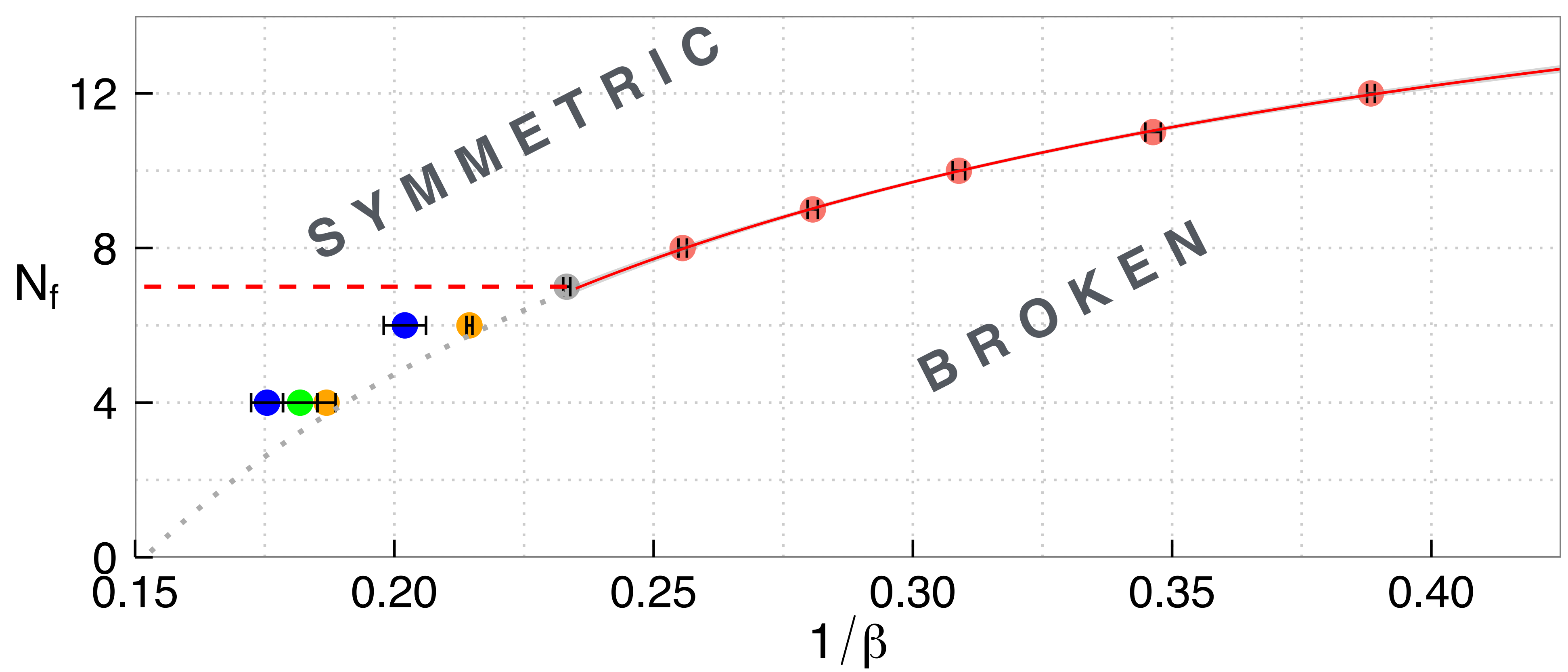
[arXiv:1506.06396]



The N_f dependence of the red line is a leading order effect separating phases with different symmetries: larger N_f implies enhanced screening

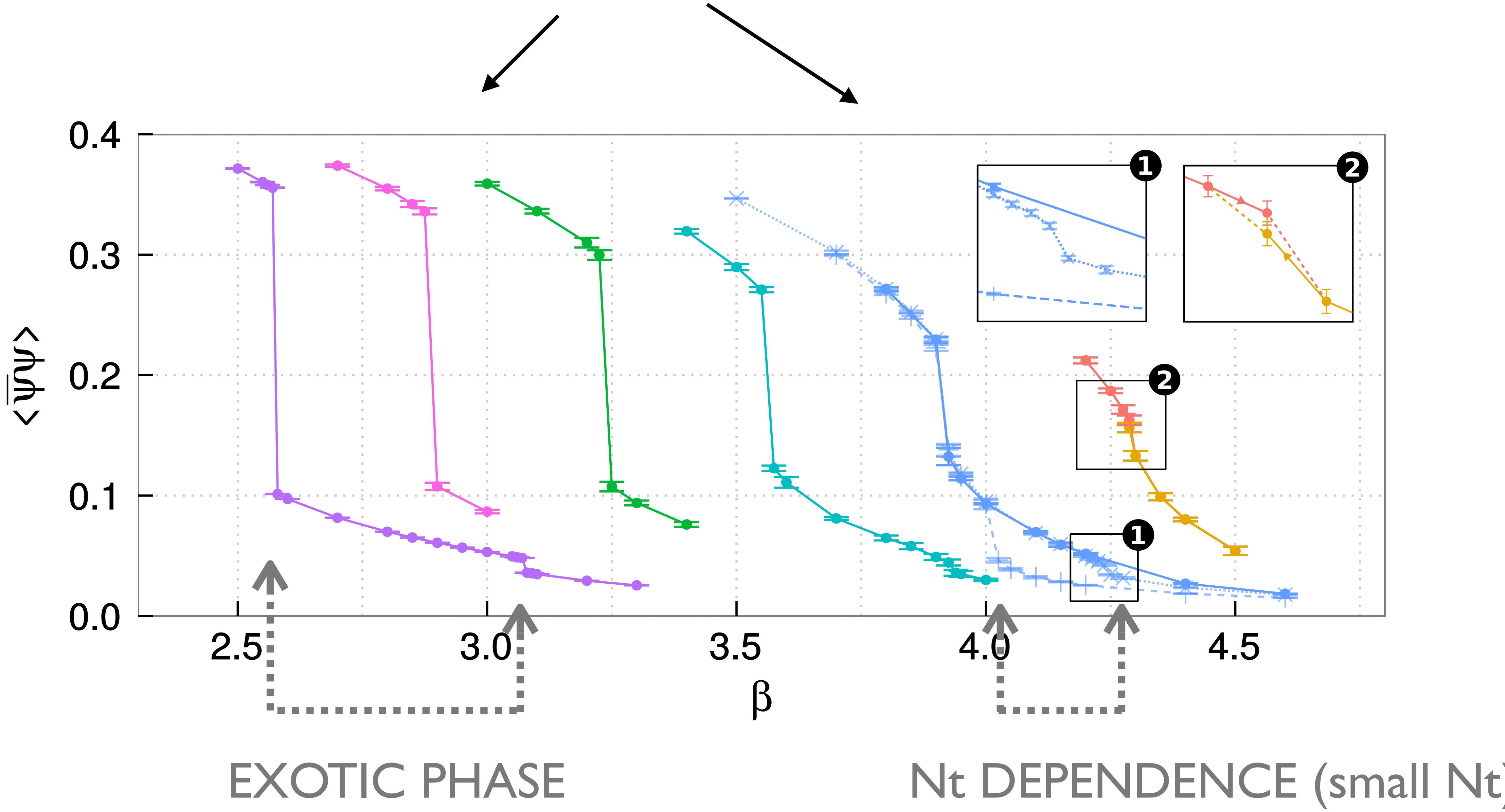
Line of bulk (T=0) chiral symmetry breaking phase transitions for $N_f \searrow N_f^c$

[arXiv:1506.06396]



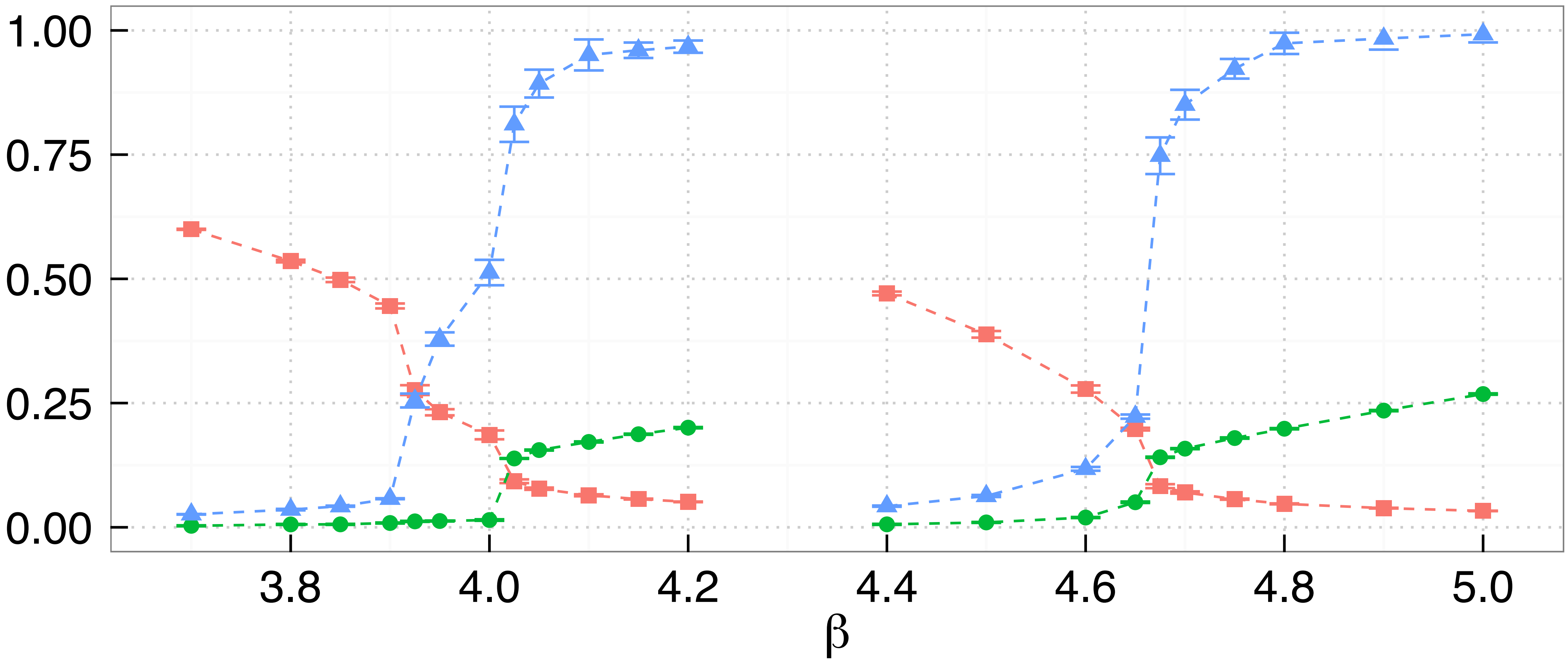
The red line is the $N_t = 1/(aT) \to \infty$ limit of an N_t-finite family of curves

Red points from sequence $N_f = 12,\ldots,7$: am=0.01   V=16c32, 12c24



NB: Exotic phase preserves exact chiral symmetry in massless limit
(edge displayed for $N_f = 12, 9, 8$ nonzero fermion mass)

Eight versus Six



- Chiral condensate (red)
- Re(Polyakov loop) (green)
- $R_\pi = \frac{\partial \langle \bar{\psi}\psi \rangle / \partial m_{valence}}{\langle \bar{\psi}\psi \rangle / m}$ connected (blue)

Conclusions I

- The lattice study carefully selects observables that undergo a sharp change due to underlying symmetries. (NB: Finite volume effects have been easily excluded)
- Results are consistent with the lower edge of the conformal window between Nf=8 and Nf=6
- This is in agreement with perturbation theory, and remarkably close to large-N QCD in the Veneziano limit prediction based on the properties of glueball dynamics.
- It is also a direct comparison between observables sensitive to chiral symmetry and observables sensitive to confinement.

Conclusions II

- Best observables to probe the lower edge:
  n-point functions sensitive to string tension (confinement)
  n-point functions sensitive to chiral symmetry
  topological quantities

- Importantly, the scalar glueball anomalous dimension discriminates between different mechanisms for the loss of conformality:

- If its magnitude increases for decreasing Nf, according to perturbation theory, then UV-IR merging (the simplest mechanism that generates BKT/ Miransky scaling) is not realised in QCD.