# The Physics of Eight Flavours

## Hunting for the Conformal Window

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# Outline

- Confusion at the Lower End
- The Challenge of Many Flavours
- A Transition at Eight Flavours
- Why Eight Flavour QCD is not Conformal
- Beyond the Physics of Eight Flavours

# Confusion at the Lower End

Renormalization Group:

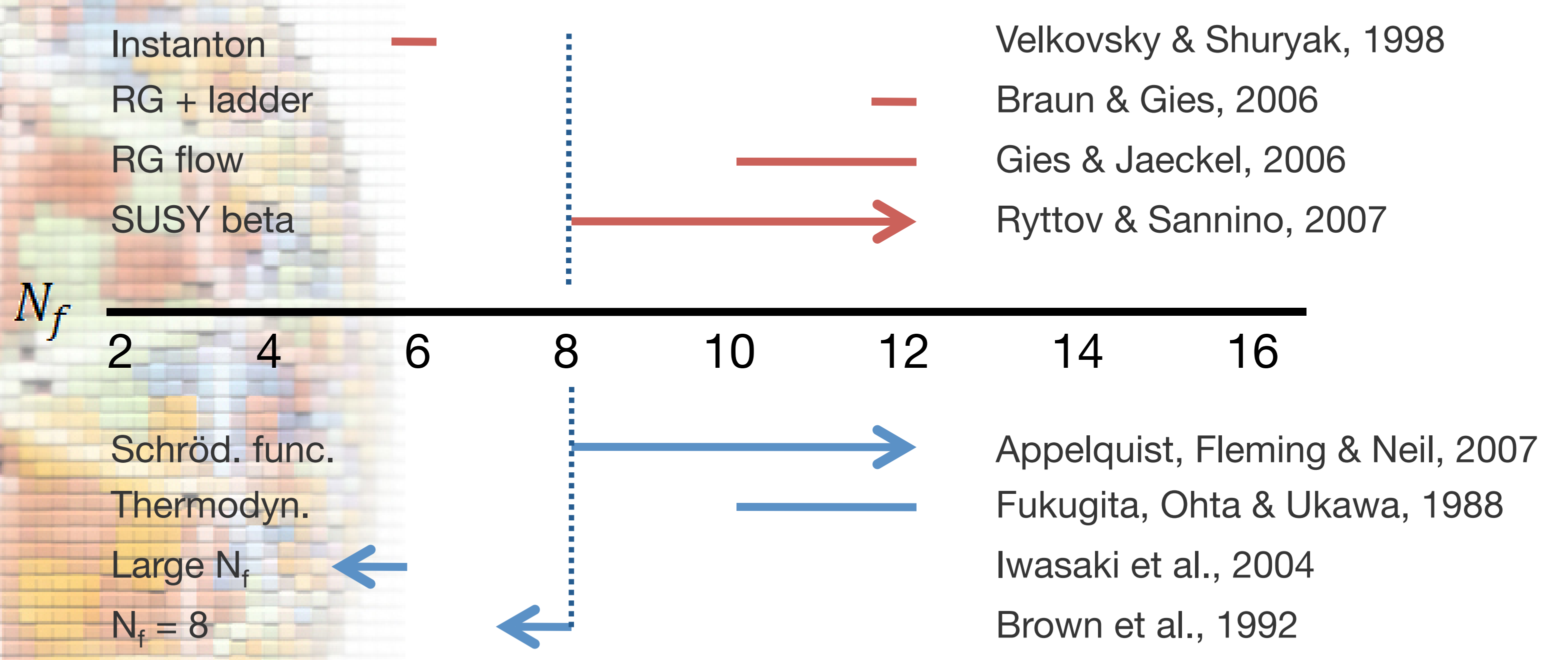
- A conformal window should exist.
- Its upper limit is at $N_{AF}$ = 16.5.
- Its lower limit should lie below $N_F$ = 12 (d.o.f. estimate)[1] .

The exact value depends on strong interactions dynamics.

Many estimates have been made, using different assumptions.

[1] Appelquist, Cohen & Schmaltz, Physical Review D 60, 1998

# Confusion at the Lower End




So far, the lattice results are inconclusive.

A confusing situation calls for a straightforward experiment.

# The Challenge of Many Flavours

The confusion illustrates the complexity of these simulations.

- Flexible and performant algorithms are needed.
- Masses need to be light to ensure approximate chirality.
- Lattice artifacts have to be suppressed by improvement.

And that is just the straightforward technical part.

- How to compare different $N_F$?
- How to set scales consistently?

# The Challenge of Many Flavours

A conformal theory may and will have a transition as a function of the bare coupling, but this has to be a bulk transition!

- Find the phase transition using light quark masses.
- Investigate the scaling properties of the transition.

If scaling analysis shows the transition is thermal, conclude that the theory is not conformal.

Avoids the issues of scale setting and is therefore universal.

# The Challenge of Many Flavours

Simulations are done on the basis of the publicly available MILC code as used for e.o.s. measurements[1], with an Symanzik O(a) improved lattice action.

$$S = -\frac{N_f}{4} Tr \ln M(am, U, u_0) + \sum_{i=p,r,pg} \beta_i(g^2) \sum_{C \in S_i} \mathrm{Re}[1 - U(C)]$$

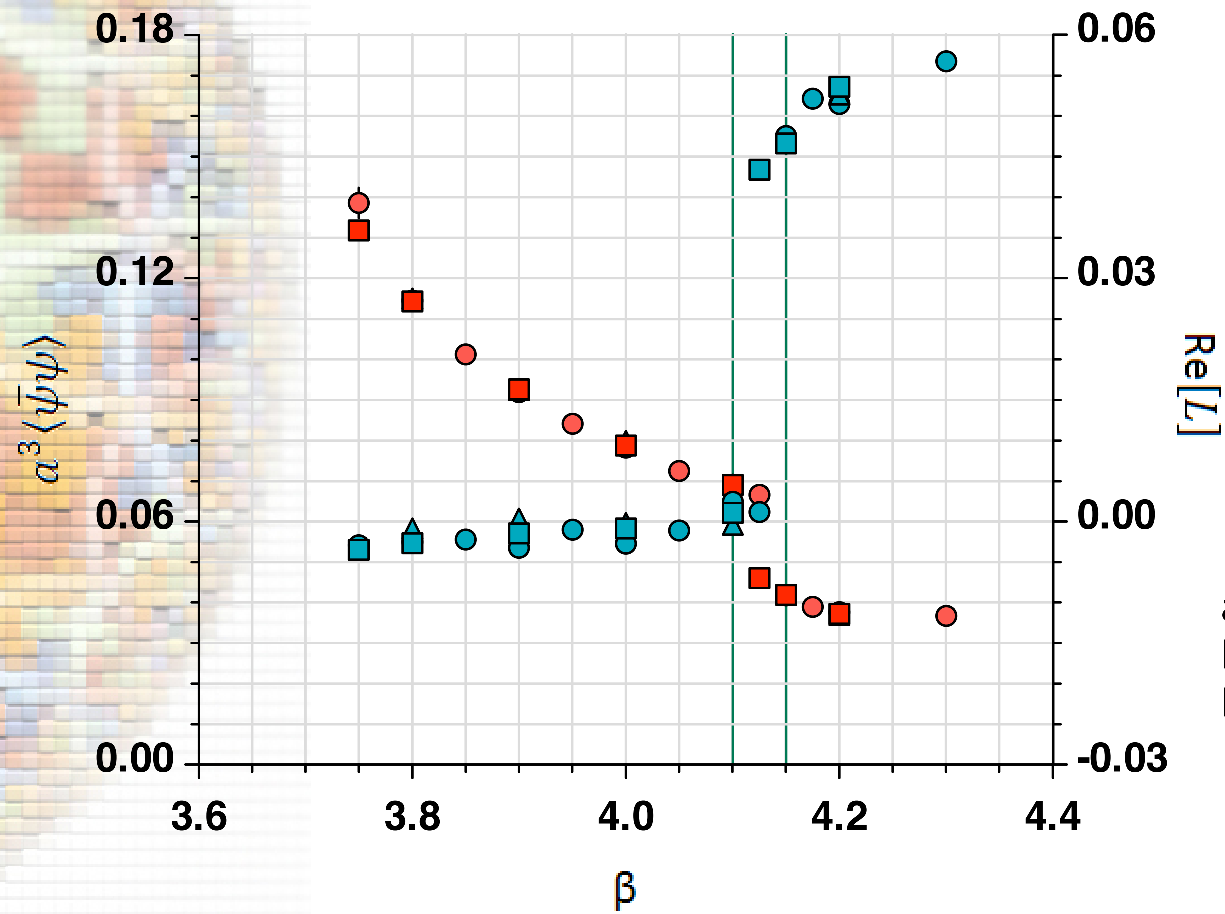
$$\beta_p \equiv \beta = \frac{10}{g_0^2}$$

$$\beta_r = -\frac{\beta}{20u_0^2}(1 + 0.4805\,\alpha_s) \qquad \beta_{pg} = -\frac{\beta}{u_0^2}(0.03325\,\alpha_s)$$

[1] C. Bernard *et al*, Physical Review D 75, 2007

# A Transition at Eight Flavours

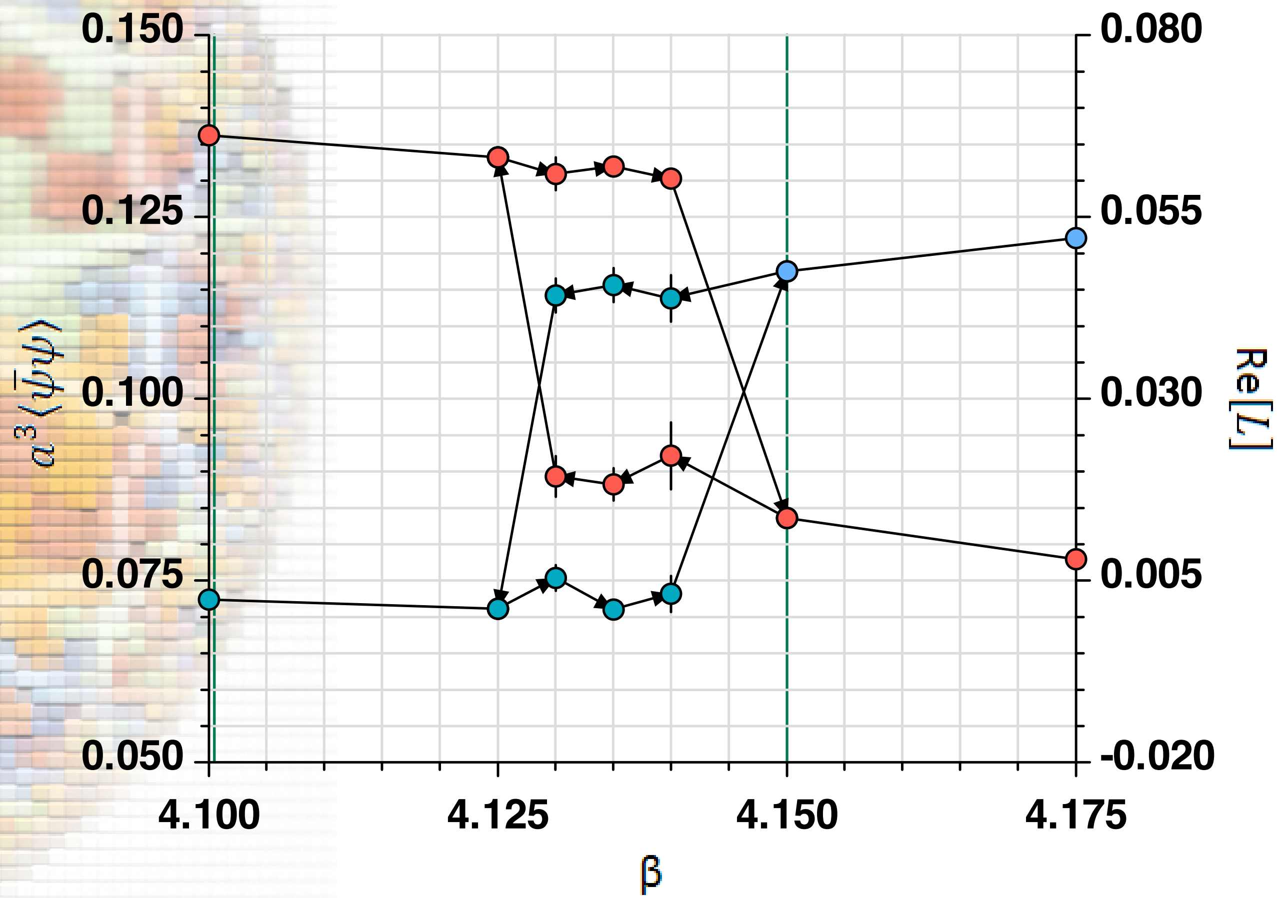
Chiral condensate and Polyakov loop vs. coupling, three volumes.




am = 0.02
$N_\tau$ = 6
$N_s$ = 12, 20, 24

# A Transition at Eight Flavours

Chiral condensate and Polyakov loop hysteresis at $12^3 \times 6$.




am = 0.02
$N_\tau$ = 6
$N_s$ = 12

# Why Eight Flavour QCD is not Conformal

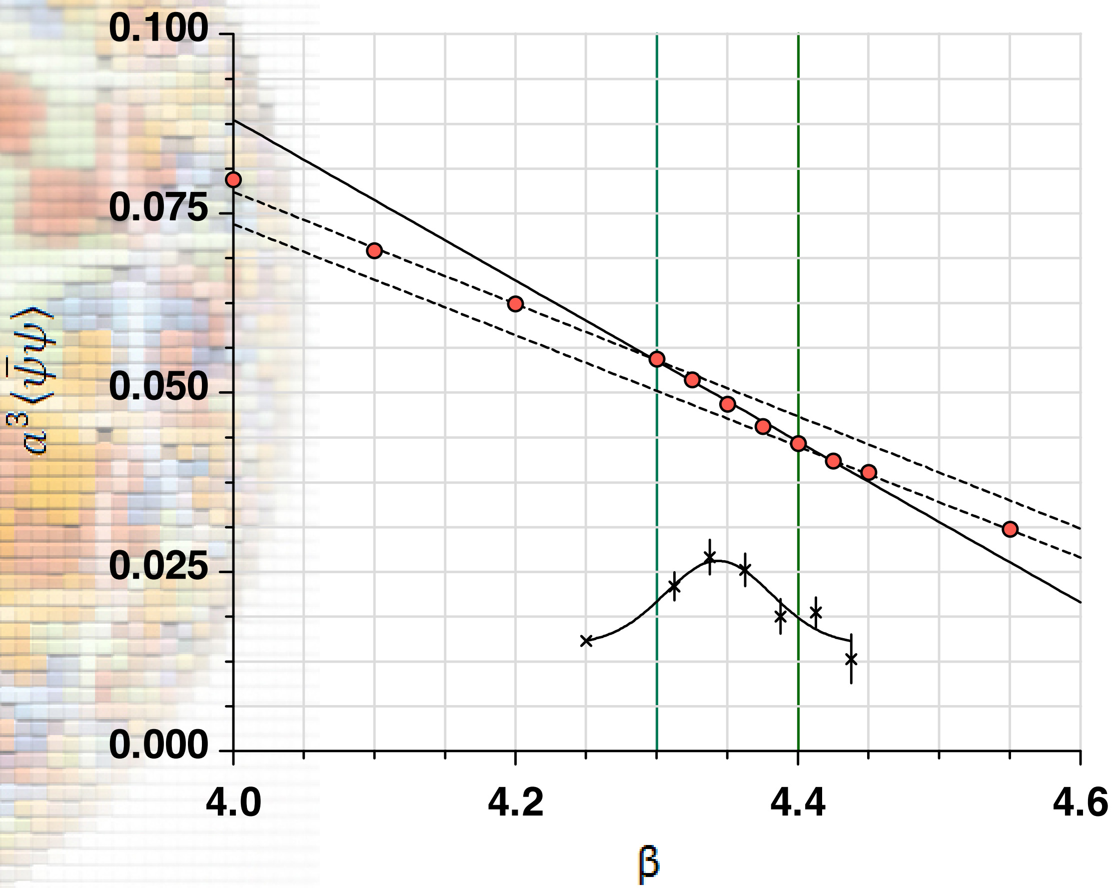
$$T_c = \frac{1}{a(\beta_c)\, N_\tau}$$

We cannot determine the physical scale directly, but we can use the perturbative relation between the lattice scale and the coupling constant.

$$a\Lambda_L = (b_0 g^2)^{-\frac{b_1}{2b_0^2}} \exp\left[-\frac{1}{2b_0 g^2}\right]$$

# Why Eight Flavour QCD is not Conformal

Chiral condensate vs. coupling at $24^3 \times 12$.




am = 0.02

$N_\tau = 12$

$N_s = 24$

# Why Eight Flavour QCD is not Conformal

$N_\tau = 6$: $\beta_c = 4.11(1)$

$N_\tau = 12$: $\beta_c = 4.34(4)$

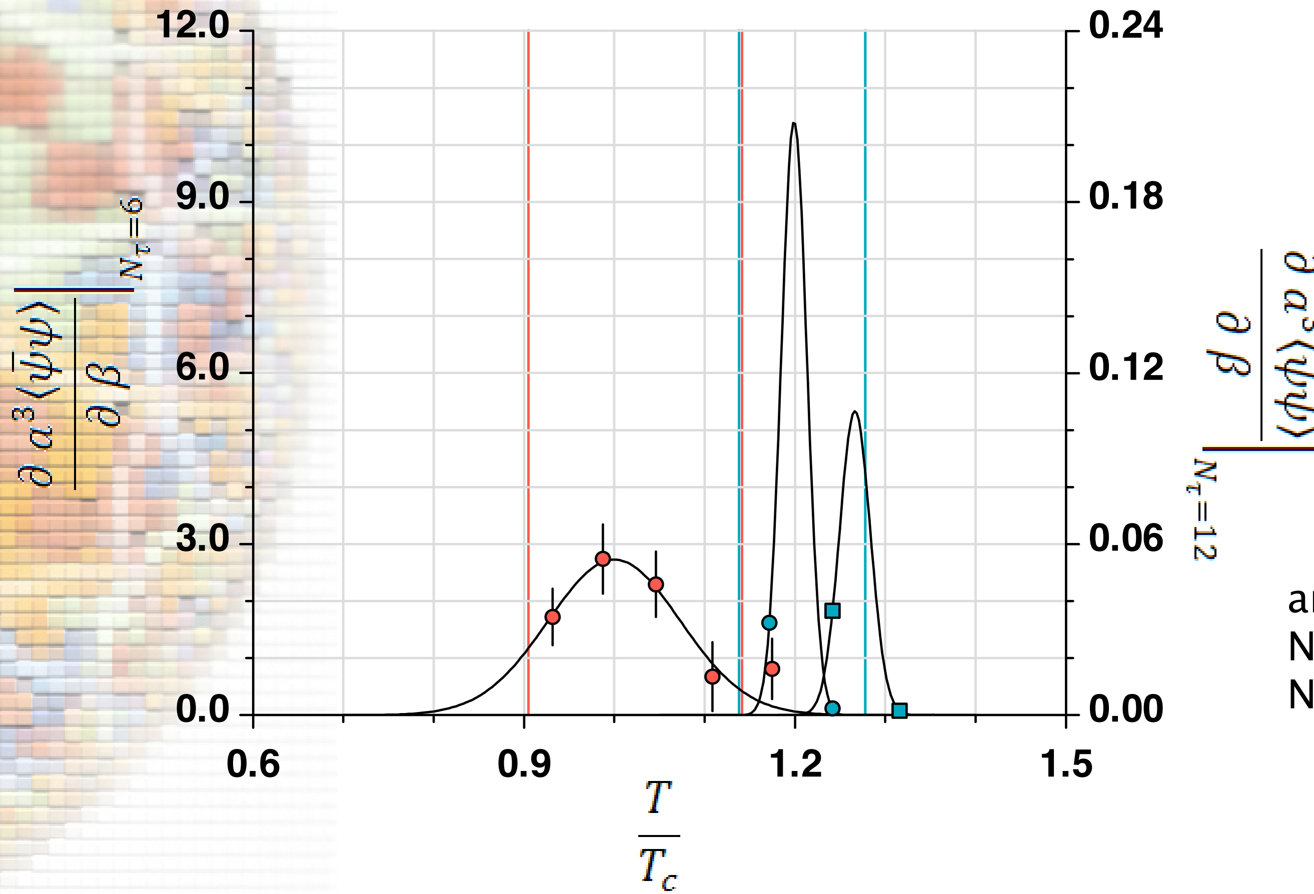
Backward extrapolation of the result at $N_\tau = 12$:

$N_\tau = 6$: $\beta_c = 4.04(4)$

Agreement well within $2\sigma$.

# Why Eight Flavour QCD is not Conformal

Rescaled derivative of chiral condensate for varying temporal extent.




am = 0.02
$N_\tau$ = 6, 12
$N_s$ = 12, 24

# Beyond the Physics of Eight Flavours

- We have determined the location of the chiral phase transition for eight flavour QCD and demonstrated its thermal nature.
- This implies that the lower limit of the conformal window must lie above eight.
- Improved lattice actions and low masses were crucial improvements over earlier studies, accounting for discrepancies.
- Result in full agreement with other recent results[1,2] .

[1] Braun & Gies, Journal of High Energy Physics 0606, 2006
[2] Appelquist, Fleming & Neil, hep-ph 0712.0609, 2007

# Beyond the Physics of Eight Flavours

- This was just a single step in a multi stage program (talk by E. Pallante).
- Work on theories with more flavours is in progress.
- Analysis of theories within the conformal window necessitates different observables, of a positive nature. These may include potentials, propagators and additional thermodynamical quantities.
- The fundamental issue of connecting different flavour numbers and scale setting will have to be tackled.

# Acknowledgements

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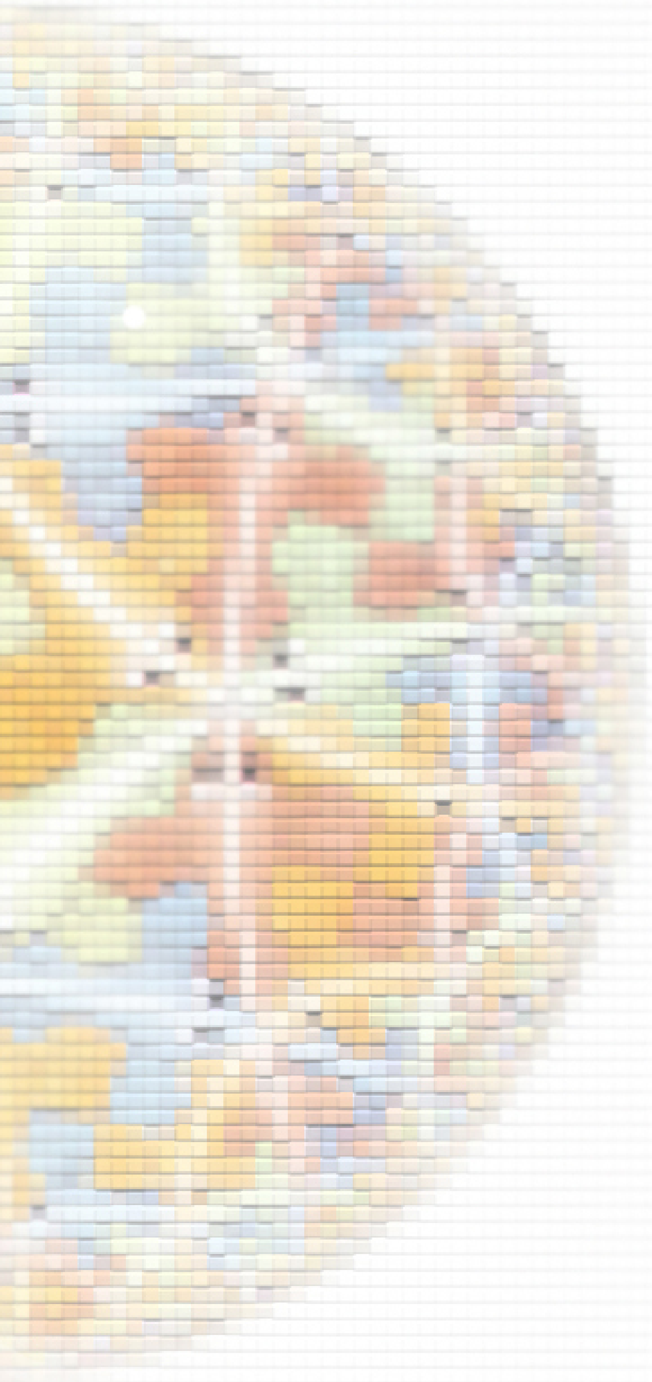
FOM

university of groningen



# Previous results in detail – analytical

Analytical estimates:

- RG flow analysis[1] suggests $N_F = 10 \pm 1$.
- A SUSY inspired closed beta function[2] gives $N_F > 8.25$.
- Instanton approaches[3] indicate a transition at $N_F = 6$.
- A ladder gap equation approach[4] produces $N_F = 12$.

Fairly consistent, pointing towards an almost saturated inequality.

[1] Gies & Jaeckel, European Physics Journal C 46, 2006
[2] Ryttov & Sannino, hep-th 0711.3745, 2007
[3] Velkovsky & Shuryak, Physics Letters B 437, 1998
[4] Braun & Gies, Journal of High Energy Physics 0606, 2006

# Previous results in detail – lattice

Lattice work so far:

- Early results [1] indicate $N_F > 10$.
- A thorough study [2] at $N_F = 8$ hinted at conformality there.
- Recent studies [3] observed $N_F < 6$.
- A new Schrödinger functional measurement [4] gives $N_F > 8$.
- Several other studies found transitions at $N_F = 8$, but their analysis was not aimed at a possible conformal phase.

[1] Fukugita, Ohta & Ukawa, Physical Review Letters 60, 1988
[2] Columbia group (Brown et al.), Physical Review D 46, 1992
[3] Iwasaki et al., Physical Review D 69, 2004
[4] Appelquist, Fleming & Neil, hep-ph 0712.0609, 2007

# Chiral susceptibilities