STATE-OF-THE-ART AND PROSPECTS: **NEUTRAL ATOM QUANTUM COMPUTING**

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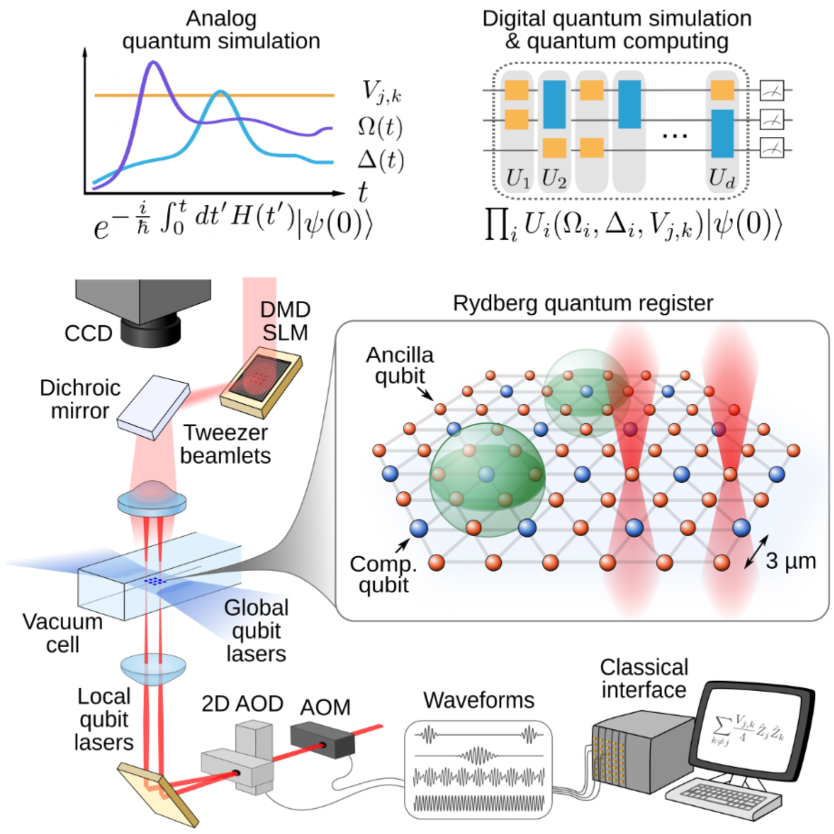
<u>Disclaimer</u>: I am cofounder and shareholder of QPerfect



AVS Quantum Sci. 3, 023501 (2021); arXiv:2011.03031

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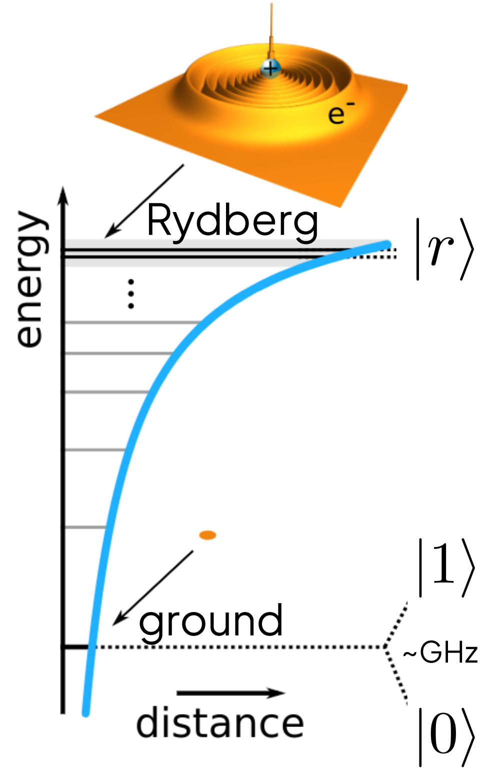
NEUTRAL ATOM QUBITS (RYDBERG INTERACTING)



DiVincenzo Criteria (2000):

1) Quantum system: Rb, Cs, K, Sr, Yb “Nature’s best qubits”
2) Initialization: Laser cooling, optical pumping
3) Long coherence times: >10^5 x gate time
4) Interactions: Rydberg mediated
5) Readout: single atom fluorescence

Platform	Strength	Weakness
Neutral atoms	Scaling	Control/readout
Trapped ions	Control/readout	Scaling
Superconducting qubits	Control/readout	Scaling
Photons	Flexibility	Scaling

I.M. Georgescu, S. Ashhab, F. Nori, Rev. Mod. Phys. 2014

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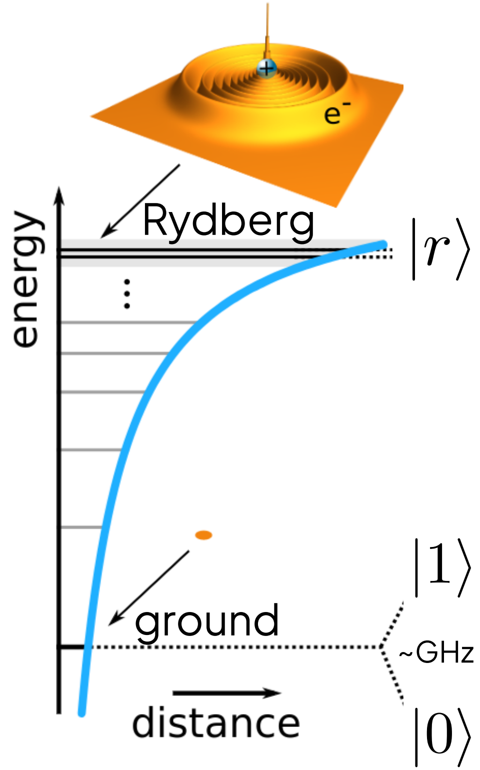

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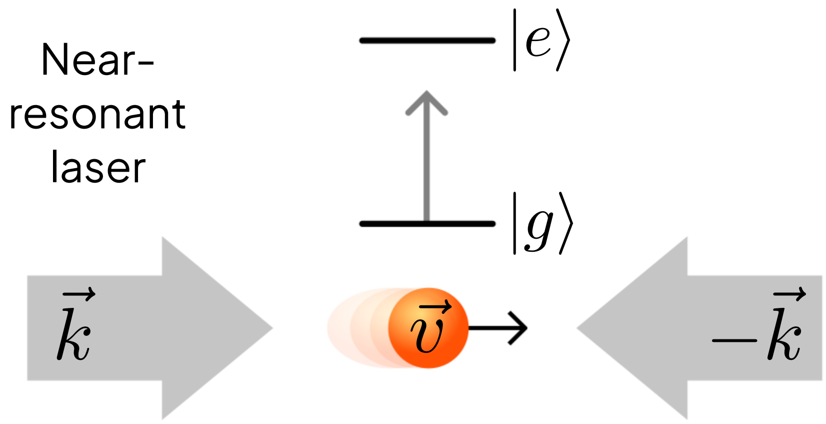
State-of-the-art 2024

Single-qubit gates: fidelity 99.9% / gate time 250 ns — Infleqtion, arXiv:2408.08288 (2024)

Two-qubit gates: fidelity 99.7% / gate time 140 ns — Caltech, arXiv:2407.20184 (2024)

QUANTUM SYSTEM: SINGLE ATOM TRAPPING

Laser cooling (Doppler effect)



Doppler shift: $-\vec{k} \cdot \vec{v}$

Momentum transfer : $\hbar\vec{k}$

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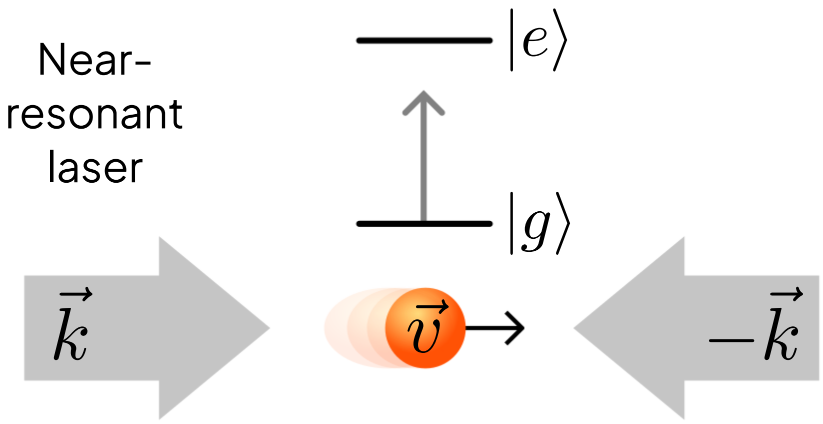

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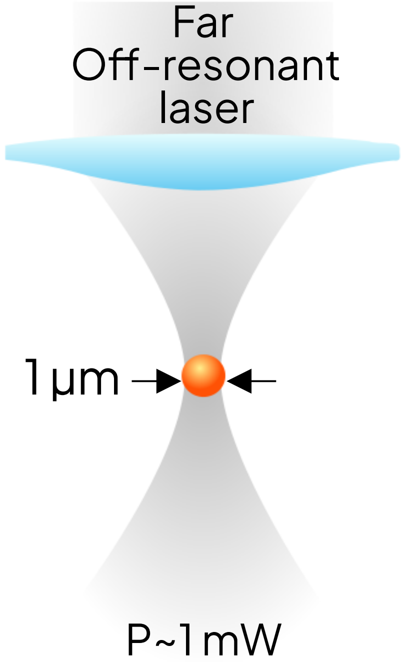
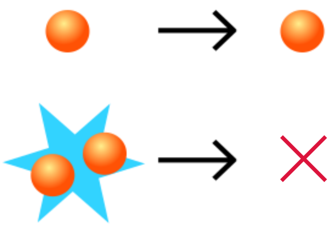
Optical trapping $F = -\nabla I(r)$



Collisional blockade



Loading probability ~ 0.5

QUANTUM SYSTEM: SINGLE ATOM TRAPPING

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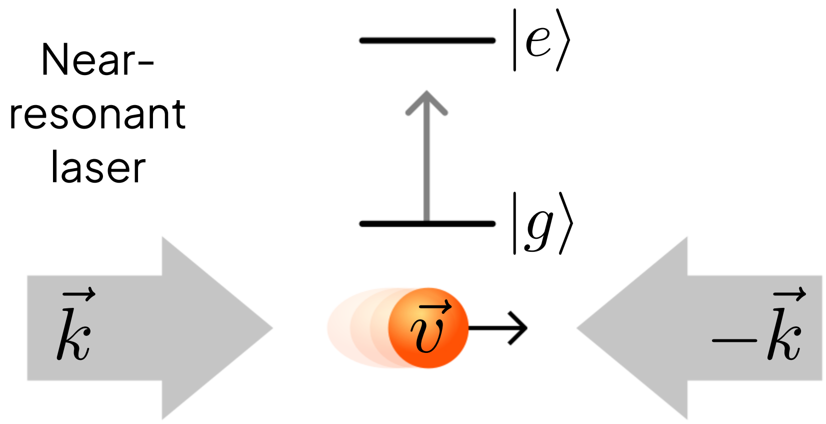

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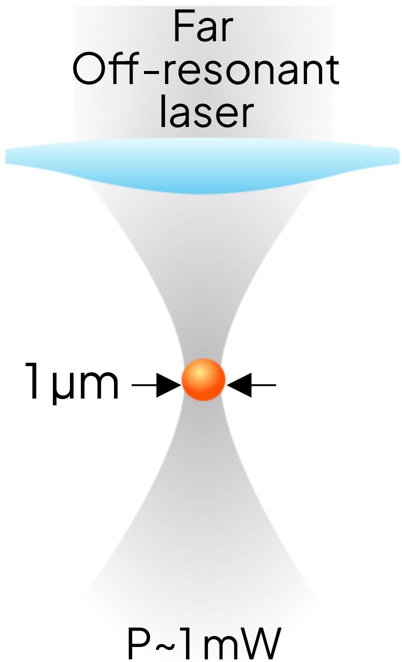

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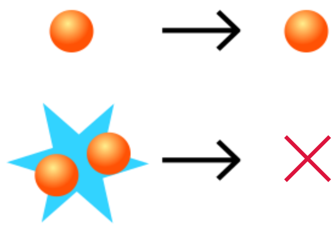
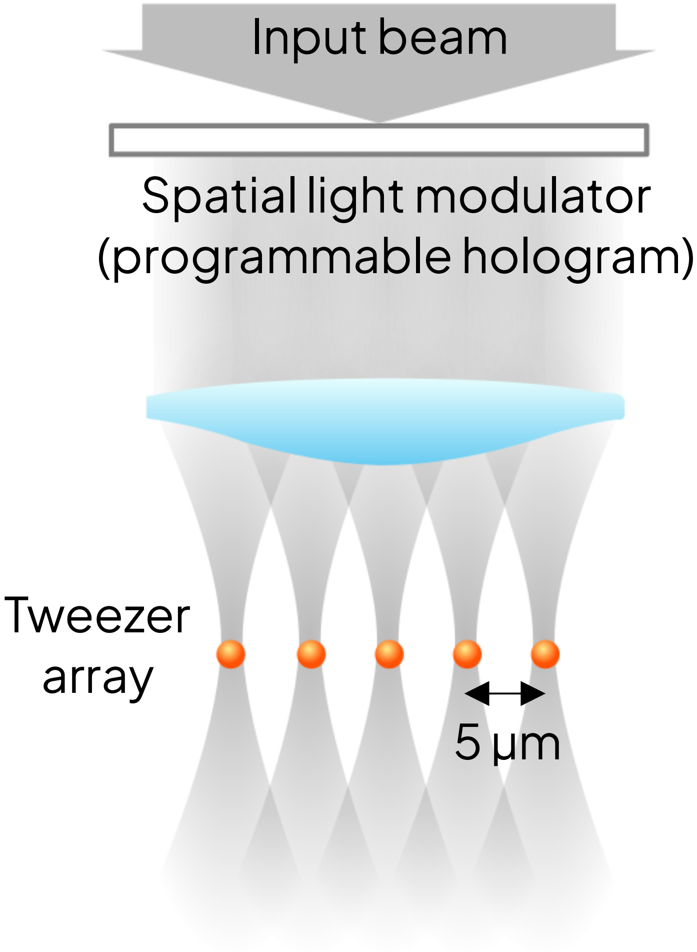


Loading probability ~ 0.5

- **T ~ 10 µK: 1000× colder than superconducting qubits, without cryogenics!**
- **Possibility for arbitrary arrangements of atoms (in 2D) including dynamical positioning**

QUANTUM SYSTEM: SCALING UP



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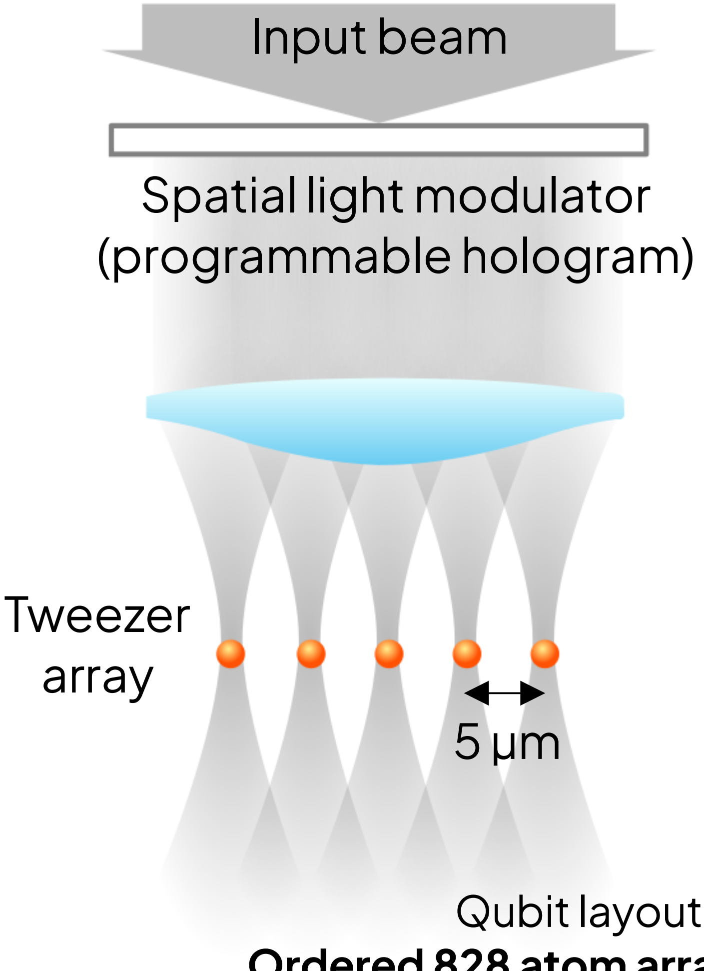
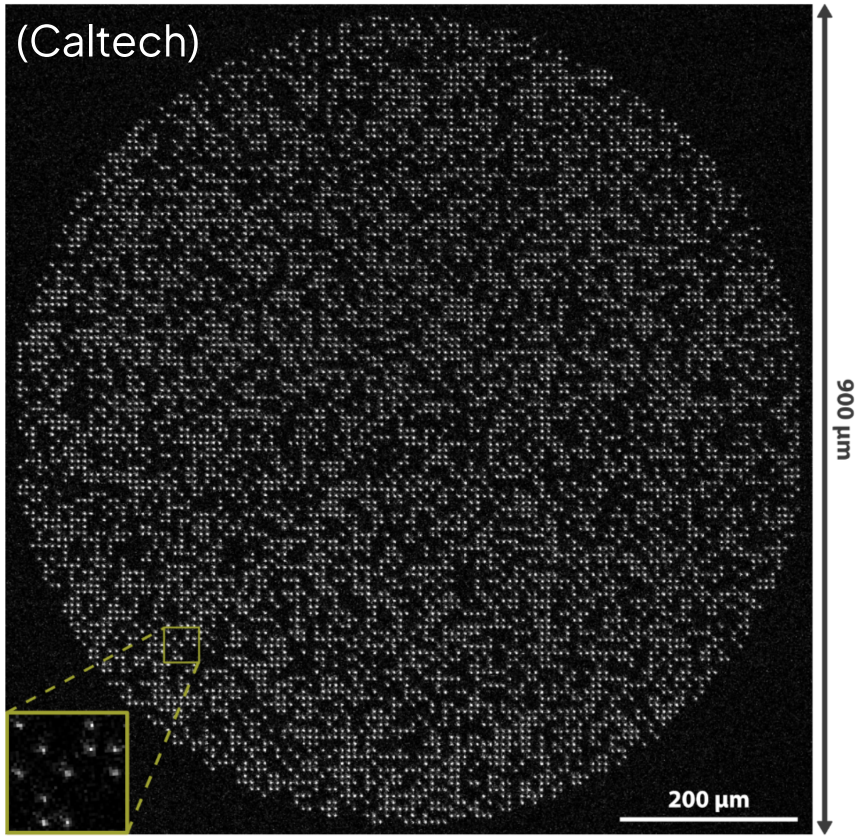


6100 atoms (bright dots) arXiv:2403.12021



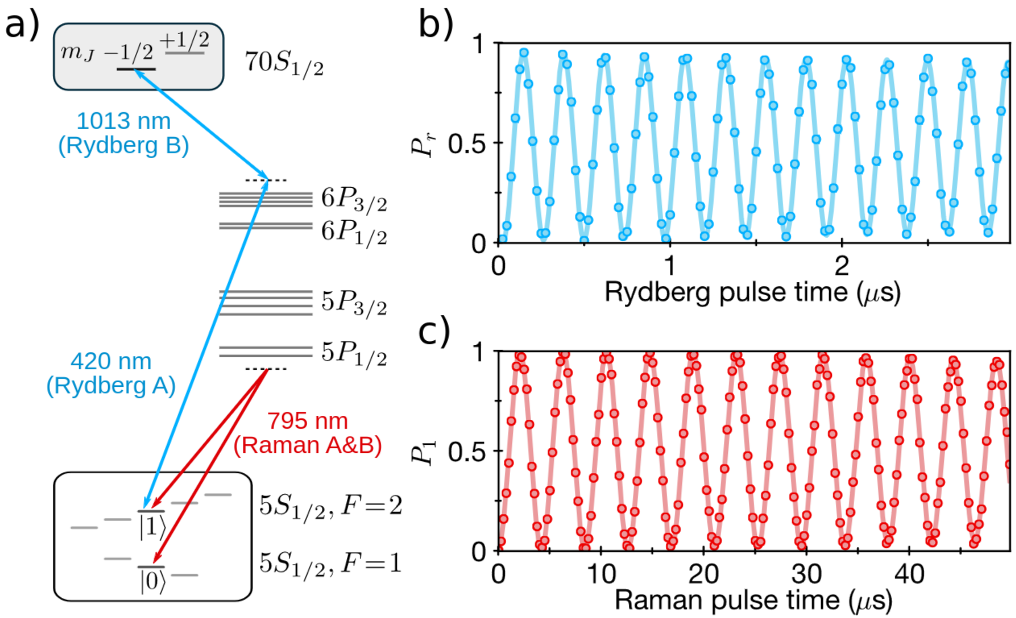
Qubit layout can be dynamically reconfigured!

Ordered 828 atom array (Pasqal) : Phys. Rev. Applied 22, 024073 (2024)

SINGLE QUBIT GATES

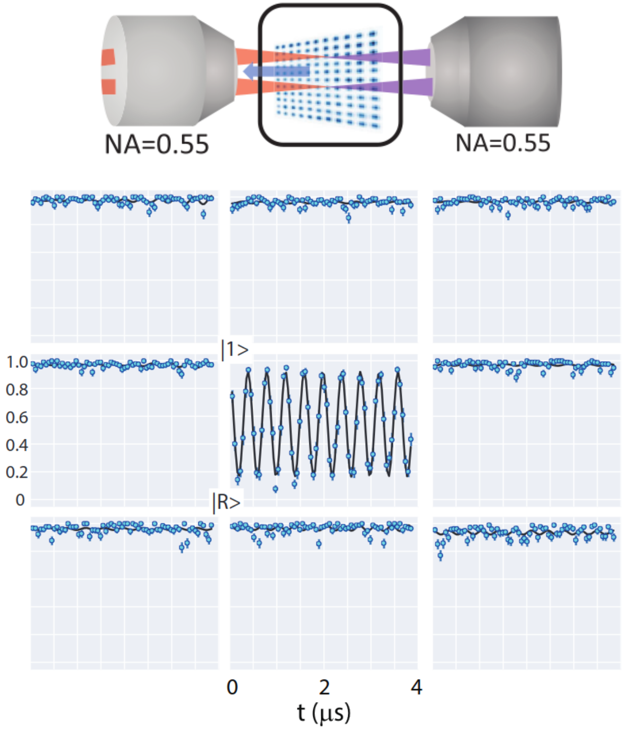
Arbitrary single qubit rotations in <5 μs

Levine et al., PRL 123, 170503 (2019)



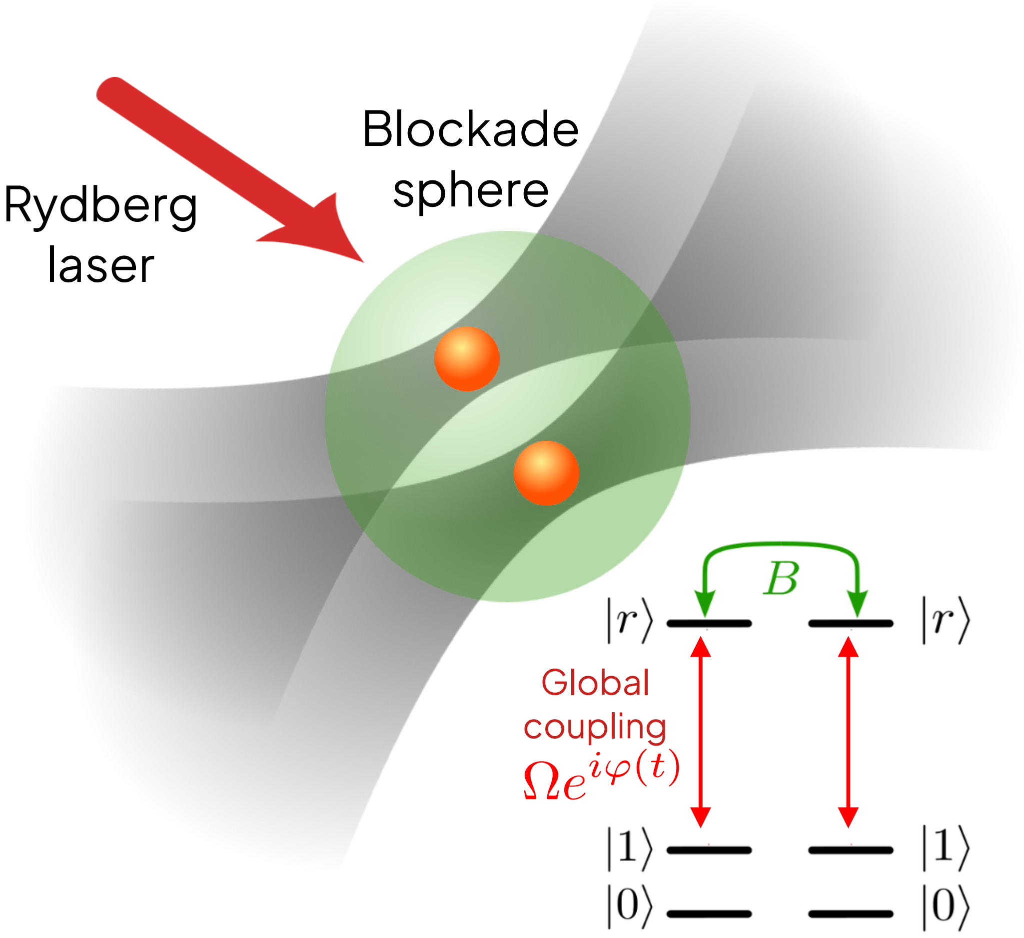
Spatial addressing with low crosstalk

Graham et al., PRL 123, 230501 (2019)



TIME-OPTIMAL (RYDBERG BLOCKADE) CZ GATE

(Strasbourg) Quantum 6, 712 (2022), PRX Quantum 4, 020336 (2023)



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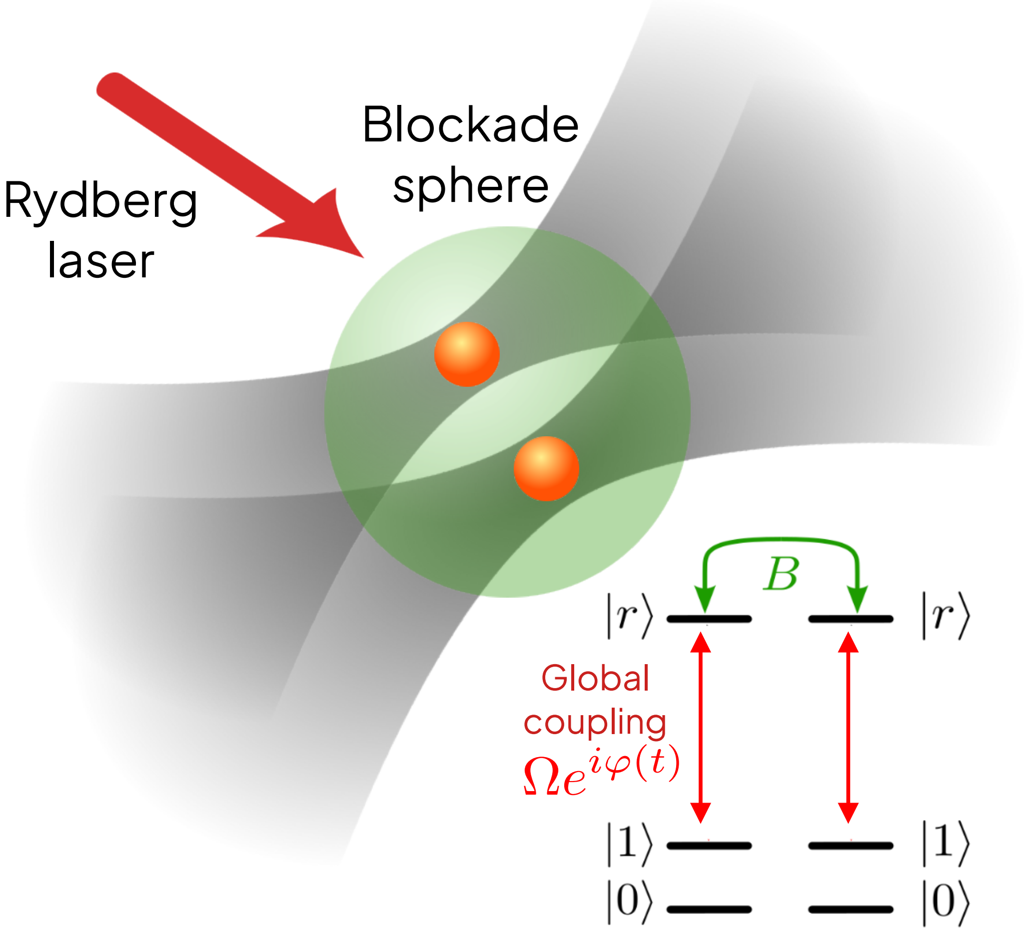

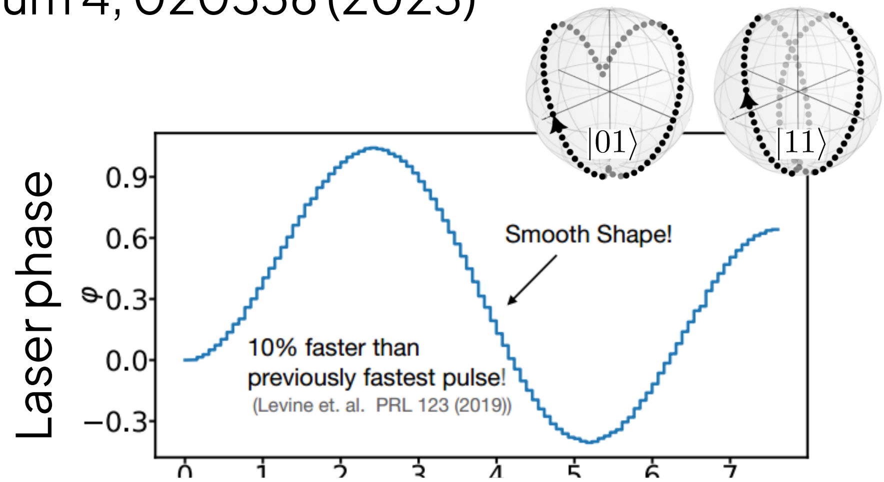

Demonstrated by several groups in 2023/24:

99.7% fidelity

Harvard, Nature 622, 268–272 (2023)
Princeton, arXiv:2406.01482 (2024)
Caltech, arXiv:2407.20184 (2024)
Infleqtion, arXiv:2408.08288 (2024)

Atomic Quantum Computing as a Service

aqcess.cesq.fr

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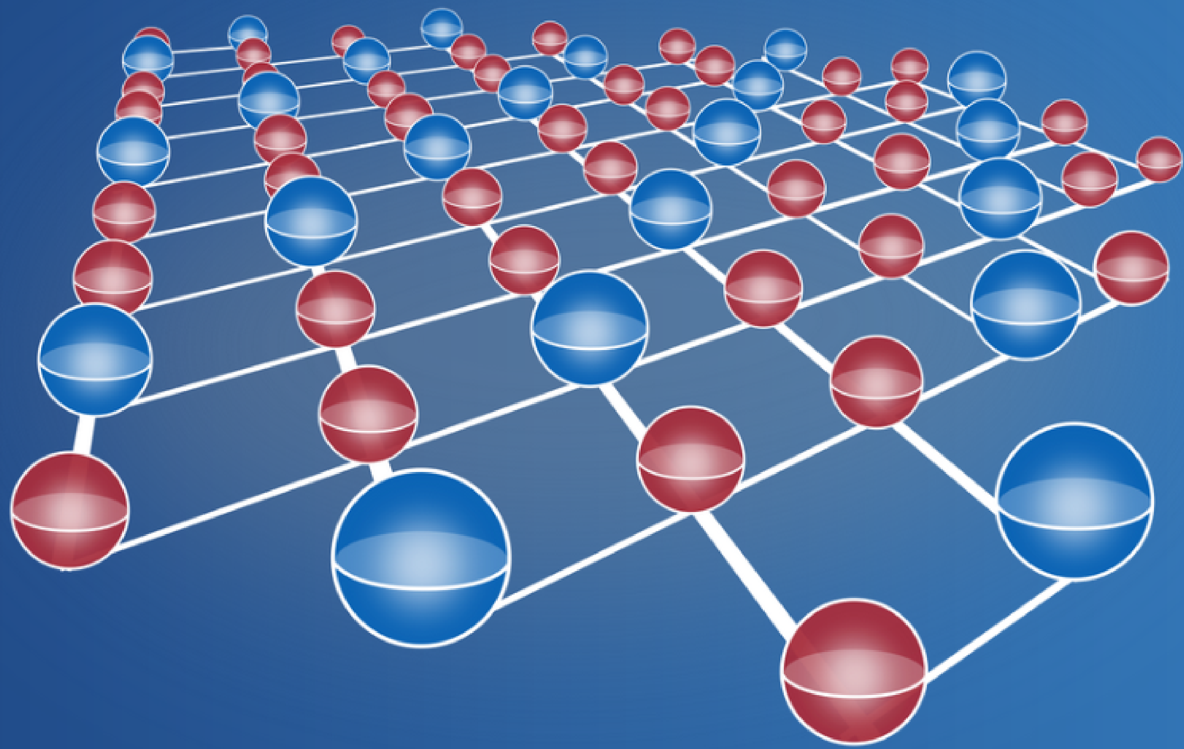

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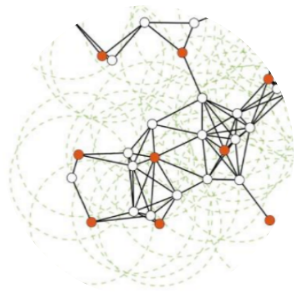
NEAR TERM USE CASES (DIGITAL QC)

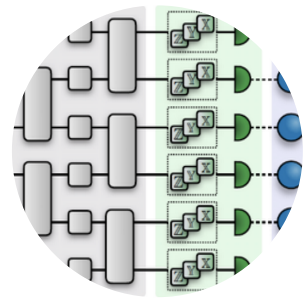
Physics

100 qubits
1000 operations

Optimization

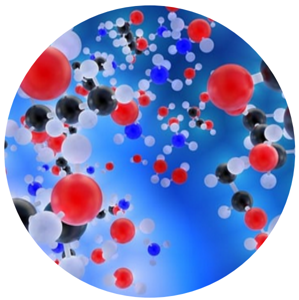


Machine learning



10k qubits
1M ops

Chemistry & Materials



Factoring

>1M qubits
>1B ops**

NISQ: narrow quantum advantage

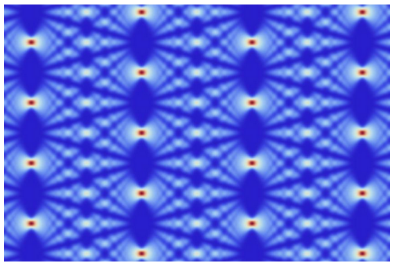
Early FTQC*

FTQC

* EFTQC : Katabarwa et al., PRX Quantum 5, 020101 (2024)
** FTQC resource estimates (physical error probability 10^{-3}) : M. E. Beverland et al., arXiv:2211.07629

CHALLENGES 3–5Y (NISQ → EARLY FTQC)

SCALING BEYOND 10K QUBITS



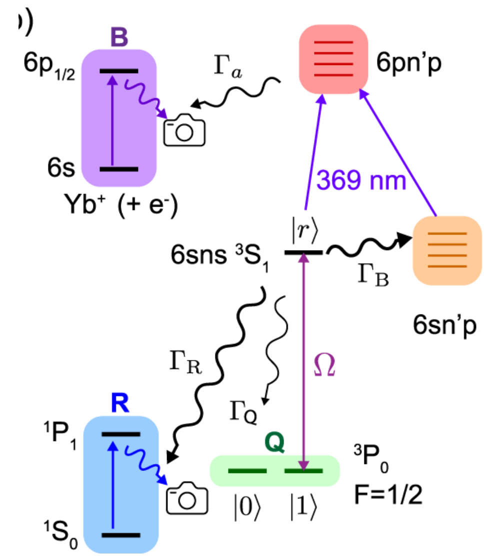
Problem: Required laser power >10W, sorting time >100s
Solution(s): Hybrid 2D + 3D (optical lattices), parallel sorting

Nature Physics 3, 556–560 (2007), PRL, 130, 180601 (2023)

SCALING BEYOND 1M OPERATIONS

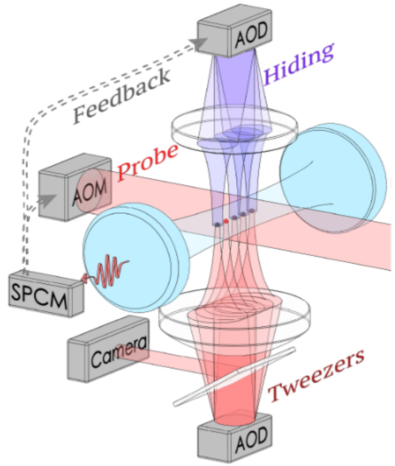
Problem: Rydberg lifetime 100 μs ~1000× gate time
Solution(s): Circular states, erasure conversion, replacement

Rev. Research 2, 022032 (2020), Nature Comms. 13, 4657 (2022), arXiv:2402.04994, arXiv:2401.16177



CHALLENGES 3–5Y (NISQ → EARLY FTQC)

FASTER MEASUREMENTS



Problem: Exposure time ~10ms – 100ms (=10^5 x gate time)
Solution(s): Cavity enhanced readout, measurement free QEC?

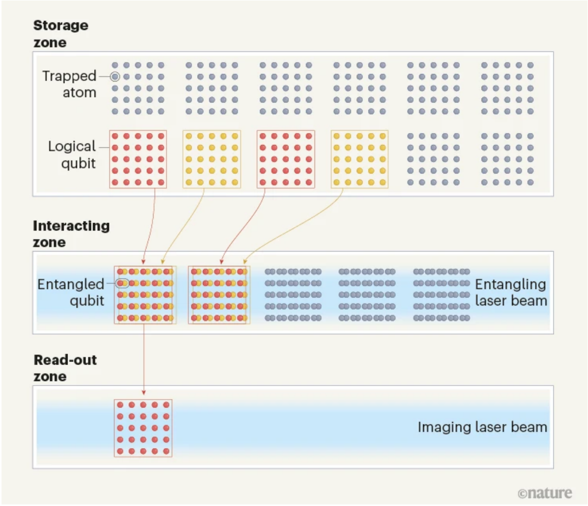
PRL 104, 203601 (2010), PRL 127 050501 (2021), PRA 108, 032407 (2023), arXiv:2408.15329

PRX Quantum, 5 010333, arXiv:2410.13568

CALIBRATION AND COMPILATION

Problem: Maintaining fidelities at scale,
Compilation time >> QPU time
Solution(s): Zoned architectures,
Parallel & real-time calibration, AI

Nature 626, 58–65 (2024),



CONCLUSIONS: NEUTRAL ATOM QUBITS

- **From a dark horse to one of the leading platforms for QC**
- **All requirements met for universal quantum computing:**
  >1000 qubits, high fidelity gates & high connectivity
- **We see a clear path to 10K+ qubits and 1M+ gates,** but not without challenges
- **This will be the decade of the quantum advantage.** Realizing the full potential of quantum computers will take longer. We need concerted French/European efforts

The path from NISQ to FTQC will be gradual, requiring to fully optimize/ co-develop each layer of the QC stack (hardware and software together)