(https://www.flickr.com/photos/brookhavenlab/6289001841)

SPC Overview:
Beyond the Standard Model

Ethan T. Neil (Colorado)
USQCD All Hands' Meeting
April 27, 2019

Lattice and BSM physics

- One of the four main categories of lattice research within USQCD as identified by the SPC is "beyond the Standard Model" (BSM).

- The "BSM" research category specifically means using lattice directly on *theories other than QCD*, which could play a role in models of new physics.

- This is a small and broad research area: efforts in many different directions (theory space is large)

What kinds of BSM models?

<u>Composite Higgs:</u> new strongly-coupled sector at the electroweak scale; Higgs is a composite bound state. (W/Z, top often have some composite part too.)
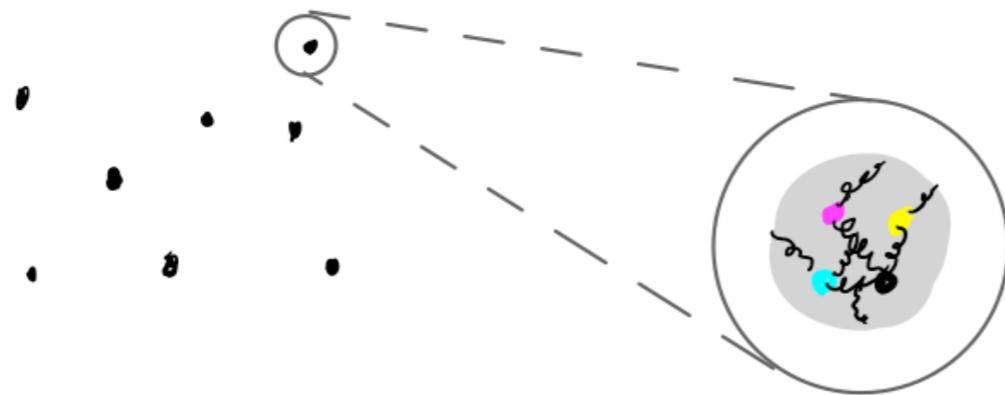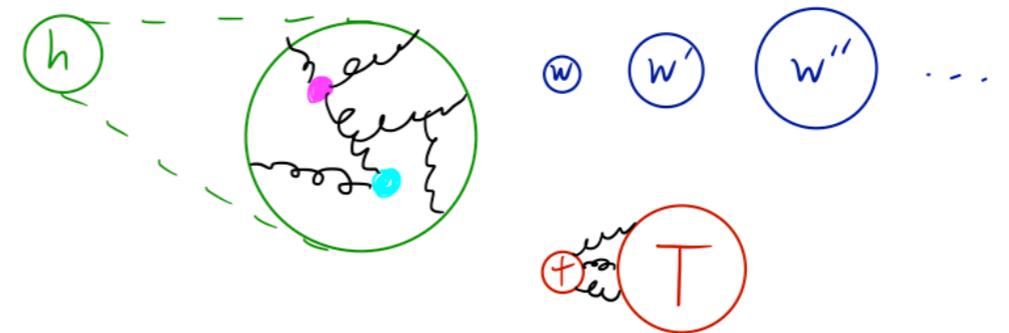
<u>Composite dark matter:</u> dark "hidden sector" which is strongly coupled. Can appear naturally with composite Higgs or GUT theories.

<u>Supersymmetry (SUSY):</u> hypothetical symmetry relating bosons to fermions. Supersymmetric SM requires *SUSY breaking*, where strong coupling can be relevant.

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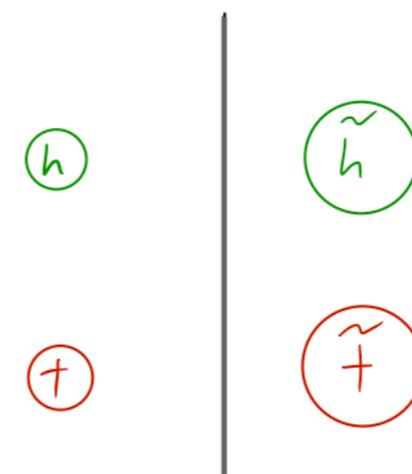
Aside from specific models, we can learn about the rich "theory space" of strongly-coupled gauge theory.
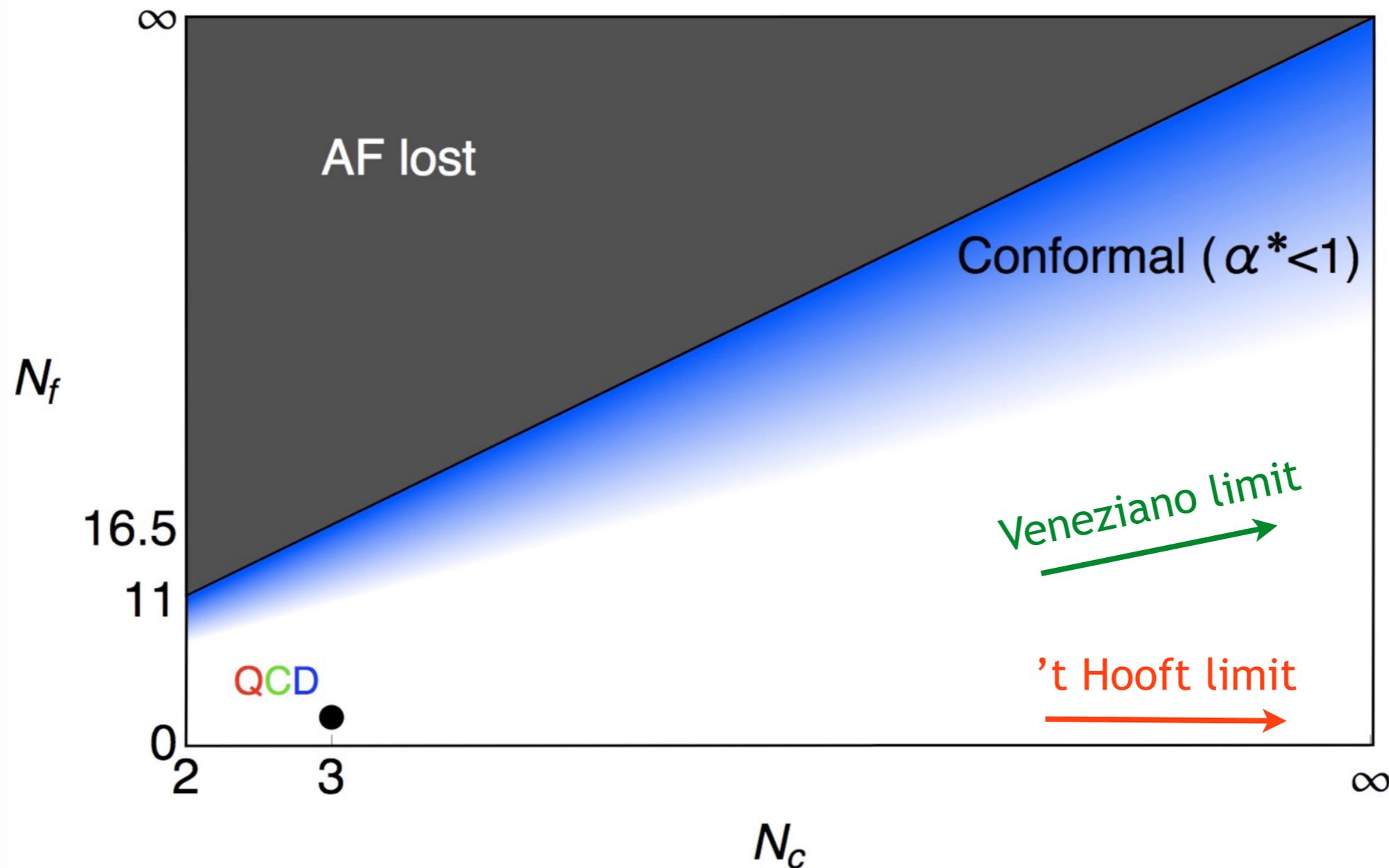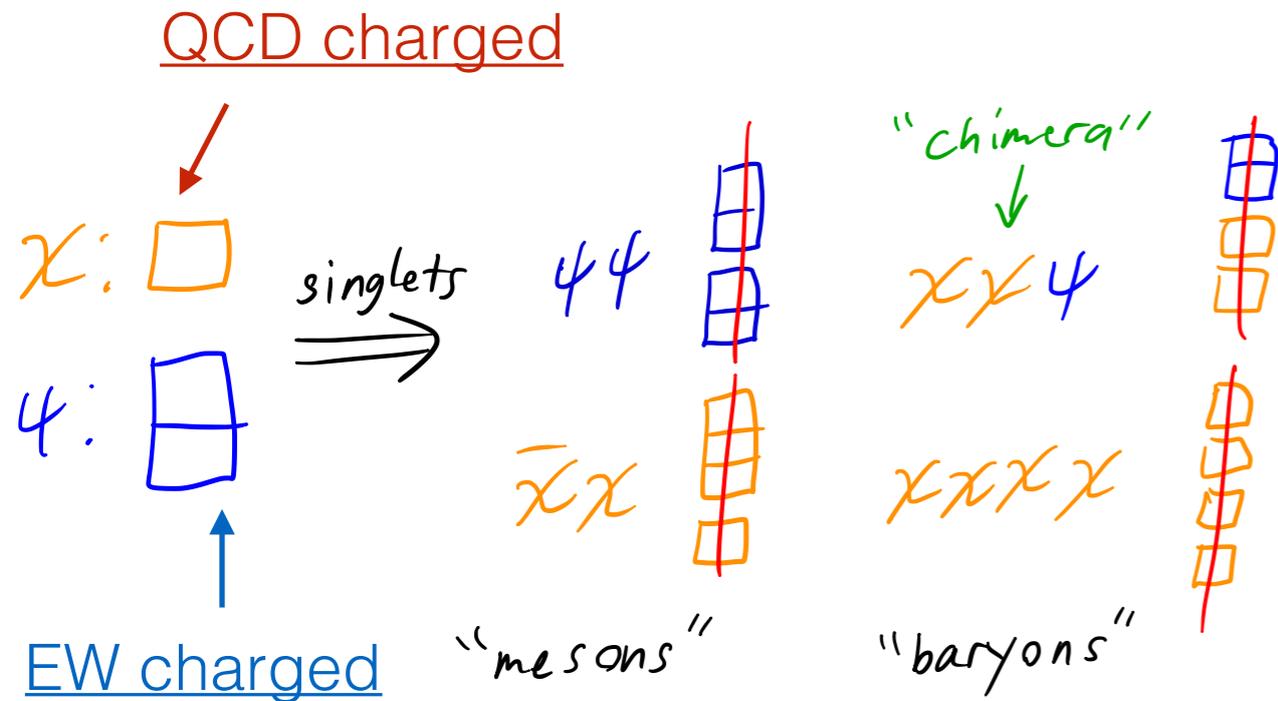

Even for just SU(N_c) with N_f fundamentals, there is a <u>rich phase structure</u> (IR-conformal phase transition), <u>emergent dynamics</u> (the 4d CFTs which appear in the conformal phase), and <u>well-established trends</u> (the 't Hooft and Veneziano large-N limits.)

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USQCD Science Highlights*

*not a complete review, biased towards projects which have proposals in currently

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SU(4) composite Higgs

QCD charged

$\chi:$ □

singlets ⟹

$\psi:$ □

EW charged

$\psi\psi$

"chimera"

$\chi\psi\psi$

$\bar{\chi}\chi$

$\chi\chi\chi\chi$

"mesons"

"baryons"

(Tel Aviv-Colorado collaboration, 1812.02727)

- UV-complete composite Higgs model (G. Ferretti), based on SU(4) gauge group with fermions in two irreps

- New work on decay constant ME for "chimera" baryon —> composite top-quark partner. Z-factor associated with chimera determines top Yukawa:
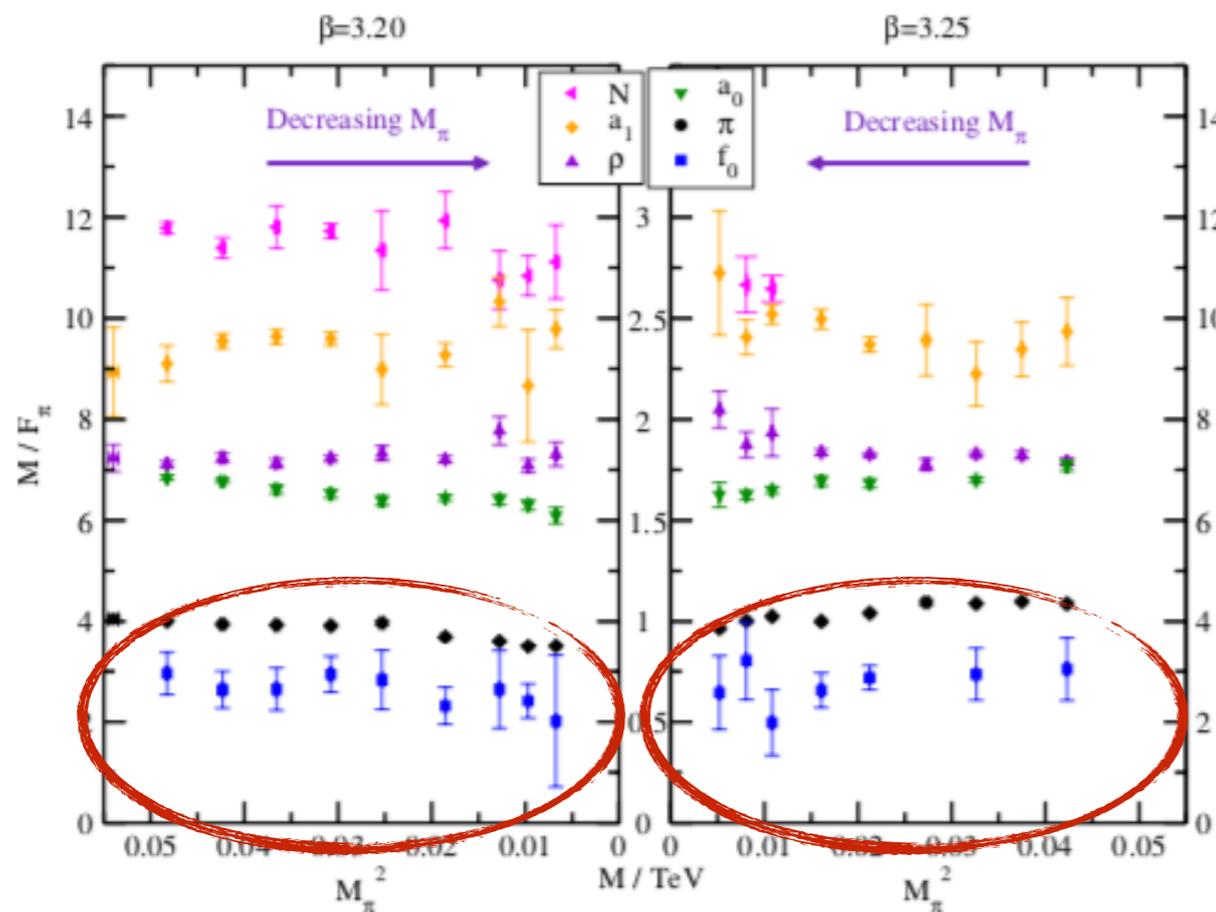
$$y_t \sim \left(\frac{g_{\mathrm{EHC}} F_6}{\Lambda_{\mathrm{EHC}}}\right)^4 \left(\frac{Z}{F_6^3}\right)^2 \frac{F_6}{M_B}$$
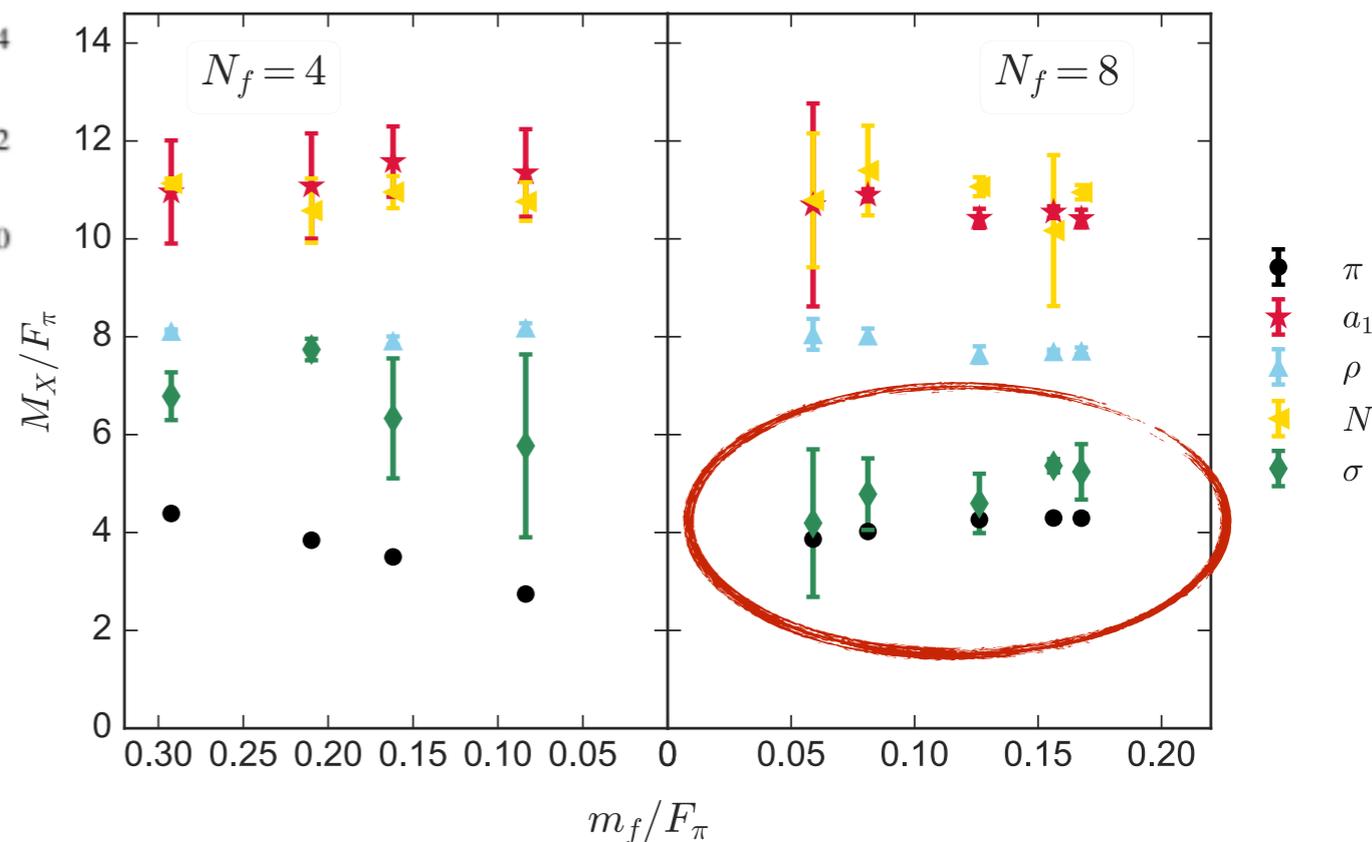
- Small size of Z/F_6^3 implies **inconsistency**: EHC coupling must be so strong that it would have to be included in the lattice sim, warping the strong dynamics.
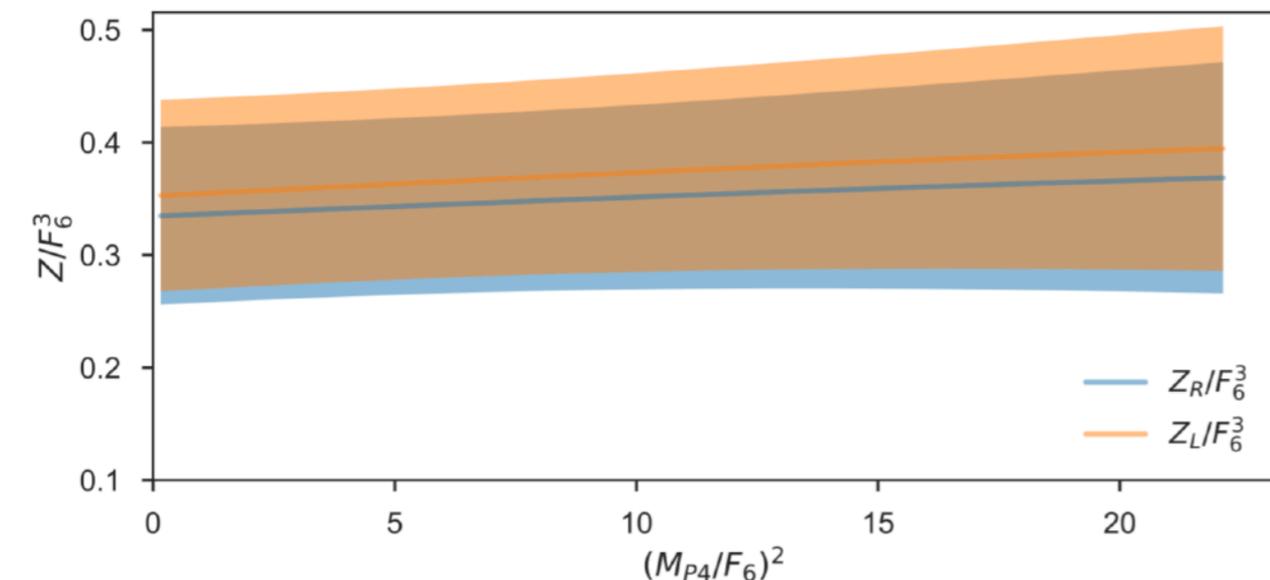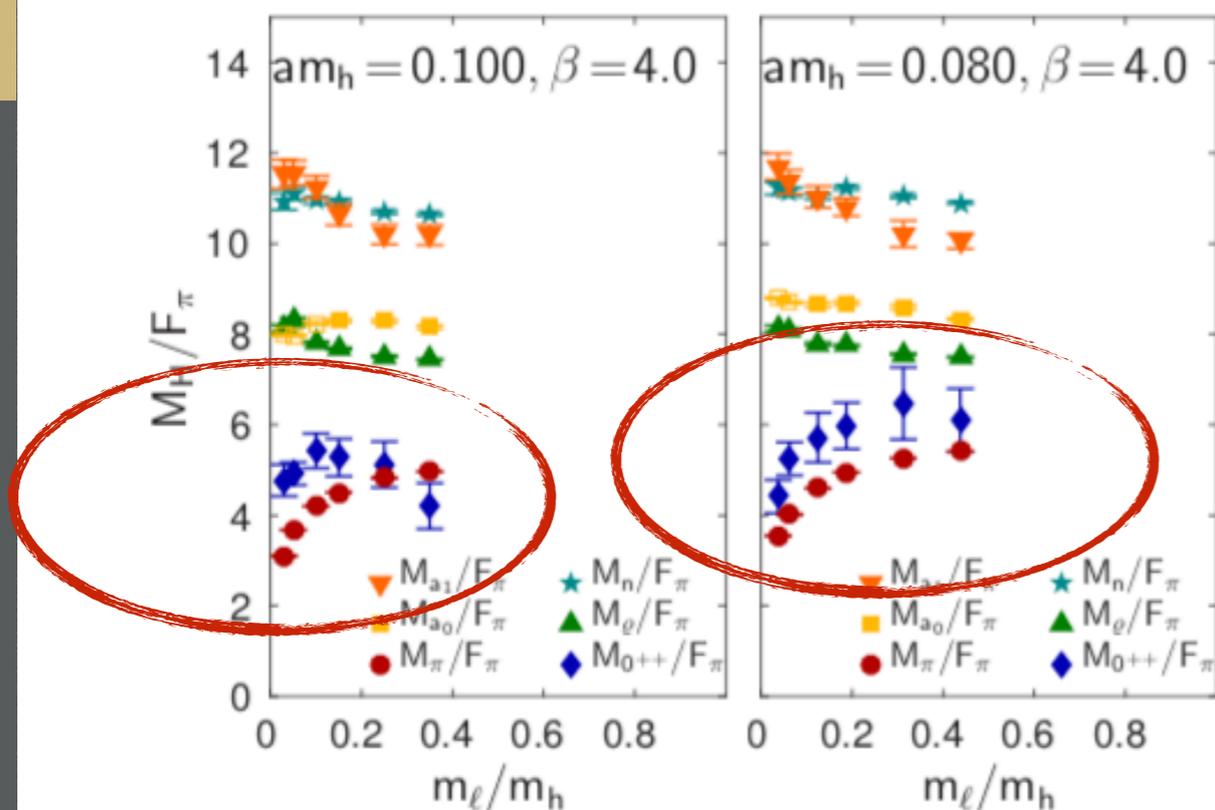
(LatHC collaboration, 1901.06324)

(LSD collaboration, 1901.06324)

(Hasenfratz, Rebbi, Witzel, 1810.01850)

- Emergence of light 0++ scalar, degenerate with or lighter than pions, in several near-conformal theories: clockwise from top left SU(3) with Nf=2 "sextet", Nf=8, Nf=4+8. Results refined and extended in last year.

- Ongoing work on exploring *how the low-energy EFT is modified* due to the 0++, both analytical and on lattice. Early results fitting "dilaton EFT" (Appelquist/Ingoldby/Piai, Golterman/Shamir, Hansen/Langaeble/Sannino) appear promising!

Step-scaling functions

(Hasenfratz, Rebbi, Witzel, update from 1810.05176)
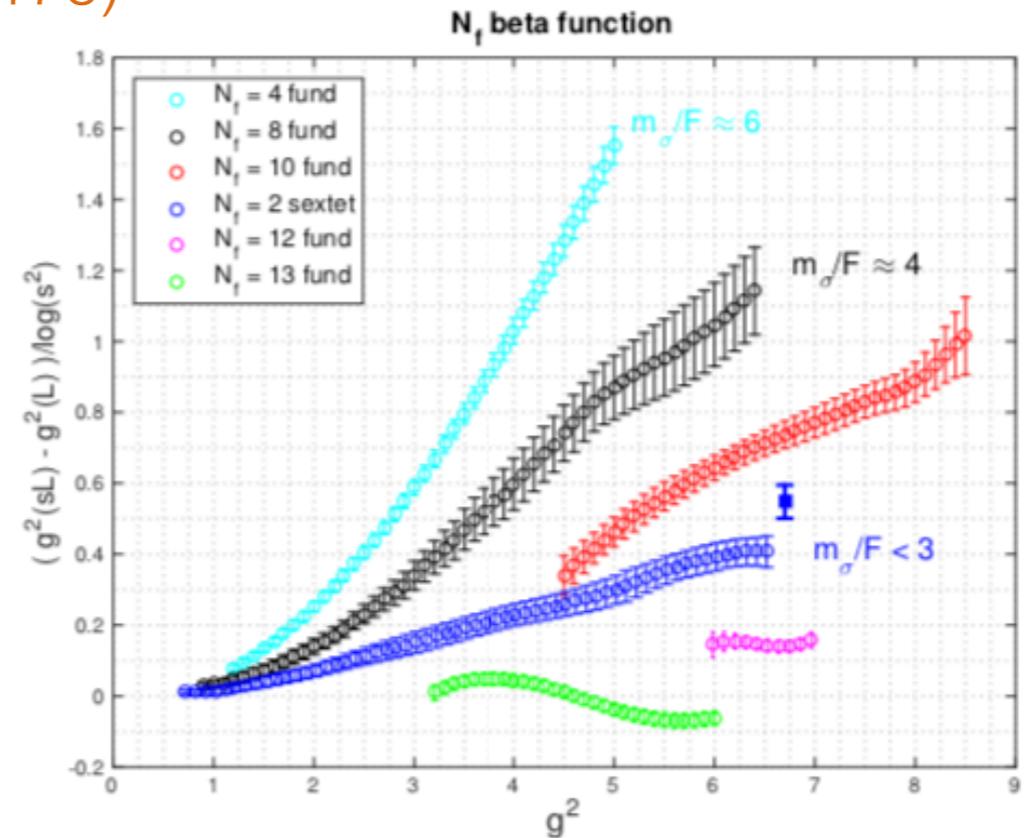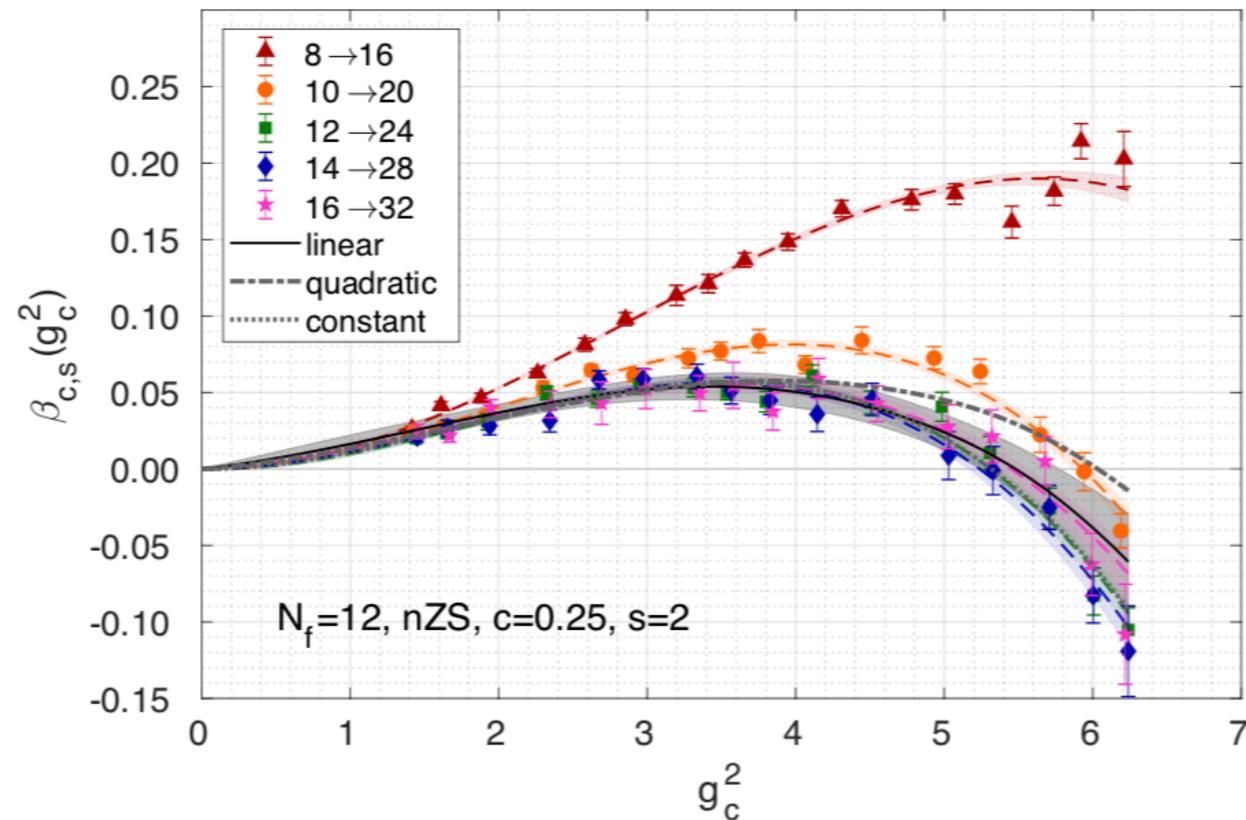
(LatHC collaboration, 1811.05024)

- Calculation of step-scaling function (discrete β-function of gauge coupling) can be used to determine location of conformal transition - here SU(3) vs. N_f

- Significant work is ongoing, discrepancies remain between results from different groups at the same value of N_f

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Operator anomalous dimensions with gradient flow

- Gradient flow cuts off high-momentum modes in a continuous way; acts like a smooth momentum cutoff

- Can be used as the basis for an RG blocking, allowing *continuous MCRG* on a single gauge ensemble!

- Two-point functions under flow —> operator anomalous dimensions. Pilot study for N_f=12 finds mass γ consistent with perturbative estimates and other lattice, <u>first result</u> for nucleon γ_N~0.05(5)

(excerpted from J. Kogut and K. G. Wilson, Phys. Rept. 12 (1974), 75-200)
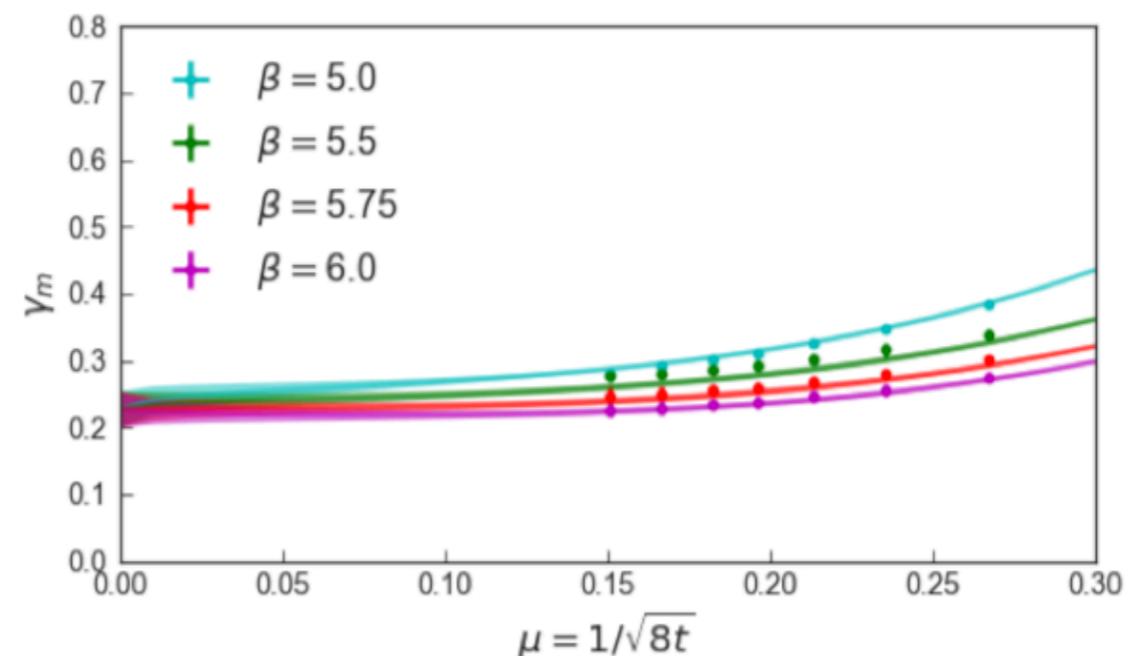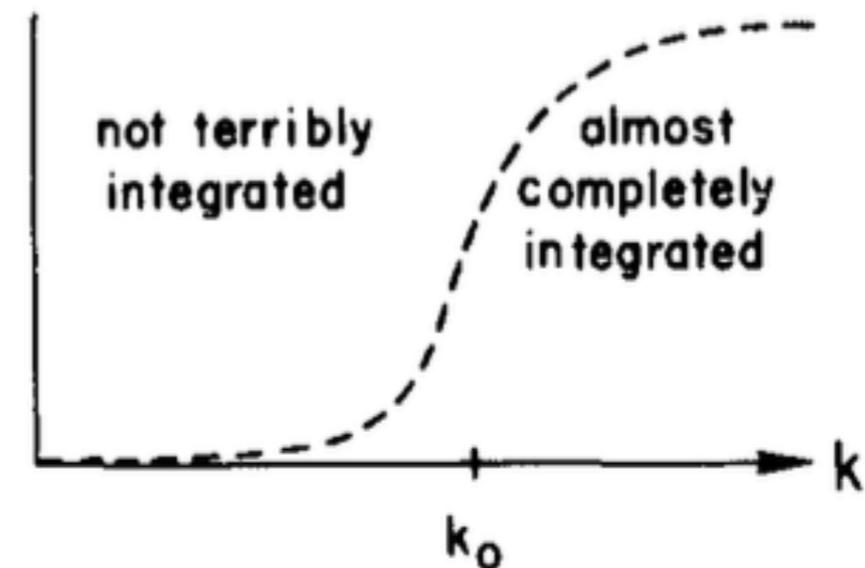
(Carosso, Hasenfratz, Neil,1806.01385)

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Fermion mass generation without symmetry breaking

(Butt and Catterall, preliminary)

- Study of an SU(2) gauge-fermion-Yukawa model on the lattice shows evidence for a phase in which fermions obtain mass through a *four-fermion condensate* - chiral symmetry is unbroken!

- More recent work in d=4 hints at a *continuous* transition from massless to massive phase in certain part of the phase diagram

- New mechanism for mass generation while preserving symmetry? Nature of UV fixed point in the vicinity of the continuous transition?

$L=8$

$\kappa=-0.05$
$\kappa=0.0$
$\kappa=0.05$

$\sigma_+^2 - 3/2$

$\kappa=0.05$

χ_{stag}

$L=6$
$L=8$
$L=12$

G
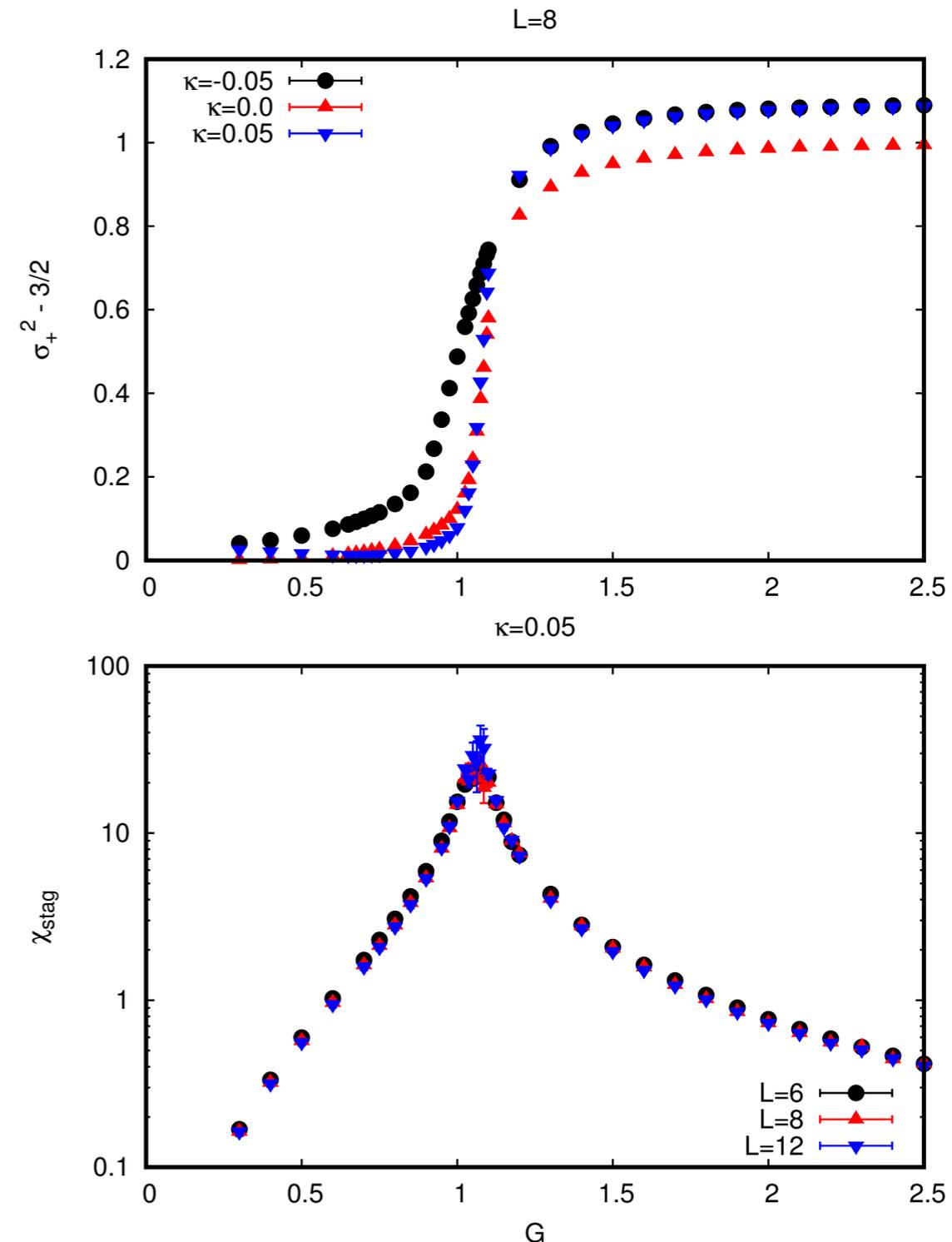
Large-N$_c$ thermodynamics

(USQCD class B proposal)   (DeGrand, Hackett, Neil, 1809.00073)
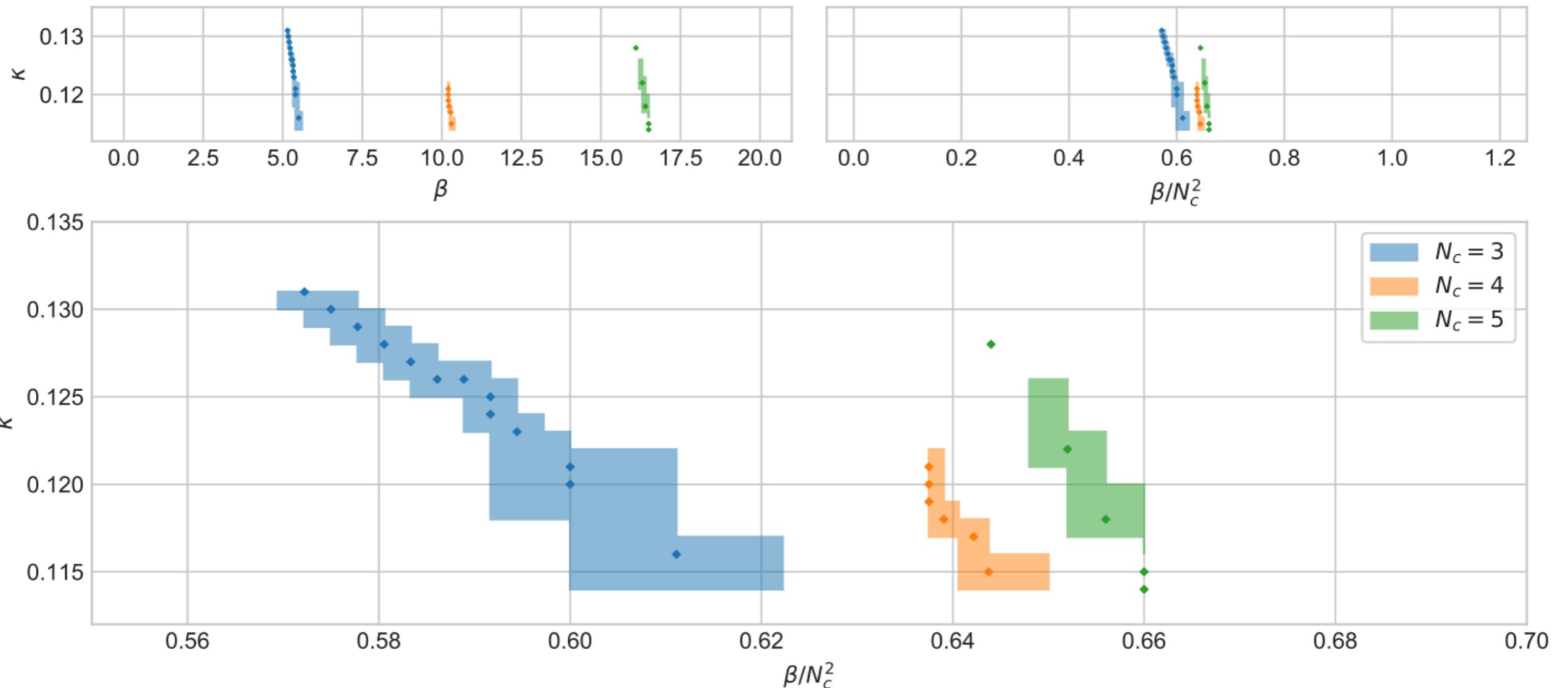
- First study of large-N thermodynamics with dynamical fermions. Large-N intuition: fermions don't matter, but in QCD we know light fermions are very important in qualitative features of confinement transition. Study with lattice!

- Brief summary: "collapse" indicates expected leading large-N scaling. Weak dependence on presence of dynamical fermions remains (zoom in on bottom panel), although fermions are relatively heavy in these studies.

2019 USQCD Proposals in BSM Physics, by PI

- **Catterall**: "Phases of a Higgs Yukawa Theory and Symmetric Mass Generation", 2.3M Sky-ch [strong QFT]

- **Kuti**: "Walking, the dilaton, the light σ-particle, and the sextet BSM model", 4.8M Sky-ch [composite Higgs]

- **Neil**: "Investigation of near-conformal anomalous dimensions using gradient-flow RG", 6.3M Sky-ch [strong QFT, composite Higgs]

- **Rebbi**: "Step-scaling beta function for 10 fundamental flavors", 4.2M Sky-ch [strong QFT]

- **Witzel**: "Composite Higgs model with four light and six heavy flavors", 8.7M Sky-ch [composite Higgs]

(BSM is 5% of the total resource request. Once again no dark matter focused efforts.)

LATTICE FOR BEYOND THE STANDARD MODEL PHYSICS 2019

MAY 2-3, 2019, SYRACUSE UNIVERSITY

http://www-hep.colorado.edu/~eneil/lbsm19/

- **Tenth** workshop in a series, connecting lattice BSM community to phenomenologists and other non-lattice theorists.

- Significant focus on connections between *lattice simulations and quantum computing* this time, as well as various BSM models.

Organizing Committee:

- Simon Catterall (Syracuse)
- Jay Hubisz (Syracuse)
- Jack Laiho (Syracuse)
- Ethan Neil (Colorado)
- Judah Unmuth-Yockey (Syracuse)
- Pavlos Vranas (LLNL)
- Scott Watson (Syracuse)