

Quantum information with Rydberg atoms

Reading-group Beamer

Based on the review by M. Saffman, T. G. Walker, and K. Mølmer

DOI: [10.1103/RevModPhys.82.2313](https://doi.org/10.1103/RevModPhys.82.2313)

Foundation review: neutral-atom quantum information, blockade physics, ensembles,
and light–matter interfaces

Roadmap

Talk flow (about 42–45 minutes)

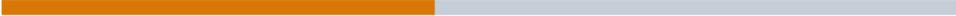
- 1 Motivation and blockade intuition (5 min)
- 2 Rydberg-atom physics and interactions (10 min)
- 3 Gate protocols, error scalings, scalability (8 min)
- 4 Experimental status in the review (6 min)
- 5 Collective encoding, many-body ideas, quantum optics (10 min)
- 6 Critical takeaways and discussion (3–5 min)

What this review tries to unify

- ▶ Single-atom two-qubit gates
- ▶ Blockaded ensembles as effective **superatoms**
- ▶ Collective qubit encoding
- ▶ Single-photon generation and quantum communication
- ▶ Many-body entanglement and simulation prospects

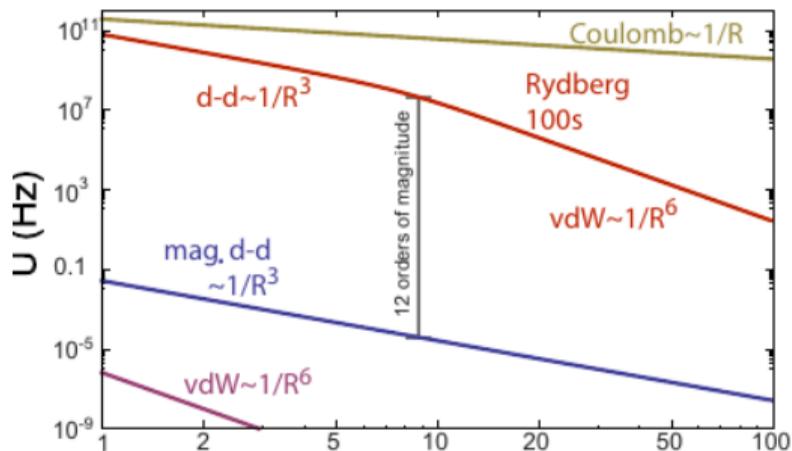
1. Why Rydberg atoms?

From weakly interacting neutral atoms to switchable long-range couplings



Saffman, Walker, and Mølmer, *Rev. Mod. Phys.* **82**, 2313–2363 (2010)

The core motivation: switchable interactions over a huge range



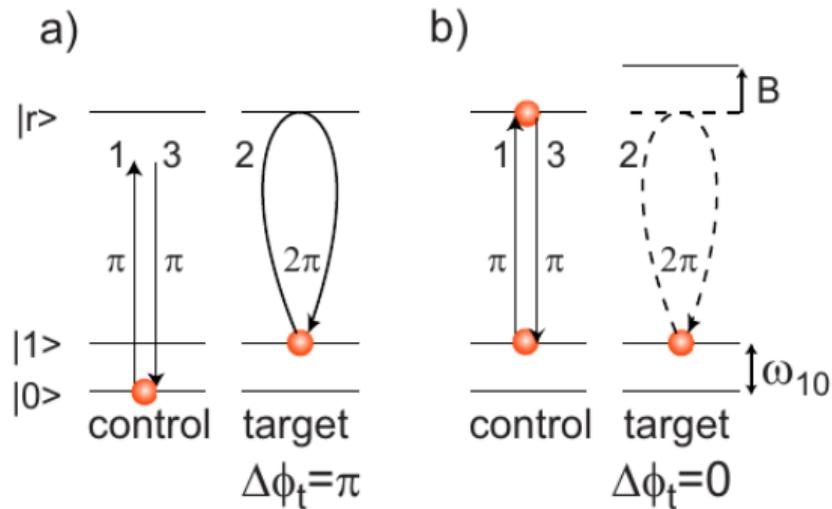
Main message of Fig. 1

- ▶ Ground-state neutral atoms interact too weakly at micron-scale separations for fast gates.
- ▶ Exciting atoms to high- n Rydberg levels creates enormous dipole moments and strong interactions.
- ▶ The review emphasizes an **interaction contrast of roughly 12 orders of magnitude** when the interaction is turned on via Rydberg excitation.

Why this matters for quantum information

- ▶ Long-lived hyperfine qubits store information.
- ▶ Short-lived Rydberg states are used only transiently as an interaction resource.
- ▶ This separates *memory* from *entangling mechanism*.

Rydberg blockade in one slide



Blockade idea

If the control atom is excited to a Rydberg state, the target atom's Rydberg transition is shifted by a blockade energy B and becomes off-resonant.

Pulse sequence and logical action

$$\pi_c - 2\pi_t - \pi_c \Rightarrow U_{CZ} = \text{diag}(1, -1, -1, -1).$$

Then one obtains a CNOT by adding single-qubit Hadamard rotations on the target qubit.

- ▶ Fast when $B \gg \Omega$
- ▶ Does not require atoms to collide
- ▶ Naturally compatible with optically resolvable separations

2. Rydberg physics and interactions

What makes these atoms so special, and what can go wrong?

Saffman, Walker, and Mølmer, *Rev. Mod. Phys.* **82**, 2313–2363 (2010)

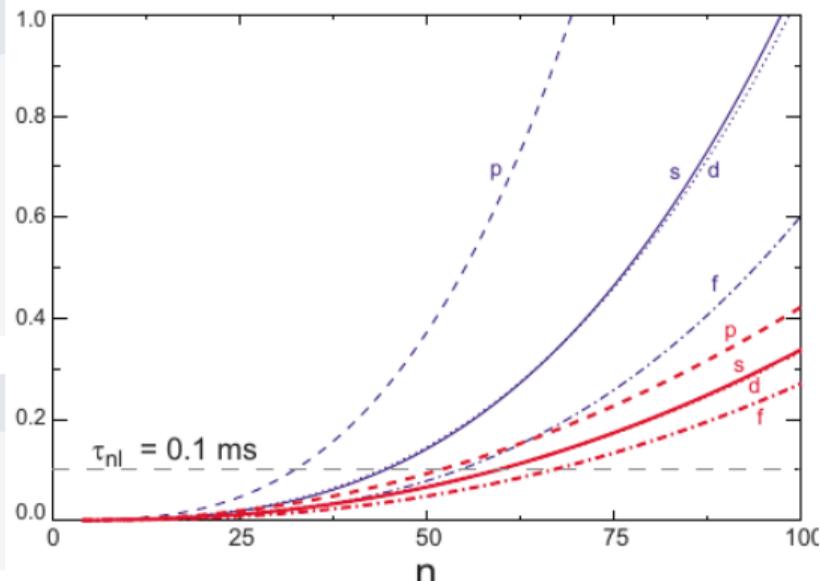
Why Rydberg atoms are extraordinary

Scalings highlighted in the review

- ▶ Dipole-dipole matrix elements grow rapidly with principal quantum number n .
- ▶ Resonant dipole interactions scale roughly as n^4 .
- ▶ Radiative lifetimes scale roughly as n^3 .
- ▶ Van der Waals interactions typically scale as n^{11} .

Operational consequence

Large n gives stronger interactions and longer lifetimes, but also stronger sensitivity to stray electric fields and blackbody effects.



For $n \gtrsim 50$, room-temperature lifetimes exceed roughly $50 \mu\text{s}$, so MHz-scale control is realistic.

From Förster to van der Waals interactions

Two interaction regimes

- ▶ At shorter range, near-resonant channel coupling gives $1/R^3$ dipole-dipole behavior.
- ▶ At longer range, the same coupling reduces to an effective $1/R^6$ van der Waals interaction.
- ▶ The crossover distance R_c depends on the Förster defect δ and the dipolar coupling strength.

$$V_{dd} = \frac{e^2}{R^3} \left(\mathbf{a} \cdot \mathbf{b} - 3(\mathbf{a} \cdot \hat{R})(\hat{R} \cdot \mathbf{b}) \right)$$

- ▶ For blockade, we mostly care about the *energy shift* of doubly excited states.
- ▶ The best atomic states are not simply those with the largest nominal interaction.

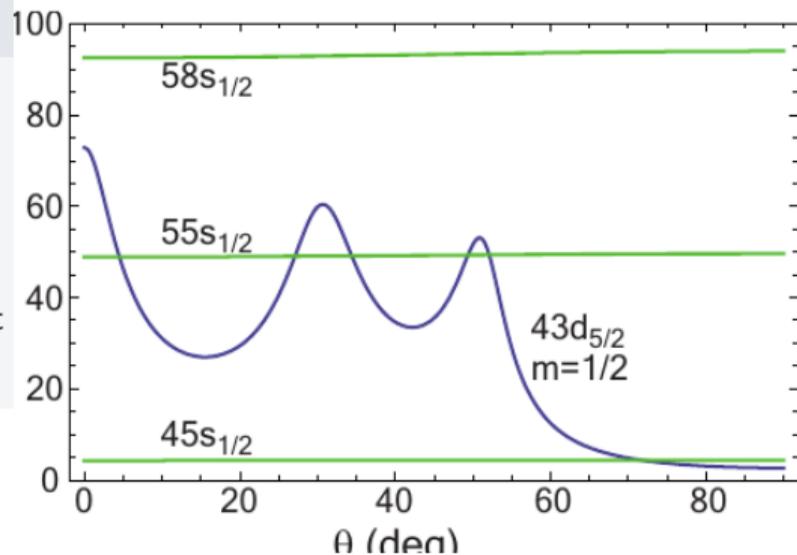


Fig. 10: even at fixed distance, the blockade shift can vary strongly with angle and state choice.

Subtleties: anisotropy, Förster zeros, and field tuning

Not every strong-looking channel is a good blockade channel

- ▶ Zeeman degeneracy creates multiple molecular eigenstates.
- ▶ Some of them are **weakly interacting Förster-zero states**.
- ▶ Because blockade performance depends on an inverse-square average over interaction shifts, a few weak channels can dominate the error budget.

What experimentalists can tune

- ▶ Choose s , p , d states carefully.
- ▶ Use magnetic or electric fields to break degeneracies.
- ▶ Exploit Stark or microwave tuning to approach resonance when desired.

Design rule of thumb

- 1 Maximize interaction strength.
- 2 Minimize angular weak spots.
- 3 Keep laser polarization and geometry aligned with the strongest channels.

Takeaway

The correct question is not “*How large is C_6 ?*” but “*What is the weakest relevant doubly excited channel seen by the laser?*”

3. Gates, error scalings, and scalability

Why blockade gates are attractive, and where the limits come from



Saffman, Walker, and Mølmer, *Rev. Mod. Phys.* **82**, 2313–2363 (2010)

Blockade formalism for an ensemble: the superatom picture

Collective enhancement

For N atoms inside one blockade volume,

$$\Omega_N = \sqrt{N} \Omega.$$

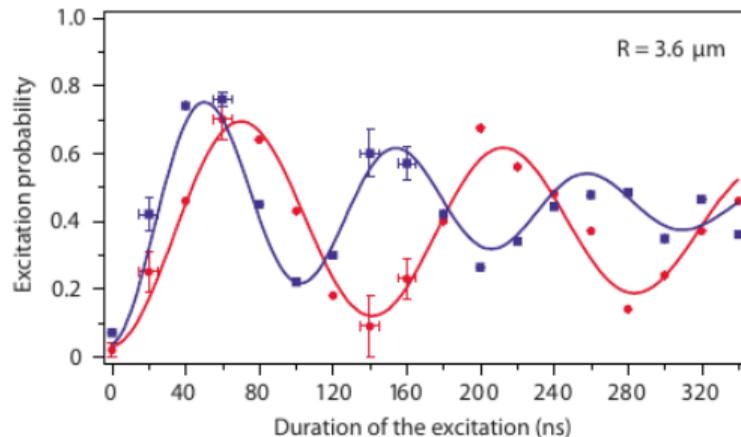
The singly excited symmetric state acts as an effective two-level partner of the collective ground state.

Residual double excitation

In the strong-blockade limit, the paper derives

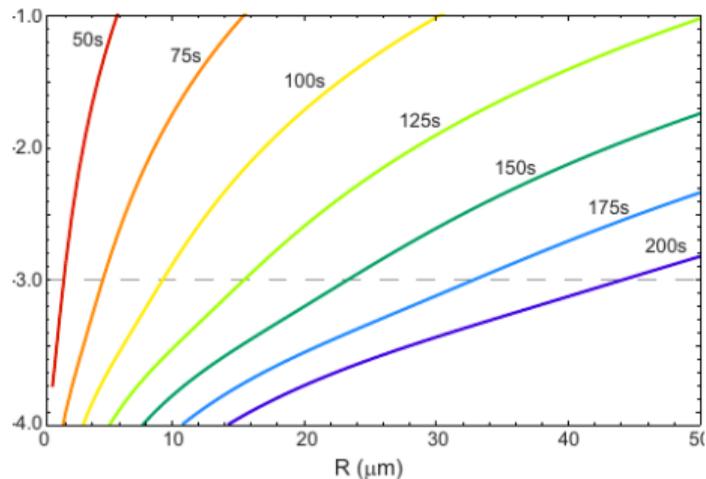
$$P_2 \simeq \frac{N-1}{N} \frac{\Omega_N^2}{2B^2},$$

where B is the effective blockade shift after averaging over all relevant doubly excited channels.



Experimentally, collective oscillations approach the expected $\sqrt{2}$ enhancement for two atoms in blockade.

Intrinsic error of the two-atom blockade gate



Competition that sets the optimum

- ▶ Faster pulses reduce spontaneous emission from the Rydberg state.
- ▶ Slower pulses improve blockade selectivity.
- ▶ Therefore the fidelity is set by a trade-off between lifetime τ and blockade shift B .

Key scaling from the review

$$E_{\min} \propto (B\tau)^{-2/3}.$$

The paper argues that **errors below 10^{-3}** should be realistic in principle.

- ▶ High- n states extend the usable interatomic separation.
- ▶ Technical errors must still be pushed below the intrinsic limit.

Beyond the basic CZ gate

Alternative protocols reviewed in the paper

- ▶ **Interaction gates:** accumulate a phase using direct Rydberg-Rydberg interaction energy.
- ▶ **Amplitude-swap gates:** directly realize a CNOT by conditionally swapping the target amplitudes.
- ▶ **Multi-control gates:** Toffoli and C_k -NOT are especially natural with blockade.

Scalability estimates (van der Waals limit)

For error target E and principal quantum number n ,

$$N_{\max}^{(2D)} \sim C_{2D} E^{1/3} n^{2/3}, \quad N_{\max}^{(3D)} \sim C_{3D} E^{1/2} n.$$

With $n = 100$ and $E = 10^{-3}$, the review quotes about 470 fully connected qubits in 2D and 7600 in 3D.

Interpretation

The promise is not merely *one gate*; it is *long-range, directly connected neutral-atom architectures*.

But the hidden assumptions are strong

- ▶ Reliable loading of one atom per site
- ▶ Site-selective control and measurement
- ▶ Low atom loss and parallel operation
- ▶ Suppression of technical noise to near the intrinsic limit

4. Experimental status in the review

What had been demonstrated by 2010, and why fidelities were still modest



Saffman, Walker, and Mølmer, *Rev. Mod. Phys.* **82**, 2313–2363 (2010)

Experimental ingredients: trapping and coherent excitation

Main hardware requirements

- ▶ Long-lived trapping of single neutral atoms
- ▶ Qubit encoding in ground hyperfine states
- ▶ Rydberg excitation with narrow-linewidth lasers
- ▶ Good control of stray electric and magnetic fields
- ▶ Ideally, traps that perturb ground and Rydberg states similarly

Representative excitation example from the review

For ^{87}Rb $100d_{5/2}$ via $5p_{3/2}$:

- ▶ 780 nm and 480 nm beams
- ▶ $\Omega/2\pi \approx 1.2$ MHz
- ▶ $P_{\text{se}} \approx 5 \times 10^{-4}$
- ▶ $P_{\text{Doppler}} \approx 4 \times 10^{-4}$ at $10 \mu\text{K}$

So sub- 10^{-3} excitation error looked feasible in principle.

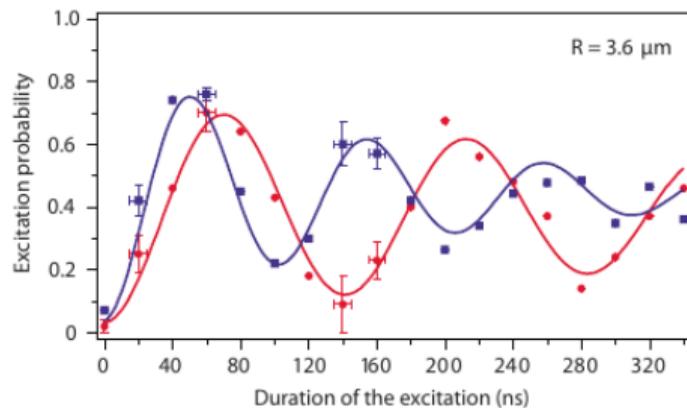
Why experiments still struggled

- ▶ Photoionization when optical traps are left on
- ▶ Imperfect optical pumping and Zeeman selectivity
- ▶ Finite temperature and motional dephasing
- ▶ Laser stability and pulse-area errors
- ▶ Atom loss during the gate sequence

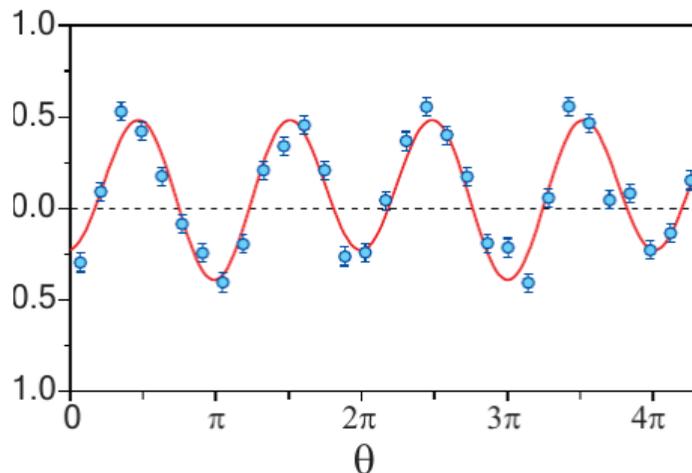
Key message

The review's theoretical story is already strong; the bottleneck is experimental control.

First convincing evidence of blockade and entanglement



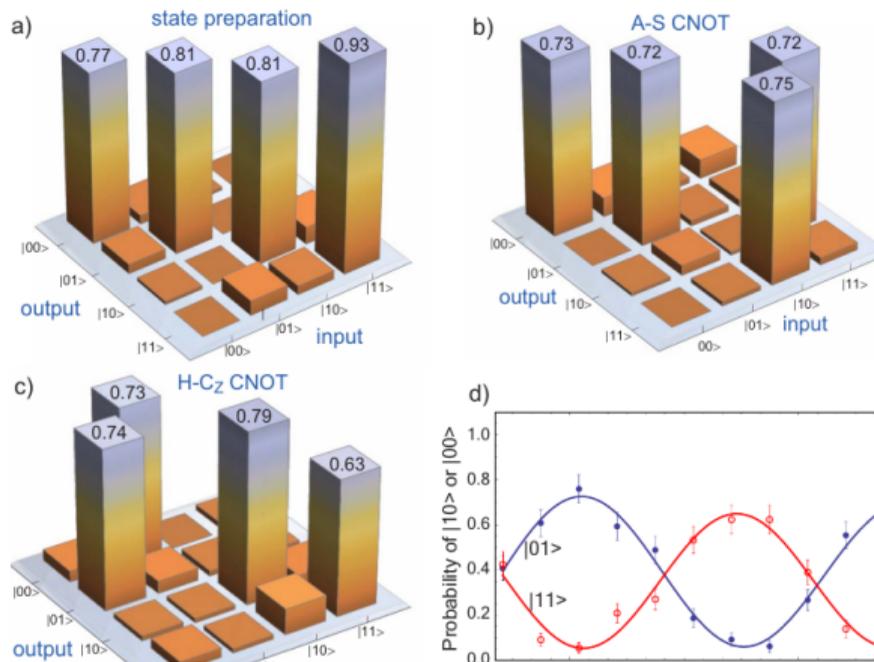
Left: collective Rabi oscillation with two atoms at $R \approx 3.6 \mu\text{m}$.



Right: parity oscillations used to extract two-atom coherence.

- ▶ Blockade led to a symmetric singly excited state and a collective oscillation frequency close to $\sqrt{2}\Omega$.
- ▶ Entanglement was verified through parity oscillations after mapping the Rydberg excitation back to long-lived ground states.
- ▶ The review quotes a raw entanglement fidelity of about $F = 0.46$ in one experiment, but about $F \approx 0.75$ after correcting for atom loss.

First two-qubit CNOT results: important, but still far from the theoretical limit



What Fig. 25 shows

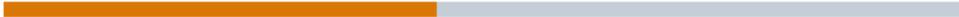
- ▶ State preparation fidelity
- ▶ Amplitude-swap CNOT truth matrix
- ▶ Hadamard-controlled- Z CNOT truth matrix
- ▶ Output oscillations versus phase gap

How the review interprets the data

- ▶ The experiments were the **first neutral-atom two-qubit gate demonstrations**.
- ▶ Deterministic entanglement fidelity was close to, but below, the entanglement threshold without loss correction.
- ▶ Main limitations: technical noise, finite temperature, and atom loss when traps were switched back on.

5. Collective encoding and many-body ideas

Why blockade is bigger than just a two-qubit gate mechanism



Saffman, Walker, and Mølmer, *Rev. Mod. Phys.* **82**, 2313–2363 (2010)

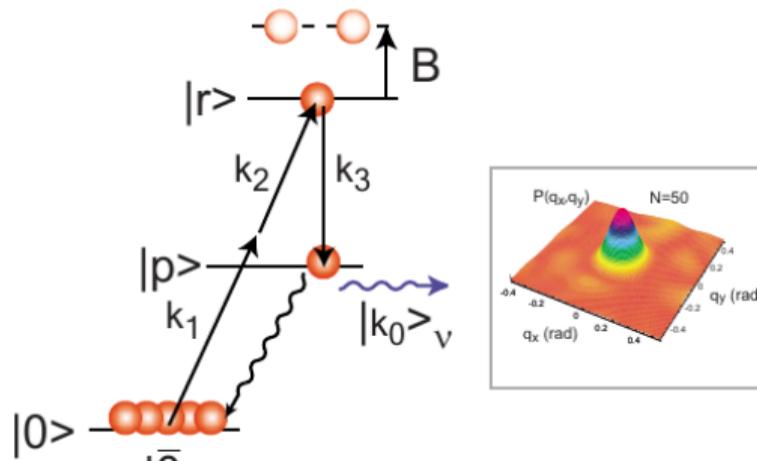
Extended samples: blockade turns many atoms into superatoms

Physical picture

- ▶ Divide a cloud into blockade spheres.
- ▶ Each sphere supports at most one Rydberg excitation.
- ▶ Excitation statistics become **sub-Poissonian**.
- ▶ Coherent driving produces collective oscillations and nonlinear response.

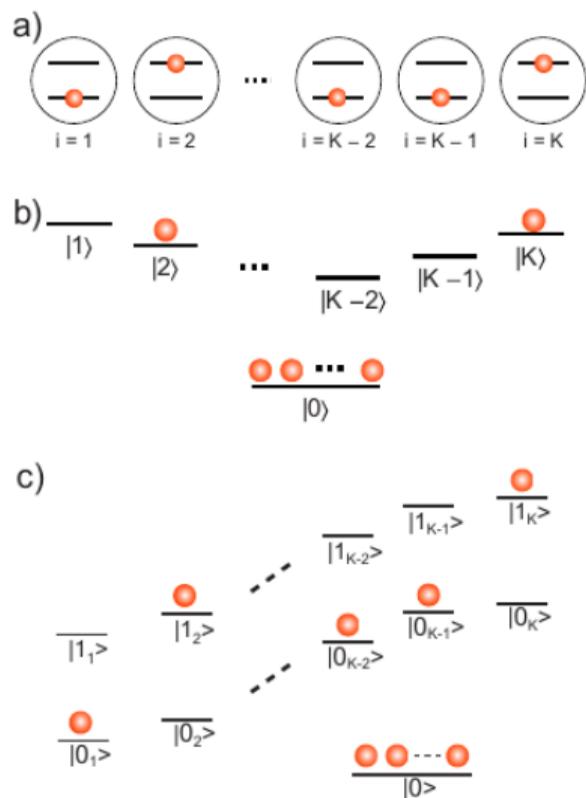
Why this is useful

- ▶ Deterministic preparation of single collective excitations
- ▶ Ensemble qubits without deterministic single-atom loading
- ▶ A bridge between quantum computing and quantum optics



Blockade can prepare a symmetric singly excited state whose decay emits a phase-matched photon.

Collective qubit encoding: one ensemble, many logical qubits



Encoding concept (Fig. 33)

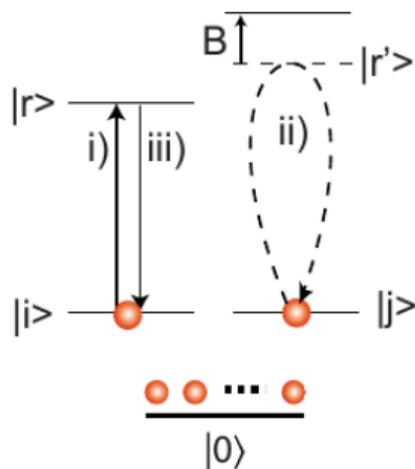
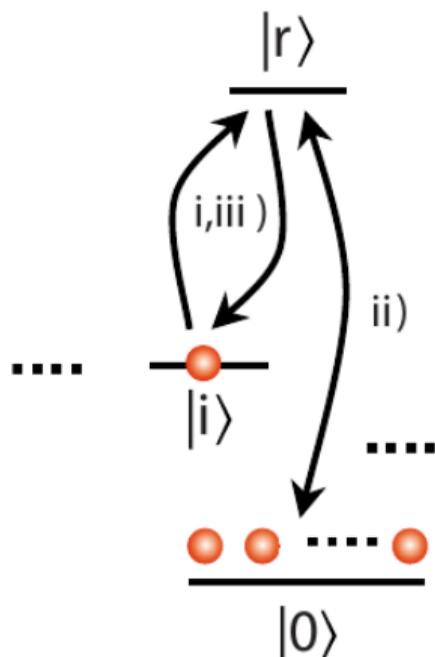
Instead of storing one qubit per atom, store a register in symmetric population patterns across many internal levels of an ensemble.

- ▶ Conventional encoding: K separate two-level systems.
- ▶ Collective encoding: one ensemble of $(K + 1)$ -level or $(2K + 1)$ -level atoms.
- ▶ Logical bit values are represented by whether a given level pair has zero or unit symmetric population.

Why this is appealing

It removes the strict need for one atom per site and exploits the symmetry naturally enforced by blockade.

How single- and two-qubit gates work in the collective scheme



Two-qubit gate by blocking a target transfer in the presence of a control excitation.

Single-qubit rotation through a temporary Rydberg excitation.

- ▶ The logic is closely analogous to the individual-atom blockade gate.
- ▶ The resource state $|0\rangle$ of the ensemble acts as a reservoir that enables collective enhancement.
- ▶ The price is increased complexity in internal-state control and error management.

How far does the review push collective ideas?

Ambitious proposal inside the review

A “1000-bit collectively encoded computer” is discussed as a conceptual architecture, especially with Cs and many accessible internal states.

Many-particle entanglement

- ▶ **Spin squeezing:** use blockade-assisted pair transfer processes to reduce collective spin variance.
- ▶ **GHZ states:** adiabatic or interaction-asymmetry-based protocols create macroscopically entangled states.

Important caveats stressed by the review

- ▶ Precise knowledge of atom number can matter.
- ▶ Collisions and inhomogeneity reduce coherence.
- ▶ Large numbers of lasers and internal transitions are required.
- ▶ The proposal is conceptually elegant, but experimentally demanding.

My reading

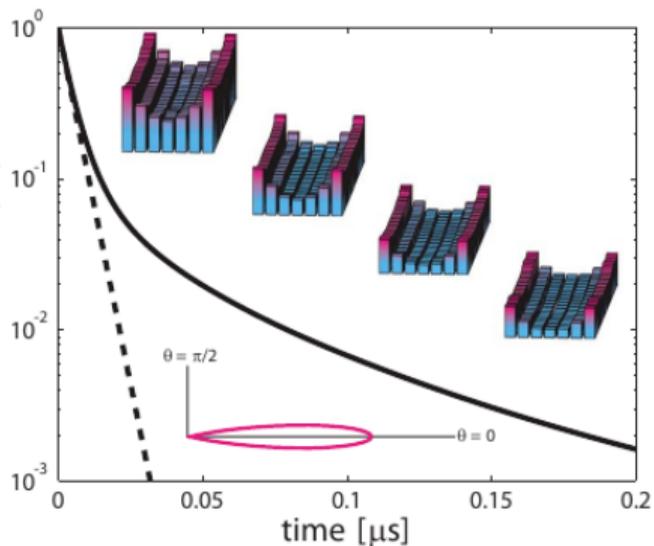
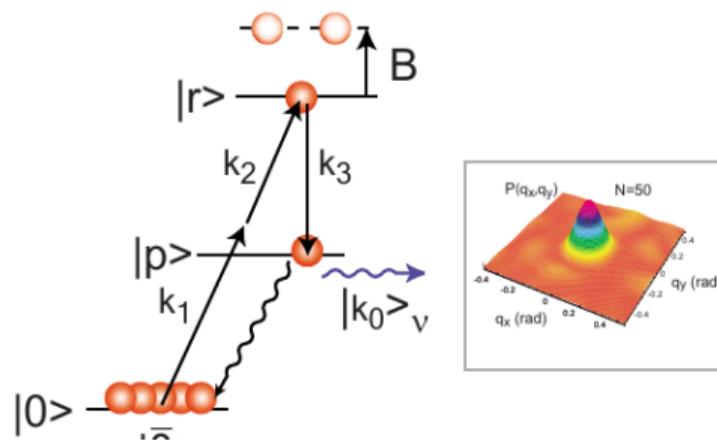
The review is strongest when arguing that blockade creates new *control primitives*; the most speculative part is the very large collective register architecture.

6. Quantum optics and interfaces

From collective excitations to photons, memories, and communication

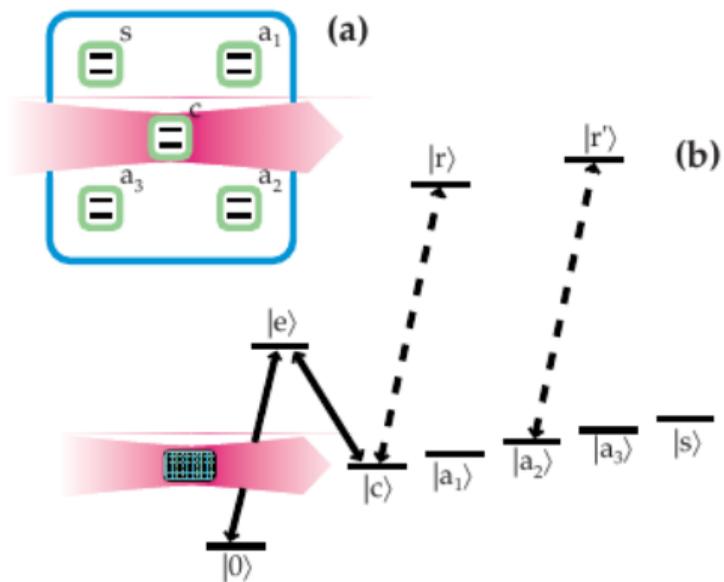
Saffman, Walker, and Mølmer, *Rev. Mod. Phys.* **82**, 2313–2363 (2010)

Cooperative single-photon emission: blockade meets phase matching



- ▶ First, blockade prepares a symmetric single collective excitation.
- ▶ Then a control pulse maps it to an optical excitation with phase $\mathbf{k}_0 = \mathbf{k}_1 + \mathbf{k}_2 - \mathbf{k}_3$.
- ▶ The resulting spontaneous emission is **directional**: the photon exits in a narrow cone determined by phase matching and collective interference.
- ▶ In the example simulated in the review, more than 95% of the photon probability lies within about 0.3 rad of the sample axis.

Quantum communication with small blockaded registers



Register-level viewpoint

A small Rydberg-blockaded ensemble can contain

- ▶ a communication qubit,
 - ▶ a storage qubit,
 - ▶ and several auxiliary qubits,
- all inside one collective register.

Protocol idea

- ▶ Emit a directional photon from one node.
- ▶ Absorb the time-reversed mode at another node.
- ▶ Use the internal auxiliary qubits for entanglement pumping and error reduction.

Broader message

Rydberg physics is not only for local gates; it also offers a deterministic interface between matter qubits and photonic channels.

Other interface ideas surveyed by the review

Hybrid and alternative paradigms

- ▶ Coupling Rydberg atoms to microwave resonators
- ▶ Cavity-QED approaches with long-lived circular Rydberg states
- ▶ Using Rydberg interactions for nonlinear optical media and photon-photon gates
- ▶ Connections to quantum simulation of long-range interacting many-body systems

Conceptual unification

The review treats Rydberg excitation as a universal interaction resource that can couple

atoms \leftrightarrow atoms \leftrightarrow light

across very different architectures.

Why this section matters

It broadens the paper from a *gate review* into a *platform review*.

7. Assessment and takeaways

How to frame this paper in a group meeting

Saffman, Walker, and Mølmer, *Rev. Mod. Phys.* **82**, 2313–2363 (2010)

How I would evaluate the paper's contribution

Why this review is influential

- ▶ It gave a coherent physics-to-architecture story.
- ▶ It connected microscopic interaction theory to gate error models.
- ▶ It did not stop at two-qubit gates: ensembles, photons, and many-body physics were already integrated into the narrative.

Its strongest claims

- ▶ Blockade is robust and flexible.
- ▶ Intrinsic gate errors should be well below what experiments had reached by 2010.
- ▶ Ensemble blockade enables qualitatively new primitives, not just quantitative speedups.

What to discuss critically

- ▶ Many proposals assume extremely clean state selectivity and atom-number control.
- ▶ Förster zeros and angular weak spots complicate the naive blockade picture.
- ▶ The gap between theoretical fidelity and measured fidelity was still very large at the time of the review.
- ▶ Collective encoding is elegant but operationally complex.

Best discussion question

Is the long-term strength of Rydberg platforms their *local digital gate model*, or their *hybrid role across gates, optics, and analog many-body physics*?

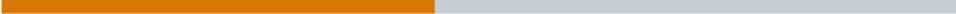
Final take-home messages

- 1 **Rydberg excitation makes neutral atoms strongly interacting on demand.**
- 2 **Blockade is the central primitive:** it explains two-qubit gates, superatoms, collective encoding, and deterministic single-excitation optics.
- 3 **Theoretical performance looked excellent already in 2010,** with intrinsic error estimates below 10^{-3} .
- 4 **The practical challenge was control, not principle:** trapping, excitation, state selectivity, and atom loss dominated the experiments.
- 5 **The review's lasting value is breadth:** it frames Rydberg atoms as a quantum-information platform, not only a gate mechanism.

Thank you!

Backup

Optional slides for Q&A or if you want to extend beyond 45 minutes



Saffman, Walker, and Mølmer, *Rev. Mod. Phys.* **82**, 2313–2363 (2010)

Backup: a compact timeline you can say out loud

A clean spoken narrative

- 1 Neutral atoms are excellent memories but weakly interacting.
- 2 Rydberg excitation provides strong, long-range, switchable interactions.
- 3 Blockade turns that interaction into a gate mechanism.
- 4 The same blockade physics creates collective excitations and superatoms.
- 5 Those collective excitations naturally interface with directional photons.
- 6 Therefore one platform spans digital gates, ensemble logic, and quantum optics.

If you need to shorten the talk

Skip the collective-register implementation details (Figs. 33, 35, 36) and keep the talk centered on blockade, experiments, and photon interfaces.

Backup: selected quantitative numbers worth remembering

Quantity	Value / statement in the review
Interaction contrast	About 10^{12} between ground-state and Rydberg-mediated interactions at the crossover scale for Rb 100s
Typical lifetime trend	For $n \gtrsim 50$, low- ℓ Rydberg lifetimes exceed about $50 \mu\text{s}$ at room temperature
Blockade-gate optimum error	$E_{\min} \propto (B\tau)^{-2/3}$
Scalability estimate	For $n = 100$ and $E = 10^{-3}$: about 470 connected qubits in 2D, 7600 in 3D
Excitation example	For $^{87}\text{Rb } 100d_{5/2}$: $P_{\text{se}} \sim 5 \times 10^{-4}$ and $P_{\text{Doppler}} \sim 4 \times 10^{-4}$
Directional emission example	More than 95% emission probability within about 0.3 rad of the axis in the simulated elongated sample

Backup: figures used in this deck

- ▶ Fig. 1: interaction strength versus distance
- ▶ Fig. 2: blockade gate pulse sequence
- ▶ Fig. 4: phase-matched single-photon emission
- ▶ Fig. 6: Rydberg lifetimes
- ▶ Fig. 10: angular dependence of blockade shift
- ▶ Fig. 14: intrinsic blockade gate error
- ▶ Fig. 23: collective Rabi oscillation
- ▶ Fig. 24: parity oscillation
- ▶ Fig. 25: CNOT data
- ▶ Fig. 33: collective encoding schemes
- ▶ Fig. 35: single-qubit gate in an ensemble
- ▶ Fig. 36: two-qubit gate in an ensemble
- ▶ Fig. 39: cooperative directional emission
- ▶ Fig. 40: small-register quantum communication