TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

Quantum computing and simulation with ultracold Rydberg atoms

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Nikhef Seminar, October 2021

QT/e CENTER FOR QUANTUM MATERIALS AND TECHNOLOGY EINDHOVEN

TU/e

Outline

Introduction

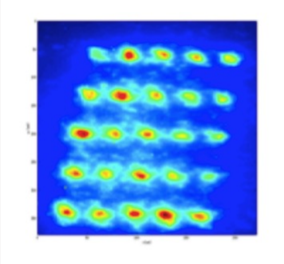
Quantum Inspire demonstrator projects KAT-1

Quantum computing vs quantum simulation

Ultracold Rydberg atoms

Long-range interaction

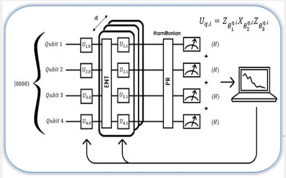
Different types of qubits



Hybrid quantum computing

Rydberg atoms in optical tweezers

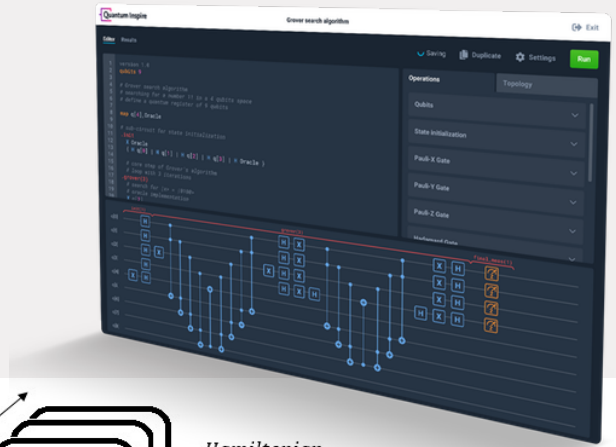
Variational Quantum Eigensolver



KAT-1 quantum computing and simulation

Hybrid quantum computer

- Variational algorithms
- Ultracold atom based
- Rydberg atoms



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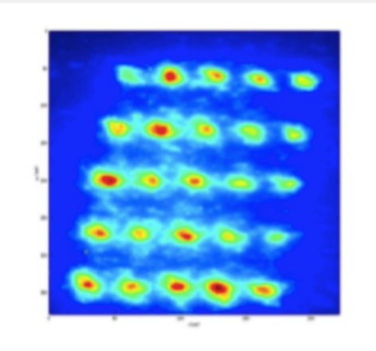
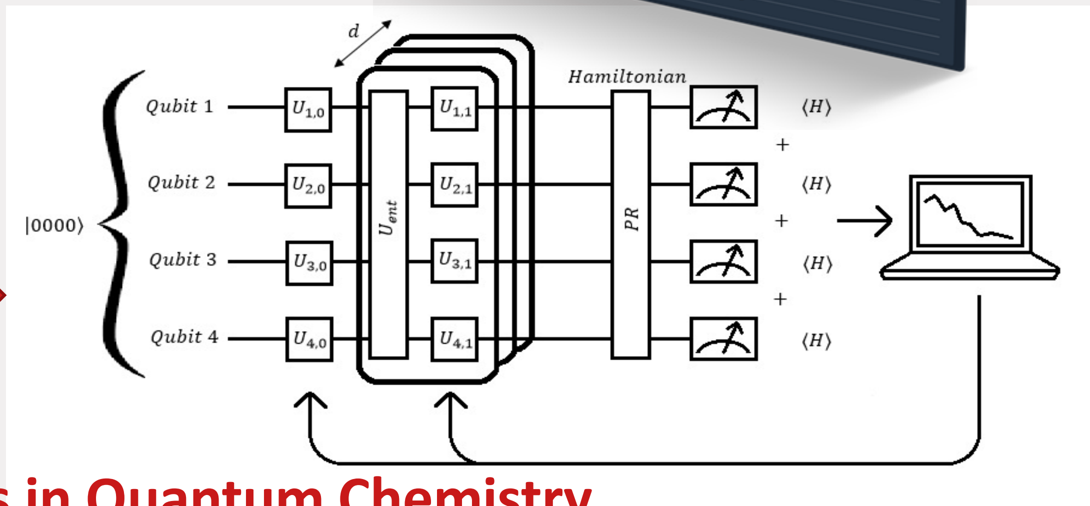
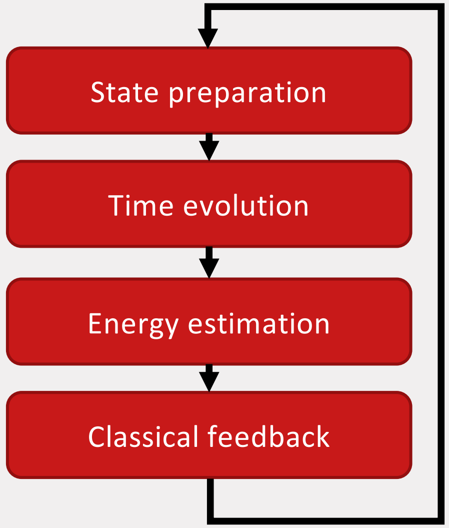
Quantum co-processor

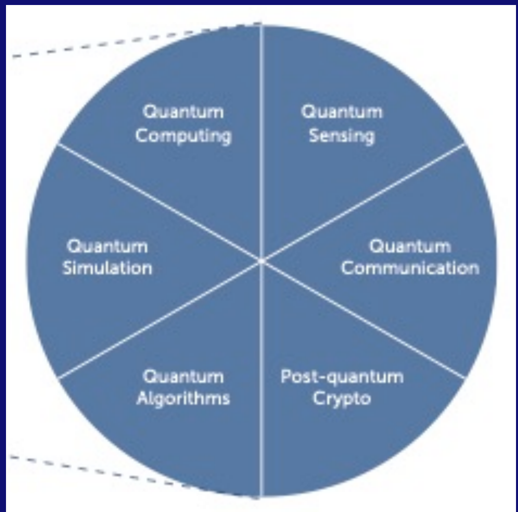


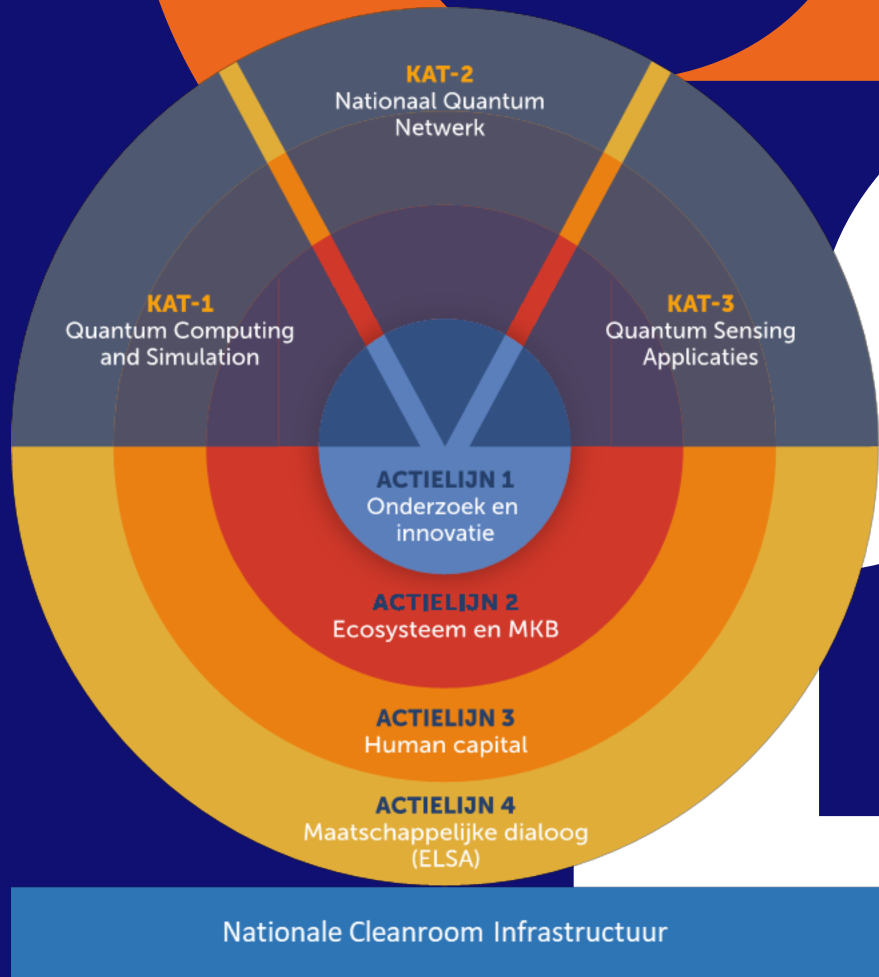




Solve problems in Quantum Chemistry

Quantum Delta Nederland

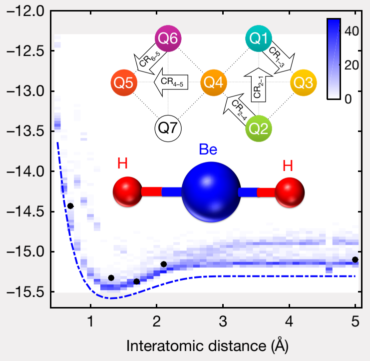




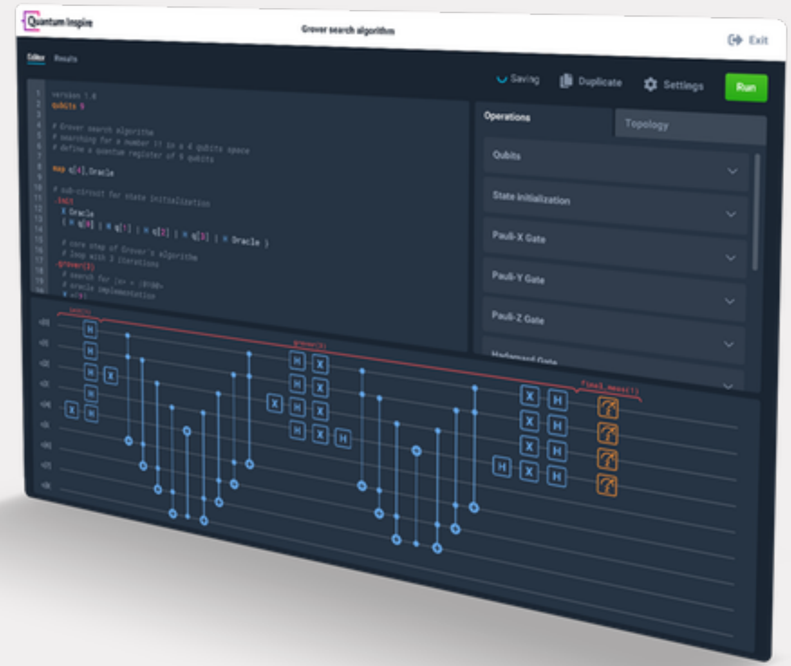
Four Action Lines
With three demonstrator projects
This is the lead for QT in the Netherlands!

Demonstrator - Rydberg hybrid quantum computer

Interesting use cases in the field of quantum chemistry:



Artificial photosynthesis
Nitrogen fixation
Quantum medicine



- Setup Rydberg platform as a robust demonstrator, scale-up from few 10s to 100 noisy qubits
- Hookup Rydberg platform to Quantum Inspire with 24/7 online access, system ready for hybrid classical-quantum calculations
- Collaboration between QT/e and experimental Rydberg lab at QuSoft on next generation Rydberg platforms

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KAT-1 Rydberg Quantum Inspire team

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Lotte Boer
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Theory

Special thanks to

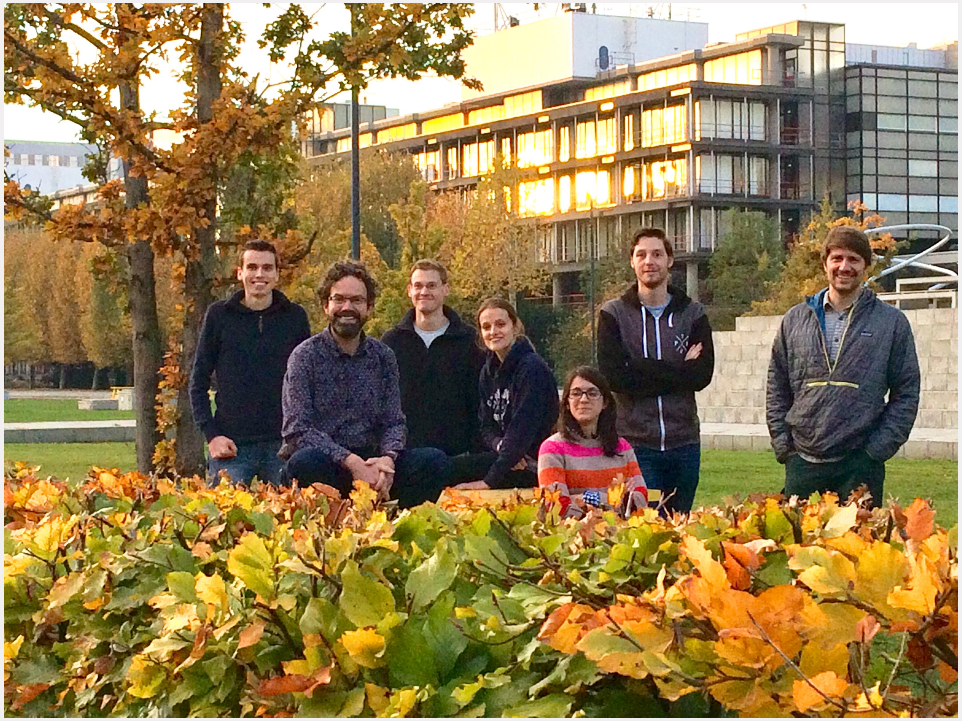
Jasper Postema

Robert de Keijzer

Gijs Groeneveld

Madhav Mohan

Marcin Plodzien



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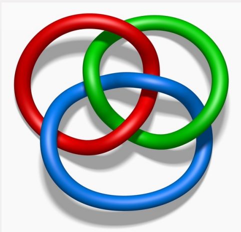
FOM

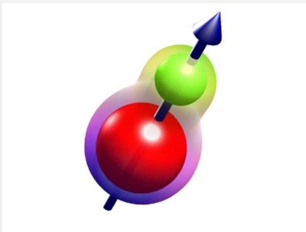
NWO Netherlands Organisation for Scientific Research

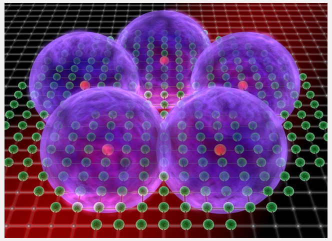
MOQS Molecular Quantum Simulations

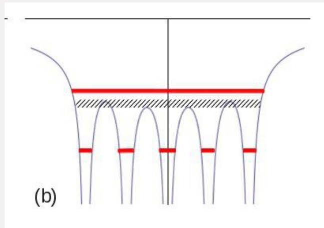
Quantum Delta Nederland

Strong interactions at different ranges









short range **long range**

quantum gases

dipolar molecules

Rydberg atoms

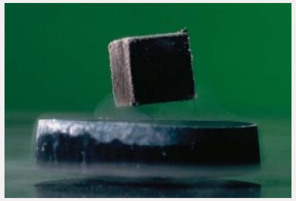
quantum plasmas

quarks

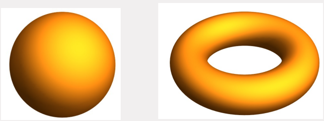
electrons and ions

M^N scaling, for all these quantum physics problems!

Quantum simulation – analog quantum computing



difficult to study
quantum system

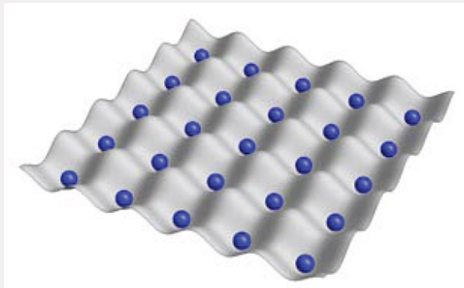


theoretical concept

$$\hat{H}$$

quantum model

Quantum simulator



well-controlled
quantum system

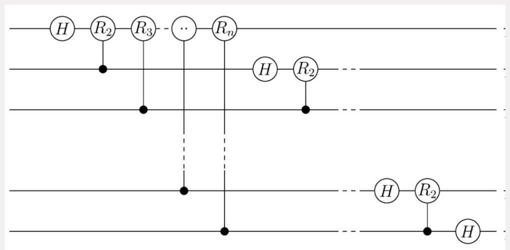
Digital quantum computing?

Currently in the NISQ regime

Noisy Intermediate Scale Quantum computers (Preskill)

- Digital simulation

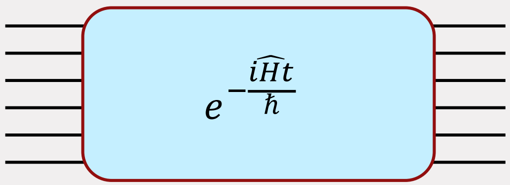
$|\psi(0)\rangle$



$|\psi(t)\rangle$

- Analog simulation

$|\psi(0)\rangle$



$|\psi(t)\rangle$

TU/e

Ultracold Rydberg atoms

High principal quantum number *n*

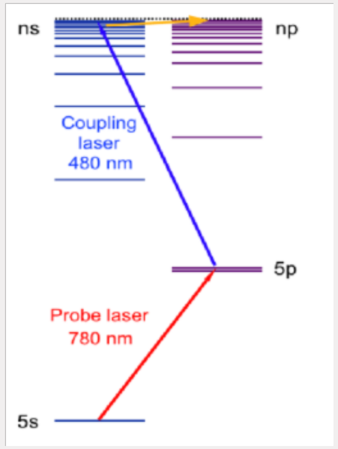
Extreme properties

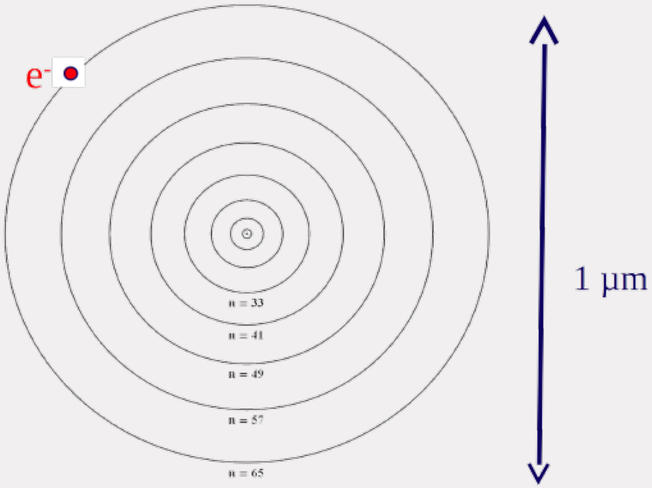
long lifetime ~ n^3

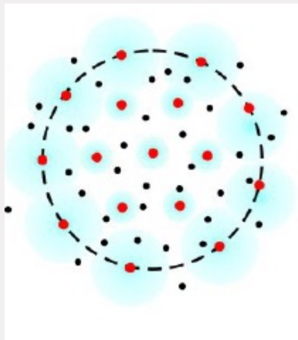
Size: order of micrometer

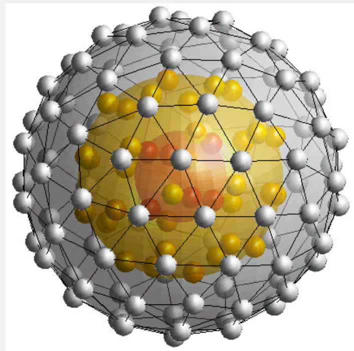
Very strong van der Waals interaction

$$C_6 \sim n^{11}$$



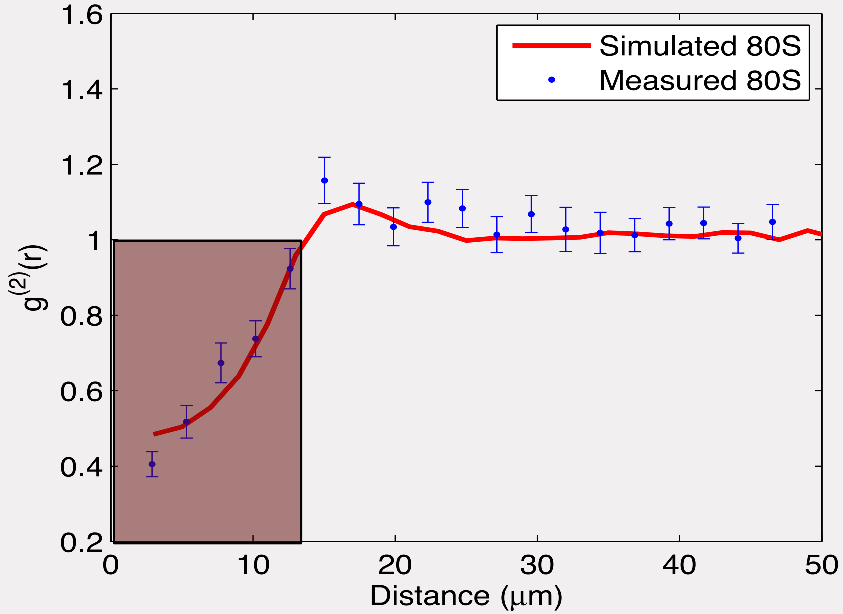


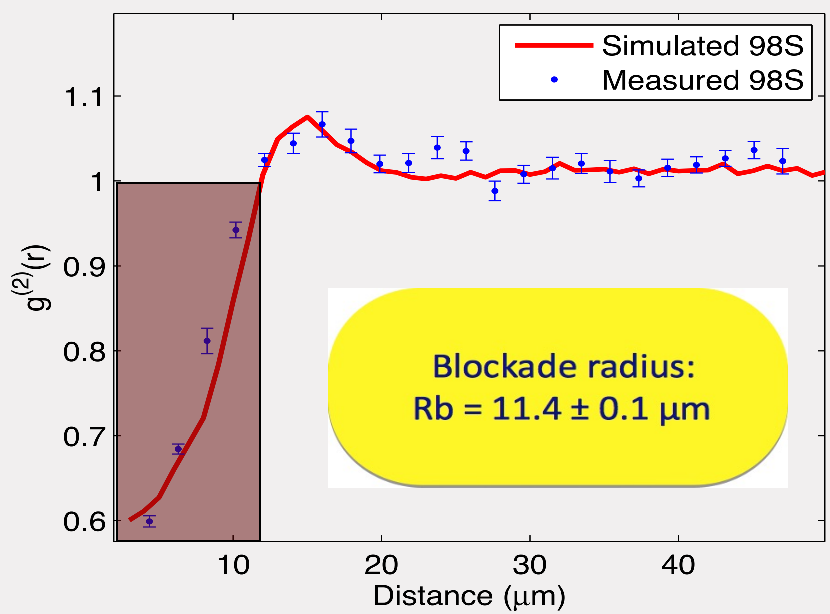




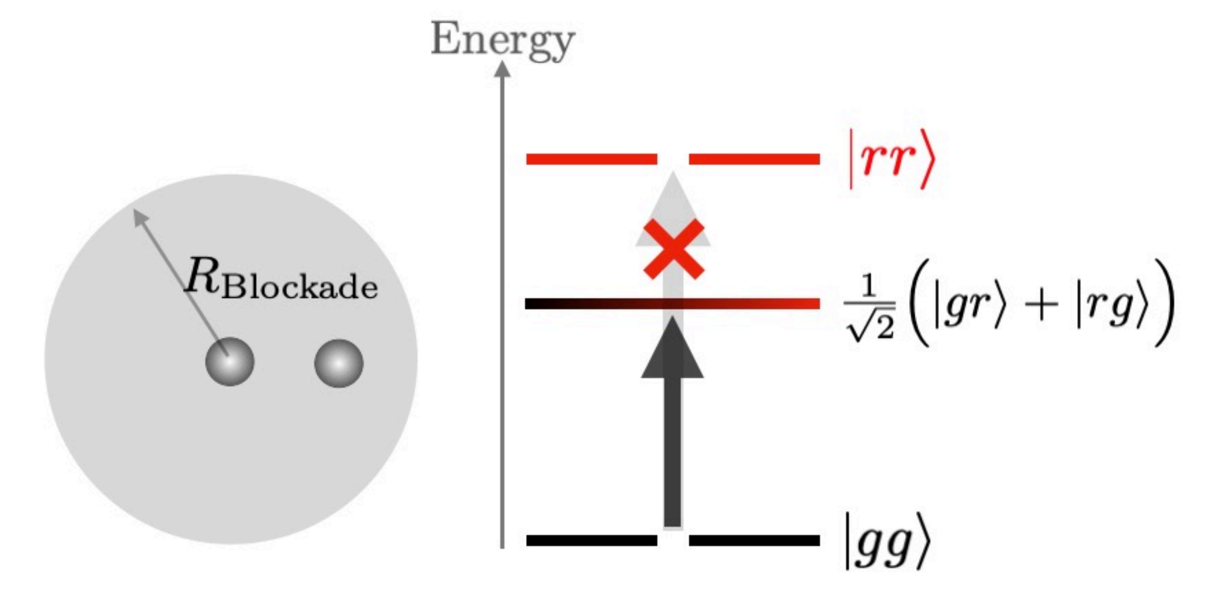
Rydberg blockade: correlations

$$g^{(2)}(r_1 - r_2) = \frac{G^2(r_1 - r_2)}{\sqrt{G^2(r_1 - r_2\,')G^2(r_1 - r_2\,')}}$$





Rydberg blockade effect

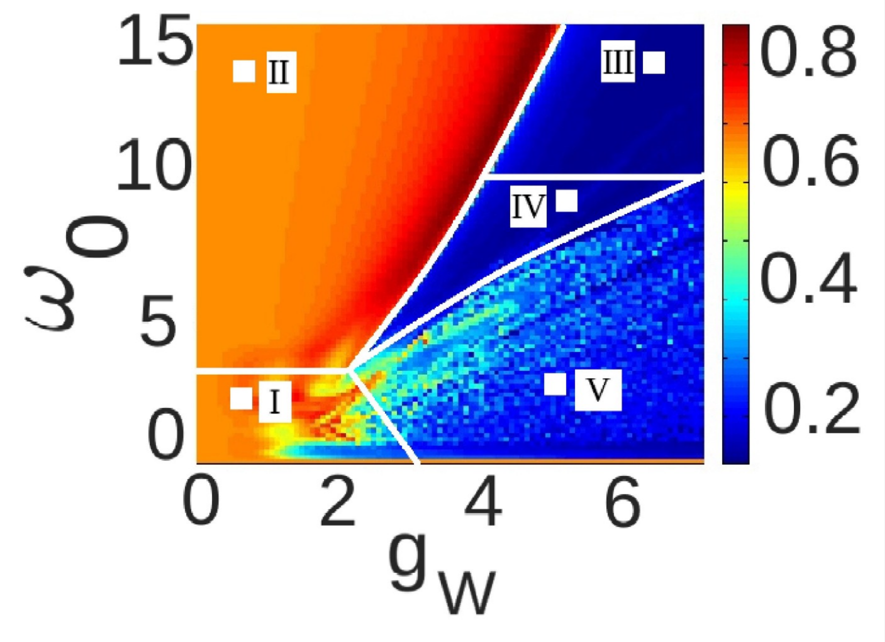


$$H = \frac{\hbar\Omega(t)}{2}\sum_i \sigma_i^x - \frac{\hbar\delta(t)}{2}\sum_i \sigma_i^z + \sum_{i<j} U_{ij} n_i n_j$$

Rydberg platform: a dedicated quantum device

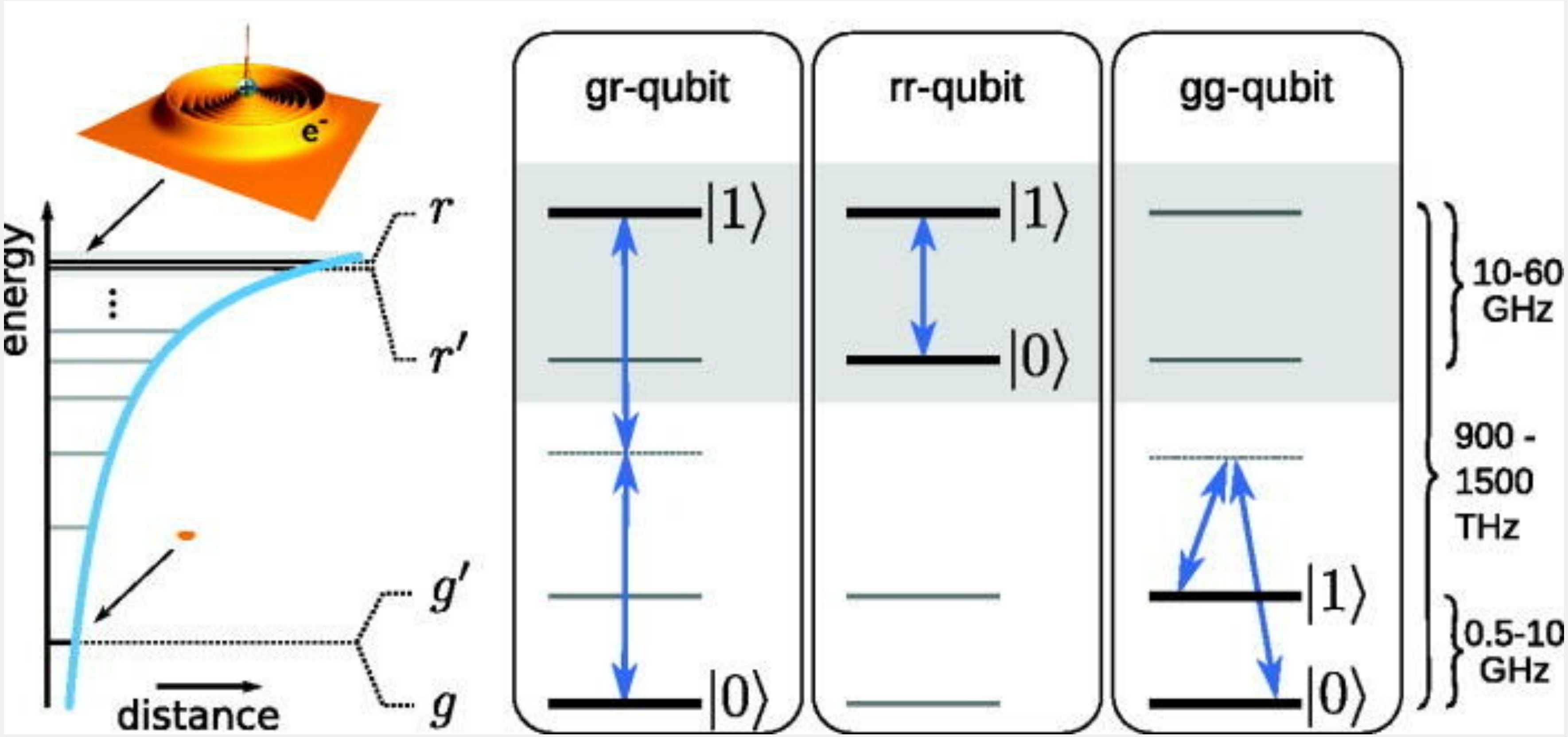
SSH model, Davydov soliton

Energy transport (solitons)



[M. Płodzień, T. Sowiński, and S. Kokkelmans, Simulating polaron biophysics with Rydberg atoms, Scientific Reports. 8, 9247 (2018)]

Rydberg atom qubits



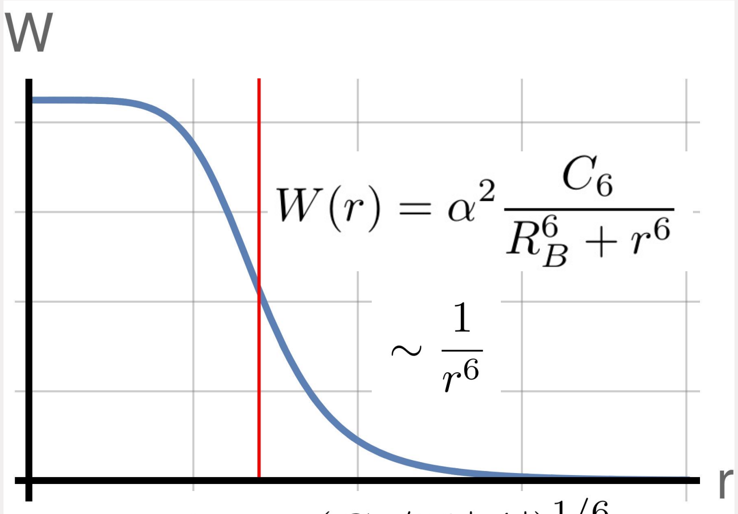
[M. Morgado and S. Whitlock, arXiv:2011.03031]

Rydberg dressing

Admixture properties of Rydberg state to atom ground state

$$|\psi\rangle \approx |g\rangle + \alpha|nS\rangle$$

$$\alpha = \frac{\Omega}{2|\Delta|}$$

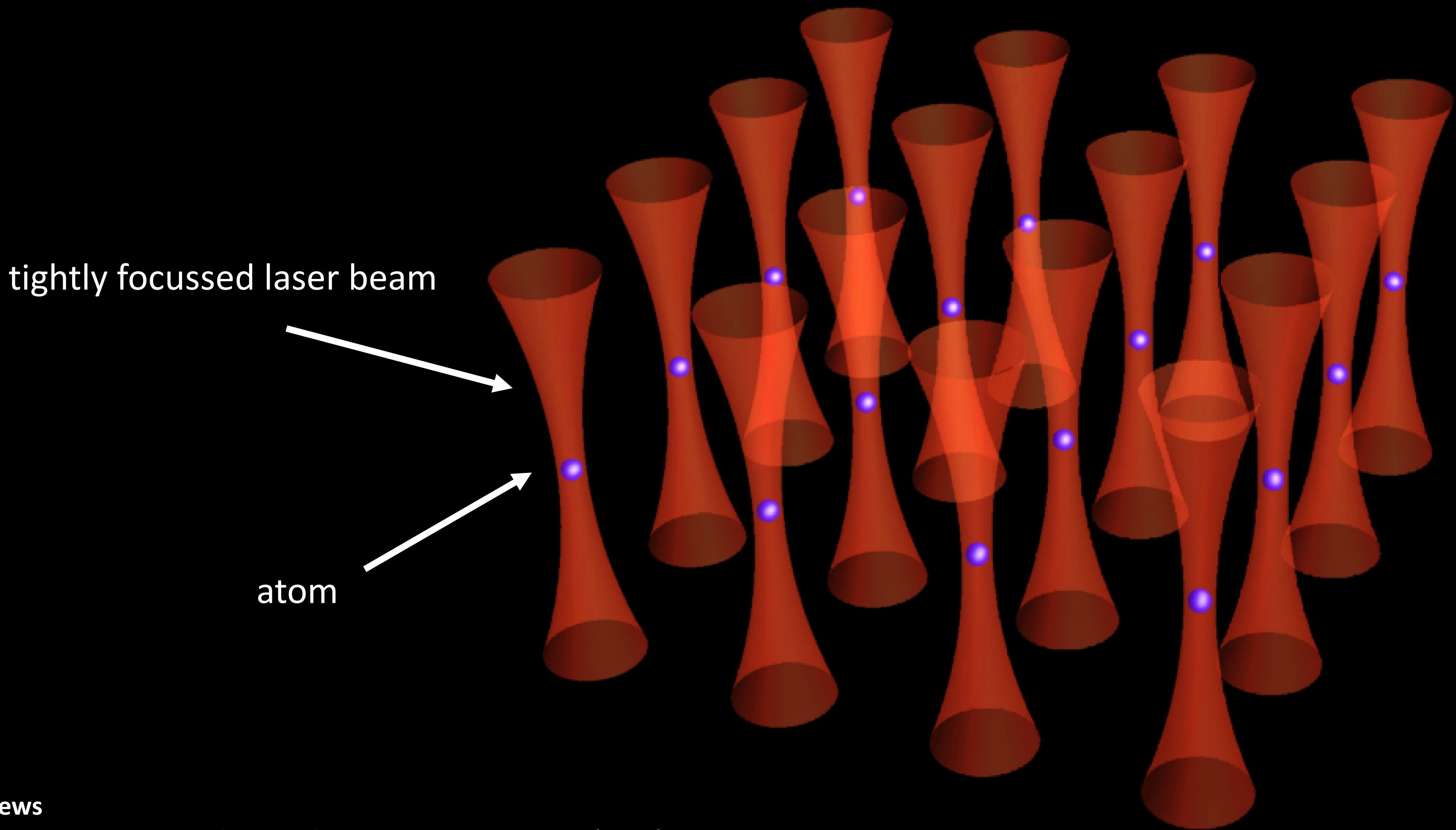


$$R_B \approx (C_6/2\hbar|\Delta|)^{1/6}$$

Dressed state acquires life-time:

$$\tau_{eff}^{-1} = \left(\frac{\Omega}{2\Delta}\right)^2 \tau_{|nS\rangle}^{-1} + \left(\frac{\Omega_1}{2\Delta_1}\right)^2 \Gamma_{5P_{3/2}}$$

Quantum simulation based on single atoms



Reviews

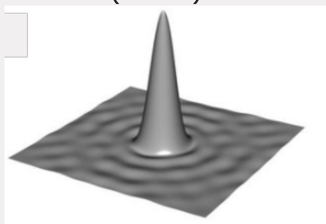
Quantum computing with neutral atoms, Quantum 4, 327 (2020)

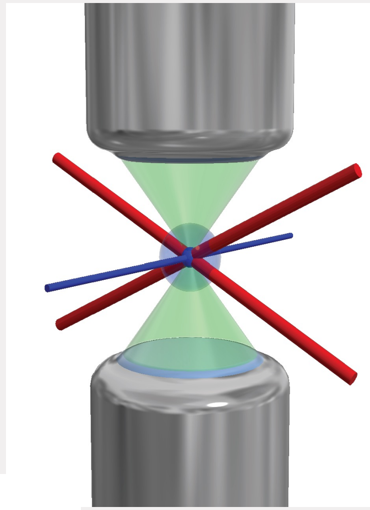
Quantum simulation and computing with Rydberg-interacting qubits, arXiv:2011.03031 (2020)

Phys. Rev. X 8, 041055 (2018)

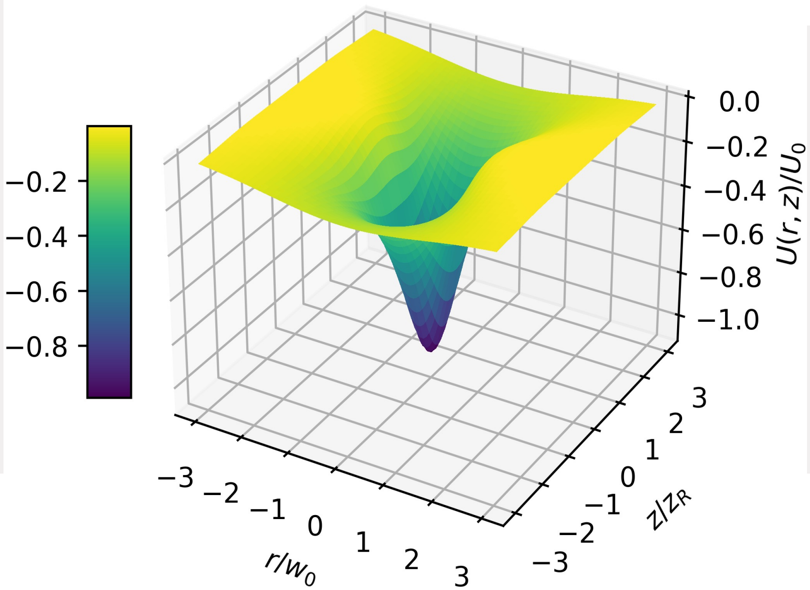
Optical tweezer

Magn. Reson. Med. **82**, 527–550 (2019)





- Highly focussed laser beam
- Diffraction limit: $d = 0.61\frac{\lambda}{\mathrm{NA}}$
- AC stark shift causes $U_{dip} \propto \frac{I(r,z)}{\delta}$
- Attractive force for δ < 0
- Radial and axial confinement



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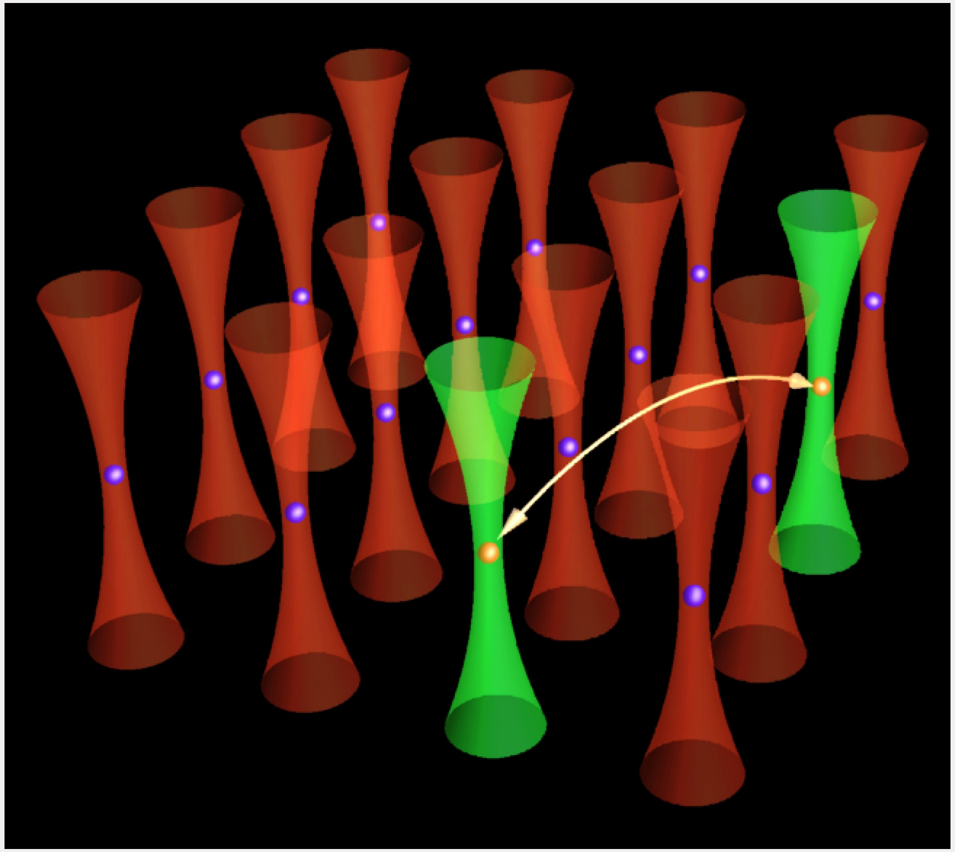
Control of the qubits (atoms) via tweezers

$$H = \frac{\hbar}{2}\sum_i \Omega_i(t)\sigma_i^x - \frac{\hbar}{2}\sum_i \delta(t)\sigma_i^z + \sum_{i<j} U_{ij}n_i n_j$$

Control over interactions:
global or local, switch or always on



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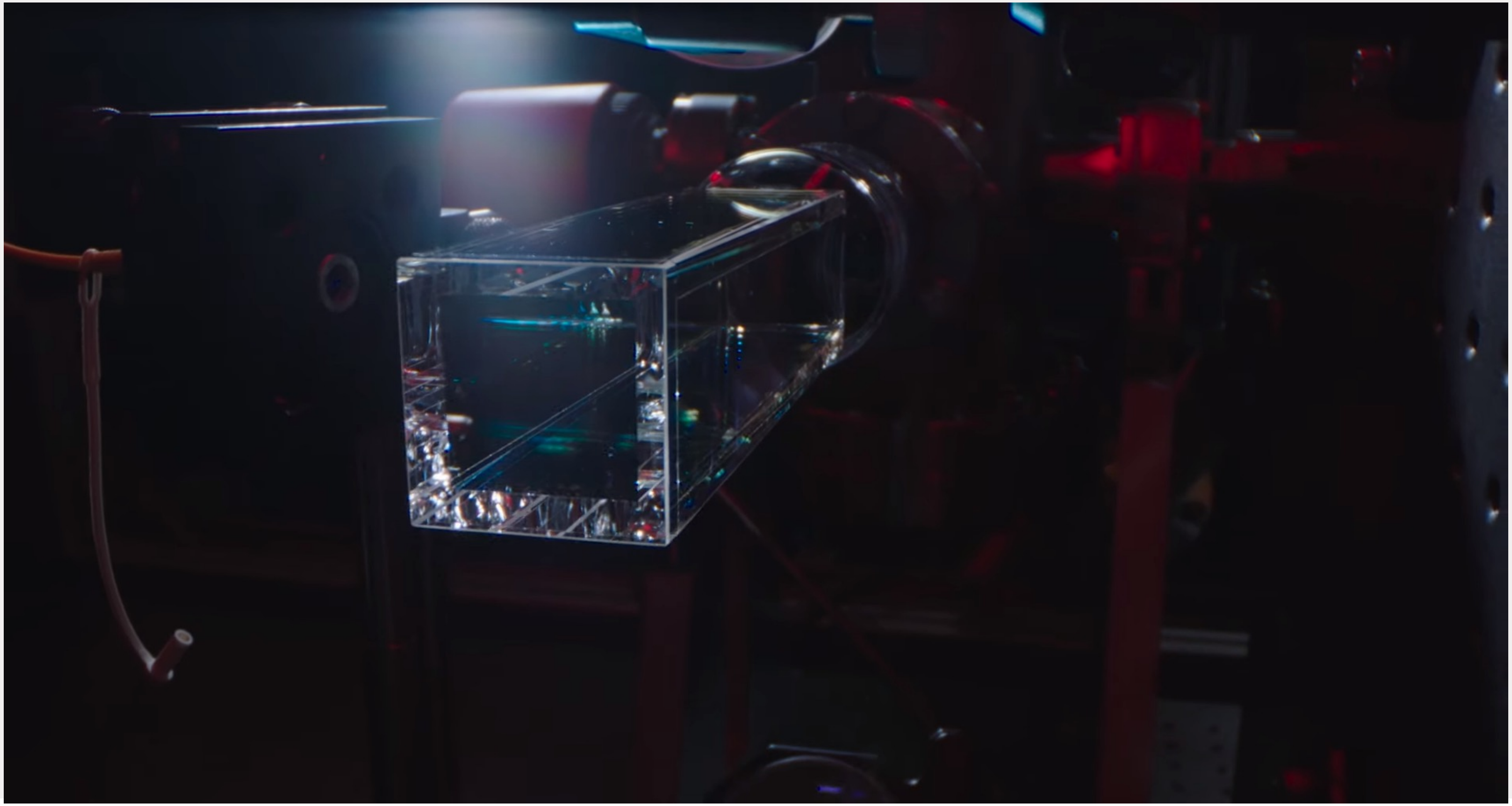
Current setup: explore tweezers with rubidium



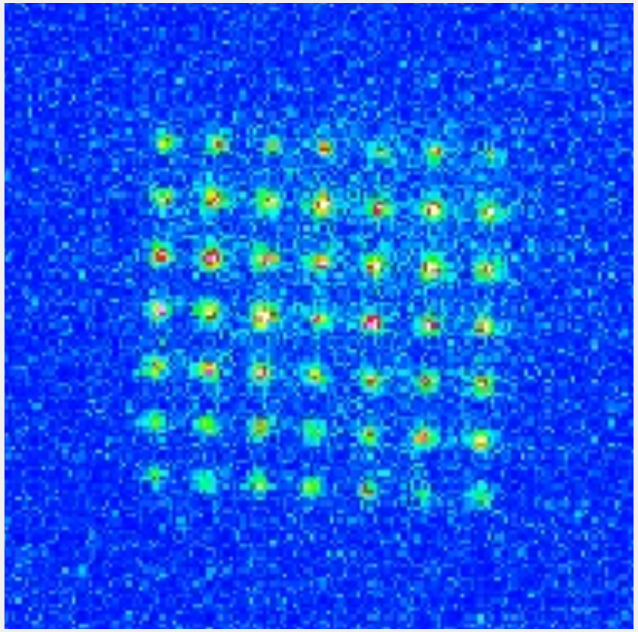
Sr atoms in optical tweezers

Work by Alex Urech and Ivo Knottnerus

UvA group: load tweezers

long lifetimes

On to sorting and larger lattices



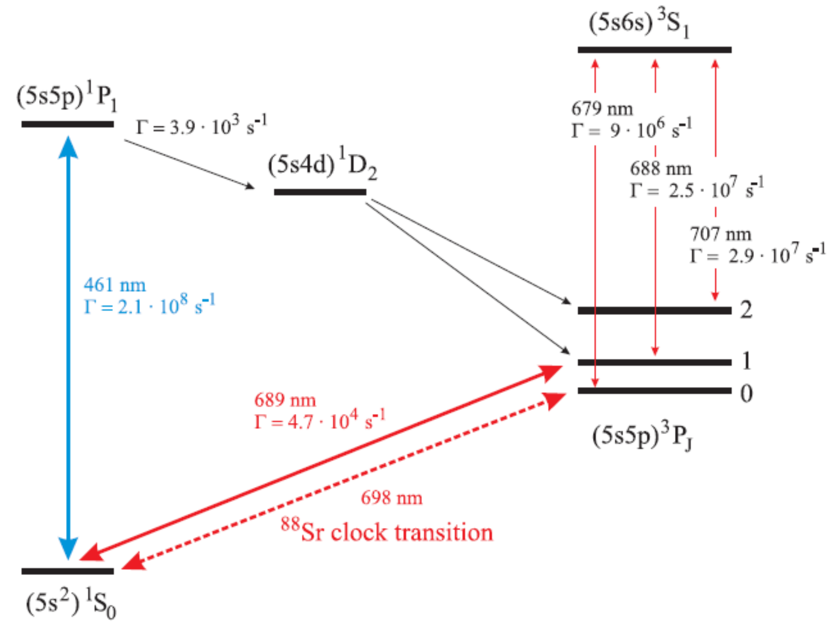


Fig. 1. Partial strontium energy level scheme. Γ denotes the spontaneous decay rate.

2020, Madjarov *et al. Nat. Phys. 16, 857 (2020):* ^{88}Sr (gr) $\mathrm{pCU}_{xy}(\pi)$, fidelity $\geq$0.991(4), decoherence time $\approx 2\mu s$, operation time 51 ns

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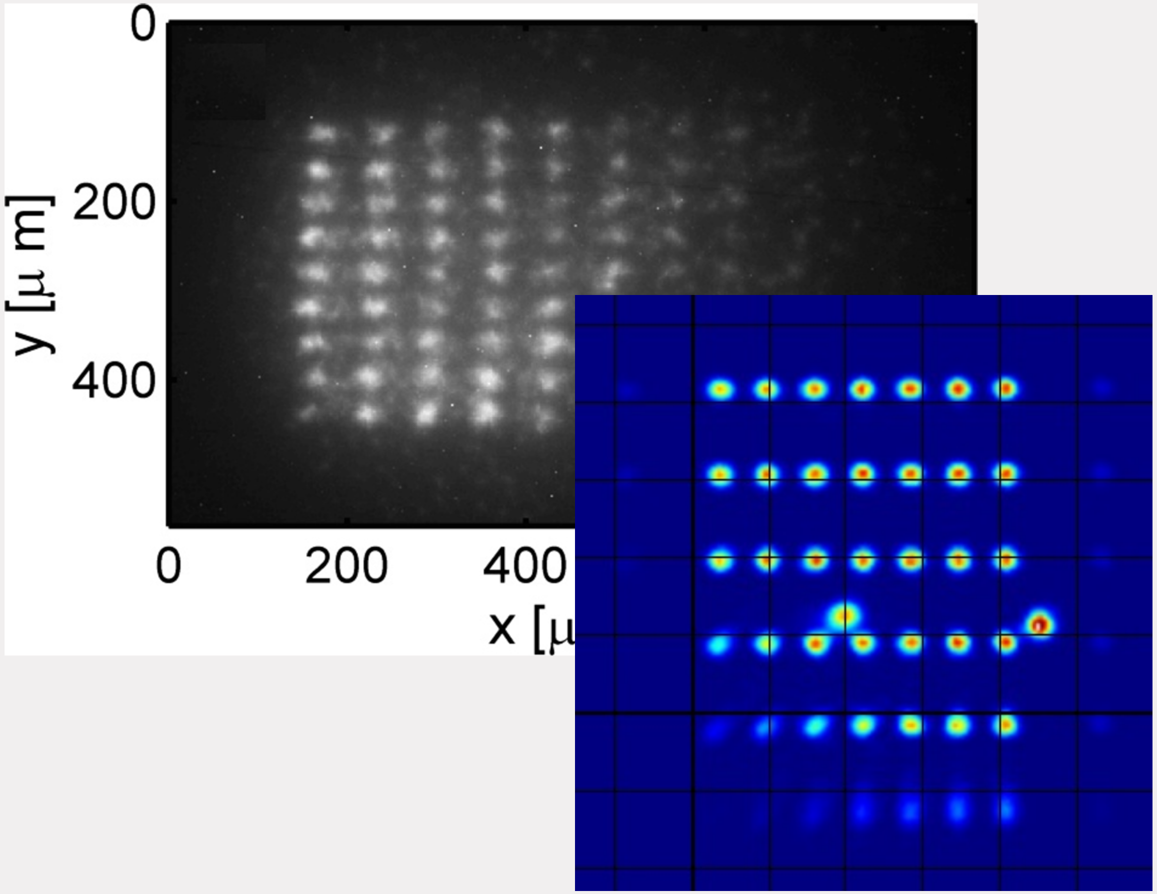
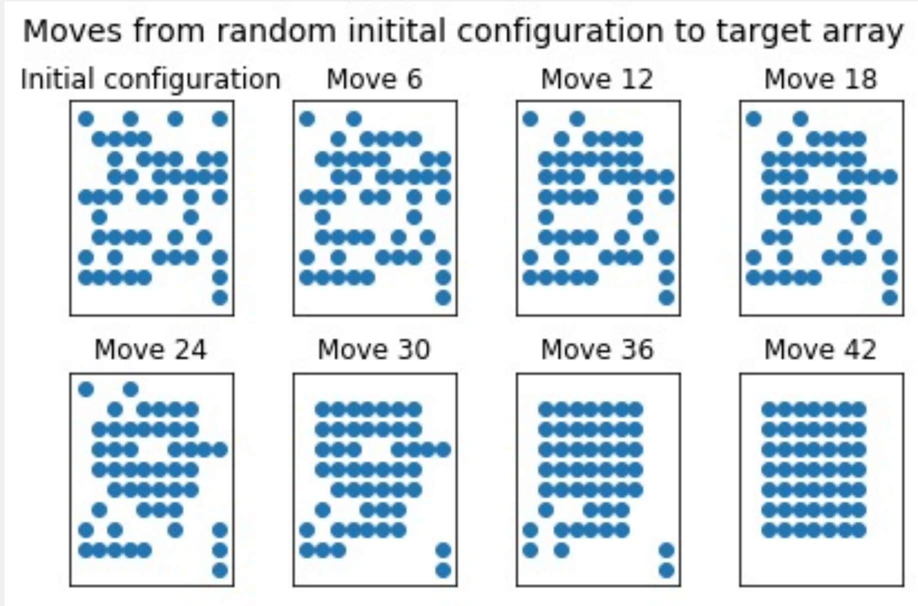
Build up demonstrator facility in Eindhoven





Work by Marijn Venderbosch, Lotte Boer, Deon JvRensburg, Ivo Knottnerus

Quantum chemistry

Born-Oppenheimer approximation:

Molecular Hamiltonian

$$H = \sum_{p,q=1}^{M} h_{pq} a_p^\dagger a_q + \sum_{p,q,r,s=1}^{M} h_{pqrq} a_p^\dagger a_q^\dagger a_r a_s$$

with interaction terms

$$h_{pq} = \int \varphi_p^*(\sigma) \left(\frac{\nabla_r^2}{2} - \sum_i \frac{Z_i}{|R_i - r|} \right) \varphi_q^*(\sigma) d\sigma \,,$$

[One-electron term]

$$h_{pqrs} = \int \frac{\varphi_p^*(\sigma_1)\varphi_q^*(\sigma_2)\varphi_s(\sigma_1)\varphi_r(\sigma_2)}{|r_1 - r_2|} d\sigma_1 d\sigma_2.$$

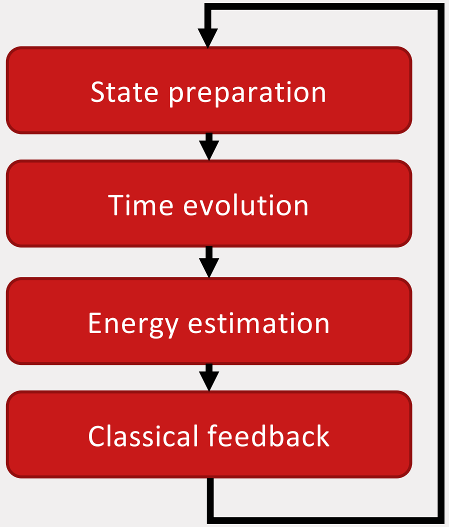
[Two-electron term]

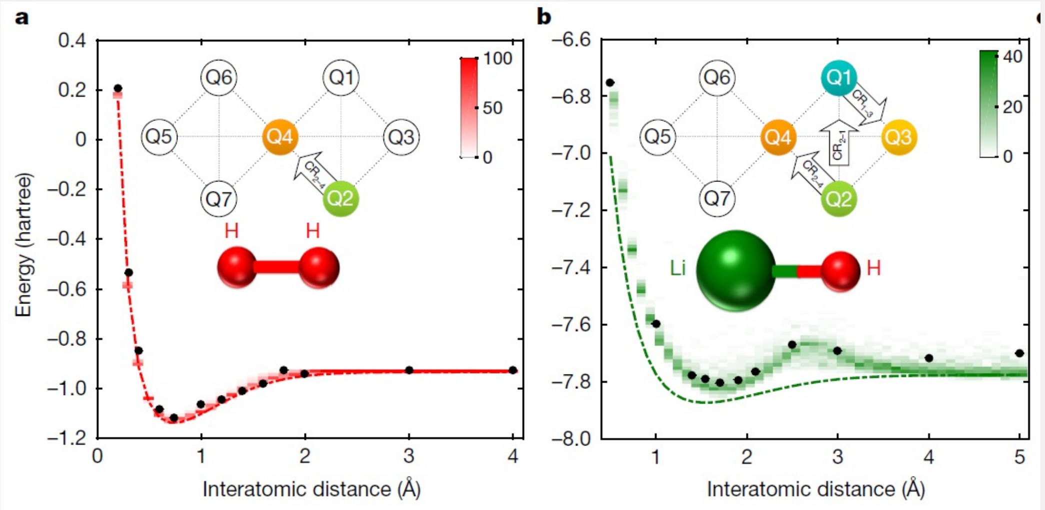
Quantum chemistry

Jordan-Wigner transformation: $a_p^\dagger, a_p \rightarrow I, X, Y, Z$

$$a_p = I^{p-1} \otimes \frac{1}{2}(X + iY) \otimes Z^{N-p}$$

$$a_p^\dagger = I^{p-1} \otimes \frac{1}{2}(X - iY) \otimes Z^{N-p}$$



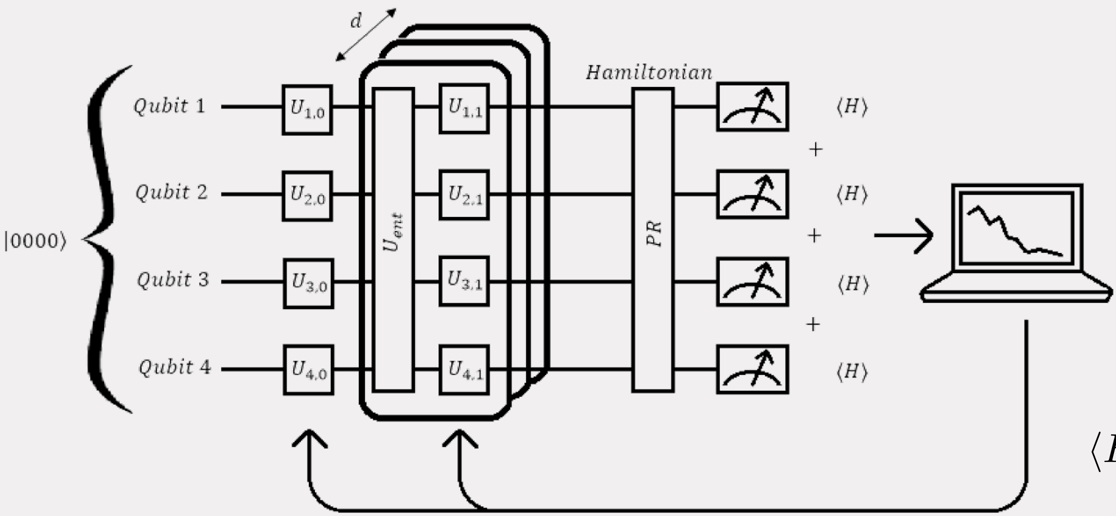


[Kandala et al, Nature 549, 242 (2017)]

VQE: Simulating the wave function

$$|\Psi(\vec{\theta})\rangle = \prod_{q=1}^{m} U_{q,d}(\vec{\theta}) \times U_{ent} \times \prod_{q=1}^{m} U_{q,d-1}(\vec{\theta}) \times U_{ent} \times \ldots \times \prod_{q=1}^{m} U_{q,0}(\vec{\theta})|\psi_{init}\rangle$$

$$U_{q,i}(\vec{\theta}) = Z_{\theta_1^{q,i}} X_{\theta_2^{q,i}} Z_{\theta_3^{q,i}}$$



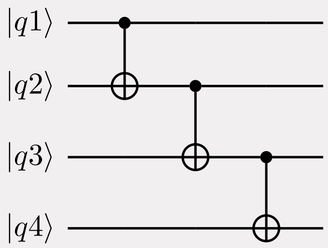
$$\langle H\rangle_{\vec{\theta}} = \langle\Psi(\vec{\theta})|H|\Psi(\vec{\theta})\rangle = \sum_k h_k \langle\Psi(\vec{\theta})|\sigma^k|\Psi(\vec{\theta})\rangle$$

Specific architecture

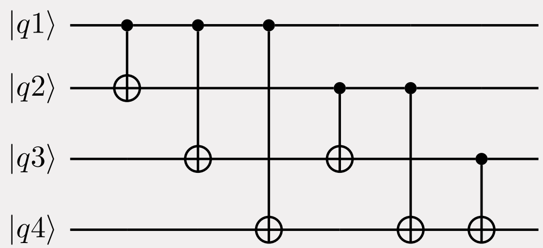
Investigate hardware-specific entanglement

- NISQ area: optimize every step!

Chain



pairs

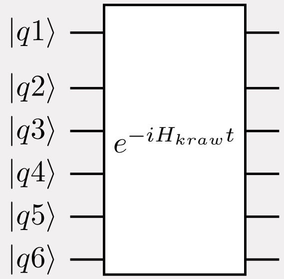


Specific architecture

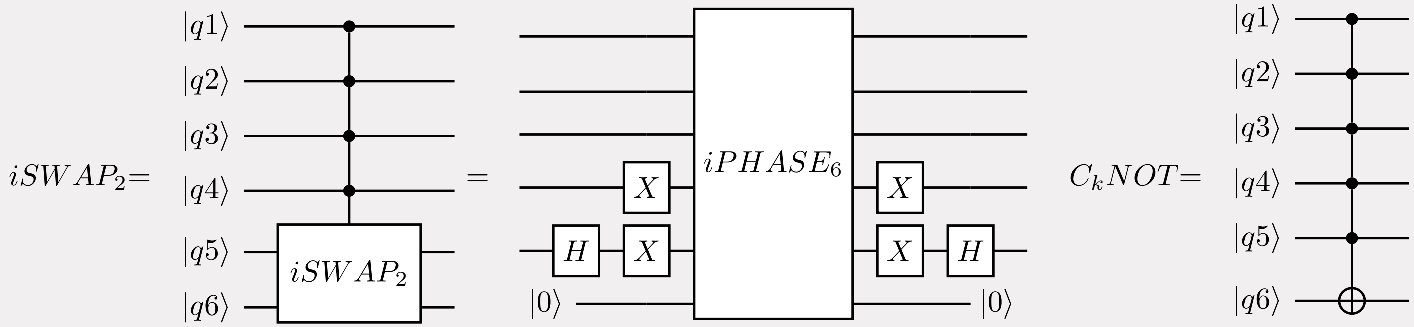
Krawtchouk chain

Multi-qubit gate

$$H^K = -\frac{J}{4}\sum_{j=1}^{N-1}\sqrt{j(N-j)}(\sigma_j^X\sigma_{j+1}^X + \sigma_j^Y\sigma_{j+1}^Y)$$



Work by Jasper Postema implementation with Rydberg atoms

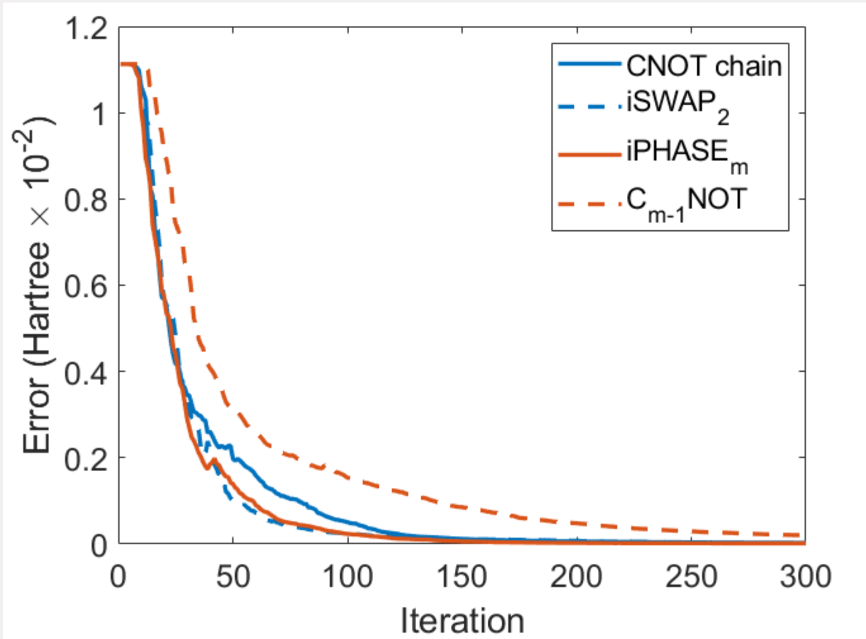


LiH molecule

VQE problem: LiH molecule (6 qubits) at depth 6, classical optimization SPSA

Compare different entangling methods

- iPHASE$_m$, C$_{m-1}$NOT and iSWAP$_2$, standard CNOT chain



[Optimization of the Variational Quantum Eigensolver, R. J. P. T. de Keijzer, V. E. Colussi, B. Skoric, and S. J. J. M. F. Kokkelmans, arXiv:2102.01781]

Pulse based vs gate based

Several proposals for quantum gates. Not always trivial and timeconsuming...

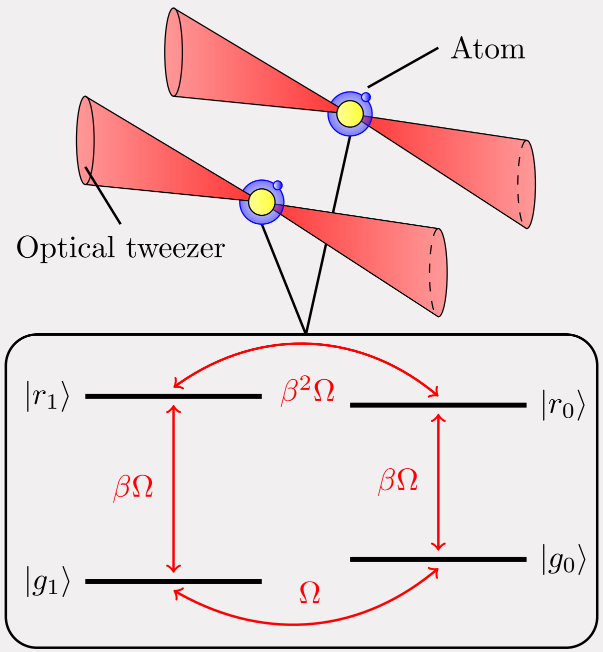
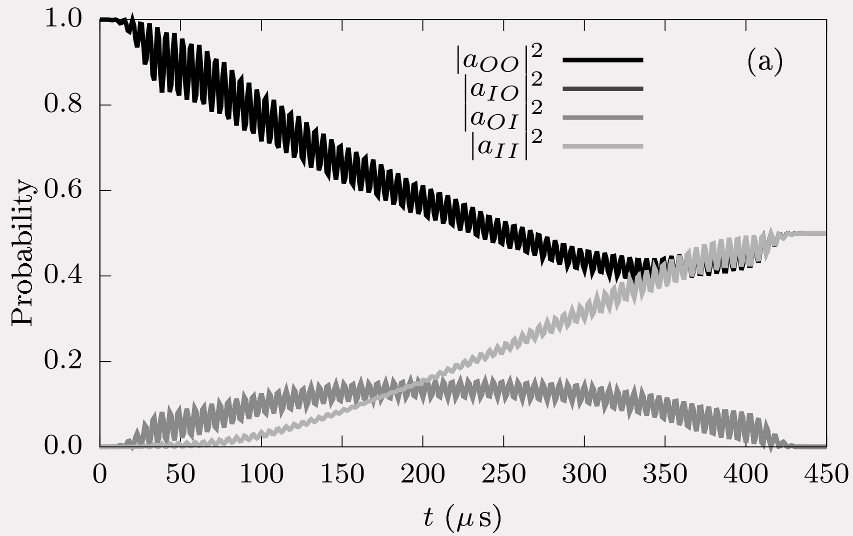


FIG. 1. Excitation scheme for using dressed qubits. The useful quantum states for qubits are the 'cross-dressed' states $|O\rangle = (|g_0\rangle + \beta|r_1\rangle)/\sqrt{1+\beta^2}$ and $|I\rangle = (|g_1\rangle + \beta|r_0\rangle)/\sqrt{1+\beta^2}$.

$$|OO\rangle \rightarrow \frac{1}{\sqrt{2}}(|OO\rangle + i|II\rangle)$$

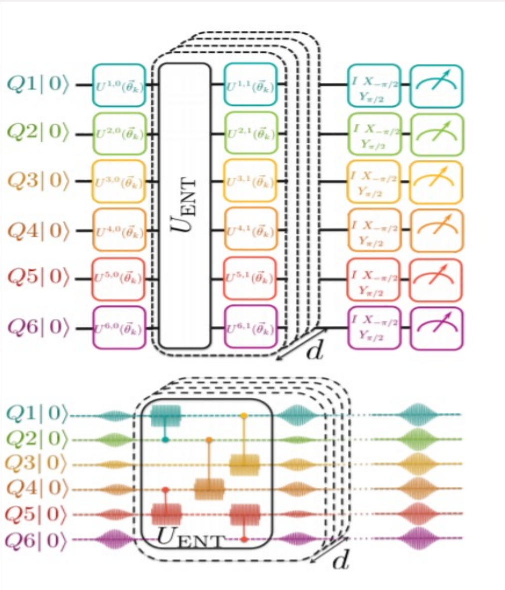


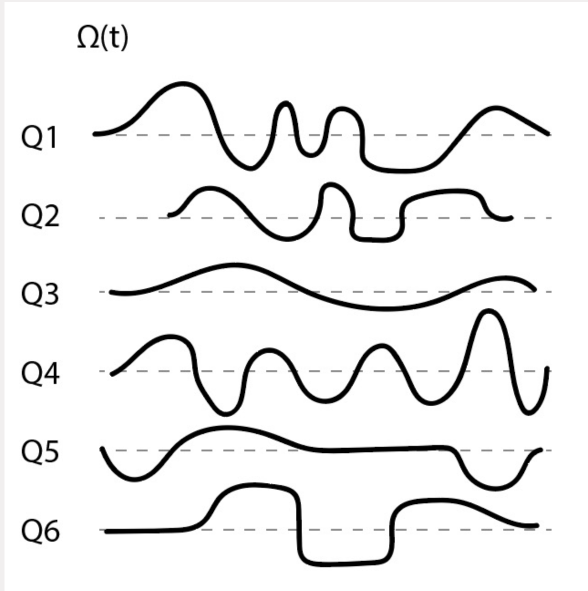
[R. V. Skannrup, R. Gerritsma, S. J. J. M. F. Kokkelmans, arXiv:2008.13622]

Optimized search through Hilbert space

NISQ regime: hardware-dependent optimisation

Gate-based computing vs. Pulse-based computing





Quantum Optimal Control

$$|\Psi_{\mathrm{UCCSD}}\rangle = e^{\hat{T}_1+\hat{T}_2}|0\rangle$$

$$\hat{T}_1 = \sum_{ia}\theta_{ia}\left(a_a^\dagger a_i - a_i^\dagger a_a\right)$$

$$\hat{T}_2 = \sum_{ijab}\theta_{ijab}\left(a_a^\dagger a_b^\dagger a_i a_j - a_j^\dagger a_i^\dagger a_b a_a\right)$$

Multi-qubit entanglement

- Realised by controled long-range Rydberg-atom interaction

Minimize

$$Tr(U^\dagger(T)\rho_0 U(T) H_{mol}) + \lambda \sum_{k=1}^{m} \frac{1}{2} \int_0^T |Z_k(t)|^2 dt$$

Subject to:

$$i\partial_t U(t) - [H_d + H_{c,Z}(t)]U(t) = 0$$

Work by Robert de Keijzer implementation with Rydberg atoms

Individual qubit rotations

$$H_c(t) = \sum_j \left(\frac{\Omega_j(t)}{2} e^{i\nu_j(t)} |0\rangle_j \langle 1|_j + \text{h.c.} \right)$$

$$\Downarrow$$

$$H_c(t) = \sum_k Z_k(t)|0\rangle_k\langle 1|_k + \overline{Z_k(t)}|1\rangle_k\langle 0|_k,$$

Rydberg interaction: global

$$H_d = \sum_{ij} \frac{C}{R_{ij}^6} |11\rangle_{ij}\langle 11|_{ij}$$

$$\Downarrow$$

$$H_d = \sum_{ij} \tilde{Q}|11\rangle_{ij}\langle 11|_{ij},$$

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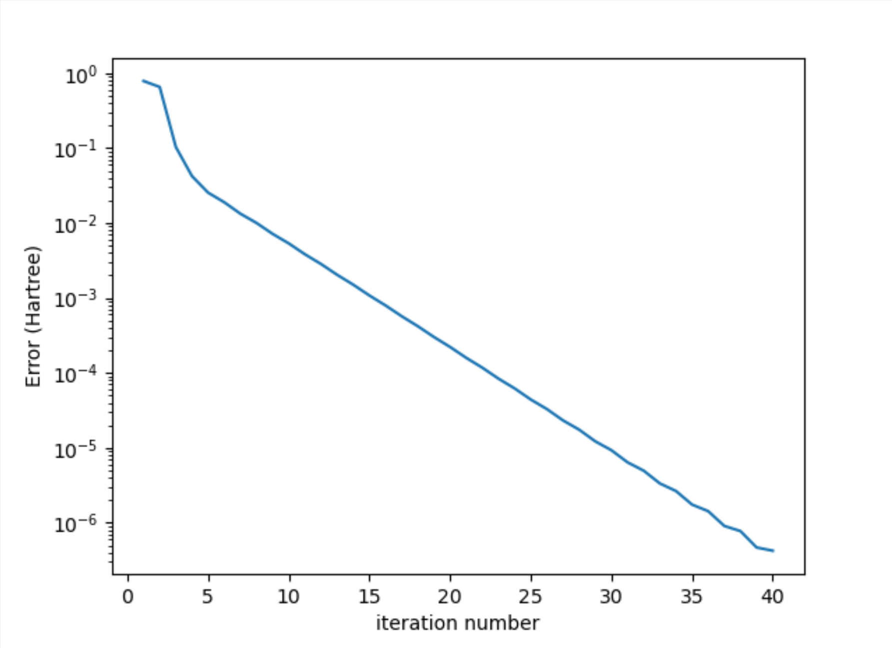
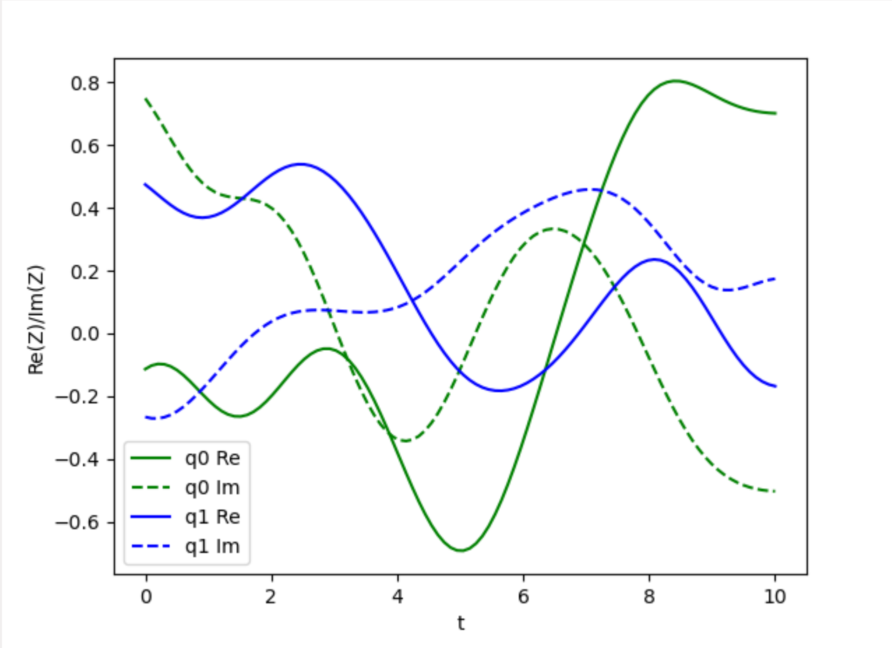
Example with "global" Rydberg coupling

H_2, two qubits





Quantum Eindhoven building

With large underground lab for quantum technology

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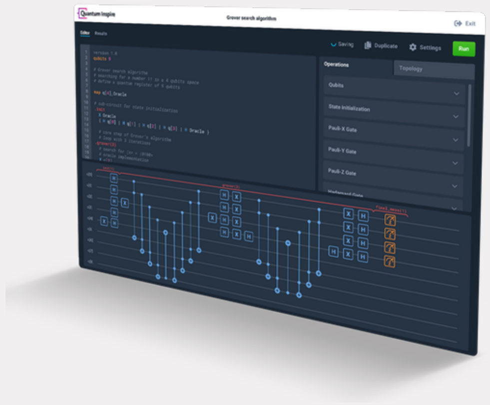
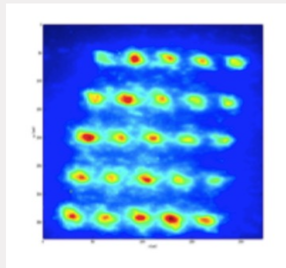
Summary/Outlook





Hybrid quantum computation:

- Quantum Inspire project QuantumDeltaNL
- Based on ultracold atoms in optical tweezers
- Interaction via Rydberg excitations

Variational quantum Eigensolver

- Investigation of hardware optimized strategies
- Different entanglement schemes: multi-qubit entanglement
- Pulse-based vs gate-based

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Thanks!

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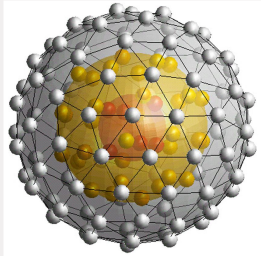

FOM

NWO
Netherlands Organisation for Scientific Research

Quantum Delta
Nederland

MOQS
Molecular Quantum Simulations
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