Classical and Quantum Simulation of Gauge Theories

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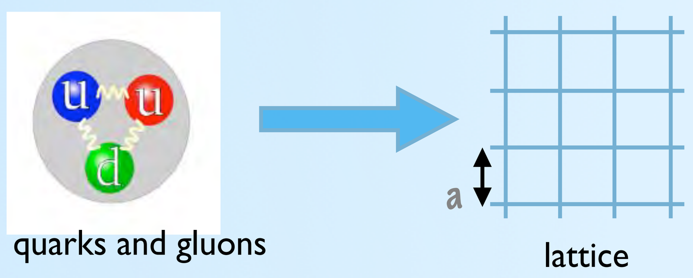
We show how to simulate models with ***gauge symmetry*** in the lattice using ***atomic and quantum optics*** tools and ***tensor network*** methods. The construction is based on ***quantum links*** that realize continuous gauge symmetry with discrete quantum variables. At low energies, quantum link models with staggered fermions emerge from a Hubbard-type model that can be quantum simulated. These systems share qualitative features with ***quantum chromodynamics***, including ***chiral symmetry breaking*** and restoration at non-zero temperature or baryon density. This allows us to investigate ***string breaking*** as well as the ***real-time evolution*** after a quench in gauge theories.

The study of ***Gauge*** theories is the study of ***Nature***.



Gauge symmetry as a fundamental principle

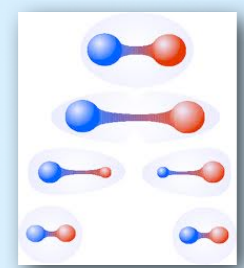
Standard model: For every force, there is a gauge boson

Gauge symmetry as an emergent phenomenon

Better understanding of spin-liquids and quantum magnetism

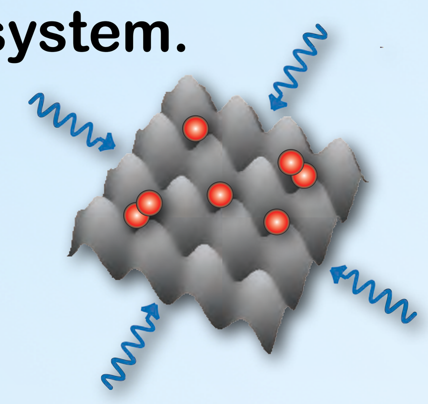
Gauge symmetry as a resource

Use the low-energy properties of these systems to implement any quantum information task.



String breaking

Feynman's universal quantum simulator: controlled quantum device which efficiently reproduces the dynamics of any other many-particle quantum system.



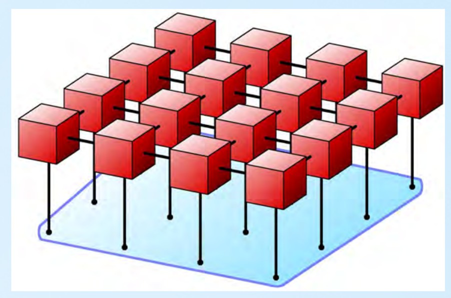
How?... cold atoms, ions, photons, superconducting circuit, etc.

Tensor network methods: variational ansatz for quantum many-body states describing the local degrees of freedom in real space

Direct access to entanglement

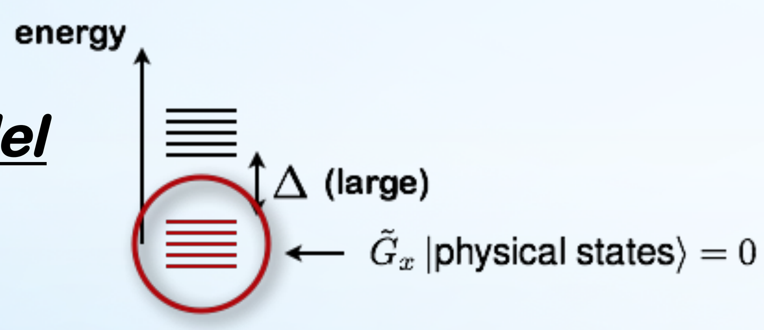
Dynamics of quantum many-body states in-and-out of equilibrium

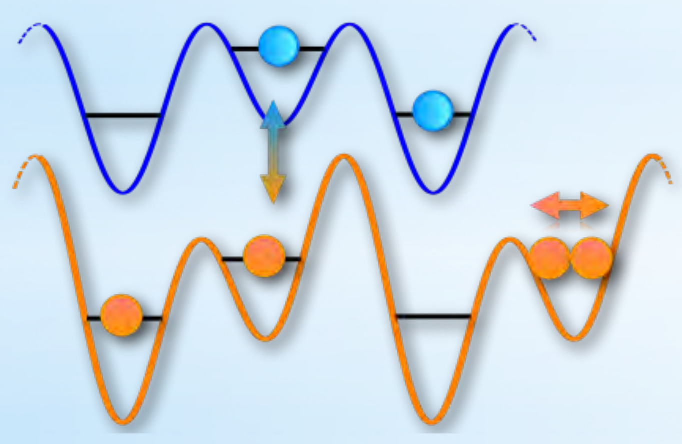
Control of global and local (gauge) symmetry



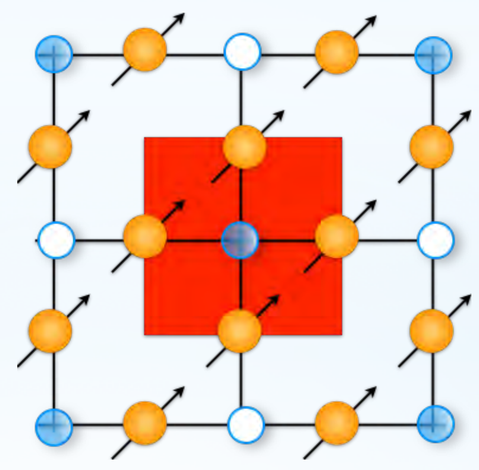
Bose + Fermi Hubbard model

$$H_{\text{microscopic}} = \Delta \sum_x G_x^2 + \cdots$$





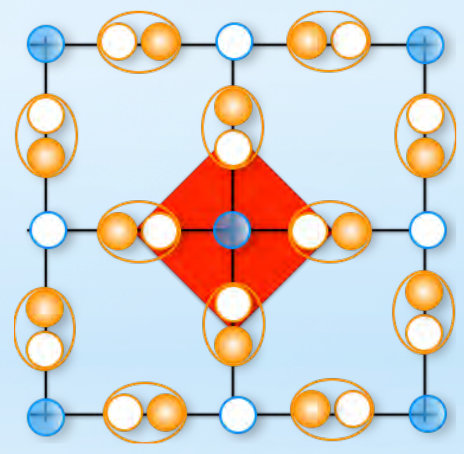
Quantum link models



$$G_{\text{vert}}|\text{phys}\rangle = 0$$

$$G_{\text{vert}}|s_{\text{vert}}\rangle = 0$$

$$|s_{\text{vert}}\rangle = \sum_{n_c, n_\psi} A^{(s_{\text{vert}})}_{n_c, n_\psi} |n_c, n_\psi\rangle$$



$$|\text{phys}\rangle = \sum_{s_1, \cdots, s_x, \cdots} a(s_1, \cdots, s_x, \cdots) \text{Tr}\left[A^{(s_1)} \cdots A^{(s_x)} \cdots\right] |s_1, \cdots, s_x, \cdot\rangle$$

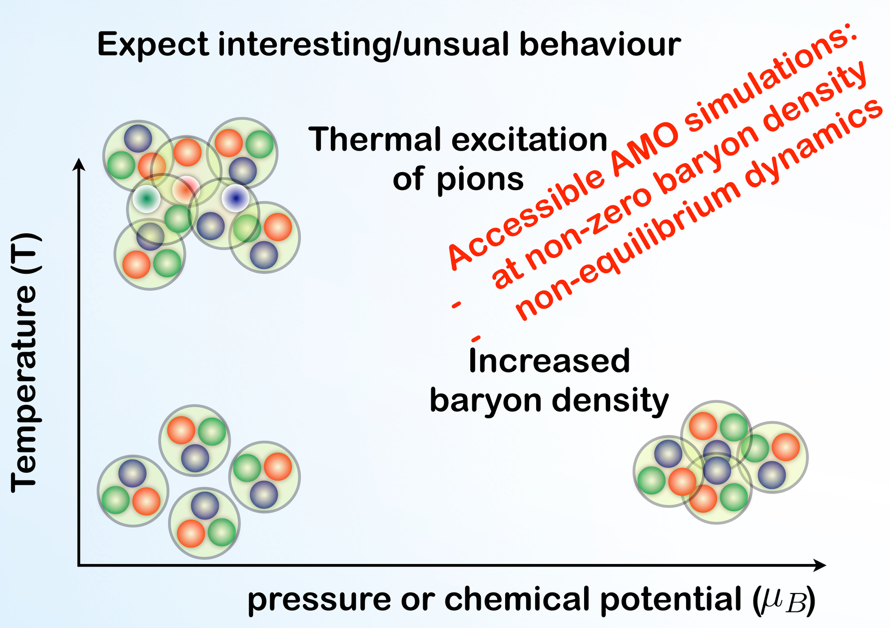
Emergent lattice gauge theory

$$H = \frac{g^2}{2}\sum_x E^2_{x,x+1} - t\sum_x \left[\psi_x^\dagger U_{x,x+1}\psi_{x+1} + \text{h.c.}\right] + m\sum_x (-1)^x \psi_x^\dagger \psi_x$$

QCD under extreme conditions

Compress or heat baryons → Hadrons overlap → Confinement is "lost"

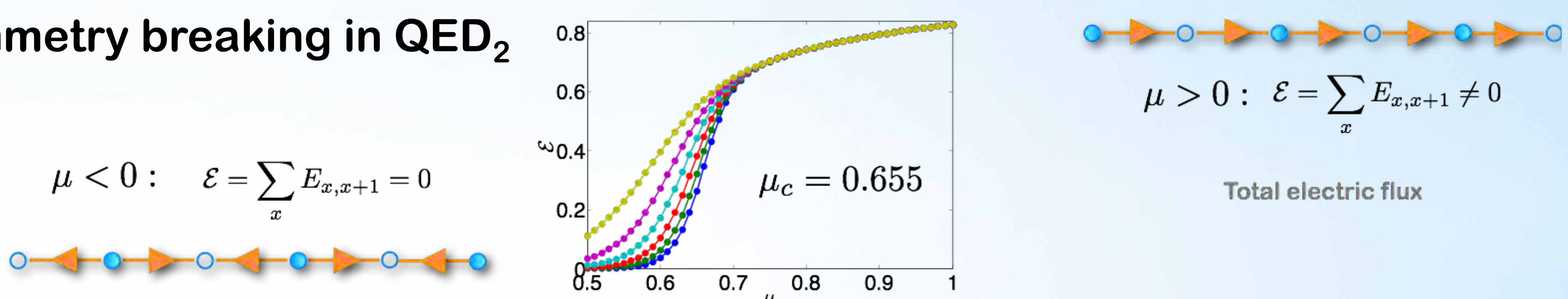
Expect interesting/unsual behaviour



Exact description of the gauge invariant subspace with tensor networks

$$H = \frac{g^2}{2}\sum_x (S^z{}_{x,x+1})^2 - t\sum_x \left[\psi_x^\dagger S^+_{x,x+1}\psi_{x+1} + \text{h.c.}\right] + m\sum_x (-1)^x \psi_x^\dagger \psi_x$$

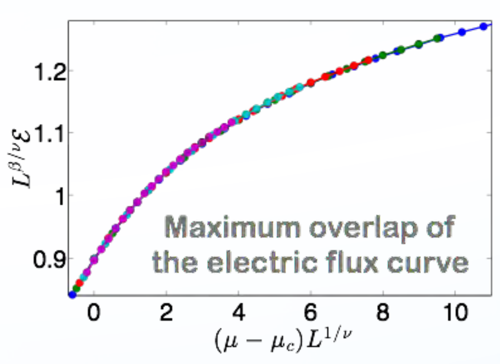
CP symmetry breaking in QED_2

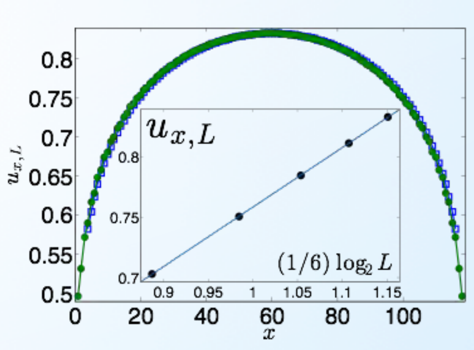


Second order phase transition: Parity and charge conjugation spontaneously broken (Ising universality class)

Critical exponents:

$$\beta = \frac{1}{8} \qquad \nu = 1$$

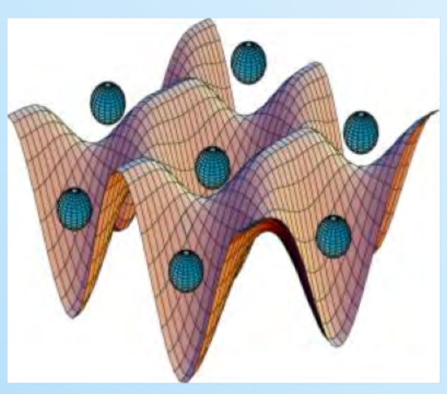




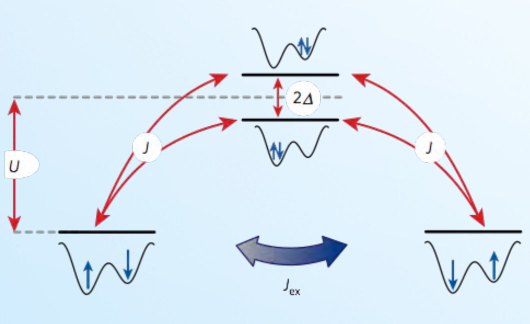
Central charge:

$$c = \frac{1}{2}$$

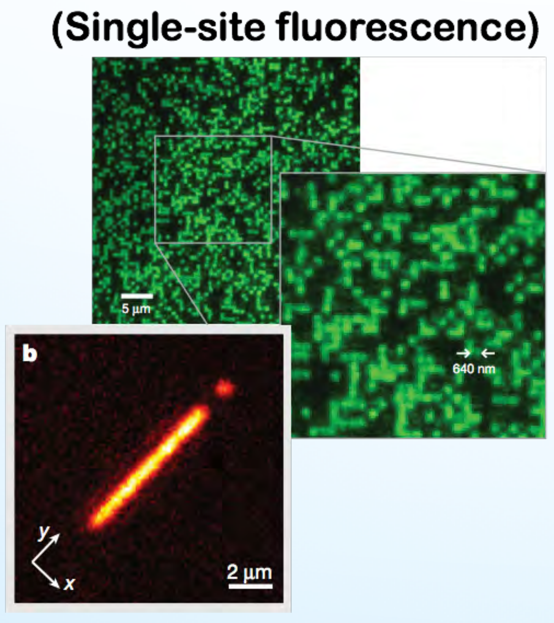
Preparation of many body states (Mott phase)



Evolution (Super-exchange)



Detection (Single-site fluorescence)



Atomic quantum simulation of dynamical gauge fields coupled to fermionic matter: from string breaking to evolution after a quench,
Phys. Rev. Lett. 109, 175302 (2012)

Atomic quantum simulation of U(N) and SU(N) non-abelian lattice gauge theories,
Phys. Rev. Lett. 110, 125303 (2013)

Superconducting circuits for quantum simulation of dynamical gauge fields,
Phys. Rev. Lett. 111, 110504 (2013)

Tensor networks for Lattice Gauge Theories and Atomic Quantum Simulation,
arXiv:1312.3127 (2013)

Related works at ICFO, Barcelona (M. Lewenstein's group) and MPQ, Munich (I. Cirac's group)

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