The fate of chiral symmetry in the quark-gluon plasma

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Symmetries of QCD and their realization

- partition function $Z = \int \mathscr{D}U \ \prod_f \det\left(D[U] + m_{\rm f}\right) \cdot {\rm e}^{-S_{\rm g}[U]}$

- $m_{\rm u} \approx m_{\rm d} \approx 0$

- Symmetries: $SU(2)_{\rm V} \times SU(2)_{\rm A} \times U(1)_{\rm V} \times U(1)_{\rm A}$
  - $U(1)_{\rm A}$ anomalous
  - $SU(2)_{\rm A}$ spontaneously broken below T_c

- Order parameter of $SU(2)_{\rm A}$ (Banks-Casher formula):

$$\langle \bar{\psi}\psi \rangle \ \propto \ \frac{1}{V}\sum_i \frac{1}{\lambda_i + m} \ \propto \ \int_{-\Lambda}^{\Lambda} d\lambda \ \frac{m}{\lambda^2 + m^2}\,\rho(\lambda) \ \xrightarrow[m\to 0]{} \ \rho(0)$$

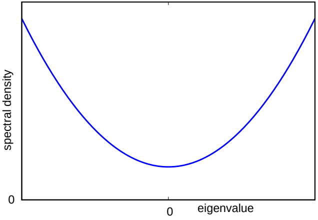
λ_i: eigenvalues of the Dirac operator, $\rho(\lambda)$: its spectral density

The finite temperature transition

Standard picture

Below T_c

- Chiral symmetry broken
- Order parameter: $\rho(0) \neq 0$



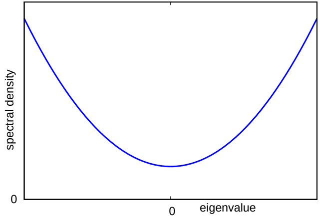
The finite temperature transition
Standard picture

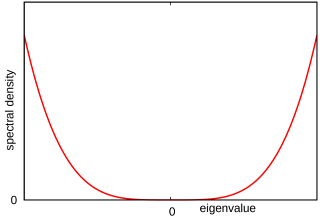
Below T_c

- Chiral symmetry broken
- Order parameter: $\rho(0) \neq 0$

Above T_c

- Chiral symmetry restored
- Order parameter $\rho(0) = 0$
- (Pseudo)gap (lowest Matsubara mode)

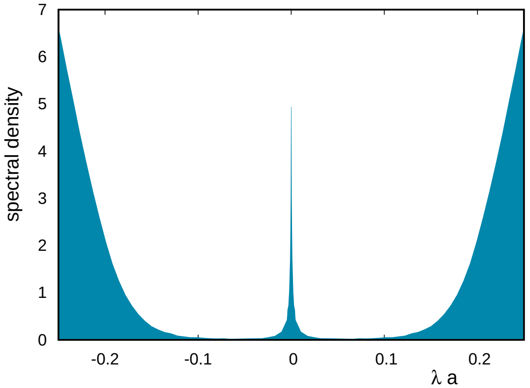




spectral density at 0 $\Longleftrightarrow$ realization of chiral symmetry

Spectral density at $T = 1.1\,T_c$ on the lattice

quenched (quark back reaction omitted)



$$Z = \int \mathscr{D}U \prod_f \cancel{\det(D[U] + m_f)} \cdot e^{-S_g[U]}$$

Peak at zero in the spectral density!

Edwards et al. PRD 61 (2000); Alexandru & Horvath, PRD 92 (2015); 2404.12298; Kaczmarek, Mazur, Sharma, PRD 104 (2021) 2021

Questions

- Why is there a peak at zero?
- How is it suppressed if the quark determinant is included?
- How does the peak influence chiral symmetry as $m \to 0$?

Instantons $\rightarrow$ zero eigenvalues of $D(A)$

- (Anti)instanton
  $\rightarrow$ zero eigenvalue of $D(A)$ with $(-)+$ chirality eigenmode

- High T:
  large instantons "squeezed out" in the temporal direction
  $\rightarrow$ dilute gas of instantons and antiinstantons

- Zero modes exponentially localized:

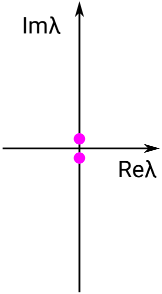
$$\psi(r) \propto e^{-\pi T r}$$

Instanton-antiinstanton pair

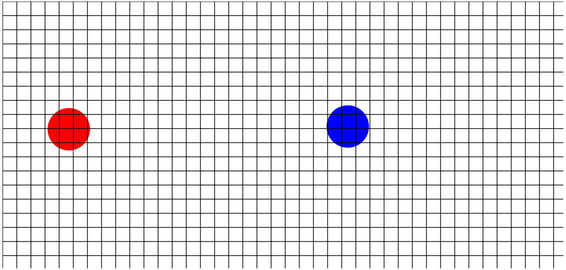
The Dirac operator in the subspace of zero modes

$$D(A) = \begin{pmatrix} 0 & iw \\ iw & 0 \end{pmatrix} \qquad w \propto e^{-\pi Tr}$$

Spectrum of $D(A)$



Instanton and antiinstanton



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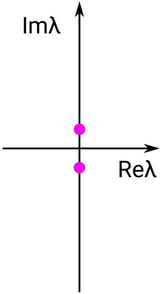

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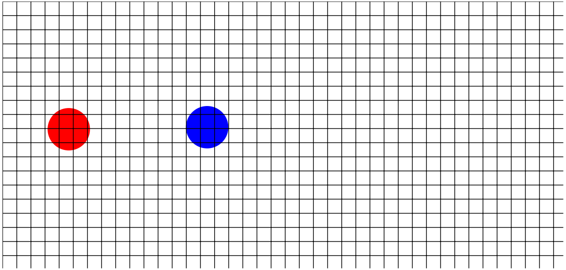

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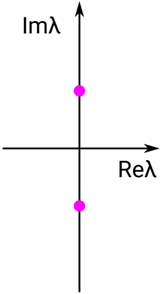

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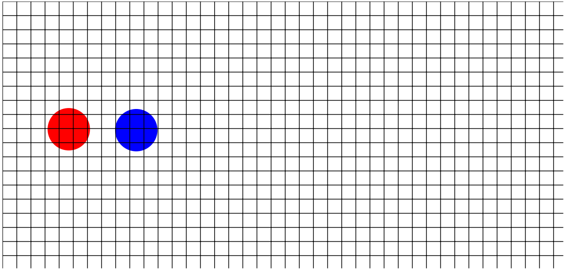

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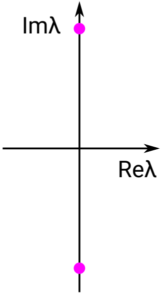

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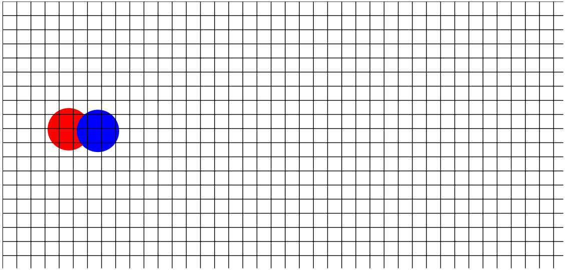

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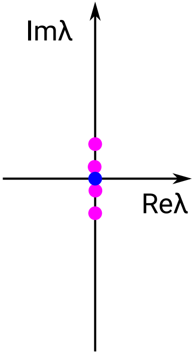
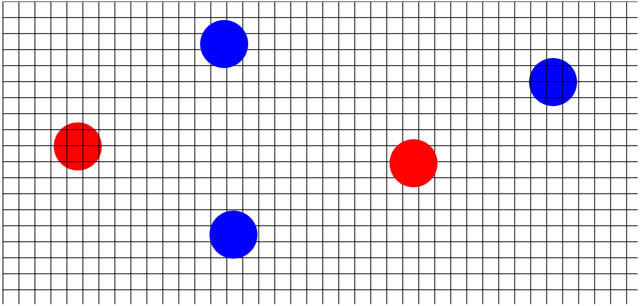


Instantons and antiinstantons



n_i instantons n_a antiinstantons

$\rightarrow$ $|n_i - n_a|$ exact zero modes + mixing near zero modes

Dirac operator in the subspace of zero modes (ZMZ)

Work by E.V. Shuryak, J.J.M. Verbaarschot, T. Schäfer (1990-2000)...

- Given n_i instantons, n_a antiinstantons in 3d box of size L^3
- Construct $(n_\mathrm{i}+n_\mathrm{a}) \times (n_\mathrm{i}+n_\mathrm{a})$ matrix:

$$D = \begin{pmatrix} \overbrace{0}^{n_\mathrm{i}} & \overbrace{iW}^{n_\mathrm{a}} \\ iW^\dagger & 0 \end{pmatrix}$$

- $w_{ij} = A \cdot \exp(-\pi T \cdot r_{ij})$ $\qquad$ r_{ij} is the distance of instanton i and antiinstanton j

Random matrix model of $D(A)$ in the zero mode zone

- How to choose instanton numbers (n_i, n_a) and locations?

- Quenched lattice $T > 1.05\, T_c \quad \rightarrow \quad$ free instanton gas

  Bonati et al. PRL 110 (2013); Vig R. & TGK, PRD 103 (2021)

  - n_i and n_a independent identical Poisson-distributed

$$p(n_i, n_a) = e^{-\chi V} \cdot \frac{(\chi V/2)^{n_i}}{n_i!} \cdot \frac{(\chi V/2)^{n_a}}{n_a!}$$

  χ is the topological susceptibility

  - Locations random (uniform)

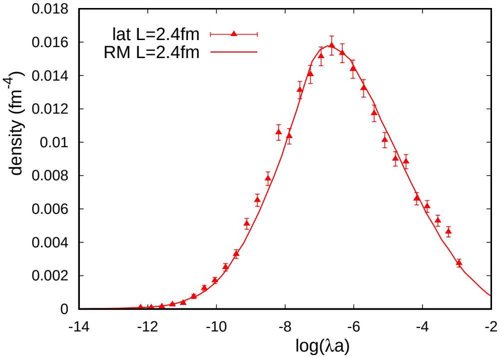
- $\rightarrow \quad$ D(A) in quenched QCD: ensemble of random matrices

Fit parameters to quenched lattice Dirac spectrum

$T = 1.1\,T_c$ overlap Dirac spectrum

- Two parameters:
  - χ – topological susceptibility: from exact zero modes $\rightarrow \chi = \langle Q^2 \rangle / V$
  - A – prefactor of the exponential mixing between zero modes
- Fit A to distribution of Dirac eigenvalues (lowest eigenvalue)

$L = 2.4$fm fit



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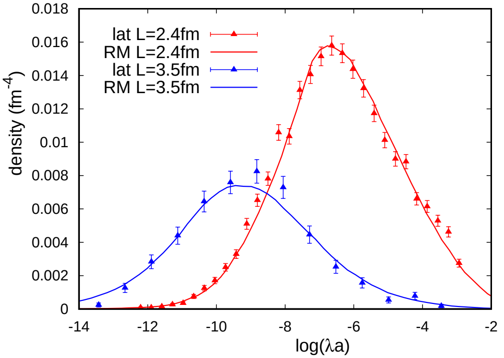
$L = 2.4$fm fit

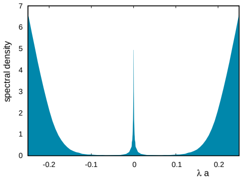
$L = 3.5$fm prediction



Random matrix model of full QCD zero mode zone

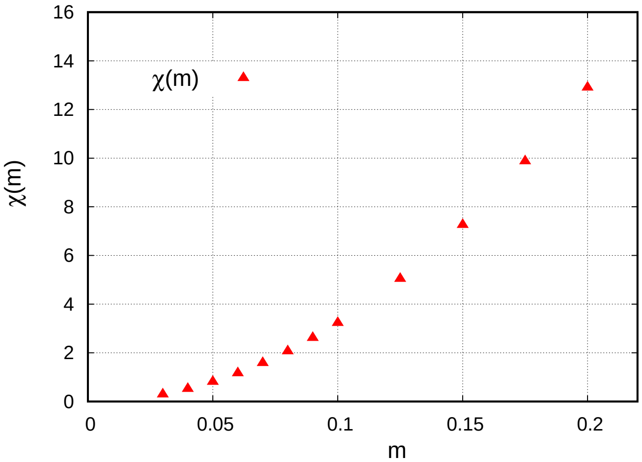
- Include $\det(D+m)^{N_f}$ in Boltzmann weight
- $\det(D+m) = \prod_{\text{zmz}}(\lambda_i + m) \times \prod_{\text{bulk}}(\lambda_i + m)$
- Bulk weakly correlated with zero mode zone
- Approximate det with $\prod_{\text{zmz}}(\lambda_i + m)$
- Consistently included in RM model:

$$P(n_i, n_a) = \underbrace{e^{-\chi_0 V} \frac{1}{n_i!} \frac{1}{n_a!} \left(\frac{\chi_0 V}{2}\right)^{n_i+n_a}}_{\text{free instanton gas with random locations}} \times \det(D+m)^{N_f}$$



Random matrix simulation: results for $N_f = 2$

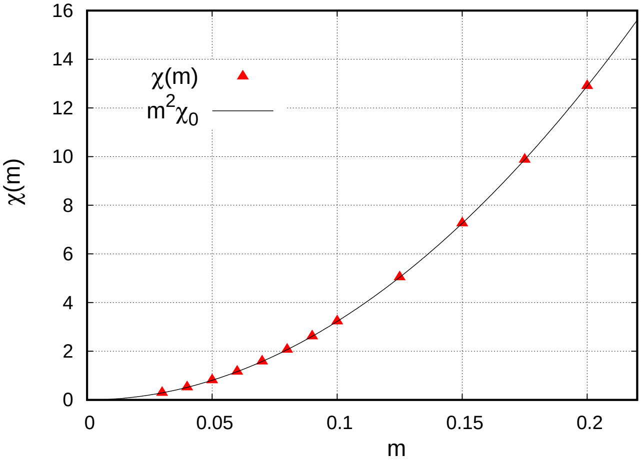
Topological susceptibility:



Random matrix simulation: results for $N_f = 2$

Topological susceptibility: $\chi(m) = m^2 \chi_0$ not a fit!

↑ quenched susceptibility



Explanation: free instanton gas

- Quark determinant for n_i instantons and n_a antiinstantons:

$$\det(D+m)^{N_f} = \prod_{n_\mathrm{i},n_\mathrm{a}} (\lambda_i + m)^{N_f} \approx m^{N_f(n_\mathrm{i}+n_\mathrm{a})}$$

if $|\lambda_i| \ll m$

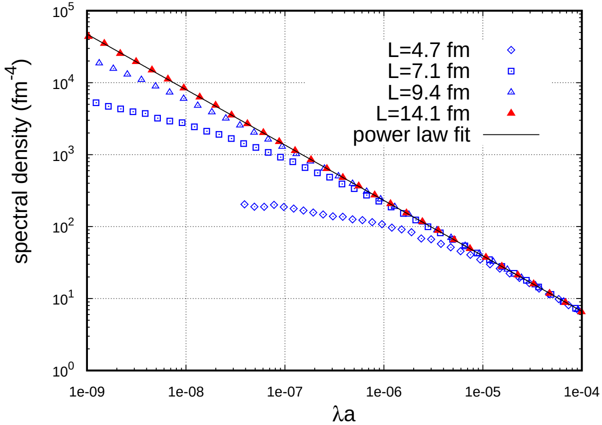
- Reweighting depends on number of topological objects, not on their type or location

$$P(n_\mathrm{i}, n_\mathrm{a}) \propto \left(\frac{\chi_0 V}{2}\right)^{n_\mathrm{i}+n_\mathrm{a}} \times \det(D+m)^{N_\mathrm{f}} \approx \left(\frac{m^{N_\mathrm{f}} \chi_0 V}{2}\right)^{n_\mathrm{i}+n_\mathrm{a}}$$

- Free gas, but susceptibility suppressed as $\chi_0 \to m^{N_\mathrm{f}} \chi_0$
- As $m \to 0$ instanton gas more dilute $\Rightarrow$ $|\lambda_i|$ smaller
- Even in the chiral limit $|\lambda_i| \ll m \implies$ free instanton gas

Spectral density singular at the origin for $V \to \infty$

RM model simulation, parameters from quenched $T = 1.1\,T_c$ overlap spectrum



$$\rho(\lambda) \propto \lambda^{\alpha}$$

fit: $\alpha = -0.770(5)$

Singular spectral density from similar instanton model:

Sharan and Teper, hep-ph/9910216

Banks-Casher for a singular spectral density?

“Banks-Casher” for singular spectral density

$$\langle \bar{\psi}\psi \rangle \;\propto\; \Big\langle \sum_i \frac{m}{m^2+\lambda_i^2} \Big\rangle \;\approx\; \underbrace{\begin{pmatrix}\text{avg. number of in-}\\ \text{stantons in free gas}\end{pmatrix}}_{m^{N_f}\chi_0 V} \cdot \frac{1}{m} \;=\; m^{N_f-1}\chi_0 V$$

$|\lambda_i| \ll m$

"Banks-Casher" for singular spectral density

$$\langle \bar{\psi}\psi \rangle \;\propto\; \langle \sum_i \frac{m}{m^2+\lambda_i^2} \rangle \approx \underbrace{\begin{pmatrix}\text{avg. number of in-}\\ \text{stantons in free gas}\end{pmatrix}}_{m^{N_f}\chi_0 V} \cdot \frac{1}{m} \;=\; m^{N_f-1}\chi_0 V$$

$$|\lambda_i| \ll m$$

$U(1)_A$ breaking susceptibility $\chi_\pi - \chi_\delta$

$$\langle \sum_i \frac{m^2}{(m^2+\lambda_i^2)^2} \rangle \approx \underbrace{\begin{pmatrix}\text{avg. number of in-}\\ \text{stantons in free gas}\end{pmatrix}}_{m^{N_f}\chi_0 V} \cdot \frac{1}{m^2} \;=\; m^{N_f-2}\chi_0 V$$

$$\rightarrow \quad \lim_{m\rightarrow 0}(\chi_\pi - \chi_\delta) \neq 0 \qquad \text{for } N_f = 2$$

Related developments & outlook

- RM model @ small $m \to$ instanton-antiinstanton molecules

  do not contribute to $\langle\bar{\psi}\psi\rangle$ and $\chi_\pi - \chi_\delta$ in the chiral limit

- Constraints on the Dirac spectrum from chiral symmetry restoration

  $\to$ consistent with free instanton gas M. Giordano, 2404.03546 (2024)

- Localization properties of eigenmodes in ZMZ

  M. Giordano and TGK, Universe 7 (2021); A. Alexandru and I Horvath, PRL 127 (2021), PLB 833 (2022)

- What is the lowest temperature where the instanton gas is ideal?

  $\to$ dynamical simulation with chiral quark action talk by A. Kotov

Related developments & outlook

- Possible new "phase" of QCD just above T_c A. Alexandru and I Horvath, PRD 100 (2019)

  structure of low eigenmodes very different @ $T \gtrsim T_c$ and $T \gg T_c$ χQCD and CLQCD, 2305.09459

- Other hints of different behavior @ $T \gtrsim T_c$ and $T \gg T_c$

  chiral spin symmetry Glozman, Prog.Part.Nucl.Phys. 131 (2023) vortices talk by C. Allton Tue.

- Maybe dilute gas of integer charges embedded in soup of light dyons?

  Mickley, Kamleh, Leinweber, PRD 109 (2024) + talk by J. Mickley Mon.

- Anderson model with off-diagonal disorder on bipartite lattice

  Chiral symmetry, power-law singularity in spectral density at zero, delocalization of modes toward zero.

  S.N. Evangelou and D.E.Katsanos, J. Phys. A 36 (2003)

Lots of things to be explored!

Conclusions

- At high T non-interacting degrees of freedom: free instantons (+ IA molecules)
- Dirac spectral density has singular peak at zero

  at any finite T, for any nonzero quark mass
- Chiral symmetry restoration nontrivial $\rightarrow$ $N_f = 2$: anomaly remains
- $SU(2)_A$ restored, but order of the $m \rightarrow 0$ and $V \rightarrow \infty$ limit still important
- Chiral limit with N_f degenerate light quarks:
  - $\langle \bar{\psi}\psi \rangle \propto m^{N_f - 1}$
  - $\chi_\pi - \chi_\delta \propto m^{N_f - 2}$

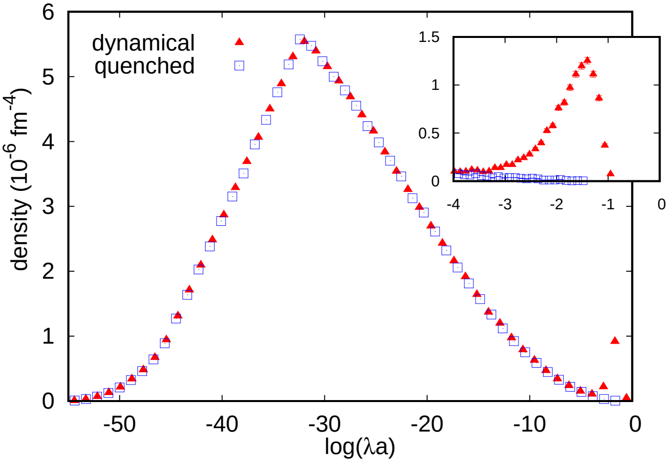
agrees with small m expansion of the free energy

Kanazawa and Yamamoto, PRD 91 (2015), JHEP 01 (2016)

BACKUP SLIDES

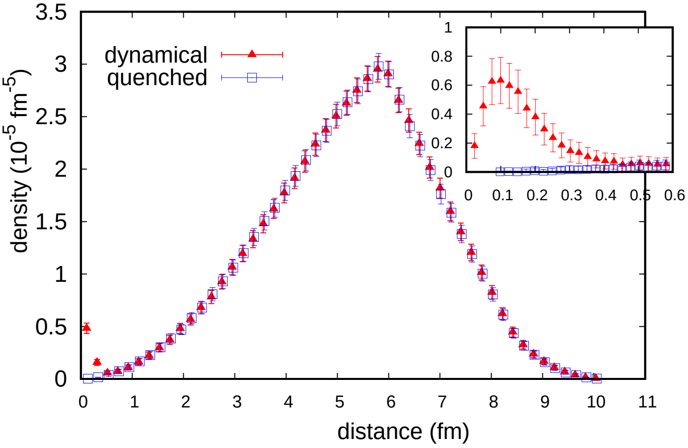
Spectral density – full QCD vs. ideal instanton gas

random matrix model, same topological susceptibility



Instanton-antiinstanton molecules

density of closest opposite charge pairs at given distance



Direct lattice simulations?

- Important to resolve small Dirac eigenvalues
  $\rightarrow$ chiral action needed JLQCD, PRD 103 (2021)

- To see spectral peak: large volume, close to T_c needed

- $\dfrac{\chi_\pi - \chi_\delta}{\chi_{\text{top}}} \propto m^{-2}$ instanton contribution independent of T

- Explore how far down in T free instanton gas persists
  - Compare eigenvalue statistics to prediction of free instanton gas
  - Can be done in each topological sector separately