Tensor Networks and the simulation of LGT

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OF QUANTUM OPTICS

MCQST

DFG FOR 5522

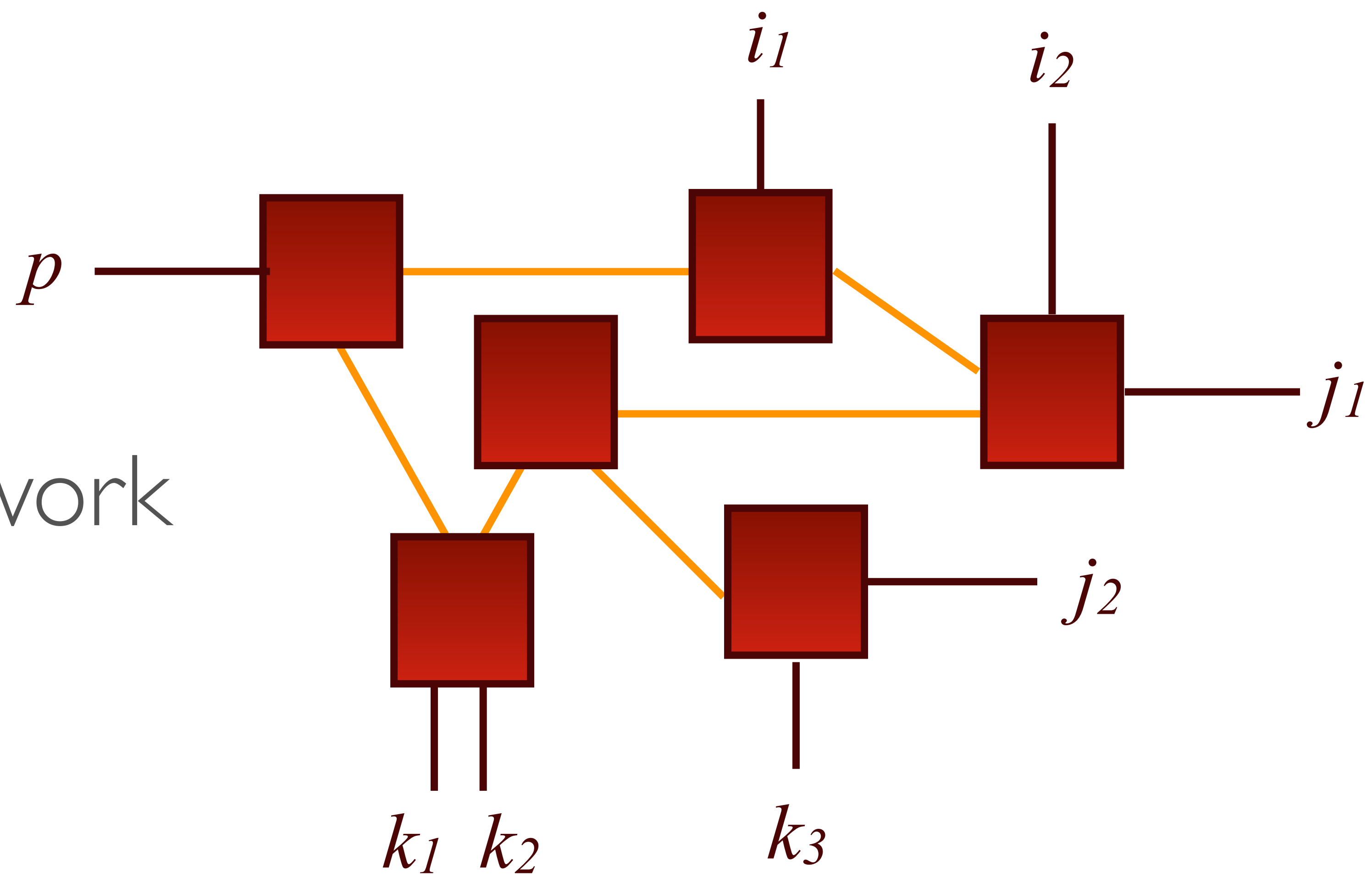
T-NiSQ

DFG TRR 360

4.11.2024

tensor network

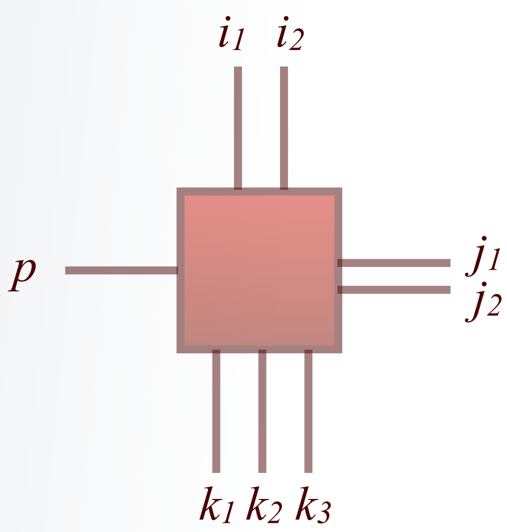
tensor = multidimensional array



tensor network (TN)

$$\{T_{i_1 i_2, j_1 j_2, k_1 k_2 k_3, p}\}$$

tensor network



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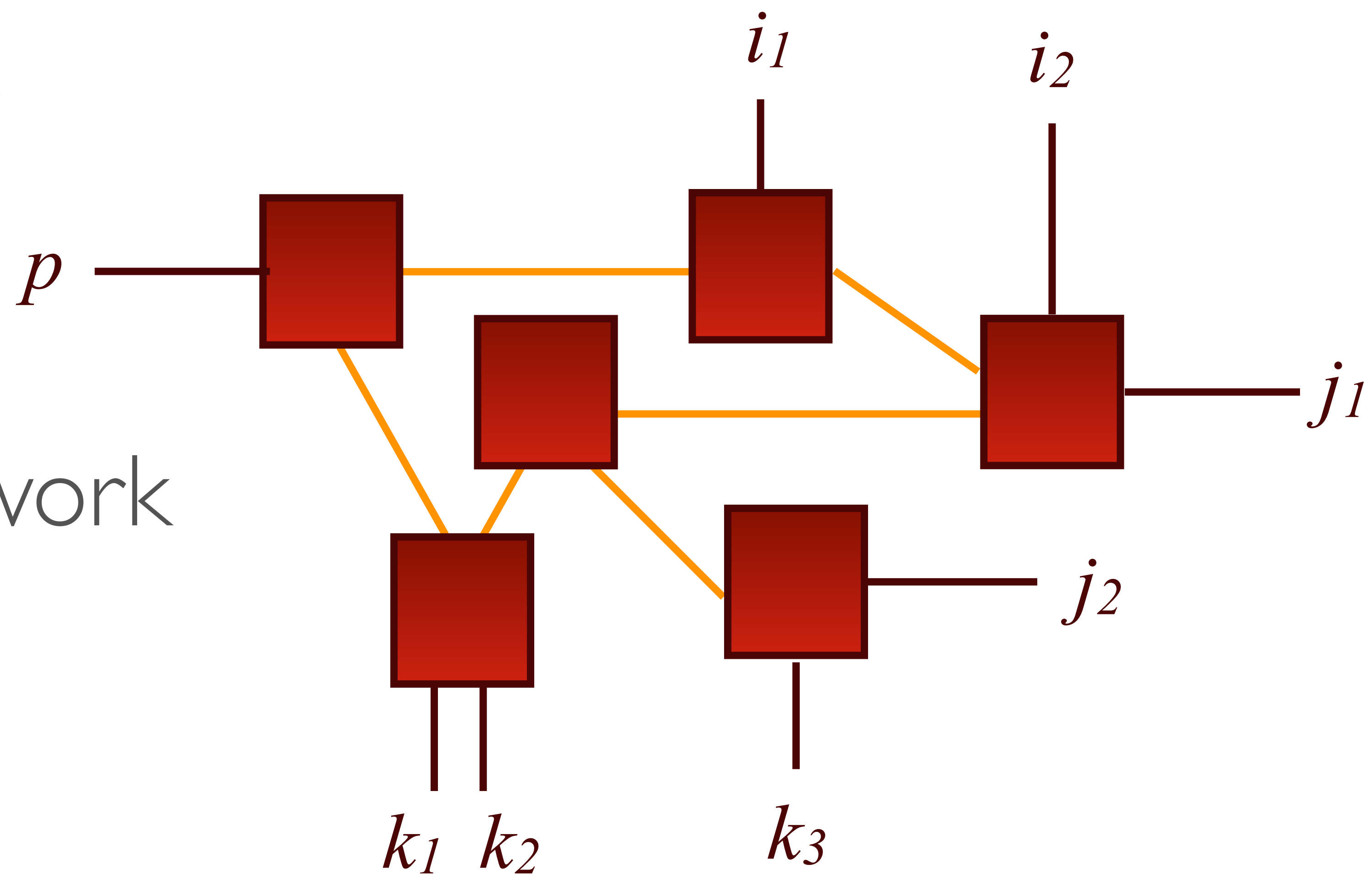

tensor network
(TN)

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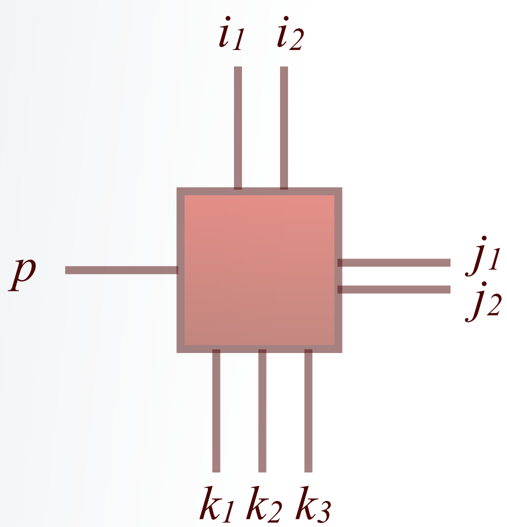
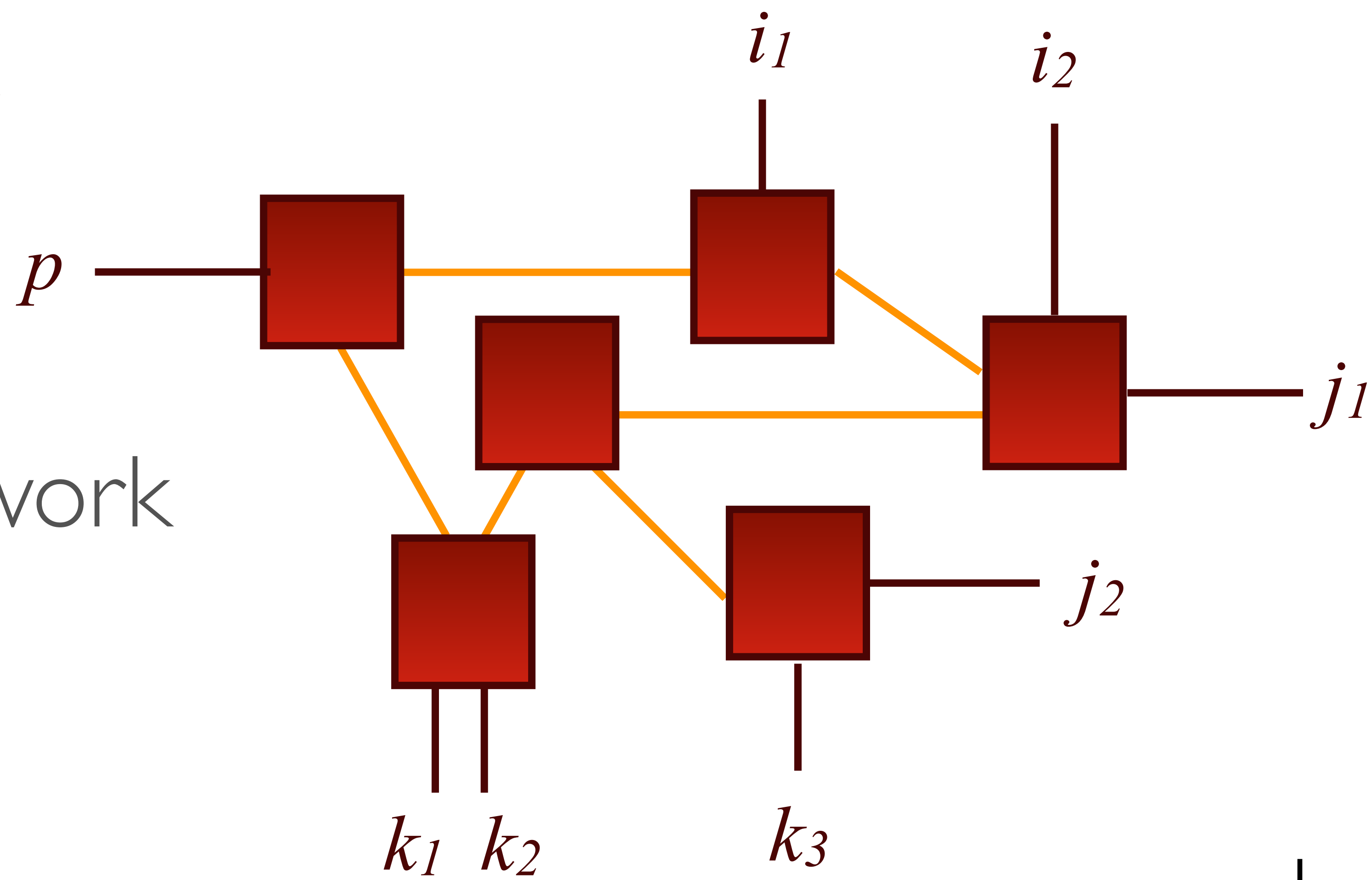
tensor network



tensor = multidimensional array

tensor network (TN)



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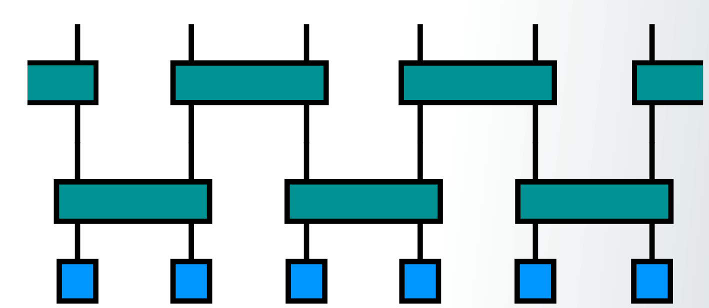
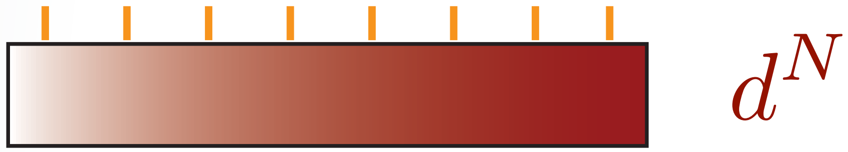


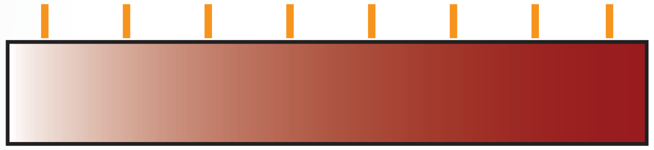
TNS: entanglement-based ansatzes for quantum many-body states

arbitrary many-body state



$$|\Psi\rangle = \sum_{i_j} c_{i_1 \ldots i_N} |i_1 \ldots i_N\rangle$$

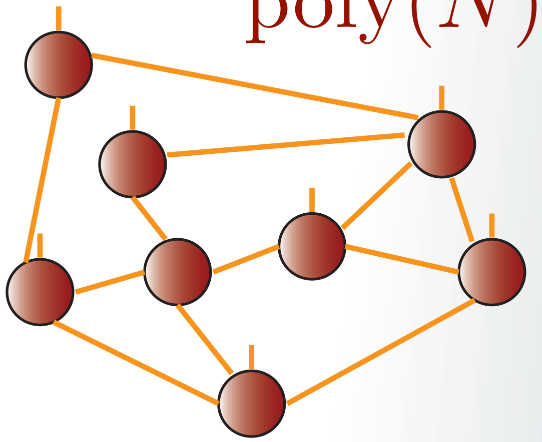
arbitrary many-body state



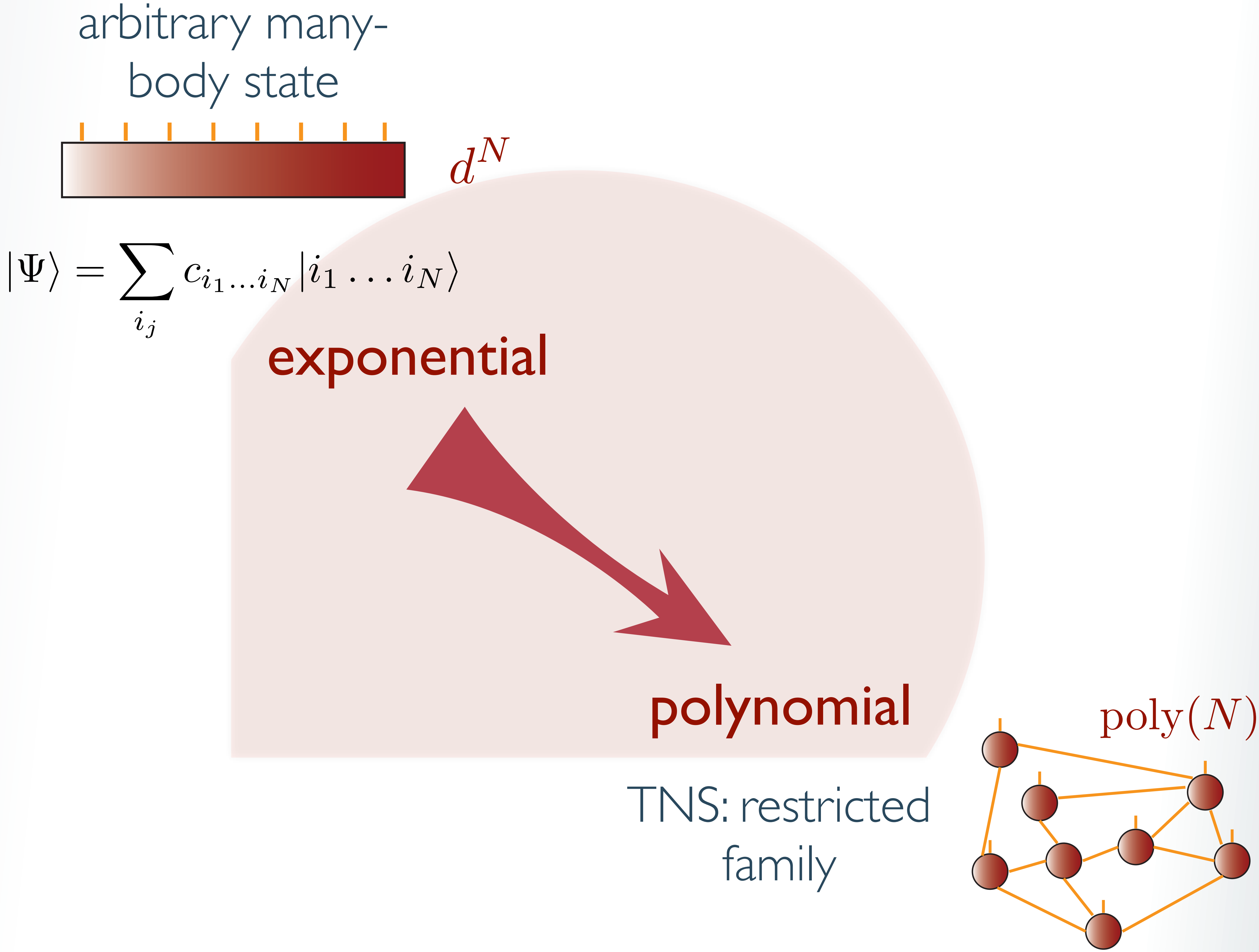
d^N

$$|\Psi\rangle = \sum_{i_j} c_{i_1 \ldots i_N} |i_1 \ldots i_N\rangle$$

TNS: restricted family



$\text{poly}(N)$


arbitrary many-body state
d^N
$|\Psi\rangle = \sum_{i_j} c_{i_1 \ldots i_N} |i_1 \ldots i_N\rangle$
exponential
polynomial
TNS: restricted family
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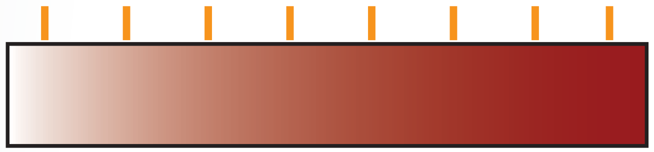
arbitrary many-body state



d^N

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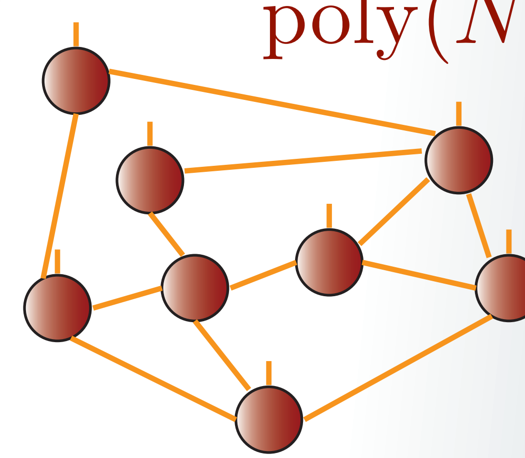


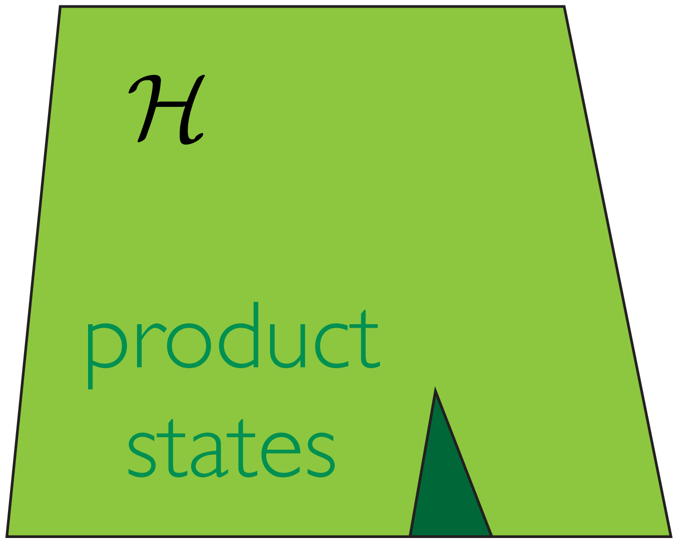
good ansatz for ground states and thermal equilibrium: area law

entanglement hierarchy

efficient numerics

finding a good ansatz

random state not
close to product



finding a good ansatz

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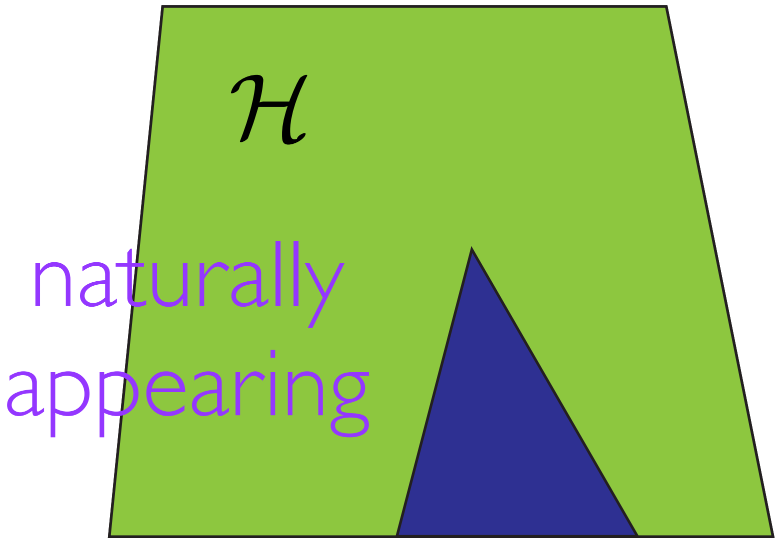

"*relevant corner*"

finding a good ansatz

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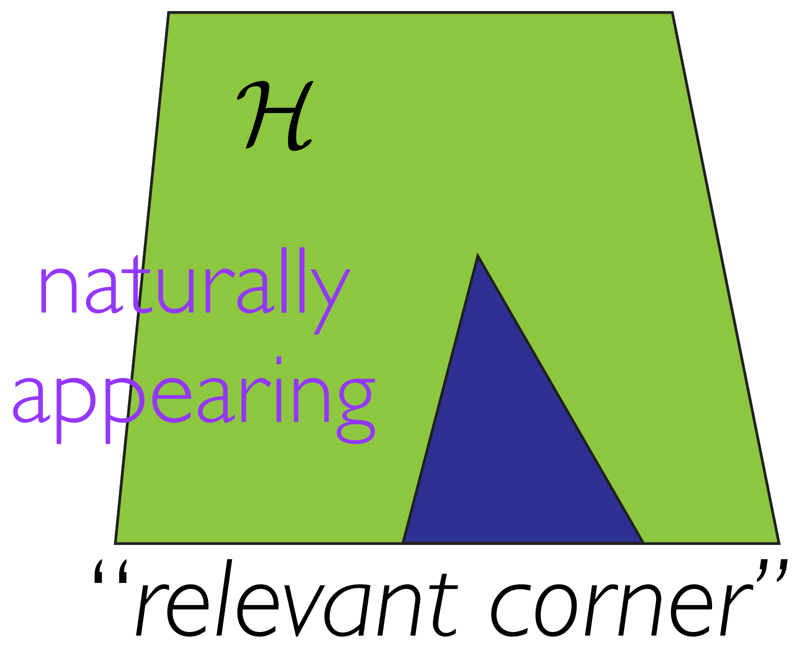
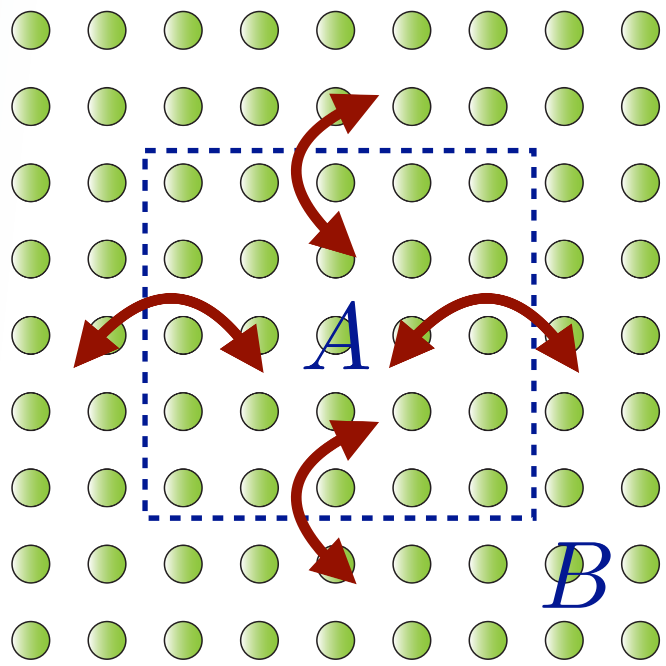
close to product





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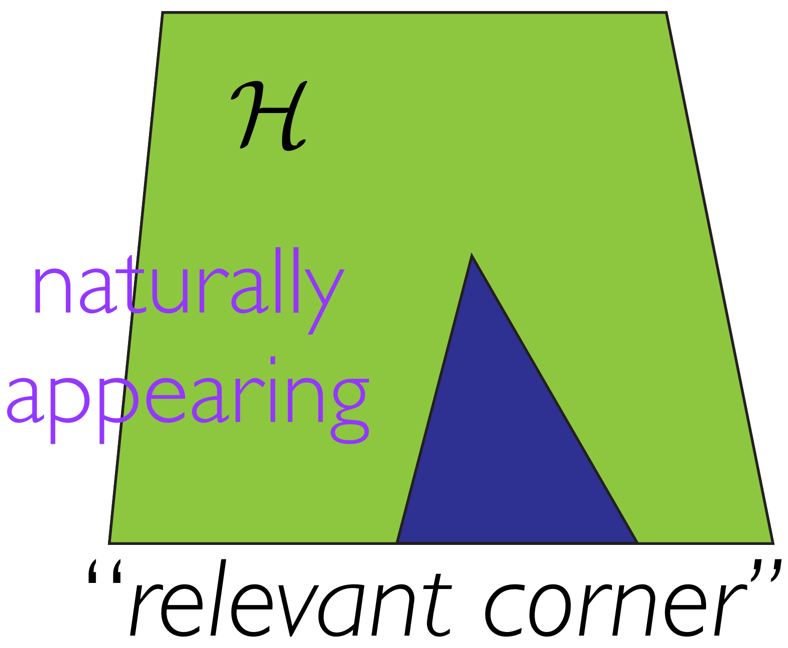
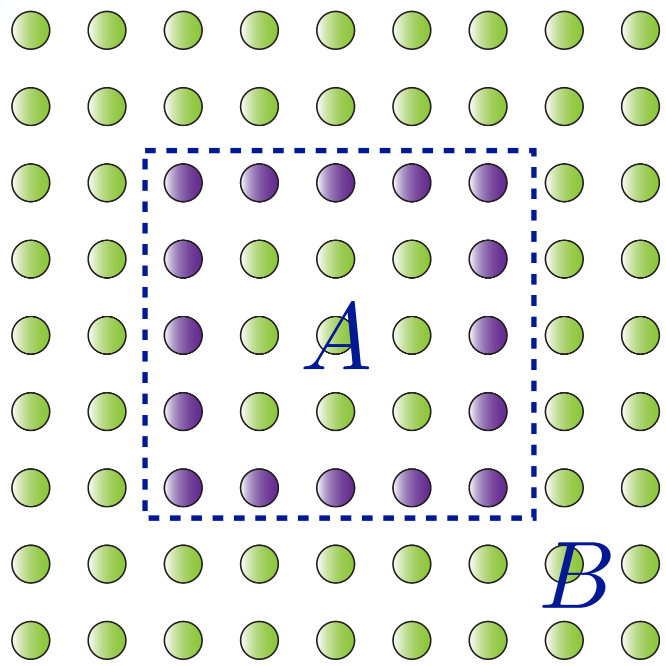




area law $S_{A\max} \propto |\delta A|$

ground states of local Hamiltonians

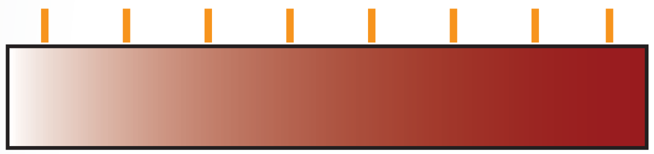
thermal equilibrium

Hastings 2007

Calabrese, Cardy 2004

Wolf, Verstraete, Hastings, Cirac, 2008

arbitrary many-body state



d^N

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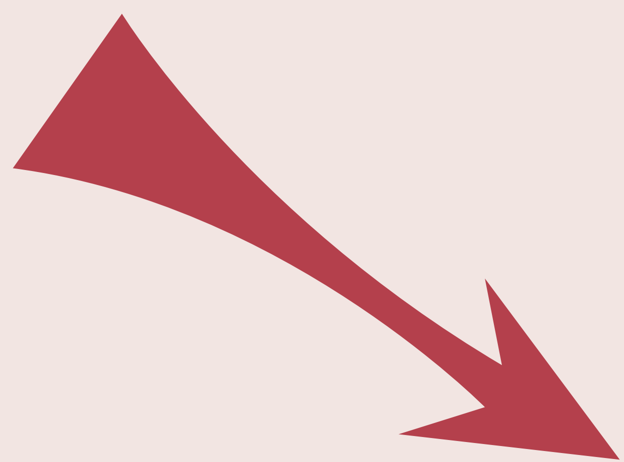
TNS: entanglement-based ansatz

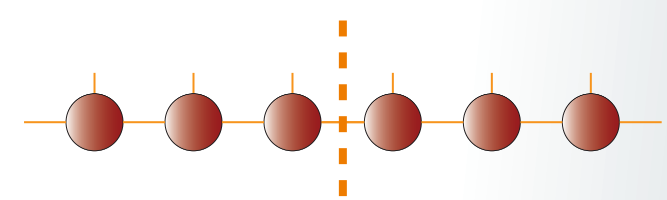
exponential



polynomial

1D: MPS

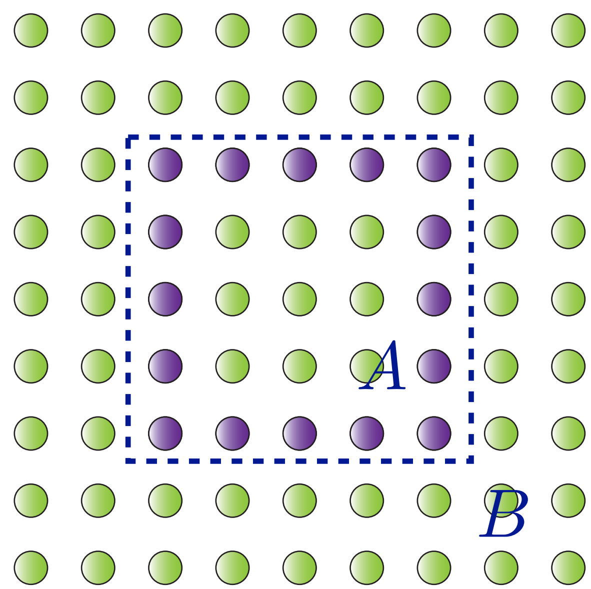
matrix product states



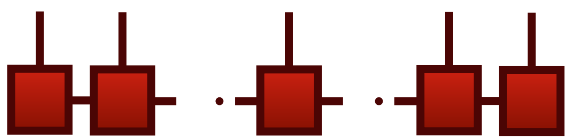
$S \leq \log(D)$

TNS = entanglement based ansatz

area law

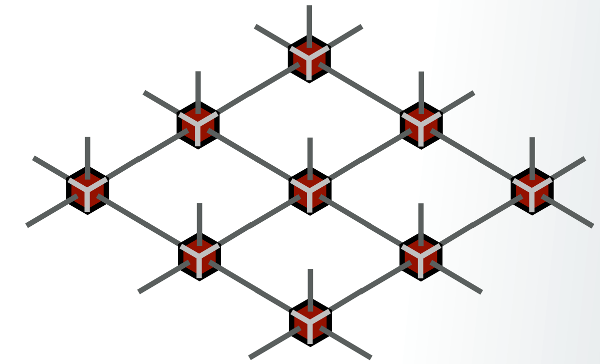


MPS



Schollwöck Ann.Phys.2011

PEPS



Verstraete et al. Adv. Phys. 2008

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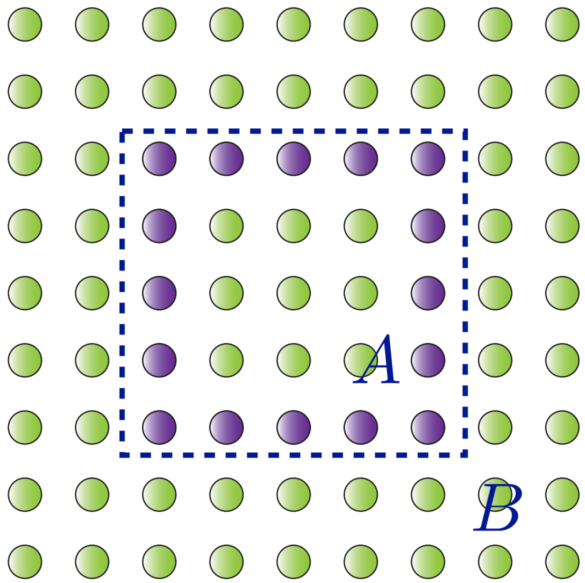
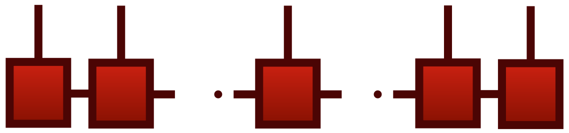
area law



MPS



Schollwöck Ann.Phys.2011

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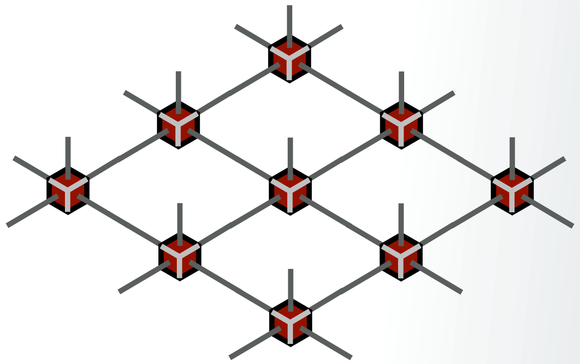


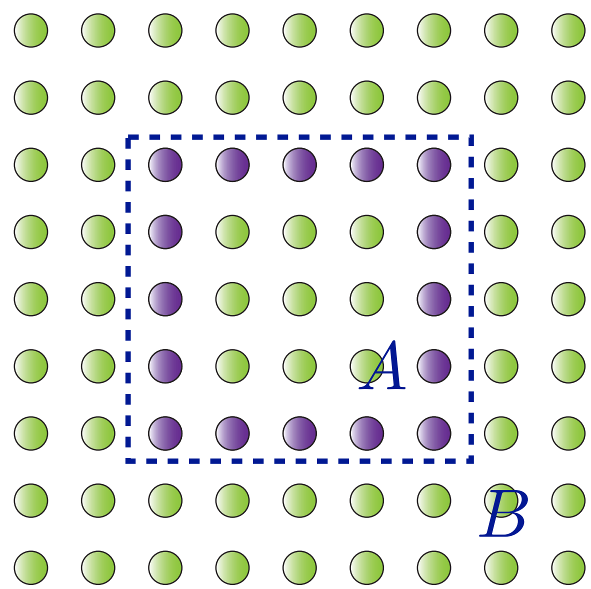
Verstraete et al. Adv. Phys. 2008

other TNS

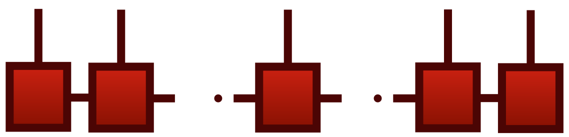
critical 1D
correlations

TNS = entanglement based ansatz

area law

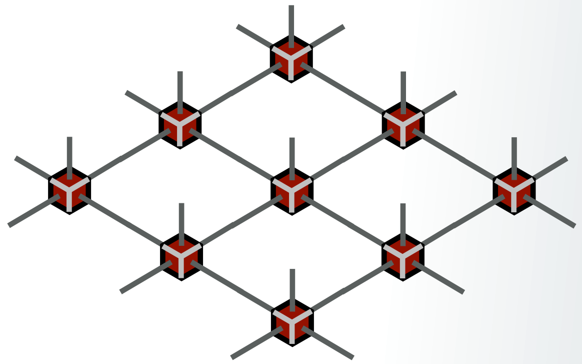


MPS



Schollwöck Ann.Phys.2011

PEPS



Verstraete et al. Adv. Phys. 2008

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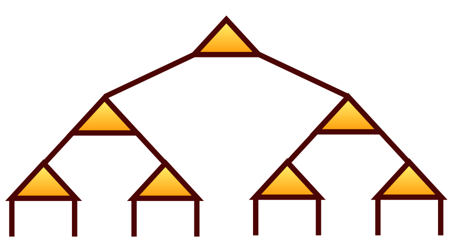
other TNS

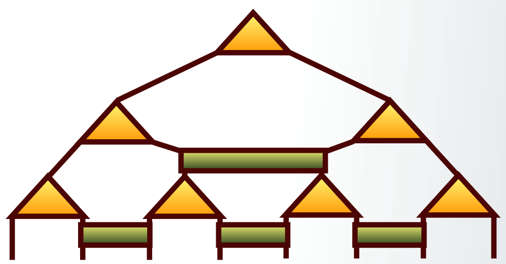
critical 1D correlations

TTN



Shi et al PRA 2006

Vidal PRL 2007 MERA



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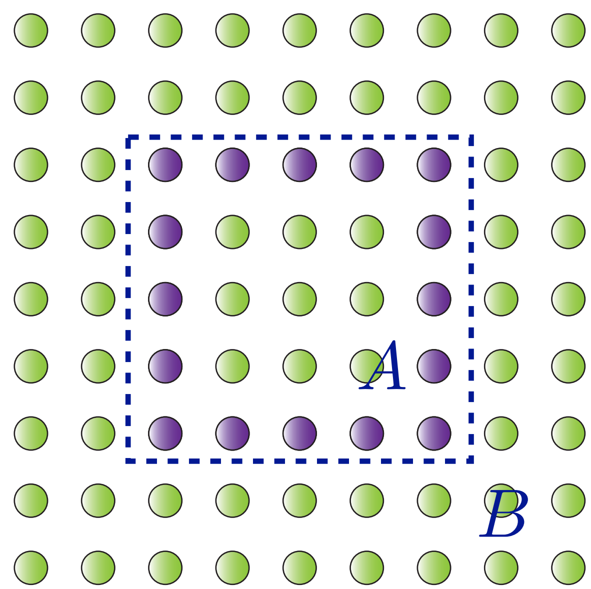

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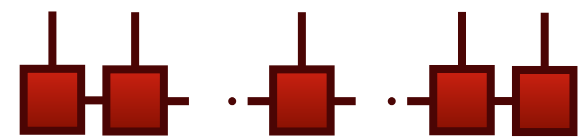

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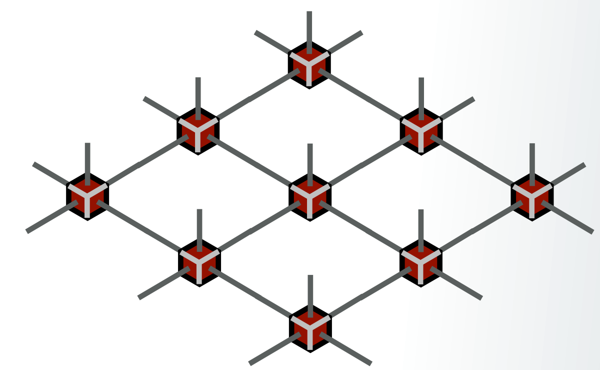

Verstraete et al. Adv. Phys. 2008

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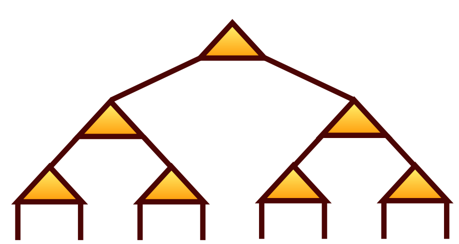
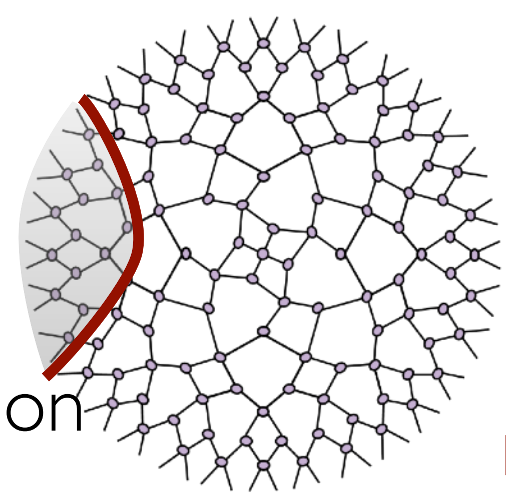
TTN

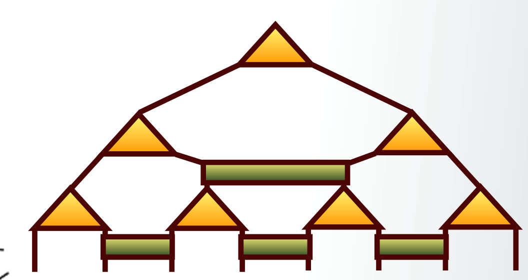


Shi et al PRA 2006



suggested connection to AdS/CFT

Vidal PRL 2007 MERA

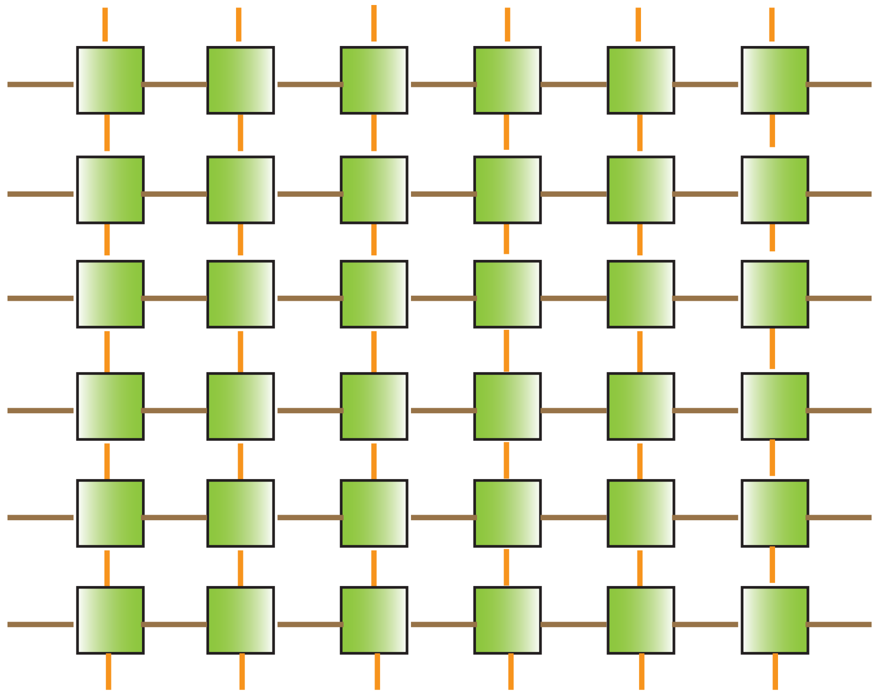


Swingle PRD 2012
Molina JHEP 2013
Nozaki et al JHEP 2012
Bao et al PRD 2015

a side comment

tensor networks may also describe partition functions (observables)

need to contract a TN



Nishino, JPSJ 1995
Levin & Wen PRL 2008
Xie et al PRL2009; Zhao et al PRB 2010

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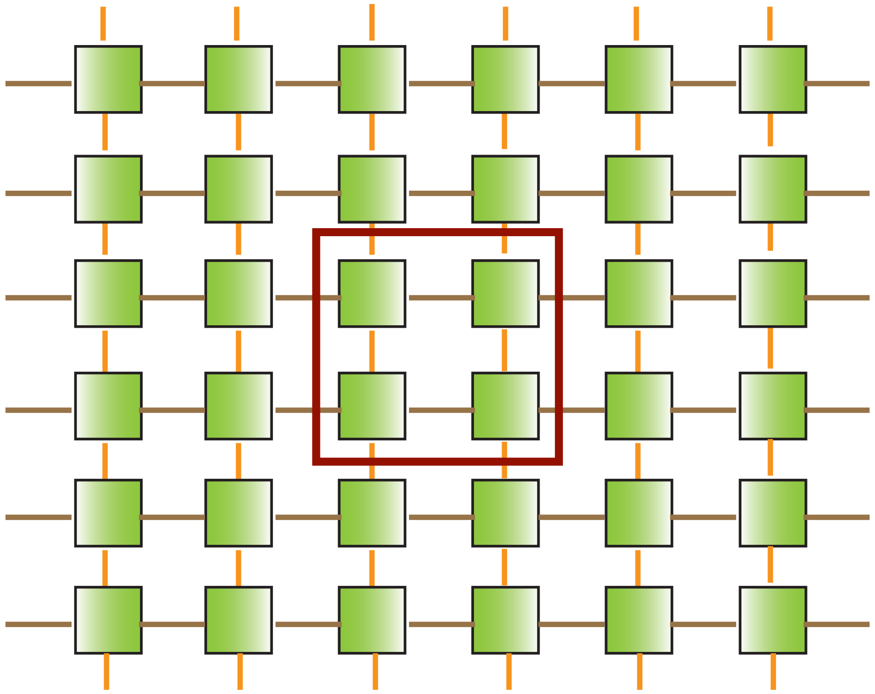

TRG approaches

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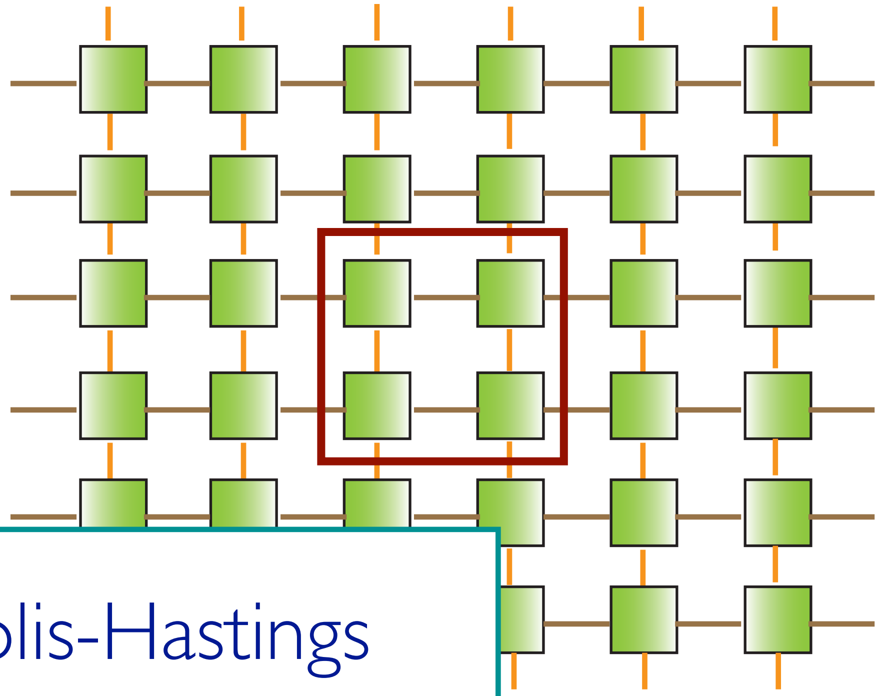
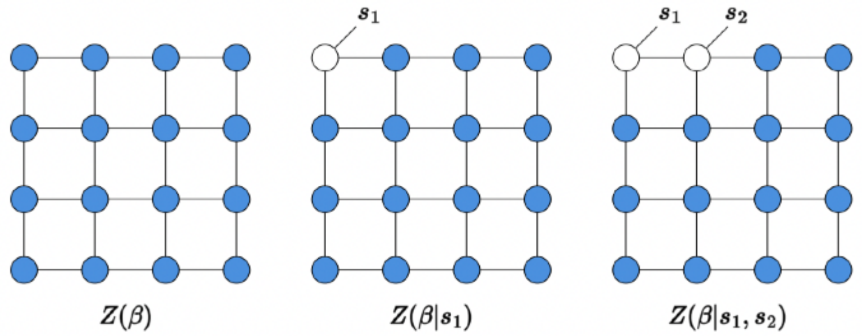


TRG approaches

Nishino, JPSJ 1995
Levin & Wen PRL 2008
Xie et al PRL2009; Zhao et al PRB 2010

TN assisted Metropolis-Hastings

collective updates



Frías-Pérez, Marien, Pérez-García, MCB, Iblisdir, SciPost Phys. 14, 123 (2023)

as ansatz

TNS are very useful in the quantum many-body context

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formal approach

classify tensors (symmetries)

great descriptive power: phases,
topological chiral states, anyons...

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numerical approach

TNS as (variational) ansätze for physical problems

efficient algorithms for GS, low excited states, thermal, dynamics

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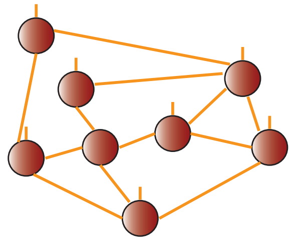
entanglement: crucial ingredient to understand QMB systems

using TNS for QFT



TNS

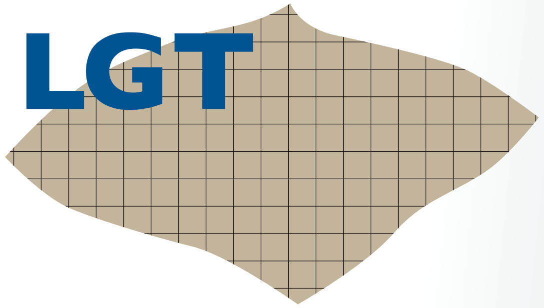
Non-perturbative for Hamiltonian systems

Extremely practical (and successful) for 1D systems (MPS)

Promising improvements for higher dimensions

ground states
low-lying excitations
thermal states
time evolution

apply to



LGT

Photo by Maria Teneva on Unsplash

early works with DMRG/TNS

Byrnes PRD2002; Sugihara NPB2004
Tagliacozzo PRB2011; Sugihara JHEP2005
Meurice PRB2013

MCB, K. Cichy 1910.00257
QTFLAG Collab.1911.00003

Photo by Maria Teneva on Unsplash

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Tagliacozzo PRB2011; Sugihara JHEP2005
Meurice PRB2013

Schwinger model
U(1) in 1D

precise equilibrium simulations, feasibility of QSim

MCB et al JHEP11(2013)158;
Rico et al PRL 2014; Buyens et al. PRL 2014;
Kühn et al., PRA 90, 042305 (2014);
MCB et al PRD 2015, Buyens et al. PRD 2016;
Pichler et al. PRX 2016;
review Dalmonte, Montangero, Cont. Phys. 2016
MCB, Cichy, Cirac, Jansen, Kühn, arXiv:1810.12838

MCB, K. Cichy 1910.00257
QTFLAG Collab.1911.00003

3+1 dimensions

Magnifico et al. Nat. Com.12, 3600 (2021)

2+1 dimensions

Felser et al. PRX10, 041040 (2020)
Robaina et al. PRL126, 050401 (2021)
Emonts et al. PRD102, 074501 (2020)

Non-Abelian in 1D

string breaking dynamics

S. Kühn et al., JHEP 07 (2015) 130;
Silvi et al., Quantum 2017
S. Kühn et al. PRX 2017

SU(3)QLM

Silvi et al, PRD 2019

finite density

S. Kuehn et al, PRL118 (2017) 071601

finite density

spectrum

entropy

1+1D RESULTS

thermal equilibrium

time evolution

finite density

spectrum

entropy

1+1D RESULTS

thermal equilibrium

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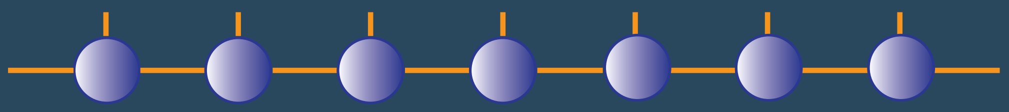
$|E_0\rangle \approx$ 

continuum limit: very precise masses for U(1), SU(2)

different techniques demonstrate suitability of the ansatz

MCB, Cichy, Cirac, Jansen JHEP11(2013)158
Buyens et al. PRL113 (2014) 091601
MCB, Cichy, Cirac, Jansen, Kühn PRX 7, 041046 (2017)

finite density

spectrum

entropy

1+1D RESULTS

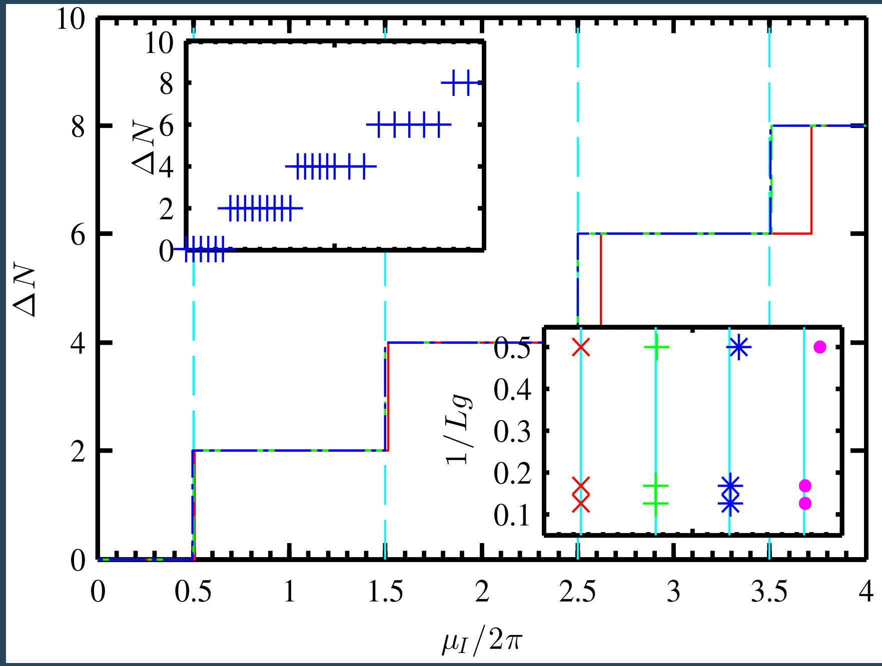
thermal equilibrium

time evolution

finite density

Schwinger model with several flavours and chemical potentials (continuum)

S. Kühn et al, PRL118 (2017) 071601



finite density

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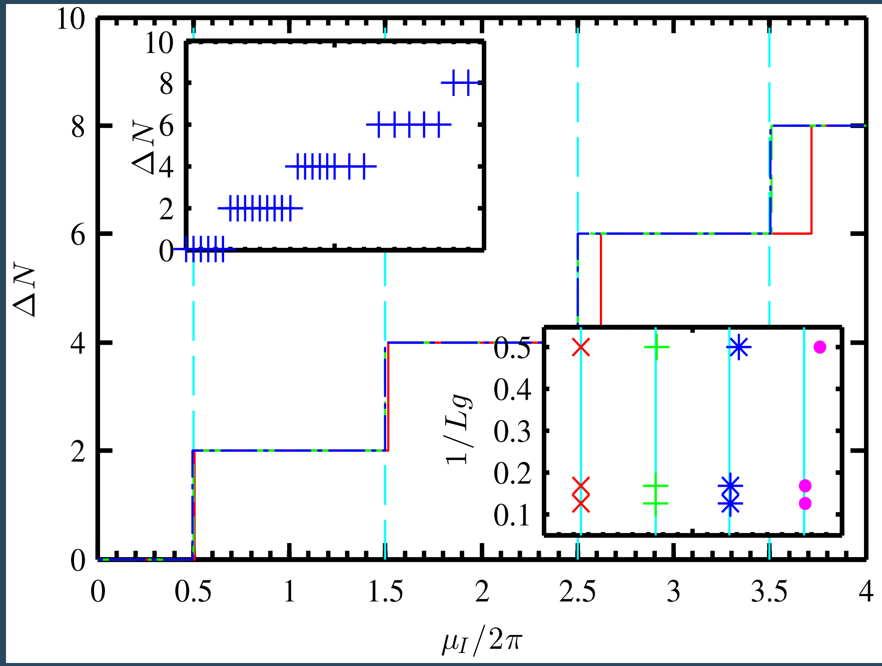
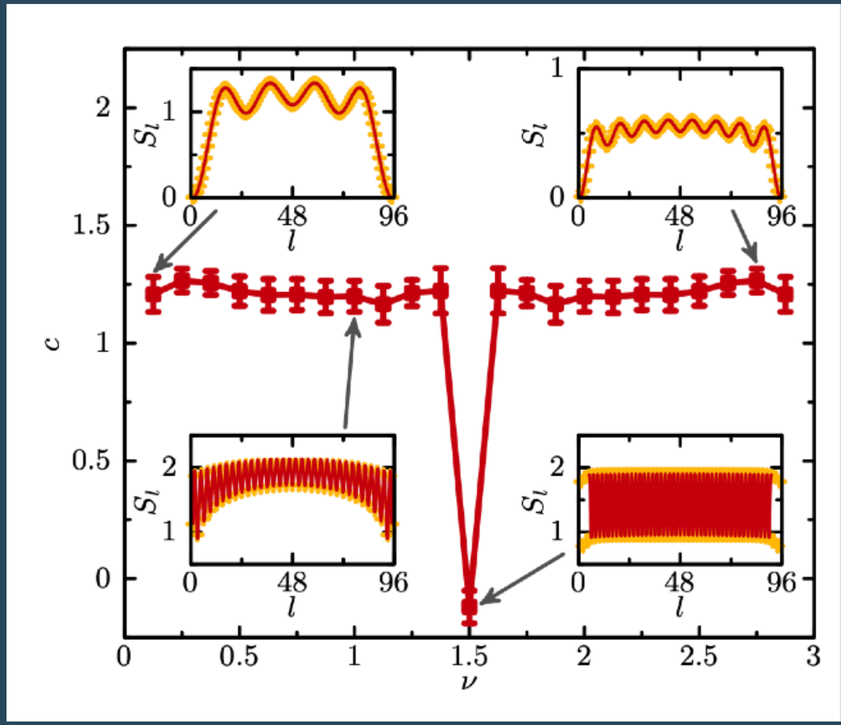
S. Kühn et al, PRL118 (2017) 071601





phase diagram of SU(2) and SU(3) QLM at finite density

Silvi et al, Quantum 1, 9 (2017)
PRD100, 074512 (2019)

some results in 2+1, 3+1 U(1)

finite density

spectrum

entropy

1+1D RESULTS

thermal equilibrium

time evolution

gauge constraints not purely local ⇒ not all entropy physical

Casini et al 2014; Gosh et al JHEP 2015
Soni, Trivedi JHEP 2016; van Acoleyen et al PRL 2016

entropy

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Casini et al 2014; Gosh et al JHEP 2015
Soni, Trivedi JHEP 2016; van Acoleyen et al PRL 2016

entropy

divergence in the continuum limit

$$S \propto \frac{c}{6} \log_2 \frac{\xi}{a}$$

Calabrese, Cardy JStatMech 2004

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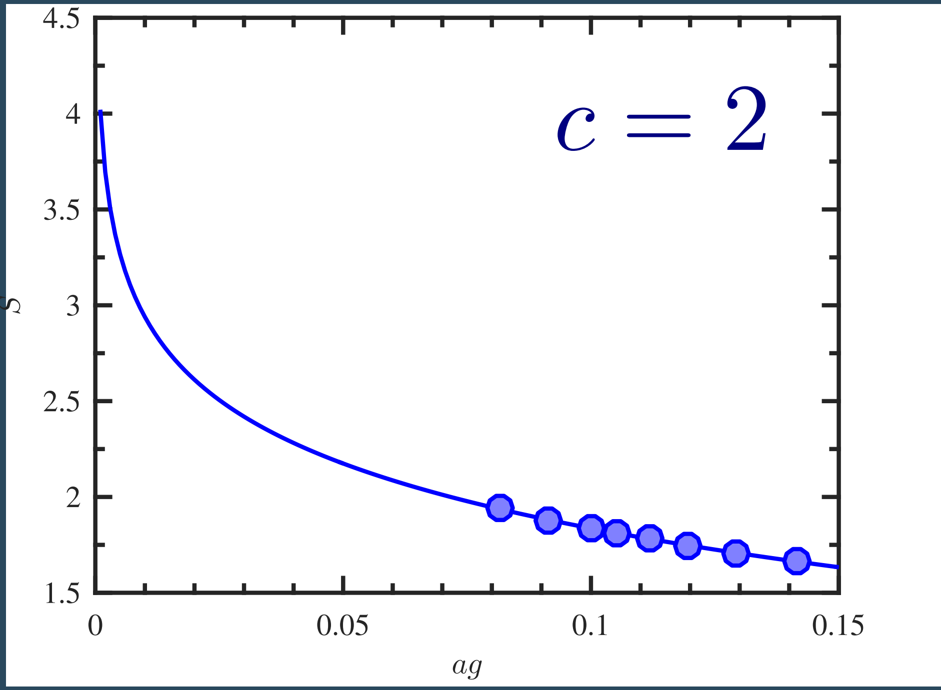
Casini et al 2014; Gosh et al JHEP 2015
Soni, Trivedi JHEP 2016; van Acoleyen et al PRL 2016

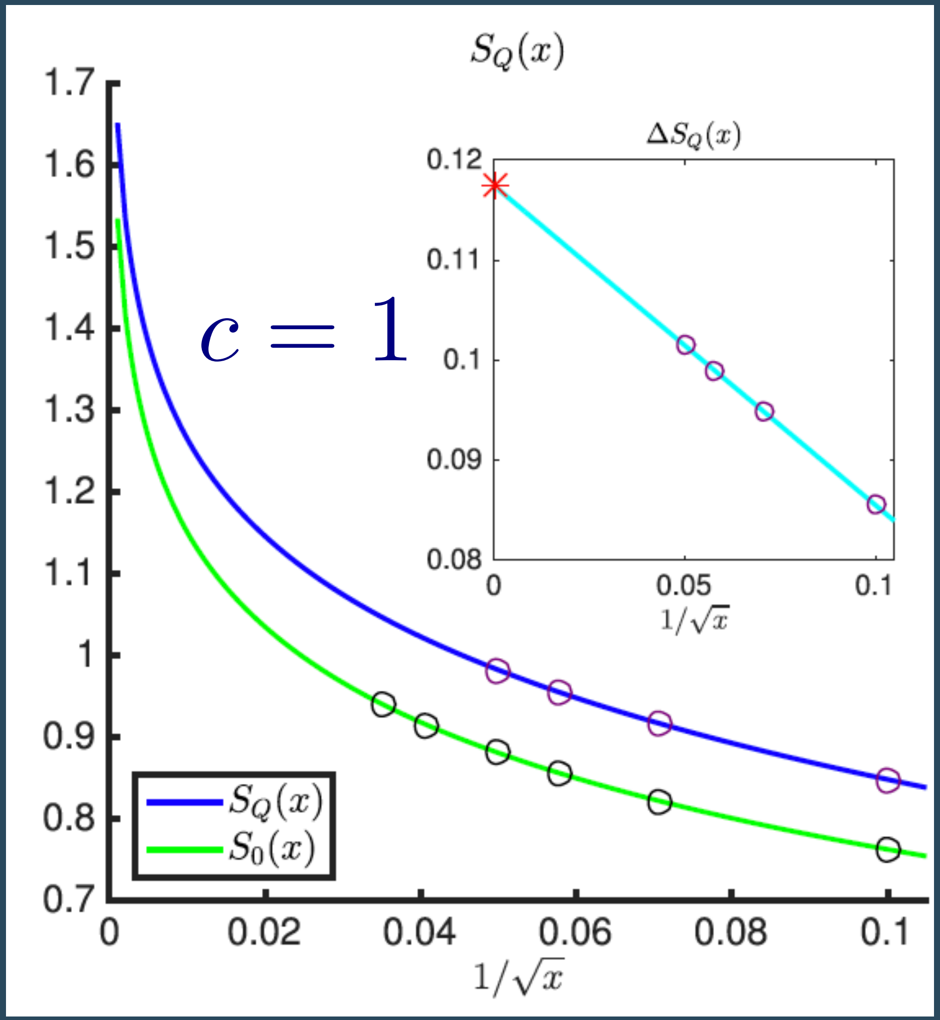
SU(2)



Kühn PRX7, 041046 (2017)

entropy

Schwinger



Buyens PRX6, 041040 (2016)

divergence in the continuum limit

$$S \propto \frac{c}{6} \log_2 \frac{\xi}{a}$$

Calabrese, Cardy JStatMech 2004

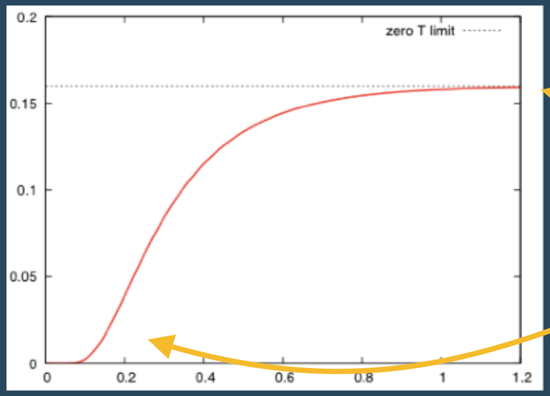
1+1D RESULTS

- spectrum
- finite density
- entropy
- thermal equilibrium
- time evolution

thermal properties Schwinger

chiral condensate at finite T: analytical for *m*/*g*=0

Sachs, Wipf 92



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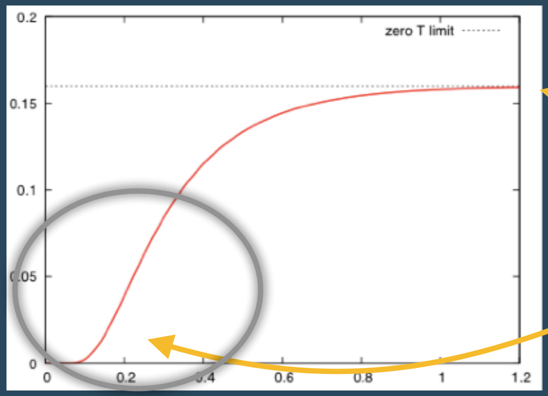
Sachs, Wipf 92

Σ/g



$T \to 0$

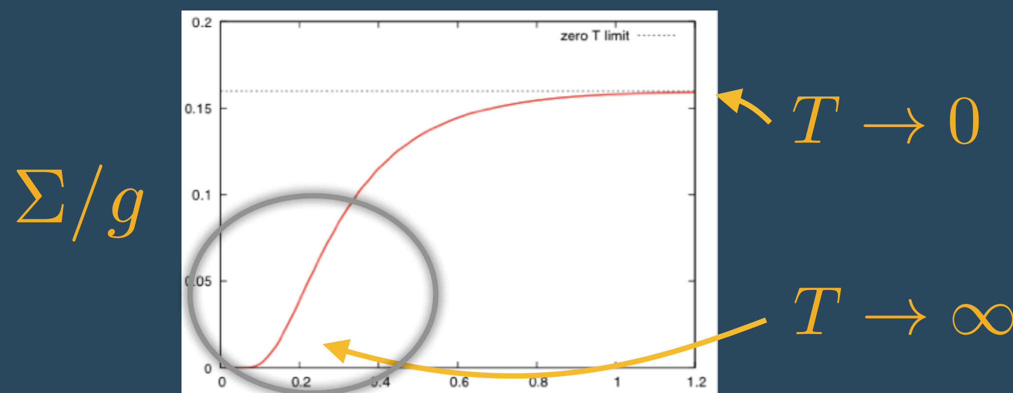
$T \to \infty$

smooth restoration of chiral symmetry

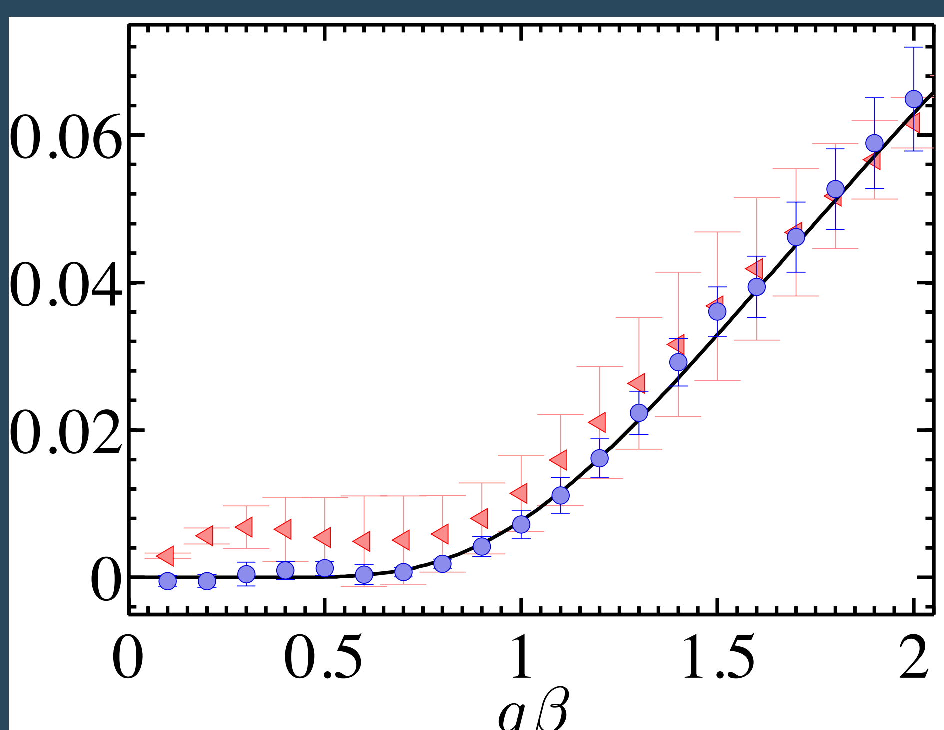
thermal properties Schwinger

chiral condensate at finite T: analytical for $m/g=0$

Sachs, Wipf 92



smooth
restoration of
chiral symmetry



PRD 92, 034519 (2015); PRD 93, 094512 (2016)

thermal properties Schwinger

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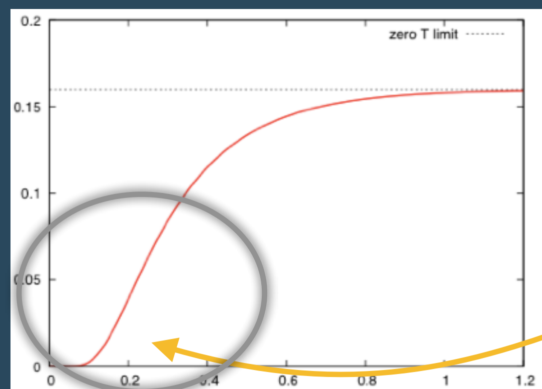
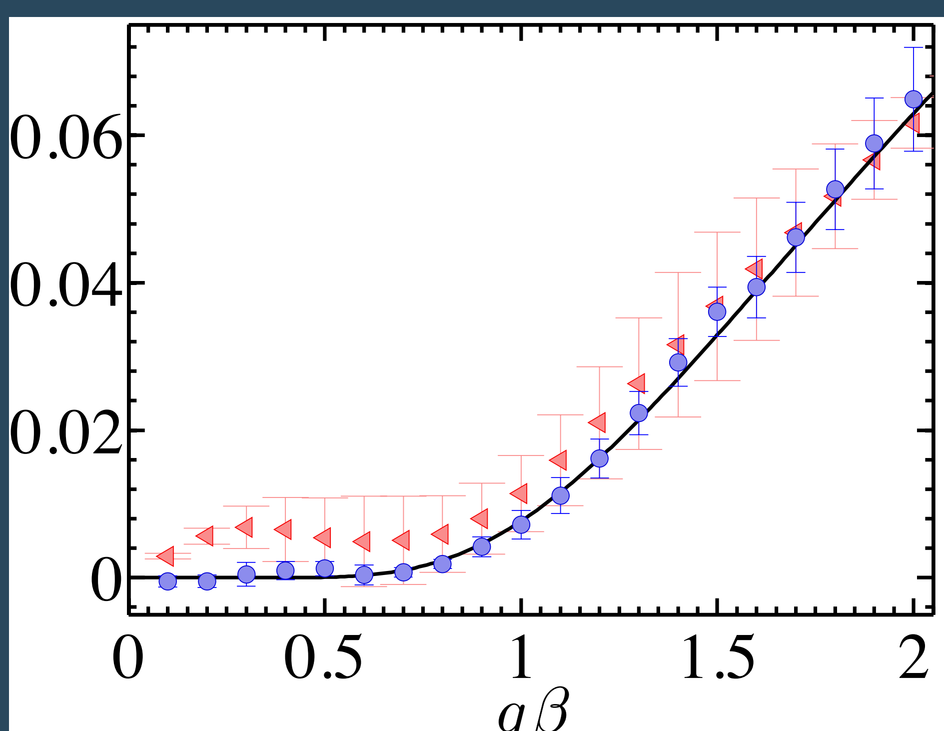
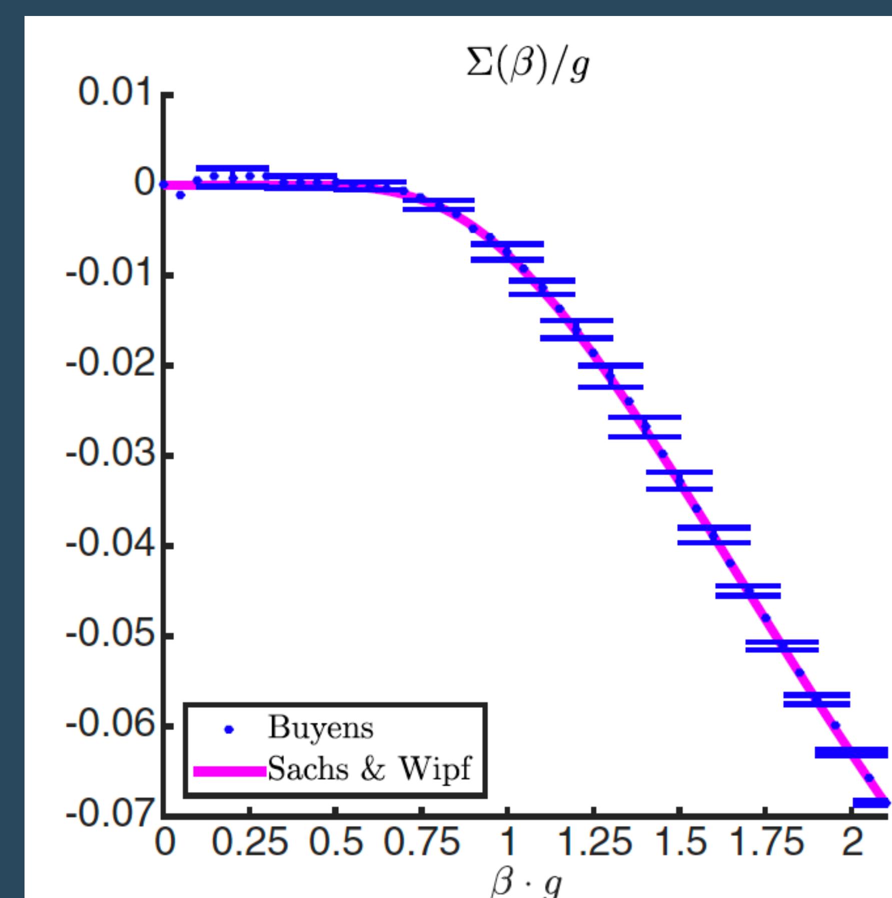


smooth
restoration of
chiral symmetry

Sachs, Wipf 92



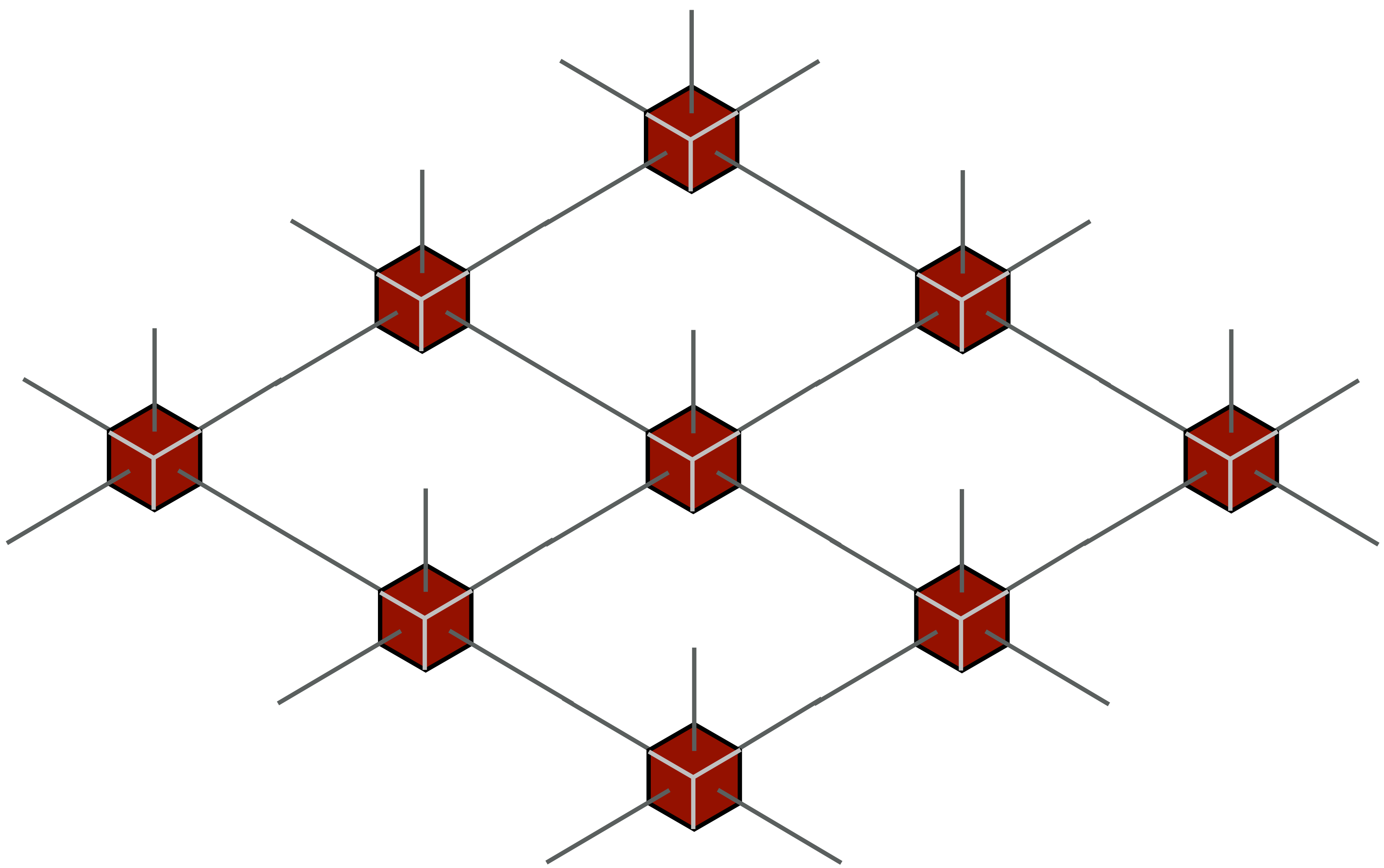
PRD 92, 034519 (2015); PRD 93, 094512 (2016)

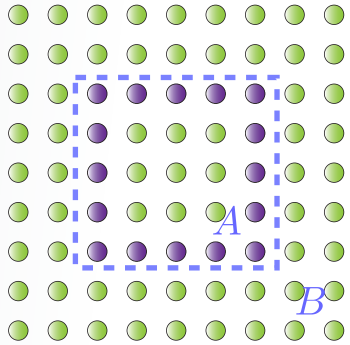


Buyens PRD 94, 085018 (2016)

beyond 1D

PEPS

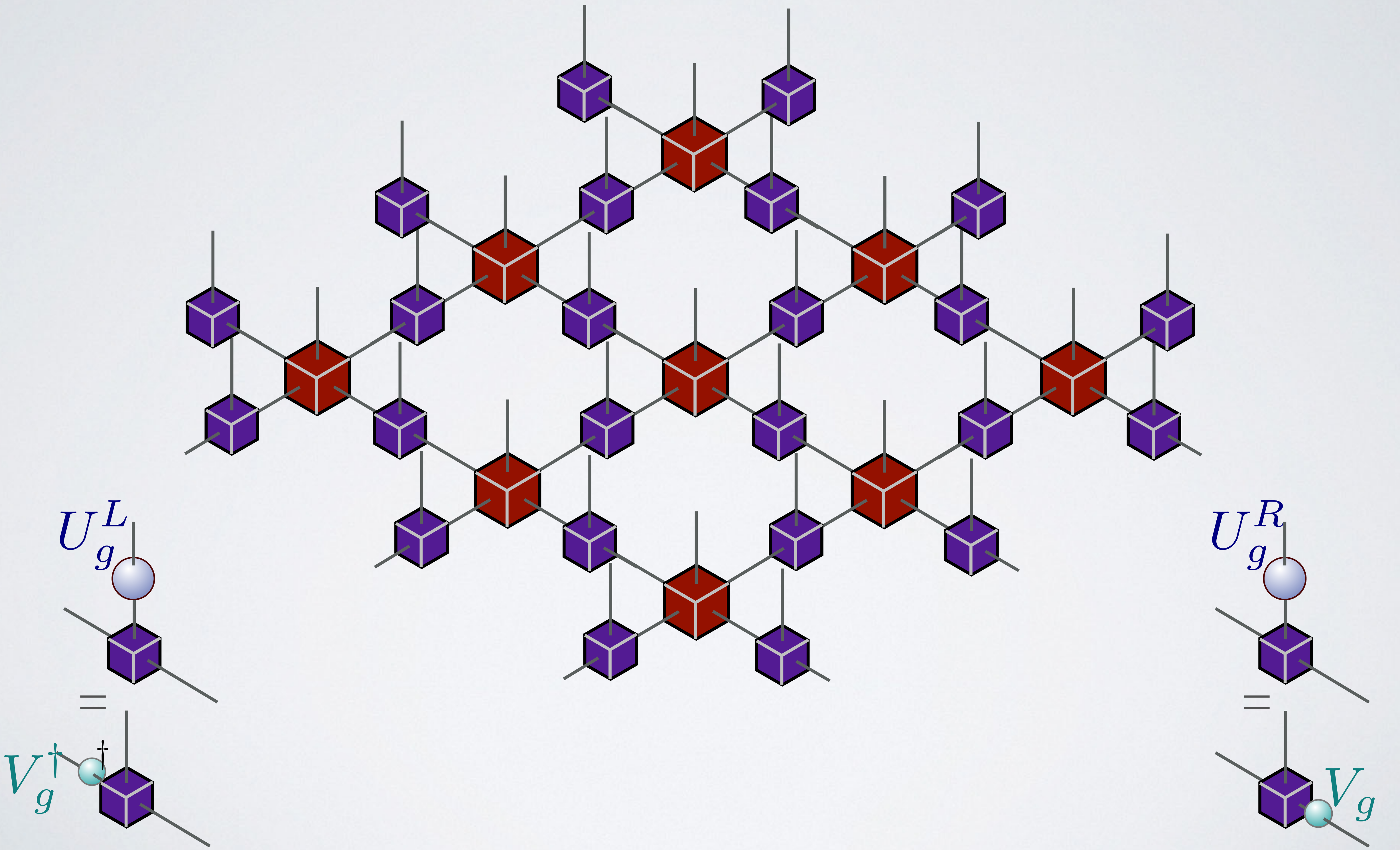




area law by construction

Verstraete, Cirac, 2004

GAUGING PEPS



In summary: TNS…

efficient numerical algorithms (small spatial dimensions) and good theoretical understanding

non-technical review: Annu Rev. CMP 2023 14:1; arXiv:2205.10345

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work well for GS, low energy, thermal equilibrium

related to area laws

In summary: TNS…

efficient numerical algorithms (small spatial

dim … ing

2023 14:1;

wor … ium

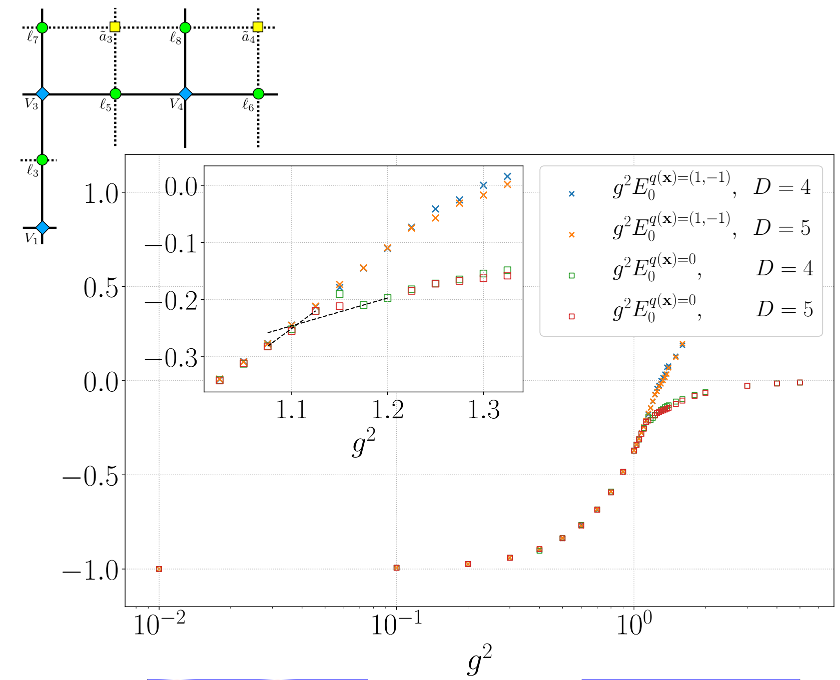
suitable for LGT

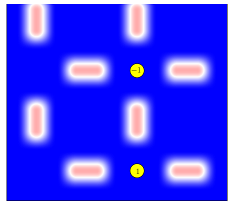
systematically explored in 1+1D

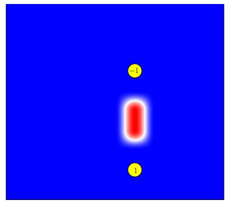
MCB, Cichy, ROPP (2020)
QTFLAG Coll. EPJD (2020)

results in higher dimensions

Robaina et al PRL 2021
Magnifico et al. Nat. Com. (2021)







In summary: TNS…

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non-technical review: Annu Rev. CMP 2023 14:1; arXiv:2205.10345

work well for GS, low energy, thermal equilibrium

related to area laws

but so much for high energy eigenstates, quenches

Osborne, PRL 2006
Schuch *et al.*, NJP 2008

Vidmar *et al.*, PRL 2017

volume law

In summary: TNS…

efficient numerical algorithms (small spatial dimensions) and good theoretical understanding

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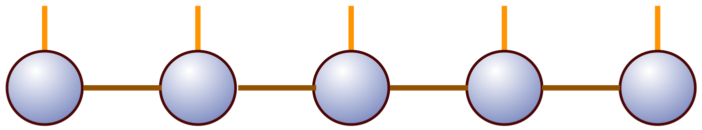
Osborne, PRL 2006
Schuch *et al.*, NJP 2008
Vidmar *et al.*, PRL 2017

volume law

new tools may allow us to access some of these regimes real time

real time evolution with MPS

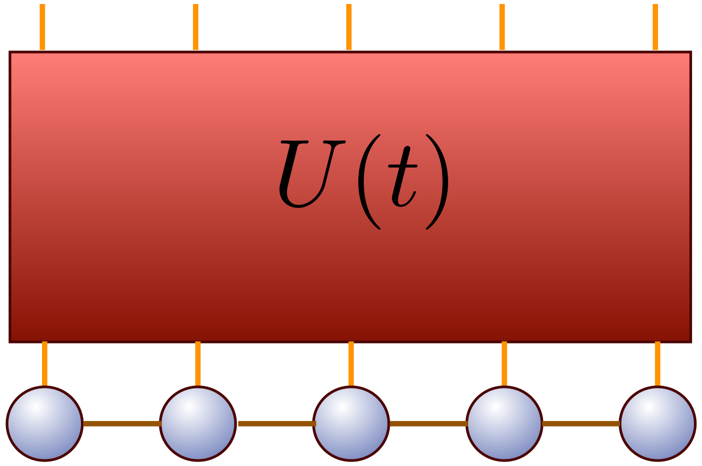


TEBD, t-DMRG

Vidal, PRL 2003, 2004

Verstraete, García-Ripoll, Cirac, PRL 2004

real time evolution with MPS



TEBD, t-DMRG

Vidal, PRL 2003, 2004

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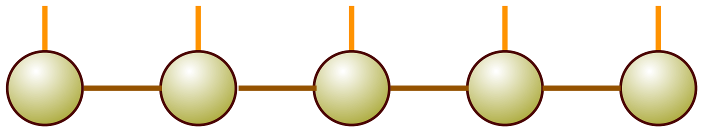
time evolved state approximated by MPS

real time evolution with MPS



TEBD, t-DMRG

Vidal, PRL 2003, 2004

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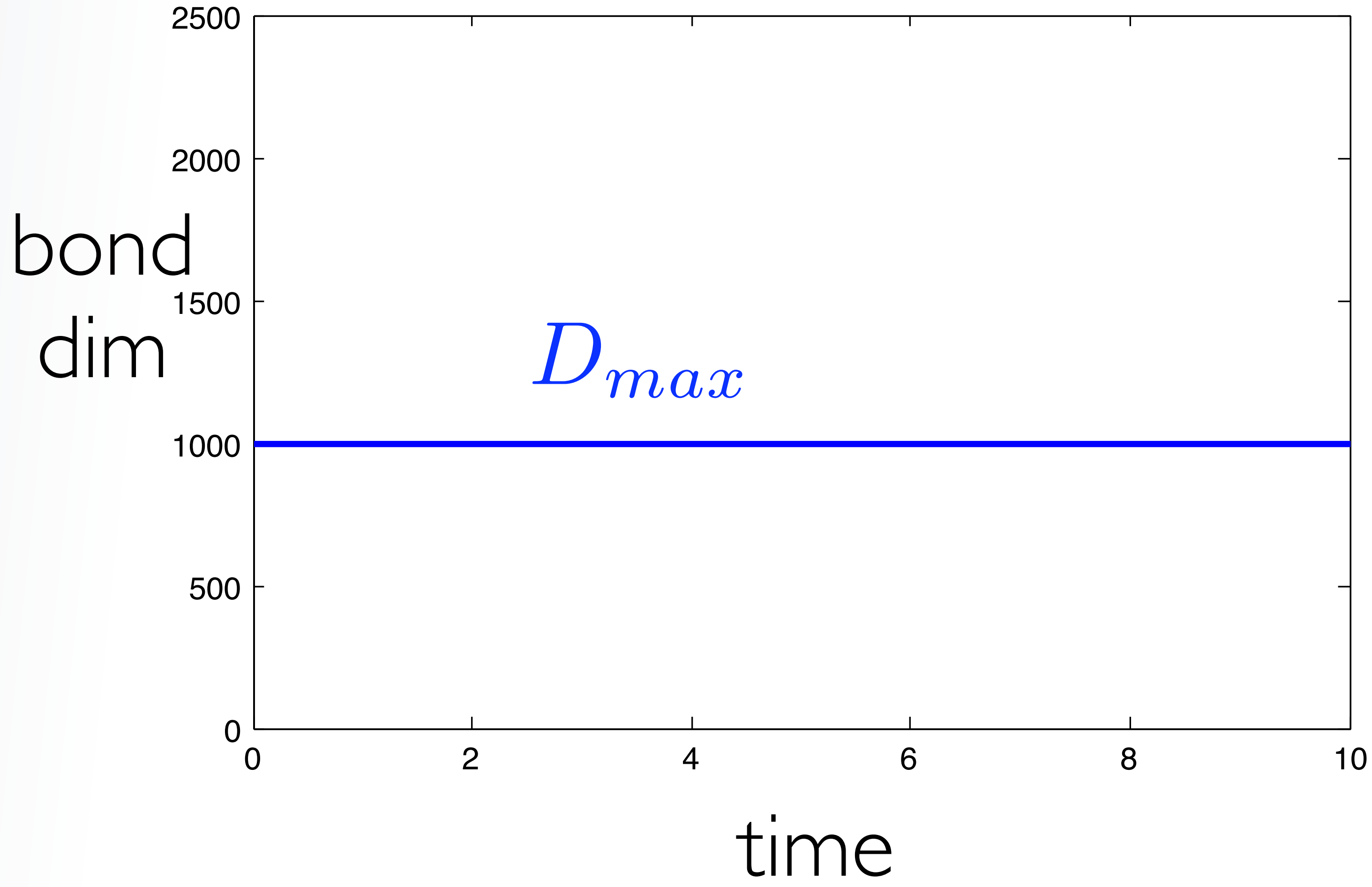
time evolved state approximated by MPS

but entanglement grows

Osborne, PRL 2006
Schuch et al., NJP 2008



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Osborne, PRL 2006
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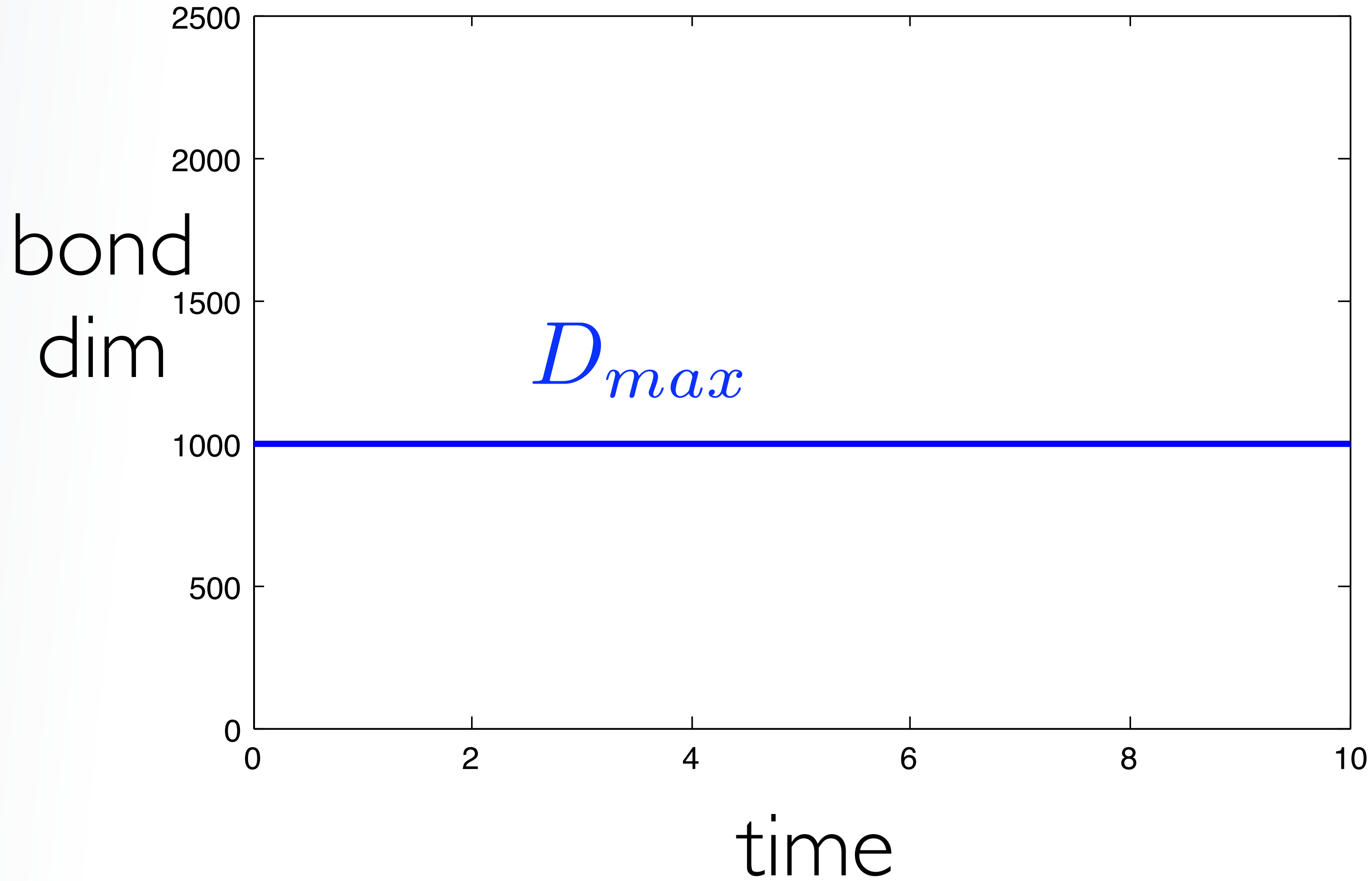
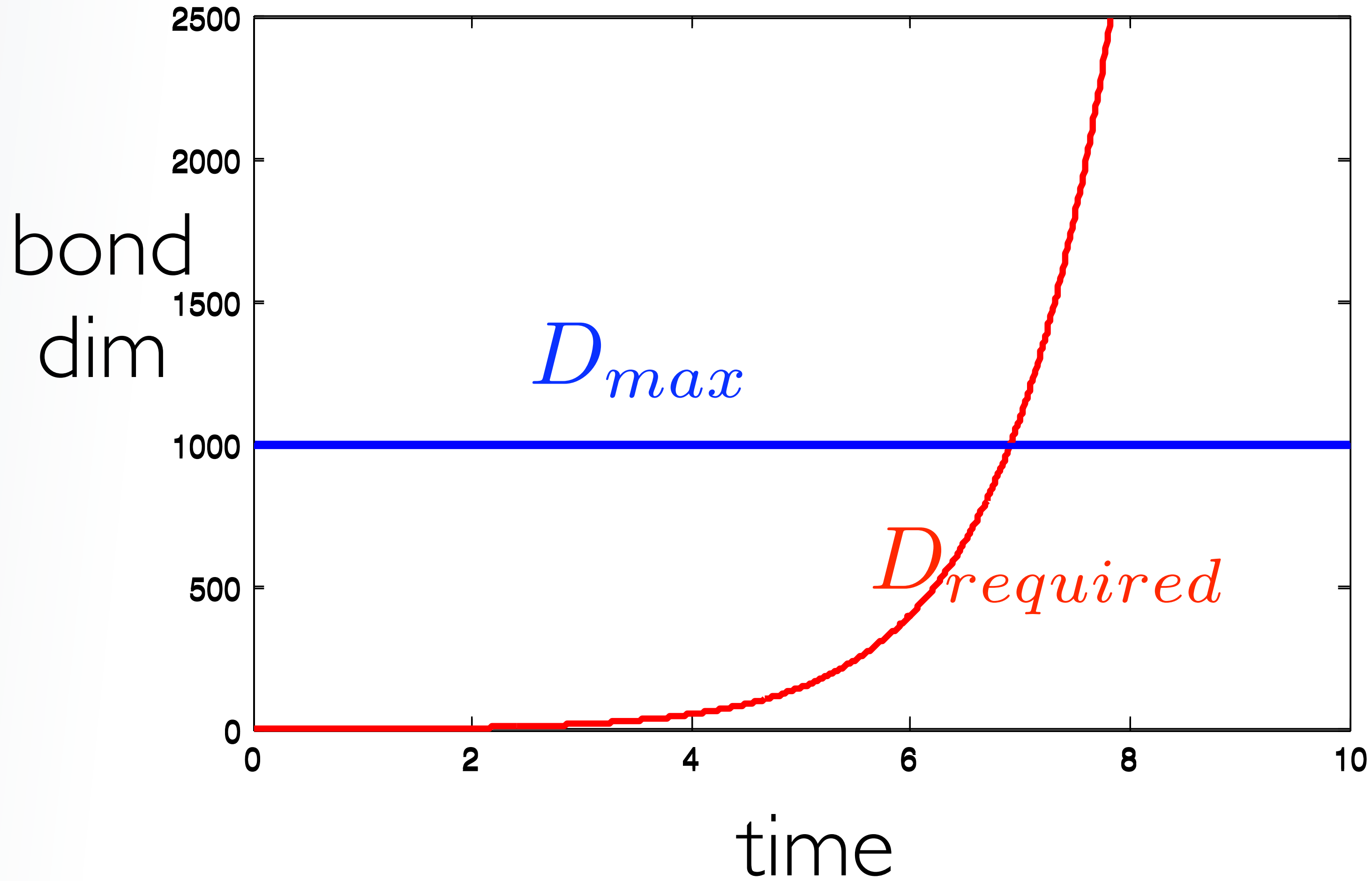


required bond for fixed precision

$$D \sim e^{\alpha t}$$

but entanglement grows

Osborne, PRL 2006
Schuch et al., NJP 2008



required bond for fixed precision

$$D \sim e^{\alpha t}$$

yet many physical situations (in closed and open quantum systems) can be successfully studied!

García-Ripoll, NJP 2006
Wall, Carr NJP 2012
Paeckel et al arXiv:1901.05824

yet many physical situations (in closed and open quantum systems) can be successfully studied!

short times, adiabatic, low energy can work well

García-Ripoll, NJP 2006
Wall, Carr NJP 2012
Paeckel et al arXiv:1901.05824

Standard evolution algorithms for LGT

Reliable for moderate times, or in some setups

Useful for quantum simulation

S. Kühn et al., Phys. Rev. A 90, 042305 (2014)
S. Kühn et al., JHEP 07 (2015) 130
Buyens et al., PRL 2014; PRX 2016
Rico et al., PRL 2014; NJP 2014; PRX 2016

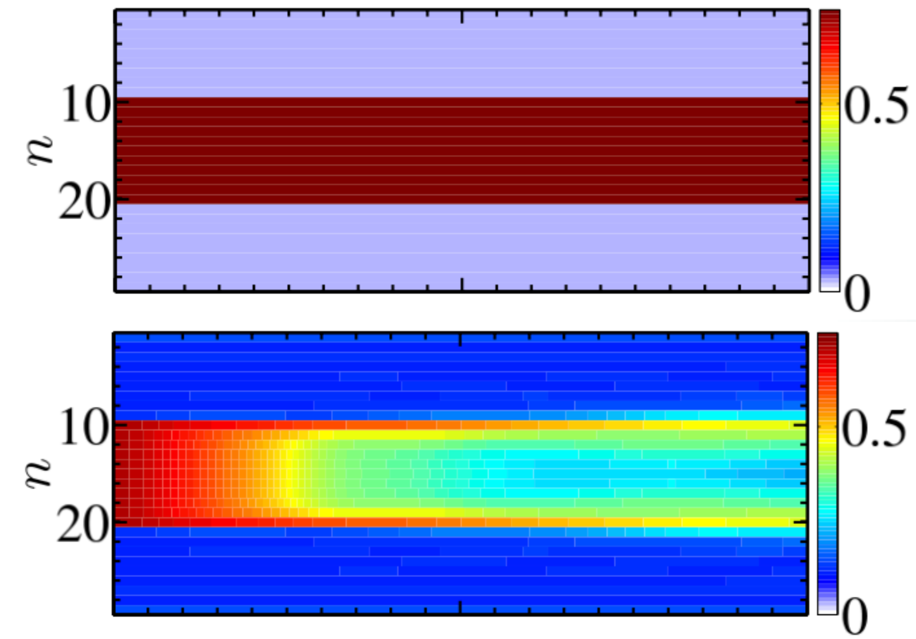
No full continuum extrapolation yet, but results near the continuum limit

string breaking

Non-Abelian string breaking phenomena with matrix product states

JHEP07(2015)130

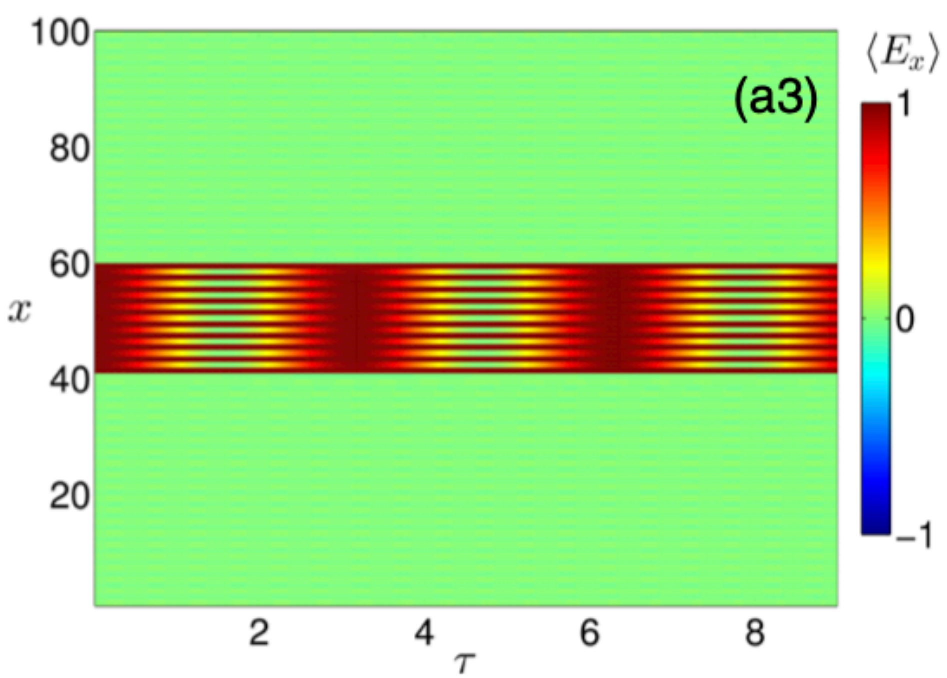
Stefan Kühn, Erez Zohar, J. Ignacio Cirac and Mari Carmen Bañuls

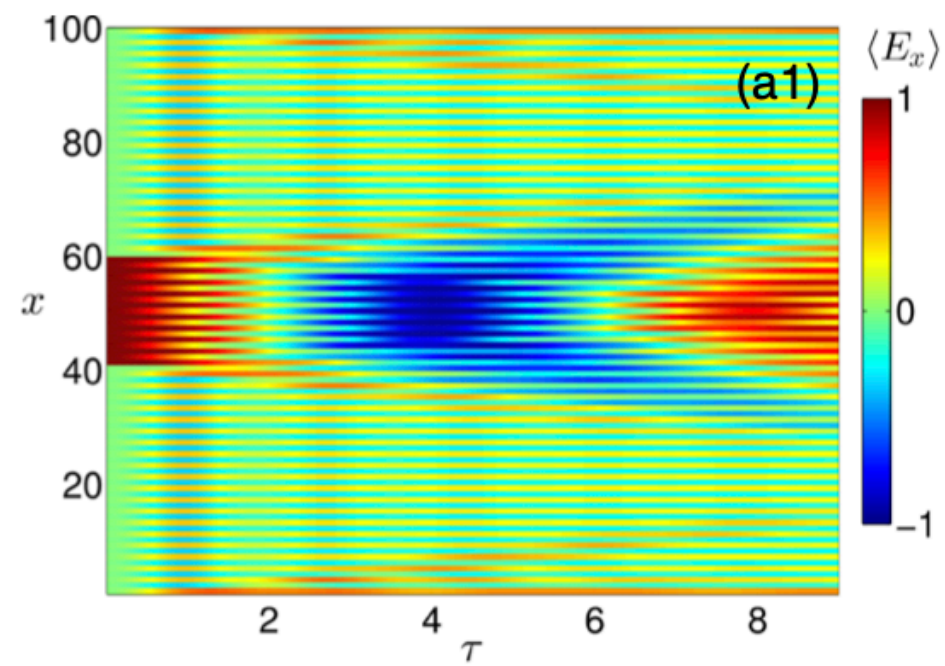


PHYSICAL REVIEW X **6,** 011023 (2016)

Real-Time Dynamics in U(1) Lattice Gauge Theories with Tensor Networks

T. Pichler,[1] M. Dalmonte,[2,3] E. Rico,[4,5,6] P. Zoller,[2,3] and S. Montangero[1]





quench scenario

Interacting vacuum (TI)

switch on background electric field α

$\Rightarrow$ pair production

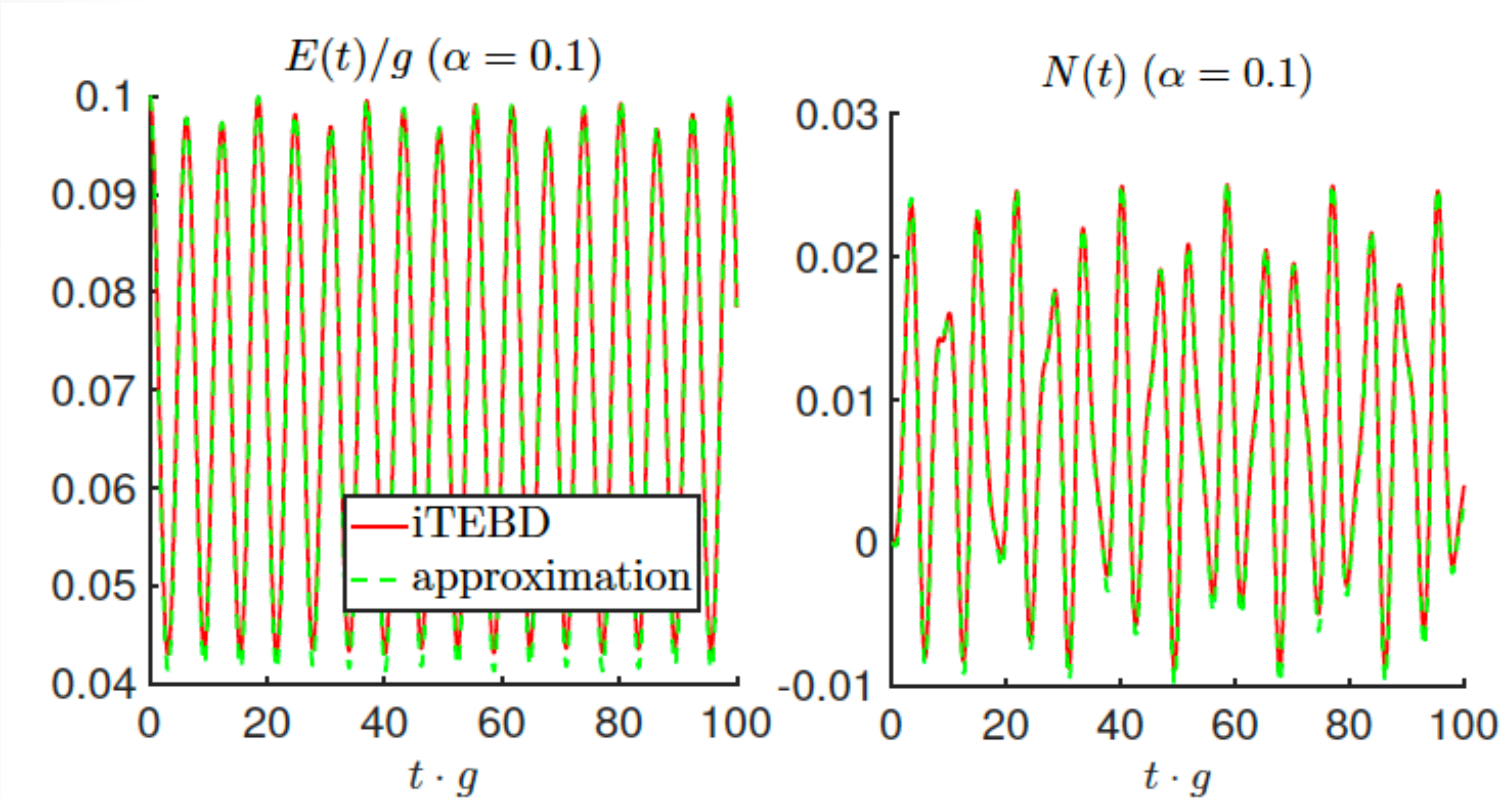
iTEBD evolution

PHYSICAL REVIEW D **96,** 114501 (2017)

Real-time simulation of the Schwinger effect with matrix product states

Boye Buyens,[1] Jutho Haegeman,[1] Florian Hebenstreit,[2] Frank Verstraete,[1,3] and Karel Van Acoleyen[1]

quench scenario



weak field

PHYSICAL REVIEW D **96,** 114501 (2017)

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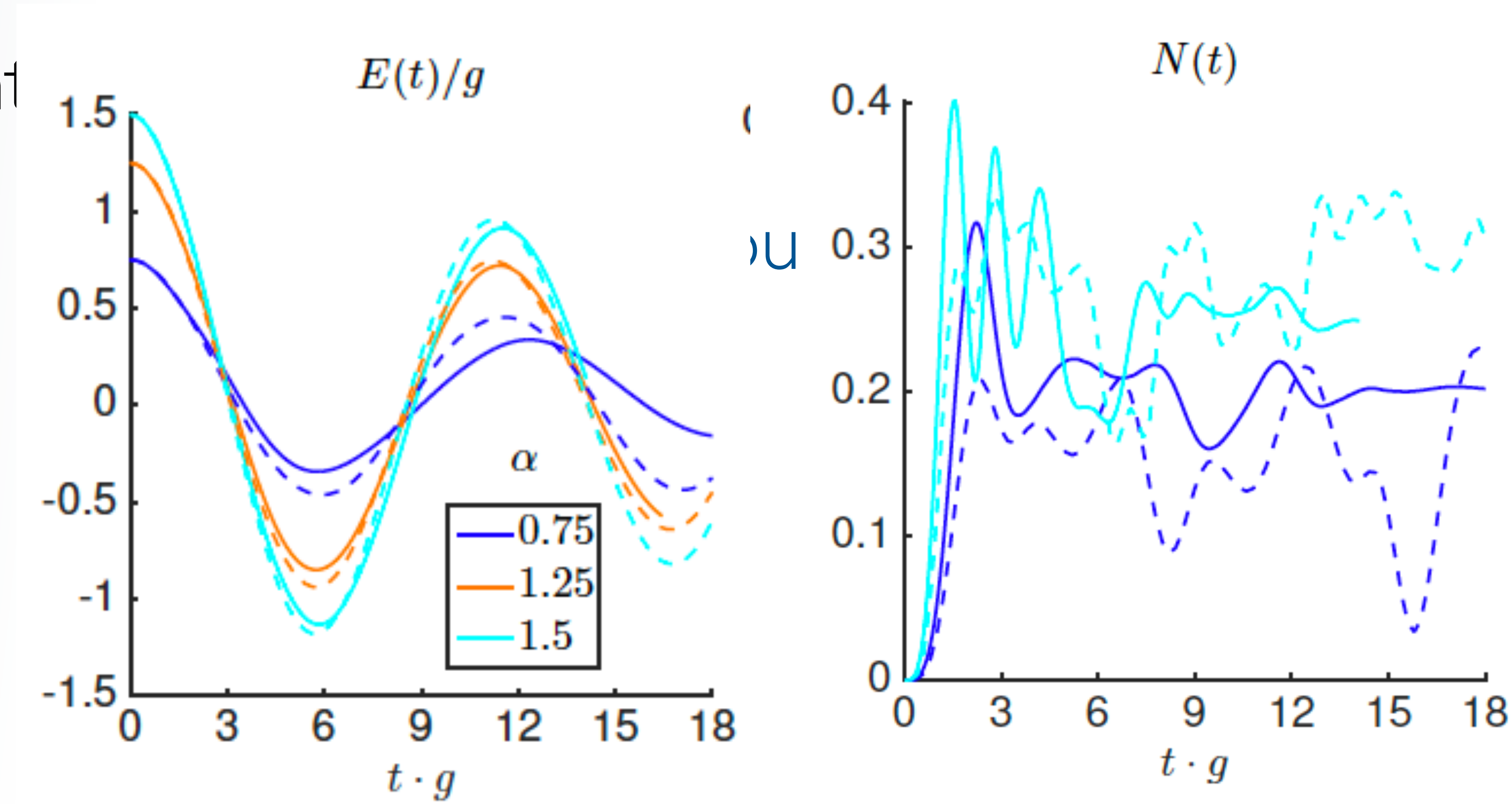

strong field

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scattering in the Schwinger model

with I. Papaefstathiou, J. Knolle, arXiv:2402.18429

scattering with MPS

uMPS formalism provides ansatz for quasiparticles

PHYSICAL REVIEW B **92**, 125136 (2015)

Scattering particles in quantum spin chains

Laurens Vanderstraeten,[1] Frank Verstraete,[1,2] and Jutho Haegeman[1]

PHYSICAL REVIEW RESEARCH **3**, 013078 (2021)

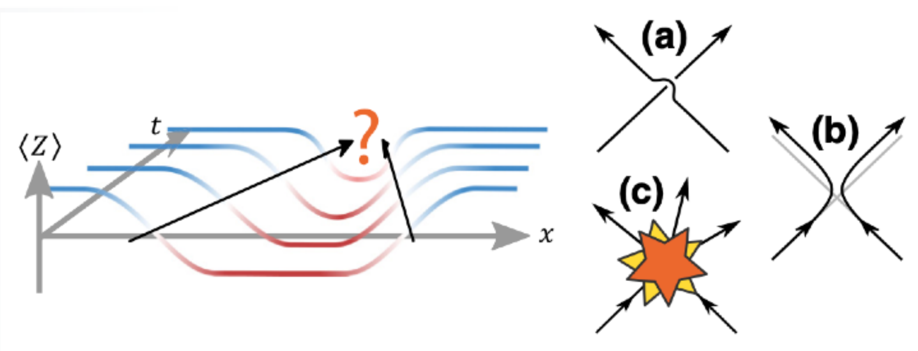
Real-time scattering of interacting quasiparticles in quantum spin chains

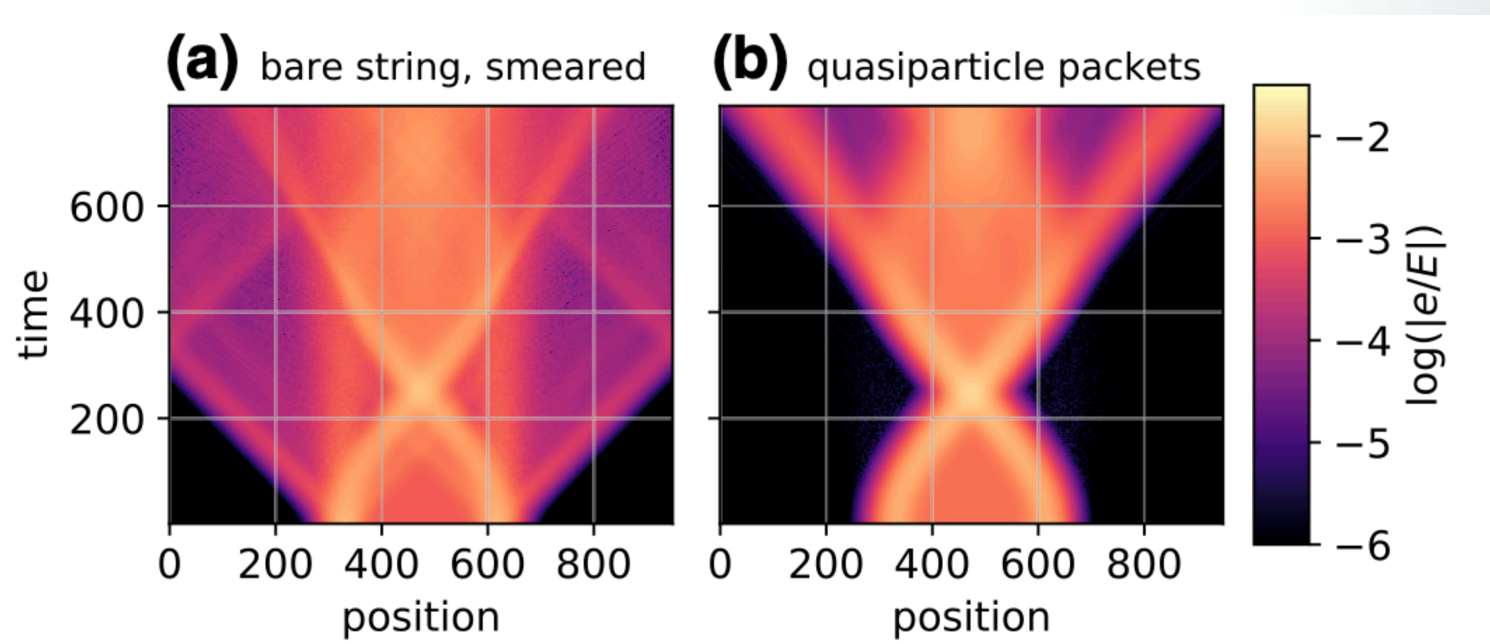
Maarten Van Damme,[*] Laurens Vanderstraeten, Jacopo De Nardis, Jutho Haegeman, and Frank Verstraete

PRX QUANTUM **3**, 020316 (2022)

Collisions of False-Vacuum Bubble Walls in a Quantum Spin Chain

Ashley Milsted,[1,2,3,4,*,‡] Junyu Liu,[1,2,†] John Preskill,[1,2,4,‡] and Guifre Vidal[3,5]





scattering in LGT

PHYSICAL REVIEW X **6,** 011023 (2016)

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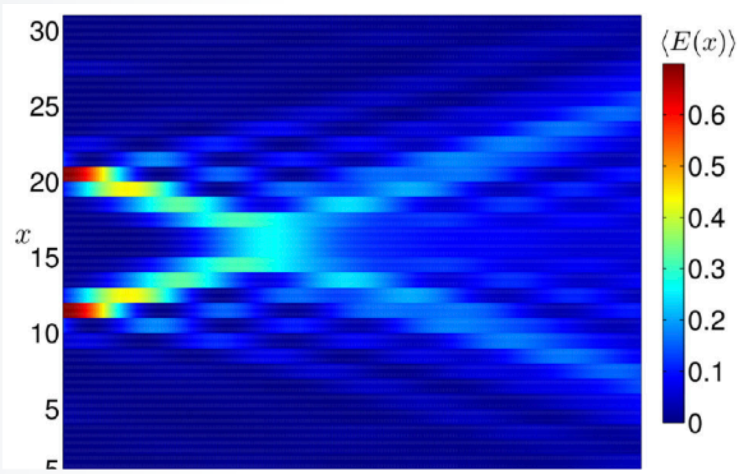
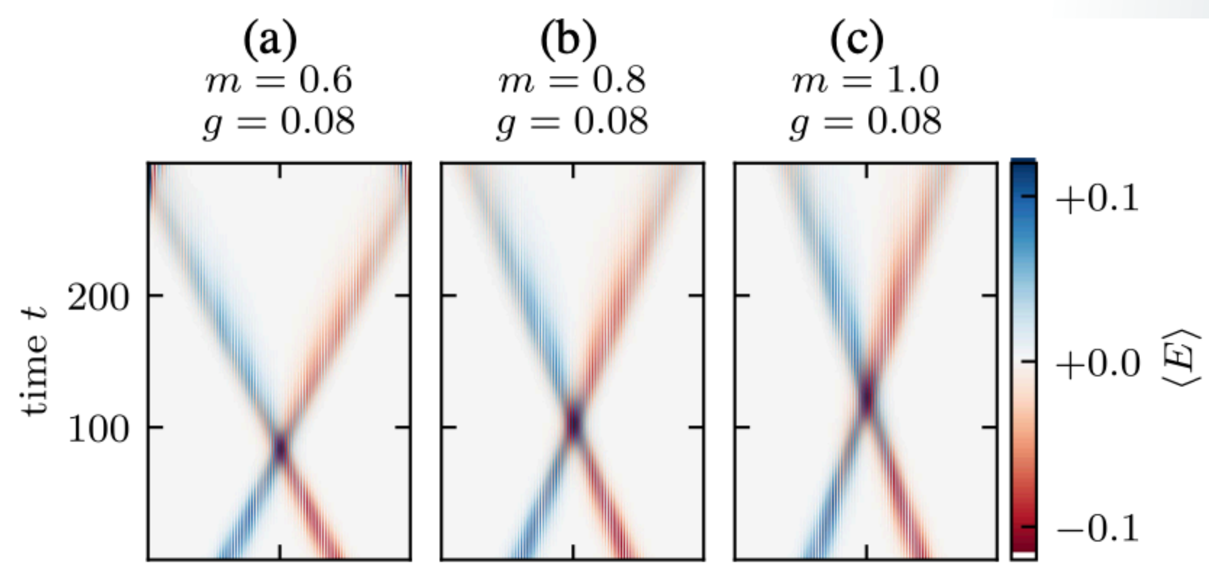


PHYSICAL REVIEW D **104,** 114501 (2021)

Entanglement generation in (1+1)D QED scattering processes

Marco Rigobello,* Simone Notarnicola, Giuseppe Magnifico, and Simone Montangero

notice also:
Surace, Lerose, New J. Phys. 23 (2021) 062001
Vovrosh et al. PRX Quantum 3, 040309 (2022)
Su, Osborne, Halimeh arXiv:2401.05489

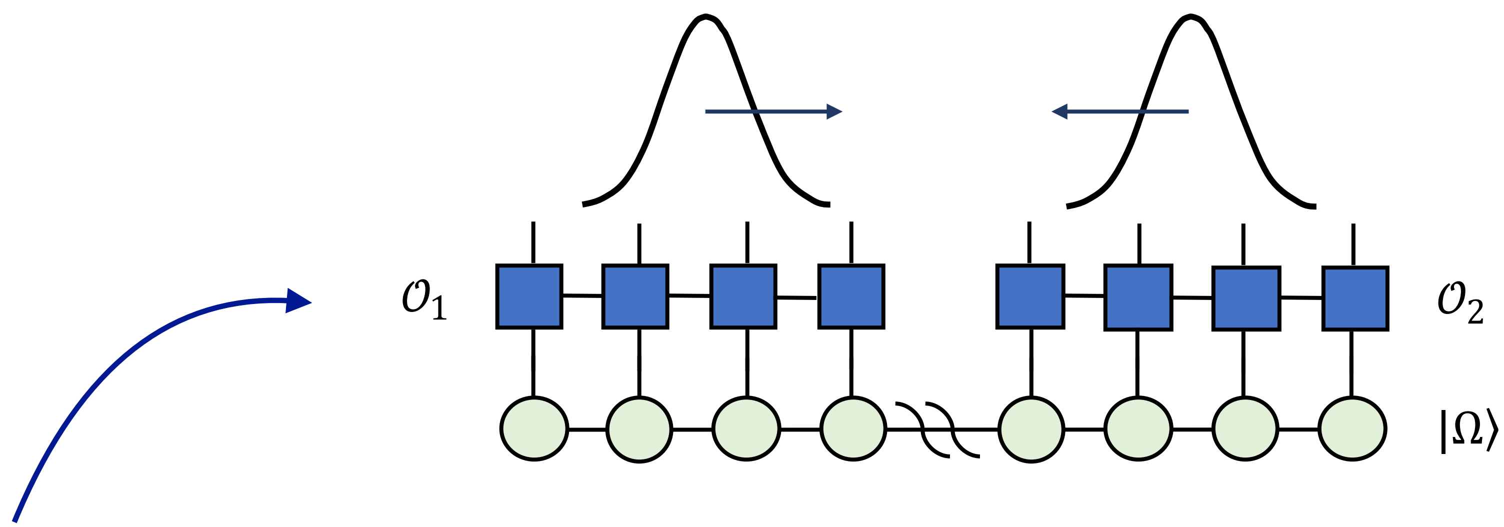


we are interested in simulation of (inelastic) scattering

inelastic scattering in the Schwinger model

collision of two vector mesons can produce two scalars

initial setup



$$\sum_n e^{-(n-n_0)^2/(2\sigma^2)} e^{-ikn} \left(\sigma_n^+ \sigma_{n+1}^- - \sigma_{n+1}^+ \sigma_n^-\right) |\Omega\rangle$$

Gaussian wavepacket with momentum k

Papaefstathiou, Knolle, MCB, arXiv:2402.18429

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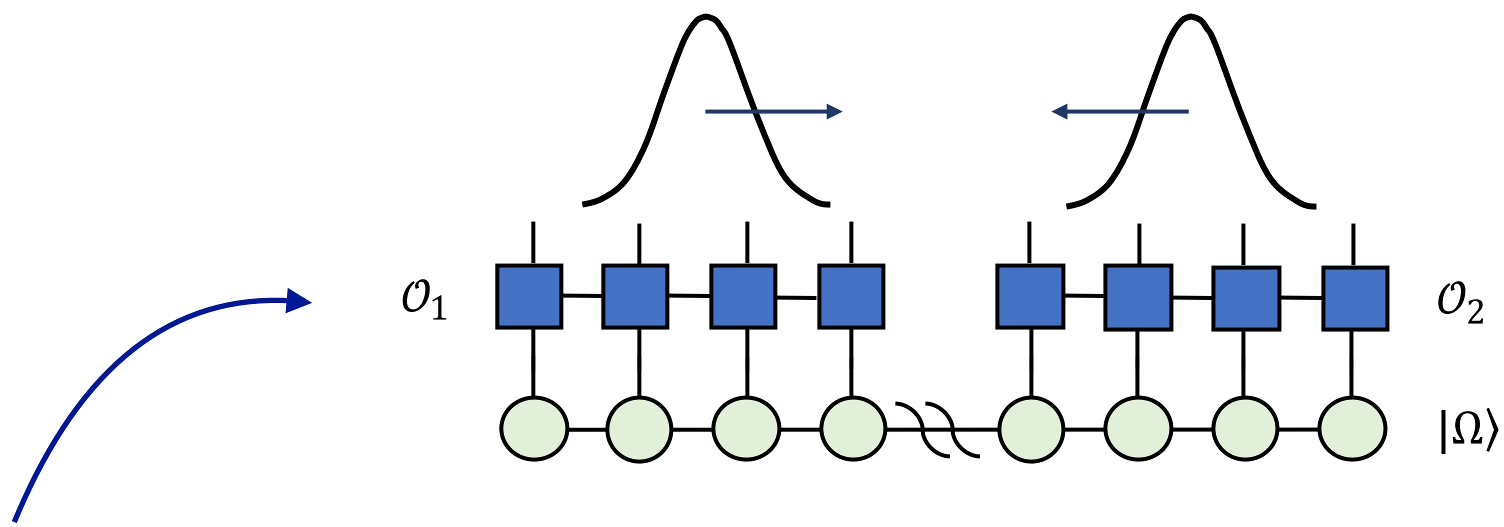

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Gaussian wavepacket with momentum k

probe the inelastic threshold

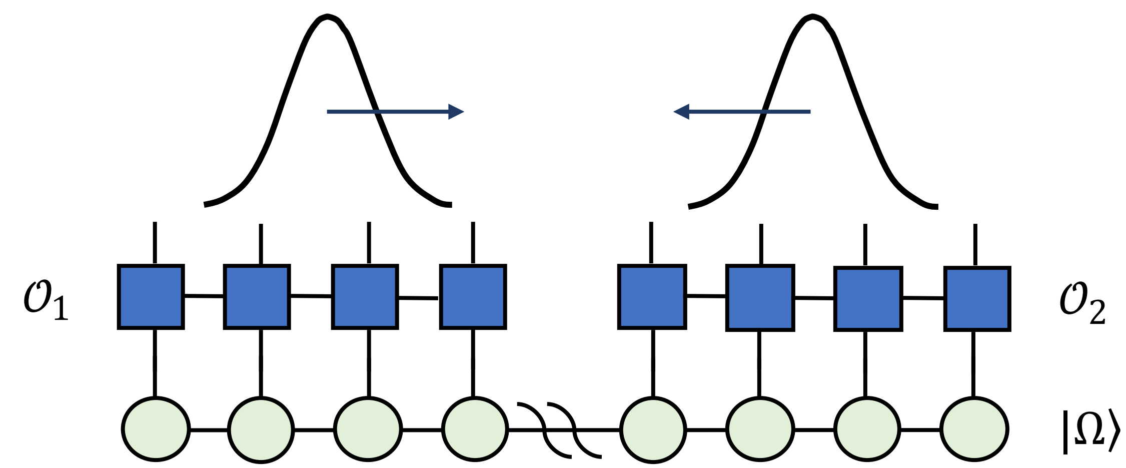
strong coupling regime

Papaefstathiou, Knolle, MCB, arXiv:2402.18429

inelastic scattering in the Schwinger model

collision of two vector mesons can produce two scalars

initial setup



inelastic threshold

continuum $2\sqrt{p^2 + M_V^2} = 2\sqrt{M_S^2}$

Papaefstathiou, Knolle, MCB, arXiv:2402.18429

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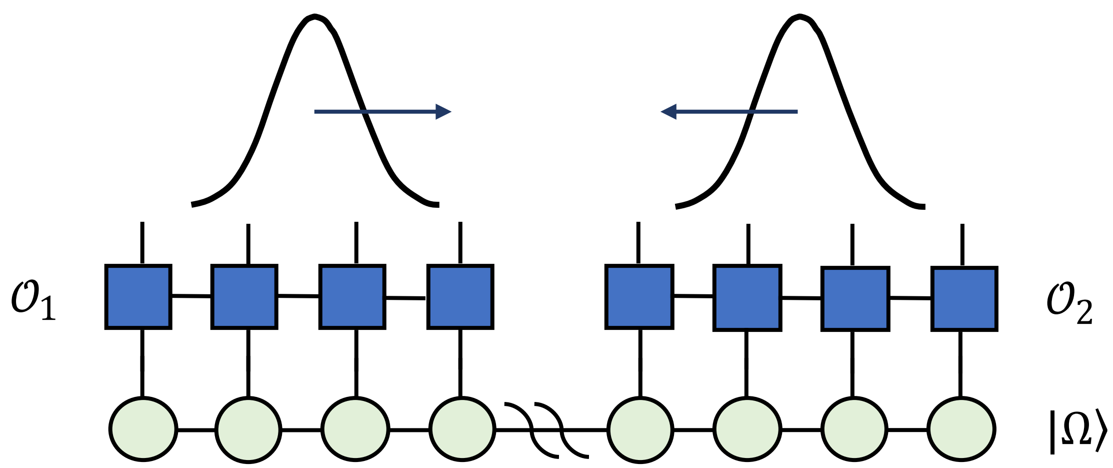

inelastic threshold

continuum $2\sqrt{p^2 + M_V^2} = 2\sqrt{M_S^2}$

lattice $k = p/(g\sqrt{x})$

$$x = 1;\ N = 100;\ \mu = 2 \cdot 10^{-5} \Rightarrow k_{\mathrm{thr}} = 1.12$$

Papaefstathiou, Knolle, MCB, arXiv:2402.18429

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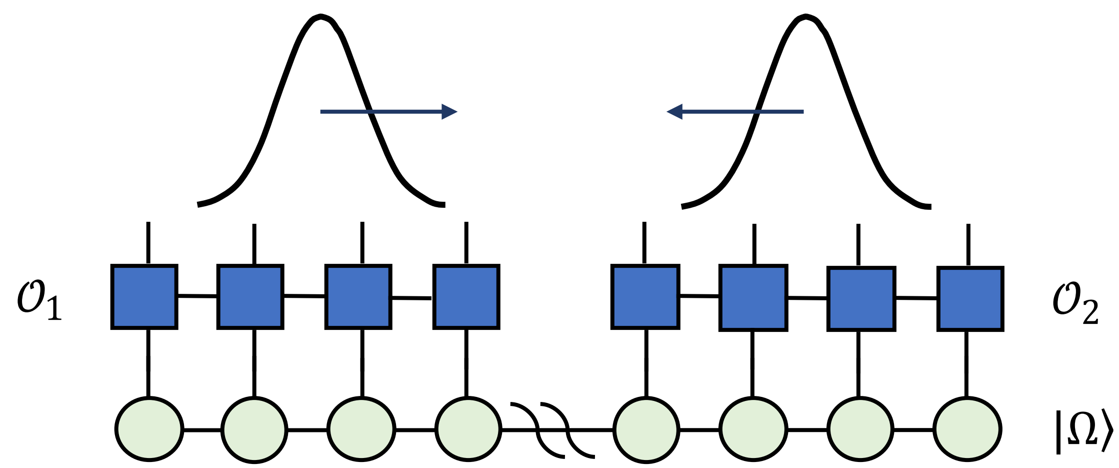


observables (mostly local)

entropy of two sites

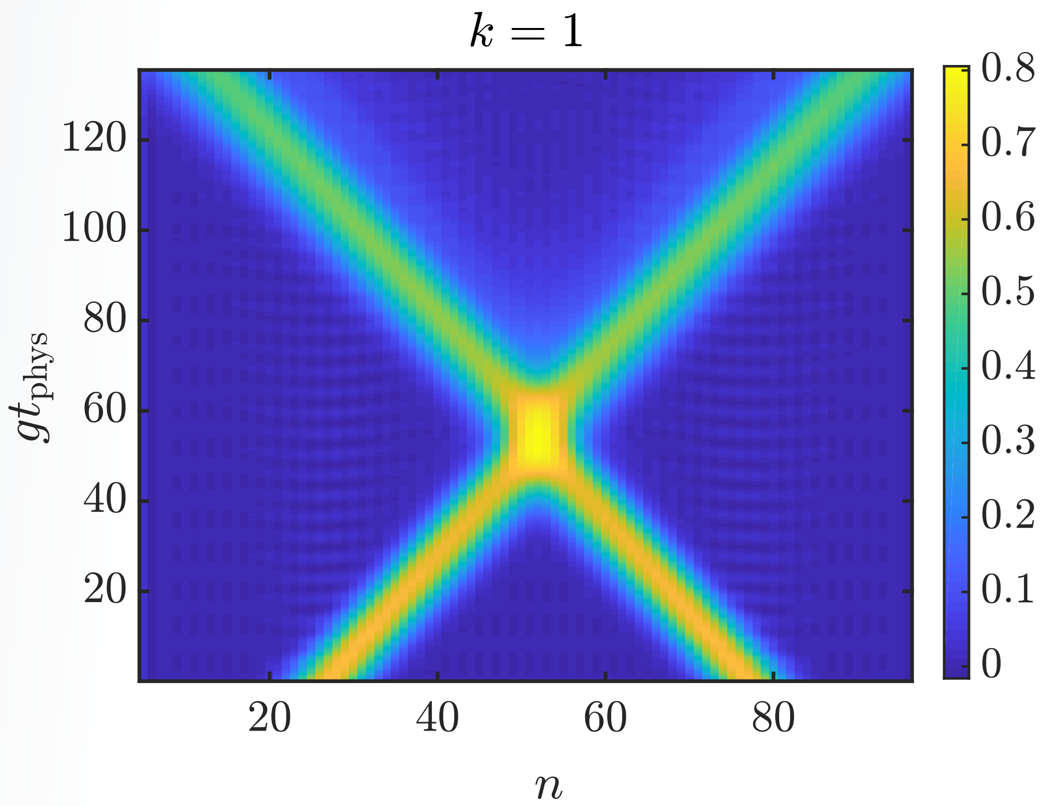
4-fermion projector (strong coupling)

electric flux correlator (not local)

Papaefstathiou, Knolle, MCB, arXiv:2402.18429

below momentum threshold

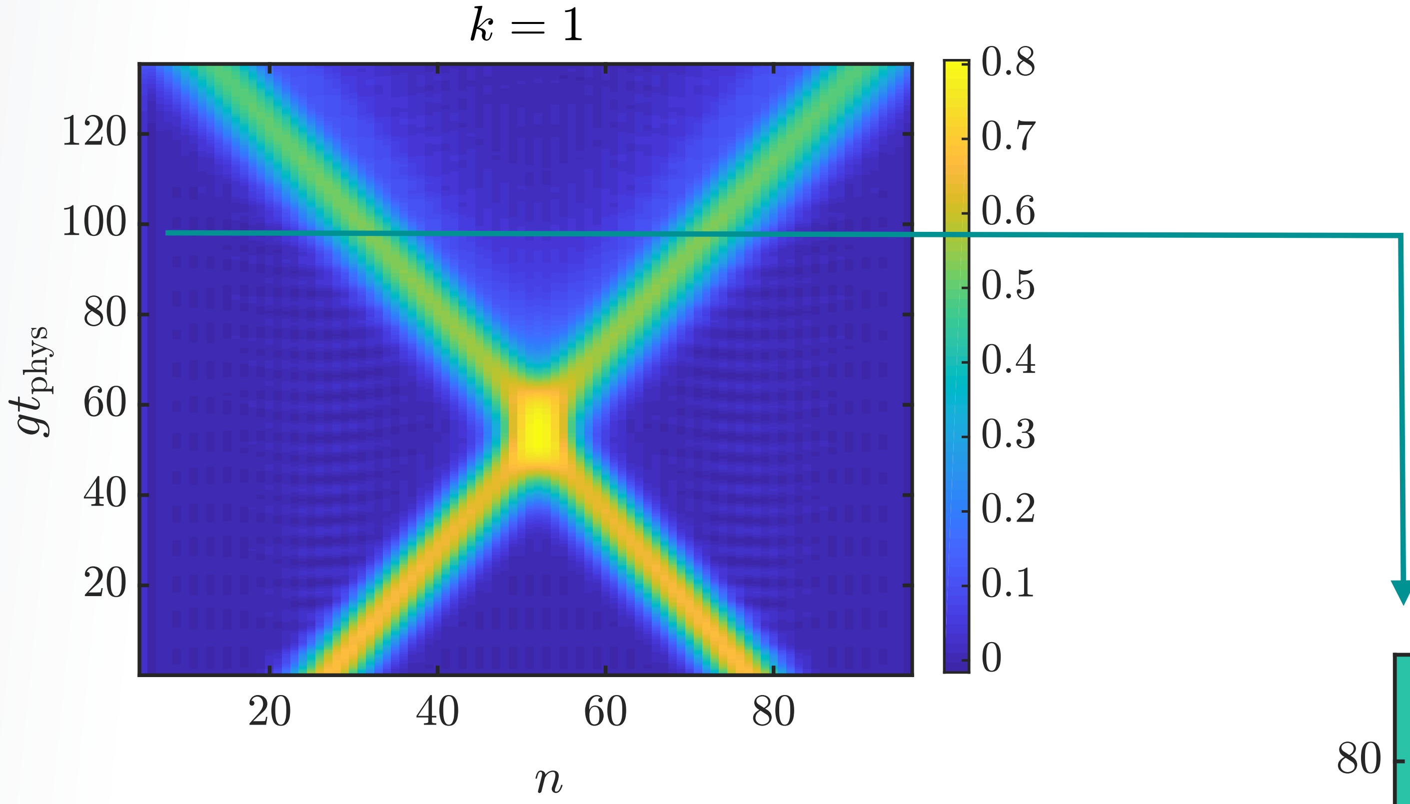
entropy of two sites



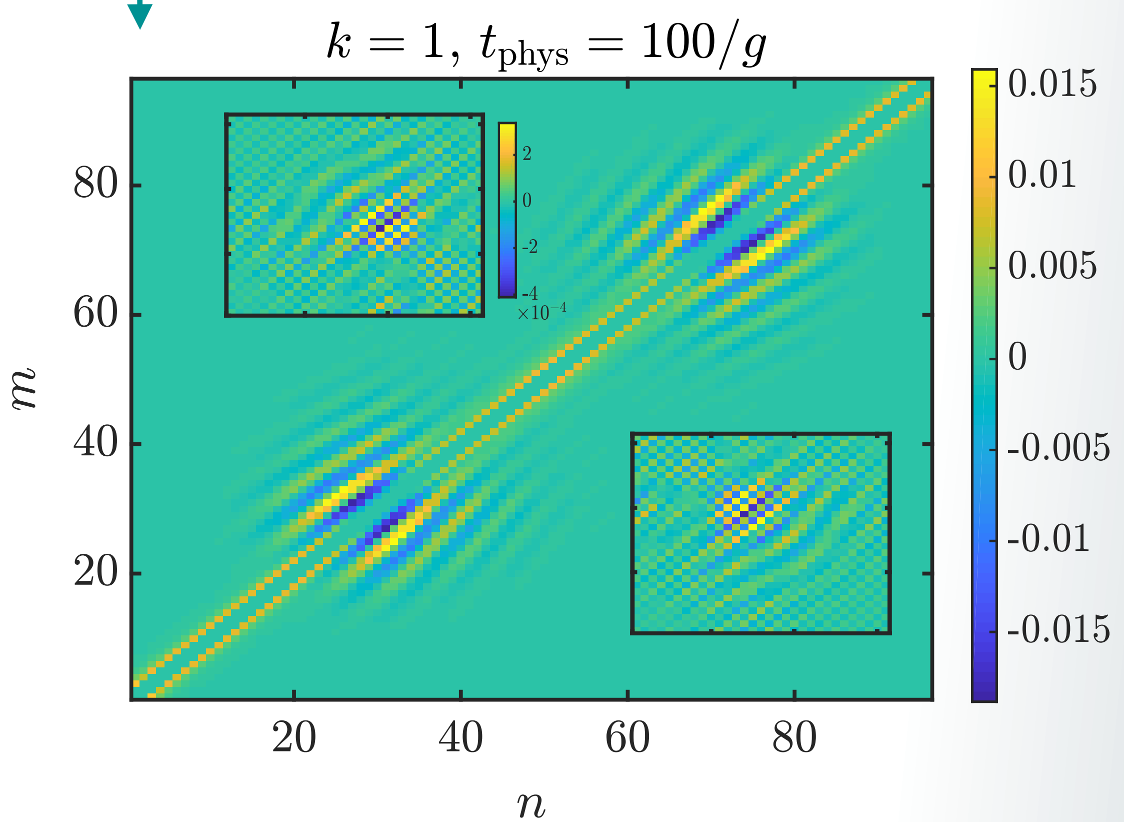
Papaefstathiou, Knolle, MCB, arXiv:2402.18429

below momentum threshold

entropy of two sites



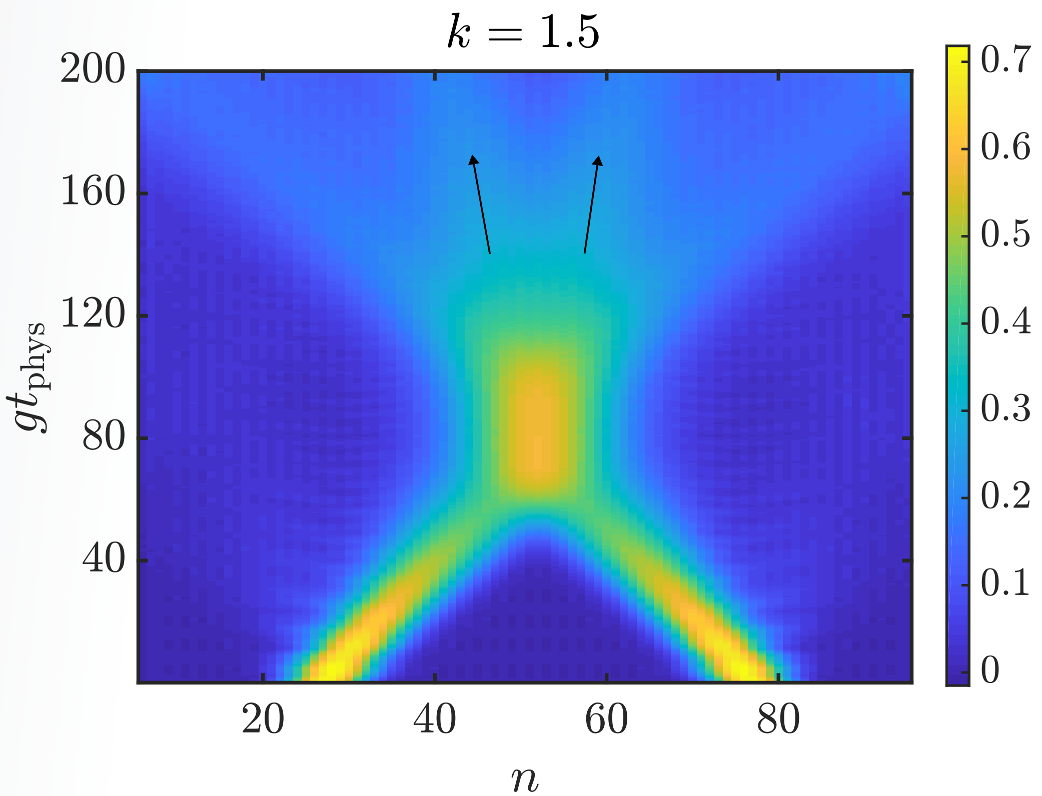
electric flux correlator



Papaefstathiou, Knolle, MCB, arXiv:2402.18429

above momentum threshold

entropy of two sites



Papaefstathiou, Knolle, MCB, arXiv:2402.18429

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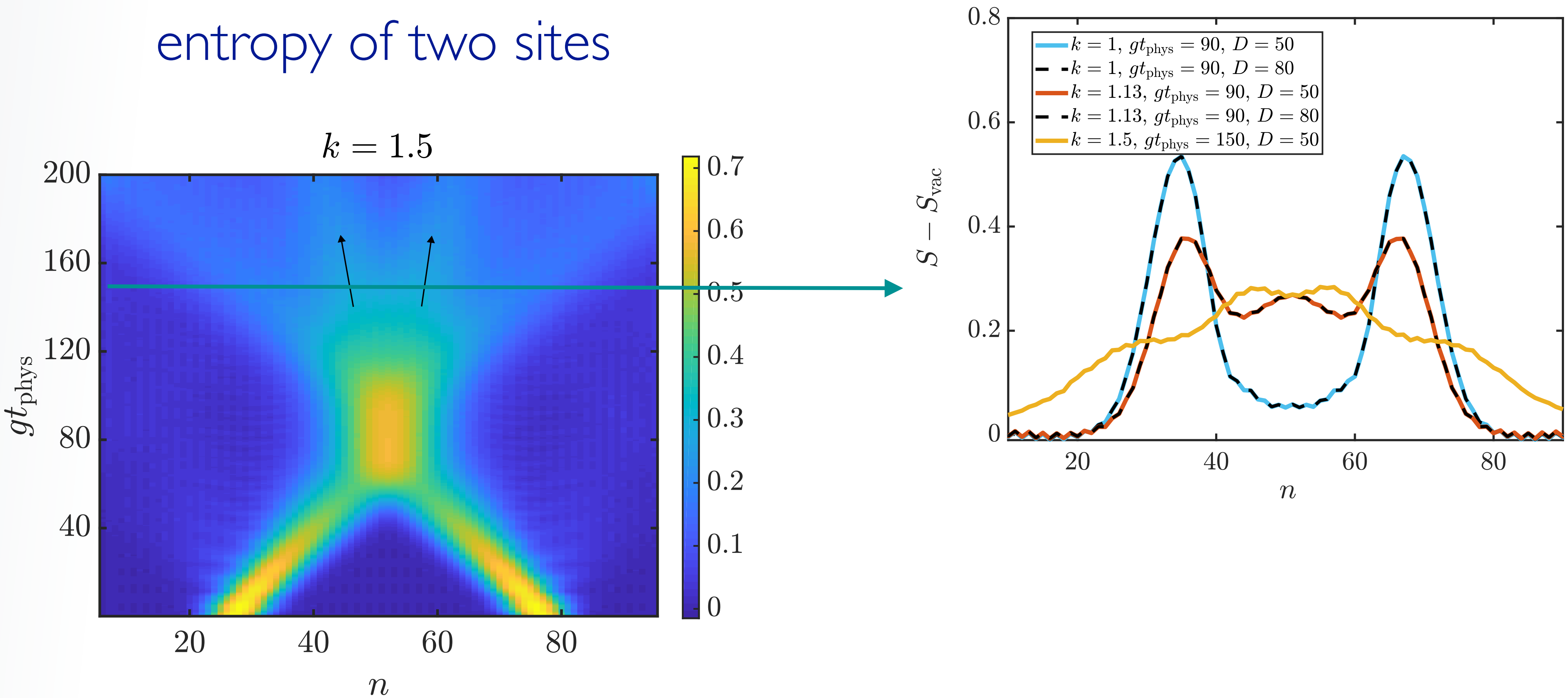
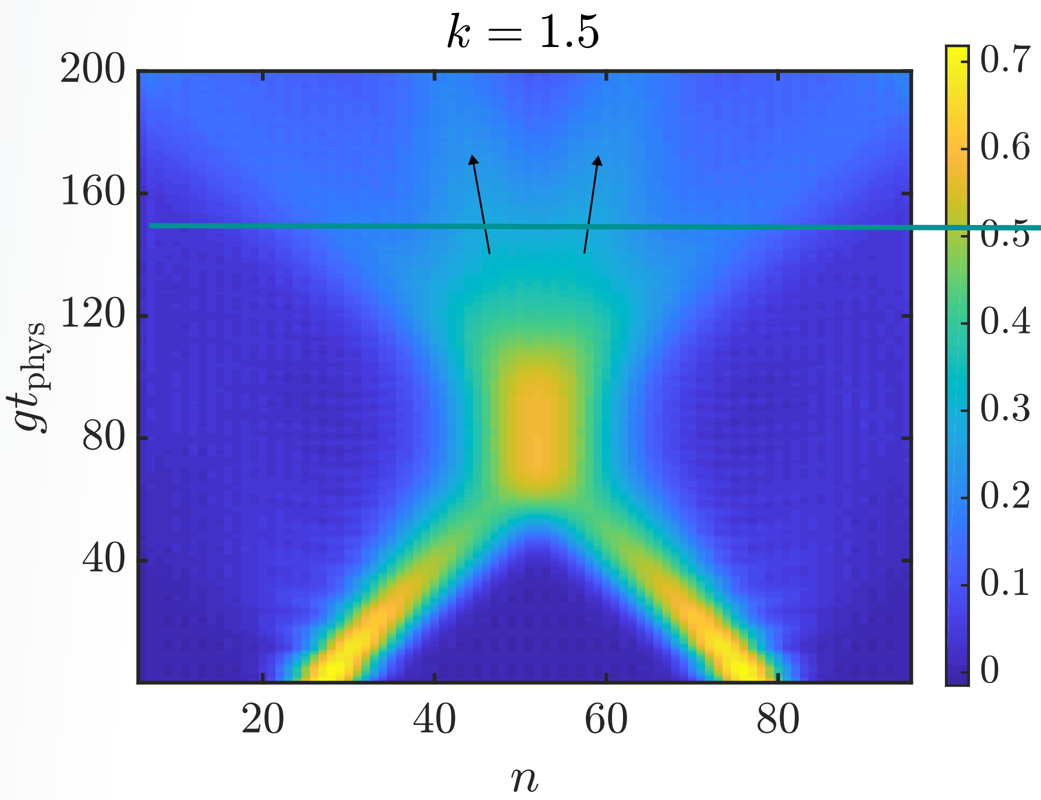
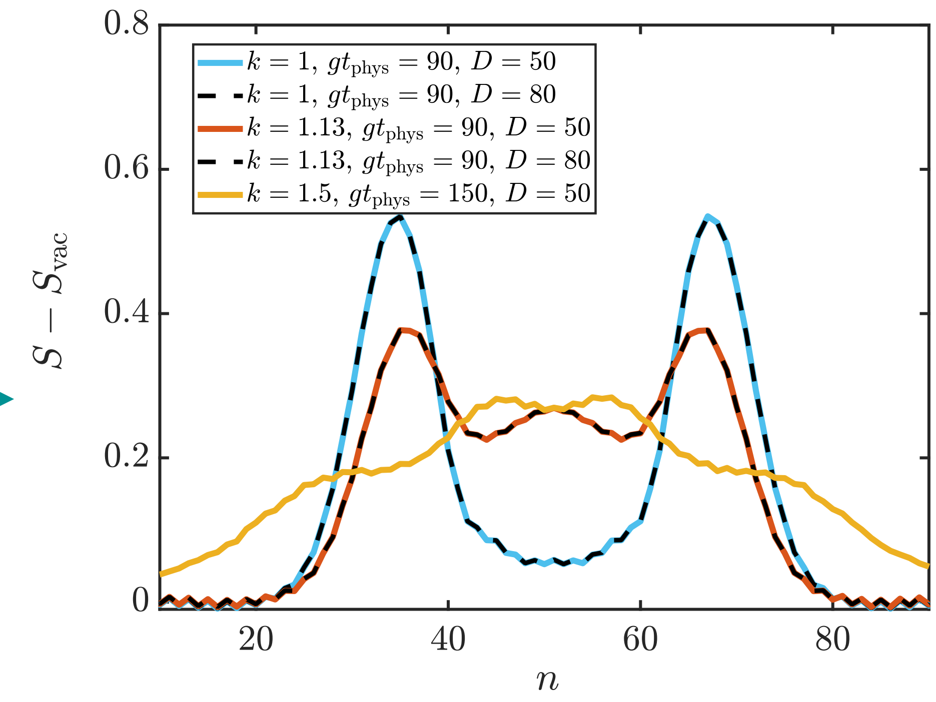


Papaefstathiou, Knolle, MCB, arXiv:2402.18429

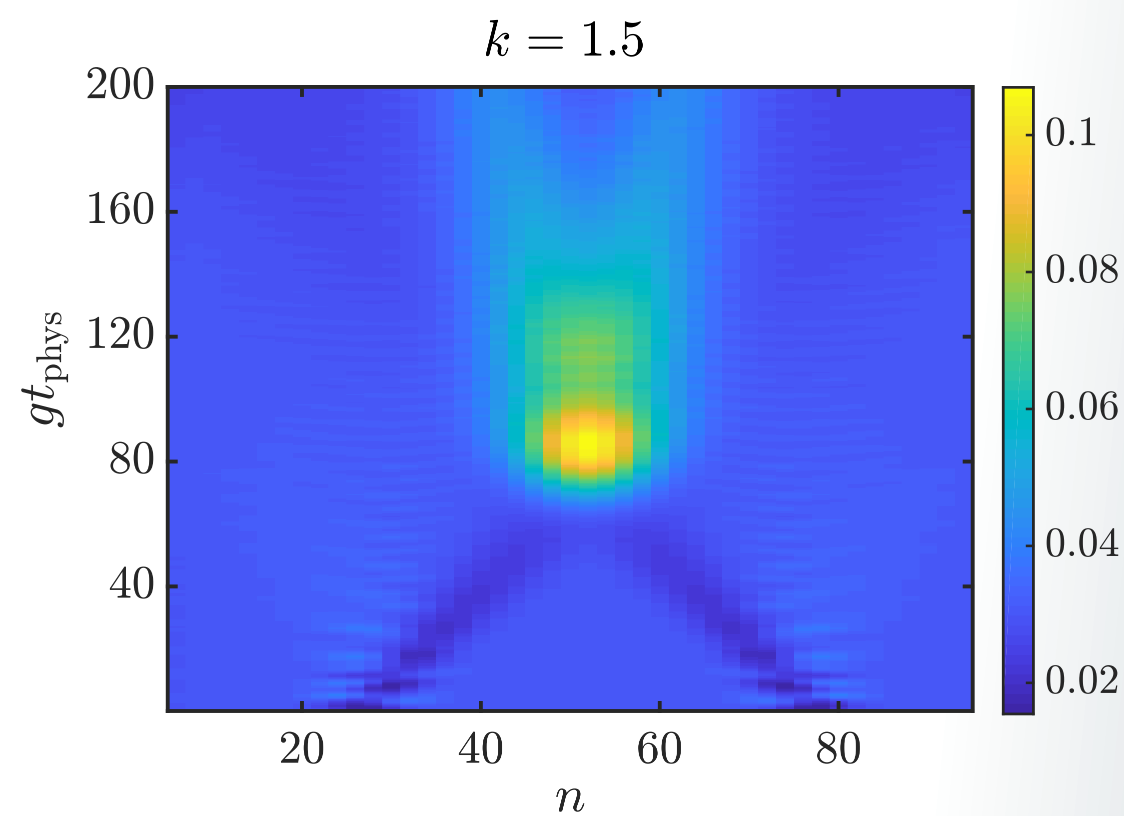
above momentum threshold

entropy of two sites





4-fermion projector



Papaefstathiou, Knolle, MCB, arXiv:2402.18429

To conclude

T-NiSQ
Tensor Networks in Simulation of Quantum Matter

DFG FOR 5522

MAX PLANCK INSTITUTE OF QUANTUM OPTICS

MCQST

TNS can be a suitable ansatz also for LGT/QFT

- real time is more challenging than equilibrium
- standard methods limited to short times
- current results: inelastic scattering
  Papaefstathiou, arXiv:2402.18429
  - momentum threshold observed
  - production detected through local observables
- other models: Thirring on lattice DQPT
  arXiv:2407.11295
- further directions
  - challenge: continuum limit

To conclude

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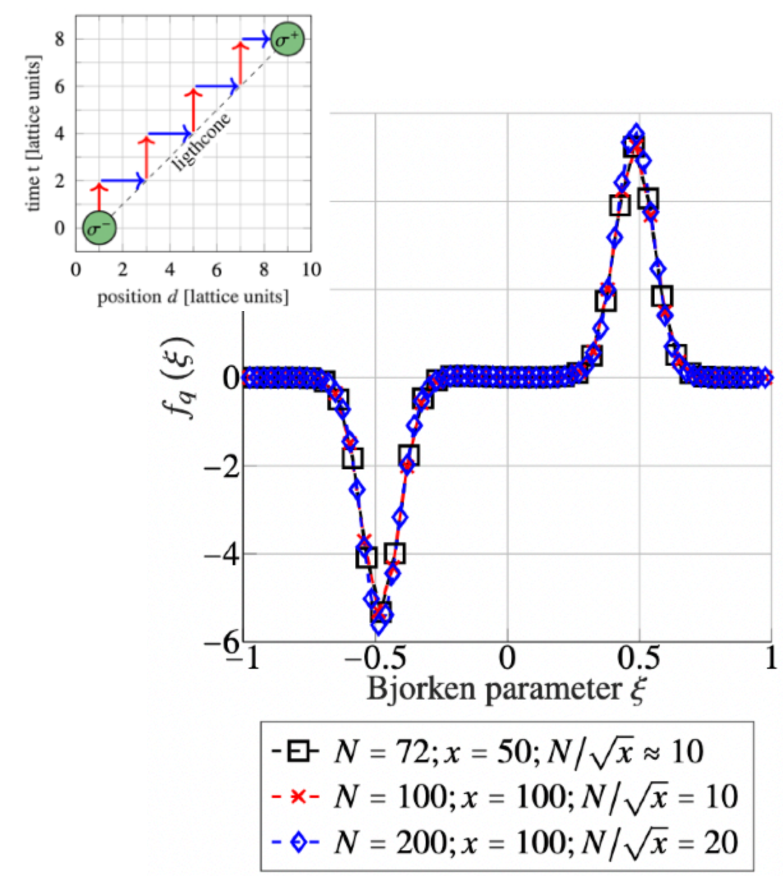

Schwinger model PDFs

Schneider, Cichy, MCB, Lin, LATTICE'24, arXiv:2409.16996

To conclude

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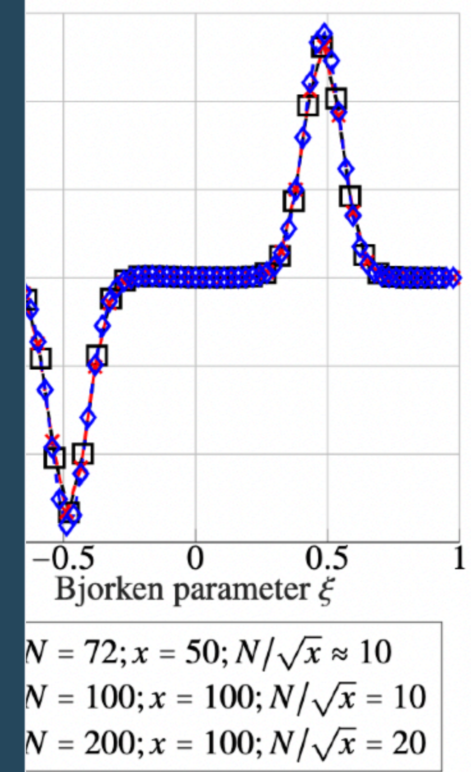
MCQST

T-NiSQ
Tensor Networks in Simulation of Quantum Matter

DFG FOR 552

TNS can be a suitable ansatz also for

alternative strategies



nger model
PDFs

Schneider, Cichy, MCB, Lin, LATTICE'24, arXiv:2409.16996

To conclude

TNS can be a suitable ansatz also for

give up description of the full state

spectral properties of the QMB Hamiltonian

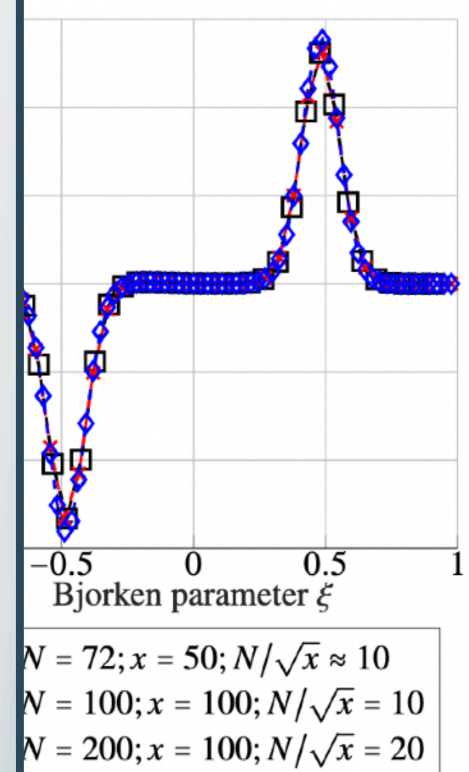
Yang, Iblisdir, Cirac, MCB, PRL124, 100602 (2020)
Papaefstathiou, Robaina, Cirac, MCB, PRD104, 014514 (2021)
Çakan, Cirac, MCB, PRB 103, 115113 (2021)
Lu, MCB, Cirac, PRX Quantum 2, 02032 (2021)
Yang, Cirac, MCB, PRB 106, 024307 (2022)
Luo, Trivedi, MCB, Cirac, PRB 109, 134304 (2024)

light-cone TN for non-equilibrium evolution of local observables

Frías-Pérez, MCB, PRB106, 115117 (2022)

transforming long-range entanglement into mixture

Frías-Pérez, Tagliacozzo, MCB, PRL132, 100402 (2024)



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Schneider, Cichy, MCB, Lin, LATTICE'24, arXiv:2409.16996

DFG FOR 552

Thanks for your attention!

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Papaefstath

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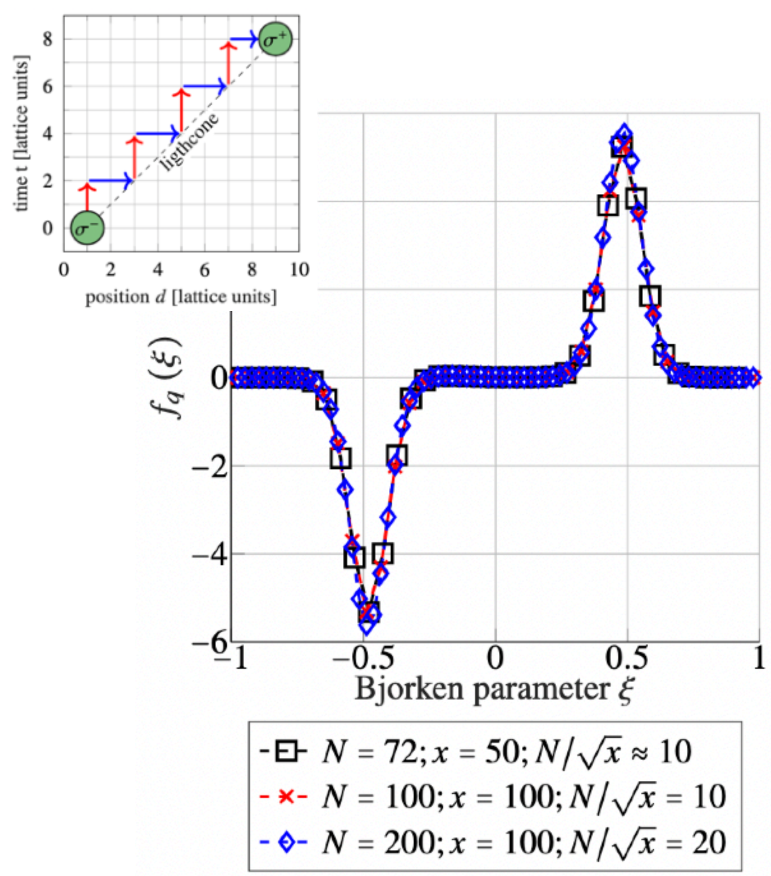
other models: Thirring on lattice DQI

further directions

- challenge: continuum limit



Schwinger model PDFs

Schneider, Cichy, MCB, Lin, LATTICE'24, arXiv:2409.16996

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alternative strategies

Recent work…

exploring spectral properties of quantum many-body systems

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spectral properties of
a QMB Hamiltonian

Yang, Iblisdir, Cirac, MCB,
PRL124, 100602 (2020)

Lu, MCB, Cirac
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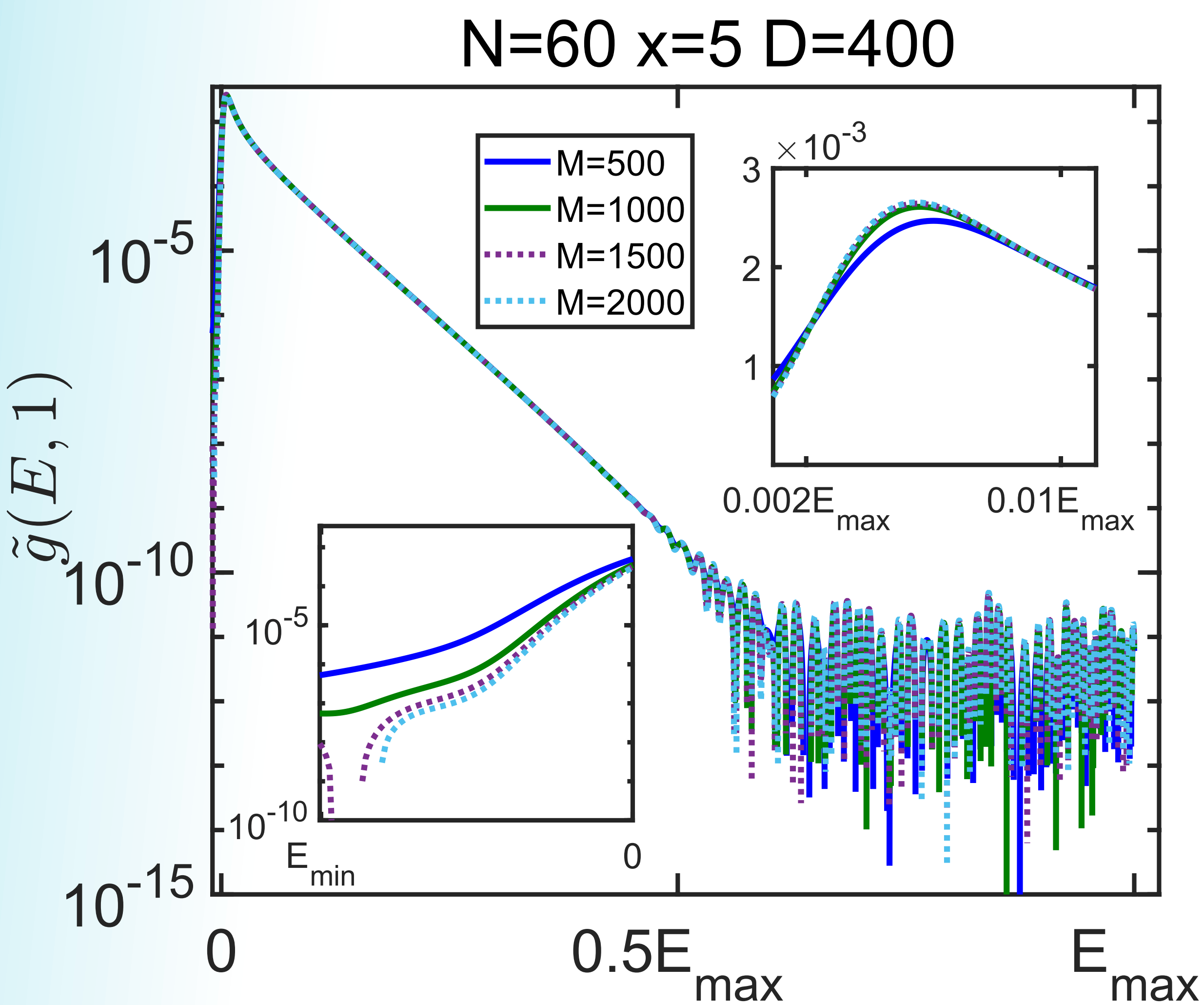
generalized density of states

can be connected to equilibrium and non-equilibrium properties

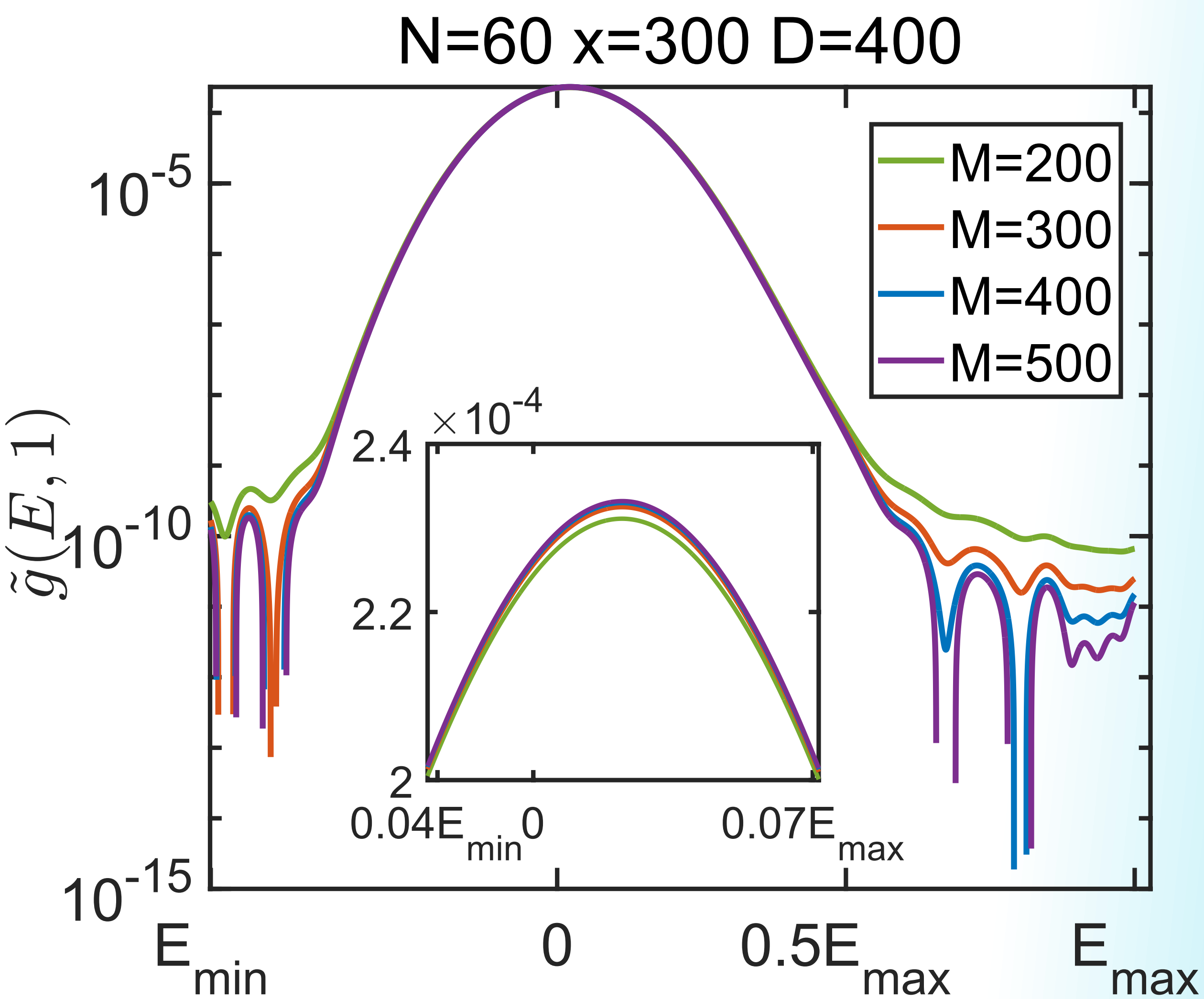
DoS of Schwinger model

large lattice spacing



asymmetric shape

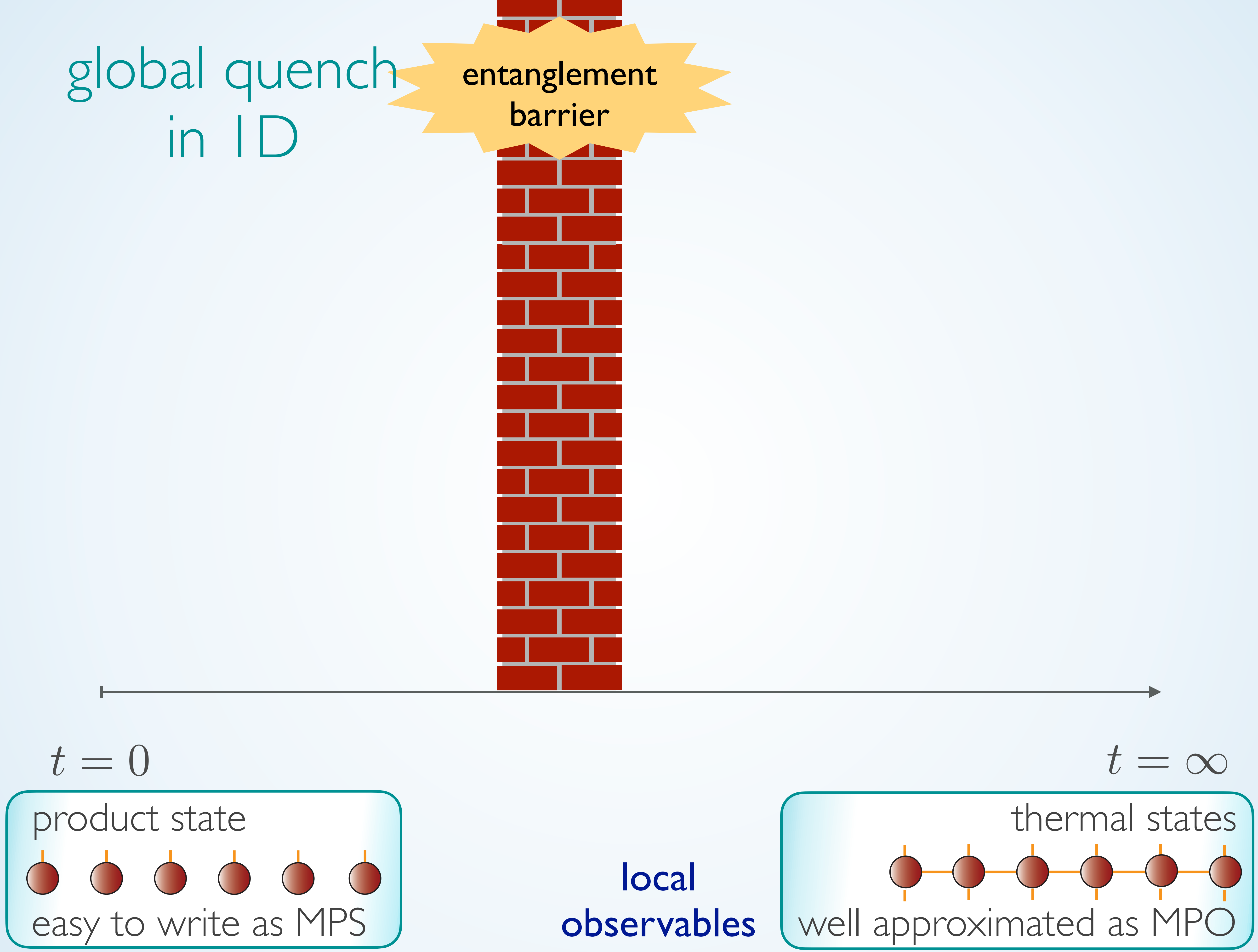
small lattice spacing



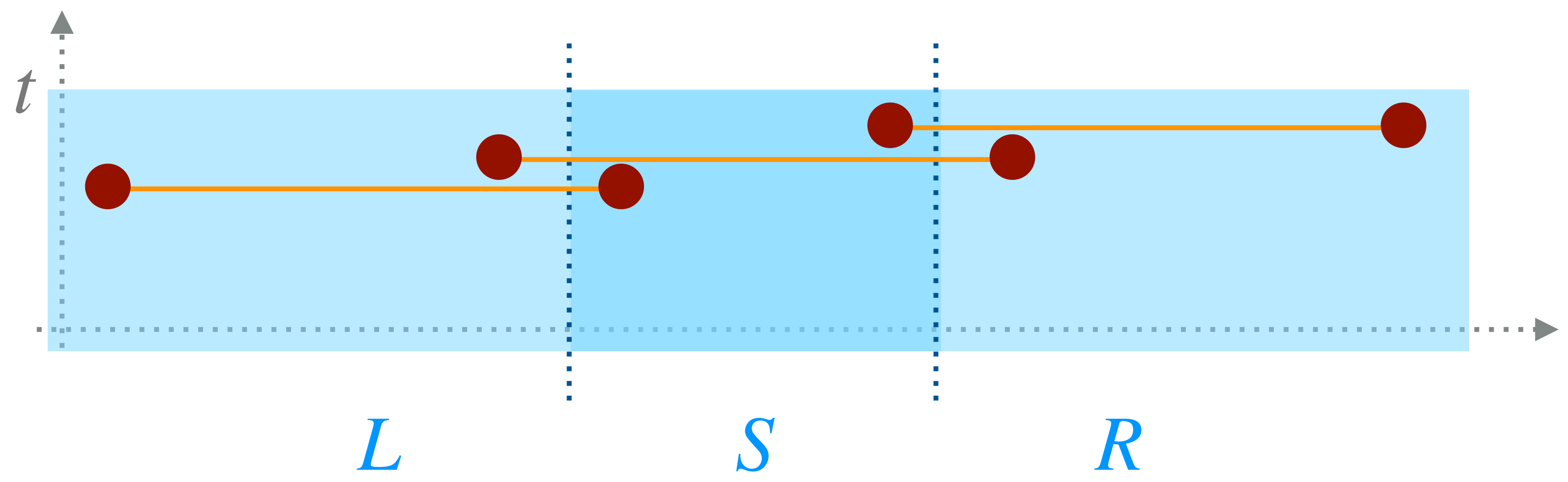
near Gaussian shape

I. Papaefstathiou et al., PRD104, 014514 (2021)

Long-range entanglement
and equilibration


global quench
in 1D
entanglement
barrier
$t = 0$
$t = \infty$
product state
easy to write as MPS
local
observables
thermal states
well approximated as MPO

back to quasiparticle intuition



Frías-Pérez, Tagliacozzo, MCB arXiv:2308.04291

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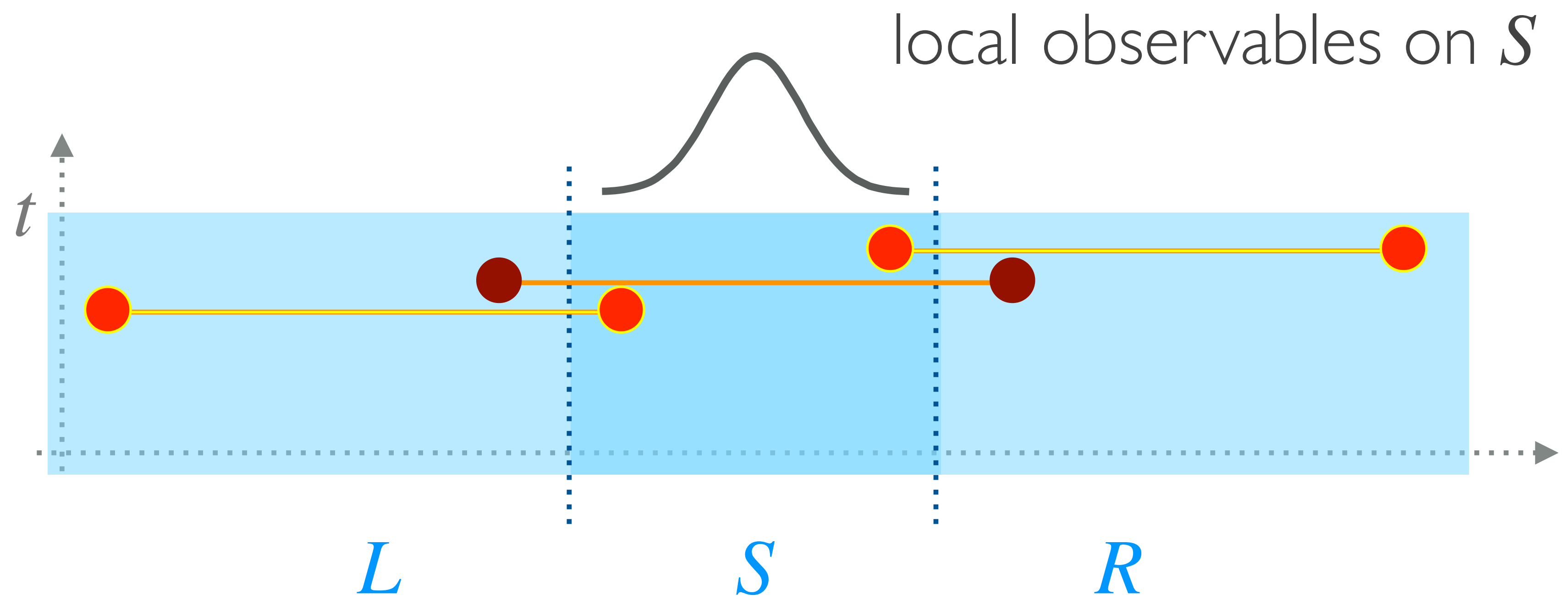

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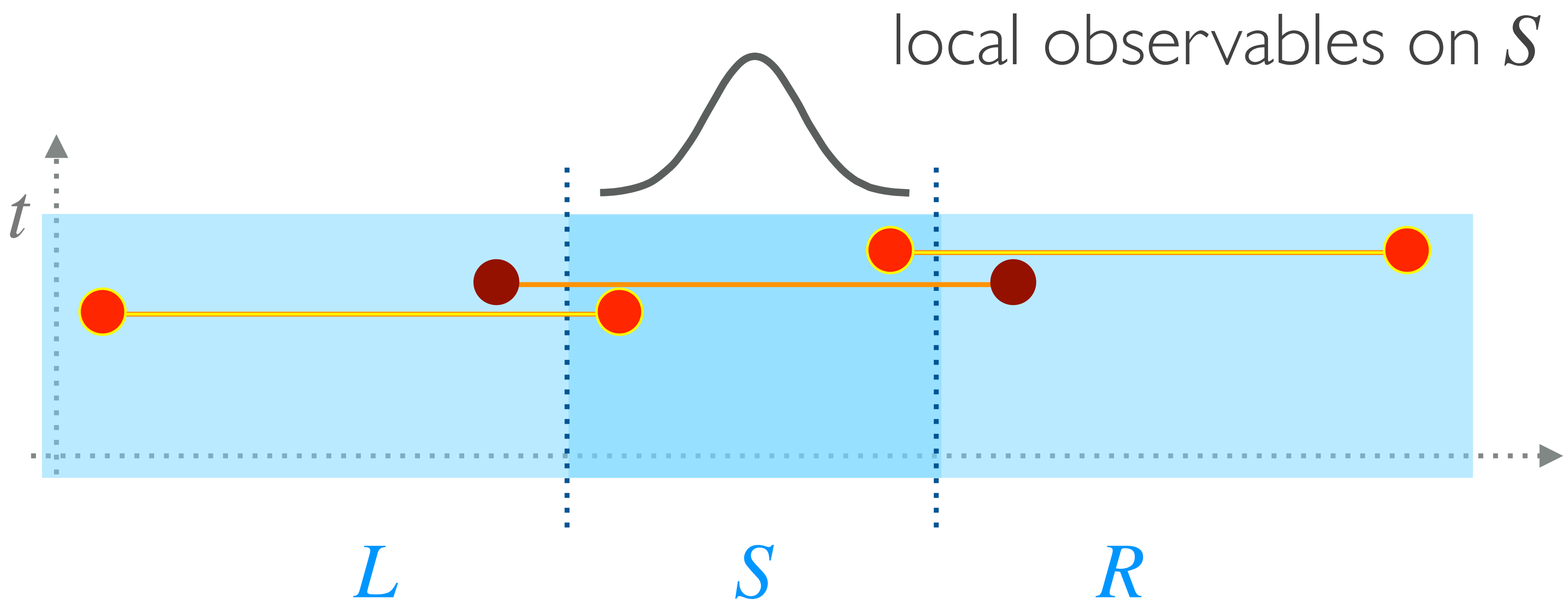
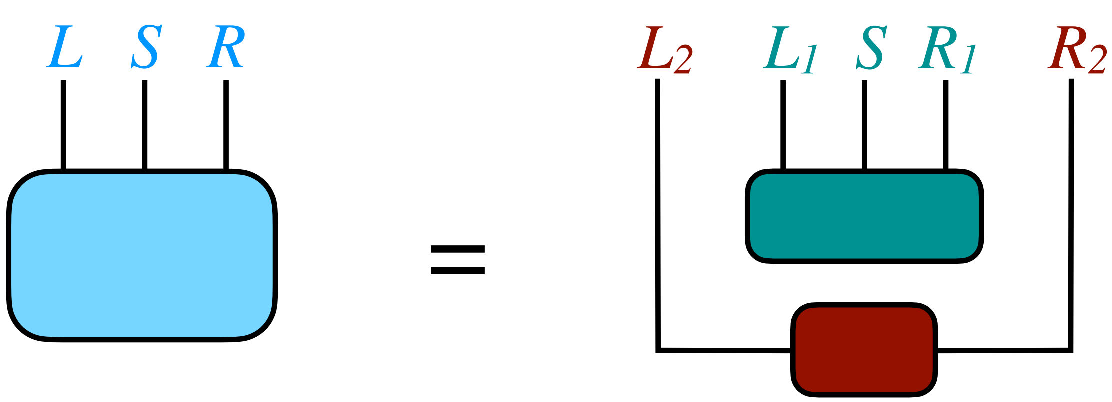


$$|\Psi_{LSR}\rangle = |\phi_{L_1SR_1}\rangle \otimes |\phi_{L_2R_2}\rangle$$

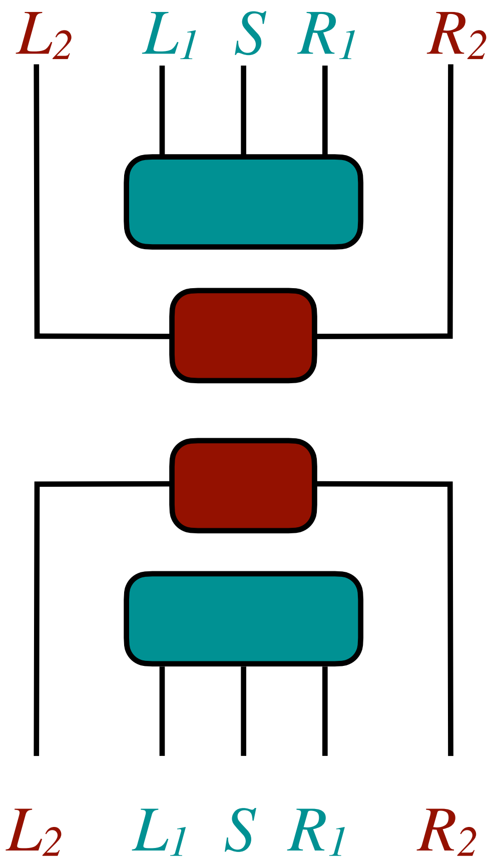


will contribute
as statistical
mixture

Frías-Pérez, Tagliacozzo, MCB arXiv:2308.04291

long-range entanglement ⇒ mixture

$$|\Psi_{LSR}\rangle\langle\Psi_{LSR}|$$



Frías-Pérez arXiv:2308.04291

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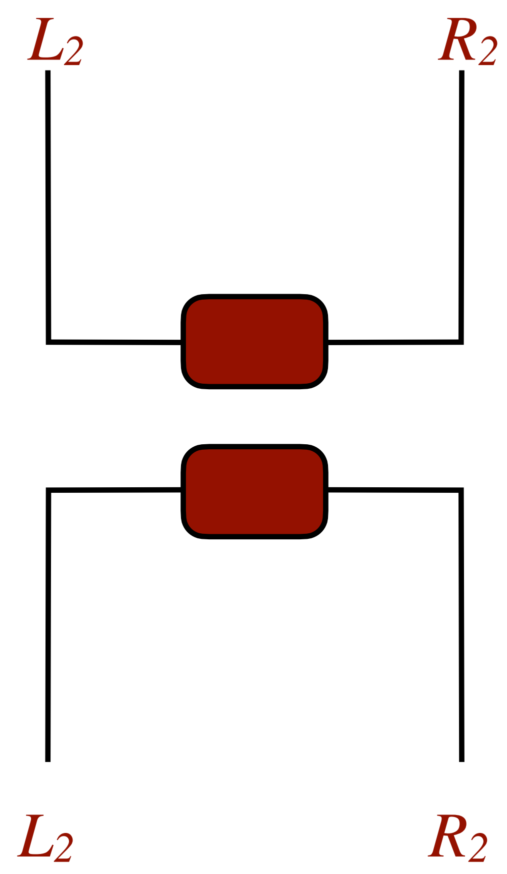

Frías-Pérez arXiv:2308.04291

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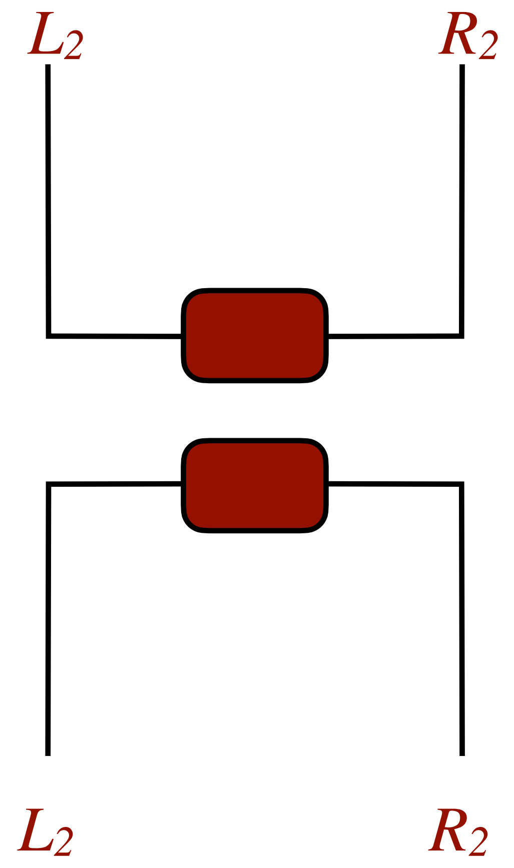
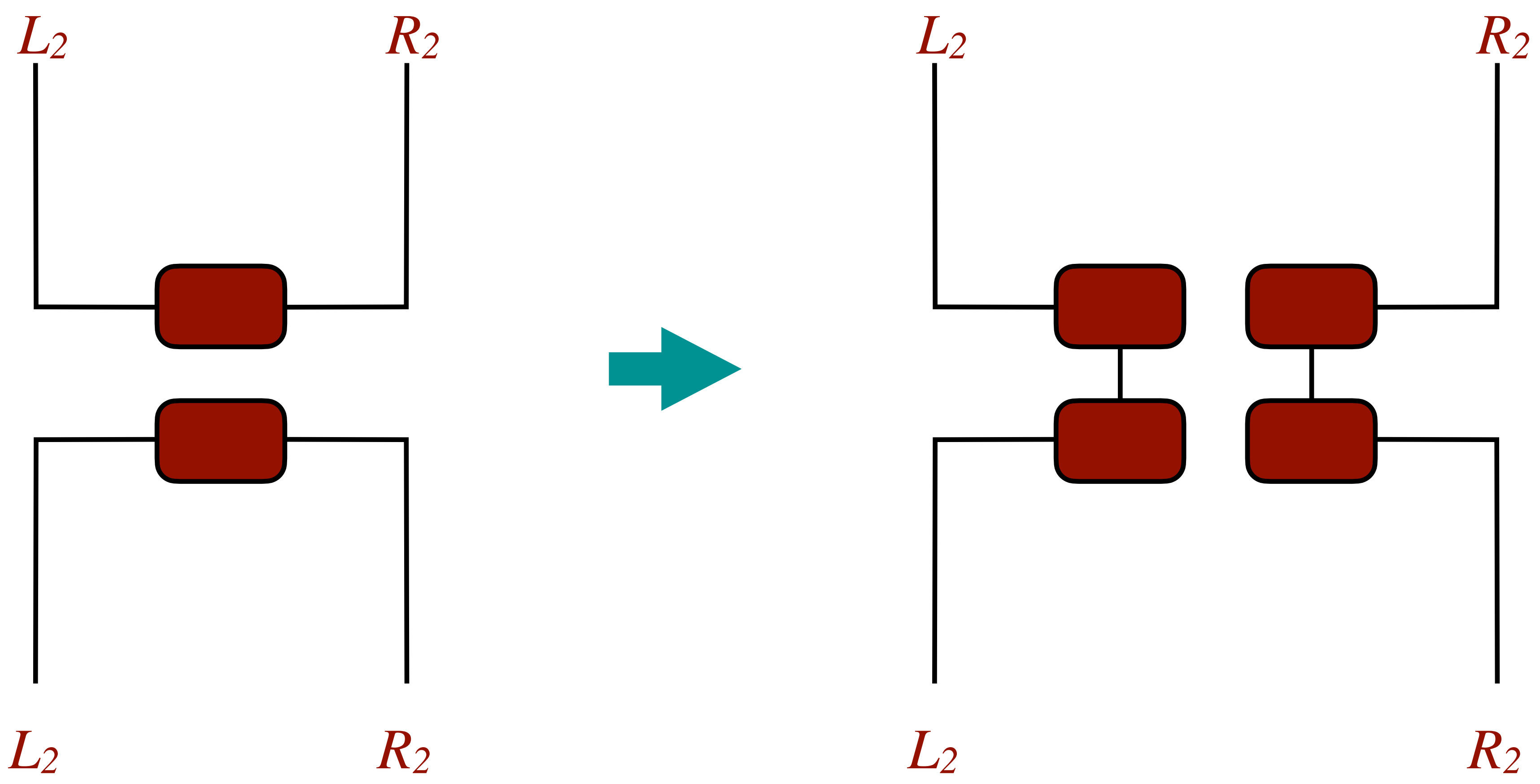


long range contribute as mixture to
local observables in neighbouring blocks

Frías-Pérez arXiv:2308.04291

long-range entanglement ⇒ mixture



$$\rho_{L_2 R_2} \Rightarrow \rho_{L_2} \otimes \rho_{R_2}$$

Frías-Pérez arXiv:2308.04291

To conclude

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TNS methods for HEP…

To conclude

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finite density

related to equilibrium simulations

thoroughly tested in 1+1D

spectrum, thermal equilibrium

Abelian and non-Abelian models

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- in general more challenging
- methods exist
- limitations for out-of-equilibrium: not yet completely understood

Thanks for your attention!

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can be a suitable ansatz also for LGT/QFT

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- uses in QFT/LGT: DQPTs, pair production scattering
  - PRD100, 094504 (2019)

limited to short times

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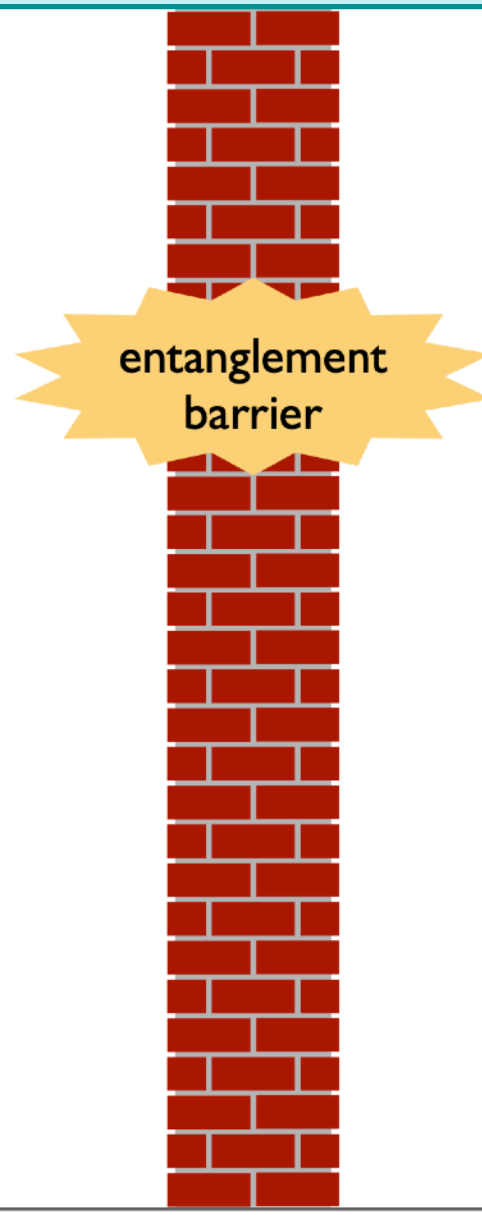

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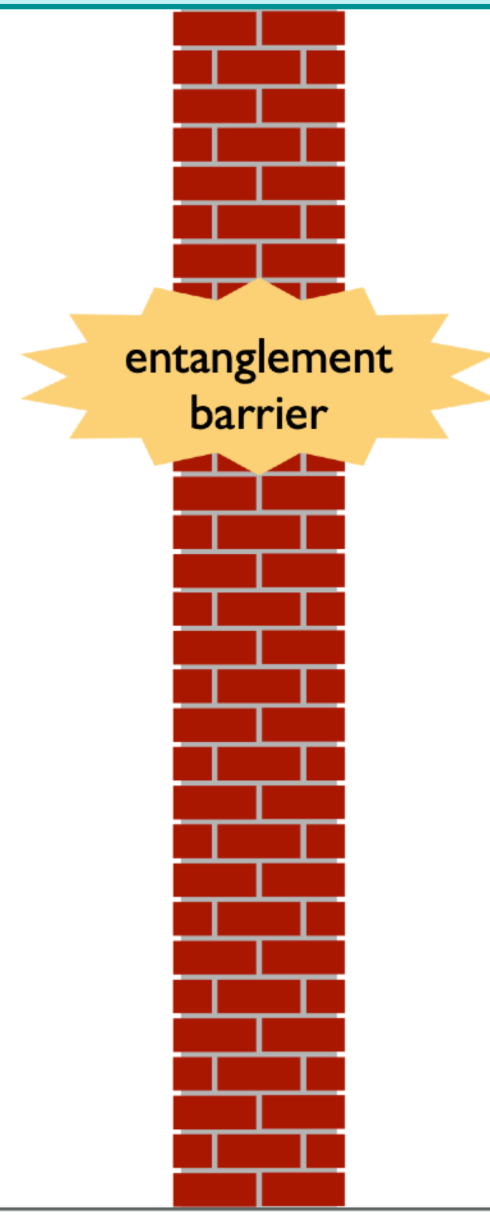

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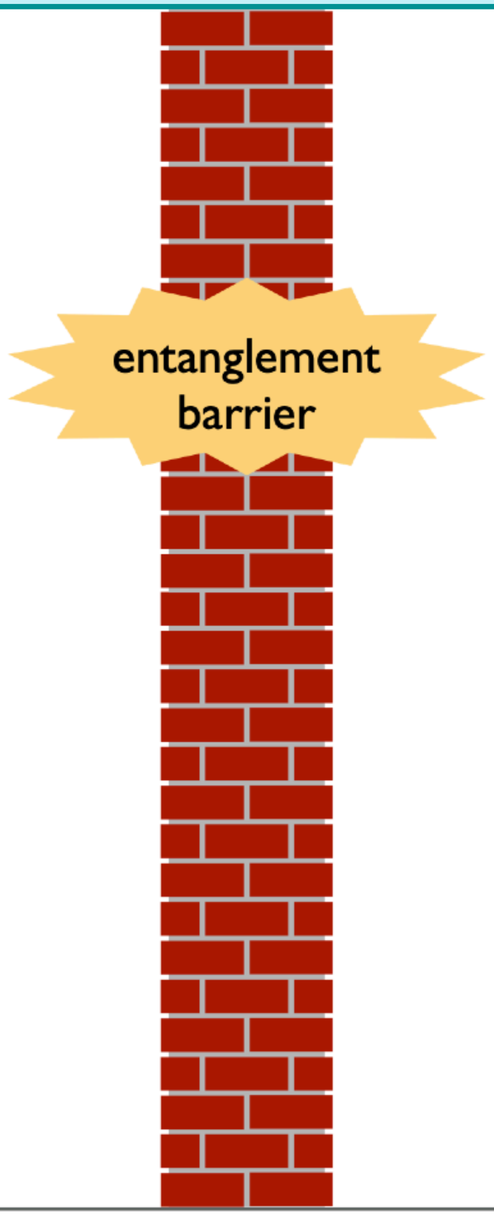

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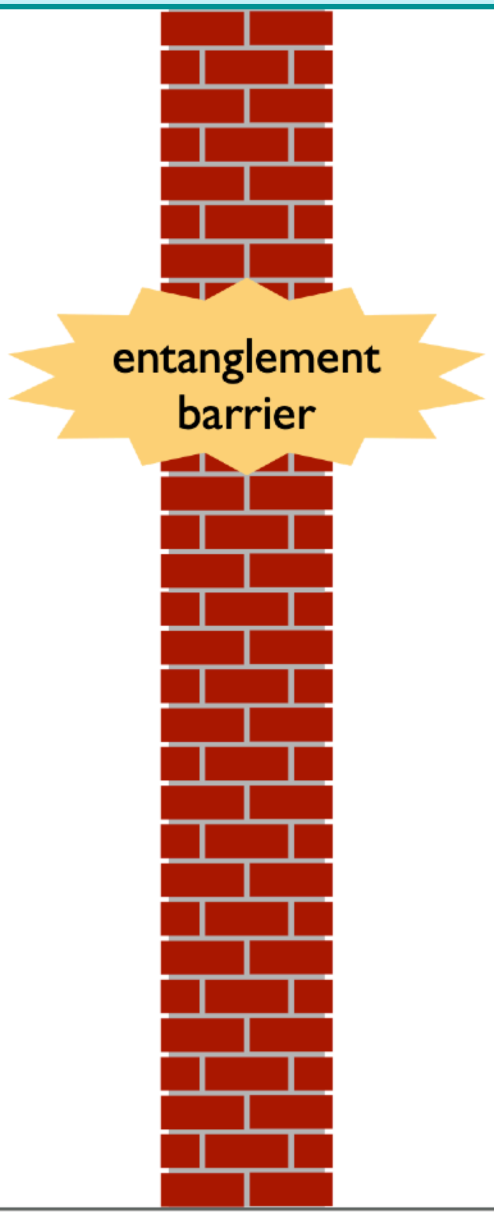

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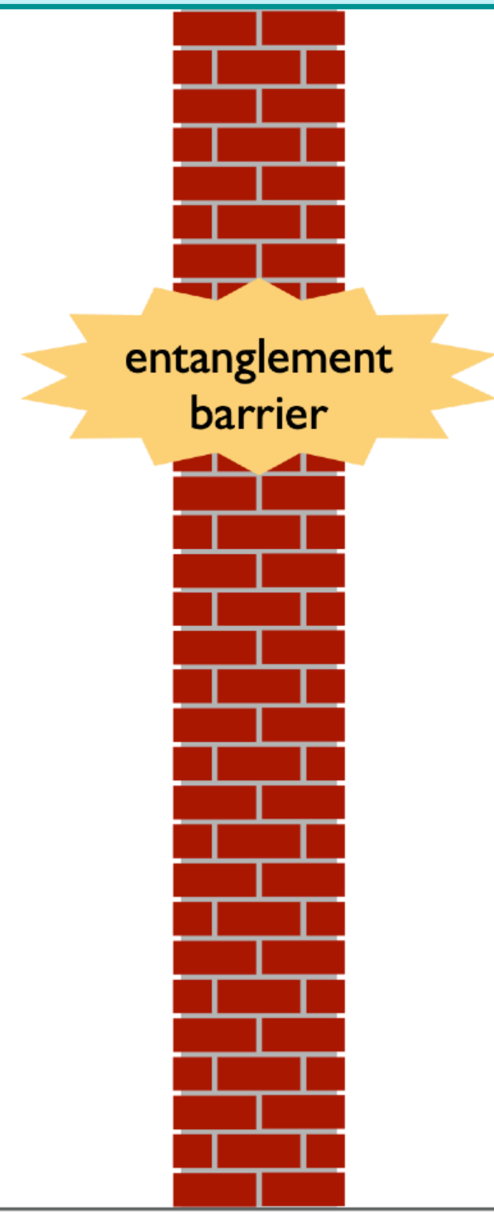

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Luca's talk

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