Quark localization in QCD above T_c

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Dirac operator

Continuum

- $\not{D} = \gamma_\mu \partial_\mu + m$
- Quark propagator $\sim$ inverse of $\not{D}$
- Banks-Casher $\langle \bar{\psi}\psi \rangle = \lim_{m\to 0} \lim_{V\to\infty} \frac{\pi\rho(0)}{V}$
- Importance of the low lying eigenvalues

Symmetries

- Anti-hermitian: $D^\dagger = -D$
- Chiral symmetry:$\{D, \gamma_5\} = 0$
- γ_5 hermiticity: $D^\dagger = \gamma_5 D \gamma_5$
- Eigenvalues come in complex conjugate pairs

Dirac spectrum below and above T_c

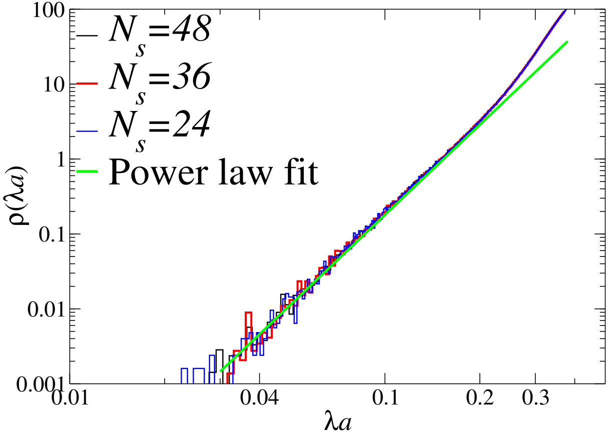
- $T < T_c$: Random Matrix statistics in the ε regime [Shuryak,Verbaarschot(1993)]
- $T \simeq T_c$: Localized eigenmodes [Garcia-Garcia,Osborn(2006)]
- $T > T_c$: lowest eigenmodes of the $SU(2)$ overlap Dirac operator follow Poisson statistics [T.G.Kovacs(2010)]
- $SU(2)$ quenched: localized-delocalized transition [T.G.Kovacs,FP(2010)]

QCD

- $SU(3)$ gauge theory 2 + 1 flavors of dynamical quarks with physical masses[Wuppertal Budapest]
- Determinant suppresses the lowest quark modes

Spectral density of the Dirac operator

$N_t = 4, a = 0.125\text{fm}, V = 27\text{fm}^3 \to 215\text{fm}^3, T = 2.6\,T_c$



- Chiral symmetry $\lim_{\lambda\to 0}\rho(\lambda) = 0$
- Scales properly with the volume
- No evidence of spectral gap
- $\rho(\lambda) = c\lambda^4$ for small λ

The spectral statistics and localization of D above T_c

RMT type spectrum

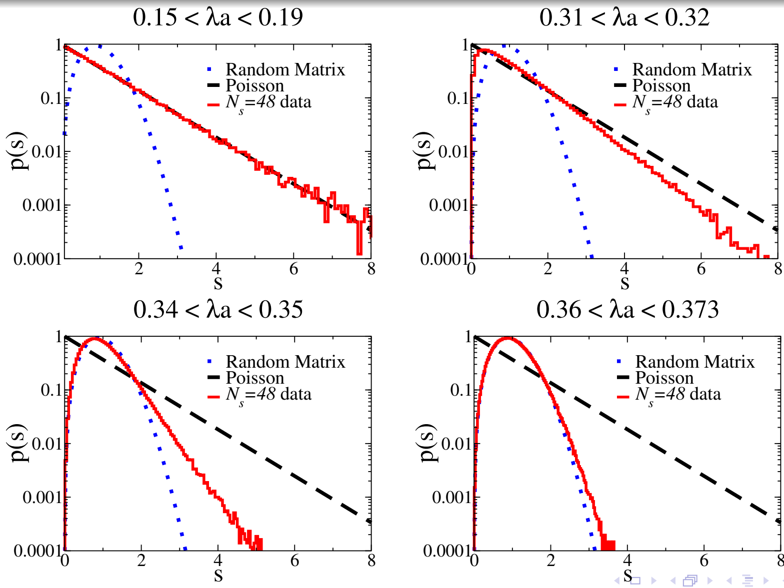
- The spectral density is large
- The eigenvectors have spatial overlap: delocalized modes
- Typical fluctuations in the gauge field mix the eigenmodes
- Eigenvalues are correlated: Wigner-Dyson statistics

Poisson type spectrum

- The spectral density is small
- The eigenvectors do not have spatial overlap: localized modes
- Typical fluctuations in the gauge field do not mix the eigenmodes
- Eigenvalues are uncorrelated: Poisson statistics

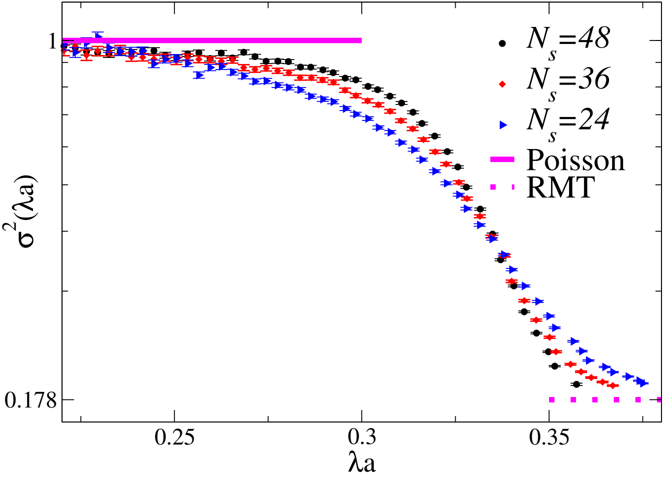
Unfolded level spacing distribution (ULSD)

$N_t = 4$, $N_s = 48$, $s = \frac{\lambda_{n+1} - \lambda_n}{\langle \lambda_{n+1} - \lambda_n \rangle}$



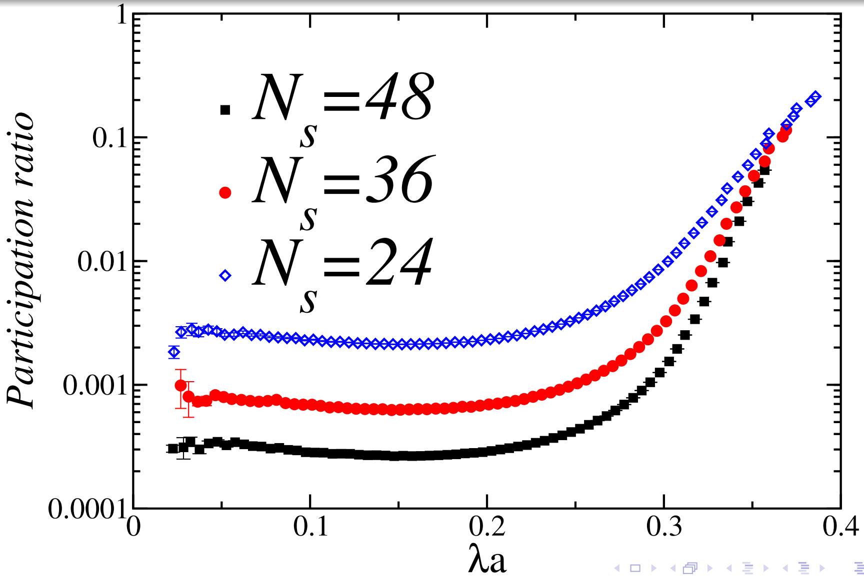
Thermodynamic limit

Variance of the *ULSD* in the spectrum for several volumes, $N_t = 4$, $a = 0.125\text{fm}$



- We can define a mobility edge(λ_c) for all V
- $\lambda_c \equiv$ Location of the inflection point of the curves
- ? Is it a real phase transition?
- √ M. Giordano's talk

QCD Dirac spectrum: Localization-Delocalization transition in terms of eigenvector statistics



Effects of localized modes

- quark propagator $\sim$ inverse of D
- Hadronic correlators: build up from quark propagators
- Lowest modes: largest weight
- They have negligible contribution to the long distance correlators

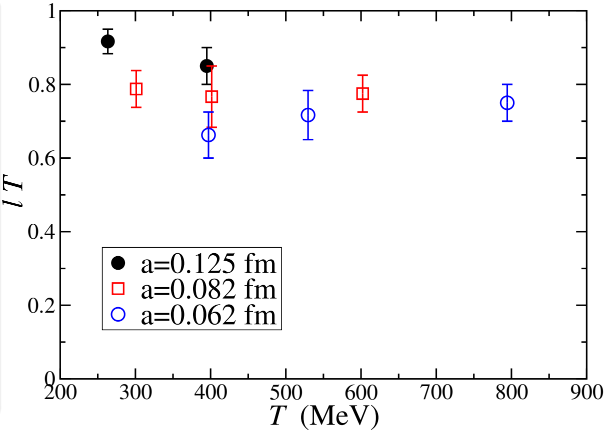
Questions:

- How large is the localization length?
- How far up in the spectrum are the eigenmodes localized?

Localization length

What detemines the localization length?

- Temperature squeezes the modes in the time direction
- Localized modes are squeezed in the same way in the spatial directions

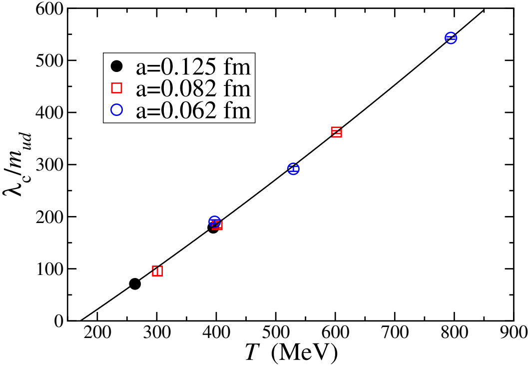


- Localization length $\sim$ inverse temperature

Mobility edge in the continuum limit

How λ_c behaves in the continuum?

- λ_c introduces an effective gap in the spectrum
- Its renormalization is similar to the quark mass
- λ_c / m_{ud} tends to finite value in the continuum limit
- Localization is physical



- $\lambda_c(T_c) = 0 \rightarrow T_c \simeq 170$ MeV

Conclusion

- Lowest part of the QCD Dirac operator consists of Poisson modes
- The Poisson modes are localized to a distance scale set by the inverse temperature
- Mobility edge is effectively a gap in the spectrum
- Is this a real phase transition? See M. Giordano's talk

Thank you for your attention!

References

[Shuryak,Verbaarschot(1993)] E. V. Shuryak and J. J. M. Verbaarschot, Nucl. Phys. A **560**, 306 (1993) [hep-th/9212088].

[Garcia-Garcia,Osborn(2006)] A. M. Garcia-Garcia and J. C. Osborn, Phys. Rev. D **75**, 034503 (2007) [hep-lat/0611019].

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