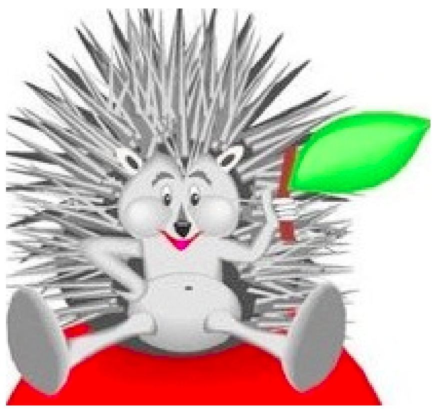
The semiclassical theory of deconfinement, chiral and Roberge-Weiss-like phase transitions



Edward Shuryak
Stony Brook University

“Probing the phase structure of strongly interacting matter: theory and experiment” GSI, March 2019

outline

- VEV of Polyakov line and the instanton-dyons
- Deconfinement transition
- Chiral symmetry breaking
- Generalized quark periodicity phases
- New set of phase transitions
- Instanton-dyons on the lattice

Instanton-dyons <=> Monopoles relation:
examples of the Poisson duality

Semiclassics at finite T and pre-clustering at freeze out

the semiclassical theory
Of gauge field solitons at finite T

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Confinement => BEC of monopoles, flux tubes (1970's)

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=> collectivization of instanton zero modes (1980's)

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=> topological objects observed but

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=> collectivization of instanton zero modes (1980's)

Lattice in 2000's
=> topological objects observed but
They are not quite instantons (?)

the semiclassical theory
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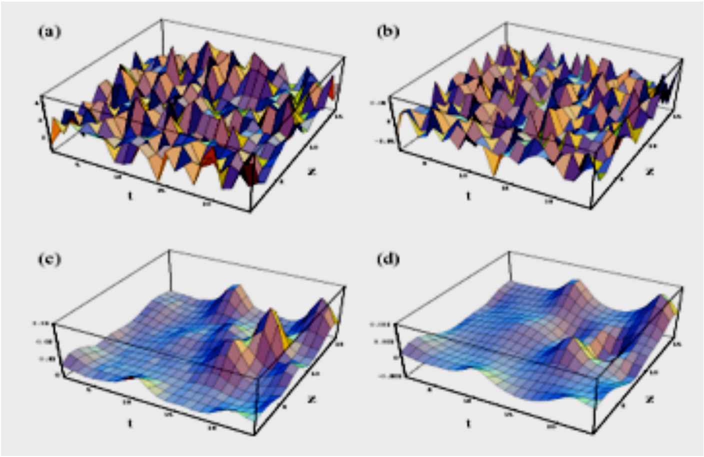
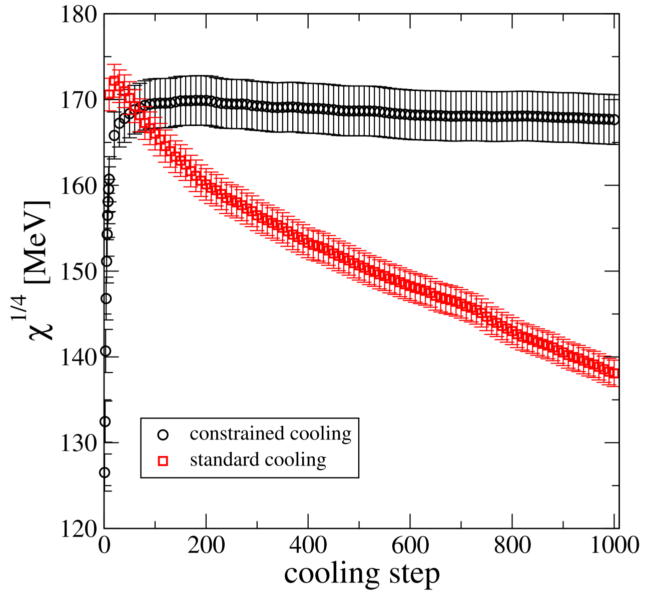
They are not quite instantons (?)

“action cooling” is known to eliminate gluons and lead to instantons

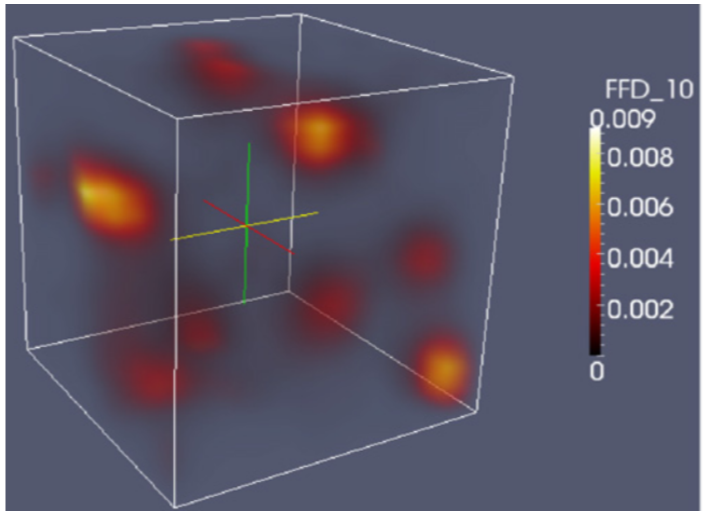


Negele et al

perhaps dyons were first observed in “constrained cooling” preserving local L



Langfeld and Ilgenfritz, 2011



while the total top.charge of the box is always integer, local bumps are not! They are all (anti)selfdual But top charge and actions Were not integers!

a lot of work on finding instanton-dyons was done by C.Gatringer et al, Ilgenfritz et al

Instantons have top.charges $Q = \pm 1$

and thus are elementary quanta of topology:
How can they have a substructure?
What about topological classification of fields?

Like a nucleon is made of 3 quarks,
an instanton is made
of Nc instanton-dyons

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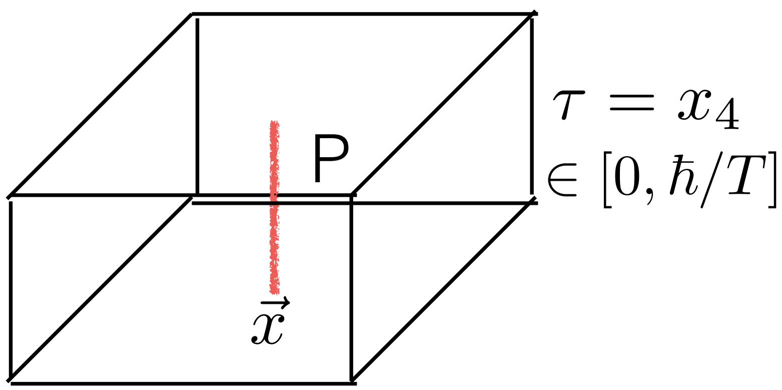
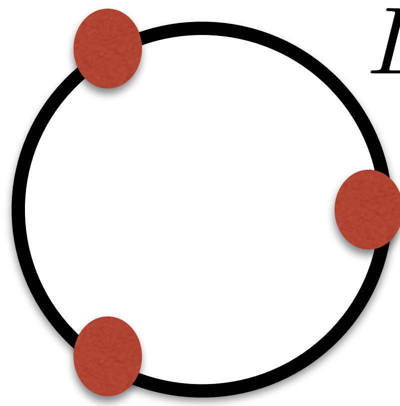
Because they have magnetic charges
They are connected by (invisible!)
Dirac strings
Thus they avoid topological charge quantization

The Polyakov line is used as order parameter for deconfinement

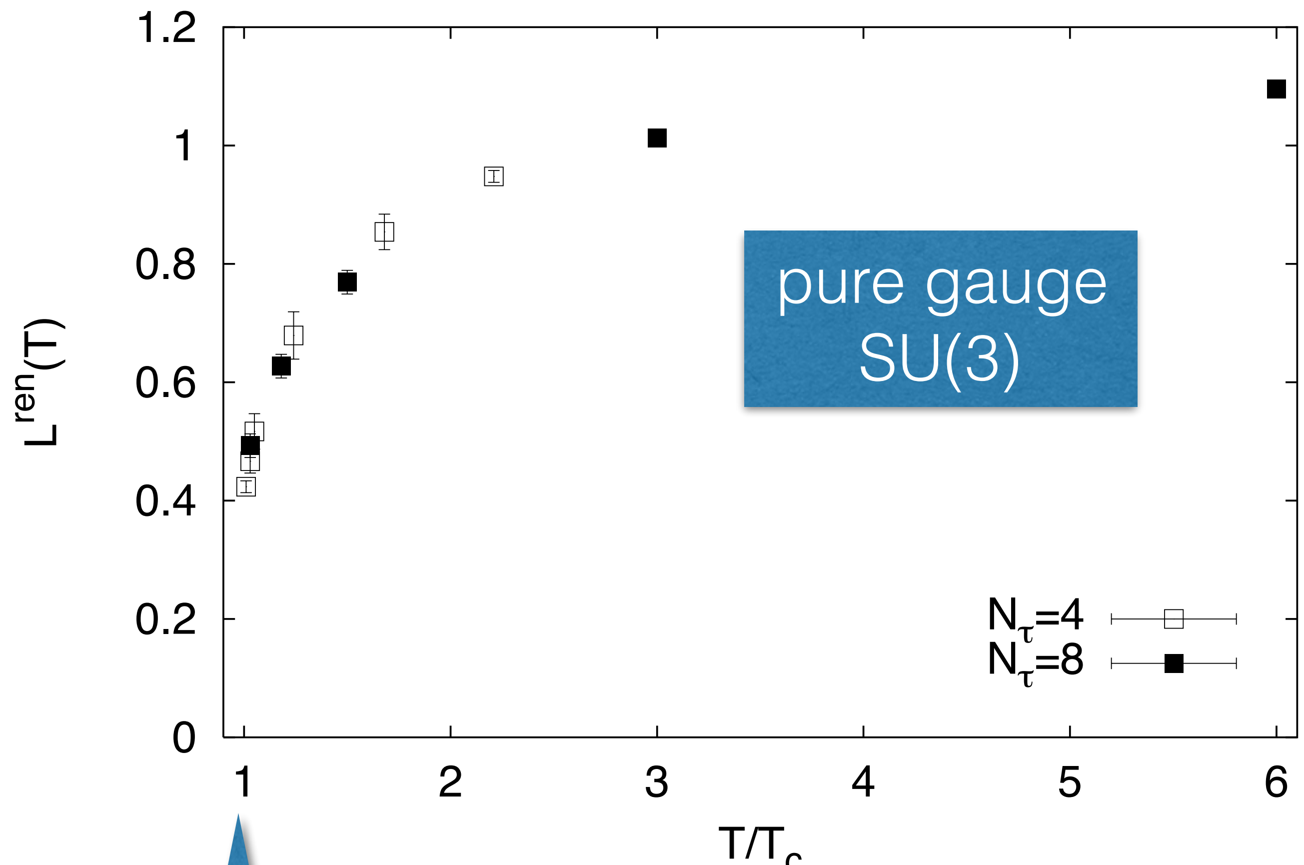




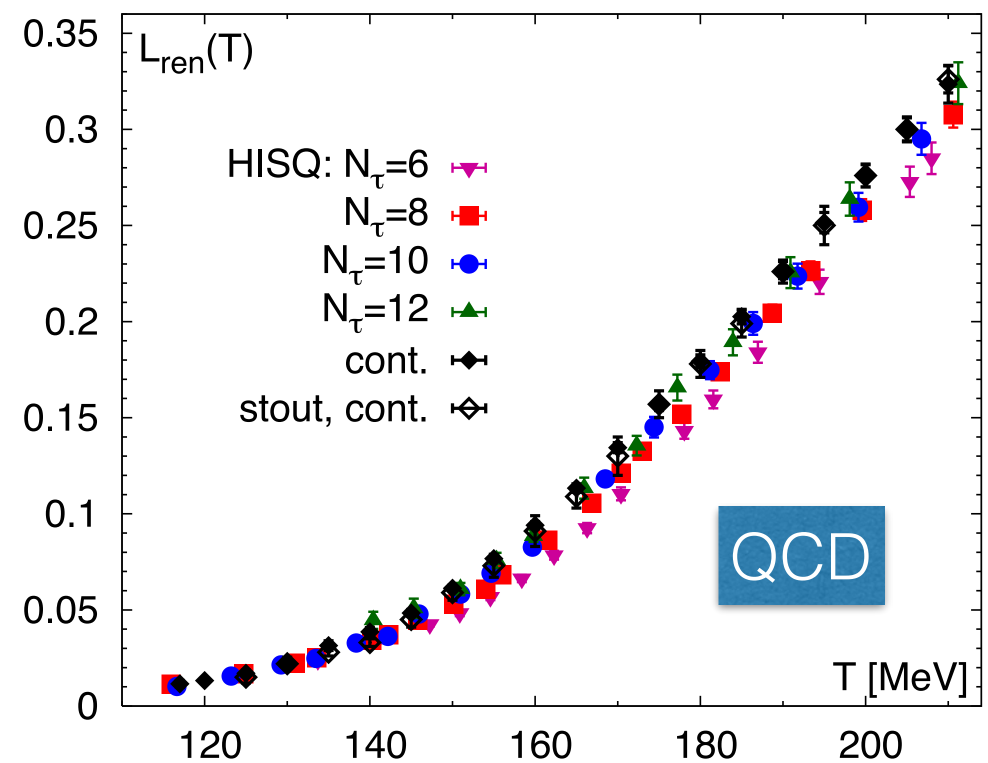
$$L = P = Pexp(i \oint A_\mu^a T^a dx_\mu)$$

$$L = diag(e^{i\mu_1}, e^{i\mu_2}, ...e^{i\mu_{Nc}})$$

$$\frac{1}{N_c} Tr(L) \sim e^{-F_q/T}$$



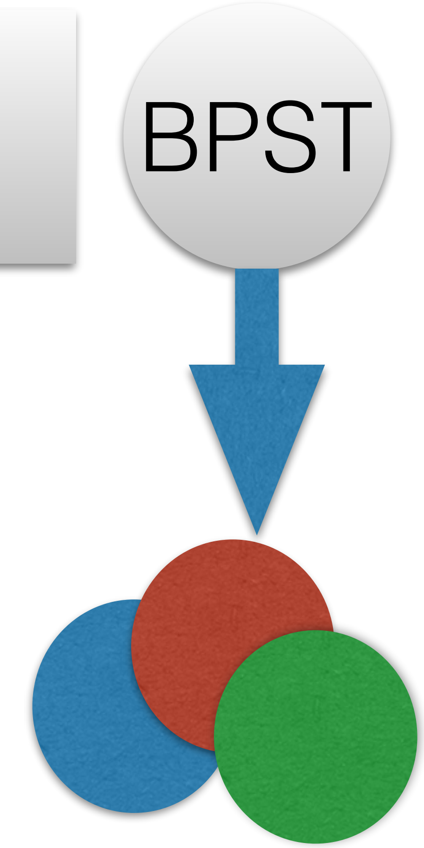
L jumps to zero the first order transition



Kaczmarek et al 2002
Bazavov et al 2016

Pisarski ``semi-QGP" paradigm, PNJL model

Non-zero Polyakov line splits instantons into Nc instanton-dyons (Kraan,van Baal, Lee,Lu 1998)



Explained mismatch of quark condensate in SUSY QCD

V.Khoze (jr) et al 2001

Explained confinement by back reaction to free energy

D.Diakonov 2012, Larsen+ES,Liu,Zahed+ES 2016

Explain chiral symmetry breaking in QCD and in setting with modified fermion periodicities

R.Larsen+ES 2017, Unsal et al 2017

$$general\, SU(N_c)$$

$$A_4 = 2\pi T diag(\mu_1, \mu_2, ...\mu_{N_c})$$

$$\nu_m = \mu_{m+1} - \mu_m$$

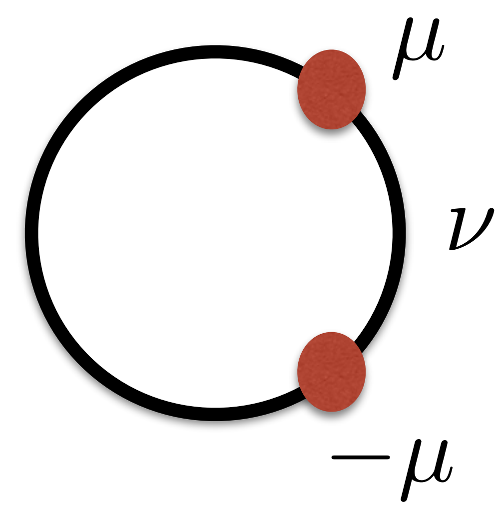
$$\sum_i \nu_i = 1$$

$$S_i = \nu_i \frac{8\pi^2}{g^2} = \nu_i (\frac{11 N_c}{3} - \frac{2N_f}{3}) log(T/\Lambda)$$

the SU(2) case is simpler

L type

$$\bar{\nu} = 1 - \nu$$



M type

$$A_4^a = \mp n_a v \Phi(vr)$$

$$A_i^a = \epsilon_{aij} n_j \frac{1 - R(vr)}{r}$$

$$\vec{E} = \vec{B}$$

together they make one instanton
instanton-dyons
=selfdual BPS mono

In SU(2) there are 4 types of dyons,
Electric and magnetic charges = +1,-1

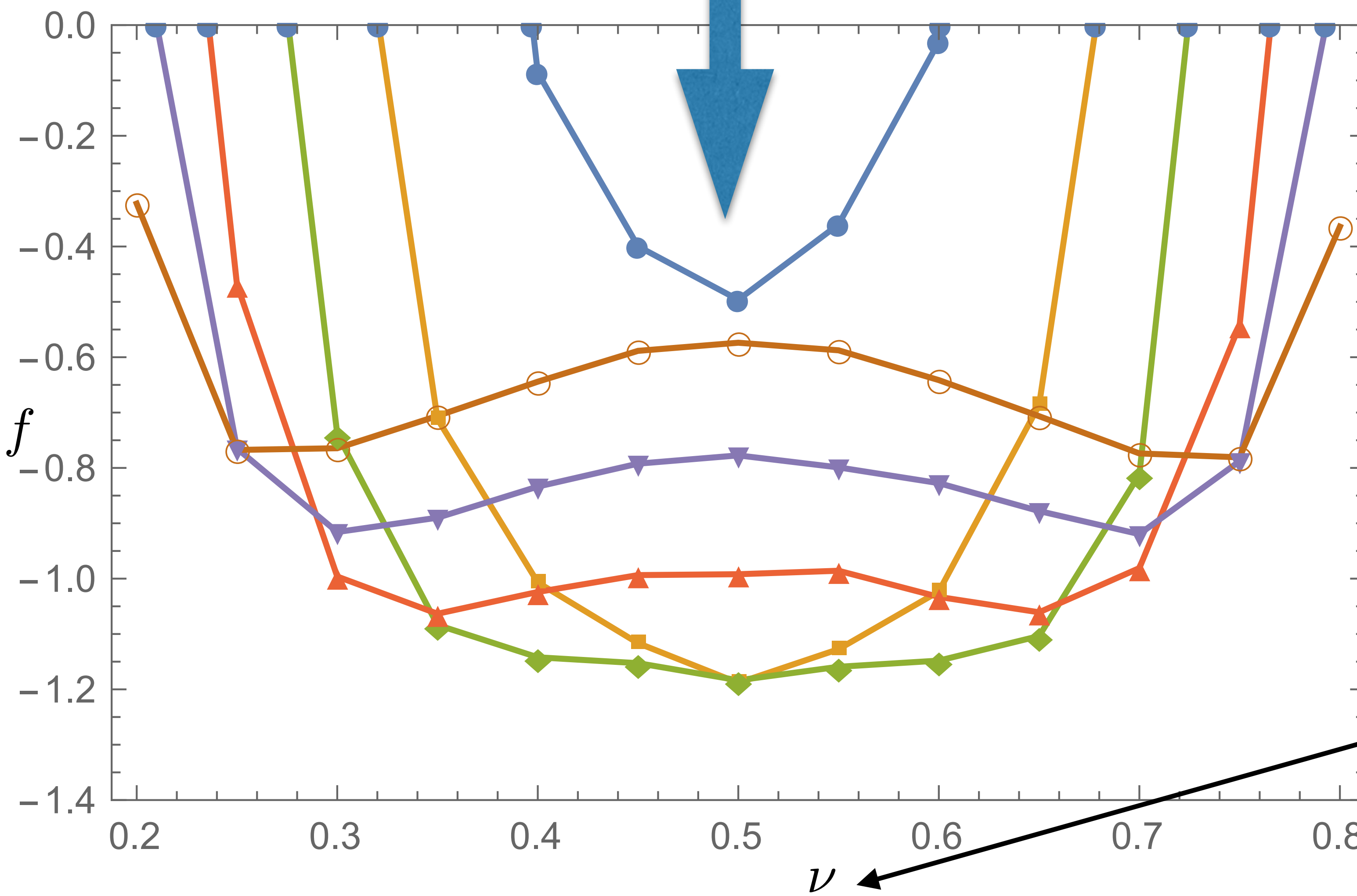
$$M, \bar{M}, L, \bar{L}$$

all one needs to do is to study their ensemble

(with Rasmus Larsen)

confined

free energy vs holonomy



$$\langle A_4^3 \rangle = v\frac{\tau^3}{2} = 2\pi T \nu \frac{\tau^3}{2}$$

$$< P >= cos(\pi\nu) \to 0$$

$$if\ \nu = 1/2$$

holonomy

$$\nu = 0\ is\ the\ trivial\ case$$

$$\nu = 1/2\ confining$$

So, as a function of the dyon density the potential changes its shape and confinement takes place

show only the "selfconsistent" input set.

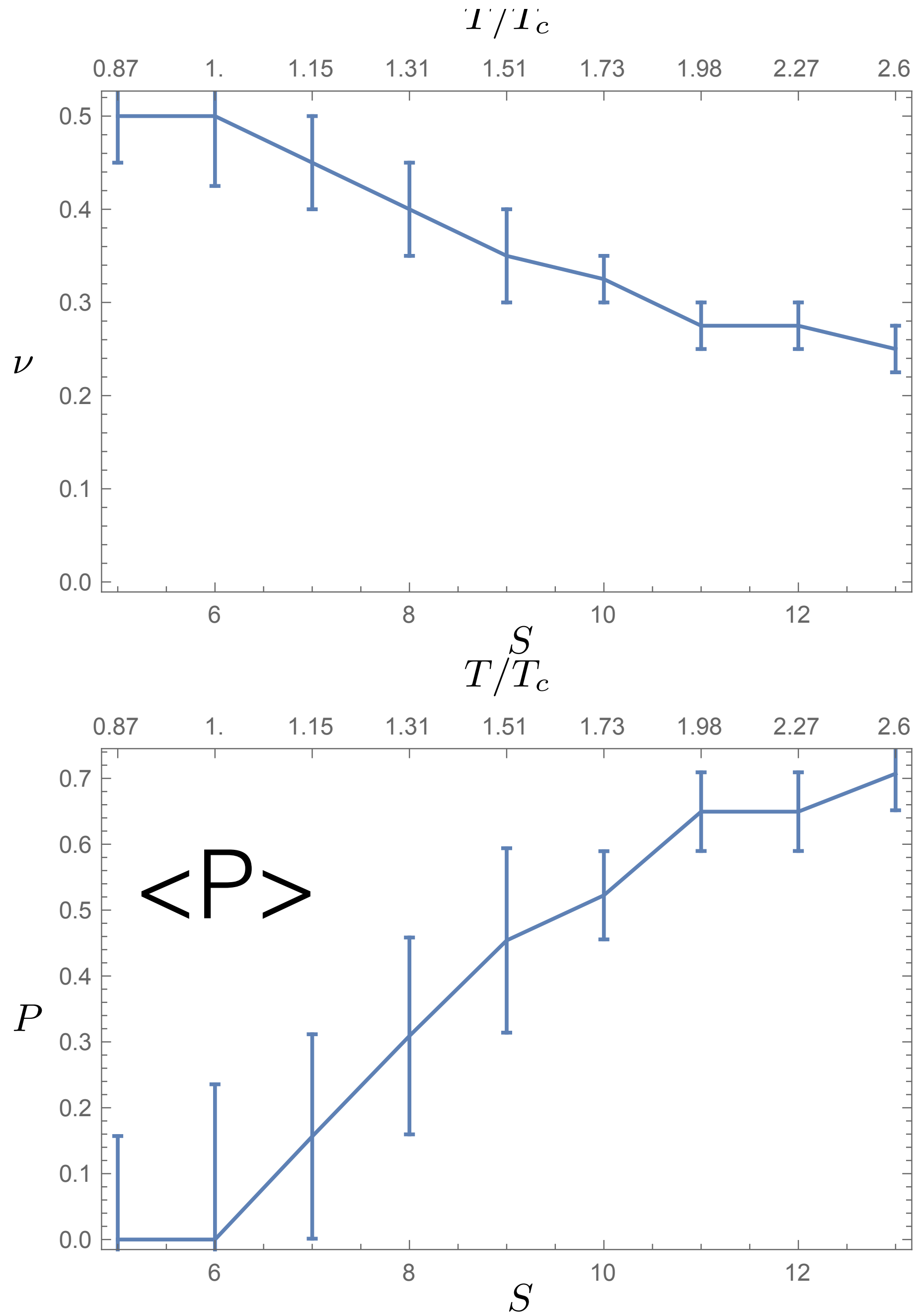


FIG. 6: Self-consistent value of the holonomy ν (upper plot) and Polyakov line (lower plot) as a function of action S (lower scales), which is related to T/T_c (upper scales). The error bars are estimates based on the fluctuations of the numerical data.

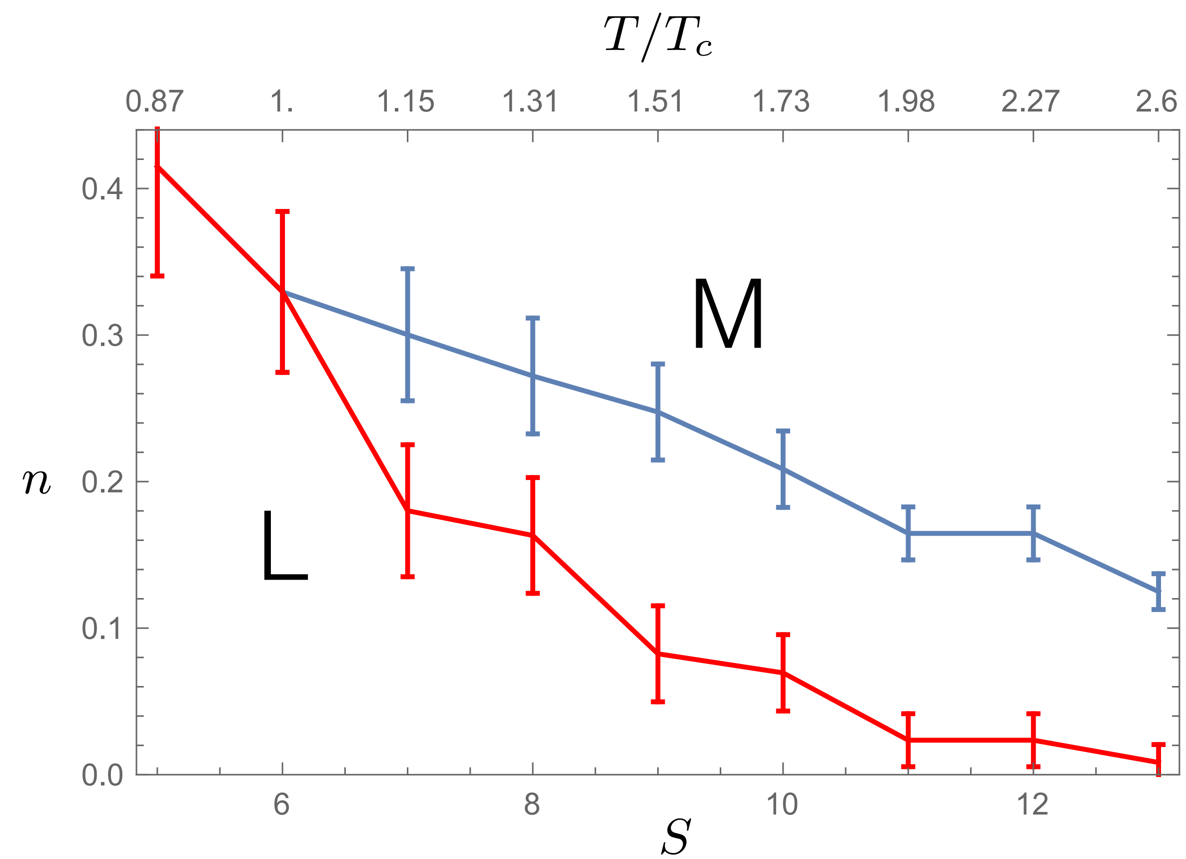


FIG. 8: (Color online). Density n (of an individual kind of dyons) as a function of action S (lower scale) which is related to T/T_c (upper scale) for M dyons(higher line) and L dyons (lower line). The error bars are estimates based on the density of points and the fluctuations of the numerical data.

confining phase is symmetric
$n_L = n_M$

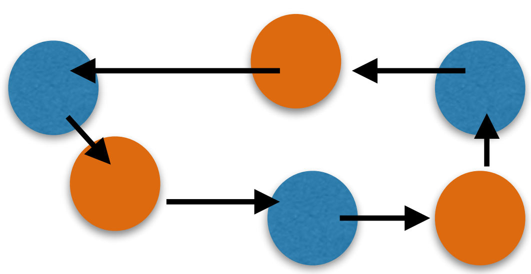
$$S = (\frac{11N_c}{3} - \frac{2N_f}{3}) log(\frac{T}{\Lambda_T}).$$

Instanton-dyon Ensemble with two Dynamical Quarks: the Chiral Symmetry Breaking

Rasmus Larsen and Edward Shuryak
Department of Physics and Astronomy, Stony Brook University, Stony Brook NY 11794-3800, USA

This is the second paper of the series aimed at understanding of the ensemble of the instanton-dyons, now with two flavors of light dynamical quarks. The partition function is appended by the fermionic factor, $(detT)^{N_f}$ and Dirac eigenvalue spectra at small values are derived from the numerical simulation of 64 dyons. Those spectra show clear chiral symmetry breaking pattern at high dyon density. Within current accuracy, the confinement and chiral transitions occur at very similar densities.

$$|<\bar{\psi}\psi>| \;=\; \pi\rho(\lambda)_{\lambda\to 0, m\to 0, V\to\infty}$$



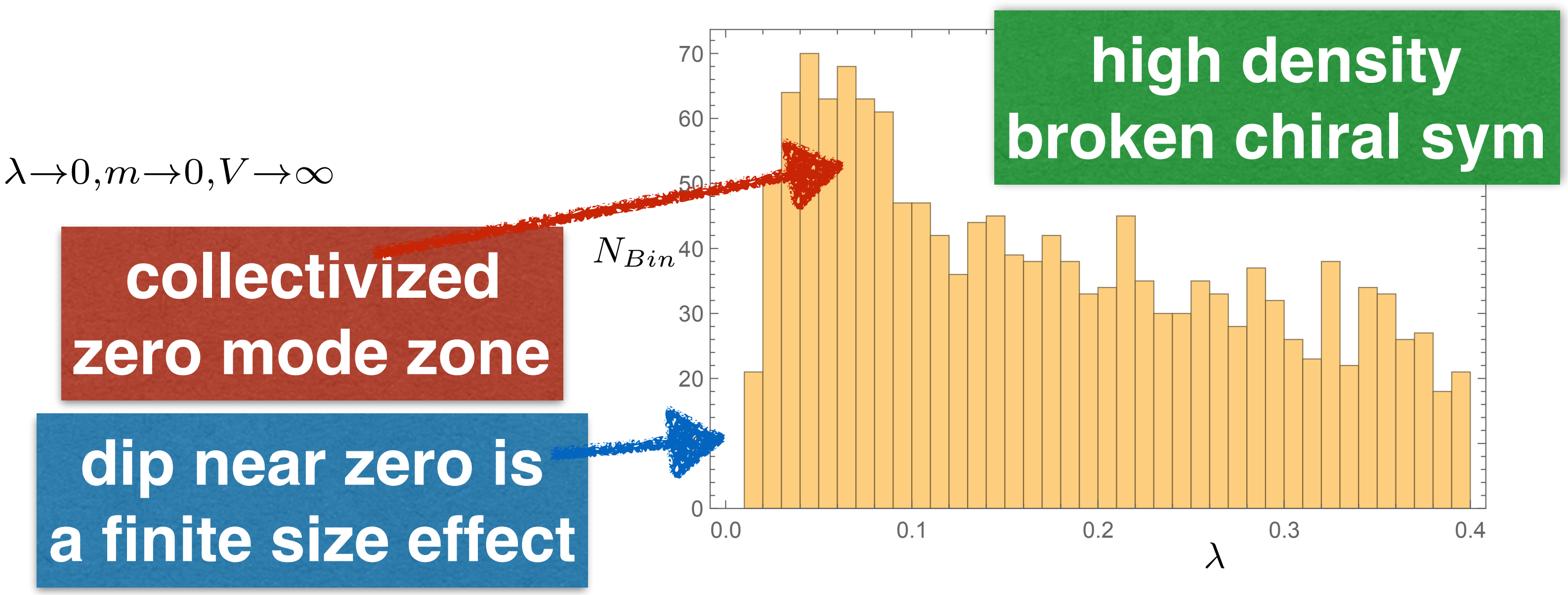
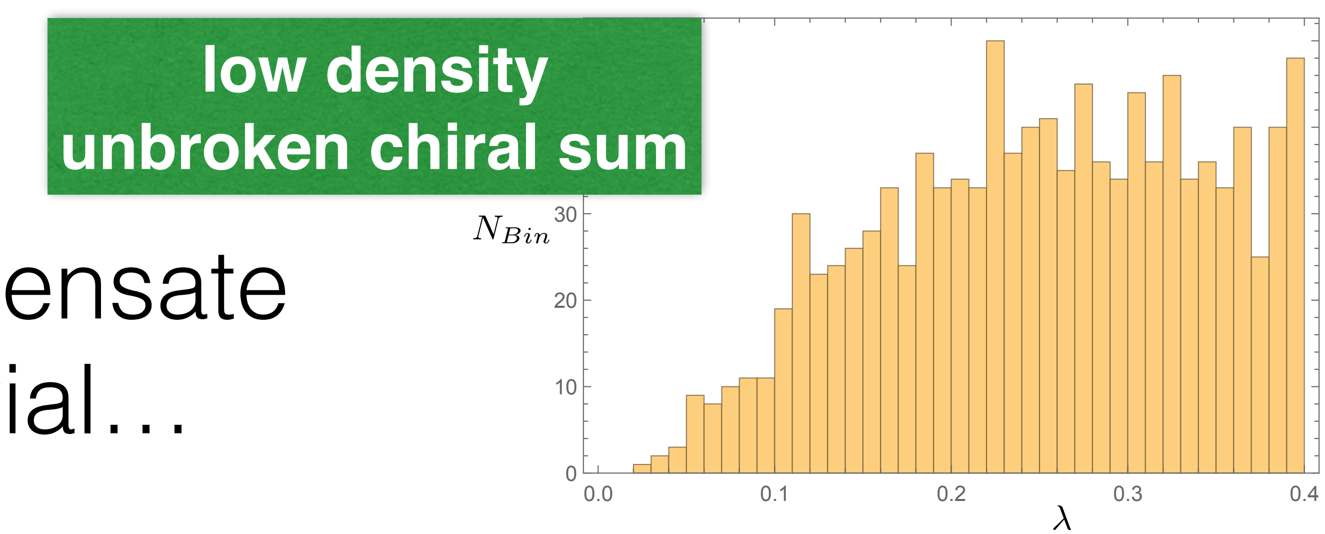


FIG. 1: Eigenvalue distribution for $n_M = n_L = 0.47$, $N_F = 2$ massless fermions.



extracting condensate
is far from trivial…

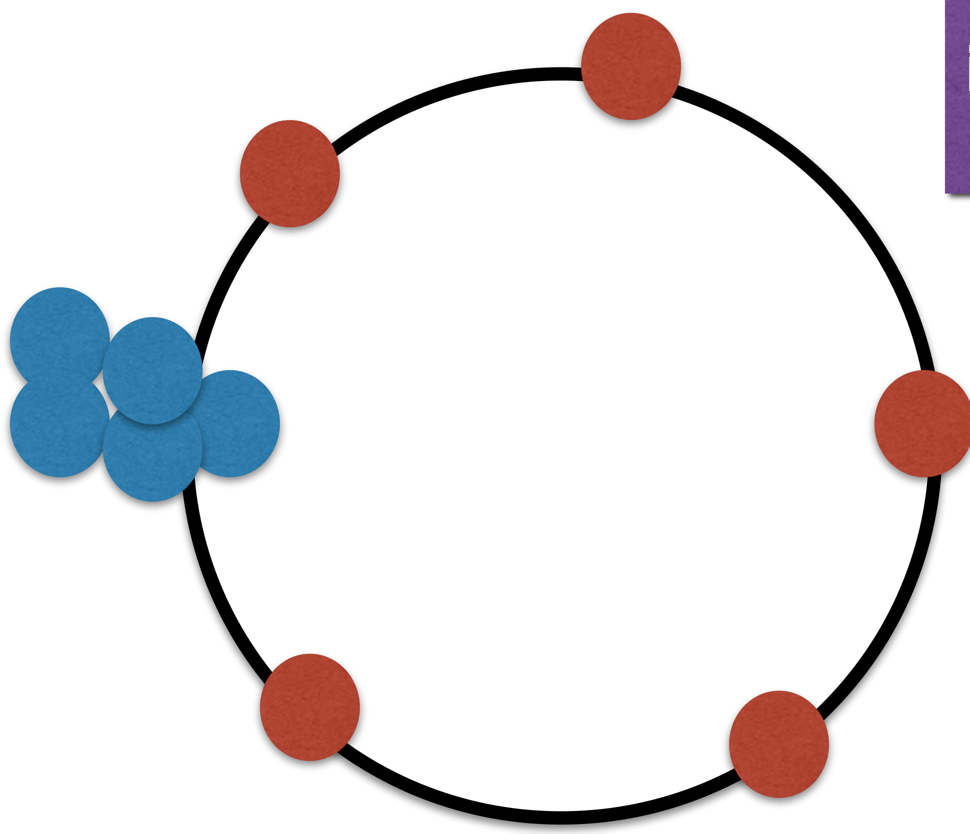
FIG. 2: Eigenvalue distribution for $n_M = n_L = 0.08$, $N_F = 2$ massless fermions.

QCD with quarks having arbitrary periodicity phases (over the Matsubara time)

$$\psi(\tau + \hbar/T) = e^{2\pi i z_f} \psi(\tau)$$

$$z_f = 0 \, bosons$$
$$z_f = -1/2 \, fermions$$

Ordinary Nc=Nf=5 QCD



P without a trace
is a diagonal unitary matrix
=> Nc phases (red dots)

quark periodicity
phases => Nf blue dots
are in this case all =pi
quarks are fermions

as a consequence,
out of 5 types of instanton-dyons
only one L has zero modes

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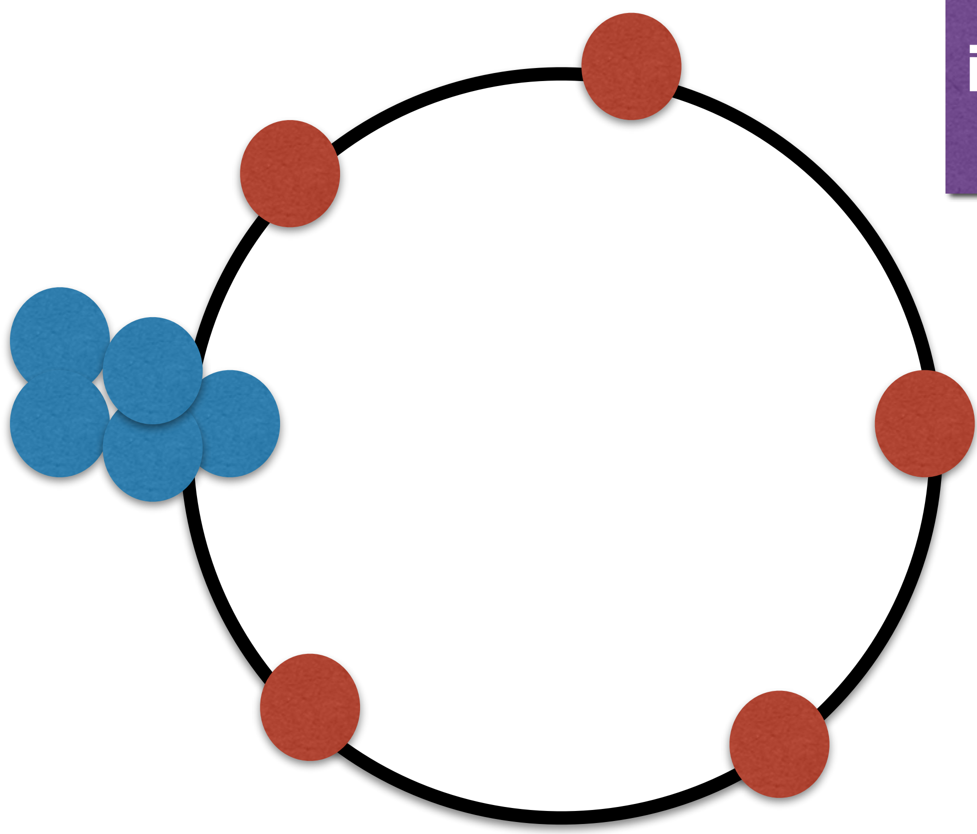

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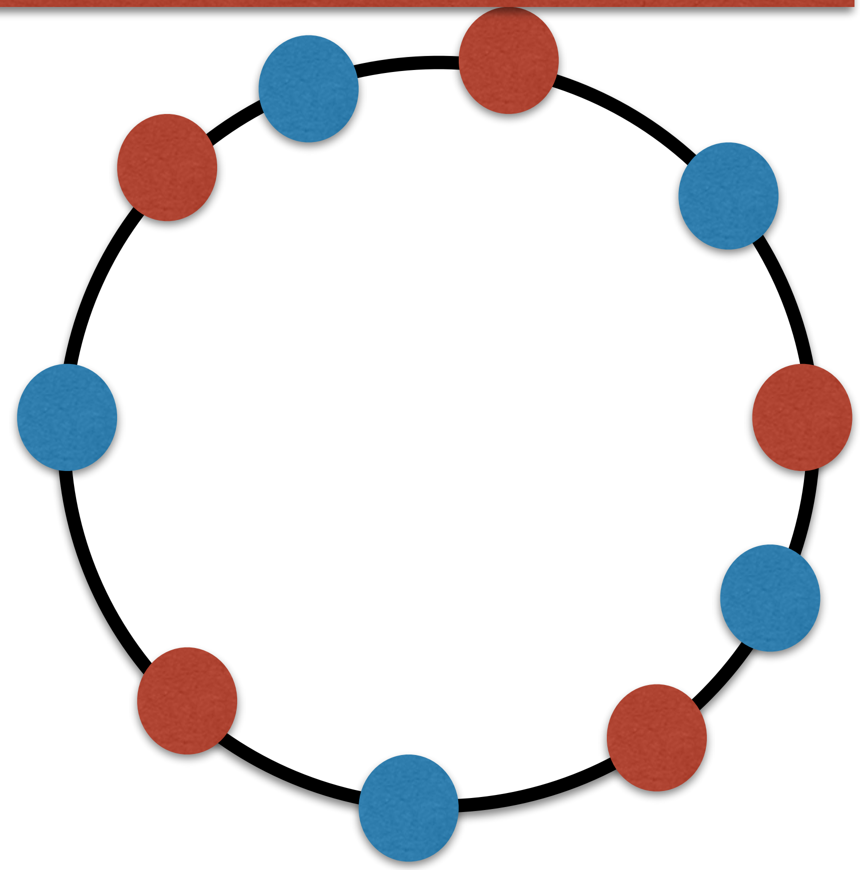
as a consequence, out of 5 types of instanton-dyons only one L has zero modes

But one can deform QCD moving fermion phases (blue dots) as we like!

still Nc=Nf=5 but with
“most democratic” arrangement
ZN-symmetric QCD

H. Kouno, Y. Sakai, T. Makiyama, K. Tokunaga, T. Sasaki and M. Yahiro, J. Phys. G 39, 085010 (2012).



quark periodicity
phases => Nf blue dots
are in this case
flavor-dependent

In this case each dyon type has
one zero mode
with one quark flavor
=>N independent topological ZMZ’s!

Both transitions are dramatically different!

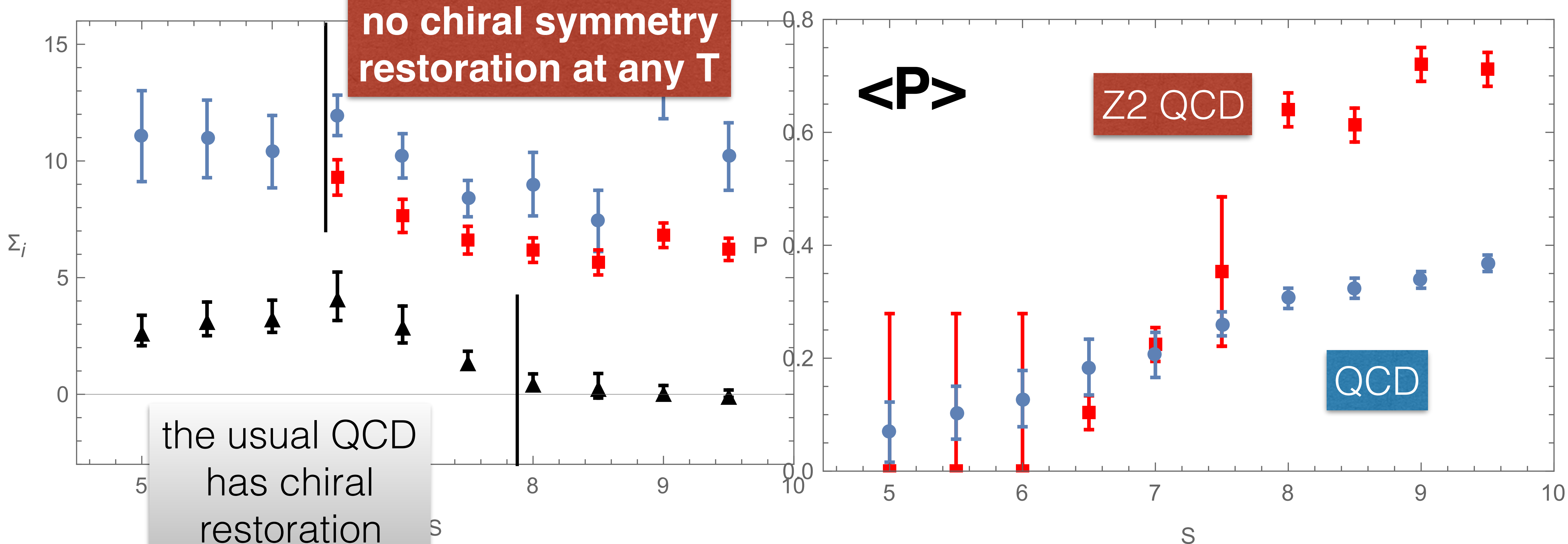
symmetric phase

u=>M

d=>L

$< \bar{u}u > \neq < \bar{d}d >$

no chiral symmetry restoration at any T



the usual QCD has chiral restoration

confining phase gets much more robust: strong first order mixed phase (flat F) is observed at medium densities

FIG. 6: Chiral condensate generated by u quarks and L dyons (red squares) and d quarks interacting with M dyons (blue circles) as a function of action S, for the Z_2-symmetric model. For comparison we also show the results from II for the usual QCD-like model with $N_c = N_f = 2$ by black triangles.

why is condensate much larger for Z2?

lattice study of Z3 QCD

Lattice study on QCD-like theory with exact center symmetry

Takumi Iritani*

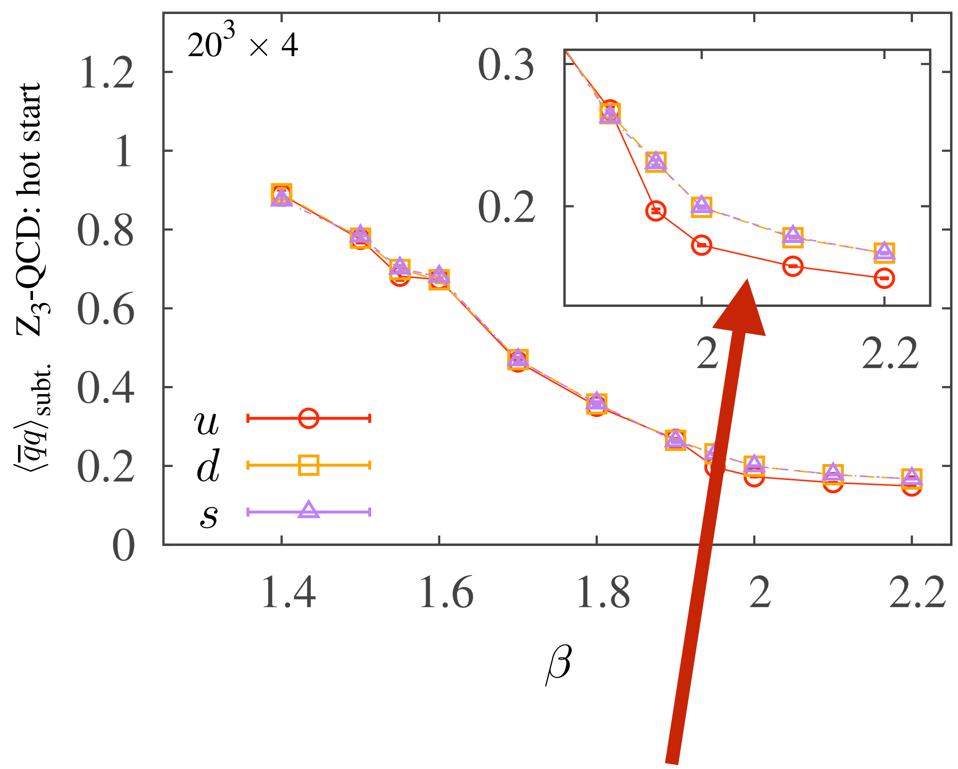
Yukawa Institute for Theoretical Physics, Kyoto 606-8502, Japan

Etsuko Itou†

High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan

Tatsuhiro Misumi‡

Department of Mathematical Science, Akita University,



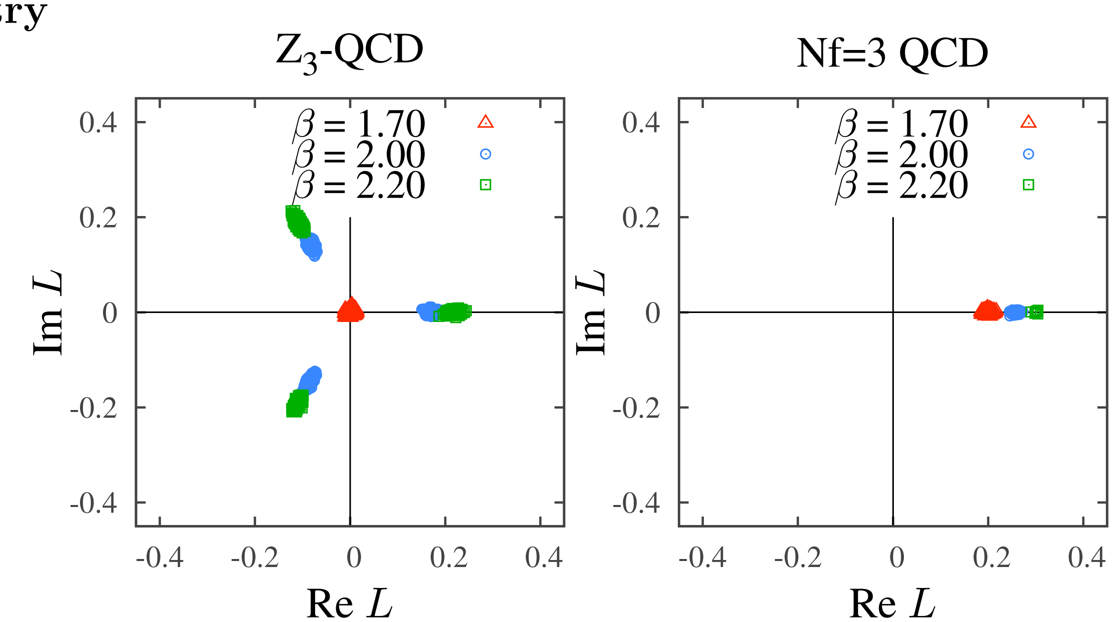
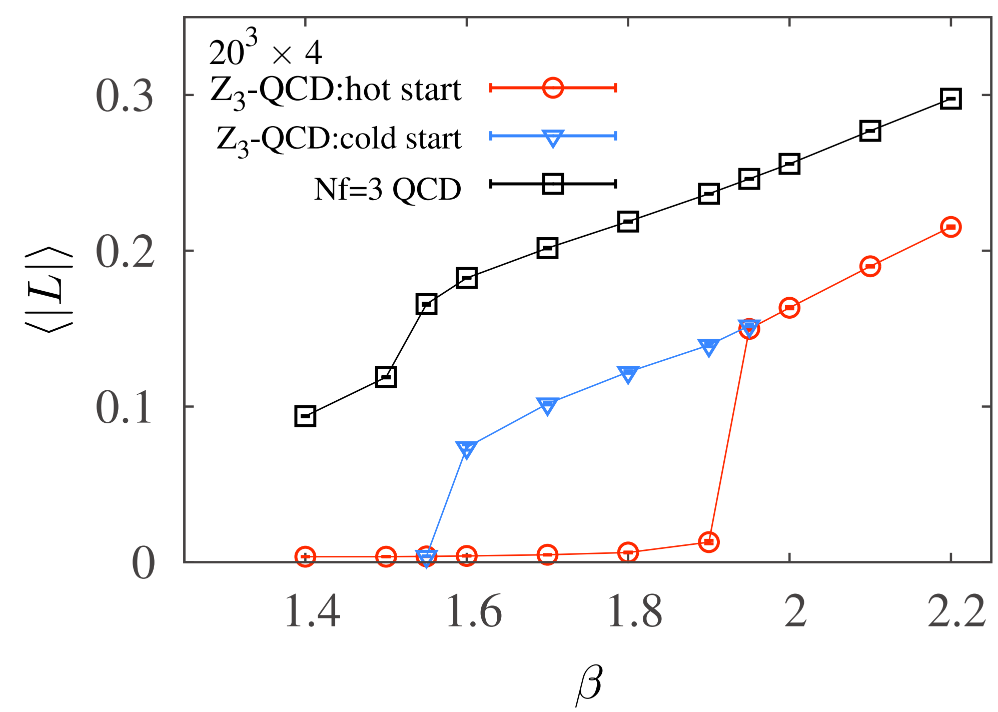


FIG. 1: Polyakov loop distribution plot in Z_3-QCD (left) and the standard three-flavor QCD (right). Based on $16^3 \times 4$ lattice for $\beta = 1.70, 2.00, 2.20$ with the same values of κ in both panels.



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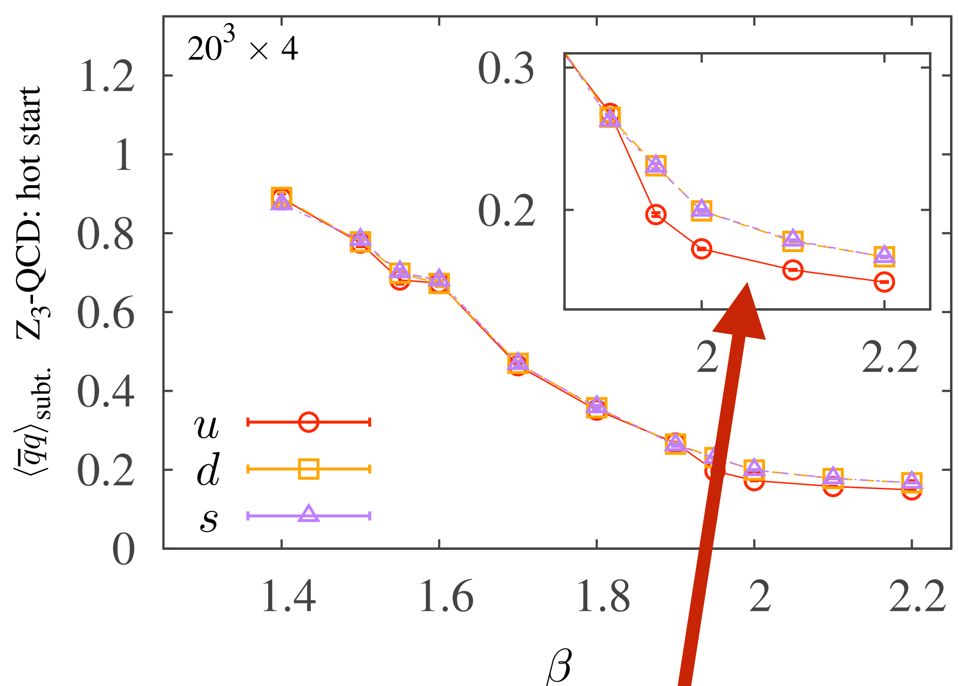

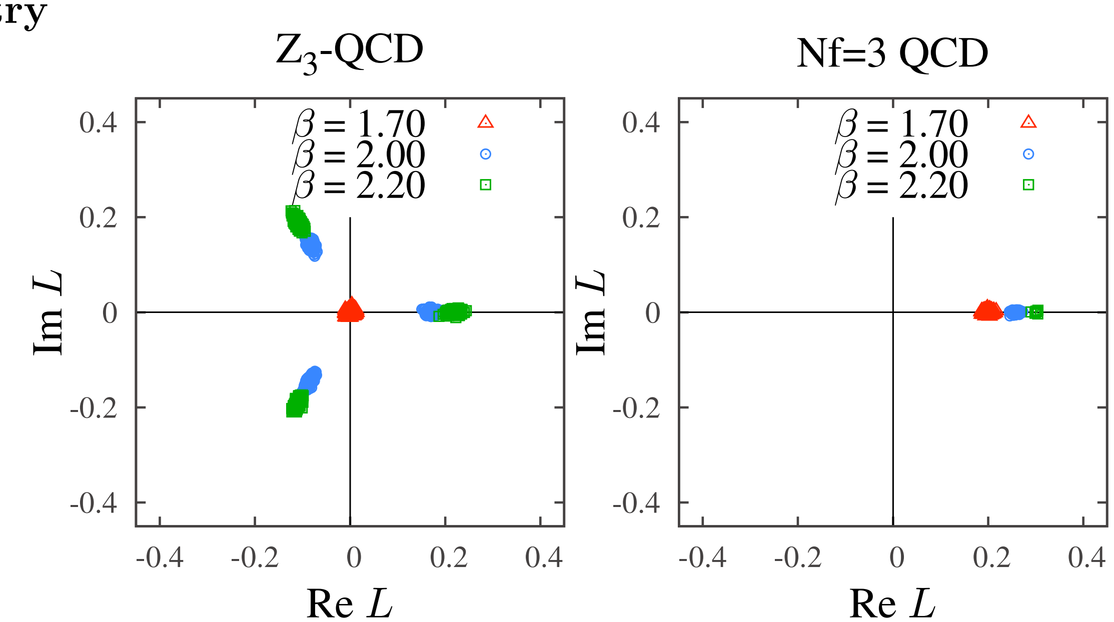

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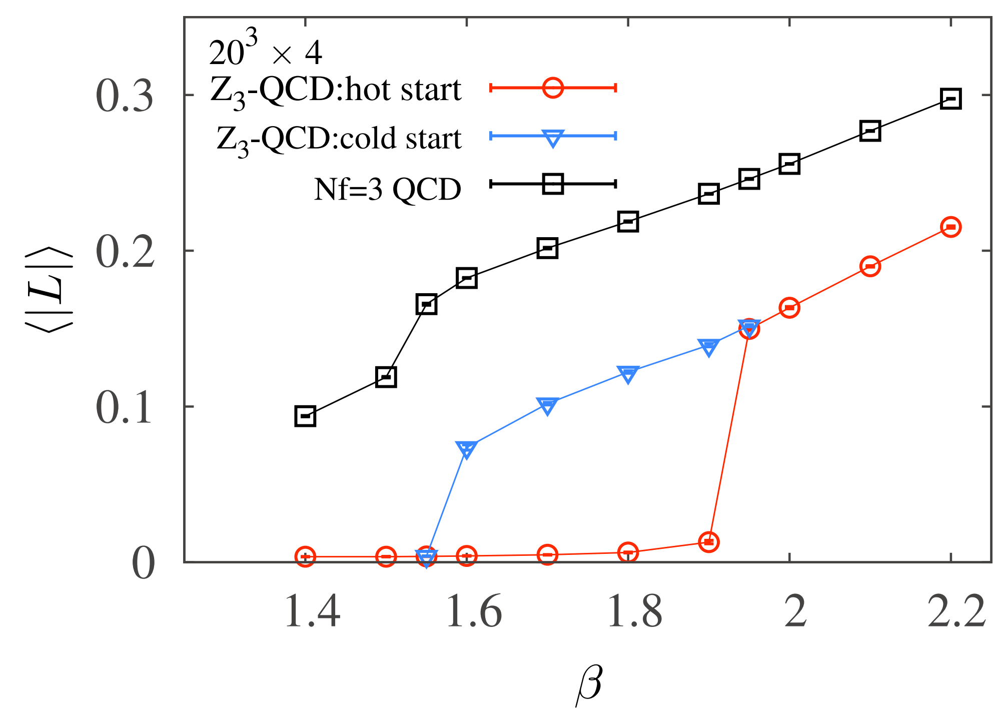
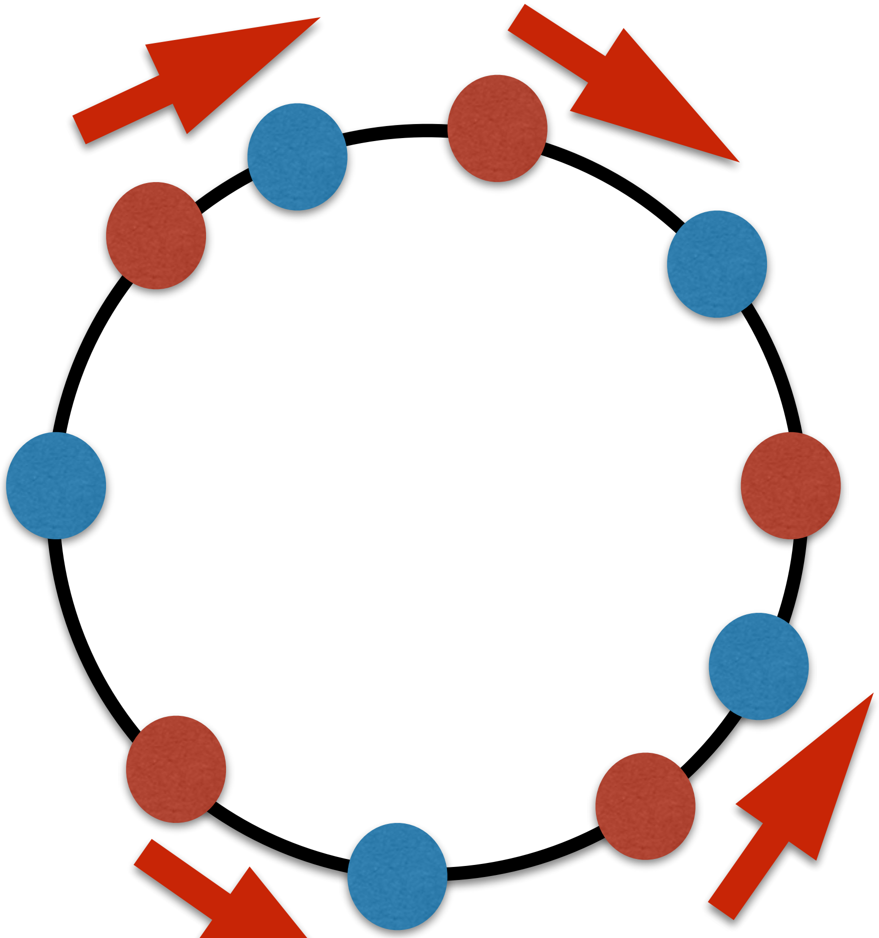


explanation: three flavors of quarks interact with three different ``liquids" of M1,M2,L instanton-dyons!

still Nc=Nf=5

with growing T all red dots move toward zero (Polyakov line L=> 1)



each time any L phase (red dot) passes the quark phase (blue dot), the quark zero mode jump to another dyon type

This leads to series of phase transitions related to Roberge-Weiss transitions, observed on the lattice at imaginary chem. potential

I suggest to call them Van Baal transitions

Dyons and Roberge - Weiss transition in lattice QCD
V.G. Bornyakov, D.L. Boyda, V.A. Goy, E. -M. Ilgenfritz, B.V. Martemyanov, A.V. Molochkov, Atsushi Nakamura, A.A. Nikolaev, V.I. Zakharov
EPJ Web Conf. 137 (2017) 03002
arXiv:1611.07789

instanton-dyons on the lattice

(with S.Sharma and R.Larsen)

the cleanness case:
domain wall fermions
Q=1 configurations
Nt=8,Nx=32, T/Tc=1,1.08

Fermionic Zero modes and topology around T_c

Rasmus Larsen, Sayantan Sharma and Edward Shuryak

We study the vacuum of 2+1 flavor QCD immediately above the chiral crossover transition temperature. Since the overlap fermions have an index theorem on a finite lattice we use the zero modes of the valence overlap quarks to probe the topological structures of the sea domain wall fermion configurations on lattices of size $32^3 \times 8$. The change in the properties of the zero modes are studied in detail by changing the boundary conditions of the overlap Dirac operator along the temporal direction. Our studies show that the zero modes have strong similarity to the instanton-dyons. We further provide evidence for this by studying in detail the properties of the near-zero eigenvectors of the overlap operator.

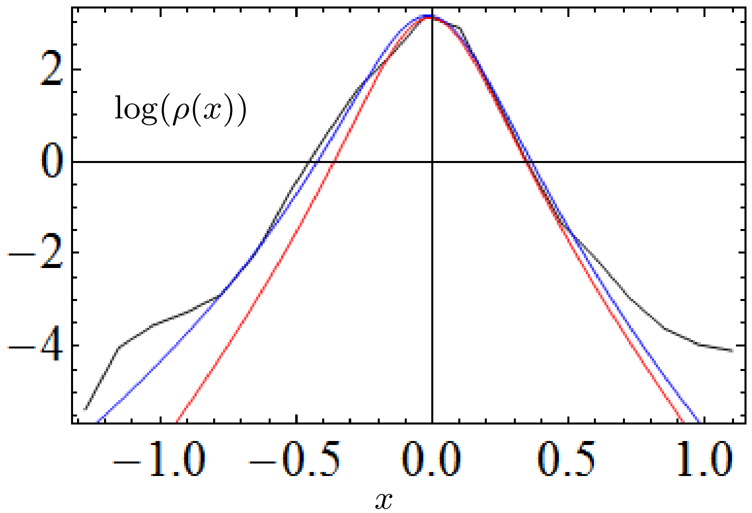


FIG. 8: $\log(\rho(x))$ of the zero mode of conf. 2960 at $\phi = \pi$ (black) and the log of the analytic formula for $P = 0.4$ and $P = 1$ though the maximum. $T = 1.08T_c$. Red peak only has been scaled to fit in height, while blue peak uses the found normalization.

extracting the shape of the fermonic zero mode and modyfying the phase one can find all 3 dyons

excellent agreement of the shape with analytic formulae

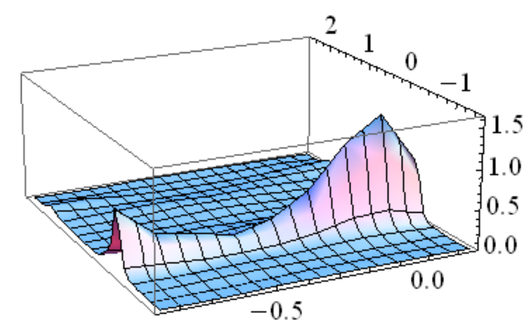


FIG. 3: $\rho(x,t)$ of the zero mode of conf. 2000 at $\phi = \pi/3$. $T = T_c$.

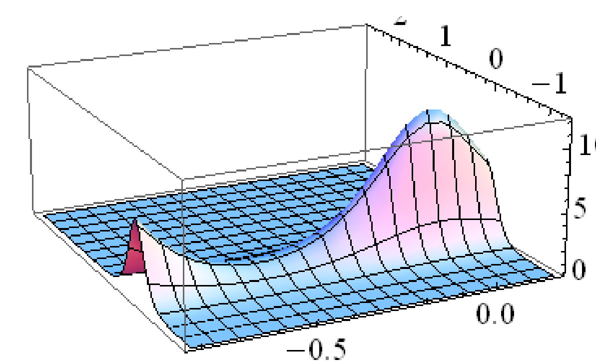


FIG. 4: Analytic zero mode density $\rho(x,t)$ at $\phi = \pi/3$. Main ... tered at the origin. Two other dyons at $(0.2, 0.0, 0.0)$ ... $2, 0.0, 0.0)$.

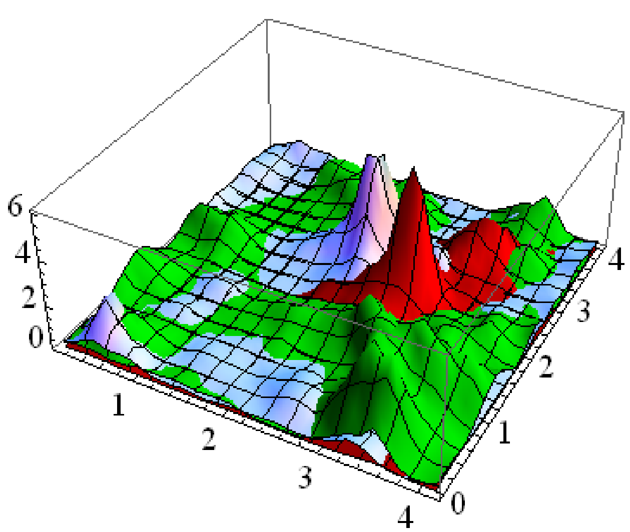


FIG. 17: $\rho(x,y)$ of the zero mode of conf. 2660 at $T = T_c$. $\phi = \pi$(red), $\phi = \pi/3$(blue), $\phi = -\pi/3$(green). Peak height has been scaled to be similar to that of $\phi = \pi$.

We found that their fields interfere with each other
the interaction between them
Is in excellent agreement with
van Baal analytic formulae

Semiclassical theory of instanton-dyon ensemble
Is in Poisson duality with monopoles

One can start in the theory
in which there is a complete theoretical control
on both and **compare two approaches directly**

N.Dorey and A.Parnachev
JHEP 0108, 59 (2001)
hep-th/0011202]

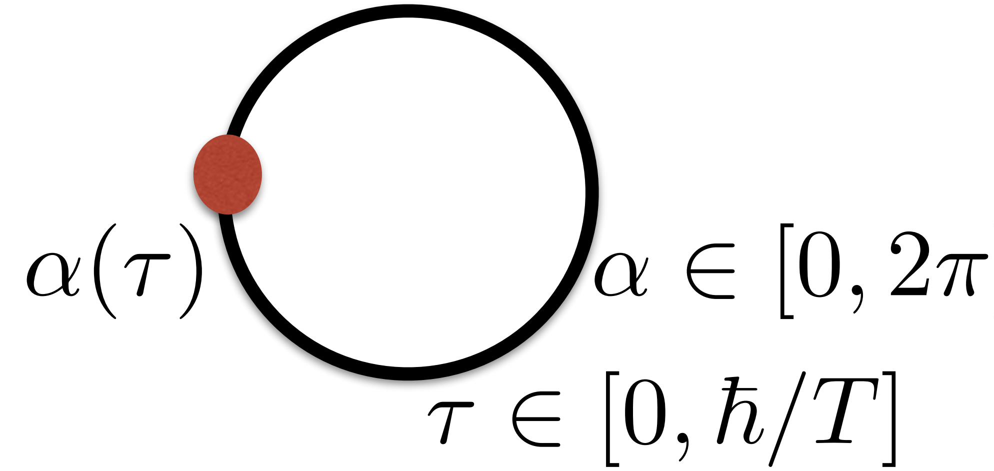
N=4 extended supersymmetry with Higgled scalar compactified on a circle

Partition function calculated in terms of monopoles ⟷ **Partition function calculated in terms of instanton-dyons**

Configurations are obviously very different
Zs also look different,
and yet they are related
by the Poisson summation formula
and thus are the same!!!

Is there any relation between the semiclassical instanton-dyons and QCD monopoles?

Adith Ramamurti,[*] Edward Shuryak,[†] and Ismail Zahed[‡]



The same phenomenon in much simpler setting:
quantum particle on a circle at finite T

A Hamiltonian vs Lagrangian approaches

$$Z_1 = \sum_{l=-\infty}^{\infty} \exp\left(-\frac{l^2}{2\Lambda T} + il\omega\right)$$

moment of inertia

Aharonov-Bohm phase

$$Z_2 = \sum_{n=-\infty}^{\infty} \sqrt{2\pi\Lambda T}\, \exp\left(-\frac{T\Lambda}{2}(2\pi n - \omega)^2\right).$$

Matsubara winding number

$$\alpha_n(\tau) = 2\pi n \frac{\tau}{\beta},$$

based on classical paths

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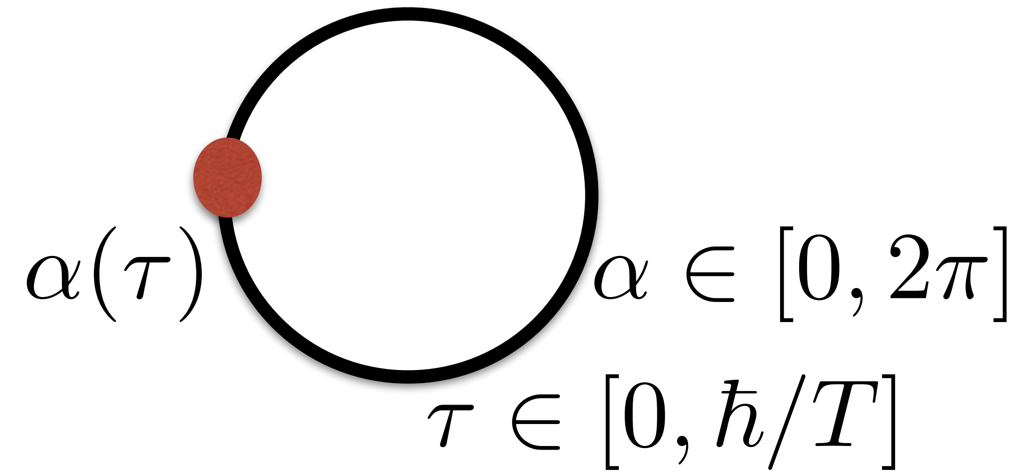

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Note completely different dependence on T and holonomy omega

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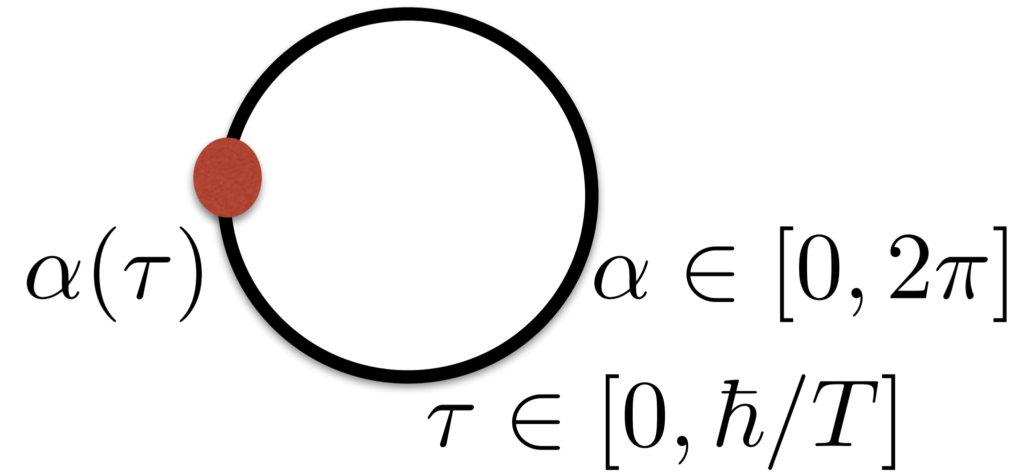

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$$Z_2 = \sum_{n=-\infty}^{\infty} \sqrt{2\pi\Lambda T} \exp\left(- \frac{T\Lambda}{2} (2\pi n - \omega)^2 \right) .$$

Matsubara winding number

$$\alpha_n(\tau) = 2\pi n \frac{\tau}{\beta} ,$$

based on classical paths

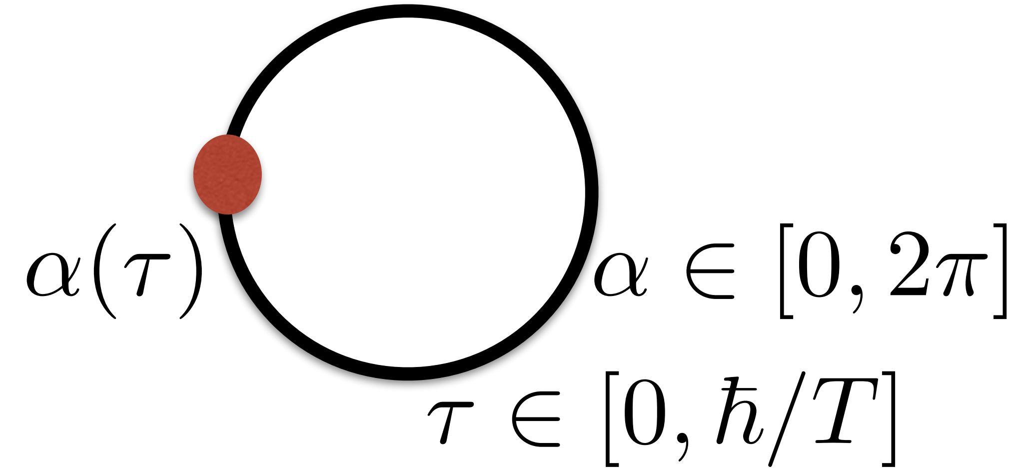
Note completely different dependence on T and holonomy omega

And yet, they are the same!
(elliptic theta function of the 3 type)

$$Z_1 = Z_2 = \theta_3\left(- \frac{\omega}{2}, \exp\left(- \frac{1}{2\Lambda T} \right) \right)$$

Is there any relation between the semiclassical instanton-dyons and QCD monopoles?

Adith Ramamurti,* Edward Shuryak,† and Ismail Zahed‡



The same phenomenon in much simpler setting: quantum particle on a circle at finite T

A Hamiltonian vs Lagrangian approaches

$$Z_1 = \sum_{l=-\infty}^{\infty} \exp\left(-\frac{l^2}{2\Lambda T} + il\omega\right)$$

$$Z_2 = \sum_{n=-\infty}^{\infty} \sqrt{2\pi\Lambda T}\, \exp\left(-\frac{T\Lambda}{2}(2\pi n - \omega)^2\right).$$

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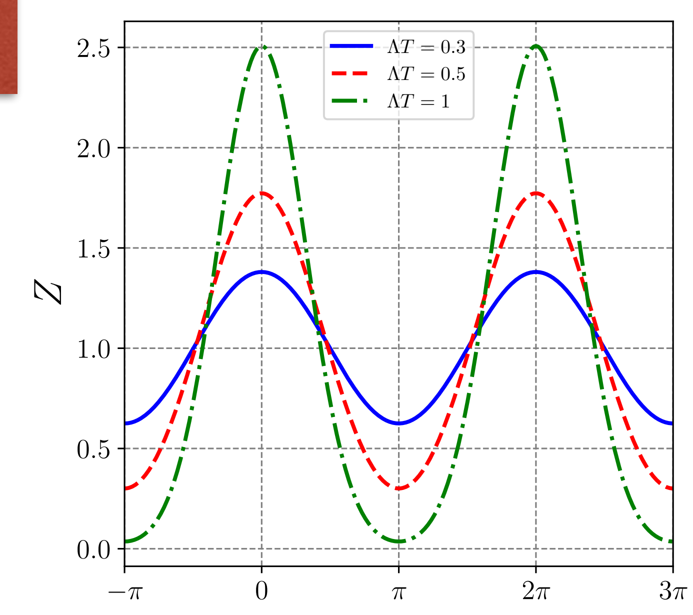

Is there any relation between the semiclassical instanton-dyons and QCD monopoles?

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instanton-dyons with winding number n

The twisted solution is obtained in two steps. The first is the substitution

$$v \to n(2\pi/\beta) - v\,, \tag{13}$$

and the second is the gauge transformation with the gauge matrix

$$\hat{\Omega} = \exp\left(-\frac{i}{\beta} n\pi\tau\hat{\sigma}^3 \right), \tag{14}$$

where we recall that $\tau = x^4 \in [0, \beta]$ is the Matsubara time. The derivative term in the gauge transformation adds a constant to A_4 which cancels out the unwanted $n(2\pi/\beta)$ term, leaving v, the same as for the original static monopole. After "gauge combing" of v into the same direction, this configuration – we will call L_n – can be combined with any other one. The solutions are all

$$S_n = (4\pi/g^2)|2\pi n/\beta - v|$$

$$\sum_{n=-\infty}^{\infty} f(\omega + nP) = \sum_{l=-\infty}^{\infty} \frac{1}{P} \tilde{f}\left(\frac{l}{P}\right) e^{i2\pi l\omega/P}$$

Poisson summation formula can be used to derive the monopole Z

$$Z_{\text{inst}} = \sum_n e^{-\left(\frac{4\pi}{g_0^2}\right)|2\pi n - \omega|}$$

$$Z_{\text{mono}} \sim \sum_{q=-\infty}^{\infty} e^{iq\omega - S(q)}$$

$$S(q) = \log\left(\left(\frac{4\pi}{g_0^2}\right)^2 + q^2\right)$$

$$\approx 2\log\left(\frac{4\pi}{g_0^2}\right) + q^2\left(\frac{g_0^2}{4\pi}\right)^2 + \ldots$$

q is angular momentum of rotating monopole, so it is electric charge

Therefore we now understand why
The density of monopoles is well fitted by an inverse power of log(T) , not power of T =>
It is because they are not really semiclassical objects!

$$S_{mono} \sim log(const/g^2) = log\big(log(T/Tc)\big)$$

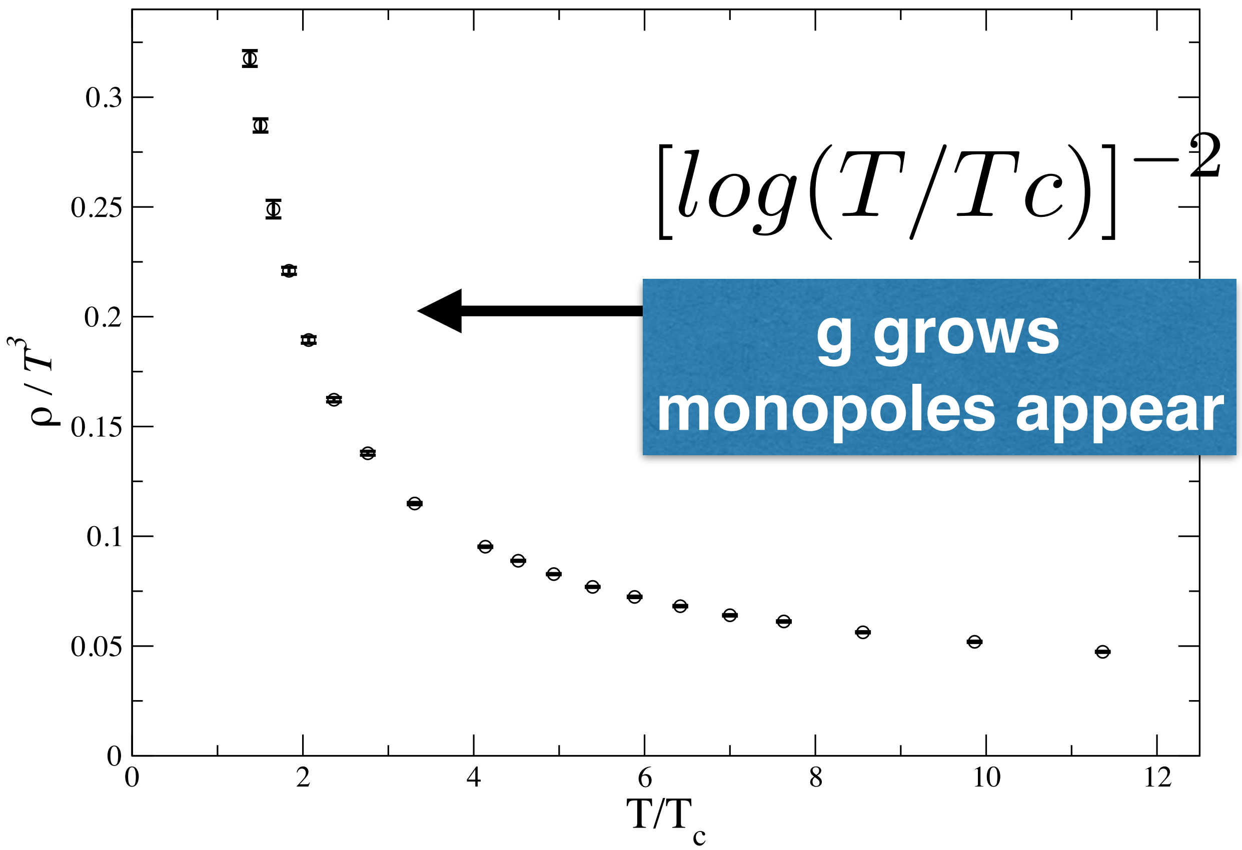


Fig. 2.6 The normalized monopole density ρ/T^3 for the $SU(2)$ pure gauge theory as a function of the temperature, in units of the critical temperature T/T_c, above the deconfinement transition.

D'Alessandro, A. and D'Elia, M. (2008). Magnetic monopoles in the high temperature phase of Yang-Mills theories. Nucl. Phys., B799:241–254. 0711.1266.

For instantons and dyons it is different

$$exp(-S) \sim exp(-const/g^2) = exp(-const' * log(T)) = 1/T^{power}$$

Semiclassical theory at finite T
And few-nucleon clusters at freeze out
(with Juan Torres-Rincon)

Standard textbook definition of the density matrix

$$P(x_0) = \sum |\psi(x_0)|^2 e^{-E_i/T} \quad ($$

As shown by Feynman, the density matrix for any quantum system can be expressed by the path integrals, over paths passing through the point x_0. Analytic continuation to Euclidean (Matsubara) time defined on a circle $\tau \in [0, \beta = \hbar/T]$ lead to its finite temperature generalization

$$P(x_0) = \int Dx(t) e^{-S_E\left(x(\tau)\right)} \quad (2)$$

taken over the periodic paths which starts and ends at x_0. This expression has led to multiple applications, perturbative (using Feynman diagrams) or numerical (e.g. lattice gauge theory). This is so well known that any references are not needed.

A novel semiclassical theory:
the path integral is dominated by minimal action (classical) path, called "flucton".
The idea was introduced by me in 1988.
Unlike WKB, this approach works for multidimensional and QFT settings.
It leads to systematic perturbative series based
on Feynman diagrams, with clear rules for each order.

An example at $T \neq 0$

anharmonic oscillator, defined by

$$S_E = \oint d\tau \left(\frac{\dot{x}^2}{2} + \frac{x^2}{2} + \frac{g}{2} x^4 \right)$$

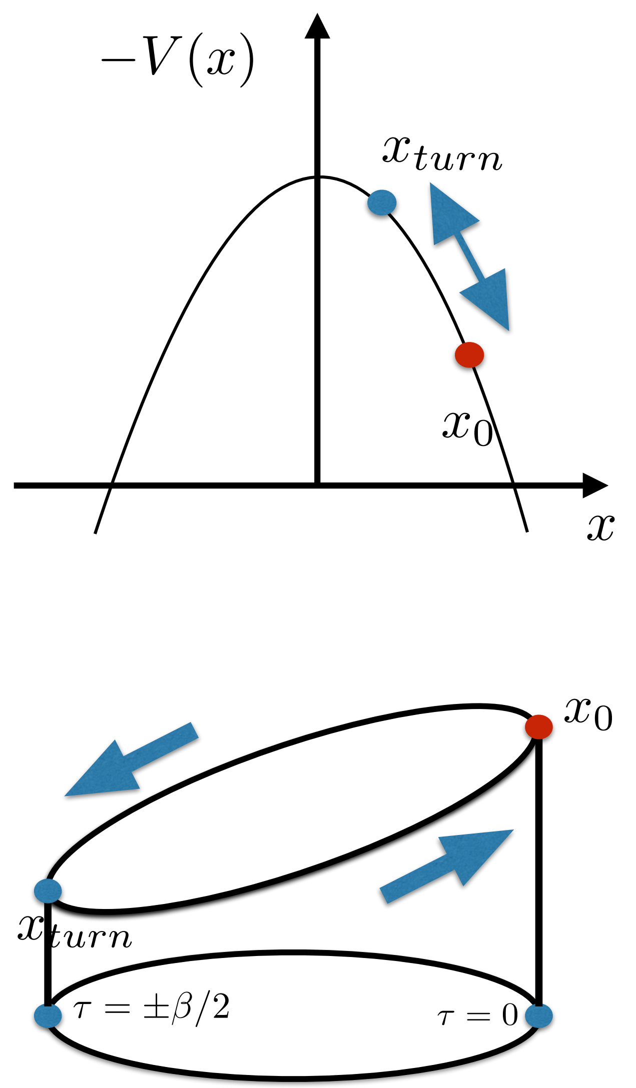


FIG. 2: Two sketches explaining properties of the flucton classical paths. The upper one shows the (flipped) potential $-V(x)$ versus its coordinate. The needed path starts from arbitrary observation point x_0 (red dot), goes uphill, turns back at the turning point x_{turn} (blue dot), and returns to x_0 during the required period $\beta = \hbar/T$. The lower plot illustrate the same path as a function of Euclidean time τ defined on a "Matsubara circle" with circumference β.

At T=0 period is infinite

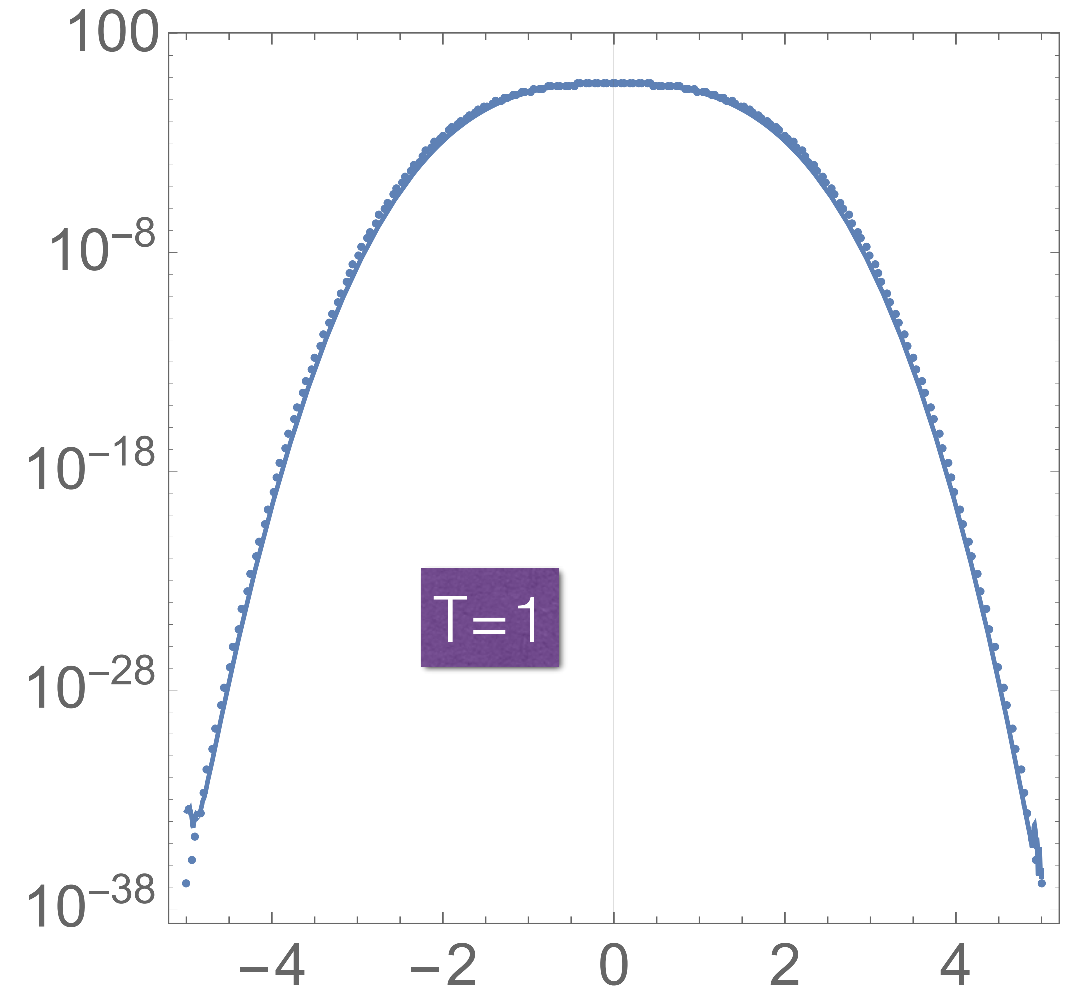
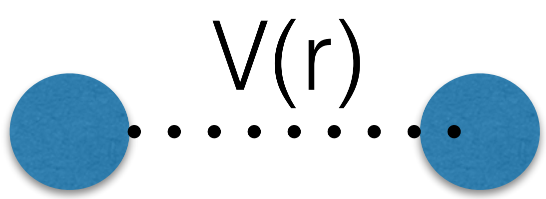
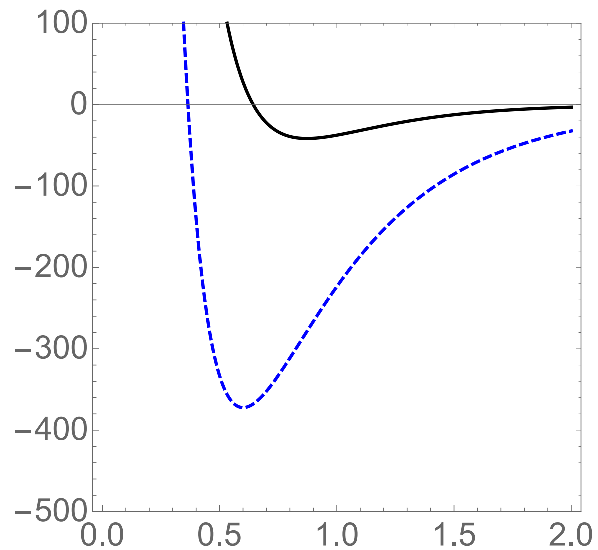


FIG. 3: Density matrix $P(x_0)$ vs x_0 for anharmonic oscillator with the coupling $g = 1$, calculated via the definition (1) (line) and the flucton method (points). The line is based on 60 wave functions found numerically: one can notice that finite number of them leads to deviations, which however happen at very distant tails, with the probability $P \sim 10^{-30}$.

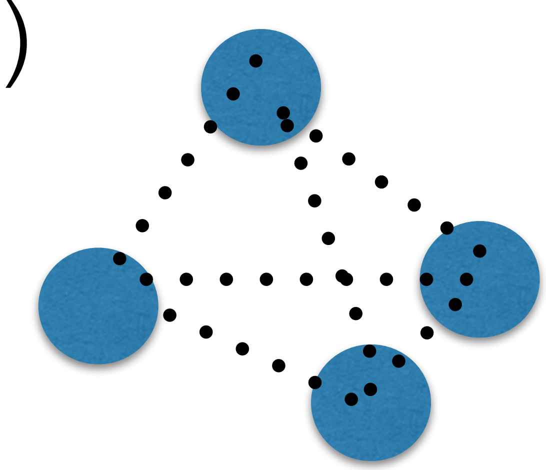
semiclassical clustering of nucleons at Tf (about 100 MeV)



$$\ddot{R} = (\frac{2}{m})\frac{\partial V(R)}{\partial R}$$



A=4



$$S = \oint d\tau\,[\frac{3m}{4}\dot{r}^2 + 6V(r)]$$

$$\ddot{R} = (\frac{4}{m})\frac{\partial V(R)}{\partial R}$$

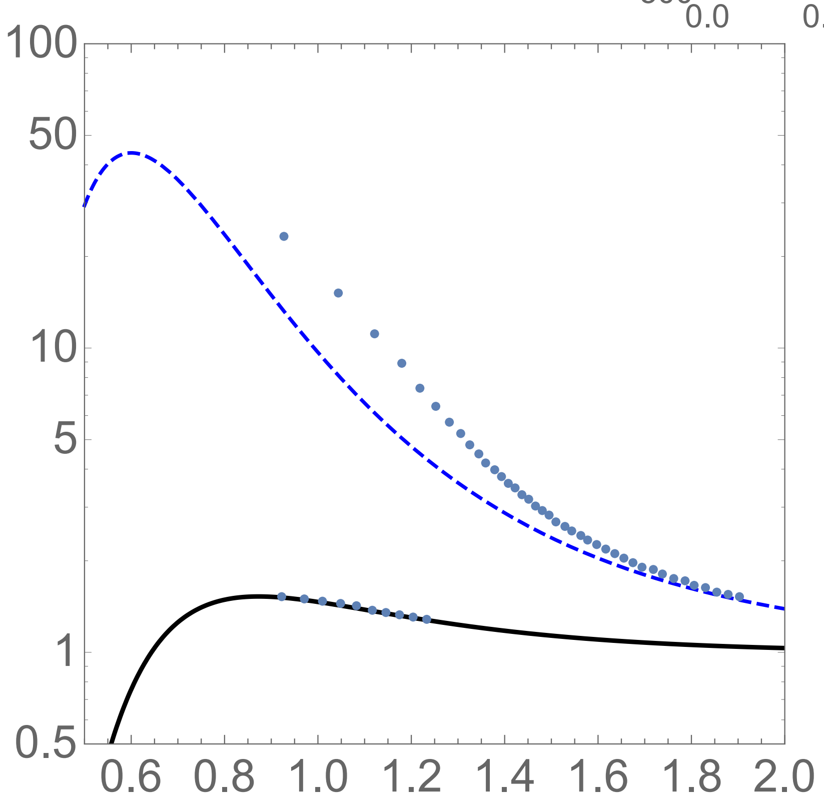
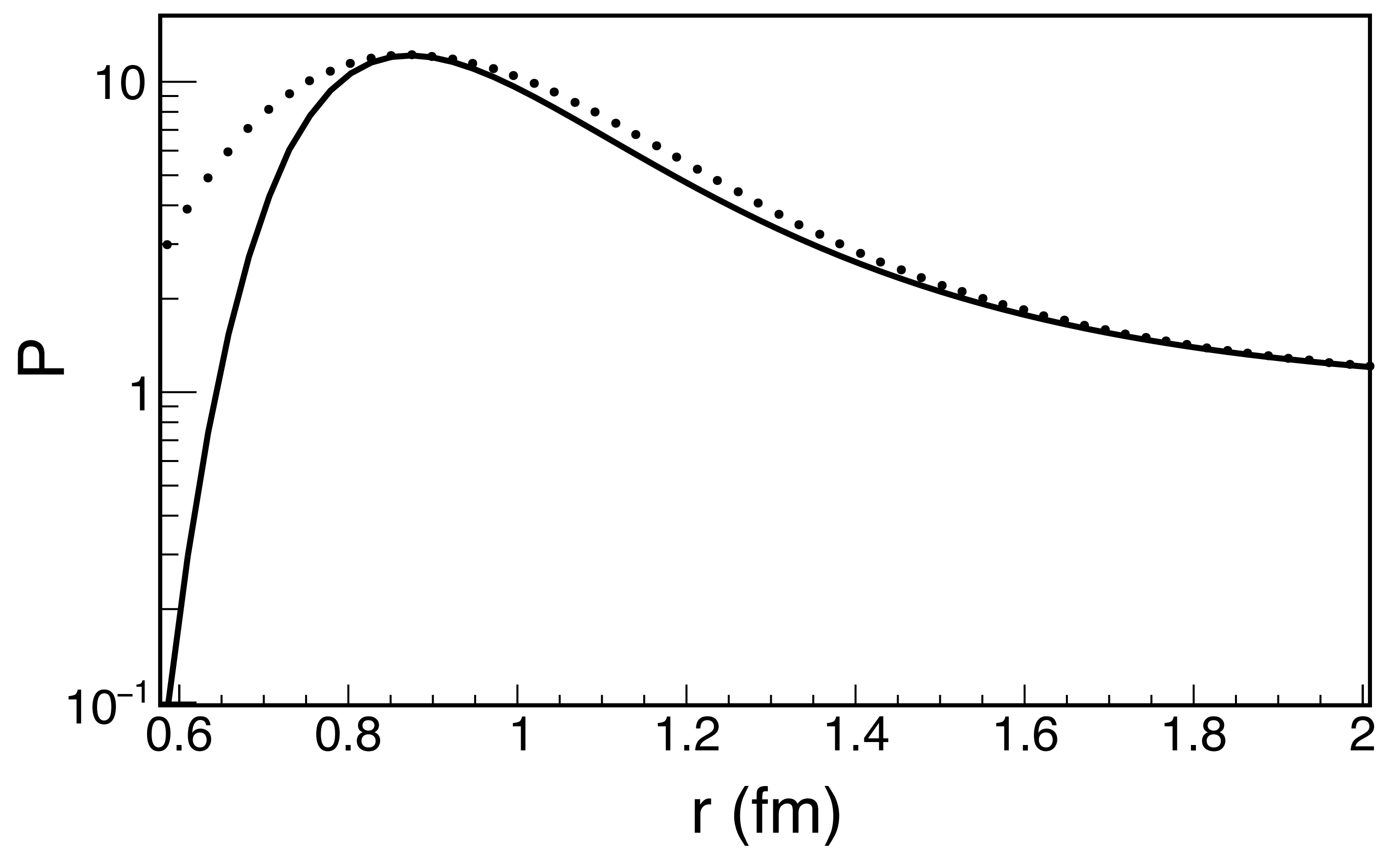
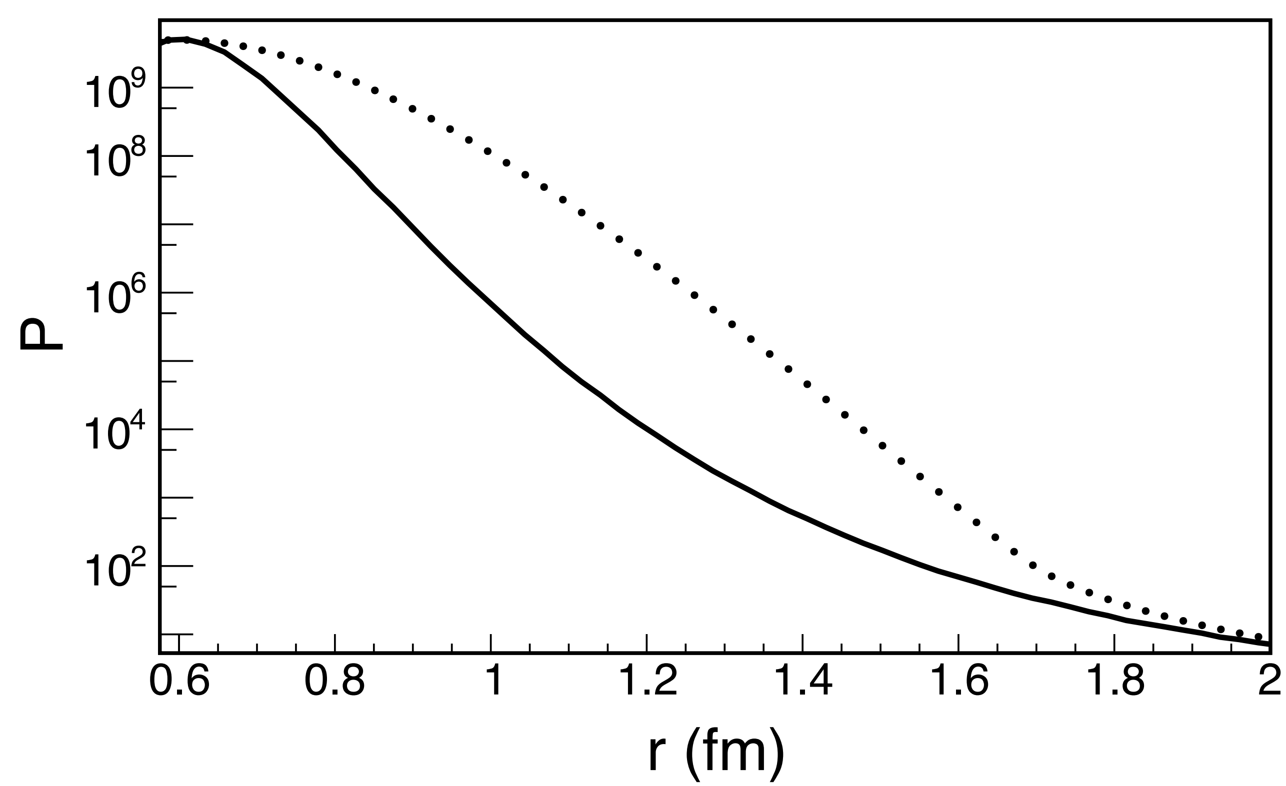


FIG. 4: The probability for two nucleons being at distance r (fm) from each other at the temperature $T = 100\,MeV$. The lower and upper curves are Boltzmann factors for Walecka potential, with sigma masses $m_\sigma = 500$ and $285\,MeV$, respectively. The dottes indicate the semiclassical probability distribution calculated via flucton method.

Two potentials: Unmodified and strongly modified (from Wambach et al spectral density of sigma





A=4 nucleons
line=exp(-V/T)
dots=flucton
Upper plot -ordinary V
Lower is Modified V

He4 and K-harmonics

Jacobi coordinates

$$\vec{\xi}[1] = \frac{\vec{x}[1]-\vec{x}[2]}{\sqrt{2}}, \quad \vec{\xi}[2] = \frac{\vec{x}[1]+\vec{x}[2]-2\vec{x}[3]}{\sqrt{6}},$$

$$\vec{\xi}[3] = \frac{\vec{x}[1]+\vec{x}[2]+\vec{x}[3]-3\vec{x}[4]}{2\sqrt{3}}$$

The radial coordinate, or *hyperdistance*, is defined as

$$\rho^2 = \sum_{m=1}^{3} \vec{\xi}[m]^2 = \frac{1}{4}\Big(\sum_{i\neq j}(\vec{x}[i]-\vec{x}[j])^2\Big) \qquad \text{(A1)}$$

The radial part of the Laplacian in these Jacobi coordinates is $\psi"(\rho) + 8\psi'(\rho)/\rho$, and using substitution $\psi(\rho) = \chi(\rho)/\rho^4$ one arrives to conventional-looking Schreodinger eqn for $K = 0$ harmonics

$$\frac{d^2\chi}{d\rho^2} - \frac{12}{\rho^2}\chi - \frac{2M}{\hbar^2}(W(\rho) - E)\chi = 0 \qquad \text{(A2)}$$

The main bound state at -28 MeV
is reproduced in literature
Unexpectedly, we found another bound state
At -8 MeV
It corresponds to known resonance!

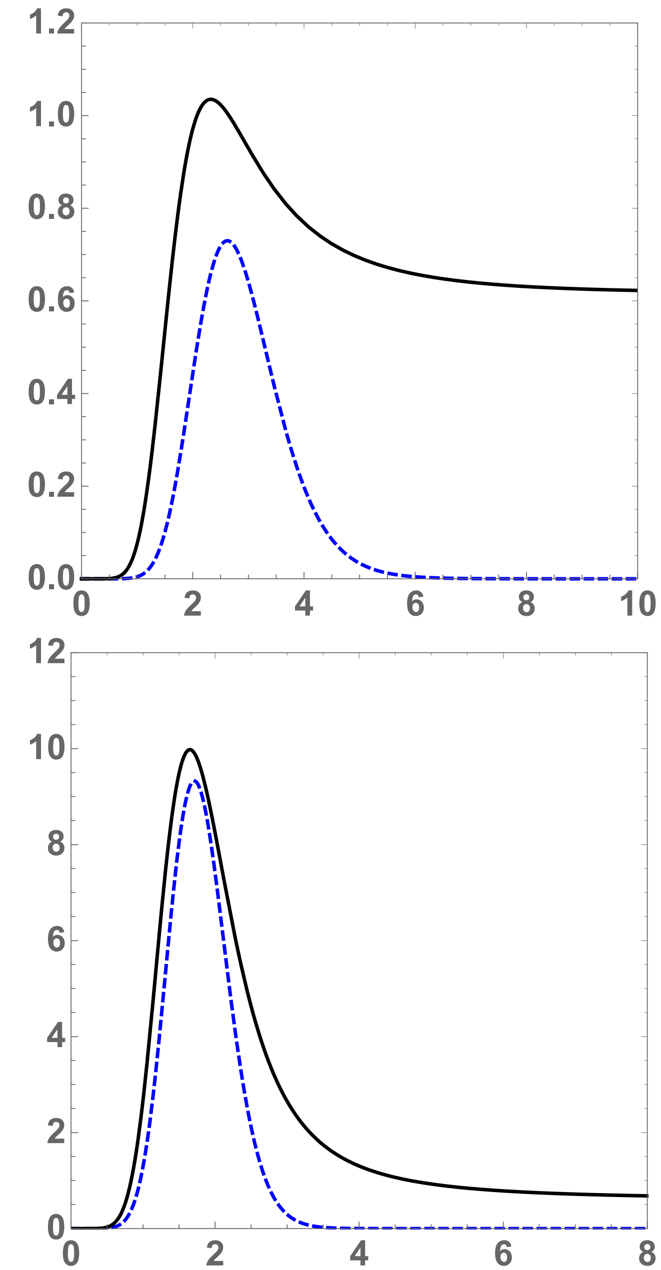


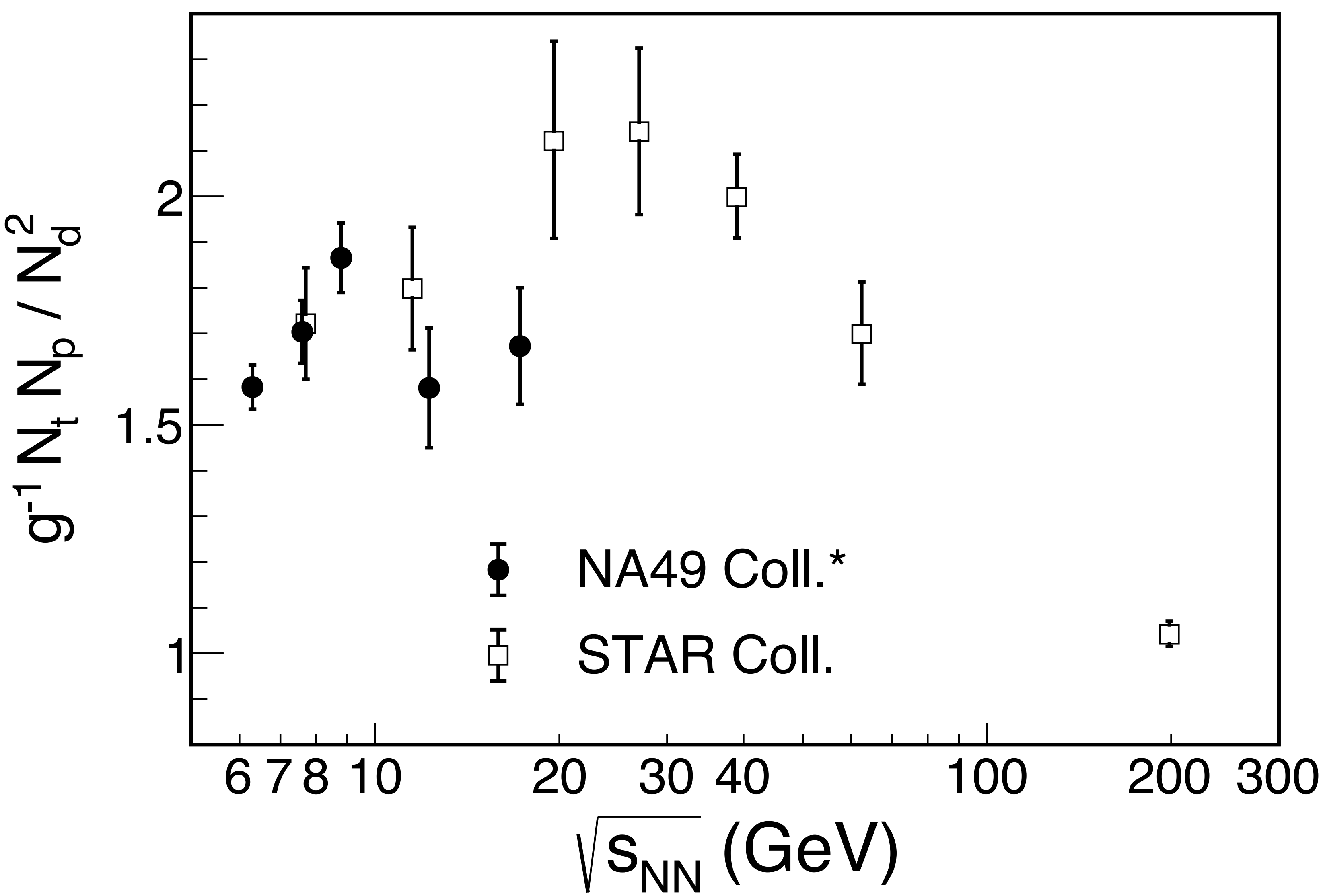
FIG. 8: The solid lines are Boltzmann-weighted density matrix, at $T = 100\,MeV$, using 40 lowest states of the K-harmonics radial equation, for the usual nuclear potential (upper plot) and the modified one (lower plot). In both case the blue dashed line show the contribution of the deepest bound state.

TABLE I: Low-lying resonances of He^4 system, from BNL properties of nuclides listed in *nndc.bnl.gov* web page. JP is total angular momentum and parity, Γ is the width. The last column is the decay channel branching ratios, in percents. p, n, d correspond to emission of proton, neutron or deuterons.

$E\,(MeV)$	JP	$\Gamma\,(MeV)$	decay modes, in %
20.21	0 +	0.50	p =100
21.01	0 -	0.84	n =24, p =76
21.84	2-	2.01	n = 37, p = 63
23.33	2-	5.01	n = 47, p = 53
23.64	1-	6.20	n = 45, p = 55
24.25	1-	6.10	n = 47, p = 50 , d=3
25.28	0-	7.97	n = 48 , p = 52
25.95	1-	12.66	n = 48 ,p = 52
27.42	2+	8.69	n = 3 , p = 3 ,d = 94
28.31	1+	9.89	n = 47 , p = 48 , d = 5
28.37	1-	3.92	n = 2, p = 2, d = 96
28.39	2-	8.75	n = 0.2, p = 0.2 , d = 99.6
28.64	0-	4.89	d=100
28.67	2+	3.78	d=100
29.89	2+	9.72	n = 0.4 , p = 0.4, d = 99.2

Newly found radial excitation

Statistical model implies that all thee resonances Are also produced and decay, some In observable channels like d+d,p+t



Extra source for t: from pre-cluster decays?

Summary

the semiclassical they based on instanton-dyons reproduces
(i) the deconfinement; (ii) chiral symmetry transitions;
(iii) not just in QCD (where quasicritical Tdec and Tchir are about the same) **but with arbitrary quark periodicity phases,** where there are more phase transitions
=>

Path integral semiclassics at nonzero T
Applied to few-nucleon
clusters at freeseout
=> very sensitive to inter-N potential

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Instanton-dyon theory is Poisson-dual to monopole theory
pro: simpler to use
con: restricted to Euclidean time and cannot be used for kinetics

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How are they related?
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instanton-dyons and monopoles correspond to two different approaches to dynamics, but they result in the same partition function