Quantum Simulations of Lattice Gauge Theories

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"easy"

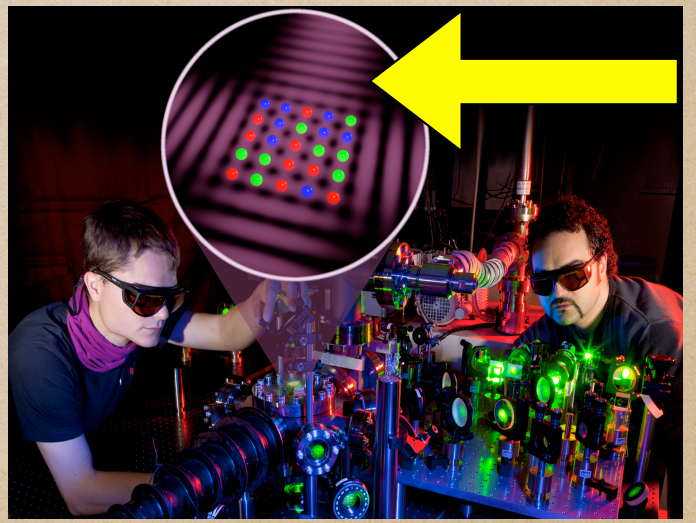
Ψ

"difficult"

classical computer

Ψ

"easy"



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quantum computer

Feynman

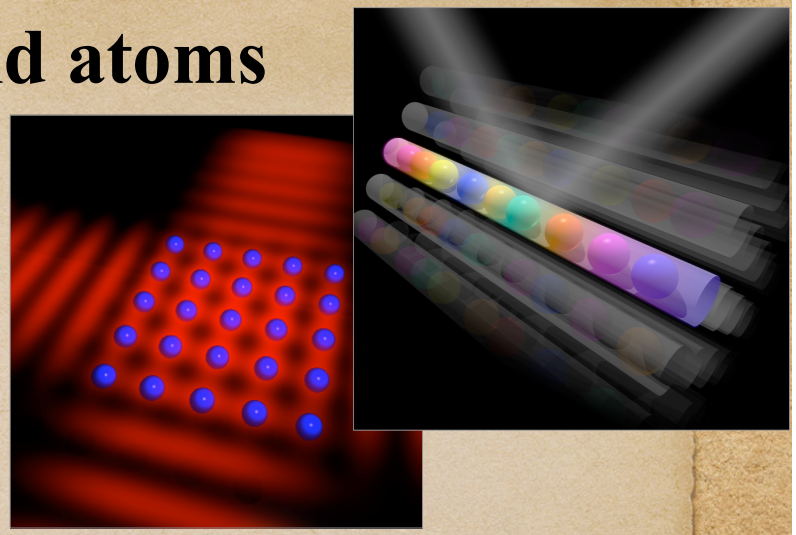
"...trying to find a computer simulation of physics, seems to me to be an excellent program to follow out...and I'm not happy with all the analyses that go with just the classical theory, because nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem because it doesn't look so easy."

since nature is quantum,
it is better simulated on a quantum computer

Quantum simulators:
dedicated quantum computers: solve (fundamental) problems that are untractable by classical hardware

R. P. Feynman, "Simulating Physics with Computers"
Int. J. Theor. Phys. 21, 467 (1982)

Quantum simulators with ultra cold atoms



Quantum Hamiltonian engineering in table-top setups

Cirac and Zoller, Nat. Phys. 2012
Inguscio and Fallani, Atomic Physics (Oxford, 2013)
M. Lewenstein et al., Ultracold atoms in optical lattices (Oxford, 2012)

Aharonov-Bohm
Berry phase
Topological insulators
Quantum Hall

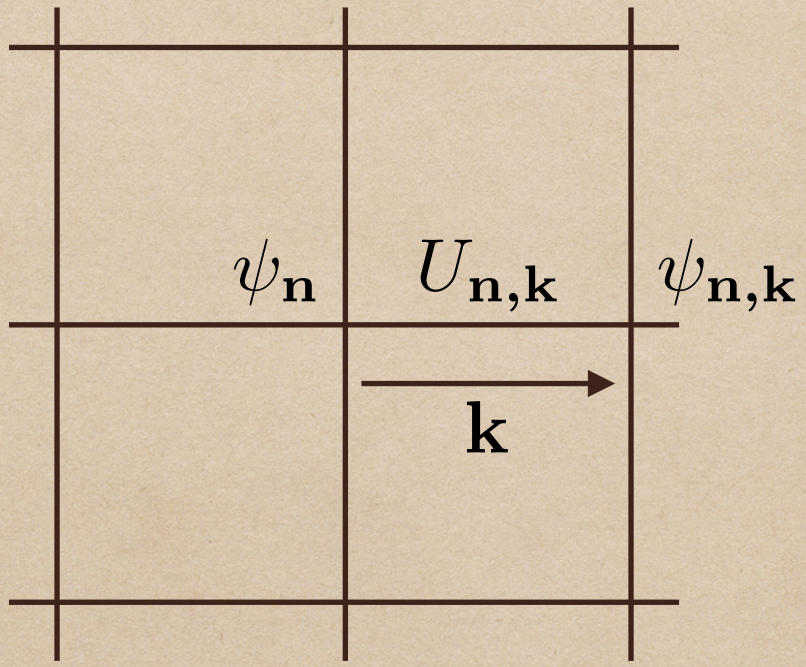
Hawking
Unruh
Dirac Eq. (Zitterbewegung + Klein paradox)
Fermi two-atom problem
Neutrino oscillations
Majorana

Extra dimensions
SU(N) fermions
Lattice Gauge theories
Supersymmetry

but see later for other options…

example: mass + hopping terms

$$H = \sum_{\mathbf{n}} M_{\mathbf{n}} \psi^{\dagger}_{\mathbf{n}} \psi_{\mathbf{n}} + t \sum_{\mathbf{n}} (\psi^{\dagger}_{\mathbf{n}} U_{\mathbf{n},\mathbf{k}} \psi_{\mathbf{n},\mathbf{k}} + \text{H.c.})$$



$U_{\mathbf{n},\mathbf{k}}$ is the connection

Simulating Gauss' law (courtesy S. Montangero)

Theories with local symmetries (to be satisfied at every point)

CLASSICAL (electrodynamics)

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$$\rho = \vec{\nabla} \cdot \vec{E}$$

Gauss' law

QUANTUM (QED)

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CLASSICAL (electrodynamics)

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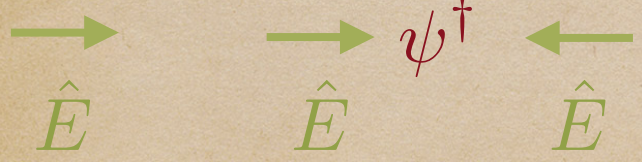
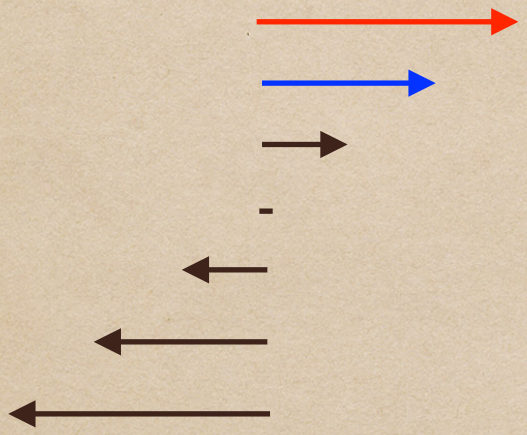
QUANTUM (QED)

Gauss' law

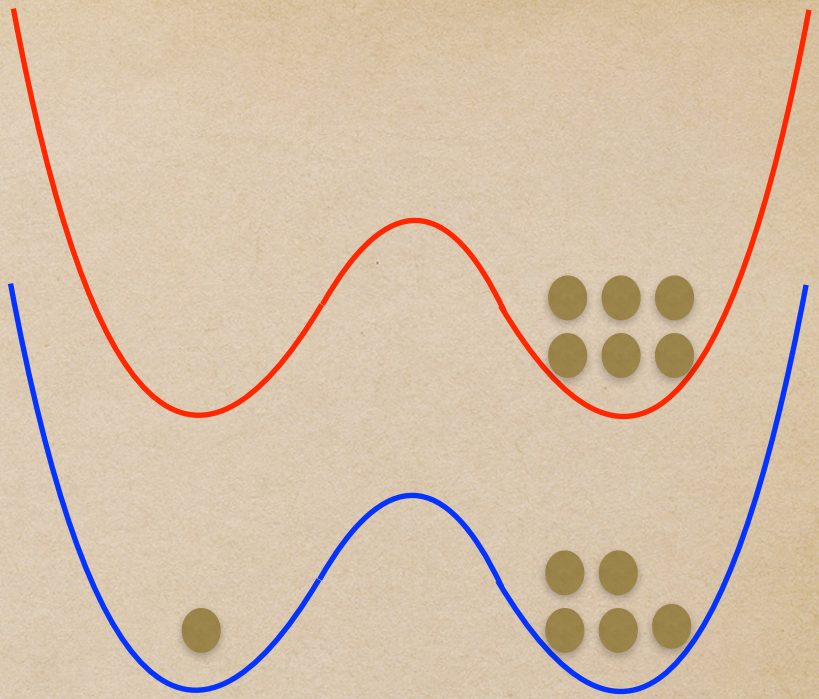


$$\psi_x^\dagger \psi_x |\Psi\rangle = \Delta E_{x,x+a} |\Psi\rangle$$

careful…

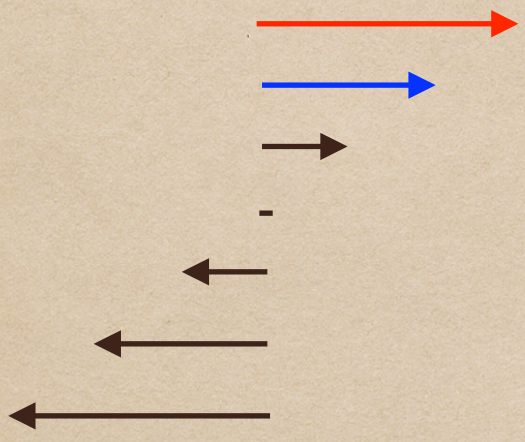


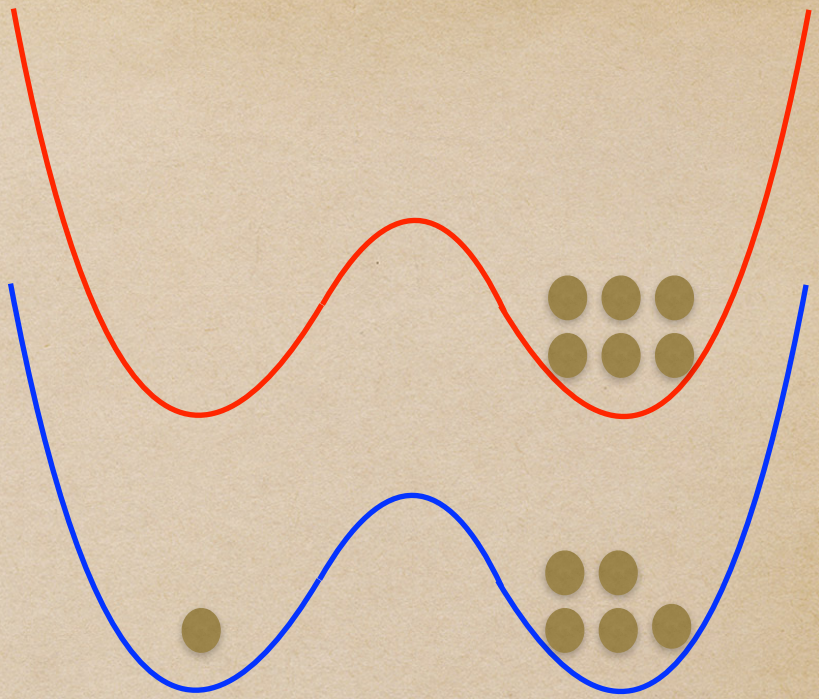
electric field



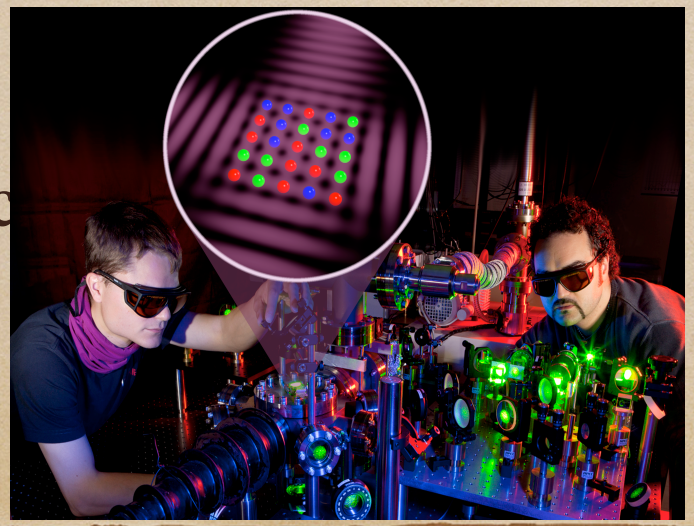
quantum simulator

careful…



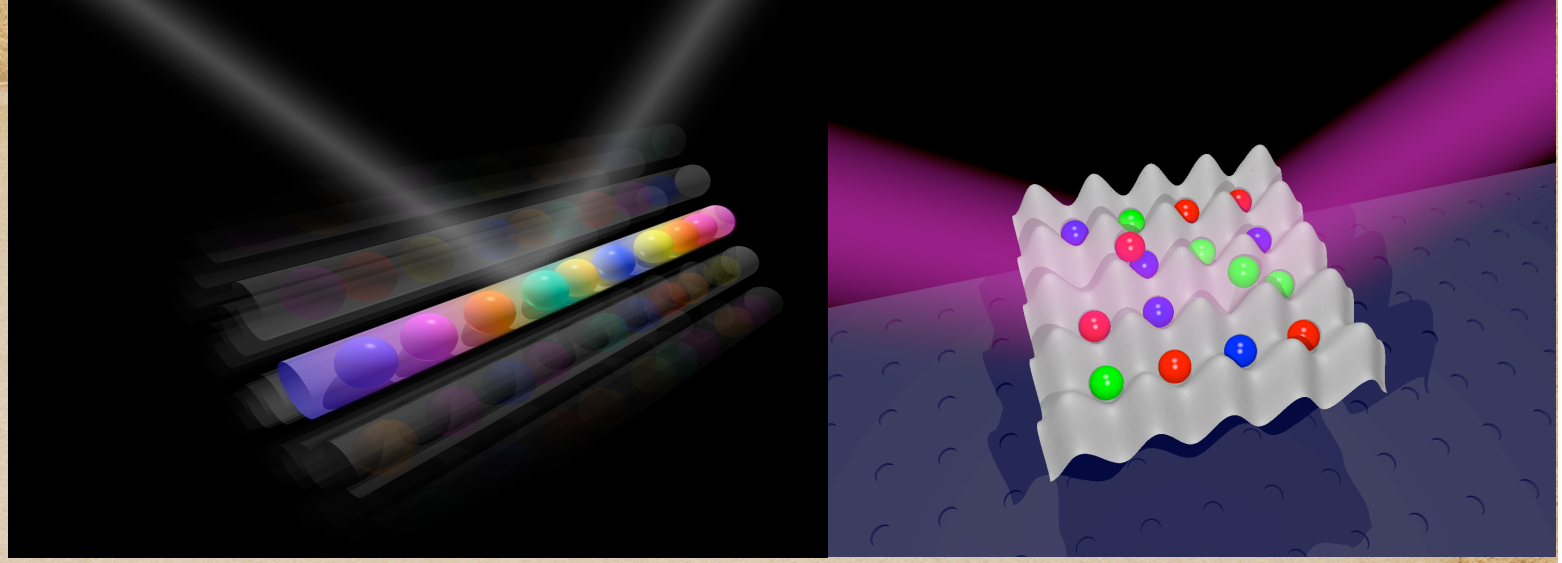


elec

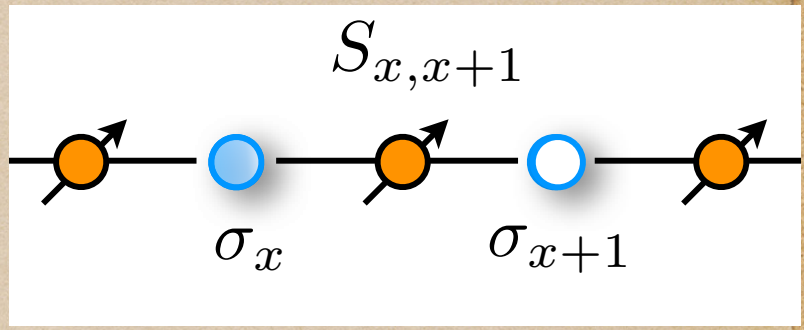


and so on…

quantum simulator



enforcing Gauss law in quantum simulation of lattice gauge theory



$$\rho - \Delta \cdot E \quad \Leftrightarrow \quad S^z_{x-1,x} + \sigma^z_x - S^z_{x,x+1} + \frac{1}{2}(-)^x$$

$$\textit{large}\ \text{white noise} \times (\rho - \Delta \cdot E)$$

enforces Gauss law by energy penalty/cost or by Zeno effect

comment on interdisciplinarity

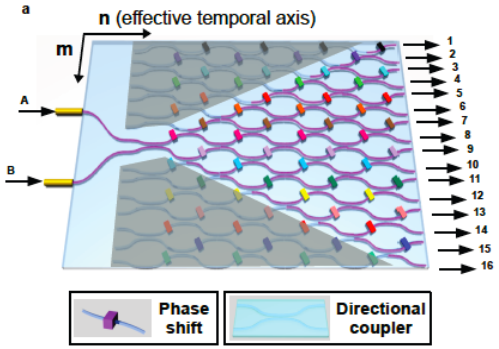
simulated and simulating physics
in general belong to two different physical disciplines
(in this case HEP high-energy physics vs
AMO atomic and molecular and optical physics)

courtesy P. Mataloni

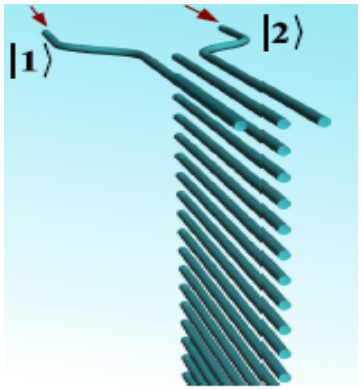
Quantum Optics Group

Dipartimento di Fisica, Sapienza Università di Roma

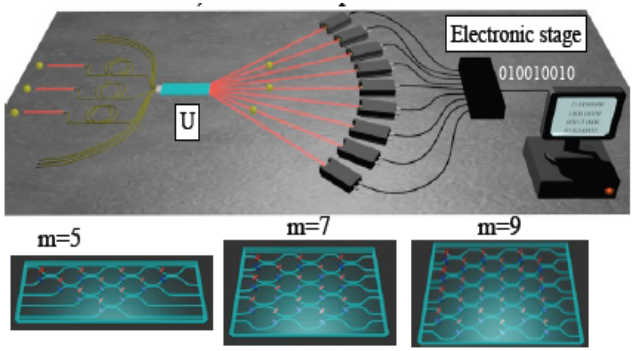
Quantum simulation through integrated photonics



1) Anderson localization of two non-interacting bosons/fermions via quantum walks



2) Study the role of particle statistics in quantum decay in a continuum and Fano resonances



3) Boson Sampling: a promising route towards *Quantum Supremacy*

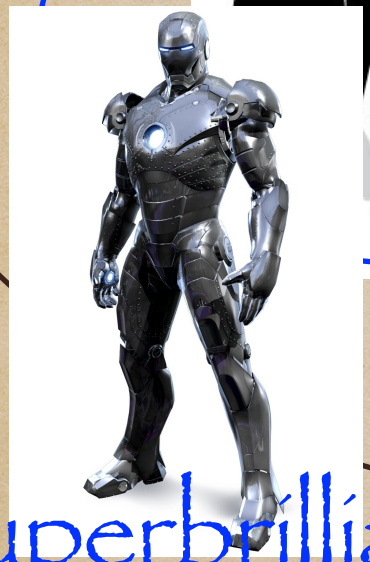
comments

- "toy" models: simple(r) physical theories that are able to capture the most salient features of the physics in question
- Q. simulators are sometimes able to realize physical models that are "unreal" (believed not to be found in Nature)
- non-perturbative regimes
- one is left to wonder about the meaning of "simulation" and Feynman's seminal intuition

brilliant vs thoughtful

brilliant

thoughtful



superbrilliant

hyperthoughtful

physicists