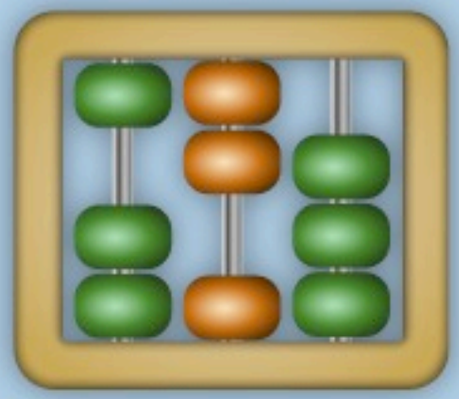


Beyond the Standard Model

USQCD - on the lattice

LQCD-ext 2011

USQCD BSM

Julius Kuti

University of California, San Diego

DOE panel review LQCD 2011

Outline

- Composite Higgs Mechanism at LHC
USQCD BSM goals

- Results of last 12 months from USQCD BSM effort
with plans for next year, including SUSY

- USQCD BSM and GPU computing

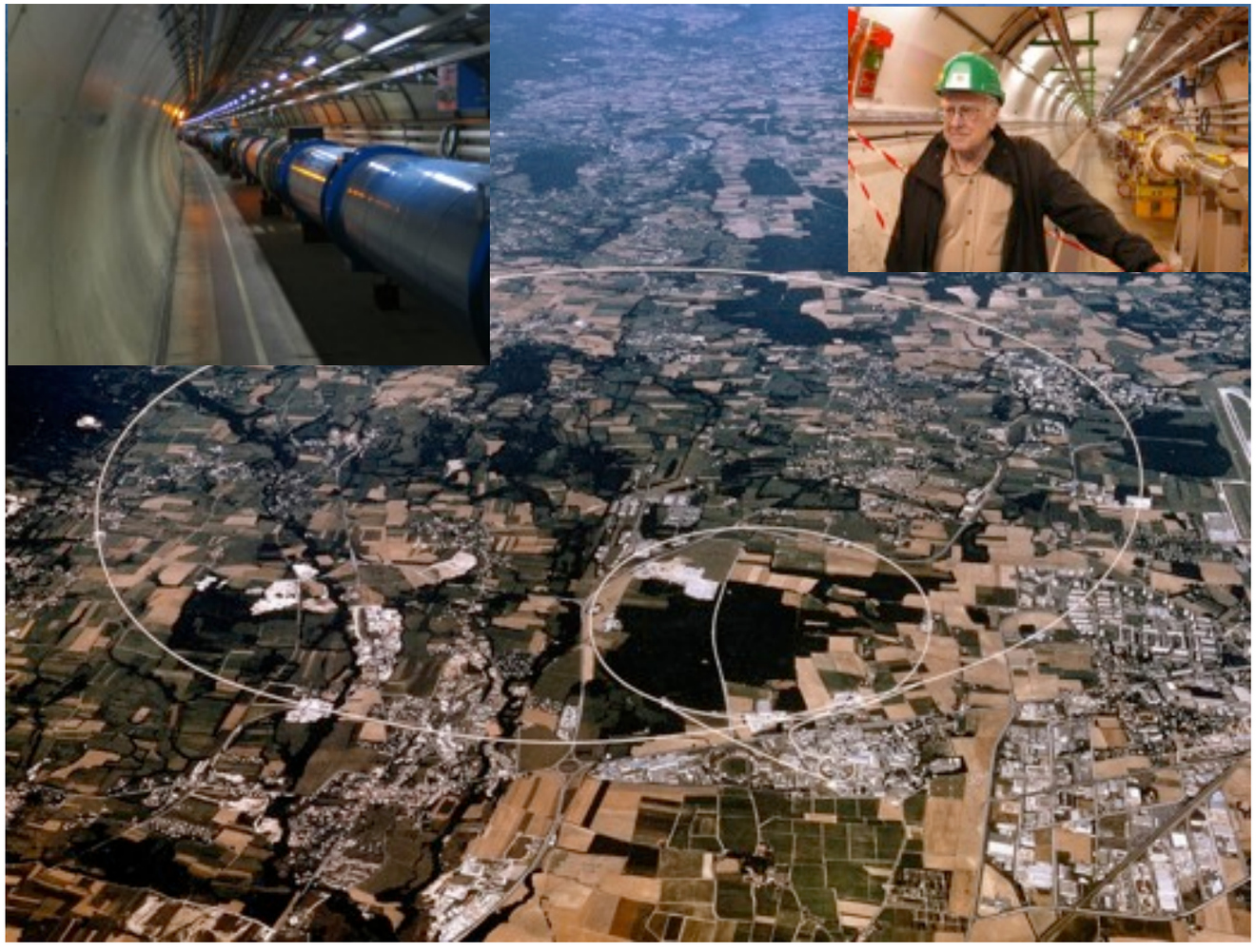
Large Hadron Collider - CERN

primary mission:

- Search for Higgs particle

- Origin of Electroweak symmetry breaking

- Is there a Standard Model Higgs particle?
- If not, what generates the masses of the weak bosons and fermions?
- New strong dynamics?
- Composite Higgs mechanism?



Primary focus of USQCD BSM effort and this report

SUSY projects are also progressing well with new simulations planned for next year

The New York Times

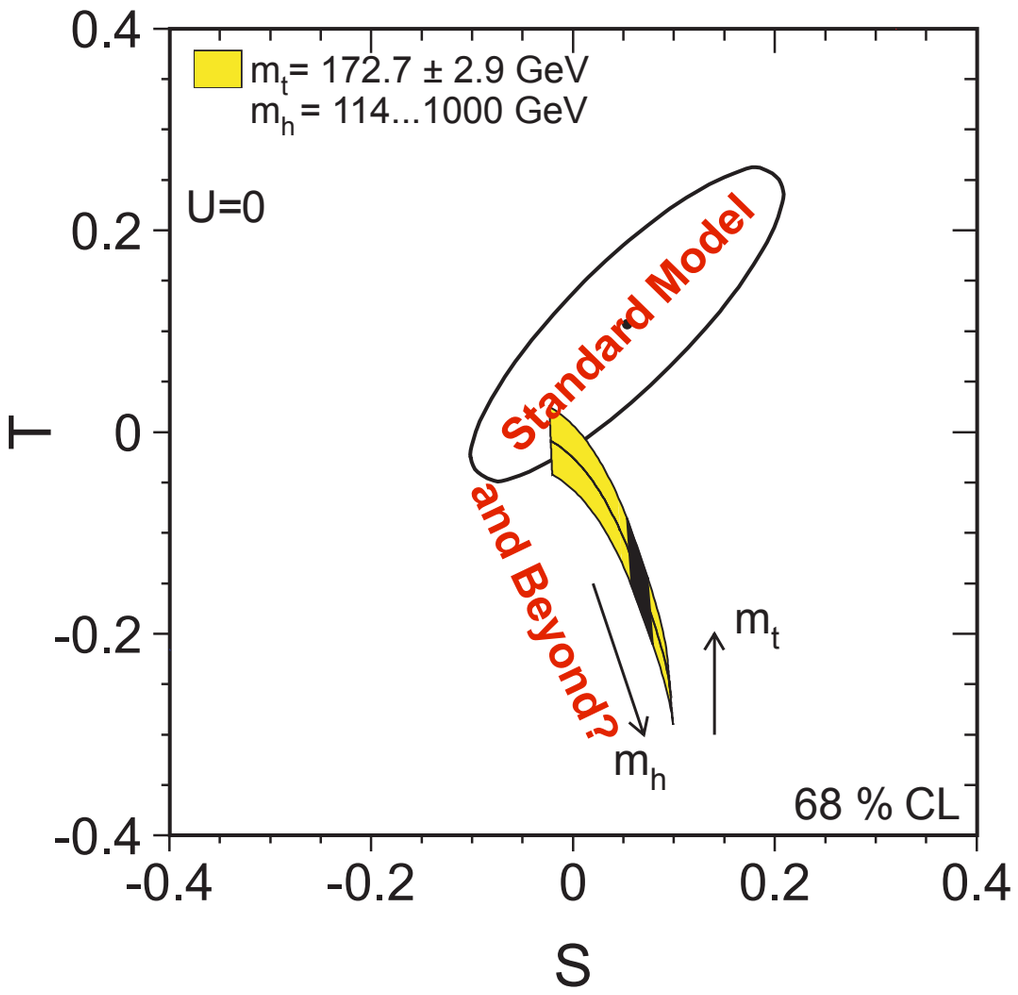
missed date by 3 days?

Friday, April 1, 2011 Last Update: 11:17 AM ET

Physicists at CERN in Geneva find the Higgs particle with unexpected characteristics

By Jane Ellis

The properties of the newly found Higgs particle shook the foundations of modern particle physics. Although its decay properties are very similar to what was expected, the mass at 507 GeV is far too heavy and the width far too narrow to accommodate what is know to be the Standard Model of modern particle physics. Physicists are turning now to lattice gauge theorists who are trying to explain with a new composite Higgs mechanism the experiments at the Large Hadron Collider. *Continued on page 11 ...*



We live in new era where BSM news will actually start coming

with Caveat Emptor:

Invariant Mass Distribution of Jet Pairs Produced in Association with a W boson in pp Collisions at 1.96 TeV
CDF Collaboration (T. Aaltonen (Helsinki Inst. of Phys.) *et al.*). FERMILAB-PUB-11-164-E. Apr 4, 2011. 8 pp.
Published in **Submitted to: Phys.Rev.Lett.**
e-Print: **arXiv:1104.0699 [hep-ex]**

Technicolor at the Tevatron.
Estia J. Eichten, Kenneth Lane, Adam Martin. FERMILAB-PUB-11-165-T. Apr 2011. 5 pp.
e-Print: **arXiv:1104.0976 [hep-ph]**

Composite Higgs mechanism - Technicolor 2.0

- The paradigm is important again

- Requires non-perturbative lattice studies

- Major BSM effort of USQCD with LQCD-ext hardware support

Primary goal of USQCD BSM effort is to find in Gauge Theory Space some viable composite Higgs mechanism which is built on the Technicolor/Extended Technicolor paradigm focus of activities during the last 12 months

USQCD BSM group also develops non-perturbative methods to investigate SUSY models

Search for successful model(s) will require:

(1) Chiral symmetry breaking in massless fermion limit

(2) Higgs mechanism when EW gauge group is gauged

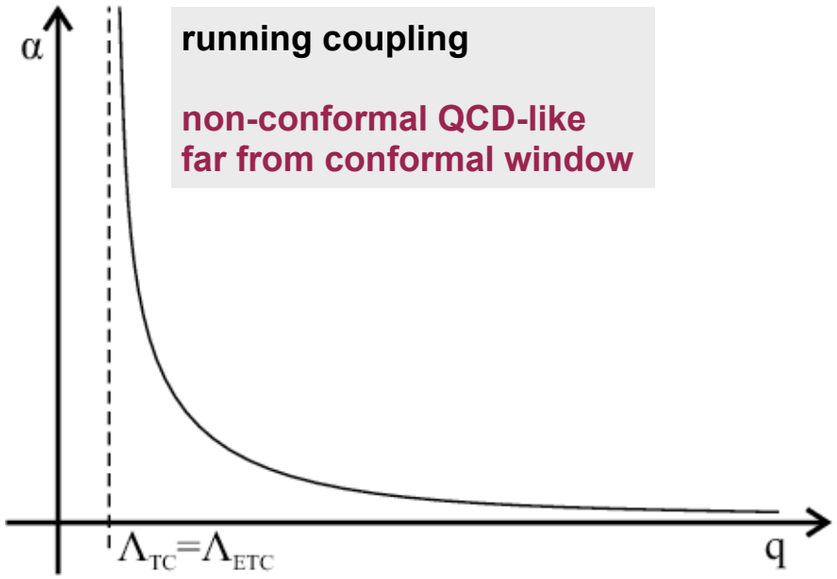
(3) model should be close to conformal window (EW precision constraints)

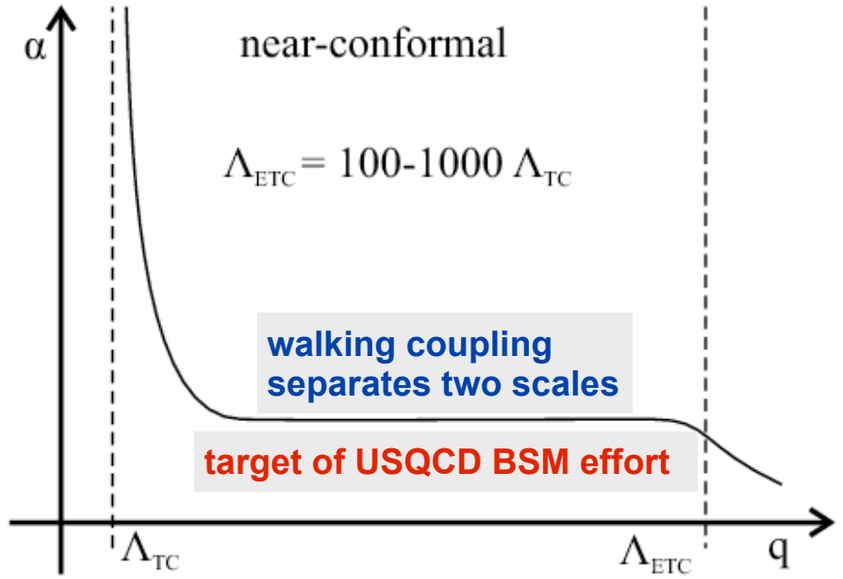
(4) walking gauge coupling to separate Technicolor scale of composite Higgs mechanism from "Extended Technicolor scale"
(ETC paradigm: origin of fermion mass generation target of future studies)

USQCD BSM has capability computing needs mostly on CPU clusters and on leadership class machines (BSM INCITE project just started)

BSM capacity computing is shifting to GPU technology (marked on application slides)

Composite Higgs mechanism? - Technicolor and Extended Technicolor



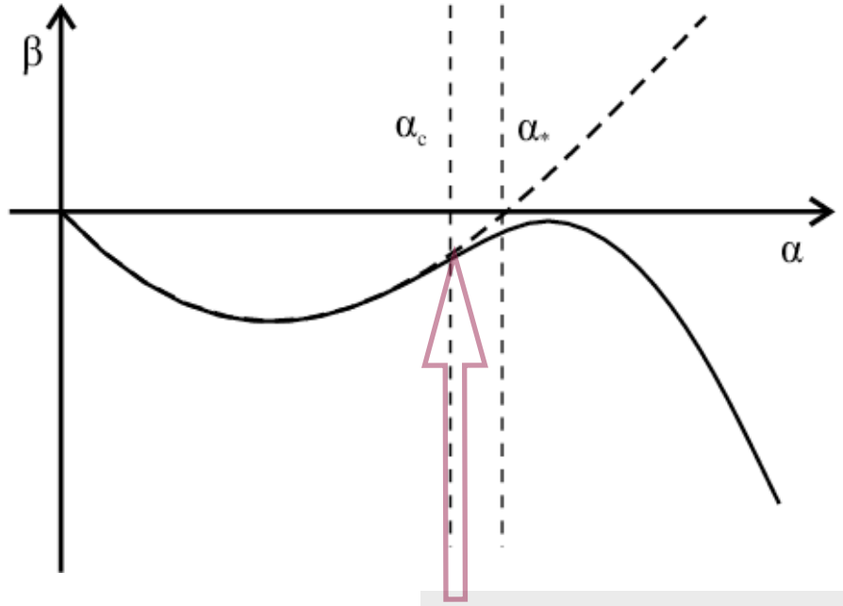


Extended Technicolor paradigm:

- requires walking gauge coupling chiral SB on $\Lambda_{TC} \sim TeV$ scale
- fermion mass generation from scale at $\Lambda_{ETC} \sim 100 - 1000\,\Lambda_{TC}$
- can solve problem of flavor changing currents
- composite Higgs mechanism
- broken Dilaton ➔ unusual composite Higgs particle in BSM ?
- can avoid conflict with EW precision constraints
- *candidate models require non-perturbative lattice studies*

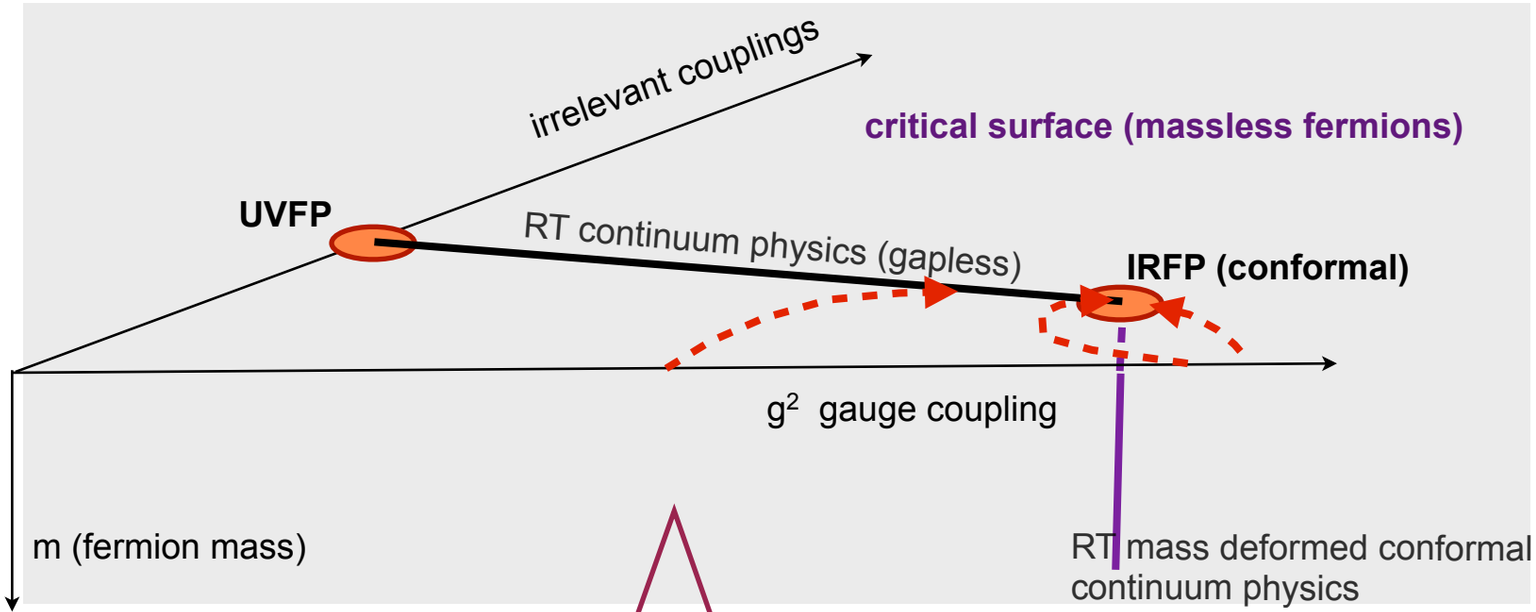
original textbook Technicolor paradigm:

- one massless fermion doublet $\begin{bmatrix} u \\ d \end{bmatrix}$ chiral SB
- three Goldstone pions
- become longitudinal components of weak bosons
- composite Higgs mechanism scale of Higgs condensate ~ F=250 GeV $\Lambda_{TC} \sim TeV$
- flavor changing currents and fermion mass generation would be problems
- conflicts with EW precision constraints

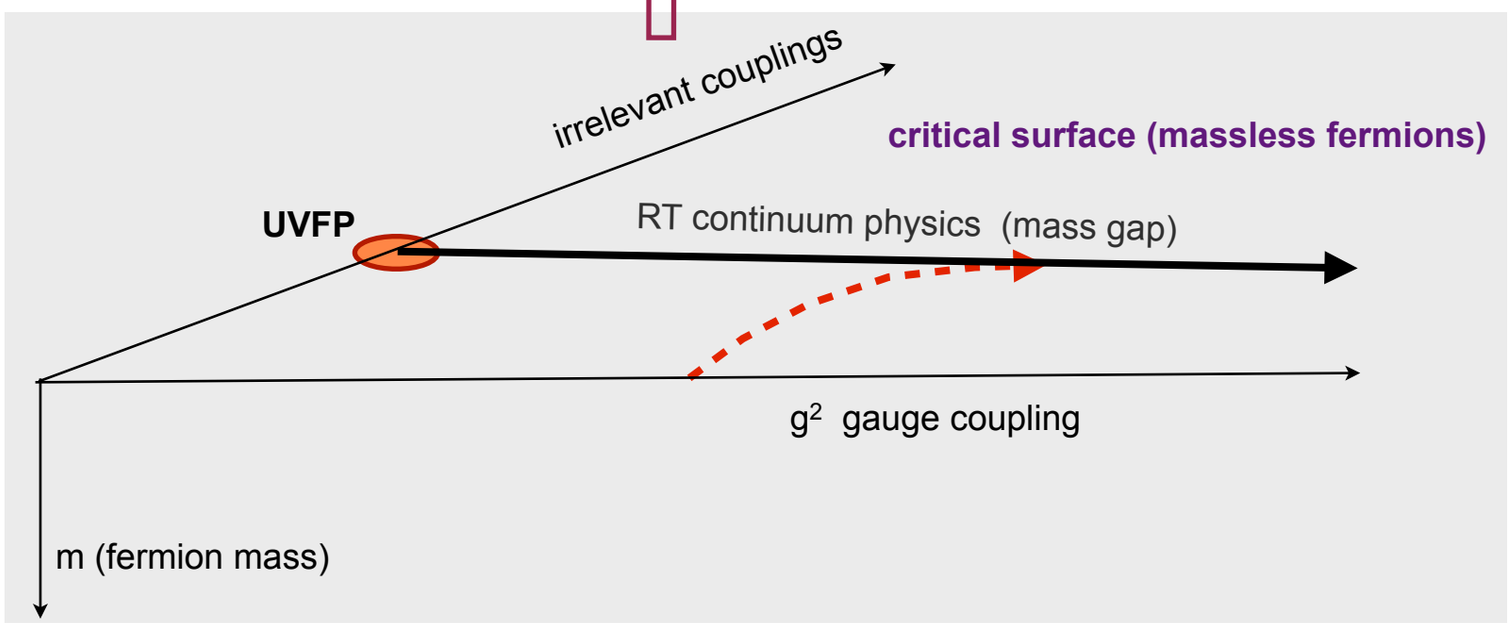


Chiral symmetry breaking turns conformal FP into walking

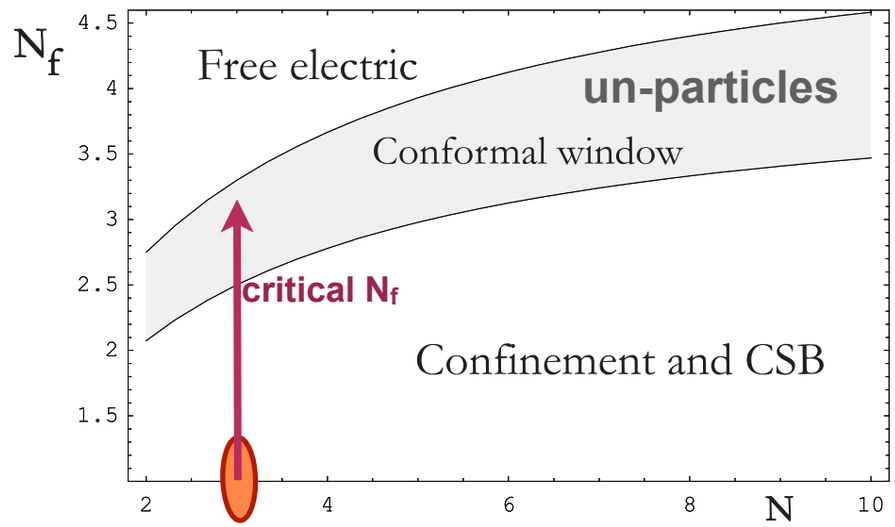
Why non-perturbative lattice? - Phases of BSM gauge theories and the running coupling:



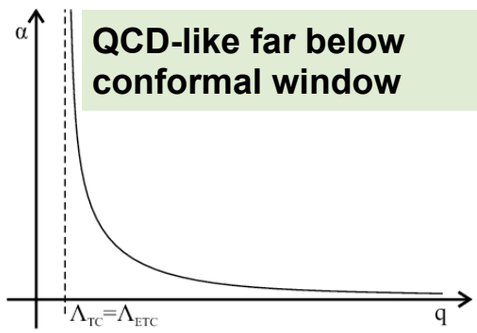
critical N_f



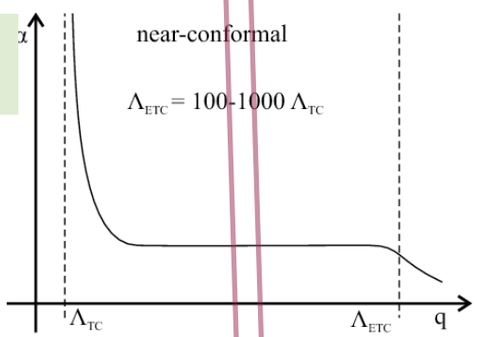
inside the conformal window:

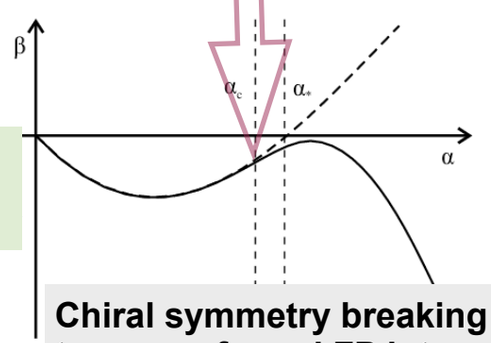


with increasing N_f walking scenario expected to arise:



QCD-like far below conformal window





walking coupling has several implications

Chiral symmetry breaking turns conformal FP into walking

USQCD BSM project sites using LQCD-ext hardware & software support

(three years ago map was empty)

Review of results from last 12 months and plans for next 12 months →

several BSM groups study the composite Higgs mechanism
TC scale - but stretched to ETC scale by walking coupling

fermion mass generation has to be built on it - some new theory on ETC scale

Twelve massless flavors and three colors below the conformal window.
Zoltan Fodor, Kieran Holland, Julius Kuti, Daniel Nogradi, Chris Schroeder. Apr 2011. 9 pp.
e-Print: **arXiv:1104.3124 [hep-lat]**

Chiral symmetry breaking in fundamental and sextet fermion representations of SU(3) color.
Zoltan Fodor, Kieran Holland, Julius Kuti, Daniel Nogradi, Chris Schroeder. Mar 2011. 14 pp.
e-Print: **arXiv:1103.5998 [hep-lat]**

Nearly conformal gauge theories on the lattice.
Zoltan Fodor (Wuppertal U. & Eotvos U.), Kieran Holland (U. Pacific, Stockton), Julius Kuti (UC, San Diego), Daniel Nogradi (Eotvos U.), Chris Schroeder (Wuppertal U.). 2010. 13 pp.
Published in **Int.J.Mod.Phys. A25 (2010) 5162-5174**

Parity Doubling and the S Parameter Below the Conformal Window.
LSD Collaboration (Thomas Appelquist , Ron Babich, Richard C. Brower, Michael Cheng, Michael A. Clark, Saul D. Cohen, George T. Fleming, Joe Kiskis, Meifeng Lin, Ethan T. Neil, James C. Osborn, Claudio Rebbi, David Schaich, Pavlos Vranas) **Submitted to: Phys.Rev.Lett.** e-Print: **arXiv:1009.5967 [hep-ph]**

Conformal or Walking? Monte Carlo renormalization group studies of SU(3) gauge models with fundamental fermions.
Anna Hasenfratz (Colorado U.). Apr 2010. 26 pp.
Published in **Phys.Rev. D82 (2010) 014506**
e-Print: **arXiv:1004.1004 [hep-lat]**

Center symmetry restoration with 2 flavor large N Yang-Mills in the adjoint representation.
Richard Galvez, Simon Catterall (Syracuse U.). 2010. 5 pp.
Published in **PoS LATTICE2010 (2010) 050**

MCRG Minimal Walking Technicolor.
Simon Catterall (Syracuse U.), Luigi Del Debbio (Edinburgh U.), Joel Giedt (Rensselaer Poly.), Liam Keegan (Edinburgh U.). Oct 2010. 7 pp.
Published in **PoS LATTICE2010 (2010) 057**
Talk given at SPIRES Conference C10/06/14.10 (Conference information coming soon)
e-Print: **arXiv:1010.5909 [hep-ph]**

Realization of Center Symmetry in Two Adjoint Flavor Large-N Yang-Mills.
Simon Catterall, Richard Galvez (Syracuse U.), Mithat Unsal (SLAC & Stanford U., Phys. Dept.). SLAC-PUB-14161. Jun 2010. 15 pp.
Published in **JHEP 1008 (2010) 010**
e-Print: **arXiv:1006.2469 [hep-lat]**

Supercurrent conservation in the lattice Wess-Zumino model with Ginsparg-Wilson fermions.
Chen Chen, Joel Giedt, Joseph Paki. Apr 2011. 19 pp.
e-Print: **arXiv:1104.1126 [hep-lat]**

Lattice Wess-Zumino model simulation with GPUs.
Joel Giedt, Chen Chen, Eric Dzienkowski (Rensselaer Poly.). 2010. 7 pp.
Published in **PoS LATTICE2010 (2010) 052**

Lattice Wess-Zumino model with Ginsparg-Wilson fermions: One-loop results and GPU benchmarks.
Chen Chen, Eric Dzienkowski, Joel Giedt (Rensselaer Poly.). May 2010. 32 pp.
Published in **Phys.Rev. D82 (2010) 085001**
e-Print: **arXiv:1005.3276 [hep-lat]**

Infrared fixed point in SU(2) gauge theory with adjoint fermions.
Thomas DeGrand (Colorado U.), Yigal Shamir, Benjamin Svetitsky (Tel Aviv U.). Feb 2011. 17 pp.
e-Print: **arXiv:1102.2843 [hep-lat]**

Sextet QCD: slow running and the mass anomalous dimension.
Benjamin Svetitsky, Yigal Shamir (Tel Aviv U.), Thomas DeGrand (Colorado U.). Oct 2010. 7 pp.
Published in **PoS LATTICE2010 (2010) 072**
Presented at SPIRES Conference C10/06/14.10 (Conference information coming soon)
e-Print: **arXiv:1010.3396 [hep-lat]**

Running coupling and mass anomalous dimension of SU(3) gauge theory with two flavors of symmetric-representation fermions.
Thomas DeGrand (Colorado U.), Yigal Shamir, Benjamin Svetitsky (Tel Aviv U.). Jun 2010. 16 pp.
Published in **Phys.Rev. D82 (2010) 054503**
e-Print: **arXiv:1006.0707 [hep-lat]**

Evidence for a First Order, Finite Temperature Phase Transition in 8 Flavor QCD.
Xiao-Yong Jin, Robert D. Mawhinney (Columbia U.). Nov 2010. 7 pp.
Published in **PoS LATTICE2010 (2010) 055**
Talk given at SPIRES Conference C10/06/14.10 (Conference information coming soon)
e-Print: **arXiv:1011.1511 [hep-lat]**

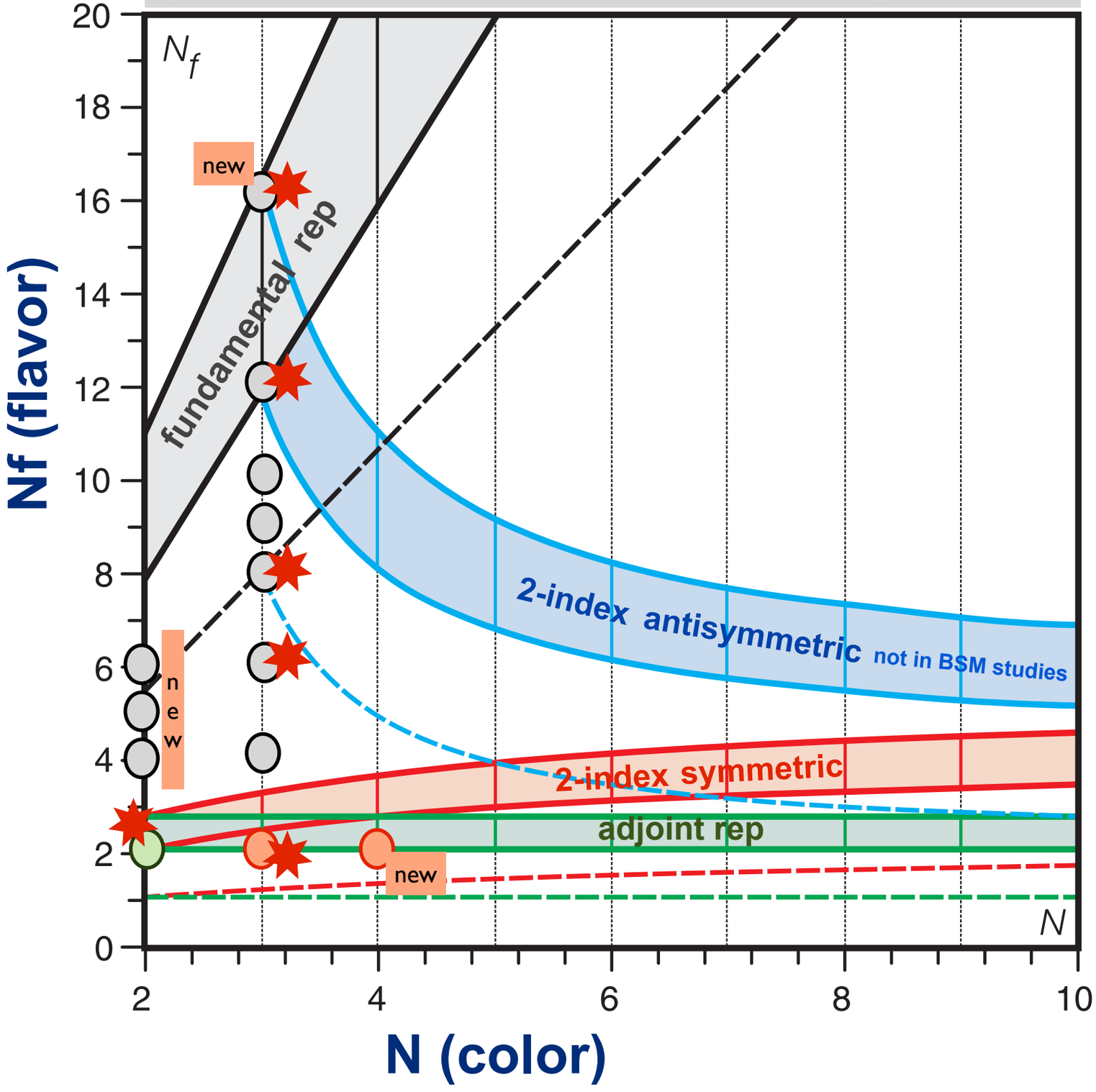
15 new USQCD BSM publications in last twelve month

over 500 citations since 2008
several papers in ~ 50-100 citation range

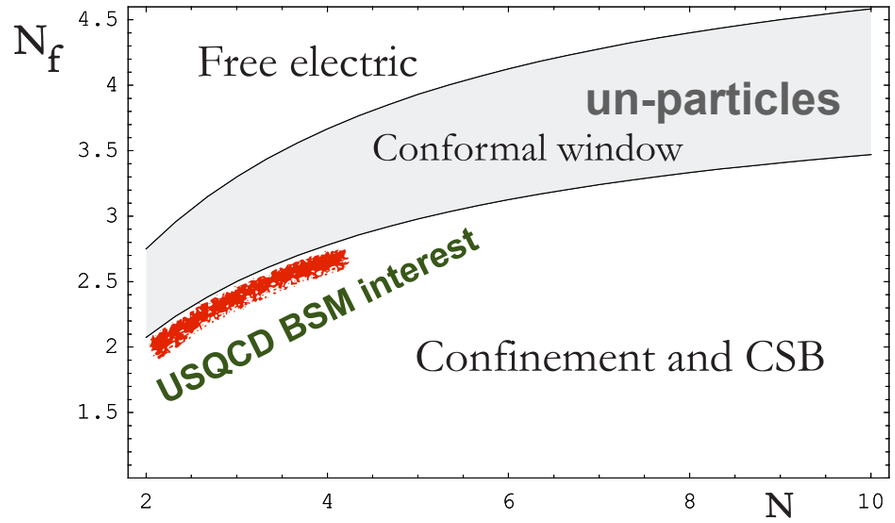
USQCD BSM is competing well world-wide in this field

USQCD BSM theory space and conformal window critically important for TC/ETC

space of color, flavor, and massless fermion representation



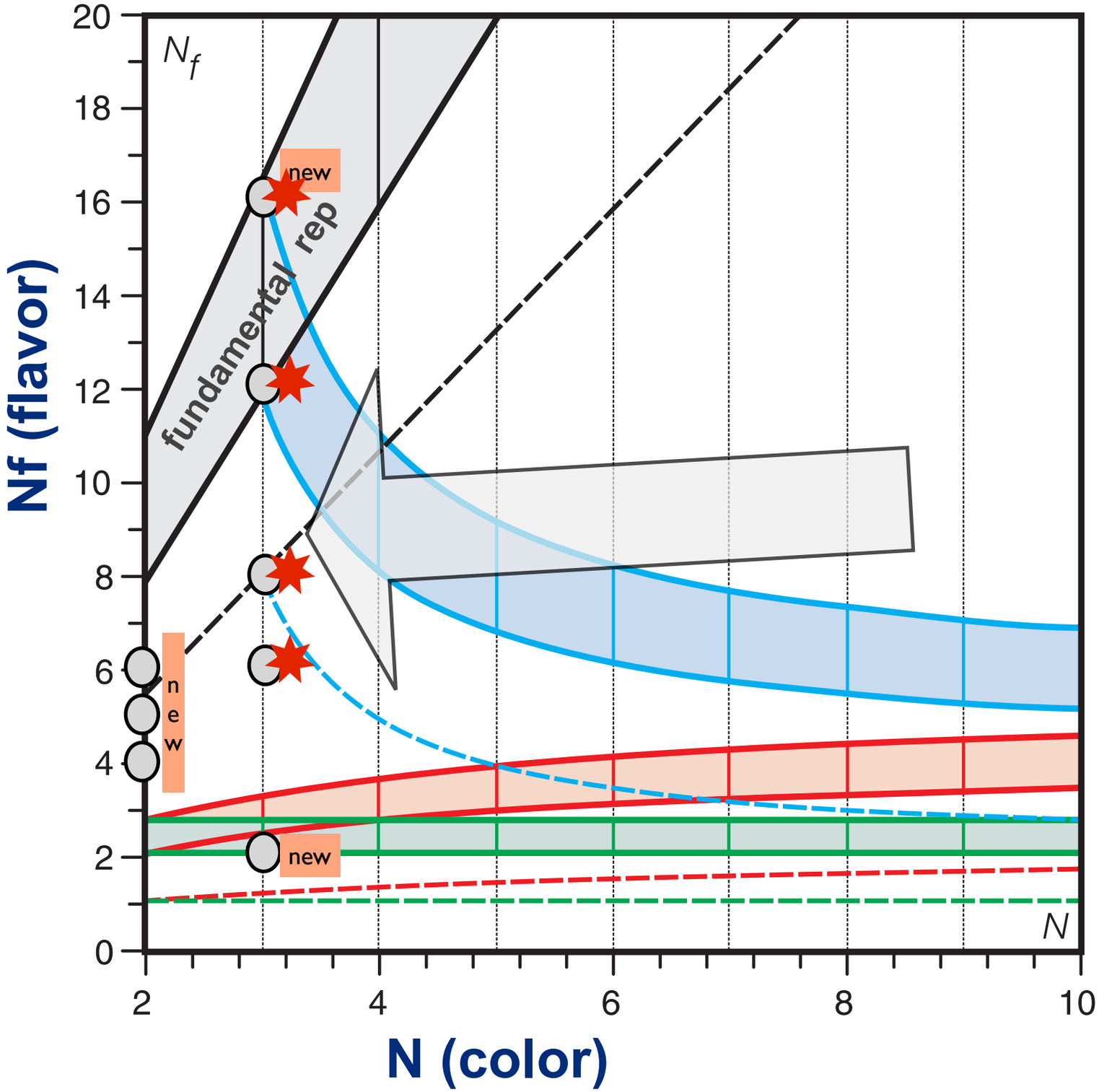
for each rep BSM interest is below conformal window but close to it:



USQCD BSM results of last 2 years in 3 reps including new projects just starting

USQCD BSM results of last 12 months in 3 reps here reported

Fundamental rep (conformal window?) Nf=6,8,12,16



results with SU(3) technicolor gauge group

USQCD BSM results reported from four groups:

- **Lattice Strong Dynamics LSD collaboration**
- **Lattice Higgs Collaboration LHC**
- **Columbia U group Jin and Mawhinney**
- **U Colorado, Boulder A. Hasenfratz**

Plans for next year:

LSD
- **SU(3) TC with *Nf=2,6* continued**
- **SU(2) TC to locate edge of conformal window *Nf=4,5,6***

LHC
- **SU(3) TC with *Nf=12* continued**
- **SU(3) TC *Nf=16* inside CW, new**

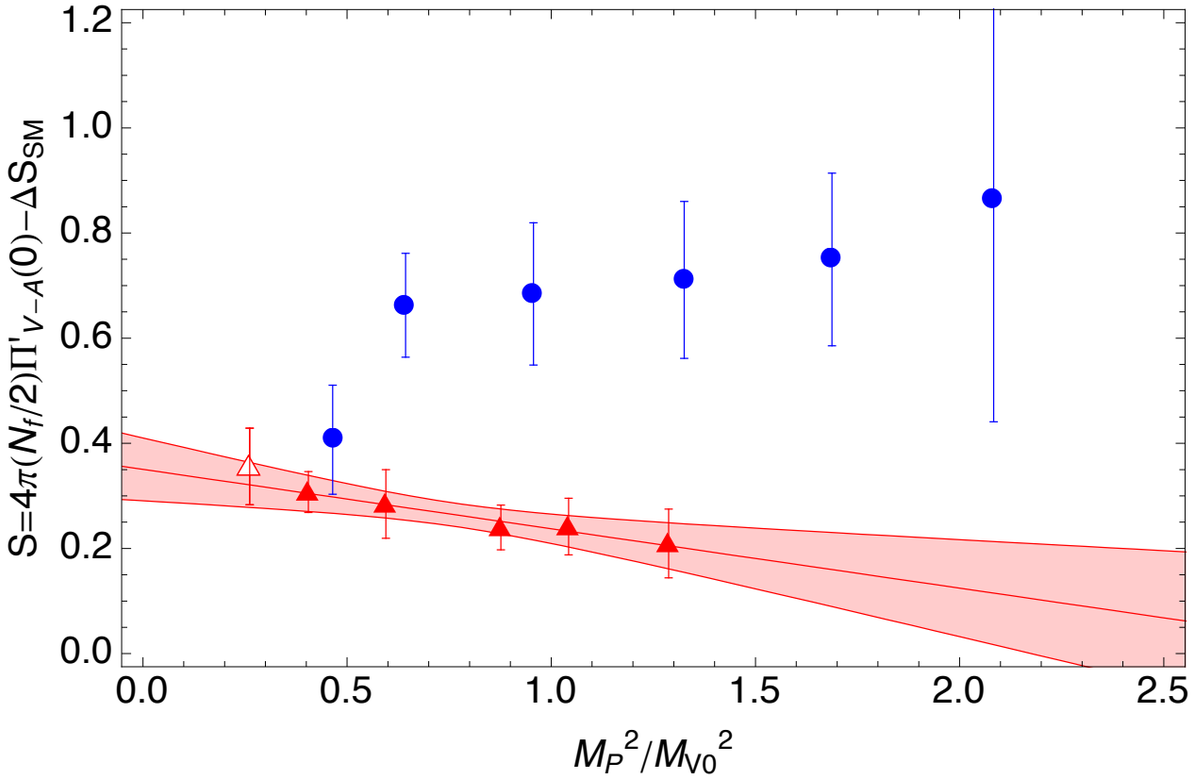
Boulder
- **SU(3) TC with *Nf=12* MCRG cont.**

Fundamental rep (conformal window?) Nf=6

Parity Doubling and the S Parameter Below the Conformal Window.
LSD Collaboration (Thomas Appelquist , Ron Babich, Richard C. Brower, Michael Cheng, Michael A. Clark, Saul D. Cohen, George T. Fleming, Joe Kiskis, Meifeng Lin, Ethan T. Neil, James C. Osborn, Claudio Rebbi, David Schaich, Pavlos Vranas) **Submitted to: Phys.Rev.Lett.** e-Print: **arXiv:1009.5967 [hep-ph]**

Lattice Strong Dynamics LSD collaboration

Nf=2 and Nf=6 S-parameters



chiral symmetry breaking

decreased split between parity partners

indication for S-parameter not following naive Nf-scaling

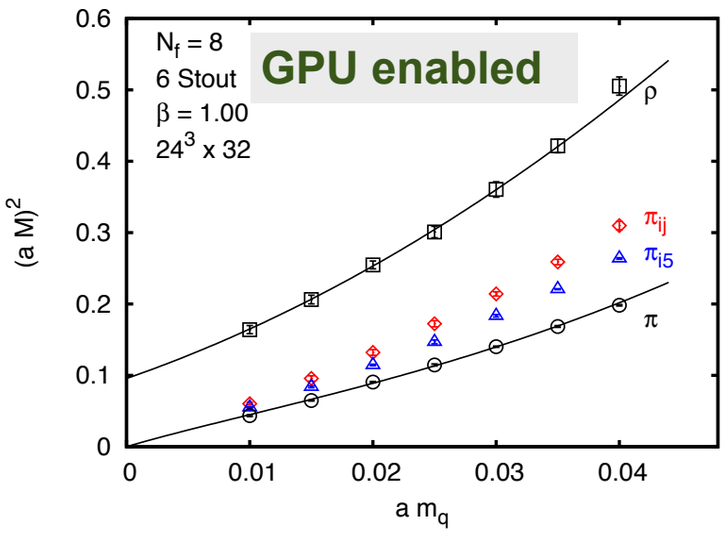
important for TC and ETC

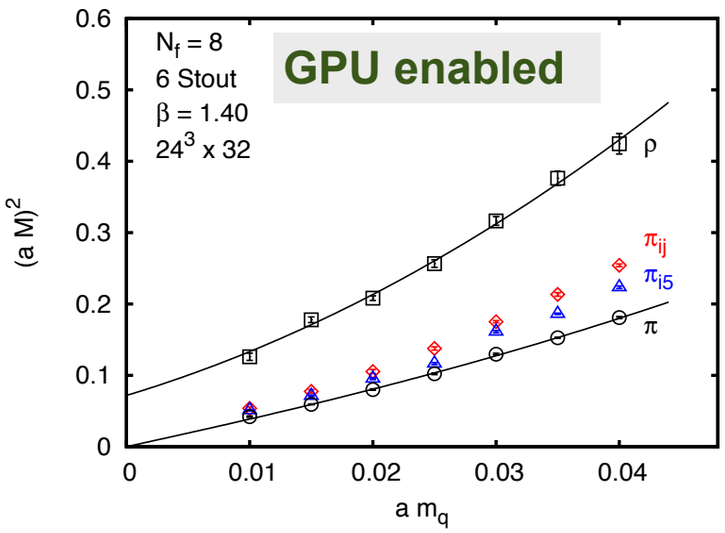
continuing ...

Fundamental rep (conformal window?) Nf=8

new: Nf=8 USQCD BSM
INCITE program just started !

imitates one full generation of techni-quarks and leptons
$SU(8)_L \otimes SU(8)_R$ **symmetry (four doublets) Farhi-Susskind TC model**





chiral symmetry breaking

Goldstone spectrum

- LHC results from last review

- consistent with Columbia group

Evidence for a First Order, Finite Temperature Phase Transition in 8 Flavor QCD.
Xiao-Yong Jin, Robert D. Mawhinney (Columbia U.). Nov 2010. 7 pp.
Published in **PoS LATTICE2010 (2010) 055**
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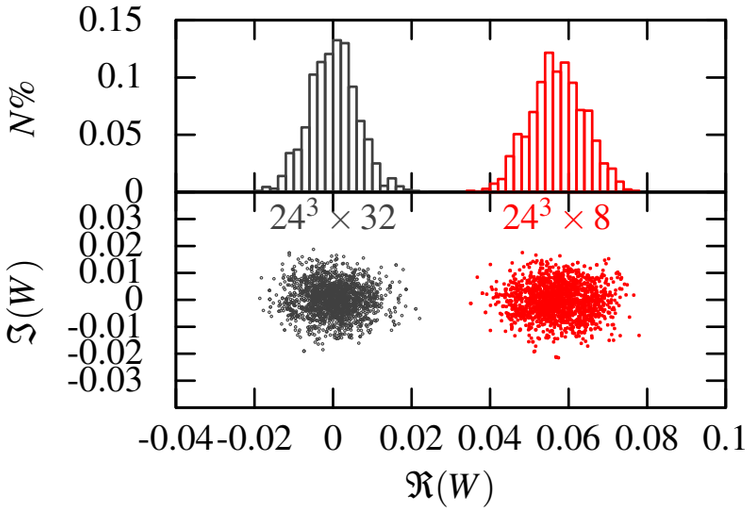
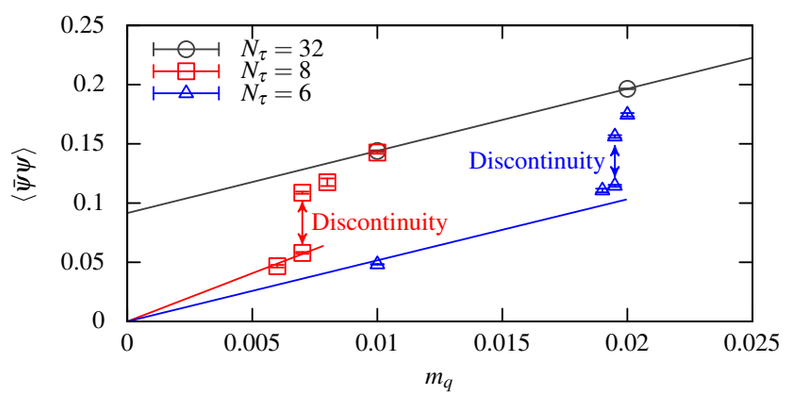
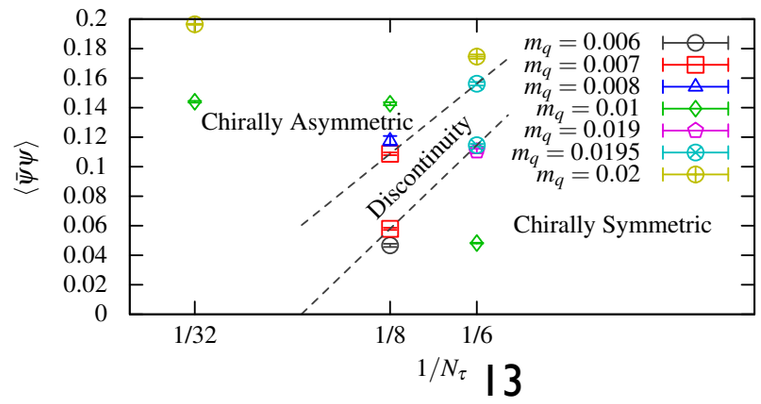
e-Print: **arXiv:1011.1511 [hep-lat]**







new Columbia group results on finite temperature transition

becomes Electroweak finite T transition in TC scenario

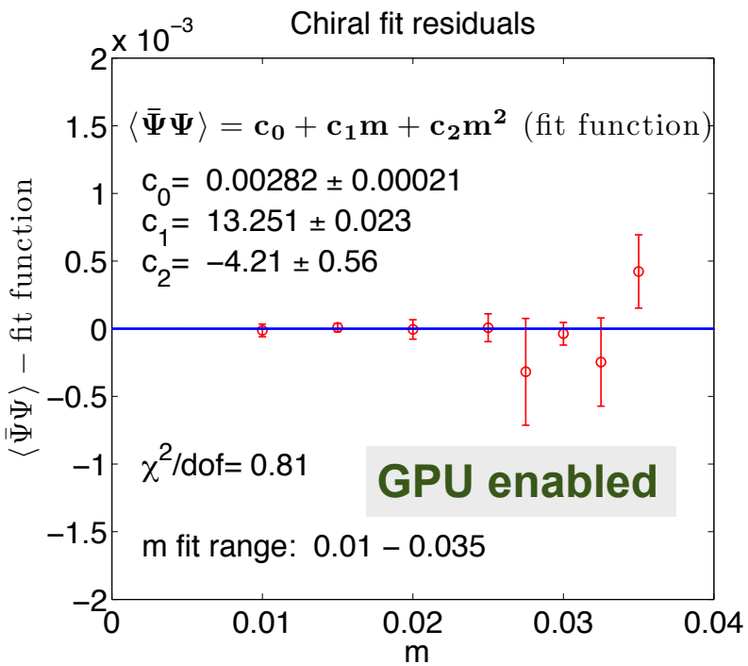
first order transition

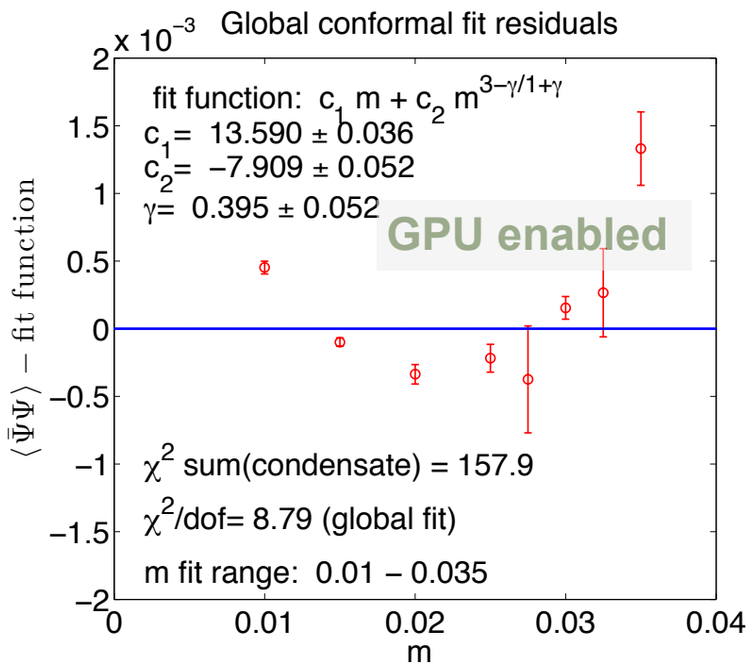
Cosmology implications?

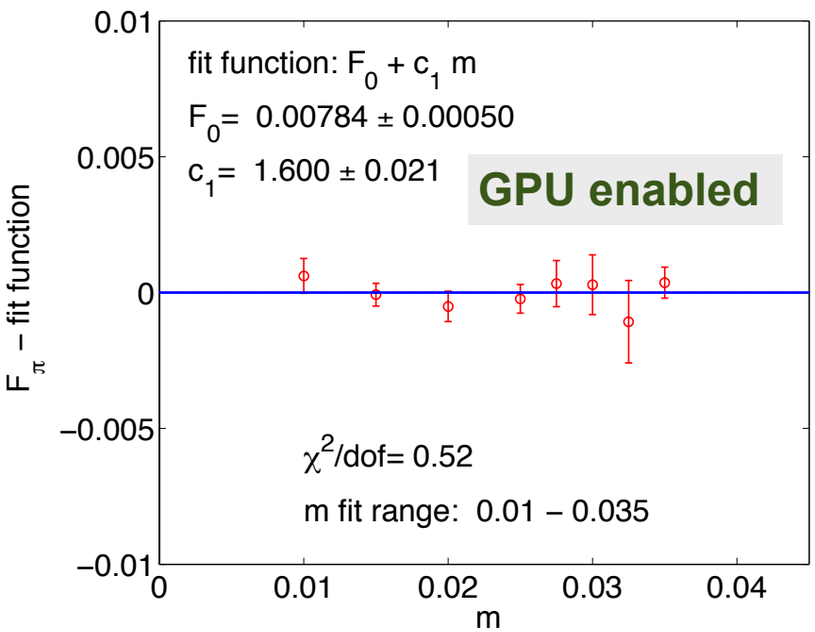
Fundamental rep (conformal window?) Nf=12

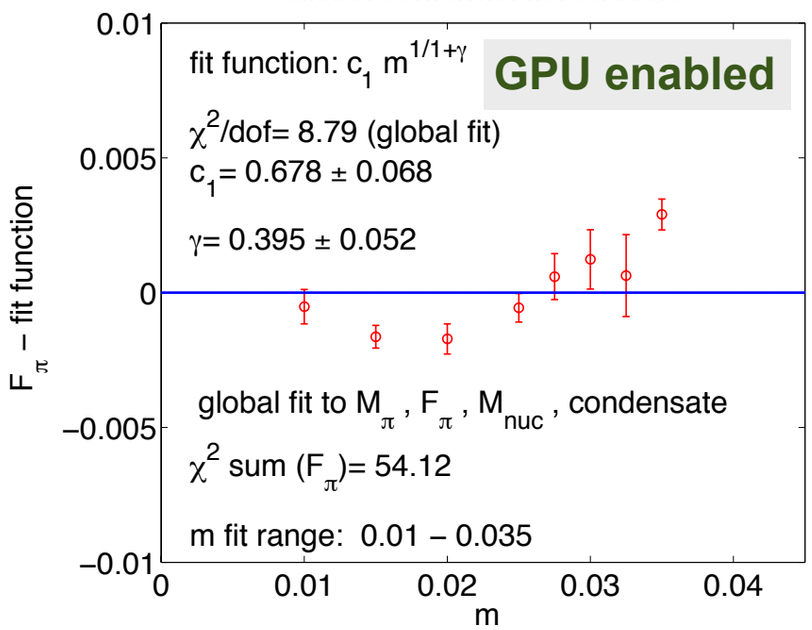
Twelve massless flavors and three colors below the conformal window.
Zoltan Fodor, Kieran Holland, Julius Kuti, Daniel Nogradi, Chris Schroeder. Apr 2011. 9 pp.
e-Print: **arXiv:1104.3124 [hep-lat]**

Lattice Higgs Collaboration (LHC)
consistent with Columbia group





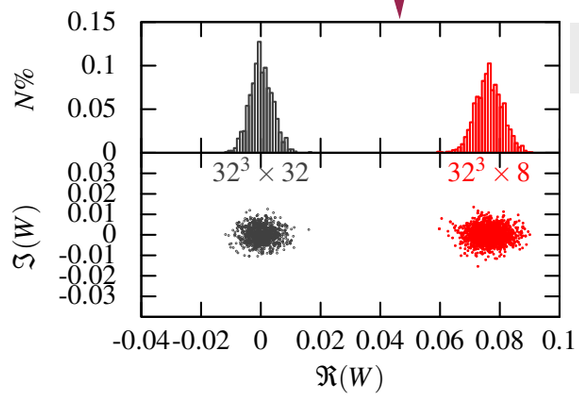




- **Global test favors chiSB below conformal window** ?
- **Earlier Yale work reported IRFP**
- **Finite temperature transition?**
- **IRFP MCRG ?**

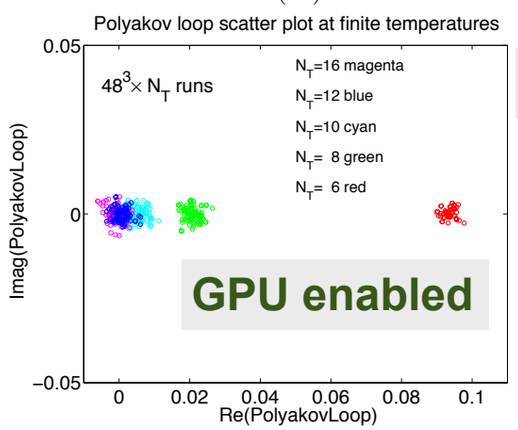
Columbia

χSB



LHC

χSB



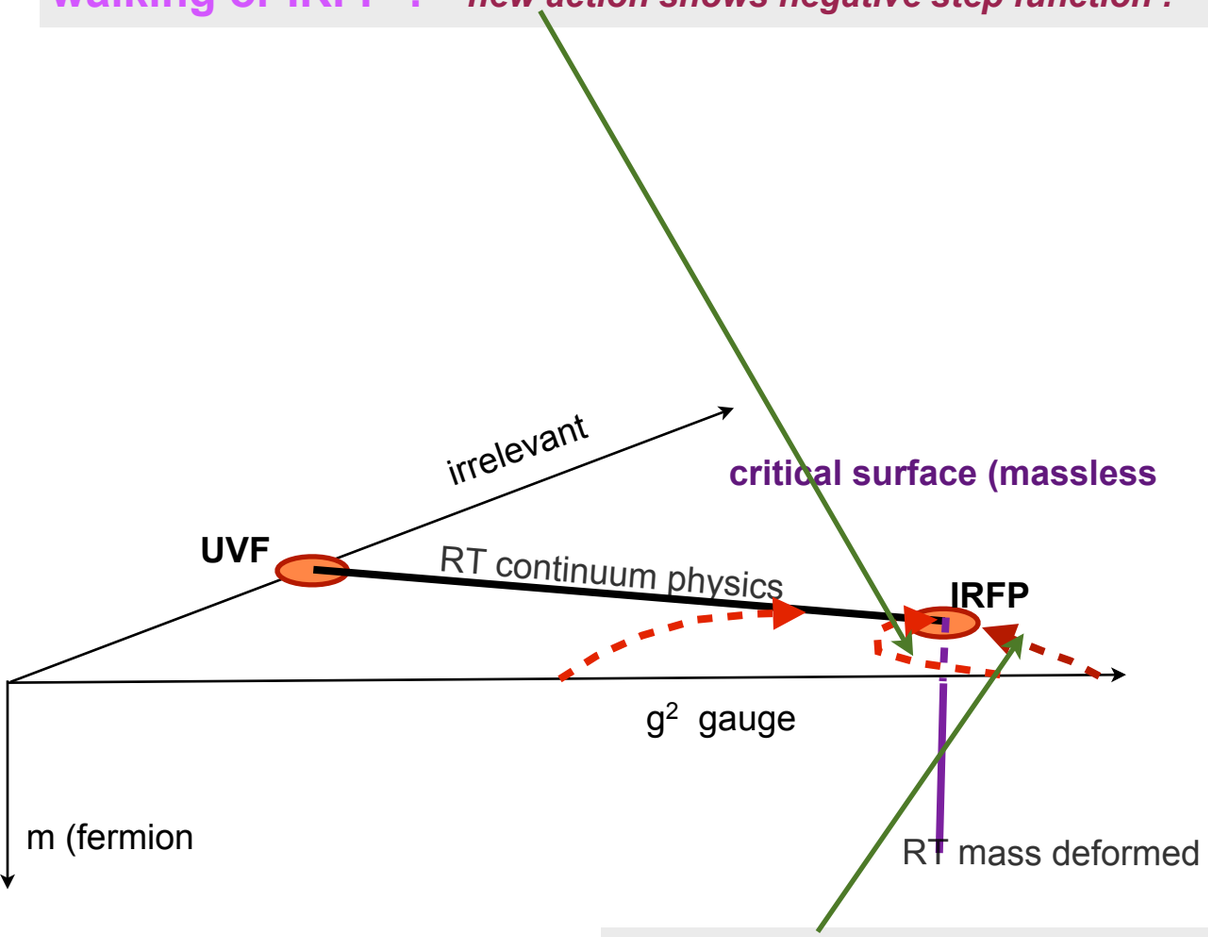
Fundamental rep (conformal window?) Nf=8,12,16 MCRG

running coupling from Monte Carlo Renormalization Group

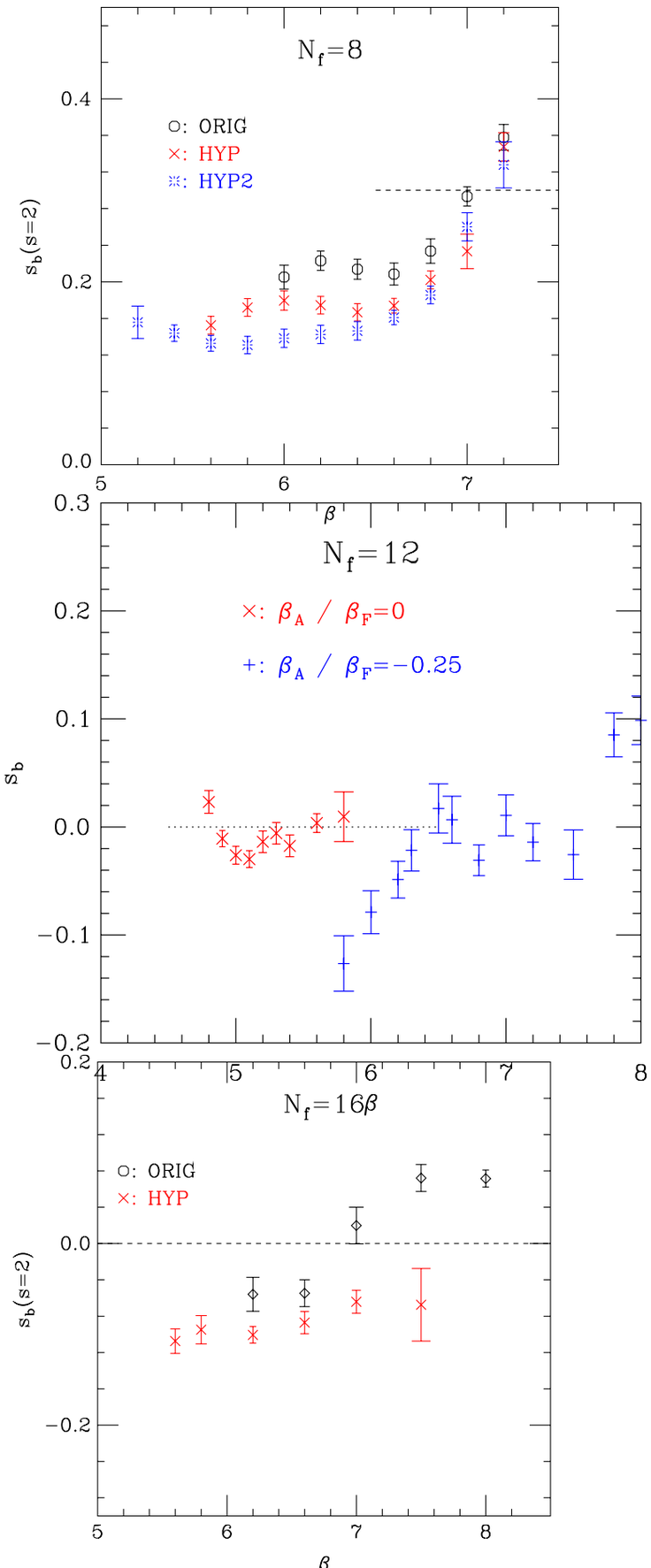
Anna Hasenfratz (Boulder)

Nf=8 below conformal window positive step beta function
gauge coupling runs without slowing down

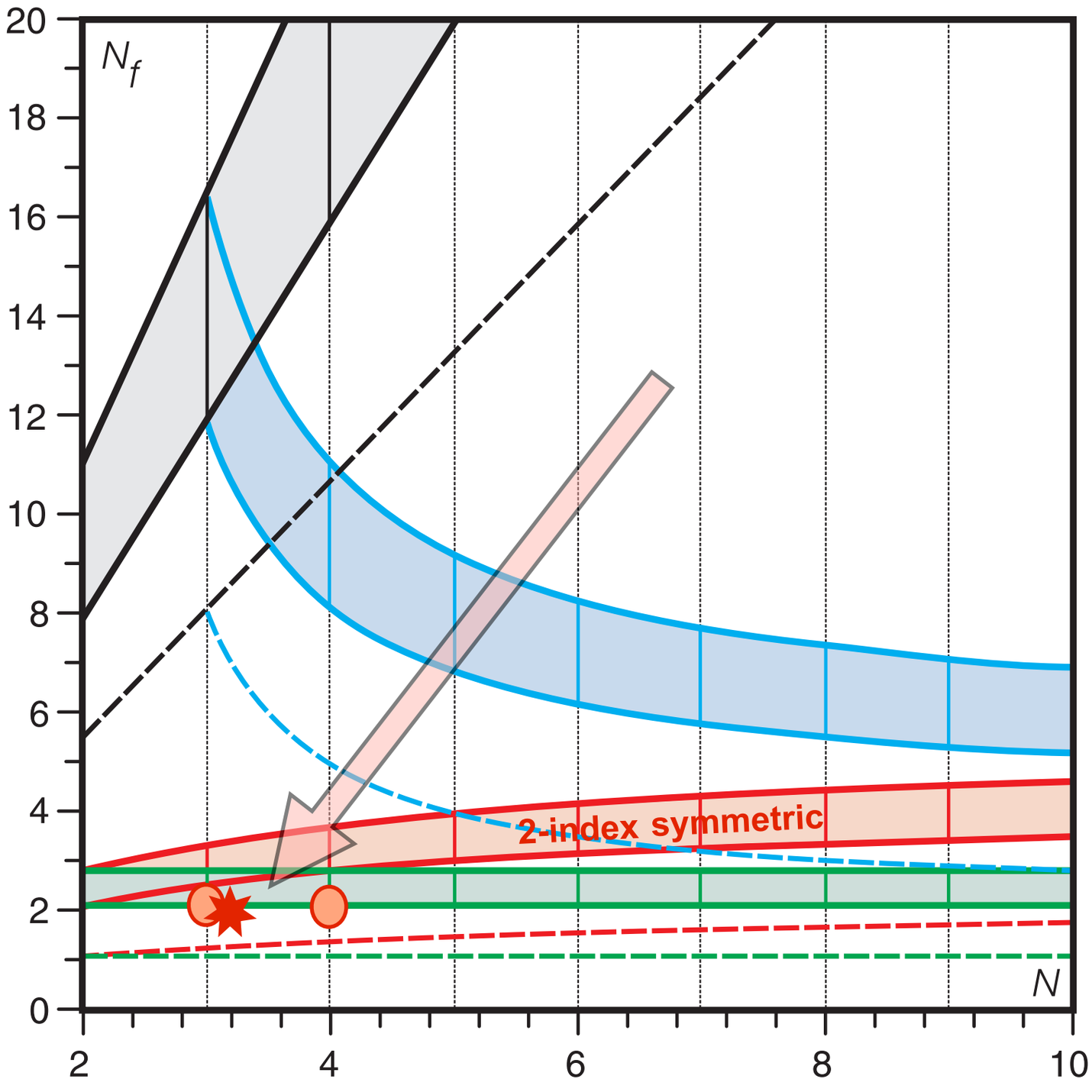
Nf=12 earlier step beta function zero within error
for large couplings slowing down or stopping
walking or IRFP ? ***new action shows negative step function !***



Nf=16 conformal IRFP
step beta function negative
backflow



2-index symmetric rep (conformal window ?) Nf=2, Nc=3,4



results with SU(3) technicolor gauge group

USQCD BSM results reported from three groups for sextet SU(3) color with Nf=2:

- Lattice Higgs Collaboration (LHC)

- Argonne based (not using USQCD resources)
Kogut-Sinclair

- U Colorado, Boulder *(DeGrand et al.)*

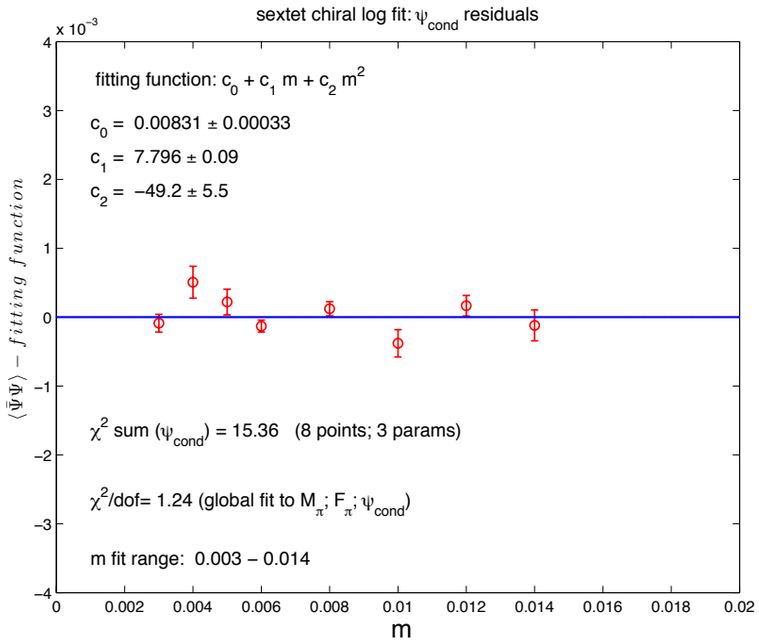
Plans for next year:

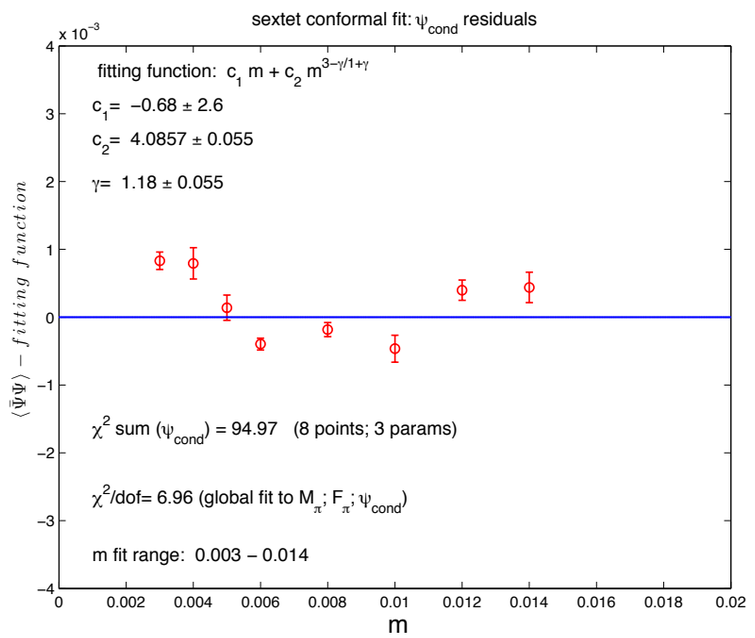
LHC
- **sextet SU(3) TC with *N=2* continued**
- **running coupling, S-parameter**

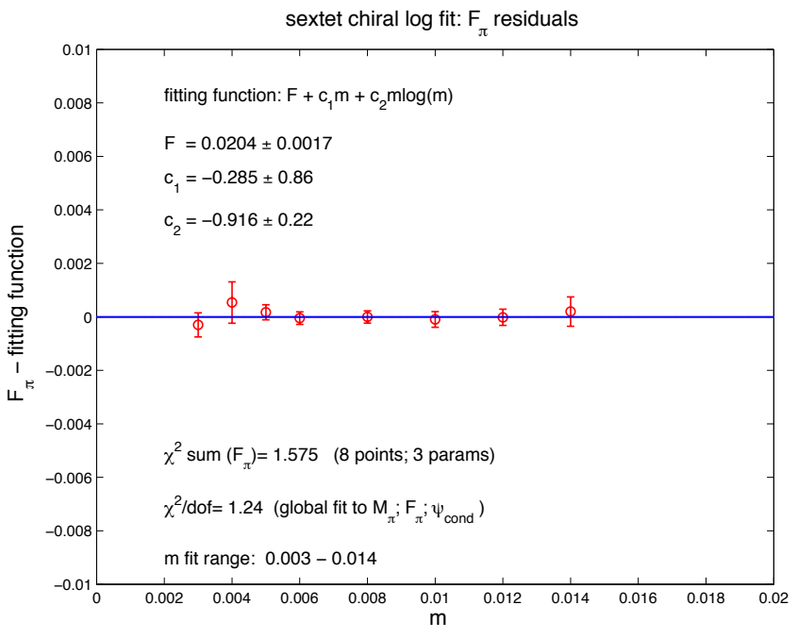
Argonne
- **continue sextet SU(3) TC with *Nf=2***
  finite temperature phase transition
- **bulk spectrum, chiral condensate**

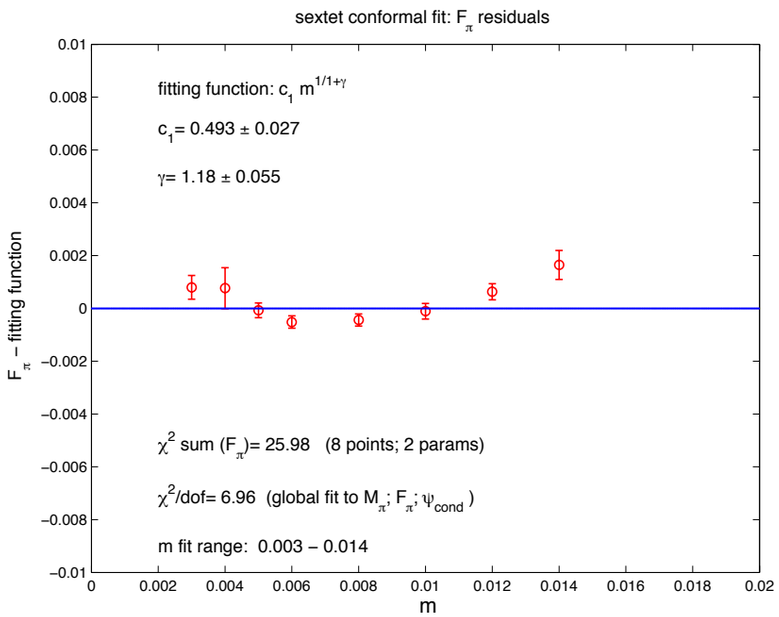
Boulder (DeGrand)
- **SU(4) 2-index symmetric TC**
  ***Nf=2* SF new**

2-index symmetric rep (conformal window ?) Nf=2









Lattice Higgs Collaboration (LHC)

consistent with Argonne result

- Global test favors chiSB

- Conformal hypothesis fails

- Below conformal window

- DeGrand et al. IRFP coupling

?

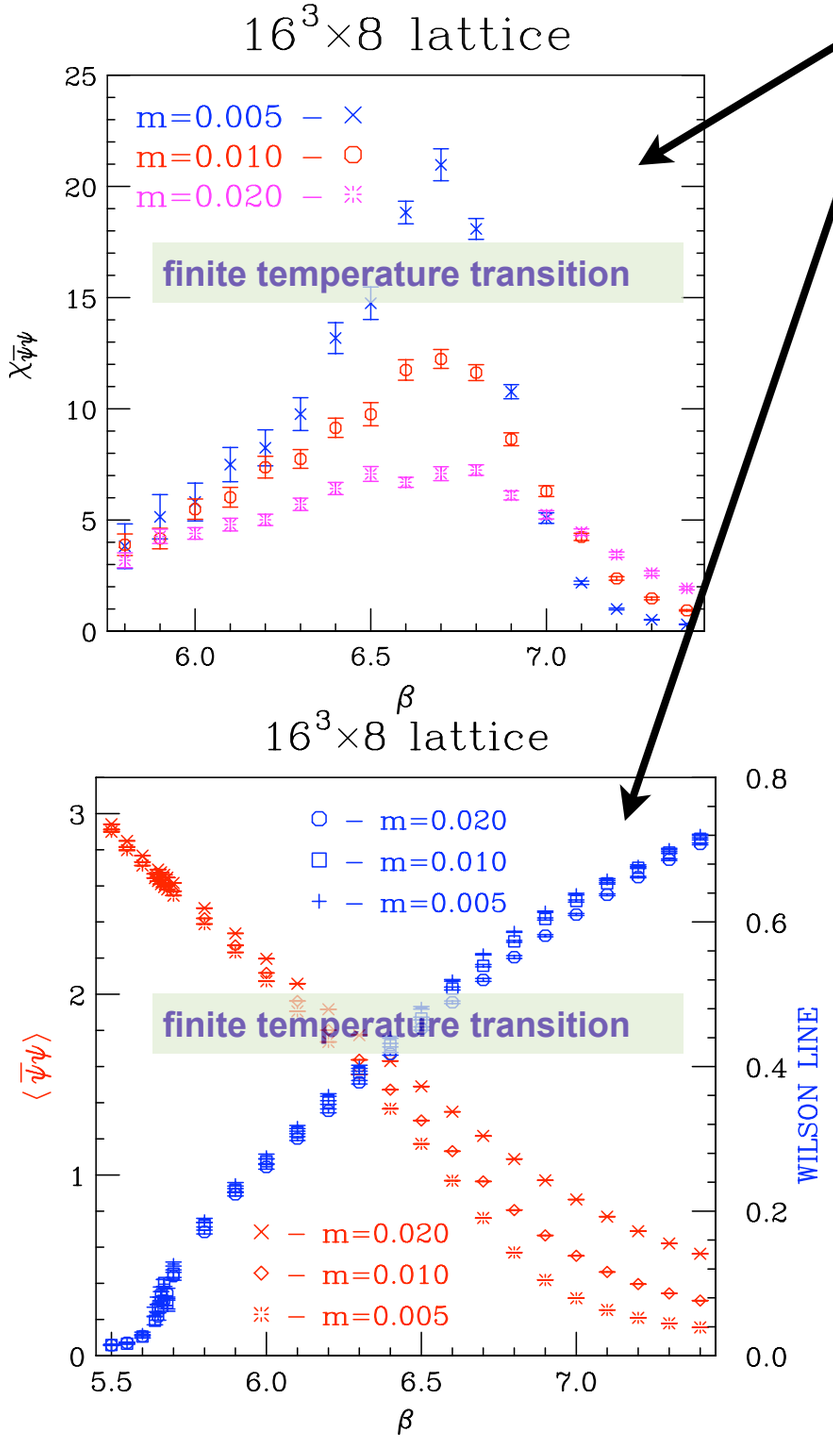
- Finite temperature transition ?

LHC sextet code fermion inverter is GPU enabled

Full RHMC GPU code is in final development stage

2-index symmetric rep (conformal window ?) Nf=2

New results with colour-sextet quarks.
D.K. Sinclair (Argonne), J.B. Kogut (Dept. of Energy, Wash., D.C. & Maryland U.). ANL-HEP-CP-10-42. Aug 2010. 7 pp.
Published in **PoS LATTICE2010 (2010) 071**
e-Print: **arXiv:1008.2468 [hep-lat]**

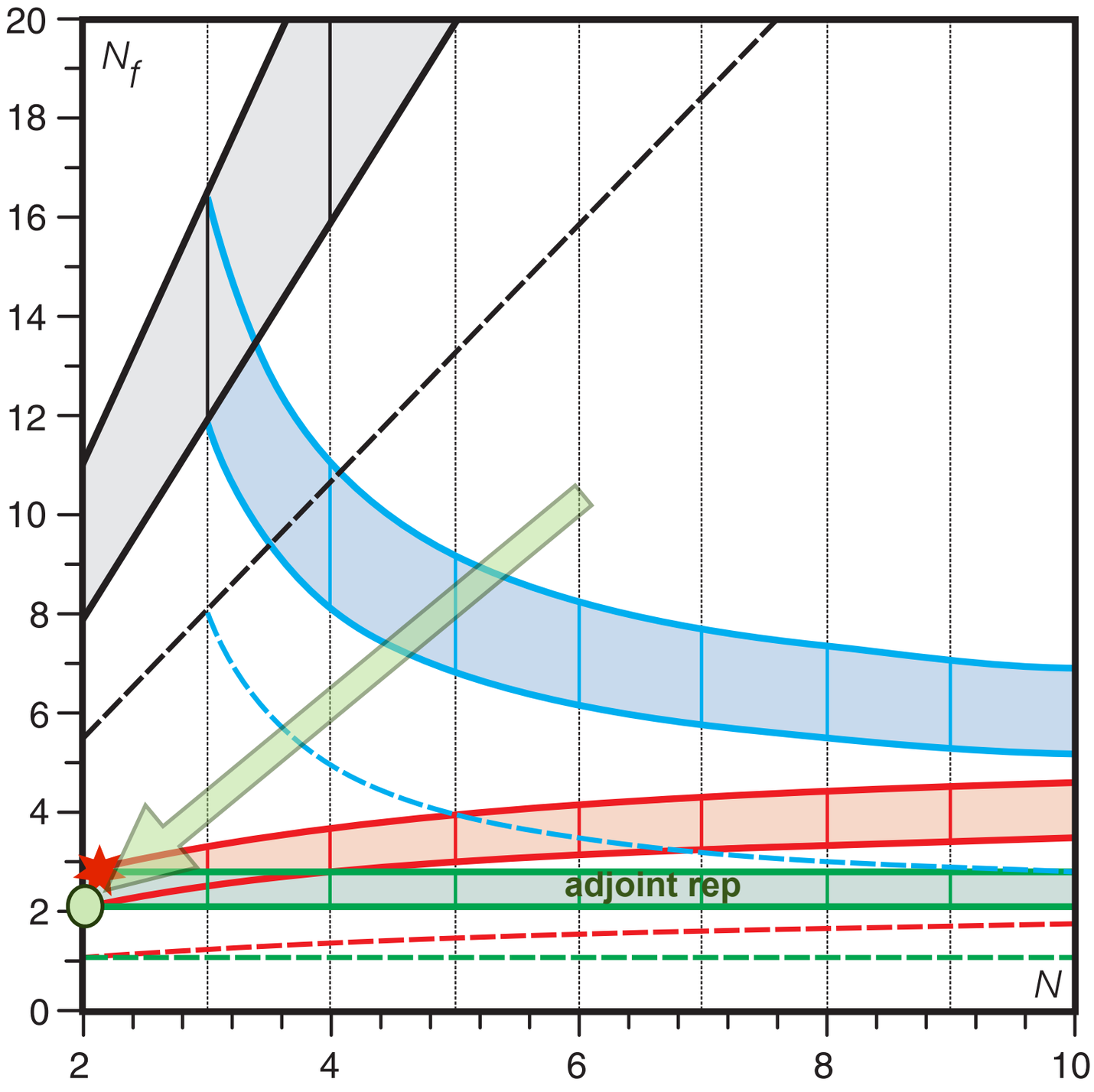


Sinclair is USQCD member but project is not using USQCD resources!

***Argonne based** (Kogut-Sinclair, pioneers in the Eighties!)*

- **finite temperature transition restoring broken chiral symmetry?**
  Argonne plans to extend the simulations to large Nt
- **Consistent with LHC tests in the bulk**
- **Model is interesting candidate below conformal window**
- **LHC will study running (walking?) coupling from V(R)/F(R)**
- **if walking coupling is established for TC/ETC, the next step is to calculate scale separation, anomalous dimension, and S-parameter**
- **DeGrand et al. are running at SU(4) color in 2-index symmetric rep with Nf=2 which is expected to be further away from conformal window provides SF technology cross-checks**

adjoint representation (conformal window ?) Nf=2



results with SU(2) technicolor gauge group

USQCD BSM results reported from two groups for Nf=2:

- Syracuse/RPI ***Catterall, Giedt***

- U Colorado, Boulder ***(DeGrand et al.)***

Plans for next year:

Syracuse/RPI:

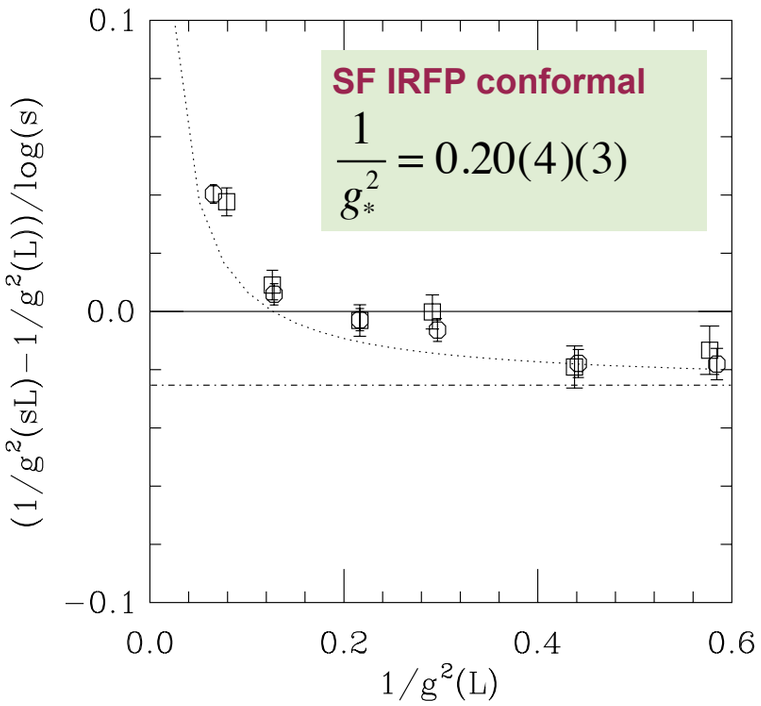
- continue work on MCRG searching for IRFP

Boulder:

- shifting to SU(4) 2-index symmetric TC with *Nf=2*

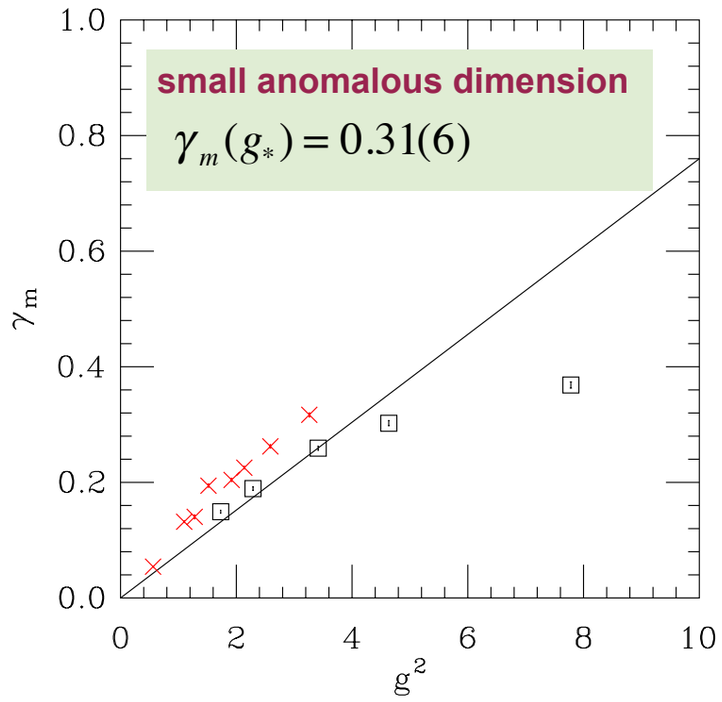
adjoint representation (conformal window ?) Nf=2

U Colorado, Boulder *(DeGrand et al.)*

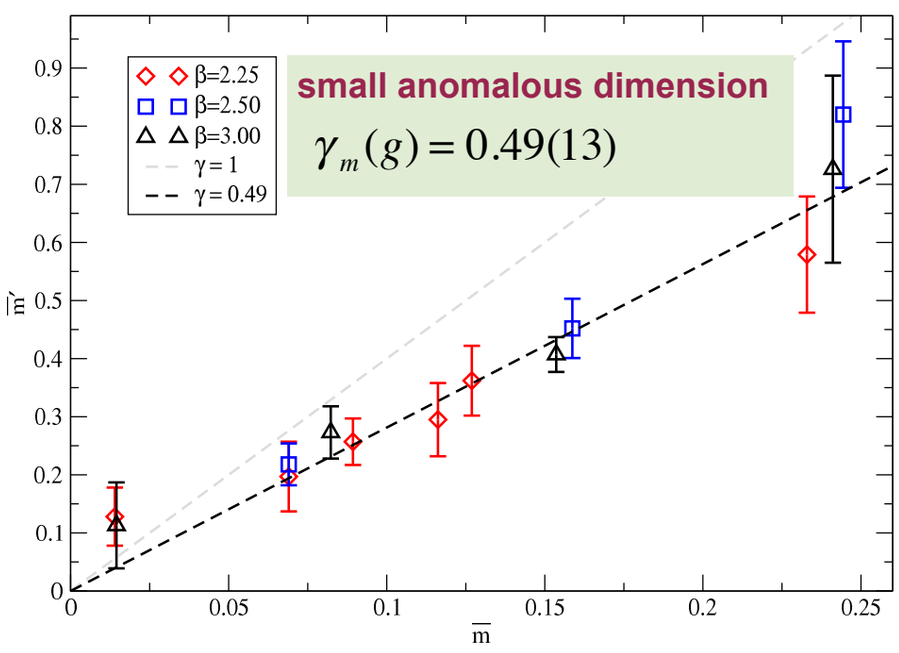


both groups finds so far that model is inside the conformal window

Syracuse/RPI *Catterall, Giedt, et al.*



two groups consistent



Lattice supersymmetry

- During last year – focus on N=4 SYM
- Theoretical formulation developed which retains exact SUSY

  Kaplan, Catterall, Unsal Phys.Rept.484:71-130,2009.
- Applications to String theory
- Parallel code developed – exploration phase diagram, fine tuning, underway

New plans for next year: focus on N=4 Supersymmetric Yang-Mills

developing GPU code for the new simulations

USQCD BSM GPU computing

The pioneers of GPU computing in lattice QCD (2005-2006):

ELSEVIER

Available online at www.sciencedirect.com
ScienceDirect

Computer Physics Communications 177 (2007) 631–639

Computer Physics Communications

www.elsevier.com/locate/cpc

Lattice QCD as a video game

Győző I. Egri [a], Zoltán Fodor [a,b,c,*], Christian Hoelbling [b], Sándor D. Katz [a,b], Dániel Nógrádi [b], Kálmán K. Szabó [b]

[a] *Institute for Theoretical Physics, Eötvös University, Budapest, Hungary*
[b] *Department of Physics, University of Wuppertal, Germany*
[c] *Department of Physics, University of California, San Diego, USA*

Received 2 February 2007; received in revised form 29 May 2007; accepted 7 June 2007

Available online 15 June 2007

with Fodor and Nogradi in the LHC collaboration, LHC has been using GPU technology early, building on Wuppertal expertise

Abstract

The speed, bandwidth and cost characteristics of today's PC graphics cards make them an attractive target as general purpose computational platforms. High performance can be achieved also for lattice simulations but the actual implementation can be cumbersome. This paper outlines the architecture and programming model of modern graphics cards for the lattice practitioner with the goal of exploiting these chips for Monte Carlo simulations. Sample code is also given.

1. Introduction

The goal of every lattice field theorist is to use a calculational platform that maximizes the performance/price ratio. In this paper a competitive but so far unused and unappreciated (at least in the lattice community) architecture will be introduced.

Pioneered at Boston University since 2007

Transformed into USCQD SciDAC project

QUDA: A library for QCD on GPUs

QUDA is a library for performing calculations in lattice QCD on graphics processing units (GPUs) using NVIDIA's "C for CUDA" API. The current release includes optimized kernels for applying the Wilson Dirac operator and clover-improved Wilson Dirac operator, kernels for performing various BLAS-like operations, and full inverters built on these kernels. Mixed-precision implementations of both CG and BiCGstab are provided, with support for double, single, and half (16-bit fixed-point) precision.

Download

Disclaimer: This package is undergoing active development, and the interface may change between releases. See the README and NEWS files for the most recent changes.

The current release is here (24 June 2010).

Past releases are here.

Contact

Please check back soon for mailing list information. For now, if you need help or find a bug, please contact one or more of the developers.

Developers: Ronald Babich, Michael Clark, Bálint Joó, Guochun Shi

Contributors: Kipton Barros, Richard Brower, Steven Gottlieb, Claudio Rebbi

If you find this code useful in your work, please cite (arXiv, SPIRES):

- M. A. Clark, R. Babich, K. Barros, R. Brower, and C. Rebbi, "Solving Lattice QCD systems of equations using mixed precision solvers on GPUs" (2009), arXiv:0911.3191 [hep-lat].

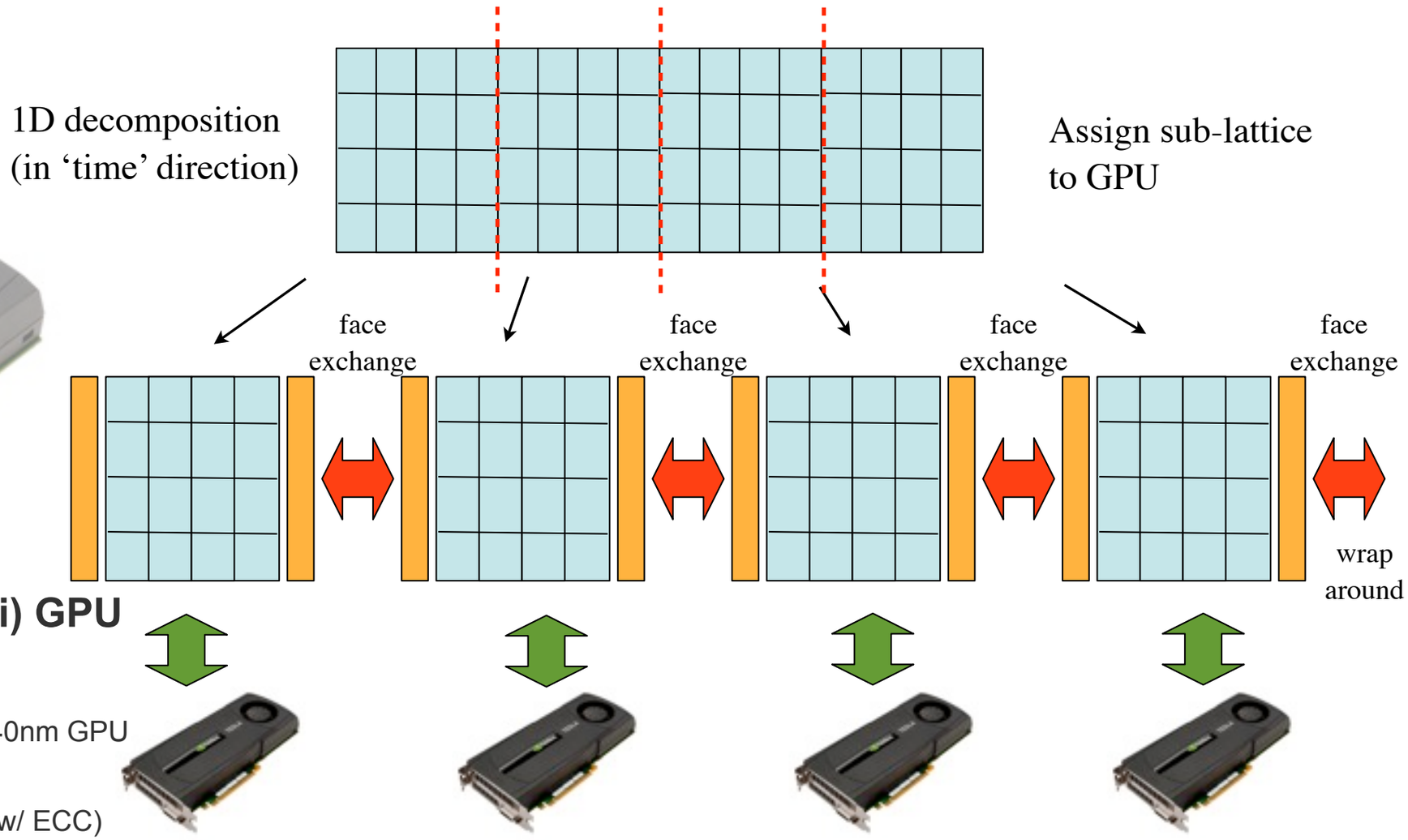
- QUDA library (“QCD on CUDA”) available here:
  - http://lattice.bu.edu/quda
- Provides optimized CG and BiCGstab solvers for Wilson and clover-improved Wilson, supporting mixed precision with reliable updates.

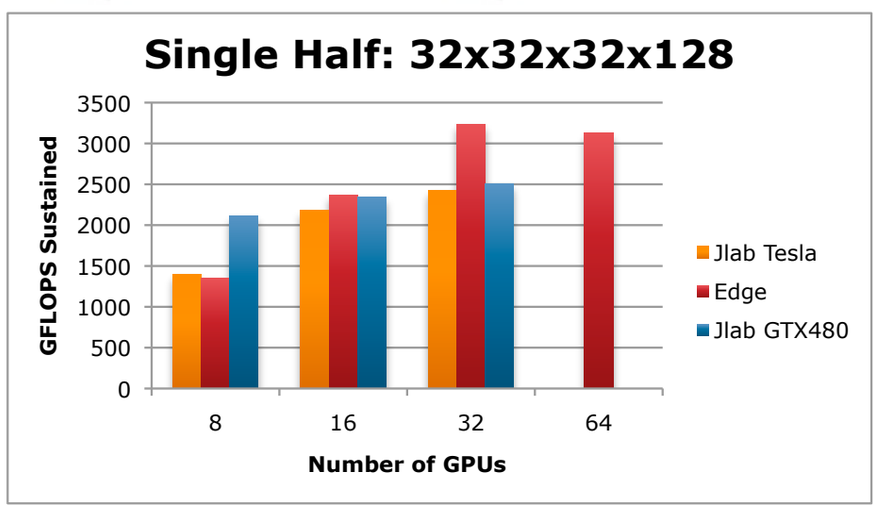
LHC BSM and QUDA Parallelization

NVIDIA Tesla C2050 (Fermi) GPU

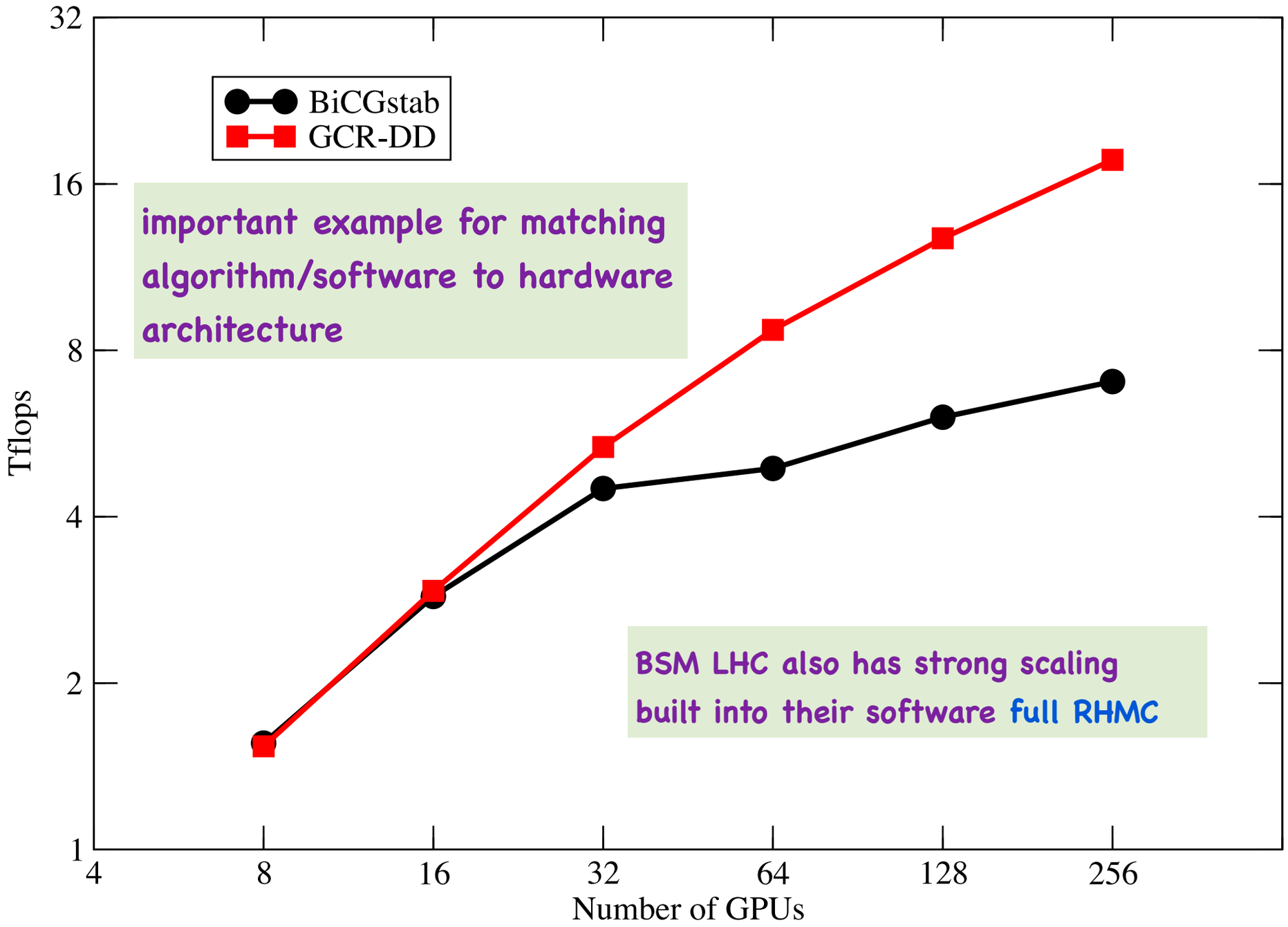
Silicon Mechanics Part Number: 19417
Manufacturer Part Number: 900-21030-2200-000

- NVIDIA® Tesla™ third-generation 40nm GPU
- 448 CUDA cores
- 3 GB GDDR5 Memory (2.625 GB w/ ECC)
- Dual Precision 515 GFlops
- Single Precision 1003 GFlops
- PCIe 2.0 x16 full-length, dual slot





QUDA strong GPU scaling : Babich, Clark, Joo, Shi, Brower, Gottlieb



important example for matching algorithm/software to hardware architecture

BSM LHC also has strong scaling built into their software full RHMC

$$V = 32^3 \times 256$$

LHC collaboration has been using GPU technology for BSM physics:

(1) full RHMC CUDA code in fundamental representation for SU(3) color

(2) Wilson and staggered fermion codes

(3) sextet SU(3) color full RHMC code is being tested

QUDA based broader USQCD BSM applications are on their way

Cost gain is up to factor 5-10, or higher !

application dependent

USQCD BSM summary and outlook

USQCD BSM effort demonstrated important capabilities in the Theory Space of gauge theories which could lead to a viable composite Higgs mechanism based on the Technicolor paradigm:

(1) can classify the gauge models based on their chiral properties

(2) can calculate phenomenologically important BSM parameters
popular example is the S-parameter

(3) can identify the IRFP inside the conformal window

(4) can find the Electroweak phase transition at finite temperature which may have cosmological significance

(5) capability is being developed to find model(s) with walking gauge coupling to enable scale separation of TC and ETC in more realistic model building

(6) it remains the most important challenge to develop definitive methods resolving IRFP (conformal) scenarios from walking gauge coupling scenarios

(7) USQCD BSM GPU technology is cost effective