Quantum simulations of high-energy physics models

In collaboration with J. Pachos (Leeds)
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DESY

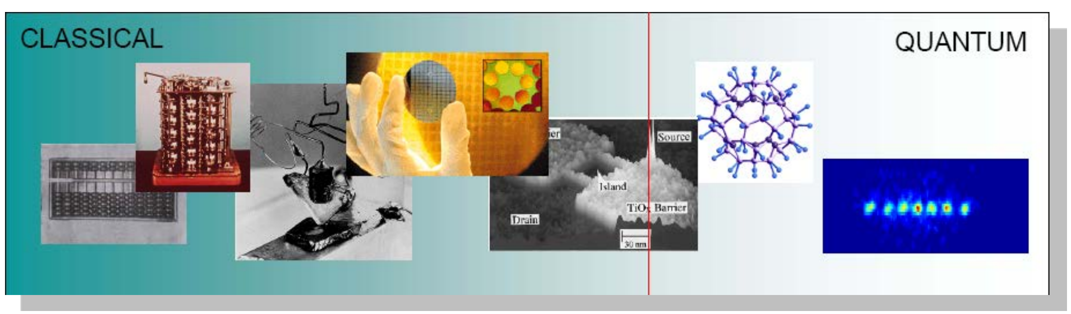
Physics Colloquium,
Zeuthen, January 19th, 2016

QUANTUM PHYSICS

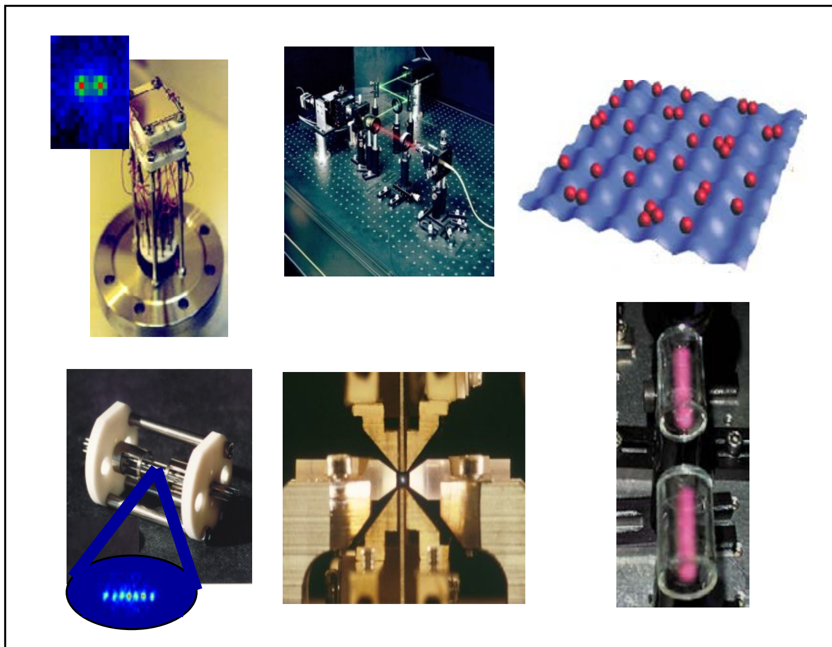
„There is plenty of room at the bottom“

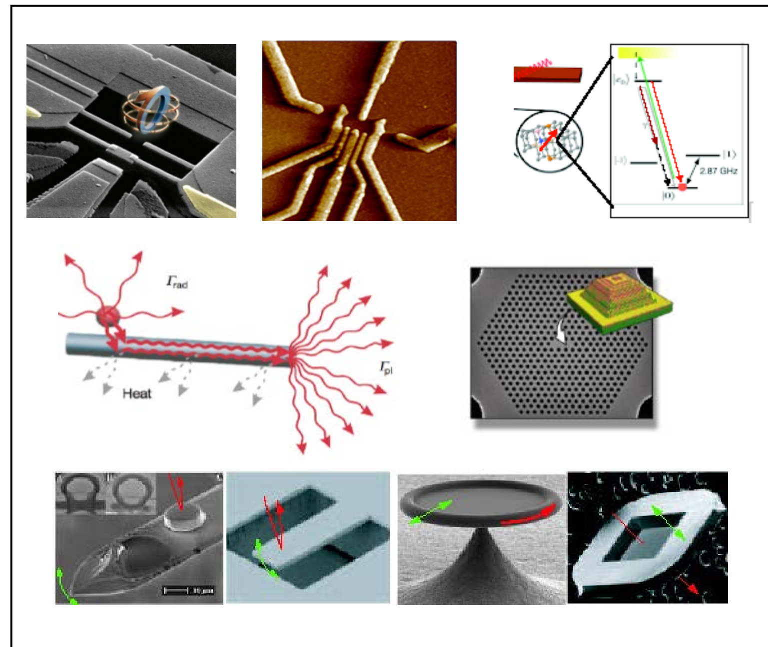
Ricard Feynman, 29.12.1959. Annual meeting of the American Physical Society, CALTECH

- When we get to the very, very small world we have a lot of new things that would happen that represent completely new opportunities for design.
- Atoms on a small scale behave like nothing on a large scale, for they satisfy the laws of quantum mechanics.
- We are working with different laws, and we can expect to do different things.



QUANTUM PHYSICS
PROGRESS





QUANTUM SIMULATION

Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

1. INTRODUCTION

On the program it says this is a keynote speech—and I don't know what a keynote speech is. I do not intend in any way to suggest what should be in this meeting as a keynote of the subjects or anything like that. I have

be understood very well in analyzing the situation. And I'm not happy with all the analyses that go with just the classical theory, because nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy. Thank you.

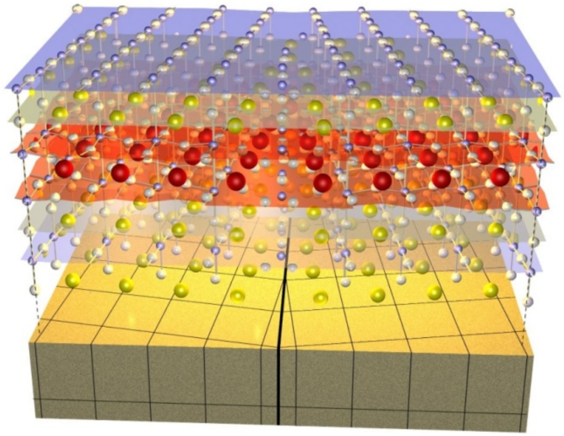
OUTLINE

- Simulating many-body systems
- Analog quantum simulation
- Cold atoms in optical lattices
- Quantum simulation of HEP models
- Tensor Networks and HEP models

SIMULATING MANY-BODY SYSTEMS

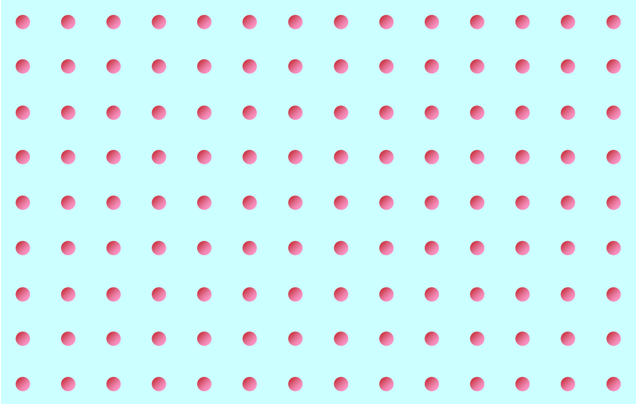
MANY-BODY SYSTEM
MODELS

PHYSICAL SYSTEM



- Dynamics
- Thermal equilibrium (T)

MODEL



Model Hamiltonian

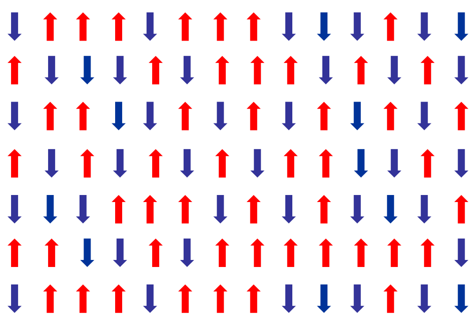
$$H = \ldots$$

Computation time/memory scales exponentially with the number of constituents

MANY-BODY SYSTEM
CLASSICAL MODELS

- EXAMPLE: classical spins

Which is the spin configuration at T=0?



$$E = E(1,2) + E(2,3) + \ldots$$

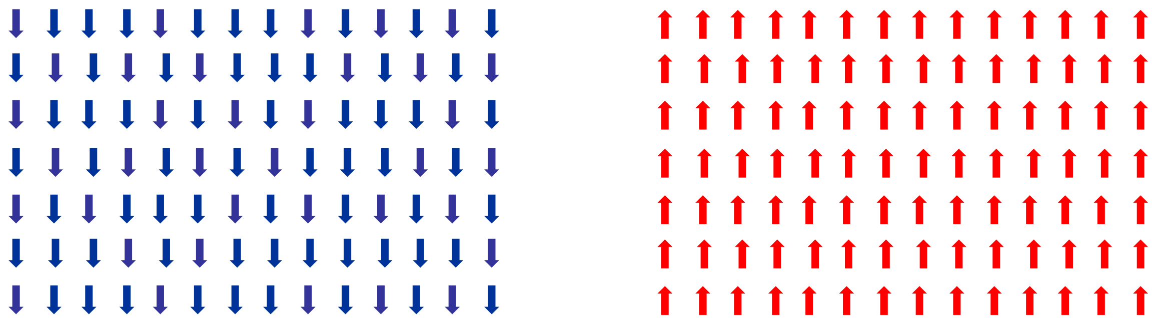
Configuration	Energy
000...000	0.274
000...001	0.298
000...010	0.345
000...011	–0.177 ●
...	...
111...111	–0.122

- There are 2^N different configurations
- Impossible if N>100

MANY-BODY SYSTEM
CLASSICAL MODELS

- EXAMPLE: classical spins + SYMMETRIES

Which is the spin configuration at T=0?

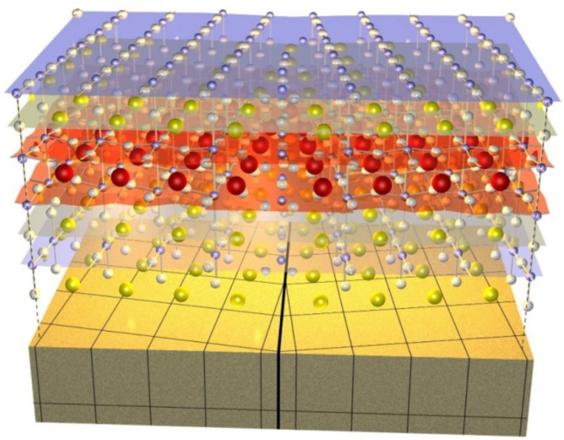


- Ferromagnetic
- Symmetries: simple

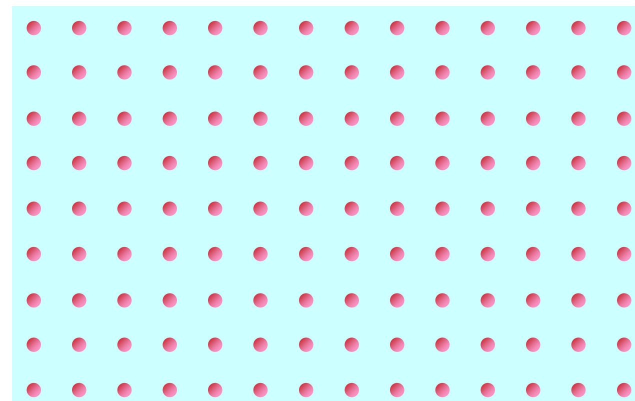
The problem is difficult in general (NP-Hard)
In practice, it may turn to be simple

MANY-BODY SYSTEM
QUANTUM MODELS

PHYSICAL SYSTEM



MODEL



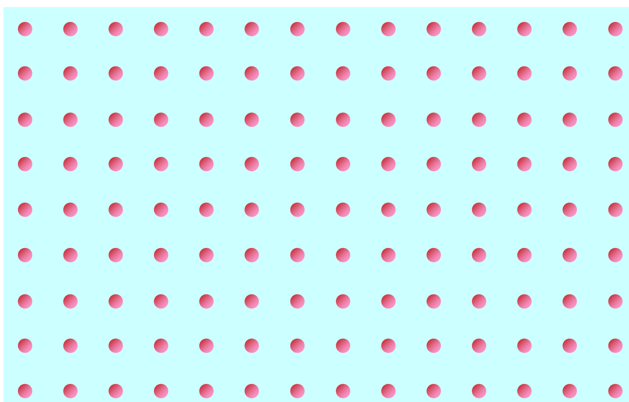
Model Hamiltonian

$$H = \ldots$$

Which is the spin configuration at T=0?

$$|\Psi\rangle = c_1\,|000\ldots0\rangle + c_2\,|000\ldots1\rangle + \ldots + c_{2^N}\,|111\ldots1\rangle$$

- Quantum spins: $|\Psi\rangle = c_1\,|000...0\rangle + c_2\,|000...1\rangle + ... + c_{2^N}\,|111...1\rangle$



N. spines	Memory
10	128 bytes
50	150 Tbytes
100	10^{29} bytes
500	10^{150} bytes

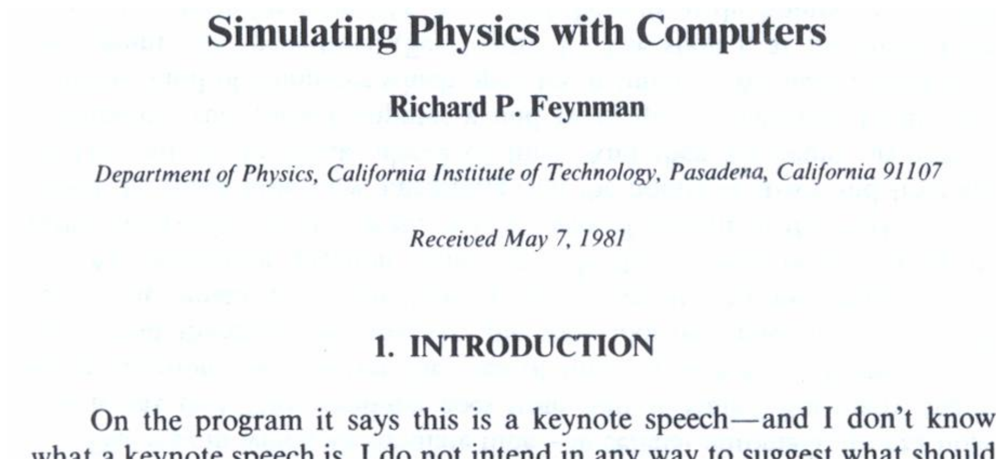
- Symmetries do not help much

- Quantum superpositions are responsible for many physical phenomena:
  - Superconductivity
  - Superfluidity
  - Giant magnetoresistence
  - Insulators (Mott, Anderson, topological)
  - Nuclear reactions
  - Chemical reactions
  - Quark confinement

- There are many theoretical techniques

In some relevant problems they fail

ANALOG QUANTUM SIMULATION



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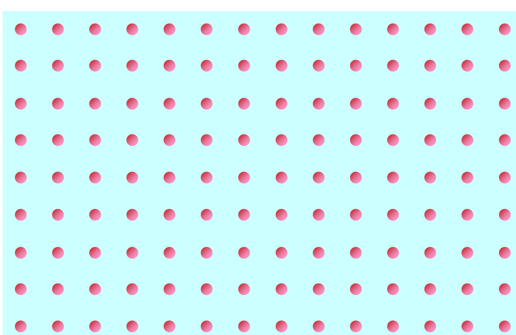
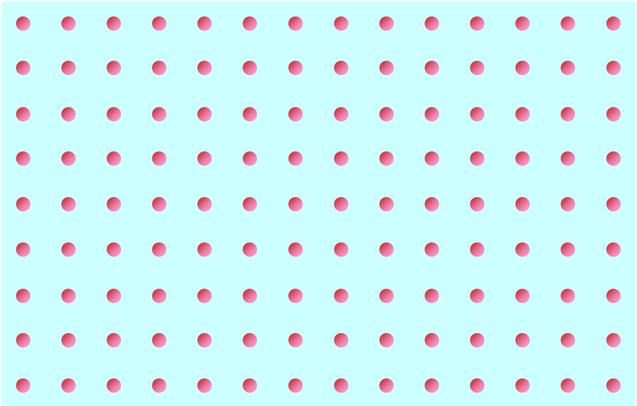


$$c_1\,|000\ldots0\rangle + c_2\,|000\ldots1\rangle + \ldots + c_{2^N}\,|111\ldots1\rangle$$

QUANTUM SIMULATORS
ANALOG

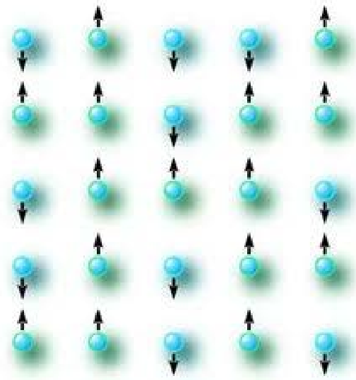
MODEL



Model Hamiltonian

$$H = \ldots$$

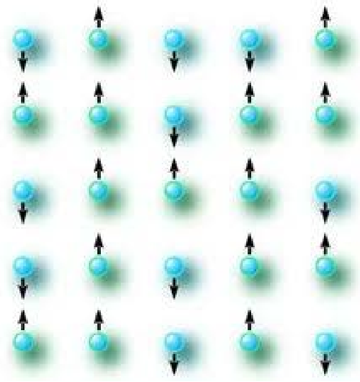
QUANTUM SIMULATOR



Model Hamiltonian

$$H = \ldots$$

QUANTUM SIMULATORS

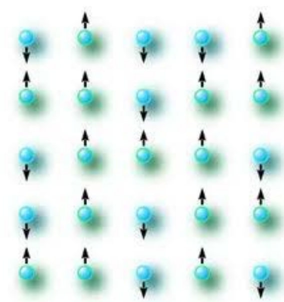


$$H = \ldots$$

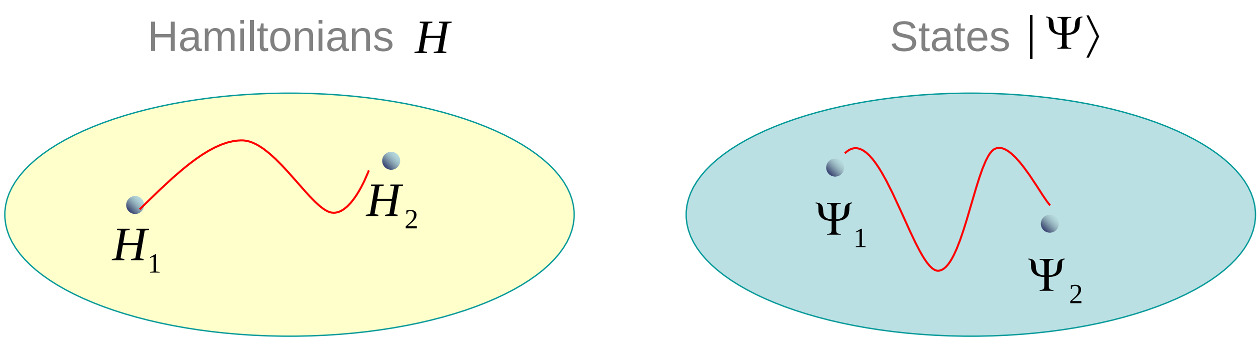
- Questions:
  - Ground state: $H|\Psi_0\rangle = E_0|\Psi_0\rangle$
  - Thermal state: $\rho \propto e^{-H/T}$
  - Dynamics: $|\Psi(t)\rangle = e^{-iHt}|\Psi(0)\rangle$
  - Physical properties: $\langle\sigma_n\rangle, \langle\sigma_n\sigma_m\rangle, \ldots$

QUANTUM SIMULATORS
ANALOG

How does it work?



- Dynamics:
- Ground state:



COLD ATOMS IN OPTICAL LATTICES

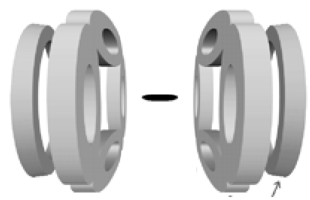
COLD ATOMS

- **Control:** External fields

Trapping:

lasers

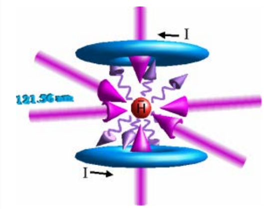
Magnetic fields



Cooling:

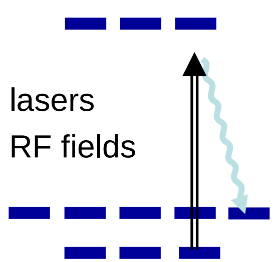
lasers

evaporation



Internal manipulation

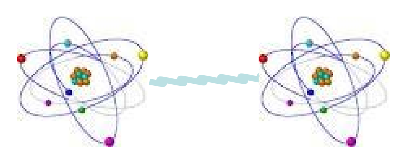
lasers
RF fields



purification
coherence
detection

Interactions

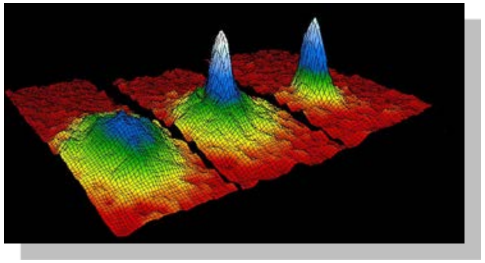
tune scattering length

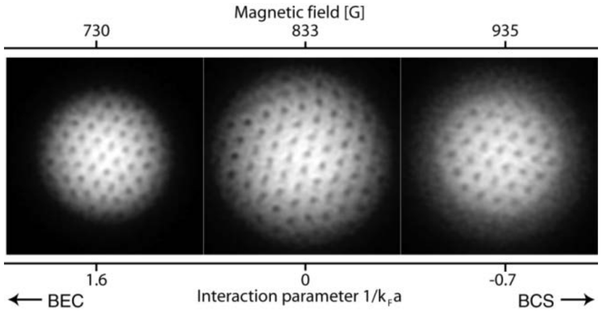


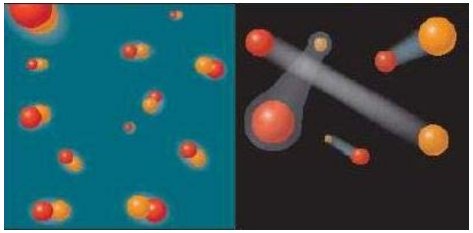
COLD ATOMS
ACHIEVEMENTS

- Many-body phenomena
  - Degeneracy: bosons and fermions (BE/FD statistics)
  - Coherence: interference, atom lasers, four-wave mixing, …
  - Superfluidity: vortices
  - Disorder: Anderson localization
  - Fermions: BCS-BEC

+ many other phenomena







COLD ATOMS

- Cold atoms are described by simple quantum field theories:

$$H = \int \Psi^\dagger_\sigma \left(-\nabla^2 + V(r)\right)\Psi_\sigma + u_{\sigma_i} \int \Psi^\dagger_{\sigma_1}\Psi^\dagger_{\sigma_2}\Psi_{\sigma_3}\Psi_{\sigma_4}$$

  - We can have bosons or fermions (or both).
  - We can have different internal states (spin).
  - The external potential, V, and interaction coefficients, u, can be engineered using lasers, and electric and magnetic fields.
  - In certain limits, one obtains effective theories that are interesting in other fields of Physics.

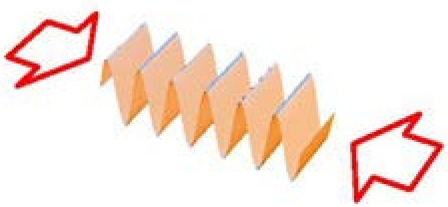
Quantum Simulations

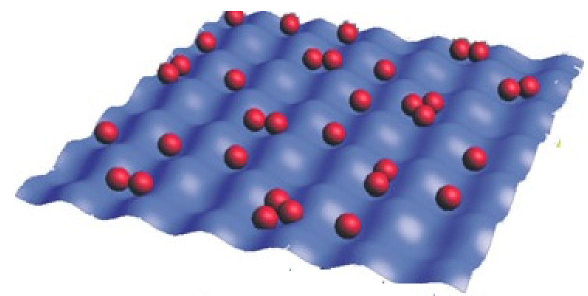
- Laser standing waves: dipole-trapping

VOLUME 81, NUMBER 15 PHYSICAL REVIEW LETTERS 12 OCTOBER 1998

Cold Bosonic Atoms in Optical Lattices

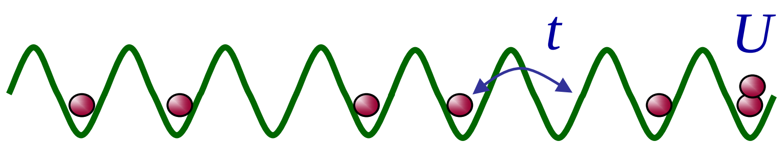
D. Jaksch,[1,2] C. Bruder,[1,3] J. I. Cirac,[1,2] C. W. Gardiner,[1,4] and P. Zoller[1,2]





- Laser standing waves: dipole-trapping

$$H = \int \Psi_{\sigma}^{\dagger} \left(-\nabla^2 + V(r) \right) \Psi_{\sigma} + u_{\sigma_i} \int \Psi_{\sigma_1}^{\dagger} \Psi_{\sigma_2}^{\dagger} \Psi_{\sigma_3} \Psi_{\sigma_4}$$

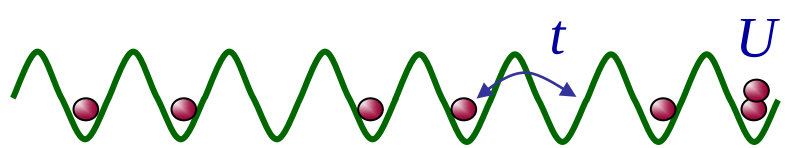


Lattice theory: Bose/Fermi-Hubbard model

$$H = -t \sum_{n} \left(a_n^{\dagger} a_{n+1} + h.c \right) + U \sum_{n} a_n^{\dagger 2} a_n^2$$

- Laser standing waves: dipole-trapping

$$H = \int \Psi_\sigma^\dagger \left(-\nabla^2 + V(r)\right)\Psi_\sigma + u_{\sigma_i} \int \Psi_{\sigma_1}^\dagger \Psi_{\sigma_2}^\dagger \Psi_{\sigma_3} \Psi_{\sigma_4}$$



Lattice theory: Bose/Fermi-Hubbard model

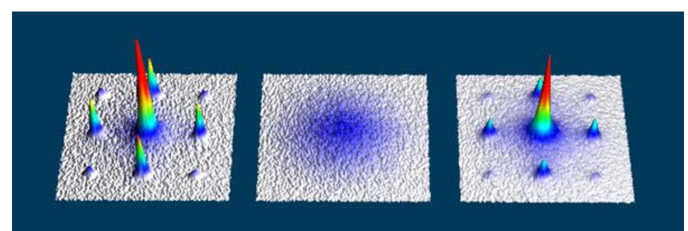
$$H = -t\sum_n \left(a_n^\dagger a_{n+1} + h.c\right) + U\sum_n a_n^{\dagger 2} a_n^2$$

articles

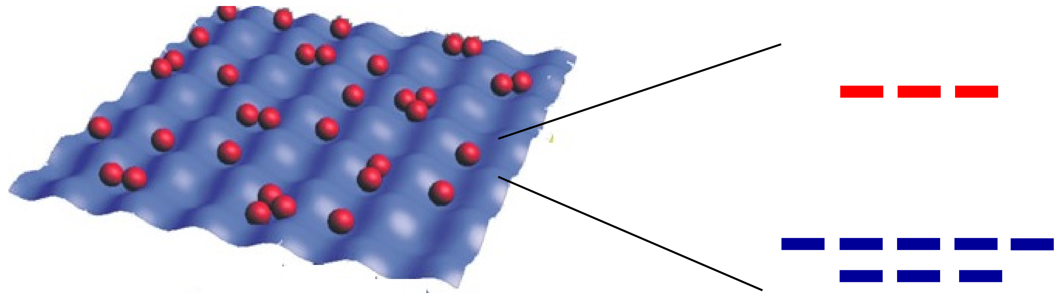
Quantum phase transition from a superfluid to a Mott insulator in a gas of ultracold atoms

Markus Greiner*, Olaf Mandel*, Tilman Esslinger†, Theodor W. Hänsch* & Immanuel Bloch*

* Sektion Physik, Ludwig-Maximilians-Universität, Schellingstrasse 4/III, D-80799 Munich, Germany, and Max-Planck-Institut für Quantenoptik, D-85748 Garching, Germany
† Quantenelektronik, ETH Zürich, 8093 Zurich, Switzerland



COLD ATOMS
QUANTUM SIMULATION



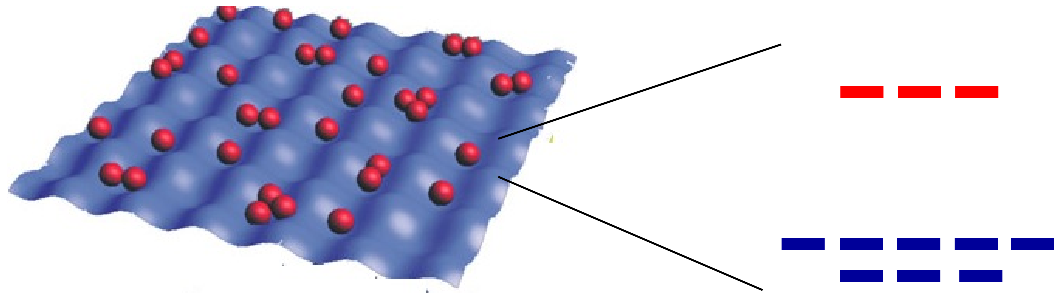
- Bosons/Fermions: $$H = -\sum_{\substack{<n,m> \\ \sigma,\sigma'}} \left(t_{\sigma,\sigma'} a^{\dagger}_{n,\sigma} a_{m,\sigma'} + h.c \right) + \sum_{\substack{n \\ \sigma,\sigma'}} U_{\sigma,\sigma'} a^{\dagger}_{n,\sigma} a^{\dagger}_{n,\sigma'} a_{n,\sigma'} a_{n,\sigma}$$

- Spins: $$H = -\sum_{\substack{<n,m> \\ \sigma,\sigma'}} \left(J_x S^x_n S^x_m + J_y S^y_n S^y_m + J_z S^z_n S^z_m \right) + \sum_{\substack{n \\ \sigma,\sigma'}} B_n S^z_n$$

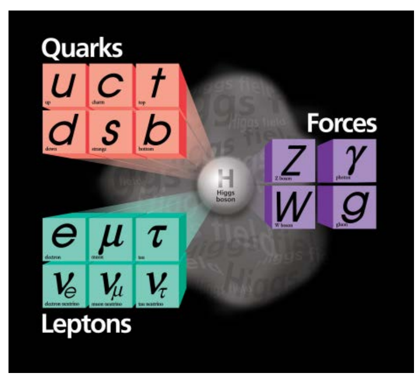
CONDENSED MATTER PHYSICS

COLD ATOMS

QUANTUM SIMULATION



HIGH ENERGY PHYSICS?



QUANTUM SIMULATIONS OF HEP MODELS

QUANTUM SIMULATION HEP MODELS

INGREDIENTS

$$S=\int \overline{\Psi}(i\gamma^{\mu}\partial_{\mu}-m)\Psi - Q\int A_{\mu}\overline{\Psi}\gamma^{\mu}\Psi - \frac{1}{4}\int F_{\mu\nu}F^{\mu\nu} + \ldots\ldots$$

- Matter + Gauge Fields
- Relativistic theory
- Gauge invariant
- Hamitonian formulation: $i\partial_t |\Psi\rangle = H|\Psi\rangle$
    - Gauss law $G(x)|\Psi\rangle = 0$

$$[H, G(x)] = 0$$

QUANTUM SIMULATION HEP MODELS
INGREDIENTS

- Problem:

$$H = \int \Psi_{\sigma}^{\dagger}\left(-\nabla^{2} + V(r)\right)\Psi_{\sigma} + u\int \Phi_{\mu}^{\dagger}\Phi_{\sigma'}\Psi_{\sigma}^{\dagger}\Psi_{\sigma'} + v\int \Phi_{\sigma}^{\dagger}\Phi_{\sigma'}^{\dagger}\Phi_{\sigma'}\Phi_{\sigma} + \ldots$$

choose *V(r)*, *u*, *v*, etc such that (in some limit), we have

$$i\partial_t |\Psi\rangle = H|\Psi\rangle \qquad [H, G(x)] = 0$$

$$G(x)|\Psi\rangle = 0$$

corresponding to

$$S = \int \overline{\Psi}(i\gamma^{\mu}\partial_{\mu} - m)\Psi - Q\int A_{\mu}\overline{\Psi}\gamma^{\mu}\Psi - \frac{1}{4}\int F_{\mu\nu}F^{\mu\nu} + \ldots\ldots$$

QUANTUM SIMULATION HEP MODELS
INGREDIENTS

- Matter + Gauge Fields

$$S=\int \overline{\Psi}(i\gamma^{\mu}\partial_{\mu}-m)\Psi-Q\int A_{\mu}\overline{\Psi}\gamma^{\mu}\Psi-\frac{1}{4}\int F_{\mu\nu}F^{\mu\nu}+......$$

➡ We need bosonic and fermionic atoms

We need interactions among themselves

$$H=\int \Psi_{\sigma}^{\dagger}\left(-\nabla^{2}+V(r)\right)\Psi_{\sigma}+u\int \Phi_{\mu}^{\dagger}\Phi_{\sigma'}\Psi_{\sigma}^{\dagger}\Psi_{\sigma'}+v\int \Phi_{\sigma}^{\dagger}\Phi_{\sigma'}^{\dagger}\Phi_{\sigma'}\Phi_{\sigma}+...$$

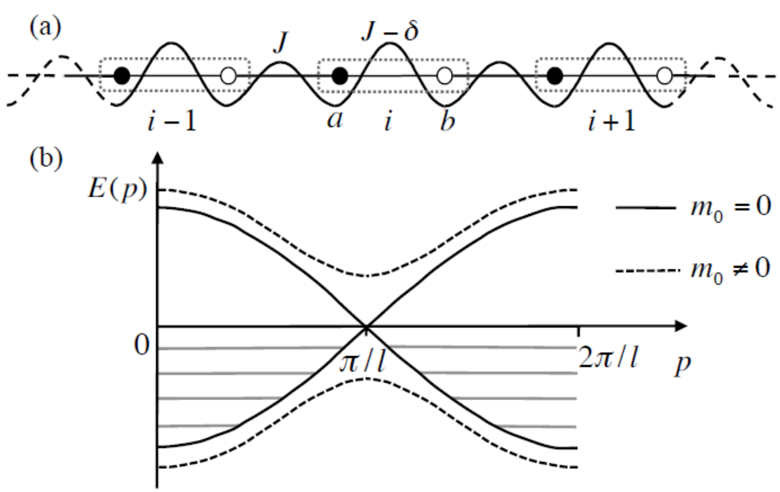
INGREDIENTS

- Relativistic

$$S = \int \overline{\Psi}(i\gamma^{\mu}\partial_{\mu} - m)\Psi - Q\int A_{\mu}\overline{\Psi}\gamma^{\mu}\Psi - \frac{1}{4}\int F_{\mu\nu}F^{\mu\nu} + \ldots\ldots$$

$$H = \int \Psi_{\sigma}^{\dagger}\left(-\nabla^{2} + V(r)\right)\Psi_{\sigma} + u\int \Phi_{\mu}^{\dagger}\Phi_{\sigma'}\Psi_{\sigma}^{\dagger}\Psi_{\sigma'} + v\int \Phi_{\sigma}^{\dagger}\Phi_{\sigma'}^{\dagger}\Phi_{\sigma'}\Phi_{\sigma} + \ldots$$

➡ Use a superlattice: it possesses the right limit in the continuum



(staggered fermions)

QUANTUM SIMULATION HEP MODELS
INGREDIENTS

$$H = \int \Psi_\sigma^\dagger \left(-\nabla^2 + V(r)\right)\Psi_\sigma + u\int \Phi_\mu^\dagger \Phi_{\sigma'} \Psi_\sigma^\dagger \Psi_{\sigma'} + v\int \Phi_\sigma^\dagger \Phi_{\sigma'}^\dagger \Phi_{\sigma'} \Phi_\sigma + \ldots$$

Lattice

Fermion-gauge field coupling

Gauge field dynamics

- Matter + Gauge Fields → Bosonic and Fermionic atoms, Low energy sector
- Relativistic theory → Lattices
- Hamitonian formulation:
  - Gauge invariance: abelian, non-abelian → Angular momentum
  - Gauss law → Interactions / Initial conditions

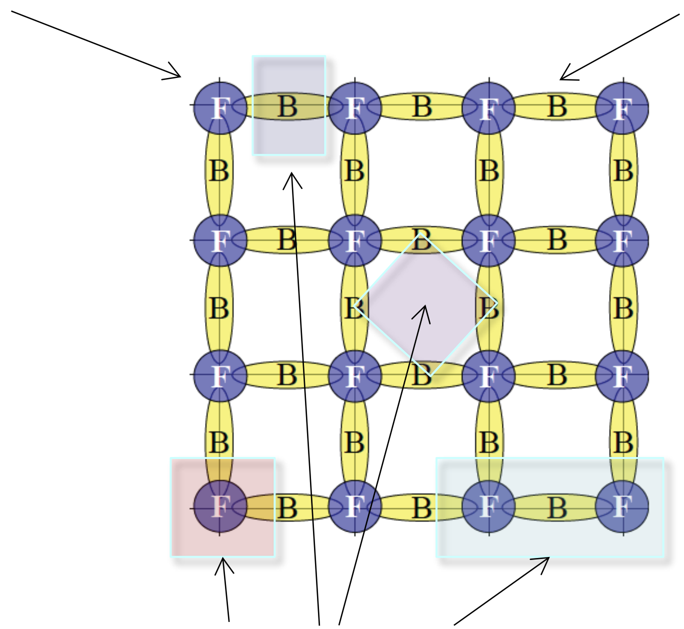
+ perturbation theory

J. Kogut and L. Susskind, Phys. Rev. D 11, 395 (1975).
J. B. Kogut, Rev. Mod. Phys. 51, 659 (1979).
J. B. Kogut, Rev. Mod. Phys. 55, 775 (1983).

HAMILTONIAN FORMULATION

Matter (Fermions): can move

Gauge fields (Bosons): Static

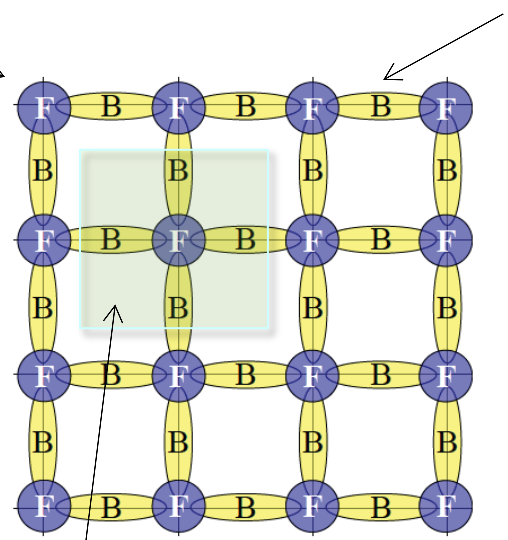


- Hamiltonian: $H = H_M + H_{KS} + H_{\text{int}}$

HEP LATTICE MODELS
HAMILTONIAN FORMULATION

Matter (Fermions): can move

Gauge fields (Bosons): Static

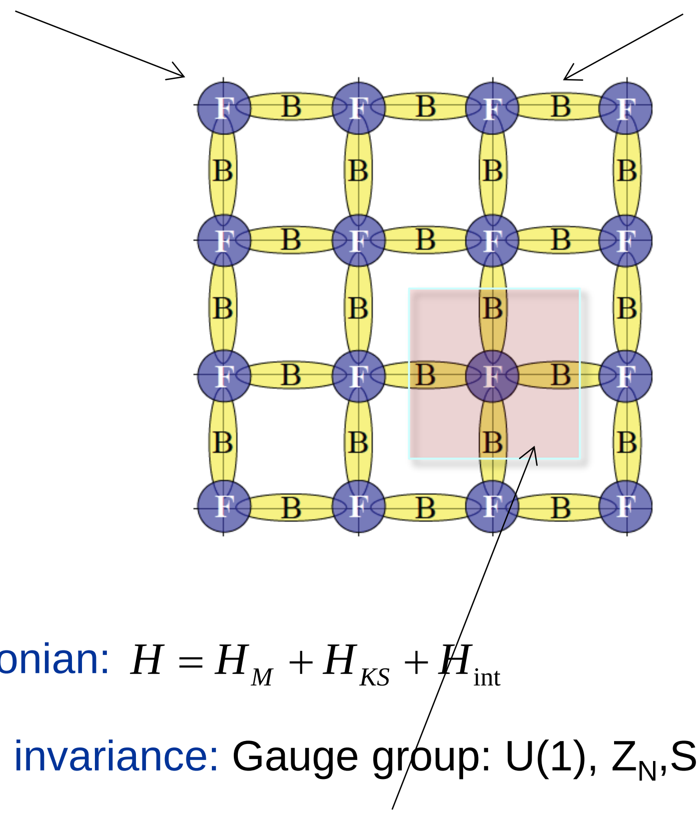


- Hamiltonian: $H = H_M + H_{KS} + H_{\text{int}}$
- Gauge invariance: Gauge group: U(1), Z_N,SU(N), etc

HAMILTONIAN FORMULATION

Matter (Fermions): can move

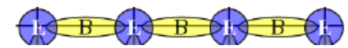
Gauge fields (Bosons): Static



- Hamiltonian: $H = H_M + H_{KS} + H_{\text{int}}$
- Gauge invariance: Gauge group: U(1), Z_N,SU(N), etc
- Gauss law: $G_{plaquette} \,|\, phys\rangle = 0$

HEP LATTICE MODELS
HAMILTONIAN FORMULATION

- Example: compact-QED in 1D



- Hamiltonians:

$$H_M = \sum_{\mathbf{n}} M_{\mathbf{n}} \psi^\dagger_{\mathbf{n}} \psi_{\mathbf{n}}$$

$$H_{int} = \epsilon \sum_{\mathbf{n},k} \left(\psi^\dagger_{\mathbf{n}} e^{i\phi_{\mathbf{n},k}} \psi_{\mathbf{n}+\hat{\mathbf{k}}} + \psi^\dagger_{\mathbf{n}+\hat{\mathbf{k}}} e^{-i\phi_{\mathbf{n},k}} \psi_{\mathbf{n}} \right)$$

$$H_{KS} = H_E = \frac{g^2}{2} \sum_{n,k} E_n^2$$

$$[E_{\mathbf{n},k}, \phi_{\mathbf{m},l}] = -i\delta_{\mathbf{nm}}\delta_{kl}$$ (ie, compact)

- Gauss law: $G_n \,|\, phys\rangle = 0$

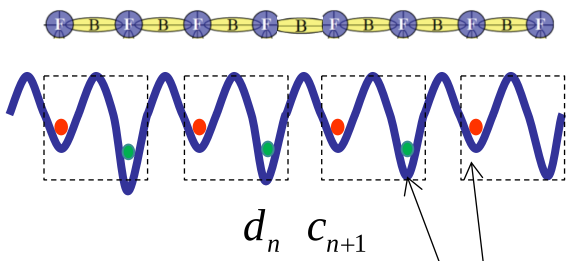
$$G_n = E_{n+1} - E_n - \psi_n^\dagger \psi_n$$

- Gauge invariance: $e^{-i\theta G_n} H e^{i\theta G_n} = H$

SCHWINGER MODEL

QUANTUM SIMULATION
SCHWINGER MODEL 1+1

- Fermions:



internal states

$$\{c_n, c_n^\dagger\} = \{d_n, d_n^\dagger\} = 1$$

$$H_M = M \sum_n (-1)^n \psi_n^\dagger \psi_n$$

$$H = \int \Psi_\sigma^\dagger \left(-\nabla^2 + V(r)\right) \Psi_\sigma + u \int \Phi_\mu^\dagger \Phi_{\sigma'} \Psi_\sigma^\dagger \Psi_{\sigma'} + v \int \Phi_\sigma^\dagger \Phi_{\sigma'}^\dagger \Phi_{\sigma'} \Phi_\sigma + \dots$$

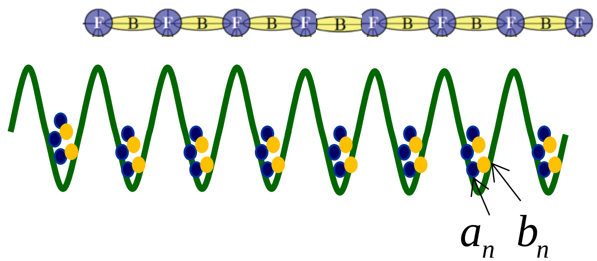
- Even sites: hole = particle
- Odd sites: fermion = antiparticle

Staggered Fermions:

L. Susskind, Phys. Rev. D **16**, 3031 (1977).
G. 't Hooft, Nucl. Phys. B **75**, 461 (1974)

QUANTUM SIMULATION
SCHWINGER MODEL 1+1

- Bosons:



internal states

$$[a_n, a_n^\dagger] = [b_n, b_n^\dagger] = 1$$

- Schwinger rep:

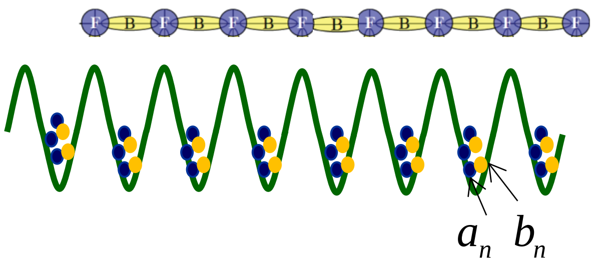
$$L_+ = a^\dagger b$$
$$L_z = \frac{1}{2}(N_a - N_b)$$
$$\ell = \frac{1}{2}(N_a + N_b)$$

$\ell >> 1$ ⇒

$$L_+ \approx \ell e^{i\phi}$$
$$L_z \approx i\partial_\phi$$

- If ℓ is small (eg 2 atoms), we obtain a truncated version
- One can also use a single atom with few internal levels (Z_M is the gauge group)

- Bosons:



internal states

$$[a_n, a_n^\dagger] = [b_n, b_n^\dagger] = 1$$

Schwinger rep:

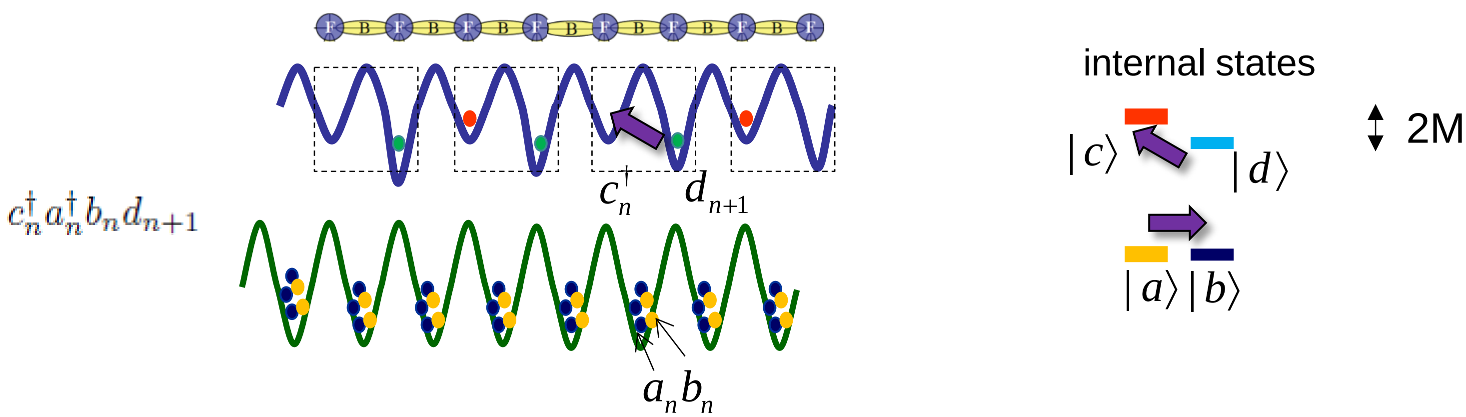
$$L_+ = a^\dagger b$$
$$L_z = \frac{1}{2}(N_a - N_b)$$
$$\ell = \frac{1}{2}(N_a + N_b)$$

$$H_E = \frac{g^2}{2}\sum_n L_{z,n}^2$$
$$= \frac{g^2}{8}\sum_n \left(N_{a,n}^2 + N_{b,n}^2 - 2N_{a,n}N_{b,n}\right)$$

$$H = \int \Psi_\sigma^\dagger \left(-\nabla^2 + V(r)\right)\Psi_\sigma + u\int \Phi_\mu^\dagger \Phi_{\sigma'} \Psi_\sigma^\dagger \Psi_{\sigma'} + v\int \Phi_\sigma^\dagger \Phi_{\sigma'}^\dagger \Phi_{\sigma'} \Phi_\sigma + \dots$$

QUANTUM SIMULATION
SCHWINGER MODEL 1+1

- Interactions:



$$H = \int \Psi_\sigma^\dagger \left(-\nabla^2 + V(r)\right)\Psi_\sigma + u\int \Phi_\mu^\dagger \Phi_{\sigma'} \Psi_\sigma^\dagger \Psi_{\sigma'} + v\int \Phi_\sigma^\dagger \Phi_{\sigma'}^\dagger \Phi_{\sigma'} \Phi_\sigma + \ldots$$

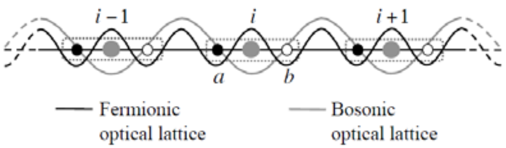
conserves angular momentum locally

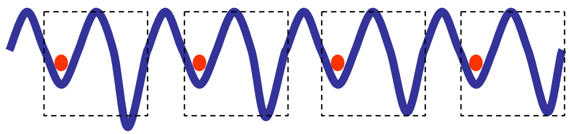
→ Gauge invariance

$$H_{int} \quad \frac{1}{\sqrt{\ell(\ell+1)}} \psi_n^\dagger a_n^\dagger b_n \psi_{n+1} \approx \psi_n^\dagger e^{i\phi_n} \psi_{n+1}$$

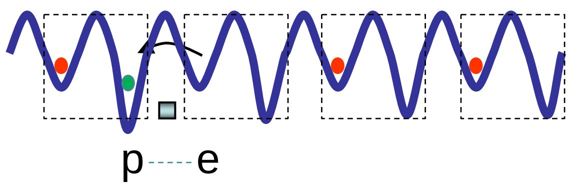
QUANTUM SIMULATION
SCHWINGER MODEL 1+1

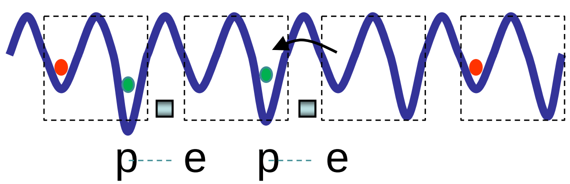
- Physical processes:

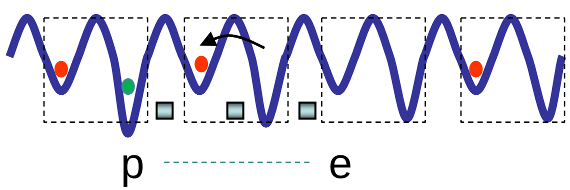


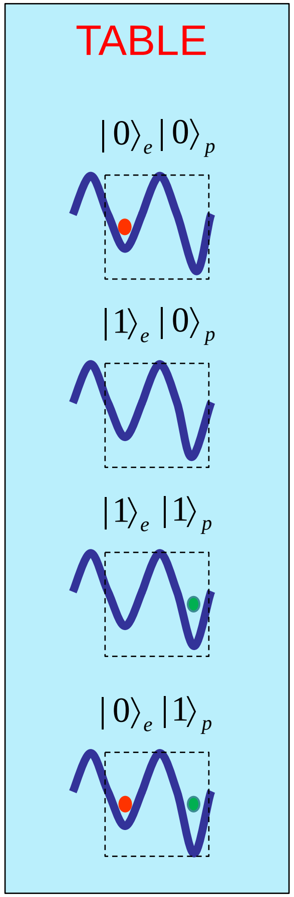


non-interacting vacuum



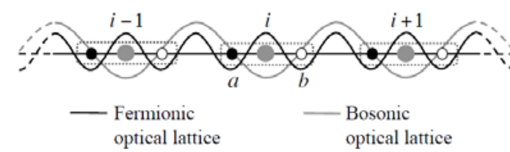


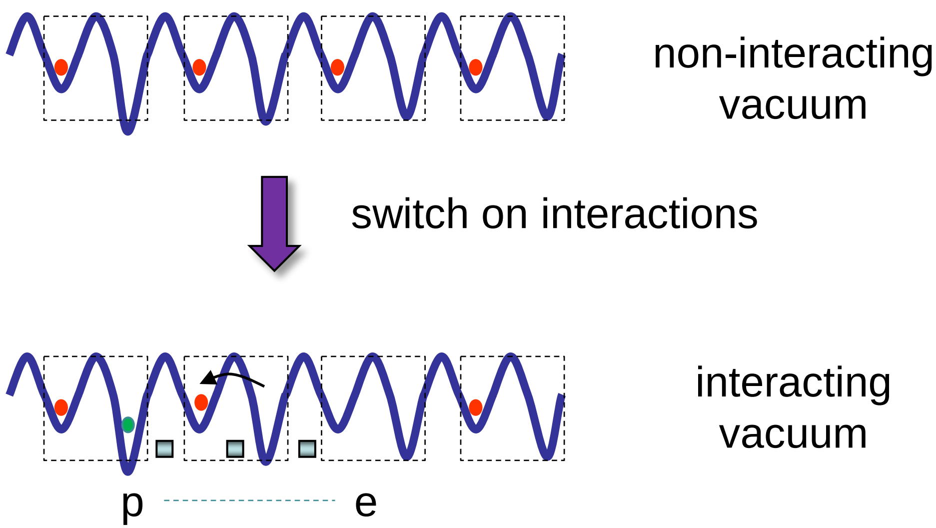


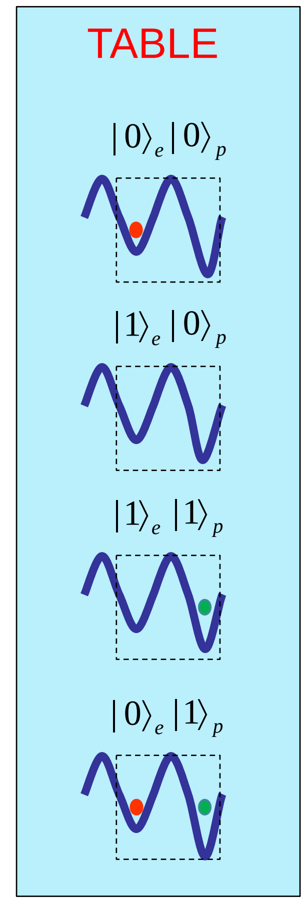


QUANTUM SIMULATION
SCHWINGER MODEL 1+1

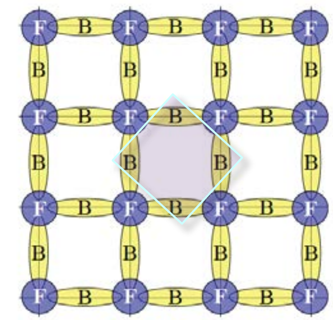
- Preparation:





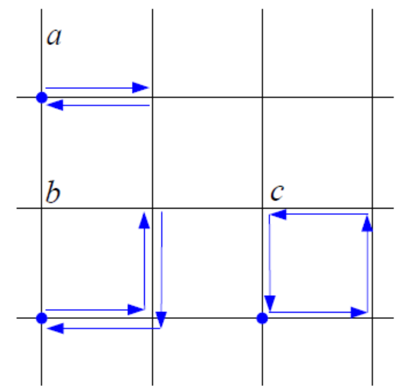


- Confinement
- Excitations: vector + scalar
- Time-dependent phenomena
- First experiments: few bosonic atoms



- Plaquette interactions:

$$H_B = -\frac{2\epsilon^4}{\lambda^3}\sum_{\mathbf{n}}\left(U_{\mathbf{n},1}U_{\mathbf{n}+\hat{1},2}U^\dagger_{\mathbf{n}+\hat{2},1}U^\dagger_{\mathbf{n},2} + h.c.\right) =$$
$$-\frac{4\epsilon^4}{\lambda^3}\sum_{\mathbf{n}}\cos\left(\phi_{\mathbf{n},1}+\phi_{\mathbf{n}+\hat{1},2}-\phi_{\mathbf{n}+\hat{2},1}-\phi_{\mathbf{n},2}\right)$$

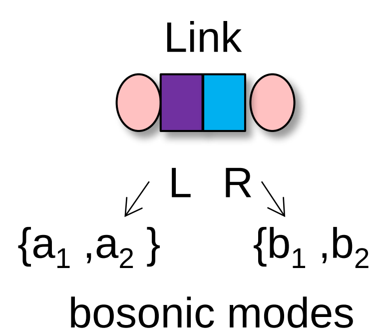


- Non-abelian gauge theories:

$$H_E = \frac{g^2}{2}\sum_{\mathbf{n},k,a}\left(E_{\mathbf{n},k}\right)_a\left(E_{\mathbf{n},k}\right)_a$$

$$H_B = -\frac{1}{g^2}\sum_{\text{plaquettes}}\left(\mathrm{Tr}\left(U_1U_2U_3^\dagger U_4^\dagger\right) + h.c.\right)$$

$$H_{int} = \epsilon\sum_{\mathbf{n},k}\left(\psi^\dagger_{\mathbf{n}}U^r_{\mathbf{n},k}\psi_{\mathbf{n}+\hat{\mathbf{k}}} + h.c.\right)$$



COLD ATOMS
EXPERIMENTAL CONSIDERATIONS

- Cold bosons in optical lattices
  - Mott insulator – superfluid transition
  - Exchange interaction (2nd order perturbation theory)
  - Dynamics
  - Anderson-Higgs mechanism in 2D
- Cold fermions in optical lattices
  - Mott insulator in 2D
- Cold fermions and bosons in optical lattices
  - Mean-field dynamics
- Techniques
  - Tuning of interactions: Magnetic/optical Feschbach resonances
  - Lattice geometry
  - Time of flight measurements
  - Single-site addressing: initializaton
  - Single-site measurement
- Challanges: temperature, decoherence, control …

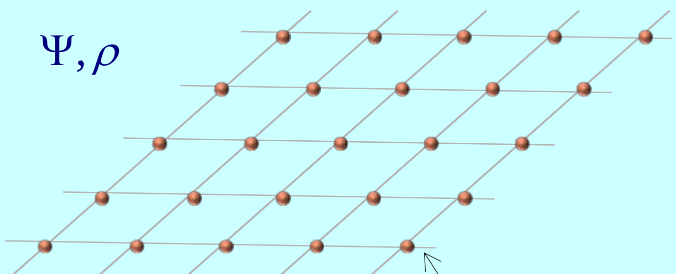

WARNING

NEW METHODS: TENSOR NETWORKS

QUANTUM STATES

MANY-BODY QUANTUM SYSTEM

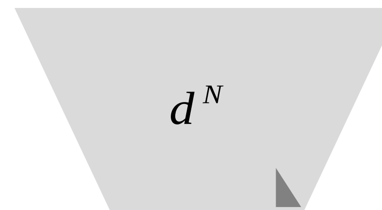
Ψ, ρ



N Spins (fermions)

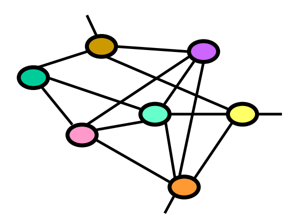
Hilbert space

$$|\Psi\rangle = \sum c^{i_1, i_2, \ldots, i_N} \, | i_1, i_2, \ldots, i_N \rangle$$



Tensor networks

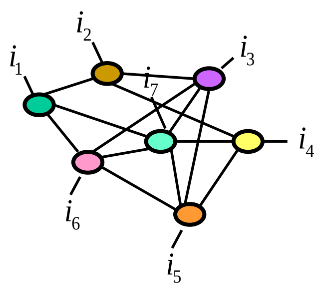
Ψ, ρ



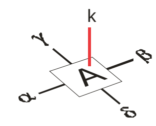
TENSORS NETWORKS
EFFICIENT DESCRIPTIONS

TENSOR NETWORK STATES:

Ψ, ρ

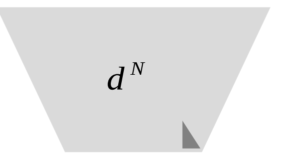


N tensors:



parameters: NdD^z

compare



- Provide a local description
- Represent a wide range of physical behavior
- Classification of (gapped) phases (in 1D)
- Bulk-boundary correspondence
- Algorithms

TENSORS NETWORKS
APPLICATIONS

1+1 dimensions:

- Schwinger models
- Non-abelian models

- T=0, finite temperature
- Dynamics

Collaboration: M. Banuls, S. Kühn (MPQ)
K. Jansen, H. Saito (Desy)
K. Cichy (Frankfurt)

2+1 dimensions:

- (non-relativistic) abelian
- (non-relativistic) non-abelian models

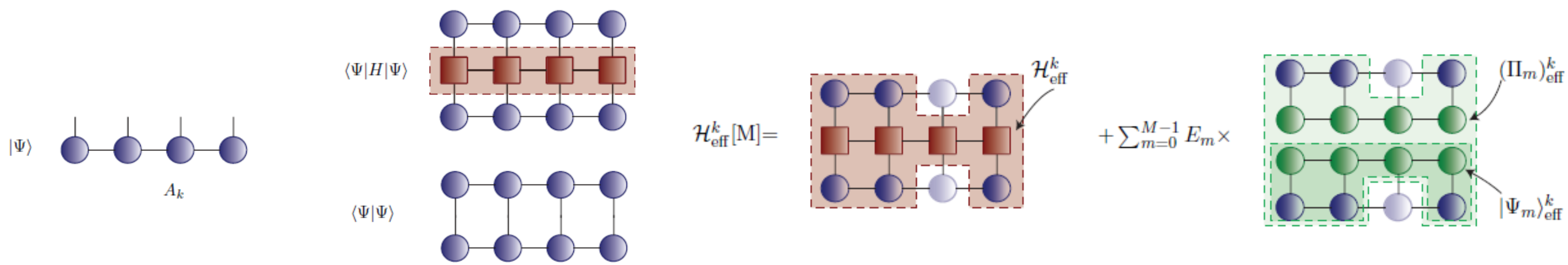
- T=0

Collaboration: E. Zohar, M. Burrello (MPQ)
T. Wahl (Cambridge)
J. Haegeman, F. Verstraete (Ghent)

NUMERICAL METHODS

SCHWINGER MODEL 1+1

- Method: Tensor networks



- Results

	Scalar binding energy		
m/g	MPS with OBC	SCE result [35]	exact
0	1.1283(10)	1.11(3)	1.12838
0.125	1.221(2)	1.22(2)	-
0.25	1.239(6)	1.24(3)	-
0.5	1.213(5)	1.20(3)	-

- Truncation + adiabatic evolution

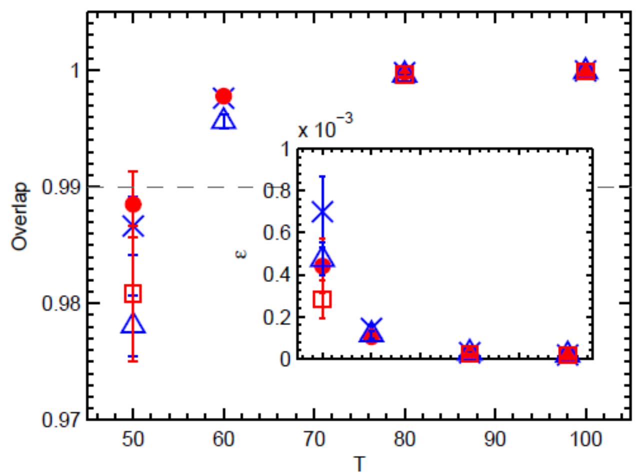


FIG. 3. Truncated cQED model with $D = 50$. Final overlap with the exact ground state at the end of the adiabatic preparation as a function of the total evolution time. The (blue) X's represent the data for $N = 50$, $d = 3$; (blue) triangles for $N = 100$, $d = 3$; (red) circles, for $N = 50$, $d = 9$; and (red) squares for $N = 100$, $d = 9$. Error bars were obtained from the difference in results with bond dimension $D = 50$ vs $D = 30$. Inset: Relative error of the energy with respect to the exact ground state.

- Broken gauge invariance:

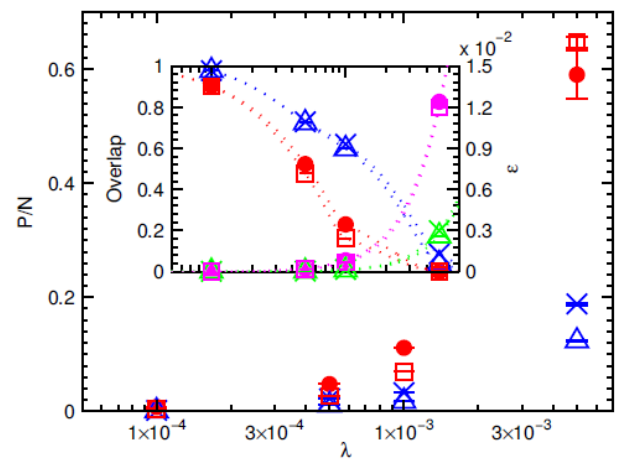
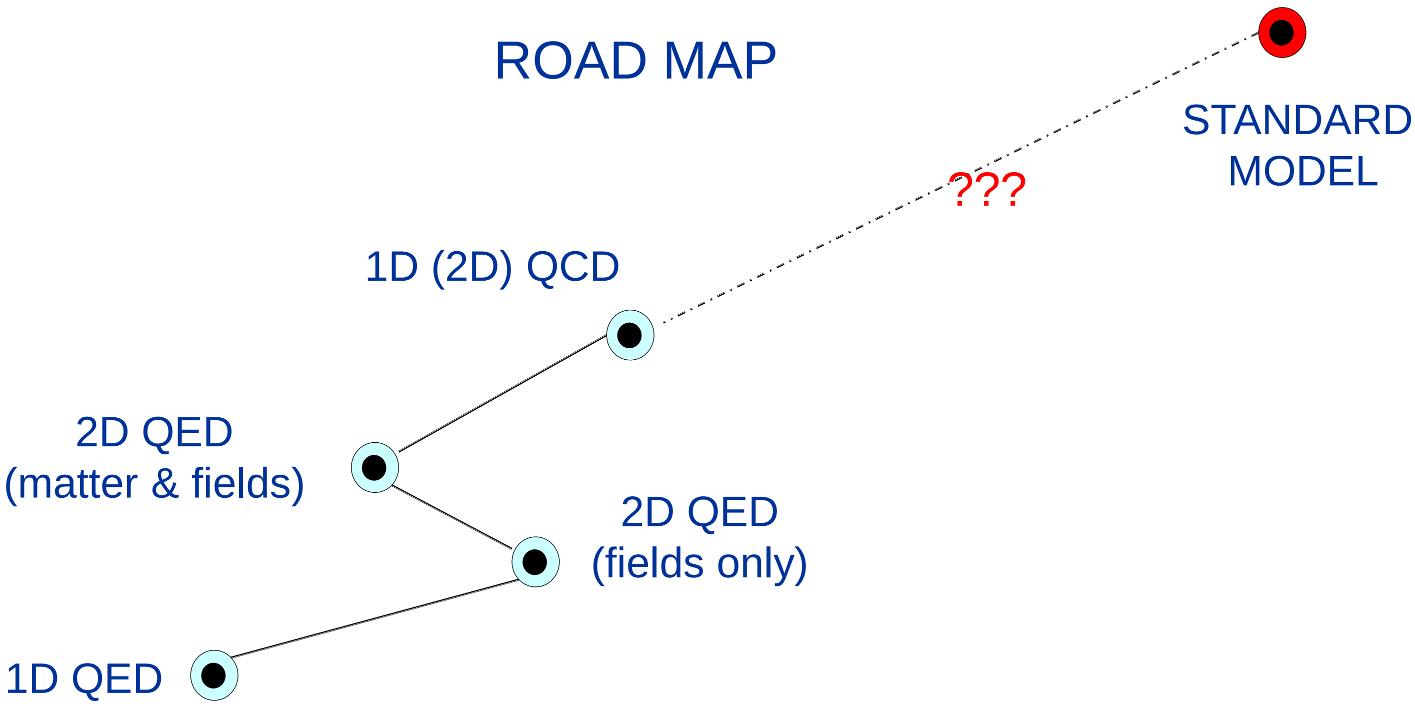


FIG. 5. Truncated cQED model. Penalty energy per site at the end of the noisy adiabatic preparation as a function of the noise strength. The [blue (green)] X's represent the values for $N = 50$, $d = 3$; the [blue (green)] triangles, the $N = 100$, $d = 3$ case; the [red (magenta)] circles, the $N = 50$, $d = 5$ case; and the [red (magenta)] squares, the $N = 100$, $d = 5$ case. Error bars were computed the same way as in the noiseless case. Inset: Overlap (blue and red symbols) and relative error in energy (green and magenta symbols) with respect to the noise-free exact ground state. As a guide for the eye, data points are connected.

QUANTUM SIMULATION
HIGH ENERGY MODELS

ROAD MAP



IC, Maraner, Pachos, PRL **105**, 19403 (2010)
Zohar, IC, Reznik, PRL **107**, 275301 (2011)
Zohar, IC, Reznik, PRL 1**09**, 125302 (2012)
Zohar, IC, Reznik, PRL **110**, 125304 (2013)
Zohar, IC, Reznik, PRA **88**, 023617 (2013)
Banuls, Cichy, IC, Jansen, JHEP **11**,158 (2013)
Saito, Banuls, Cichy, IC, Jasnen
Kühn, IC, Banuls, PRA **90**, 042305 (2014)
Banuls, Cichy, IC, Jansen, Saito, arXiv:1505:00279
Kühn, Zohar, IC, Banuls, arXiv:1505.04441

See also:

Kapit,Mueller, PRA**83**, 033625 (2011)
Banerjee,…, Wiese, Zoller, PRL**109**, 175302 (2013)
Banerjee,…, Wiese, Zoller, PRL**110**, 125303 (2013)
Gauge fields: Lewenstein et al