Finite Correlation Length Scaling with Infinite Projected Entangled-Pair States

Corboz, P.; Czarnik, P.; Kapteijns, G.; Tagliacozzo, L.

DOI
10.1103/PhysRevX.8.031031

Publication date
2018

Document Version
Final published version

Published in
Physical Review X

License
CC BY

Citation for published version (APA):
Finite Correlation Length Scaling with Infinite Projected Entangled-Pair States

Philippe Corboz,1 Piotr Czarnik,2 Geert Kapteijns,1 and Luca Tagliacozzo3
1Institute for Theoretical Physics and Delta Institute for Theoretical Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, Netherlands
2Institute of Nuclear Physics, Polish Academy of Sciences, Radzikowskiego 152, PL-31342 Kraków, Poland
3Department of Physics and SUPA, University of Strathclyde, Glasgow G4 0NG, United Kingdom and Departament de Física Quàntica i Astrofísica, Universitat de Barcelona, Barcelona 08028, Spain

(Received 28 March 2018; revised manuscript received 12 June 2018; published 30 July 2018)

We show how to accurately study two-dimensional quantum critical phenomena using infinite projected entangled-pair states (iPEPS). We identify the presence of a finite correlation length in the optimal iPEPS approximation to Lorentz-invariant critical states which we use to perform a finite correlation length scaling analysis to determine critical exponents. This is analogous to the one-dimensional finite entanglement scaling with infinite matrix product states. We provide arguments why this approach is also valid in 2D by identifying a class of states that, despite obeying the area law of entanglement, seems hard to describe with iPEPS. We apply these ideas to interacting spinless fermions on a honeycomb lattice and obtain critical exponents which are in agreement with quantum Monte Carlo results. Furthermore, we introduce a new scheme to locate the critical point without the need of computing higher-order moments of the order parameter. Finally, we also show how to obtain an improved estimate of the order parameter in gapless systems, with the 2D Heisenberg model as an example.

DOI: 10.1103/PhysRevX.8.031031 Subject Areas: Computational Physics, Quantum Information, Strongly Correlated Materials

I. INTRODUCTION

In recent years there has been a very active development of tensor network variational ansätze for describing strongly correlated quantum many-body systems [1–5]. Tensor networks exploit the fact that ground states and low-energy states of local Hamiltonians are typically only weakly entangled, where the entanglement entropy of a region scales only with its surface rather than with its volume—a property known as the area law of entanglement [6–11]. As a consequence, the information contained in these states can be compressed and described by using specific tensor networks where the elementary tensors have finite bond dimension \( D \), such as one-dimensional matrix product states (MPS) [12–14] and 2D projected entangled-pair states (PEPS) [1,15,16] (also called tensor product states [17,18]).

In particular, in 1D, infinite MPS (iMPS) have successfully been used to characterize the universal properties of critical systems. This at first sight seems counterintuitive since 1D critical states violate the area law of entanglement [19–23] while an iMPS with finite \( D \) can only describe states fulfilling the area law, i.e., noncritical states with a finite correlation length \( \xi \) [12–14]. However, with increasing \( D \), \( \xi_D \) increases, improving the accuracy of the approximate state in a systematic way. As a result local observables follow the universal scaling laws characteristic of the underlying critical point. In the scaling regime \( \xi_D \) acts as a cutoff on the exact, diverging correlation length, similarly to a finite system size. The possibility to tune \( \xi_D \) by varying the bond dimension can be practically used to extract critical exponents in a very similar way as in standard finite-size scaling approaches. This powerful approach is known as finite entanglement scaling, and is also called finite correlation length scaling (FCLS) [24–27].

An important question is whether a similar approach can also be designed in 2D, which would be highly desirable since most critical exponents can only be computed numerically [28]. However, the situation in 2D seems different because unlike in 1D there exist critical states with an area law [35–41] and there are known examples of exact critical infinite projected entangled-pair states (iPEPS) with a finite \( D \) [40,42]. The latter include 2D classical states [43] and ground states of generalized Rokhsar-Kivelson (RK) Hamiltonians at their critical point.

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article’s title, journal citation, and DOI.
When the RK Hamiltonian is critical the low-energy excitations’ energy-momentum dispersion relation is $E(k) \propto k^2$ with $z \geq 2$ and the RK states effectively describe the partition function of 2D classical models [41–51]. Besides RK states, it is currently still unclear whether a generic quantum critical 2D state, obeying the area law, can be exactly represented by finite-$D$ iPEPS.

Here we focus on a special case of quantum phase transition, a critical point with low-energy excitations exhibiting a linear energy-momentum dispersion relation, $E(k) \propto k$. The linear dispersion is the footprint of an enhanced emerging symmetry, where energy and momentum (or space and time) play a very similar role and thus these critical points are called Lorentz-invariant critical points. For such a critical point there are no known examples of a finite-$D$ iPEPS that exactly represents the critical state [51–53].

In this paper we provide arguments justifying that an iPEPS with finite $D$ cannot represent a Lorentz-invariant critical state exactly. The finite $D$ always induces a finite correlation length $\xi_D$ in the iPEPS state, in complete analogy to the 1D case. Lorentz-invariant critical points could thus describe a class of states which, despite fulfilling the area law of entanglement, cannot be faithfully represented by an iPEPS with a finite $D$ (see also Ref. [54]). As a positive consequence, this allows us to the apply the ideas of FCLS also in 2D for the accurate and systematic study of quantum critical phenomena.

In order to demonstrate the applicability and power of FCLS in 2D, we present state-of-the-art simulation results for interacting spinless fermions on the honeycomb lattice where we find critical exponents in agreement with quantum Monte Carlo (QMC) results. Furthermore, we introduce a new scheme to locate the critical point, based on the order parameter $m$ and its derivative (called the $m'/m$ approach). Similar to the usual Binder cumulant approach, this scheme does not require the a priori knowledge of the critical exponents, but it is simpler since it is not based on higher moments of the order parameter, which are computationally expensive to obtain with iPEPS. We also show how FCLS can be used to obtained improved estimates of order parameters in gapless systems, with the 2D Heisenberg model as an example.

Our reasoning seems to indicate that the mismatch between finitely correlated iPEPS and critical states has a geometric origin. The finite $D$ in iPEPS, in the scaling regime, transforms the continuous space-time into a landscape of towers in imaginary time separated by valleys. The intertower separations are at the scale of the lattice spacing, but the finite correlation along the towers provides the infrared cutoff that is ultimately responsible for the appearance of the finite correlation length in the system, as sketched in Fig. 1.

This paper is organized as follows. Section II provides a brief introduction to iPEPS, followed by a heuristic discussion about the effects of encoding the ground state of a 2D Hamiltonian at a Lorentz-invariant quantum critical point with an iPEPS in Sec. III. In Sec. IV, we explain how to perform a FCLS analysis with iPEPS in practice. In Sec. V, we present our numerical results for the interacting spinless fermion model and explain the $m'/m$ scaling approach. The extrapolation technique based on FCLS to improve the extrapolation for the order parameter to its exact infinite-$D$ value is explained in Sec. VI. Finally, in Sec. VII, we summarize our main findings and conclusions.

II. INFINITE PROJECTED ENTANGLED-PAIR STATES

An iPEPS [1,15,16] (also called a tensor product state [17,18]) is an efficient variational tensor network ansatz for two-dimensional ground states of local Hamiltonians in the thermodynamic limit, and can be seen as a natural generalization of (infinite) matrix product states to two dimensions. The ansatz consists of a periodically repeated unit cell of tensors with one tensor per lattice site. In the present work, we used a cell with 2 tensors arranged in a checkerboard pattern. Each tensor has one physical index, carrying the local Hilbert space of a lattice site, and 4 (3) auxiliary indices on a square (honeycomb) lattice. As in a MPS, the accuracy of the ansatz is systematically controlled by the bond dimension $D$ of the auxiliary indices. In recent years iPEPS has become a very powerful approach which has been applied to a broad range of challenging problems, including frustrated spin systems and strongly correlated electron systems; see, e.g., Refs. [41,55–66] and references therein.
The optimization of the tensors (i.e., finding the optimal variational parameters) in this work is done by first performing an imaginary time evolution \[67-69\] and then further improving the state using a variational optimization \[70\] (see also Ref. \[71\]). The contraction of the 2D tensor network is done using a variant \[60\] of the corner transfer matrix (CTM) method \[72,73\], where the accuracy of the contraction is controlled by dimension \(\chi\) of the boundary tensors; see, e.g., Ref. \[67\] for details. In order to improve the efficiency we exploited global Abelian symmetries in the tensor network ansatz \[74,75\].

### III. LORENTZ-INvariant CRITICAL POINTS

Lorentz-invariant critical points are points in the phase diagram of a many-body systems in which (i) the Hamiltonian is gapless and (ii) the low-energy excitations’ dispersion relation depends linearly on the momentum \(k\), \(E(k) = \epsilon k\), where \(E\) is the energy of the excitation and \(\epsilon\) is the sound velocity.

The linear dispersion relation implies that the system at low energy becomes Lorentz invariant. The Lorentz transformations mix space and time. In order to understand the role of “time” in the ground state of a critical system it is better to appeal to the universality of the critical point. In this way we can describe the same scenario in terms of a classical 3D system where the extra dimension will represent the time. The low-energy emerging properties at the critical point of both the 2D quantum system and the 3D classical system are the same, provided that we choose a critical point of both the 2D quantum system and the 3D classical system are the same, provided that we choose a critical 3D classical system in the same universality class as the 2D quantum system.

One way to construct a 3D classical system in the same universality class of our 2D quantum system is to represent the time. The low-energy emerging properties at the critical point of both the 2D quantum system and the 3D classical system are the same, provided that we choose a critical point of both the 2D quantum system and the 3D classical system are the same, provided that we choose a critical 3D classical system in the same universality class as the 2D quantum system.

One way to construct a 3D classical system in the same universality class of our 2D quantum system is through the correspondence between classical and quantum mechanics. From the partition function of a classical model we can write the ground-state space projector \(|\Omega\rangle\langle\Omega| = \lim_{\beta \to \infty} \exp(-\beta H)/Z\), with \(Z = \text{tr}[\exp(-\beta H)]\) \[76\], and the ground-state expectation values \(\langle O \rangle = \text{tr}[\Omega|\Omega\rangle\langle O|\Omega\rangle]\), with \(\Omega\) an arbitrary operator. This is done by (i) dividing the Euclidean time \(\beta\) into many small intervals, \(\beta/N_t = \delta\beta\).

In this way (ii) the expectation value of an operator is written in terms of a large power of a certain operator \(\langle O \rangle = \text{tr}(T^{N_t} \Omega)\), where \(T = \exp(-\delta\beta H)\). We (iii) insert the resolution of the identity in a preferred basis of the Hilbert space \(\mathbb{T} = \sum_{\{n\}} |\{n\}\rangle\langle\{n\}|\) before and after each \(T\).

This allows us to identify a “classical” transfer matrix. (iv) As a consequence of the locality of the Hamiltonian \(H\) and the fact that \(\delta\beta \ll 1\), \(T\) can be expressed approximately (with an error that scales to zero as \(\delta\beta \to 0\) faster than \(\delta\beta^2\)) as the contraction of local Boltzmann weights, by, for example, performing a Trotter-Suzuki expansion of \(T\) together with a singular value decomposition of the resulting local terms \[77-79\]. As a result we can express the ground space projector of a 2D Hamiltonian (and consequently all ground-state expectation values) as the infinite contraction of a simple 3D tensor network.

The construction holds for any 2D quantum system and becomes exact in the limit \(\delta\beta \to 0\). The emerging Lorentz symmetry close to a Lorentz-invariant critical point allows us to exchange the role of the Euclidean time \(\beta\) with any of the space directions. As a consequence, the correlation length in the time direction is proportional to the correlation in the space direction \(\xi_s = v\xi_t\), where \(v\) is the velocity appearing in the low-energy dispersion relation and \(\xi_s\) and \(\xi_t\) denote the correlation length and correlation time, respectively.

We now give an argument in favor of the fact that by encoding the 3D tensor network in a 2D iPEPS with finite bond dimension we force the correlation time \(\xi_t\) to be finite.

#### A. Finite correlation time

The easiest way to understand why a finite \(D\) induces a finite correlation time is to represent a 2D cut of the 3D tensor network in which we represent only \(x, t\) of the \(x, y, t\) coordinates. We describe the process of encoding the 3D network in a 2D iPEPS as if we were actually performing an imaginary time evolution. The 2D cut of the infinite tensor network is represented in Fig. 2. There, as usual, tensors are represented by geometric shapes and the lines attached to them represent their indices. Lines connecting two tensors encode the contraction of the two tensors with

![FIG. 2. (a) The ground space projector can be represented as an infinite 3D tensor network, spanning the three directions \(x, y, t\). As usual, tensors are represented here by geometric shapes and lines attached to them are their indices. A line joining two tensors represents the tensor contraction. Here we represent a projection of the 3D tensor network in 2D, where the vertical direction is the Euclidean time \(t\), while the horizontal direction is the spatial direction \(x\). (b) By using a boundary state we can approximate the full 3D network as the computation of the norm of a 2D iPEPS state. We contract one layer of the tensor network, the transfer matrix \(T\), with the boundary iPEPS state \(|v_0\rangle\) (first line). The bond dimension of the iPEPS state would increase exponentially number of time steps, and thus we approximate the iPEPS state by truncating its bond dimension back to \(D\) (second to fourth line) using appropriate projectors (yellow tensors). We iterate these last two steps many times until the boundary state has actually converged. The converged iPEPS represents our best approximation of the ground state \(|\Omega\rangle\) with finite bond dimension \(D\).](image-url)
The fixed point iPEPS tensors are the result of many contraction and projection steps. Here we expand explicitly the iPEPS into its elementary constituents along the imaginary time direction (vertical in the figure), made by the original constituents of the 3D network (cyan tensors) and projectors (yellow tensors) used at each step to project the evolved iPEPS to a state with bond dimension $D$. The result is that the infinite 3D tensor network becomes very anisotropic, and we observe the appearance of quasi-one-dimensional time channels. (b) The equal space, nonequal time correlation function $\langle \Omega | \mathcal{O}(t_0) \mathcal{O}(t_1) | \Omega \rangle$. The insertion of the local operators $\mathcal{O}$ at two different times $t_0$ and $t_1$ is indicated by purple tensors. The contraction of the network outside the selected time channel produces the two environment tensors represented as rectangles on the left and the right of the time channel. The correlation function thus assumes a one-dimensional structure. The projectors provide a timelike MPS state. Since the bond dimension of the MPS state is finite and equal to $D$, we expect that these correlations either do not decay or decay exponentially with the time separation $t_1 - t_0$.

iMPS with finite bond dimension cannot be critical. The correlations in those states either do not decay or decay exponentially. This means that we expect $\langle \Omega | \mathcal{O}(t_0) \mathcal{O}(t_1) | \Omega \rangle \propto \exp(-|t_1 - t_0|/\xi)$. Since these correlations are generated by powers of $T$ that is a function of $H$, the approximation scheme has introduced an effective finite correlation length in the imaginary time direction, as if the Hamiltonian was gapped. The approximation thus acts like a relevant perturbation to the critical Hamiltonian [81].

Thanks to the theorem proven by Hastings and Koma [82], the ground state of a gapped Hamiltonian has exponentially decaying correlation functions, and this we
think is the physical origin of the finite correlation length we observe in our simulations.

This reasoning seems to suggest that the best iPEPS approximation to a critical ground state, in the scaling limit, where we can think of our system as a continuous system, transforms a smooth 3D solid geometry, into a “Swiss cheese,” in which the size of holes (the valleys between different channels) is of the order of the lattice spacing and the correlation length along the channels actually provides the IR cutoff inducing all the phenomenology observed numerically. An illustration of this is sketched in Fig. 1.

A legitimate question is how to accommodate in this picture the existence of iPEPS with finite bond dimension and polynomially decaying correlations functions, such as those that are the ground state of generalized RK Hamiltonians. These states are known to describe a picture the existence of iPEPS with finite bond dimension $\chi$ used in the CTM contraction; i.e., in general scaling ansätze depend on both $\xi_D$ and $\xi_\chi$, e.g.,

$$m(g, D, \chi) = \xi_D^{-\beta/\nu} \mathcal{M}(g, D, \xi_D / \xi_\chi).$$

In order to solve this issue we eliminate the $\chi$ dependence by extrapolating the data in $\chi$, and perform a scaling analysis based on $\xi_D := \xi(g = 0, D, \chi \to \infty)$ only, so that the scaling ansatz reduces to Eq. (5). In the following we numerically demonstrate that this scaling ansatz can be used to extract critical properties in the 2D quantum case.

V. SPINLESS FERMIONS ON THE HONEYCOMB LATTICE

We consider a model of interacting spinless fermions on the honeycomb lattice at half filling, given by the Hamiltonian,

$$\hat{H} = -t \sum_{\langle i, j \rangle} [\hat{c}_i^\dagger \hat{c}_j + \text{H.c.}] + V \sum_{\langle i, j \rangle} \hat{n}_i \hat{n}_j,$$

where the first term describes a nearest-neighbor hopping with amplitude $t$ and the second term a repulsive nearest-neighbor interaction with strength $V$, with $\hat{n}_i = \hat{c}_i^\dagger \hat{c}_i$. This model has been intensely studied in the past [84–89] and is known to undergo a continuous phase transition between a Dirac semimetals phase and a charge-density wave (CDW) phase at a critical coupling of $V_c/t = 1.356(1)$ [84]. In the continuum limit the transition belongs to the chiral Ising Gross-Neveu universality class with a dynamical critical exponent $z = 1$.

The CDW order parameter is given by

$$m = |n_A - n_B|,$$

where $n_A$ and $n_B$ are the particle densities on sublattices $A$ and $B$, respectively. Figure 4(a) shows the order parameter as a function of interaction strength $V/t$ for different bond dimensions $D$, where one can clearly observe the finite-$D$ effects, i.e., no sharp phase transition at $V_c/t = 1.356$, but a systematic suppression of $m$ with increasing $D$, very similar to standard finite-size effects.

We first test the scaling ansatz at the critical point, i.e., $g = (V - V_c)/V_c = 0$, with $V_c/t = 1.356$, where Eq. (2) reduces to

$$m(g = 0, D, \chi) = \xi_D^{-\beta/\nu} \mathcal{M}(0, \xi_D, \xi_D / \xi) \sim \xi_D^{-\beta/\nu}. \quad (5)$$

To what extent FCLS can also be applied to 2D quantum systems using iPEPS has not been explored yet. This generalization is also more challenging because the effective correlation length is affected by both the bond dimension $D$ of the ansatz and the boundary dimension $\chi$ used in the CTM contraction; i.e., in general scaling
The latter relation is obtained by taking a sufficiently large $\chi$ such that $m$ is fully converged in $\chi$. Figure 4(b) shows that $m$ converges rapidly in $\chi$ such that no extrapolation in $\chi$ is needed. However, the correlation length $\xi$ displays a stronger dependence on $\chi$ [90], shown in Fig. 4(c). We determine $\xi_D$ for each value of $D$ by extrapolating $\xi(D,\chi)$ to the infinite $\chi$ limit. We do this by performing linear extrapolations in $1/\chi$ using different ranges of data points, and determining the average and standard deviation of these extrapolations [91]. We clearly find that even at the largest bond dimension the state is not critical, i.e., that the finite $D$ induces a finite correlation length, similarly as in 1D with MPS. Finally, Fig. 4(d) shows a log-log plot of $m$ versus $\xi_D$, where a linear fit yields an estimate for $\beta/\nu = 0.64(2)$ in agreement with the QMC result $\beta/\nu = 0.65(4)$ from Ref. [84].

Next, we check if we can consistently determine the critical point $V_c$ based on this result for $\beta/\nu$. Using the scaling ansatz Eq. (2) at the critical point in the large $\chi$ limit, we obtain

$$y = m(g = 0, D, \chi \to \infty)_{\xi_D}^{\beta/\nu} = \text{const},$$

i.e., a constant independent of $D$. In Fig. 5(a), we plot $y$ as a function of $D$ for different values of $V/t$, and Fig. 5(b) shows the deviation from a straight line (computed by the

standard deviation of $y$) as a function of $V/t$ (where $\xi_D$ is determined for each value of $V/t$). The smallest deviation is obtained for $V/t = 1.356$, consistent with the QMC result. (A similar result is also obtained using $\beta/\nu = 0.65$.)

We next attempt to perform a data collapse using the following two ansätze (again in the large $\chi$ limit),

$$m(g, D)_{\xi_D}^{\beta/\nu} = M(g_{D}^{1/\nu}),$$

$$m(g, D) g^{-\beta} = \tilde{M}(g_{D}^{1/\nu}),$$

to determine the critical exponents $\nu$ and $\beta$ (with $V_c/t = 1.356$), shown in Fig. 6. By varying the range of data points and by taking the error bar of $\xi_D$ into account, we obtain the following estimates: $\beta = 0.51(1)$ and $\nu = 0.79(2)$, in agreement with the QMC result $\beta = 0.52(3)$, $\nu = 0.80(3)$ [84].

A. Determining the critical point based on $m'/m$

A standard method to determine the critical point without knowledge of the critical exponents is by the Binder cumulant, which is invariant at the critical point for different system sizes (or bond dimensions). However, this
would require computing the fourth-order moment of the order parameter, which is difficult in a 2D tensor network approach. Here, we introduce an alternative approach based on the derivative of the order parameter with respect to \( g \), which in the large \( \chi \) limit is expected to obey the following ansatz:

\[
m'(g, D) = \xi_D^{-(\beta - 1)/\nu} \mathcal{M}'(g_0^{1/\nu}).
\]

(9)

Thus, at the critical point, \( g = 0 \),

\[
m_c'(D) = m'(g = 0, D) \sim \xi_D^{1/\nu}.
\]

(10)

Thus, we have found an expression for \( \xi_D^{1/\nu} \) which can be used to rewrite scaling functions:

\[
\mathcal{M}(g_0^{1/\nu}) = \mathcal{P}\left(\frac{m_c'(D)}{m_c(D)}\right).
\]

(11)

Dividing Eq. (9) by \( m \) and multiplying by \( g \) yields

\[
g \frac{m'(g, D)}{m(g, D)} = \tilde{\mathcal{M}}(g_0^{1/\nu}) = \mathcal{P}\left(\frac{m_c'(D)}{m_c(D)}\right).
\]

(12)

Thus, we can plot \( y = (V - V_c)/\{[m'(g, D)]/[m(g, D)]\} \) versus \( x = (V - V_c)/\{[m_c'(D)]/[m_c(D)]\} \) as a function of \( V \), and for the correct choice of \( V_c \), the data for different values of \( D \) collapse onto a single curve. The best data collapse, shown in Fig. 7(a), is obtained for \( V_c/t = 1.356(2) \) in agreement with the QMC result. The numerical derivative has been obtained by taking the derivative of polynomial fits to \( m \) versus \( V/t \) data.

Finally, we can combine Eqs. (11) and (8),

\[
m(g, D)g^{-\beta} = \tilde{P}\left(\frac{m_c'(D)}{m_c(D)}\right),
\]

(13)

to perform a data collapse and extract the exponent \( \beta \), shown in Fig. 7, yielding a consistent value of \( \beta = 0.53(1) \).

FIG. 7. (a) Data collapse using Eq. (12) yielding \( V_c/t = 1.356(2) \). (b) Data collapse based on Eq. (13) giving \( \beta = 0.53(1) \).

VI. IMPROVED EXTRAPOLATIONS OF ORDER PARAMETERS

The effective correlation length \( \xi_D \) can also be used to perform an improved extrapolation of the order parameter in a gapless system. As an illustration, we present results for the two-dimensional \( S = 1/2 \) Heisenberg model on a square lattice. Figures 8(a) and 8(b) show the correlation length \( \xi \) and (b) staggered magnetization \( m \) as a function of inverse \( \chi \) for different values of \( D \). A linear extrapolation yields \( m = 0.307 \pm 0.002 \), which is in agreement with the QMC result \( m = 0.30743(1) \). (d) Order parameter as a function of inverse \( D \).

VII. SUMMARY AND CONCLUSION

In this paper, we have demonstrated the usefulness and applicability of finite correlation length scaling in two dimensions based on iPEPS by determining the critical exponents and critical point of an interacting spinless fermion model on a honeycomb lattice. Our findings are in agreement with the QMC results from Ref. [84]. Furthermore, we introduced a new approach to determine the critical point based on the derivative of the order parameter, which does not require the computation of higher-order moments of the order parameter.
parameter or extrapolations of the effective correlation length in $\chi$, making it a particularly useful approach for 2D tensor network calculations. We stress that iPEPS can also be applied to models which are inaccessible to QMC simulations due to the negative sign problem, making it a promising tool to study critical properties of challenging open problems.

From the theoretical point of view, we have possibly identified a class of models whose ground states are hard to encode with iPEPS with finite bond dimension, despite obeying the area law of entanglement. We have given an intuitive argument that the mismatch between the exact critical states and the finitely correlated iPEPS we obtain has a geometric origin. The iPEPS seems to approximate the smooth continuous 3D geometry with a landscape of towers separated by valleys, where the finite correlation time along the towers could be the ultimate reason for the appearance of the finite correlation length.

Our results are also relevant to field theories. The operator content of a field theory is known to depend on the appearance of the finite correlation length. From the theoretical point of view, we have possibly identified a class of models whose ground states are hard to encode with iPEPS with finite bond dimension, despite obeying the area law of entanglement. We have given an intuitive argument that the mismatch between the exact critical states and the finitely correlated iPEPS we obtain has a geometric origin. The iPEPS seems to approximate the smooth continuous 3D geometry with a landscape of towers separated by valleys, where the finite correlation time along the towers could be the ultimate reason for the appearance of the finite correlation length.

Our results are also relevant to field theories. The operator content of a field theory is known to depend on the geometry and the boundary conditions of the space on which the theory is defined [94,95]. It would be important to understand the effects of the landscape of towers and valleys on the operator content of the corresponding field theory. Furthermore, our results seem to suggest that $D$ would act as a regulator in any continuum limit of the theory defined on the lattice. The bond dimension of the iPEPS should indeed increase in order to keep the ratio between the relevant physical quantities and the correlation length fixed as we approach the continuum limit.

**ACKNOWLEDGMENTS**

We acknowledge discussions with Andreas Läuchli and Michael Rader. L.T. acknowledges the long-time discussions and collaboration with Andrea Coser on similar problems studied in the context of Gaussian tensor networks. This project was supported by the European Research Council (ERC) under the European Unions Horizon 2020 research and innovation programme (Grant Agreement No. 677061), and by the Nardowoe Centrum Nauki (National Science Center) under Project No. 2016/23/B/ST3/00830. Work at the University of Strathclyde was supported by the EPSRC Programme GrantDesOEQ (EP/P009565/1). This project is part of the Delta-ITP consortium, a program of the Netherlands Organization for Scientific Research (NWO) that is funded by the Dutch Ministry of Education, Culture and Science (OCW).

*Note added.*—Similar results have been reported by Rader and Läuchli [96].


[28] There have been promising developments in analytical bootstrap [29,30], but the accuracy has not yet reached the level of numerical calculations (see, e.g., Refs. [31–34]).


For example, the 2D classical partition function of the critical 2D Ising model represented as an iPEPS with $D = 2$.


[76] If H is gapless, a projector onto a well-defined state can be obtained by first opening an infinitesimally small gap of order ε modifying H → H + εβH and then taking the limit β → ∞. We avoid similar details in the rest of the section.