From the Deep Past to the Far Future:

1. Pioneering Lattice Simulations beyond the Standard Model,
2. The Exascale Project

- In the early 80's molecular dynamics algorithms for fermion field theories with good scaling and equilibration properties were developed. Microcanonical algorithms were generalized to canonical algorithms and theories with non-negative fermion determinants were simulated.
- State-of-the-art computing was needed in high energy physics for the first time. Array processors, large mainframes, vector processors, dedicated special purpose machines etc. were enlisted. The National Supercomputing Initiatives of the NSF and the DOE were begun and close contacts with industrial corporations developed.
- QCD thermodynamics and spectroscopy studies were begun.
- But it was recognized early on that computing resources in the teraflop range were needed to extract continuum predictions with controlled error bars. Statistical mechanics and RG developments of the 70's were benchmarks for expectations.
- Lattice community, which took a long term approach to improved infrastructure, developed. Precursors to today's USQCD and other groups in Europe and Japan.

Hierarchal Mass Scales: Fermions in various representations of the gauge group

- LGT made important contributions to the Higgs sector of the Standard Model. Triviality bounds etc.
- Other problems of Grand Unified Models, such as the need for Hierarchal mass scales and dynamical symmetry breaking mechanisms.
- A 1983 study of chiral symmetry breaking in SU(2) QCD with fermions in the SU(2) color representations I=1/2, 1, 3/2 and 2. Testing Technicolor, Tumbling, MAC ideas.
  1. Found evidence for hierarchal mass scales in the quenched approximation: coupling required for a condensate to form followed Casimir scaling, $C_2(I)\ g^2_{mom}$ ~4 for I= 3/2 and 2.
  2. Found evidence for hierarchal scales of chiral symmetry restoration temperatures: $T_{I=1}/T_{I=1/2}$ ~8.
  3. Although chiral symmetry breaking and confinement could have identical scales in the I=1/2 theory, theories with fermions in higher representations could have chiral condensates at scales exponentially higher in energy.
- A 1985 study showed that these qualitative results survived unquenching.
- A 1987 study did SU(3) analogues.
- A 1987 study of Supersymmetric SU(2) Yang Mills, one Majorana Adjoint fermion, found chiral symmetry breaking.

Disparate chiral symmetry breaking scales in Quenched SU(2) QCD with l=1/2 and l=1 fermions

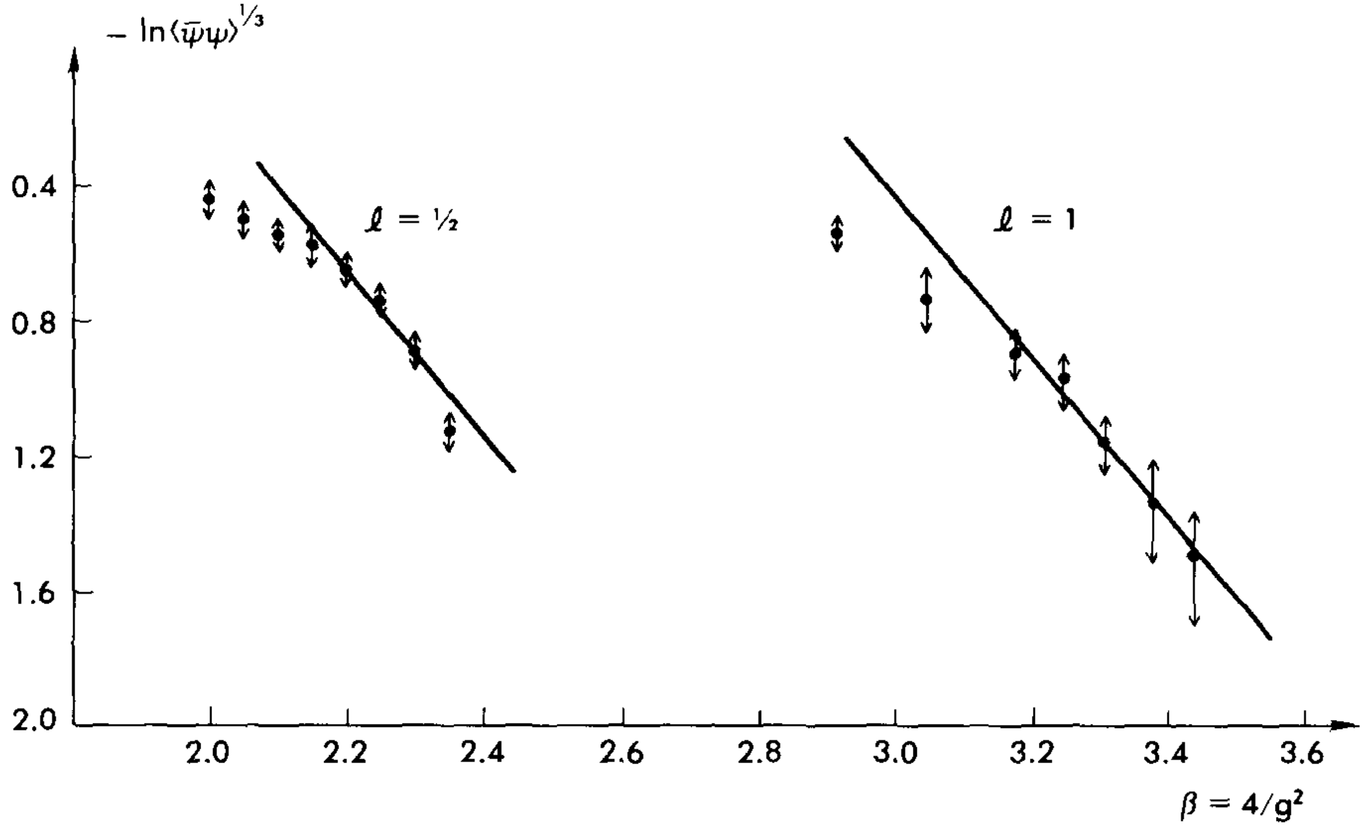

Fig. Comparison of $l = 1/2$ and $l = 1$ data.

References

- Hierarchal Mass Scales: Fermions in various representations of the gauge group

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4. Chiral Symmetry Breaking with Octet and Sextet Quarks, PL 145B, 239 (1984). Kogut, Shigemitsu, Sinclair.
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SU(2) and SU(3) QCD with Many N_f Flavors

- For SU(3) gauge theory with N_f fundamental flavors of Dirac fermions, the perturbative beta function reads, $\beta(g) = -\beta_0 g^3/(16\pi^2) - \beta_1 g^5/(16\pi^2)^2$, where $\beta_0 = 11-2N_f/3$ and $\beta_1=102-38N_f/3$.
- So, fermions screen the color charge and destroy asymptotic freedom: the first coefficient changes sign at N_f=16.5 and the second changes sign at N_f=8.05.
- So, naively, for N_f between 8.05 and 16.5 the theory is asymptotically free and infrared stable.
- For SU(2), the corresponding range in from 5.55 and 11.
- In the early 1980's there were many small lattice studies of the order of the finite temperature deconfinement and chiral symmetry breaking transitions as a function of N_f, SU(N) color, m_{quark}, etc.
- Must distinguish between bulk transitions which are caused by lattice artifacts and real finite temperature effects. Must work in the scaling window, on lattices with sufficient temporal and spatial extents. Not easy!

In NP B295[FS21], 465 (1988) bulk transitions in the 8 and 12 flavor versions of SU(2) and SU(3) guage theories were done using microcanonical, molecular dynamics, simulation methods. In this case, simulations are done at fixed “energy” instead of at fixed “temperature (coupling)” and the Maxwell construction is observed because the simulation can reach into regions of metastability. In the thermodynamic limit the “S” curves are replaced by discontinuities.

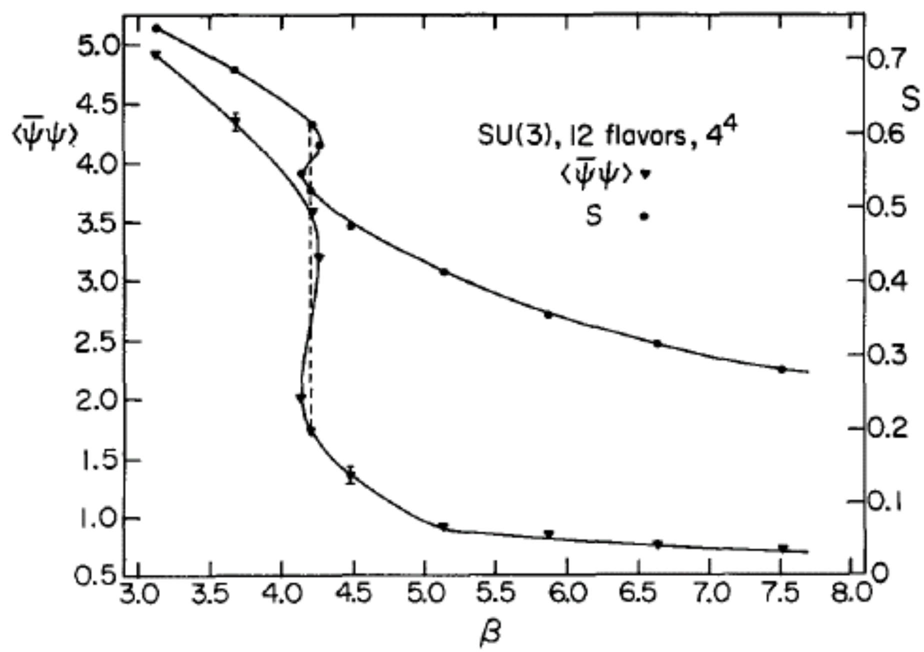
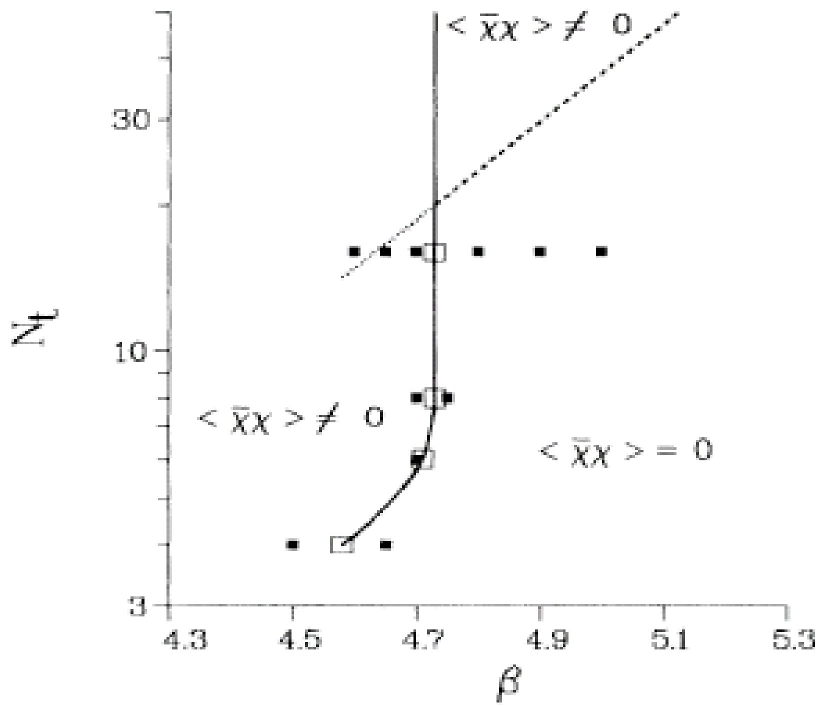


Fig. 3. $\langle\bar{\psi}\psi\rangle$ and Wilson line WL measured on a 4^4 lattice for SU(3) gauge theory with $N_f = 12$.

PRD 46, 5655 (1992). 8 flavor QCD simulation shows a solid line of bulk first order chiral transitions. The finite temperature transition of the continuum limit is conjectured to be the dashed line which only becomes apparent in the weak coupling scaling region for temporal extents N_t greater than 16 lattice spacings. Only the 'wedge' between the solid and dashed lines is useful for spectroscopy calculations that relate to the continuum theory. The nature of the dashed line is not known.



SU(2) and SU(3) QCD with Many N_f Flavors

- This last study illustrates a point made in the earlier pioneering works:
  1. Finding continuum physics in naïve lattice theories with many fermions requires large lattices. Finite size effects grow stronger as N_f increases.
  2. Naïve actions have unphysical, bulk transitions which must be worked around or eliminated by improvement schemes.

– Another problem which these studies haven't faced, is that the determination of the order of these transitions is not easy and is strongly influenced by 1. lattice size, 2. form of the lattice action and 3. the accuracy of the ensemble generation algorithm.

– Point 3 has become very clear in recent studies of transitions in baryon-rich (isospin rich) environments where Binder cumulants were seen to have strong $(dt)^2$ corrections. Solution: Use the Rational Hybrid Monte Carlo algorithm which has no time step discretization errors.

– Now Conformal, or "almost" conformal theories like walking technicolor, which may be consistent with experiment and may describe electroweak symmetry breaking, should be done.

References

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  1. Deconfinement and Chiral Symmetry Restoration at Finite Temperatures in SU(2) and SU(3) Gauge Theories, PRL 50, 393 (1983). Kogut, Stone, Wyld, Gibbs, Shigemitsu, Shenker, Sinclair.
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2. The Exascale Project

- The lattice community has distinguished itself by planning ahead. You thought you were copying the experimental community, but, in fact, you left them in the dust: they did not do the R&D over the last few decades to make affordable accelerators to probe the Tevascale and they (and therefore, we) are facing extinction.
- The Office of Advanced Scientific Computing Research (ASCR) is planning their facilities for the next decade. They must reach the Exascale, a million times the present Terascale, to face the new challenges in renewable energy, new energy sources, environmentally integrated modeling, etc.
- The problems of high energy physics beyond the standard model will require this level of computing power to be relevant and realistic.
- There will be an **Exascale Workshop** in the near future which will look into applications for this new frontier. You are looking at its project manager (with Walt Polansky on the ASCR side). Keep an eye on the ASCR web site. Plan to attend, contribute to a panel study and a written report.
- Influence policy before it influences you!