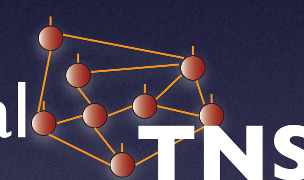
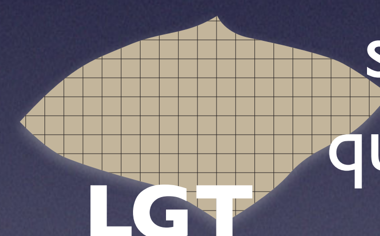
TENSOR NETWORK STATES FOR LATTICE GAUGE THEORIES



about classical simulations of a quantum problem



Mari-Carmen Bañuls

with K. Cichy (Poznan), K. Jansen (DESY), H. Saito, J.I. Cirac (MPQ), S. Kühn (Perimeter)

QUANTERA QTFLAG

MPQ Max-Planck-Institut für Quantenoptik (Garching b. München)

Würzburg, 2.8.2018

TENSOR NETWORKS

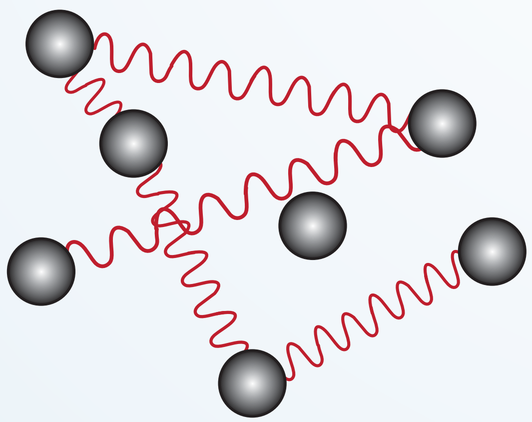
WHAT ARE TNS?

- TNS = Tensor Network States

A general state of the N-body Hilbert space has exponentially many coefficients

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

N



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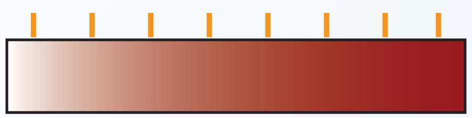
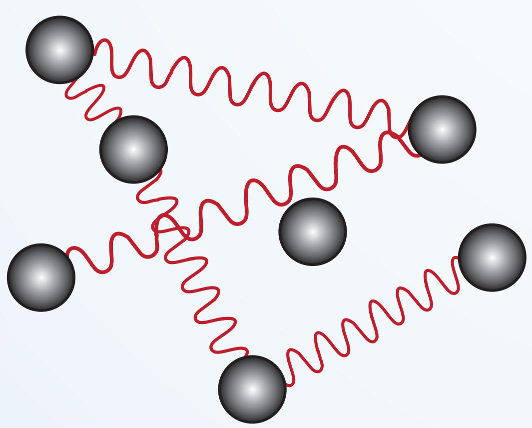


N-legged tensor

d^N

N



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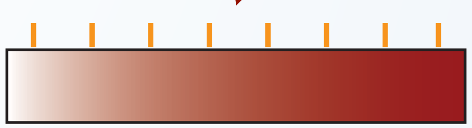

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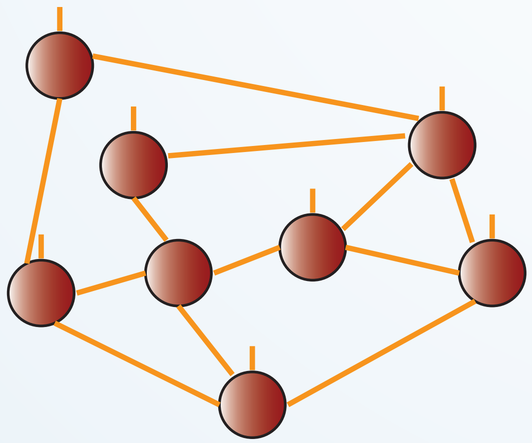


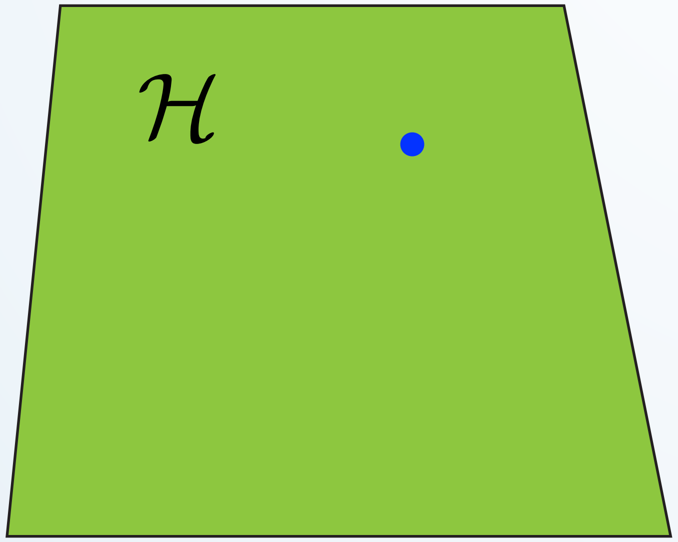
$\mathrm{poly}(N)$

A TNS has only a polynomial number of parameters

WHY SHOULD TNS BE USEFUL?

States appearing in Nature are peculiar

State at random from Hilbert space is not close to product



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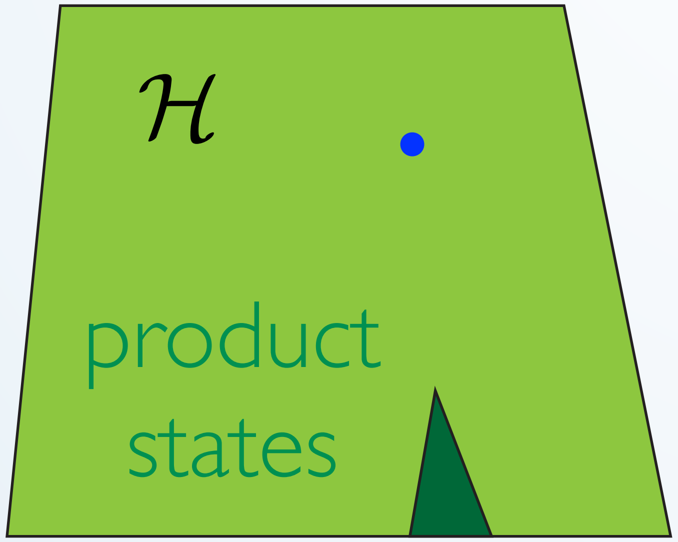

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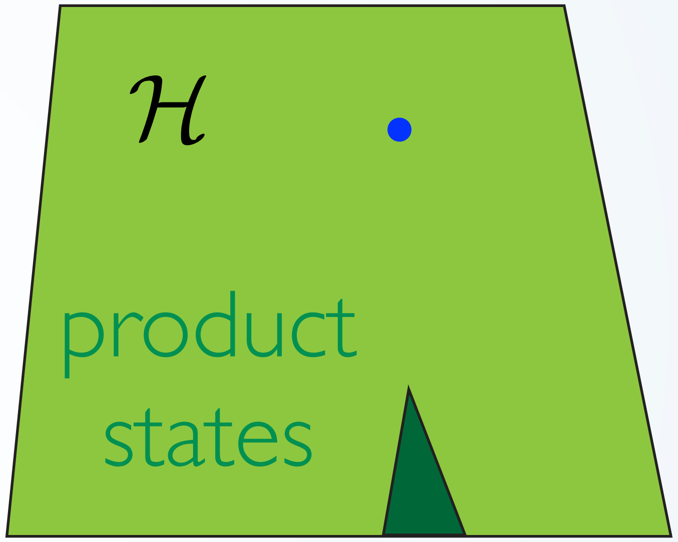

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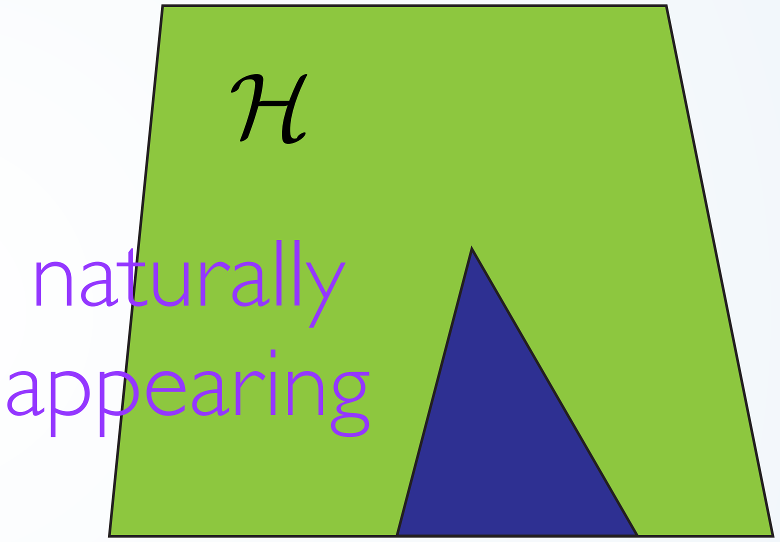

We look for the particular corner of the Hilbert space

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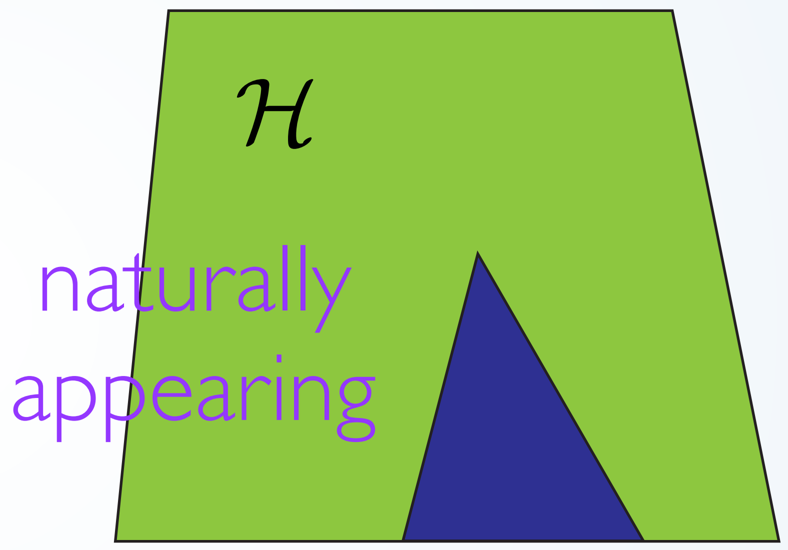

We look for states with *little* entanglement

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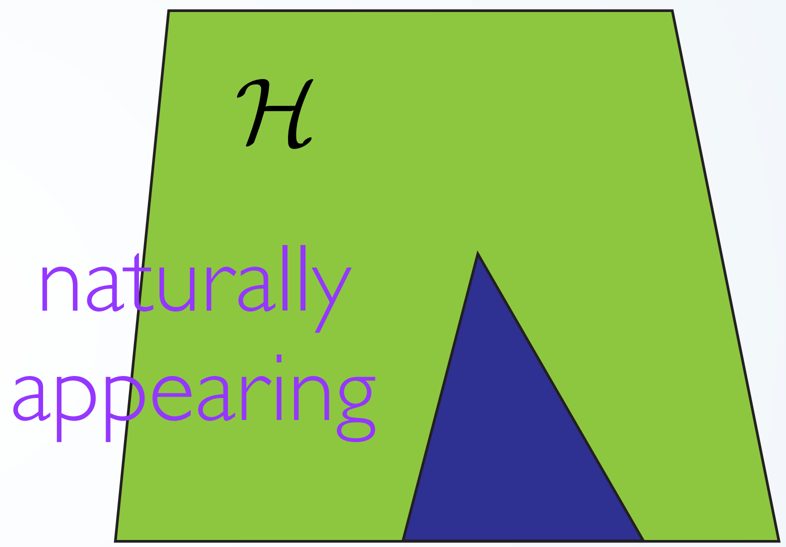
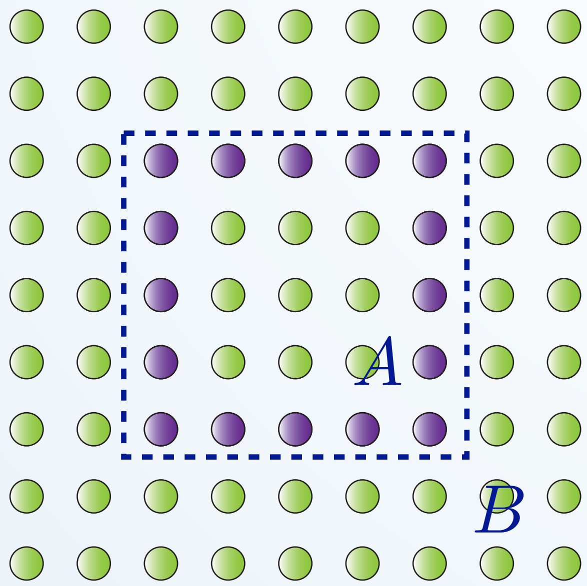


area law



Hastings 2007

Calabrese, Cardy 2004; Wolf 2006

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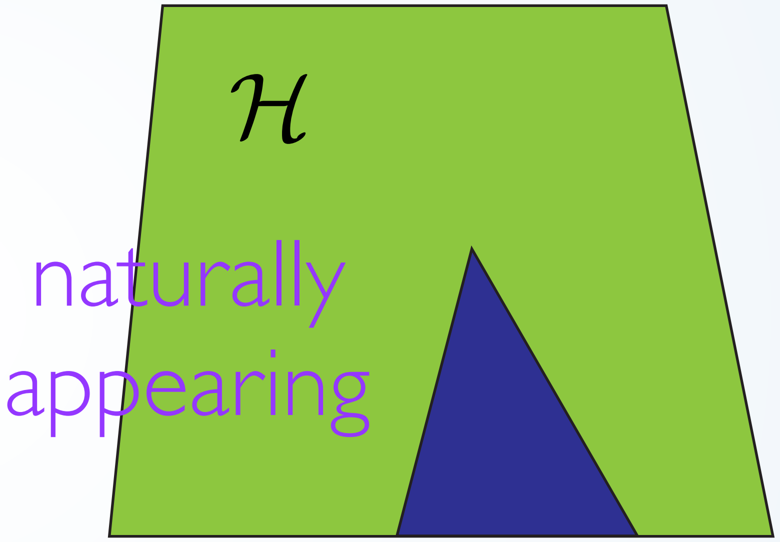

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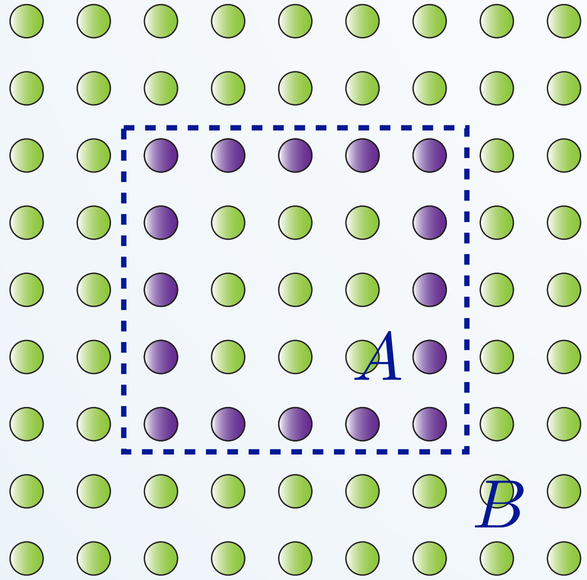

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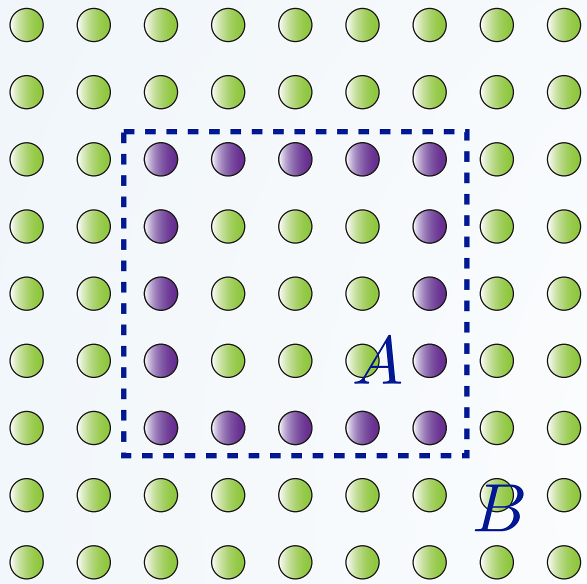

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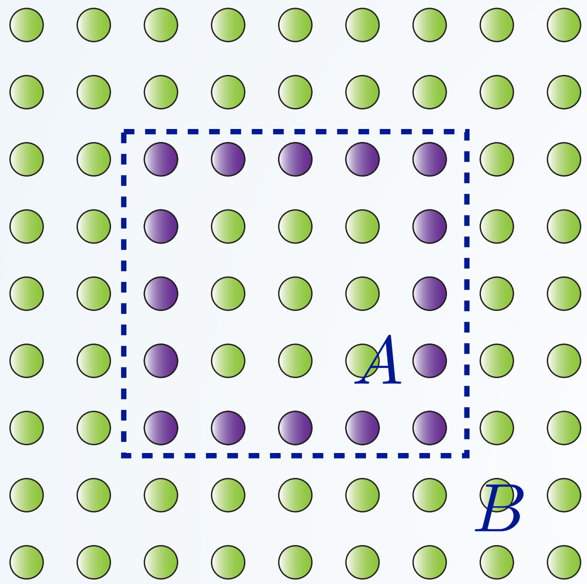

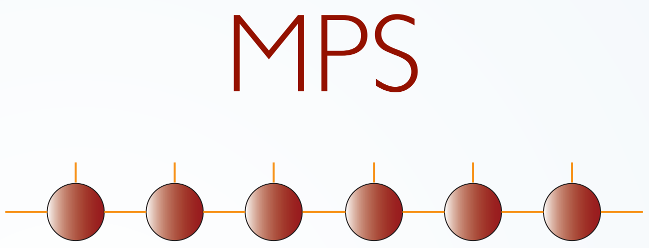

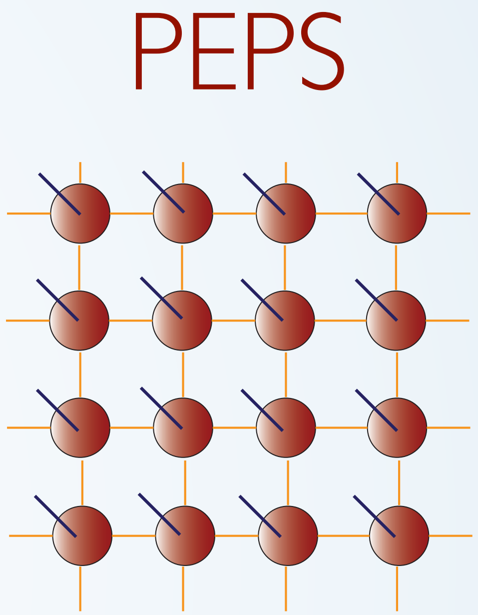

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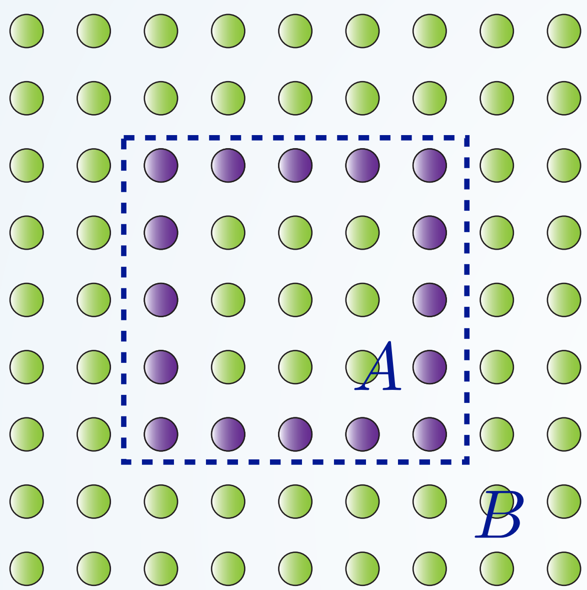
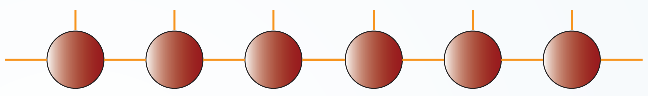
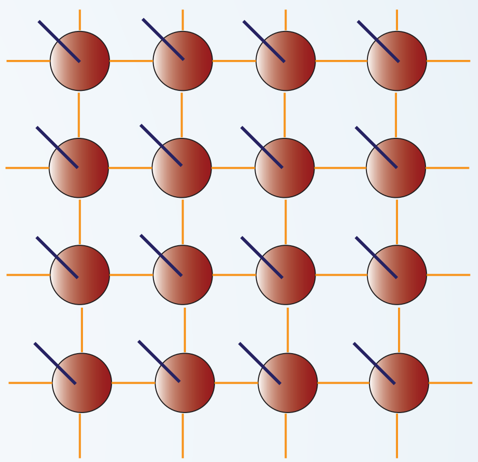


MPS



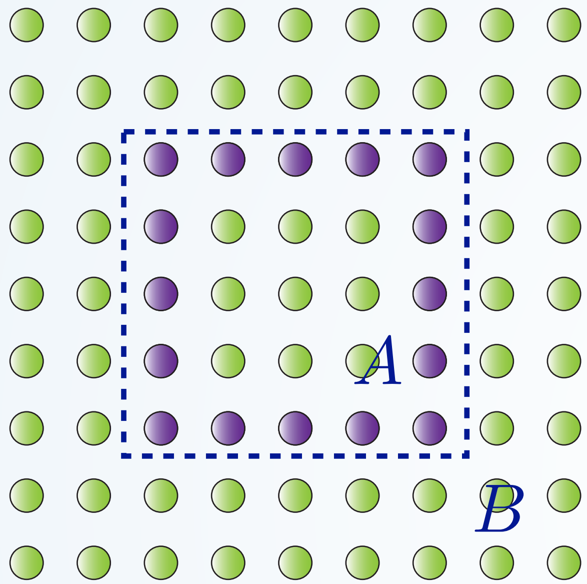
PEPS



other TNS

TNS = entanglement based ansatz

area law



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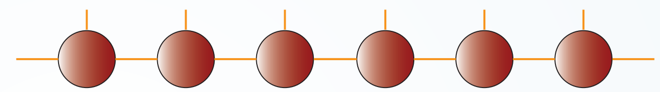

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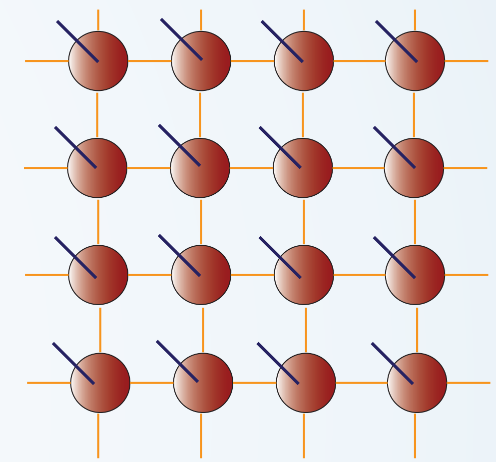
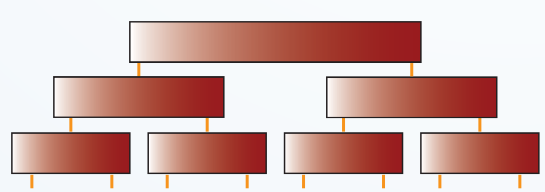
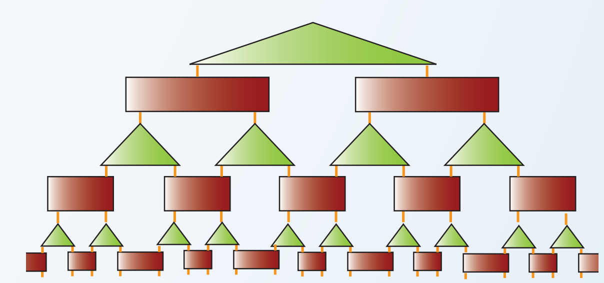


other TNS

TTN



MERA



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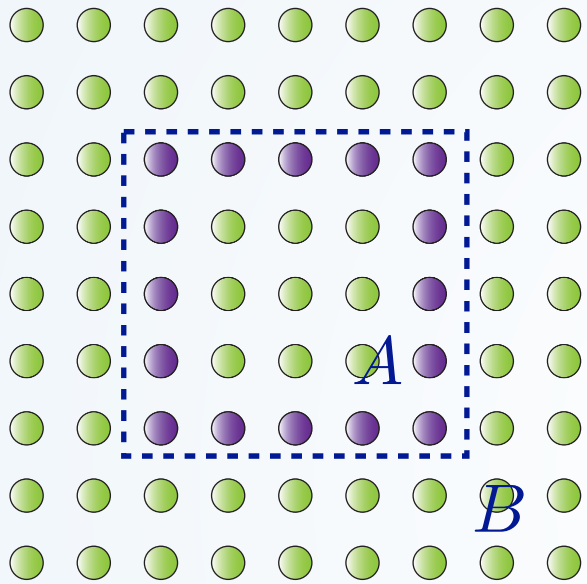

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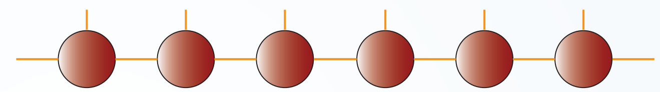

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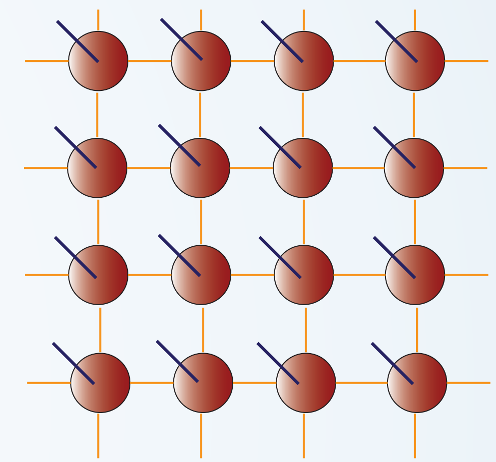
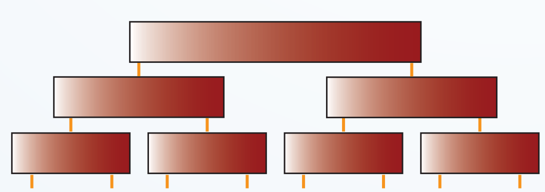


other TNS

TTN



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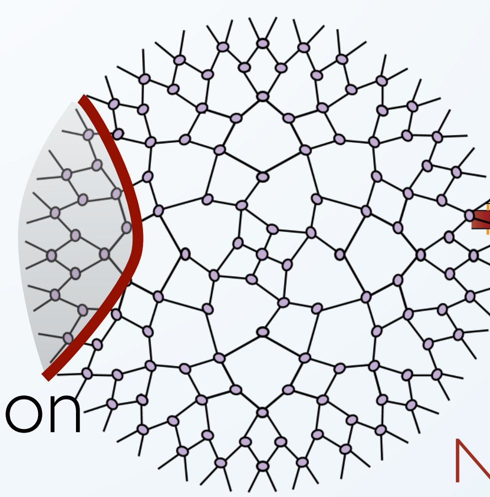
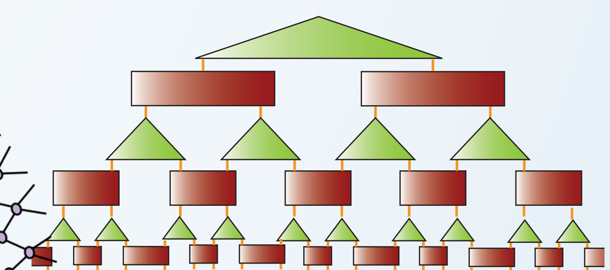
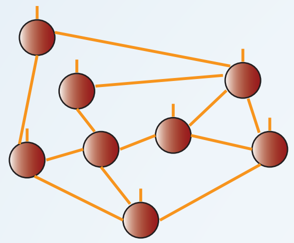




suggested connection
to AdS/CFT

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

WHY FOR LGT?



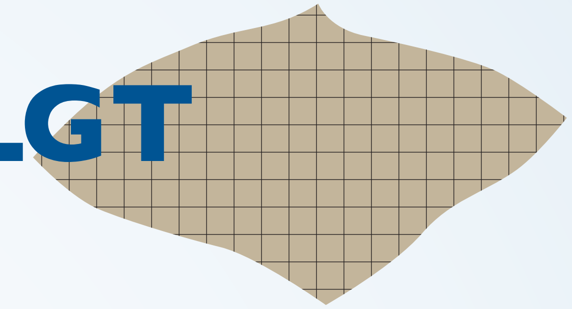
TNS

Non-perturbative for Hamiltonian systems

Extremely successful for 1D systems (MPS)

Promising improvements for higher dimensions

ground states
low-lying excitations
thermal states
time evolution



LGT

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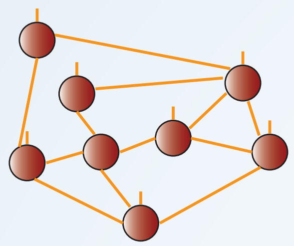

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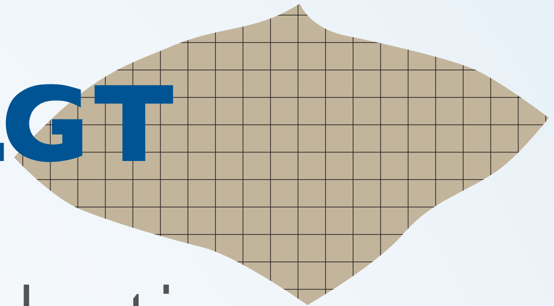

LGT

Non-perturbative way of solving QFT (QCD)

Mostly path-integral formalism & MC

4D lattice

spectrum
finite T
64^3x96
chemical potential
time evolution

USING TNS FOR LGT

USING TNS FOR QMB

a formal approach

no sign problem

numerical algorithms

USING TNS FOR QMB

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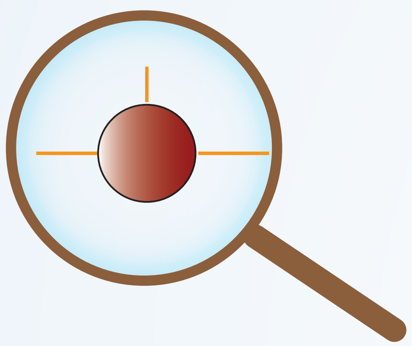

classifying tensors

constructing states

Chen et al PRB 2011
Schuch et al PRB 2011
Wahl et al PRL 2013; Yang et al PRL 2015
Haegeman et al, Nat. Comm. 2015

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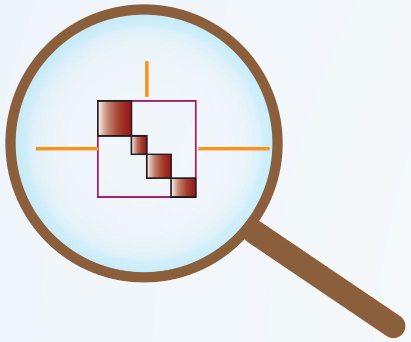

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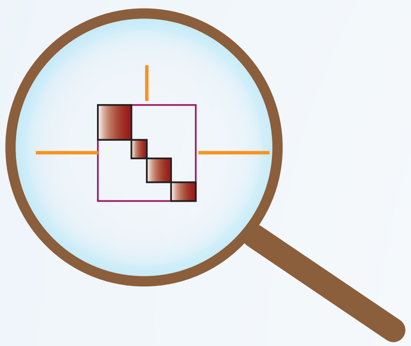

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great descriptive power: phases, topological chiral states, anyons...

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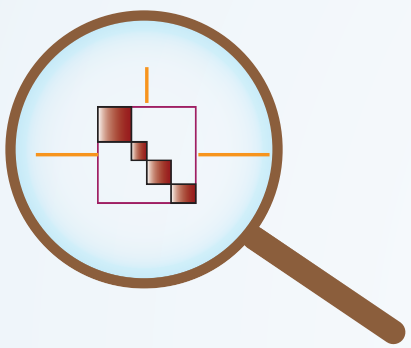

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tensor networks describe
partition functions (observables)

need to contract a TN
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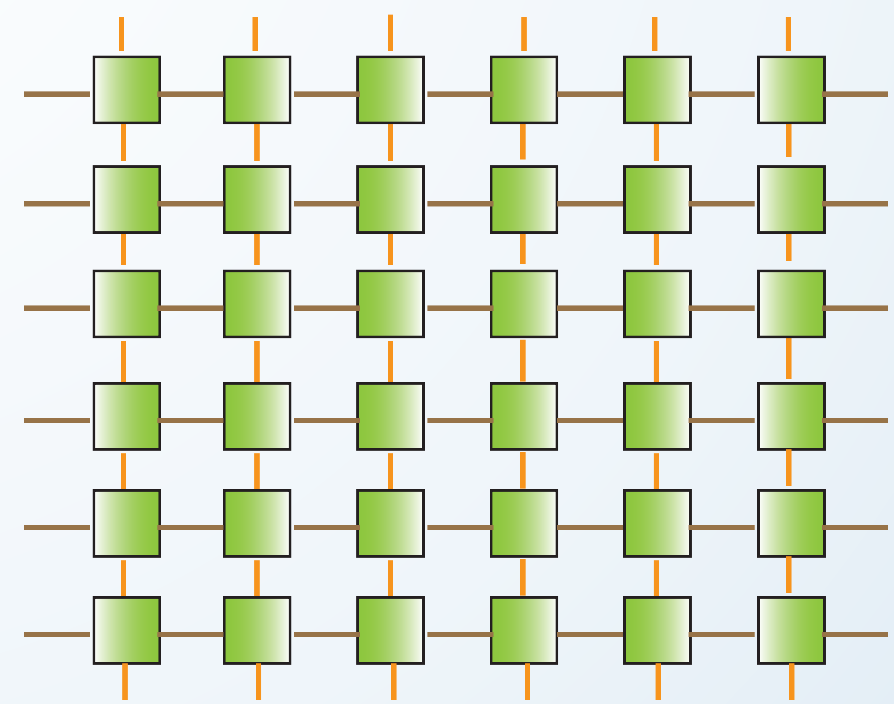

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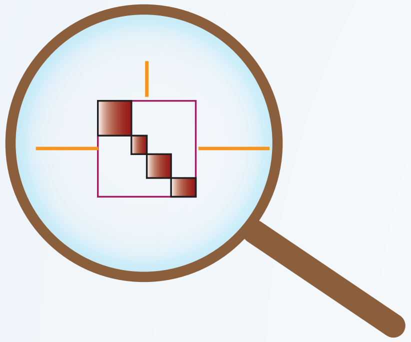

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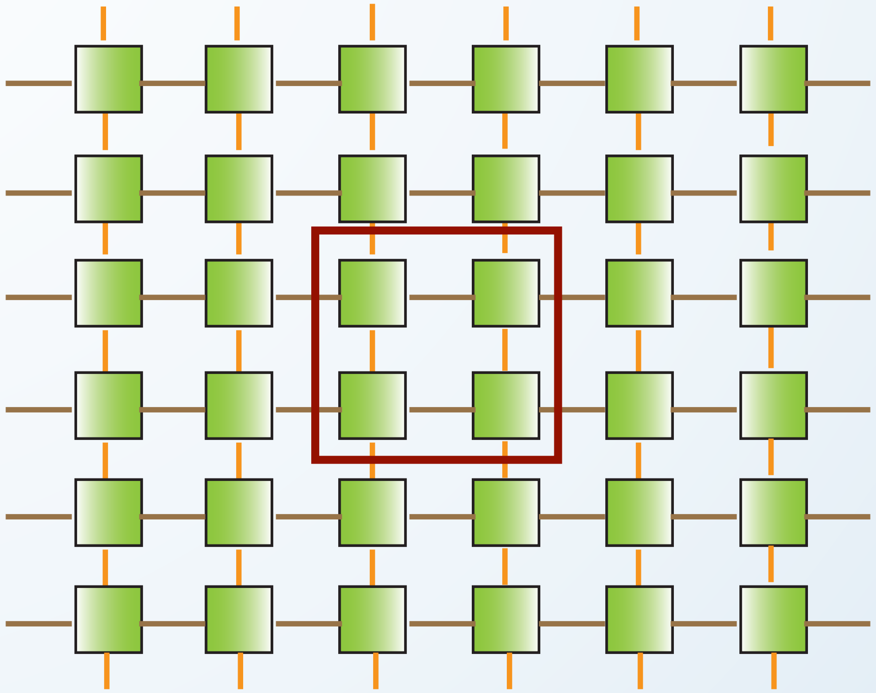

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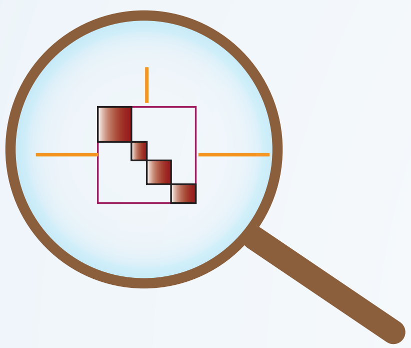

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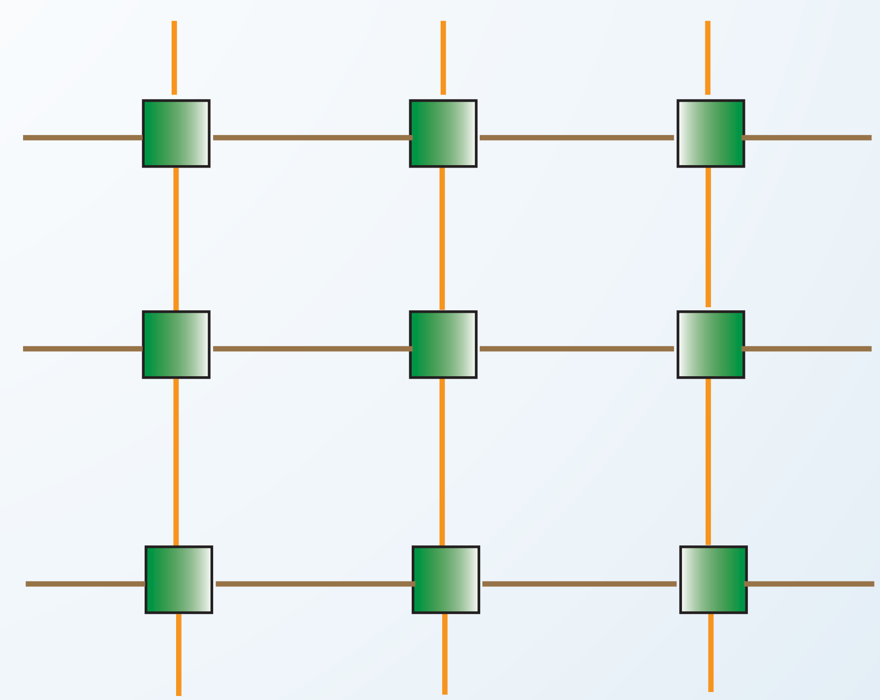

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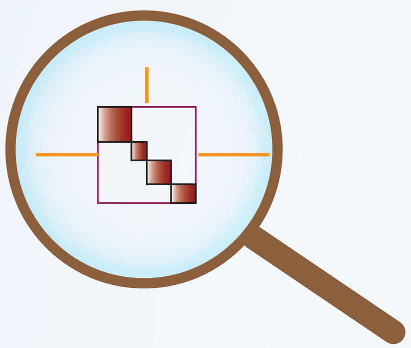

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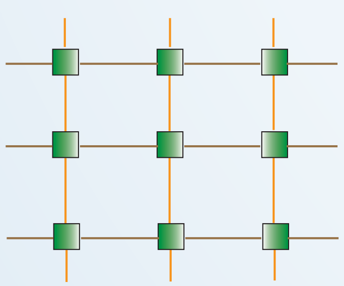

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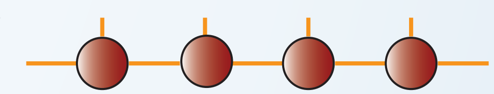

TNS as ansatz for the state

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

White PRL 1992; Schollwöck RMP 2011
Vidal PRL 2003; Verstraete et al PRL 2004
Verstraete et al Adv Phys 2008; Orús Ann Phys 2014

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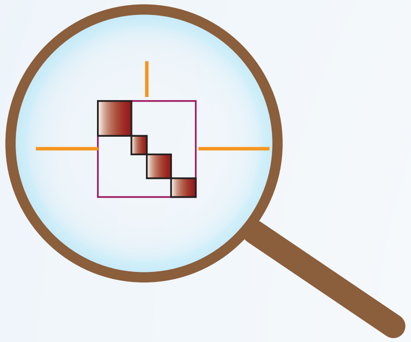

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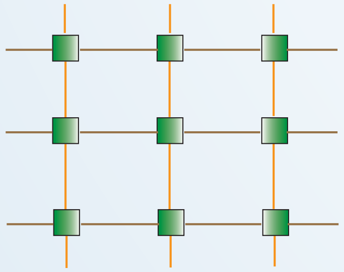

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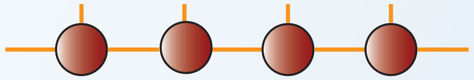

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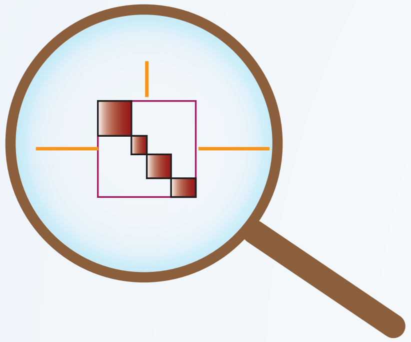

gauging the symmetry

explicitly invariant states

general prescriptions, U(1), SU(2)

Tagliacozzo et al PRX 2014
Haegeman et al PRX 2014
Zohar et al Ann Phys 2015

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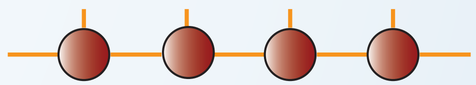

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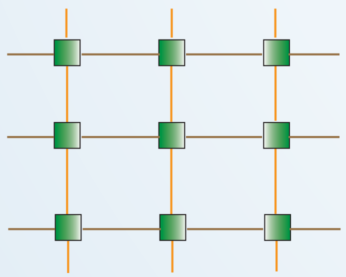
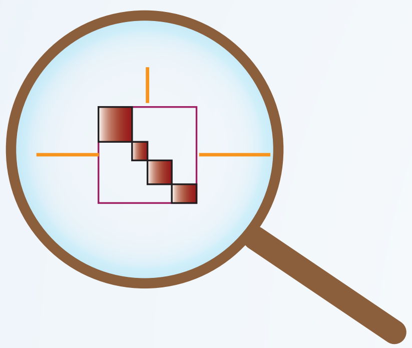


USING TNS FOR LGT

a formal approach



gauging the symmetry

explicitly invariant states

general prescriptions, U(1), SU(2)

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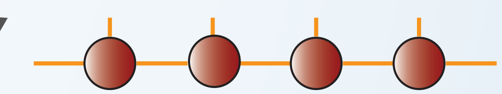
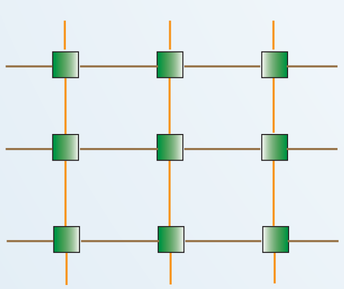
no sign problem

numerical algorithms

tensor networks describe partition functions (observables)

TNS as ansatz for the state





TRG approaches to classical and quantum models

Liu et al PRD 2013
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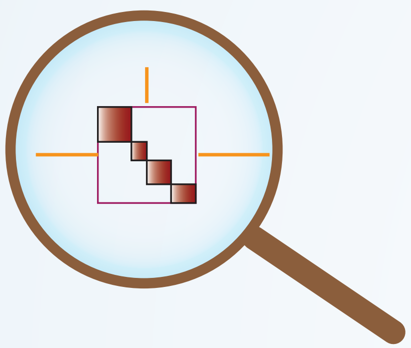

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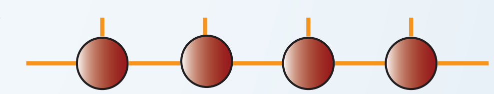

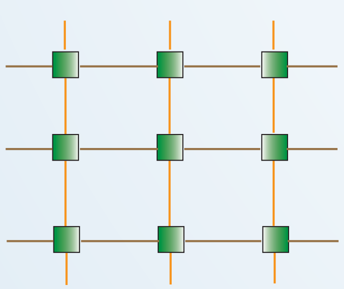

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next...

a possible LGT-TNS roadmap...

a wishful LGT-TNS roadmap...

full LQCD in 3+1 dimensions

a wishful LGT-TNS roadmap...

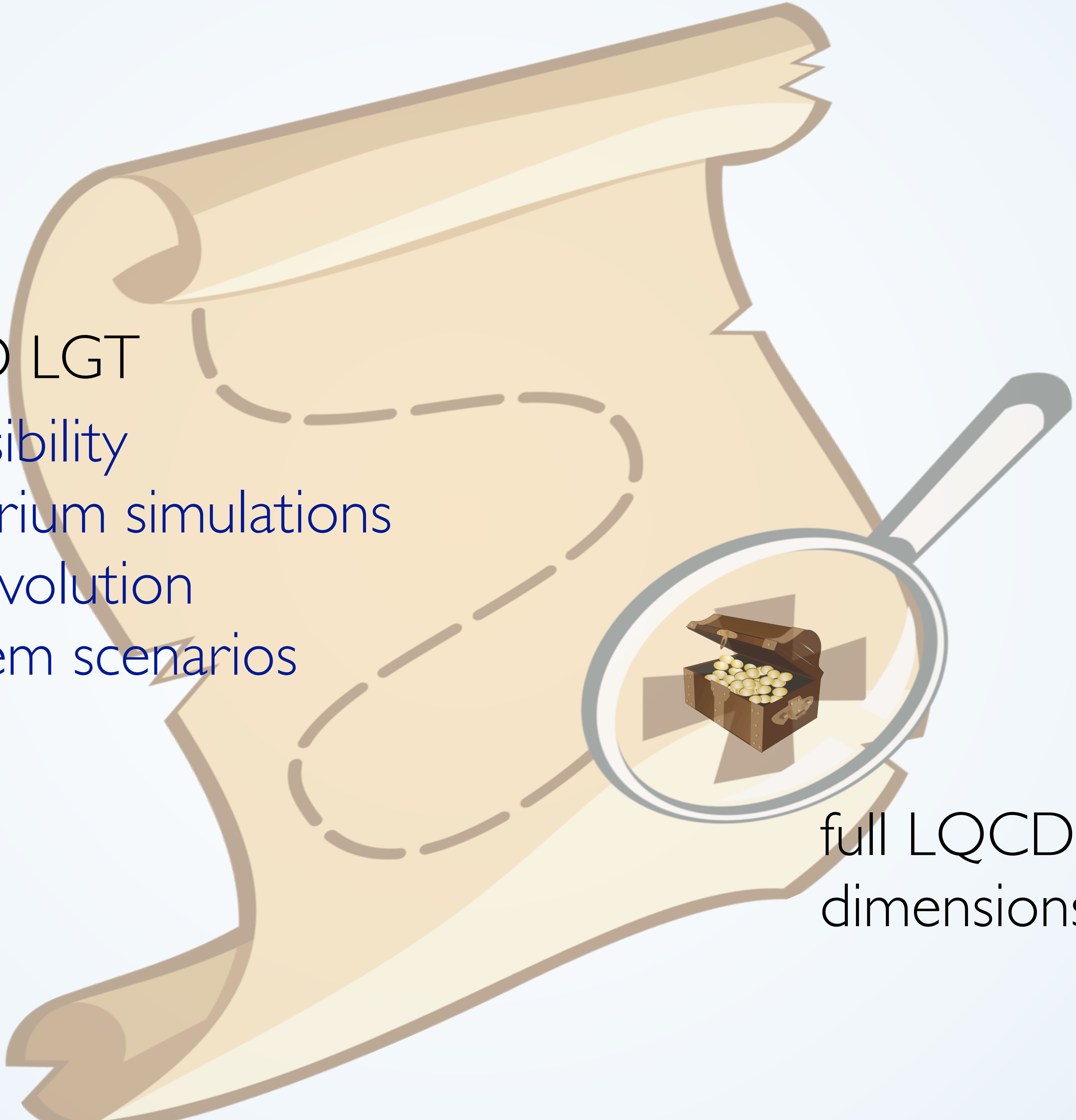
1+1D LGT

feasibility

precise equilibrium simulations

time evolution

sign problem scenarios



full LQCD in 3+1 dimensions

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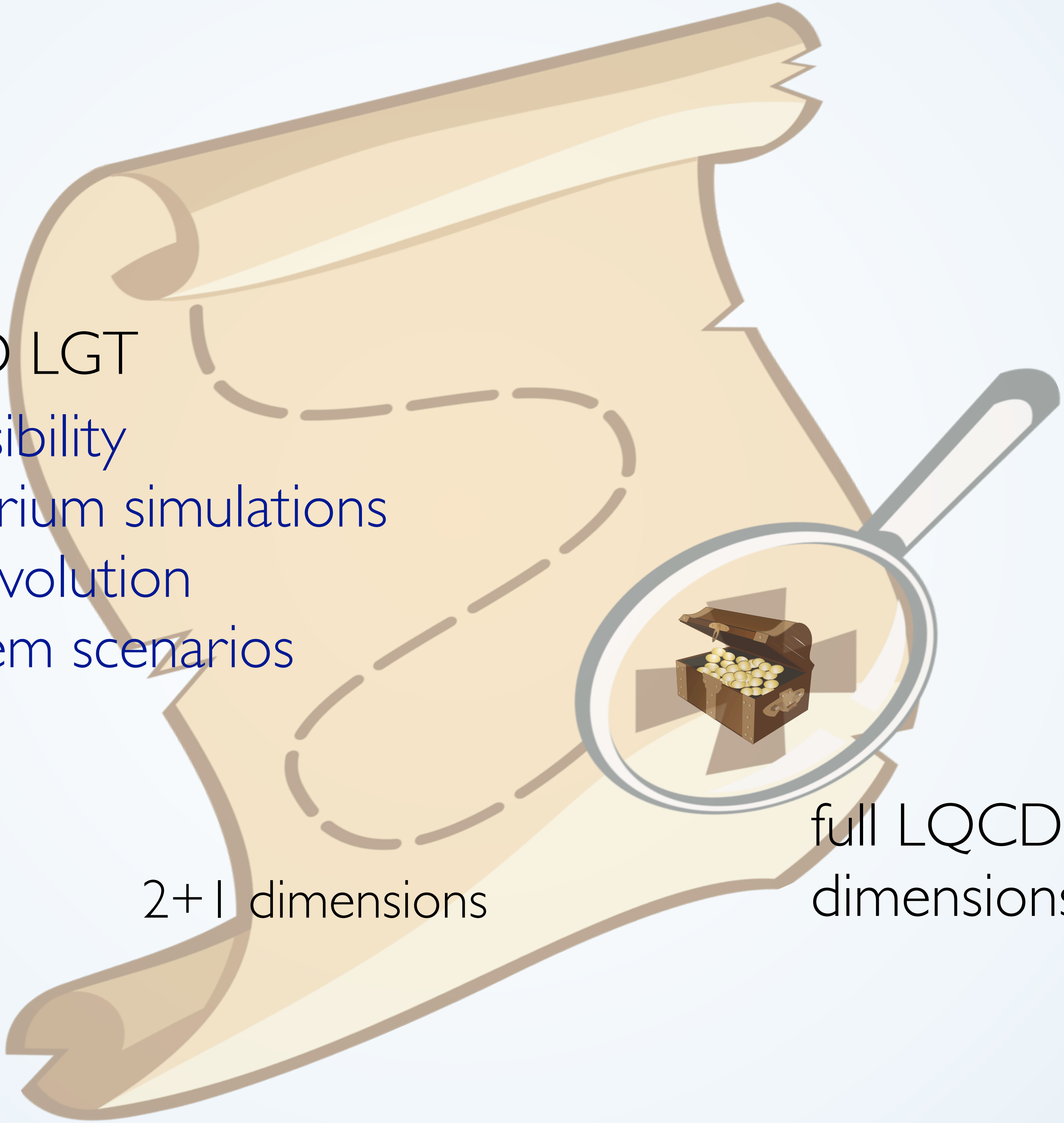

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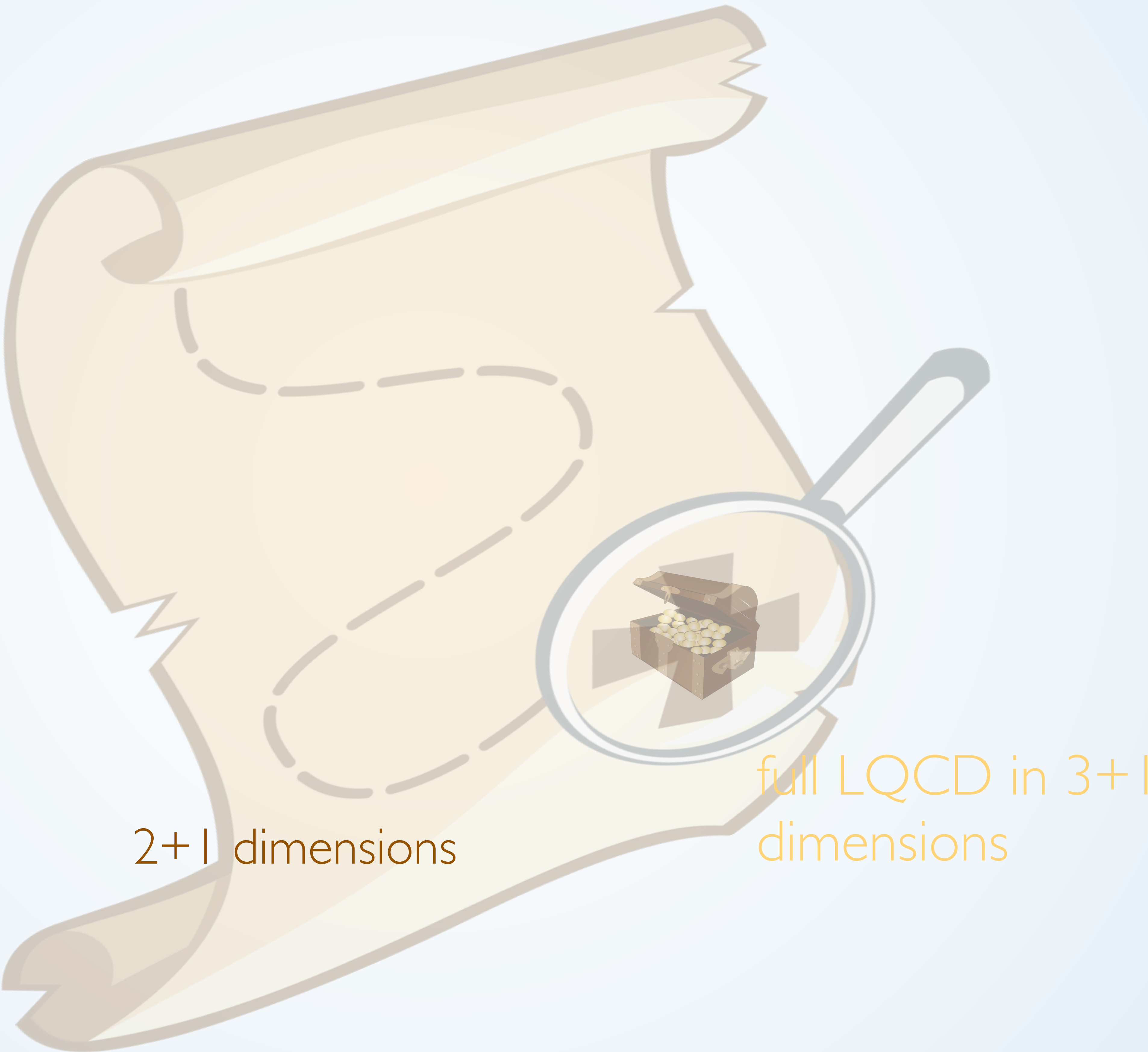
2+1 dimensions

full LQCD in 3+1 dimensions

an ongoing LGT-TNS roadmap...



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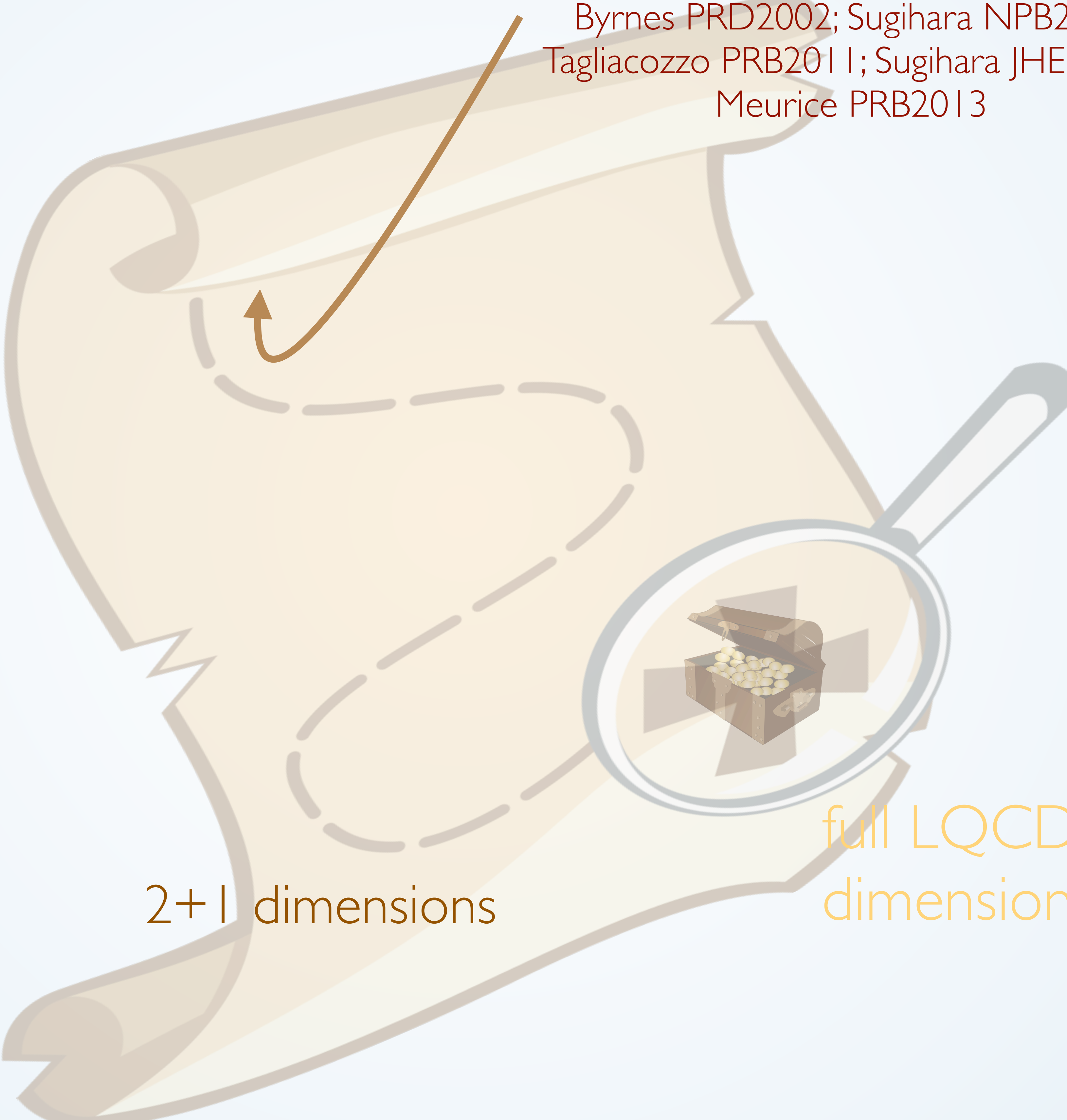

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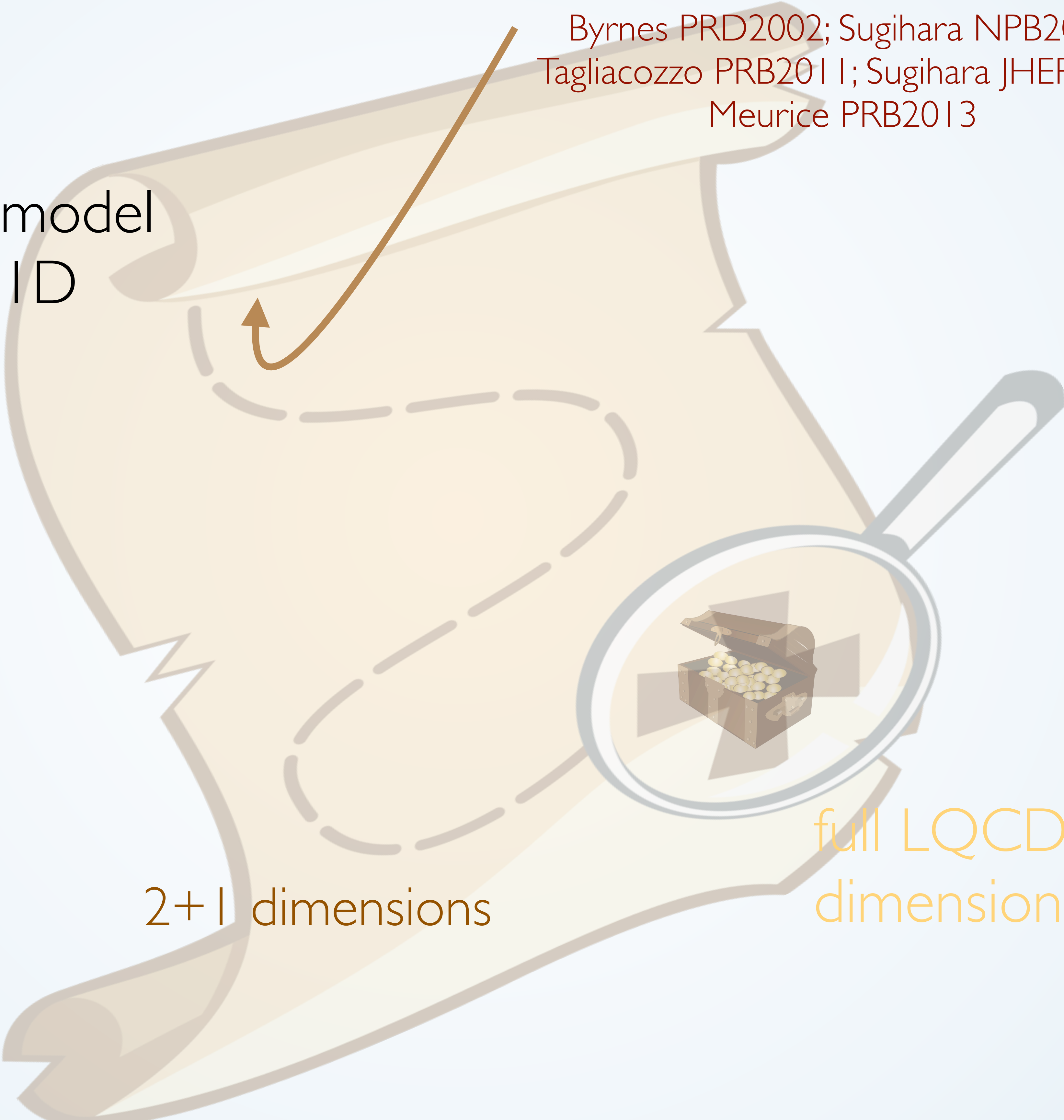

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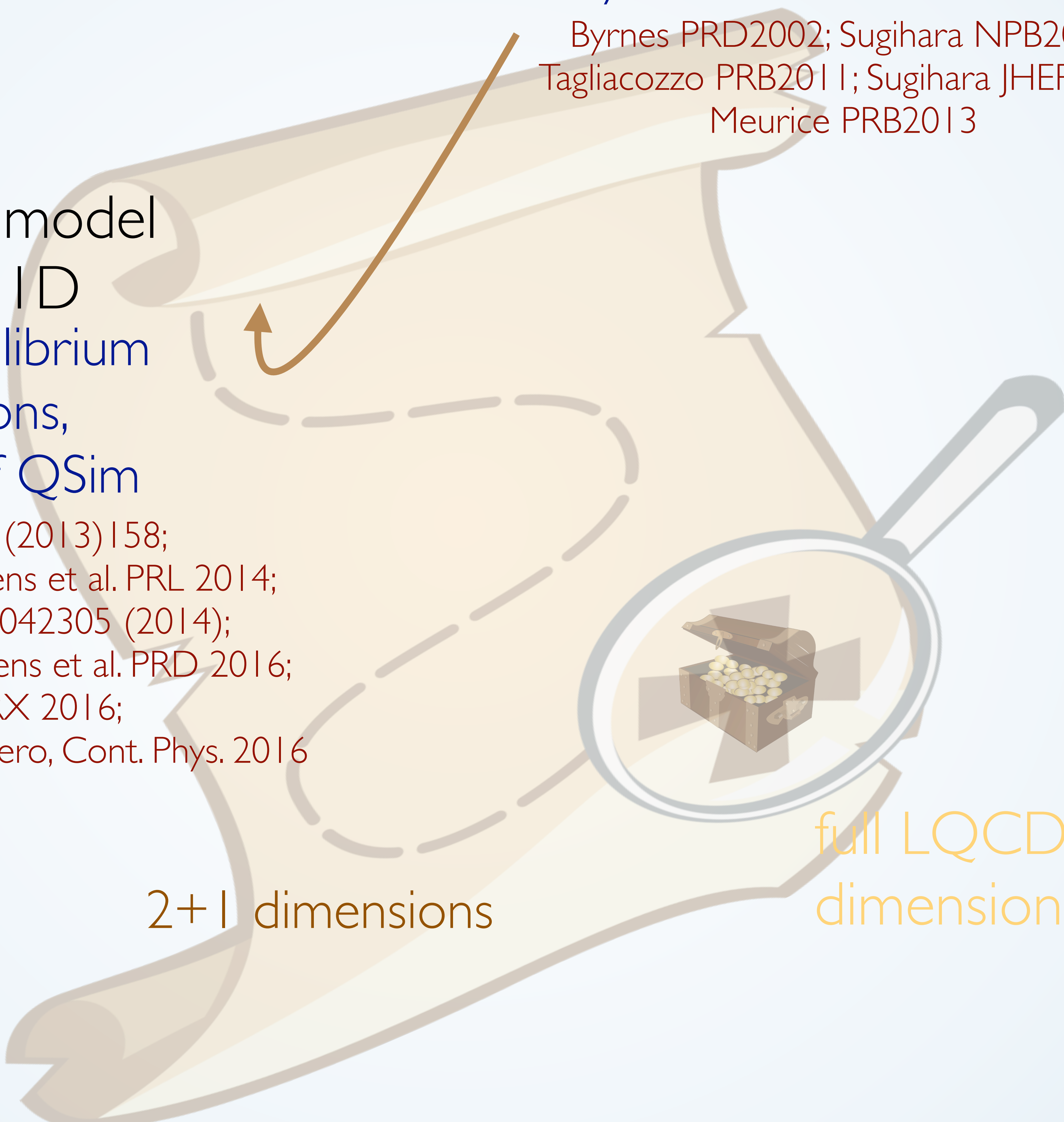

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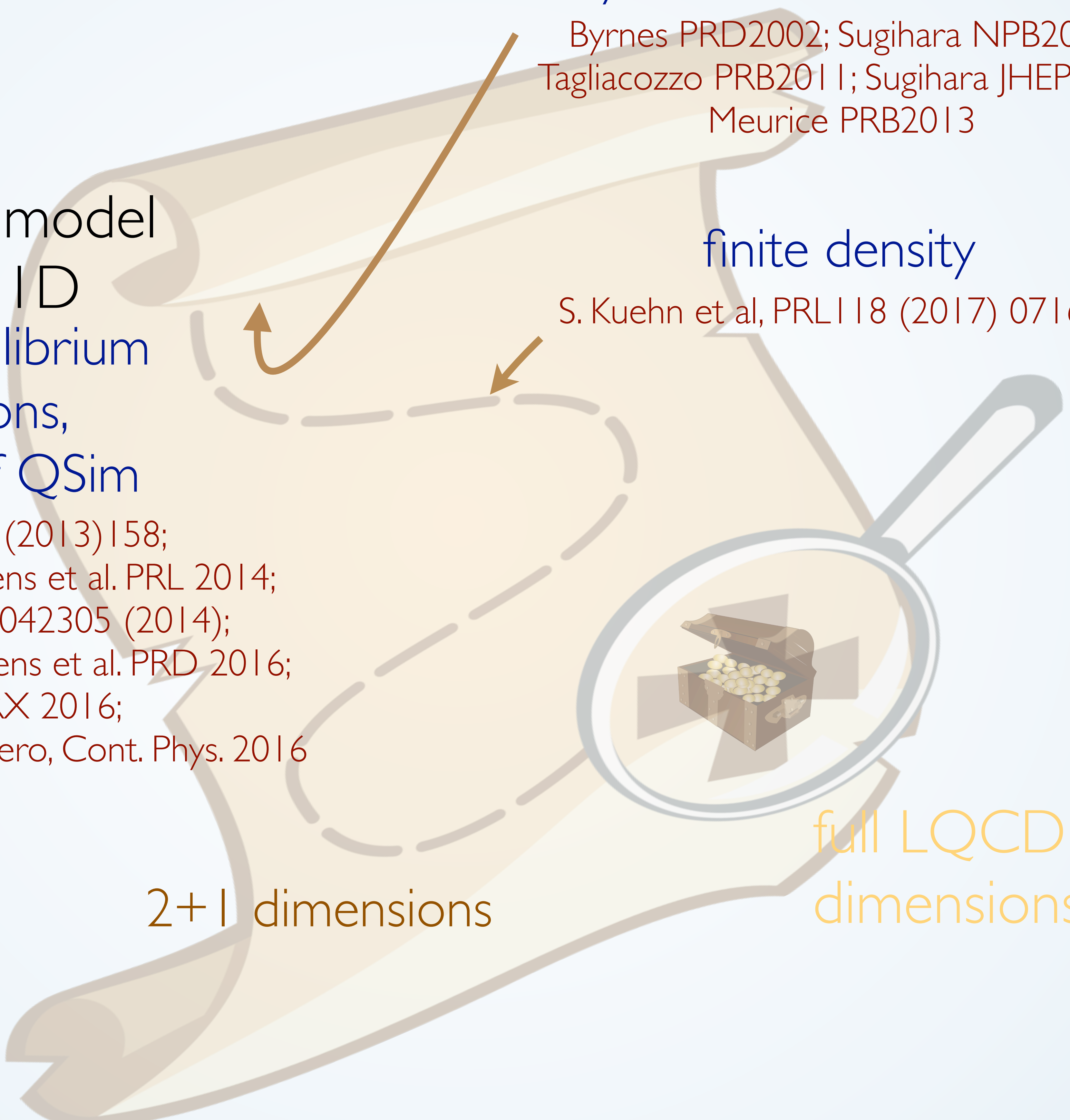

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other 1+1 D models

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SOLVING LGT WITH TNS

GENERAL STRATEGY

Hamiltonian formulation

- acting on a Hilbert space

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⟶ choose proper basis

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fermions

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- gauge bosons require attention
  - ⟶ truncating, integrating out (also QLinks)

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★ Common ingredients for quantum simulation

SCHWINGER MODEL

continuum

$$H = \int dx \left[-i\bar{\Psi}\gamma^1\partial_1\Psi + g\bar{\Psi}\gamma^1 A_1\Psi + m\bar{\Psi}\Psi + \tfrac{1}{2}E^2 \right]$$

plus constraint: Gauss' Law

$$\partial_1 E = g\bar{\Psi}\gamma^0\Psi$$

SCHWINGER MODEL

discretized

$$H = -\frac{i}{2a}\sum_n \left(\phi_n^\dagger e^{i\theta_n}\phi_{n+1} - \text{h.c.}\right) + m\sum_n (-1)^n \phi_n^\dagger \phi_n + \frac{ag^2}{2}\sum_n L_n^2$$

plus constraint: Gauss' Law

$$L_n - L_{n-1} = \phi_n^\dagger \phi_n - \frac{1}{2}\left[1 - (-1)^n\right]$$

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$$|\ldots s_e\, \ell\, s_o\, \ell\, s_e\, \ell\, s_o \ldots\rangle$$

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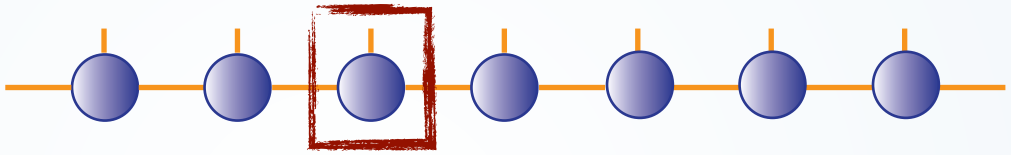
work directly in the physical subspace

MCB, Cichy, Cirac, Jansen JHEP11(2013)158

SPECTRUM

COMPUTING THE LOW ENERGY LEVELS

Efficient algorithms to find ground state and excitations

$|E_0\rangle \simeq$ 

variational, imaginary time...

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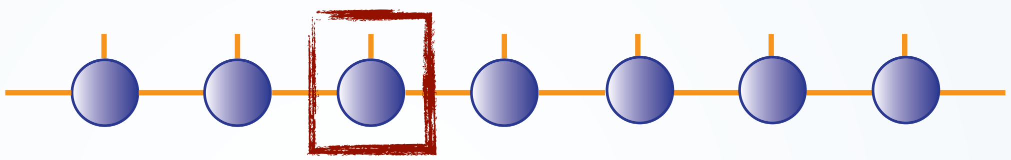
$|E_0\rangle \simeq$ 

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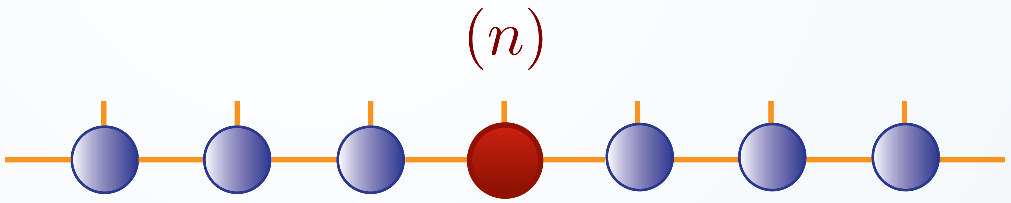
$\sum_n e^{ikn}$ 

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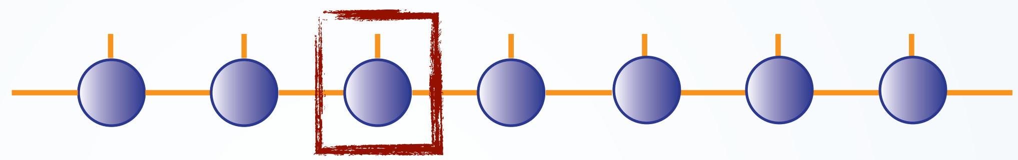
$|E_0\rangle \simeq$ 

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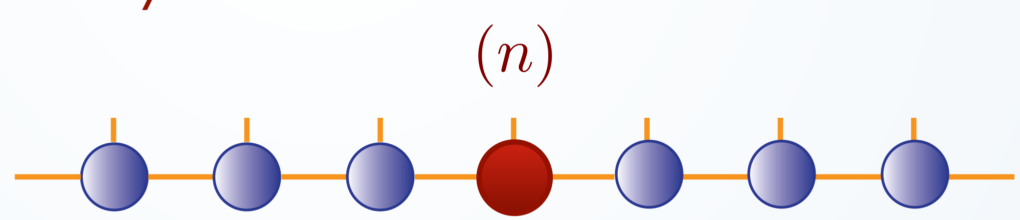
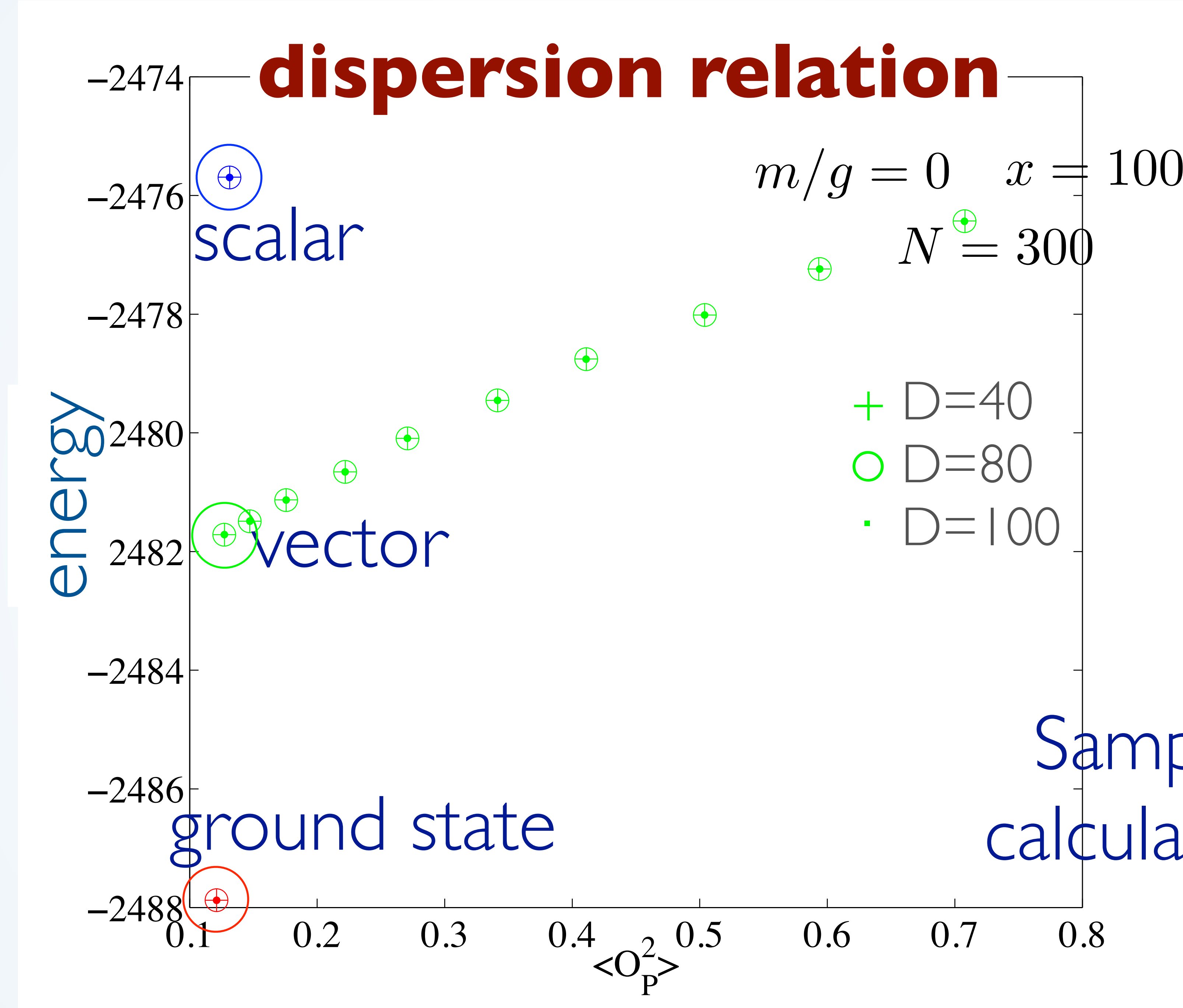
$\sum_n e^{ikn}$ 

Different strategies possible for LGT

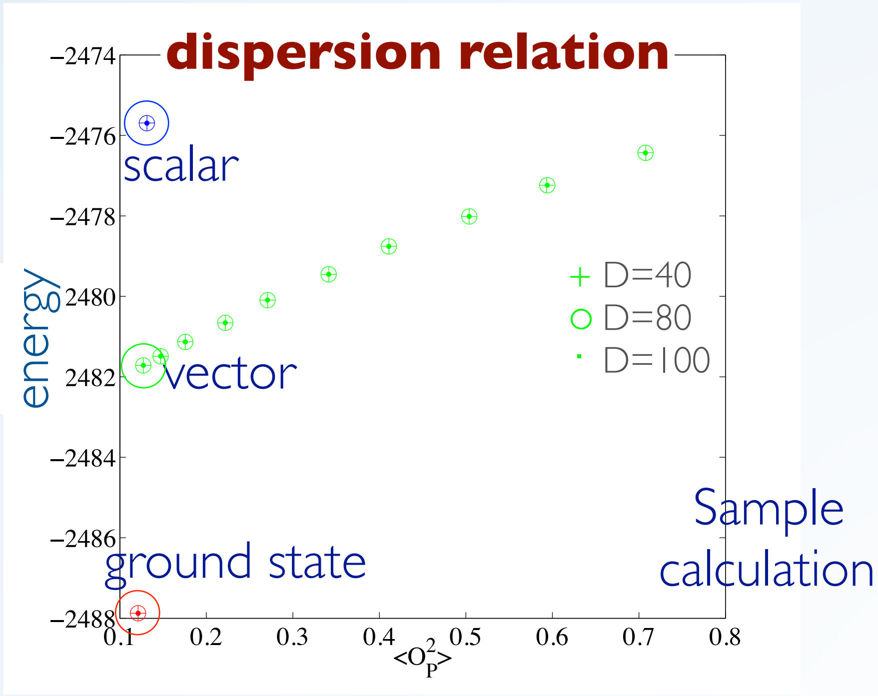
truncate the gauge dof, integrate out

explicit symmetries in tensors



Sample calculation

MCB, Cichy, Cirac, Jansen JHEP11(2013)158
Buyens et al. PRL113 (2014) 091601



$$m/g = 0 \quad x = 100$$

$$N = 300$$

MCB, Cichy, Cirac, Jansen JHEP11(2013)158
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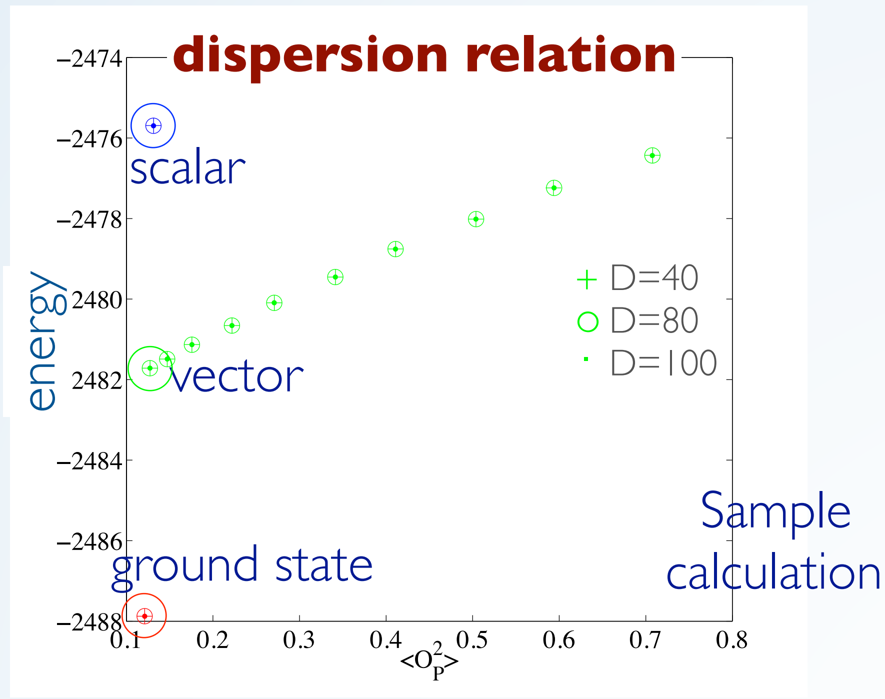

after the continuum limit

m/g

$x \to \infty$

x

finite-size

infinite chain

N

convergence

D

very precise for all masses

m/g	DMRG	MPS with OBC	SCE	MPS with OBC
0	0.5641859	0.56414(26)	1,128379	1.1283(10)
125	0.53950(7)	0.53946(20)	1.22(2)	1.221(2)
0.25	0.51918(5)	0.51915(14)	1.24(3)	1.239(6)
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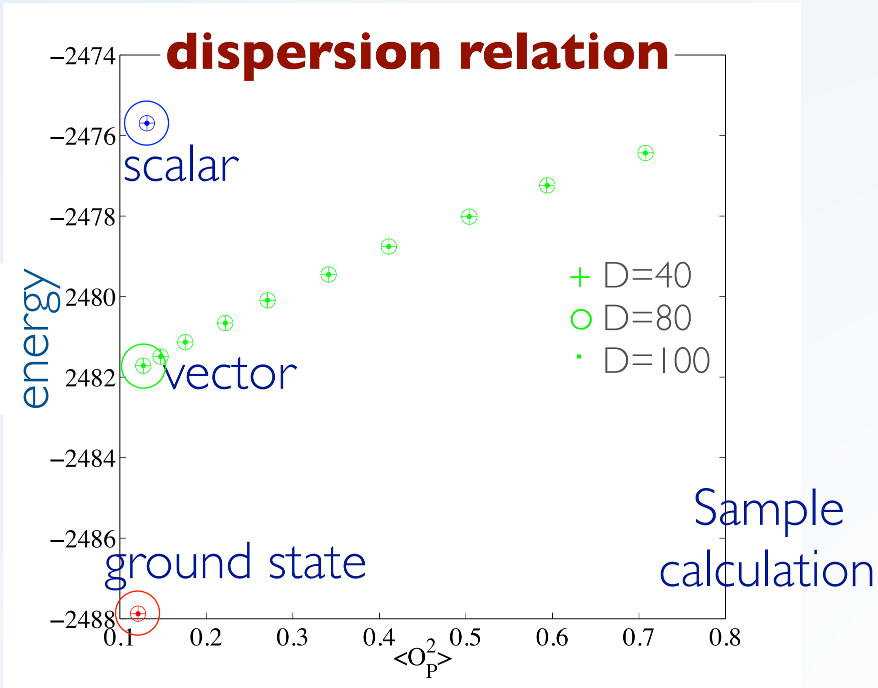

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also for SU(2) LGT

MCB, Cichy, Cirac, Jansen, Kühn PRX 7, 041046 (2017)

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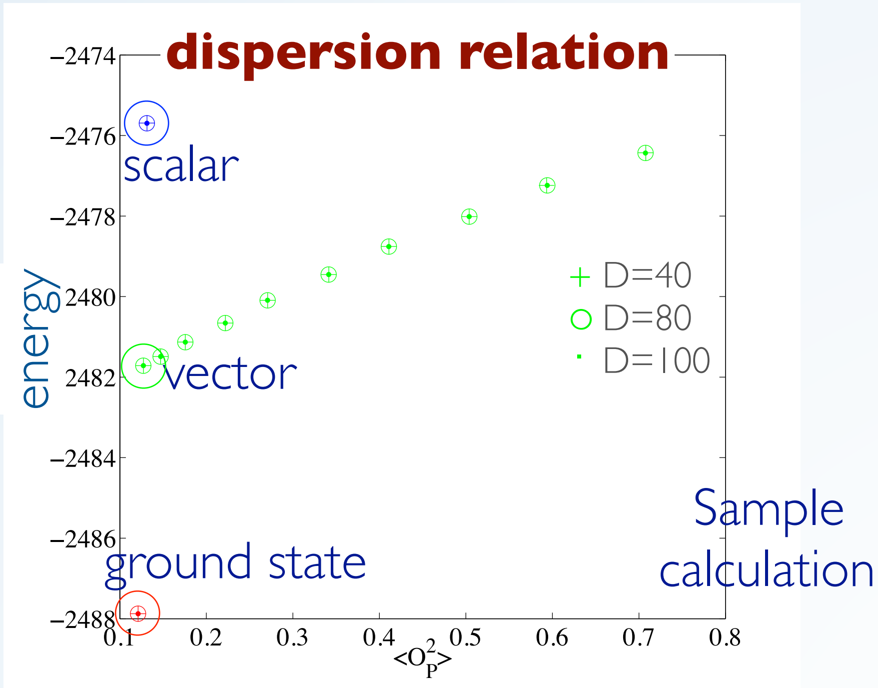

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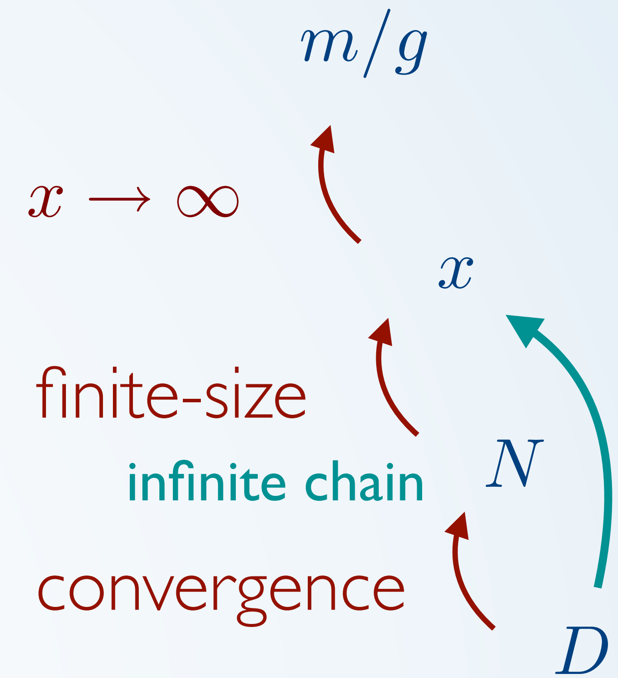

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MCB, Cichy, Cirac, Jansen, Kühn PRX 7, 041046 (2017)

real time, too

Buyens et al. PRL113 (2014) 091601, PRD96 (2017) 114501

MCB, Cichy, Cirac, Jansen JHEP11(2013)158
Buyens et al. PRL113 (2014) 091601

ENTROPY

Entropy can be efficiently computed from MPS state

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gauge constraints not purely local ⇒ not all entropy physical

Casini et al 2014; Gosh et al JHEP 2015
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SU(2)

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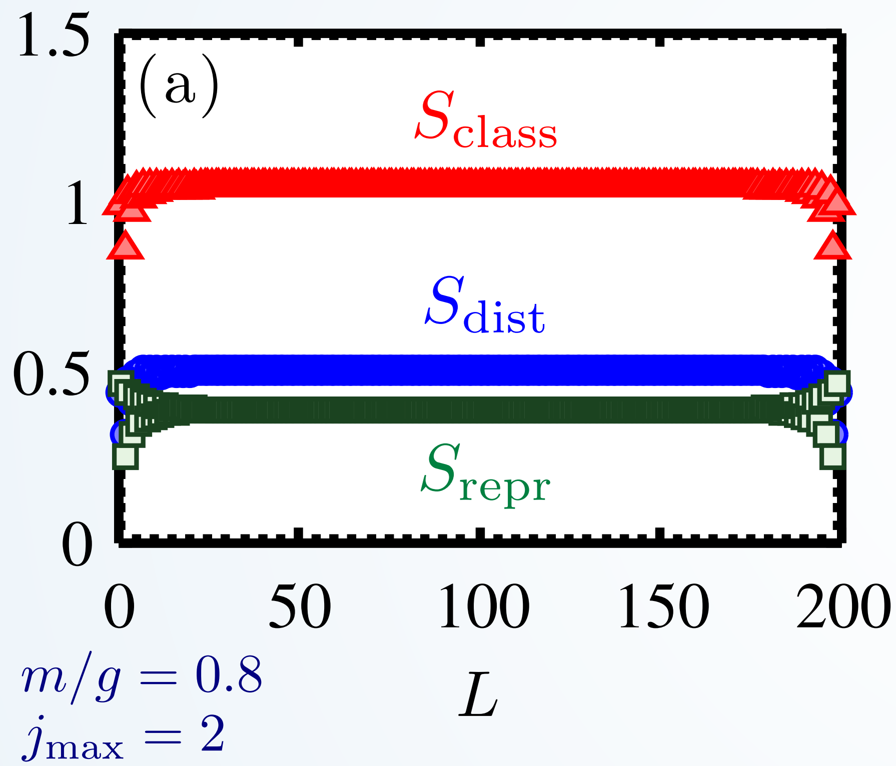

PRX7, 041046 (2017)

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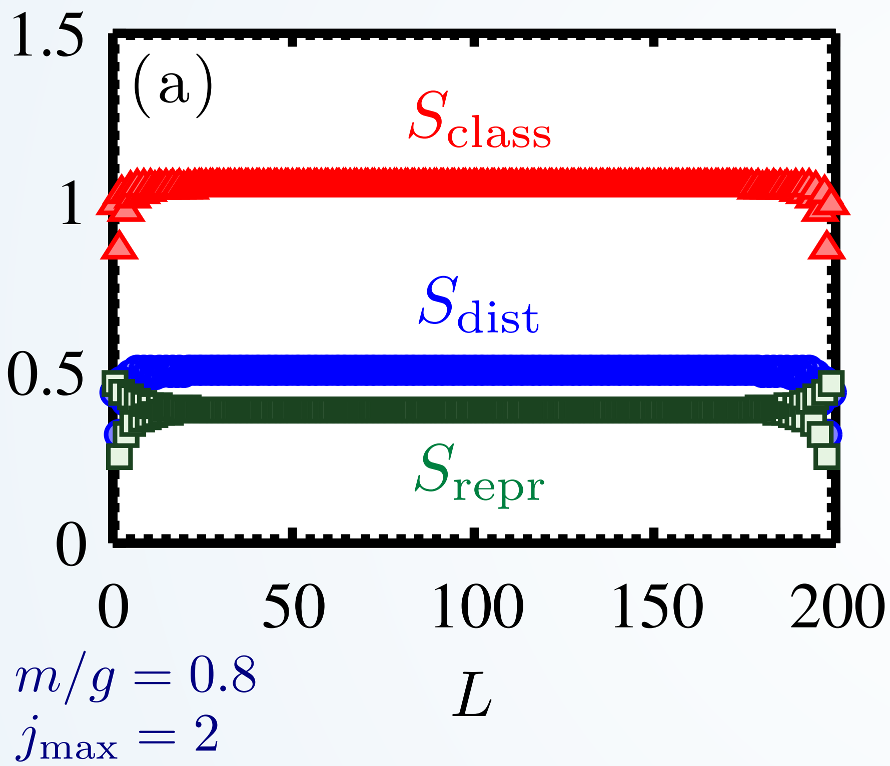

PRX7, 041046 (2017)

divergence in the continuum limit

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

Calabrese, Cardy JStatMech 2004

Entropy can be efficiently computed from MPS state

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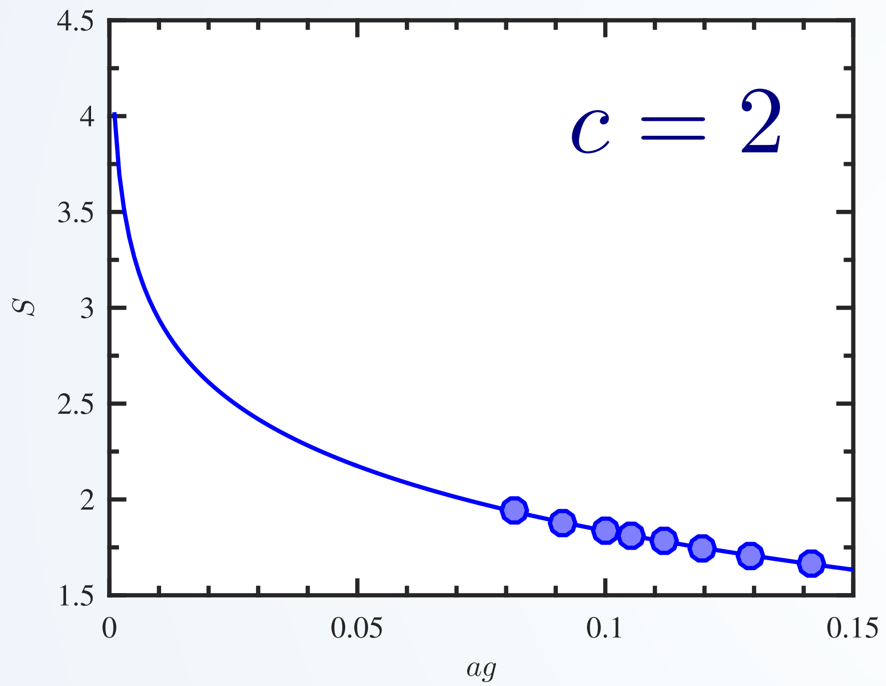

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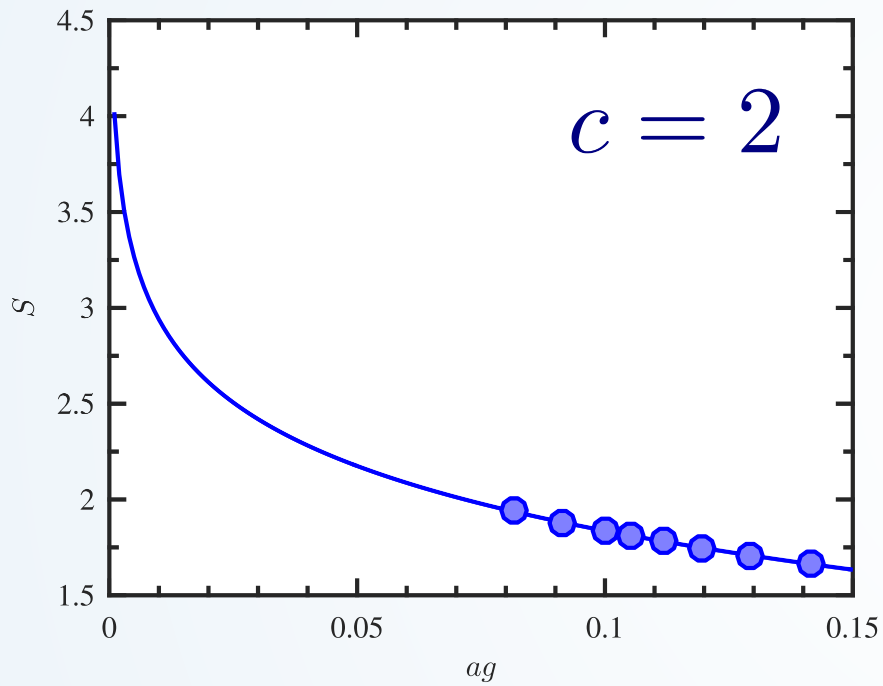
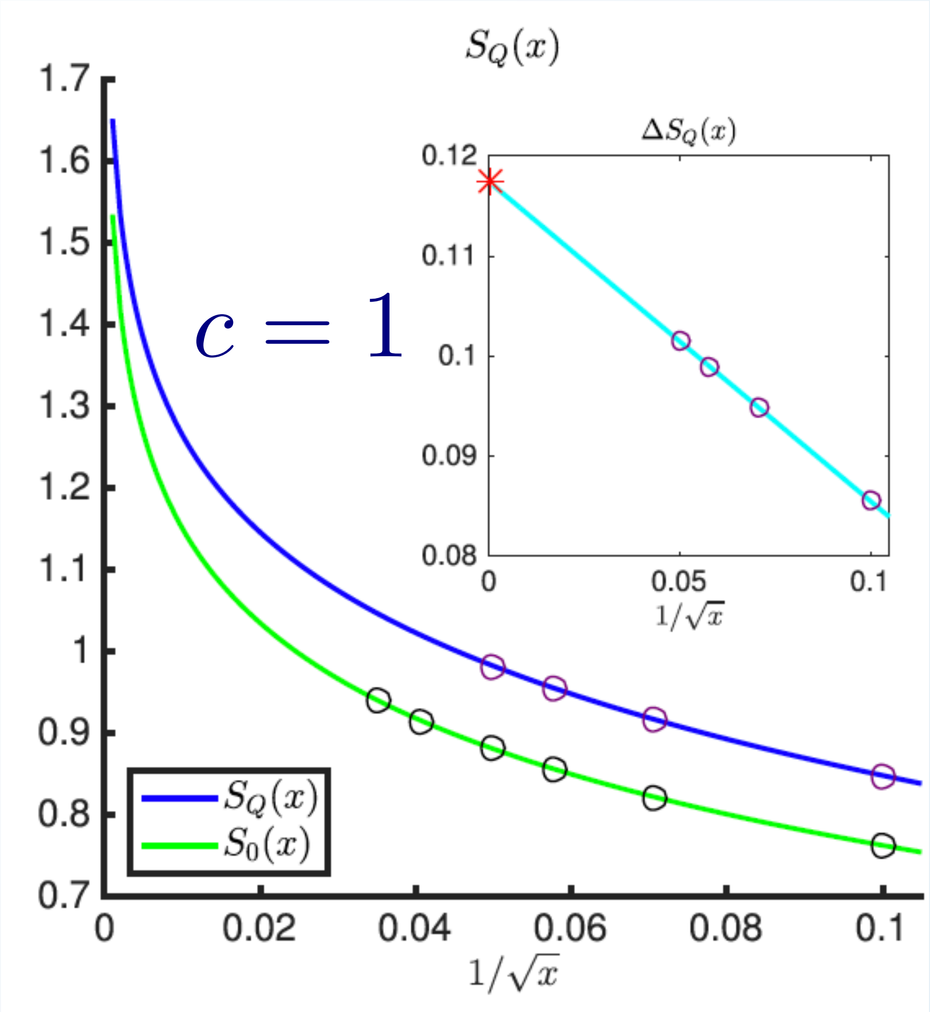


PRX7, 041046 (2017)

Schwinger



Buyens PRX6, 041040 (2016)

divergence in the continuum limit

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

Calabrese, Cardy JStatMech 2004

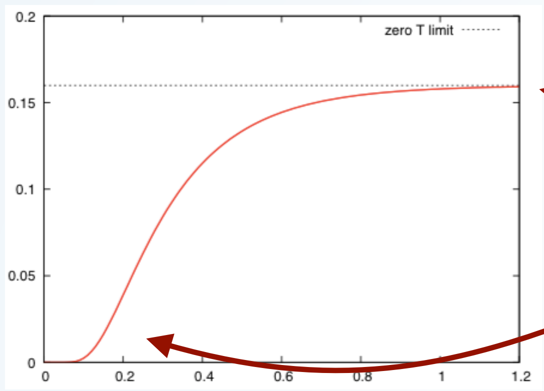
THERMAL EQUILIBRIUM

THERMAL PROPERTIES SCHWINGER

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

Sachs, Wipf 92

$\frac{\Sigma}{g}$



$T \to 0$

$T \to \infty$

THERMAL PROPERTIES SCHWINGER

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Sachs, Wipf 92

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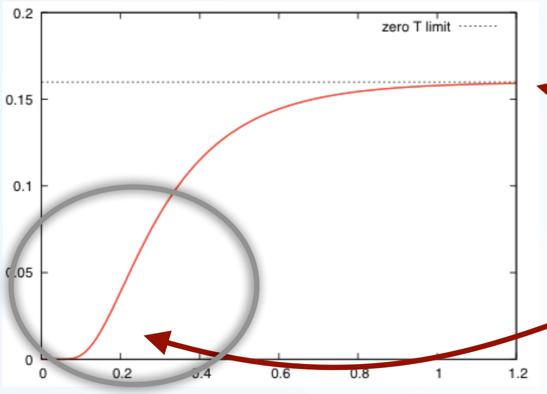

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smooth
restoration of
chiral symmetry

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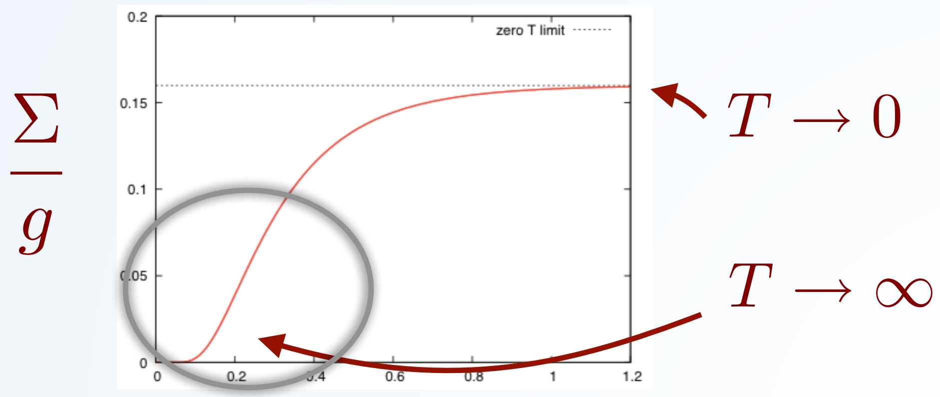
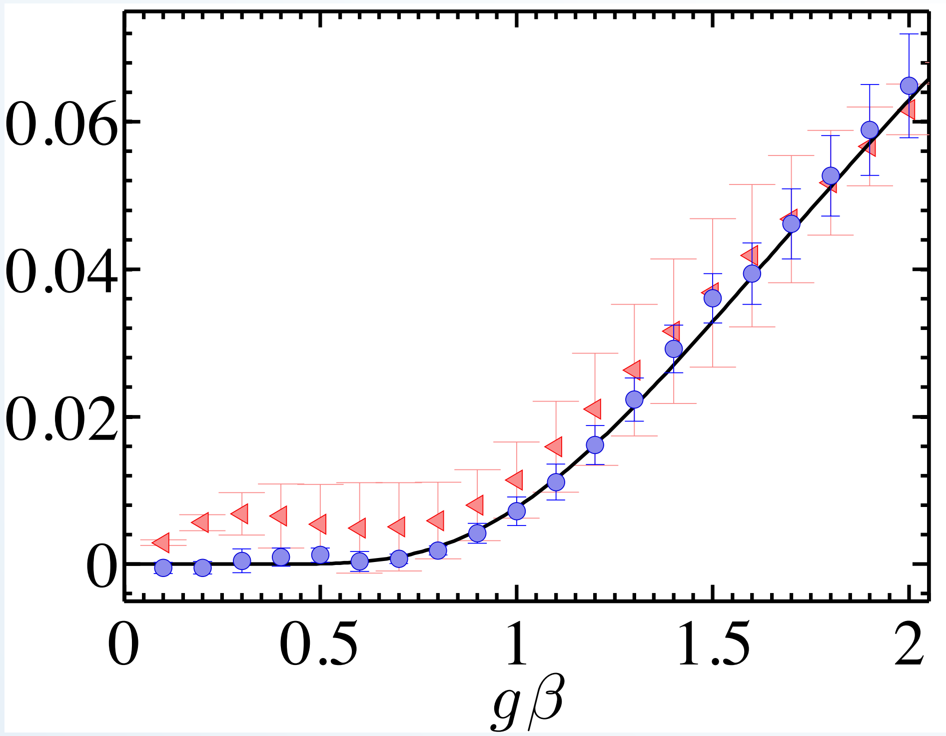


smooth restoration of chiral symmetry



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

THERMAL PROPERTIES SCHWINGER

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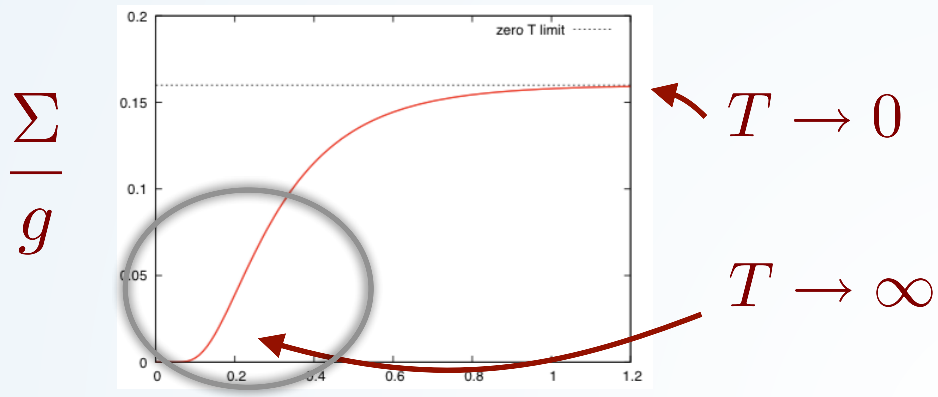

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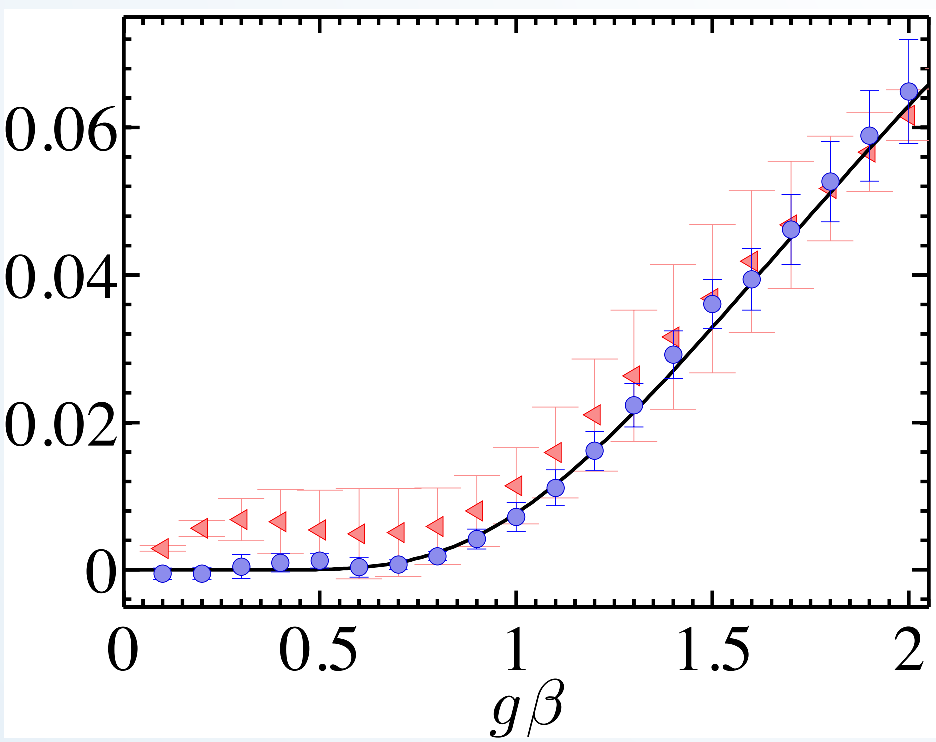
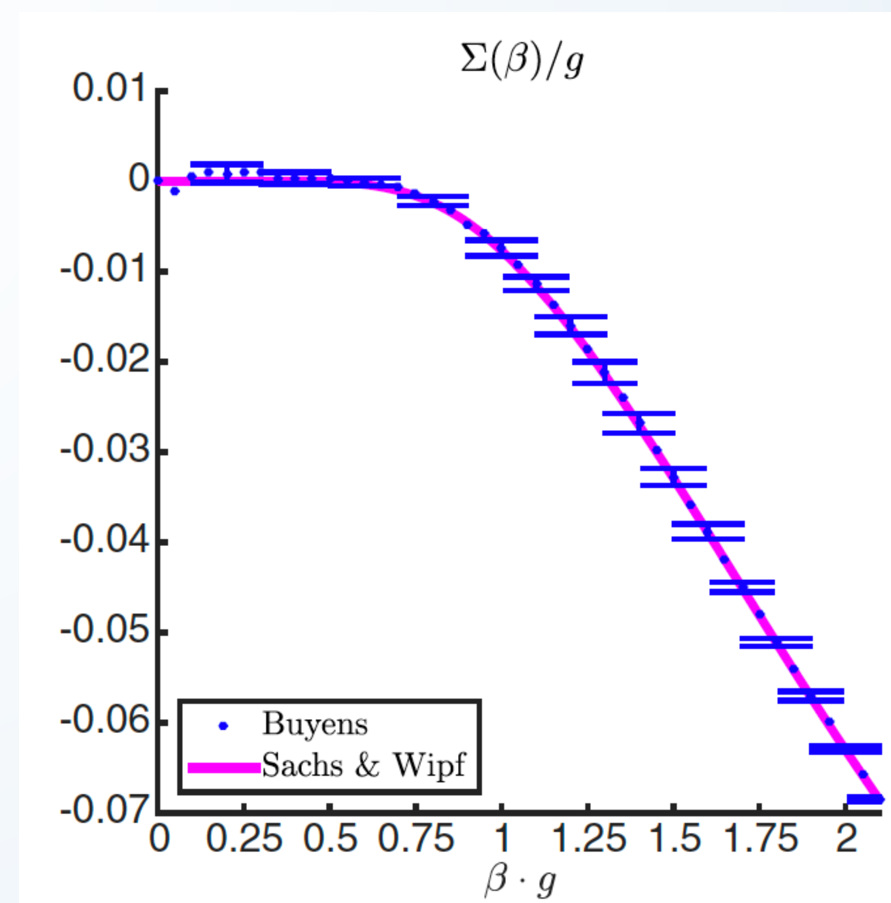
Sachs, Wipf 92



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



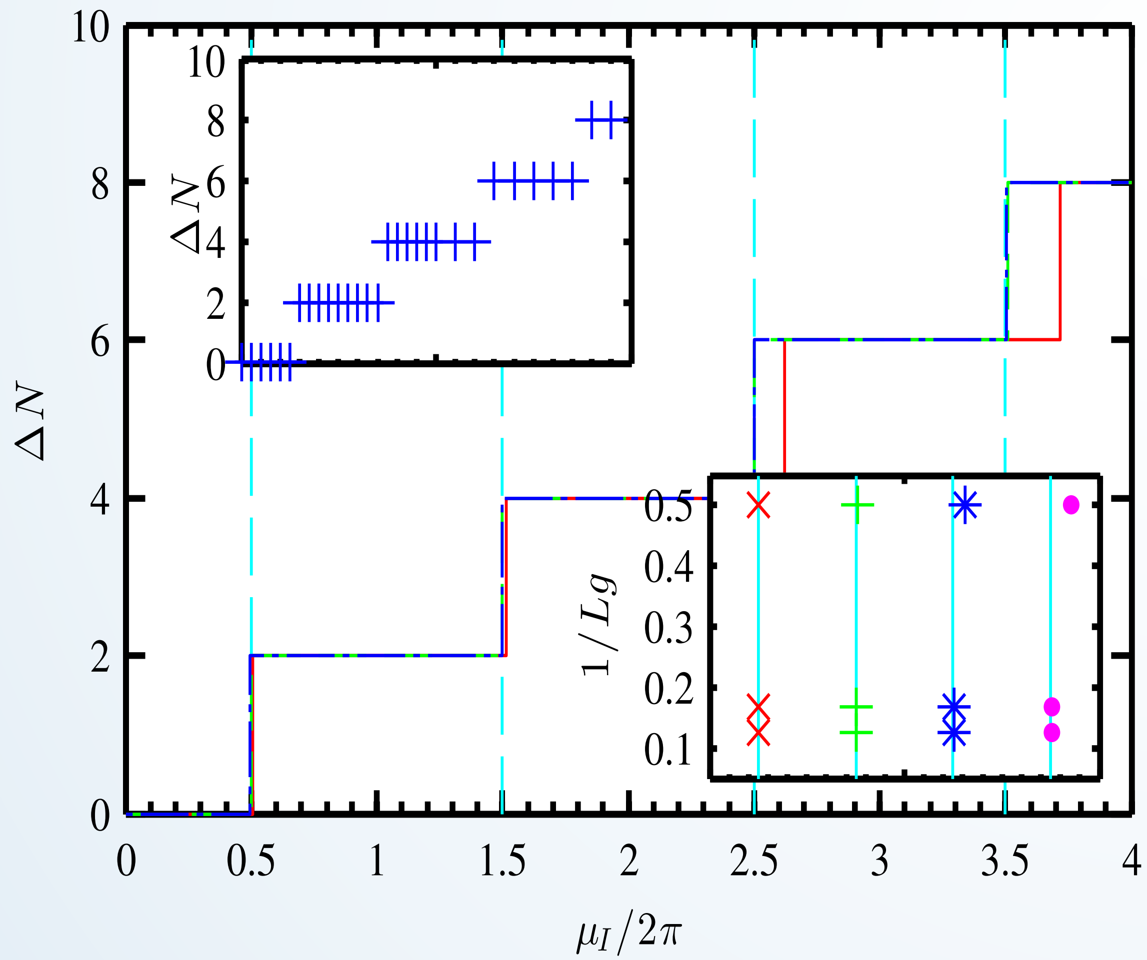
Buyens PRD 94, 085018 (2016)

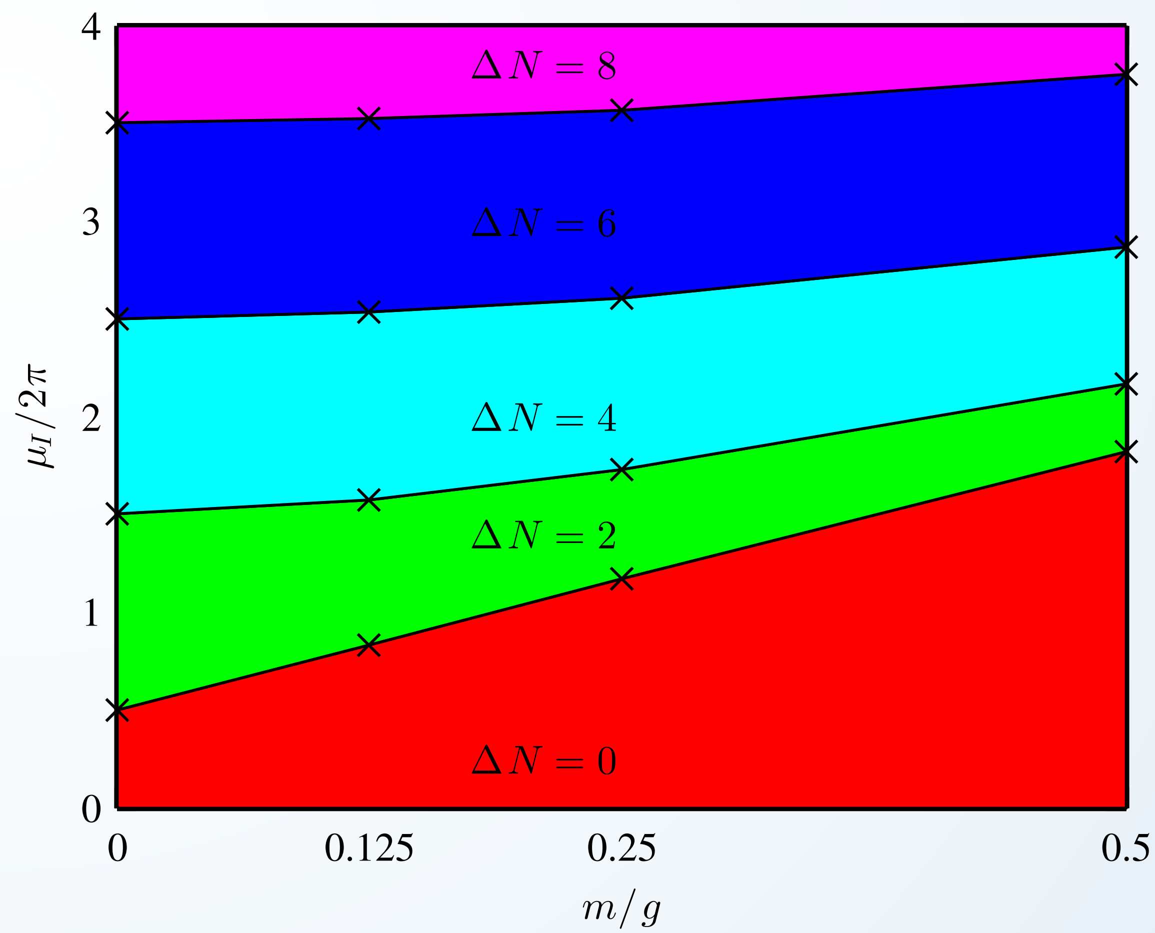
CHEMICAL POTENTIAL

FINITE DENSITY WITH MPS

Several fermion flavors, different chemical potentials

- ground state density changes (first order PT)
- Montecarlo has sign problem





S. Kuehn et al, PRL118 (2017) 071601

To conclude...

TNS = entanglement based ansatz

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feasibility for LQFT   thoroughly tested in 1+1D

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- high numerical precision attainable (controlled errors)
- spectrum, thermal equilibrium, finite density, (some) dynamics
- Abelian and non-Abelian models

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Related: proposals for quantum simulation of LGT with ultracold atoms

Zohar et al. PRL 2010, 2012 ,
Tagliacozzo et al., Nat. Comm. 2013
Banerjee et al., PRL 2012
Rico et al. PRL 2014
Pichler et al, PRX 2016
Zohar, Burrello, PRD 2015

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QUANTERA
QTFLAG

THANKS

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Zohar, Burrello, PRD 2015

next step… 2+1 D

QUANTERA QTFLAG

2D

ACTIVE RESEARCH: PEPS FOR LGT

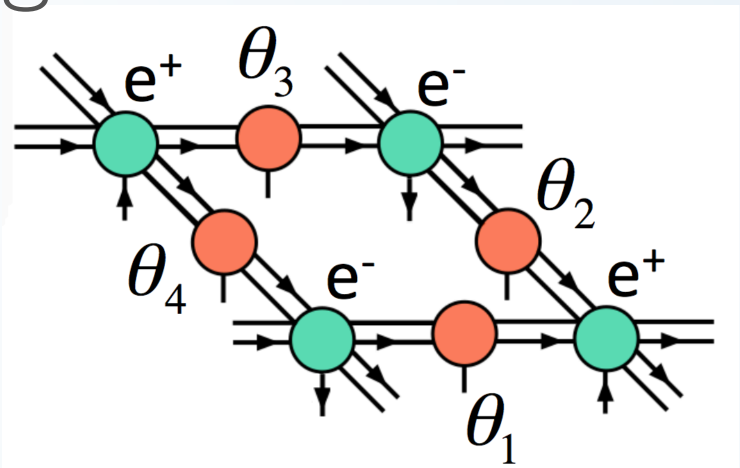
explicitly gauge invariant PEPS

restricted ansatz calculations

Tagliacozzo et al PRX 2014
Haegeman et al PRX 2014
Zohar et al Ann Phys 2015
arXiv:1807.01294

standard PEPS toolbox contains all ingredients for full variational computation

computational cost, required D



Zapp, Orús PRD 2017

restriction of the ansatz may be better strategy

e.g. fully Gaussian PEPS

Zohar, Cirac PRD 2018