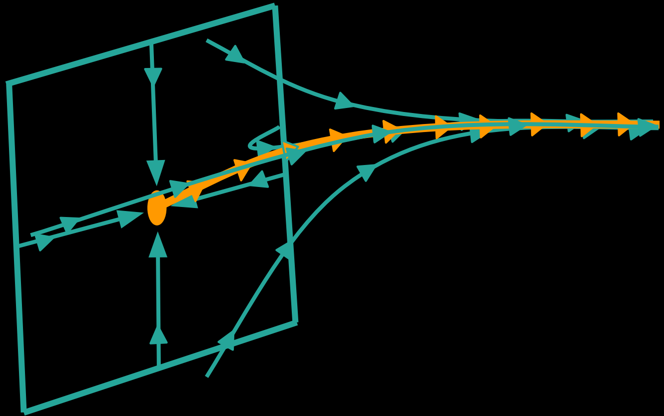
2023 LATTICE

Non-perturbative RG β-function of 8-flavor SU(3) gauge theory



Curtis Taylor Peterson
in collaboration with Anna Hasenfratz

Why $N_f = 8$?

[Hasenfratz, A., Schaich, D., Veernala, A. *JHEP* **06** (2015) 143]
*[LatKMI *PRD* **96**, 014508 (2017)]
*[LSD Collaboration *PRD* **99**, 014509 (2019)]
*[Appelquist, T., Ingoldby, J., Piai, M. *PRD* **126**,191804 (2021)]
*[LSD Collaboration, arXiv:2305.03665]
*[Hasenfratz, A. *PRD* **106**, 014513 (2022)]

- Popular BSM model
  - e.g., LatKMI*, LSD* and Appelquist et al.*
    - Consistent with *both* conformal hyperscaling and dilaton $\chi\mathrm{PT}$
- No evidence of chiral symmetry breaking even at much stronger couplings*

- Must simulate in strongly-coupled regime to better understand infrared dynamics
  - Limited by bulk first-order phase transition (PT)

Objective

- Access strongly-coupled regime
  - Pauli-Villars improvement †
- Untangle strongly-coupled behavior
  - Continuous β-function×

†,×[Hasenfratz, Mon. 13:30]
†,×[Shamir, Mon. 13:50]
×[Witzel, Mon. 14:30]
×[Kuti, 14:50]

Realizing our objective

*[Hasenfratz, A., Shamir, Y., Svetitsky, B. *PRD* **104**, 074509 (2021)]
*[Kuti, J., Fodor, Z., Holland, K., Wong, K. H. *PoS*, LATTICE2021 (**2021**) 321]
*[Hasenfratz, A., Peterson, C.T., Witzel, O., van Sickle, J. *PRD* **108**, 014502 (2023)]

Access strongly-coupled regime

- ❖ Problem: bulk first-order phase transitions (PT)
  - ➢ Triggered by strong UV fluctuations
  - ➢ Occur at finite g_0^2
- ❖ Partial resolution: introduce heavy Pauli-Villars bosons*
  - ➢ Counteract UV fluctuations
  - ➢ Push PT to larger g_0^2

Untangle strongly-coupled behavior

- ❖ Continuous β-function method (CBFM)*

$$g^2_{\mathrm{GF}}(t; L, g_0^2) \sim \langle t^2 E(t) \rangle^{\dagger}$$

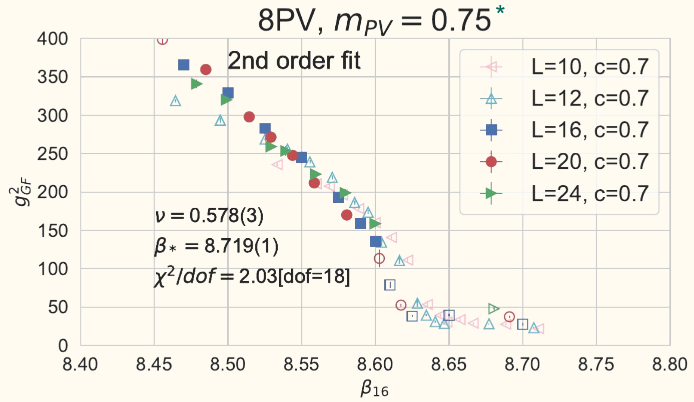
$$\beta_{\mathrm{GF}}(t; g_0^2) \equiv -t \frac{\mathrm{d}}{\mathrm{d}t} g^2_{\mathrm{GF}}(t; g_0^2)$$

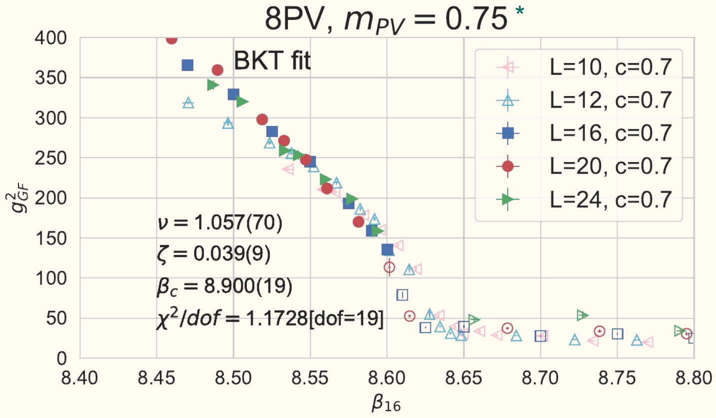
1. $L/a \to \infty$ extrapolation of $g^2_{\mathrm{GF}}(t; L, g_0^2)$ at fixed β_b & t/a^2
2. $a^2/t \to 0$ extrapolation of $\beta_{\mathrm{GF}}(t; g_0^2)$ at fixed g^2_{GF}

†$E(t)$ is the Yang-Mills energy density; we consider Wilson & clover "operators"

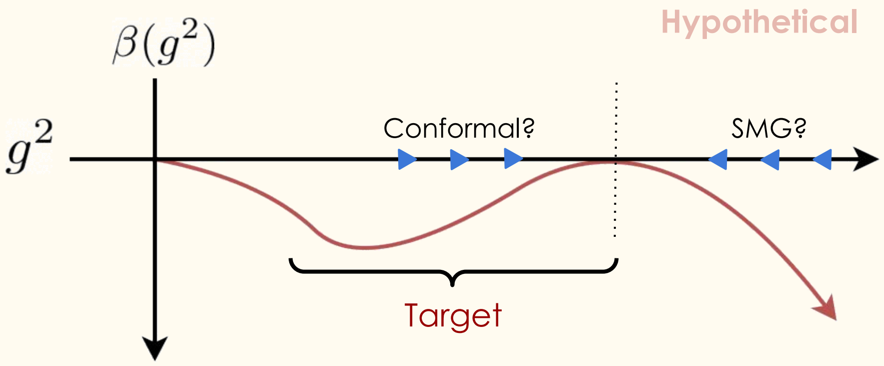
The β-function

*[Hasenfratz, A. *PRD* **106**, 014513 (2022)]





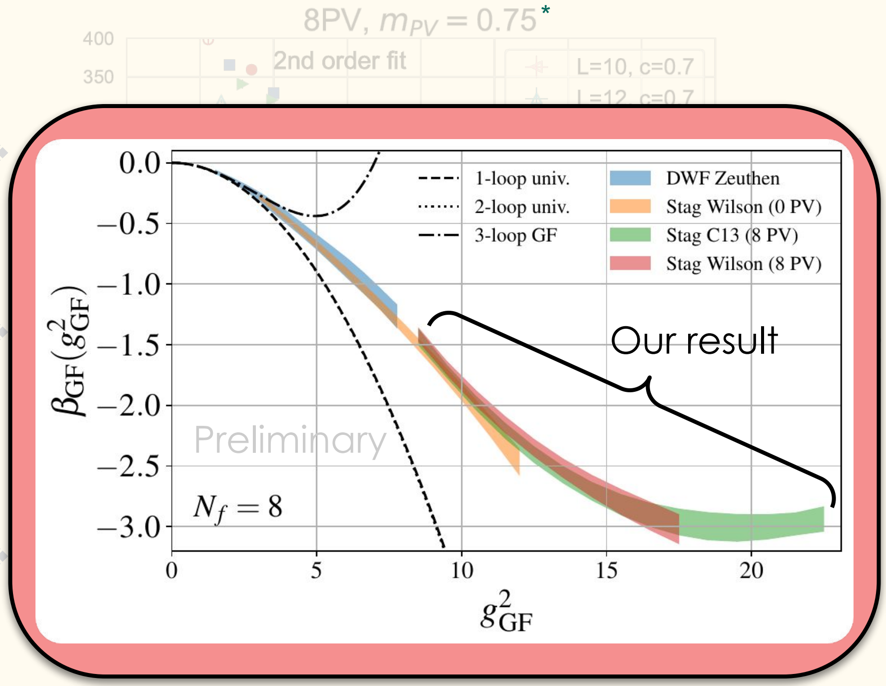
- Finite-size scaling* suggests renormalization group (RG) β-function just touches zero



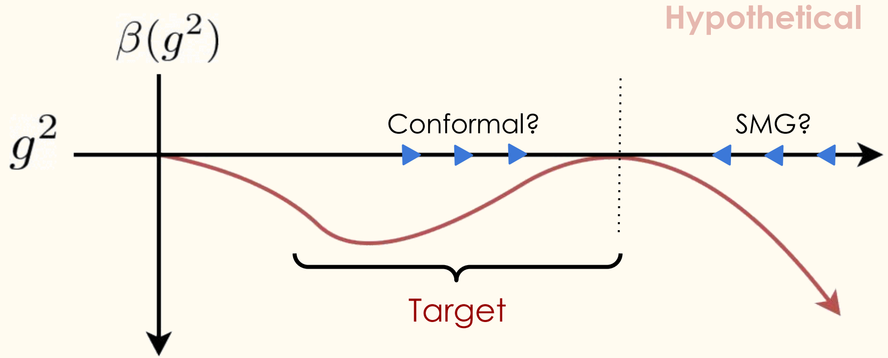
*[Hasenfratz, A., Schaich, D., Veernala, A. *JHEP* **06** (2015) 143]
*[Artz, Harlander, Lange, Neumann, Prausa *JHEP* **06** (2019) 121]
*[Hasenfratz, A., Witzel, O., Rebbi, C. *PRD* **107**, 114508 (2023)]

The β-function

*[Hasenfratz, A. *PRD* **106**, 014513 (2022)]



❖ Finite-size scaling* suggests renormalization group (RG) β-function just touches zero



*[Hasenfratz, A., Schaich, D., Veernala, A. *JHEP* **06** (2015) 143]
*[Artz, Harlander, Lange, Neumann, Prausa *JHEP* **06** (2019) 121]
*[Hasenfratz, A., Witzel, O., Rebbi, C. *PRD* **107**, 114508 (2023)]

Simulation details

*[Osborn, J., Jin, X.Y. *PoS* 256 (2016)]
[Hasenfratz, A., Shamir, Y., Svetitsky, B. *PRD* **104**, 074509 (2021)]
*[Hasenfratz, A., Neil, E., Shamir., Y, Svetitsky, B., Witzel, O. *In Preparation* (2023)]

- nHYP-smeared staggered fermions & adjoint-plaquette gauge action
  - Pauli-Villars (PV) improvement
  - Use MILC* & Quantum EXpressions* (QEX)
  - Symmetric volumes ($L/a = 24, 32, 36, 40$)
    - (Anti-"")periodic BC's for fermion(gauge)
  - $8.8 \leq \beta_b \equiv 6/g_0^2 \leq 9.9$ (8 total)
  - $am_f = 0$
- Gauge flows (GF) run with MILC & QEX
  - Run Wilson flow & modified rectangle flow*
  - Measure Wilson & clover operator

Pauli-Villars action

8 degenerate PV/fermion
$am_{\mathrm{PV}} = 0.75$

Flow action

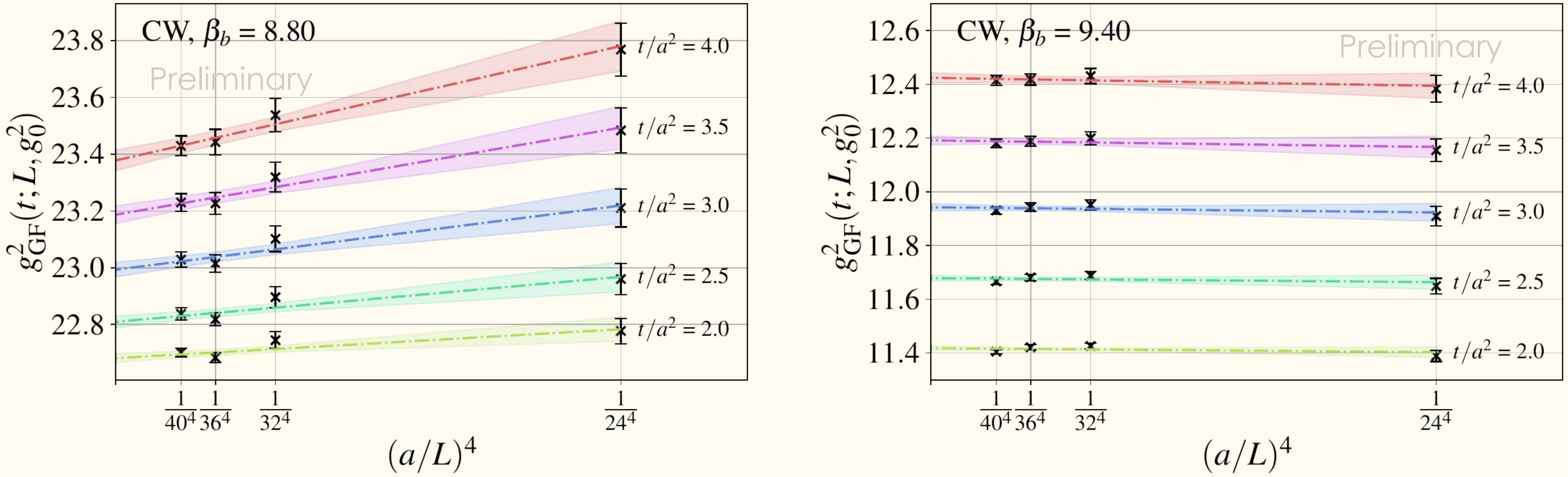
$$\mathcal{S}_f = c_p \mathcal{S}_p + c_r \mathcal{S}_r \quad (c_p + 8c_r = 1)$$

$c_p = 1 \rightarrow$ "Wilson flow"
$c_p = 1/3 \rightarrow$ "C13 flow"

*[David Schaich's modified MILC code: github.com/daschaich/KS_nHYP_FA]
*[QEX main branch: github.com/jcosborn/qex]
*[Curtis Peterson's fork of QEX: github.com/ctpeterson/qex]

Infinite volume extrapolation

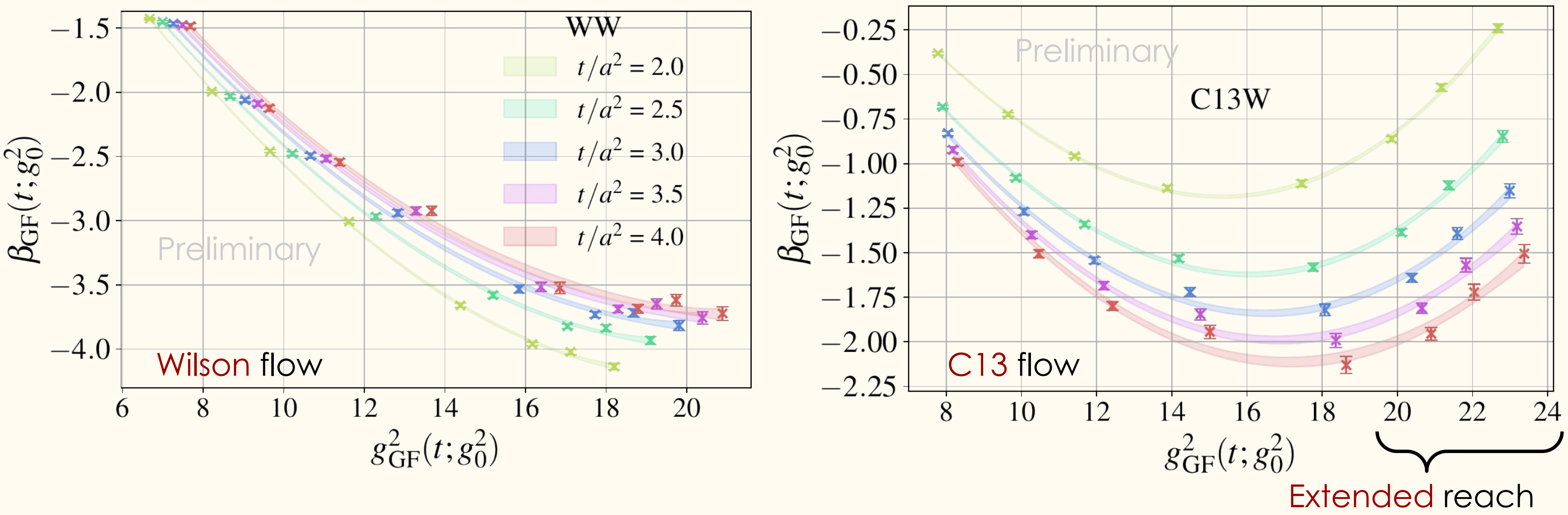
C13 flow
(see supplement for Wilson flow)



Extrapolate $g^2_{\mathrm{GF}}(t; L, g_0^2)$

linearly in $(a/L)^4 \to 0$ at fixed β_b and t/a^2

Interpolation

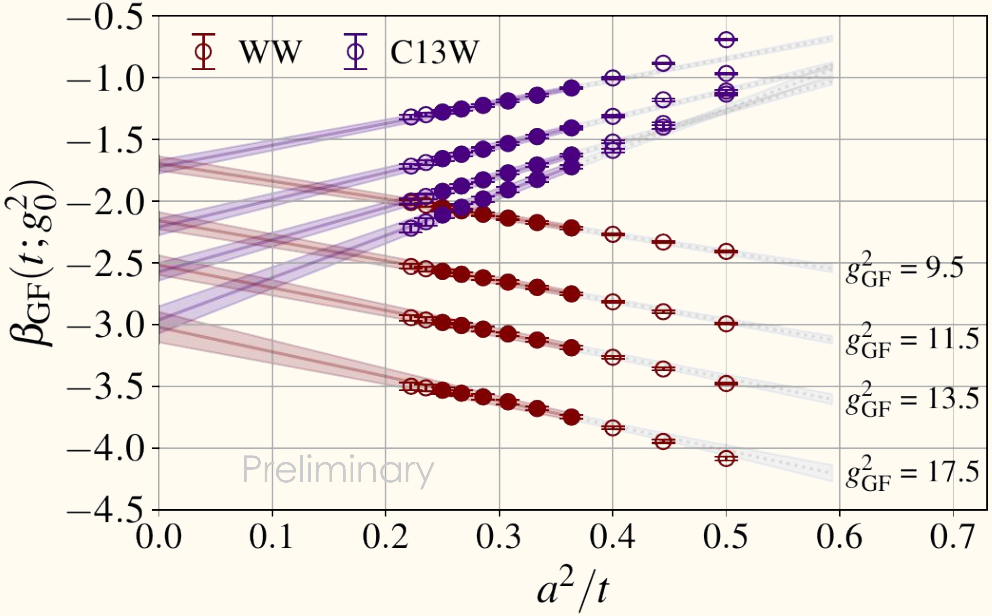


Interpolate $\beta_{\mathrm{GF}}(t; g_0^2)$ in $g^2_{\mathrm{GF}}(t; g_0^2)$ at fixed t/a^2

We use a cubic polynomial

Continuum Extrapolation

- Linear extrapolation in a^2/t at fixed $g^2_{\rm GF}(t; g_0^2)$
  - $2.6 \le t/a^2 \le 4.2$
- WW & C13W consistent
  - WC also consistent
  - C13C plagued by nonlinear discretization effects
    - Under investigation

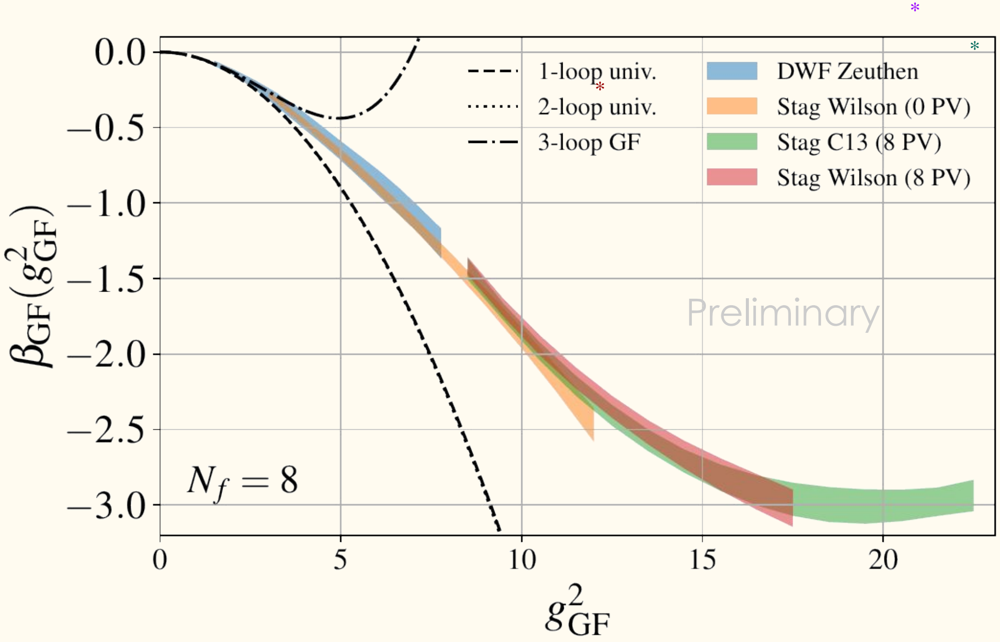


Conclusions & future directions

*[Hasenfratz, A., Schaich, D., Veernala, A. *JHEP* **06** (2015) 143]
*[Artz, Harlander, Lange, Neumann, Prausa *JHEP* **06** (2019) 121]
*[Hasenfratz, A., Witzel, O., Rebbi, C. *PRD* **107**, 114508 (2023)]

- Range of $g^2_{\rm GF}$ extended 2x
  - Closest IRFP possibly at $g^2_{\rm GF} > 22$
    - No signs of χSB up to $g^2_{\rm GF} \sim 22$
  - Negative curvature $8 \lesssim g^2_{\rm GF} \lesssim 22$
- Overlap between 8PV staggered and previously published results

- Generating & analyzing step-scaling ensembles
- Simulating on strong-coupling side of phase transition
- Extending finite-size scaling ensembles



Acknowledgements

U. Colorado: Alpine

USQCD: Fermilab LQ1, BNL SDCC

NSF Graduate Research Fellowship (GRFP)

Fontera Computational Science Fellowship (FCSF)

curtis.peterson@colorado.edu
github.com/ctpeterson
curtistaylorpeterson.com

GF β-function

[Carosso, A., Hasenfratz, A., Neil, E. *PRL* **121**, 201601 (2018)]
[Lüscher, M., *JHEP* **08** (2010) 71]
[Makino, H., Morikawa, O., Suzuki, H. *PTEP* **05**, 099201 (2021)]

- GF describes a real-space RG transformation in infinite volume when combined with appropriately-defined coarse graining step

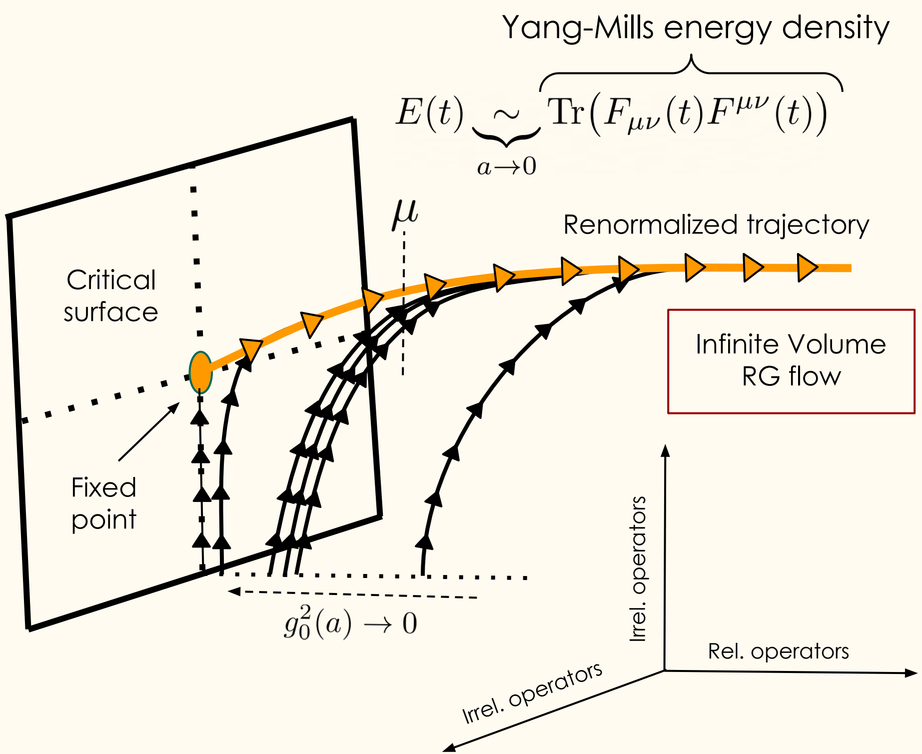
- Define a renormalized running coupling ($\mu^2 \propto 1/8t$)
  - Common choice in LGT studies is to use the flowed Yang-Mills energy density, since it does not renormalize*

$$g^2_{\mathrm{GF}}(t; g_0^2) \equiv \mathcal{N}\langle t^2 E(t)\rangle$$

  - Describes flow along renormalized trajectory with corresponding β-function

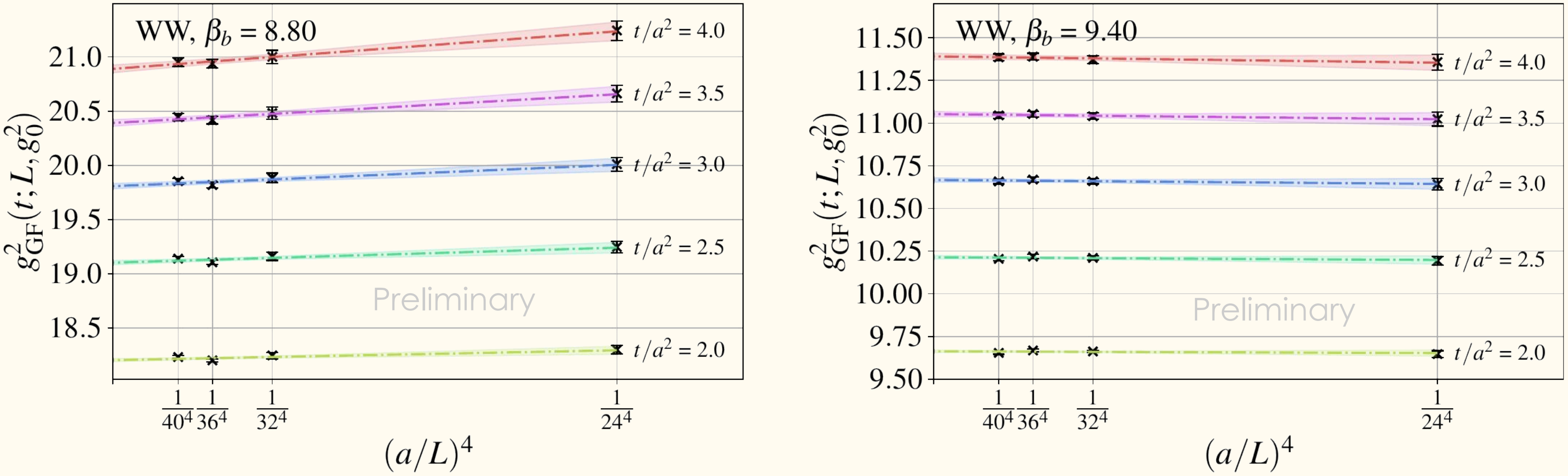
$$\beta_{\mathrm{GF}}(t; g_0^2) = -t\frac{\mathrm{d}}{\mathrm{d}t} g^2_{\mathrm{GF}}(t; g_0^2)$$

*$\mathcal{N} = 128\pi^2/3(N^2-1)$ chosen such that the GF coupling matches $\overline{\mathrm{MS}}$ at tree level



Infinite volume extrapolation

Wilson flow



Extrapolate $g^2_{\mathrm{GF}}(t; L, g_0^2)$

linearly in $(a/L)^4 \to 0$ at fixed β_b and t/a^2