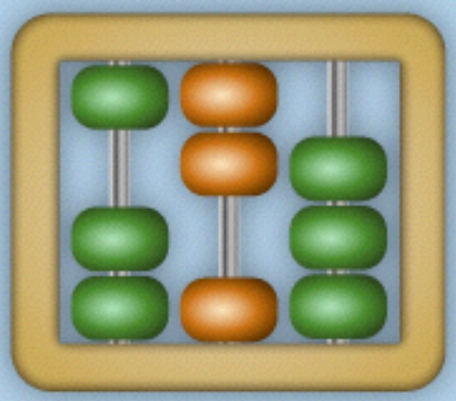


Lattice 2016

Near-conformal composite Higgs

or PNGB with partial compositeness?

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

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

Julius Kuti

University of California, San Diego

34th International Symposium on Lattice Field Theory, 24-30 July 2016

What is our composite Higgs paradigm?

the Higgs doublet field — elementary scalar?

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

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

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 in flavor/color space:

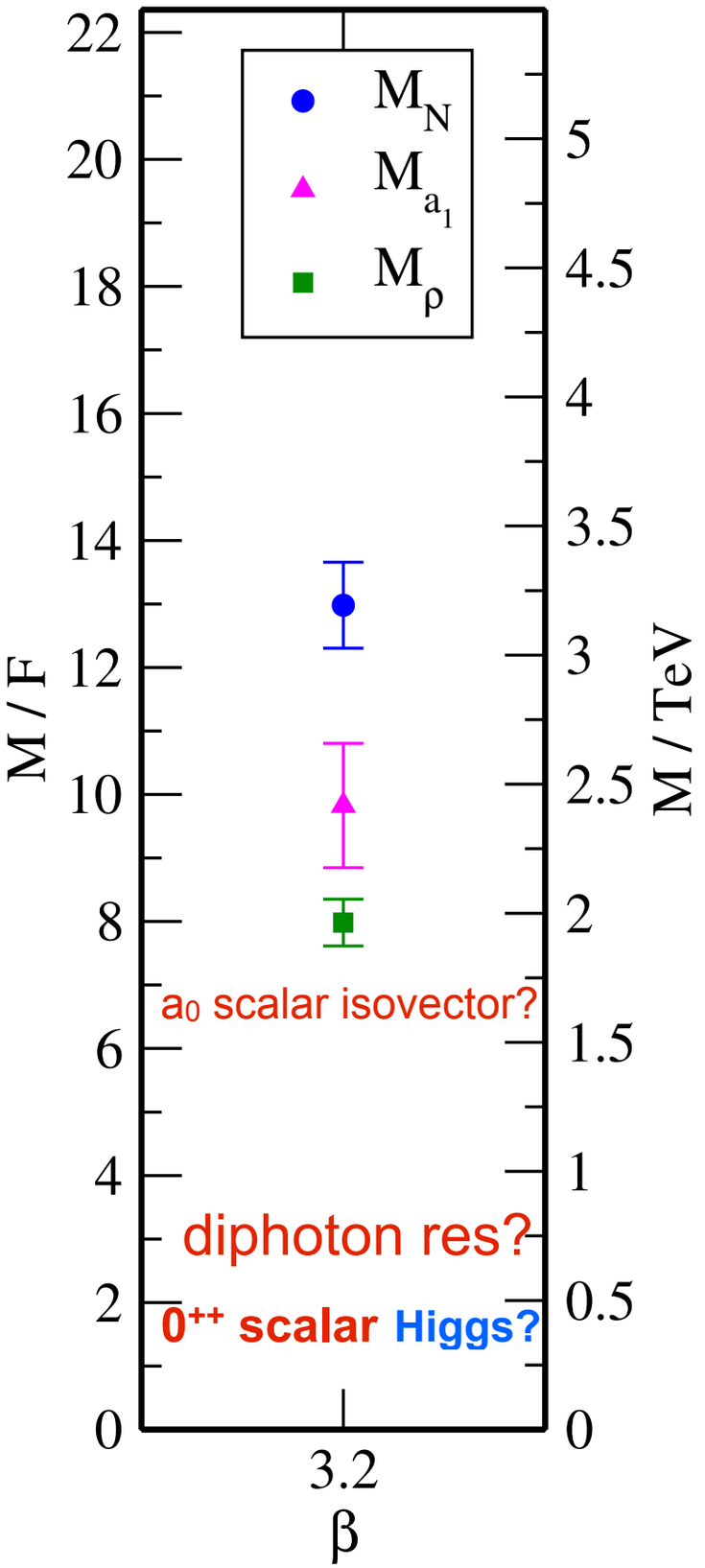
$$\mathcal{L}_{Higgs} \to -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{Q}\gamma_\mu D^\mu Q + \ldots$$

light scalar separated from 2-3 TeV resonance spectrum

unlike QCD

requires BSM field theory tools for LHC apps in semi-realistic setting

unlike QCD



BSM lattice challenges

We want to understand:

light scalar separated from 2-3 TeV resonance spectrum

multiple scalars in models close to CW?

Resonance spectrum?

what is the eta'?

entangled scalar-goldstone dynamics sigma model or dilaton?
how to decouple and isolate the light scalar?

bridge between UV and IR scale?
scale-dependent gauge coupling - high precision

predictions without UV completions?
related phenomenology

consistent EW embedding → dark matter

BSM needs new lattice tools → RMT, ππ-scattering, …

scaled up QCD cannot do the job

The light 0++ scalar not scaled up QCD!

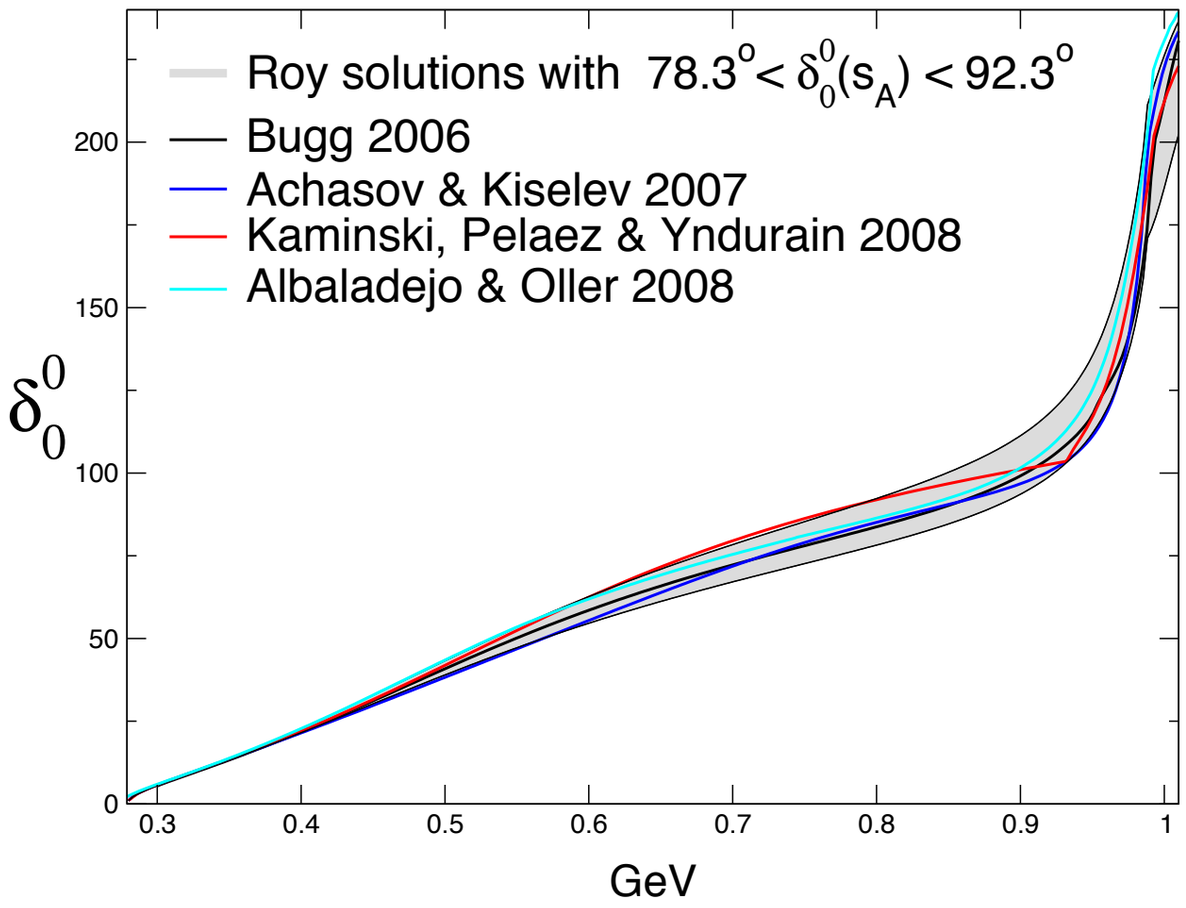
the failure of old Higgs-less technicolor:

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

in Particle Data Book

$$\sqrt{s_\sigma} = (400 - 1200) - i\,(250 - 500)\ \text{MeV}$$

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



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

Leutwyler:
dispersion theory combined with ChiPT

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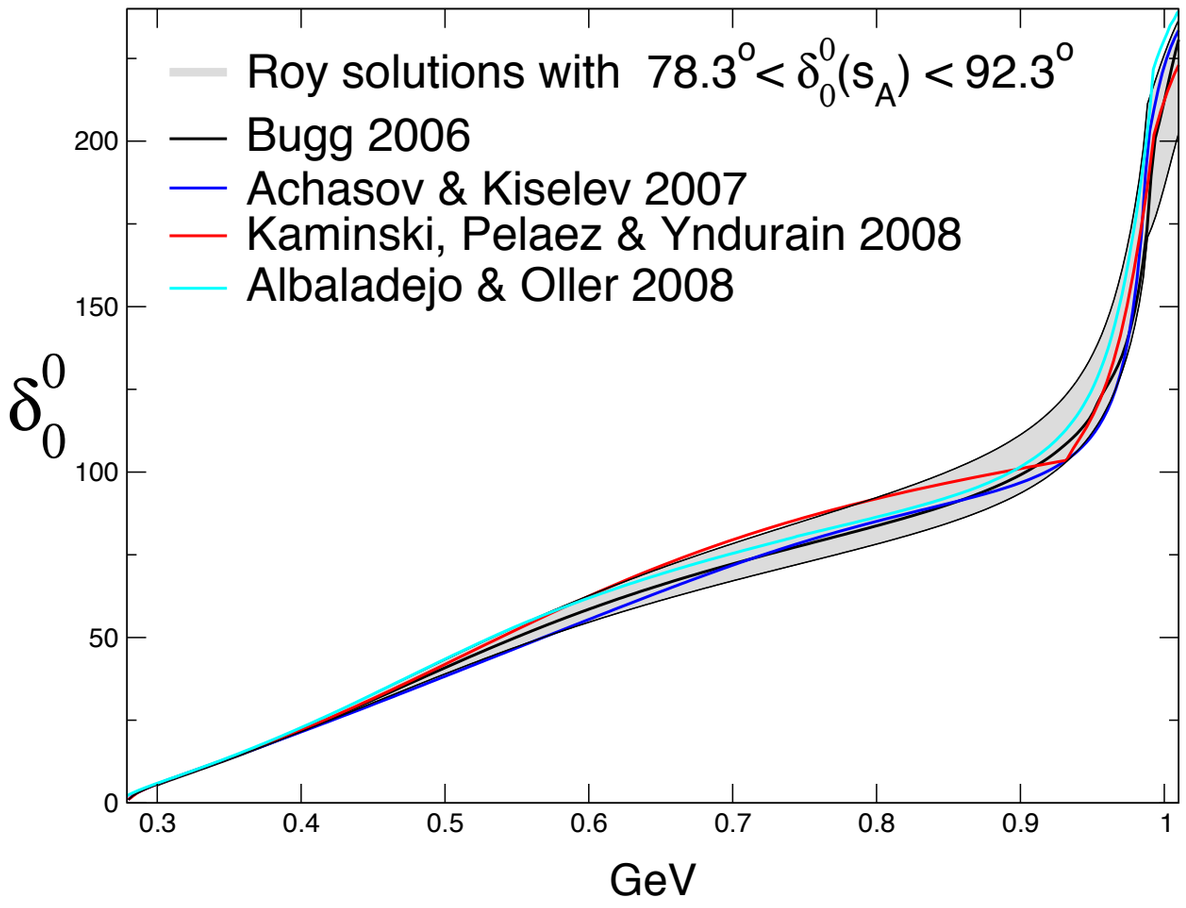

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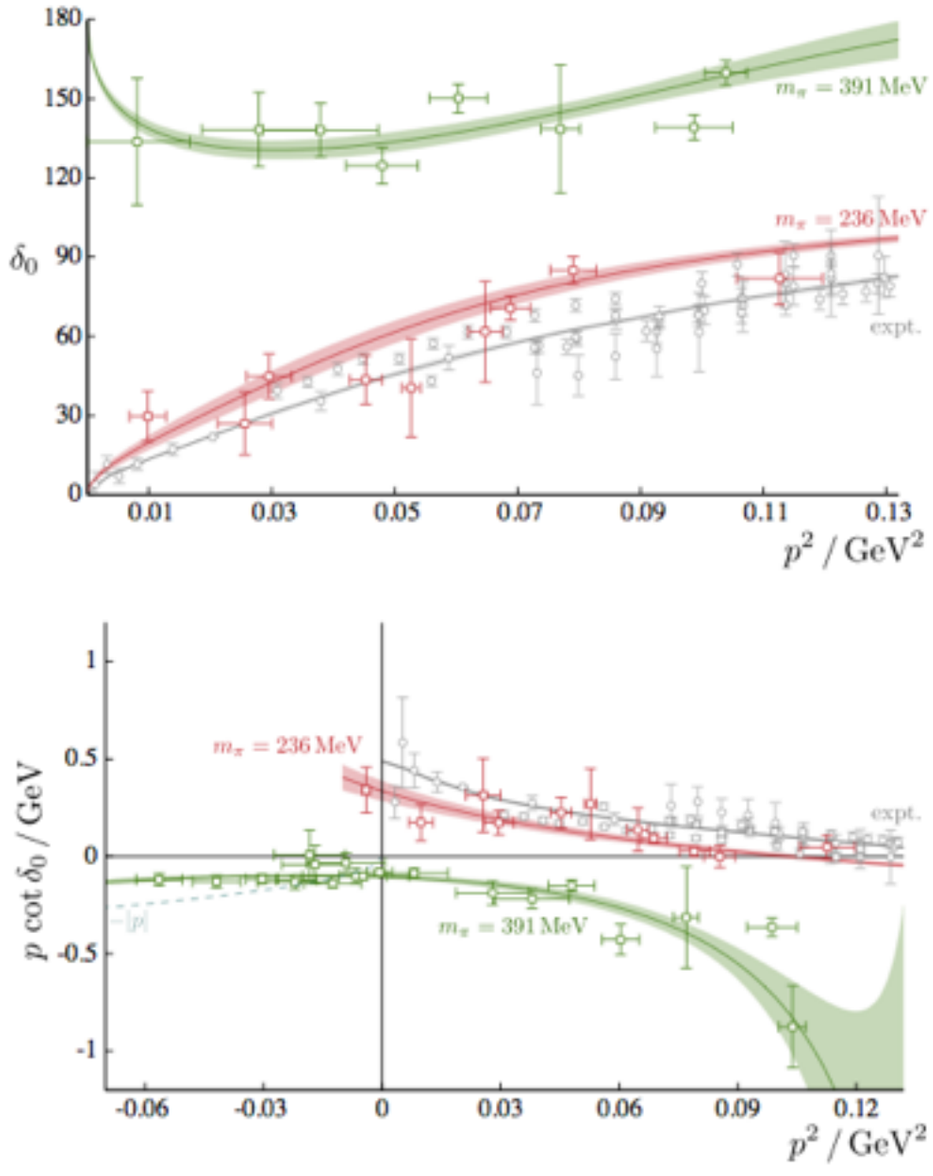
Isoscalar $\pi\pi$ scattering and the σ meson resonance from QCD

Raul A. Briceño,[1,2,*] Jozef J. Dudek,[1,2,†] Robert G. Edwards,[1,‡] and David J. Wilson[3,§]
(for the Hadron Spectrum Collaboration)



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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

Light scalar mass renormalizes F!
Will require new low energy effective action need to work in the Higgs mechanism and coupling to top loop

Isoscalar $\pi\pi$ scattering and the σ meson resonance from QCD

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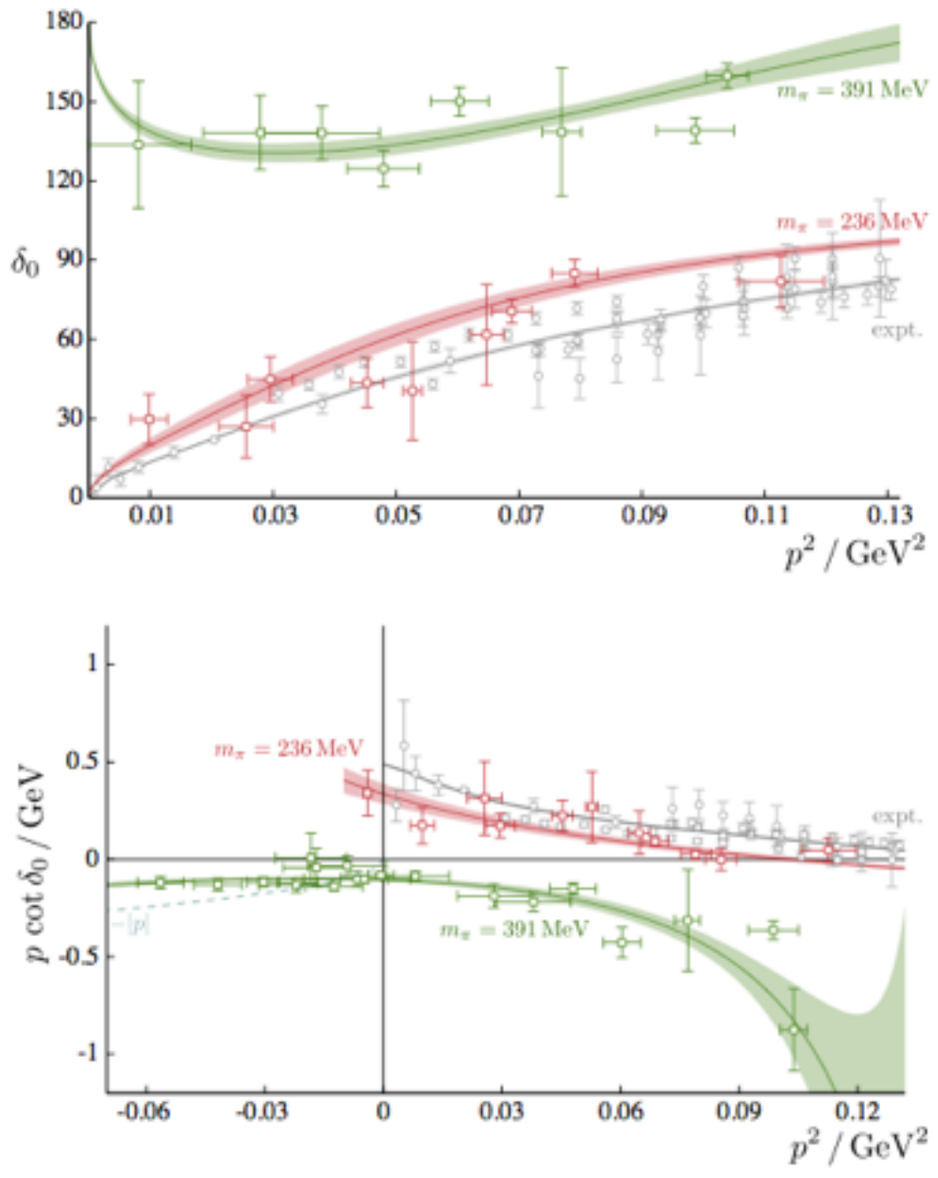
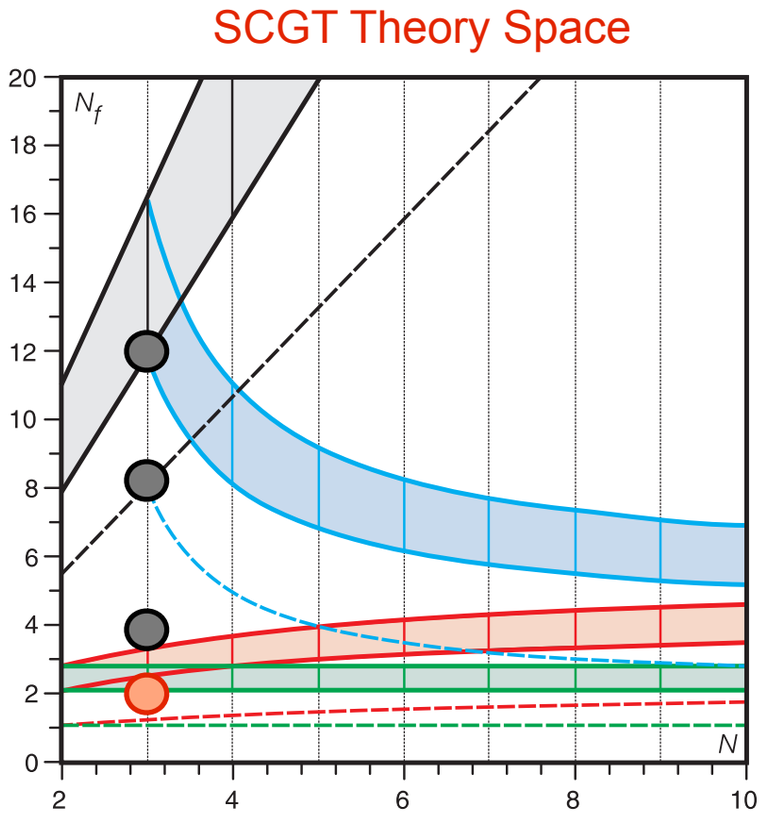


4 lattice BSM theories with light scalars and SU(3) color:



sextet from haystack:
Marciano in QCD
Sannino and Tuominen BS

early lattice work:
Boulder/Tel Aviv
LatHC (also Kogut-Sinclair)
some recent CP^3 work

Nf = 4+4 and Nf=4+8 are popular in fundamental rep: LatKMI and LSD
talks at this conference

Near the conformal window?

- β-function
- mass of the light composite scalar

Tag *minimal* for the sextet model?
gauge group is SU(3) and may need fermion doublets in UV completion

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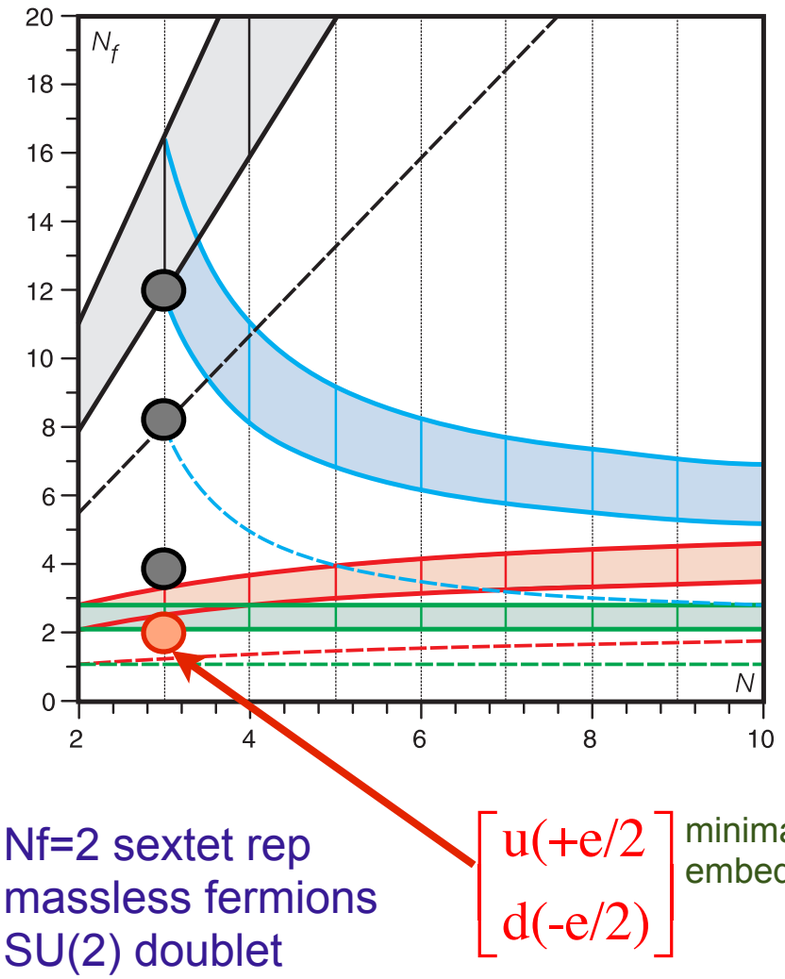

Nf=2 sextet rep
massless fermions
SU(2) doublet
3 Goldstones > weak bosons
minimal realization of Higgs mechanism
adding lepton doublets is a choice
adding EW singlet massive flavor
is also a choice

QCD intuition for near-conformal compositeness is 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

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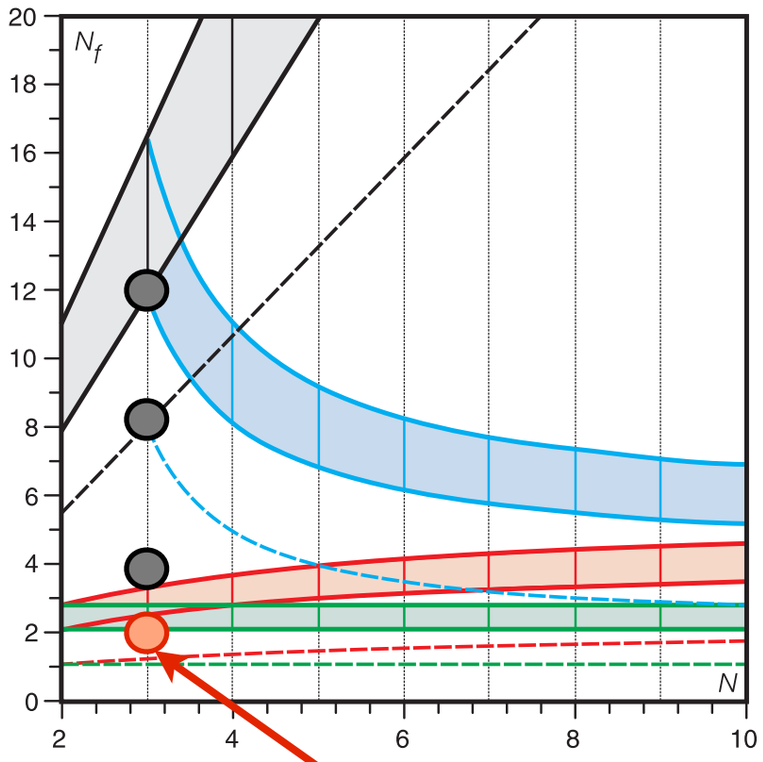

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$\begin{bmatrix} u(+e/2 \\ d(-e/2) \end{bmatrix}$ minimal EW embedding

$\begin{bmatrix} u(+2/3) \\ d(-1/3) \end{bmatrix}$

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4 lattice BSM theories with light scalars and SU(3) color:

our homework assignments:

Conformal:

Exhibit zero in beta function

measure the scaling violation exponent ω

show that mass deformed spectroscopy works including conformal scaling violation

Chiral Symmetry Breaking:

Show that $F \cdot L \sim \sqrt{Nf}$

drive the running coupling g(L) into this volume
this excludes then any zeros in the beta function

decouple light scalar in p-regime PT and
drive to epsilon regime and RMT

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before we get carried away with BSM:

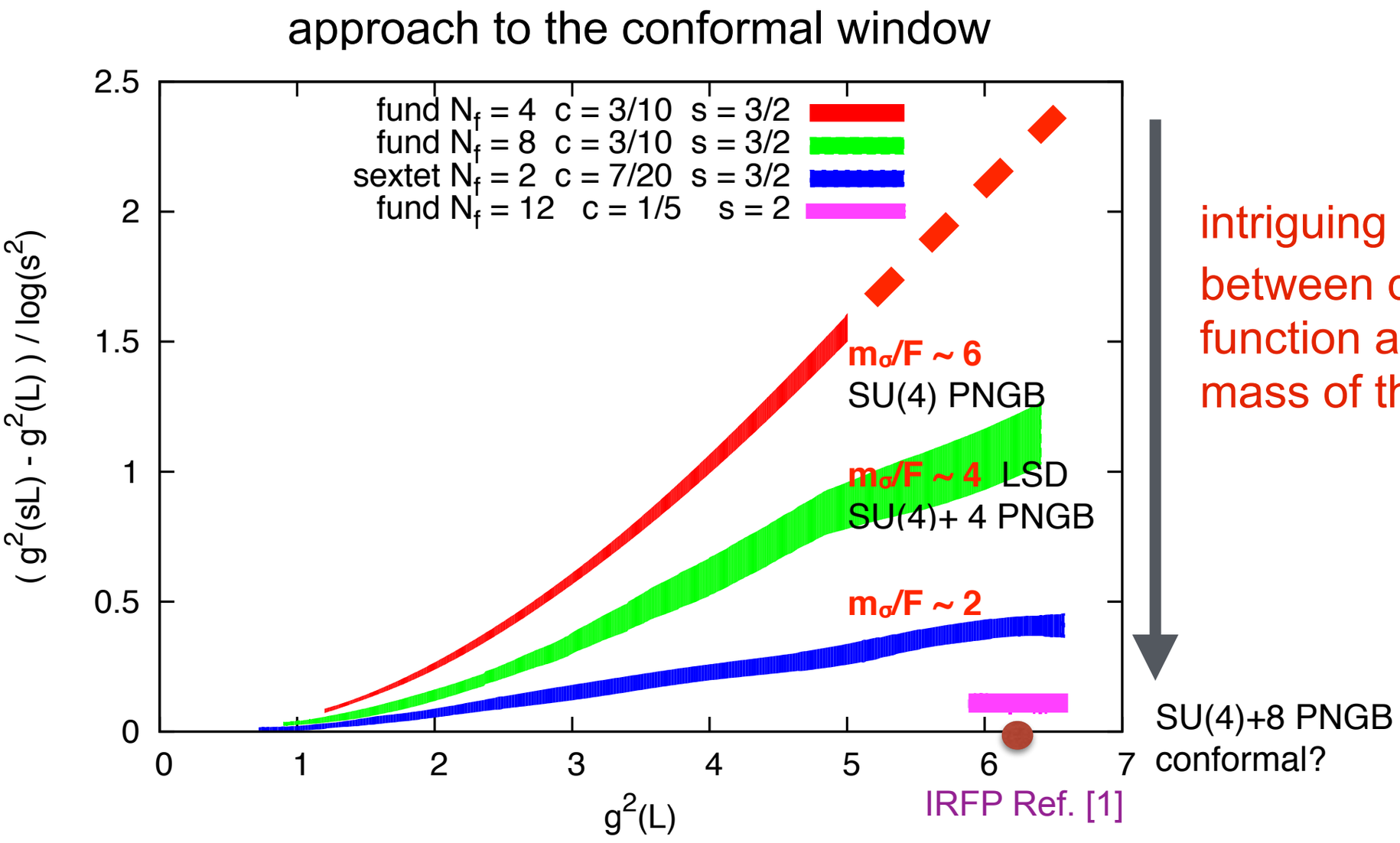
I come to bury Caesar, not to praise him.

(spoken by Marc Antony)

4 lattice BSM theories with light scalars and SU(3) color:

scale-dependent coupling of the 4 lattice BSM models

gradient flow method with high accuracy



intriguing correlation between decreasing beta-function and decreasing mass of the light scalar

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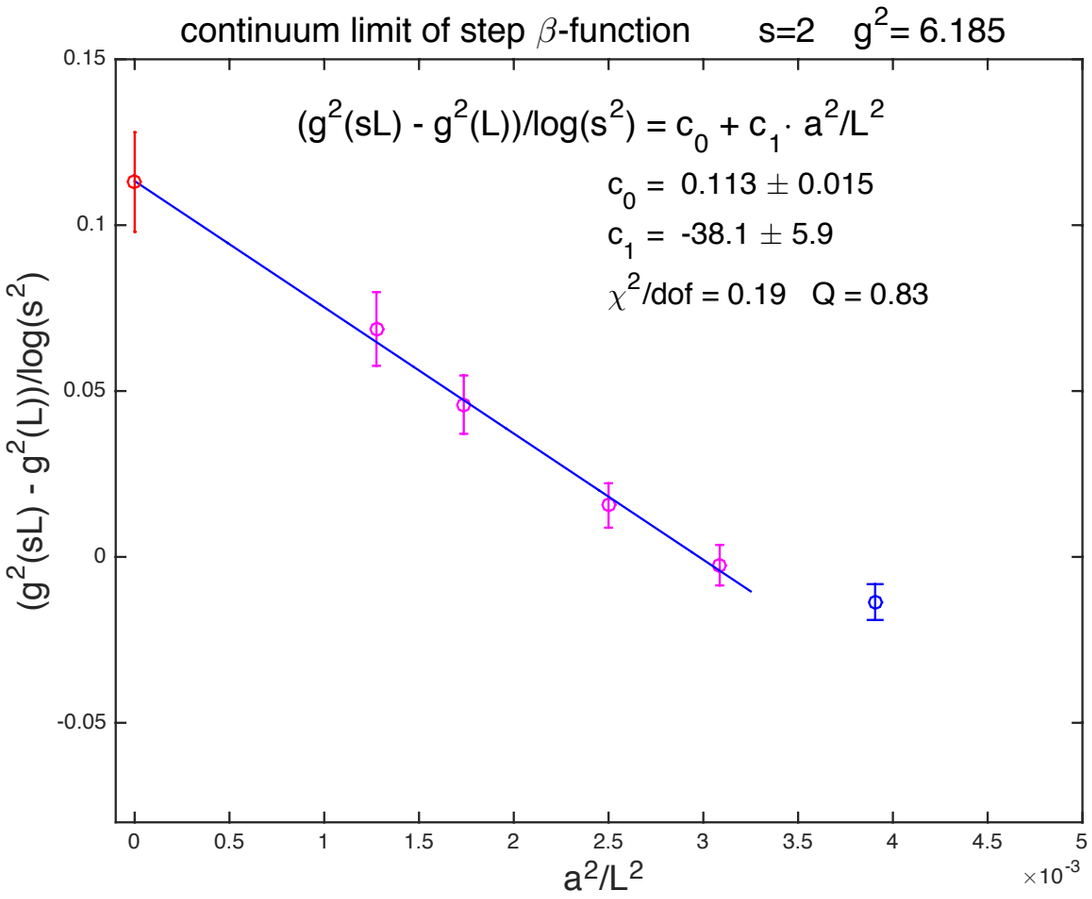
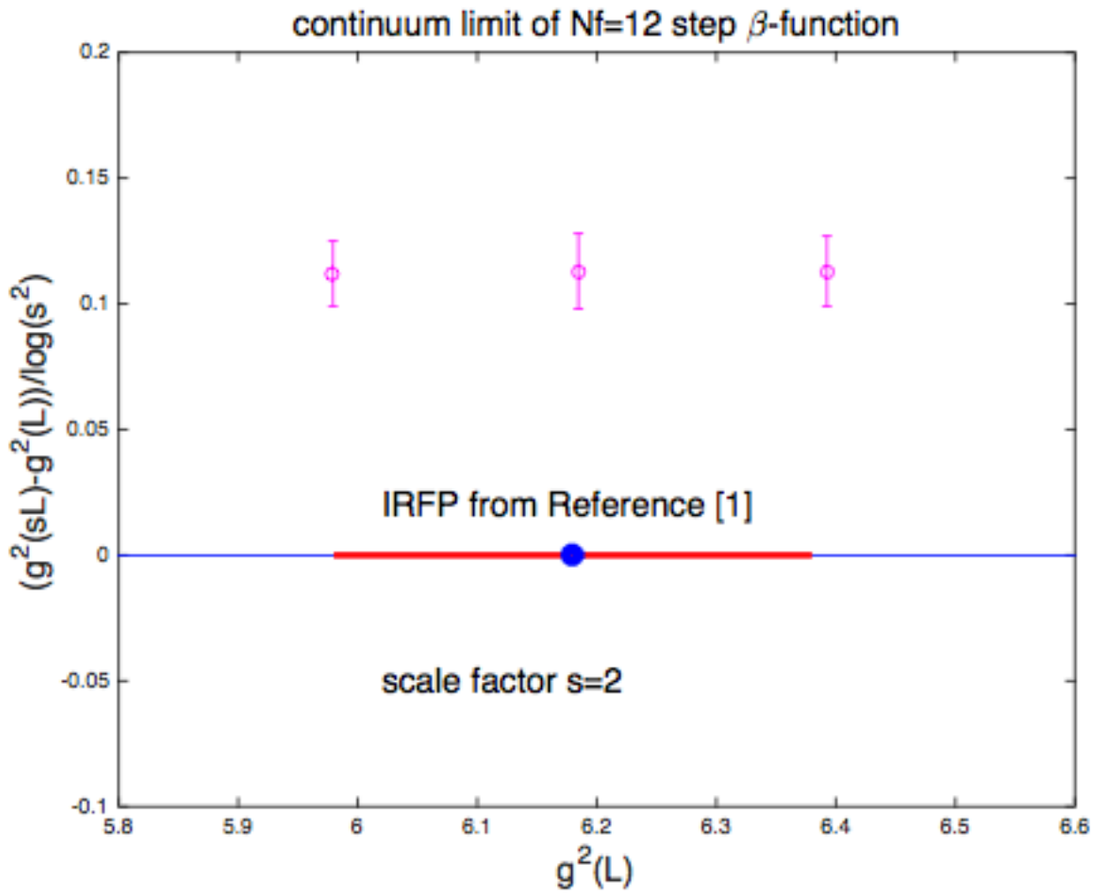




could be near-conformal but no IRFP

in our new Nf=12 work: Dani Nogradi Tue 14:00 BSM Bldg. 67 Room 1027

- interpolations is eliminated by tuned targeting in the previously published range in Ref. 1 of our paper
- statistics with per mille accuracy in the renormalized coupling
- large volumes are used for correct continuum extrapolation

4 lattice BSM theories with light scalars and SU(3) color:

Comparing near conformal light Higgs and PNGB with partial compositeness
two USQCD directions

Nf=4

SU(4)⊗SU(4)→SU(4)
massless fermions chiSB
rotated vacuum
with EW quantum numbers

zero mass PNGB (composite Higgs)

will require intriguing and complicated dynamics
with consistency requirements
is the focus on PNGB or light σ-like scalar?

Nf =4 added

to make partial compositeness work with large anomalous dimension for baryon operator:

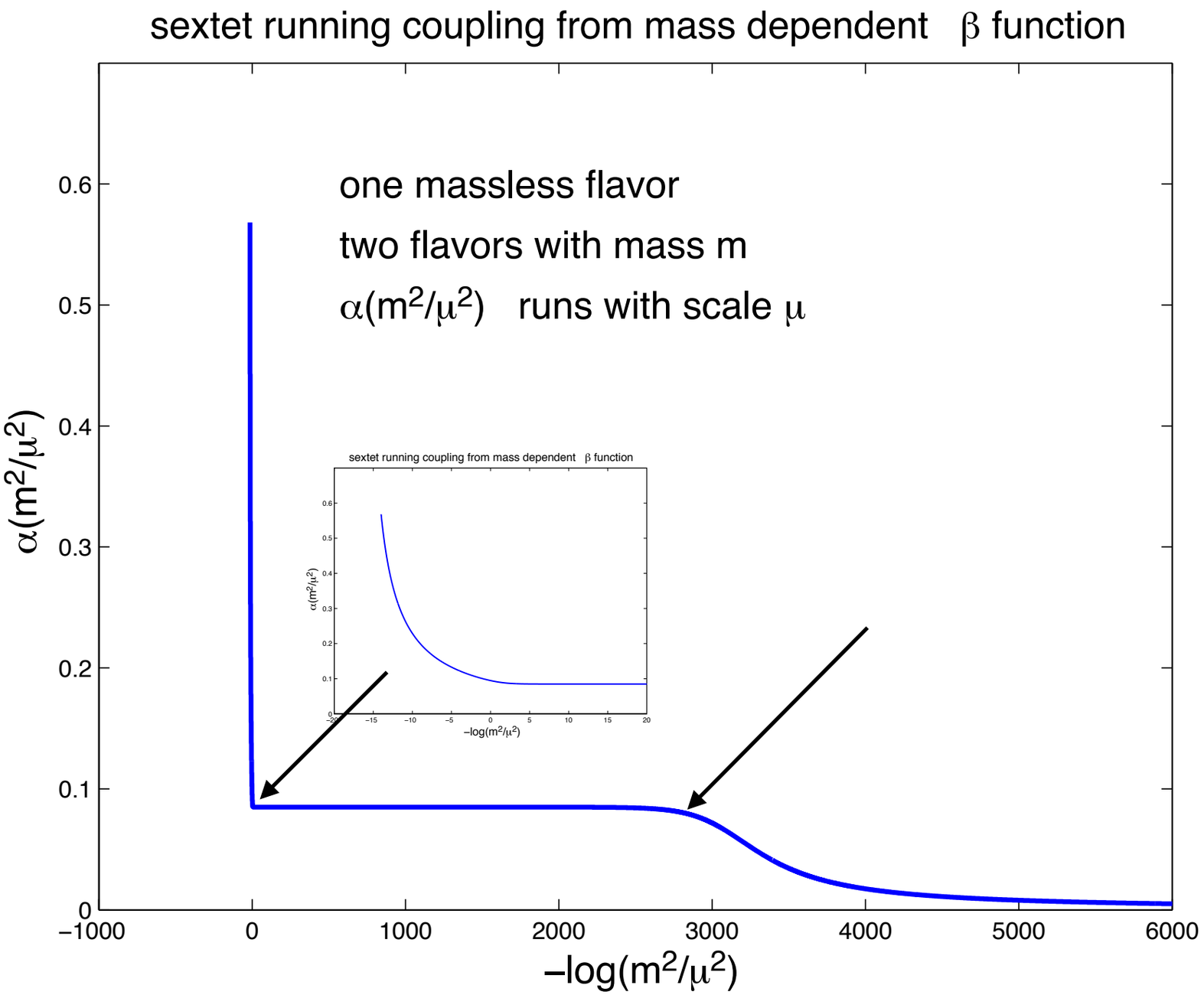
extra 4 flavors (or 8?) to keep model near-conformal
fermions are massive

near-conformal σ-like light scalar?

in comparison, near conformal σ-like light scalar of sextet model is simple in the 500 GeV range
tunable?

relying on large mass anomalous dimension
for fermion mass generation and flavor problem

scale-dependent coupling mass dependent tuning?



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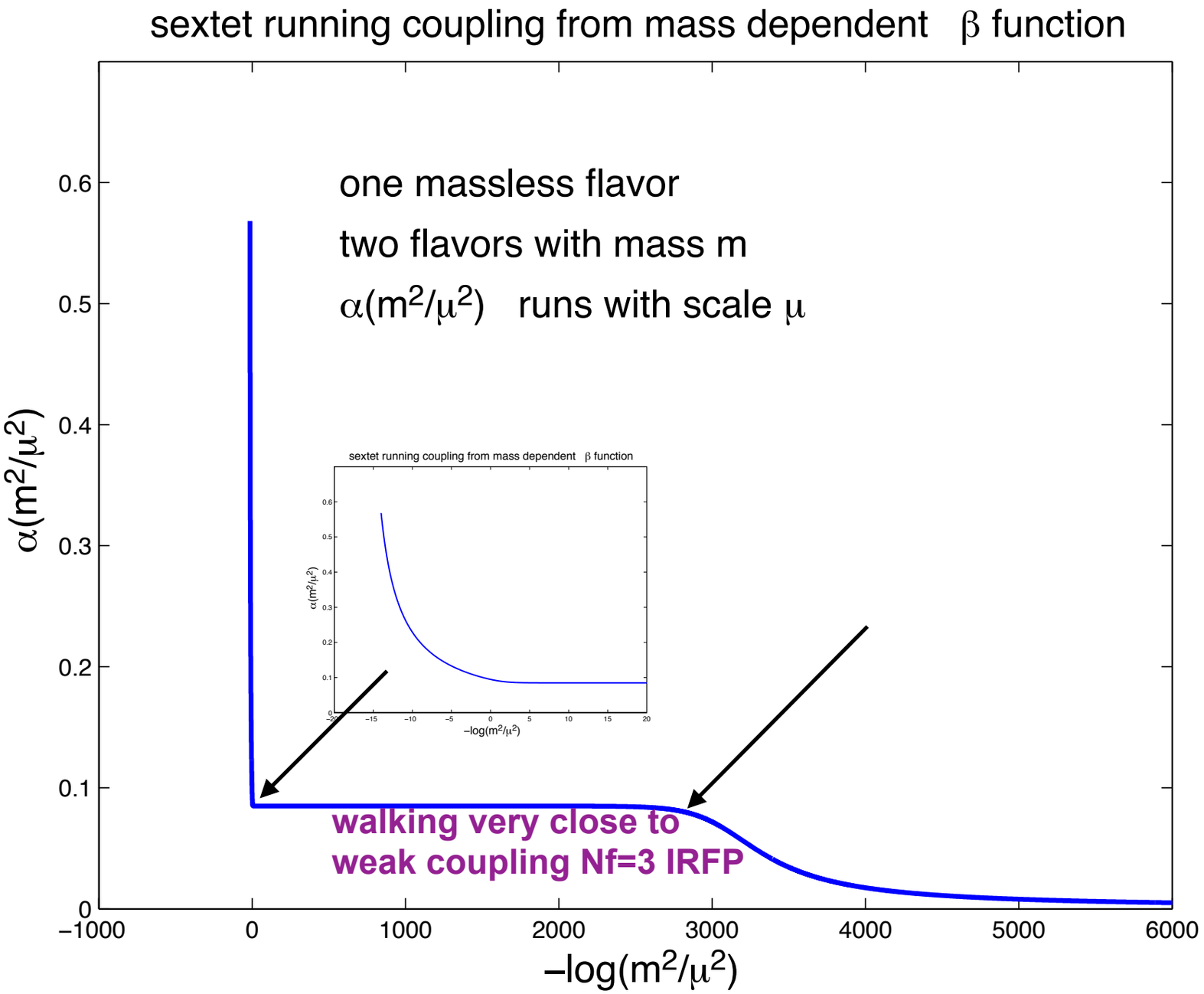

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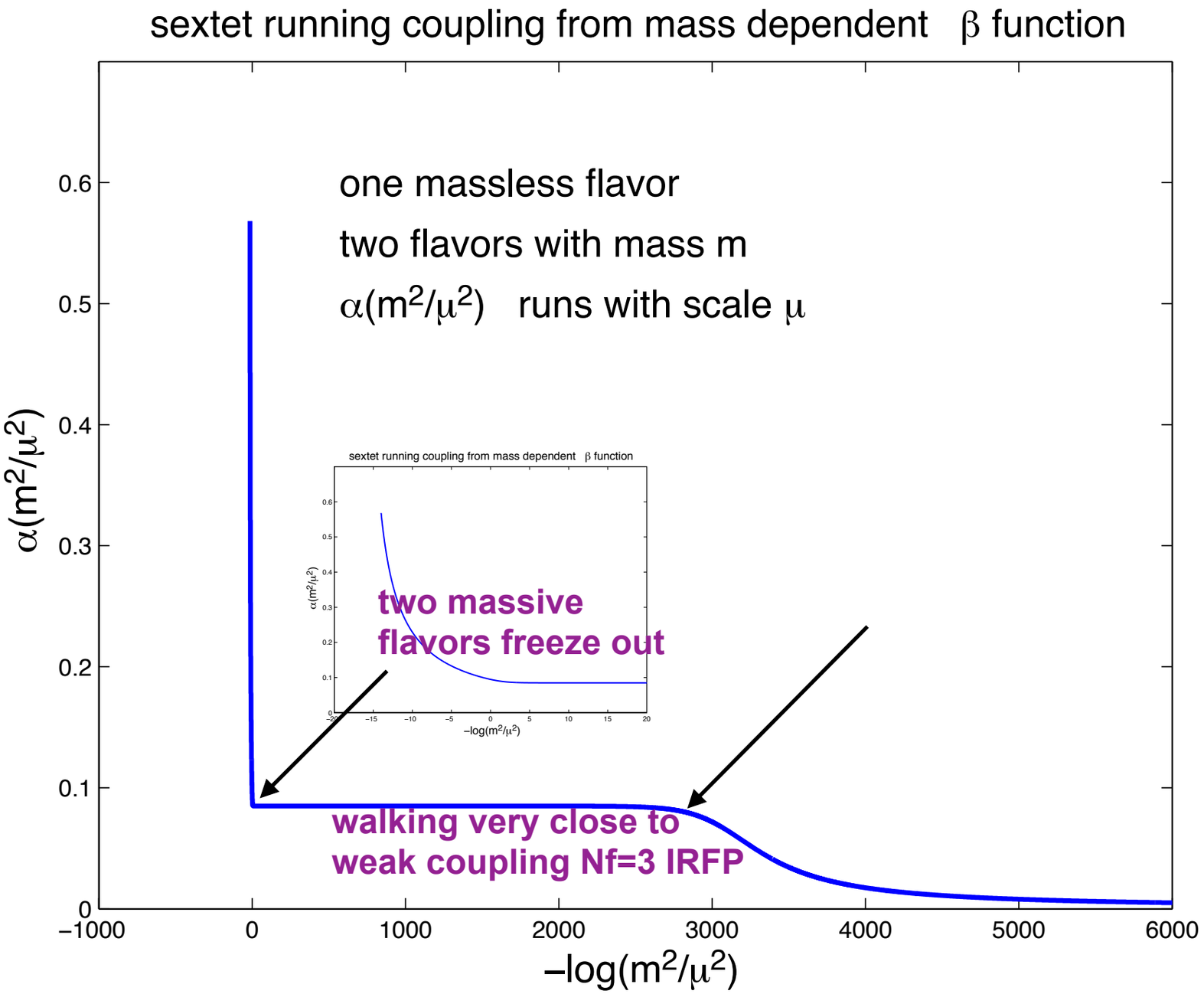

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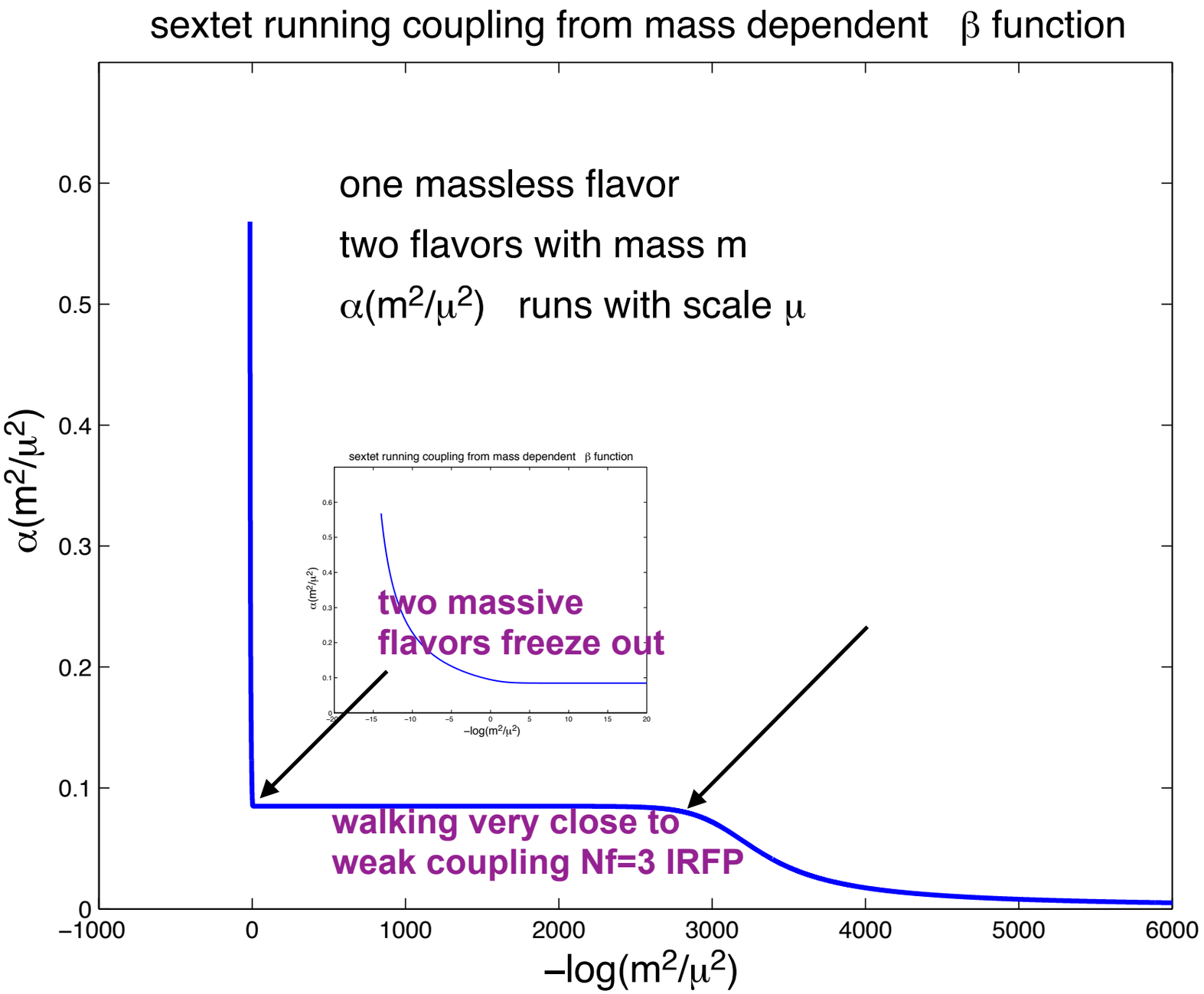


in 1+2 freeze-out scenario anything to learn about strong coupling dynamics of single massless flavor?

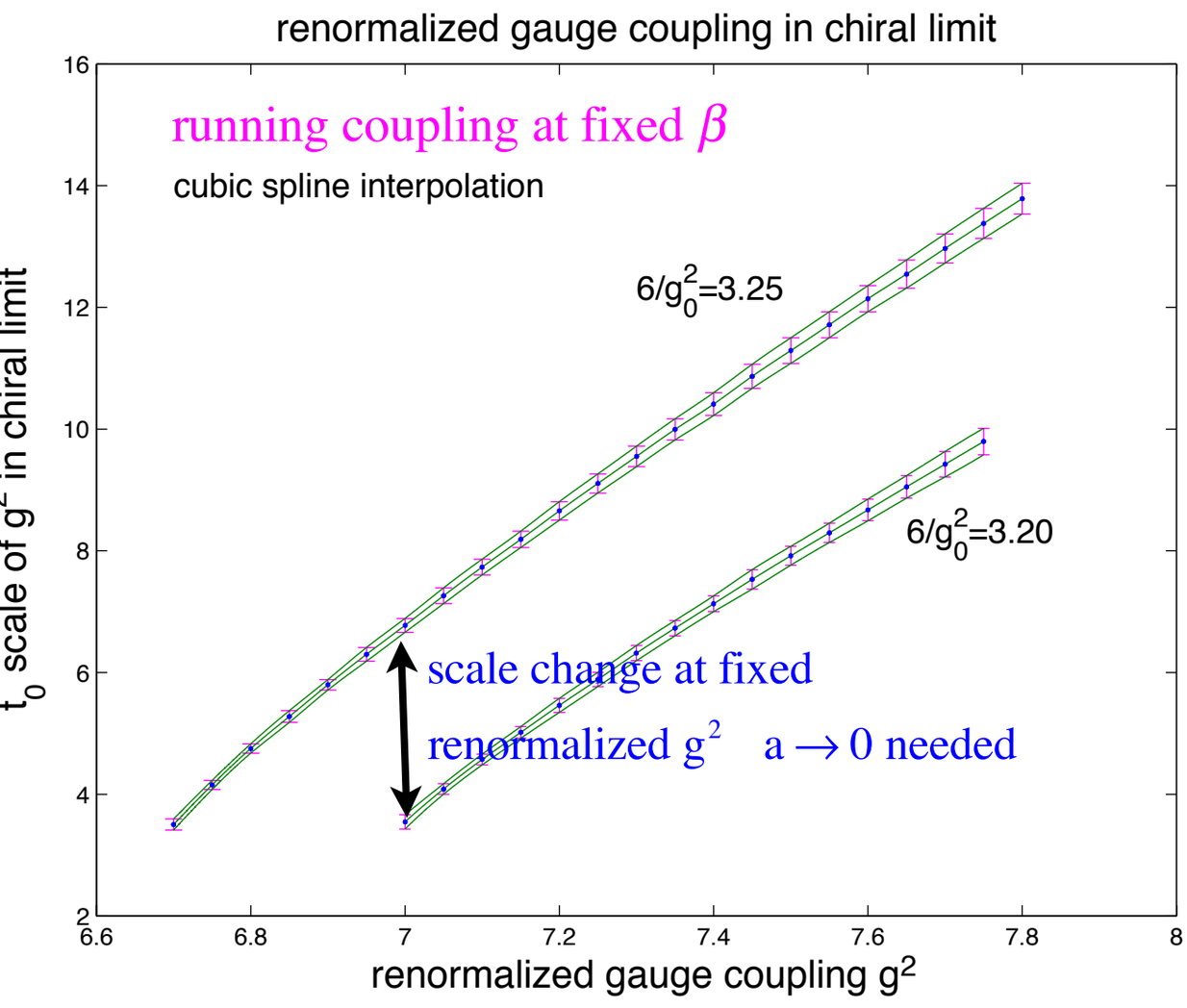
Similarly, in 2+1 freeze-out scenario anything to learn about strong coupling dynamics of doublet massless flavor?

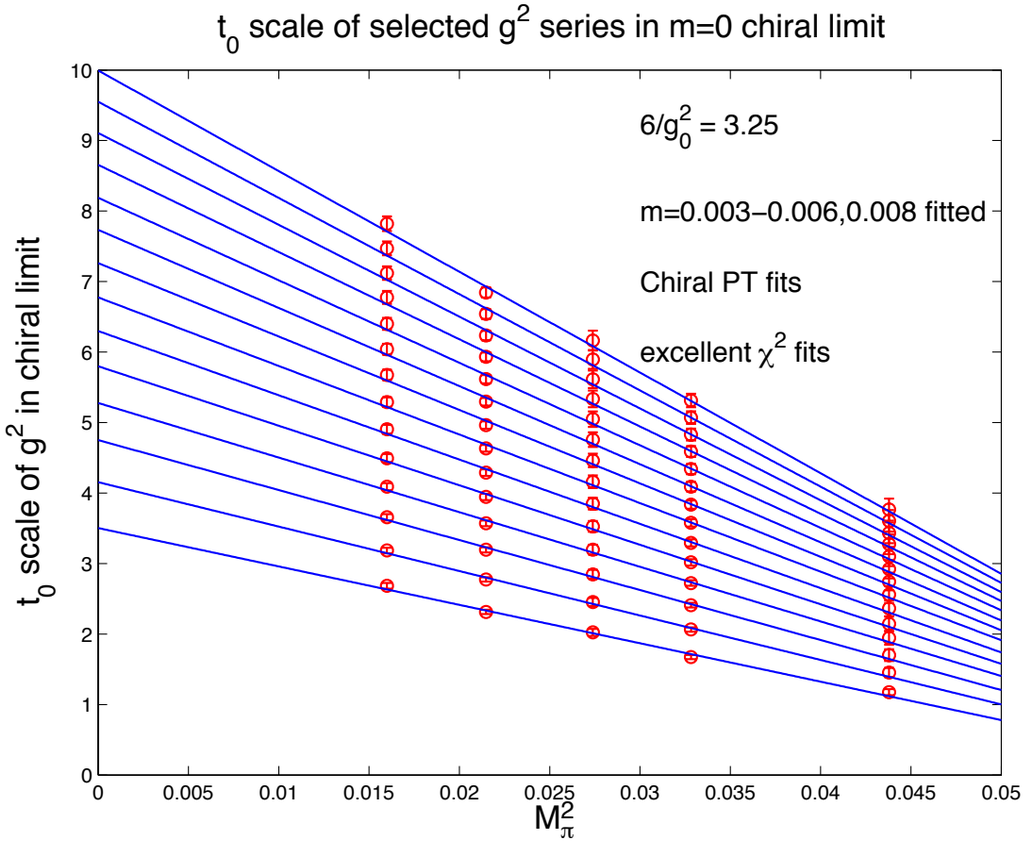
Not likely that light scalar mass can be tuned effectively with added third EW singlet fermion with tunable mass

four-fermion operator?

scale-dependent coupling in p-regime

bridge between UV scale and IR scale





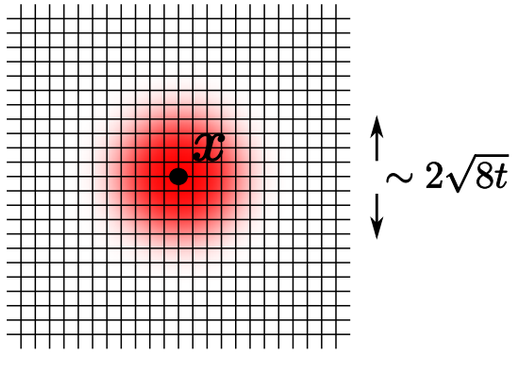
leading dependence of $g^2(t,m)$ on M_π^2 is linear

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



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

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

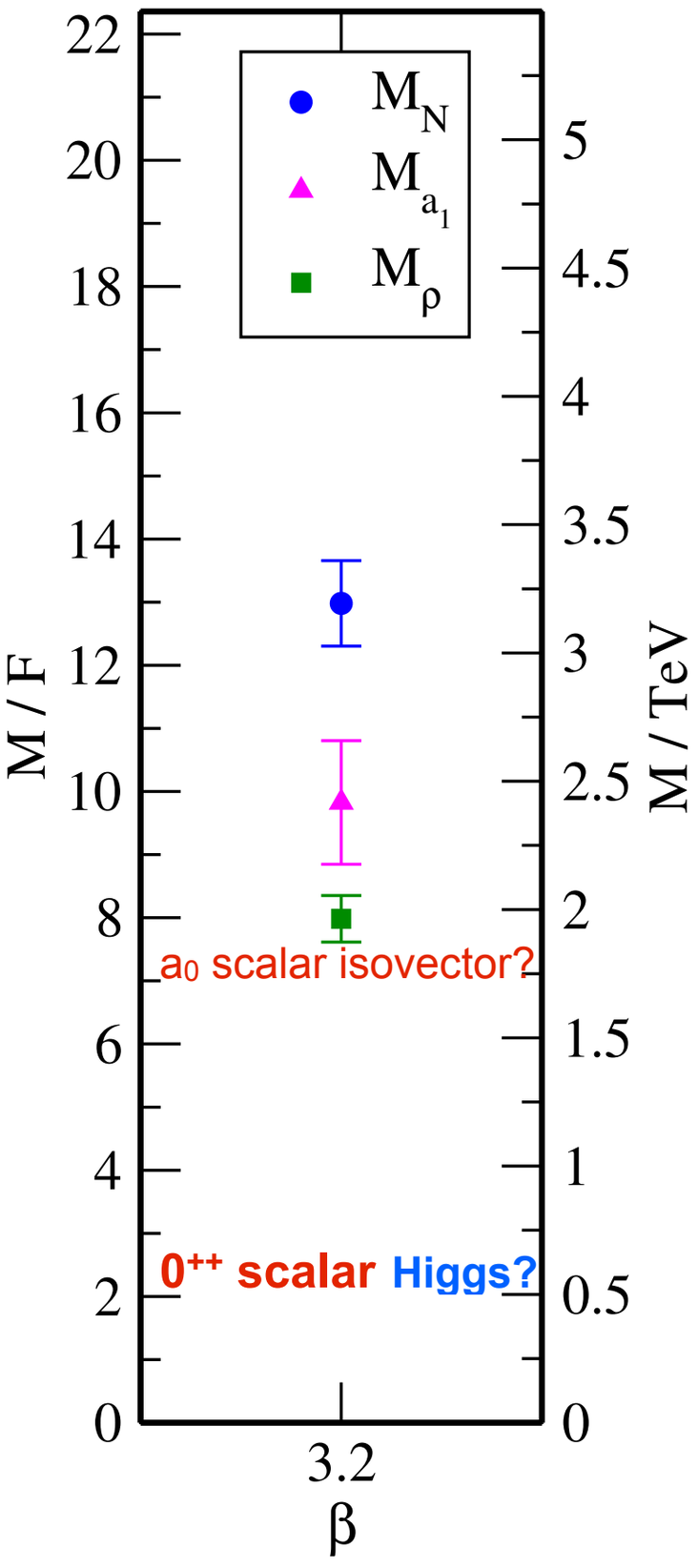
RMT regime?

light 0++ scalar and spectrum

sextet model

$L_{at}HC$

also CP^3



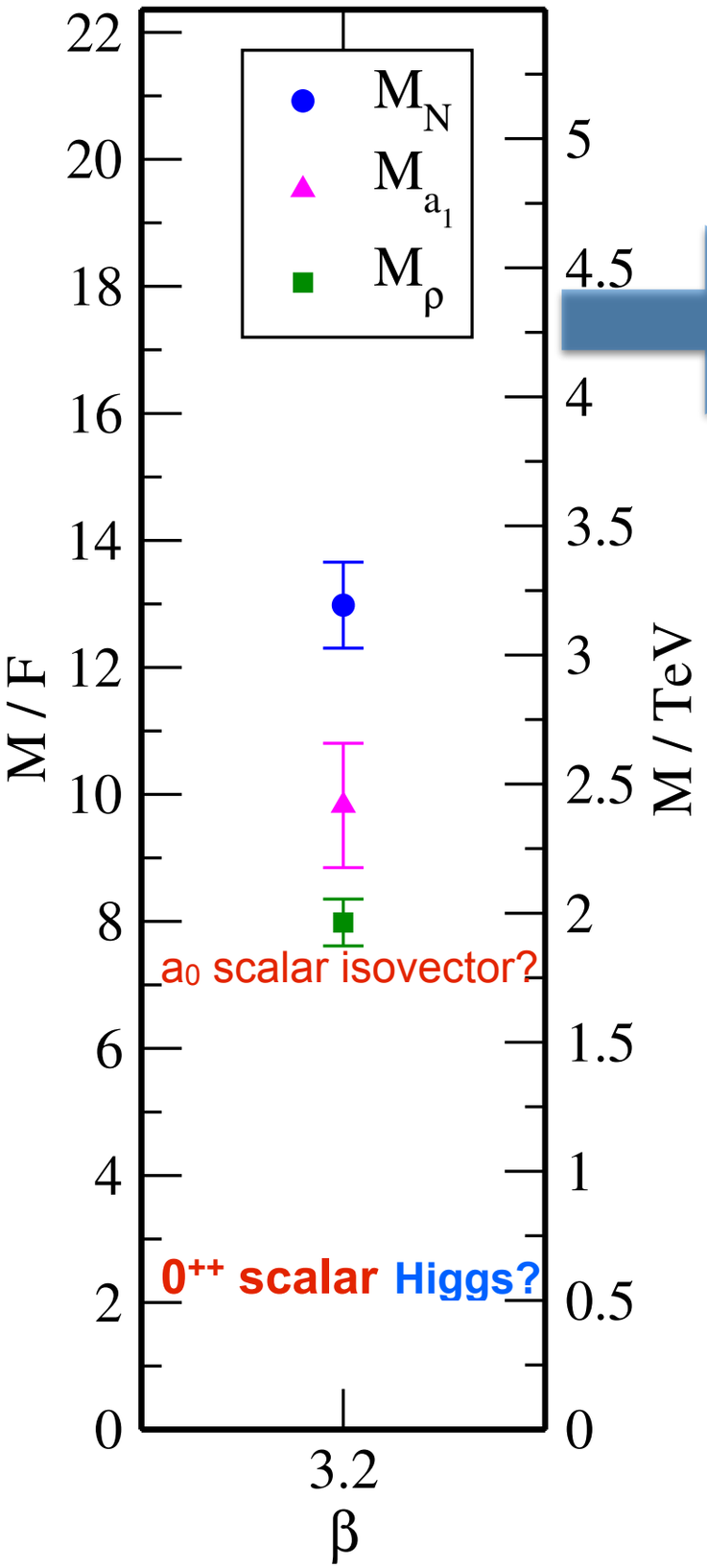
new result on pseudo-scalar singlet (aka η')

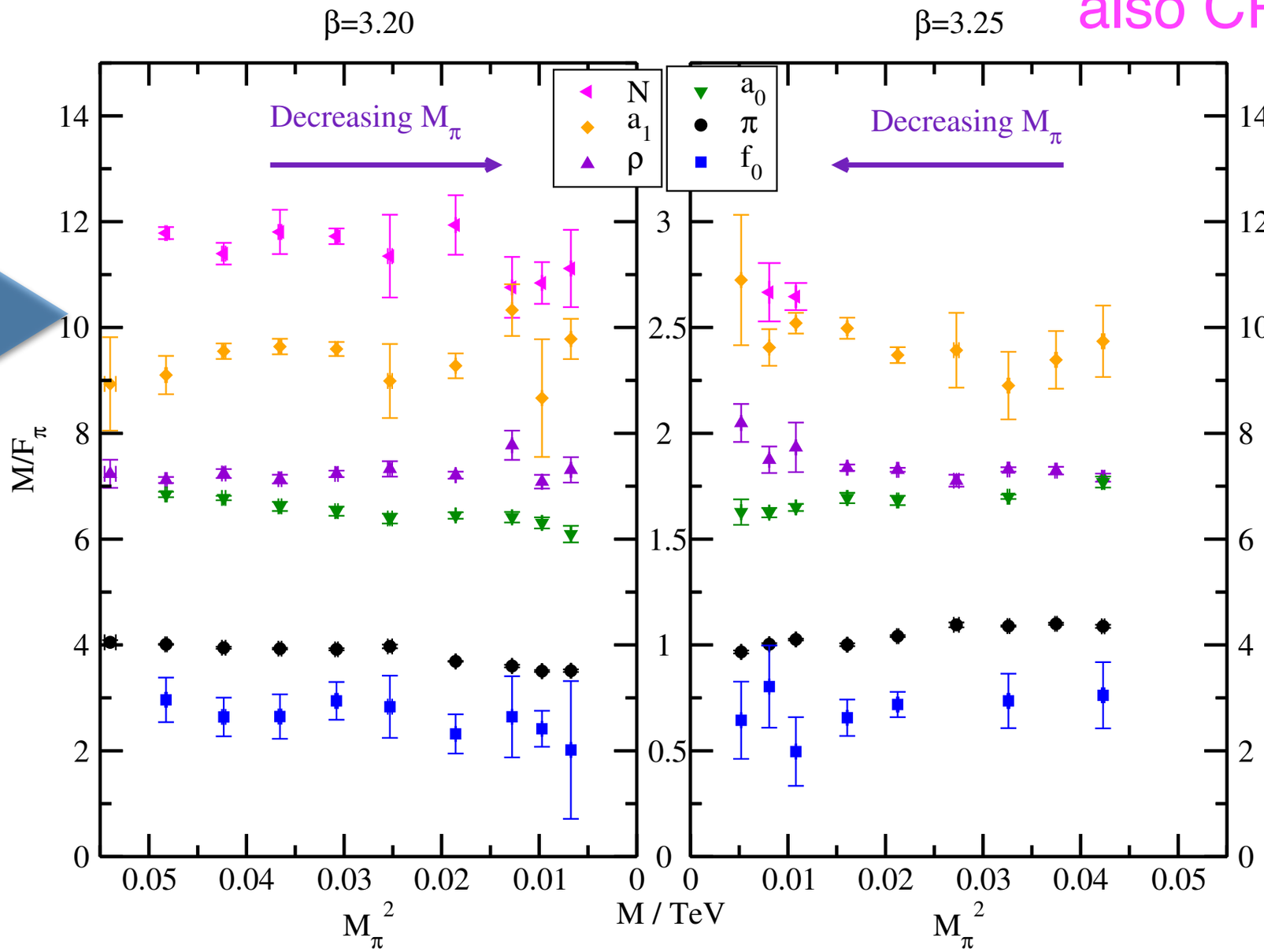
Ricky Wong Tue 15:40 pm

BSM in Bldg. 67 Room 1027

light 0++ scalar and spectrum sextet model LatHC

also CP3





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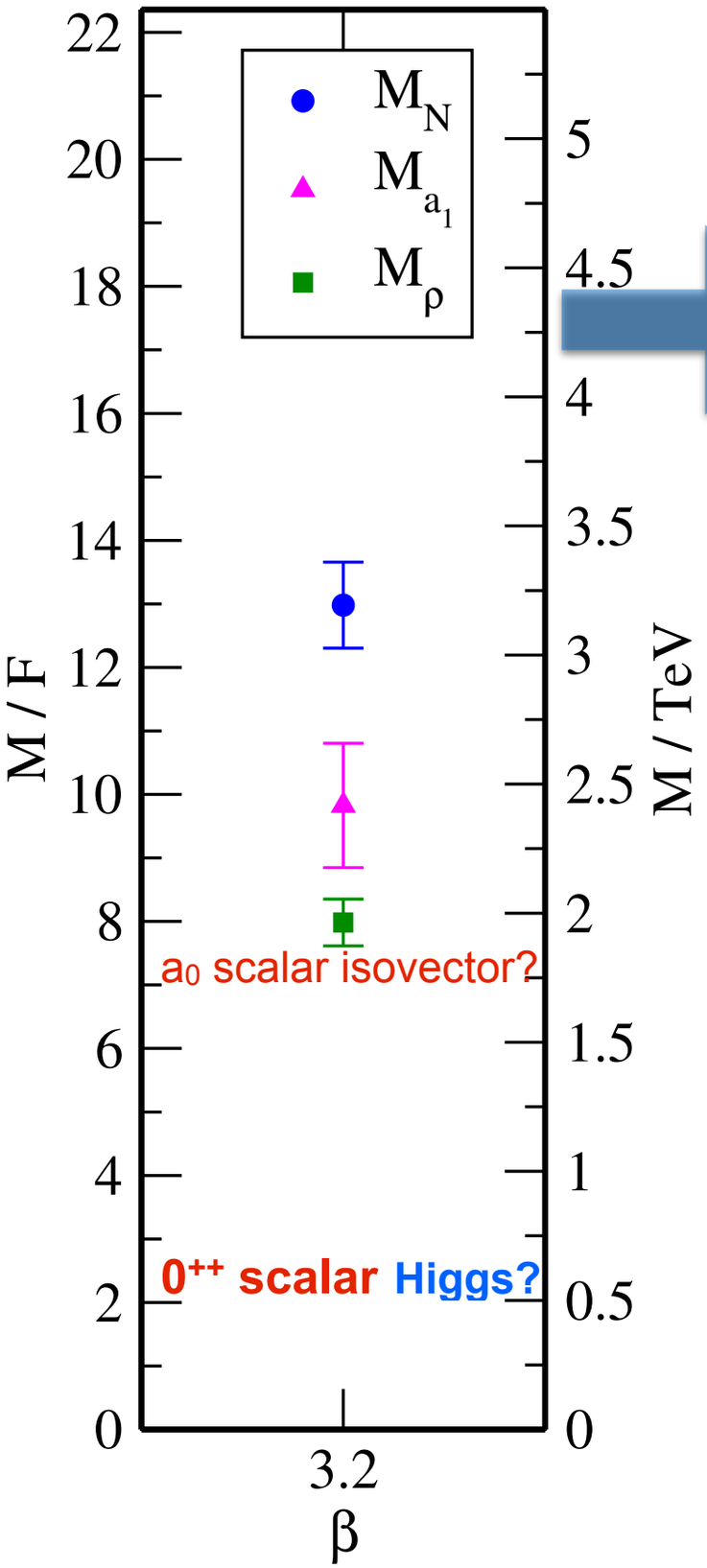

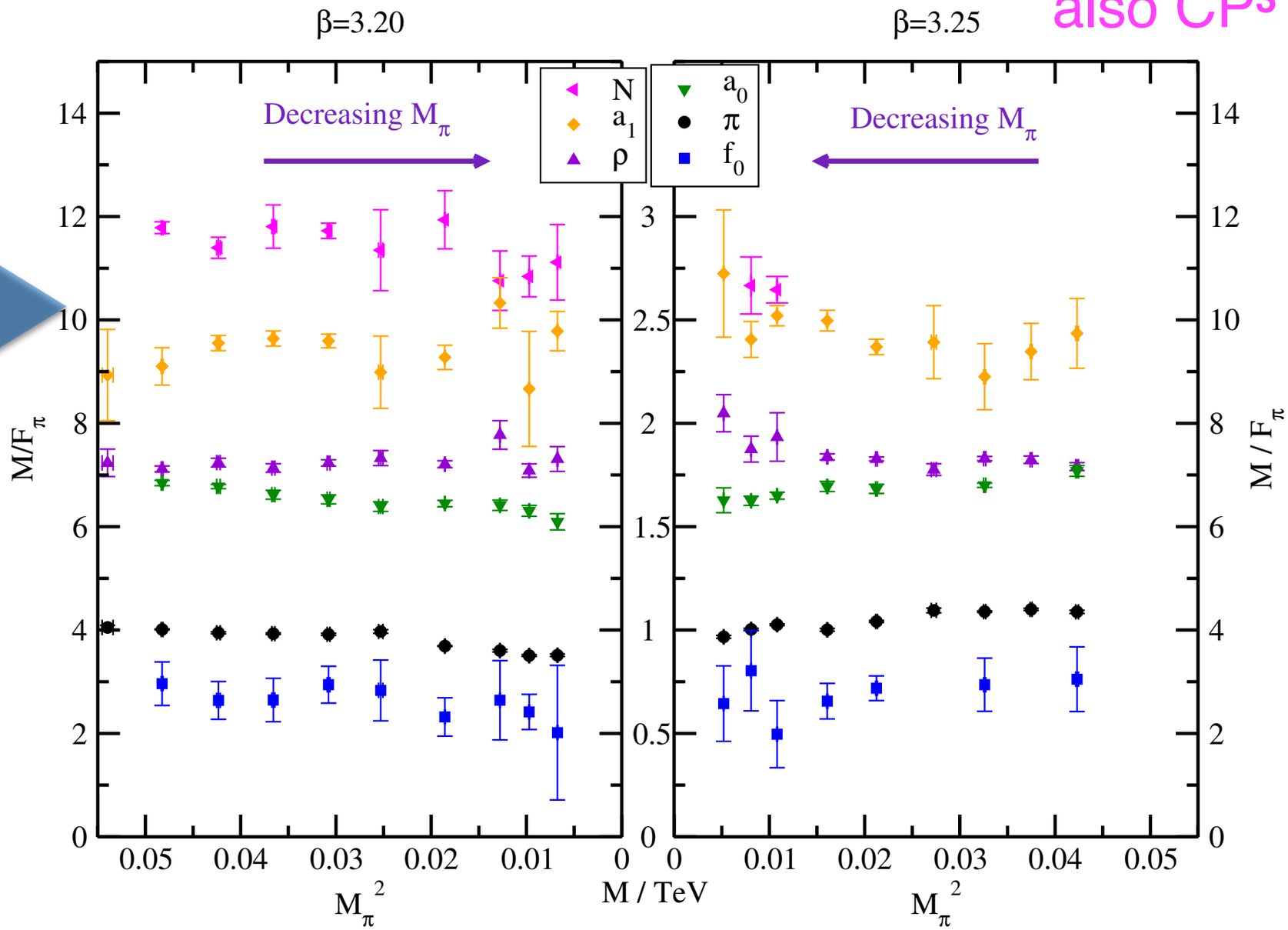

new result on pseudo-scalar singlet (aka η')

Ricky Wong Tue 15:40 pm

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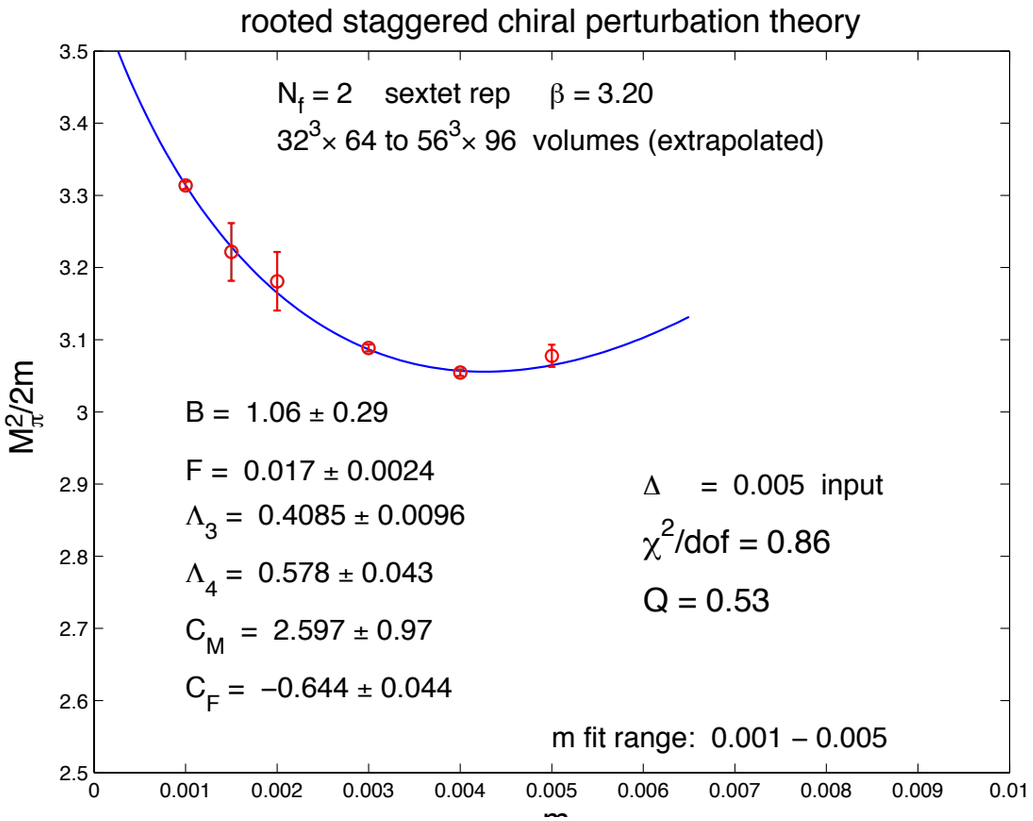
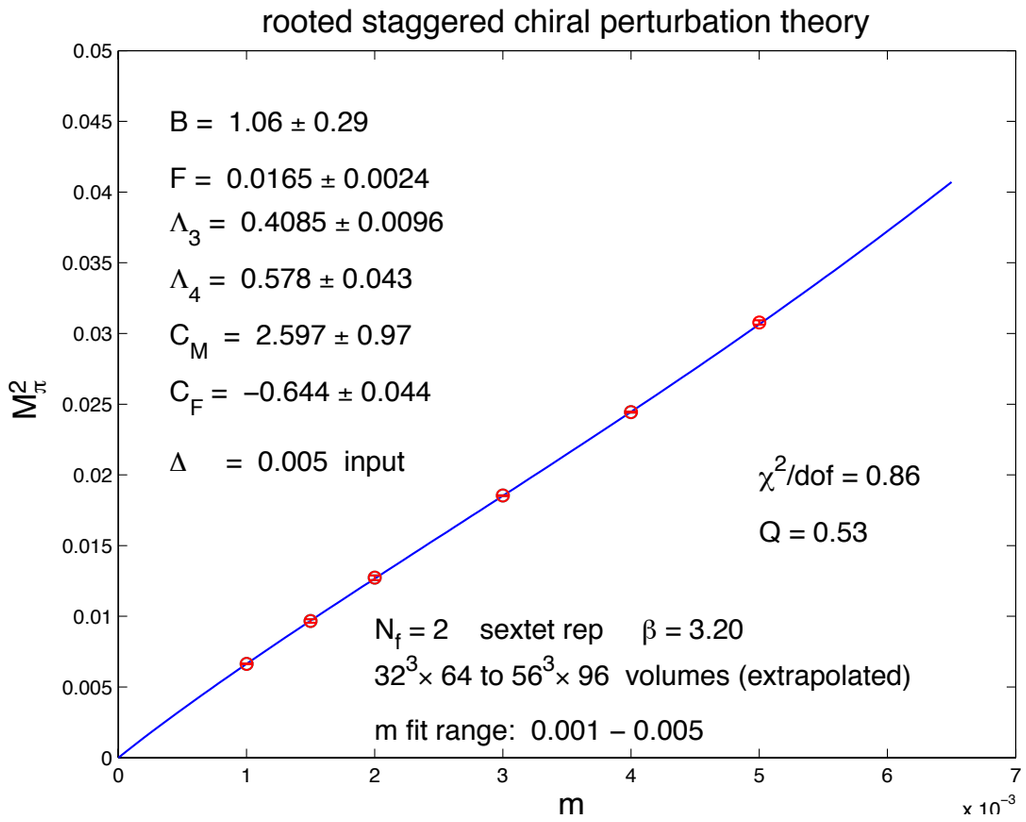
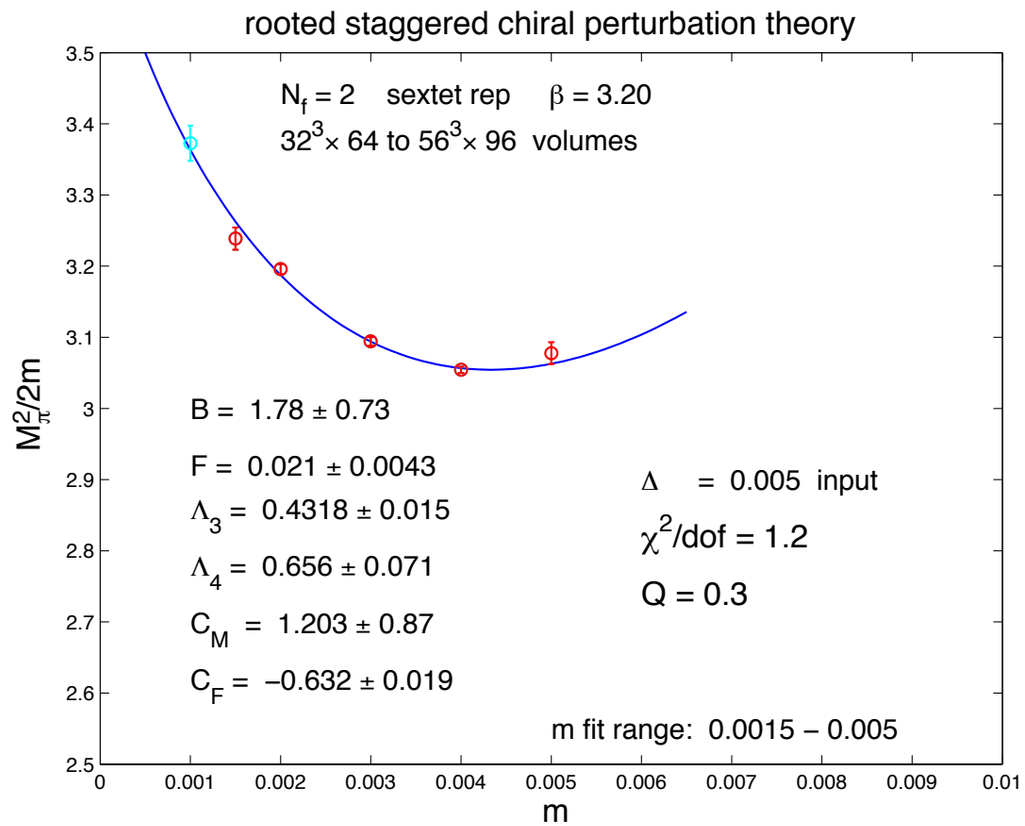
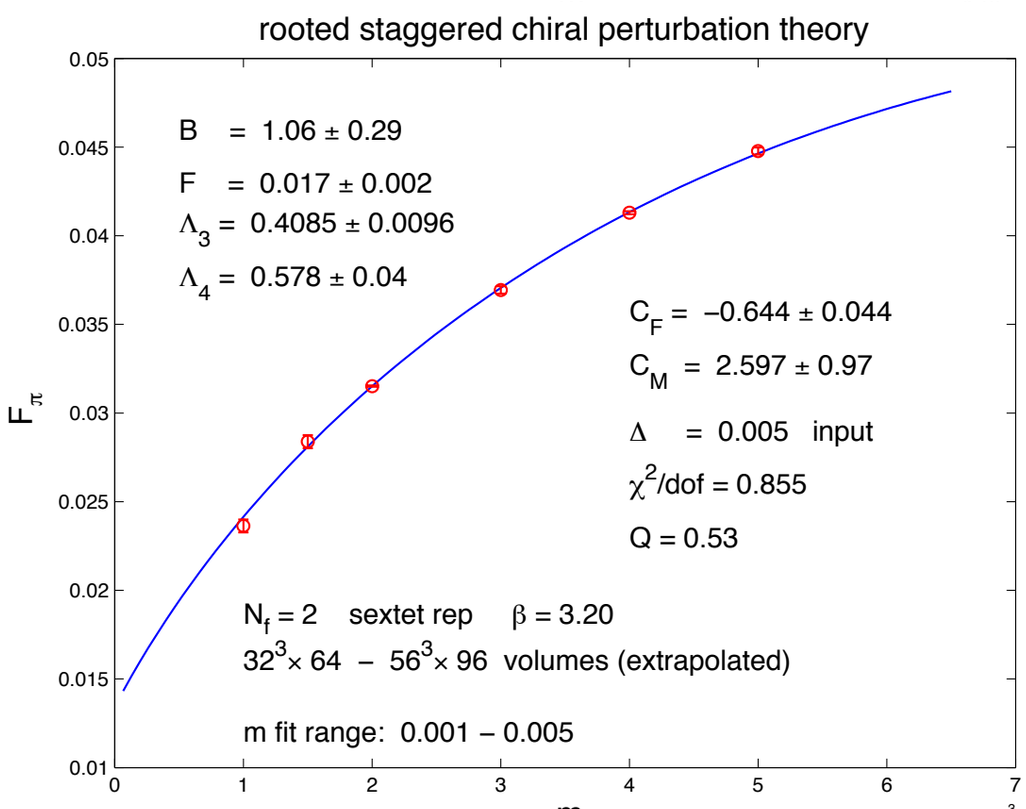
does not fit mass-deformed hyper-scaling

rsChiPT analysis of Mpi and Fpi fitting results

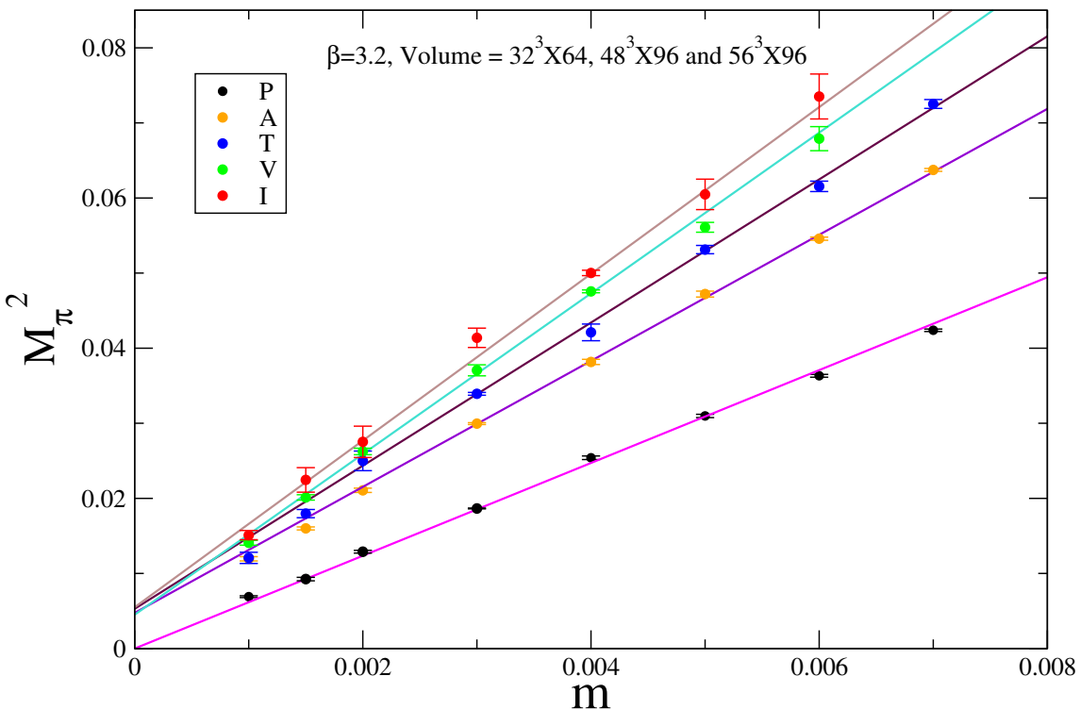


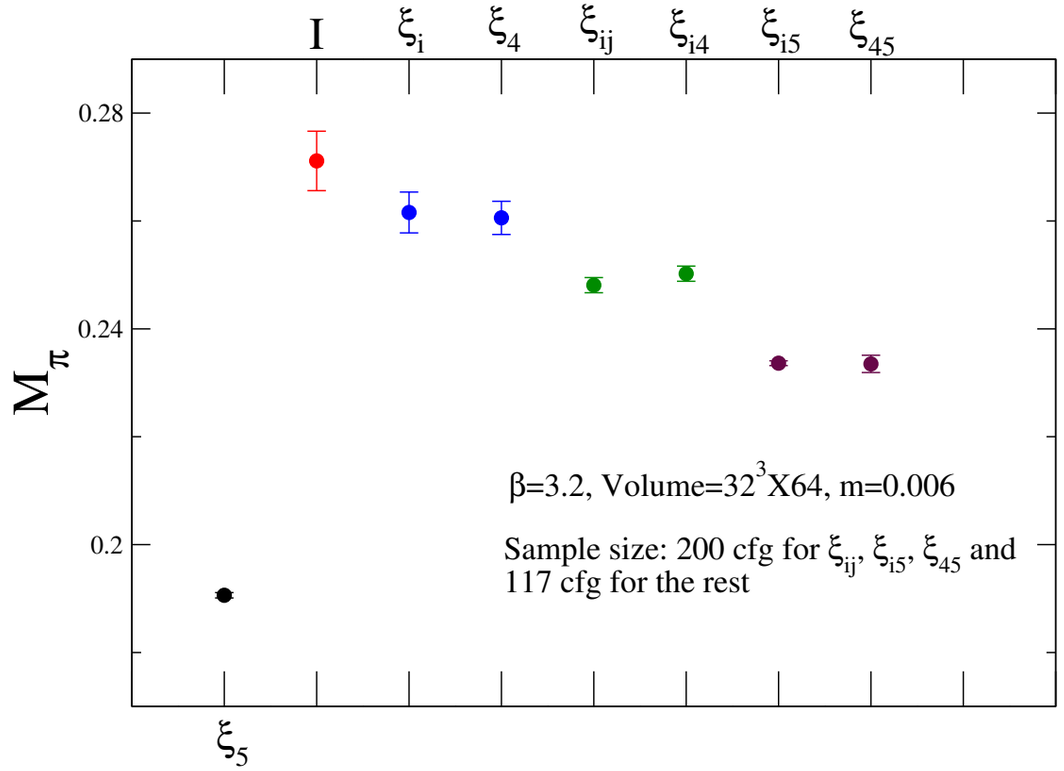


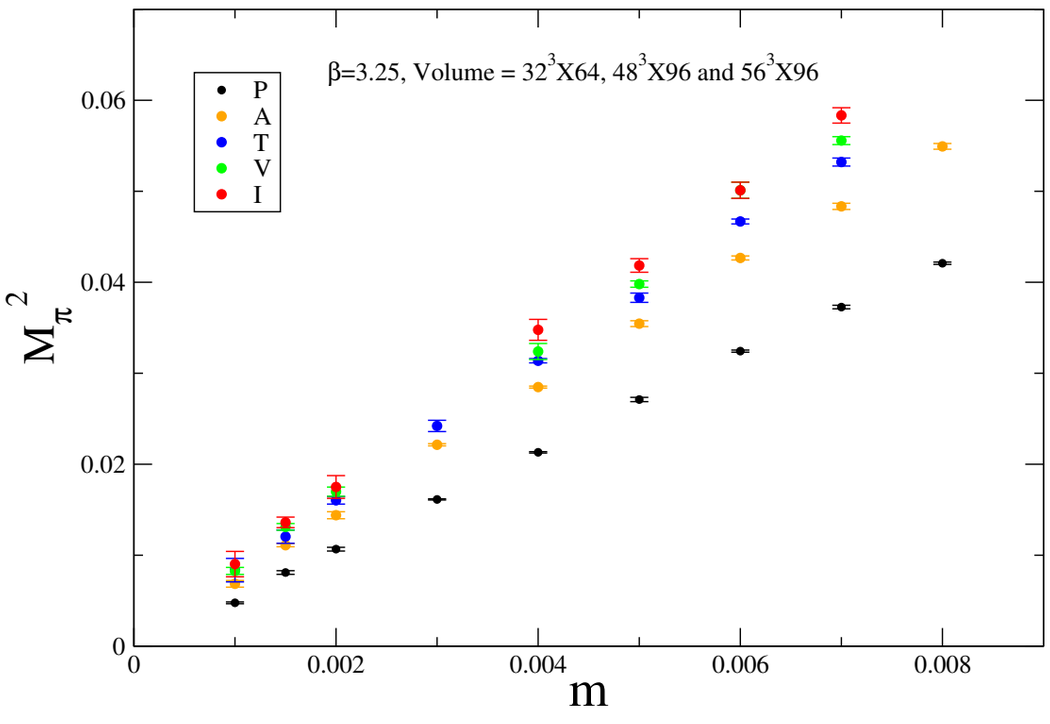


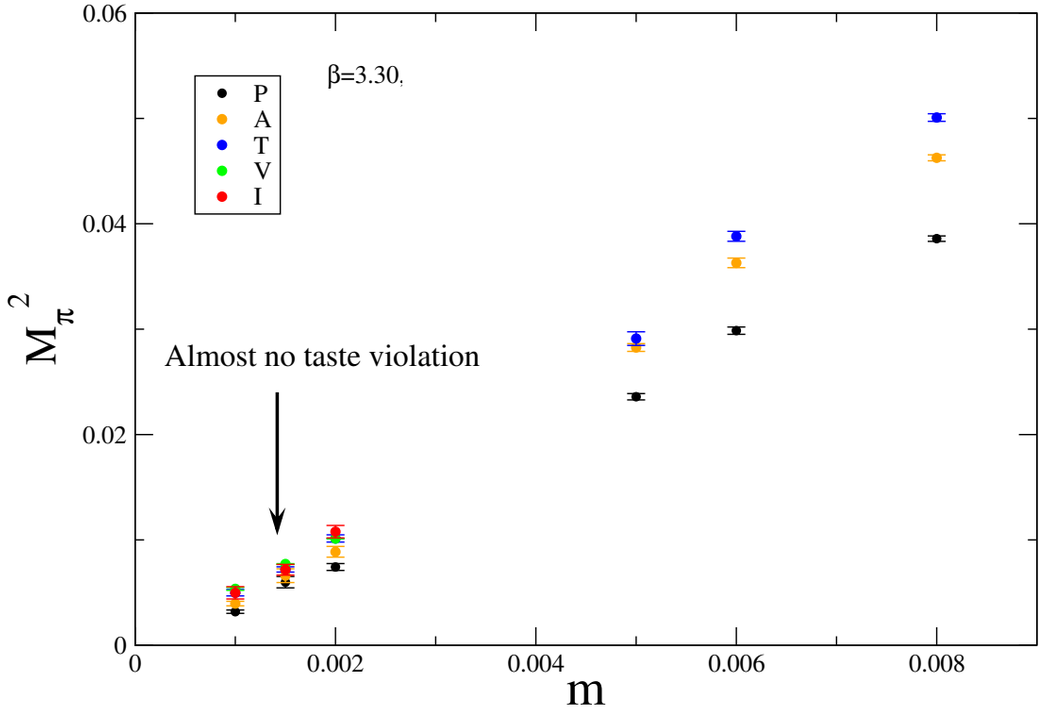


Goldstone spectrum, lattice scale, chiPT









some outstanding spectroscopy problems:

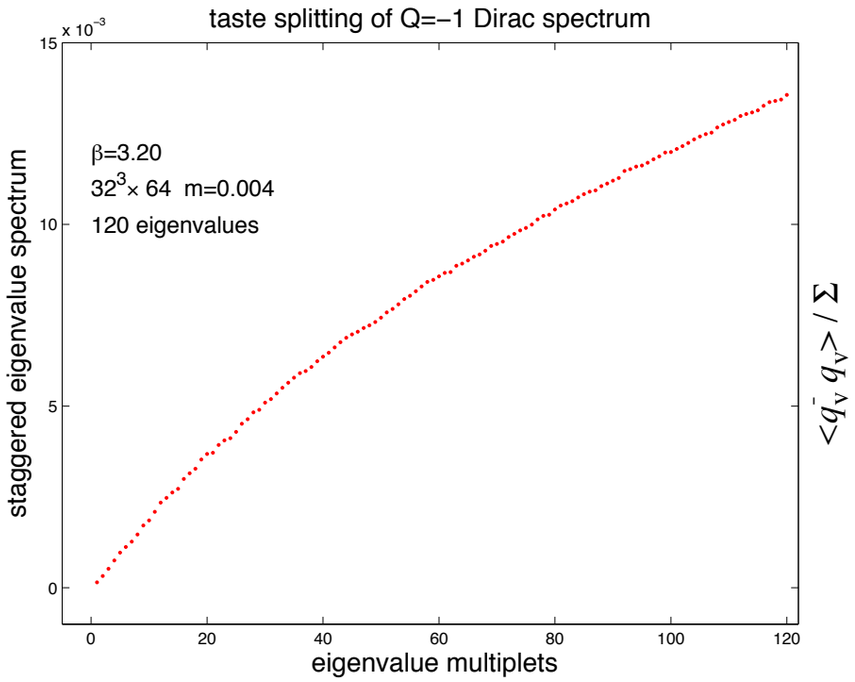
1. effective low energy theory for Goldstone dynamics coupled to the low mass scalar

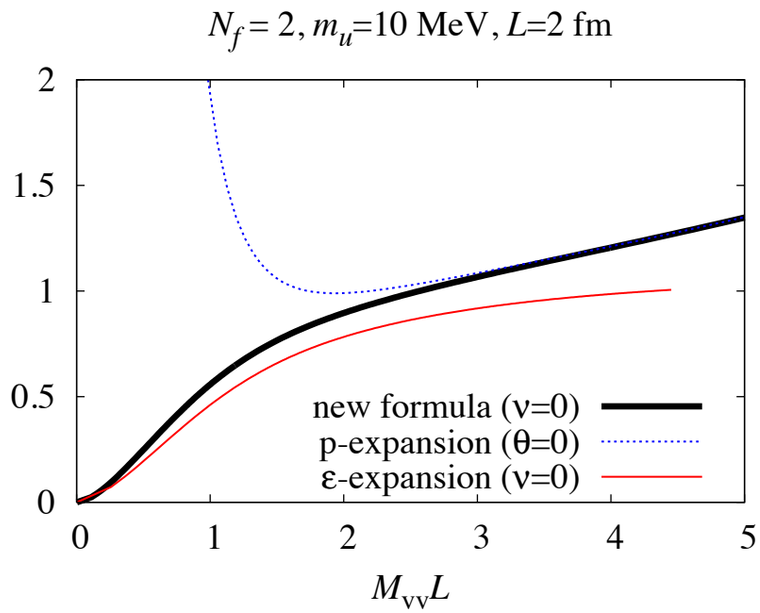
p-regime: nonlinear sigma model or dilaton?

crossover from p-regime to epsilon regime and RMT will be more effective in decoupling the light scalar

2. effect of slow topology on the analysis
ChiPT at fixed topology?

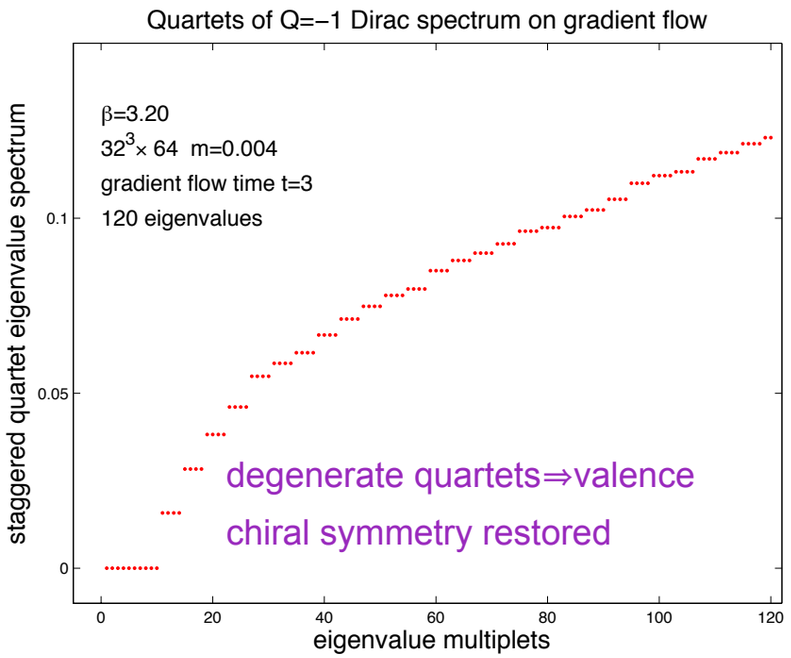
mixed action

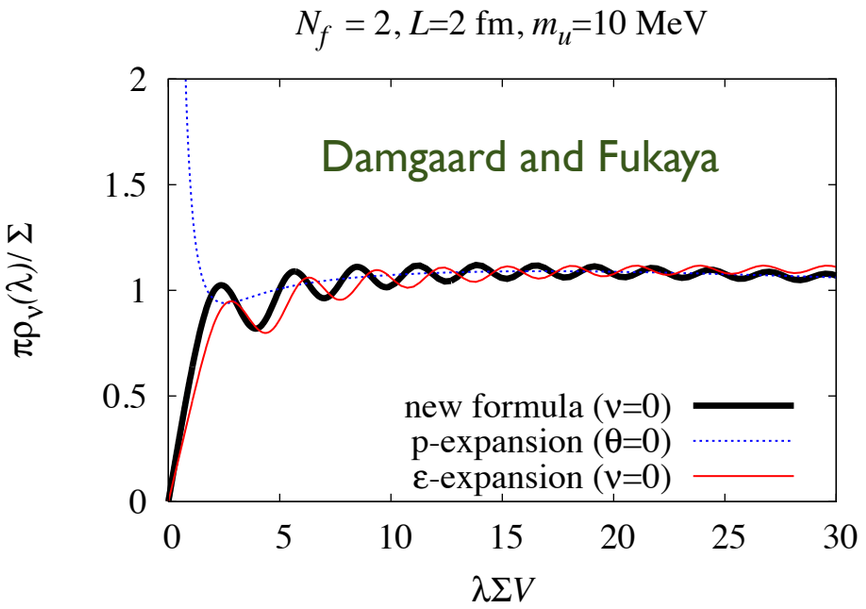




idea for improvement:

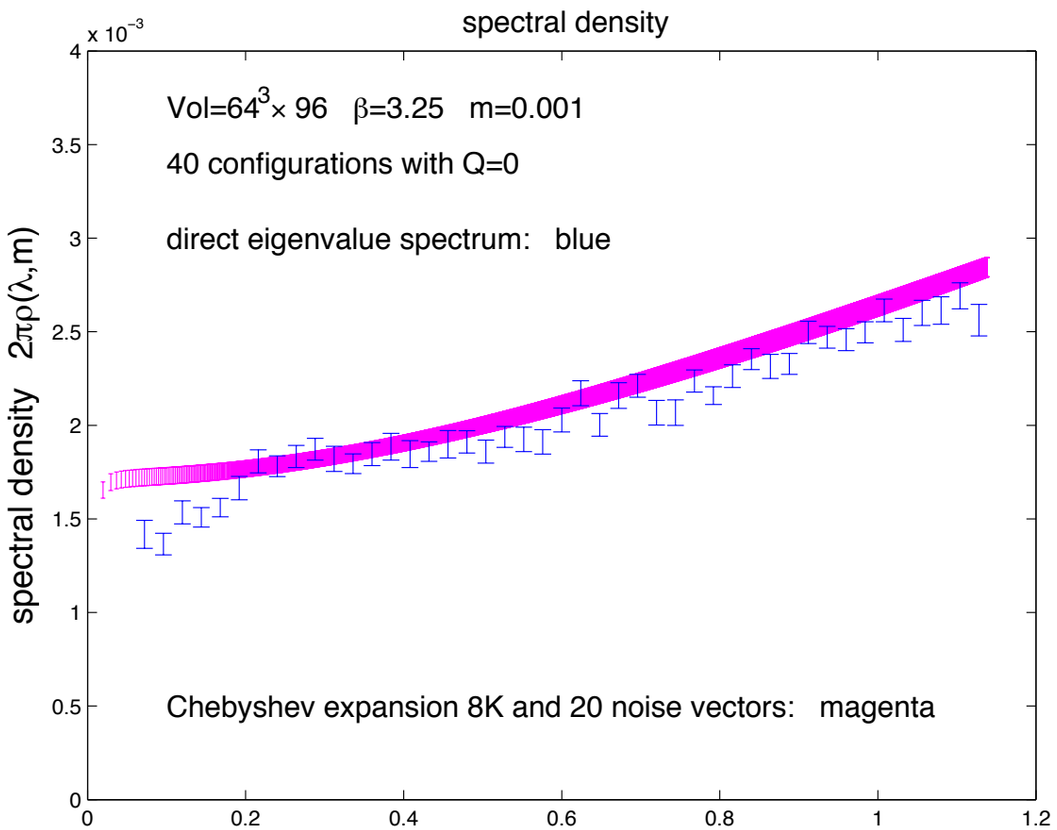
- use the gauge configurations generated with sea fermions
- taste breaking makes chiPT analysis complicated
- in the analysis use valence Dirac operator with gauge links on the gradient flow
- taste symmetry is restored in valence spectrum
- Mixed Action analysis should agree with original standard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

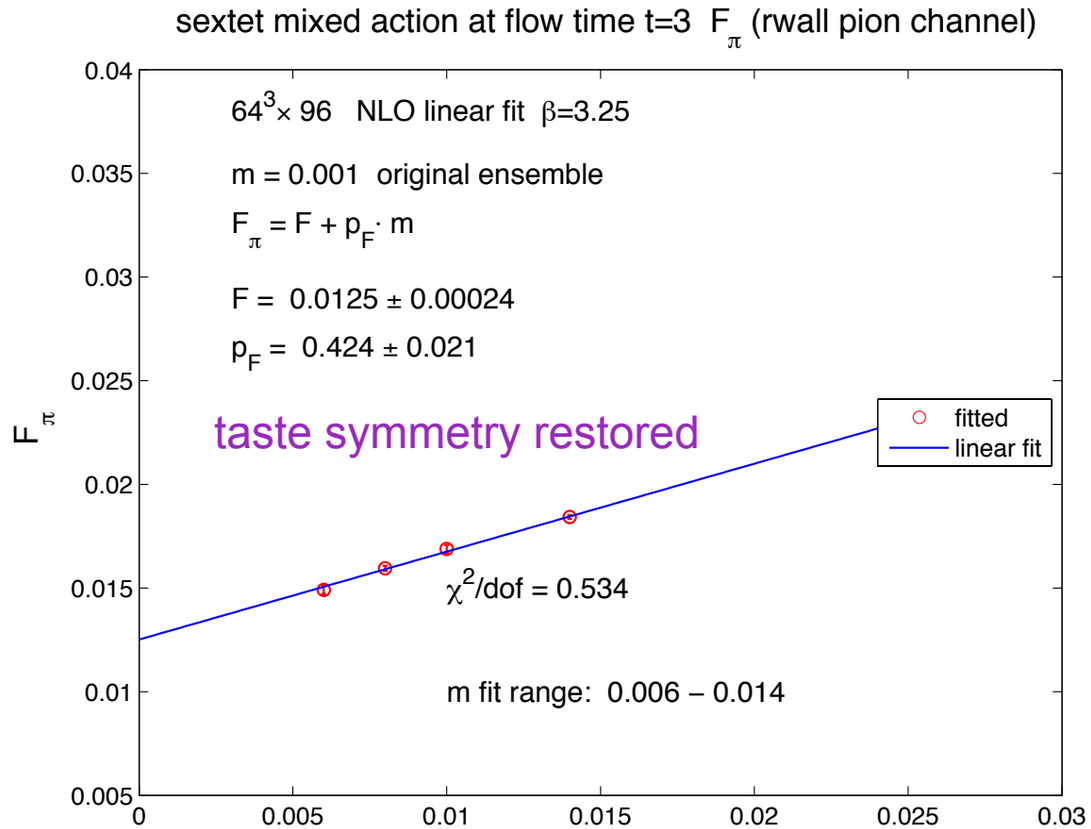


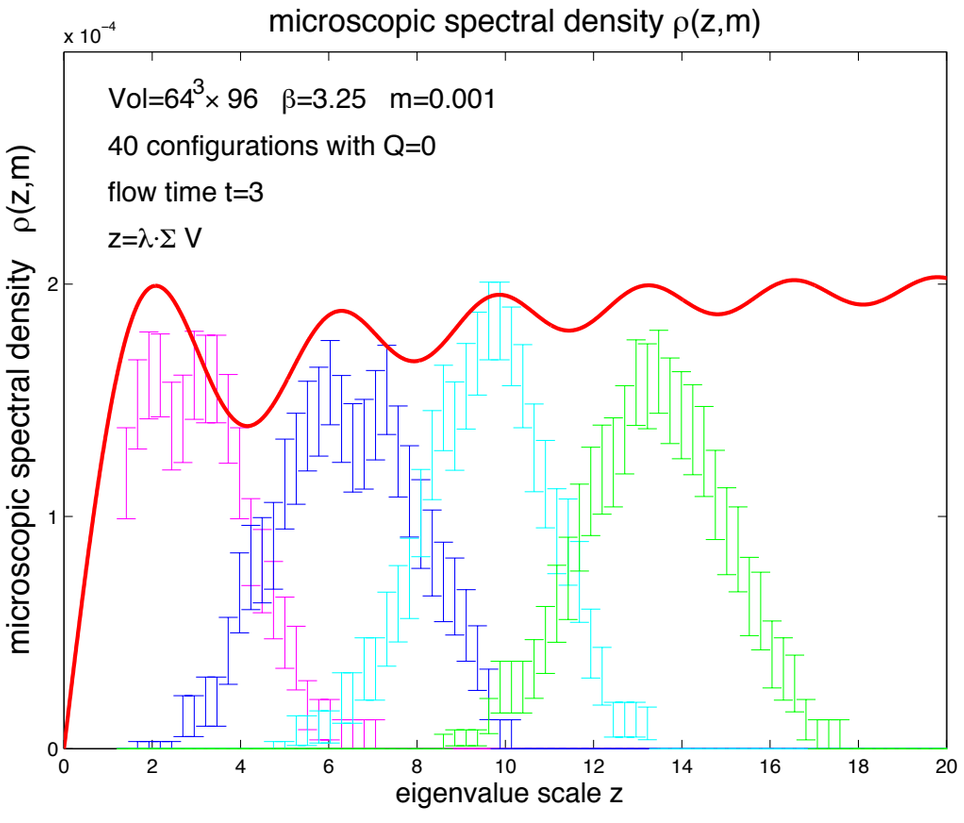


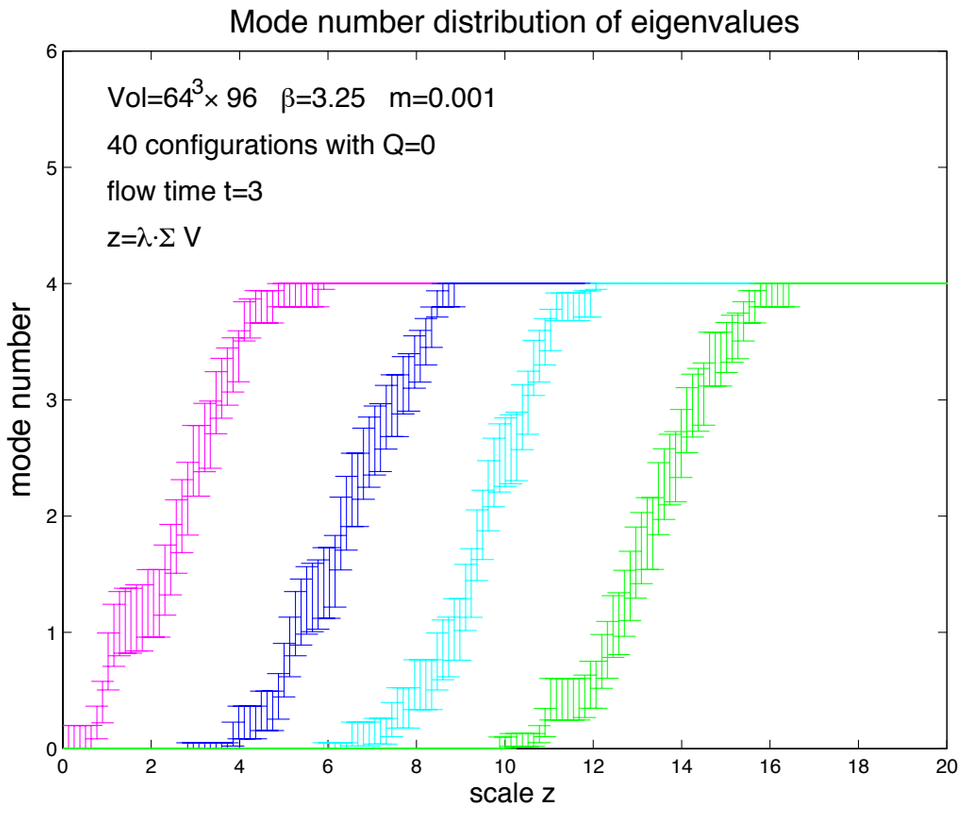
new analysis in crossover and RMT regime with mixed action on gradient flow

mixed action RMT regime





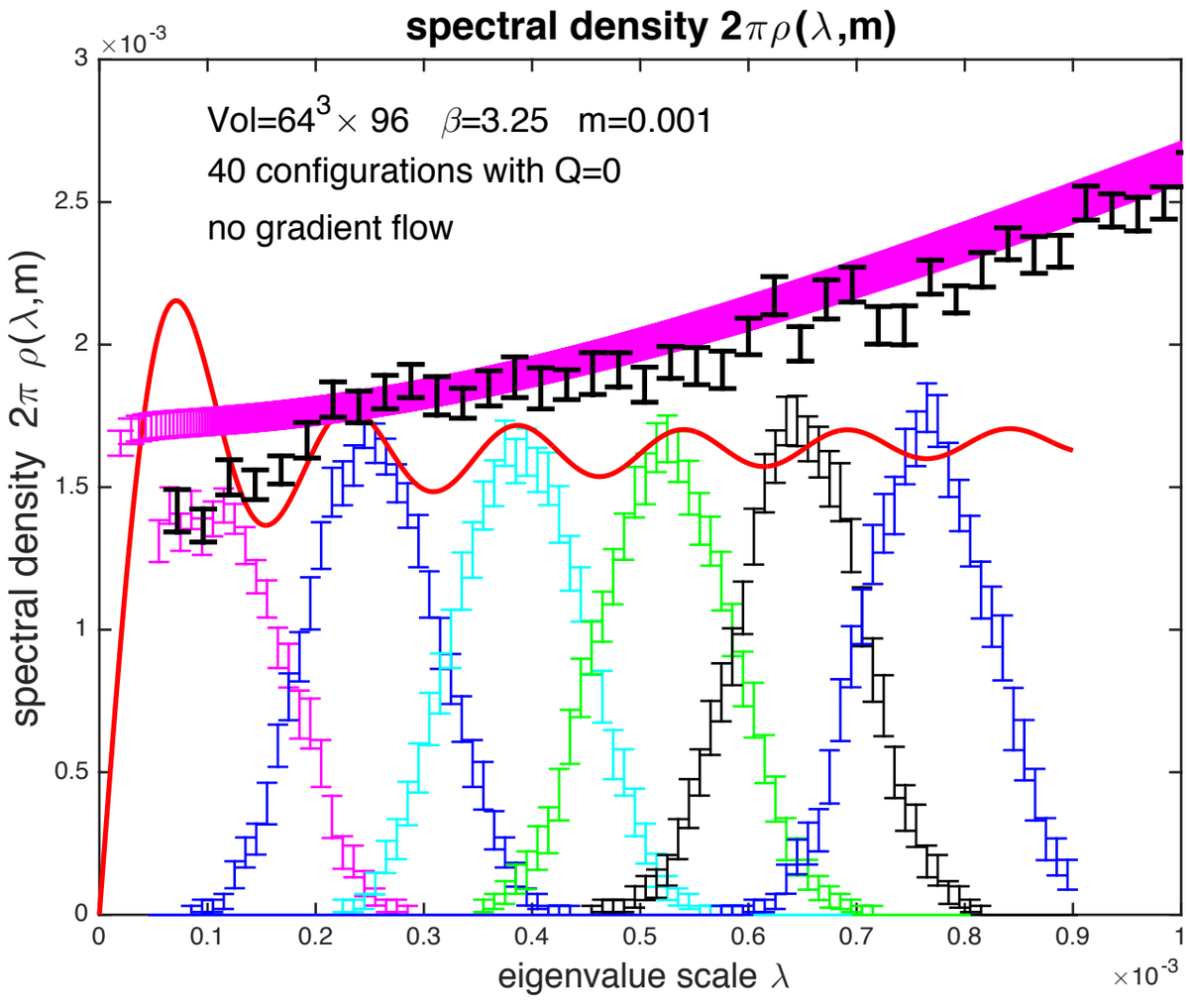


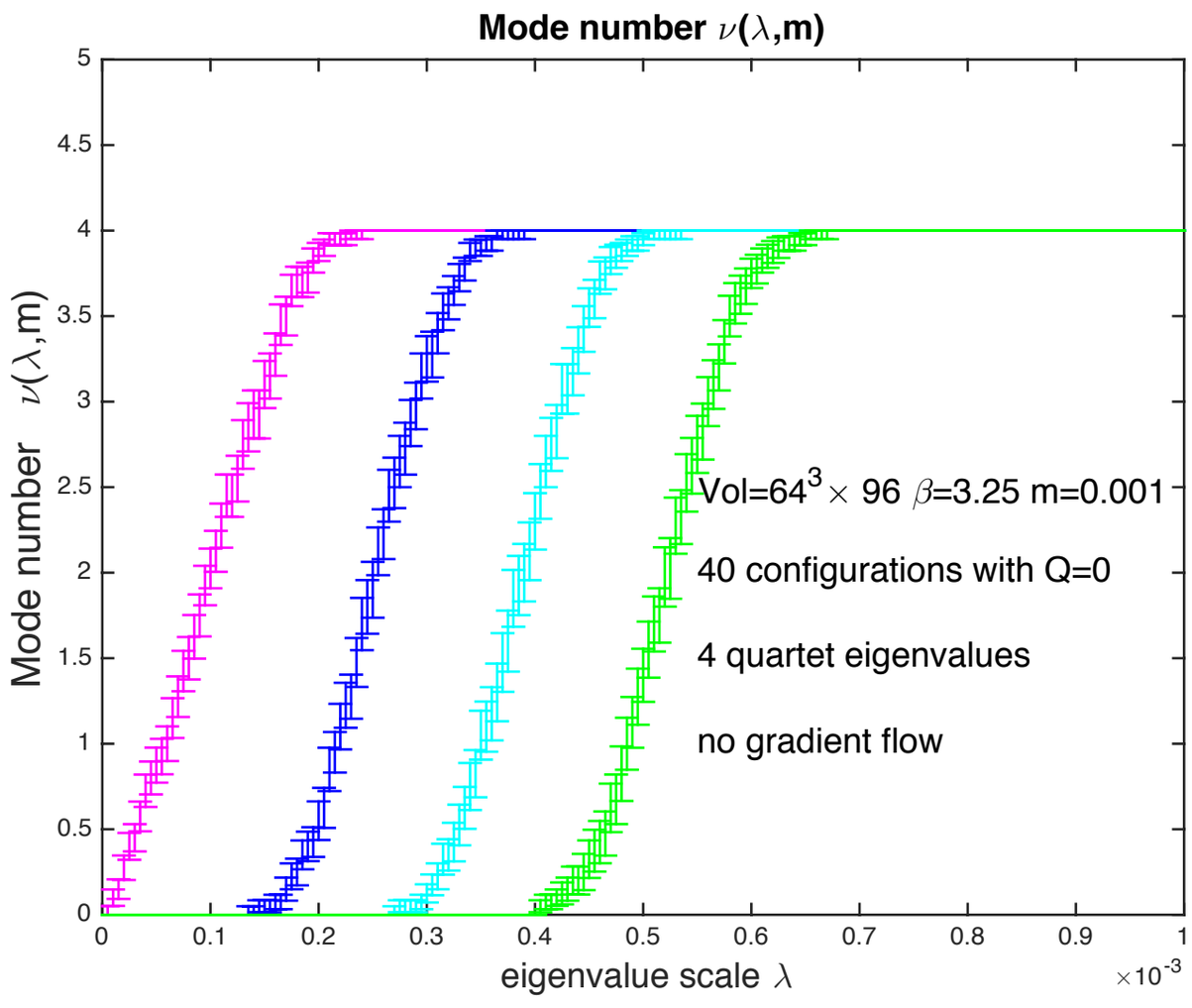


The chiral condensate

RMT spectrum t=0

reached on original configurations without flow, or MA:





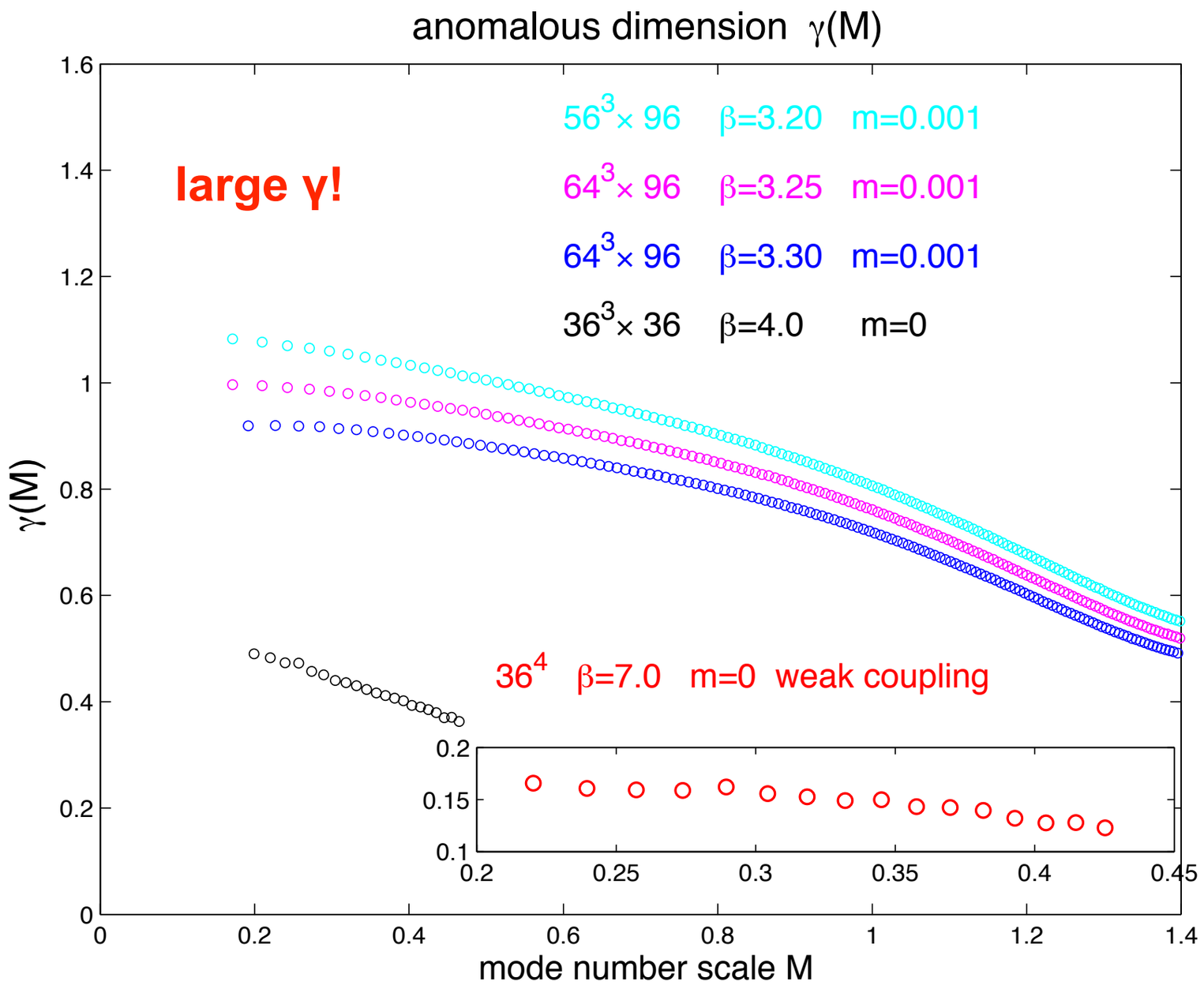
The chiral condensate mass anomalous dimension

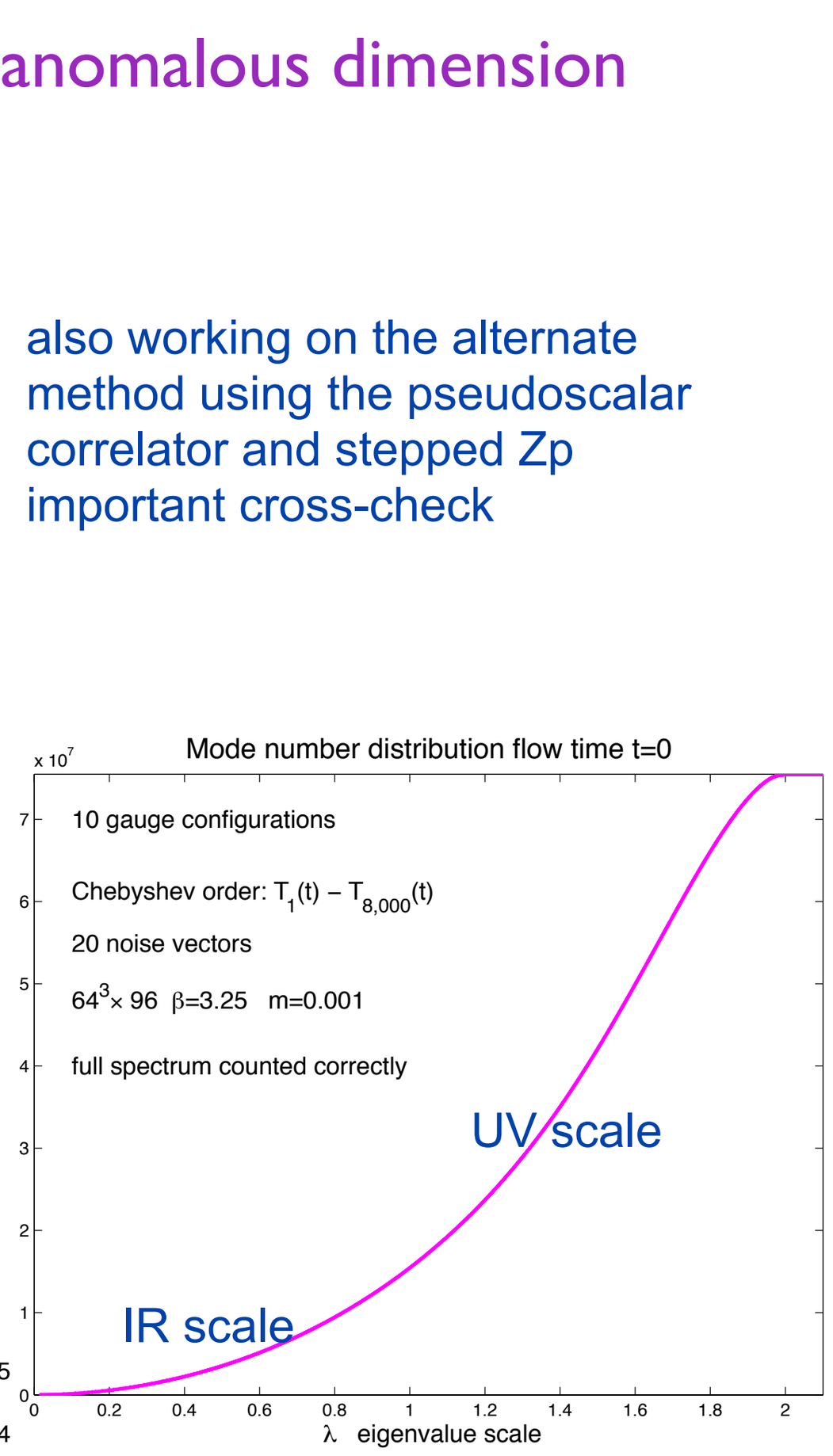
Del Debbio-Zwicky and collaborators, Patella,
Boulder group with lead from Anna Hasenfratz

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

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

also working on the alternate method using the pseudoscalar correlator and stepped Zp important cross-check





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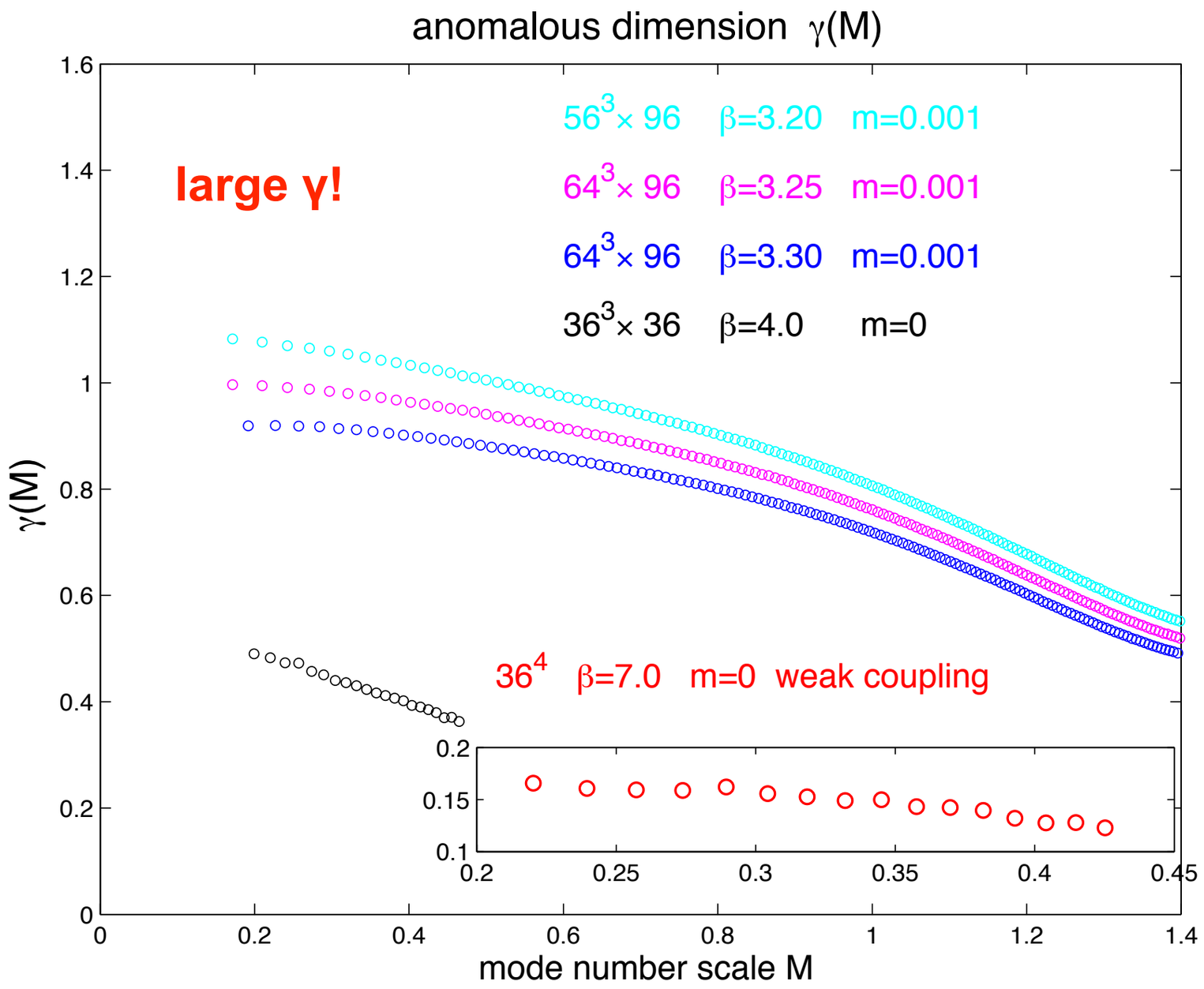

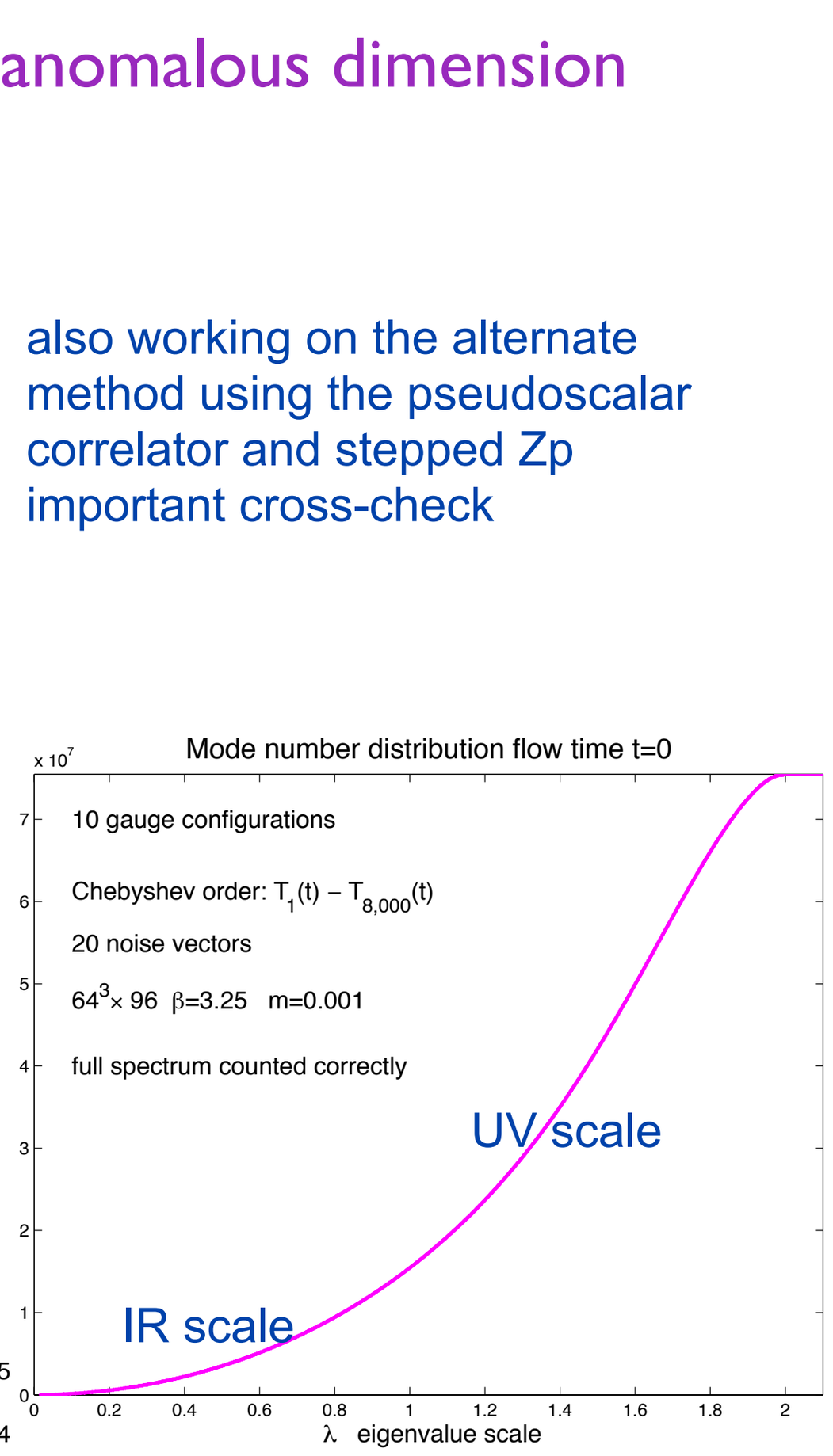

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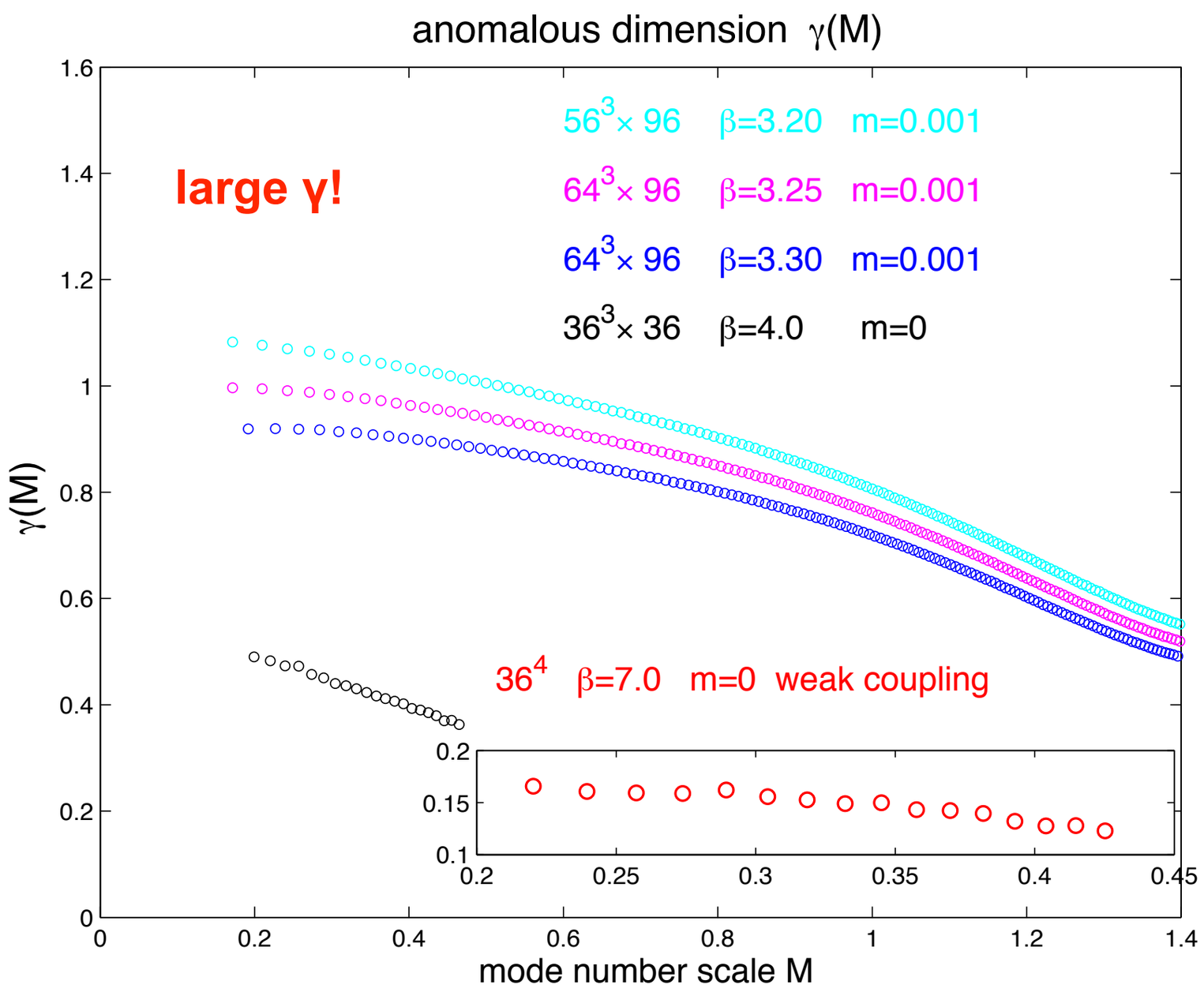
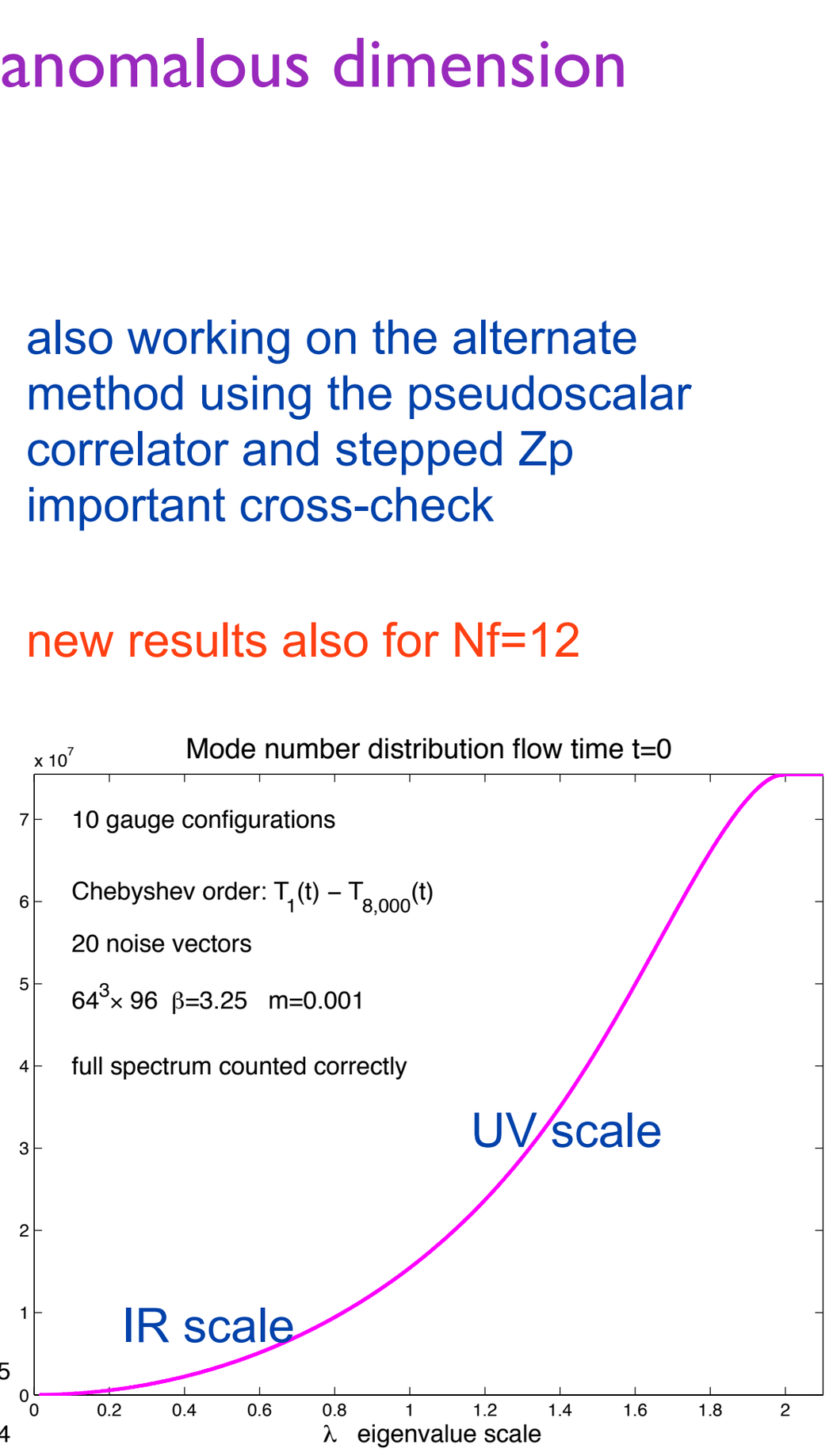
new results also for Nf=12





eta' ? diphoton bump? Witten-Veneziano

PHYSICAL REVIEW D **92,** 111501(R) (2015)

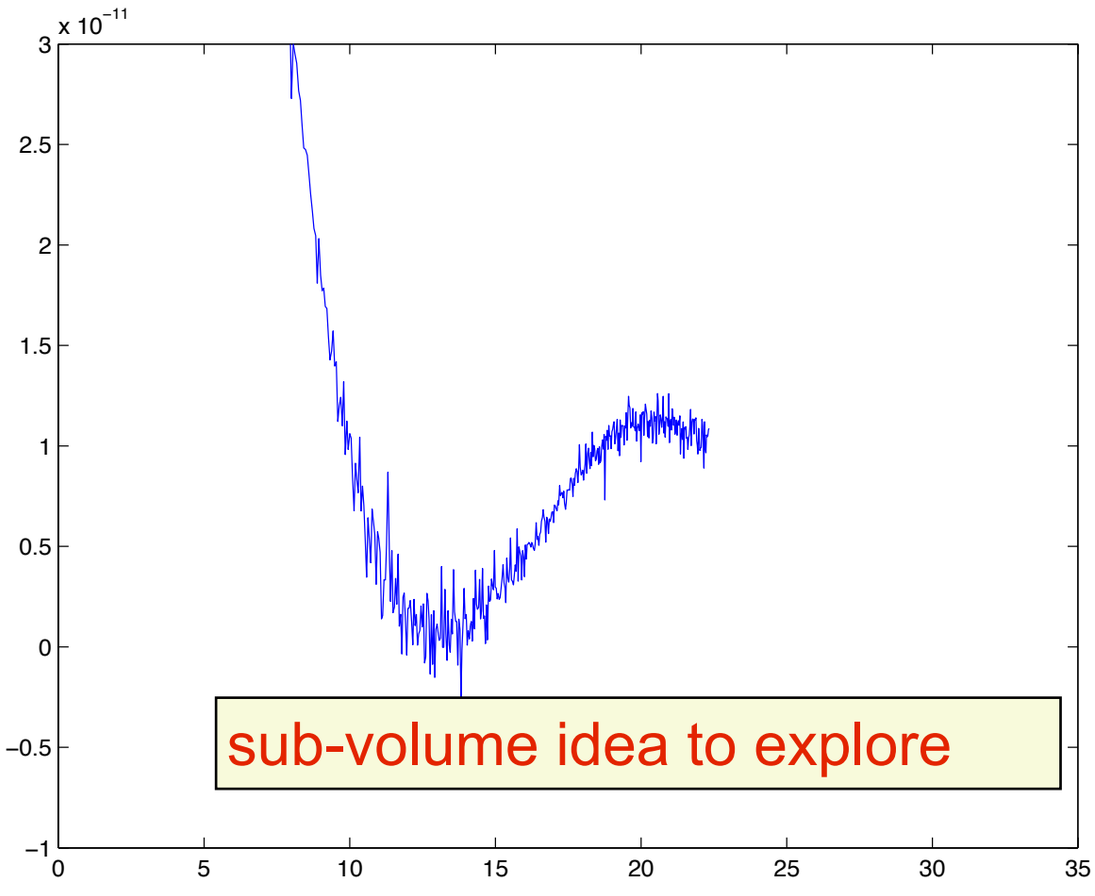
η' meson mass from topological charge density correlator in QCD

H. Fukaya,[1] S. Aoki,[2,3] G. Cossu,[4] S. Hashimoto,[4,5] T. Kaneko,[4,5] and J. Noaki[4]
(JLQCD Collaboration)

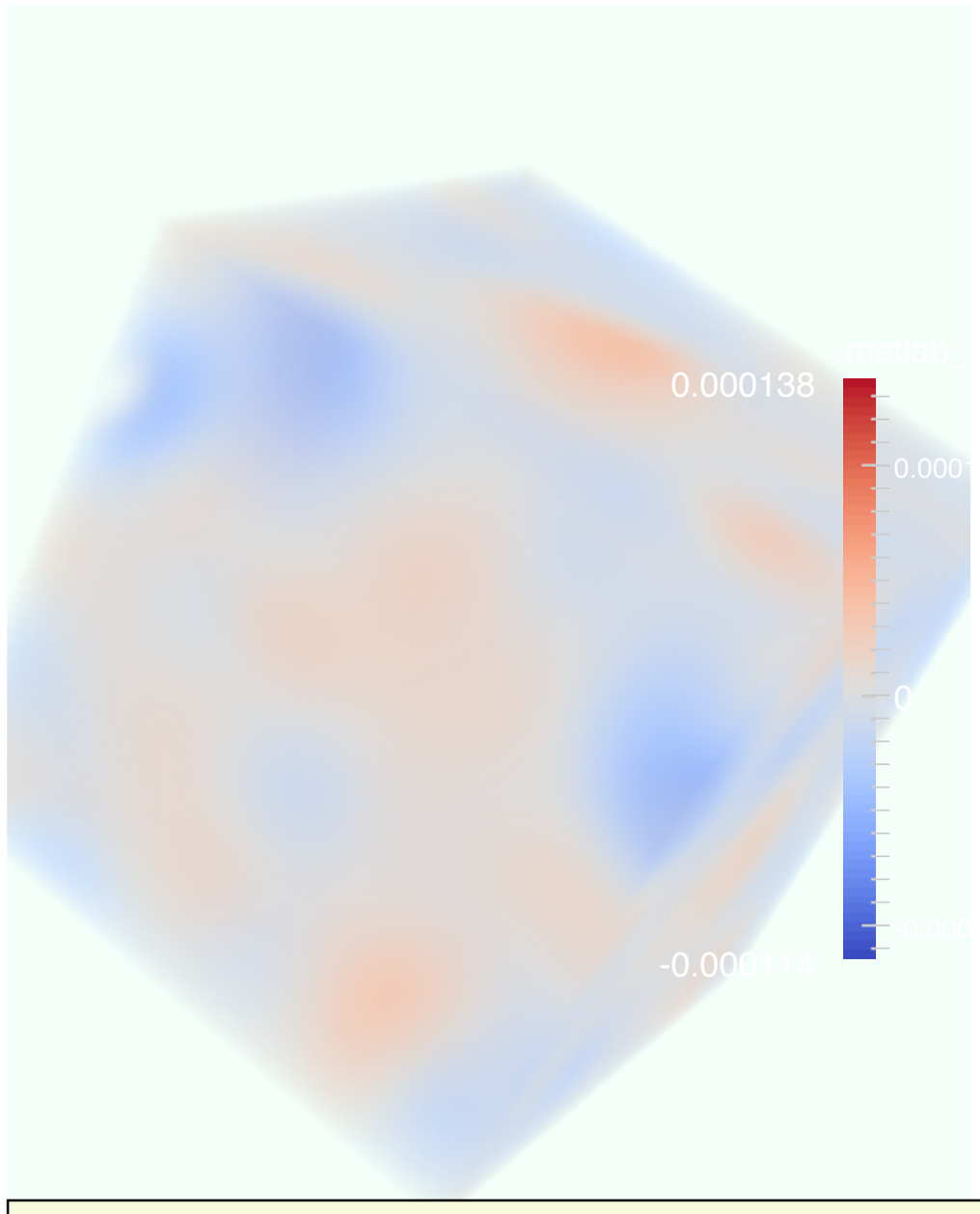
$$\lim_{|x|\to\infty}\langle\rho(x)\rho(0)\rangle_Q = \frac{1}{\Omega}\left(\frac{Q^2}{\Omega} - \chi_t - \frac{c_4}{2\chi_t\Omega}\right) + \mathcal{O}(\Omega^{-3})$$

$$c_4 = -(\langle Q^4\rangle - 3\langle Q^2\rangle^2)/\Omega.$$

$$C(t_1 - t_2) \equiv \langle Q(t_1)Q(t_2)\rangle = \sum_{\vec{x}_1,\vec{x}_2}\langle\rho(x_1)\rho(x_2)\rangle$$

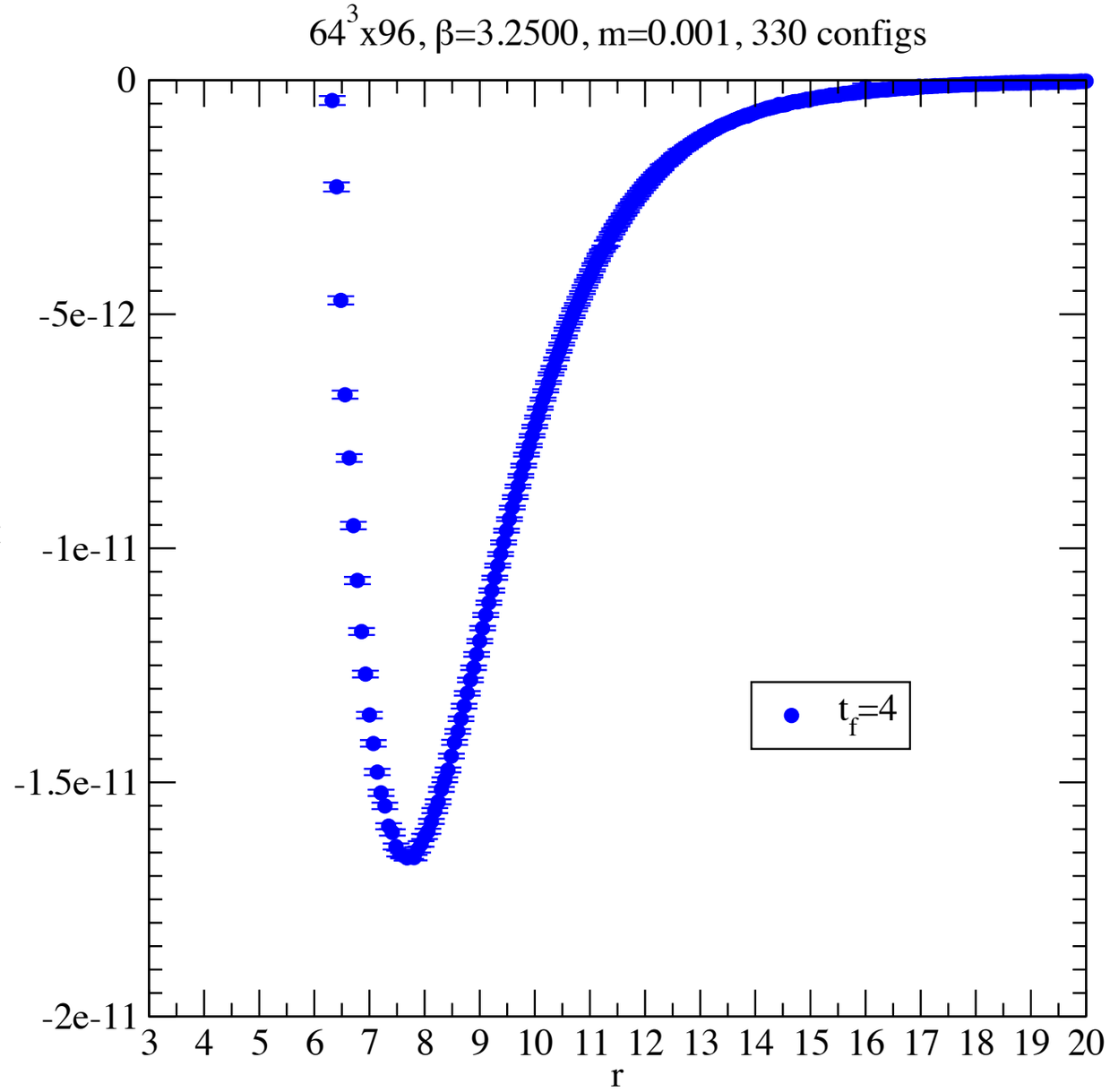


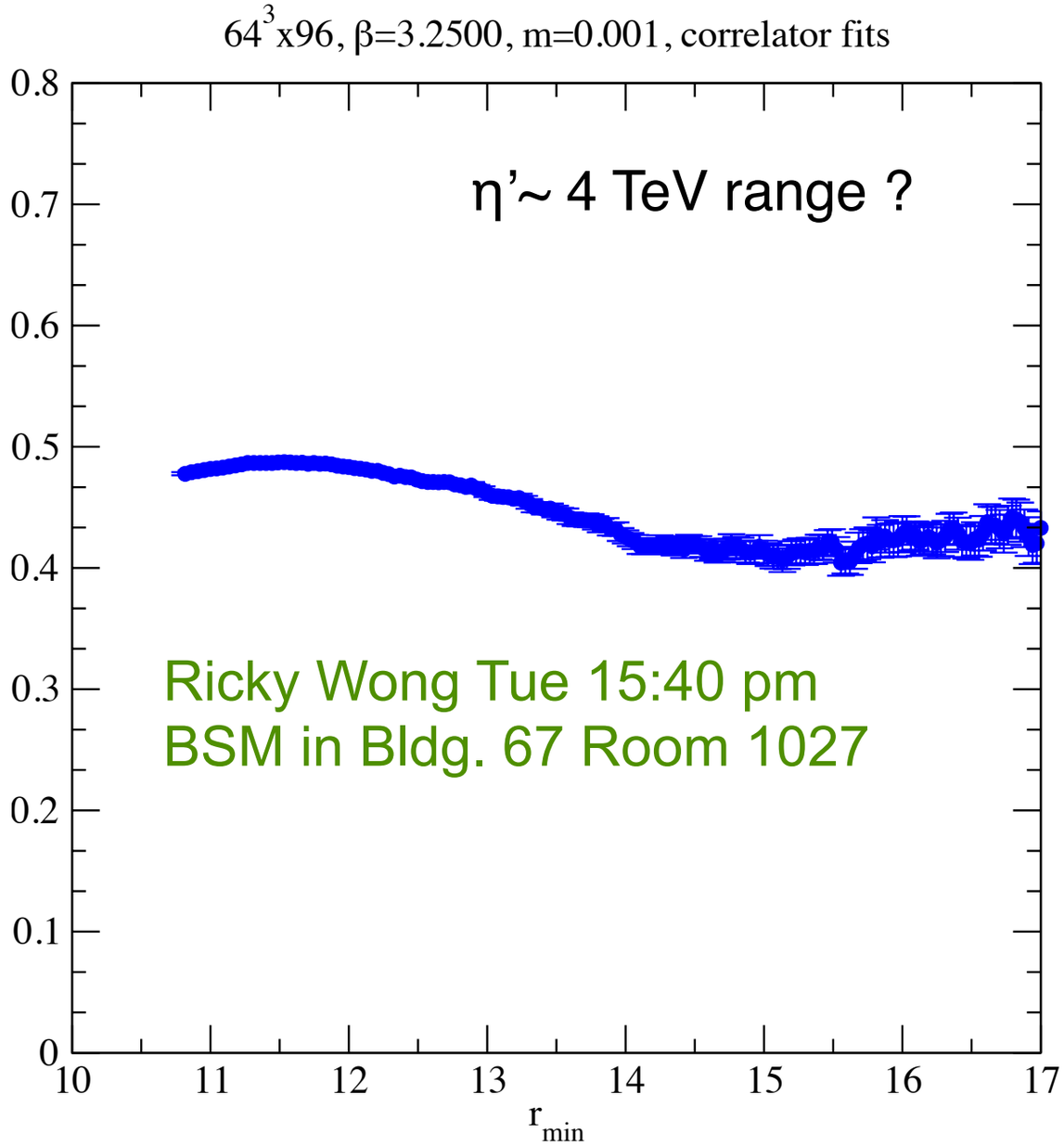
sub-volume idea to explore



sextet model topological charge density

eta' ? diphoton bump? it is not





$\partial_\mu J_5^\mu \sim 2N_f(N \pm 2)q(x)$ flavor singlet current

\+ sign in 2-index symmetric rep

\- sign in 2-index antisymmetric rep

factor 5 enhancement in WV formula

Early universe

Kogut-Sinclair EW phase transition

Relevance in early cosmology (order of the phase transition?)

L_{at}HC is doing a new analysis

- 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?

topic: challenges of baryon spectroscopy and dark matter implications?

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.

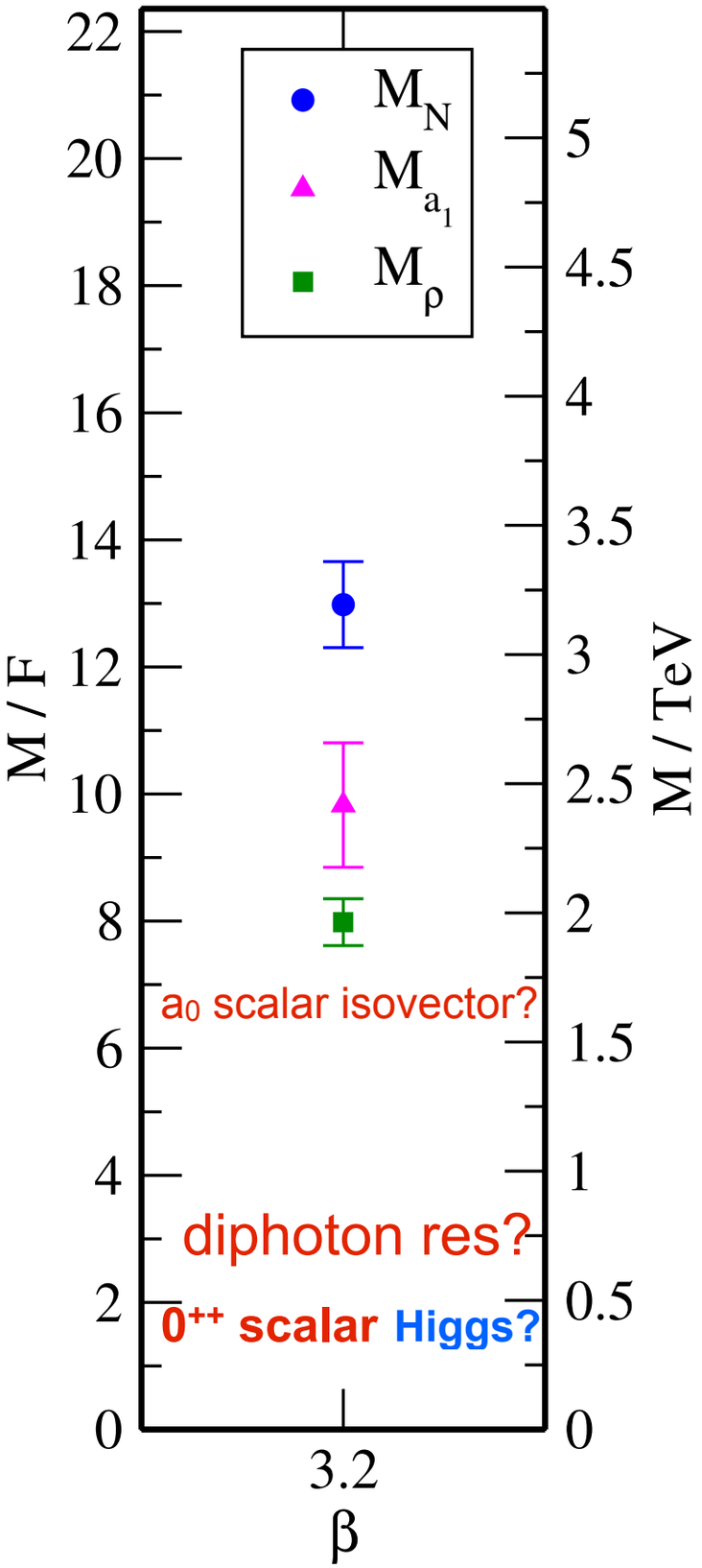
Fermions in the 6-representation carry 2 indices, ψ_{ab}, and transform as

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

and the singlet can be constructed explicitly as

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

unlike QCD



BSM lattice challenges

light scalar separated from resonance spectrum developing

multiple scalars in models close to CW we do not know

Resonance spectrum building up

what is the eta'? very heavy

entangled scalar-goldstone dynamics sigma model or dilaton ?
how to decouple and isolate the light scalar ?

bridge between UV and IR scale in the works
scale-dependent gauge coupling - high precision

predictions without attempted UV completions ?
related phenomenology

consistent EW embedding → dark matter

BSM needs new lattice tools → RMT, ππ-scattering, …