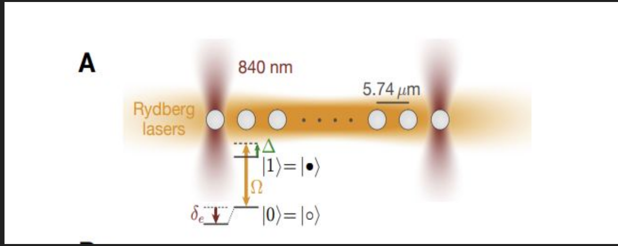
Rydberg Atom Cat States

ECE405 - Arjun Kulkarni

Background: Rydberg Atoms & Cat States

What are Rydberg atoms?

- Neutral atoms excited to high principal quantum number
- Huge dipole moments $\longrightarrow$ strong, long-range interactions
- Enable fast entanglement through Rydberg blockade



What is a Schrödinger cat / GHZ state?

$$|GHZ_N\rangle = \frac{1}{\sqrt{2}}(|0101\ldots\rangle + |1010\ldots\rangle)$$

A macroscopic superposition—extremely fragile and highly entangled.

Why they matter: Ultimate test of quantum coherence. Resource for metrology, error correction, and quantum networking

Fig. 1A (Rydberg energy levels & addressing beams)

Why This Problem Matters

Macroscopic superpositions are hard but essential:

- Enable Heisenberg-limited sensing
- Provide error-correcting “cat qubits”

Rydberg arrays are a promising platform:

- Programmable geometry
- Collective excitation + blockade → natural GHZ generator

What was missing before this paper:

- Large GHZ (>10 qubits) with high fidelity
- Controlled manipulation of these states (phases, distribution)

What the Paper Contributes

Creates GHZ cat states up to N = 20 qubits

Using optimized many-body control pulses (RedCRAB), they achieve:

- Combined GHZ population: 0.78 (inferred)
- Coherence amplitude: 0.30
- GHZ fidelity: ≥ 0.542(18) ⟶ meets N-partite entanglement threshold.

Introduces an optimal-control protocol

- Shapes laser detuning $\Delta(t)$ and Rabi frequency $\Omega(t)$
- Outperforms adiabatic ramps
- Creates entanglement near theoretical speed limits

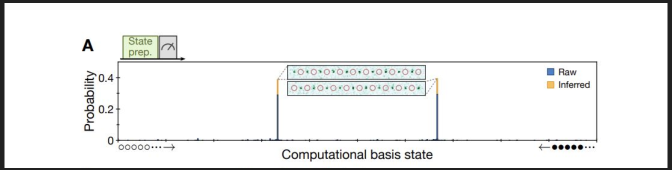


Fig 2a: (20-atom GHZ population)

Technical Method

How GHZ states are generated:

1. Prepare all atoms in $|0\rangle$
2. Apply global Rydberg laser with time-dependent:
   - $\Omega(t)$: Rabi frequency
   - $\Delta(t)$: detuning
3. Use Rydberg blockade + tailored detuning sweep $\longrightarrow$ ground state follows into GHZ superposition
4. Local edge light shifts (δ_e) suppress undesired states
5. Optimal-control pulses (RedCRAB) exploit controlled diabetic transitions

How GHZ phase is measured:

- Apply staggered field δ□ to induce phase φ = Nδ□t
- Measure parity oscillations after U_x rotation

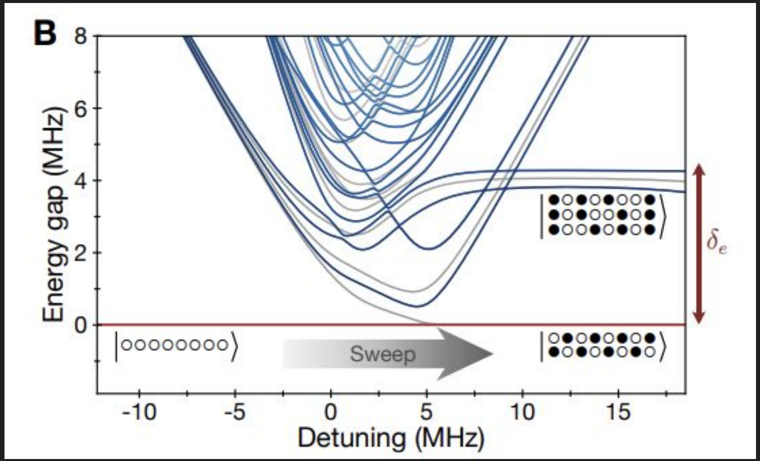


Fig. 1B (energy spectrum & adiabatic path)

How This Work Transforms the Field

A hardware benchmark:

- GHZ fidelity > 0.5 across N = 4–20
- Demonstrates coherent, programmable many-body control

Advances toward scalable quantum tech:

- Entanglement distribution = step toward quantum repeaters / networks
- GHZ as resource for metrology and error correction
- Shows Rydberg arrays can compete with superconducting and ion-trap platforms

Key insight:

- Rydberg systems can create and manipulate large entangled states in microseconds, which is faster than most competing technologies.

Critical Discussion

Limitations:

Coherence limited by:

- Doppler shifts
- Rydberg lifetime (~150 μs)
- Laser phase noise
- Imperfect detection

Competing platforms:

- Trapped ions: Very coherent but slower
- Superconducting circuits: GHZ up to 20 qubits (parallel 2019 papers)
- Microwave cavity photons: Large cat states but different architecture

Final Reflection

If I had learned only one important thing from this paper, it is that:

- Optimal control + Rydberg blockade enables fast, large-scale Schrödinger cat states, proving that Rydberg arrays are a competitive platform for scalable quantum entanglement.