RECENT ADVANCES IN QUANTUM COMPUTING AND TECHNOLOGY

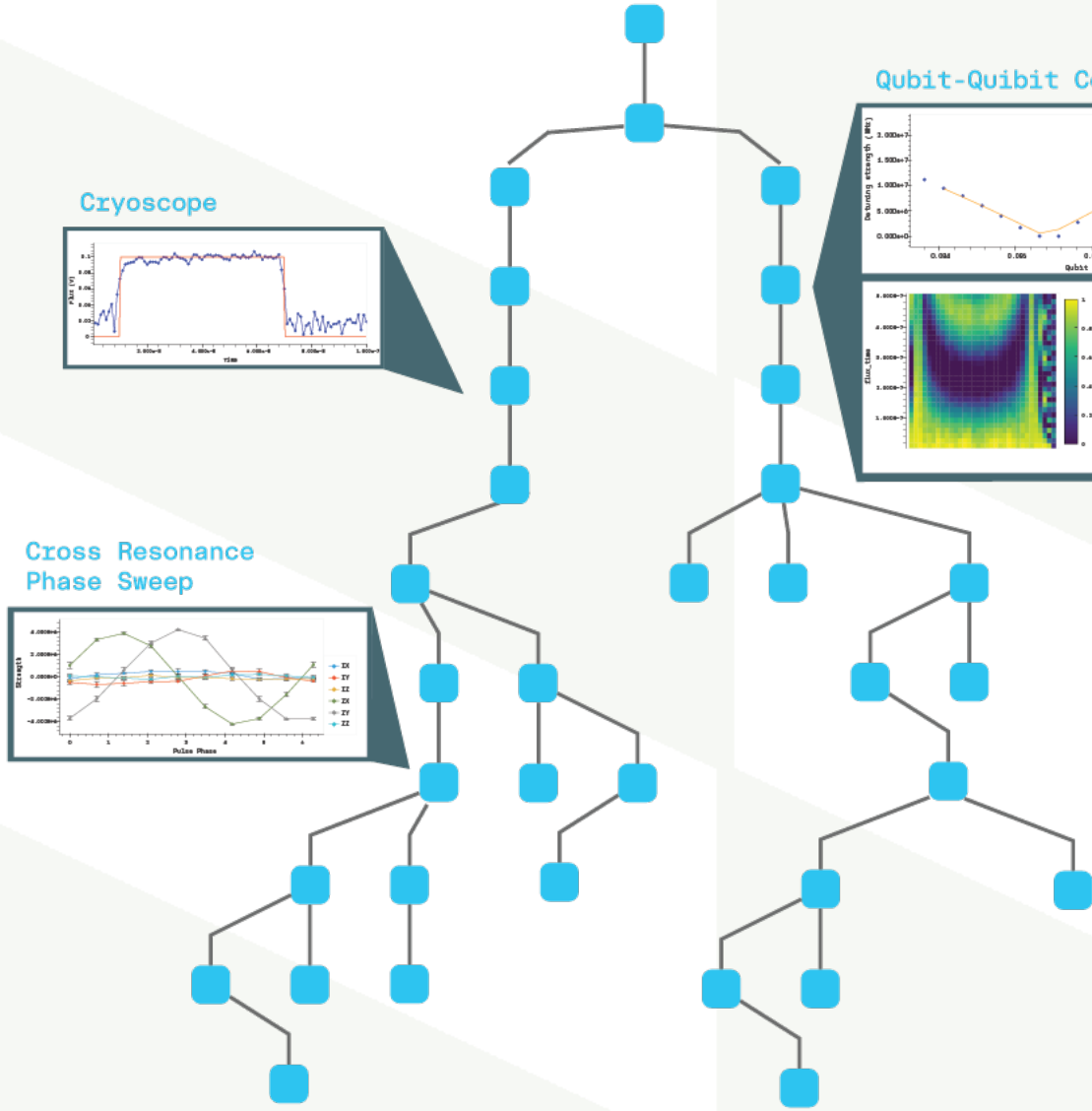
Improving flux-based gates in superconducting QPUs through Automated Calibration & Model Learning

Anurag Saha Roy

qruise

QruiseOS

Fully automated comprehensive characterization and bring-up of superconducting quantum computers



Cryoscope

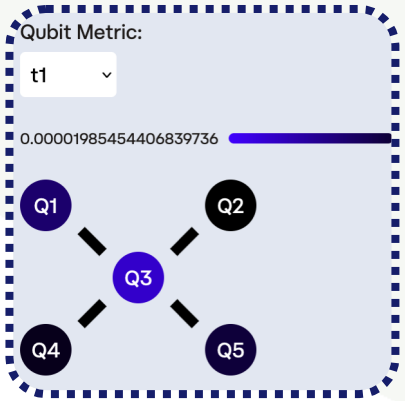
Qubit-Quibit Coupling

Cross Resonance Phase Sweep

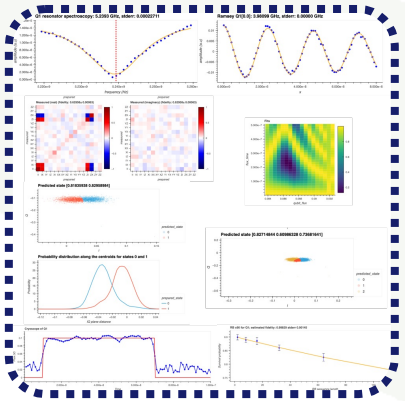
and many more Experiments!

- Amplitdue Rabi
- Coupler Spectroscopy
- CPMG Noise Spectroscopy
- Cross Resonance Amplitude Sweep
- Cross Resonance Phase Sweep
- Cross Resonance Tomography
- Cryoscope
- DRAG Calibration
- Filter Spectroscopy
- Flux Crosstalk Ramsey
- Flux Spectroscopy
- Optimal Control RX90
- Orbit Calibration
- Ping Pong
- Pulsed Spectroscopy
- Punch Out
- Quantum Process Tomography
- Qubit-Qubit Coupling
- Ramsey
- Randomized Benchmarking
- Readout Contrast
- Readout Discriminator
- Resonator Spectroscopy
- T1
- T2 Echo
- T2 Star Ramsey

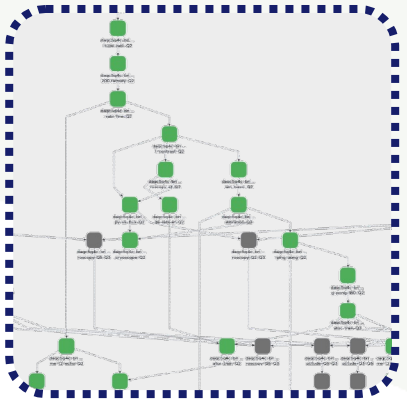
QruiseOS: Rapid & Comprehensive Bring-up



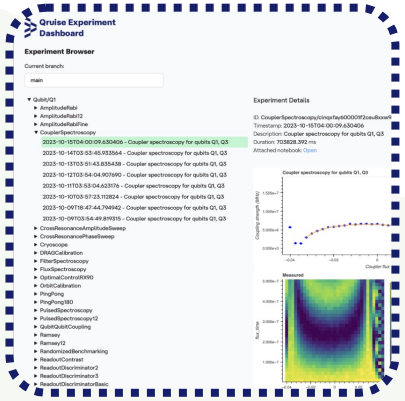
Database to store & retrieve system models



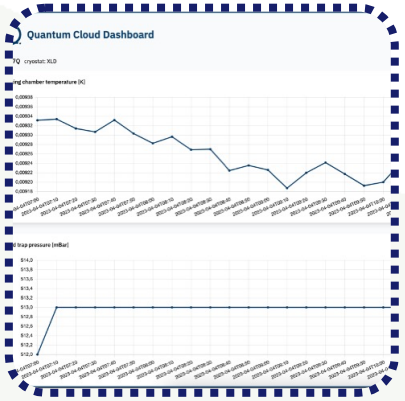
Library of 40+ experiments + Bring your own



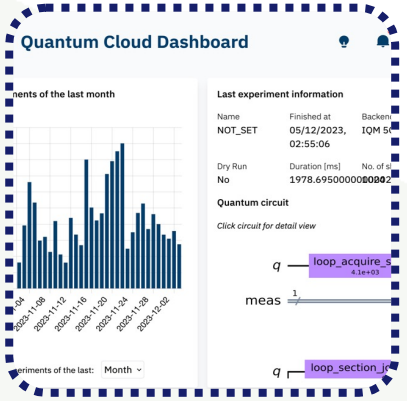
Graph-based dependency & execution



Experiment Storage, Sharing & Reproducibility



System state tracking & monitoring

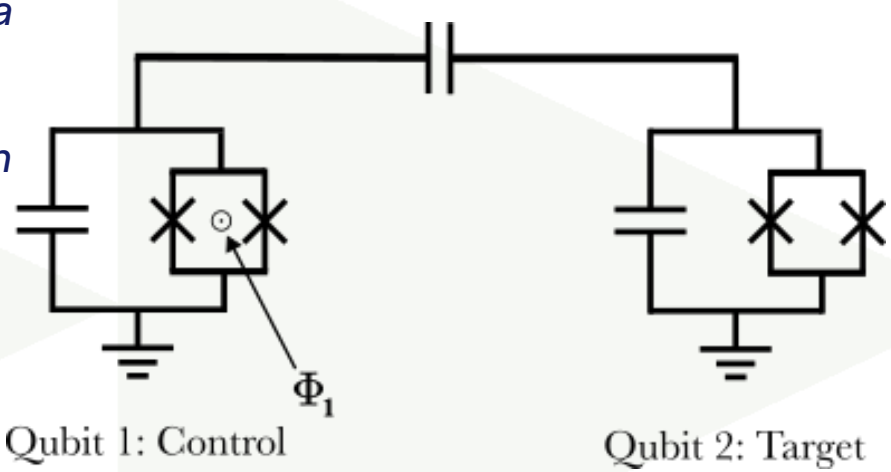


Private Quantum Cloud with Qiskit integration

Storage and Retrieval of System Models

- *alpha*
- *amplitude*
- *anhar_raw*
- *coupling_of_flux.a*
- *coupling_of_flux.b*
- *coupling_of_flux.c*
- *coupling_of_flux.g12*
- *crosstalk*
- *delta_fit.b*
- *delta_fit.c*
- *deltas*
- *drag*
- *fidelity*
- *freq_of_flux.d*
- *freq_of_flux.freq*
- *freq_of_flux.phi_0*
- *freq_of_flux.phi*
- *freq_raw*
- *gs*
- *relax_time*
- *resonance_fluxes.flux*
- *spam*
- *stretched_exp_fit.alpha*
- *stretched_exp_fit.theta*
- *t2*
- *x180_amplitude*
- *x180_ef.amplitude*
- *x180_ef.duration*
- *x180_ef.freq*
- *x180.amplitude*
- *x180.drag*
- *x180.duration*
- *x90_randomized_benchmarking.a*
- *x90_randomized_benchmarking.alpha*
- *x90_randomized_benchmarking.b*
- *x90_randomized_benchmarking.epc*
- *x90_randomized_benchmarking.spam*
- *x90.amplitude*
- *x90.drag_optimal_control*
- *x90.drag*
- *x90.duration*
- *zz_coupling_coupler_flux*
- *zz_coupling*

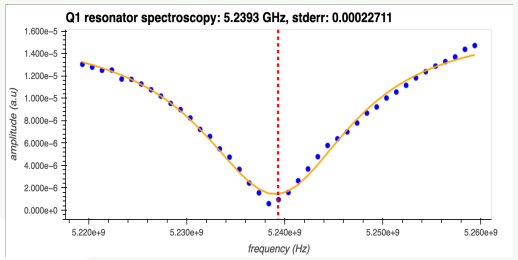
- 40+ parameters for a typical tunable qubit model
- Versioning of models
- Retrieval and updating of model parameters



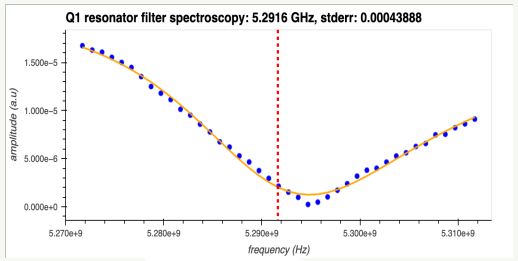
40+ Distinct 1 and 2 Qubit Experiments

- Resonator Spectroscopy
- Resonator Filter Spectroscopy
- Pulsed Qubit Spectroscopy
- Amplitude Rabi
- Ramsey
- Amplitude Rabi
- T2 Echo
- T1
- Readout 0-1 Contrast (Coarse)
- Readout 0-1 Discriminator Training
- DRAG calibration
- Calibrate π/2 amplitude with Ping-Pong
- Calibrate π amplitude with Ping-Pong
- Ping-Pong for 1-2 state
- Pulsed Qubit Spectroscopy
- Pulsed Qubit Spectroscopy per Flux
- Amplitude Rabi between 1 and 2 state
- Readout 0-1-2 Discriminator Training
- Ramsey 1-2
- T2 Echo
- T2* Ramsey
- v-to-hz
- AllXY
- Randomized benchmarking
- Optimal control of Gaussian π/2-pulses
- Cryoscope
- Pi-half ORBIT
- Correlated readout error
- Qubit-qubit spectroscopy
- Coupling spectroscopy
- Cross resonance amplitude sweep
- Cross resonance phase sweep
- Tune cross-resonance pulse duration
- 2 qubit Quantum Process Tomography
- Flux crosstalk calibration
- ZZ coupling
- Two-qubit Randomized Benchmarking
- Interleaved RB for Cross Resonance gate
- Closed Loop CZ calibration
- Quantum Noise Spectroscopy (QNS)

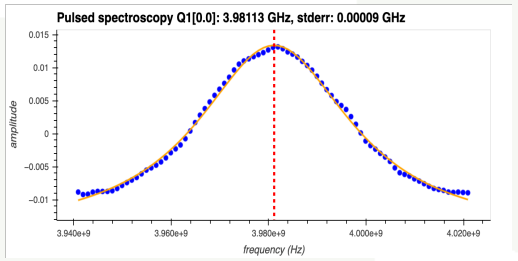
Starting from basic calibration...



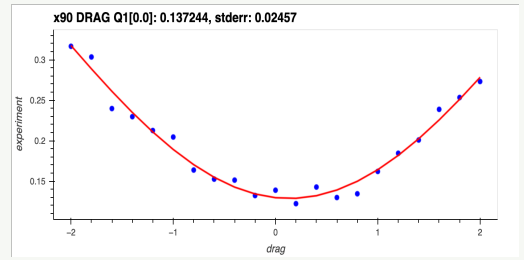
Resonator Spectroscopy



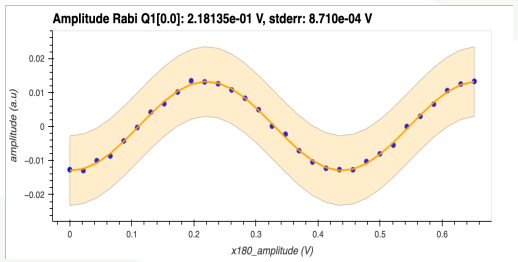
Filter Spectroscopy



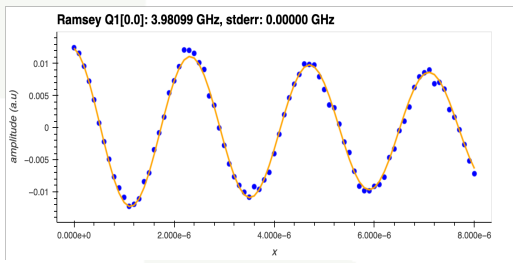
Pulsed Qubit Spectroscopy



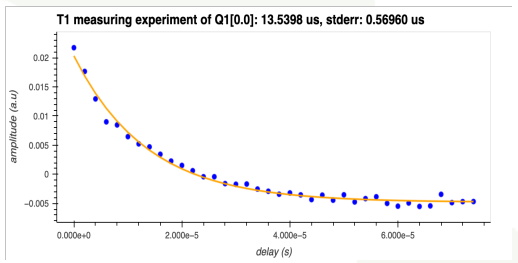
DRAG Calibration



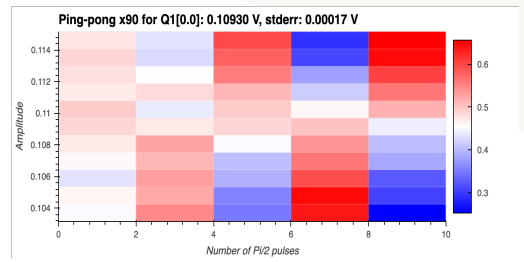
Qubit Amplitude Rabi



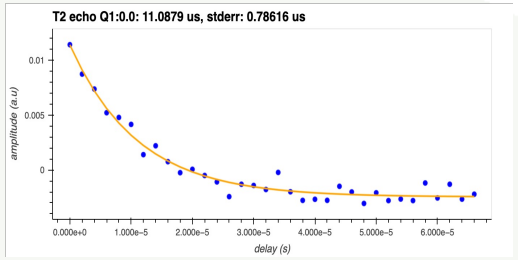
Qubit Ramsey



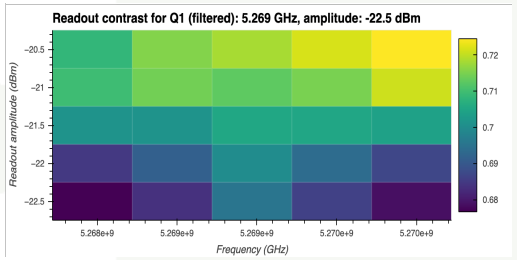
T_1 - Qubit Lifetime



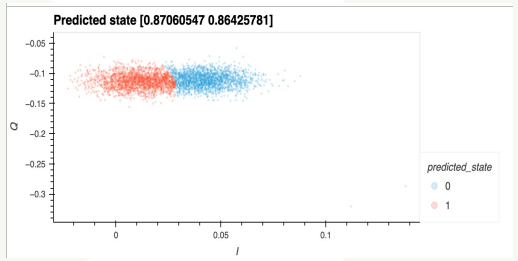
$\pi/2$-pulse Ping Pong



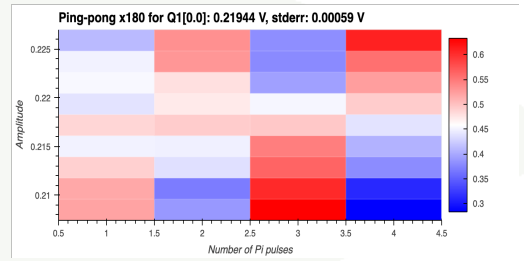
T_2 Echo - Qubit Dephasing



0-1 Readout Contrast

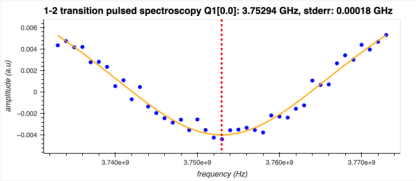


0-1 Discriminator Training

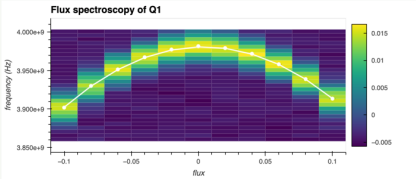


π-pulse Ping Pong

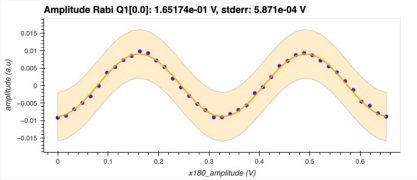
To more in-depth characterization;



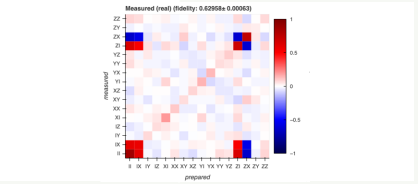
Qubit Spectroscopy 1-2 state



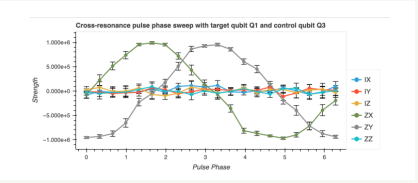
Qubit Flux Spectroscopy



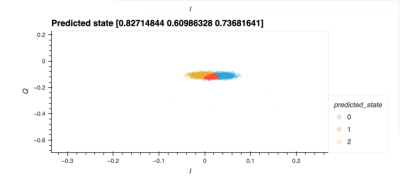
Amplitude Rabi 1-2



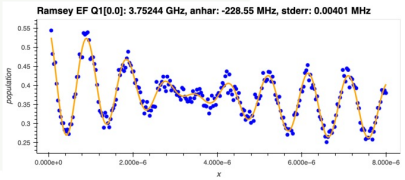
2-Qubit QPT



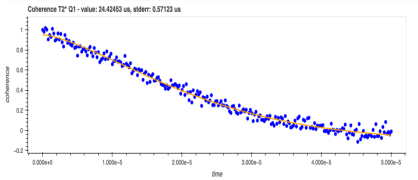
Cross Resonance Phase



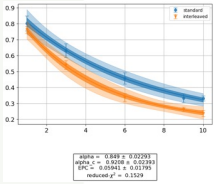
0-1-2 Discriminator Training



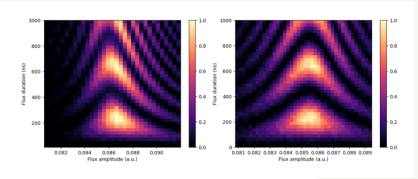
Ramsey 1-2 state



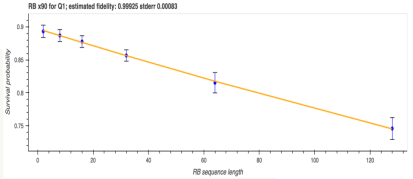
T_2^*- Ramsey



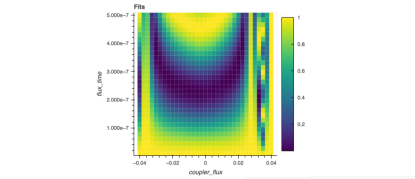
2 Qubit Interleaved RB



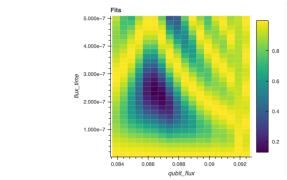
Flux Pulse Pre-compensation



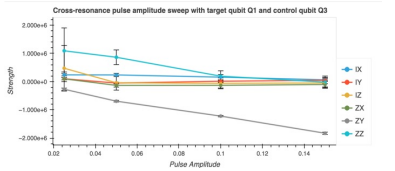
1Q Randomized Benchmarking



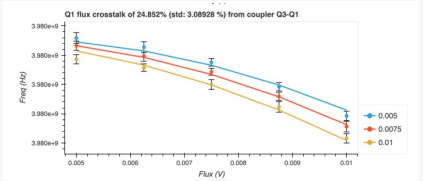
Coupling Spectroscopy



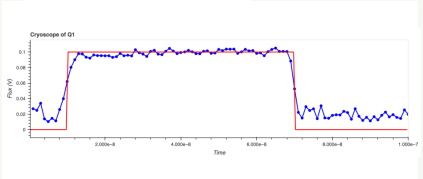
Qubit-Qubit Spectroscopy



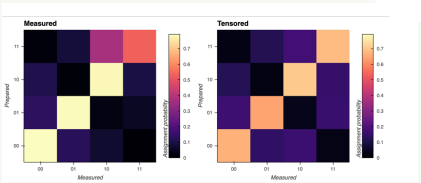
Cross Resonance Amplitude



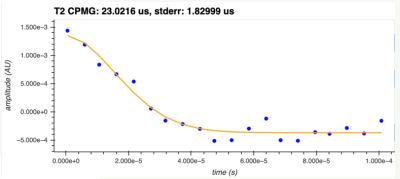
Flux Crosstalk Calibration



Cryoscope



Correlated Readout Error

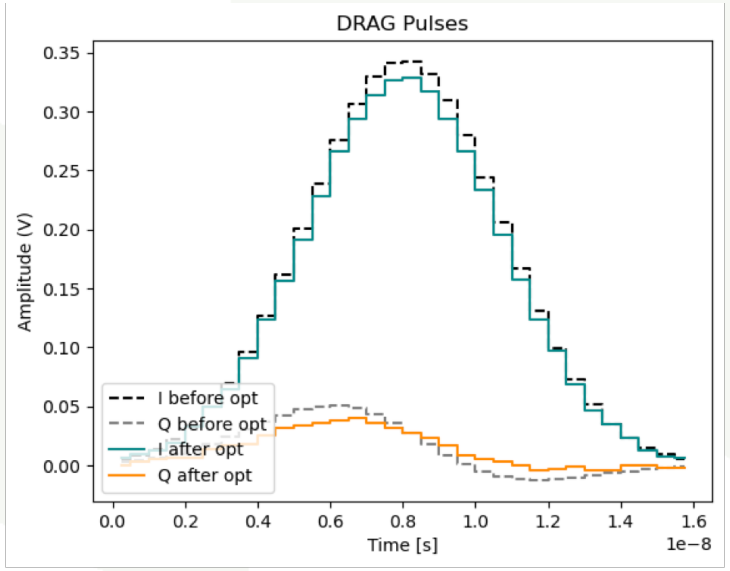


Quantum Noise Spectroscopy

As well as advanced pulse shaping tools...

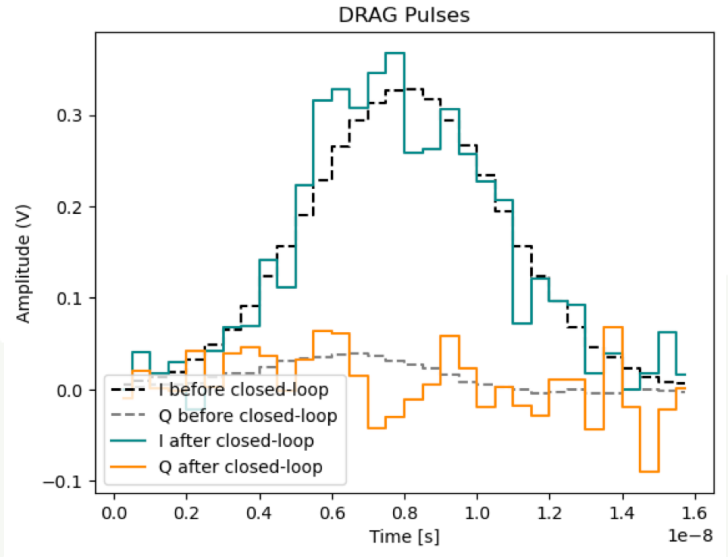
Fast-Calibration:

```
Fidelity: 99.81131232826081%
```



Open-loop Calibration:

```
Fidelity: 99.99999999993814%
```

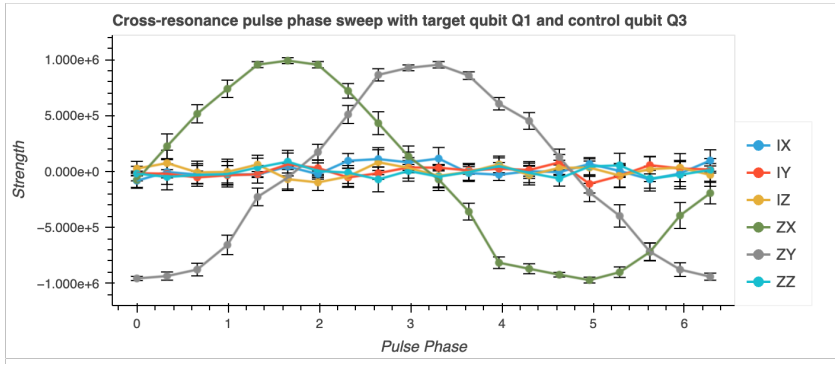


Closed-loop Calibration:

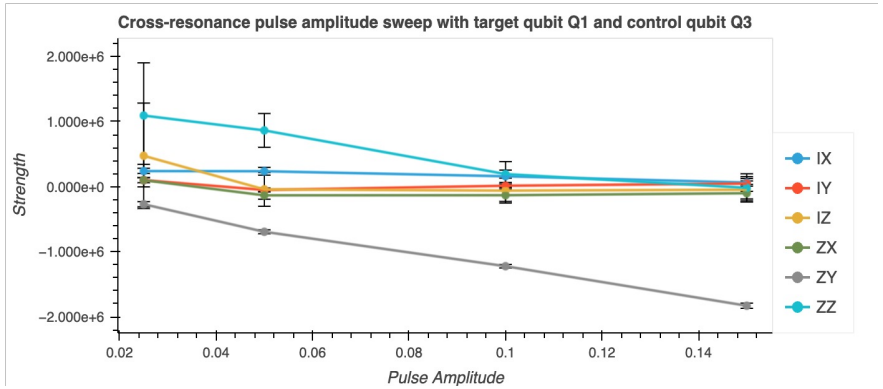
```
Fidelity: 99.96916758146601%
```

Optimization of a fast pi-half drag pulse with a piecewise-constant ansatz

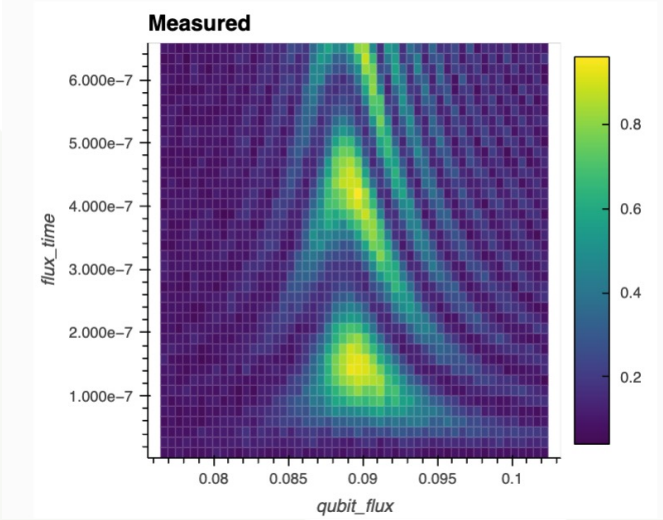
For both 1 and various 2Q Gate Optimizations



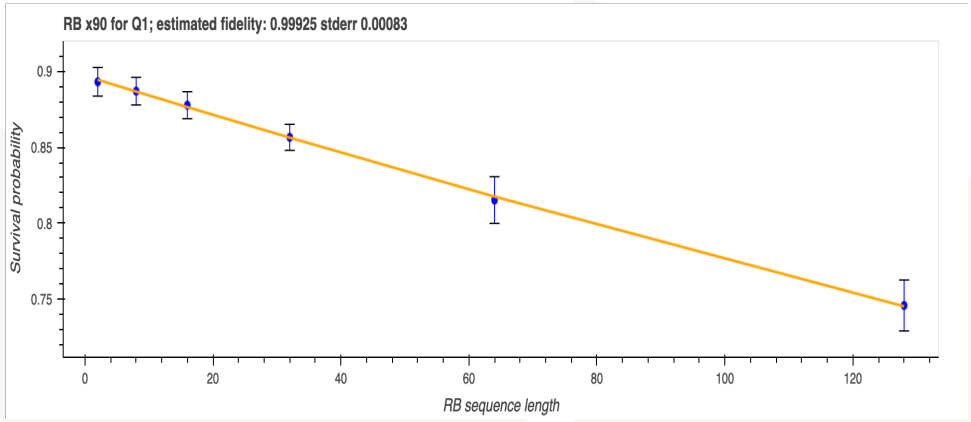
Cross Resonance Phase



Cross Resonance Amplitude

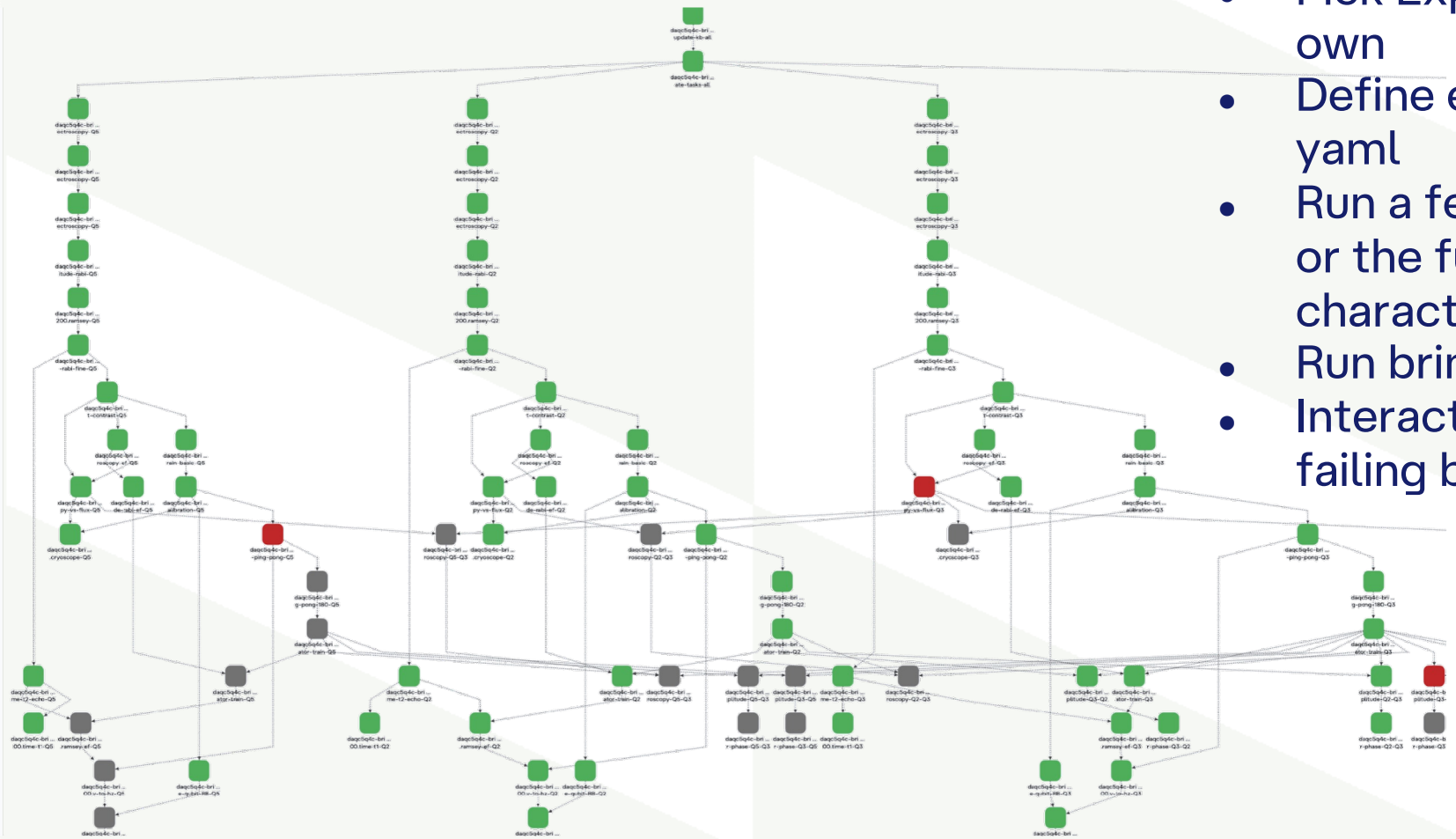


CZ Chevron Characterization



1Q Randomized Benchmarking

DAG based Experiment Execution



- Pick Experiments from library or bring your own
- Define experiment dependencies using yaml
- Run a few nodes for quick gate calibration or the full library for system characterization
- Run bring-up on schedule or on-demand
- Interactively debug experiments to fix failing bring-up workflows

Currently running 40 experiments per qubit nightly on a 5Q-4C QPU takes a couple of hours.

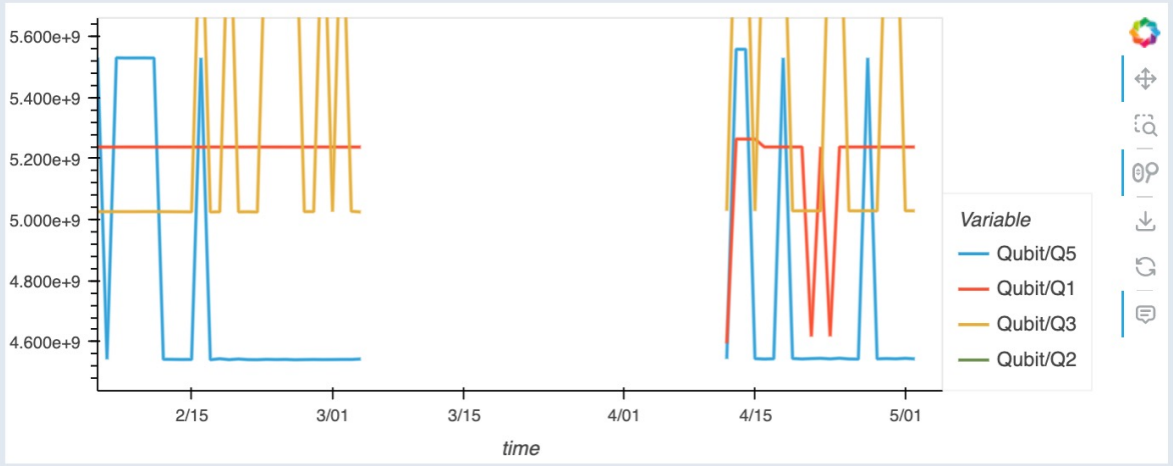
Experiment Browser

- View all past experiments and experiment results
- Re-run any experiment on demand
- Analyse trends in system parameters or experiment outcomes

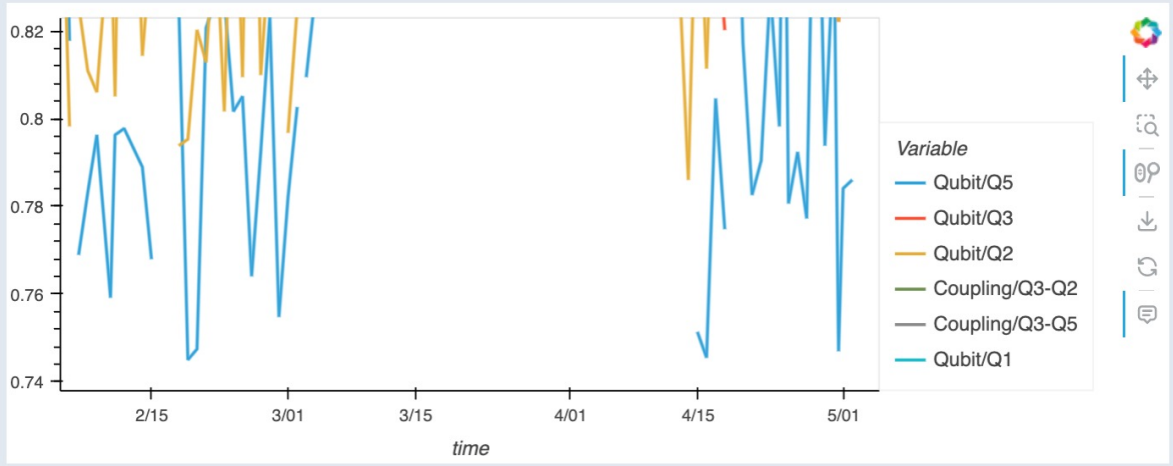
Currently deployed on a 5Q-4C QPU with 20,000+ experiments from last 10 months

Historical System State Tracking

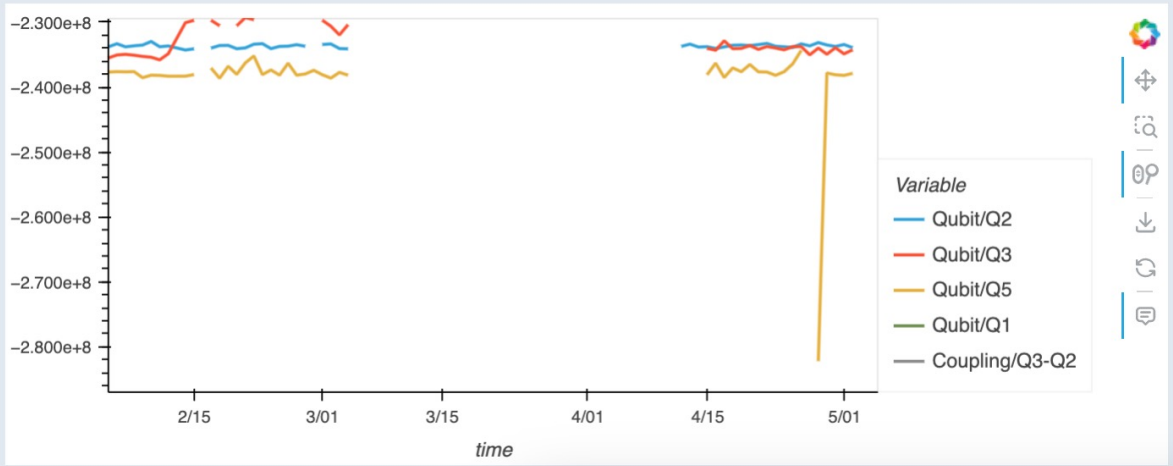
Qubit frequency



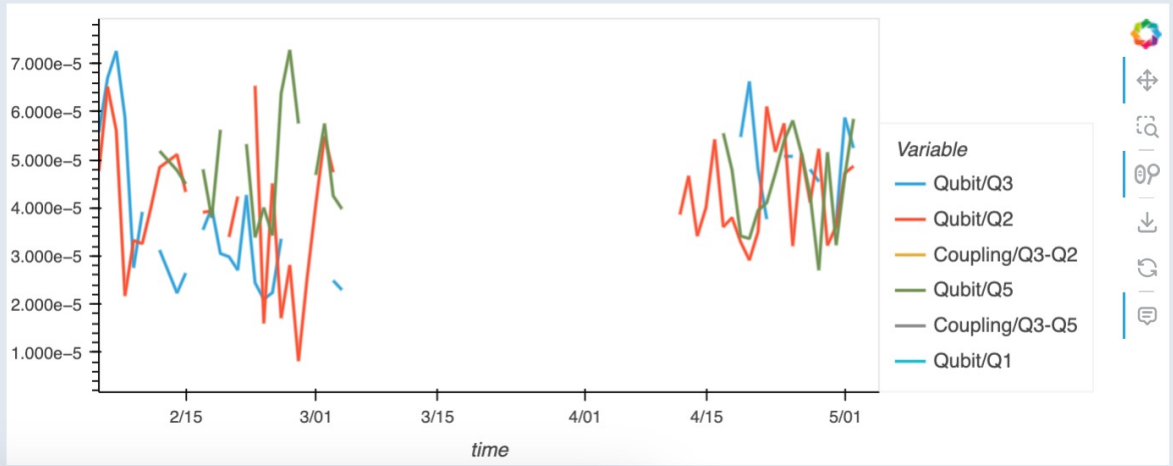
Discriminator performance



Anharmonicity



T1



Currently deployed on a 5Q-4C QPU with 20,000+ experiments from last 10 months

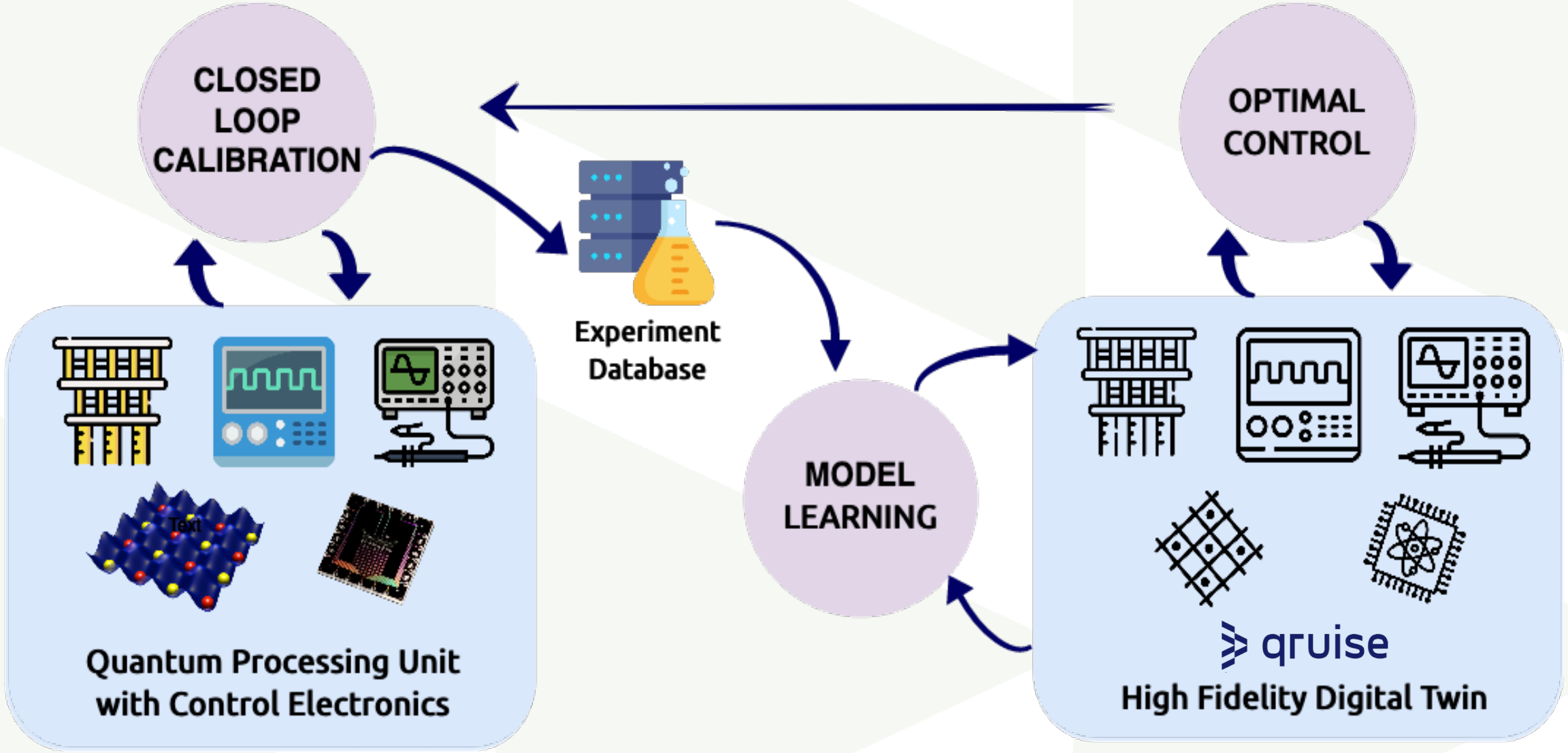
What do I do with all this data?

Don’t stop here!

- Need for calibration proved the model is broken.
- We don’t understand why calibrated pulses work better.
- We don’t understand why calibrated pulses aren’t perfect.
- We don’t understand how to improve the system.

Model Learning using **QruiseML**

The Model Learning Loop



Example Case Study:

Learning and correcting CZ chevrons

CZ via bipolar flux pulse (DiCarlo's SNZ)

V. Negîrneac et al. Phys. Rev. Lett. 126, 220502 (2021)

System Hamiltonian: $H = H_{q1} + H_{q2} + H_{int} + H_{drive}$

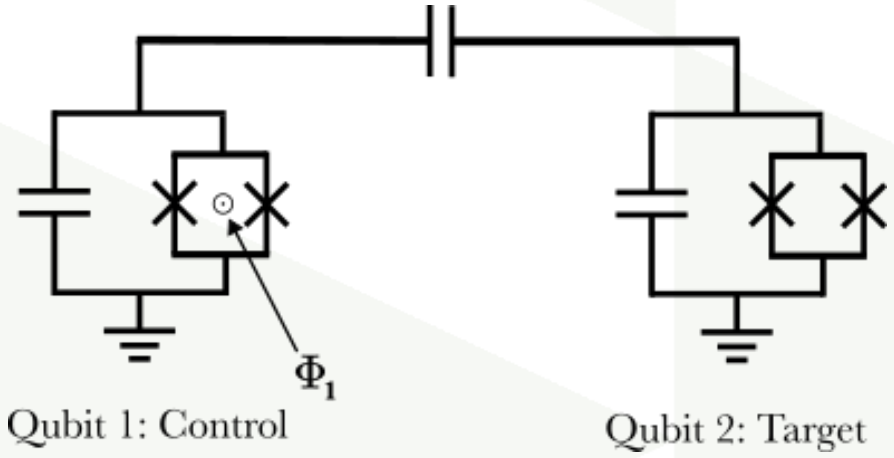
$$H/\hbar = \sum_{i=A,B} \left[\omega_i b_i^\dagger b_i - \frac{\delta_i}{2} \left(b_i^\dagger b_i - 1 \right) b_i^\dagger b_i \right] + g_{AB}(b_A + b_A^\dagger)(b_B + b_B^\dagger) + \omega_A \lambda_A(\phi_0, \phi_{\text{off}}, \phi_{\text{ext}}(t))\, b_A^\dagger b_A$$

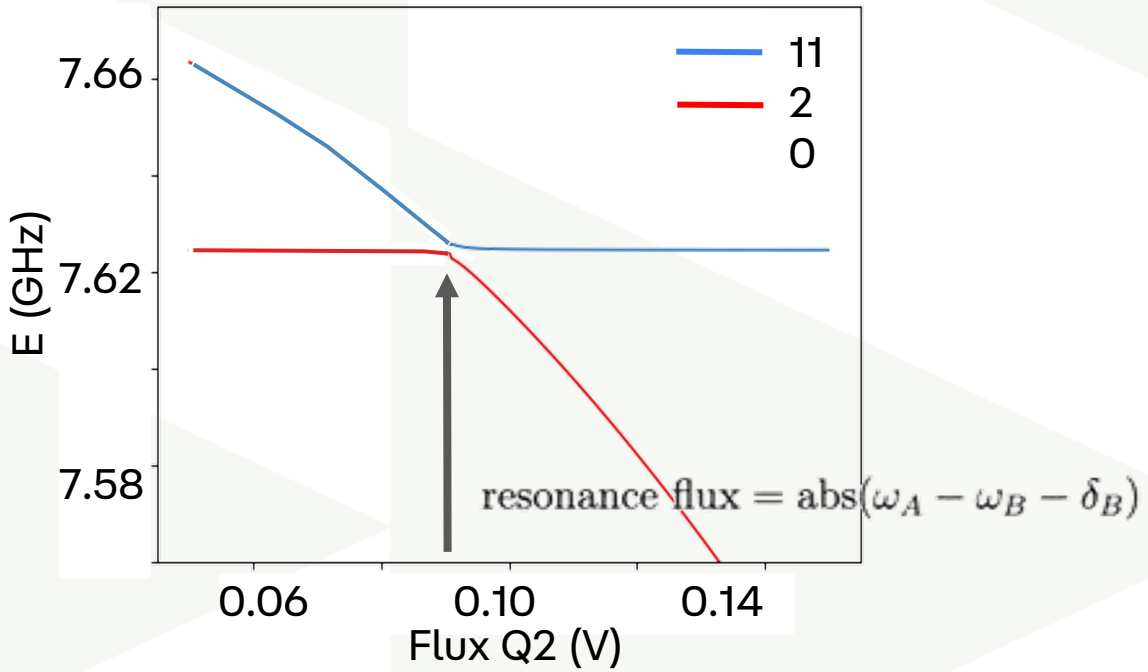
g_{AB} = coupling strength between qubit A and B at zero flux

$\phi_{\text{ext}}(t)$ = external flux on control qubit A

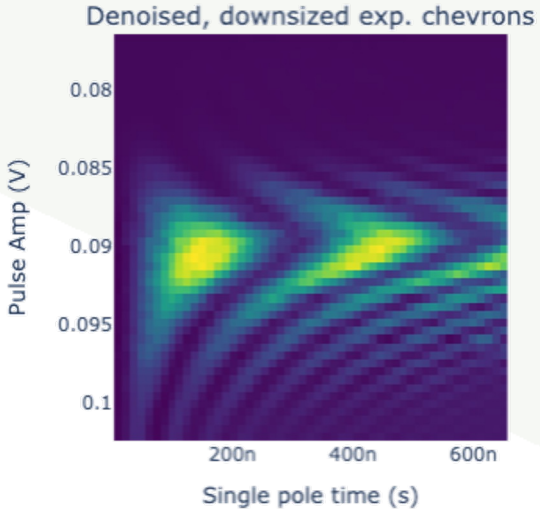
$\lambda_A(\phi_0, \phi_{\text{off}}, \phi_{\text{ext}}(t))$ = function of control qubit flux offset, periodicity and external flux

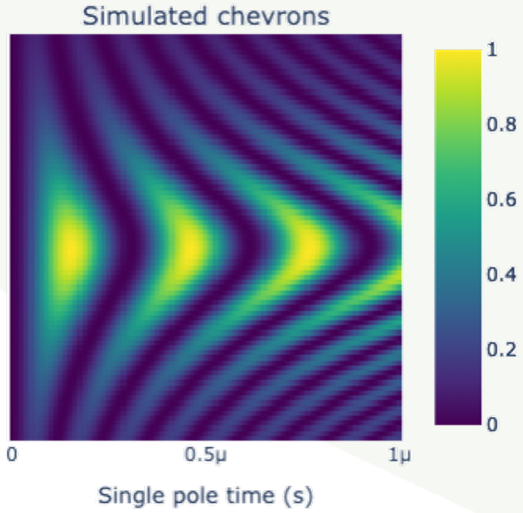
Hardware schematic diagram:

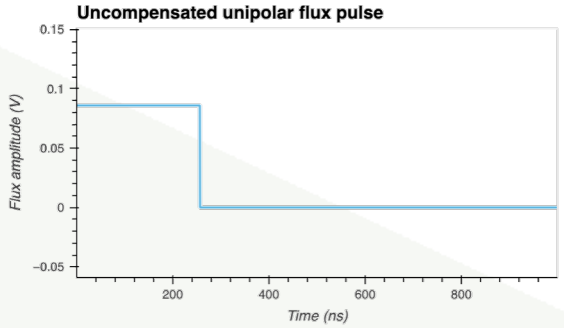




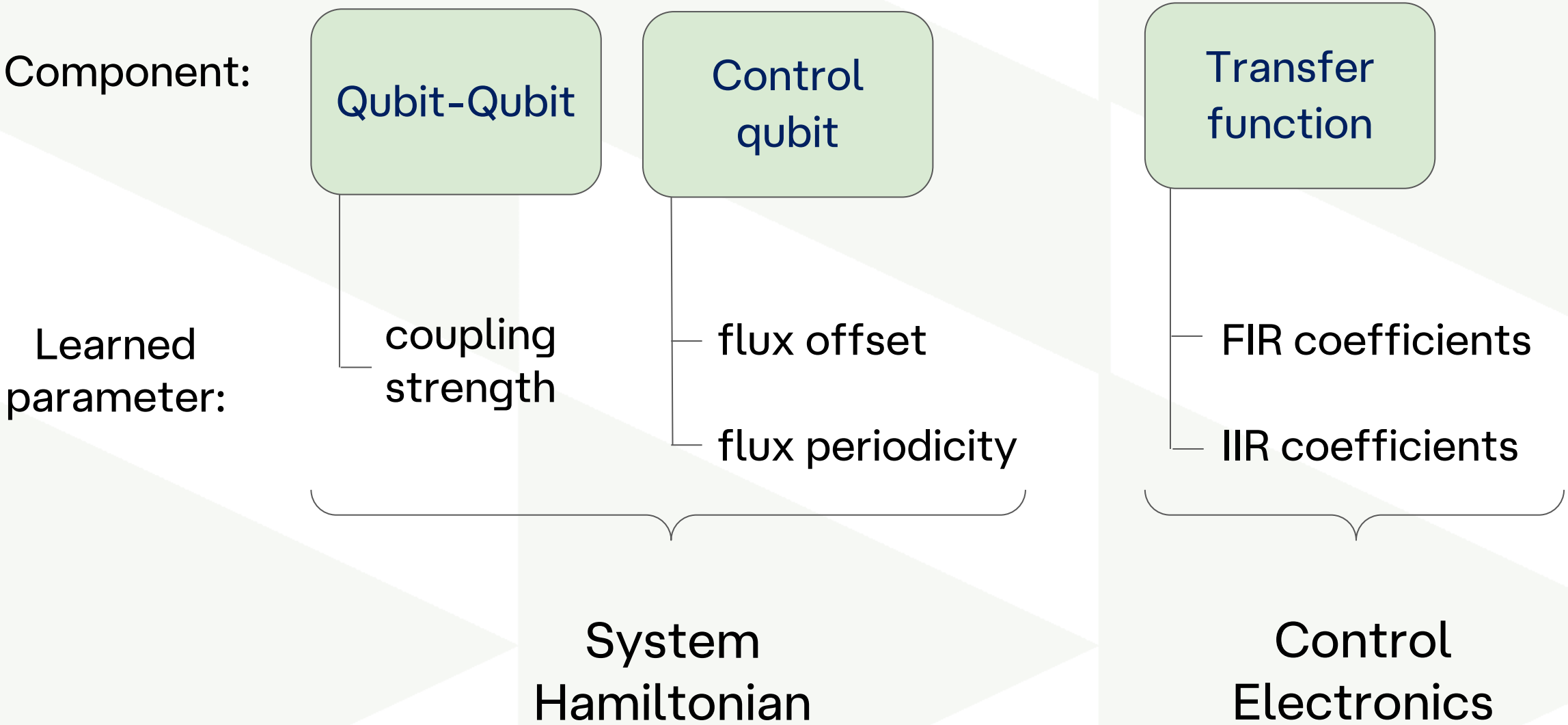
Learn from the unipolar chevron



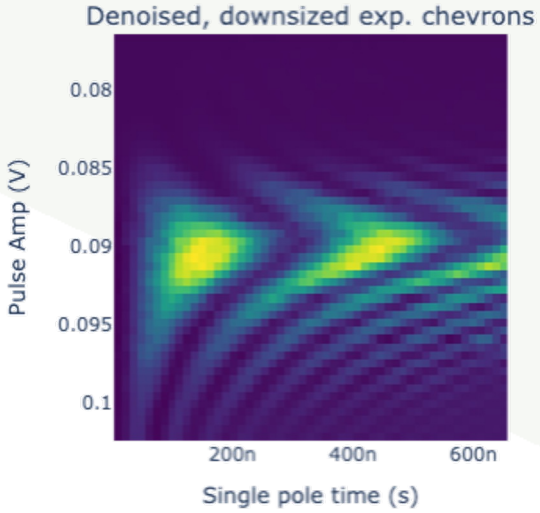


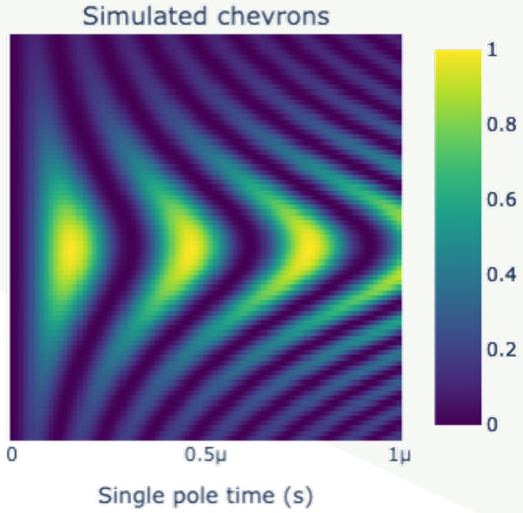


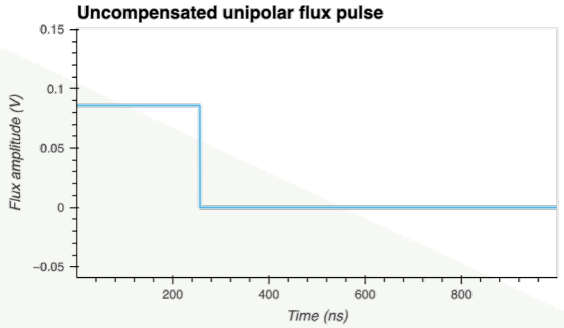
83 learned parameters



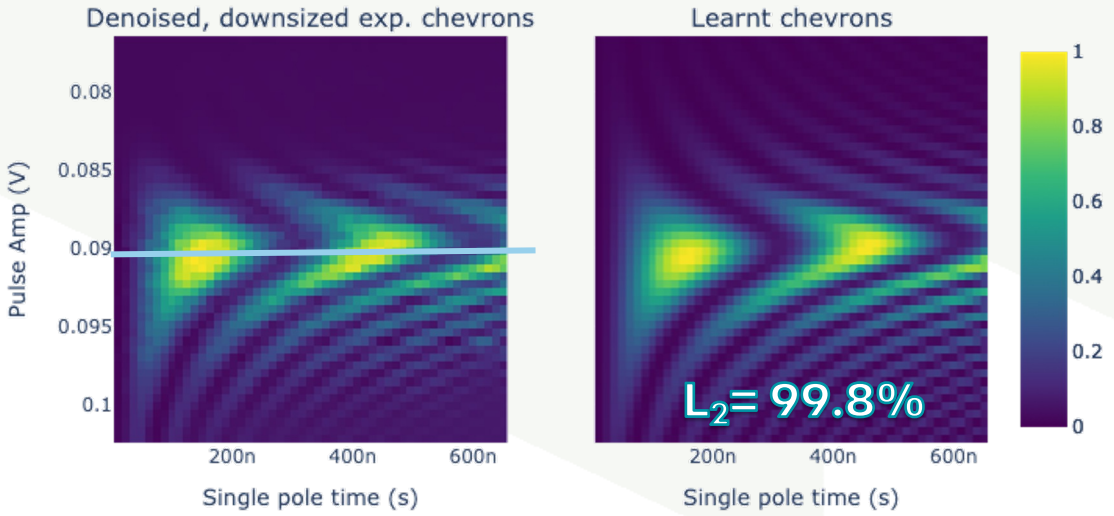
Learn from the unipolar chevron

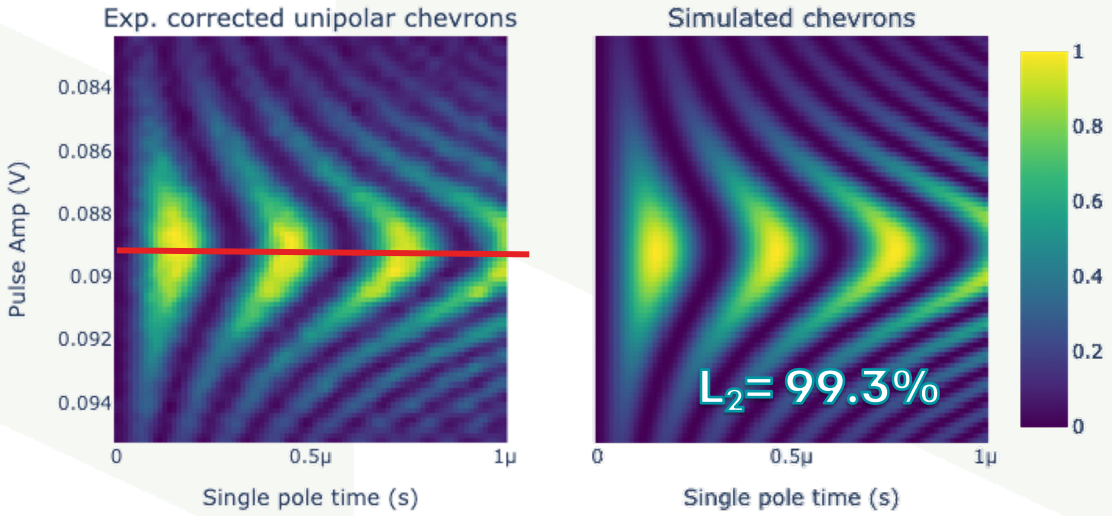


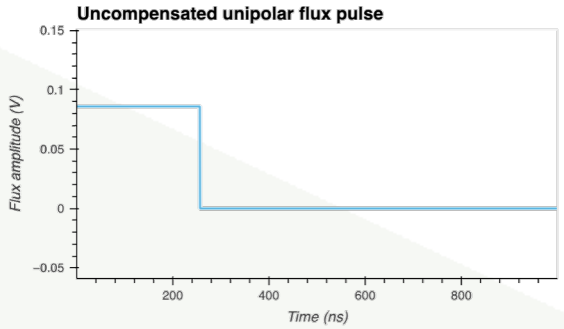


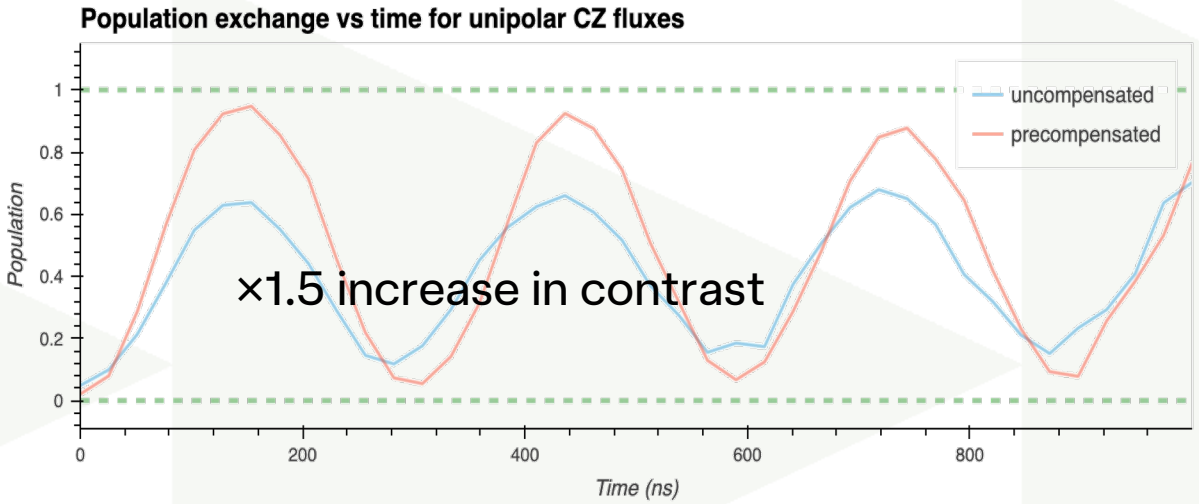


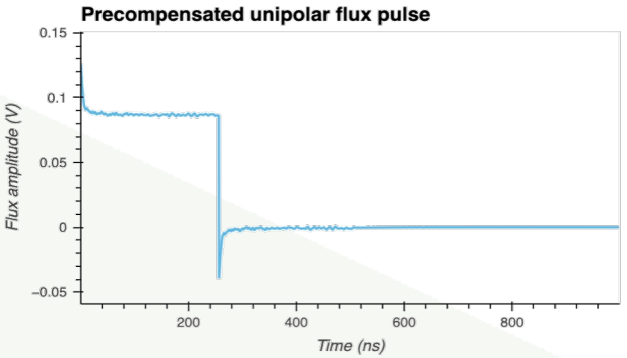
Learn from the unipolar chevron



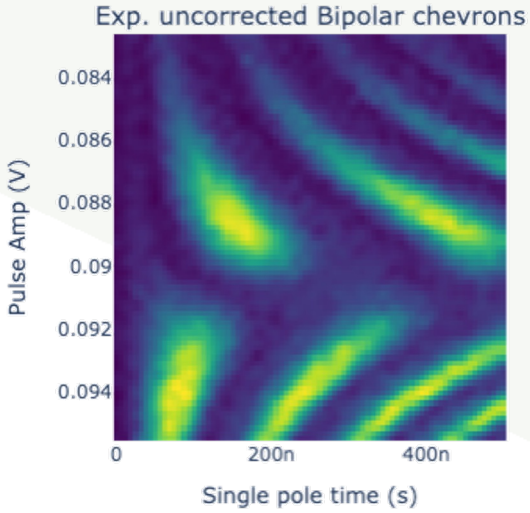


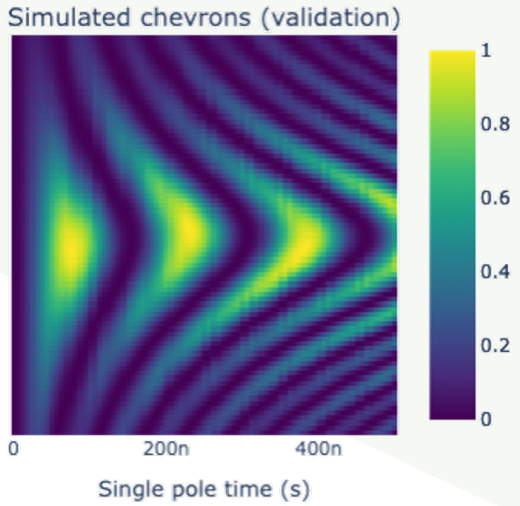


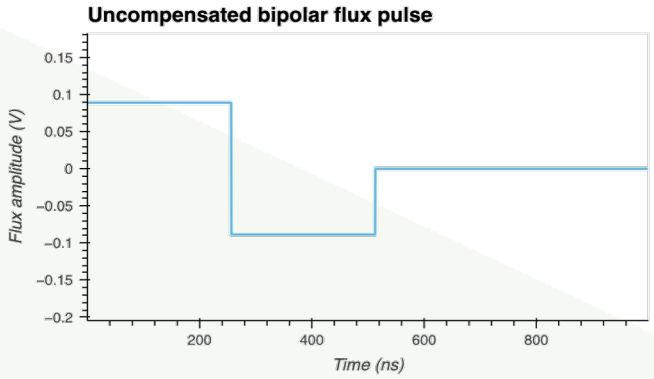




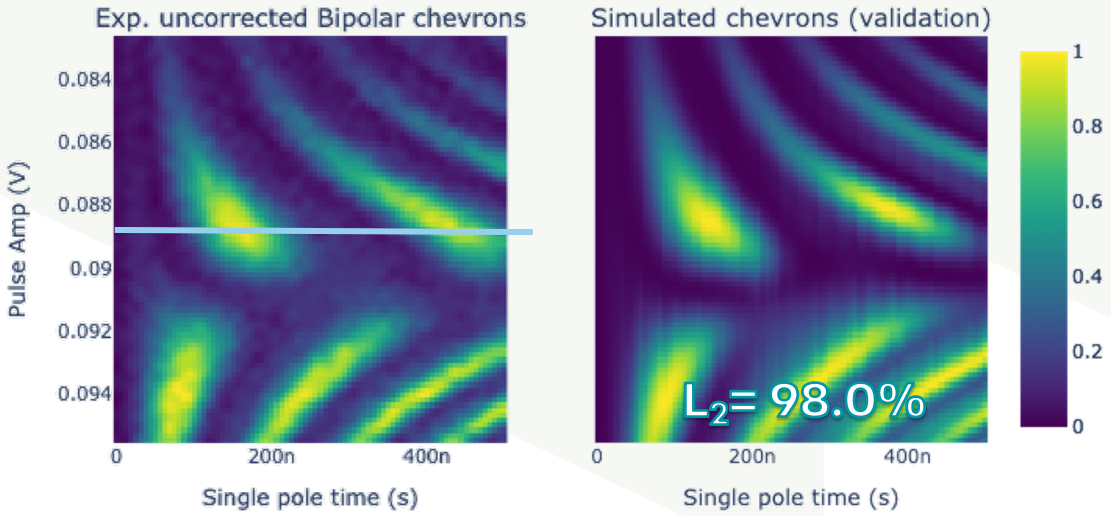
Validate by using the learned model on bipolar pulses

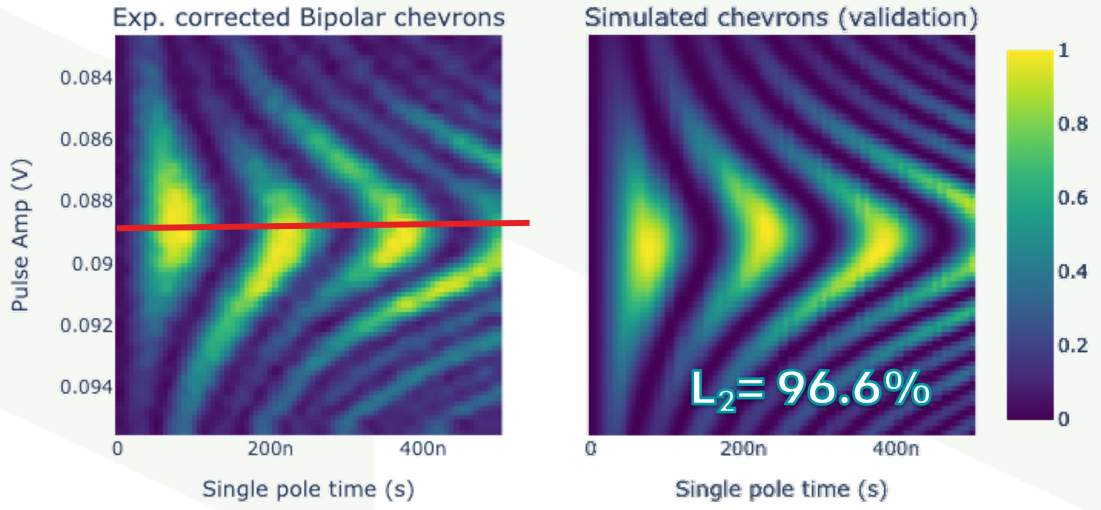


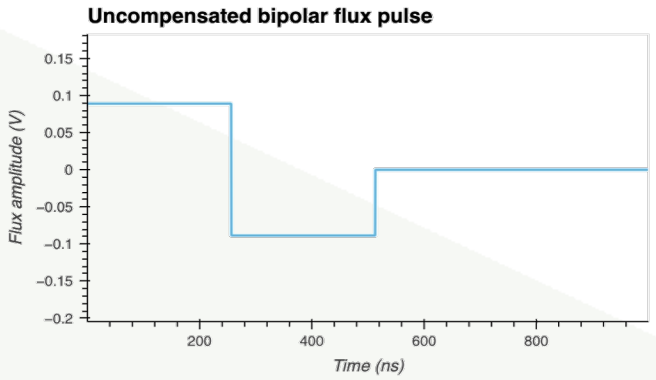


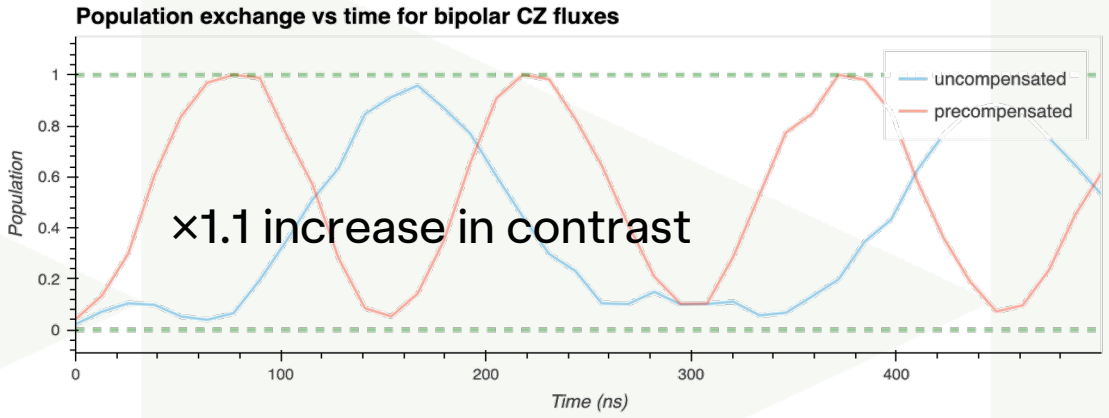


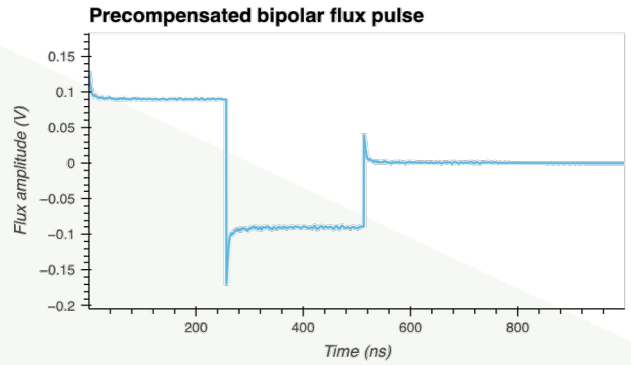
Validate by using the learned model on bipolar pulses











Why model learning?

- We showed learning of 83 parameters from 1 chevron plot, with validation and pulse correction.

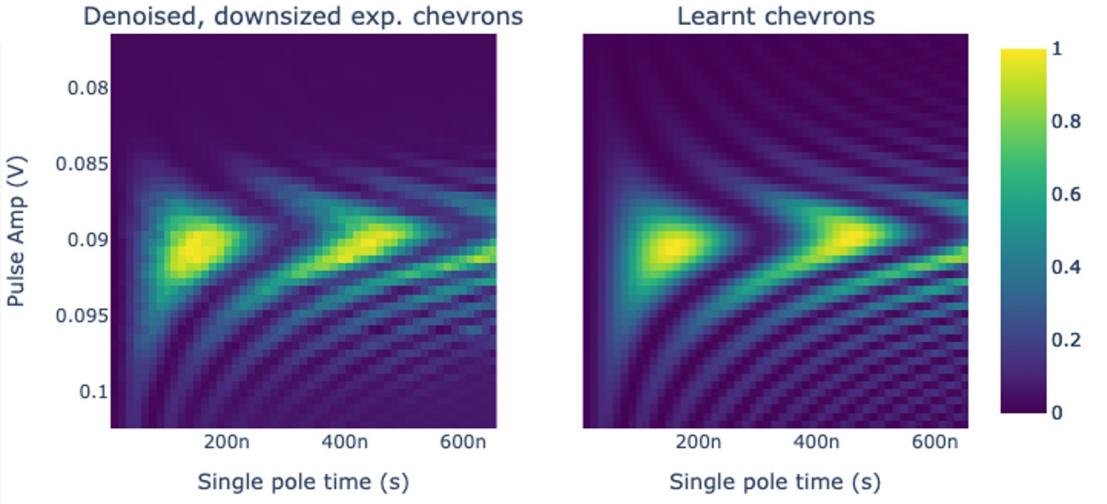
- Learn any parameters from any relevant data set.
- No need for dedicated experiments for each parameter.
- You probably already have the all data needed from bring-up.

- Provides better insight into your device’s behavior.

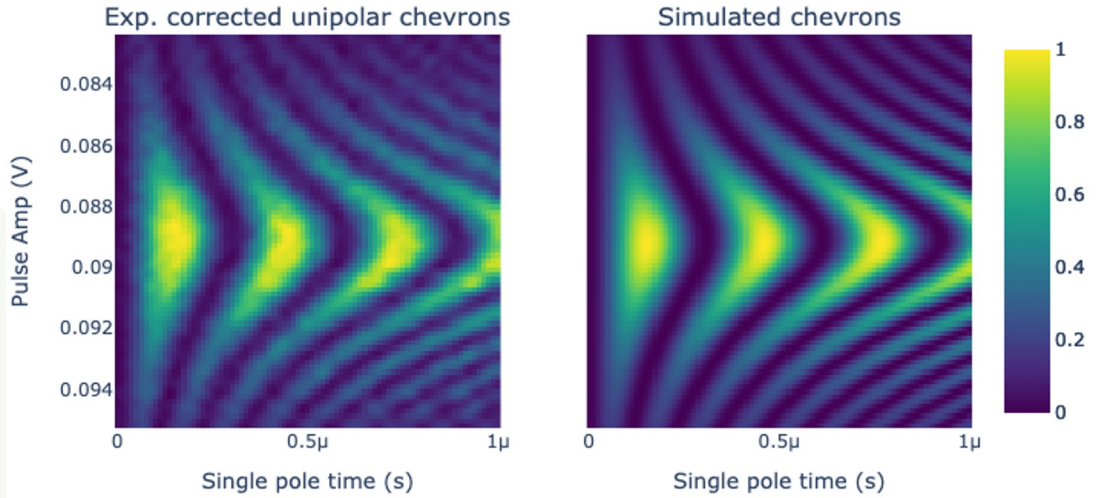
Summary of Automated Calibration & Model-based Learning

- Rapid Automated Calibration for quick bring-up of flux-based gates
- Heterogeneous learning from multiple experiments simultaneously.
- Case Study: Learned from cryoscope and unipolar chevrons, and validated learning by correcting both unipolar and bipolar chevrons

Learning from unipolar chevrons



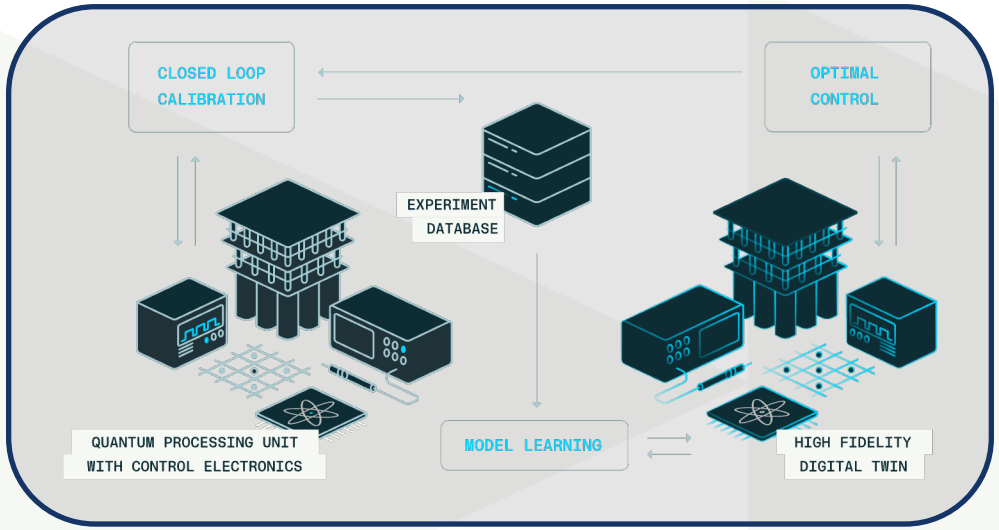
Validation with precompensted pulses



Come talk to us!

anurag@qruise.com

Learn about QruiseOS and QruiseML ⭐
Explore partnership opportunities 🔍
Try a Hands-on Demo 💡



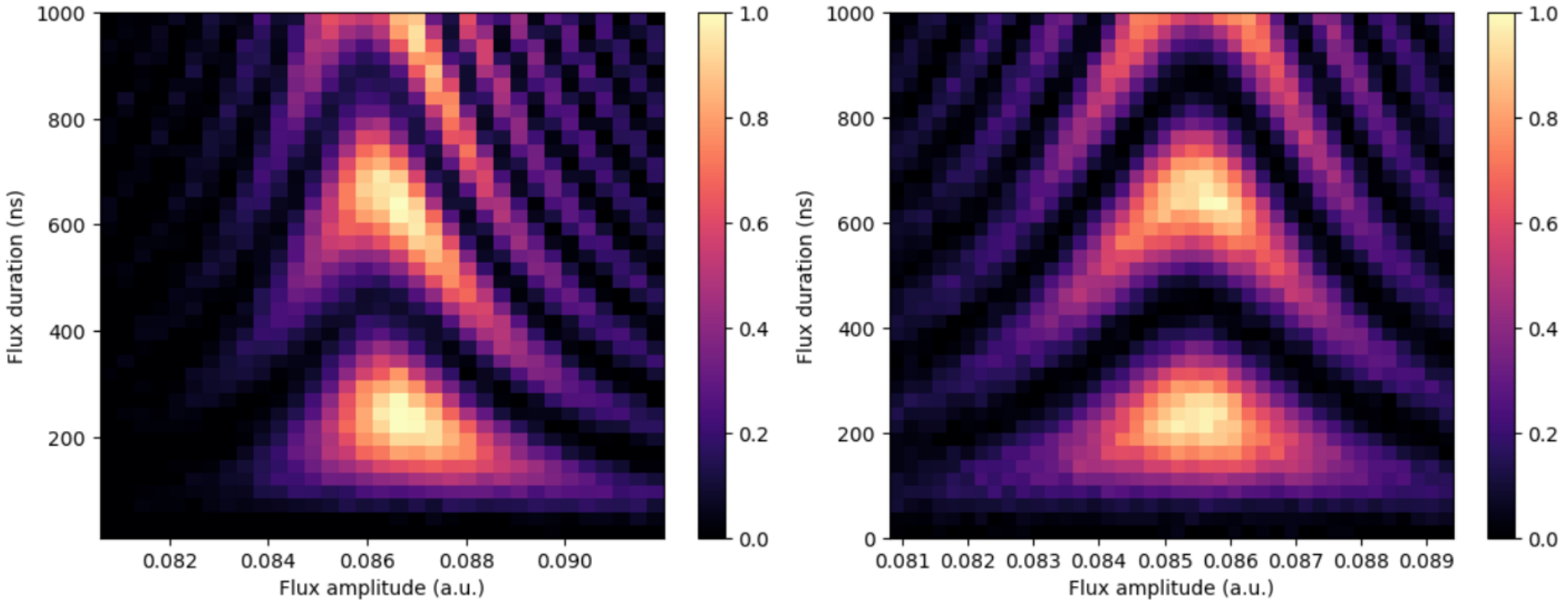
WE ARE HIRING

Experimentalists | Software Engineers
Theorists | Quantum Engineers
(Anywhere in Europe, CET +/- 1)

qruise

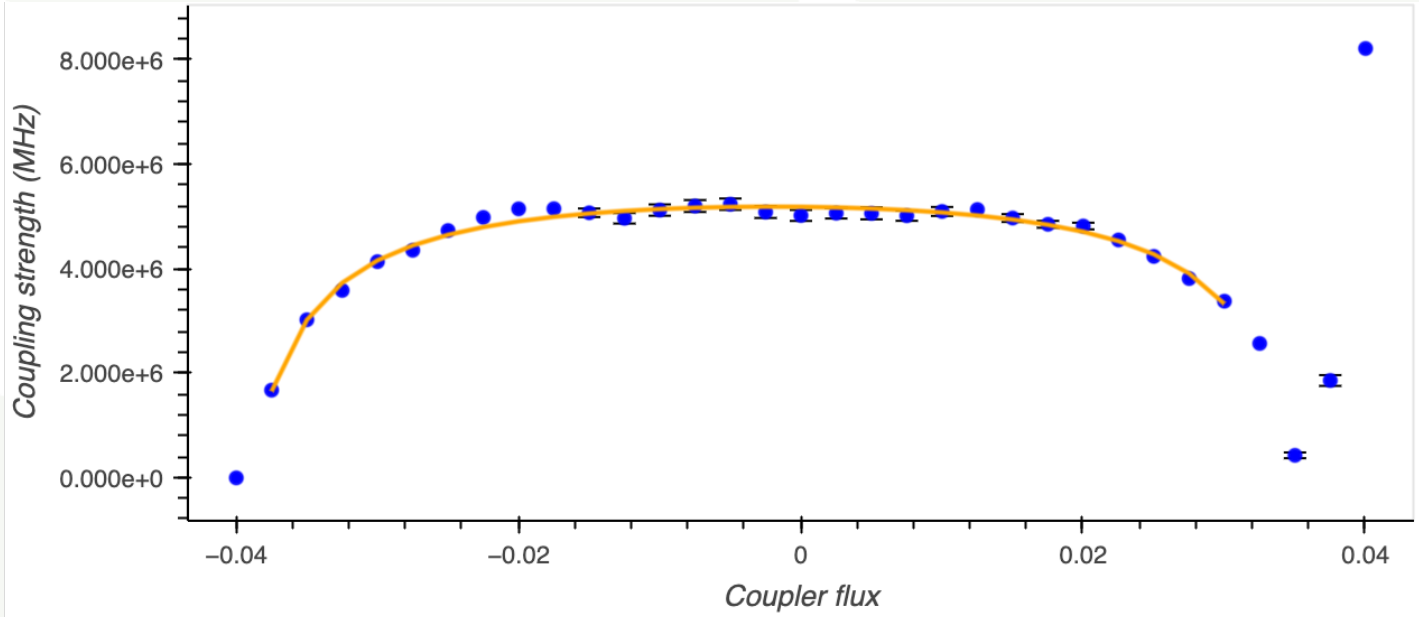
Some example experiments with pretty plots!

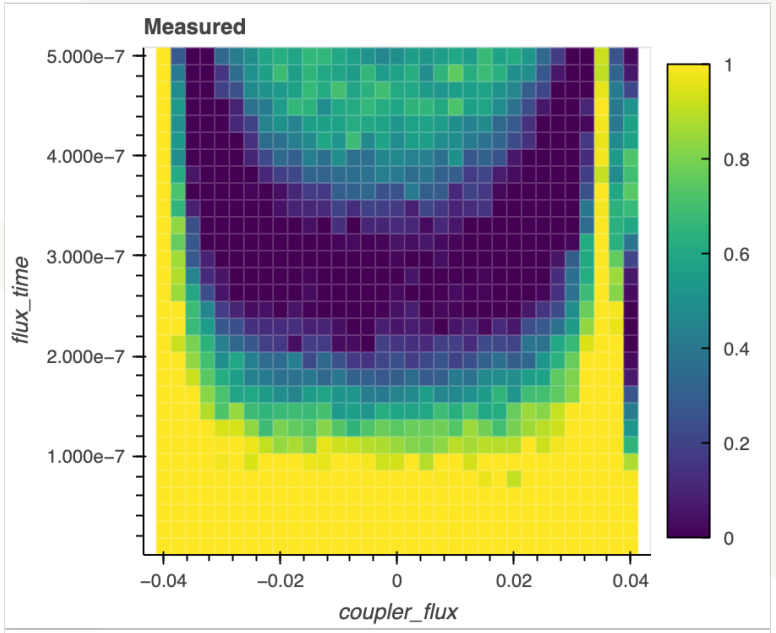
Flux Pre-Compensation

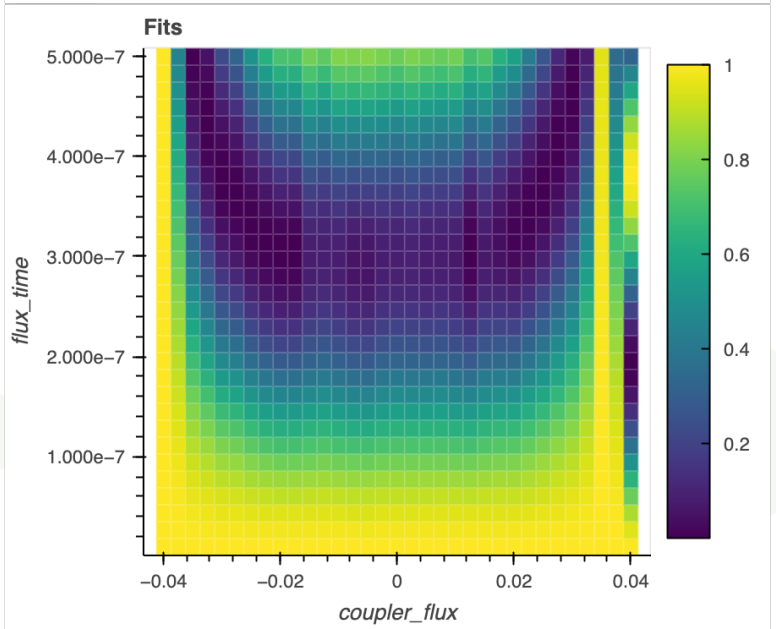


Pre-compensation of flux pulses to produce symmetric 2 qubit chevrons

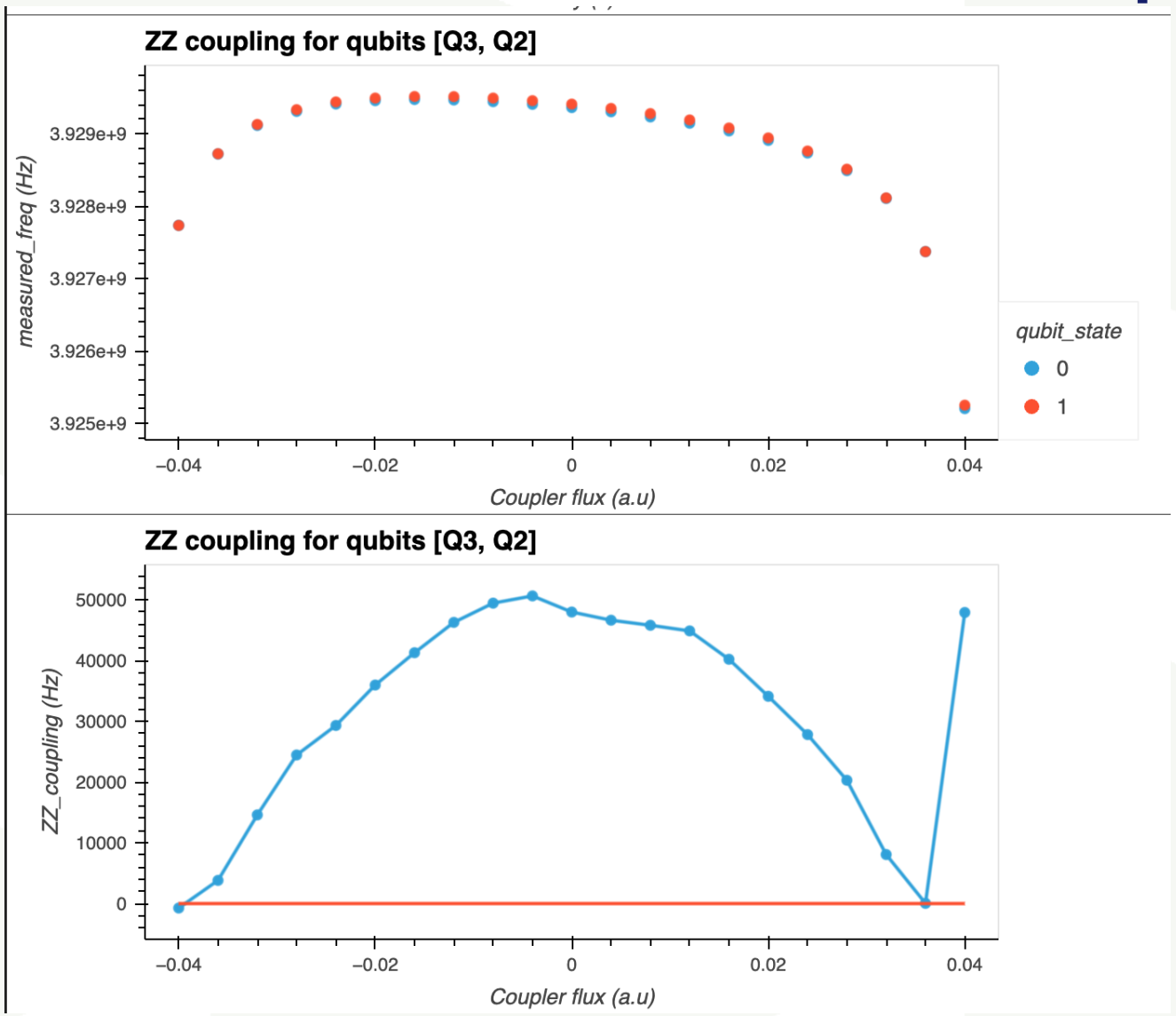
Calibration of Tunable Coupler



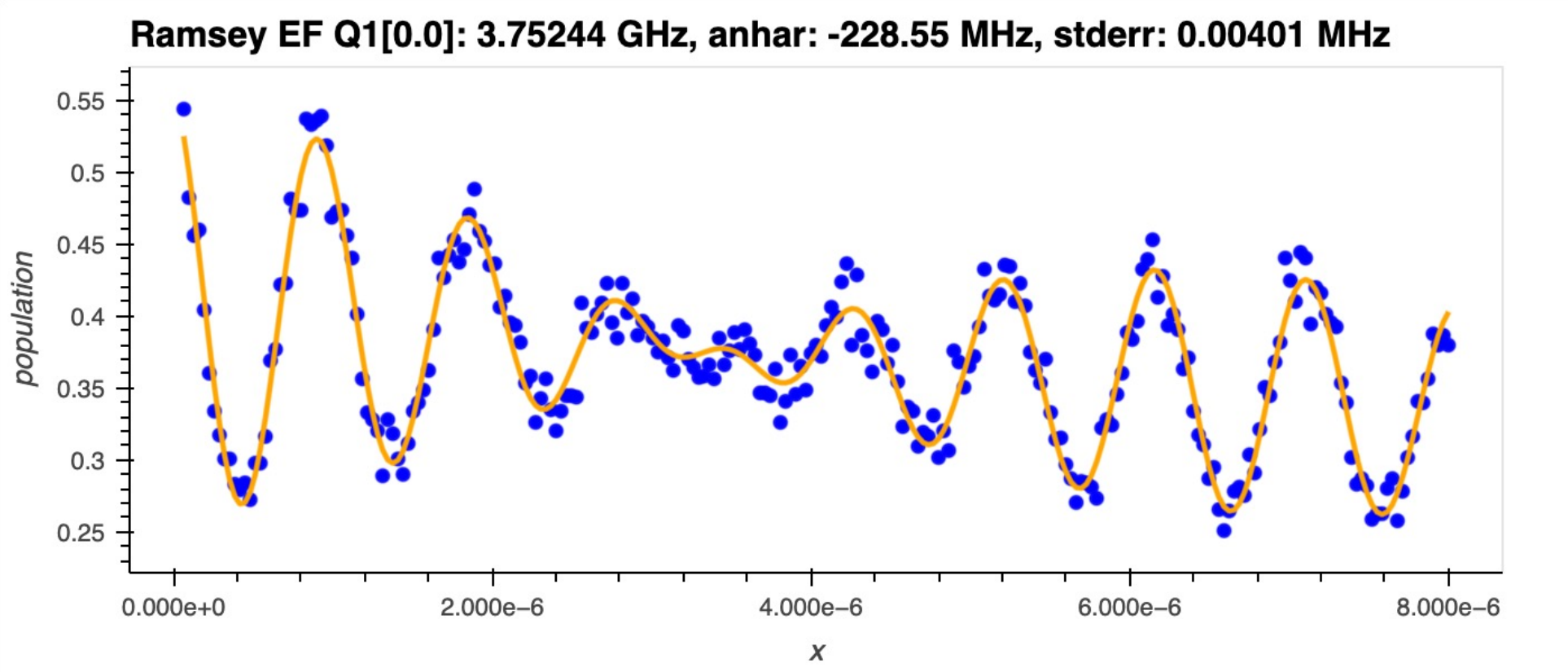




Flux dependent Residual ZZ Coupling

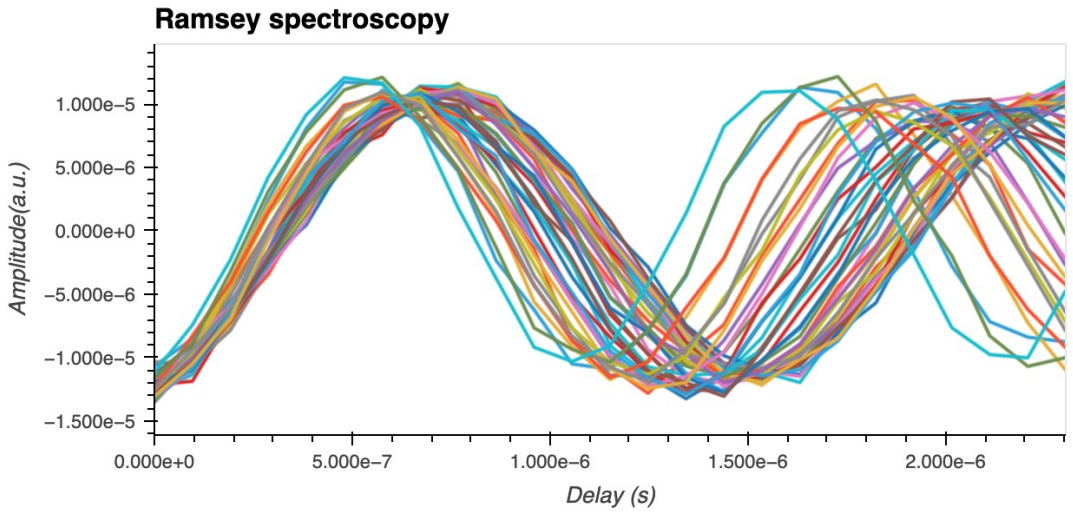


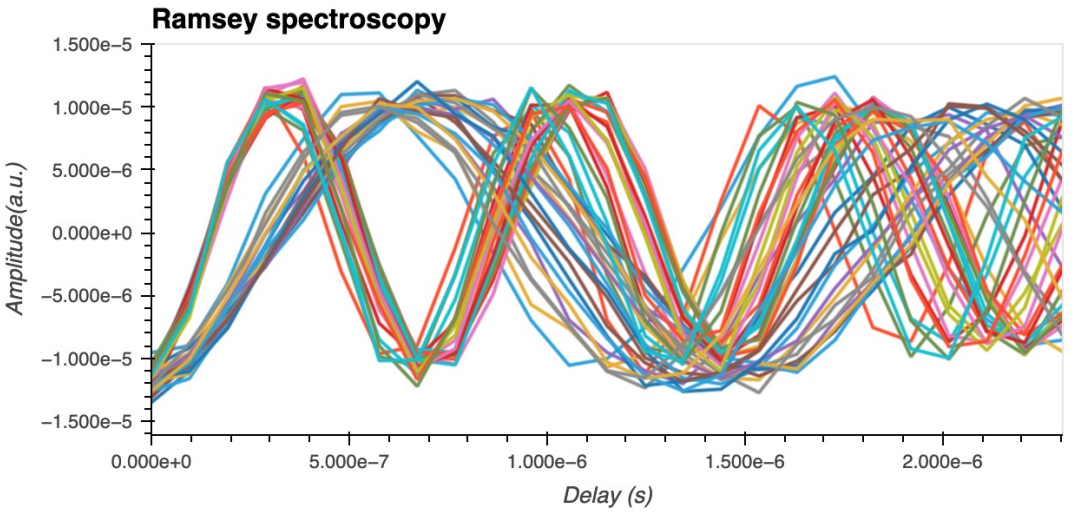
Quasiparticle Tunneling in Ramsey EF

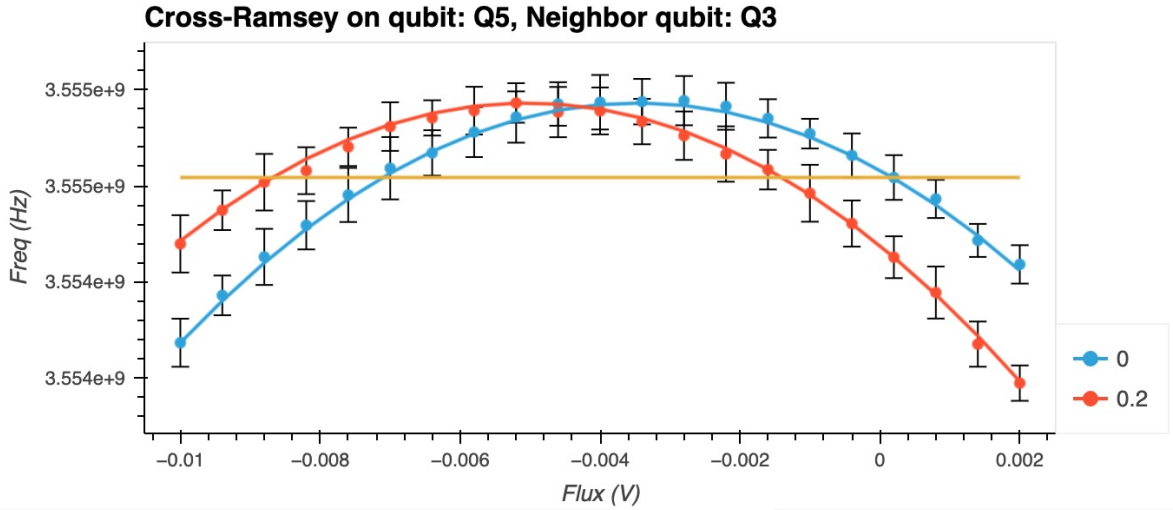


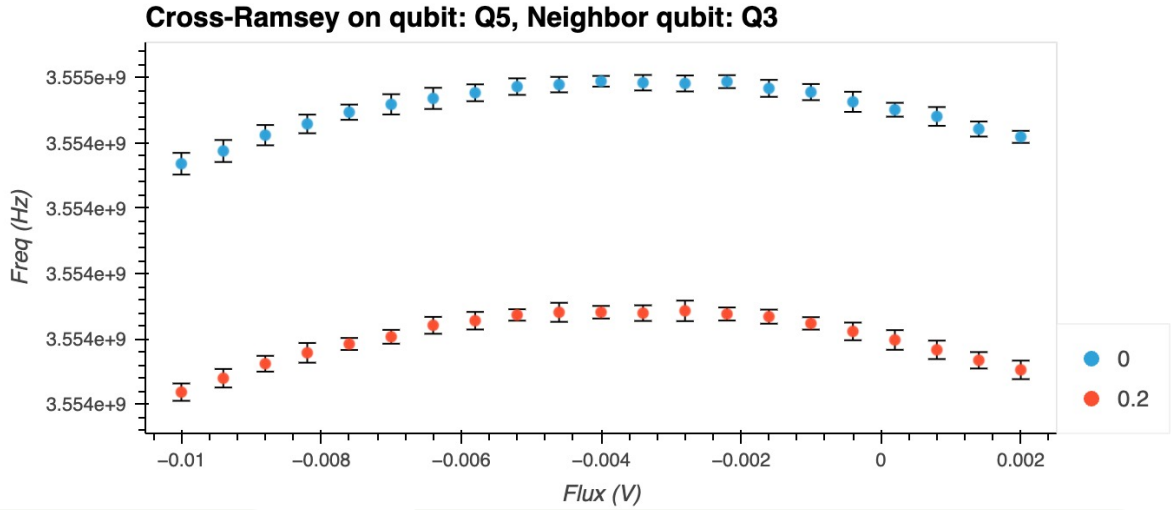
Ristè, D., Bultink, C., Tiggelman, M. et al. Millisecond charge-parity fluctuations and induced decoherence in a superconducting transmon qubit. Nat Commun 4, 1913 (2013)

Crosstalk compensation changing qubit freq.





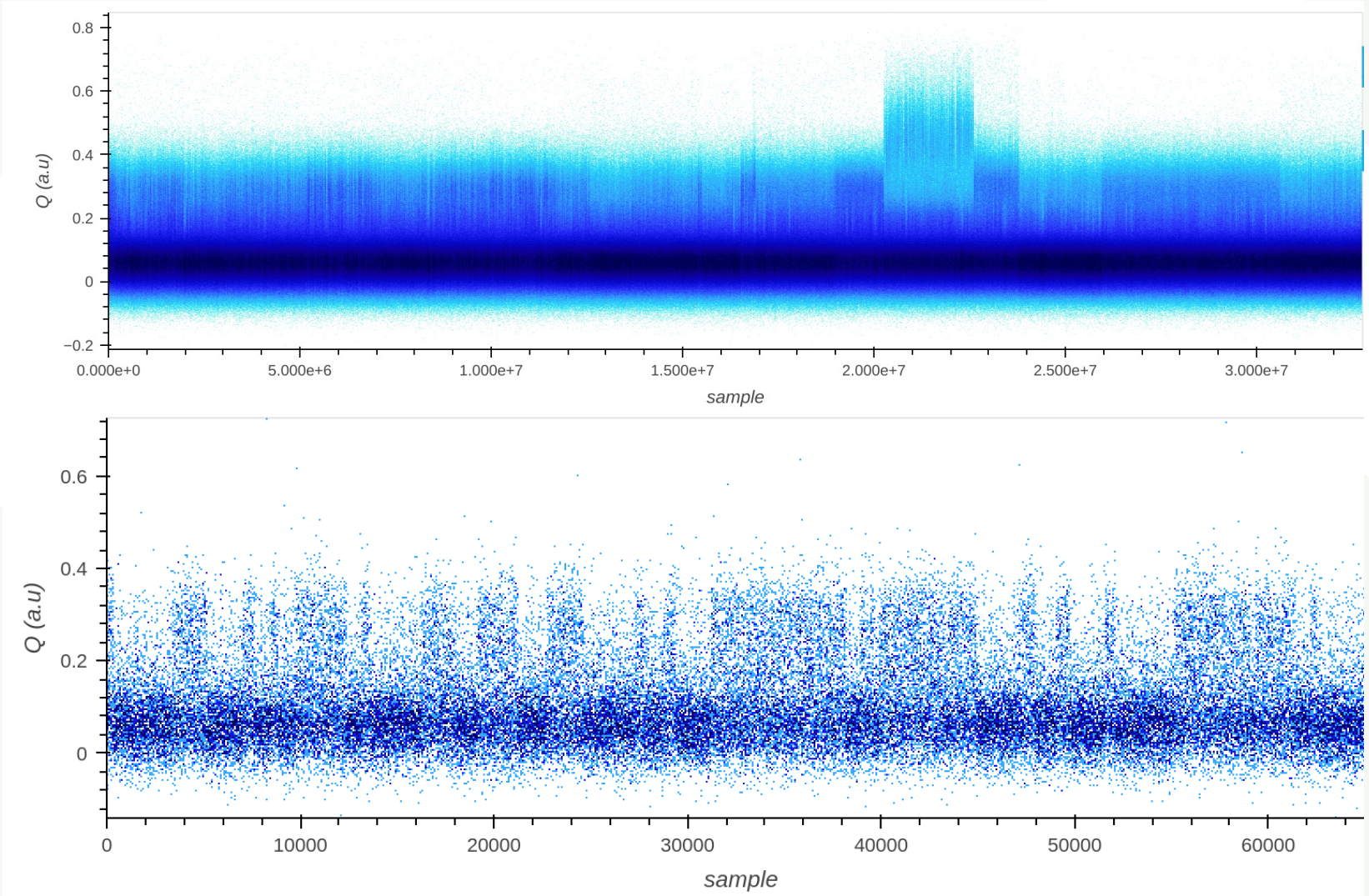




Before Cross-talk Compensation

After Cross-talk Compensation

Telegraphic Noise during extended operation



30 Million Shots

64K Shots

Result of repeatedly running the same RB circuit over 1 hour