Infrared properties of a prototype pNGB model for beyond-SM physics

Anna Hasenfratz[1*], Claudio Rebbi[2], Oliver Witzel[3]

[1]University of Colorado Boulder, [2]Boston University, [3]University of Edinburgh,
[*]presenter

in part based on PRD93, 114514 (2016)
with Richard Brower, Evan Weinberg

LATTICE 2016

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

Infrared properties of a prototype dilaton-like or pNGB Higgs model for beyond-SM physics

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Composite Higgs Models

Most strongly coupled BSM models are effective models, describing part of the dynamics. The goal is to

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

$$\mathcal{L}_{SM\,0} \longrightarrow \mathcal{L}_{SM}$$

Composite Higgs Models

Most strongly coupled BSM models are effective models, describing (some) part of the dynamics:

New strong dynamics coupled to SM can do it:

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

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

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

The construction has to

- give mass to the SM gauge fields
- give mass to the SM fermions :
  4-fermion interaction or partial compositness
- give mass to $\mathcal{L}_{SD}$ fermions and generate 4-fermion interactions: $\mathcal{L}_{UV}$ sector

$$\left.\right\} \mathcal{L}_{SD} = \mathcal{L}_{SD1} + \mathcal{L}_{SD2} + \ldots$$

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New strong dynamics coupled to SM can do it:

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

This could come from a UV complete theory

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What is $\mathcal{L}_{SD}$?

The most promising candidates for $\mathcal{L}_{SD}$ are chirally broken in the IR but conformal in the UV: (Luti&Okui(hep-lat/00409274), Dietrich&Sannino(hep-ph/0611341) ,Vecchi(1506.00623), Ferretti(1312.5330, talk at Edinburgh, June 2016),…..

conformal | chirally broken

UV → IR

Λ_{UV} Fermion masses Λ_{IR} Higgs dynamics

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Many possibilities:

- SU(3) gauge with 4 flavors
- SU(4) with 2 different representation
- etc.

Ma, Cacciapaglia,JHEP1603,211
Vecchi, 1506.00623
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Add enough fermions to drive the system into the conformal window;
If the fermions are massive*, they will decouple at Λ_{IR}

Many possibilities:
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- SU(4) with 2 different representation
- etc.

Ma, Cacciapaglia,JHEP1603,211
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* What gives mass to the additional fermions?
That is dynamics beyond Λ_{UV} .

Lattice realization: 4+8 mass-split model

R. Brower, A. H, C. Rebbi, E. Weinberg ,
O. Witzel, PRD93, 114514 (2016)

conformal | chirally broken

UV → IR

Λ_{UV} Fermion masses Λ_{IR} Higgs dynamics

Add 8 "heavy" fundamental flavors: $N_f = 4+8 = 12$:
→ conformal dynamics

SU(3) gauge with 4 light fundamental flavors:
pNGB or prototype dilaton-Higgs

Ma, Cacciapaglia,JHEP1603,211
Vecchi, 1506.00623

The construction

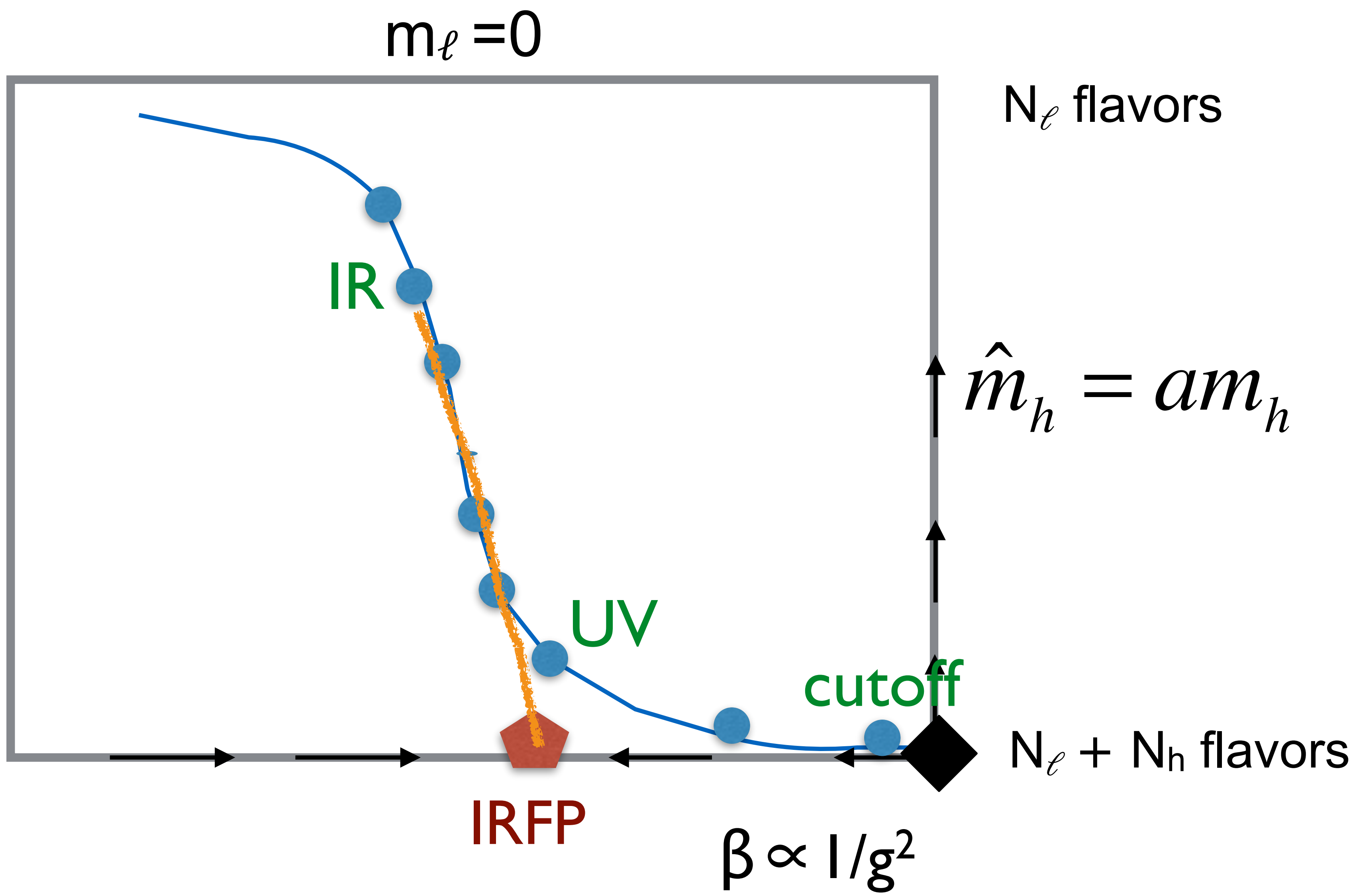
- ensures chiral symmetry breaking in the IR
- "walking" is arbitrarily tunable by m_h
- anomalous dimensions are that of the conformal IRFP

This system is a prototype - many similar models are possible

Why UV conformal?

Predictivity and tunable walking

Phase diagram of $N_h = 8$ "heavy" and $N_\ell = 4$ light or massless flavors



Parameters:

g^2, m_h, m_ℓ

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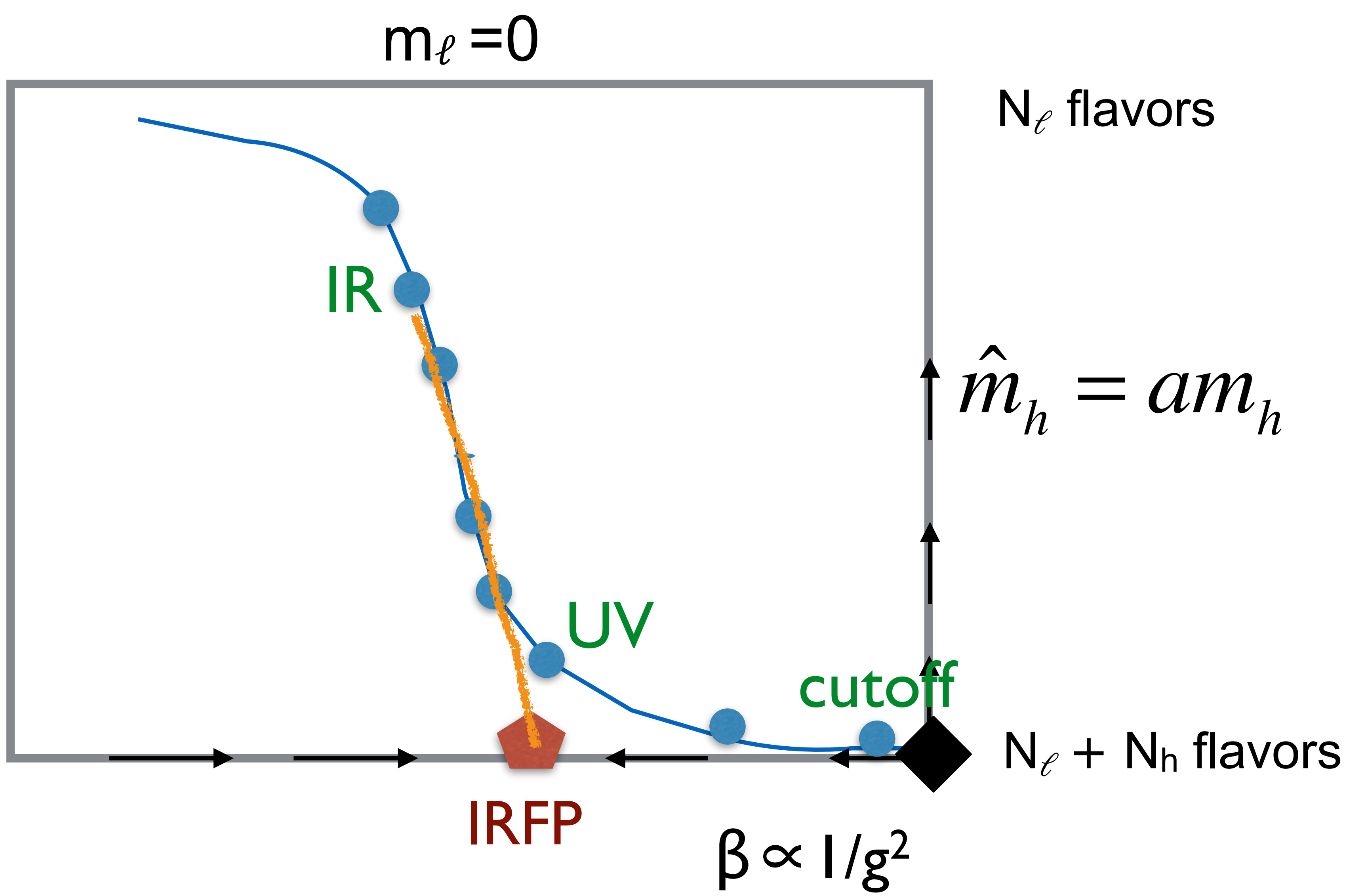

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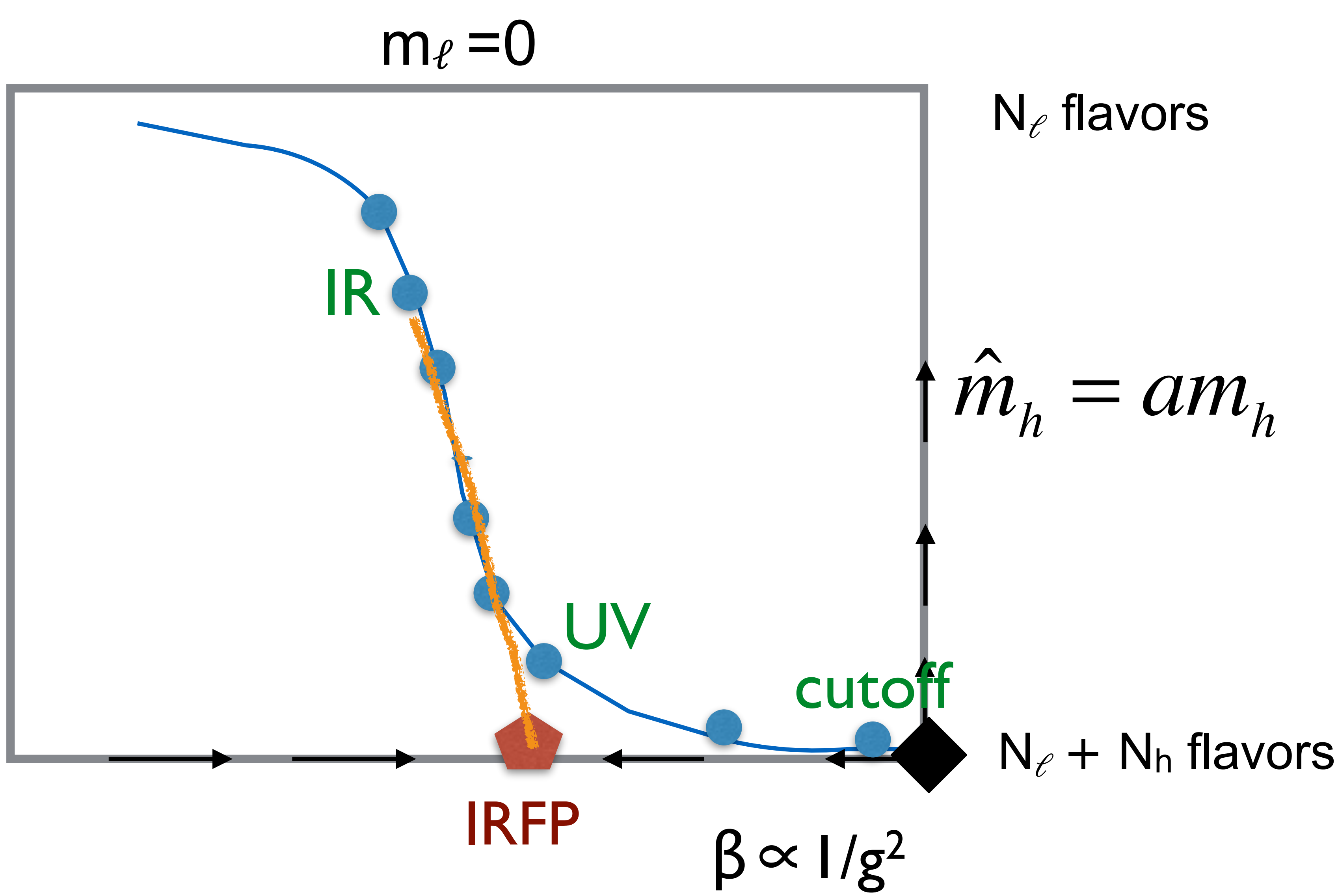

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Sets the scale

F_π or M_N

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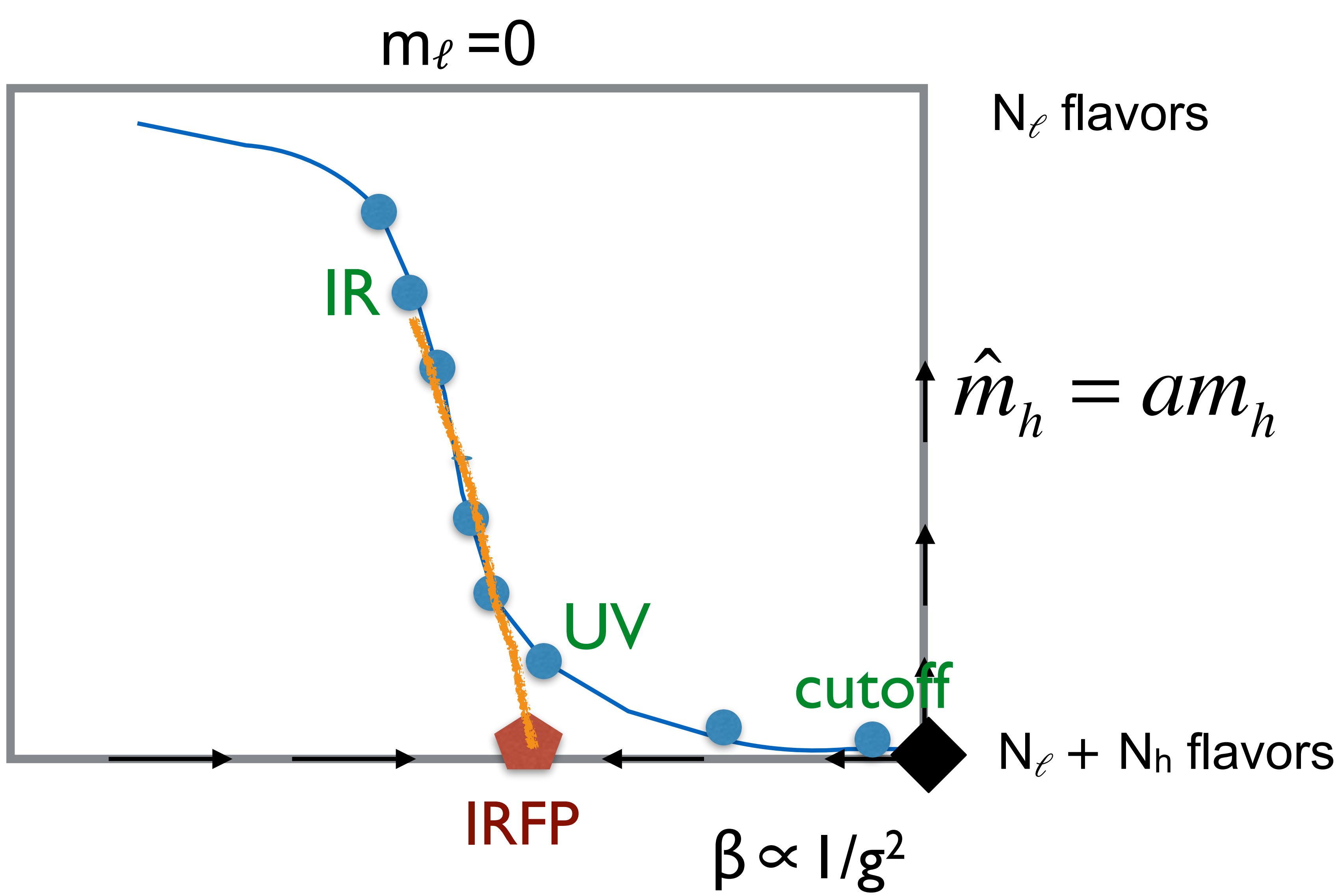

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Hyperscaling:

only m_ℓ/m_h matters

Lattice realization: mass-split model

Questions for lattice study:

- What is the spectrum - light and heavy?
- What is the effect of the 8 heavy flavors on the light spectrum?
- Is the heavy spectrum present in the IR dynamics?
- How does the coupling run/walk ?
- What is the anomalous dimension at the IRFP: $\psi\psi\psi$ and $\bar{\psi}\psi$.

This talk: hyperscaling relations that governs the spectrum
and a few illustrative examples

Next talk by Claudio Rebbi : many more details!

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Hyperscaling in mass-split models

In conformal systems Wilson RG considerations predict the mass dependence of all dimensional quantities (hyperscaling)

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

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

$$g \to g^\star$$

Any 2-point correlation function at large b 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

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

where $F_H(m_\ell / m_h)$ is a universal function

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Hyperscaling in mass-split models

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 the $m_\ell=0$ chiral limit dimensionless ratios are independent of m_h

If F_π is known, the rest of the spectrum is predicted - no more free parameters

- True for light, heavy and mixed spectrum
- This is very different from QCD!

Corrections to scaling

The gauge coupling in N_f=12 runs slow -

$g \to g^\star$ is not a (very) good approximation, corrections are needed

Cheng, A.H.,Y. Liu,Petropoulos, Schaich,PRD90 (2014) 014509

Ratios scale as

$$M_{H_1}/F_\pi = \tilde{\Phi}_H(m_\ell/m_h)(1+c_0 m_h^\omega)$$

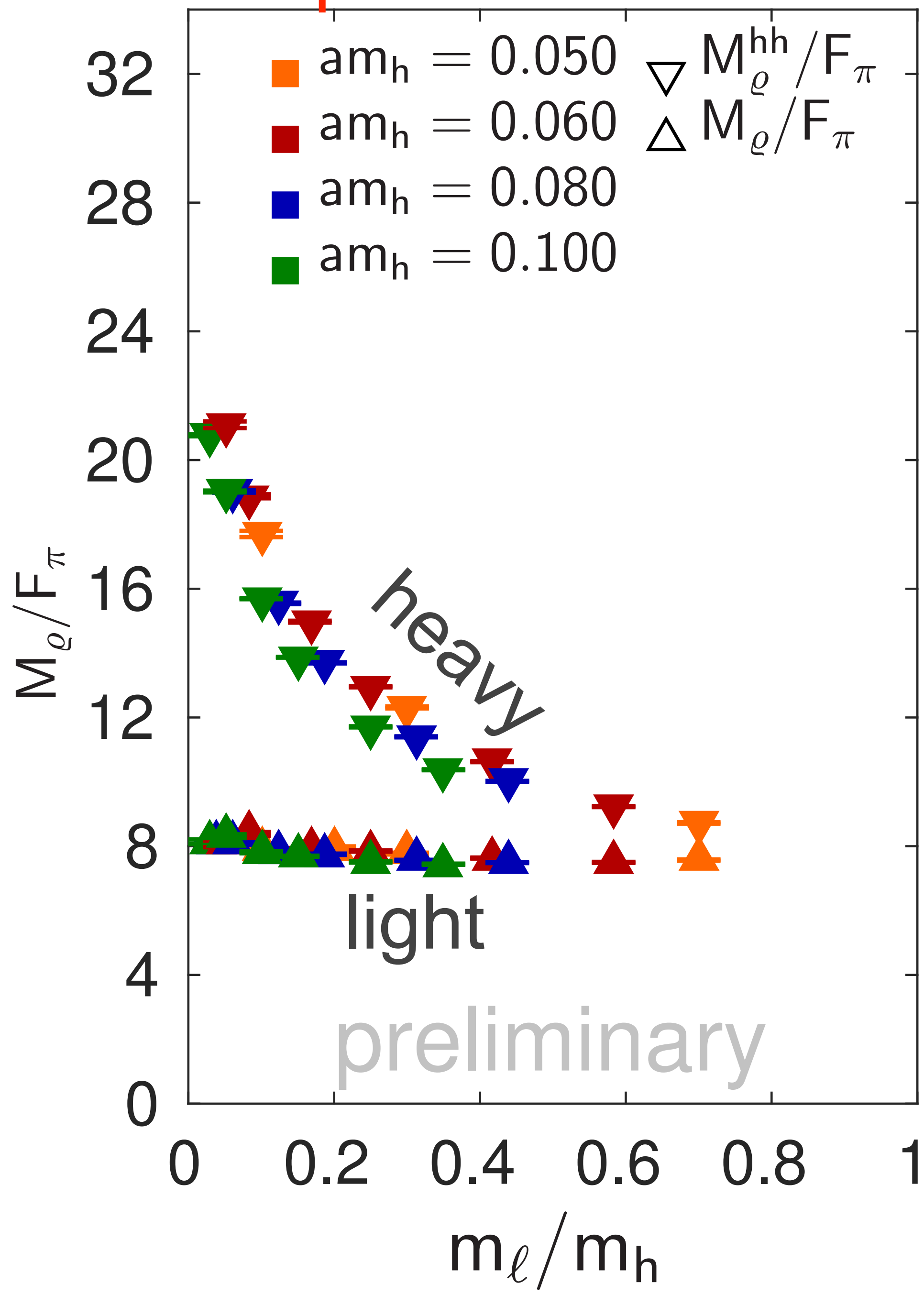
c_0 depends on g^2 and the observable, ω is universal : both can be determined from N_f=12 studies

Hyperscaling at work

Our "prototype" model: SU(3) gauge with 4 + 8 fundamental fermions
N_h=8 "heavy" and N_ℓ=4 "light" flavors

Numerical studies: β=4.0, am_h=0.050,0.060,0.080,0.100, am_ℓ=0.003-0.035

ρ meson



Scaling violations are mostly from F_π

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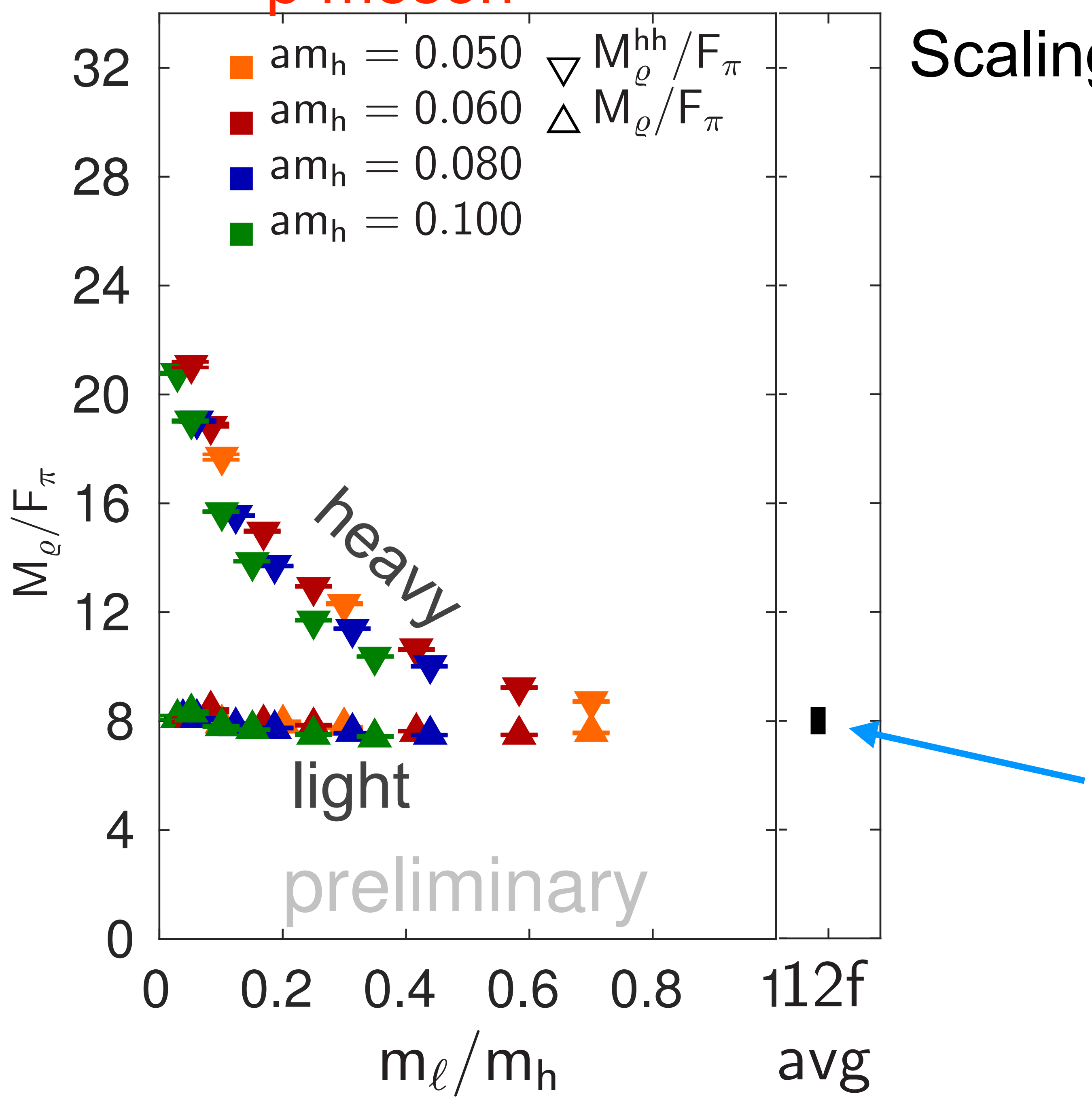

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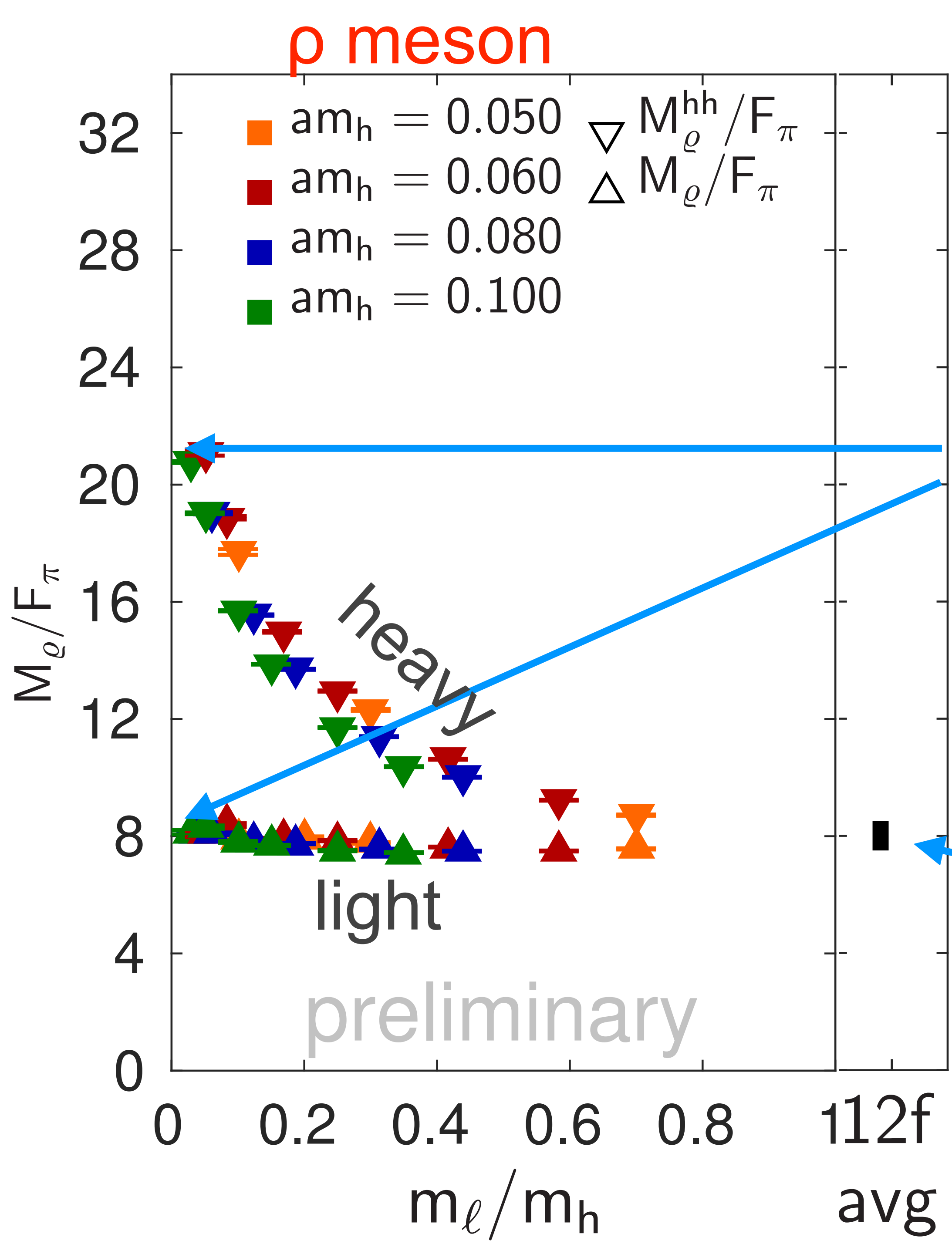

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Heavy-heavy vector is ~2.6 times the light-light and independent on m_h

Very different from QCD

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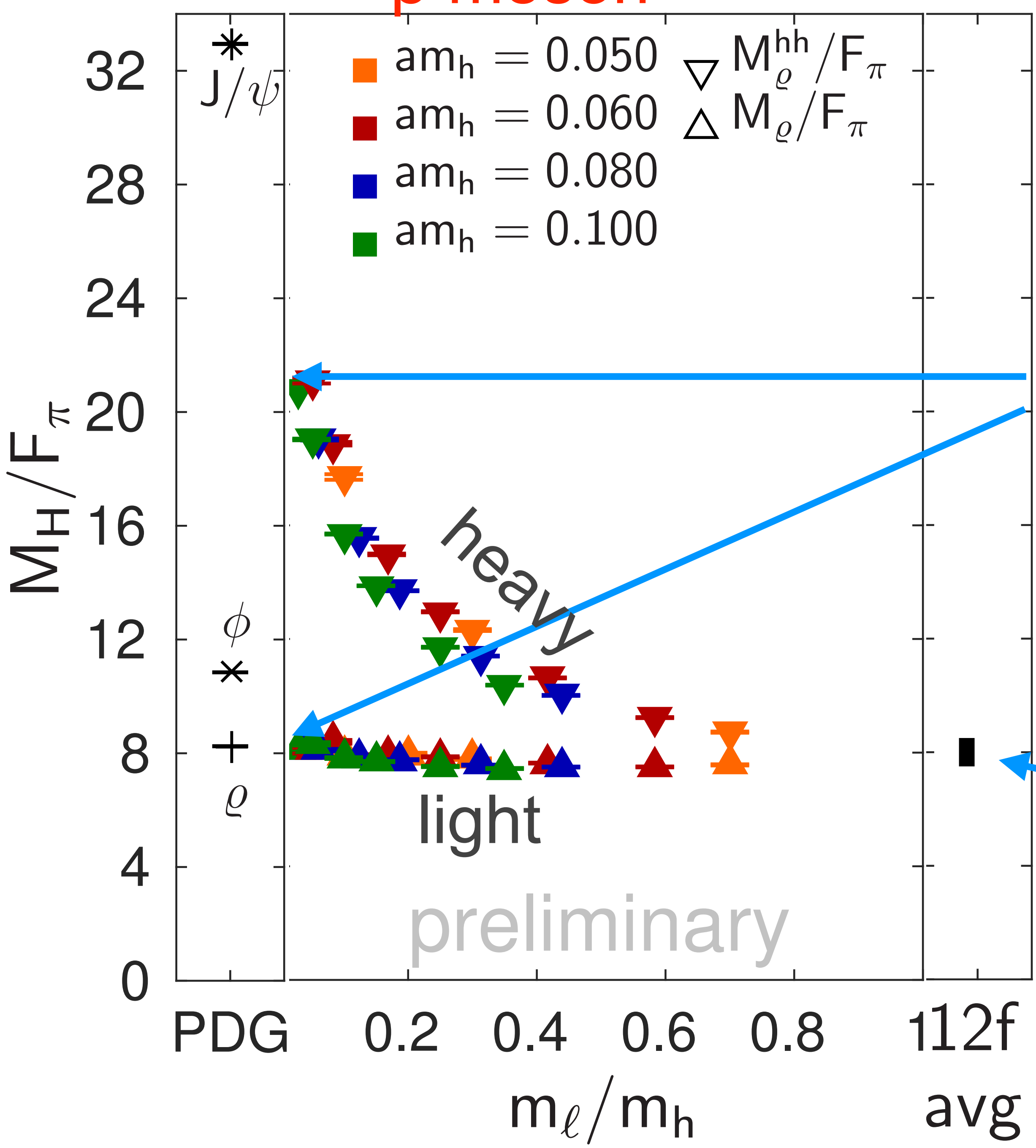

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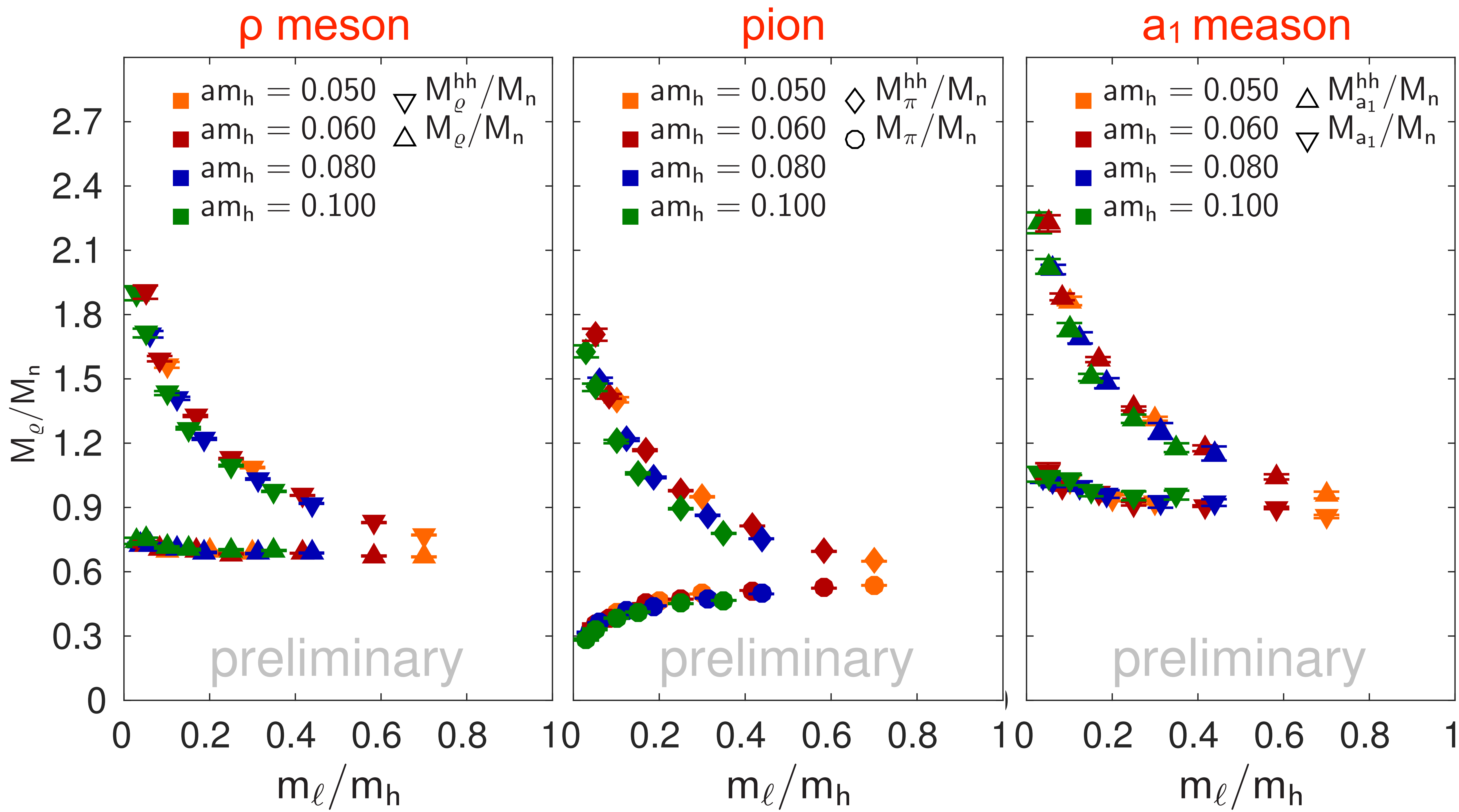
Hyperscaling at work - vs nucleon mass



Hyperscaling -with small corrections - is satisfied for all hadrons

Heavy states are not far from light ones :

precise values could be strongly model dependent

Summary

Mass-split system is phenomenologically well motivated effective model

- Chiral symmetry is broken in the IR
- Conformal behavior in the UV ensures otherwise elusive properties
- Different IR and UV systems are easy to combine

Hyperscaling at the conformal IRFP makes the model very predictive:

- The spectrum depends only on m_ℓ / m_h
- It is independent of g^2 and m_h in the $m_\ell = 0$ limit

In the $m_\ell = 0$ chiral limit

- The light spectrum is 4 - 8 times F_π
- The heavy spectrum is only 2 - 3 times above the light one, could be within reach of experiments

Our model is prototype for both pNGB and dilaton-Higgs scenario where the scale is set by F_π =SM vev or F_π = (SM vev) / sin(χ)

Next talk (Claudio Rebbi) : many more details

Backup slides

The fate of 12 flavors:

There are over dozen studies of N_f=12:

- They are all consistent with conformal behavior:
  - Finite size scaling
  - Eigenmode spectrum, chiral condensate
  - Finite T phase diagram, etc
- Many predict consistent anomalous dimension ~0.25
- Cheng et al in 1404.0984 illustrated the t-shift improvement with N_f=12 and found g^{*2} = 6.18(20) (statistical errors only)
- Fodor et al in 1607.06121 exclude an IRFP in the narrow (5.98 - 6.38) range. Investigations over a larger range of couplings and studies of systematic effects, e.g. in extrapolations, are warranted.
- A robust calculation covering g^{*2} ~ 8-9 is needed to either
  - identify an IRFP with good accuracy
  - find evidence of spontaneous chiral symmetry breaking