Strongly coupled near- or conformal systems with fundamental fermions

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Strongly coupled gauge fermion systems

- Could open up a whole new world of physical phenomena (technicolor related and other)
- They are inherently non-perturbative
- Lattice methods are the most reliable way to study them

Disclaimer

This is a relatively new field within lattice studies and we frequently generate more questions than what we solve.

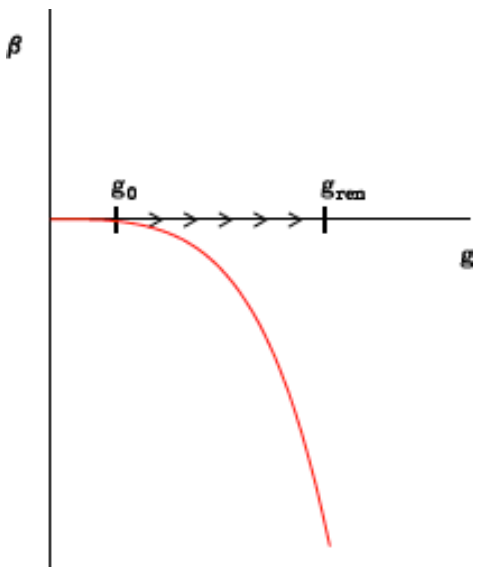
- Progress is steady but do not expect final answers yet.

Technicolor-inspired electroweak symmetry breaking

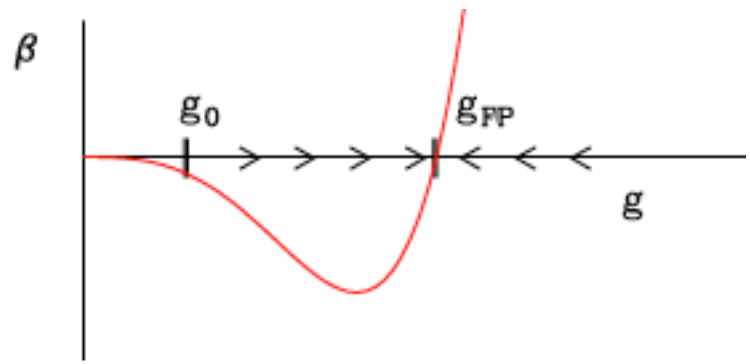
Renormalization group β function at 2 loops

$$\beta(g^2) = \frac{dg^2}{d\log(\mu^2)} = \frac{b_1}{16\pi^2}g^4 + \frac{b_2}{(16\pi^2)^2}g^6 + \ldots$$

$$b_1 = -11 + \frac{2}{3}N_f\,,$$
$$b_2 = -102 + \frac{38}{3}N_f$$



$N_f < 8.05$



$8 < N_f < 16.5$

Few fermions: QCD like

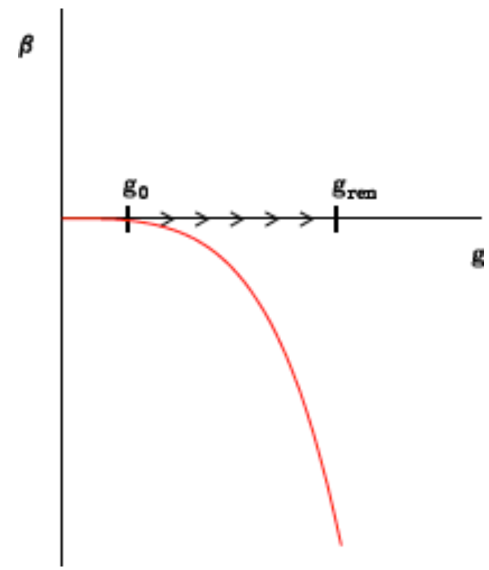
–Asymptotically free, chirally broken and confining

–Technicolor:

- –pions are massless Goldstones
  - → could describe EW symmetry breaking if $F_{TC} \sim v_{EW} \sim 250$ GeV (scaled-up QCD)

–Extended technicolor:

- –add techni & SM fermion coupling to generate mass for SM fermions

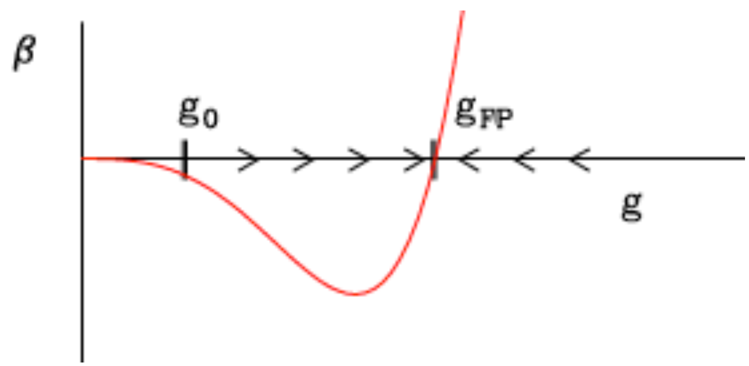


Can get complicated when one tries to satisfy the EW precision data

More fermions: conformal systems

– Asymptotically free

– at g_{FP} the gauge coupling is an irrelevant operator (Banks-Zaks IRFP)



– Conformal theory at the IRFP

–No confinement

–No chiral symmetry breaking

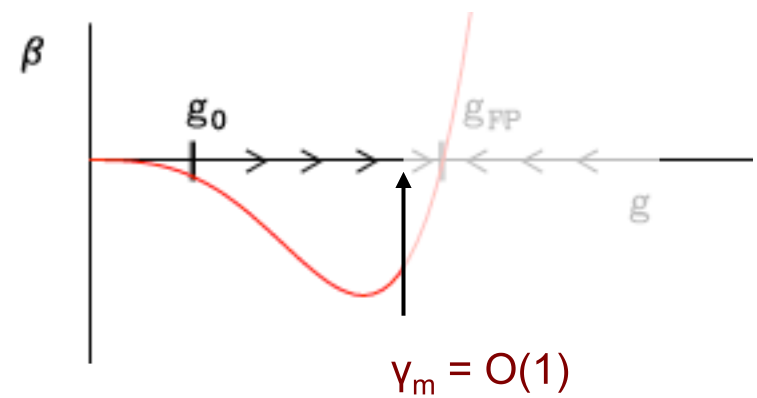
→ Conformal technicolor

→ Unparticle models

The continuum theory defined at the IRFP is interesting on its own right: if it has non-trivial exponents ($\gamma_m \neq 0$) it is a non-perturbative FP in 4D!

The conformal window

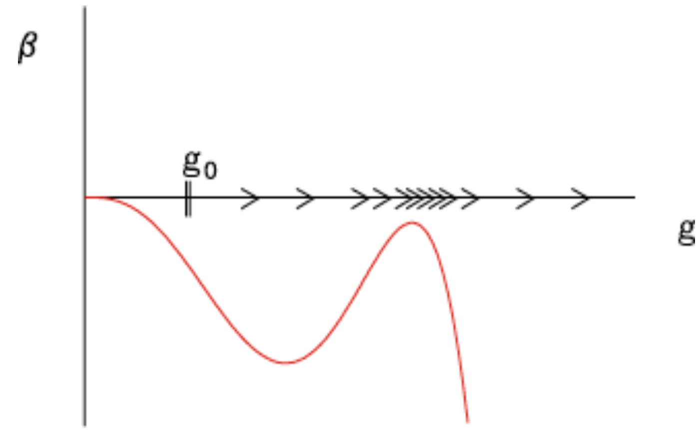
- 2-loop perturbation theory predicts IRFP when $N_f > 8.05$
  ($b_2 < 0$, $(g^*)^2 = -b_2/b_1$)



- Improved prediction from S-D equations
  As g increases the anomalous mass dimension γ_m also increases
  - if $\gamma_m < O(1)$ when $g=g_{FP}$, an IRFP develops
  - if $\gamma_m = O(1)$ while $g<g_{FP}$, chiral symmetry breaks, the fermions decouple, the system does not develop an IRFP

Walking technicolor

The gauge coupling changes slowly and the anomalous mass dimension remains large across an extended energy scale



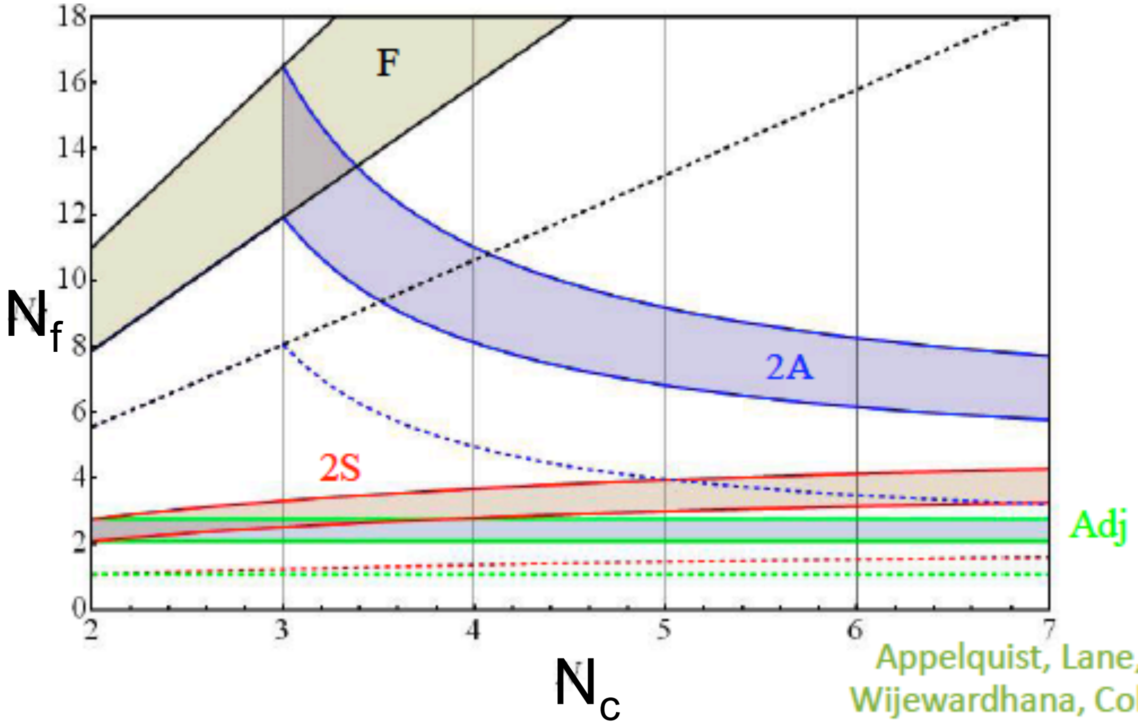
To satisfy electroweak precision data one needs large $<\bar{\psi}\psi>_{ETC}$, but small $<\bar{\psi}\psi>_{TC}$

$$<\bar{\psi}\psi>_{ETC} = <\bar{\psi}\psi>_{TC} \exp\left(\int_{TC}^{ETC} \frac{d\mu}{\mu}\gamma(\mu)\right)$$

Scaled-up QCD does not do this → but walking TC could

Roadmap for the conformal window

S-D type calculations



Shaded: conformal
Below : confining
Above: IR free

fermion representation:
Fundamental
Adjoint
2Symmetric
2Antisymm

Appelquist, Lane, Mahanta, Wijewardhana, Cohen, Georgi, Yamawaki, Shrock, Dietrich, Sannino, Tuominen

Needs non-perturbative verification!

Strongly coupled systems are interesting

An IR fixed point with large anomalous dimensions can describe

- Walking TC
- UV fixed points with non-perturbative properties

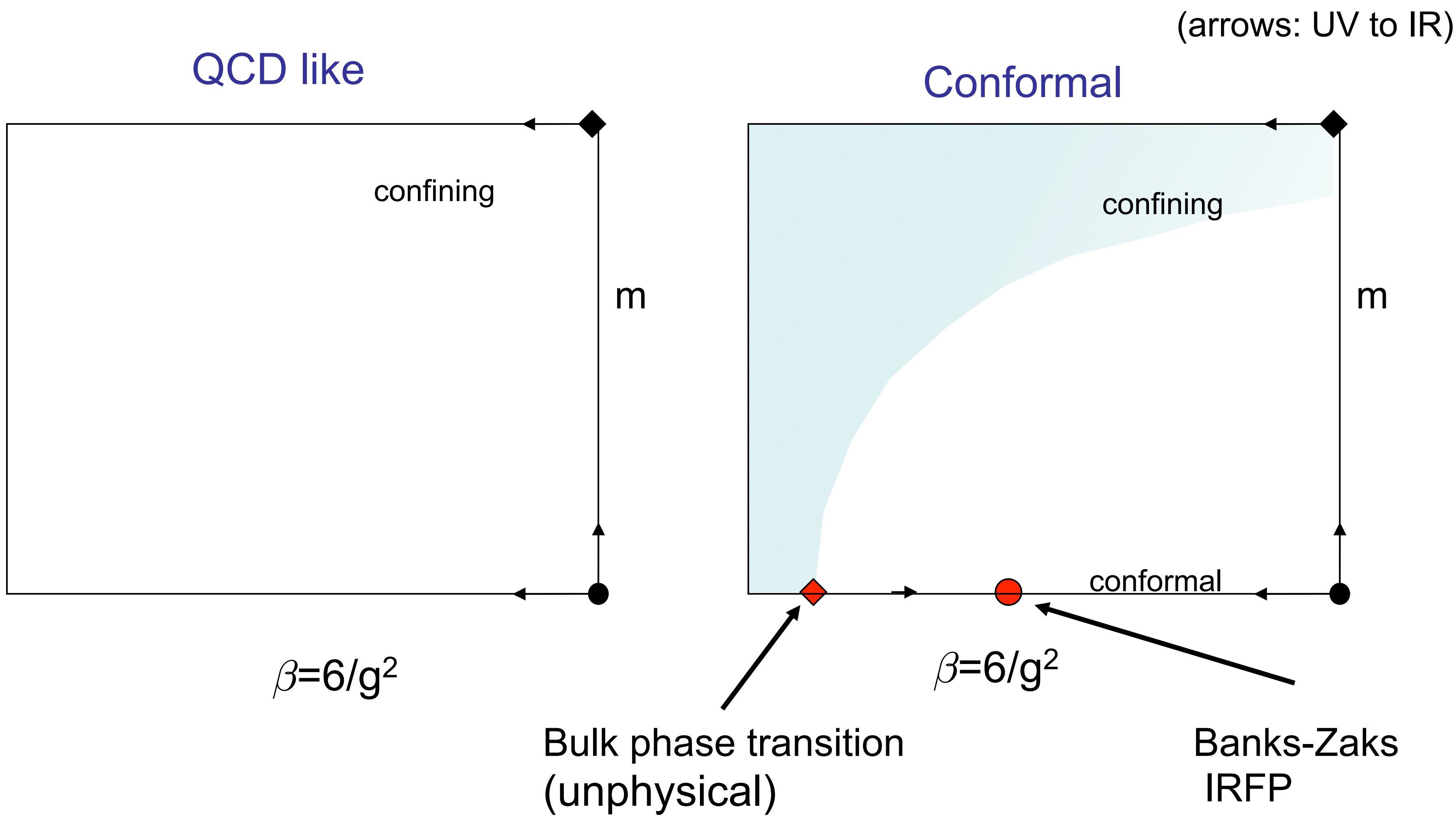
But strongly coupled systems are non-perturbative

- Perturbative methods are not reliable
- We don't even know what the physical fields are!

Lattice simulations are designed to study non-pertubative systems

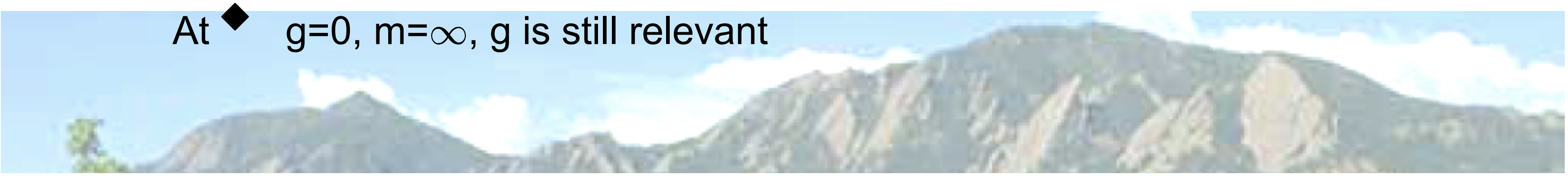
- We know how to do QCD
- SU(N_c) with N_f flavors – can it be much more difficult

The lattice phase diagram

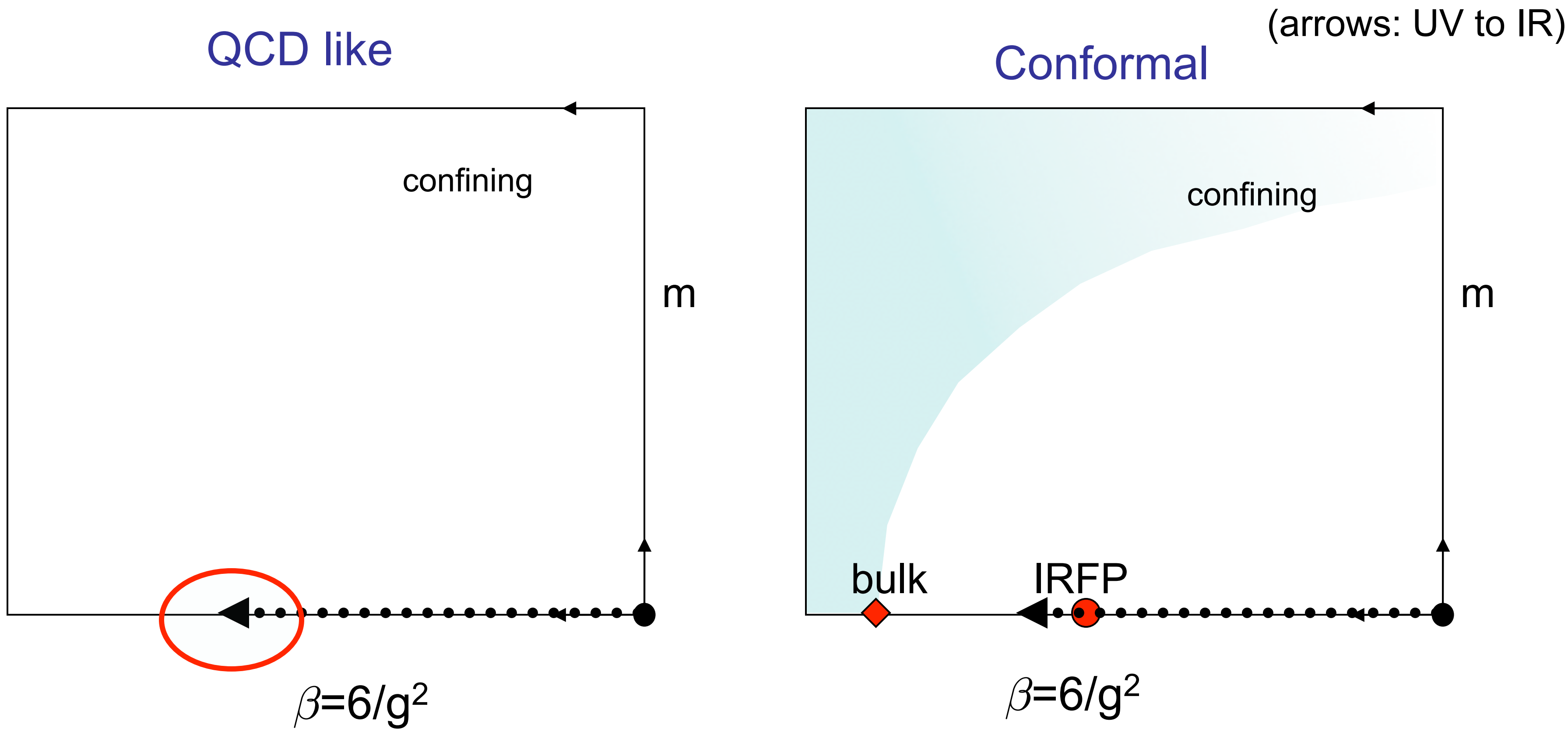


At ● g=0, m=0, both couplings are relevant

At ◆ g=0, m=∞, g is still relevant

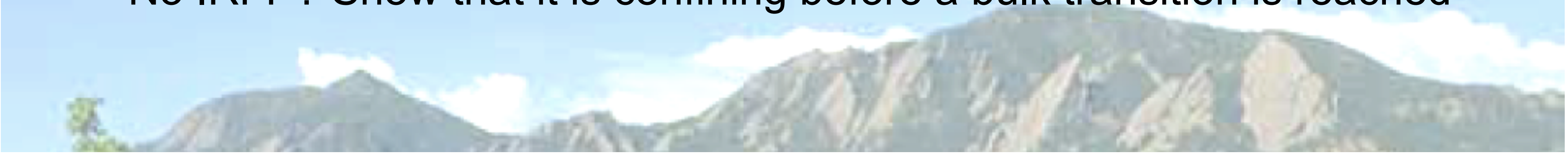


How can we distinguish QCD-like and conformal systems?



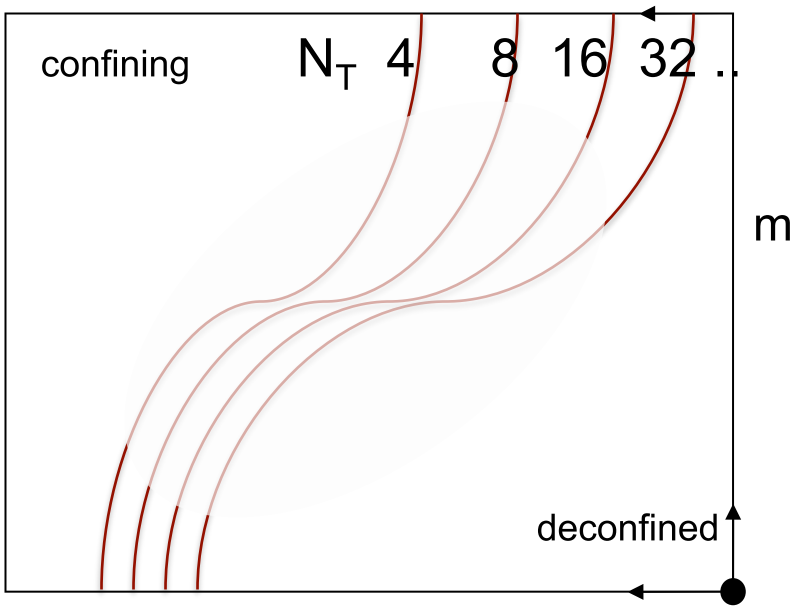
Lattice simulations can connect the perturbative FP and strong coupling

- Found IRFP ? Done ✔
- No IRFP? Show that it is confining before a bulk transition is reached



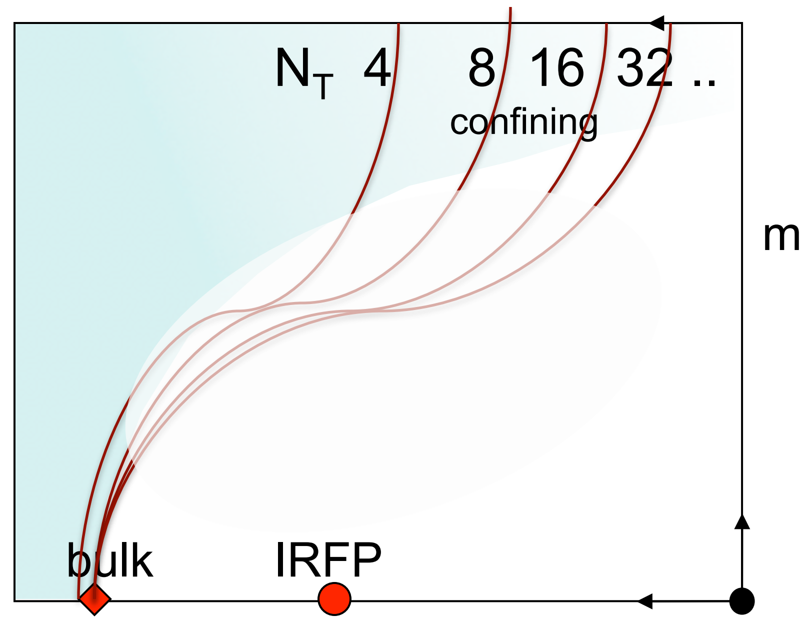
Finite temperature and bulk phase transitions

QCD like



$\beta_c \rightarrow \infty$ as $N_T \rightarrow \infty$

Conformal

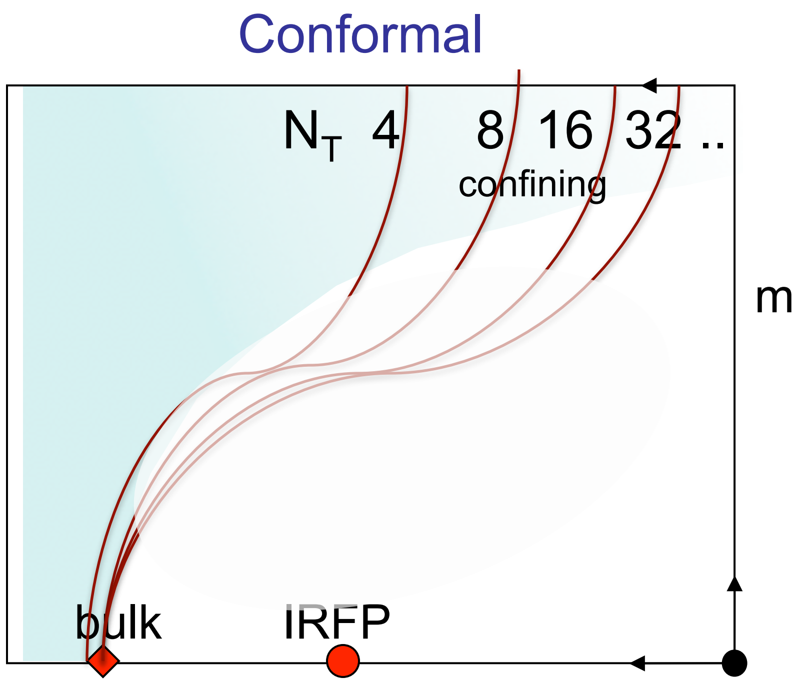


$\beta_c \rightarrow \beta_{bulk}$ as $N_T \rightarrow \infty$

In a conformal system

- finite temperature transitions run into a bulk (T=0) transition
- β_{bulk} separates strong coupling (confining) and weak coupling (conformal) phases

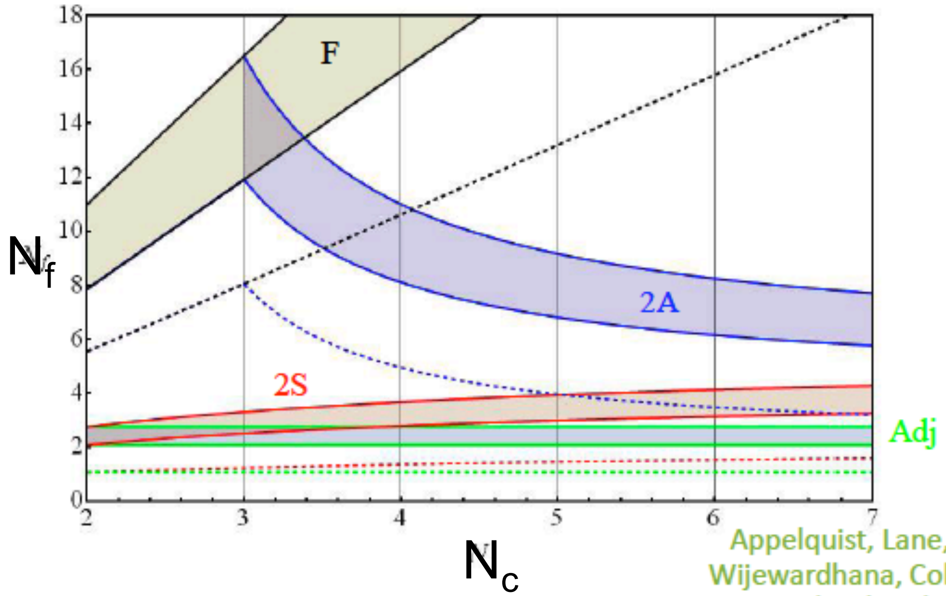
Finite temperature and bulk phase transitions



$\beta_c \rightarrow \beta_{bulk}$ as $N_T \rightarrow \infty$

In (some) conformal systems this phase diagram turns out to be quite a bit more complicated

Models:



Appelquist, Lane, Mahanta, Wijewardhana, Cohen, Georgi, Yamawaki, Shrock, Dietrich, Sannino, Tuominen

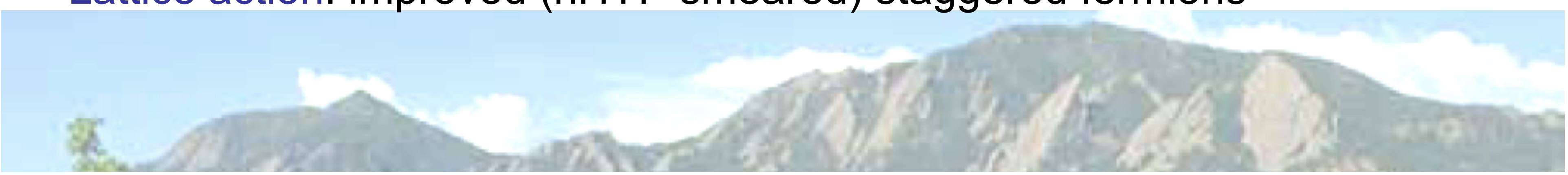
Many of these systems have been studied. Here I consider two :

SU(3) gauge + N_f = 12 and 8 fundamental flavors

N_f=12 : quite controversial, was thought to be conformal for a while, than confining, than……..

N_f=8 : is considered confining, but something strange is happening….

Lattice action: improved (nHYP smeared) staggered fermions



The multi-prong lattice approach

- Connect the perturbative and strongly coupled regime
  - Calculate the RG β function (the step scaling function) and look for a zero or the backward flow of the RG equation
    - Schrodinger functional method
    - Twisted Polyakov loop, Wilson loop ratio, etc
    - Monte Carlo Renormalization Group (MCRG)
- Find bulk transition
  - Study the phase diagram
- Scaling of hadronic & gluonic observables
  - Observables scale differently in conformal and confining systems Can this be distinguished from other systematical effects?
- Physical observables
  - Anomalous dimension, S parameter

The step scaling function around a UVFP

The *bare* differential step scaling function $s_b\,(\beta)$

$$s_b(\beta) = \beta - \beta' \quad \text{where} \quad \xi(\beta) = \xi(\beta')/2 \qquad (\beta = 2N_c/g_0^2)$$

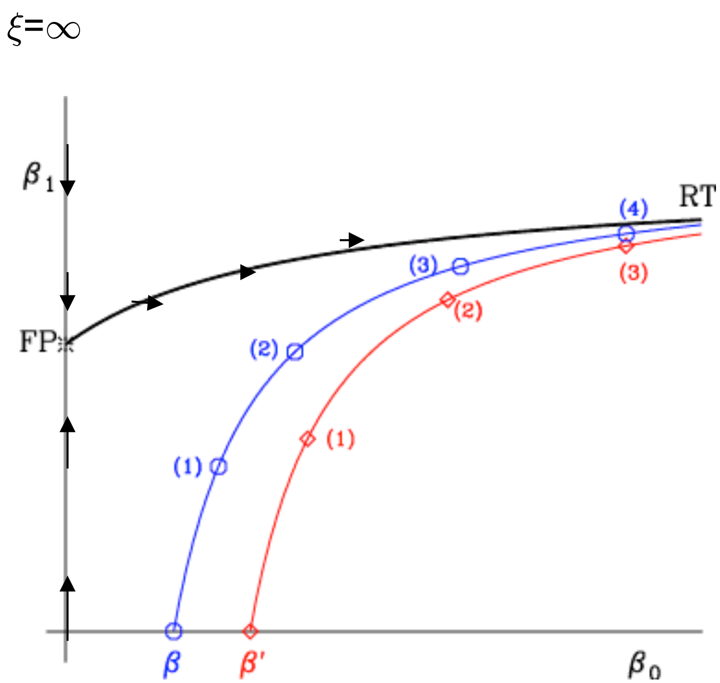
ξ is the correlation length defined by some physical mass

- Can be measured directly or
- Use RG flow : $s_b(\beta)$ is the projection of the RG flow to a lower dimensional coupling space

$s_b(\beta)$ *has the opposite sign of the RG* β *function*

The MCRG method

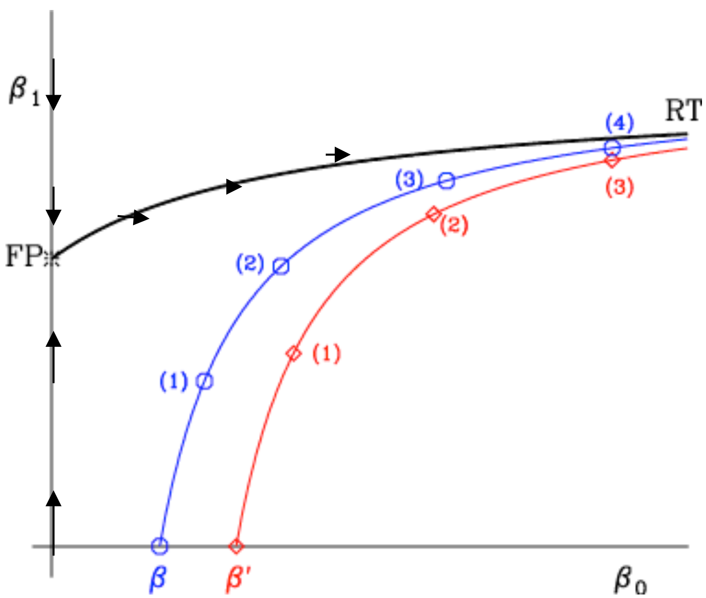
- Under repeated blocking the RG flow lines approach the fixed point of the system in the irrelevant directions and flow away in the relevant ones. The speed of the flow is related to the scaling dimensions



Following the flow lines is very difficult

The 2-lattice matching MCRG method

- 2-lattice matching is a real-space MCRG.
  It identifies the “projection” of the RG flow along the line (plane) of the simulation parameters in the gauge coupling :



– Do simulations at β and β' (m=0)

– RG block and compare the blocked actions

– if $S(\beta^{(n)}) = S(\beta'^{(n-1)}) \rightarrow a(\beta)=a(\beta')/2$

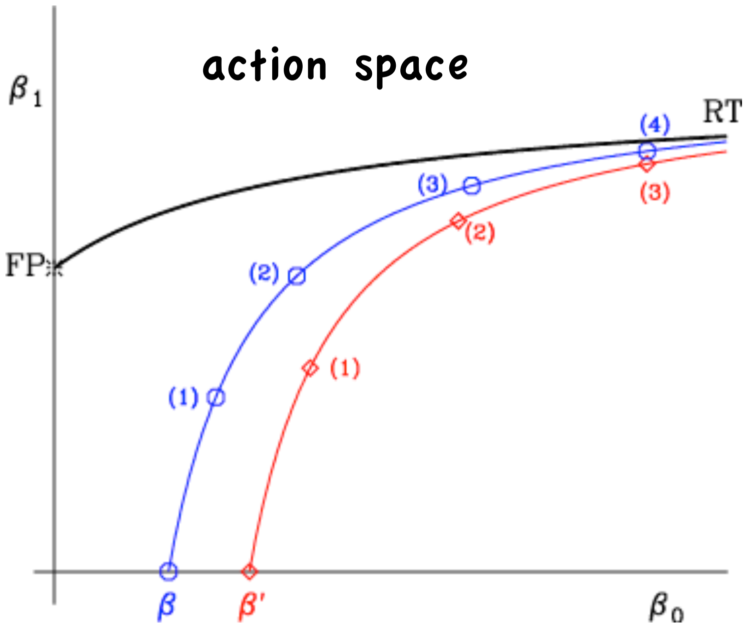
the step scaling function is

$$s_b(\beta) = \lim_{n_b \to \infty} (\beta - \beta')$$

The step scaling function & MCRG

If $S(\beta^{(n)}) = S(\beta'^{(n-1)}) \rightarrow a(\beta)=a(\beta')/2,\ s_b(\beta) = \beta-\beta$

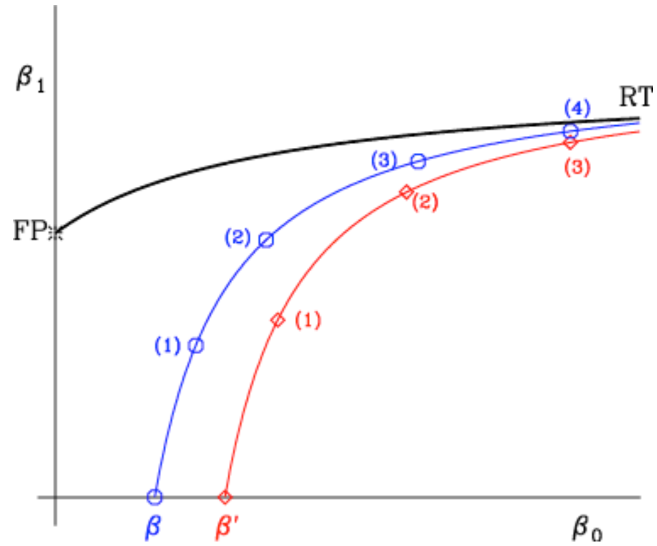
MCRG finds (β,β') pairs by matching blocked lattice actions



Two actions are identical if all operator expectations values agree

Match operators (local expectation values) after several blocking steps

Where all the bodies are buried (and what to do with them)



- The RG flow might not reach the renormalized trajectory
  - Improved blocking is essential
  - Compare different blocking levels
- The blocked lattices are small, finite volume effects are significant
  - Careful matching on identical volumes helps;
  - Compare different volumes
- Spurious lattice fixed points can effect the results
  - Check the phase structure

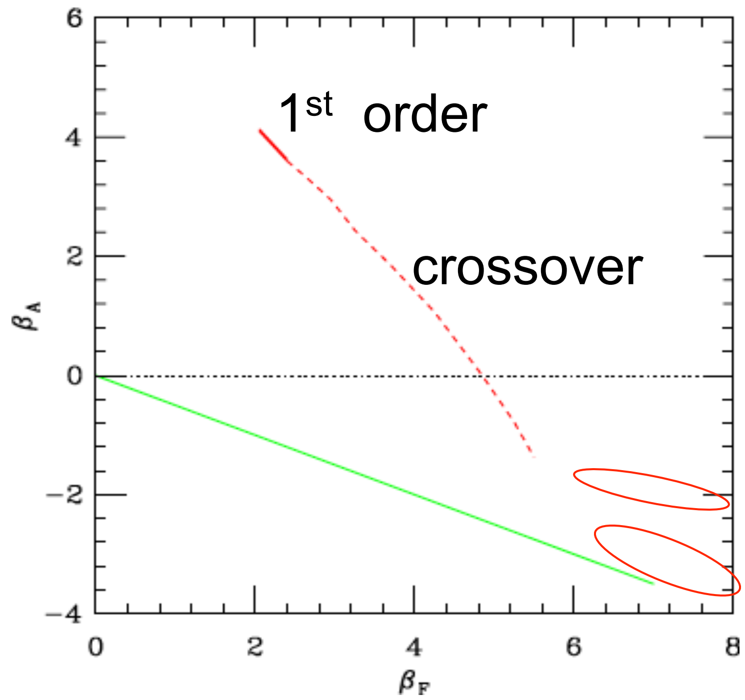
Results for N_f = 12 flavors

ArXiv:1106.5293

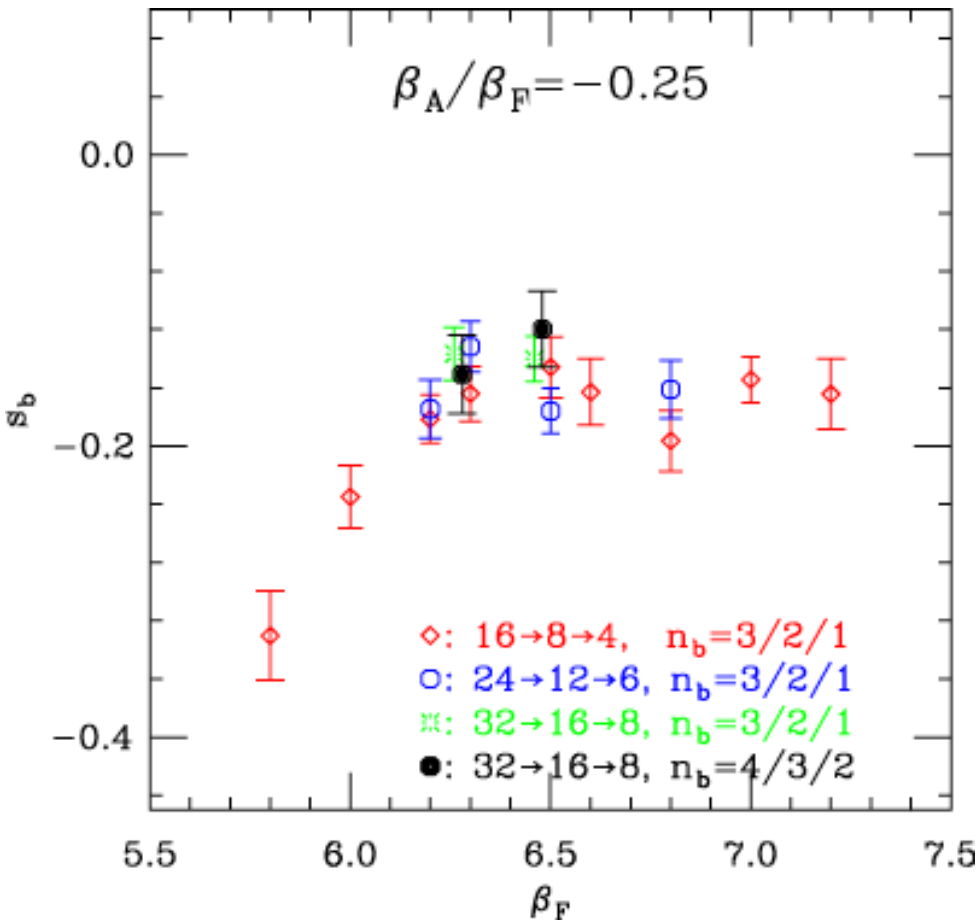
- Improved actions : plaquette + negative adjoint plaquette gauge action to avoid a spurious FP. Results with $\beta_A/\beta_F = -0.25$ and $\beta_A/\beta_F = -0.15$.

- Improved blocking : HYP smeared

- Improved finite volume corrections:
  2 levels of correction



The step scaling function $N_f = 12$



Results from many blocking levels, many volumes are all consistent.

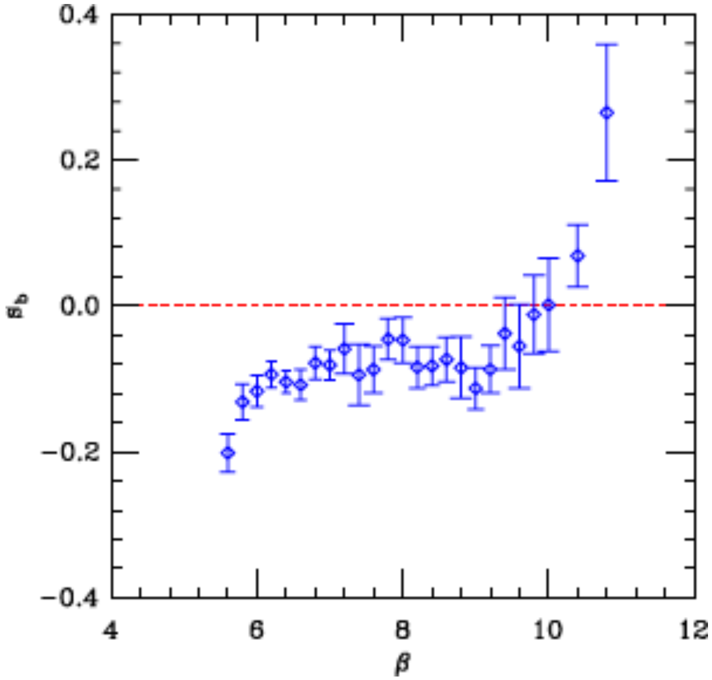
At $\beta_F=\infty$ the step scaling function $s_b>0$

In the investigated β range it is negative

→ There has to be an IRFP (around/above β=11.0)

→ Indicates a conformal system

The step scaling function – a different action



$S_b(\beta)$ can be followed through the IRFP

With β_A/β_F = -0.15 the IRFP is closer and I can find the IRFP

(16→8 →4 matching)

Summary of MCRG matching

MCRG:

requires matching on identical volumes for optimization

With an action that avoids spurious fixed points

- Optimized, volume-matched MCRG gives consistent results for Δβ (the step scaling function)
- s_b for Nf=12 fermions, SU(3) gauge is consistently negative, indicating an IRFP and conformal dynamics

Phase diagram studies

N_f=12 and 8 flavors, SU(3) gauge + nHYP' fermions (arXiv:1111.2317)
(A. Cheng, A.H., G. Petropoulos, D. Schaich)

Why now?

- There is a contradiction between MCRG & spectral results.
  We are investigating different coupling regions:
  - MCRG : $6/g^2 \sim 3.7$
  - LHC : $6/g^2 \sim 2.2$

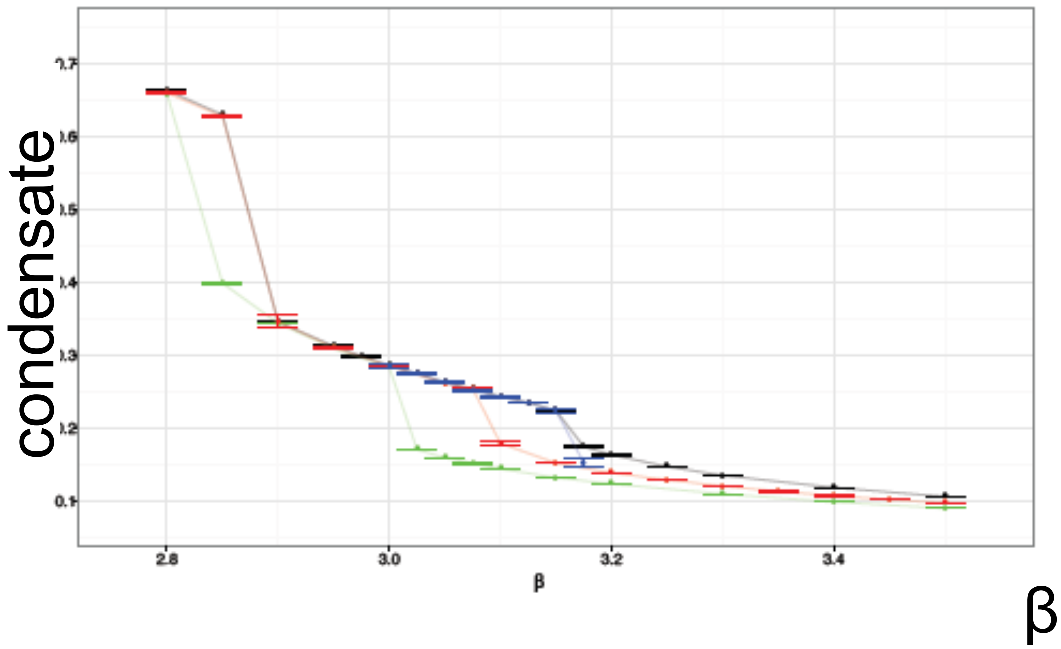
The action:

- Fundamental-adjoint gauge : $\beta_A/\beta_F = -0.25$
- nHYP projection has numerical problems when the smeared link develops near-zero eigenvalues
  - small tweak of the HYP parameters can fix that! $(\alpha_1,\alpha_2,\alpha_3)$=(0.40,0.50,0.50) will do the trick

Previous results on the phase stucture N_f=12

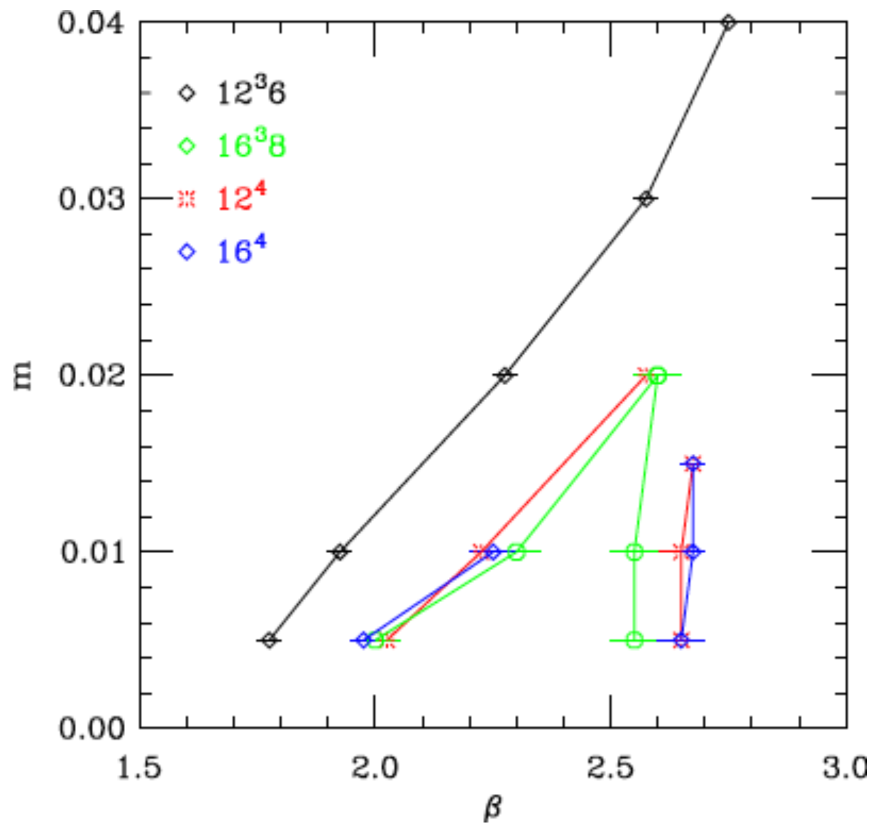
Groningen-INFN group found 2 first order transitions (2010,2011)

m=0.025, N_T=6,8, 10 and T=0 (unimproved staggered)



Indication of two first order transitions;
Both transitions are running into a bulk trasition

Phase diagram β-m plane N_f=12

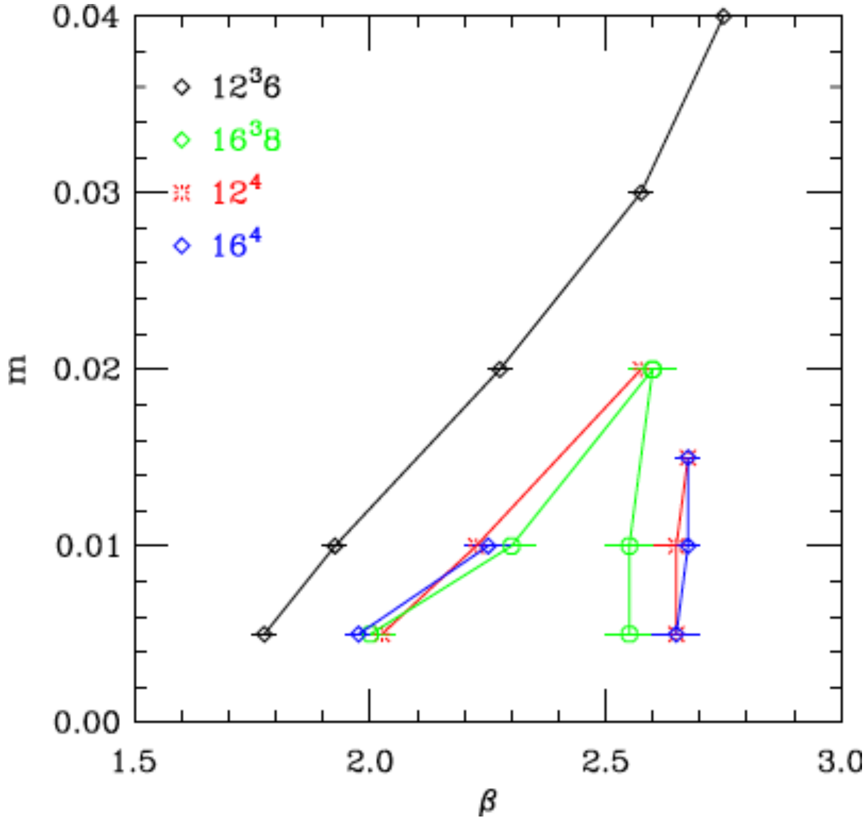


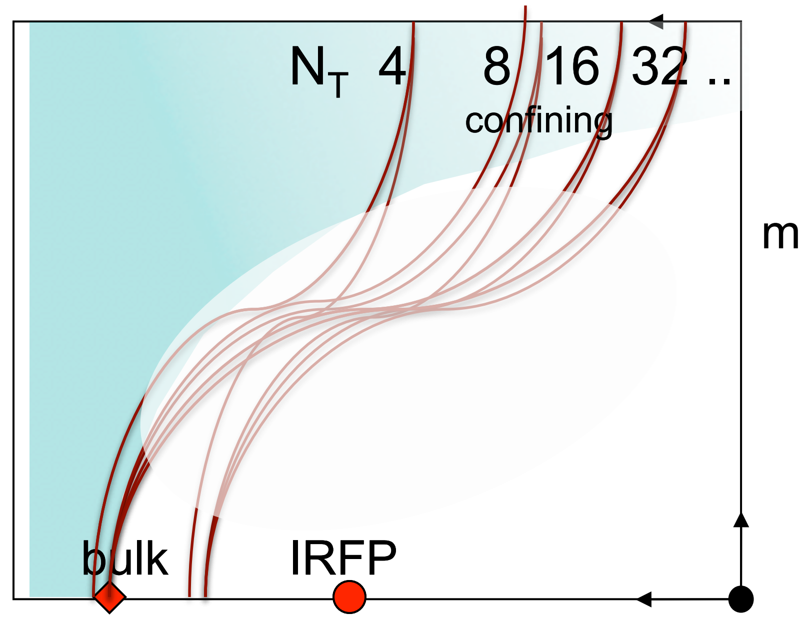
First order transitions at small mass turning into crossover

Finite temperature phase transitions converge to zero temperature “bulk” transitions

Results are consistent with Deuzeman et al. though we use a different lattice action

Phase diagram β-m plane N_f=12



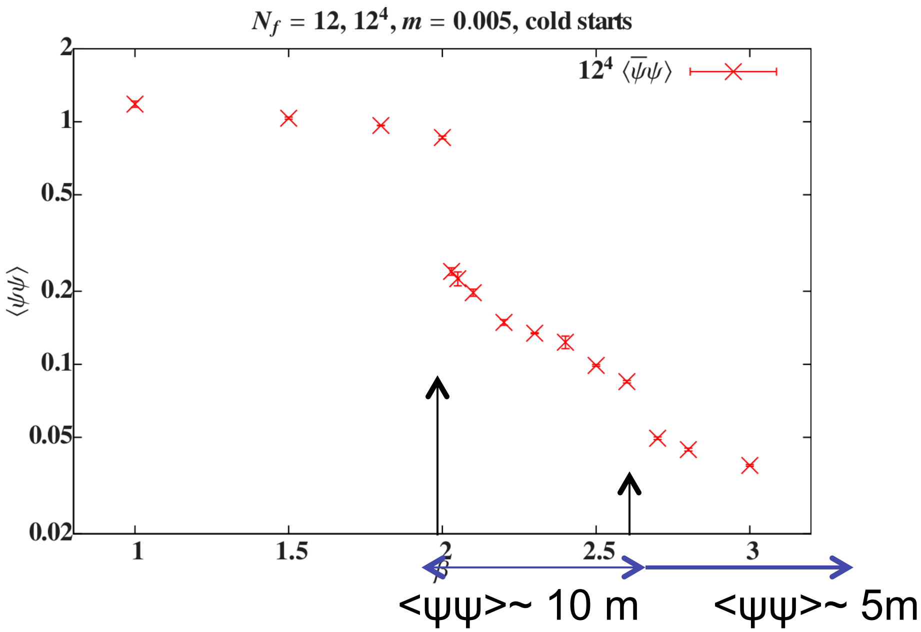


$\beta_c \to \beta_{bulk}$ as $N_T \to \infty$

It is as the finite T transitions fissioned into two before converging to bulk transitions

Phase diagram N_f=12

What are the three phases?



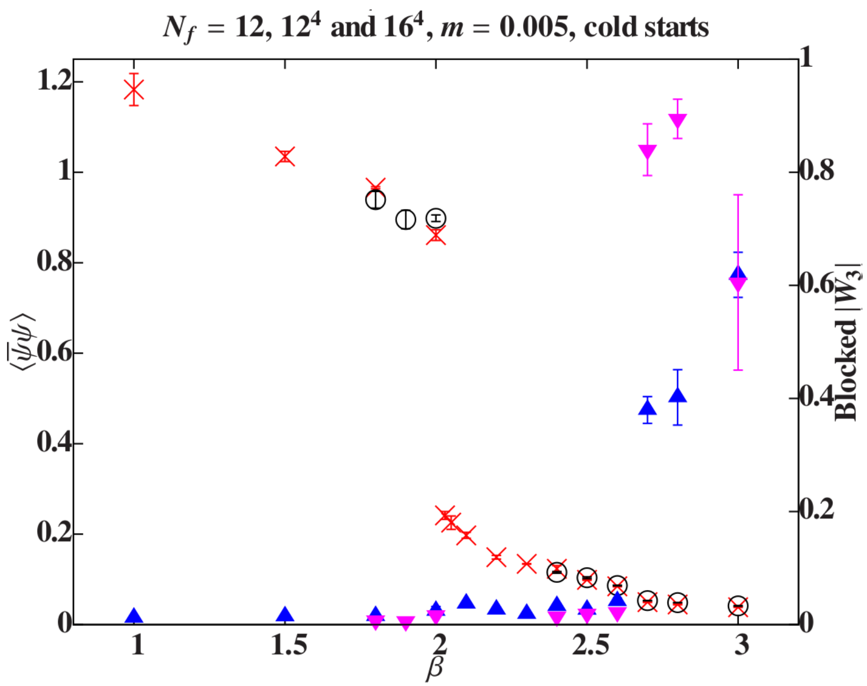
Chiral condensate extrapolates to zero in the chiral limit on the weak coupling side of the “big” jump

→ Chiral restoring transition

Is it deconfining?

Phase diagram

Is it deconfining? Polyakov line is very noisy but the blocked Poly line is sensitive:



Blocked Poly line is measured on RG blocked lattices:

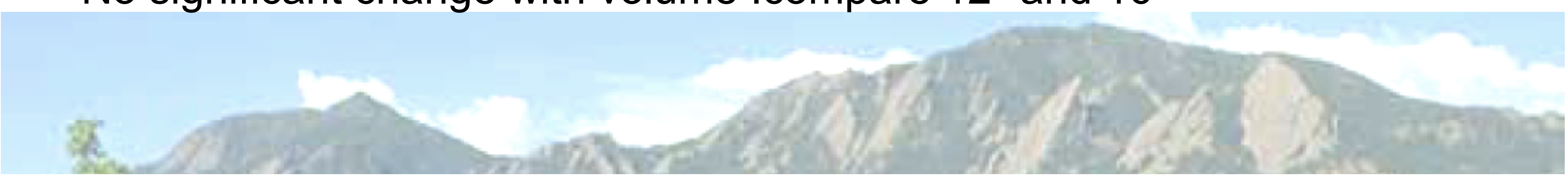
- improved Poly line

or

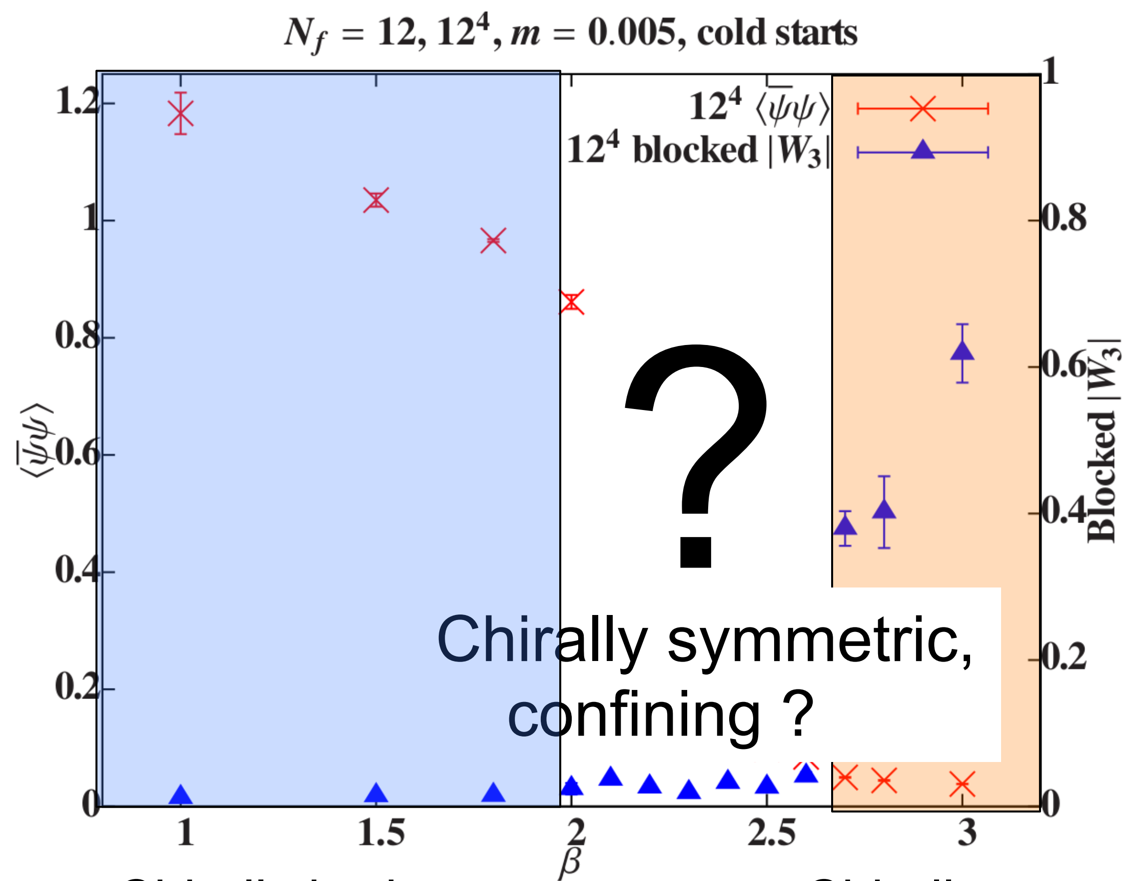
- Poly line on renormalized trajectory, after removing UV fluctuations

The blocked Polyakov line sees the “weak” transition strongly but hardly changes at the “strong” transition

No significant change with volume :compare 12^4 and 16^4



Phase diagram



Chirally broken,
confining

Chirally symmetric,
deconfined

The intermediate phase

possibly only a lattice artifact (bordered by 1st order phase transitions)

BUT

it does not go away with increasing volume, bordered by bulk transitions

its existence is inconsistent with a QCD-like confining, chirally broken scenario.

even if the IM phase is only a lattice artifact, it can shed light to symmetry breaking patterns of lattice fermions (think of the Aoki phase with Wilson fermions)

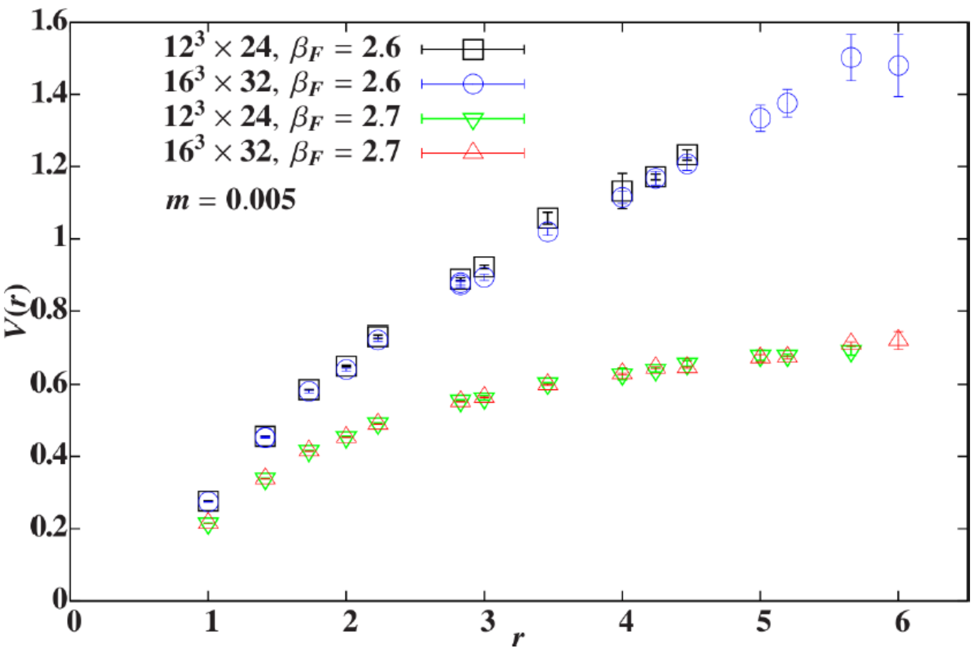
BUT

with the inclusion or some other operator a continuous transition & continuum limit might be reached. (?)

Intermediate phase:

Confining:

- Polyakov line is small
- Static potential on 12^3,16^3 volumes (no volume dependence!) shows a linear term: r_0=2.1 – 2.7, $\sqrt{\sigma}$ =0.40 -- 0.48



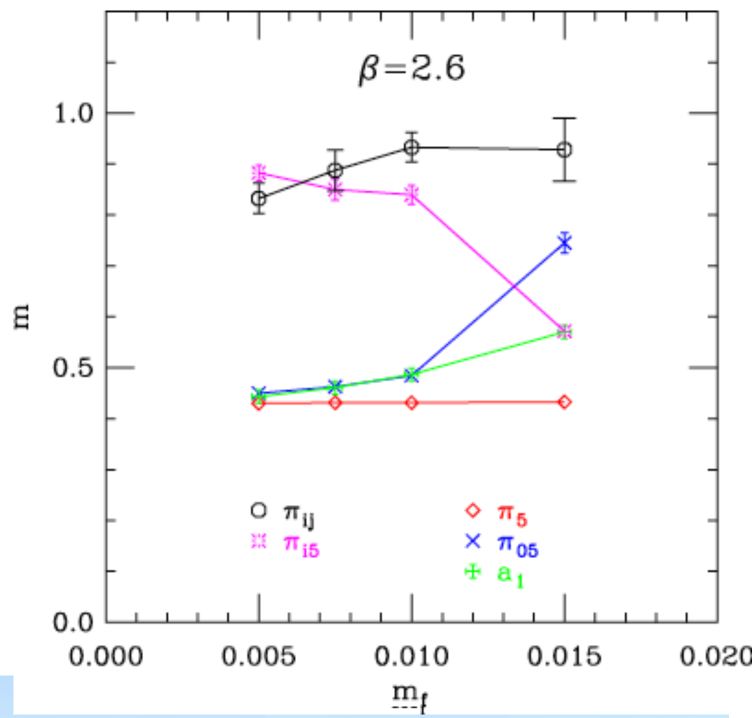
β=2.6 – IM phase

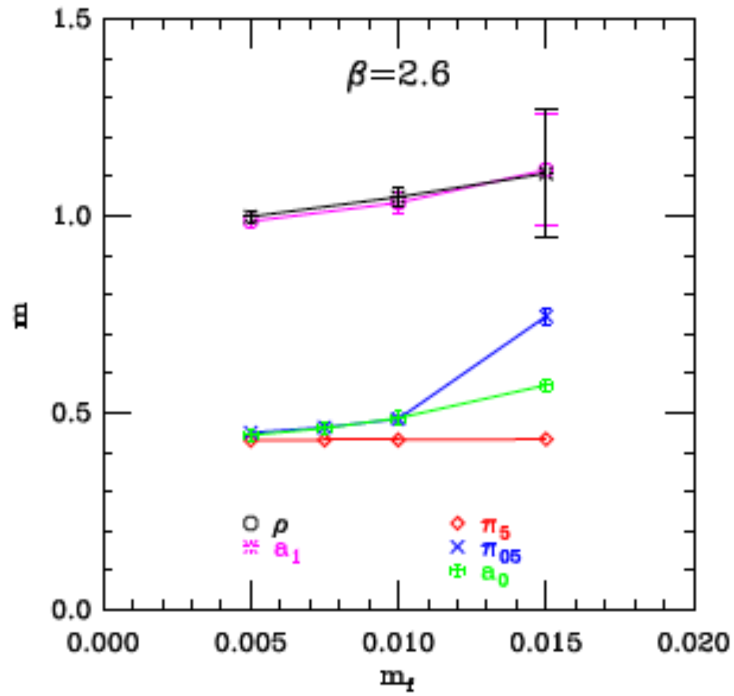
β=2.7 – weak coupling

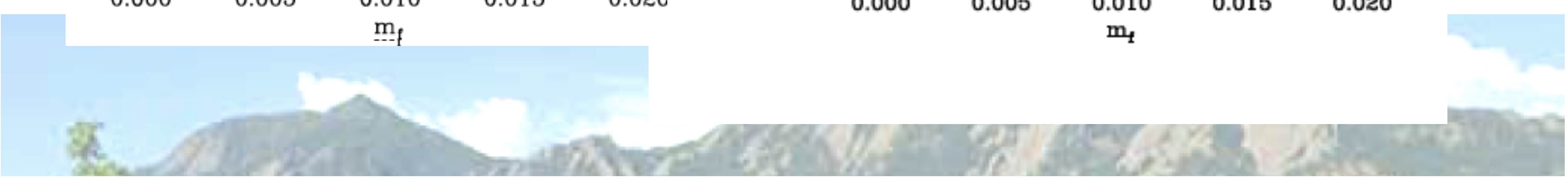
Intermediate phase:

Chirally symmetric:

- $\langle \bar{\psi}\psi \rangle \to 0$ as m→ 0
- The meson spectrum is parity degenerate
  (very different from a QCD-like spectrum with barely any finite volume effects)







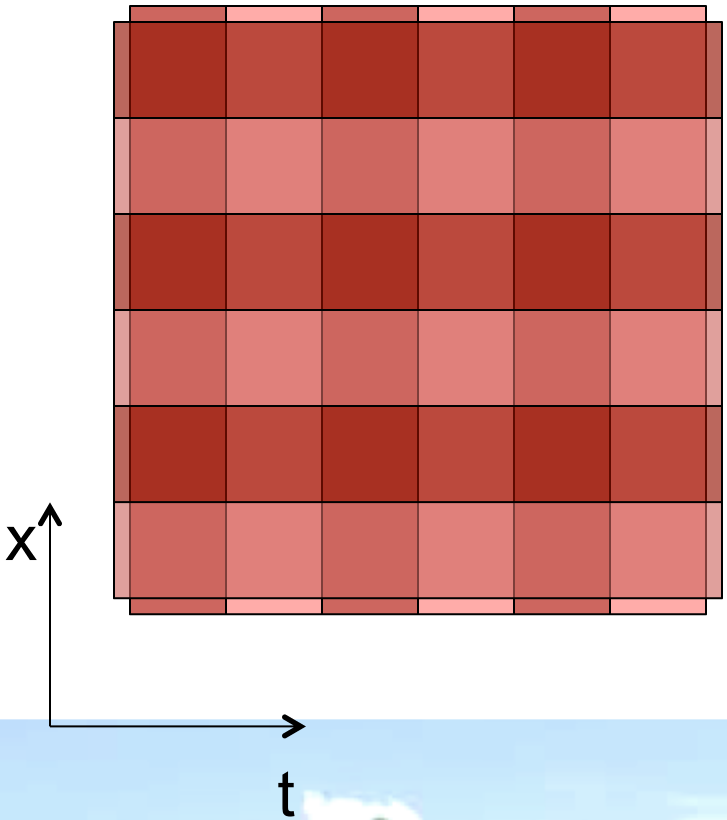
Intermediate phase:

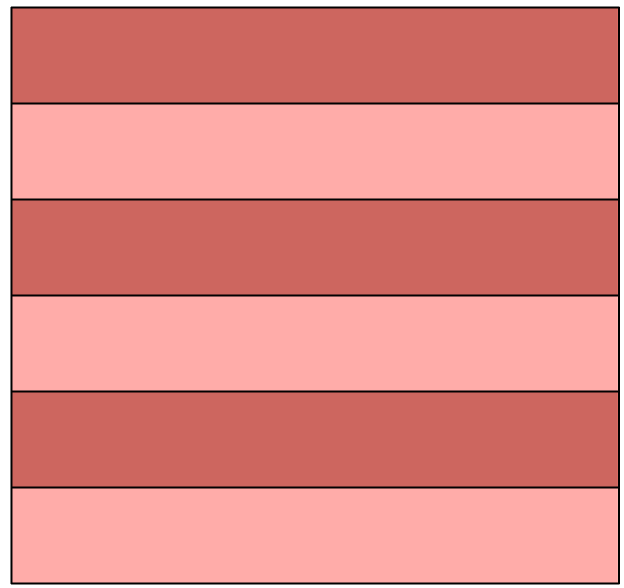
Weird property: single-site translational symmetry

$$\psi_n \rightarrow \psi_{n+\mu}\ ,\ U_{n,\mu} \rightarrow U_{n+\mu,\mu}$$

is broken!

Plaquette expectation value is “striped”



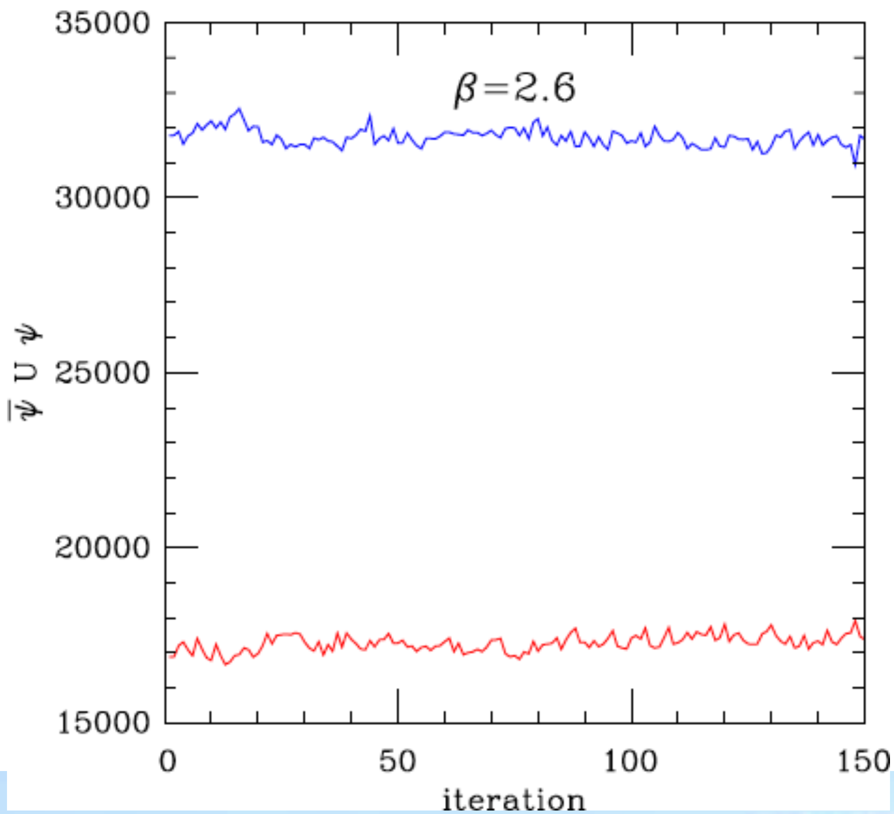


Intermediate phase

Translational symmetry breaking occurs at the fermionic level:

$$\bar{\psi}_n U_\mu(n)\psi_{n+\mu} \neq \bar{\psi}_{n+\mu} U_\mu(n+\mu)\psi_{n+2\mu}$$

Order parameter!



n even

n odd

Intermediate phase

It is a strange phase.

- It is not consistent with the perturbative $g^2 = 0$ fixed point
- It has a small correlation length
- It does not closeoff as the volume increases → only strange, forced scenarios can make it consistent with a QCD-like chirally broken continuum limit

Chirally symmetric & confining phase is nor supposed to exist at all

- There is no continuum limit here (1st order transitions)
- Lattice might generate new relevant interactions

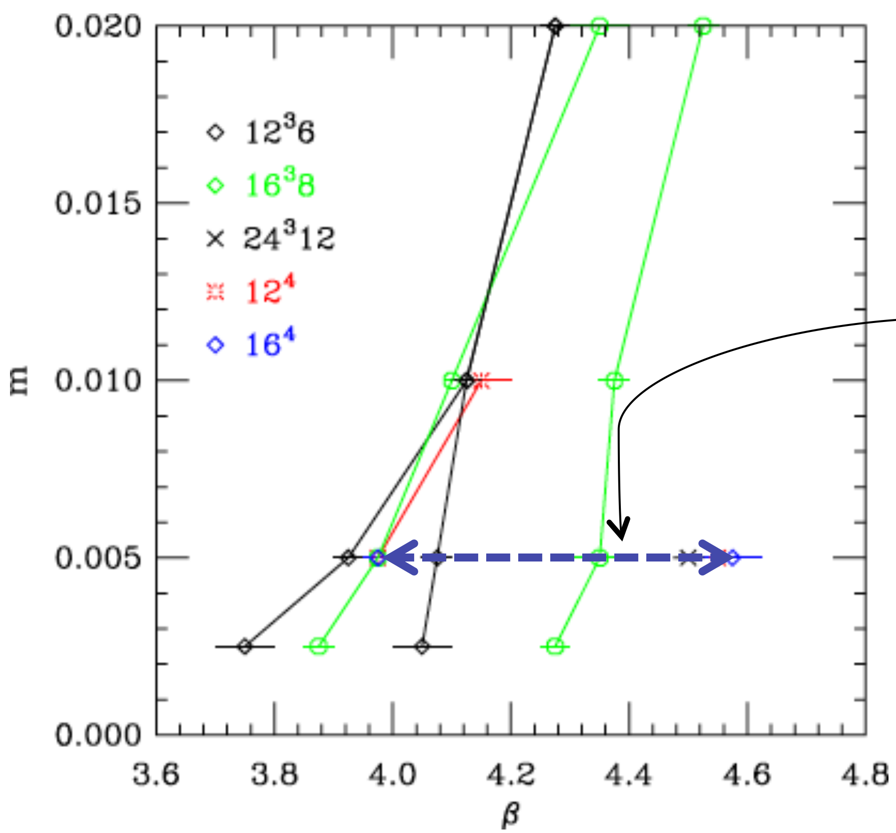
Does it exist in any other system than $N_f = 12$?

No for $N_f = 4$ ✓

Intermediate phase with N_f = 8

The phase diagram is eerily similar to N_f = 12 :

2 transitions, converging (likely) to bulk ones, intermediate phase

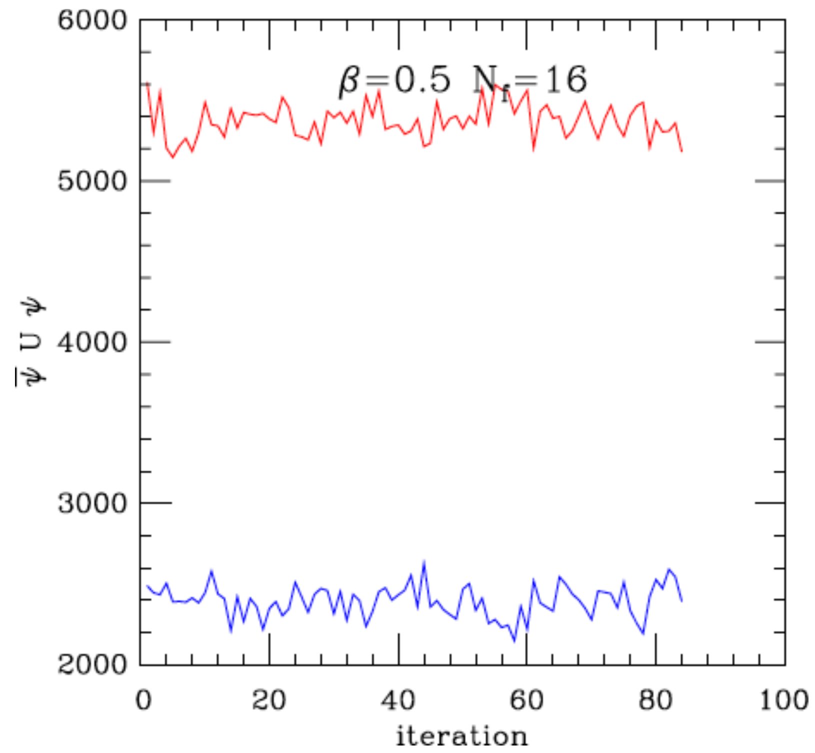


intermediate phase
with the same properties as
N_f = 12

Intermediate phase with $N_f = 16$

We don't have the phase diagram but there is an intermediate phase:

$$\bar{\psi}_n U_\mu(n)\psi_{n+\mu} \neq \bar{\psi}_{n+\mu} U_\mu(n+\mu)\psi_{n+2\mu}$$



This is strange as 16 flavors have no staggering at the level of the action!

Conclusion: more questions than answers

SU(3) gauge with N_f =12 fundamental flavors is the test case of BSM calculations:

- MCRG indicates an IRFP at relatively weak coupling
- The phase structure in the strong coupling is complicated
  - There are two sets of phase transitions
  - The finite temperature phase transitions are limited by bulk transitions
  - The intermediate phase that is chirally symmetric but confining
  - The intermediate phase break single-site translational symmetry
- This is inconsistent with QCD-like behavior, again suggesting conformality

N_f = 8, 16 systems show the same IM phase – is this an indication of IR conformality?