Beyond Standard Model on the Lattice

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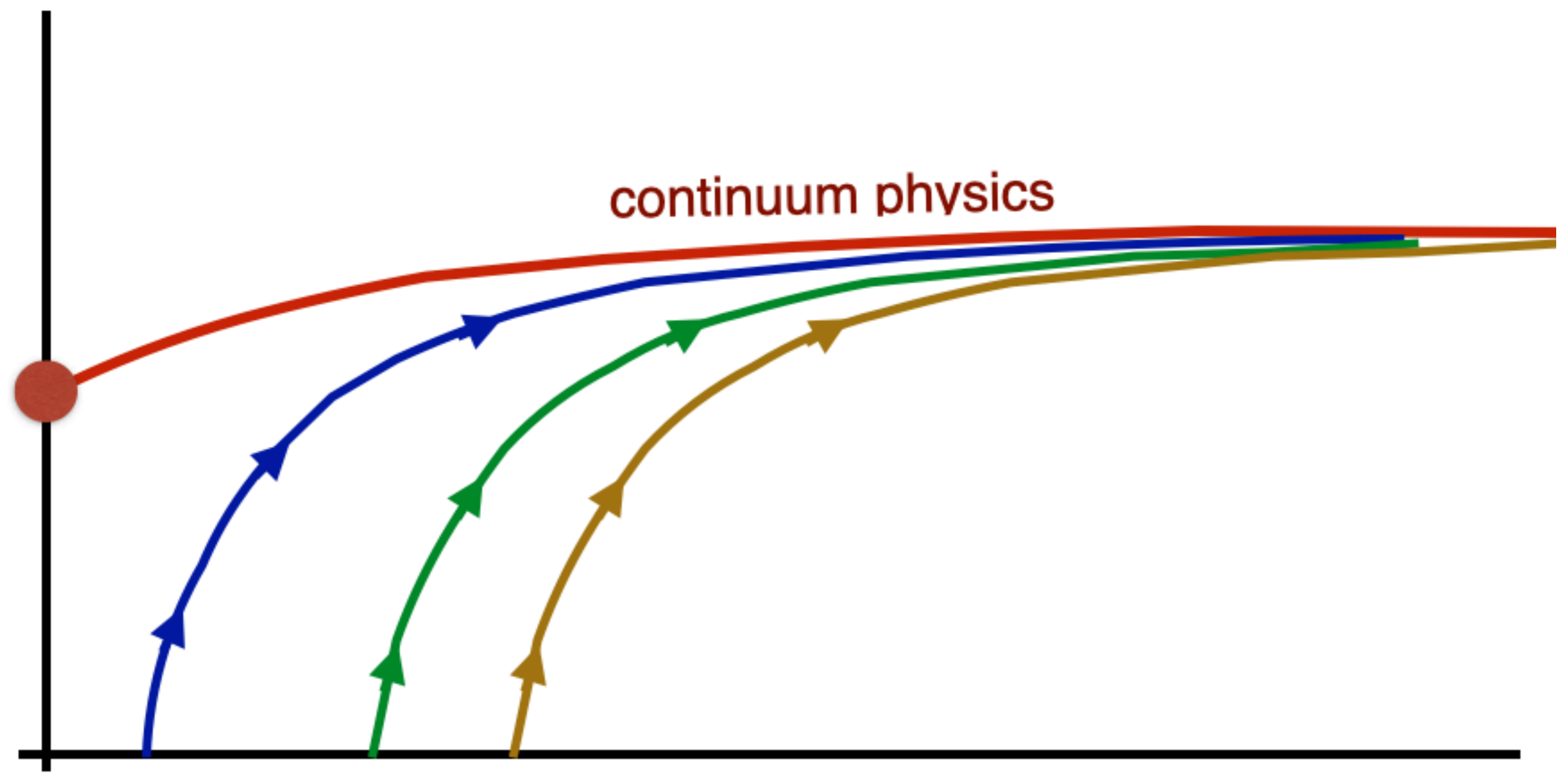
Lattice Gauge Theory Contributions to New Physics Searches

June 16, 2023



Lattice gauge theory contribution to physics searches

U(1)xSU(2)xSU(3) + new physics ⇄ Experiments

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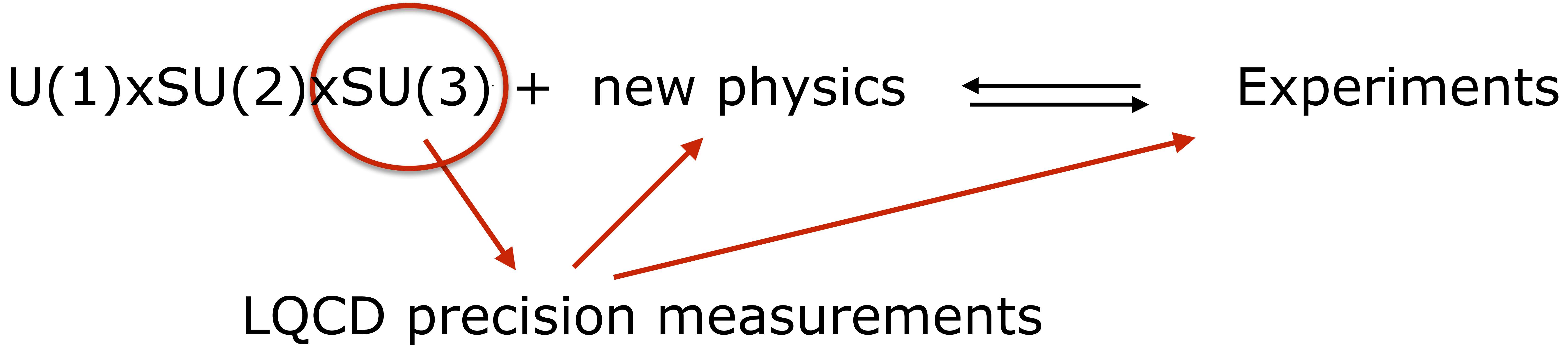

Lattice gauge theory contribution to physics searches

U(1)xSU(2)xSU(3) + new physics ⟺ Experiments

New physics:

- EW breaking
- SM parameters / ν masses
- flavor structure
- scale separation from SM to gravity
- dark matter
- CP violation

What models could describe it? How?
Strongly coupled ? ⟺ Lattice BSM :

Composite Higgs models

What triggers EW symmetry breaking?

"new physics" is $SU(N_{sd})$ gauge with N_{sd} fermions (some rep)

- chirally broken
- 3 of the *massless* Goldstone bosons break EW symmetry
- spectrum: all other states appear in a strongly interacting sector (e.q. dark matter, etc)
- finite temperature phase transition (gravitational waves?)

Composite Higgs models

Two broad possibilities:

Higgs:

(A) Higgs is the σ isosinglet scalar, dilaton of broken scale symmetry

- $f_{PS} = vev$ of standard model : predictive
- very long "walking scaling" is needed - does it exist?

(B) Higgs is pseudo Nambu-Goldstone boson : naturally light

- $f_{PS} = vev/\sin(\chi)$: less predictive

Fermion masses (two more):

(A) generated by $(\bar{\psi}\psi)(\bar{\Psi}\Psi)$ interaction: very long "walking scaling" is needed

(B) "partial compositeness" :generated by $(\psi)(\Psi\Psi\Psi)$: large anomalous dimension for $\Psi\Psi\Psi$ is needed

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Questions for Lattice : is the system conformal/near conformal? (RG β function)

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Questions for Lattice : What are the anomalous dimensions? (RG γ function)

Composite Higgs models

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Questions for Lattice : bound state spectrum: singlet scalar, baryons, etc

Phases of gauge-fermion systems

$SU(N_c)$ gauge with N_f fundamental flavors

$$\beta = \mu^2 \frac{dg^2}{d\mu^2} = b_0 g^4 + b_1 g^6 + \ldots$$

The coefficients of $\beta(g^2)$ are known perturbatively up to 5 loops

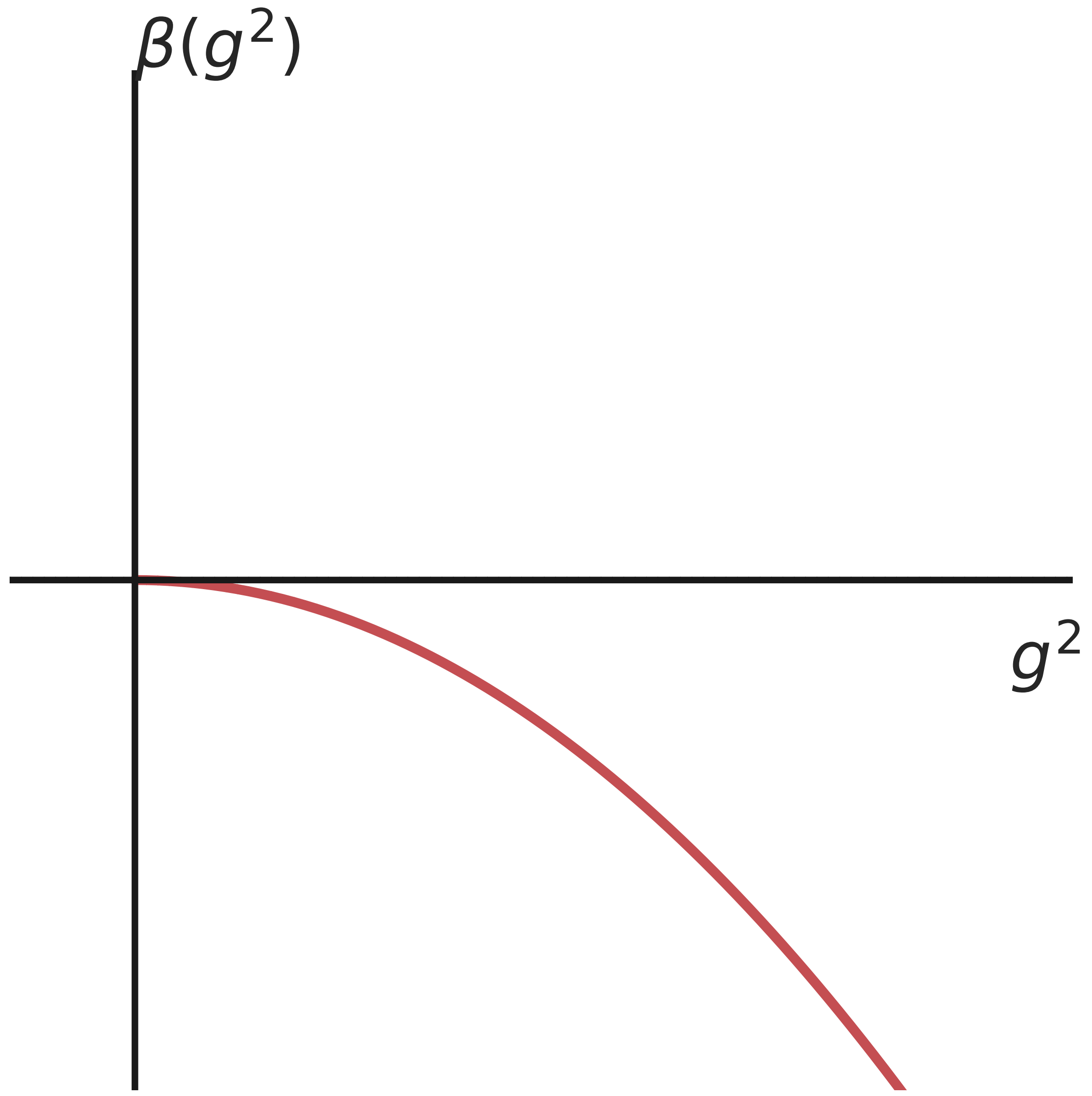
$$b_0 = \frac{1}{16\pi^2}(-\frac{11}{3}N_c + \frac{2}{3}N_f), \qquad b_1 = \frac{1}{(16\pi^2)}(-\frac{34}{3}N_c^2 + N_f(\frac{10}{3}N_c + \frac{N_c^2 - 1}{N_c}))$$

$b_2, \quad b_3, \ldots$ depend on the RG scheme

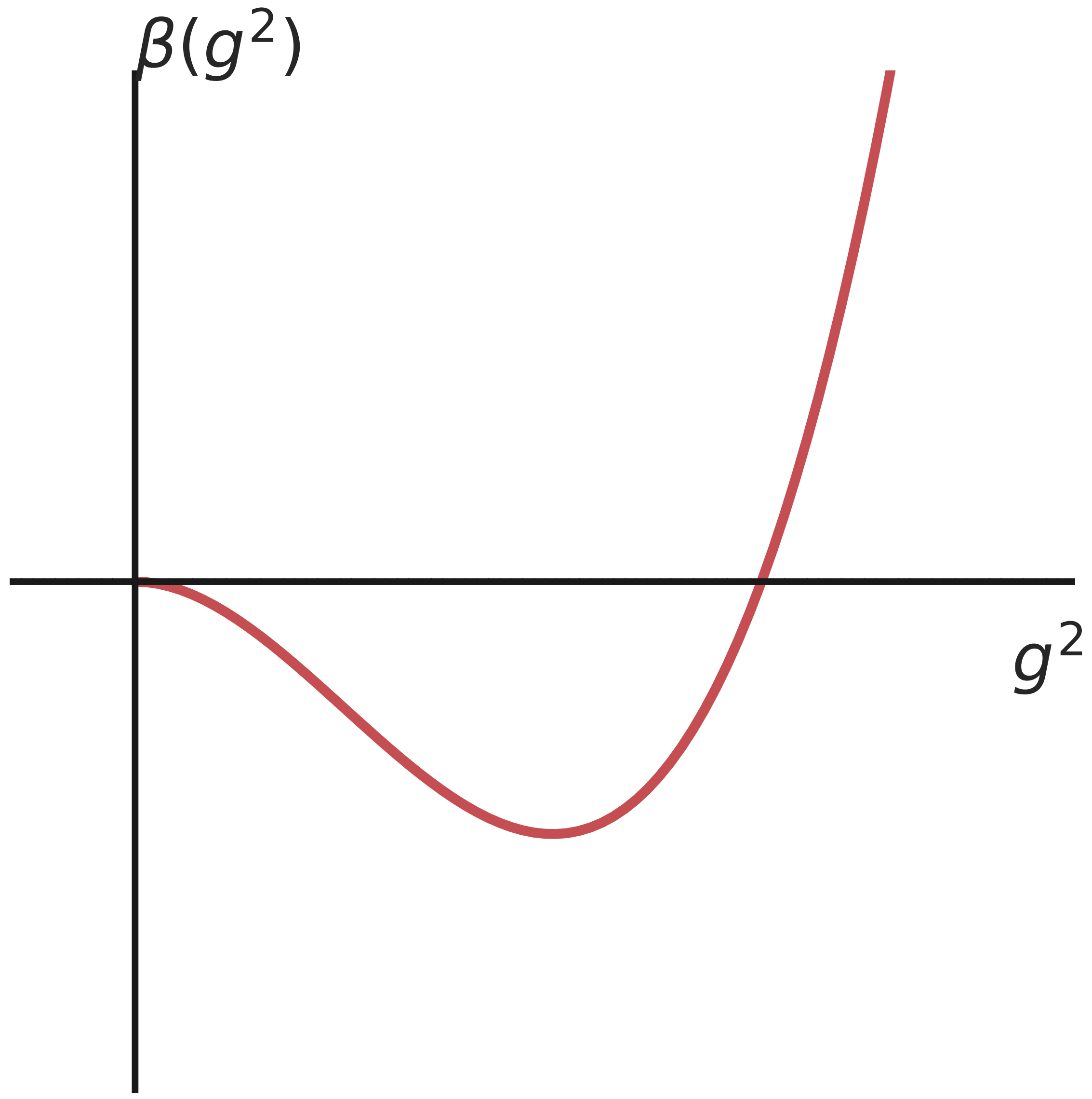
Conformal or chirally broken?

SU(3) gauge + N_f fermions

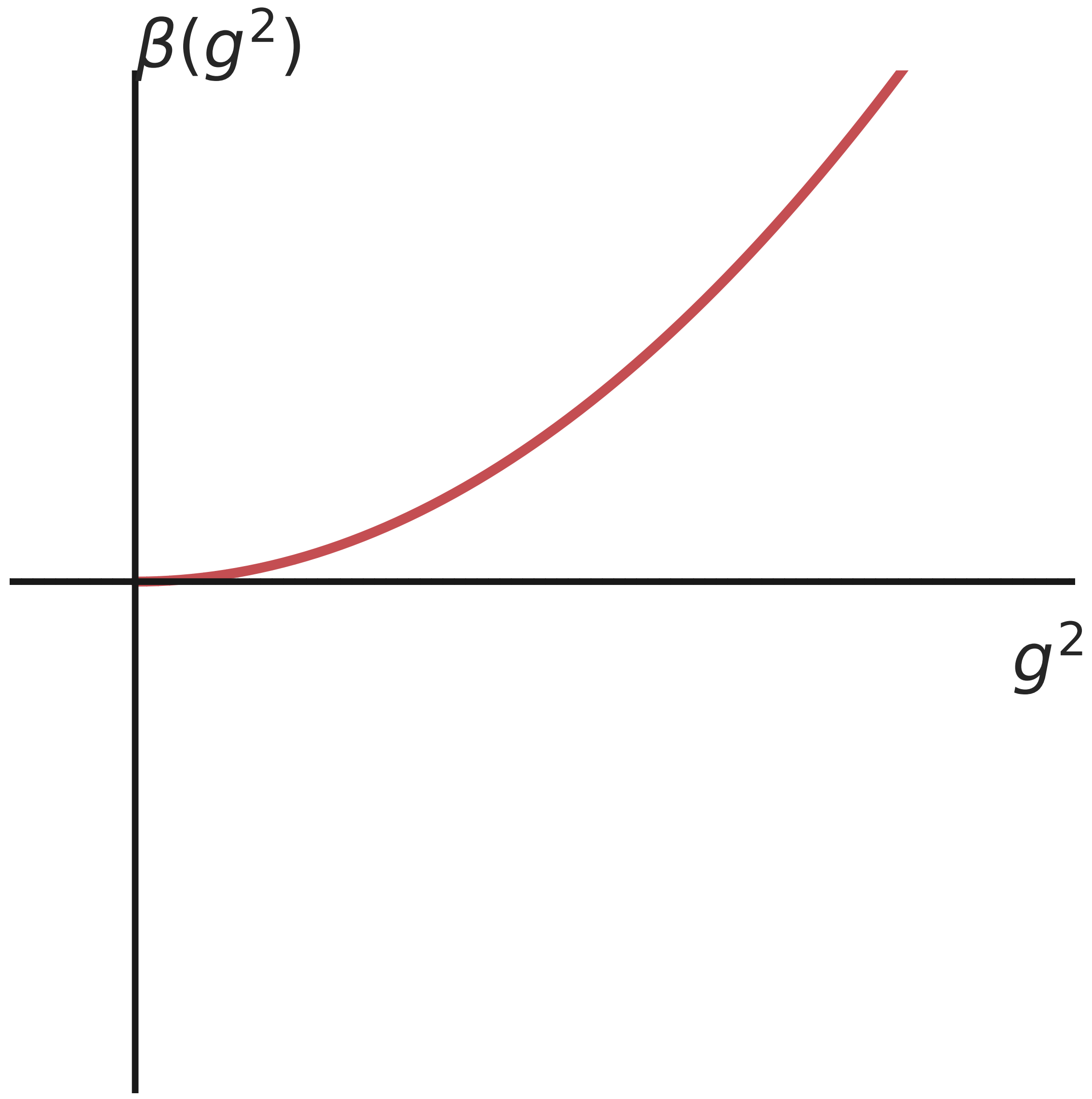
small N_f (<8)
Confining



$N^* < N_f < N^{IF}$
Conformal



$N_f > N^{IF} = 16.5$
Infrared free



Perturbatively: the IR fixed point emerges at $g_0^2 = \infty$ at $N_f = N^*$, moves to $g_0^2 = 0$ as $N_f \to N^{IF}$

Conformal or chirally broken?

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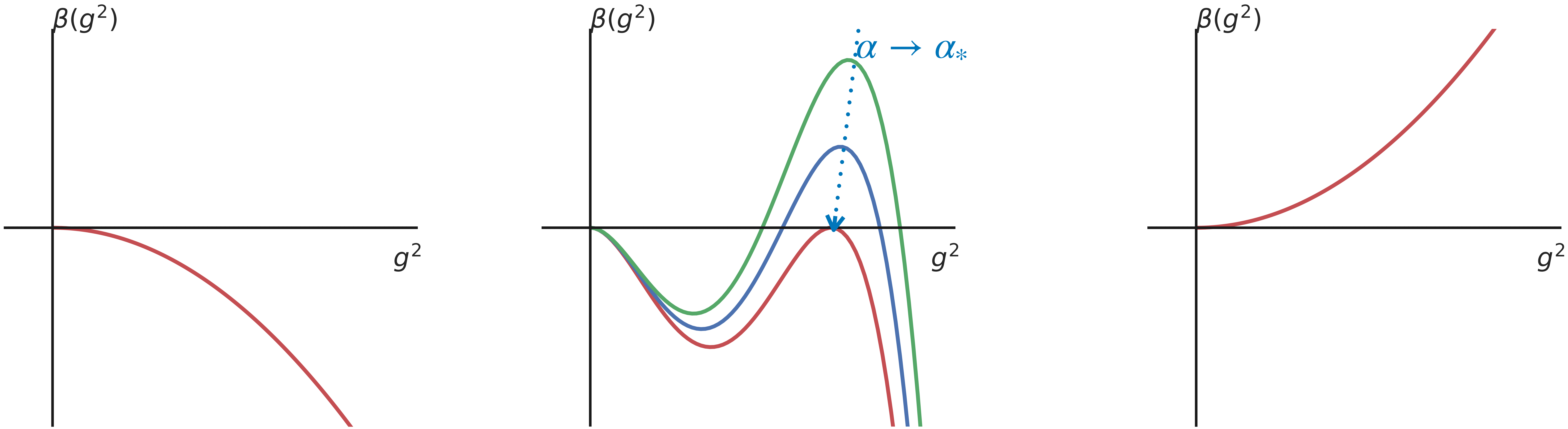

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Nonperturbatively: the IR fixed point could emerge at finite g_*^2 e.g.

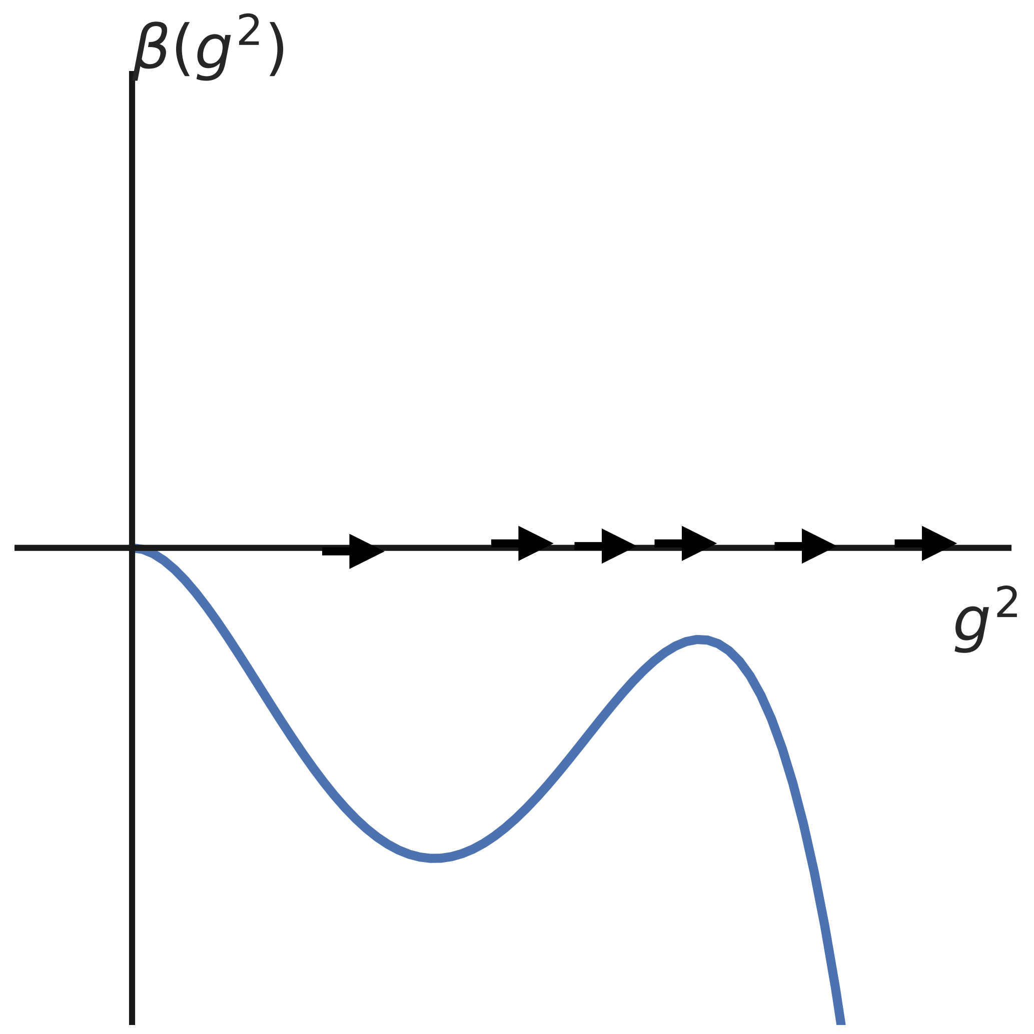
$$\beta(g) \sim (\alpha - \alpha_*) - (g - g_*)^2$$

Kaplan et al PRD80,125005 (2009)
L. Vecchi PRD82, 045013 (2010)
Gorbenko et al JHEP10, 108 (2018)

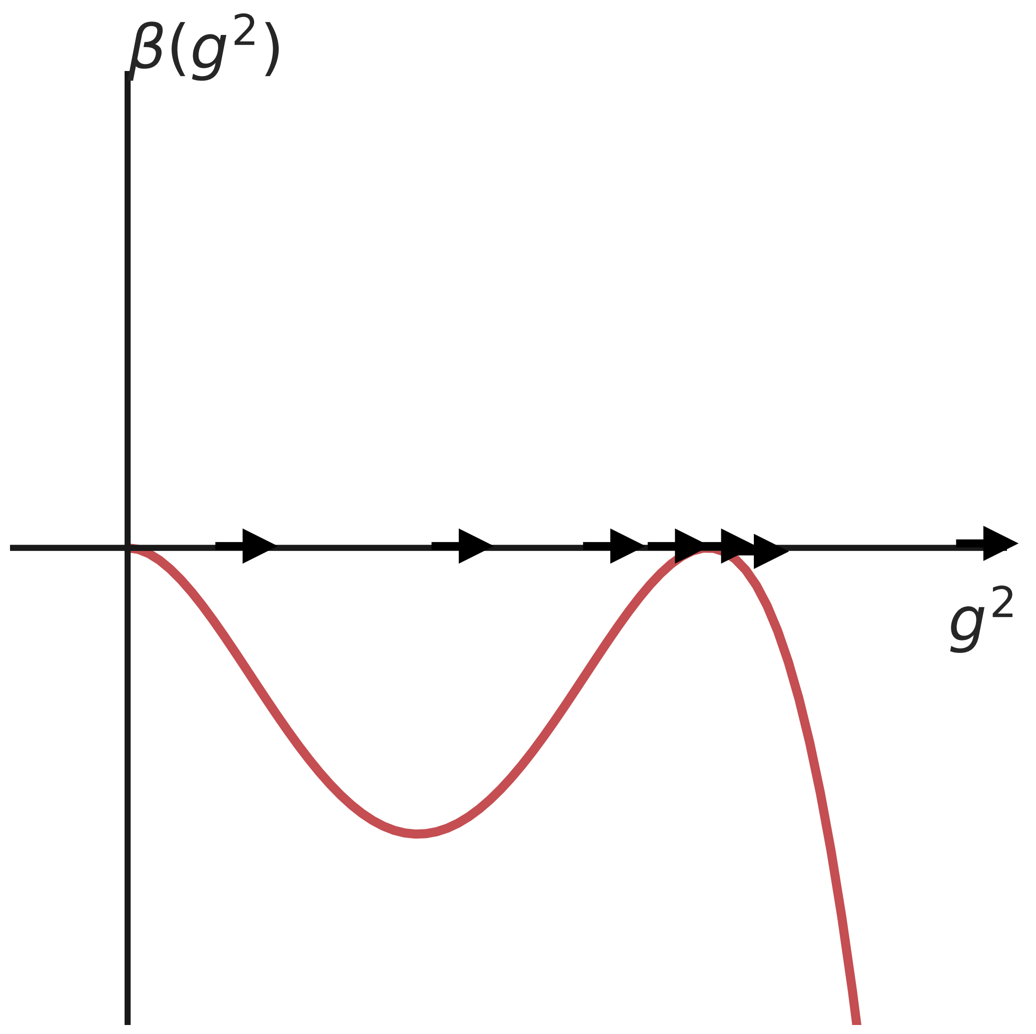
Conformal or chirally broken?

SU(3) gauge + N_f fermions

Walking



conformal sill



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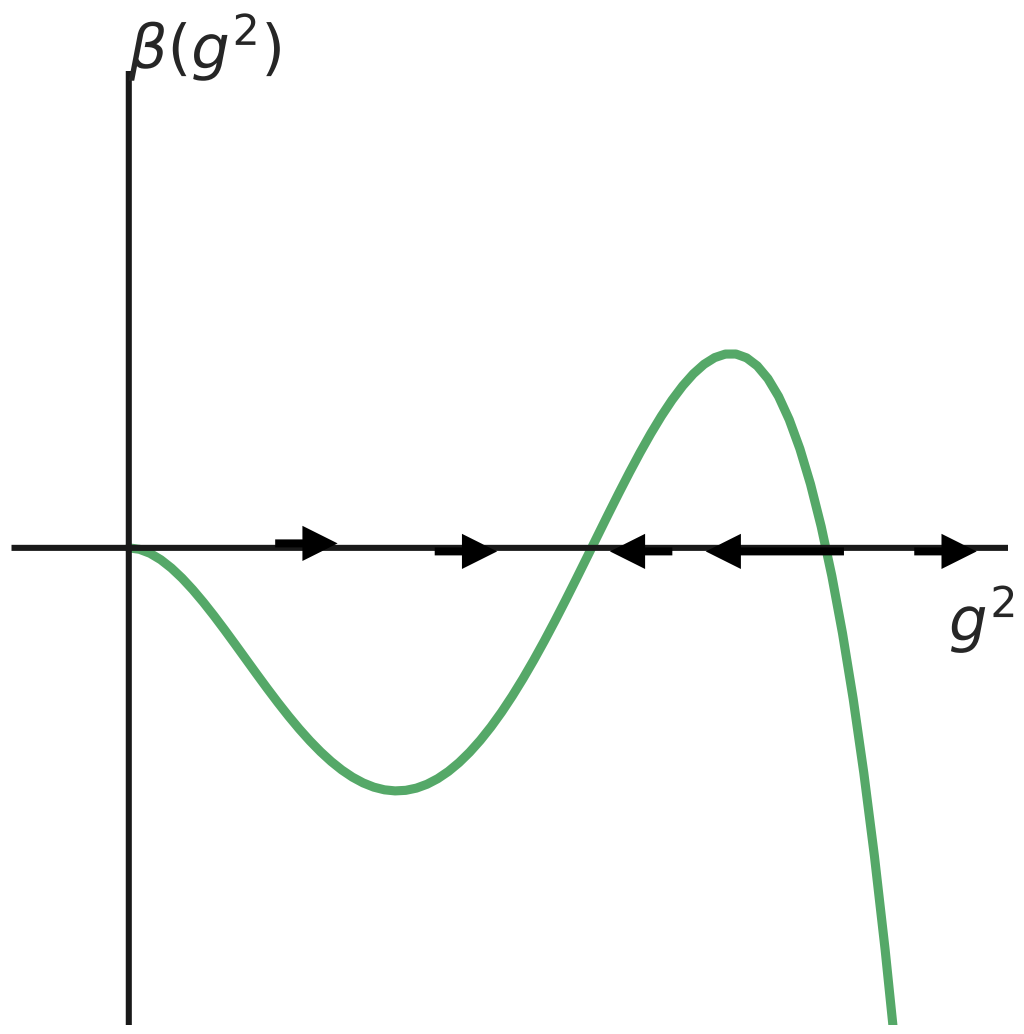


Walking:

Is it “walking” slow enough?

At the sill:

- Could be mass-split
- or use the strong coupling phase(?)

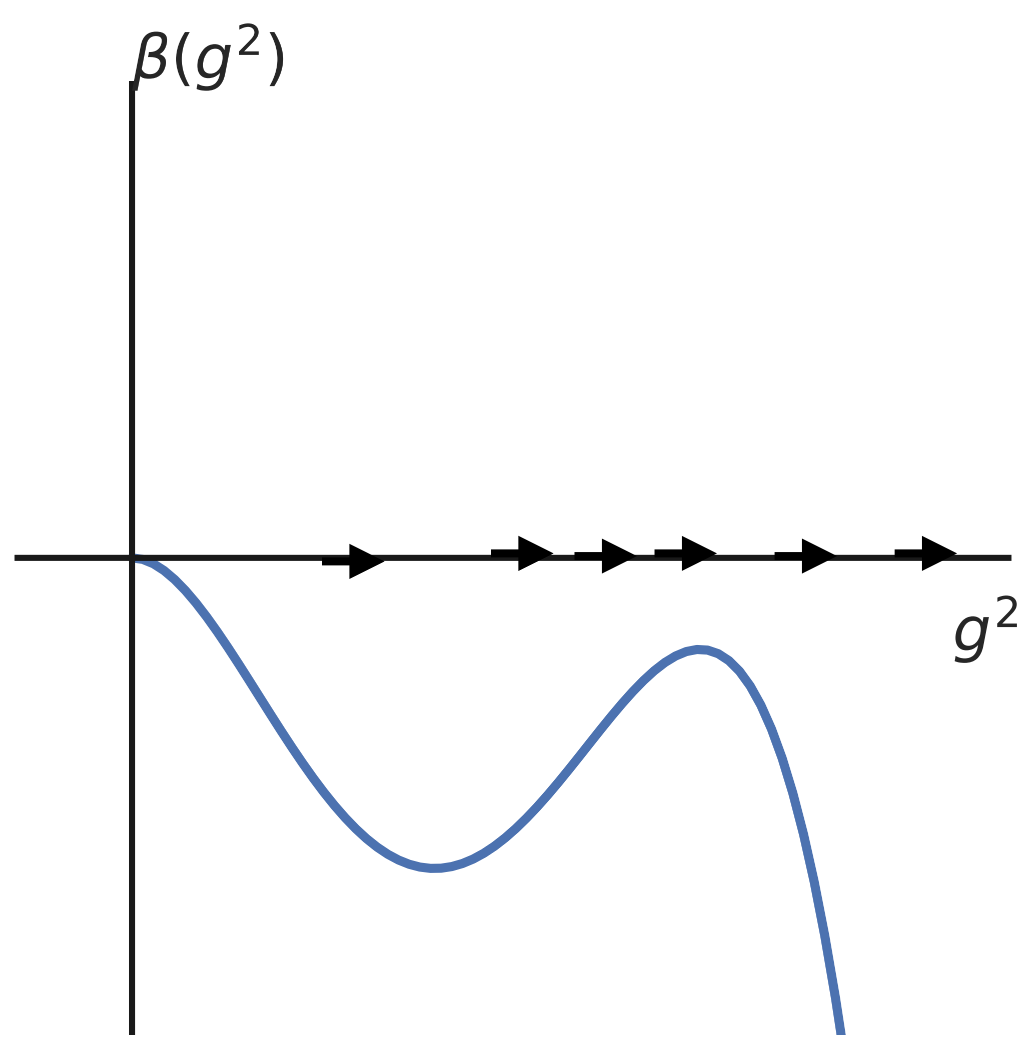
Conformal → mass-split

- Give mass to some flavors;
- When decouple, χSB
- Heavy mass controls “walking”

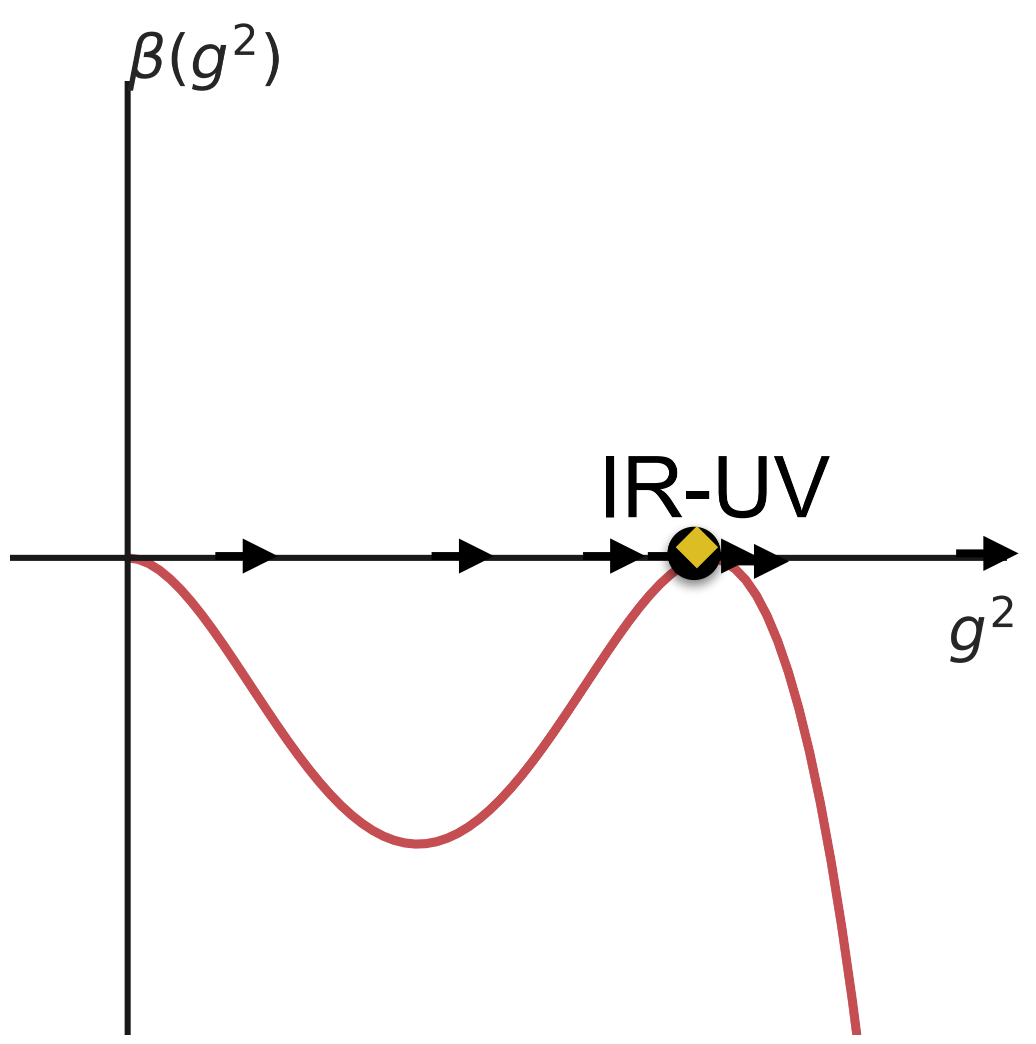
Conformal or chirally broken?

SU(3) gauge + N_f fermions

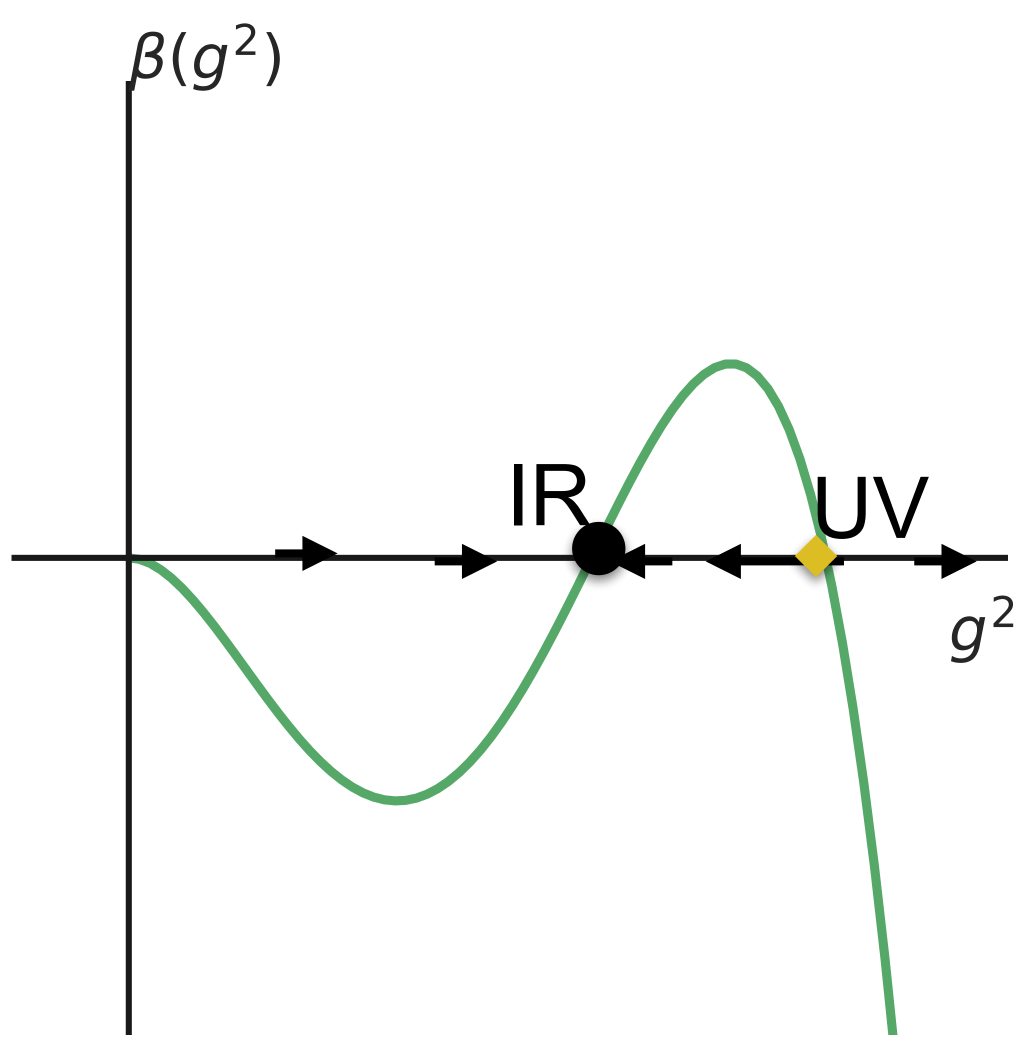
Walking



conformal sill



conformal



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Gradient flow vs continuous RG transformations

GF can be *interpreted* as continuous real space RG with $\mu \propto 1/\sqrt{8t}$

- in infinite volume
- for *local* operators

A. Carosso, AH, E. Neil,
PRL 121,201601 (2018)

- $g^2_{GF} = \mathcal{N} t^2 < E(t) > \quad \Longrightarrow \quad \beta_{GF}(a; g^2_{GF}) = -t \dfrac{dg^2_{GF}(a;t)}{dt}$

- $\mathcal{O} = \bar{\psi}(x)\Gamma\psi(x)$ or $G_{\mathcal{O}}(x_4, t) = \langle\, \mathcal{O}(\bar{p} = 0, x_4; \mathbf{t})\ \mathcal{O}(\bar{p} = 0, 0; \mathbf{t} = \mathbf{0})\,\rangle$,

$$\Longrightarrow \quad t \frac{d \log G_{\mathcal{O}}(t, x_4)}{d\, t} = d_{\mathcal{O}} + \gamma_{\mathcal{O}}(t) + \eta_\psi(t)$$

- remove η_ψ by dividing with the vector operator

The continuous β function (CBF)

GF renormalized coupling: $g^2_{GF}(t) = \mathcal{N} t^2 \langle E(t) \rangle$

- $\langle E \rangle \propto (\Box U - 1)$ or (Clover) etc RG β function :

$$\beta(g_{GF}) = -t \frac{dg^2_{GF}}{dt}$$

AH, O. Witzel, *Phys.Rev.D* 101 (2020) 3

Fodor et al,EPJWeb Conf.175, 08027 (2018)

The RG picture is valid only

- in infinite volume limit : extrapolate in $(a/L)^4 \to 0$ while $\sqrt{8t} \ll L$
- in $am_f = 0$ chiral limit : extrapolate $am_f \to 0$ (only in confining regime)

Continuum limit :

- $t/a^2 \to \infty$ while keeping g^2_{GF} (or t) fixed

Same approach as $N_f = 0{,}2$

AH,C.Peterson, O.Witzel, J.VanSickle
2301.08274

Lattice: The continuous β function (CBF)

After 15+ years the sill of the conformal window is still debated ….

Why?

- -Many flavor system suffer from *bulk phase transitions* in strong coupling
- -Limits the accessible coupling range : cutoff effect!

Solution:

- -Improve the gauge action
- -E.q.: add heavy Pauli-Villars bosons to the action to "regularize" fermions

Recent successes: N_f=4+4, 8, 10;

QCD simulations could also benefit

Taming lattice artifacts with PV bosons

AH, Shamir, Svetitsky, PRD104, 074509 (2021)

$$S = \frac{6}{g_0^2} \sum_p ReTrV_\Box + \frac{1}{2} \sum_{n,\mu} \left(\bar{\psi}_n \gamma_\mu(n) U_\mu(n) \psi_{n+\mu} + cc \right) + am_f \sum_n \bar{\psi}_n \psi_n$$

Integrate out the fermions: an effective gauge action (hopping expansion)

$$S_{eff}^{(f)} = \frac{N_s}{(2am_f)^4} \sum_p ReTrV_\Box + c \frac{N_s}{(2am_f)^6} \sum_{6link} ReTrV_{\text{6-link}} \cdots$$

Bare gauge coupling $\beta = 6/g_0^2$ decreases to compensate, leading to rough gauge configurations, large cutoff effects

Taming lattice artifacts with PV bosons

AH, Shamir, Svetitsky, PRD104, 074509 (2021)

➡ Compensate with **heavy Pauli-Villars bosons**

-same interaction as fermions but with *bosonic statistics*

$$S_{eff}^{(PV)} = -\frac{N_s}{(2am_f)^4} \sum_p ReTrV_{\square} - c\frac{N_s}{(2am_f)^6} \sum_{6link} ReTrV_{6\text{-}link} \cdots$$

-$S_{eff}^{(PV)} < 0 \longrightarrow \beta = 6/g_0^2$ increases;

- Keep $am_{PV} \sim \mathcal{O}(1)$ fixed: in the IR $(a \to 0)$ the PV bosons decouple

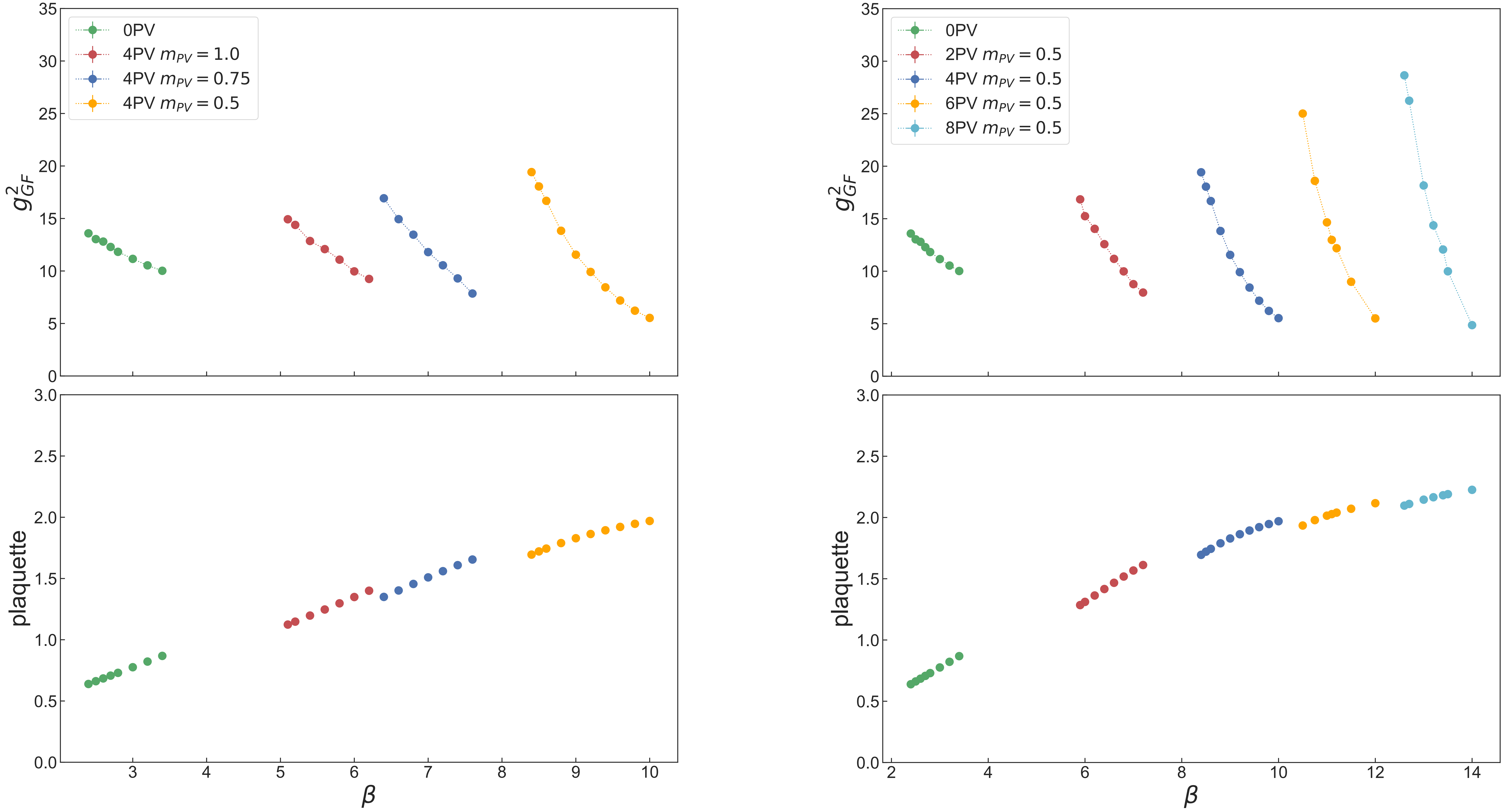
(do not change physics_

- range of effective gauge action is $\sim exp(-2am_{PV})$

Add many PV bosons reduce the lattice fluctuations

Compare different PV, m_{PV}

AH, Shamir, Svetitsky, PRD104, 074509 (2021)



$N_f = 12$

- plaquette is determined by thin link $\beta = 6/g^2$
- accessible parameter space in g^2 opens up

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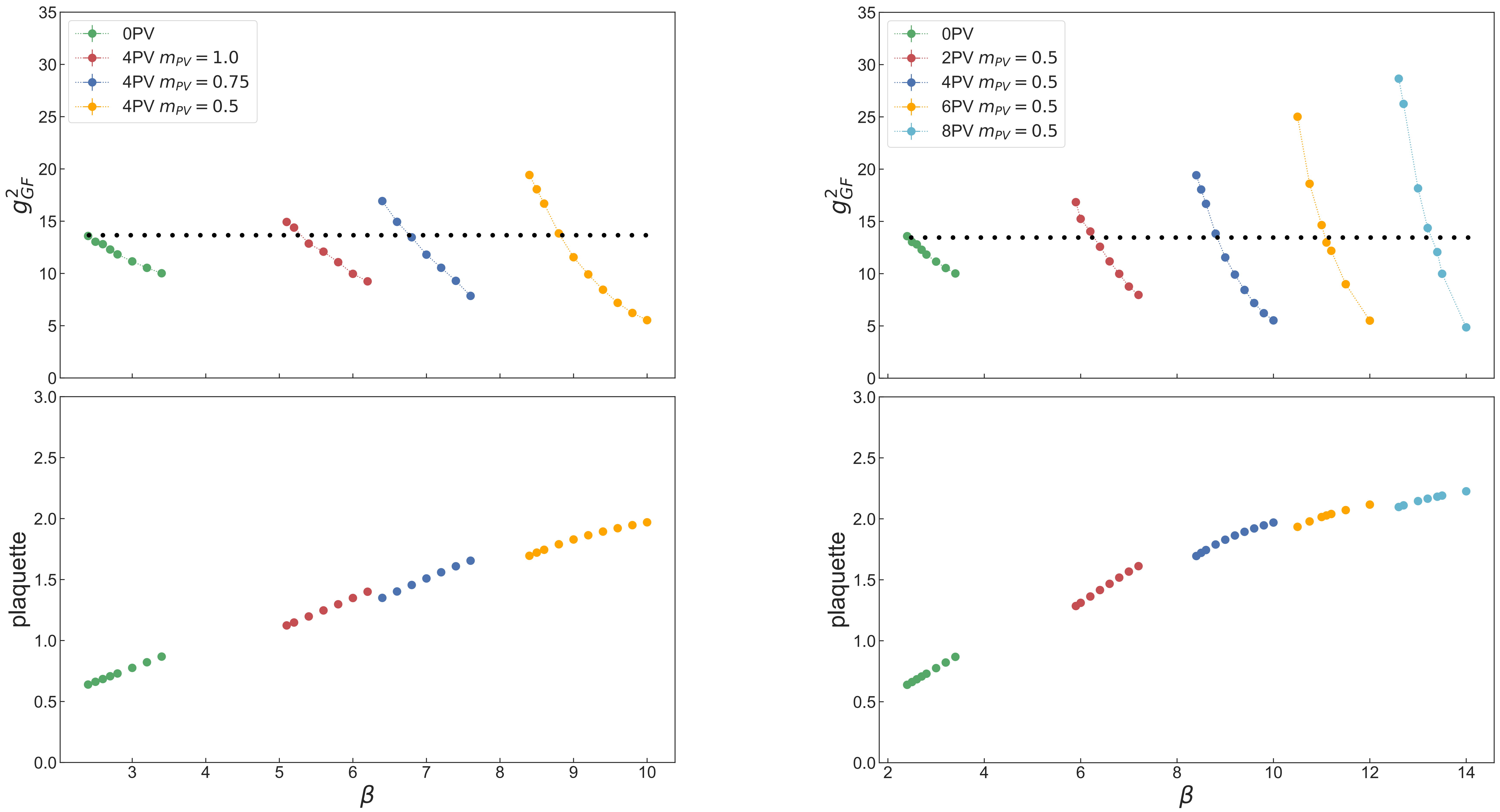

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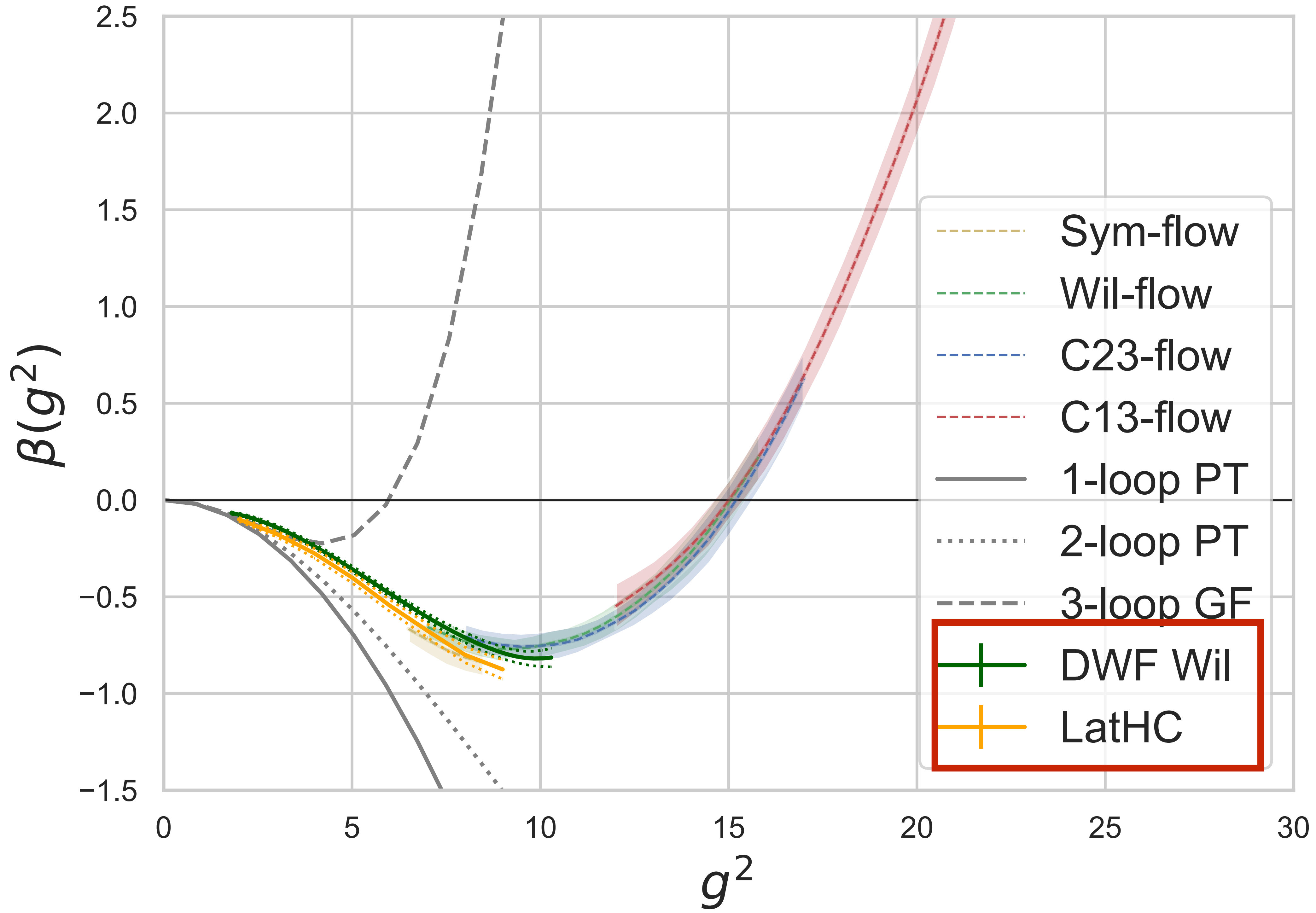
$N_f = 10$ fundamental flavors

A.H.,Neil, Shamir, Svetitsky, Witzel,
arXiv:2306.07236



Prior simulations:

-staggered (LatHC)

-domain wall (Boulder)

limited to $g^2 \lesssim 10$

New simulations

-add PV bosons : opens parameter space from $g^2 \approx 10$ to $g^2 \gtrsim 25$

-use several gradient flow actions: find RT close to simulation action (but Gaussian FP to IRFP is *universal*)

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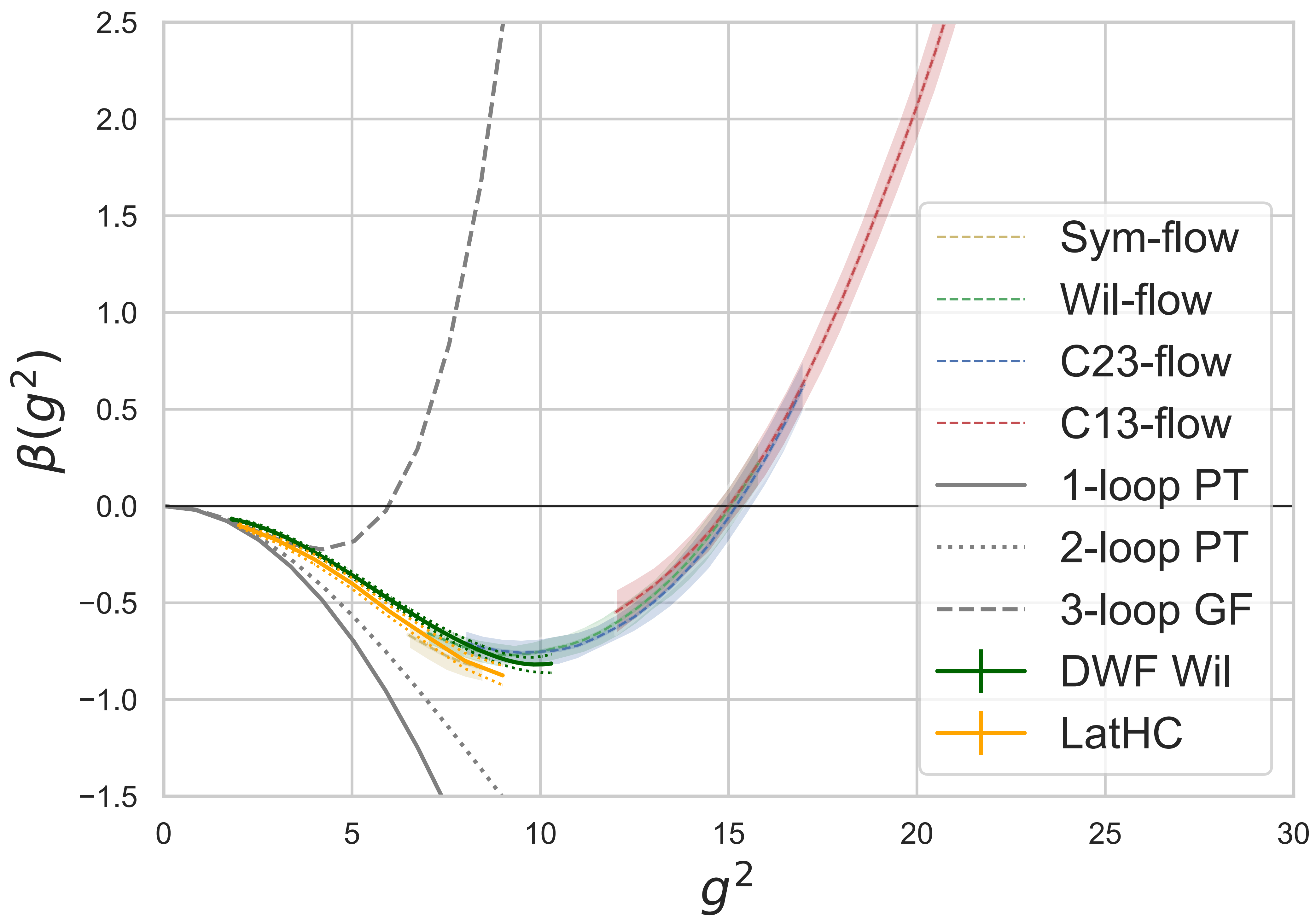

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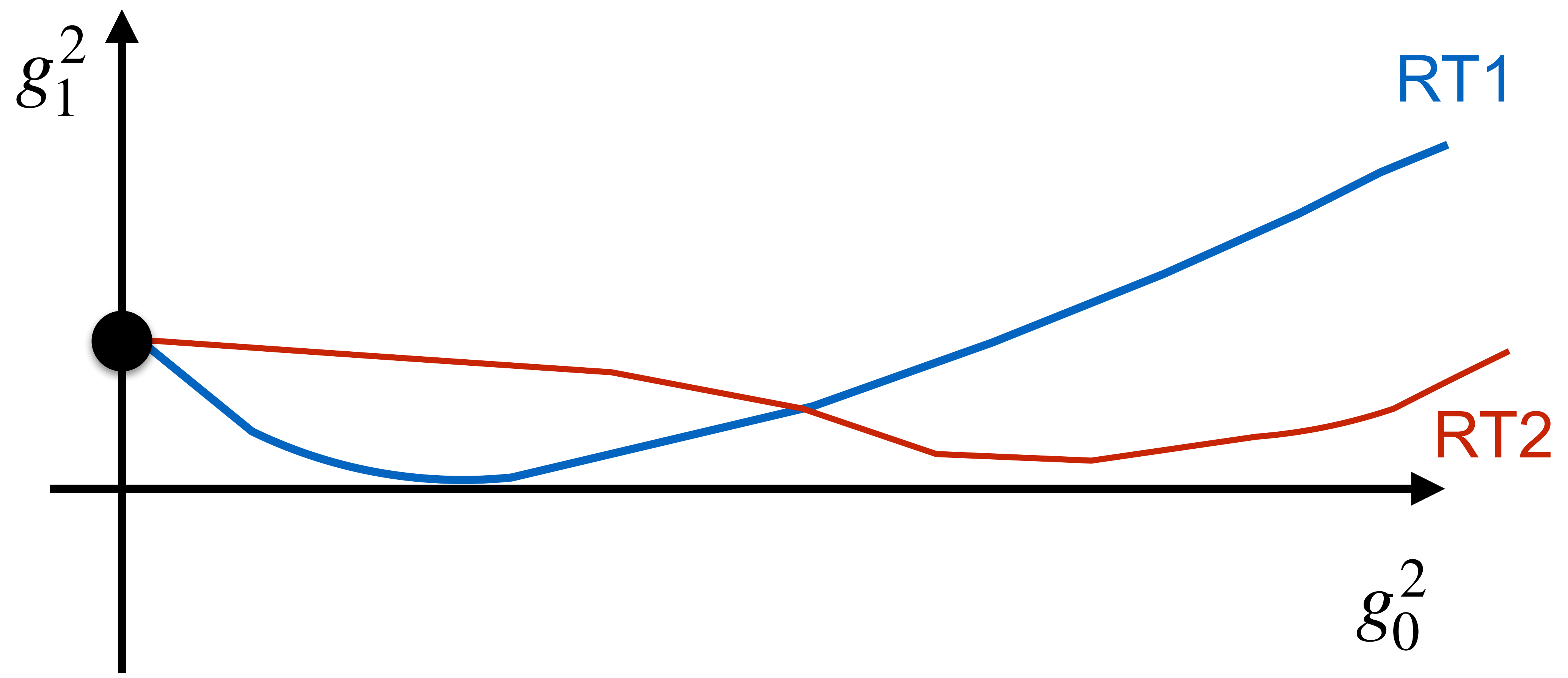

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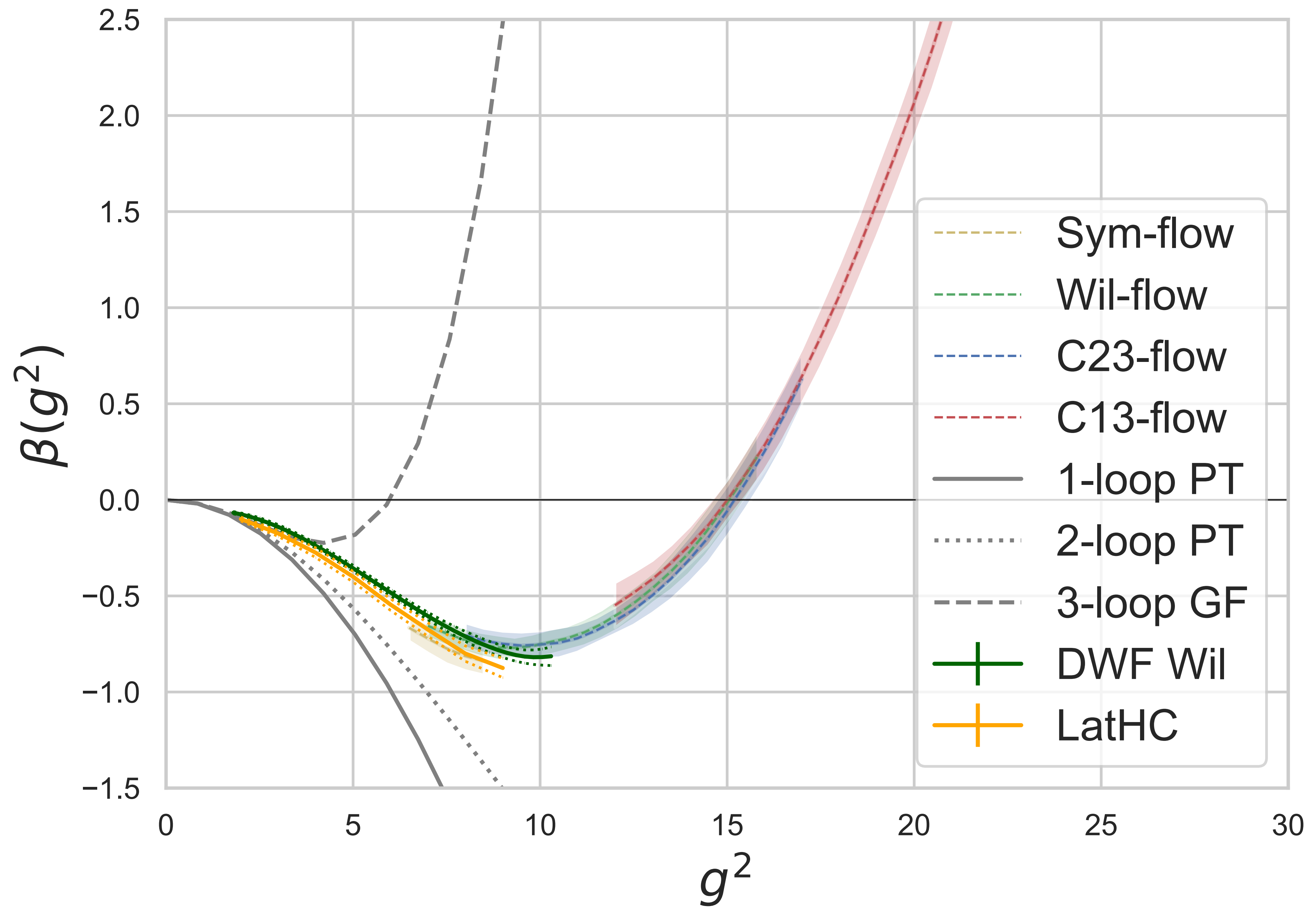
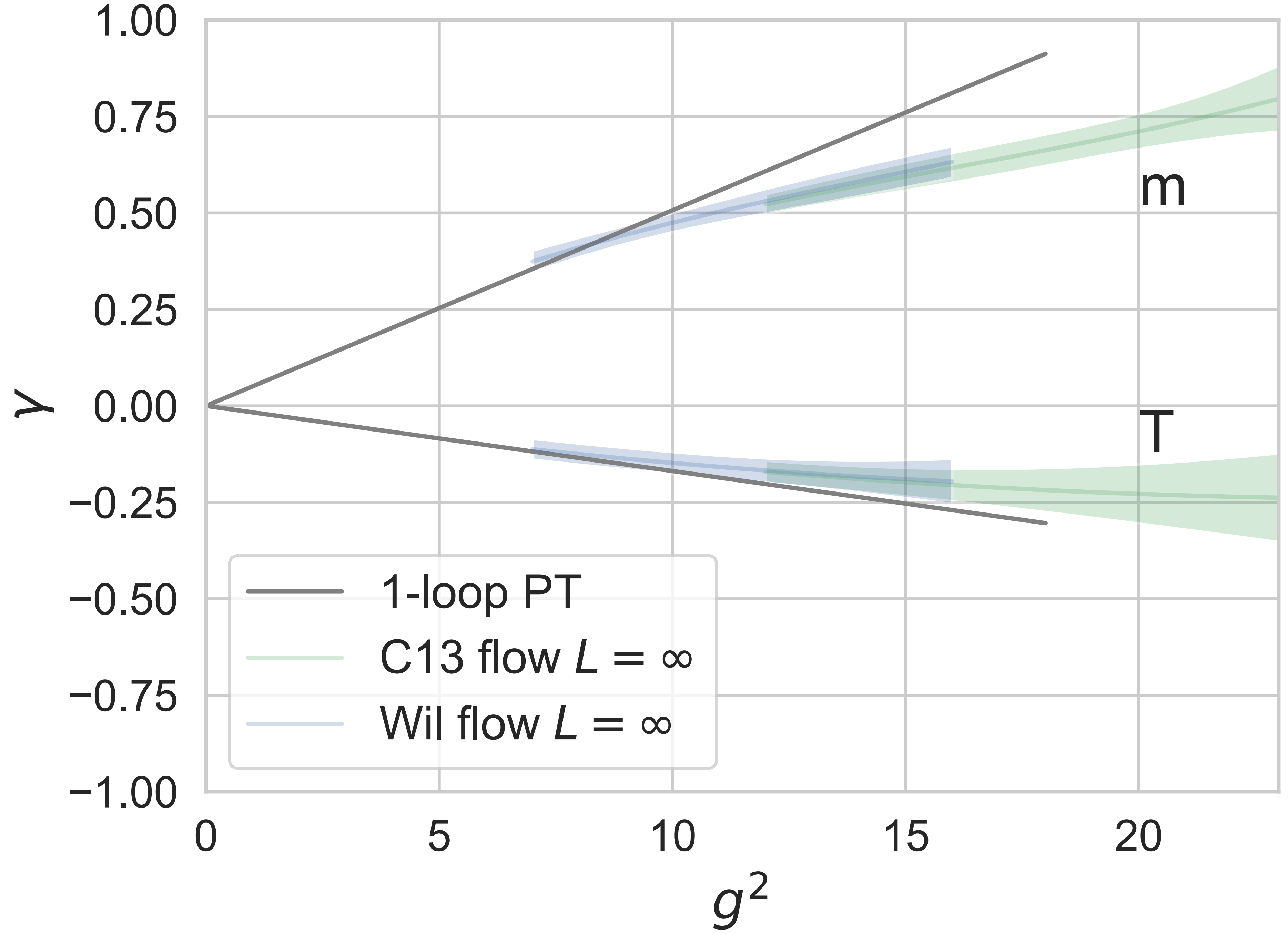


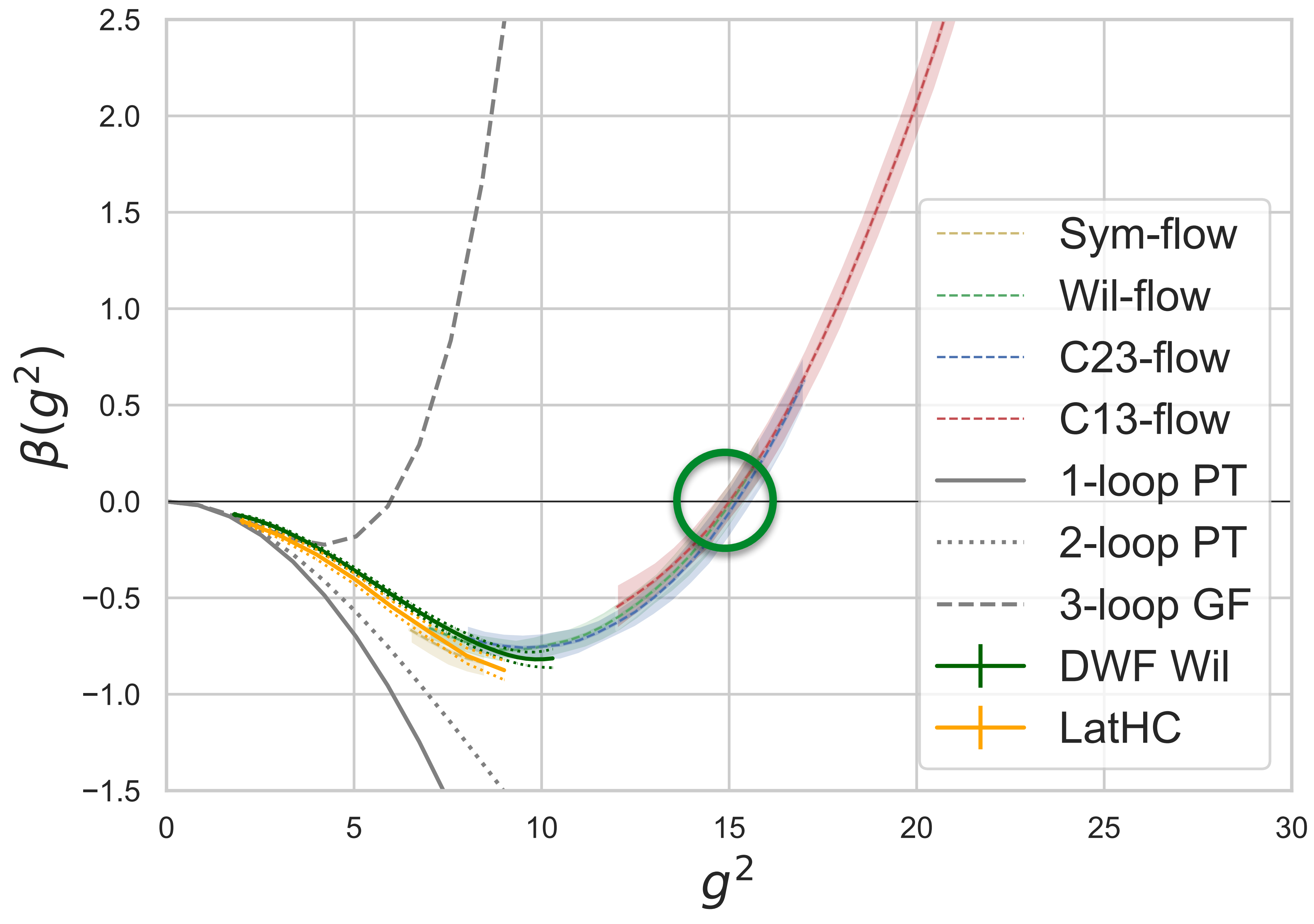


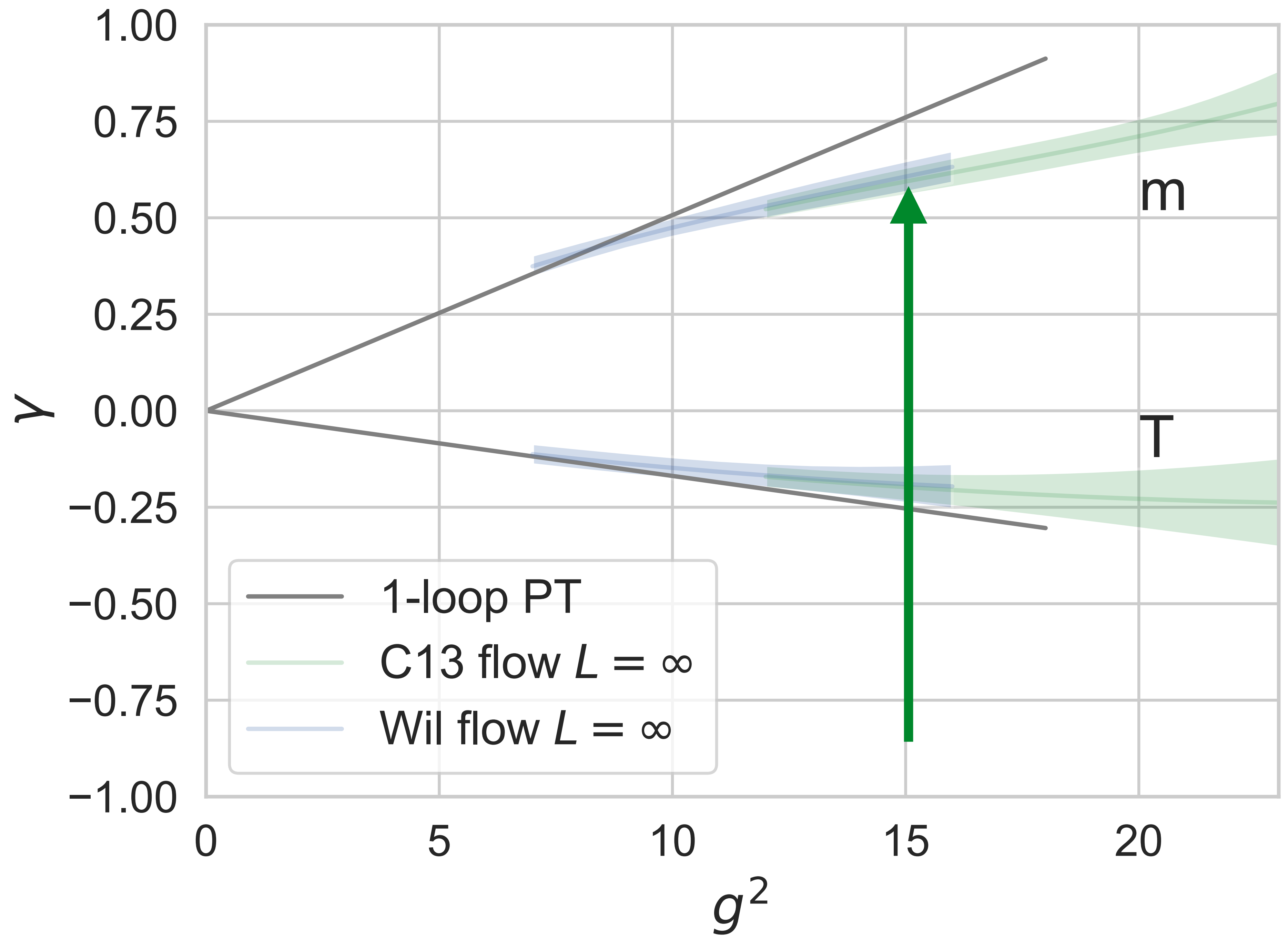
IRFP at $g^2 \simeq 15$

Anomalous dimension $\gamma_m^* \simeq 0.60$
(not even close to the conformal sill)

$N_f = 10$ fundamental flavors

A.H.,Neil, Shamir, Svetitsky, Witzel,
arXiv:





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Partial composite top in a 2-rep model

- $SU(4)$ gauge theory — *hypercolor* — new strong sector with scale $\Lambda_{HC} \sim 5$ TeV

Ferretti,Karateev, JHEP03, 077 (2014)

- N_6 Majorana fermions Q in sextet $\boxminus$ rep $\Longrightarrow$ composite Higgs field in Goldstone sector
- N_4 Dirac fermions q in quartet $\square$ rep $\Longrightarrow$ $B = Qqq$ is a chimera baryon of HC

Partial compositeness: Mix massless t quark with B via

$$V_{\text{top}}^{\text{HC}} = G_R \bar{t}_L B_R + G_L \bar{t}_R B_L + \text{h.c.} \quad — \quad t \equiv \text{top quark}, B \equiv Qqq$$

tB is really $tQqq$ — a four-Fermi interaction from a gauge theory — EHC — at a much higher scale Λ_{EHC}:

$$G_{L,R} \sim g_{\text{EHC}}^2 / \Lambda_{\text{EHC}}^2$$

THE PROBLEM: Λ_{EHC} is large (*flavor violations!*) $\Longrightarrow$ $G_{L,R}$ are much too small
unless Qqq has a large anomalous dimension γ, and then

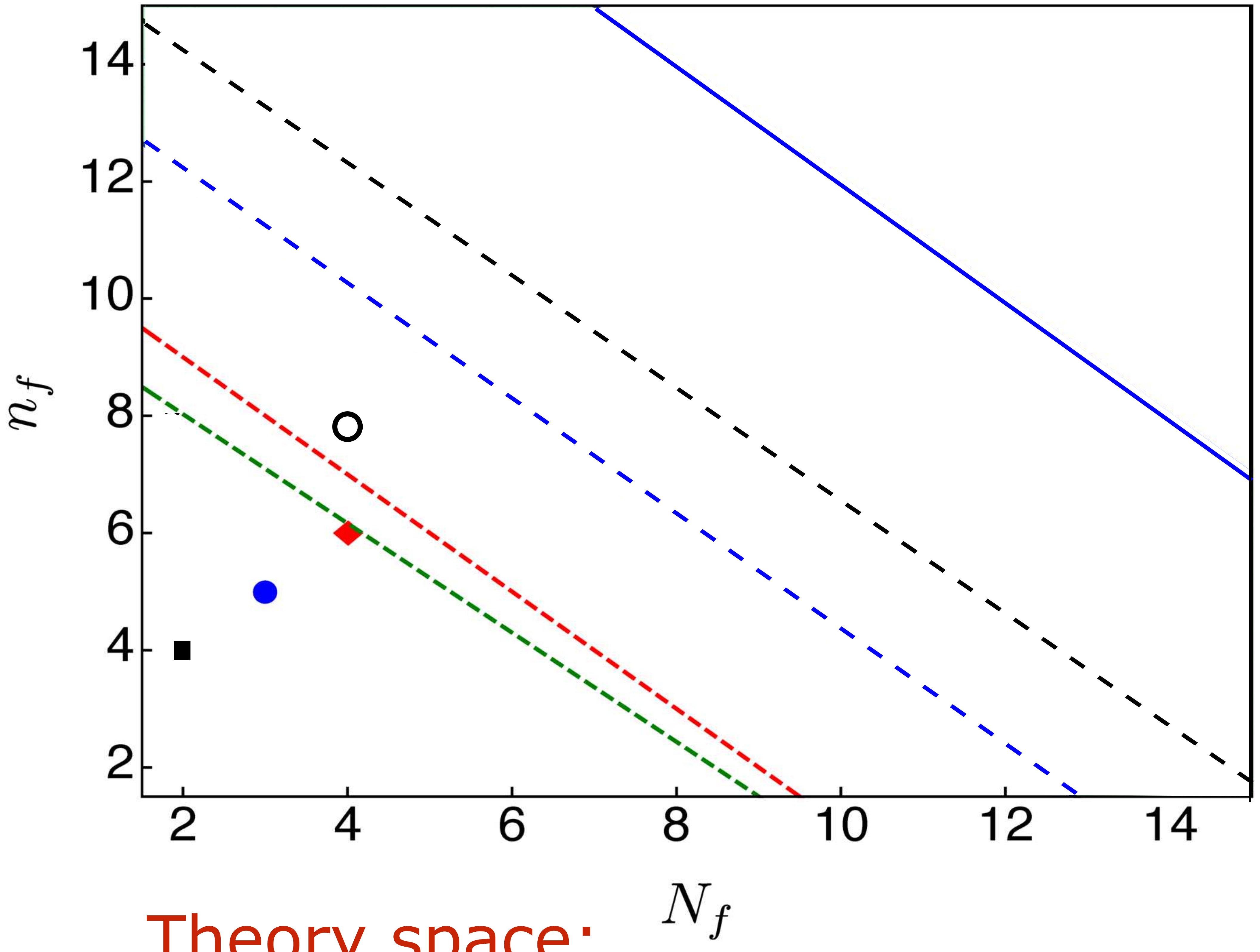
$$\Lambda_{\text{EHC}}^{-2} \longrightarrow \Lambda_{\text{EHC}}^{-(2-\gamma)}$$

THE HOPE: Large γ appears near the sill of the conformal window $\Longrightarrow$ Choose N_4, N_6 appropriately.

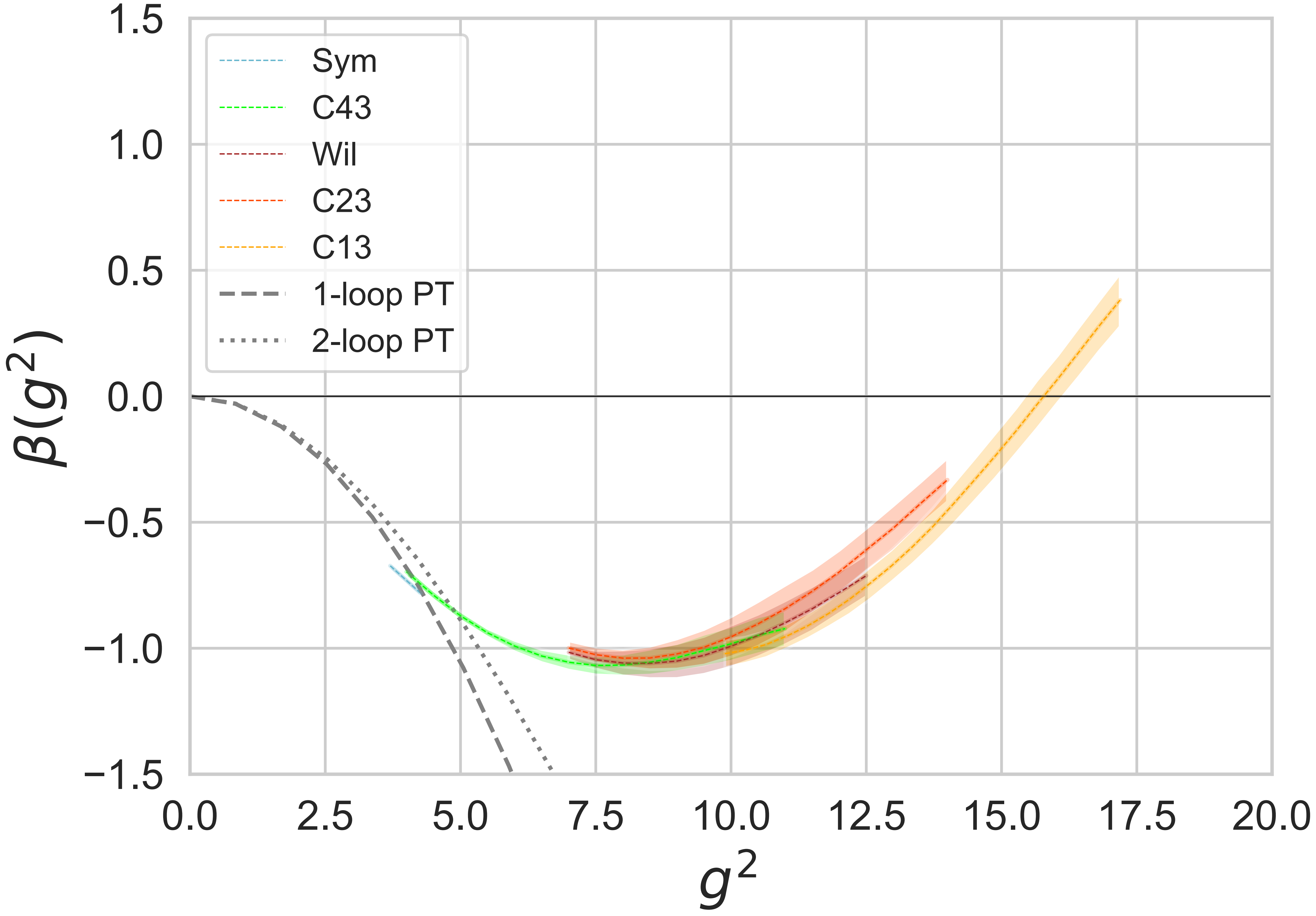
Slide from B. Svetitsky’s talk at ETC*
“Gradient flow in QCD and beyond….”

Composite Higgs+Partial composite top in a 2-rep model

A.H.,Neil, Shamir, Svetitsky, Witzel,
Phys.Rev.D 107 (2023) 11, 114504



Theory space:
Blue circle: M6 model;
red diamond: M11 model;
black square: 2+2 model;
open circle: 4+4 model(this work)

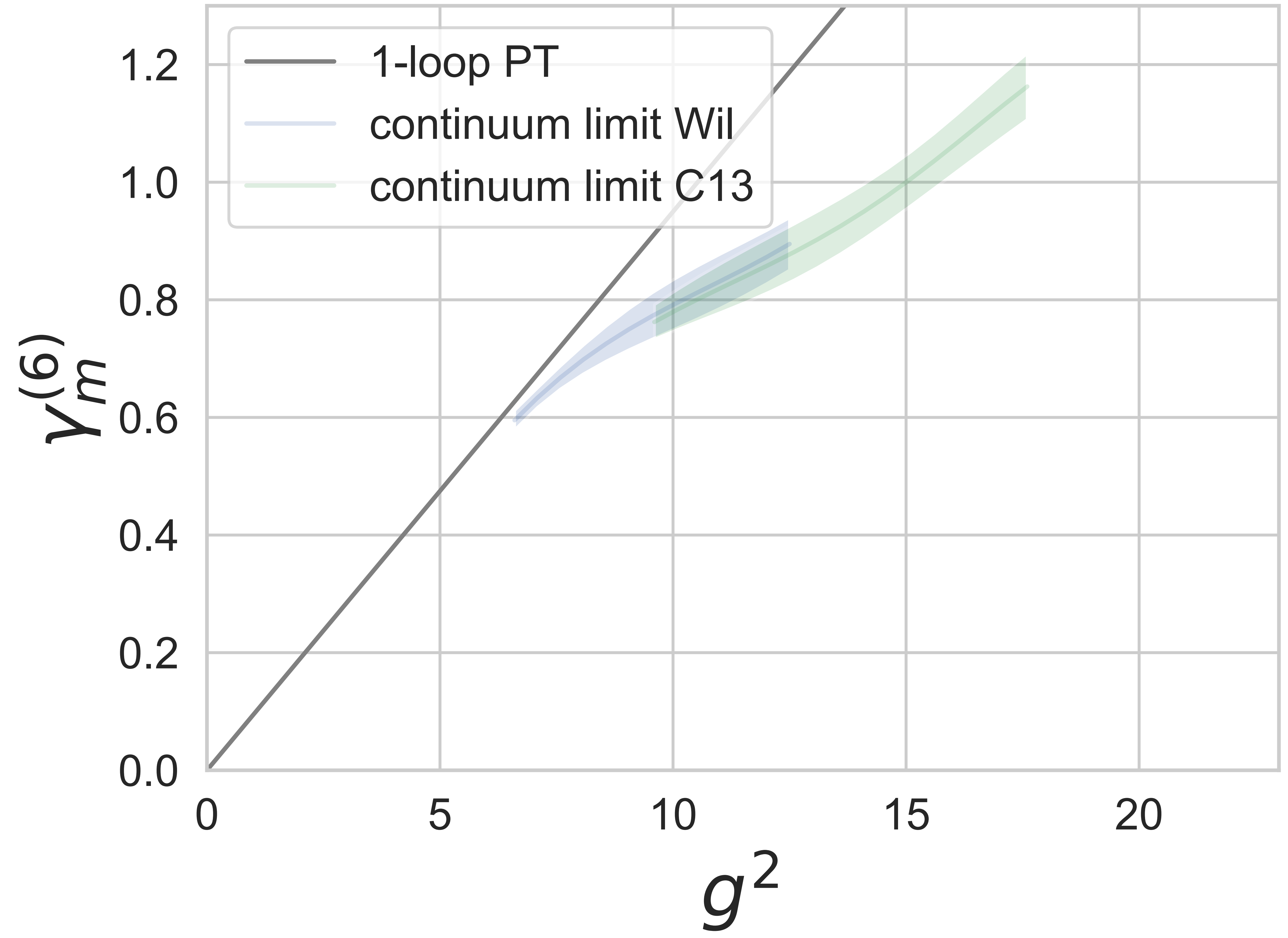


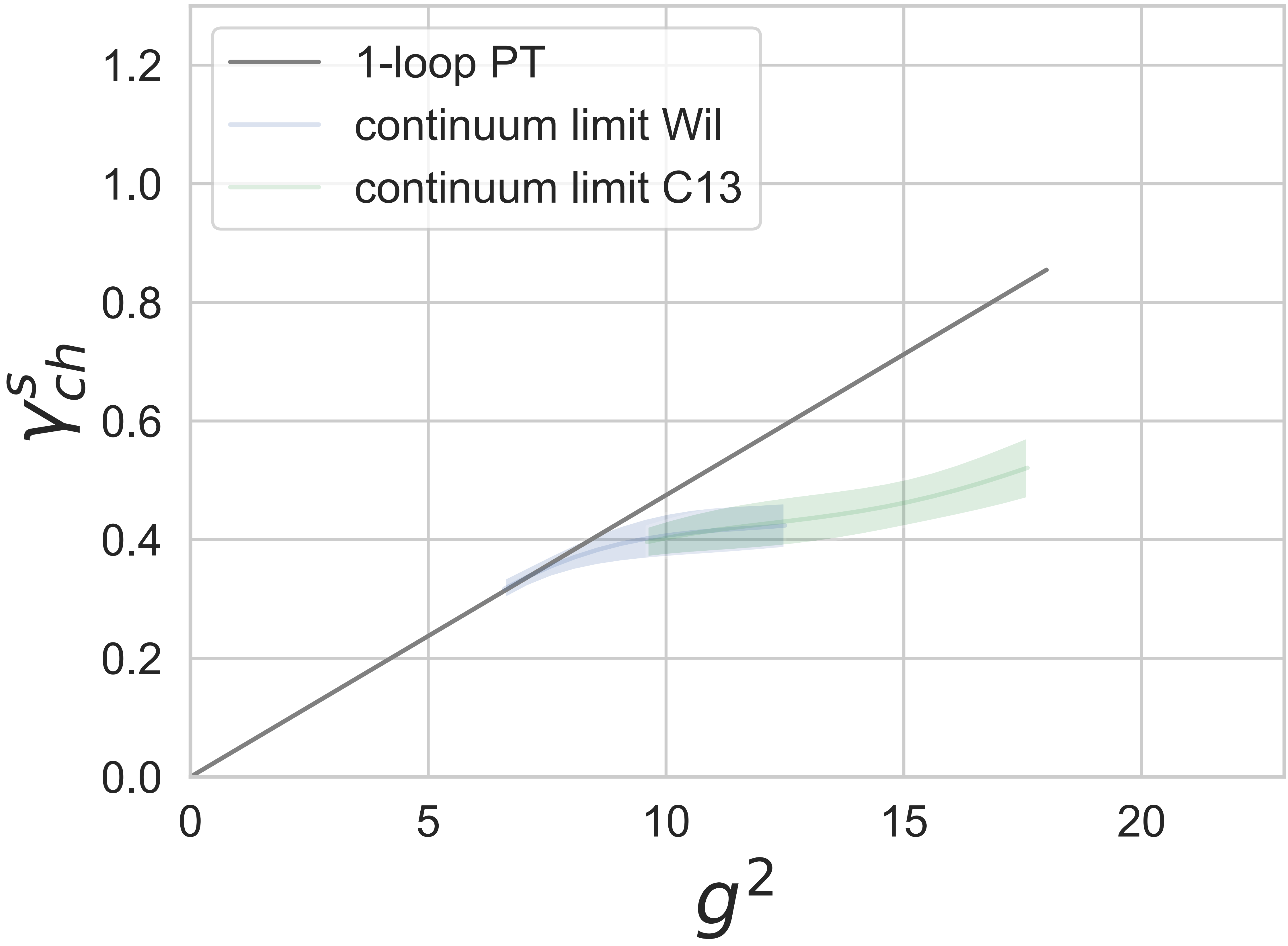
Simulations: Wilson fermions + PV boson and several GF action

IRFP at $g^2 \simeq 16$

Composite Higgs+Partial composite top in a 2-rep model

A.H.,Neil, Shamir, Svetitsky, Witzel, PRD





Mass anomalous dimension:
not far from the conformal sill

Chimera anomalous dimension:
but partial compositeness does not work

$N_f = 8$ & Symmetric mass generation

SMG is a new paradigm:

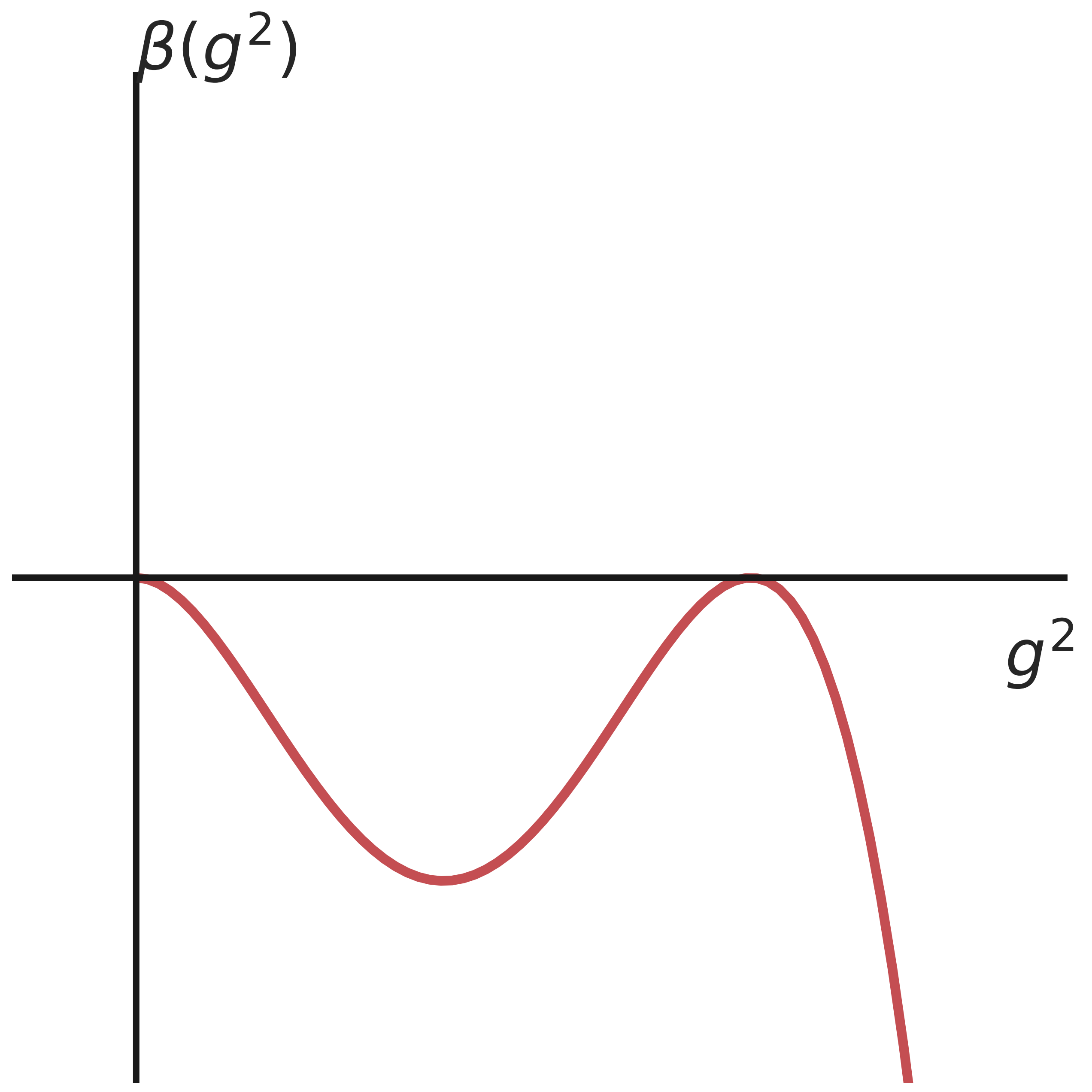
SMG phase is confining, but chirally symmetric

- spectrum is parity doubled
- possible only without 't Hooft anomalies
- $N_f = 8$ continuum or 2 sets of staggered fields are anomaly free

Does SMG exist in 4D? likely YES

Can it describe a BSM system? possibly YES

Ayyar, Chandrasekharan PRD91,065035 (2015)
Catterall et al PRD104,014503 (2021)
Catterall PRD107,014501 (2022)
A.H. PRD 106 (2022) 014513
D. Tong,JHEP 007(2022)001



$N_f = 8$: phases

$N_f = 8$ is 2 sets of staggered fermions (Kaehler-Dirac)

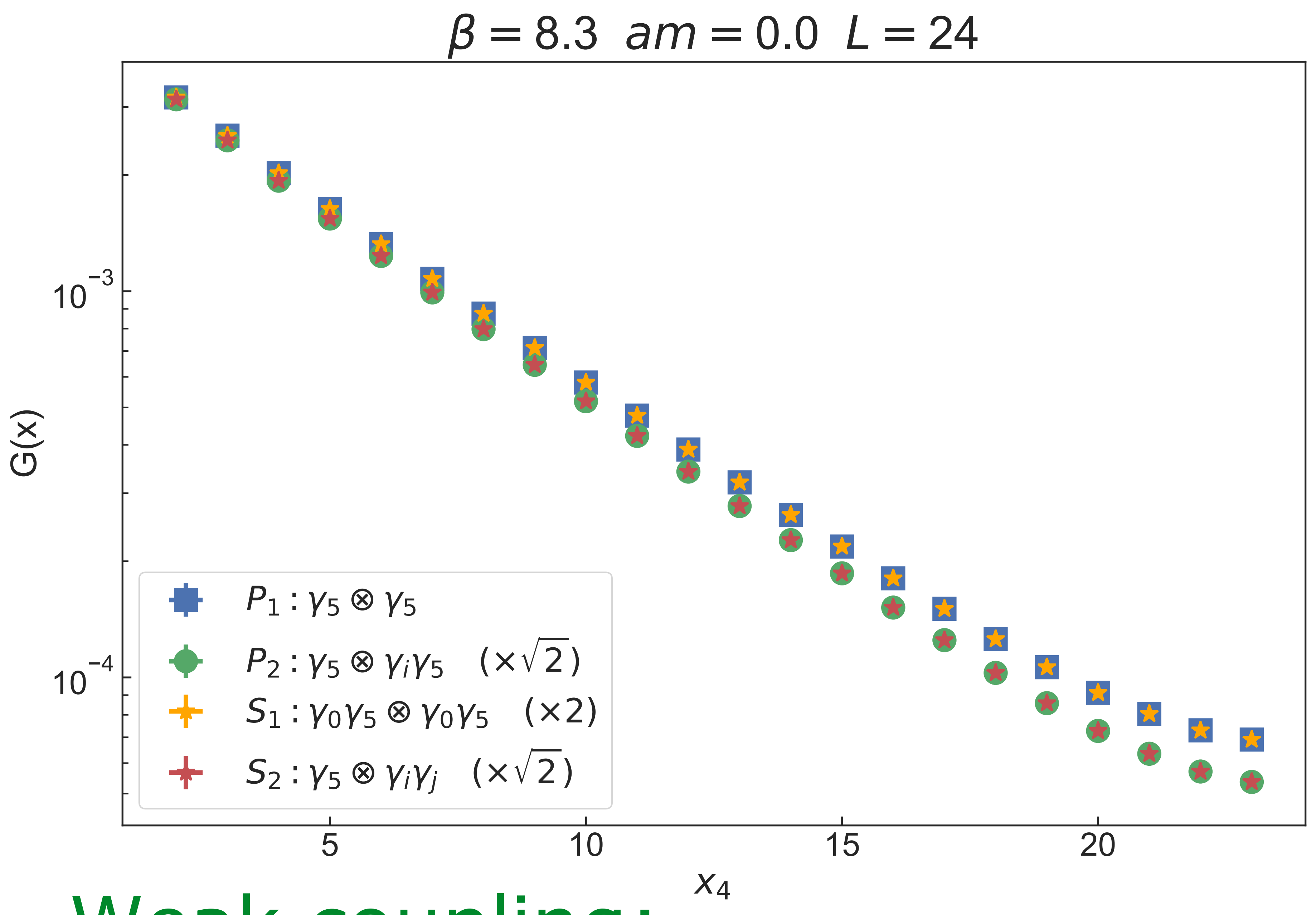
Two phases: weak coupling: conformal

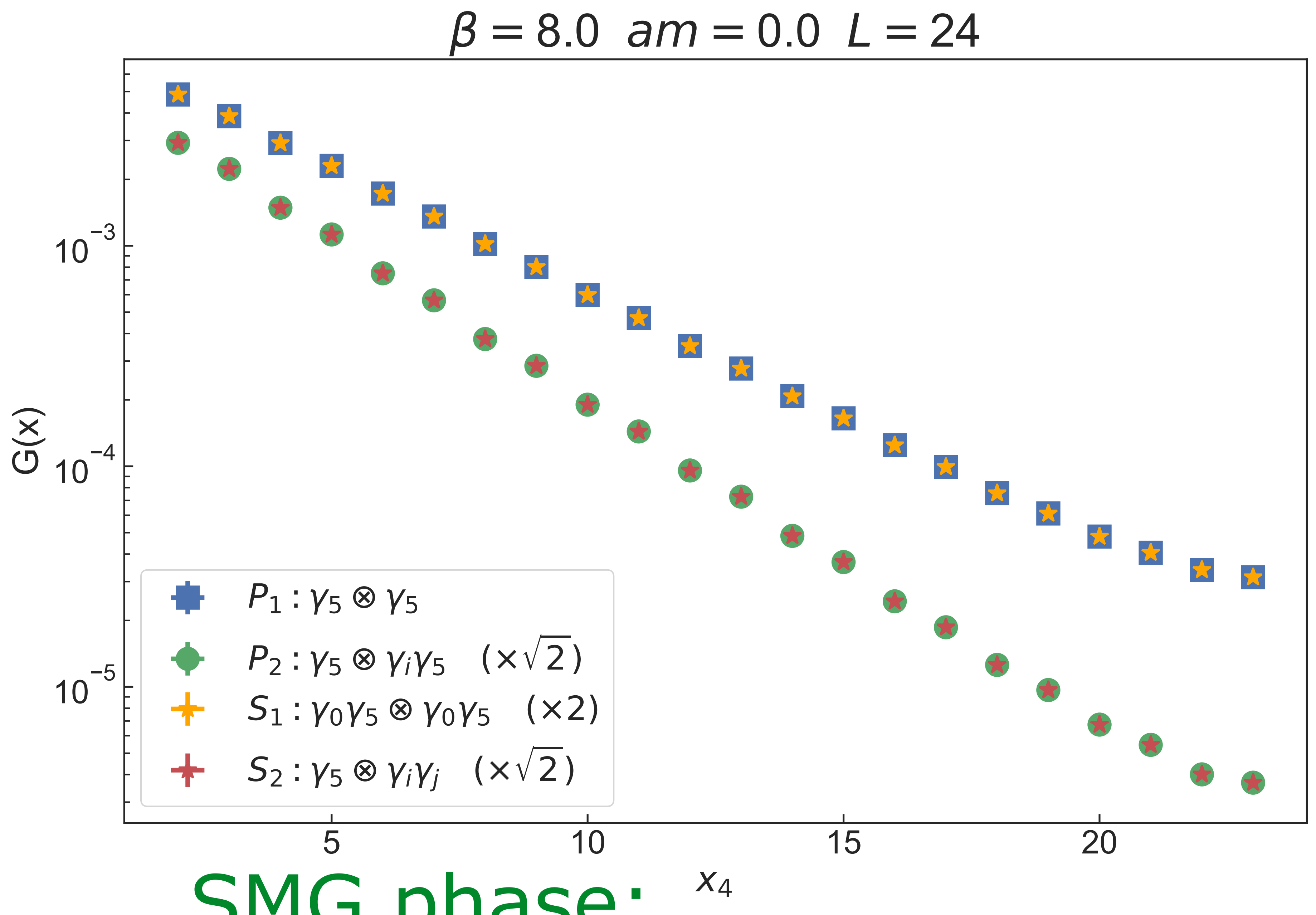
strong coupling: gapped but parity doubled

Catterall et al PRD104,014503 (2021)
Catterall PRD107,014501 (2022)

A.H. PRD 106 (2022) 014513

Meson correlators:





Weak coupling:

- -Pion, scalar degenerate
- -taste breaking small

SMG phase:

- -Pion, scalar degenerate
- -taste symmetry is broken

$N_f = 8$: spectrum

$N_f = 8$ is 2 sets of staggered fermions (Kaehler-Dirac)
weak coupling: conformal
strong coupling: gapped but parity doubled

Catterall et al PRD104,014503 (2021)
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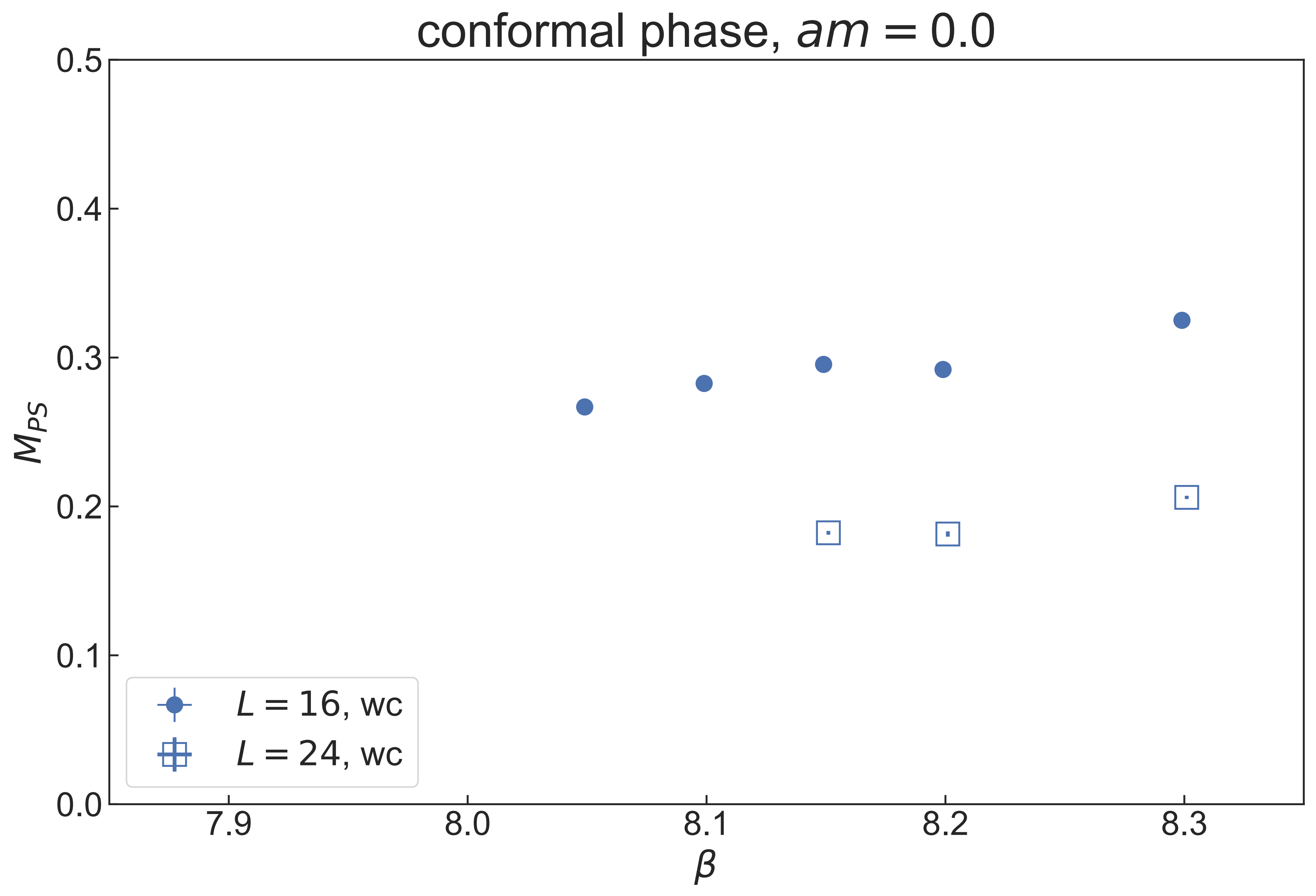
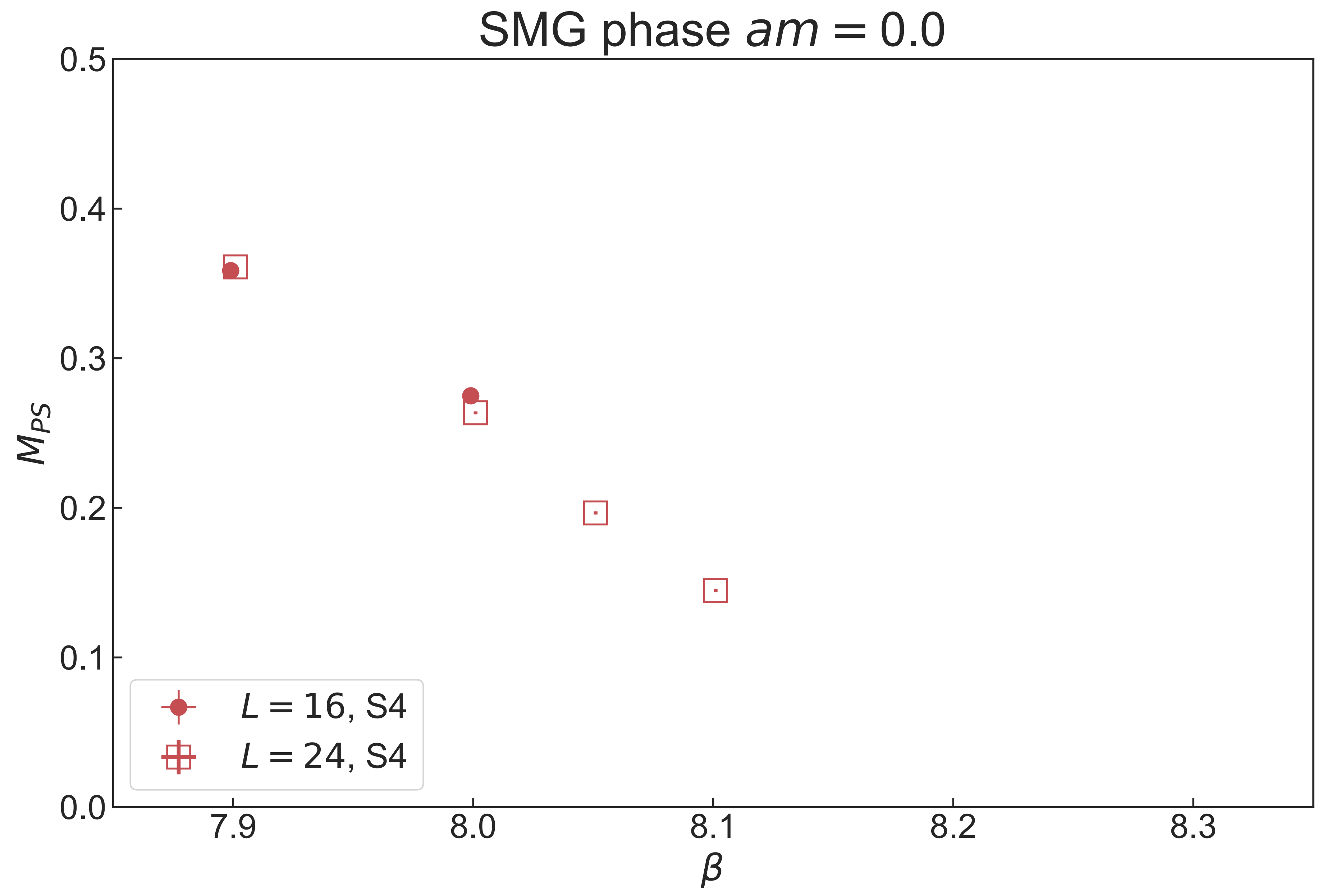
A.H. PRD 106 (2022) 014513

Meson spectrum:





Weak coupling: $M_H \propto 1/L$,

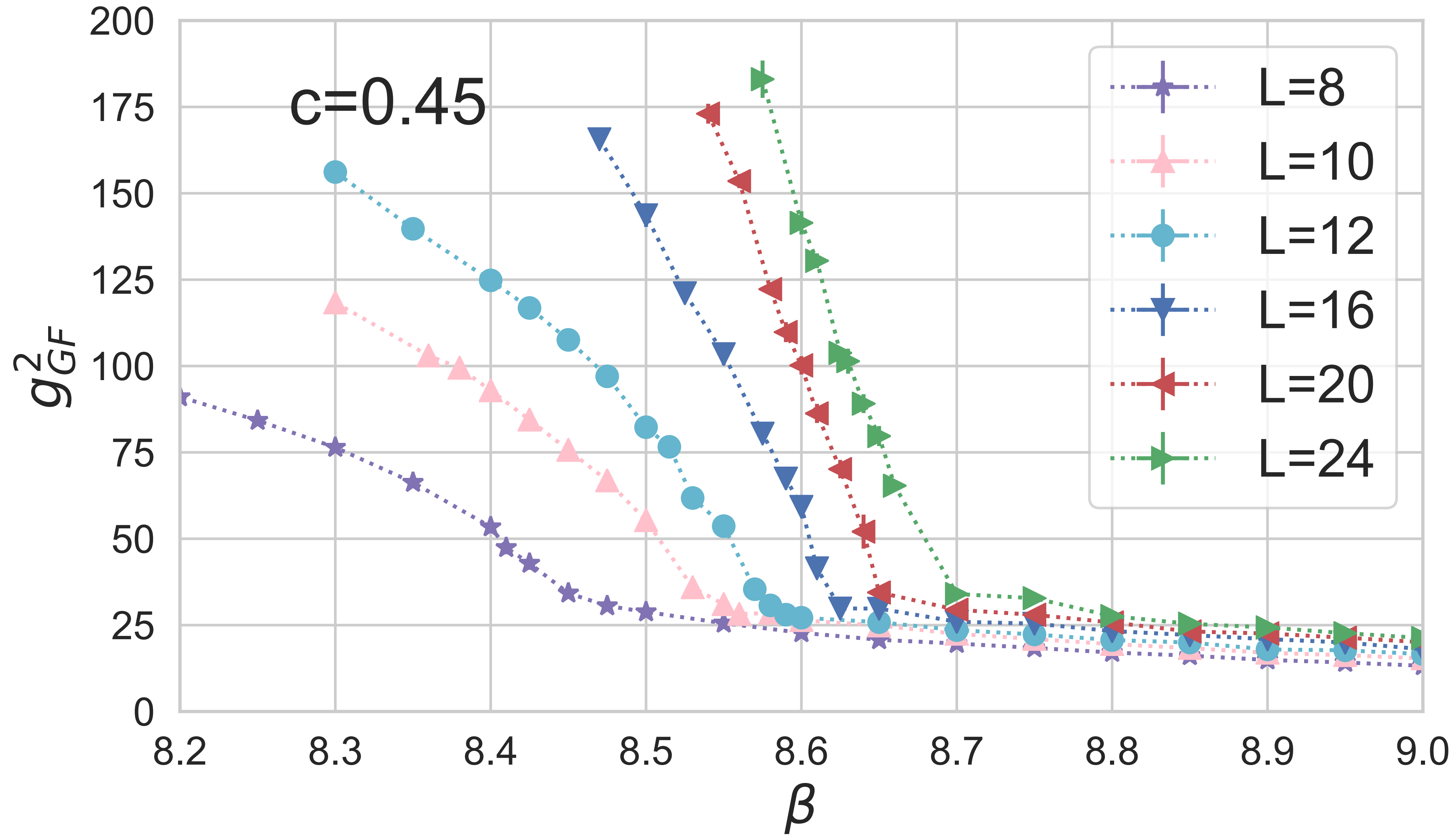
SMG: Volume independent
"pion" is massive

$N_f = 8$: order of phase transition

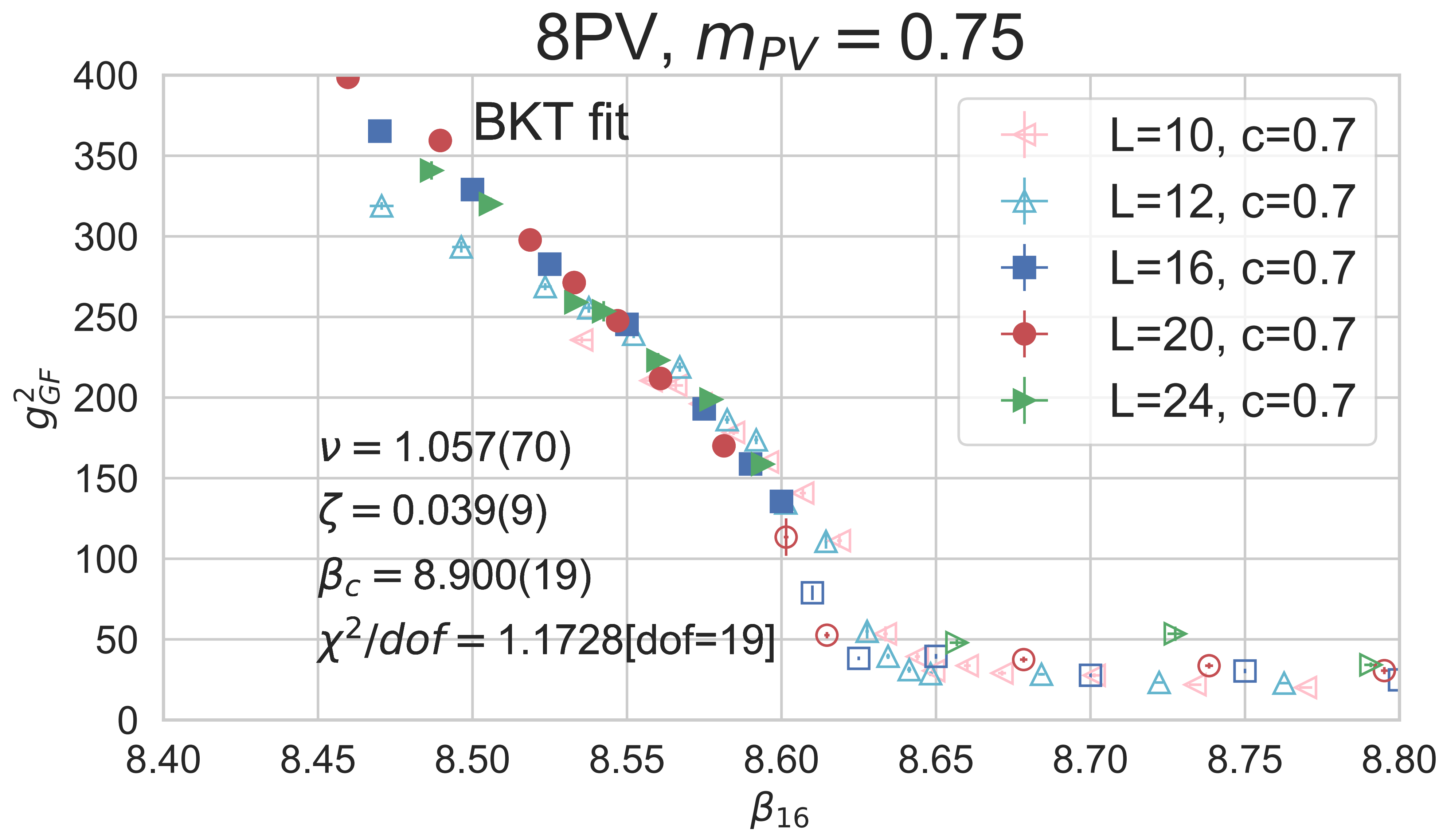
A.H. PRD 106 (2022) 014513

-Numerical simulations show a phase transition with 8 flavors

- Finite size scaling from strong coupling suggest BKT* transition: $\xi \propto e^{-\zeta(\beta-\beta_c)^{-\nu}}$



renormalized coupling at $\mu = c/L$



Finite size scaling/curve collapse of renormalized coupling

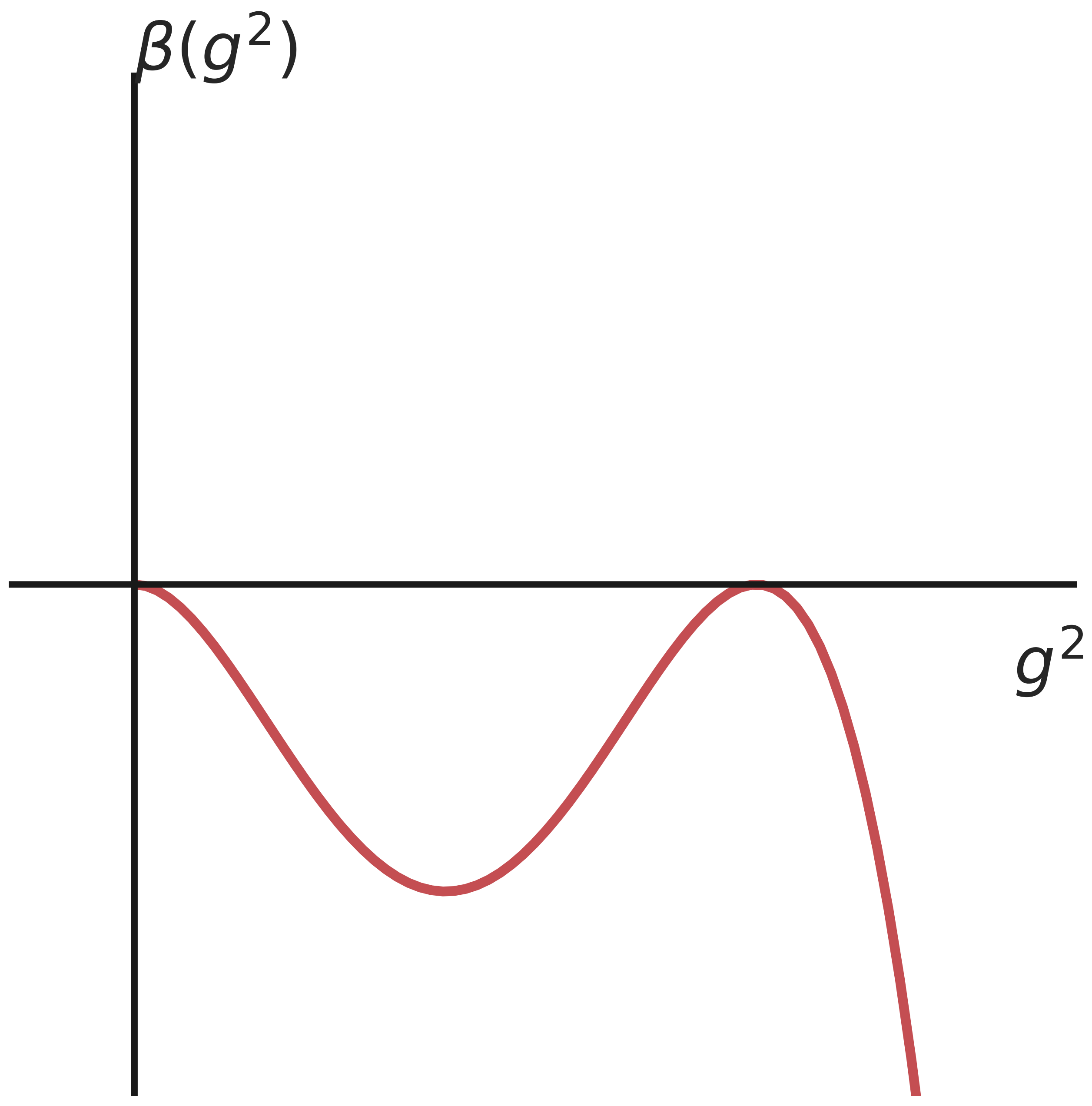
*Berezinsky, Kosterlitz, Thouless

$N_f = 8$: β function

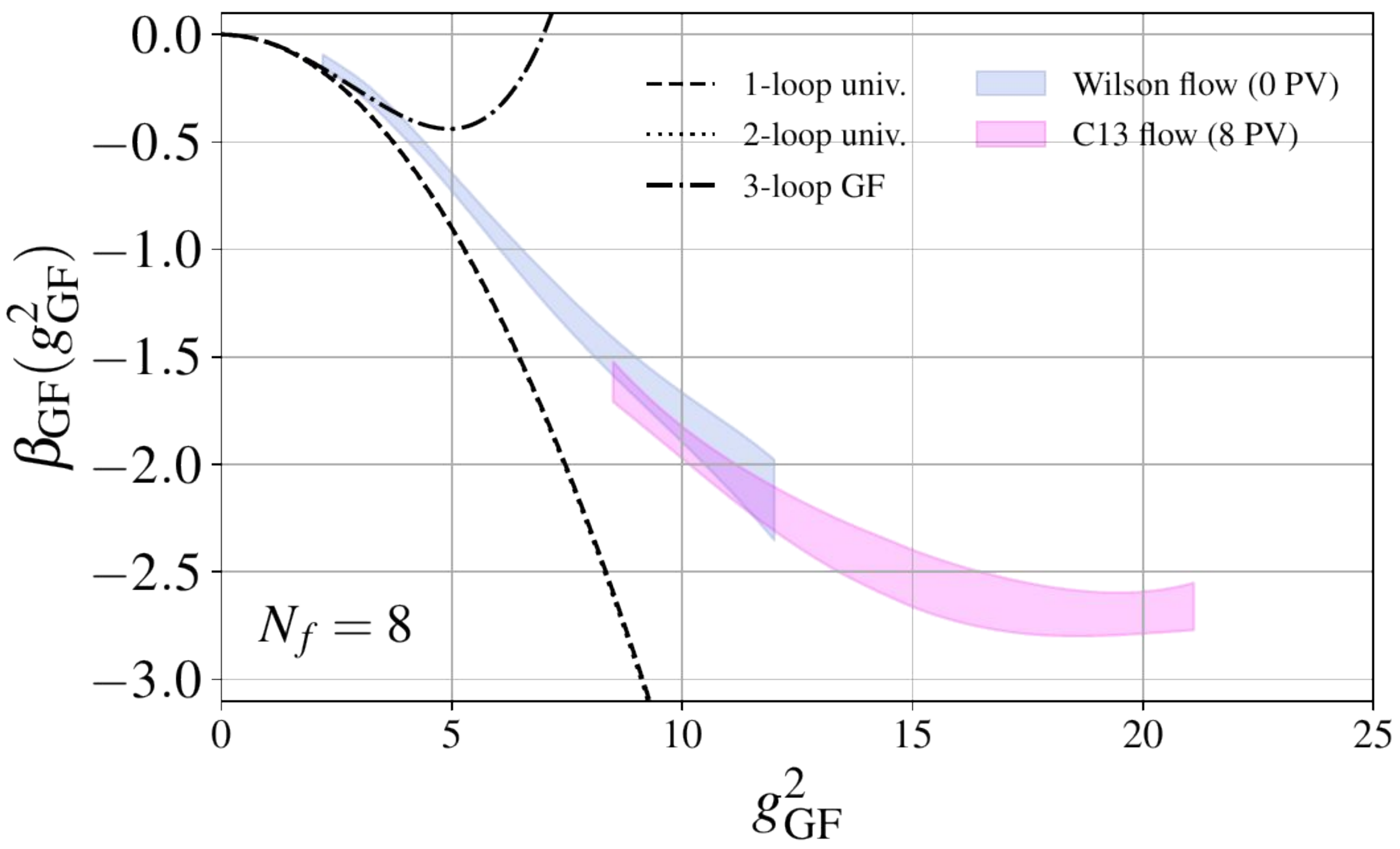
A.H., C. Peterson, in prep

if true, $N_f = 8$ is the sill of the conformal window!

β function



If at the sill



Numerical result so far
(blue: no PV)

Alternative to Composite Higgs (Symmetric mass generation ?)

G.Rossi,2306.00189,2306.00115, Capitani et al PRL123 (2019) 6

Rossi, Frezzotti suggested a lattice phase:

-strongly coupled confining

-chirally symmetric

They couple it to the standard model

-give mass to $W^{\pm}, Z$

-give mass to fermions

-no Higgs: 125GeV resonance is $W^{+}W^{-}/ZZ$ bound state

(Are pheno constraints satisfied?)

Speculative but novel

Lattice BSM, Lattice QCD

They exist in synergy:

LBSM uses simulation codes, methods are developed for QCD

- often need more flexibility
- less precision

Methods developed for LBSM can have direct application to LQCD

- renormalization group β and γ functions:
  LQCD Λ_{QCD}, α_{strong}, renormalization schemes
- gauge action improvement: Pauli-Villars fields

Theoretical developments benefit everyone, even beyond the lattice

EXTRA SLIDES