Engineering dynamical gauge fields in atomic and optical systems: challenges and perspectives

GGI - What's next - 05/05/2015

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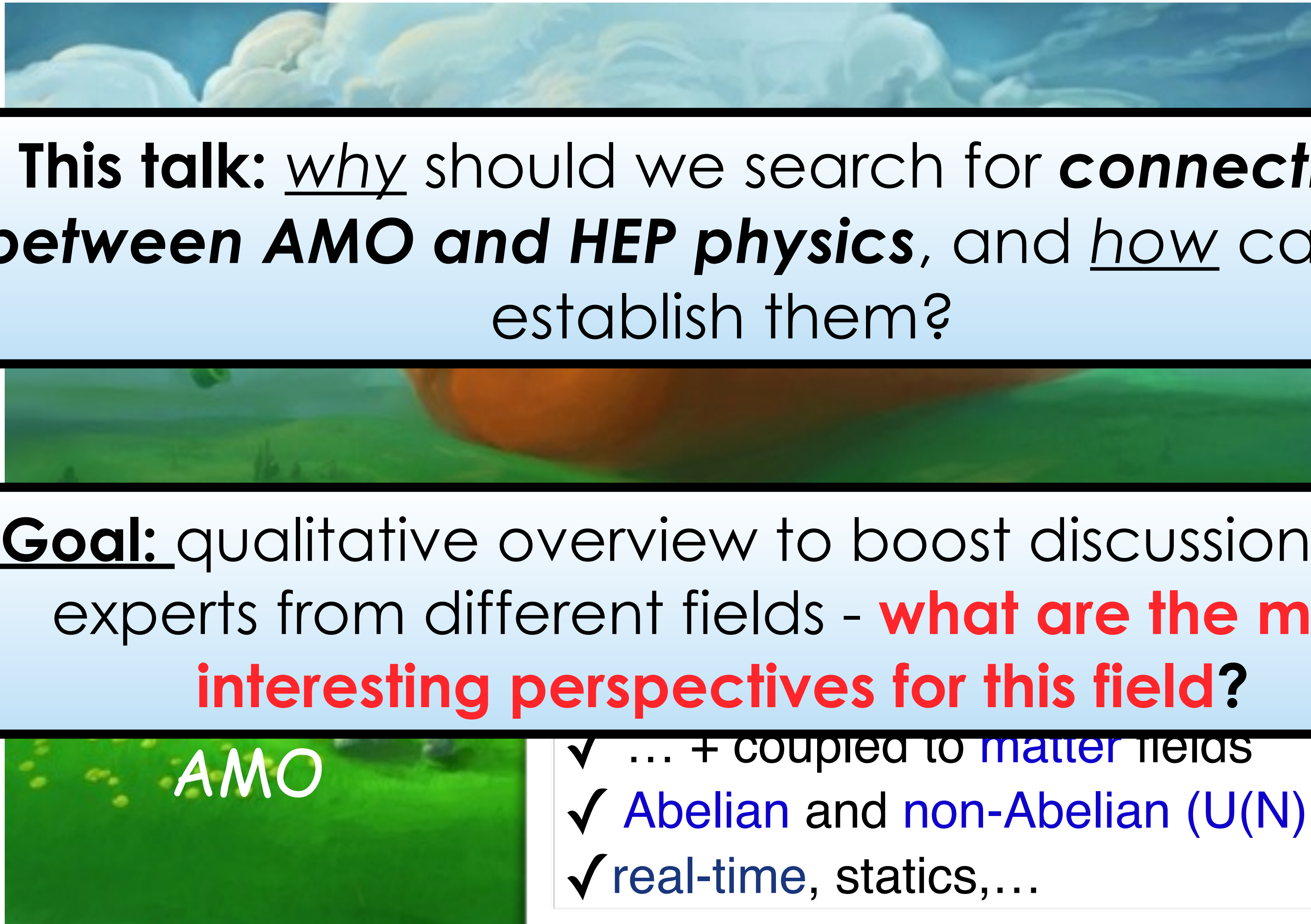
SFB FoQuS Foundations and Applications of Quantum Science

UQUAM ultracold quantum matter

Joint work with **A. Glätzle, P. Hauke, P. Zoller** (Innsbruck), **R. Nath** (Innsbruck-Pune), **R. Moessner, I. Rousochatzakis** (Dresden), **I. Bloch, C. Gross** (MPQ Garching) **E. Rico** (Bilbao), **S. Montangero, T. Pichler, P. Silvi** (Ulm), **P. Stebler, M. Boegli, U.-J. Wiese** (Bern), **D. Banerjee** (Desy), **E. Martinez, D. Nigg, T. Monz, R. Blatt** (Innsbruck), **M. Mueller** (Madrid)

AMO and HEP



This talk: _why_ should we search for ***connections between AMO and HEP physics***, and _how_ can we establish them?

Goal: qualitative overview to boost discussion with experts from different fields - **what are the most interesting perspectives for this field?**

✓ … + coupled to matter fields

✓ Abelian and non-Abelian (U(N), SU(N))

✓ real-time, statics,…

Outline

Why shall we try to establish **connections between QI, AMO and HEP**?

1) observe new phenomena, explore new physics

2) use AMO systems as quantum simulators

Gauge theories in HEP and condensed matter systems

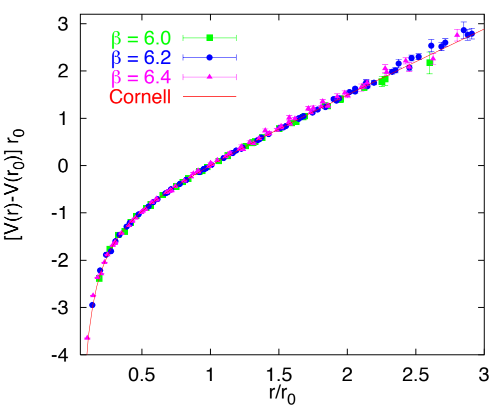
Synthetic matter: atoms, ions, circuits, etc.

Key element: develop a **framework to build this connection. How?**

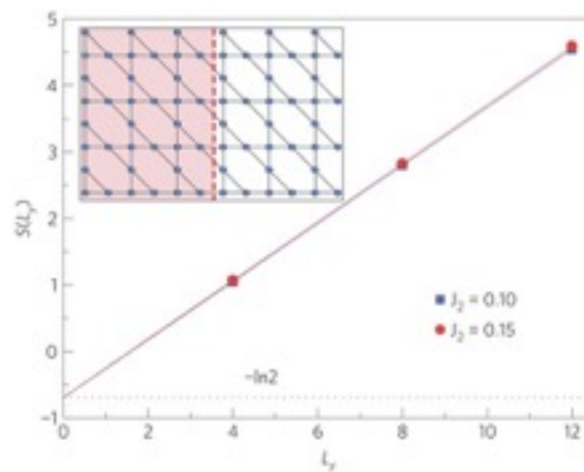
Why? 1) Known and novel physics in the lab!

Experiments in condmat and HEP can be challenging - explore features of gauge theories in controlled environments to check theories

Physics of toy models (‘t Hooft model, (walking) technicolor, many-spin interactions in spin systems, ...) and correlated phenomenology (entanglement in frustrated systems, string tension in confining theories, Higgs,....)



String tension of quenched QCD, Bali’s review PhysRep.2001



Entanglement entropy of a Z-2 spin liquid, Jiang et al., NatPhys.2012

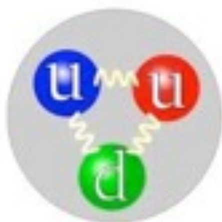
Cold atomic gases as controllable and tunable platforms to observe and investigate **novel many-body effects**

Why? 2) From Classical to Quantum simulation of gauge theories

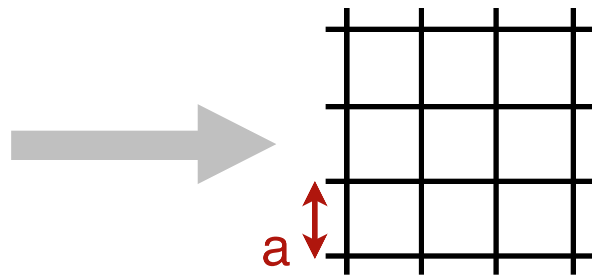
Many phenomena in gauge theories stand beyond our current capabilities

-> use synthetic systems as quantum simulators

Lattice QCD in (less than) a nutshell



quarks and gluons



lattice

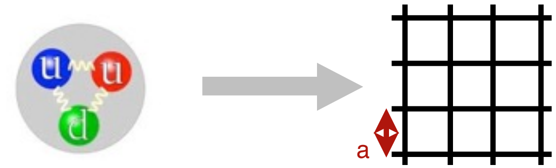
K. Wilson (1974)

non-perturbative approach to fundamental theories of matter (e.g. QCD)
→ classical statistical mechanics
Montecarlo simulations are possible!

Lattice QCD in (less than) a nutshell

Remarkable achievements

1) first evidence of *quark-gluon plasma*
2) *ab-initio* estimate of protonic mass
3) low-lying *hadron spectrum*
4) determination of *CKM matrix*
many more…



K. Wilson (1974)

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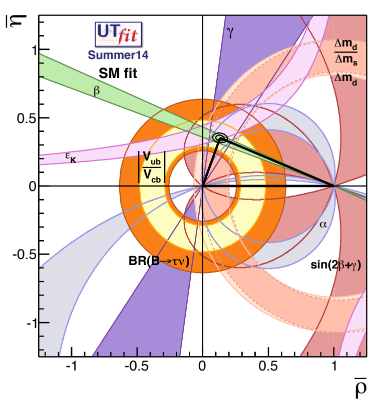
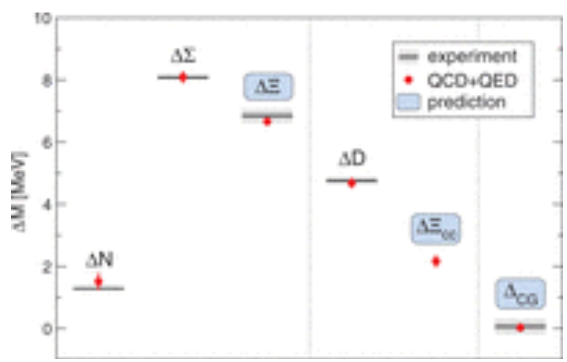
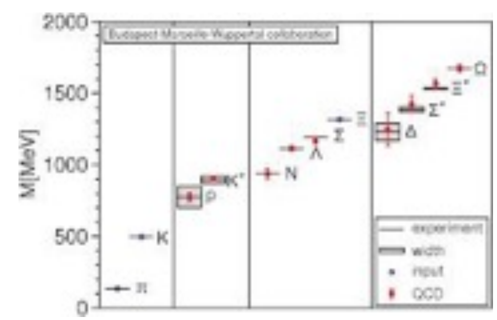


UFit, utfit.org



BMW, Science 2015



BMW, Science 2008

A. Ukawa, *Kenneth Wilson and lattice QCD, arXiv.1501.04215*

Still, a lot of interesting open problems

Real-time dynamics: no known *reliable algorithm*

***Finite- and large-density regimes*:** Montecarlo suffers from *severe sign problem*

Ideal test-bed applications for quantum simulators

Experiments in heavy ion collider (LHC, Brookhaven, …) - **intrinsic real-time dynamics, thermalization**, prethermalization, etc…

Relevant for *ab initio* **nuclear physics**, astrophysics / color superconductivity, …

A. Ukawa, *Kenneth Wilson and lattice QCD,* arXiv.1501.04215; U.-J. Wiese, *Annalen der Physik 525, 777 (2013).*

What is quantum simulation

Feynman's lecture '*Simulating Physics with Computers'*

"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."

R. P. Feynman, Int. J. Theor. Phys. (1982).

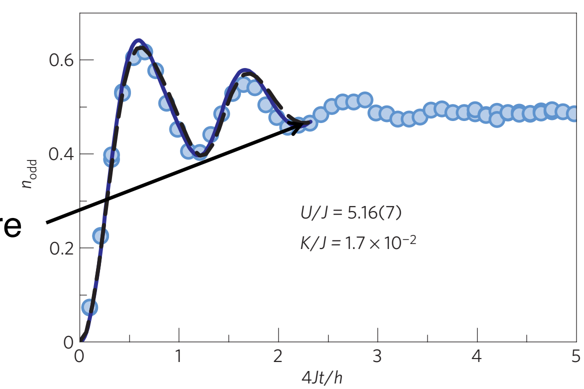
$$\dim\mathcal{H} \propto e^N!$$

Physics at equilibrium (sign problem, entanglement,...)

Time-evolution of many-particle quantum systems

quench

DMRG (theory)
Breaks down here

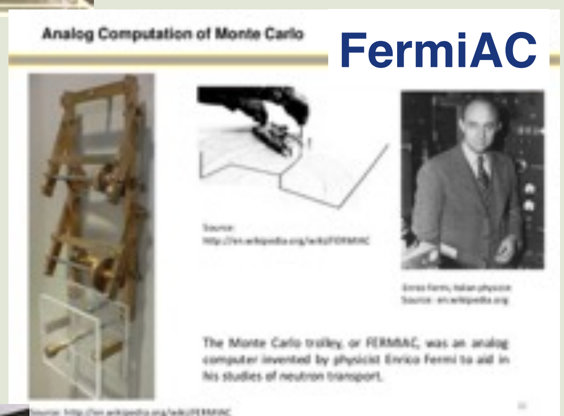


S. Trotzky et al.,
Nature Physics, 2232 (2012)

Classical digital and analog computation

Analog classical simulators


Antikythera



FermiAC


Wind tunnel

Digital classical simulators


Pascaline

Supercomputers

Quantum digital and analog computation

Analog quantum simulators

Basic idea: **Emulation** - Build a *Hamiltonian / Lagrangian / Liouvillian* using the following:

Synthetic systems

s

Sr

Wind tunnel

Platforms: cold atoms, ions, Rydbergs, molecules, superconductors, …

Digital quantum simulators

Basic idea: *Trotterize* a time-evolution

$$U(t) \equiv e^{-iHt/\hbar} = e^{-iH\Delta t_n/\hbar} \ldots^{-iH\Delta t_1/\hbar}$$

S. Lloyd, Science (1996)

Pl

su

ph

Ca

Ra

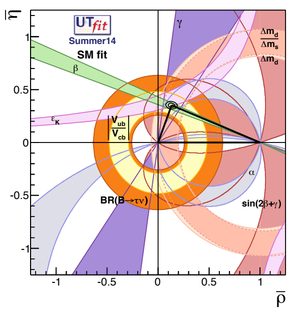
Supercomputers

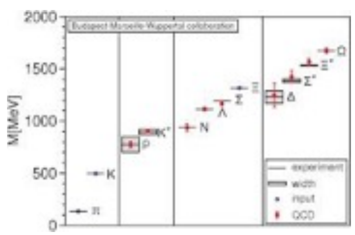
Quantum Annealers

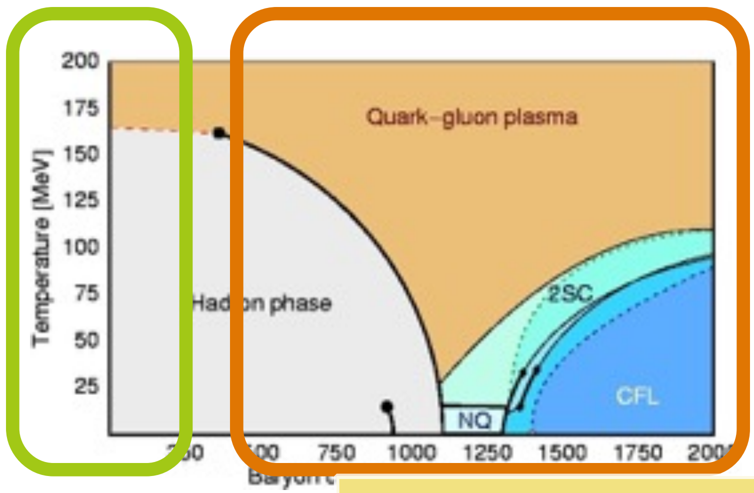
Cirac and Zoller, NatPhys. 2012; Georgescu et al., RMP2014

Complementing classical and quantum simulations

Quantum simulators **complement** (and do not substitute!!!!) classical simulations!







Moreov

1) call for novel applications of know

validation (see P

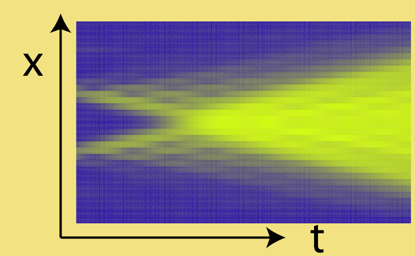
2) are ideal 'stimulators' for novel cla

renormalization group (see works at

Entanglement based numerical methods

use entanglement based numerical methods to simulate regimes which are challenging for MonteCarlo, e.g. dynamics

E. Rico, T. Pichler, MD, P. Zoller and S. Montangero, PRL 112, 201601.

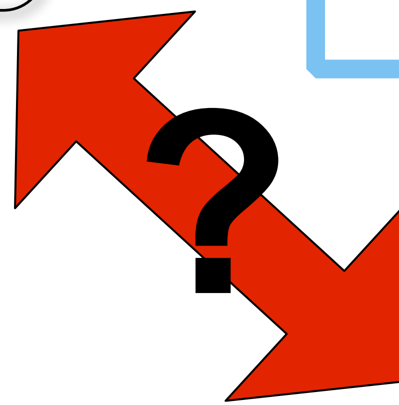


However ...

High Energy - *field theories*

$$\mathcal{L} = \frac{1}{2g^2}\mathrm{Tr}F_{\mu\nu}F_{\mu\nu} + \dots$$

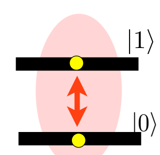
We need a **generic framework** to establish this connection: ***quantum link models***



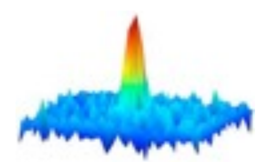
NB: some *ad hoc* solutions can be found for specific models - *Wilson's* ***Schwinger model*** and ***CP(N) models with finite t-angle***

Synthetic systems

Spins



Bosons



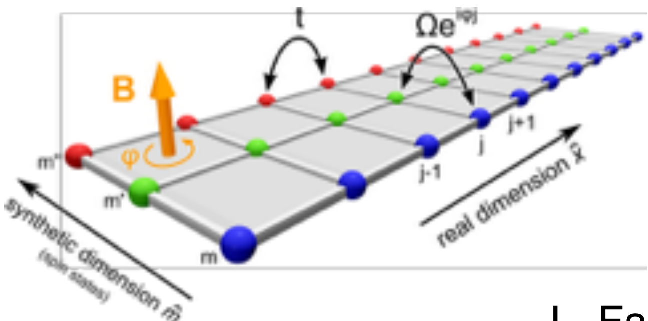
Fermions

$^{40}K,\ ^{87}Sr$

Review on dynamical gauge fields and quantum simulation: *U.-J. Wiese, Annalen der Physik 525, 777 (2013).*

Intermezzo - static vs dynamical gauge fields

Static **gauge fields:** particles hopping around a plaquette acquire a finite (Peierls) phase



L. Fallani   M. Inguscio
LENS, Florence

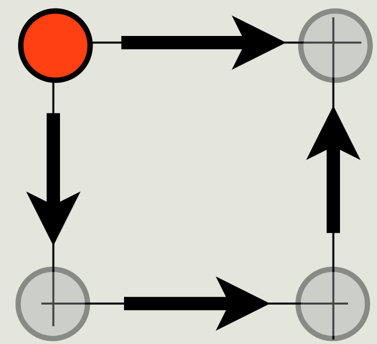
Fermions coupled to **static gauge fields** realized!
arXiv.1502.02495

Theory: M. Rider, P. Zoller, MD

$$H = -t\psi_x^\dagger e^{i\varphi_{x,x+1}}\psi_{x+1} + \text{h.c.}$$

Theory Review: J. Dalibard et al., Rev. Mod. Phys. (2011)
Exp.: Munich, Hamburg, NIST/Maryland, Florence, ETH, …
Theory: many active groups

Dynamical **gauge fields:** particles hopping around a plaquette assisted by **additional link degrees of freedom**



$$H' = -t\sum_{i,j}\psi_j^\dagger S_{ij}^+\psi_i + \text{H. c.}$$

Dynamical gauge fields and cold atoms:
ICFO, MPQ, Cornell, ….

D-theories / Quantum link models in a nutshell

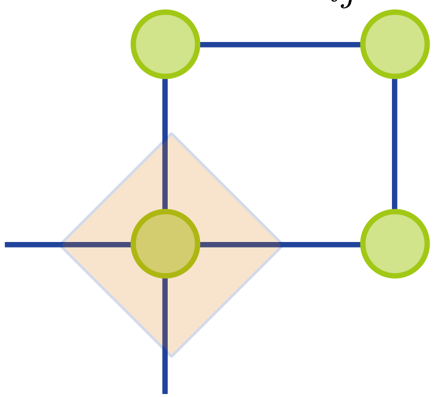
U(1) Wilson's theory

fermions

$\psi^\dagger_\sigma$

parallel transporters

$\mathcal{U}_{ij} = e^{iaA_{ij}}$



$$E_{ij} = -i\partial/\partial(aA_{ij})$$
$$[\mathcal{U}_{ij}, \mathcal{U}^\dagger_{ij}] = 0$$
$$[\mathcal{U}_{ij}, E_{ij}] = \mathcal{U}_{ij}$$

Gauge invariance

$$G_j = n_j + \sum_{\vec{k}} [E_{j,j-\vec{k}} - E_{j,j+\vec{k}}]$$

$$H = \sum_{\square} [\mathcal{U}_\square + \mathcal{U}^\dagger_\square] + t \sum_{<ij>} [\psi^\dagger_i \mathcal{U}_{ij} \psi_i + h.c.]$$

$$[G_j, H] = 0$$

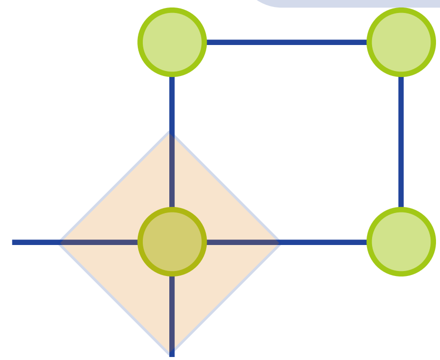
U(1) Quantum link model

$\mathcal{U}_{ij} = S^+_{ij}$

Gauge fields spanning ***finite-d Hilbert spaces***

fermions

$\psi^\dagger_\sigma$



$$E_{ij} = S^z_{ij}$$
$$[\mathcal{U}_{ij}, \mathcal{U}^\dagger_{ij}] = 2E_{ij}$$
$$[\mathcal{U}_{ij}, E_{ij}] = \mathcal{U}_{ij}$$

Gauge invariance

$$G_j = n_j + \sum_{\vec{k}} [E_{j,j-\vec{k}} - E_{j,j+\vec{k}}]$$

$$H = \sum_{\square} [\mathcal{U}_\square + \mathcal{U}^\dagger_\square] + t \sum_{<ij>} [\psi^\dagger_i \mathcal{U}_{ij} \psi_i + h.c.]$$

$$[G_j, H] = 0$$

D-theories: historical note

First proposal: Horn, 1981 (SU(2), U(1))

Proposed in condensed matter for explaining some features of High-Tc (dimer models): Rokshar and Kivelson, 1988 (U(1))

Rediscovered independently by Orland and Rohrlich, 1990 (U(2))

Full general formulation by Brower, Chandrasekharan and Wiese, 1995-1999 (U(N), SU(N), etc…)

Widely used nowadays in condensed matter and quantum information: loop models, stabilizer codes, dimer models, …

Obvious key questions

Global symmetries, fermions?

As in a Wilson LGT. All fermions can be used (Kogut-Susskind, Wilson, domain wall, …)

Lattice, dimensionality?

Can be defined an any lattice - care with non-bipartite (Abelian)

Which gauge symmetries?

U(N), SU(N), SO(N), ZN, ….

Continuum limit???

Care must be taken - known for QCD

Brower, Chandrasekharan and Wiese, Phys. Rev. D 1999. *U.-J. Wiese, Annalen der Physik 525, 777 (2013).*

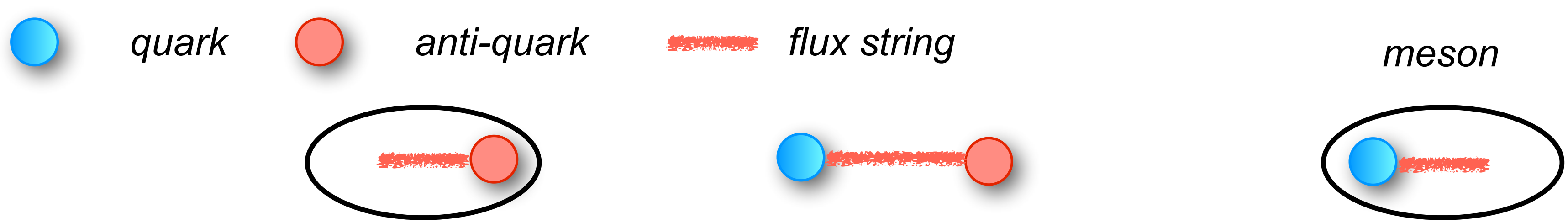
Working example: Schwinger model

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

$$U_{x,x+1} = S^-_{x,x+1} \qquad E_{x,x+1} = S^z_{x,x+1}$$

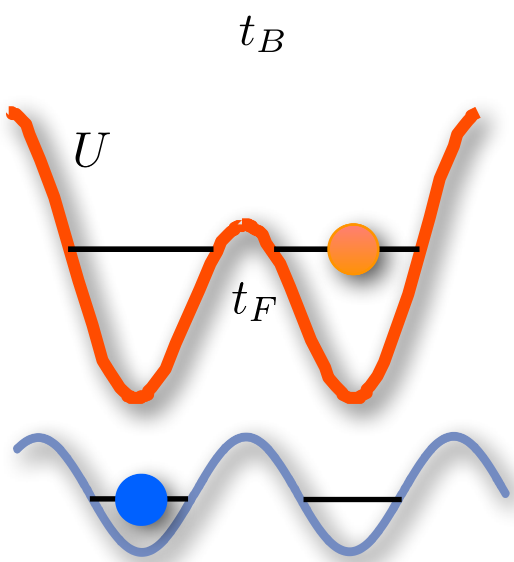
$$\tilde{G}_x = \psi_x^\dagger\psi_x + E_{x,x+1} - E_{x-1,x} + \frac{(-1)^x - 1}{2},$$

$$[H, G_x] = 0$$



Brower, Chandrasekharan and Wiese, Phys. Rev. D 1999. *U.-J. Wiese, Annalen der Physik 525, 777 (2013).*

Analog quantum simulator: some setups



$$H = -t_f(c_1^\dagger c_2 + h.c.) - t_B(b_1^\dagger b_2 + h.c.) + U \sum_j n_{F,j} n_{B,j}$$

$$U \gg t_F, t_B$$

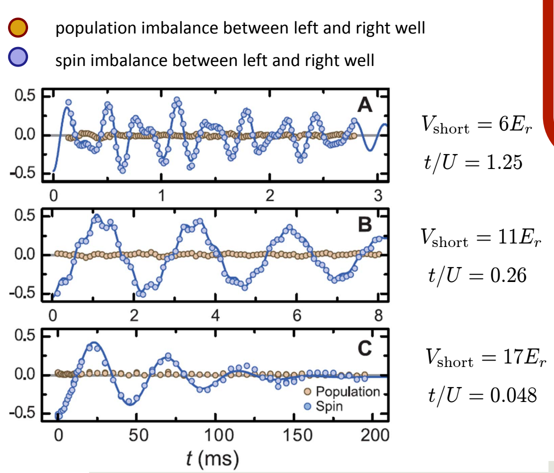
$$S^z = \frac{n_{B,1} - n_{B,2}}{2}$$

Exactly the building block we need!

$$H_{\text{hop}} = J \sum_x \left(\psi_{x+1}^\dagger S_{x,x+1}^\dagger \psi_x + \text{h.c.} \right)$$

Local conserved quantity!

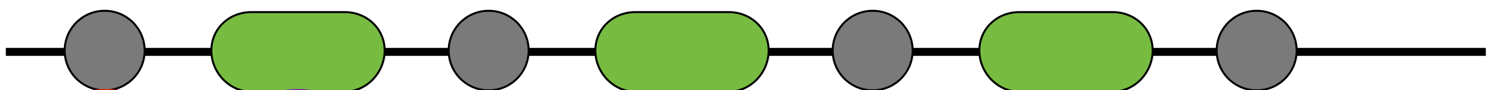
$$G_x = n_{F,x} + n_{B,x} \qquad [H_{\text{hop}}, G_x] = 0$$



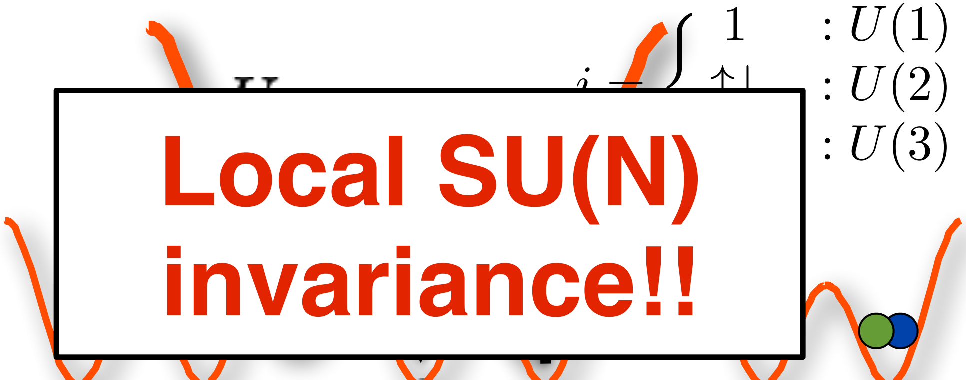
Experimentally demonstrated (with bosons) (Munich, JQI)

Alkaline-earth atoms: U(N)/SU(N) setups

$$H_{U(N)} = -t \sum_{x,y} \sum_{\sigma,\alpha} [(\psi_x^\sigma)^\dagger U_{xy}^{\sigma\alpha} \psi_y^\alpha + \mathrm{h.c.}] + \sum_x \sum_\alpha m_\alpha (\psi_x^\alpha)^\dagger \psi_x^\alpha$$



Fermions ψ_x^α $U_{xy}^{\sigma\alpha}$ Gauge fields



$$\begin{cases} 1 & : U(1) \\ \uparrow\downarrow & : U(2) \\ & : U(3) \end{cases}$$

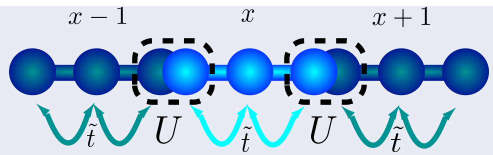
Local SU(N) invariance!!

$$H_{ex} \simeq \frac{t^2}{U} \vec{S}_1 \vec{S}_2$$

G. Pagano et al., Nat. Phys 2014

A Kaleidoscope: gauge theories in synthetic systems

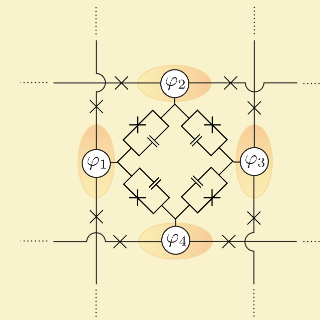
Ultracold atoms



Tewari et al. (PRL2006);
Kapit and Mueller, PRA 2010
Banerjee, MD et al. PRL 2012, PRL 2013
Stannigel et al., PRL 2014
Zohar et al, PRL 2012, PRL 2013, PRA2013
Notarnicola et al., Meurice et al., arxiv.2015;

Circuit QED

Marcos et al., PRL 2013,
Ann. Phys. 2014
Works in Bilbao

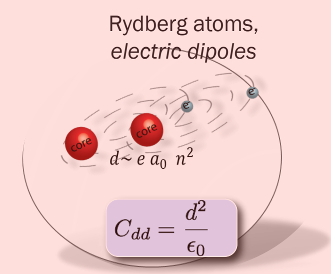


Digital approaches

Byrnes and Yamamoto, PRA 2006.
Weimer et al., Nat. Phys. 2010.
Tagliacozzo et al., Ann. Phys. 2012,
Tagliacozzo et al., Nat. Comm. 2013

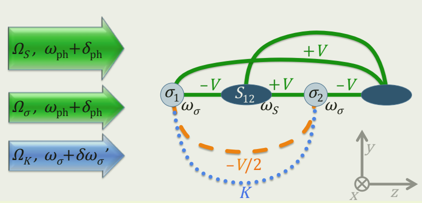
Rydberg atoms

A. Glätzle, MD et al., PRX 2014; arXiv2014



Trapped ions

Hauke, MD et al.,
PRX 2013; Nath, MD
et al. arxiv.
1504.01474



Conclusions

Dynamical gauge fields: a good playground for exploring particle physics phenomena in AMO

Quantum links: practical framework for implementations

U(1) theories: many platforms, **building block experiments** are already along the way

U(N) / SU(N): more challenging, **require 'special' atomic species** (Florence, Kyoto, Munich, Amsterdam, JILA,…)

And perspectives

Nuclear physics in *SO(3) models*

CP(N) models using Alkaline-earth-like atoms

Open questions and challenges:

1) Wilson's theories?
2) Plaquette terms?
3) Simpler implementations
4) Light-from-chaos and loss of gauge invariance (for Abelian theories)
5) Gauge theories as open quantum systems

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Alex Glätzle

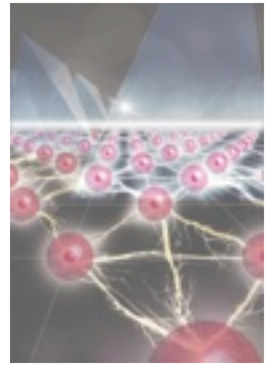
Rejish Nath

Peter Zoller

MPK Dresden

Roderich Moessner

Ioannis Rousochatzakis



I. Bloch, C. Gross (MPQ), R. Gerritsma, F. Schmidt-Kaler (Mainz), R. Blatt's group (Innsbruck), K. Stannigel, D. Marcos, P. Hauke (Innsbruck), M. Hafezi (JQI), S. Diehl (Dresden)

Einstein Institute / ITP Univ Bern

Uwe-Jens Wiese

Debasish Banerjee

Pascal Stebler

Michael Bögli

Bilbao

Enrique Rico

Madrid

Markus Müller

Thank you

Atoms U(1): Banerjee, MD, M
Wiese, Zoller, PRL ***109****, 1756*
Atoms SU(N)/U(N): Banerjee,
Wiese, Zoller, PRL ***110****, 1253*
Quantum Zeno: Stannigel, Hauke, Marcos, Hafezi, Diehl, MD, Zoller, PRL ***112****, 120406;*
Trapped Ions: Hauke, Marcos, MD, Zoller, PRX ***3****, 041018 (2013);*
Ions in 2D: Nath, MD et al., arXiv.1504.01474
Rydberg atoms: Glaetzle, MD et al., PRX 4, 041037; and PRL 114, 173002
TN approaches: Rico, Pichler, MD, Zoller, Montangero, PRL ***112****, 201601.*

Review on dynamical gauge fields and quantum simulation: *U.-J. Wiese, Annalen der Physik 525, 777 (2013).*