QCD Thermodynamics with Domain Wall Fermions

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Outline

- Domain Wall Fermion (DWF) Thermodynamics
- **RBC Collaboration: DWF Thermo with L_s=32**
  - Residual chiral symmetry breaking.
  - Chiral condensate and susceptibility
  - Lattice scale and hadron spectrum.
  - Results for T_c
- **HotQCD Collaboration: DWF Thermo with L_s=96**
  - *Preliminary* results for chiral condensate and Wilson line
- Conclusions/Outlook

QCD Thermodynamics

- **Goals: Understand QCD at finite temperature and density.**
- Current calculations with $\mu = 0$.
- Important Quantities:
  - Pseudo-critical temperature: $\mathbf{T_c}$
  - Equation of State (EoS): **p(T), ε(T), s(T)**
- EoS applicable in hydrodynamic modeling of heavy ion collisions.
- Learn something about QGP in early universe.

Why Domain Wall Fermions?

- Many recent, high-precision thermodynamic lattice QCD calculations done with staggered fermions
- Staggered fermions – 16 “rooted”, non-degnerate pions instead of 3 natural pions (DeTar).
- Do the heavier pions affect thermodynamics?
- DWF have correct chiral symmetry, with residual breaking parameterized by $\mathbf{m_{res}}$.
- DWF more expensive than staggered.
- Previous studies of QCD thermo with DWF at $N_t=4$ – Lattices too coarse for DWF (**RBC 2000**).

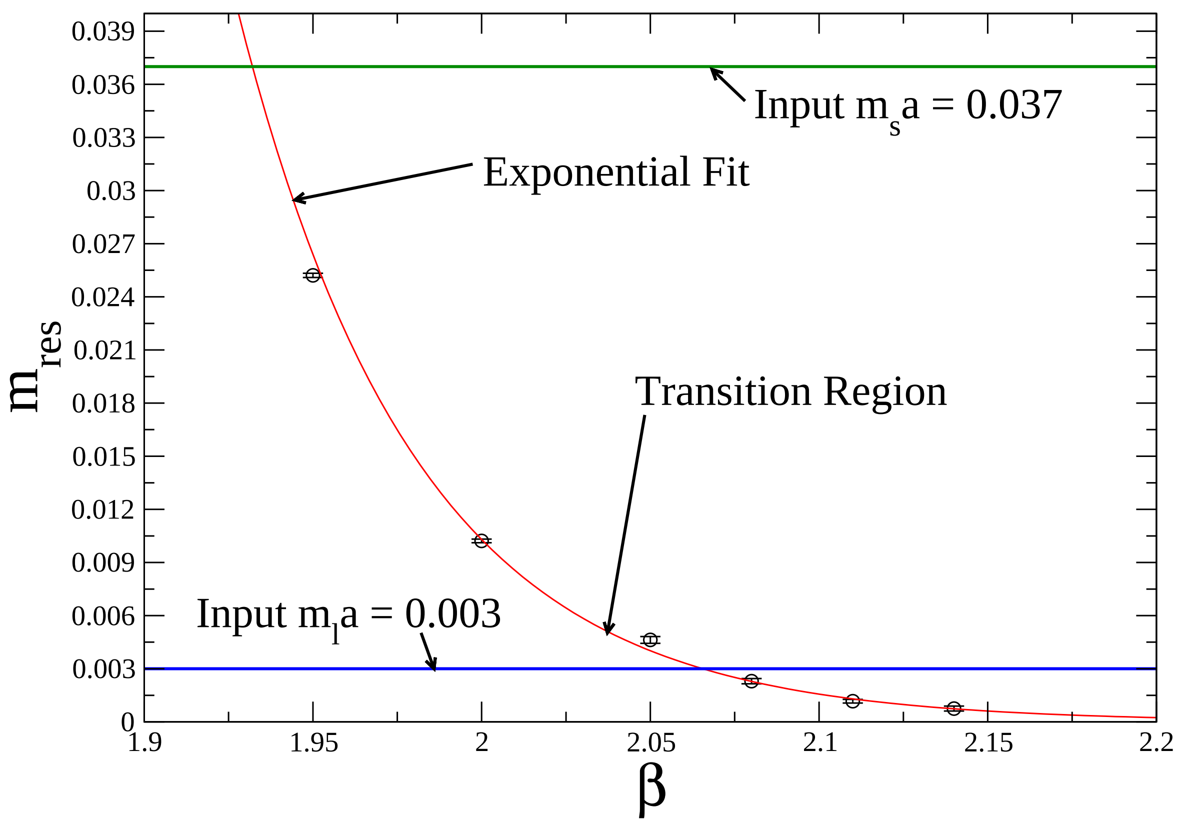
RBC L_s = 32 DWF Project

- **Goal: Explore critical region with DWF N_t=8**
- Lattices fine enough that DWF formulation is working well.
- **16^3x8** lattice volumes, **Iwasaki** gauge action
- **L_s=32** to control residual chiral symmetry breaking
- **2+1 flavors** of dynamical quarks, generated using Rational Hybrid Monte Carlo (RHMC)
- $m_l a$ = .003, $m_s a$ = .037, $m_{res} a$(esimated) = .008
- Light quarks about ¼ strange quark mass

RBC L_s = 32 DWF Project

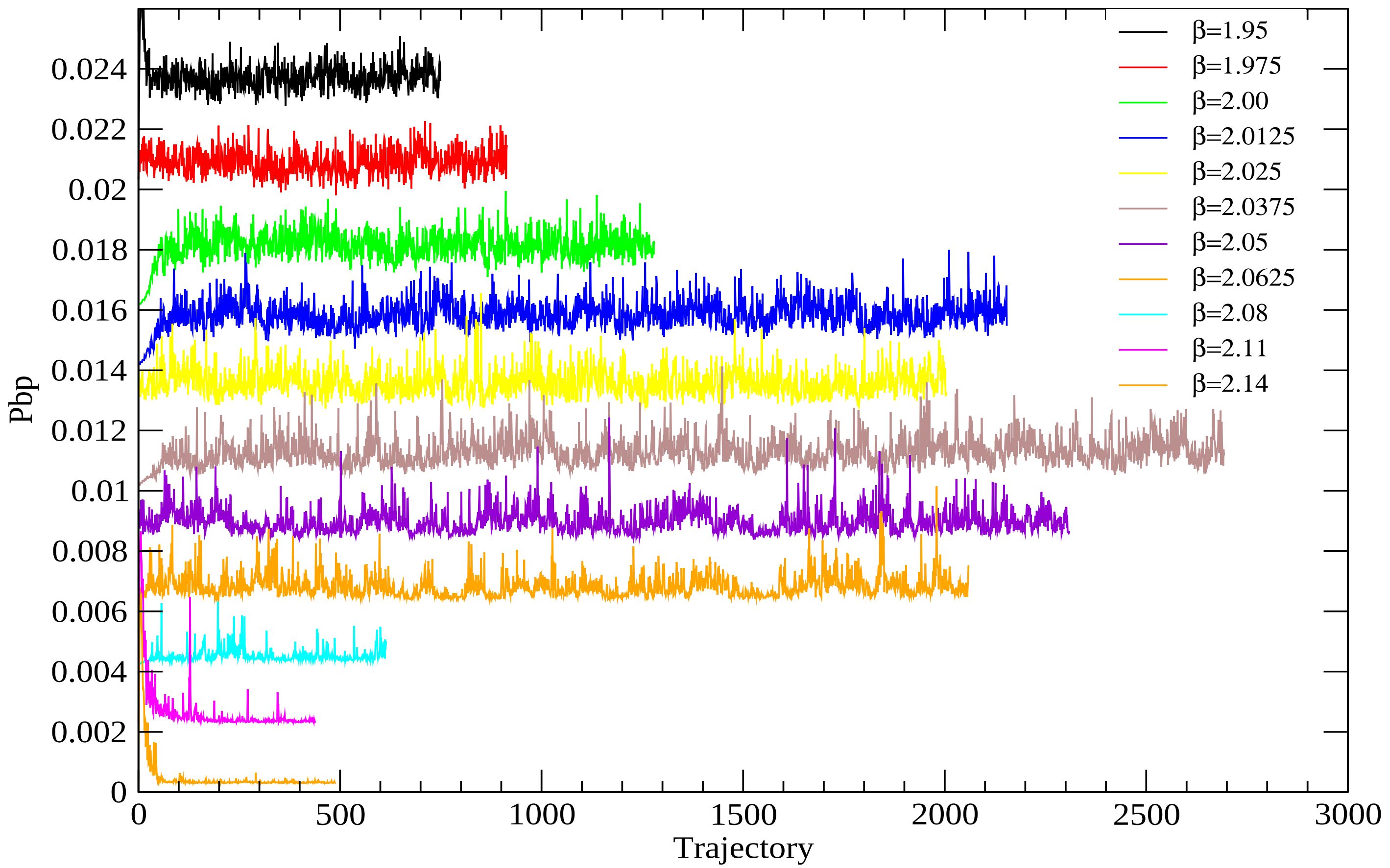
- 11 ensembles at different gauge couplings: **$1.95 < \beta < 2.14$**, corresponding to 1.0 Gev < a^{-1} < 1.8 GeV
- $\Delta\beta = .01 \rightarrow$ approximately 3% change in scale.
- 500 – 2500 trajectories per ensemble.
- Transition region: $2.00 < \beta < 2.0625$, 6 ensembles with spacing $\Delta\beta = .0125$. 2000+ trajectories per ensemble.
- Measure chiral condensate, Wilson line.
- Locate $\boldsymbol{\beta_c}$ using susceptibility peaks.
- Zero temperature measurements at $\beta = 2.025$ to set lattice scale.

Residual Chiral Symmetry Breaking

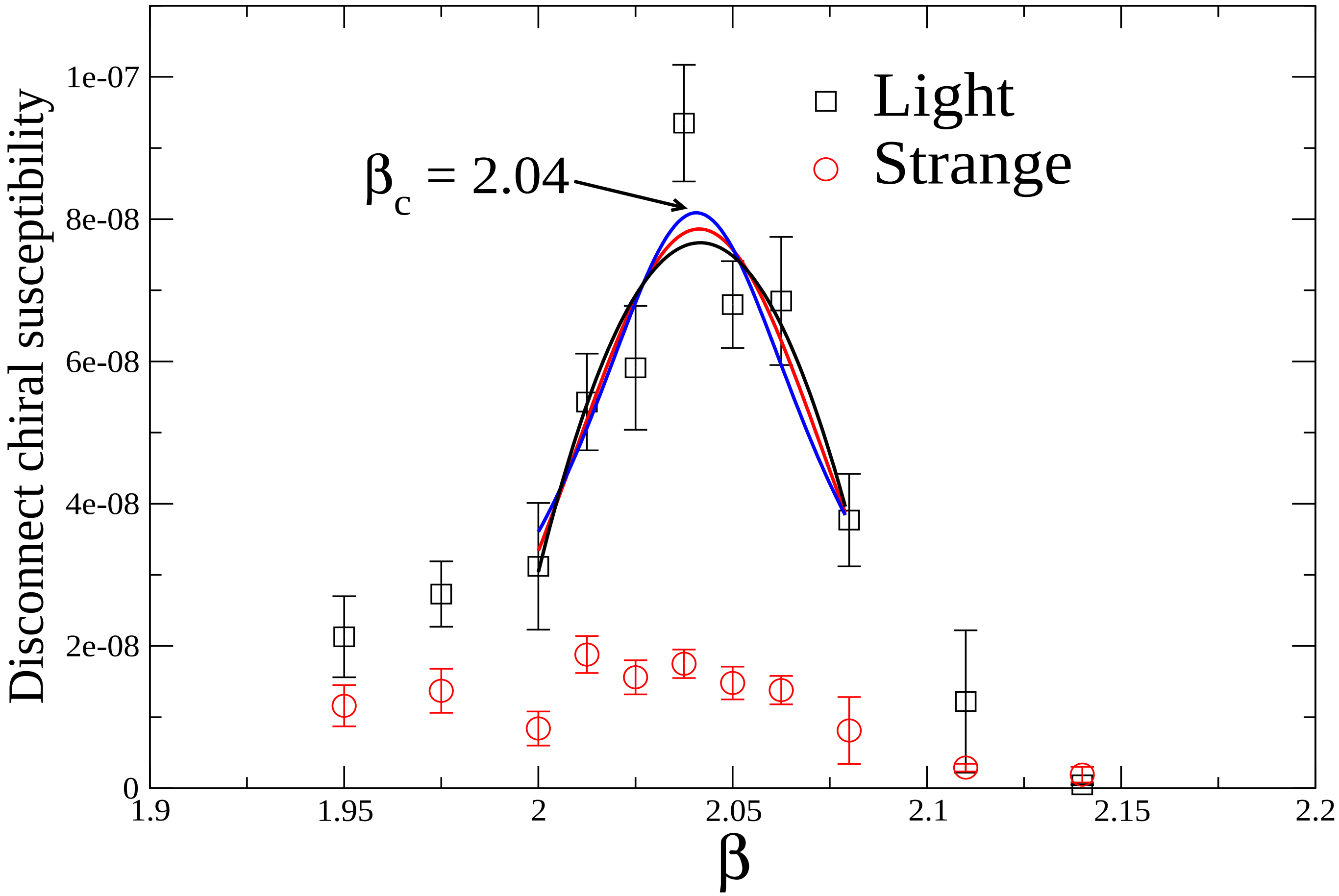


- $\mathbf{m_{res}}$ increases exponentially with decreasing β for L_s=32
- Total quark mass is not fixed with β → increases as we go to coarser lattices
- $\mathbf{m_{res}}$ dominated by non-perturbative lattice dislocations, suppressed by only $1/L_s$

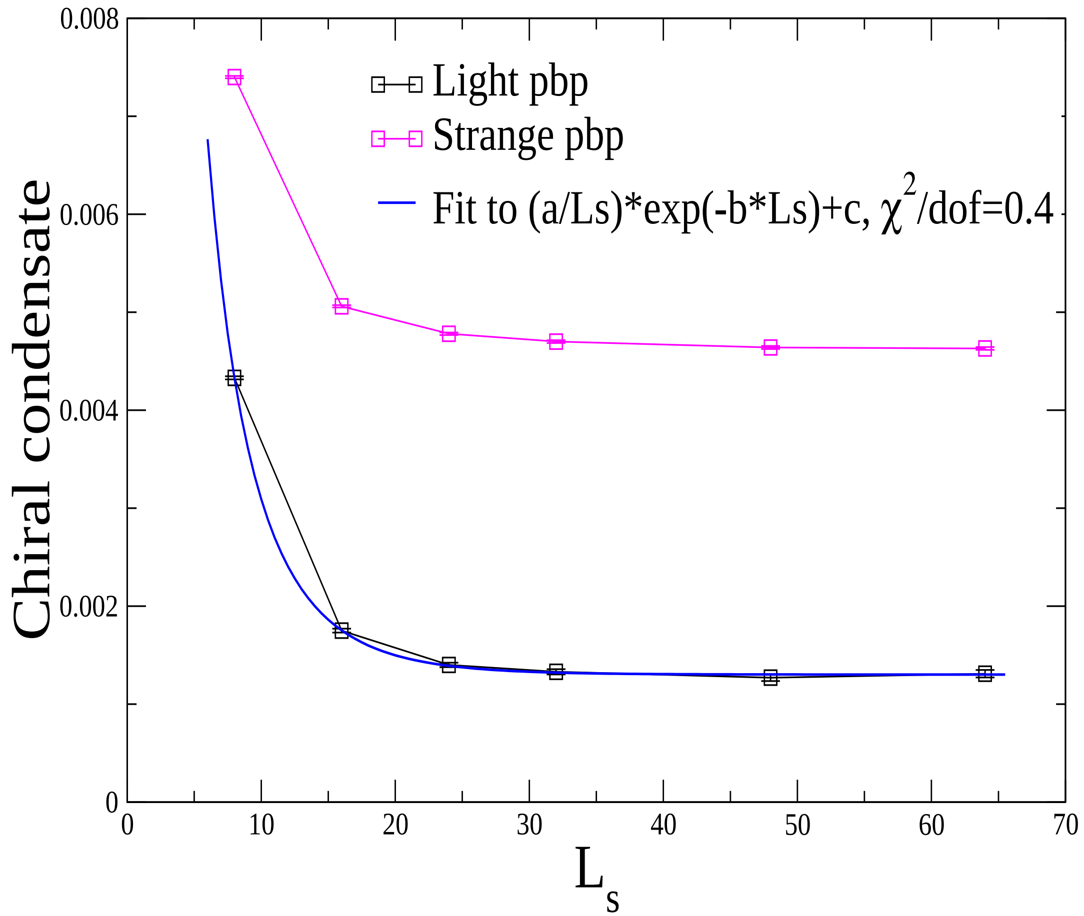
Chiral Condensate



Chiral Susceptibility

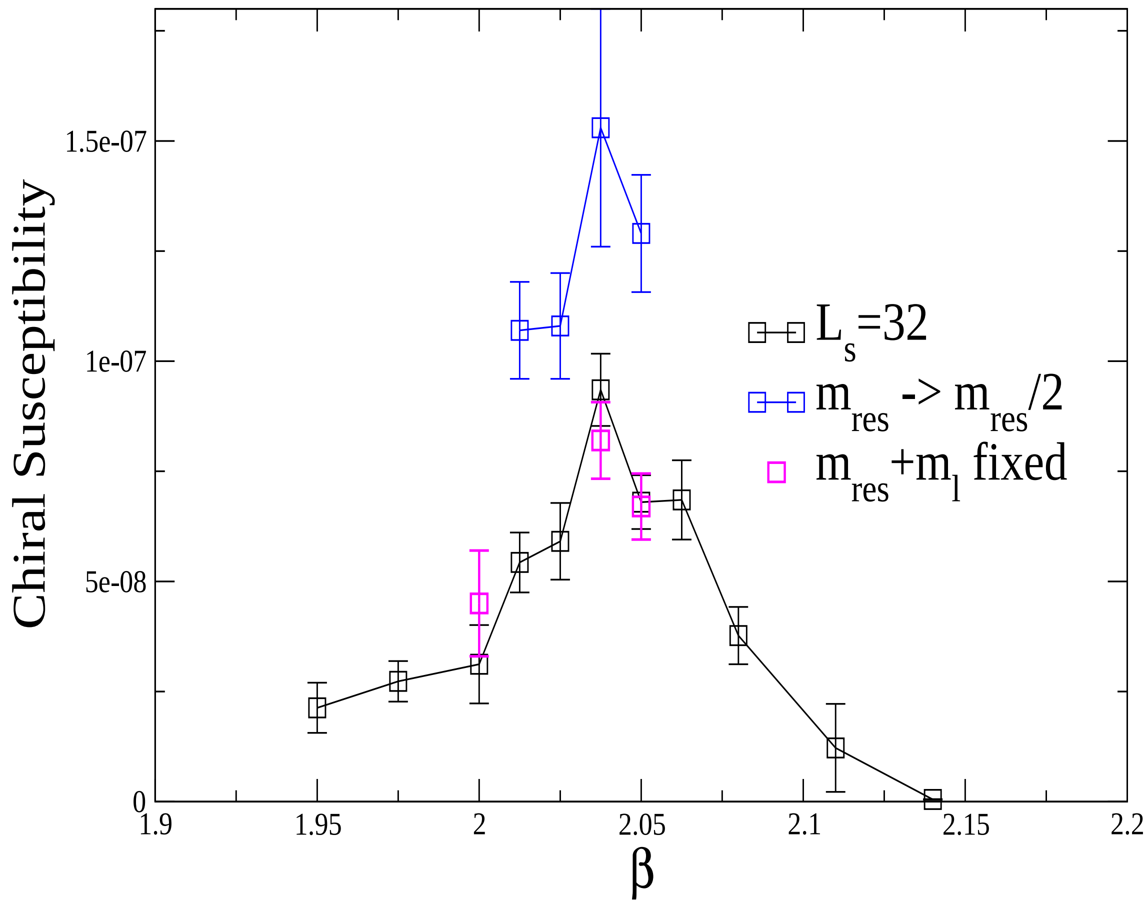


Chiral condensate vs. L_s



- At large L_s, m_{res} dominated by small lattice dislocations.
- Chiral condensate does not change very much at large L_s
- Conclusion → Chiral condensate is not affected by contributions from localized modes.

Susceptibility vs. L_s



- Changing L_s to 64 (reducing m_{res} by factor of 2) increases chiral susceptibility
- Changing L_s to 96, but keeping (m_l+m_{res}) fixed has little effect on susceptibility.
- Conclusion → Susceptibility seems to be function of total light quark mass (m_l+m_{res}).

Scale Setting

- 16^3 x 32 lattice volume at β = 2.025, near susceptibility peak of $\beta_{\mathbf{c}} \approx \mathbf{2.04}$
- Scale setting using Sommer parameter: r_0 = 0.469(7) fm. (Easy comparison with other T_c calculations, not extremely sensitive to quark mass)
- At β = 2.025, r_0/a = 3.08(9) corresponds to a^{-1} = 1.3 GeV
- At β = β_c, r_0/a = 3.25(18).
- Inflated error bar from uncertainty in β_c, chiral extrapolation, finite volume effects.
- Corresponds to **T_c = 170 MeV**.
- Hadron spectrum also measured:
- **Pion: m_π = 300 MeV Kaon: m_K = 490 MeV**
- Setting scale using m_ρ gives rough (10%) agreement.

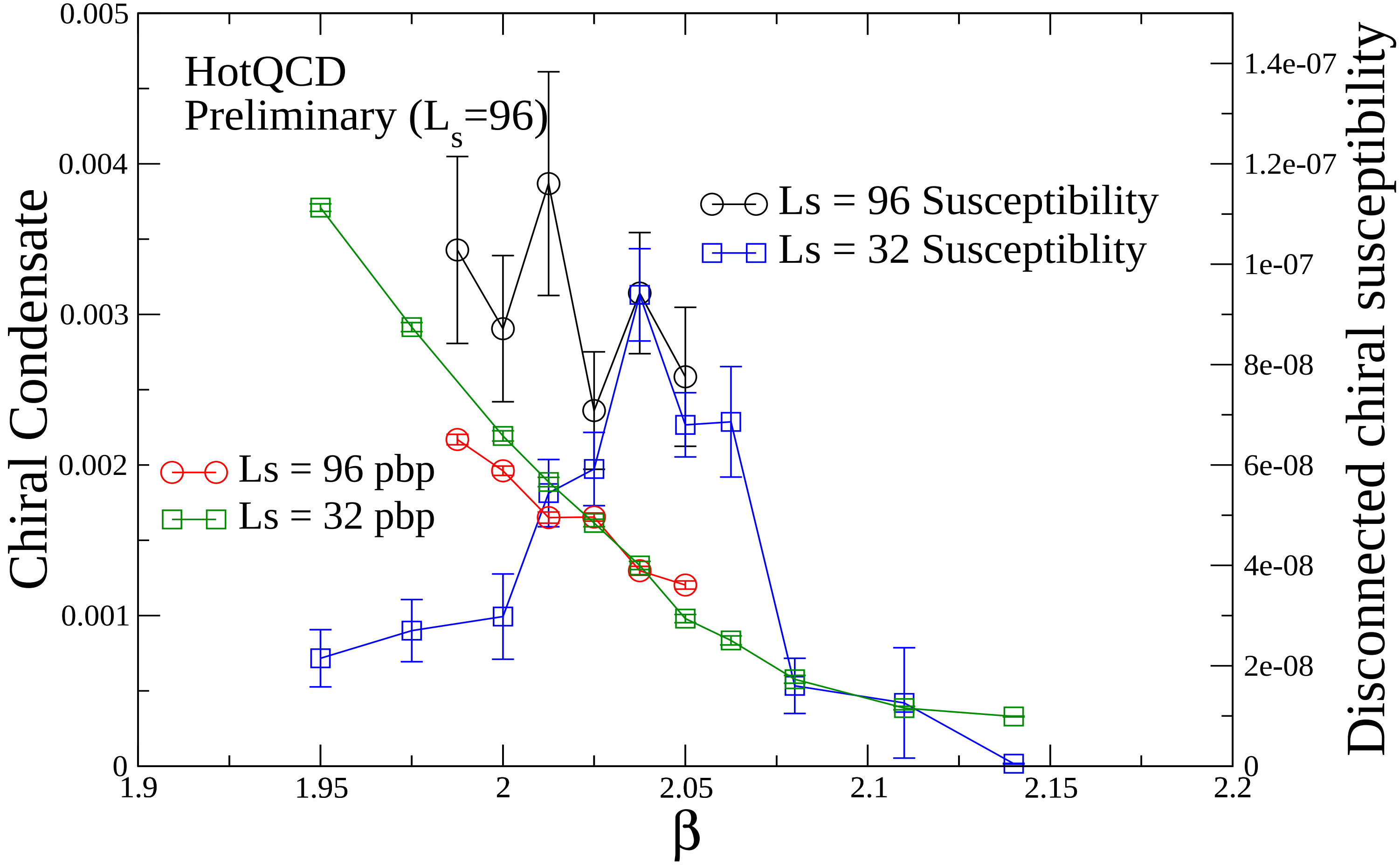
T_c for L_s = 32

- Best estimate from L_s = 32 calculation, **T_c = 170(10)(17) MeV**
- First error from estimate of scale at β_c.
- Estimate of second error – from lack of chiral and continuum extrapolation. Use staggered calculation as guide → chiral extrapolation should be similar, continuum → ???
- Lower than some recent staggered results, large error bar
- **Several major caveats:**
  - Light quark mass not constant in transition region. Estimated effect: shifts T_c lower by 3%, but error is uncontrolled.
  - Total light quark mass dominated by m_{res}, especially at strong coupling. Could this cause adverse effects?
  - Small aspect ratio (16^3x8)
  - No chiral or continuum extrapolation possible as yet.
- Exploratory, “proof of principle” calculation.

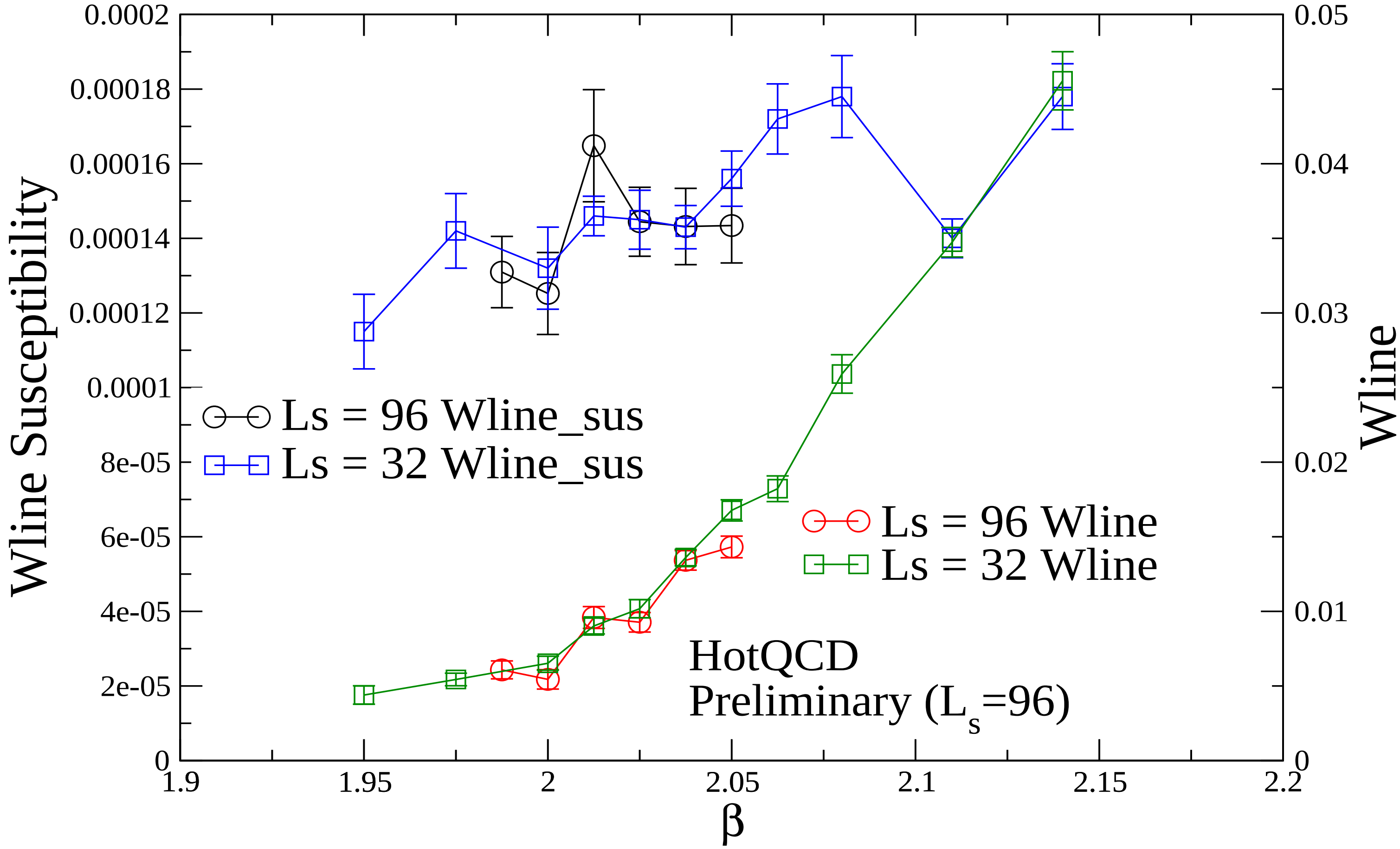
HotQCD Ls=96 Project

- **HotQCD**: Collaborations of collaborations involving RBC-Bielefeld, MILC, LLNL, LANL.
- **Goals: Lattice thermodynamics (T_c, EoS) using p4, asqtad (talk by R. Gupta) and DWF actions.**
- DWF with $L_s = 96$
- Addresses *some* of caveats from Ls = 32 calculation:
  - Suppress m_{res} by factor of 3, so total quark mass is not dominated by m_{res}.
  - Quark masses adjusted so that $(m_l + m_{res})a$ is constant at each value of β. Light mass is 15% of strange mass.
- 6 values of β → $1.9875 < \beta < 2.05$ → more to be added.
- Currently 1000+ trajectories at each β.
- Expect β_c at stronger coupling compared to L_s=32.

Chiral Condensate



Wilson line



Wline Susceptibility
Wline
β
0.0002
0.00018
0.00016
0.00014
0.00012
0.0001
8e-05
6e-05
4e-05
2e-05
0
0.05
0.04
0.03
0.02
0.01
0
1.9
1.95
2
2.05
2.1
2.15
2.2
Ls = 96 Wline_sus
Ls = 32 Wline_sus
Ls = 96 Wline
Ls = 32 Wline
HotQCD
Preliminary (L_s=96)

Conclusions/Outlook

- **RBC calculation with L_s=32 (complete)** → "proof of principle" for DWF thermodynamics.
- T_c = 170(10)(17) MeV, but with several caveats.
- Improved **HotQCD calculation with L_s = 96 (in progress)** → Total light quark mass constant in transition region, light quark mass 15% of strange quark mass.
- Critical region seems to shift to stronger coupling with L_s=96 compared to L_s=32, but β_c not determined accurately for L_s=96. Evidence of shoulder? (Karsch)
- L_s = 96 is an expensive way to suppress m_{res} - exploring other alternatives to more efficiently do this: "Vranas Auxiliary Determinant DWF" (talk by D. Renfrew)