Title: Gate-Based Quantum Simulation of Strongly Correlated Fermions - Philipp Preiss

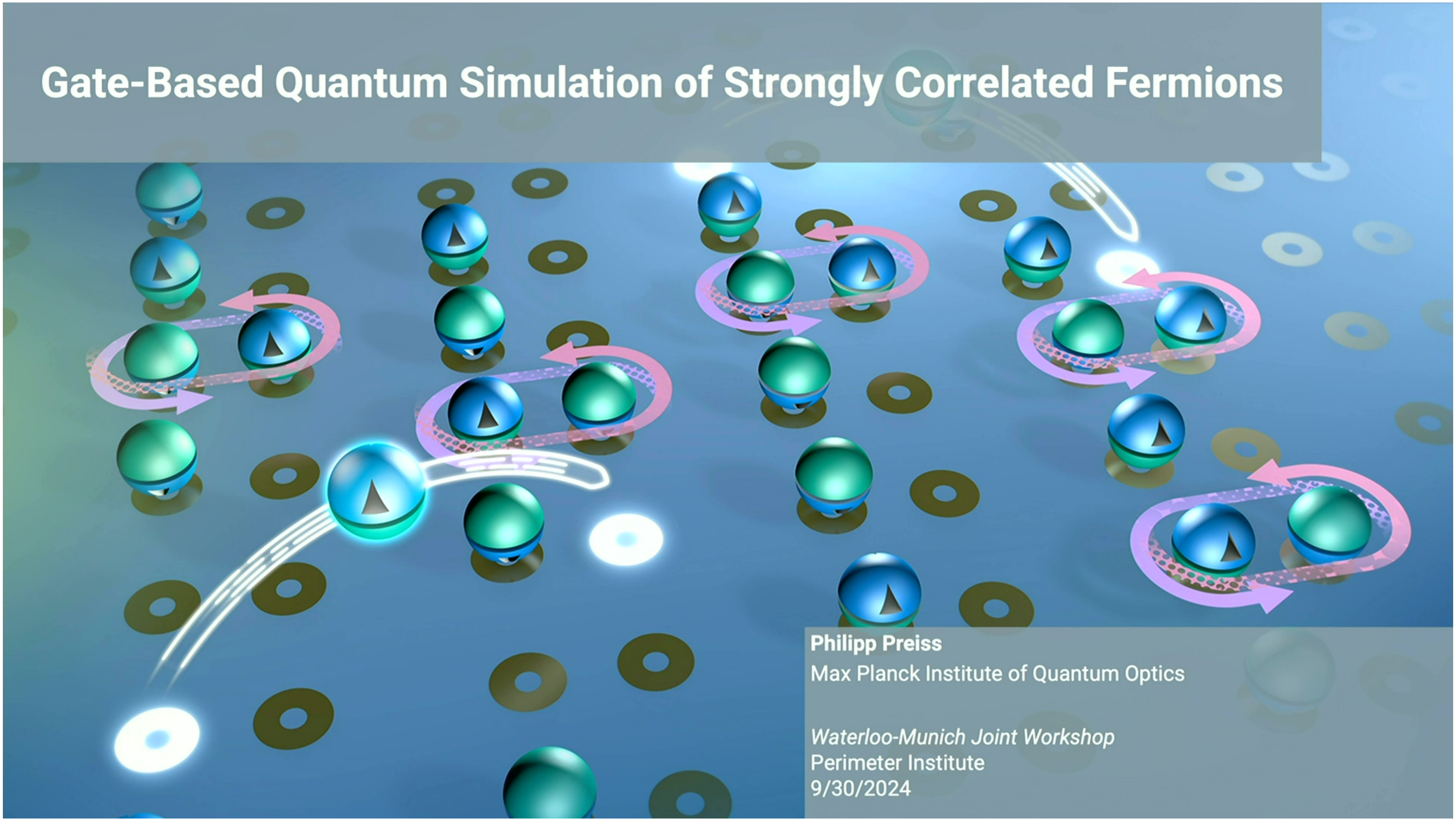
Speakers: Philipp Preiss

Collection/Series: Waterloo-Munich Joint Workshop

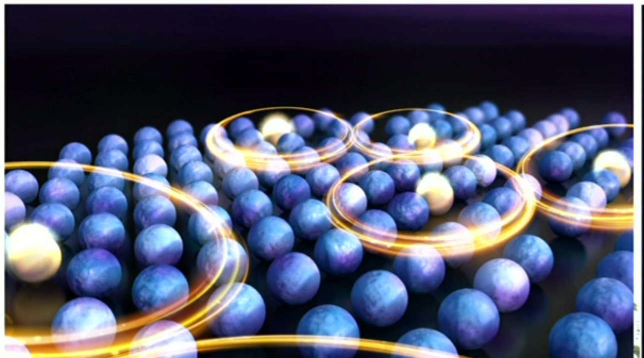
Subject: Quantum Information

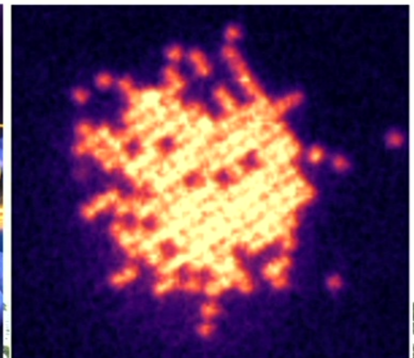
Date: September 30, 2024 - 11:00 AM

URL: https://pirsa.org/24090181


Gate-Based Quantum Simulation of Strongly Correlated Fermions
Philipp Preiss
Max Planck Institute of Quantum Optics
Waterloo-Munich Joint Workshop
Perimeter Institute
9/30/2024

Quantum Many Body Division





Ultracold atoms in optical lattices

- Quantum simulation
- Bose- and Fermi-Hubbard models
- Quantum computing

Immanuel Bloch

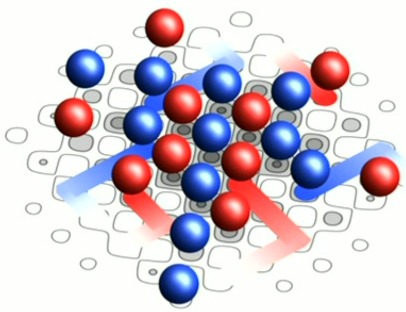
https://www.quantum-munich.de/

See also
Johannes Zeiher's talk on Thursday:
Rydberg simulation and computation

Ultracold Fermions @ MPQ

Two new Fermi microscope experiments

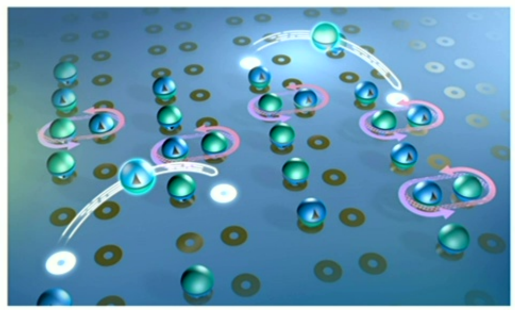
UniRand
Random unitaries in lattices



- Optical lattice assembly
- Combine tweezers + lattice

FermiQP
Hybrid digital/analog simulator

with Titus Franz



- Fermi Hubbard systems
- Gate-based simulation

Li 1.0
Fermion Microscope

Titus Franz & Timon Hilker

- Fermi Hubbard simulation
- Gate-based approach to fermions

Teams@MPQ

UniRand


Naman Jain

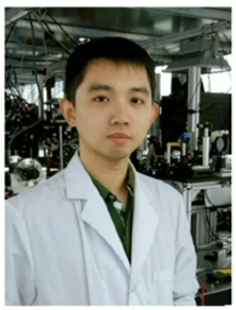

Daniel Dux


Jin Zhang


Xinyi Huang


Marcus Culemann

FermiQP


Liyang Qiu

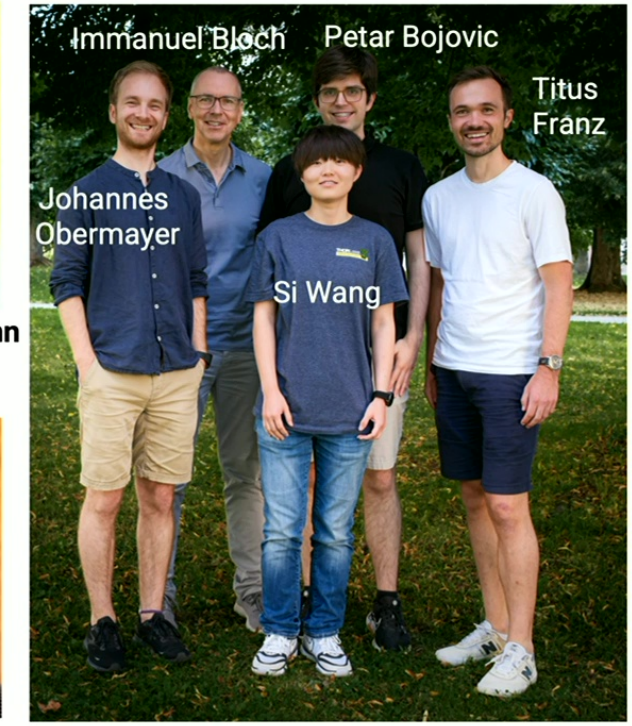

Luca Muscarella


Janet Qesja

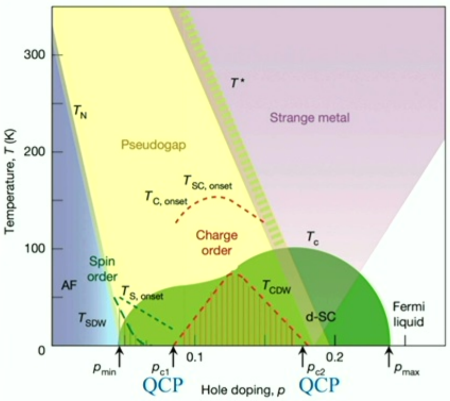

Andreas v Haaren


Robin Groth

Lithium 1.0

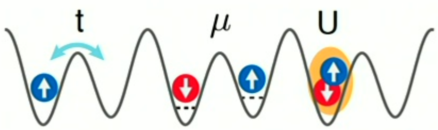


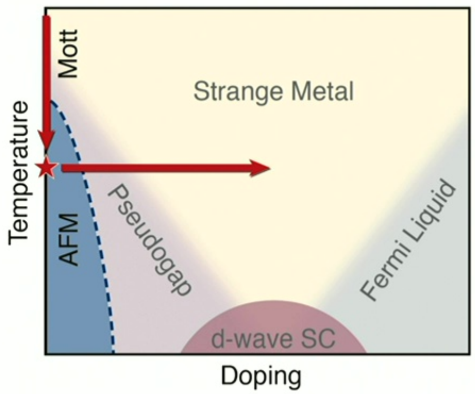
Many-fermion problems



Condensed matter physics

Quantum Simulation of the Fermi-Hubbard model

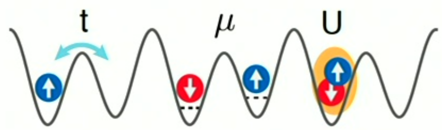


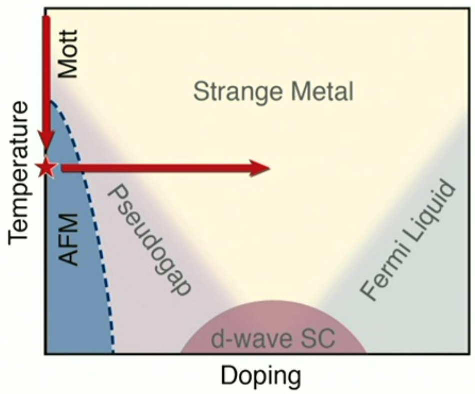


- Minimalistic model for solid state systems
- Relation to cuprates, high T_c superconductors

M. Qin ... S. Zhang, Phys. Rev. X **10**, 031016 (2020)
H. Xu, C.-M. Chung ... S. Zhang, *arxiv* 2303.08376 (2023)

Quantum Simulation of the Fermi-Hubbard model





PHYSICAL REVIEW X **10**, 031016 (2020)

Absence of Superconductivity in the Pure Two-Dimensional Hubbard Model

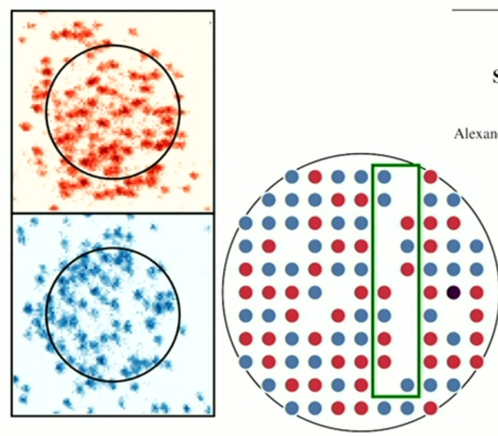
Mingpu Qin,[1,2,*] Chia-Min Chung,[3,4,*] Hao Shi,[5] Ettore Vitali,[6,2] Claudius Hubig,[7]
Ulrich Schollwöck,[3,4] Steven R. White,[8] and Shiwei Zhang[5,2]

PHYSICAL REVIEW X **11**, 031007 (2021)

Stripes, Antiferromagnetism, and the Pseudogap in the Doped Hubbard Model at Finite Temperature

Alexander Wietek,[1,*] Yuan-Yao He,[1] Steven R. White,[2] Antoine Georges,[1,3,4,5] and E. Miles Stoudenmire[1]
[1]*Center for Computational Quantum Physics, Flatiron Institute, 162 Fifth Avenue, New York, New York 10010, USA*
[2]*Department of Physics and Astronomy, University of California, Irvine, California 92697-4575 USA*
[3]*Collège de France, 11 place Marcelin Berthelot, 75005 Paris, France*
[4]*CPHT, CNRS, École Polytechnique, IP Paris, F-91128 Palaiseau, France*
[5]*DQMP, Université de Genève, 24 quai Ernest Ansermet, CH-1211 Genève, Switzerland*

(Received 12 October 2020; revised 24 March 2021; accepted 11 May 2021; published 12 July 2021)

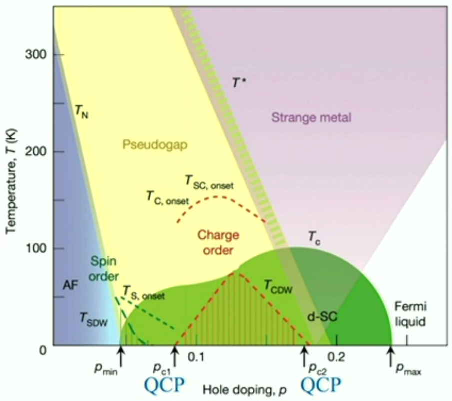


- Minimalistic model for solid state systems
- Relation to cuprates, high T_c superconductors

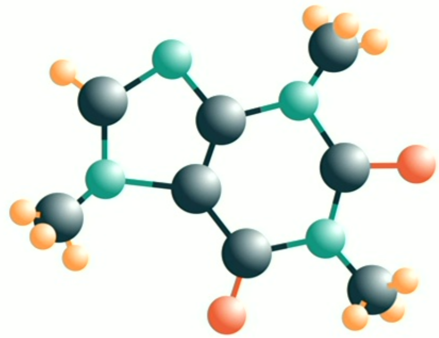
M. Qin … S. Zhang, Phys. Rev. X **10**, 031016 (2020)
H. Xu, C.-M. Chung … S. Zhang, *arxiv* 2303.08376 (2023)

S. Hirthe … T. Hilker, Nature **613**, 463 (2023)
D. Bourgund … T. Hilker, *arxiv* 2212.14156 (2023)

Many-fermion problems

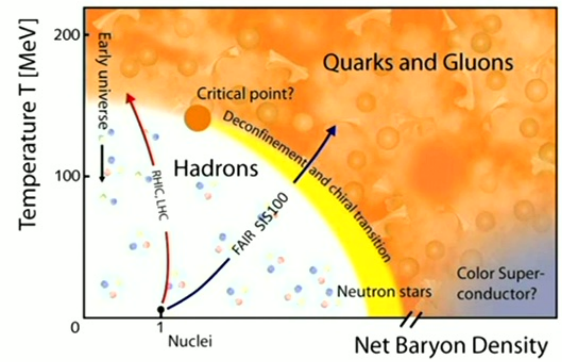


Condensed matter physics



Quantum chemistry

Material science



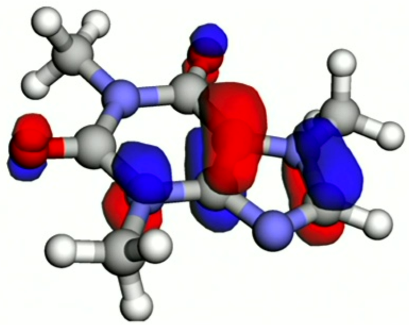
High energy physics

$$\mathcal{H} = \sum_{ij} h^{(1)}_{ij}\, c_i^\dagger c_j + \sum_{ijkl} h^{(2)}_{ijkl}\, c_i^\dagger c_j^\dagger c_k c_l$$

Fermions are every where in nature: electrons, neutrons, protons etc.

- Exchange statistics make the many-body problem particularly hard
- Monte Carlo methods suffer from the “sign problem”

Quantum Chemistry with quantum devices



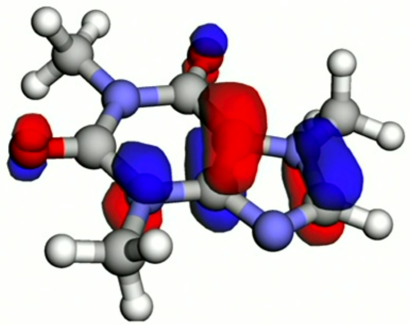
$$\mathcal{H} = \sum_{ij} h_{ij}^{(1)} \, c_i^\dagger c_j + \sum_{ijkl} h_{ijkl}^{(2)} \, c_i^\dagger c_j^\dagger c_k c_l$$

State of the art:

Simulation of few fermionic modes with ions/SCqubits

A. Kandala … J.M. Gambetta,, Nature **549**, 242 (2017)
C. Hempel … C. Roos, PRX **8**, 031022 (2018)
P.J.J. O'Malley … J.M. Martinis, PRX **6**, 031007 (2016)
… and many more

Quantum Chemistry with quantum devices



$$\mathcal{H} = \sum_{ij} h_{ij}^{(1)} \, c_i^\dagger c_j + \sum_{ijkl} h_{ijkl}^{(2)} \, c_i^\dagger c_j^\dagger c_k c_l$$

State of the art:

Simulation of few fermionic modes with ions/SCqubits

A. Kandala … J.M. Gambetta,, Nature **549**, 242 (2017)
C. Hempel … C. Roos, PRX **8**, 031022 (2018)
P.J.J. O'Malley … J.M. Martinis, PRX **6**, 031007 (2016)
… and many more

Electron to qubit mapping

Jordan-Wigner or Bravyi-Kitaev transformation

$$c_j^\dagger = \sigma_j^+ e^{(-i\pi \sum_{k=1}^{j-1})\sigma_k^+ \sigma_k^-}$$

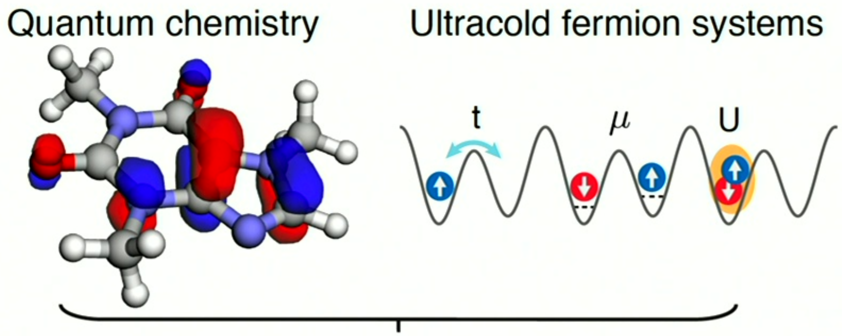
Hydrogen molecule in spin form:

$$\begin{aligned} H^{\mathrm{BK}} = {} & f_0 \mathcal{I} + f_1 \sigma_0^z + f_2 \sigma_1^z + f_3 \sigma_2^z + f_4 \sigma_1^z \sigma_0^z + f_5 \sigma_2^z \sigma_0^z \\ & + f_6 \sigma_3^z \sigma_1^z + f_7 \sigma_2^x \sigma_1^z \sigma_0^x + f_8 \sigma_2^y \sigma_1^z \sigma_0^y + f_9 \sigma_2^z \sigma_1^z \sigma_0^z \\ & + f_{10} \sigma_3^z \sigma_2^z \sigma_0^z + f_{11} \sigma_3^z \sigma_2^z \sigma_1^z + f_{12} \sigma_3^z \sigma_2^x \sigma_1^z \sigma_0^x \\ & + f_{13} \sigma_3^z \sigma_2^y \sigma_1^z \sigma_0^y + f_{14} \sigma_3^z \sigma_2^z \sigma_1^z \sigma_0^z, \end{aligned} \quad \text{(B1)}$$

Difficult to solve fermionic problems with spins

D. Gonzalez-Cuadra … P. Zoller., arXiv: 2303.06985 (2023)

Quantum chemistry and cold fermions



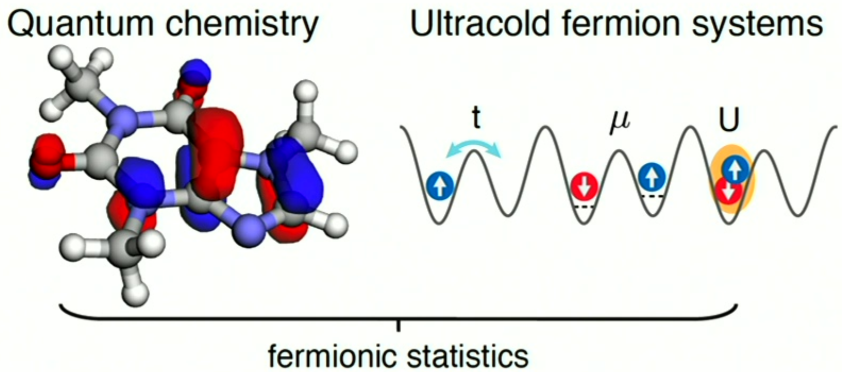
fermionic statistics

quantum numbers
particle number **N**, magnetization $\mathbf{S_z}$, total spin **S**

Ultracold fermions

- Conserved quantum numbers
- Targeted preparation of total spin S

Quantum chemistry and cold fermions



quantum numbers
particle number **N**, magnetization $\mathbf{S_z}$, total spin **S**

Ultracold fermions
- Conserved quantum numbers
- Targeted preparation of total spin S

But
- Translationally invariant Hamiltonians
- Short-range interactions

Analogue Quantum Chemistry Simulation
J. Argüello-Luengo… I. Cirac., Nature **574,** 215 (2019)

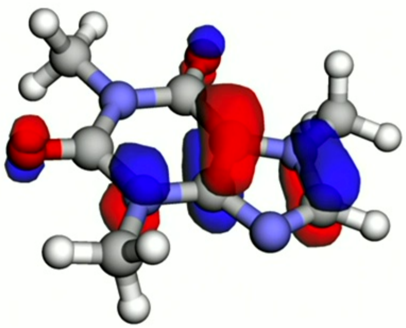
Quantum Chemistry with Superlattices

Daniel Dux | Jin Zhang | Naman Jain

Christian Gogolin

covestro

Bundesministerium für Bildung und Forschung



- Chemicals/polymers company
- Exploring quantum methods for computational chemistry
- Optimization problems for molecules

G.-L. Anselmetti *et al.*, New J. Phys. **23** (2021) 113010
O. Oumaruet *al.*, arxiv:2212.07957 (2022)
T. O'Brien *et al.*, *Nature Physics*. **19** 1787 (2023)

Can quantum chemistry problems be mapped to ultracold fermions in lattices?

Our work: F. Gkritsis, ..., P.Preiss, arXiv 2409.05663 (2024)

Variational Quantum Eigensolvers

- Trial wavefunction with few parameters

$$|\Psi_{trial}\rangle = U(\vec{\varphi},\vec{\theta})|\Psi_0\rangle$$

- Evaluate energy functional

$$\mathcal{H} = \sum_{ij} h_{ij}^{(1)}\, c_i^\dagger c_j + \sum_{ijkl} h_{ijkl}^{(2)}\, c_i^\dagger c_j^\dagger c_k c_l$$

$$E_{var}(\vec{\varphi},\overrightarrow{\theta}) = \langle\Psi_{\mathrm{trial}}|H|\Psi_{\mathrm{trial}}\rangle$$

- Minimize $E_{var}(\vec{\varphi},\overrightarrow{\theta})$ to approximate ground state

G-L Anselmetti *et al.*, New J. Phys. **23** (2021) 113010

Variational Quantum Eigensolvers

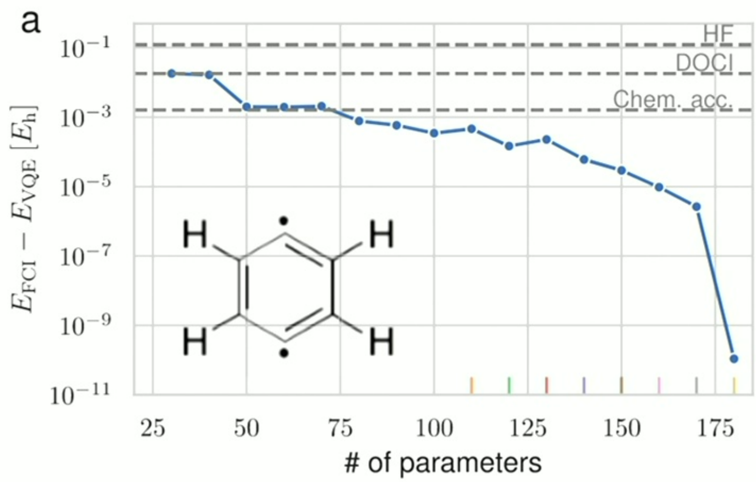
- Trial wavefunction with few parameters

$$|\Psi_{trial}\rangle = U(\vec{\varphi}, \vec{\theta})|\Psi_0\rangle$$

- Evaluate energy functional

$$\mathcal{H} = \sum_{ij} h_{ij}^{(1)}\, c_i^\dagger c_j + \sum_{ijkl} h_{ijkl}^{(2)}\, c_i^\dagger c_j^\dagger c_k c_l$$

$$E_{var}(\vec{\varphi}, \overrightarrow{\theta}) = \langle \Psi_{\text{trial}}|H|\Psi_{\text{trial}}\rangle$$

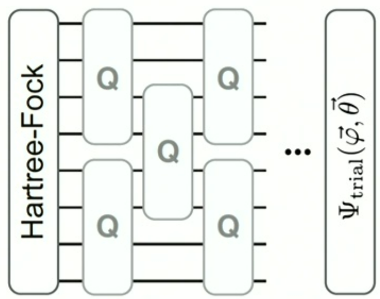


- Minimize $E_{var}(\vec{\varphi}, \overrightarrow{\theta})$ to approximate ground state

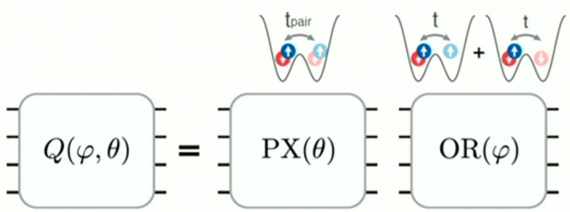
G-L Anselmetti *et al.*, New J. Phys. **23** (2021) 113010

Fermionic algorithms

Quantum number preserving (QNP) fabrics



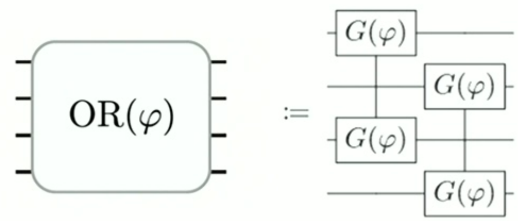
local
universal
expressive



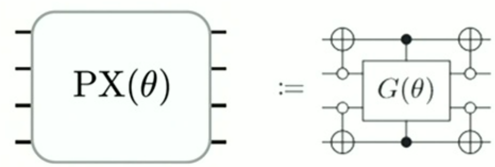
- Good quantum numbers N, S_z, S
- Universal parametrization of the wavefunction

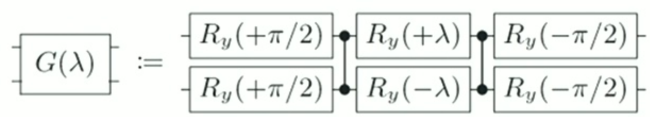
Spin representation:

tunneling



pair tunneling





G-L Anselmetti *et al.*, New J. Phys. **23** (2021) 113010

Fermion mapping

RESEARCH ARTICLE | PHYSICS

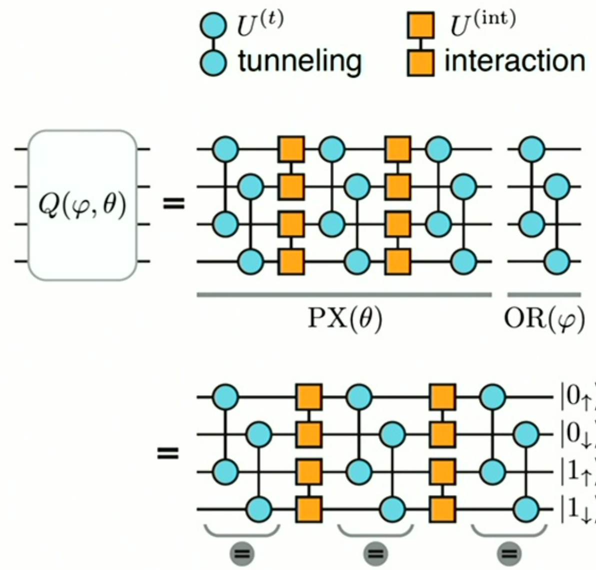
Fermionic quantum processing with programmable neutral atom arrays

D. González-Cuadra, D. Bluvstein, M. Kalinowski, R. Kaubruegger, N. Maskara, P. Naldesi, T. V. Zache, A. M. Kaufman, M. D. Lukin, H. Pichler, B. Vermersch, Jun Ye, and P. Zoller Authors Info & Affiliations

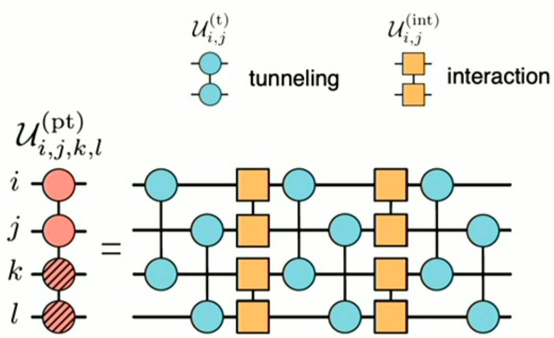
Edited by Jean Dalibard, College de France, Paris, France; received March 15, 2023; accepted July 26, 2023

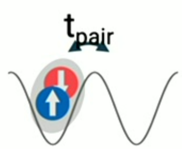
August 22, 2023 | 120 (35) e2304294120 | https://doi.org/10.1073/pnas.2304294120

QNP fabric with fermion terms



Arbitrary fermionic terms from tunneling and interaction



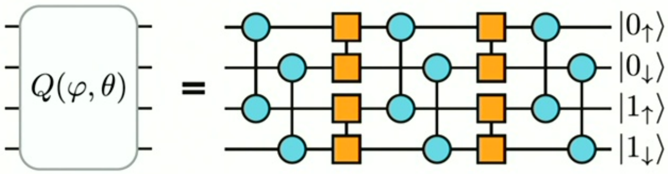


D. Gonzalez-Cuadra *et al.*, PNAS **120**, e2304294120 (2023)

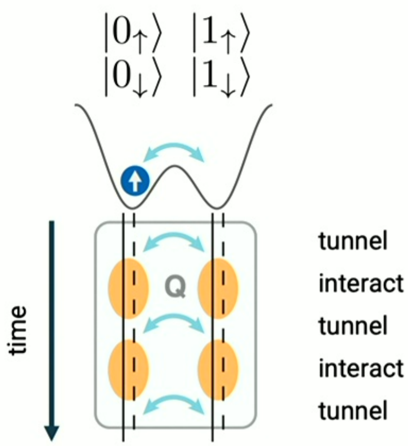
- Tunneling operations with ‘locked' parameters
- Depth 5 (c.f. spin scheme: 17 CNOTs + rotations)

Lattice realization

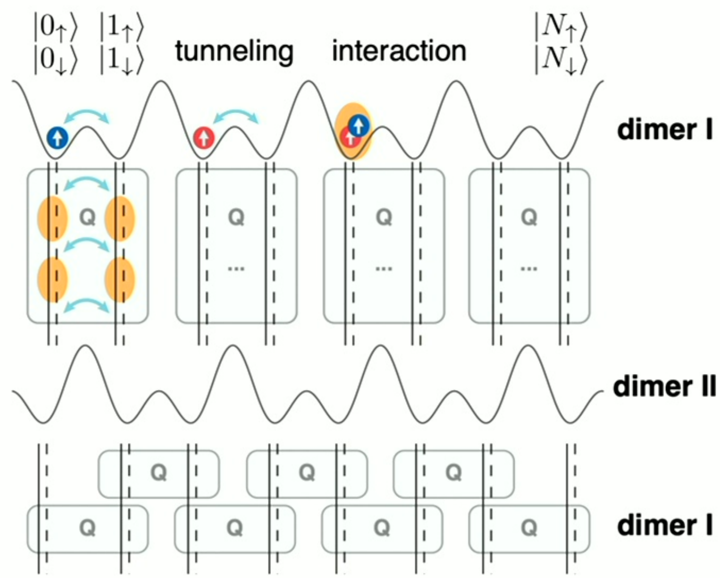
Q-gate representation



Double-well



Superlattice



Hubbard superlattice naturally realizes the full QNP fabric

Experimentally friendly U$^{(t)}$

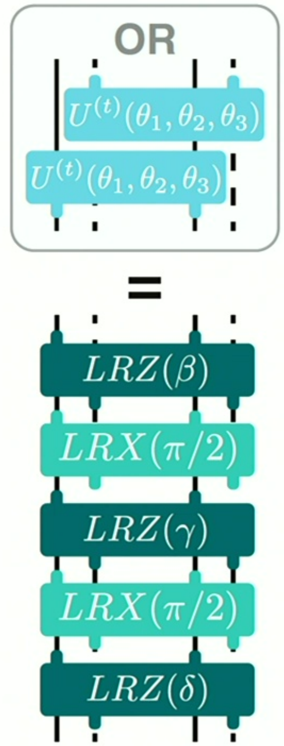
$$\mathcal{U}^{(t)}_{i,j}\left(\vec{\theta}\right) \equiv e^{-i\left[\frac{\theta_1}{2}\left(e^{-i\theta_2}c_i^\dagger c_j+\text{H.c.}\right)+\frac{\theta_3}{2}\left(n_i-n_j\right)\right]}$$

$U^{(t)}$

generalized tunneling
complex tunneling + bias

Lattice X
real tunneling

Lattice Z
bias



Local bias

Tunneling pi/2 'beamsplitter'

Local bias

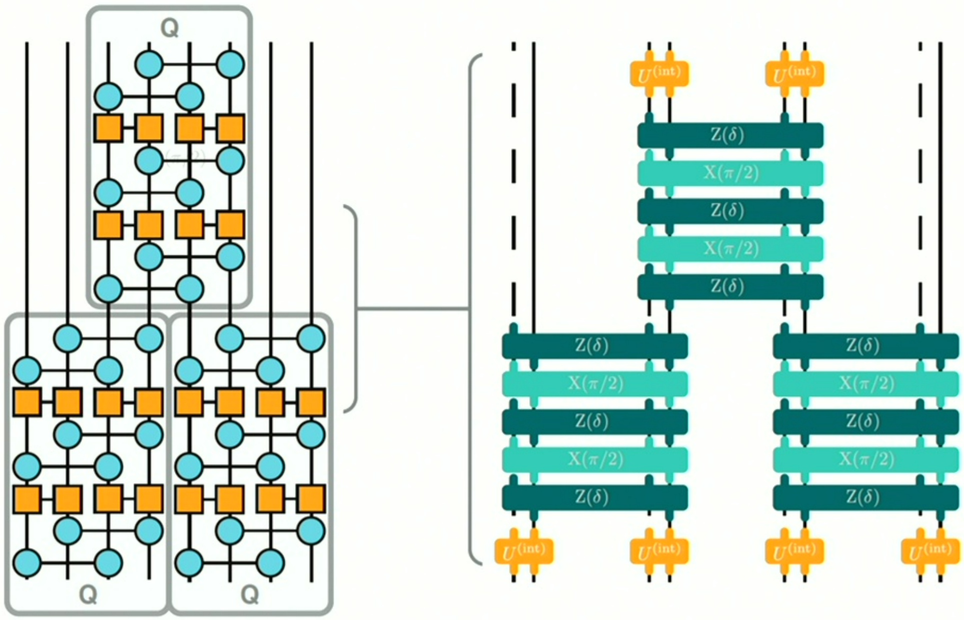
Tunneling pi/2 'beamsplitter'

Local bias

Freedom to choose experimental realization

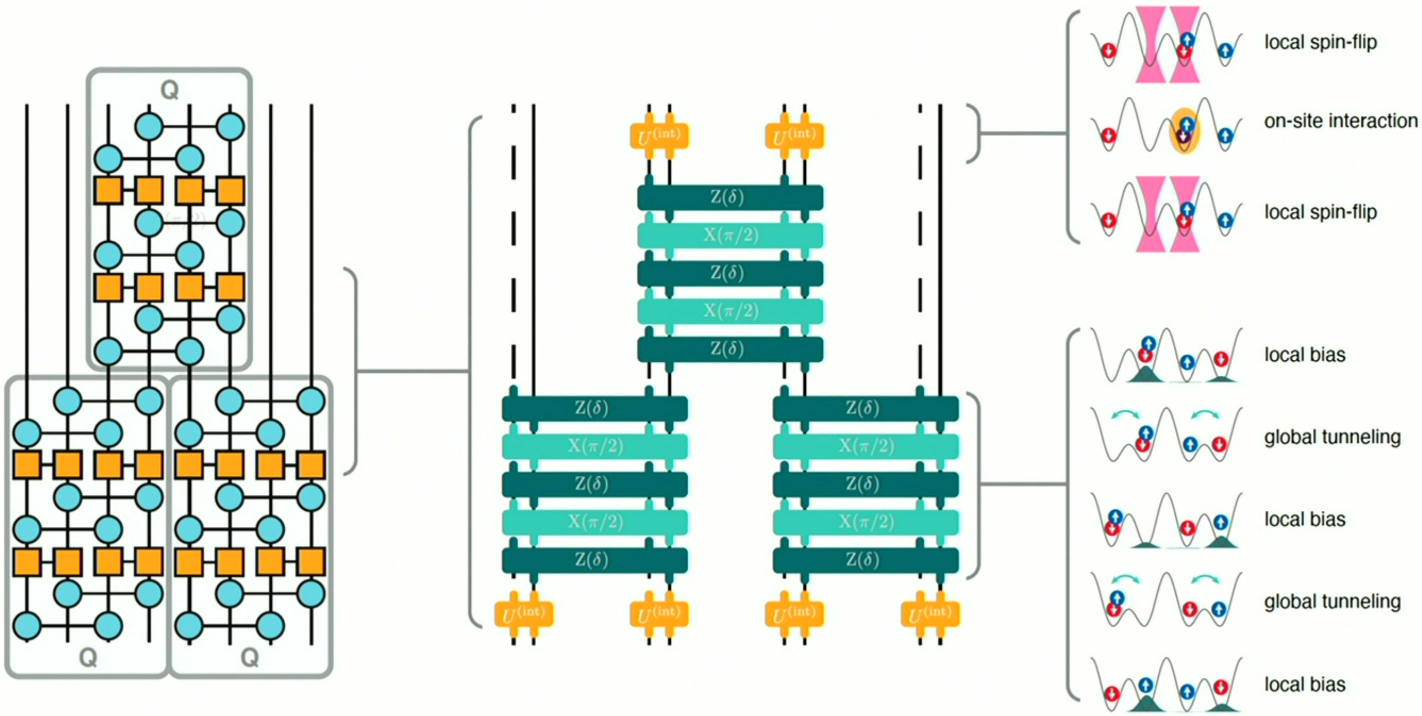
Z3X2: Three bias and two tunneling pulses

Fermionic circuits



- **Local** bias and interaction
- **Global** tunneling/beamsplitter pulses

Fermionic circuits



- **Local** bias and interaction
- **Global** tunneling/beamsplitter pulses

Measurements in VQE

- Trial wavefunction with few parameters

$$|\Psi_{trial}\rangle = U(\vec{\varphi},\vec{\theta})|\Psi_0\rangle$$

- Evaluate energy functional

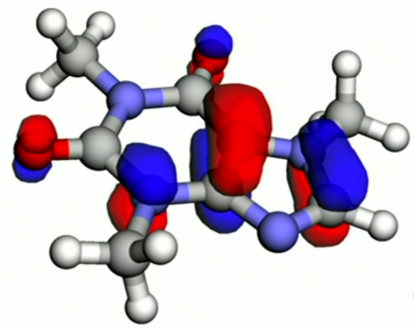
$$\mathcal{H} = \sum_{ij} h_{ij}^{(1)}\, c_i^\dagger c_j + \sum_{ijkl} h_{ijkl}^{(2)}\, c_i^\dagger c_j^\dagger c_k c_l$$

$$E_{var}(\vec{\varphi},\overrightarrow{\theta}) = \langle\Psi_{\text{trial}}|H|\Psi_{\text{trial}}\rangle$$

- Minimize $E_{var}(\vec{\varphi},\overrightarrow{\theta})$ to approximate ground state

Measuring the energy is extremely challenging

G-L Anselmetti *et al.*, New J. Phys. **23** (2021) 113010



m active spin orbitals

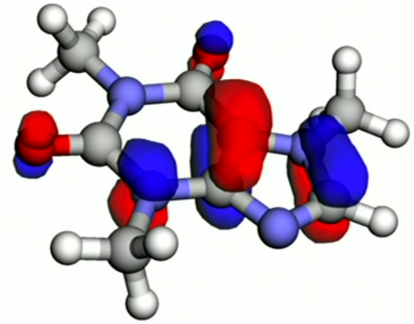
1. Types of terms

- Long-range off-diagonal coherences $\langle c_{\sigma,i}^\dagger c_{\sigma',j}^\dagger c_{\sigma',k} c_{\sigma,l}\rangle$
- Measurements can only access densities $\langle n_{\sigma,i} n_{\sigma',j}\rangle$

2. Number of terms

- Hamiltonian with m^4 correlator terms
- E.g. for m=100 need to measure 10^8 (small) quantities

Double Factorization: Coherences



- Approximate H by basis rotations into n_l 'leaves'
- Each leaf is **diagonal in $\boldsymbol{n_i n_j}$**

$$\hat{H} \approx \hat{H}_{\mathrm{DF}} = U_0 \, \hat{p}^{(1)} \, U_0^\dagger + \sum_{l=1}^{n_l} U_l \, \hat{p}_l^{(2)} \, U_l^\dagger$$

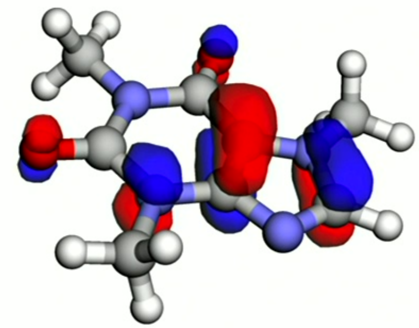
$$n_l \leq m(m+1)/2$$

$$\hat{p}^{(1)} = \sum_{i=1}^{m} h_i \hat{n}_i \qquad \hat{p}_l{}^{(2)} = \sum_{i,j=1}^{m} h_{i,j}^l \hat{n}_i \hat{n}_j$$

- Only density-density measurements required $\langle n_{\sigma,i} n_{\sigma',j} \rangle$

O. Oumarou, ..., C. Gogolin., arXiv:2212.07957(2022)
E. Hohenstein, ..., R. Parrish, J. Chem. Phys. 158, 114119 (2023)

Double Factorization: Coherences



- Approximate H by basis rotations into n_l 'leaves'
- Each leaf is **diagonal in $\boldsymbol{n_i n_j}$**

$$\hat{H} \approx \hat{H}_{\mathrm{DF}} = U_0\, \hat{p}^{(1)}\, U_0^\dagger + \sum_{l=1}^{n_l} U_l\, \hat{p}_l^{(2)}\, U_l^\dagger$$

$$n_l \leq m(m+1)/2$$

$$\hat{p}^{(1)} = \sum_{i=1}^{m} h_i \hat{n}_i \qquad \hat{p_l}^{(2)} = \sum_{i,j=1}^{m} h_{i,j}^l \hat{n}_i \hat{n}_j$$

- Only density-density measurements required $\langle n_{\sigma,i} n_{\sigma',j} \rangle$

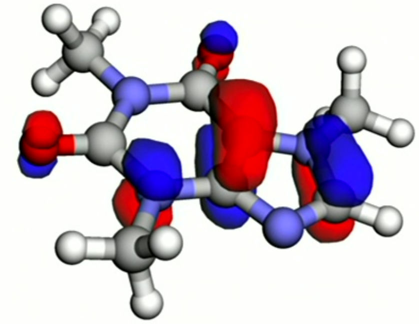
Basis rotations $\boldsymbol{U_l}$ from Double Factorization:

- U_l can be implemented by orbital rotations
- Brick-wall structure with linear depth
- Subset of state preparation!

Simple access to off-diagonal coherences

O. Oumarou, ..., C. Gogolin., arXiv:2212.07957(2022)
E. Hohenstein, ..., R. Parrish, J. Chem. Phys. 158, 114119 (2023)

Number of terms



Dealing m⁴ terms

- In principle need m^2 different bases

$$\hat{H} \approx \hat{H}_{\mathrm{DF}} = U_0\, \hat{p}^{(1)}\, U_0^\dagger + \sum_{l=1}^{n_l} U_l\, \hat{p}_l^{(2)}\, U_l^\dagger$$

$$n_l \leq m(m+1)/2$$

$$\hat{p_l}^{(2)} = \sum_{i,j=1}^{m} h_{i,j}^{l} \hat{n}_i \hat{n}_j$$

Double Factorization:

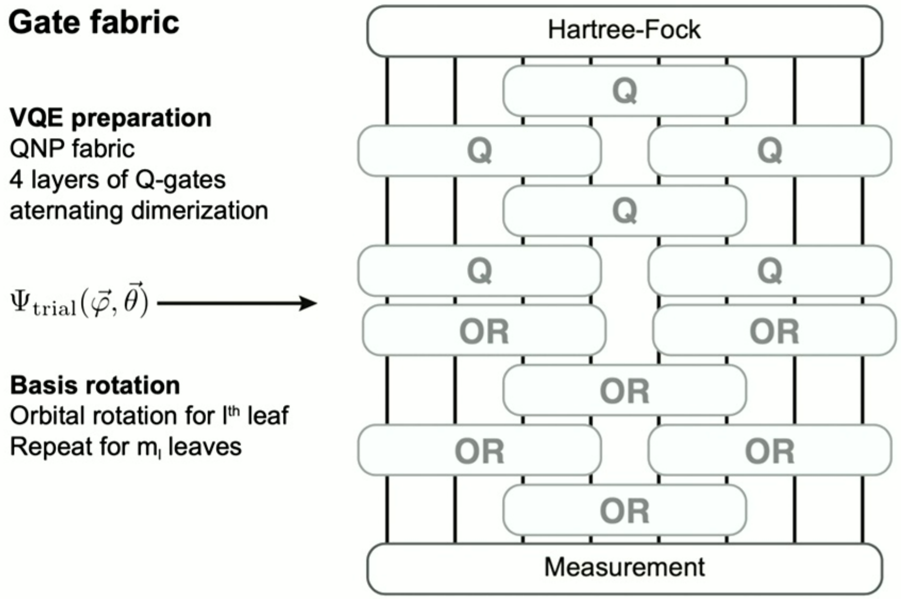
- Minimize n_l for target accuracy
- Conditions U_l for minimal variance
- Automatically assigns shot counts

Shot count reduction

- In practice need $n_l \ll m^2/2$ different bases
- E.g. for HF with m=16 orbitals: 16 bases instead of 136
- Reduces shout counts by 1-2 orders of magnitude

O. Oumarou, ..., C. Gogolin., arXiv:2212.07957(2022)
E. Hohenstein, ..., R. Parrish, J. Chem. Phys. 158, 114119 (2023)

Double factorization



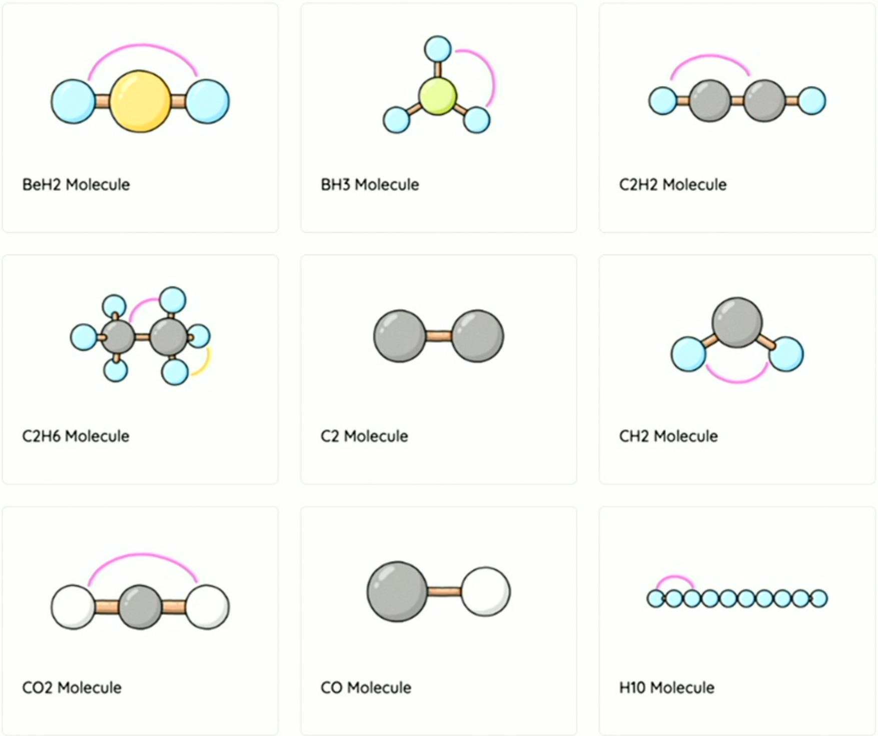
- Measure different 'leaves'
- State prep is identical
- Only the final basis rotation changes

Code integration

```
import pennylane as qml

H, qubits = qml.qchem.molecular_hamiltonian(symbols, coordinates)
print("Number of qubits = ", qubits)
print("The Hamiltonian is ", H)
```

```
Number of qubits =  4
The Hamiltonian is    (-0.2427450126094144) [Z2]
+ (-0.2427450126094144) [Z3]
+ (-0.042072551947439224) [I0]
+ (0.1777135822909176) [Z0]
+ (0.1777135822909176) [Z1]
+ (0.12293330449299361) [Z0 Z2]
+ (0.12293330449299361) [Z1 Z3]
+ (0.16768338855601356) [Z0 Z3]
```

Qchem (35)



Code integration

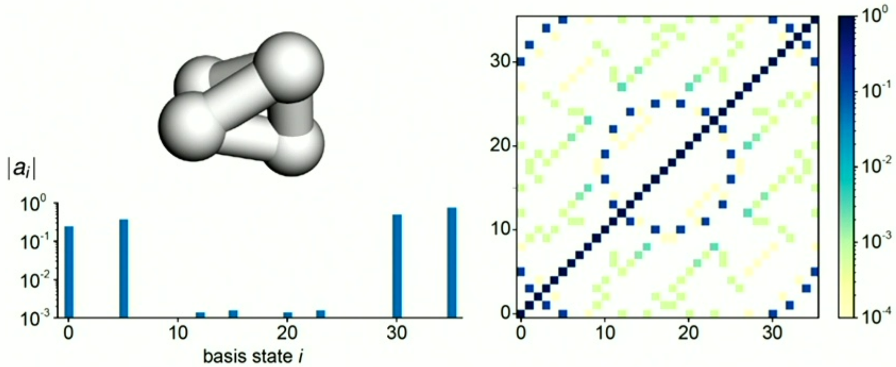
```python
import pennylane as qml

H, qubits = qml.qchem.molecular_hamiltonian(symbols, coordinates)
print("Number of qubits = ", qubits)
print("The Hamiltonian is ", H)
```

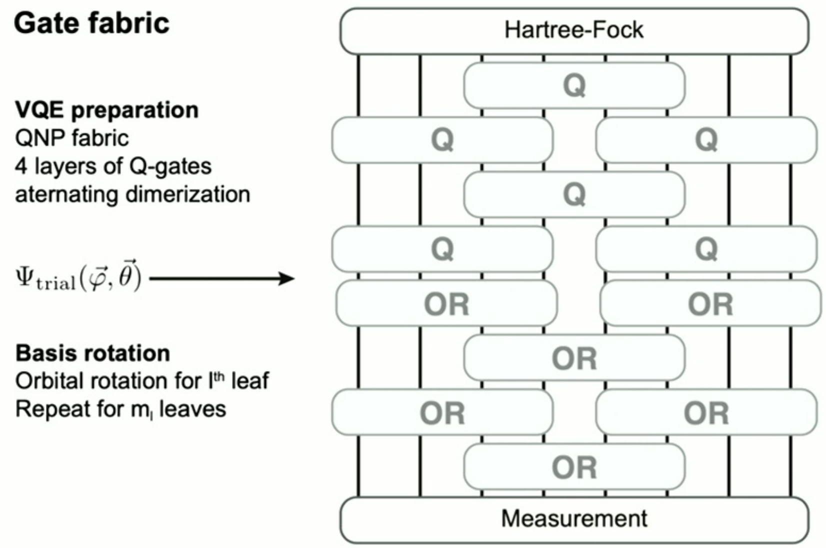
```
Number of qubits =  4
The Hamiltonian is    (-0.2427450126094144) [Z2]
+ (-0.2427450126094144) [Z3]
+ (-0.042072551947439224) [I0]
+ (0.1777135822909176) [Z0]
+ (0.1777135822909176) [Z1]
+ (0.12293330449299361) [Z0 Z2]
+ (0.12293330449299361) [Z1 Z3]
+ (0.16768338855601356) [Z0 Z3]
```

```
Circuit for leaf 6 to be run 41219 times:
0: ─╭HartreeFock(2.00,2.00)─
1: ─├HartreeFock(2.00,2.00)─
2: ─├HartreeFock(2.00,2.00)─
3: ─├HartreeFock(2.00,2.00)─╭LatticeRZ(-2.36)─╭LatticeRX(1.57)─╭LatticeRZ(1.57)─╭LatticeRX(1.57
4: ─├HartreeFock(2.00,2.00)─│                 │                │                │
5: ─├HartreeFock(2.00,2.00)─╰LatticeRZ(-2.36)─╰LatticeRX(1.57)─╰LatticeRZ(1.57)─╰LatticeRX(1.57
6: ─├HartreeFock(2.00,2.00)─
7: ─╰HartreeFock(2.00,2.00)─

                      ╭LatticeRZ(-2.36)─╭LatticeRX(1.57)─╭LatticeRZ(1.57)─╭LatticeRX(1.57)
──╭LatticeRZ(10.21)─│                 │                │                │
                      ╰LatticeRZ(-2.36)─╰LatticeRX(1.57)─╰LatticeRZ(1.57)─╰LatticeRX(1.57)
──╰LatticeRZ(10.21)─

──╭LatticeRZ(10.21)─╭Uint(1.10)─
                      ╰Uint(1.10)─╭LatticeRZ(-2.36)─╭LatticeRX(1.57)─╭LatticeRZ(4.71)─╭LatticeRX(
──╰LatticeRZ(10.21)─╭Uint(1.10)─│                 │                │                │
                      ╰Uint(1.10)─╰LatticeRZ(-2.36)─╰LatticeRX(1.57)─╰LatticeRZ(4.71)─╰LatticeRX(

                      ╭LatticeRZ(-2.36)─╭LatticeRX(1.57)─╭LatticeRZ(4.71)─╭LatticeRX(1.57)
──╭LatticeRZ(-0.79)─│                 │                │                │
                      ╰LatticeRZ(-2.36)─╰LatticeRX(1.57)─╰LatticeRZ(4.71)─╰LatticeRX(1.57)
──╰LatticeRZ(-0.79)─
```

Example: Tetrahedral H_4

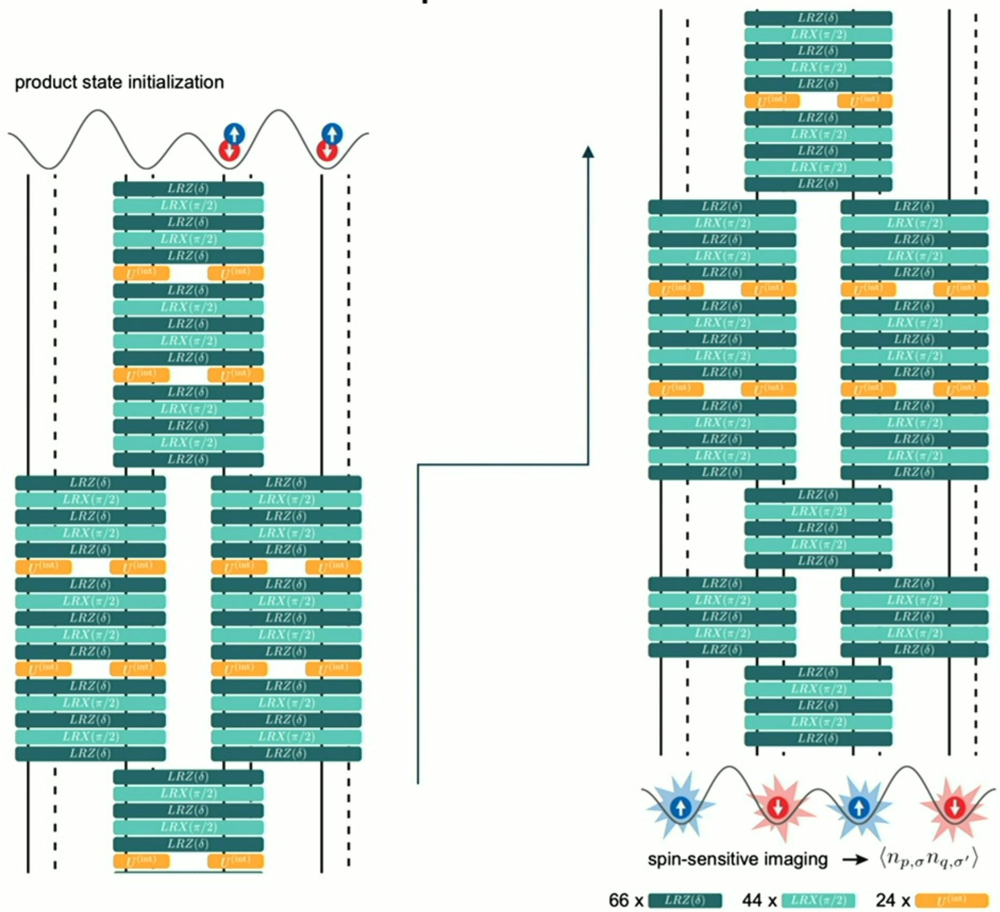
- Paradigmatic 'strongly correlated' molecule





F. Zhang *et al.*, Phys Rev Research **3**, 013039 (2021)

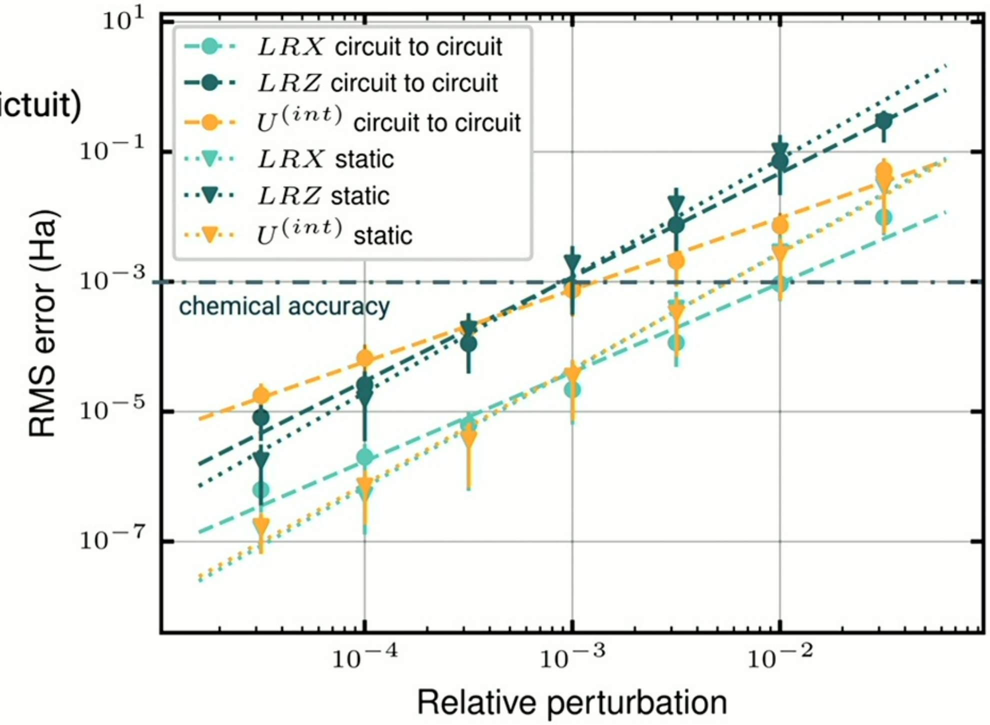
Example: Tetrahedral H_4



Error analysis: H_4

Evaluate precision requirements

- Errors on fundamental LRX, LRZ, Uint gates
- Model static errors and slow fluctuations (circuit-to-cictuit)



- Distorted H_4 molecule
- 8 modes = 2 double-wells
- Depth 83 in native gates

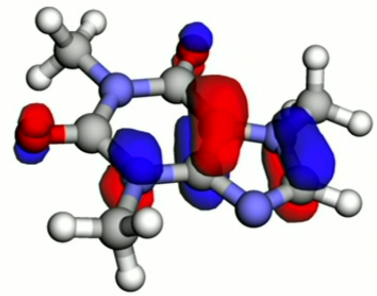
Chemical accuracy (1mHa) requires

- 150,000 measurements
- $\frac{\delta t}{t} \approx 10^{-2}$
- $\frac{\delta \mu}{\mu} \approx 10^{-3}$

Quantum Chemistry with optical lattices

Requirements for small test molecules

- Fermionic superlattice system in 1D or 2D
- *Local* potential shifting
- *Global t*unneling operations
- *Local* spin-flip for interactions
- Gate errors 10^{-2} to 10^{-3}
- 100k -200k realizations

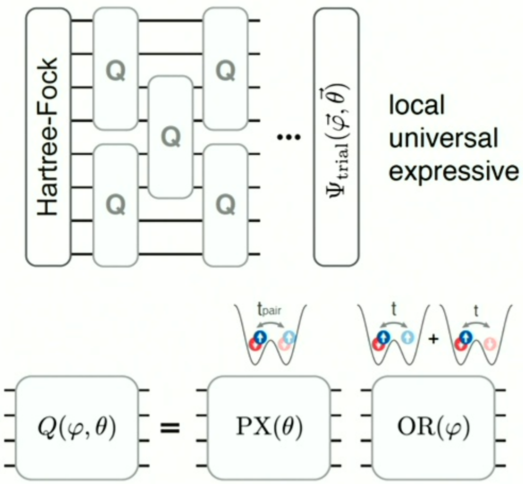


	molecule	active space	basis	RC-DF	layers	shots	depth	qubit depth
#1	H_4 tetrahedral	(4e, 4o)	cc-pvdz	$n_l = 4$	4	1.0×10^5	83	109
#2	H_4 tetrahedral	(4e, 4o)	sto-3g	$n_l = 3$	6	1.3×10^5	117	154
#3	H_4 square	(4e, 4o)	sto-3g	$n_l = 7$	7	4.9×10^5	134	175
#4	H_4 square	(4e, 4o)	sto-3g	$n_l = 7$ + FFF	7	3.0×10^5	134	175
#5	HF distance 1Å	(10e, 6o)	sto-3g	$n_l = 16$ + FFF	5	5.5×10^5	110	141

Concrete roadmap for realization of a molecular wavefunction with ultracold fermions

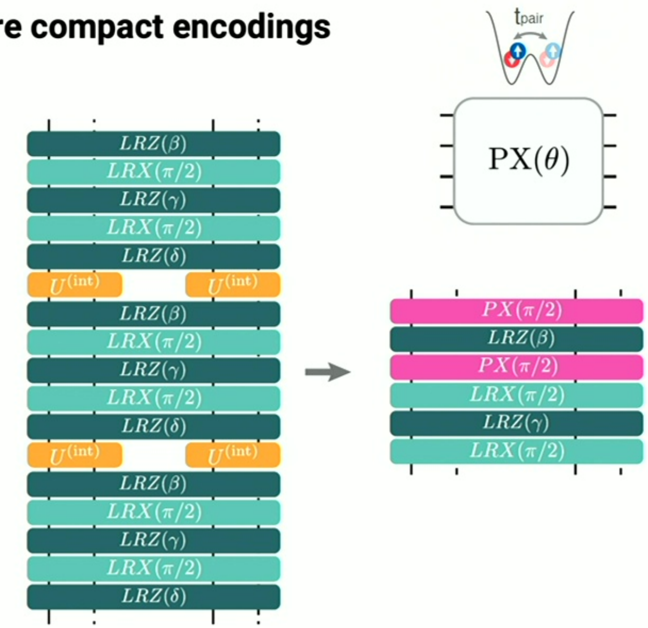
Open questions

Gate counts (fermions vs. qubits)



- Here: Circuit structure *fixed* for fermions and qubits
- No scaling advantage

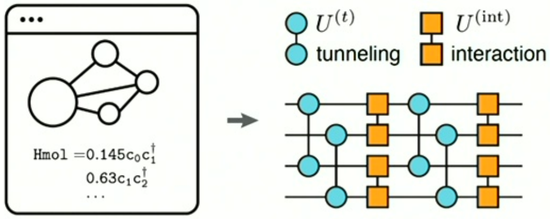
More compact encodings



Ongoing collaboration with L. Escalera, B. Schiffer, I. Cirac

Alternative fermionic ansatz: Q. Li, … A. Bayat Phys. Rev. Res. **5**, 043175 (2023)

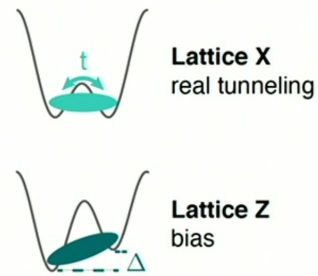
Summary

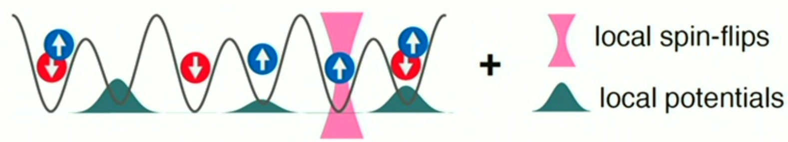


1. Mapping of variational ansatz for fermions
2. End-to-end workflow from Hamiltonian to pulse sequence
3. Noise limits on gates
4. Classical pre-optimization & double factorization

Next steps: Towards hardware implementations

- Precise control of motional sta
- Local and global control
- Control over interactions



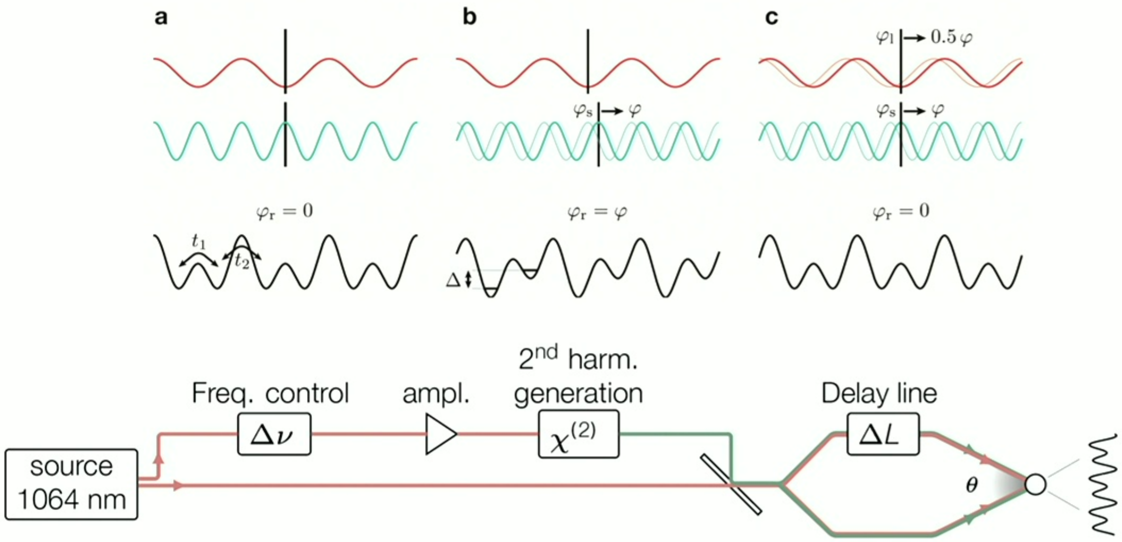


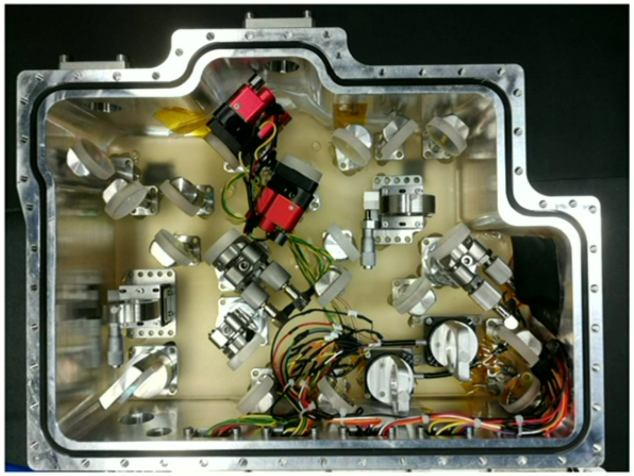
Our work: F. Gkritsis, ..., P.Preiss, arXiv 2409.05663 (2024)

Optical Superlattices (Li 1.0)

Bichromatic xy-(super)lattices in evacuated setups with tunable relative phase

- Large homogeneous system
- High phase stability

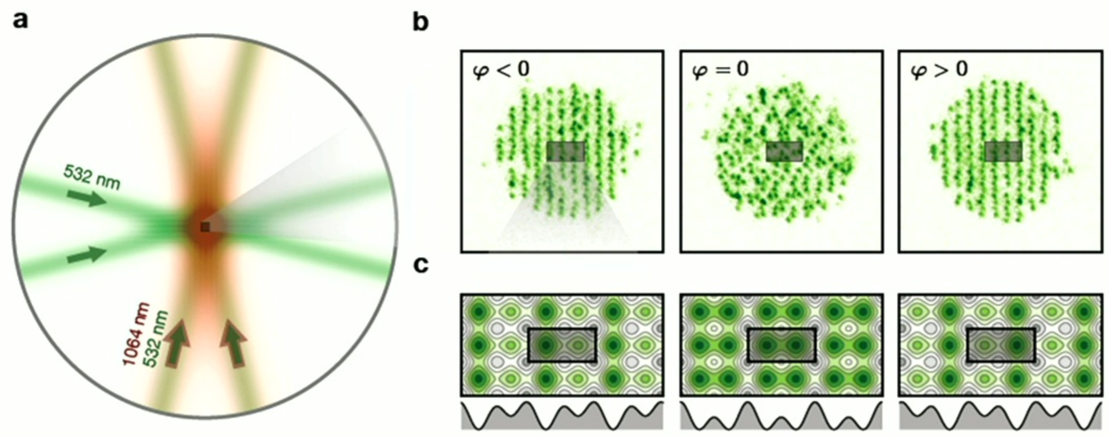




Dominik Bourgund, PhD Thesis, LMU Munich (2023)

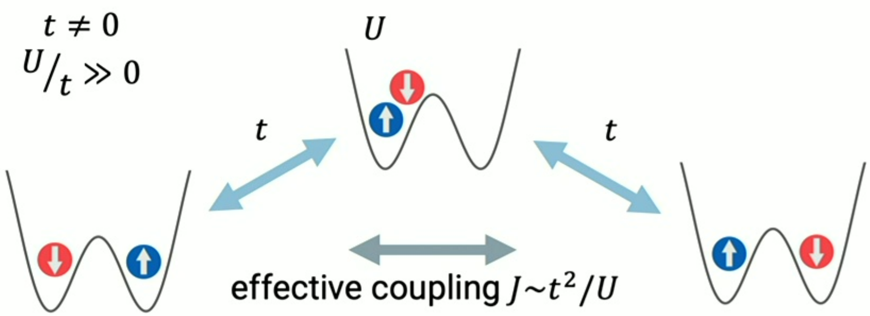
Optical Superlattices (Li 1.0)

Bichromatic xy-(super)lattices in evacuated setups with tunable relative phase

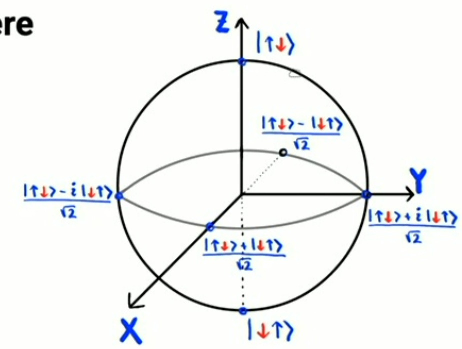


Two-qubit collisional gates

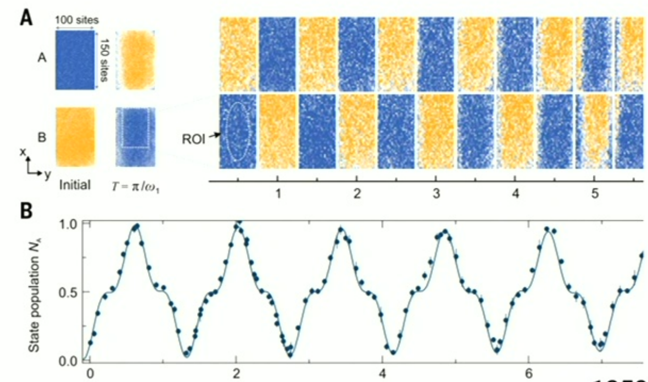
Superexchange coupling



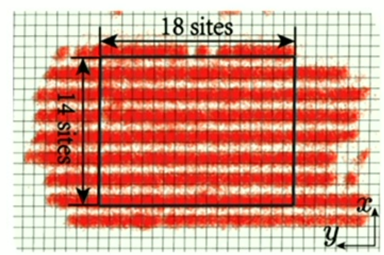
Singlet/Triplet Bloch sphere



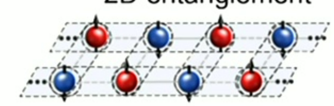
Realization by Jan Wei Pan group



1250 atom pairs
99.3(1)% fidelity



2D entanglement



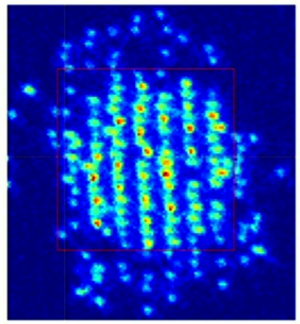
B. Yang, ..., J.-W Pan, Science **369** 550 (2020)
W.Y. Zhang...J.-W. Pan: Arxiv: 2210:02936 (2022)

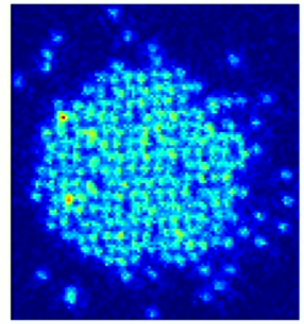
Fermionic Quantum Processing

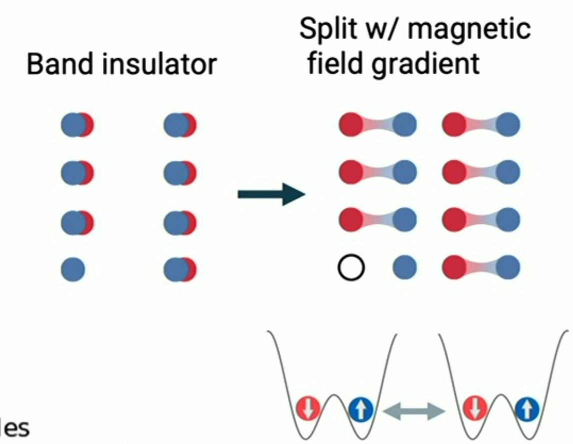
State preparation

- One atom per site
- Total Sz per double-well = 0

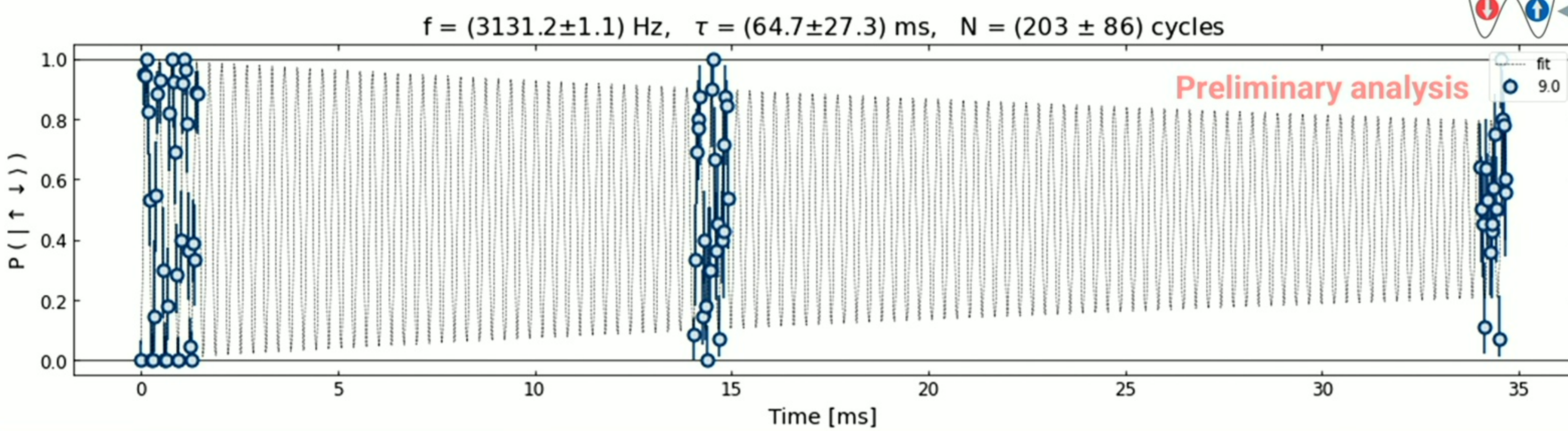
Post-select with full spin/charge resolution





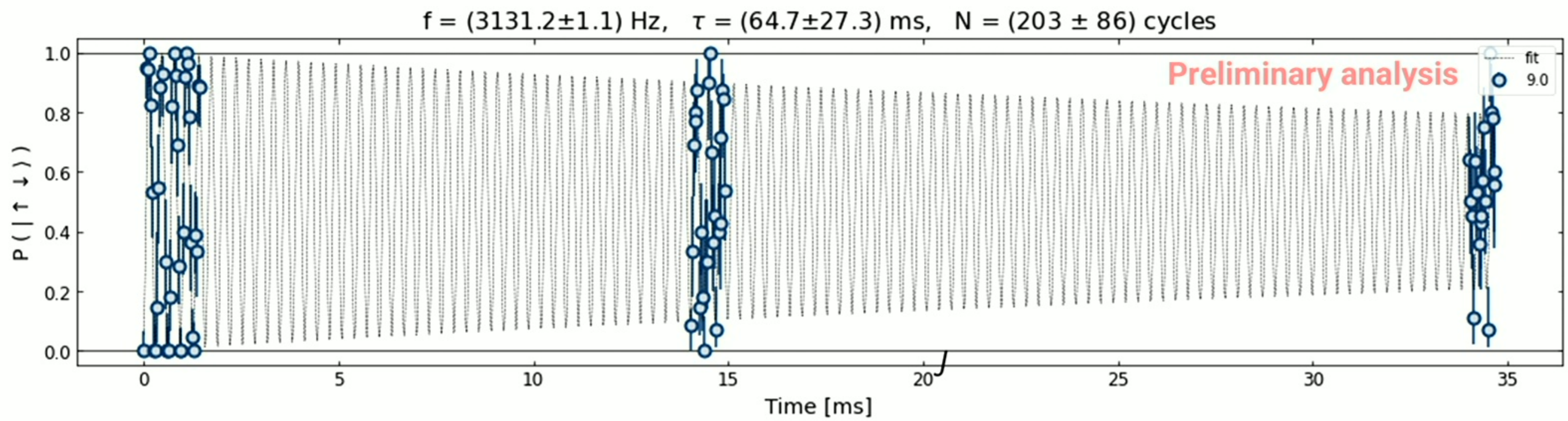


SWAP Rabi oscillations



Fermionic Quantum Processing

SWAP Rabi oscillations



π pulse: SWAP

$|\Psi\rangle = |\downarrow,\uparrow,\rangle$ → $|\Psi\rangle = |\uparrow,\downarrow\rangle$

$\pi/2$ pulse: $\sqrt{SWAP}$

$|\Psi\rangle = |\downarrow,\uparrow,\rangle$ → $|\Psi\rangle = (|\downarrow,\uparrow\rangle + i|\uparrow,\downarrow\rangle)/\sqrt{2}$

SWAP fidelity $F_\pi = 99.7(1)\%$ [PRELIMINARY]

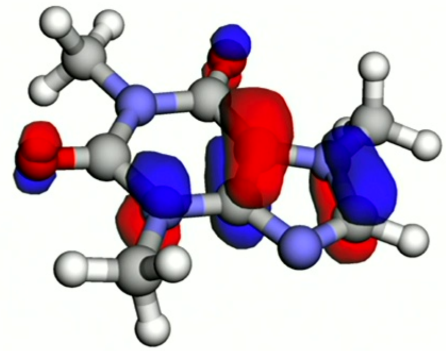
Record entangling gate fidelities possible

Current two-qubit gate records:
Evered, ..., Lukin, *Nature* **622**, 268–272 (2023)
Bing-Shiun Tsai, ..., Endres, *arXiv*:2407.20184 (2024)

Summary

Simulating quantum chemistry with ultracold fermions

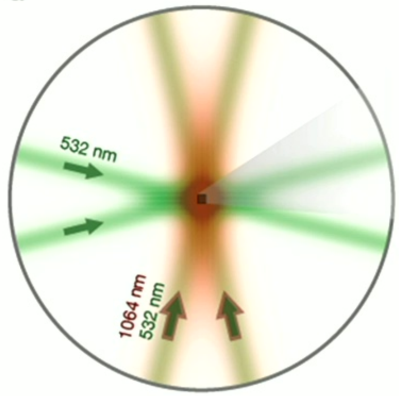
- Fermionic quantum circuits
- Perparing chemical wavefunctions in superlattices



Superlattice collisional gates

- Highly stable optical potentials
- >99% fidelity entangling gates on ~50 atoms

a



New machines

- UniRand: Random unitaries in optical lattices
- FermiQP: Hybrid analog-digital simulation
- Fast lattice cooling techniques

See also
Poster by **Luca Muscarella**

Thank you for your attention