Simulations for the Development of Quantum Computational Devices for HEP

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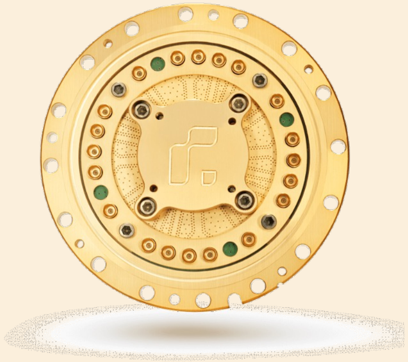
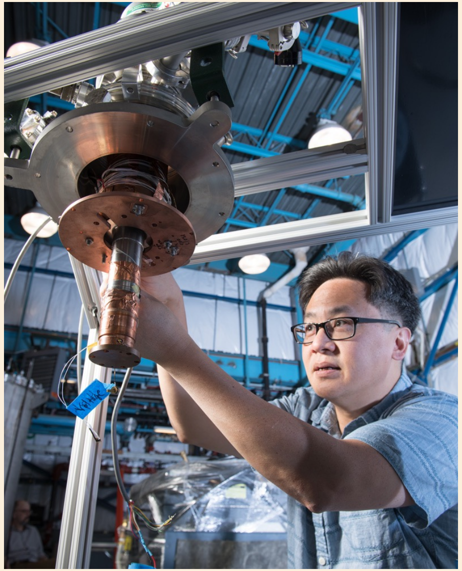
CompF6: Quantum Computing, July 20, 2022

Quantum devices for HEP

Qubits	Qudits	Sensors
		
Rigetti QPU	SQMS 3D Cavity	Search for Dark Matter

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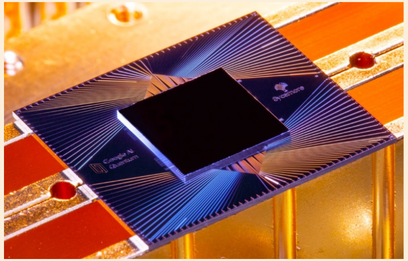
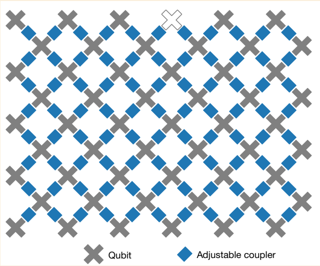
Qudits?

- Qubits are two level devices $|0\rangle$ and $|1\rangle$
  2D Superconducting cavities, Ion Traps, …





Google Sycamore 54 qubit QPU

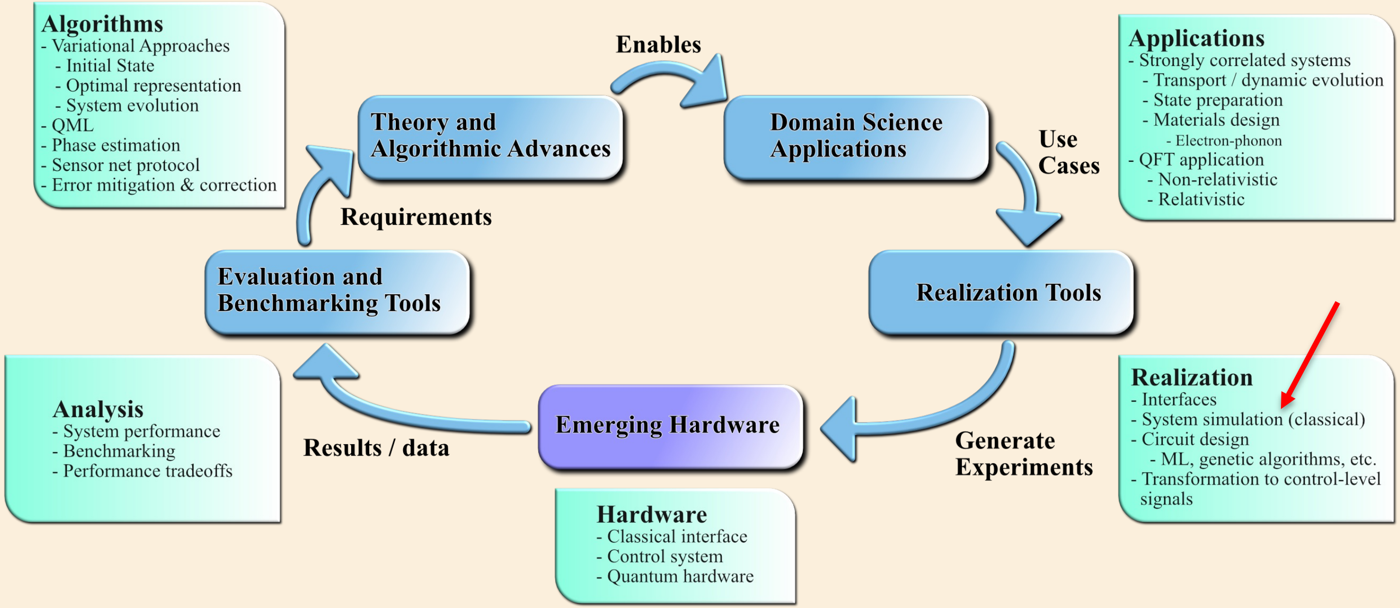
- Qudits are multilevel devices
  e.g. ququart (4 levels) is equivalent to 2 qubits
  $|0\rangle \sim |00\rangle,\ |1\rangle \sim |01\rangle, |2\rangle \sim |10\rangle, |3\rangle \sim |11\rangle$

A multi-cell 3D SRF cavity structure driven by an embedded superconducting transmon qubit

Strong interest in HEP algorithms on multilevel, multimode Qudit devices

Where can simulations fit in?

Co-design cycle



Classical simulations with fast turn-around time are important for device and algorithm design

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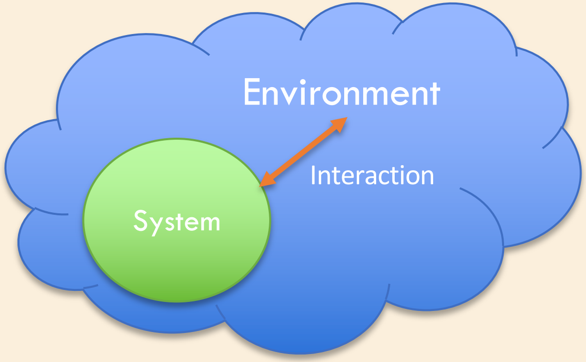
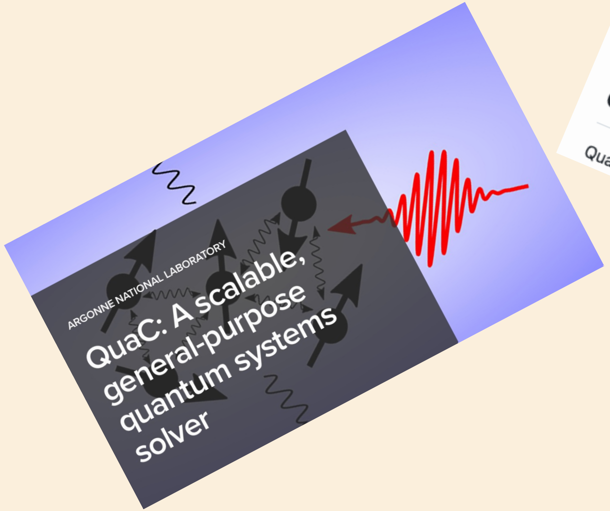
Open Quantum System Simulations

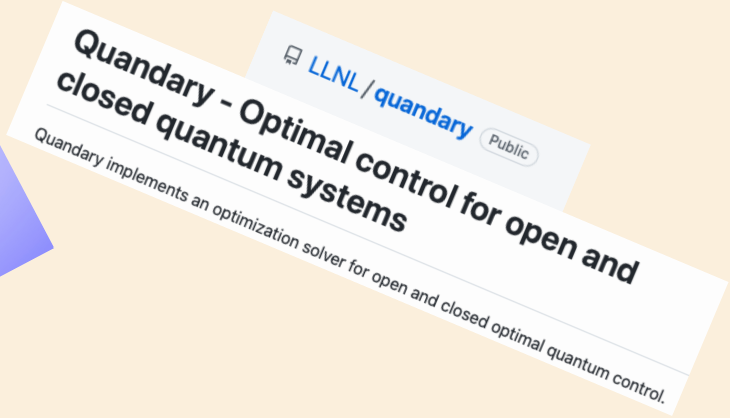


Includes device's interaction with environment (noise & decoherence)

Evolves density matrix with *Lindblad master equation* $\frac{d\rho(t)}{dt} = \sum_i \gamma_i L(C_i)[\rho(t)]$

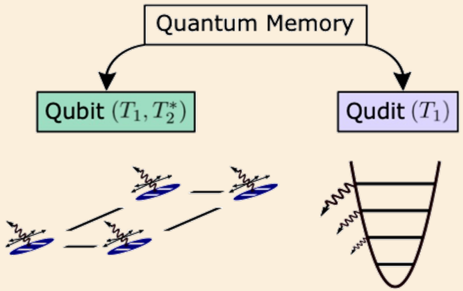
- *Real world behavior of device*
- *Gate design*
- *Optimal control*

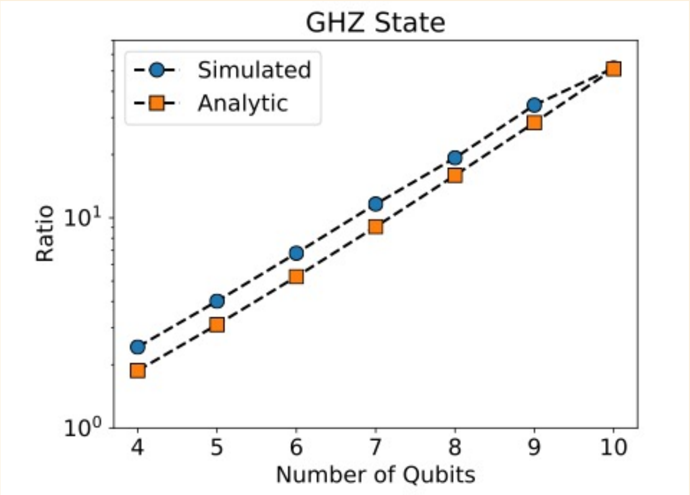


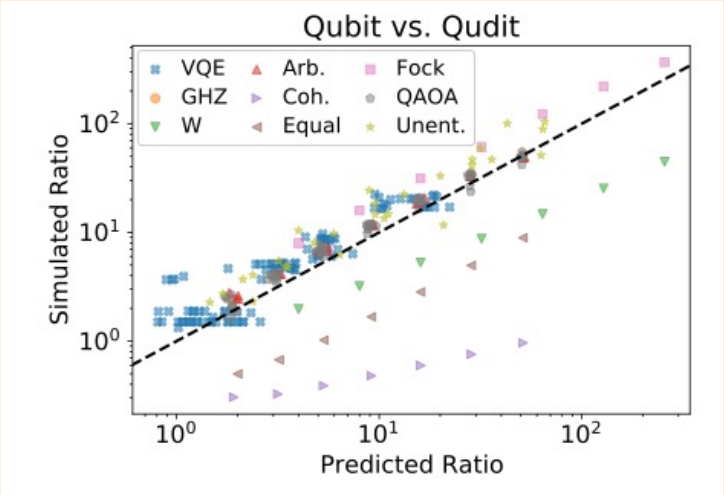


Example: Quantum memory – Qubit vs. Qudit

- Used QuaC to simulate and compare systems with
  - Multiple qubits
  - A multilevel qudit device







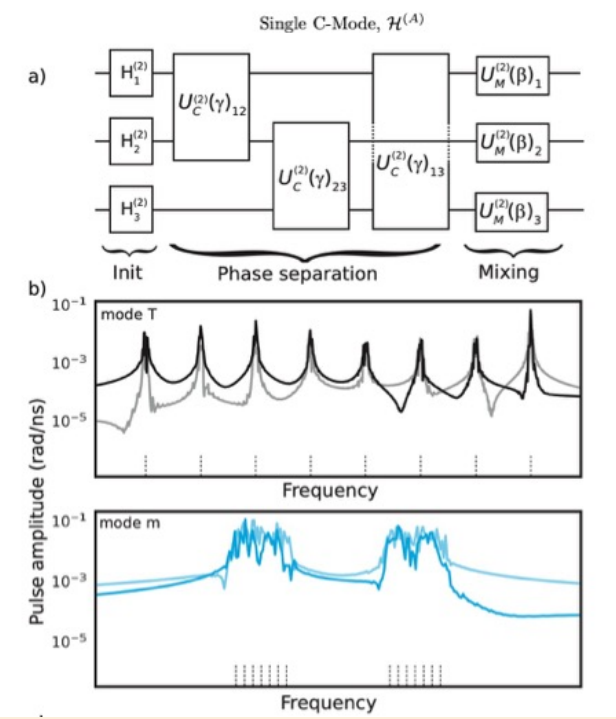
Otten, Kapoor, Özgüler, Holland, Kowalkowski, Alexeev, Lyon, Phys. Rev. A **104**, 012605 (2021)

Example – Optimal Control

Juqbox.jl

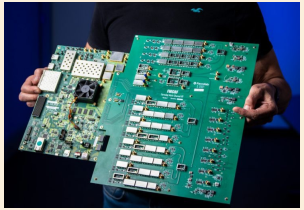
Juqbox.jl is a package for solving quantum optimal control problems in closed quantum systems, where the evolution of the state vector is governed by Schroedinger's equation.

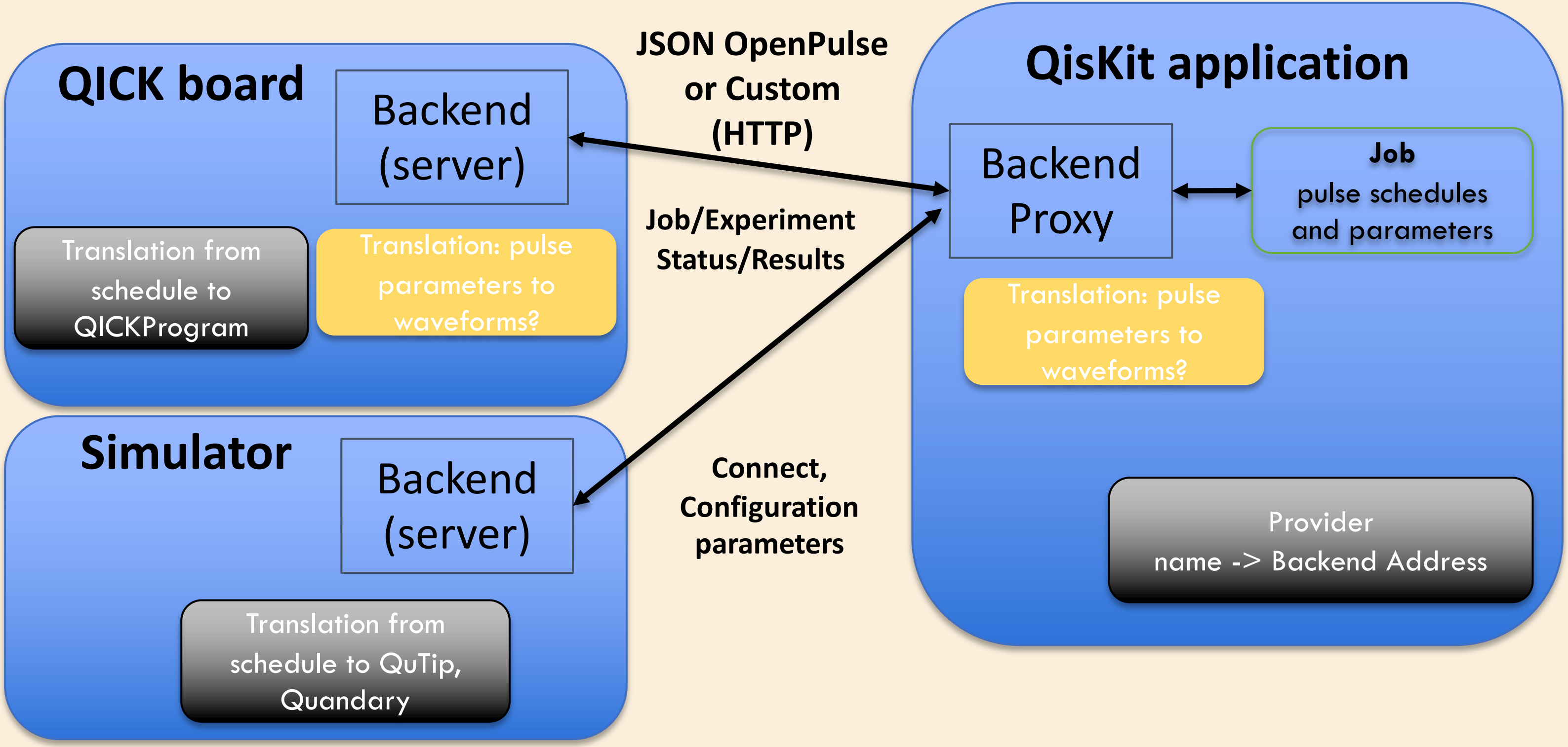
- Used Juqbox to determine optimal pulses for a QAOA in for a 8 level system



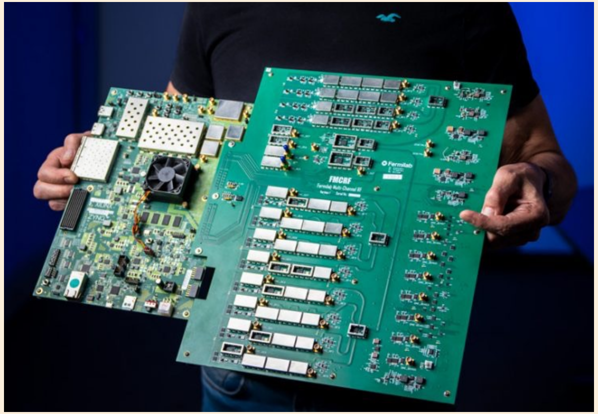
Özgüler and Venturelli,
Numerical Gate Synthesis for Quantum Heuristics on Bosonic Quantum Processors, arXiv:2201.07787

Fermilab QICK Control System





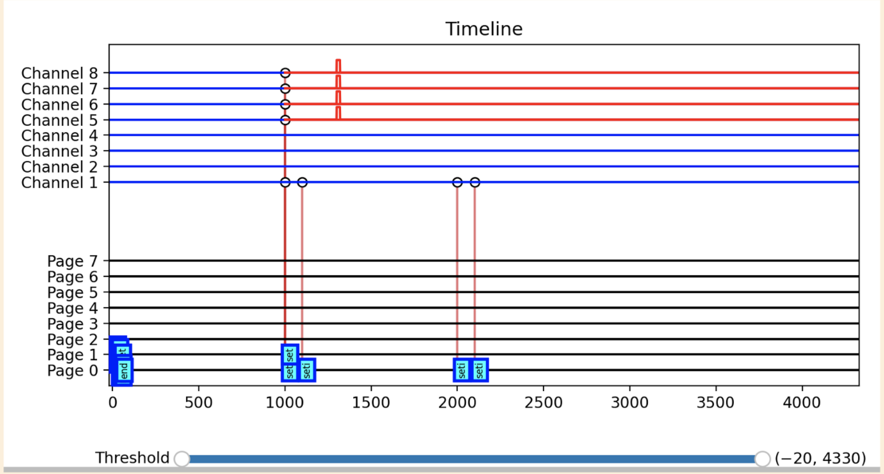
Fermilab QICK Control System



Simulation for code validation

```
// Program

        regwi 0, $1, 50;
        regwi 0, $2, 100;
        regwi 3, $16, 69905067;              //freq = 100.00000047683716 MHz
        regwi 3, $17, 0;                     //phase = 0
        regwi 3, $19, 1000;                  //gain = 1000
        regwi 3, $21, 0;                     //t = 0
        regwi 3, $20, 589844;                //stdysel | mode | outsel = 0b01001 | length = 20
        synci 200;
        regwi 0, $15, 0;
        regwi 0, $14, 0;
LOOP_J: regwi 0, $31, 49152;                 //out = 0b1100000000000000
        seti 0, 0, $31, 100;                 //ch =0 out = $31 @t = 0
        regwi 0, $31, 0;                     //out = 0b0000000000000000
        seti 0, 0, $31, 110;                 //ch =0 out = $31 @t = 0
        condj 0, $2, <, $1, @LABEL;
        regwi 3, $20, 589844;                //stdysel | mode | outsel = 0b01001 | length = 20
        regwi 3, $21, 0;                     //t = 0
        set 7, 3, $16, $17, $18, $19, $20, $21; //ch = 7, out = $16,$18,$19,$20 @t = $21
LABEL:  synci 20;
        mathi 0, $15, $15, +, 1;
        memwi 0, $15, 1;
        loopnz 0, $14, @LOOP_J;
        end;
```



Desired Simulation Functionality

- Supports sufficient size parameters (# qubits, # qudit levels, modes)
- Performant: Quick turnaround time. High performance libraries HPC, GPU, TPU
- Friendly interface – use the system as you would a real device
- Interfaces with community standard gate circuit-building tools (e.g. IBM Qiskit)
  - Accepts standard instruction formats like QASM
- Can be driven from pulse descriptions and sequences
- Include a library of Hamiltonians and device profiles to get started quickly
- Usuable from cloud services and HEP batch systems (HEPCloud)

- Many toolkits to drive Qubits (IBM Qiskit, Google CIRQ). Are they expressive enough to drive Qudits?

Summary

- Simulations can play a critical role in development of quantum computational devices

- Tools with desired functionality would be especially useful, enabling,
  - Development, Testing, Validation and Debugging
  - Design of algorithms and system building blocks (e.g. multi-level gates)
  - … *Without tying up the in-high-demand hardware*

- Simulation of control systems will be fruitful – serve as a mock system

- Leverage HEP’s long experience with simulations