

Title: Lattice gauge theories with cold atoms

Date: Aug 14, 2015 03:00 PM

URL: <http://pirsa.org/15080036>

Abstract: Can high energy physics can be simulated by low-energy, nonrelativistic, many-body systems, such as ultracold atoms? Ultracold atomic systems lack the type of symmetries and dynamical properties of high energy physics models: in particular, they do not manifest local gauge invariance nor Lorentz invariance, which are crucial properties of the quantum field theories which are the building blocks of the standard model of elementary particles.

However, it will be shown that there are ways to configure atomic system to manifest both local gauge invariance and Lorentz invariance. In particular, local gauge invariance can arise either as an effective, low energy, symmetry, or as an "exact" symmetry, following from the conservation laws in atomic interactions. Such quantum simulators may lead to new type of (table-top) experiments, to test various QCD phenomena, as the confinement of dynamical quarks, phase transitions, and other effects.





Democritus
H. T. Bruggen
Rijksmuseum

atoms - dust particle [1].



Heraclitus
H. T. Bruggen
Rijksmuseum

time - river



Analogous gravity
W. G. Unruh
Private collection

(1) On the Nature of Things (*De Rerum Natura*), Lucritius, 50-75BC.

3. Criteria for evaluating analogical arguments [@]

3.1 Commonsense guidelines

Logicians and philosophers of science have identified ‘textbook-style’ general guidelines for

Information loss?

X

✓

?

✓

- (G1) The more similarities (between two domains), the stronger the analogy.
- (G2) The more differences, the weaker the analogy.
- (G3) The greater the extent of our ignorance about the two domains, the weaker the analogy.
- (G4) The weaker the conclusion, the more plausible the analogy.
- (G5) Analogies involving causal relations are more plausible than those not involving causal relations.
- (G6) Structural analogies are stronger than those based on superficial similarities.
- (G7) The relevance of the similarities and differences to the conclusion (i.e., to the hypothetical analogy) must be taken into account.
- (G8) Multiple analogies supporting the same conclusion make the argument stronger.

@  Stanford Encyclopedia of Philosophy

3. Criteria for evaluating analogical arguments [@]

3.1 Commonsense guidelines

Logicians and philosophers of science have identified 'textbook-style' general guidelines for

Information loss?

X

✓

?

✓

- (G1) The more similarities (between two domains), the stronger the analogy.
- (G2) The more differences, the weaker the analogy.
- (G3) The greater the extent of our ignorance about the two domains, the weaker the analogy.
- (G4) The weaker the conclusion, the more plausible the analogy.
- (G5) Analogies involving causal relations are more plausible than those not involving causal relations.
- (G6) Structural analogies are stronger than those based on superficial similarities.
- (G7) The relevance of the similarities and differences to the conclusion (i.e., to the hypothetical analogy) must be taken into account.
- (G8) Multiple analogies supporting the same conclusion make the argument stronger.

@  Stanford Encyclopedia of Philosophy

Lightpost-space of analogous arguments



trivial

surprising

does not make sense at all



Proof (by negation)

- The analogy completely does not make sense.
Therefore it is incorrect. However it works.
Therefore it should be of some (moderate) interest.

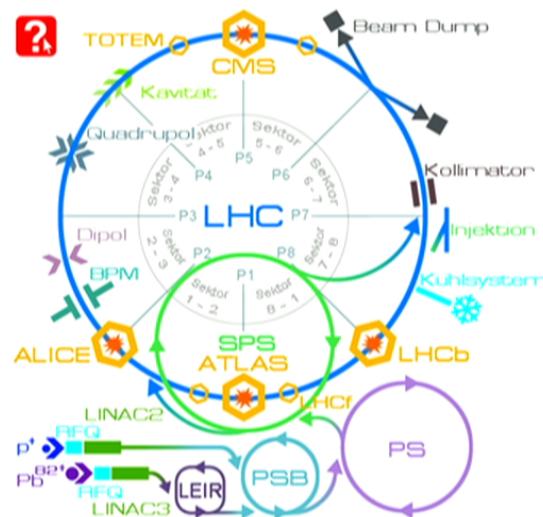
QED.

Proof (by negation)

- The analogy completely does not make sense.
Therefore it is incorrect. However it works.
Therefore it should be of some (moderate) interest.

QED.

Example #2: $16 <$ orders of magnitude



PROOF: THE FLOWING TALK MAKES NO SENSE.

QED.

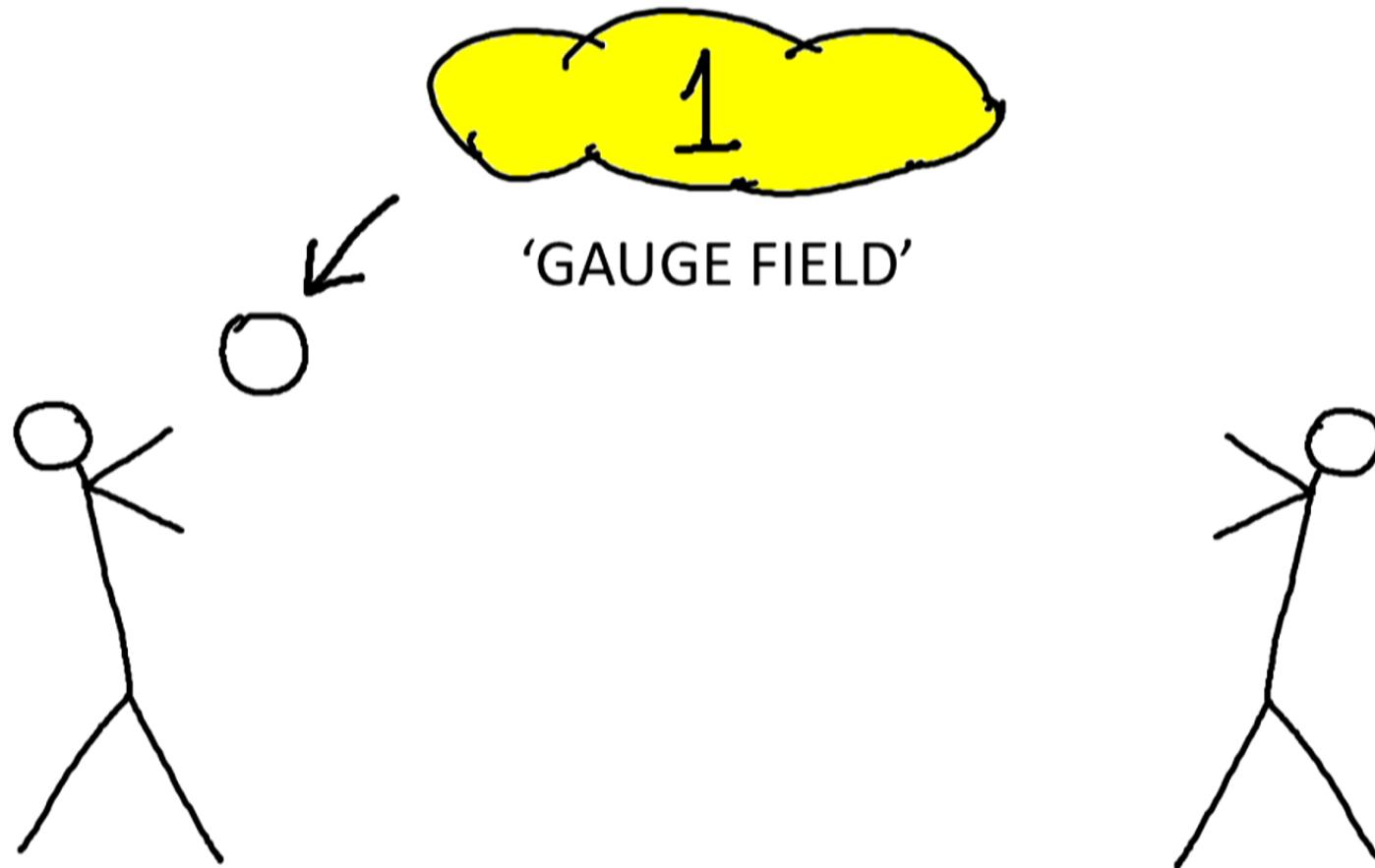
LATTICE GAUGE THEORIES with COLD ATOMS

Happy birthday...!

Bill Unruh , Perimeter, August 14th 2015

WITH I. J. CIRAC, AND E. ZOHAR.

CLOUD DEGREES OF FREEDOM



GAUGE FIELDS

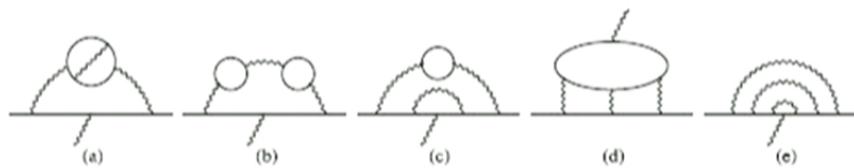
Abelian Fields	Non-Abelian fields
Maxwell theory	Yang-Mills theory
Massless	Massless
Long-range forces	<u>Confinement</u>
Chargeless	Carry charge
Linear dynamics	Self interacting & NL

CALCULATE!

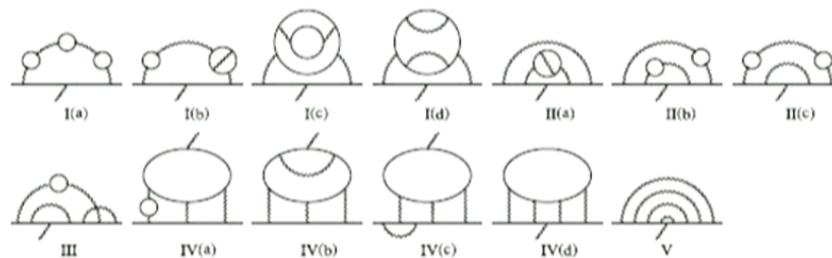
e.g., the anomalous electron magnetic moment:

$$(g-2)/2 = \dots$$

... +



+



+ ...

891 vertex diagrams

Requirements

1. ■ Fields

Fermion Matter fields

Bosonic gauge fields

2. ■ Relativistic invariance

Causal structure, in the continuum limit

3. ■ Local gauge invariance

Exact, or low energy, effective

REQUIREMENT 1.

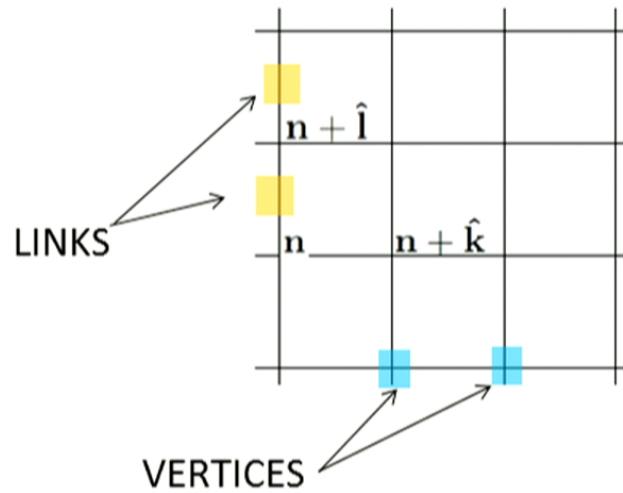
Fermion fields := Matter

Bosonic, Gauge fields:= Interaction mediators

One needs **both** bosons and fermions

LATTICE GAUGE THEORIES DEGREES OF FREEDOM

Gauge field degrees of freedom:
 $U(1)$, $SU(N)$, etc, unitary matrices



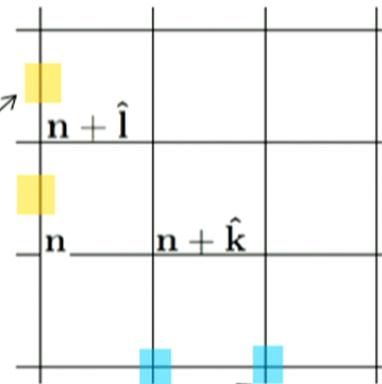
Matter degrees of freedom :
Spinors

$$\psi_{\mathbf{n}} = (\psi_{\mathbf{n},a}) = \begin{pmatrix} \psi_{\mathbf{n},1} \\ \psi_{\mathbf{n},2} \\ \dots \end{pmatrix}$$

LATTICE GAUGE THEORIES DEGREES OF FREEDOM

Gauge field degrees of freedom:
 $U(1)$, $SU(N)$, etc, unitary matrices

LINKS

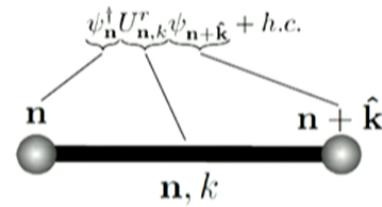


VERTICES

Matter degrees of freedom :
Spinors

$$\psi_{\mathbf{n}} = (\psi_{\mathbf{n},a}) = \begin{pmatrix} \psi_{\mathbf{n},1} \\ \psi_{\mathbf{n},2} \\ \dots \end{pmatrix}$$

Local Gauge invariance



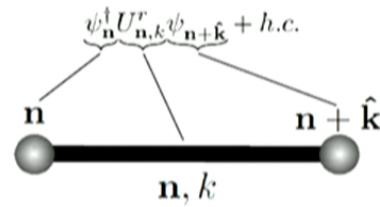
$$\psi_{\mathbf{n}} \rightarrow V_{\mathbf{n}}^r \psi_{\mathbf{n}}$$

$$U_{\mathbf{n},k}^r \rightarrow V_{\mathbf{n}}^r U_{\mathbf{n},k}^r V_{\mathbf{n}+\hat{\mathbf{k}}}^{\dagger r}$$

$$H_{int} = \epsilon \sum_{\mathbf{n},k} (\psi_{\mathbf{n}}^{\dagger} U_{\mathbf{n},k}^r \psi_{\mathbf{n}+\hat{\mathbf{k}}} + h.c.)$$

A symmetry that is satisfied **for each link separately**

Local Gauge invariance



$$\psi_n \rightarrow V_n^r \psi_n$$

$$U_{n,k}^r \rightarrow V_n^r U_{n,k}^r V_{n+\hat{k}}^{\dagger r}$$

$$H_{int} = \epsilon \sum_{n,k} (\psi_n^\dagger U_{n,k}^r \psi_{n+\hat{k}} + h.c.)$$

A symmetry that is satisfied **for each link separately**

Toy Example: U(1)



$$H = \sum_n M_n \psi_n^\dagger \psi_n + \epsilon \sum_n (\psi_n^\dagger \psi_{n+1} + h.c.)$$

Toy Example: U(1)

$$H = \sum_n M_n \psi_n^\dagger \psi_n + \epsilon \sum_n (\psi_n^\dagger U_n \psi_{n+1} + h.c.)$$

Invariance under a **local** gauge transformations:

$$\psi_n \rightarrow e^{-i\Lambda_n} \psi_n \quad ; \quad \psi_n^\dagger \rightarrow \psi_n^\dagger e^{i\Lambda_n}$$

$$\phi_n \rightarrow \phi_n + \Lambda_{n+1} - \Lambda_n$$

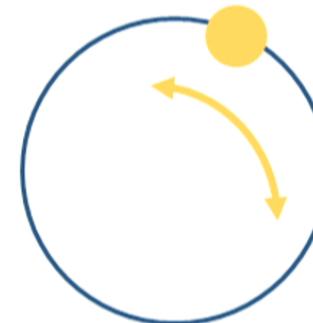
Toy Example U(1): ON LINKS

Gauge field kinetic energy:

$$H_E = \frac{g^2}{2} \sum_n L_n^2$$

$$L |m\rangle = m |m\rangle$$

$$u_m(\phi) = \langle \phi | m \rangle = \frac{1}{\sqrt{2\pi}} e^{im\phi}$$



Mechanical Analog

3. ■

Local gauge invariance:
IN ATOMIC SYSTEMS???

COLD ATOMS OPTICAL LATTICES

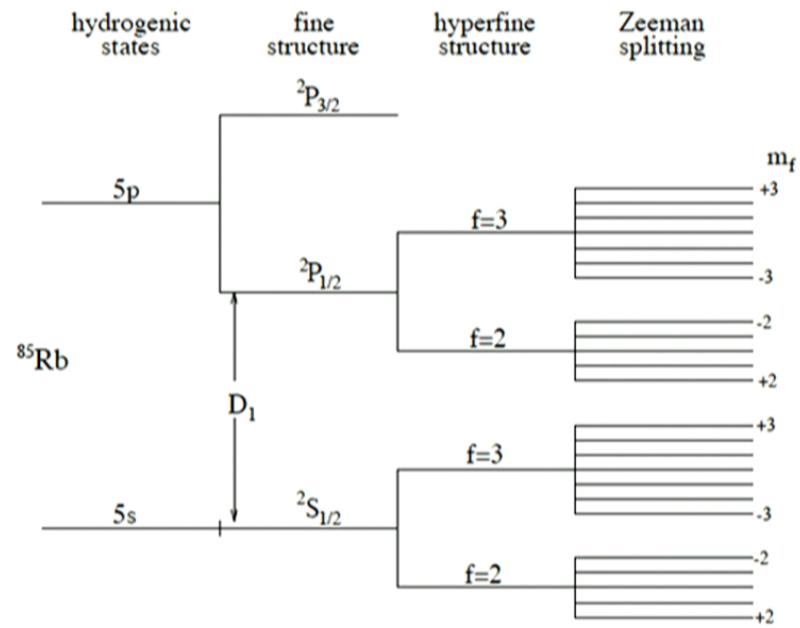
Laser Standing waves: dipole trapping



COLD ATOMS OPTICAL LATTICES

Laser Standing waves: dipole trapping





Level diagram of ^{85}Rb . $\mathbf{I} = 5/2$. The splittings are not to scale.

QUANTUM SIMULATIONS COLD ATOMS – EXPERIMENTS

PRL 103, 080404 (2009)

PHYSICAL REVIEW LETTERS

week ending
21 AUGUST 2009



Experimental Demonstration of Single-Site Addressability in a Two-Dimensional Optical Lattice

Peter Würz,¹ Tim Langen,¹ Tatjana Gericke,¹ Andreas Koglbauer,¹ and Herwig Ott^{1,2,*}

¹*Institut für Physik, Johannes Gutenberg-Universität, 55099 Mainz, Germany*

²*Research Center OPTIMAS, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany*

(Received 18 March 2009; published 21 August 2009)

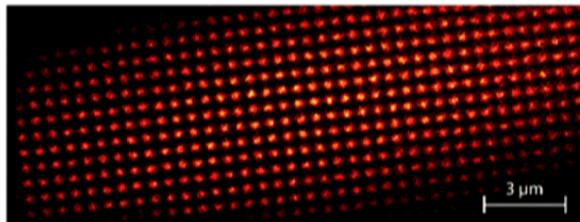


FIG. 1 (color online). Electron microscope image of a Bose-Einstein condensate in a 2D optical lattice with 600 nm lattice spacing (sum obtained from 260 individual experimental realizations). Each site has a tubelike shape with an extension of 6 μm perpendicular to the plane of projection. The central lattice sites contain about 80 atoms.

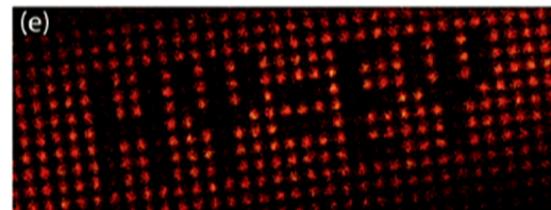
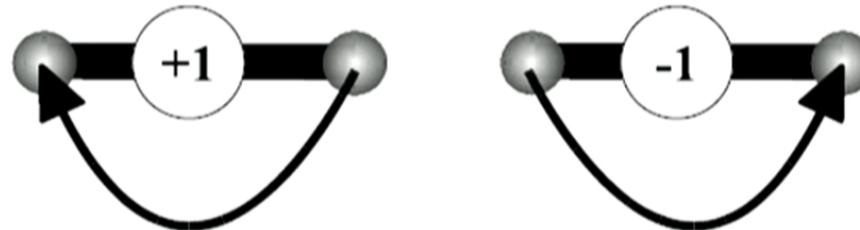


FIG. 2 (color online). Patterning a Bose-Einstein condensate in a 2D optical lattice with a spacing of 600 nm. Every emptied site was illuminated with the electron beam (7 nA beam current, 100 nm FWHM beam diameter) for (a),(b) 3, (c),(d) 2, and (e) 1.5 ms, respectively. The imaging time was 45 ms. Between 150 and 250 images from individual experimental realizations have been summed for each pattern.

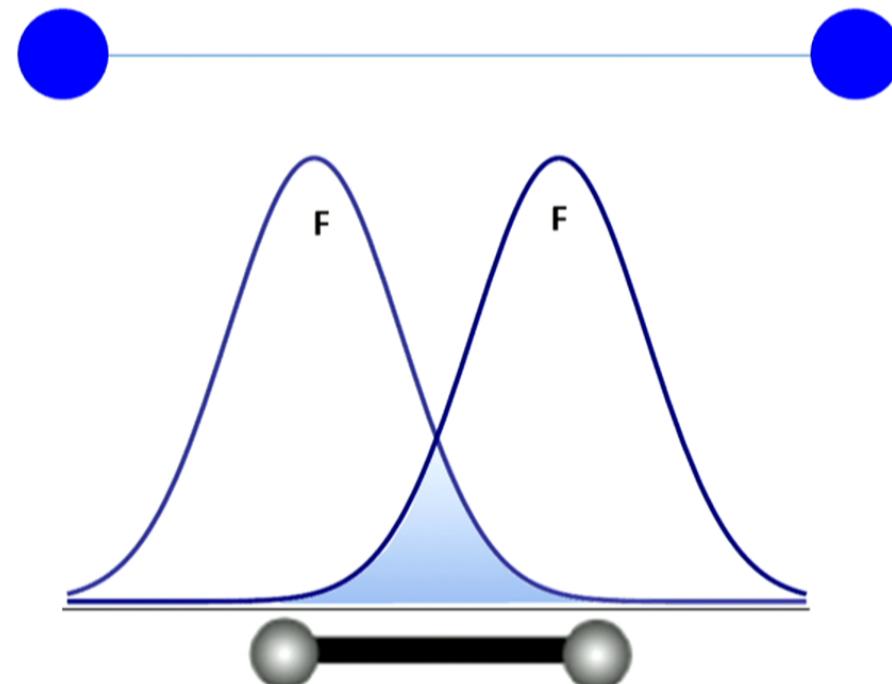
REQUIREMENT 3.

The theory has to be local gauge invariant.

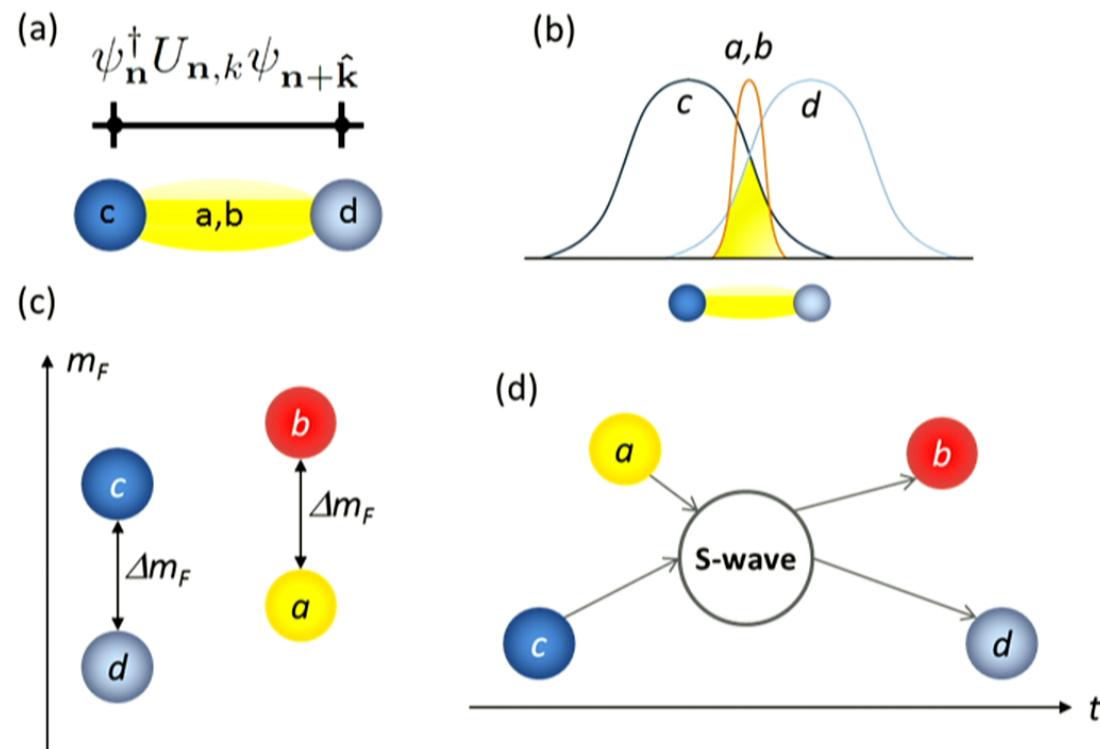
local gauge invariance = “charge” conservation

$$\underbrace{\psi_{\mathbf{n}}^\dagger e^{i\phi_{\mathbf{n},k}} \psi_{\mathbf{n}+\hat{\mathbf{k}}}} + \underbrace{\psi_{\mathbf{n}+\hat{\mathbf{k}}}^\dagger e^{-i\phi_{\mathbf{n},k}} \psi_{\mathbf{n}}}$$


TUNNELING OF FERMIONS



REALIZING A LINK



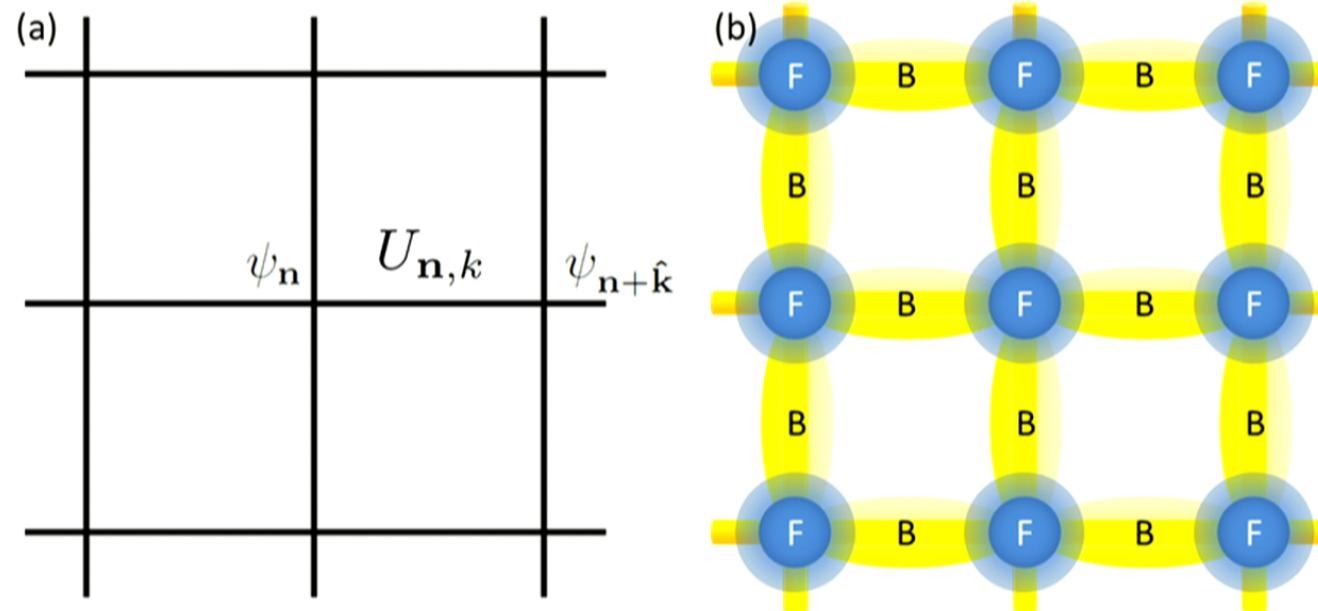
SCHWINGER MODEL: cQED D=1

Quantum Simulation of The Schwinger model (with staggered fermions):

$$H = M \sum_n (-1)^n \psi_n^\dagger \psi_n + \alpha (\psi_n^\dagger U_n \psi_{n+1} + H.c.) + \frac{g^2}{2} \sum_n L_{nz}^2$$

 F-B scattering: link interaction
 B-B Scattering: electric energy

QS: U(1) KOGUT-SUSKIND

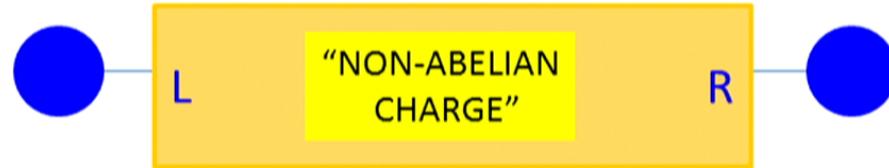


NON ABELIAN Yang-Mills

The STANDARD MODEL is built of particular non-abelian theories, that are Yang-Mills QFTs.
(Celebrating this year 60 since their discovery).

Renormalization ('t Hooft), and asymptotic Freedom (Wiltczek, Gross, Polizer), have been proved for Yang-Mills theories.

LEFT AND RIGHT SIDES OF THE LINK



$$[L_a, R_b] = 0$$

$$(G_{\mathbf{n}})_a = \text{div}_{\mathbf{n}} E_a = \sum_k \left((L_{\mathbf{n},k})_a - (R_{\mathbf{n}-\hat{\mathbf{k}},k})_a \right)$$

$$[L_a, U^r] = T_a^r U^r ; \quad [R_a, U^r] = U^r T_a^r$$

$$[L_a, L_b] = -i f_{abc} L_c ; \quad [R_a, R_b] = i f_{abc} R_c ;$$

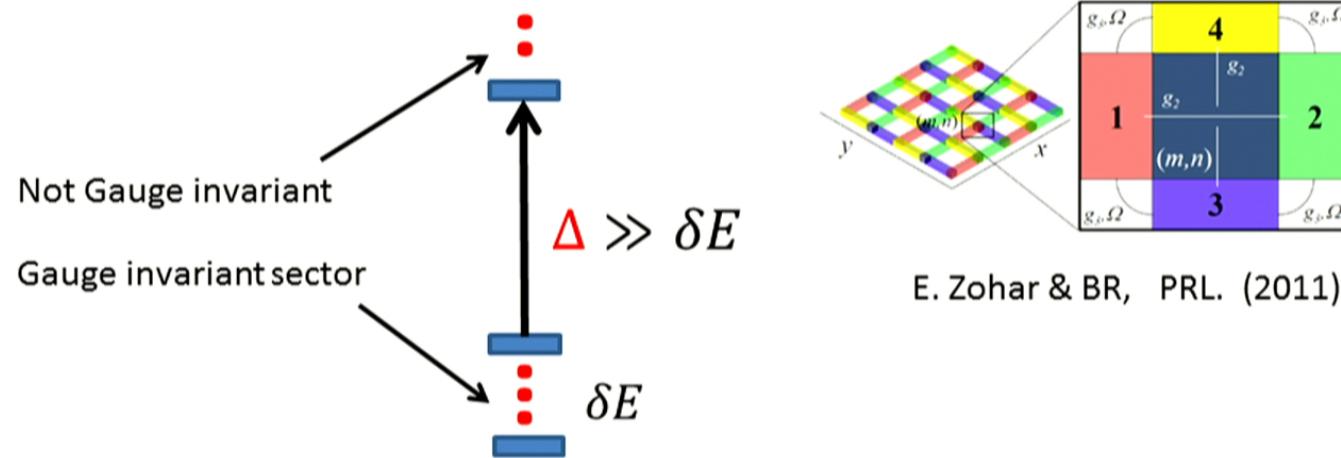
$$\sum_a L_a L_a = \sum_a R_a R_a \equiv \sum_a E_a E_a$$

MECHANICAL ANALOG:
BODY AND LABORATORY
REPRESENTATIONS FOR A
TOP'S ANGULAR MOMENTUM

“Emerging” Local Gauge Invariance at low enough energies

Gauss's law is added as a constraint.

Low energy effective gauge invariant KS Hamiltonian.



E. Zohar & BR, PRL. (2011)

QS: MODELS

	1+1 with matter	2+1 Pure	2+1 with matter
$U(1)$	Full KS + trunc.	Full KS + trunc.	Full KS + trunc.
\mathbb{Z}_3	Full	Full	Full
$SU(2)$	YM + trunc.	YM + trunc. (st. c.)	YM + trunc. (st. c.)

KS = Kogut Susskind

YM = Yang Mills theory

st. c= Strong coupling limit

QS: SU(2) W. ANGULAR MOMENTUM CONSERVATION

