Driving 'not so' forbidden state transitions in a frequency-tunable transmon

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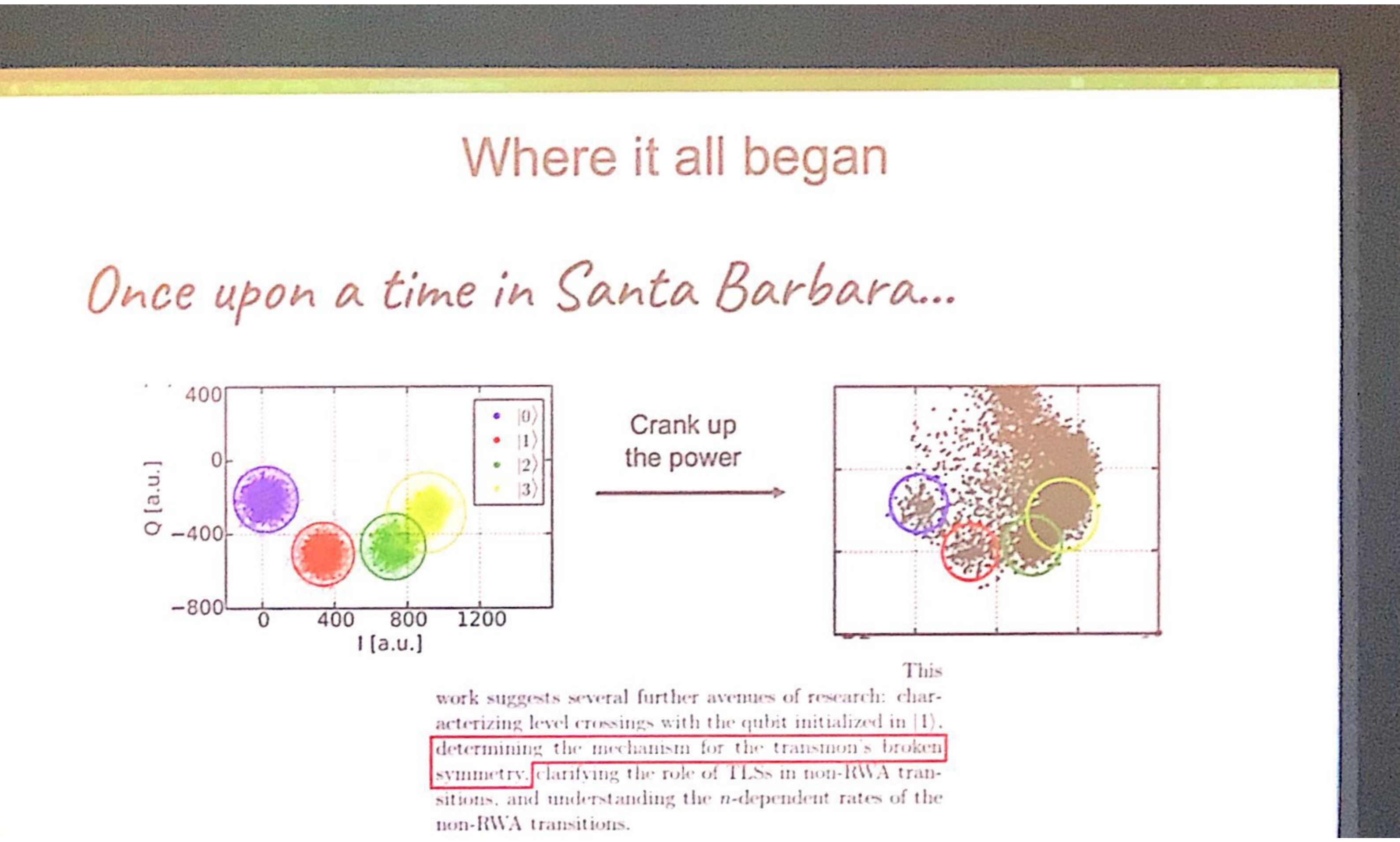
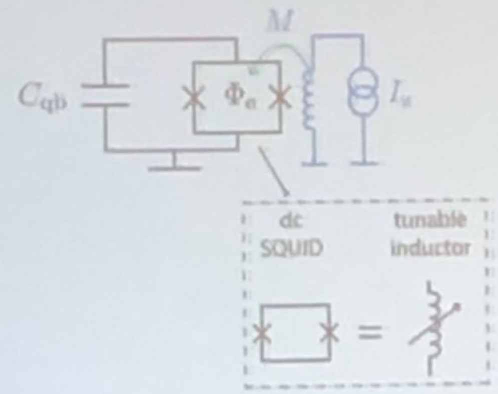
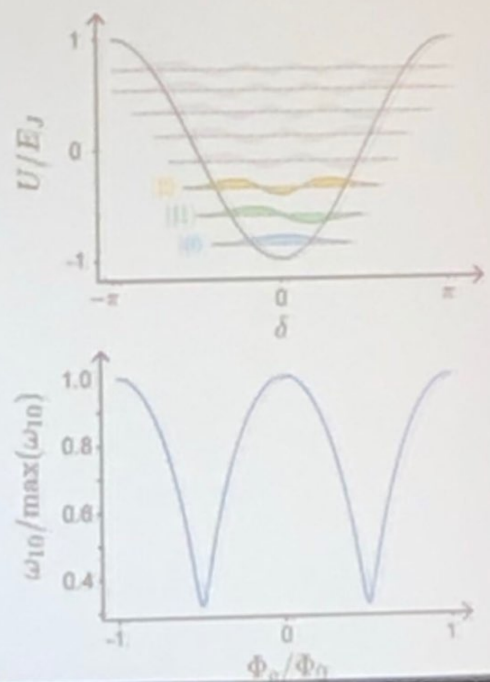

Where it all began
Once upon a time in Santa Barbara...
400
0
−400
−800
0
400
800
1200
Q [a.u.]
I [a.u.]
|0⟩
|1⟩
|2⟩
|3⟩
Crank up
the power
This
work suggests several further avenues of research: char-
acterizing level crossings with the qubit initialized in |1⟩,
determining the mechanism for the transmon's broken
symmetry, clarifying the role of TLSs in non-RWA tran-
sitions, and understanding the n-dependent rates of the
non-RWA transitions.

The Isolated Transmon

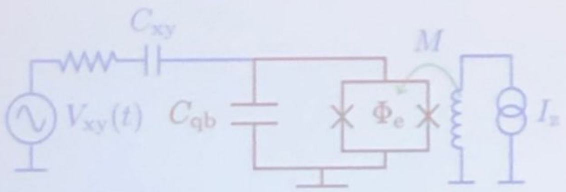




$$H_0 = \frac{\hat{Q}^2}{2C_{qb}} \underbrace{-E_J(\Phi_e)\cos(\hat{\delta})}_{U}$$

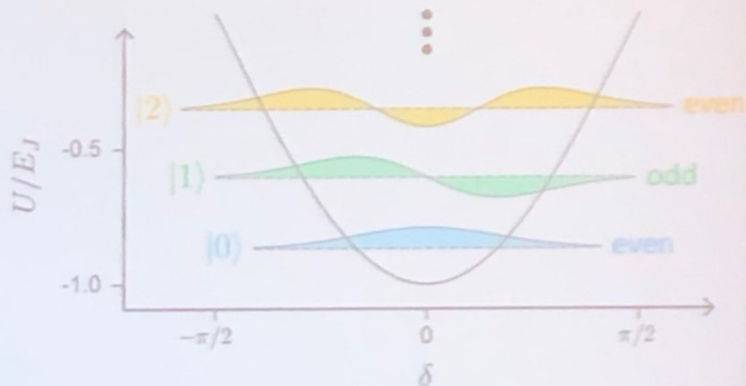
$E_J(\Phi_e) \equiv$ Effective Josephson Energy

The Driven Transmon



$$H = \underbrace{\frac{\hat{Q}^2}{2C_\Sigma} - E_J(\Phi_{\mathrm{e}})\cos(\hat{\delta})}_{H_0} + \underbrace{\frac{C_{\mathrm{xy}}}{C_\Sigma} V_{\mathrm{xy}} \hat{Q}}_{H_{\mathrm{drive}}}$$

$$C_\Sigma = C_{\mathrm{qb}} + C_{\mathrm{xy}}$$



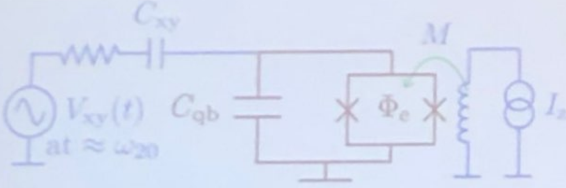
Anharmonic Transmon

$\hat{Q}$ has odd parity, and therefore only couples states of opposite parity!

$$\implies \langle 1|\hat{Q}|0\rangle \neq 0$$

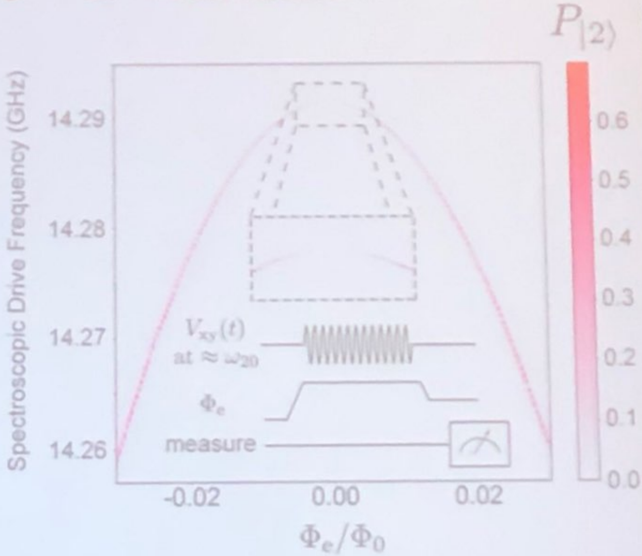
$$\implies \boxed{\langle 2|\hat{Q}|0\rangle = 0}$$

Spectroscopy of the 0→2 Transition



$$H = \underbrace{\frac{\hat{Q}^2}{2C_\Sigma} - E_J(\Phi_e)\cos(\hat{\delta})}_{H_0} + \underbrace{\frac{C_{xy}}{C_\Sigma} V_{xy} \hat{Q}}_{H_{\mathrm{drive}}}$$

$$C_\Sigma = C_{qb} + C_{xy}$$

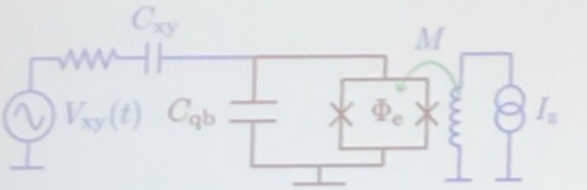


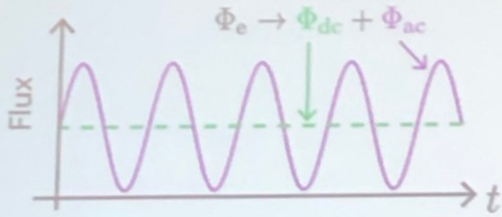
But $\langle 2|\hat{Q}|0\rangle = 0$ so why isn't $P_{|2\rangle}$ identically zero?

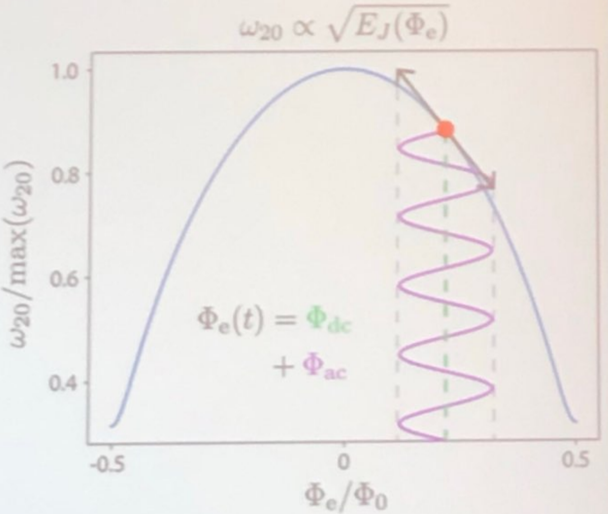
$P_{|2\rangle} = 0$ at $\Phi_e = 0$

$\implies$ magnetic in origin

02 Drive Mechanism

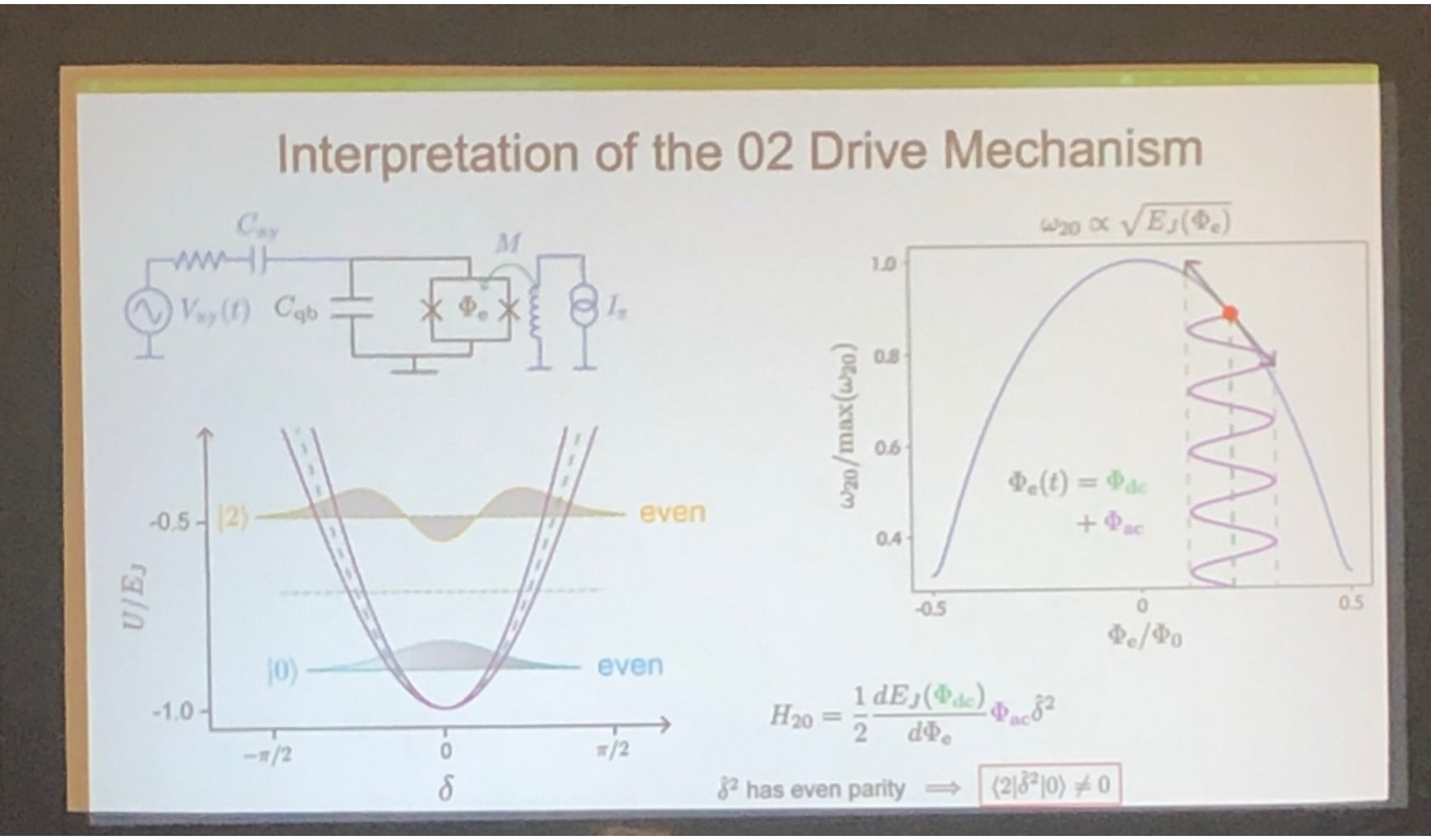






$$H = \frac{\hat{Q}^2}{2C_\Sigma} - E_J(\Phi_{dc} + \Phi_{ac})\cos(\hat{\delta}) + \frac{C_{xy}}{C_\Sigma} V_{xy}(t)\hat{Q}$$

$$\Longrightarrow \quad = H_0 + H_{drive} + \underbrace{\frac{1}{2}\frac{dE_J(\Phi_{dc})}{d\Phi_e}\Phi_{ac}\hat{\delta}^2}_{H_{20}}$$

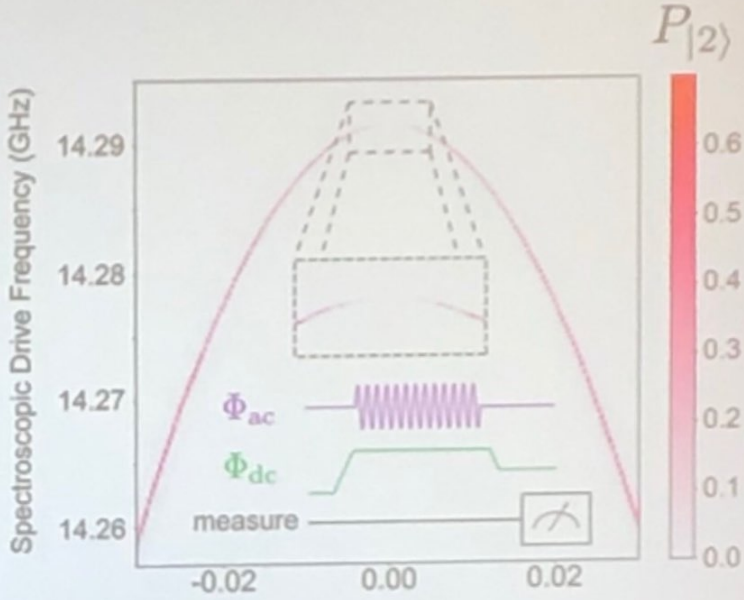

Interpretation of the 02 Drive Mechanism
C_{xy}
M
$V_{xy}(t)$
C_{qb}
Φ_e
I_z
$|2\rangle$
even
$|0\rangle$
even
-0.5
-1.0
U/E_J
$-\pi/2$
0
$\pi/2$
δ
$\omega_{20} \propto \sqrt{E_J(\Phi_e)}$
1.0
0.8
0.6
0.4
$\omega_{20}/\max(\omega_{20})$
$\Phi_e(t) = \Phi_{dc} + \Phi_{ac}$
-0.5
0
0.5
Φ_e/Φ_0
$H_{20} = \frac{1}{2}\frac{dE_J(\Phi_{dc})}{d\Phi_e}\Phi_{ac}\hat{\delta}^2$
$\hat{\delta}^2$ has even parity $\Longrightarrow$ $\boxed{\langle 2|\hat{\delta}^2|0\rangle \neq 0}$

02-Spectroscopy Revisited

$$H_{20} = \frac{1}{2}\frac{dE_J(\Phi_{\mathrm{dc}})}{d\Phi_{\mathrm{e}}}\Phi_{\mathrm{ac}}\hat{\delta}^2$$

$$\langle 2|\hat{\delta}^2|0\rangle \neq 0$$

$$\boxed{P_{|2\rangle} \to 0 \text{ as } \frac{dE_J(\Phi_{\mathrm{dc}})}{d\Phi_{\mathrm{e}}} \to 0}$$



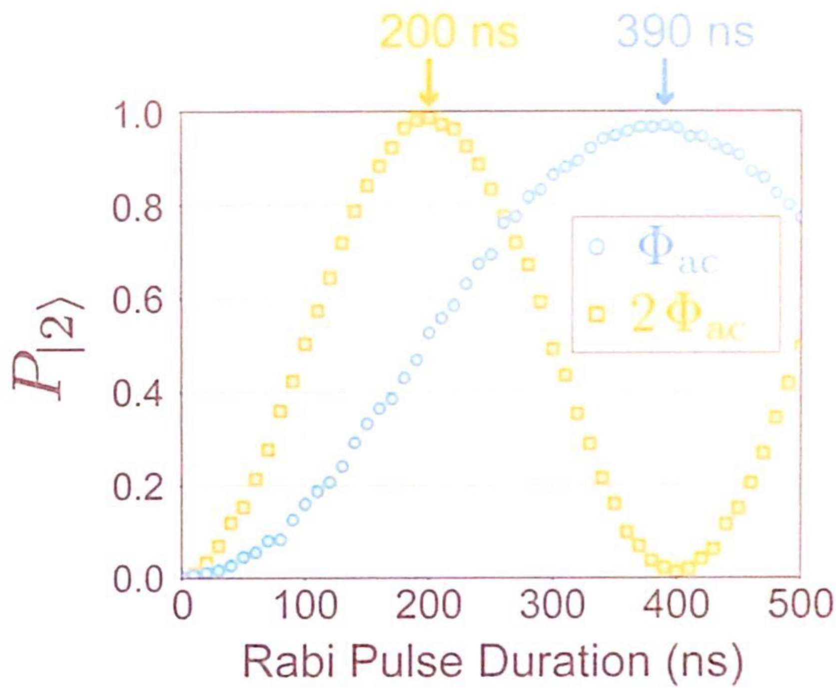
Rabi Frequency vs Drive Amplitude

$$H_{20} = \frac{1}{2}\frac{dE_J(\Phi_{\rm dc})}{d\Phi_{\rm e}}\Phi_{\rm ac}\hat{\delta}^2$$
$$\propto \Phi_{\rm ac}$$

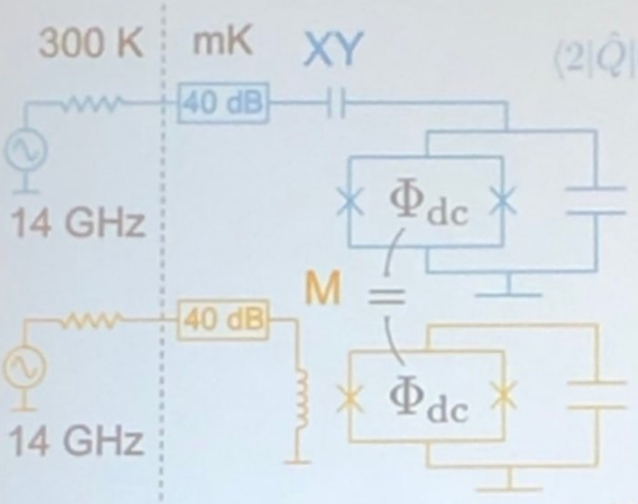
$$\omega_R = \langle 2|H_{20}|0\rangle/\hbar$$
$$\propto \Phi_{\rm ac}$$

Rabi frequency scales linearly with ac flux amplitude.

- Note that the $f_{20}/2$ transition is not forbidden at any flux, but scales as (drive amplitude)^2.



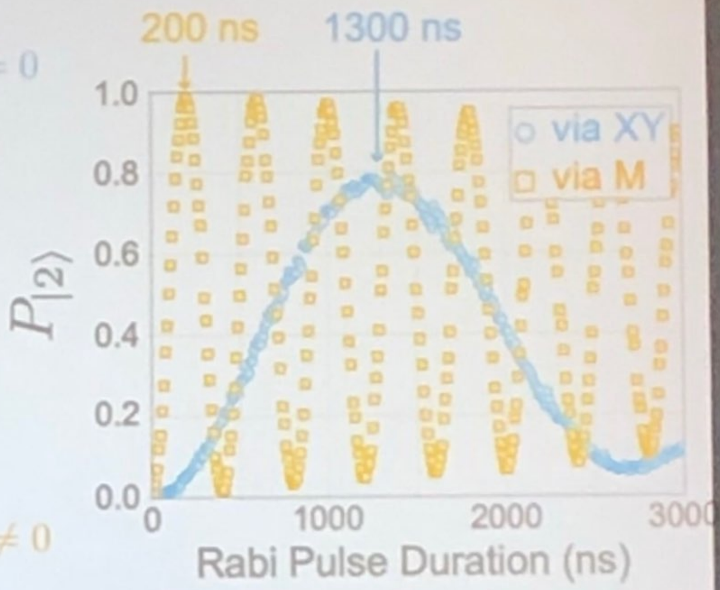
Parasitic 02 Coupling via XY



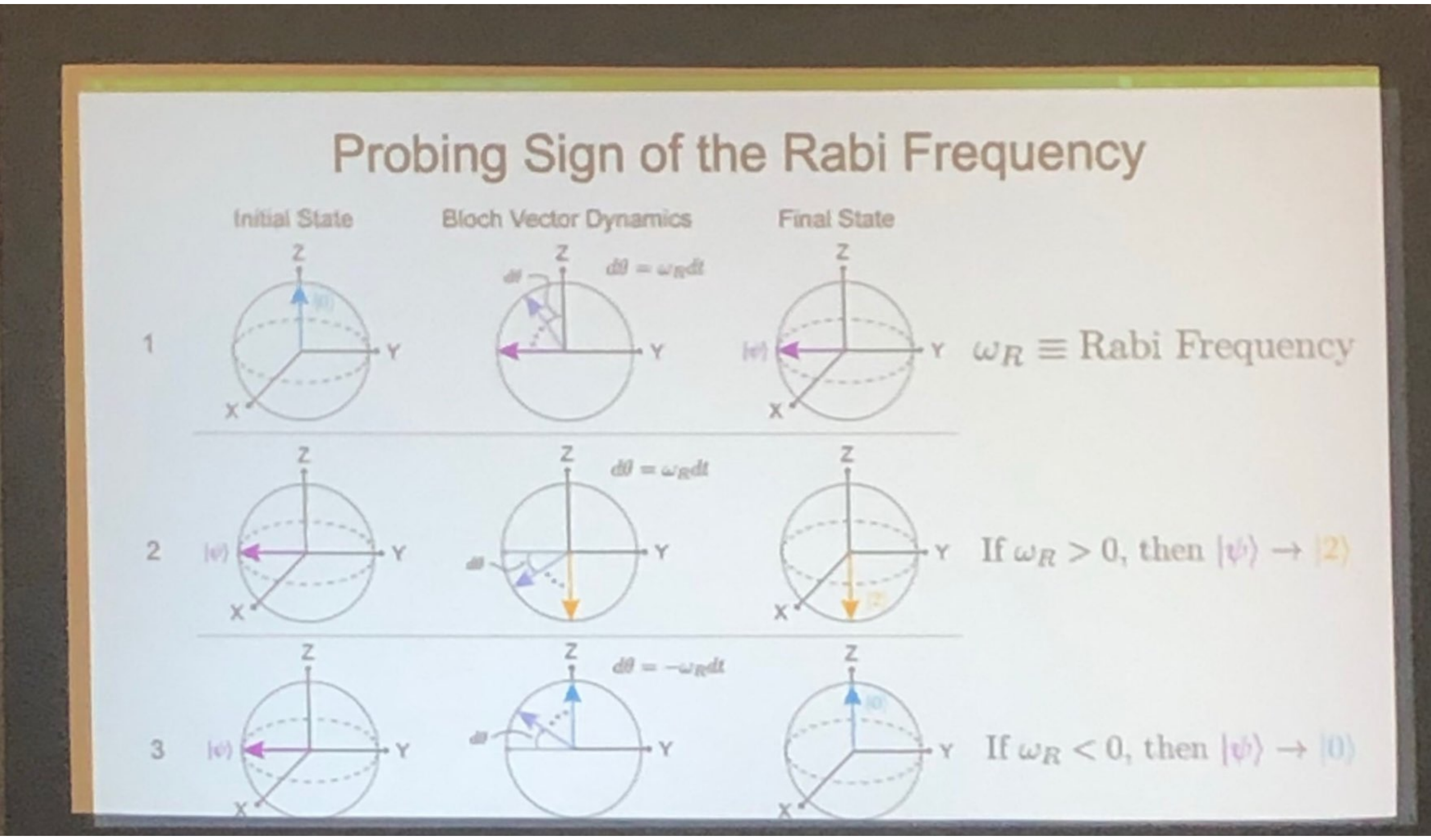
$\langle 2|\hat{Q}|0\rangle = 0$

$\langle 2|\hat{\delta}^2|0\rangle \neq 0$

*Same frequency and power for XY and M drives.

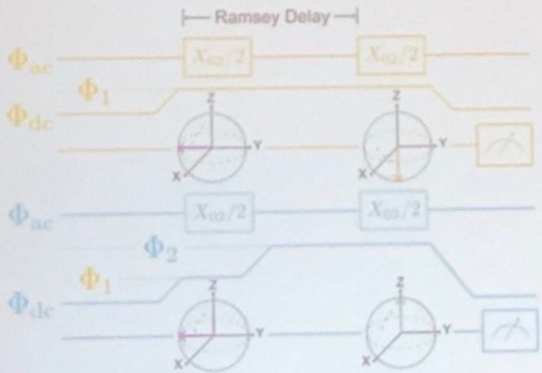


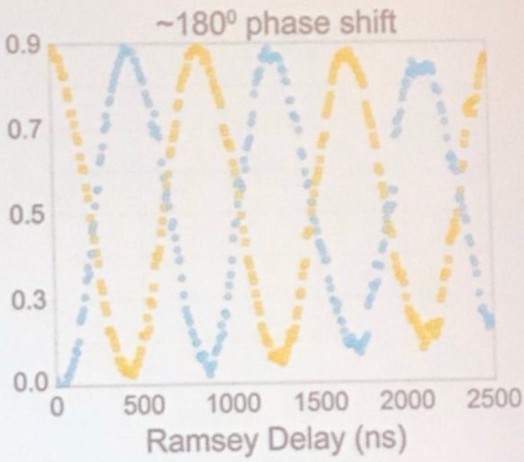
200 ns / 1300 ns ⇒ 15% (-16 dB)

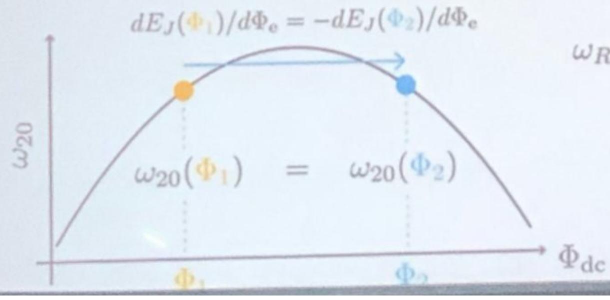


Probing Sign of the Rabi Frequency
Initial State
Bloch Vector Dynamics
Final State
1
$d\theta = \omega_R dt$
$\omega_R \equiv$ Rabi Frequency
2
$d\theta = \omega_R dt$
If $\omega_R > 0$, then $|\psi\rangle \to |2\rangle$
3
$d\theta = -\omega_R dt$
If $\omega_R < 0$, then $|\psi\rangle \to |0\rangle$

Probing Sign of the Rabi Frequency







$$\omega_R \propto \frac{dE_J(\Phi_{dc})}{d\Phi_e}$$

Second X/2 gate acts as a -X/2 gate as Rabi frequency changes sign.

Summary

- Parametric modulation of E_J couples |0> and |2>.
- Explained the origin of the 0->2 Rabi oscillations discovered by Sank *et al.*, PRL 117.
- Detailed understanding of all parasitic couplings is important for high-fidelity control.