# Is the Higgs elementary or composite?

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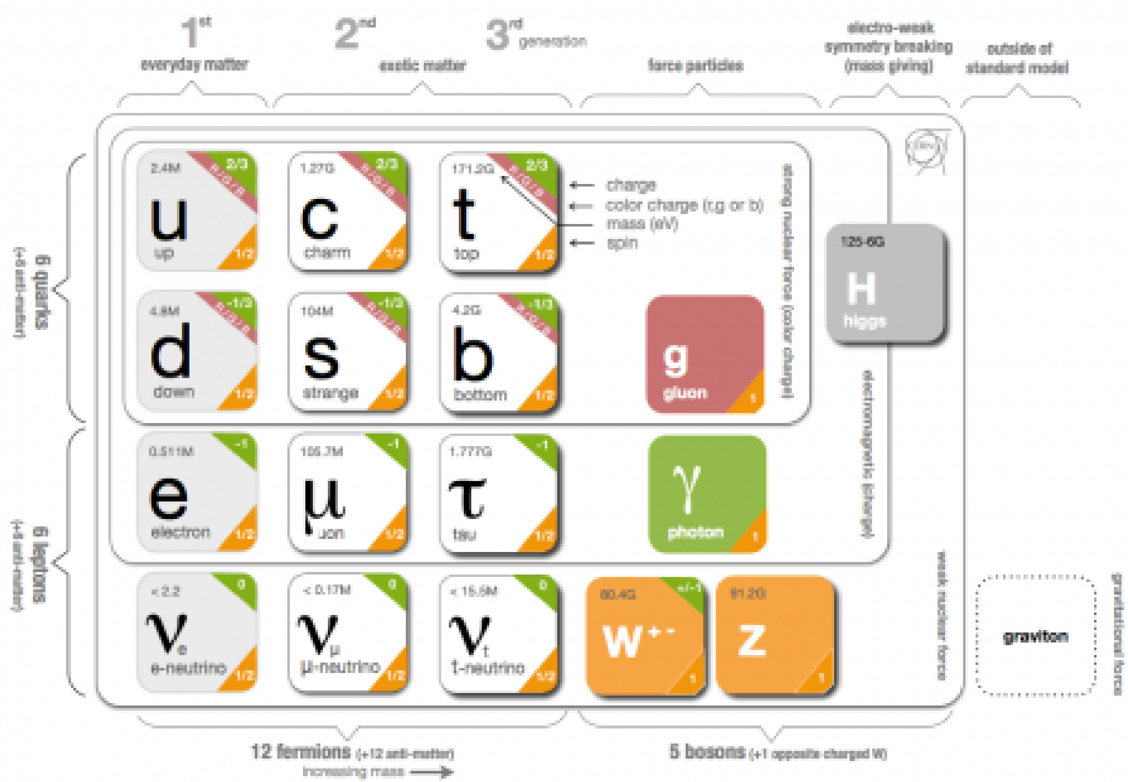
# Motivation

The Standard Model of particle physics is extraordinarily precise both experimentally and theoretically




Have already seen during this school of course ...

## Motivation

The visible Universe is correctly described by the Standard Model

Experimental and theoretical matching is in some cases $1 : 10^{12}$

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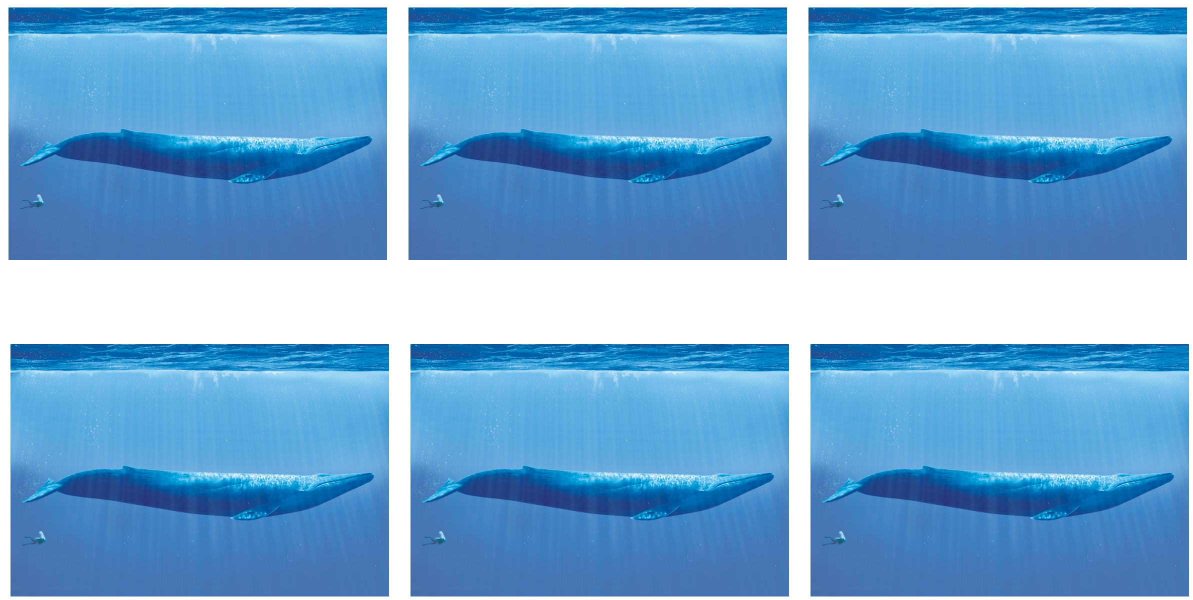


Yet the theory is very simple (in some sense...)

## Motivation

### Last missing piece: Higgs boson

- July 4, 2012, LHC CERN, experimental confirmation
- 2013, Nobel prize to Peter Higgs, Francois Englert for theory

## Motivation

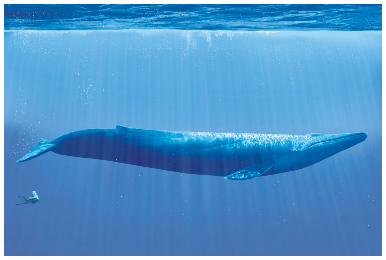
But!

Gravity is not included $\longrightarrow$
Standard Model expected to break down $\Lambda_{cutoff} = 10^{19}\ GeV$

No problem for accelerators, etc.: sensitive to $\sim 10^4\ GeV$

But as a result elementary Higgs boson mass is actually (in GeV)

$125 = 10\,000\,000\,000\,000\,000\,125 - 10\,000\,000\,000\,000\,000\,000$

 : $6 \cdot 10^7 \cdot$ 

## Motivation

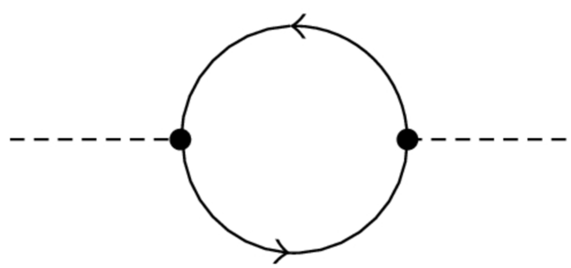
Higgs mass (in GeV)

$$125 = 10\,000\,000\,000\,000\,000\,125 - 10\,000\,000\,000\,000\,000\,000$$

$$m^2_{Higgs} = m^2_{bare} - const\ \Lambda^2_{cutoff}$$

Because of additive renormalization of mass

Top loop most significant



Even though theory is renormalizable, cutoff is physical

## Motivation

This is called Naturalness problem or fine tuning problem

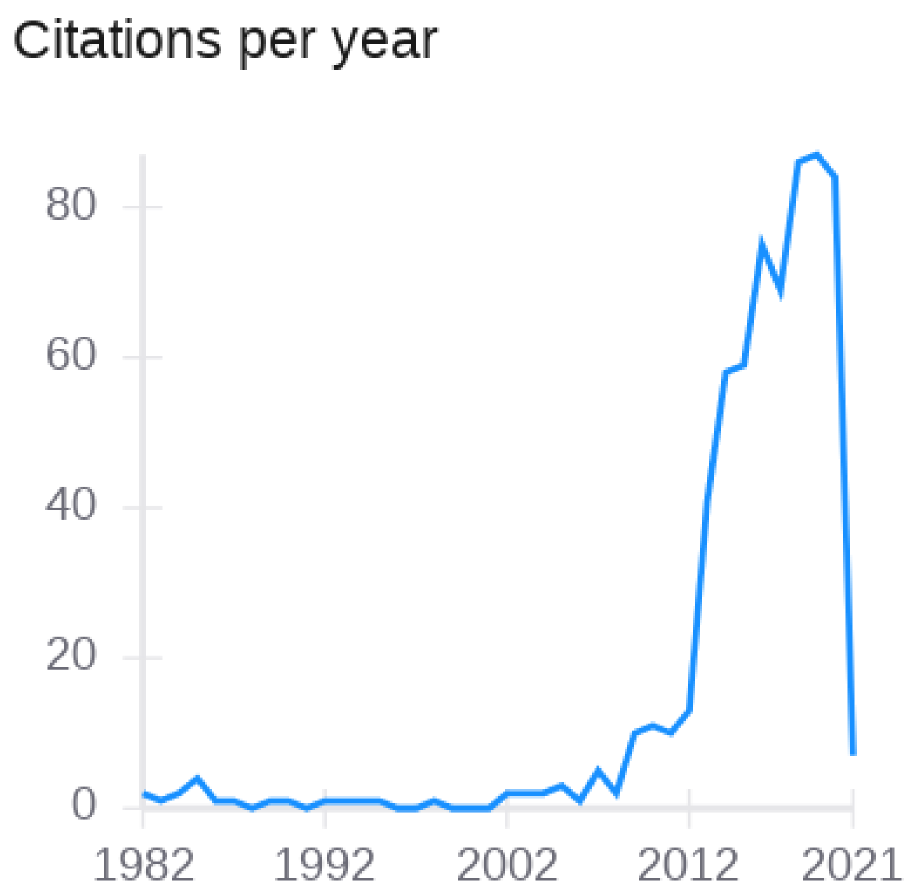
Why is it present for elementary scalar?

No symmetry to protect $m_{Higgs} = 0 \longrightarrow$ additive mass renormalization

For example fermion masses are protected by chiral symmetry $\longrightarrow$ multiplicative renormalization $\longrightarrow$ no Naturalness problem

See for more: https://inspirehep.net/literature/144074

1979 Gerard 't Hooft: Naturalness, chiral symmetry, and spontaneous chiral symmetry breaking,



## Why is this a problem?

Imagine tax laws are: if profits below \$200 $\longrightarrow$ no tax, if profits above \$200 $\longrightarrow$ 30% tax

- income: \$6000, costs: \$5500
  profits: \$500 $\longrightarrow$ 30% tax $\longrightarrow$ natural
- income: \$600, costs: \$500
  profits: \$100 $\longrightarrow$ no tax $\longrightarrow$ natural
- income: \$2000, costs: \$1900
  profits: \$100 $\longrightarrow$ no tax $\longrightarrow$ natural
- income: \$100.000, costs: \$80.000
  profits: \$20.000 $\longrightarrow$ 30% tax $\longrightarrow$ natural

Why is this a problem?

Imagine company filing with IRS (or NAV in Hungary):

- Revenue: \$ 10 thousand quadrillion + 125
- Costs: \$ 10 thousand quadrillion
- Profit = Revenue - Costs = \$125 $\rightarrow$ no tax

IRS (or NAV) might not say definitely something is illegal, but would find it suspicious ...

## Motivation

Similarly, such a fine tuning of the Higgs mass: suspicious

Haven't seen anything like this elsewhere in Nature

Fine Tuning Problem - Hierarchy Problem - Naturalness Problem

Only present if *elementary* Higgs, not if *composite*!

Example: QCD, *composite* hadrons, no problem

## Motivation

Suggestion: Higgs is a composite particle

Basic building blocks can build up other composite particles

Similarly to QCD, lots of hadrons

Prediction for LHC: lots of new particles

Key: testable

## Motivation

Not the only possible solution to Fine Tuning Problem

Example: supersymmetry

Challenge to all proposals: reproduce the extraordinarily precise results we already know from Standard Model $\rightarrow$ at low energies extensions of the Standard Model should not differ much from Standard Model, only at higher energies $\sim O(10\, TeV)$

Also: should provide testable predictions for LHC

Motivation

Summary: replace elementary Higgs by composite particle of new, so far undetected, gauge theory coupled to new, so far undetected, fermions

Sometimes called technigluons, technifermions (but not always)

Large set of ideas

Often use QCD terminology and QCD analogy

## Outline

- Motivation, Naturalness (done already)

- QCD review
  - Elementary quarks, gluons
  - Composite hadrons
  - No fine tuning problem
  - Symmtries and their breaking (chiral symmetry): explicit, spontaneous, anomalous
  - Spontaneous breaking, Goldstone theorem, effective theory, chiral perturbation theory

- Composite Higgs models
  - New elementary building blocks, new gauge fields and new fermions
  - Predictions of new particles
  - Two large classes of models: Little Higgs, Strong Dynamics
  - Problems

QCD review

## Elementary quarks and gluons

$$\mathcal{L} = -\frac{1}{2g^2}\mathrm{Tr}\, F_{\mu\nu}F_{\mu\nu} + \sum_{i=1}^{N_f} \bar{\psi}_i(D + m_i)\psi_i$$

$g$: single dimensionless coupling, $D$ Dirac operator, $m_i$ masses for each flavor $i = 1, \ldots, N_f$

In Nature: $N_f = 6$, $(u, d, s, c, b, t)$

Symmetries: vector + axial

## QCD review - symmetries

$$\delta\psi_i = i\omega_{ij}\psi_j \qquad\qquad \delta\bar{\psi}_i = -i\bar{\psi}_j\omega_{ji}$$

Vector symmetry, $\omega_{ij}$ Hermitian, $U = e^{i\omega}$ unitary $\to SU(N_f)$

Symmetry even if $m_i \neq 0$

$$\delta\psi_i = i\omega_{ij}\gamma_5\psi_j \qquad\qquad \delta\bar{\psi}_i = i\bar{\psi}_j\gamma_5\omega_{ji}$$

Axial symmetry, $\omega_{ij}$ Hermitian, $U = e^{i\omega}$ unitary $\to SU(N_f)$

Only symmetry if $m_i = 0$, reminder: $\{\gamma_5, \gamma_\mu\} = 0$, $\{\gamma_5, D\} = 0$

## QCD review - symmetries

$$SU(N_f) \times SU(N_f)$$

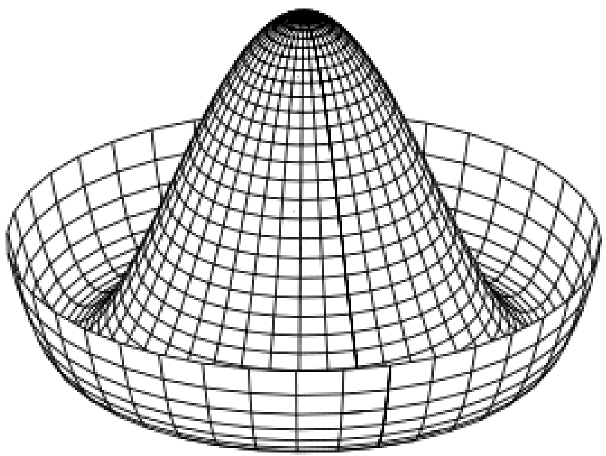
Symmetry if $m_i = 0$: the Lagrangian $\mathcal{L}$ is invariant

Spontaneous symmetry breaking: $\mathcal{L}$ (or Hamiltonian) invariant with some $G$ but vacuum $|0\rangle$ is not

Subgroup $H \subset G$ leaves $|0\rangle$ invariant: $G/H$ coset

QCD review - spontaneous symmetry breaking

Goldstone theorem: there are as many massless particles as the dimension of $G/H$: one for each breaking direction



Breaking direction is flat because $\mathcal{L}$ invariant $\longrightarrow$ no quadratic term $\longrightarrow$ massless mode

## QCD review - spontaneous chiral symmetry breaking

In massless QCD: $G = SU(N_f) \times SU(N_f)$ broken spontaneously, $H = SU(N_f)$ corresponding to axial

There are $N_f^2 - 1$ massless particles $\rightarrow$ pions

Two light flavors, $(u, d)$, there are 3 pions

Order parameter $\Sigma = \langle 0|\bar{\psi}_i \psi_i|0\rangle \neq 0$

If symmetry would not be spontaneously broken: $\Sigma = 0$

## QCD review - explicit symmetry breaking

In QCD $m_i \neq 0$ but for $(u, d, s)$ they are small, with $(u, d)$ even smaller

$\mathcal{L}$ is not invariant with $m_i \neq 0$ but change $\delta\mathcal{L}$ small

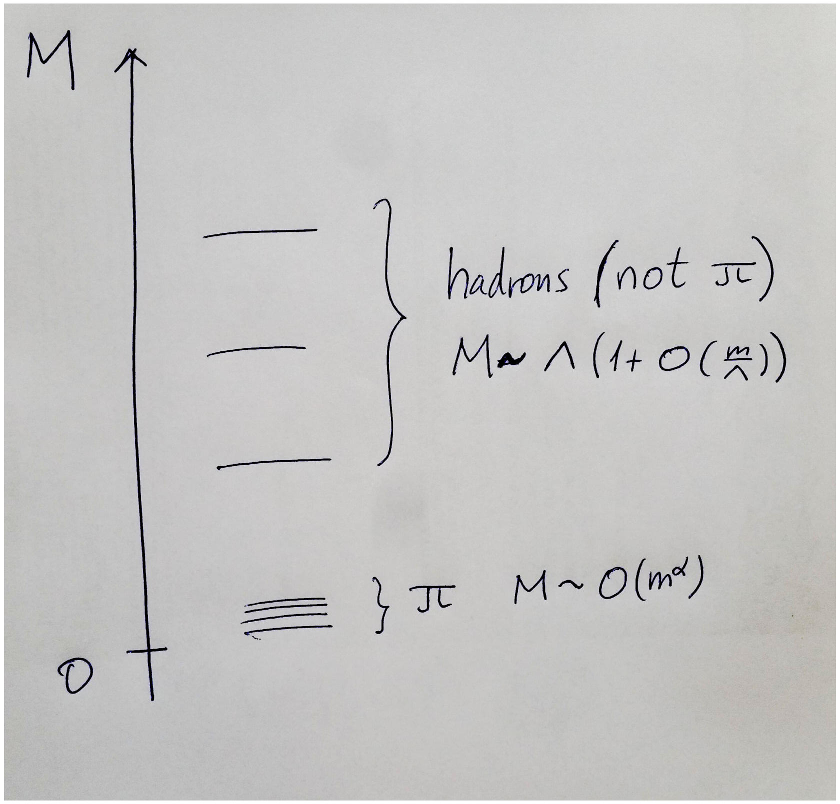
Massless Goldstones become massive but in $m_i \to 0$ limit $M_{Goldstone} = 0$

$$M_{Goldstone} \sim m^{\alpha}(1 + \ldots)$$

With $\alpha > 0$

## Consequence for the spectrum of particles

Observable particles: gauge singlet because of confinement: hadrons




$\Lambda = \Lambda_{QCD}$ dynamically generated scale

## QCD review - symmetry breaking

QCD with $N_f = 2$ flavors $(u, d)$: 3 Goldstones: 3 $\pi$

QCD with $N_f = 3$ flavors $(u, d, s)$: 8 Goldstones: 3 $\pi$, 3 $K$, $\eta, \eta'$

More about $\eta, \eta'$ later

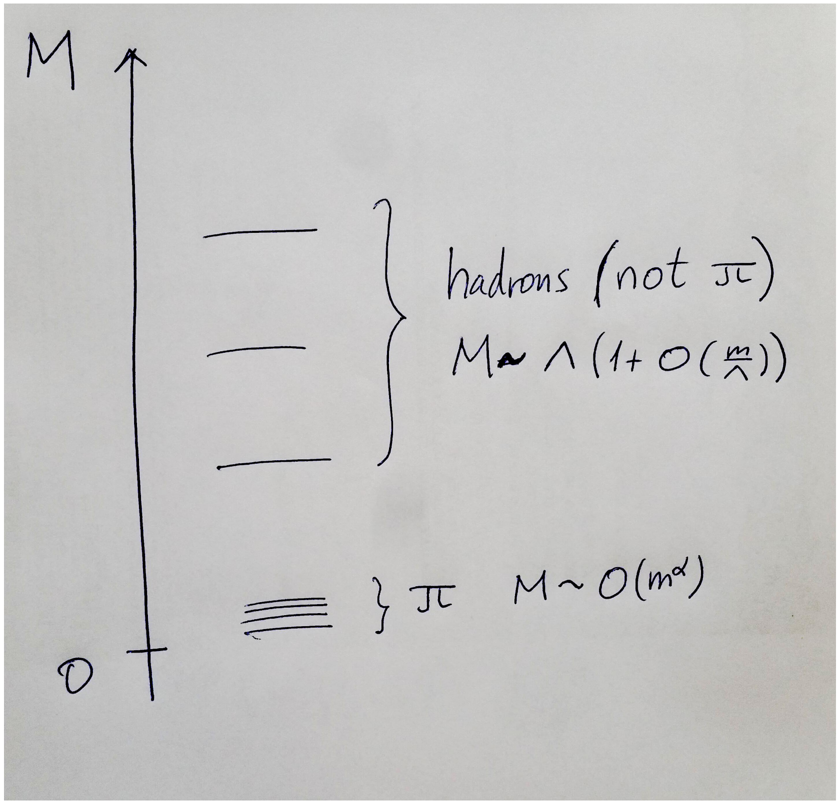
In QCD: $m_\pi = 135\ MeV$, $m_K = 497\ MeV$, $m_\varrho = 775\ MeV$

$m_{u,d} = O(MeV)$ really small, $m_s$ order of magnitude larger

Goldstone picture applies to 3 $\pi$, less so to 3 $K$

## QCD review - symmetry breaking

Summary: with $N_f = 2$ QCD there are 3 light particles $M_\pi \sim m^\alpha$ and all the rest are heavy $M \sim \Lambda$



3 $\pi$ very light $\rightarrow$ low energy effective theory only for them

Same situation in general with $G/H$ spontaneous symmetry breaking and Goldstone bosons

What can this low energy EFT be?

Start from the original symmetry $SU(N_f) \times SU(N_f)$, look for a variable transforming appropriately and representing the pions (Goldstones)

$$U \in SU(N_f) \qquad (g_1, g_2) \in SU(N_f) \times SU(N_f) \qquad U \rightarrow g_1 U g_2^{-1}$$

In field theory $U(x)$

What is $\mathcal{L}_{eff}(U)$ ?

What is $\mathcal{L}_{eff}(U)$ ? (assume $m_i = m$)

- Dimension 4
- Lorentz invariant scalar
- Contain 2 derivatives for kinetic term
- $SU(N_f) \times SU(N_f)$ invariant if $m = 0$
- $SU(N_f) \times SU(N_f)$ breaking to $SU(N_f)$ if $m \neq 0$

$$\mathcal{L}_{eff} = \frac{F^2}{2} \text{Tr}\, \partial_\mu U(x) \partial_\mu U^\dagger(x) - m\Sigma \text{Re}\, \text{Tr}\, U(x)$$

$U$ is dimensionless, $dim(F) = 1$, $dim(\Sigma) = 3$ (remember $\Sigma = \bar{\psi}_i \psi_i$)

Note: $F$ is decay constant of $\pi$

Last term $\text{Tr}\, U$ breaks $SU(N_f) \times SU(N_f)$ to $SU(N_f)$:

$$\text{Tr}\, U \to \text{Tr}\, (g_1 U g_2^{-1}) = \text{Tr}\, (g_2^{-1} g_1 U)$$

equals $\text{Tr}\, U$ only if $g_1 = g_2 \to SU(N_f) \subset SU(N_f) \times SU(N_f)$ unbroken

$\mathcal{L}_{eff}$ fixed by symmetry considerations

Low energy effective theory: should be good description if we only ask about properties of pions

$U(x) = e^{iT_a\phi_a(x)/F}$ where $\phi_a$ scalar fields, $T_a$ generators of $SU(N_f)$, $a = 1 \dots N_f^2 - 1$

In calculations expand $U = 1 + iT_a\frac{\phi_a}{F} - T_aT_b\frac{\phi_a\phi_b}{2F^2} + \dots$

Assume normalized basis $\mathrm{Tr}\, T_aT_b = \delta_{ab}$

## Home work

Expand $\mathcal{L}_{eff}$ to quadratic order in $\phi$

Obtain free theory of scalar fields with mass term

$\longrightarrow$ at low energy pions are free

Obtain $\alpha$ in $M_{Goldstone} = M_\pi \sim m^\alpha$

Low energy EFT can give properties of $\pi$

This was simple example, many more can be given

Note: $\mathcal{L}_{eff}$ only leading order EFT, there are loop corrections

Note: there is a $U(1)$ component for both vector and axial, flavor singlet

$$\delta\psi_i = i\psi_i \qquad \delta\bar{\psi}_i = -i\bar{\psi}_i$$

$$\delta\psi_i = i\gamma_5\psi_i \qquad \delta\bar{\psi}_i = i\bar{\psi}_i\gamma_5$$

The axial $U(1)$ is anomalous

Anomalous symmetry breaking: $\mathcal{L}$ invariant but path integration measure not invariant

Similar to explicit breaking

No Goldstone theorem $\rightarrow \eta'$ not light but heavy, $M_{\eta'} = 958\,MeV$

Summary so far: QCD has very special spectrum, light particles separated from heavy particles

All of this because of Goldstone theorem, spontaneous symmetry breaking

No elementary particles in spectrum

No fine tuning, everything is natural, no quadratic divergences

## Motivation

Class of theories considered:
new non-abelian gauge theory sector $+$ new (massless) fermions

Spontaneous chiral symmetry breaking $\longrightarrow$ electroweak symmetry breaking

Goldstone bosons $\longrightarrow$ eaten by $W$ and $Z$

Spin 0 scalar composite particle (like $\sigma$-meson): Higgs

Non-perturbative dynamics (like QCD)

## Motivation

This is an old idea! (Weinberg, Susskind, ..., late 70's)

Many early problems

- scaled up QCD doesn't work ($\Lambda_{QCD} = \Lambda \sim O(100) GeV$)
- S-parameter large?
- Higgs heavy (or Higgsless)
- many new massless particles?
- large FCNC vs. quark masses

## Motivation

Problems may be due to QCD intuition and/or perturbation theory

We have lattice tools now to address them

Let's use lattice QCD techniques to do first principle calculations

Close to conformal window $\rightarrow$ very different properties from QCD

## Motivation

Typical quantity: $\langle \mathcal{O}(x)\mathcal{O}(0)\rangle$

QFT vacuum expectation value: quantum mechanics for infinitely many degrees of freedom

$$\langle \mathcal{O}(x)\mathcal{O}(0)\rangle = \frac{\int DA_\mu D\psi D\bar{\psi}\mathcal{O}(x)\mathcal{O}(0)e^{-S}}{\int DA_\mu D\psi D\bar{\psi}e^{-S}}$$

Perturbation theory or other analytical approach doesn't work

Numerical evaluation (as in QCD)

## Motivation

Space-time lattice $\longrightarrow$ finite number of variables $\longrightarrow$ path integral finite dimensional

Reasonable lattice: $32^4$ $\longrightarrow$ 33 554 432 dimensional integral (for $SU(3)$)

Even numerical integration is hopeless

Only approach: stochastic evaluation $\longrightarrow$ Monte-Carlo methods

## Motivation

Key numerical difficulty: fermions (Grassmann variables)

Numerical cost: orders of magnitude more than without fermions

Main ingredient: inversion of Dirac operator

Dirac equation $D\psi = \eta$, where $D = \gamma_\mu(\partial_\mu + A_\mu) + m$

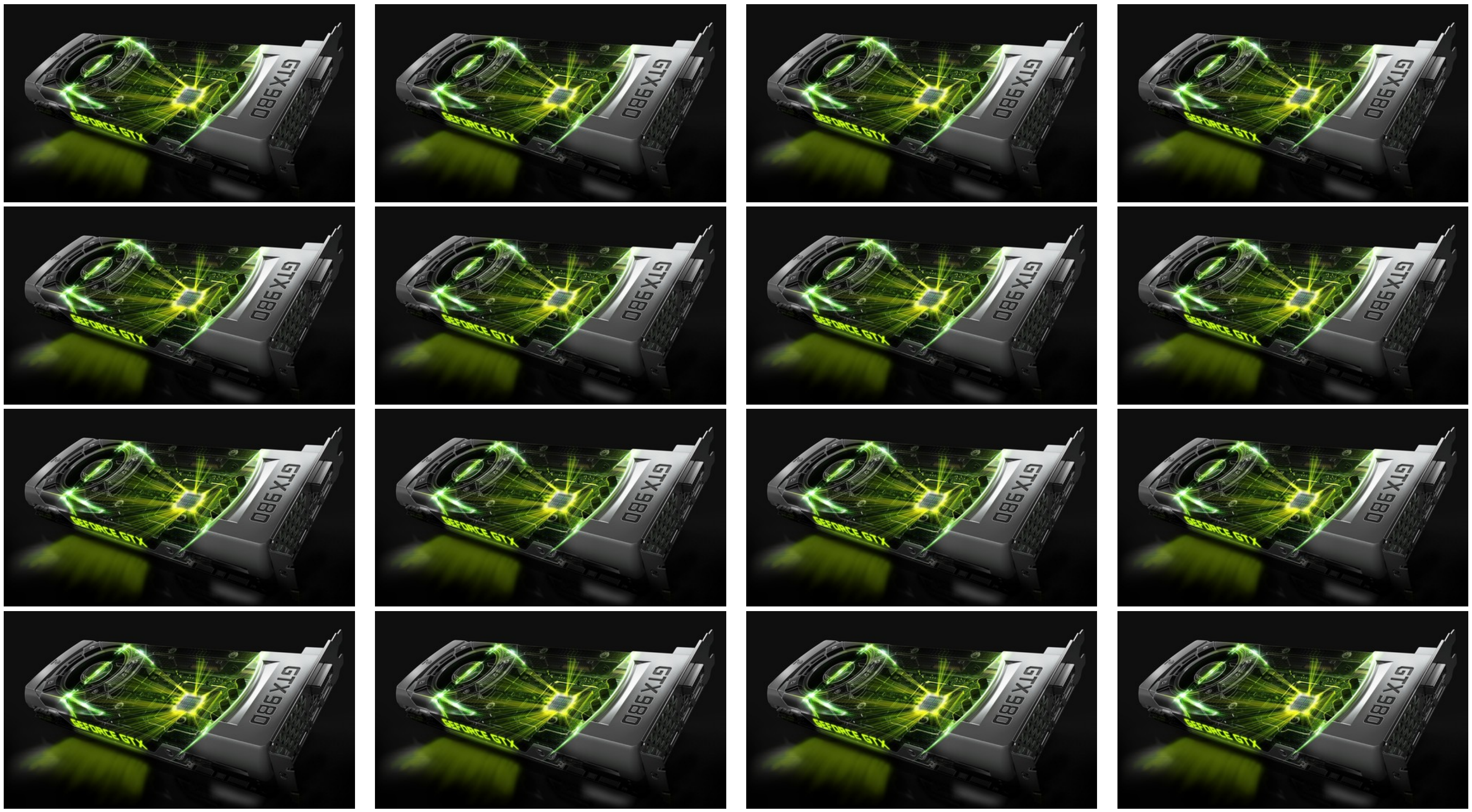
Need to invert $10^7 \times 10^7 \ldots\ldots 10^{10} \times 10^{10}$ matrices

## High performance computing


Supercomputers - very expensive $$$

# Motivation

## High performance computing




## Much better price/performance

## Motivation

Computers give vacuum expectation values with statistical errors

Can extract physical quantities $\rightarrow$ compare with experiment

Key steps:

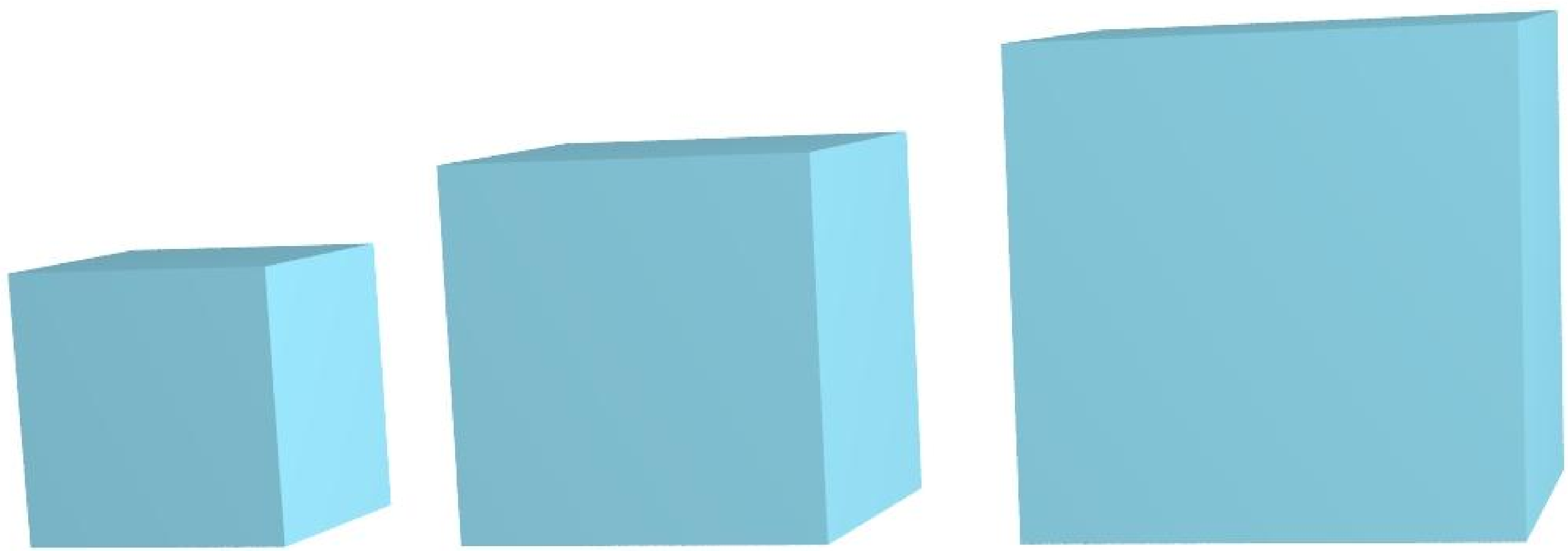
- (technical) $m \rightarrow 0$ limit
  need massless Goldstones, eaten by $W$ and $Z$

- $N^4$ lattice, $N \rightarrow \infty$, infinite volume extrapolation

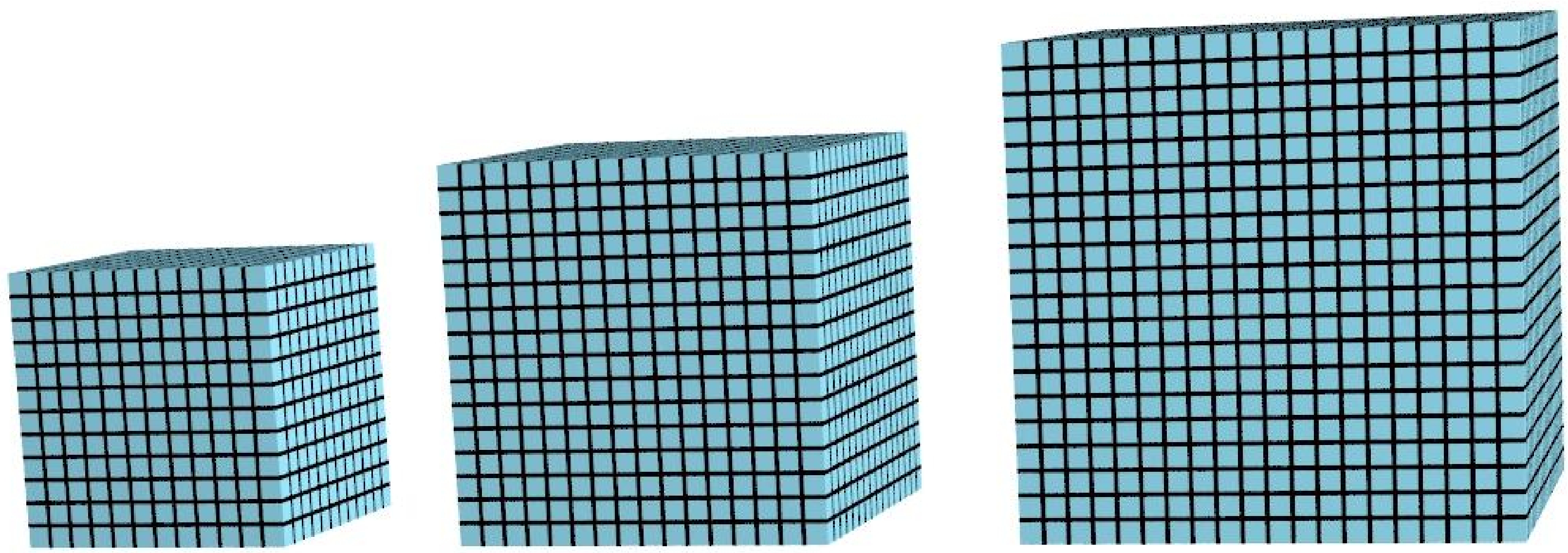
- lattice spacing $a \rightarrow 0$, continuum limit

All 3 are tricky in their own way

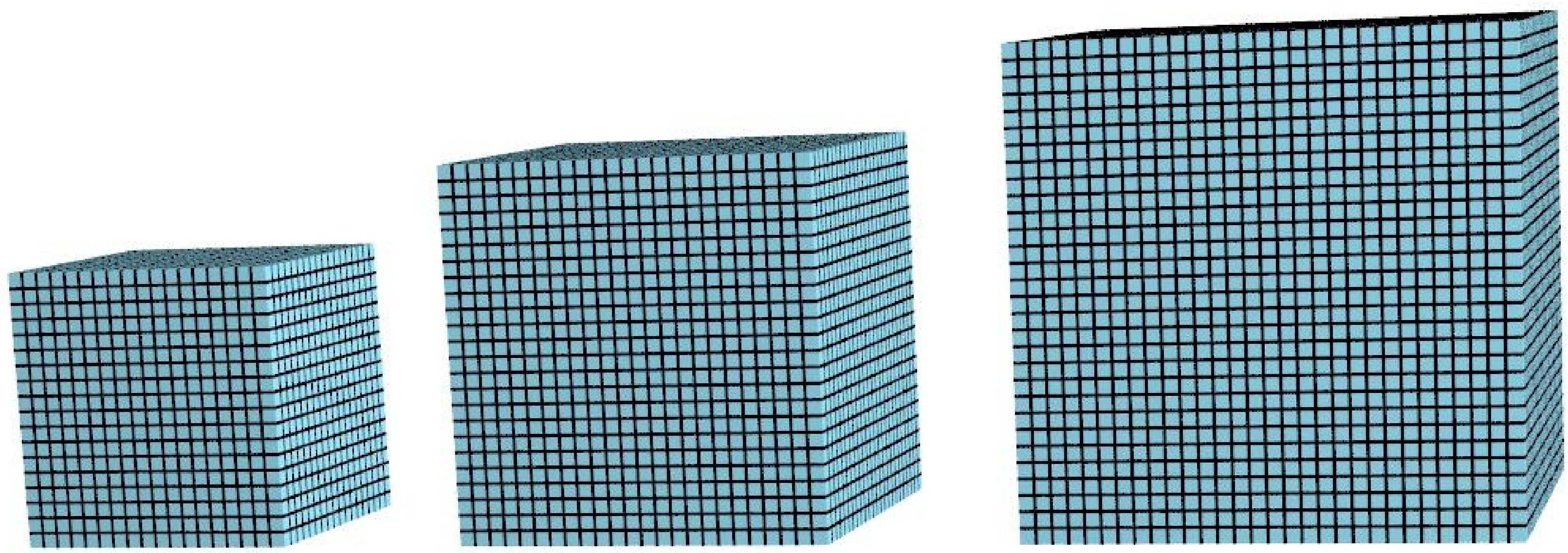
Continuum



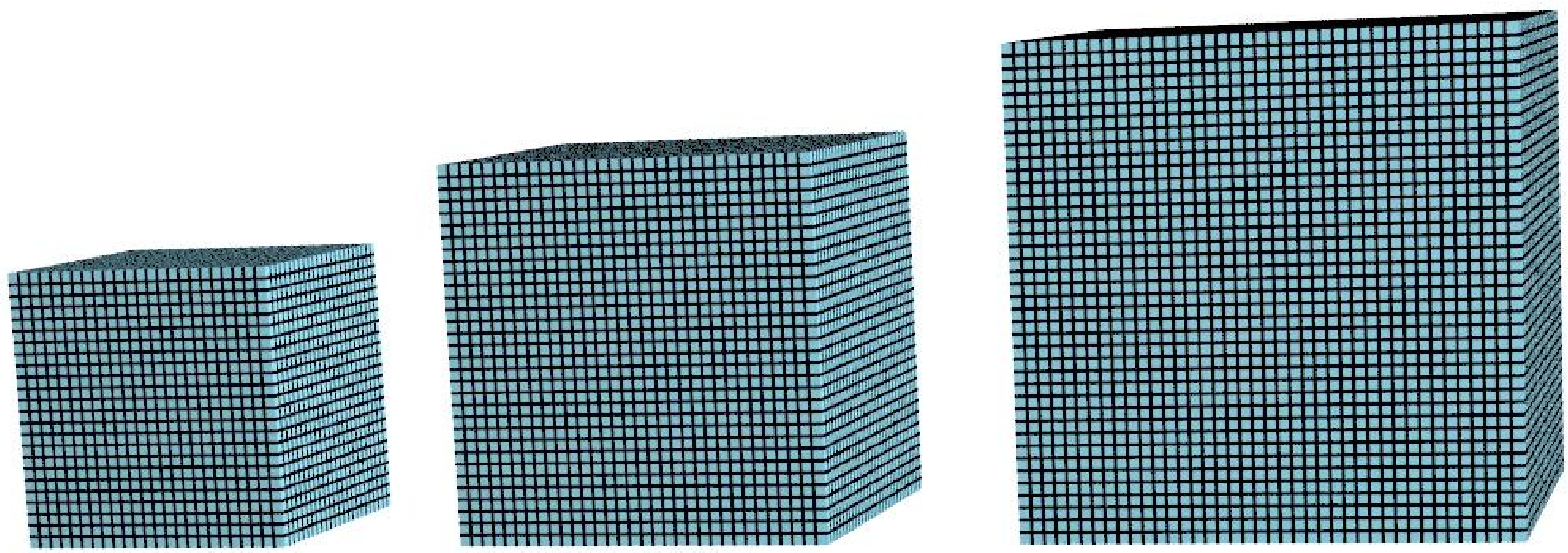
Lattice - continuum limit



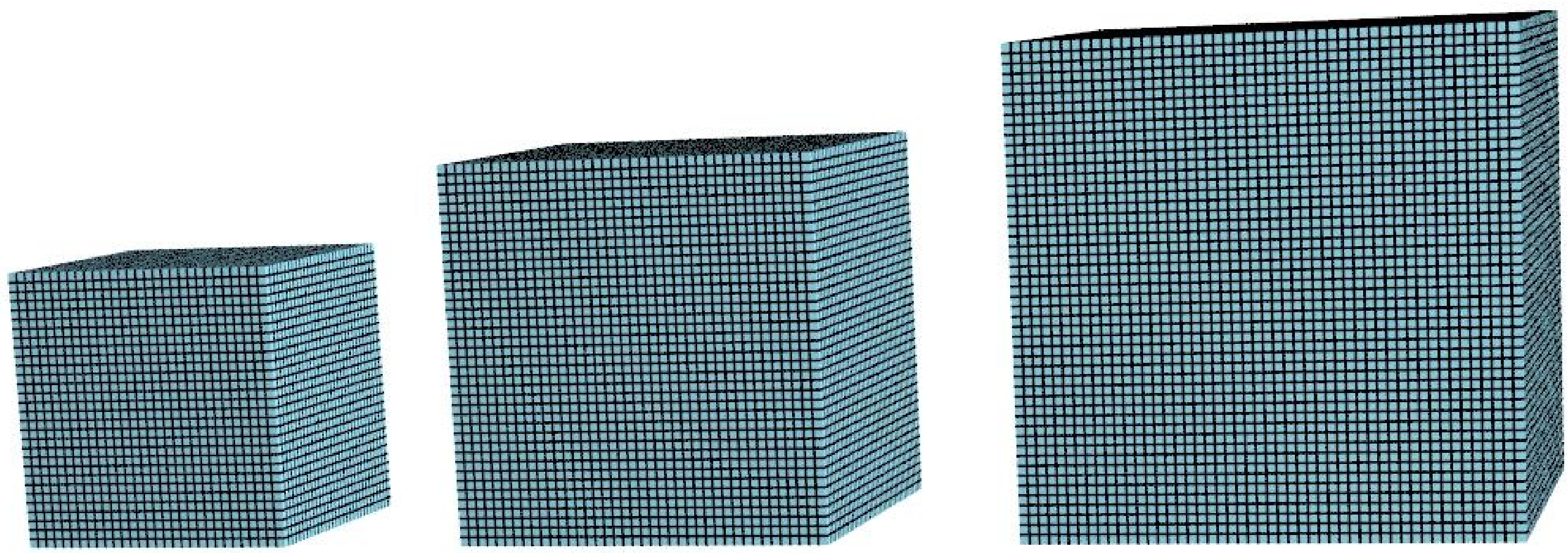
Lattice - continuum limit



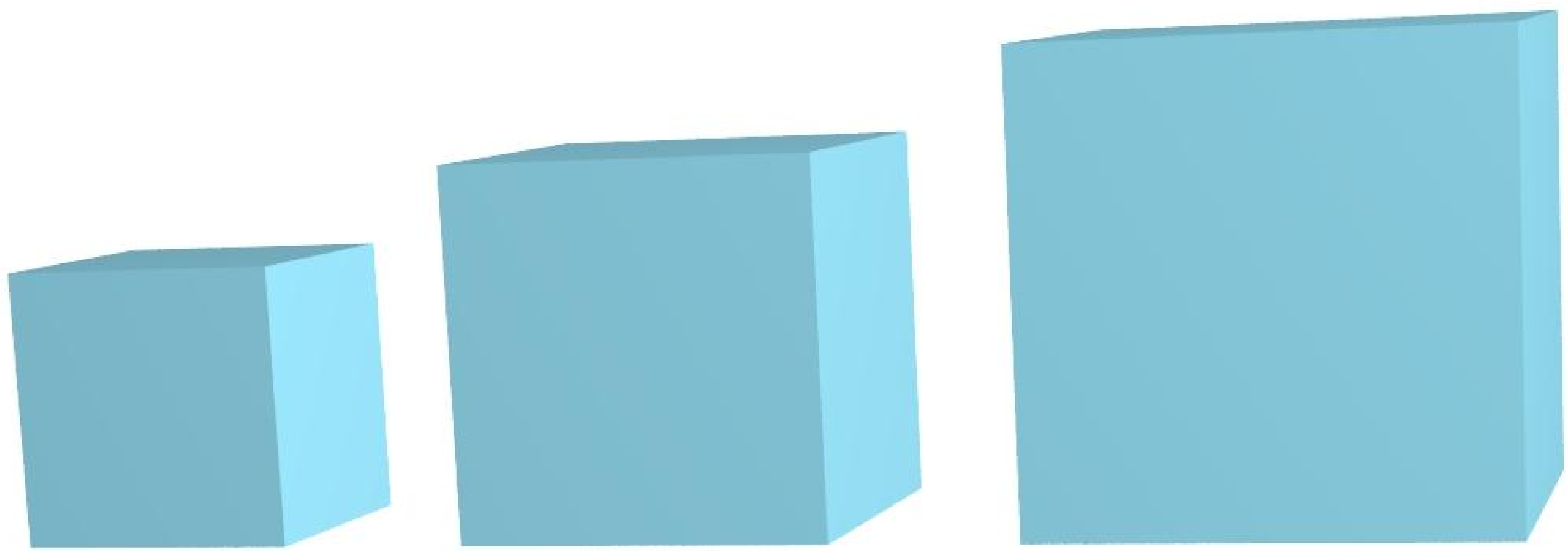
## Lattice - continuum limit



## Lattice - continuum limit



Continuum



## Motivation

Many theories to choose from

Hope to convince you that $SU(3)$ with

$N_f = 2$ and $R =$ sextet is a minimal model

and is promising phenomenologically

## Outline and summary

- Sextet model – expectations, conformal window
- Particle spectrum from lattice
- Light scalar – Higgs
- Running coupling
- Conclusion (caveats, difficulties, questions)

## Why $SU(3)$ sextet $N_f = 2$?

Dietrich, Sannino, Tuominen: hep-ph/0405209, hep-ph/0611341

- Asymptotically free
- Perturbatively: just below conformal window (Schwinger-Dyson)
- Slowly changing coupling? (FCNC vs. quark masses)
- Perturbatively: small $S$-parameter
- Complex representation: exactly 3 Goldstones $\longrightarrow$ eaten by $W$ and $Z$

## Why $SU(3)$ sextet $N_f = 2$?

Very similar to $N_f = 2$ QCD

$R = fundamental$ replaced by $R = sextet = 2 - index - symm$

But very different properties

$f_\pi = 250\ GeV$

Much closer to the conformal window than QCD

## Conformal window

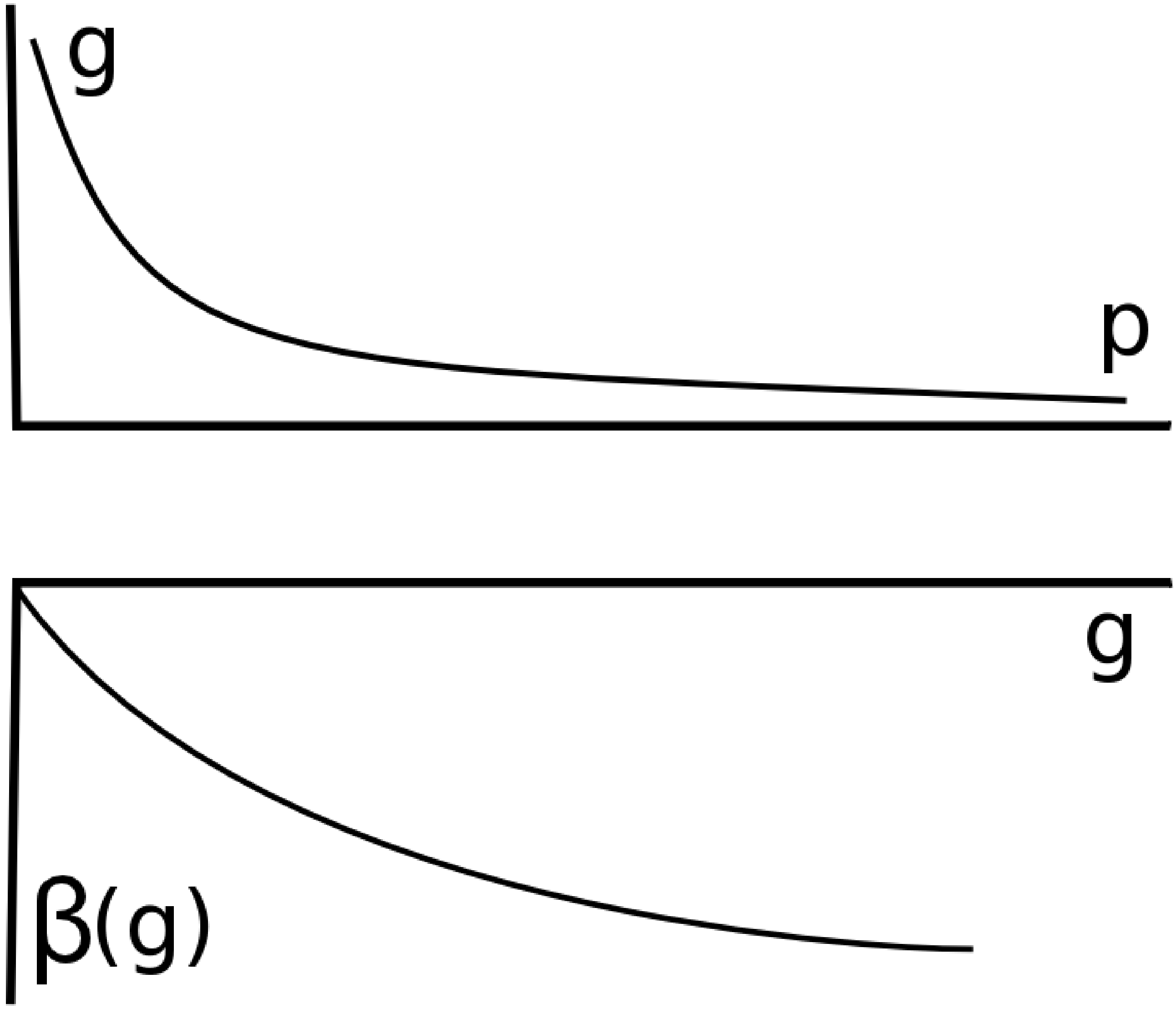
$SU(N)$ gauge theory with $N_f$ fermions in $R$

$$
\begin{aligned}
\beta(g) &= \mu\frac{dg}{d\mu} = \beta_1\frac{g^3}{16\pi^2} + \beta_2\frac{g^5}{(16\pi^2)^2} \\
\beta_1 &= -\frac{11}{3}N + \frac{4}{3}N_f T(R) \\
\beta_2 &= -\frac{34}{3}N^2 + \left(\frac{5}{3}N + C_2(R)\right)4T(R)N_f
\end{aligned}
$$

Asymptotic freedom: $\beta_1 < 0$, perturbation theory reliable

$$
N_f < \frac{11N}{4T(R)}
$$

## Asymptotic freedom



## Conformal window, $N_f$-dependence

Non-trivial fixed point $\beta(g_*) = 0$:

Exists if $\beta_1 < 0$ and $\beta_2 > 0$ Banks-Zaks

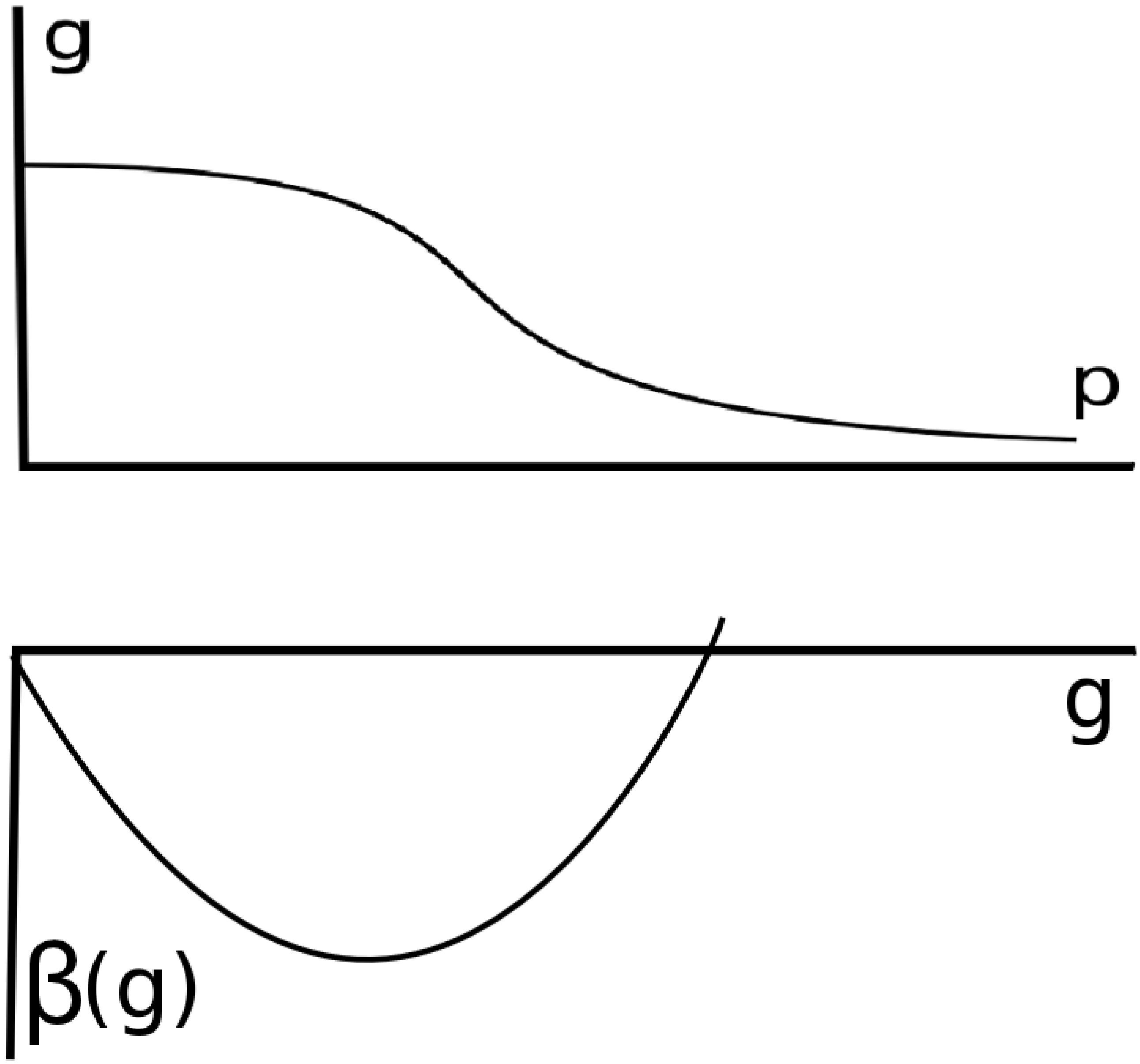
$$g_* = 4\pi\sqrt{-\frac{\beta_1}{\beta_2}}$$

$$N_f^{low} = \frac{34N^2}{4T(R)(5N+3C_2(R))} < N_f < \frac{11N}{4T(R)} = N_f^{up}$$

This $N_f$ range is the conformal window in 2-loop approximation

Fixed point $g_*$ an IR fixed point.

## Infrared fixed point



## Conformal window, $N_f$-dependence

How trustworthy is this?

$$N_f^{low} = \frac{34N^2}{4T(R)(5N+3C_2(R))} < N_f < \frac{11N}{4T(R)} = N_f^{up}$$

Upper end of the conformal window: loss of asymptotic freedom
$\longrightarrow$ perturbation theory is trustworthy, even 1-loop is enough

$g_* = 4\pi\sqrt{-\frac{\beta_1}{\beta_2}}$ is small because $\beta_1$ is small

Lower end of the conformal window: 2-loop is suspect

$g_* = 4\pi\sqrt{-\frac{\beta_1}{\beta_2}}$ is large because $\beta_2$ is small

## Conformal window, $N_f$-dependence

Where we know what we are doing: close to upper end of the conformal window

E.g. $N = 3$, $R = fund$, $N_f^{up} = 16.5$

E.g. $N = 3$, $R = sextet$, $N_f^{up} = 3.3$

For example $N_f = 16$ fundamental or $N_f = 3$ sextet: 2-loop result is probably okay, a non-trivial weakly interacting 4D CFT

## Conformal window, $N_f$-dependence

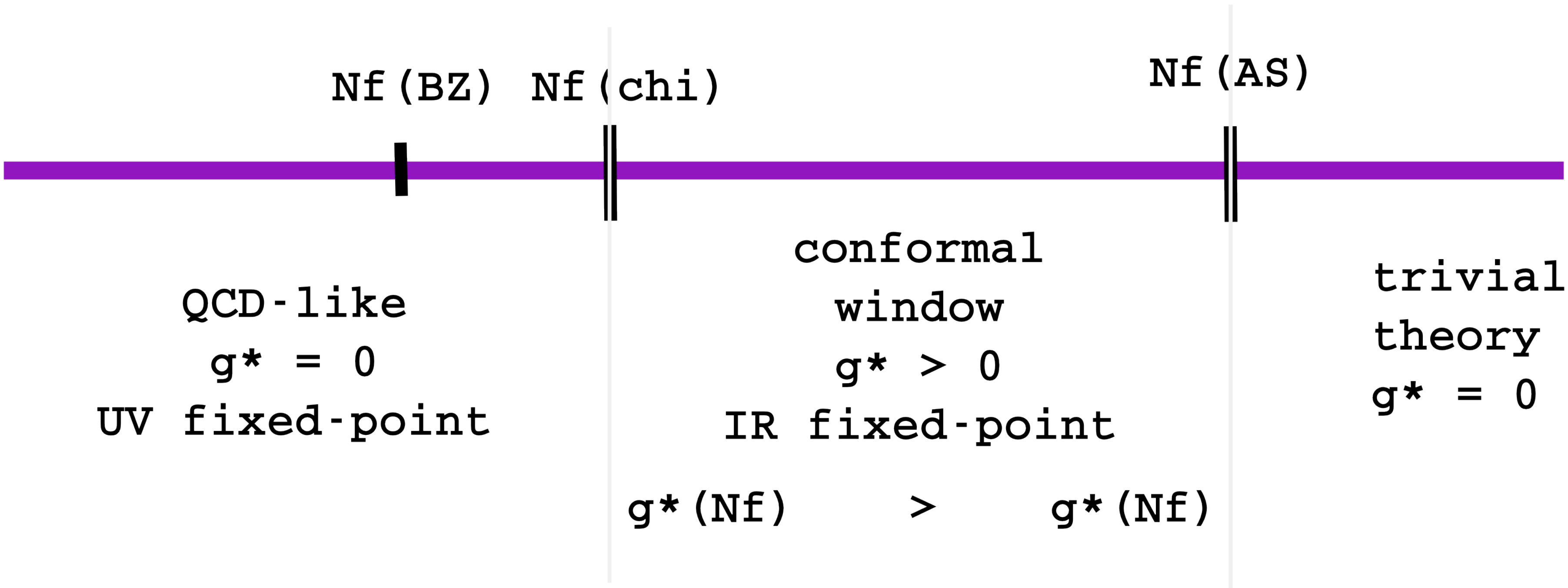
Even though 2-loop result is unreliable for $N_f^{low}$ the lesson is that there exists an $N_f^{low}$ but we can't compute it in perturbation theory

Is real $N_f^{low}$ smaller or larger than 2-loop $N_f^{low}$?

Probably larger.

As $N_f$ decreases from upper end of conformal window $g_*$ grows $\longrightarrow$ if not too large still CFT $\longrightarrow$ as it gets large chiral symmetry breaks $\longrightarrow$ scale is generated $\longrightarrow$ conformal symmetry lost $\longrightarrow$ no IR fixed point $\longrightarrow$ we are outside the conformal window.

## Conformal window, $N_f$-dependence summary




$N_f$ increases from left to right

Examples

## Perturbative 2-loop $N_f^{low}$

$SU(2)$

- $R : j = 1/2, \quad 5.551... < N_f < 11$
- $R : j = 1, \quad 1.0625 < N_f < 2.75$
- $R : j = 3/2, \quad 0.32 < N_f < 1.1$

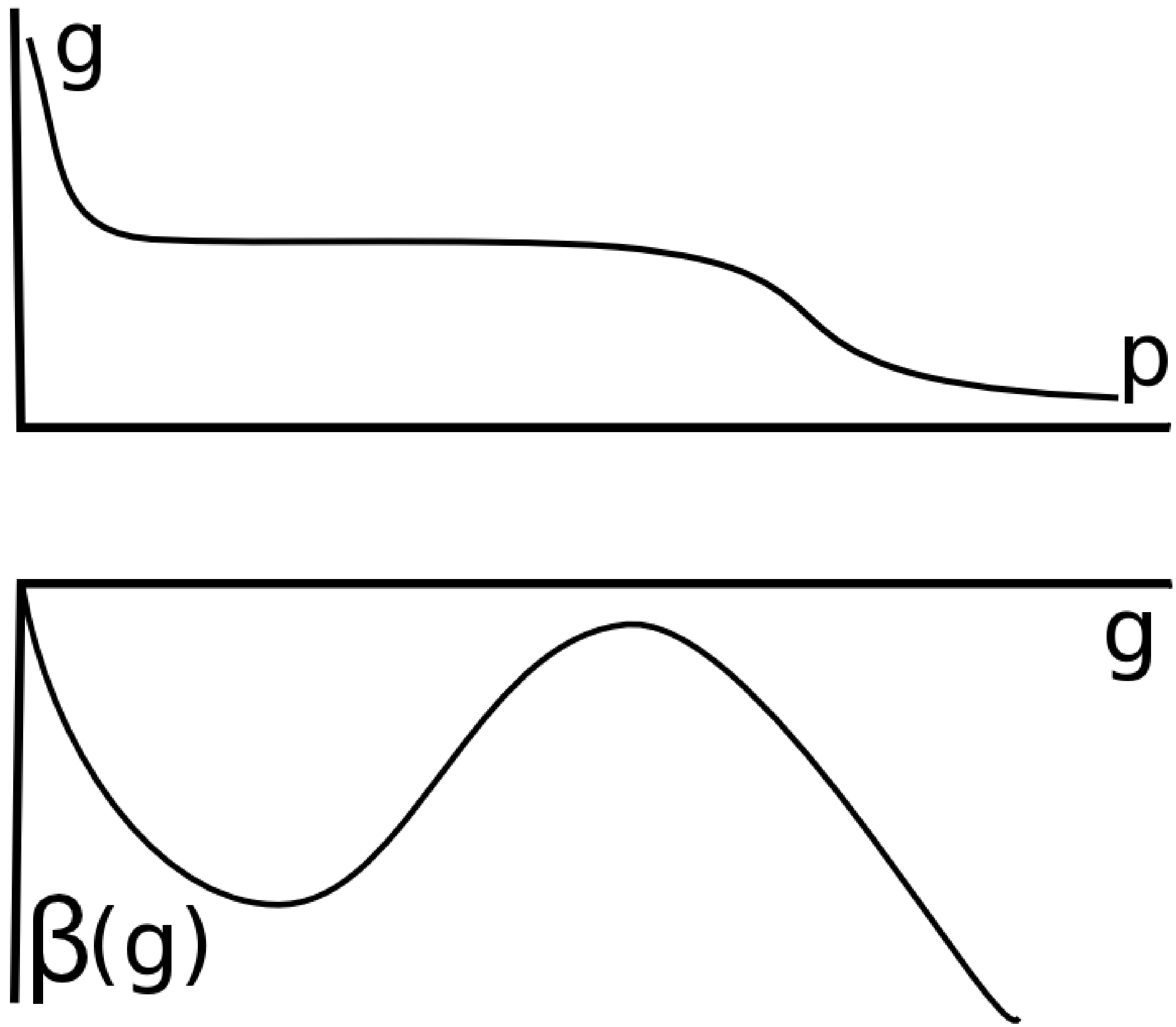
Examples

## Perturbative 2-loop $N_f^{low}$

$SU(3)$

- $R = fund, \quad 8.05... < N_f < 16.5$
- $R = sextet, \quad 1.224 < N_f < 3.3$
- $R = adj, \quad 1.0625 < N_f < 2.75$

$N_f$ just below lower end of conformal window



## Non-perturbative (lattice) studies

We only study the model in isolation as $SU(3)$ gauge theory with $N_f = 2$ fermions in sextet

Forget about rest of Standard Model

Questions for this talk

- Does chiral symmetry breaking happen?
- Particles in the spectrum? Light Higgs?
- Running coupling (is it walking?)

# Lattice setup

## Particle spectrum

- Finite lattice spacing $a$
- Finite volume $L$
- Finite fermion mass $m > 0$
- Chiral limit $m \to 0$ in large volumes
- Decrease lattice spacing (2 values at the moment)
- Express things in chiral limit in dimensionless combinations
- $f_\pi = 250 GeV$ scale setting

# Lattice setup

## Particle spectrum

- Staggered fermions (fast!)
- Need rooting trick for $N_f = 2$
  from QCD: as long as $m$ finite, not too small, it's okay
- Stout-improvement
- Symanzik tree level improved gauge action
- $\beta = 3.20$ and $3.25$

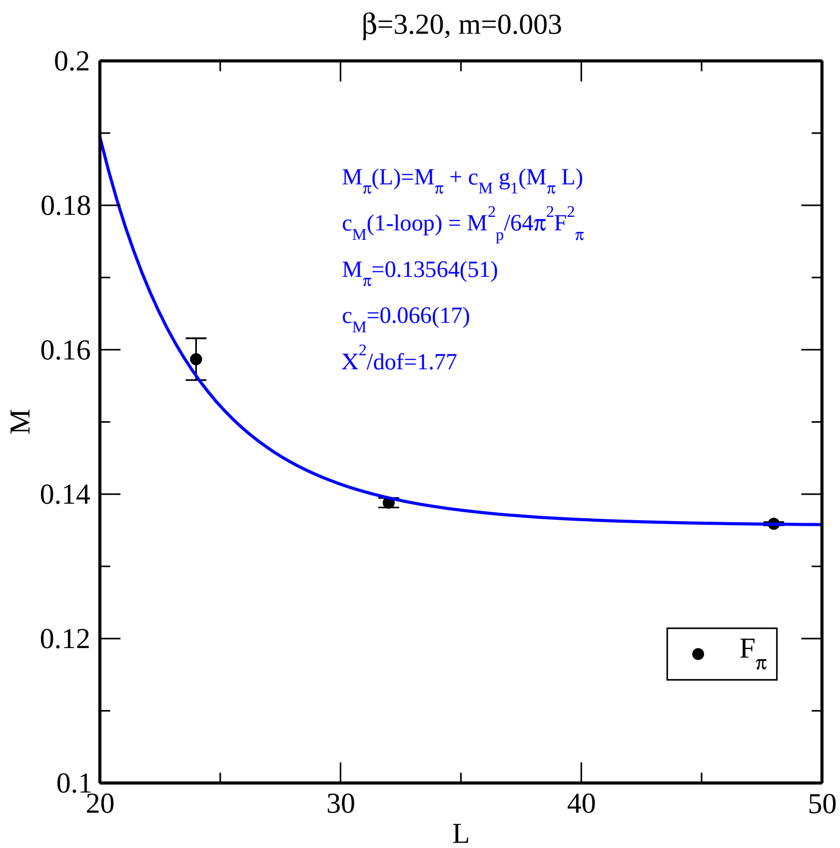
# Lattice

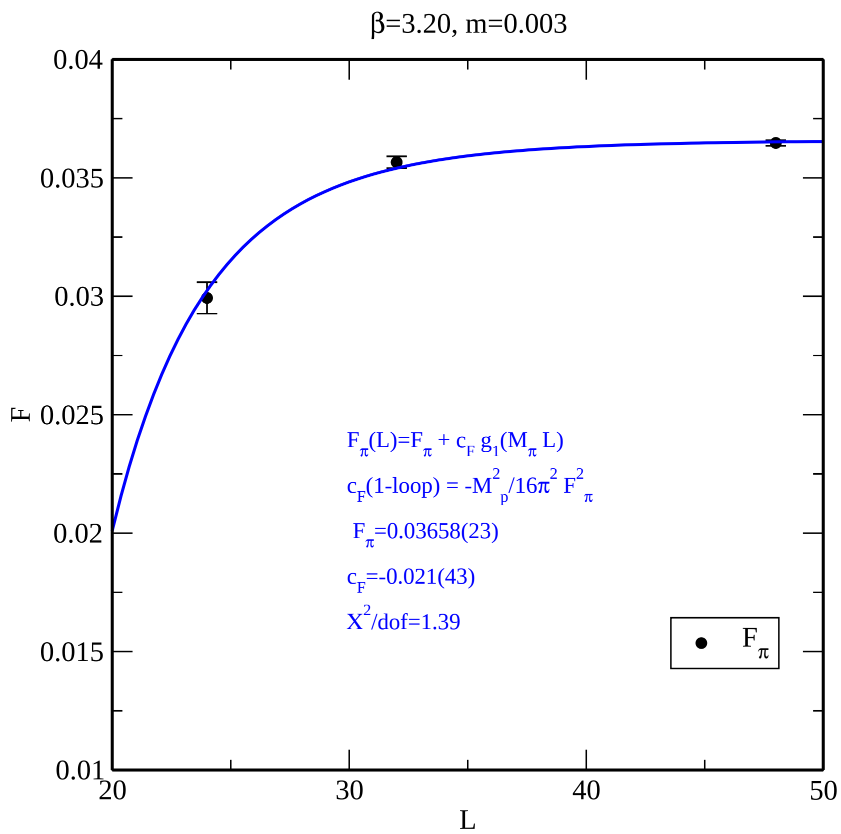
## Particle spectrum (staggered fermions)

Using QCD terminology consider

$$m_\pi \quad f_\pi \quad m_{a_0} \quad m_\rho \quad m_{a_1} \quad m_N \quad m_{\eta'} \qquad m_{f_0} = m_{0^{++}} = m_{Higgs}$$

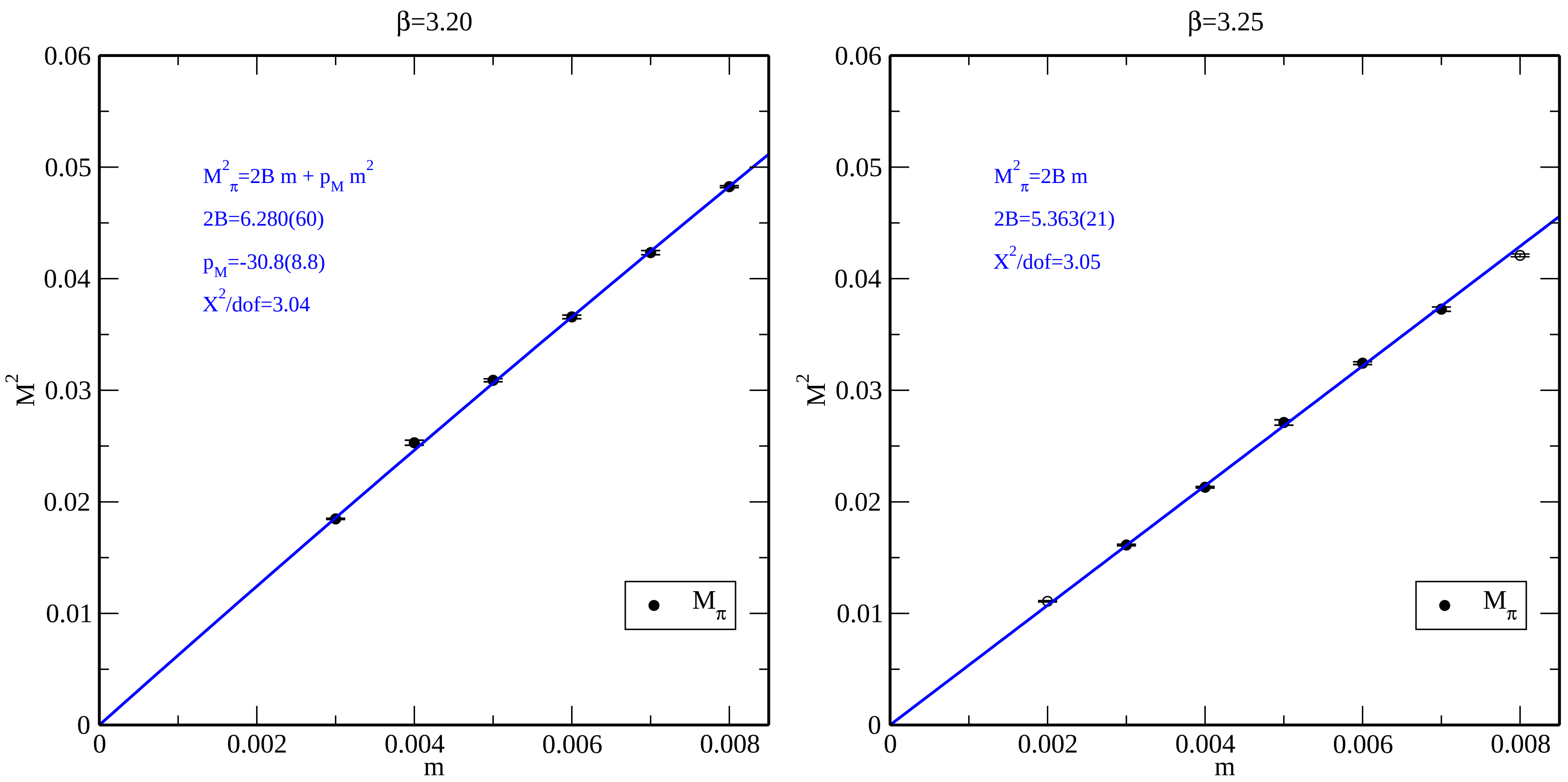
# Lattice – finite volume effects



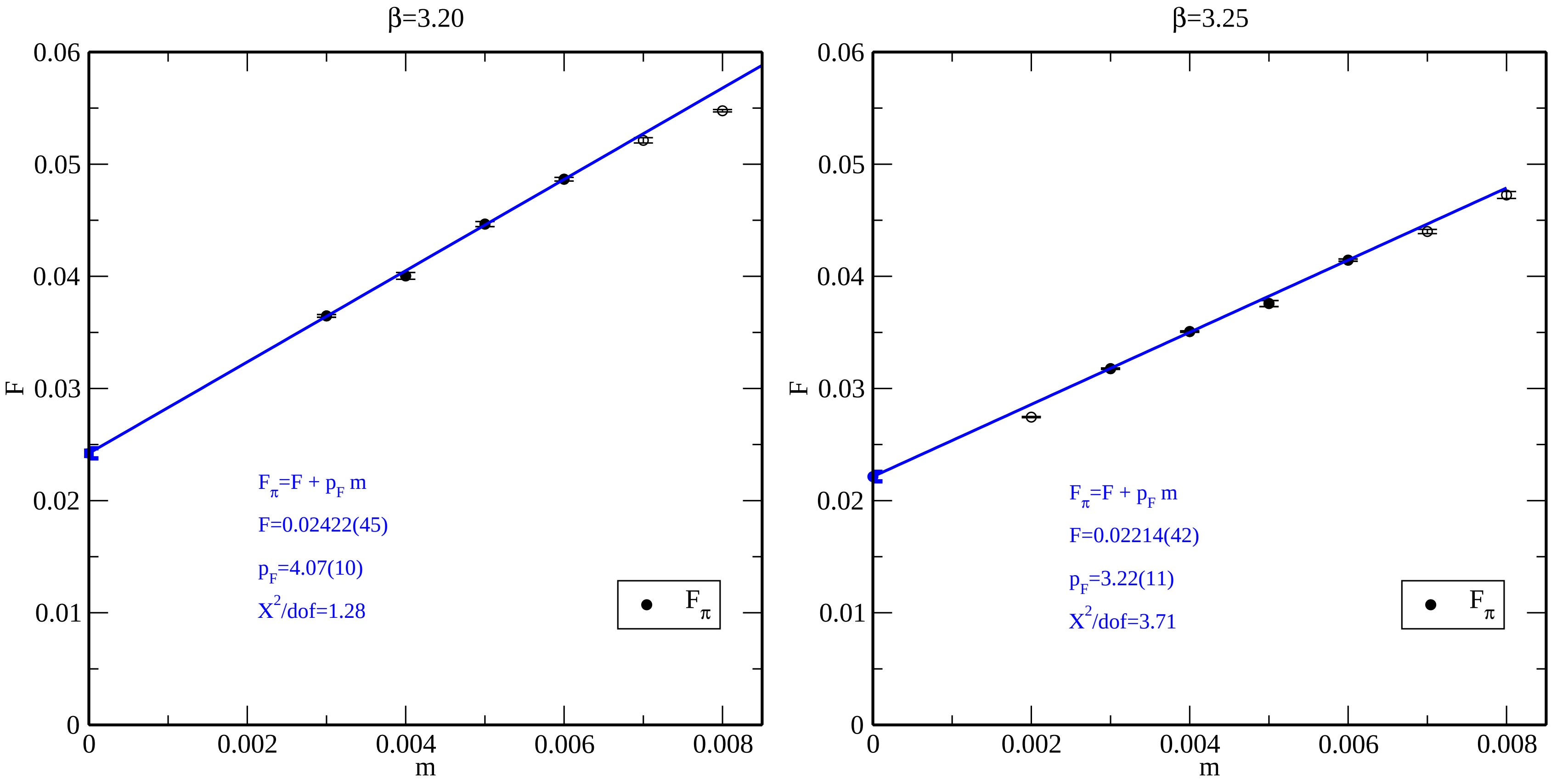

Already at $\beta = 3.20$ and $m = 0.003$, $32^3$ is not enough, $m_\pi L > 6-7$ needed

# Lattice - pseudo-scalar meson



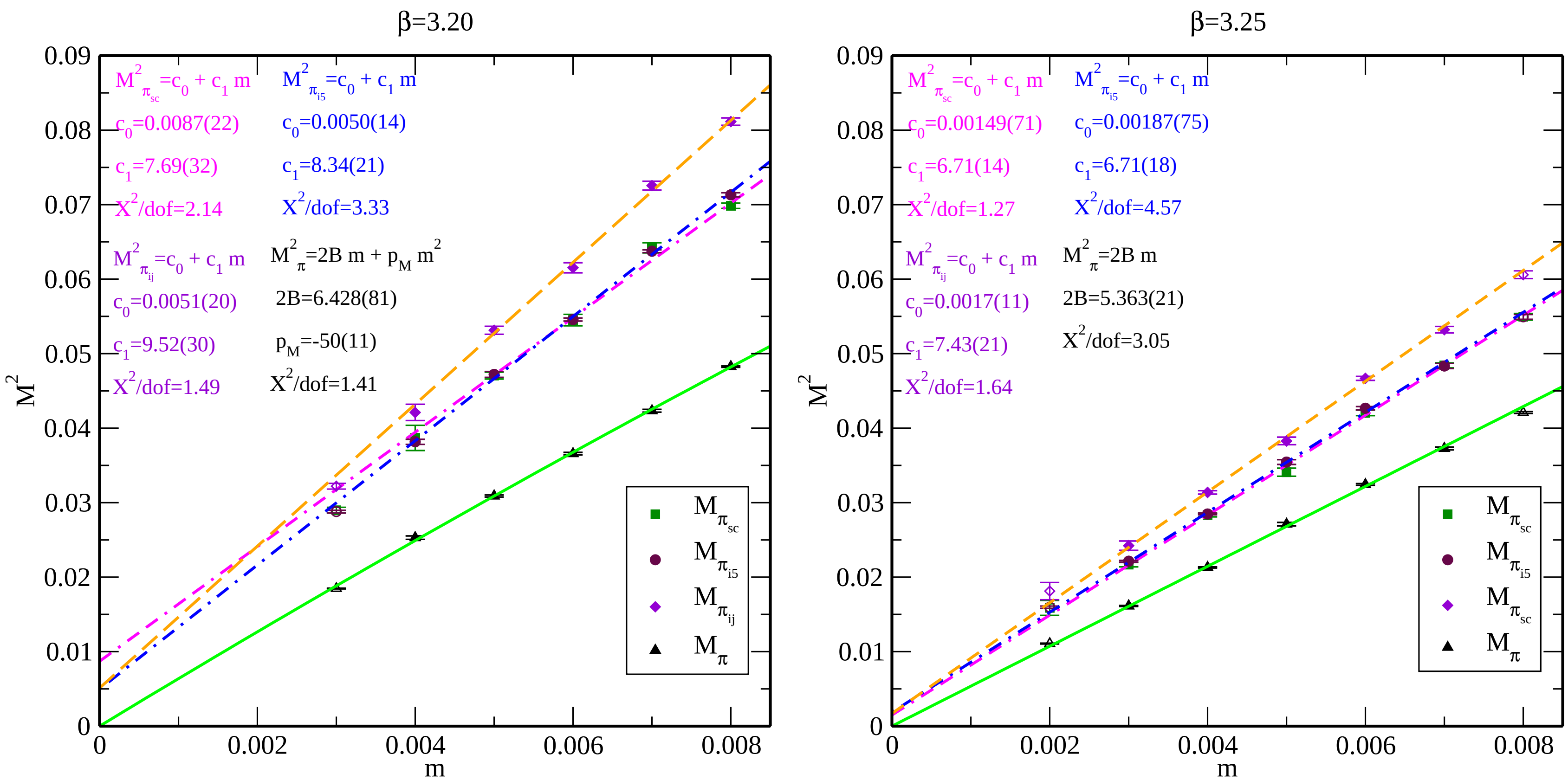

Unable to resolve chiral logs

# Lattice - pseudo-scalar meson



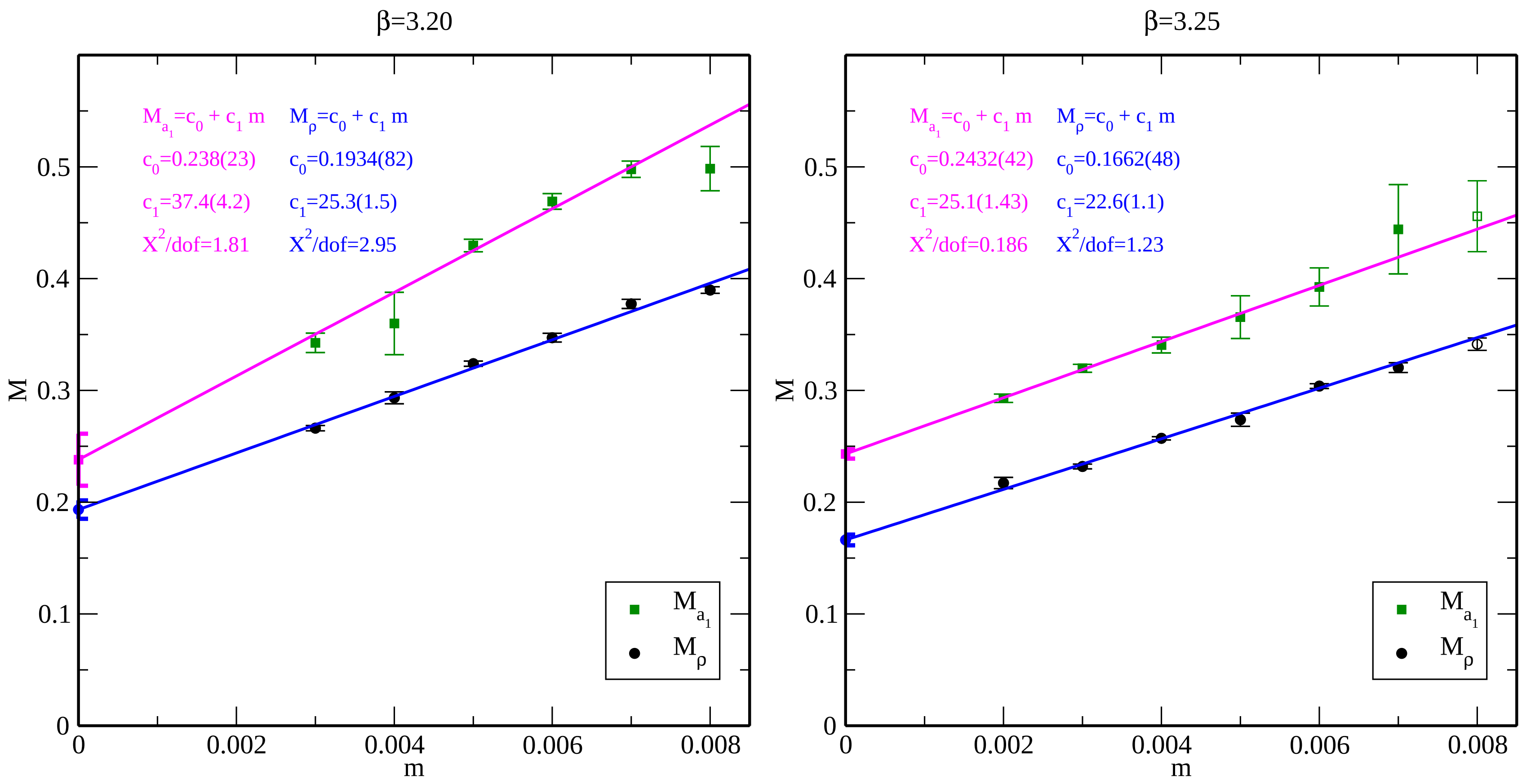

Much stronger $m$-dependence than in QCD

# Lattice - pseudo-scalar meson




Note the different slopes, in QCD parallel

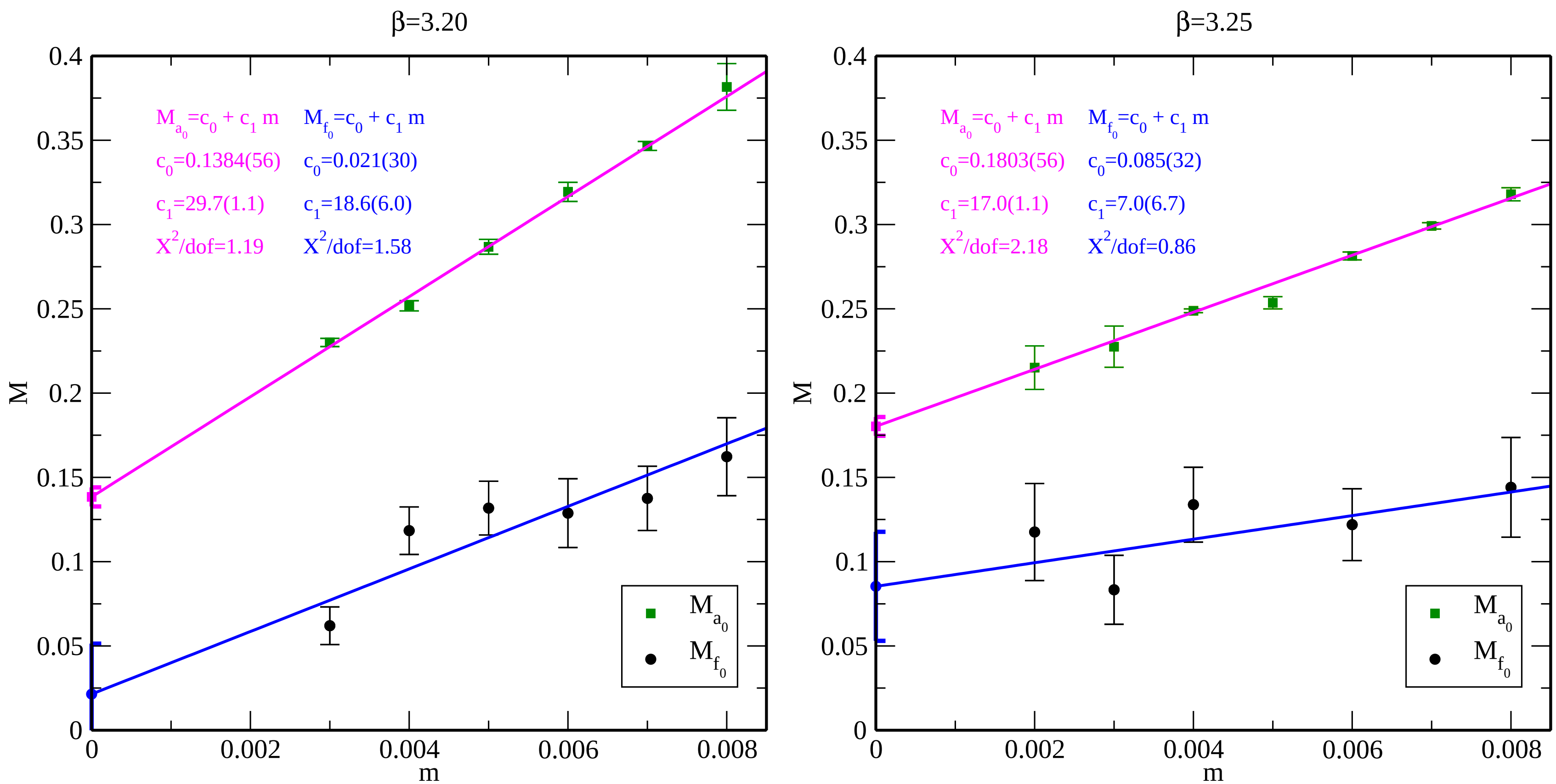
# Lattice - vector mesons $\varrho$ and $a_1$




Within reach of LHC Run 2

Small splitting: $S \sim VV - AA$, small?

# Lattice - scalar mesons $f_0$ and $a_0$




Remember $f_0$ is the Higgs!

Difficult channel, disconnected fermion graphs

$\beta = 3.25$ preliminary, topology?

# Lattice - baryons

Baryon states very diferent from QCD

$3 \otimes 3 \otimes 3 = 1 \oplus 2 \times 8 \oplus 10$

$6 \otimes 6 \otimes 6 = 1 \oplus 2 \times 8 \oplus 10 \oplus \overline{10} \oplus 3 \times 27 \oplus 28 \oplus 2 \times 35$

But!

singlet in QCD: $\varepsilon_{abc}\,\psi_a\,\psi_b\,\psi_c$, $\epsilon_{abc}$ anti-symmetric

singlet in sextet: $\varepsilon_{abc}\,\varepsilon_{def}\,\psi_{ad}\,\psi_{be}\,\psi_{cf} = T_{ABC}\,\psi_A\,\psi_B\,\psi_C$

$a, b, \ldots = 1, 2, 3$ $A, B, C = 1, 2, 3, 4, 5, 6$

$T_{ABC}$ symmetric

## Lattice - baryons

As a result, very different wave functions

"color" : symmetric, spin-flavor: anti-symmetric

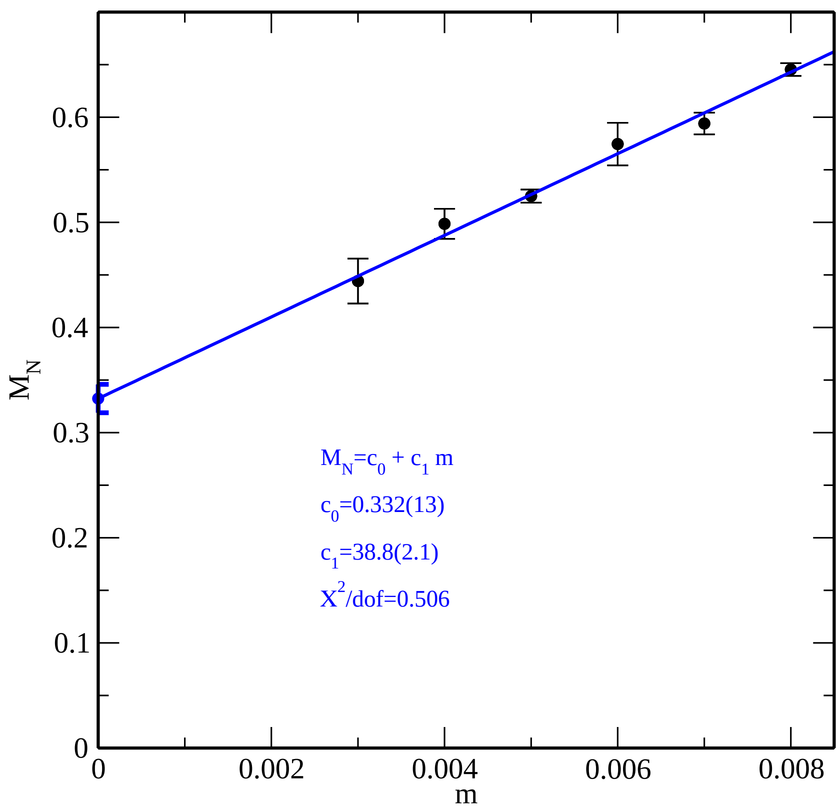
Non-relativistic notation (suppress "color" index):

$$|\psi\rangle = |\uparrow u, \uparrow d, \downarrow u\rangle + |\downarrow u, \uparrow u, \uparrow d\rangle + |\uparrow d, \downarrow u, \uparrow u\rangle -$$

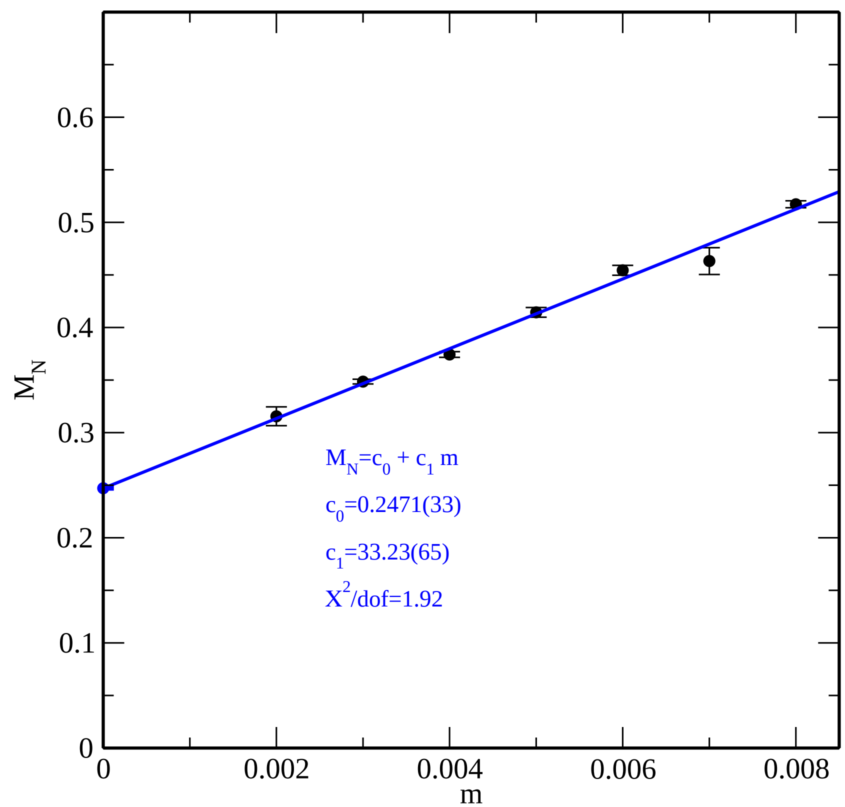
$$|\downarrow u, \uparrow d, \uparrow u\rangle - |\uparrow d, \uparrow u, \downarrow u\rangle - |\uparrow u, \downarrow u, \uparrow d\rangle$$

# Lattice - baryons

$\beta = 3.20$




$\beta = 3.25$




Dark matter?

## Lattice - $\eta'$

Extract from gluonic operator

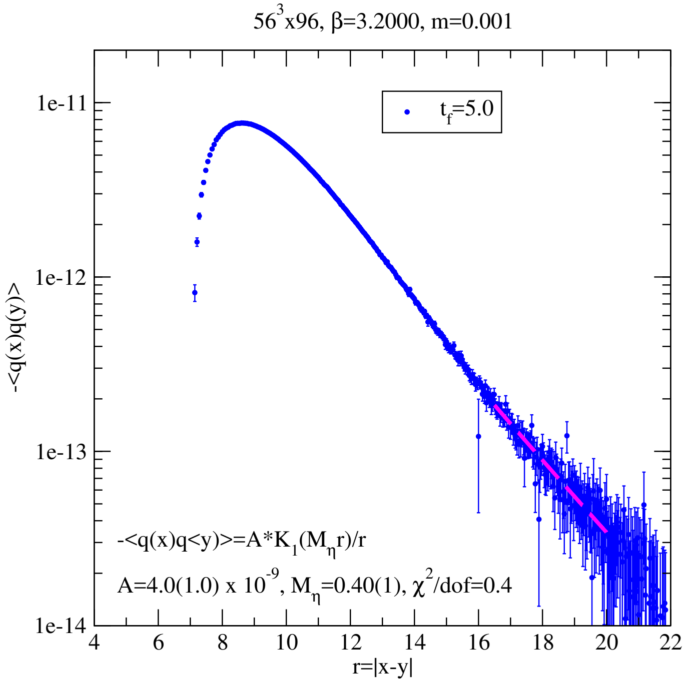
$$q(x) = \frac{1}{32\pi^2}\varepsilon_{\mu\nu\rho\sigma}F_{\mu\nu}(x)F_{\rho\sigma}(x)$$

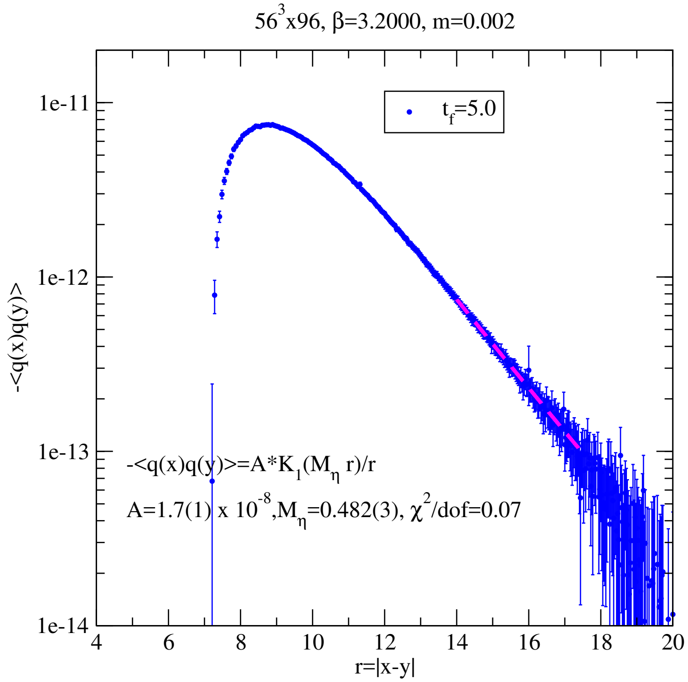
$$-\langle q(x)q(y)\rangle \sim \frac{K_1(m_{\eta'}r)}{r} \qquad r = |x-y|$$

Measure on gradient flow $\longrightarrow$ less noisy

# Lattice - $\eta'$

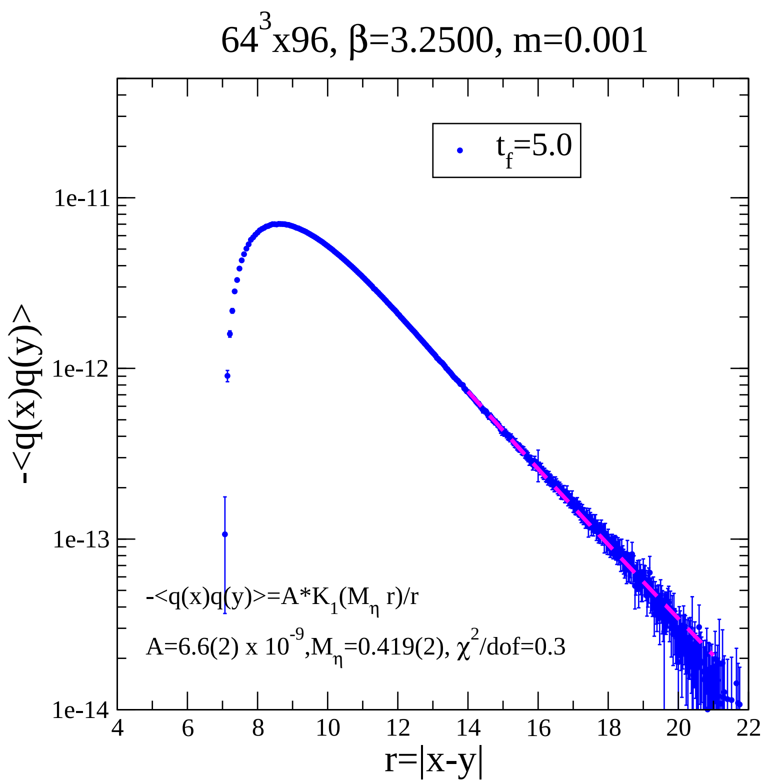
## $\beta = 3.20$, preliminary



## Lattice - $\eta'$

### $\beta = 3.25$, preliminary



## Spectrum summary 1

$$m_{f_0}/f_\pi \sim 1 - 2 \qquad m_{f_0} \sim 250 - 500\, GeV$$

$$m_{a_0}/f_\pi \sim 6 - 8 \qquad m_{a_0} \sim 1.5 - 2\, TeV$$

$$m_{\varrho}/f_\pi \sim 7 - 8 \qquad m_{\varrho} \sim 1.8 - 2\, TeV$$

$$m_{a_1}/f_\pi \sim 10 - 11 \qquad m_{\varrho} \sim 2.5 - 2.7\, TeV$$

$$m_N/f_\pi \sim 11 - 14 \qquad m_N \sim 2.7 - 3.5\, TeV$$

$$m_{\eta'}/f_\pi \sim 13 - 18 \qquad m_{\eta'} \sim 3.2 - 4.5\, TeV$$

Light scalar separated from the 2-3 TeV region

Higgs at $250 - 500\,GeV$ ??

What we measure is not "the" Higgs

Coupling to SM: top loop

$$m^2_{Higgs} = m^2_{sextet\; f_0} - const\; m^2_{top}$$

Foadi, et al.

Other particles expected to be effected less

## Spectrum summary 2

Model seems consistent with $\chi PT$

Model gives rise to a light scalar

New particles with definite properties in 2-3 TeV region

Potential dark matter candidate as well

## Important caveats

- Slow topology change
- Unestimated systematics
- Only $20 - 30\%$ change in lattice spacing
- Coupled scalar-pion dynamics ignored in $\chi PT$
- etc.

## More lattice results - running coupling

Running scale: $\mu$

Need: $1/L < \mu < 1/a$

Separating 3 scales difficult, instead

$$1/L = \mu < 1/a$$

Running scale is finite volume

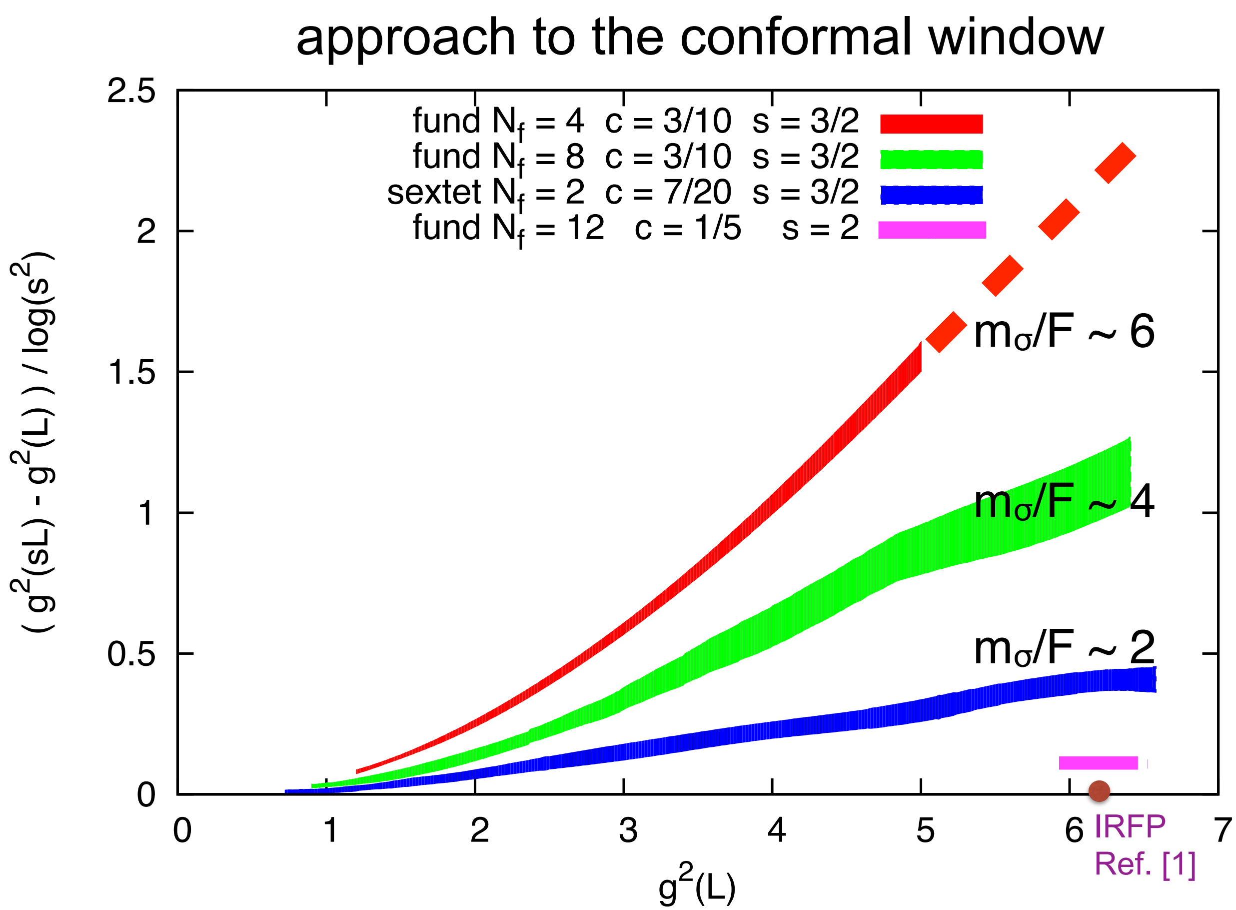
## Running coupling

Running scale: $\mu = 1/L$, using gradient flow

$$g^2(L) \sim \langle t^2 E(t) \rangle \qquad c = \frac{\sqrt{8t}}{L} = const$$

Discrete $\beta$-function: $\frac{g^2(sL) - g^2(L)}{\log(s^2)}$ $\quad s = 3/2, 2$

# Running coupling, extrapolated to continuum



## Running coupling summary (for sextet)

No sign of fixed point in the $0 < g^2 < 6.5$ range

3-loop fixed point in $\overline{\mathrm{MS}}$ : $g^2 = 6.28$

4-loop fixed point in $\overline{\mathrm{MS}}$ : $g^2 = 5.73$

Schwinger-Dyson: no fixed point

## Summary and questions

- Sextet model is a minimal composite Higgs model
- Particle spectrum shows chiral symmetry breaking
- Light scalar emerges
- Running coupling consistent with it

## Summary and questions

- Lower end of conformal window $\longrightarrow$ light scalar?
- Slow running $\longrightarrow$ light scalar?
- Why light? Dilatation symmetry?
- $m_\rho/f_\pi \sim 8$ for $SU(3)$ largely $N_f$ and $R$ independent?

## Work in progress and future outlook

### Haven't talked about lots of things

- Chiral condensate from Dirac eigenvalues (GMOR)
- Mass anomalous dimension
- Thermodynamics
- etc.

Thank you for your attention!