An Old Qubit Contender Becomes New Again: Neutral Atoms

Ben Bloom, PhD
CTO and Co-Founder at
Atom Computing

March 29 2022

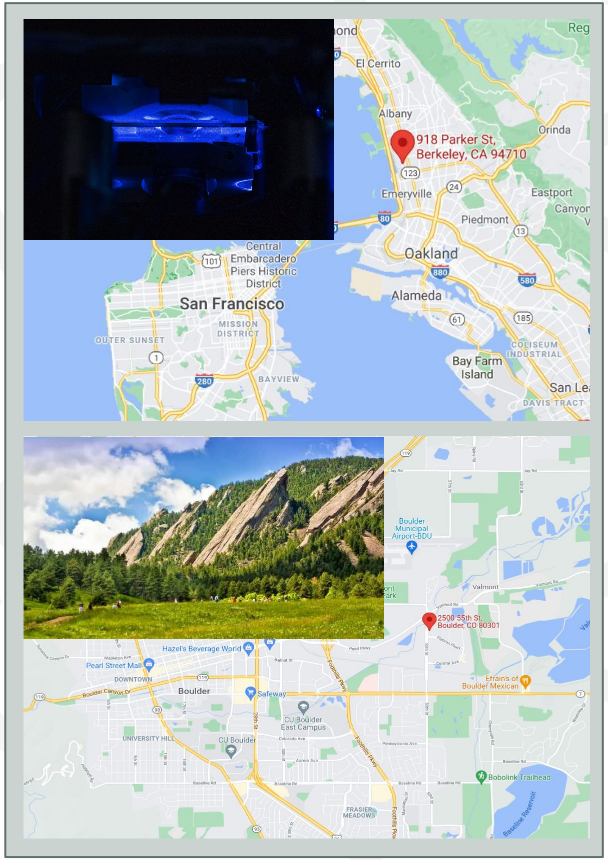
What is Atom Computing?

Neutral Atom Startup Founded in 2018

- Based in **Berkeley, CA**
- Opened a second location in **Boulder, CO**
- Satellite Offices in North Carolina and Austin

Our goal: to develop neutral atoms trapped in light as a highly-scalable, externally-accessible platform for quantum computing

- Pursuing gate-based, near-neighbor couplings
- Focused on achieving capabilities and qubit numbers compatible with known error correction schemes



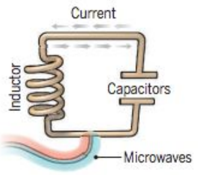
LONG-TERM GOAL

LARGE-SCALE QUANTUM COMPUTATION

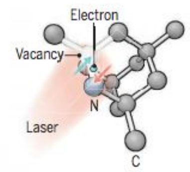
TOWARD

ERROR CORRECTION

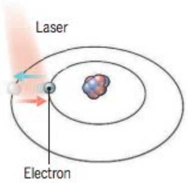
Quantum computing architectures



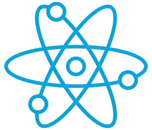
Superconducting loops



Diamond vacancies



Trapped ions



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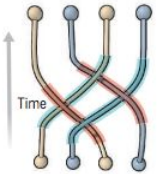


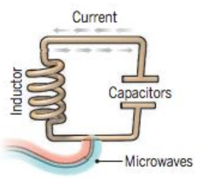
Topological qubits

Silicon quantum dots

Common ingredients regardless of underlying platform

Quest for Qubits by Gabriel Popkin
Science 354, 1090 (2016)

Quantum computing architectures



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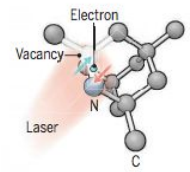

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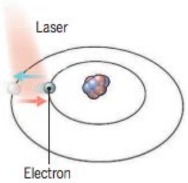

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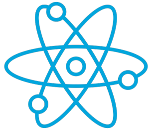

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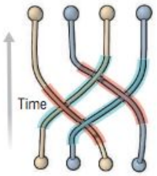

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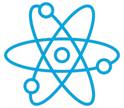
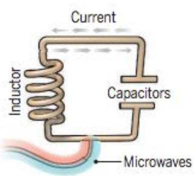


HIGH-QUALITY QUBITS

Quantum computing architectures



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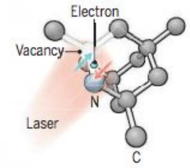

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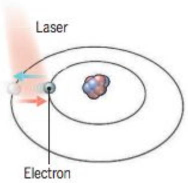

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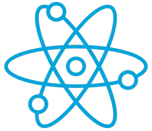

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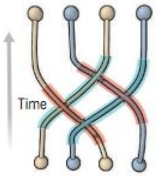

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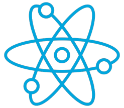

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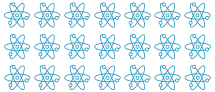
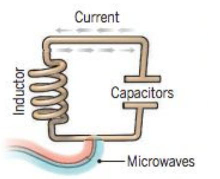


SCALABLE TO MANY QUBITS

Quantum computing architectures



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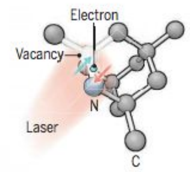

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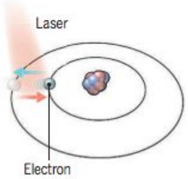

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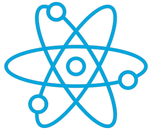

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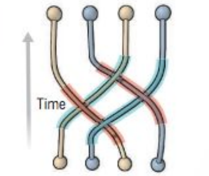

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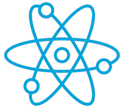

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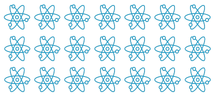
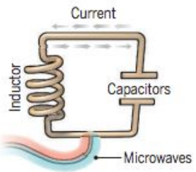


SCALABLE TO MANY QUBITS

UNIVERSAL GATE SET

Quantum computing architectures



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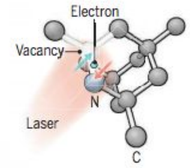

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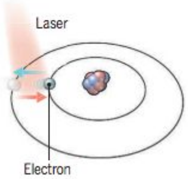

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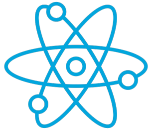

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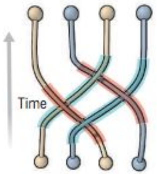

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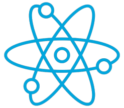
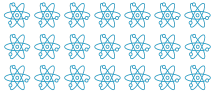


HIGH-QUALITY QUBITS

- Long coherence times
- High-efficiency readout



SCALABLE TO MANY QUBITS

- Wireless control

UNIVERSAL GATE SET

- Tunable Rydberg-mediated interactions

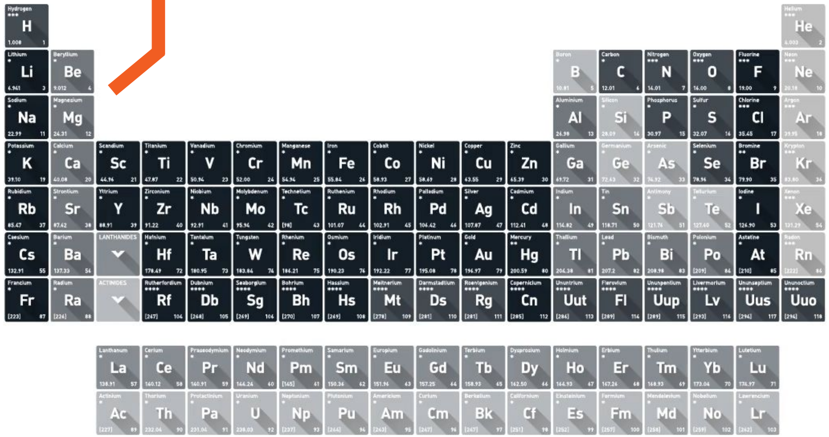
Relevant work includes: Browaeys, Endres, Greiner, Kaufman, Lukin, Pichler, Regal, Saffman, Thompson, Vuletic, Weiss

atom computing

Why Use Neutral Atoms?

1. Naturally identical and stable
2. Large qubit count
3. Wireless gates and position control
4. Strong interactions available for two-qubit gates

We use alkaline earth elements for naturally stable qubits

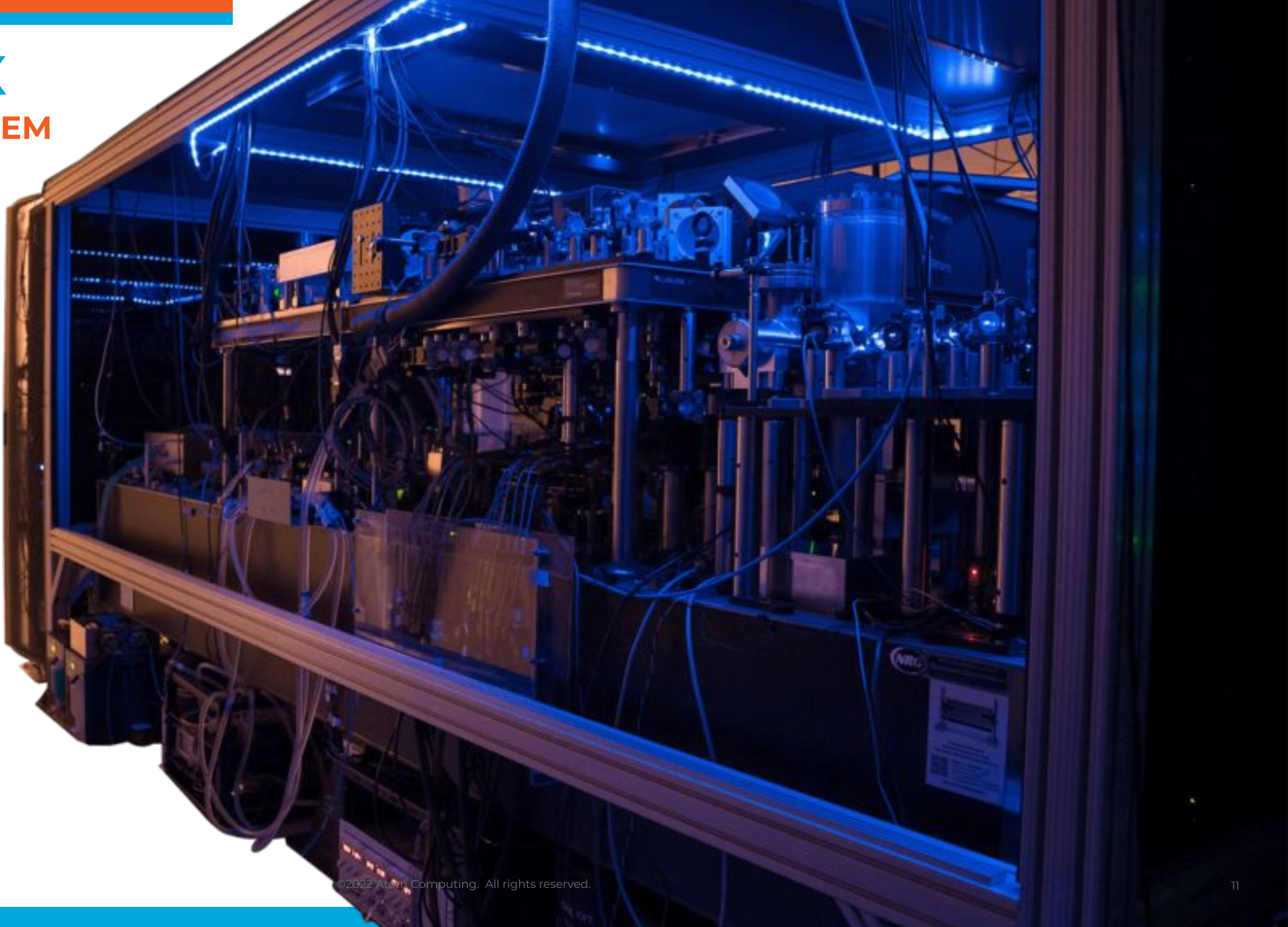


PHOENIX

OUR REAL-LIFE IMPLEMENTATION

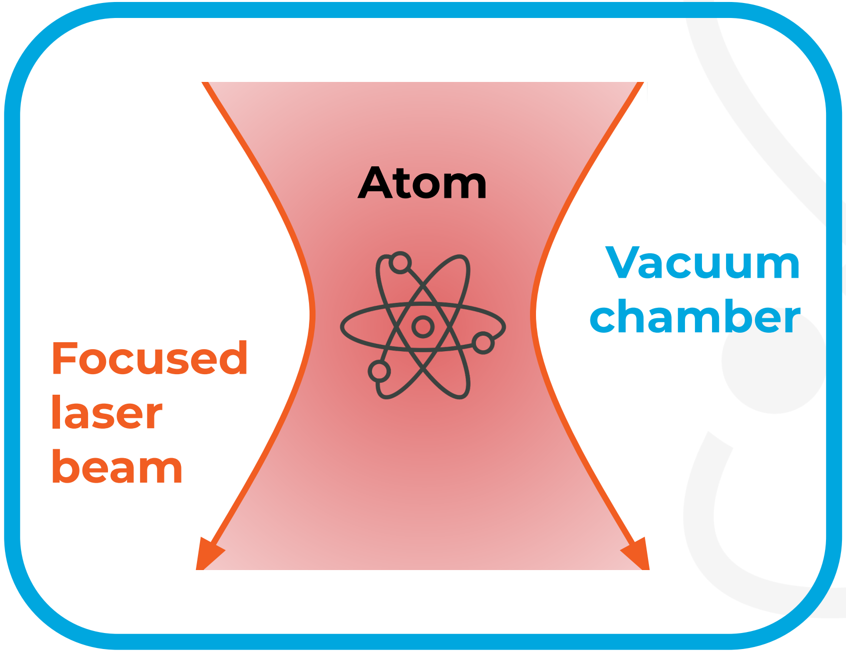
PHOENIX

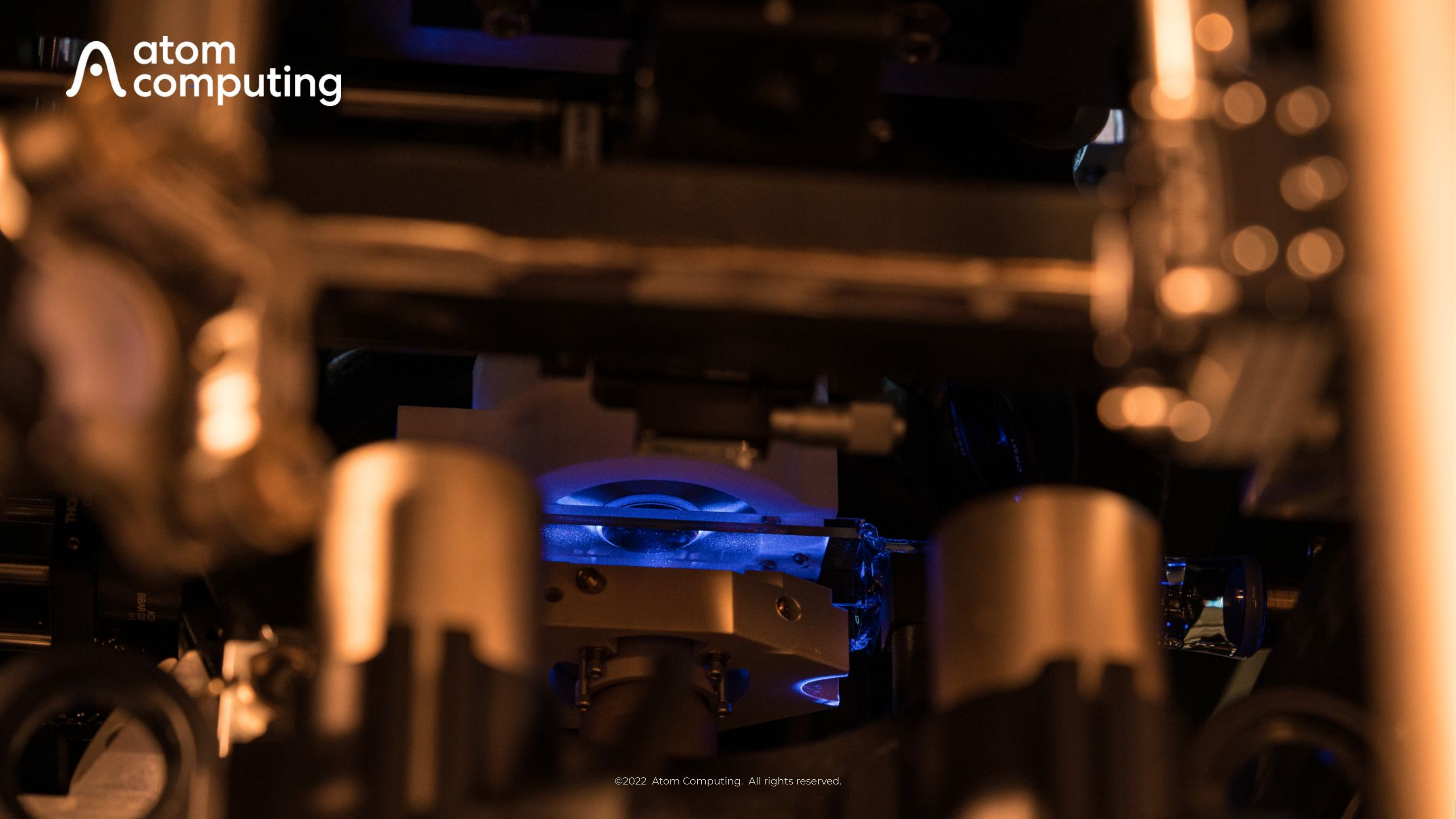
100 QUBIT SYSTEM



atom computing

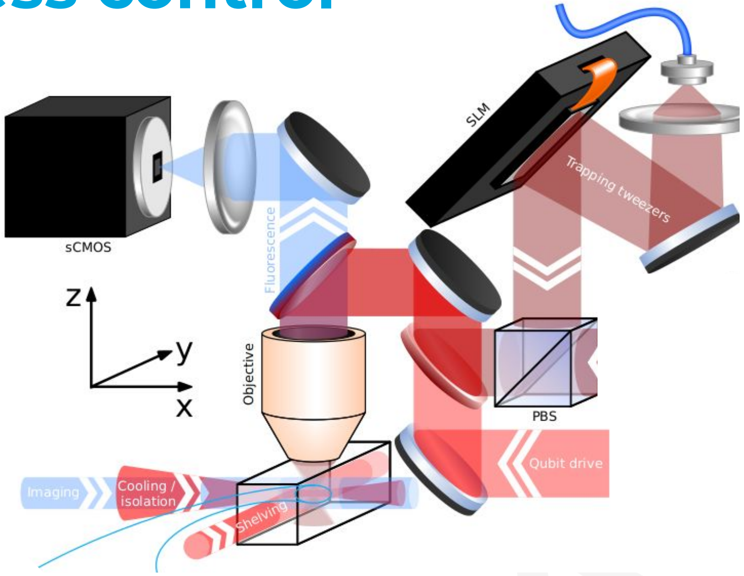
What Are Neutral Atom Qubits?





Scalable design with wireless control

Optically-defined trapping

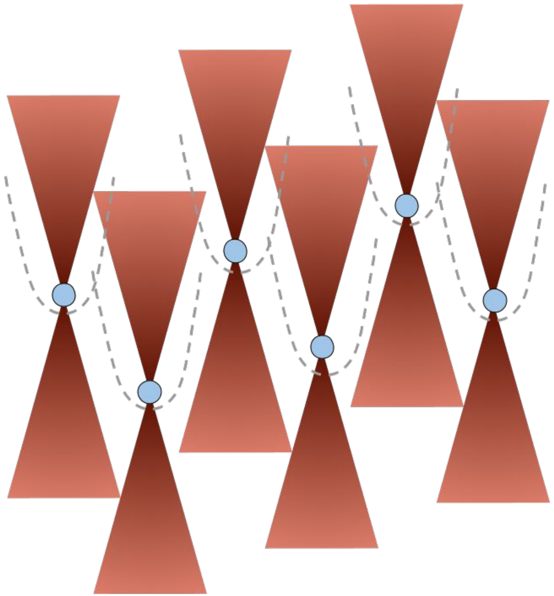


Set-up of holographic trap generation via Spatial Light Modulator (SLM)

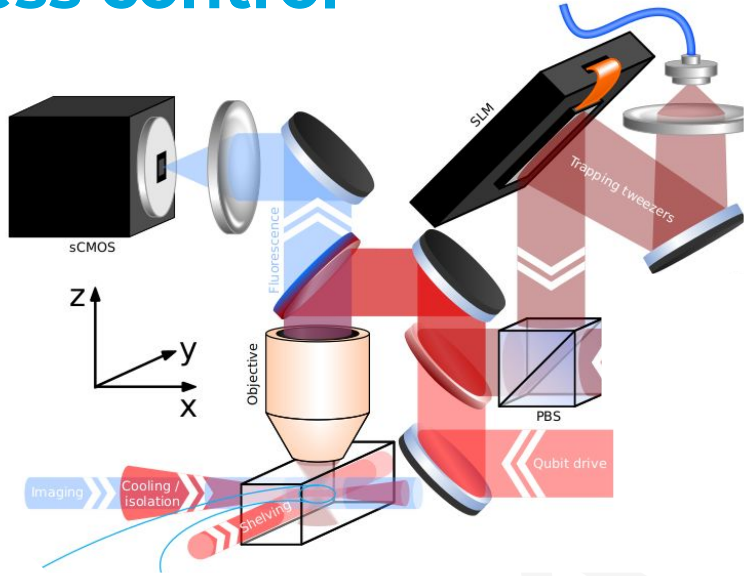
Scalable design with wireless control

Optically-defined trapping

Optical tweezers scalable up to 100s of traps



Schlosser, et. al, PRL (2002).



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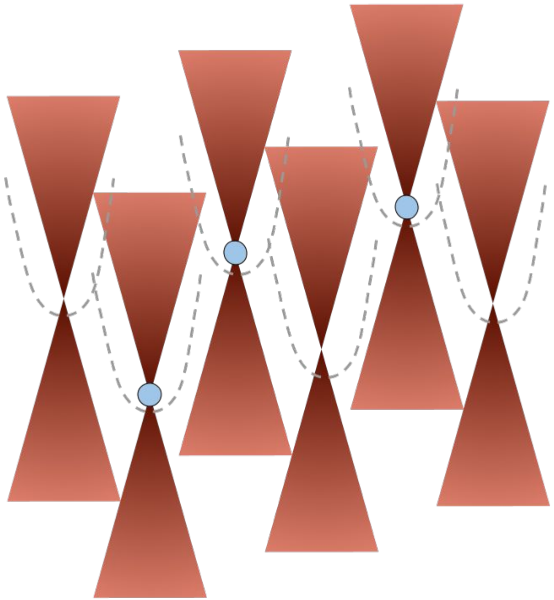

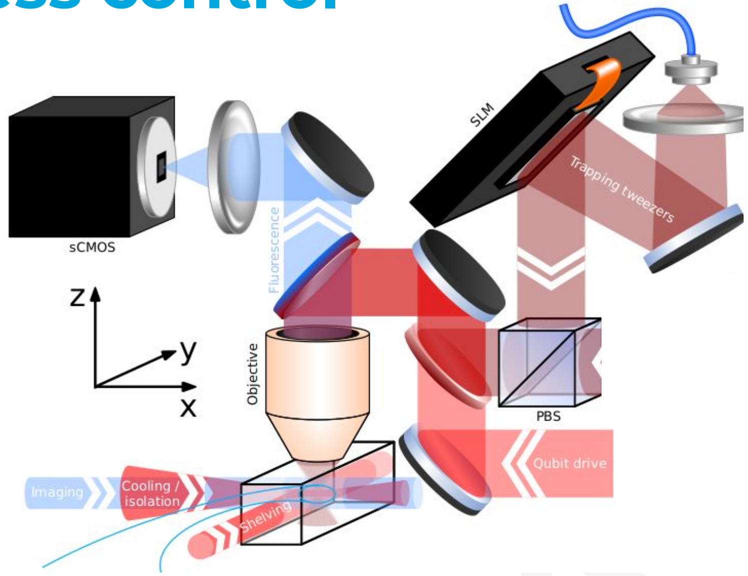

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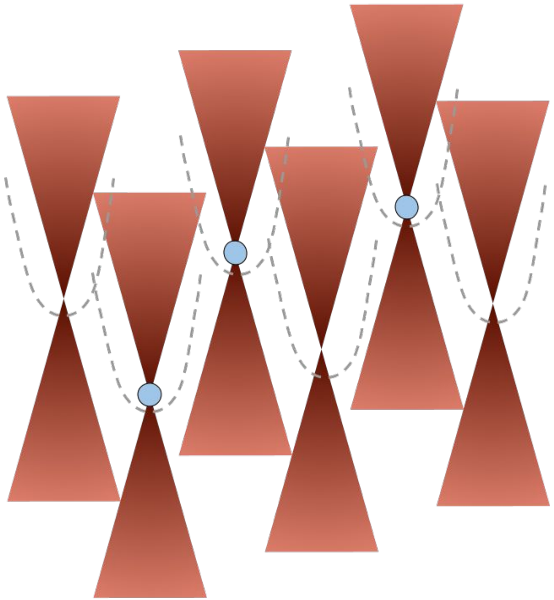

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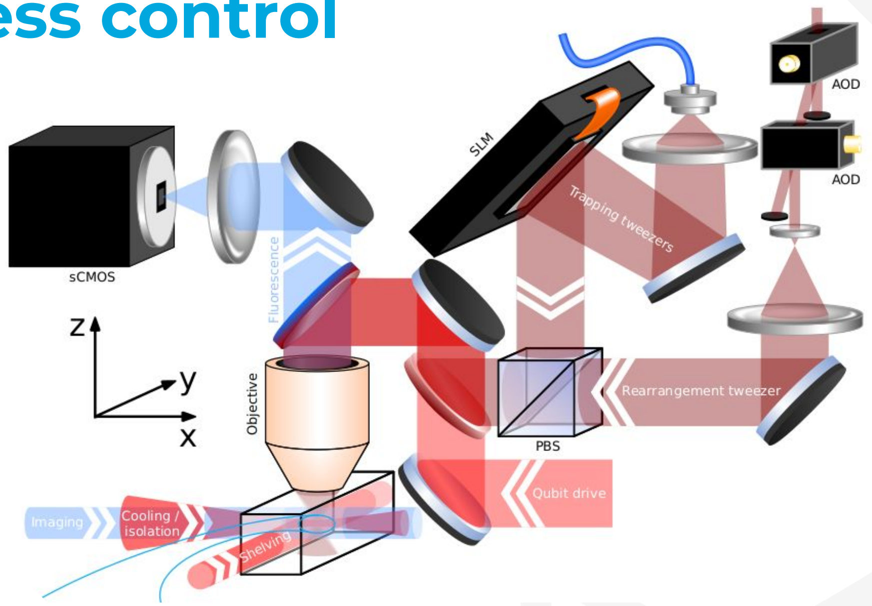
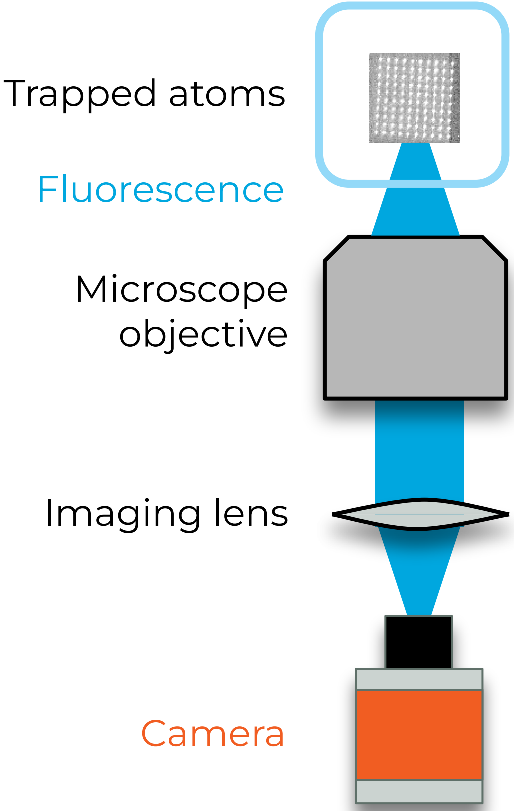
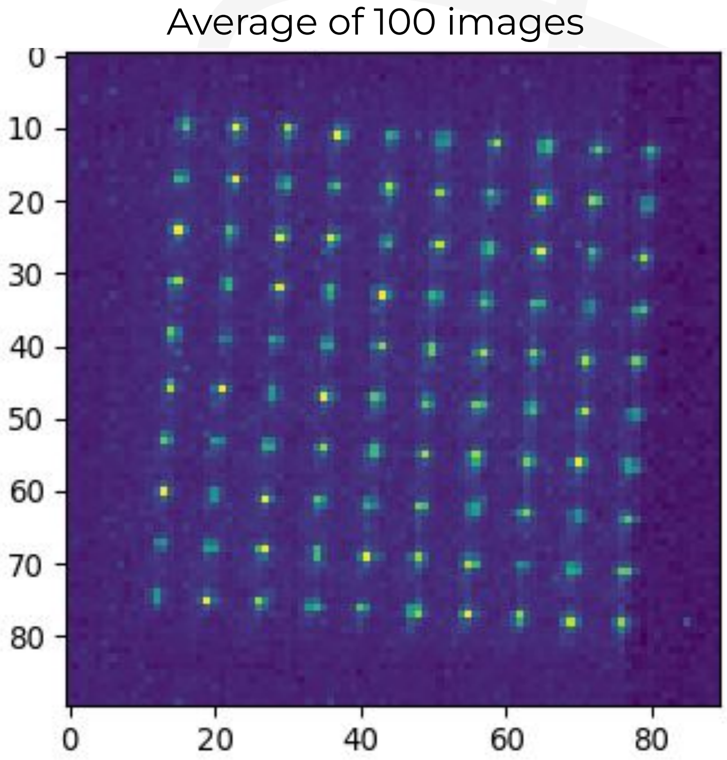


Set-up of holographic trap generation via Spatial Light Modulator (SLM)

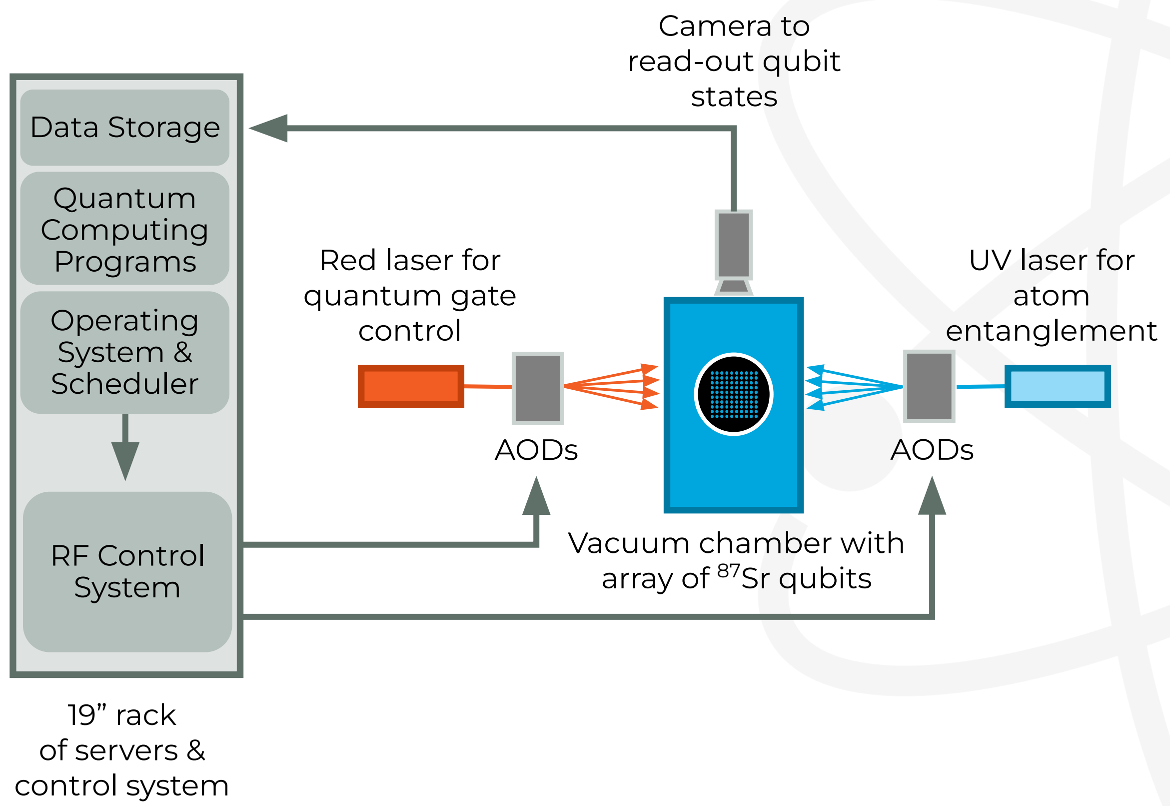
Single moving tweezer is able to fill vacancies; process referred to as rearrangement.

Atom Readout Via Imaging

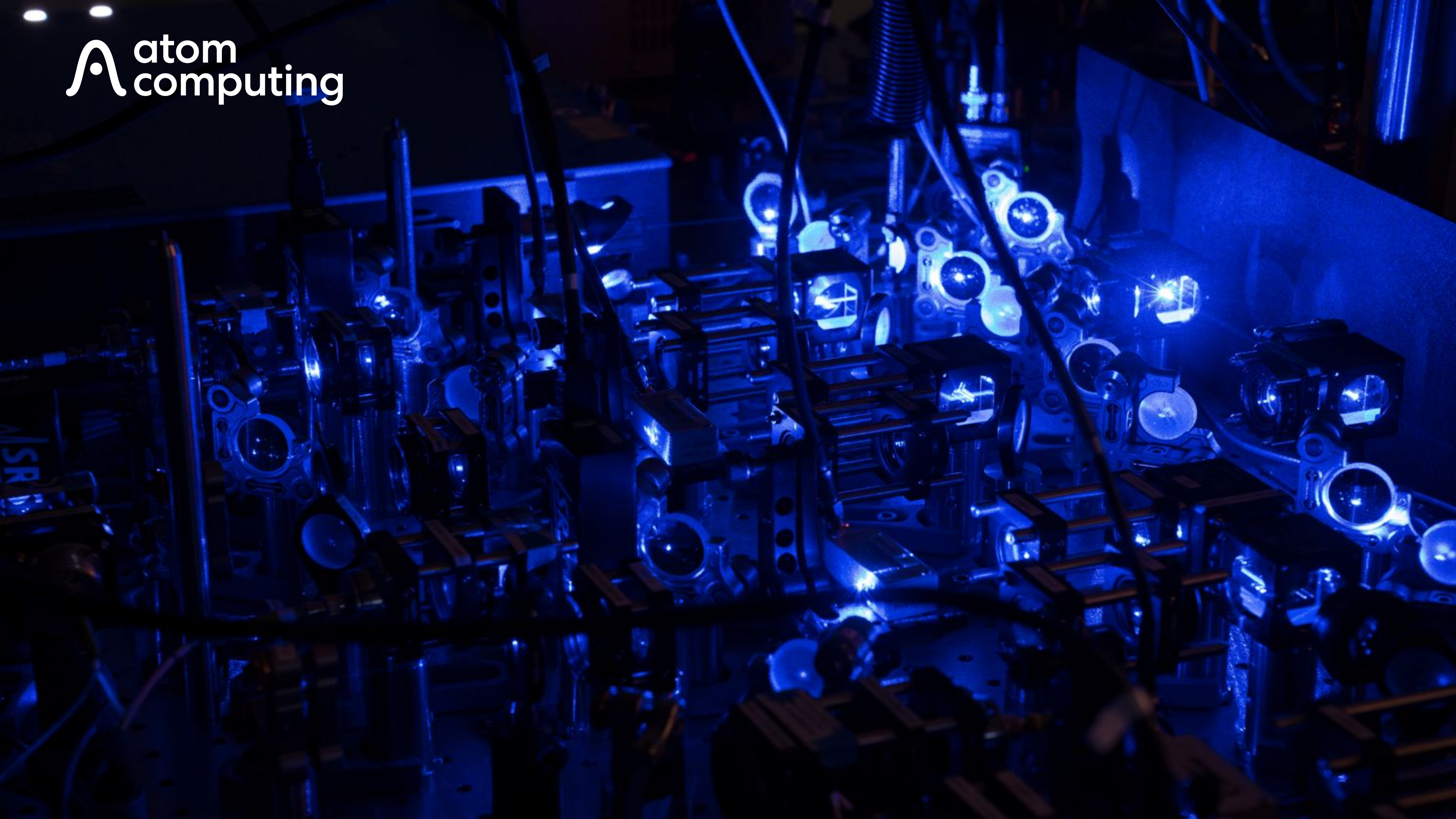




Anatomy of Our Quantum Computer



atom computing


atom
computing

How to Rearrange Atoms in 2D

Spatial Light Modulators (SLMs)

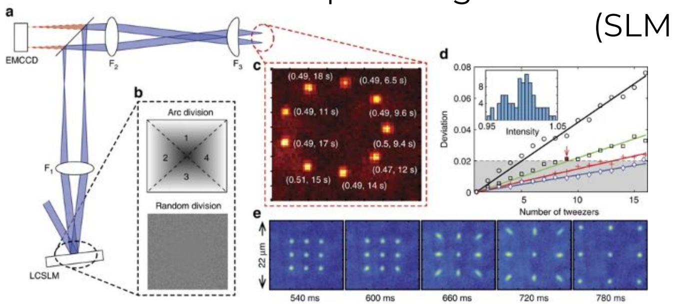
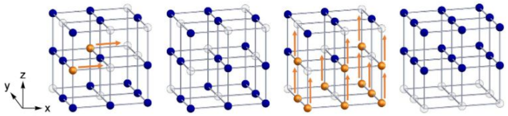


Diagram from Nature Comms 13317

Jaewook Ahn

Shuffling / State Dependent Lattices



Weiss + Others

Acousto-optic deflectors (AODs)

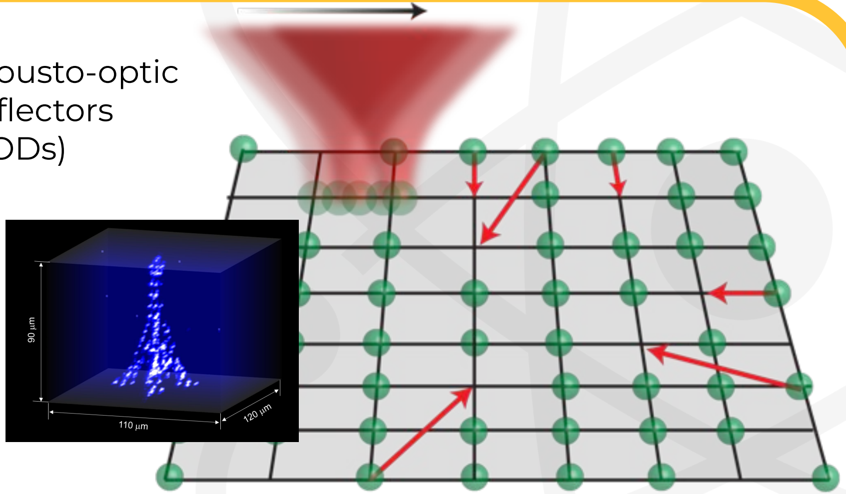


Diagram from: Regal Lab (JILA)

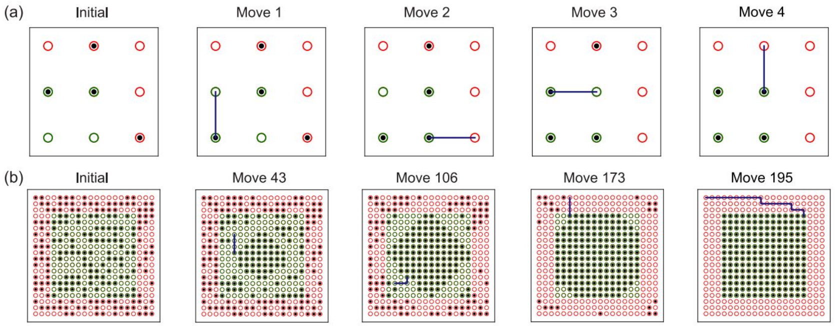
Browaeys + Others

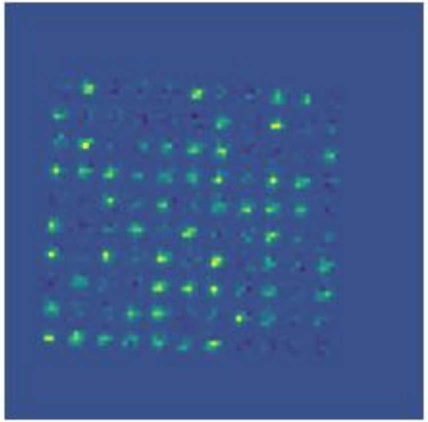
atom computing

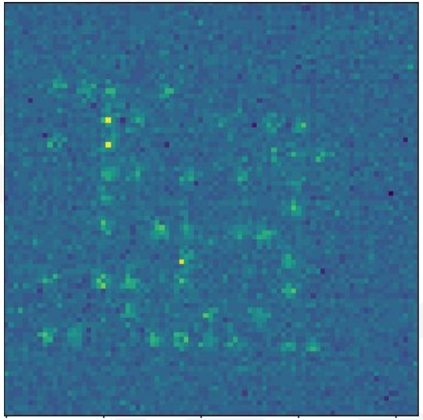
Autonomous Rearrangement

The system must make its own decisions about which moves to play in order to achieve a desired target pattern

Use the “Compression Algorithm” to efficiently fill a compact array and avoid collisions







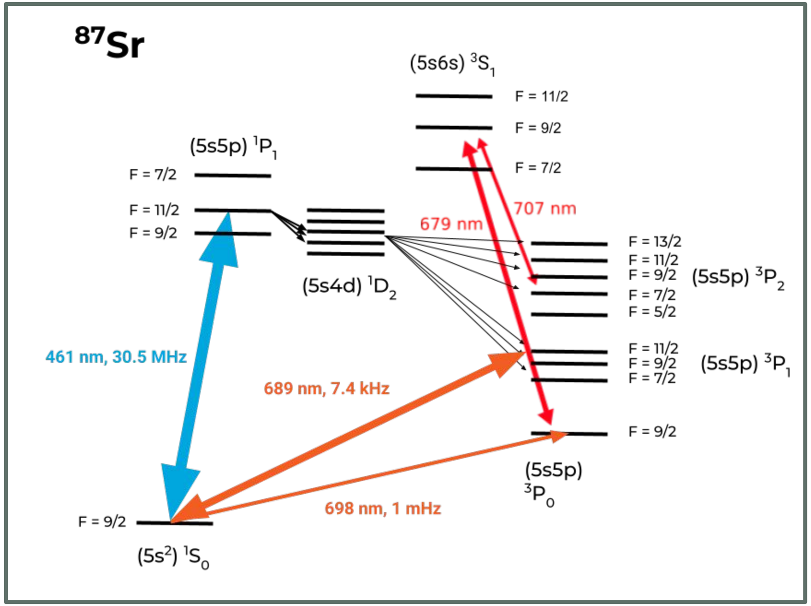
Schymik, Kai-Niklas, et al. "Enhanced atom-by-atom assembly of arbitrary tweezer arrays." Physical Review A 102.6 (2020): 063107.

The Qubit is "Inside" the Atom

Benefits of alkaline earth atoms (2-valence electron atoms):

- Rich level structure: multiple long-lived excited states, variety of optical transitions & variety of linewidths

- Trapped Rydberg states



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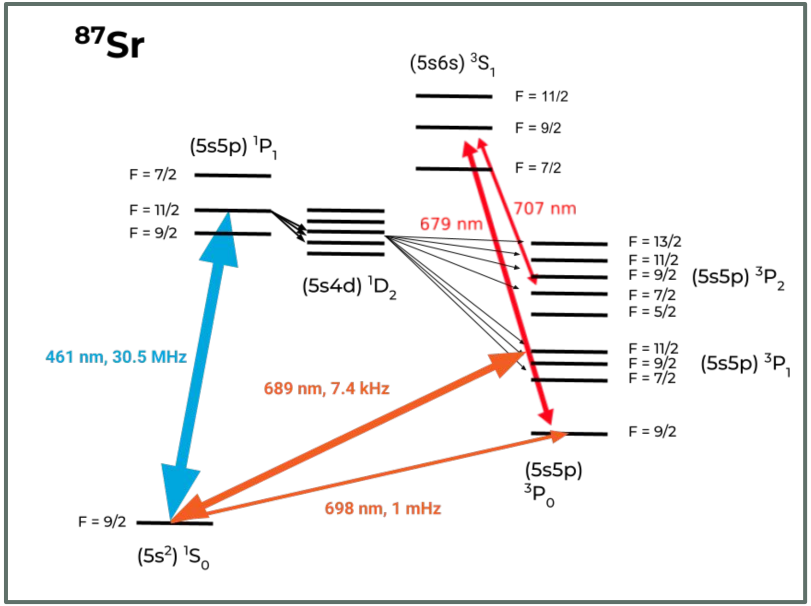
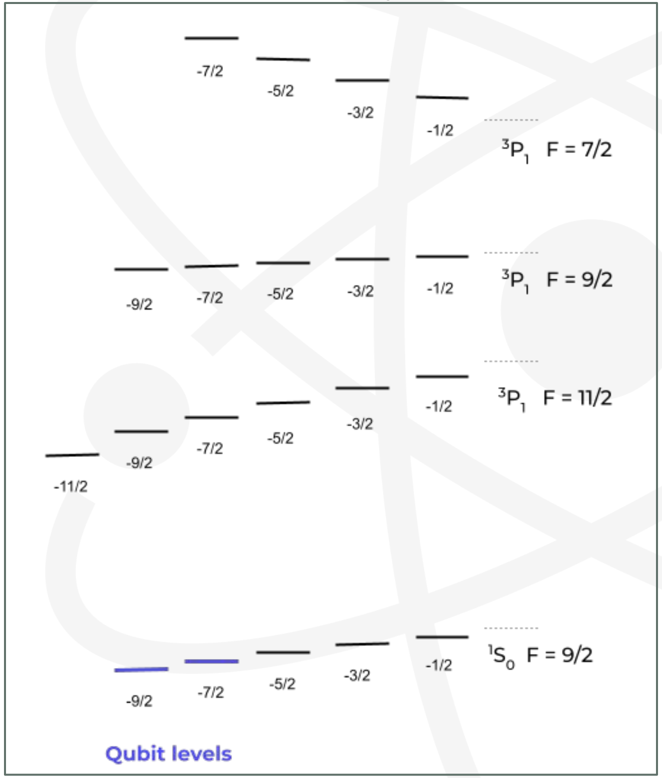


m_F levels for $^1S_0$ and $^3P_1$

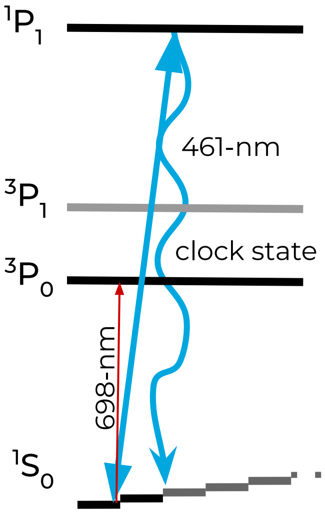


atom computing

Wireless control

Nuclear spin readout

Spin selective readout utilizes clock-state ($^3P_0$-manifold) in 2-step process:



Shelving references: Nagourney, PRL (1986), Sauter, PRL (1986).

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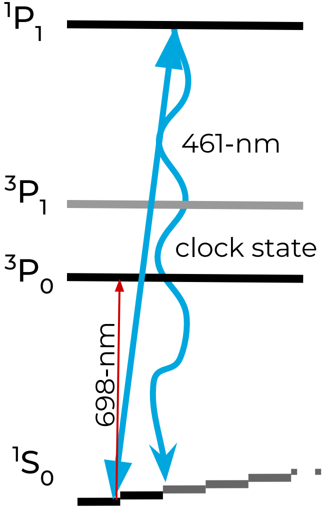

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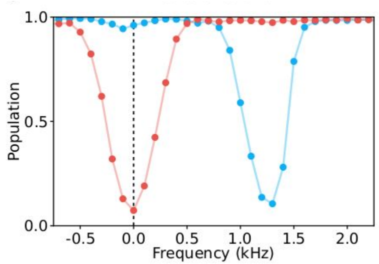
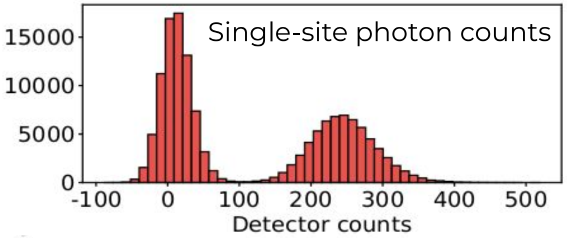


2. Apply imaging light resonant with ground state.



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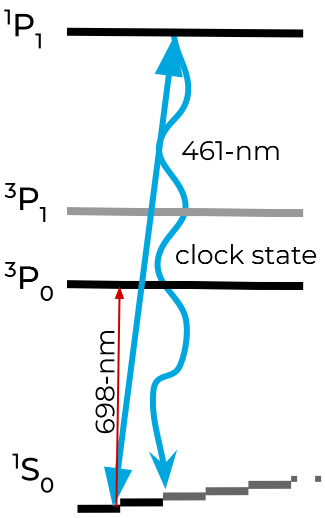

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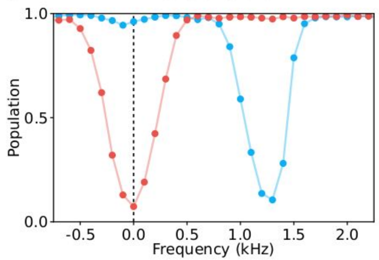

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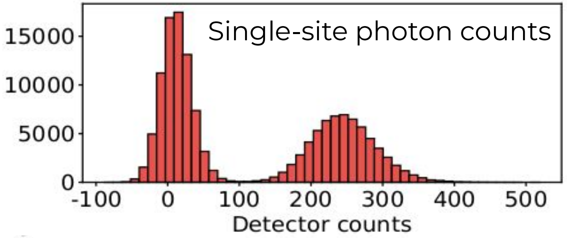
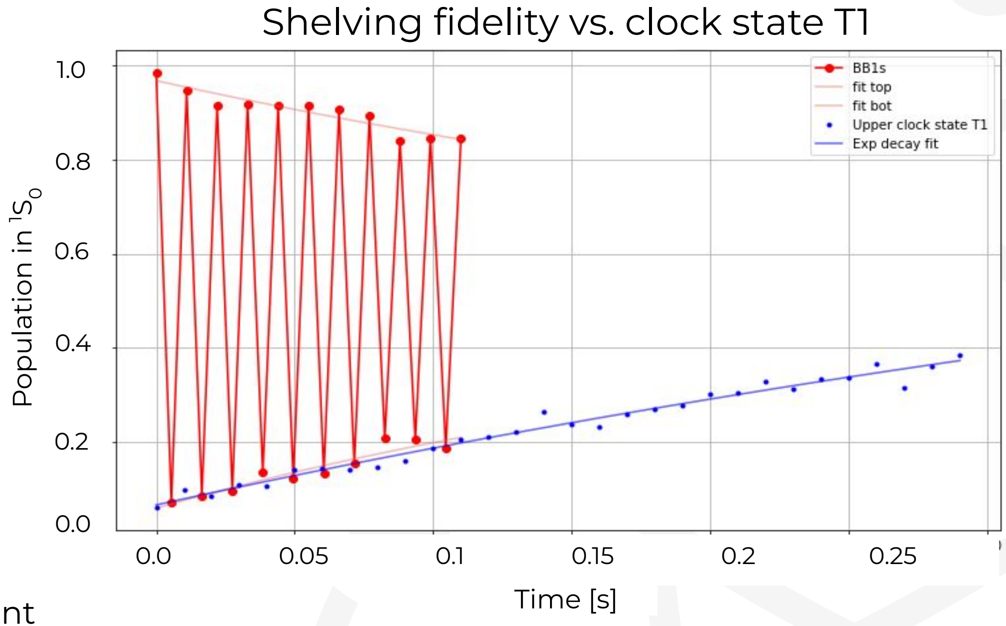


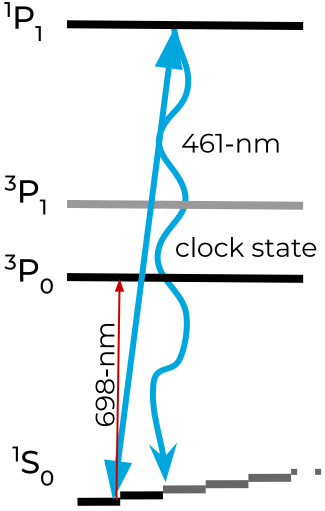


Shelving references: Nagourney, PRL (1986), Sauter, PRL (1986).

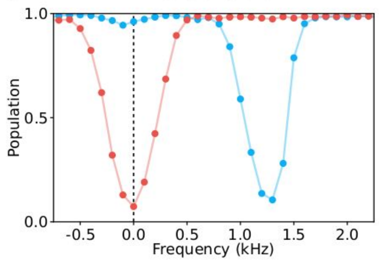
Wireless control

Nuclear spin readout

Spin selective readout utilizes clock-state ($^3P_0$-manifold) in 2-step process:



1. *Shelve* the |0> or |1> population into $^3P_0$, F=9/2



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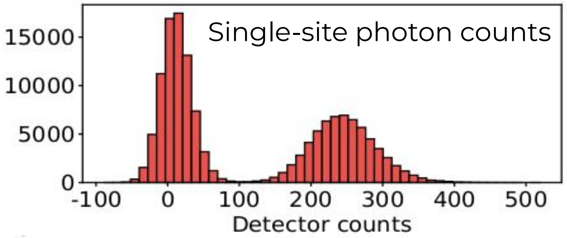
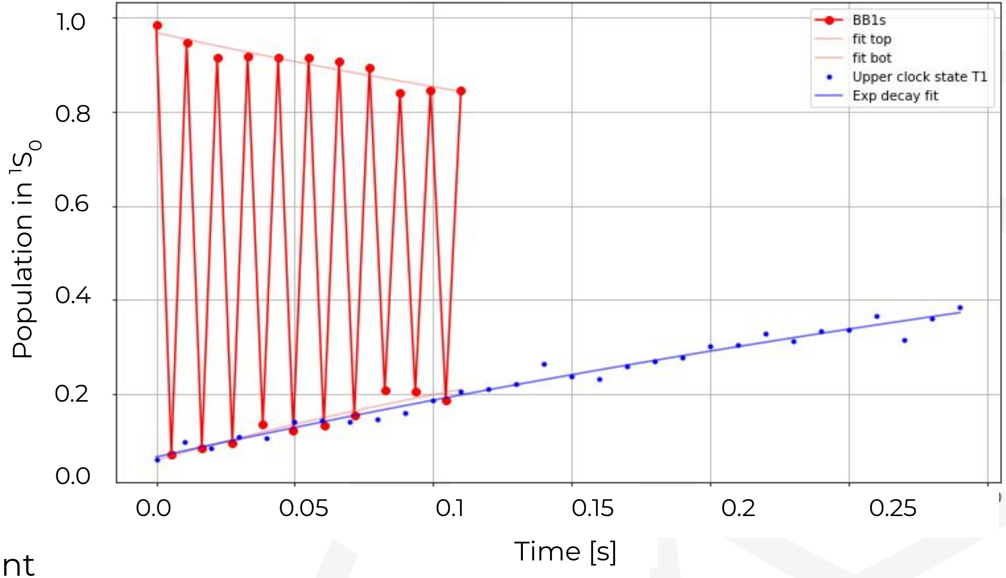


Shelving fidelity vs. clock state T1

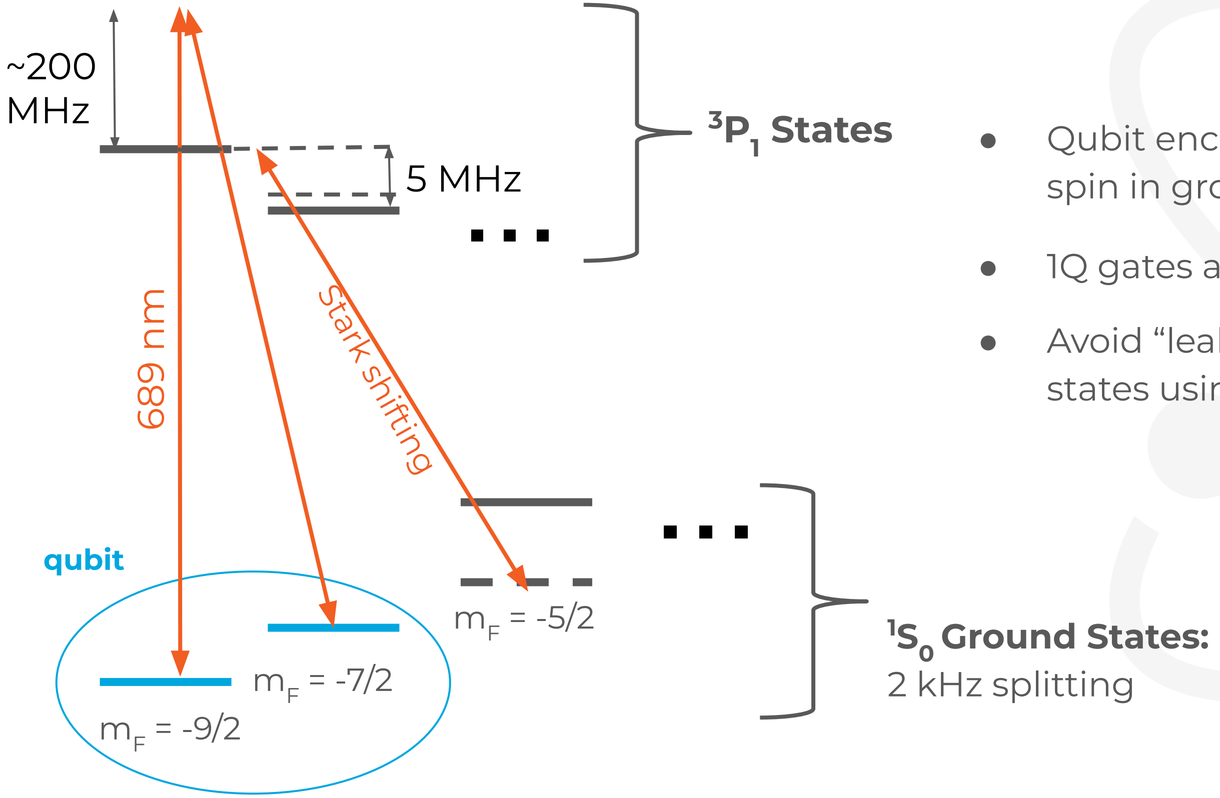


Measured fidelity	T1 decay time	Corrected fidelity
0.985	687 ms	0.993

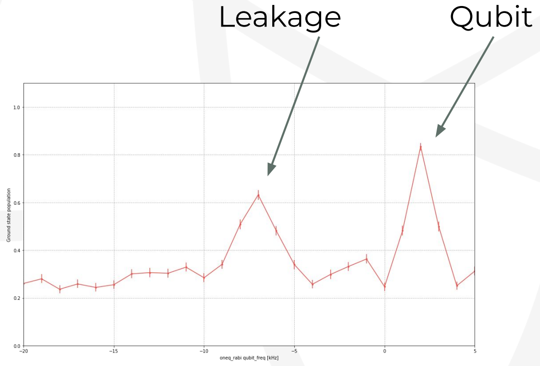
Shelving references: Nagourney, PRL (1986), Sauter, PRL (1986).

atom computing

Single-Qubit Manipulations in ^{87}Sr



- Qubit encoded in m_F = -9/2, -7/2 nuclear spin in ground state.
- 1Q gates actuated by 2-photon transition.
- Avoid “leakage” to other nuclear spin states using a Stark shift beam.

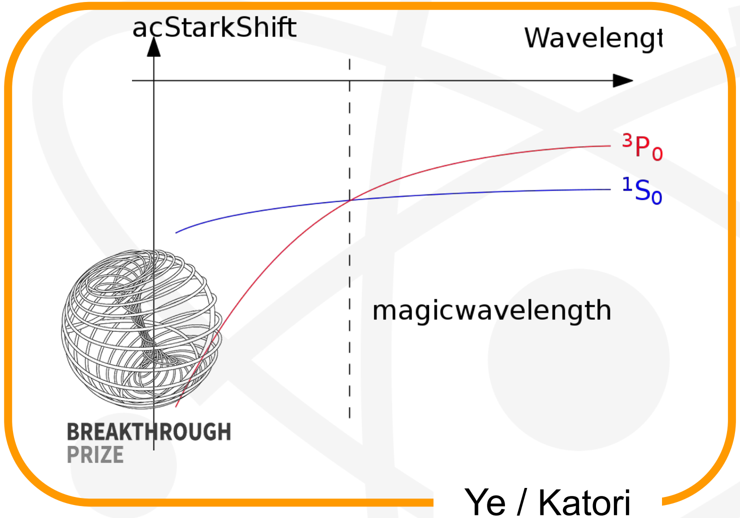


But will the qubit be stable?

- Motional Decoherence?
- Scattering?
- Does everything in nature just drive this super-low-frequency qubit?

Motional Decoherence in Neutral Atoms

- Different electronic states see different trap potentials ***except*** at a magic wavelength where the energy difference between the two electronic states is identical ***everywhere*** in the trap.
- However…we're not talking about optical qubits today, instead we are talking about $^1S_0$ atoms in different m_F states:



Ye / Katori

Let's Google for our favorite PDF describing polarizability (i.e. Rauschenbeutel)

- J = 0
  - No Vector or Tensor Shift! Don't have to worry about mixing different F States
- In this far off resonance simplification, F is the same for the two state Scalar polarizabilities are equal! (more discussion to come)

$$\alpha_F^{(K)} = (-1)^{K+F+1}(2F+1)\sqrt{2K+1}\sum_{n'J'}|\langle n'J'\|\mathbf{d}\|nJ\rangle|^2 \times \sum_{F'}(-1)^{F'}(2F'+1)\begin{Bmatrix}1&K&1\\F&F'&F\end{Bmatrix}\begin{Bmatrix}F&1&F'\\J'&I&J\end{Bmatrix}^2 \times \frac{1}{\hbar}\mathrm{Re}\left(\frac{1}{\omega_{n'J'F'}-\omega_{nJF}-\omega-i\gamma_{n'J'F'nJF}/2} + \frac{(-1)^K}{\omega_{n'J'F'}-\omega_{nJF}+\omega+i\gamma_{n'J'F'nJF}/2}\right). \quad \text{(B37)}$$

atom computing

Scattering

Rayleigh

Decoherence due to elastic Rayleigh scattering

H. Uys,[1,2*] M.J. Biercuk,[1,3] A.P. VanDevender,[1] C. Ospelkaus,[1] D. Meiser,[4] R. Ozeri,[5] and J.J. Bollinger[1†]

Rayleigh scattering does not cause decoherence IFF:

- The ***Amplitudes*** of the the Rayleigh scattering rates for each qubit state are the same.
- Here again we are winning because the qubits are so close in energy space that their scattering amplitudes are nearly identical when illuminated with off-resonant light.

Raman

Lattice-induced photon scattering in an optical lattice clock

Sören Dörscher, Roman Schwarz, Ali Al-Masoudi, Stephan Falke,[*] Uwe Sterr, and Christian Lisdat[†]

Fundamentally, the optical dipole matrix element couples to **L** and in AE-like elements these are fundamentally decoupled from **I**, when detuning is larger than the HFS

$i \to f$	F'	m'_F	$\Gamma/(10^{-4}\,\mathrm{s}^{-1})$
${}^1S_0 \to {}^1S_0$	9/2	7/2	3×10^{-16}
		9/2	5.57
${}^3P_0 \to {}^3P_0$	9/2	7/2	5×10^{-10}
		9/2	5.57
${}^3P_0 \to {}^3P_1$	7/2	7/2	1.99
	9/2	7/2	0.45
		9/2	1×10^{-10}
	11/2	7/2	0.05
		9/2	6×10^{-10}
		11/2	2.49
${}^3P_0 \to {}^3P_2$	7/2	7/2	0.37
	9/2	7/2	0.26
		9/2	0.76
	11/2	7/2	0.08
		9/2	0.53
		11/2	0.50
	13/2	7/2	0.01
		9/2	0.11
		11/2	0.22

Why does every laser not just drive this qubit?

Let's try and drive a two-photon transition!

$$\Omega_{eff} = \frac{\Omega_a\Omega_b}{2}\left(\sum_i \frac{\langle -9/2|T_q^{(1)}|i\rangle\langle i|T_q^{(1)}|-7/2\rangle}{\Delta - E_i}\right)$$

Let's make it far off resonance, i.e $\Delta >> E_i$

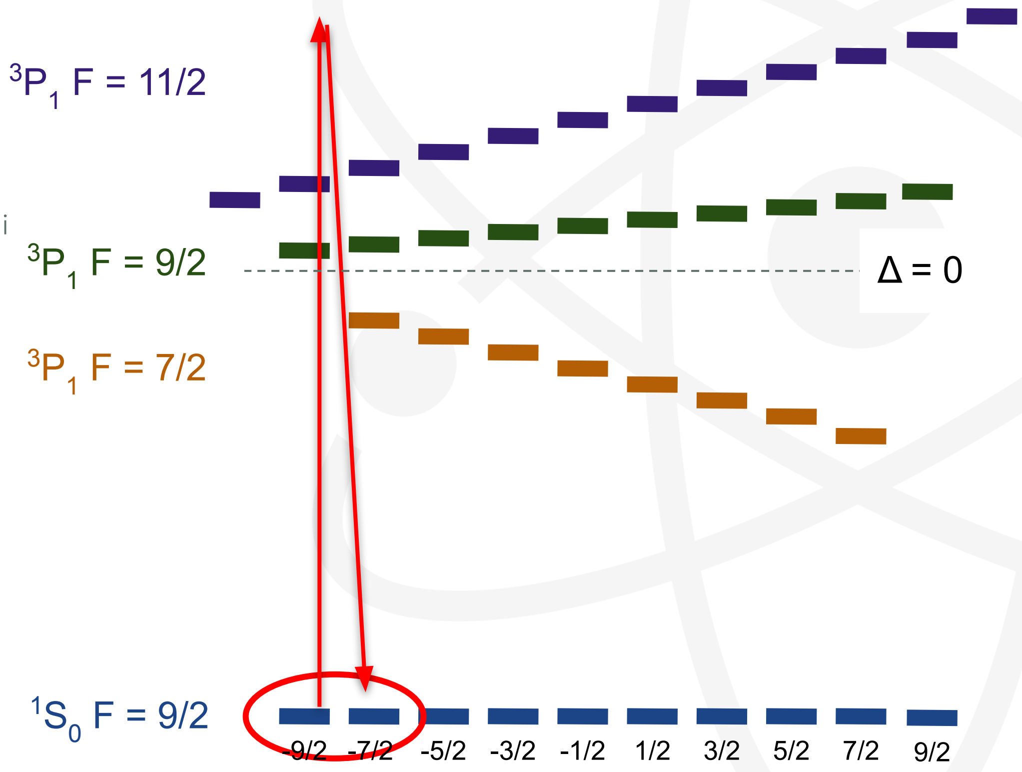
$$\frac{\Omega_a\Omega_b}{2}\sum_i \frac{C_i}{\Delta - E_i} \approx \frac{\Omega_a\Omega_b}{2}\sum_i \frac{C_i}{\Delta}\left(1 + \frac{E_i}{\Delta} + \dots\right)$$

Who doesn't love CG identities...

$$\sum_{j=|j_1-j_2|}^{j_1+j_2} \sum_{m=-j}^{j} \langle j_1\, j_2\, m_1\, m_2 \mid j_1\, j_2\, j\, m\rangle\langle j_1\, j_2\, m_1'\, m_2' \mid j_1\, j_2\, j\, m\rangle = \delta_{m_1,m_1'}\,\delta_{m_2,m_2'}\,/;$$

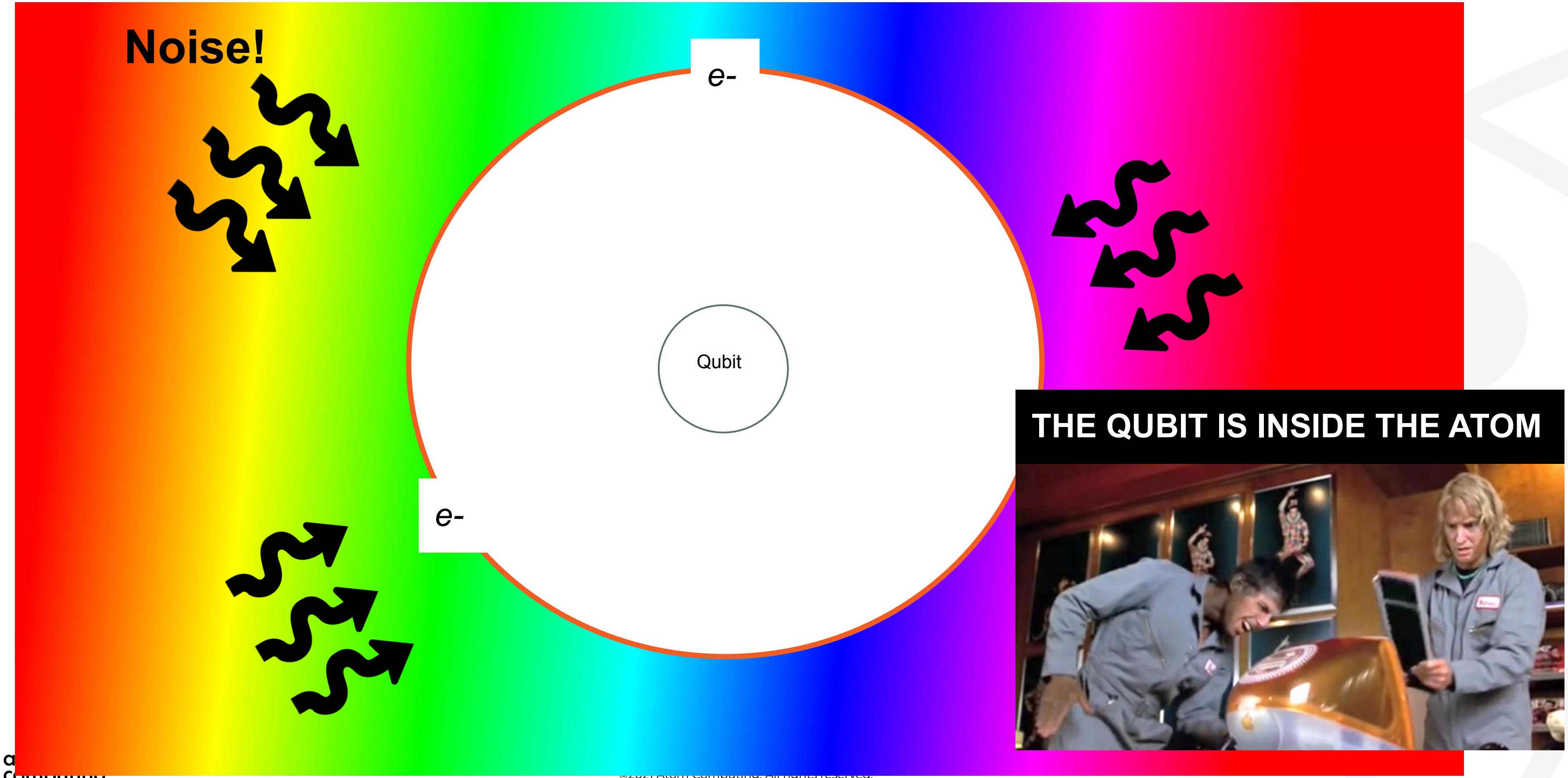
$$\mathit{PhysicalQ}(\{j_1, m_1\}, \{j_2, m_2\}, \{j_1 + j_2, m_1 + m_2\})$$

$\Omega_{eff} \sim 1 / \Delta^2$ when detuned farther than the HFS!



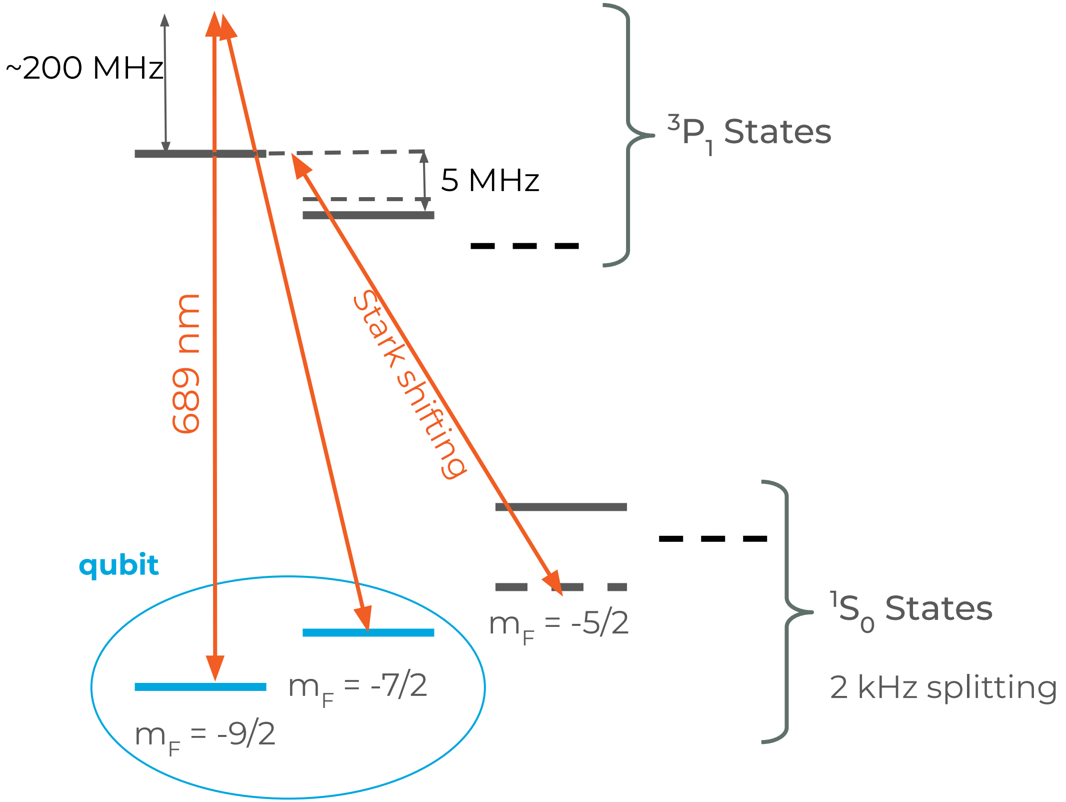
atom computing

Ben's idea of what this Qubit is like...



Wireless control

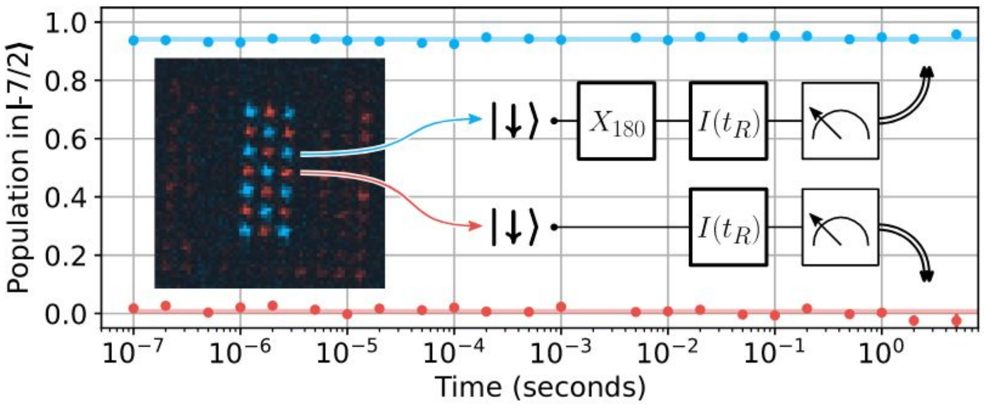
Single-Qubit Manipulations



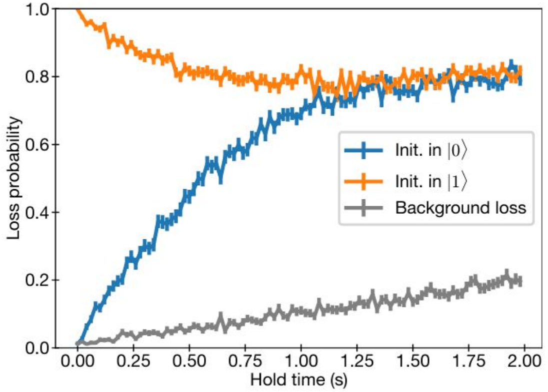
"T1" Measurement

Driving each qubit independently, columns in parallel

Nuclear-spin qubit!



Neutral atom hyperfine qubit

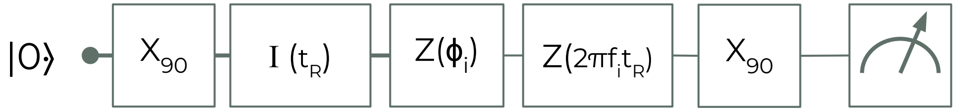


ArXiv: 2110.14645 GVL

Qubit characterization

T2 Measurement

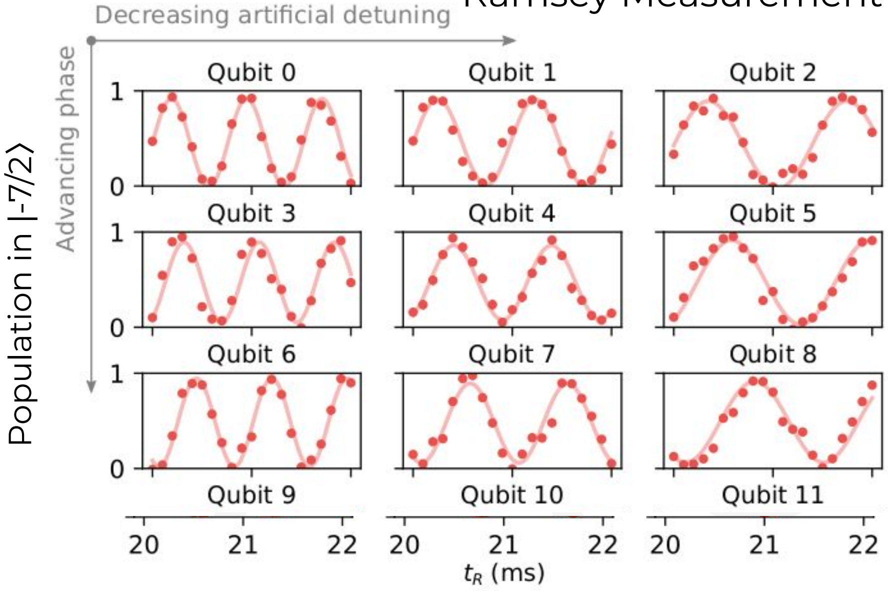
Ramsey circuit:



Qubit-specific combination of static phase ϕ_i and artificial detuning f_i.

$T_2^* \sim 21 \pm 7$ seconds

Ramsey Measurement

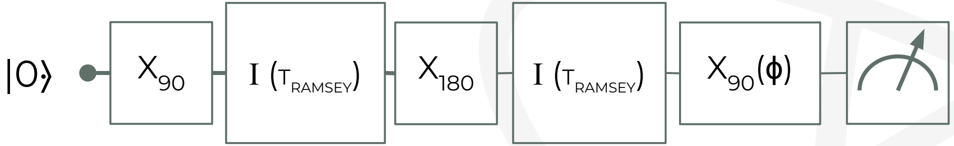


Time [seconds]

Qubit characterization

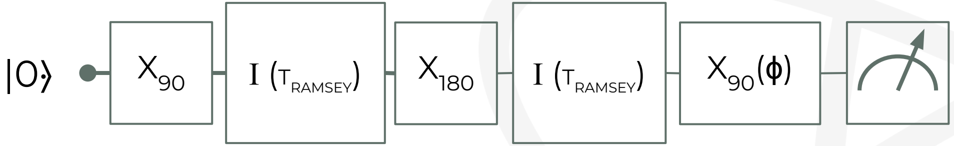
T2 Measurement

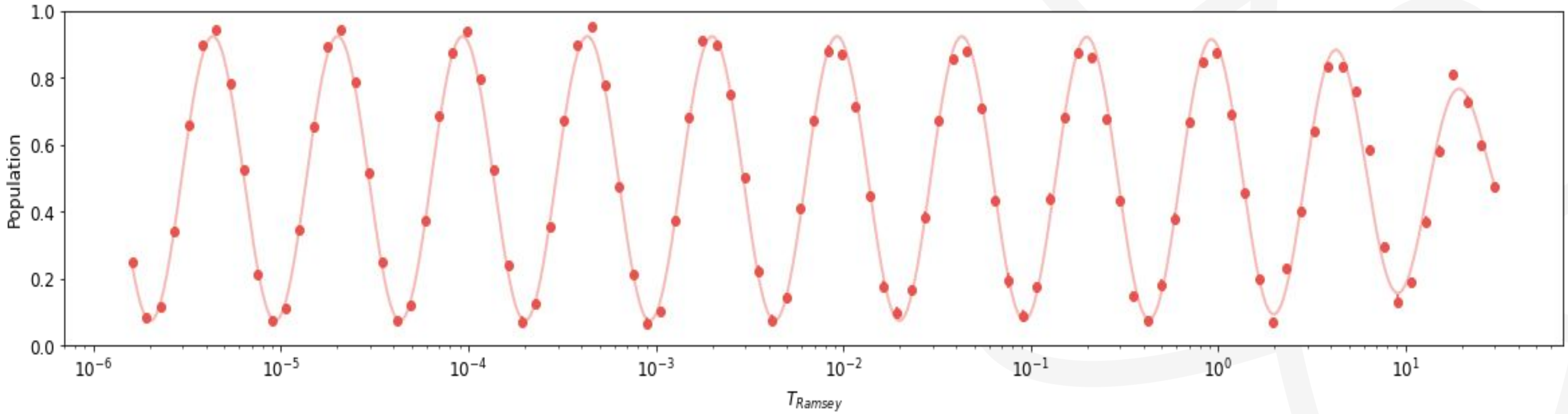
Ramsey-echo circuit:



Qubit characterization
T2 Measurement

Ramsey-echo circuit:



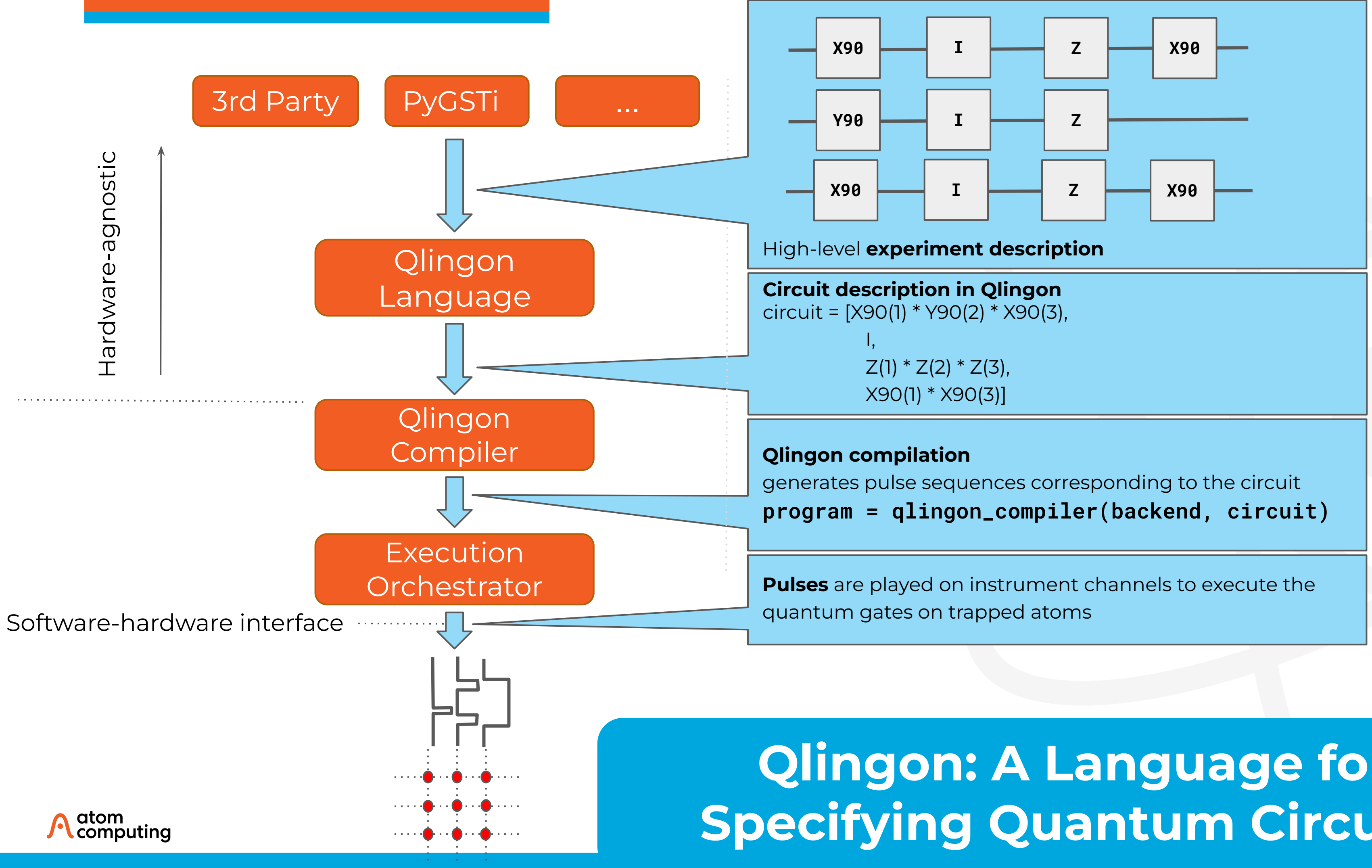


$T_2^{ECHO} \sim 42 \pm 6$ seconds

FROM QUBITS TO QUANTUM COMPUTING

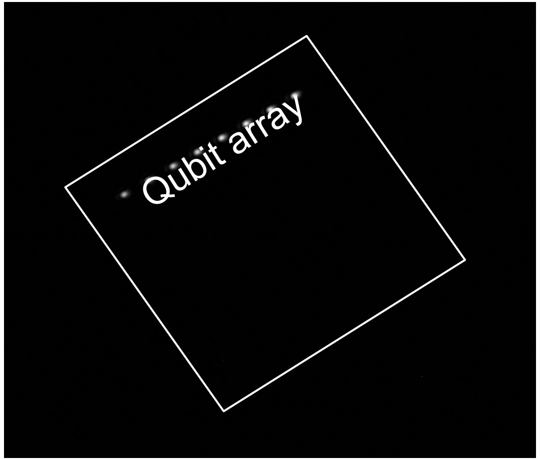
SOFTWARE & AUTOMATION

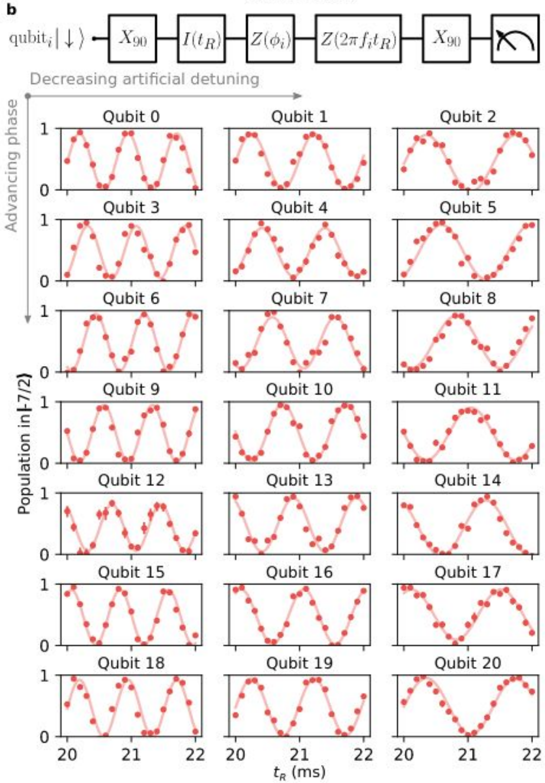
Qlingon: A Language for Specifying Quantum Circuits



Driving Specific Qubits

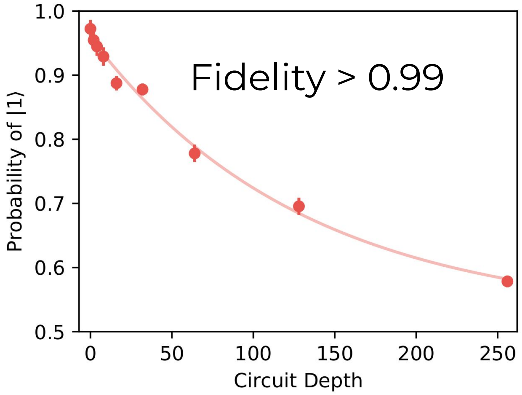
- Driving each qubit independently.
- Choose which sites, what phase, and what amplitude to drive.





Single qubit gate fidelity

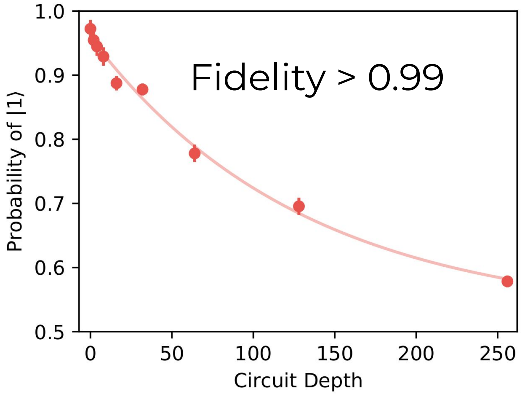
Randomized Benchmarking and Gate Set Tomography (GST)



* averaging a subset (#21 atoms)

Single qubit gate fidelity

Randomized Benchmarking and Gate Set Tomography (GST)



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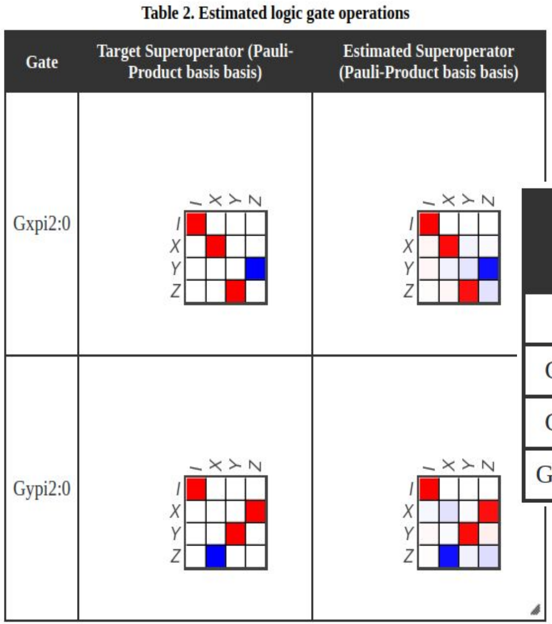


Table 2. Estimated logic gate operations

Gate	Target Superoperator (Pauli-Product basis basis)	Estimated Superoperator (Pauli-Product basis basis)
Gxpi2:0		
Gypi2:0		

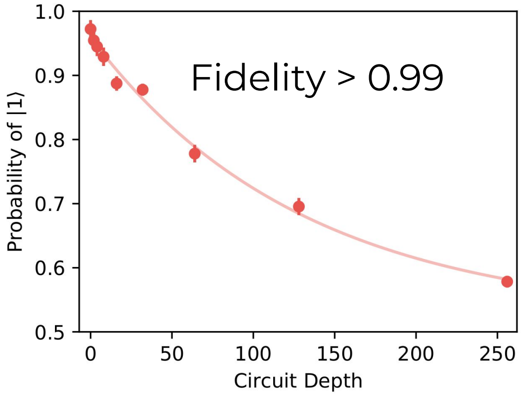
Gate	Avg. Gate Infidelity TP	Avg. Gate Infidelity CPTP
[]	0.008299	0.012885
Gxpi2:0	0.002856	0.003909
Gypi2:0	0.008019	0.008229
Gzmpi2:0	0.000781	0.002361

** averaging a subset (#10 atoms)

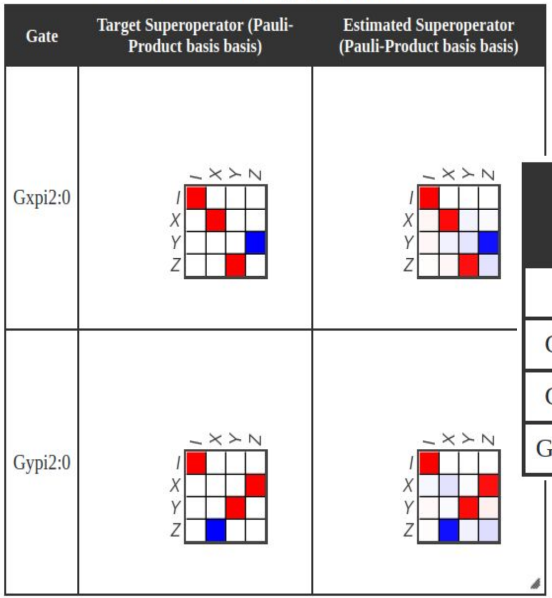
E. Nielsen *et. al.* Quantum 5, 557 (2012)

Single qubit gate fidelity

Randomized Benchmarking and Gate Set Tomography (GST)



* averaging a subset (#21 atoms)



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Gzmpi2:0	0.000781	0.002361

** averaging a subset (#10 atoms)

Can we have better gates?

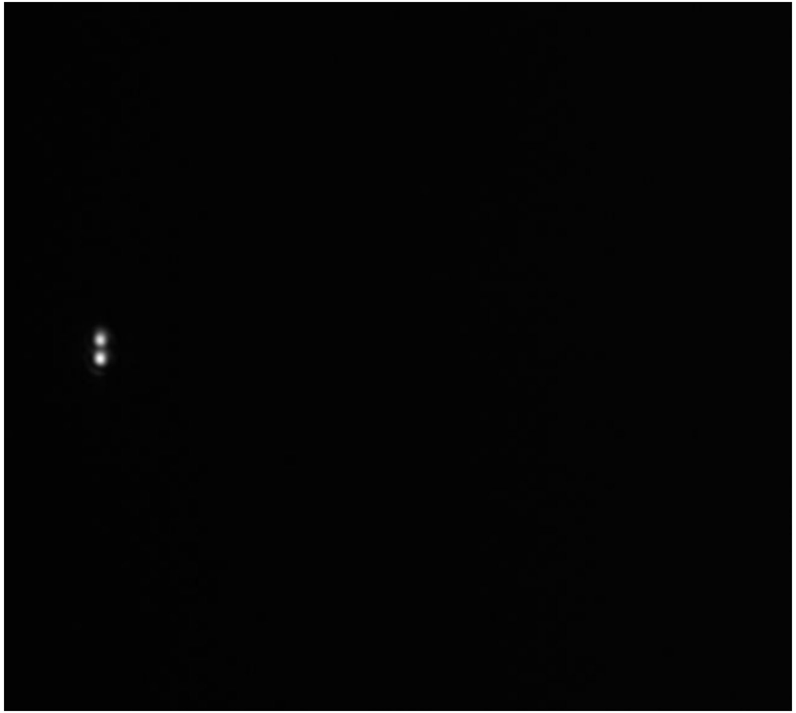
We are mainly limited by coherent errors -detuning and gate duration.

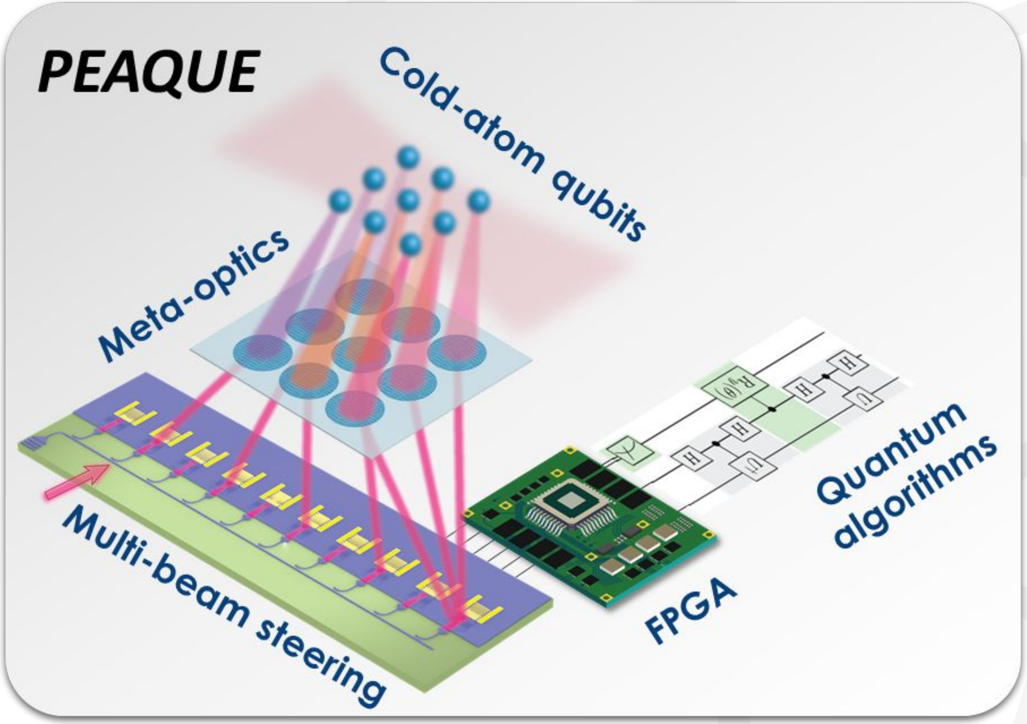
Next steps to reduce errors and increase array uniformity:

- Pulse shaping
- Composite pulsed
- Faster gates

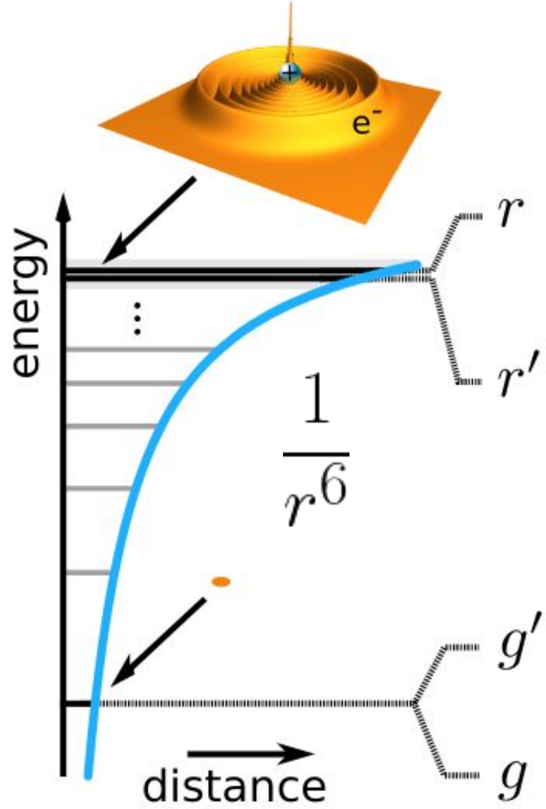
E. Nielsen *et. al.* Quantum 5, 557 (2012)

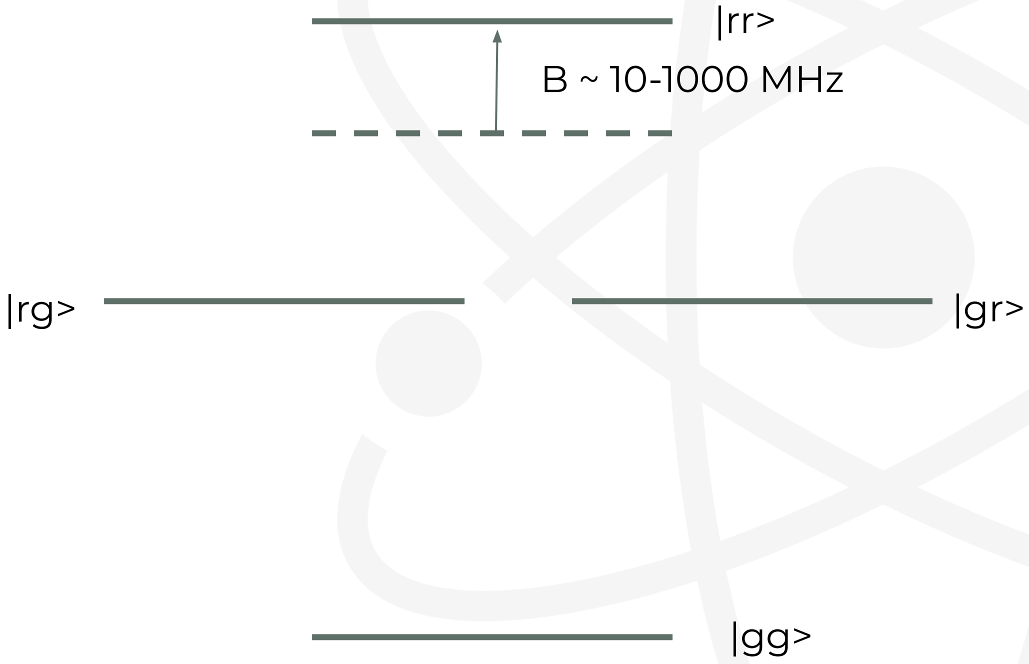
Gates with Single-Site Addressing





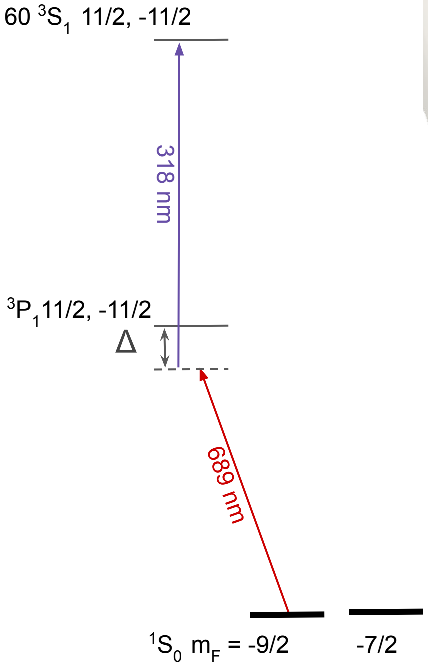
Rydberg-Rydberg Mediated 2Q Gates

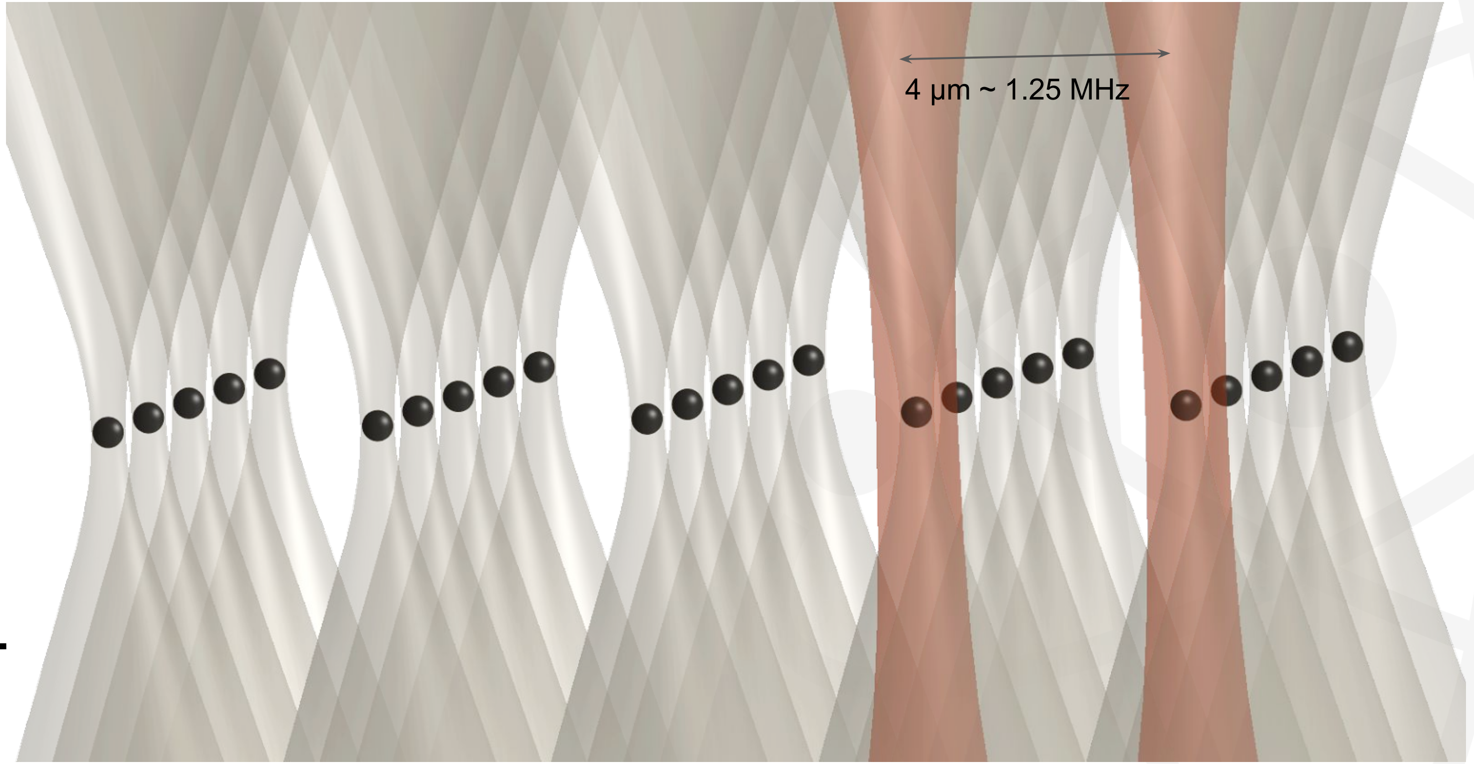




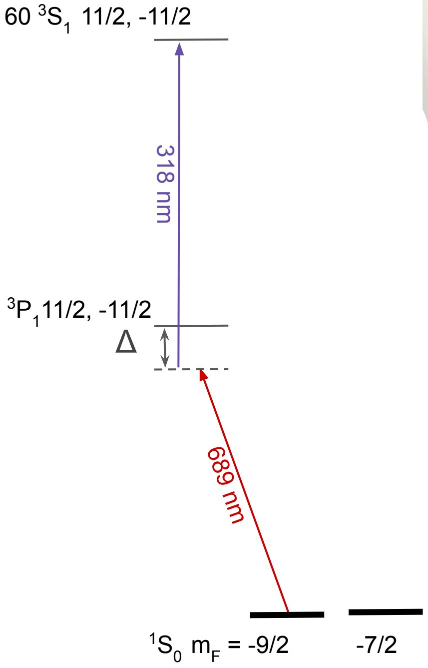
Morgado et al, ArXiv: 2011.03.031

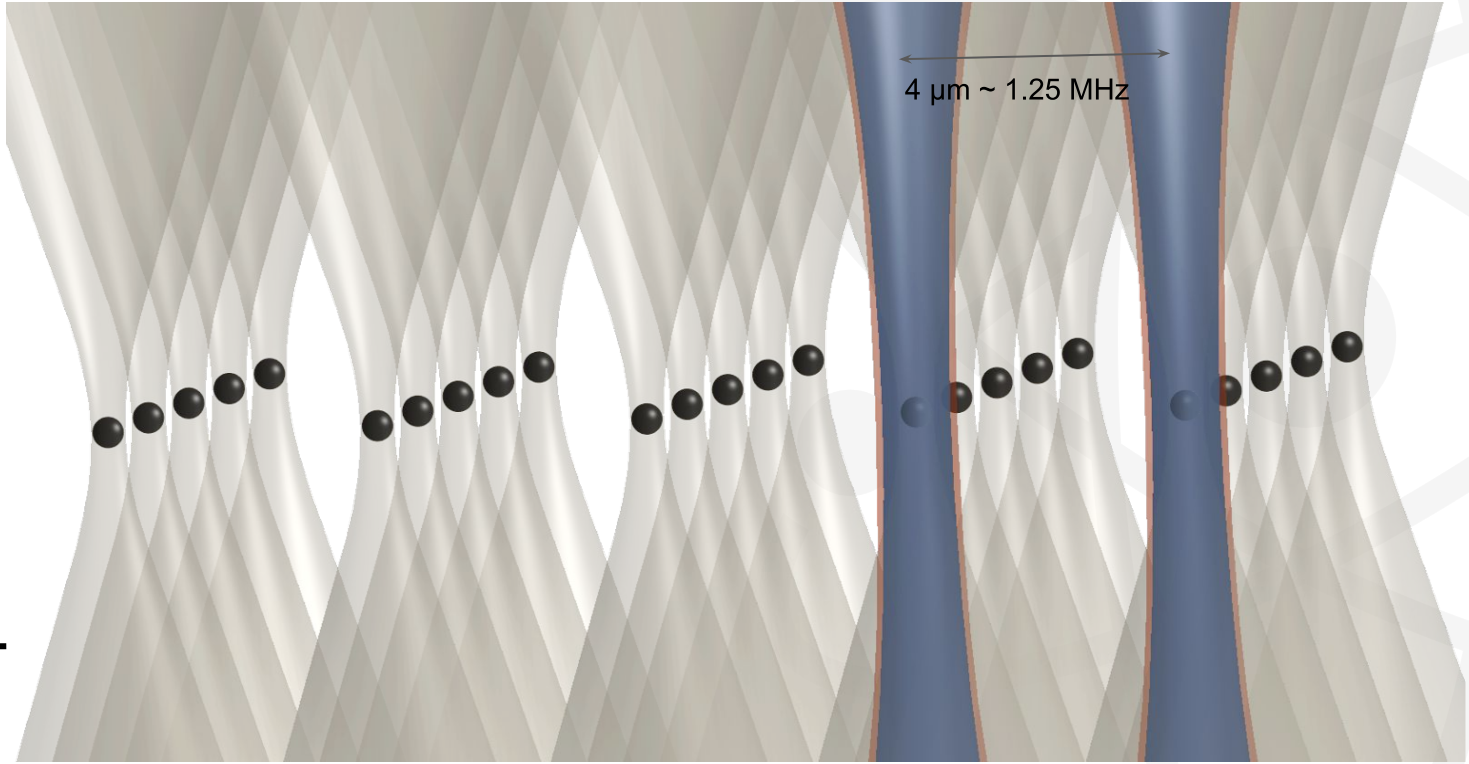
2q gate
Addressing scheme





2q gate
Addressing scheme

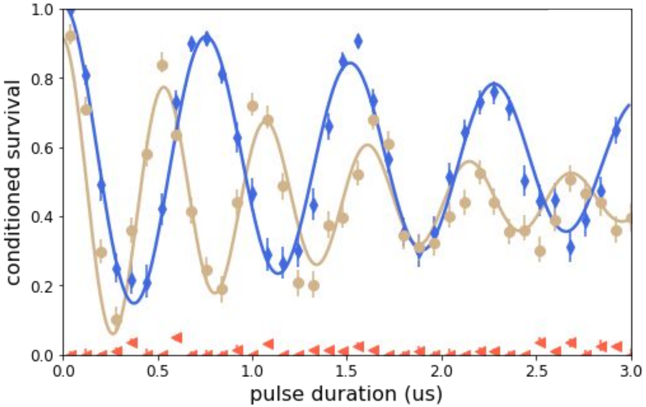


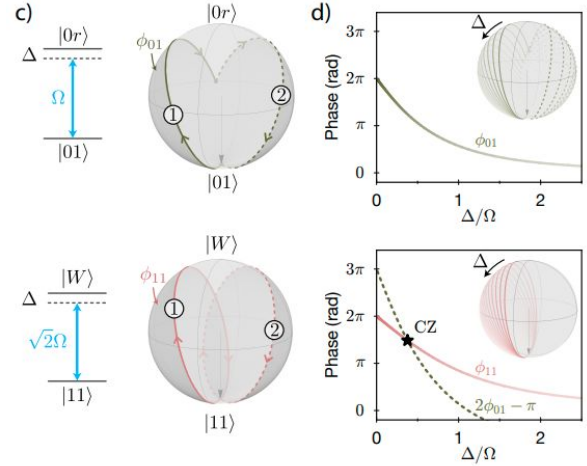


2q gate: ingredients

Coherent Rabi oscillation

- Single atom
- Blockaded Oscillation
- Rydberg-Rydberg Population





[Levine, ... Lukin, PRL 123(17) 170503]

C_Z:

$|00\rangle \rightarrow |00\rangle$

$|01\rangle \rightarrow e^{i\phi_{01}}|01\rangle$

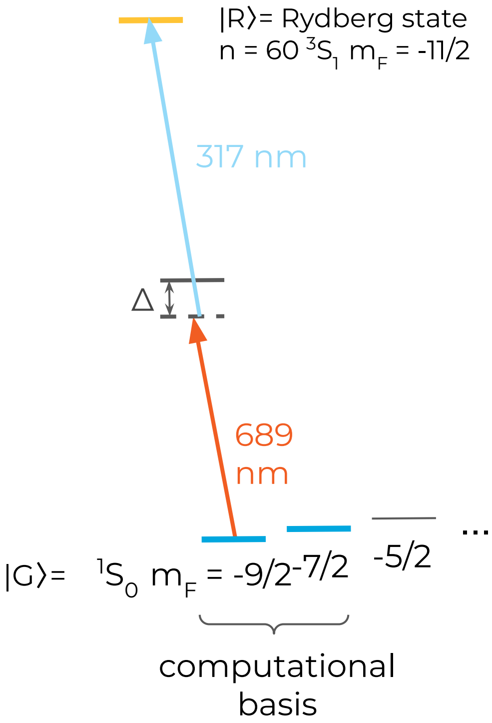
$|10\rangle \rightarrow e^{i\phi_{10}}|10\rangle$

$|11\rangle \rightarrow e^{i\phi_{11}}|11\rangle$

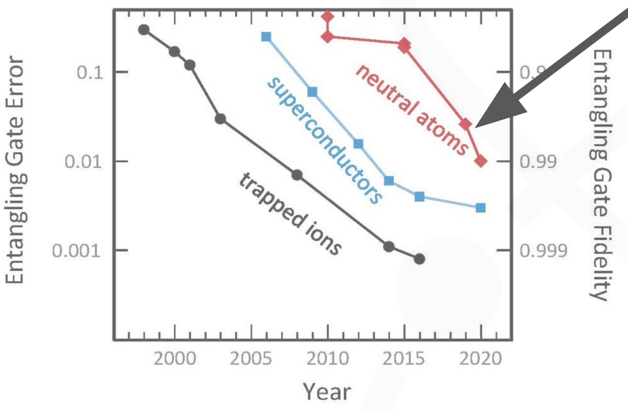
atom computing

OUTLOOK

A Look at What Our Competitors Are Saying…



Two-Qubit (Entangling) Gate Performance



A wave of interest, development, and investment started for Neutral Atom Computing.

Note: All data performed on exactly 2 qubits

Q. Turchette... Phys. Rev. Lett. 81, 3631 (1998)
C. Sackett... Nature 404, 256 (2000)
M. A. Rowe... Nature 409, 791 (2001)
D. Leibfried... Nature 422, 412 (2003)
J. Benhelm... Nature Physics 4, 463 (2008)
C. J. Balance, Phys. Rev. Lett. 117, 060504 (2014)
J. P. Gaebler... Phys. Rev. Lett. 117, 060505 (2016)

M Steffen... Science 313 (5792), 1423 (2006)
L. DiCarlo... Nature 460, 240 (2009)
J. M. Chow... Phys. Rev. Lett 109, 060501 (2012)
R. Barends... Nature 508, 500 (2014)
S. Sheldon... Phys. Rev. A 93, 060302 (2016)
M. Kjaergaard... arXiv:2001.08838 (2020)

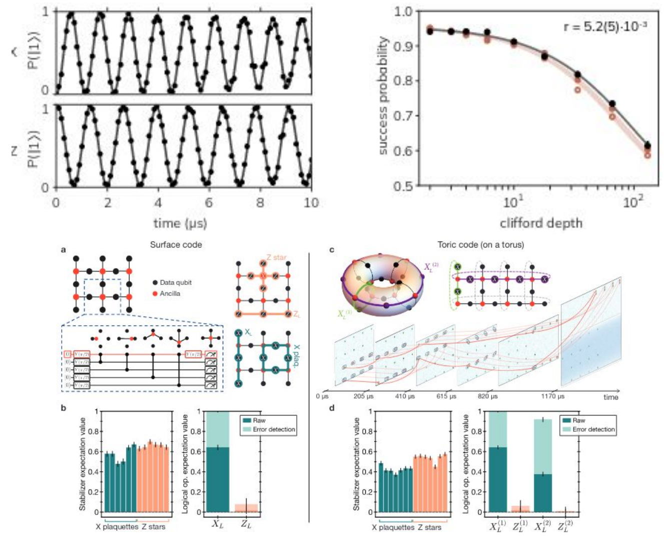
T. Wilk... Phys. Rev. Lett. 104, 010502 (2010)
L. Isenhowe... Phys. Rev. Lett. 104, 010503 (2010)
K. M. Maller... Phys. Rev. A 92, 022336 (2015)
Y.-Y. Jau... Nature Physics 12, 71 (2016)
H. Levine... Phys. Rev. Lett. 123, 170503 (2019)
I. S. Madjarov... arXiv 2001.04455 (2020)

atom computing

In the last Year...

We've seen

- Long lived (many second) bell states using strontium - Kaufman
- The debut of two Yb platforms with
  - Universal gate sets - Thompson
  - **150 ns** 1Q gates - Kaufman
- A full platform for running higher connectivity circuits through mid-circuit atom rearrangement including Toric codes, surface codes, etc etc - Greiner, Vuletic, Lukin



Kaufman
GVL

Neutral Atom Quantum Computers are entering the scene.


atom
computing
FAN TRAY
ADC IN 0
ADC IN 1
ADC IN 2
ADC IN 3
ADC IN 4
ADC IN 5
ADC IN 6
ADC IN 7
ADC/DAC IO
USB-C
EXT SYNC
RF OUT 0
RF OUT 1
RF OUT 2
RF OUT 3
RF OUT 4
RF OUT 5
RF OUT 6
RF OUT 7
REF IN
CLK OUT
PPS IN
UART MMC
UART ARM/BMC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bbloom@atom-computing.com

Thank you!