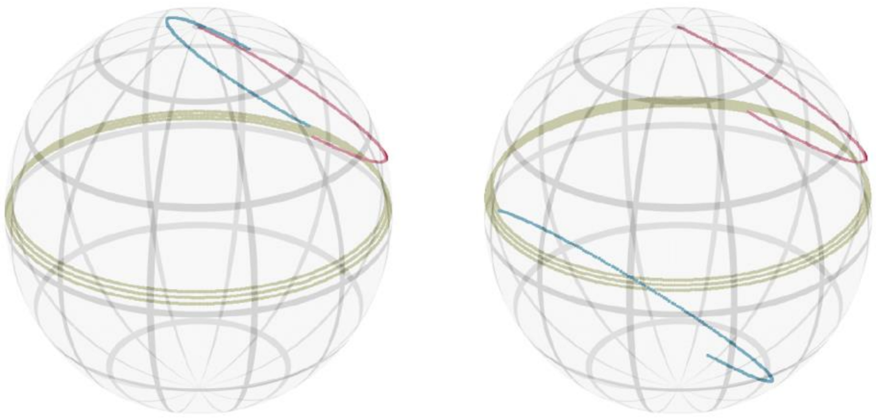
Interdisciplinarity!

Experimental imposter!

L4 Quantum information and computing (QIC) 2019-20

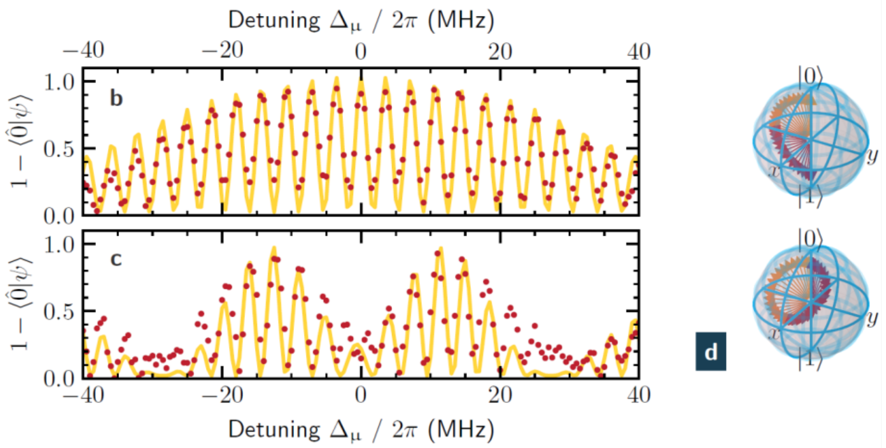
Lecture Notes 2019-20

May 10, 2020



Interdisciplinarity!

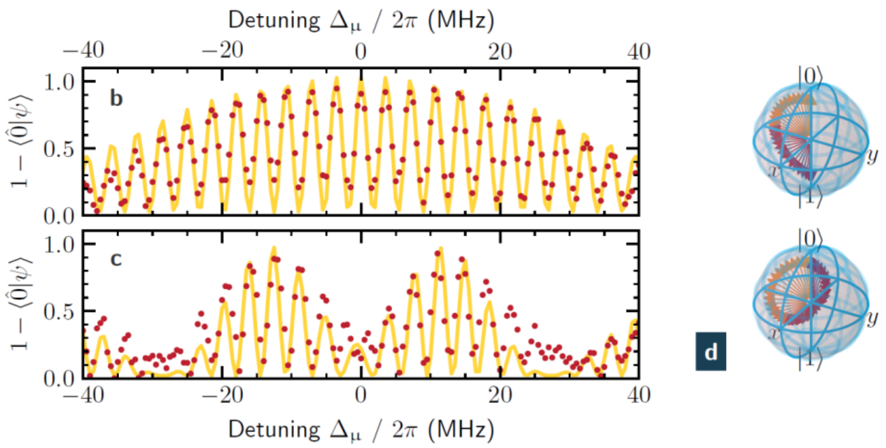
Experimentalists



Interdisciplinarity!

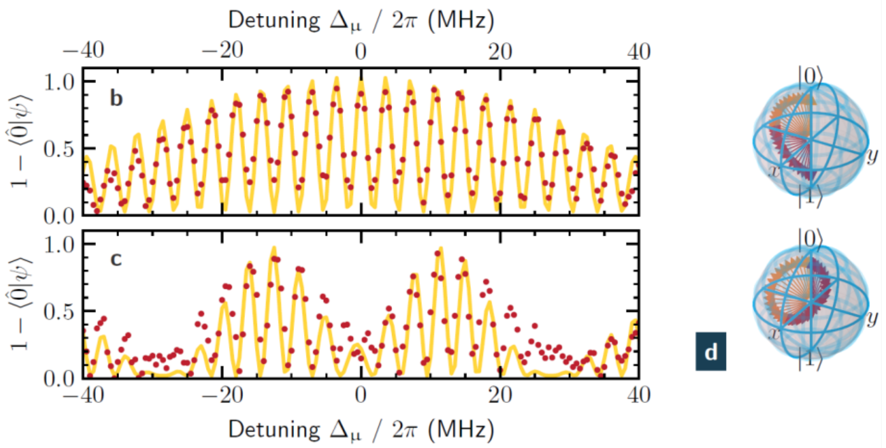
Experimentalists

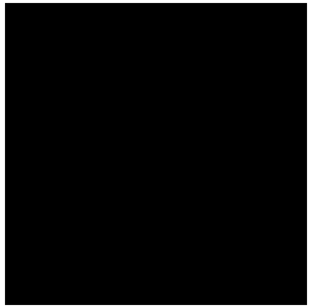
Computer scientists

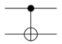


Interdisciplinarity!

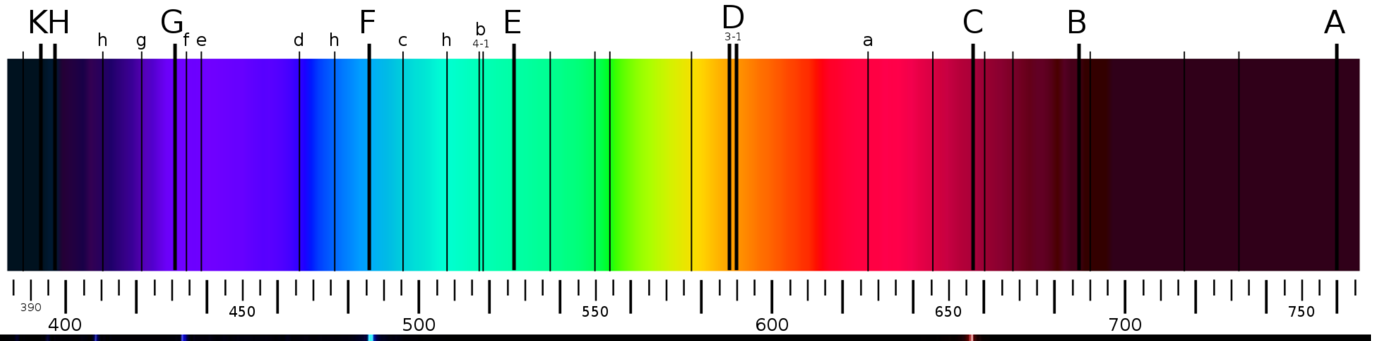
Experimentalists ⟷ Computer scientists

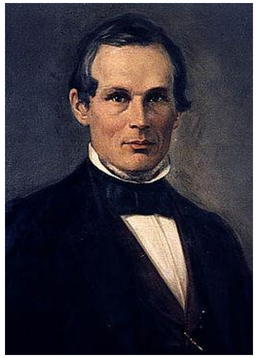




Operator	Gate(s)		Matrix
Pauli-X (X)	X	⊕	$\begin{bmatrix}0 & 1\\1 & 0\end{bmatrix}$
Pauli-Y (Y)	Y		$\begin{bmatrix}0 & -i\\i & 0\end{bmatrix}$
Pauli-Z (Z)	Z		$\begin{bmatrix}1 & 0\\0 & -1\end{bmatrix}$
Hadamard (H)	H		$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$
Phase (S, P)	S		$\begin{bmatrix}1 & 0\\0 & i\end{bmatrix}$
$\pi/8$ (T)	T		$\begin{bmatrix}1 & 0\\0 & e^{i\pi/4}\end{bmatrix}$
Controlled Not (CNOT, CX)			$\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&0&1\\0&0&1&0\end{bmatrix}$
Controlled Z (CZ)	Z		$\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&-1\end{bmatrix}$
SWAP			$\begin{bmatrix}1&0&0&0\\0&0&1&0\\0&1&0&0\\0&0&0&1\end{bmatrix}$

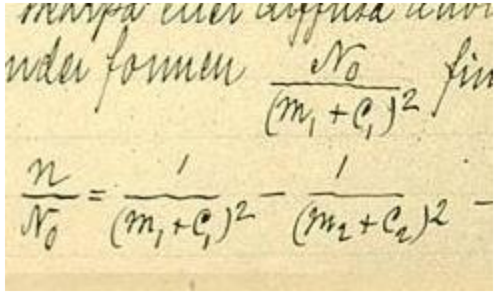
Rydberg atoms - the dark horse of quantum computing?





Angstrom 1862

Balmer 1885



Rydberg 1888

Rydberg atoms - the dark horse of quantum computing?

Outline:

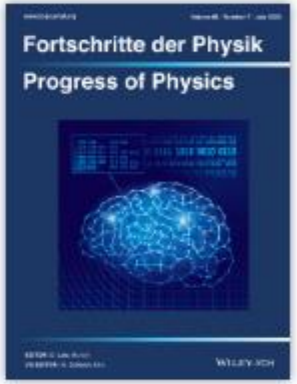
1. Ingredients to build a quantum computer

2. Rydberg atoms

3. Rydberg atom quantum computing: current state of the art

4. Some open questions

DiVincenzo 5



Volume 48, Issue 9-11
September 2000
Pages 771-783

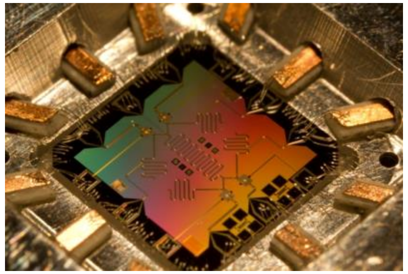
1. A scalable physical system with well characterized qubits
2. The ability to initialize the state of the qubits to a simple fiducial state, such as $|000...\rangle$
3. Long relevant decoherence times, much longer than the gate operation time
4. A "universal" set of quantum gates
5. A qubit-specific measurement capability

Qubit Init. Read-out Scalable

Gates Coherence

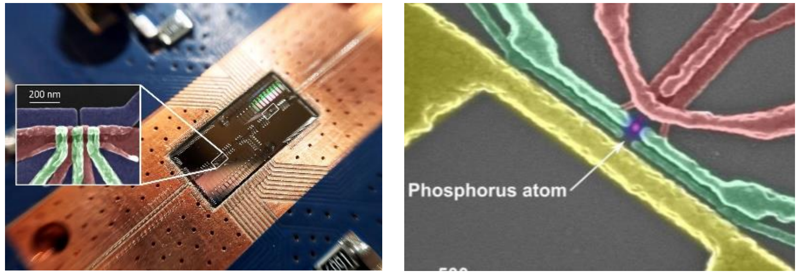
5 Qubit candidates

Superconductors



IBM, Google, D-wave, etc

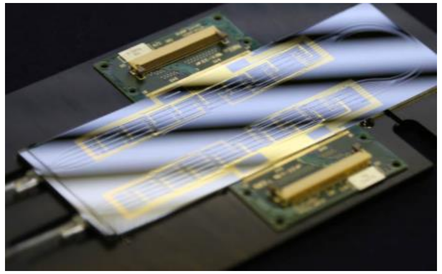
Semiconductors



P in Si

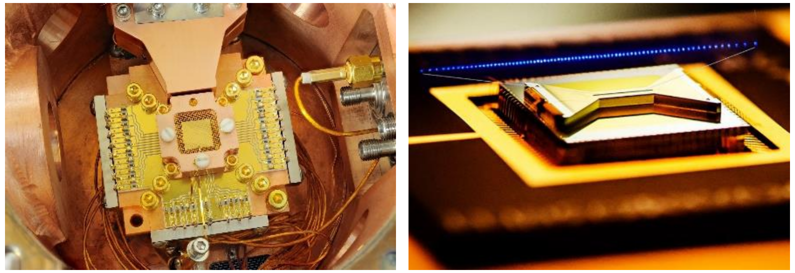
Silicon Quantum Computing

Photons



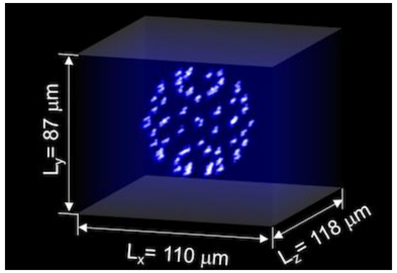
PsiQuantum

Ions



IonQ

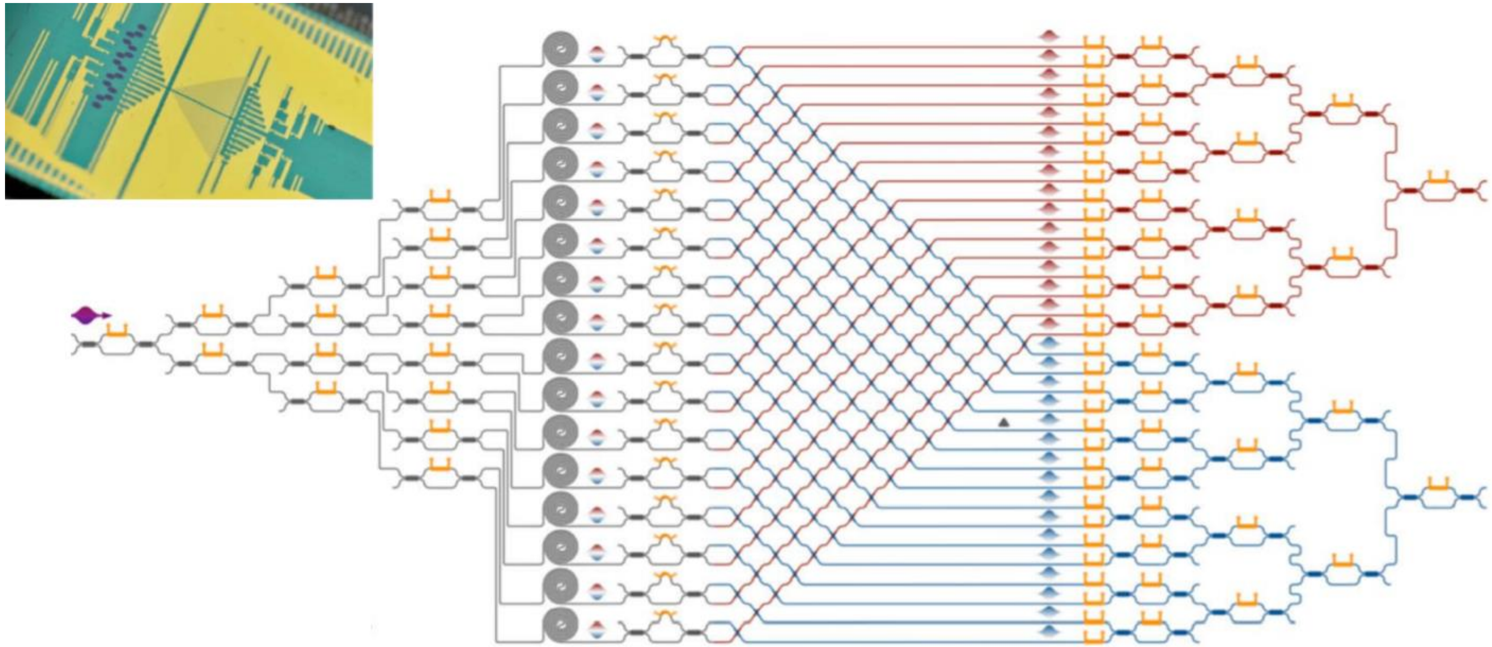
Atoms



Pasqal, Atom computing

Multidimensional quantum entanglement with large-scale integrated optics

Jianwei Wang[1,2,*,†], Stefano Paesani[1,*], Yunhong Ding[3,4,*,†], Raffaele Santagati[1], Paul Skrzypczyk[5], Alexia Salavrakos[6], Jordi Tura[7], Remigiusz Augusiak[8], Laura Mančinska[9], Davide Bacco[3,4], Damien Bonneau[1], Joshua W. Silverstone[1], Qihuang Gong[2], Antonio Acín[6,10], Karsten Rottwitt[3,4], Leif K. Oxenløwe[3,4], Jeremy L. O'Brien[1], Anthony Laing[1,†], Mark G. Thompson[1,†]



Science 08 Mar 2018:
eaar7053
DOI: 10.1126/science.aar7053

THE QUANTUM DAILY
QUANTUM COMPUTING AND BEYOND

NEWS ⌄ INSIGHTS ⌄ RESOURCES ⌄

Home › Business › PsiQuantum Raises $215 Million with new $150m round led by Atomico

Business | Capital Markets | Startups

PsiQuantum Raises $215 Million with new $150m round led by Atomico

By **Quantum Analyst** - April 7, 2020

Massive hype!

DiVincenzo 5

Qubit	Init.	Gates	Read-out	Coherence	Scalable
Atoms	Motion	Motion			3D
Ions					1D
Photons		Weak int.			
P in Si				Si host	Wires
Super-					10 mK

Scalable Qubit Arrays for Quantum Computing and Optimisation (SQuAre)

SQuARE

This project is an EPSRC Prosperity Partnership with M Squared Lasers that aims to develop a new platform for quantum computing based on scalable arrays of neutral atoms that is able to overcome the challenges to scaling of competing technologies. We will develop new hardware to cool and trap arrays of over 100 qubits that will be used to perform both analogue and digital quantum simulation by exploiting the strong long-range interactions of highly excited Rydberg atoms. Together with the quantum software team lead by Prof. Andrew Daley, we will design new analogue and digital algorithms tailored for the neutral-atom platform to target industrially-relevant computation and optimisation problems.

http://photonics.phys.strath.ac.uk/rydberg-quantum-devices/

Sunday, April 28, 2013

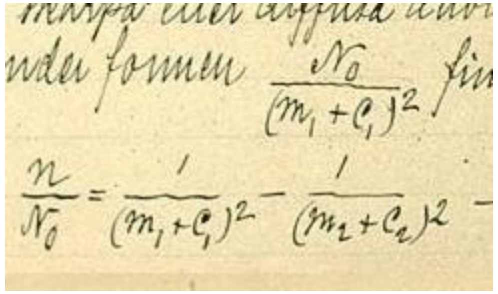
Storage and Control of Optical Photons

Authors of the paper in Physical Review Letters (reference [1]).
Left to Right:
(*top row*) D. Maxwell, D. J. Szwer, D. Paredes-Barato,
(*middle row*) H. Busche, J. D. Pritchard, A. Gauguet,
(*bottom row*) K. J. Weatherill, M. P. A. Jones, C. S. Adams.

Authors:
David Szwer and Hannes Busche

Affiliation:
Joint Quantum Centre (JQC) Durham-Newcastle, Department of Physics, Durham University, UK.

Rydberg atoms - the dark horse of quantum computing?



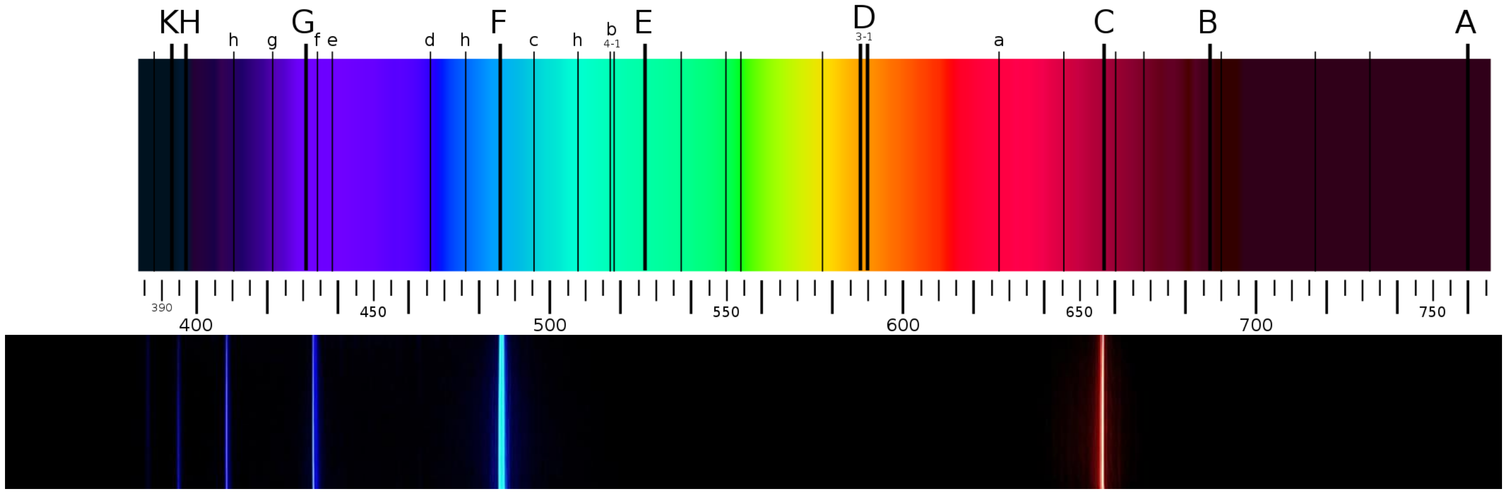
Rydberg 1888

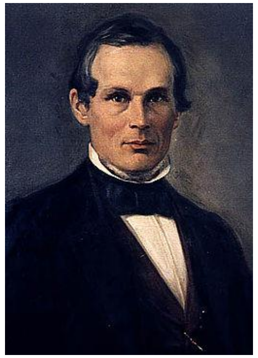
What are `Rydberg' atoms?

Highly-excited Rydberg states $E_n = -\frac{R_{\mathrm{H}}}{n^2}$ $E_n = -R_{\mathrm{Cs}}\frac{1}{(n-\delta)^2}$

Why are they useful?

Rydberg atoms - the dark horse of quantum computing?





Angstrom 1862

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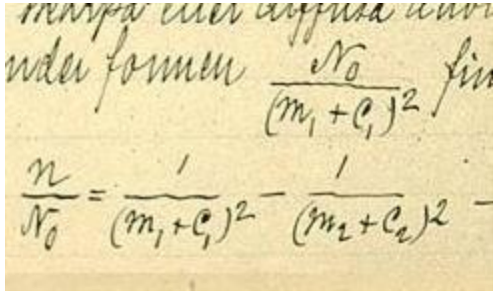
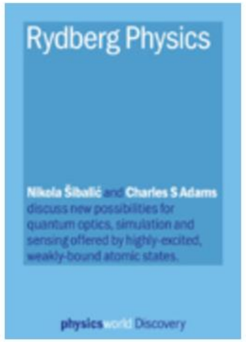


under formen $\frac{N_0}{(m_1+C_1)^2}$ fin

$$\frac{n}{N_0} = \frac{1}{(m_1+C_1)^2} - \frac{1}{(m_2+C_2)^2}$$

Rydberg 1888

https://iopscience.iop.org/book/978-0-7503-1635-4



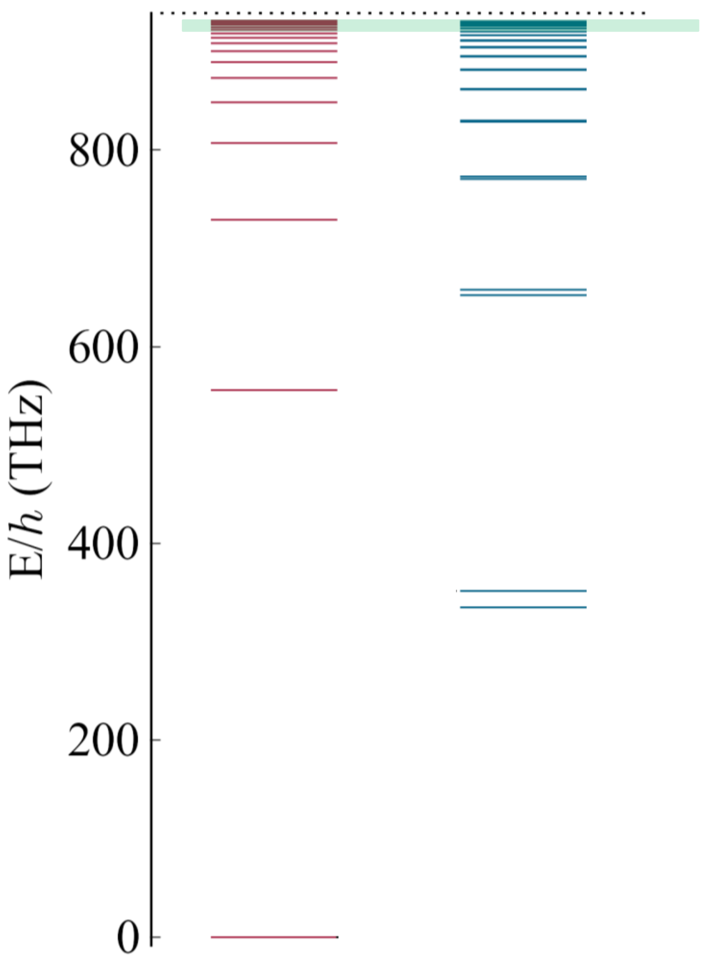
Authors

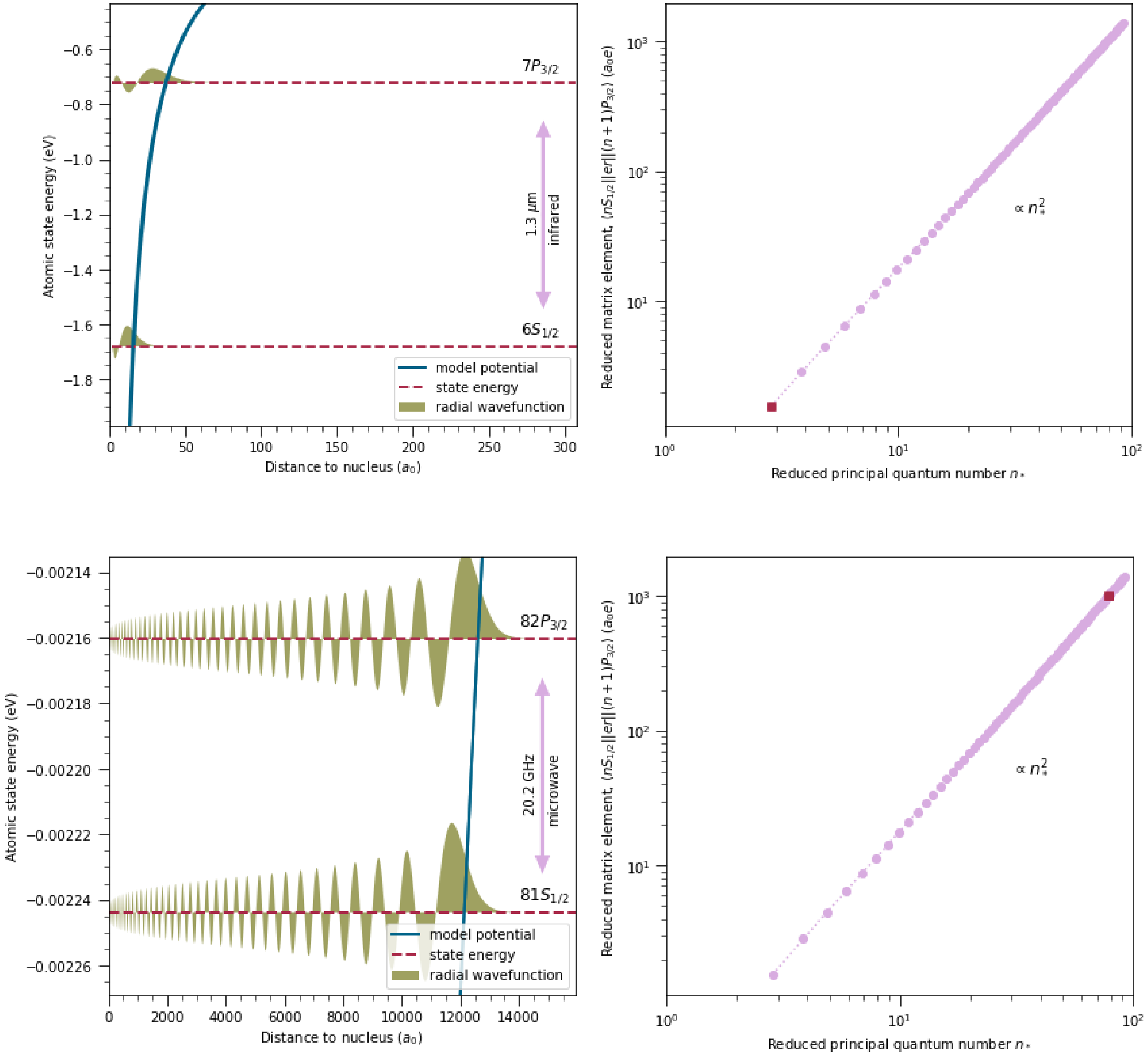
Nikola Šibalić and

Charles S Adams

Published

November 2018





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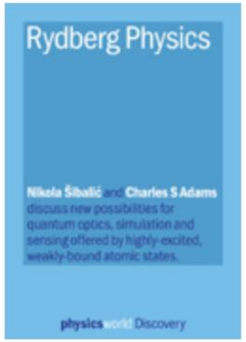

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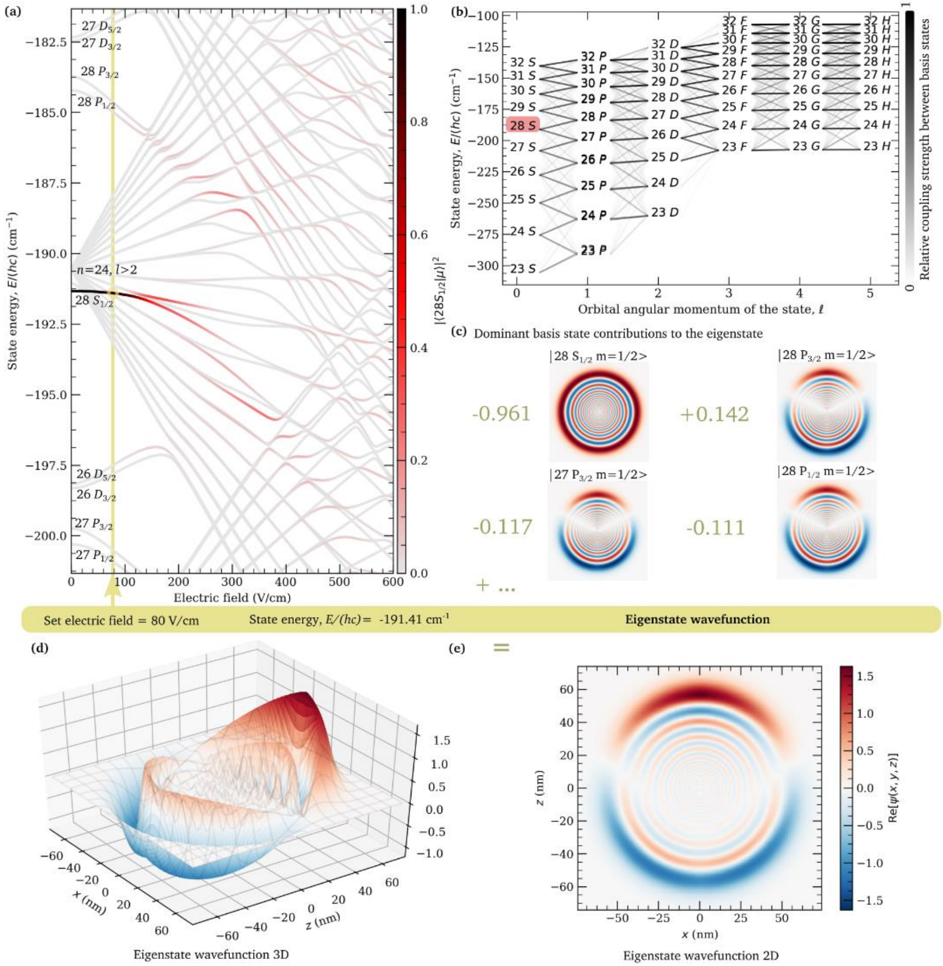
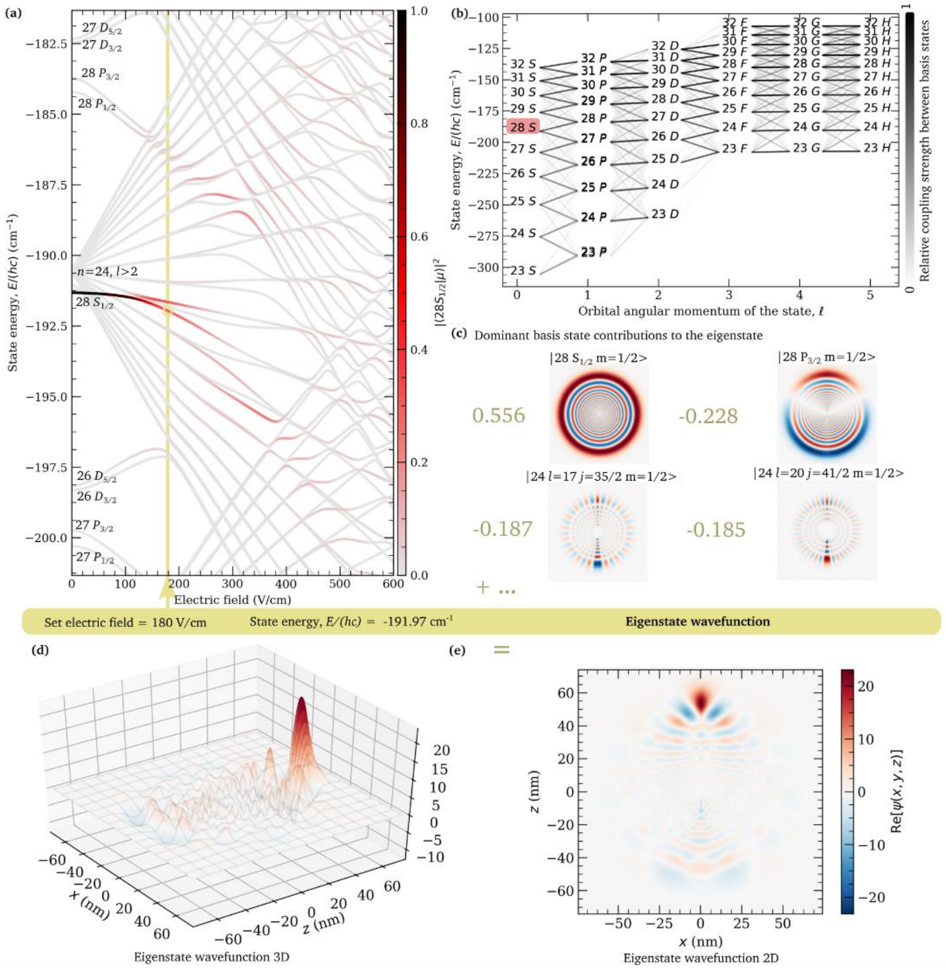


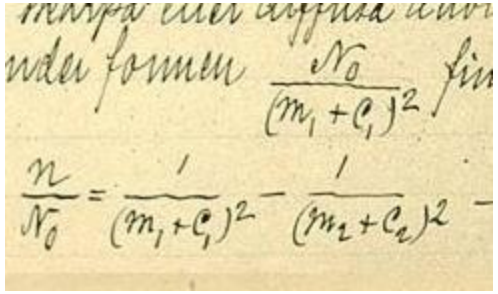


Nikola Sibalic

Quantum Computing

IBM and the Unitary Fund Unite for Open Source Projects for Quantum Computing

Rydberg atoms - the dark horse of quantum computing?



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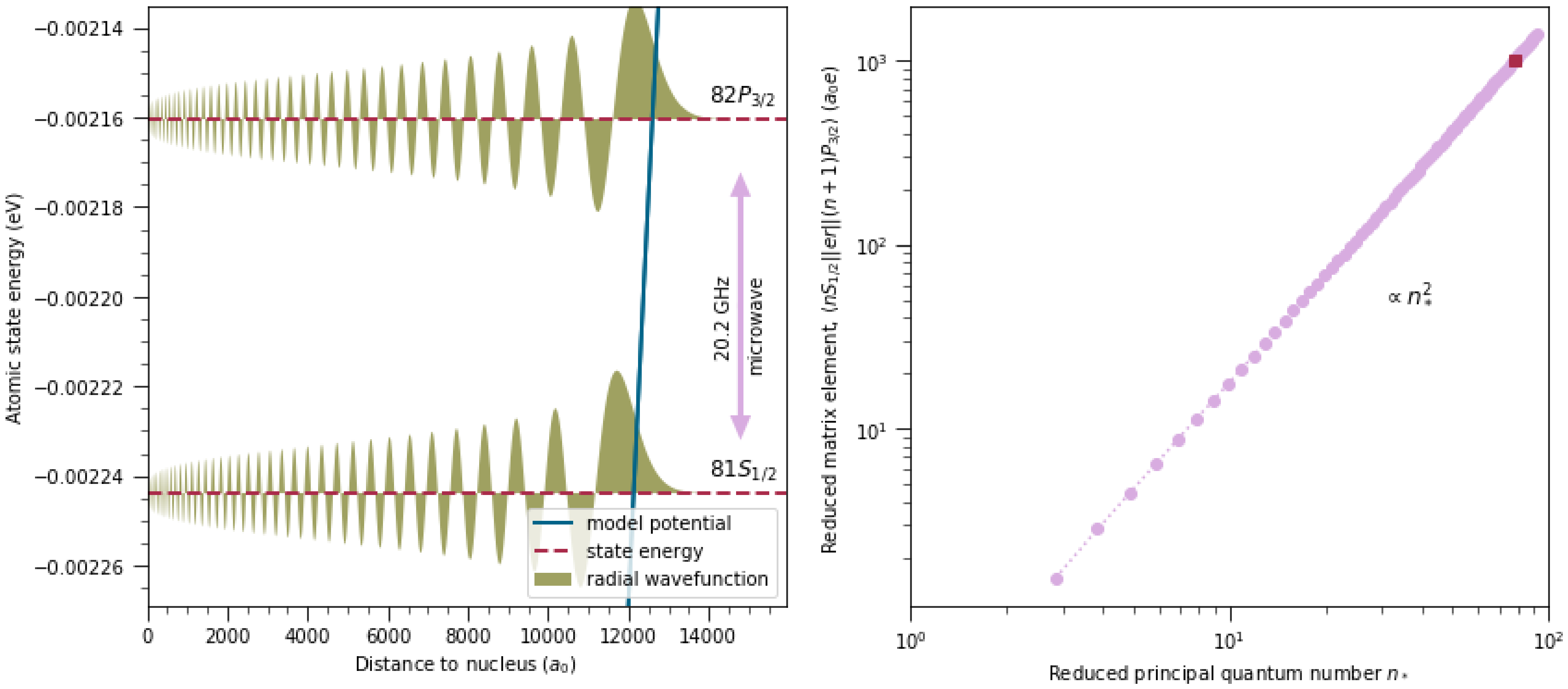
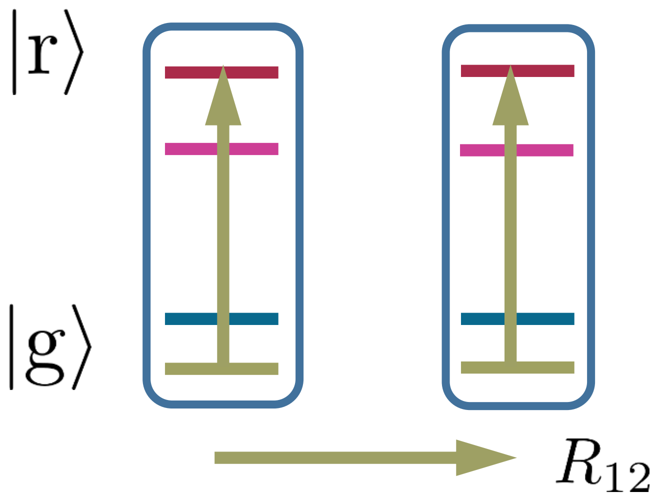
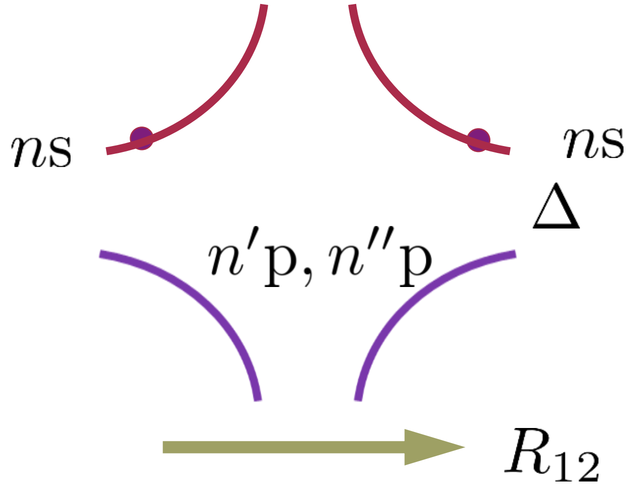


Dipole-dipole interactions

$|\mathrm{r}\rangle = n\mathrm{s}$ $|\mathrm{r}'\rangle = |n\mathrm{p}\rangle$ $n\mathrm{s}, n\mathrm{s}$ pairs couple to nearest $n'\mathrm{p}, n''\mathrm{p}$ pair





$$V_{\mathrm{vdW}} = \frac{V^2}{\Delta}$$

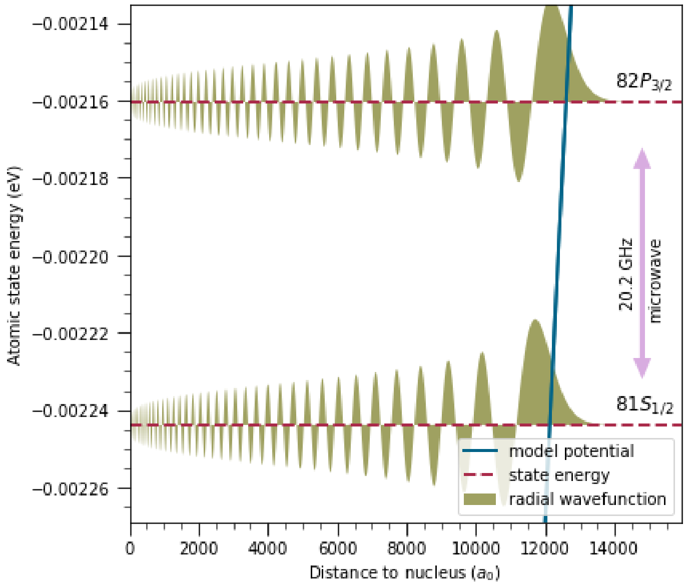
$$V_{\mathrm{vdW}} = \frac{C_6}{R_{12}^6} \qquad C_6 = c_6 n^{11}$$

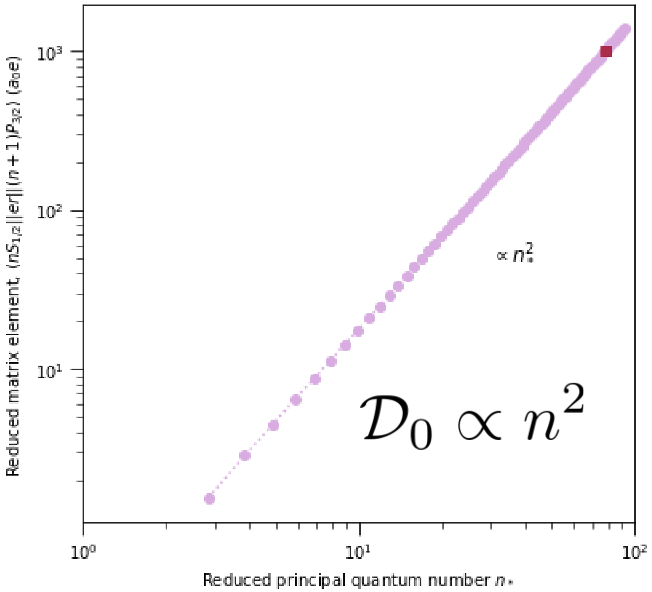
$$\mathcal{H}_{\mathrm{dd}} = \hbar \begin{pmatrix} 0 & 0 & 0 & V \\ 0 & \omega' & V & 0 \\ 0 & V & \omega'' & 0 \\ V & 0 & 0 & \Delta \end{pmatrix} \begin{matrix} |\mathrm{r},\mathrm{r}\rangle \\ \\ \\ |\mathrm{r}',\mathrm{r}''\rangle \end{matrix}$$

$$V = \frac{\mathcal{D}_0^2/\hbar}{4\pi\epsilon_0 R_{12}^3}$$

Near-field dipole-dipole

sign of shift depends on whether nearest pair is above or below in energy





$$V = \frac{\mathcal{D}_0^2/\hbar}{4\pi\epsilon_0 R_{12}^3}$$

$$V_{\mathrm{vdW}} = \frac{V^2}{\Delta} \qquad \Delta \propto 1/n^3$$

$$V_{\mathrm{vdW}} = \frac{C_6}{R_{12}^6} \qquad C_6 = c_6 n^{11}$$

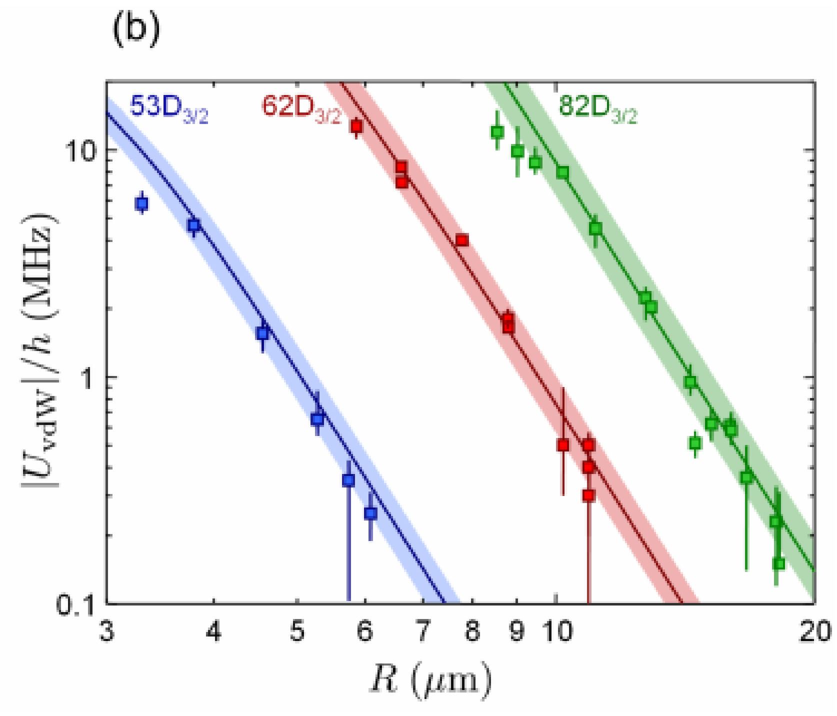
IOP Publishing Journal of Physics B: Atomic, Molecular and Optical Physics
J. Phys. B: At. Mol. Opt. Phys. 49 (2016) 152001 (19pp) doi:10.1088/0953-4075/49/15/152001

Topical Review

Experimental investigations of dipole–dipole interactions between a few Rydberg atoms

Antoine Browaeys, Daniel Barredo and Thierry Lahaye

Laboratoire Charles Fabry, Institut d'Optique, CNRS, Univ Paris Sud 11, 2 Avenue Augustin Fresnel, F-91127 Palaiseau Cedex, France



How do we put two atoms X microns apart?

How do we put two atoms X microns apart?

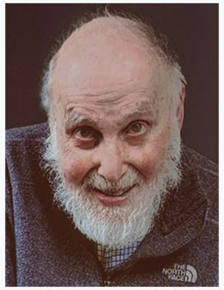
NATURE PHYSICS | VOL 16 | FEBRUARY 2020 | 132–142 |

Many-body physics with individually controlled Rydberg atoms

Antoine Browaeys* and Thierry Lahaye

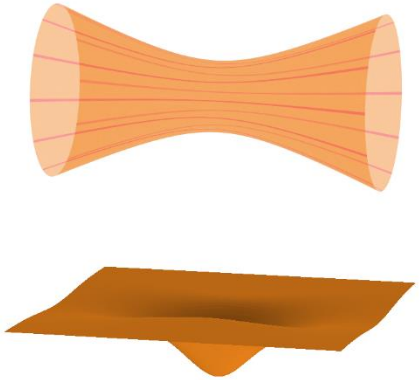
Optical tweezer for single atoms

Arthur Ashkin



Arthur Ashkin via video phone, December 2018

Born	September 2, 1922 (age 96) Brooklyn, New York, U.S.
Education	Columbia University (BS) Cornell University (MS, PhD)
Known for	Optical tweezers
Awards	Nobel Prize in Physics (2018)



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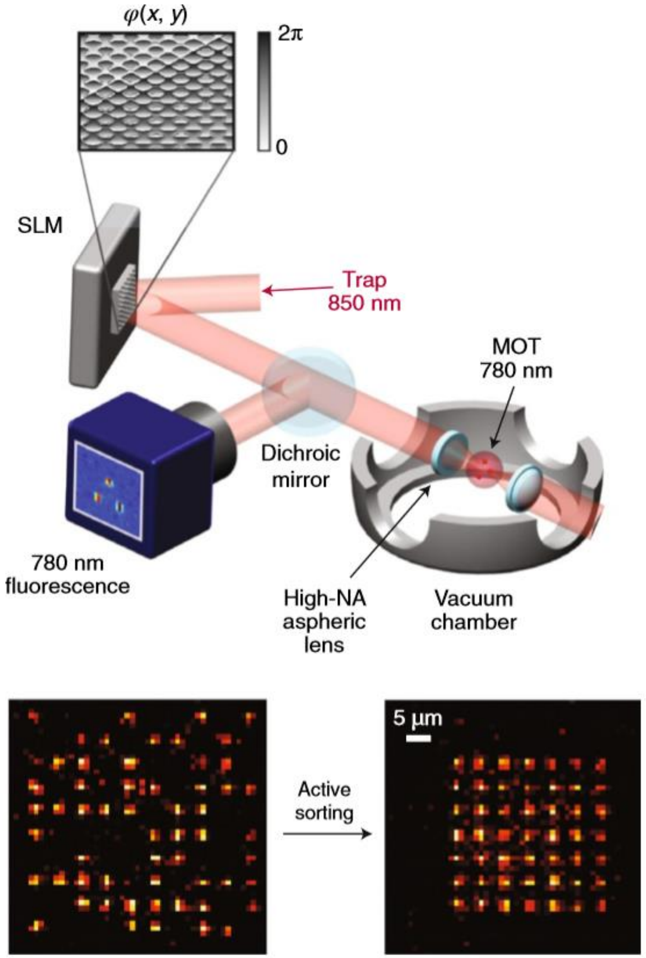
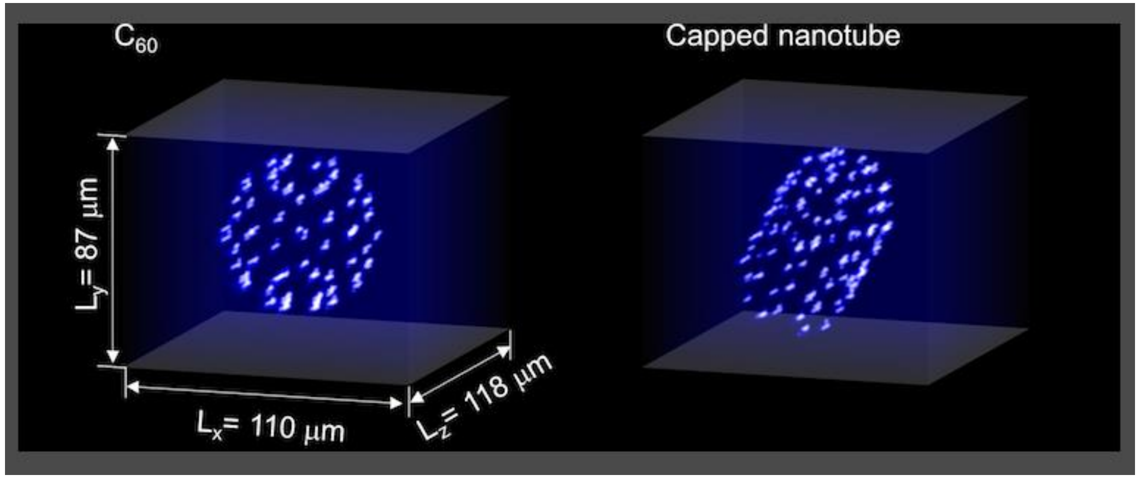


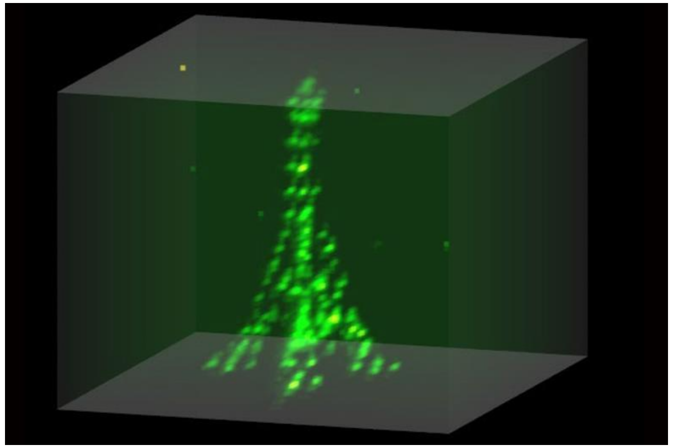
c

How do we put two atoms X microns apart?

Qubit	Init.	Gates	Read-out	Coherence	Scalable
Atoms	Motion	Motion			3D
Ions					1D
Photons		Weak int.			
P in Si				Si host	Wires
Super-					10 mK



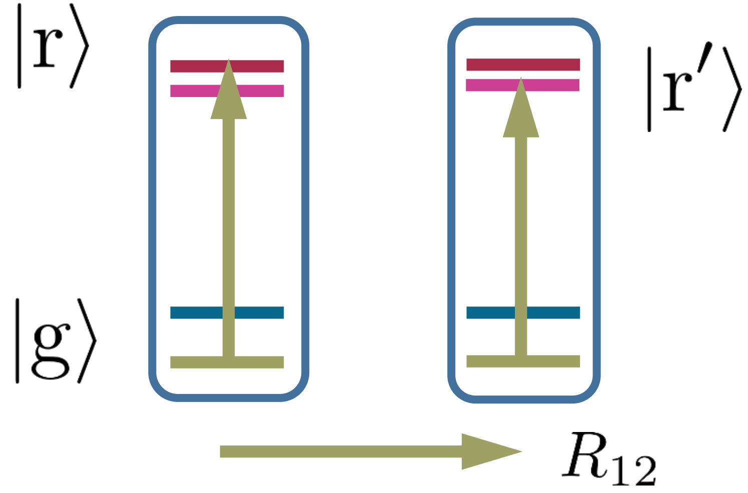
Daniel Barredo, Vincent Lienhard, Sylvain de Léséleuc, Thierry Lahaye, and Antoine Browaeys. Synthetic three-dimensional atomic structures assembled atom by atom. *Nature*, 561(7721):79–82, September 2018.



Exploiting the giant dipolar interactions

$$\mathcal{H}_{\rm dd} = \hbar \begin{pmatrix} 0 & 0 & 0 & V \\ 0 & \omega' & V & 0 \\ 0 & V & \omega'' & 0 \\ V & 0 & 0 & \Delta \end{pmatrix}$$

Select states with Δ *zero or use electric fields to tune to zero*

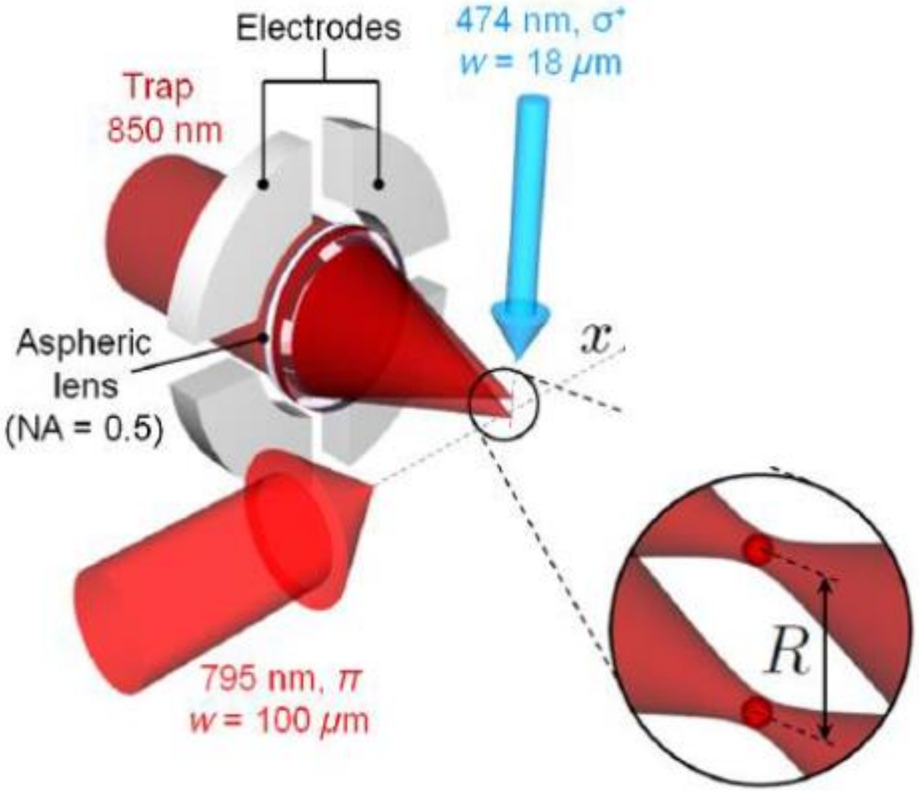


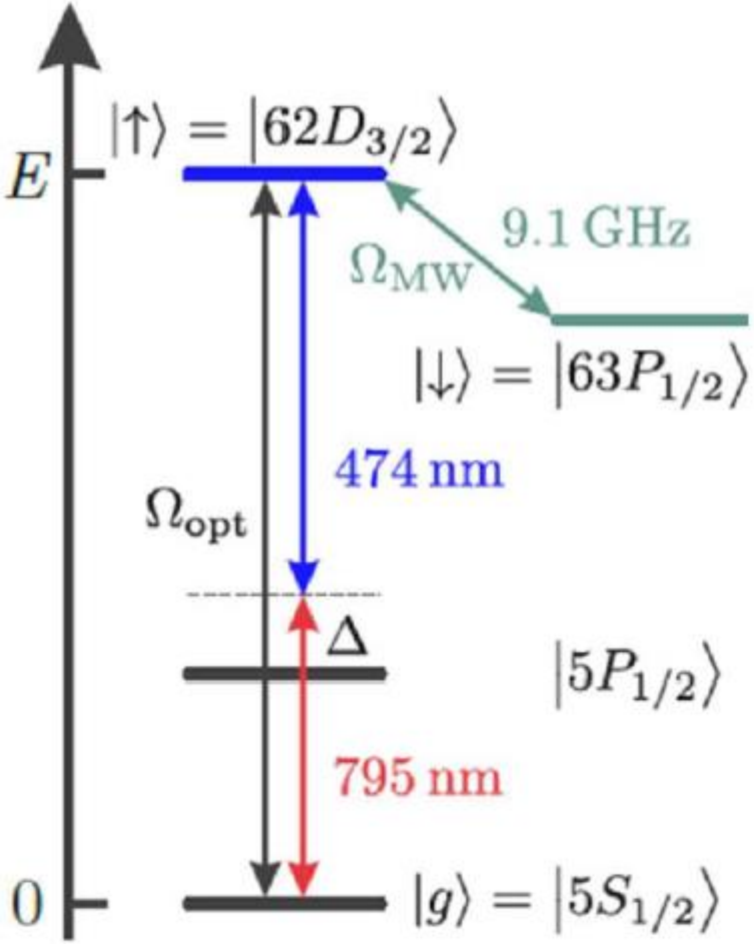
$$\mathcal{H}'_{\rm dd} = \hbar \begin{pmatrix} 0 & V \\ V & 0 \end{pmatrix}$$

Henning Labuhn **Antoine Browaeys** **Thierry Lahaye**

Sylvain Ravets **Daniel Barredo**

TRIANGLE DE LA PHYSIQUE



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tern

Exploiting the giant dipolar interactions

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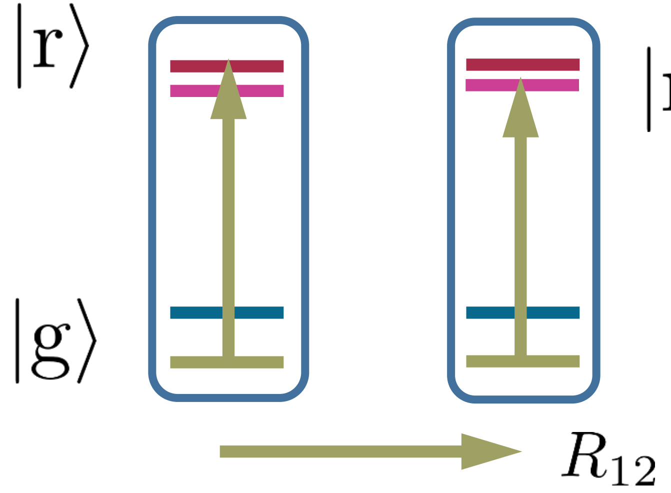

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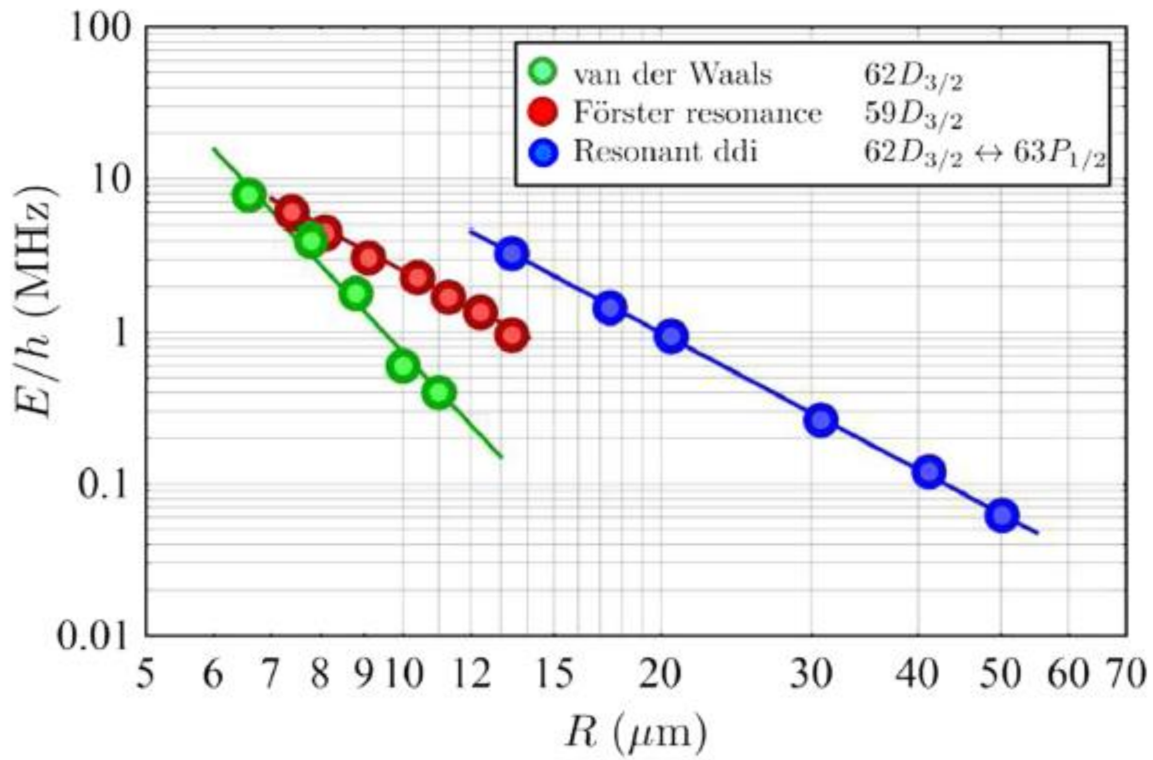
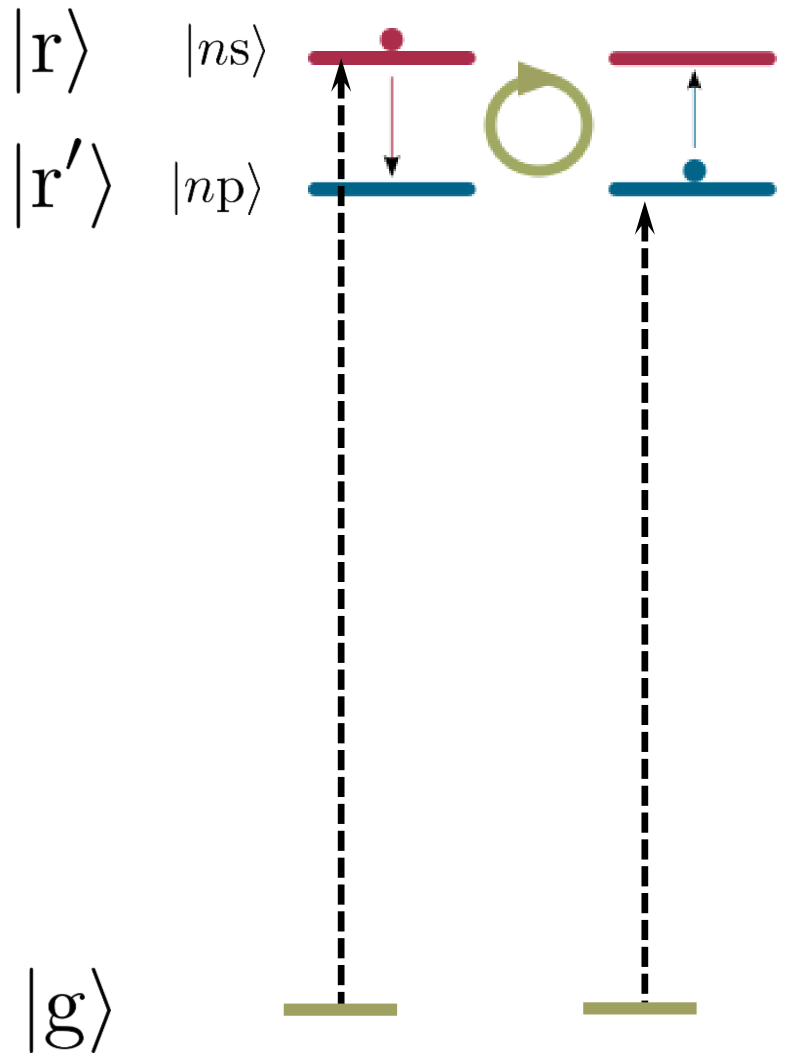


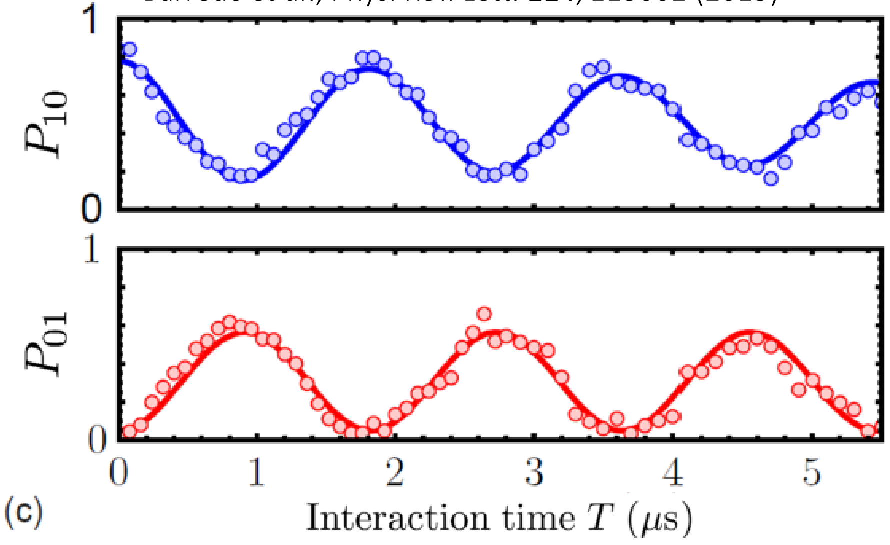
Interaction over 50 microns!

Scaling up to 1000 qubits with all-to-all couplings!

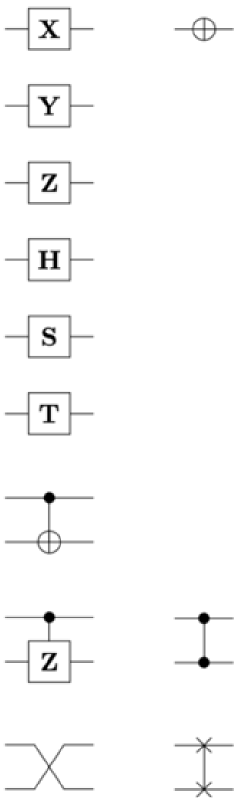


$$\mathcal{H} = \hbar \begin{pmatrix} 0 & V \\ V & 0 \end{pmatrix} \begin{matrix} |\mathrm{r}, \mathrm{r}'\rangle & ns, np \\ |\mathrm{r}', \mathrm{r}\rangle & np, ns \end{matrix}$$

Barredo *et al.*, Phys. Rev. Lett. **114**, 113002 (2015)



https://en.wikipedia.org/wiki/Quantum_logic_gate



Operator	Gate(s)	Matrix
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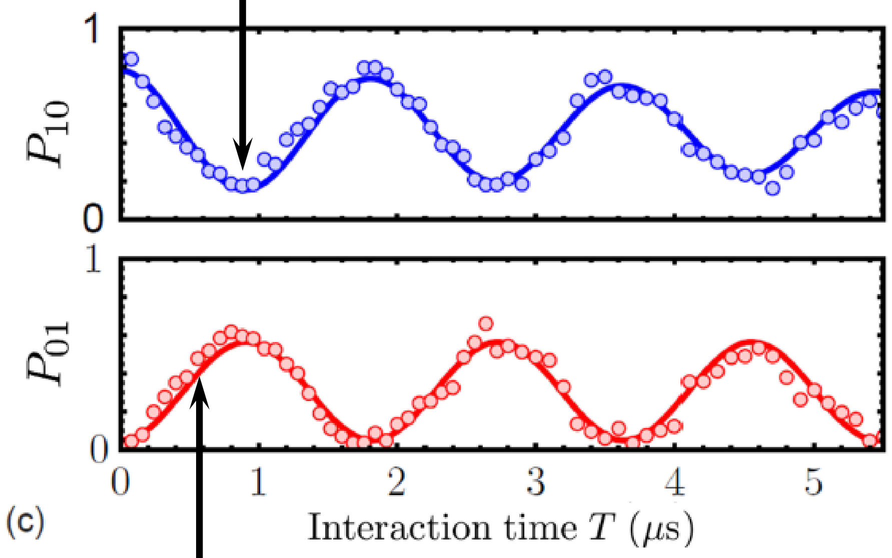
Pauli-Y (Y)	Y	$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$
Pauli-Z (Z)	Z	$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$
Hadamard (H)	H	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$
Phase (S, P)	S	$\begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$
$\pi/8$ (T)	T	$\begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix}$
Controlled Not (CNOT, CX)		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$
Controlled Z (CZ)	Z	$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$
SWAP		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

https://en.wikipedia.org/wiki/Quantum_logic_gate

Operator	Gate(s)		Matrix
Pauli-X (X)	X	⊕	$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$
Pauli-Y (Y)	Y		$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$
Pauli-Z (Z)	Z		$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$
Hadamard (H)	H		$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$
Phase (S, P)	S		$\begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$
$\pi/8$ (T)	T		$\begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix}$
Controlled Not (CNOT, CX)			$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$
Controlled Z (CZ)	Z		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$
SWAP			$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

$$\mathrm{SWAP} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$



$$\sqrt{\mathrm{SWAP}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \frac{1}{2}(1+\mathrm{i}) & \frac{1}{2}(1-\mathrm{i}) & 0 \\ 0 & \frac{1}{2}(1-\mathrm{i}) & \frac{1}{2}(1+\mathrm{i}) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

https://en.wikipedia.org/wiki/Quantum_logic_gate

Operator	Gate(s)	Matrix
Pauli-X (X)	X	$\begin{bmatrix}0 & 1\\ 1 & 0\end{bmatrix}$
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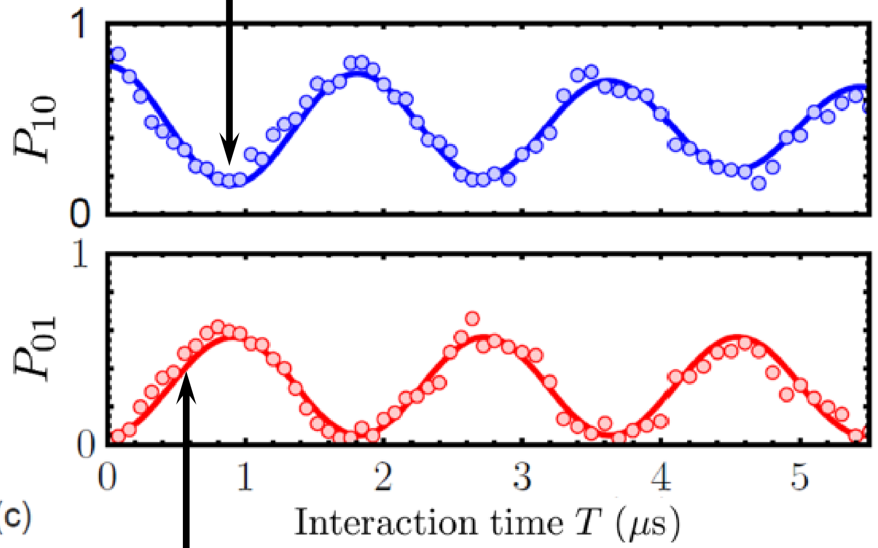
Pauli-Z (Z)	Z	$\begin{bmatrix}1 & 0\\ 0 & -1\end{bmatrix}$
Hadamard (H)	H	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix}$
Phase (S, P)	S	$\begin{bmatrix}1 & 0\\ 0 & i\end{bmatrix}$
$\pi/8$ (T)	T	$\begin{bmatrix}1 & 0\\ 0 & e^{i\pi/4}\end{bmatrix}$
Controlled Not (CNOT, CX)		$\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1\\ 0 & 0 & 1 & 0\end{bmatrix}$
Controlled Z (CZ)	Z	$\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & -1\end{bmatrix}$
SWAP		$\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$

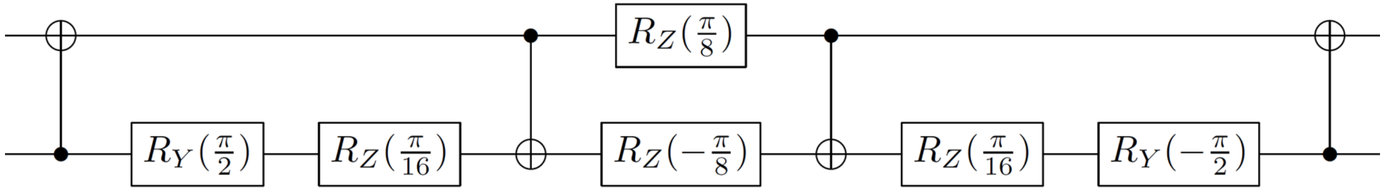
$$\mathrm{SWAP} = \begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}.$$



(c)

$$\sqrt{\mathrm{SWAP}} = \begin{bmatrix}1 & 0 & 0 & 0\\ 0 & \frac{1}{2}(1+\mathrm{i}) & \frac{1}{2}(1-\mathrm{i}) & 0\\ 0 & \frac{1}{2}(1-\mathrm{i}) & \frac{1}{2}(1+\mathrm{i}) & 0\\ 0 & 0 & 0 & 1\end{bmatrix}.$$

$\sqrt{\mathrm{SWAP}}$



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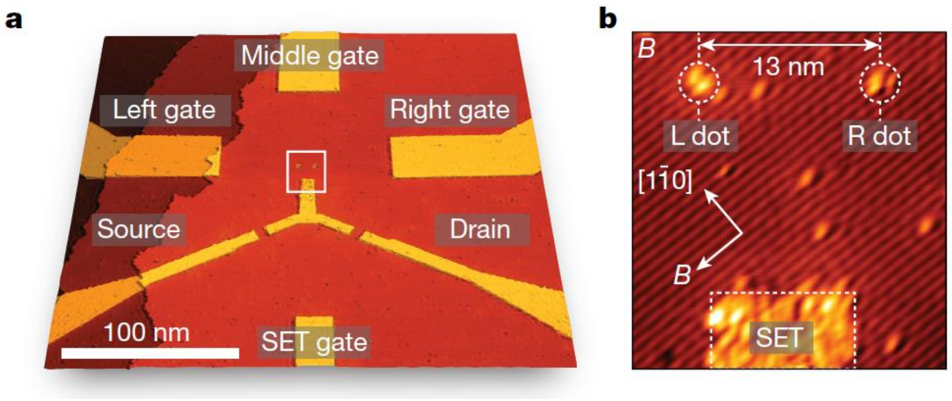
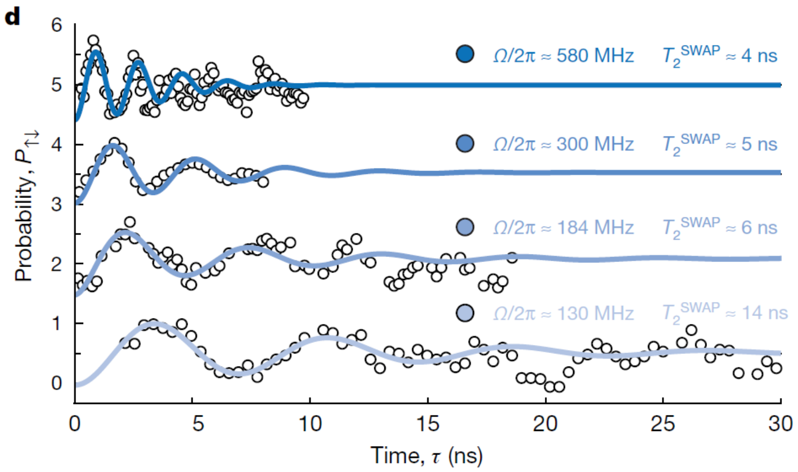
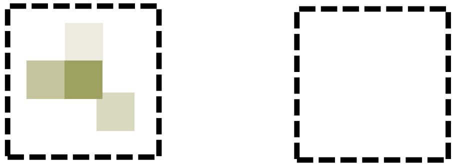
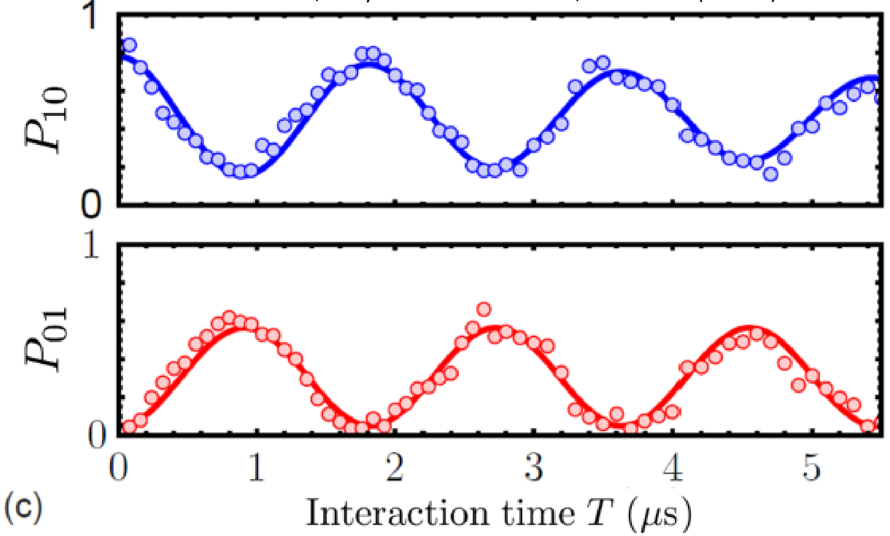




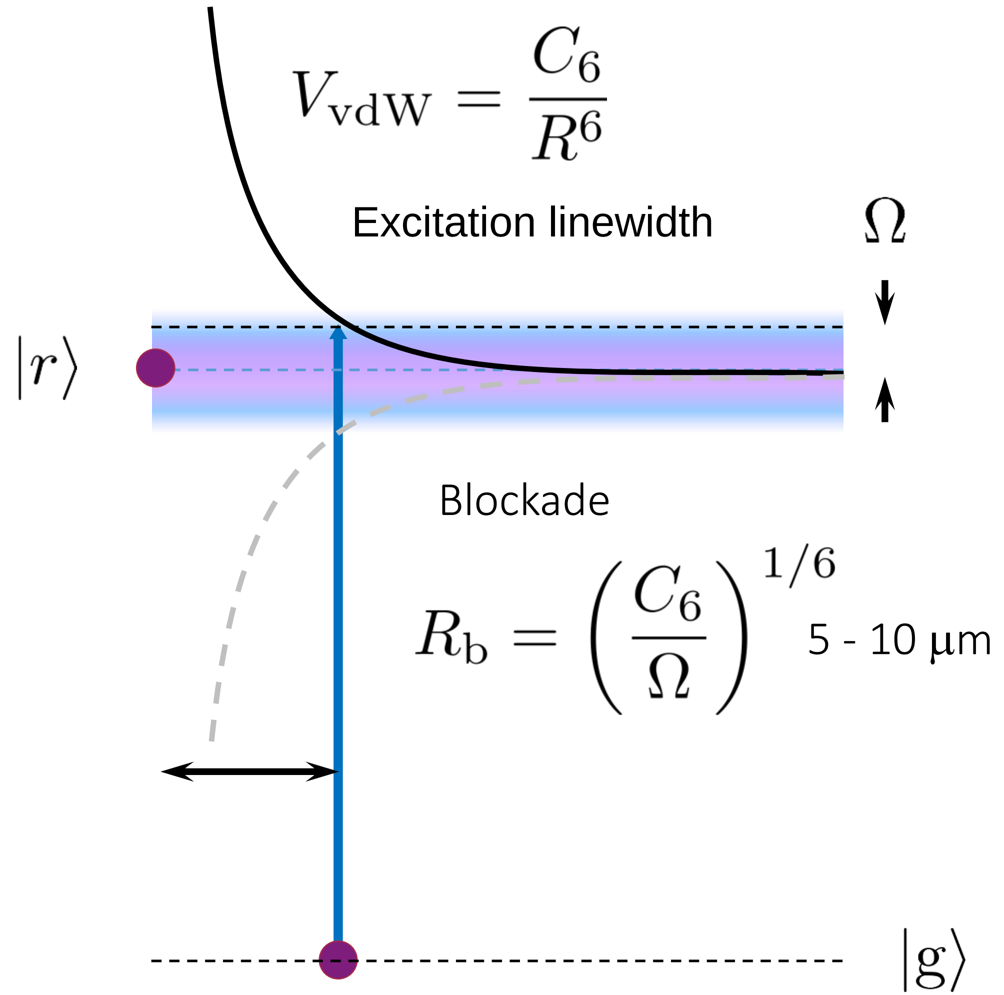
Compare:
Rydberg atoms



Barredo *et al.*, Phys. Rev. Lett. **114**, 113002 (2015)



Rydberg blockade



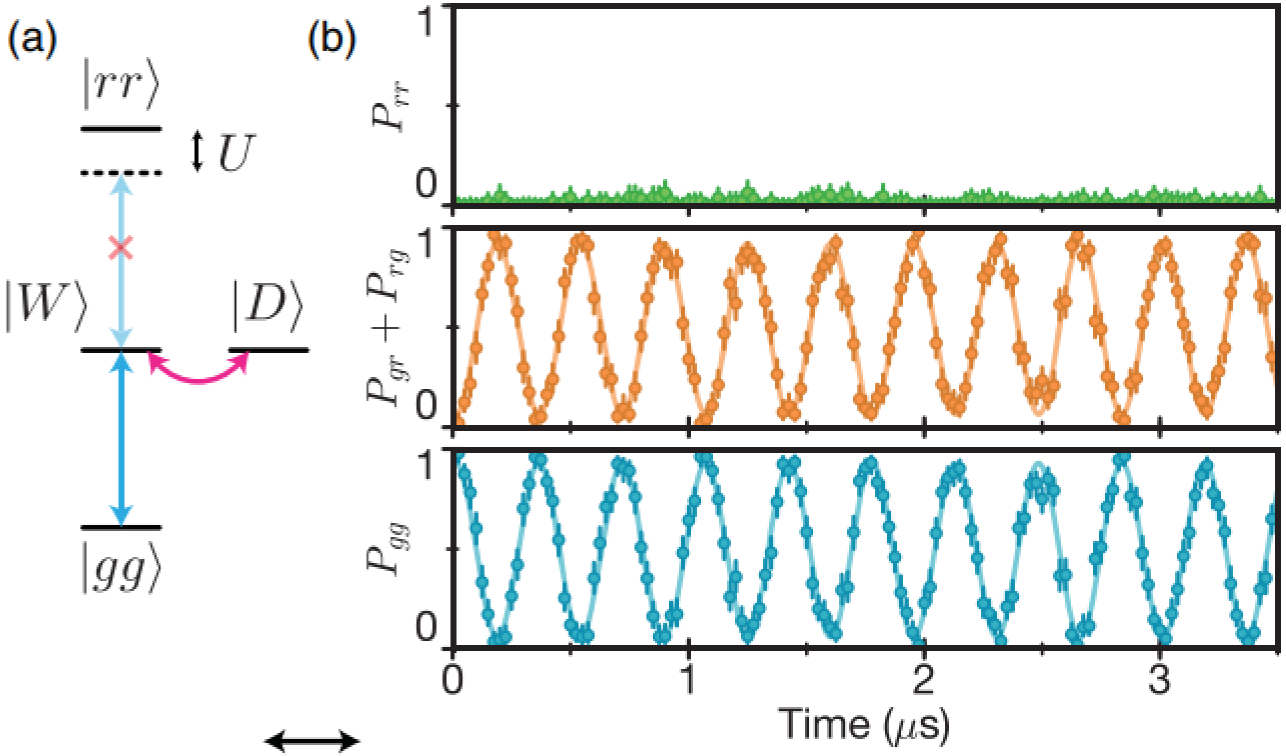
$R_{12} < R_{\mathrm{b}}$ (cannot excite two atoms)

High-Fidelity Control and Entanglement of Rydberg-Atom Qubits

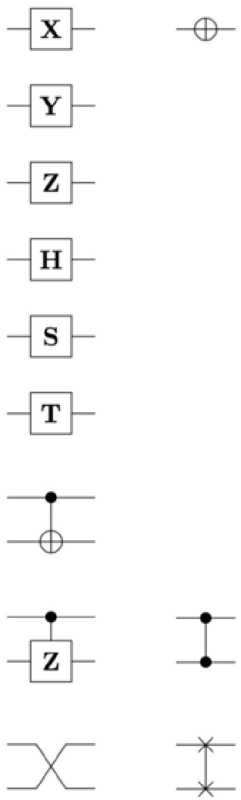
Harry Levine,[1*] Alexander Keesling,[1] Ahmed Omran,[1] Hannes Bernien,[1] Sylvain Schwartz,[2] Alexander S. Zibrov,[1]
Manuel Endres,[3] Markus Greiner,[1] Vladan Vuletić,[4] and Mikhail D. Lukin[1]
[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*Laboratoire Kastler Brossel, ENS-PSL Research University, CNRS, Sorbonne Université, Collège de France, 24 rue Lhomond, 75005 Paris, France*
[3]*Division of Physics, Mathematics and Astronomy, California Institute of Technology, Pasadena, California 91125, USA*
[4]*Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

(Received 12 June 2018; published 20 September 2018)

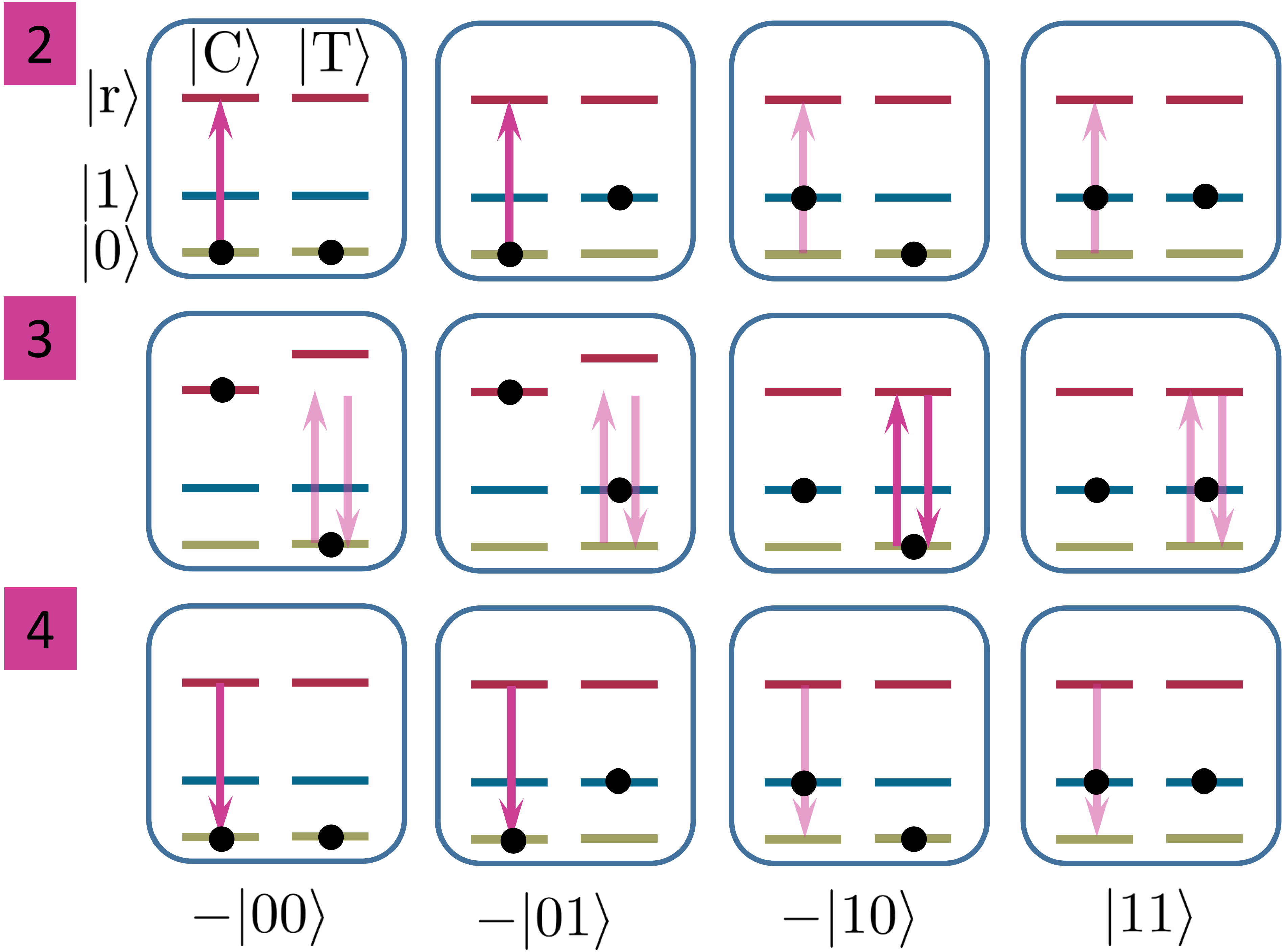
We next turn to two-atom control. To this end, we position two atoms at a separation of 5.7 μm, at which the Rydberg-Rydberg interaction is $U/\hbar = 2\pi \times 30$ MHz $\gg \Omega = 2\pi \times 2$ MHz. In this so-called Rydberg blockade regime, the laser field globally couples both atoms from $|gg\rangle$ to the symmetric state $|W\rangle = (1/\sqrt{2})(|gr\rangle + |rg\rangle)$ at an enhanced Rabi frequency of $\sqrt{2}\Omega$ [see Fig. 3(a)] (here



https://en.wikipedia.org/wiki/Quantum_logic_gate

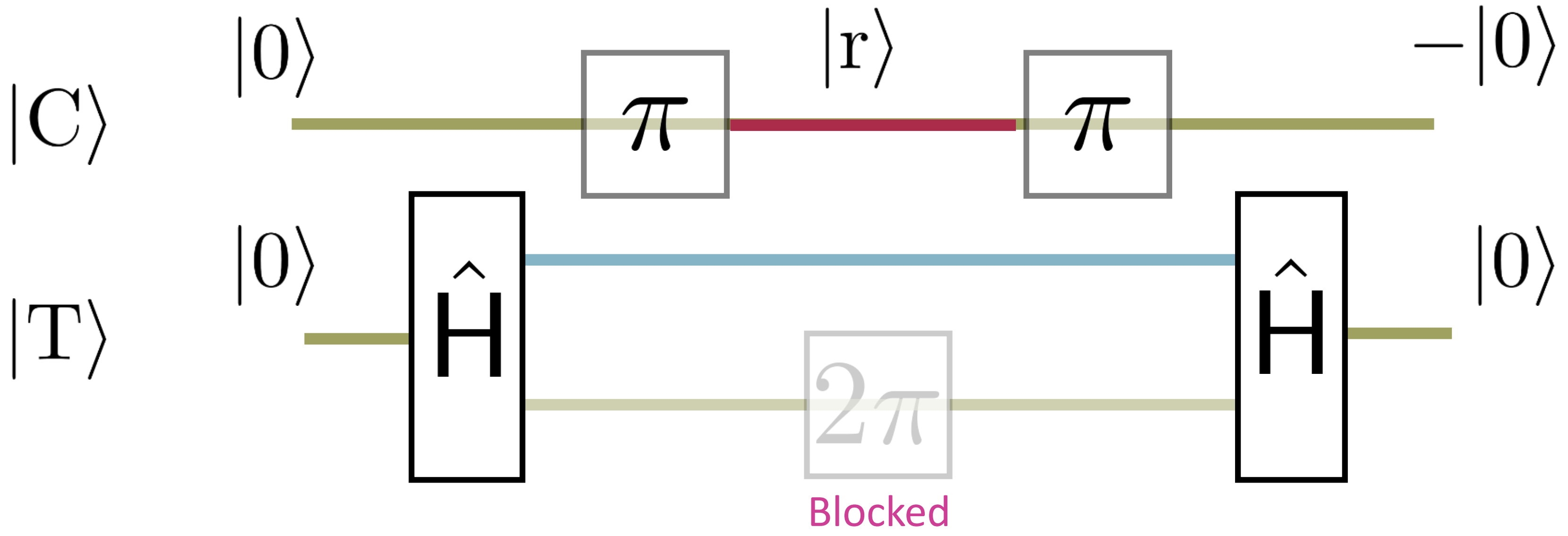


Operator	Gate(s)	Matrix
Pauli-X (X)	X	$\begin{bmatrix}0 & 1\\1 & 0\end{bmatrix}$
Pauli-Y (Y)	Y	$\begin{bmatrix}0 & -i\\i & 0\end{bmatrix}$
Pauli-Z (Z)	Z	$\begin{bmatrix}1 & 0\\0 & -1\end{bmatrix}$
Hadamard (H)	H	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$
Phase (S, P)	S	$\begin{bmatrix}1 & 0\\0 & i\end{bmatrix}$
$\pi/8$ (T)	T	$\begin{bmatrix}1 & 0\\0 & e^{i\pi/4}\end{bmatrix}$
Controlled Not (CNOT, CX)		$\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&0&1\\0&0&1&0\end{bmatrix}$
Controlled Z (CZ)	Z	$\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&-1\end{bmatrix}$
SWAP		$\begin{bmatrix}1&0&0&0\\0&0&1&0\\0&1&0&0\\0&0&0&1\end{bmatrix}$

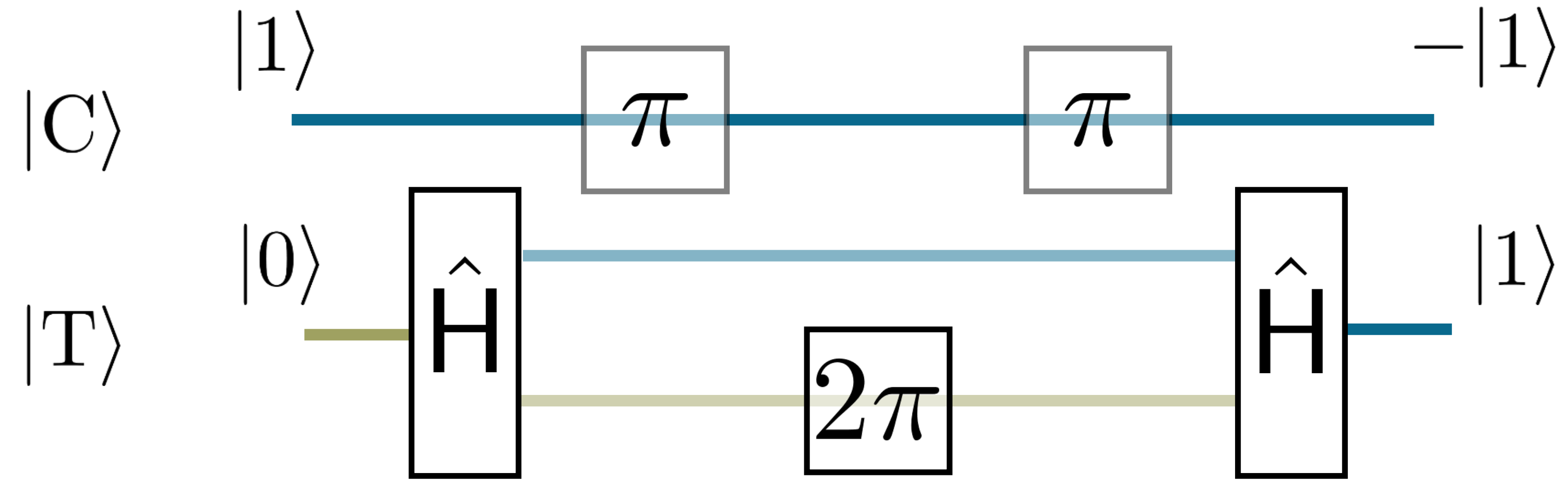

2
3
4
$|C\rangle$
$|T\rangle$
$|r\rangle$
$|1\rangle$
$|0\rangle$
$-|00\rangle$
$-|01\rangle$
$-|10\rangle$
$|11\rangle$

Complete 5 pulse CNOT

Case 1:



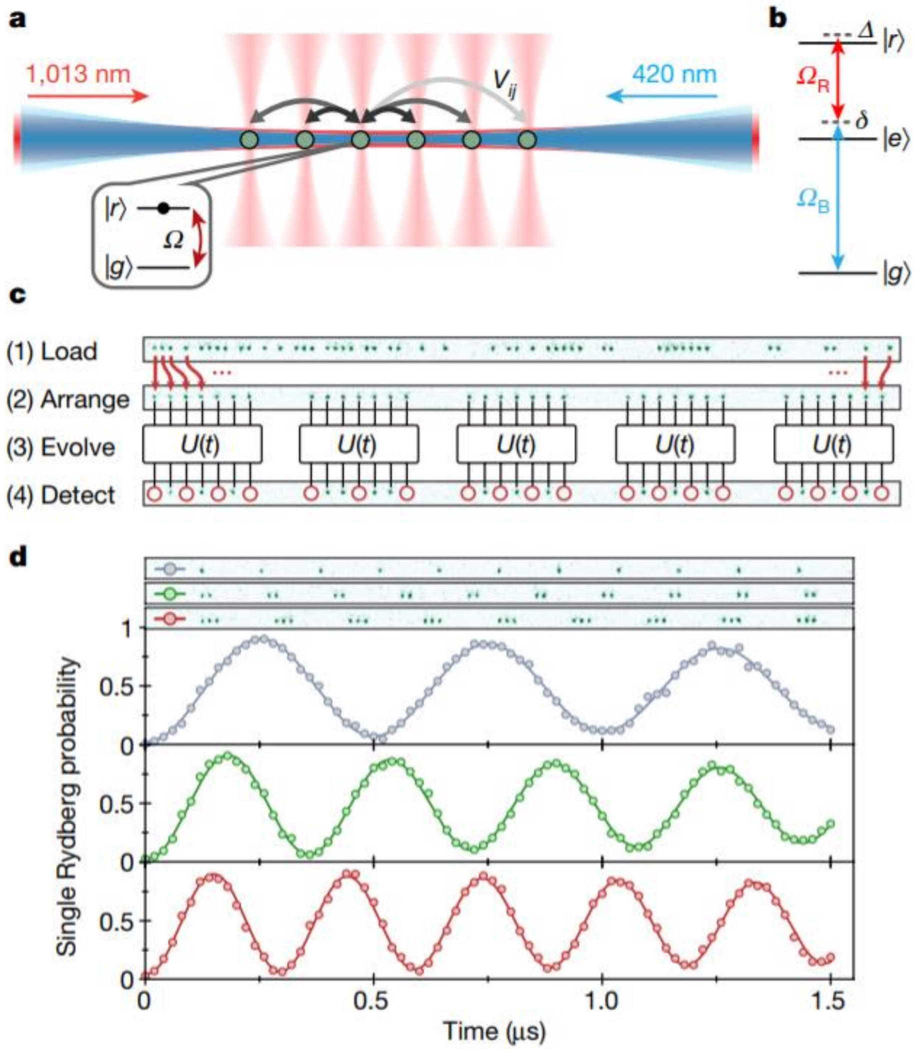
Case 2:

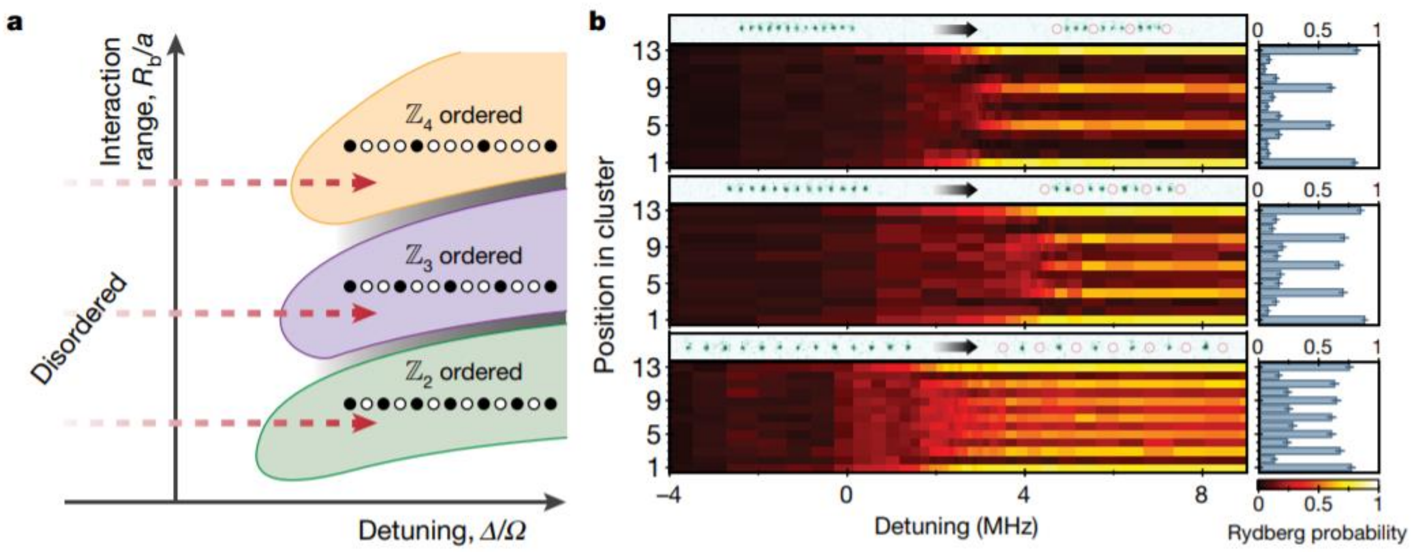


Probing many-body dynamics on a 51-atom quantum simulator

30 NOVEMBER 2017 | VOL 551 | NATURE | 579

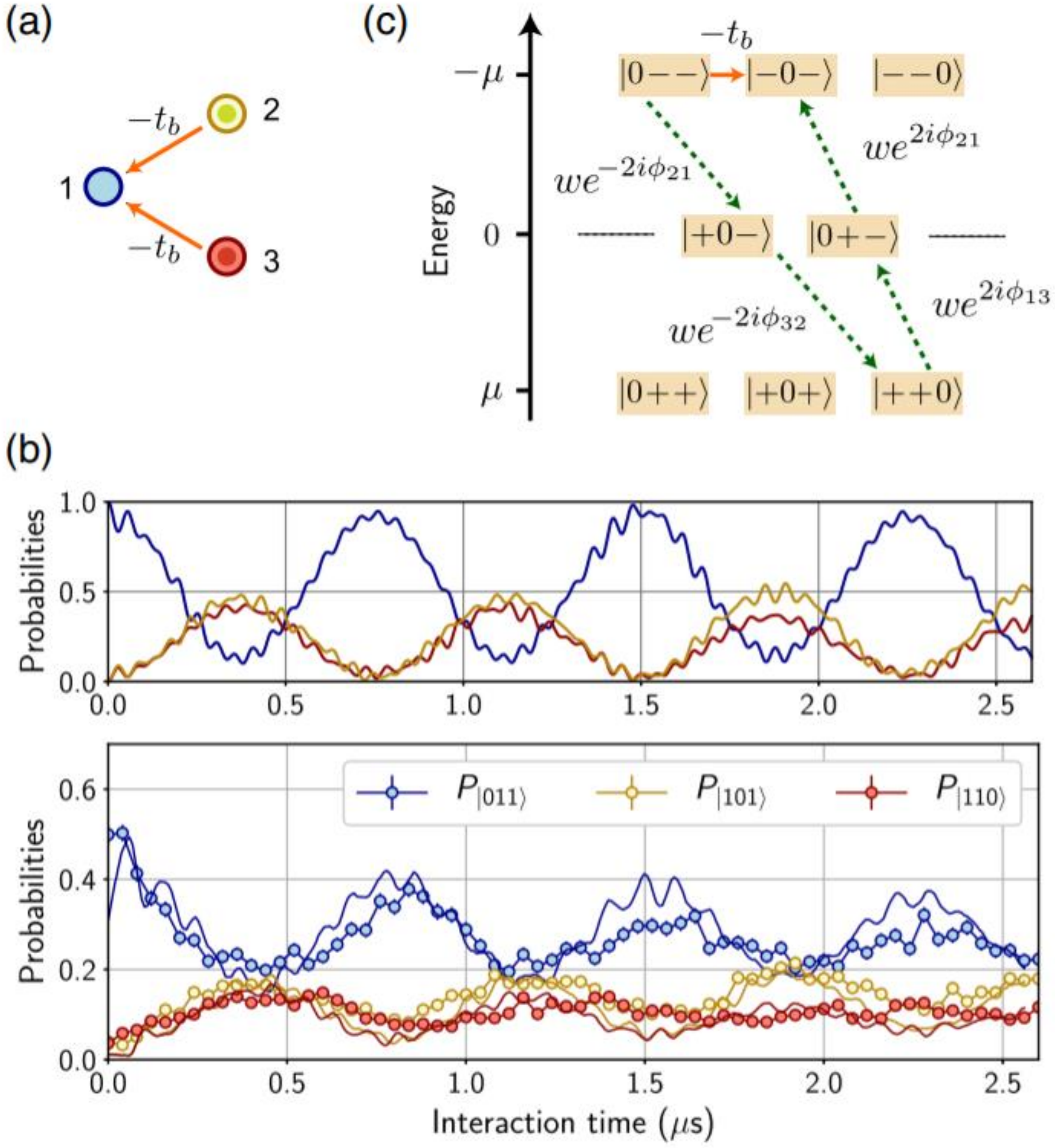
Hannes Bernien[1], Sylvain Schwartz[1,2], Alexander Keesling[1], Harry Levine[1], Ahmed Omran[1], Hannes Pichler[1,3], Soonwon Choi[1], Alexander S. Zibrov[1], Manuel Endres[4], Markus Greiner[1], Vladan Vuletić[2] & Mikhail D. Lukin[1]





Realization of a Density-Dependent Peierls Phase in a Synthetic, Spin-Orbit Coupled Rydberg System

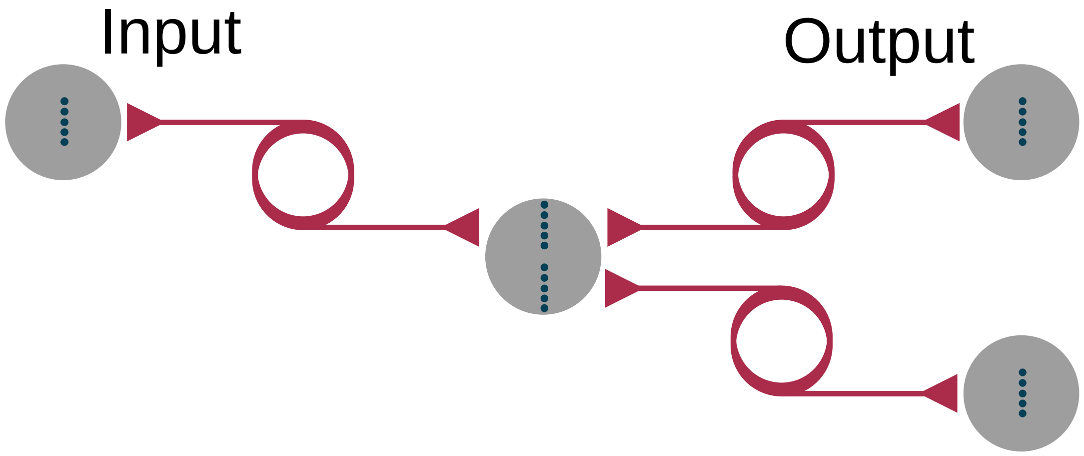
Vincent Lienhard,[1,*] Pascal Scholl,[1,*] Sebastian Weber,[2] Daniel Barredo,[1] Sylvain de Léséleuc,[1] Rukmani Bai,[2] Nicolai Lang,[2] Michael Fleischhauer,[3] Hans Peter Büchler,[2] Thierry Lahaye,[1] and Antoine Browaeys[1]



@DurhamQlm

Quantum light and matter

Quantum network



The Robustness of a Collectively Encoded Rydberg Qubit

Nicholas L. R. Spong,[1] Yuechun Jiao,[1,2] Oliver D. W. Hughes,[1]
Kevin J. Weatherill,[1] Igor Lesanovsky,[3,4] and Charles S. Adams[1]

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[2] *State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Laser Spectroscopy, Shanxi University, Taiyuan 030006, China*
[3] *Institut für Theoretische Physik, Auf der Morgenstelle 14, 72076 Tübingen, Germany*
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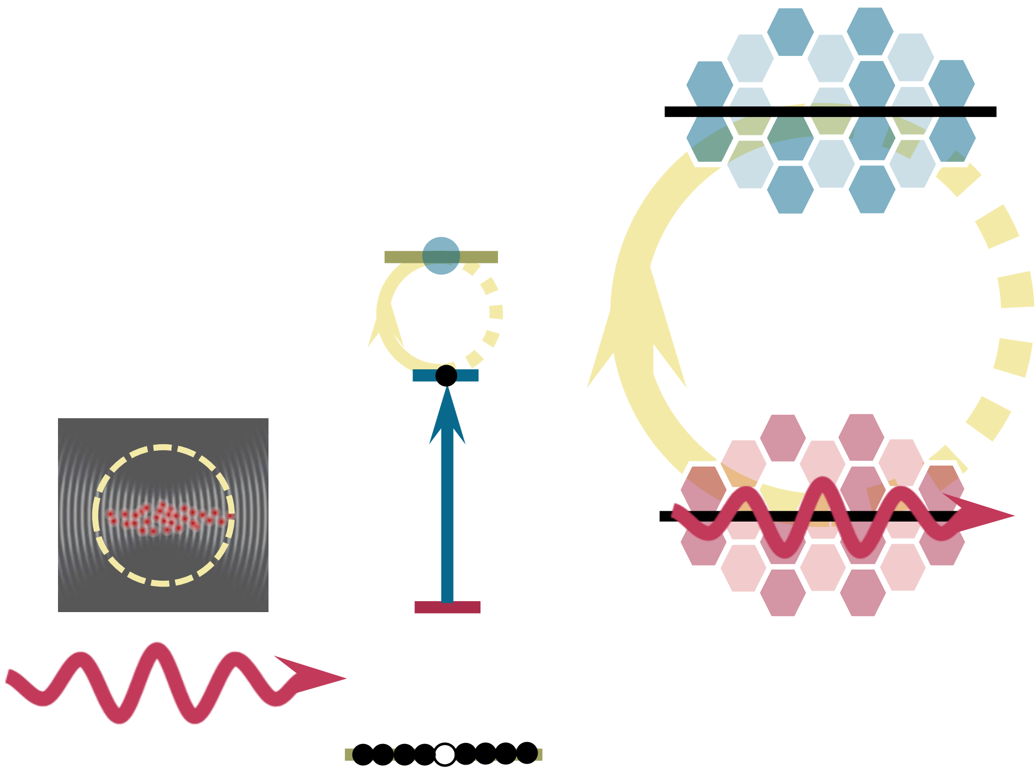
(Dated: August 4, 2020)

Stored single photon



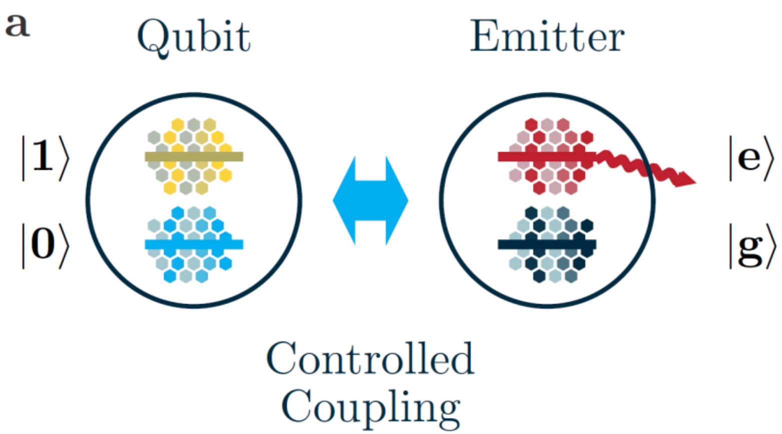
$$|1\rangle = \frac{1}{\sqrt{N}} \sum_{j=1}^{N} \mathrm{e}^{\mathrm{i}(\boldsymbol{k}\cdot\boldsymbol{R}_j - \omega_{\mathrm{r}'} t)} |\mathrm{g}_0 \mathrm{g}_1 \ldots \mathrm{r}'_j \ldots \mathrm{g}_N\rangle$$

$$|0\rangle = \frac{1}{\sqrt{N}} \sum_{j=1}^{N} \mathrm{e}^{\mathrm{i}(\boldsymbol{k}\cdot\boldsymbol{R}_j - \omega_{\mathrm{r}} t)} |\mathrm{g}_0 \mathrm{g}_1 \ldots \mathrm{r}_j \ldots \mathrm{g}_N\rangle$$

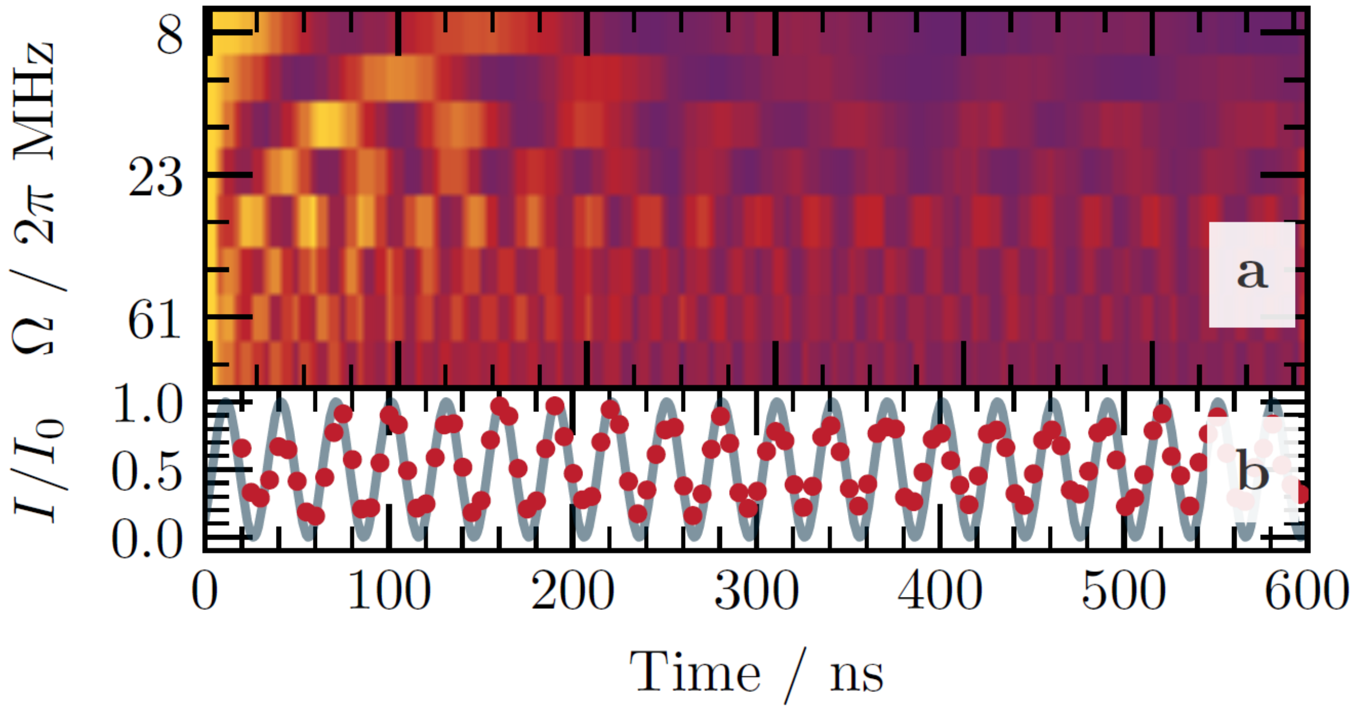
Collectively-encoded qubit

Continuous weak measurement

Strong driving



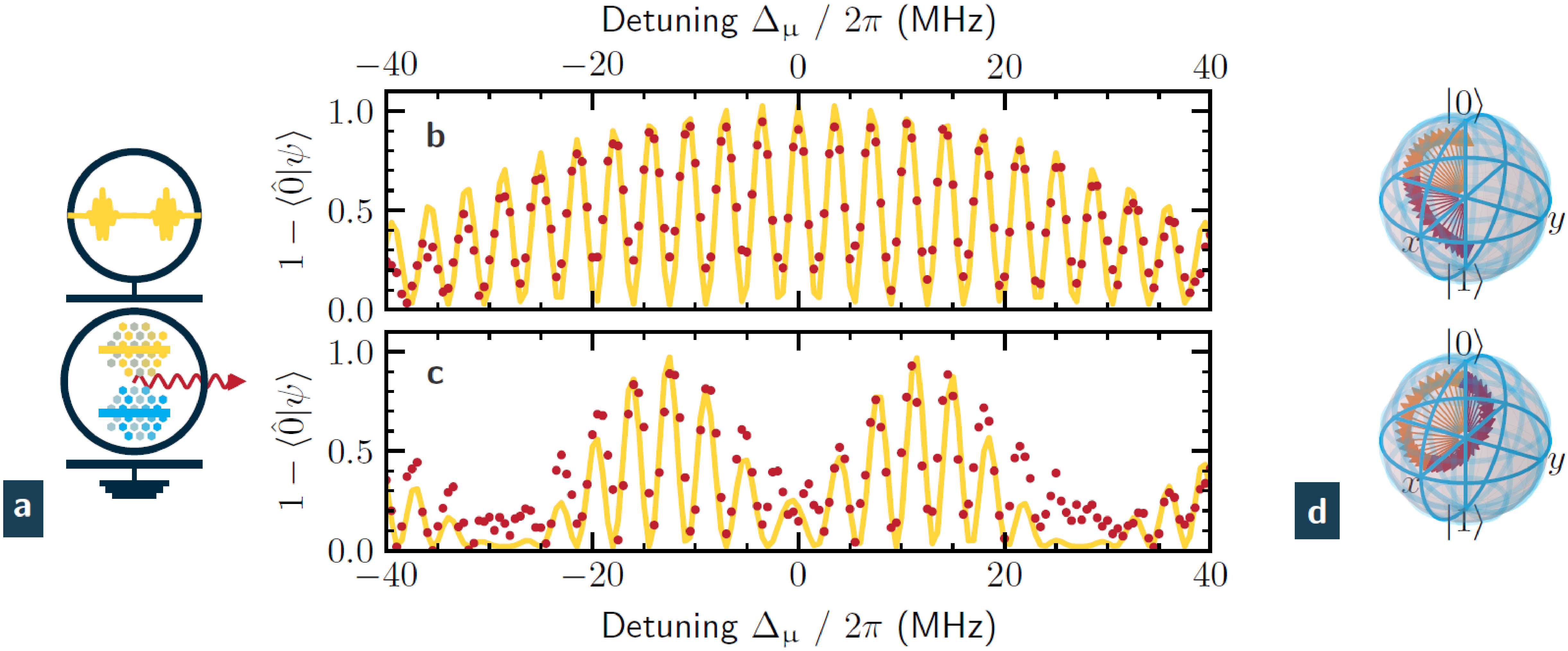
Weak coupling



Rabi frequencies > 70 MHz

Oscillations persist

Single qubit rotations



Open questions

1. Is a discrete gate model the best paradigm for quantum computing?

2. As there is no reason to restrict ourselves to binary logic, why not focus on higher dimensionality?

Asymptotic Improvements to Quantum Circuits via Qutrits

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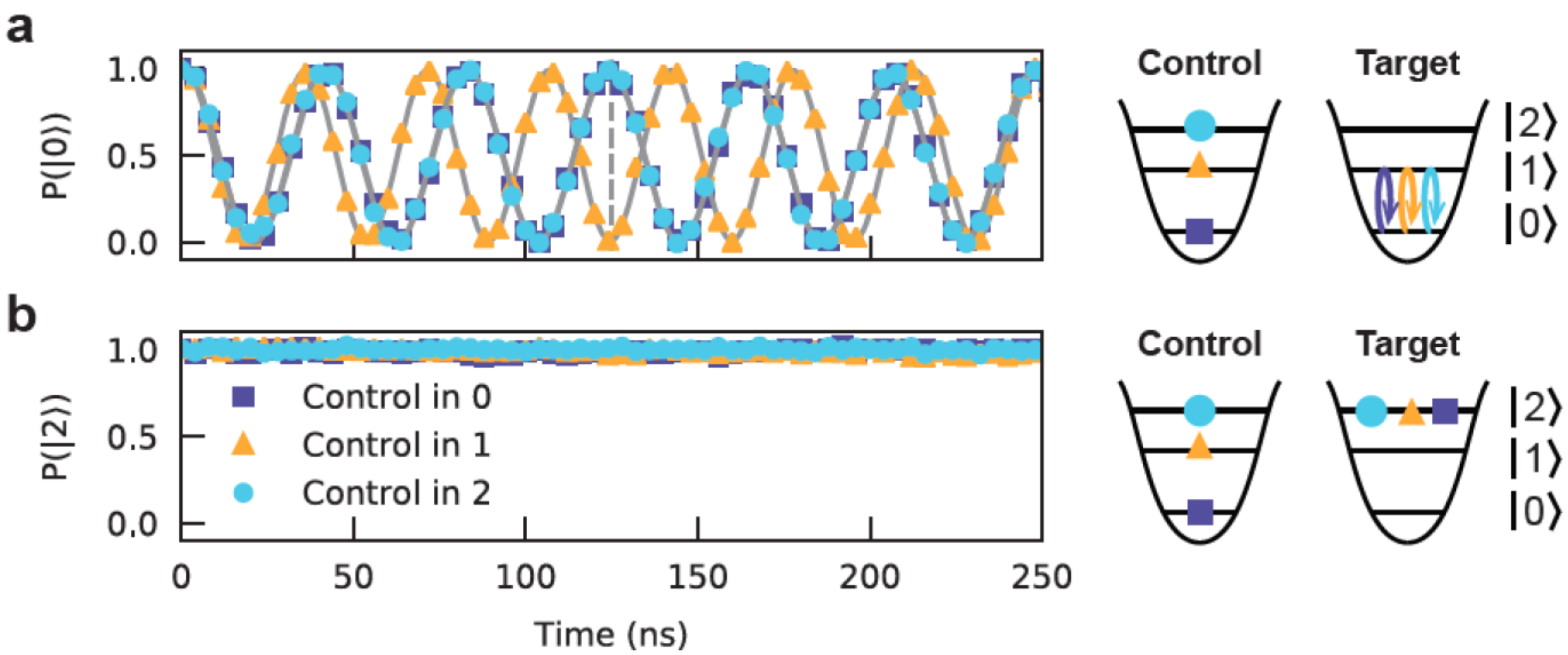
Pranav Gokhale, Jonathan M. Baker, Casey Duckering, Natalie C. Brown, Kenneth R. Brown, and Frederic T. Chong. 2019. Asymptotic Improvements to Quantum Circuits via Qutrits. In *ISCA '19: 46th International Symposium on Computer Architecture, June 22–26, 2019, PHOENIX, AZ, USA.* ACM, New York, NY, USA, 13 pages. https://doi.org/10.1145/3307650.3322253

Quantum Information Scrambling in a Superconducting Qutrit Processor

M. S. Blok[1*], V. V. Ramasesh[1*], T. Schuster[2], K. O'Brien[2], J.M. Kreikebaum[1], D. Dahlen[1], A. Morvan[1], B. Yoshida[3], N. Y. Yao[2] and I. Siddiqi[1]
[1] *Lawrence Berkeley National Laboratory & Department of Physics, University of California Berkeley, CA 94720, USA.*
[2] *Department of Physics, University of California, Berkeley, California 94720, USA.*
[3] *Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada.*
[*] *These authors contributed equally to this work.*
(Dated: March 9, 2020)



QUTRIT ROTATIONS AND GATE-SET

A convenient set of generators to describe qutrit rotations are the Gell-Mann matrices:

$$\lambda_1 \equiv s_x^{01} = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad \lambda_2 \equiv s_y^{01} = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad \lambda_3 \equiv s_z^{01} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

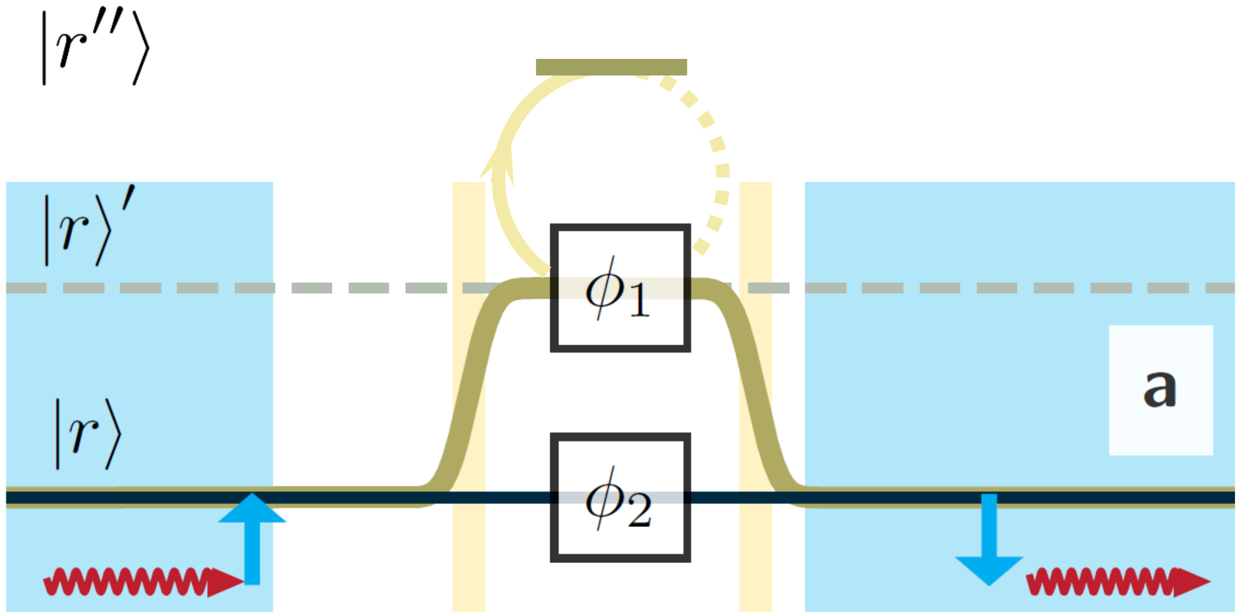
$$\lambda_4 \equiv s_x^{02} = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \qquad \lambda_5 \equiv s_y^{02} = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix} \qquad \lambda_6 \equiv s_x^{12} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

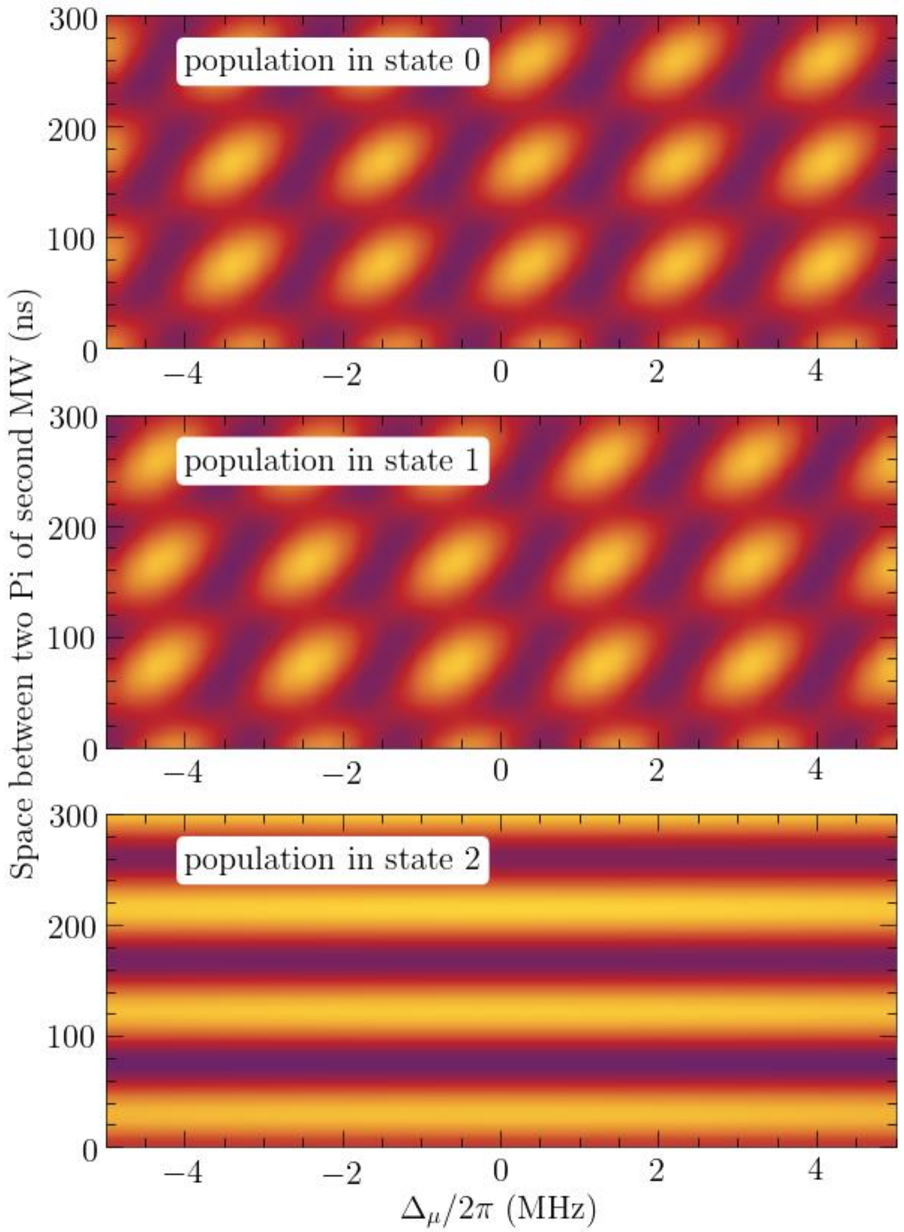
$$\lambda_7 \equiv s_y^{12} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} \qquad \lambda_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

Collectively-encoded qutrit

$$|\psi\rangle = a|0\rangle + b|1\rangle + c|2\rangle$$

2nd microwave field





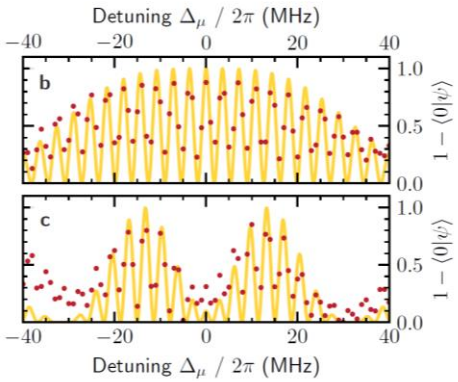
Acknowledgements

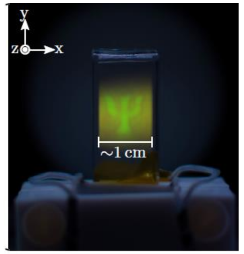
Rydberg polariton interferometry

Current: Yuechun Jiao, **Oliver Hughes, Max Festenstein** , Kevin Weatherill

Former: **Nick Spong**, **Teodora Ilieva**, Hannes Busche, **Simon Ball**, Paul Huillery, **Chloe So,** Charles Moehl, Matt Jones

Collaborators:, **Igor Lesanovsky**



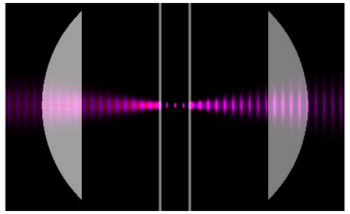


THz imaging

Current: **Lucy Downes**, Andrew McKellar, Shuying Chen, **Nourah Almuhawish**, **Matthew Jamieson**, **Kevin Weatherill**

Former: Dan Whiting

Nanocells



Current: **Tom Cutler**, Dani Pizzey, Ifan Hughes, Vahid Sandoghdar, Jan Renger

Former: **Kate Whittaker**, **James Keaveney**

Simultons

Current: Robert Potvliege, Steven Wrathmall

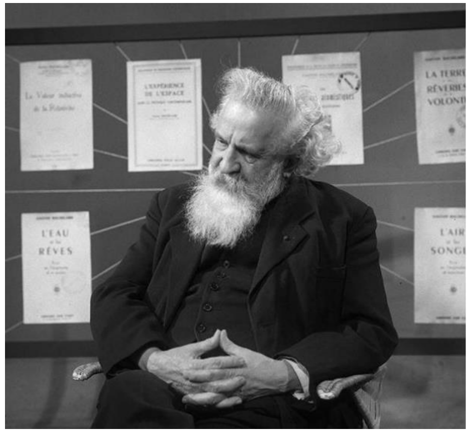
Former: **Tommy Ogden**, **Kate Whittaker**, **James Keaveney**

Funding

EPSRC COHERENCE SEVENTH FRAMEWORK PROGRAMME MARIE CURIE ACTIONS RySQ FUNDING OPPORTUNITIES FUTURE & EMERGING TECHNOLOGIES Durham University [dstl]

Une simple image, si elle est nouvelle, ouvre un monde,

Gaston Bachelard (1884 - 1962)



"information is in continuous construction"

Scientists, in trying to learn about the world, create a new world.

Une simple image, si elle est nouvelle, ouvre un monde,

Gaston Bachelard (1884 - 1962)