Conformal dimensions in large charge sectors using “qubit” formulations

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Collaborators
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Use a large conserved charge “Q” sectors to identify a small parameter.

Then, use Effective Field Theory ideas and “radial” quantization to solve for the conformal dimensions as a perturbative expansion.

In O(N) models conformal dimensions emerge as an expansion of the form

$$D_Q = c_{3/2} Q^{3/2} + c_{1/2} Q^{1/2} + c_0 + \mathcal{O}(1/Q^{1/2})$$

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Challenge: Computing D_Q using Monte Carlo methods suffers from severe signal to noise ratio problems with conventional methods for large Q.

Simplest Example: O(2) model at the 3d Wilson-Fisher fixed point

$$\left\langle e^{iQ\theta_x} \; e^{-iQ\theta_y} \right\rangle \sim \left(\frac{1}{|x-y|} \right)^{D_Q}$$

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Non-trivial Example: O(4) model at the 3d Wilson-Fisher fixed point.

$SO(4) \sim SU(2) \times SU(2)$

Representations: (q_L, q_R)

Hence we now need to compute

$$\left\langle O_x^{q_L,q_R} \; (O^\dagger)_y^{q_L,q_R} \right\rangle \sim \left(\frac{1}{|x-y|} \right)^{D_{q_L,q_R}}$$

New ideas for studying CFTs using Monte Carlo Methods!

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Worldline Formulations

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Qubit Formulations

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Banerjee, SC, Orlando PRL 120, (2016) 061603

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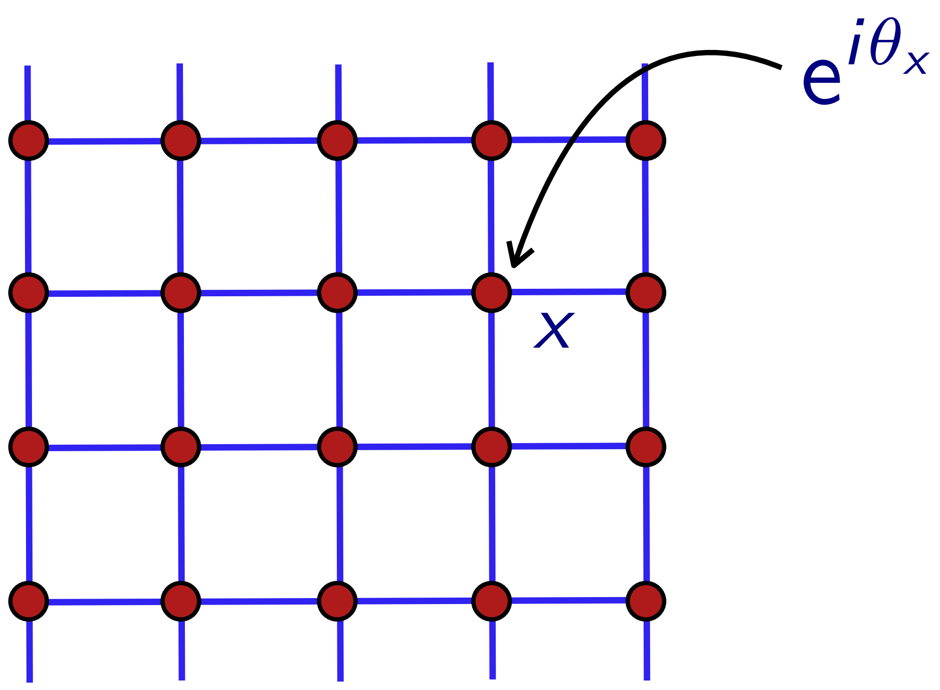
$$Z = \int [d\theta] \; e^{\,\beta \sum_{x,\alpha} \cos(\theta_x - \theta_{x+\alpha})}$$



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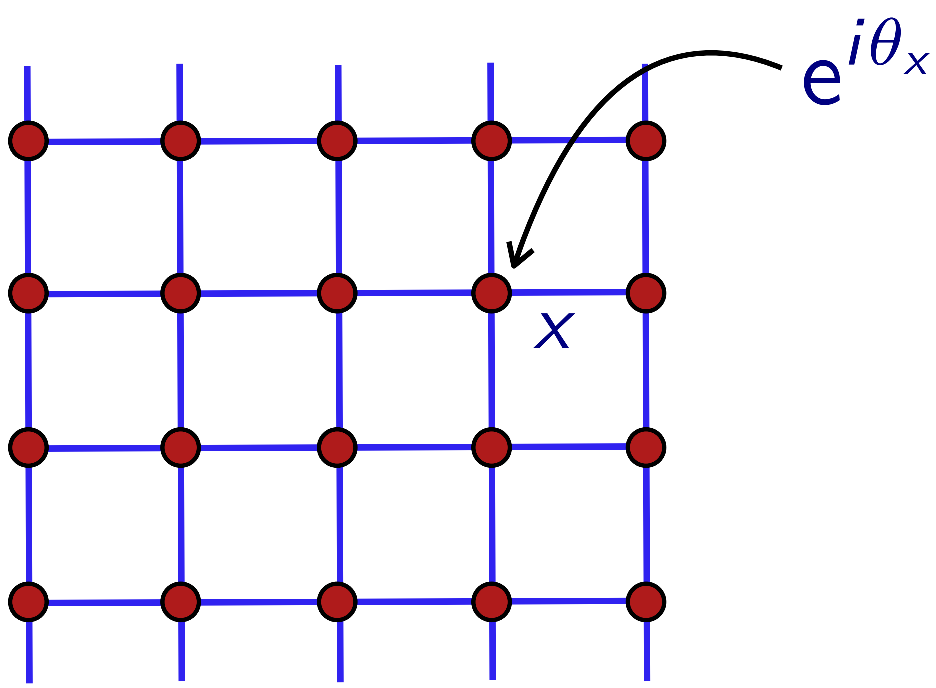
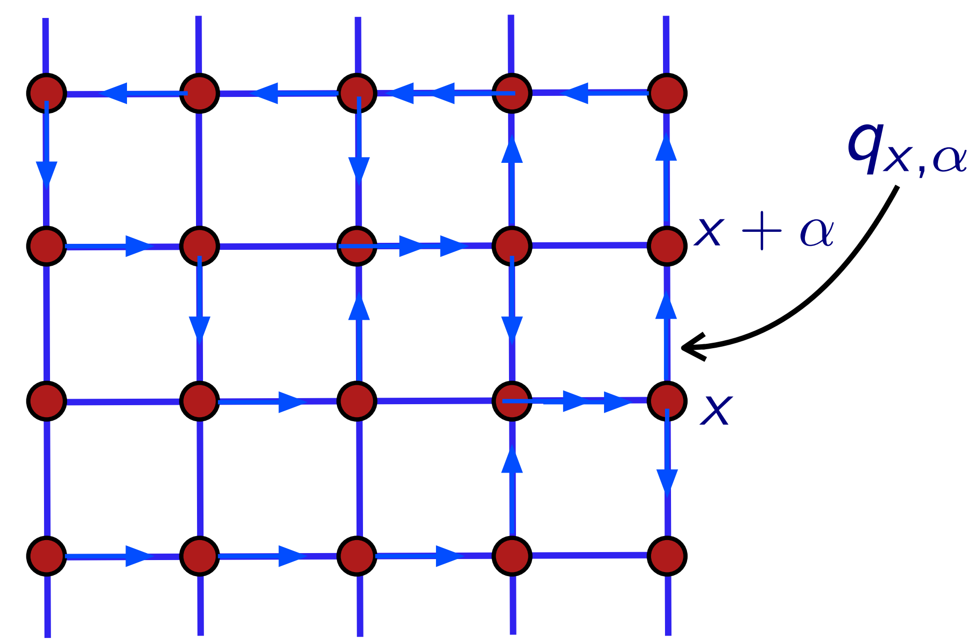


Worldline

$$Z = \sum_{[q]} \Big[\prod_{x,\alpha} I_{q_{x,\alpha}}(\beta/2)\Big] \Big[\prod_{x} \delta\Big(\sum_{\alpha}(q_{x,\alpha} - q_{x-\alpha,\alpha})\Big)\Big]$$



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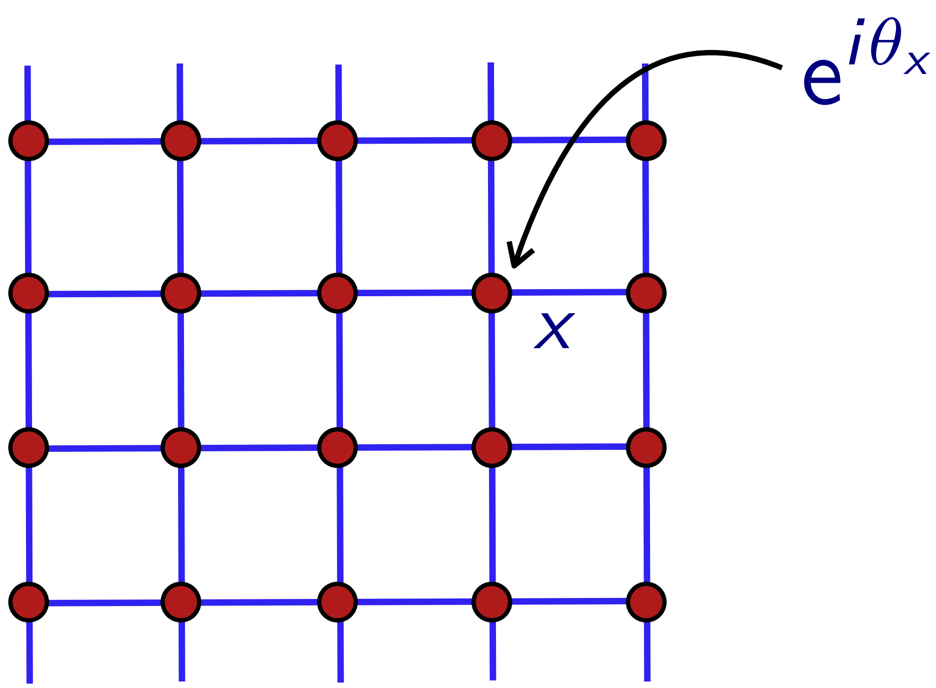

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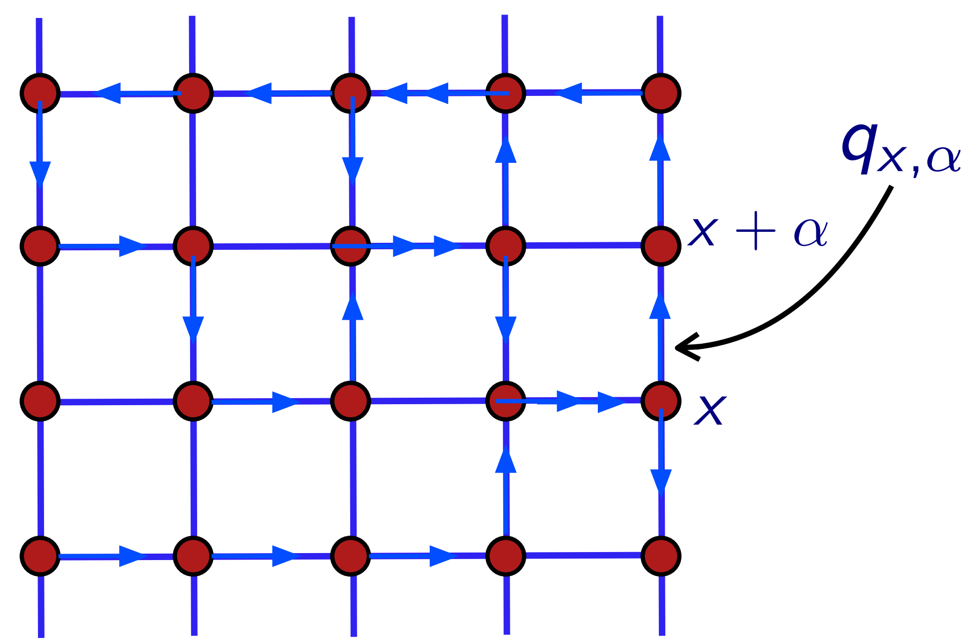

The worldline approach allows us to efficiently create and annihilate charges at various space-time separations using worm algorithms.

Partition function with sources and sinks

$$Z_Q = \sum_{[q]} \left[\prod_{x,\alpha} I_{q_{x,\alpha}}(\beta/2) \right] \left[\prod_{x \neq x_i, x_f} \delta\Big(\sum_{\alpha} (q_{x,\alpha} - q_{x-\alpha,\alpha}) \Big) \right]$$

$$\delta\Big(\sum_{\alpha} (q_{x_i,\alpha} - q_{x_i-\alpha,\alpha} - Q \Big) \; \delta\Big(\sum_{\alpha} (q_{x_f,\alpha} - q_{x_f-\alpha,\alpha} + Q \Big)$$

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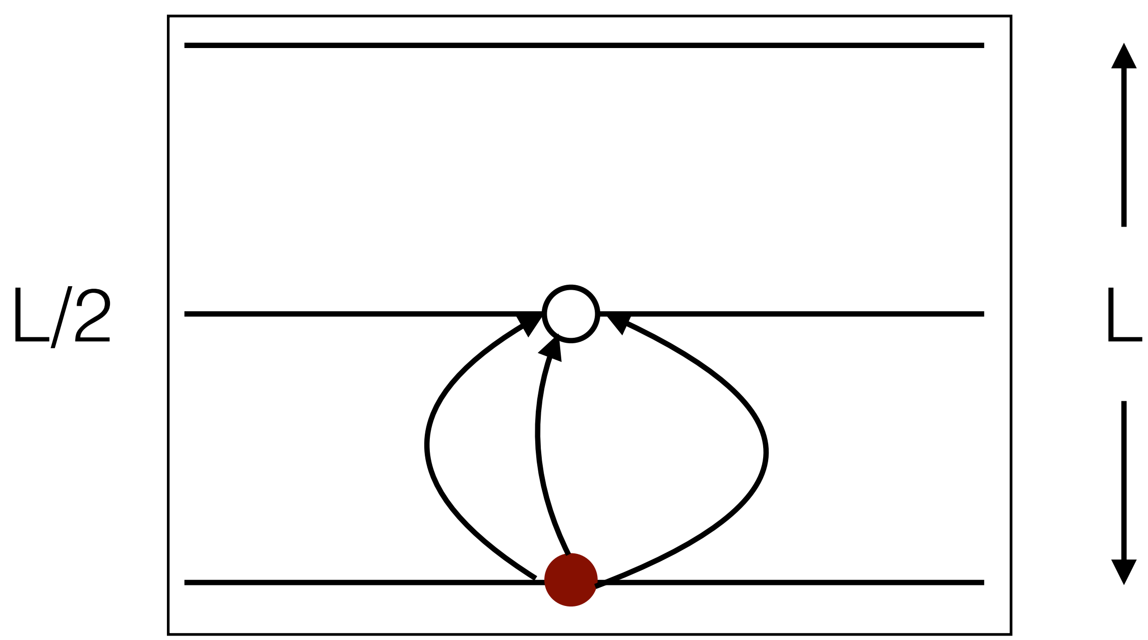

L x L box

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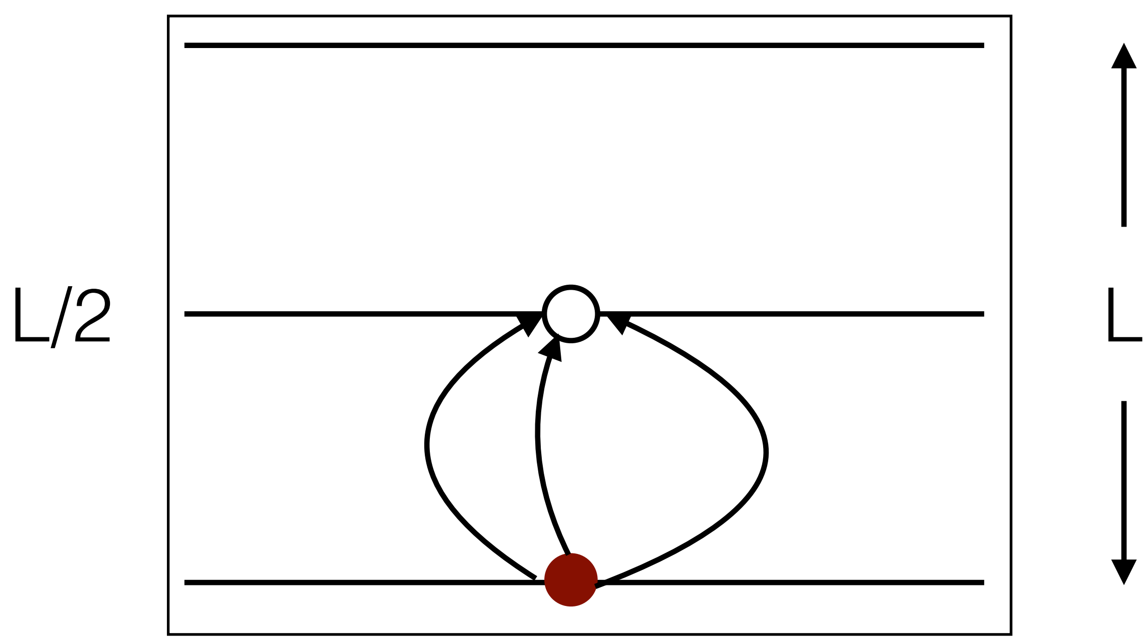

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Scaling:

$$Z_Q \sim 1/L^{D_Q}$$

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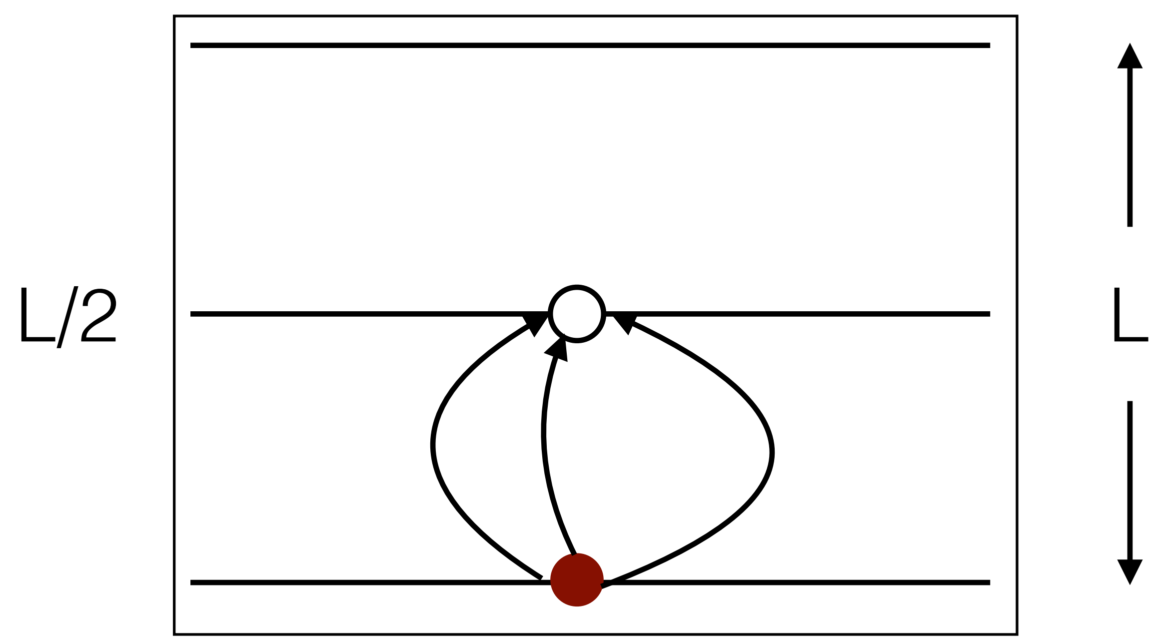

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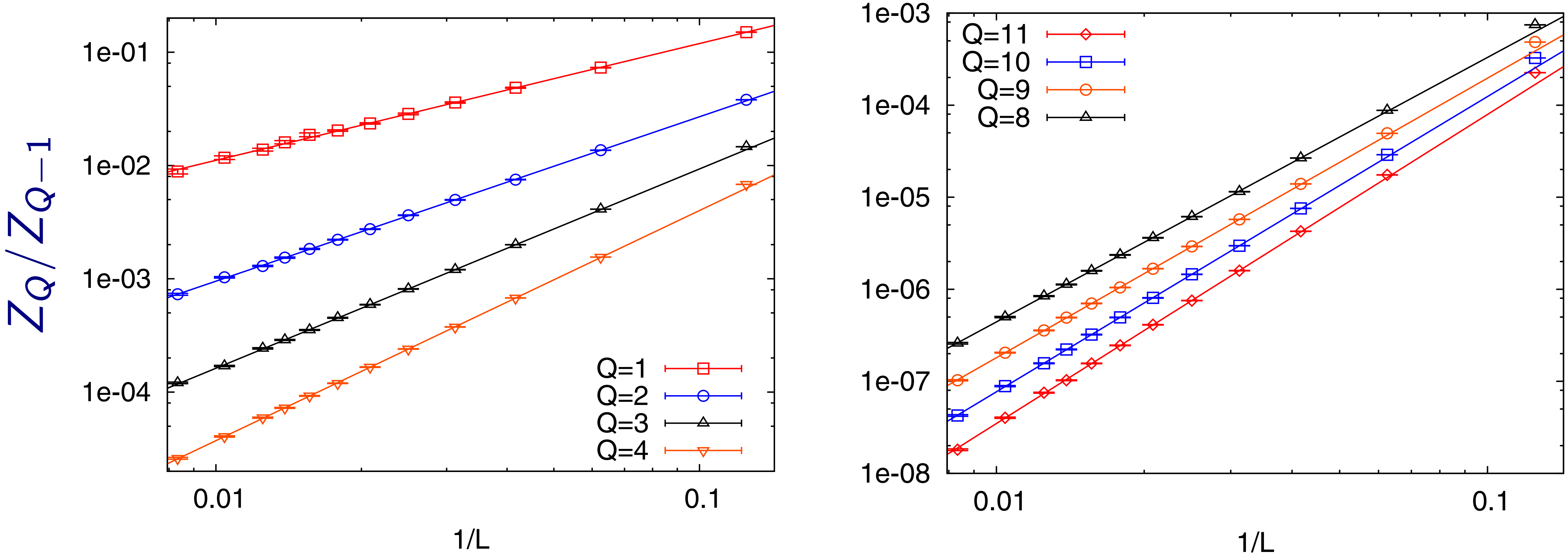
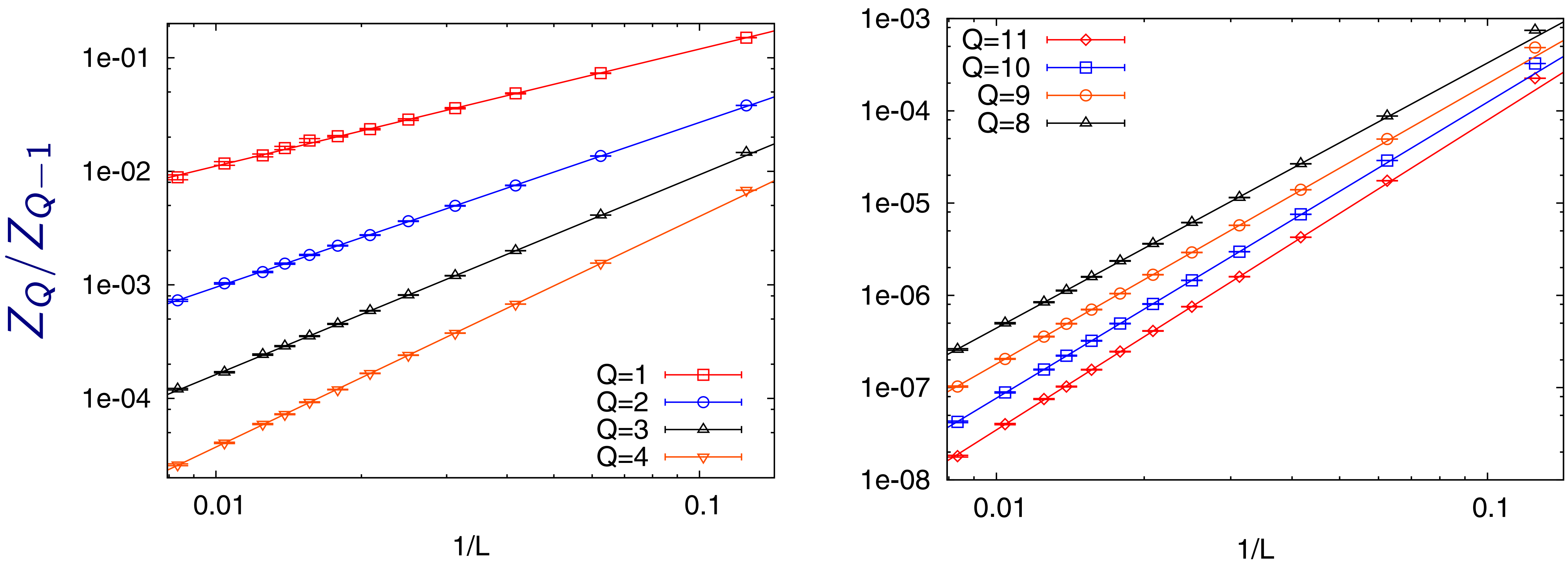
Worm algorithms can compute

$$Z_Q/Z_{Q-1} \sim 1/L^{\Delta_Q}$$

$$\Delta_Q = D_Q - D_{Q-1}$$



Z_Q/Z_{Q-1}
1e-01
1e-02
1e-03
1e-04
0.01
0.1
1/L
Q=1
Q=2
Q=3
Q=4
1e-03
1e-04
1e-05
1e-06
1e-07
1e-08
0.01
0.1
1/L
Q=11
Q=10
Q=9
Q=8



Our results:

Q	$\Delta(Q)$	$D(Q)$	Q	$\Delta(Q)$	$D(Q)$
1	0.516(3)	0.516(3)	7	1.332(5)	6.841(8)
2	0.722(4)	1.238(5)	8	1.437(4)	8.278(9)
3	0.878(4)	2.116(6)	9	1.518(2)	9.796(9)
4	1.012(2)	3.128(6)	10	1.603(2)	11.399(10)
5	1.137(2)	4.265(6)	11	1.678(5)	13.077(11)
6	1.243(3)	5.509(7)	12	1.748(5)	14.825(12)

Previous work only up to Q=4 Hasenbusch, Vicari, PRB 84 (2011) 125136

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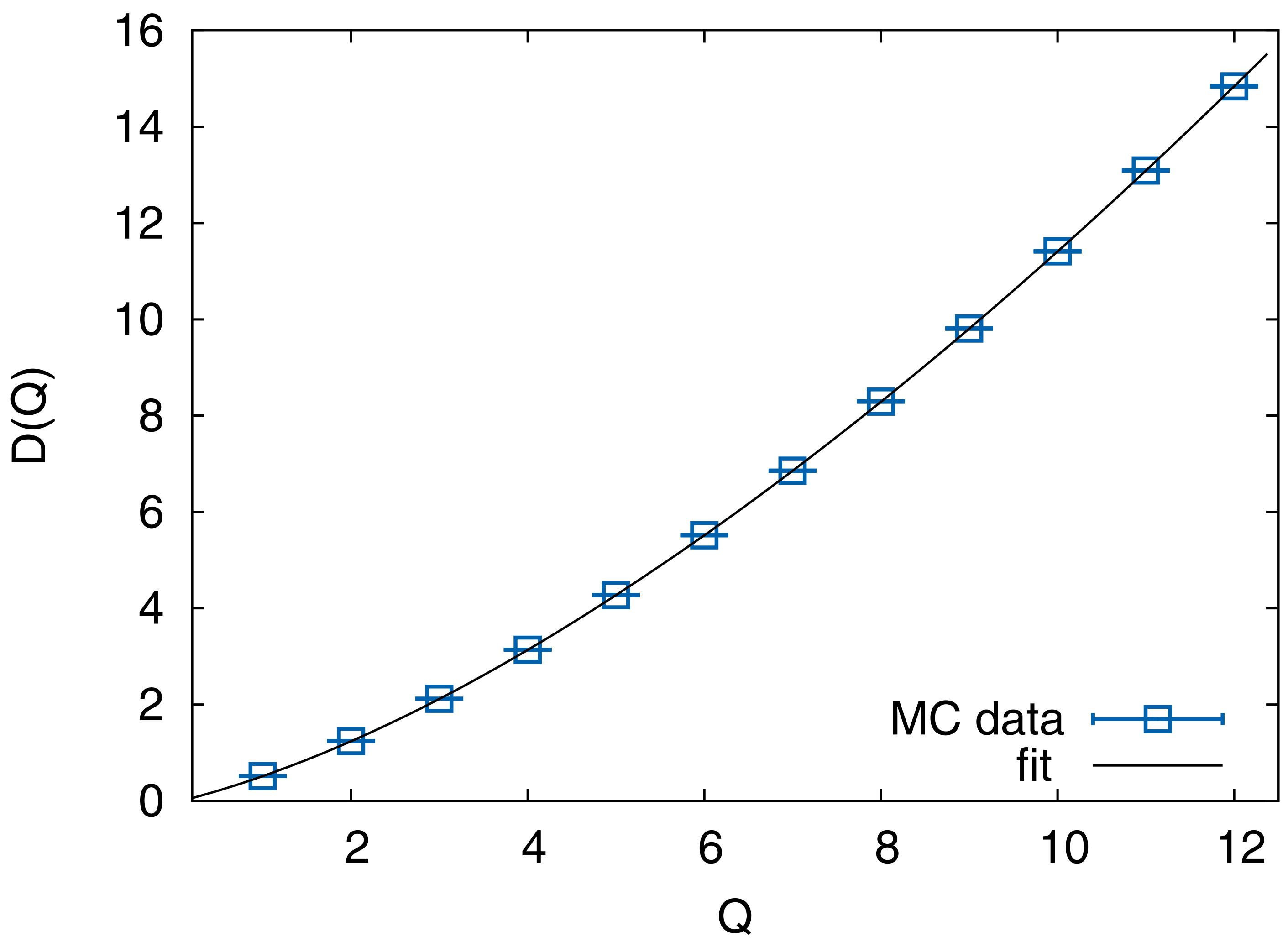

Fit Data: $D_Q \;=\; 1.195(10)\; Q^{3/2} \;+\; 0.075(10)\; Q^{1/2} \;-\; 0.094$

analytic calculation

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Qubit formulation of the O(4) Wilson-Fisher fixed point!

Qubit Formulations of QFTs

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Fermions are already qubits, but with anti-commutation relations.

Insight from non-perturbative Wilson's RG

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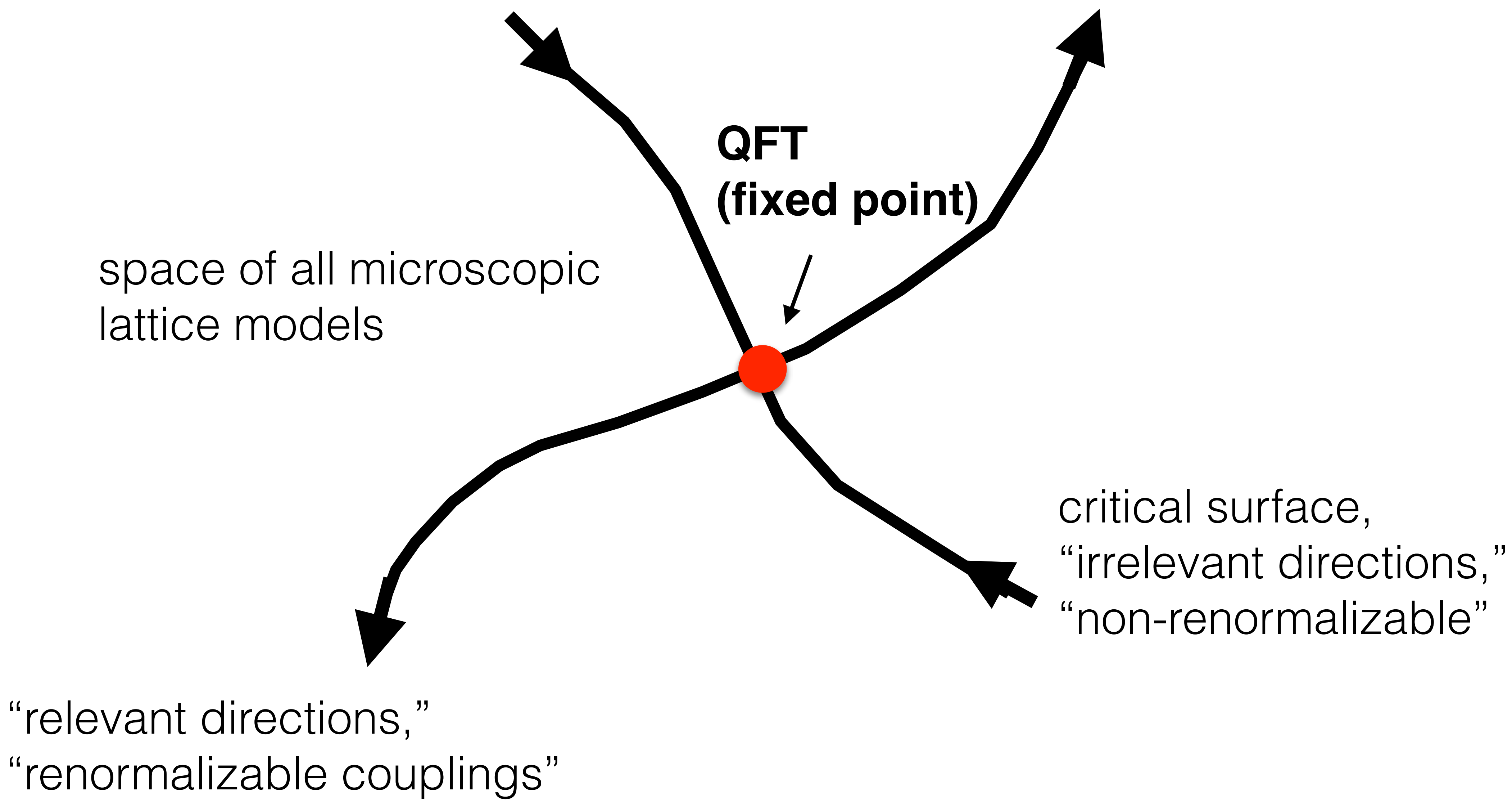

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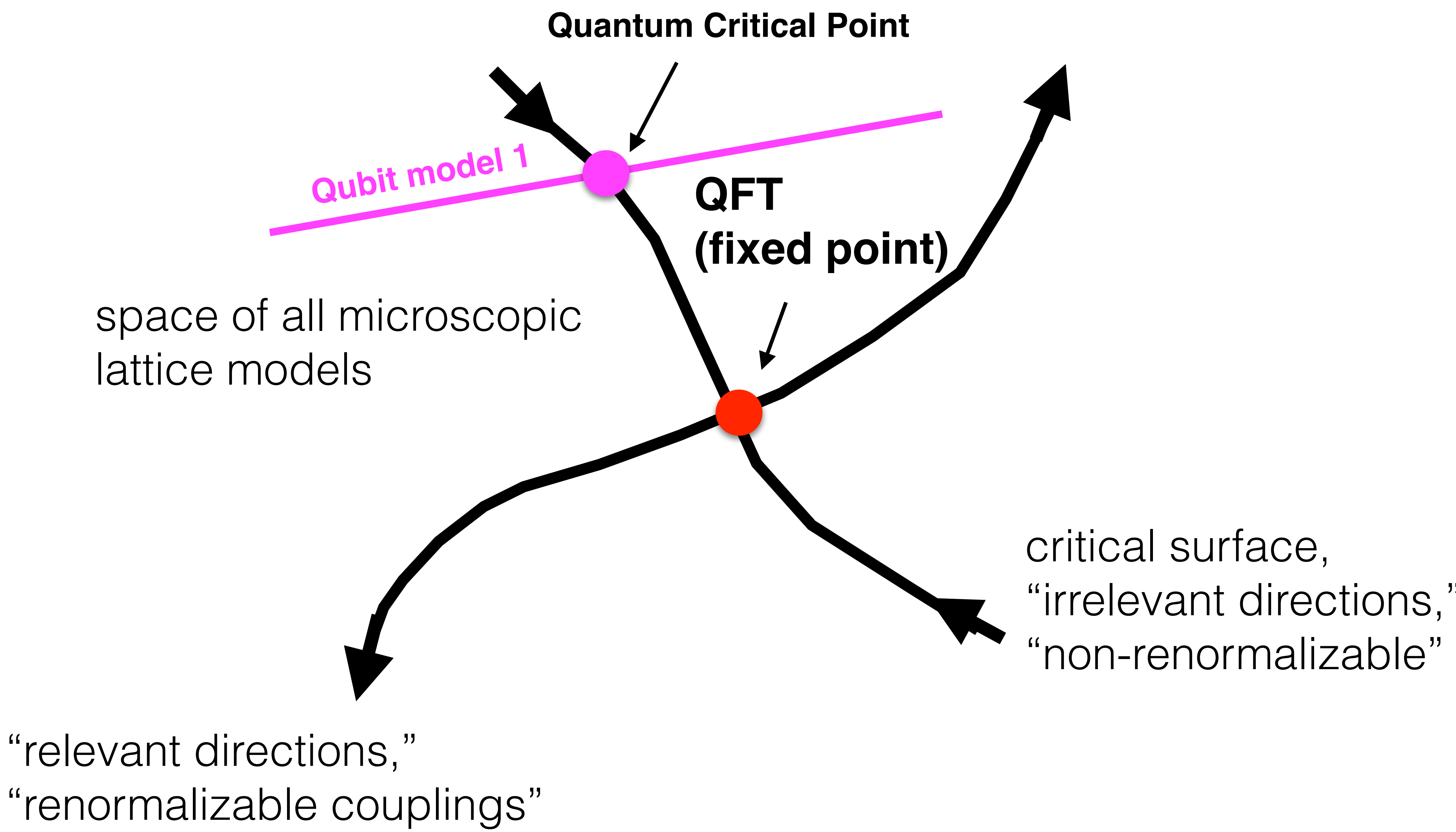

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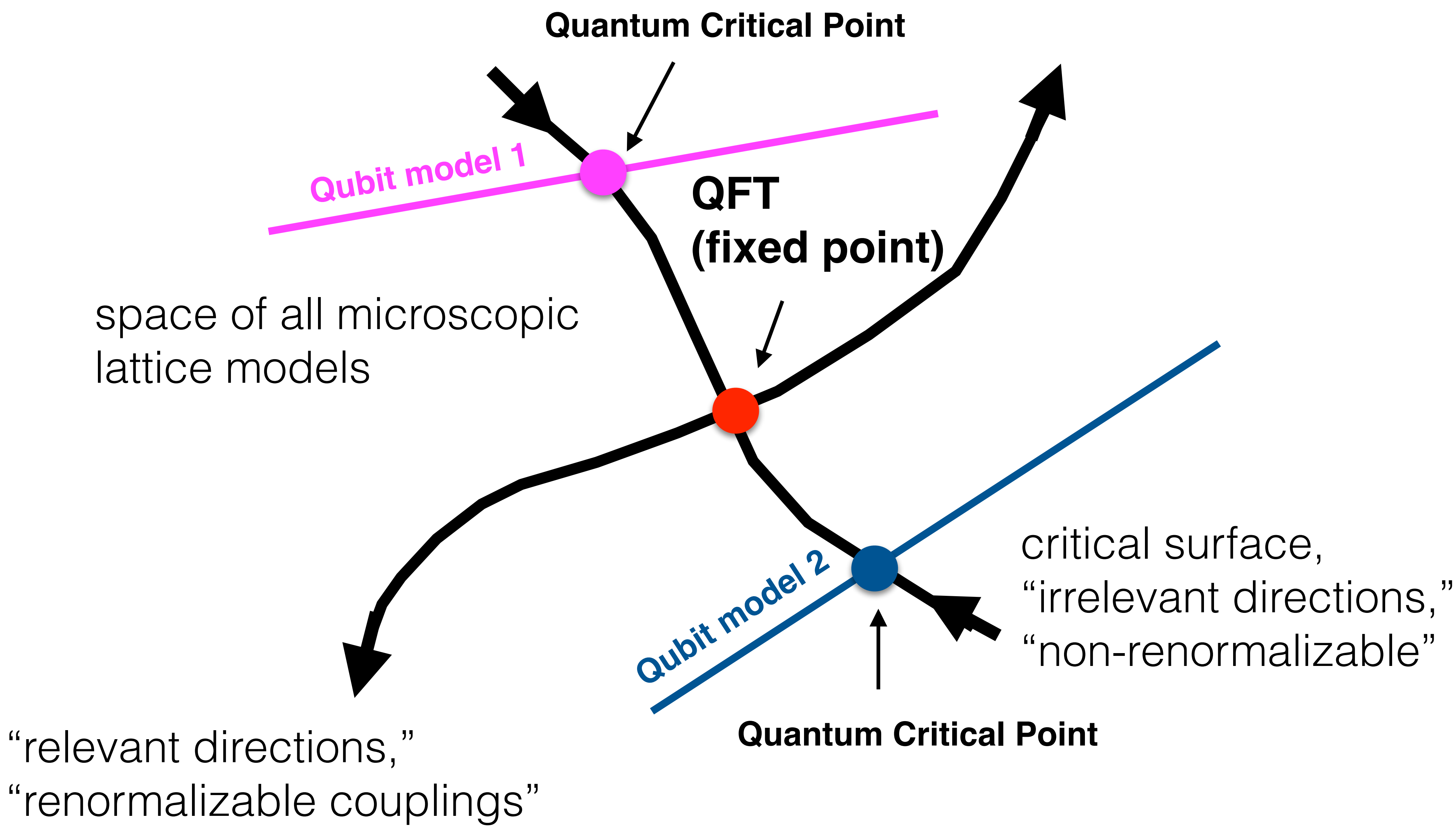

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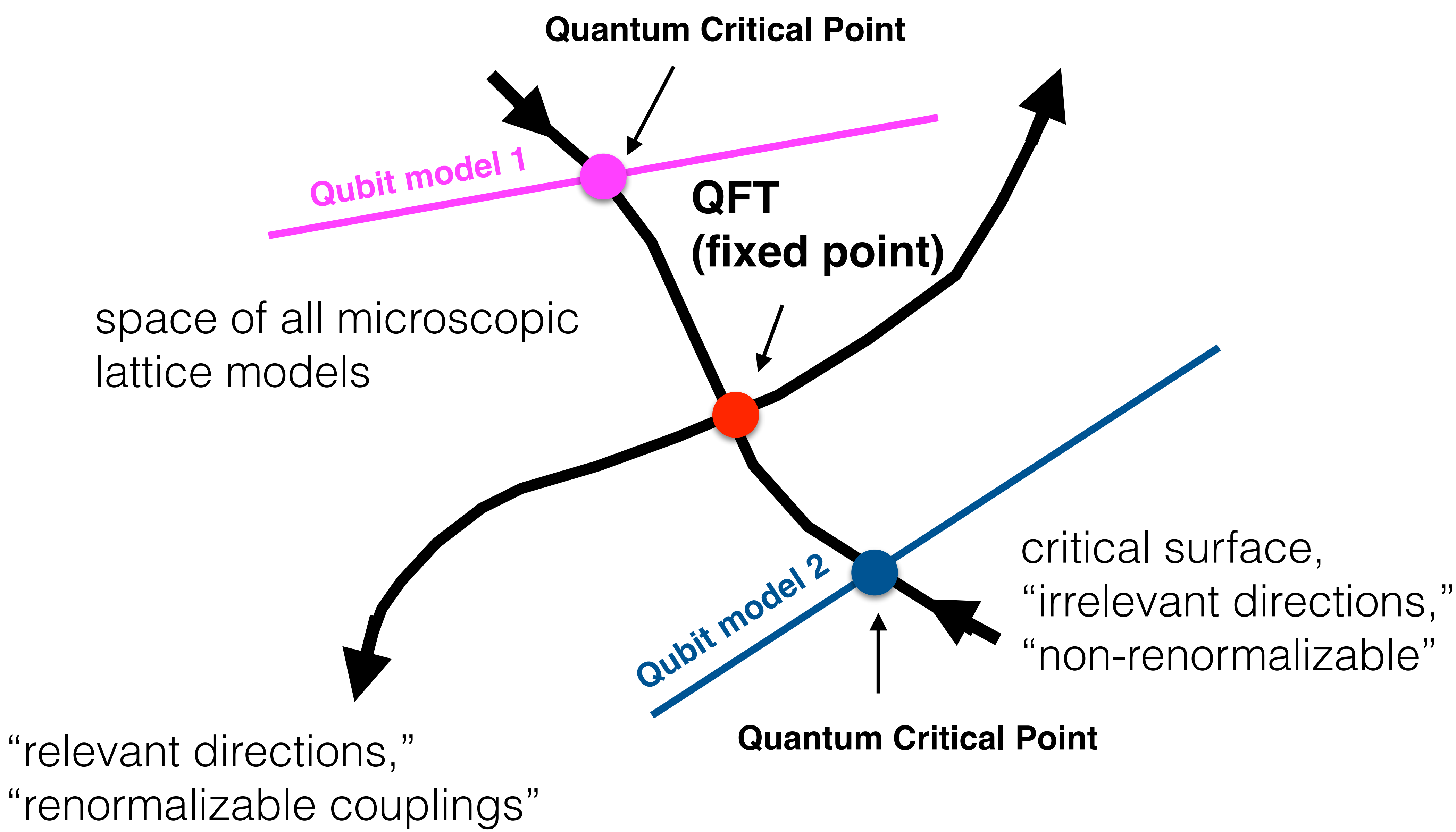

It is important to identify the Quantum Critical Points
that lead to the QFT of interest.

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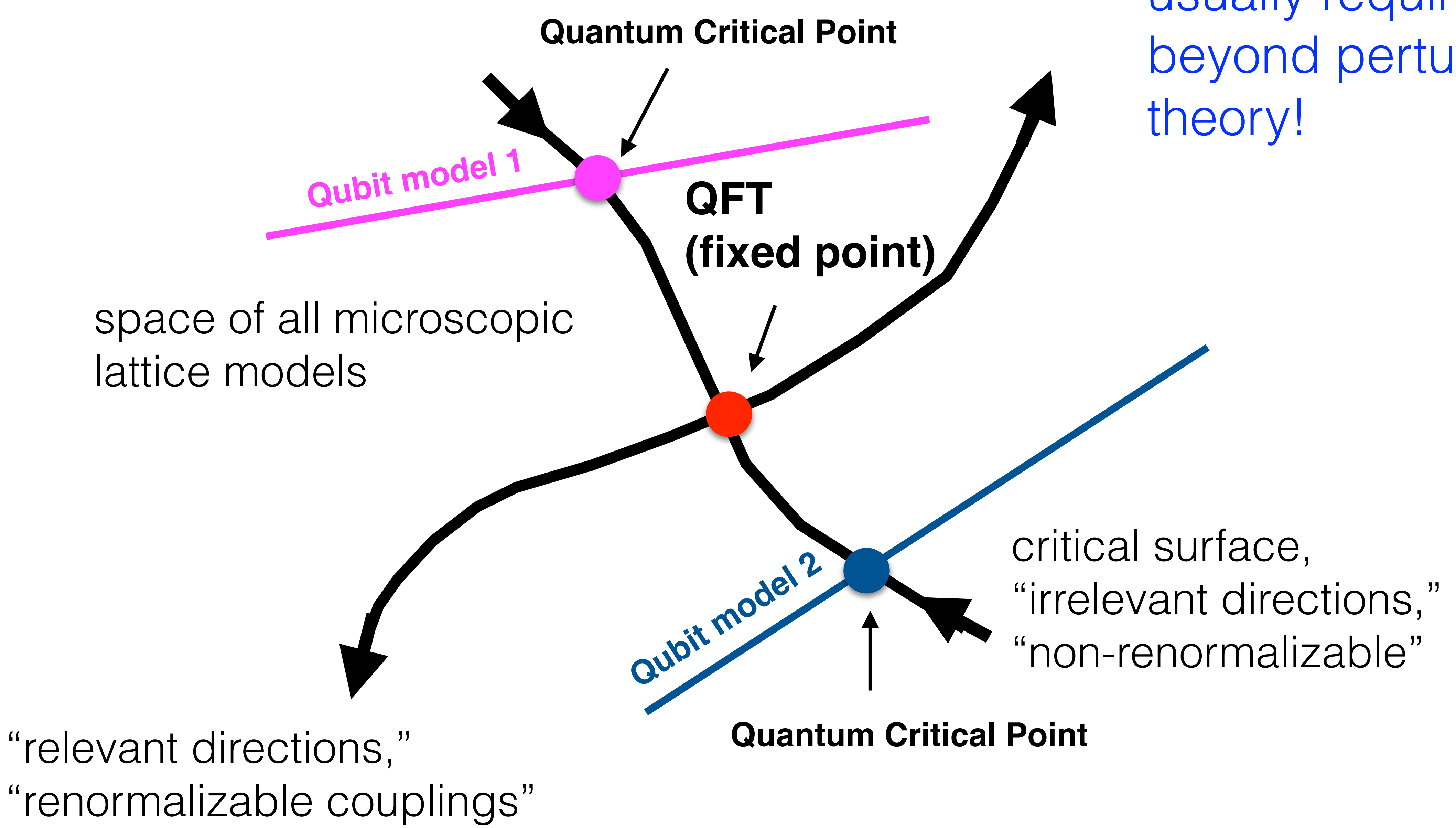

Identifying QCPs usually requires tools beyond perturbation theory!

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This talk: They helped us to explore the large Q-expansion in the O(4) model!

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d=2, Wilson-Fisher fixed point

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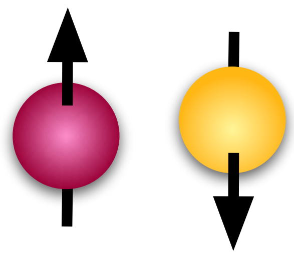
Q: Can we reproduce these features using a Qubit Hamiltonian?

A: Yes! Here we focus on d=2 Wilson-Fisher point!

Use two qubits per site:



$|s, \mathbf{r}\rangle$ $\quad$ $|m, \mathbf{r}\rangle, m = 0, +1, -1$

singlet $\quad$ triplet

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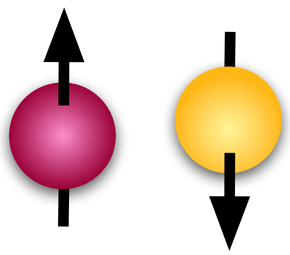

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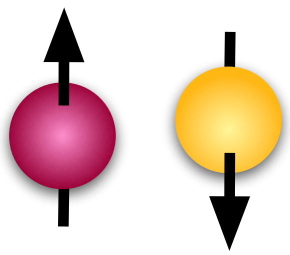

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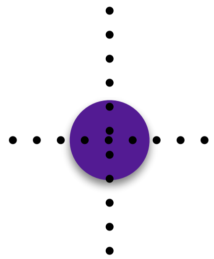

Fock
Vacuum

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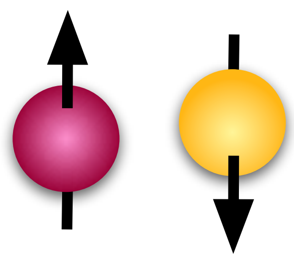

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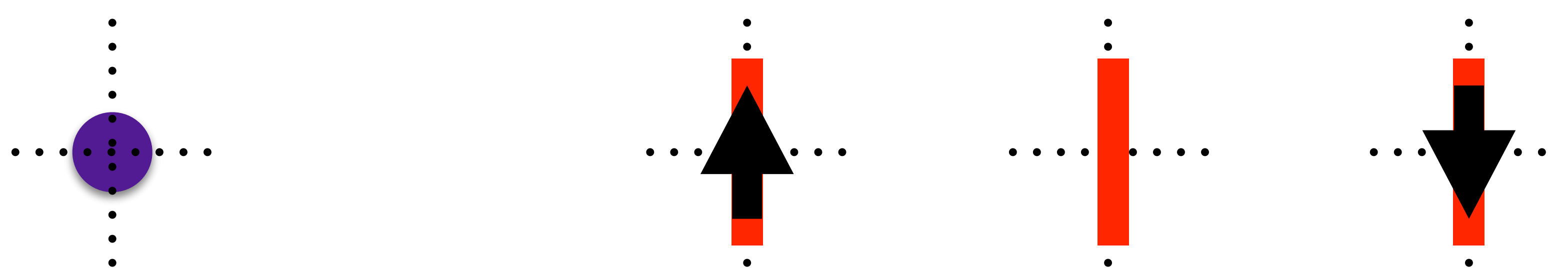

Fock Vacuum

Spin-1 particle

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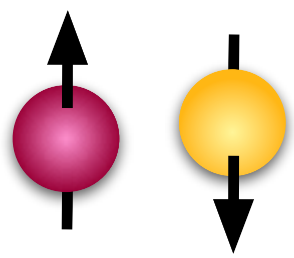

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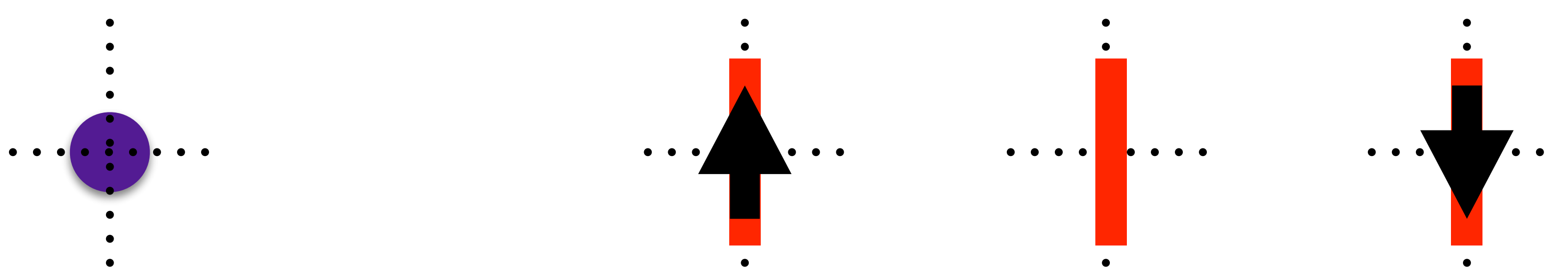

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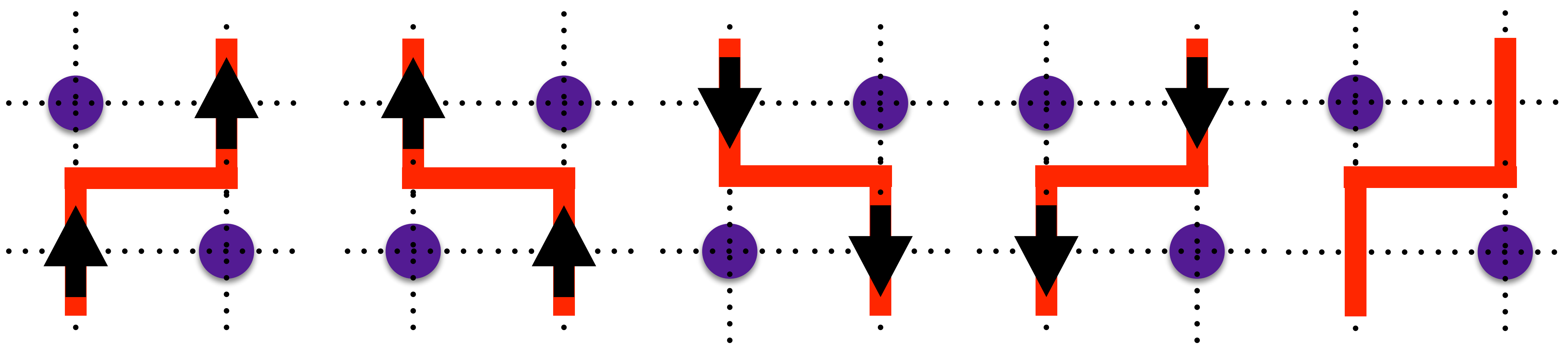
O(3) invariant Hamiltonian

$$H = J_t \sum_{\mathbf{r}} \sum_{m} |m, \mathbf{r}\rangle\langle m, \mathbf{r}| - \sum_{\langle \mathbf{r}, \mathbf{r}' \rangle} \left(J_h H^h_{\mathbf{r},\mathbf{r}'} + J_p H^p_{\mathbf{r},i} \right)$$

Hopping term



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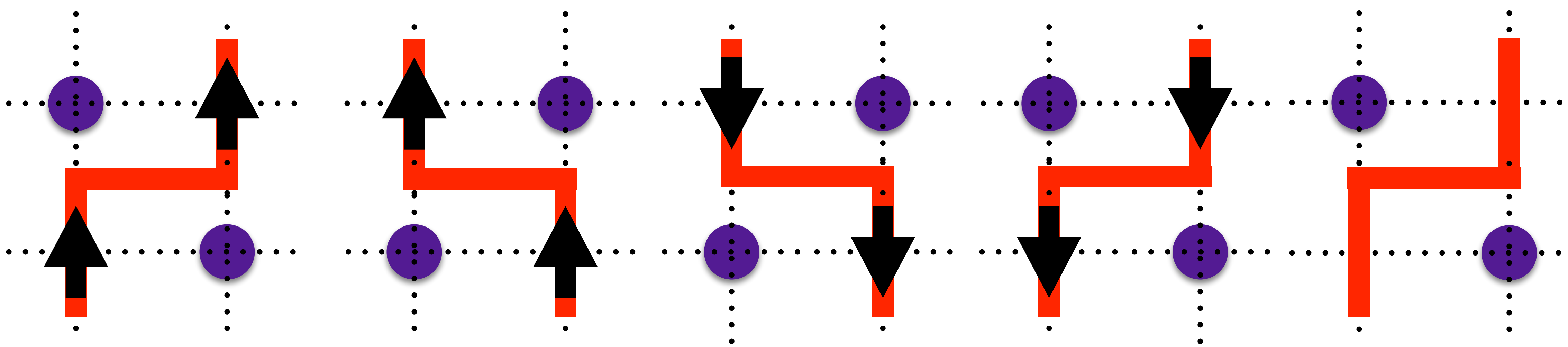
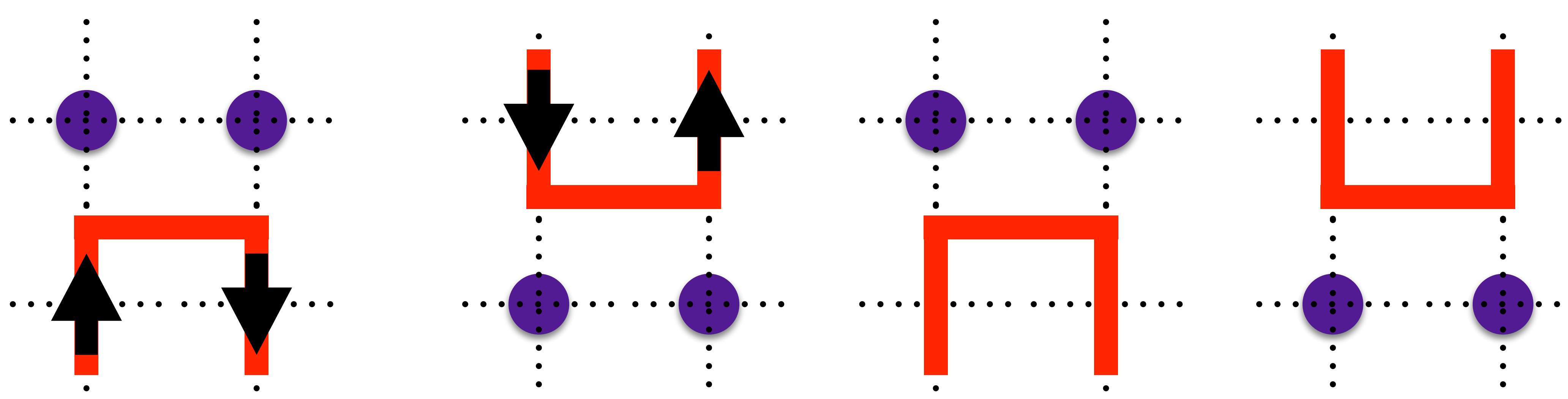


Pair Creation/Annihilation term



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$$Z = \sum_k \int [dt_k ... dt_1] \mathrm{Tr}\Big(e^{-(\beta - t_k)H_1}(-H_2)\; e^{-(t_k - t_{k-1})H_1} \cdots (-H_2) e^{-(t_1)H_1}\Big)$$

$$Z = \sum_{[s,m]} \prod_{\langle ij \rangle} W_{\langle ij \rangle}$$

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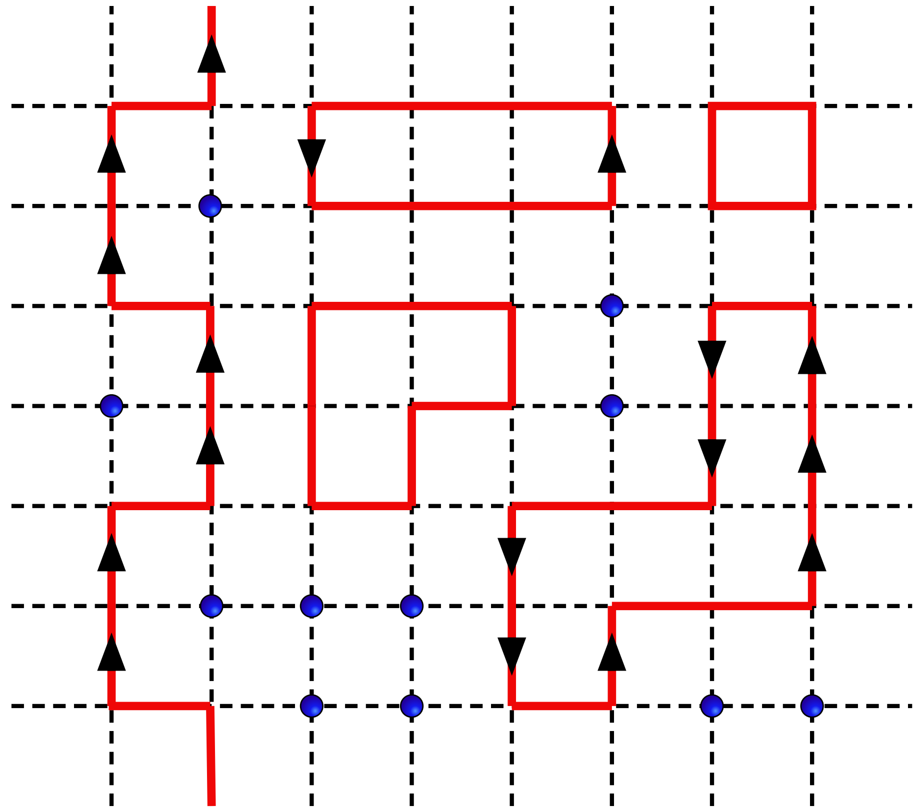


$$W_s \;=\; \varepsilon J \qquad W_t \;=\; \exp(-\varepsilon J_t)$$

$$J_h \;=\; J_p \;=\; J$$

Euclidean Qubit O(3) Model

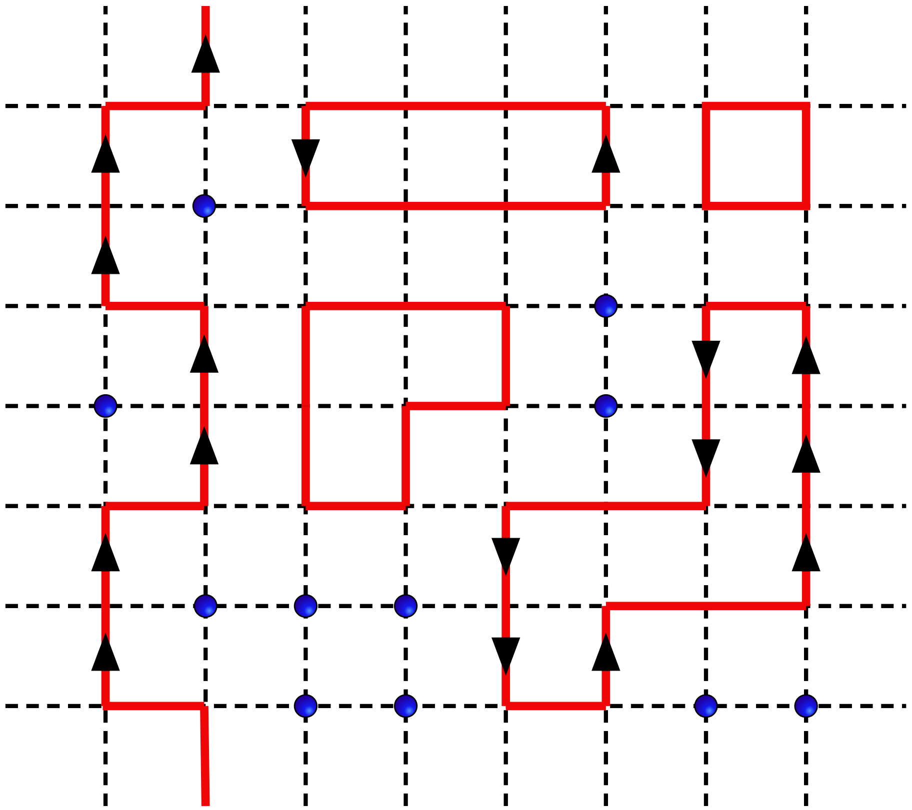
$$Z = \sum_k \int [dt_k ... dt_1] \mathrm{Tr}\Big(e^{-(\beta - t_k)H_1}(-H_2)\ e^{-(t_k - t_{k-1})H_1} \cdots (-H_2) e^{-(t_1)H_1}\Big)$$

$$Z = \sum_{[s,m]} \prod_{\langle ij \rangle} W_{\langle ij \rangle}$$

Relativistic Limit

$$\varepsilon = 1$$

$$W_t = W_s$$



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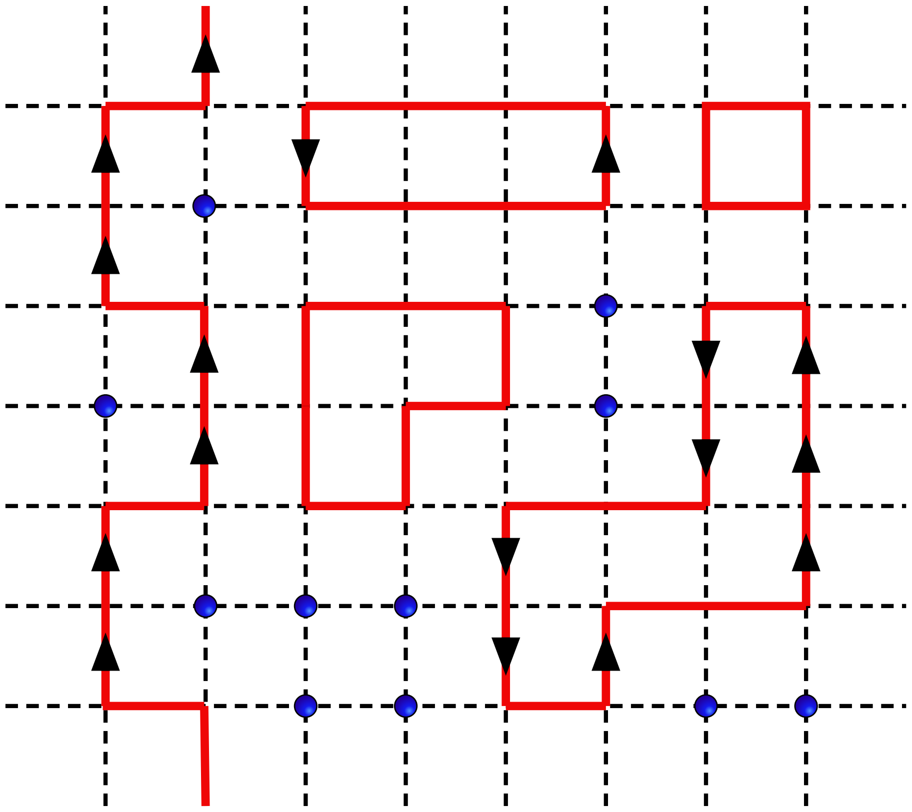

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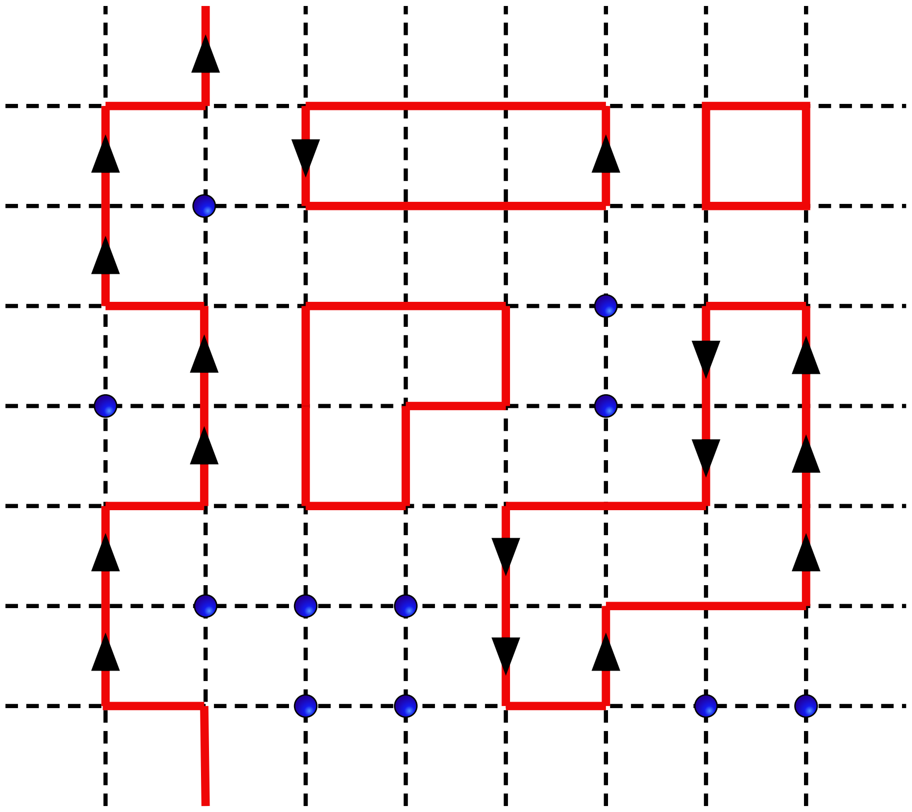


Relativistic Limit $\varepsilon = 1$, $W_t = W_s$

Hamiltonian limit $\varepsilon \to 0$

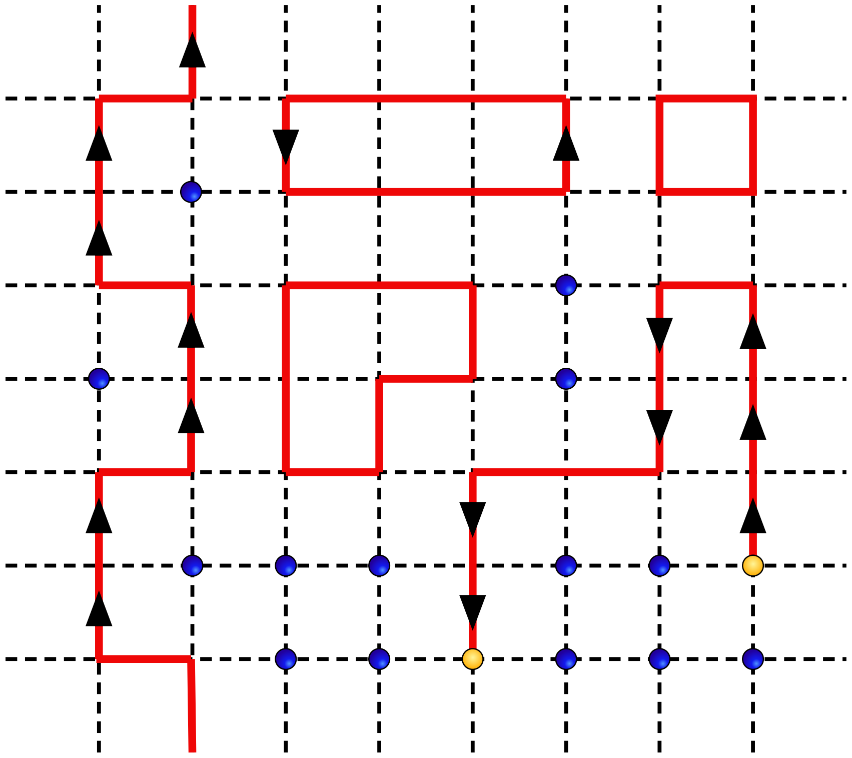
Can study using classical QMC
(directed loop/worm algorithms)

$W_s = \varepsilon J \qquad W_t = \exp(-\varepsilon J_t)$

$J_h = J_p = J$

Order Parameter Suceptibility

$$\chi = \frac{1}{ZL^d} \sum_{\mathbf{r},\mathbf{r}'} \int_0^{\beta} dt \; \mathrm{Tr}\left(e^{-(\beta - t)H} a_{\mathbf{r},\mathbf{m}} e^{-tH} a^{\dagger}_{\mathbf{r}',\mathbf{m}} \right)$$



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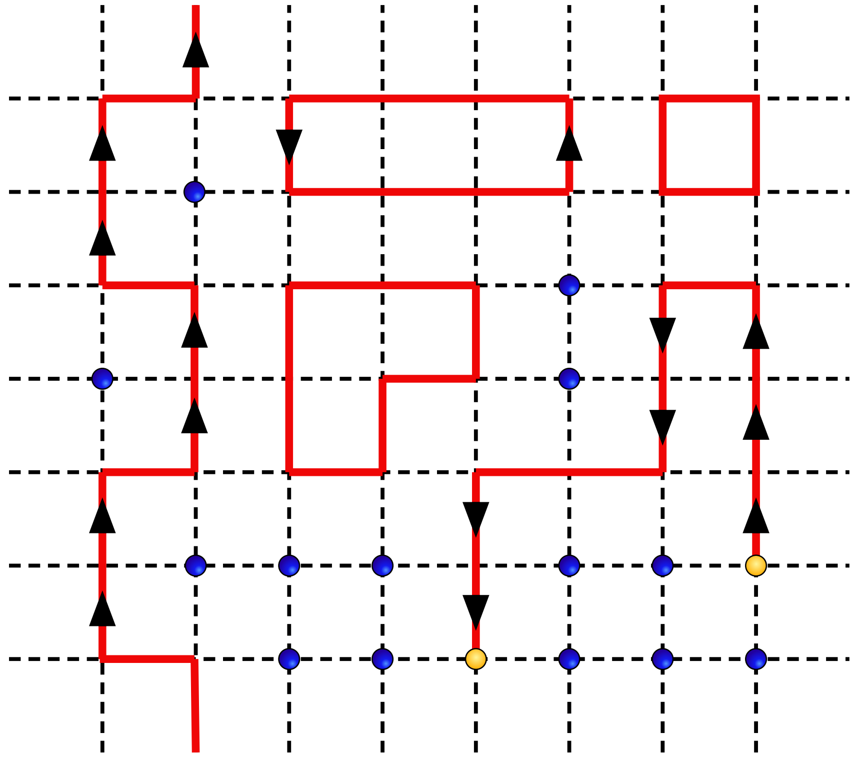
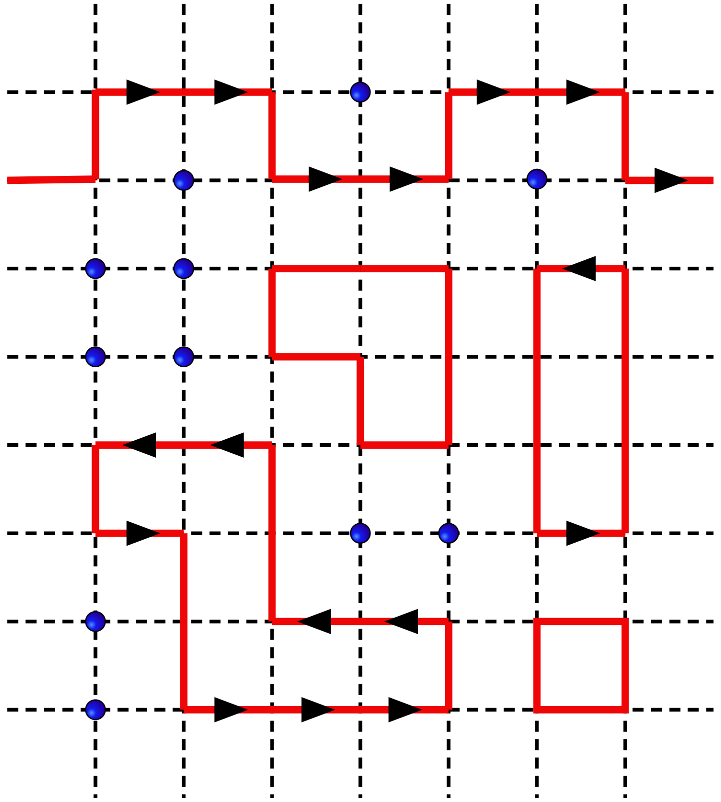


Winding Number Susceptibility

$$\rho_s = \frac{1}{L^{d-2}\beta} \langle \ (Q_w)^2 \ \rangle$$



Wilson-Fisher fixed point

$$\nu = 0.7113(11), \quad \eta = 0.0378(6)$$

Pelisetto and Vicari Phys. Repts. (2002)

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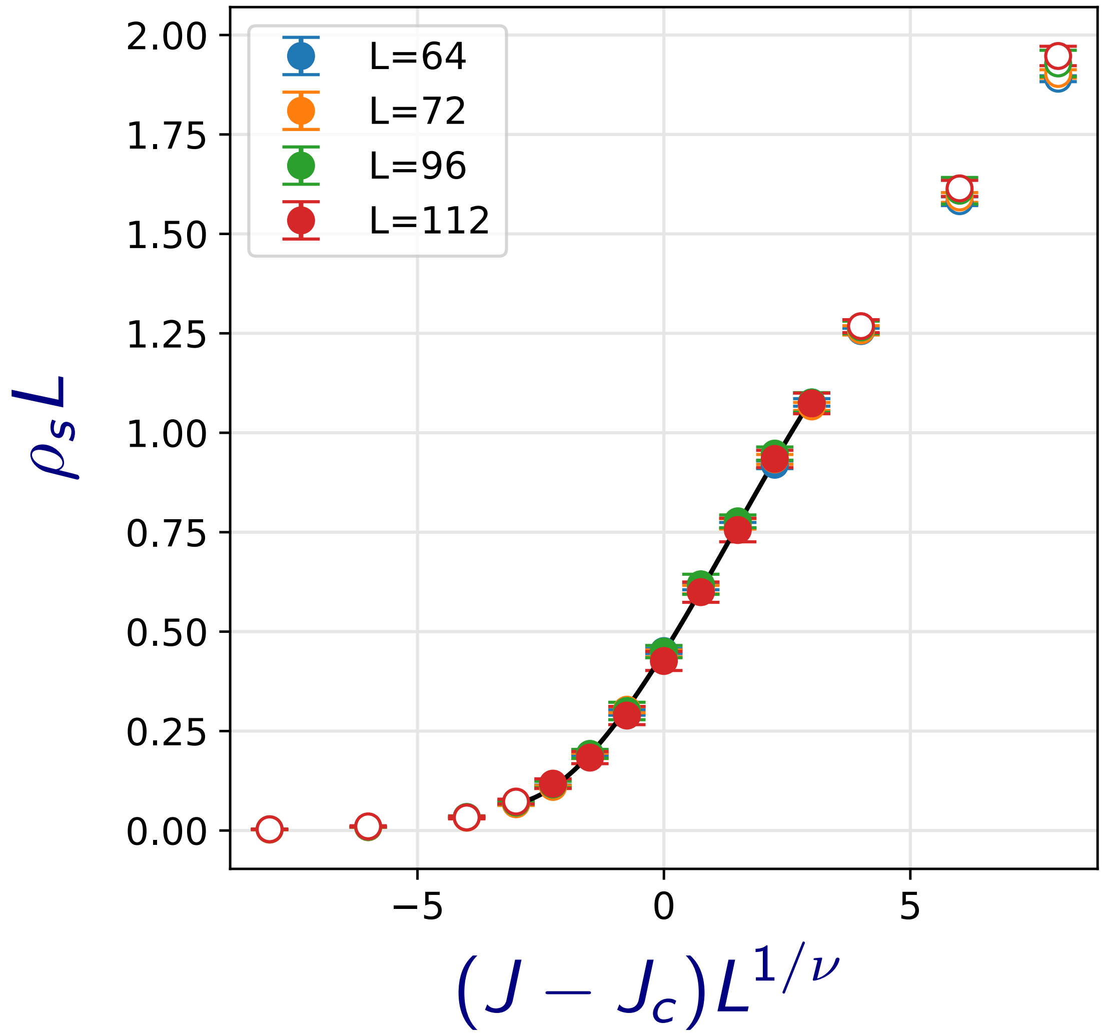

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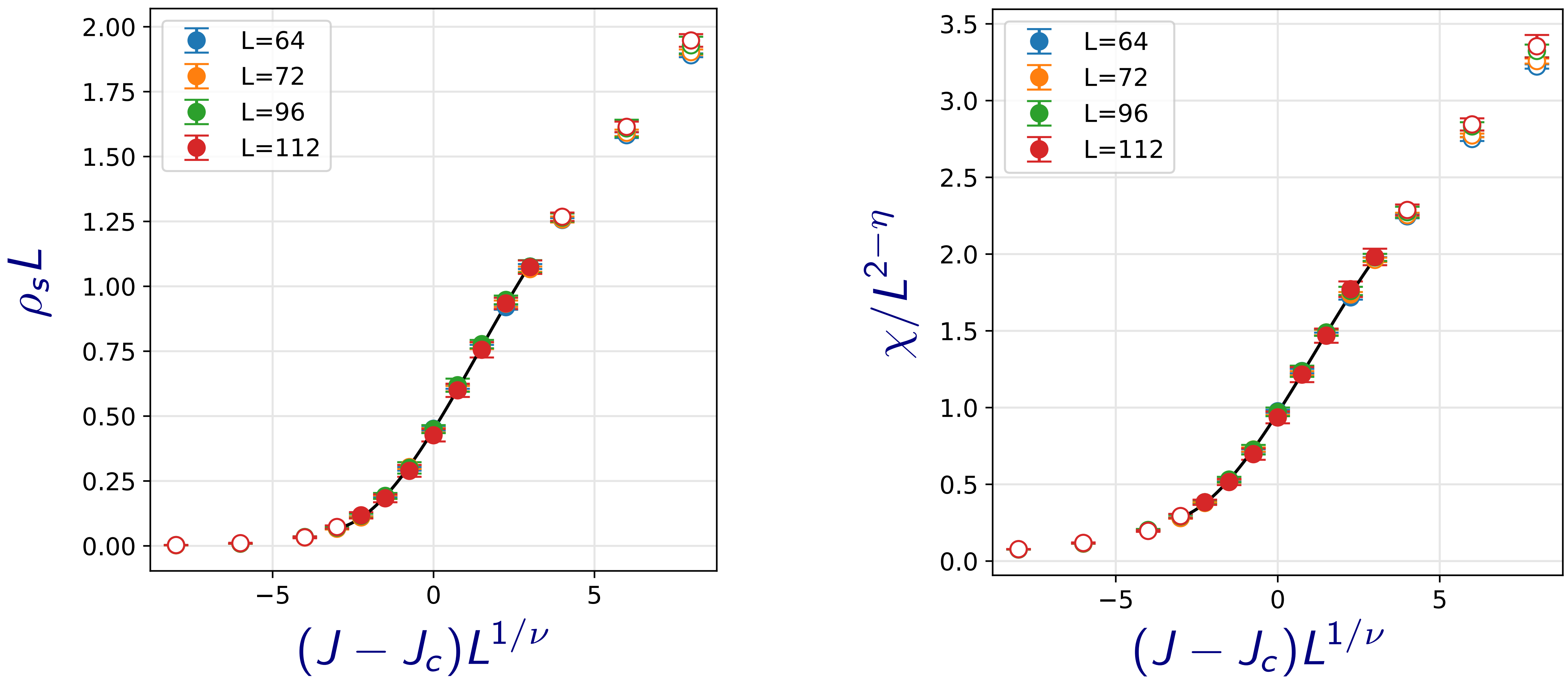

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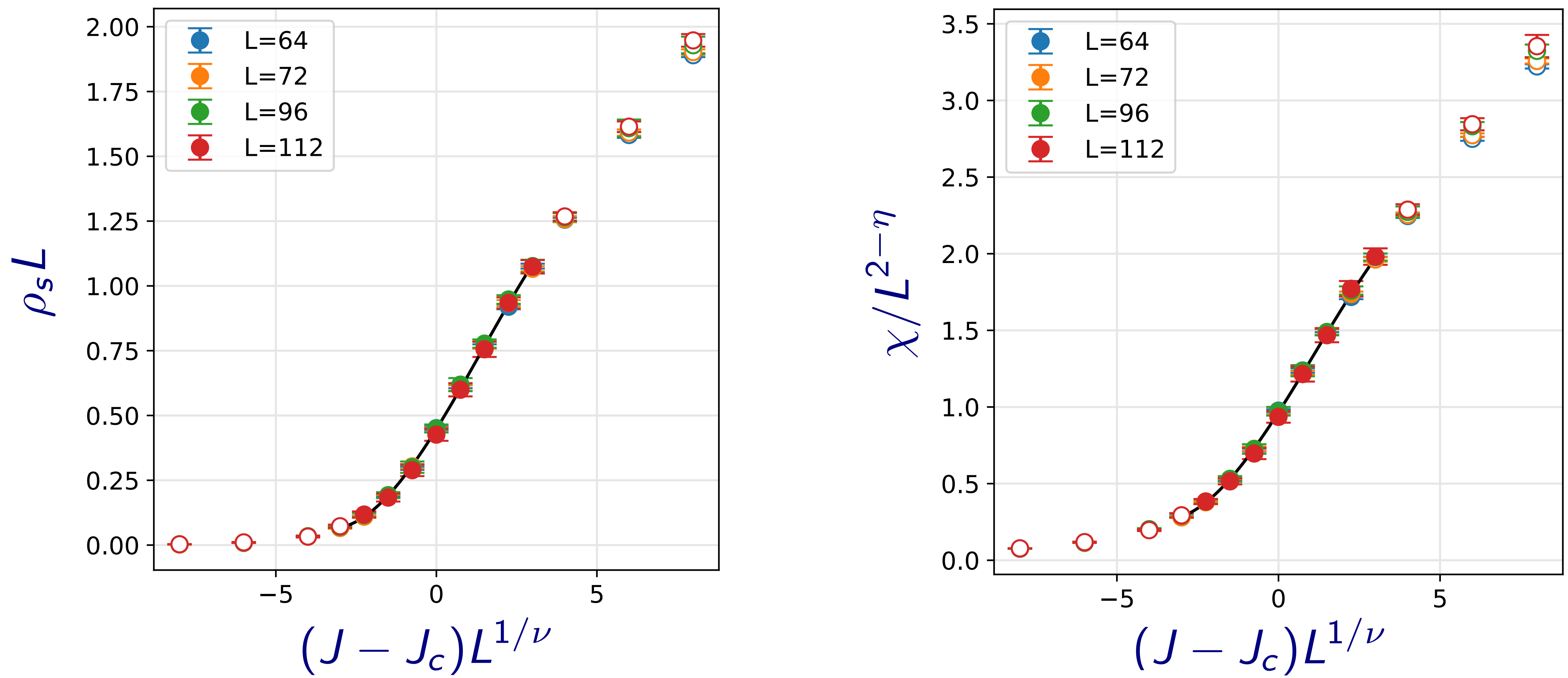

$\chi^2 = 0.53, J_c = 0.244329(11)$
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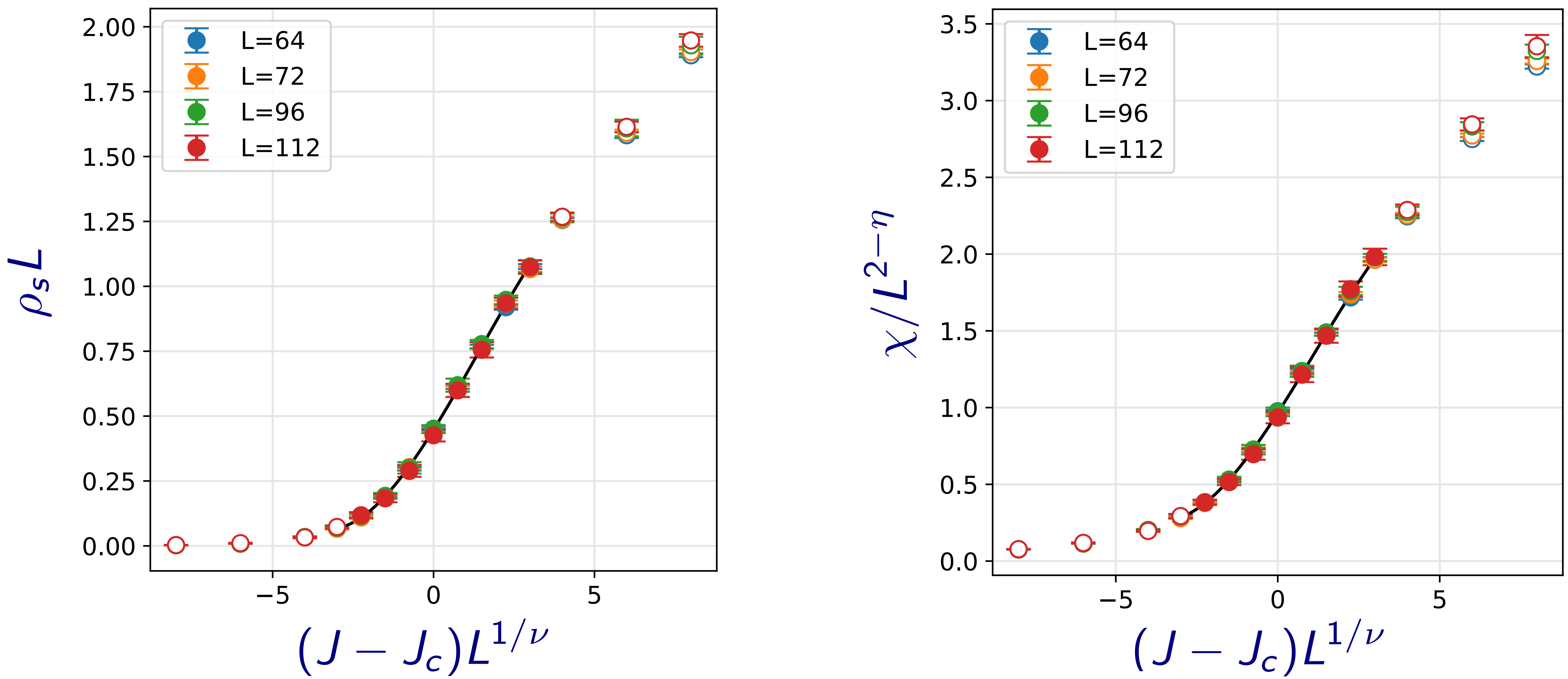

$\chi^2 = 0.53, J_c = 0.244329(11)$
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We see the Gaussian fixed point in d=3+1. We also see asymptotic freedom in d=1+1 but with caveats!

Euclidean Qubit O(4) Model

Banerjee,SC,Orlando,Reffert, 1902.09542

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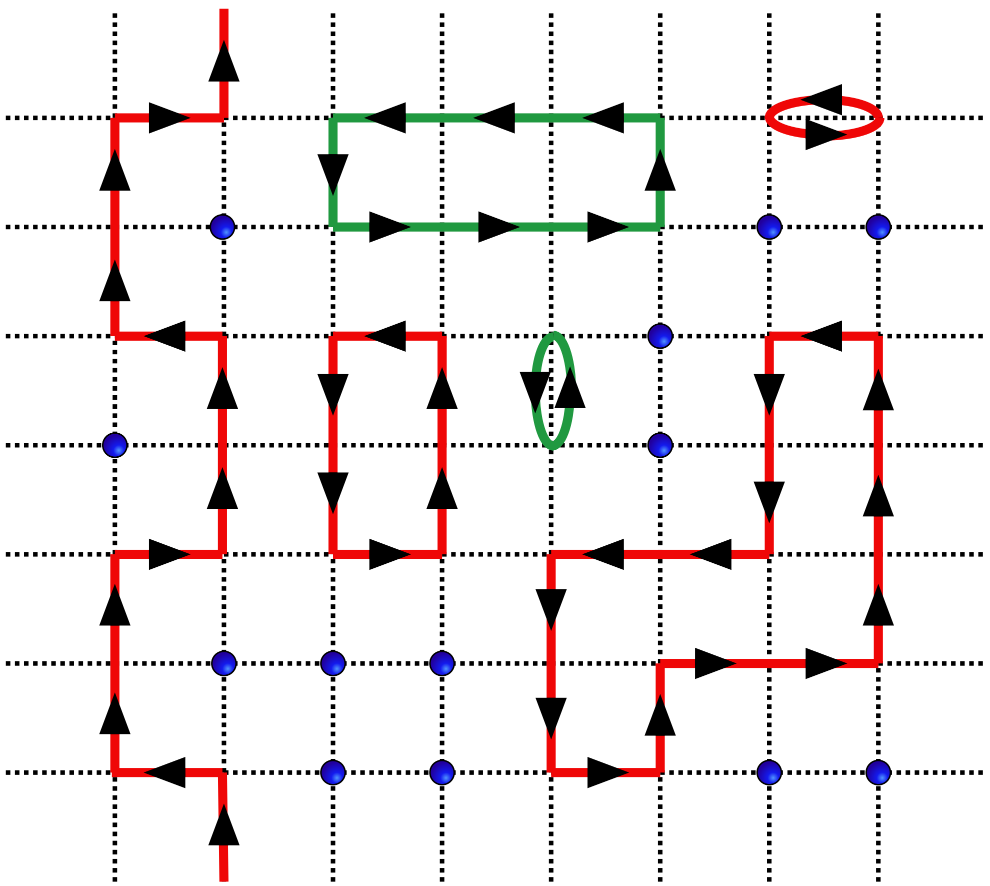
Needs five states per lattice site.



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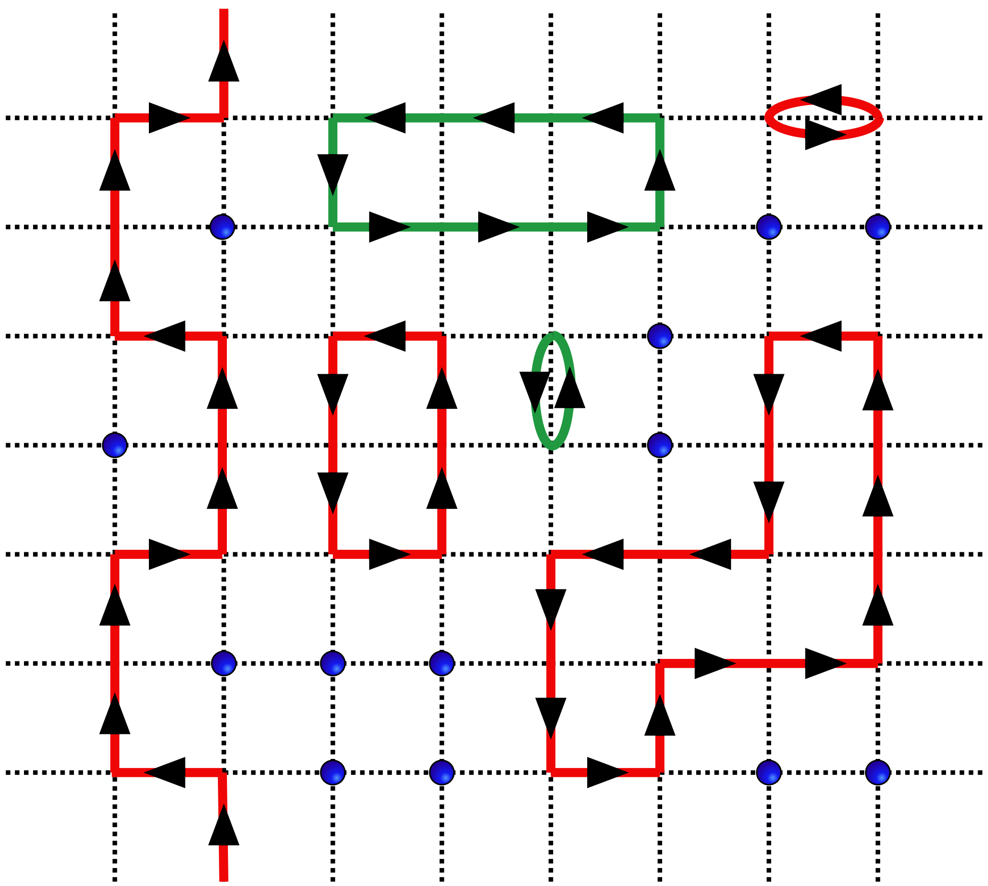

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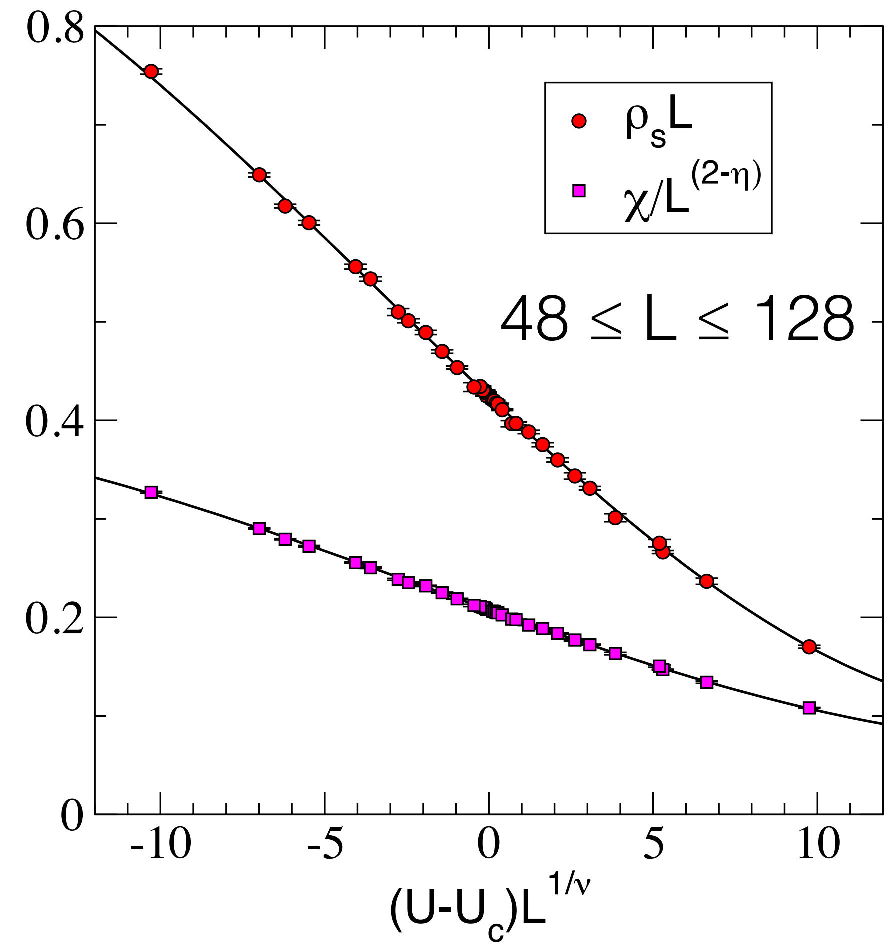

$$U_c = 1.655394(3)$$

$$\nu = 0.746(3), \eta = 0.0353(10)$$

Pelisetto, Vicari Phys. Repts. (2002)

$$\nu = 0.749(2), \eta = 0.0365(10)$$

Large charge results at the O(4) Wilson-Fisher fixed point

Q	D(Q,Q) (this work)	D(Q,Q) (from [26])	Q	D(Q,Q) (this work)	D(Q,Q) (from [26])
1/2	0.515(3)	0.5180(3)	1	1.185(4)	1.1855(5)
3/2	1.989(5)	1.9768(10)	2	2.915(6)	2.875(5)
5/2	3.945(6)	-	3	5.069(7)	-
7/2	6.284(8)	-	4	7.575(9)	-
9/2	8.949(10)	-	5	10.386(11)	-

[26] Hasenbusch, Vicari, PRB 84 (2011) 125136

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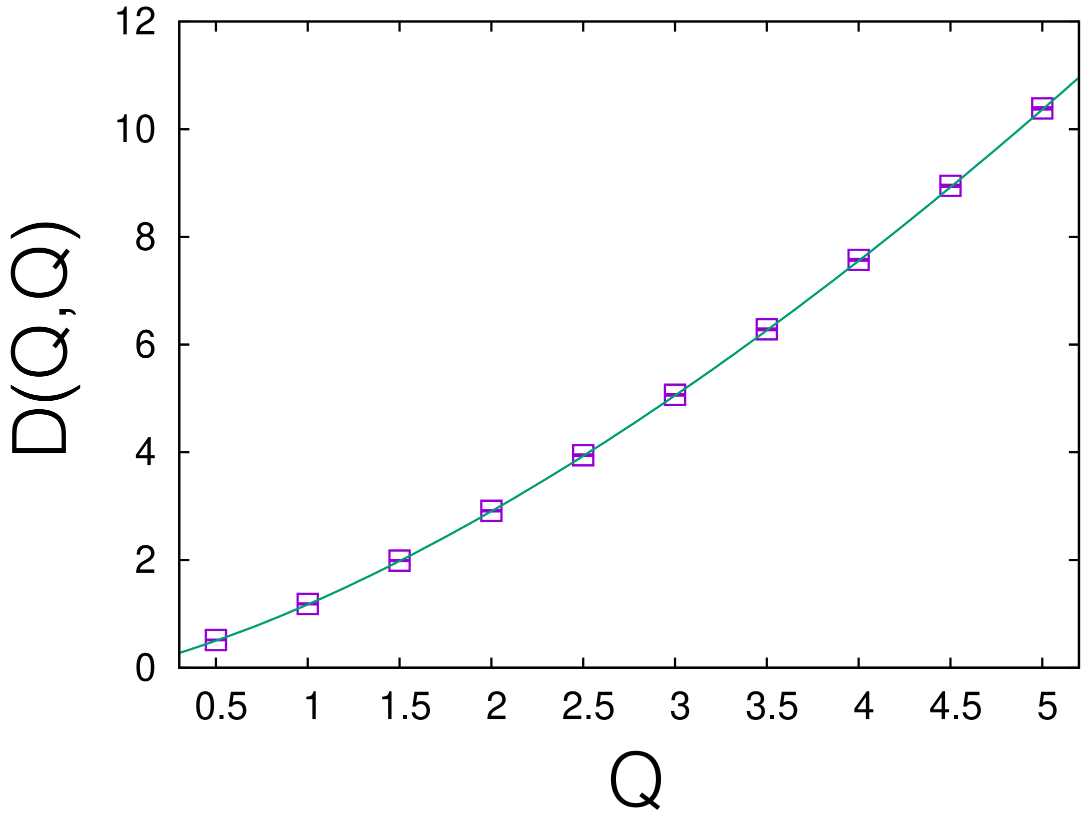

$$D(Q,Q) = 1.068(4)\ Q^{3/2} + 0.083(3)\ Q^{1/2} - 0.094$$

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Construction of Qubit models for quantum computers, must occur in two steps:

A. First perform Monte Carlo calculations to identify the quantum critical point where the correct QFT emerges.

B. Then study the theory close to the quantum critical point on the quantum computer.