Prospects for lattice field theory beyond the standard model

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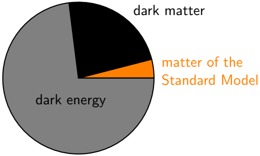
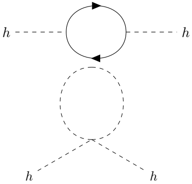
Shortcomings of the standard model

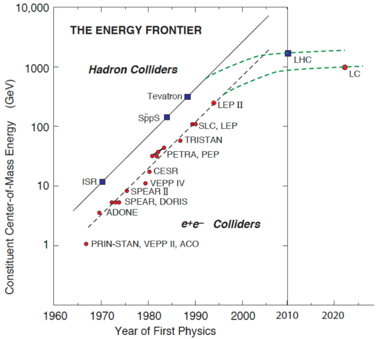
- missing pieces of the standard model
  - explanation for dark matter/dark energy
  - gravitational interactions
  - neutrino masses ...
- aesthetic imperfection of the standard model
  - parametrization or explanation
  - hierarchy problem
  - missing unification or symmetry
  - flavor hierarchy
- missing understanding
  - confinement mechanism
  - quantum gravity
  - gauge/gravity duality





$\sim \Lambda_{\mathrm{BSM}}^2$

What can be expected from colliders?



[J. Nash, talk at 2010 IOP meeting]

- speed is slowing down and will stop eventually
- but there might be an oasis just a few miles away
- . . . or it just means a free way to quantum gravity

Where is new physics hiding?

Our current BSM collider discoveries are constraints.

Directions for new observations:

- energy
- precision
- cosmology
- from on-shell to off-shell discoveries

Solution to SM problems without constraint violation:

- small coupling to the Standard Model
- large suppression of $\frac{1}{\Lambda_{BSM}}$
- large gap to new physics

Important contributions required from the lattice

- precision input for QCD contributions:
  - new routes towards detection
  - QCD-corrections to observed anomalies

  $\rightarrow$ not covered in this talk
- test of BSM strong interactions, goals at different levels
  - test specific models to add constraints – like an experiment
  - fundamental concepts behind the suggested models
  - theory space of strong interactions
    relevant for model building and our general understanding

  interplay with conceptual questions about strong interactions

BSM concept: Supersymmetry

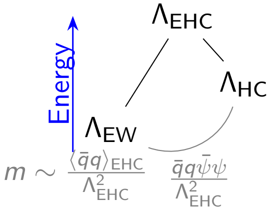
- original motivation for SUSY BSM: hierarchy problem
  solution by symmetry: boson-fermion cancellation
- needs unknown (non-perturbative) breaking mechanism
- heavily investigated regarding BSM and collider signatures (MSSM etc.)
- dark matter: standard WIMP scenario
- general concepts with may applications: gauge/gravity duality etc.

Shifted perspective of SUSY applications:

supersymmetric gauge theories $\leftrightarrow$ analytic predictions, dualities

BSM concept: Composite Higgs/ technicolor

- solve hierarchy problem by new strong interactions [S. Weinberg (1976)]
- naturally leads bound states as possible dark matter
- generate fermion masses from effective operators of extended hyper color theory
- constraints:
  - need bound state Higgs much lighter than other bound states
  - FCNC need to be suppressed
  - electroweak precision data



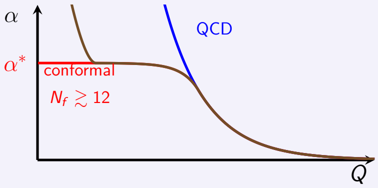
BSM concept: Composite Higgs/ technicolor scenarios

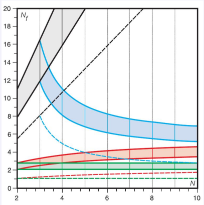
Walking scenario

$$\beta(g) = -\frac{1}{(4\pi)^2}\left(\frac{11N_c}{3} - \frac{4}{3}T_R N_f\right) g^2 - \beta_1 g^5 + \dots$$

- conformal window: $N_{f,L} < N_f < N_{f,U}$ [T. Banks, A. Zaks (1981)]
- near conformal running enhances condensate over FCNC

  $\langle \bar{q}q \rangle_{\mathrm{EHC}} \sim \left(\frac{\Lambda_{\mathrm{EHC}}}{\Lambda_{\mathrm{HC}}}\right)^{\gamma_m} \langle \bar{q}q \rangle_{\mathrm{HC}}$, γ_m large [T. Appelquist et al. (1987),Yamawaki et al. (1986)]
- light scalar, possibly dilaton-like





[Dietrich, Sannino (2007)]

BSM concept: Composite Higgs scenarios

Walking scenario

Higgs from scalar pNGb

- spontaneous symmetry breaking generates light Higgs
  [D. B. Kaplan, H. Georgi (1984)]
- requirements for chiral symmetry group,
  e. g. by $\mathrm{SU}(2N_f) \to \mathrm{Sp}(2N_f)$ (pseudoreal)
- HC chiral symmetry breaking preserves $G_{SM} = \mathrm{SU}(2)_L \times U(1)$
- scalar field generated at Λ_{HC} gets lower scale vev. v (EW breaking scale)

BSM concept: Composite Higgs scenarios

Walking scenario

Higgs from scalar pNGb

Partial compositeness [Kaplan (1991)]

- need to generated vastly different fermion masses
- large top mass generated by coupling with fermion bound state $\lambda \bar{\psi} B$
- UV theories classified according to symmetries [G. Ferretti, D. Karateev (2013)]
- 3 fermion operator (B) needs enhancement: combine with walking ? [V. Ayyar et al. (2018), A. Hasenfratz et al. (2023)]

Review: [T. DeGrand (2015), R. Contino (2009)]

BSM concept: Strongly interacting dark matter

bound state of strong interactions: glueball, meson, baryon, gluino-glue. . .

- dark matter needs to be stable, but can cover large mass range
- not visible by current direct detection
- astronomical observations limit self interaction, hints for small non-vanishing self interactions
- relic abundance, $\rho_{\text{DM}} = 5\rho_{\text{baryon}}$:
  - thermal freeze-out dark matter, e. g. WIMP and SIMP
  - SIMP: 3→2 process by Wess-Zumino-Witten term
    [Y. Hochberg et al. (2014)]
  - asymmetric dark matter
  - . . .
- first order transitions lead to gravitational wave signatures in early universe

Review: [G. D. Kribs, E. T. Neil (2016)]

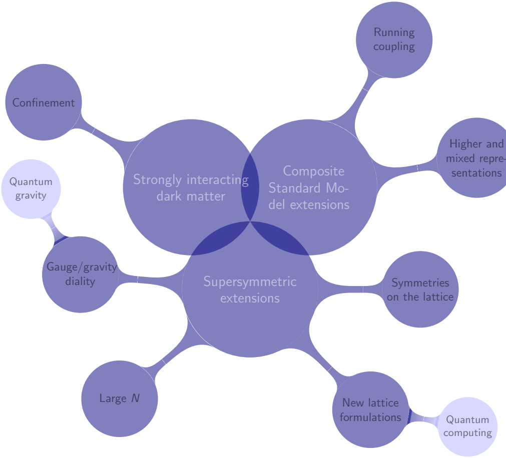
Other BSM concepts

Not covered in detail, though investigated on the lattice

- symmetric mass generation
  (see talk by David Tong (Wed), S. Catterall (Fri))
- scalar gauge theories
  (talk by G. Catumba (Fri) on 2HDM, poster by E. Carstensen)
- QCD Axions, closely related to QCD-vacuum structure
  (talk by J. J. Hernández (Mo), many related talks)
- Hosotani mechanism
- extra dimensions
- quantum gravity
- ...

Beyond model building: BSM to extend our understanding

- standard model extension introduce new concepts
- challenge our knowledge of strong interactions
- provide new analytic approaches due to symmetries/properties of BSM strong interactions



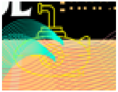
Topics considered in this talk

1. composite dark matter
   SU(4) (hyper) stealth dark matter
   SU(2), Sp(4) $N_f = 2$ as SIMP candidate
2. composite Higgs and walking/conformal behavior
   SU(2) $N_f = 2$
   Sp(4) $N_f = 2 + N_{f,AS} = 3$ antisymmetric: partial compositeness
   SU(3) $N_f = 8$ near conformal and SMG
   SU(2) $N_f = 1$ adjoint QCD
3. progress of supersymmetric theories
   supersymmetric gauge theories in 4d
   gauge-gravity duality in lower dimensions

Hiding dark matter from direct detection

Some basic considerations:

- stable dark matter bound state:
  $\Rightarrow$ baryonic bound state
- neutrality by confinement: larger interactions at higher energies in early universe
- avoid leading electromagnetic interactions:
  $\Rightarrow$ scalar baryons (even $N_c > 2$)
- meson decay, but no conflict with ew precision data:
  $\Rightarrow$ small Higgs coupling
- coupling to the standard model only by polarizability and Higgs boson exchange highly suppressed



Hidden, but still close to detection.

Stealth dark matter models

Stealth dark matter: SU(4), $N_f = 4$ [T. Appelquist et al. [LSD] (2015)]

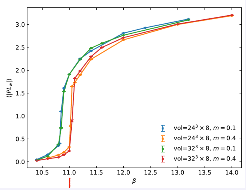
- direct detection limits: em polarizability [T. Appelquist et al. (2015)] and Higgs coupling [T. Appelquist et al. (2014)]
- $M_{DM} > 0.2$ TeV
- bound state masses [T. Appelquist et al. (2014)] and towards baryon scattering [R. C. Brower et al.2023]
- gravitational wave signatures from phase transition [R. C. Brower et al.2021]
- important difficult challenge: self interactions

Hyper stealth dark matter [V. Ayyar [LSD] arXiv:2402.07362]

- SU(4) $N_f = 1$ light (plus heavy flavors)
- no light pNGbs, less detection constraints
- light flavor with possible tiny electroweak coupling (η' decay)
- lowest possible mass in this framework: $M_{DM} \sim$ few GeV

Gravitational wave signals from first order transition

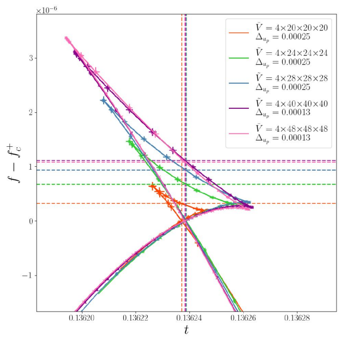
Phase transitions of hyper stealth dark matter [Talk by S. Park (Fri)]



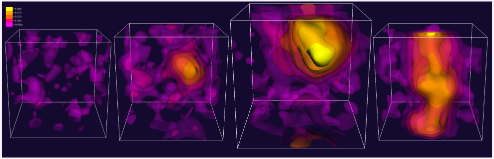
Domain-Wall fermions, signature of 1st order confinement trans.

Density of states in finite temperature Sp(4)

[Talk D. Mason (Wed)]



Resolving the critical bubble in Yang-Mills theory [poster R. Seppä, talk D. Weir (Mon)]



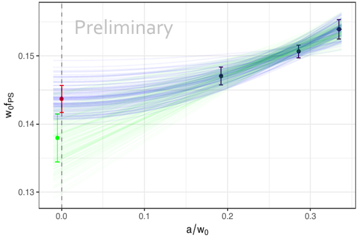
SU(2) gauge theory, dark matter and composite Higgs

SU(2) gauge theory with $N_f = 2$ fundamental flavors:

- dark matter with SIMP scenario
- composite Higgs theory: scalar pNGBs
- can be extended to walking technicolor by adding adjoint fermions [T. A. Ryttov, F. Sannino (2008)] [GB, S. Piemonte (2021)]
- lattice studies:
  - particle spectrum
  - scattering and self interactions
  - ...

Talk by L. S. Bowes and S. Martins (Fri):

- exp. clover Fermion action
- target smaller fermion masses for singlet meson decay: $m_\sigma < 2m_{ps}$



Summary: [R. Arthur et al. (2016)]

Sp(4) gauge theories as composite Higgs and dark matter

- $SU(2N_f) \to Sp(2N_f)$ chiral symmetry breaking for $Sp(2N_c)$ theory: scalar pNGbs
- $SU(2) = Sp(2)$, $N_f = 2$ simplest example with Wess-Zumino-Witten term (SIMP dark matter)
- $Sp(4)$, $N_f = 2$ next complicated choice
- $N_f = 2 + N_{f,AS} = 3$ allows for partial compositeness
- larger N_c might provide a larger parameter range for SIMP

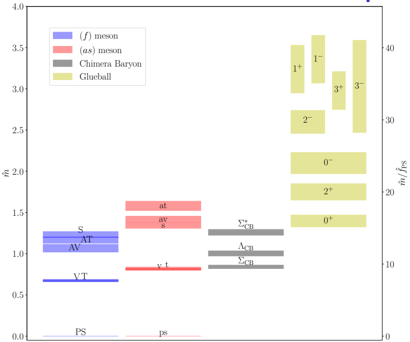
  [M. Hansen et al. (2016)]

Lattice investigations of Sp(4)

Recent investigations

- scan of theory space: quenched meson and glueball spectroscopy in the large N_c limit: Sp($2N_c$) for $N_c = 2, 3, 4$ [E. Bennett et al. (2023)]
- analysis of the top partner (chimera baryon)
- dynamical $N_f = 2 + N_{f,AS} = 3$ spectroscopy
- $N_f = 2$ dark matter self interaction (meson scattering) provides lower bound of dark pion mass: 100 MeV [Y. Dengler et al. (2024)]
- important missing information for partial compositeness: anomalous dimension of chimera baryon (see SU(4) partial compositeness model [V. Ayyar et al. (2018), A. Hasenfratz et al. (2023)])

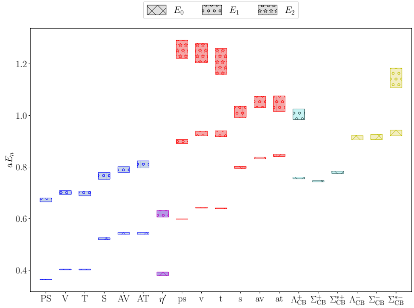
Particle spectrum of Sp(4)



[E. Bennett et al. Phys.Rev.D 109 (2024)]

massless continuum limit from quenched simulations

gradient flow units



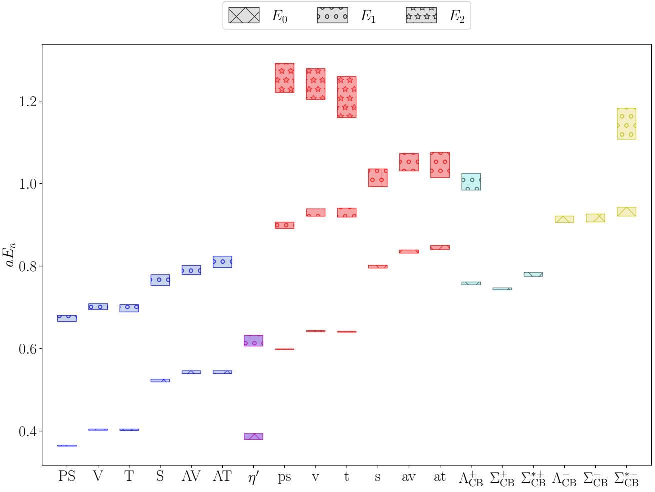
[E. Bennett et al. (2024)]

single ensemble, in lattice units

Spectroscopy using spectral densities (see Talk by H. Hsiao Fri)

Further results: flavor singlet mesons (Talk by F. Zierler, Tue)

Particle spectrum of Sp(4)



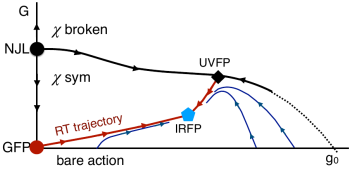
Considerations of walking scenario and conformal window

- landscape of gauge theories with gauge group G, N_f fermions possible in multiple representations
- conjectured IR behavior has to be confirmed with lattice data
- methods:
  - scaling of particle spectrum
  - Schrödinger functional
  - gradient flow
  - mode number
  - ...
- conformal: scaling of masses $M_H \sim m^{1/\gamma_m}$
- requires also control of phase transition, topology, etc.
- recent new methods: gradient flow [A.Carosso et al. (2018),C. T. Peterson et al. (2021)], Pauli-Villars fields

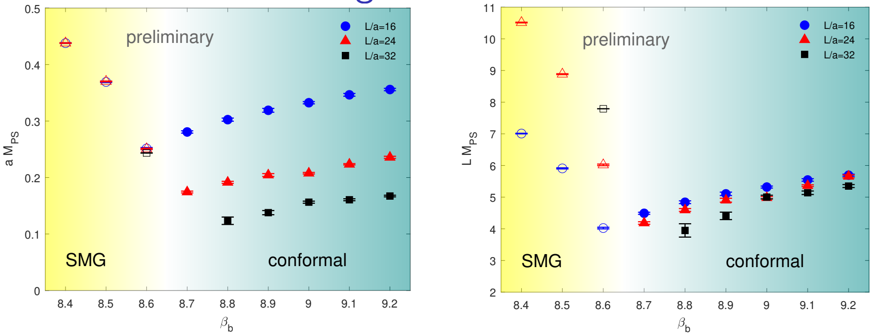
SU(3) with $N_f = 8$ possible edge of conformal window

Indications for a rich phase space with staggered fermions [A. Hasenfratz PRD 106 (2022)]

- no clear signal from running coupling, but observation of two phases, separated by continuous phase transition
- weak coupling phase: looks conformal
- strong coupling: SMG chiral symmetric, confining
- Pauli-Villars fields to avoid bulk transitions



SU(3) with $N_f = 8$ walking theory and symmetric mass generation



- SMG phase: mass gap independent of volume
- conformal phase: mass scaling given by the volume
- more details need to be explored

see talks by A. Hasenfratz, O. Witzel

Conformal window for fermions in the adjoint representation

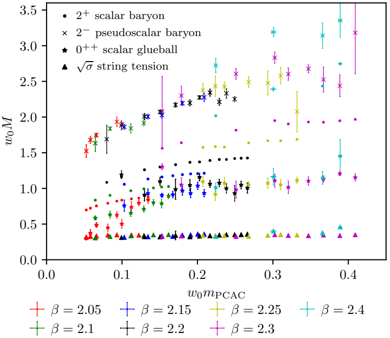
- hard to determine conformal window: limited range of scales on the lattice, mass deformations
- SU(3) N_f fundamental: large number of investigations
- motivation for considering adjoint rep.: lower $N_{f,L}$ might be better for pheno.
- adjoint representation: $N_f = 2$ investigated as MWT seems to be inside conformal window [S. Catterall, F. Sannino (2007), L. Del Debbio et al. (2010)...] like also $N_f = 3/2$ [GB et al. (2018)]

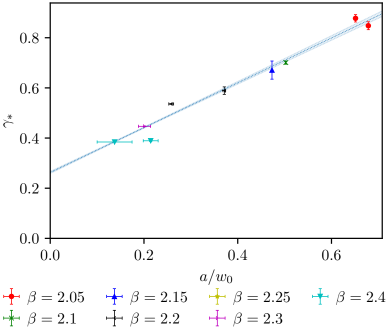
$N_f = 1$ very challenging, new data [A. Athenodorou et el. (2024)]:

- large volumes with Wilson fermions
- large coupling range
- smallest possible masses

Review: [GB et al. (2022)]

$N_f = 1$ adjoint QCD





- conformal-like: light scalar
- neither agreement with conformal scaling, nor with chiral perturbation theory
- γ^* from mode number shows β dependence

poster by E. Bennett: improved strategies for further investigations

Tensions and systematics

EFT powerful framework, how to extend to walking case?

- recent new investigations of relations between different approaches [M. Golterman, Y. Shamir (2024)]
- dilaton EFT and soft theorems: R. Zwicky (Tue)

Other general questions:

- How to think about lattice artefacts and scaling corrections?
- What kind of additional fixed points might be induced?
- Why is there such a light scalar in the theories with adjoint fermions?
- How large can anomalous dimensions be in practice?

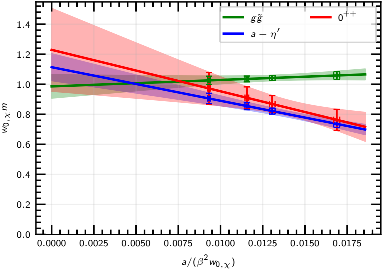
Supersymmetry on the lattice

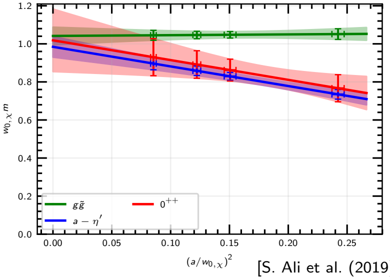
Supersymmetry on the lattice can only be fine-tuned or accidental

- short explanation: $\left\{Q\,,\,\bar{Q}\right\} \sim \gamma^\mu P_\mu$, but space-time symmetries are broken
- long explanation: conflict between locality and symmetry (like chiral symmetry), but no Ginsparg-Wilson solution
- accidental:
  $\mathcal{N}=1$ supersymmetric Yang-Mills theory:
  chiral symmetry $\leftrightarrow$ SUSY
  $\mathcal{N}=4$ supersymmetric Yang-Mills theory:
  subset of SUSY $\leftrightarrow$ full SUSY
- lower dimensional theories allow alternative solutions

Review: [GB,S. Catterall et al. (2016), D. Schaich (2018)]

Supersymmetric gauge theories in four dimensions





[S. Ali et al. (2019)]

- $\mathcal{N}=1$ supersymmetric Yang-Mills theory: SUSY recovered on the lattice
- non-perturbative properties like phase transitions and condensate determined on the lattice
- towards SQCD (tuning of $O(10)$ counterterms): talk by H. Herodotou (Tue)

New twists to $\mathcal{N} = 1$ supersymmetric Yang-Mills theory

Gluino condensate in SYM:

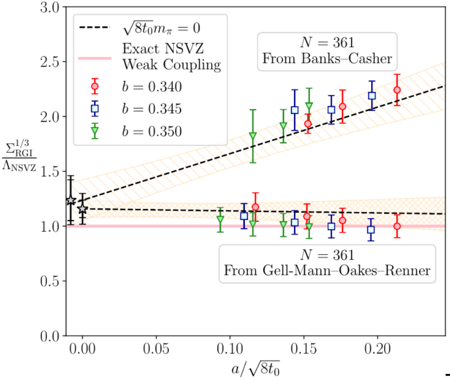
$$\Sigma = \begin{cases} 2e\Lambda^3/N & \text{strong coupling [G. C. Rossi, G. Veneziano (1984)]} \\ \Lambda^3 & \text{weak coupling [V. A. Novikov et al. (1984)]} \\ N\Lambda^3 & \text{twisted bc [M. Anber, E. Poppitz (2023)]} \end{cases}$$

- analytically calculable, but three different results are obtained
- previous studies of the condensate: Domain-Wall fermions: [J. Giedt et al. (2009)]; overlap and gradient flow [GB et al.(2019)][S. Piemonte, GB (2020)]

$\mathcal{N} = 1$ SYM on the lattice: the chiral condensate

- new simulations based on twisted twisted Eguchi-Kawai: lattice formulation of large N SYM with Wilson fermions

[A. Gonzalez-Arroyo, M. Okawa (2013)]



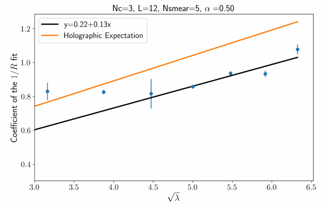
Methods:
1) mode number from lowest eigenmodes of Wilson-Dirac
2) GMOR relation

N_c dependence as predicted by weak coupling result [C. Bonanno et al. (2024)]

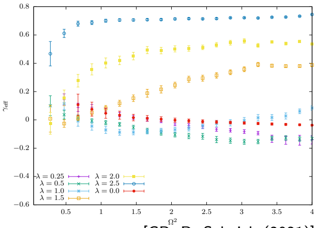
Talk by C. Bonanno (Mon)

$\mathcal{N} = 4$ supersymmetric Yang-Mills theory

- combining the space-time and R symmetries to preserve one SUSY on the lattice, recover 15 SUSY in continuum limit
- main obstacle has been overcome: simulations have reached larger couplings [S. Catterall et al. (2023)]
- promising first data indicates correctness of the method, waiting for coming investigations
- interesting: RG flow with conformal theory



[S. Catterall et al. (2023)]

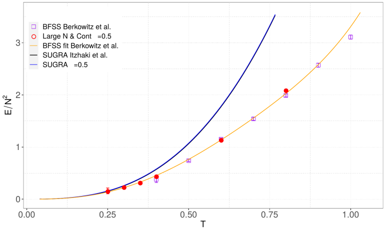


[GB, D. Schaich (2021)]

Review: [S. Catterall et al. (2016), D. Schaich (2018)]

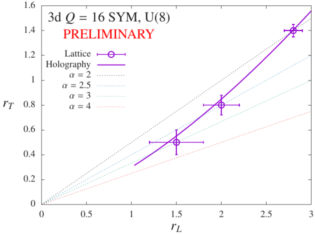
Supersymmetry and gauge/gravity duality

- towards quantum gravity on the lattice
- evidence for gauge/gravity duality conjectures
- extend beyond large N_c strong coupling limit



[S. Pateloudis et al. [MCSMC] (2023)]

Poster by D. Schaich:
Maximal SUSY in 3d



$r_L^2 \times r_T$ torus, critical T_c

Conclusions

- long standing problem, how to fix the standard model might still require new solutions
- like collider experiment: quite mature developments for BSM strong interactions can be further constrained by lattice simulations
- after years of investigations: still surprised and puzzles in the landscape of strongly interacting theories
- BSM leads to new perspectives on strong interactions
- interesting interplay to theoretical developments like gauge/gravity duality

Thanks for all the contributions, discussions, and input material. Unfortunately not all could be covered in this talk.