Sextet BSM model
2019

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

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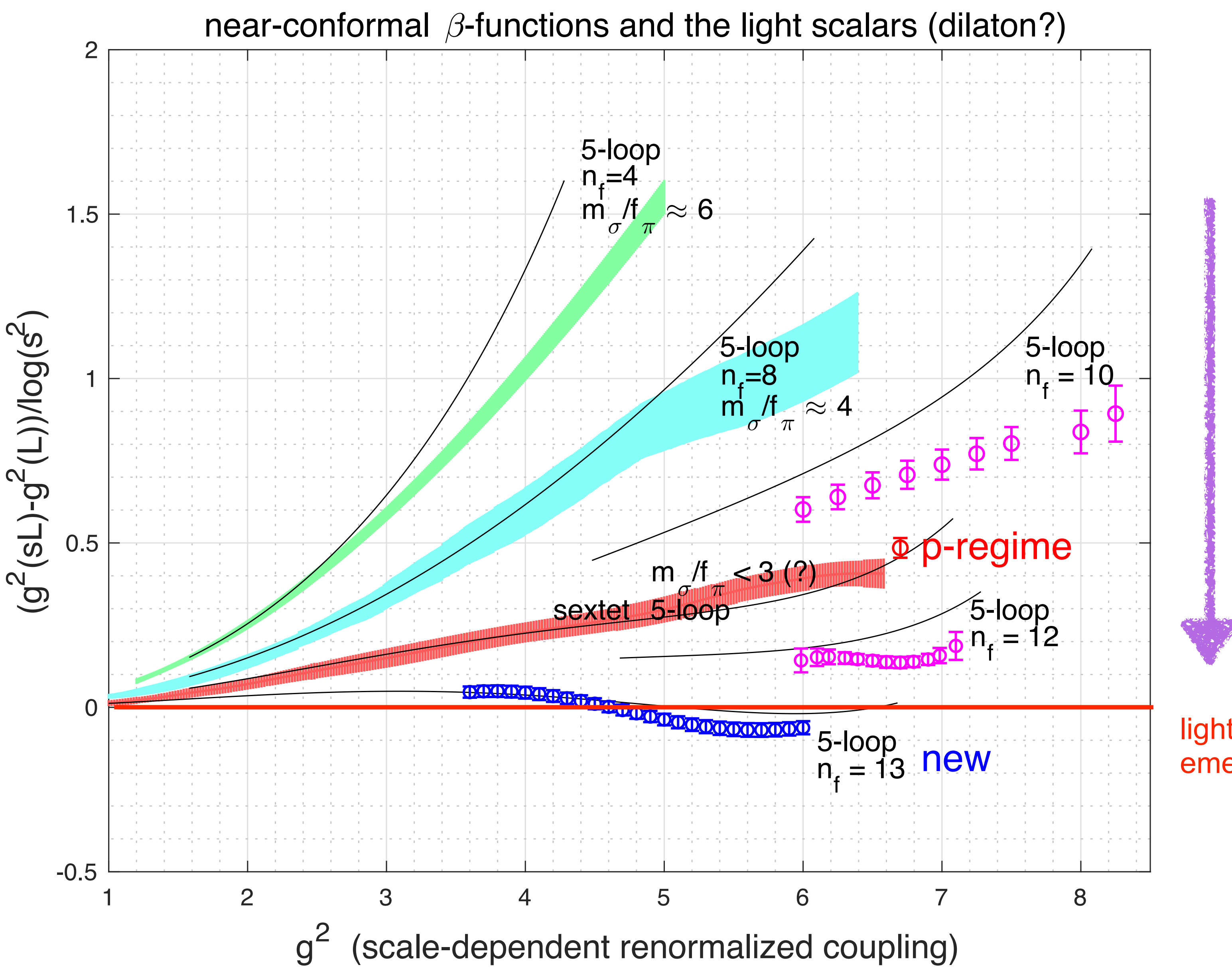
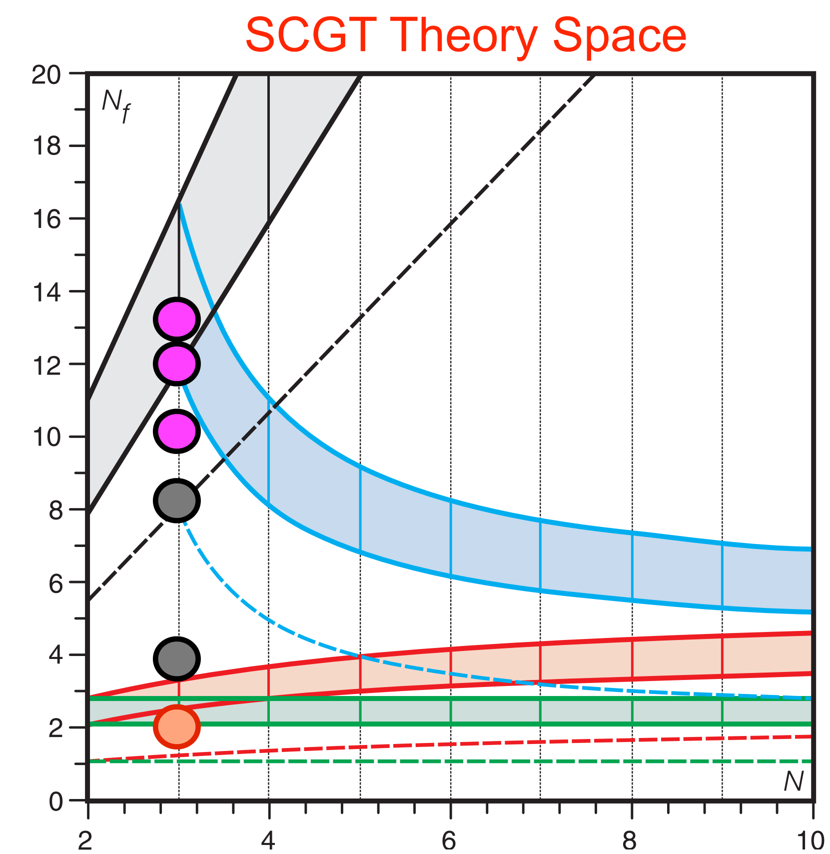
road map of near-conformal β-functions and emergent light scalars…



light 0++ scalar emerging



to illustrate: sextet SU(3) color rep

one massless fermion doublet $\begin{bmatrix} u \\ d \end{bmatrix}$

χSB on Λ~TeV scale

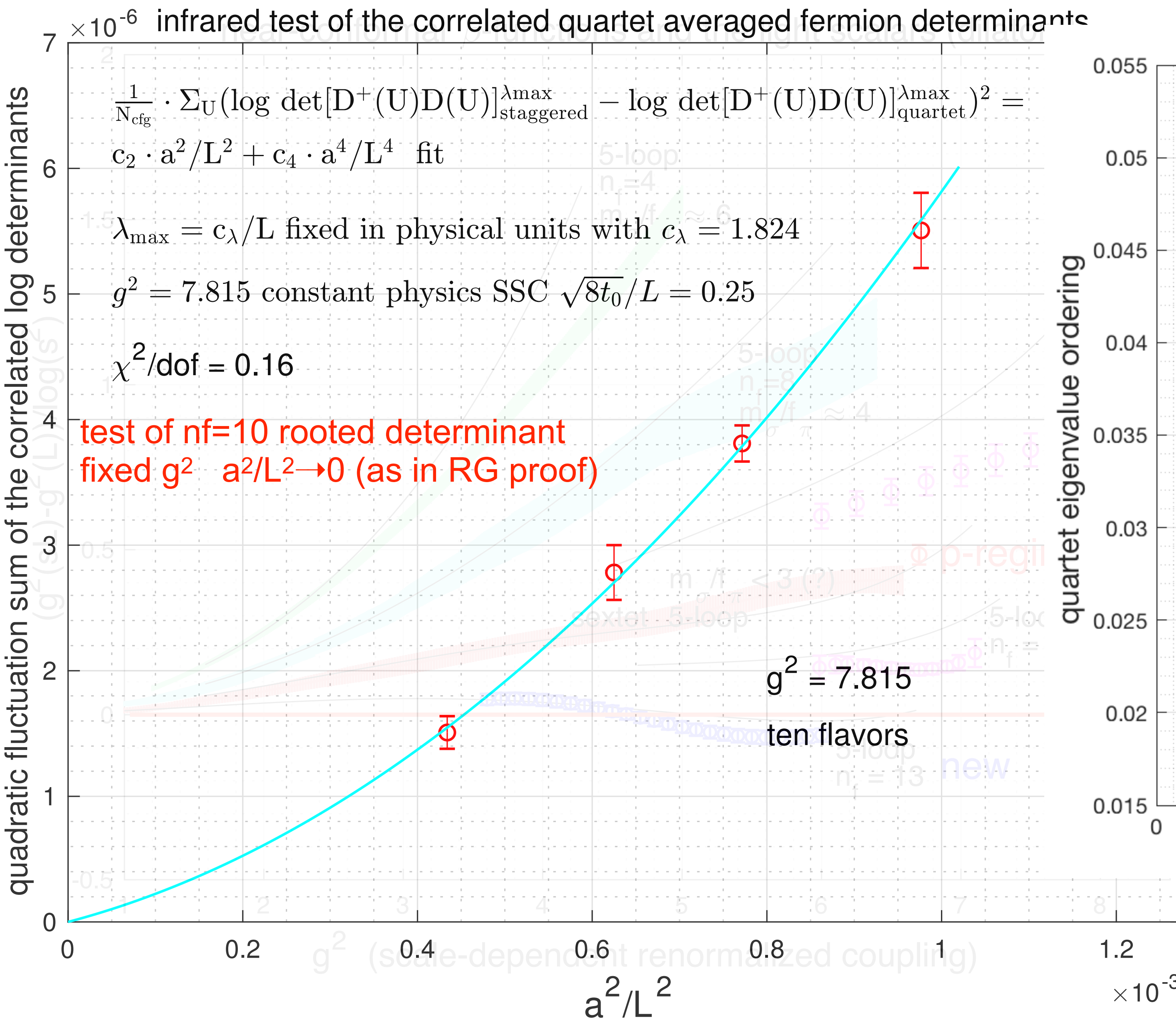
three Goldstone pions
become longitudinal
components of weak bosons

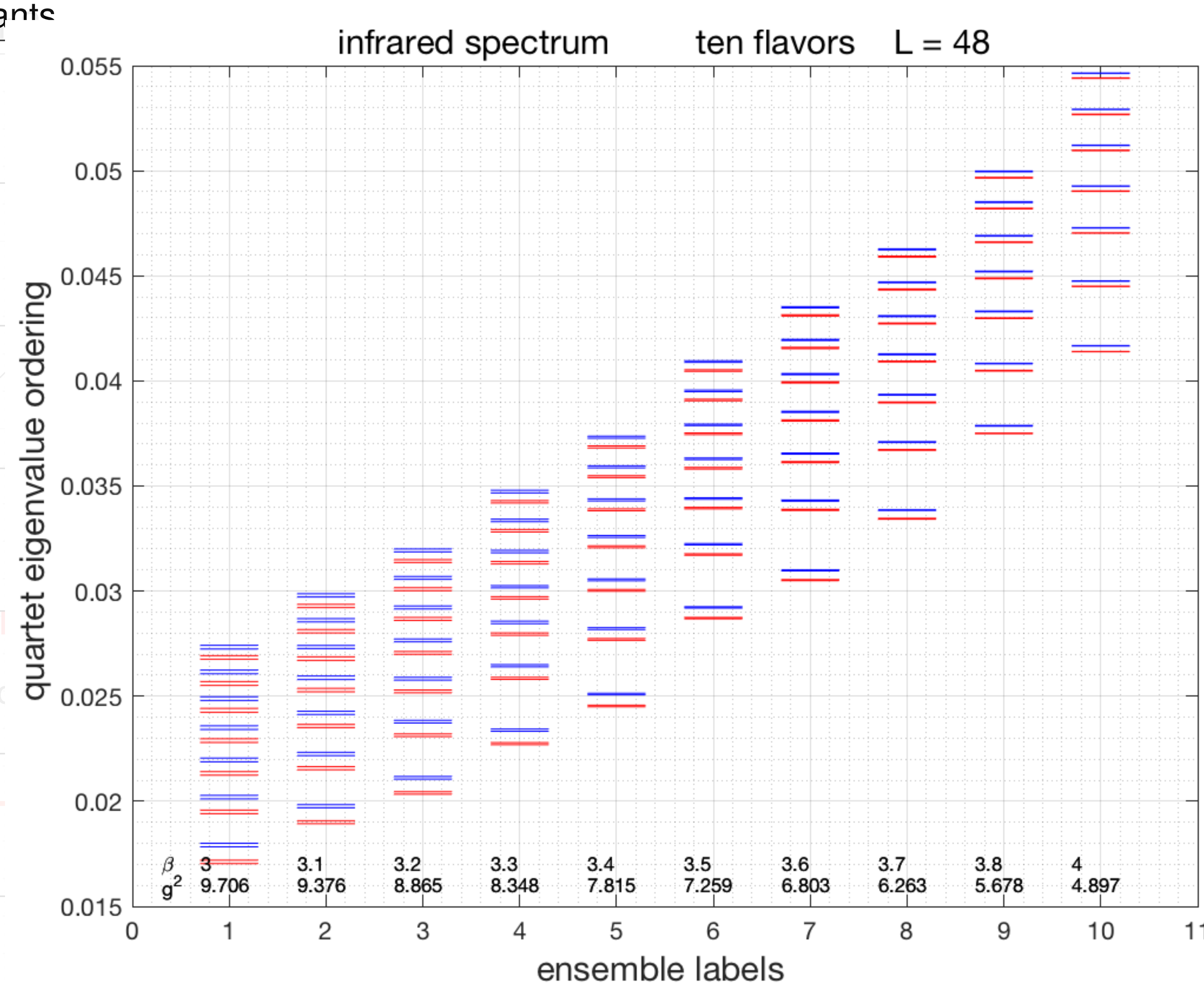
if Susskind and Weinberg only knew …

composite Higgs mechanism

- spoiler alert: controversies around the nf=10 and nf=12 β-functions
- LatHC reports nf=13 conformal IRFP — journal publications in preparation

road map of near-conformal β-functions and emergent light scalars…





- two zeros of 5-loop β-function collide between nf=12 and nf=13 and turn into complex conjugate pair of zeros
- sextet model closest to CW among near-conformal (except perhaps nf=12?) complex pair of CFT?
- what are the tantalizing BSM field theory questions?

tantalizing big questions in the sextet case study:

How light is the emergent 0++ scalar?

Needs the origin of near-conformal walking?

Needs IR EFT like σ-model, or dilaton, or …?

IR EFT needs new strategy to reach massless chiral limit

new walking paradigm?

with this motivation, review of our recent results and the proposed plan, but:

> Tantalus, a king of ancient Phrygia in Greek mythology, made the mistake of gravely offending the gods. As a punishment, once dead the king was forced to stand in a pool of water, with fruit hanging just over his head. The water would recede every time the king tried to take a sip, and the fruit would lift away every time he reached to take a bite.

origin of the emergent light 0++ scalar σ-particle?

if Higgs-like particle of linear σ-model:

$SU(2)\otimes SU(2)\sim O(4)$ for sextet model

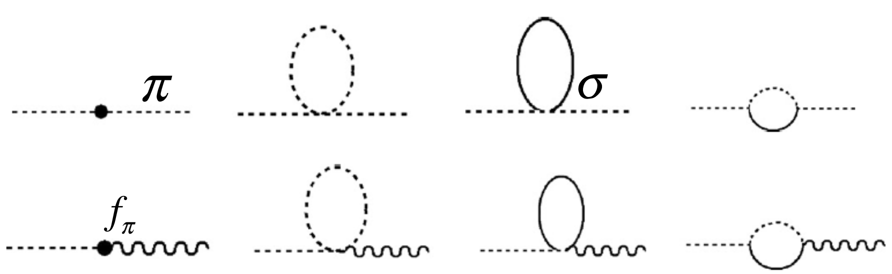
$$L=\frac{1}{2}\left(\partial_\mu\vec{\pi}\right)^2+\frac{1}{2}\left(\partial_\mu\sigma\right)^2-\frac{1}{2}\mu^2\left(\sigma^2+\vec{\pi}^2\right)+\frac{1}{4}g\left(\sigma^2+\vec{\pi}^2\right)^2-\varepsilon\sigma$$

triviality analysis in $m_\sigma/f_\pi < 3$ range
$m_\pi = 0$ circa 1987-1988

$m_\sigma^2 \geq 3m_\pi^2$ tree level relation

$m_\sigma^2 \geq 2m_\pi^2$ with loop corrections

non-linear σ-model → dilaton EFT:

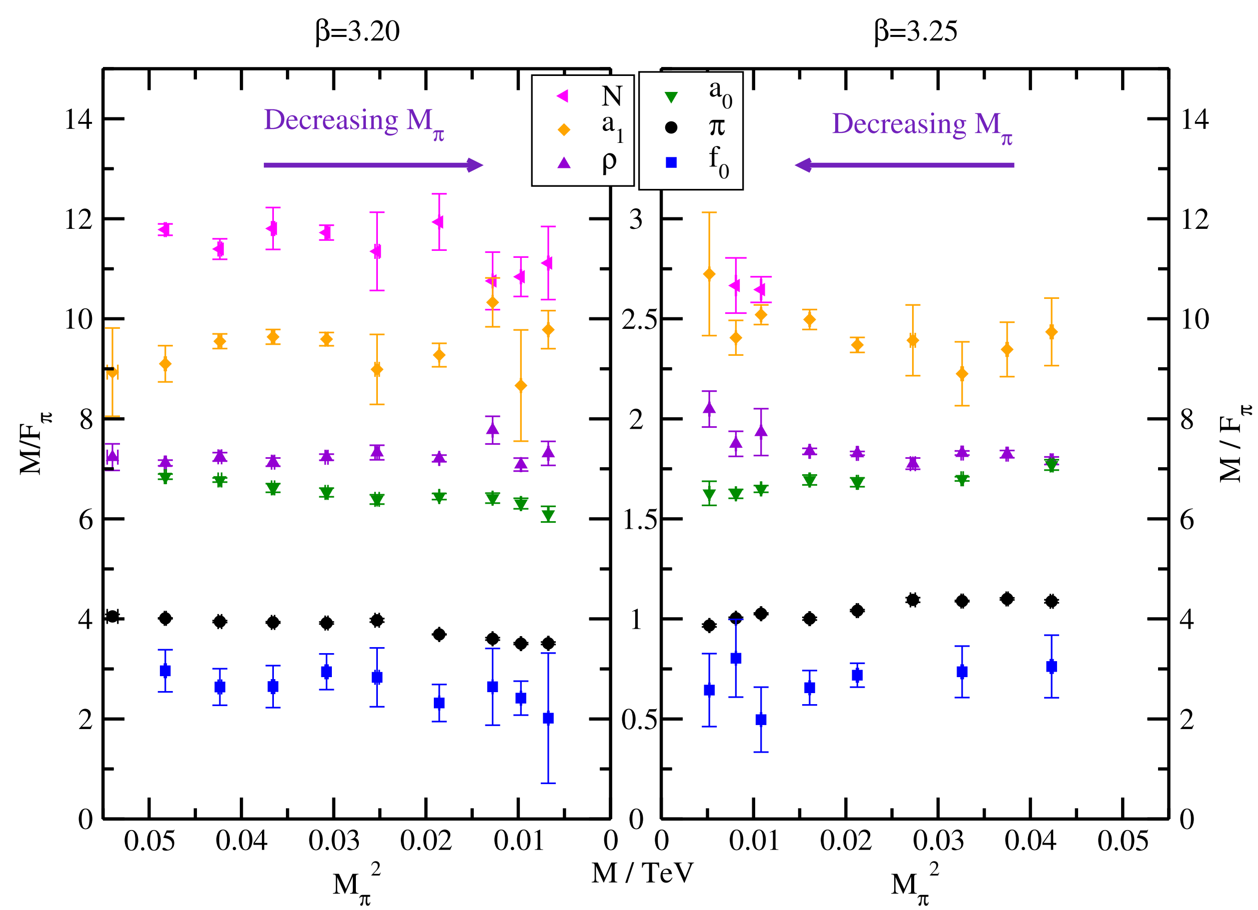


p-regime data: 0++ is tracking the Goldstone pion with $m_\pi^2 \geq m_\sigma^2$, not like linear σ-model
New EFT is needed to extrapolate data to massless chiral limit

$$L=\frac{1}{2}\partial_\mu\sigma\,\partial_\mu\sigma-V(\sigma)+\frac{f_\pi^{\,2}}{4}\left(D_\mu\Sigma^\dagger D_\mu\Sigma\right)\cdot\left(1+2a\frac{\sigma}{f_\pi}+b\frac{\sigma^2}{f_\pi^{\,2}}+b_3\frac{\sigma^{\,3}}{f_\pi^{\,3}}+\ldots\right)$$

$\Sigma=e^{i\pi^a\tau^a/f_\pi}$ with τ^a Pauli matrices

$$V(\sigma)=\frac{1}{2}m_\sigma^2\cdot\sigma^{\,2}+d_3\left(\frac{m_\sigma^2}{2f_\pi}\right)\cdot\sigma^{\,3}+d_4\left(\frac{m_\sigma^2}{8f_\pi^{\,2}}\right)\cdot\sigma^{\,4}+\ldots$$



linear σ-model limit (SM): $a=b=d_3=d_4=1$

dilaton EFT will require $a=b^2$, $b_3=0$ and special y(μ) in L

analyze dilaton EFT first and test if non-linear σ-model limit exists without special anomalous dimension y(M) in L

dilaton EFT with σ(x) dilaton field and π^a(x) Goldstone bosons of sextet flavor doublet:

$$L=\frac{1}{2}\partial_\mu\chi\partial_\mu\chi - V_d(\chi) + \frac{f_\pi^2}{4}\left(\frac{\chi}{f_d}\right)^2 tr\left[\partial_\mu\Sigma^\dagger\partial_\mu\Sigma\right] - \frac{f_\pi^2 m_\pi^2}{4}\left(\frac{\chi}{f_d}\right)^y tr\left(\Sigma+\Sigma^\dagger\right)$$

$y=3-\gamma$ where γ is the mass anomalous dimension

$\chi(x)=f_d\, e^{\sigma(x)/f_d}$ describes the dilaton field $\sigma(x)$

pion field $\Sigma=e^{i\pi^a\tau^a/f_\pi}$ with τ^a Pauli matrices, tree level pion mass $m_\pi^2=2Bm$

literature has long history
Golternan-Shamir
Appelquist et al.
we do our own analysis

Appelquist et al.
notation for comparison

$$V_\sigma=\frac{m_d^2}{2f_d^2}\left(\frac{\chi^2}{2}-\frac{f_d^2}{2}\right)^2$$ relevant deformation of IRFP theory

$$V_d=\frac{m_d^2}{16 f_d^2}\chi^4\left(4\ln\frac{\chi}{f_d}-1\right)$$ nearly marginal deformation

- f_π — Goldstone decay constant
- $m_\pi=2mB$ — Goldstone pions
- f_d — dilaton decay constant
- m_d — dilaton mass

$F_\pi,\ M_\pi,\ F_d\ ,\ M_d$ with mass deformation

$$M_\pi^2\cdot F_\pi^{2-y}-2B_\pi\cdot f_\pi^{(2-y)}\cdot m=0$$ general V indep. scaling law

$$F_\pi^{(4-y)}\cdot(1-f_\pi^2/F_\pi^2)-2y\cdot n_f f_\pi^{(6-y)}B_\pi/m_d^2 f_d^2\cdot m=0 \quad \boxed{V'_\sigma(\chi=F_d)}$$

$$3F_\pi^2/M_\pi^2-f_\pi^2/M_\pi^2-2M_d^2/m_d^2\cdot f_\pi^2/M_\pi^2-y(y-1)n_f f_\pi^4/m_d^2 f_d^2=0 \quad \boxed{V''_\sigma(\chi=F_d)}$$

$$F_\pi^{(4-y)}\cdot\log(F_\pi/f_\pi)-y\cdot n_f f_\pi^{(6-y)}B_\pi\cdot m/m_d^2 f_d^2=0 \quad \boxed{V'_d(\chi=F_d)}$$

$$(F_\pi^2/M_\pi^2)\cdot(3\log(F_\pi/f_\pi)+1)-(M_d^2/m_d^2)\cdot(f_\pi^2/M_\pi^2)-y(y-1)n_f f_\pi^4/2m_d^2 f_d^2=0 \quad \boxed{V''_d(\chi=F_d)}$$

M_π, F_π, M_d input data at each m

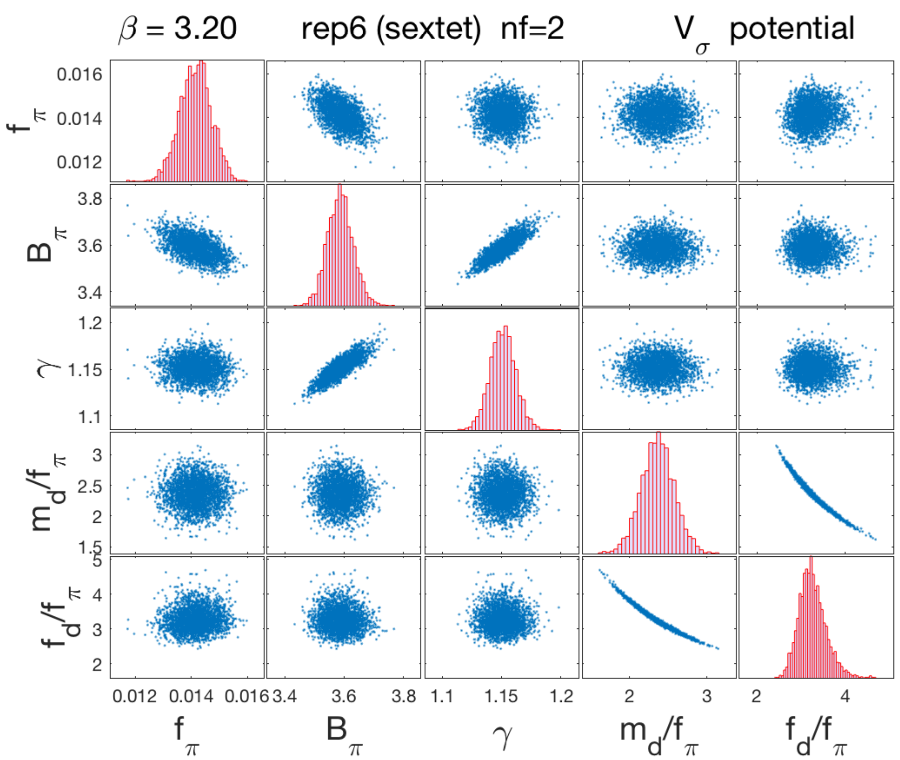
$f_\pi,\ B,\ f_d\ ,\ m_d\ ,\ y$ fitted for all m

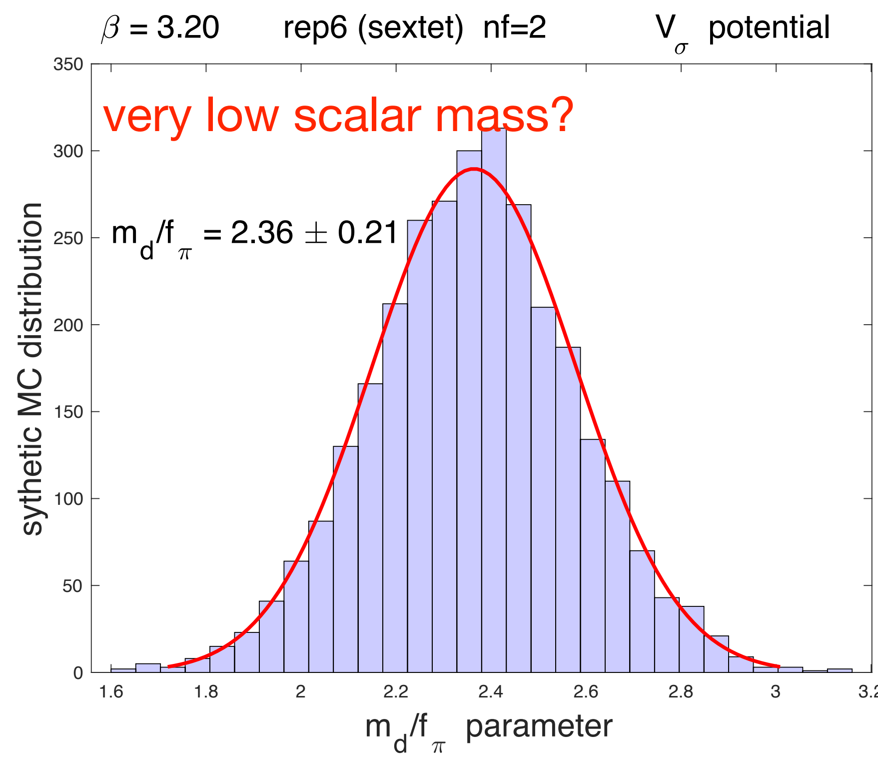
IML: Implicit Maximum Likelihood test

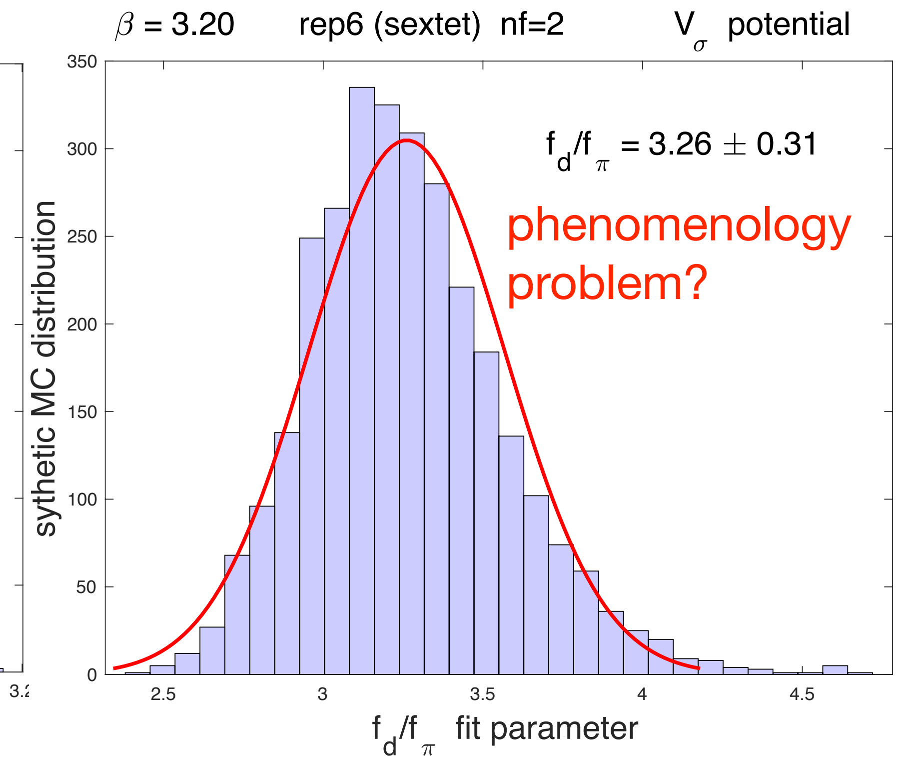
IML is very different from ML fitting

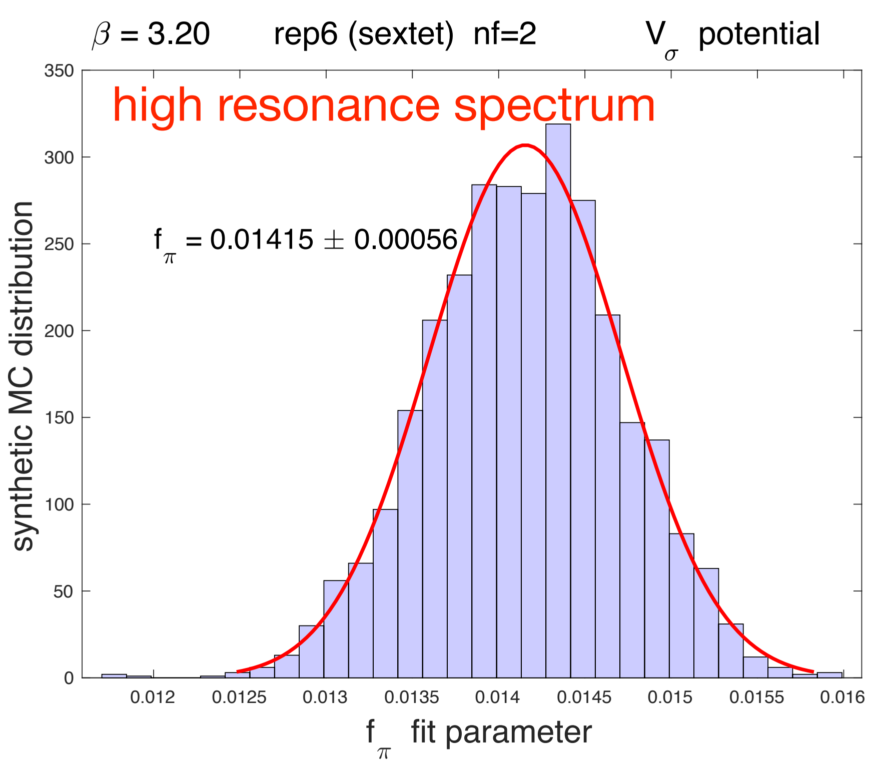
Perfect fits for V_σ!

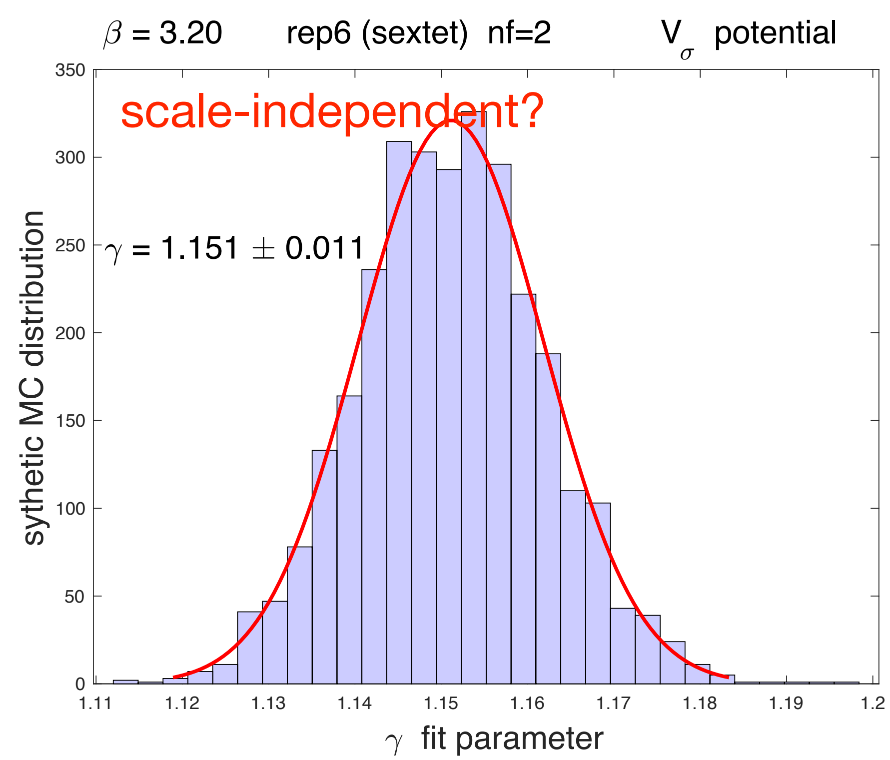
V_d fails!


β = 3.20 rep6 (sextet) nf=2 V_σ potential
f_π
B_π
γ
m_d/f_π
f_d/f_π


β = 3.20 rep6 (sextet) nf=2 V_σ potential
very low scalar mass?
m_d/f_π = 2.36 ± 0.21
sythetic MC distribution
m_d/f_π parameter

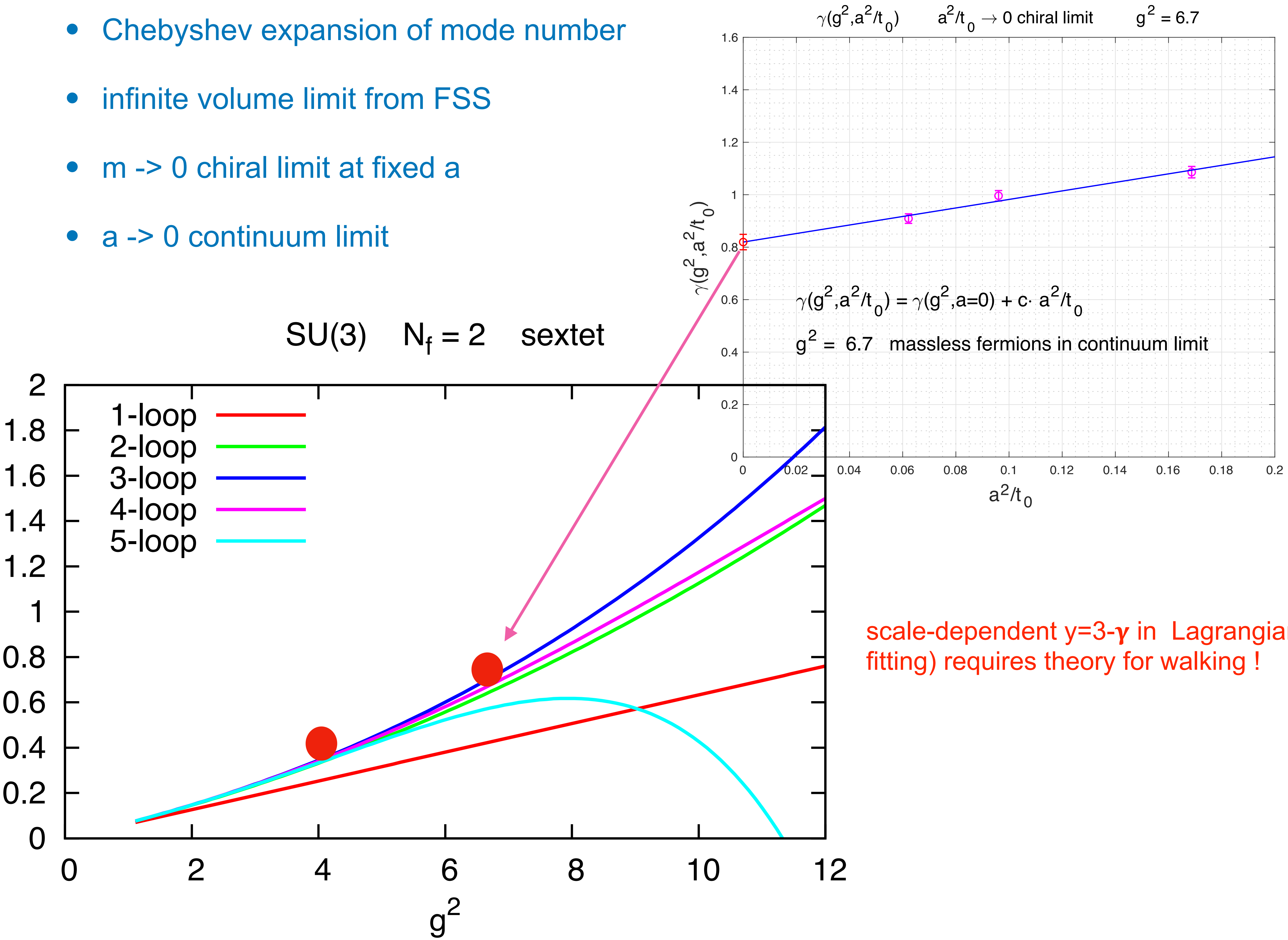

β = 3.20 rep6 (sextet) nf=2 V_σ potential
f_d/f_π = 3.26 ± 0.31
phenomenology
problem?
sythetic MC distribution
f_d/f_π fit parameter


β = 3.20 rep6 (sextet) nf=2 V_σ potential
high resonance spectrum
f_π = 0.01415 ± 0.00056
synthetic MC distribution
f_π fit parameter

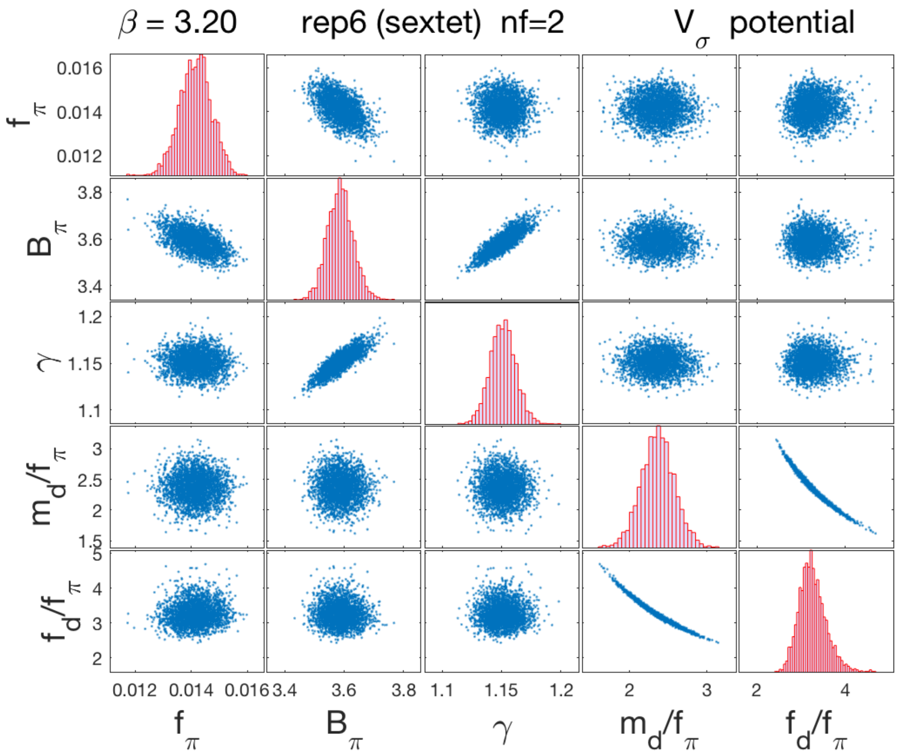

β = 3.20 rep6 (sextet) nf=2 V_σ potential
scale-independent?
γ = 1.151 ± 0.011
synthetic MC distribution
γ fit parameter

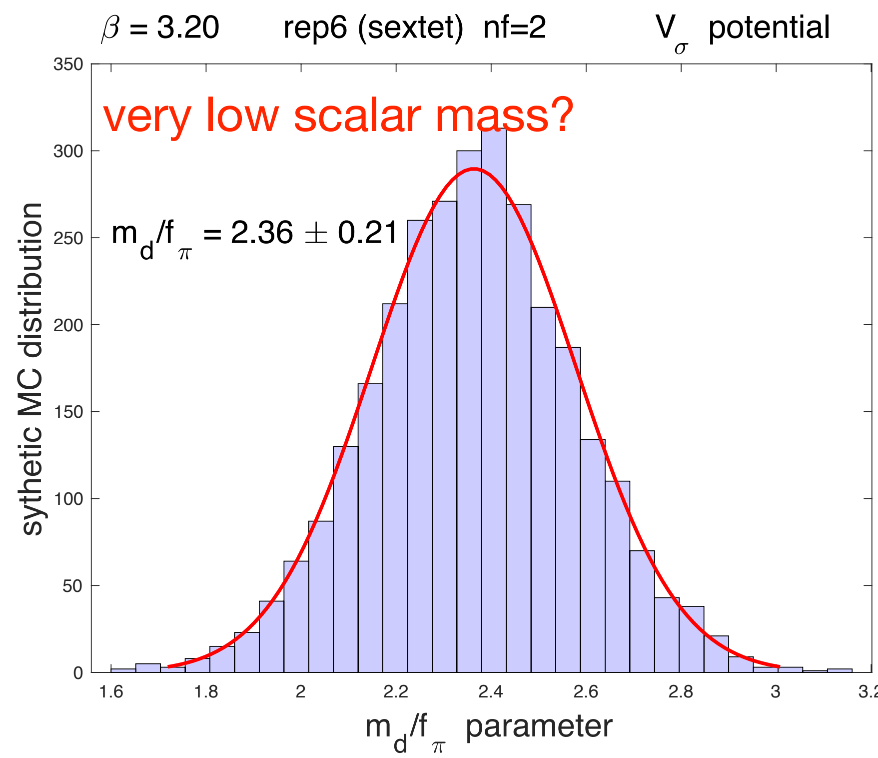
scale dep. anomalous dimension γ from Dirac spectrum: sextet data

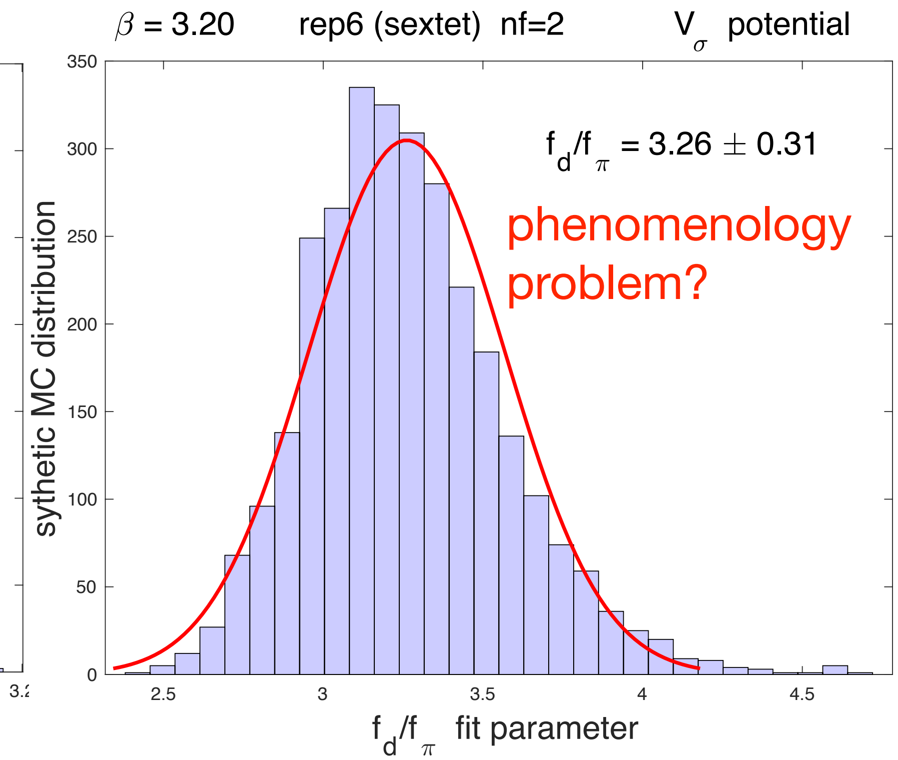
- Chebyshev expansion of mode number
- infinite volume limit from FSS
- m -> 0 chiral limit at fixed a
- a -> 0 continuum limit

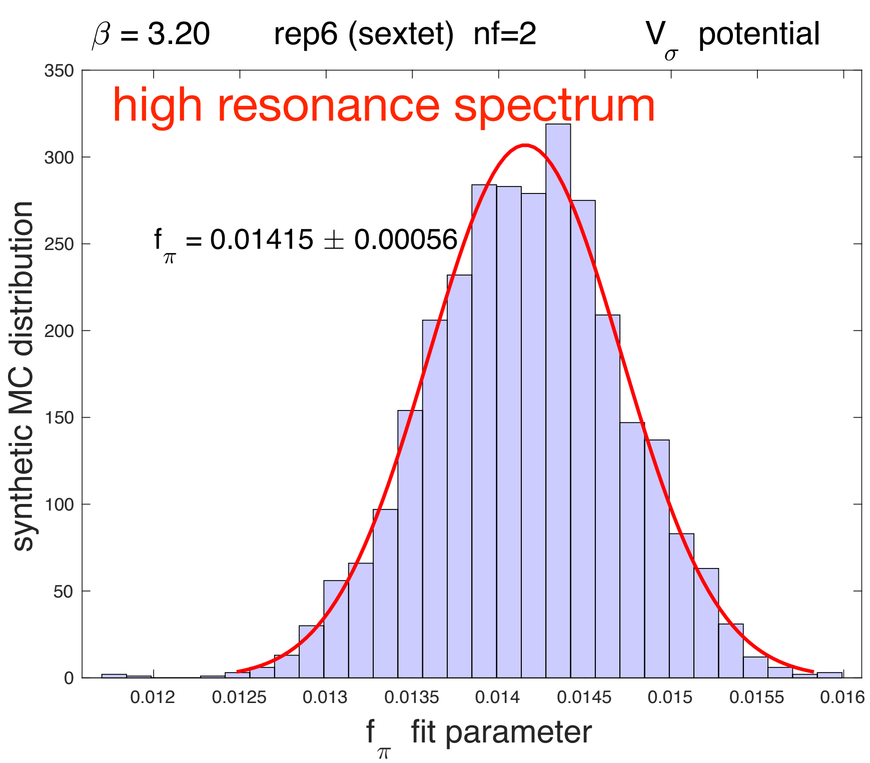


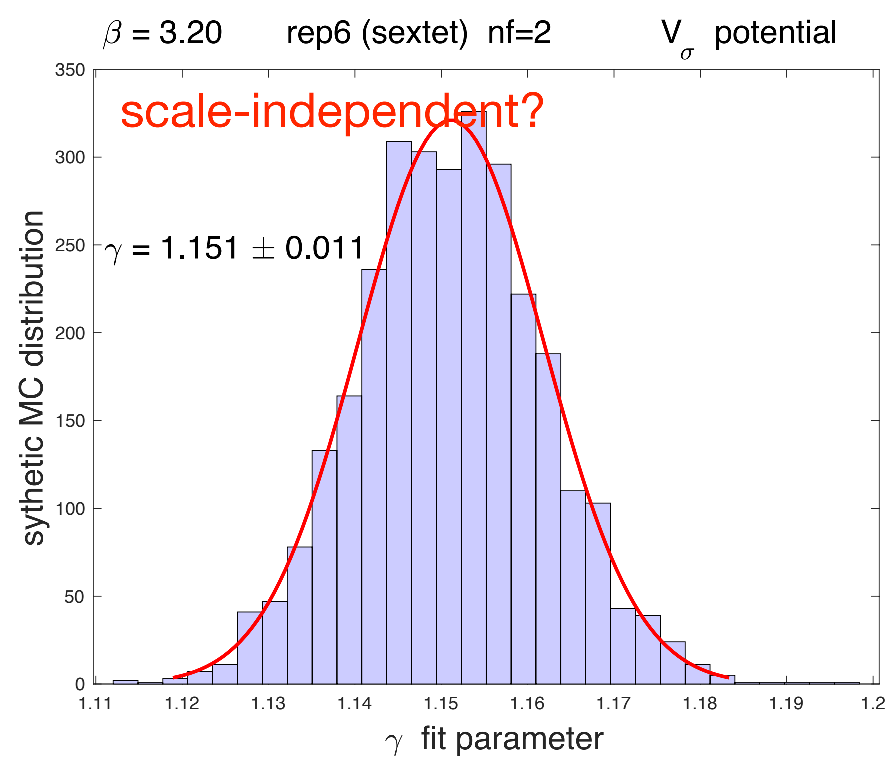
scale-dependent y=3-**γ** in Lagrangian (and in fitting) requires theory for walking !











- the dilaton potential of Shamir-Golterman as tree level theory expanding around IRFP is inconsistent
- similar conclusion at nf=8 and one lattice spacing
- consistent LatHC analysis for two lattice spacing, with third under construction
- only m_d/f_π is sensitive to scalar mass input

beyond tree-level analysis requires two orders of magnitude drop in fermion mass: switch from p-regime to epsilon regime and related RMT

epsilon regime and RMT

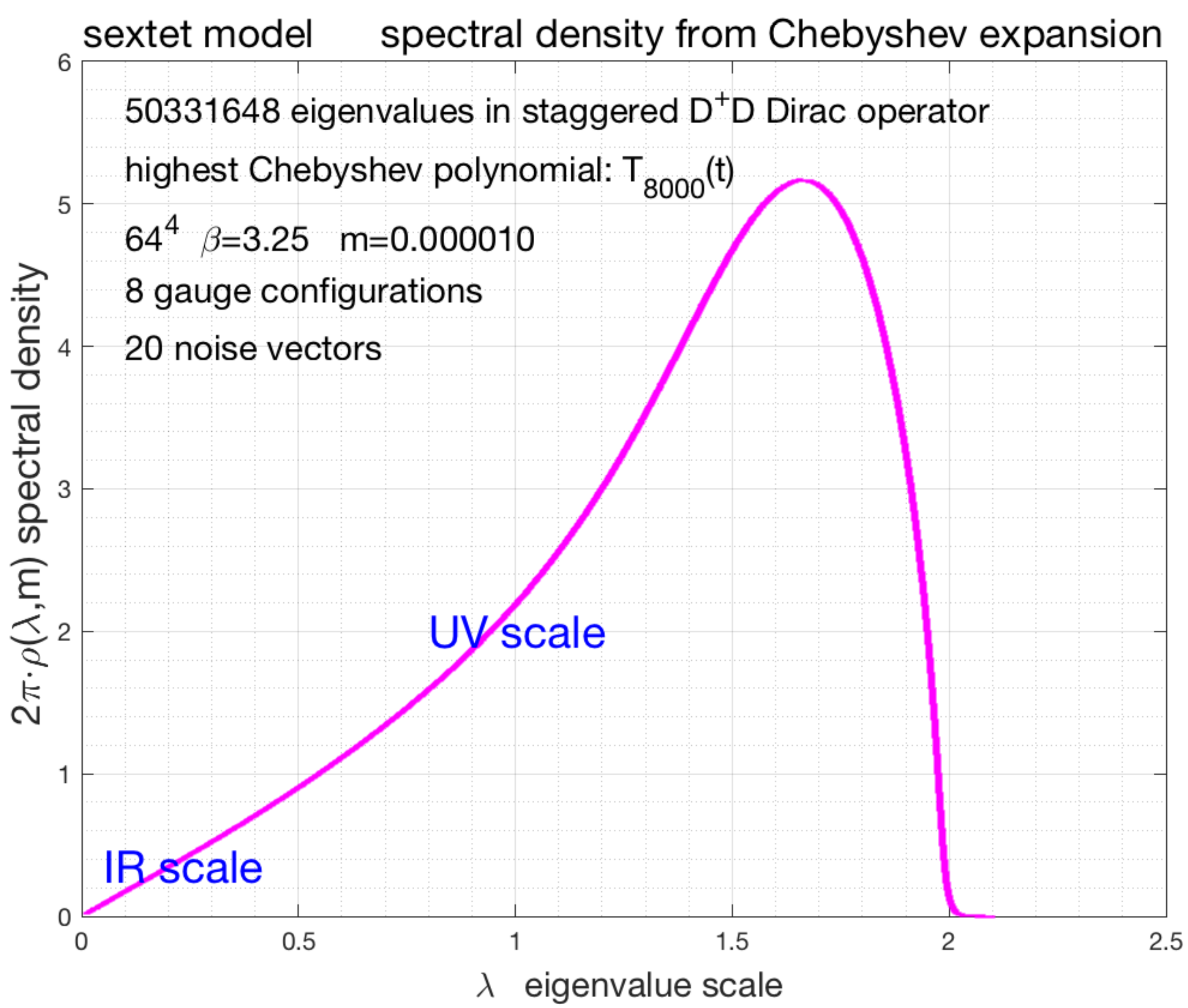
$$\mathcal{L}_\varepsilon = \frac{1}{2}\partial_\mu\chi\partial_\mu\chi - V_d(\chi) + \frac{m_\pi^2 f_\pi^2}{4}\left(\frac{\chi}{f_d}\right)^y \mathrm{tr}\left[\Sigma_0 + \Sigma_0^\dagger\right]$$

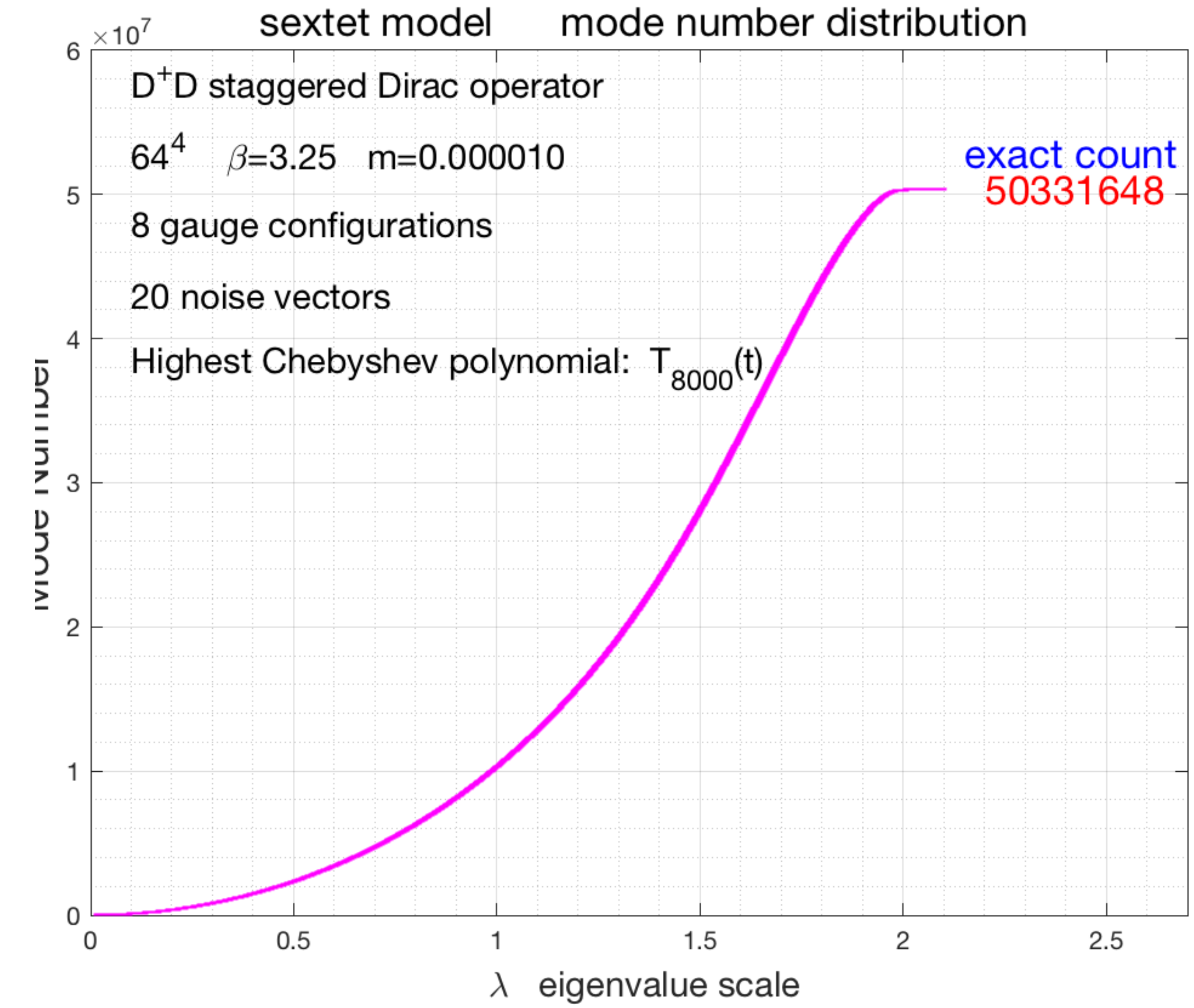
epsilon regime with very small fermion mass deformation

$$\mathcal{L}_\delta = \frac{1}{2}\partial_\mu\chi\partial_\mu\chi - V(\chi) + \frac{f_\pi^2}{4}\left(\frac{\chi}{f_d}\right)^2 \mathrm{tr}\left[\partial_t\Sigma_0\ \partial_t\Sigma_0^\dagger\right]$$

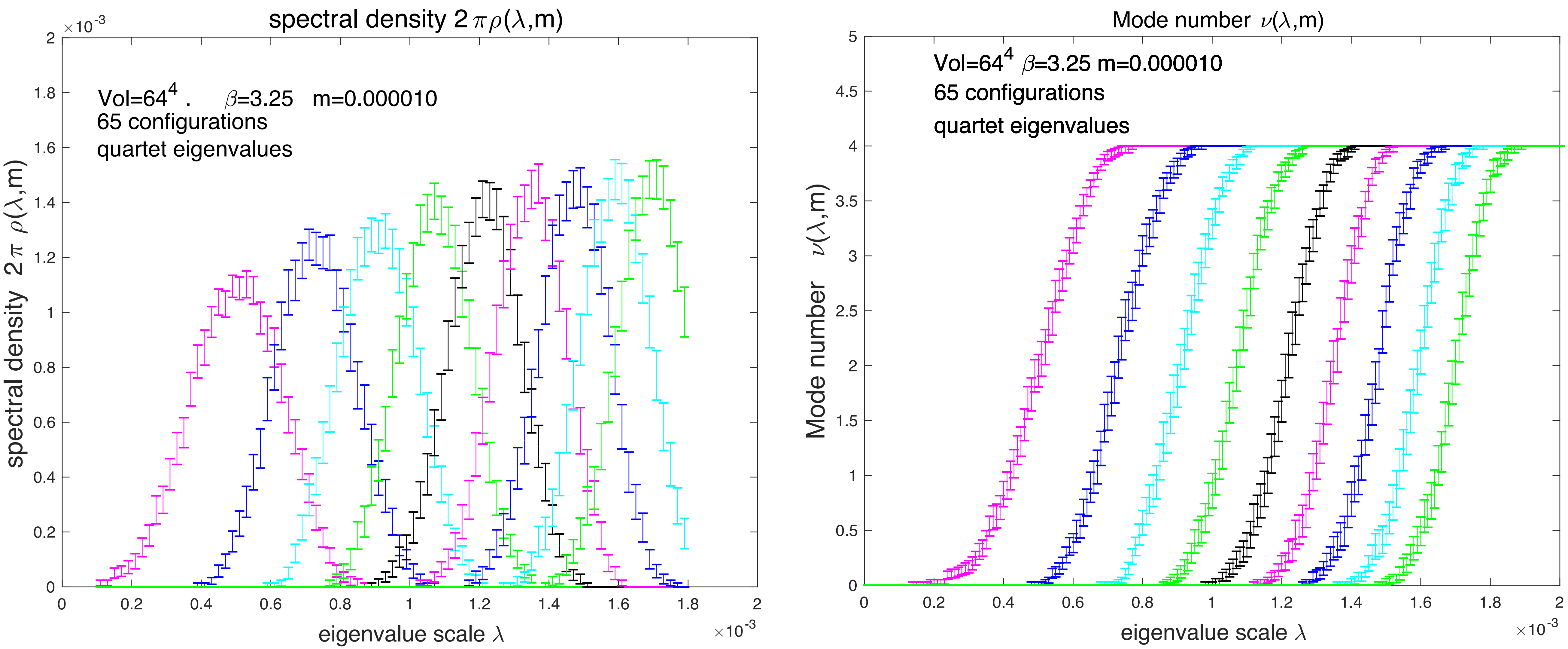
delta regime m=0
very small fermion mass deformation can be added

new ensembles at equivalent p-regime pion mass Mpi ~ 100 and size volume 64^4





epsilon regime and RMT



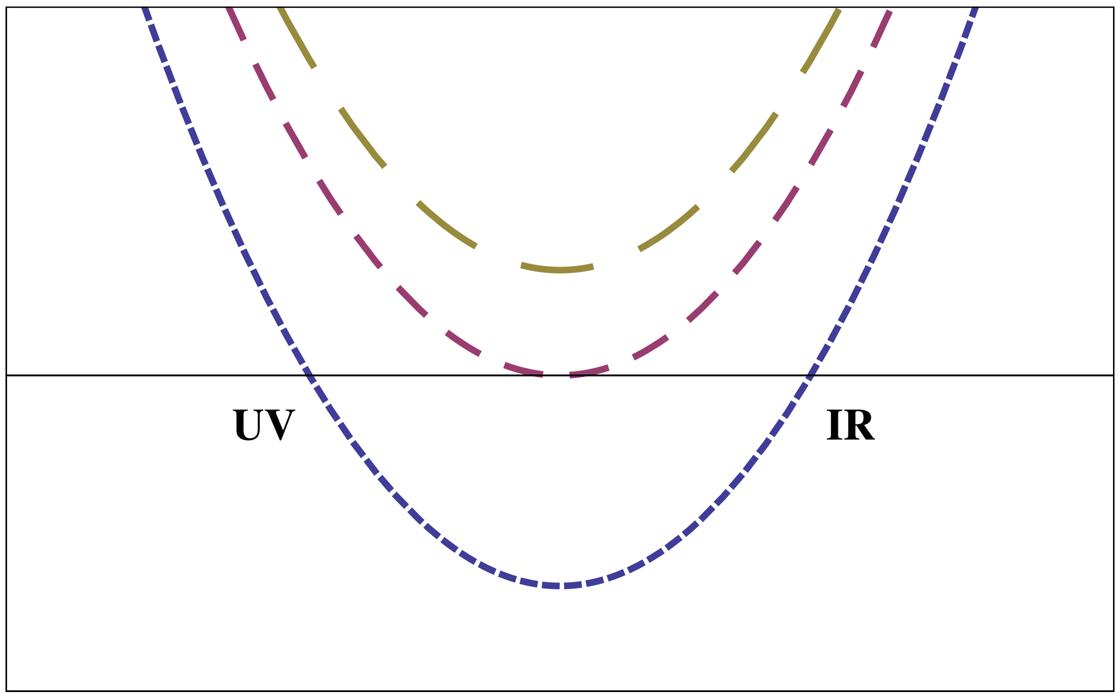
successful testing

ongoing analysis (preliminary results not shown)

we exhausted our current gpu allocation

walking and complex CFT

PHYSICAL REVIEW D **82,** 045013 (2010) Luca Vecchi 2010



$$\mathcal{L}_{\mathrm{CFT}} + \frac{f}{2}\mathcal{O}^{\dagger}_{ij}\mathcal{O}^{ij}$$

$$\Lambda \frac{d\bar{f}}{d\Lambda} = v\bar{f}^2 + (2\Delta - d)\bar{f} + a$$

$$\beta'_{\bar{f}}|_{\pm} = \pm 2\sqrt{D}$$

$$\Delta_{\pm} = \frac{d}{2} \pm \sqrt{D}$$

walking and complex CFT new paradigm?
flavor symmetry group is the same for walker and the CFT!

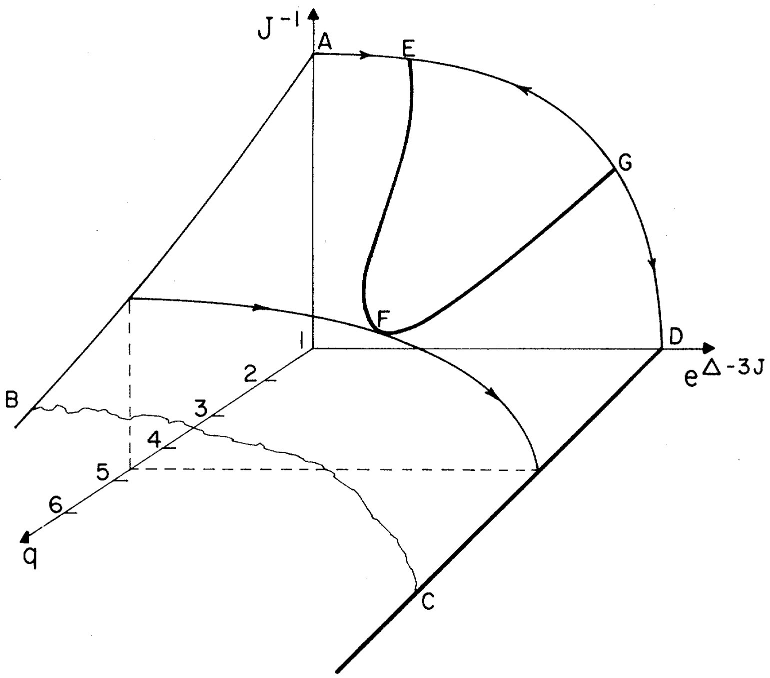
we started work earlier on the realization of walking based on this idea

to distinguish near-conformal and conformal finite volume correlators (drifting scaling exponents distinguished from fixed conformal exponents).
we ran into difficulty not knowing the conformal exponents of the complex theory.

Rychkov et al. turned to a two-dimensional example (Potts model) for very detailed realization without apparently knowing about Vecchi

We ask now: can we realize on the lattice Potts conformal field theories for continuous Q (flavor)

walking and complex CFT



Potts model   Q potts spin ~ flavor
described by CFT

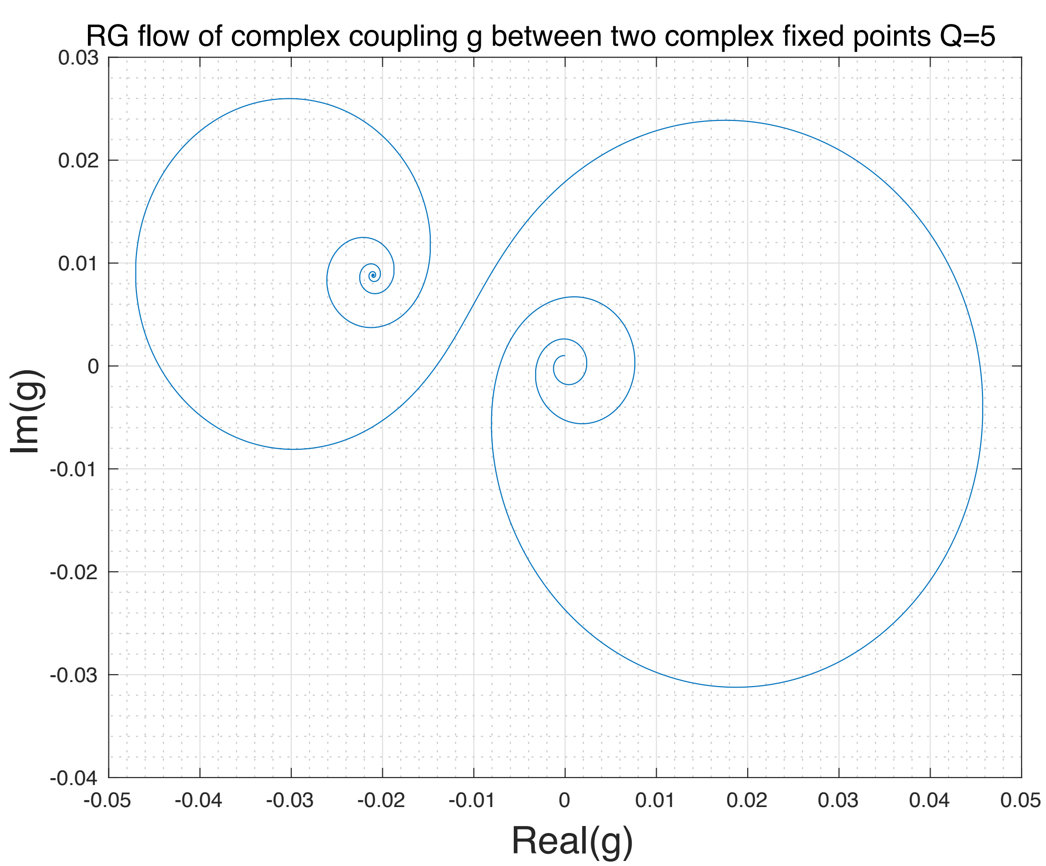
Q=2 - 4 pair of real CFT with pair of zeros of the beta function works for continuous Q in cluster rep

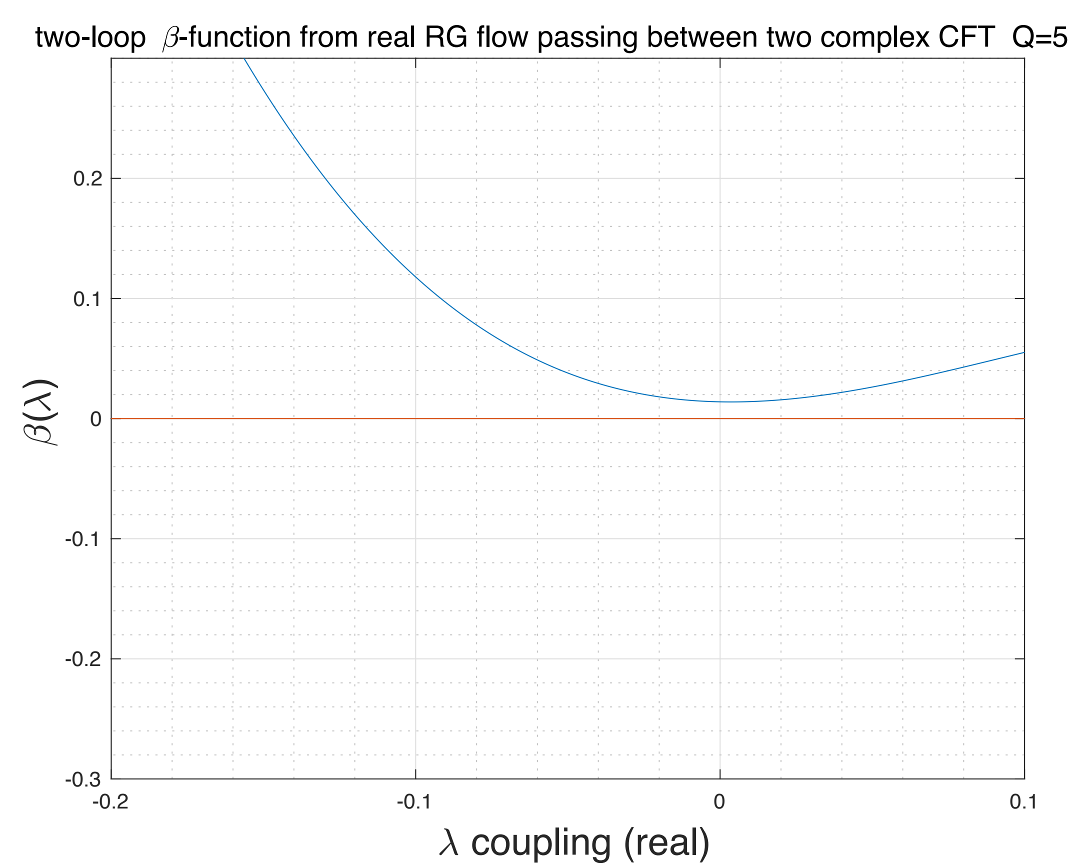
Q > 4 complex CFT, like Q=5, 6, 7 …

What was identified before as Q=5 Potts is near-conformal and walking, supported by the complex pair, not critical in very well defined sense

We have very efficient CUDA code working on lattice realization of the complex CFT paradigm

more in my BSM workshop talk





Thank you