USQCD All Hands 2016

Minimal near-conformal composite Higgs

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

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USQCD All Hands 2016

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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:

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

has to be unlike QCD

light scalar separated from
2-3 TeV resonance spectrum

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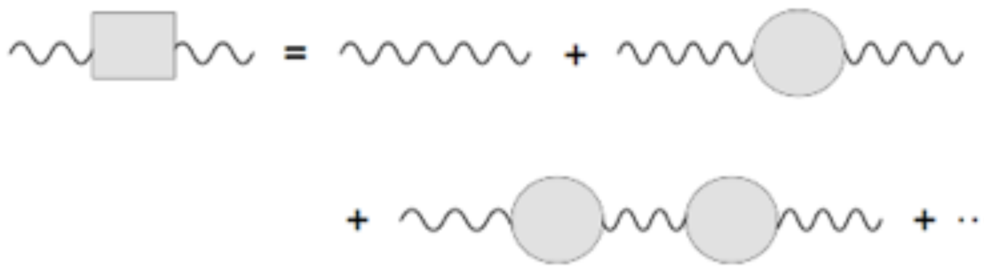
has to be unlike QCD

light scalar separated from 2-3 TeV resonance spectrum

yes, I know, there is perhaps the diphoton bump at 750 GeV!

composite Higgs mechanism

- m=0 fermion doublet SU(2) flavor sextet rep in our proposal
- light scalar is the excitation of the chiral condensate
- Goldstone particle important in composite Higgs mechanism …
- f_π sets the EW scale ~ 250 GeV and gauge coupling g

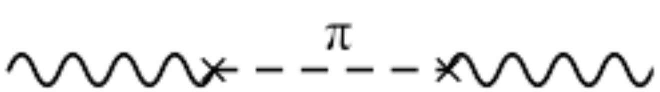


$$G_{\mu\nu}(q) = \frac{-i}{q^2 - g^2\Pi(q^2)/2}(P_T)_{\mu\nu}\,, \qquad (P_T)_{\mu\nu} \equiv \eta_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}$$

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

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

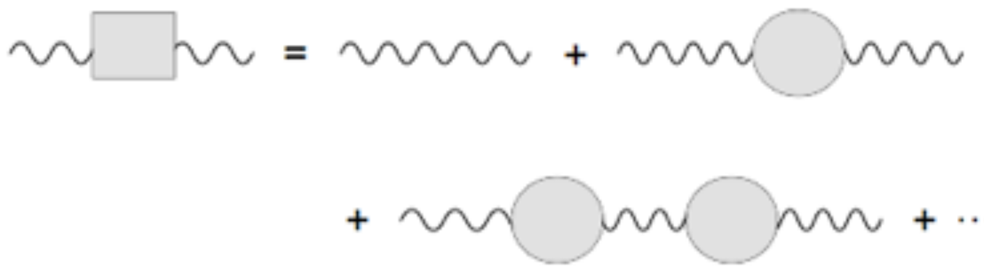
$$\langle 0|J^+_\mu|\pi^-(p)\rangle = i\frac{f_\pi}{\sqrt{2}}p_\mu$$



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

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

composite Higgs mechanism



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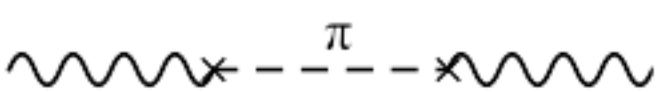

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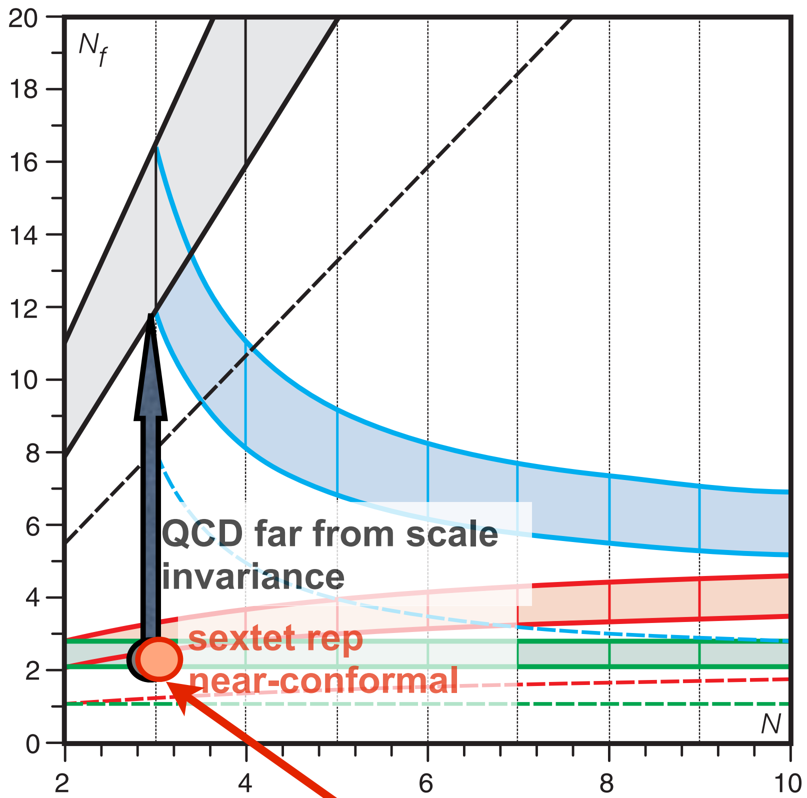
Higgs mechanism does not depend on hypercharge content of fermion multiplet after EW is gauged!

Goldstone content and hypercharge content are important if model wants more than just to be a gauge theory study.

I will discuss in this context the BSM models in play with focus on our sextet proposal.

light 0++ scalar sextet doublet model diphoton?

SCGT Theory Space



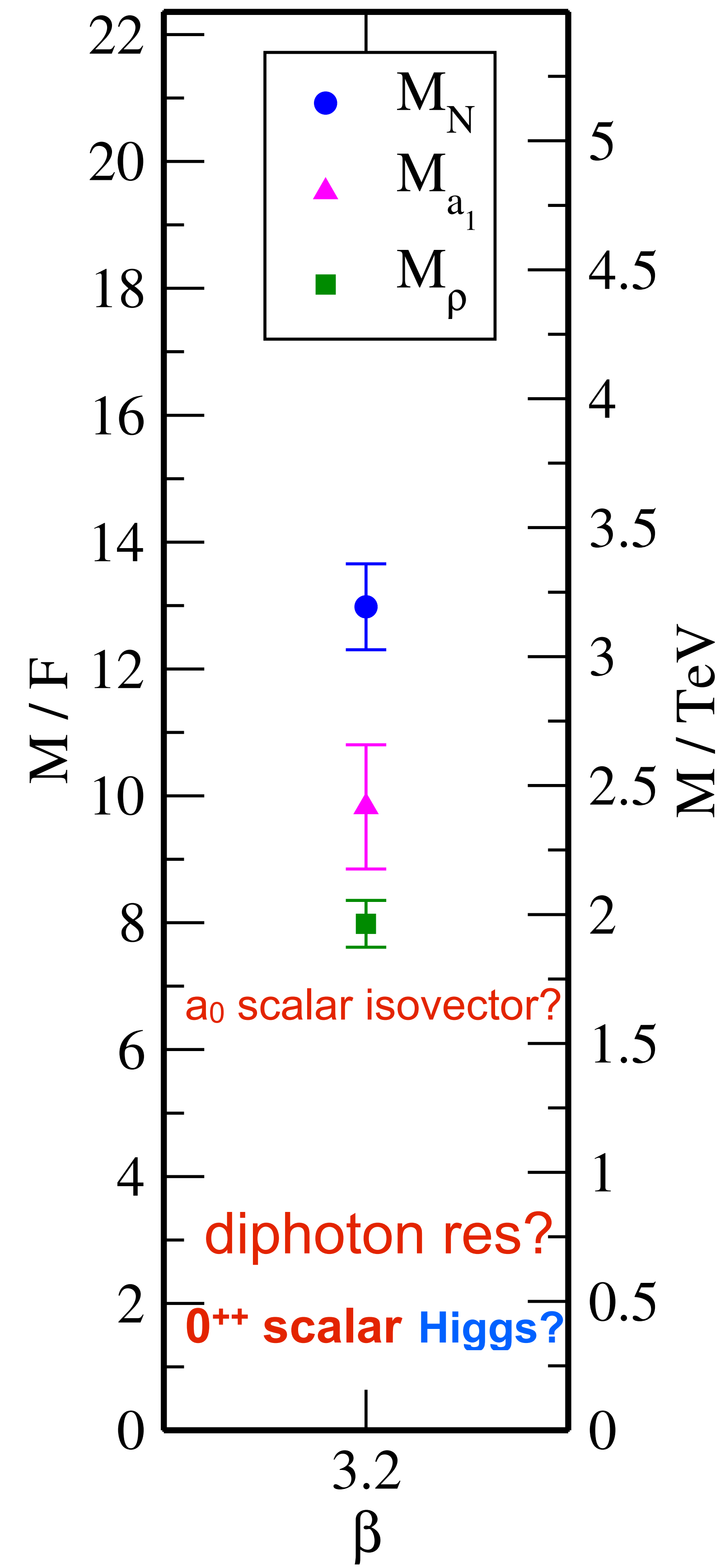
$\begin{bmatrix} u(+e/2) \\ d(-e/2) \end{bmatrix}$ minimal EW embedding

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
tuning lever

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

QCD intuition for near-conformal
compositeness is plain wrong

composite Higgs-like scalar close to the
conformal window with 2-3 TeV new physics



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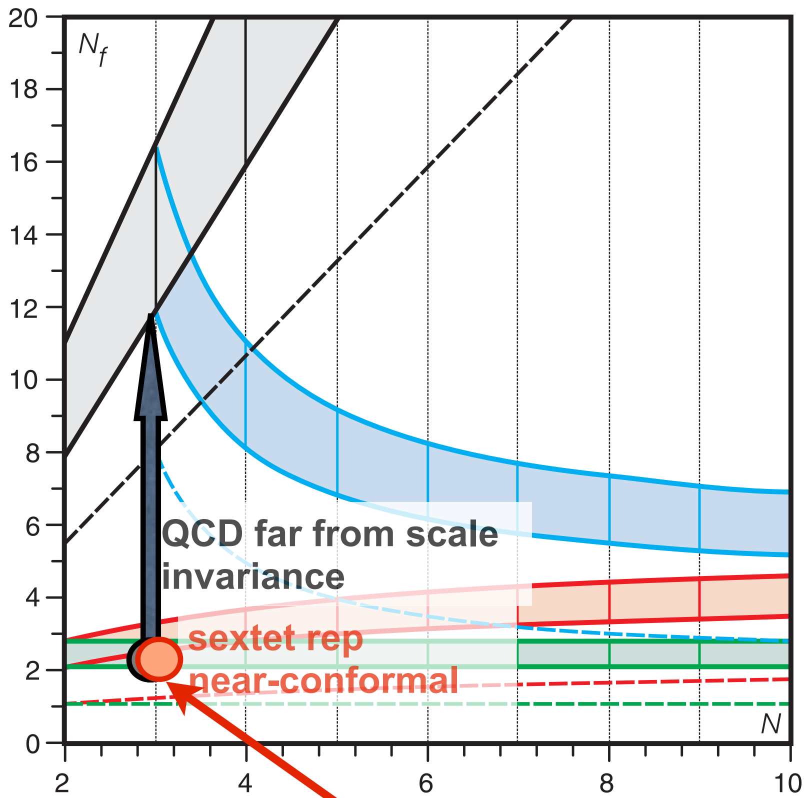

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composite Higgs-like scalar close to the conformal window with 2-3 TeV new physics

minimal composite near-conformal Higgs

USQCD White Paper

chiSB is driving it

two anomaly solutions

EW embedding understood

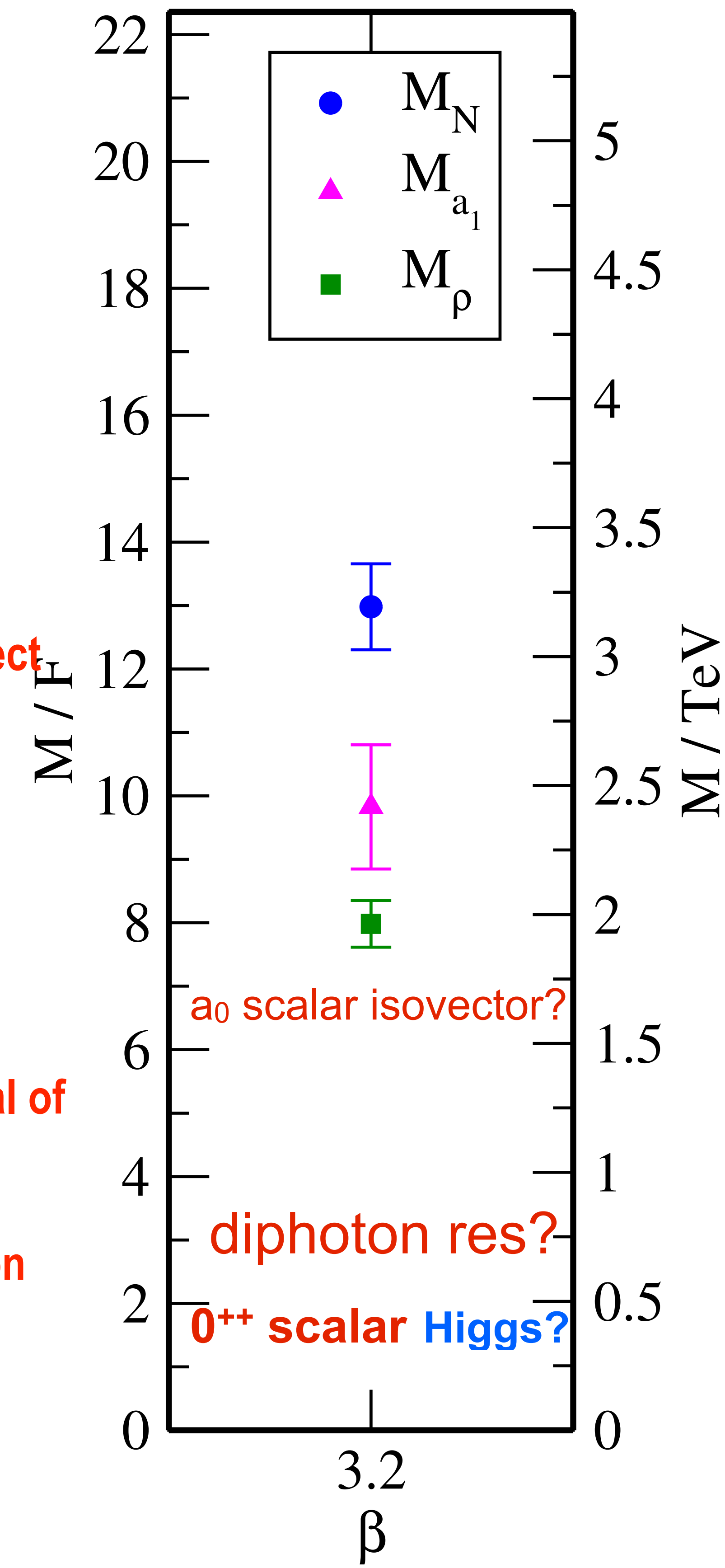
baryon does not violate direct DM searches

750 GeV diphoton bump?

coupled scalar-goldstone dynamics?

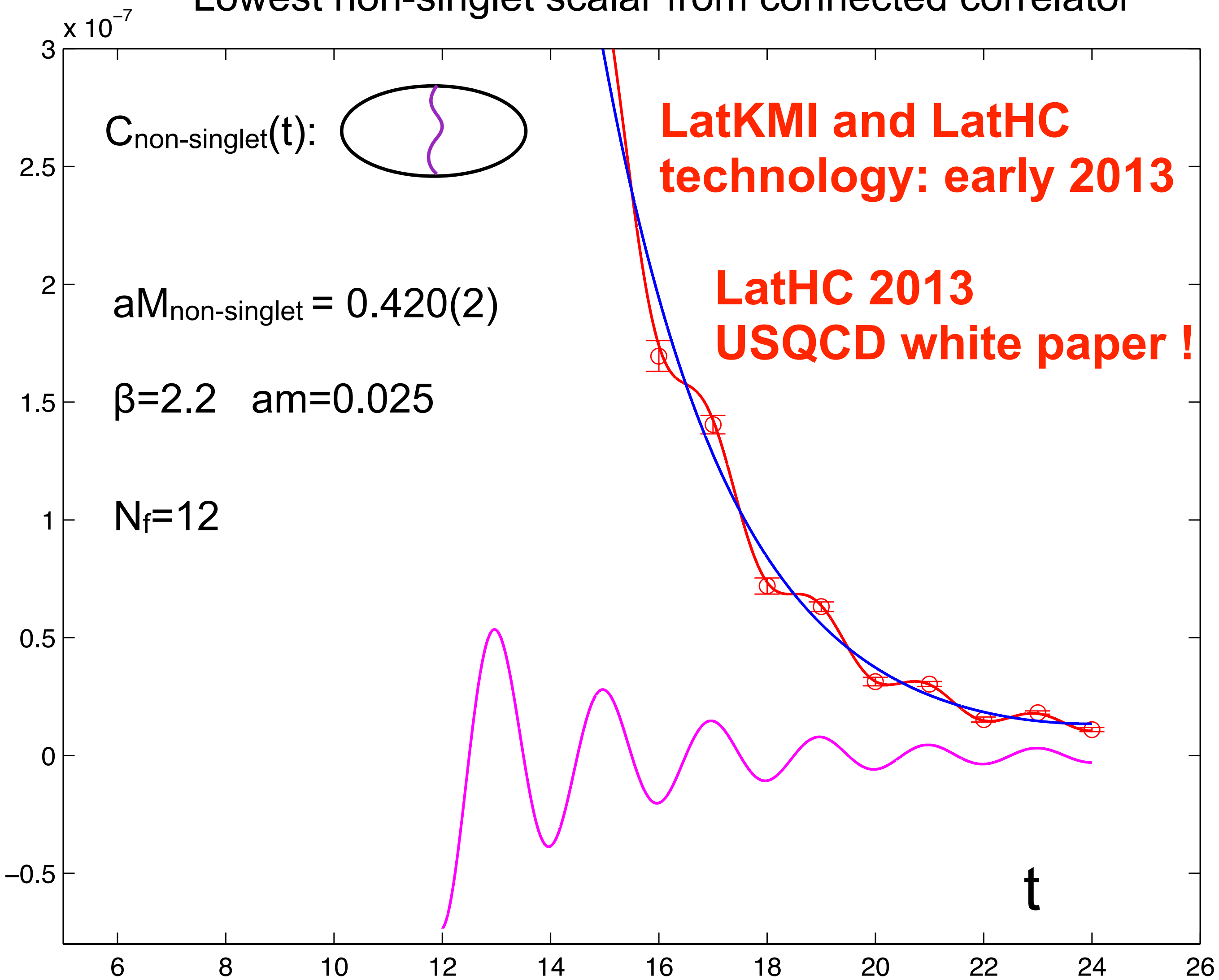
constraint effective potential of composite scalar?

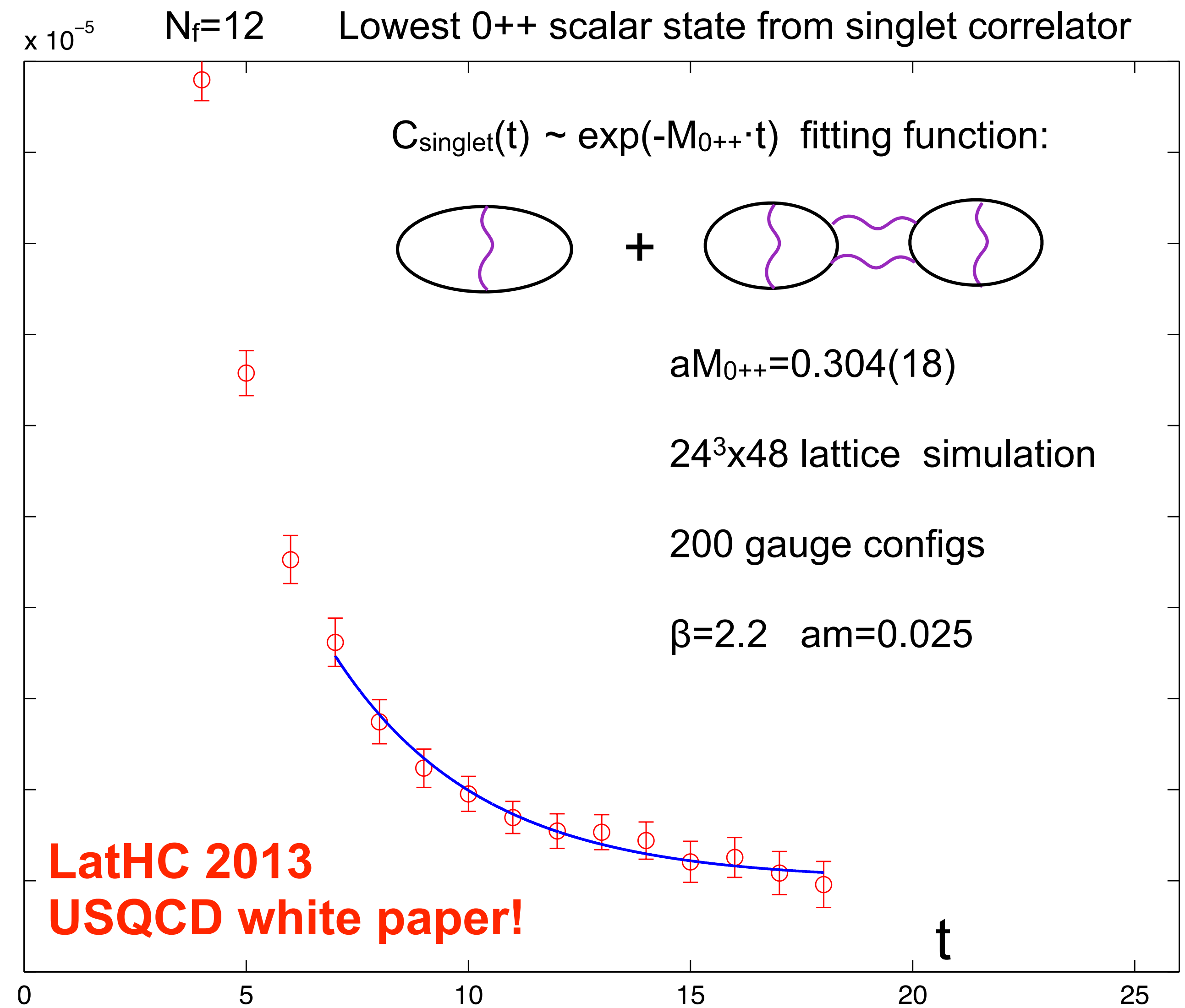
Electroweak phase transition



light 0++ scalar   LatKMI and LatHC early history in 2013

test of technology:





$$C(t) = \sum_n \left[A_n e^{-m_n(\Gamma_S \otimes \Gamma_T)t} + (-1)^t B_n e^{-m_n(\gamma_4\gamma_5\Gamma_S \otimes \gamma_4\gamma_5\Gamma_T)t}\right]$$

staggered correlator

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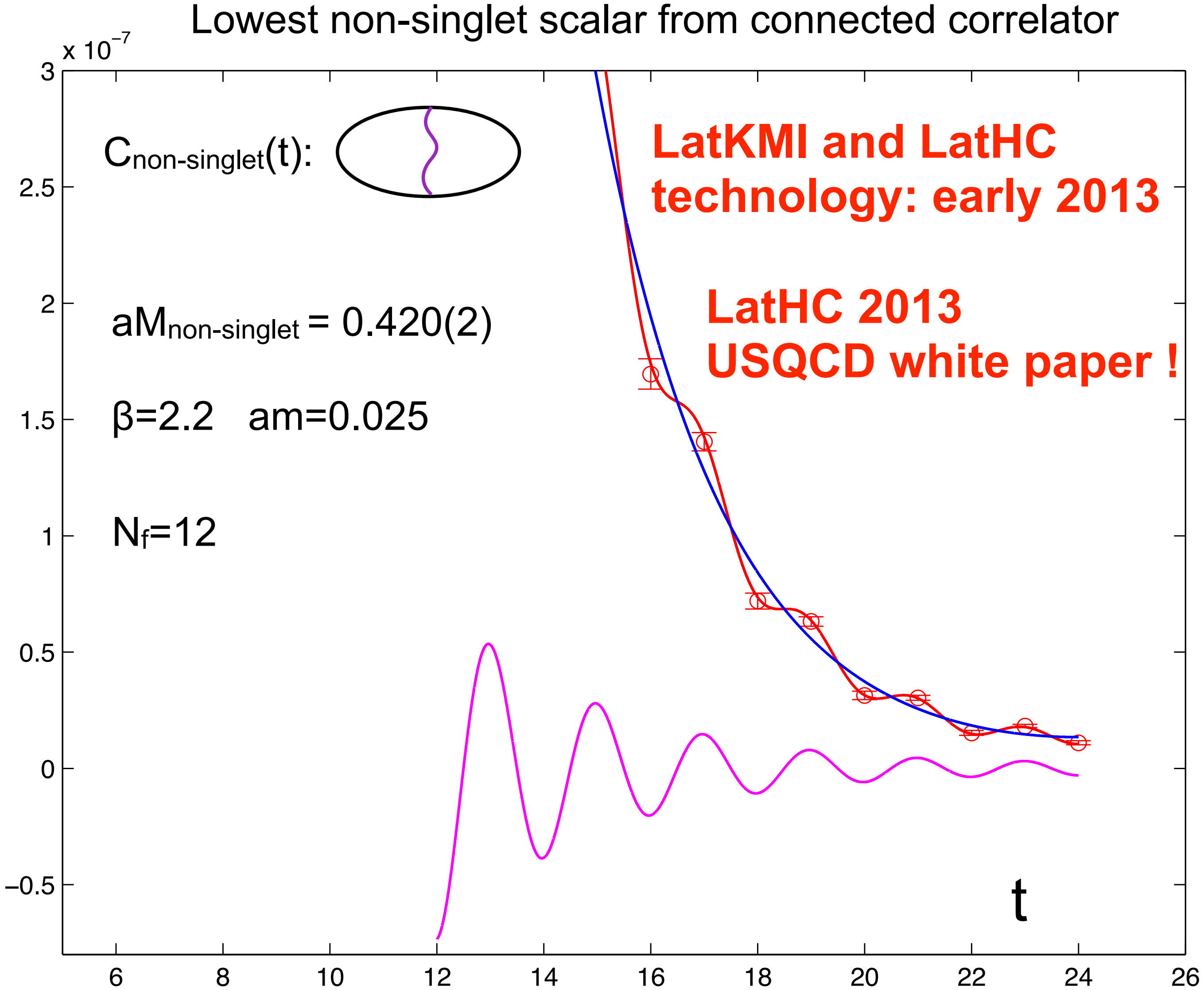

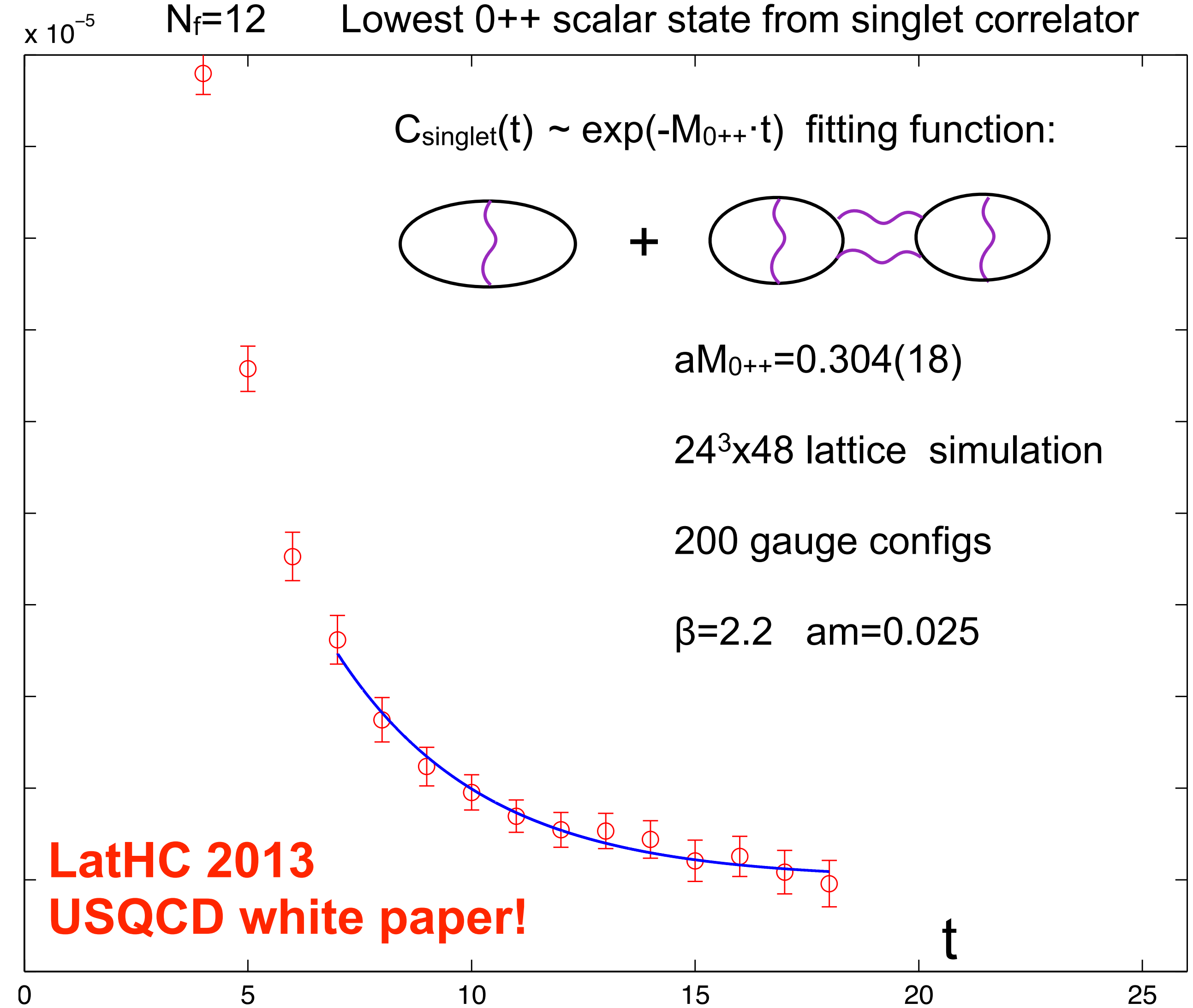

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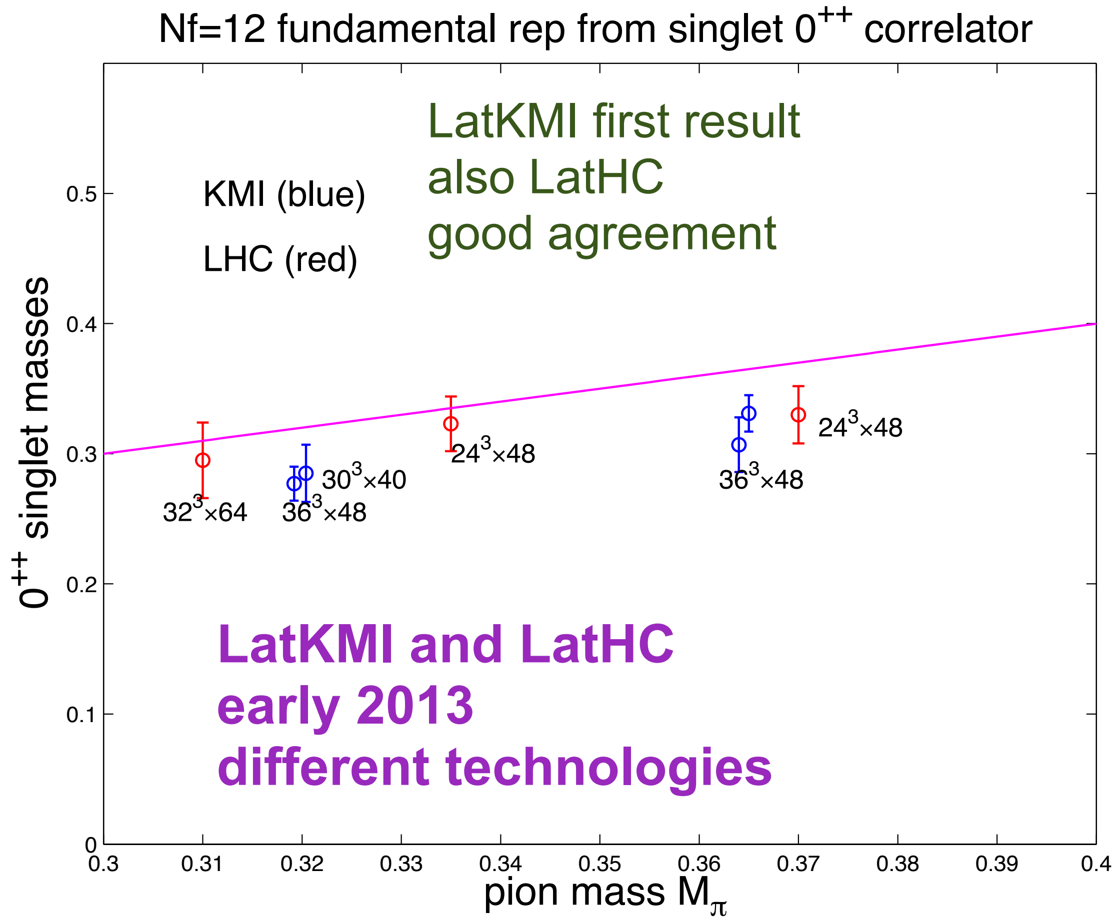
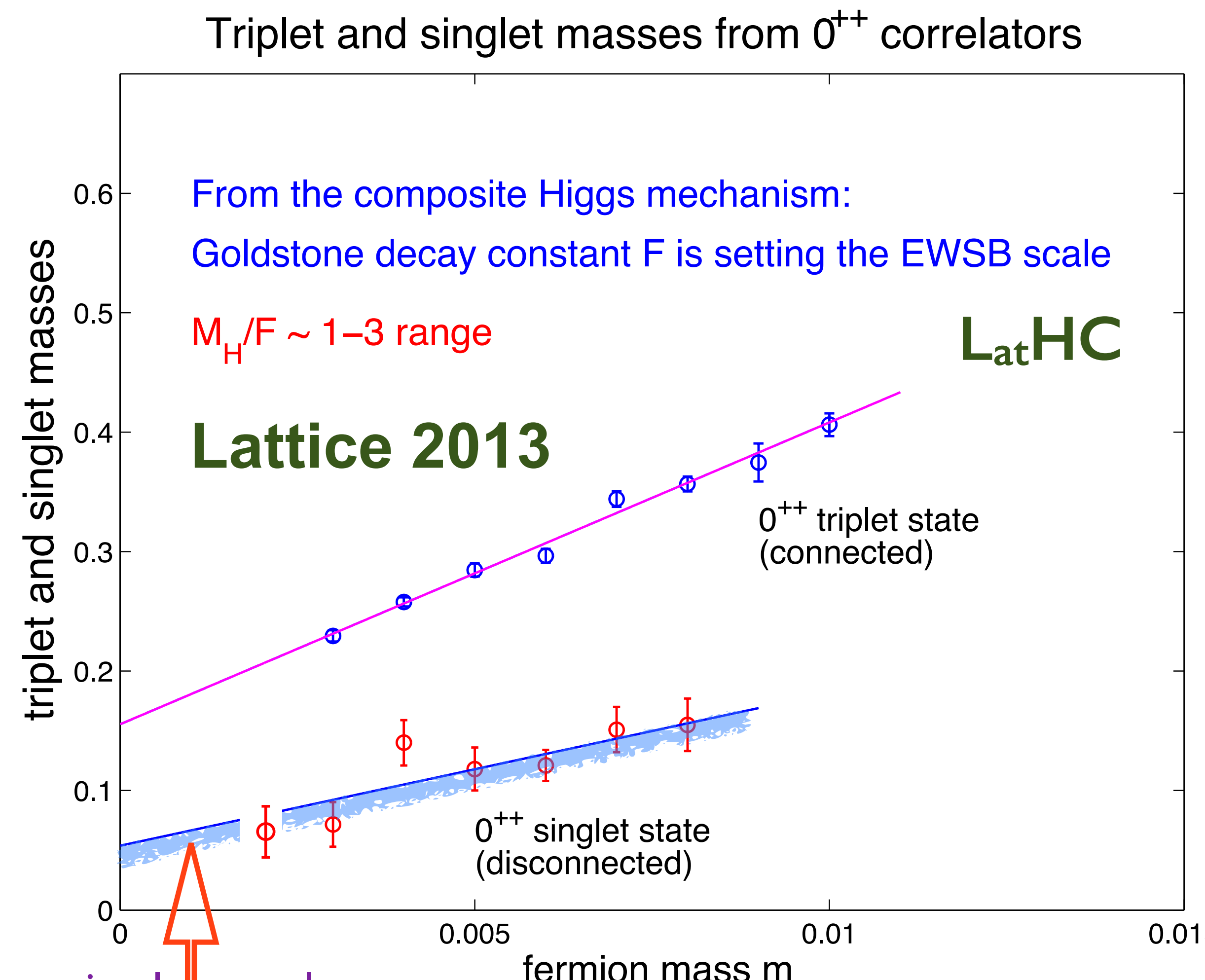
staggered correlator

similar analysis in sextet model with N_f=2   since 2013

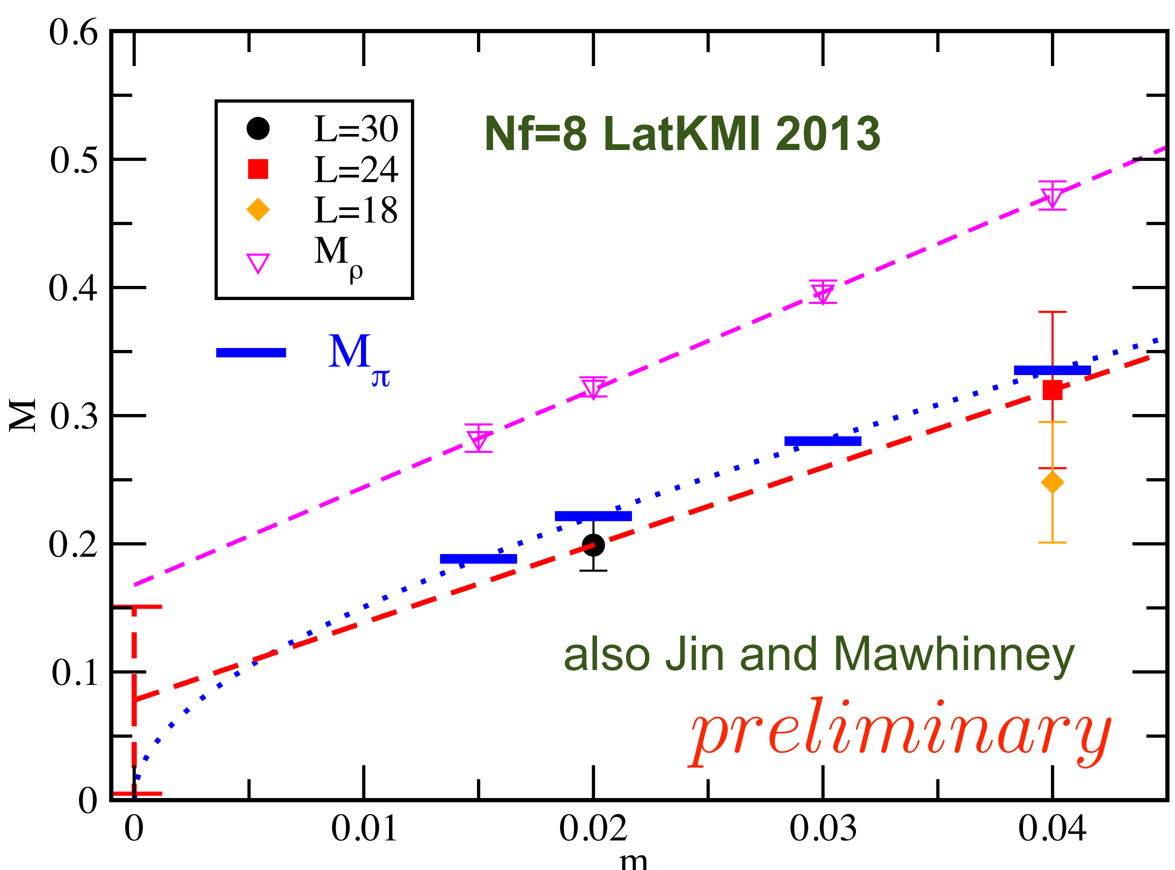
light 0++ scalar   LatKMI and LatHC early history in 2013



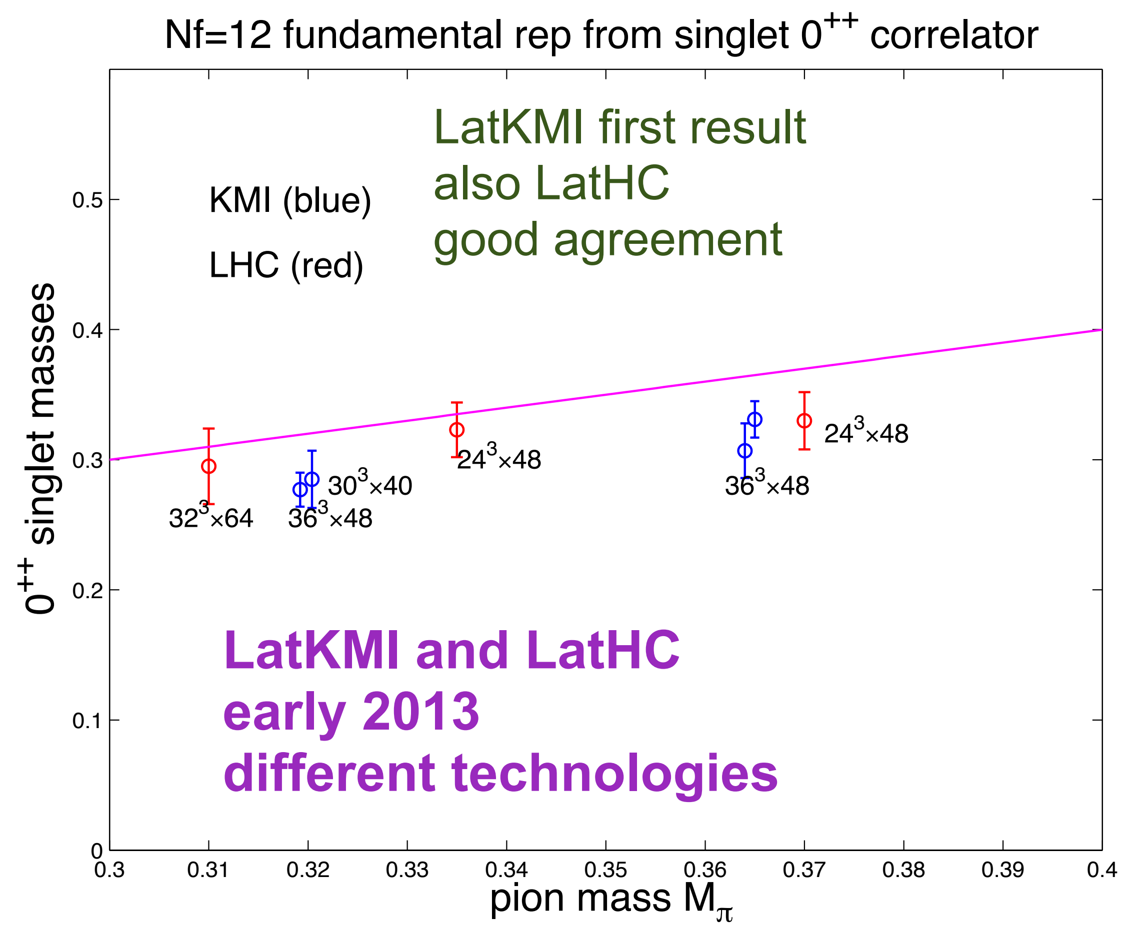
LatHC group focus on sextet model



running large volumes
m fit range 0.001 - 0.002



light 0++ scalar   LatKMI and LatHC early history in 2013



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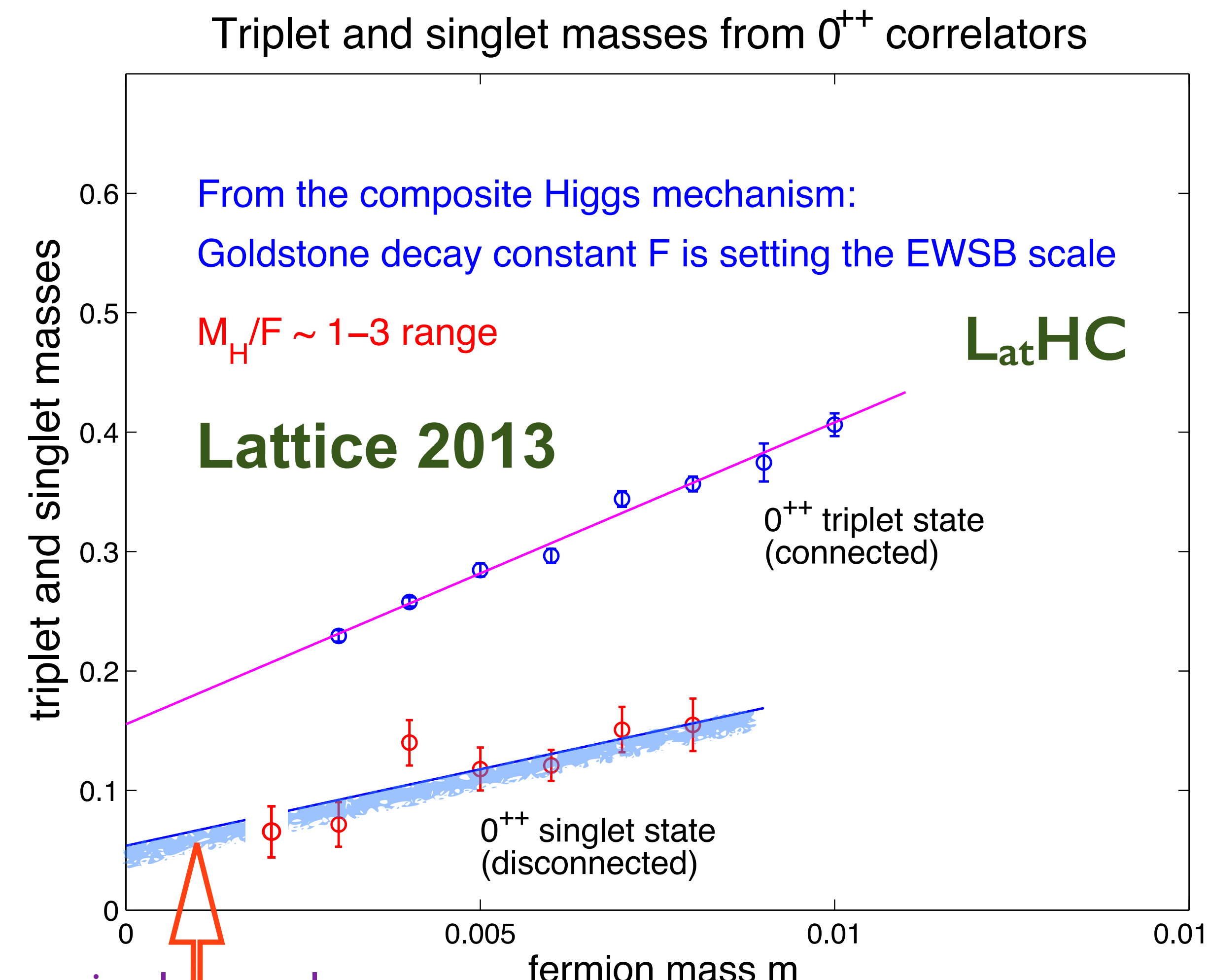

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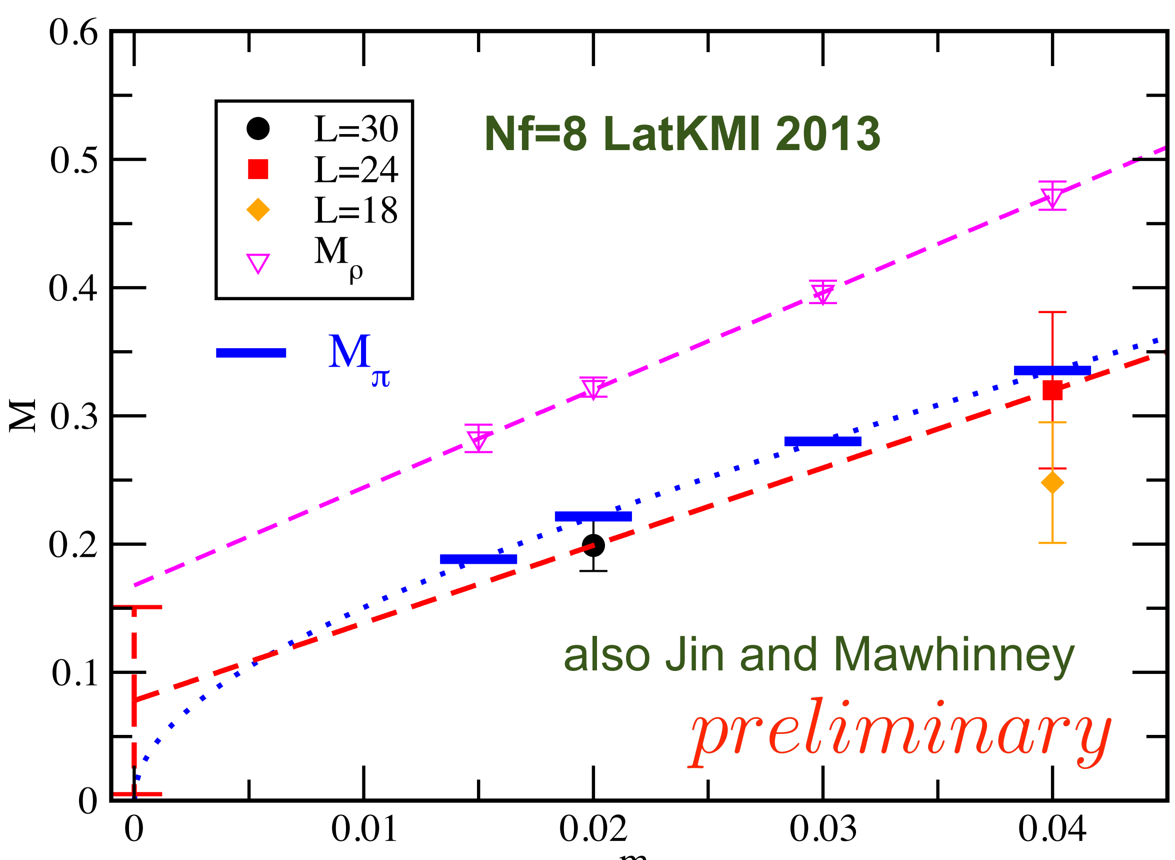


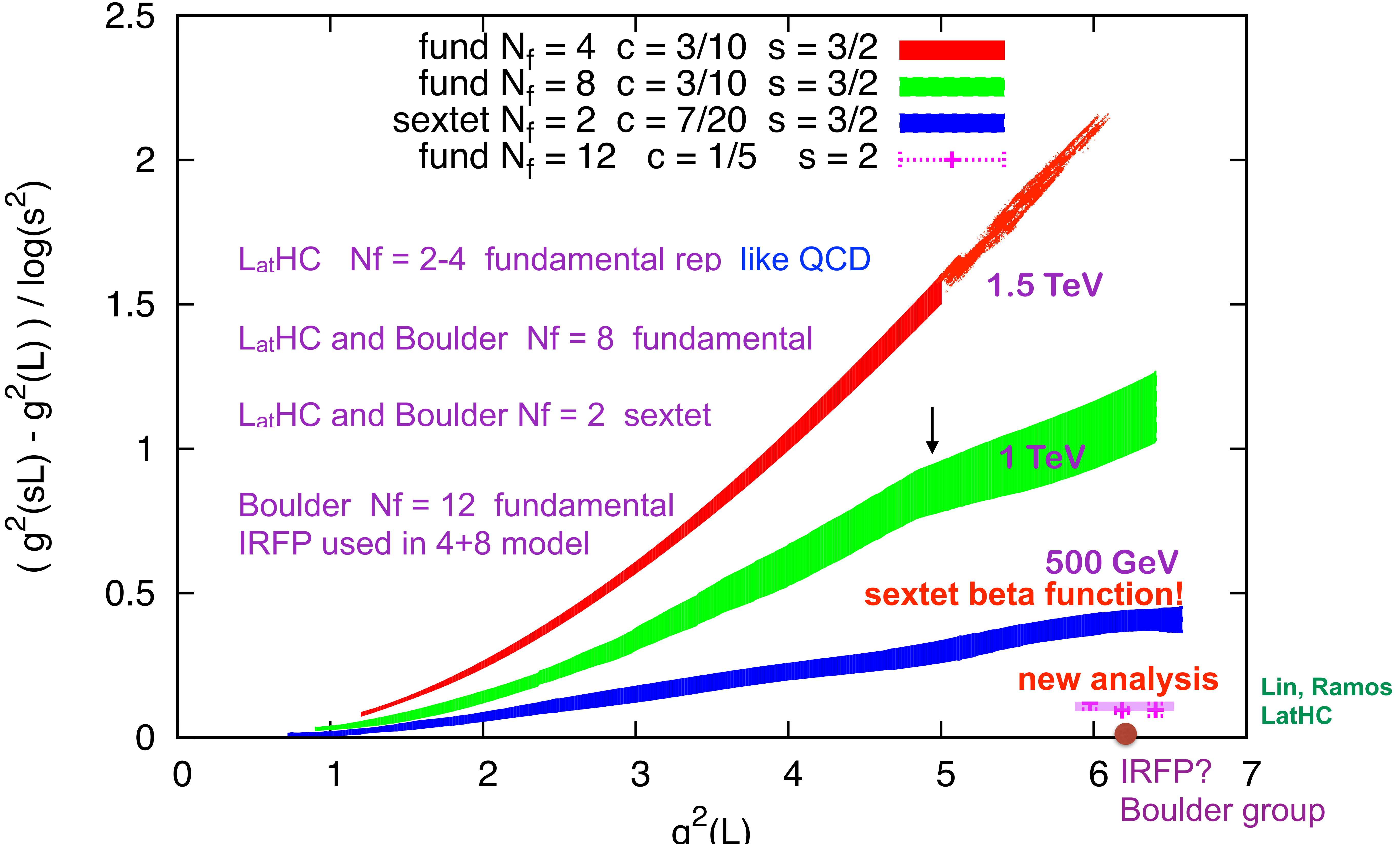
LSD 2016 Nf=8 2.0
scalar at 1 TeV with 63 goldstones

new nf=4+8 study scalar at 1 TeV

how do the scalars compare?

scale-dependent coupling of 4 lattice BSM models

gradient flow based method with high accuracy



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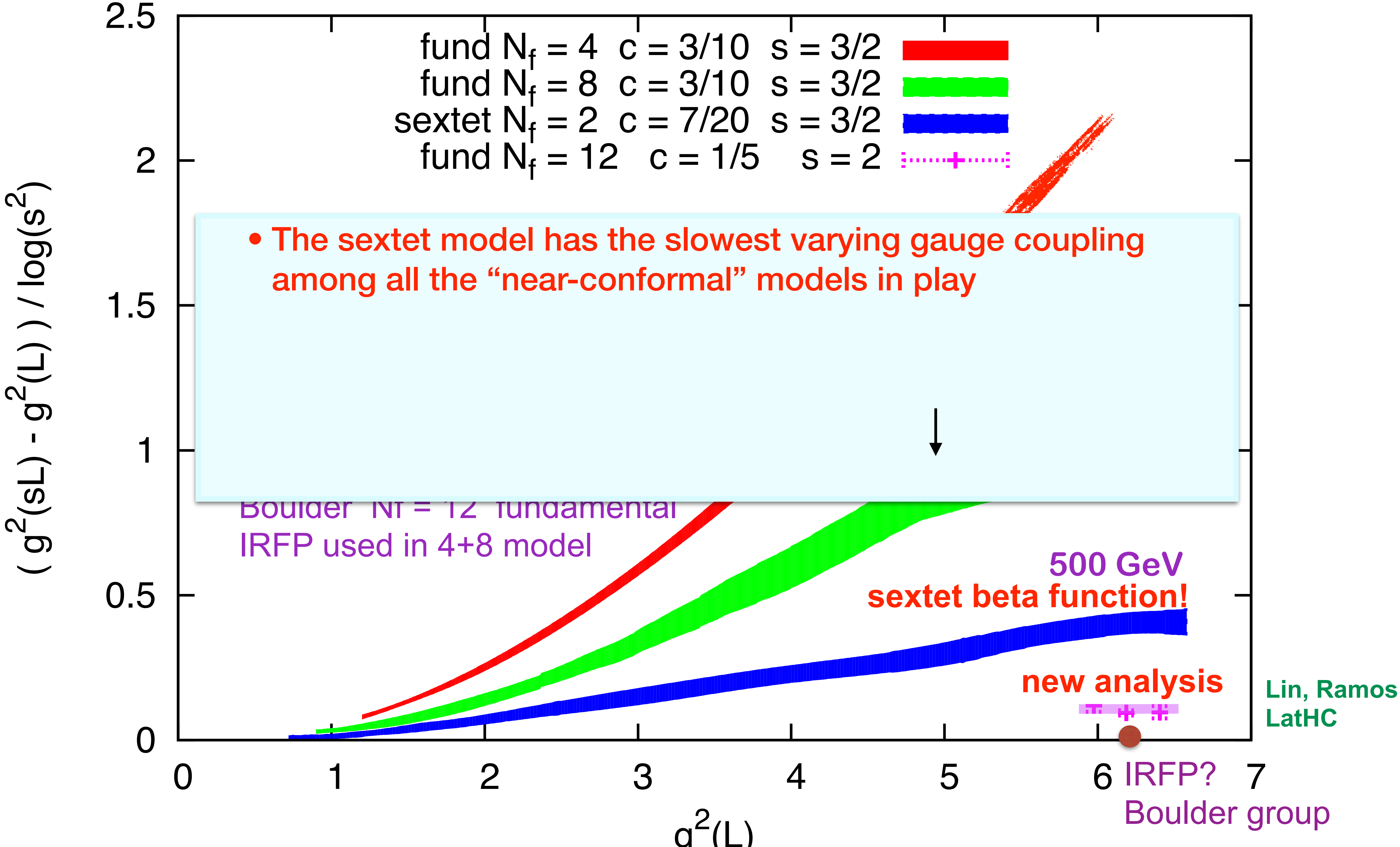

- The sextet model has the slowest varying gauge coupling among all the “near-conformal” models in play

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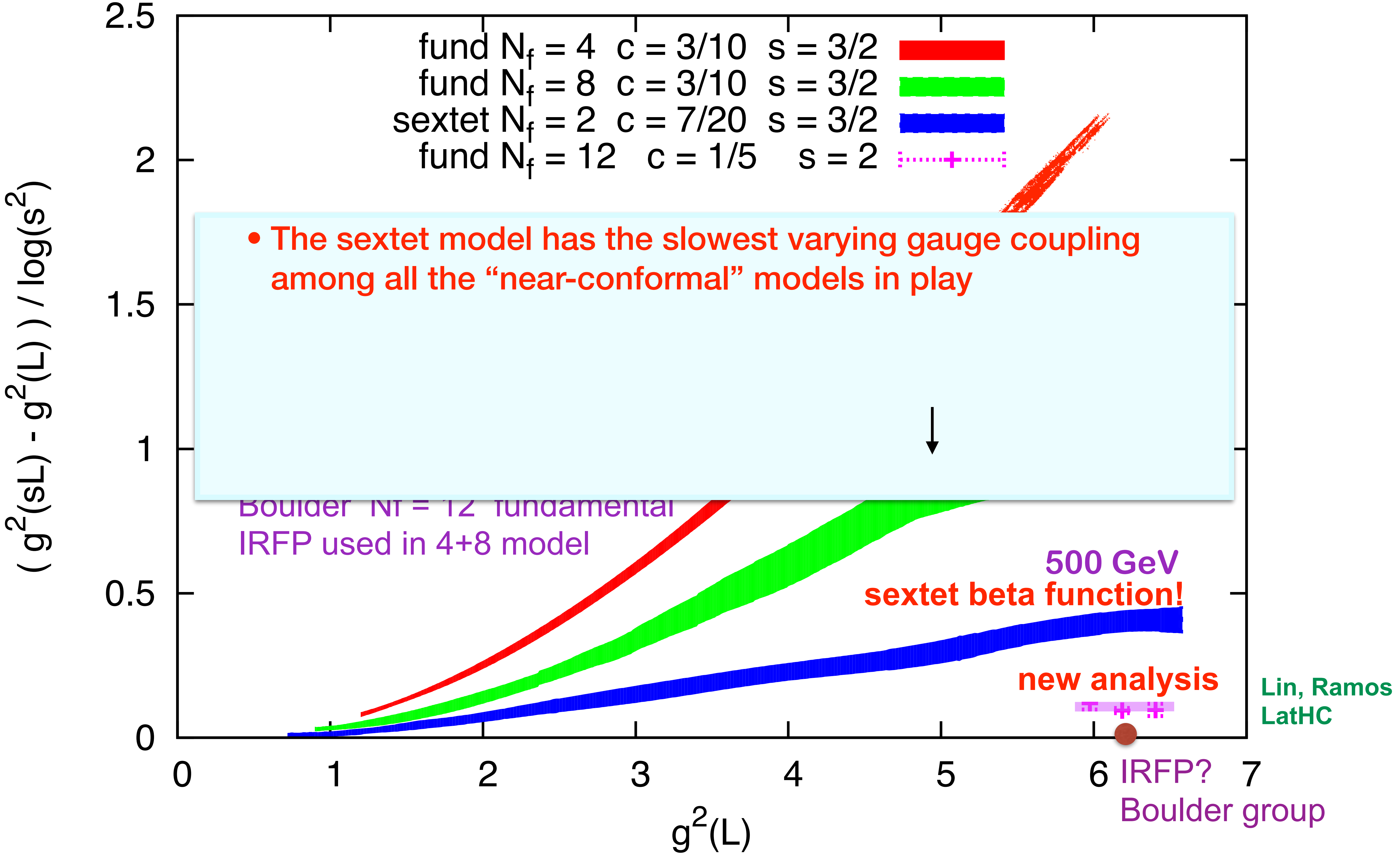

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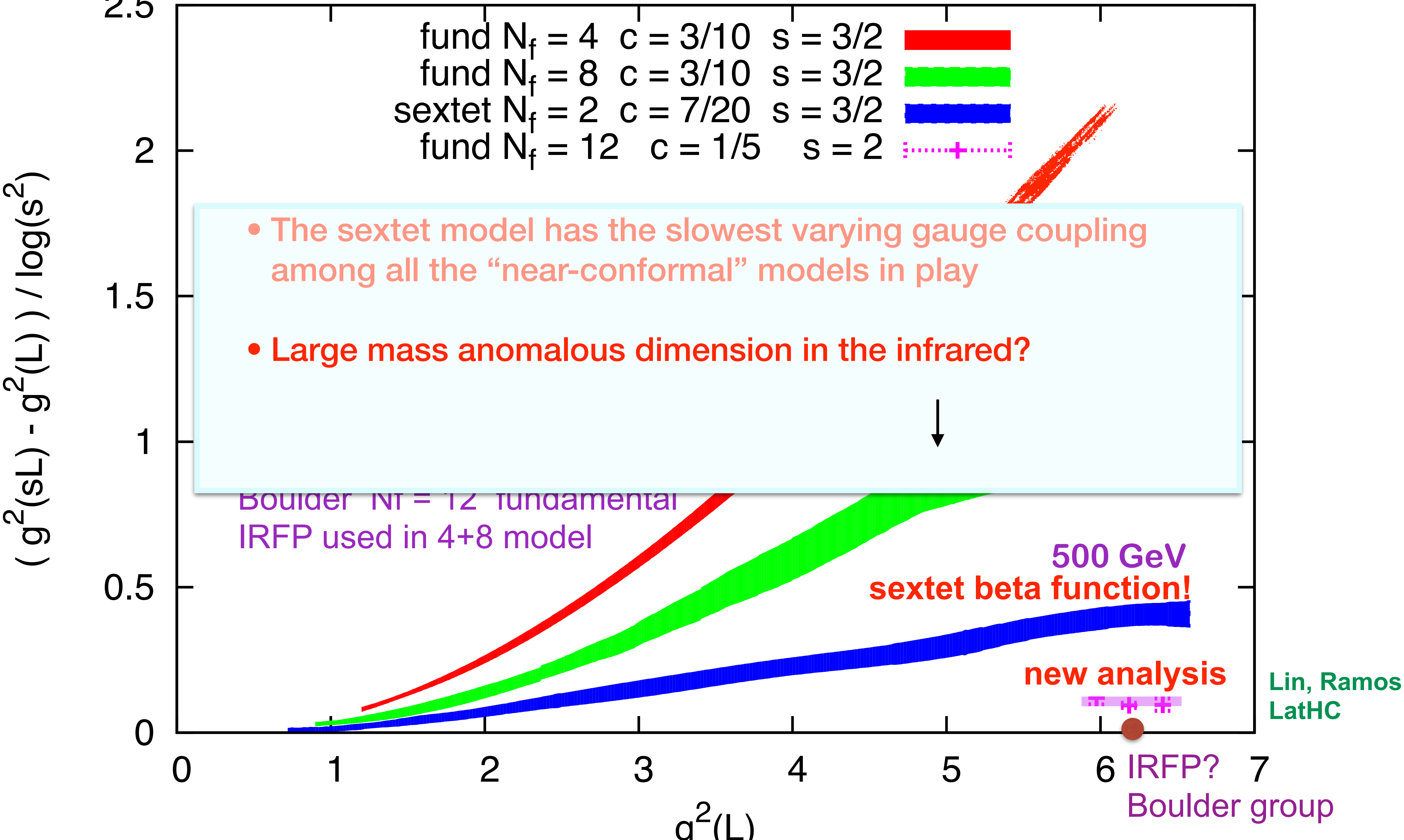

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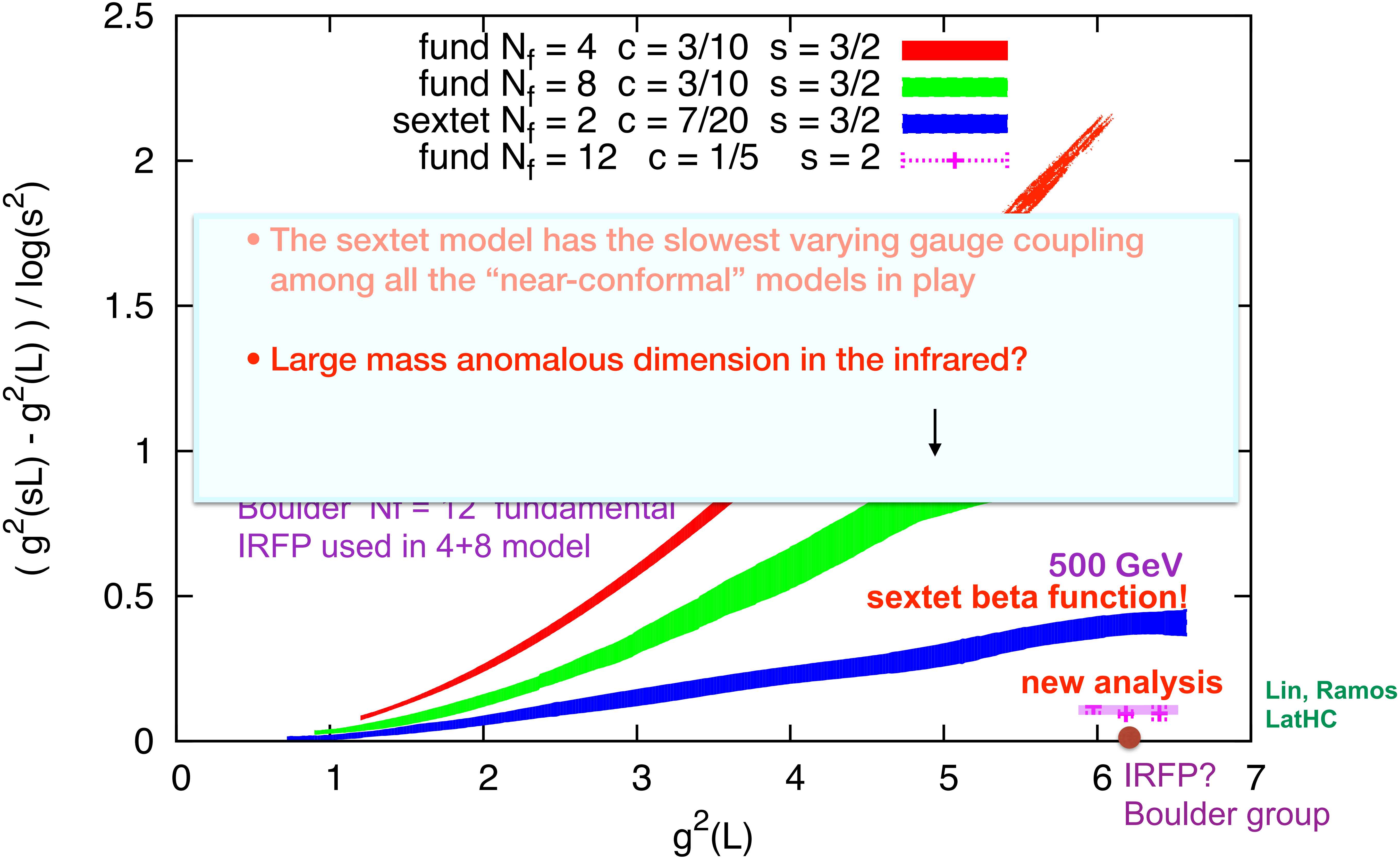

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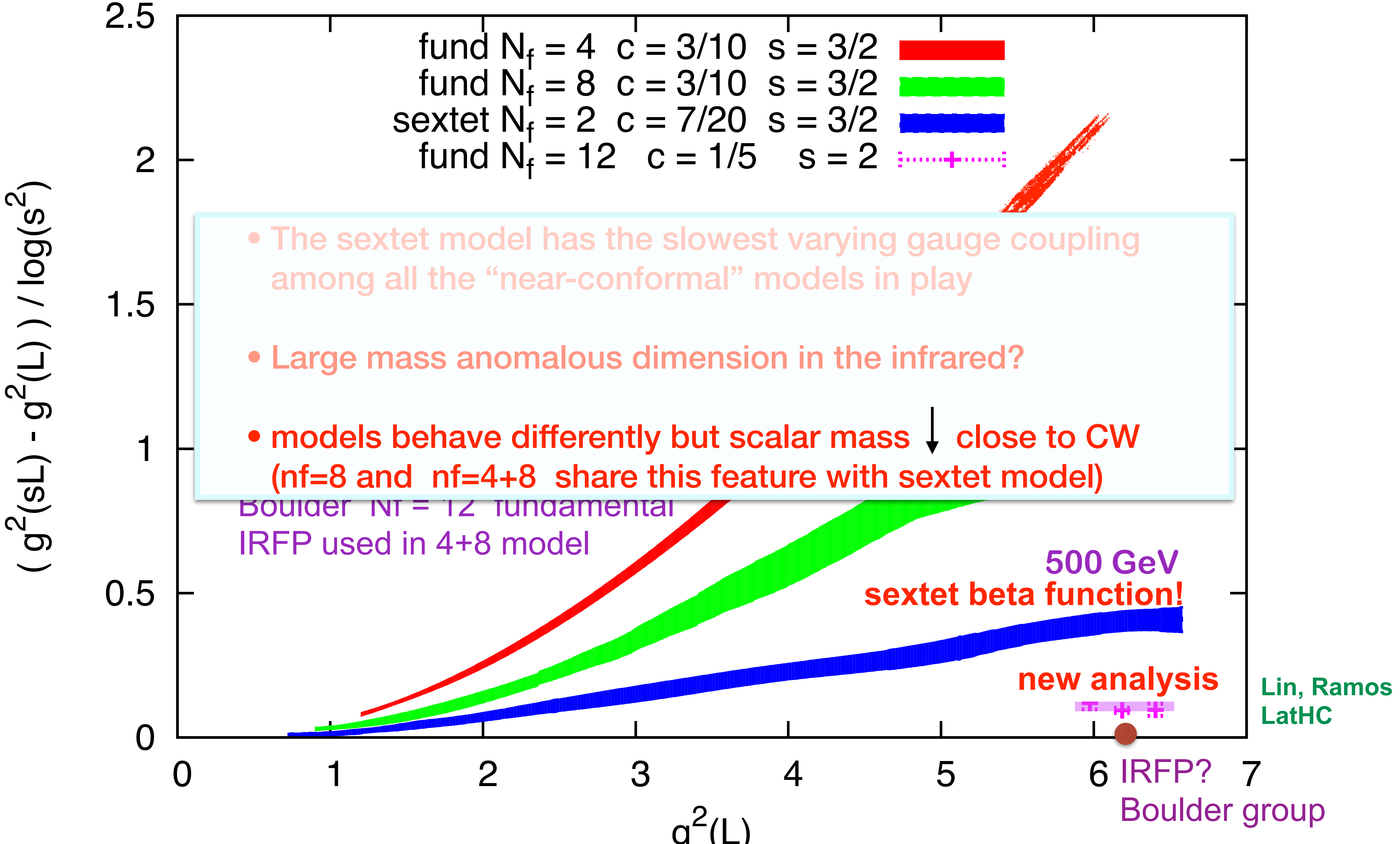
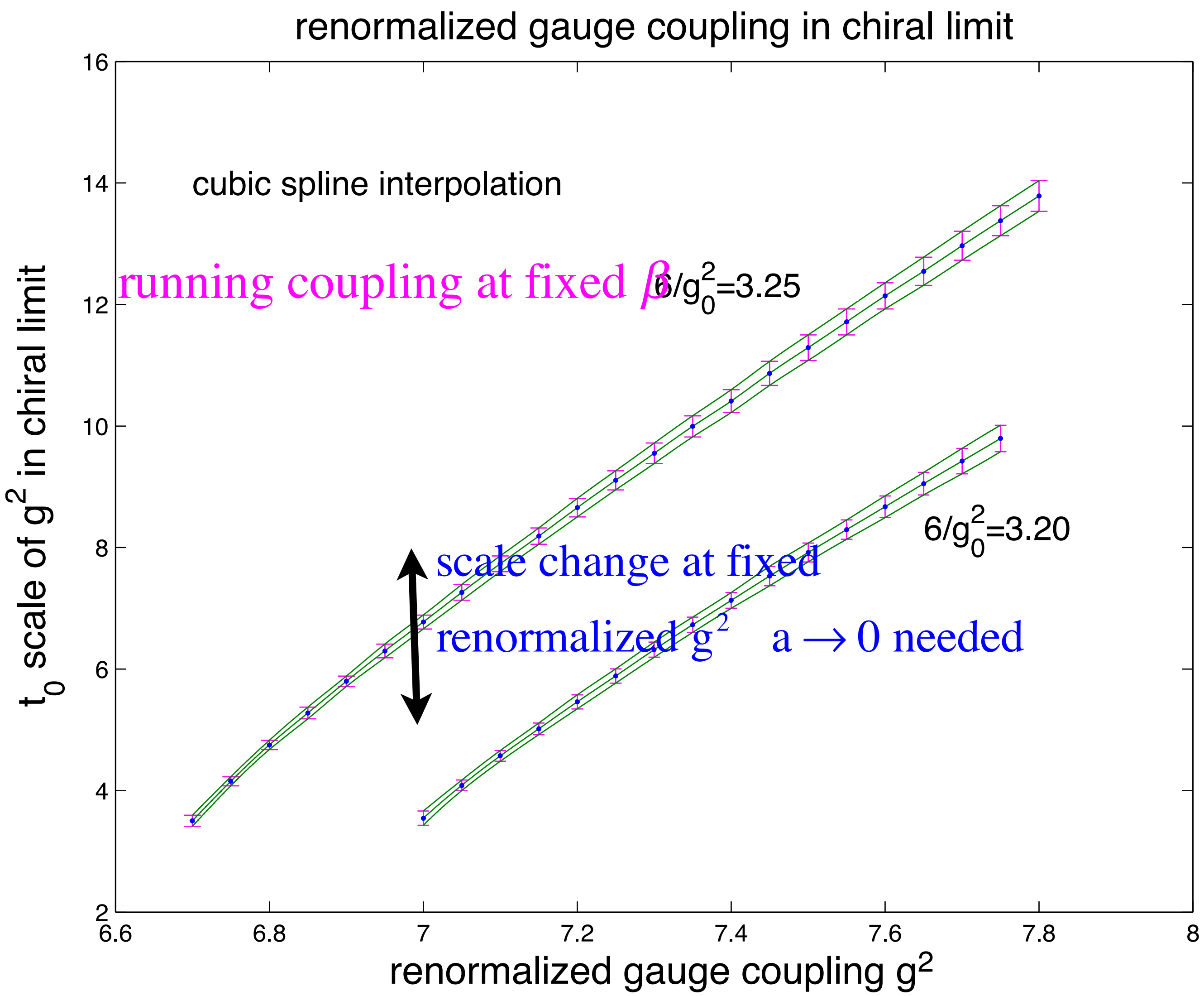
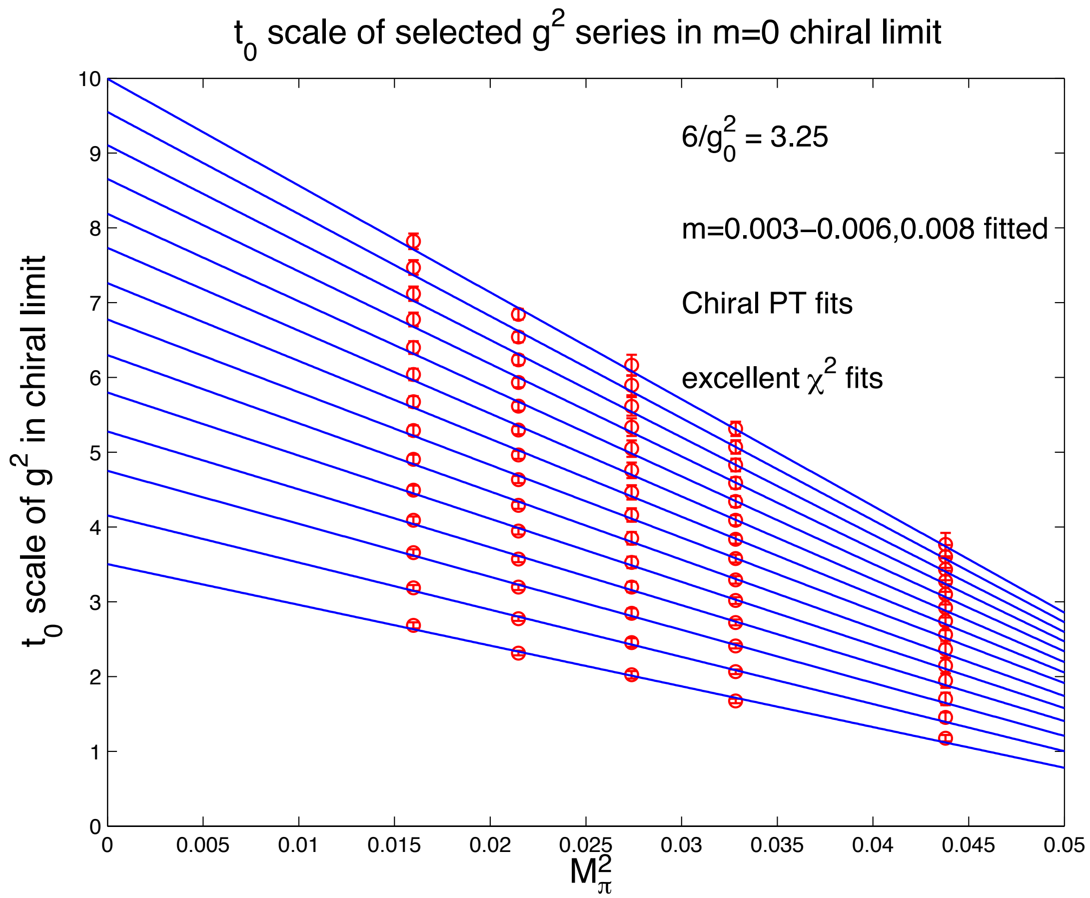


- The sextet model has the slowest varying gauge coupling among all the "near-conformal" models in play
- Large mass anomalous dimension in the infrared?
- models behave differently but scalar mass ↓ close to CW (nf=8 and nf=4+8 share this feature with sextet model)

scale-dependent coupling of the 3 lattice BSM models

bridge between UV scale and IR scale





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

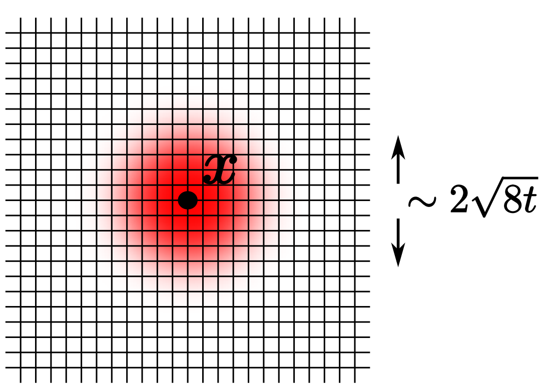
leading dependence of g^2(t,m) on M_π^2 is linear

based on gradient flow chiPT Bär and Golterman

works better than expected

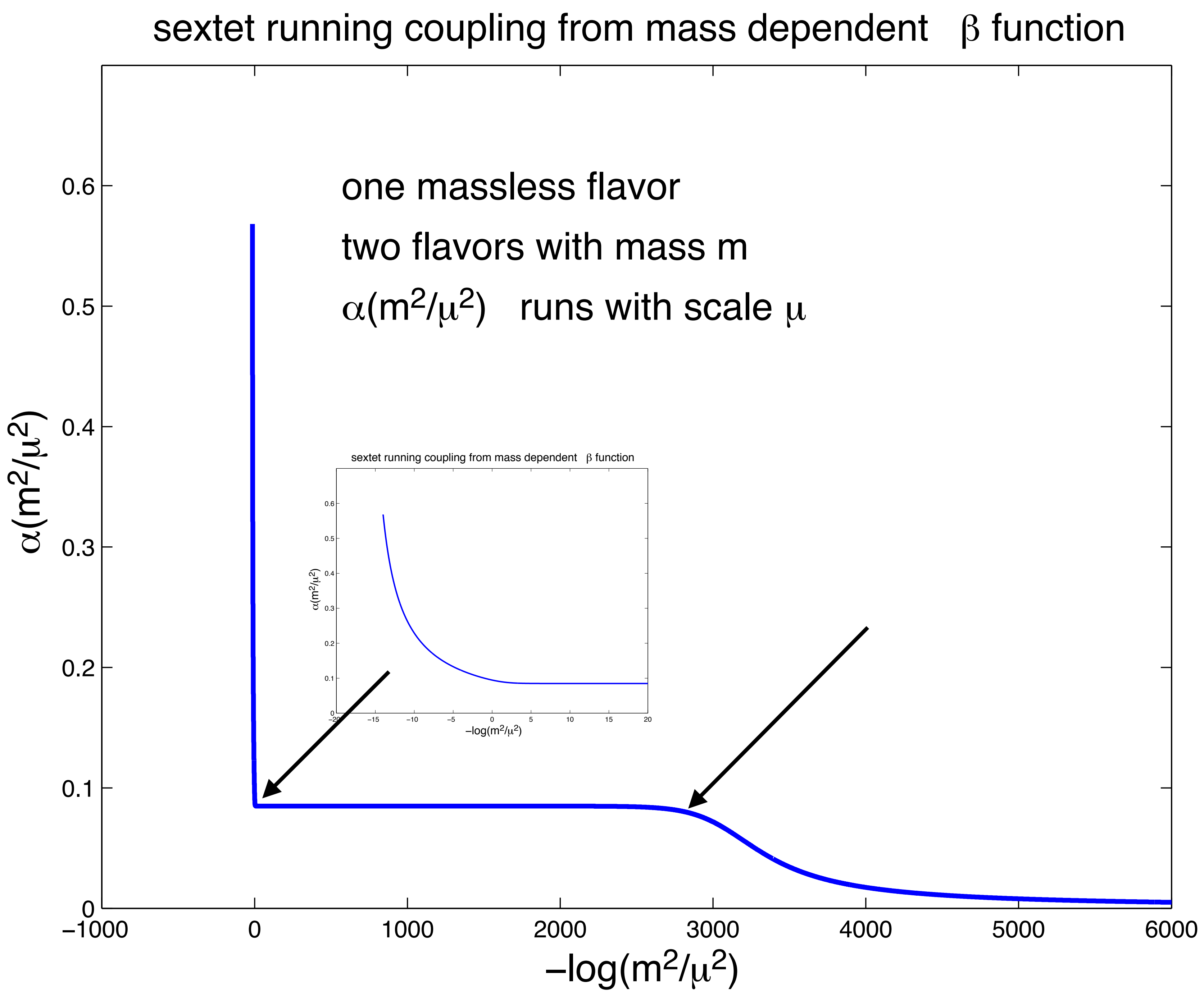
chiral logs are not detectable

decoupling of the scalar has to be better understood

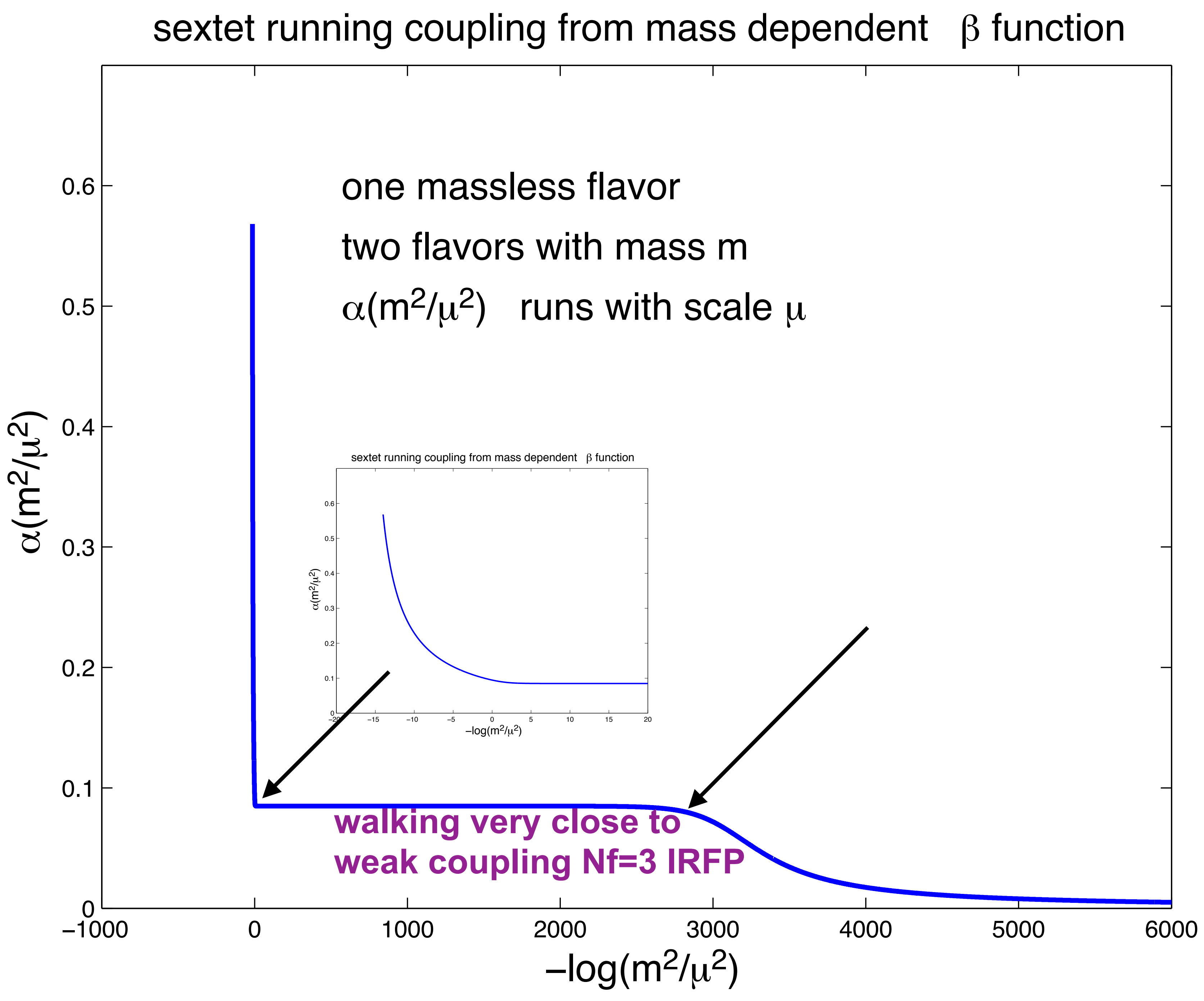


topic: how to do this right in ChiPT with low lying scalar coupled to Goldstone dynamics?

scale-dependent coupling mass dependent tuning?



scale-dependent coupling   mass dependent tuning?



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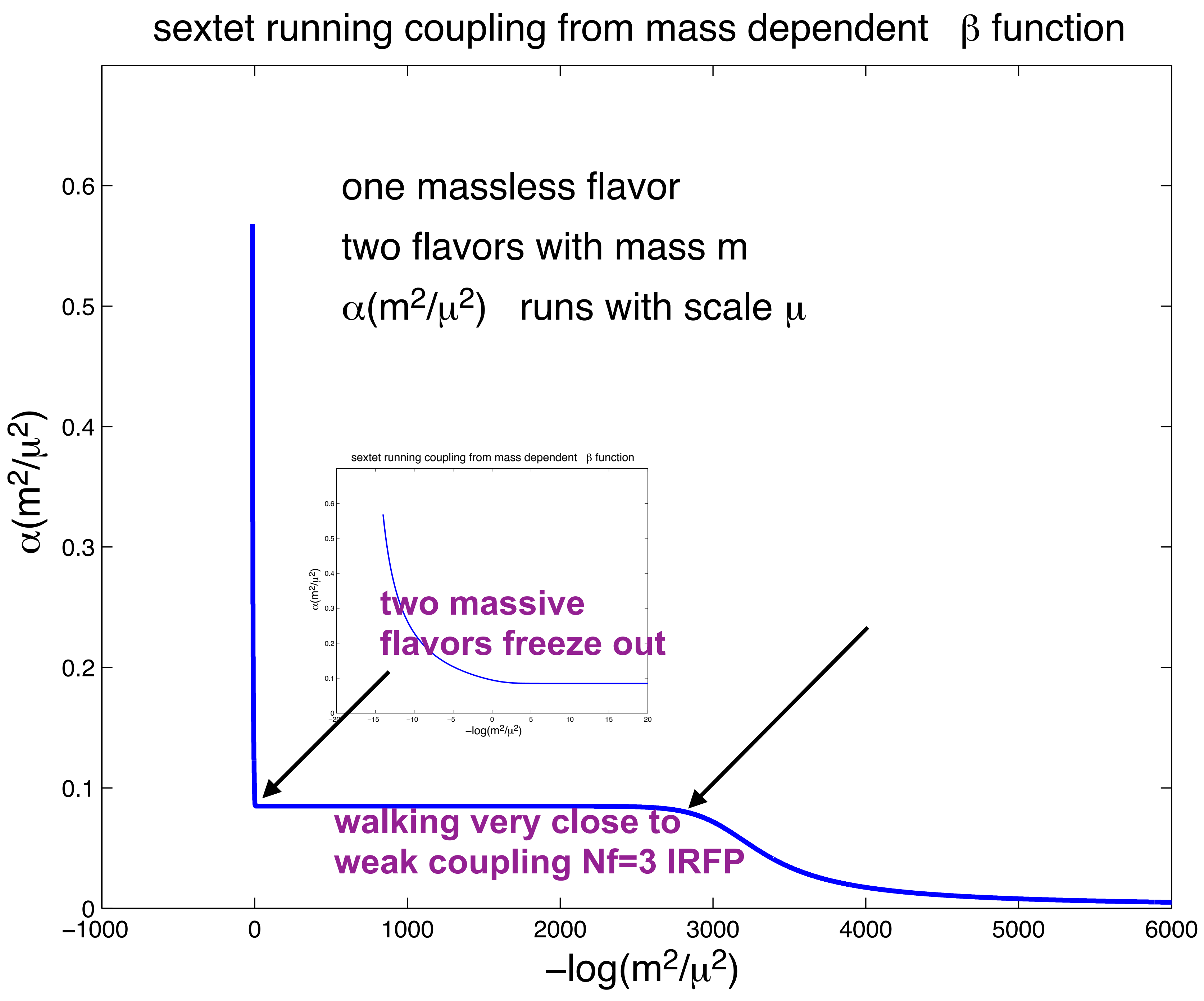

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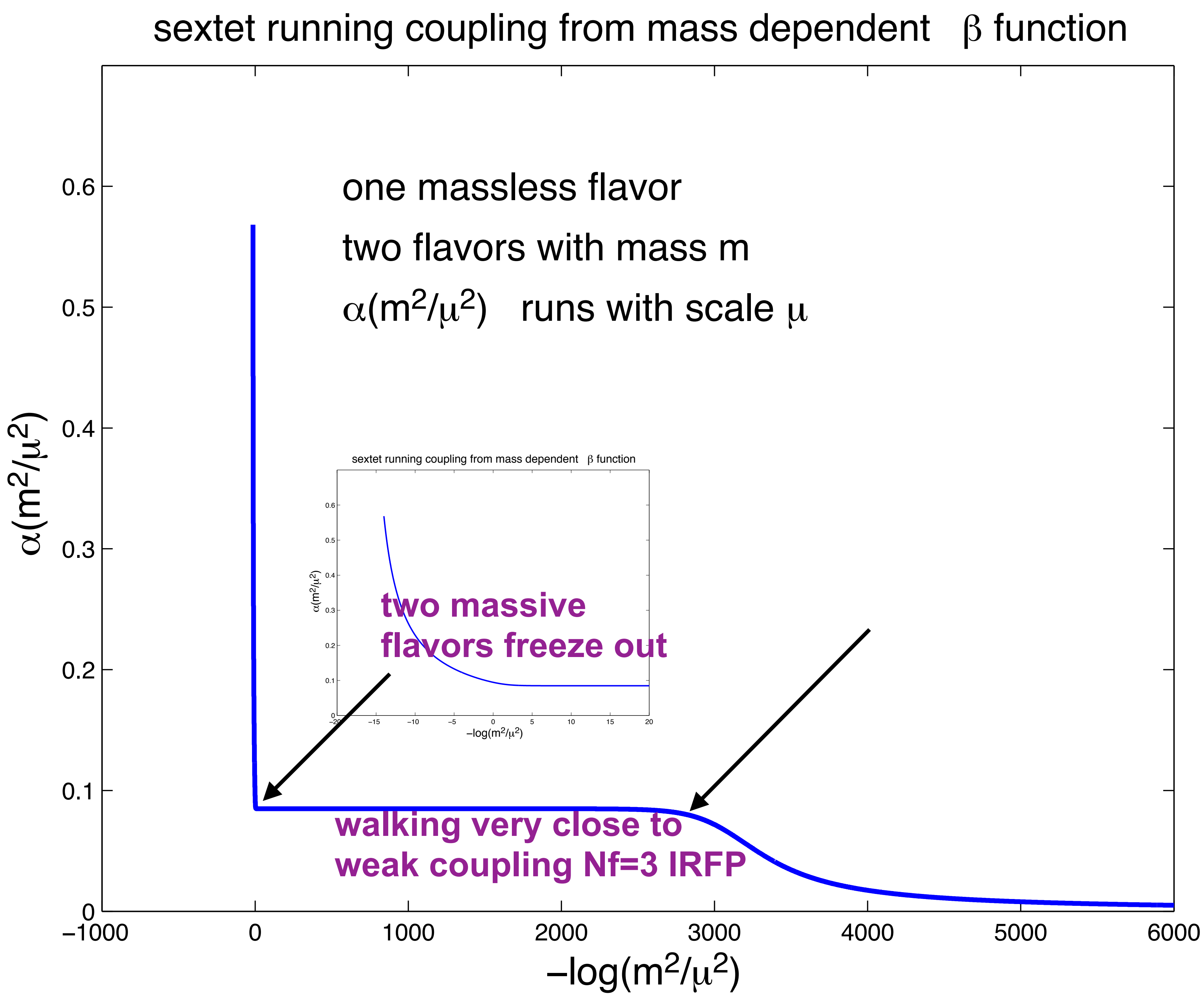


in 1+2 freeze-out scenario anything to learn about strong coupling dynamics of single massless flavor?

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

Not clear that light scalar mass can be tuned effectively
LSD 4+8 model

topic: reverse pulling from IRFP with 4-fermion operator?

important issues:

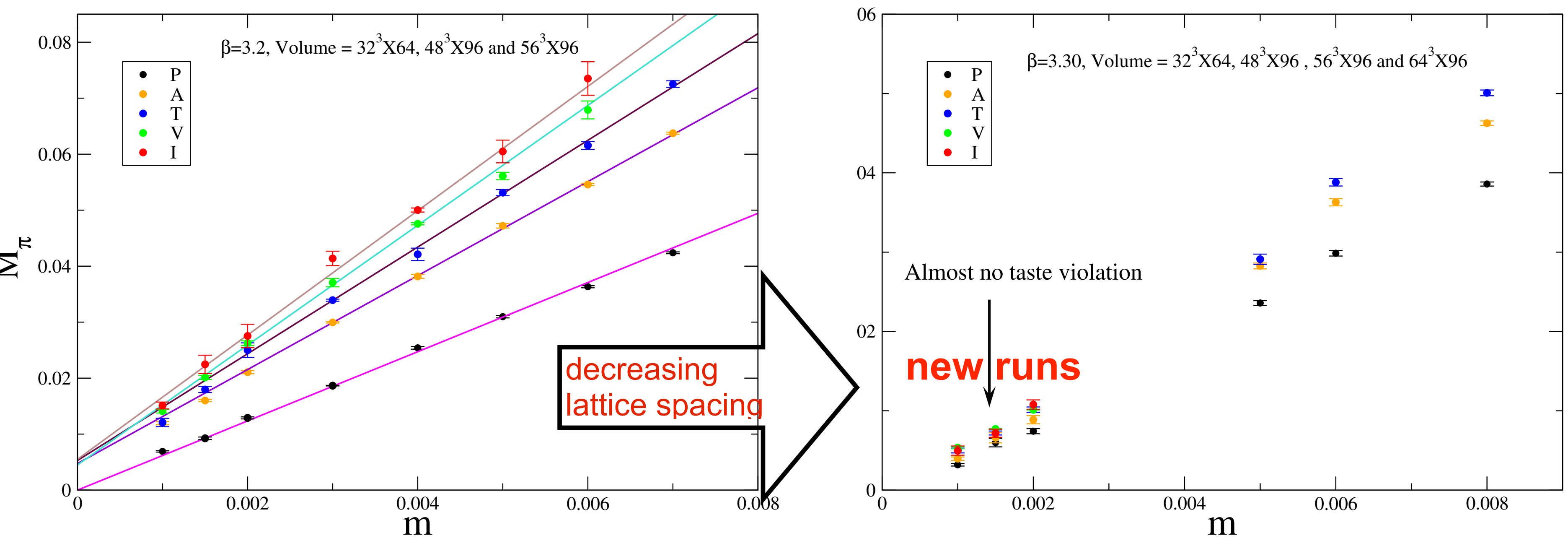
1. chiral symmetry breaking

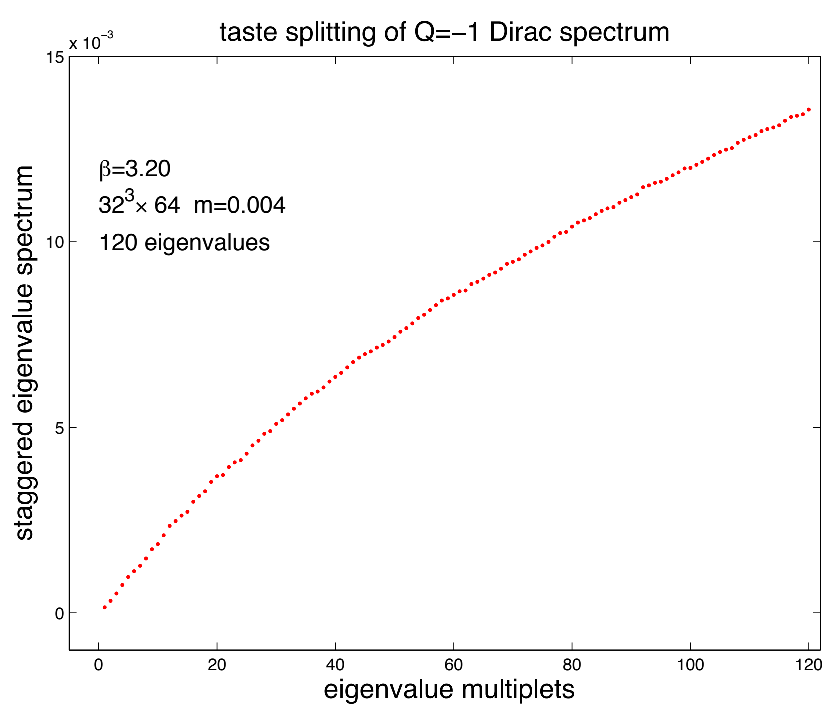
2. mass anomalous dimension

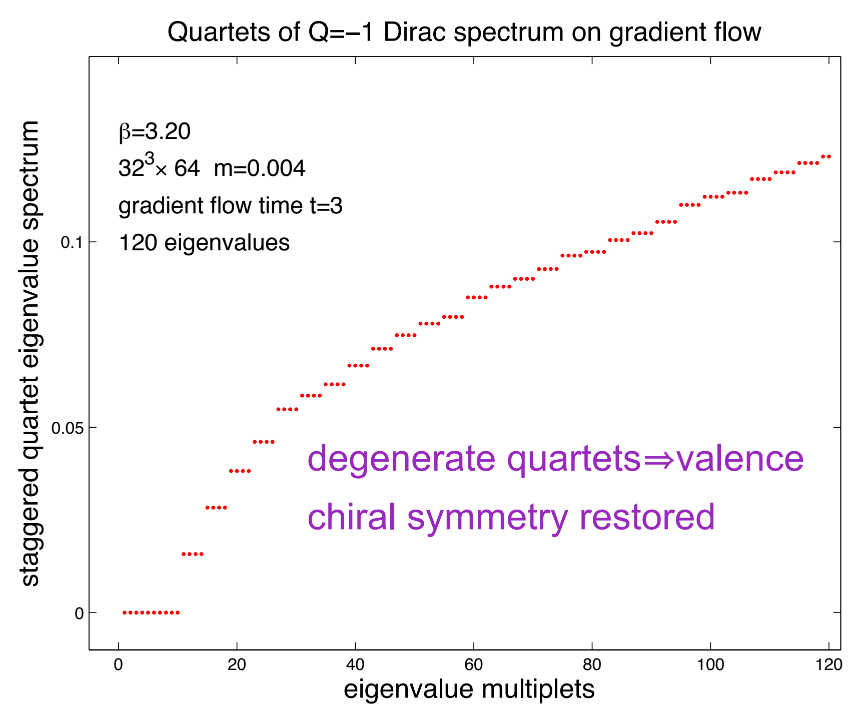
3. effective low energy theory for Goldstone dynamics coupled to the low mass scalar sigma model or dilaton?

4. SPC asked about the diphoton

mixed action added to our toolset



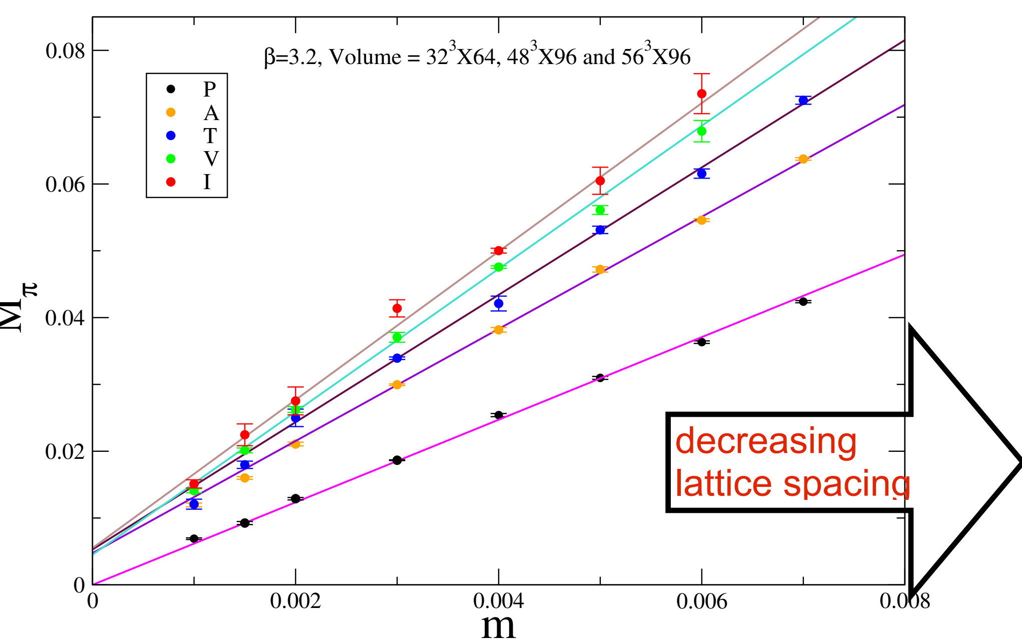


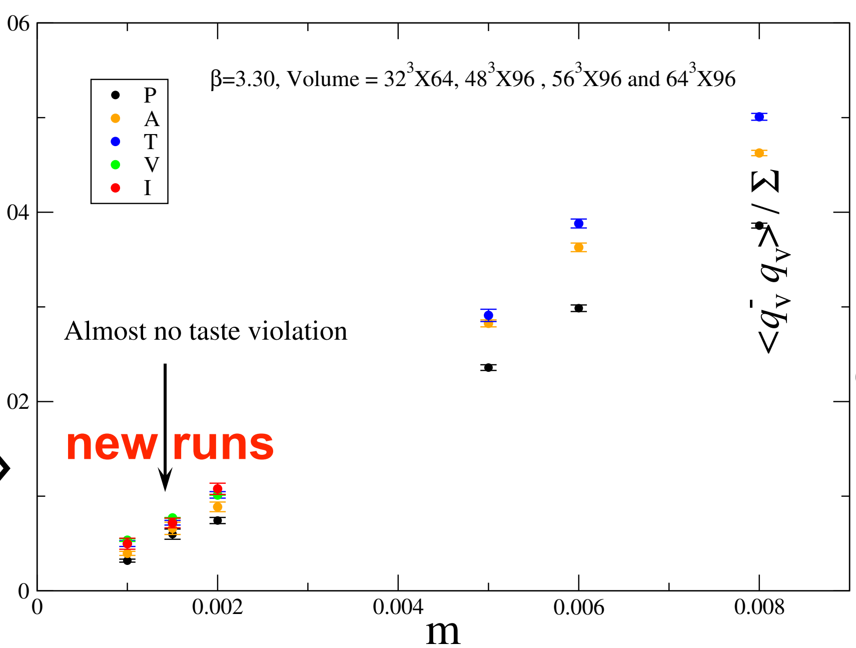


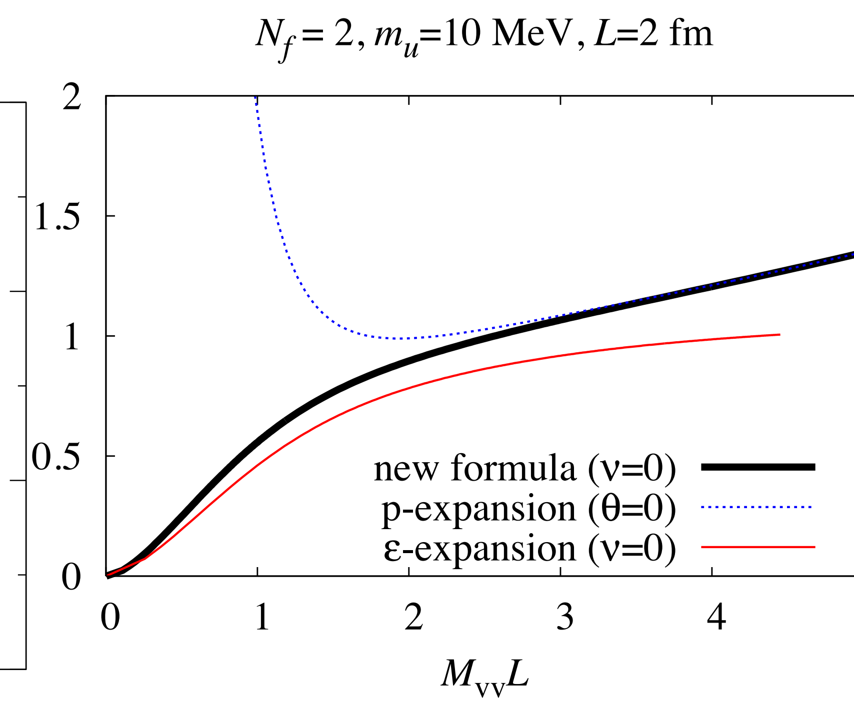
idea for improvement:

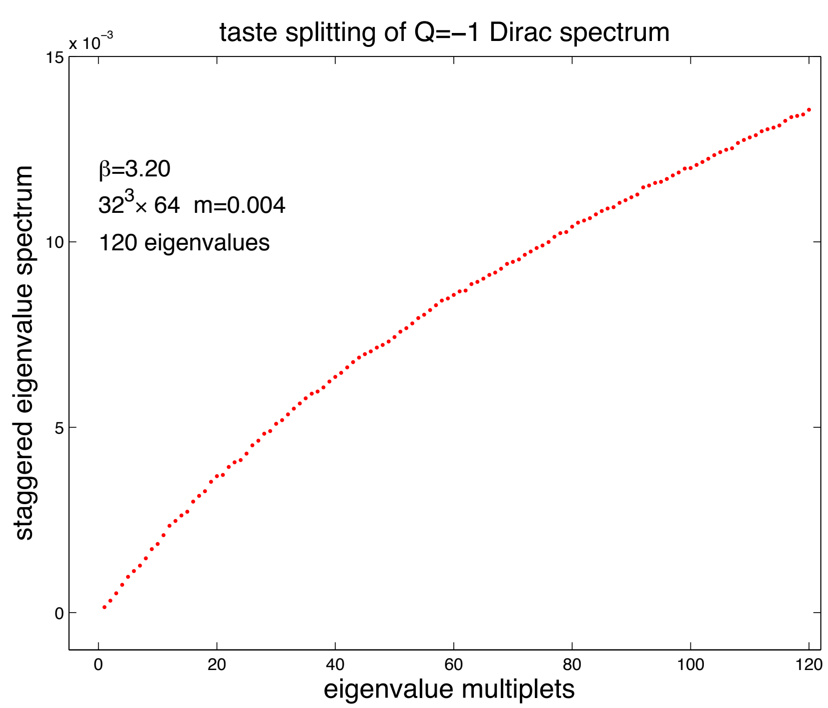
- use the gauge configurations generated with sea fermions
- taste breaking makes chiPT analysis complicated
- in the analysis use valence Dirac operator with gauge links on the gradient flow
- taste symmetry is restored in valence spectrum
- Mixed Action analysis should agree with original standard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

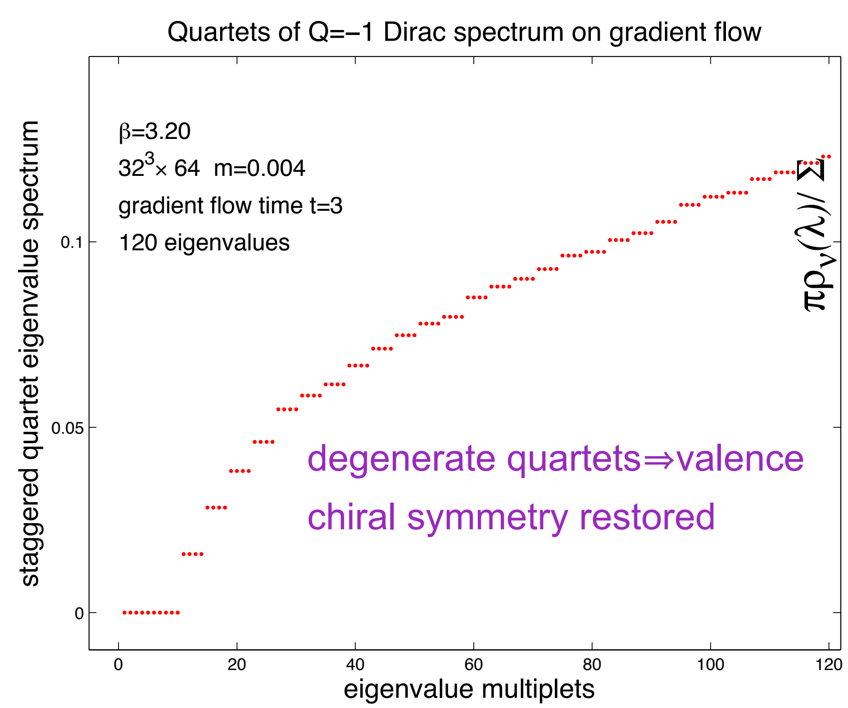
mixed action added to our toolset

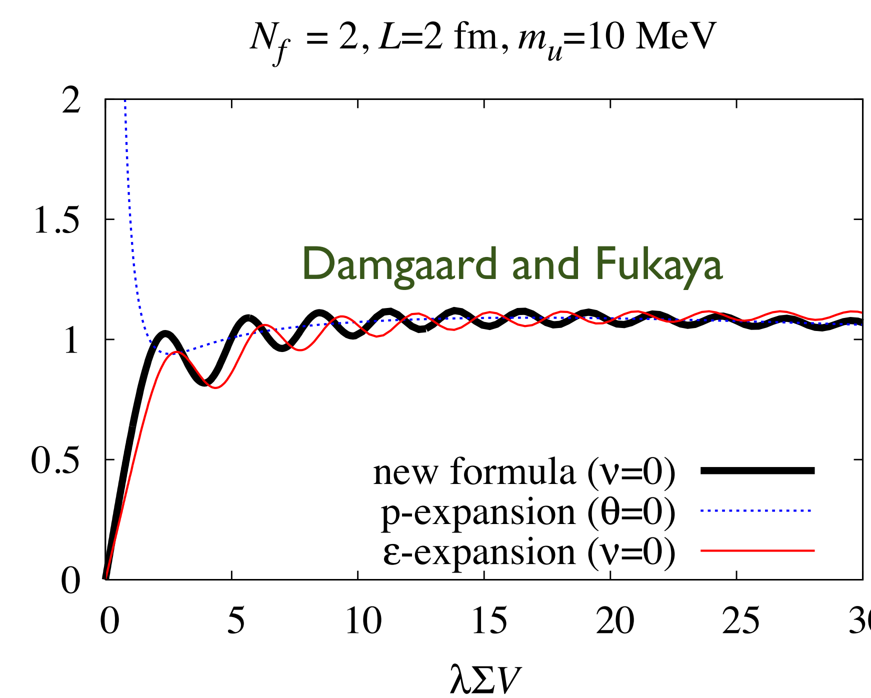






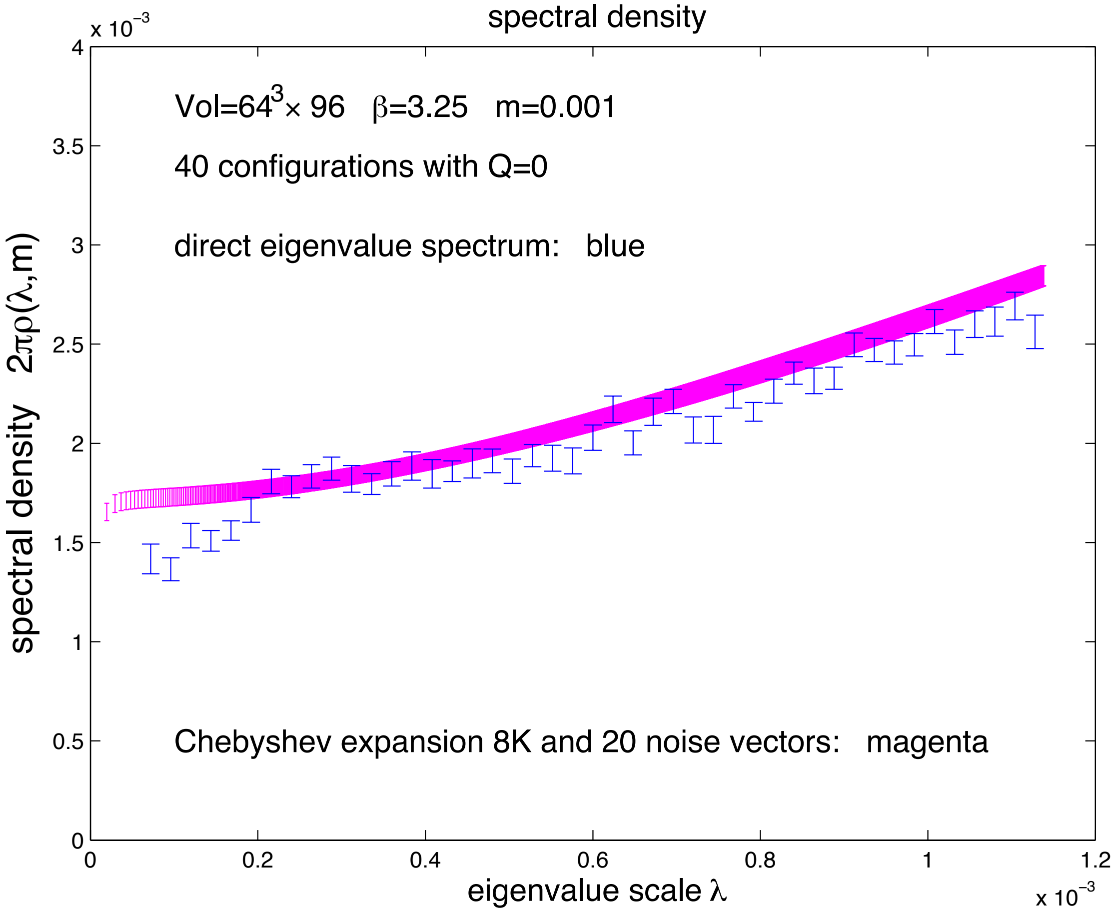


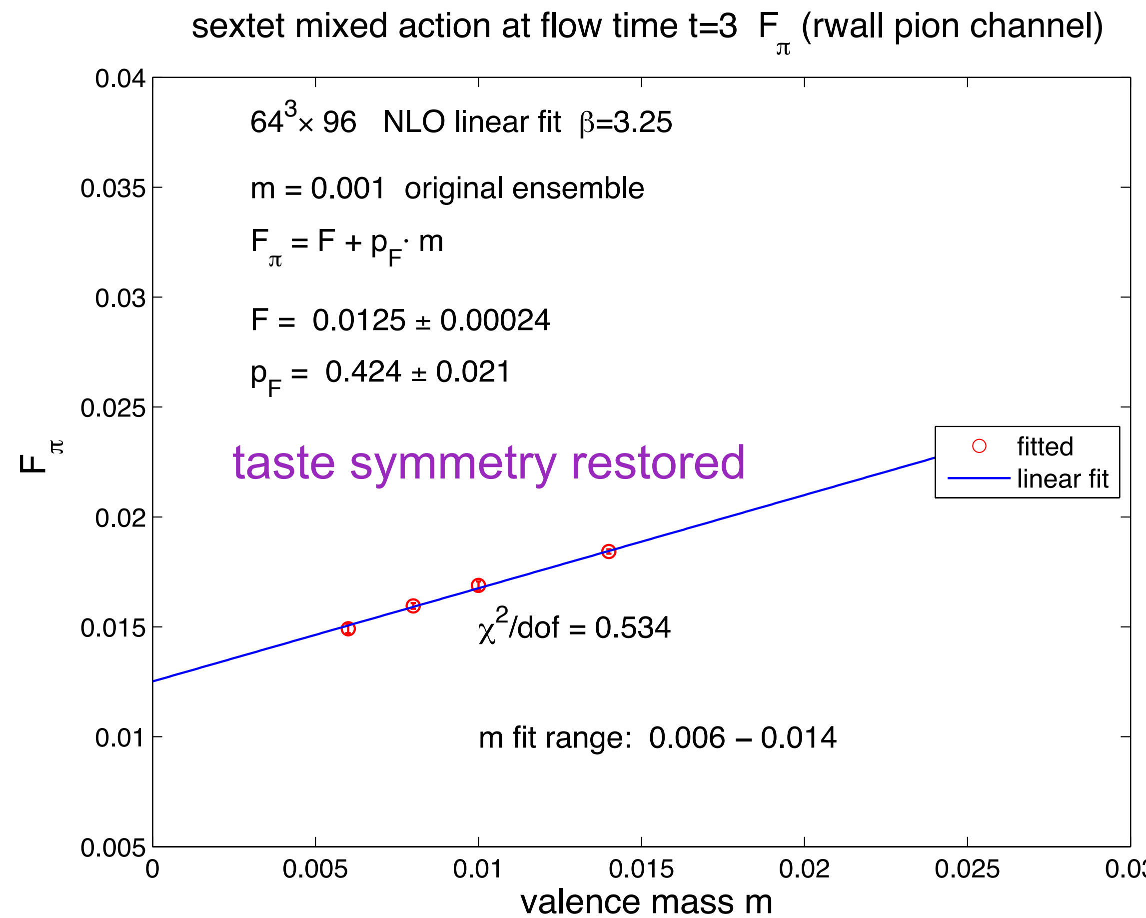


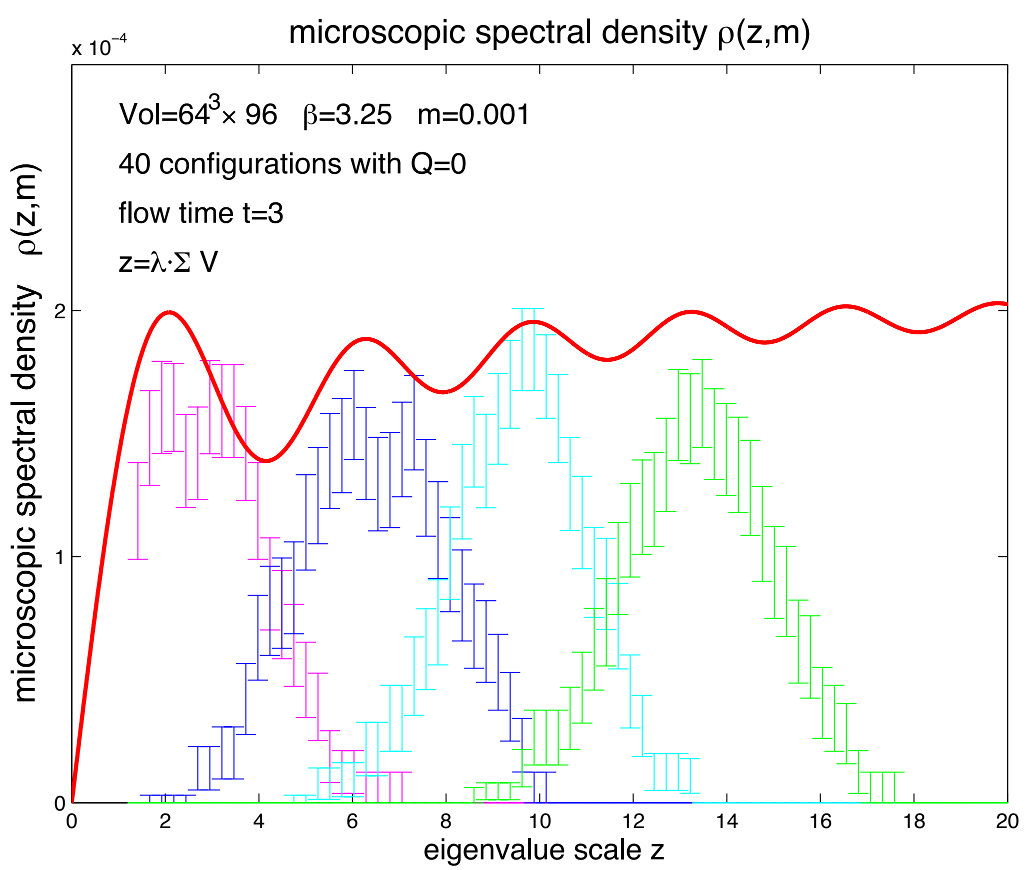


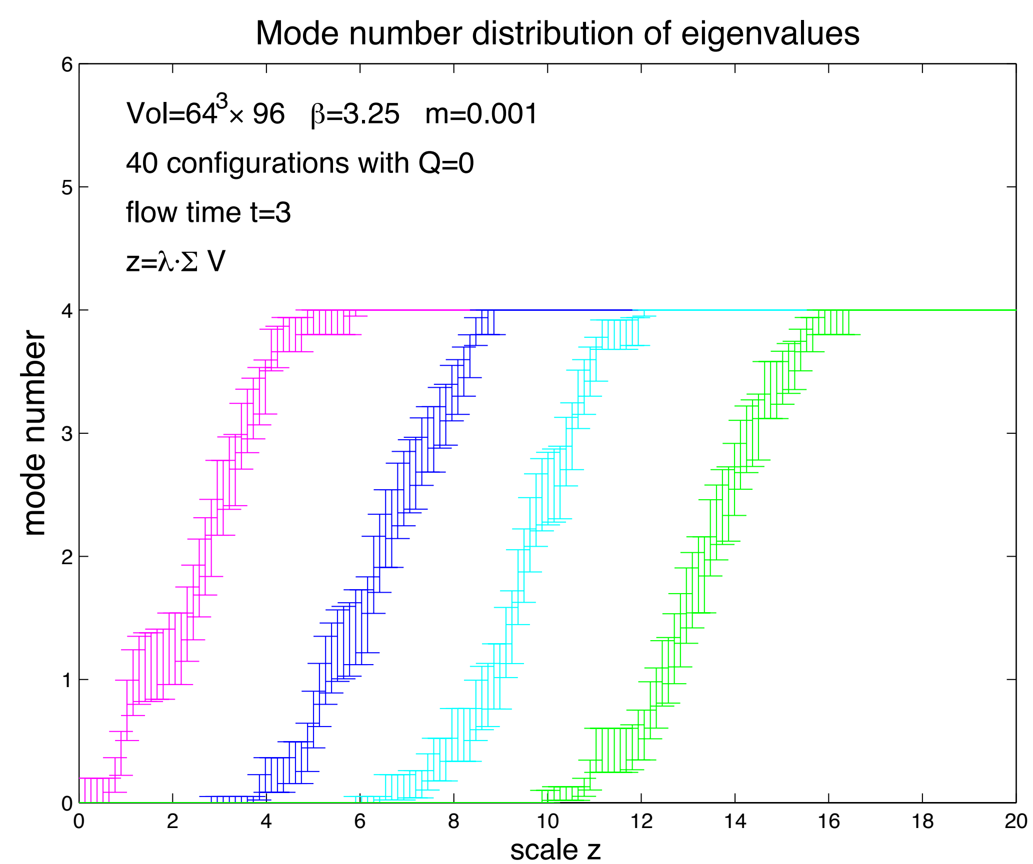
new analysis in crossover and RMT regime opens up with mixed action on gradient flow

mixed action p-regime and crossover to RMT







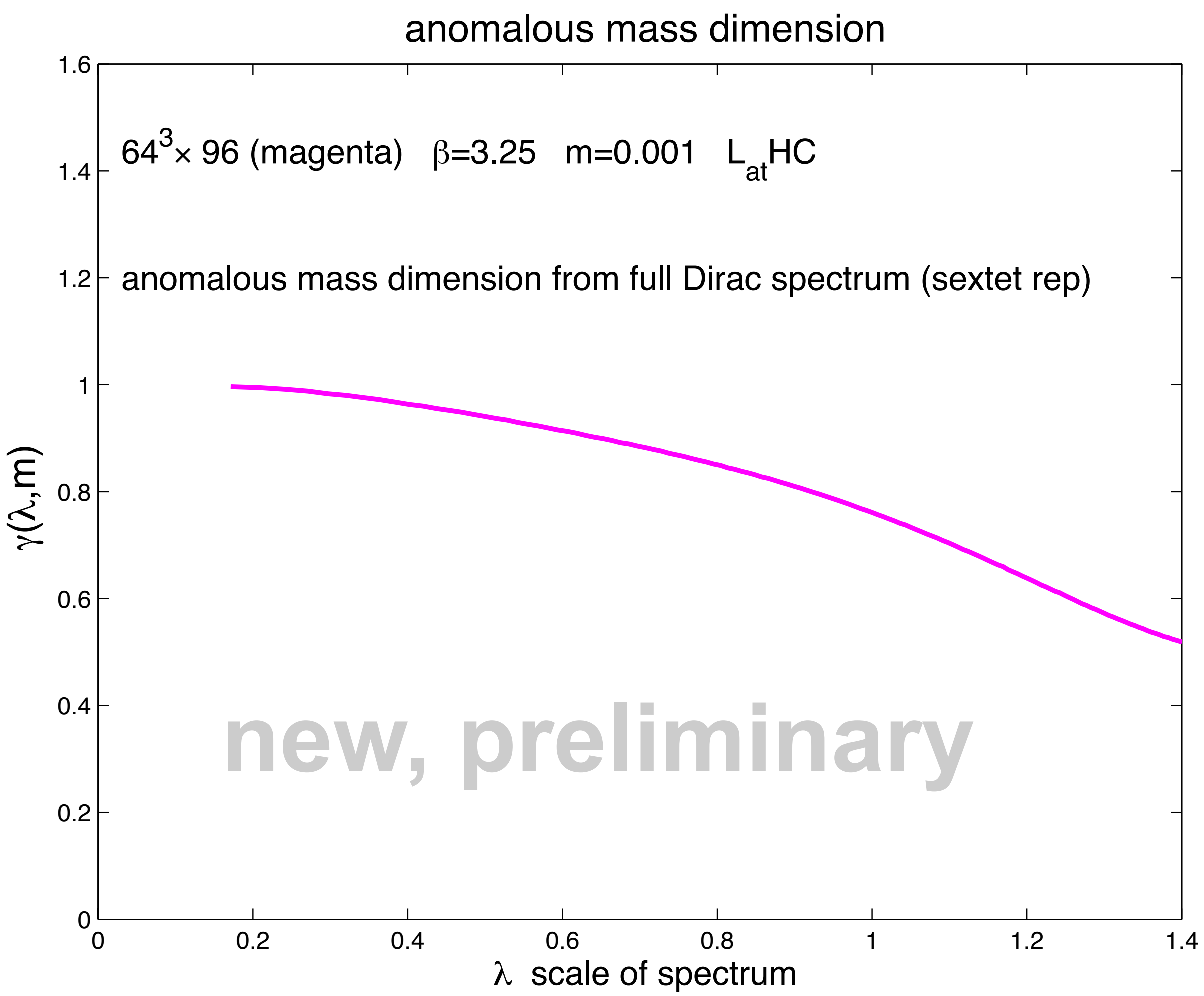


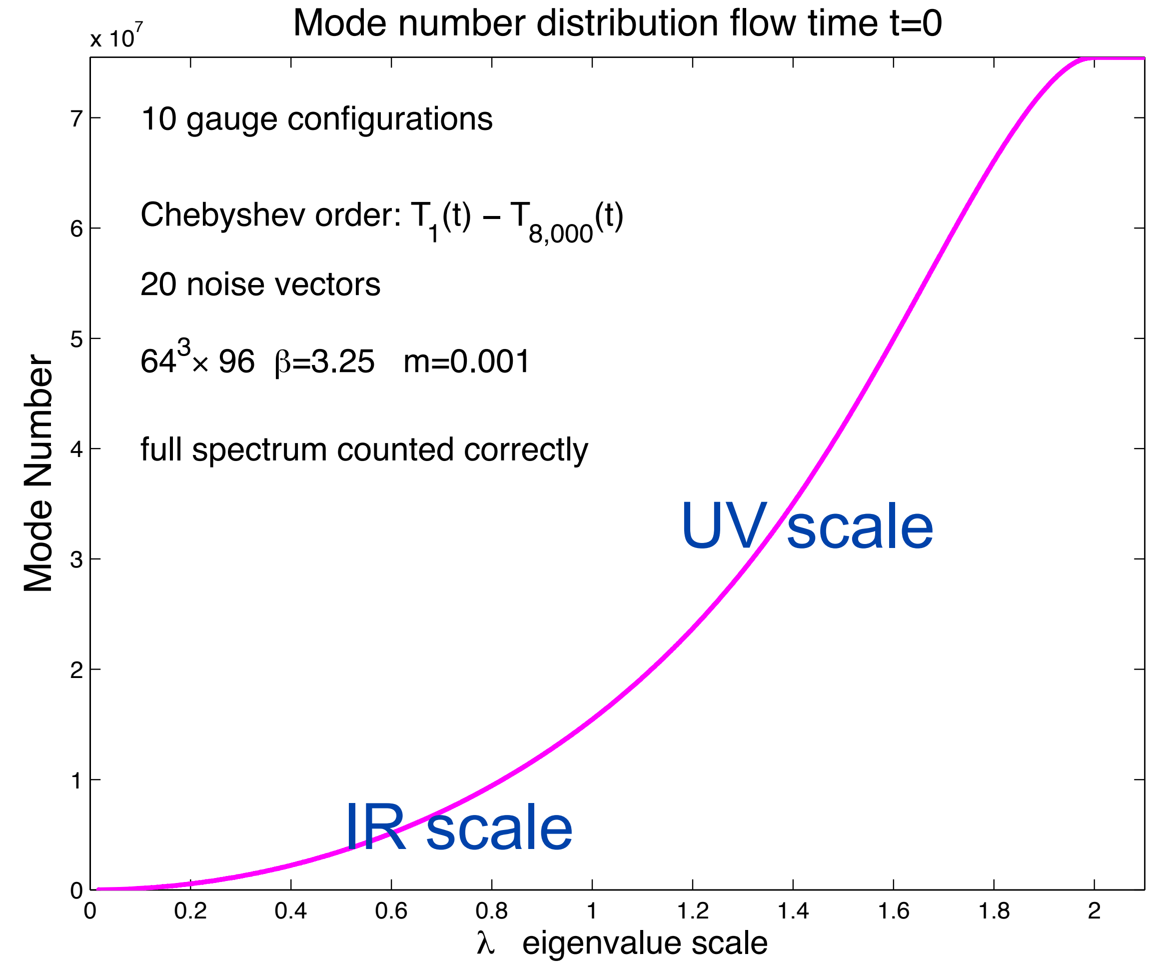
The chiral condensate   mass anomalous dimension

Del Debbio and collaborators and Boulder group pioneered fitting procedures

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

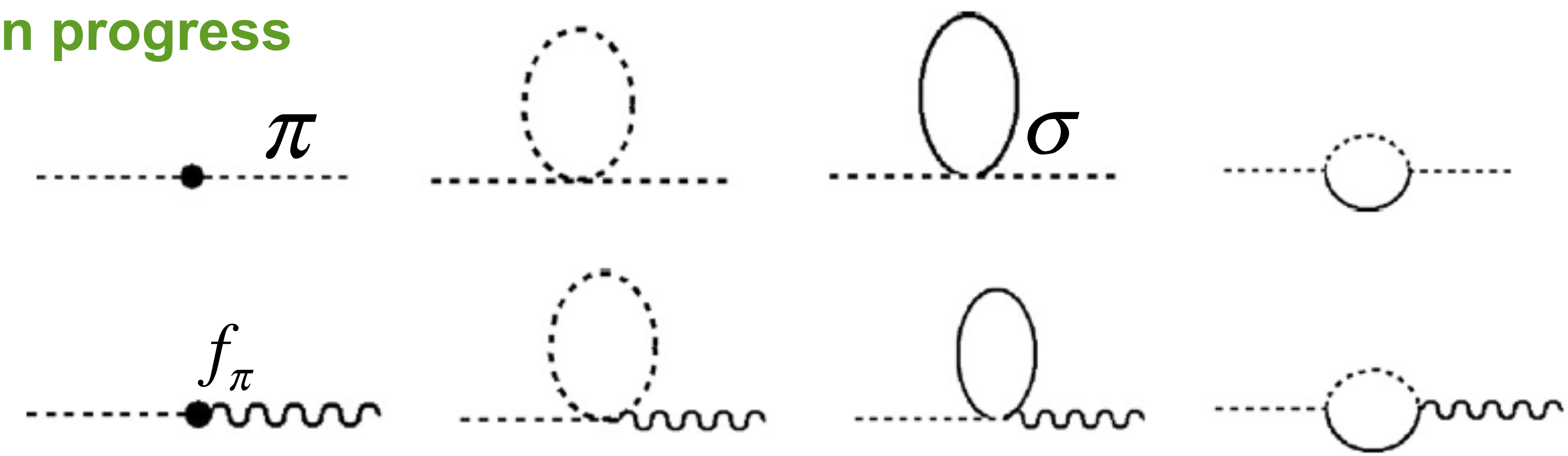
or equivalently, $\nu(M, m) \approx const \cdot \lambda^{\frac{4}{1+\gamma_m(\lambda)}}$, with $\gamma_m(\lambda)$ fitted





Goldstone dynamics coupled to low mass scalar

work in progress



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

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

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_π = 0.07- 0.013 range of the p-regime, and go lower in the RMT regime

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

how to differentiate from effective dilaton action?

composite Veff(σ)?

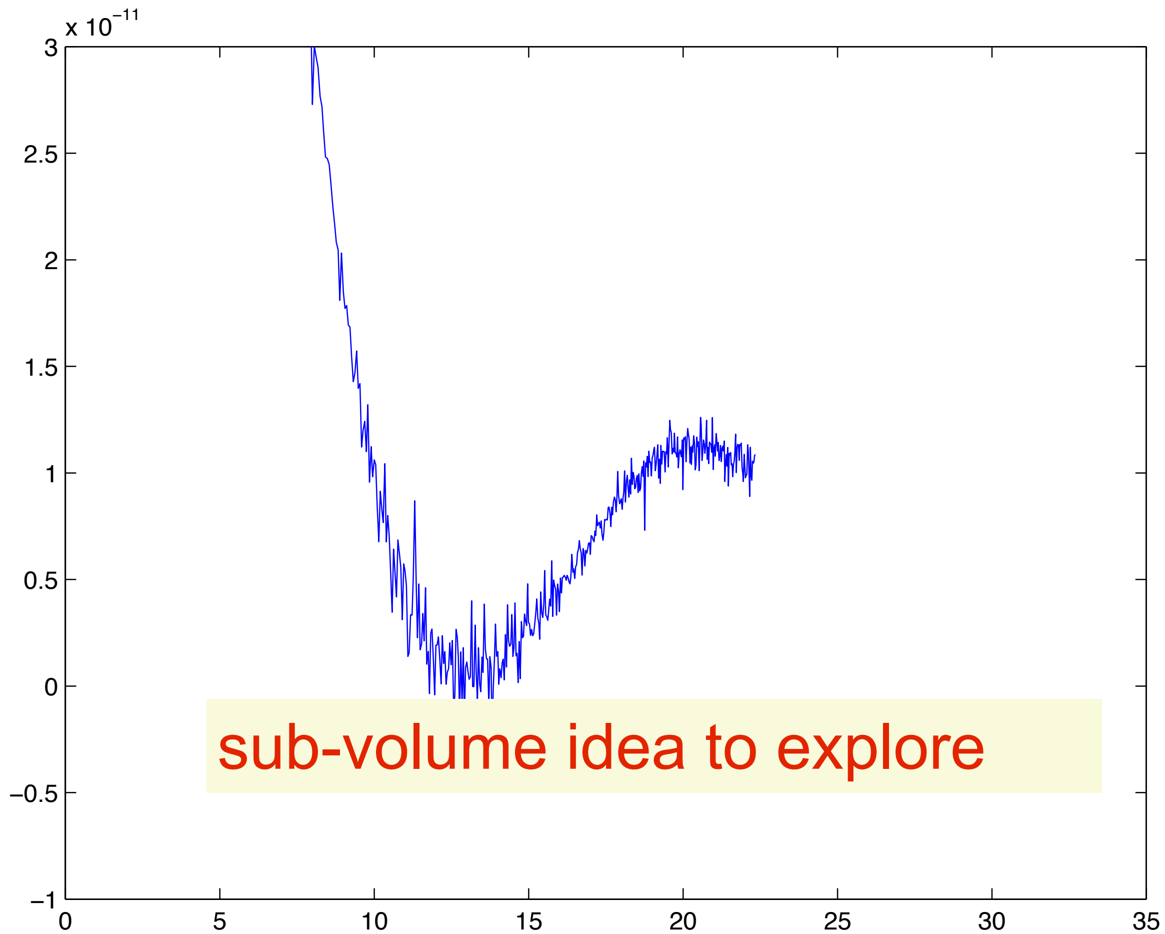
Golterman-Shamir not applicable

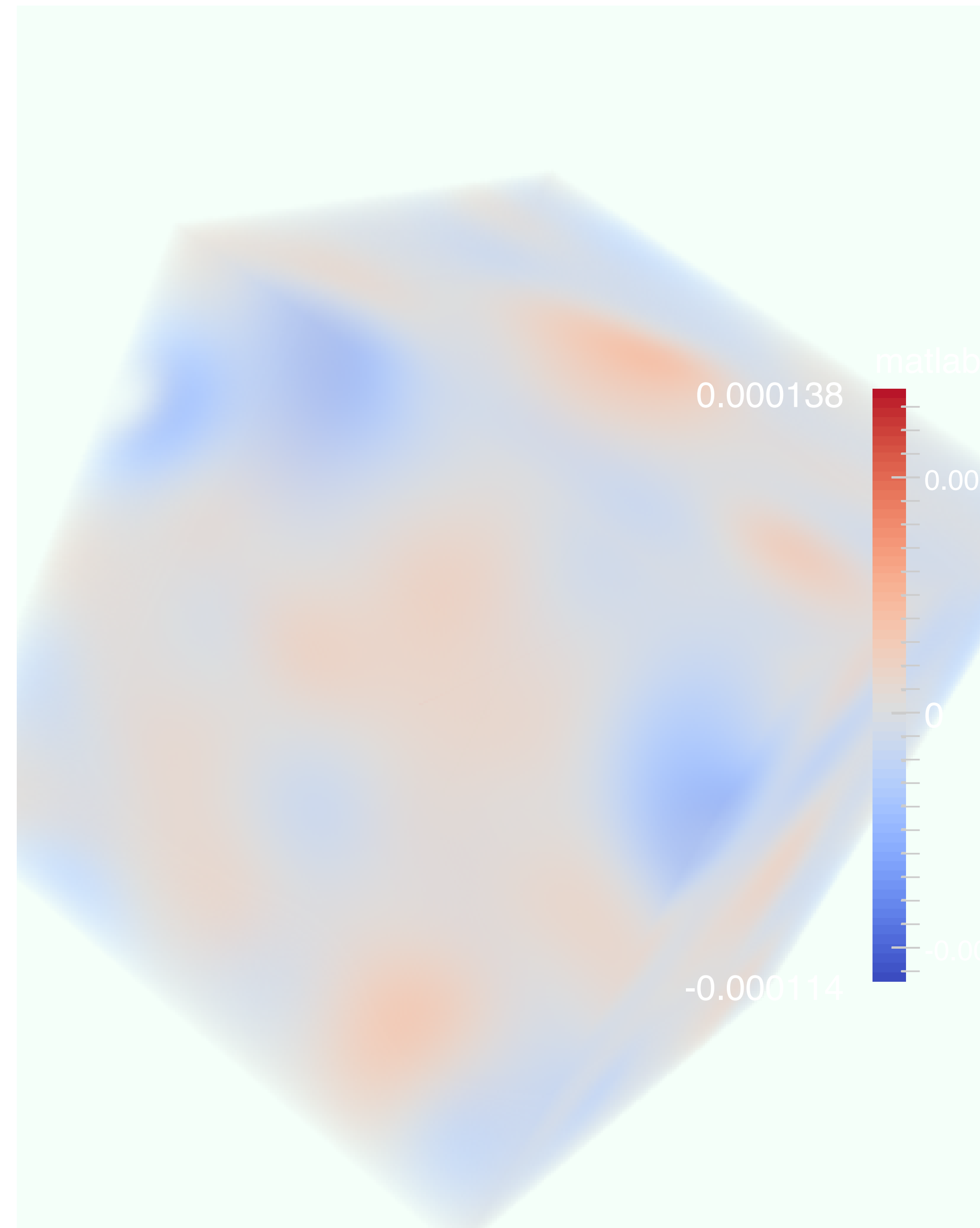
diphoton bump? eta' or scalar?

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

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

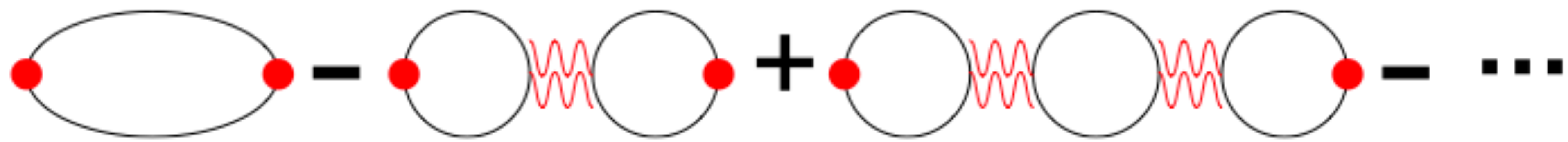
$$C(t_1 - t_2) \equiv \langle Q(t_1)Q(t_2)\rangle = \sum_{\vec{x}_1,\vec{x}_2}\langle\rho(x_1)\rho(x_2)\rangle$$





LatHC technology for visualizing topological density

diphoton bump?   eta' or scalar?



$$\int d^3x \langle \eta'(\vec{x},t)\eta'^{\dagger}(\vec{0},0)\rangle = C_{\gamma_5}(t) - N_f D_{\gamma_5}(t) = A_{\eta'} e^{-m_{\eta'}t} + \cdots ,$$

$$m_0^2 = m_{\eta'}^2 - m_\pi^2 = \frac{2N_f}{f_\pi^2}\chi_{\rm top} \qquad \chi_t = \frac{m_q \Sigma}{N_f} + \mathcal{O}(m_q^2)$$

$$\chi_{\rm top} = \frac{\left\langle Q_{\rm top}^2 \right\rangle}{VT}, \quad Q_{\rm top} = \int \rho_{\rm top}(x)\, d^4x$$

$$\lim_{|x|\to \rm large} \langle mP(x) mP(0)\rangle_Q$$

$$= \frac{1}{V}\left(\frac{Q^2}{V} - \chi_t - \frac{c_4}{2\chi_t V}\right) + O(e^{-m_\eta |x|})$$

Early universe

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

- Nf=2 Qu=2/3 Qd = -1/3 sextet 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

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

the model is worth studying
without resources ➙ wrong results
growing list we need to do:

spectroscopy and S-parameter

eta’ or second scalar? Or bust?

EW phase transition

baryon size for better estimate of freeze-out

F from RMT with imaginary chemical potential on links

light scalar coupled to photons and weak bosons
…