

# Exploring the Conformal Window for Strongly Coupled Theories of Electroweak Symmetry Breaking

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Witzel and the LSD collaboration, and with special thanks to Evan  
Weinberg and Oliver Witzel

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## The electroweak theory after the Higgs

The discovery of the Higgs puts in place the final piece of the electroweak jigsaw puzzle,

but the model still needs an ultraviolet completion.

One possibility is an underlying strongly coupled theory.

## Models of electroweak symmetry breaking based on strong dynamics

There is a long history of strongly coupled theories of electroweak symmetry breaking:

Technicolor    Weinberg, Susskind (1979)

Extended Technicolor    Dimopolous, Susskind '79; Eichten, Lane '80

Walking technicolor    Appelquist, Terning, Wijewardhana (1991)

## The Higgs and nothing else?

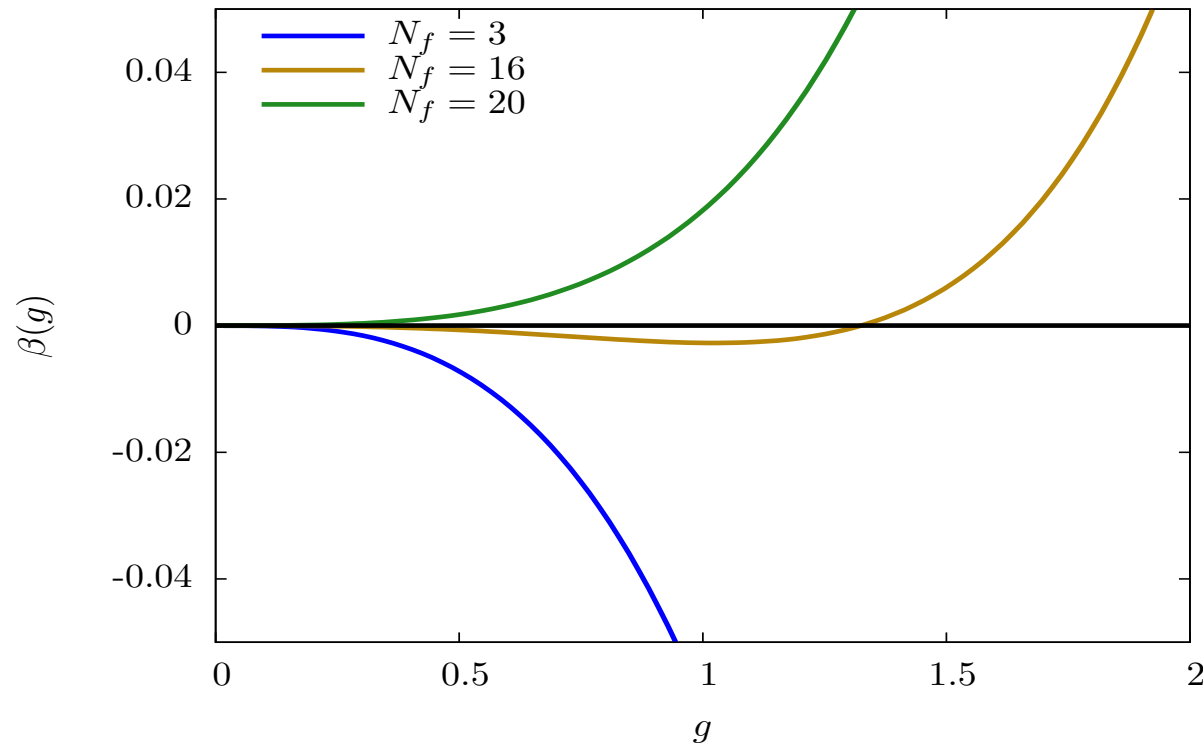
but these model now face challenges:

they must produce a 125GeV scalar, with standard model couplings to quarks and leptons;

3 massless Goldstone bosons, to provide the longitudinal components of the W's and Z;

and everything else must be pushed to a higher scale.

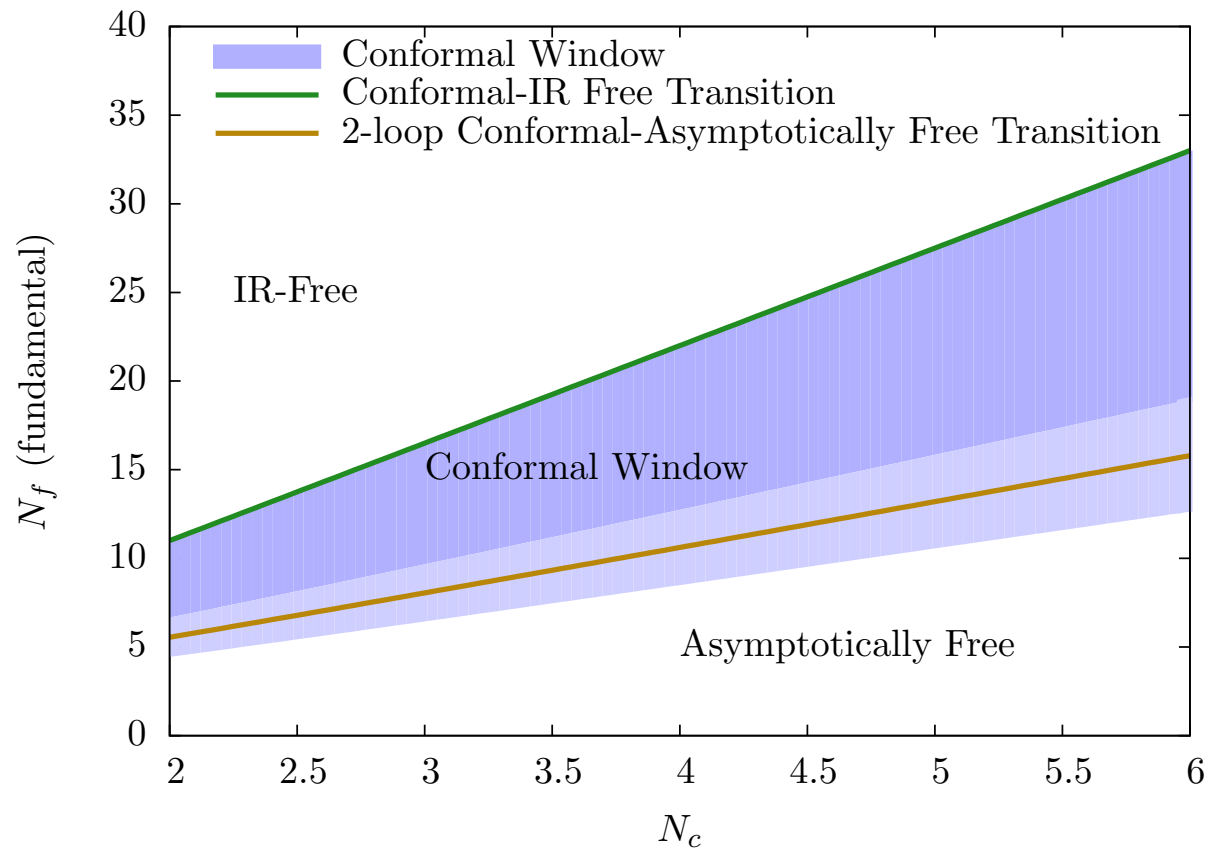
## Conformal fixed point



$SU(3)$  with  $N_f$  flavors.

A possibility is that the theory has a conformal fixed point, or comes very close to one. [Caswell \(1974\)](#), [Banks, Zaks \(1982\)](#)

## Searching for theories



Unlike QCD (SU(3) with given number of flavors) the spectrum of theories which need to be investigated is very large.

## Computational framework

The study of strong dynamics requires lattice computational methods.

Very brief recap:

The theory is discretized on a Euclidean space-time lattice

$$\langle \mathcal{O} \rangle = Z^{-1} \int d\bar{\psi} d\psi dU \mathcal{O}(\bar{\psi}, \psi, U) e^{-S_g(U) - \bar{\psi} D(U) \psi}$$

The fermions are integrated over

$$\langle \mathcal{O} \rangle = Z^{-1} \int dU \langle \mathcal{O} \rangle_{\bar{\psi}, \psi}(U) e^{-S_g(U)} \text{Det}[D(U)]$$

## Computational framework, continued

The determinant is calculated with bosonic variables

$$\langle \mathcal{O} \rangle = Z^{-1} \int dU d\phi^* d\phi \langle \mathcal{O} \rangle_{\bar{\psi}, \psi}(U) e^{-S_g(U) - \phi^* D(U)^{-1} \phi}$$

One introduces momenta  $\Pi$  conjugate to  $U$ , and a Gaussian extraction of  $\phi^*$ ,  $\phi$ , together with a Hamiltonian evolution of  $U$ ,  $\Pi$ , is used for a stochastic sampling of all configurations

$$\langle \mathcal{O} \rangle = Z^{-1} \int dU d\Pi d\phi^* d\phi \langle \mathcal{O} \rangle_{\bar{\psi}, \psi}(U) e^{-S_g(U) - \Pi^2 - \phi^* D(U)^{-1} \phi}$$

Hybrid MD,  $\rightarrow$  (with an accept-reject step to correct for errors in the Hamiltonian evolution) Hybrid Monte Carlo



## Computational challenges

The numerical simulations are very demanding.

Discretizations of the Dirac action:

**Wilson** convenient, but breaks chiral symmetry;

**Kogut-Susskind or staggered** preserves one non-singlet chiral symmetry, introduces extra fermions (taste);

**domain wall, overlap** preserve chiral symmetry, computationally costly.

Obtaining the correct topological distribution with Hybrid Monte Carlo may be a problem.

# The Lattice Strong Dynamics collaboration

[www.yale.edu/LSD/](http://www.yale.edu/LSD/)



## Lattice **S**trong **D**ynamics Collaboration



James Osborn



Chris Schroeder  
Pavlos Vranas  
Enrico Rinaldi



Rich Brower  
Michael Cheng  
Claudio Rebbi  
Oliver Witzel  
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David Schaich



Ethan Neil  
Sergey Syritsyn



Tom Appelquist  
George Fleming  
Gennady Voronov



Meifeng Lin



Mike Buchoff

14

and Evan Berkowitz, LLNL

## The LSD research program

Simulations: SU(3) with  $N_f = 2, 6, 8, 10$ , domain wall; SU(3),  $N_f = 8$ , staggered; SU(2),  $N_f = 2, 6$ , Wilson; SU(4),  $N_f = 2, 3, 4$ , Wilson.

Toward TeV Conformality (Phys.Rev.Lett. 104 (2010) 071601)

Parity Doubling and the S Parameter Below the Conformal Window (Phys.Rev.Lett. 106 (2011) 231601)

WW Scattering Parameters via Pseudoscalar Phase Shifts (Phys.Rev. D85 (2012) 074505)

Approaching Conformality with Ten Flavors (arXiv:1204.6000 hep-ph)

Lattice calculation of composite dark matter form factors (Phys.Rev. D88 (2013) 1, 014502)

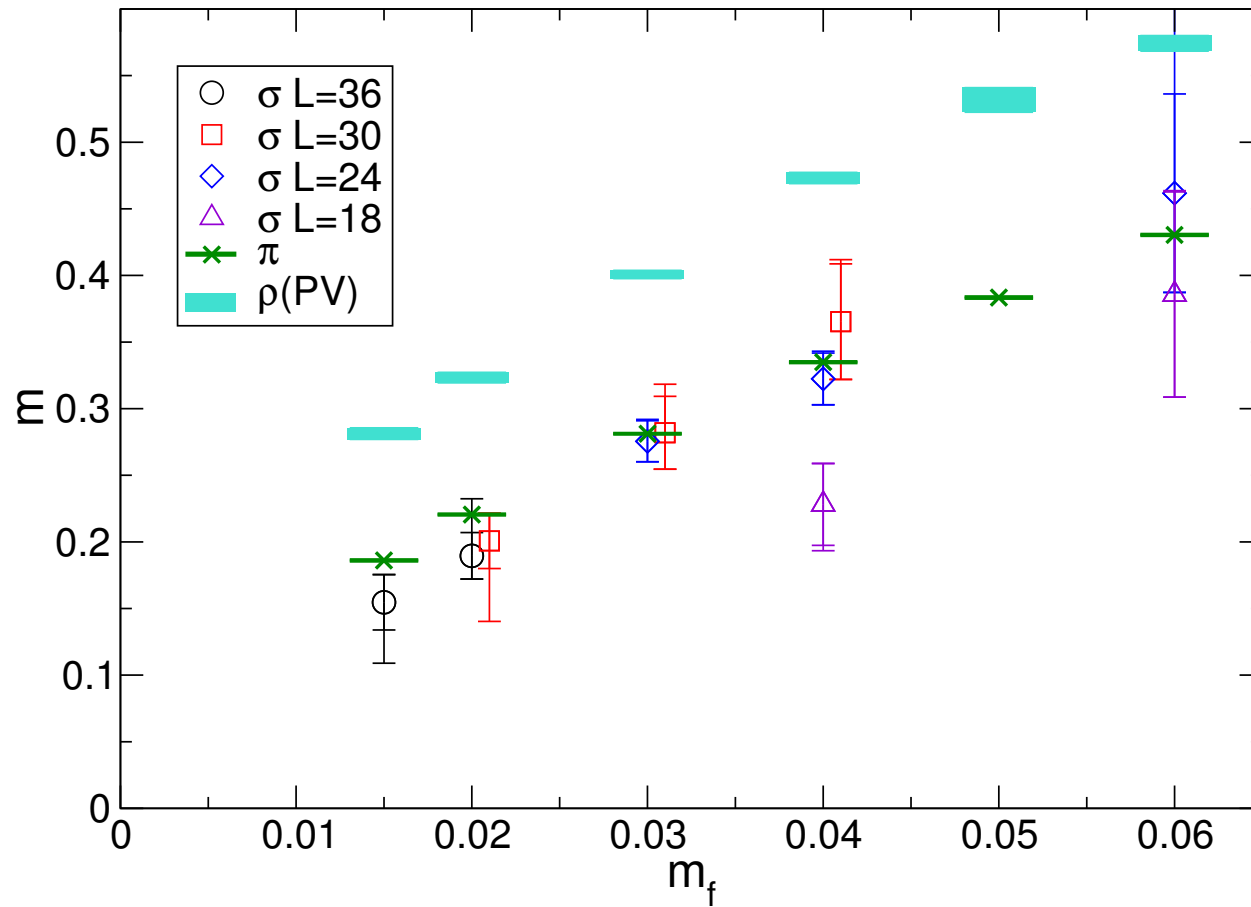
Two-Color Theory with Novel Infrared Behavior (Phys.Rev.Lett. 112 (2014) 111601)

Composite bosonic baryon dark matter on the lattice: SU(4) baryon spectrum and the effective Higgs interaction (arXiv:1402.6656 hep-lat)

Maximum-Likelihood Approach to Topological Charge Fluctuations in Lattice Gauge Theory (arXiv:1403.2761 hep-lat)

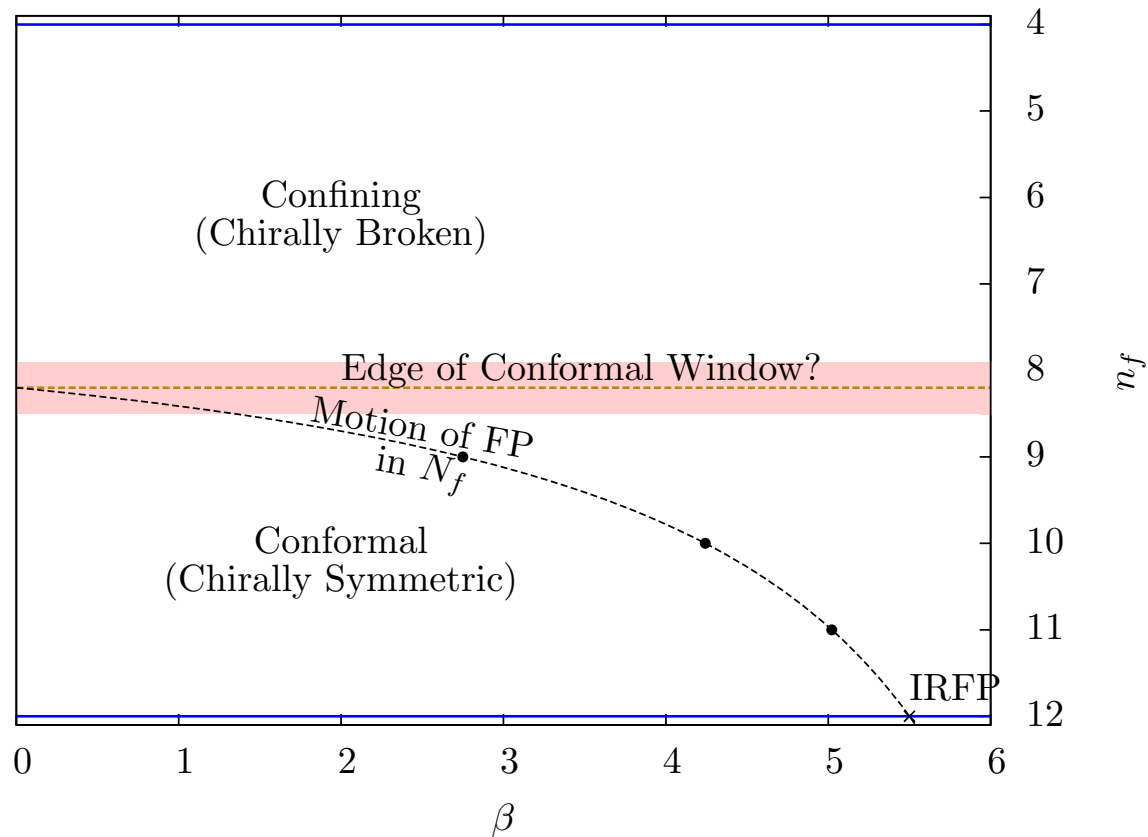
Lattice simulations with eight flavors of domain wall fermions in SU(3) gauge theory (arXiv:1405.4752 hep-lat)

## Theories with a light scalar



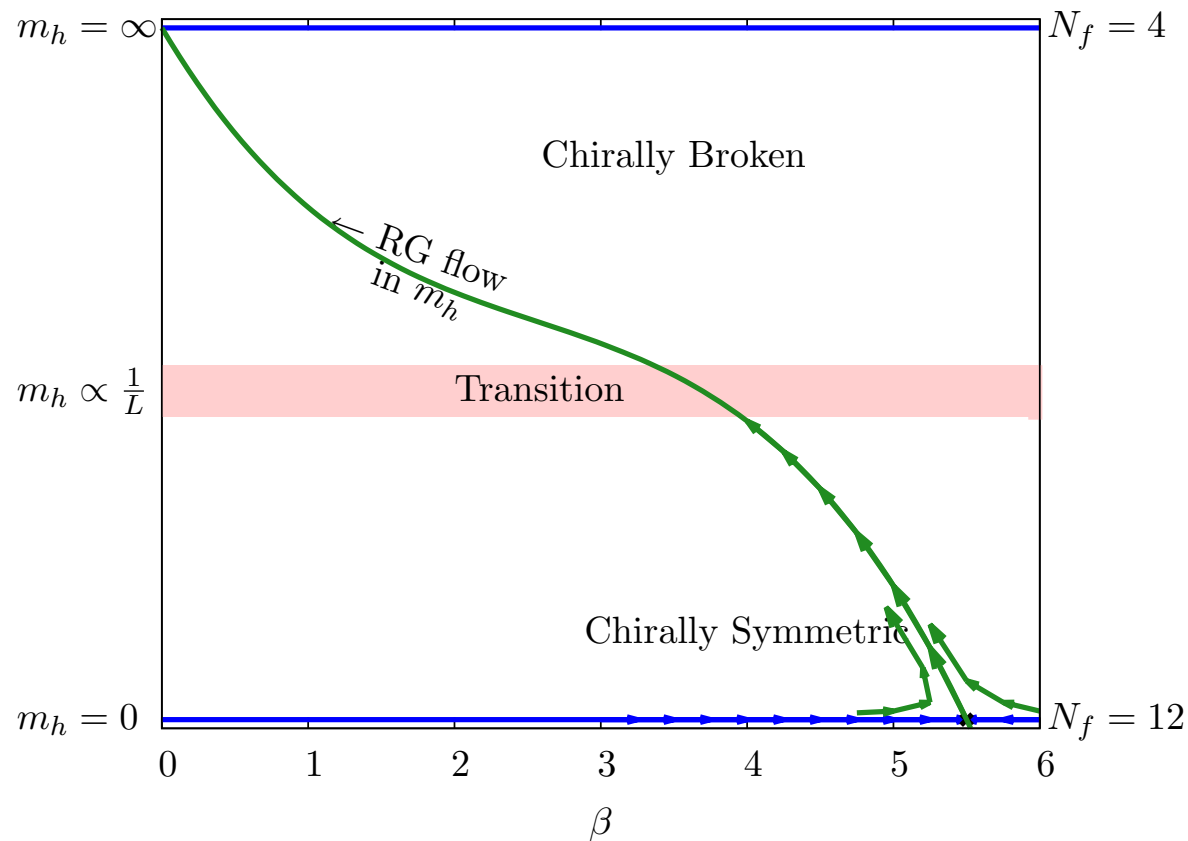
Tantalizing evidence from the LatKMI collaboration (Y. Aoki et al.,  
arXiv:1403.5000 [hep-lat])

## IRFP in SU(3)



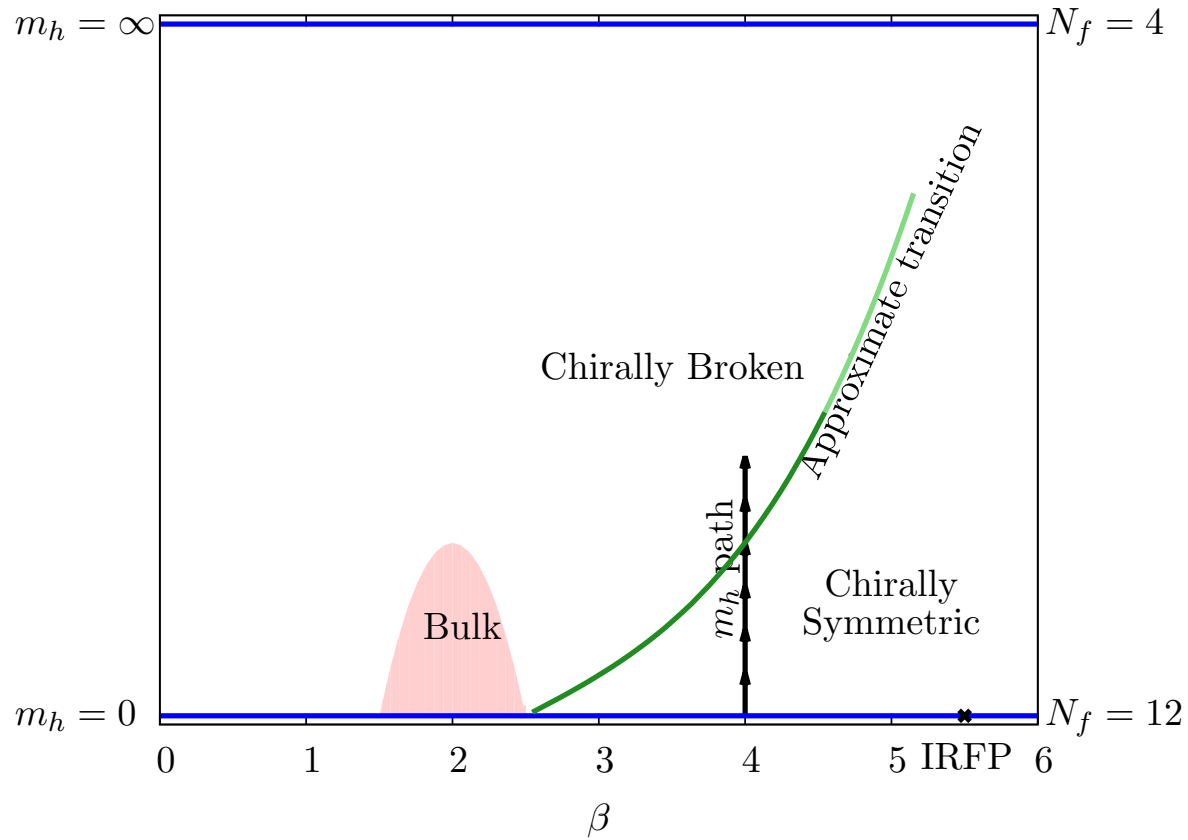
Looking for a possible infrared fixed-point in an SU(3) theory with variable number of fermions.  $\beta \propto 1/g^2$  (standard lattice notation)

## SU(3) with 4 light and 8 heavy flavors



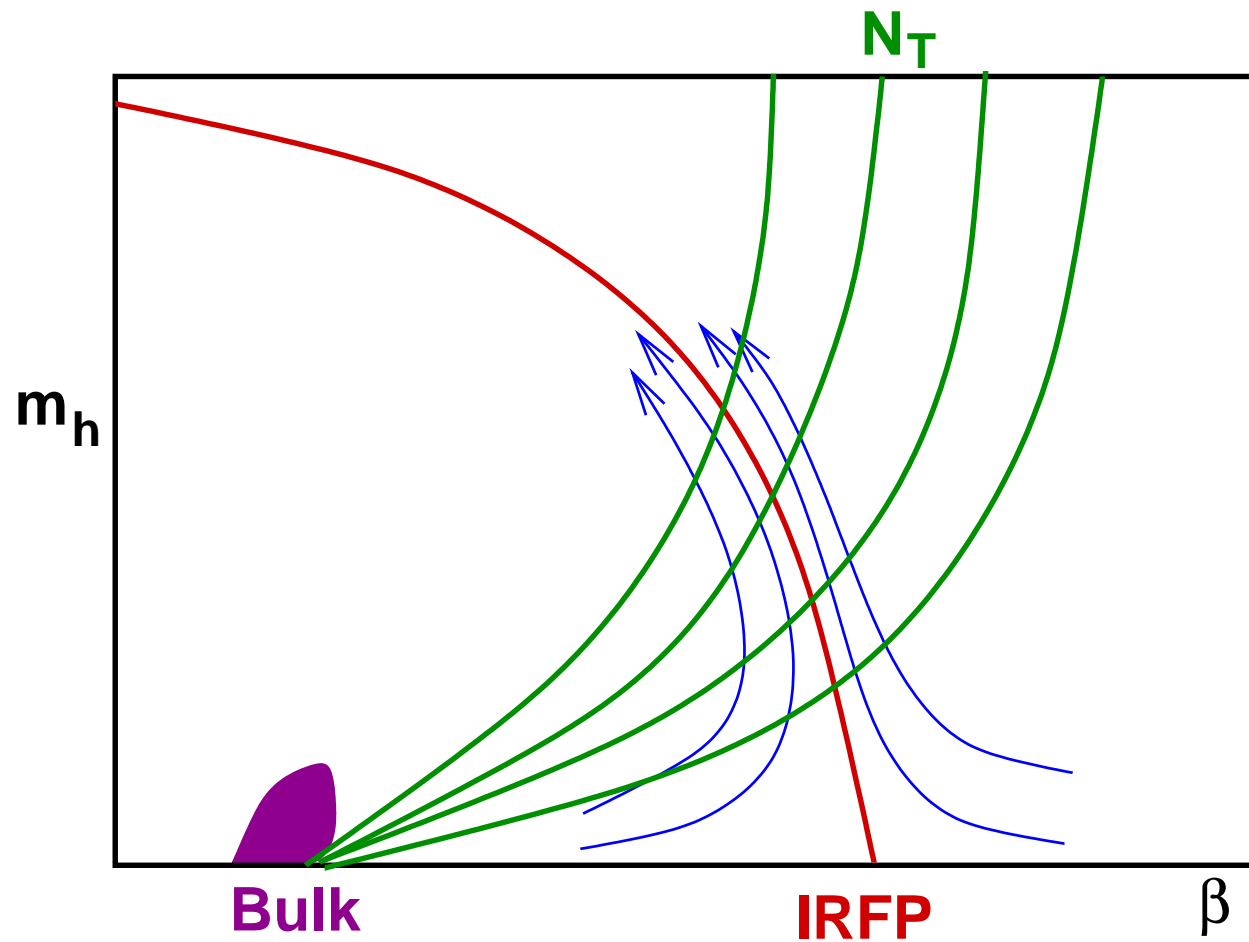
Varying  $N_f$  can only be done in steps. We consider an SU(3) theory with 4 light fermions plus 8 fermions of variable mass  $m_h$ .  $m_h$  is a relevant parameter.

## 4 light and 8 heavy flavors, continued



An important part of the effort is to find the appropriate window in  $\beta$  and  $m_h$ .

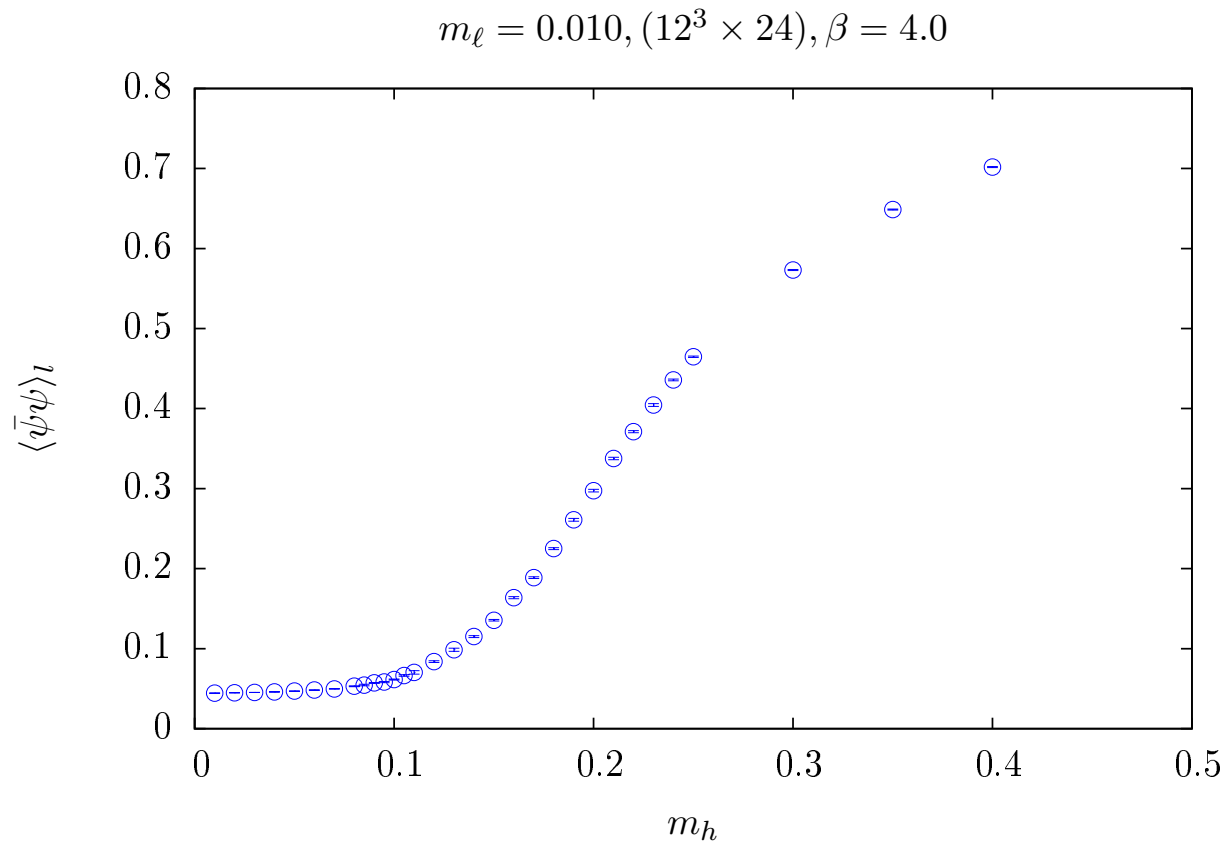
Another view, with  $T$



$T = 1/(N_T a)$  ( $a$  is the lattice spacing)

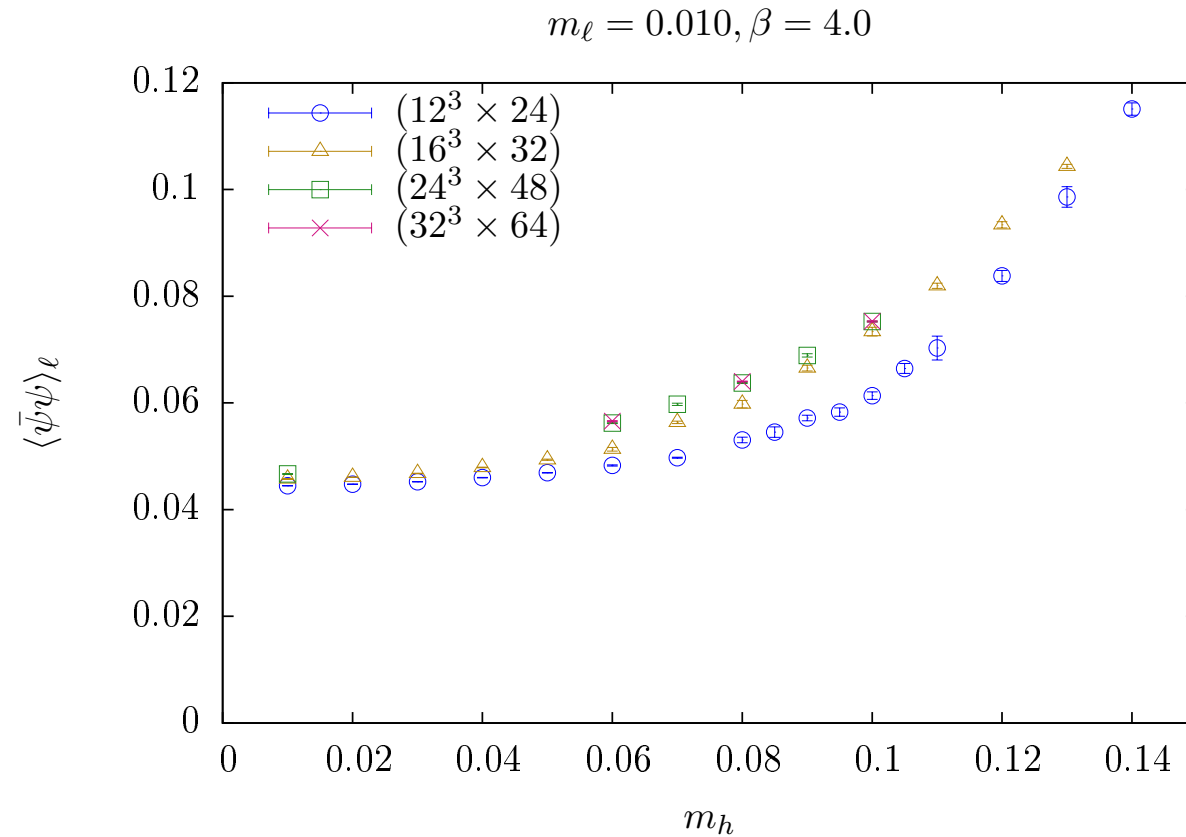


## The light fermion condensate



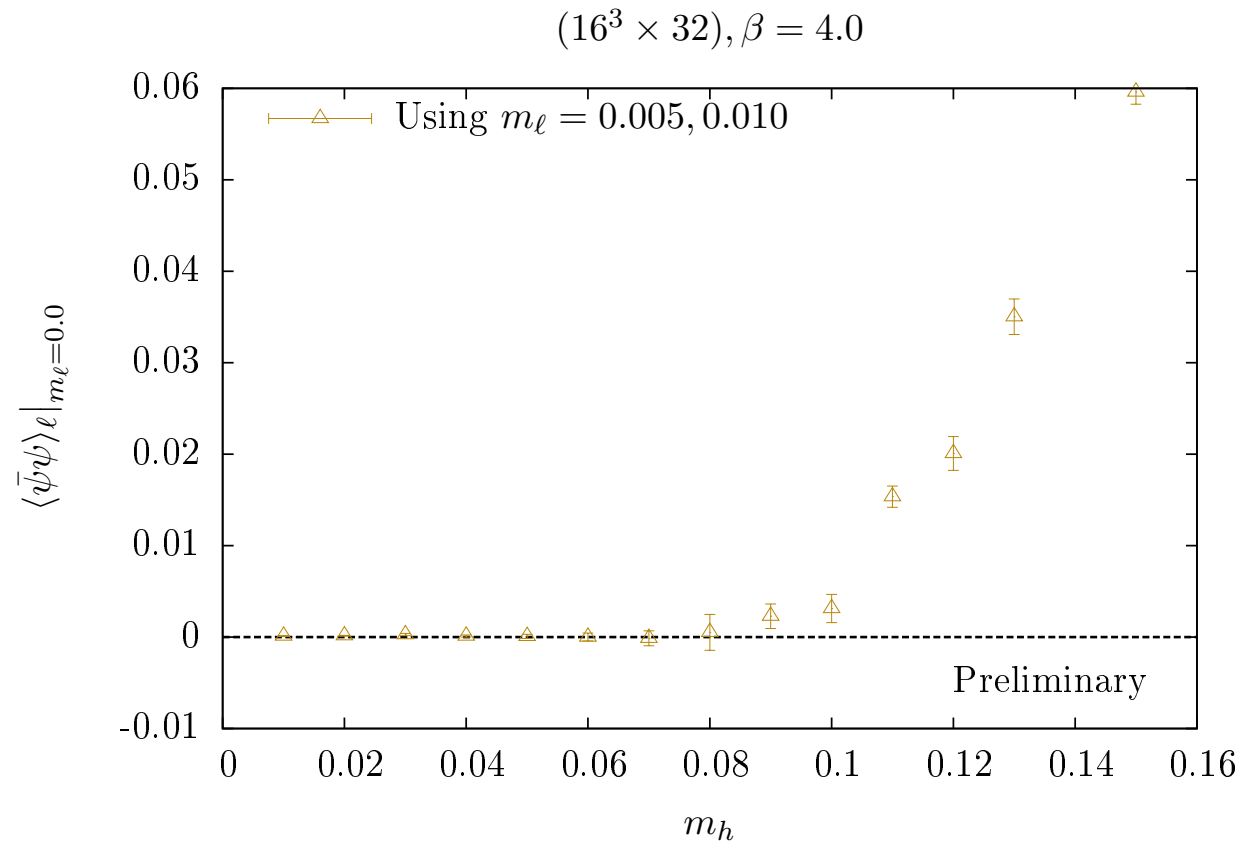
The light fermion condensate  $\langle \bar{\psi}\psi \rangle$  shows a marked dependence on the mass of the 8 heavy fermions.

# The light fermion condensate, volume dependence



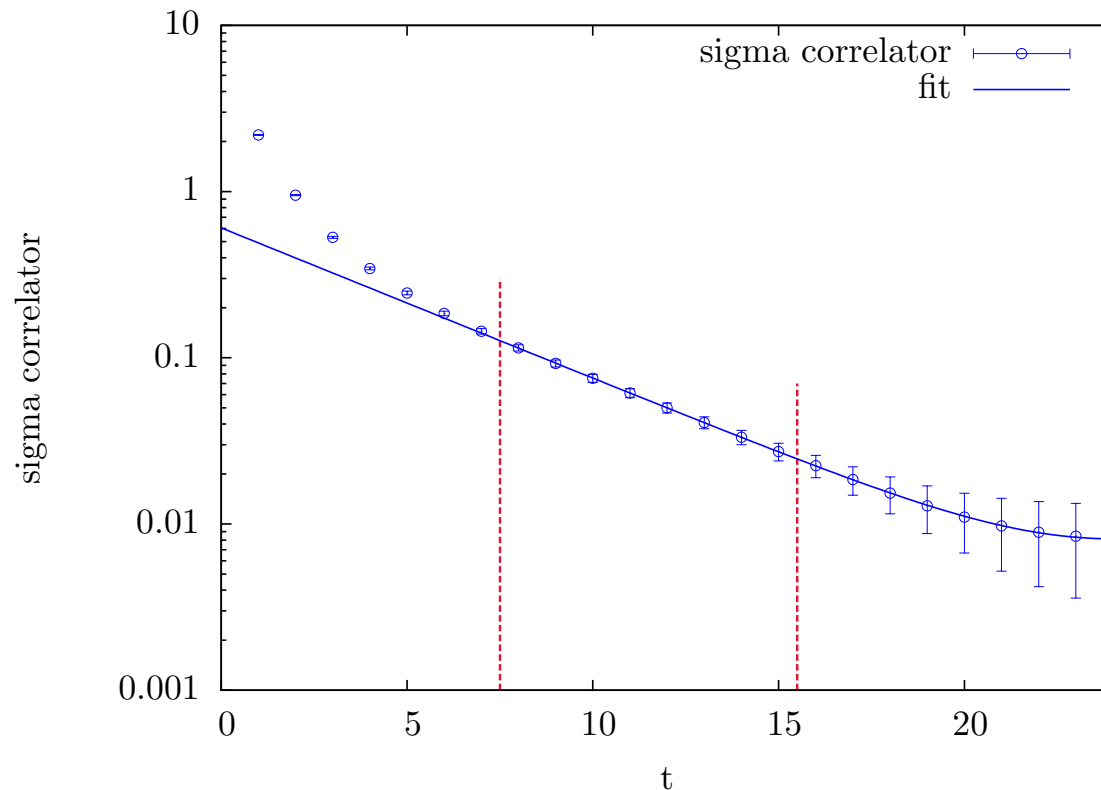
The transition appears to occur at smaller  $m_h$  as the volume increases.

## The light quark condensate, extrap. to $m_l = 0$



The extrapolation to  $m_l = 0$  indicates a transition from a chirally broken theory for  $m_h \gtrsim 0.08$  to a chirally symmetric theory for  $m_h \lesssim 0.08$ .

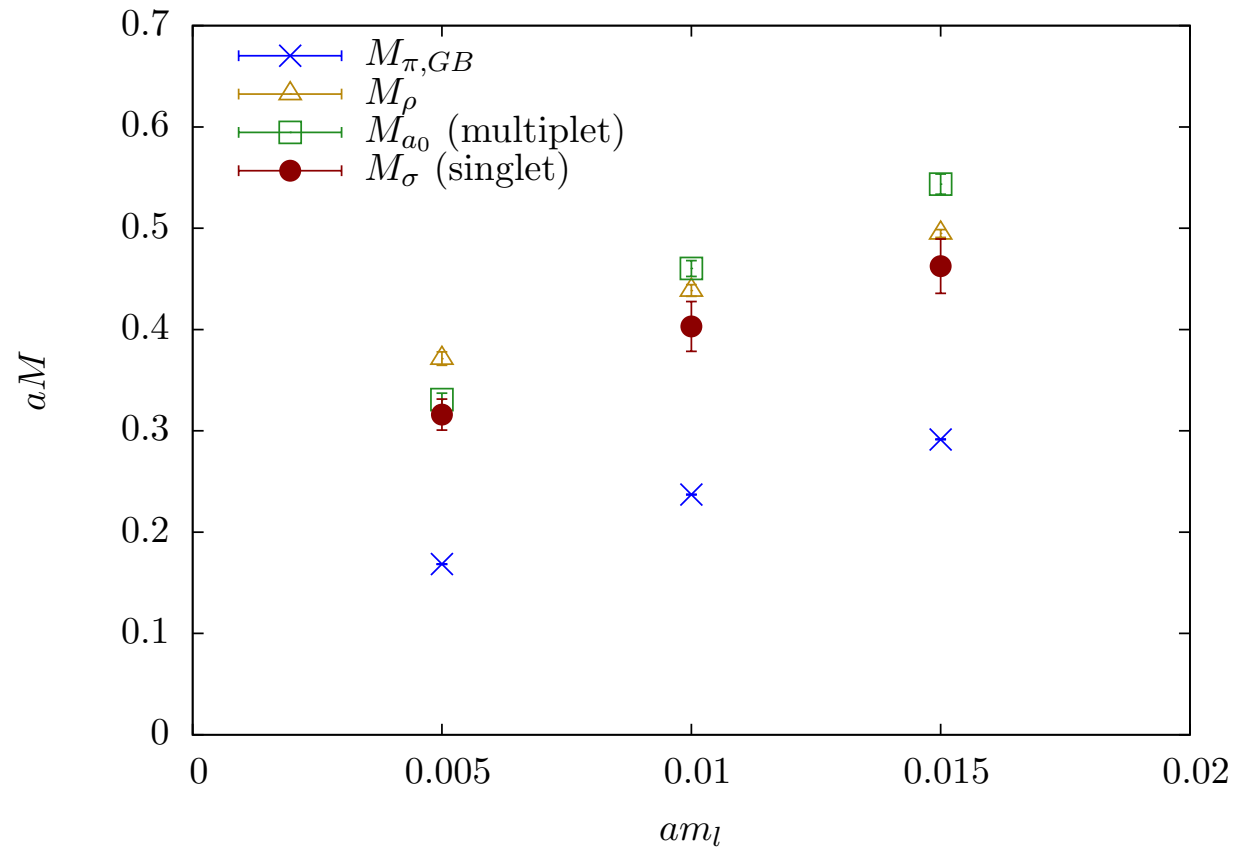
## The singlet scalar correlator



Masses are evaluated from the rate of decay in Euclidean time of correlators:  $\sum_{\vec{x}} \langle \bar{\psi}\psi(0) \bar{\psi}\psi(\vec{x}, t) \rangle$ . The singlet scalar correlator requires the calculation of disconnected diagrams.

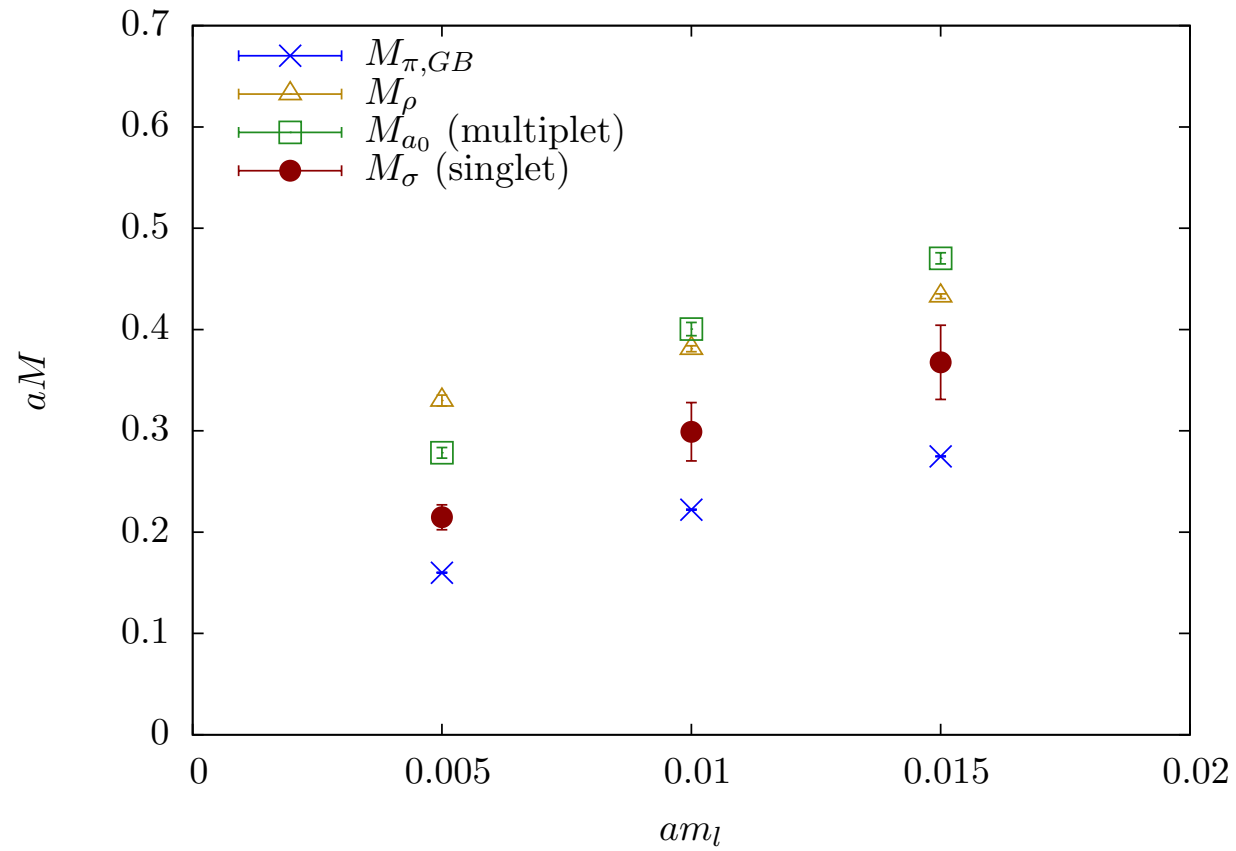
$(24^3 \times 48, m_l = 0.005, m_h = 0.080)$

## The singlet scalar mass



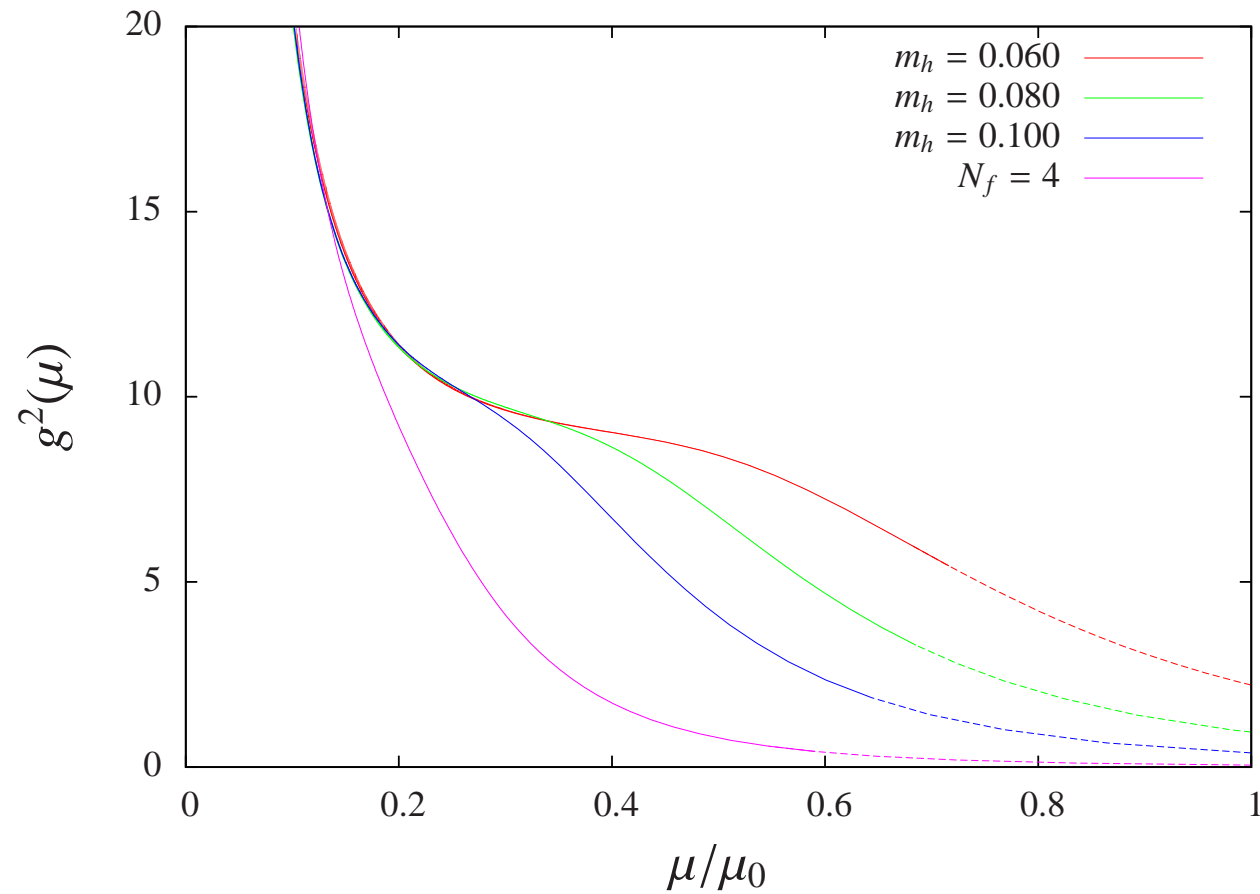
$$m_h = 0.100$$

## The singlet scalar mass, continued



$$m_h = 0.080$$

## Renormalization flow



The Wilson flow (Lüscher, 2010) may be used to study scaling.

## Conclusions

The spectrum of non-QCD strongly coupled gauge theories with fermions is still largely unexplored.

Studying the properties of these theories is interesting per se.

The theory of electroweak symmetry breaking may be found among them.