Autonomous stabilization of an entangled state of two transmon qubits

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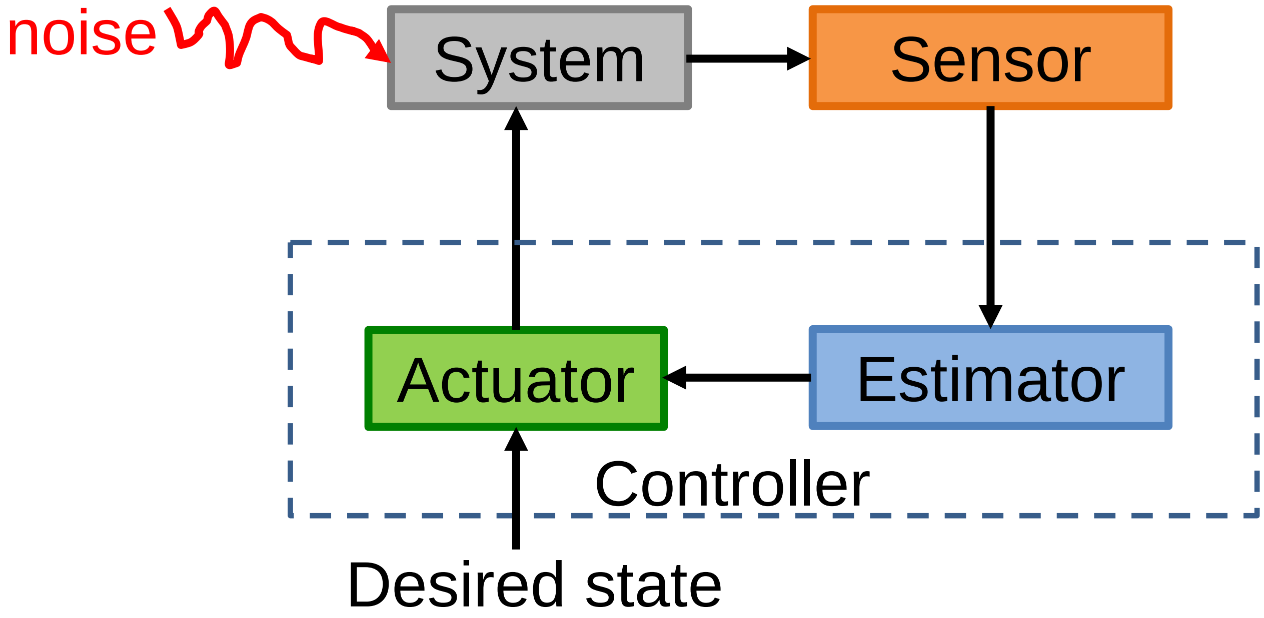
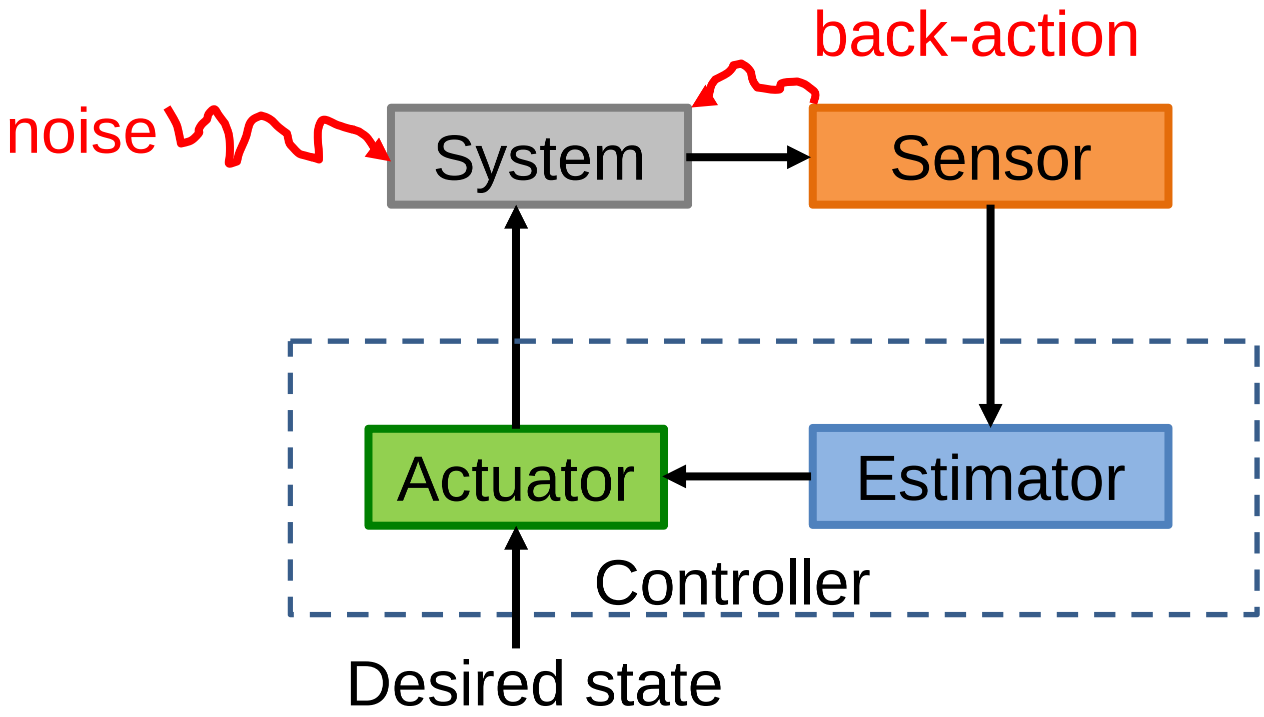
Classical feedback

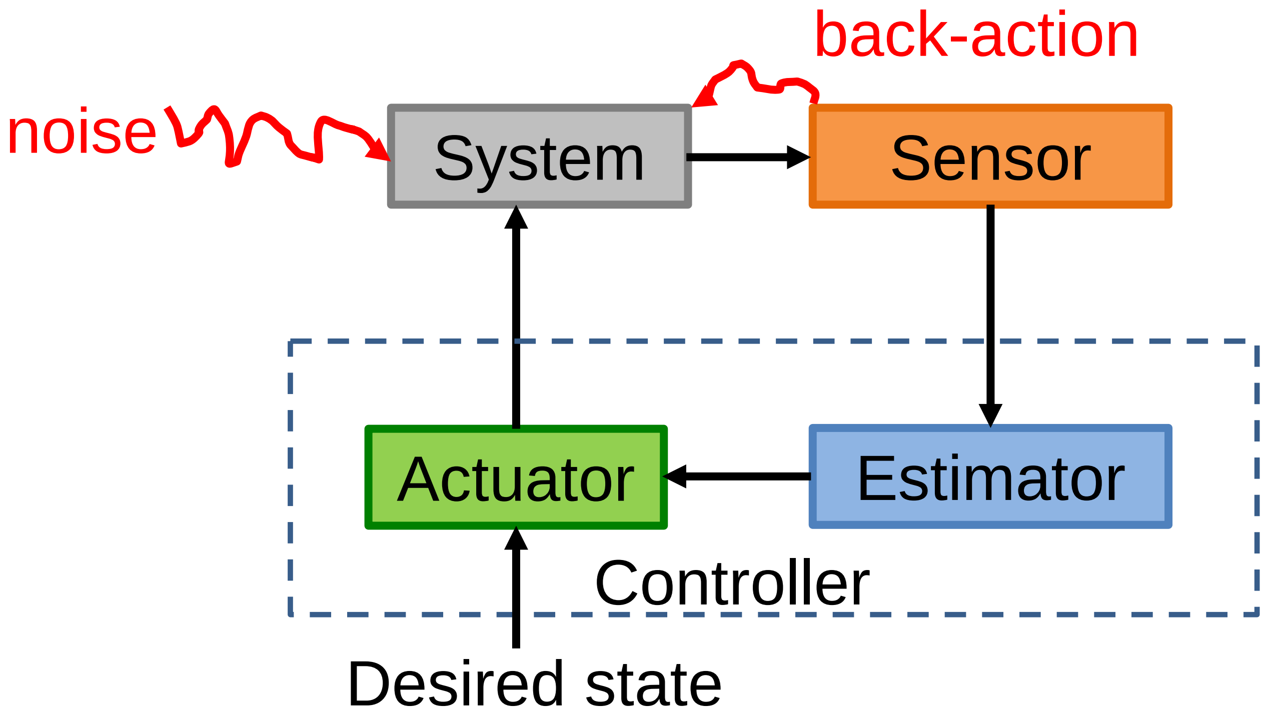


Quantum feedback



“back-action” : in general, measuring the state of a quantum system can perturb it

Quantum feedback

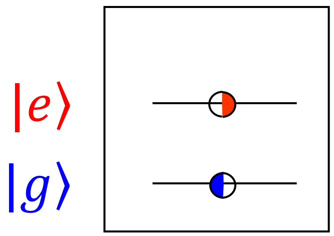


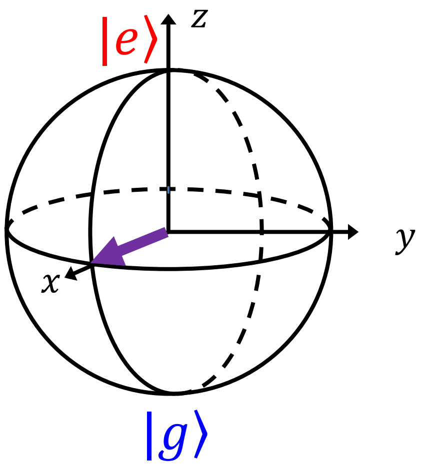
"back-action" : in general, measuring the state of a quantum system can perturb it

Challenge → design feedback such that back-action absent when in desired state

Resources for quantum computing

Qubit : two level quantum system





System state : $|\psi\rangle$

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|g\rangle + |e\rangle\ )$$

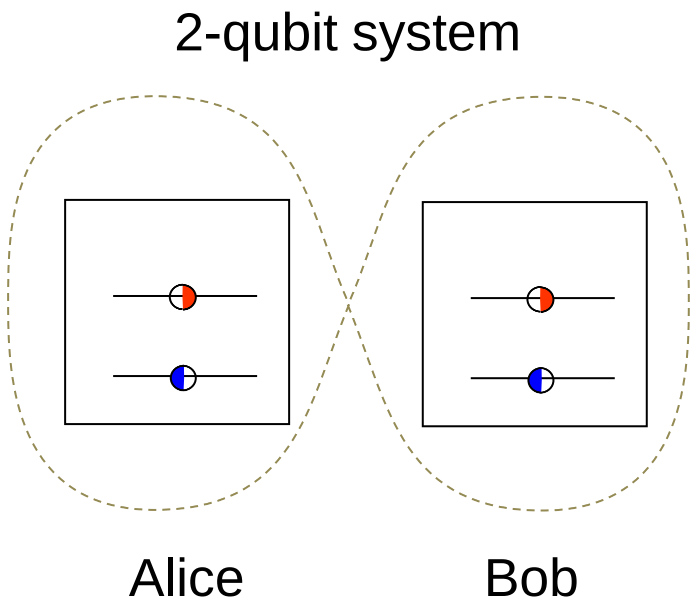
superposition

$$\langle Z\rangle = 0, \langle X\rangle = 1$$

Measure Z ➔ back-action randomly gives +1 or -1, average = 0

Measure X ➔ No back-action, X = +1 always

Resources for quantum computing



$$|\psi\rangle = \frac{1}{\sqrt{2}}(|ge\rangle - |eg\rangle)$$

$$\langle Z_A\rangle = \langle Z_B\rangle = 0, \langle Z_A Z_B\rangle = -1$$

$$\langle X_A\rangle = \langle X_B\rangle = 0, \langle X_A X_B\rangle = -1$$

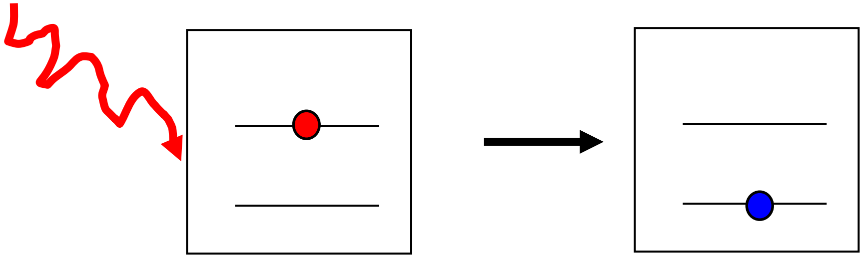
entanglement

Measure individual qubits ➔ back-action gives +1 or -1 randomly

Measure joint parity ➔ no back-action, parity = -1 always

Challenges : decoherence

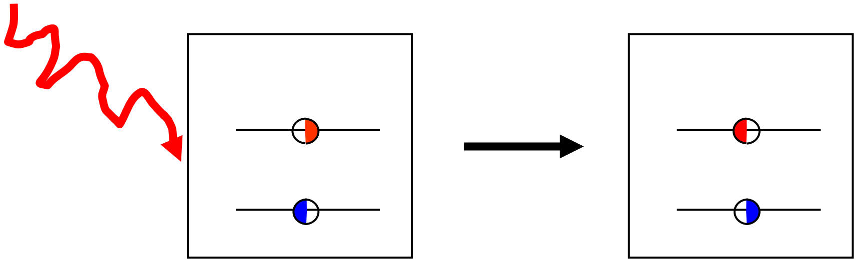
Environmental noise



$|e\rangle$ $\quad$ $|g\rangle$

Relaxation : T_1

Environmental noise

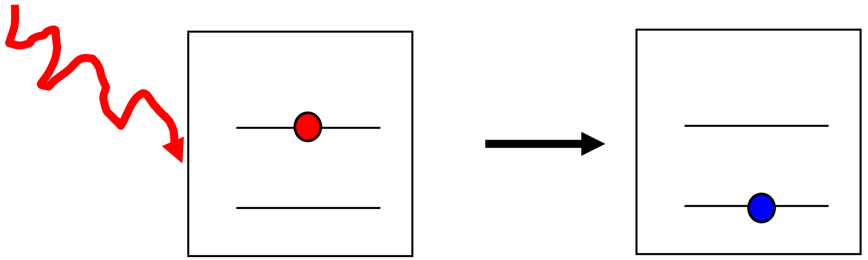


$$\frac{|g\rangle + |e\rangle}{\sqrt{2}} \qquad \frac{|g\rangle - |e\rangle}{\sqrt{2}}$$

Dephasing : T_ϕ

Challenges : decoherence

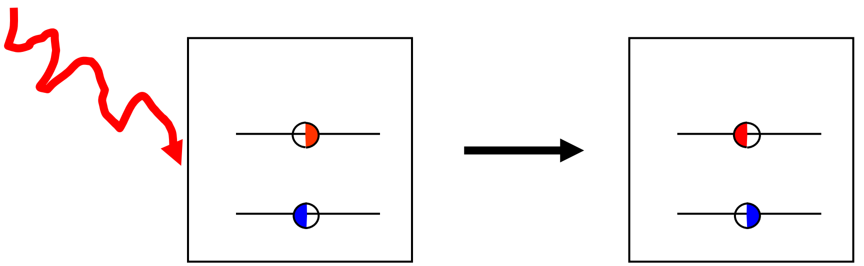
Environmental noise



$|e\rangle$ $\qquad$ $|g\rangle$

Relaxation : T_1

Environmental noise



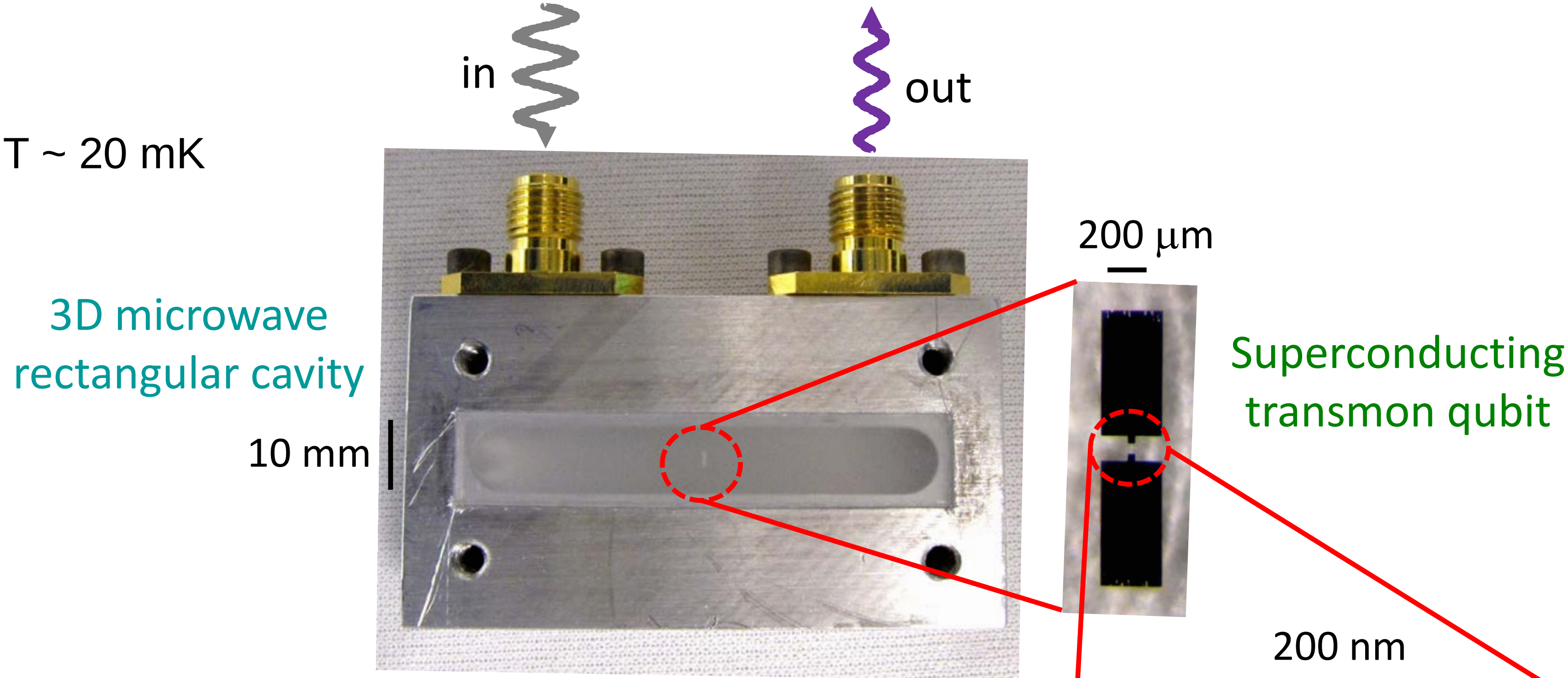
$\frac{|g\rangle + |e\rangle}{\sqrt{2}}$ $\qquad$ $\frac{|g\rangle - |e\rangle}{\sqrt{2}}$

Dephasing : T_ϕ

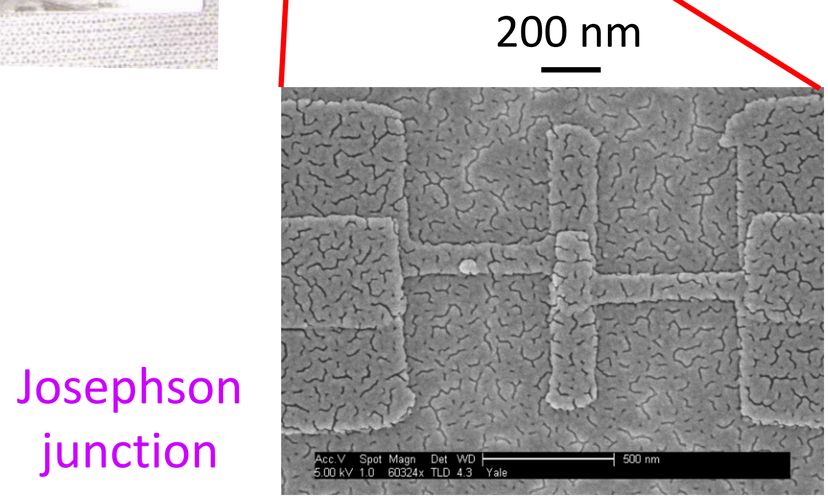
Solution: Quantum feedback

➔ maintain superposition/entanglement against decoherence

Circuit QED architecture

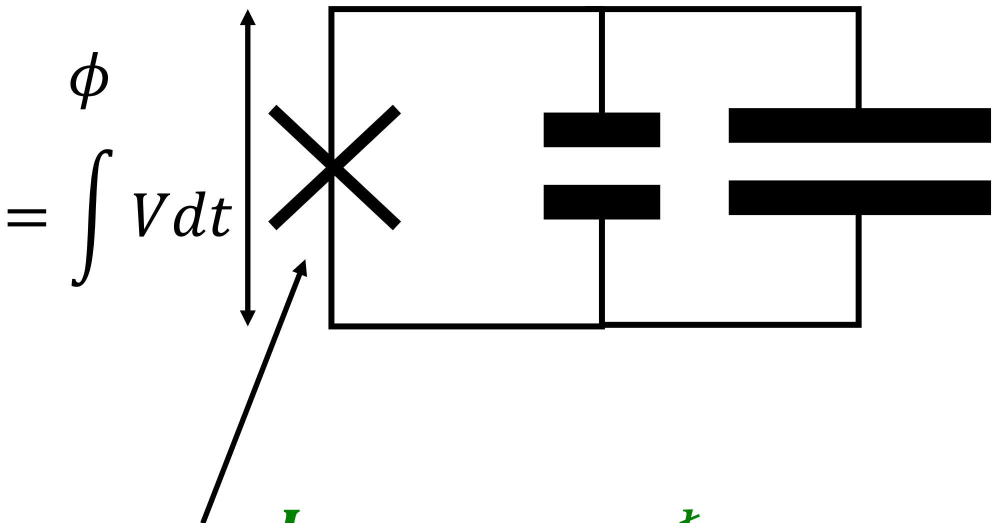


Blais et al., Phys. Rev. A (2004)
Wallraff et al., Nature (2004)
Paik et al., Phys. Rev. Lett. (2011)



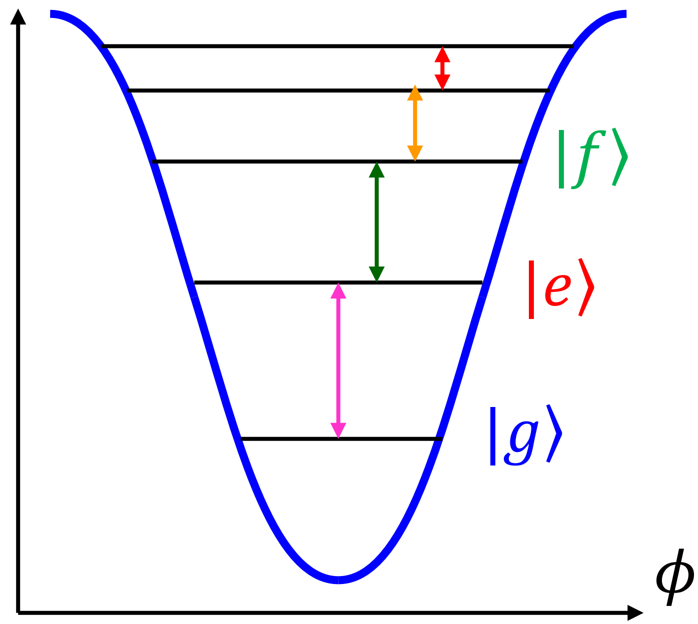
Superconducting transmon qubit

Josephson junction with shunting capacitor ➔ anharmonic oscillator



$$\boldsymbol{L = \frac{L_J}{\cos(\phi/\phi_0)}, \phi_0 = \frac{\hbar}{2e}}$$

Potential energy

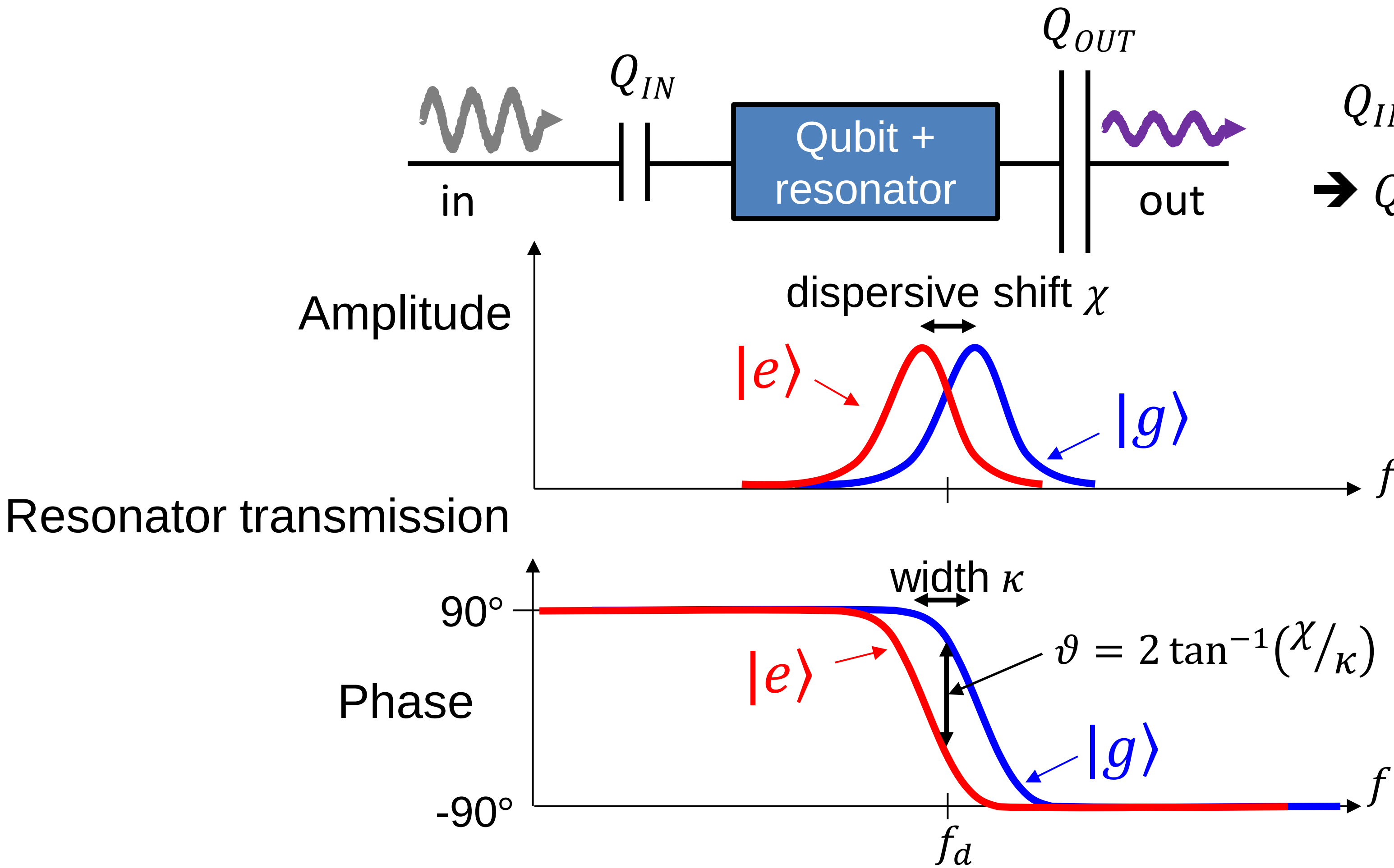


lowest two levels form qubit

Qubit frequency ~ 4 – 10 GHz, T_1, T_ϕ ~ 10 – 100 μs

Koch et al., Phys. Rev. A (2007)

How do we measure the qubit : dispersive readout



$Q_{IN} \gg Q_{OUT}$

➔ Q_{OUT} sets κ

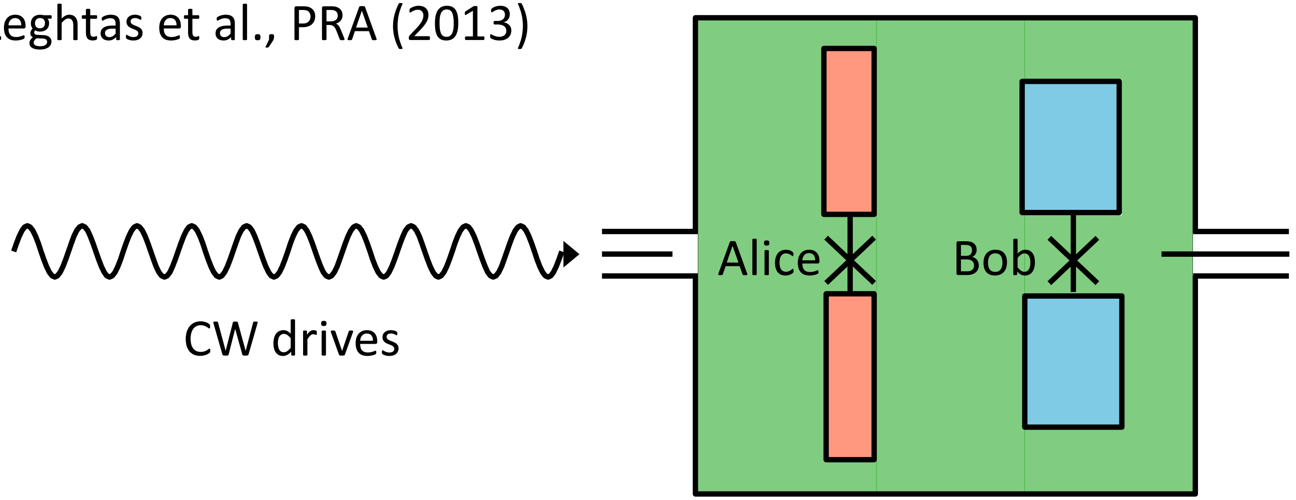
"Quantum non-demolition" measurement of Z

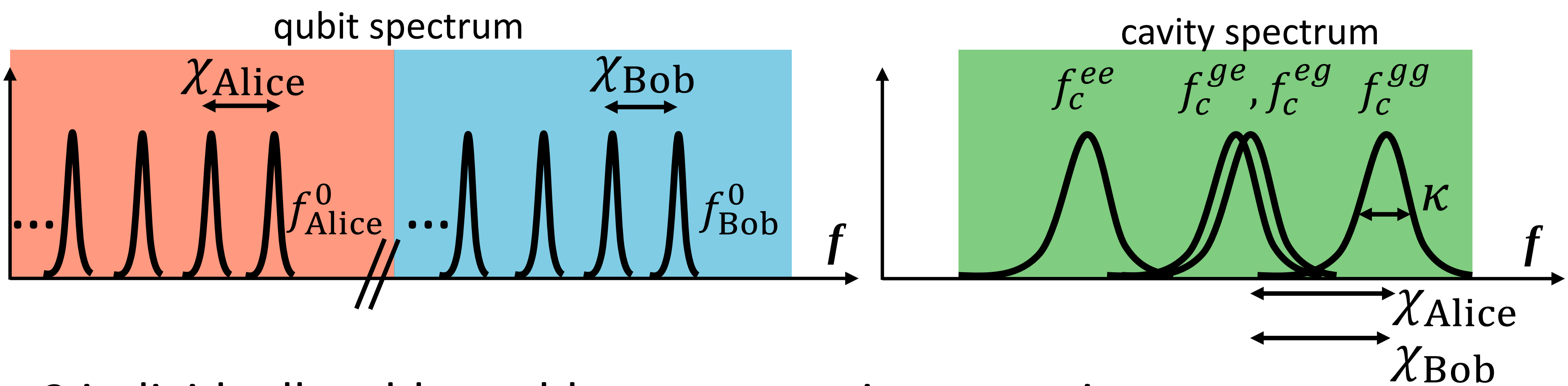
➔ No back-action if state is $|g\rangle$ or $|e\rangle$

Multiple single-qubit feedback experiments : ENS, Berkeley, Delft, Yale, ETH

Autonomous stabilization of Bell state $|\phi_{-}\rangle = \{|ge\rangle - |eg\rangle\}/\sqrt{2}$

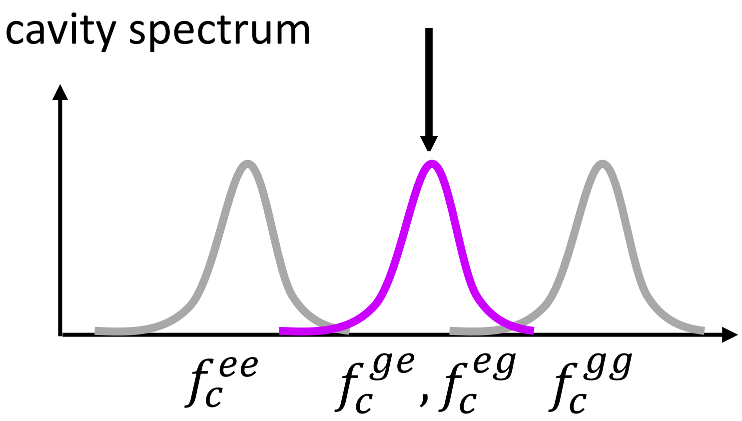
Z. Leghtas et al., PRA (2013)



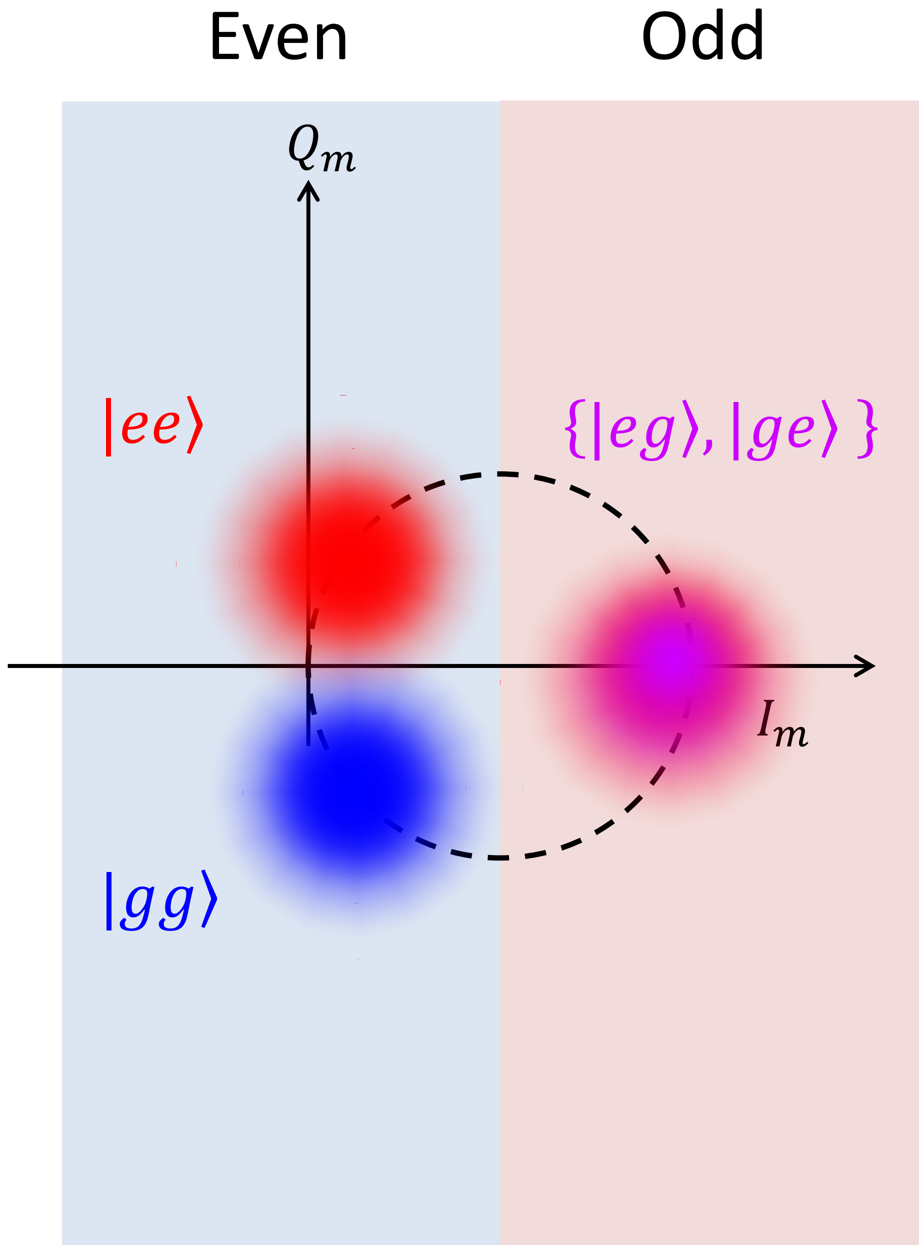


- 2 individually addressable transmons in one cavity
- Almost equal and large dispersive shifts ($\chi_{Alice} \sim \chi_{Bob} > \kappa$)
- Autonomous ➔ No external controller

Why $\chi_{Alice} \sim \chi_{Bob}$: quasi-parity measurement

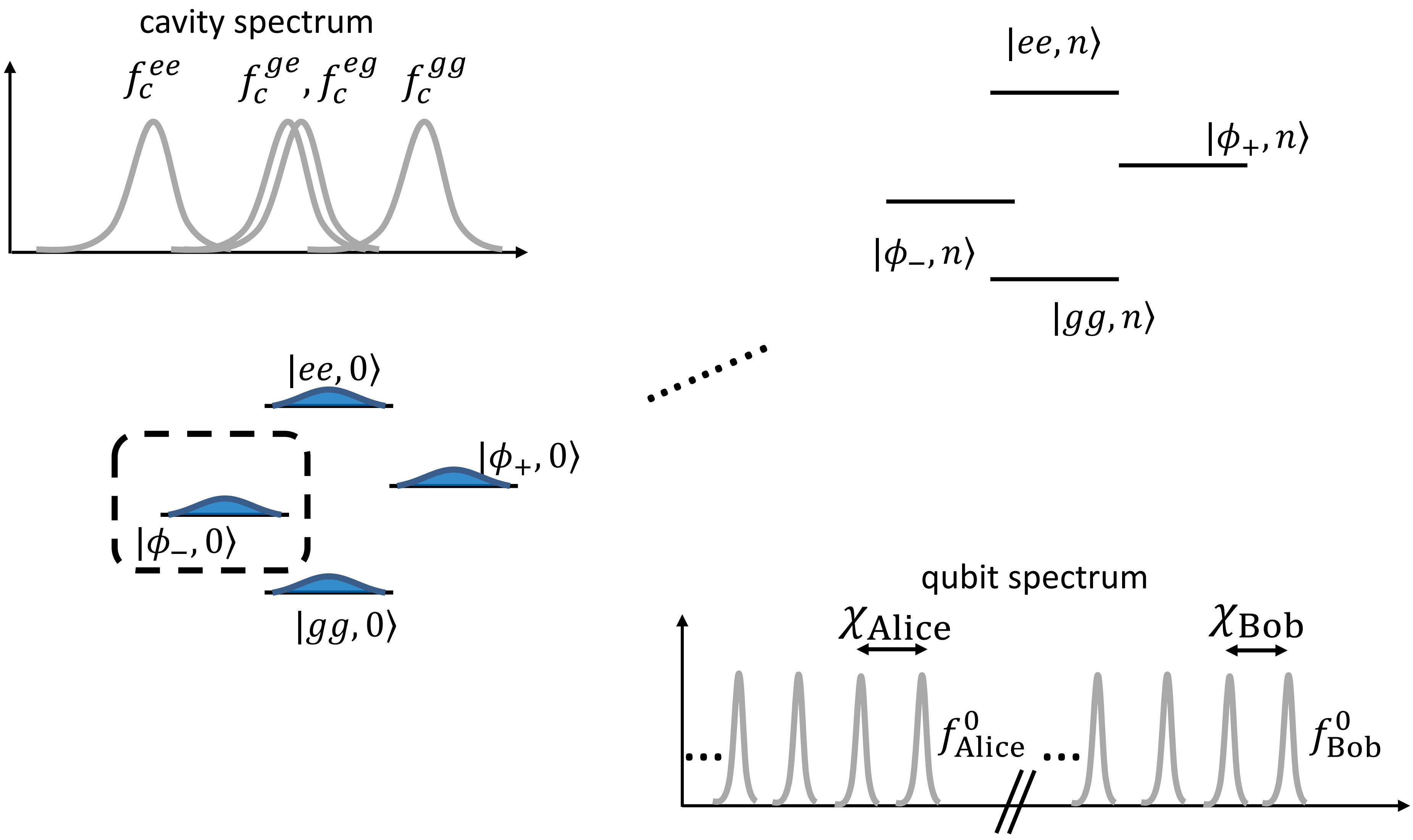


Equal χ



- Distinguish even and odd parity
- No back-action if state is $|\phi_-\rangle = \{|ge\rangle - |eg\rangle\}/\sqrt{2}$

Autonomous stabilization of Bell state $|\phi_-\rangle = \{|ge\rangle - |eg\rangle\}/\sqrt{2}$



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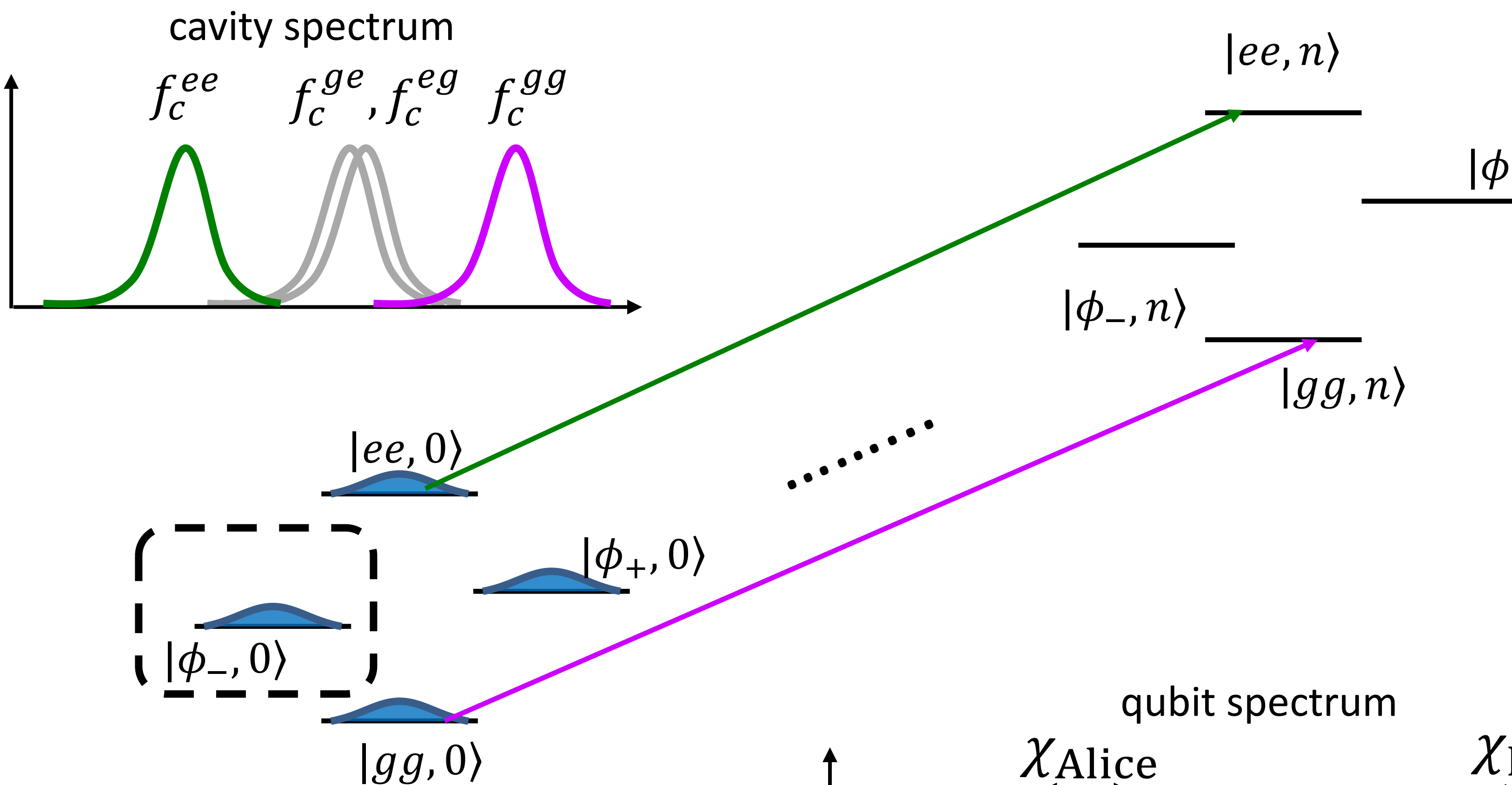
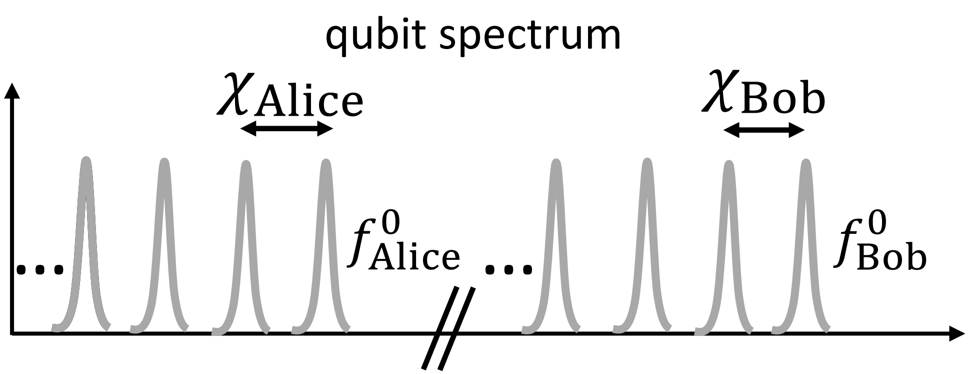


- Select even parity: $|gg,0\rangle$, $|ee,0\rangle$ pumped to n photon manifold
  – cavity drives with average $\bar{n}$ photons ($n \sim \bar{n}$)



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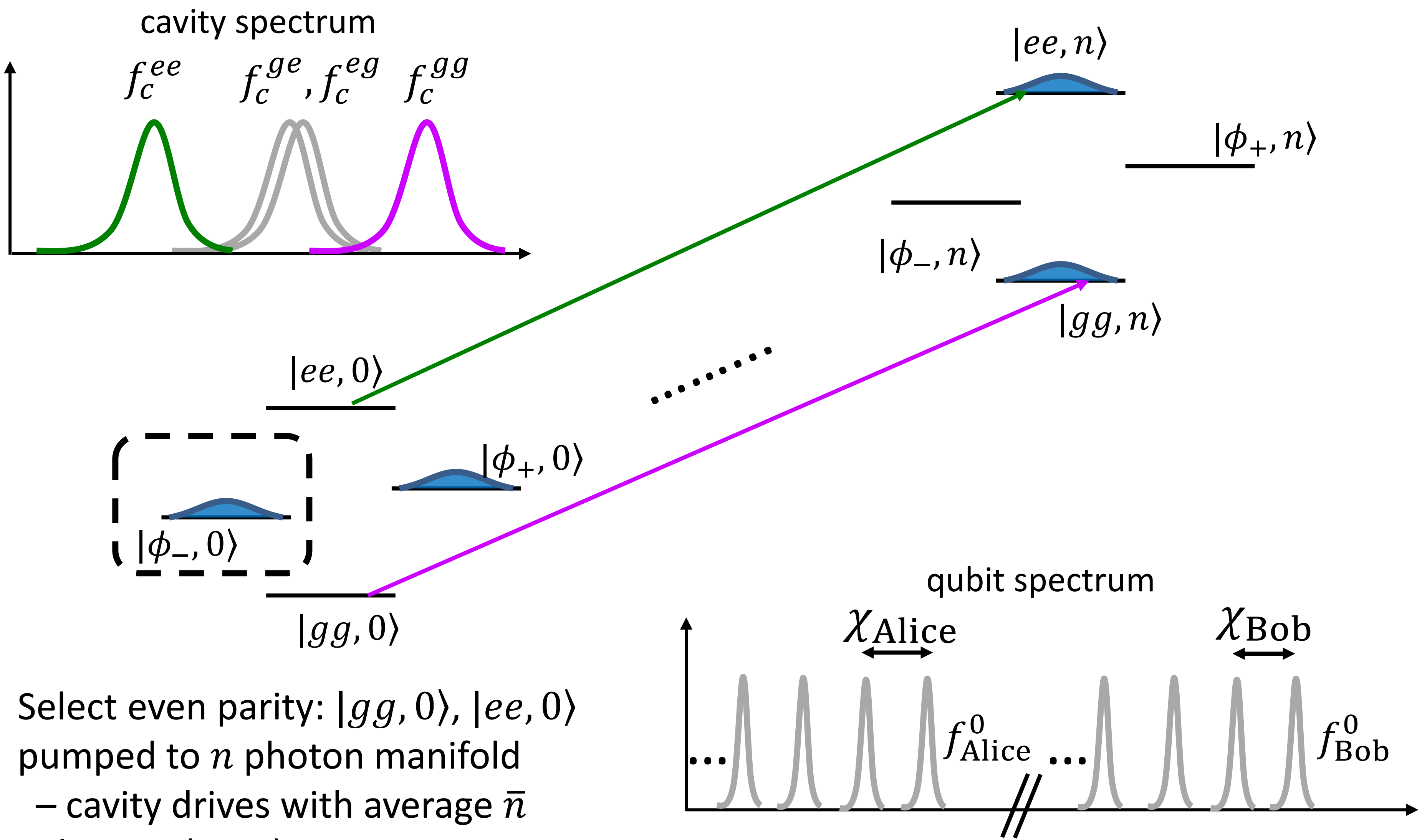

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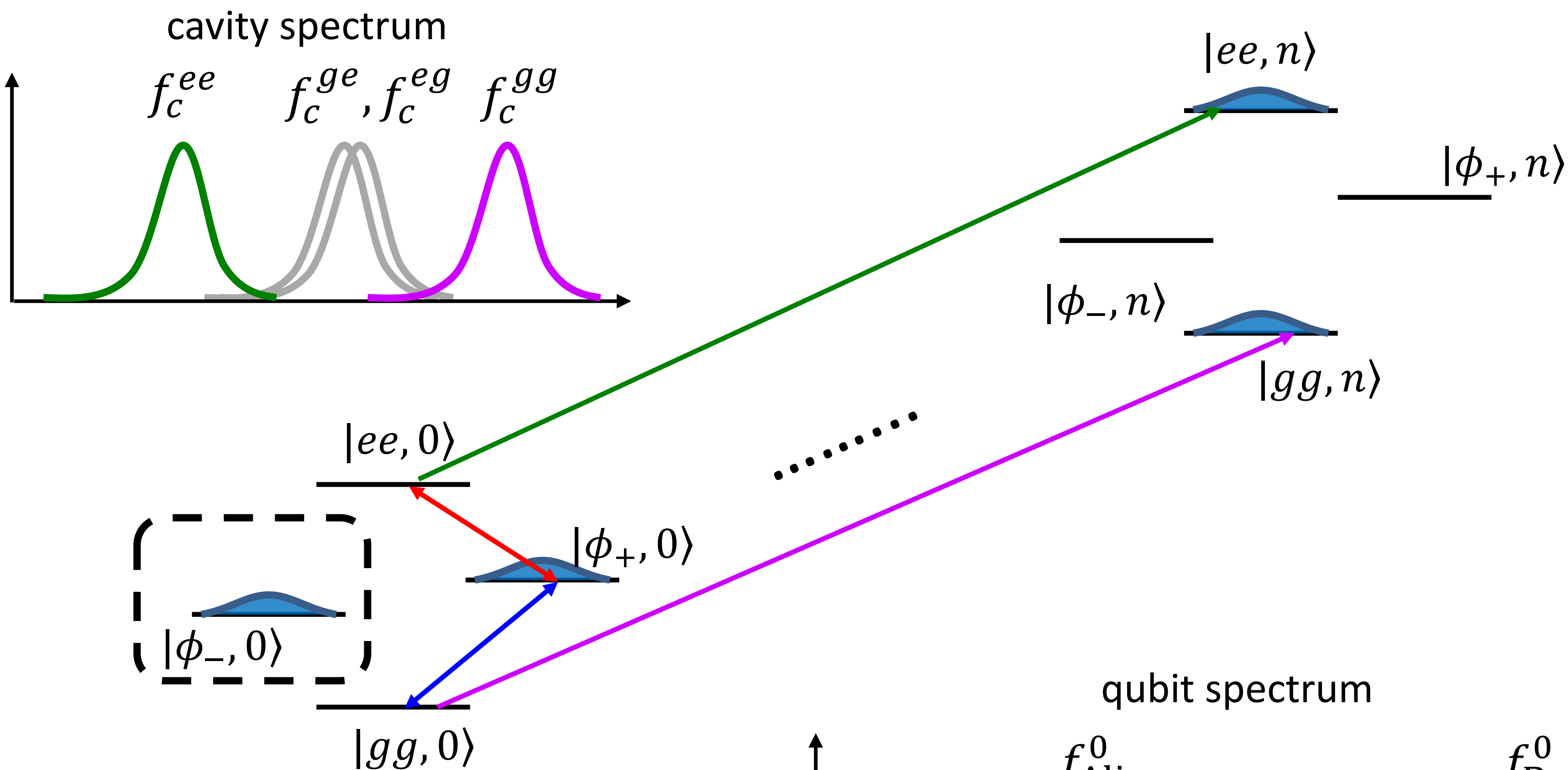
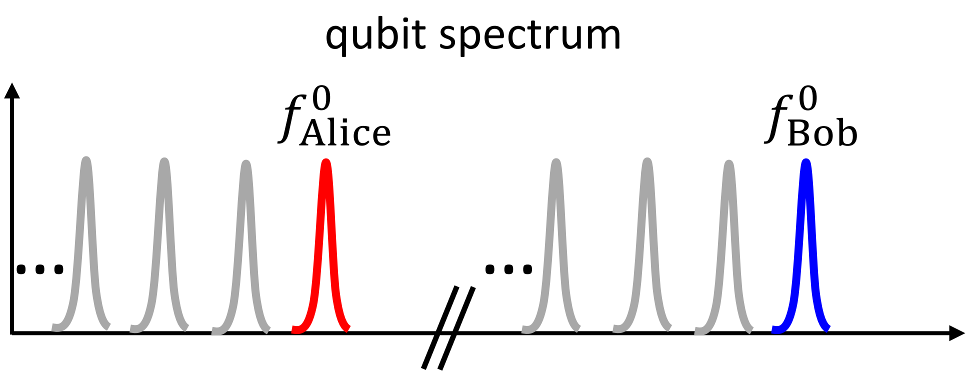
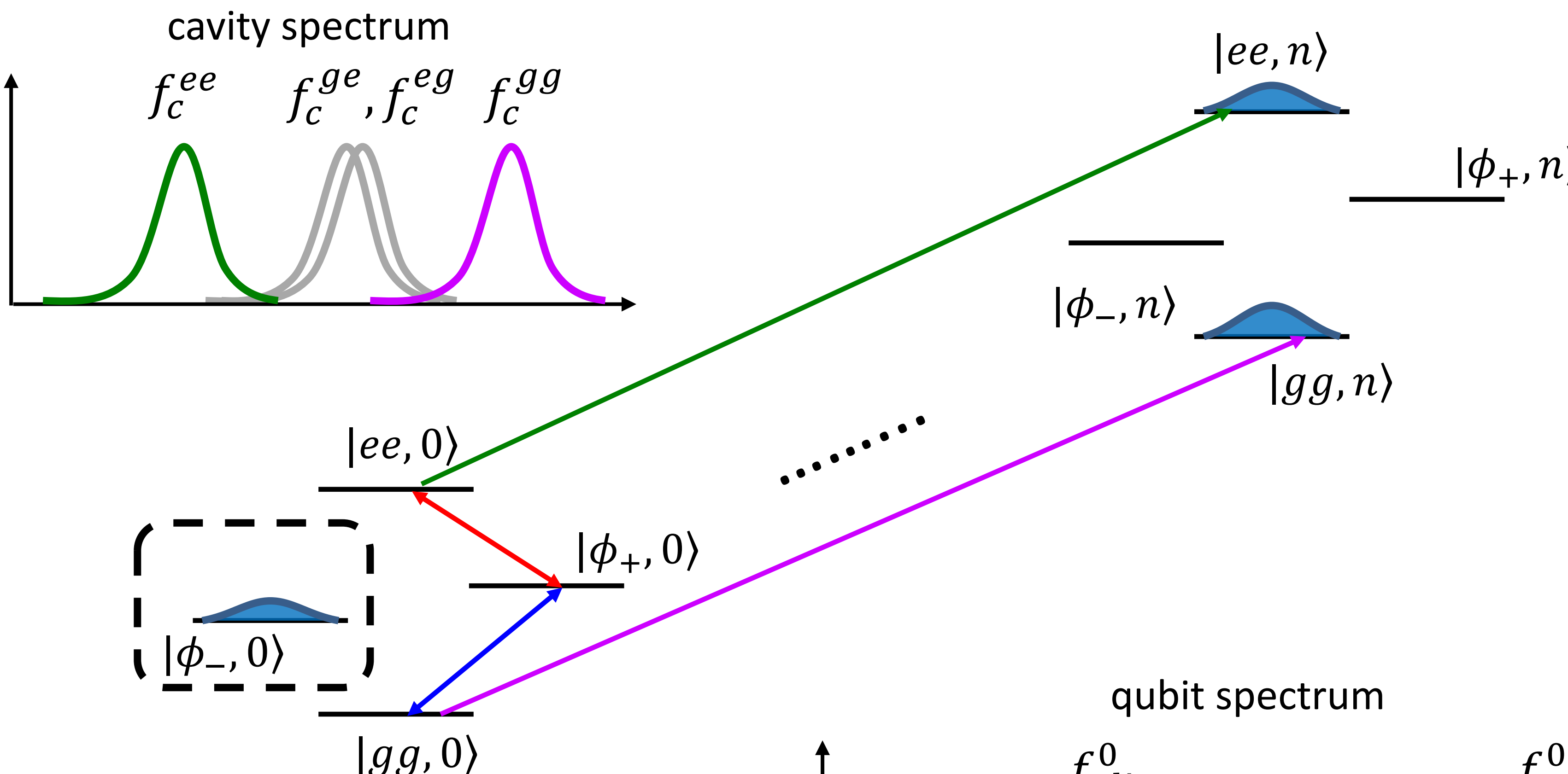
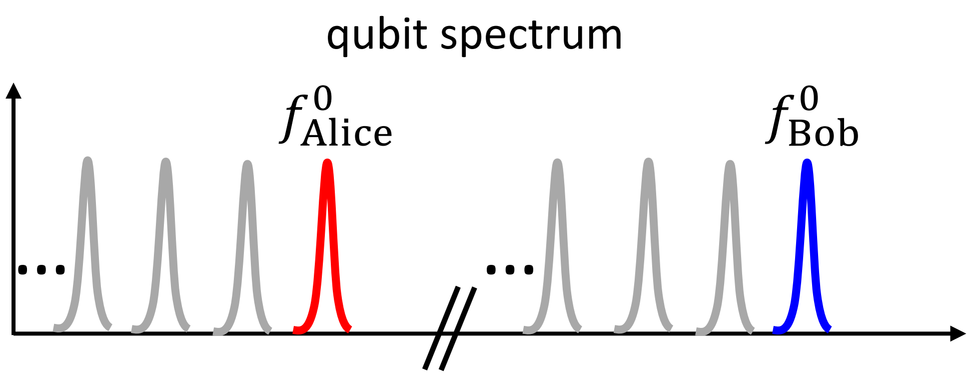


- Select even parity
- Select Bell state: $|\phi_+, 0\rangle$ pumped to n photon manifold
  – by phase of drives



Autonomous stabilization of Bell state $|\phi_-\rangle = \{|ge\rangle - |eg\rangle\}/\sqrt{2}$





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- Select Bell state: $|\phi_+,0\rangle$ pumped to n photon manifold
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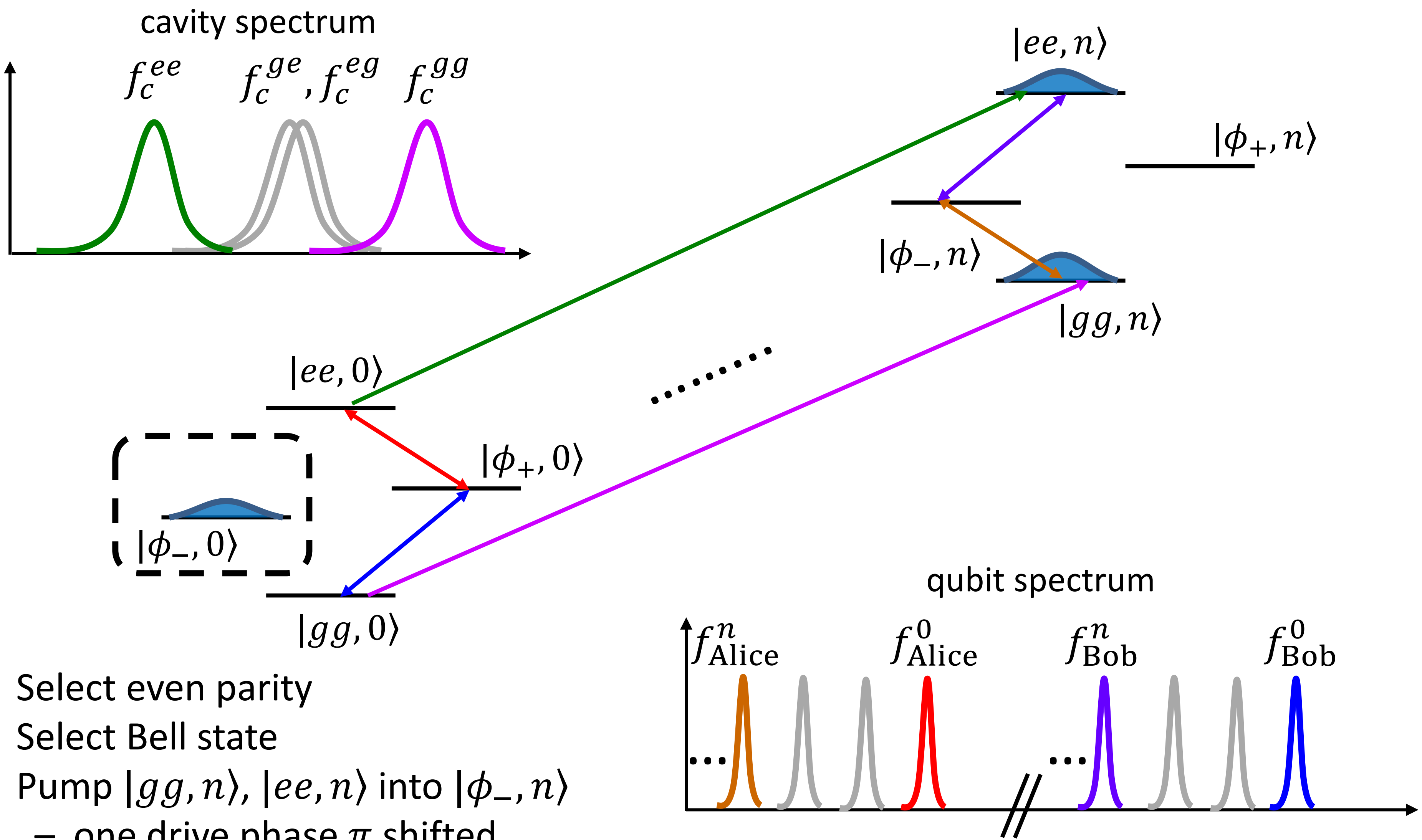
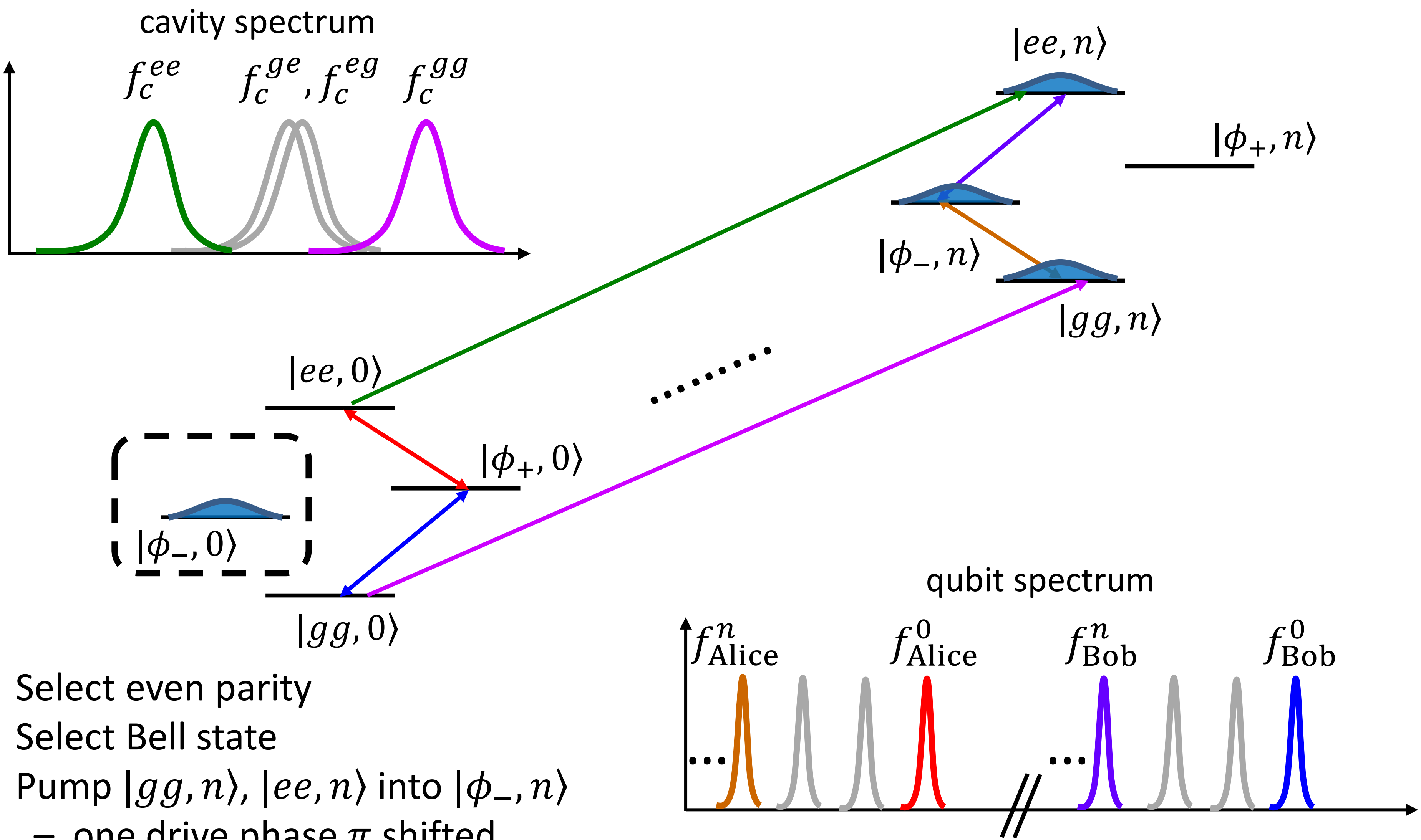


- Select even parity
- Select Bell state
- Pump $|gg, n\rangle$, $|ee, n\rangle$ into $|\phi_-, n\rangle$
  - one drive phase π shifted

Autonomous stabilization of Bell state $|\phi_-\rangle = \{|ge\rangle - |eg\rangle\}/\sqrt{2}$



- Select even parity
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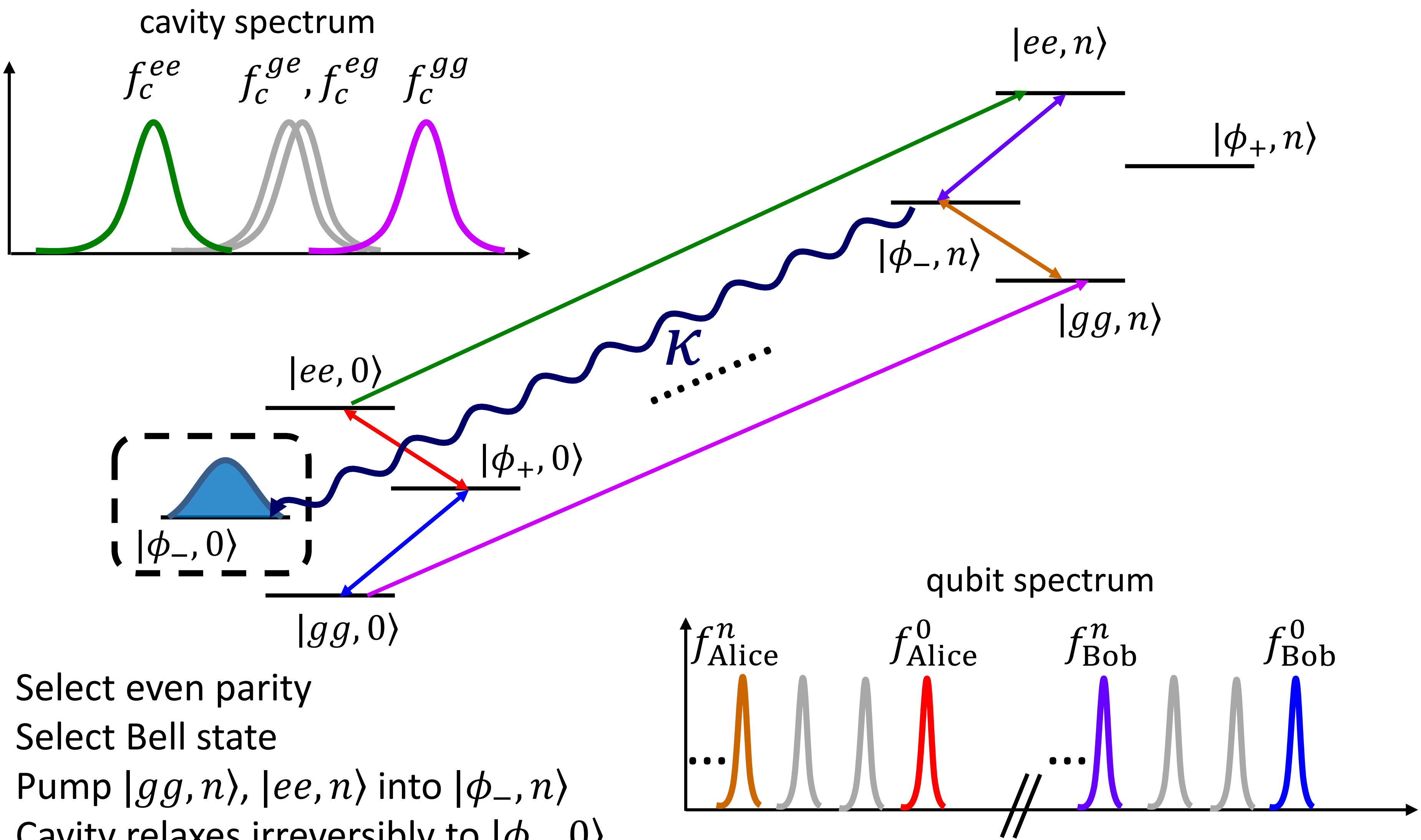
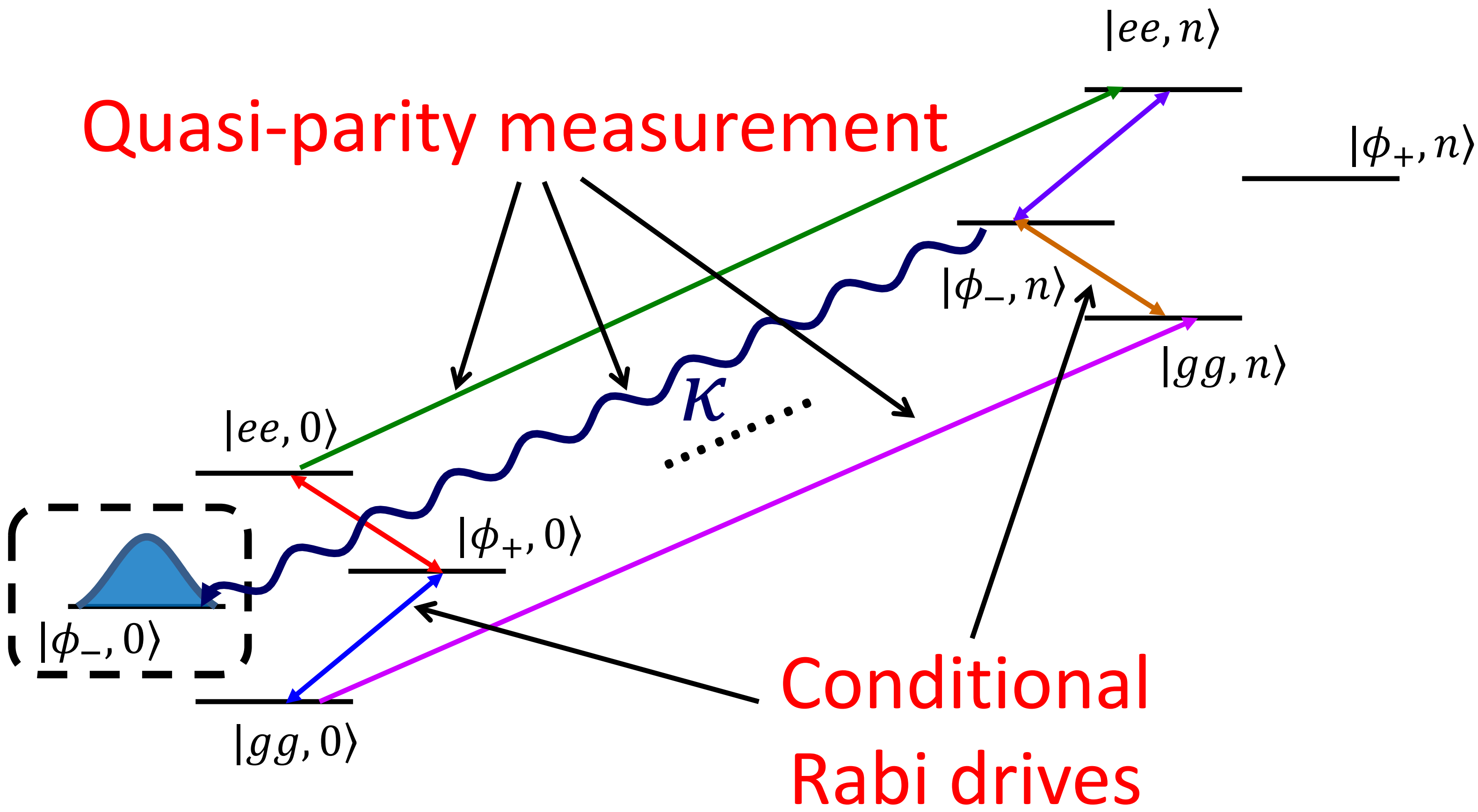
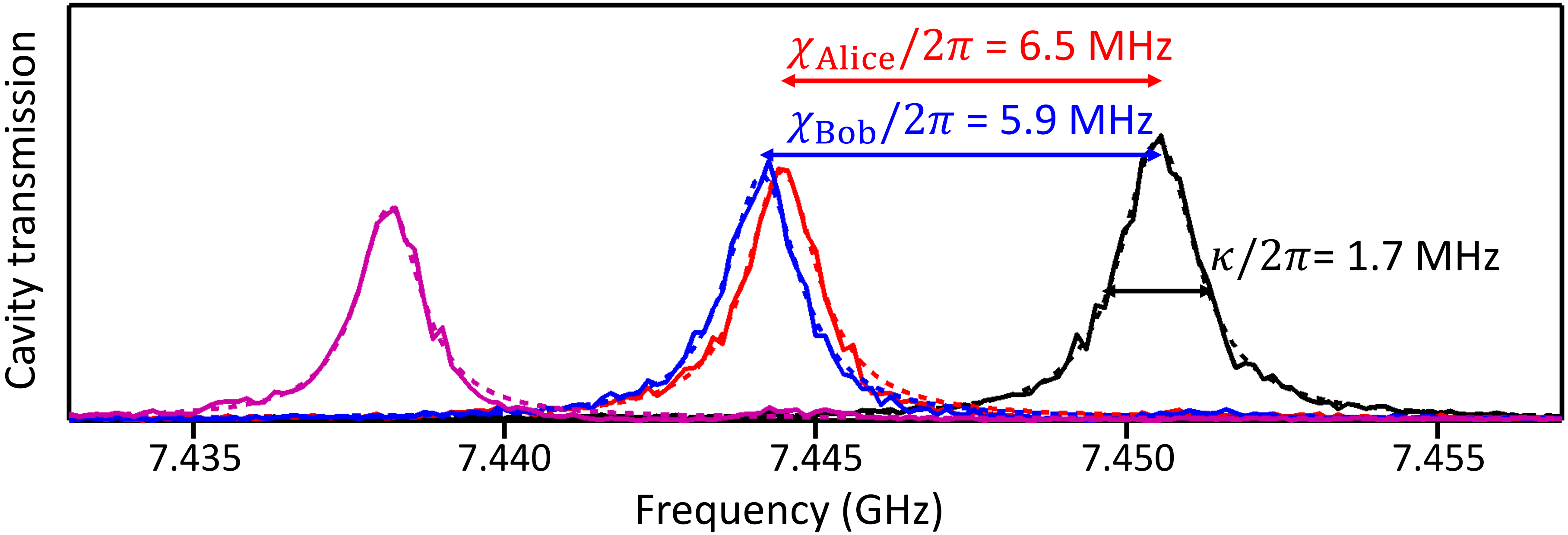


- Select even parity
- Select Bell state
- Pump $|gg,n\rangle$, $|ee,n\rangle$ into $|\phi_-,n\rangle$
- Cavity relaxes irreversibly to $|\phi_-,0\rangle$
  – rate κ

Autonomous stabilization of Bell state $|\phi_-\rangle = \{|ge\rangle - |eg\rangle\}/\sqrt{2}$



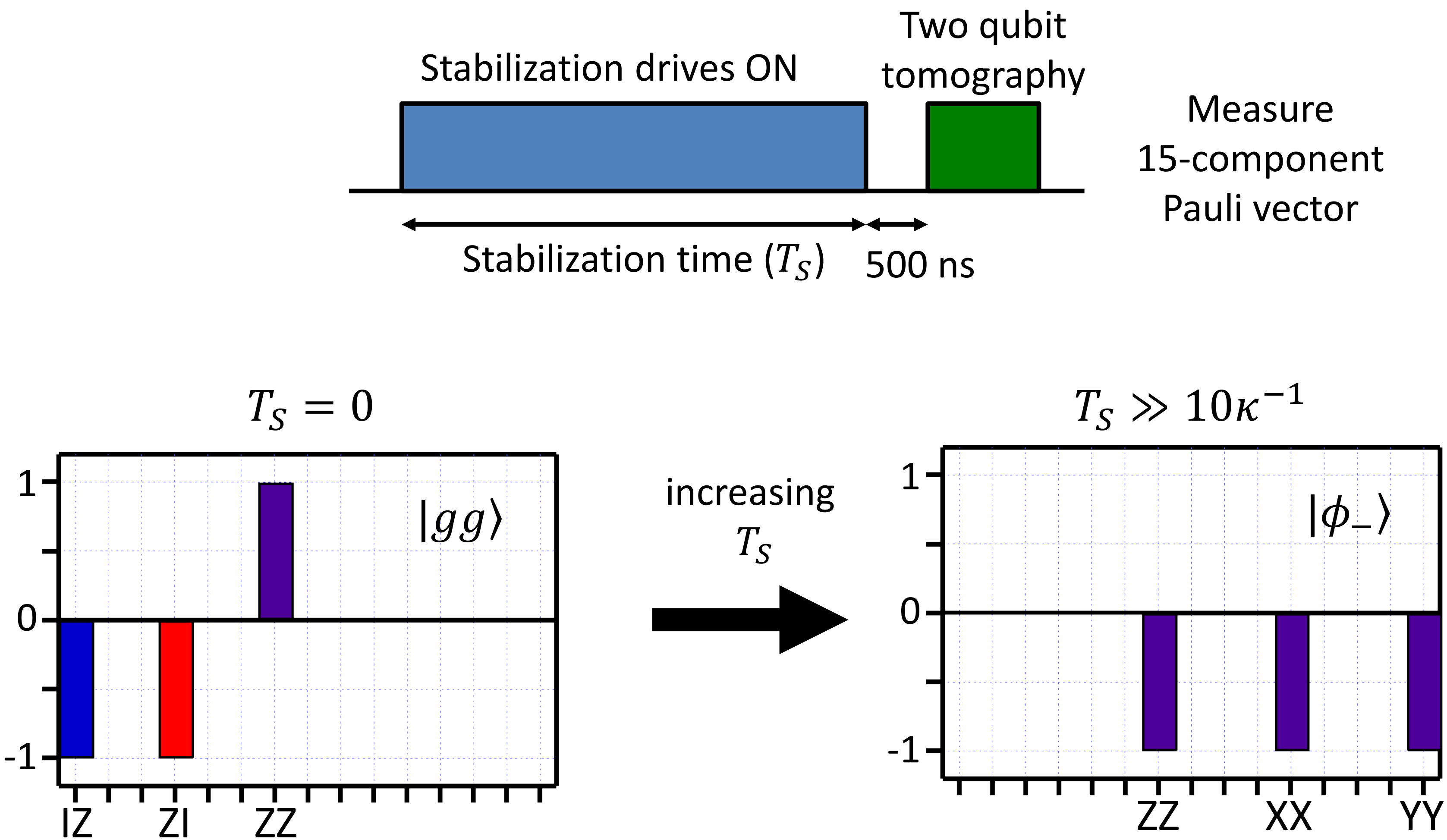
System-reservoir characteristics



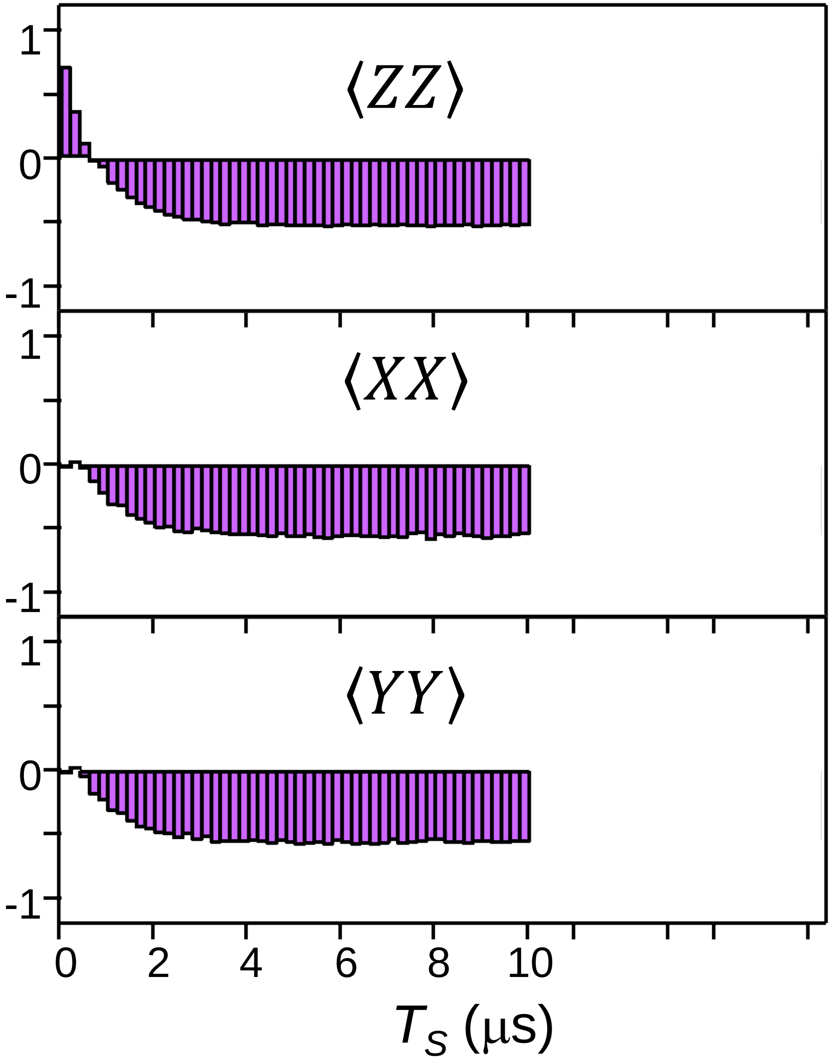
	Qubit frequency (GHz)	T_1 (μs)	T_ϕ (μs)	κT_1	κT_ϕ
Alice	5.238	16	11	170	120
Bob	6.304	9	36	100	380

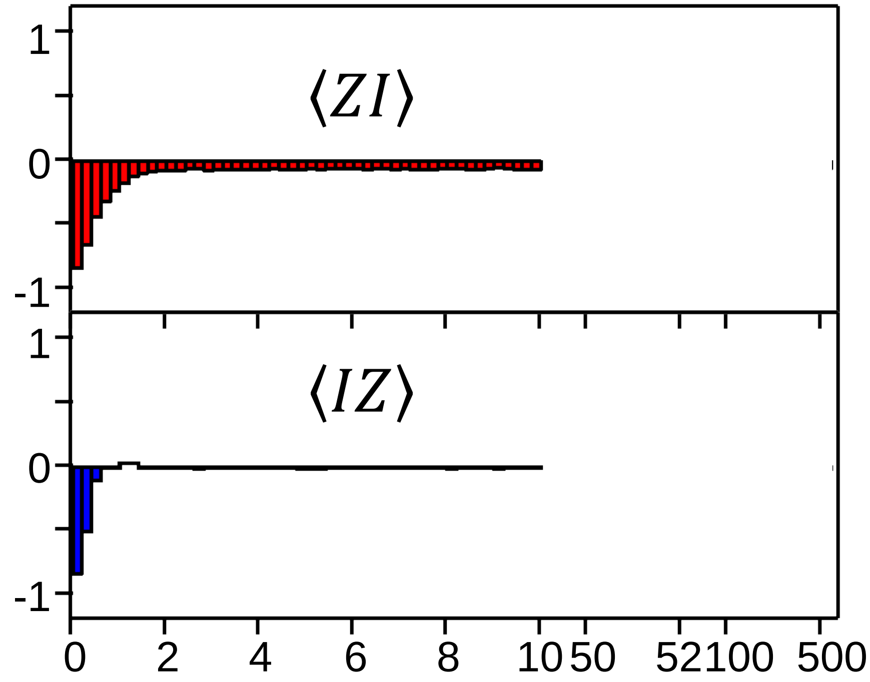
Achieve $\kappa T_1, \kappa T_\phi > 100$

Experiment protocol



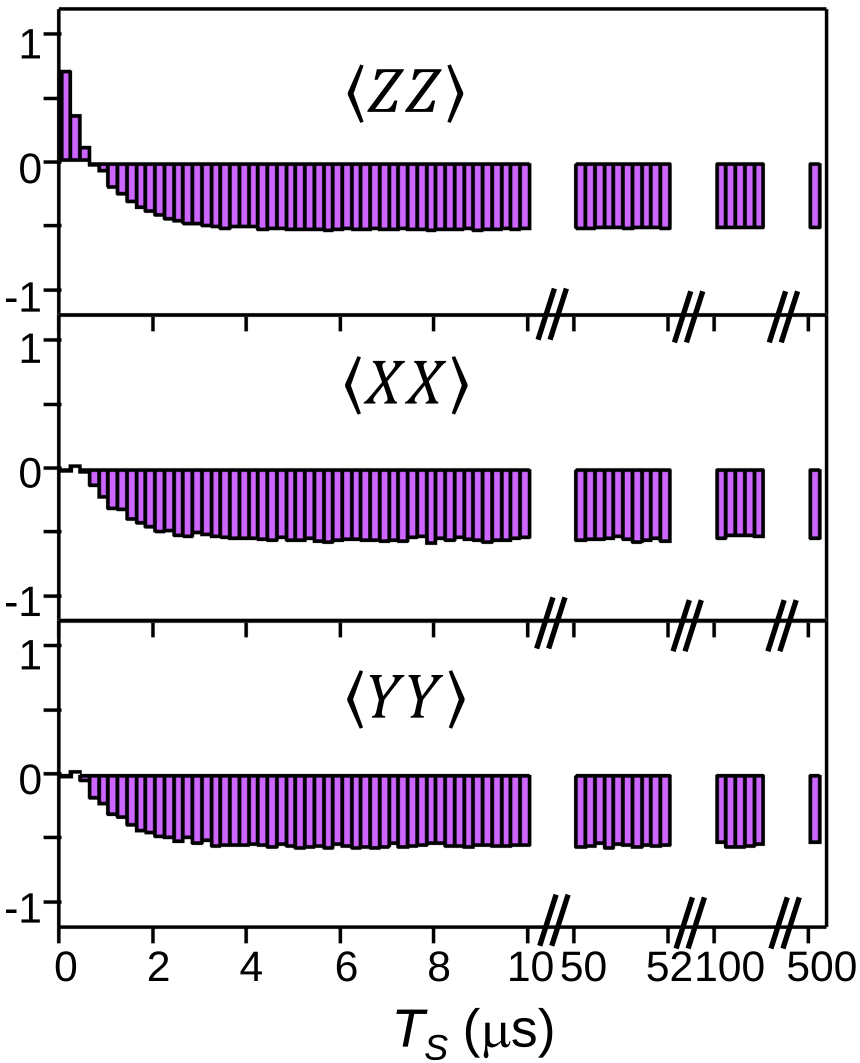
Tomography results vs T_S

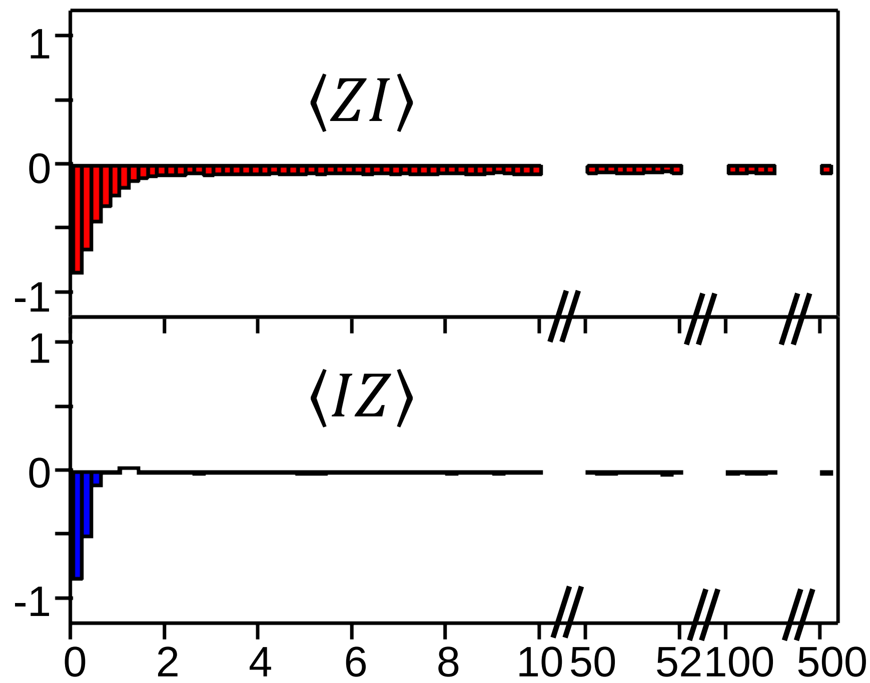




Converges to $|\phi_-\rangle$

Tomography results vs T_S



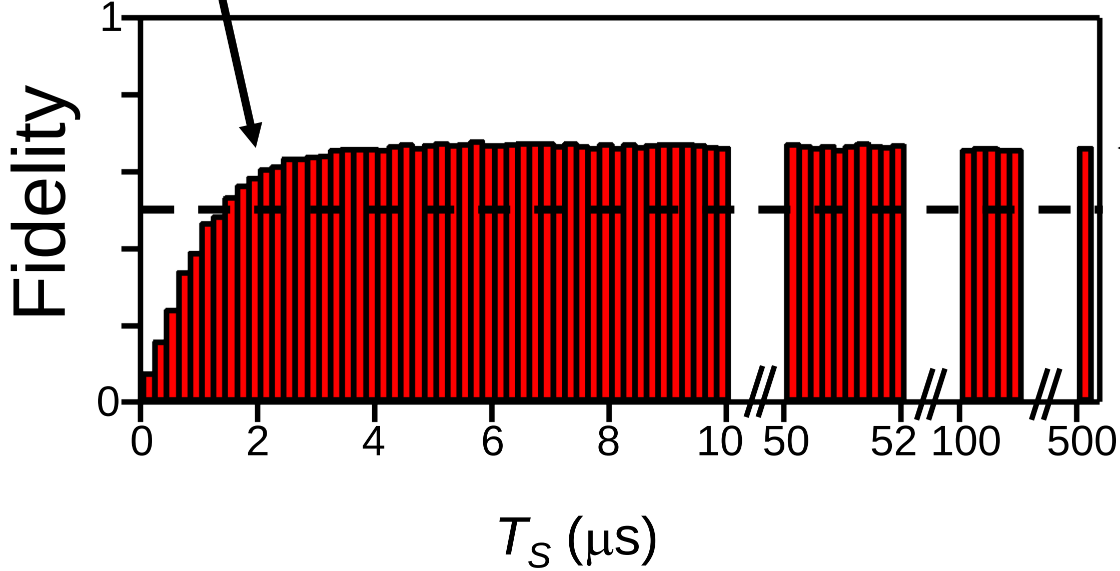


Converges to $|\phi_-\rangle$

And remains stable much longer than T_1, T_ϕ

Fidelity to Bell state

Exponential rise, τ = 960 ns ~ $10\kappa^{-1}$

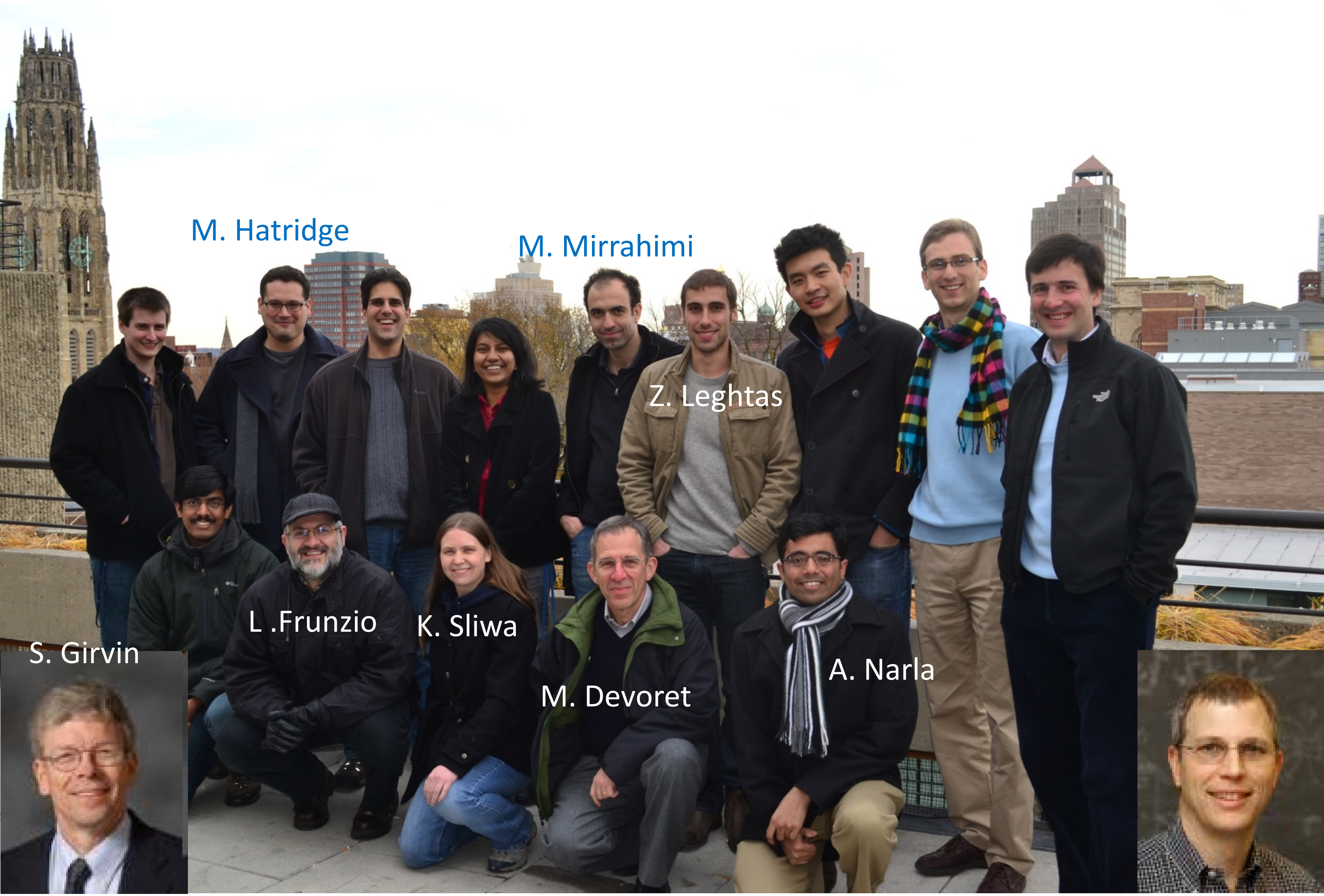


Steady-state = 67 %, above 50 % threshold for entanglement

- Improved to 77 % by monitoring cavity output
- Expect above 90 % in future version with improved T_1

S. Shankar et al., arXiv:1307.4349, to appear in Nature

Qulab and friends



Thank you