Title: Approaching Lattice Gauge Theories with Tensor Networks â€“ From real-time dynamics to overcoming the sign problem - Stefan KÃ¼hn

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Abstract: <p>In recent years there has been quite some effort to apply Matrix Product States (MPS) and more general Tensor Networks (TN) to lattice gauge theories. Contrary to the standard Euclidean-time Monte Carlo approach, which faces a major obstacle in the sign problem, numerical methods based on TN are free from the sign problem and allow to some extent simulating time evolution. Moreover, TN are also a suitable tool to explore proposals for potential future quantum simulators for lattice gauge theories.</p>

<p> </p>

<p>In this talk I am going to present some examples where these possibilities allow novel insight into lattice gauge theories. After briefly introducing MPS, I will mainly focus on two models: The first part of the talk is going to be about the Schwinger model. I will show how MPS can help to explore proposals for potential future quantum simulators for this model by studying their spectral properties and simulating adiabatic preparation protocols for the interacting vacuum.</p>

<p>Furthermore, I will show an explicit example where TN allow to overcome the Monte Carlo sign problem in a lattice calculation by studying the zero-temperature phase structure for the two-flavor case at non-zero chemical potential with MPS.</p>

<p> </p>

<p>In the second part, I am focusing on a non-Abelian gauge model, namely a 1+1 dimensional SU(2) lattice gauge theory. Using MPS, the phenomenon of string breaking in this theory can be studied in real time, thus allowing to gain new insight into this process. Moreover, I will show how the gauge field can be integrated out for systems with open boundary conditions and how to obtain a formulation which allows to address the model more efficiently with MPS.</p>

Approaching Lattice Gauge Theories with Tensor Networks

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From real-time dynamics to overcoming the sign problem

Stefan Kühn

Max Planck Institute of Quantum Optics

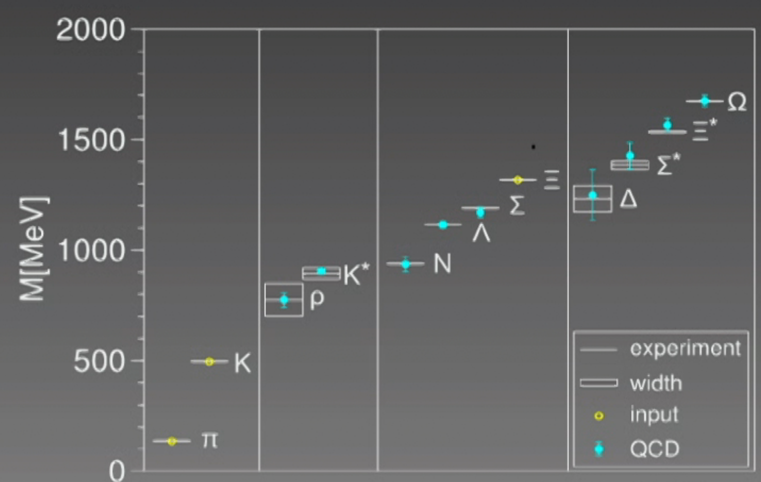
in collaboration with

Mari Carmen Bañuls	MPQ
Krzysztof Cichy	Goethe-University, Frankfurt am Main
J. Ignacio Cirac	MPQ
Karl Jansen	NIC, DESY Zeuthen
Hana Saito	CCS Tsukuba
Erez Zohar	MPQ

Motivation

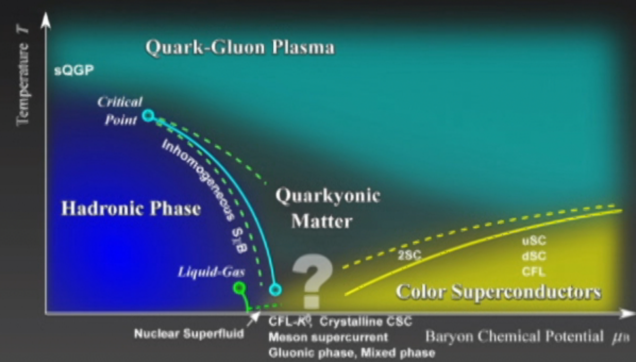
Lattice gauge theory

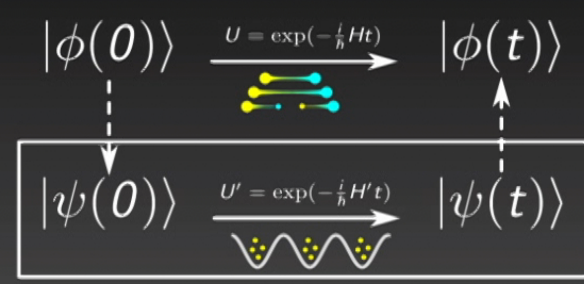
- Formulate the theory on a discretized space-time lattice
  $\Rightarrow$ Momentum cutoff due to the lattice spacing
- Allows non-perturbative study of gauge theories
- Monte Carlo simulations in Euclidean time for mass spectra, phase diagrams, ...



S. Dürr et. al. Science 322 1224 (2008)

Motivation





Monte Carlo simulations

- Sign problem
- No real-time dynamics
- No access to wave function

Quantum simulation

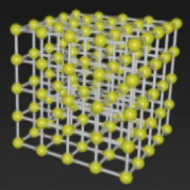
- Sign problem free
- Real-time dynamics
- Finite number of DOF
- Noise

K. Fukushima and T. Hatsuda, Rep. Prog. Phys. 74, 014001 (2011)
E. A. Martinez *et al.* Nature 534, 516 (2016)

Matrix Product States (MPS)

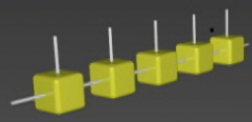
Monte Carlo

- ✓ Expectation values
- ✗ Access to the ground state wave function
- ✗ Sign problem free



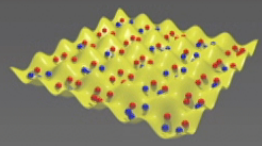
Matrix Product States

- ✓ Ground states / Low lying excitations
- ✓ Time evolution
- ✓ Sign problem free



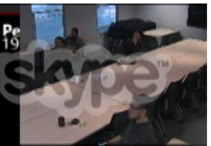
Quantum simulation

- ✓ Ground states / Low lying excitations
- ✓ Time evolution
- ✓ Sign problem free
- ✓ Gauge invariance



Outline

1. Motivation
2. Matrix Product States
3. The Schwinger model
   - **Quantum simulation**
   - Phase structure for two-flavors
4. SU(2) Lattice Gauge Theory
   - **Dynamics of string breaking**
   - Integrating out the gauge field
5. Conclusion & Outlook



Matrix Product States (MPS)

MPS ansatz

- Coming from quantum information theory
- Fulfill the area law: $S(L) \propto L^{d'-1} \overset{\text{d}'=1}{=} \text{const}$
- MPS ansatz with open boundary conditions (OBC) for system with N sites

$$|\psi\rangle = \sum_{i_1, i_2, \ldots, i_N} A^{i_1} A^{i_2} \ldots A^{i_N} \, |i_1\rangle \otimes |i_2\rangle \otimes \cdots \otimes |i_N\rangle$$

Matrix Product States (MPS)

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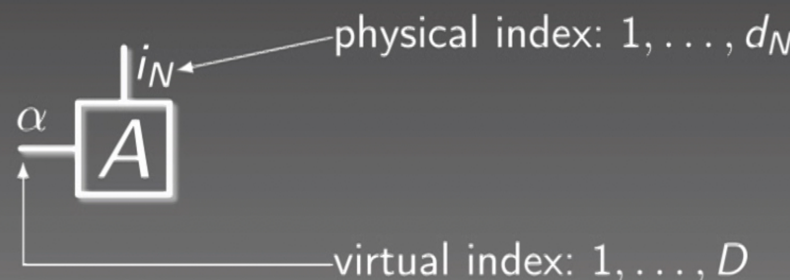
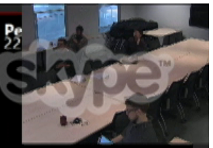
- Tensor $A^{i_N} \in \mathbb{C}^{D \times 1}$





Matrix Product States (MPS)

Scaling

- Number of parameters in the MPS with OBC

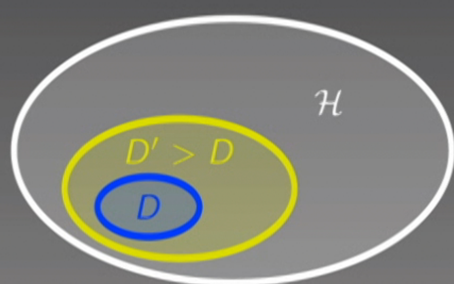
$|\psi\rangle =$ 

$$(N-2)D^2 d + 2Dd = \mathcal{O}(ND^2 d)$$

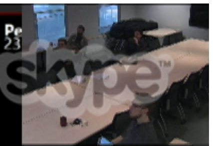
- Dimension of the full Hilbert space

$$d^N$$

- Quantum information: Physically relevant states $D \ll d^{\lfloor \frac{N}{2} \rfloor}$.



M. B. Hastings, Journal of Statistical Mechanics 2007 (2007)
G. Vidal Phys. Rev. Lett. 93, 040502 (2004)
F. Verstraete, D. Porras, J.I. Cirac Phys. Rev. Lett. 93, 227205 (2004)



Schwinger model

Lattice Hamiltonian in temporal gauge

- Lattice formulation with Kogut-Susskind staggered fermions

$$H = -\frac{i}{2a}\sum_{n=1}^{N-1}\sum_{f=1}^{F}\left(\phi^{\dagger}_{n,f} L^{+}_{n} \phi_{n+1,f} - \text{h.c}\right) + \sum_{n=1}^{N}\sum_{f=1}^{F}\left((-1)^n m_f + \kappa_f\right)\phi^{\dagger}_{n,f}\phi_{n,f} + \frac{ag^2}{2}\sum_{n=1}^{N-1} L_n^2$$

Kinetic part + Coupling to gauge field   Mass term   Chemical potential   Electric energy

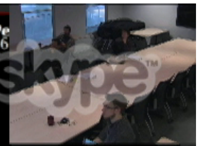
- Additional constraint: Gauss Law

$$G_n|\chi\rangle = q_n|\chi\rangle, \qquad [H, G_n] = 0 \quad \forall n$$

$$G_n = L_n - L_{n-1} - \sum_{f=1}^{F}\phi^{\dagger}_{n,f}\phi_{n,f} - \frac{F}{2}\left(1 - (-1)^n\right)$$

Staggered charge Q_n

J. Kogut, L. Susskind, Phys. Rev. D 11 395 (1975)



Schwinger model

Lattice Hamiltonian in temporal gauge

- Dimensionless formulation

$$W = -i\, x \sum_{n=1}^{N-1} \sum_{f=1}^{F} \left(\phi^{\dagger}_{n,f} L^{+}_{n} \phi_{n+1,f} - \text{h.c} \right)$$

$$+ \sum_{n=1}^{N} \sum_{f=1}^{F} \left((-1)^n \mu_f + \nu_f \right) \phi^{\dagger}_{n,f} \phi_{n,f} + \sum_{n=1}^{N-1} L_n^2$$

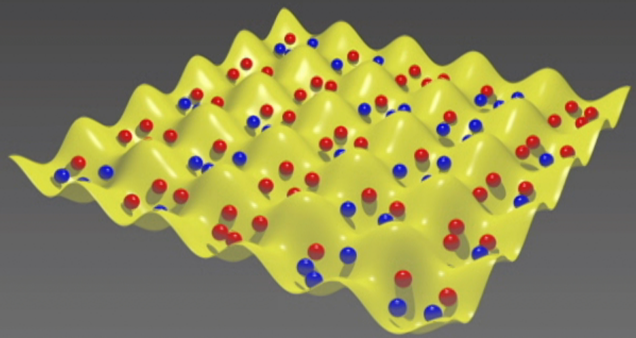
x: $1/(ag)^2$ μ_f: $2m_f/ag^2$ ν_f: $2\kappa_f/ag^2$

$$\xrightarrow{a \to 0} \quad \Psi_f = \begin{pmatrix} \psi_{1,f} \\ \psi_{2,f} \end{pmatrix}$$

- Compact formulation: $L_n^{+} = \exp(i\theta_n)$, $\theta_n \in [0, 2\pi]$

$$[\theta_n, L_m] = i\delta_{nm} \quad \Rightarrow \quad L_n^{+} \text{ acts as raising operator}$$

Exploring a quantum simulator for the single flavor case



Schwinger model: Quantum simulation

Quantum simulator

- Focus on the single-flavor case $F = 1$
- For a single flavor the chemical potential is only a constant energy offset
  $\Rightarrow$ Set $\nu = 0$
- Electric field has to be truncated to a small value to obtain finite dimensional Hilbert spaces

Questions:

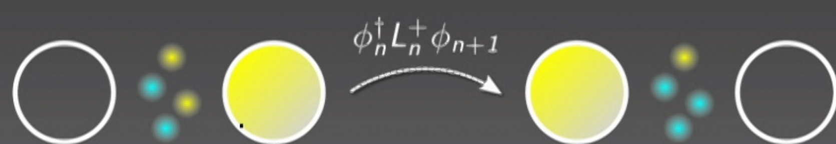
- How close is that to the full model?
- How can one prepare the interacting vacuum?
- How does gauge invariance breaking noise affect the process?

Schwinger model: Quantum simulation

cQED model

- Links are populated by two bosonic species
- Link operators (Schwinger representation)

$$L_n^+ = \frac{a_n^\dagger b_n}{\sqrt{\frac{N_0}{2}\left(\frac{N_0}{2}+1\right)}}, \quad L_n = \frac{1}{2}\left(a_n^\dagger a_n - b_n^\dagger b_n\right)$$



- Number of particles per link is fixed to an even number N_0
- Local Hilbert space dimension $d = N_0 + 1$
- **Same** $U(1)$ **symmetry** as the Schwinger model

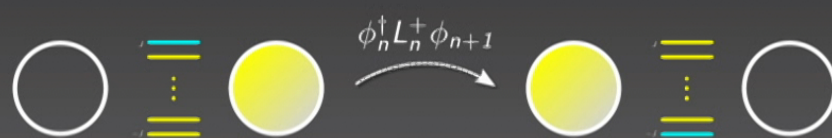
E. Zohar, J.I. Cirac, B. Reznik, Phys. Rev. A 88, 023617 (2013)

Schwinger model: Quantum simulation

$\mathbb{Z}_d$ model

- Use angular momentum eigenstates $|\varphi^k\rangle$ to construct the link operators
- Identify $|\varphi^{J+1}\rangle$ with $|\varphi^{-J}\rangle$

$$L_n^+ = \sum_{k=-J}^{J} |\varphi_n^{k+1}\rangle\langle\varphi_n^k|, \quad L_n = \sum_{k=-J}^{J} k|\varphi_n^k\rangle\langle\varphi_n^k|$$



- $\mathbb{Z}_d$ **symmetry**, **different** form Schwinger model
- Local Hilbert space dimension $d = 2J + 1$
- Gauss Law is fulfilled modulo d:

$$U(n)|\chi\rangle = \left[\exp\left(i\frac{2\pi}{d}G(n)\right) - \mathbb{1}\right]|\chi\rangle = 0 \quad \forall n$$

A. De La Torre, J. Iguain, Am. J. Phys. 66, 1115 (1998)

Schwinger model: Quantum simulation

Overview:

Model	Gauge symmetry	Link dimension d
Schwinger model	$U(1)$	∞
cQED model	$U(1)$	$N_0 + 1$
$\mathbb{Z}_d$ model	"$\mathbb{Z}_d$"	$2J + 1$

Schwinger model: Quantum simulation

Effect of the finite dimension

- Extrapolate to the continuum similar to lattice calculations
- Gather a range of values for bond dimension D, system size N and coupling strength x
- Extrapolate:

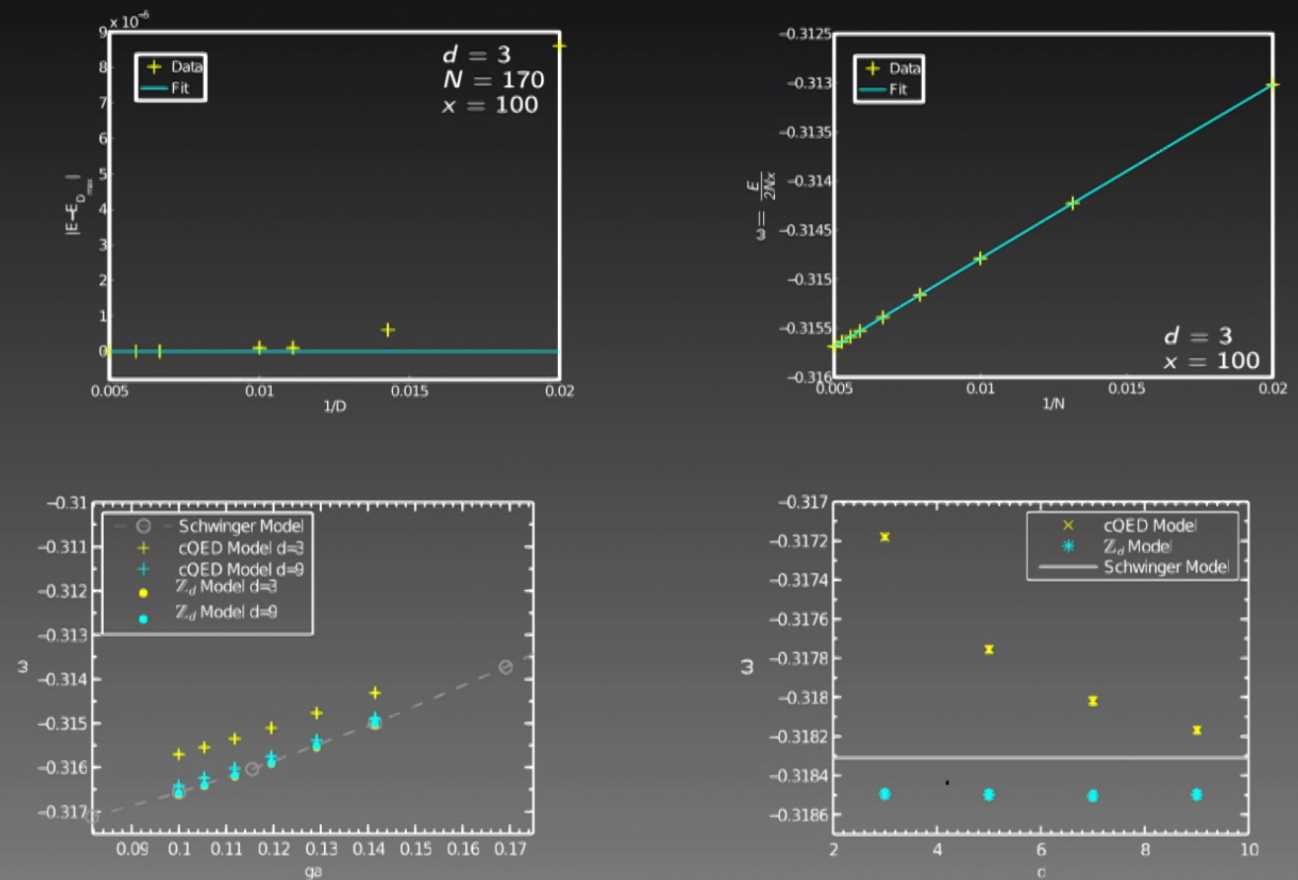
  Bond dimension: $D \in [50, 200]$

  → Finite size: $N \in [50, 200]$

  → Continuum: $x \in [50, 100]$

Schwinger model: Quantum simulation

Spectrum



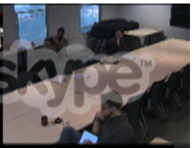
SK, J.I. Cirac, M.C. Bañuls, Phys. Rev. A 90, 042305 (2014)

Schwinger model: Quantum simulation

Adiabatic ground state preparation

- Start with the strong coupling ground state $x = 0$

$$W = -ix\sum_{n=1}^{N-1}\left(\phi_n^\dagger L_n^+\phi_{n+1} - \text{h.c}\right) + \sum_{n=1}^{N}(-1)^n\mu\phi_{n,f}^\dagger\phi_{n,f} + \sum_{n=1}^{N-1}L_n^2$$



Schwinger model: Quantum simulation

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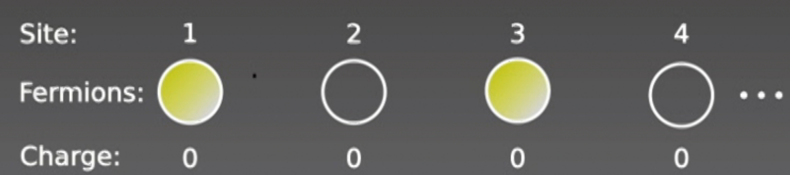


- State fulfills Gauss Law

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

- Adiabatically ramp x during time T to desired final value x_F

Schwinger model: Quantum simulation

Adiabatic ground state preparation

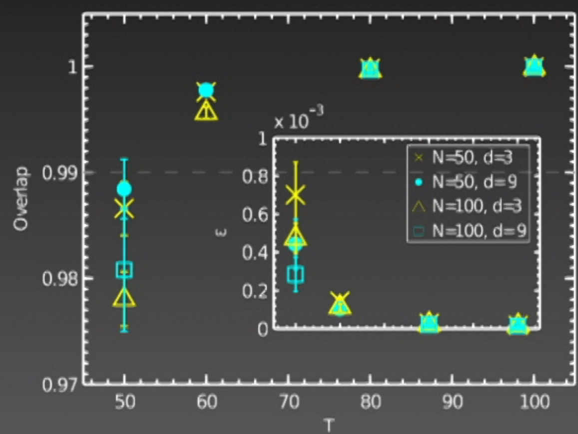
- Choice of the ramp

$$x(t) = x_F \left(\frac{t}{T}\right)^3.$$

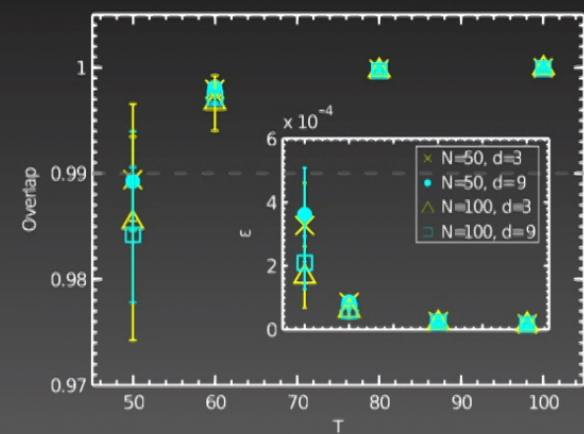
- To check the success monitor the overlap and the error in energy with respect to the variational results
- Success criterion: Overlap ≥ 0.99 with variational results

Schwinger model: Quantum simulation

cQED model



$\mathbb{Z}_d$ model



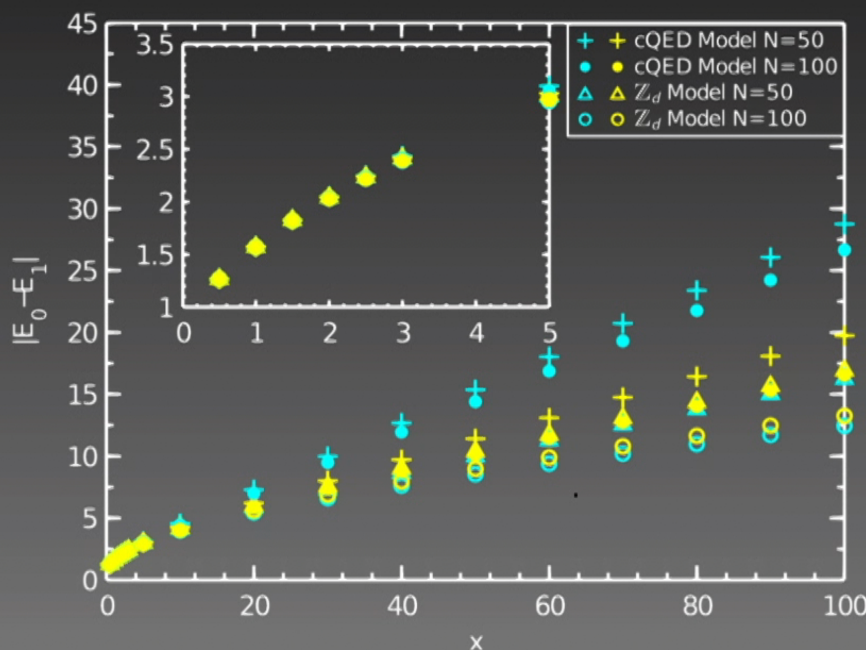
- Errors at the beginning are due to non-adiabaticity
- Almost no dependency on system size

SK, J.I. Cirac, M.C. Bañuls, Phys. Rev. A 90, 042305 (2014)

Schwinger model: Quantum simulation

Adiabatic ground state preparation

- Maximum ramping speed depends on the gap
- Numerical result for the gap



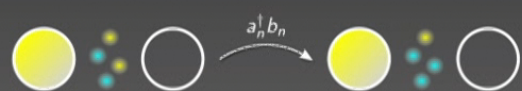
SK, J.I. Cirac, M.C. Bañuls, Phys. Rev. A 90, 042305 (2014)

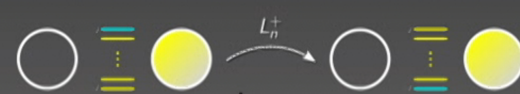
Schwinger model: Quantum simulation

Ground state preparation in the presence of noise

- Mimic gauge invariance breaking noise
- Assume noise strength proportional to x

$$\lambda x(t) \sum_n (a_n^\dagger b_n + b_n^\dagger a_n) \qquad\qquad \lambda x(t) \sum_n (L_n^+ + L_n^-)$$

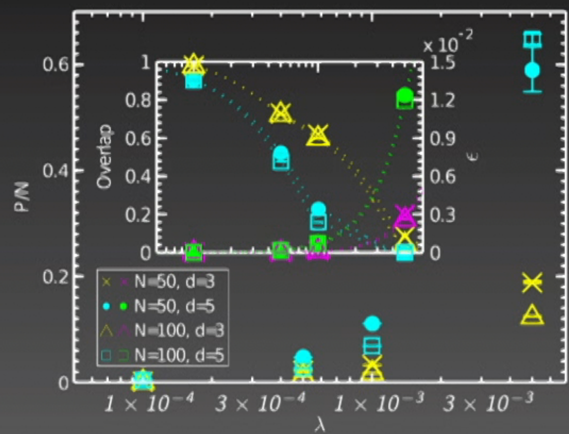




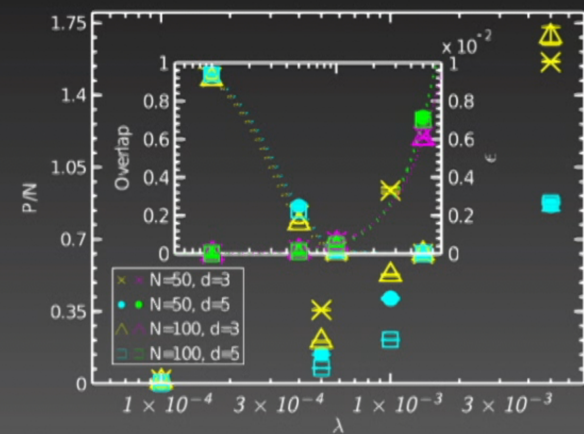
- Take $T = 100$ which guaranteed successful evolution in the noise free case
- Monitor the violation of Gauss Law per particle P/N

Schwinger model: Quantum simulation

cQED model



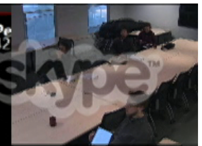
$\mathbb{Z}_d$ model



- Almost no dependency on system size
- Deviation of energy $\leq 1.5\%$

SK, J.I. Cirac, M.C. Bañuls, Phys. Rev. A 90, 042305 (2014)

Phase structure for two flavors at $T = 0$



Schwinger model: Phase structure for two-flavors

Model system

- Two flavors $F = 2$ at non-vanishing isospin chemical potential

$$\frac{\mu_I}{2\pi} = \frac{N}{4\pi x}(\nu_2 - \nu_1) \neq 0$$

- Cannot be accessed with Monte Carlo due to the sign problem
- For $m/g = 0$ analytical work found an infinite number of phases characterized by the isospin number

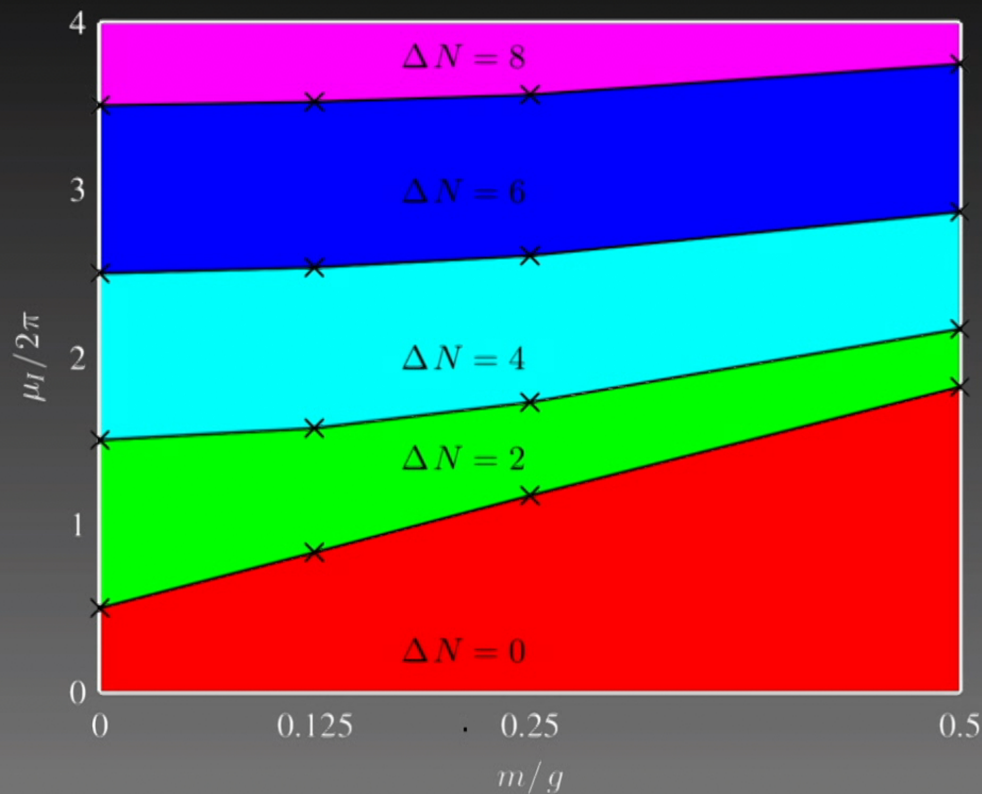
$$\Delta N = N_1 - N_2, \qquad N_i = \sum_{k=1}^{N} \phi^{\dagger}_{n,i}\phi_{n,i}$$

- The massive case cannot be addressed analytically

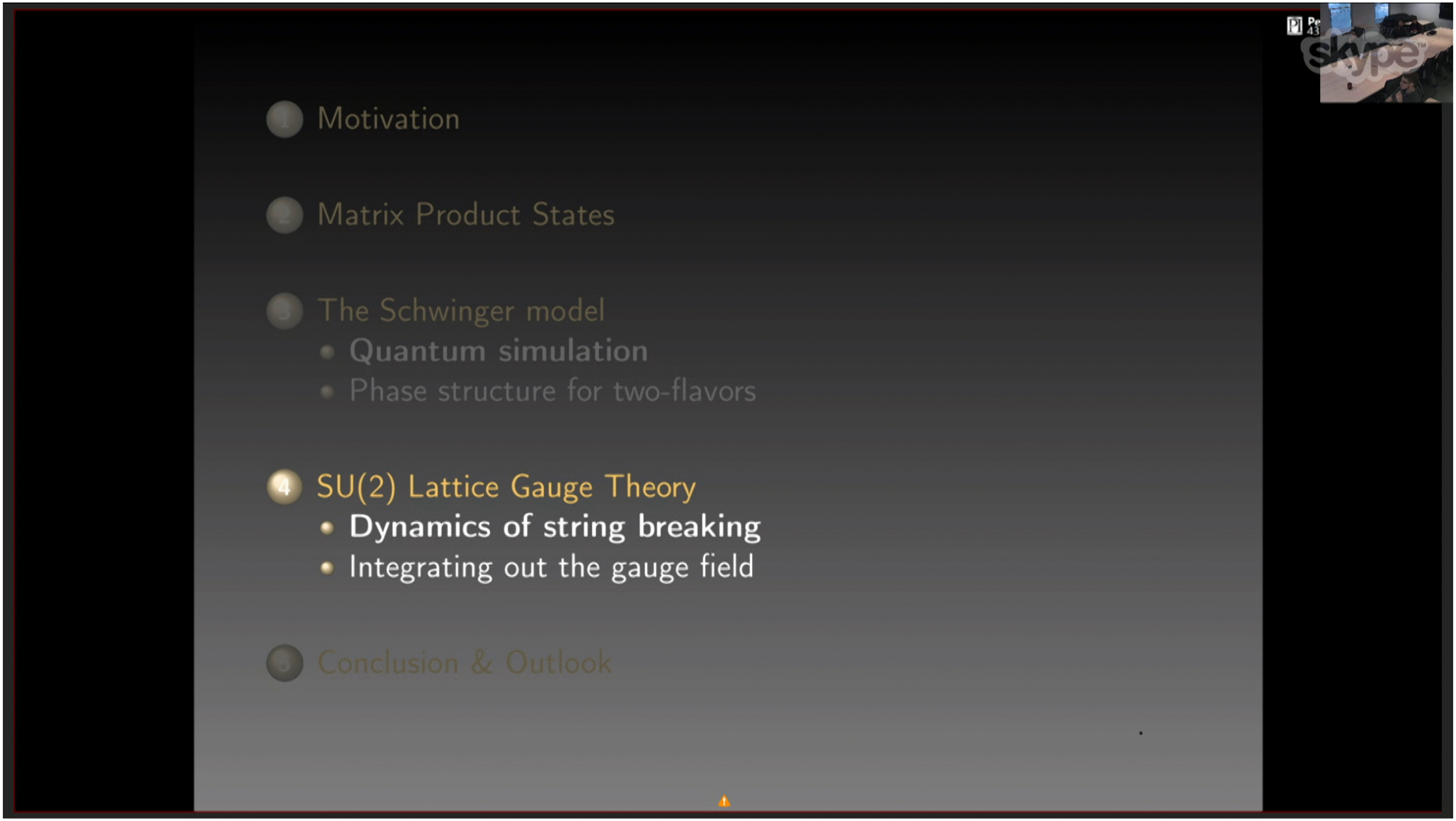
R. Narayanan, Phys. Rev. D 86, 125008 (2012)
R. Lohmayer, R. Narayanan, Phys. Rev. D 88, 105030 (2013)

Schwinger model: Phase structure for two-flavors

Phase structure at $T = 0$



M.C. Bañuls, K. Cichy, J.I. Cirac, K. Jansen, SK, arXiv:1611.00705 (2016)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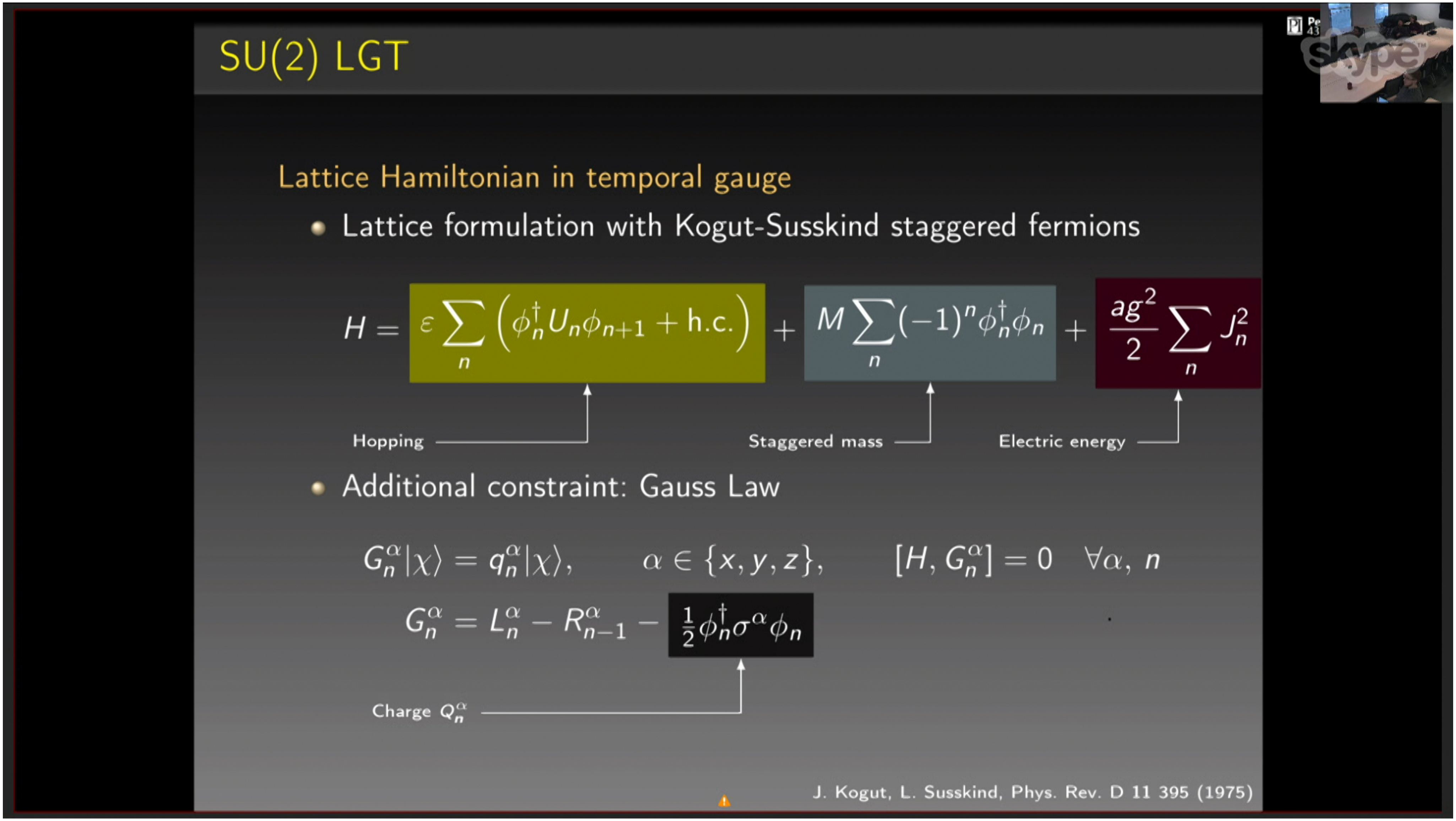

SU(2) LGT
Lattice Hamiltonian in temporal gauge
Lattice formulation with Kogut-Susskind staggered fermions
$H = \varepsilon \sum_n \left(\phi_n^\dagger U_n \phi_{n+1} + \text{h.c.}\right) + M \sum_n (-1)^n \phi_n^\dagger \phi_n + \frac{ag^2}{2} \sum_n J_n^2$
Hopping
Staggered mass
Electric energy
Additional constraint: Gauss Law
$G_n^\alpha |\chi\rangle = q_n^\alpha |\chi\rangle, \quad \alpha \in \{x, y, z\}, \quad [H, G_n^\alpha] = 0 \quad \forall \alpha, n$
$G_n^\alpha = L_n^\alpha - R_{n-1}^\alpha - \frac{1}{2}\phi_n^\dagger \sigma^\alpha \phi_n$
Charge Q_n^α
J. Kogut, L. Susskind, Phys. Rev. D 11 395 (1975)

SU(2) LGT

Lattice Hamiltonian in temporal gauge

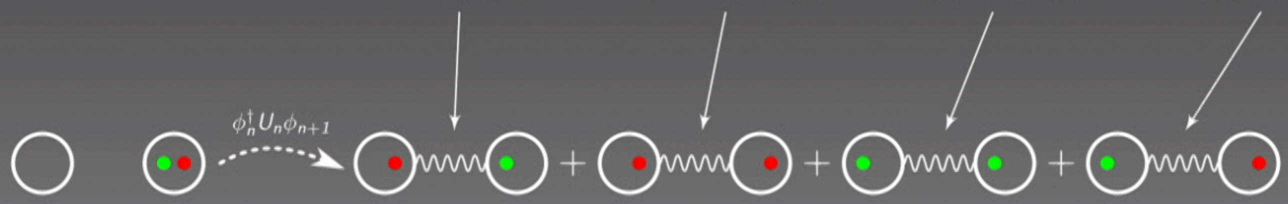
- Lattice formulation with Kogut-Susskind staggered fermions

$$H = \varepsilon \sum_n \left(\phi_n^\dagger U_n \phi_{n+1} + \text{h.c.} \right) + M \sum_n (-1)^n \phi_n^\dagger \phi_n + \frac{ag^2}{2} \sum_n J_n^2$$

- Hopping term

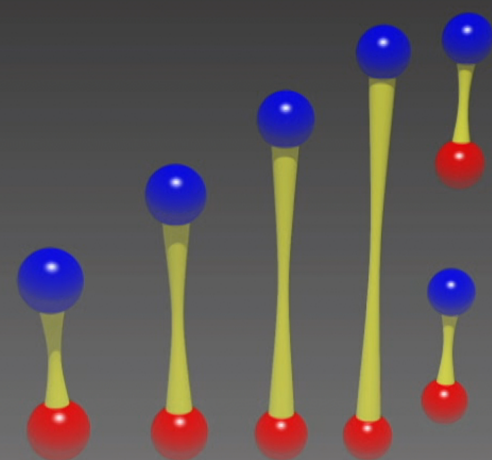
$$\phi_n^\dagger U_n \phi_{n+1} = \begin{pmatrix} \phi_r^\dagger & \phi_g^\dagger \end{pmatrix} \begin{pmatrix} U_{n,00} & U_{n,01} \\ U_{n,10} & U_{n,11} \end{pmatrix} \begin{pmatrix} \phi_r \\ \phi_g \end{pmatrix}$$

$$= \phi_r^\dagger U_{n,00} \phi_r + \phi_r^\dagger U_{n,01} \phi_g + \phi_g^\dagger U_{n,10} \phi_r + \phi_g^\dagger U_{n,11} \phi_g$$

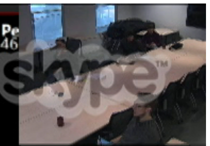


J. Kogut, L. Susskind, Phys. Rev. D 11 395 (1975)

Dynamics of string breaking



SU(2) LGT: Dynamics of string breaking



Problem

- Link Hilbert spaces are infinite dimensional

Truncation

- U_n are nothing but Wigner matrices for spin 1/2
- Allows to define generators for left and right gauge transformations L_n^α and R_n^α
- Suitable basis for the gauge links: $|jmm'\rangle$
- U_n can be decomposed as over the irreps for each j
- Truncate at finite value j_{max}

$$d = \sum_{j=0,\frac{1}{2},1,\dots}^{j_{\mathrm{max}}} (2j+1)^2$$

- For all the following $j_{\mathrm{max}} = 1/2 \Leftrightarrow d = 5$

E. Zohar, M. Burrello, Phys. Rev. D 91 054506 (2015)

SU(2) LGT: Dynamics of string breaking

Strong coupling ground state

- Neglect the hopping

$$H = \varepsilon \sum_n \left(\phi_n^\dagger U_n \phi_{n+1} + \text{h.c} \right) + M \sum_n (-1)^n \phi_n^\dagger \phi_n + \frac{ag^2}{2} \sum_n J_n^2$$

- Strong coupling ground state

Site:	1	2	3	4	5	6	7	8
Sign:	-	+	-	+	-	+	-	+

SU(2) LGT: Dynamics of string breaking

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- Strong coupling ground state

Site:	1	2	3	4	5	6	7	8
Sign:	-	+	-	+	-	+	-	+

$4Q_n^\alpha Q_n^\alpha$:	0	0	0	0	0	0	0	0

- Charge square

$$4Q_n^\alpha Q_n^\alpha = (n_r - n_g)^2$$

SU(2) LGT: Dynamics of string breaking

Generating strings

- Manipulate fermionic content in gauge invariant way

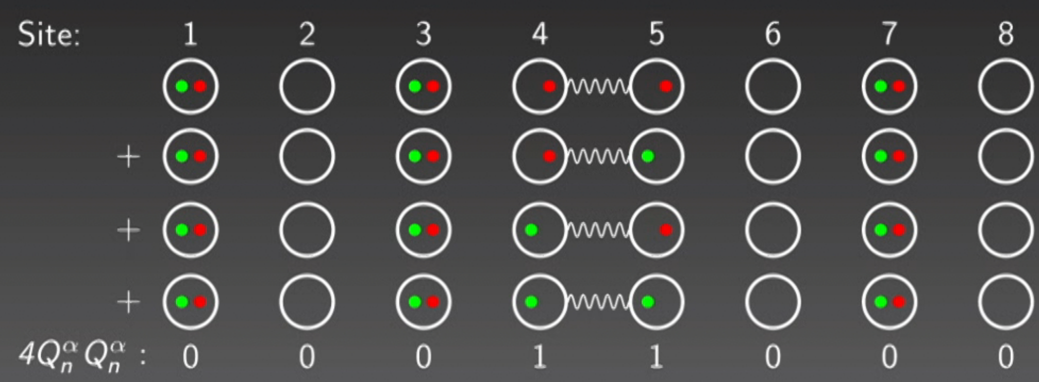
Site:	1	2	3	4	5	6	7	8
Sign:	-	+	-	+	-	+	-	+
$4Q_n^\alpha Q_n^\alpha$:	0	0	0	0	0	0	0	0

SU(2) LGT: Dynamics of string breaking

Generating strings

- Manipulate fermionic content in gauge invariant way

$$S = \phi_4^\dagger U_4 \phi_5$$



$\Rightarrow$ Two charges connected by a flux tube

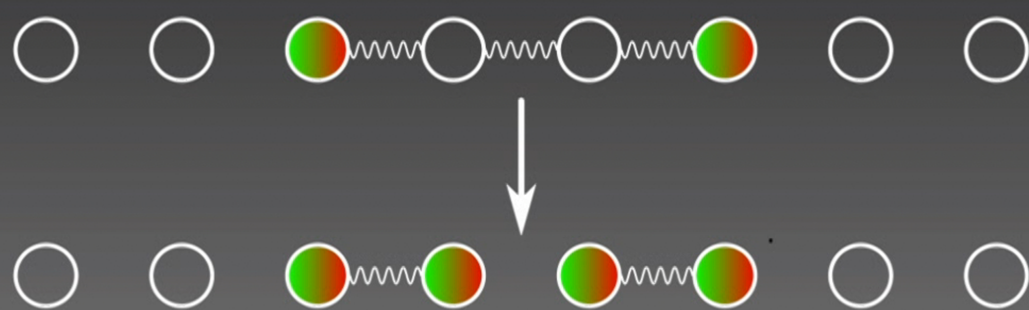
- Energy increase $2M + \frac{ag^2}{2} J_4^2$
- Also longer strings are possible

$$S = \phi_n^\dagger U_n U_{n+1} U_{n+2} \dots U_{n+l} \phi_{n+l+1}$$

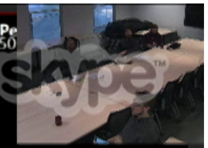
SU(2) LGT: Dynamics of string breaking

String breaking

- Energy increase due to the string proportional to its length
- If flux energy exceeds $2M$ system can lower its energy by creating a quark-antiquark pair and reducing the flux
- At a certain length it is favorable to break the string



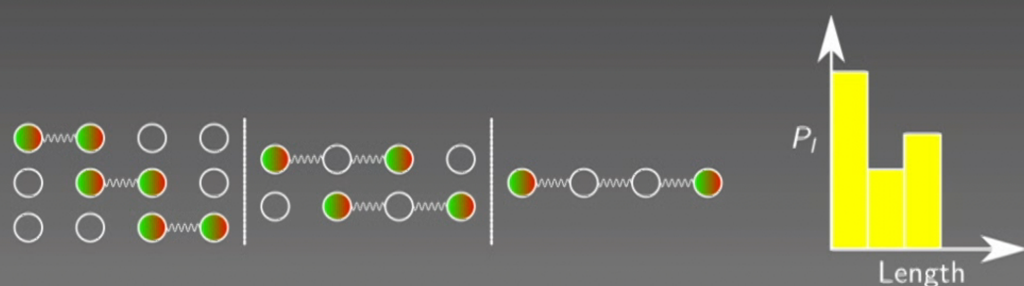
SU(2) LGT: Dynamics of string breaking



Detecting string breaking

- Flux configuration
- $Q_n^\alpha Q_n^\alpha$
- String: object with finite flux in some region an no flux outside
  $\Rightarrow$ construct projectors P_{nl}
- Create histograms from the string length from these projectors

$$P_l = \frac{\sum_{n=1}^{N-l}\left(\langle\Psi|P_{nl}|\Psi\rangle - \langle\Omega|P_{nl}|\Omega\rangle\right)}{\#\text{ strings of length } l}$$



SU(2) LGT: Dynamics of string breaking

Real-time dynamics in the presence of static external charges

Procedure

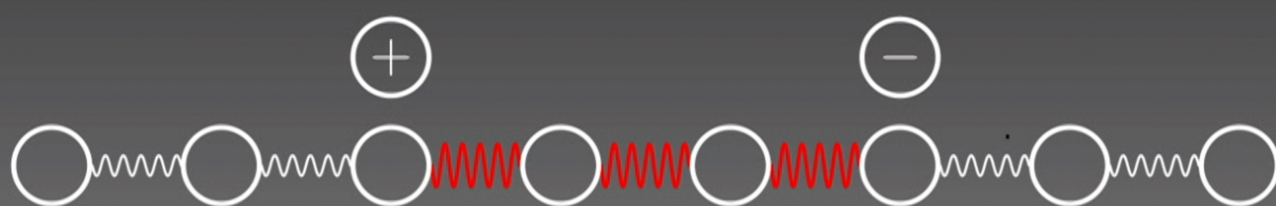
- Compute the interacting vacuum

SU(2) LGT: Dynamics of string breaking

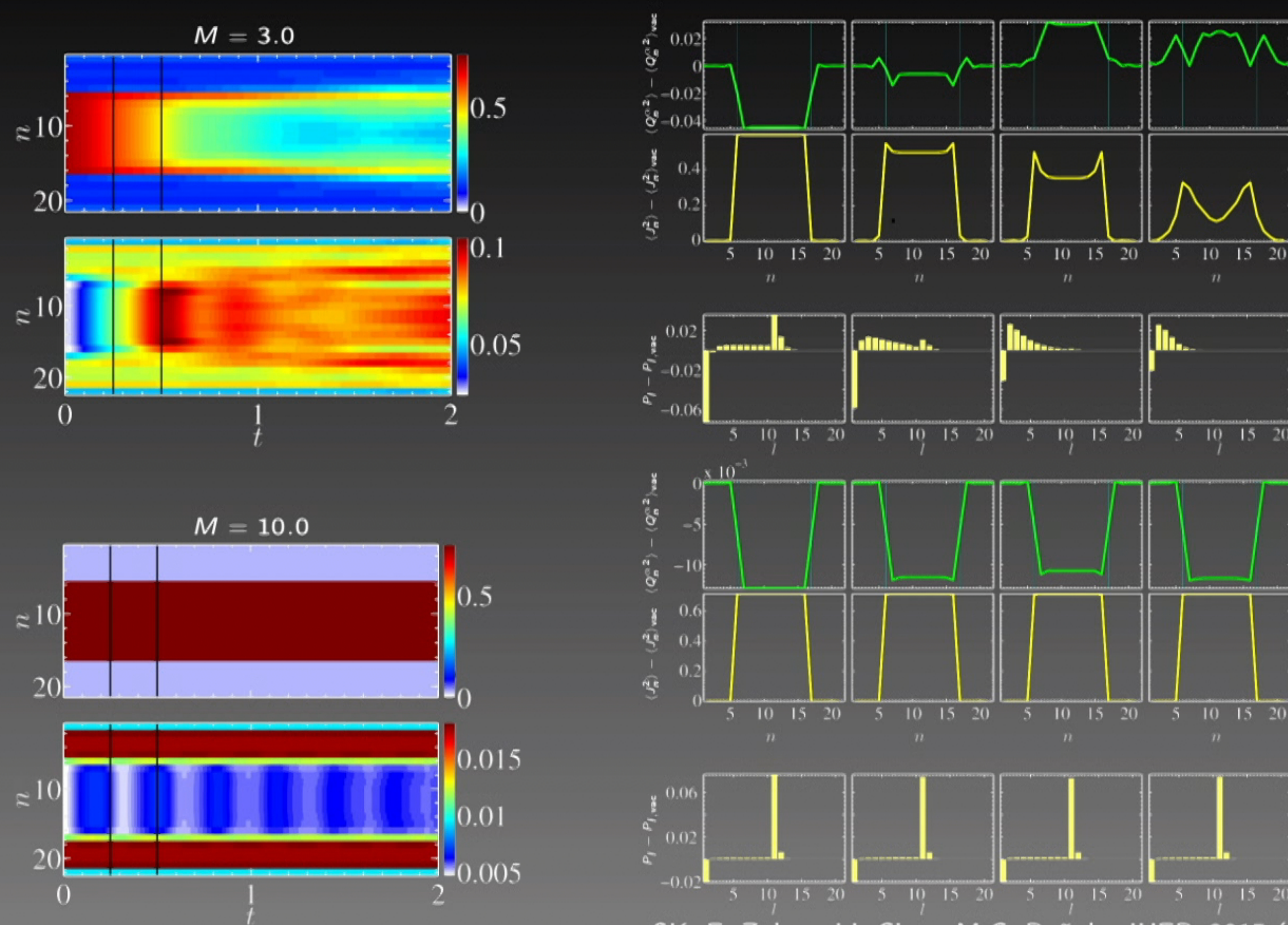
Real-time dynamics in the presence of static external charges

Procedure

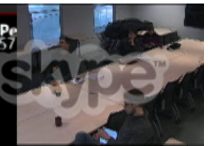
- Compute the interacting vacuum
- Generate a string on top between the two heavy external charges
- Look at real-time evolution



SU(2) LGT: Dynamics of string breaking



SK, E. Zohar, J.I. Cirac, M.C. Bañuls, JHEP, 2015 (2015)



SU(2) LGT: Dynamics of string breaking

Real-time dynamics in the presence of dynamical charges

Procedure

- No external charges anymore
- Compute the interacting vacuum

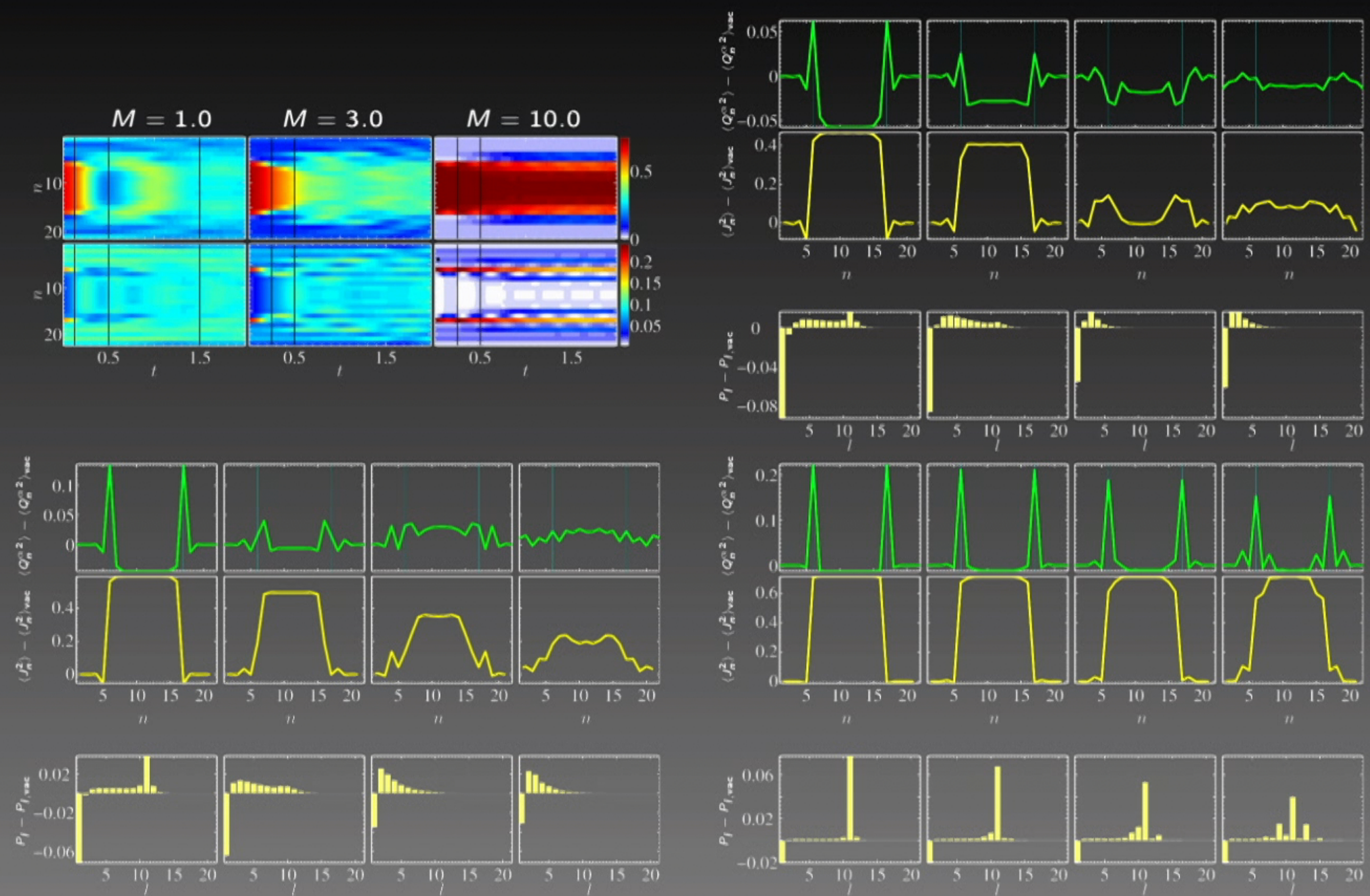
SU(2) LGT: Dynamics of string breaking

Real-time dynamics in the presence of dynamical charges

Procedure

- No external charges anymore
- Compute the interacting vacuum
- Generate a string on top by applying a string operator
- Look at real-time evolution

SU(2) LGT: Dynamics of string breaking



SK, E. Zohar, J.I. Cirac, M.C. Bañuls, JHEP, 2015 (2015)

Integrating out the gauge field

SU(2) LGT: Integrating out the gauge field

Previous approach

- Basis for the gauge links $|jmm'\rangle$
- Truncate at a finite value j_{max}

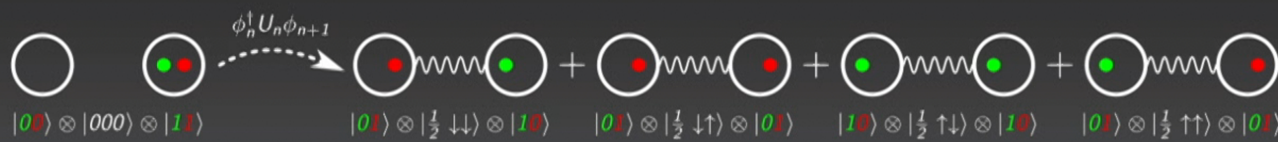
$$d = \sum_{j=0,\frac{1}{2},1,\ldots}^{j_{\text{max}}} (2j+1)^2 \overset{j_{\text{max}}\to\infty}{\longrightarrow} \mathcal{O}\left(j_{\text{max}}^3\right)$$

$\Rightarrow$ Computationally expensive

SU(2) LGT: Integrating out the gauge field

Color neutral basis

- Hamiltonian does not contain any terms with uncontracted color indices
  $\Rightarrow$ Applied to a color neutral superposition the result is a color neutral superposition again



- Superposition is characterized by fermionic occupation number and by the value of j

$$|0\rangle \otimes |0\rangle \otimes |2\rangle \longrightarrow |1\rangle \otimes \left|\tfrac{1}{2}\right\rangle \otimes |1\rangle$$

C.J. Hamer Nuclear Physics B 195 503 (1982)

SU(2) LGT: Integrating out the gauge field

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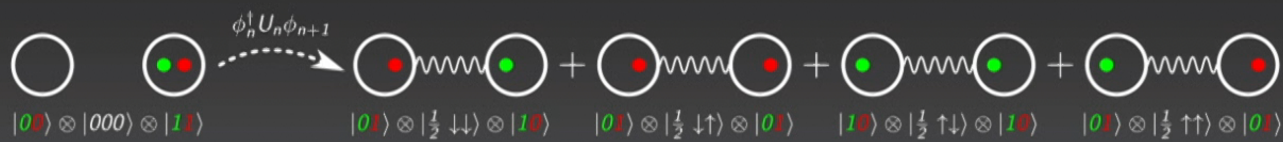

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$$H = \varepsilon \sum_n \left(\phi_n^\dagger U_n \phi_{n+1} + \text{h.c.}\right) + M \sum_n (-1)^n \phi_n^\dagger \phi_n + \frac{ag^2}{2} \sum_n J_n^2$$

- Mass term as well as electric energy are diagonal in this basis
- Matrix elements for the hopping term are available

C.J. Hamer Nuclear Physics B 195 503 (1982)

SU(2) LGT: Integrating out the gauge field

Color neutral basis

- Gauss Law allows to reconstruct the color electric flux for OBC

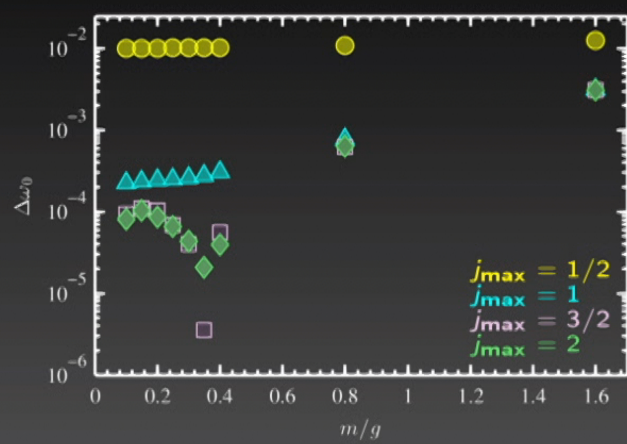
$$j_{n+1} = \begin{cases} j_n \pm \frac{1}{2} & \text{if site is singly occupied} \\ j_n & \text{else} \end{cases}$$

- To remove ambiguity introduce levels $|1_-\rangle$, $|1_+\rangle$

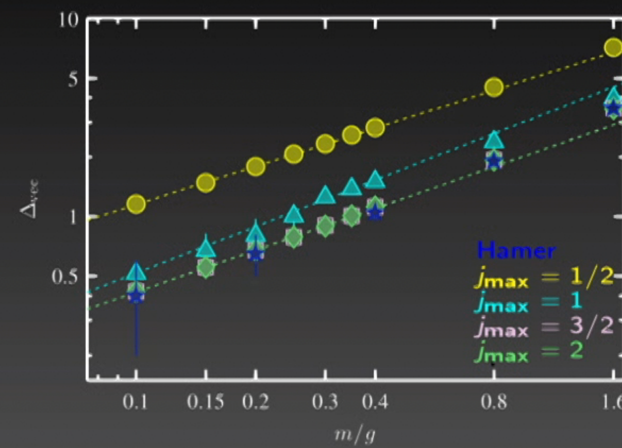
- Formulation on the gauge invariant subspace where the gauge degrees of freedom are integrated out

SU(2) LGT: Integrating out the gauge field

Ground state



Vector mass gap



Critical exponent for the vector mass gap

j_{max}	Exponent
1/2	0.639(43)(5)
1	0.781(93)(65)
3/2	0.700(29)(11)
2	0.700(29)(12)

C.J. Hamer Nucl. Phys. B 195, 503 (1982)

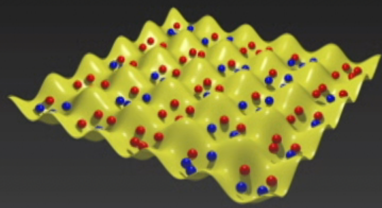
1. Motivation
2. Matrix Product States
3. The Schwinger model
   - **Quantum simulation**
   - Phase structure for two-flavors
4. SU(2) Lattice Gauge Theory
   - **Dynamics of string breaking**
   - Integrating out the gauge field
5. Conclusion & Outlook

Conclusion & Outlook

Conclusion

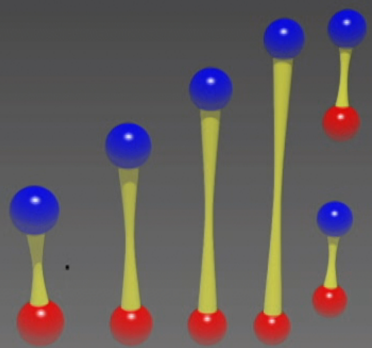
Schwinger model

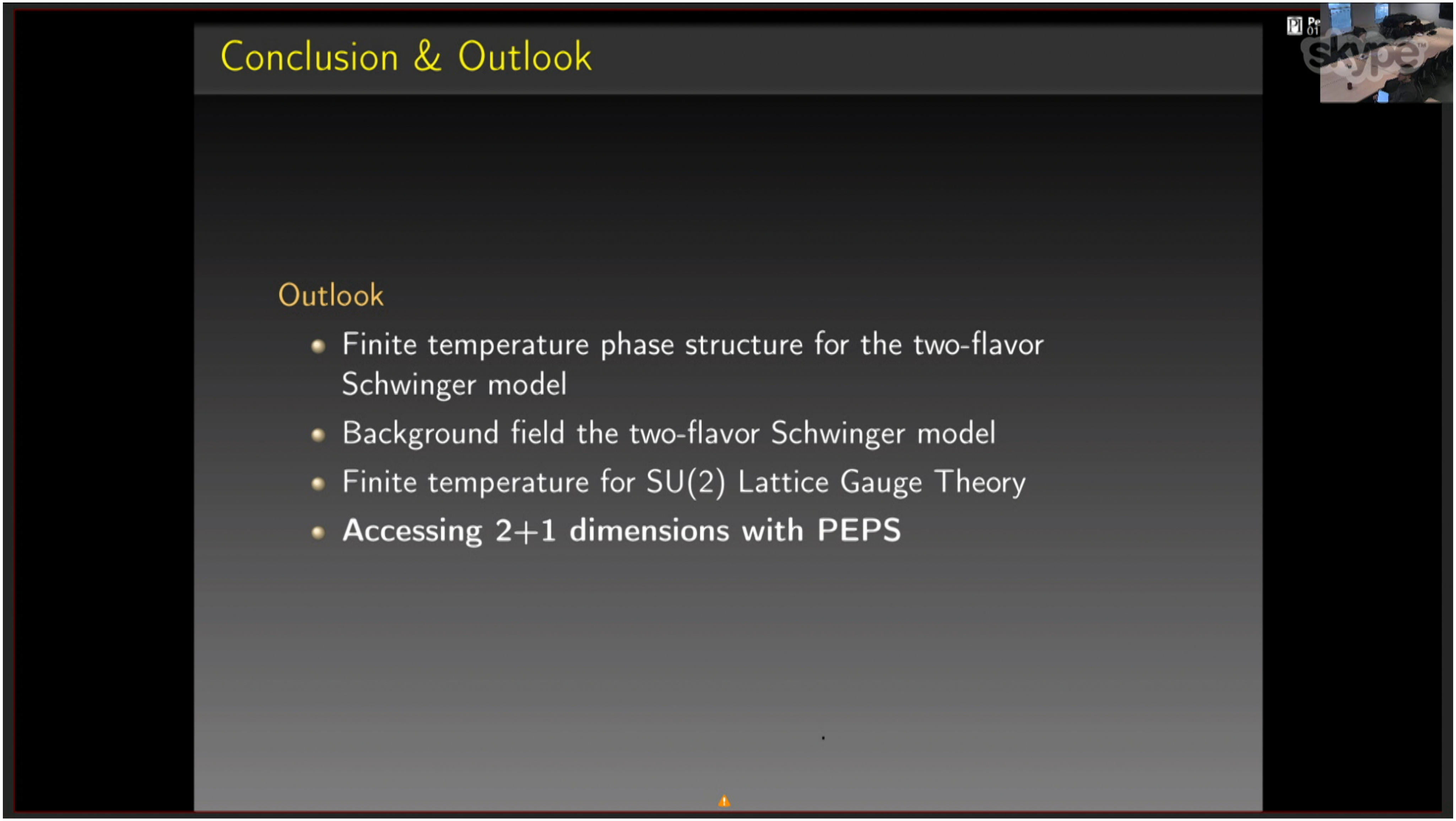
- Powerful tool to **benchmark quantum simulators**
- **Access parameter regimes** in which Monte Carlo suffer from the **sign problem**



SU(2) Lattice Gauge Theory

- **Real-time dynamics** of string breaking
- **Access** to all kinds of local observables
- Spectral calculations with **efficient basis formulation**




Conclusion & Outlook
Outlook
Finite temperature phase structure for the two-flavor Schwinger model
Background field the two-flavor Schwinger model
Finite temperature for SU(2) Lattice Gauge Theory
Accessing 2+1 dimensions with PEPS
skype


Thank you for your attention!