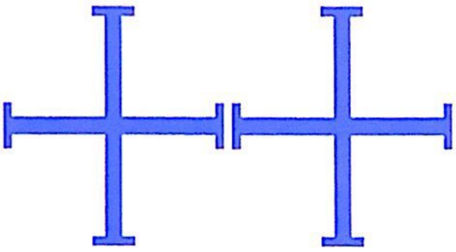
Coupling between transmon qubits

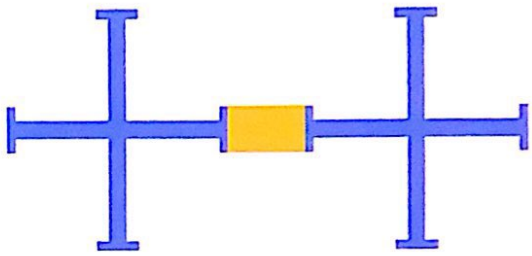
Fixed coupling

Simple design, large detunings



Adjustable coupling

Strong interaction on demand



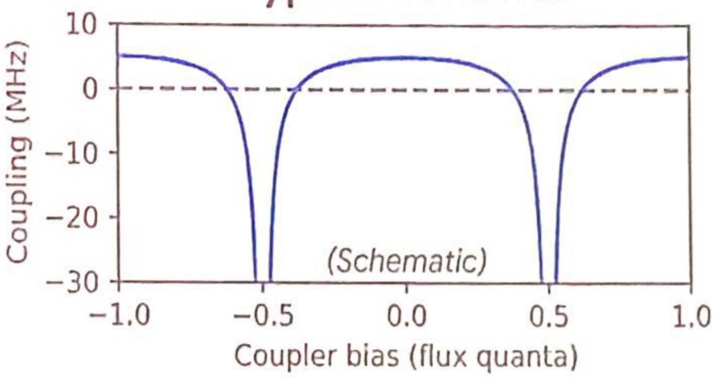
Fixed coupling		Adjustable coupling
~ 10 MHz	**Coupling**	~ 0 to 40 MHz
~ 1 GHz	**Detuning**	~ 10 MHz
~ 40 ns	**Gate length**	~ 10 ns

Barends et al., *Nature* (2014)

Neill thesis (UCSB, 2017)

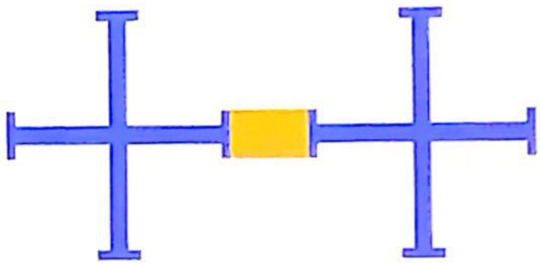
Coupling between transmon qubits

Typical behavior



Adjustable coupling

Strong interaction on demand



Coupling ~ 0 to 40 MHz

Detuning ~ 10 MHz

Gate length ~ 10 ns

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Neill thesis (UCSB, 2017)

2D arrays of qubits and couplers

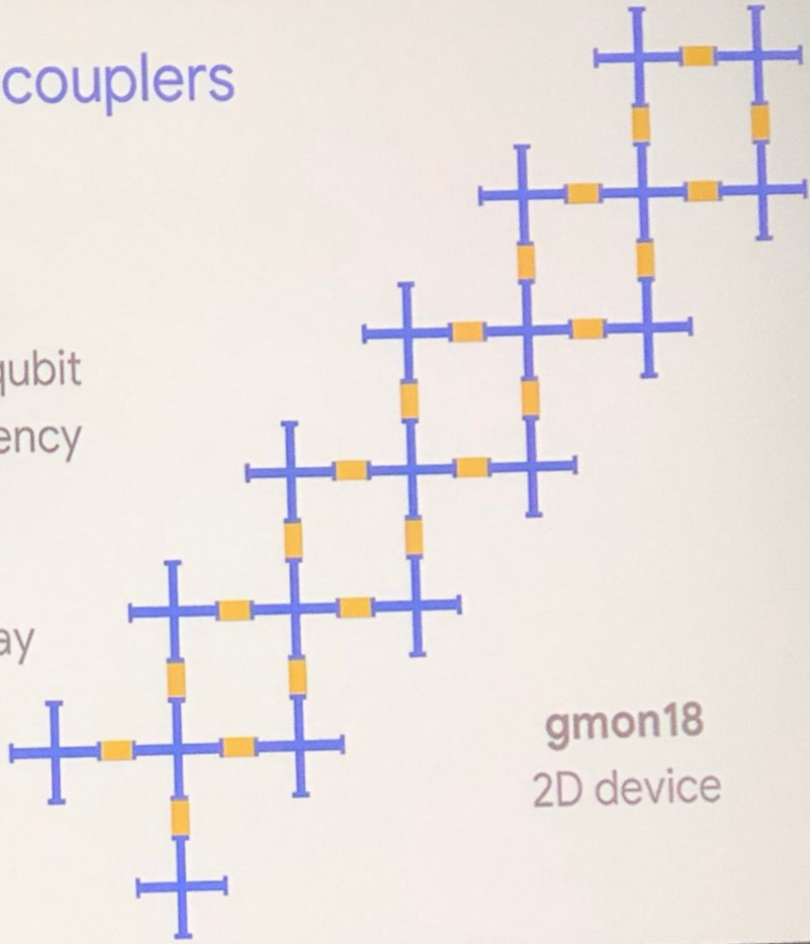
Complicates qubit bringup

Up to 4 couplers touching each qubit

Coupler bias affects qubit frequency

Double the control lines

n qubits → 2*n* couplers in 2D array



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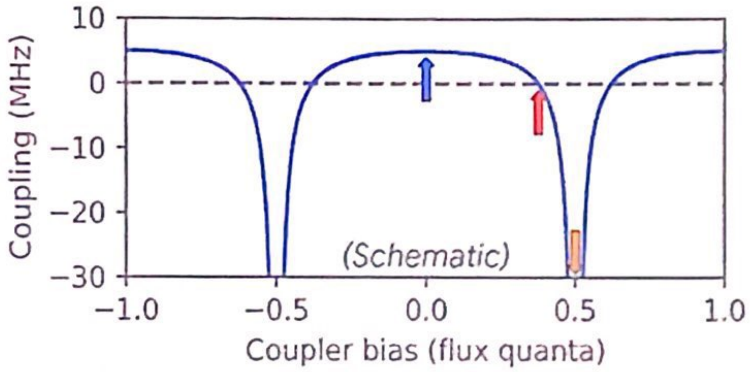
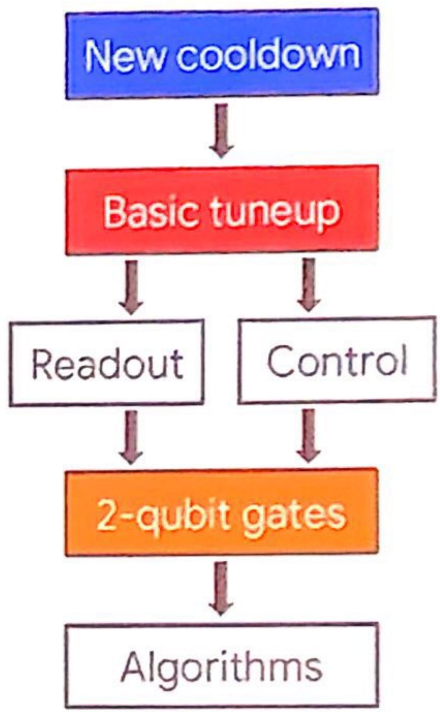
Strategy for automatic calibration of processors

Optimus: Calibrate qubits automatically using a graph of calibration dependencies

Integrate couplers: Add experiments at key points

1. Find a safe coupler bias
2. Turn the coupling off
3. Pulse on strong coupling





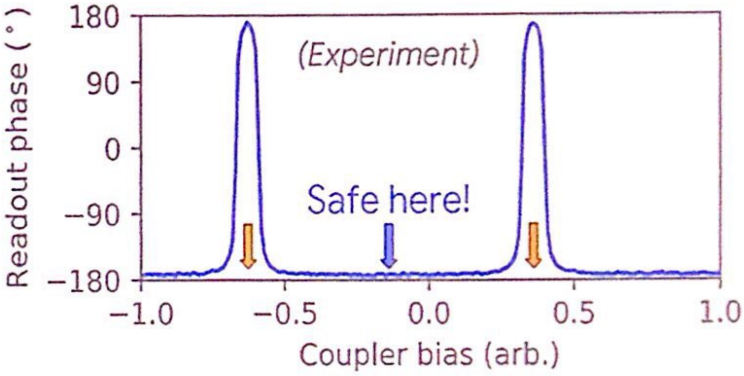
Kelly et al., arXiv:1803.03226

Step 1: Place couplers at safe bias

Coupler shifts qubit frequency
in high-coupling region

Readout resonator measurement
without costly qubit bringup

1. Place qubit near max frequency
   a. Turn off the other qubit
2. Measure readout resonator



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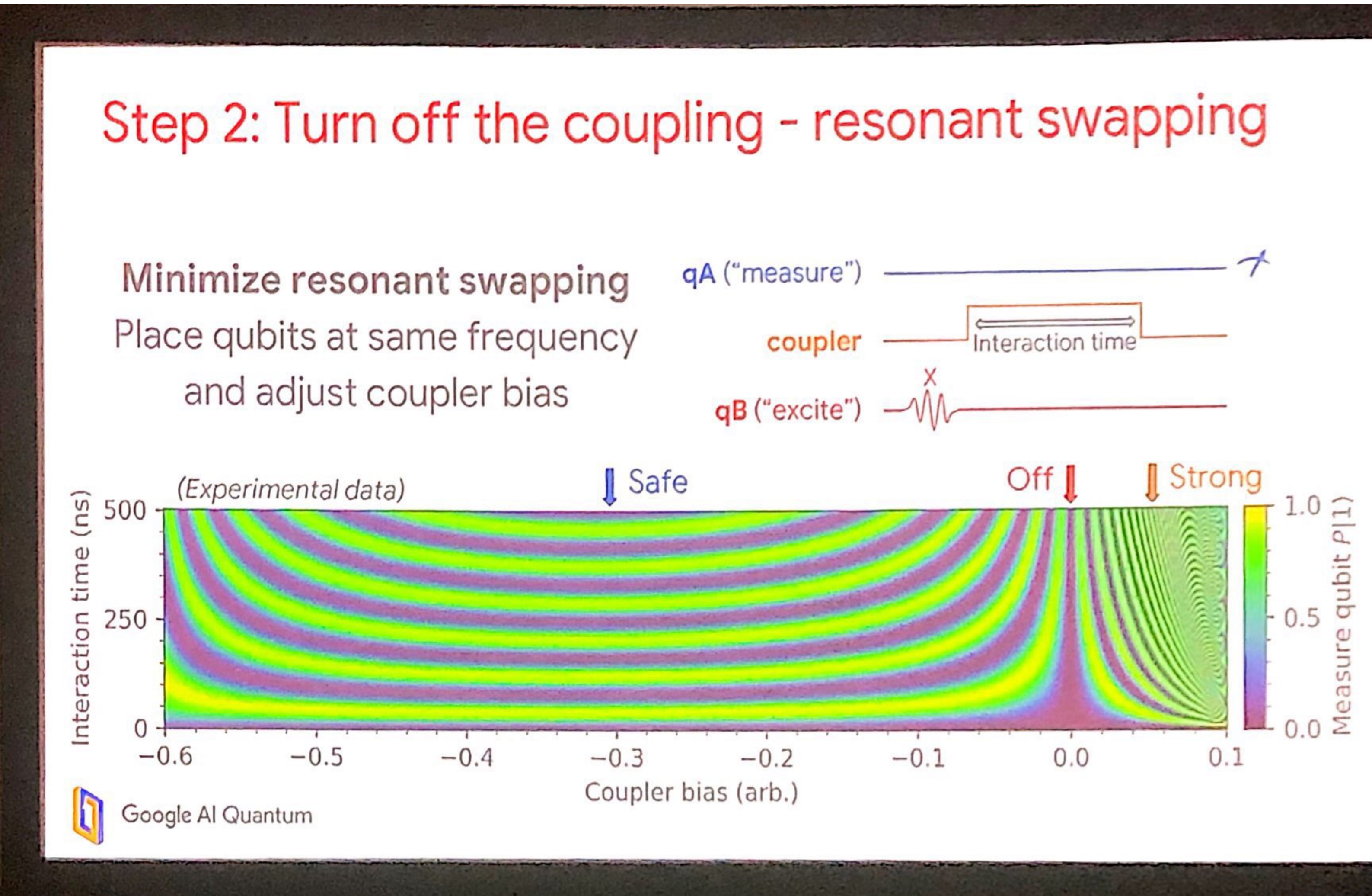
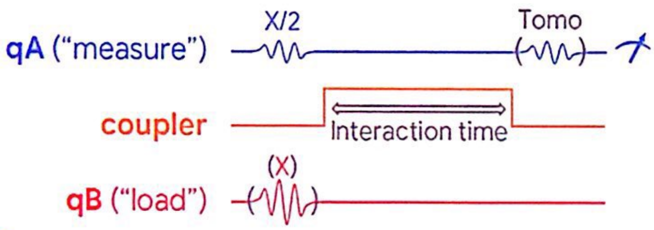


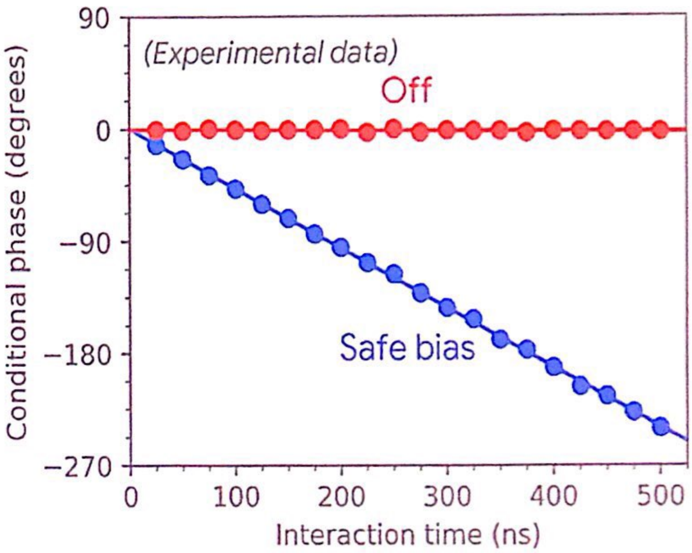
Step 2: Turn off the coupling - resonant swapping
Minimize resonant swapping
Place qubits at same frequency
and adjust coupler bias
qA ("measure")
coupler
Interaction time
X
qB ("excite")
(Experimental data)
Safe
Off
Strong
Interaction time (ns)
500
250
0
−0.6
−0.5
−0.4
−0.3
−0.2
−0.1
0.0
0.1
Coupler bias (arb.)
1.0
0.5
0.0
Measure qubit P|1⟩
Google AI Quantum

Step 2: Turn off the coupling - conditional phase

Minimize conditional phase
Leave qubits detuned
and adjust coupler bias

Accumulate phase over time
and take the slope





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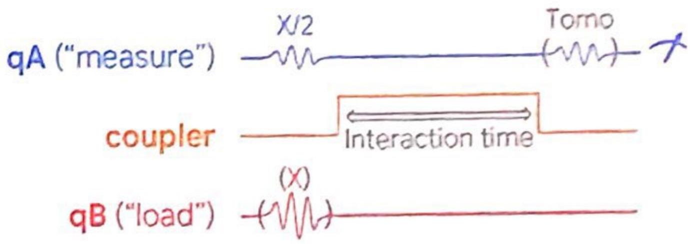
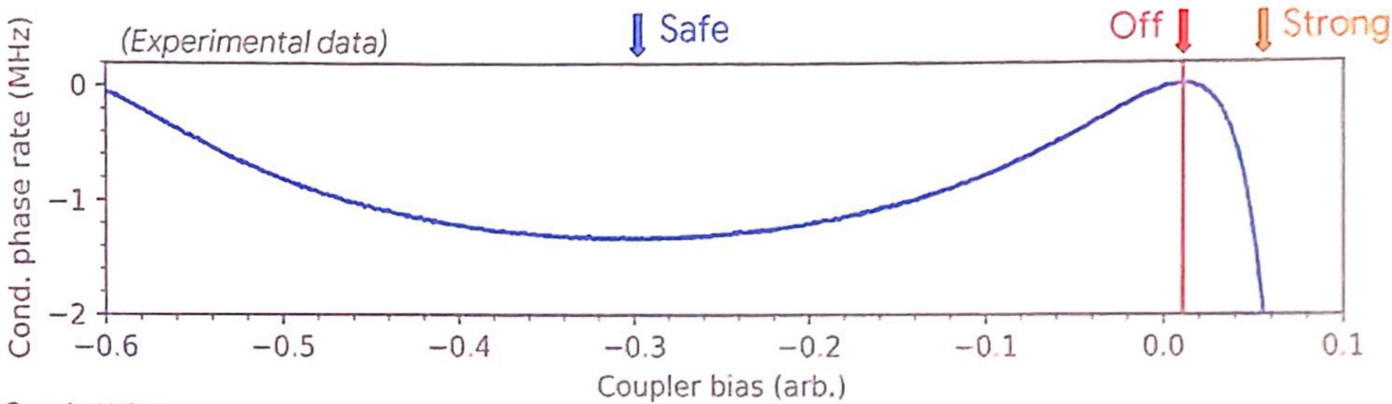
Step 2: Turn off the coupling - conditional phase

Minimize conditional phase

Leave qubits detuned
and adjust coupler bias





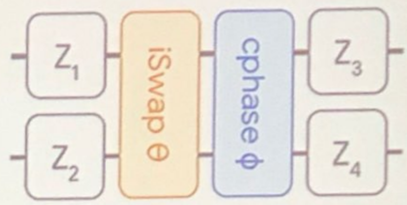
Step 3: Entangling gate

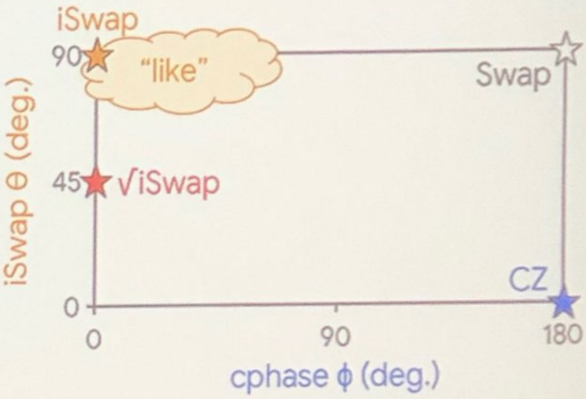
Natural gate for our hardware:
iSwap-like, with some conditional phase

1. Tune up pulses
2. Use cross-entropy benchmarking to *model what we did*

Related talks
Brooks Foxen, B42.8 (12:39 pm, this room)
Pedram Roushan, B29.9 (12:51 pm, 162A)

Model for arbitrary photon-conserving gate





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Step 3: Entangling gate - iSwap-like

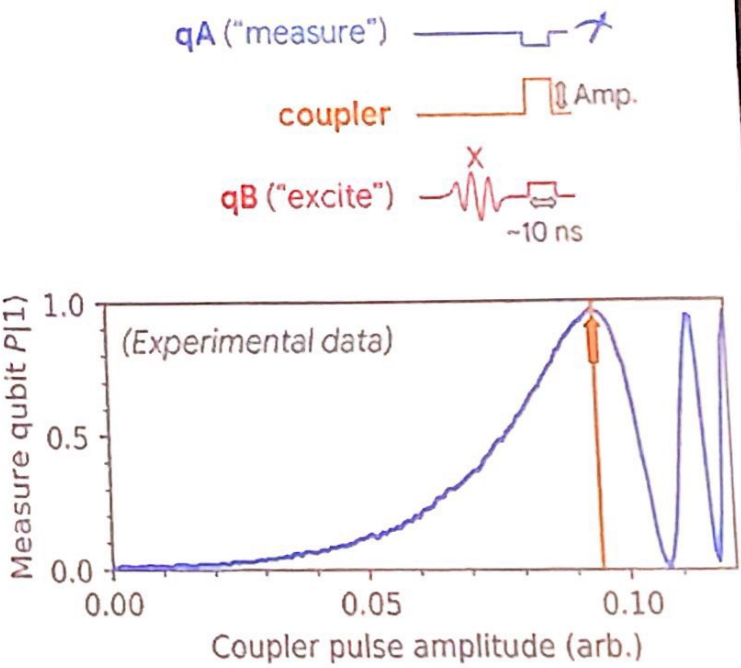
Pulse coupling on

Bring qubits to the same frequency and pulse to transfer one photon

Characterize gate

Cross-entropy benchmarking

(iSwap θ, cphase ϕ)



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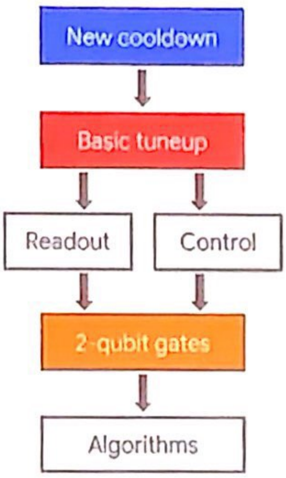
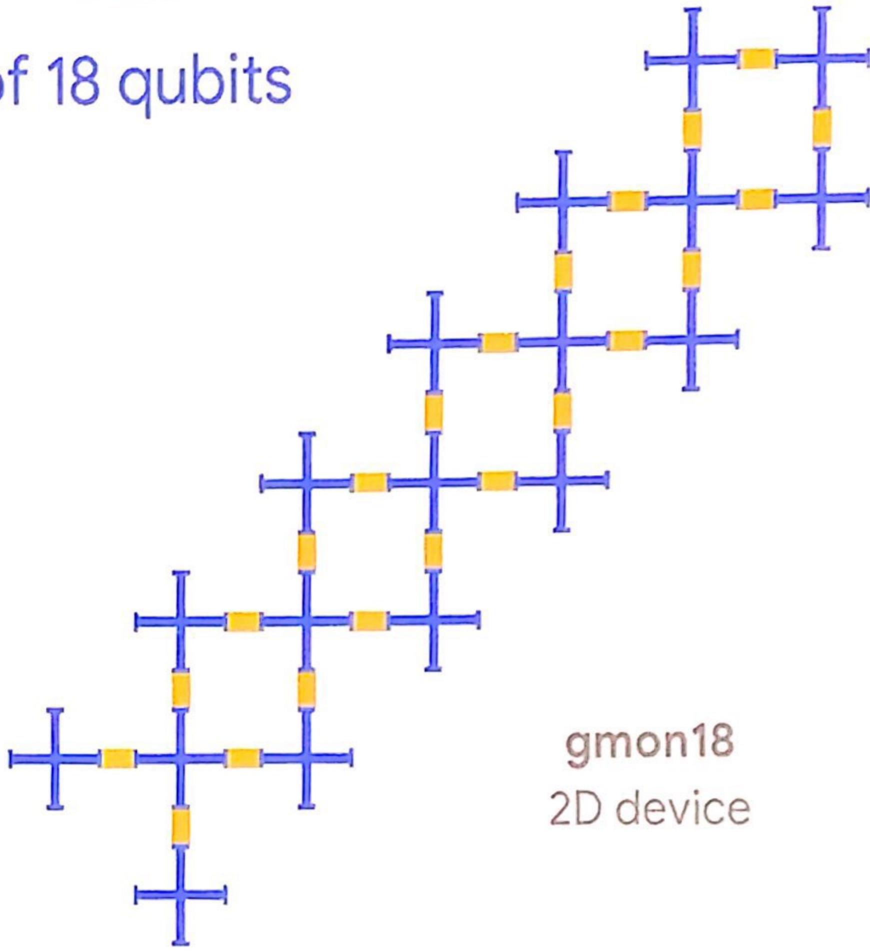
Review: calibrate grid of 18 qubits

Select qubit frequencies

Paul Klimov, V35.13 (Thursday)

Automatically calibrate





gmon18

2D device

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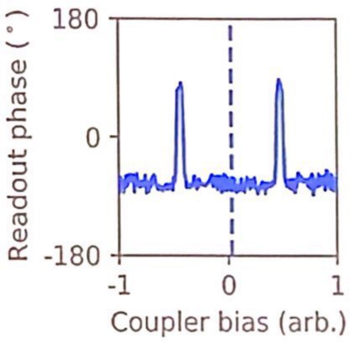
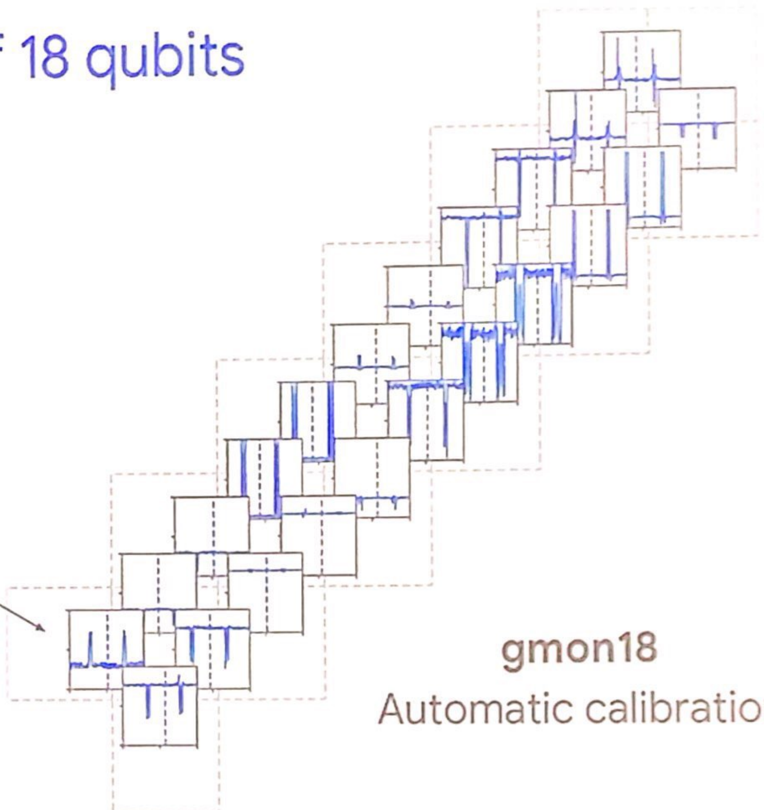
Review: calibrate grid of 18 qubits

1. Safe coupler bias

Only do once





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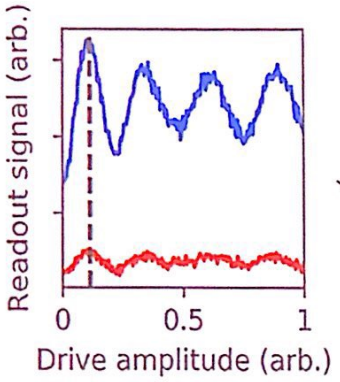
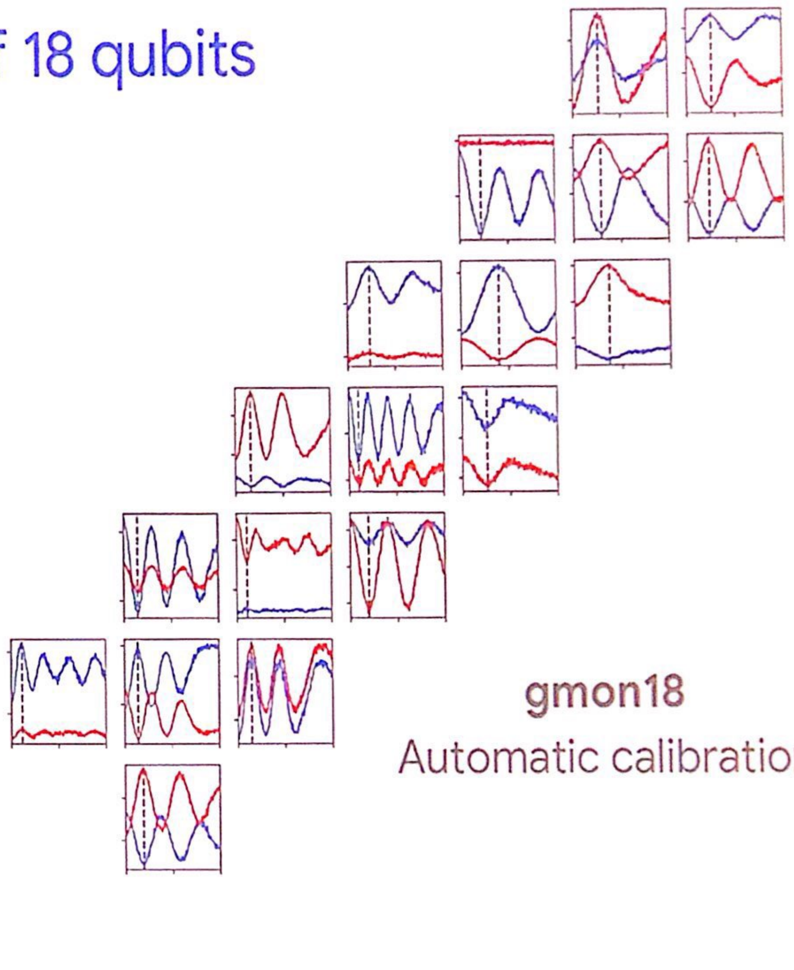
Automatic calibration

Review: calibrate grid of 18 qubits

Rabi oscillations

π pulse





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Automatic calibration

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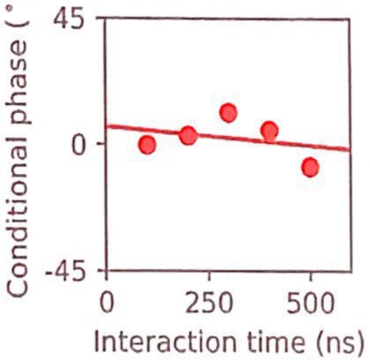
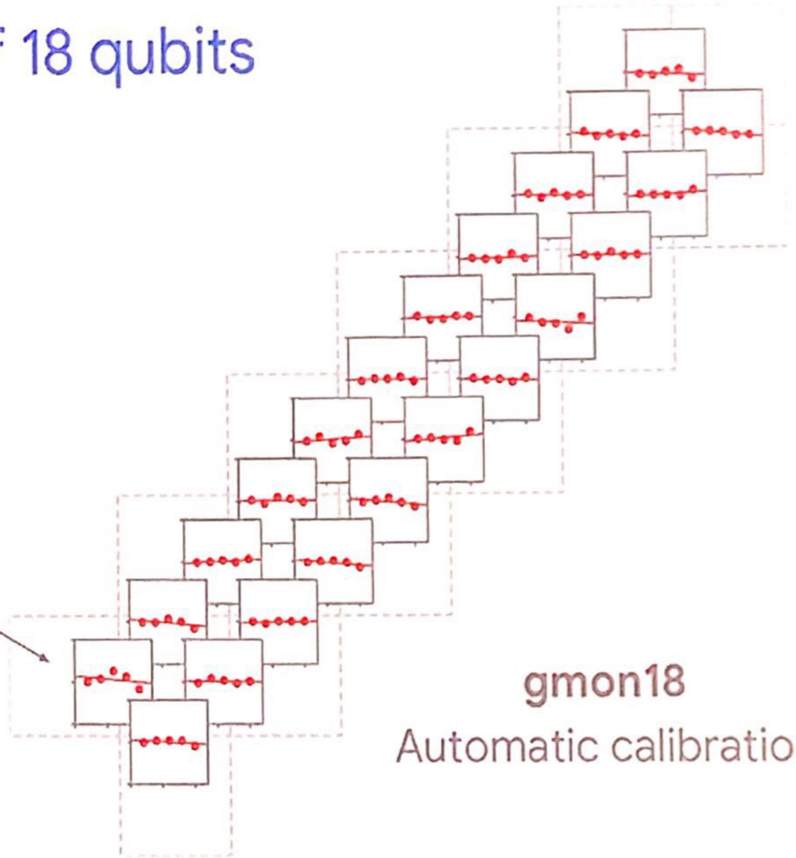
Review: calibrate grid of 18 qubits

2. Coupling off

Conditional phase





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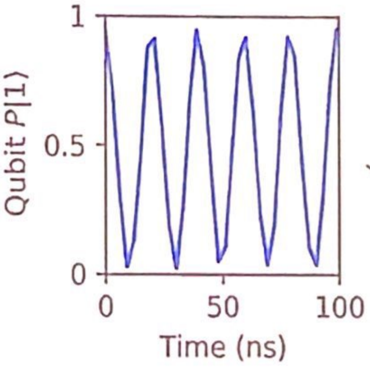
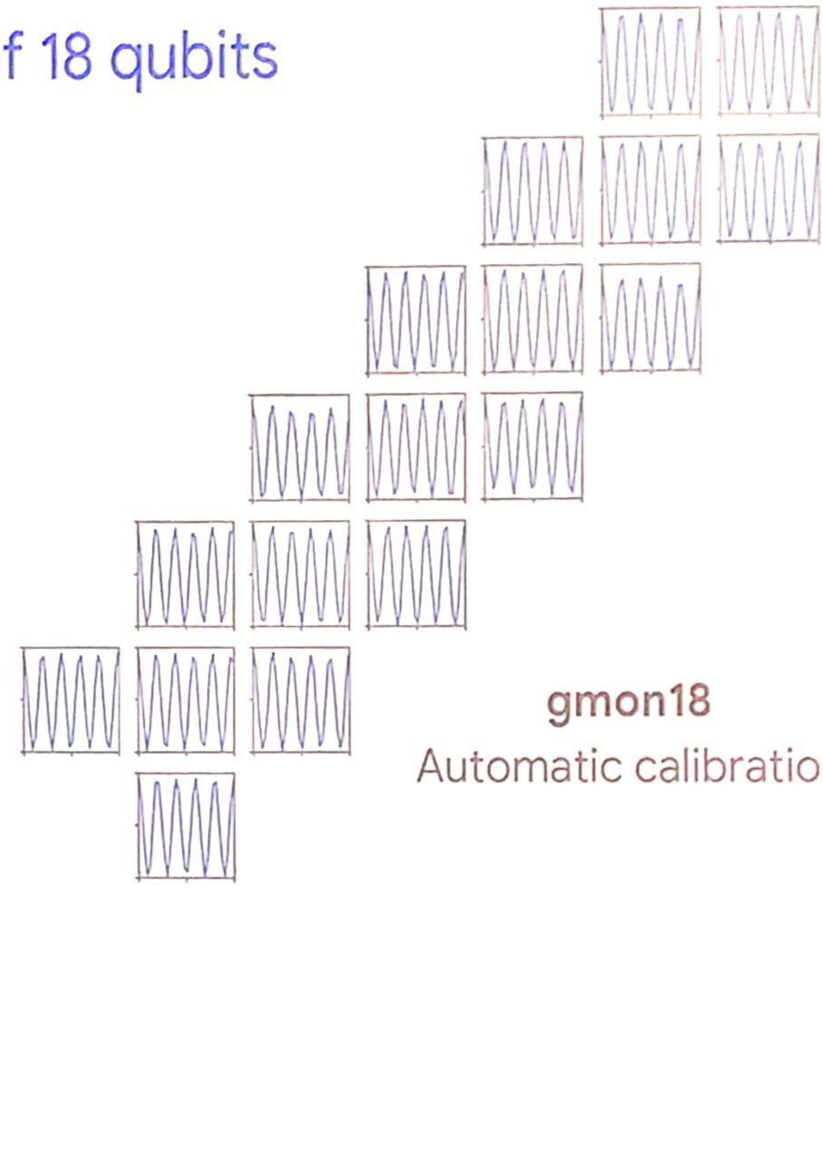
Automatic calibration

Review: calibrate grid of 18 qubits

Ramsey

Qubit frequency





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Automatic calibration

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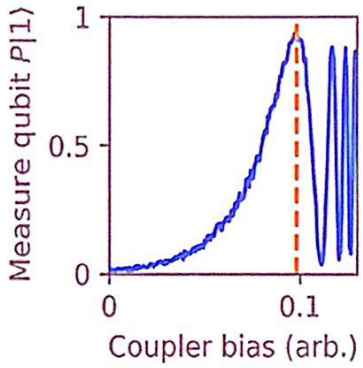
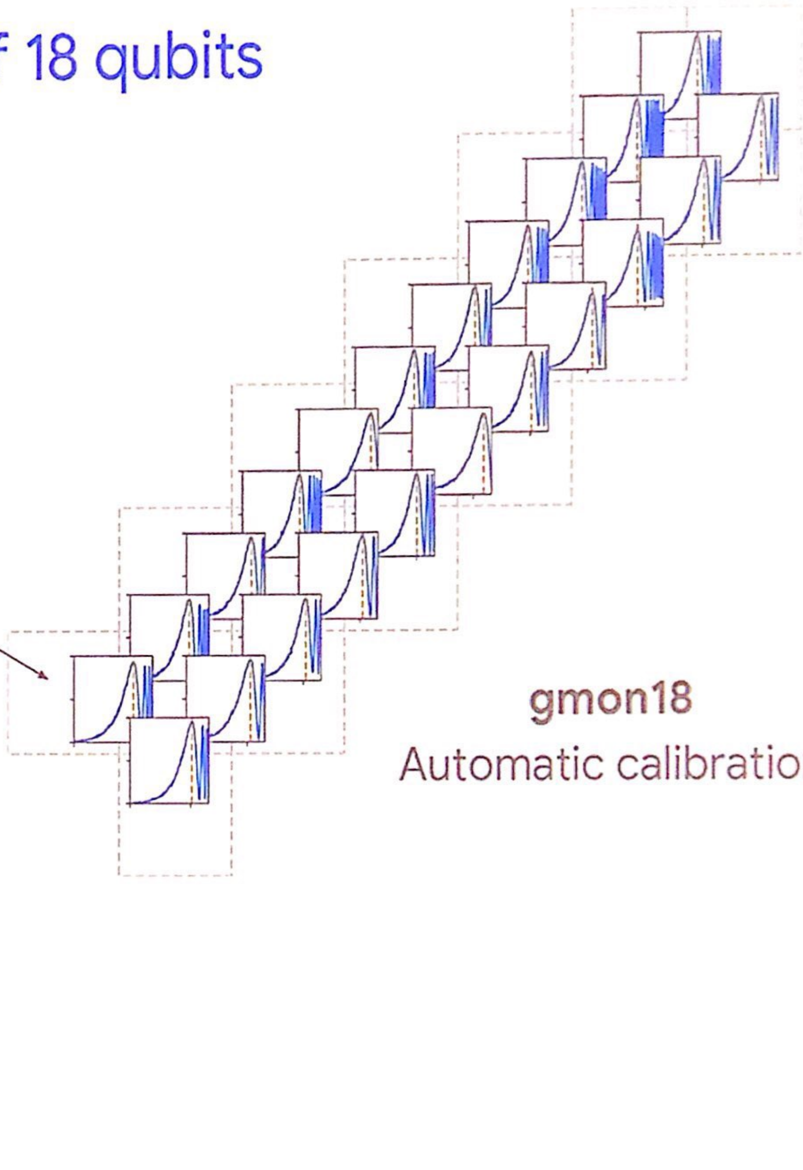
Review: calibrate grid of 18 qubits

3. iSwap-like gate

After, characterize (θ, ϕ)





gmon18

Automatic calibration

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Conclusion & Acknowledgements

Adjustable couplers add flexibility and complexity

Calibrate 2D arrays automatically with 3 key experiments