Title: Tensor Networks for nonabelian Gauge Theory

Date: Nov 25, 2014 03:30 PM

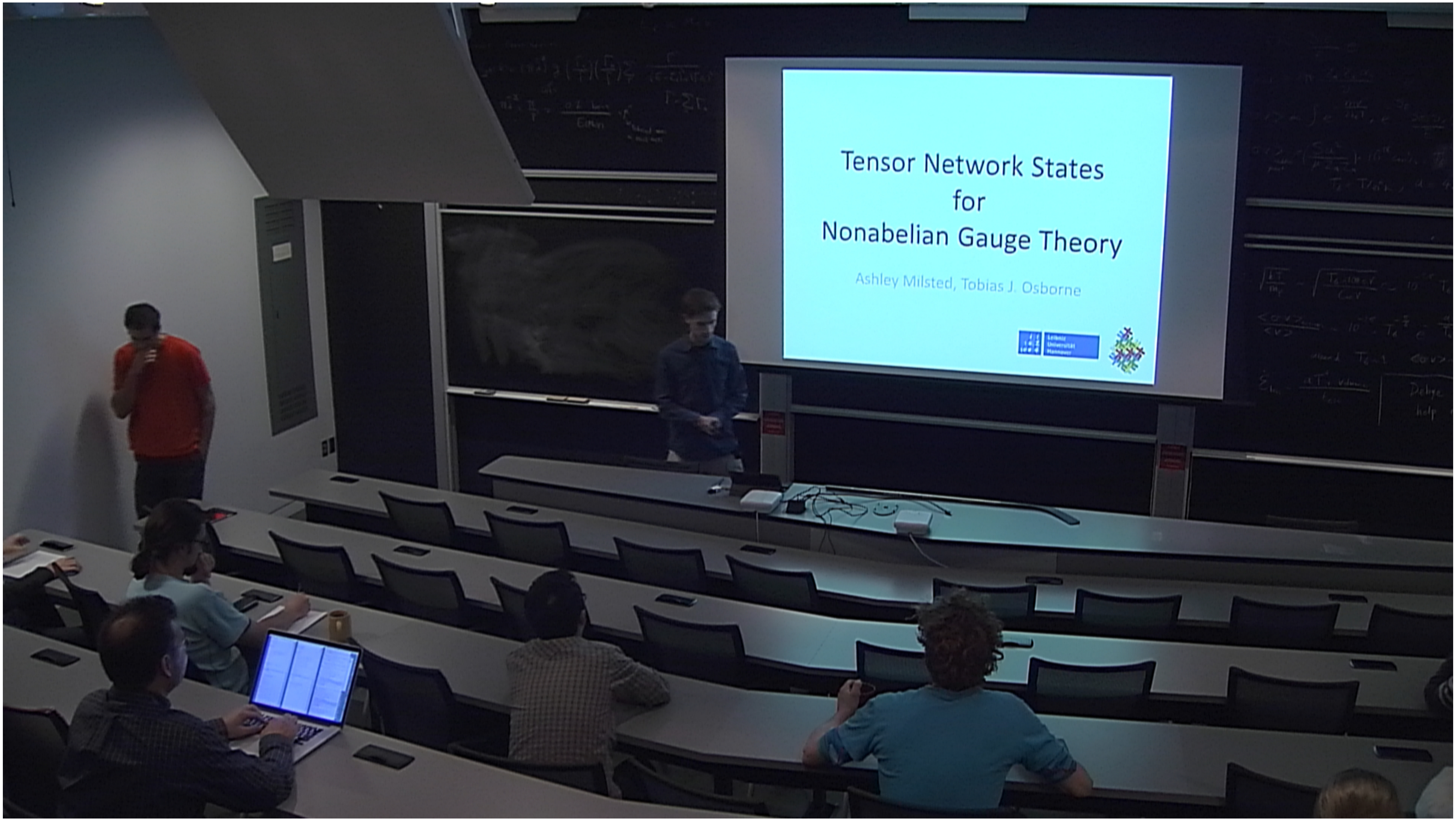
URL: http://pirsa.org/14110178

Abstract: <p>We present an analytic, gauge invariant tensor network ansatz for the ground state of lattice Yang-Mills theory for nonabelian gauge groups. It naturally takes the form of a MERA, where the top level is the strong coupling limit of the lattice theory. Each layer performs a fine-graining operation defined in a fixed way followed by an optional step of adiabatic evolution, resulting in the ground state at an intermediate coupling. The ansatz is very much in the spirit of Kogut and Susskind's Hamiltonian approach to understanding confinement by starting from the strong coupling limit and perturbing, but exploiting a tensor network structure to go beyond perturbative approaches.</p>

Tensor Network States for Nonabelian Gauge Theory

Ashley Milsted, Tobias J. Osborne

Leibniz Universität Hannover


Tensor Network States
for
Nonabelian Gauge Theory
Ashley Milsted, Tobias J. Osborne

non-perturbative phenomena:

IR behaviour of QCD

confinement

hadron spectrum

non-perturbative methods:

strong coupling in **lattice** QCD
(analytical, perturbative)

J. Kogut, L. Susskind, Phys Rev D **11**, 395 (1975)
K. Wilson, Phys Rev D **10**, 2445 (1974)

monte carlo simulation (of **lattice** models)

S. Dürr, Z. Fodor, J. Frison, C. Hoelbling, R. Hoffmann,
S. D. Katz, S. Krieg, T. Kurth, L. Lellouch, T. Lippert,
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example: ϕ^4 theory

$$S_{\phi^4,c} = \int \mathrm{d}x \left[\frac{1}{2}\left(\partial_\mu\phi\partial^\mu\phi - \mu_0^2\phi^2\right) - \frac{\lambda}{4!}\phi^4\right]$$

...in **discrete space** (1D), continuous time...

$$\tilde{H}_{\phi^4} = \sum_n \left[\frac{\pi_n^2}{2} + \frac{(\phi_n - \phi_{n+1})^2}{2} + \frac{\tilde{\mu}_0^2}{2}\phi_n^2 + \frac{\tilde{\lambda}}{4!}\phi_n^4\right]$$

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$$\mathcal{H}_{\phi^4} = \bigotimes_{n=1}^{N} L^2(\mathbb{R})$$

...with **cutoff**, becomes a **spin system**...

$$\mathcal{H}_{\phi^4,d} = \bigotimes_{n=1}^{N} \mathbb{C}^d$$

lattice **correlation length**

$$\xi_{\mathrm{lat}} = a\xi_{\mathrm{phys}}$$

determines **lattice spacing** *a*

(dimensional transmutation)

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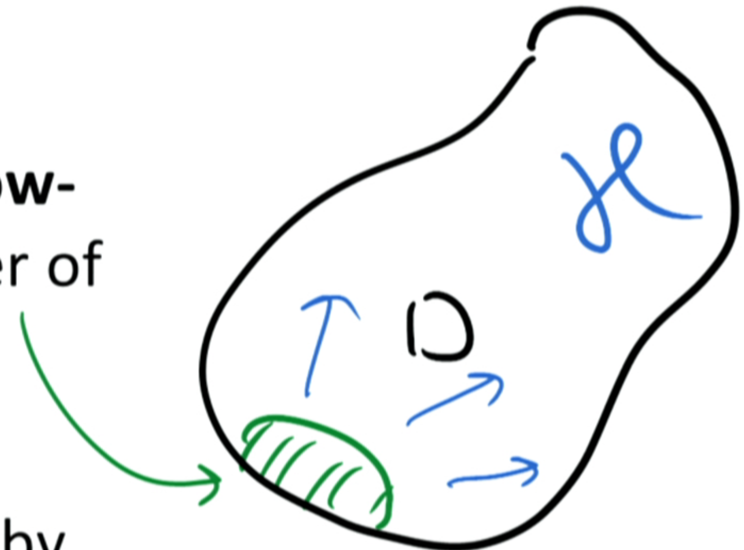
Tensor Network States

Parameterize the **low-entanglement** corner of Hilbert space



Choose how much by adjusting the **bond dimension** D

Matrix Product States

$$|\Psi(A)\rangle = \sum_{\{s\}=0}^{d-1} v_L^\dagger \left[\prod_{i=-\infty}^{+\infty} \overset{d \times D \times D}{A^{s_i}} \right] v_R \, |\vec{s}\rangle$$

M. Fannes, B. Nachtergaele, and R. F. Werner, Commun. Math. Phys. (1965–1997) **144**, 443 (1992)
F. Verstraete, V. Murg, and J. Cirac, Adv. Phys. **57**, 143 (2008)
J. I. Cirac and F. Verstraete, J. Phys. A **42**, 504004 (2009)

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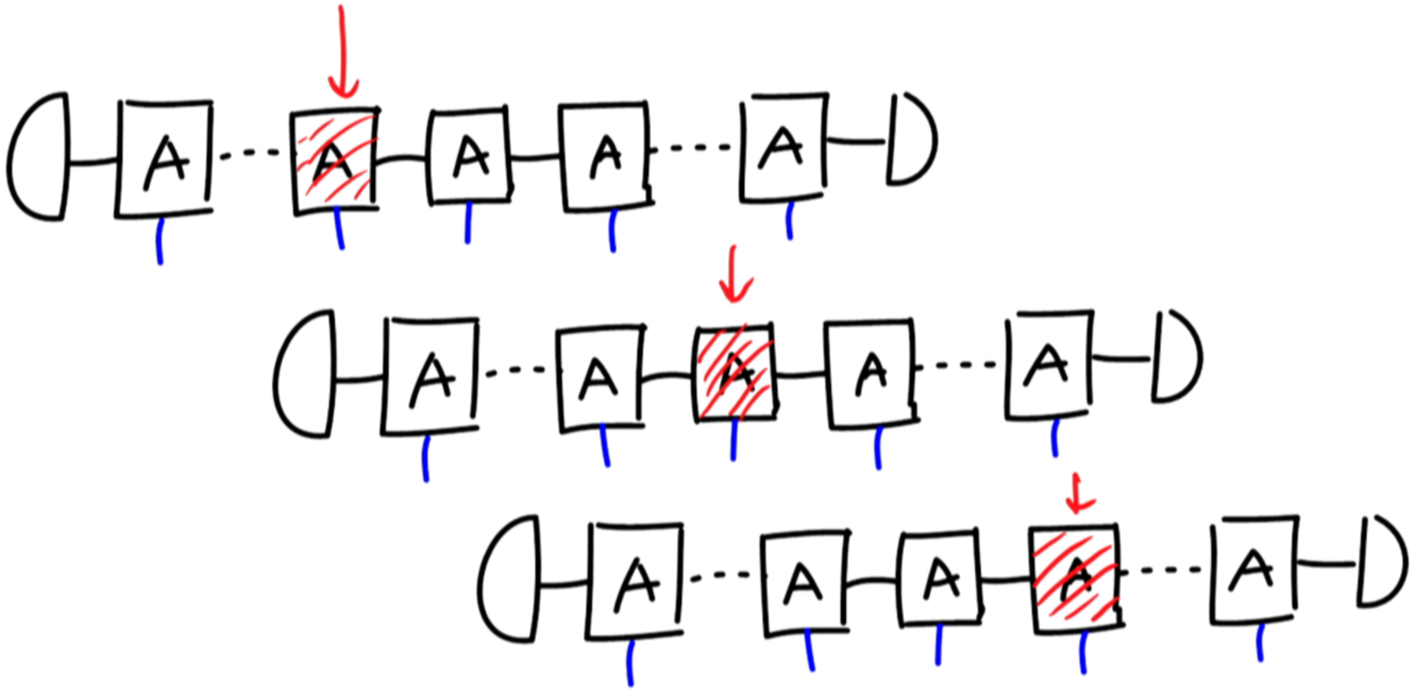
J. I. Cirac and F. Verstraete, J. Phys. A **42**, 504004 (2009)

use as a **variational class**

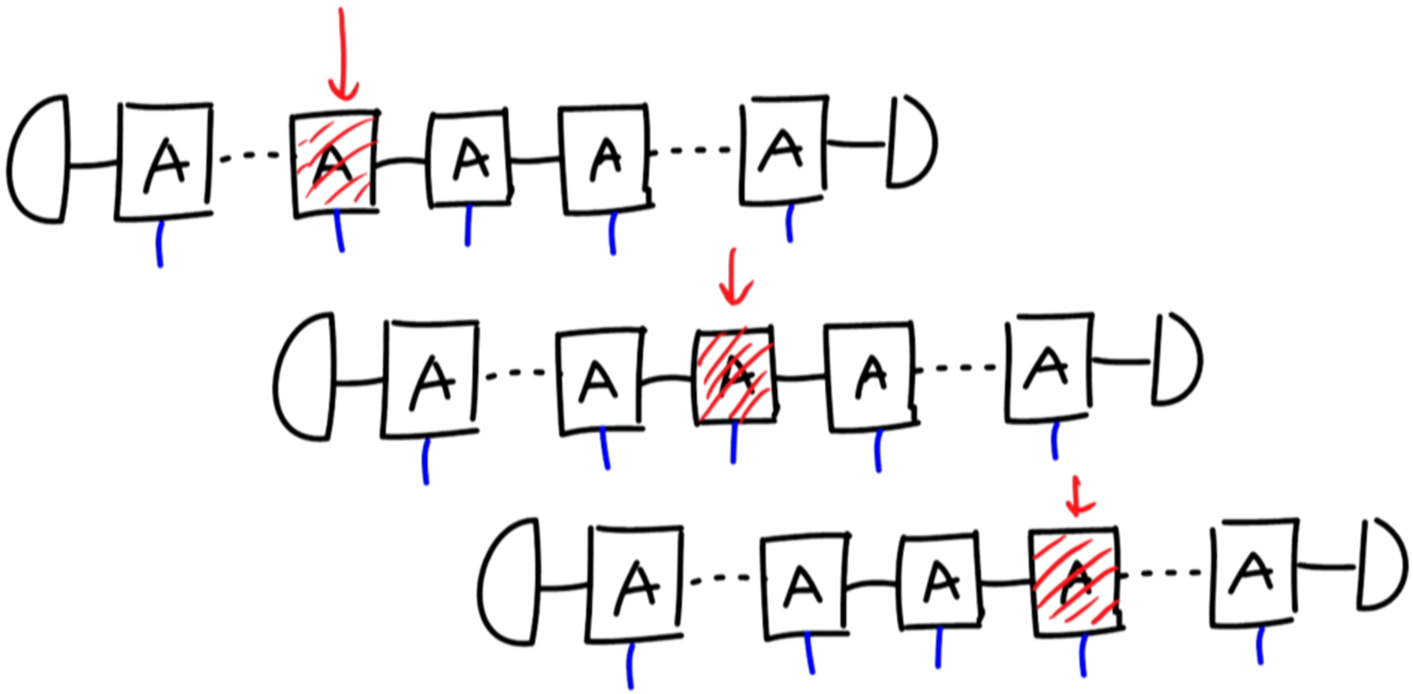
$$|\Psi(A)\rangle$$

(i)DMRG



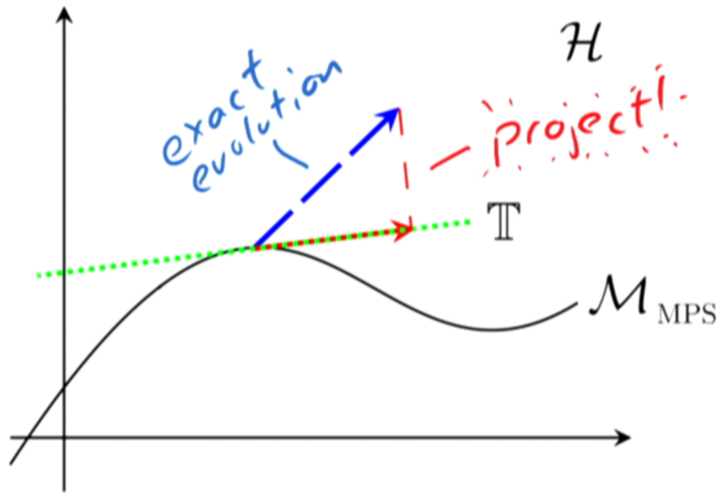
S. R. White, PRL 69, 2863 (1992), U. Schollwöck, Ann Phys 326, **96** (2011),
I. P. McCulloch, arXiv: 0804.2509 (2008)

(i)DMRG



S. R. White, PRL 69, 2863 (1992), U. Schollwöck, Ann Phys 326, **96** (2011),
I. P. McCulloch, arXiv: 0804.2509 (2008)

MPS **tangent plane** methods



directly applicable to **infinite MPS**

J. Haegeman, T. J. Osbone, F. Vestraete, Phys Rev B **88**, 075133 (2013)

J. Haegeman, C. Lubich, I. Oseledets, B. Vandereycken, F. Verstraete, arXiv:1408.5056 (2014)

Time Dependent Variational Principle

J. Haegeman, J. I. Cirac, T. J. Osborne, I. Pižorn, H. Verschelde, and F. Verstraete, PRL **107**, 070601 (2011)

A. Milsted, J. Haegeman, T. J. Osbonre, F. Verstraete, Phys Rev B **88**, 155116 (2013)

nonlinear **conjugate gradient**

A. Milsted, J. Haegeman, T. J. Osborne, Phys Rev D **88**, 085030 (2013)

low-lying **excitations**, dispersion relations

J. Haegeman, B. Pirvu, D. J. Weir, J. I. Cirac, T. J. Osborne, H. Verschelde, and F. Verstraete, Phys Rev B **85**, 100408 (2012)

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open source implementation

evoMPS

python™

```python
import scipy as sp
import evoMPS.tdvp_uniform as mps

Sx = sp.array([[0., 1.], [1., 0.]])
Sy = 1.j * sp.array([[0., -1.], [1., 0.]])
Sz = sp.array([[1., 0.], [0., -1.]])

ham = (-sp.kron(Sx, Sx) - 0.5 * sp.kron(Sz, sp.eye(2)))

sim = mps.EvoMPS_TDVP_Uniform(8, 2, ham.reshape(2, 2, 2, 2))

eta = 1
while eta > 1E-10:
    sim.update()
    print sim.h_expect.real, sim.S_hc #energy, entropy
    sim.take_step(0.08) #imaginary time evolution
    eta = sim.eta.real #"state convergence tolerance"

sim.update()
print sim.excite_top_triv(0, k=20) #excitations with p=0
```

http://amilsted.github.io/evoMPS/

some applications

anyons

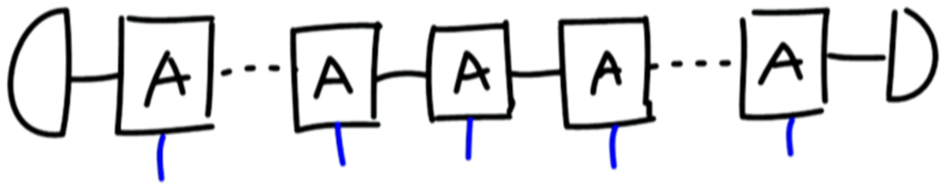
S. Singh, R. N. C. Pfeifer, G. Vidal, and G. K. Brennen, Phys Rev B **89**, 075112 (2014)
P. E. Finch, H. Frahm, M. Lewerenz, **A. Milsted**, T. J. Osborne, Phys Rev B **90**, 081111 (2014)
A. Milsted, E. Cobanera, M. Burrello, G. Ortiz, Phys Rev B **90**, 195101 (2014)
D. Poilblanc, A. Feiguin, M. Troyer, E. Ardonne, P. Bonderson, Phys Rev B **87**, 085106 (2013)
...

open systems

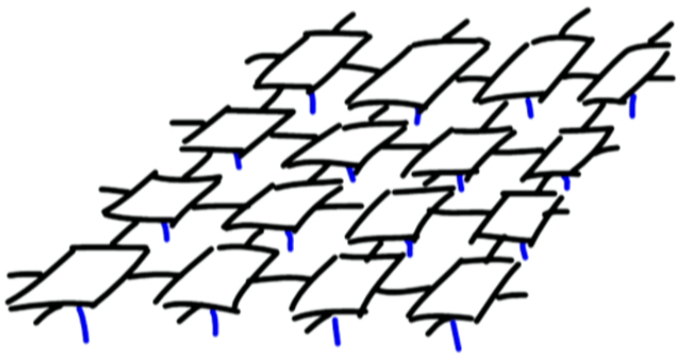
F. Transchel, **A. Milsted**, T. J. Osborne, arXiv: 1411.5546 (2014)
E. M. Stoudenmire, S. R. White, New J Phys **12**, 055026 (2010)
S. R. White, PRL **102**, 190601 (2009)
F. Verstraete, J. J. Garcia-Ripoll, J. I. Cirac, PRL **93**, 207204 (2004)
M. Zwolak, G. Vidal, PRL **93**, 207205 (2004)
...

quantum fields

...next section...

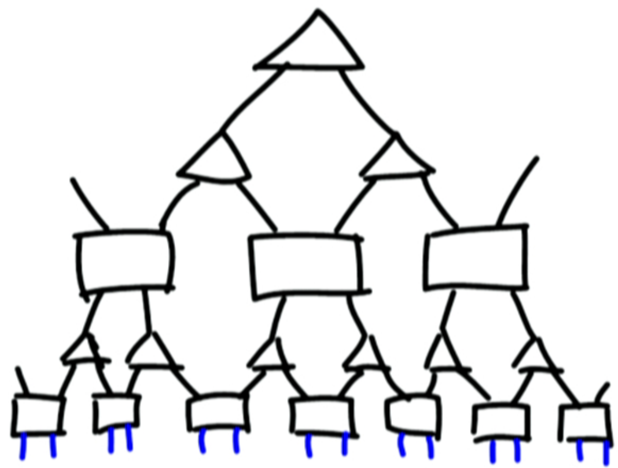


MPS



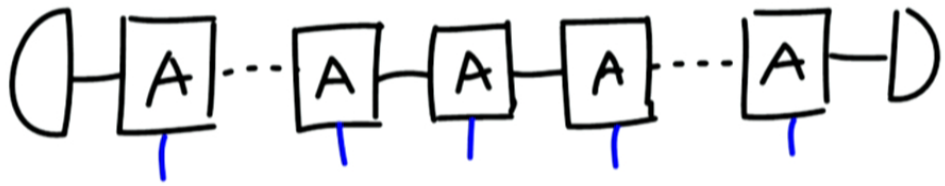
PEPS

F. Verstaete, J. I. Cirac,
cond-mat/0407066

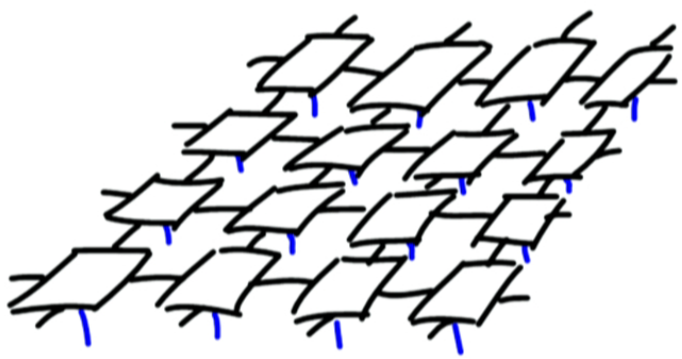


MERA

G. Vidal PRL **99**, 220405



MPS



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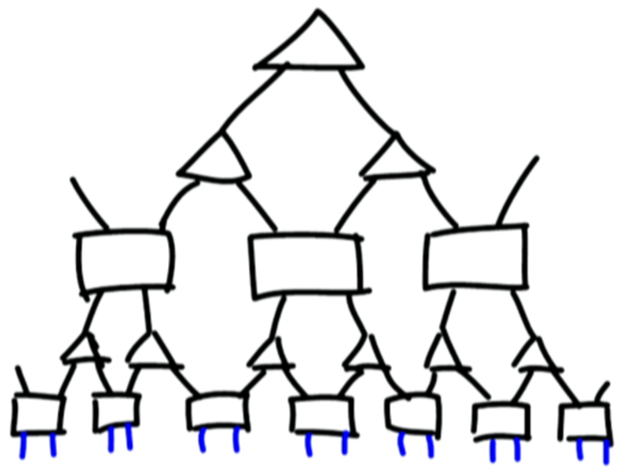

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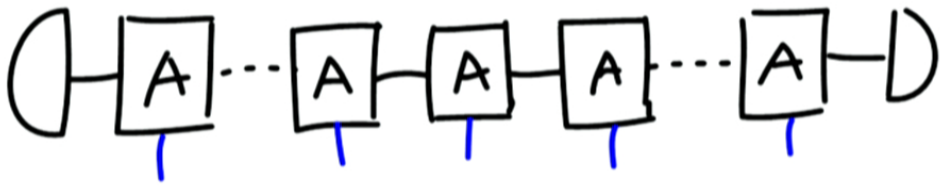

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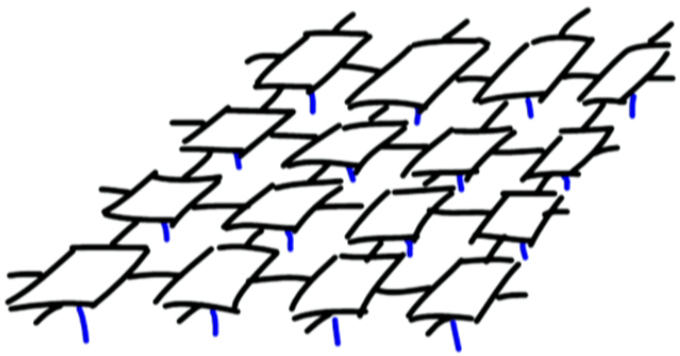

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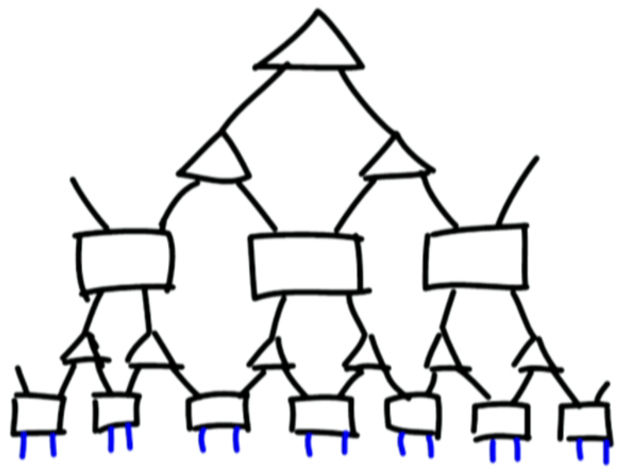

MERA

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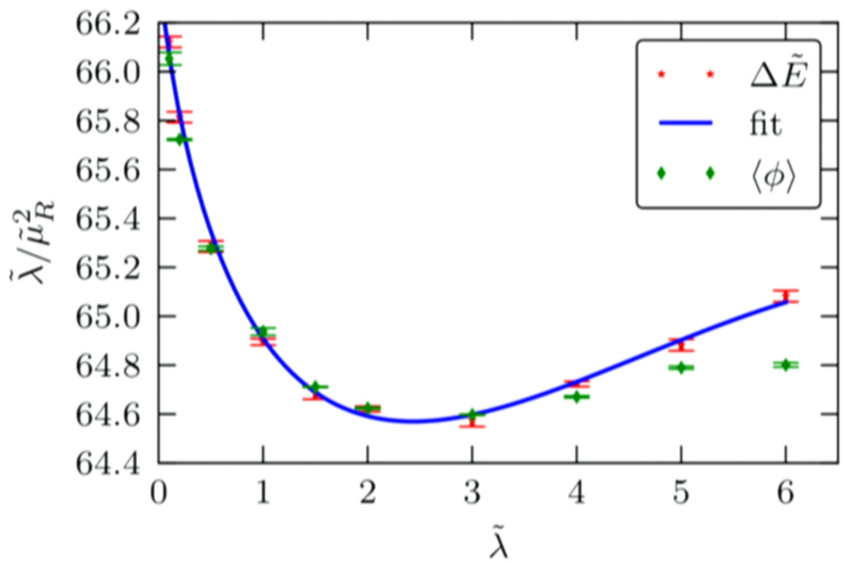
ϕ^4 critical point with MPS

$$a \to 0 \implies \tilde{\lambda} \to 0$$



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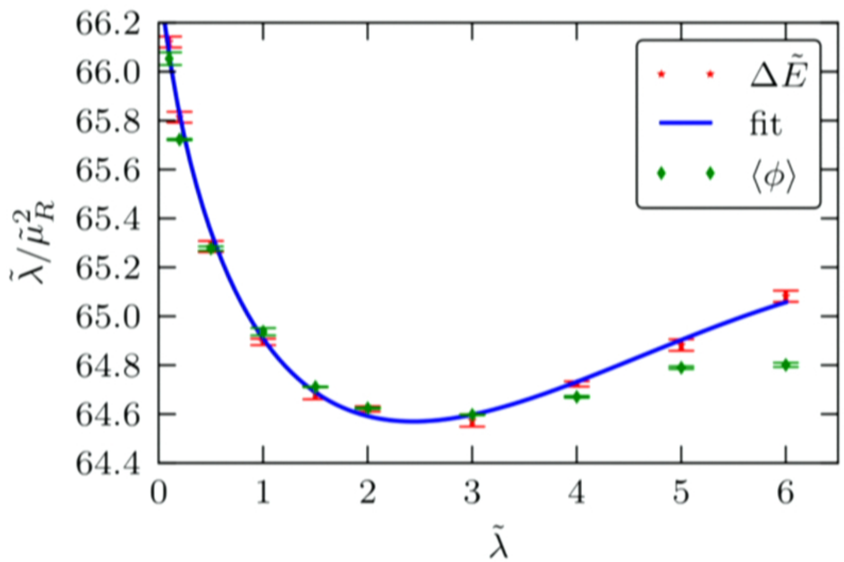

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lattice gauge theory

MPS for Schwinger model

M. C. Bañuls, K. Cichy, J. I. Cirac, K. Jansen, H. Saito, PoS **LATTICE 2013**

B. Buyens, J. Haegeman, K. Van Acoleyen, H. Verschelde, F. Verstraete, PRL **113**, 091601 (2014)

MERA for LGT (discrete groups)

L. Tagliacozzo, G. Vidal, Phys Rev B **83**, 115127 (2011)

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L. Tagliacozzo, A. Celi, M. Lewenstein, Phys Rev X **4**, 041024 (2014)

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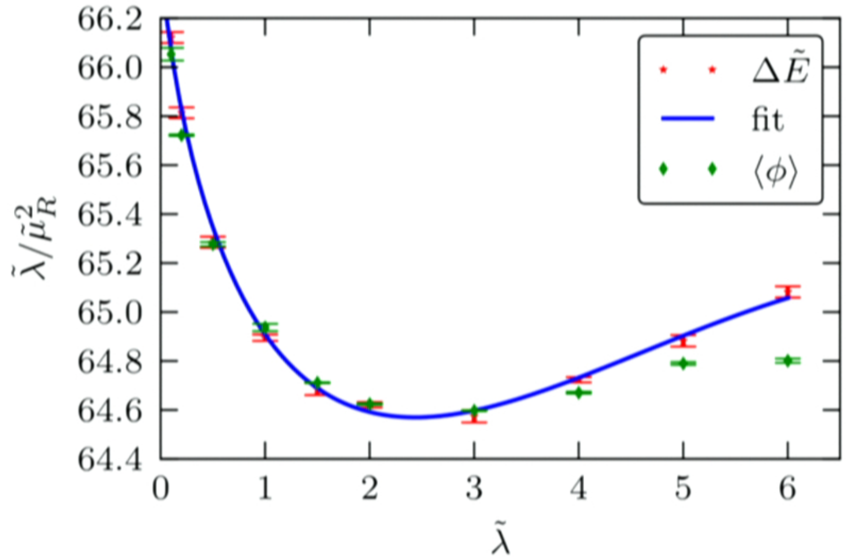

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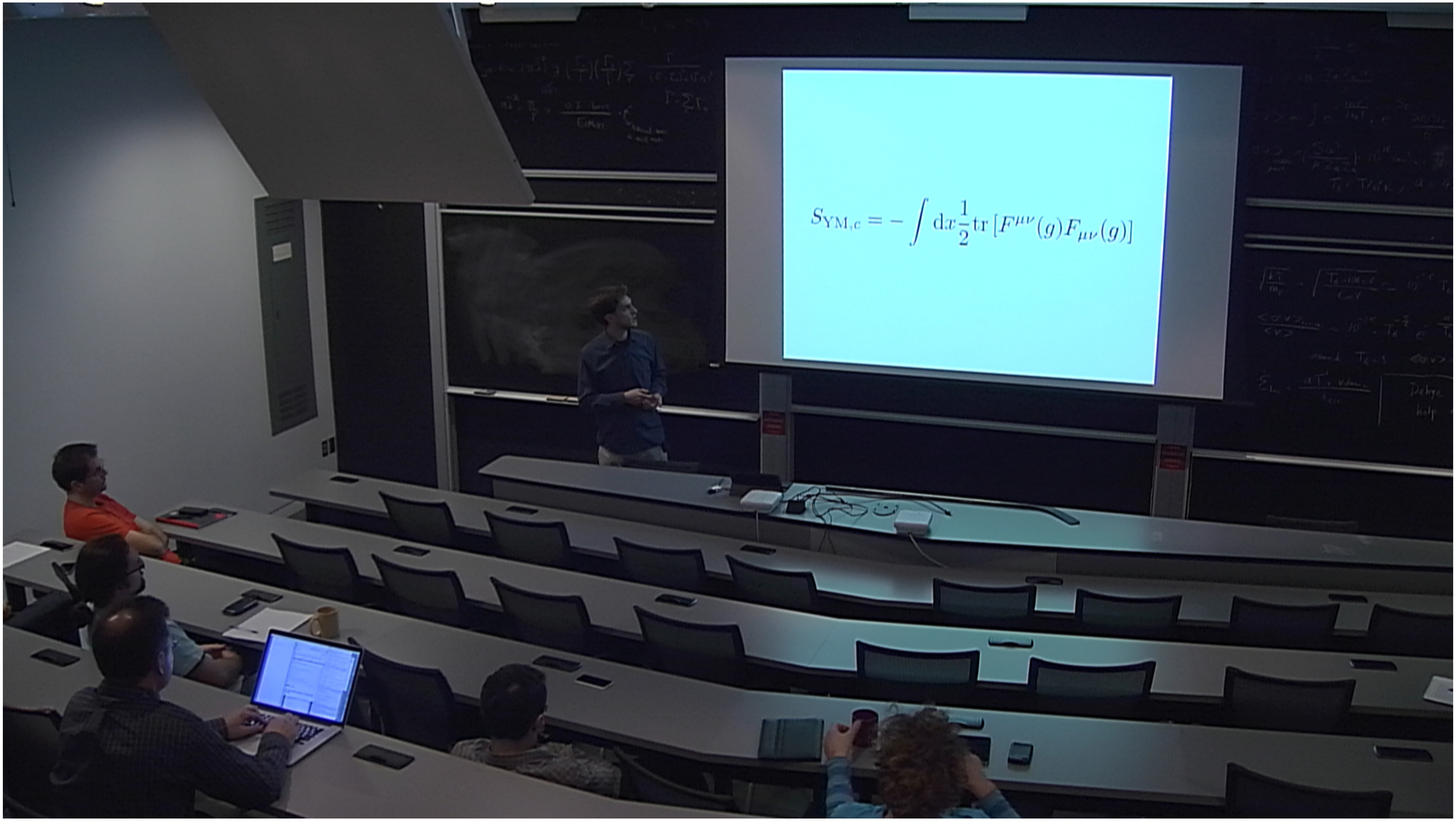
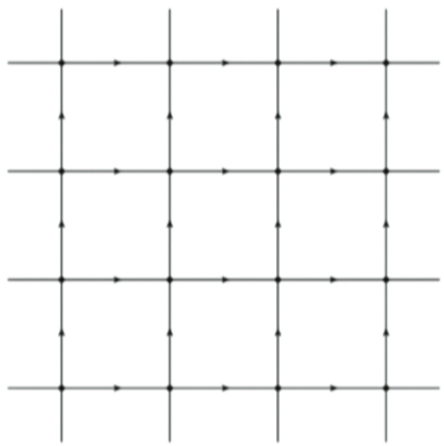
Yang-Mills theory

and the Kogut-Susskind Hamiltonian


$S_{\mathrm{YM},c} = -\int \mathrm{d}x \frac{1}{2} \mathrm{tr}\left[F^{\mu\nu}(g)F_{\mu\nu}(g)\right]$

...**discretized** on a spatial graph and **quantised**, becomes...

$$H(g_H) = \frac{g_H^2}{2a} \sum_{e \in E} \triangle_e + \frac{1}{g_H^2 a} \left(2 - \sum_{\Box} \mathrm{Re}(\mathrm{tr}(\widehat{u}_{\Box})) \right)$$



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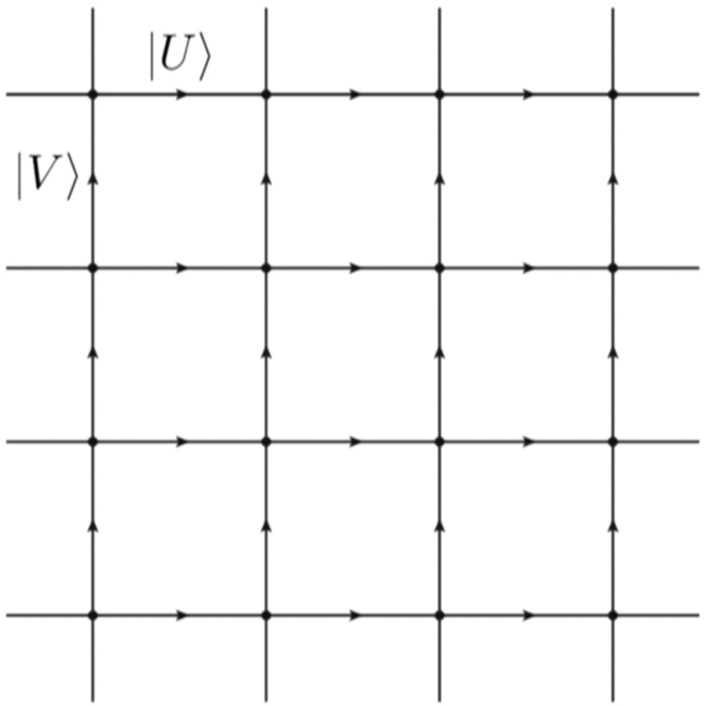
J. Kogut, L. Susskind, Phys Rev D **11**, 395 (1975)

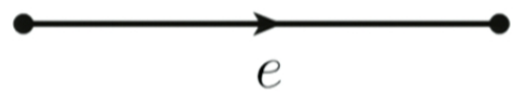


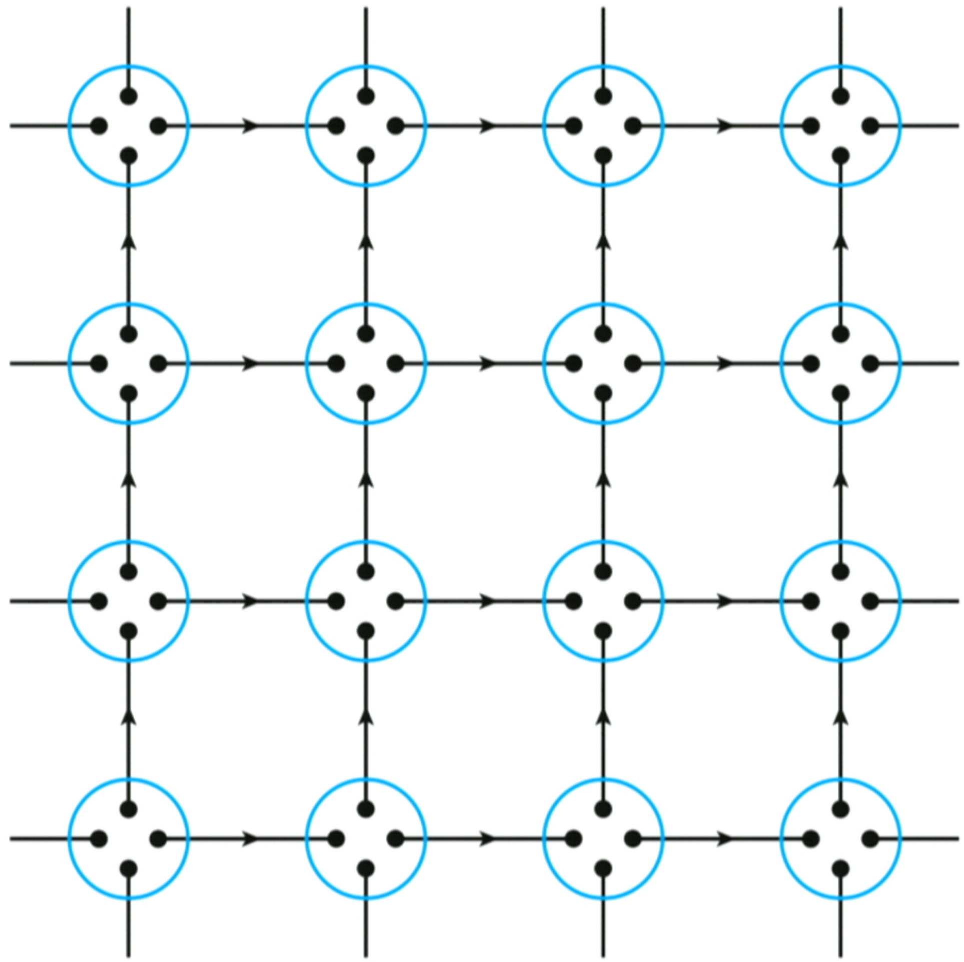
$$\mathcal{H}_{\mathrm{YM}} = \bigotimes_{e \in \mathrm{edges}} L^2(G)$$

$$|\psi\rangle_e = \int \psi(U)\, |U\rangle_e \, \mathrm{d}U$$

“fourier” basis - bipartite structure

$$|\psi\rangle \rightarrow \sum_{l} \sum_{j,k=-l}^{l} \widehat{\psi}^{l}_{jk} |j\rangle_l \otimes |k\rangle_l$$





gauge transformations

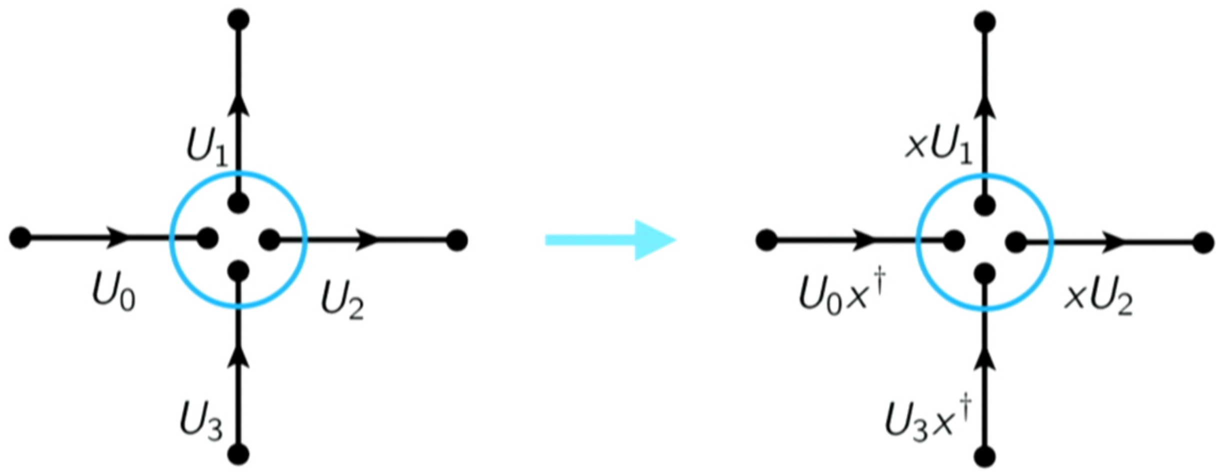
rotations

$$L_U|V\rangle \equiv |UV\rangle$$

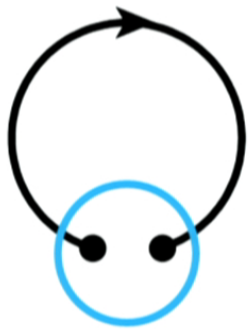
$$R_U|V\rangle \equiv |VU^\dagger\rangle$$

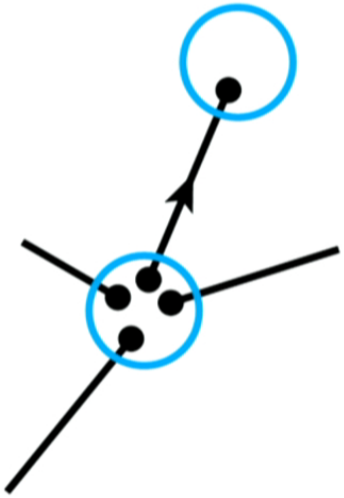
gauge transformations

$$x \mapsto \bigotimes_{e \in E} L_{x_{e_-}} R_{x_{e_+}}, \quad x \in G$$



gauge invariant states





$$\psi(U) = \psi(x^{-1}Ux)$$

e.g.

$$\psi(U) = \delta(U - \mathbb{I})$$

$$\psi(U) = \psi(x^{-1}U)$$

$$|\omega_0\rangle \equiv |00\rangle_0$$

graph manipulation moves

(quantum parallel transport)

controlled rotations

$$CL \equiv \int |U\rangle\langle U| \otimes L_U \, dU$$

$$CR \equiv \int |U\rangle\langle U| \otimes R_U \, dU$$

graph manipulation moves

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$$CL \equiv \int |U\rangle\langle U| \otimes L_U \, dU$$

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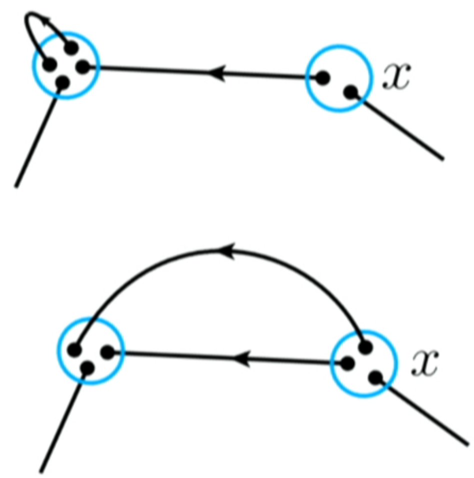
graph manipulation moves
(quantum parallel transport)

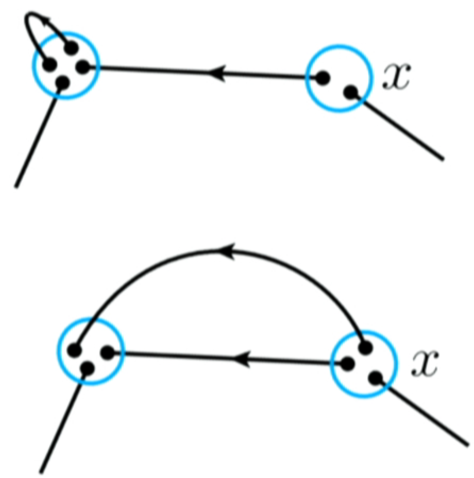
$$CL(L_x \otimes \mathbb{I})CL^\dagger = L_x \otimes L_x$$



J. Baez, Adv. Math. **117**, 253-272 (1996)
E. Dennis, A. Kitaev, A. Landahl, and J. Preskill, J. Math. Phys. **43**, 4452 (2002)
M. Aguado and G. Vidal, PRL **100**, 070404 (2008)
O. Buerschaper, M. Aguado, and G. Vidal, Phys Rev B **79**, 085119 (2009)
R. König, B. W. Reichardt, and G. Vidal, Phys Rev B **79**, 195123 (2009)

graph manipulation moves
(quantum parallel transport)

$$CL(L_x \otimes \mathbb{I})CL^\dagger = L_x \otimes L_x$$



J. Baez, Adv. Math. **117**, 253-272 (1996)
E. Dennis, A. Kitaev, A. Landahl, and J. Preskill, J. Math. Phys. **43**, 4452 (2002)
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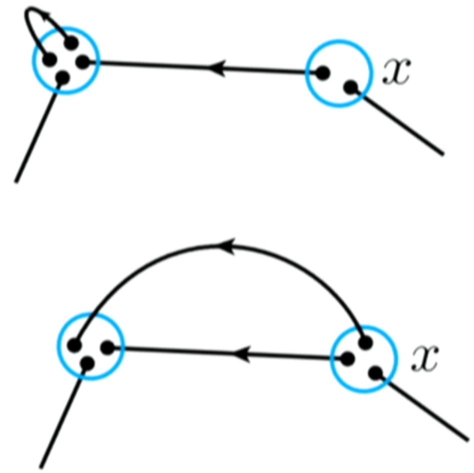

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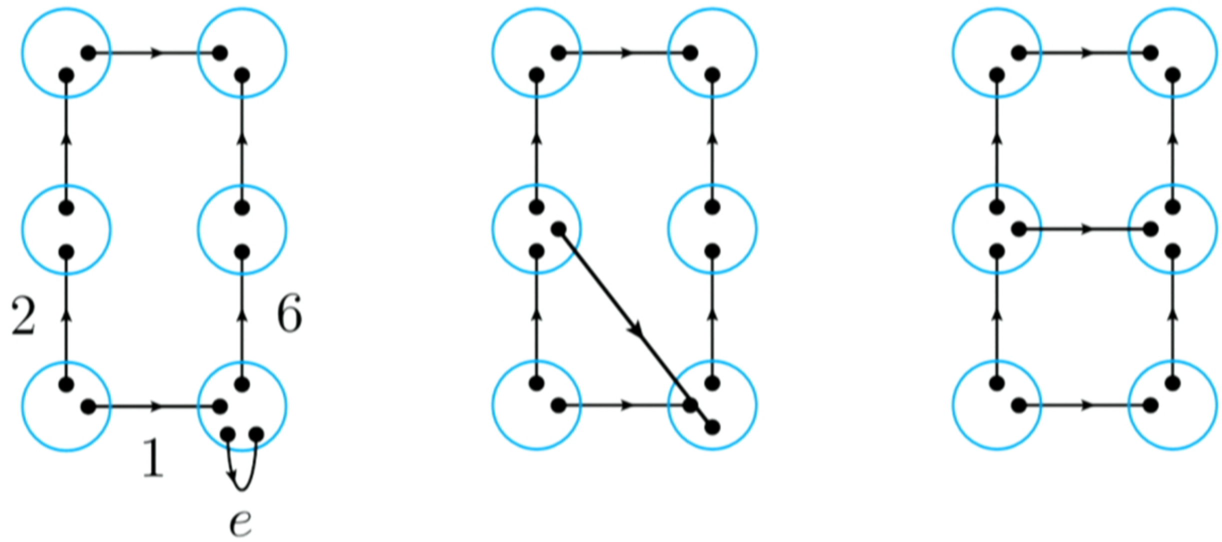
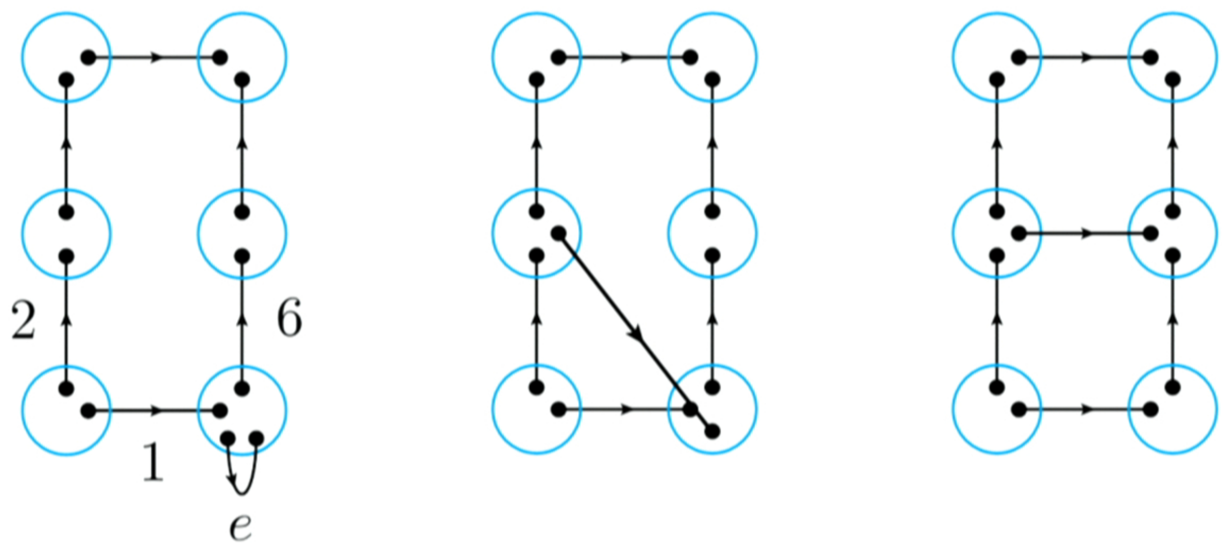
edge addition



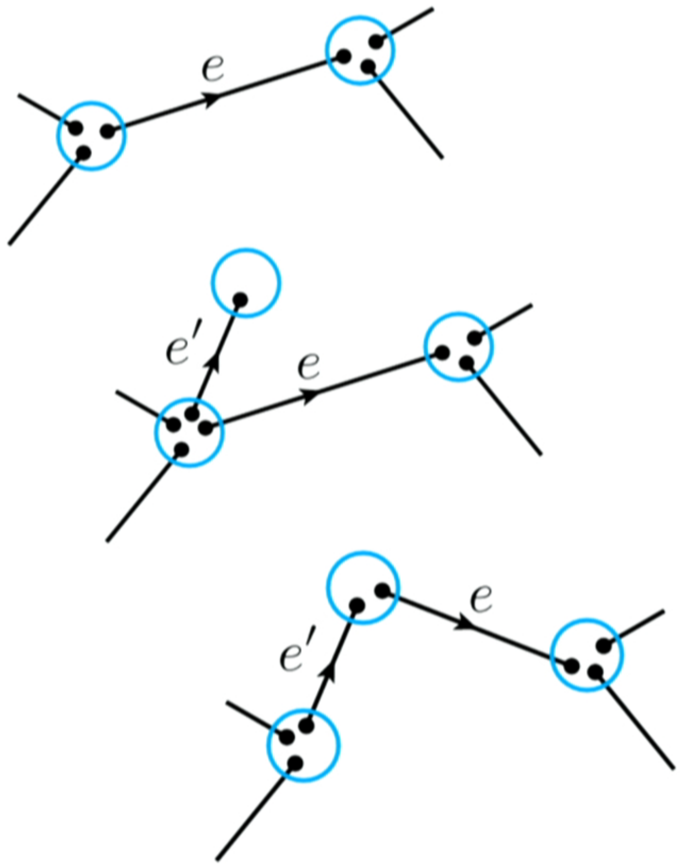
$$CR_{6,e}CL_{2,e}CL_{1,e}(|\Psi\rangle \otimes |\mathbb{I}\rangle)$$

edge addition



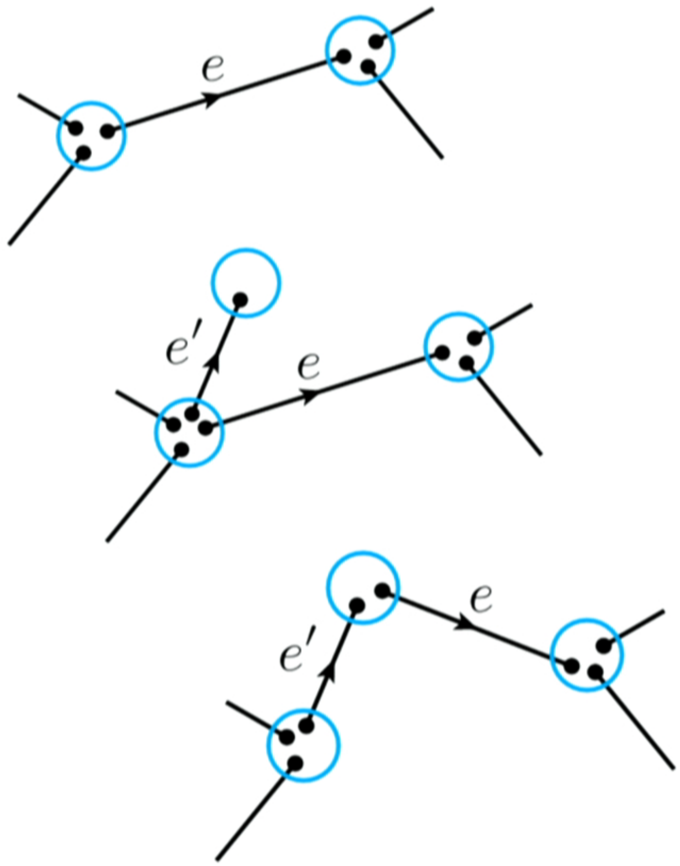
$$CR_{6,e}CL_{2,e}CL_{1,e}(|\Psi\rangle \otimes |\mathbb{I}\rangle)$$

edge subdivision



$$CL_{e',e}(|\Psi\rangle \otimes |\omega_0\rangle)$$

edge subdivision



$$CL_{e',e}\left(|\Psi\rangle \otimes |\omega_0\rangle\right)$$

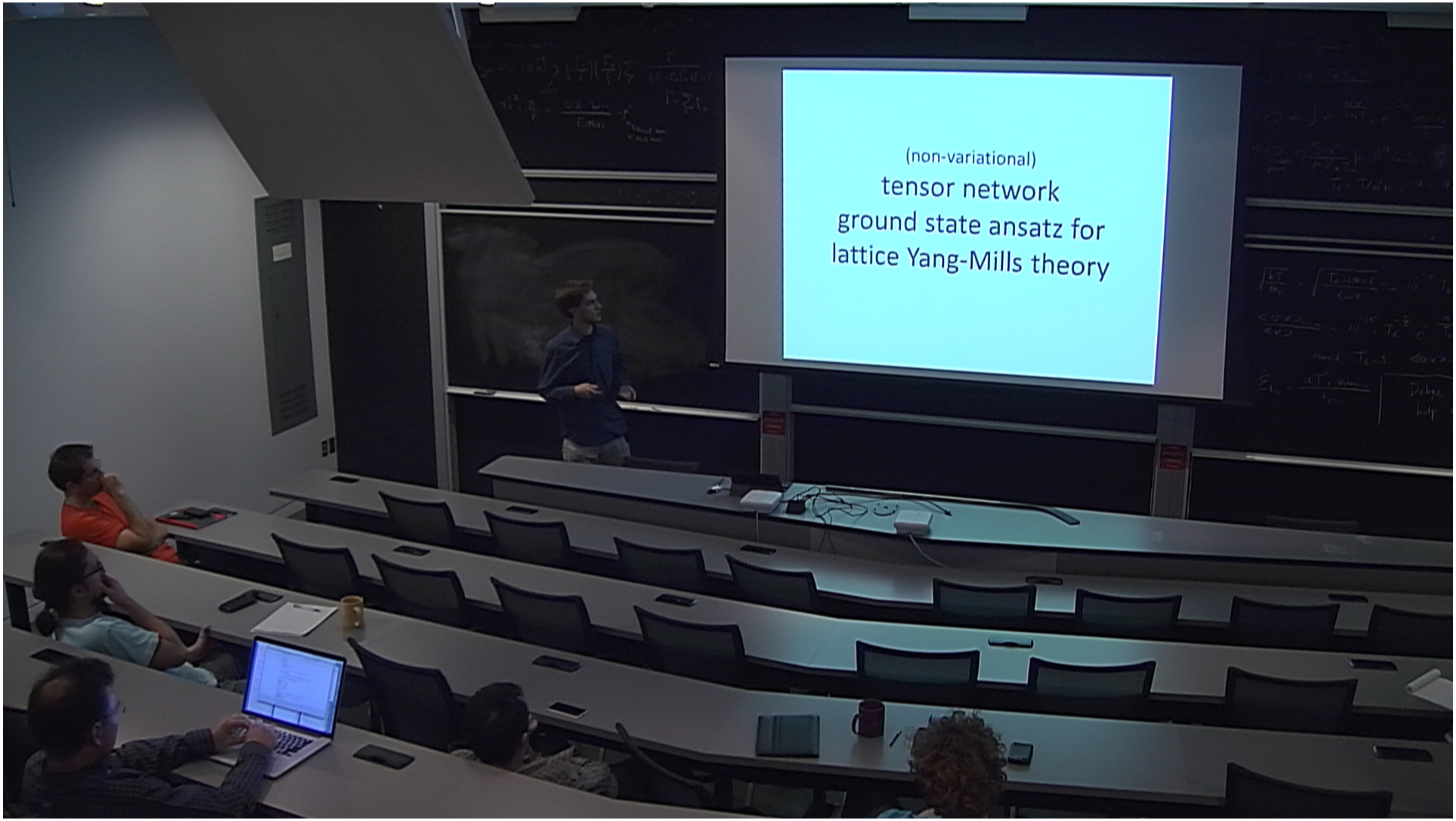
graph manipulation moves

(quantum parallel transport)

controlled rotations

$$CL \equiv \int |U\rangle\langle U| \otimes L_U \, dU$$

$$CR \equiv \int |U\rangle\langle U| \otimes R_U \, dU$$


(non-variational)
tensor network
ground state ansatz for
lattice Yang-Mills theory

properties of the ansatz:

manifestly **gauge invariant**

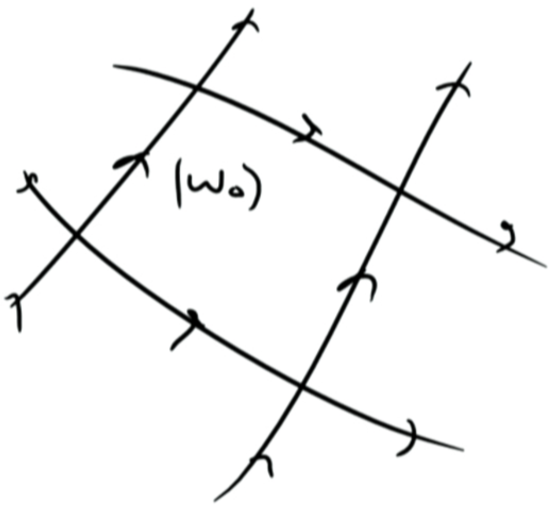
a **contractible** tensor network

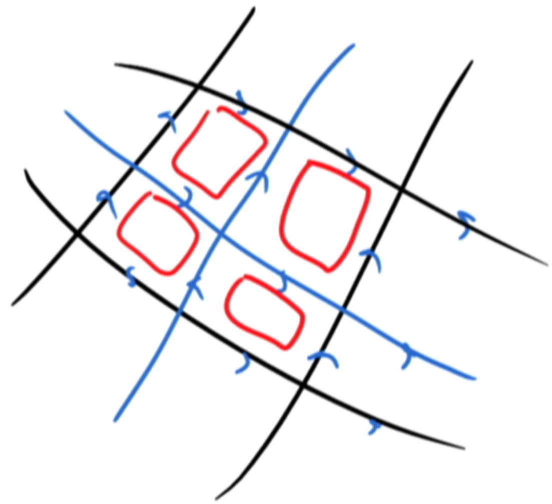
Lorentz-invariant **continuum limit**

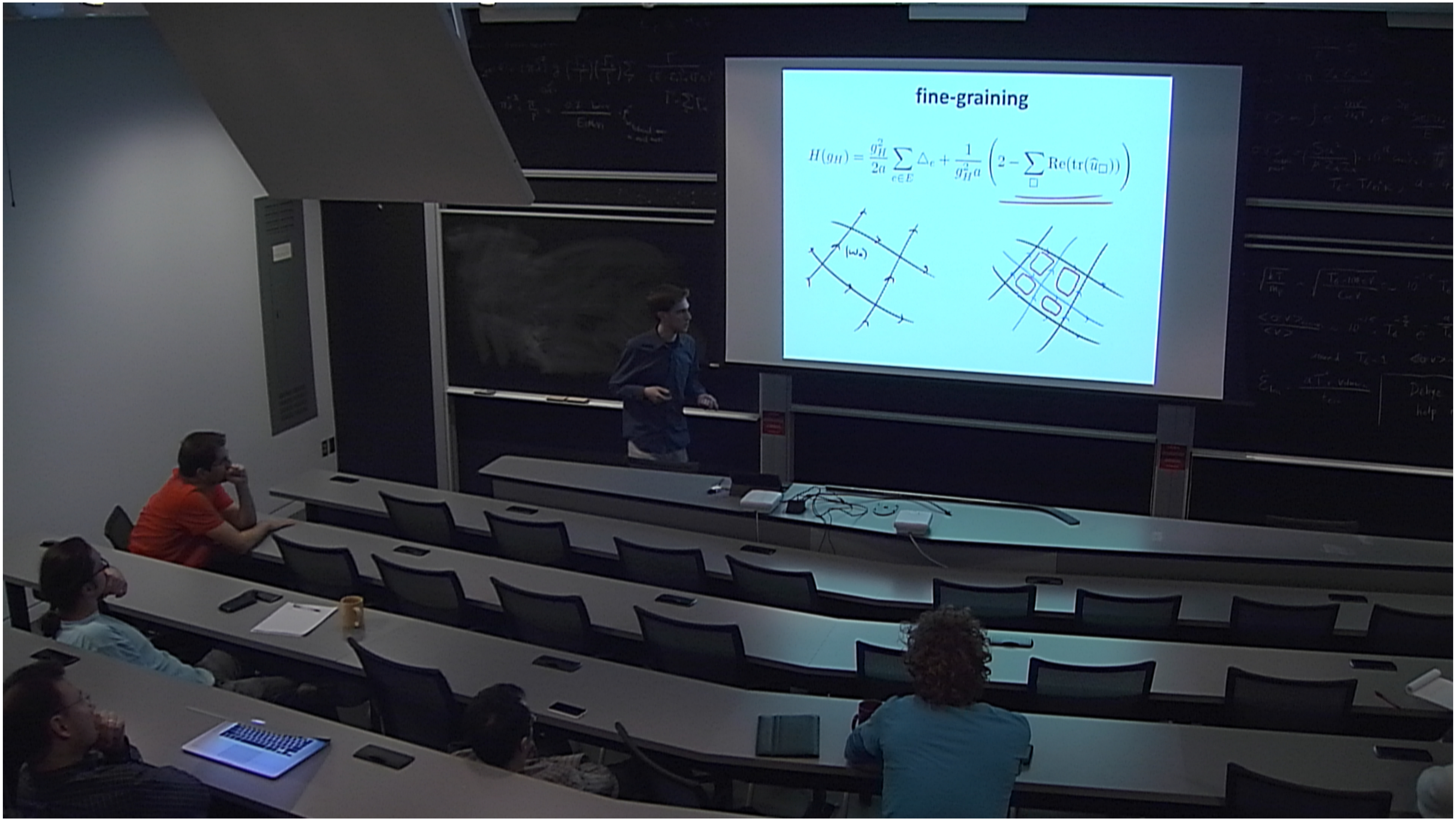
only **irrelevant** (UV) errors
(captures **large scale** physics)

fine-graining

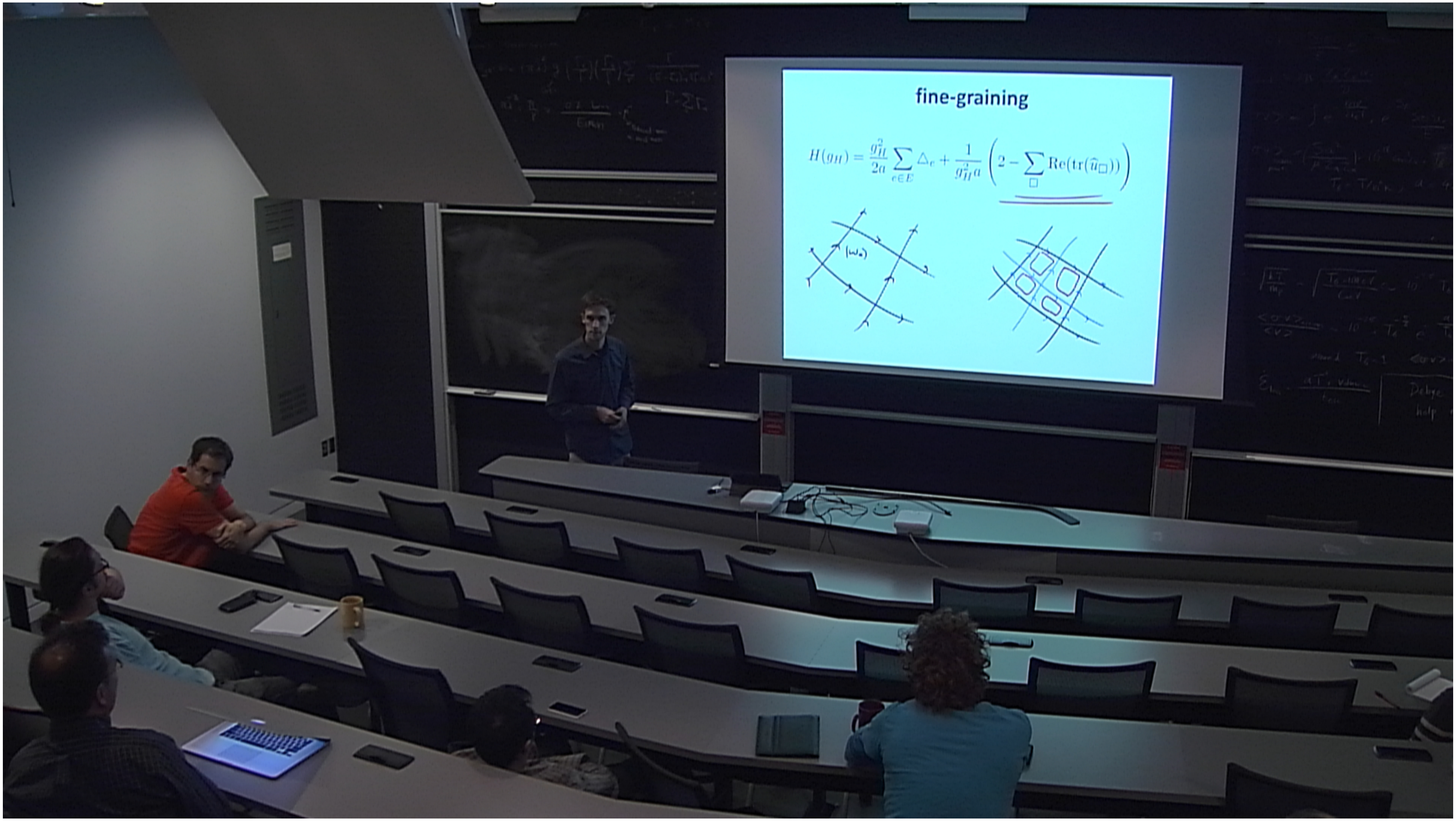
$$H(g_H) = \frac{g_H^2}{2a} \sum_{e \in E} \triangle_e + \frac{1}{g_H^2 a} \left(2 - \sum_{\square} \mathrm{Re}(\mathrm{tr}(\widehat{u}_\square)) \right)$$







fine-graining
$$H(g_H) = \frac{g_H^2}{2a}\sum_{e\in E}\Delta_e + \frac{1}{g_H^2 a}\left(2 - \sum_{\square}\mathrm{Re}(\mathrm{tr}(\widehat{u}_\square))\right)$$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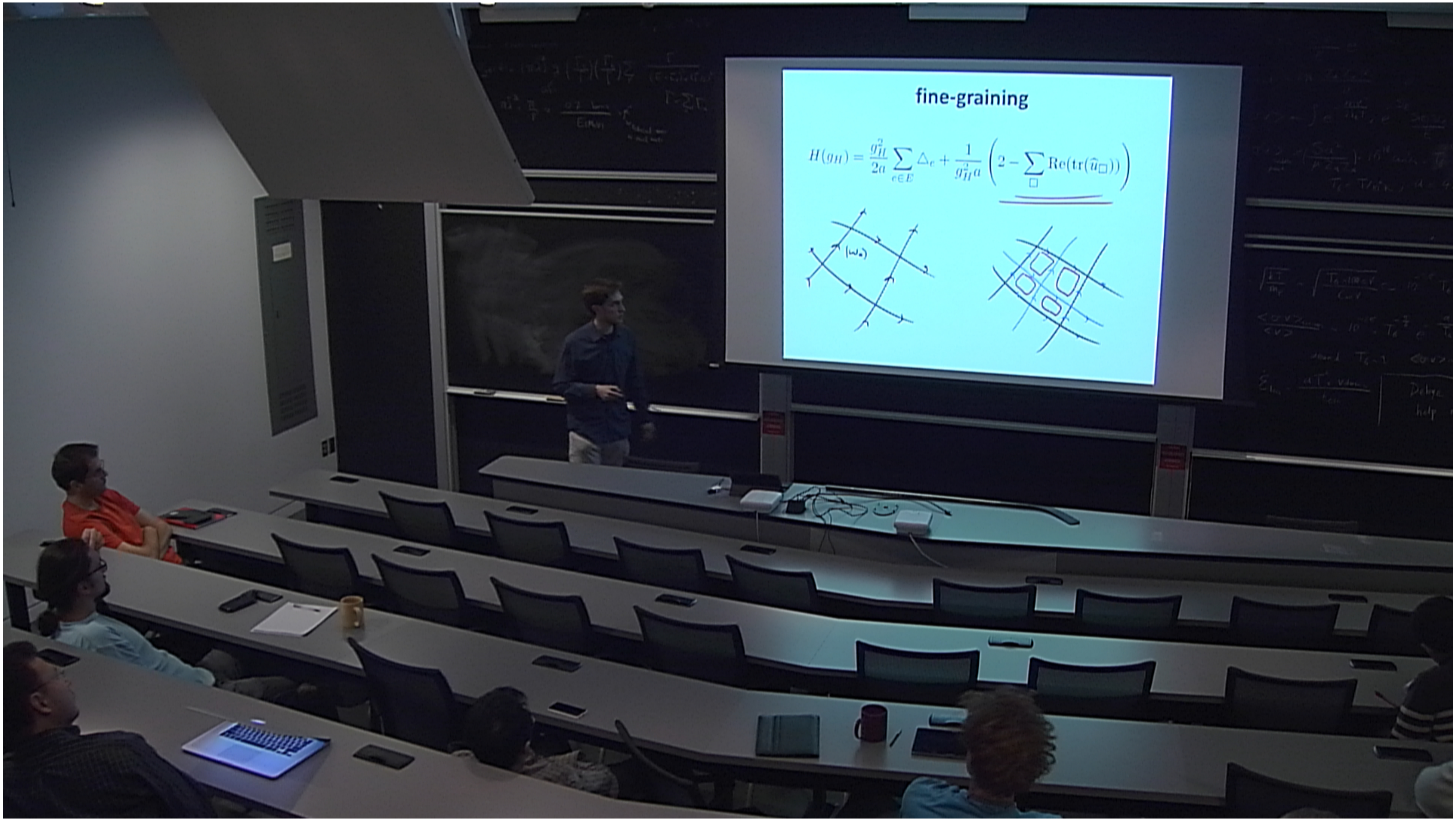

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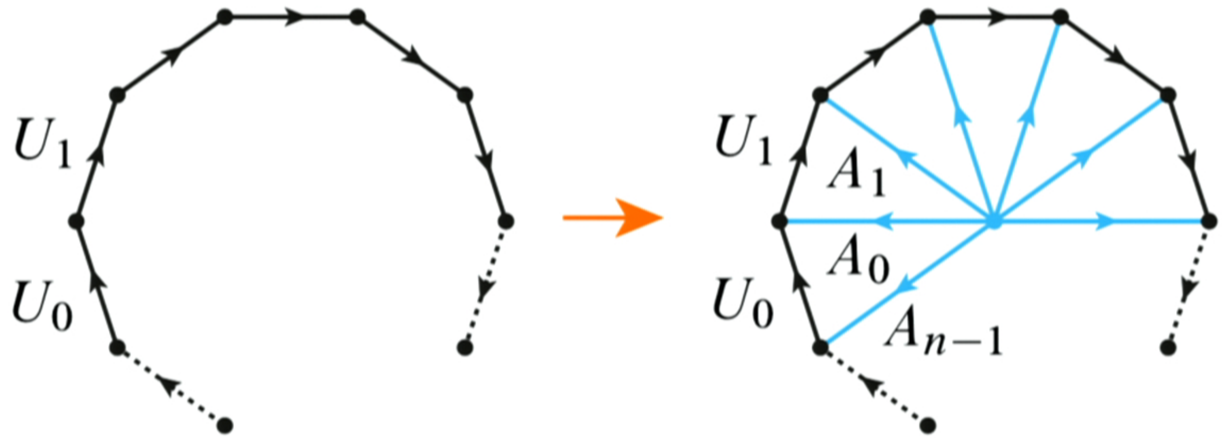
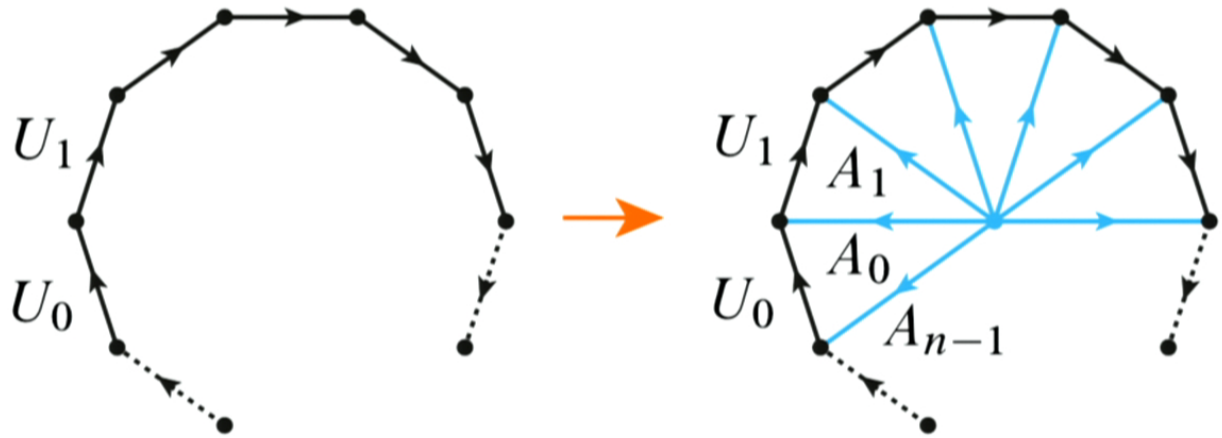
classical gauge field **interpolation**

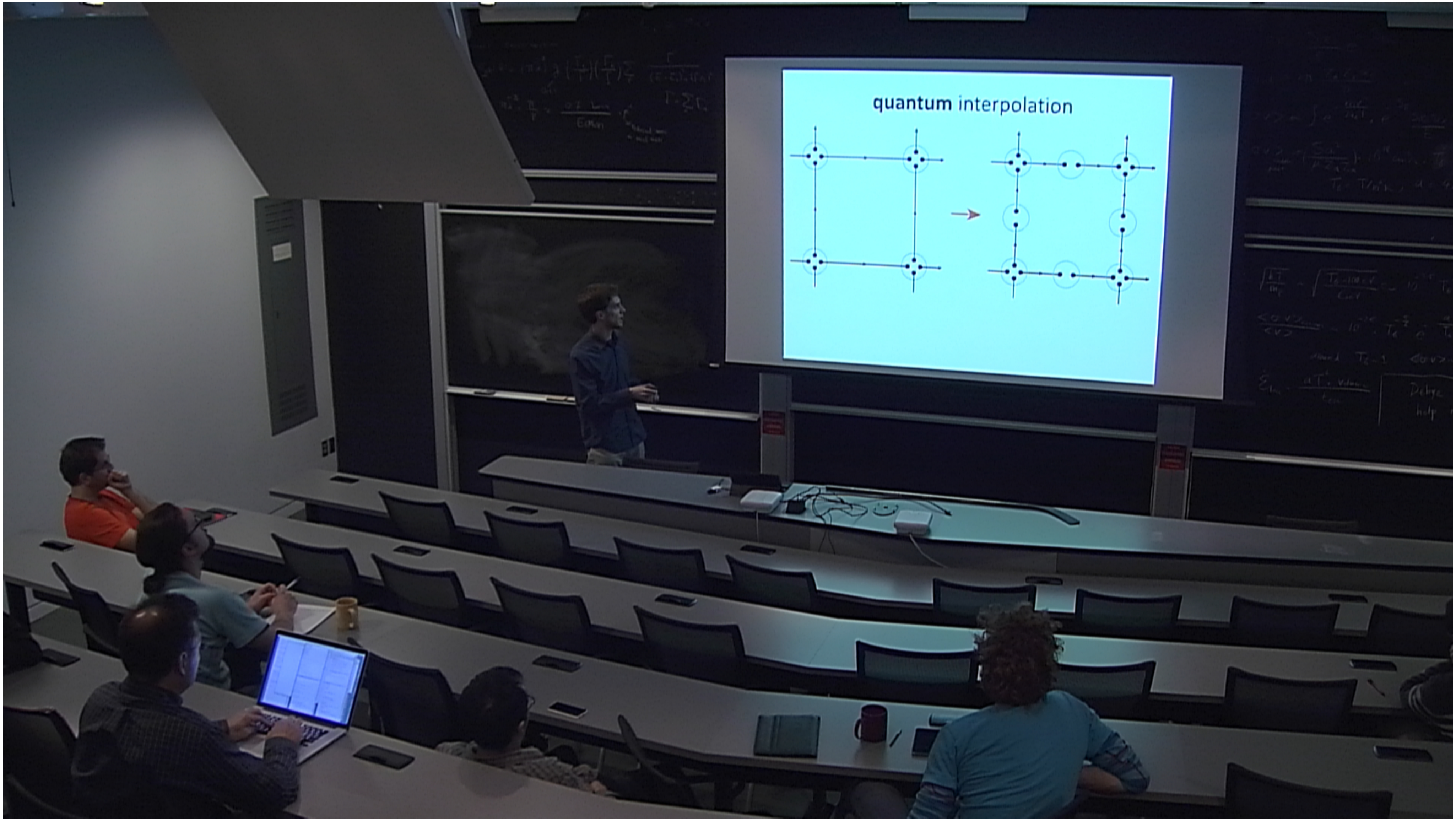


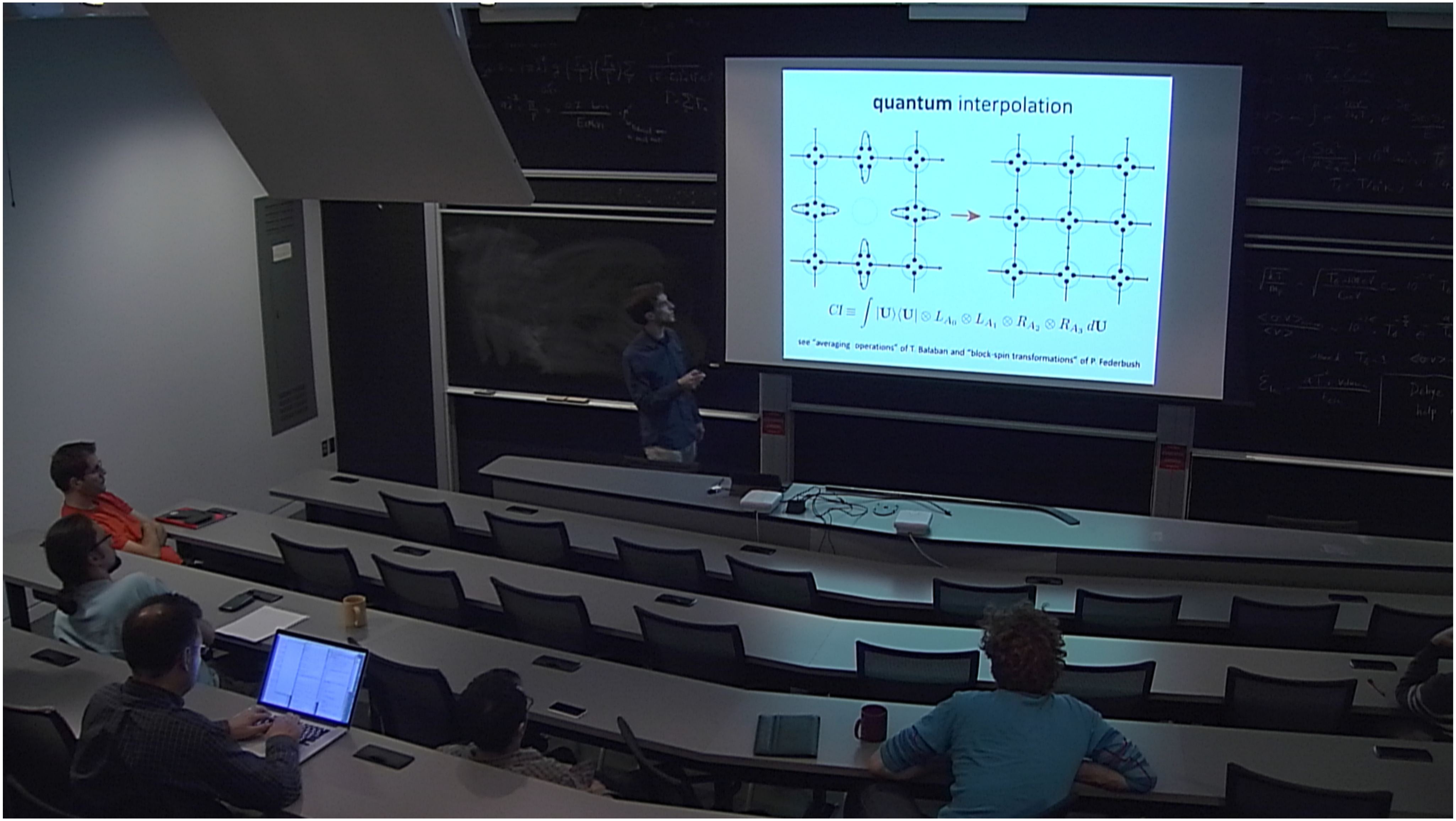
$$2 - \sum_{\Box} \mathrm{Re}(\mathrm{tr}(\widehat{u}_{\Box})) = 2 - 4n\cos\left(\frac{\phi - 2\pi k}{n}\right)$$

classical gauge field **interpolation**

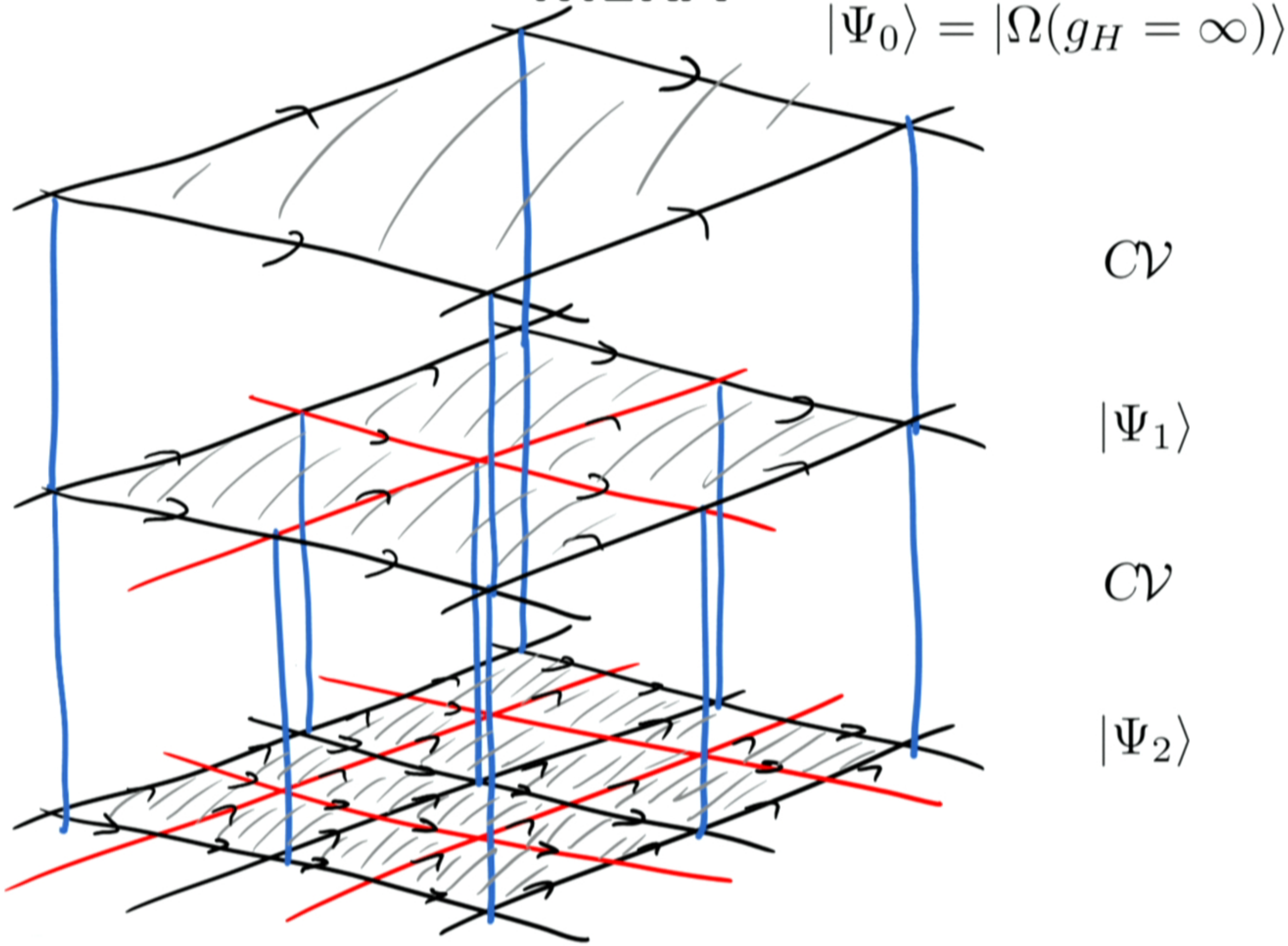


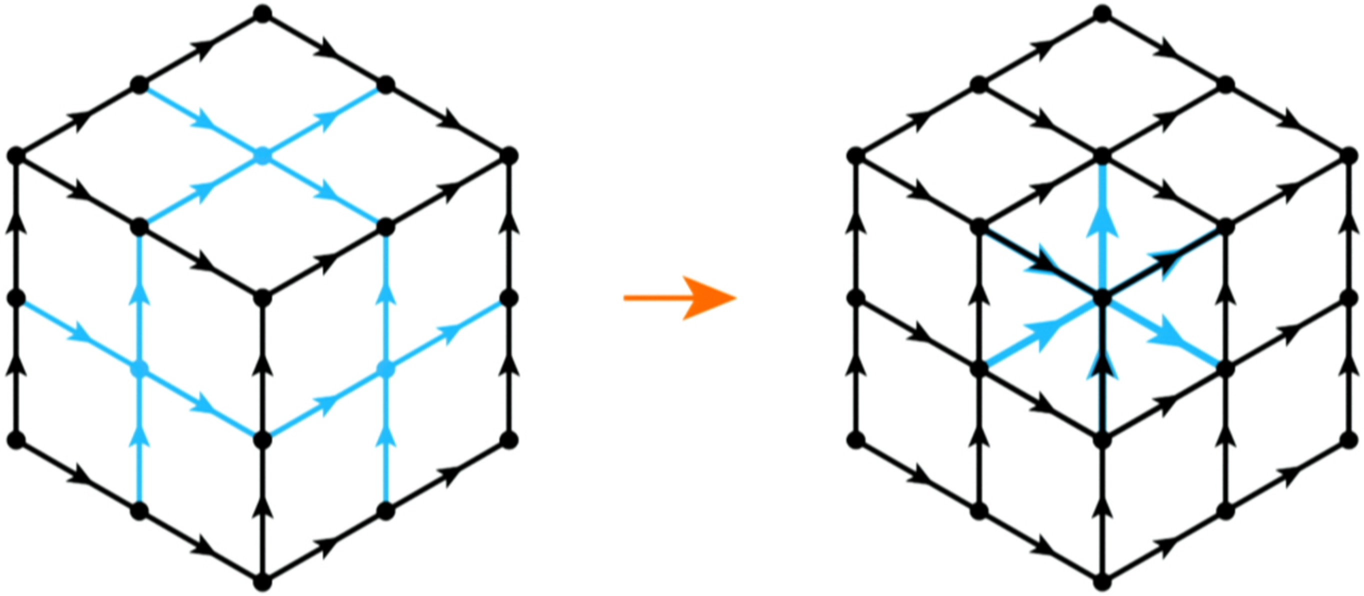
$$2 - \sum_{\square} \mathrm{Re}(\mathrm{tr}(\widehat{u}_{\square})) = 2 - 4n\cos\left(\frac{\phi - 2\pi k}{n}\right)$$


quantum interpolation


quantum interpolation
$CI \equiv \int |\mathbf{U}\rangle\langle\mathbf{U}| \otimes L_{A_0} \otimes L_{A_1} \otimes R_{A_2} \otimes R_{A_3}\, d\mathbf{U}$
see "averaging operations" of T. Balaban and "block-spin transformations" of P. Federbush

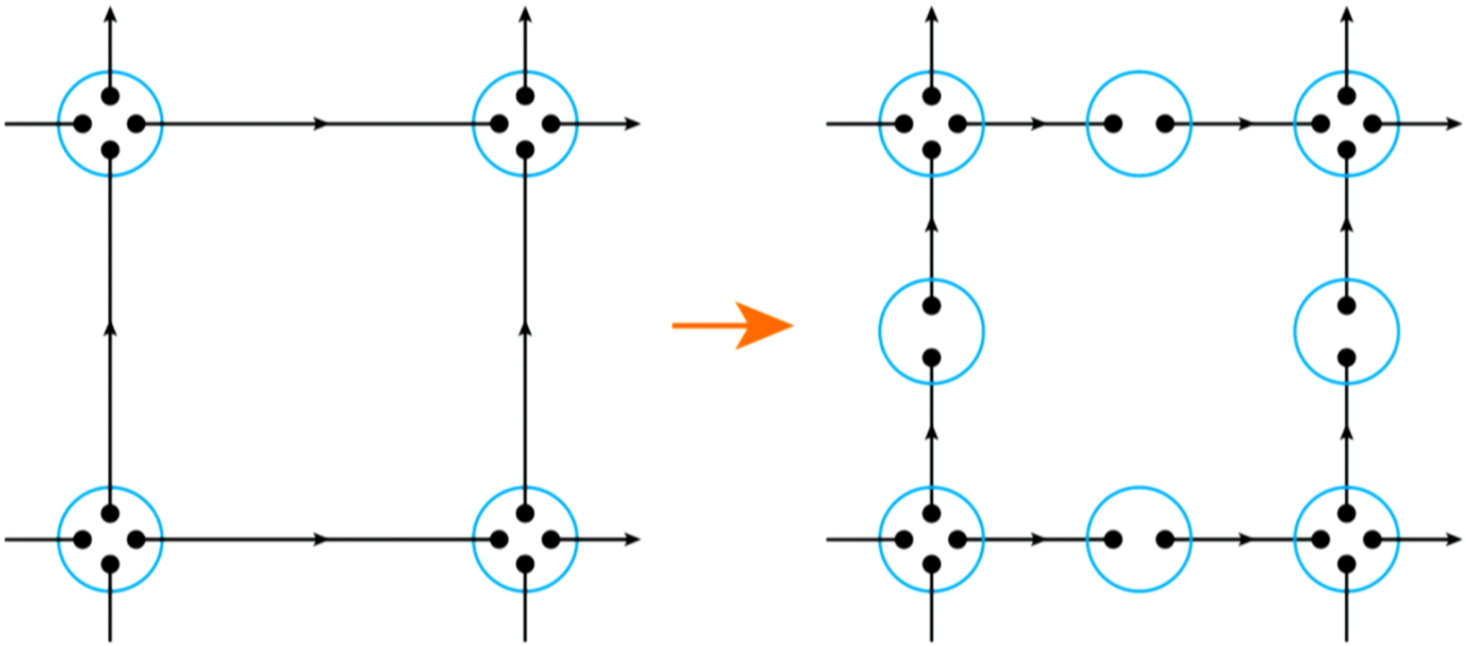
MERA


$|\Psi_0\rangle = |\Omega(g_H = \infty)\rangle$
$C\mathcal{V}$
$|\Psi_1\rangle$
$C\mathcal{V}$
$|\Psi_2\rangle$

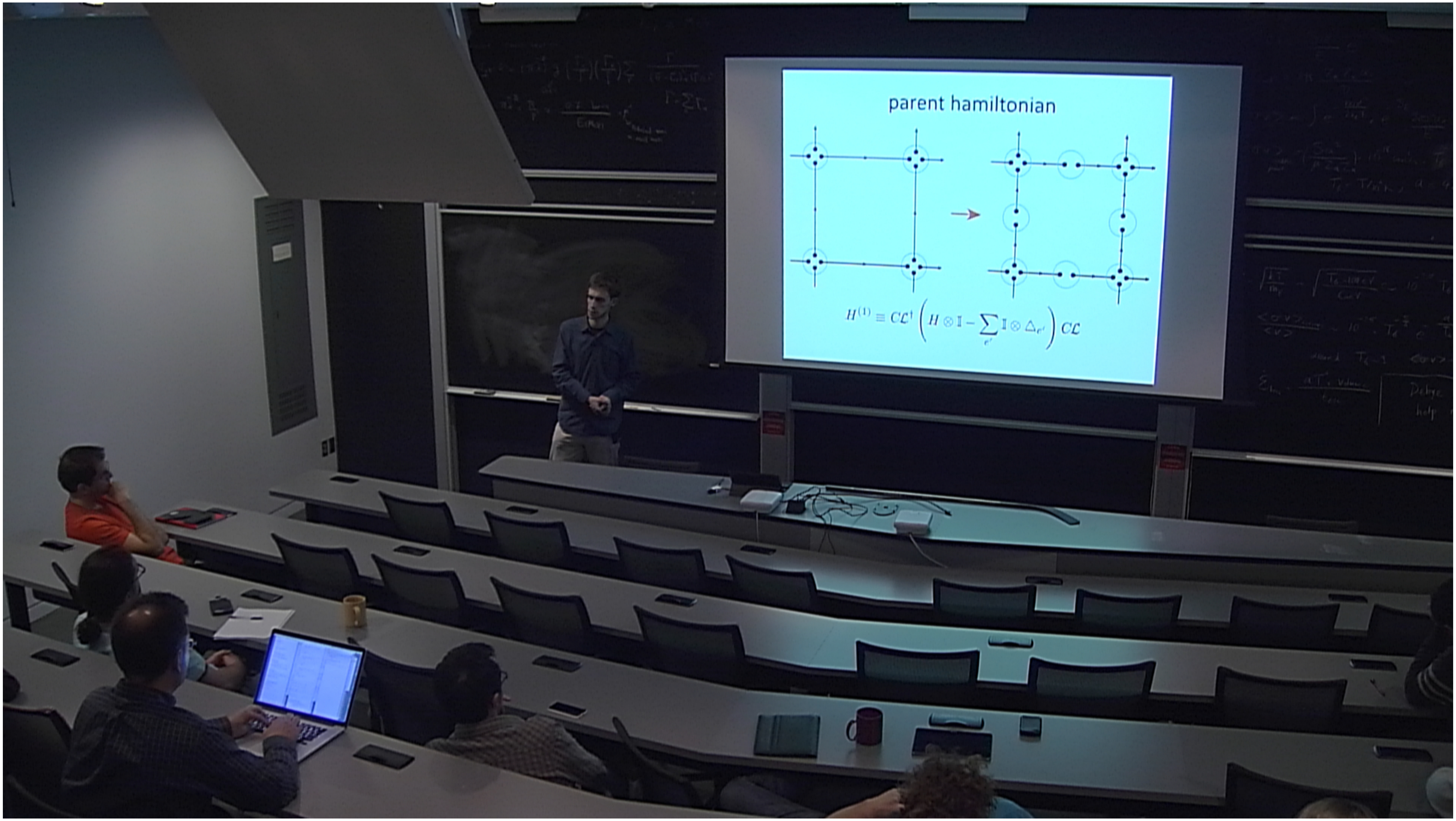


$$|\Psi_m\rangle \approx |\Omega(g_H(m))\rangle$$

parent hamiltonian



$$H^{(1)} \equiv C\mathcal{L}^{\dagger}\left(H \otimes \mathbb{I} - \sum_{e'} \mathbb{I} \otimes \triangle_{e'}\right) C\mathcal{L}$$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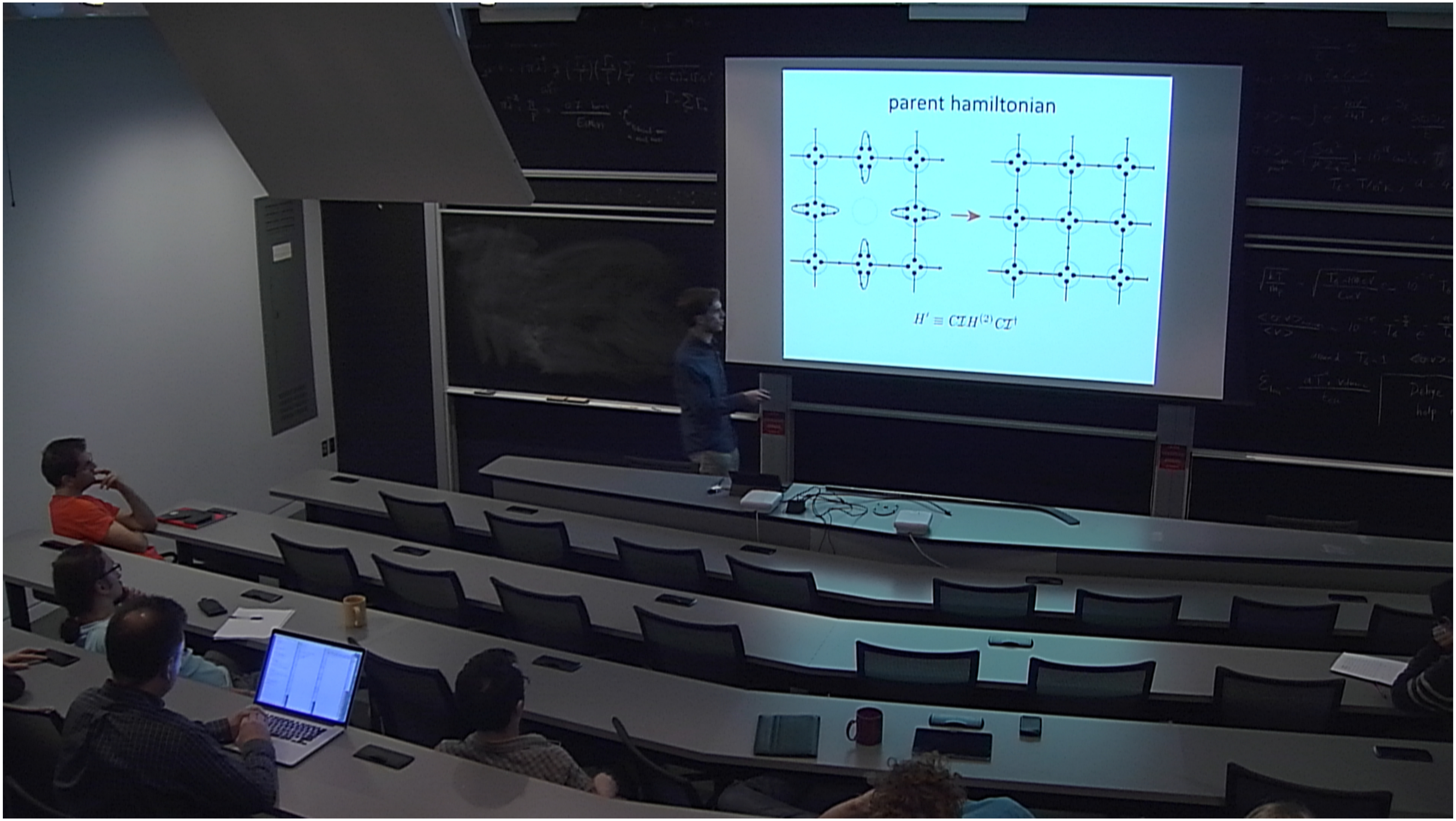
parent hamiltonian
$H' \equiv C\mathcal{I}H^{(2)}C\mathcal{I}^{\dagger}$

improved ansatz

quasi-adiabatic continuation $\mathcal{U}$

$$|\Psi_m\rangle = \mathcal{U}_{m-1} C\mathcal{V} |\Psi_{m-1}\rangle, \quad m = 1, 2, \ldots$$

$$|\Psi_m\rangle = |\Omega(g'_H)\rangle$$

S. Bachmann, S. Michalakis, B. Nachterhaele, R. Sims, Commun Math Phys **309**, 835 (2011)
M. B. Hastings, X-G. Wen, Phys Rev B **72**, 045141 (2005)
T. J. Osborne, Phys Rev A **75**, 032321 (2007)


conjectures:
1. $CV|\Omega(g_H)\rangle \approx |\Omega(g_H')\rangle$
2. $H', H(g_H')$ are in the same phase


properties of the ansatz:
manifestly gauge invariant
a contractible tensor network
Lorentz-invariant continuum limit
errors correctible via adiabatic step


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manifestly gauge invariant
a contractible tensor network
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errors correctible via adiabatic step

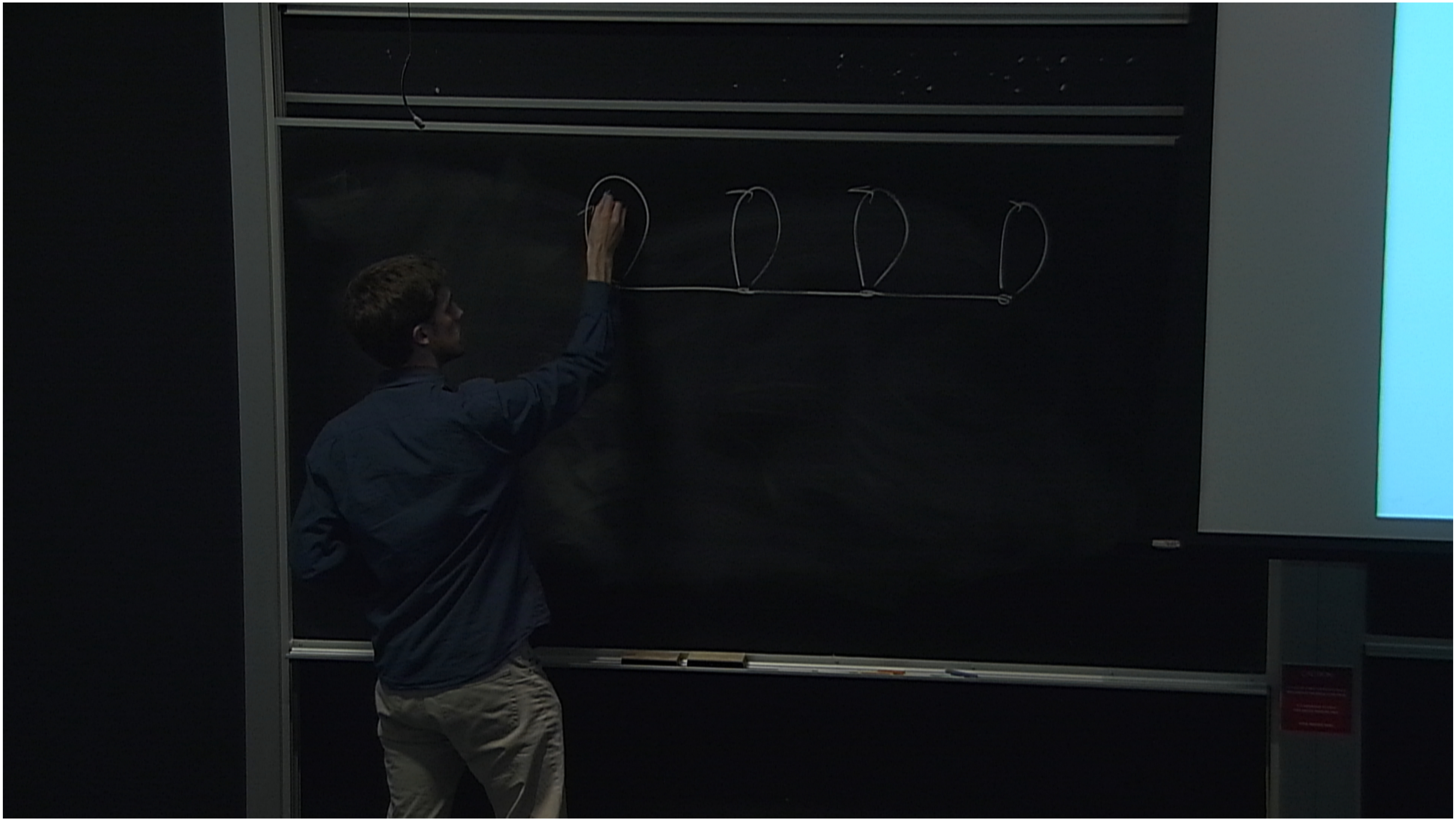
the plan

analytical calculations for QCD at **low energies** (perturbative or not)

avoid the sign problem with fermions

study **dynamical** properties

(…prove confinement?)




this project is **open source**!
github.com/tobiasosborne/Lattice-gauge-theory-and-tensor-networks

evoMPS

Leibniz Universität Hannover

Thank you for your attention!

In summary:

Non-variational ground state ansatz
for nonabelian lattice gauge theory
which is a **MERA**

adiabatic improvement step to correct errors

ERC grant: QFTCMPS
Cluster of excellence: EXC 201 Quantum Engineering and Space-Time Research