Large scale separation from mass-split models

Anna Hasenfratz

University of Colorado **Boulder**

Workshop on
Bound states in strongly coupled systems
Galileo Institute, Florence
March 14 2018

Non-perturbative investigations of
Composite Higgs BSM systems exhibiting

Large scale separation from mass-split models

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This is

Part 1: Set the stage - (theoretical) introduction

Next talk

Part 2: O. Witzel - much more details

Mostly based on

R. Brower, A.H. , Claudi Rebbi, E. Weinberg, Oliver Witzel,
Phys.Rev. D93 (2016) 075028

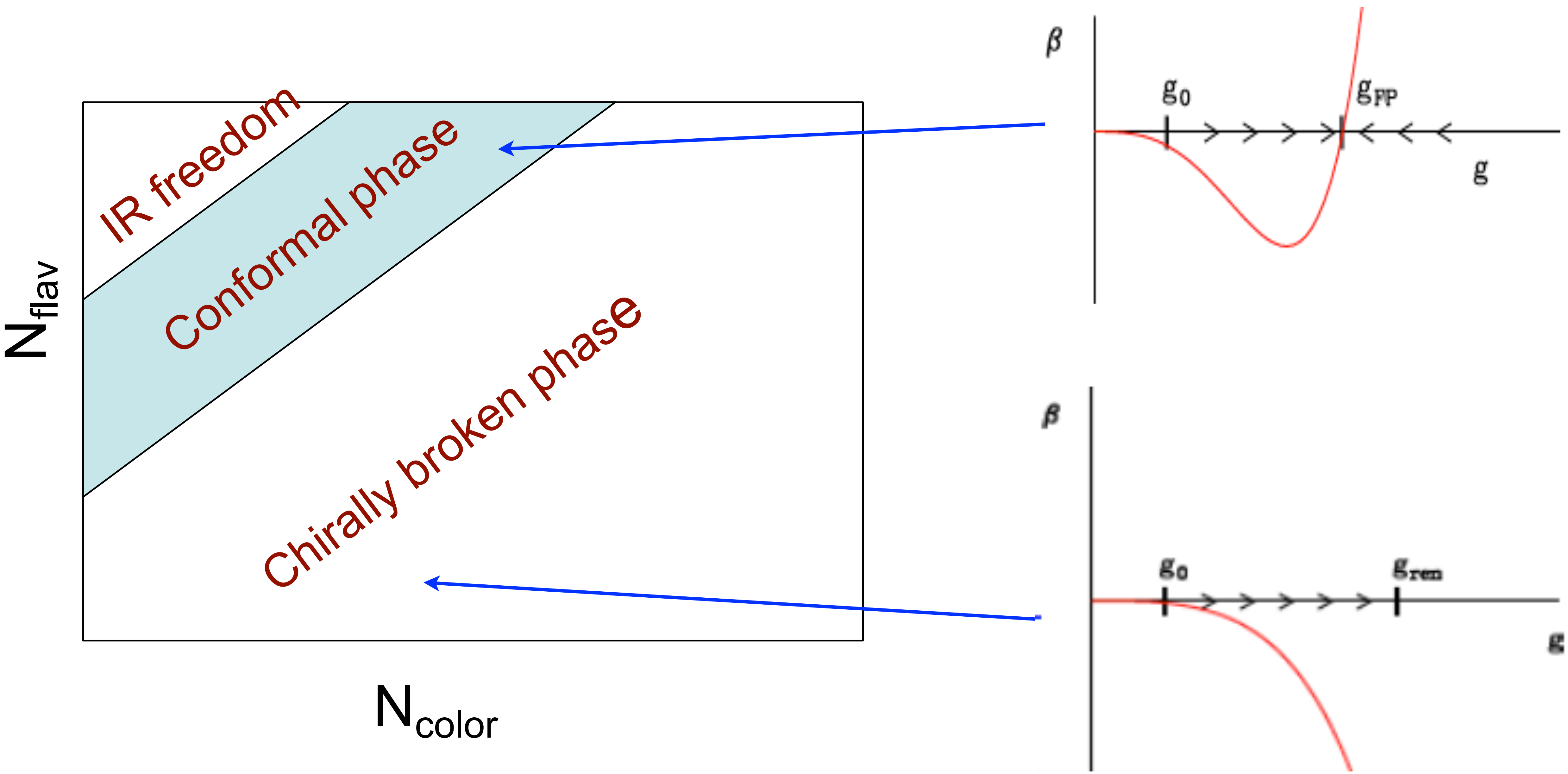
A.H. , Claudi Rebbi, Oliver Witzel, Phys.Let. B773 (2017) 86

Beyond QCD :

it's a wild world out there …

At fixed N_c :

- small N_f : chirally broken, QCD-like
- $N_f^* < N_f < N_f^{(IF)}$: conformal
- $N_f^{(IF)} < N_f$: IR free



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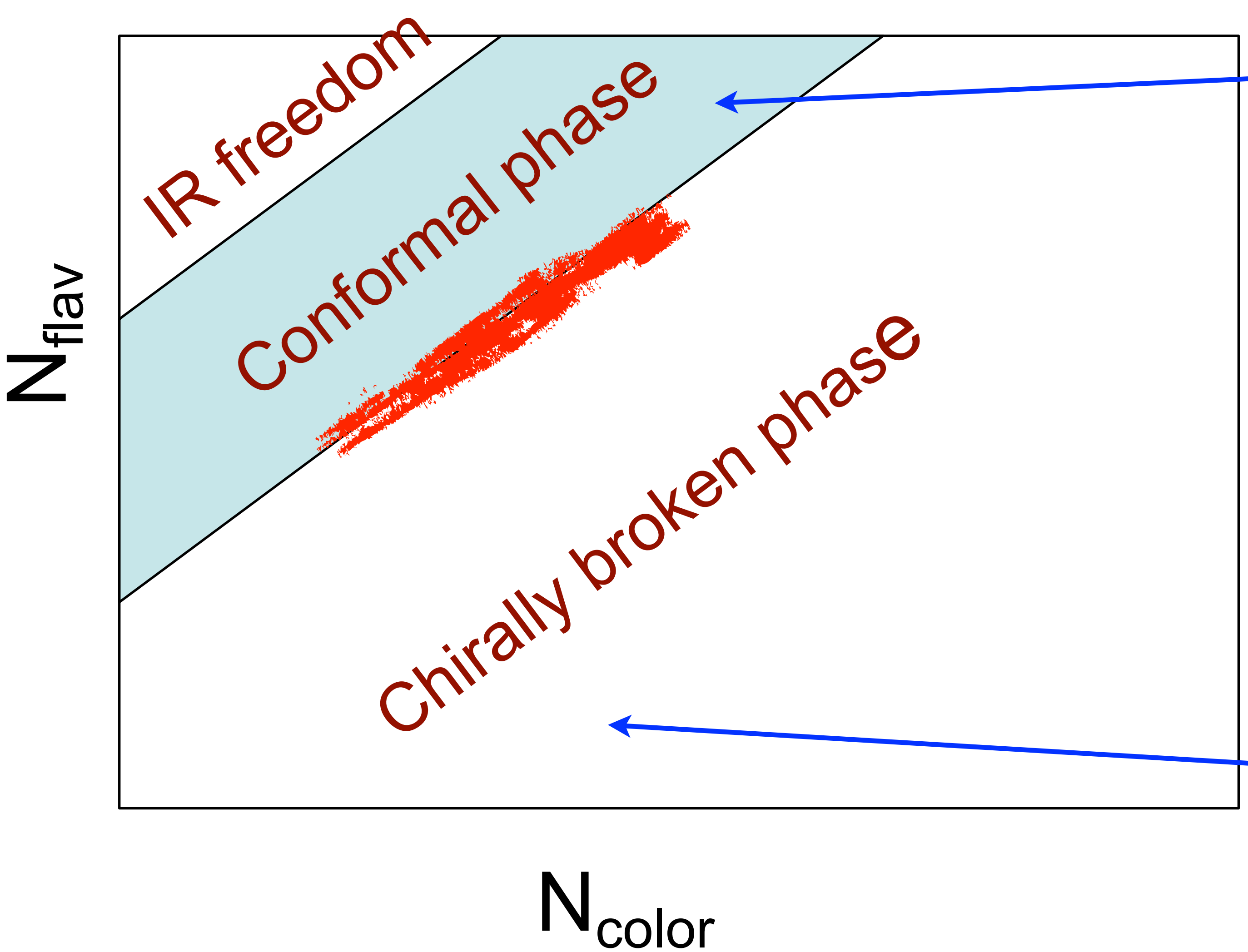

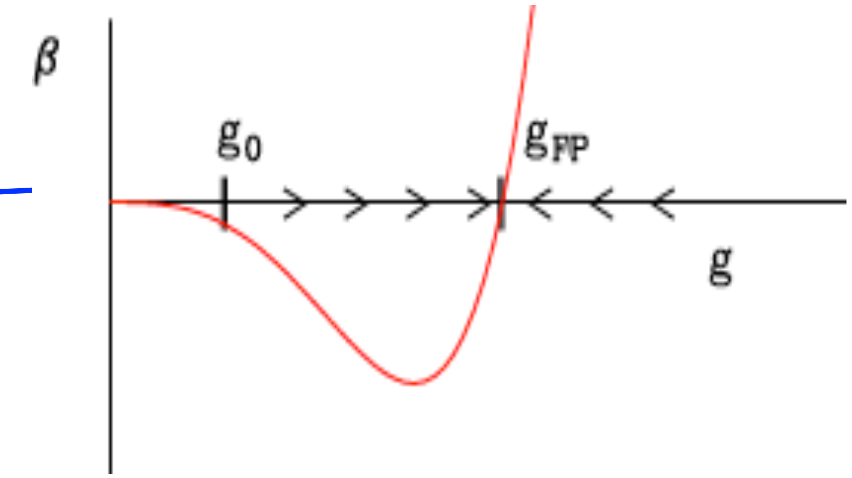

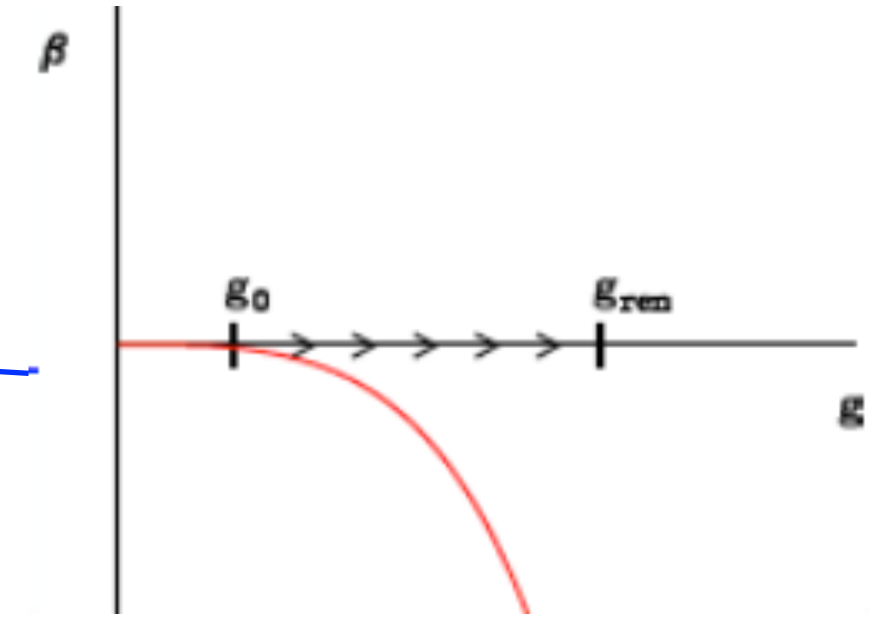

(Near-)Conformal systems

are the basis of most composite Higgs models

Start with Higgsless, massless SM $\longrightarrow$ Full SM

$$\mathcal{L}_{SM\,0} \quad \to \quad \mathcal{L}_{SM}$$

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Start with Higgsless, massless SM $\longrightarrow$ Full SM

$$\mathcal{L}_{SD} + \mathcal{L}_{SM\,0} + \mathcal{L}_{int} \quad \rightarrow \quad \mathcal{L}_{SM} + \dots$$

Full SM + additional states from strong dynamics $\mathcal{L}_{SD}$

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The construction ideally will

- predict the 125GeV Higgs
- give mass to the SM gauge fields
- give mass to the SM fermions :
  (4-fermion interaction or partial compositness?)

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- give mass to $\mathcal{L}_{SD}$ fermions: $\mathcal{L}_{UV}$ sector

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$$\mathcal{L}_{UV} \quad \rightarrow \quad \mathcal{L}_{SD} + \mathcal{L}_{SM\,0} + \mathcal{L}_{int} \quad \rightarrow \quad \mathcal{L}_{SM} + \ldots$$

This could be a UV complete theory

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Composite Higgs models

$\mathcal{L}_{SD}$:SU(N_c) gauge, N_f fermions, chirally broken, coupled to the SM

- EW symmetry breaking : emerges from massless pions of $\mathcal{L}_{SD}$
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No experimental sign of either scenario (yet):
➠ plausible BSM scenarios require (very)
large scale separation between $\mathcal{L}_{SD}$ and $\mathcal{L}_{SM}$

$$\mathcal{L}_{SD} + \mathcal{L}_{SM\,0} + \mathcal{L}_{int} \quad \to \quad \mathcal{L}_{SM} + \ldots$$

Large scale separation

- is natural if the model is built near a conformal IRFP

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“Foolproof” realization:

Take N_f above the conformal window

- Split the masses: $N_f = N_\ell + N_h$

  N_h flavors are massive, $m_\ell \ll m_h \ll \Lambda_{\text{cut-off}}$ $\longrightarrow$ decouple in the IR

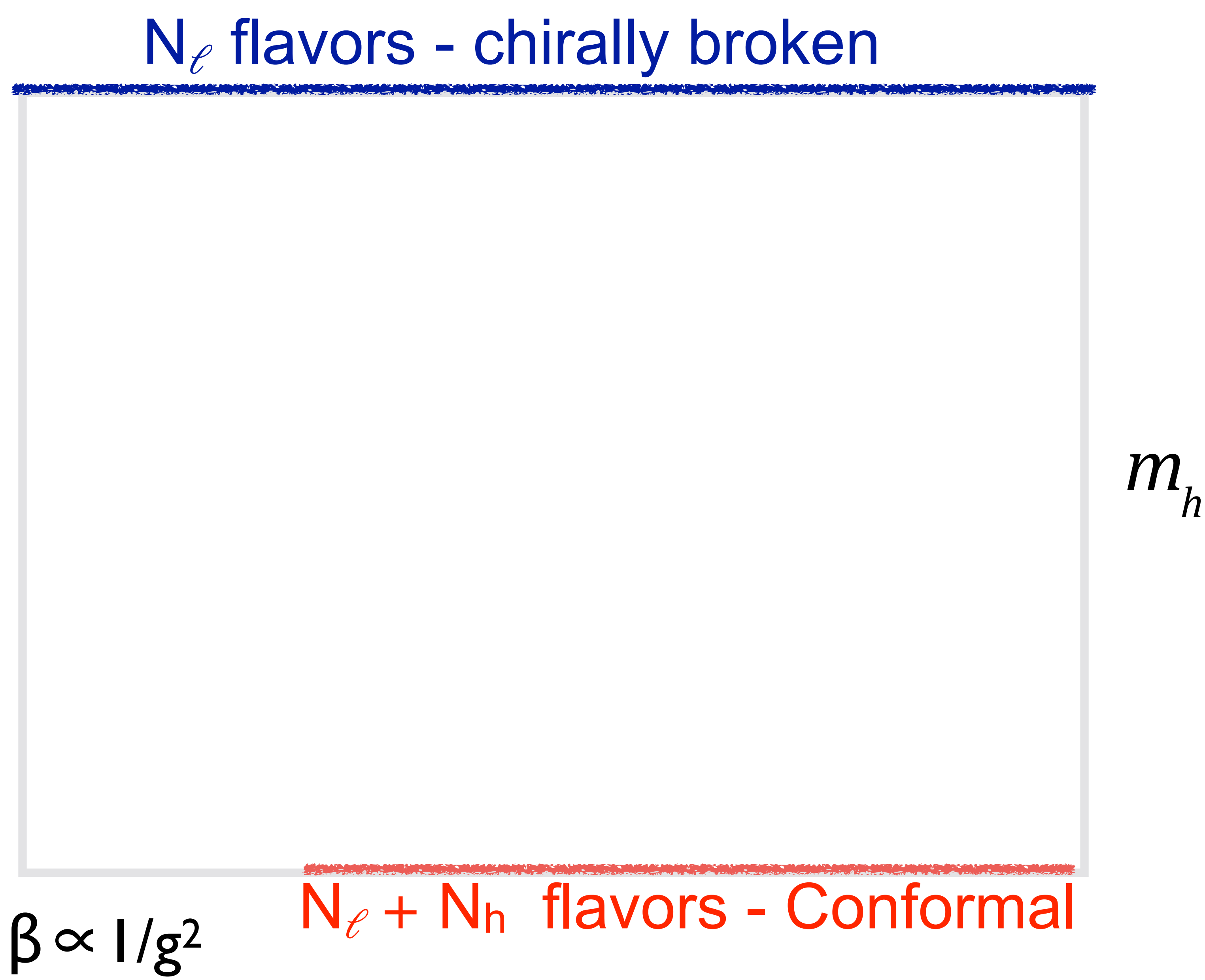
  N_ℓ (= 2 - 4) flavors are massless, $m_\ell = 0 \longrightarrow$ spont. chirally broken

A mass-split model

- shows conformal properties in the UV
- chirally broken in the IR
- large scale separation controlled by m_h

Phase diagram of mass-split model

Mass-split model, N_ℓ (=4) + N_h (=8) ; $m_\ell = 0$:



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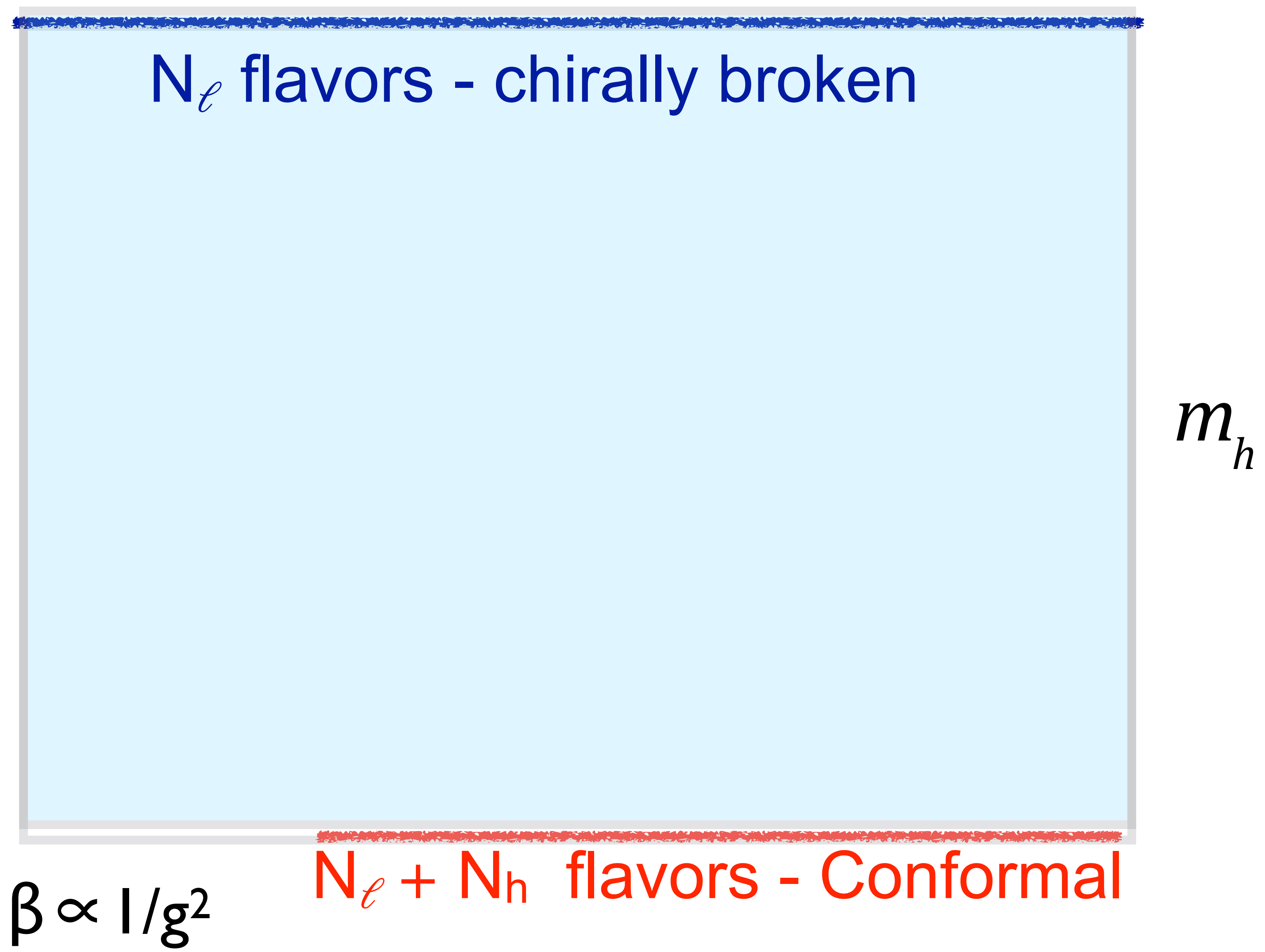

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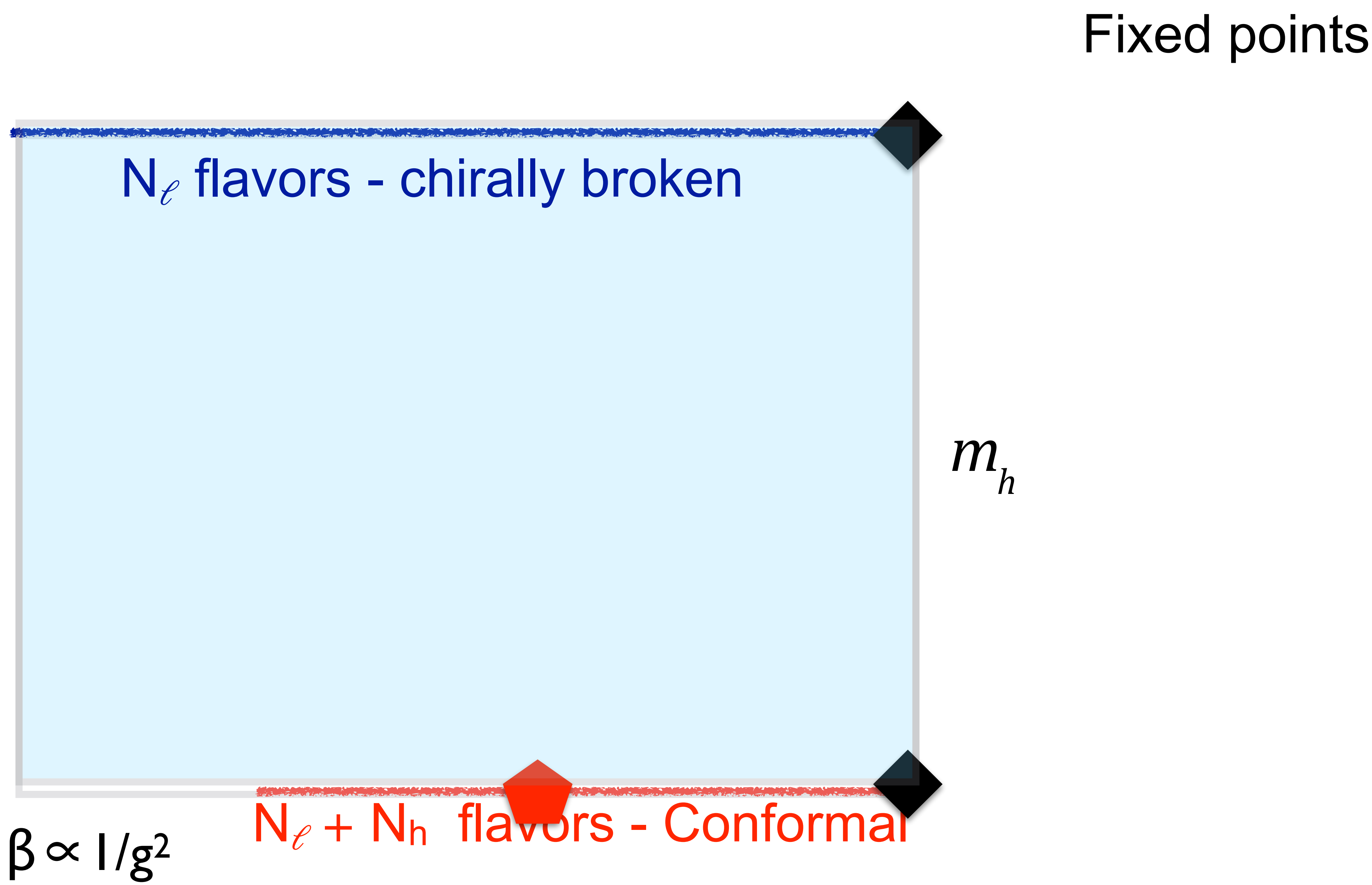


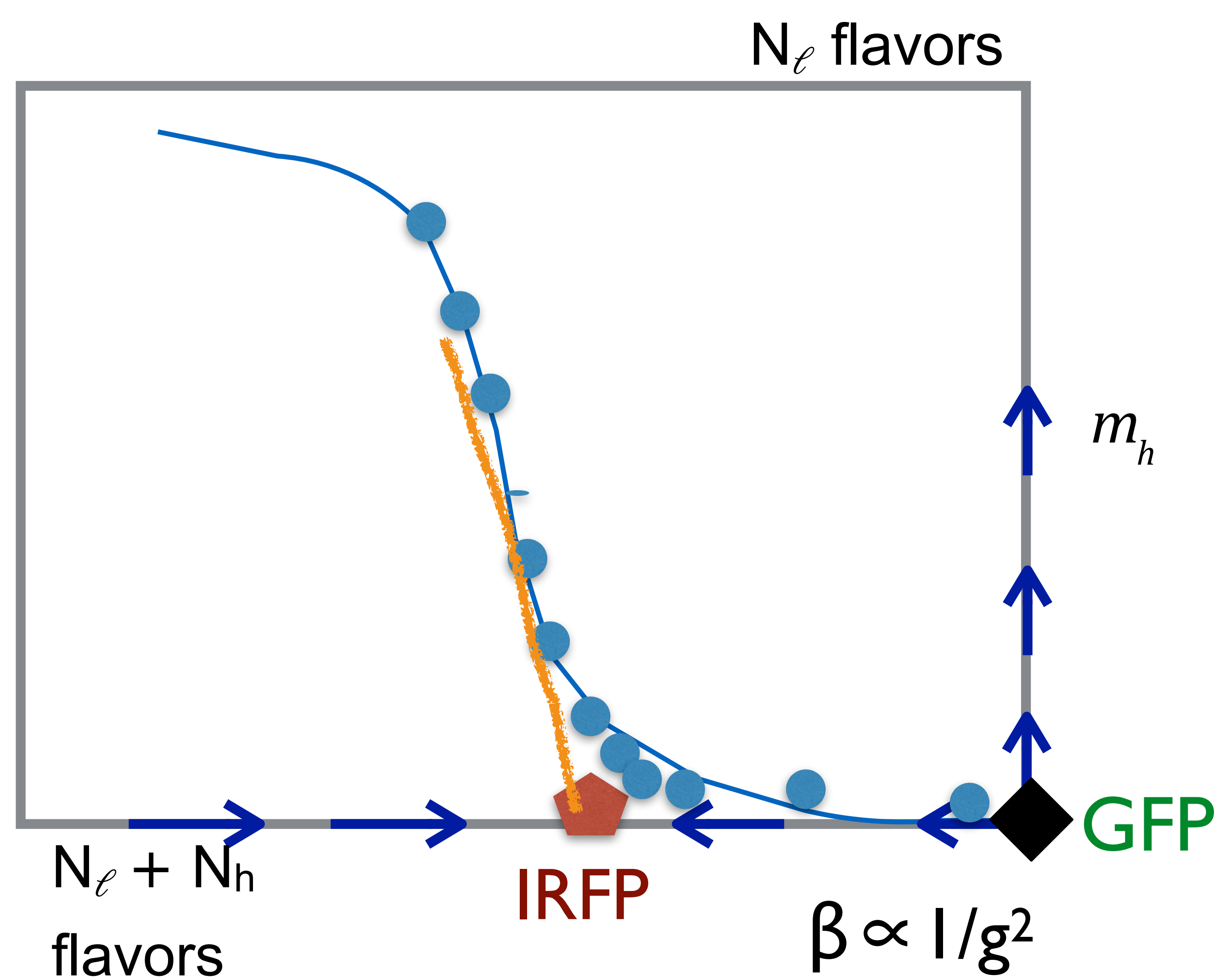
Wilson RG for mass-split models

Use Wilson RG description in conformal systems:

- start with bare parameters at the UV scale
- run RG from $\Lambda_{\text{cut-off}}$ to low energy μ
- continuum (infinite cut-off) system:
  tune bare couplings to criticality while keeping μ fixed

Mass-split model, $m_\ell = 0$:

- RG flow runs toward the IRFP, lingers around, then flows along RT
- IR physics is along the RT



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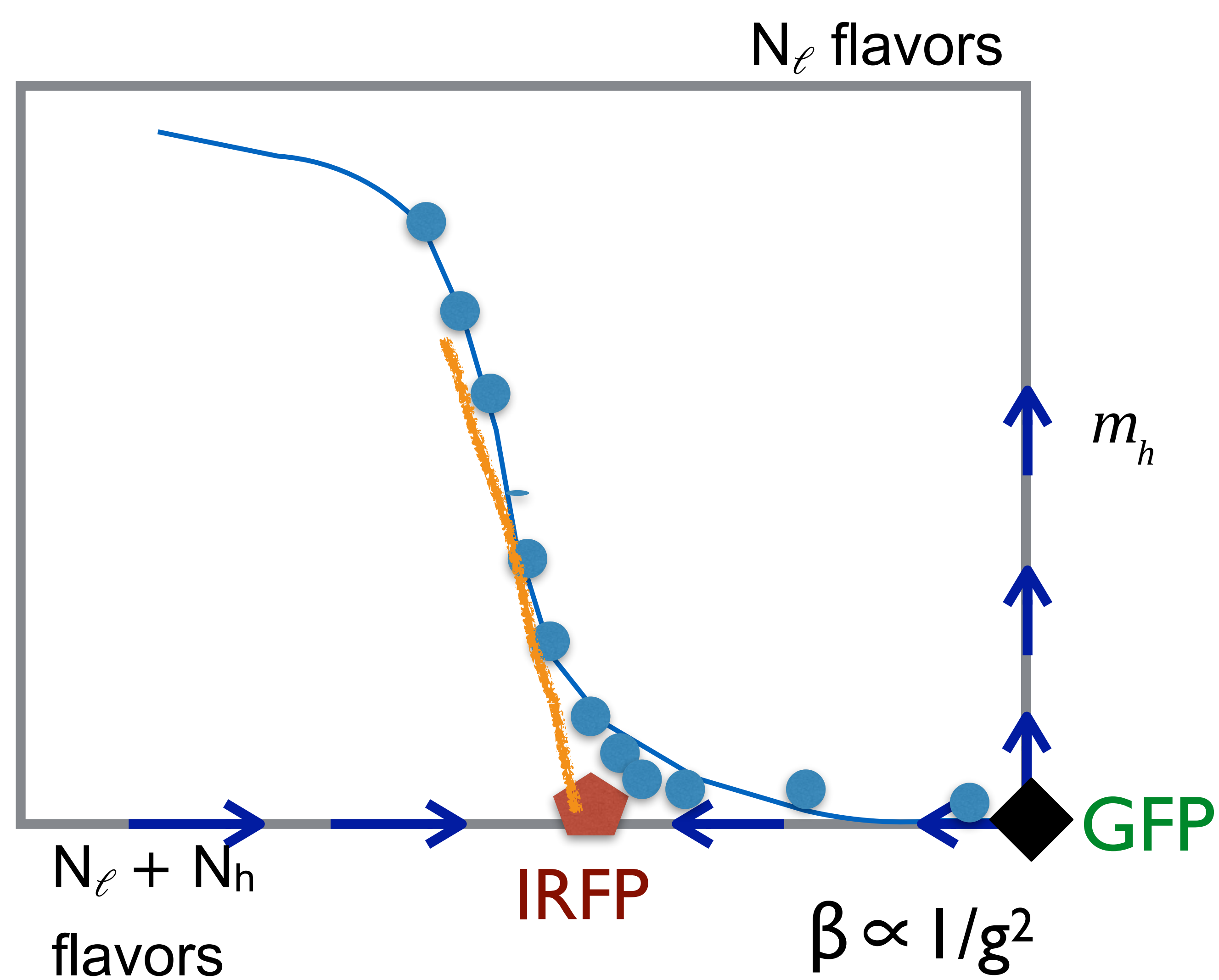

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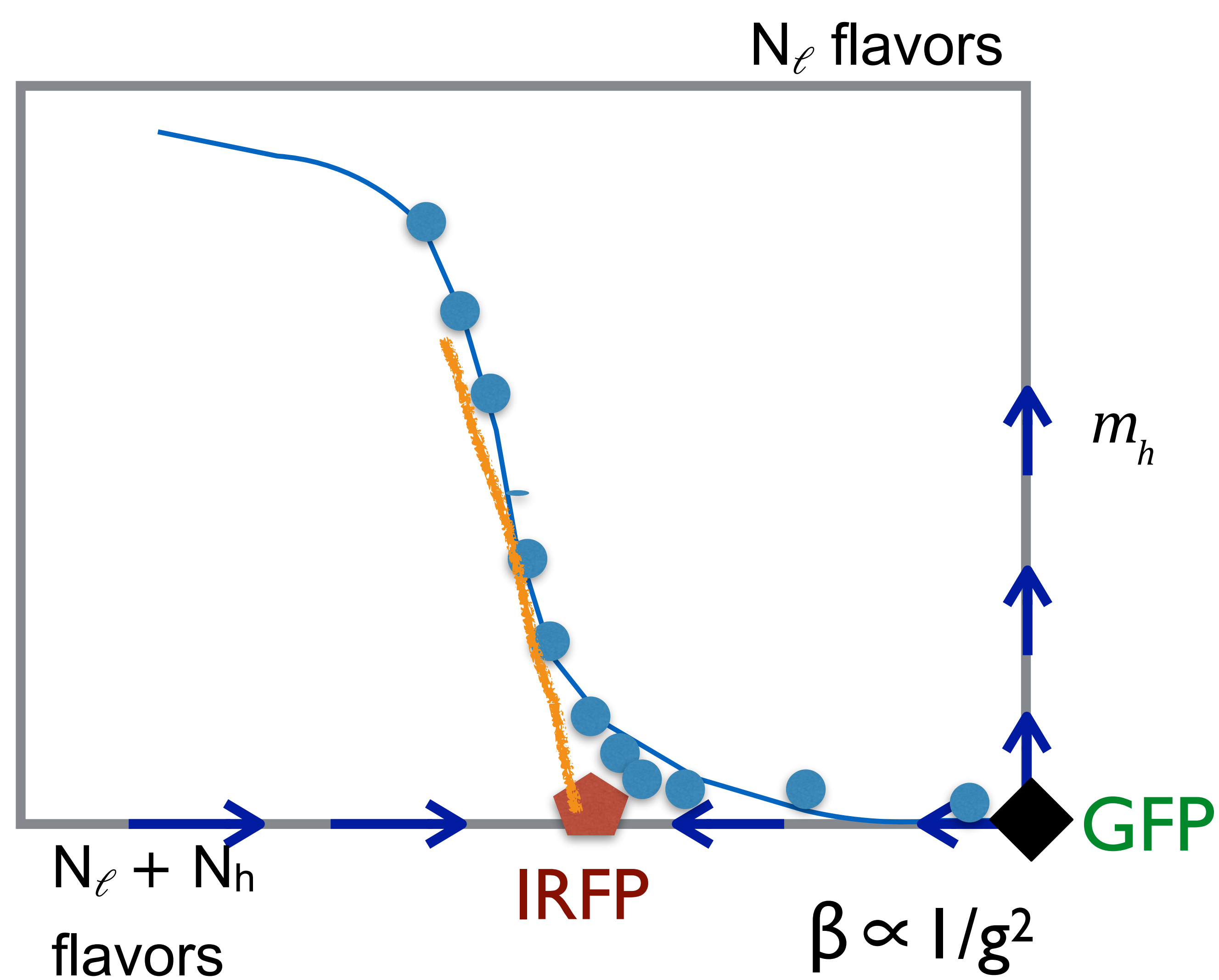
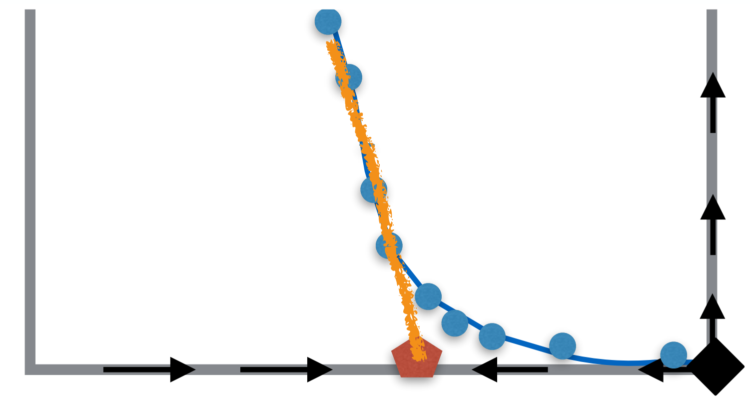
Makes the coupling walk!



Running/walking coupling



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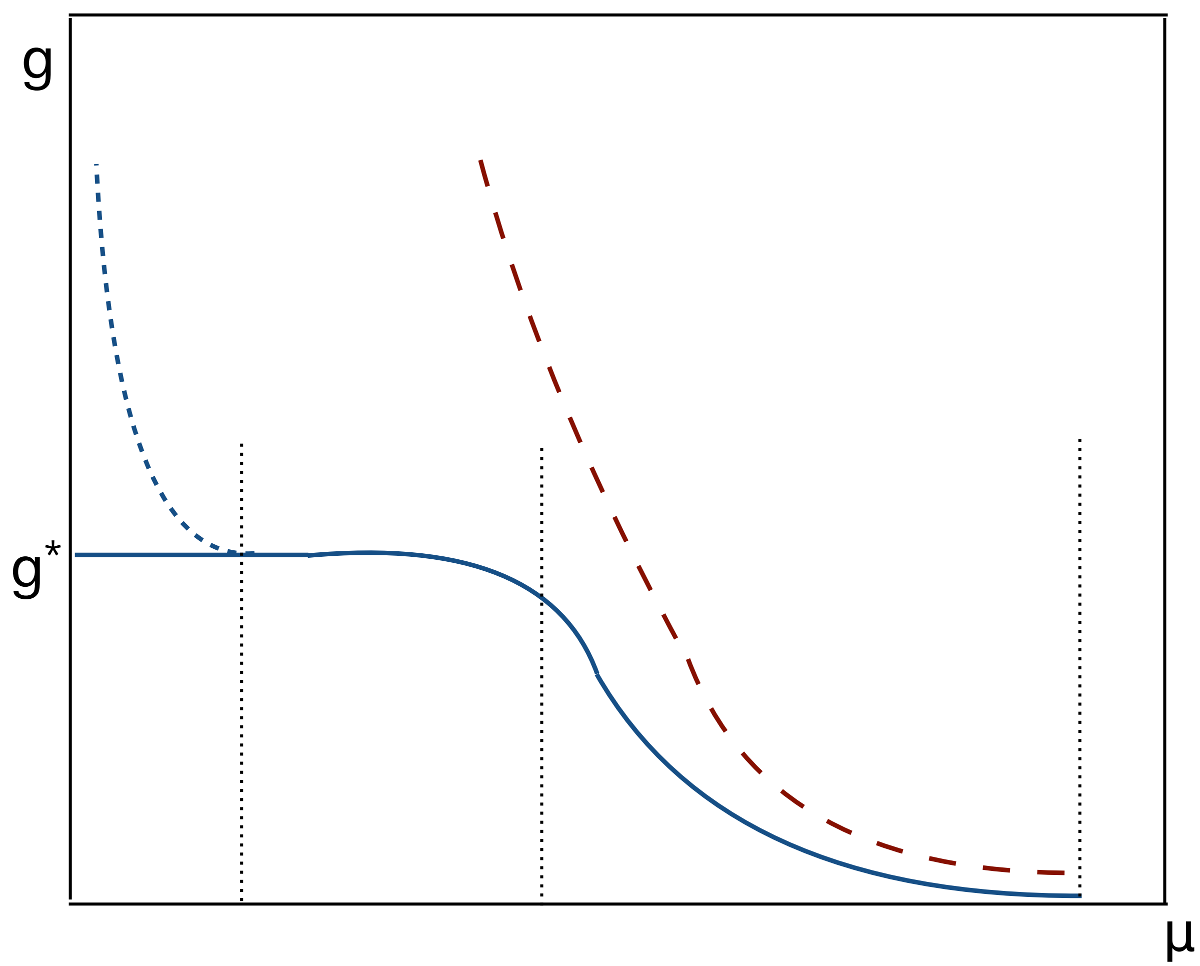

3 regions:

- UV :
  from cut-off to g ~ g*
- walking: m_h small, g~g*
- IR :
  heavy flavors decouple, N_ℓ light flavors are chirally broken

walking can be tuned by
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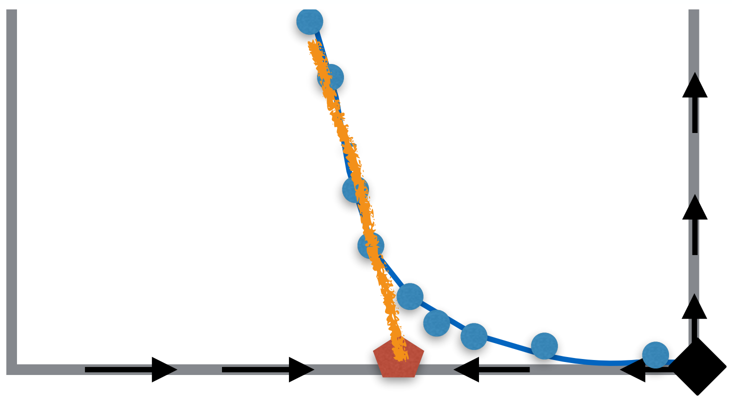

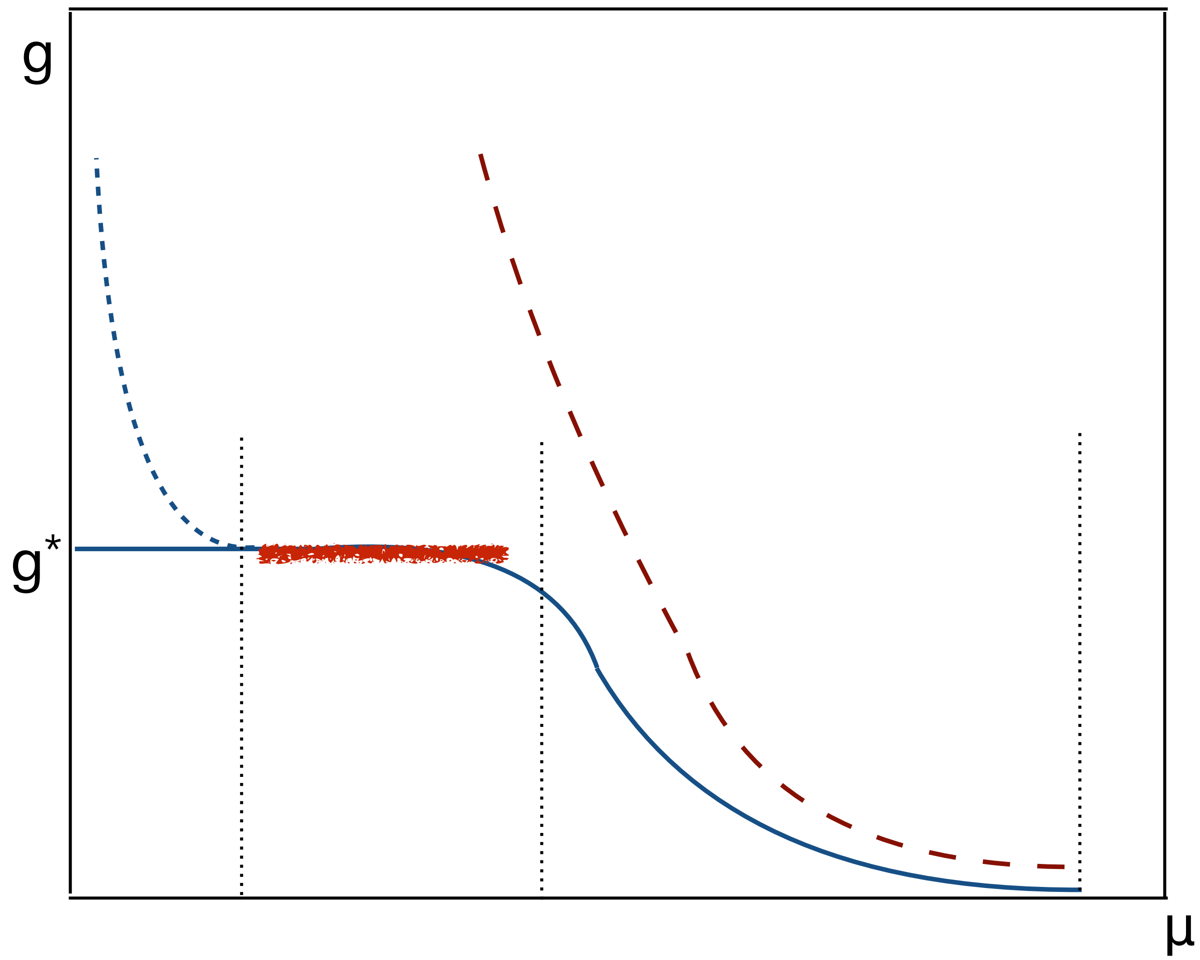

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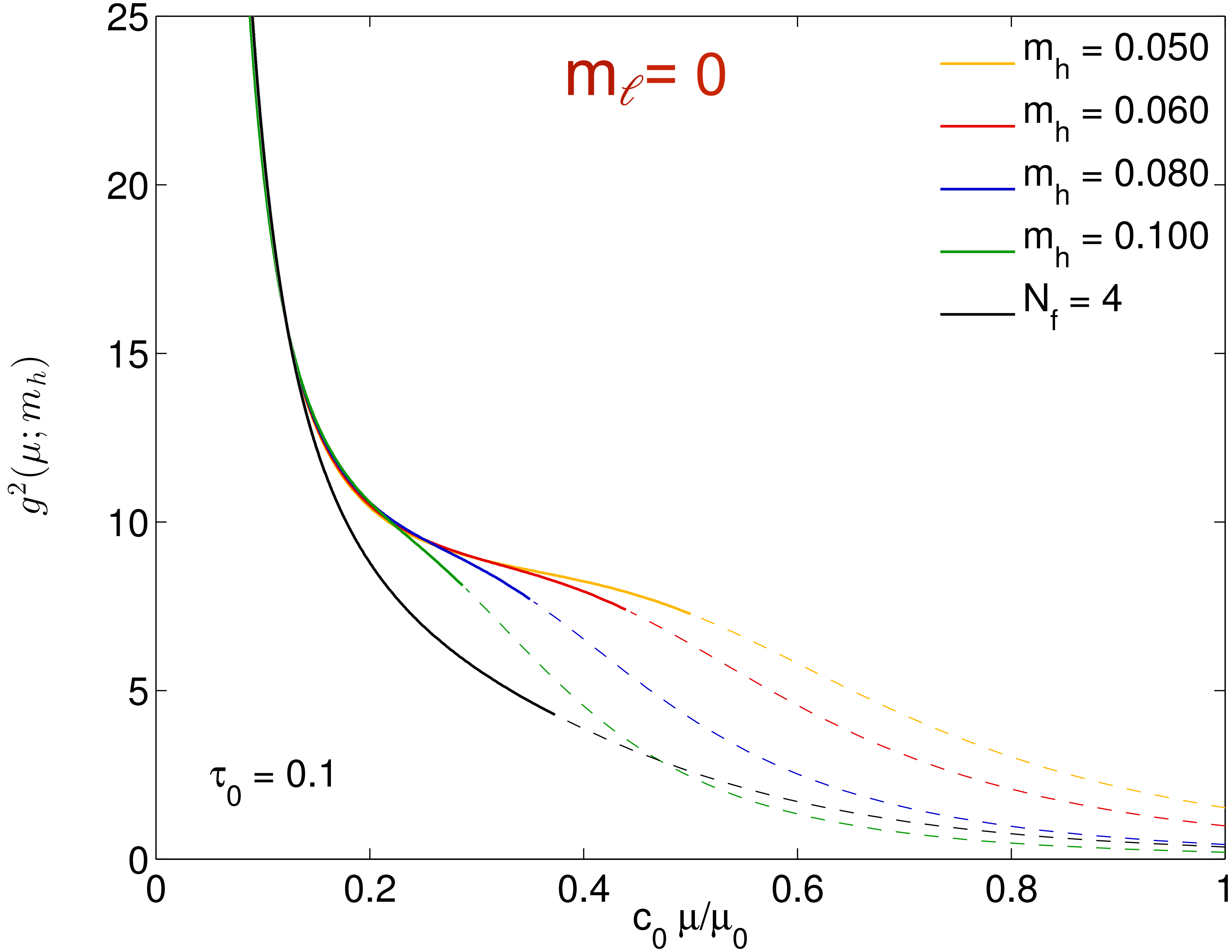
Example: 4ℓ+$8h$

Numerical result



4 light (massless)
8 heavy flavors

SU(3) with 12 degenerate flavors is conformal

$g^2_{GF}(\mu)$ develops a "shoulder" as $m_h \rightarrow 0$: this is walking !

Walking range can be tuned arbitrarily with m_h

N_f=4 : running fast

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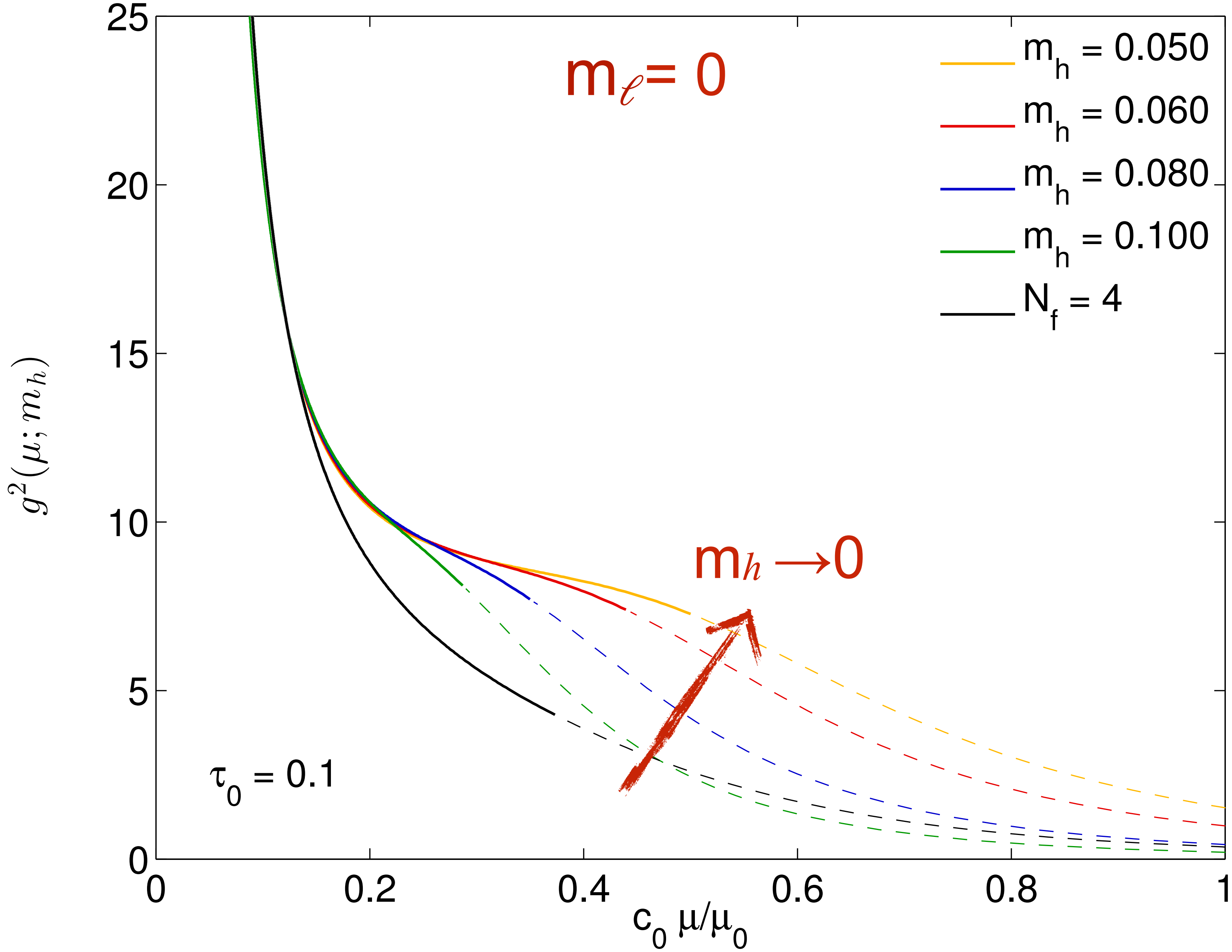

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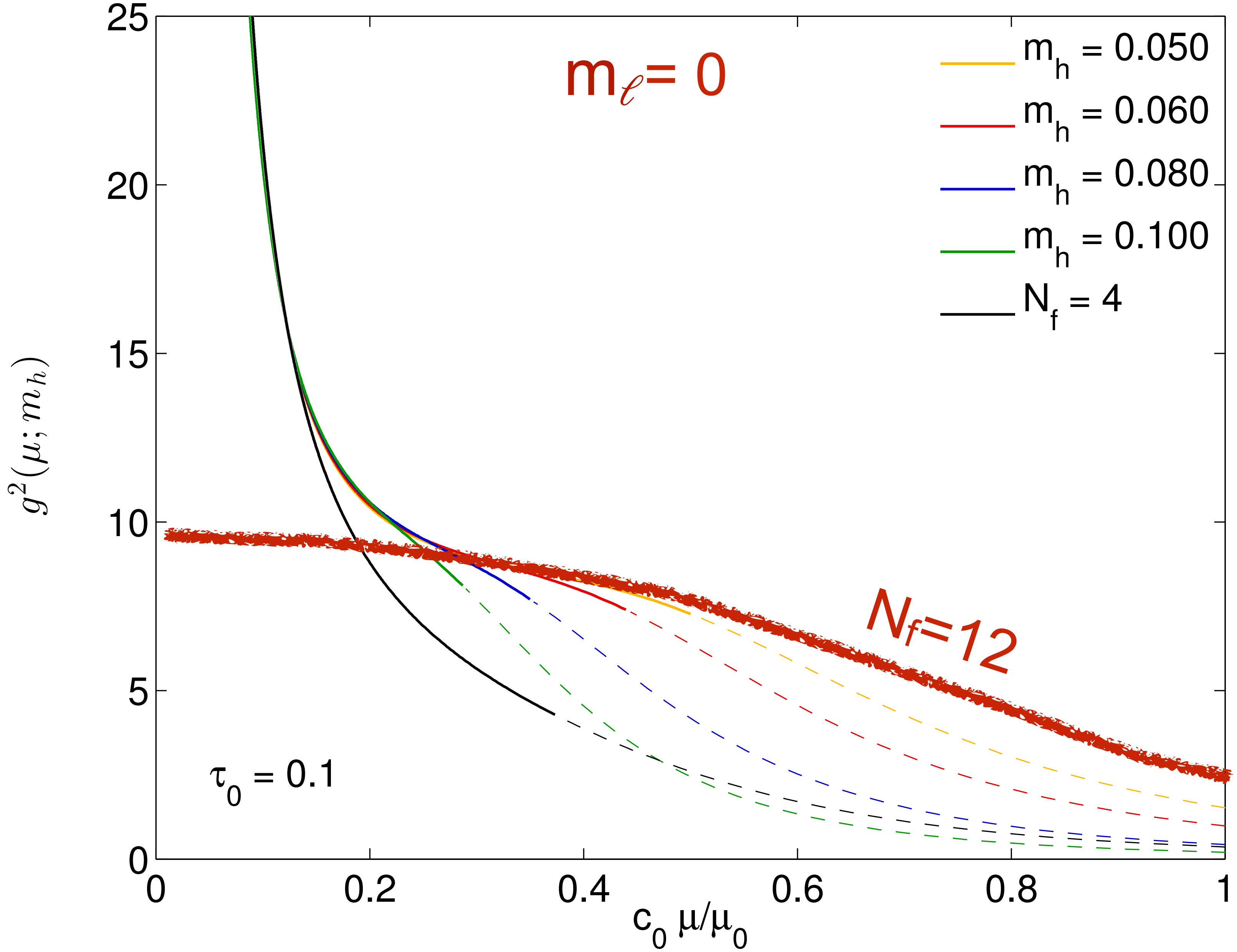

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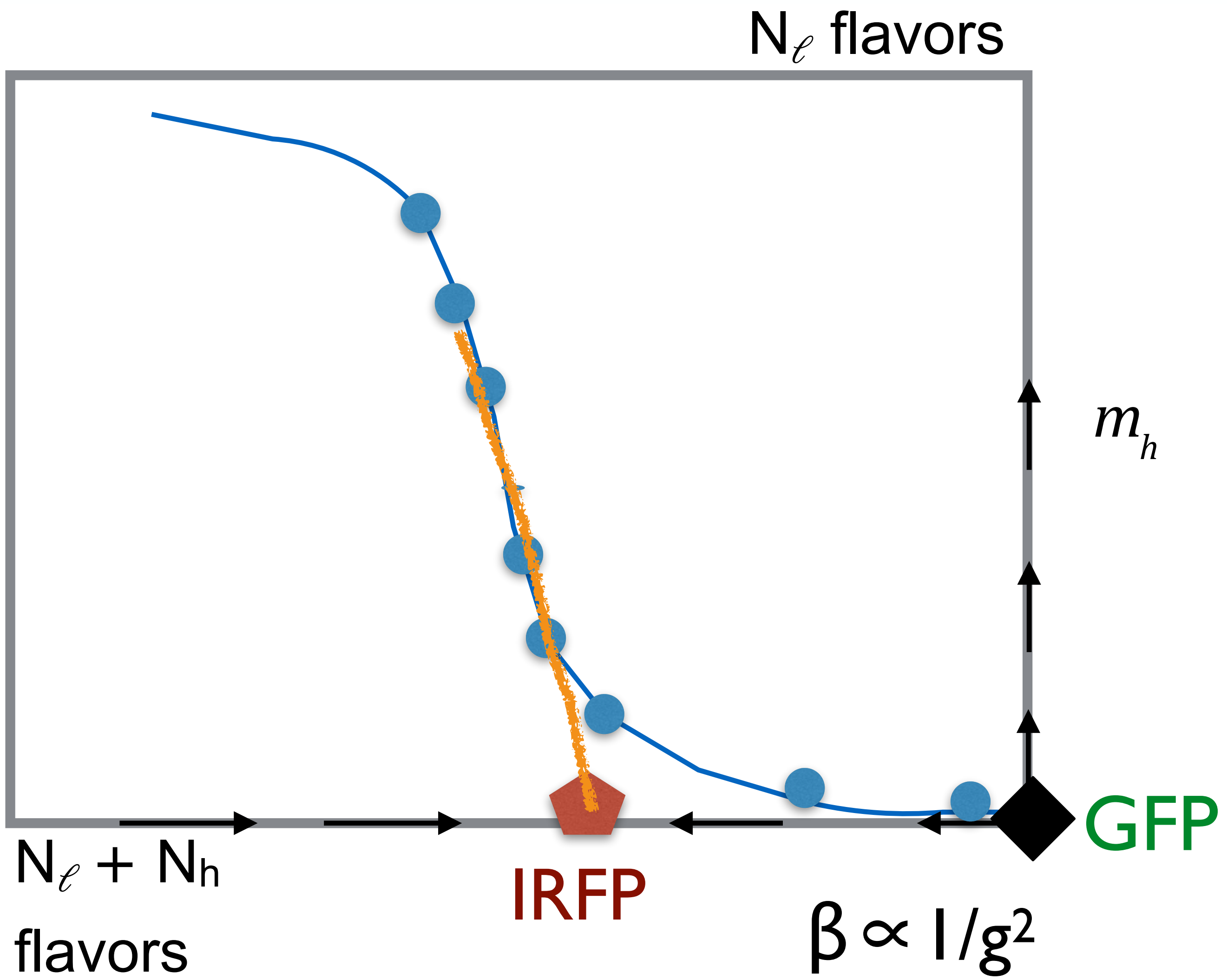
Mass-split models



How predictive is this model?

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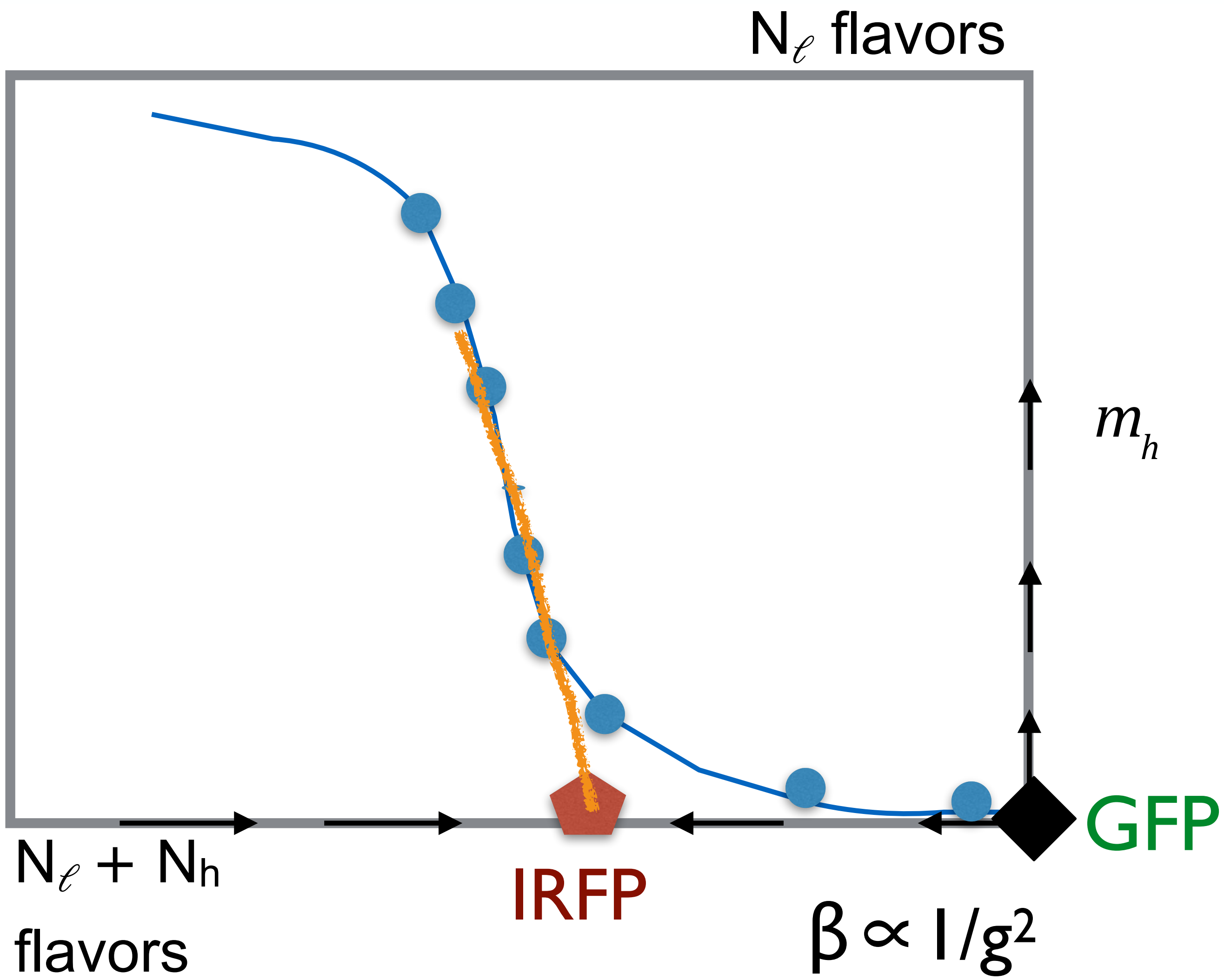

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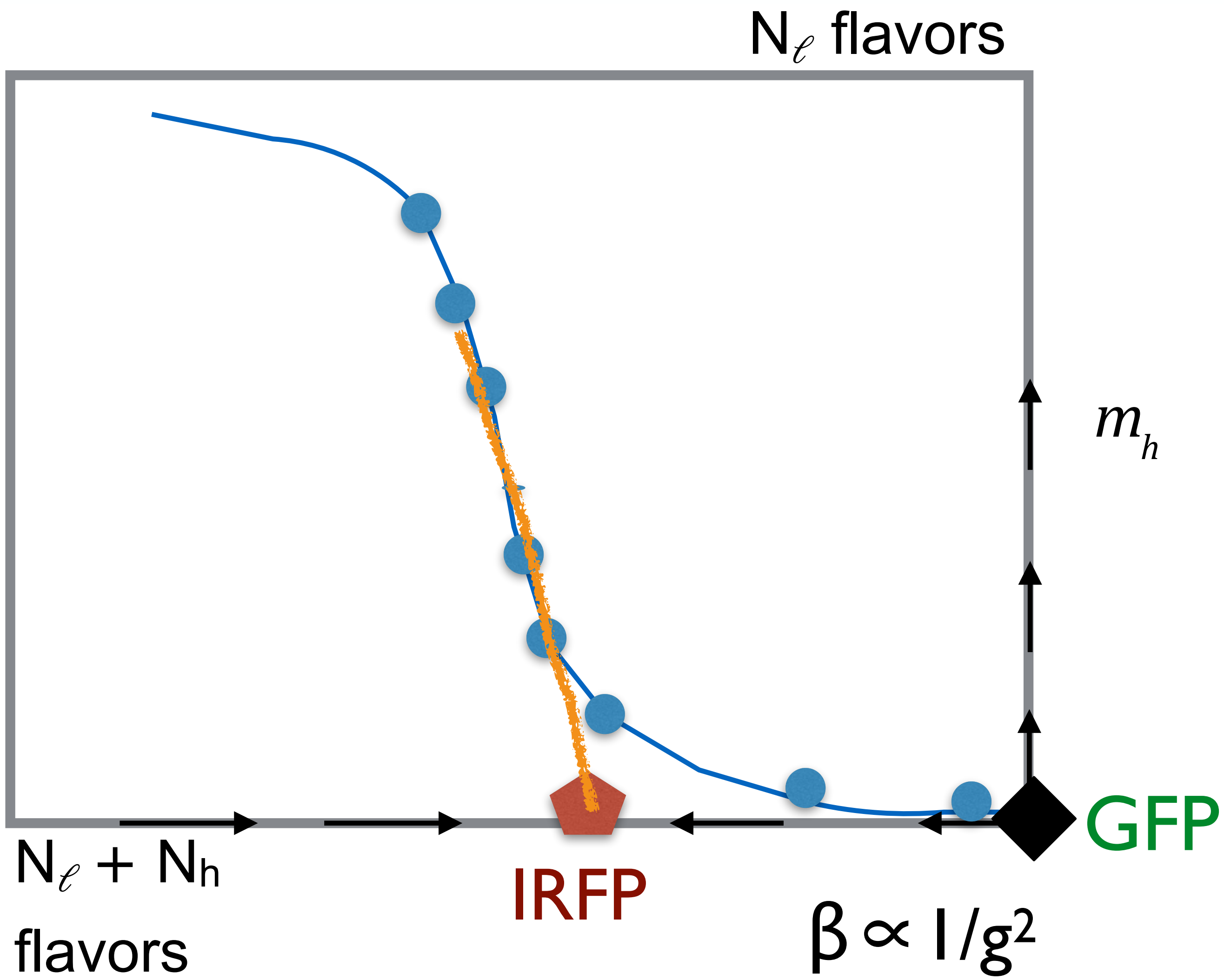

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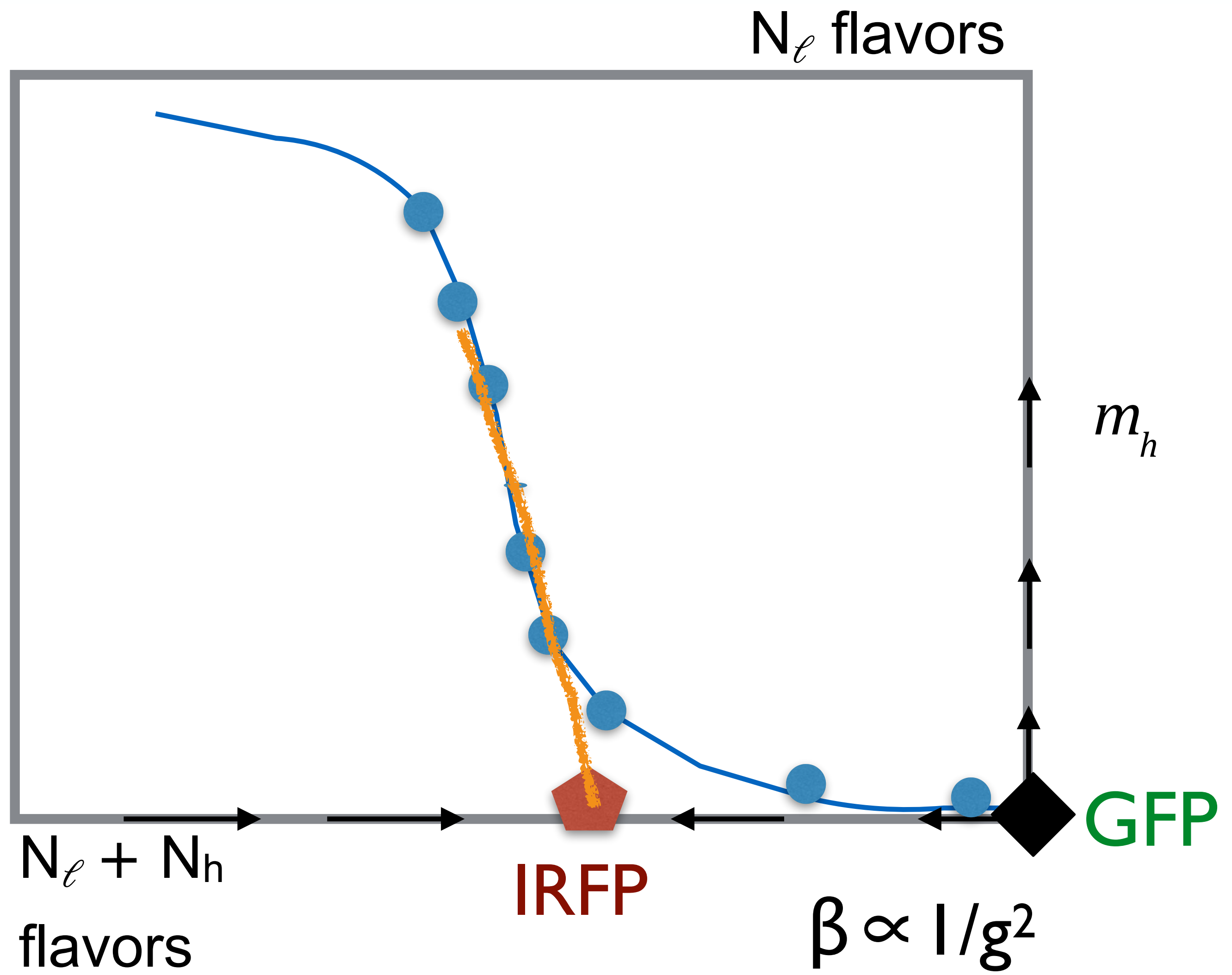

How predictive
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The only free parameter is m_h :

- sets the lattice scale (like g^2 in QCD)
- tune it with g_0 to control scale separation/walking

Hyperscaling around IRFP restricts the spectrum

Hyperscaling in mass-split system

In conformal systems Wilson RG predicts hyperscaling in the basin of attraction of the fixed point

If the scale changes as $\mu \to \mu' = \mu / b, \;\; b > 1$
the couplings run as

$$\hat{m}(\mu) \to \hat{m}(\mu') = b^{y_m} \hat{m}(\mu) \quad \text{(increases)}$$

$$g \to g^\star$$

and any 2-point correlation function scales as

$$C_H(t; g_i, \hat{m}_i, \mu) \to b^{-2y_H} C_H(t/b; g^\star, b^{y_m}\hat{m}_h, b^{y_m}\hat{m}_\ell, \mu)$$

$$\equiv b^{-2y_H} C_H(t/b; g^\star, b^{y_m}\hat{m}_h, \hat{m}_\ell / \hat{m}_h, \mu)$$

since

$$C_H(t) \propto e^{-M_H t} \longrightarrow aM_H \propto (\hat{m}_h)^{1/y_m} F_H(m_\ell / m_h)$$

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Hyperscaling in mass-split system

Masses scale as

$$aM_H \propto (\hat{m}_h)^{1/y_m} F_H(m_\ell / m_h)$$

Ratios are universal functions of m_ℓ/m_h

$$M_{H_1} / M_{H_2} = \Phi_H(m_\ell / m_h),$$

$$M_{H_1} / F_\pi = \tilde{\Phi}_H(m_\ell / m_h)$$

In terms of F_π the spectrum is predictable - no free parameters

- in the $m_\ell=0$ chiral limit the spectrum is independent of m_h
- true for light-light, heavy-light and heavy-heavy spectrum

This is very different from QCD!

Hyperscaling in mass-split system

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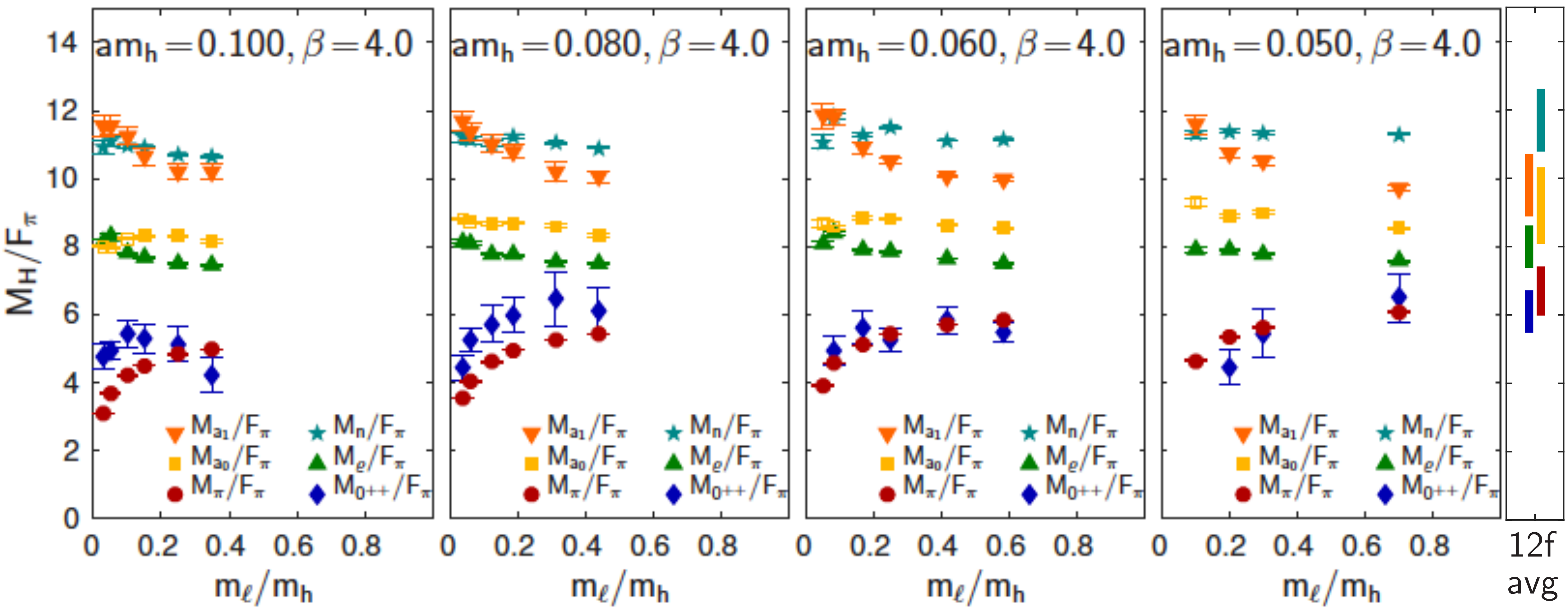
Brief summary of mass-split systems:

- predictive like QCD:
  - m_h replaces g^2
  - conformal FP replaces the Gaussian FP in the UV
- IR properties are not QCD - like:
  - the bound state masses in physical units (like F_π) are independent of m_h when m_ℓ=0, even for heavy flavors
  - the anomalous dimensions in the UV are controlled by the conformal FP
  - walking can be tuned arbitrarily

Sample numerical results for 4ℓ+$8h$

Light-light spectrum (4ℓ+$8h$)

in terms of m_ℓ/m_h at m_h = 0.05, 0.06, 0.08, 0.10



- approaches N_f=12 as $m_\ell/m_h \to 1$: M_H/F_π ratios are finite
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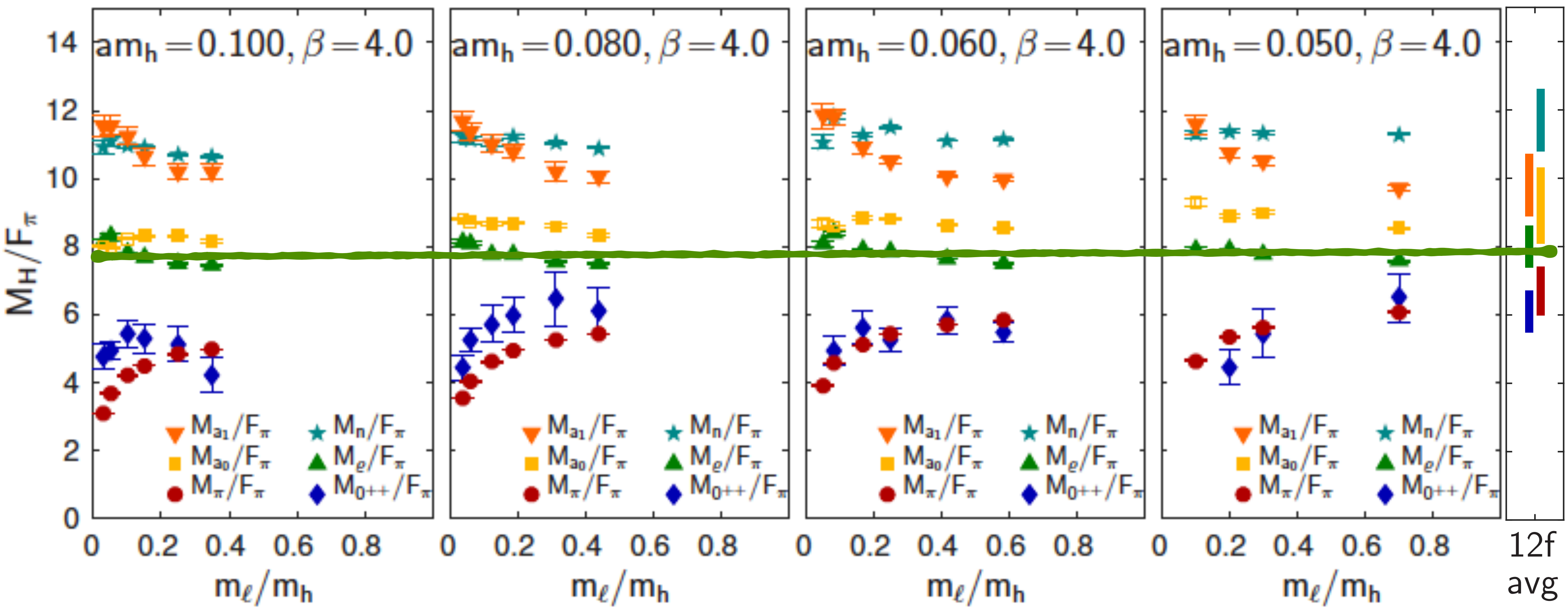

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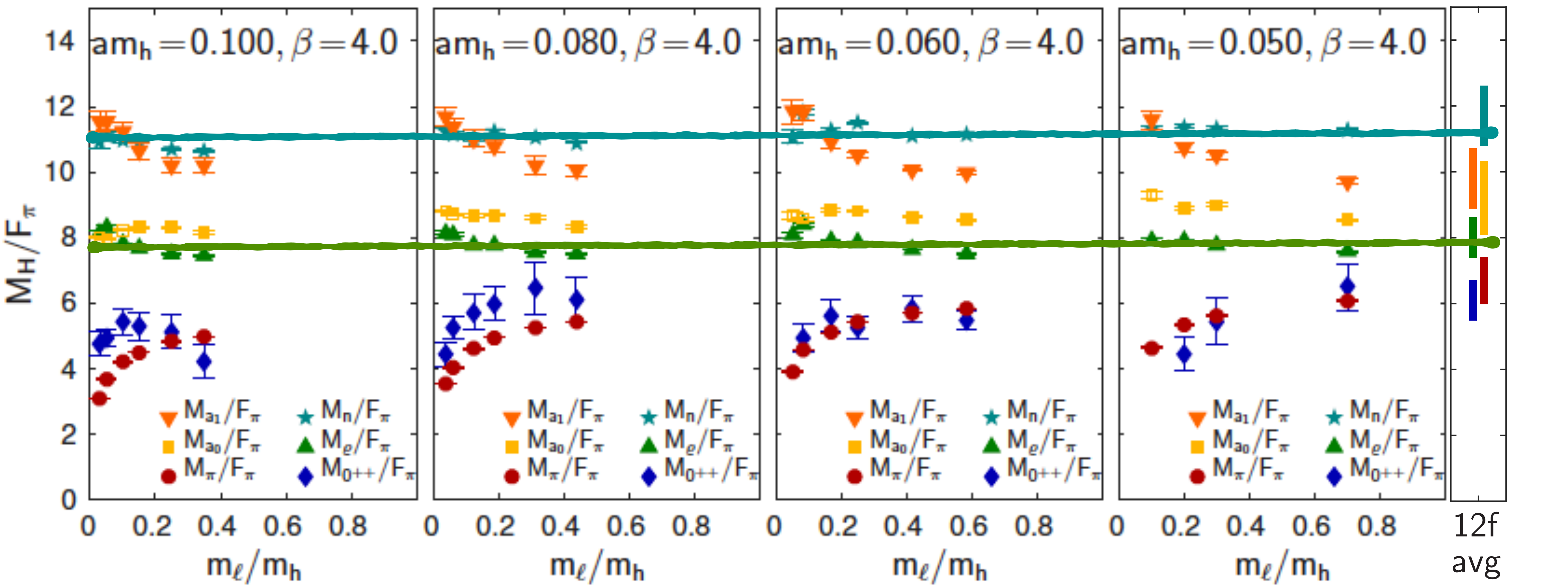

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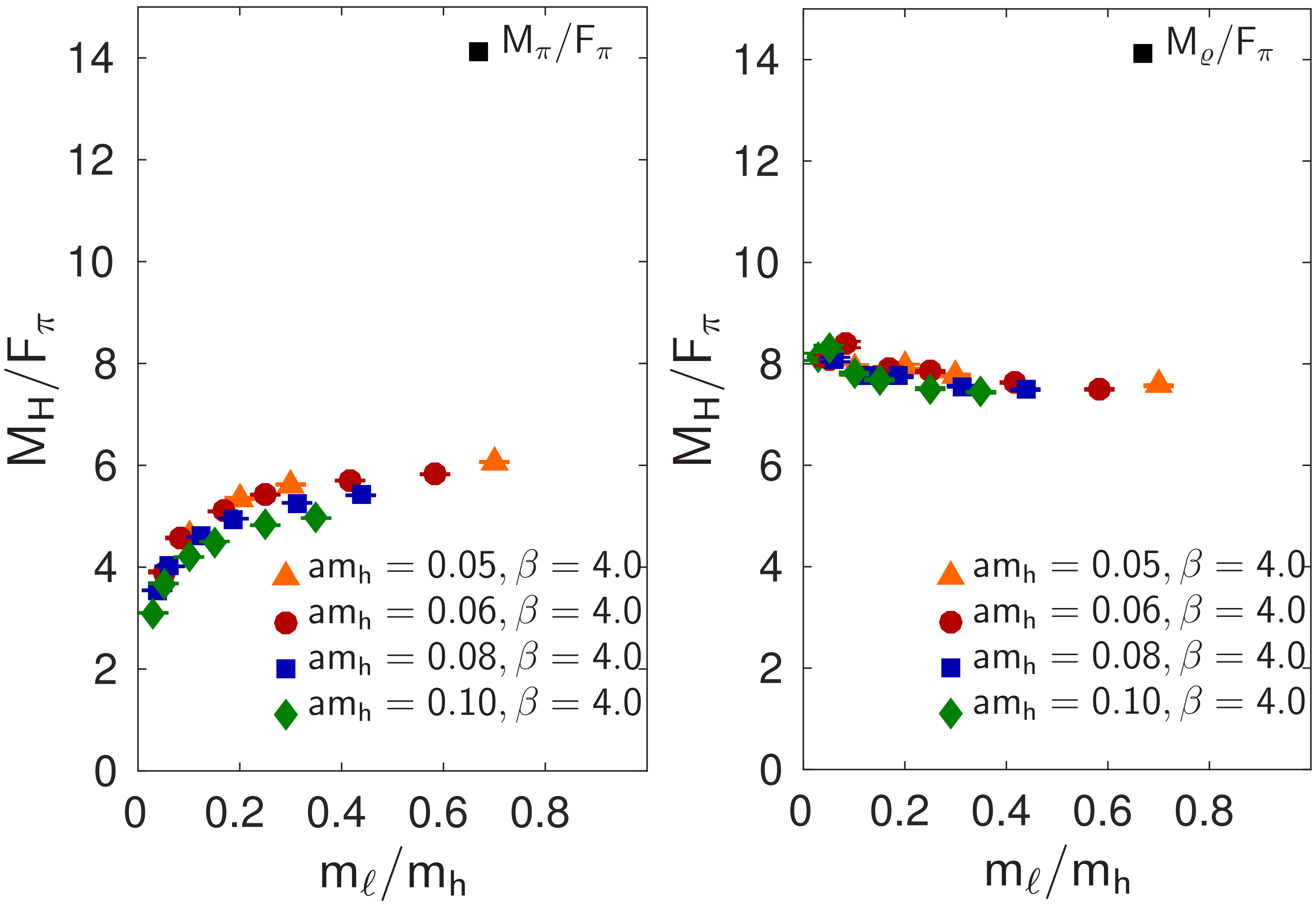
Hyperscaling

Ratios depend on m_ℓ/m_h but not on m_ℓ, m_h or g^2

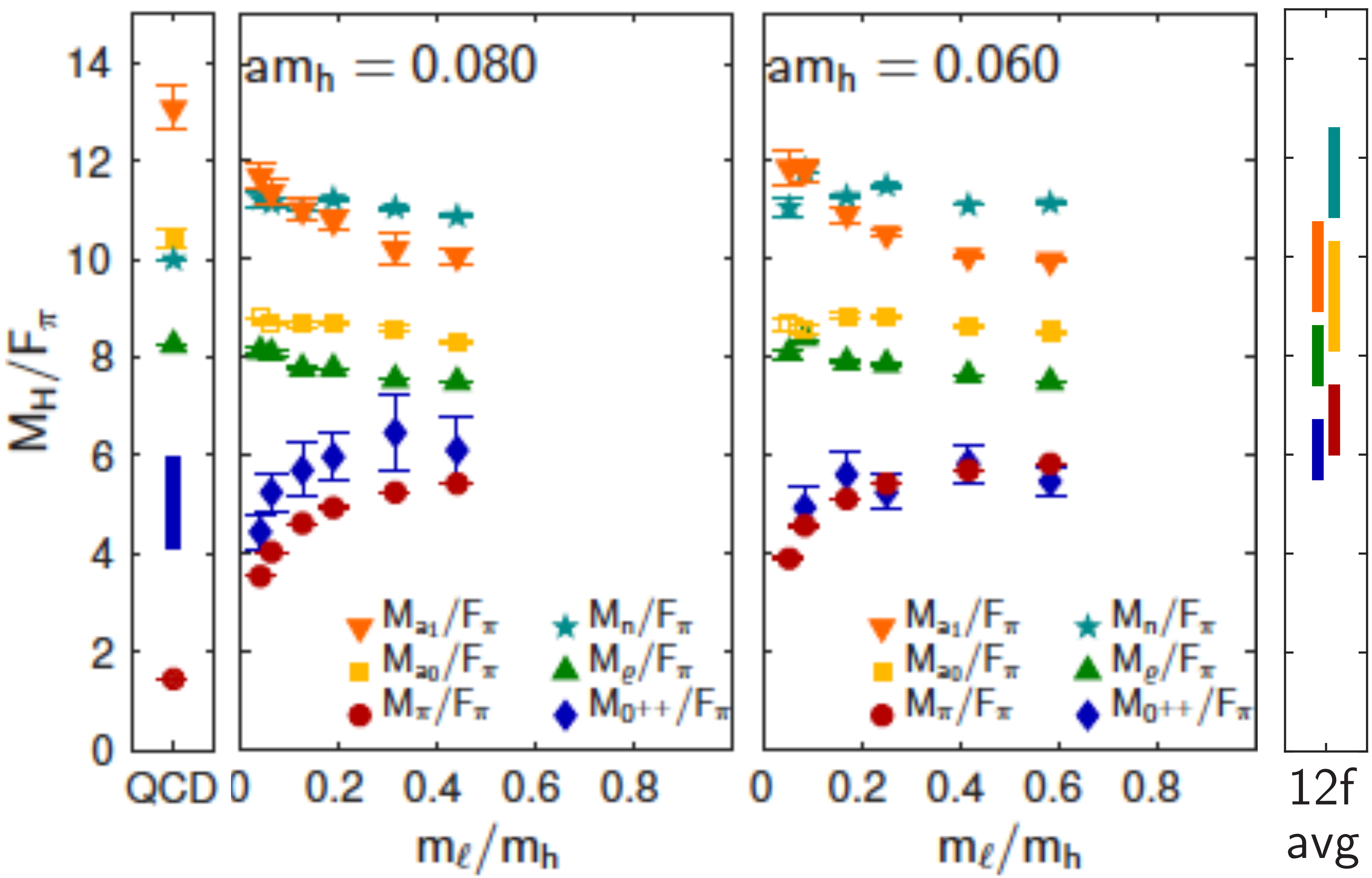


four different
m_h =0.05 — 0.10
on each panel

similar for other
states

Compare to QCD

QCD: $m_\ell \to 0$, $m_h \to \infty$; not in the basin of attraction of the IRFP (no hyperscaling)



Connected spectrum is mainly valence fermions

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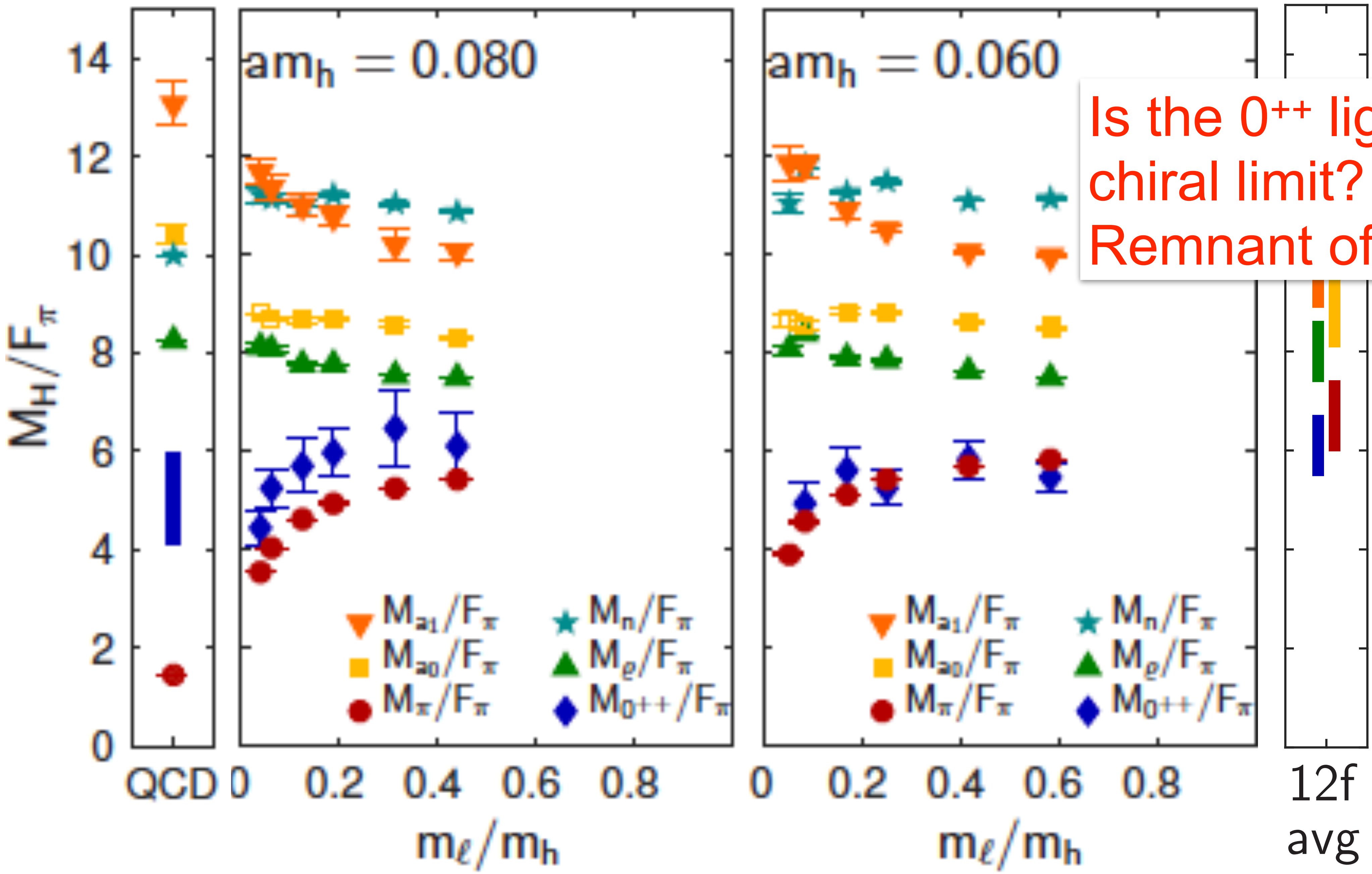

Is the 0^{++} light in the chiral limit?
Remnant of conformal FP?

Connected spectrum is mainly valence fermions

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- IR properties are not QCD - like:
  - the bound state masses in physical units (like F_π) are independent of m_h when m_ℓ=0, even for heavy flavors
    most dramatic difference - see next talk
  - the anomalous dimensions in the UV are controlled by the conformal FP
  - walking can be tuned arbitrarily

Hyperscaling

Ratios depend on m_ℓ/m_h but not on m_ℓ, m_h or g^2

Phys.Let. B773 (2017) 86