Is lattice simulation of two-dimensional super Yang-Mills possible?

KANAMORI Issaku

RIKEN NiSHiNA CENTER

Jan. 8, 2009 @ Sapporo Winter School 2009

Refs.

I.K. and H.Suzuki, Nucl.Phys.B in press [arXiv:0809.2856[hep-lat]]

I.K., H.Suzuki and F.Suginio, Phys.Rev. D77 (2008), 091502

I.K., work in progress

Introduction

Lattice Simulation of 2-dim super Yang-Mills is now possible

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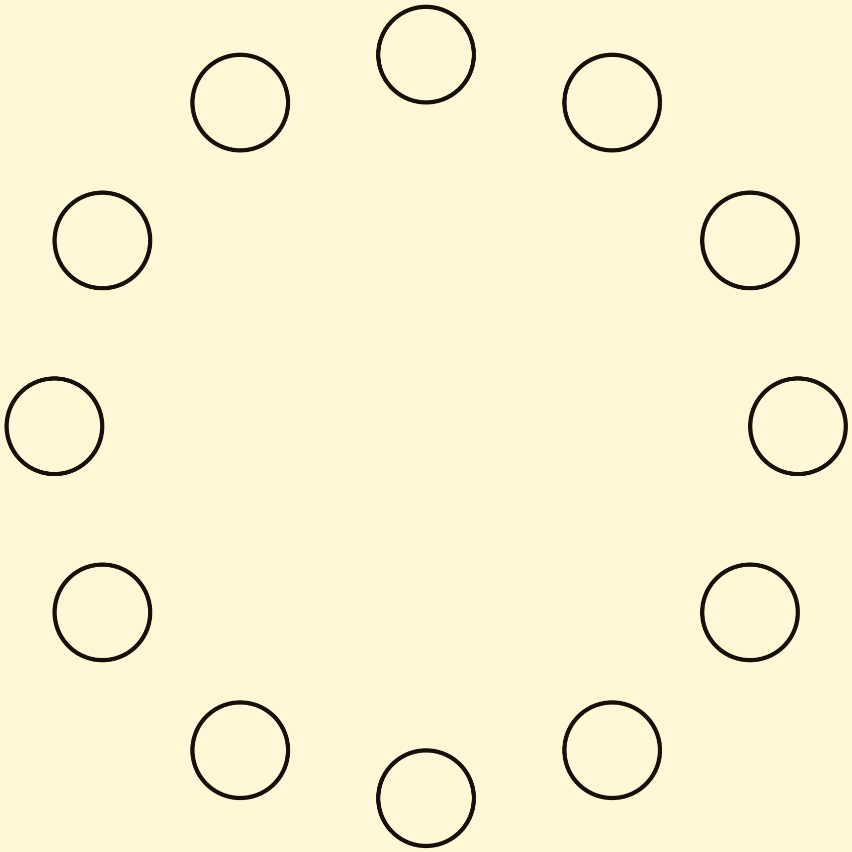
Plan

1. Introduction & Motivation
2. Formulation: Sugino model
3. What should we measure?
   Partially Conserved Super Current (PCSC)
4. Simulation result
5. Application: observing spontaneous SUSY breaking
6. Conclusion

One Example of Spontaneous Symmetry Breaking



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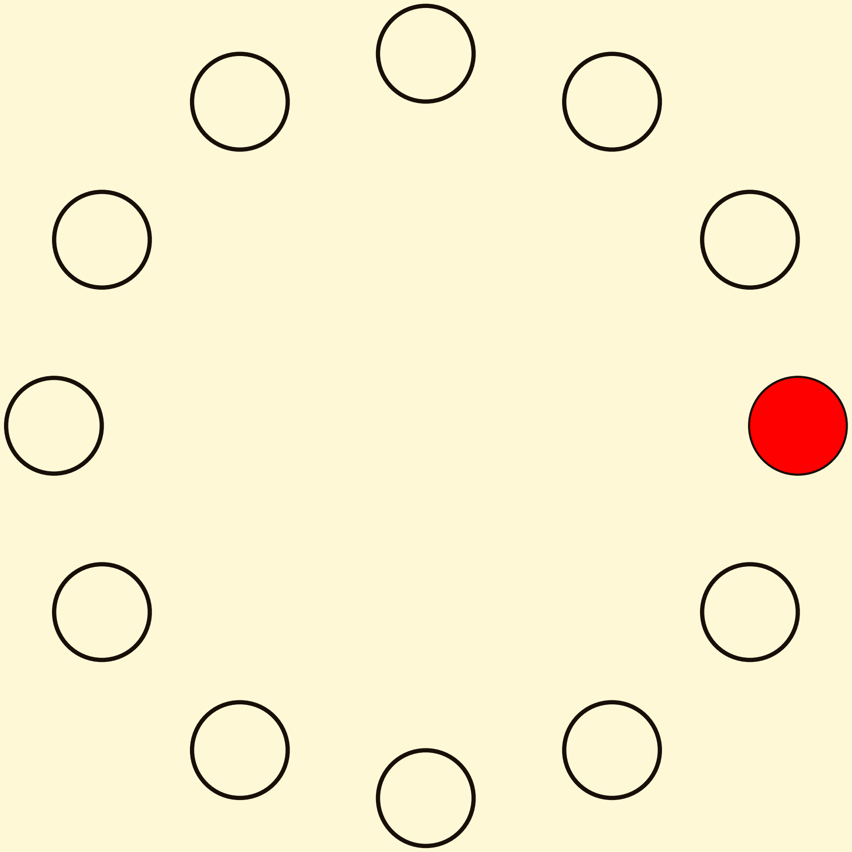

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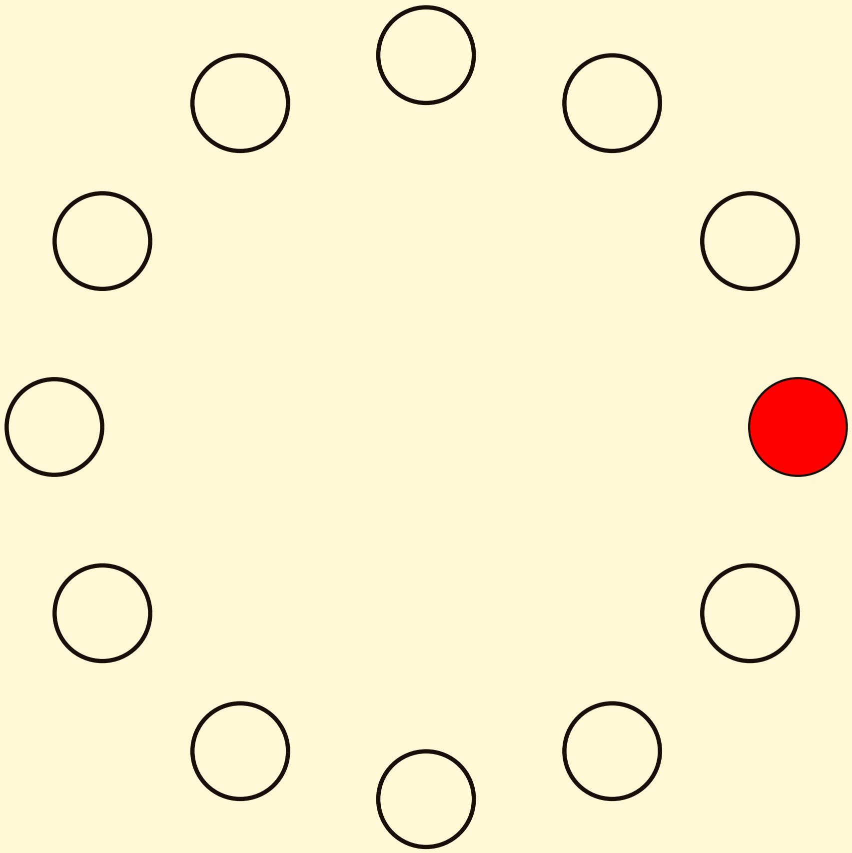

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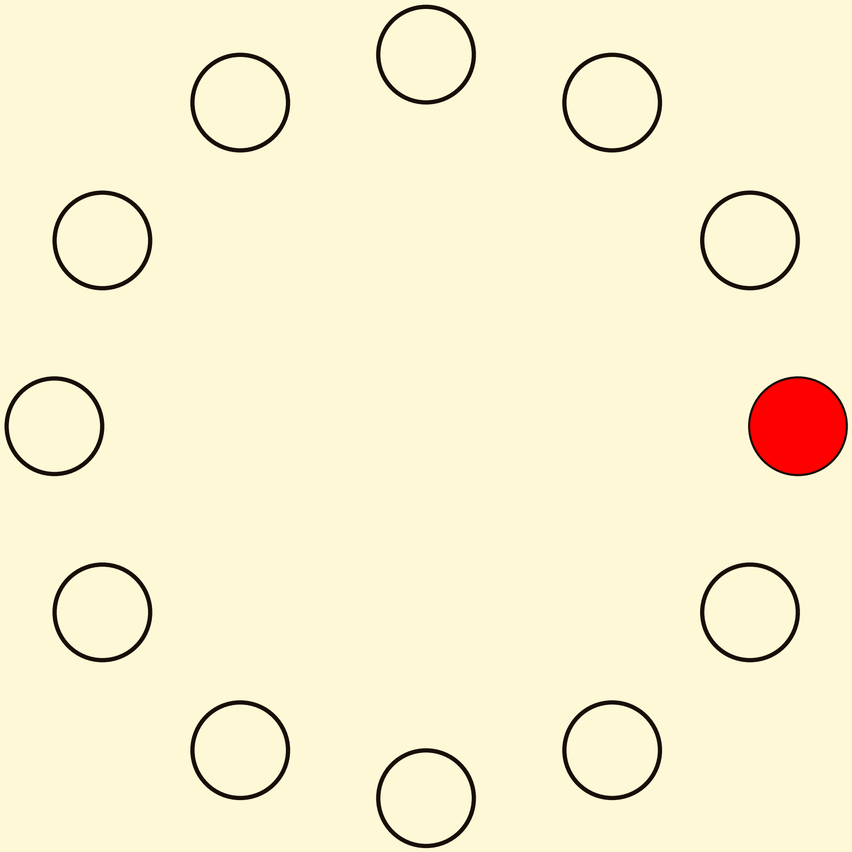

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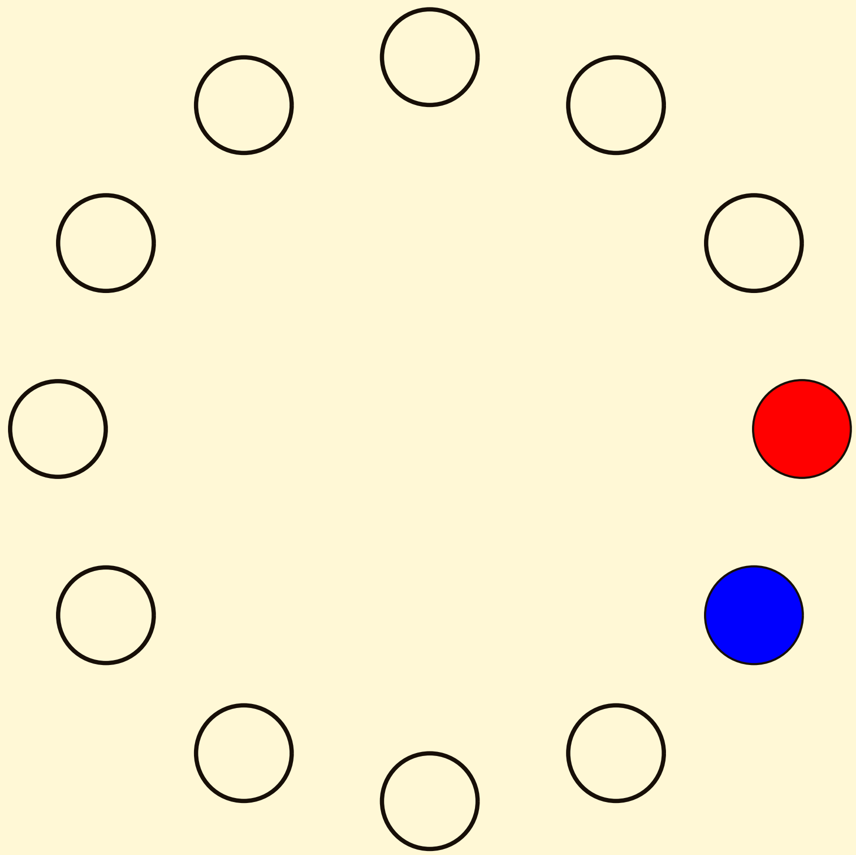

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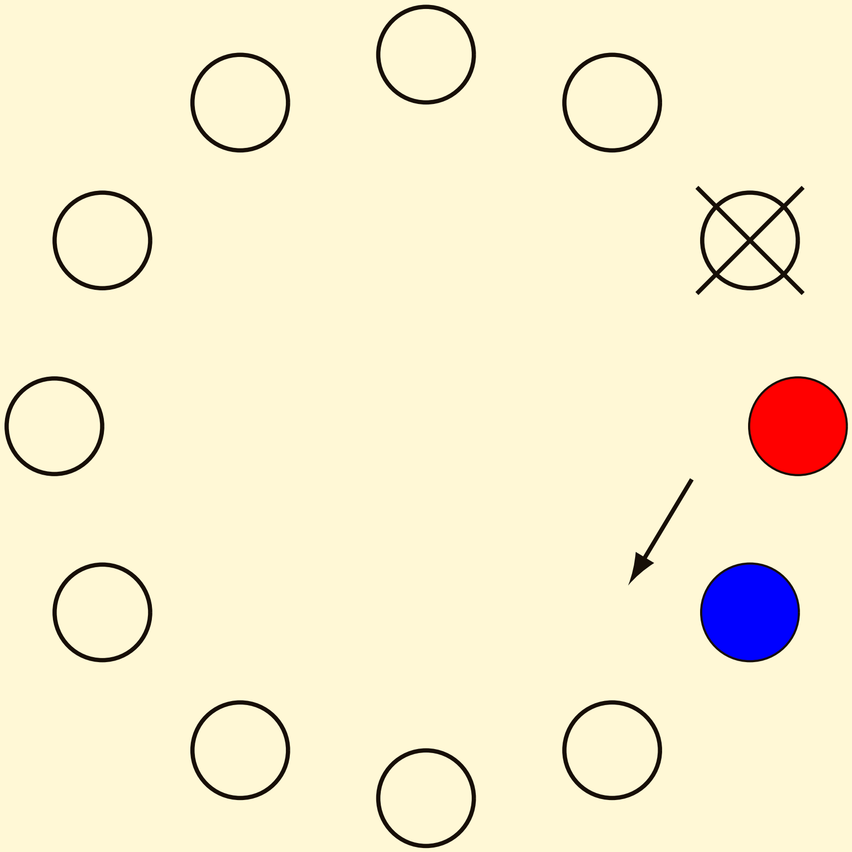

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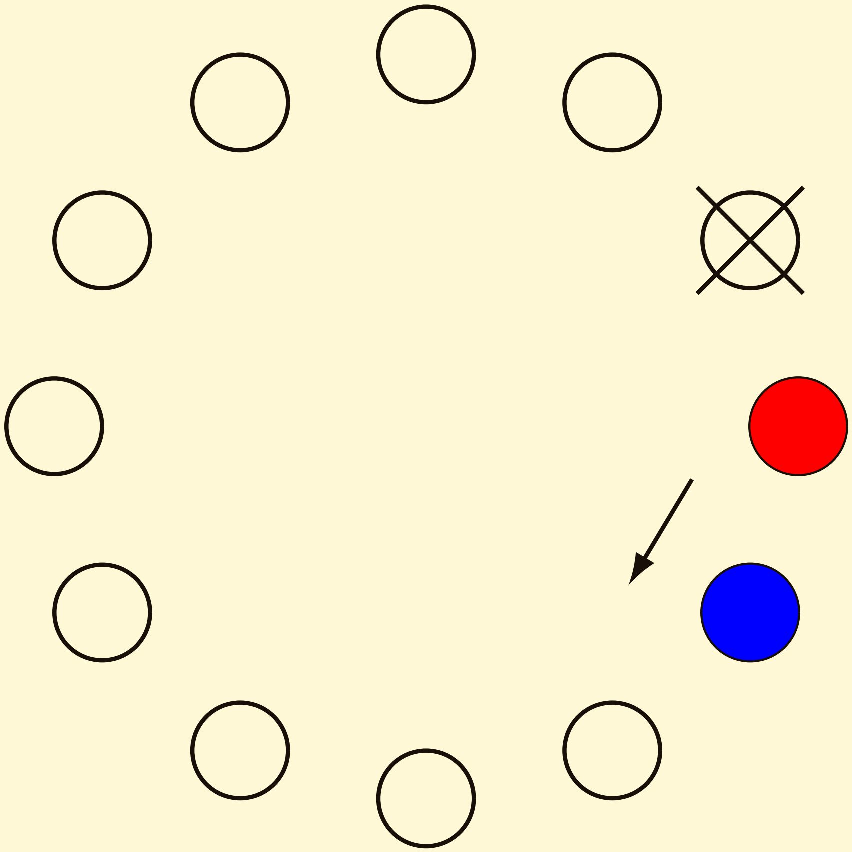
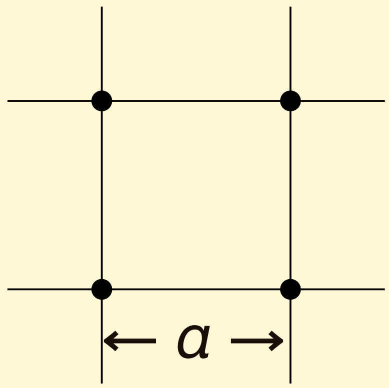


the poor
first victim

Lattice Scenario à la Kawamoto

Lattice: non-perturbative regularization

continuum limit ($a \to 0$) in the end



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- QCD (gauge theory)
- gravity

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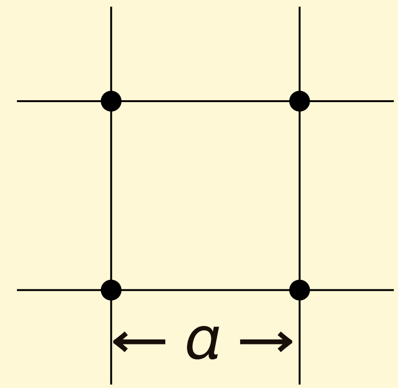

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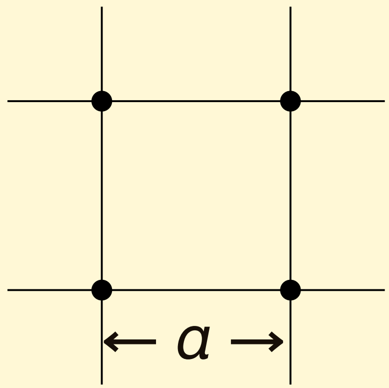

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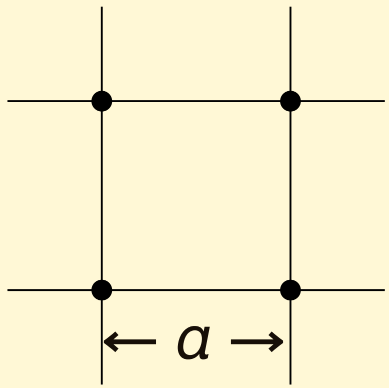

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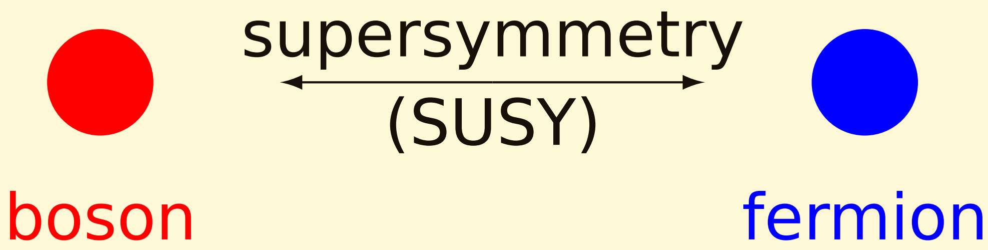
what is fermions?

$\Rightarrow$putting supersymmetry = understanding fermions



Motivation

Lattice simulation: a non-perturbative method for field theory

- SUSY breaking
  Why our world is *n*ot supersymmetric?
- gauge/string duality
  tool for strong coupling gauge theory
- SUSY can be a symmetry of beyond Standard Model
  worth developing simulation techniques
  (will be found in LHC ?)
- "Experiment" for theoretical analysis
  poster by Suzuki

Formulation

Scalar Q for $\mathcal{N} \geq 2$ on lattice

SUSY on lattice: impossible?($\because$ $Q \sim \sqrt{P}$)

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$\Downarrow$

If $\mathcal{N} \geq 2$, it is possible!

(Models for SYM)

Cohen-Kaplan-Katz-Ünsal, Sugino, Catterall,
D'Adda-I.K.-Kawamoto-Nagata,
Suzuki-Taniguchi,Kikukawa-Sugino,...
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- topological twist $\Rightarrow$ scalar Q on a site
- simulation: Catterall, Suzuki, Fukaya-I.K.-Suzuki-Takimi, I.K-Suzuki-Sugino

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Two types

1. Keep the whole SUSY (at finite a)

   DKKN; Nagata; Arianos-D'Adda-Feo-Kawamoto-Saito; Kato-Sakamoto-So

2. partially at finite a, the whole is (automatically) restored in $a \to 0$

   CKKU;Sugino

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   We confirm this scenario in the simulation

Sugino model

Sugino, JHEP 01(2004)067

target: 2-dim $\mathcal{N}=(2,2)$ SYM

nilpotent Q (Twisted) SUSY Algebra, continuum

$$Q^2 = \delta_{\phi}^{(\text{gauge})} \quad Q_0^2 = \delta_{\bar{\phi}}^{(\text{gauge})} \quad \{Q, Q_0\} = 2i\partial_0 + 2\delta_{A_0}^{(\text{gauge})}$$

Action (dimensional reduction from 4-dim $\mathcal{N}=1$)

$$S = \frac{1}{g^2}\int d^2x\,\mathrm{tr}\left\{\frac{1}{2}F_{MN}F_{MN} + \Psi^T C\Gamma_M D_M \Psi + \hat{H}^2\right\}$$

$\Psi^T = (\psi_0, \psi_1, \chi, \eta/2)$ (under a suitable rep. of Γ_M)

$A_M =$ (gauge field, scalar)

$\hat{H} =$ aux. field

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Q-exact action (continuum)

$$S = Q(\dots) = \frac{1}{g^2}\int d^2x \, \mathrm{tr}\Big\{\frac{1}{4}F_{01}^2 + D_\mu\phi D_\mu\overline{\phi} + \frac{1}{4}[\phi,\overline{\phi}]^2 + i\psi_\mu D_\mu\eta + \cdots - \frac{1}{4}\eta[\phi,\eta] + \cdots\Big\}$$

$$QA_\mu = \psi_\mu \qquad Q\psi_\mu = iD_\mu\phi$$
$$Q\phi = 0 \qquad \dots$$

$$Q_0A_0 = \frac{i}{2}\eta \qquad Q_0\eta = -2iD_0\overline{\phi}$$
$$Q_0A_1 = -\chi \qquad Q_0\chi = iD_1\overline{\phi}$$
$$Q_0\overline{\phi} = 0 \qquad \dots$$

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$$Q_0A_0=\frac{i}{2}\eta \quad Q_0\eta=-2iD_0\overline{\phi}$$
$$Q_0A_1=-\chi \quad Q_0\chi=iD_1\overline{\phi}$$
$$Q_0\overline{\phi}=0 \quad \dots$$

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target: 2-dim $\mathcal{N} = (2,2)$ SYM

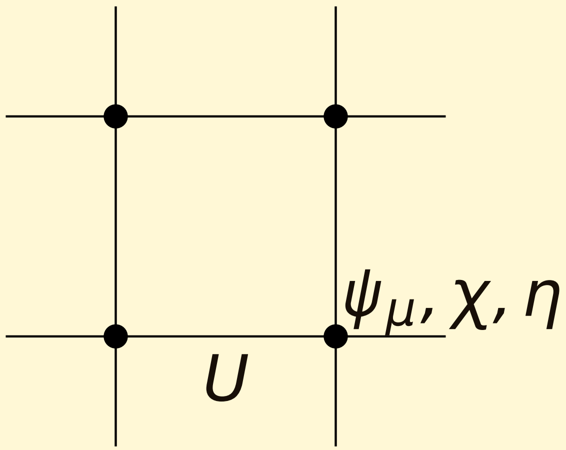
nilpotent Q Lattice version

$$Q^2 = \delta_\phi^{(\mathrm{gauge})}$$

Q-exact action (lattice)

$$S = Q(\ldots) = S[U(x,\mu), \phi(x), \overline{\phi}(x), H(x) \quad \text{bosons}$$
$$\eta(x), \chi(x), \psi_0(x), \psi_1(x)] \quad \text{fermions}$$

$$QU(x,\mu) = i\psi_\mu(x)U(x,\mu)$$
$$Q\psi_\mu(x) = i\psi_\mu(x)\psi_\mu(x) - i(\phi(x) - U(x,\mu)\phi(x+\hat{\mu})U(x,\mu)^{-1})$$
$$Q\phi = 0$$
$$\vdots$$



Symmetries

(continuum) $\Rightarrow$ (lattice)

- 4 supercharges: $\{Q_0, Q_1, \tilde{Q}, Q\}$ $\Rightarrow$ Q
- R-symmetry: $U(1)_A, U(1)_V, Z_2$ $\Rightarrow$ $U(1)_A$

($U(1)_A$: a rotational symmetry on 2-3 plane)

Scenario

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We will confirm this scenario

What should we measure?

to check the restoration of SUSY

Scenario

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Powerful non-perturbative tool

- Simulation! : conservation of “super current”

In which stage is SUSY broken?

Target: 2-dim $\mathcal{N} = (2, 2)$ SYM, SU(2)
lattice model + scalar mass term
+ thermal B.C.

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1. lattice artifact

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PCSC relation
(Separate the effect of lattice artifact)
satisfied $\Rightarrow$ the lattice artifact vanishes
not satisfied $\Rightarrow$ does not vanish

PCSC relation

4 supercharges: $Q_A = \{Q_0, Q_1, \tilde{Q}, Q\}$

Partially conserved supercurrent:

$$\partial_\mu \mathcal{J}^A_\mu = 0 \Rightarrow \boxed{\partial_\mu \mathcal{J}^A_\mu = \mu^2/g^2\, Y^A} \text{ (PCSC)} \quad \mu\text{: scalar mass}$$

$$\langle \partial_\mu \mathcal{J}^A_\mu(x) X^A(0)\rangle - \frac{\mu^2}{g^2}\langle Y^A(x) X^A(0)\rangle = -i\delta^2(x)\langle Q^A X^A(0)\rangle$$

$$\boxed{\text{measure } \frac{\langle \partial_\mu \mathcal{J}^A_\mu(x) X^A(0)\rangle}{\langle Y^A(x) X^A(0)\rangle} \text{ as a function of } \mu^2/g^2}$$

$$Y^A = -2\left[C(\Gamma_2 \operatorname{tr}(A_2\Psi) + \Gamma_3 \operatorname{tr}(A_3\Psi))\right]^A$$
$$\sim (\text{scalar}) \times (\text{fermion})$$

$$X^A = \frac{1}{g^2}\left[\Gamma_0(\Gamma_2 \operatorname{tr}(A_2\Psi) + \Gamma_3 \operatorname{tr}(A_3\Psi))\right]^A$$

Possible Divergences: No Problem

IF the 2 point funcs. have divergence...

$\mathcal{O}(a)$ lattice artifacts in $\mathcal{J}$ and Y

$\Rightarrow \mathcal{O}(a) \times \infty$ can be finite

$\Rightarrow$ need to remove such extra effects

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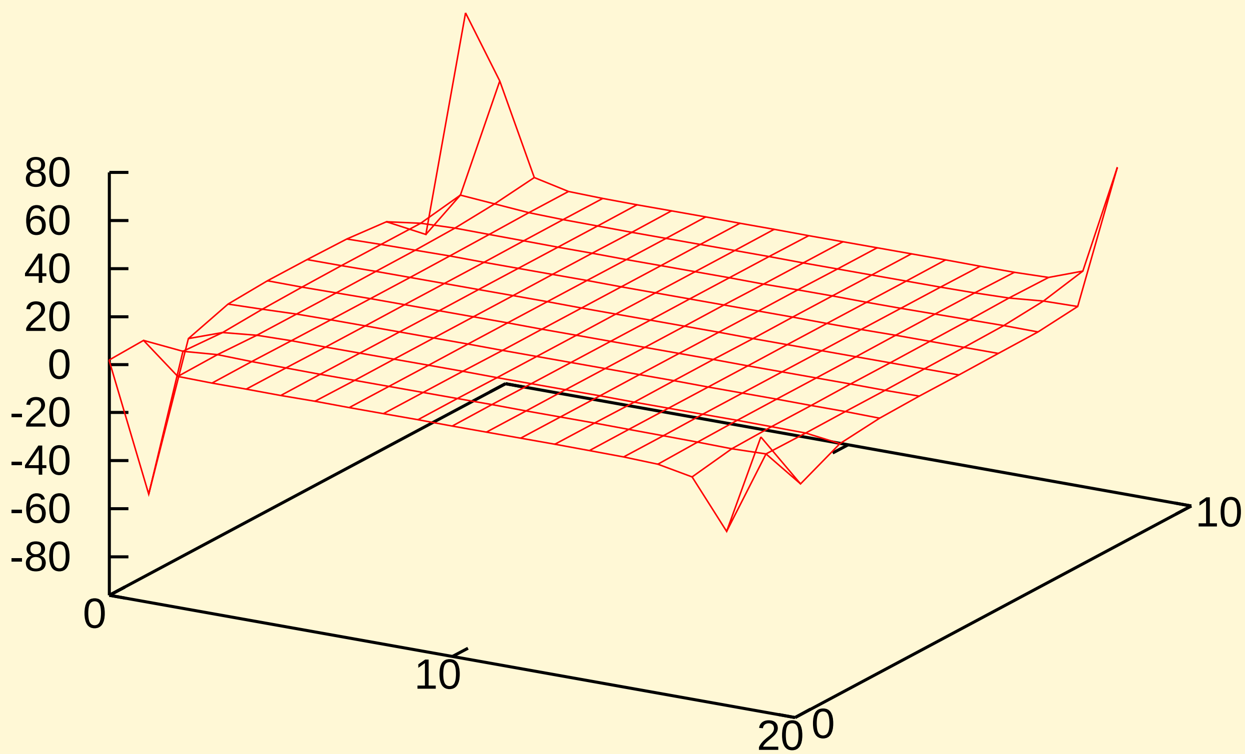
Simple analysis is OK

Simulation Result

PCSC relation

$$\langle \partial_\mu \mathcal{J}^A_\mu(x) X^A(0)\rangle - \frac{\mu^2}{g^2}\langle Y^A(x) X^A(0)\rangle = -i\delta^2(x)\langle Q^A X^A(0)\rangle$$



20×10, $ag = 0.1414$, input $\mu^2/g^2 = 1.0$, $\mathcal{J}$ for Q_0

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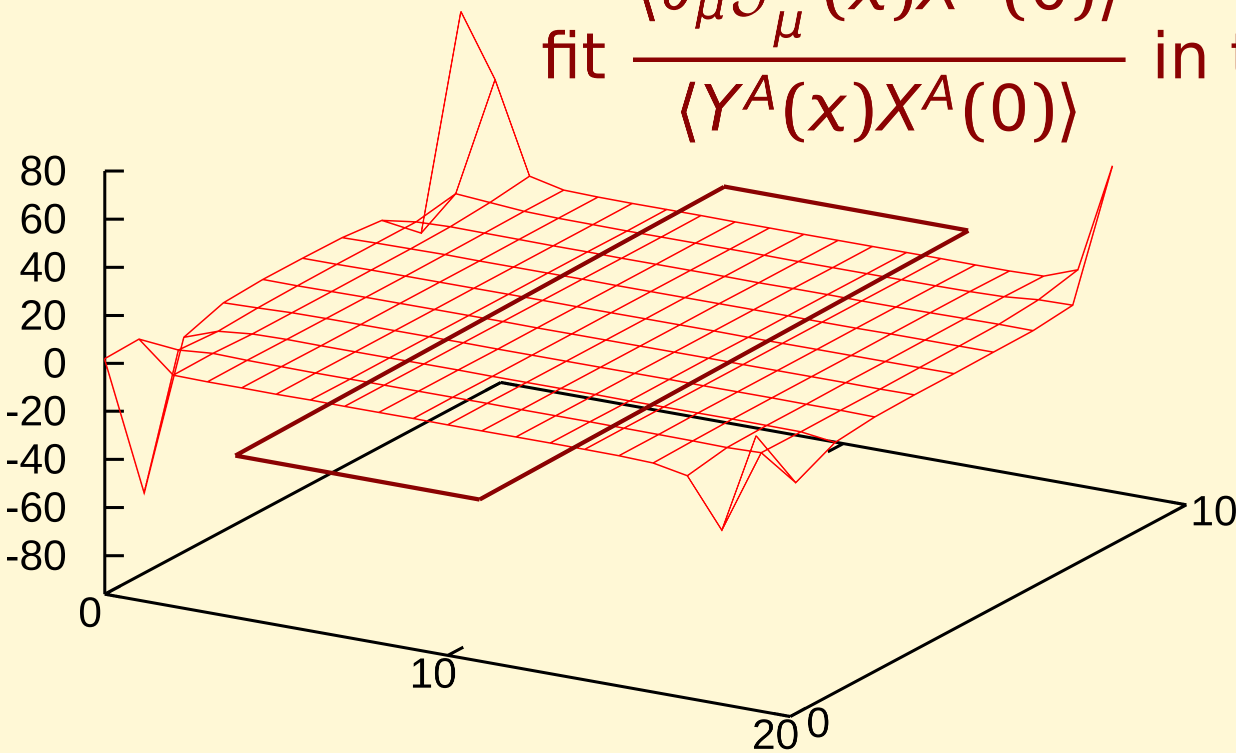

fit $\dfrac{\langle \partial_\mu \mathcal{J}^A_\mu(x) X^A(0)\rangle}{\langle Y^A(x) X^A(0)\rangle}$ in this region

$$\left(\sim \frac{\mu^2}{g^2}\right)$$

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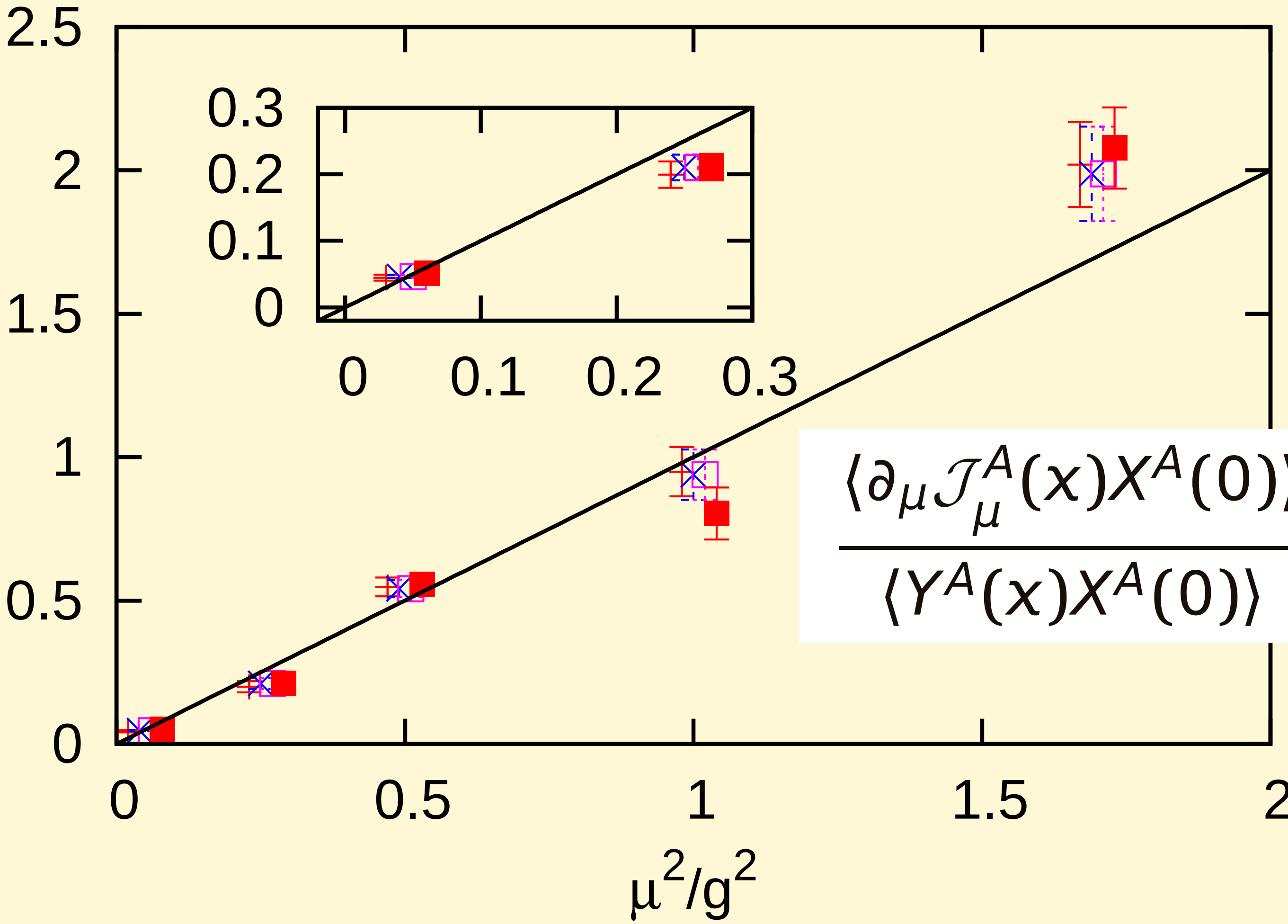
PCSC relation (continuum limit)



$$\frac{\langle \partial_\mu \mathcal{J}^A_\mu(x) X^A(0)\rangle}{\langle Y^A(x) X^A(0)\rangle} \sim \frac{\mu^2}{g^2}$$

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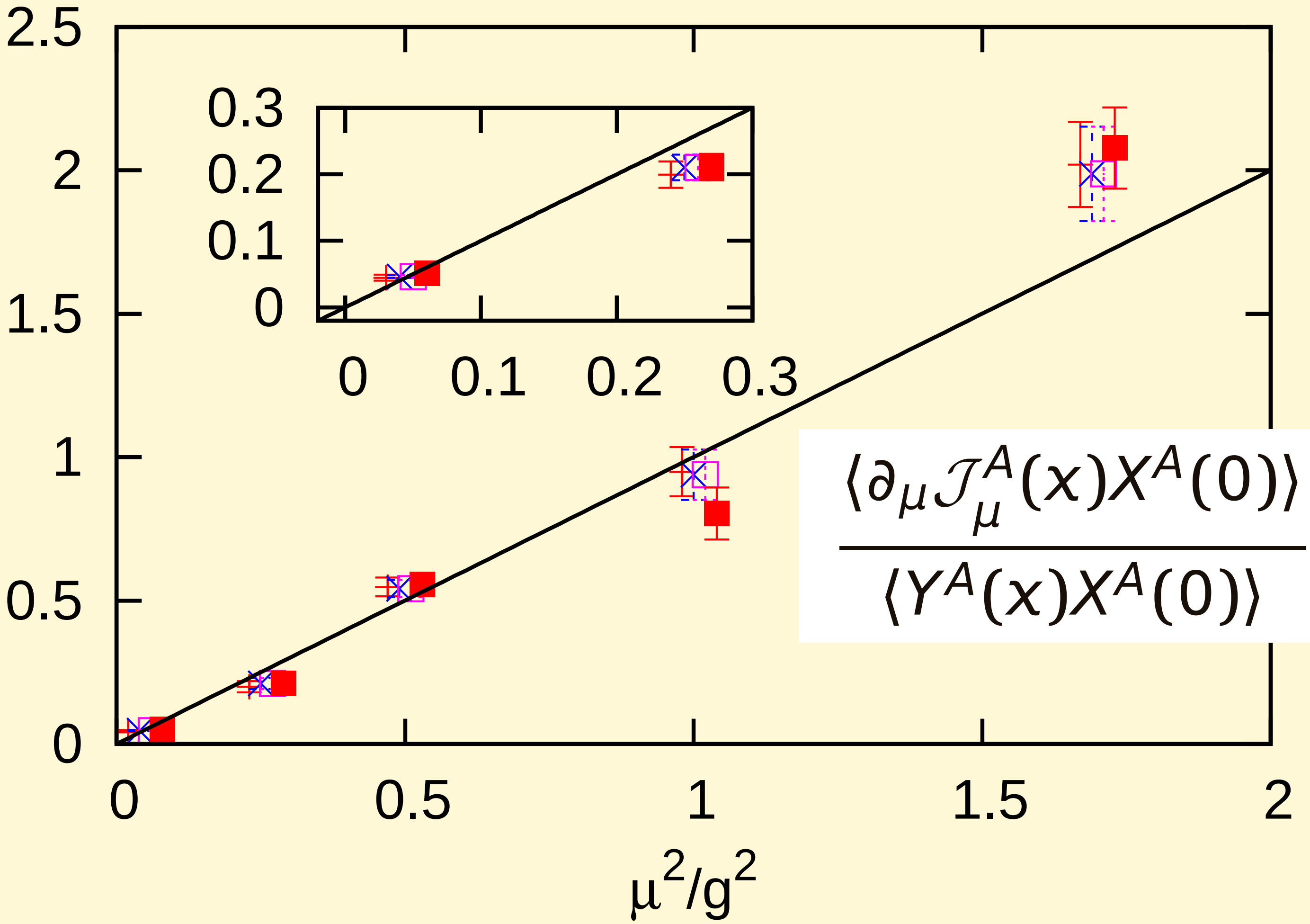
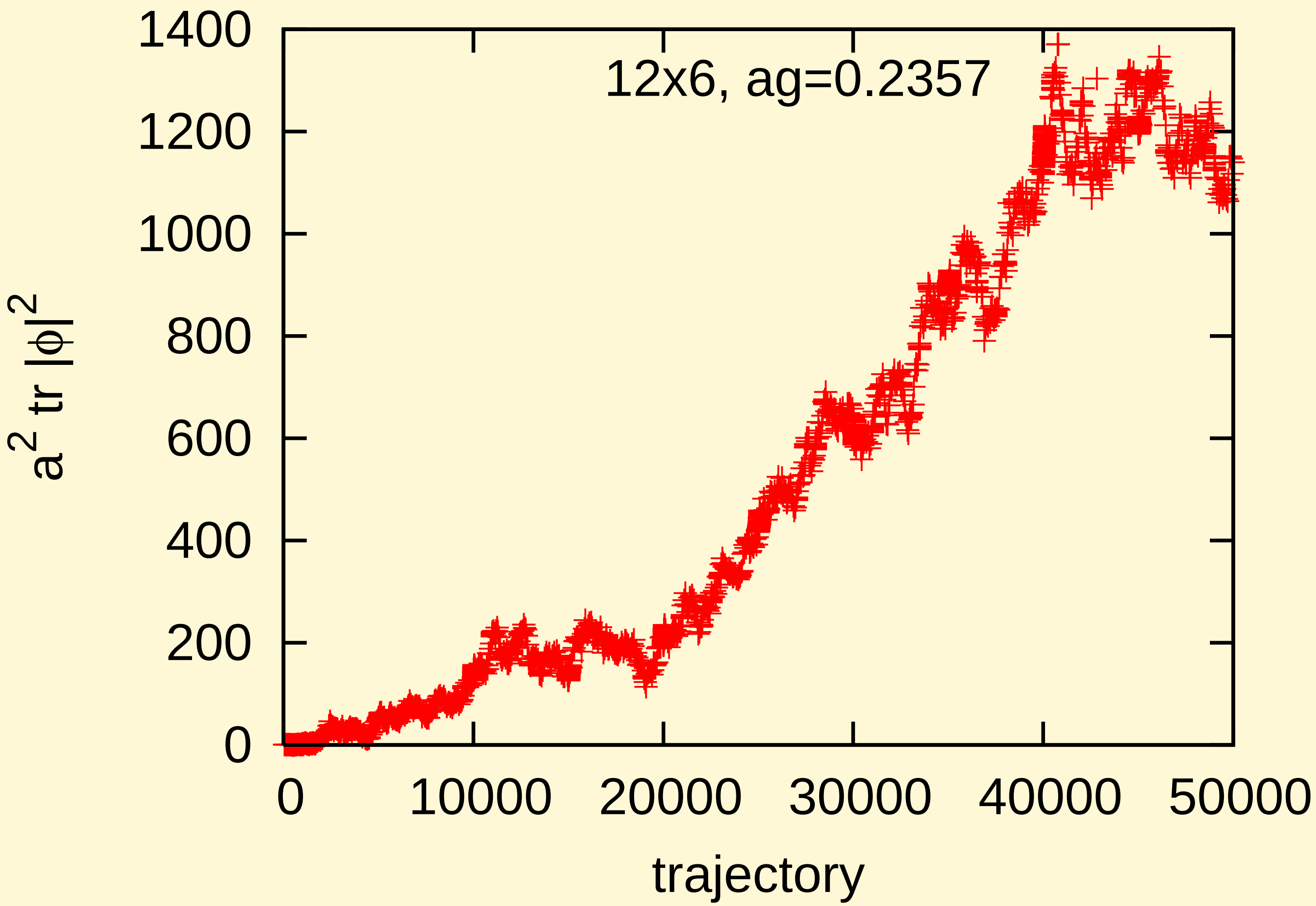


$$\frac{\langle \partial_\mu \mathcal{J}^A_\mu(x) X^A(0)\rangle}{\langle Y^A(x) X^A(0)\rangle} \sim \frac{\mu^2}{g^2}$$

PCSC is satisfied ⇒ no SUSY breaking due to lattice artifact

massless case: never thermalized

because of the flat direction in the potential

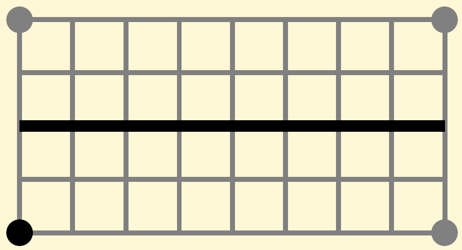


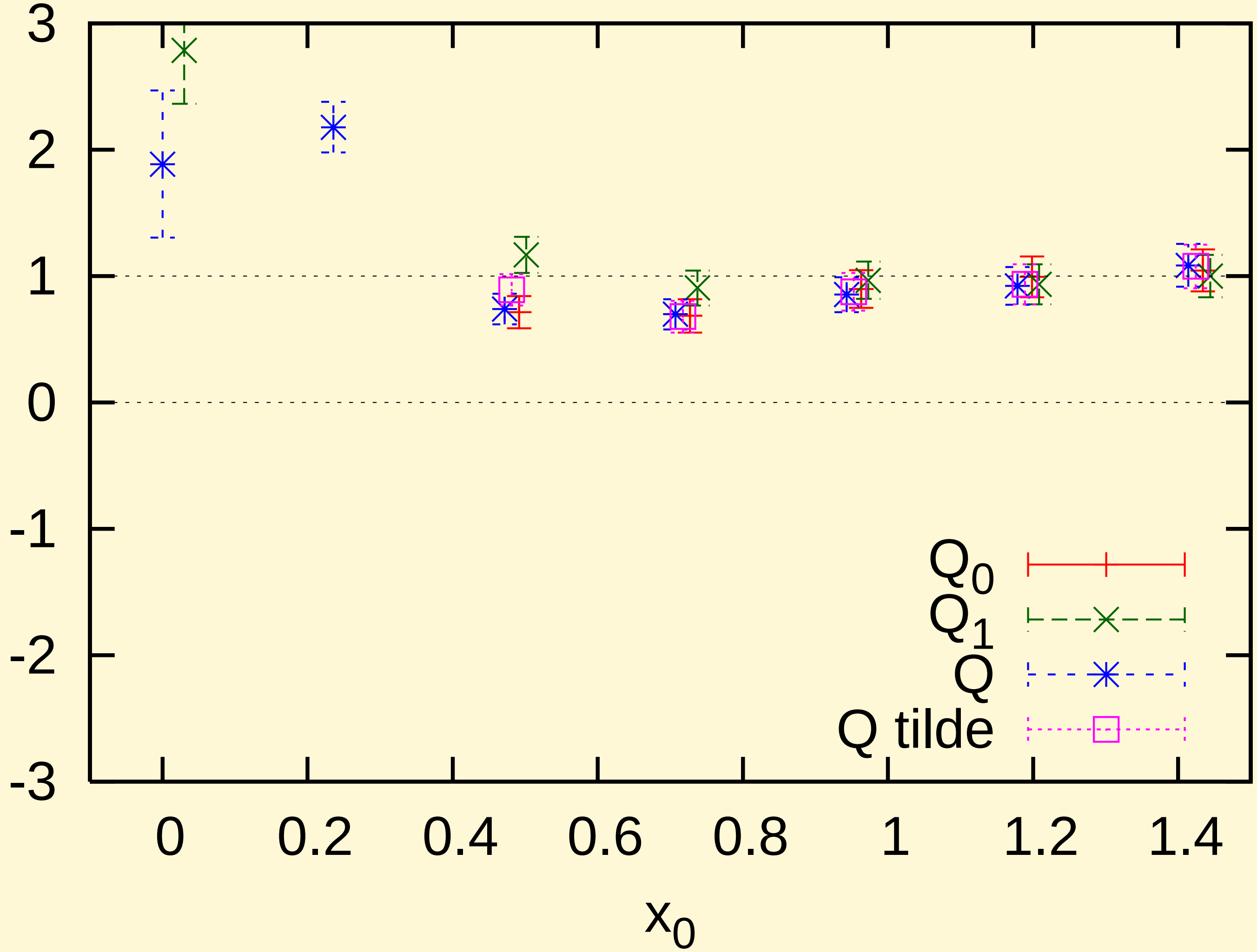
cannot be used in the measurement

anti-PBC ⇒ PBC: Noisy

$$\frac{\langle \partial_\mu \mathcal{J}_\mu^A(x) X^A(0)\rangle}{\langle Y^A(x) X^A(0)\rangle} \sim \frac{\mu^2}{g^2} + \delta(x) \qquad \mu^2/g^2 = 1, \boxed{\text{anti-PBC}}$$

12x6
$ag = 0.2367$





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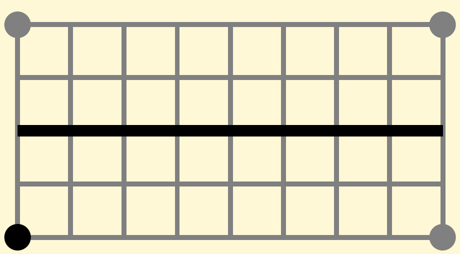

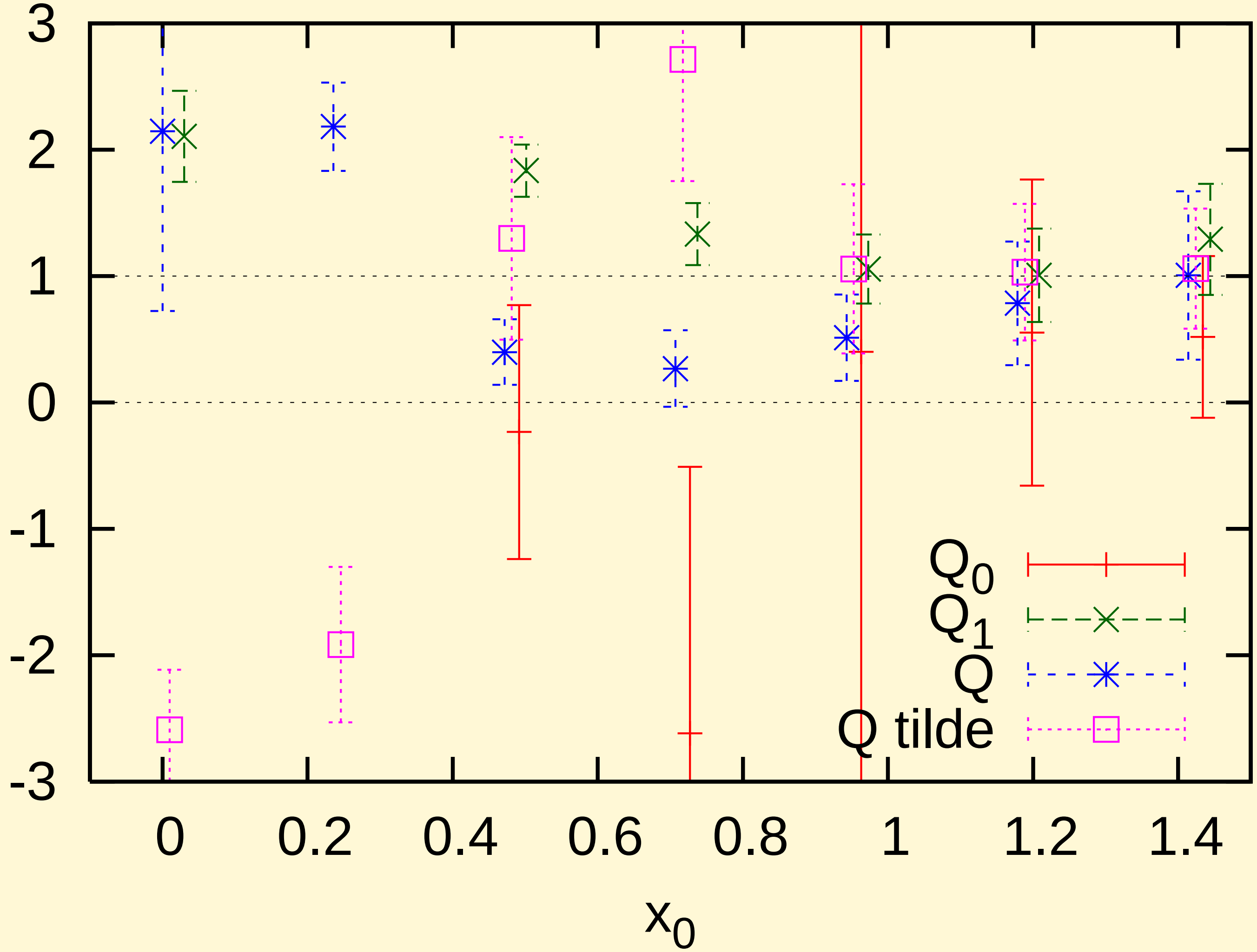

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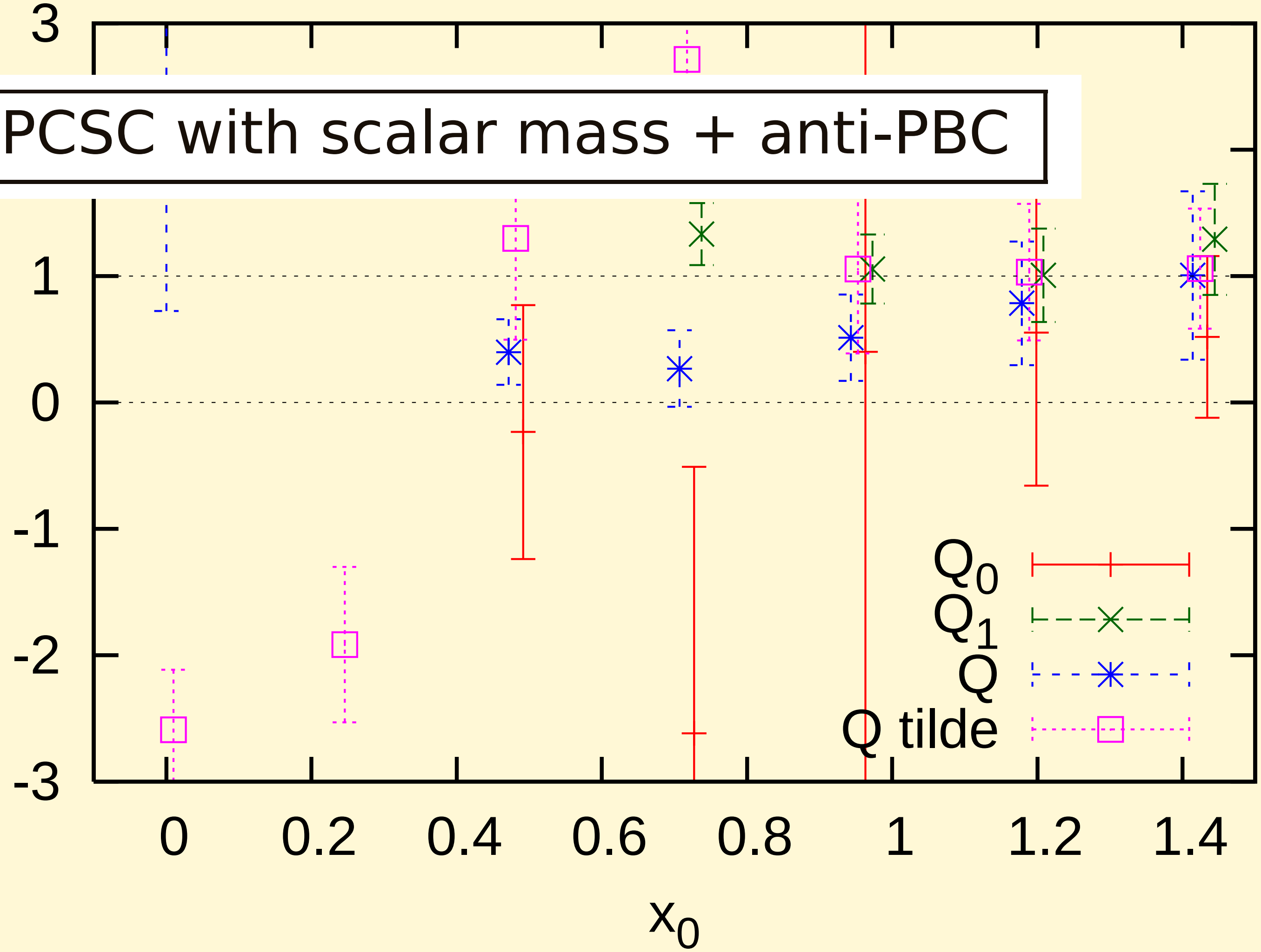
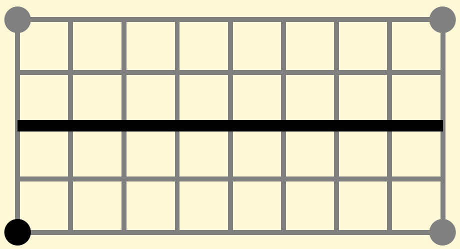
$\mu^2/g^2 = 1$, PBC Too noisy!

Eventually, PCSC with scalar mass + anti-PBC

12x6

$ag = 0.2367$





Simulation detail

- Computer: Riken Super Combined Cluster (RSCC)
- Algorithm: Rational Hybrid Monte Carlo (RHMC)
  + Multi-time step acceleration
- lattice size: 12×6–30×10
- $ag = 0.2357,\ 0.2,\ 0.1768,\ 0.1414$
- 800–1,800 configurations

Applications

Choice of the scalar mass

PCSC relation $\Rightarrow$ lattice simulation works

Application

- Observing spontaneous SUSY breaking

Choice of the scalar mass

PCSC relation $\Rightarrow$ lattice simulation works

Application

- Observing spontaneous SUSY breaking

... before that,

flat direction? (How to “define” the theory)

- Define as an extrapolation of $\mu \to 0$
- Small mass: $\mu < 1/L$
- large N_C
- (unstable)

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Observing SUSY breaking

cf. I.K.-Suzuki-Sugino

- order parameter $\langle \mathcal{H} \rangle = \frac{1}{2} \langle Q \mathcal{J}_0^{(0)} \rangle$ $\quad (\{Q, Q_0\} = 2i\partial_0)$
- measure under thermal boundary condition
- extrapolate the scalar mass to zero
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  ground state energy density $\mathcal{E}$

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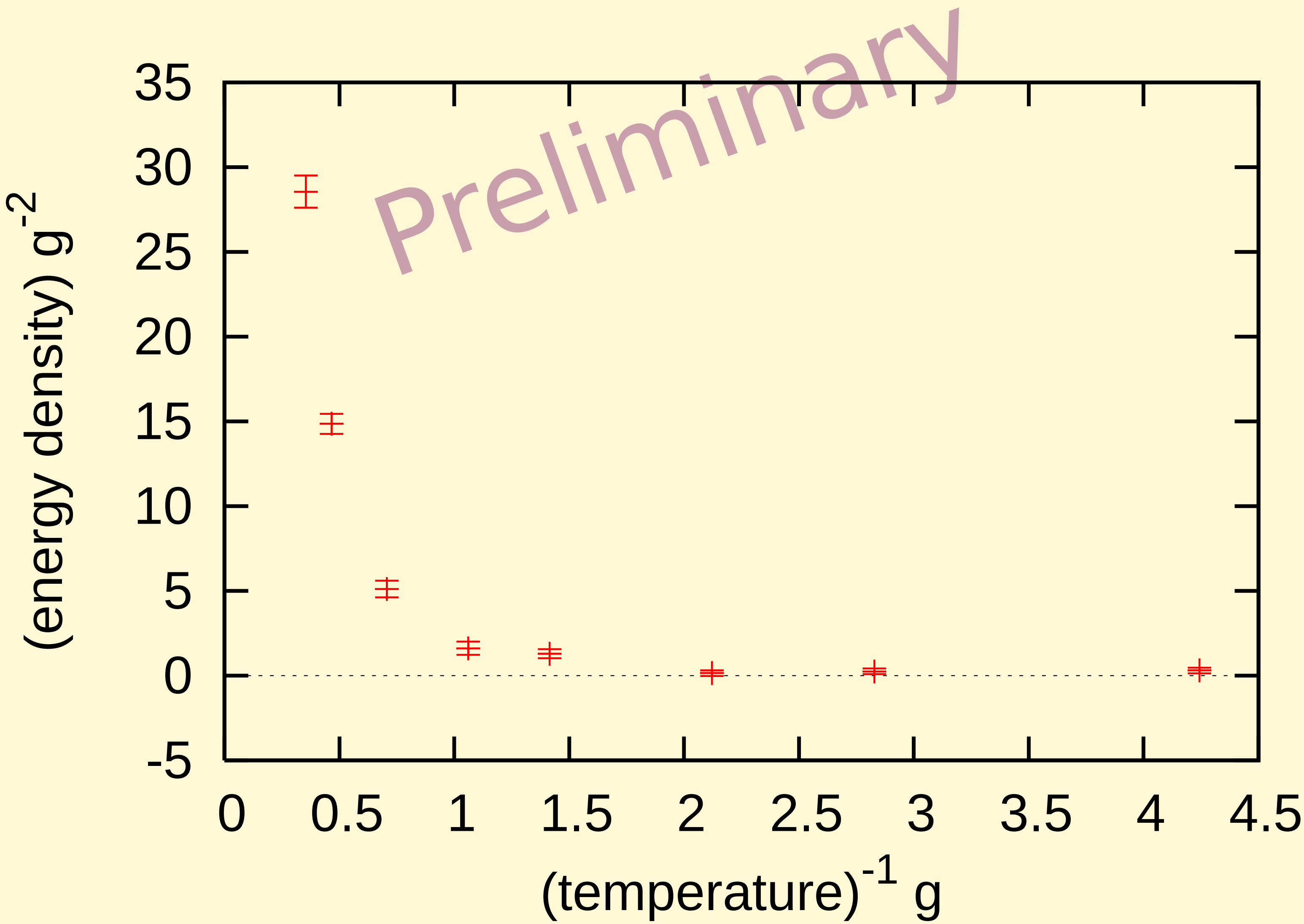
Cf. No analytic result for this system
(maybe broken? a conjecture by Hori-Tong)

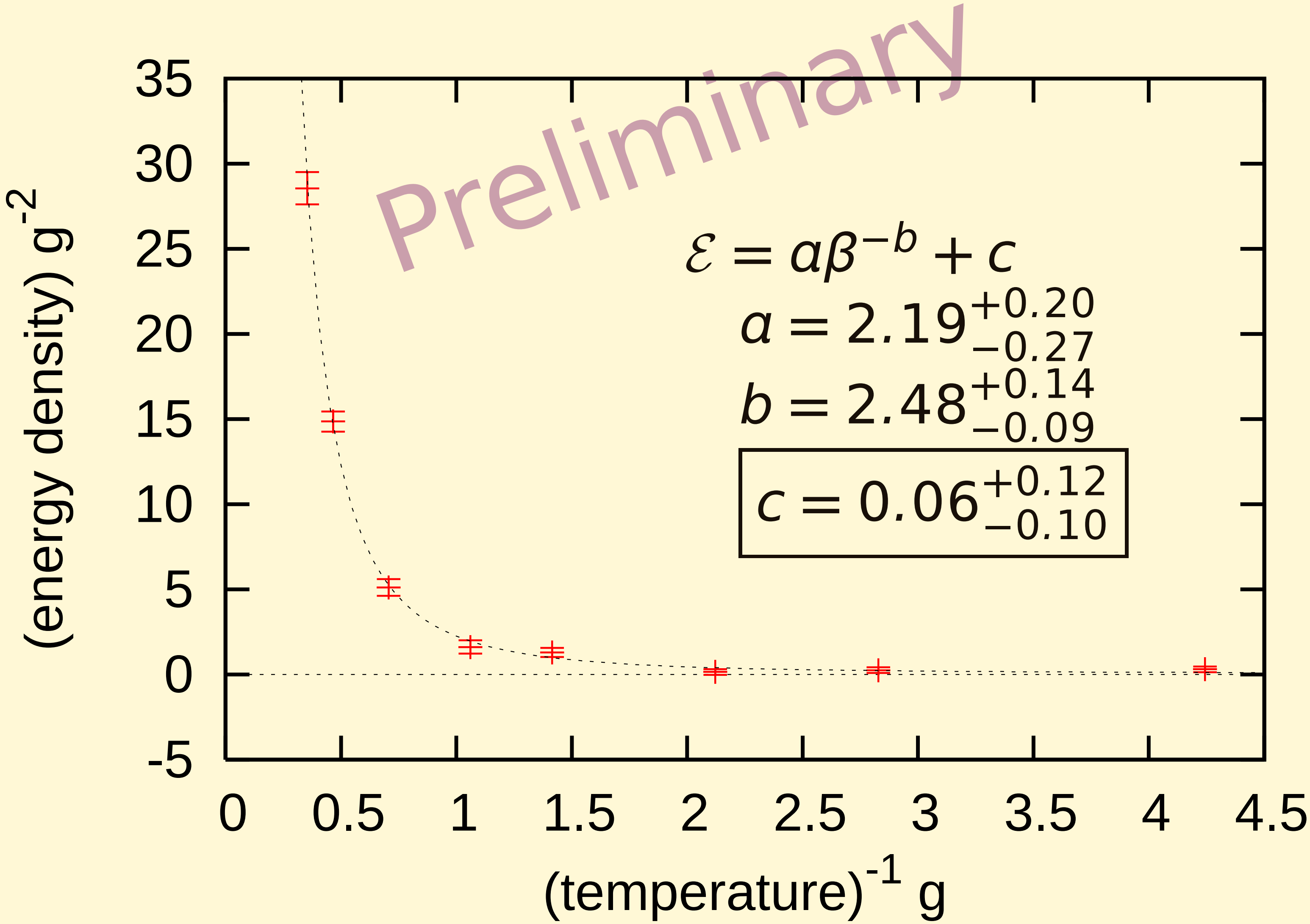
not broken?



Preliminary
35
30
25
20
15
10
5
0
-5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
(temperature)$^{-1}$ g
(energy density) g^{-2}

not broken?

Ground state energy is consistent with 0



Conclusion

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Lattice simulation of 2-dim super Yang-Mills is now possible

Formulation with 1 nilpotent Q
$\Rightarrow$whole SUSY is restored in the cont. limit (no lat. artifact)

- simulation: 2-dim $\mathcal{N} = (2, 2)$ SYM, SU(2) (Sugino model)
- scalar mass term $\Rightarrow$ Partially Conserved Super Current (PCSC) relation

Application

- Observing (no) spontaneous SUSY breaking
- $\vdots$ (Poster by Suzuki)

Thank you.