LETTER

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To catch and reverse a quantum jump mid-flight

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In quantum physics, measurements can fundamentally yield discrete and random results. Emblematic of this feature is Bohr's 1913 proposal of quantum jumps between two discrete energy levels of an atom[1]. Experimentally, quantum jumps were first observed in an atomic ion driven by a weak deterministic force while under strong continuous energy measurement[2–4]. The times at which the discontinuous jump transitions occur are reputed to be fundamentally unpredictable. Despite the non-deterministic character of quantum physics, is it possible to know if a quantum jump is about to occur? Here we answer this question affirmatively: we experimentally demonstrate that the jump from the ground state to an excited state of a superconducting artificial three-level atom can be tracked as it follows a predictable 'flight', by monitoring the population of an auxiliary energy level coupled to the ground state. The experimental results demonstrate that the evolution of each completed jump is continuous, coherent and deterministic. We exploit these features, using real-time monitoring and

First, we developed a superconducting artificial atom with the necessary V-shaped level structure (see Fig. 1a and Methods). It consists, besides the ground level $|G\rangle$, of one protected, dark level $|D\rangle$—engineered to couple only minimally to any dissipative environment or any measurement apparatus—and one ancilla level $|B\rangle$, whose occupation is monitored at rate Γ. Quantum jumps between $|G\rangle$ and $|D\rangle$ are induced by a weak Rabi drive Ω_{DG}—although this drive can eventually be turned off during the jump, as explained later. Because a direct measurement of the dark level is not feasible nor desired, the jumps are monitored using the Dehmelt shelving scheme[2]. Thus, the occupation of $|G\rangle$ is linked to that of $|B\rangle$ by the strong Rabi drive Ω_{BG} ($\Omega_{DG} \ll \Omega_{BG} \ll \Gamma$). In the atomic physics shelving scheme[2–4], an excitation to $|B\rangle$ is recorded by detecting the emitted photons from $|B\rangle$ with a photodetector. From the detection events—referred to in the following as 'clicks'—one infers the occupation of $|G\rangle$. On the other hand, from the prolonged absence of clicks (to be defined precisely below; see also Supplementary Information section II), one infers that a quantum jump

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Biography

1982: PhD, Paris University
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1984: Professor at CEA-Saclay

2002- : F. W. Beinecke Professor at Yale,
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Research interest

quantum superconducting tunnel junction circuits and their applications to information processing

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Quantum jump

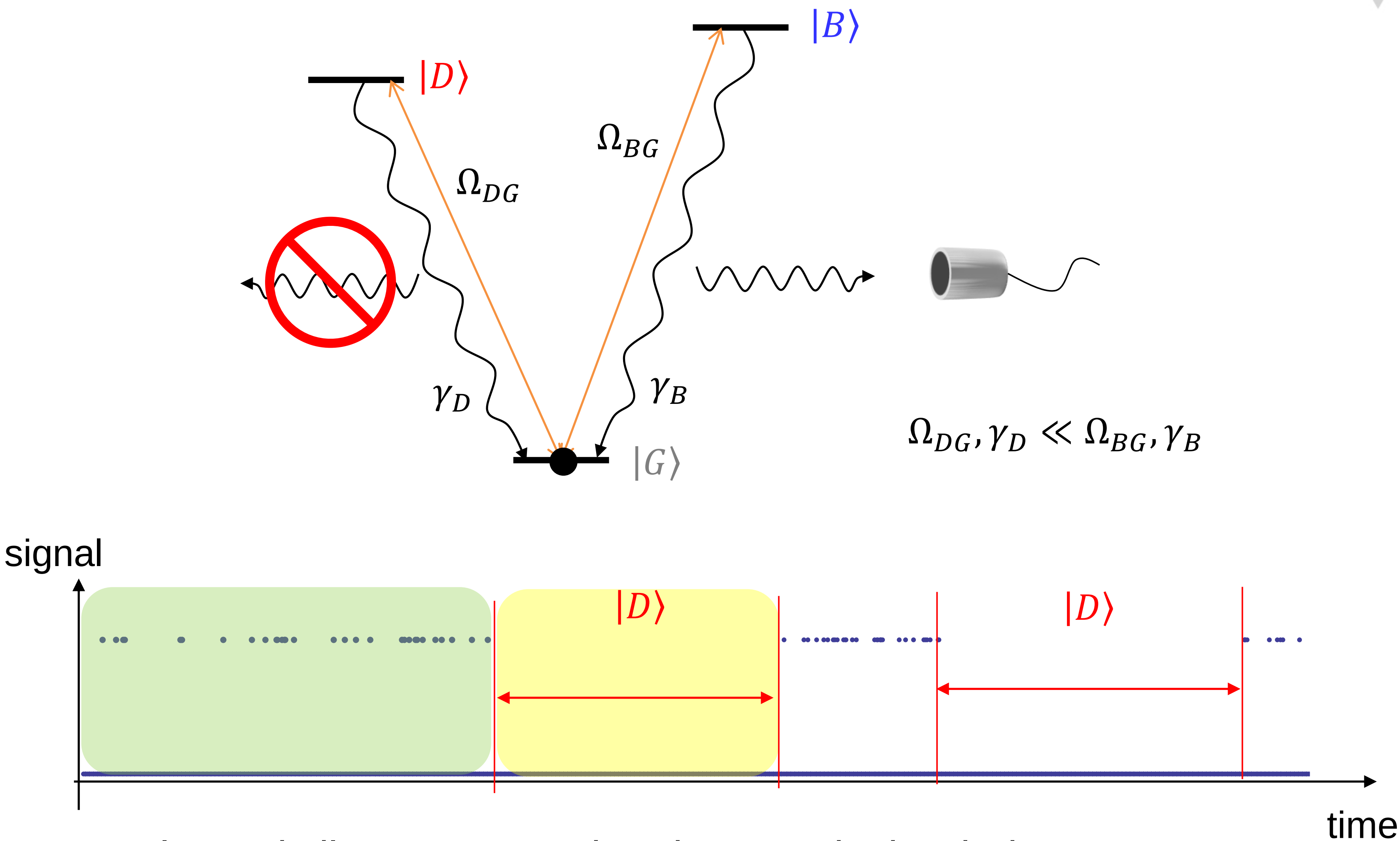
The famous physicist Niels Bohr first conceived of the notion of quantum jumps, or quantum leaps, in 1913. Bohr understood quantum jumps as objective events in which **an atom emits or absorbs a photon, causing an electron to jump** from one energy level – or quantum state – to another inside the atom. But a few decades later, when physicists began to understand how the act of measuring can affect the result in quantum mechanics, the assumed objectivity of quantum jumps required a second look.

Then in the early 1990s, physicists developed quantum trajectory theory, showing that **quantum jumps are not caused by the emission of a photon, but by the detection of a photon**. If an emitted photon is not detected, then there is no quantum jump. In other words, quantum jumps are detector-dependent, which is in marked contrast to Bohr's objective emission events.

Quantum jumps represent the collapse of the wave function due to a measurement.

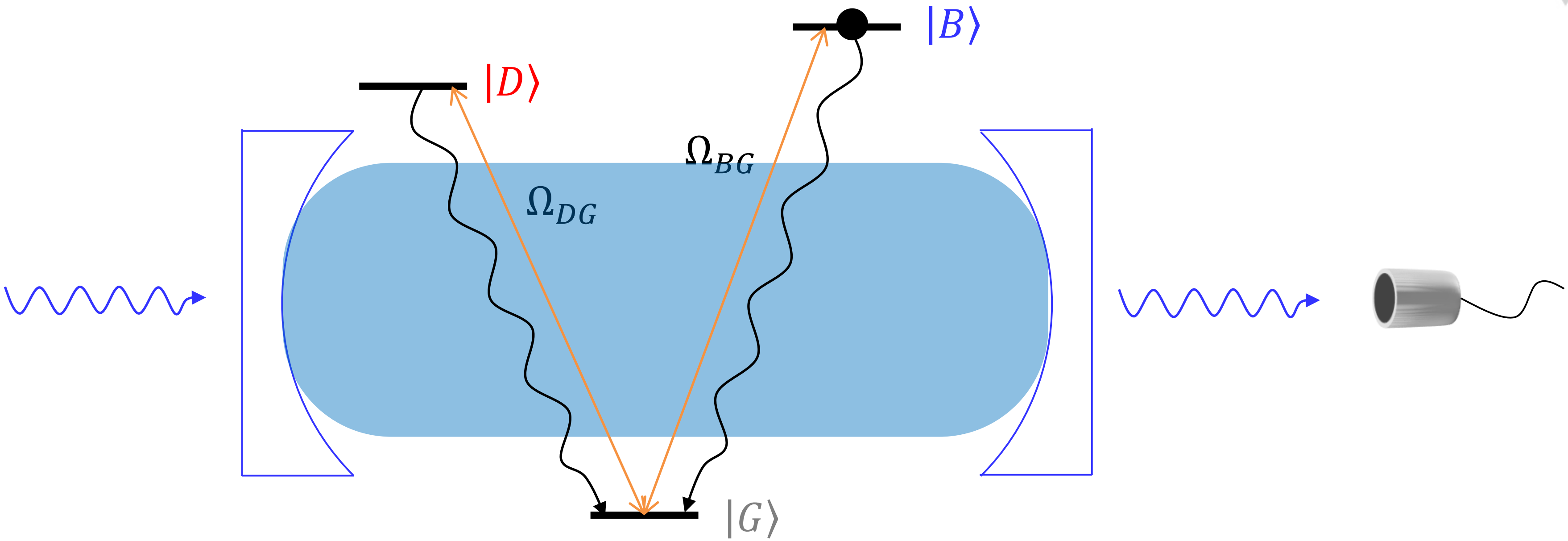
https://phys.org/news/2012-06-quantum-events.html

Monitoring quantum jumps



Prolonged silence means that the state is the dark state

Indirect detection

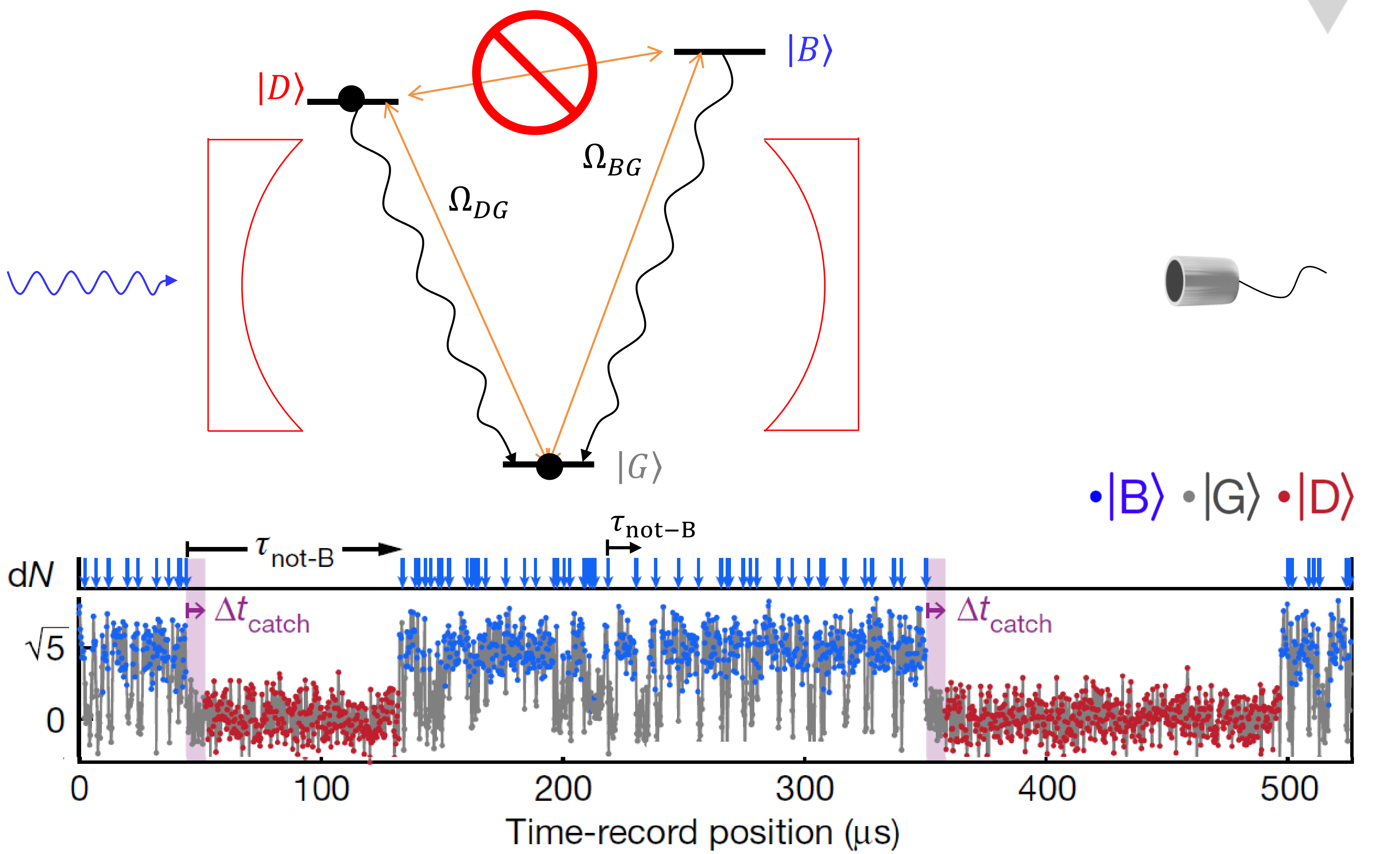


$$\hat{H}/\hbar = \omega_B \hat{b}^\dagger \hat{b} + \omega_D \hat{d}^\dagger \hat{d} + \left(\omega_C + \chi_B \hat{b}^\dagger \hat{b}\right)\hat{c}^\dagger \hat{c}$$

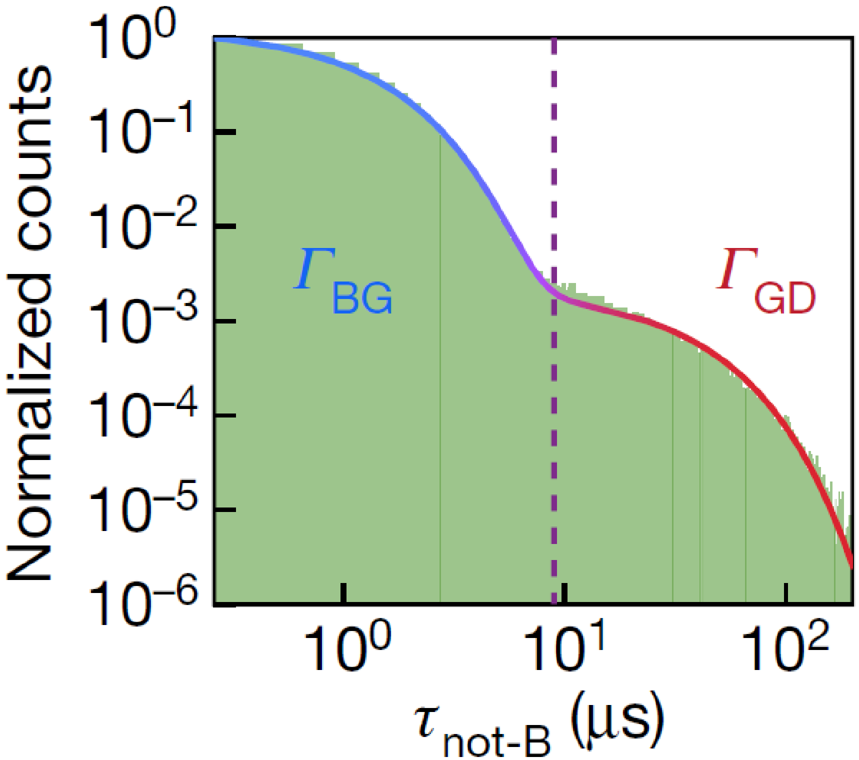
$\omega_B \,/\, 2\pi = 5570.349MHz$
$\omega_D \,/\, 2\pi = 4845.255\text{MHz}$
$\omega_C \,/\, 2\pi = 8979.64\text{MHz}$

Resonance frequency of the cavity depends on the state of the atom

Indirect detection



The histogram of τ_{not-B}

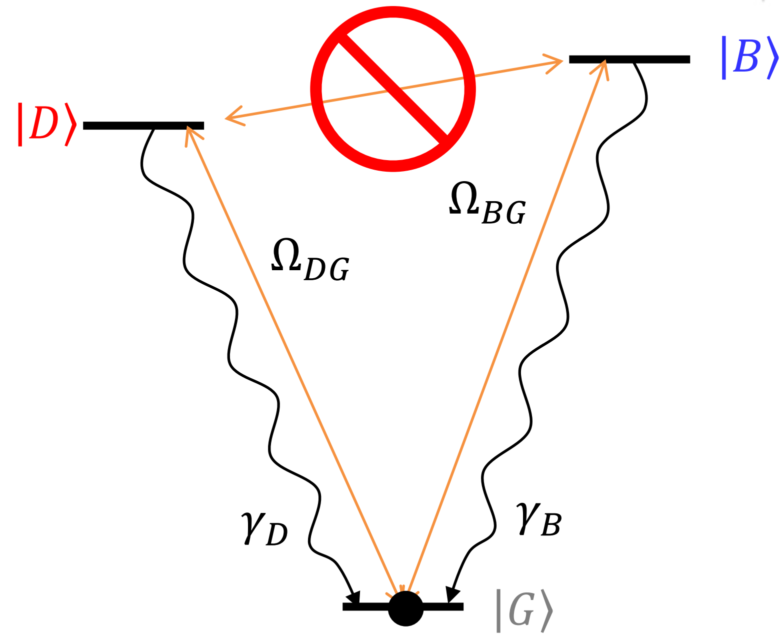


On average, the time spent in the G state is $1\mu s$

State evolution without signal

$$|\psi\rangle = C_G|G\rangle + C_B|B\rangle + C_D|D\rangle$$

$$C_G(0) = 1, C_B(0) = C_D(0) = 0$$



$$\frac{d}{dt}\begin{pmatrix} C_G \\ C_B \\ C_D \end{pmatrix} = \frac{1}{2}\begin{pmatrix} 0 & -\Omega_{BG} & -\Omega_{DG} \\ \Omega_{BG} & -\gamma_B & 0 \\ \Omega_{DG} & 0 & \cancel{-\gamma_D} \end{pmatrix}\begin{pmatrix} C_G \\ C_B \\ C_D \end{pmatrix}$$

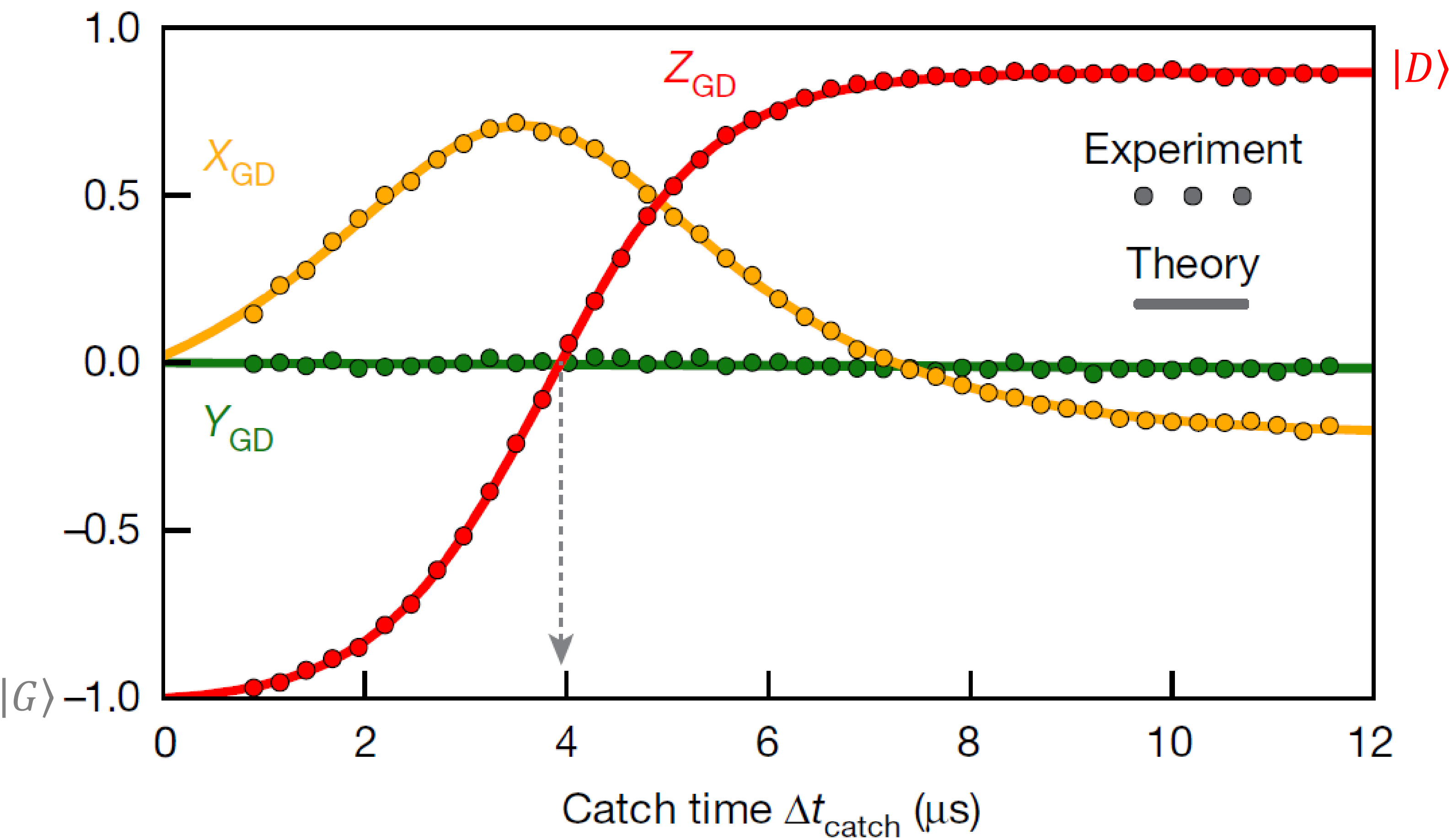
$$\dot{C}_B = 0 = \Omega_{BG} C_G - \gamma_B C_B$$

$$|\psi\rangle = \exp\left(-\frac{\Omega_{BG}^2}{2\gamma_B}t\right)\left(|G\rangle + \frac{\Omega_{BG}}{\gamma_B}|B\rangle\right) + \left[\exp\left(-\cancel{\frac{\gamma_D}{2}}t\right) - \exp\left(-\frac{\Omega_{BG}^2}{2\gamma_B}t\right)\right]\frac{\gamma_B \Omega_{DG}}{\Omega_{BG}^2}|D\rangle$$

$$C_D/C_G = \frac{\Omega_{DG}}{\Omega_{BG}^2 \,/\, \gamma_B}\left[\exp\left(\frac{\Omega_{BG}^2}{2\gamma_B}t\right) - 1\right]$$

$\left(\frac{\Omega_{BG}^2}{2\gamma_B}\right)^{-1}$: the mean time between clicks

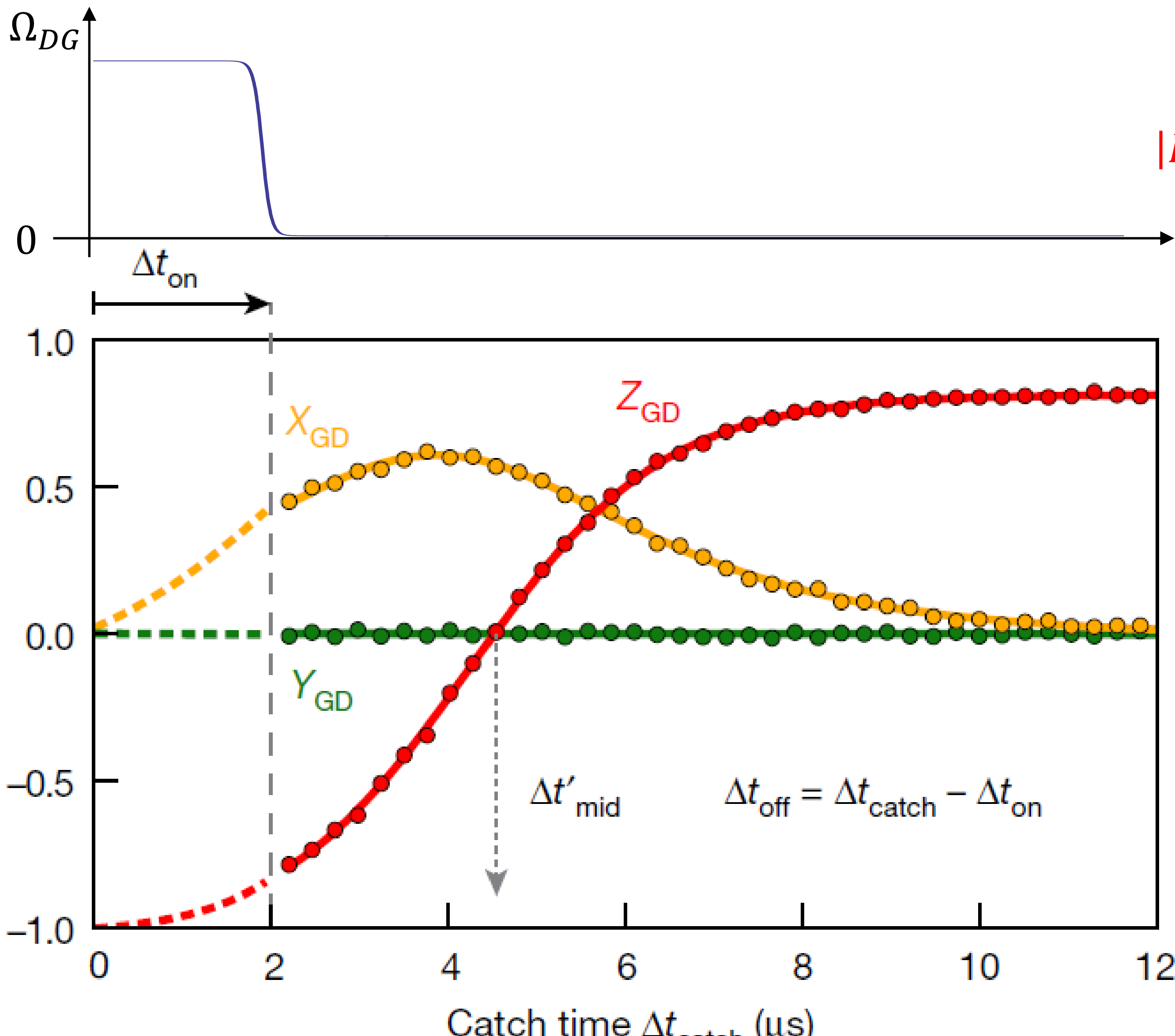
State evolution without signal

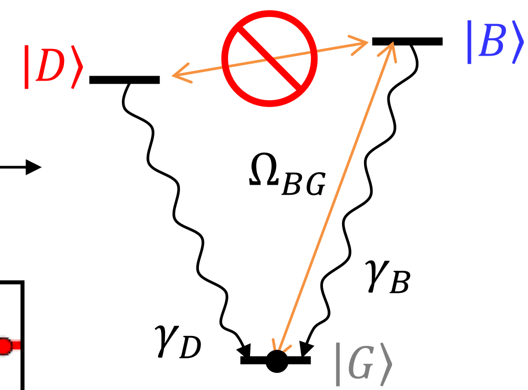


$$X_{GD} = \langle \sigma_x \rangle$$
$$Y_{GD} = \langle \sigma_y \rangle$$
$$Z_{GD} = \langle \sigma_z \rangle$$

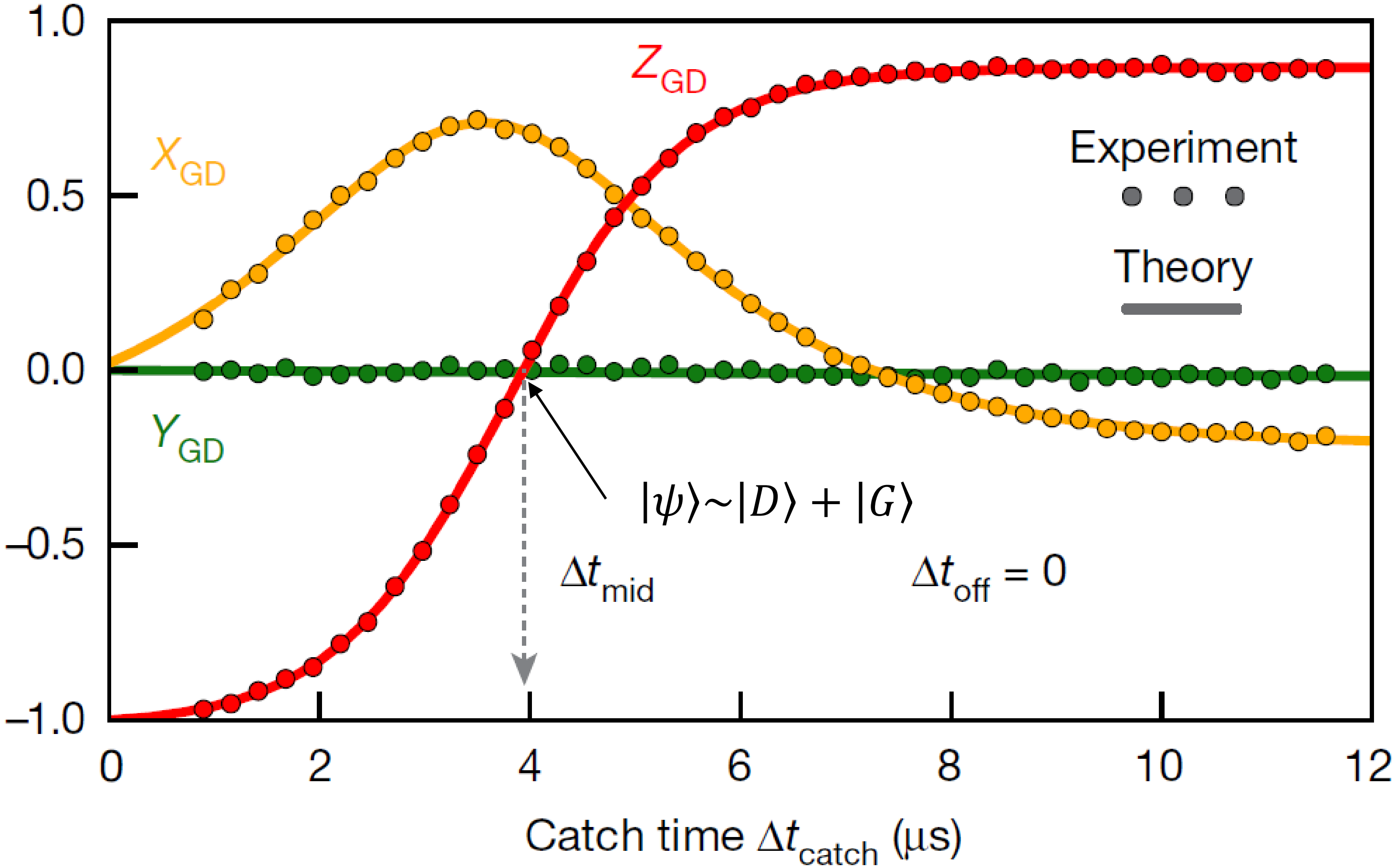
$$2\pi/\Omega_{DG} = 50\mu s$$

State evolution without signal





State evolution without signal



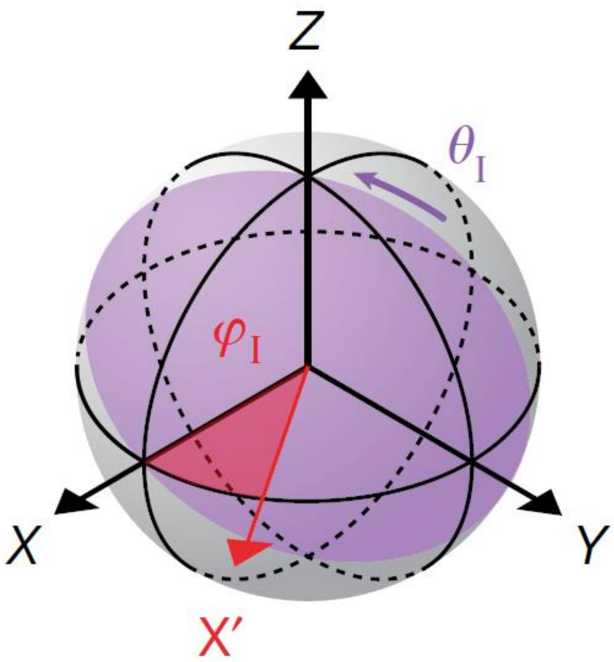
$X_{GD} = \langle \sigma_x \rangle$

$Y_{GD} = \langle \sigma_y \rangle$

$Z_{GD} = \langle \sigma_z \rangle$

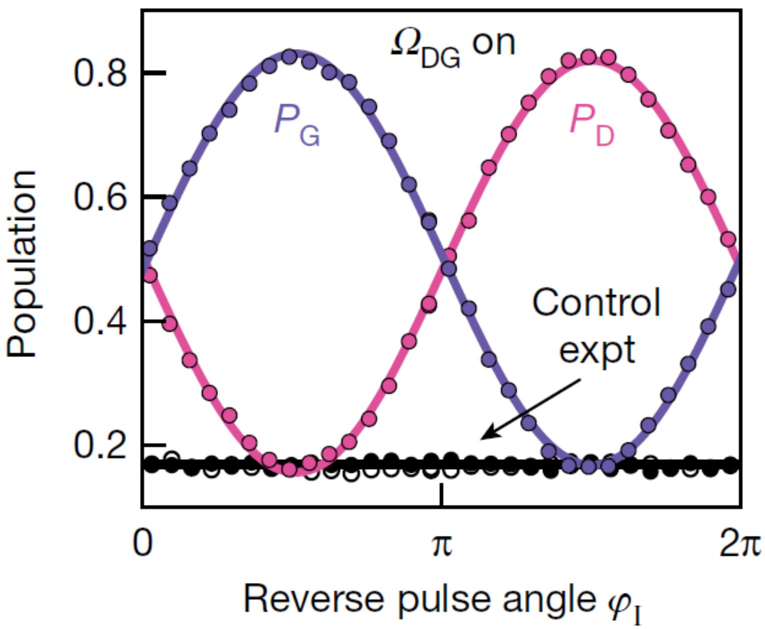
By applying $\pi\ /\ 2$ pulse at Δt_{mid}, the quantum jump can be reversed!

$\pi/2$ Pulse



$\theta_I(=\pi/2)$: pulse area

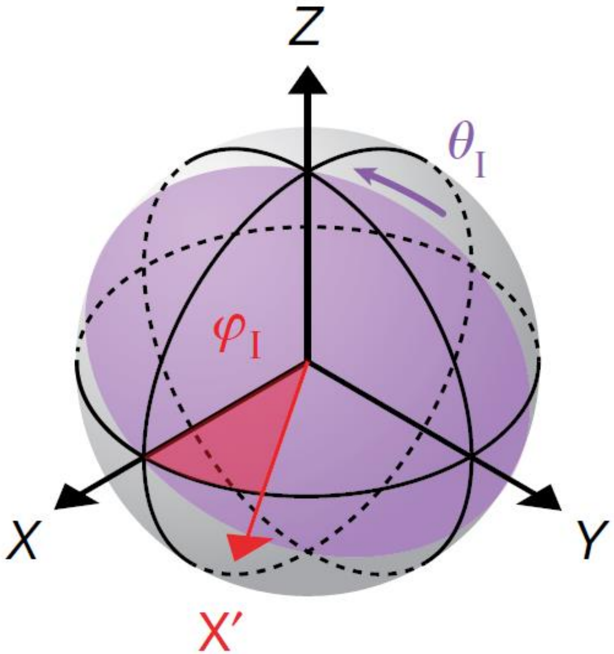
φ_I : phase of pulse



P_G : Probability in the ground state

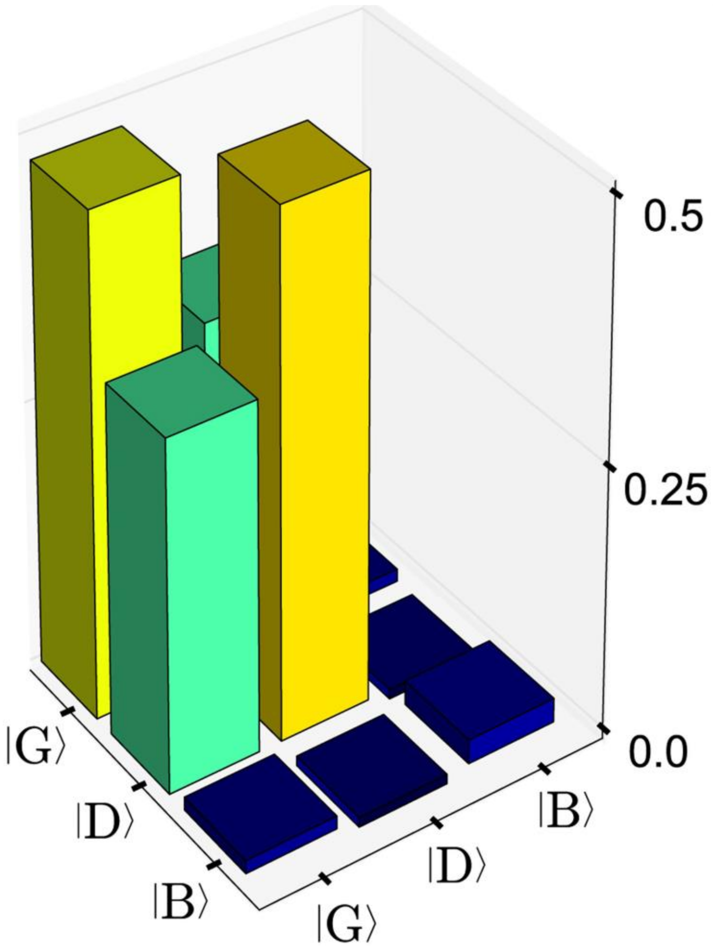
P_D : Probability in the dark state

State at Δt_{mid}



θ_I : pulse area

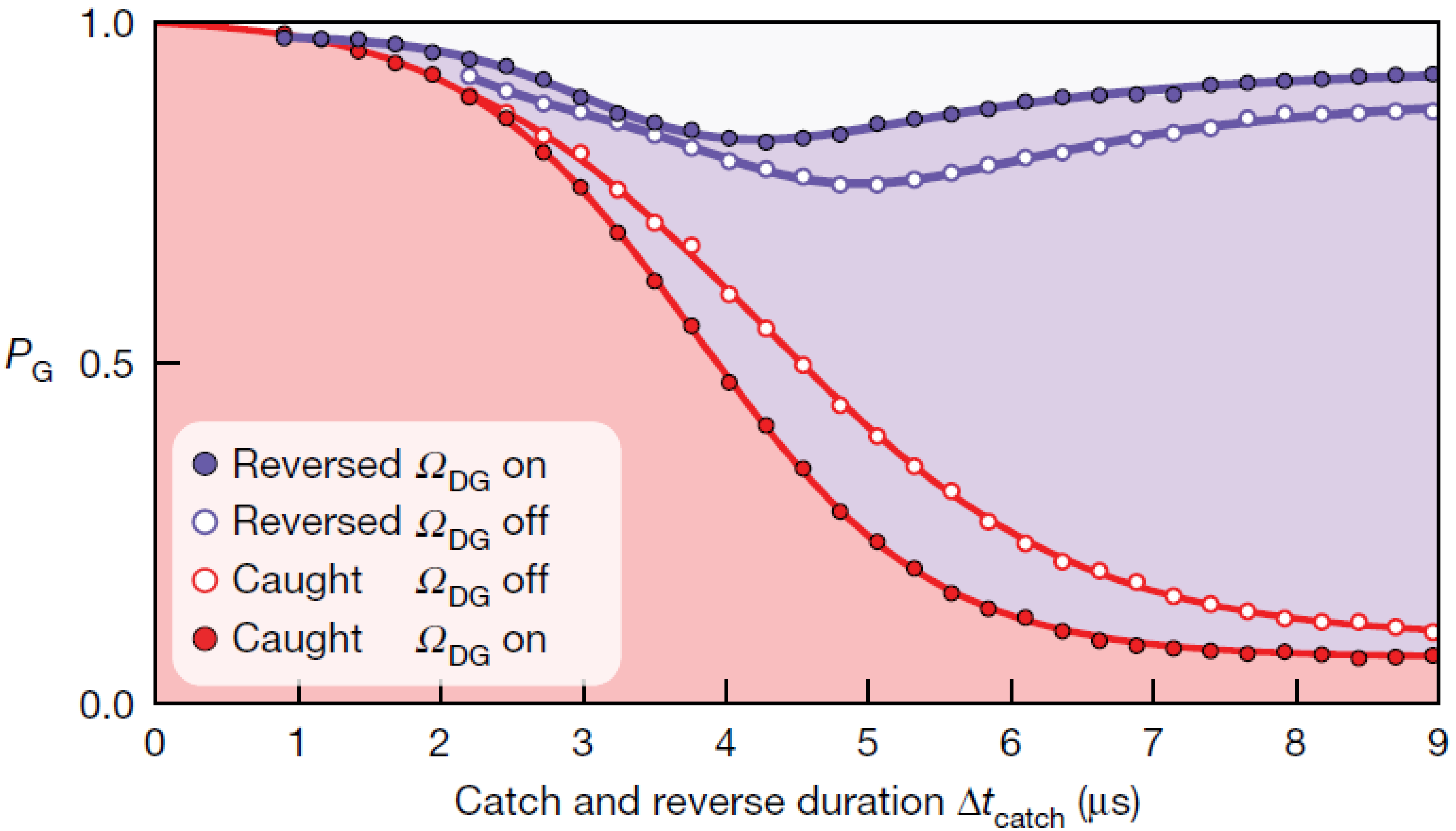
φ_I : phase of pulse



Density matrix at Δt_{mid}

Reverse the quantum jump

The controller is programmed with the optimal reverse pulse parameters



P_G : Probability in the ground state