CU CZ

FROM ZERO TO QUERO

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THE ABSTRACTION GAP

Where Existing CZ Gate Visualizations Fall Short:

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

- *CZ Gates*
- *Static energy-level diagrams*
- *Bloch spheres showing final phase differences*

Existing Assumptions:

- Phase accumulation is already understood
- Intermediate dynamics are not critical
- Population vs phase distinction is implicit

What remains hidden:

- When the phase accumulates
- Why |01⟩ and|11⟩ behave differently under the same pulse
- How blockade alters the effective Hamiltonian
- The fact that states return to themselves while still entangling

HOW WE'RE ADDRESSING THE GAP:

Dynamic Blockade: Show time-dependent blockade and intermediate Rydberg populations to reveal gradual entanglement.

Phase Evolution: Track phase accumulation continuously during the pulse, highlighting contributions from different intervals.

State-Dependent Dynamics: Illustrate why |01⟩ and |11⟩ respond differently to conditional Hamiltonians and instantaneous energy shifts.

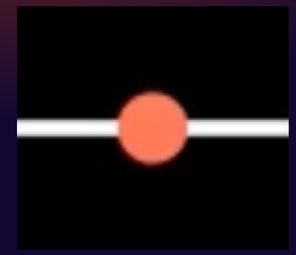
Hamiltonian Insight: Visualize instantaneous eigenenergies and dressed-state interactions to link dynamics with final CZ phase.

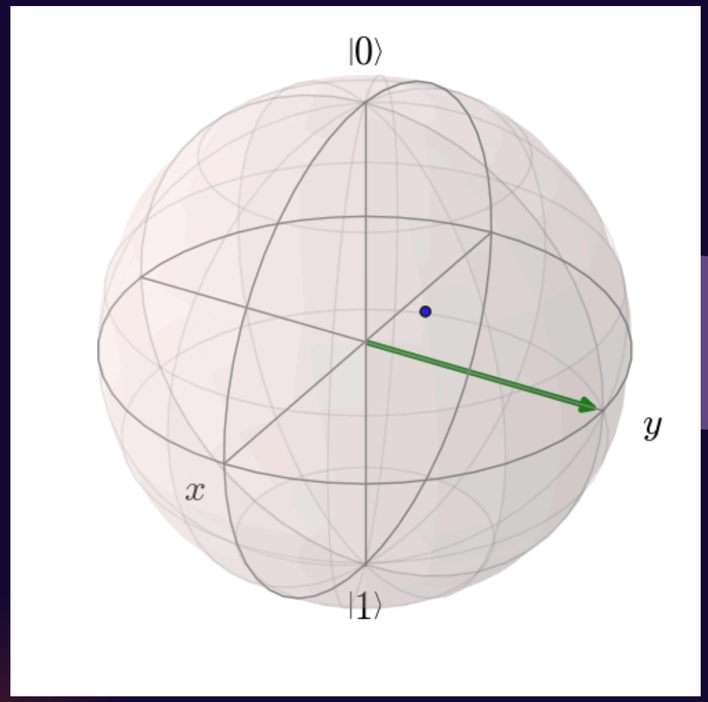
Blockade–Phase Connection: Relate blockade strength and pulse parameters directly to conditional phase and entanglement fidelity.

VISUALIZATION CHOICES

We chose to represent:

- Electrons with oscillating superpositions are represented as circles with a halo. The phase accumulation is represented by the total rotation of its accompanying arrow.
- North and south poles mark the relevant computational states, where labels connect the trajectory to the instantaneous state in the system.
- A dot at the south pole marks the initial state, followed by a thin line that traces the dot's trajectory, showing the state's evolution over time.
- A time indicator on the right synchronizes and guides the viewer through the dynamics.

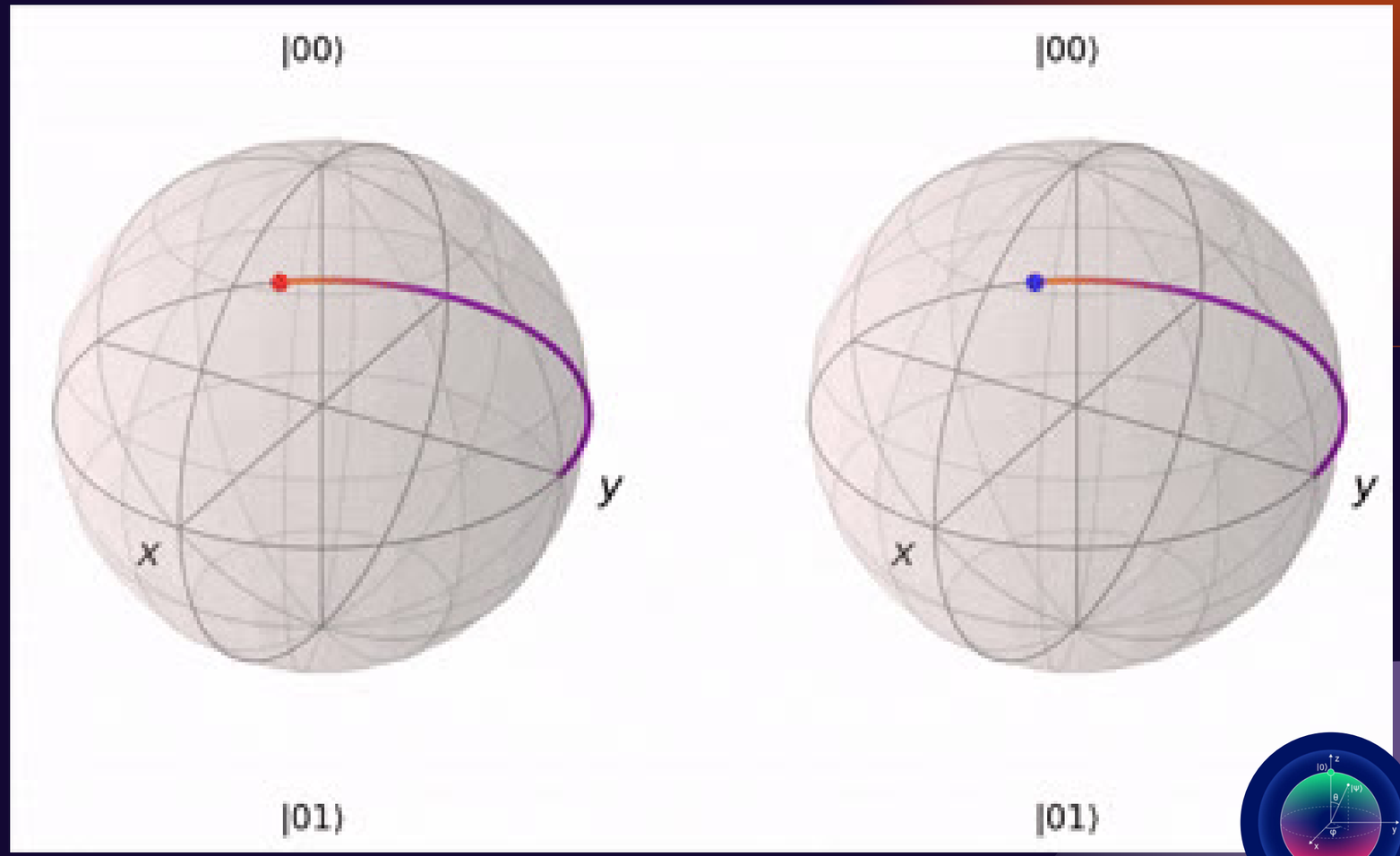




SINGLE QUBIT PHASE

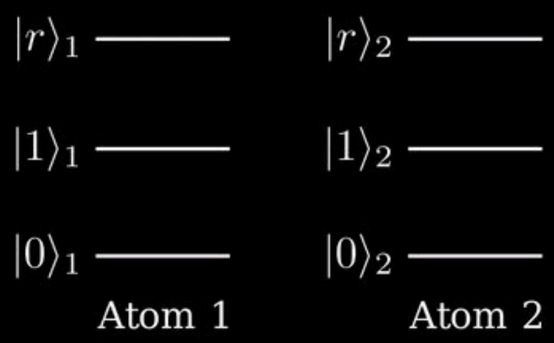
- The phases on |01⟩ and |10⟩ are single-qubit Z rotations
- The extra −π on |11⟩ is the entangling resource
- The CZ gate is defined only up to local Z rotations

$$
\begin{aligned}
|00\rangle &\rightarrow |00\rangle \\
|01\rangle &\rightarrow |01\rangle e^{i\phi} \\
|10\rangle &\rightarrow |10\rangle e^{i\phi} \\
|11\rangle &\rightarrow |11\rangle e^{i(2\phi-\pi)}
\end{aligned}
$$

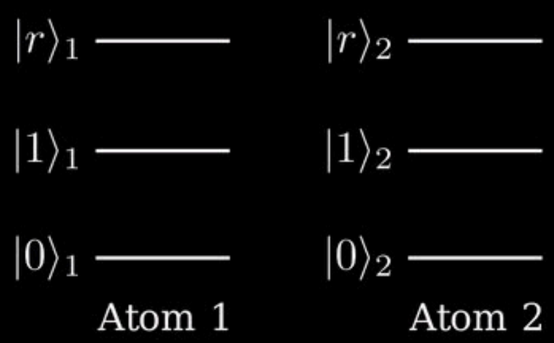


(Levine, Keesling et. al., 2019)

|11>



|10>



ENERGY LEVEL DYNAMICS

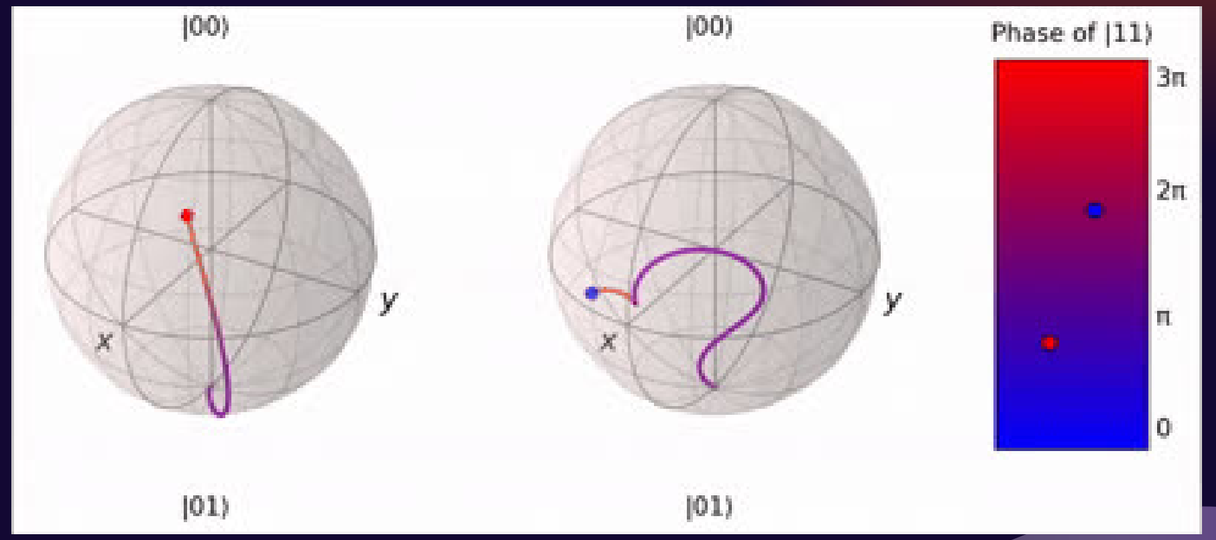
- Each column represents a Rubidium atom with a single valence electron.
- When a Raman laser is used to couple the |1> ground state and the Rydberg (|r>) State, the electron's superposition oscillates between the two according to its Rabi Frequency.
- The electron's superposition does not fully reach the Rydberg State in the |11> configuration due to Rydberg Blockading.
- The |11> configuration oscillates at a rate of $2^{(1/2)}$ times the oscillation in |10>, and the same ratio applies for its phase accumulation.

(Urban, Johnson, et. al., 2009)

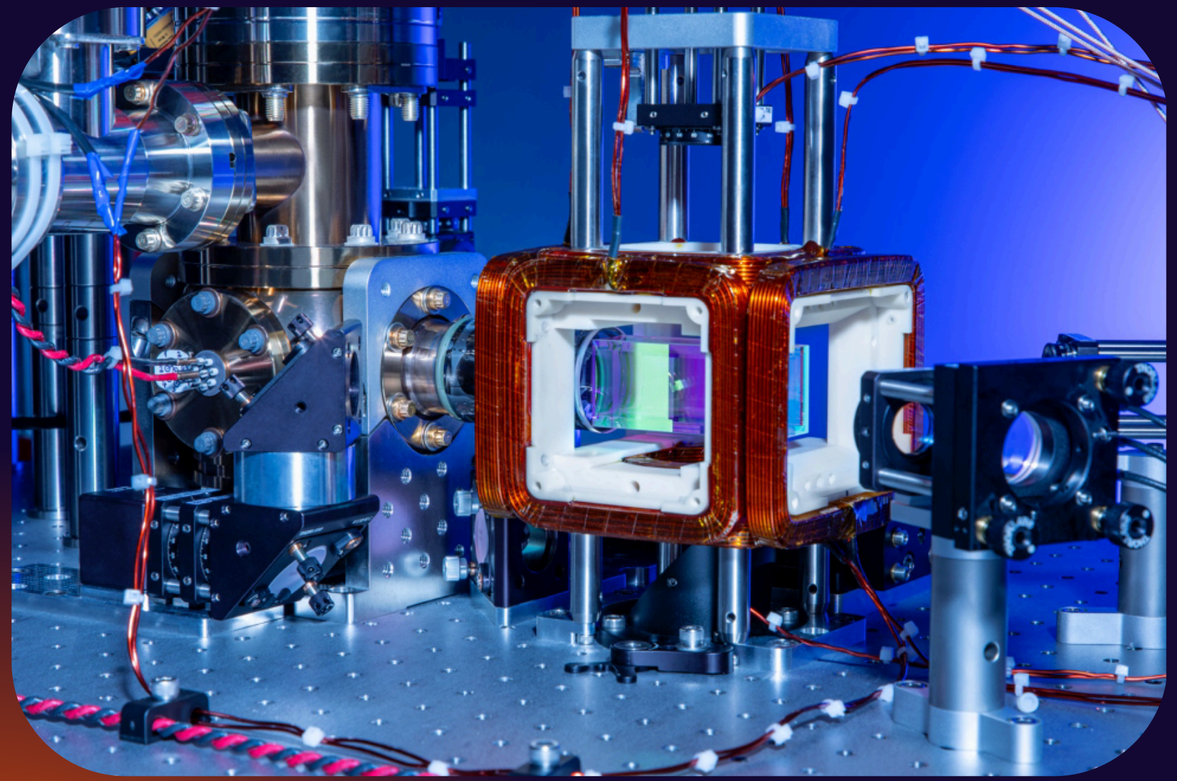
(Bosch, Wimberger, 2025)

BLOCH SPHERE PHASE ACCUMULATION

- Phase evolution can be visualized as motion around the Bloch sphere
- States return to the same population while accumulating a non-zero phase
- Different computational states follow different trajectories
- These trajectory differences generate the CZ gate
- The two spheres correspond to different computational states experiencing different effective Hamiltonians:
  - For states like |01⟩, the atom evolves as an isolated driven system and accumulates a phase e^iϕ.
  - For |11⟩, the Rydberg interaction modifies the energy landscape, changing the trajectory and causing additional phase accumulation.



$$H(t) = \sum_{i=1}^{2} \left[\frac{\Omega(t)}{2} \left(|r\rangle\langle 1|_i + |1\rangle\langle r|_i \right) - \Delta(t) \, |r\rangle\langle r|_i \right] + V \, |rr\rangle\langle rr|$$



INDUSTRY RELEVANCE

- The two spheres correspond to different computational states experiencing different effective Hamiltonians:
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FUTURE DIRECTIONS

REAL INPUT VARIABLES

- We can create our models to be time-dependent on the Rabi Frequency (Omega) and the detuning parameter (Delta).
- We can also create our live time evolutions so they are actually dependent on the Hamiltonian.

3D-MODELING

- Reproduce the project in a 3D Blender environment and allow users to interact with the model.

EXPANSION TO OTHER CIRCUITS

- Create a visualization of the W state.
- Implement the idea and visualizations of double-qubit CZ gates to Multi-Controlled Phase Gates (CCZ, CkZ).

THANK YOU

QUACKERS + QUERA @ MIT IQUHACK