TENSOR NETWORK STATES FOR 1+1D LATTICE GAUGE THEORIES

Mari-Carmen Bañuls

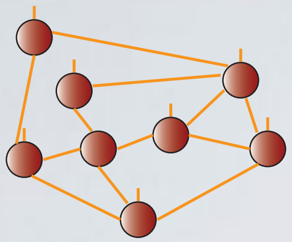
with K. Cichy (Frankfurt), K. Jansen (DESY), H. Saito, J.I. Cirac, S. Kühn (MPQ)

MPQ

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

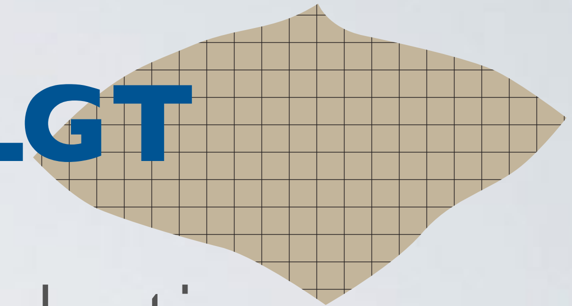
Mainz MITP 20.9.2017

WHY?



TNS

LGT



Non-perturbative way of solving QFT (QCD)

Mostly path-integral formalism & MC

4D lattice

spectrum
finite T
large 3+1 dim lattices
chemical potential
time evolution

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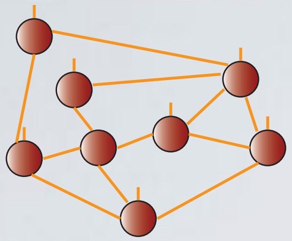

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Non-perturbative for Hamiltonian systems

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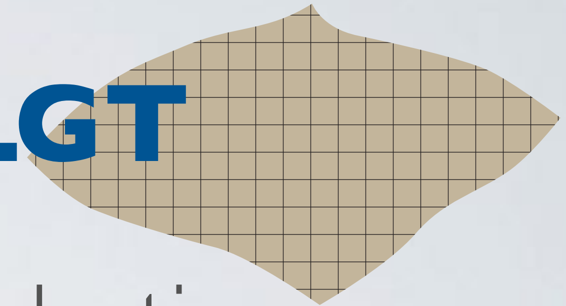

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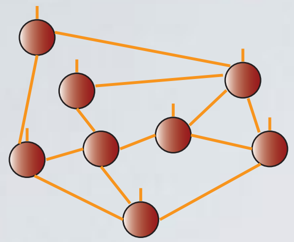

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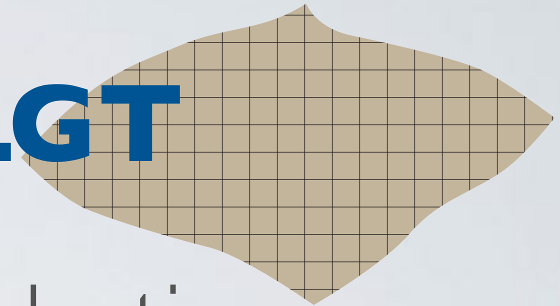
Non-perturbative for Hamiltonian systems

Extremely successful for 1D systems (MPS)



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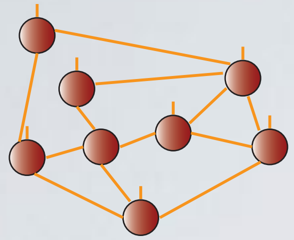

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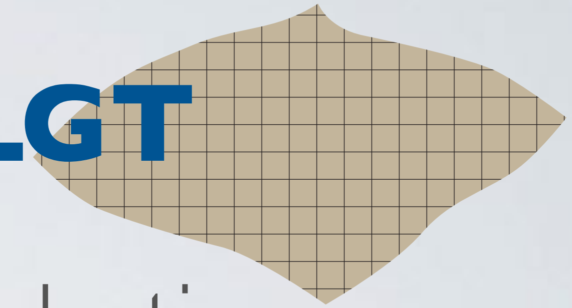

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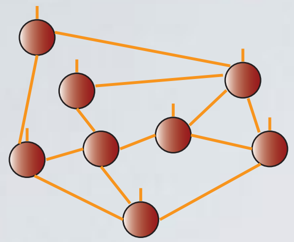

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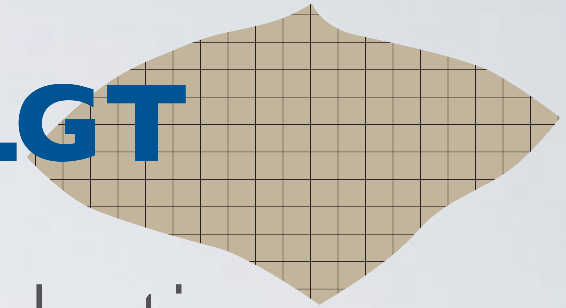
ground states
low-lying excitations
thermal states
time evolution



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In this talk...

Using TNS/MPS for LGT

Overview of *recent* results:

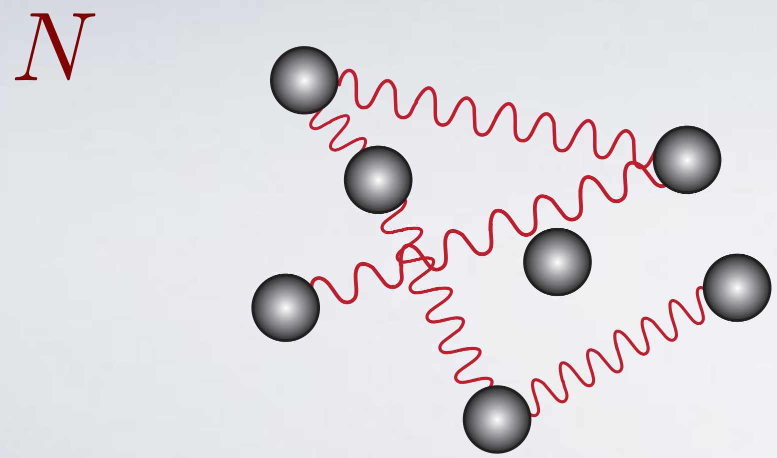
from Abelian to non-Abelian

WHAT ARE TNS?

- TNS = Tensor Network States

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

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



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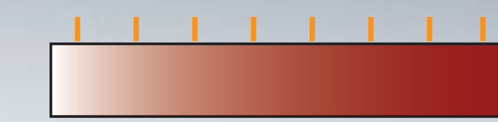
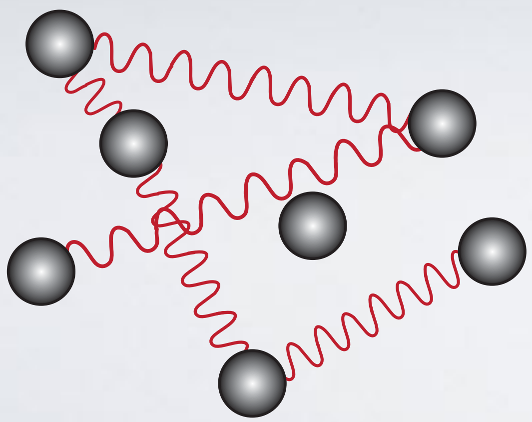


N-legged tensor

N



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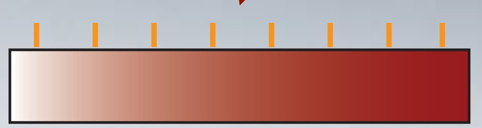

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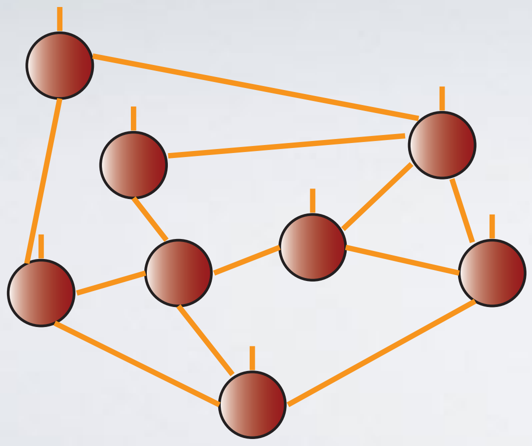

$\mathrm{poly}(N)$

A TNS has only a polynomial number of parameters

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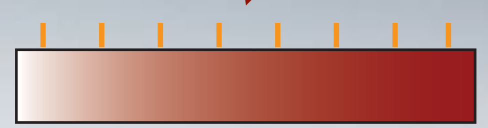

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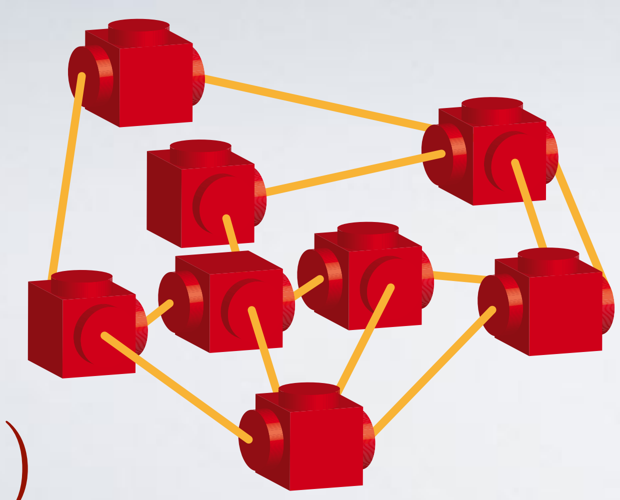

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USING TNS FOR QMB

a formal approach

numerical algorithms

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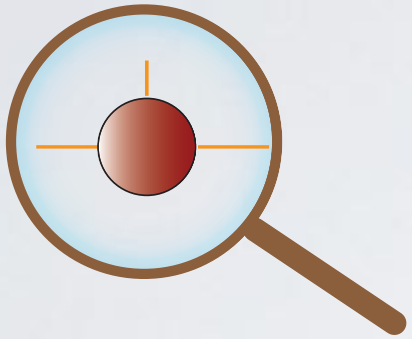

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constructing states

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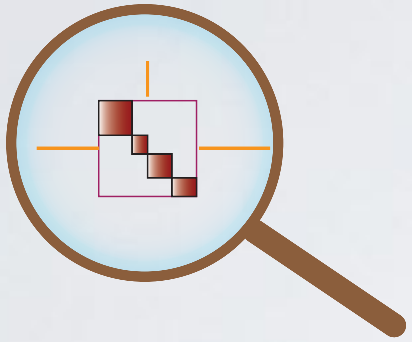

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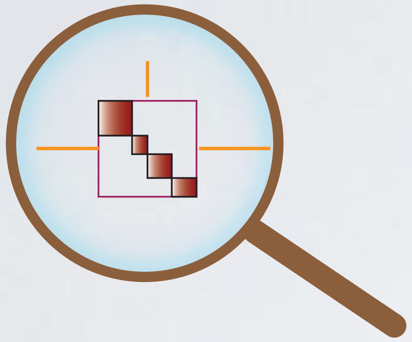

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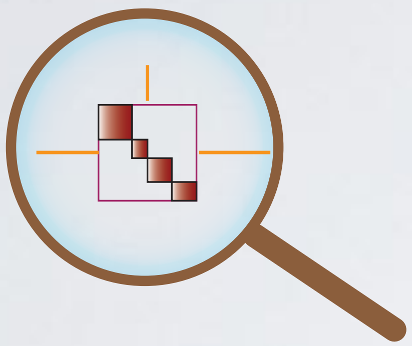

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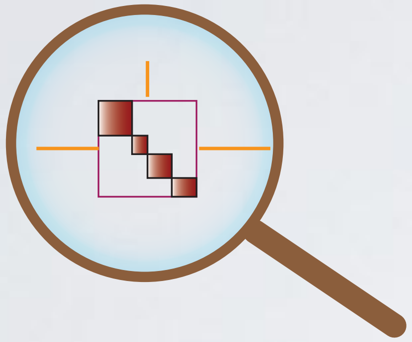

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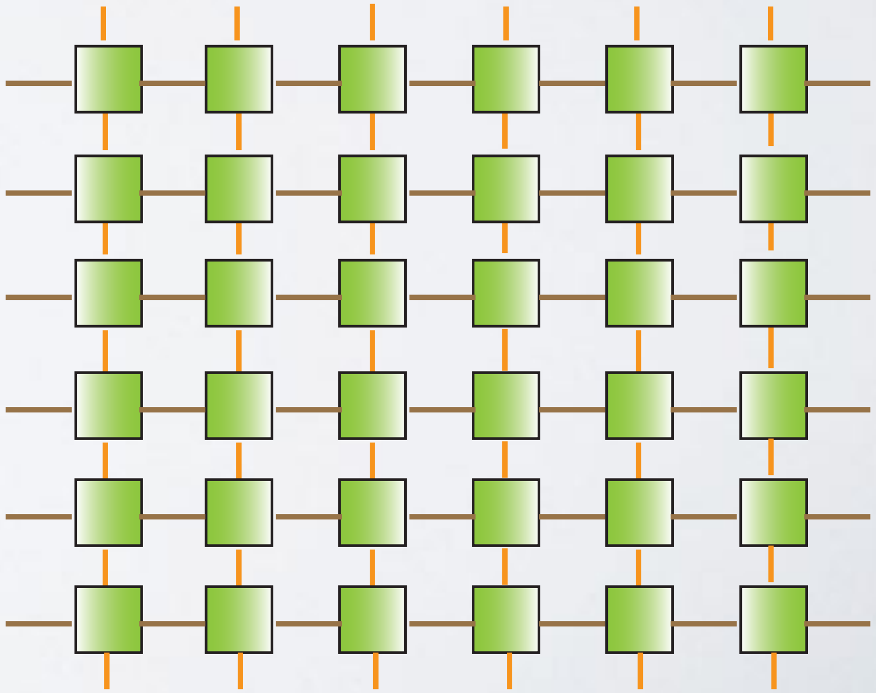

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Nishino, JPSJ 1995
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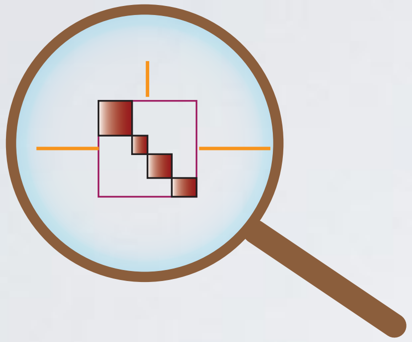

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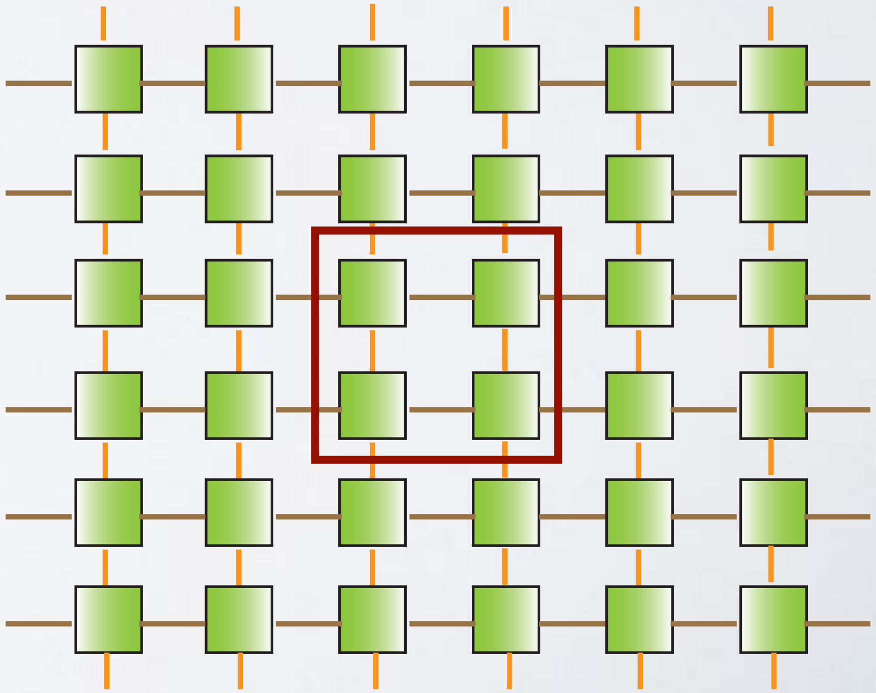

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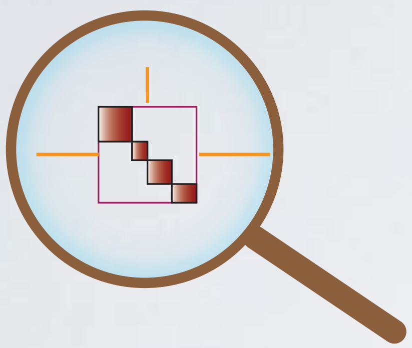

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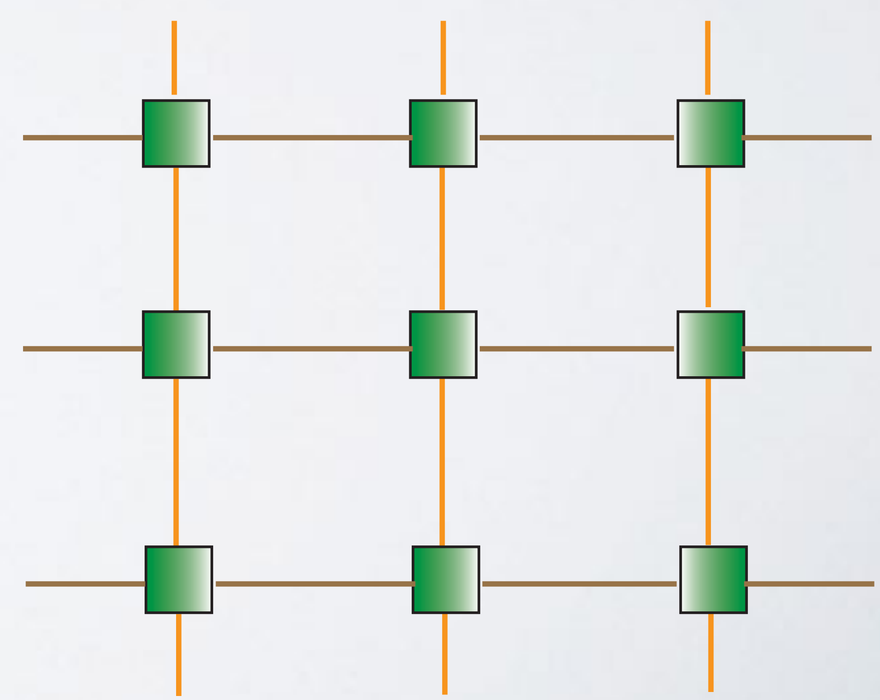

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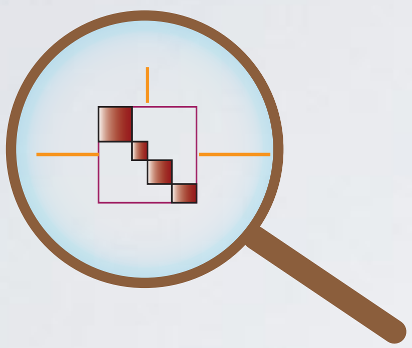

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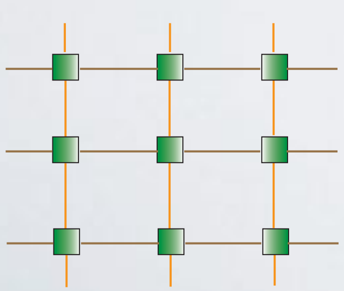

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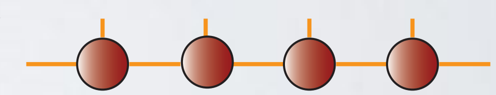


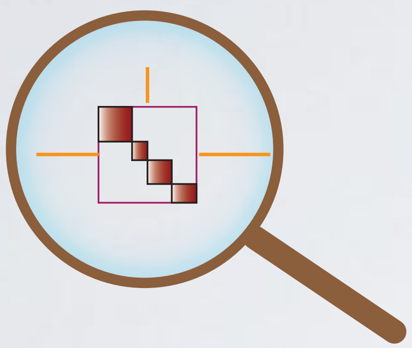
TNS as ansatz for the state

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

USING TNS FOR LGT

a formal approach



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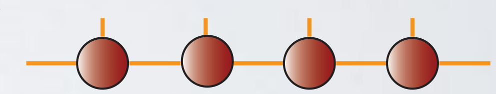

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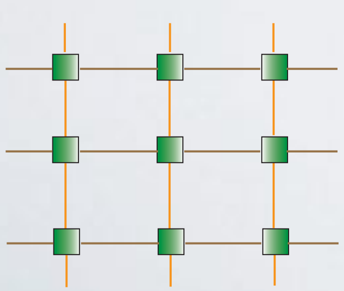

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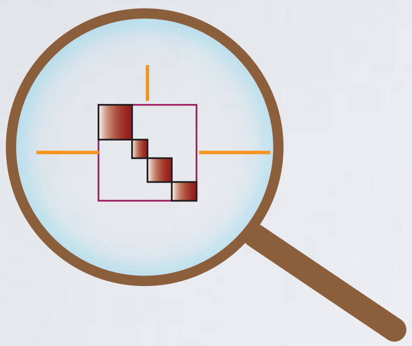

gauging the symmetry

explicitly invariant states

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

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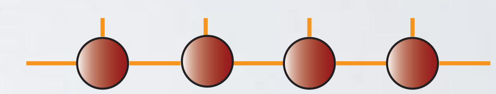

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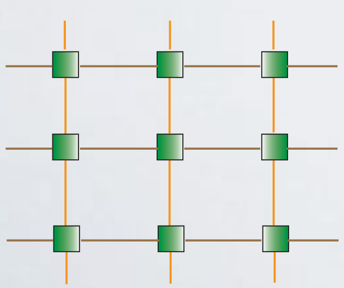

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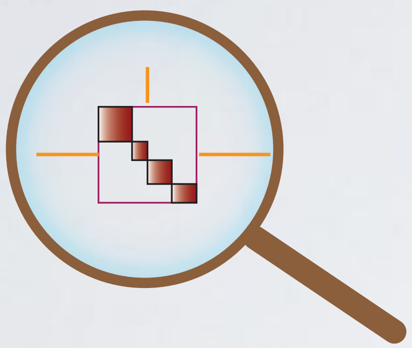

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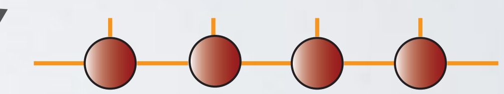

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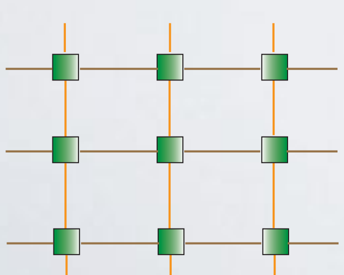

TRG approaches to classical
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USING TNS FOR LGT

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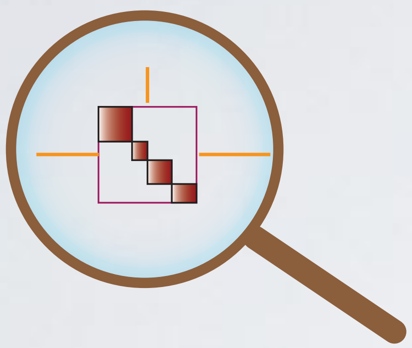

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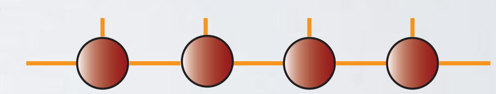

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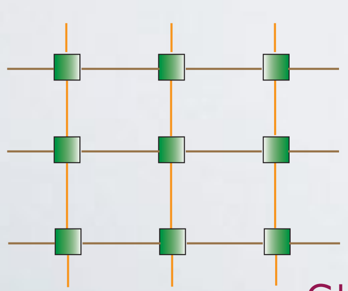

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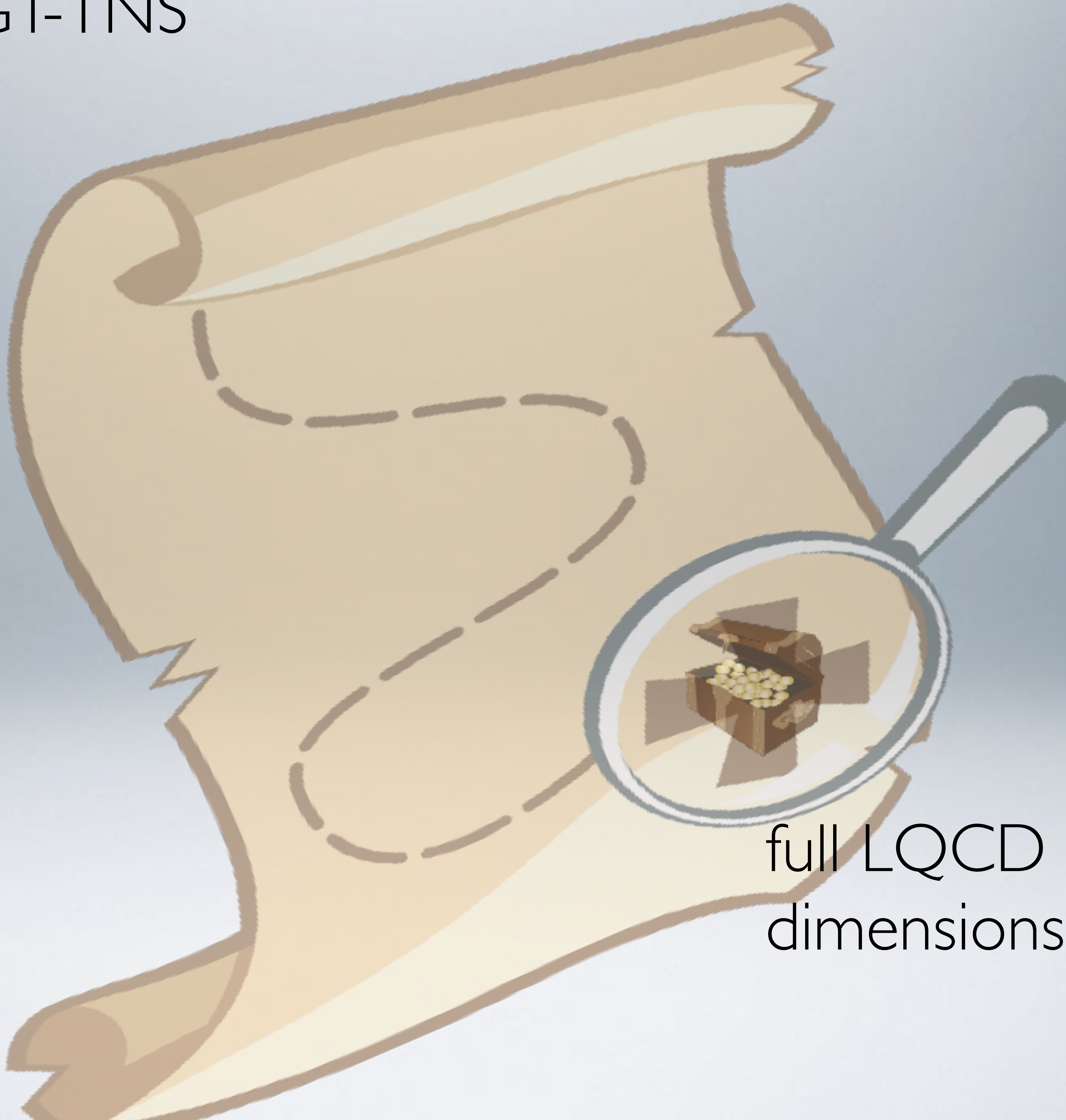
next...

a possible LGT-TNS roadmap...

a wishful LGT-TNS roadmap...



full LQCD in 3+1 dimensions

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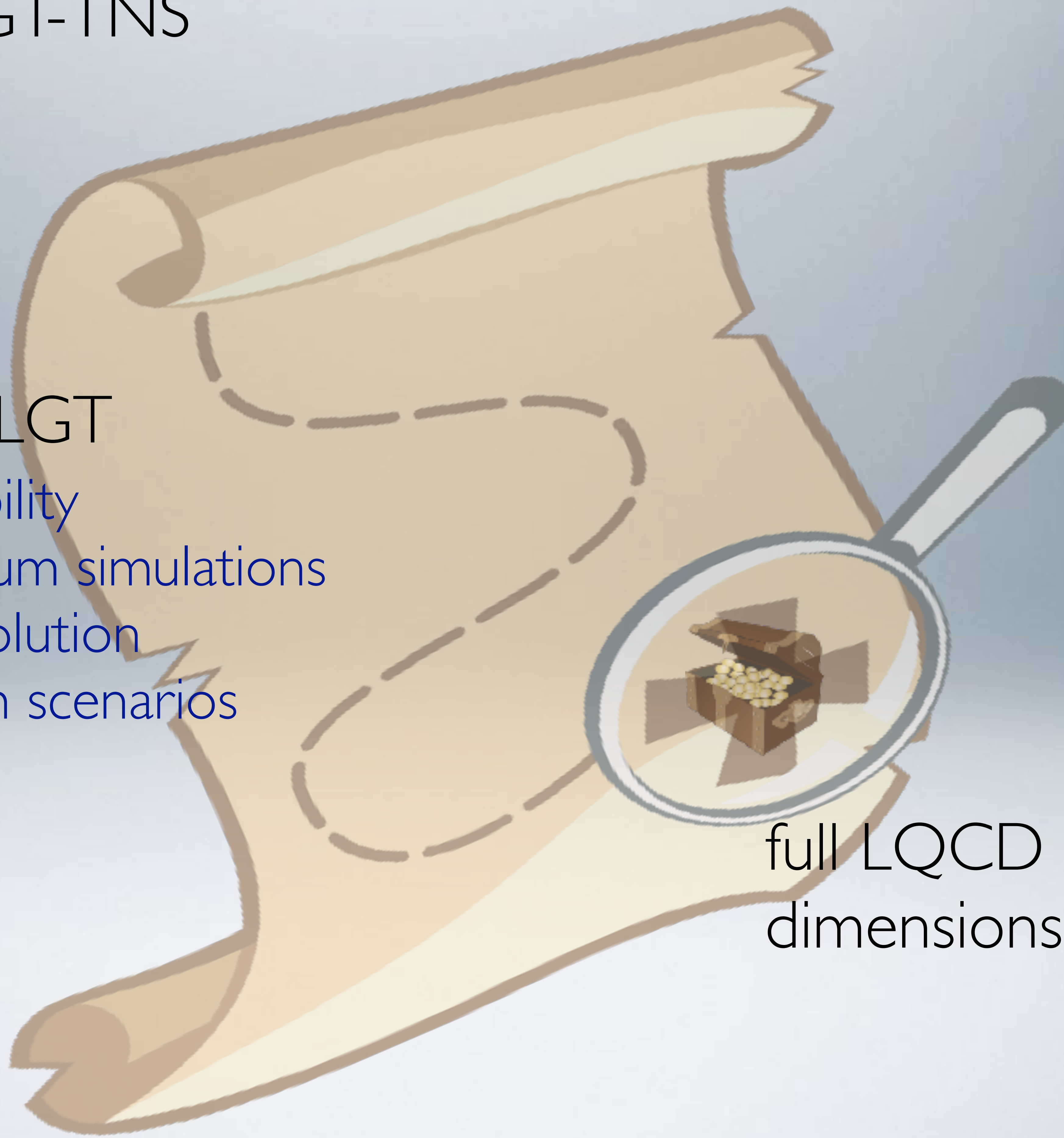

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feasibility

precise equilibrium simulations

time evolution

sign problem scenarios

full LQCD in 3+1 dimensions

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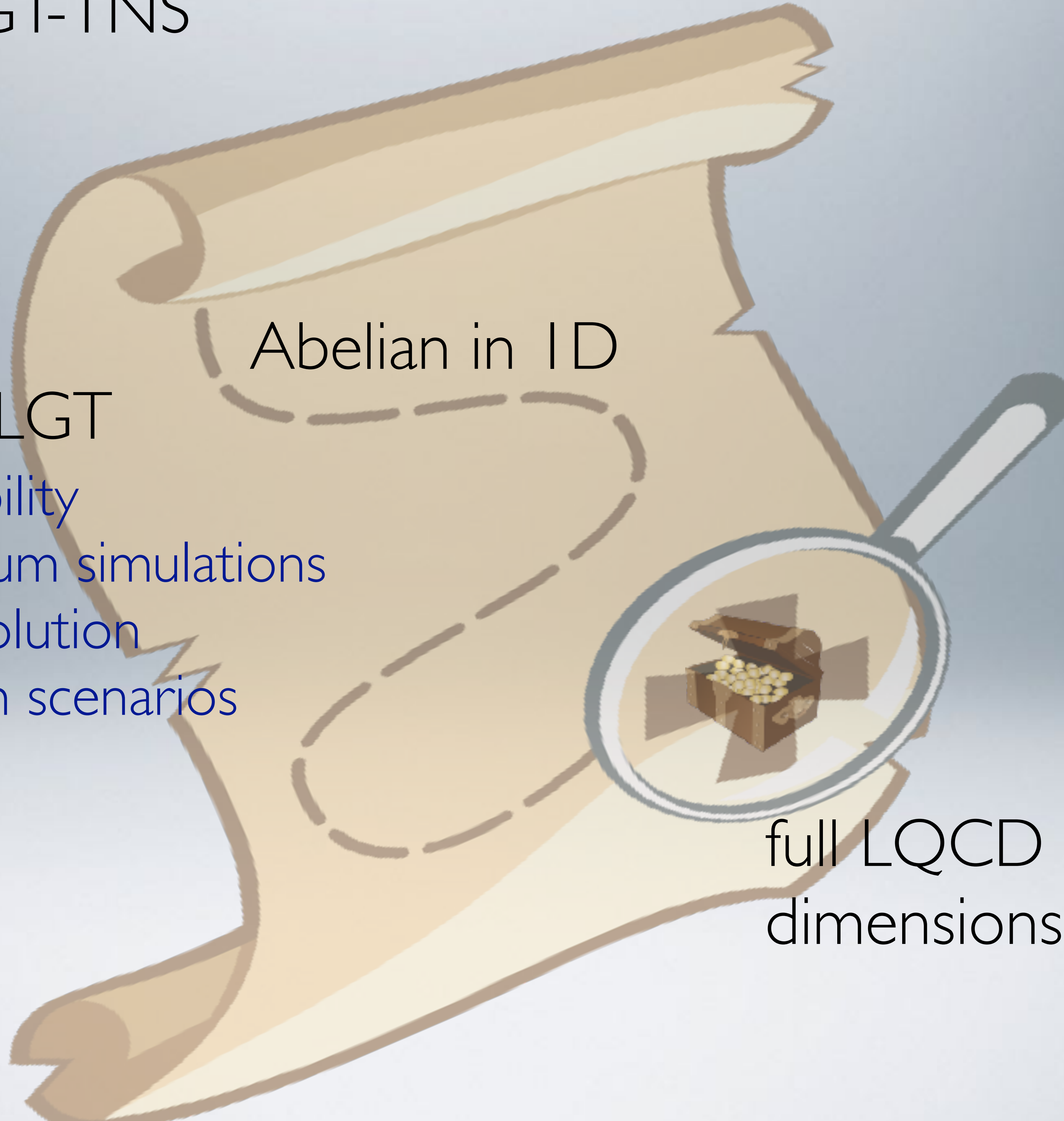

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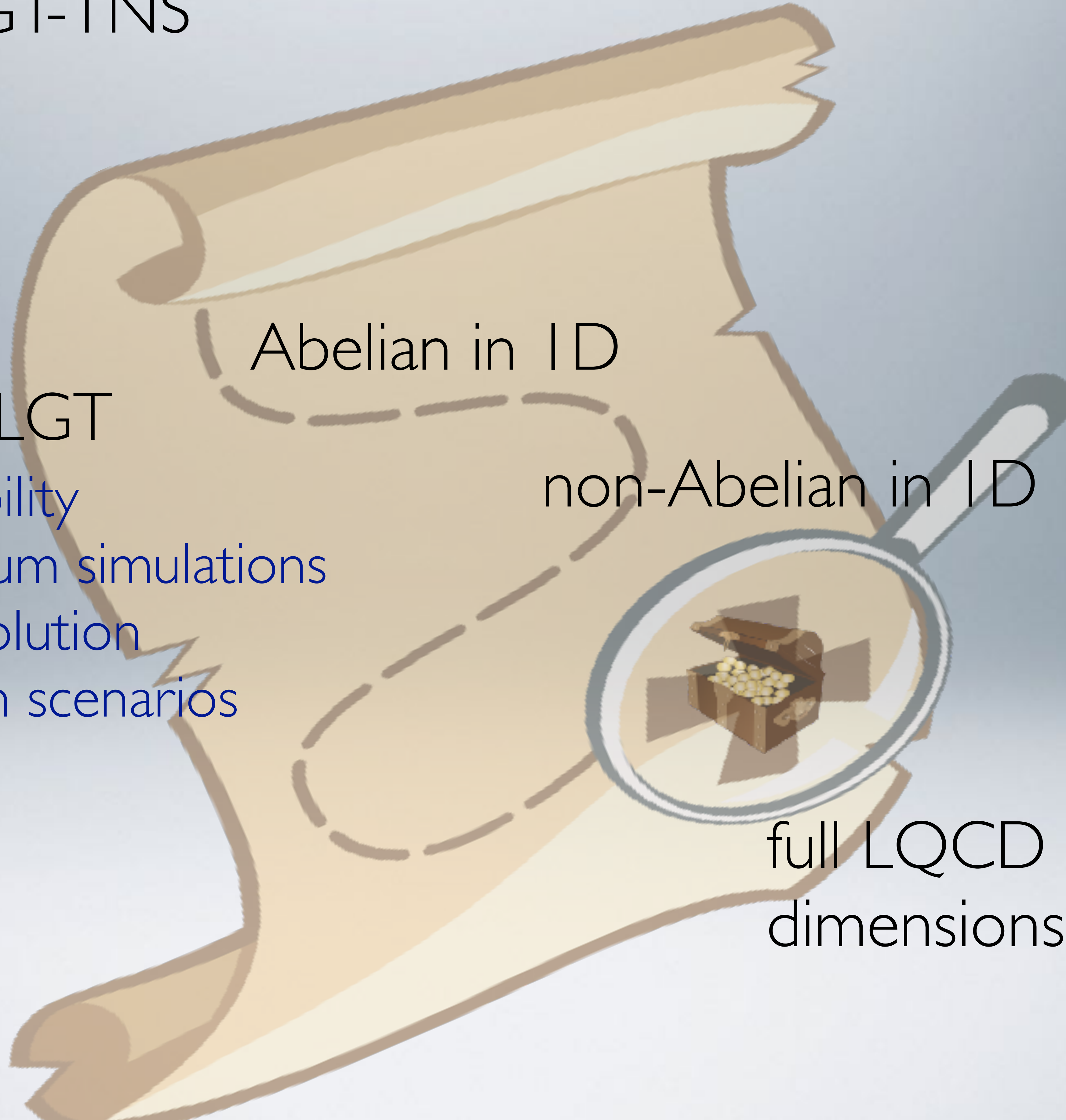

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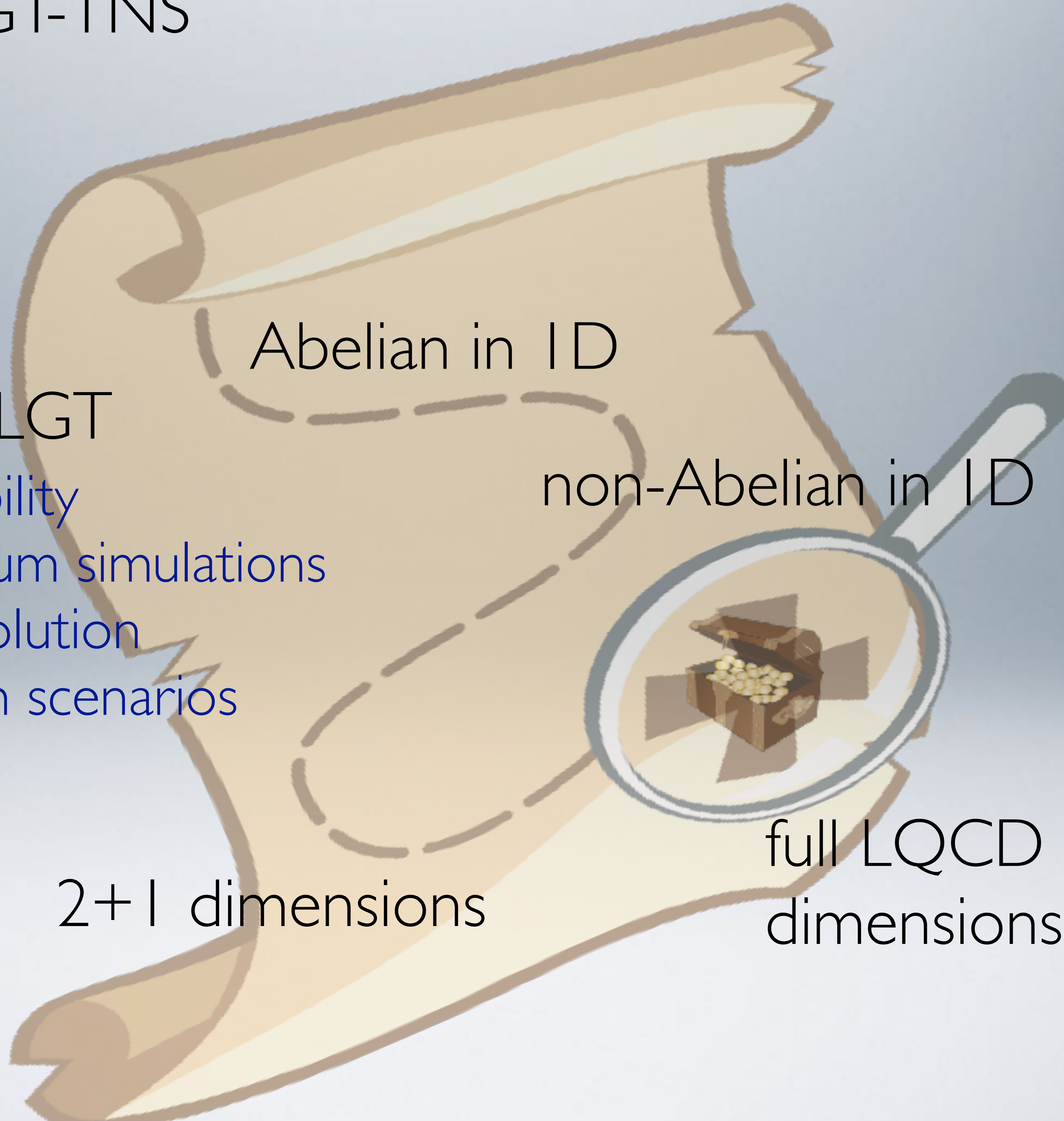

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full LQCD in 3+1 dimensions

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Byrnes et al. PRD 2002

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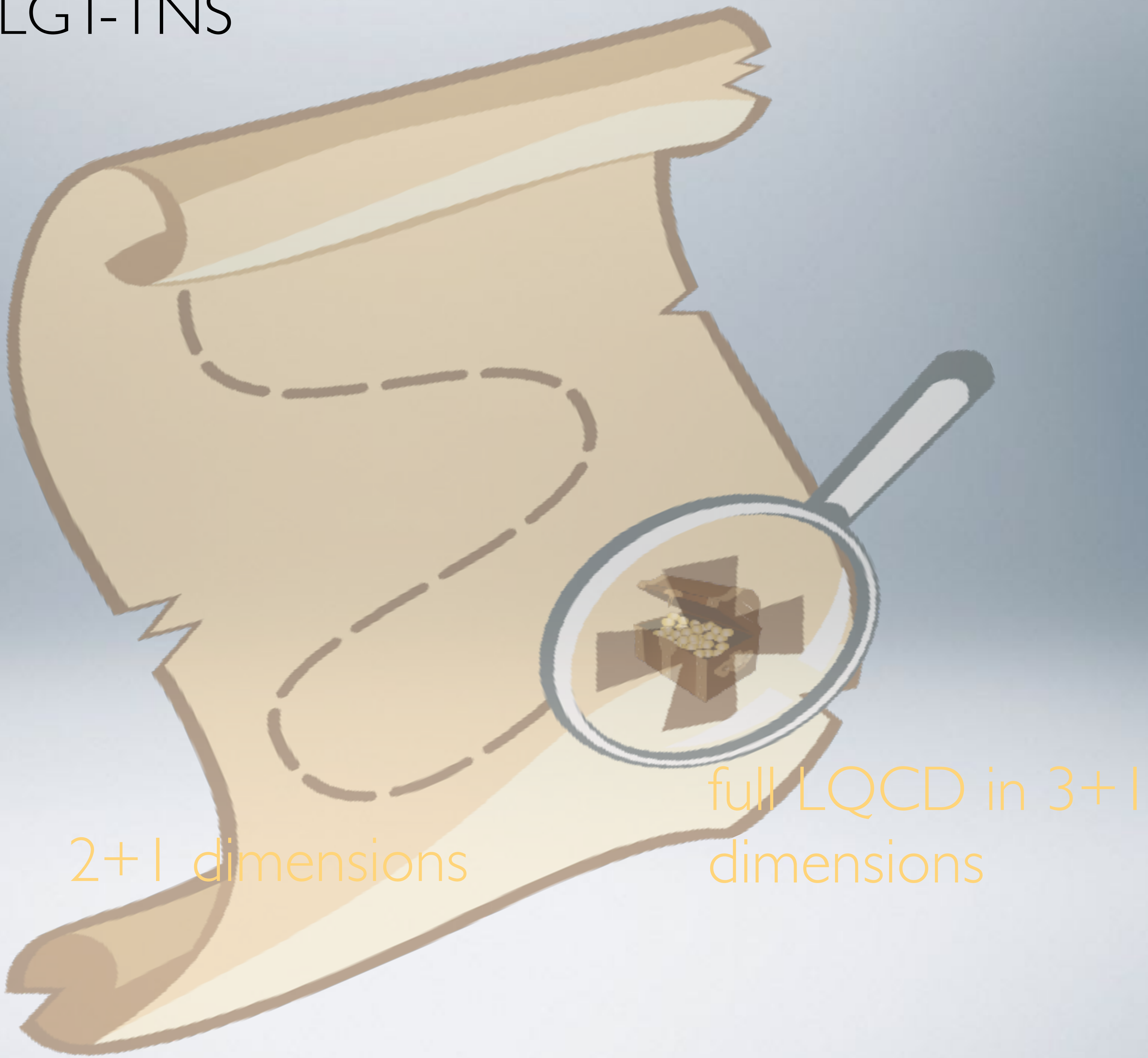
TNS for classical gauge models

Meurice et al. 2013

an ongoing LGT-TNS roadmap...



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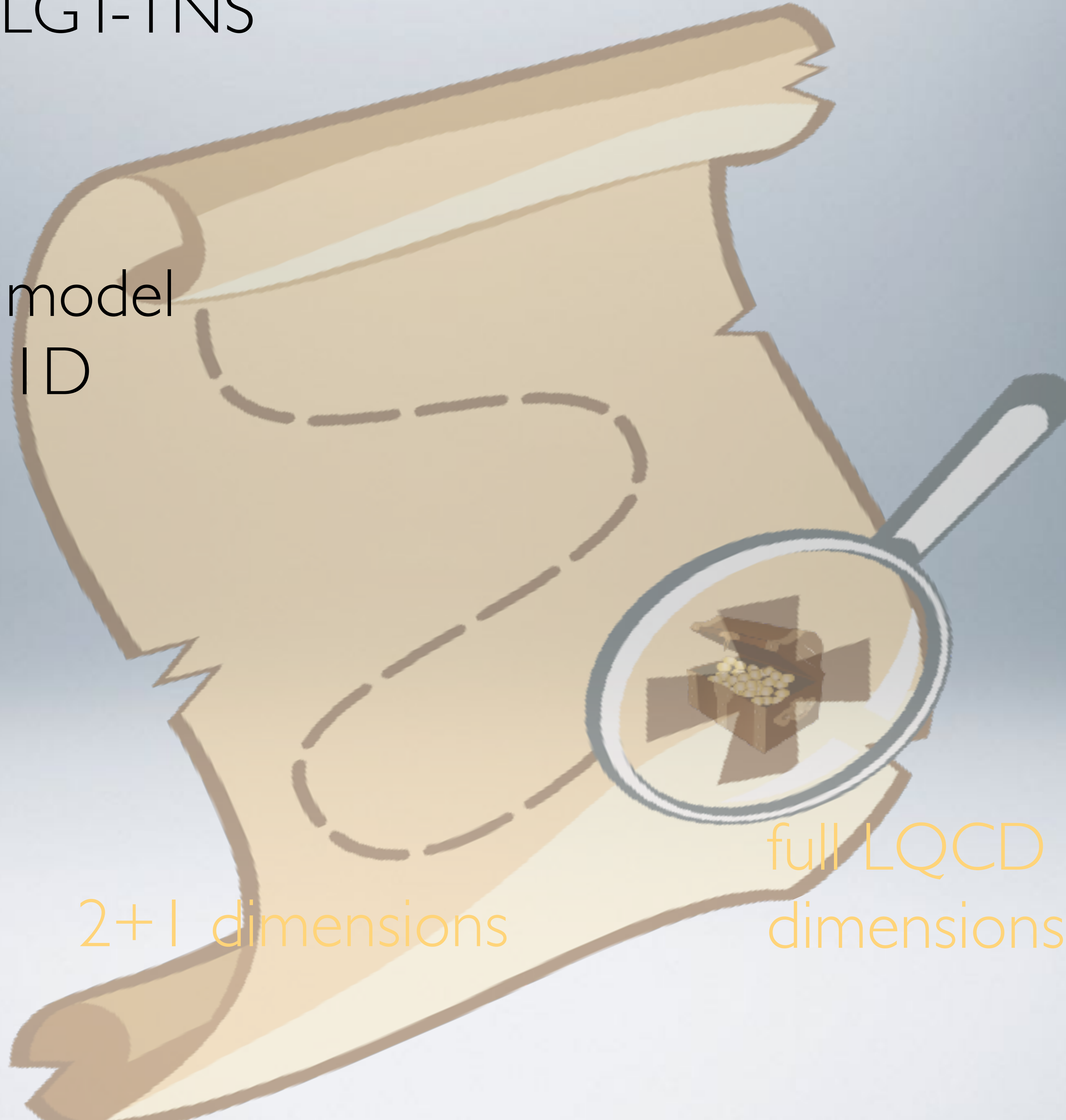

Schwinger model
U(1) in 1D

2+1 dimensions

full LQCD in 3+1 dimensions

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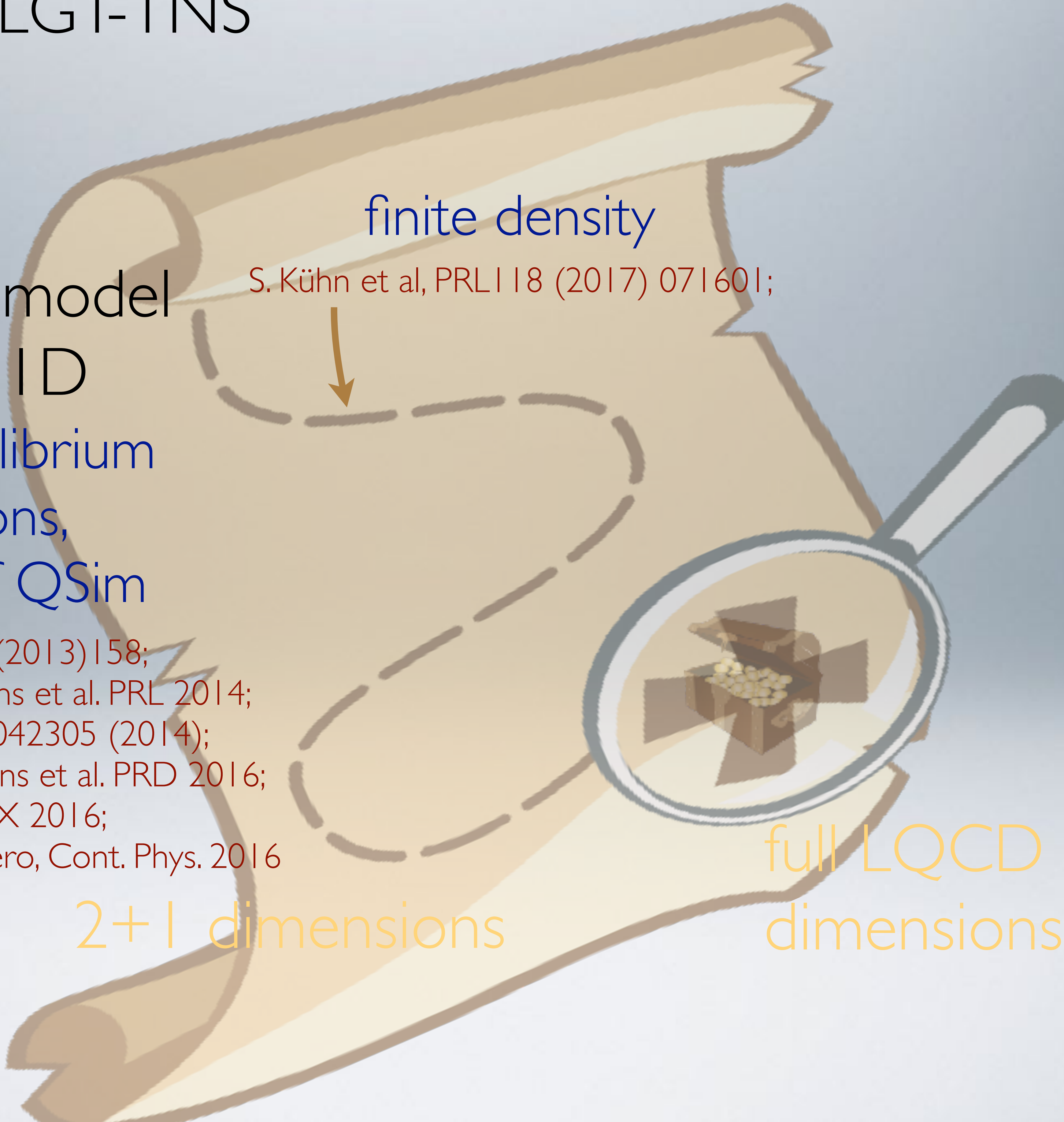

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precise equilibrium simulations, feasibility of QSim

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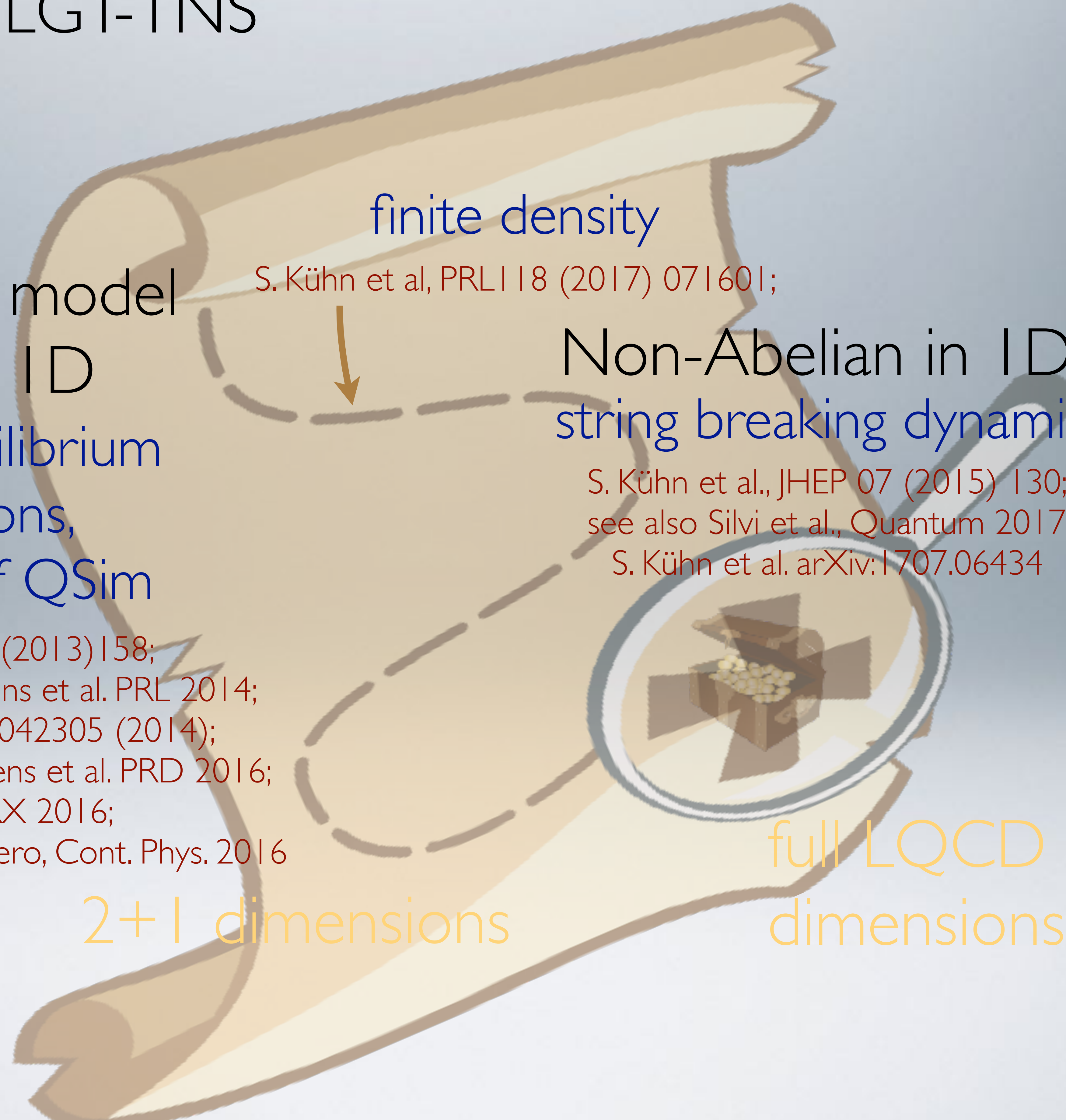

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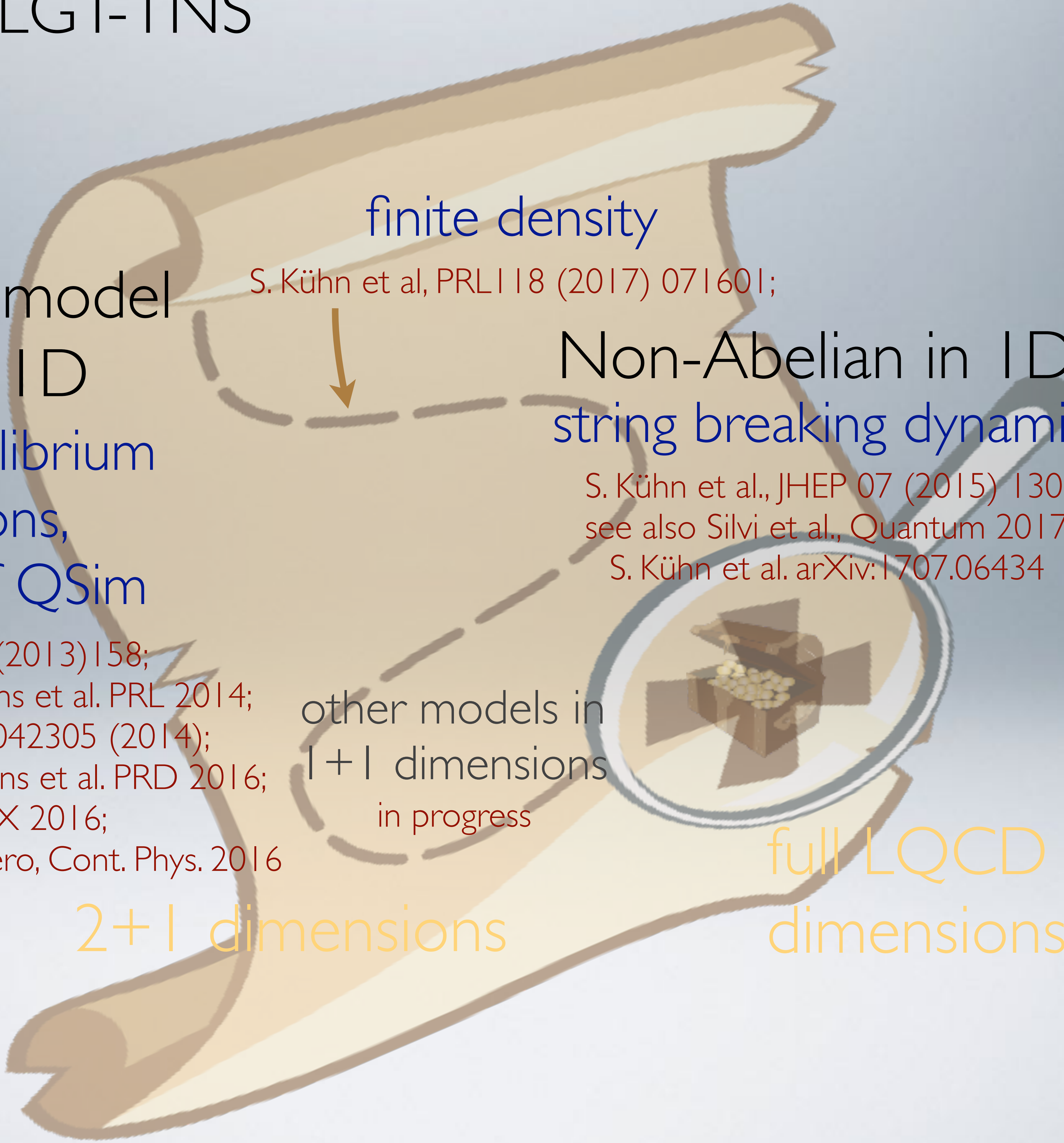

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R. Orús' talk

full LQCD in 3+1 dimensions

SOLVING LGT WITH TNS

GENERAL STRATEGY

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Hamiltonian formulation

- acting on a Hilbert space

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- acting on a Hilbert space

Finite dimensional degrees of freedom

- gauge dof require attention

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Common ingredients for quantum simulation

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Hamiltonian formulation

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gauge dof require attention

Common ingredients for quantum simulation

Schwinger model example

SCHWINGER MODEL

continuum

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

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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SCHWINGER MODEL

MPS representation

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

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can be implemented with explicitly gauge invariant tensors, truncating values of electric flux

Buyens et al., PRL 2014;
Silvi et al, NJP 2014;
See also Buyens et al., PRD 2017

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$|\ell_0\ldots s_e\;s_o\;s_e\;s_o\ldots\rangle$ non-local terms

COMPUTING CONTINUUM QUANTITIES

JHEP11(2013)158

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Scan parameters

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m/g mass gaps and GS energy density in the continuum $x \to \infty$

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x $x \in [5,\ 600]$

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Scan parameters

m/g — mass gaps and GS energy density in the continuum $x \rightarrow \infty$

x — $x \in [5,\ 600]$

N — $N \propto x$ (up to ~850)

JHEP11(2013)158

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Scan parameters

m/g	mass gaps and GS energy density in the continuum $x \to \infty$
x	$x \in [5,\ 600]$
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D	$D \in [20,\ 120]$

JHEP11(2013)158

COMPUTING CONTINUUM QUANTITIES

Scan parameters

m/g — mass gaps and GS energy density in the continuum $x \to \infty$

$x \to \infty$

x — $x \in [5,\ 600]$

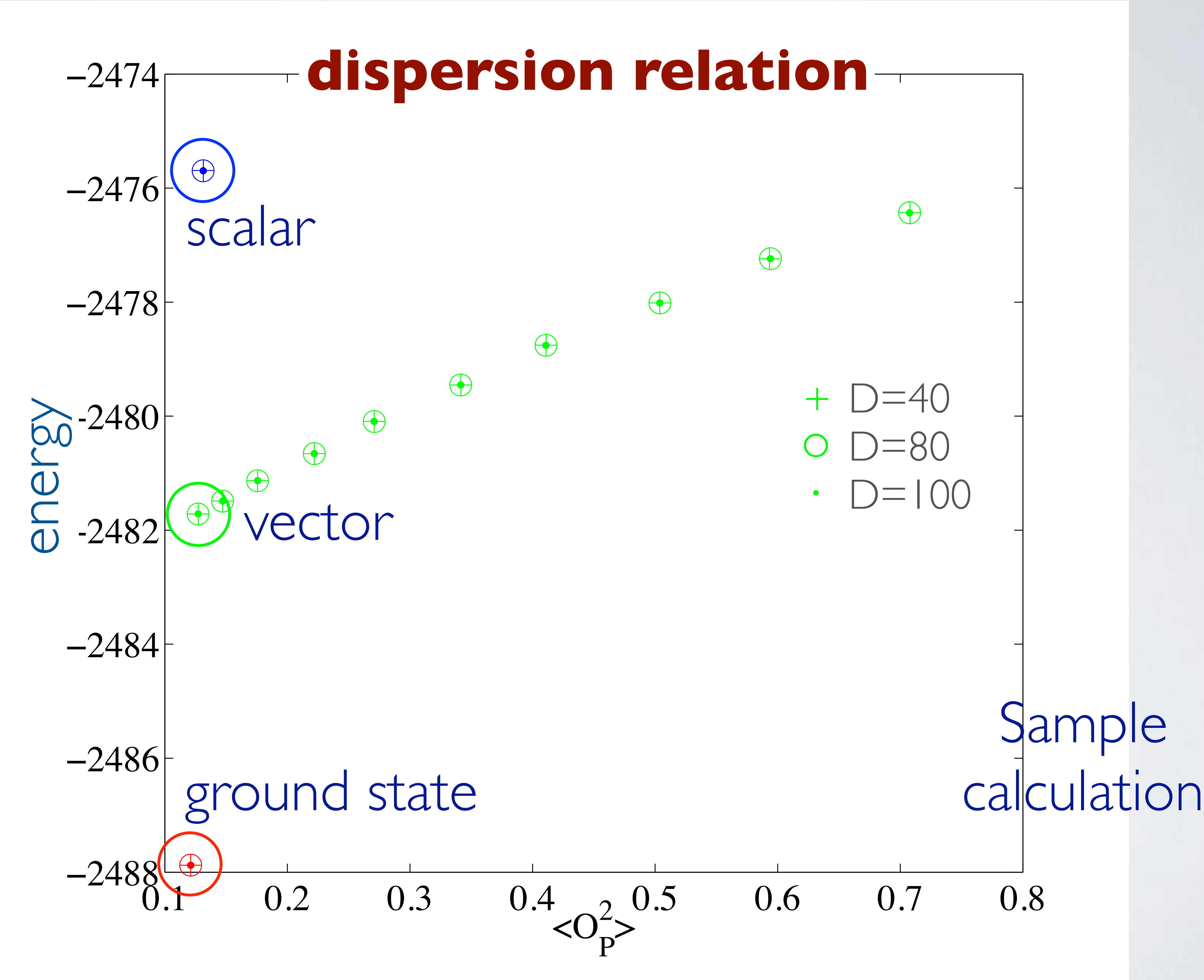
finite-size

N — $N \propto x$ (up to ~850)

convergence

D — $D \in [20,\ 120]$

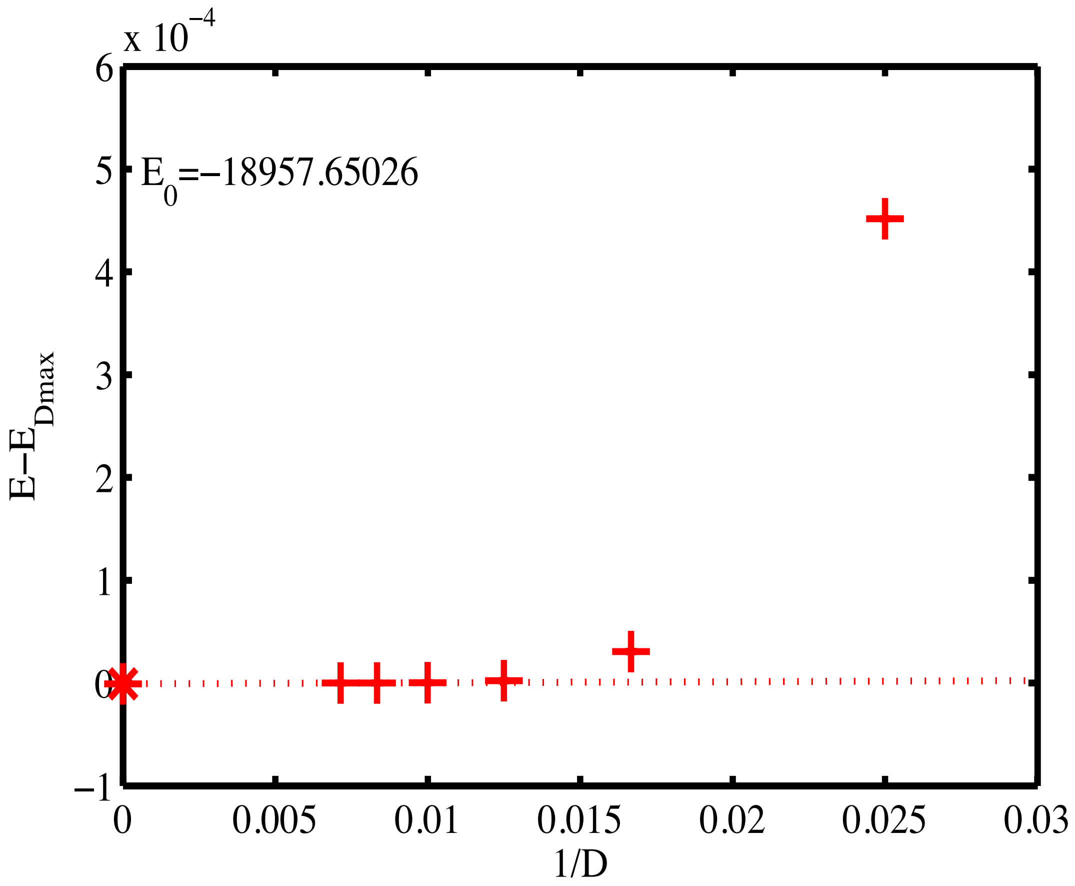
JHEP11(2013)158


dispersion relation
energy
scalar
vector
ground state
D=40
D=80
D=100
Sample calculation
–2474
–2476
–2478
-2480
-2482
–2484
–2486
–2488
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
<O_P^2>

I truncation error

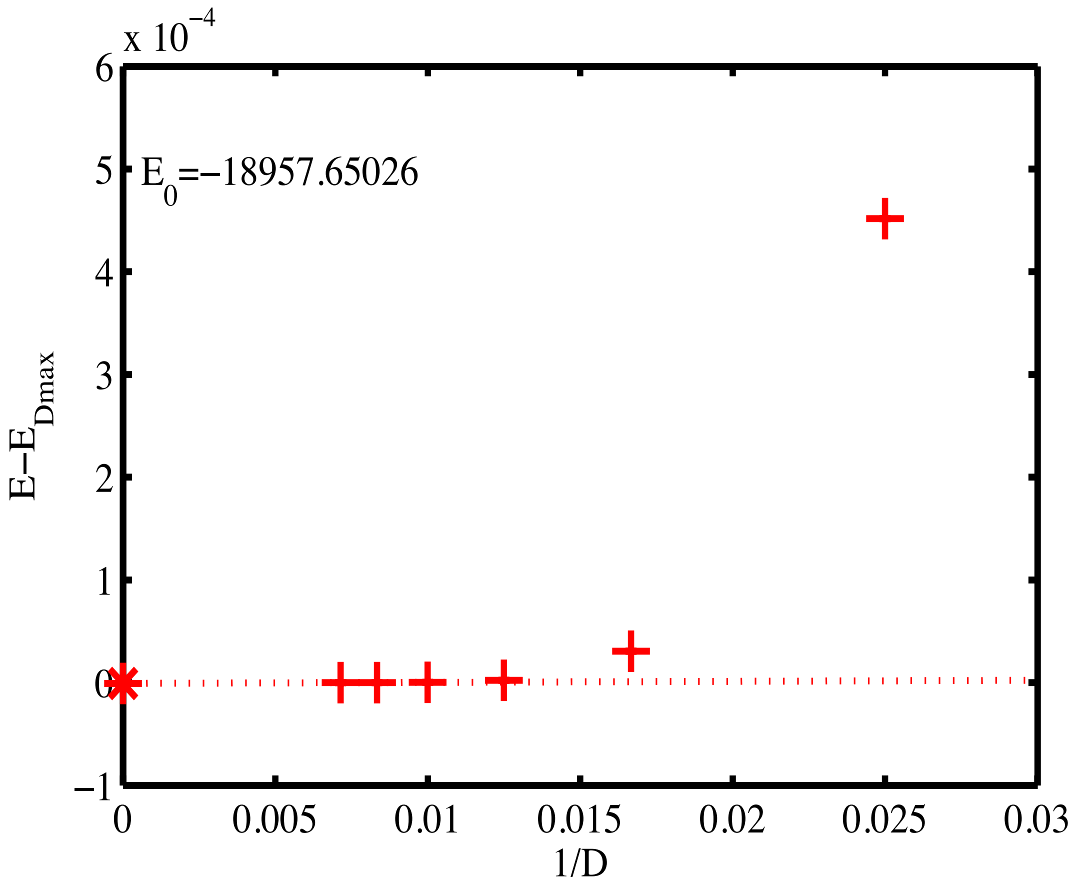
$m/g = 0 \quad x = 100$

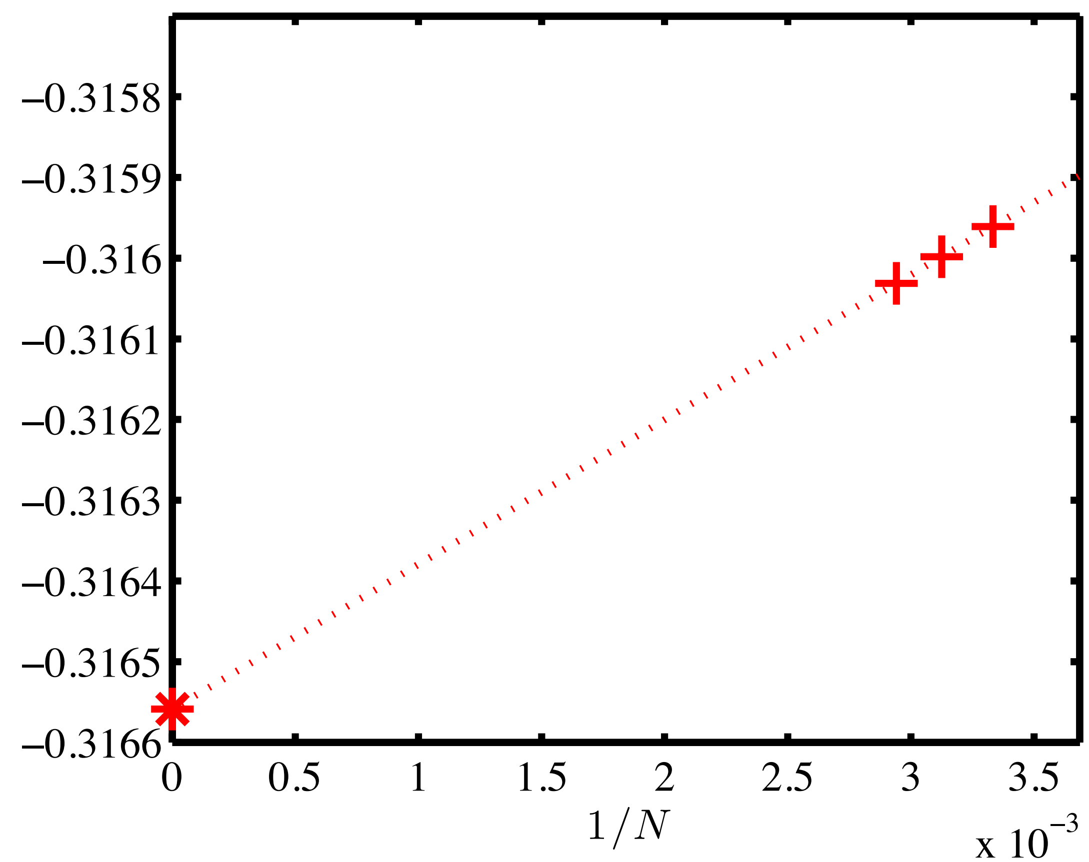
$N = 300$



JHEP11(2013)158

2 finite-size scaling $m/g = 0 \quad x = 100$





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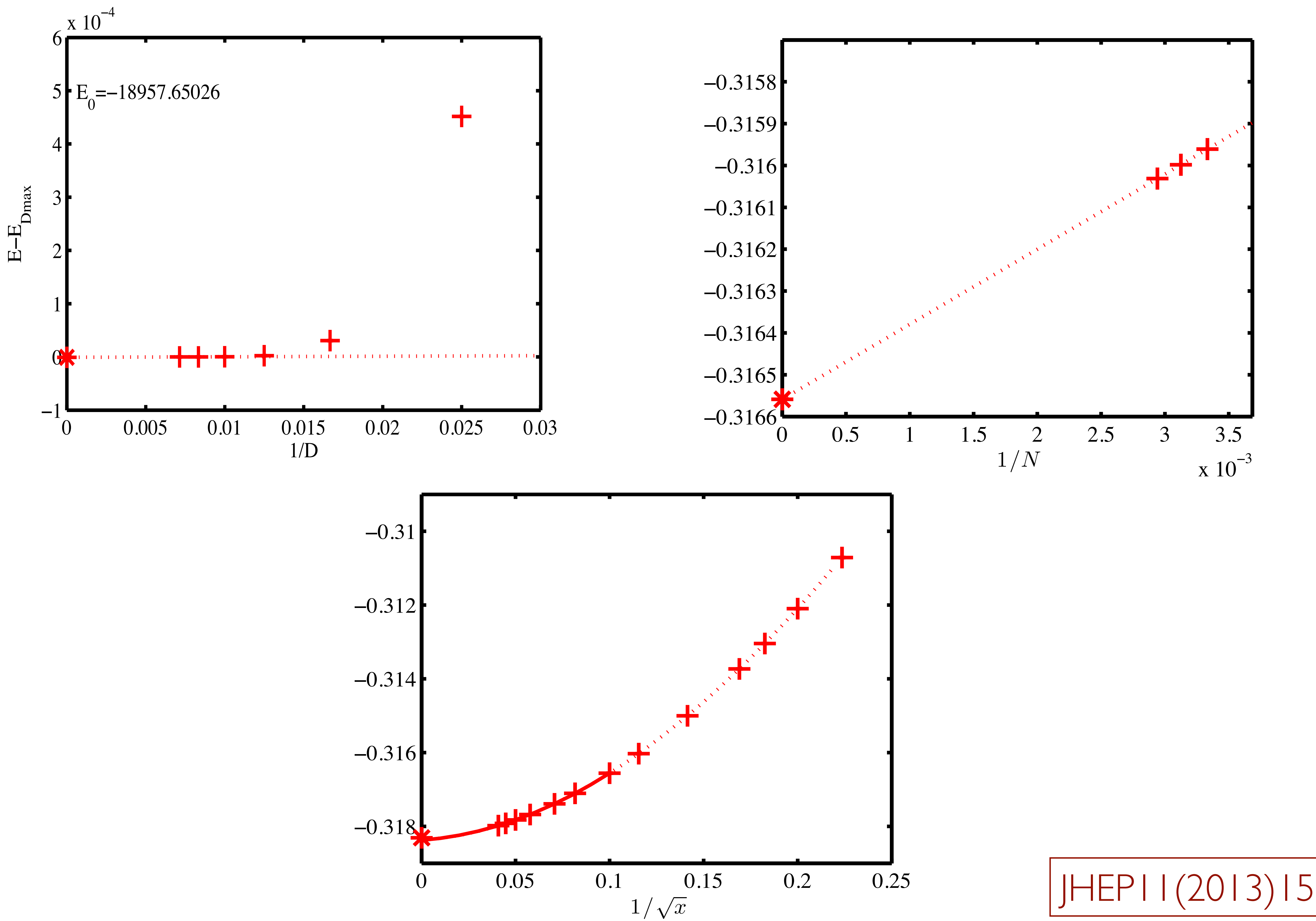
3 continuum limit $m/g = 0$



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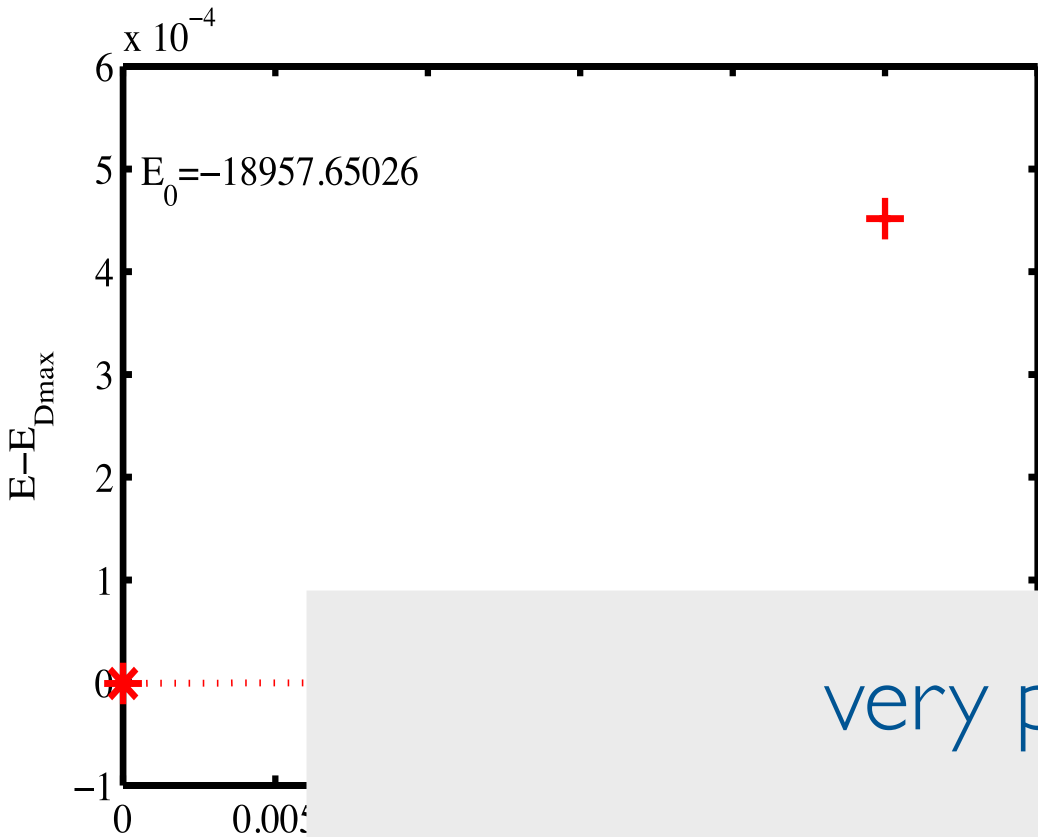
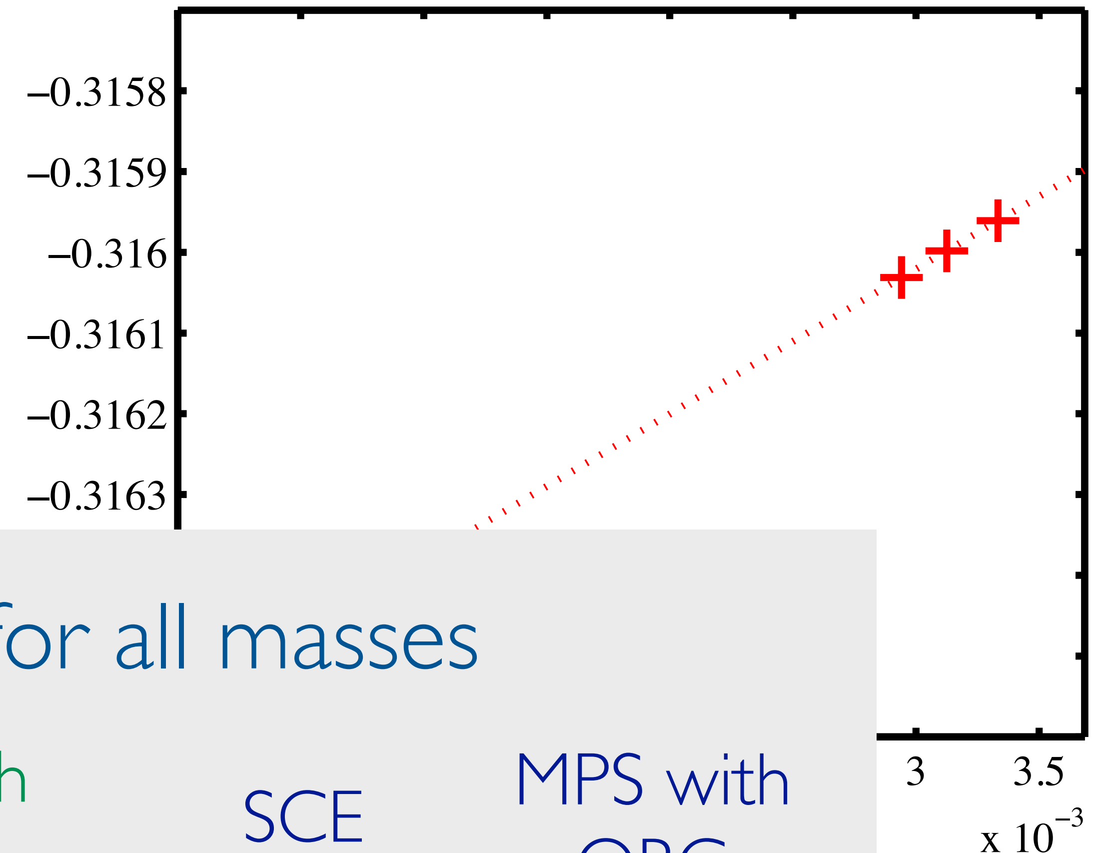
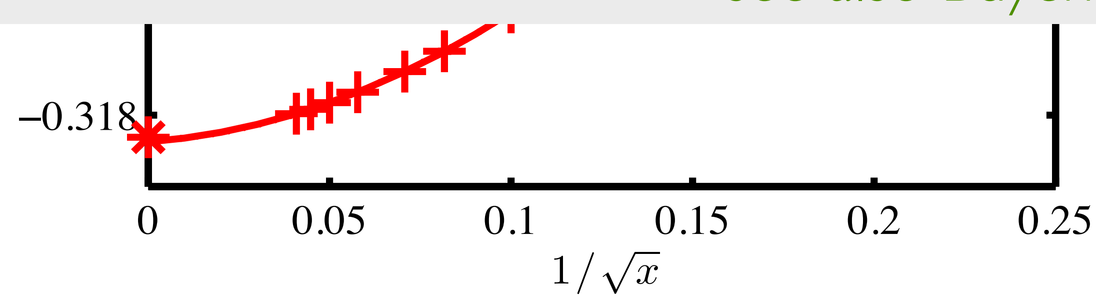




very precise for all masses

m/g	DMRG	MPS with OBC	SCE	MPS with OBC
0	0.5641859	0.56414(26)	1,128379	1.1283(10)
0,125	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)
0,5	0.48747(2)	0.48748(6)	1.20(3)	1.231(5)

see also Buyens et al., PRL 2014



JHEP11(2013)158

TESTBENCH: SCHWINGER MODEL

Relevant states can be described as MPS

TN allow reliable continuum limit

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Relevant states can be described as MPS

- Mass spectrum
- Chiral condensate (order parameter of chiral symmetry breaking)

TN allow reliable continuum limit

MCB, Cichy, Jansen, Cirac, JHEP11(2013)158
PoS 2014 arXiv:1412.0596;
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Real time evolution

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Thermal equilibrium states well approximated by MPO

- Temperature dependence of chiral condensate

MCB, Cichy, Cirac, Jansen, Saito, PRD 2015, PRD 2016

also Buyens et al., PRD 2016

BEYOND SCHWINGER

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Scenario suffering from sign-problem

- chemical potential S. Kuehn et al, PRL118 (2017) 071601
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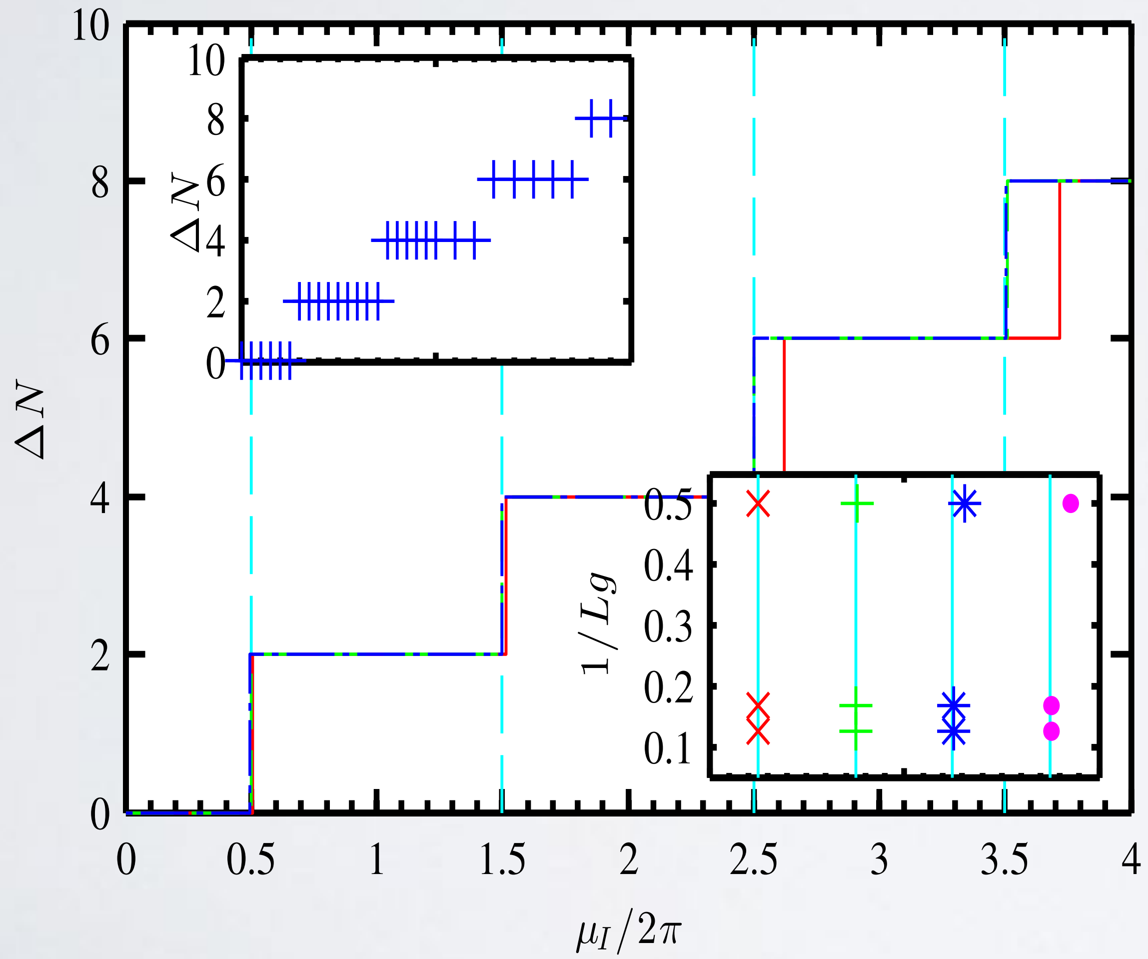
Non-Abelian model

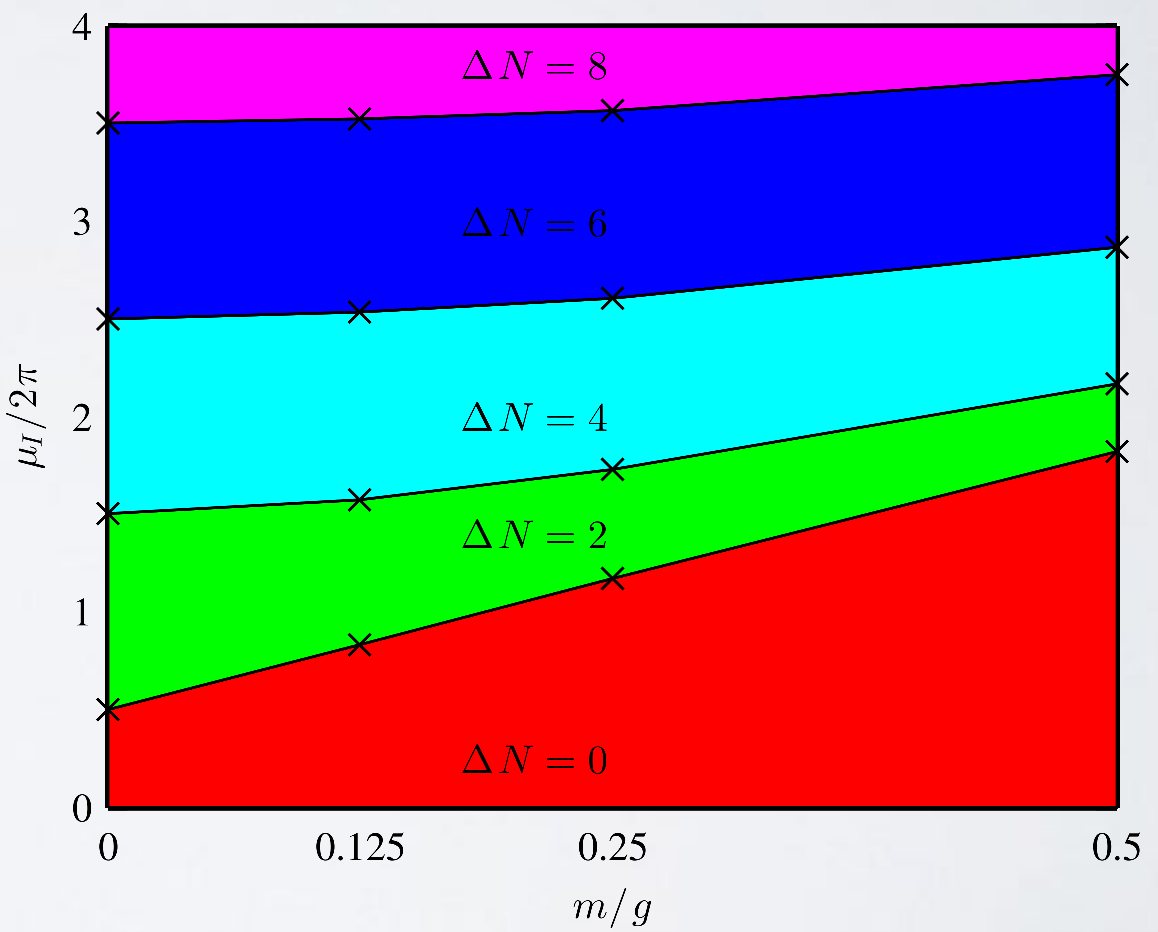
- SU(2) natural next step

FINITE DENSITY WITH MPS

Several fermion flavors, chemical potentials

ground state density changes (first order PT)





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Multiflavour Schwinger model

- Phase diagram at finite density: no sign problem

S. Kühn et al., PRL 118, 071601 (2017)

NON-ABELIAN

SU(2) MODEL

SU(2) matrices

$$H = \frac{1}{2a}\sum_{n,b,c}\left(\phi_n^{b\,\dagger} U_n^{bc}\phi_{n+1}^c + \text{h.c.}\right) + m\sum_{n,b}(-1)^n \phi_n^{b\,\dagger}\phi_n^b + \frac{ag^2}{2}\sum_n \mathbf{J}_n^2$$

Kogut-Susskind '75

plus non-Abelian Gauss' Law $\quad G_n^\nu |\Psi_{\text{phys}}\rangle = 0$

$$G_n^\nu = L_n^\nu - R_{n-1}^\nu - Q_n^\nu,$$

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SU(2) MODEL

S. Kühn et al., JHEP 07 (2015) 130

SU(2) MODEL

Truncating the gauge dof

S. Kühn et al., JHEP 07 (2015) 130

SU(2) MODEL

Truncating the gauge dof

gauge invariant truncation

also for quantum simulations!

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Tagliacozzo et al PRX 2014
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- gauge invariant truncation
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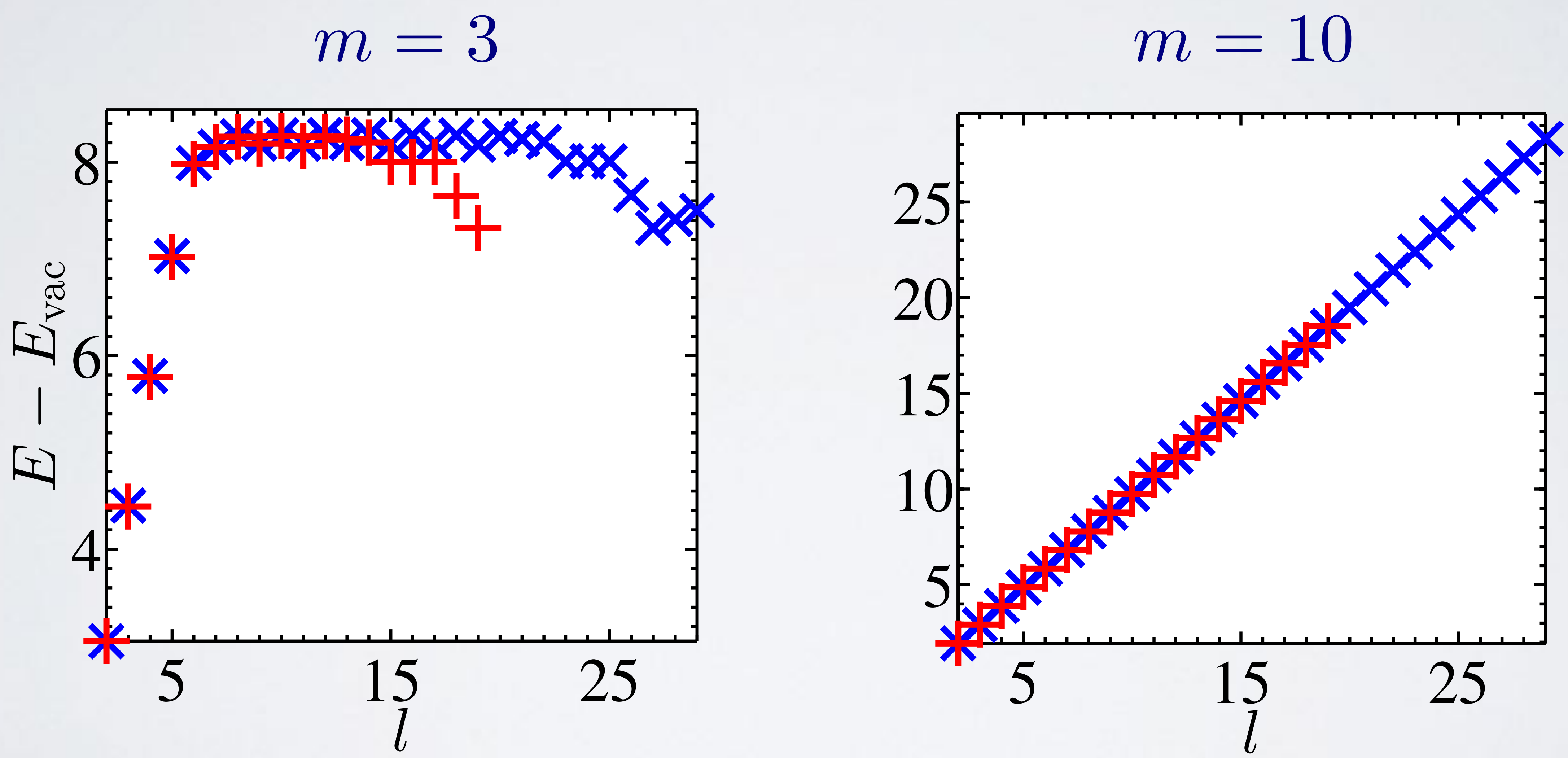
Simulated **statical and dynamical** properties

S. Kühn et al., JHEP 07 (2015) 130

SU(2) STRING BREAKING

Ground state energy with external charges



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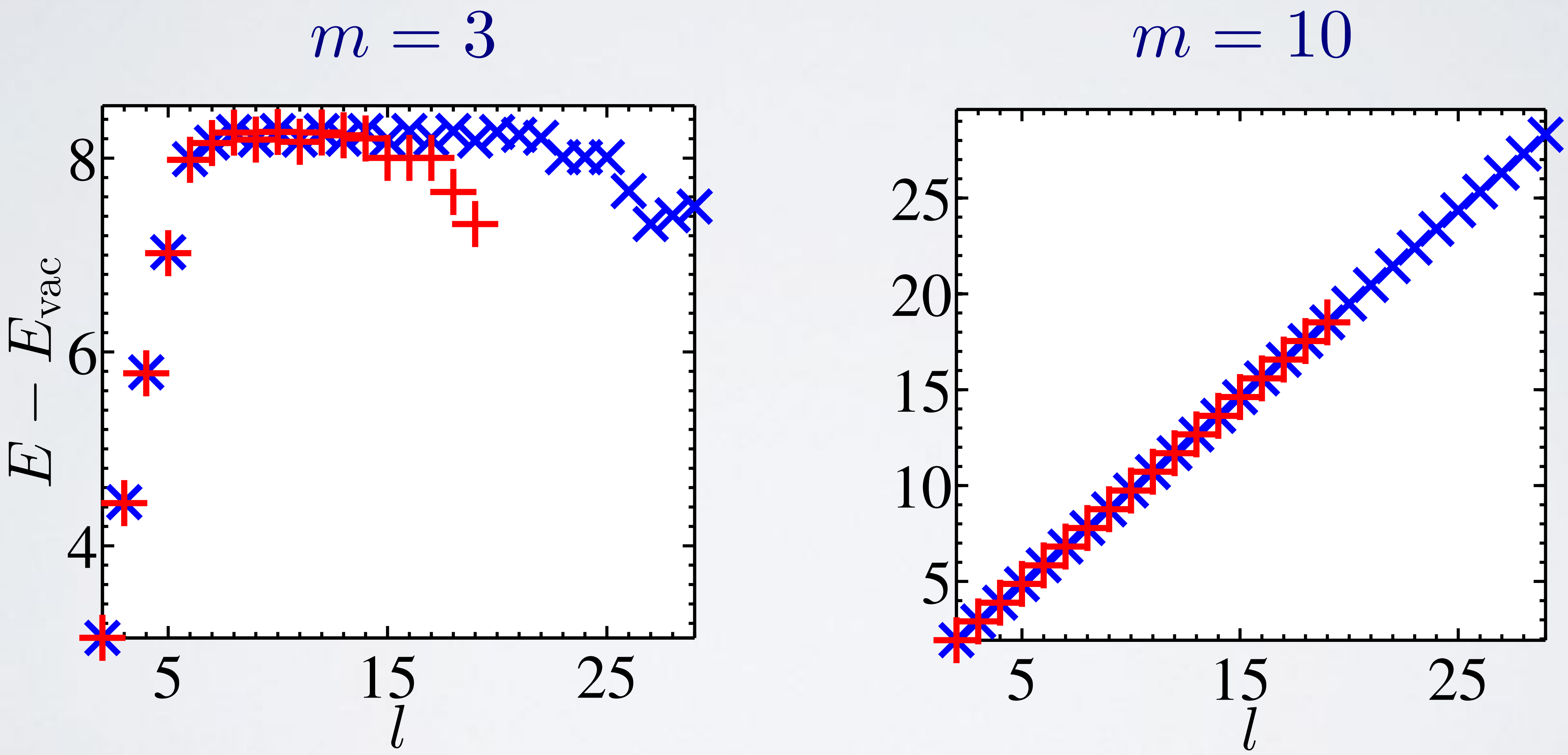
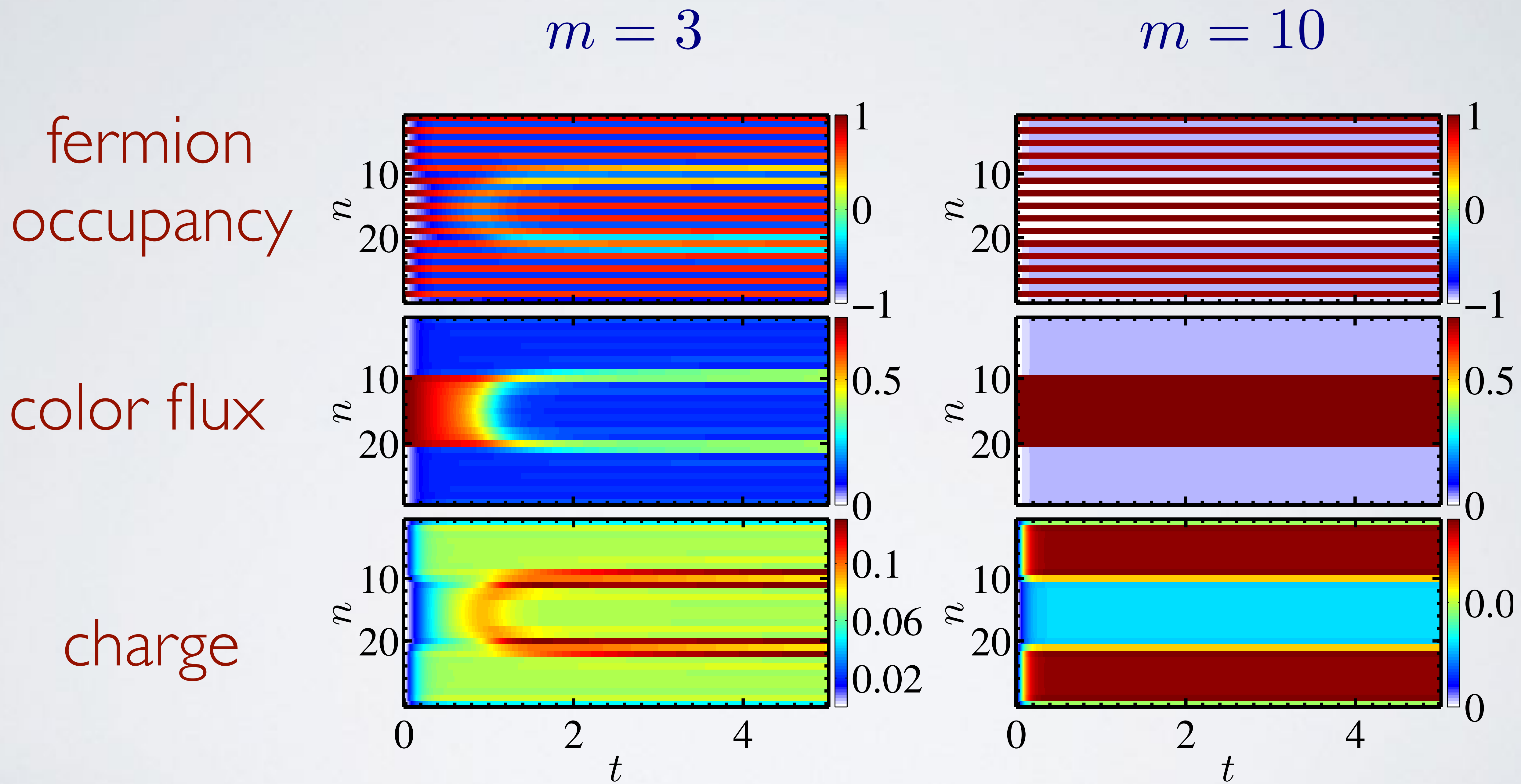


Proposed observables to detect string

S. Kühn et al., JHEP 07 (2015) 130

SU(2) STRING BREAKING



external charges,
imaginary time

S. Kühn et al., JHEP 07 (2015) 130

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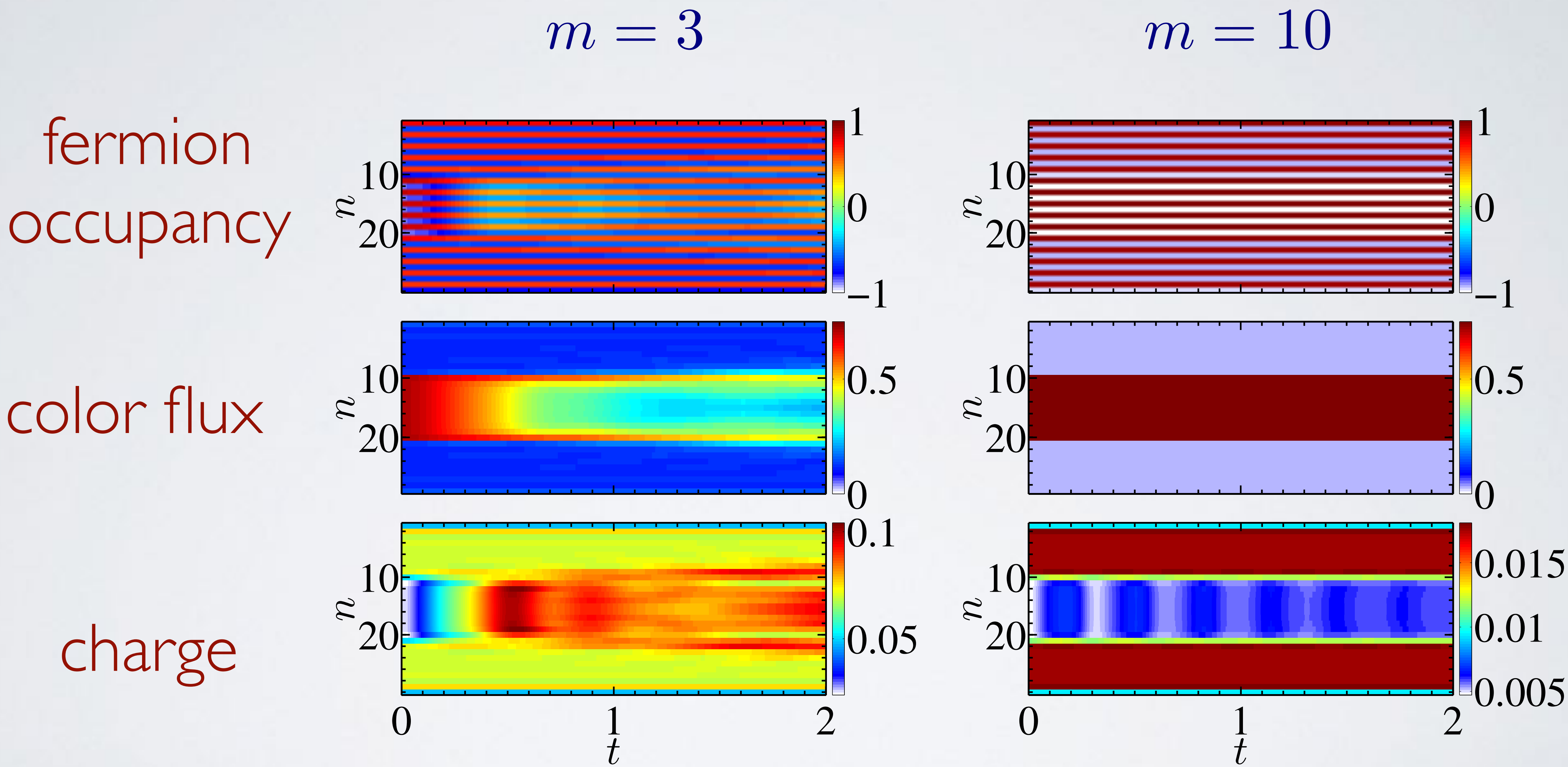

external charges, real time

S. Kühn et al., JHEP 07 (2015) 130

SU(2) MODEL

MCB, Cichy, Cirac, Jansen, Kühn arXiv:1707.06434

SU(2) MODEL

Without truncating the gauge dof

Physical subspace

MCB, Cichy, Cirac, Jansen, Kühn arXiv:1707.06434

SU(2) MODEL

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Physical subspace

Physical states: color singlets

Hamer '82

$$|\ldots n\, j\;\; n\, j\; \ldots\rangle$$

representing gauge invariant combination

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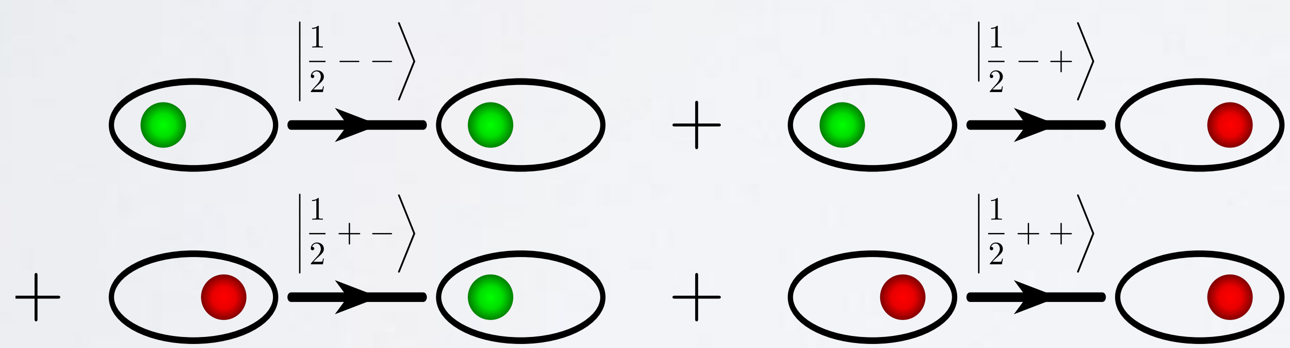

$$|0 \; 1 \; \frac{1}{2} \; 1 \; 0\rangle$$

MCB, Cichy, Cirac, Jansen, Kühn arXiv:1707.06434

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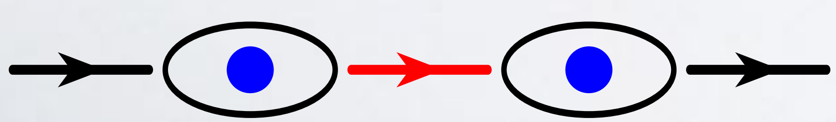
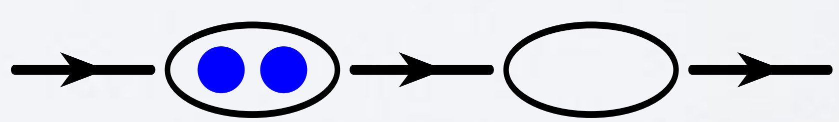
$$(-1)^{j_2-j_1-1/2}\sqrt{\frac{2j_2+1}{2j_1+1}}$$



$|\ldots j_1 \; 1 \; j_2 \; 1 \; j_1 \ldots\rangle$



$|\ldots j_1 \; 2 \; j_1 \; 0 \; j_1 \ldots\rangle$

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Gauss law

MCB, Cichy, Cirac, Jansen, Kühn arXiv:1707.06434

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Gauge law $\quad j,\;\; j \pm 1/2$

MCB, Cichy, Cirac, Jansen, Kühn arXiv:1707.06434

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encode

MCB, Cichy, Cirac, Jansen, Kühn arXiv:1707.06434

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encode $\quad \{|0\rangle,\, |1+\rangle,\, |1-\rangle,\, |2\rangle\}$

MCB, Cichy, Cirac, Jansen, Kühn arXiv:1707.06434

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$$|\ldots\ \tilde{n}\ \tilde{n}\ \ldots\rangle$$

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dimension of physical space $4^N\left(1-\sum_{k=1}^{N}\frac{C_k}{4^k}\right)$

$C_k = (2k)!/(k+1)!k!$

MCB, Cichy, Cirac, Jansen, Kühn arXiv:1707.06434

SU(2) MODEL

Isometric relation between reduced and full basis

$$|\ldots\ \tilde{n}\ \tilde{n}\ \ldots\rangle \longrightarrow |\ldots n^1 n^2\ j\ell\ell'\ n^1 n^2 \ldots\rangle$$

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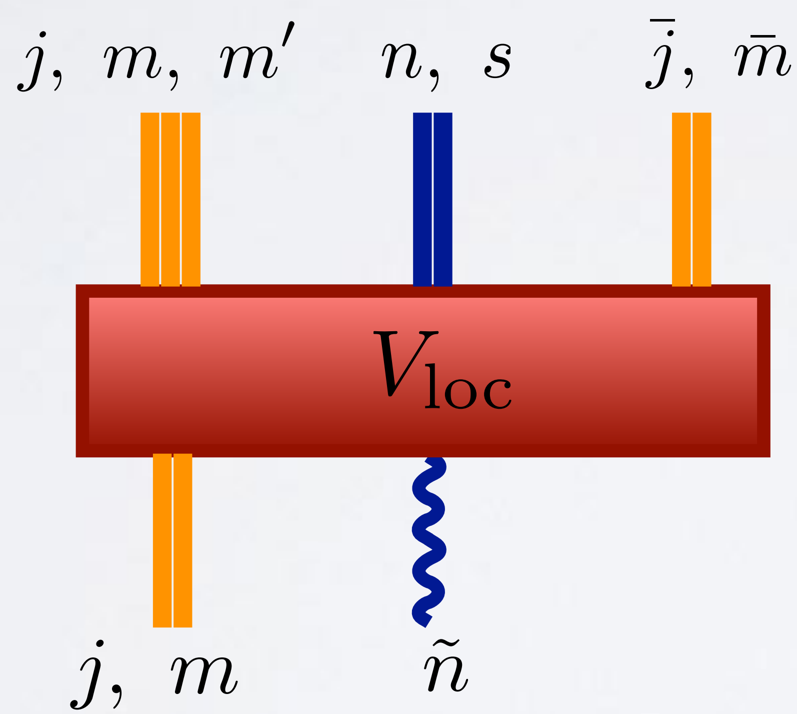

constructed from local pieces

$$\sum_j \sum_{\tilde{n}} \sum_{m,m'=-j}^{j} \sum_{s=-|q|}^{|q|} \frac{C(jm', qs; j+q\ \bar{m})}{\sqrt{2(j+q)-1}} |jmm'; ns; j+q, m'+s\rangle\langle jm; \tilde{n}|$$

MCB, Cichy, Cirac, Jansen, Kühn arXiv:1707.06434

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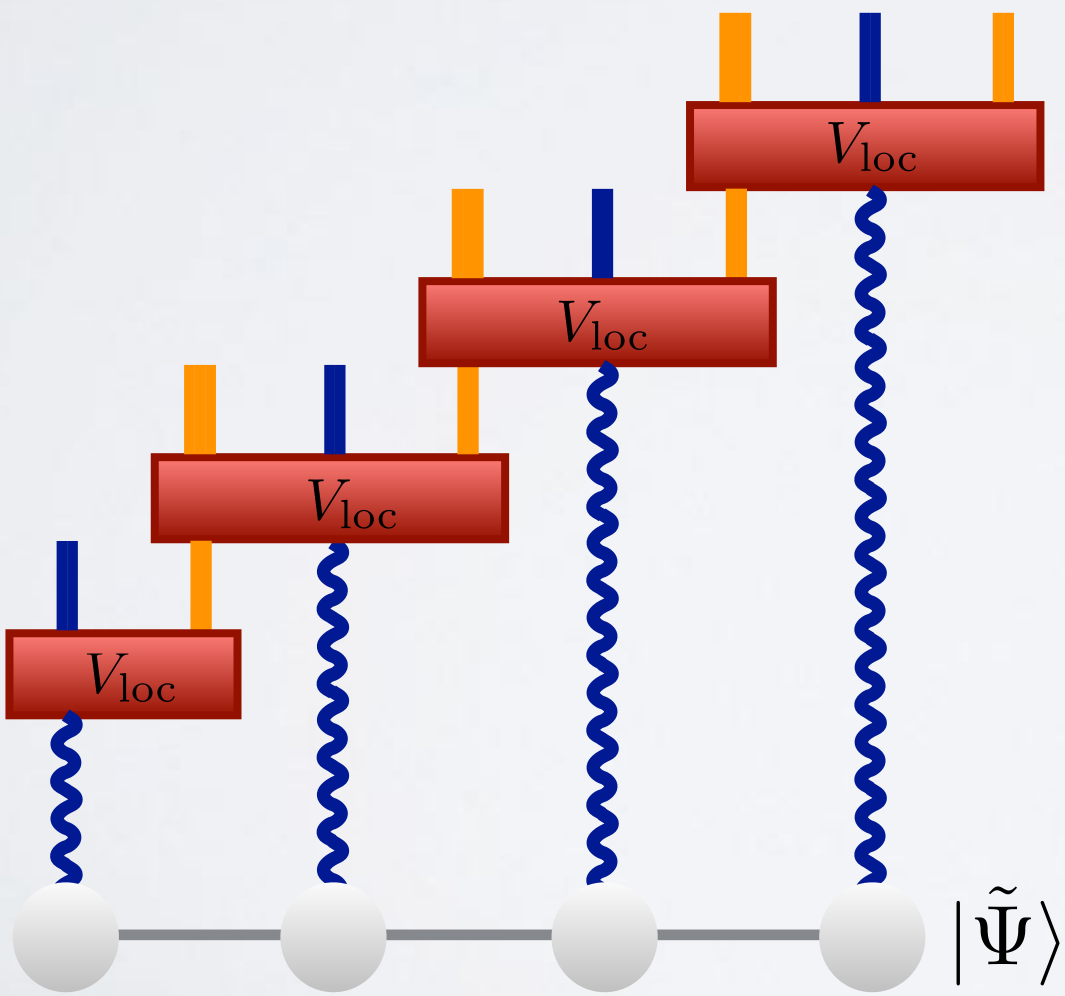

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efficient calculation of spectral properties and entropies

MCB, Cichy, Cirac, Jansen, Kühn arXiv:1707.06434

SU(2) MODEL

We can study the effect of the truncation in j

e.g. ground state energy compared to full model

MCB, Cichy, Cirac, Jansen, Kühn arXiv:1707.06434

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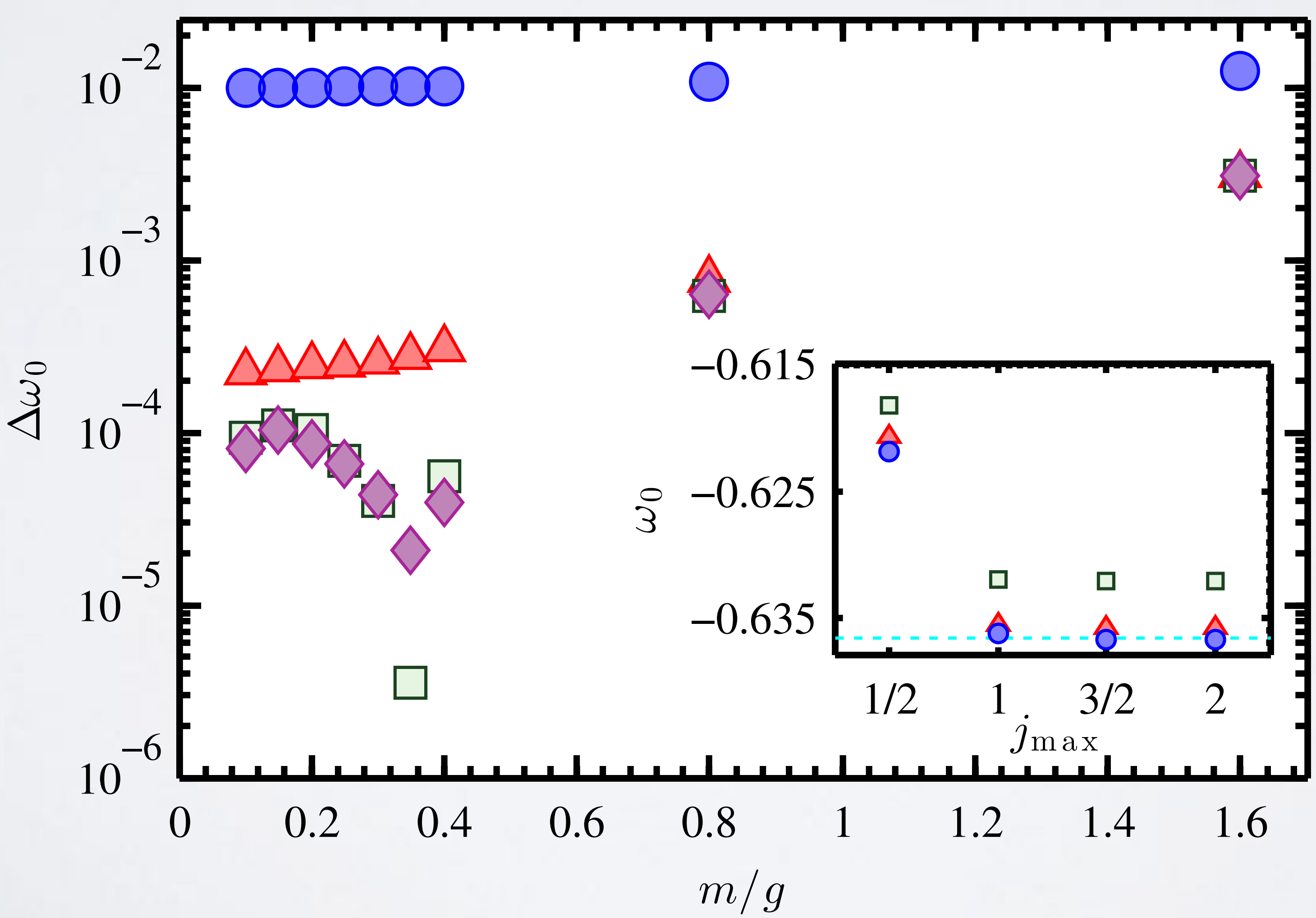

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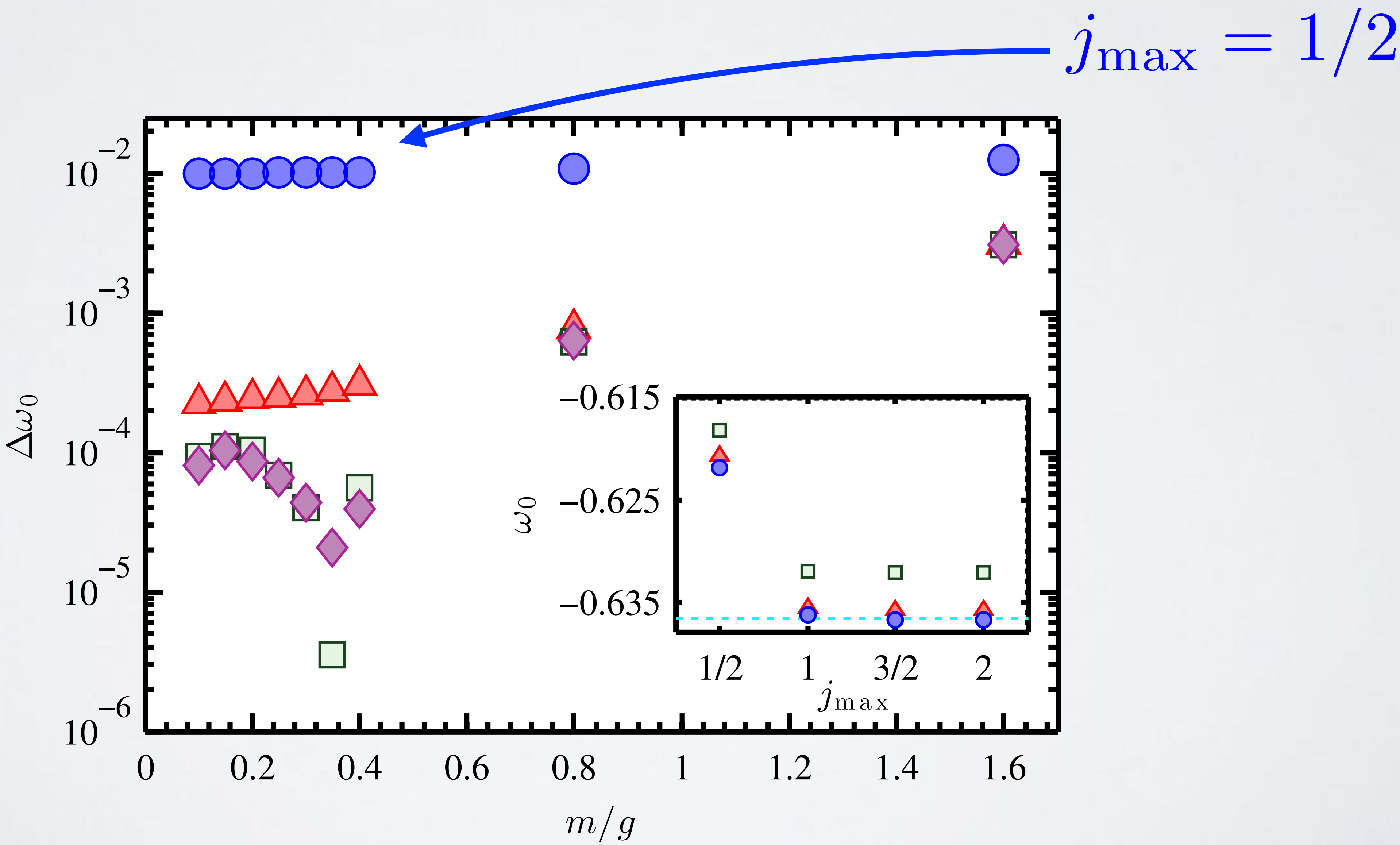

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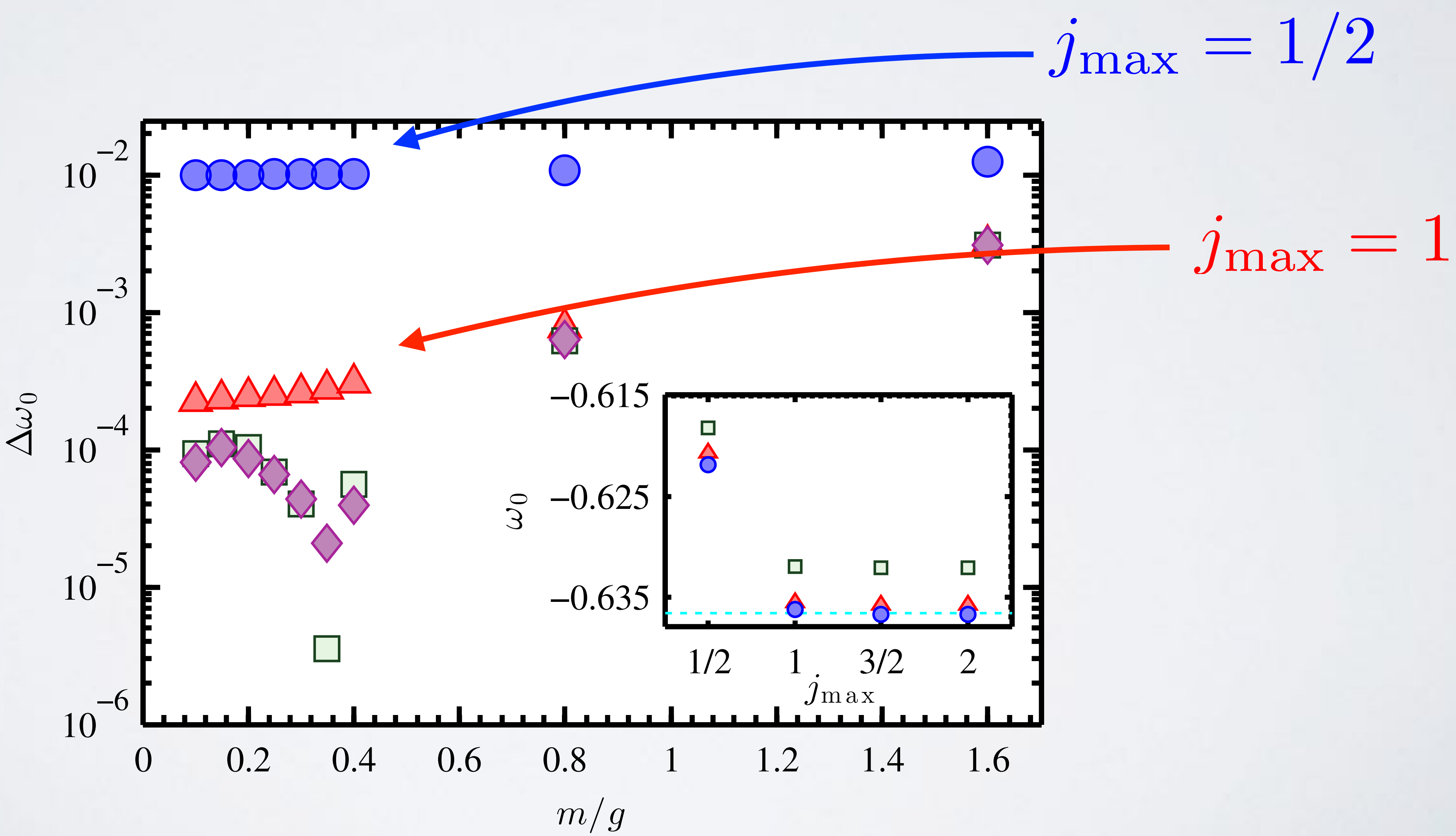

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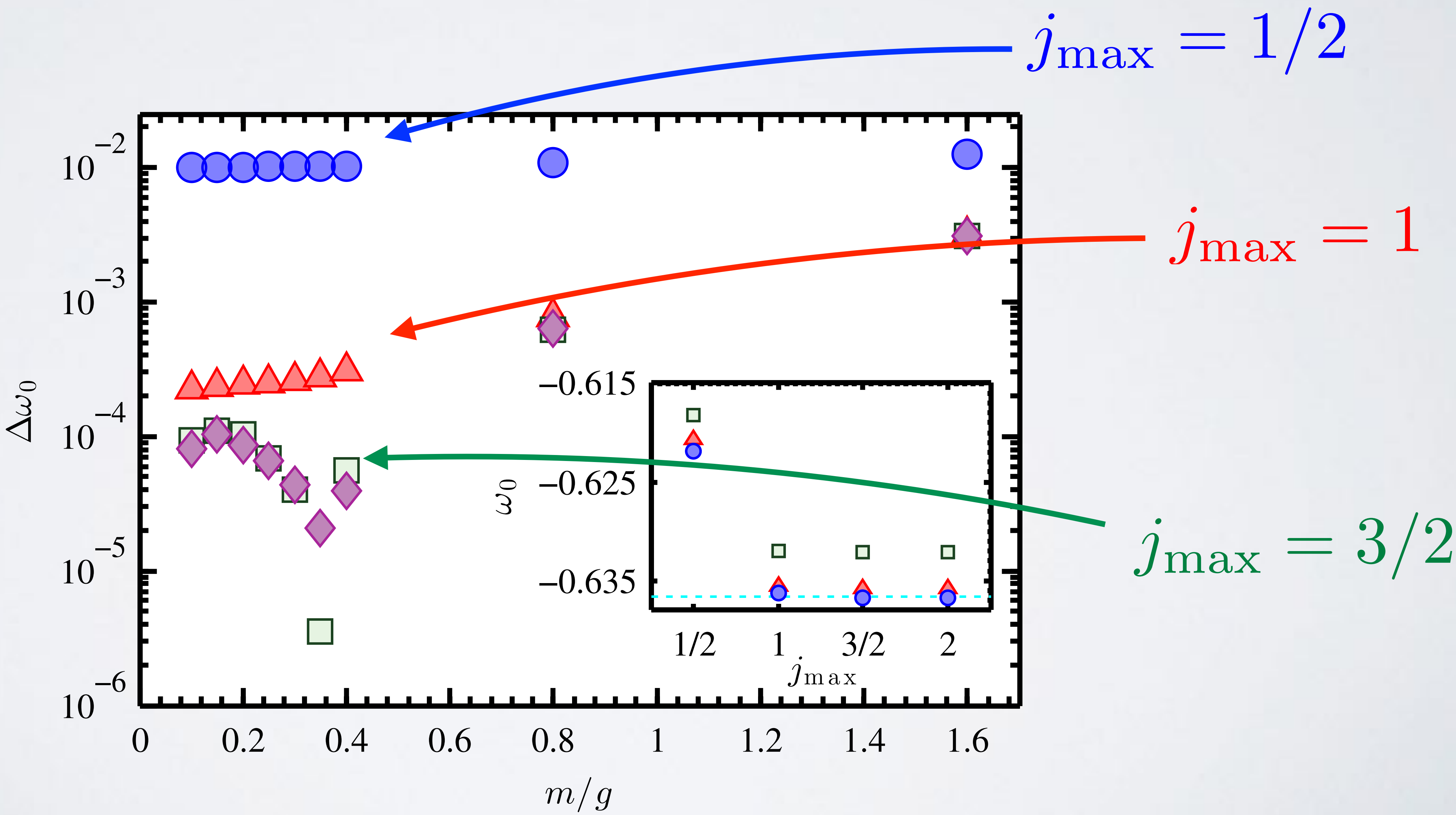

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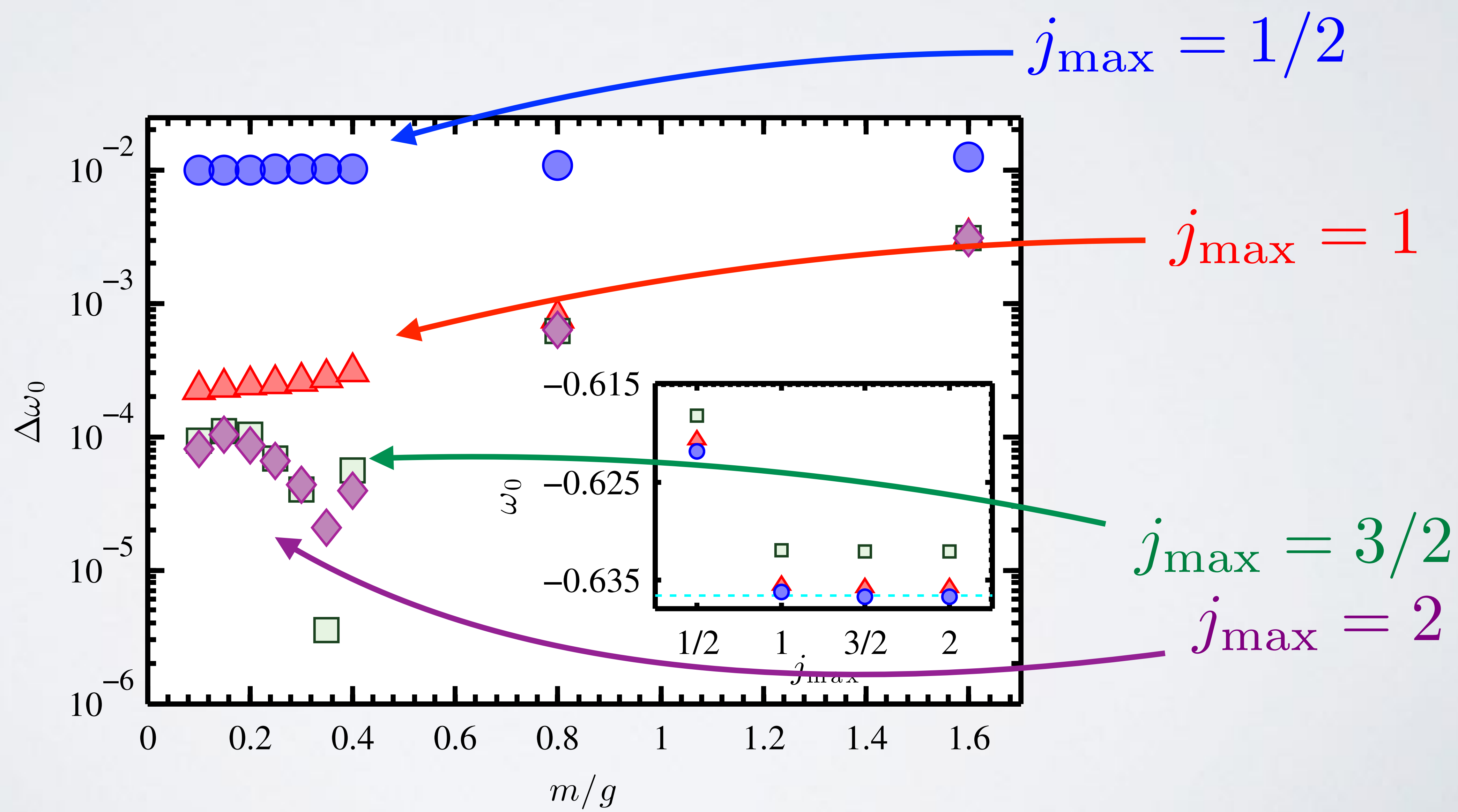

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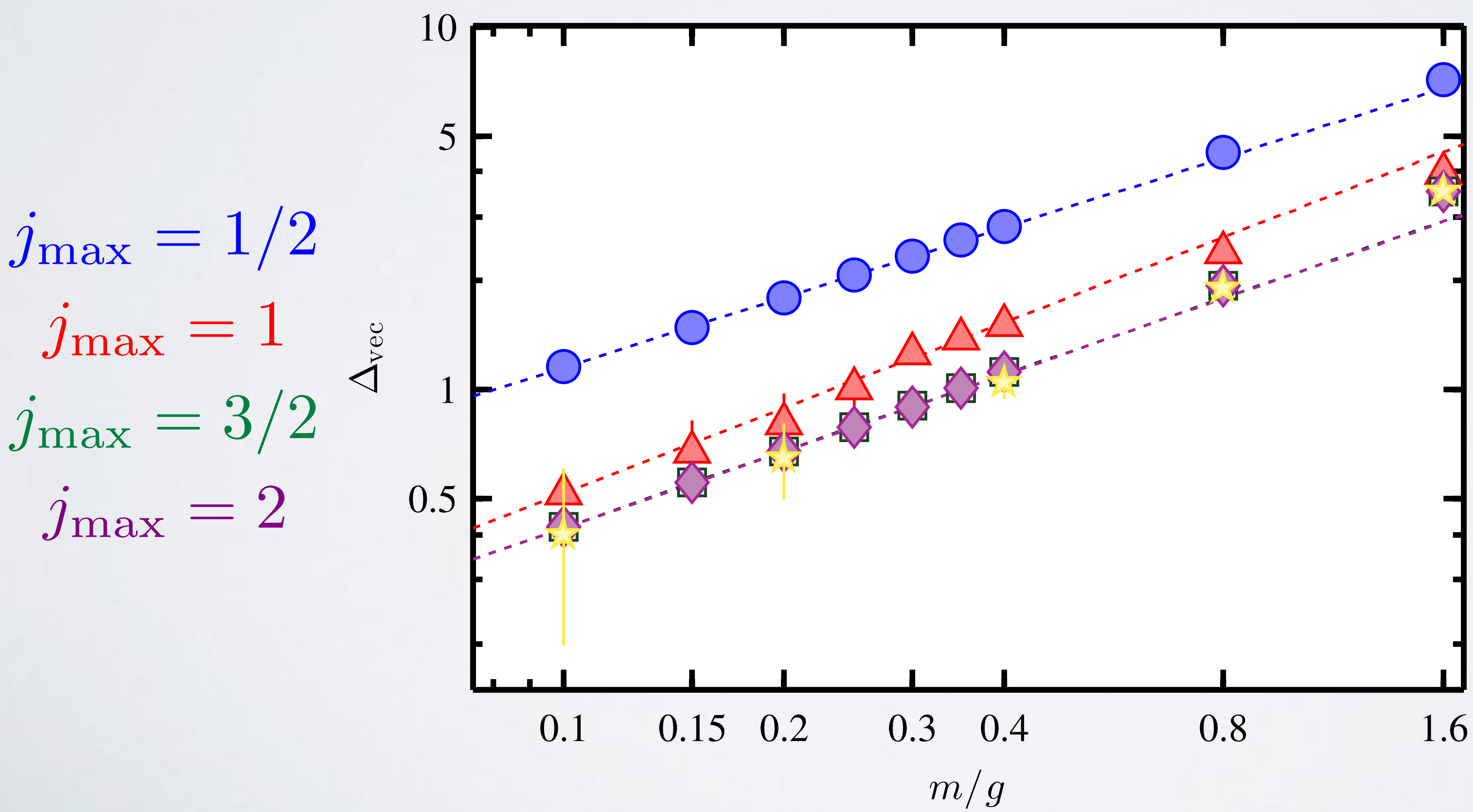

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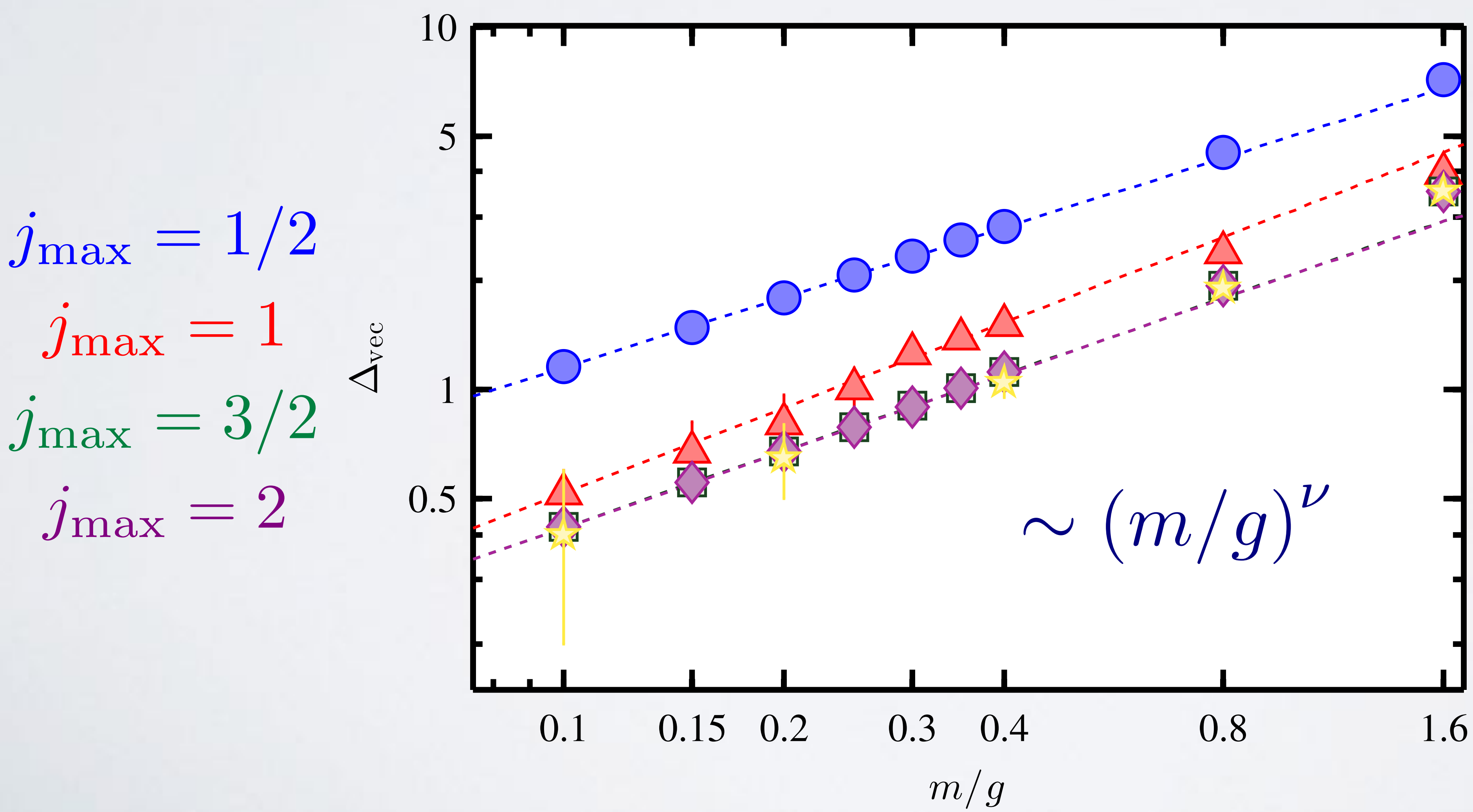

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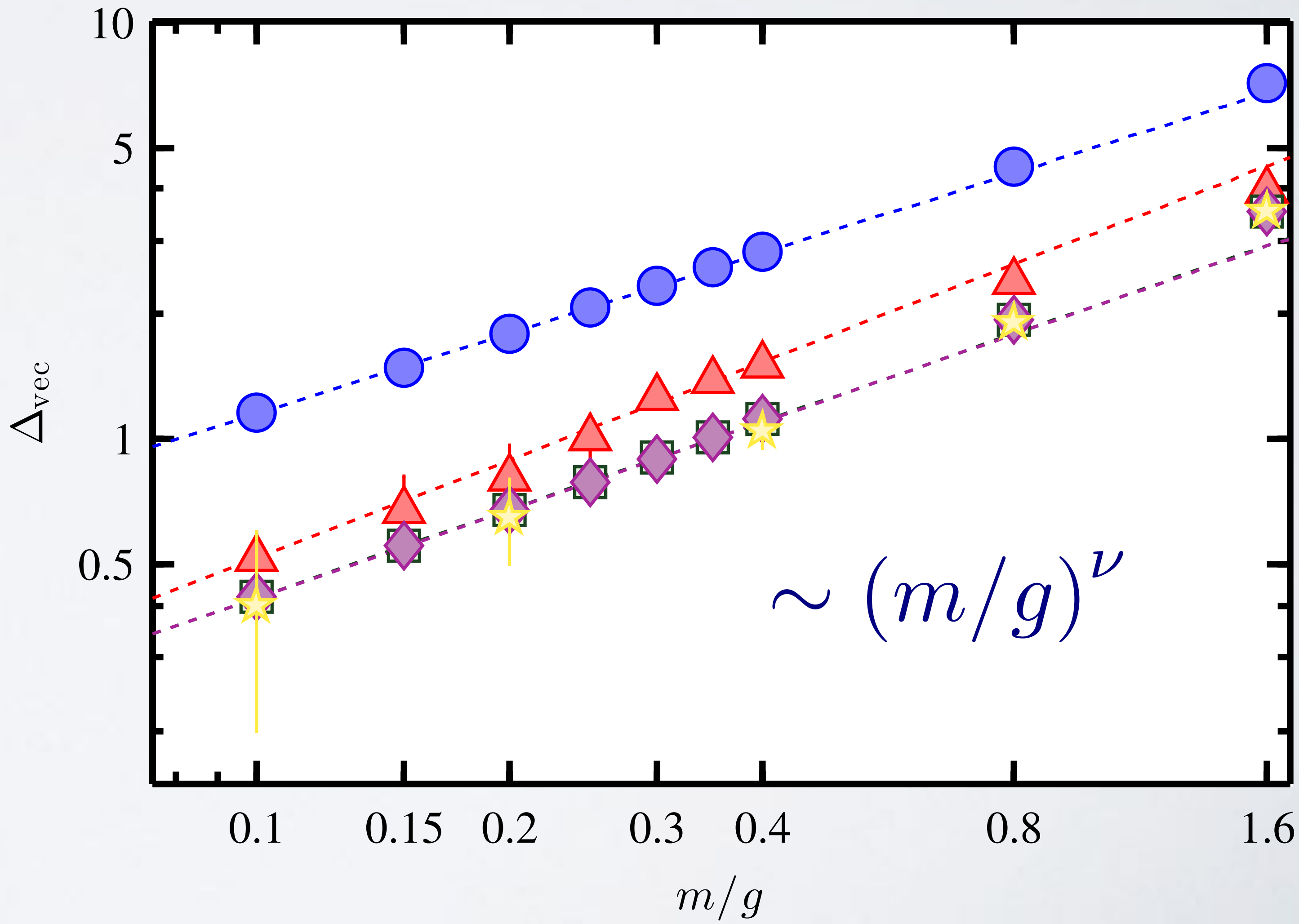
critical exponent

$j_{\max} = 1/2$	~0.639
$j_{\max} = 1$	0.781(93)(75)
$j_{\max} = 3/2$	0.700(29)(11)
$j_{\max} = 2$	0.700(29)(11)



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We can compute entropies efficiently

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gauge constraints not purely local $\Rightarrow$ not all entropy physical

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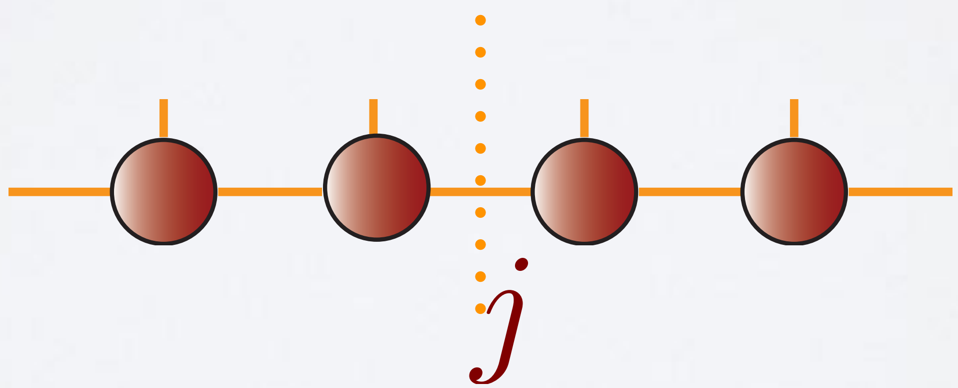
gauge constraints not purely local ⇒ not all entropy physical

$$S(\rho) = -\sum_j p_j \log_2(p_j) + \sum_j p_j S(\rho_j)$$



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

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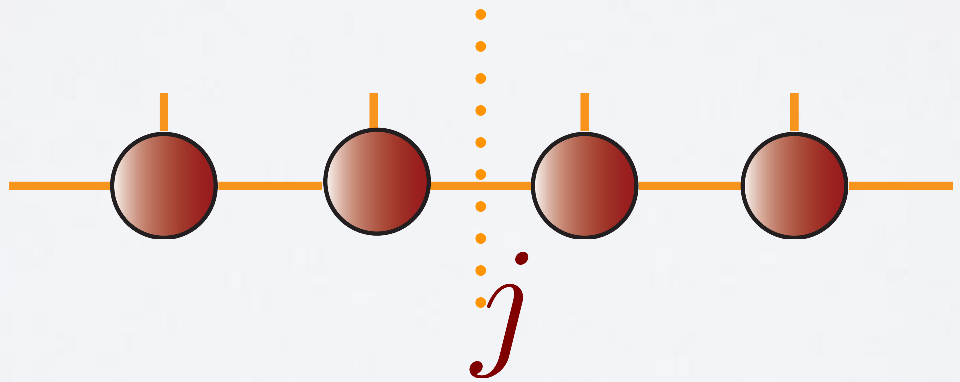
$$S(\rho) = -\sum_j p_j \log_2(p_j) + \sum_j p_j \log_2(2j+1) + \sum_j p_j S(\bar{\rho}_j)$$



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SU(2) MODEL

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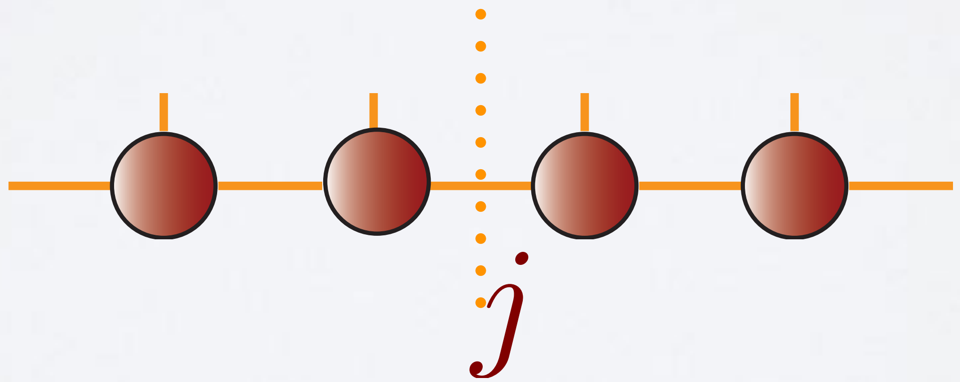
$$S(\rho) = -\underbrace{\sum_j p_j \log_2(p_j)}_{S_{\text{class}}} + \sum_j p_j \log_2(2j+1) + \sum_j p_j S(\bar{\rho}_j)$$



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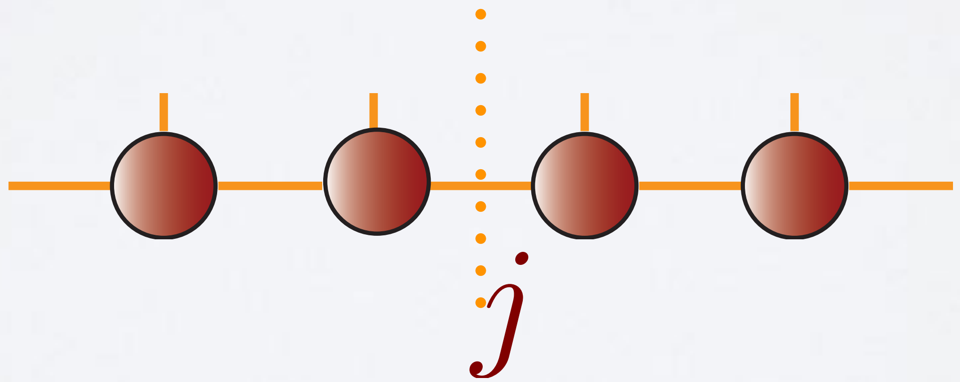
$$S(\rho) = -\underbrace{\sum_j p_j \log_2(p_j)}_{S_{\text{class}}} + \underbrace{\sum_j p_j \log_2(2j+1)}_{S_{\text{repr}}} + \sum_j p_j S(\bar{\rho}_j)$$



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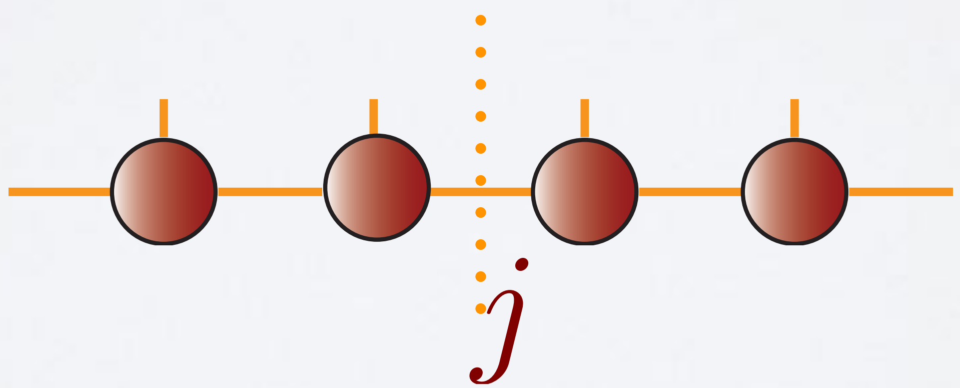

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S_{class} S_{repr} S_{dist}

divergence continuum limit

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

Calabrese, Cardy JStatMech 2004

spin theory gapped

SU(2) MODEL

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MCB, Cichy, Cirac, Jansen, Kühn arXiv:1707.06434

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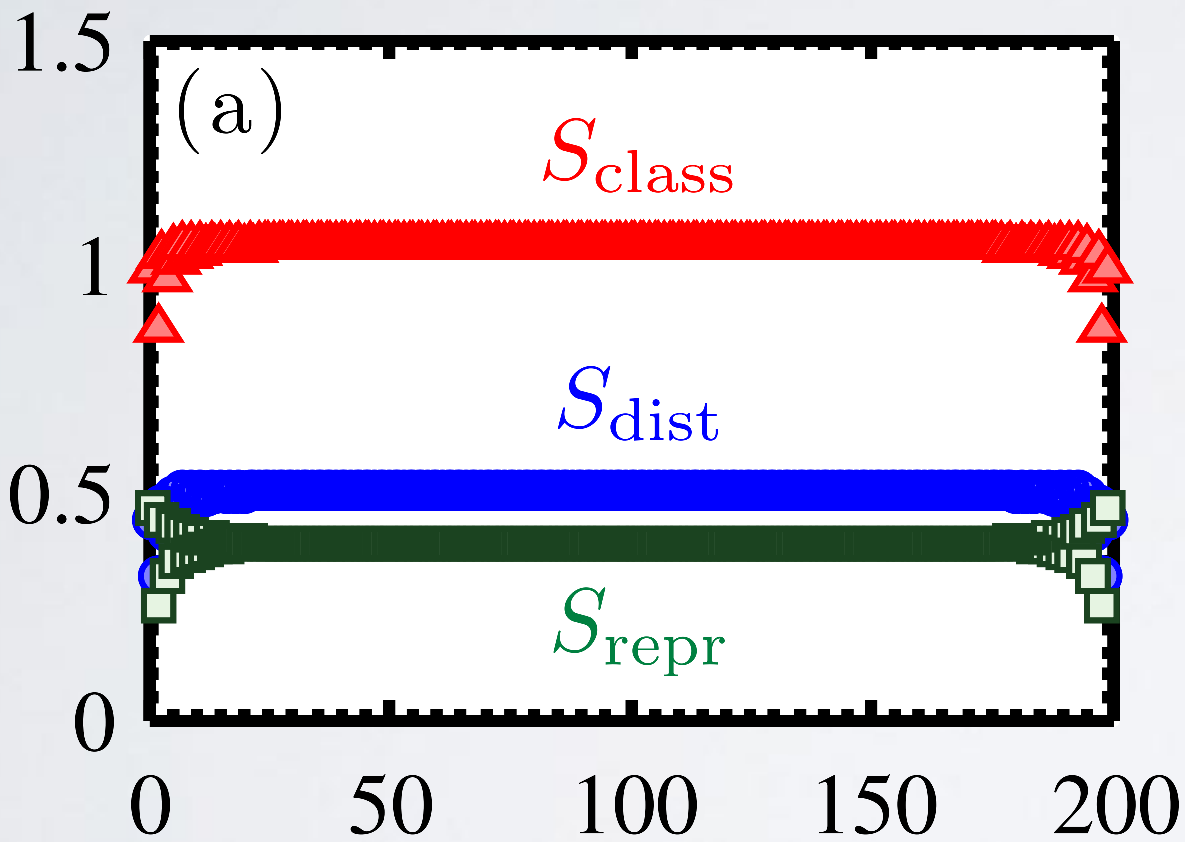

$m/g = 0.8$
$j_{\max} = 2$

spin theory gapped

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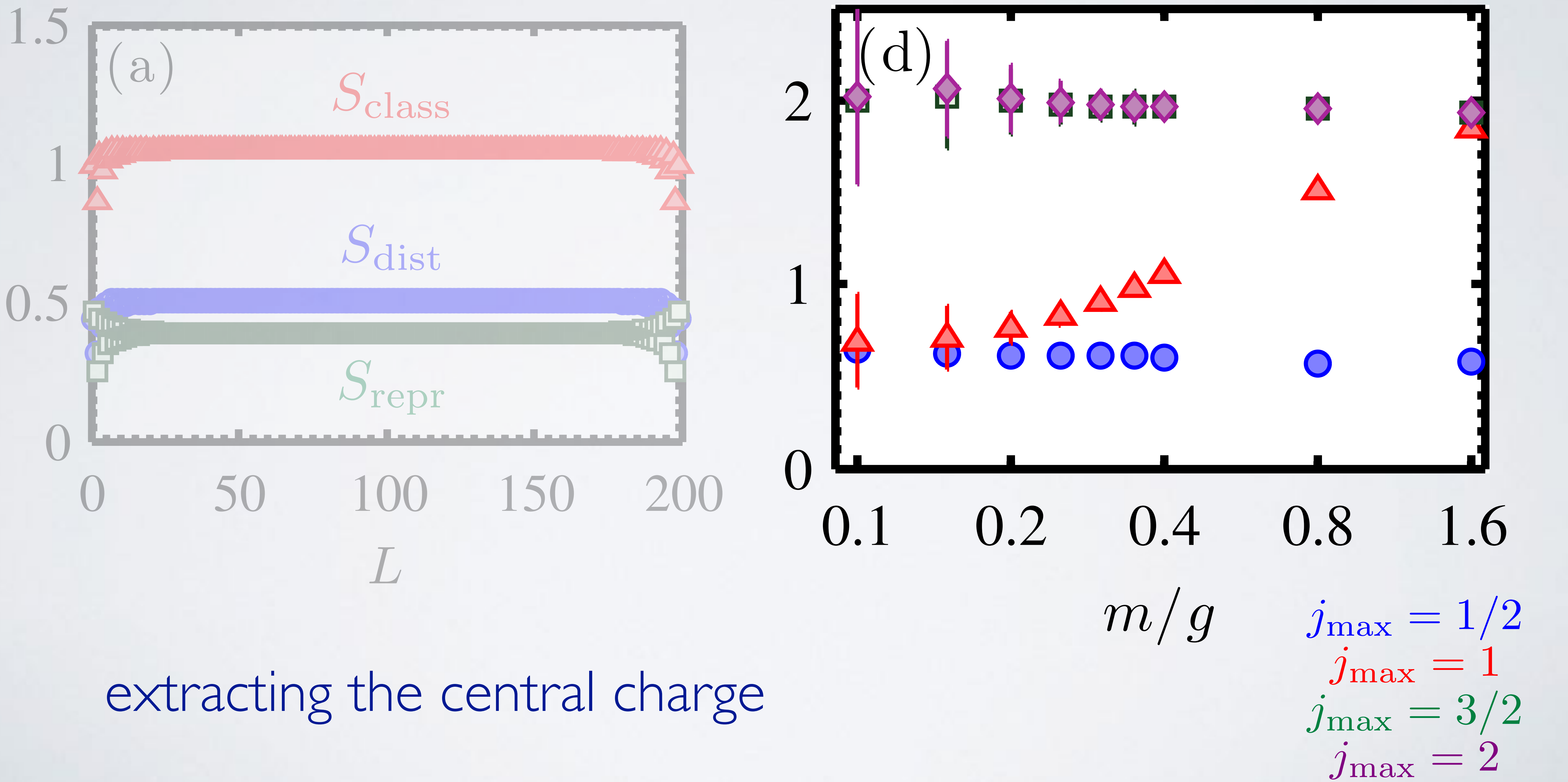
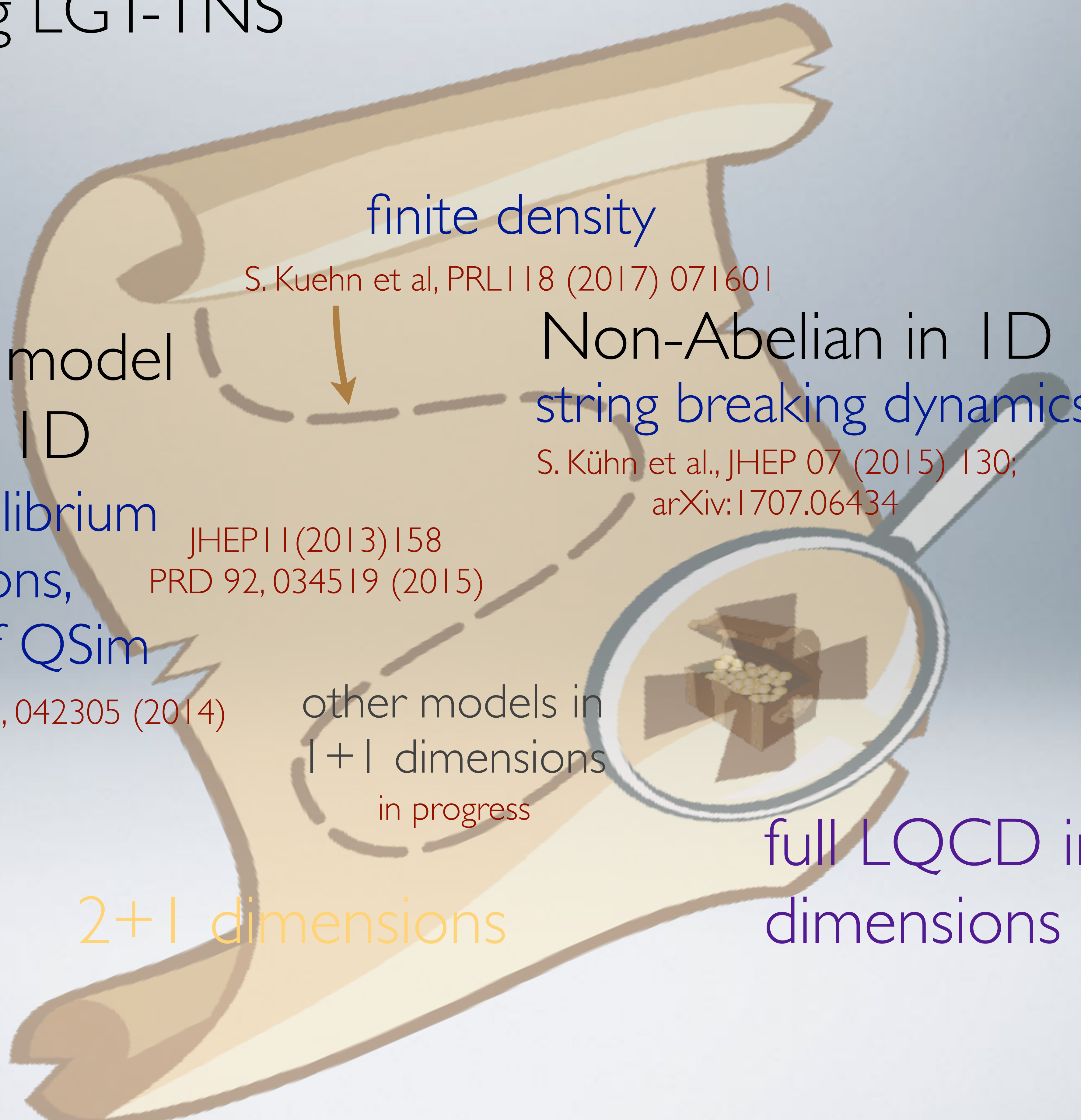


extracting the central charge

MCB, Cichy, Cirac, Jansen, Kühn arXiv:1707.06434

our ongoing LGT-TNS roadmap...



To conclude...

TNS = entanglement based ansatz

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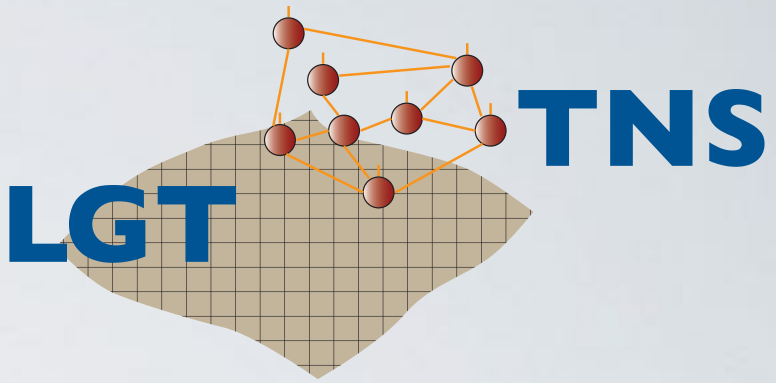

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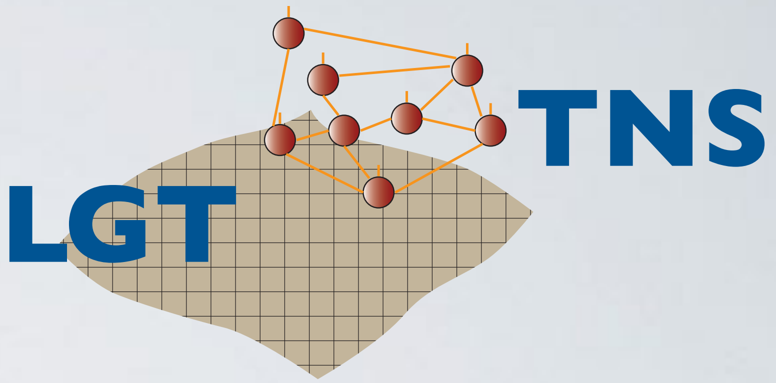
THANKS



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