Dear Claude, thank you for all the help teaching me rsChiPT and rooting with me for the composite Higgs

Enjoy your new freedom and help me with new homework I will discuss in the talk

Bernardfest 2016

Rooting for the composite Higgs
(with Claude)

and with the Lattice Higgs Collaboration ($\mathrm{L_{at}HC}$)

Zoltan Fodor, Kieran Holland, JK, Santanu Mondal, Daniel Nogradi, Chik Him Wong

Julius Kuti

University of California, San Diego

Bernardfest 2016

March 26, 2016 Washington University, St. Louis

What is our composite Higgs paradigm?

the Higgs doublet field

elementary scalar?

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} \pi_2 + i\,\pi_1 \\ \sigma - i\,\pi_3 \end{pmatrix} \qquad \frac{1}{\sqrt{2}}(\sigma + i\,\vec{\tau}\cdot\vec{\pi}) \equiv M$$

$$D_\mu M = \partial_\mu M - i\,g\,W_\mu M + i\,g' M\,B_\mu\,, \qquad \text{with} \qquad W_\mu = W_\mu^a \frac{\tau^a}{2}\,, \quad B_\mu = B_\mu \frac{\tau^3}{2}$$

The Higgs Lagrangian is

spontaneous symmetry breaking

Higgs mechanism

$$\mathcal{L} \;=\; \frac{1}{2}\mathrm{Tr}\left[D_\mu M^\dagger D^\mu M\right] - \frac{m_M^2}{2}\mathrm{Tr}\left[M^\dagger M\right] - \frac{\lambda}{4}\,\mathrm{Tr}\left[M^\dagger M\right]^2$$

strongly coupled gauge theory

fermions (Q) in gauge group reps:

$$\mathcal{L}_{Higgs} \rightarrow -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{Q}\gamma_\mu D^\mu Q + \ldots$$

light scalar separated from 2-3 TeV resonance spectrum

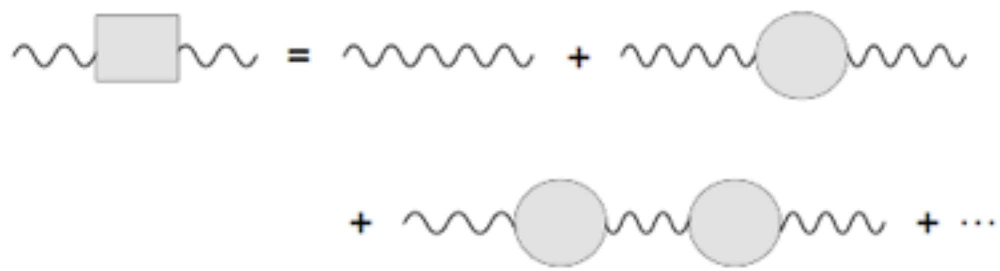
has to be unlike QCD

needle in the BSM haystack?

QCD in 1971 was a needle in the haystack!

composite Higgs mechanism as text book scaled QCD example:

the origin of Technicolor



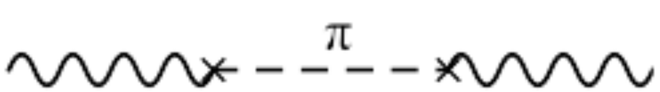
$$G_{\mu\nu}(q) = \frac{-i}{q^2 - g^2\Pi(q^2)/2}(P_T)_{\mu\nu}\,, \qquad (P_T)_{\mu\nu} \equiv \eta_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}$$

$$i\Pi_{\mu\nu}(q) = -\int d^4x\, e^{-iq\cdot x}\langle 0|T\left(J^+_\mu(x)J^-_\nu(0)\right)|0\rangle$$

$$\Pi_{\mu\nu}(q) = \left(\eta_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\right)\Pi(q^2)\,.$$

$$\langle 0|J^+_\mu|\pi^-(p)\rangle = i\frac{f_\pi}{\sqrt{2}}p_\mu$$

Since we want something different from scaled up QCD, to understand the role of the composite Higgs, the chiral condensate and the goldstone will play a critically important if model would become relevant for LHC predictions …



$$\Longrightarrow \qquad \Pi(q^2) = \frac{f_\pi^2}{2}$$

$$m_W = \frac{gf_\pi}{2} \simeq 29\,\mathrm{MeV}$$

The light 0++ scalar

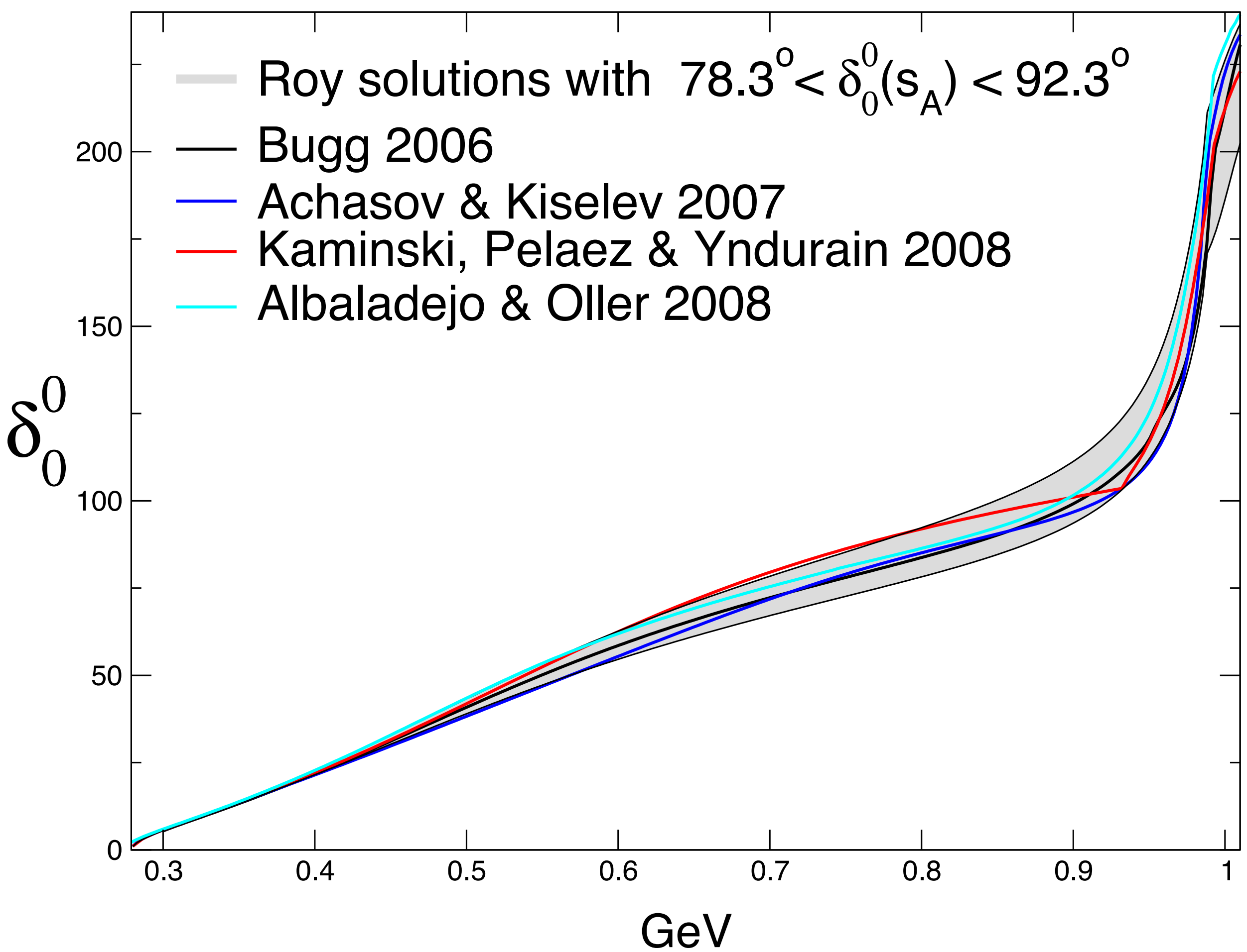
not scaled up QCD!

the failure of old Higgs-less technicolor:

0^{++} scalar in QCD (bad Higgs impostor)

$\sqrt{s_\sigma}$ = (400 - 1200) - i (250 - 500) MeV estimate in Particle Data Book

π-π phase shift in 0^{++} "Higgs" channel



broad M_σ ~ 1.5 TeV in old technicolor, based on scaled up QCD, hence the tag "Higgs-less"

This is expected to be different in near-conformal strongly coupled gauge theories

Low scalar mass renormalizes F!
Will require new low energy effective action

$$\sqrt{s_\sigma} = 441\,^{+16}_{-8} - i\,272\,^{+9}_{-12.5}\ \mathrm{MeV}$$

Leutwyler:
dispersion theory combined with ChiPT

Outline of some homework list:

Scale dependent renormalized coupling

matching scale dependent coupling from
UV to IR with chiSB

Near-conformal SCGT

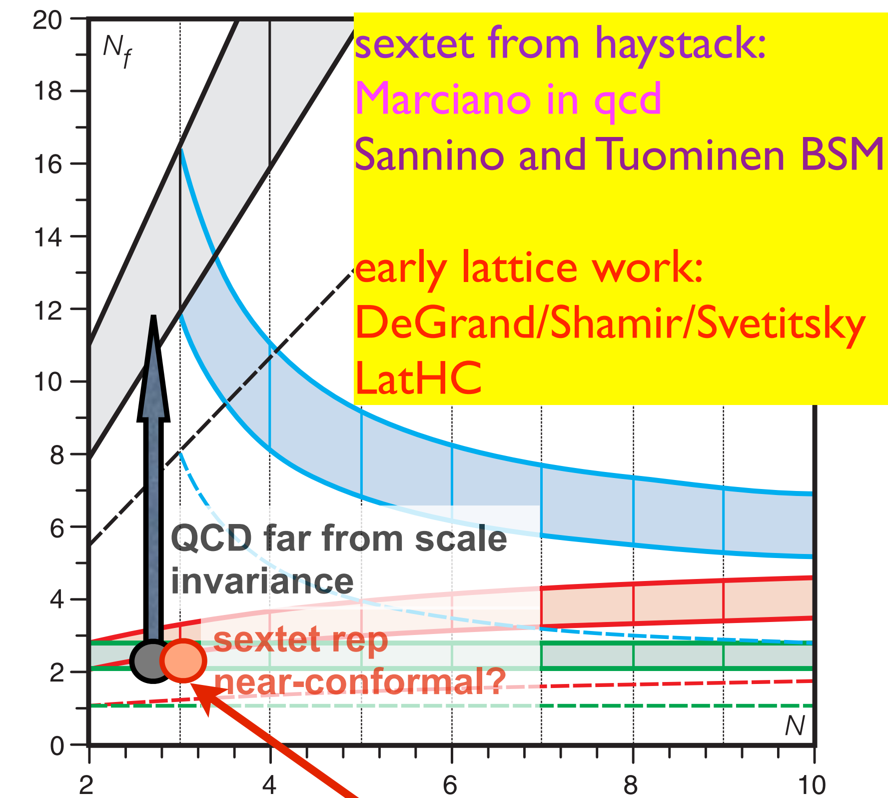
light scalar close to conformal window effective theory?
scale setting and spectroscopy
taste breaking and mixed action

Early universe

EW phase transition, sextet baryon, and dark matter

Summary

SCGT Theory Space



$\begin{bmatrix} u(+e/2) \\ d(-e/2) \end{bmatrix}$ minimal EW embedding

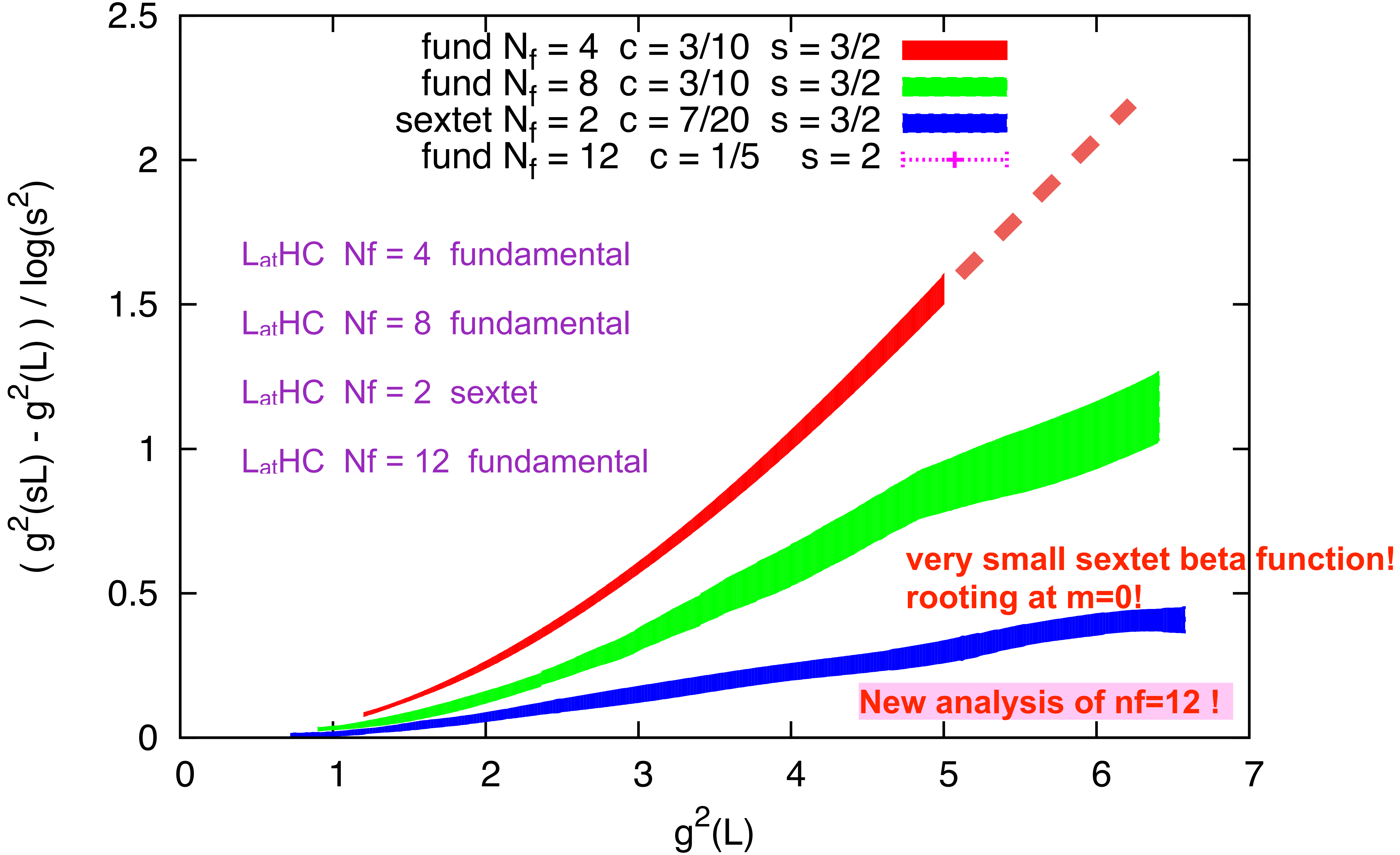
Nf=2 sextet rep
massless fermions
SU(2) doublet
3 Goldstones > weak bosons
minimal realization of Higgs mechanism
adding lepton doublets is a choice
adding EW singlet massive flavor
is also a choice

QCD intuition for near-conformal
compositeness is plain wrong

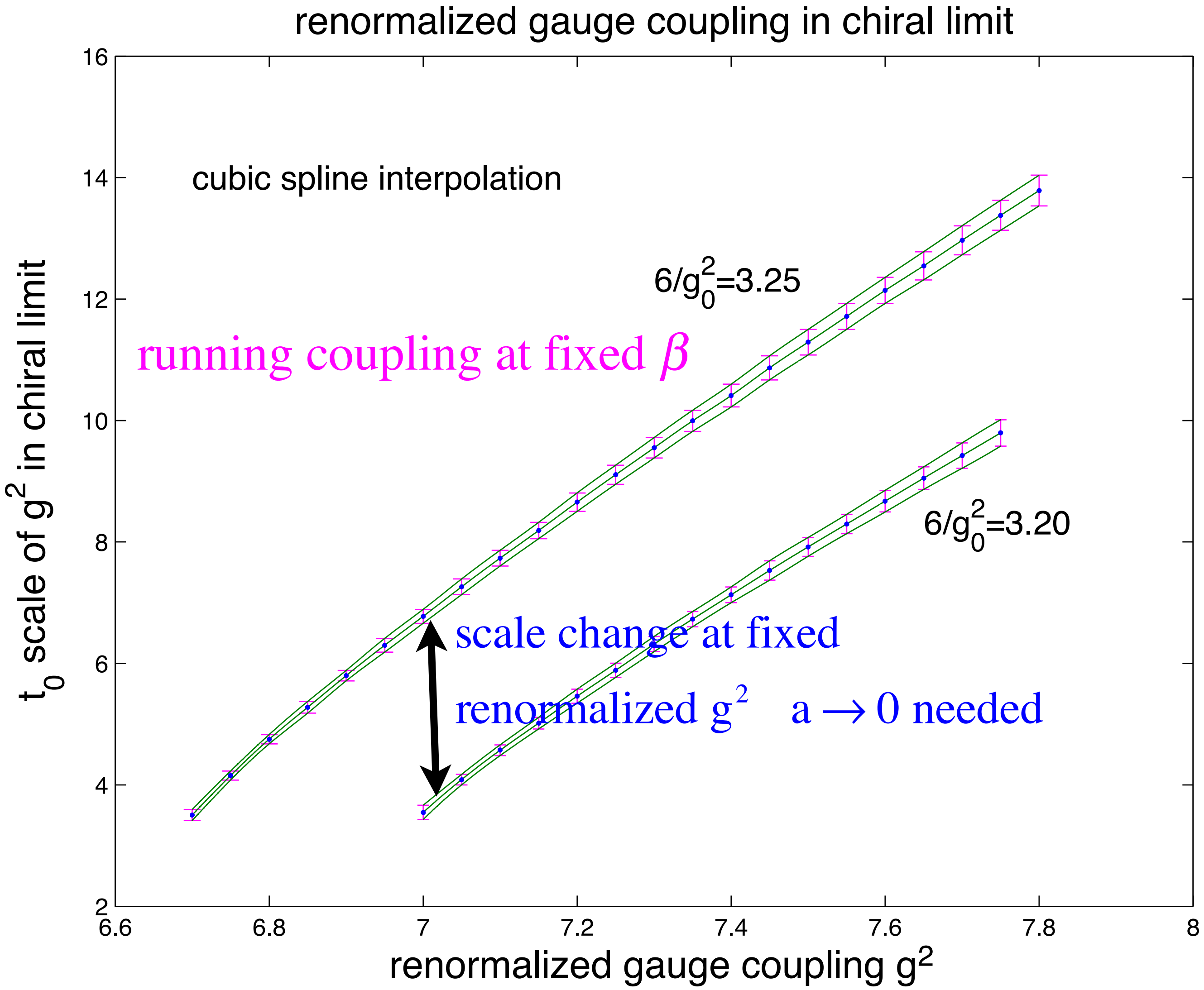
Technicolor thought to be scaled up QCD
motivation of the project:
composite Higgs-like scalar close to the
conformal window with 2-3 TeV new physics

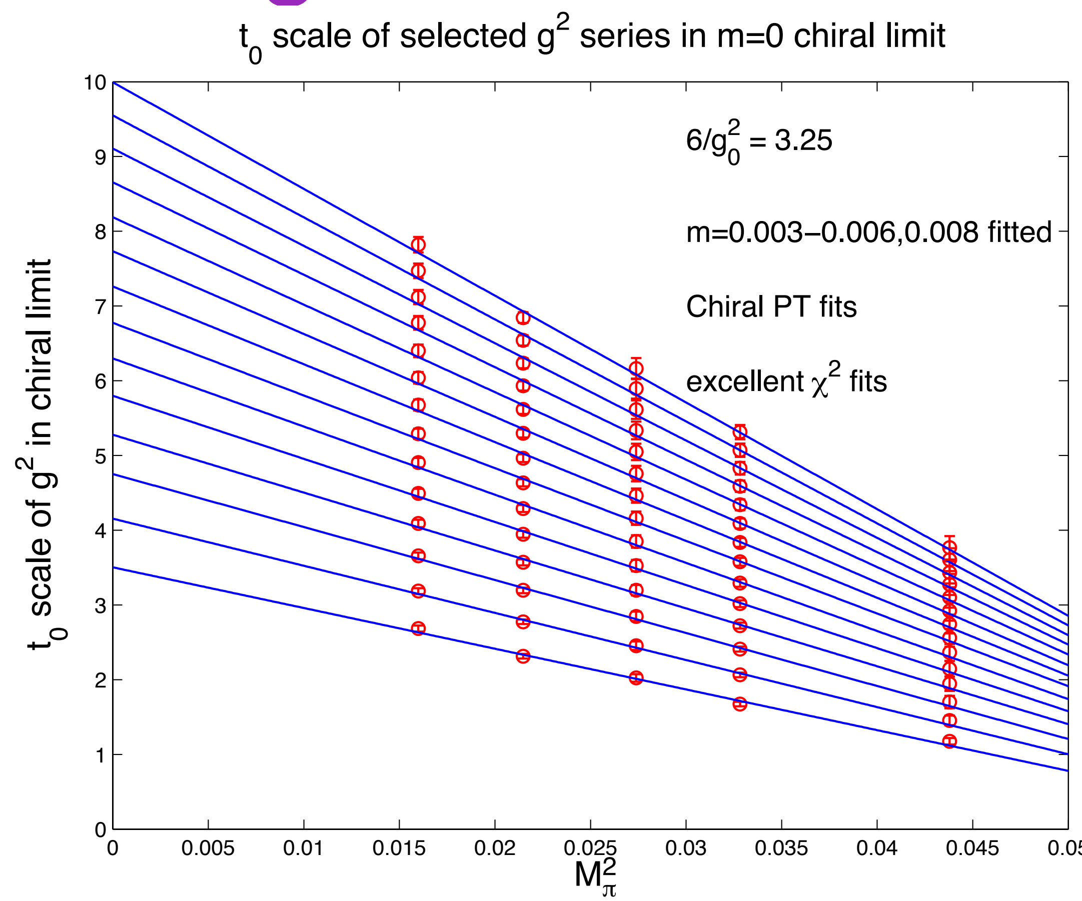
scale-dependent coupling and beta-function

without the gradient flow based method this accuracy would not have been possible



scale-dependent coupling matching IR to UV





the two scale dependent couplings to be matched to leave no room for further speculations on conformal fixed points

leading dependence of $g^2(t,m)$ on M_π^2 is linear

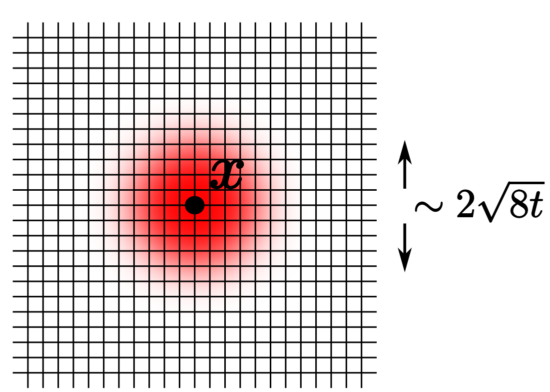
based on gradient flow chiPT Bär and Golterman

works better than expected

chiral logs are not detectable

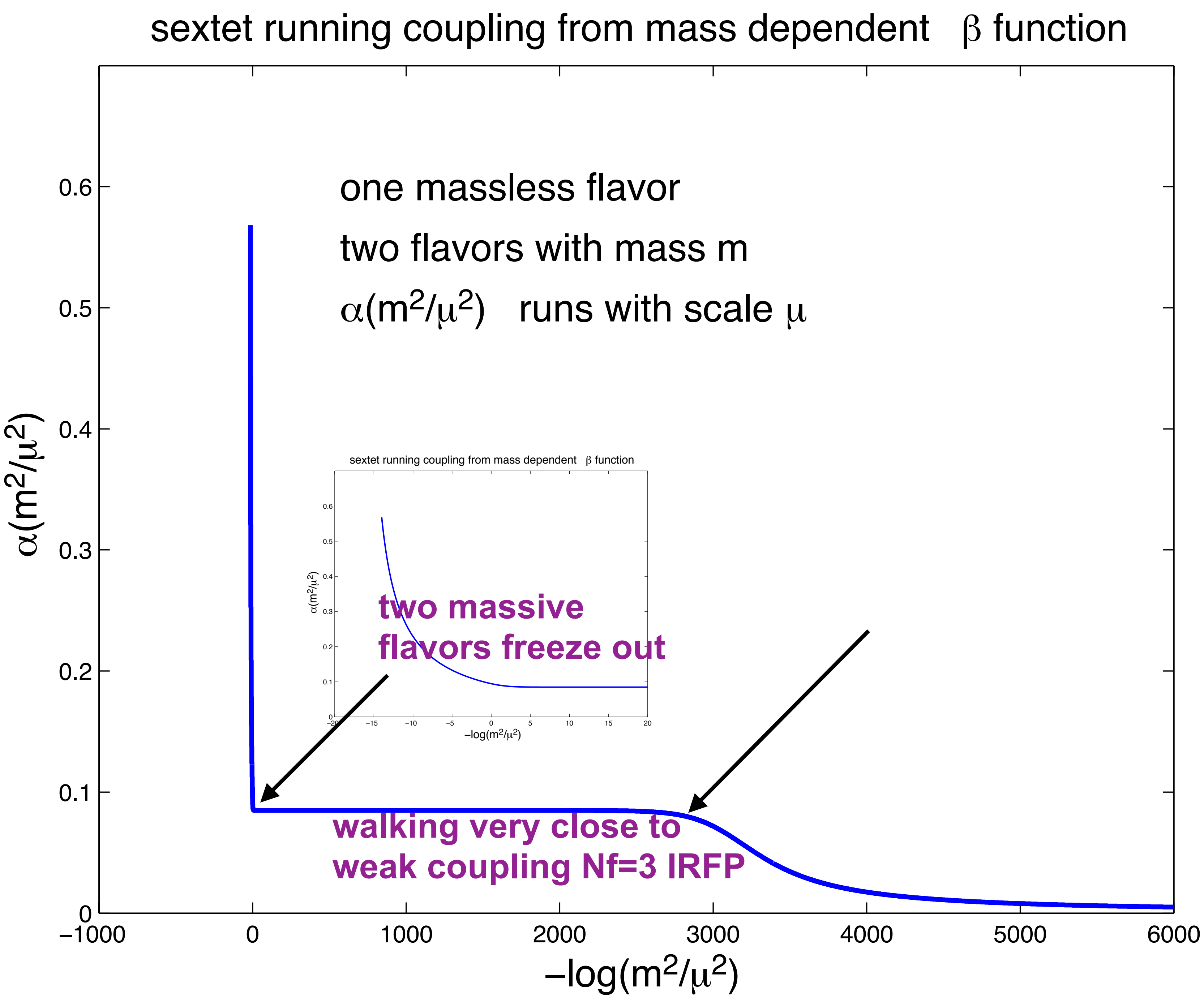
decoupling of the scalar has

to be better understood



hw: how to do this right in rooted staggered ChiPT with low lying scalar coupled to Goldstone dynamics?

scale-dependent coupling mass dependent tuning?



in 1+2 freeze-out scenario anything to learn about strong coupling dynamics of single massless flavor?

Similarly, in 2+1 freeze-out scenario anything to learn about strong coupling dynamics of doublet massless flavor?

Not likely that light scalar mass can be tuned this way

near-conformal light Higgs (dilaton-like?)

$$m_\sigma^2 \simeq -\frac{4}{f_\sigma^2}\langle 0|\left[\Theta_\mu^\mu(0)\right]_{NP}|0\rangle$$

$$\partial_\mu \mathcal{D}^\mu = \Theta_\mu^\mu = \frac{\beta(\alpha)}{4\alpha} G_{\mu\nu}^a G^{a\mu\nu}$$

$$\langle 0|\Theta^{\mu\nu}(x)|\sigma(p)\rangle = \frac{f_\sigma}{3}(p^\mu p^\nu - g^{\mu\nu}p^2)e^{-ipx}$$

$$\langle 0|\partial_\mu \mathcal{D}^\mu(x)|\sigma(p)\rangle = f_\sigma m_\sigma^2 e^{-ipx}$$

$$\left[\Theta_\mu^\mu\right]_{NP} = \frac{\beta(\alpha)}{4\alpha}\left[G_{\mu\nu}^a G^{a\mu\nu}\right]_{NP} \qquad \frac{m_\sigma}{f_\sigma} \to ?$$

Partially Conserved Dilatation Current (PCDC)

Will gradient flow based technology make the argument less slippery?

Dilatation current

Bardeen et al., Ellis, Yamawaki, Miransky, Appelquist, ...

simple model to illustrate the dilaton: $L = \frac{1}{2}\partial\phi^2 + \frac{1}{2}\partial\psi^2 - \frac{\tau}{4}\phi^2\psi^2$

Nambu-Freund, Drummond, Colemen-Weinberg

$\psi = 0$ is flat potential for any $\langle\phi\rangle = M$ spontaneous symmetry breaking of scale invariance

$$\theta_{\mu\nu} = \partial_\mu\phi\partial_\nu\phi + \partial_\mu\psi\,\partial_\nu\psi - g_{\mu\nu}\left(\frac{1}{2}\partial\phi^2 + \frac{1}{2}\partial\psi^2 - \frac{\tau}{4}\phi^2\psi^2\right) - \frac{1}{6}(\partial_\mu\partial_\nu - g_{\mu\nu}\partial^2)(\phi^2+\psi^2)$$

$\langle 0|\theta_{\mu\nu}|\sigma(p)\rangle = -\frac{1}{3}(p_\mu p_\nu - g_{\mu\nu}p^2)F_\sigma$ with $F_\sigma = M$

from Coleman-Weinberg potential (dimensional transmutation):

$\lambda(\phi^4+\psi^4)$ term is dynamically generated $\lambda = \frac{3(\tau^2+\lambda^2)}{64\pi^2}$

trace of $\theta_{\mu\nu}$ on quantum level gives $\langle 0|\theta_\mu^\mu|\sigma(p)\rangle = \mu_\sigma^2 F_\sigma$ dilaton gets mass

for small τ coupling $\frac{\mu_\sigma^2}{m^2} \approx \frac{\tau^2}{16\pi^2}$ m is the mass of ψ excitations

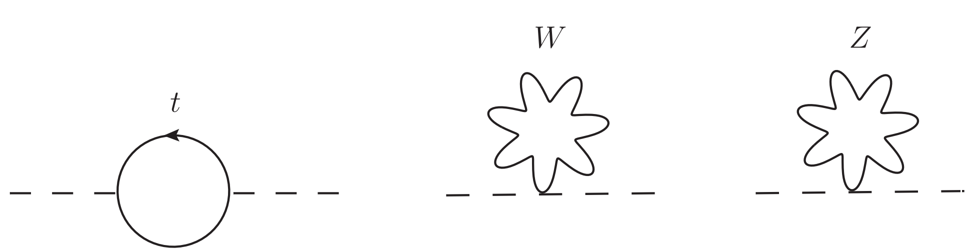
dilaton mass can be arbitrary small in m^2 units

but forbidden to become exactly zero by onset of vacuum instability

light composite scalar, but
how light is light ?

few hundred GeV Higgs impostor?

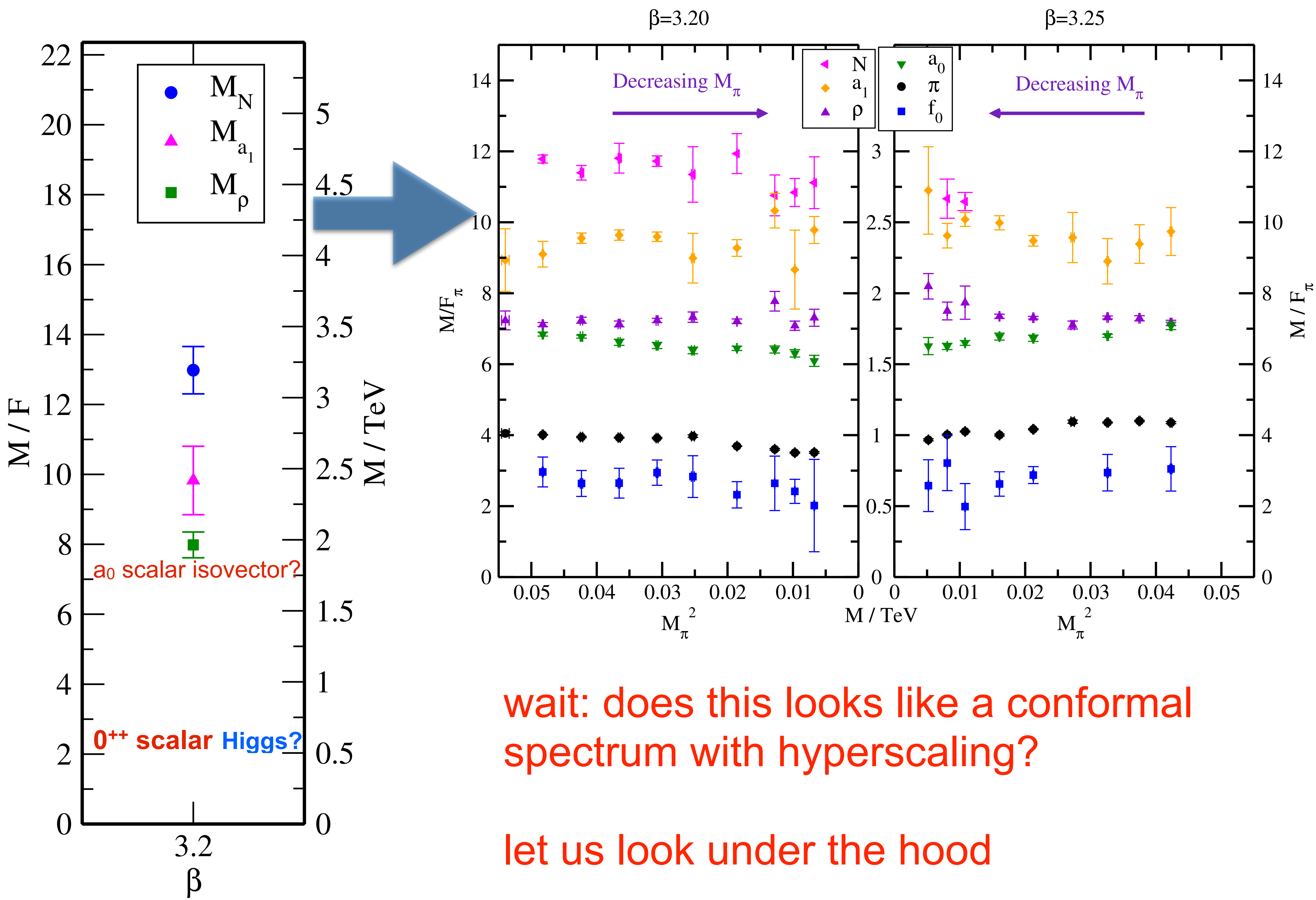
Foadi, Fransden, Sannino
open for spirited theory discussions



$$\delta M_H^2 \sim -12\kappa^2 r_t^2 m_t^2 \sim -\kappa^2 r_t^2 (600\,\mathrm{GeV})^2$$

light 0++ scalar and spectrum

sextet model LatHC

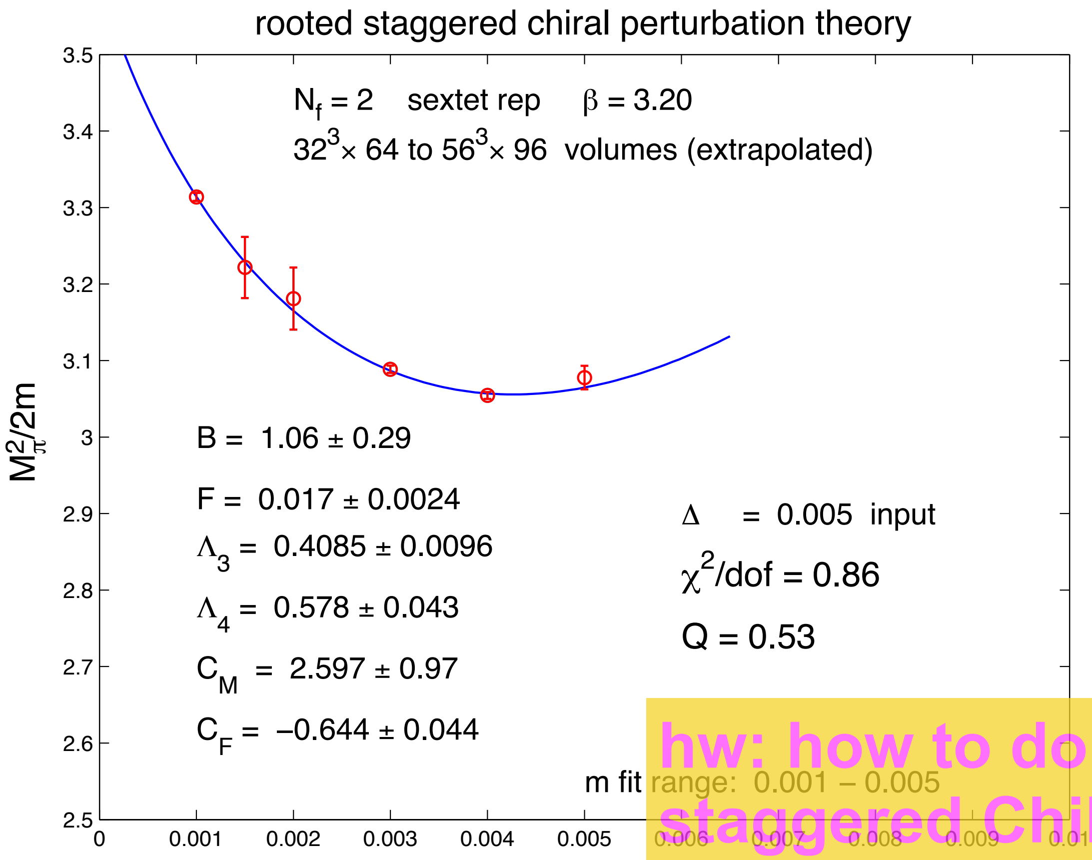


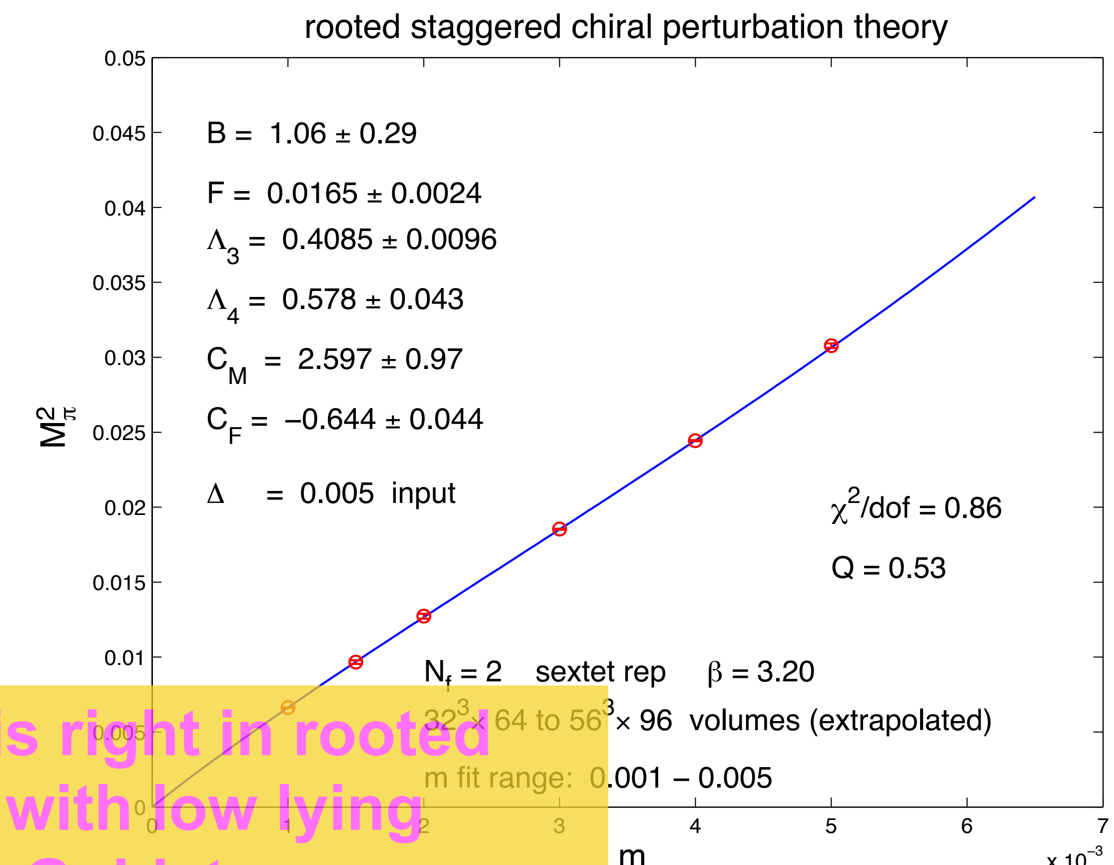
wait: does this looks like a conformal spectrum with hyperscaling?

let us look under the hood

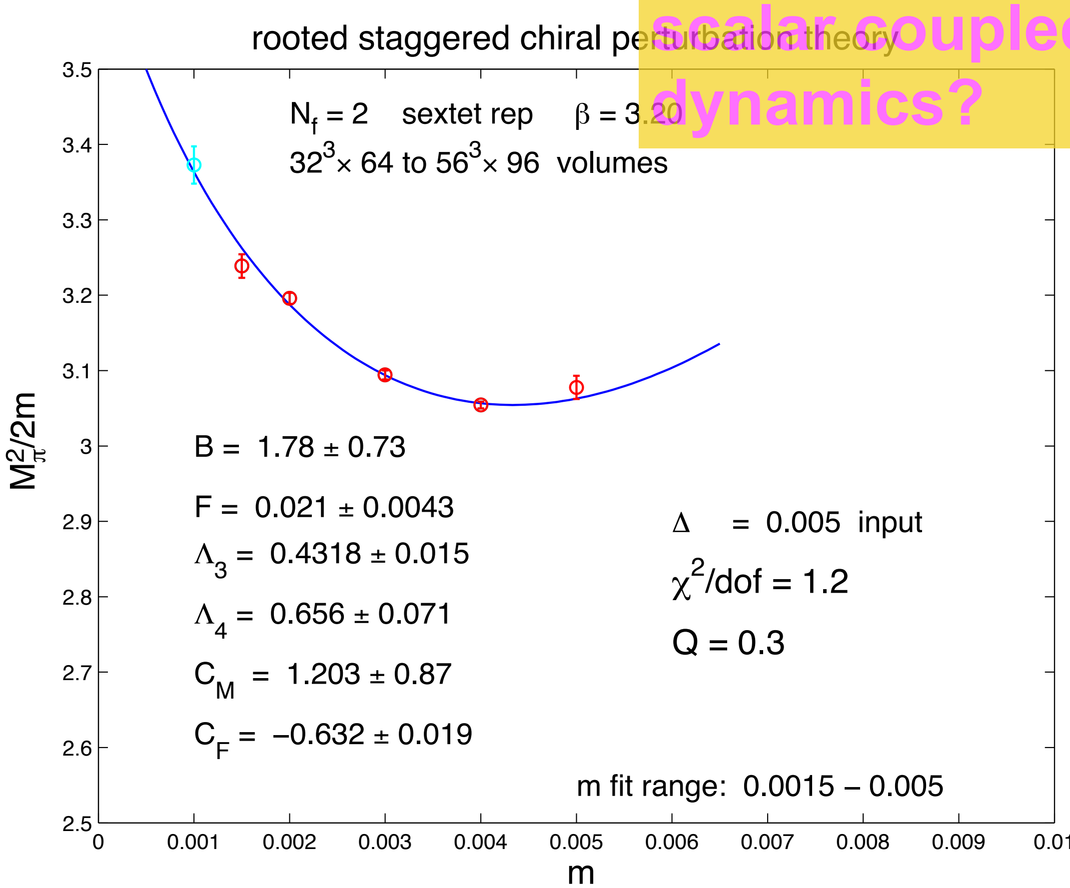
rsChiPT analysis of Mpi and Fpi

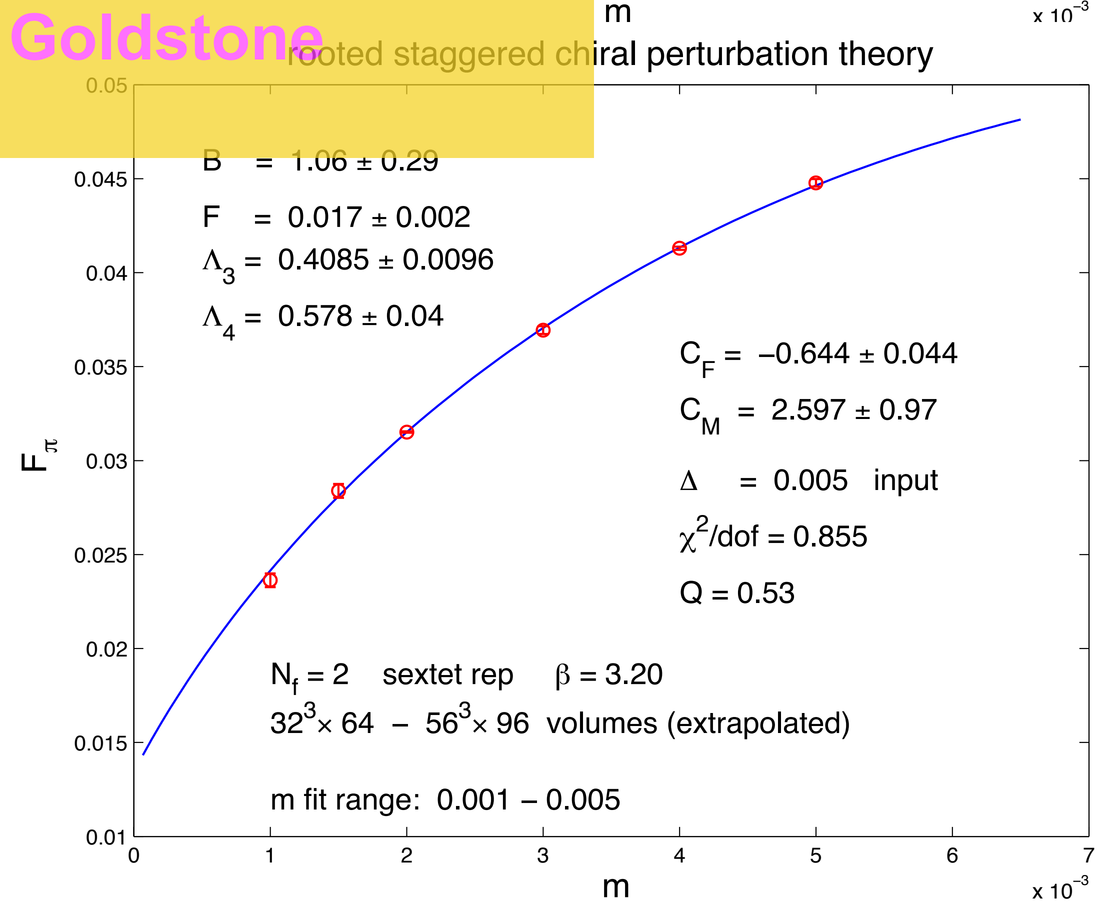
fitting results





hw: how to do this right in rooted staggered ChiPT with low lying scalar coupled to Goldstone dynamics?





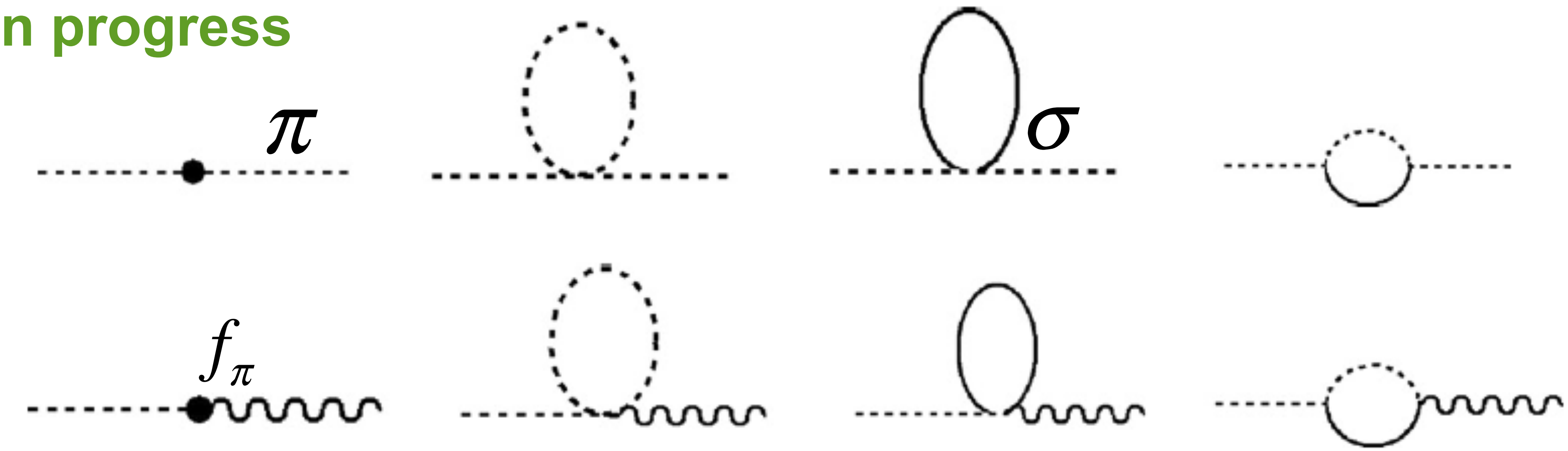
two outstanding spectroscopy problems:

1. effective low energy theory for Goldstone dynamics coupled to the low mass scalar
HW: nonlinear sigma model or dilaton?

2. effect of slow topology on the analysis
HW: srChiPT at fixed topology?

Goldstone dynamics coupled to low mass scalar

work in progress



$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - V(h) + \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left[1 + 2a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + \ldots\right] \qquad \Sigma = e^{i\sigma_a \pi^a / v}$$

$$V(h) = \frac{1}{2}m_h^2 h^2 + d_3\,\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + d_4\,\frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \ldots$$

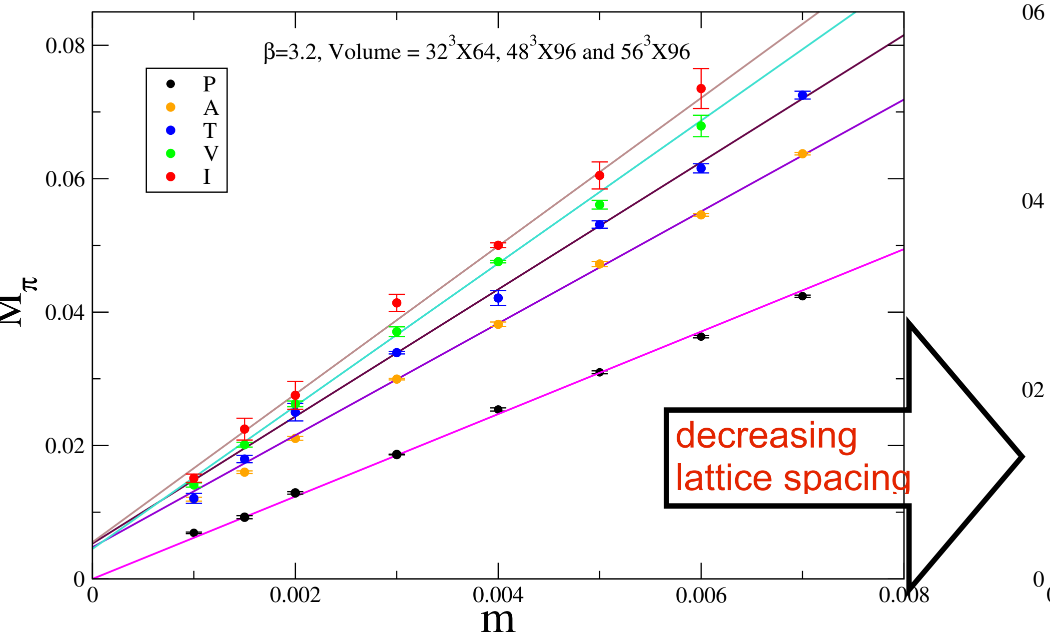
M_π, F_π, M_σ are calculated now to 1-loop: extended chiral SU(2) flavor dynamics

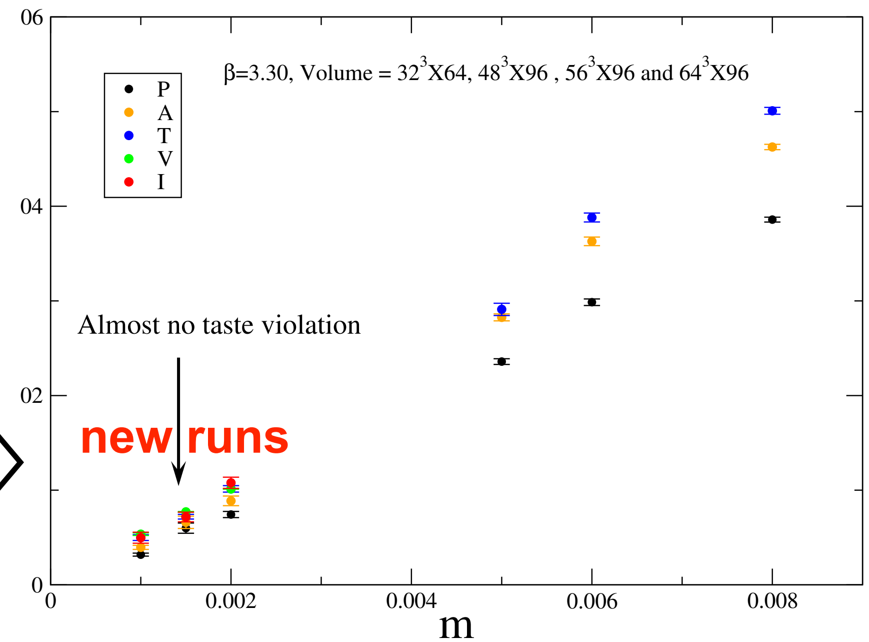
We are analyzing the small pion mass region in the $M_\pi = 0.07$- 0.013 range of the p-regime, and lower in the RMT regime

To reach the nonlinear sigma model range requires very small pion masses

cutoff effects from taste breaking?

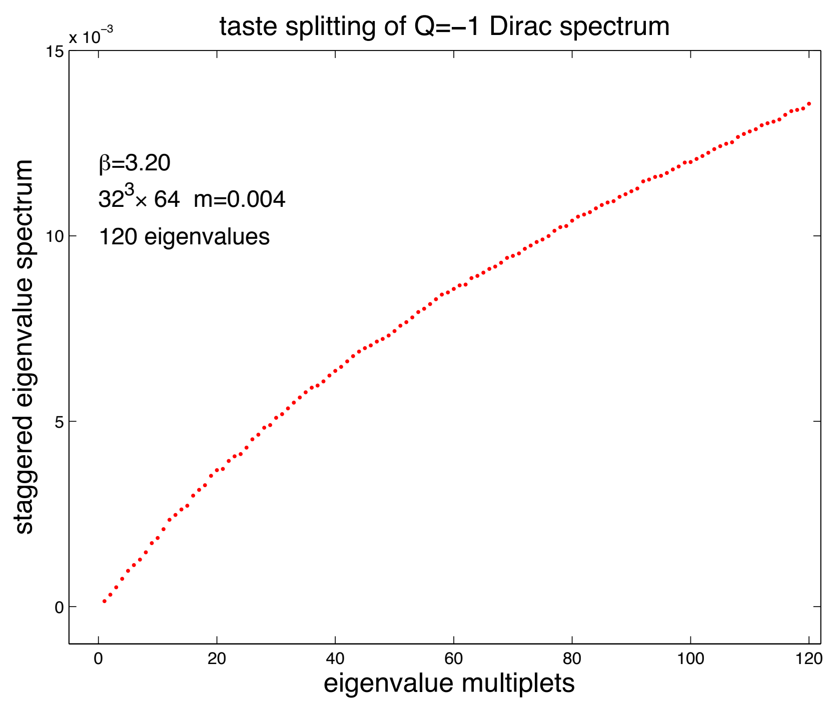
taste breaking and mixed action Claude again

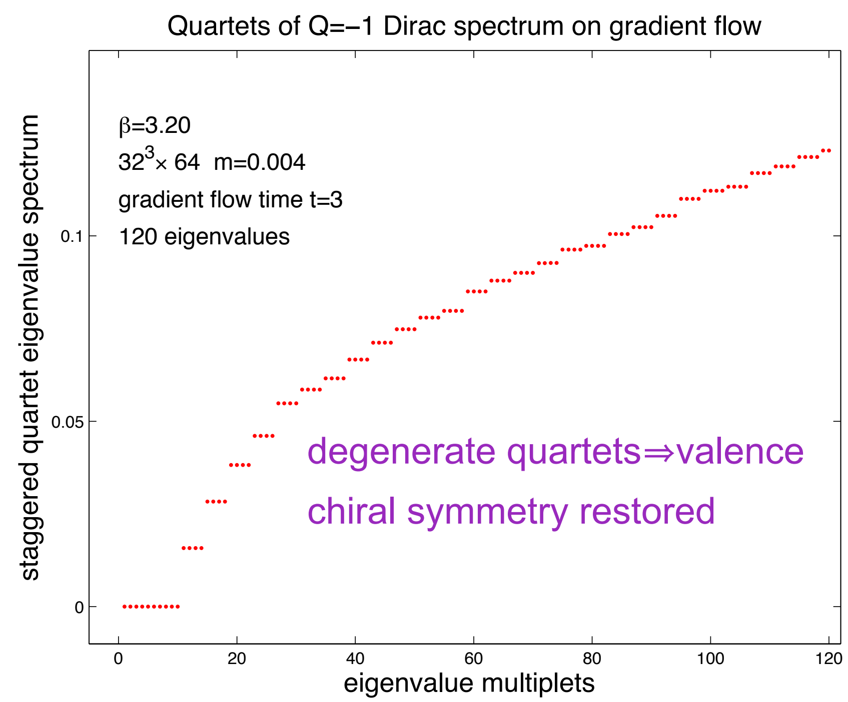


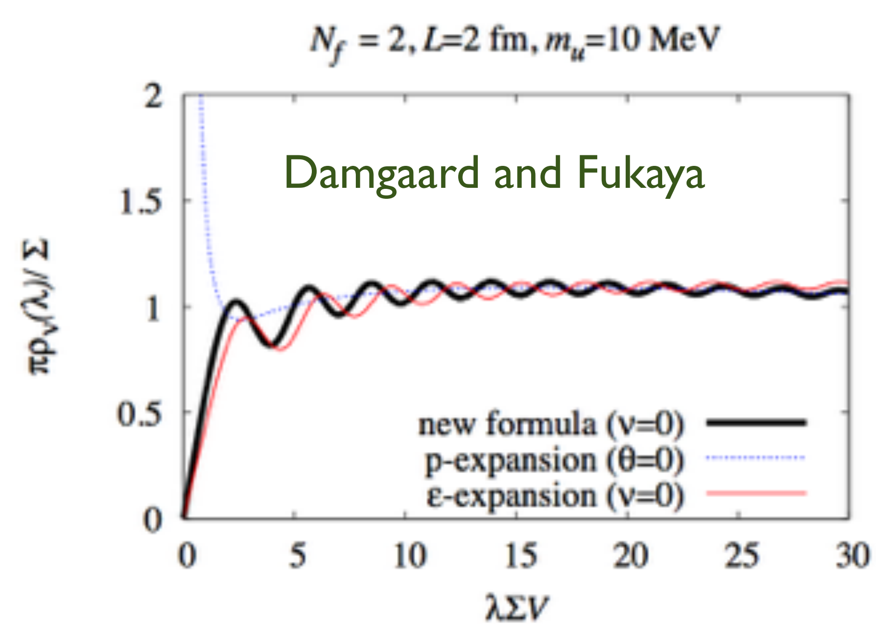


idea for improvement:

- use the gauge configurations generated with sea fermions
- taste breaking makes chiPT analysis complicated
- in the analysis use valence Dirac operator with gauge links on the gradient flow
- taste symmetry is restored in valence spectrum
- Mixed Action analysis should agree with original standard analysis when cutoff is removed: this is OK!

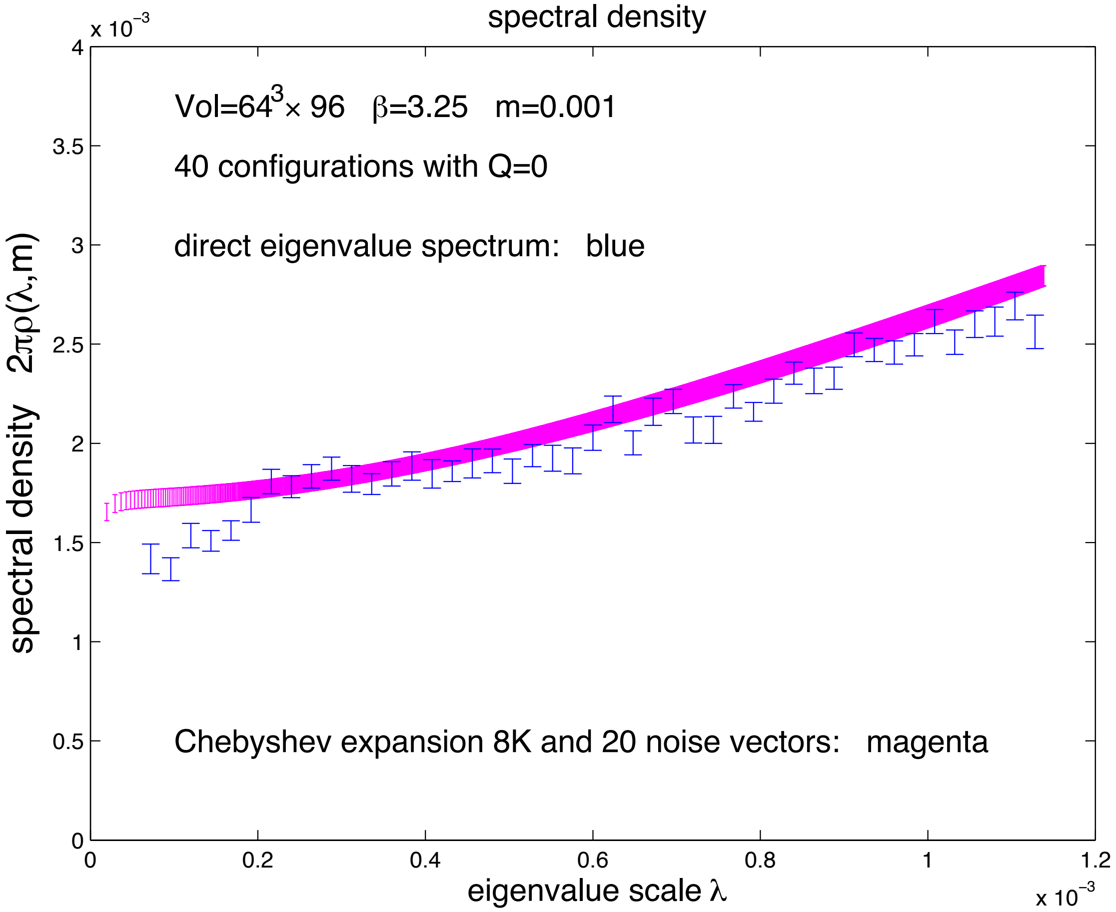


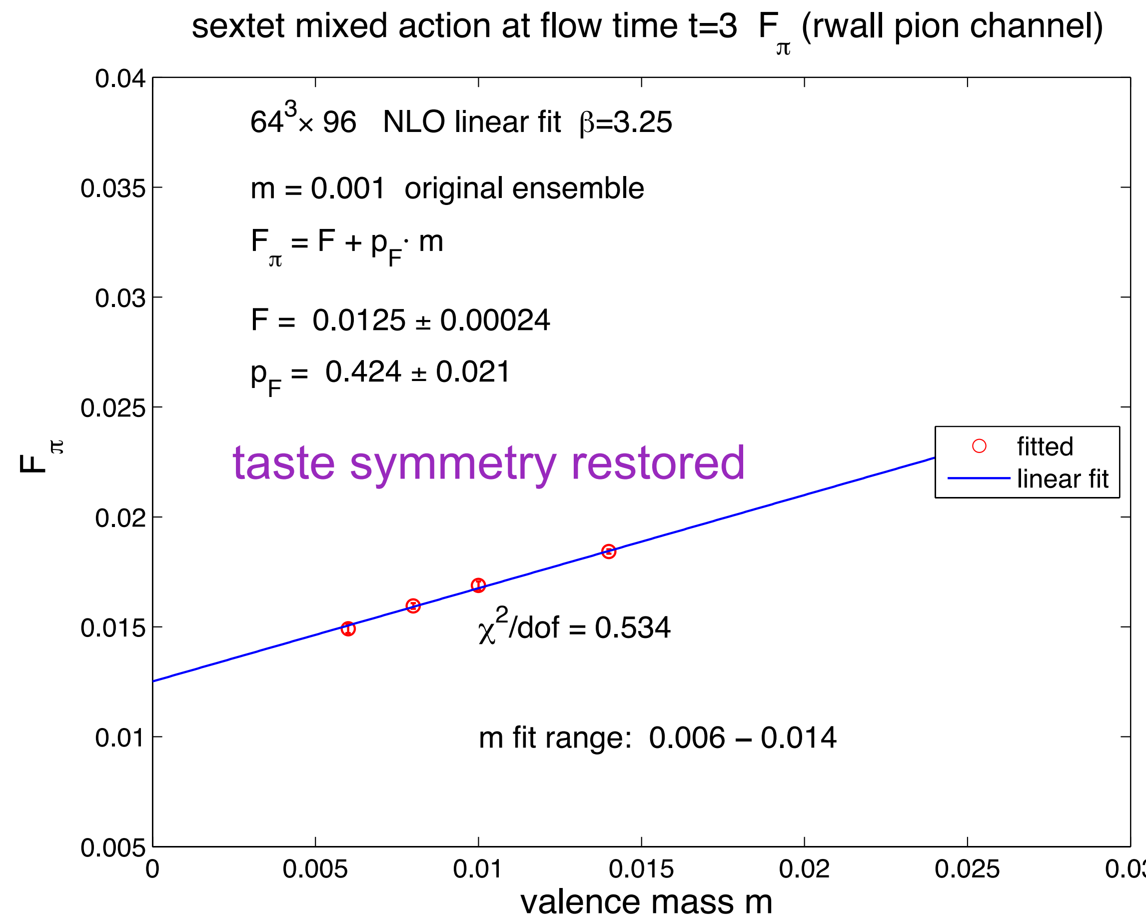


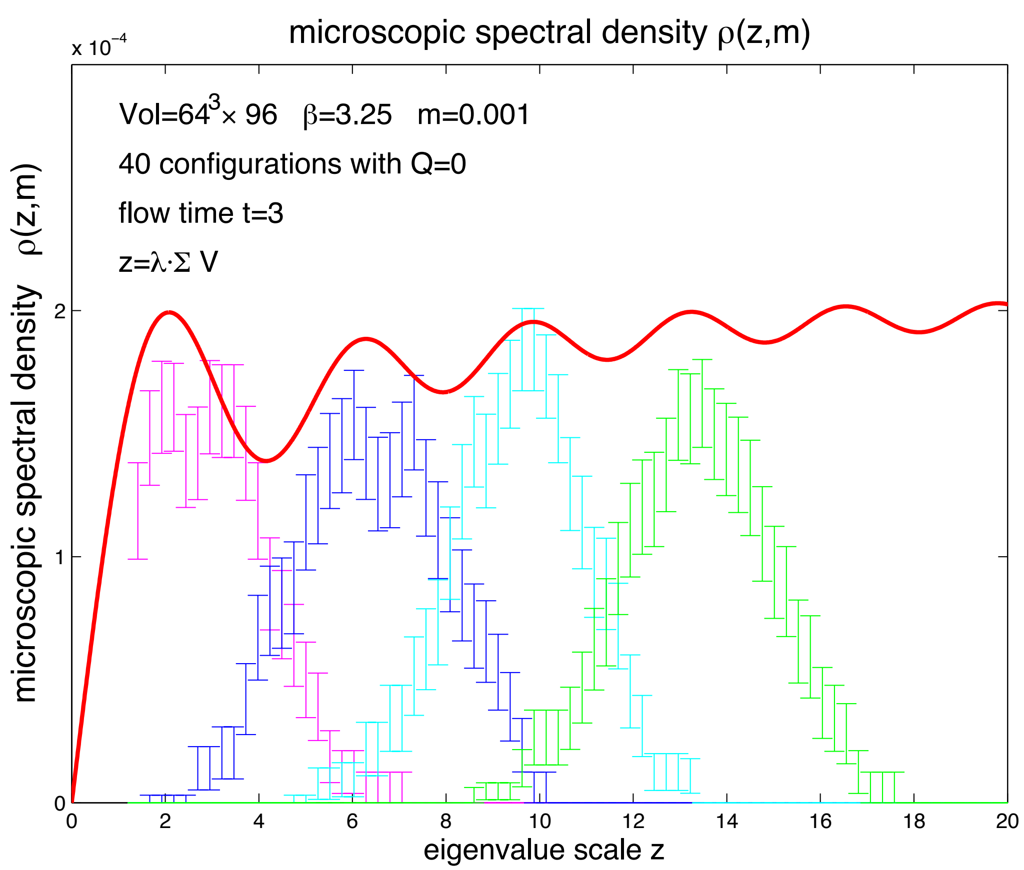


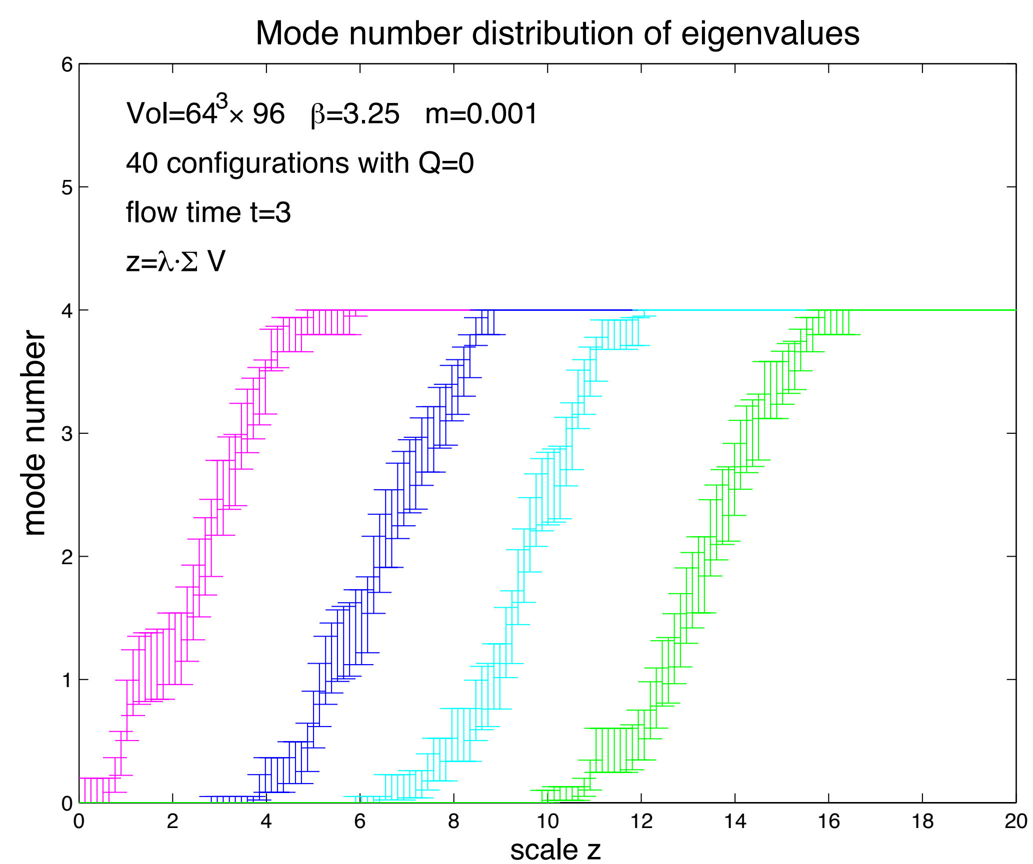
new analysis in crossover and RMT regime opens up with mixed action on gradient flow

taste breaking and mixed action RMT regime







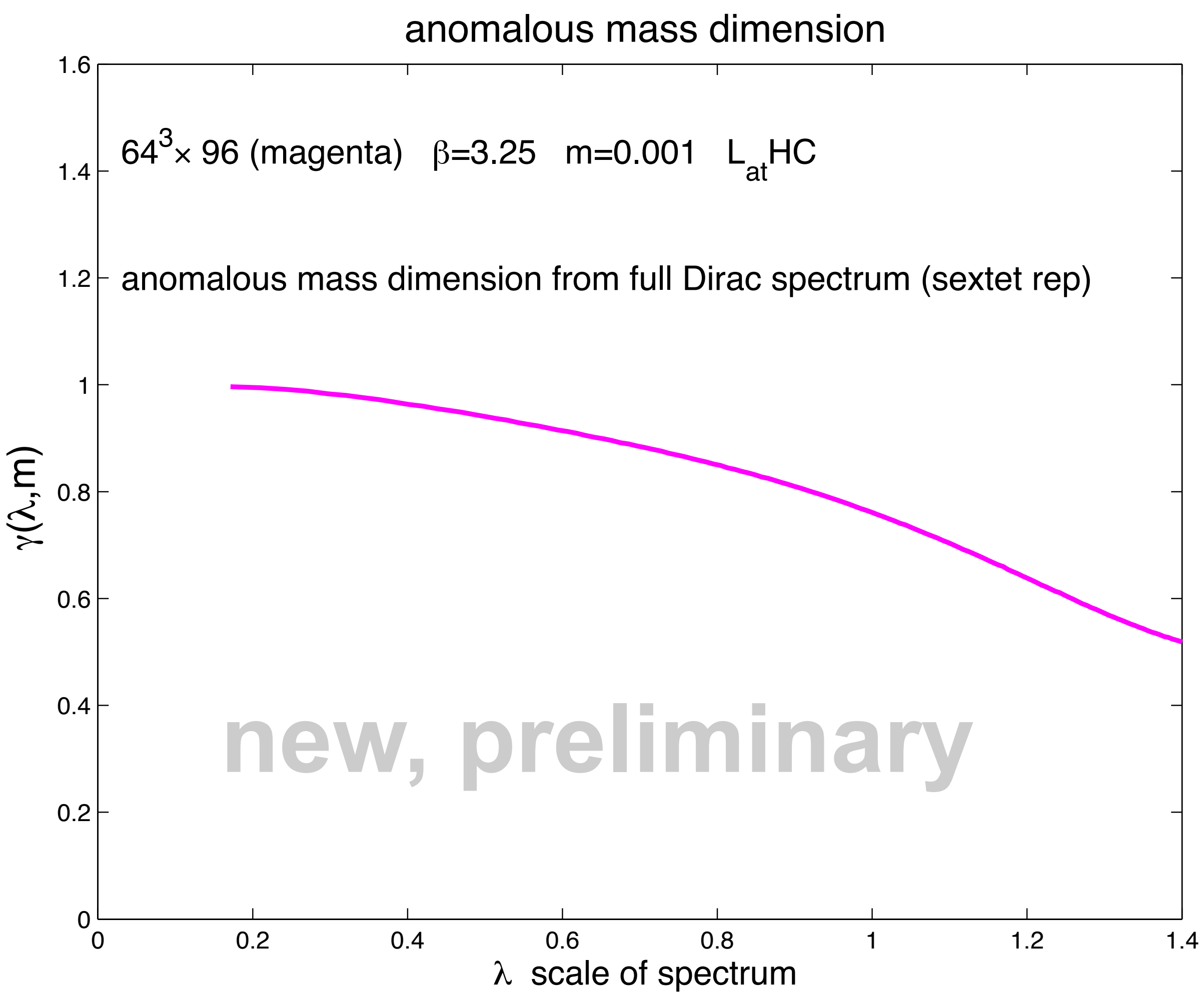


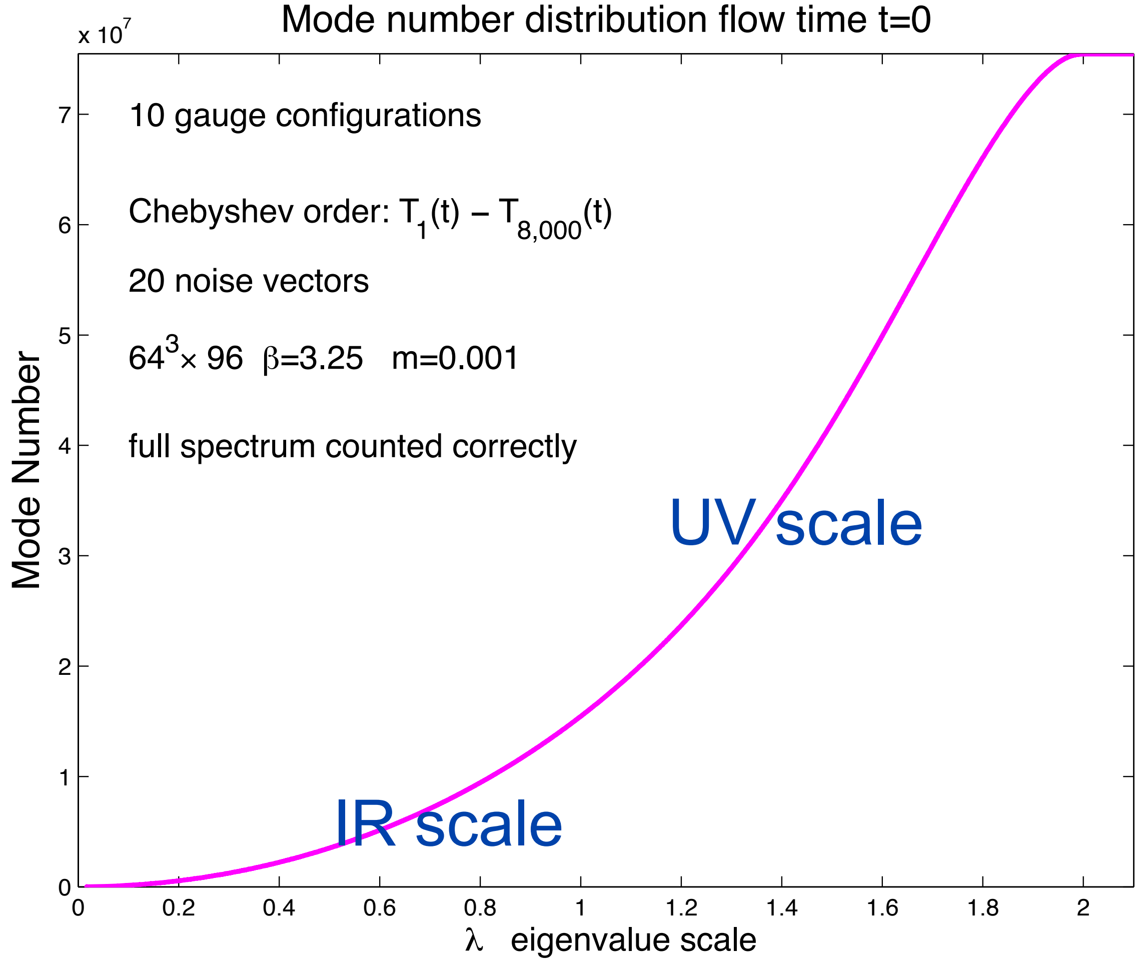
The chiral condensate   mass anomalous dimension

Del Debbio and collaborators and Boulder group pioneered fitting procedures

$$\nu_R(M_R, m_R) = \nu(M, m) \approx const \cdot M^{\frac{4}{1+\gamma_m(M)}},$$

or equivalently, $\nu(M, m) \approx const \cdot \lambda^{\frac{4}{1+\gamma_m(\lambda)}}$, with $\gamma_m(\lambda)$ fitted





How to match λ scale and g^2 ?

Early universe

Kogut-Sinclair EW phase transition
Relevance in early cosmology (order of the phase transition?)
$\mathrm{L_{at}HC}$ is doing a new analysis using different methods

- Nf=2 Qu=2/3 Qd = -1/3 fundamental rep
  udd neutral dark matter candidate

- dark matter candidate sextet Nf=2
  electroweak active in the application

- 1/2 unit of electric charge (anomalies)

- rather subtle sextet baryon
  construction (symmetric in color)

- charged relics not expected?

Three $SU(3)$ sextet fermions can give rise to a color singlet. The tensor product $6 \otimes 6 \otimes 6$ can be decomposed into irreducible representations of $SU(3)$ as,

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

where irreps are denoted by their dimensions and $\overline{10}$ is the complex conjugate of 10.

Fermions in the 6-representation carry 2 indices, ψ_{ab}, and transform as

$$\psi_{aa'} \longrightarrow U_{ab}\; U_{a'b'}\; \psi_{bb'}$$

and the singlet can be constructed explicitly as

$$\varepsilon_{abc}\; \varepsilon_{a'b'c'}\; \psi_{aa'}\; \psi_{bb'}\; \psi_{cc'}.$$

hw: challenges of baryon spectroscopy?

Summary: model exhibits chiSB with a light composite scalar (near-conformal)

Nothing like QCD: waiting for more help from Claude!