Caloron gas, localization and chiral restoration in high-T QCD

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QCD finite temperature crossover

- Deconfinement (center symmetry spontaneously broken)
- Chiral symmetry restored

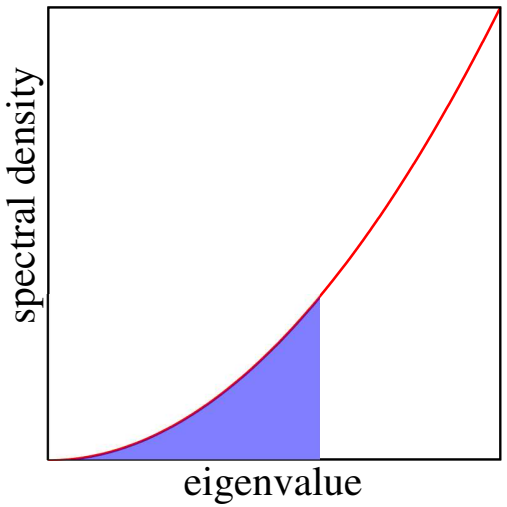
QCD finite temperature crossover

- Deconfinement (center symmetry spontaneously broken)
- Chiral symmetry restored
- Localized quark modes appear at the low-end of the Dirac spectrum
  - Happens at sharp critical T_c^{loc}
  - QCD $T_{crossover} \approx T_c^{loc}$
  - Quenched $T_c = T_c^{loc}$

Above T_c low Dirac eigenmodes are localized

Well above T_c

- Chiral symmetry restored
- Lowest eigenmodes localized
- Eigenvalue statistics: Poisson



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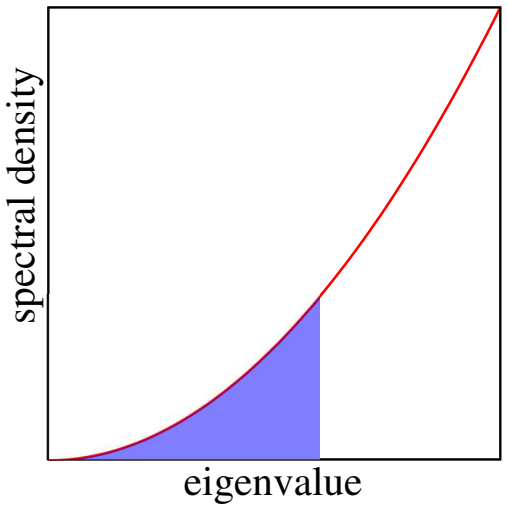
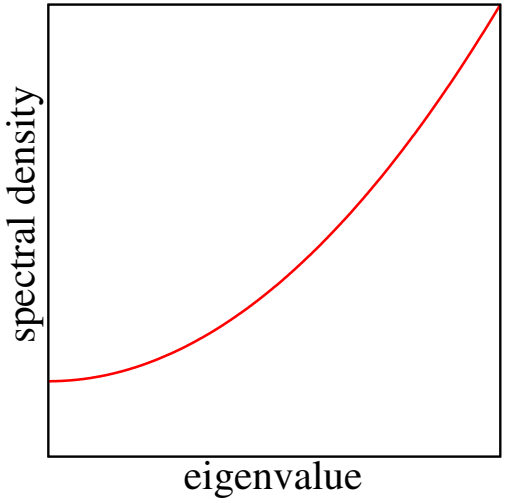


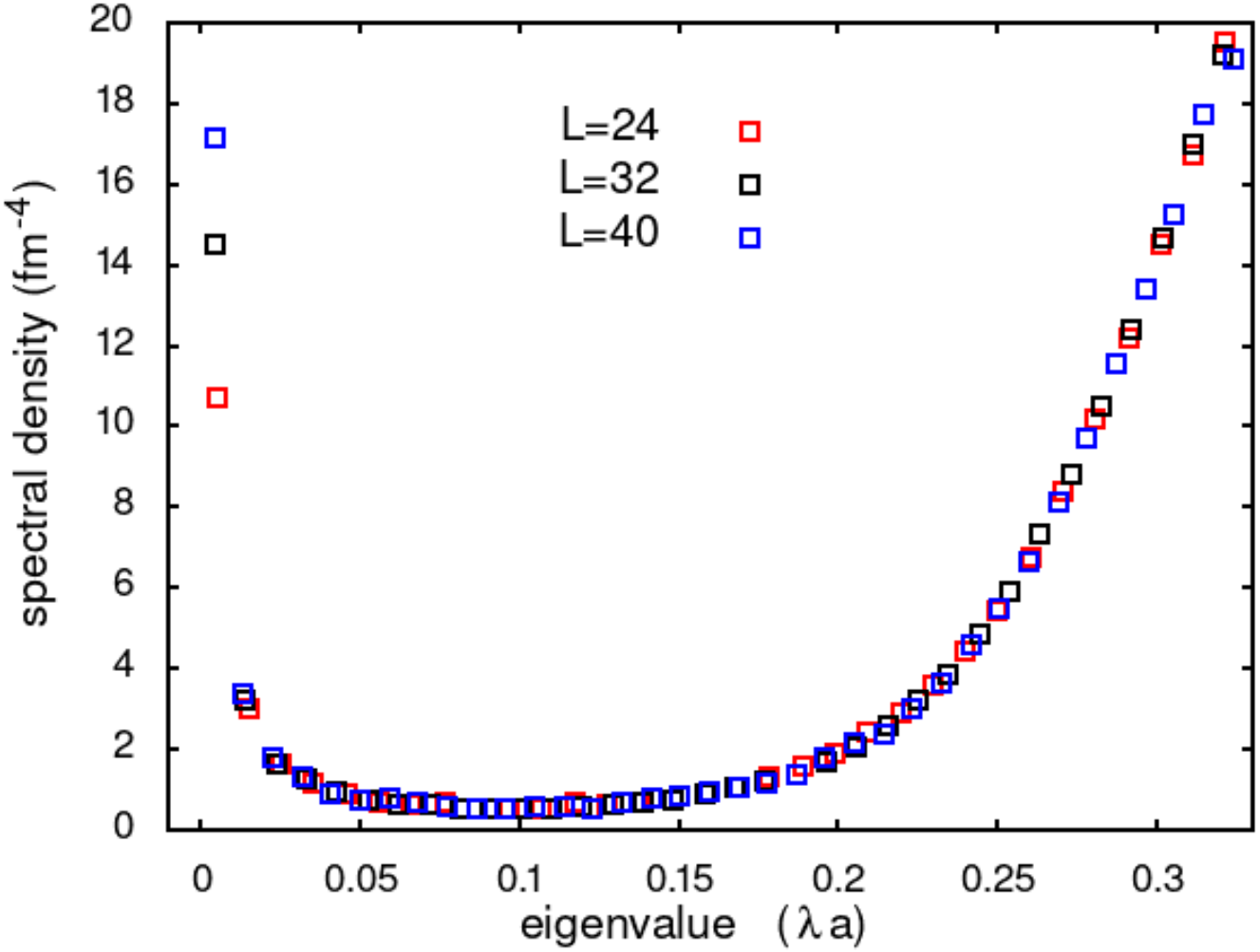
Below T_c

- Chiral symmetry broken
- All eigenmodes delocalized



Just above T_c

Overlap spectral density quenched, ($N_t = 6$, $T = 1.04\,T_c$)



Spectral peak at $\lambda = 0$

- Accumulation of near-zero modes

  Edwards et al. 2000; Alexandru & Horvath 2015

- Spectral peak is not a quenched artifact

  Alexandru & Horvath 2015

- Spectral density at $\lambda = 0$ nonzero
  $\Rightarrow$ chiral symmetry not restored

- What is the physics of modes in the peak?

- Are they just ordinary localized modes?

Are near-zero Dirac modes related to topology?

- Instanton $\longrightarrow$ quark zero mode
- Instanton + antiinstanton $\longrightarrow$ two cmplx conj. modes
- Above T_c
  - Instanton density falls sharply
  - Zero modes exponentially localized
  - $r_I, r_A \ll d_{IA} \quad \Rightarrow \quad |\lambda_{IA}|$ small
- Can the spectral peak be explained by I-A pairs?

Counting instantons $=$ counting Dirac modes?

The zero-mode zone (ZMZ)

- Assume that $|\lambda| < \lambda_{\mathrm{ZMZ}}$ are the topology-related ev.-s
- Total number (incl. 0-modes): $n_{\mathrm{I}} + n_{\mathrm{A}}$
- Number of zero modes: $|n_{\mathrm{I}} - n_{\mathrm{A}}| = Q$
- Can all be counted if we know λ_{ZMZ}
- Simplest model: free caloron gas
- Check consistency with expected number distributions

Distribution of topological charge

Is it consistent with free caloron gas? $(T = 1.04\,T_c)$

Free caloron gas

$\Rightarrow$ instanton and antiinstanton distributions independent, Poisson

$\Rightarrow$ distribution of Q can be computed; only parameter to fit: susceptibility

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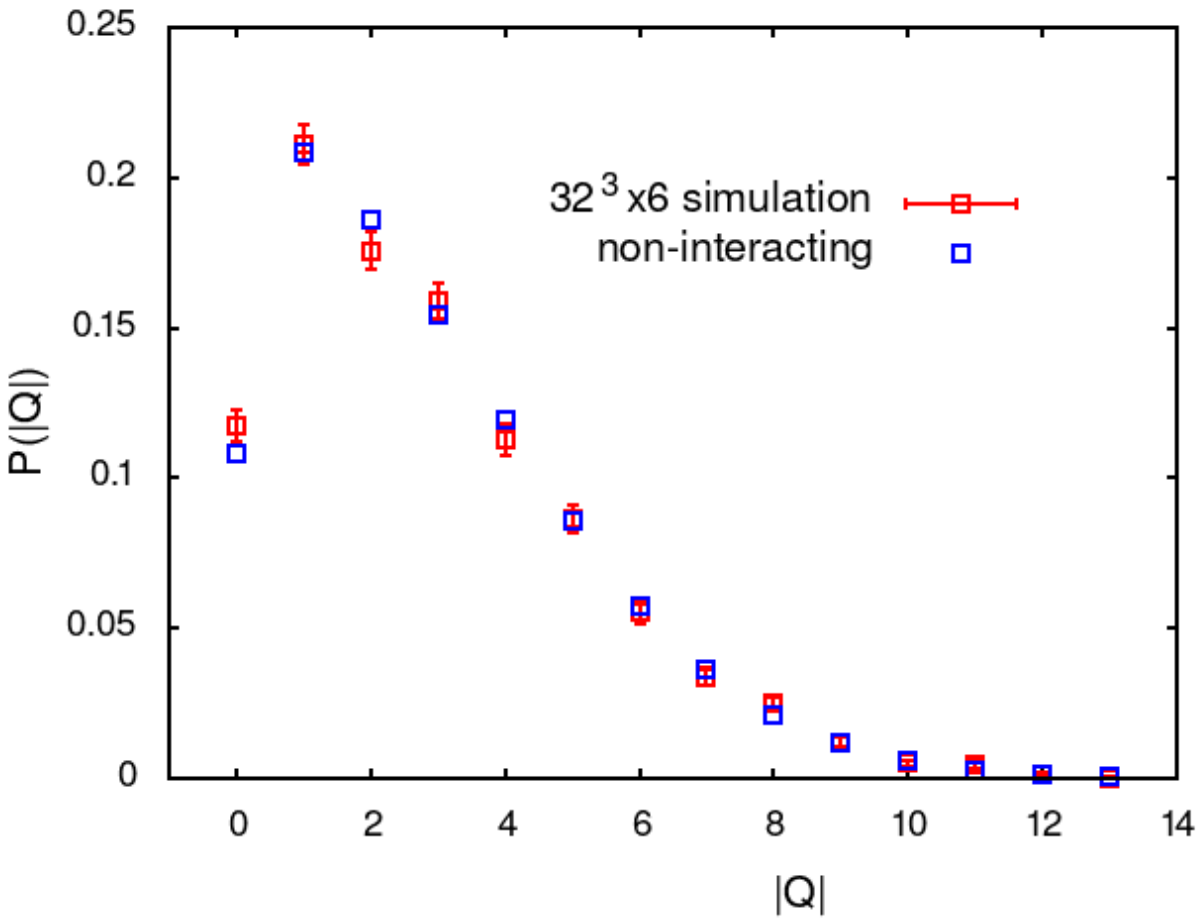

Distribution of the number of topological objects

$T = 1.04\,T_c$

Free instanton-antiinstanton gas $\Rightarrow$ $\langle n_{\mathrm{I}} + n_{\mathrm{A}} \rangle = \langle Q^2 \rangle$ determines λ_{ZMZ}

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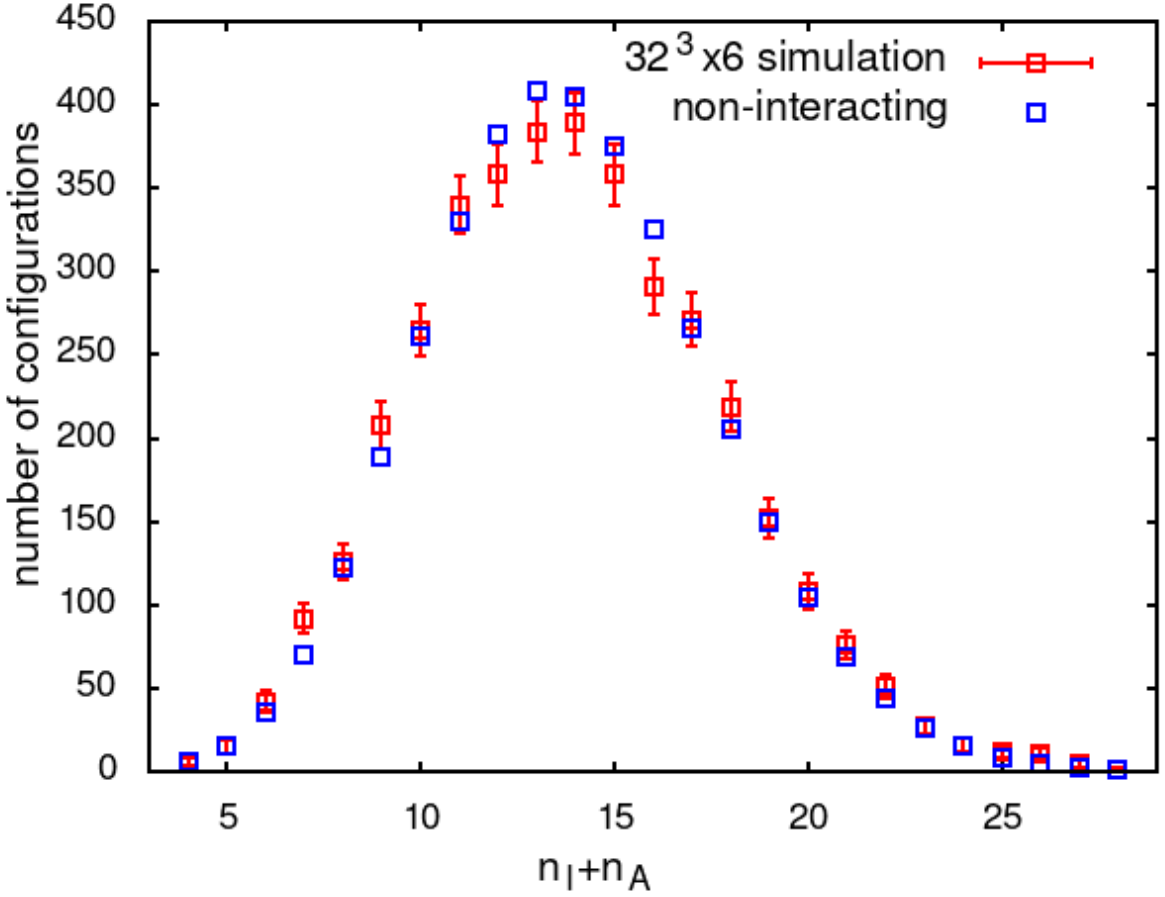
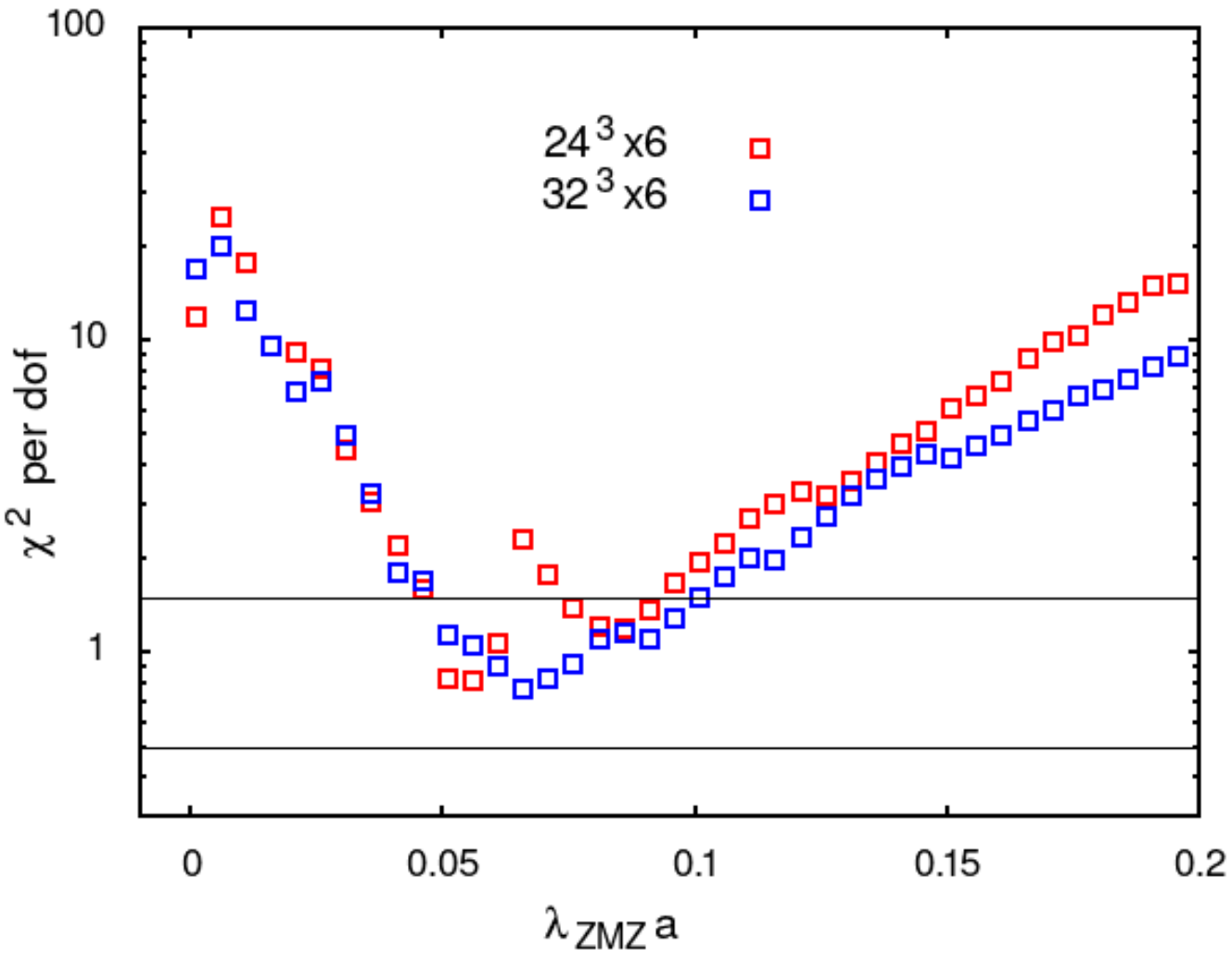


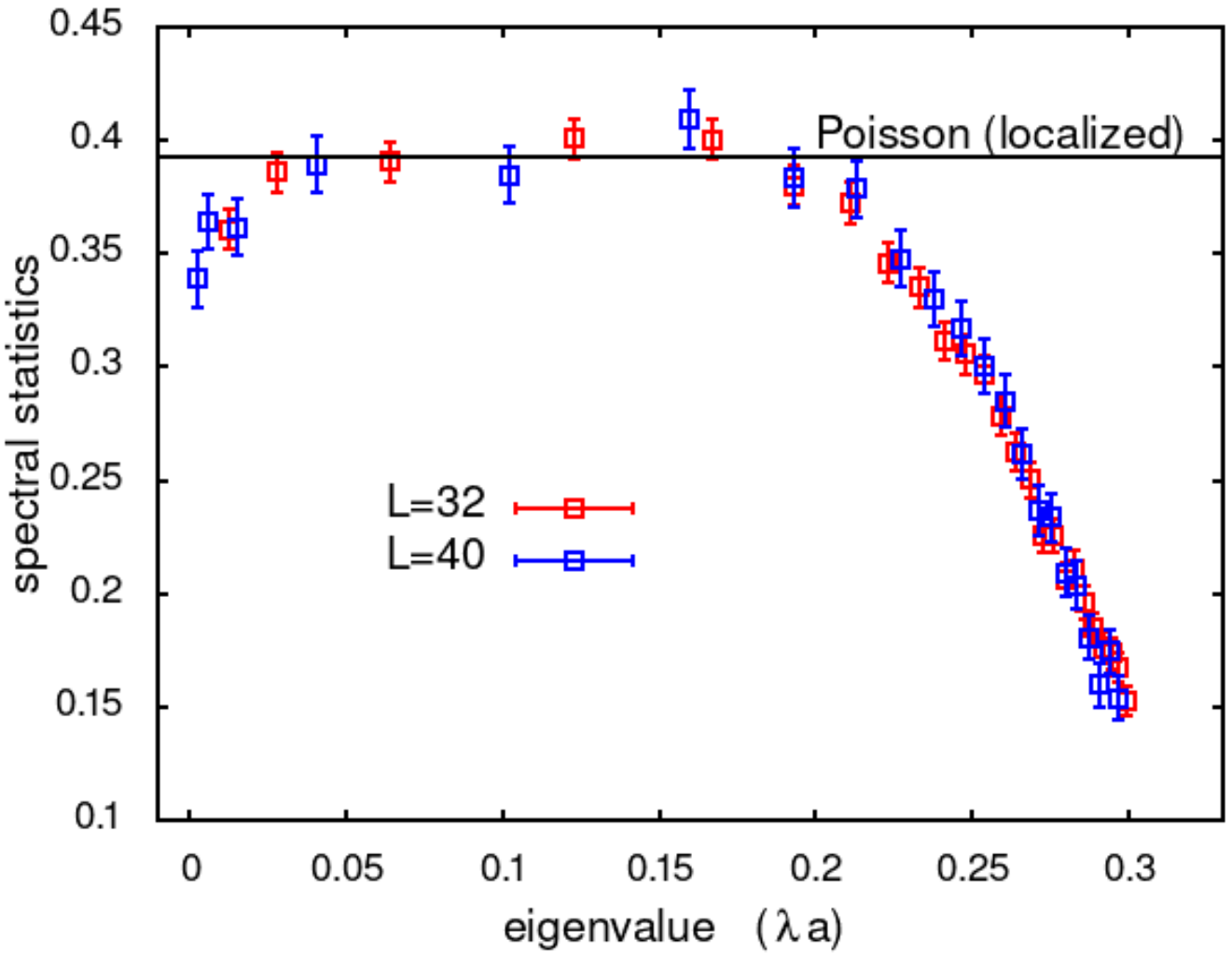
Is λ_{ZMZ} a special point in the spectrum?

Try to fit distribution of $n_I + n_A$ with Poisson using different λ_{ZMZ}



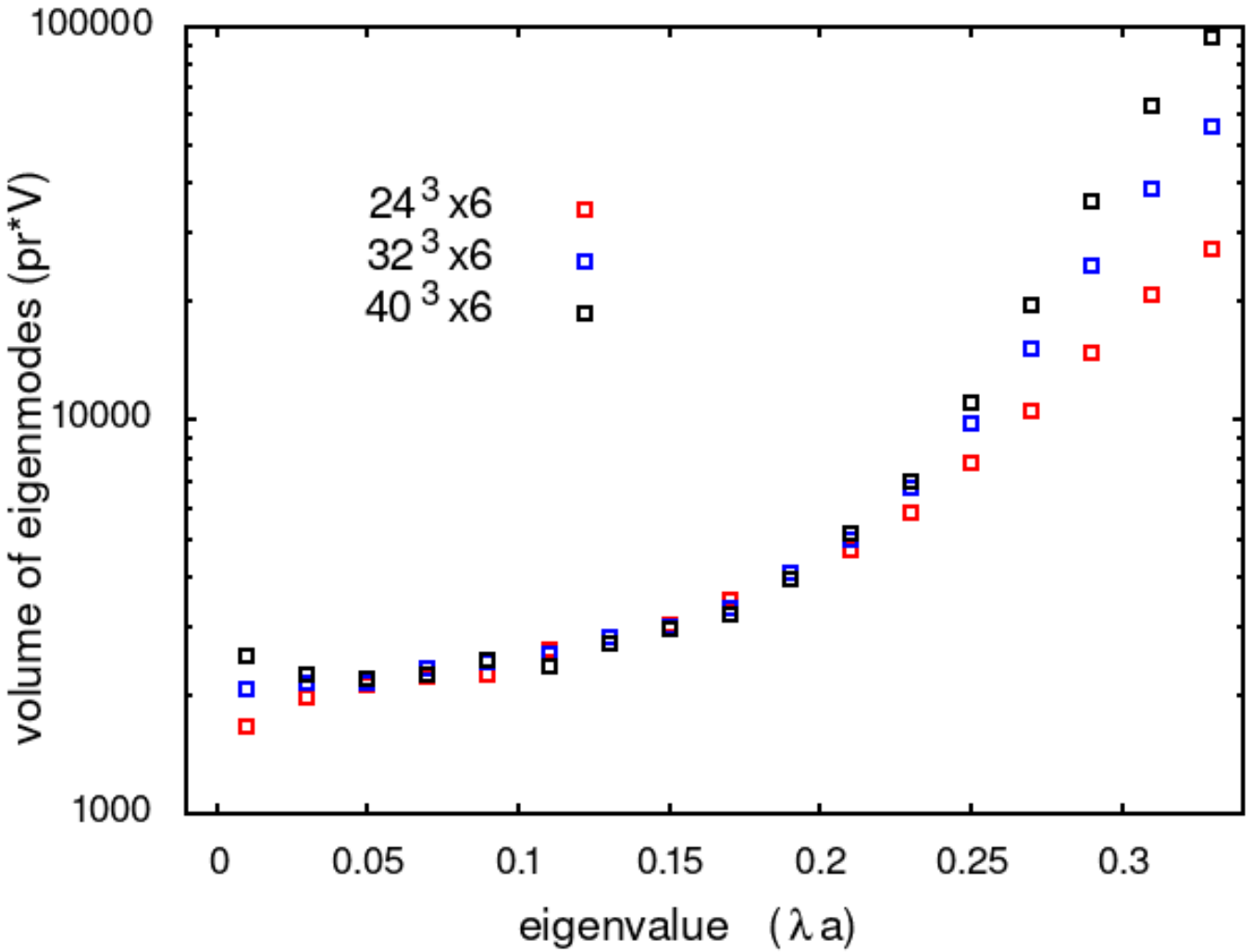
ZMZ: unusual spectral statistics in localized regime

Spectral statistics along the spectrum $1.04\,T_c$



Zero-mode zone: localized modes?

$T = 1.04\,T_c$



Conclusions

Dirac spectrum just above T_c

- Chiral Dirac operator can identify topology-related zero-mode zone in the dirac spectrum
- Quenched:
  statistics consistent with non-interacting caloron gas
- Structure of the Dirac spectrum above T_c
  - Zero-mode zone - caloron eigenmodes
  - Ordinary localized modes
  - Delocalized modes
- Generic feature, not a quenched artifact
- Chiral symmetry restoration is not trivial

Questions, speculations

- Are there caloron interactions with dynamical fermions?
- What happens in real QCD around T_c?
- Possible analogy with Golterman-Shamir localized modes in the Aoki phase?
- Connection to Alexandru-Horvath chiral polarization?
- There is interesting physics going on in the ZMZ and chiral fermions are suitable for exploring it.

Zooming in on the zero-mode zone

Spectral density of the log of the eigenvalues quenched, ($N_t = 6$, $T = 1.04\,T_c$)