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ON WITH PURPOSE

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Enabling Robust Quantum Computer System by Understanding the Calibration Data

Qiang GUAN,

GUANS Lab

Kent State University

About Me

Education

- Ph.D. in Computer Science and Engineering
  - High Performance Computing, Cloud.

Industry (Engineer)

- 2 years of firmware engineer
- 1 year of simulation software engineer

Research

- Department Of Energy (DoE): Los Alamos National Laboratory
  - Postdoc (1 year): HPC system.
  - Scientist (3 years): Resilience, data visualization, workflow system, quantum computing.

Green Ubiquitous Autonomous Networking System (GUAN'S) Lab

We are a computer science research group at the Kent State University. Our aim is to design next-generation hybrid hetrogenous HPC-Cloud computing systems and workflow tools for current HPC, Big Data, and Deep Learning AI communities.

AI

We build AI models for science (physics, medicine, social good)

System

We build HPC and Cloud System

Quantum

We do quantum AI and program on quantum computers

VR

We build VR and eye-tracking systems

NSF

NIH National Institute of Mental Health

U.S. DEPARTMENT OF ENERGY

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http://www.guans.cs.kent.edu/

GUAN SYSTEM LABORATORY

Something You May Be Familiar

Sheldon Cooper:

Quantum physics makes me so happy.

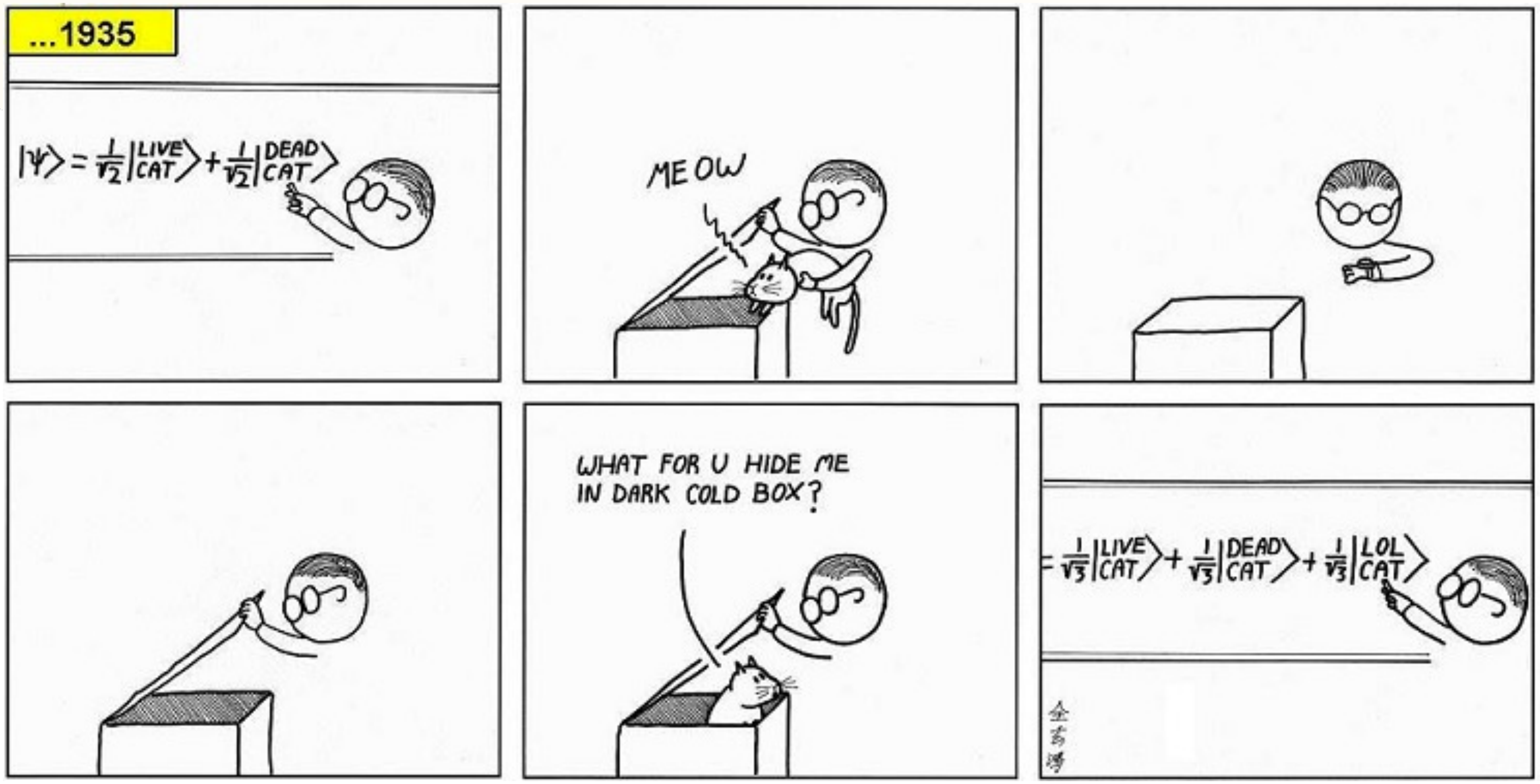
Leonard Hofstadter:

Yeah? I'm glad.

Sheldon Cooper:

It's like looking at the universe naked.

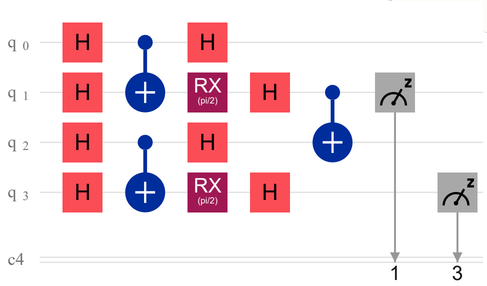
A Very Famous Cat



Overview

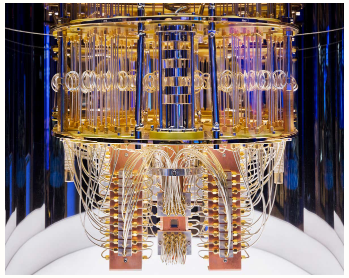
Programmer

Application



- *Application Characterization*
- *Quantum Vulnerability Factor*

Quantum Computers



- *Hardware Noise Characterization*
- *Performance Metrics*
- *Visual Tools*

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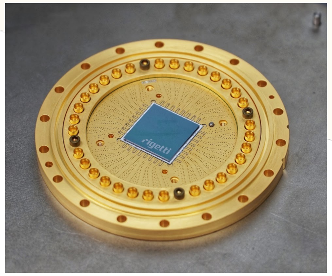
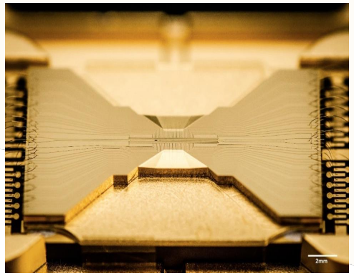
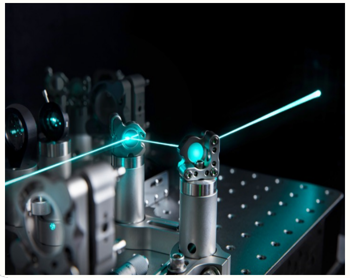
Quantum Computing for Real



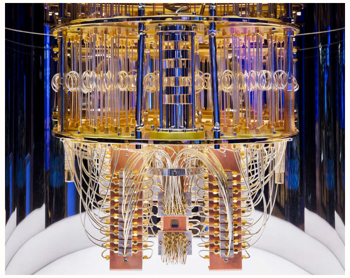
Rigetti



IonQ



Honeywell



IBM-Q

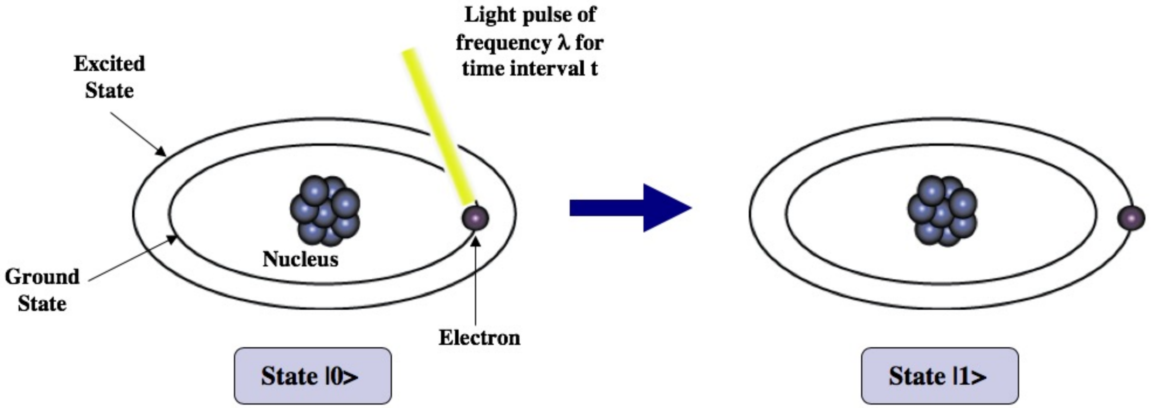
Google

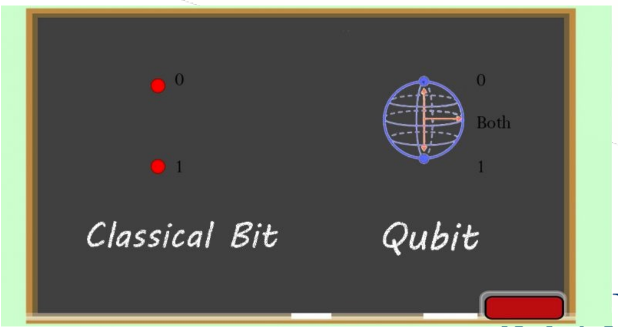
Quantum computers now with a larger number of qubits

- 127 qubits
- 1,000 qubits 2023

Qubit

- A bit of data is represented by a single atom that is in one of two states denoted by |0> and |1>. A single bit of this form is known as a *qubit*
- A physical implementation of a qubit could use the two energy levels of an atom. An excited state representing |1> and a ground state representing |0>.





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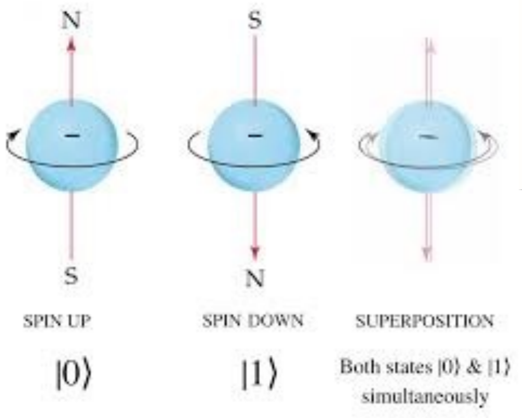
Superposition

- A single qubit can be forced into a *superposition* of the two states denoted by the addition of the state vectors: (Flipping coin example)
  - $|\psi\rangle = \alpha 1\ |0\rangle + \alpha 2\ |1\rangle$
- Where $\alpha 1$ and $\alpha 2$ are complex numbers and $|\alpha 1|+|\alpha 2| = 1$

A qubit in superposition is in both states |1> and |0 at the same time



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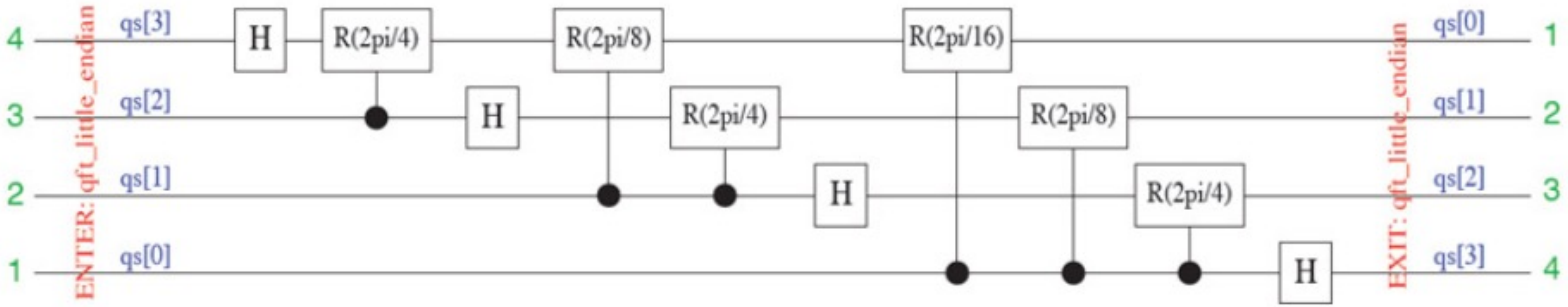
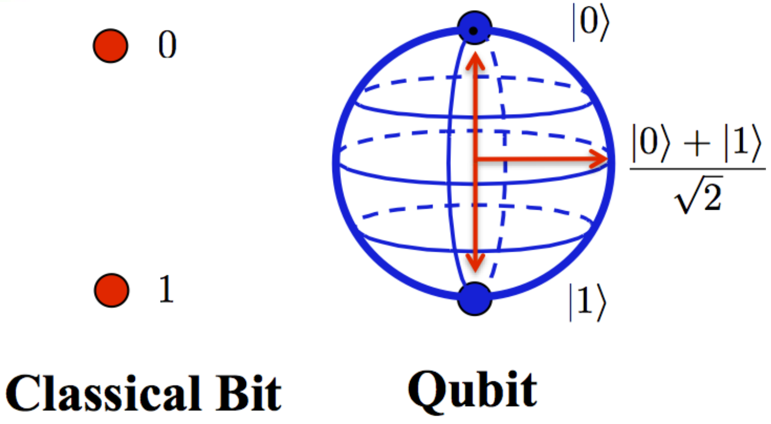
Entanglement: Quantum Communication

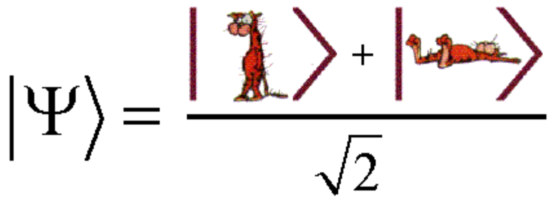
- *Entanglement* is the ability of quantum systems to exhibit correlations between states within a superposition.
- Imagine two qubits, each in the state |0> + |1> (a superposition of the 0 and 1.) We can entangle the two qubits such that the measurement of one qubit is always correlated to the measurement of the other qubit.

Quantum Circuit

- It is all about *Gate* and *State Changes*







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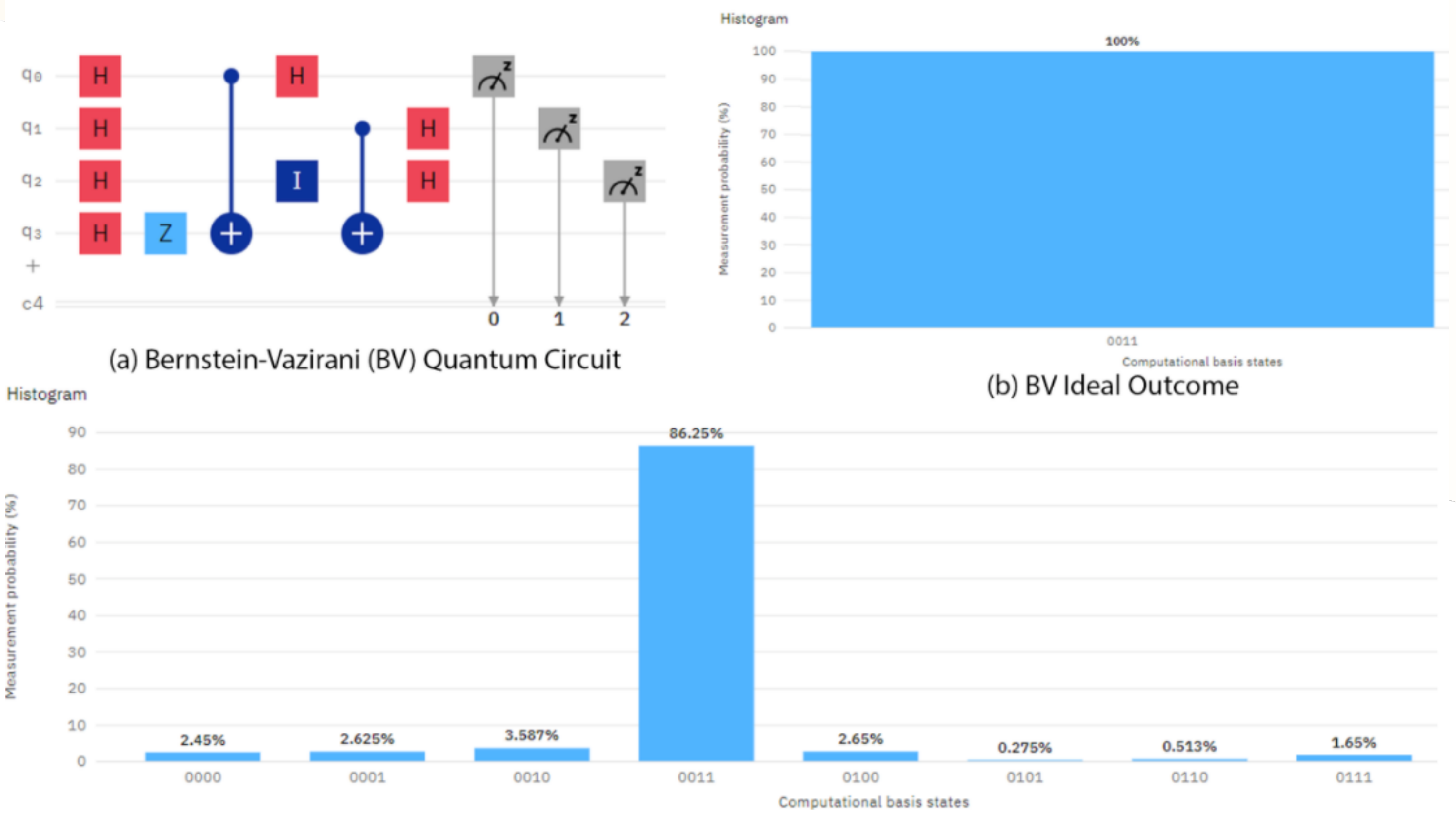
Biggest Challenge: Noise

- **NISQ device: Noisy Intermediate Scale Quantum device**



(a) Bernstein-Vazirani (BV) Quantum Circuit

(b) BV Ideal Outcome

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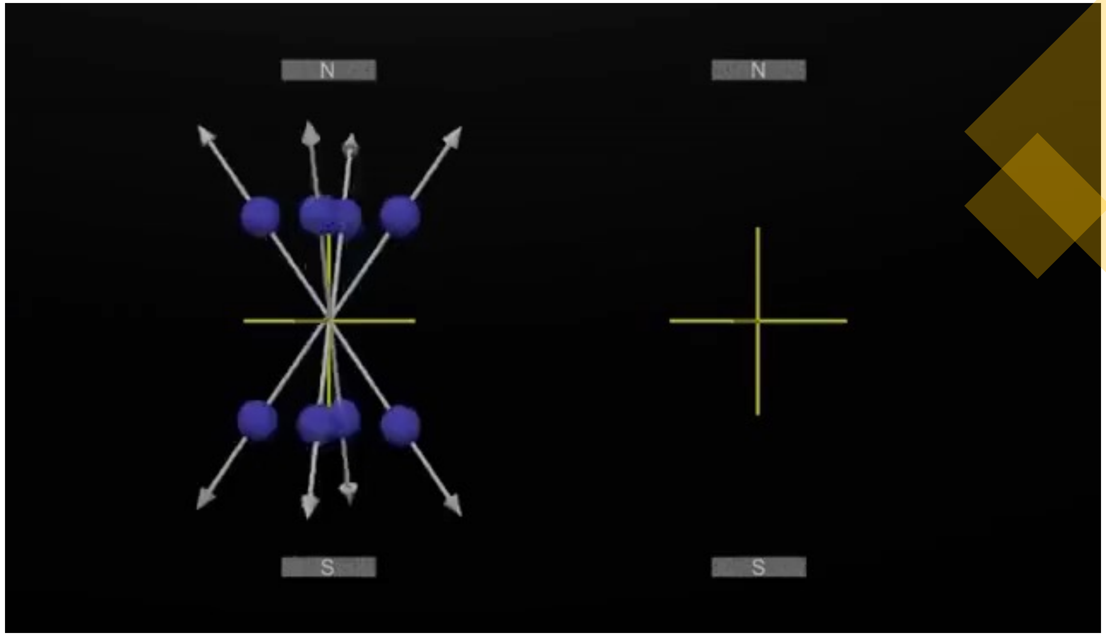
Quantum Errors

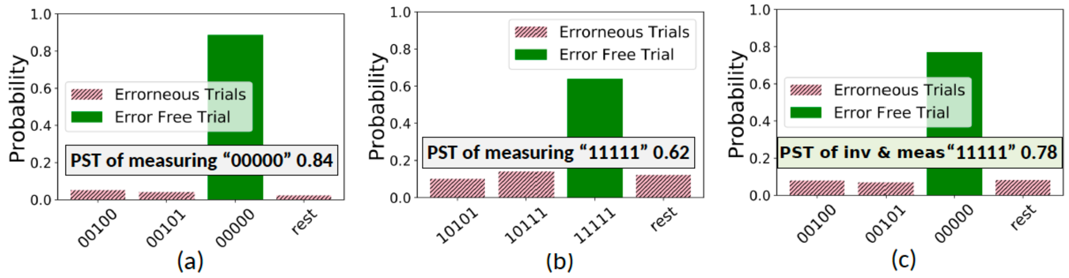
- **T1**
  - A qubit in high energy state $|1>$ naturally decays to lower energy state $|0\ >$, the time associate with this decay is called as the T1 (spin-lattice) Coherence Time (time that qubit would relax to state $|0\ >$)
- **T2**
  - Aka spin-spin relaxation process, is the effect of environment or other qubits on target qubit, which indicates the time for a qubit to get affected by the environment
- **Quantum operation errors**
  - single-qubit gate errors (also known as U3 gate errors)
  - single qubit readout errors
  - two qubit gate errors (referred to as CX/CNOT gate errors)



Qubit	Frequency	T1	T2	SX Error	Readout	CNOT
0	4.968703012	69.9676087	56.20196768	2.64E-04	3.54E-02	cx0_1: 1.010e-2
1	4.77009228	40.15346697	63.52262621	5.86E-04	3.32E-02	cx1_2: 2.343e-2, cx1_0: 1.010e-2
2	5.015166231	75.44901956	133.6973479	3.66E-04	2.57E-02	cx2_3: 1.087e-2, cx2_1: 2.343e-2
3	5.25925911	65.14892639	136.0921078	3.30E-04	2.11E-02	cx3_4: 1.159e-2, cx3_2: 1.087e-2
4	4.997604649	80.21439012	160.4948487	2.66E-04	2.11E-02	cx4_3: 1.159e-2

Impact of Quantum Fidelity Analysis

- **Most important part of having meaningful result is controlled (none error quantum environment)**
  - In quantum system level errors causes are mostly hardware related.
  - T1, T2, Frequency, Readout, CNOT, and single gate error rate are the most common ones.
- **Analyzing these errors based on time interval and characterizing them is a new approach that has never been done**



*Tannu et al, Micro'19

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Temporal Analysis and Prediction: Motivation

- **Analyzing these errors based on time interval and characterizing them is a new approach that has never been done.**
- **Prediction of errors can save time (long waiting time – IBMQ) and money (cost – AWS Braket) and reduce the uncertainty of the results.**
  - Stationary / non stationary (KPSS ADF test)
  - Temporal model : $E_m\ (t)$
  - Delay / waiting: $E_m\ (t + \tau(t))$, $\tau(t)$ is the delay model (waiting time).
- **Selection of quantum machine:**
  - Noise state
  - Qubit capacity
  - Qubit topology
  - Cost

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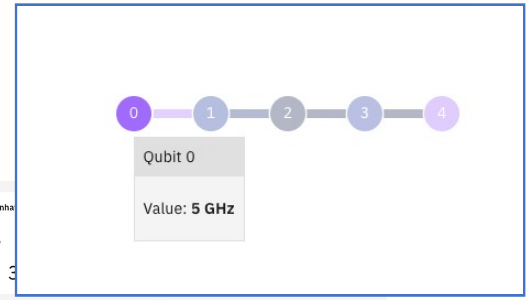
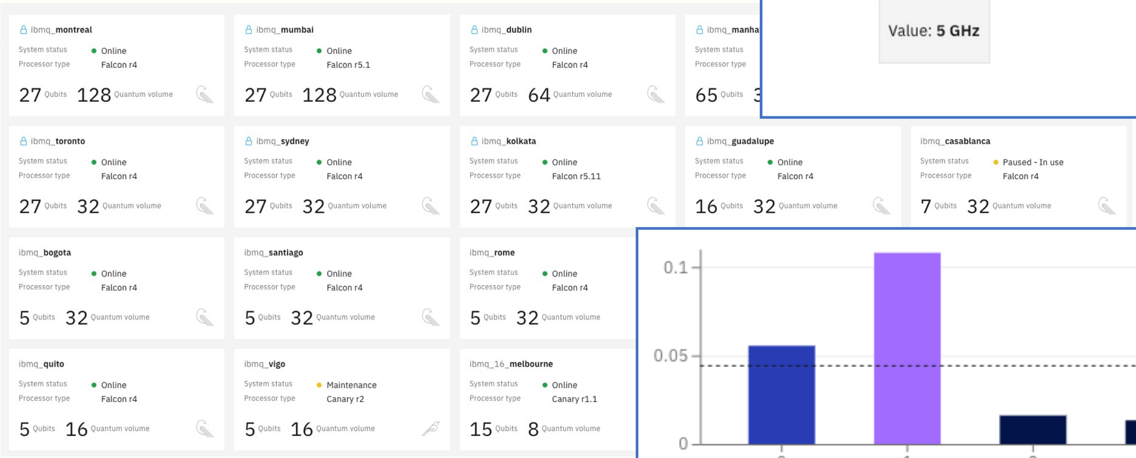
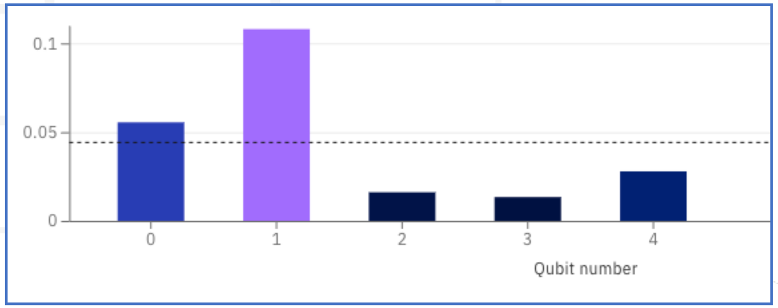
Data Collection

- **IBMQ Machine (IBM Research Hub Member):**
  - 60 days of IBM Q machines (4) in 2019
  - ~60 days of IBM Q machines (12 + 9) in 2021
  - Attributes of collection
    - Processor
    - QV
    - Qubits
    - Topology
    - Noise state (t1,t2, ….)
- **AWS Braket: (planning)**

Time Interval	Collected Attributes	# of Machines
09/11/2019	# Q, F, T1, T2, RE, SQU3, CNOT	1
09/12/2019 -09/13/2019	# Q, F, T1, T2, RE, SQU3, CNOT	2
09/14/2019 - 11/11/2019	# Q, F, T1, T2, RE, SQU3, CNOT	4
06/26/2020 - 09/15/2020	T1, T2, F, SQU3 through PGM	1
12/02/2020 - 02/17/2021	# Q, F, T1, T2, RE, SQU3, CNOT	11
02/18/2021 - 03/24/2021	# Q, F, T1, T2, RE, SQU3, CNOT	21







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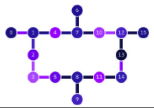
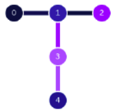
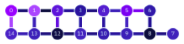
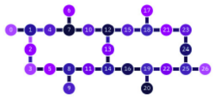
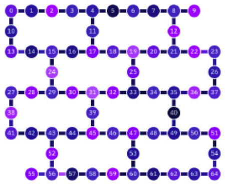
NISQ IBM

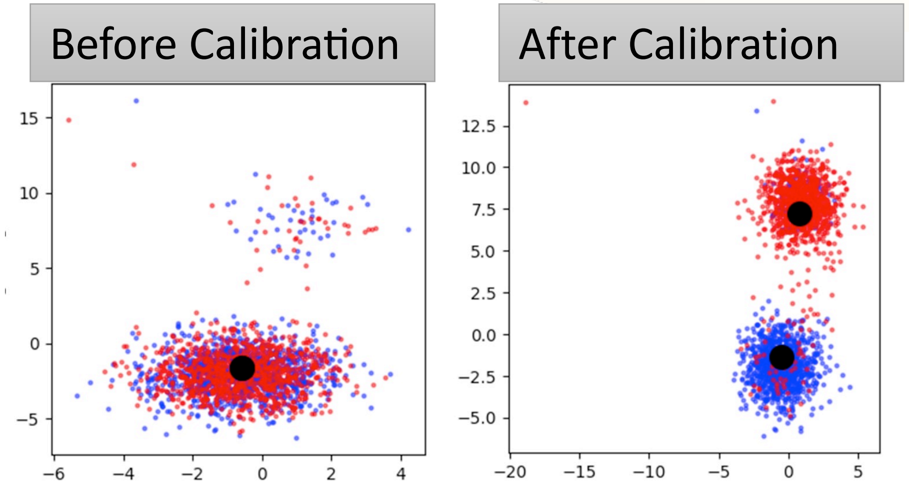
- Processor Type
- Topology
- Quantum Volume

Category	Topology
Linear (**L**)	
Ring (**R**)	
Tree (**T**)	
Mesh (**M**)	
Double Ring (**DR**)	
Octuple Ring (**OR**)	

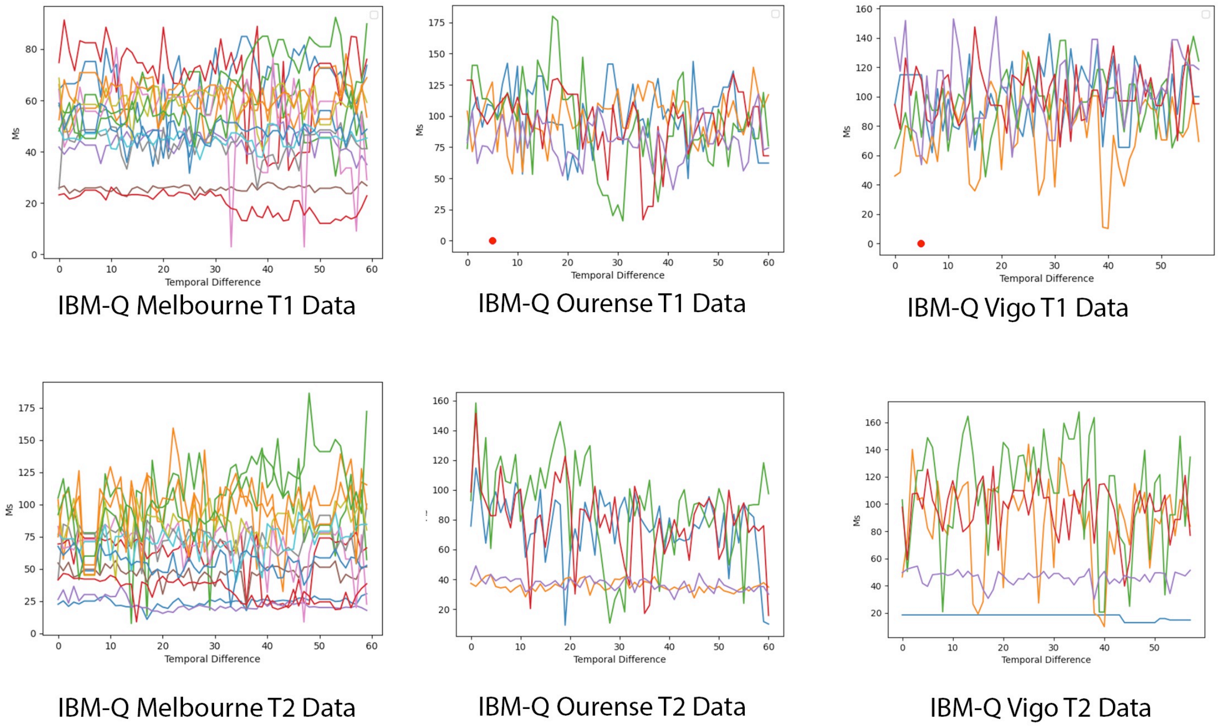
Machine	# of Qubits	Processor	Quantum Volume	Topology*	# of Qubit Connections
Armonk	1	Canary r1.2	1	NaN	NaN
Vigo	5	Canary r2	16	T	4
Valencia	5	Canary r2	16	T	4
Sandiago	5	Falcon r4	32	L	4
Rome	5	Falcon r4	32	L	4
Quito	5	Falcon r4	16	T	4
Ourense	5	Canary r2	16	T	4
Lima	5	Falcon r4	8	T	4
Athens	5	Falcon r4	32	L	4
Bogota	5	Falcon r4	32	L	4
Belem	5	Falcon r4	16	T	4
Yorktown	5	Canary r1	8	M	6
Casablanca	7	Falcon r4	32	T	6
Melbourne	15	Canary r1.1	8	M	20
Guadalupe	16	Falcon r4	32	R	16
Toronto	27	Falcon r4	32	DR	27
Sydney	27	Falcon r4	32	DR	27
Paris	27	Falcon r4	32	DR	27
Mumbai	27	Falcon r5	128	DR	27
Montreal	27	Falcon r4	128	DR	27
Kolkata	27	Falcon r5.11	32	DR	27
Dublin	27	Falcon r4	64	DR	27
Manhattan	65	Hummingbird r2	32	OR	72

Calibration

- **Pulse Generated Method**
  - IBM-Q Armonk
- **Heuristic Calibration Data**



Pulse Generated Method



Heuristic Calibration Data

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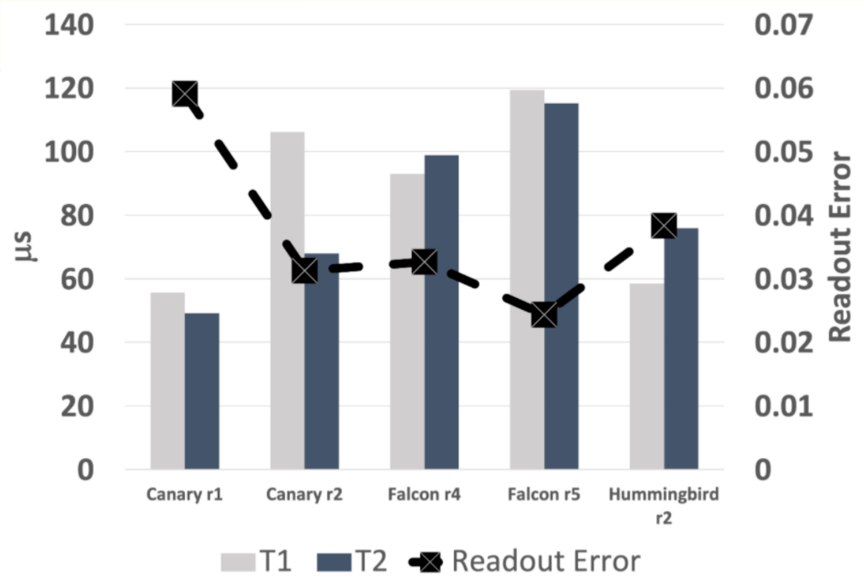
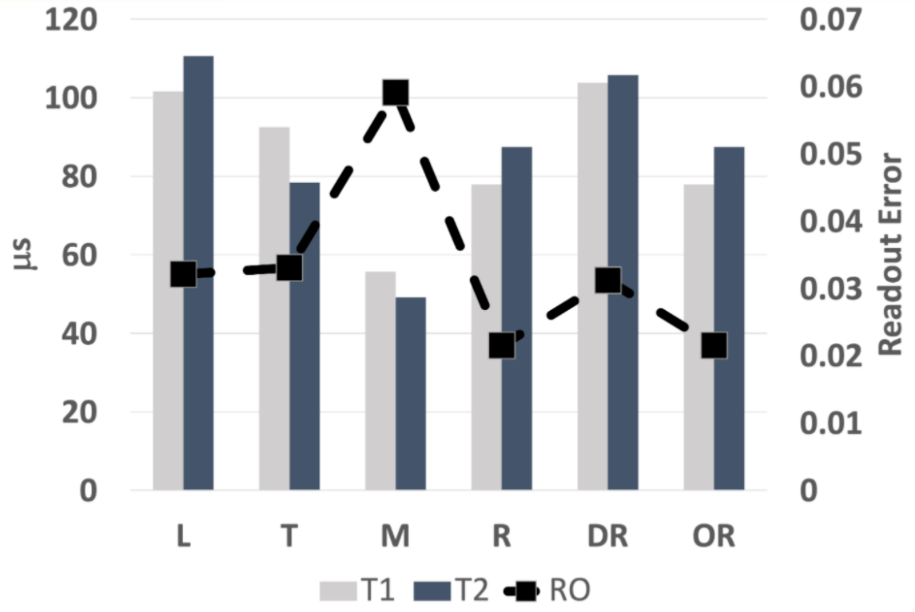
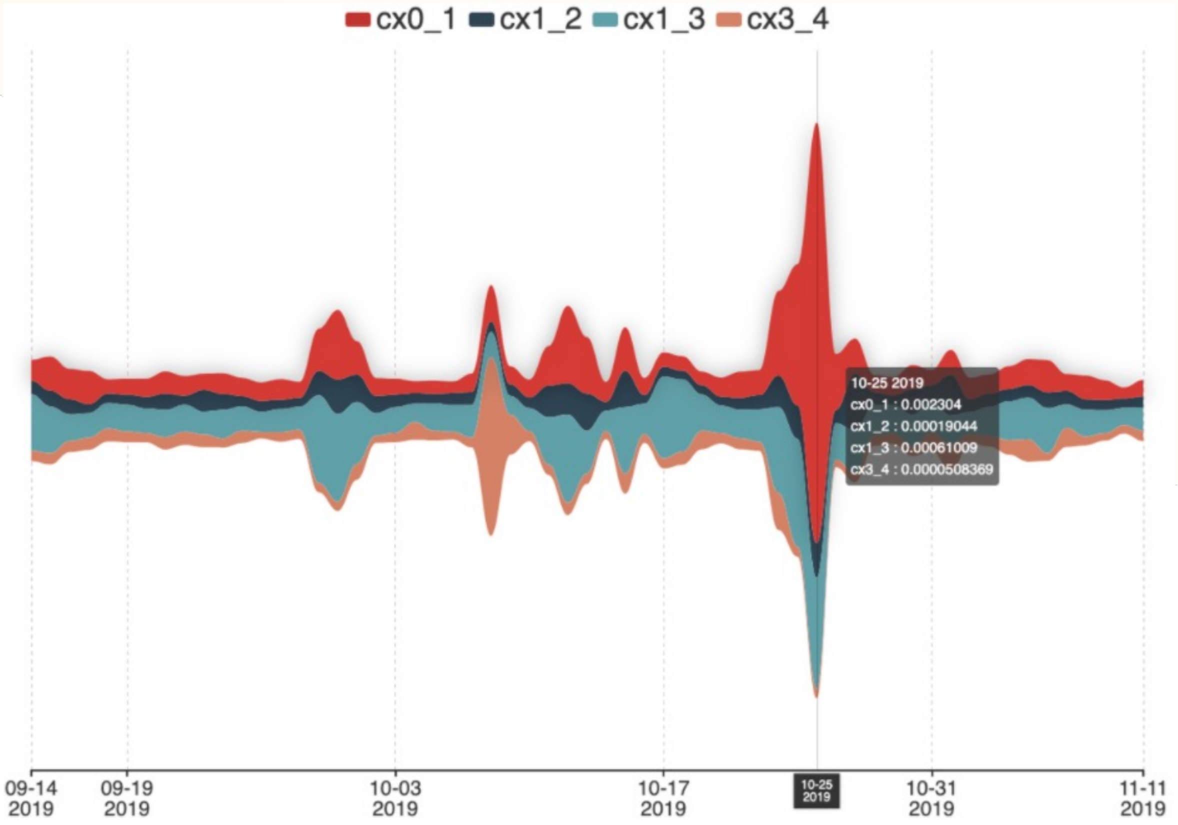
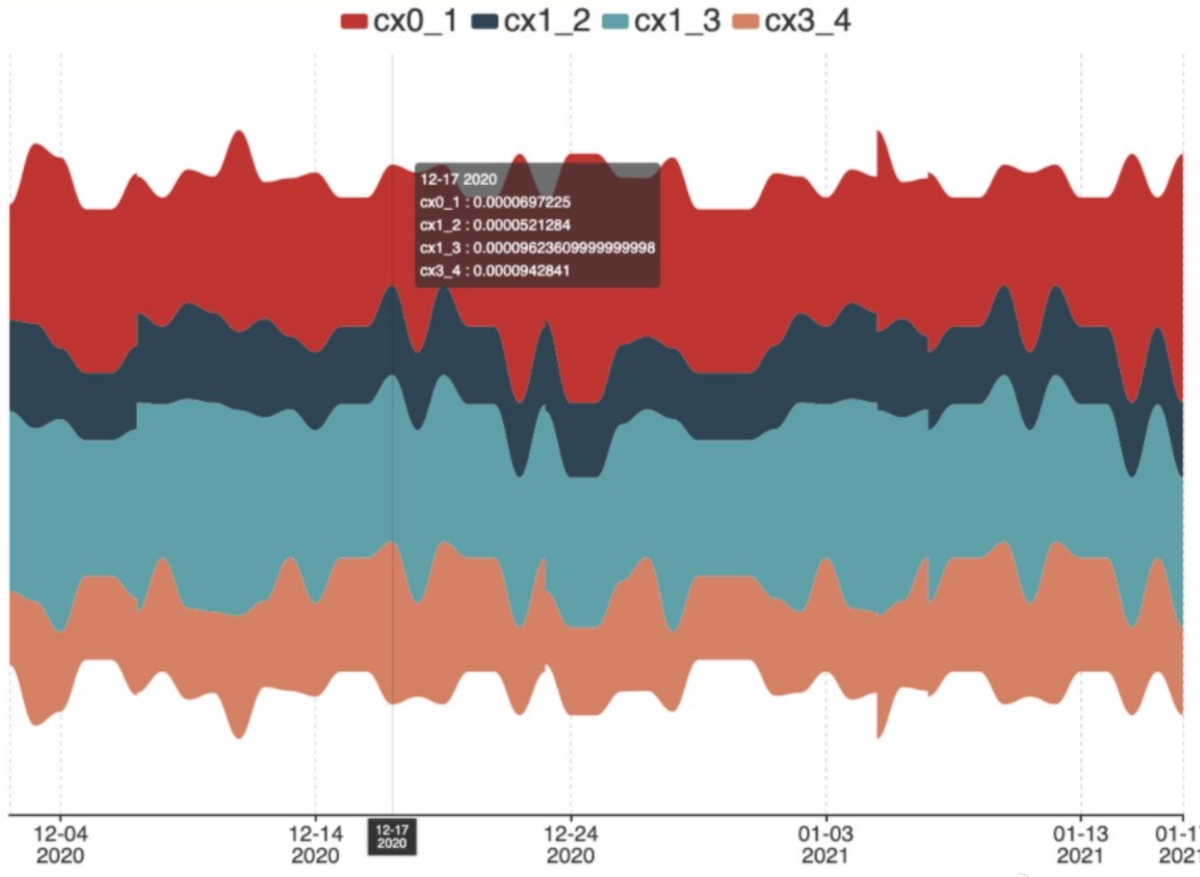
Observations: Processor Type



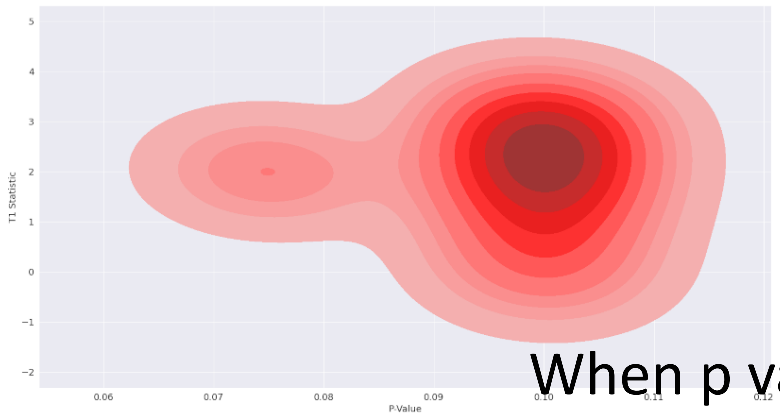


Observation: Stability (2019 vs 2021)

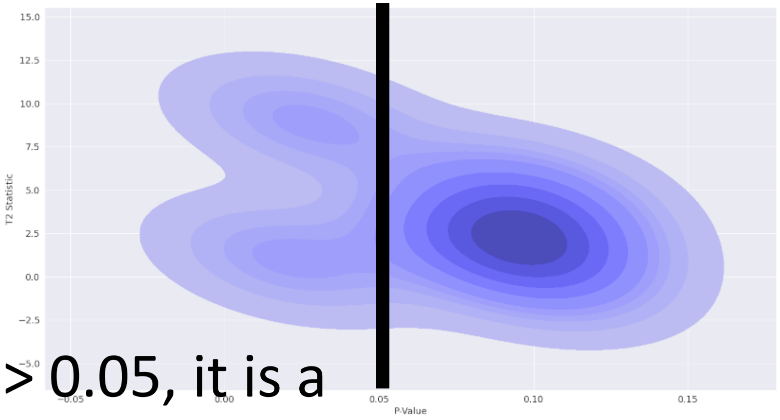




KPSS Test IBM-Q Melbourne: Stationary Test

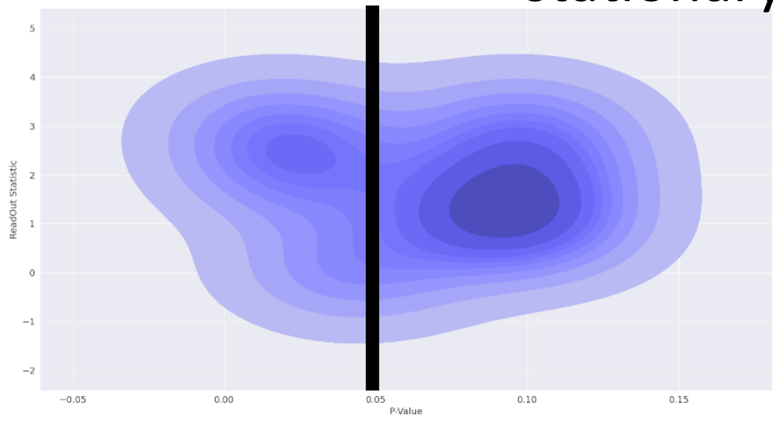


(a)

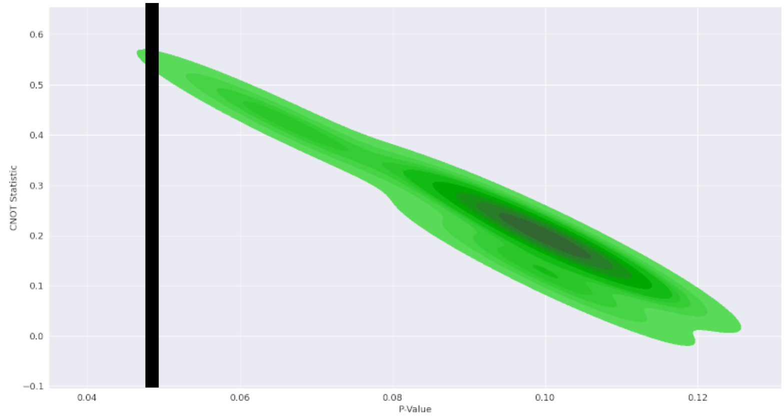


(b)

When p vale > 0.05, it is a stationary state



(c)



(d)

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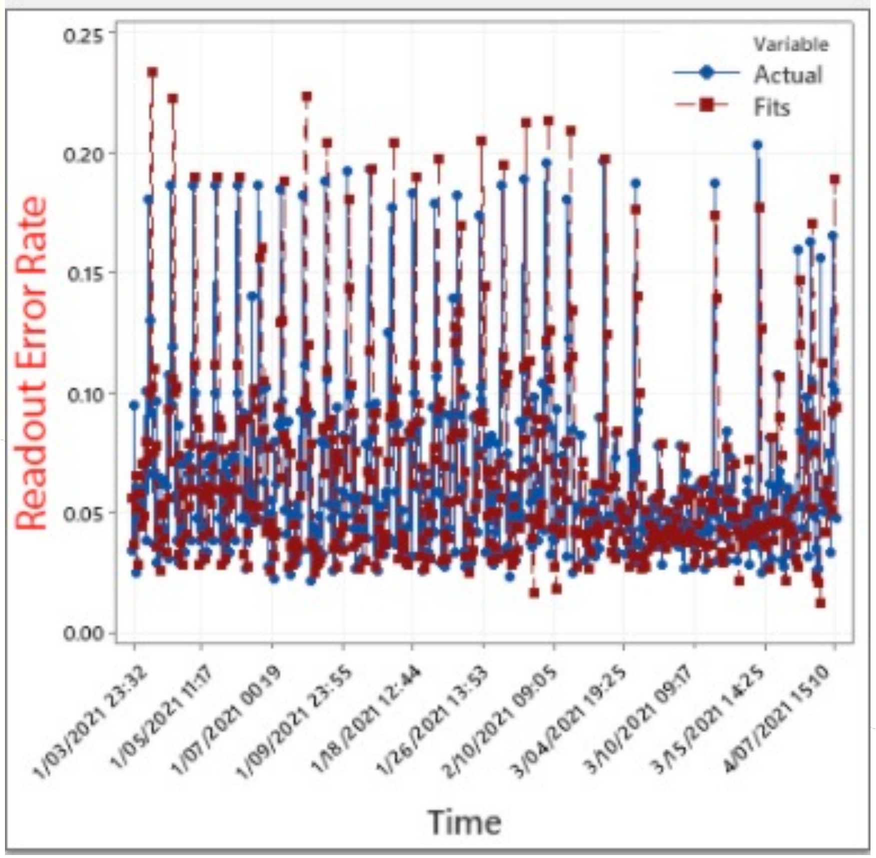
Temporal Analysis: Prediction

- ARIMA: Autoregressive Integrated Moving Average
- Exponential Smoothing

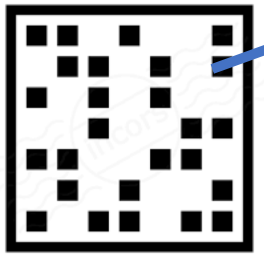


Fidelity Degradation for Comparing NISQ Machines

Qubit	Frequency	T1	T2	SX Error	Readout	CNOT
0	4.968703012	69.9676087	56.20196768	2.64E-04	3.54E-02	cx0_1: 1.010e-2
1	4.77009228	40.15346697	63.52262621	5.86E-04	3.32E-02	cx1_2: 2.343e-2, cx1_0: 1.010e-2
2	5.015166231	75.44901956	133.6973479	3.66E-04	2.57E-02	cx2_3: 1.087e-2, cx2_1: 2.343e-2
3	5.25925911	65.14892639	136.0921078	3.30E-04	2.11E-02	cx3_4: 1.159e-2, cx3_2: 1.087e-2
4	4.997604649	80.21439012	160.4948487	2.66E-04	2.11E-02	cx4_3: 1.159e-2

Calibration Time Series

Degradation Detection



Fidelity Degradation Matrix

d_{ij} : 1 or 0 (whether or not a fidelity degradation event occurring on the *ith* sampling time for the *jth* attribute)

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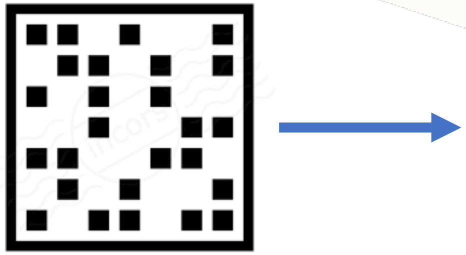
Fidelity Degradation Analysis



	Evaluation Metrics
FDR	Fidelity Degradation Rate
MTBFD	Mean Time Between Fidelity Degradation
FDD	Fidelity Degradation Depth
CDF	Cumulative Distribution Function
FDC	Fidelity Degradation Correlation
SQ	Sensitive Qubits
DQP	Distance between Correlated Qubit Pairs

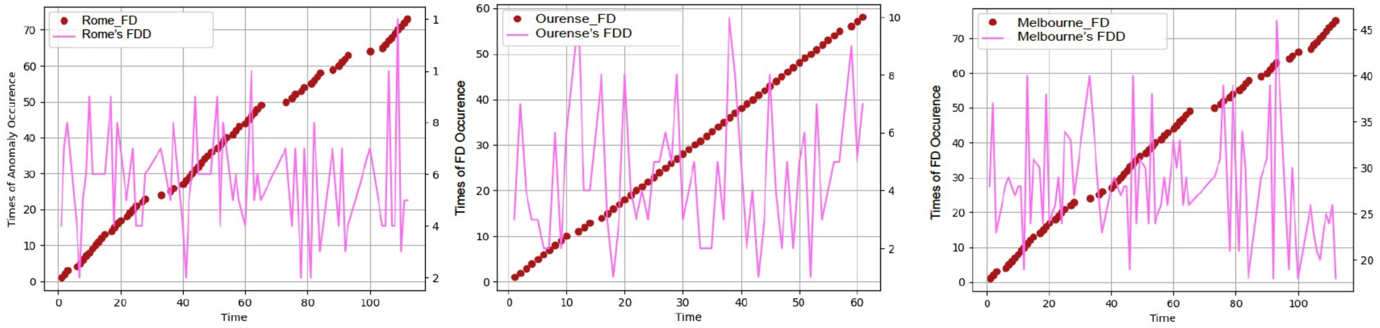
FDR

Machine \ Attr	T1	T2	R-O Error	CNOT-Error	Average
Athens	0.2333	0.2140	0.2018	0.2083	0.2147
Bogota	0.2053	0.2123	0.2053	0.1996	0.2059
Rome	0.1912	0.1877	0.2000	0.1996	0.1944
Santiago	0.2211	0.1895	0.1877	0.1623	0.1916
Linear Topology	0.2114	0.1996	0.1978	0.1924	0.2003
Vigo	0.1759	0.1889	0.1593	0.1713	0.1740
Ourense	0.2197	0.2262	0.2230	0.2254	0.2235
Tree Topology	0.1917	0.2024	0.1822	0.1908	0.1918
Melbourne (**Mesh Topology**)	0.2187	0.2222	0.2041	0.2193	0.2170

MTBFD

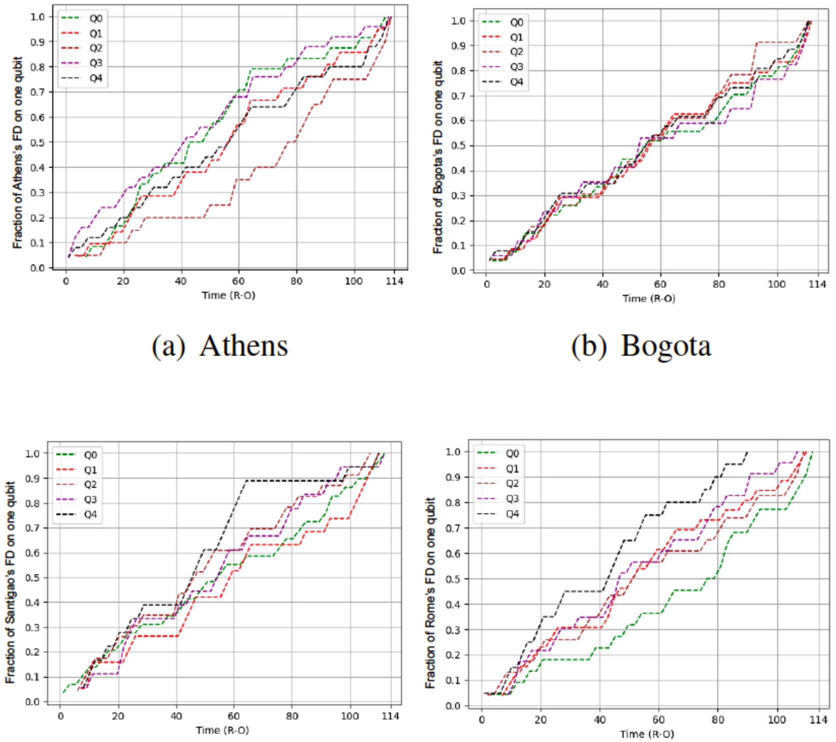
Qubit \ Machine	Athens	Bogota	Rome	Santiago	Ourense	Vigo
Q0	4.515	4.606	5.561	4.56	4.604	5.539
Q1	4.851	4.515	4.8	5.124	4.604	6.0
Q2	4.957	4.851	5.124	5.429	4.519	6.085
Q3	4.653	5.494	5.124	6.08	4.281	5.468
Q4	4.851	4.957	5.182	5.365	4.519	5.610
Average	4.765	4.884	5.158	5.311	4.561	5.740

FDD



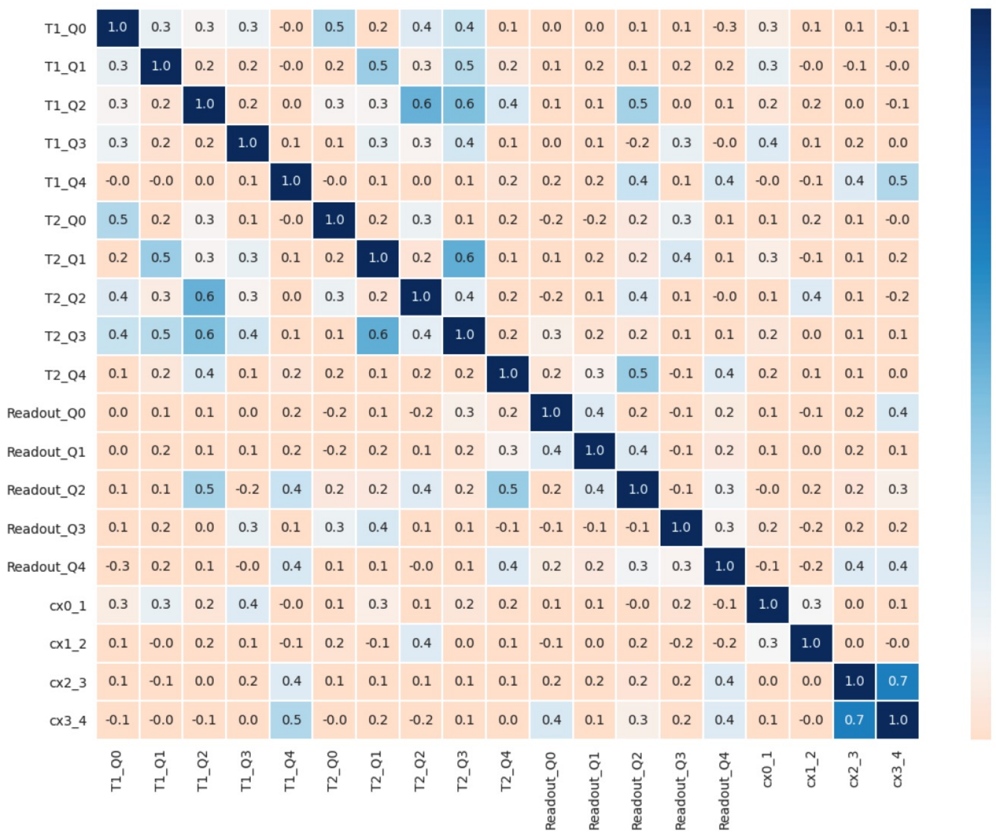
(d) Rome (e) Ourense (f) Melbourne

CDF



(a) Athens (b) Bogota

(c) Santiago (d) Rome



FDC

TABLE IV: Ratio of Having a Strong Correlation between attributes of T1 and T2

Topology	Ratio of strong correlation on special diagonals	Rate of strong correlation for all pairs
Linear	18/20 (90%)	45/100 (45%)
Tree	8/10 (80%)	18/50 (36%)
Mesh	15/15 (100%)	66/225 (29.3%)
Total	41/45 (91.1%)	129/375 (34.4%)

SQ

Machine	SQ
Athens	Q4
Bogota	Q0, Q3
Santiago	Q1, Q2, Q3, Q4
Rome	Q0, Q1
Orense	Q2
Vigo	Q0, Q2, Q3, Q4

DSP

TABLE V: Melbourne's strong correlated qubit pairs and weak correlated qubit pairs

Distance Between Qubit Pair	1	2	3	4	5	6	7	8
Strong Correlation Pairs	3	2	4	3	2	0	0	0
Weak Correlation Pairs	3	6	2	6	2	2	0	1

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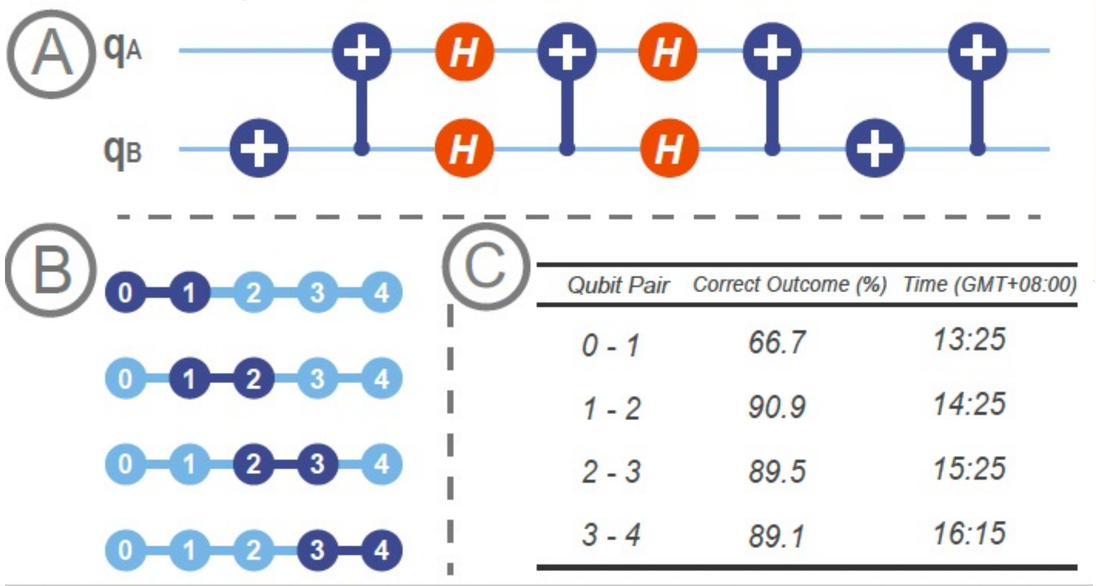
VACSEN: Visualizing the Quality of Quantum Computers

Comparing performance (NOISE) between backends

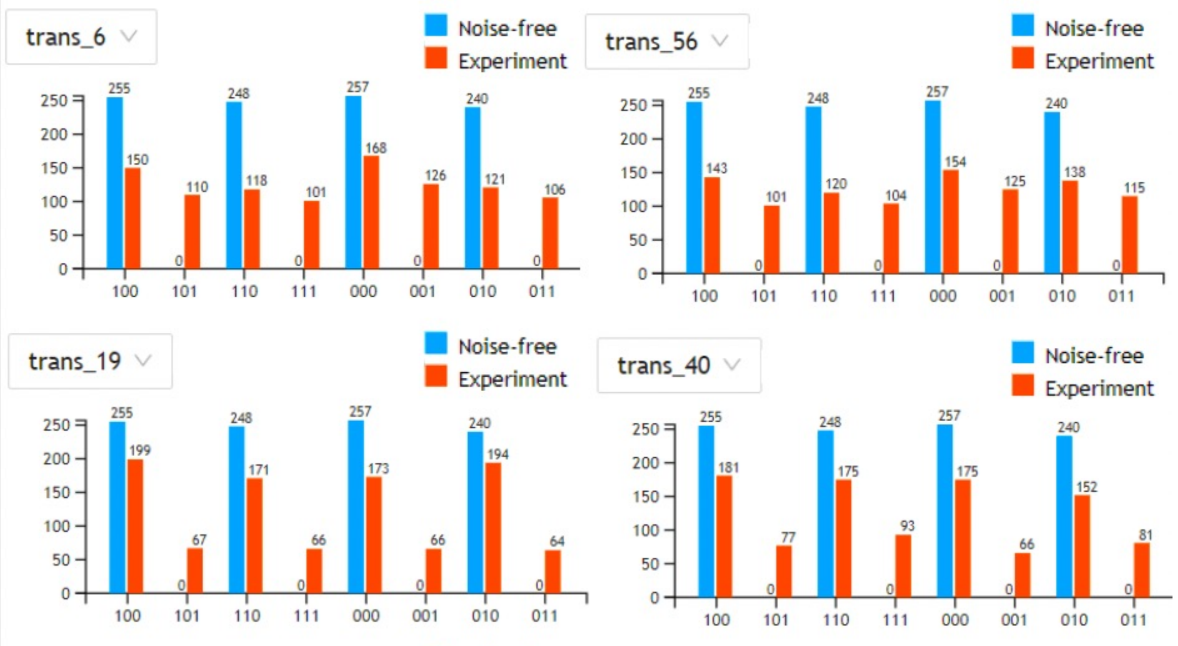
Tracking the performance of backends

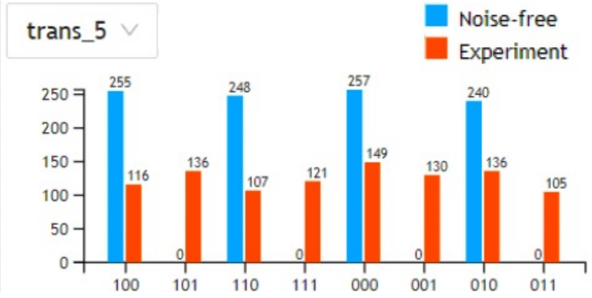
Comparing the transpilations of the circuits

Motivation



Qubit Pair	Correct Outcome (%)	Time (GMT+08:00)
0 - 1	66.7	13:25
1 - 2	90.9	14:25
2 - 3	89.5	15:25
3 - 4	89.1	16:15





Compiled Circuit	Fidelity (%)
trans_6	55.5%
trans_56	55.4%
trans_19	73.9%
trans_40	68.3%
trans_5	50.6%

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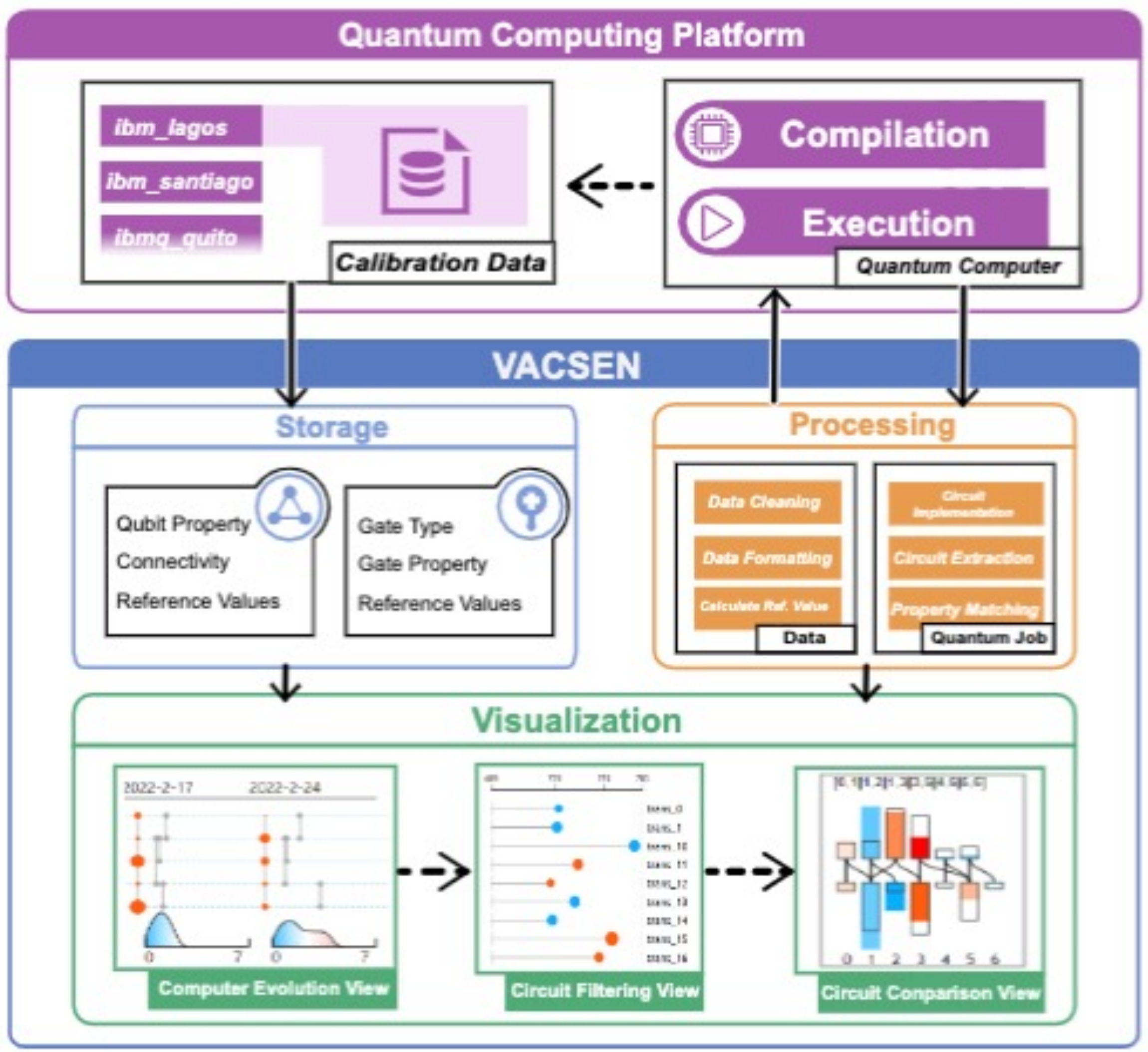
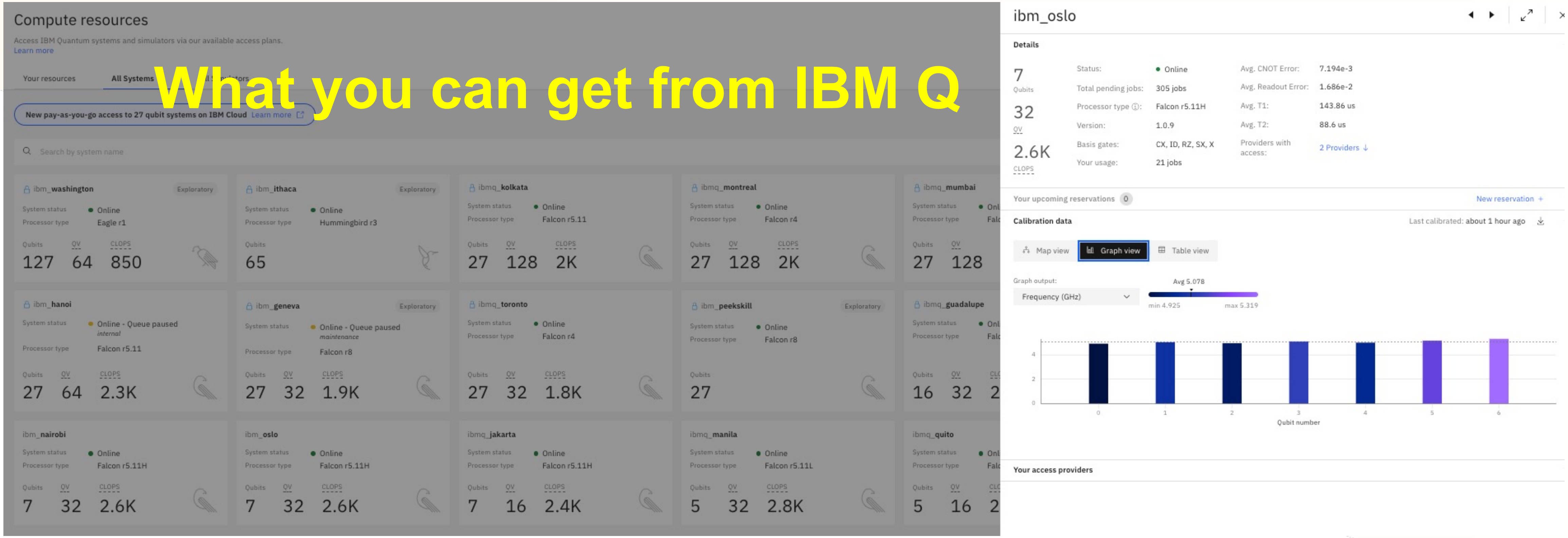
VACSEN System

- **A Visualization Approach for Noise Awareness in Quantum Computing**
  - Visual interface
  - Noise awareness
  - Backend selection
  - Transpile selection
  - Adapt to Qiskit



What you can get from IBM Q



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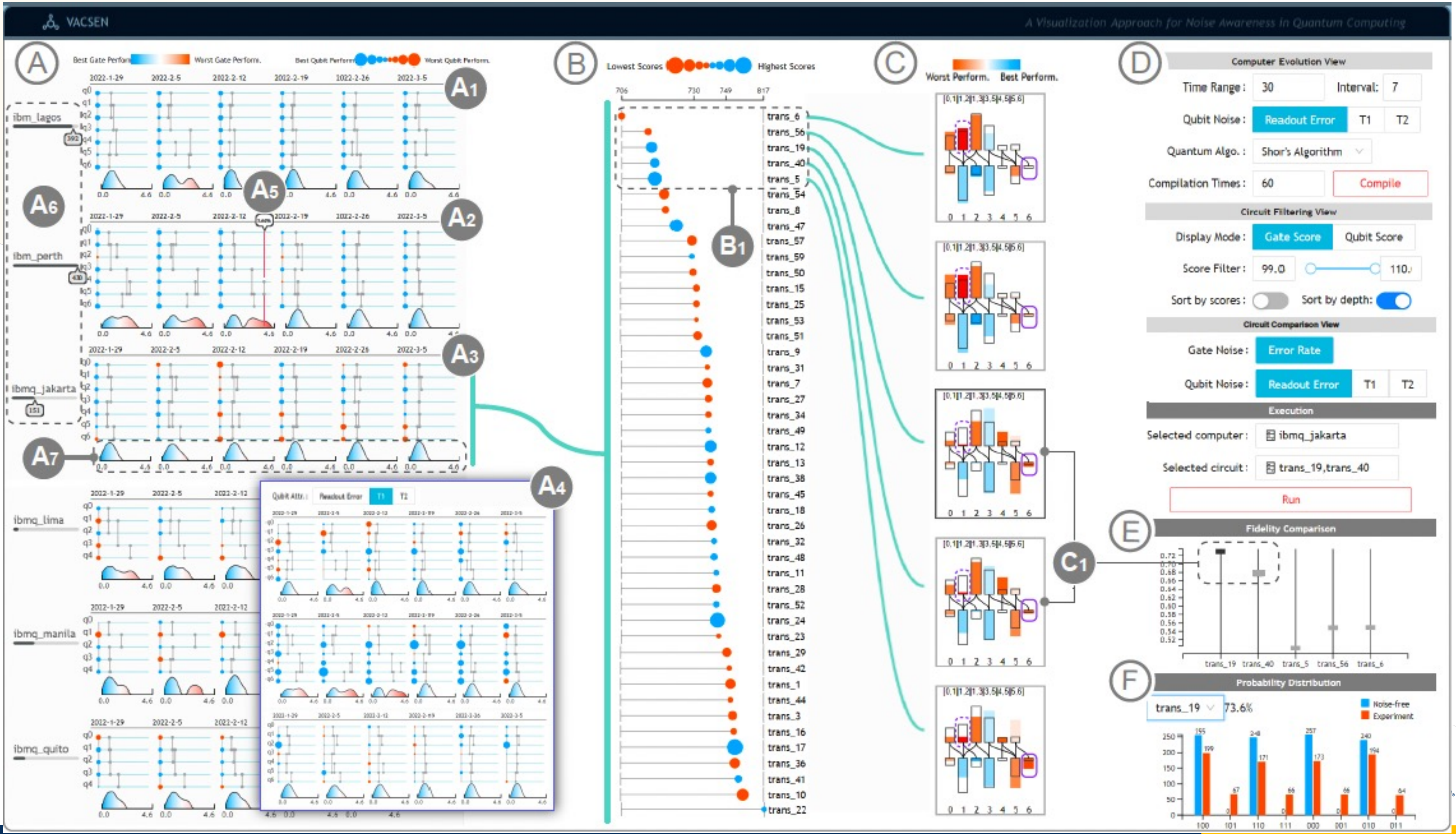

VACSEN
A Visualization Approach for Noise Awareness in Quantum Computing
Best Gate Perform.
Worst Gate Perform.
Best Qubit Perform.
Worst Qubit Perform.
ibm_lagos
ibm_perth
ibmq_jakarta
ibmq_lima
ibmq_manila
ibmq_quito
Lowest Scores
Highest Scores
Worst Perform.
Best Perform.
Computer Evolution View
Time Range: 30
Interval: 7
Qubit Noise: Readout Error T1 T2
Quantum Algo.: Shor's Algorithm
Compilation Times: 60
Compile
Circuit Filtering View
Display Mode: Gate Score Qubit Score
Score Filter: 99.0
Sort by scores:
Sort by depth:
Circuit Comparison View
Gate Noise: Error Rate
Qubit Noise: Readout Error T1 T2
Execution
Selected computer: ibmq_jakarta
Selected circuit: trans_19,trans_40
Run
Fidelity Comparison
Probability Distribution
trans_19 73.6%
Noise-free
Experiment

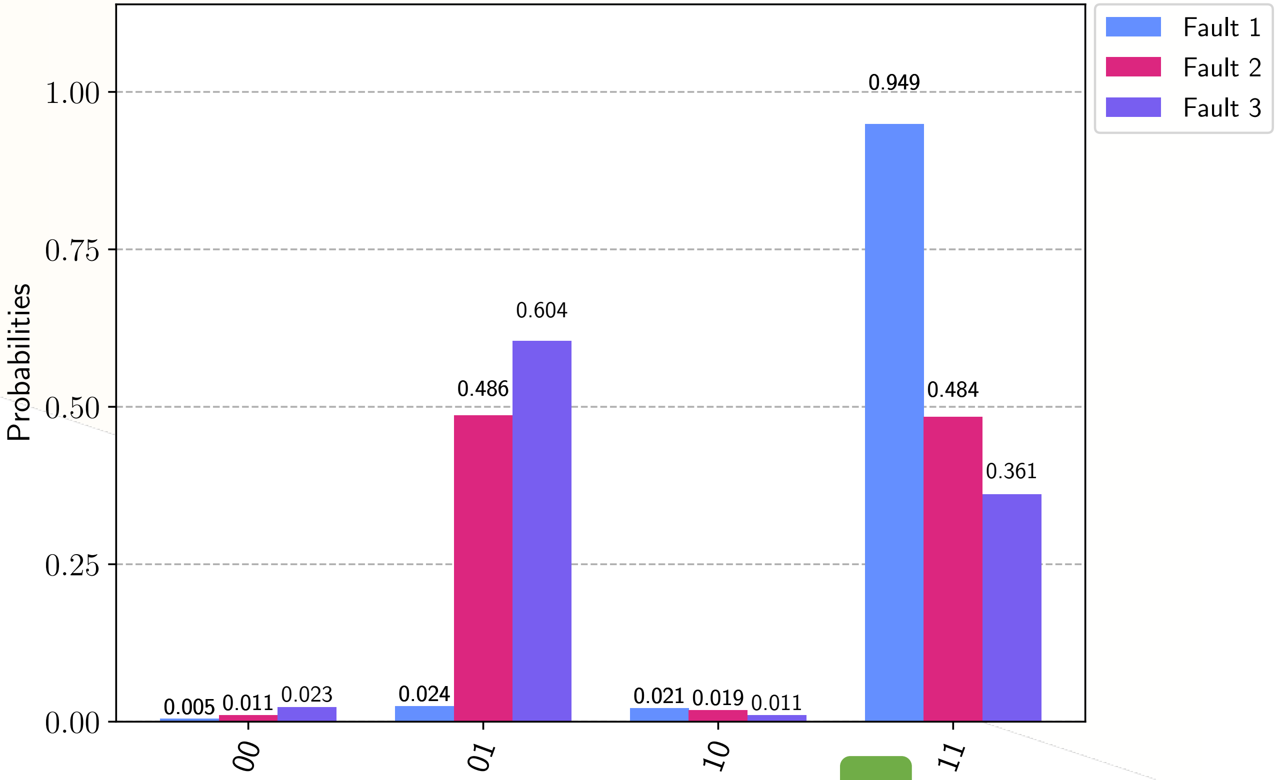
Quantum Vulnerability Factor

- **Similar to Architecture/Program Vulnerability Factor**
- **How to understand the vulnerability of the application?**
  - Comparison between application
  - Cost-effective protection
- **QVF: Michelson Contrast [1]**

$$Contrast = \frac{P(A) - P(B)}{P(A) + P(B)}$$

$$\boxed{QVF = 1 - (Contrast + 1)/2}$$

- **[0,1]**
  - Closer to 1 is worse
- **Example:**
  - Fault 1: QVF = 0.03
  - Fault 2: QVF = 0.5
  - Fault 3: QVF = 0.63



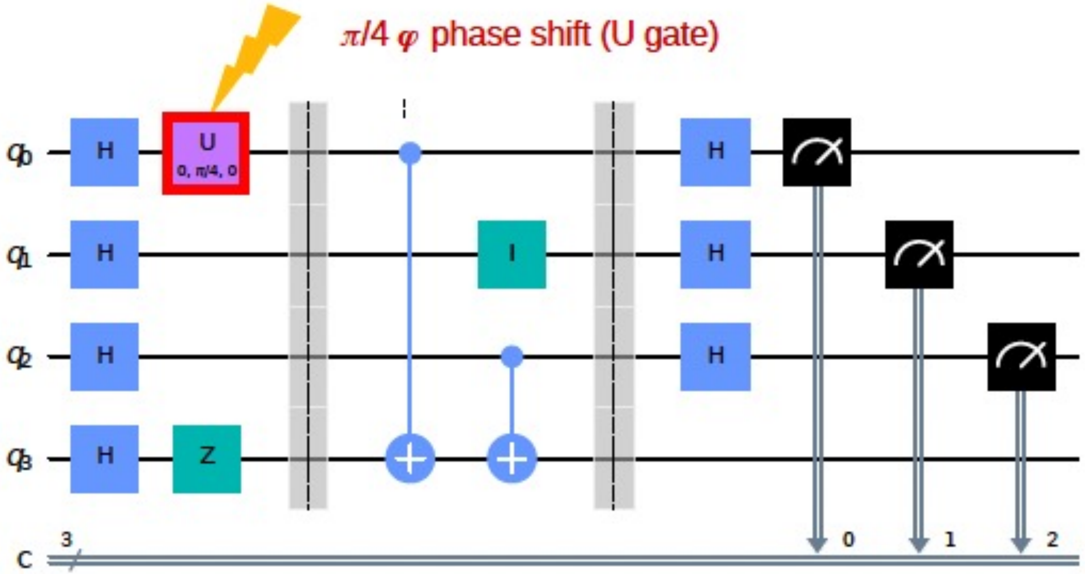
[Oliveira et al., 2021]

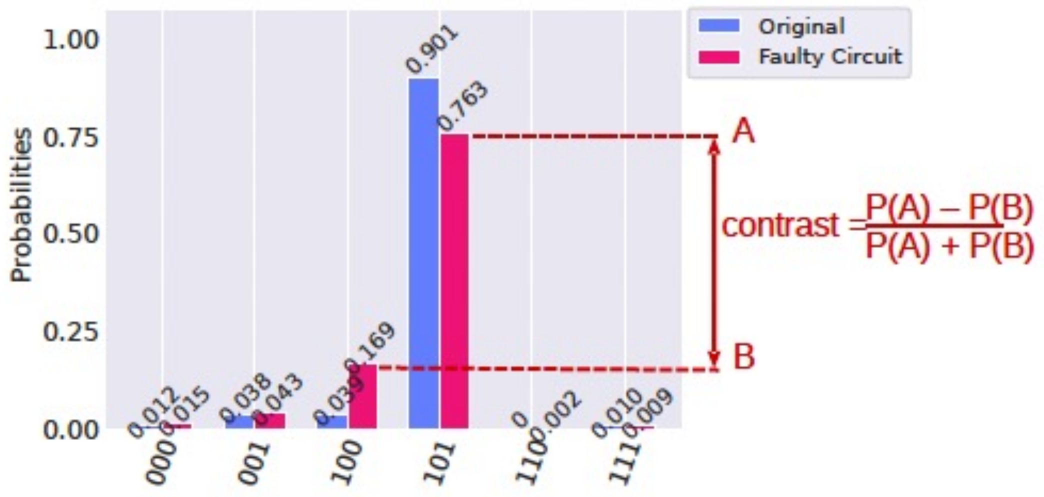
[1] H. Kukkonen, J. Rovamo, K. Tiippana, and R. N¨as¨anen, “Michelson contrast, rms contrast and energy of various spatial stimuli at threshold,” Vision research, vol. 33, no. 10, pp. 1431–1436, 1993.

QuFI

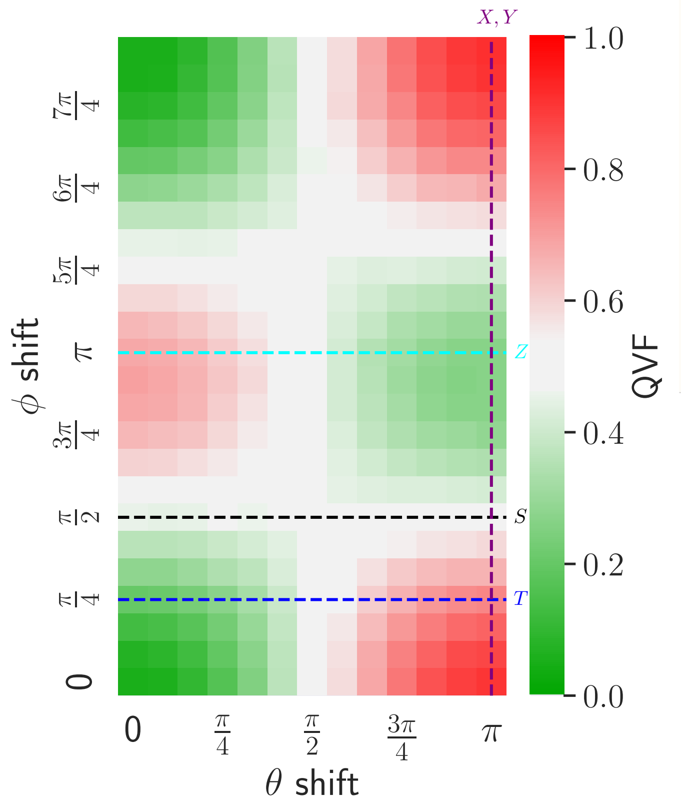
- **Quantum Fault Injector:**
- **Identifies circuit/qubit sensitivity to transient faults**
- **Built upon IBM qiskit**
- **Highly flexible**
  - Multiple injections on neighboring qubits
  - Simulators and real machines
  - Adding over intrinsic noise
- **Based on new metric:**
  - **Quantum Vulnerability Factor** (**QVF**) [Oliveira et al., 2021]
- **Open source [https://github.com/QuTAM/QuFI]**

Transient Fault Injection Example





QVF Heatmaps



Bernstein-Vazirani
(4 qubits)

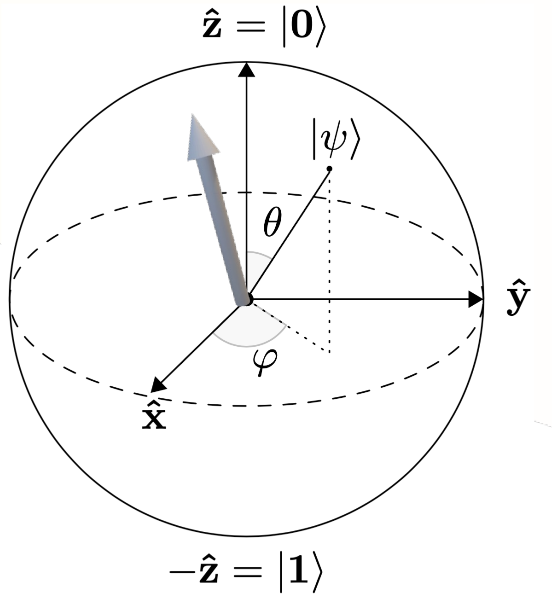
Incorrect output more probable

Dubious output

Correct output more probable

Heatmaps:

- Quickly visualize effect on selected circuit
- Identify most critical points
- Target for future hardening techniques



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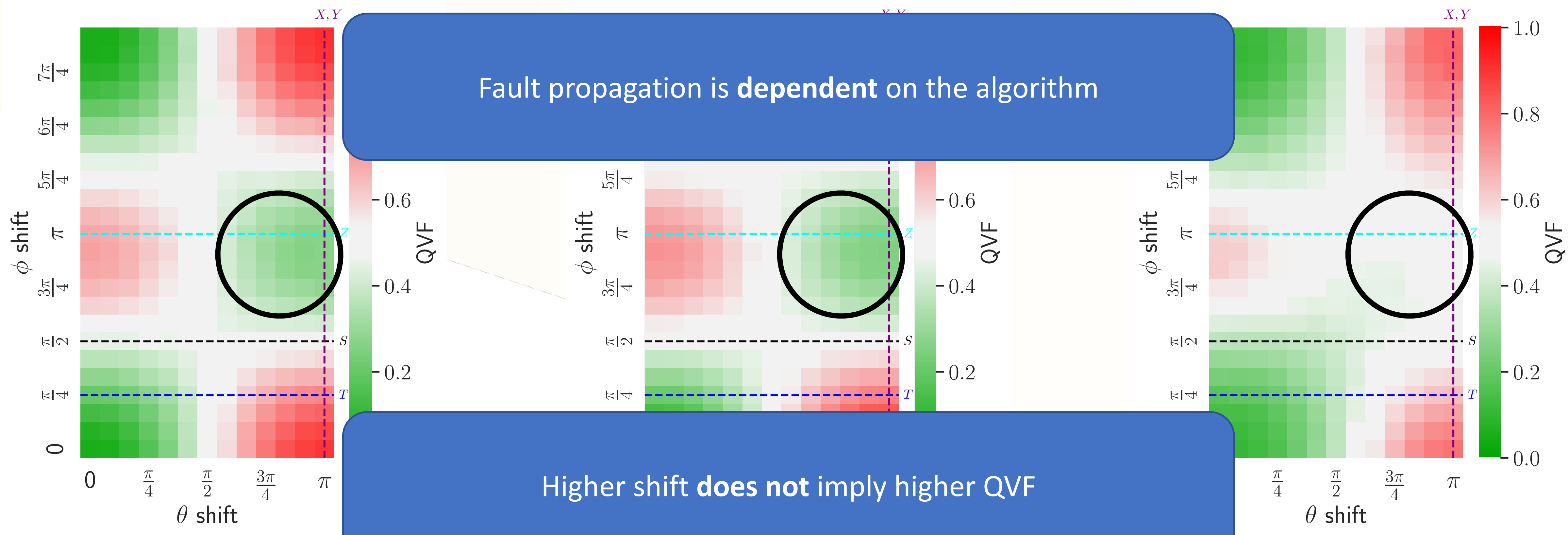
QVF Heatmaps - Single Injection



Fault propagation is **dependent** on the algorithm

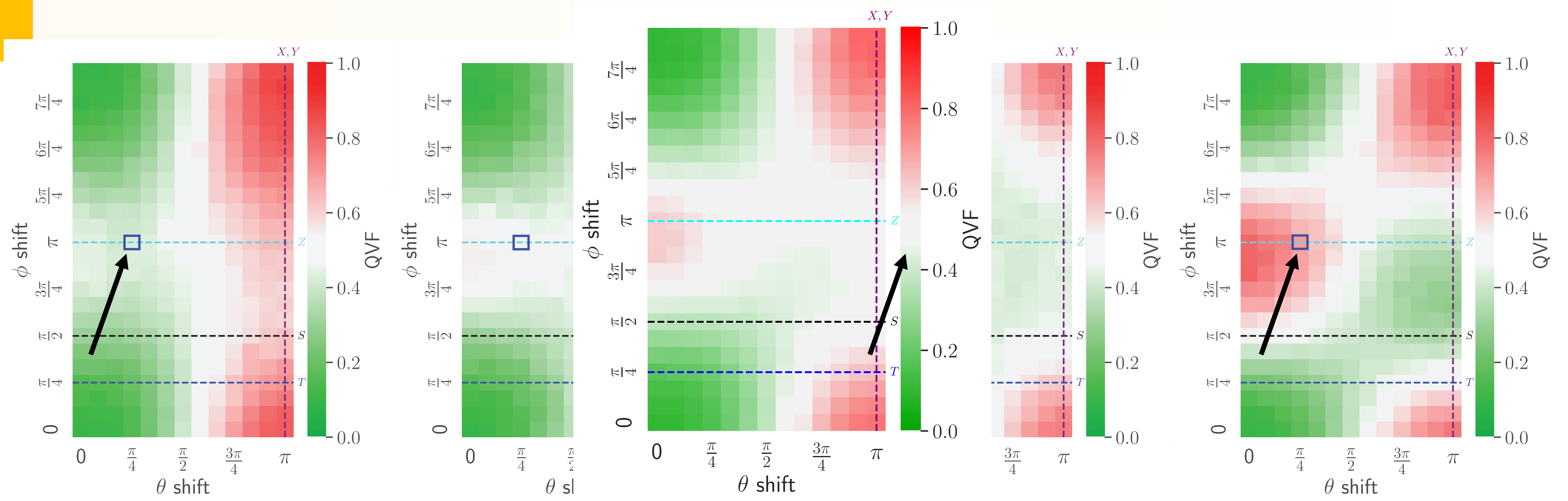
Higher shift **does not** imply higher QVF

Bernstein-Vazirani (4 qubits)

Deutsch-Josza (4 qubits)

Quantum Fourier Transform (4 qubits)

Qubit by qubit close-up, QFT



Qubit #1

Qubit #2

Qubit #3

Qubit #4

Quantum Fourier Transform
(4 qubits)

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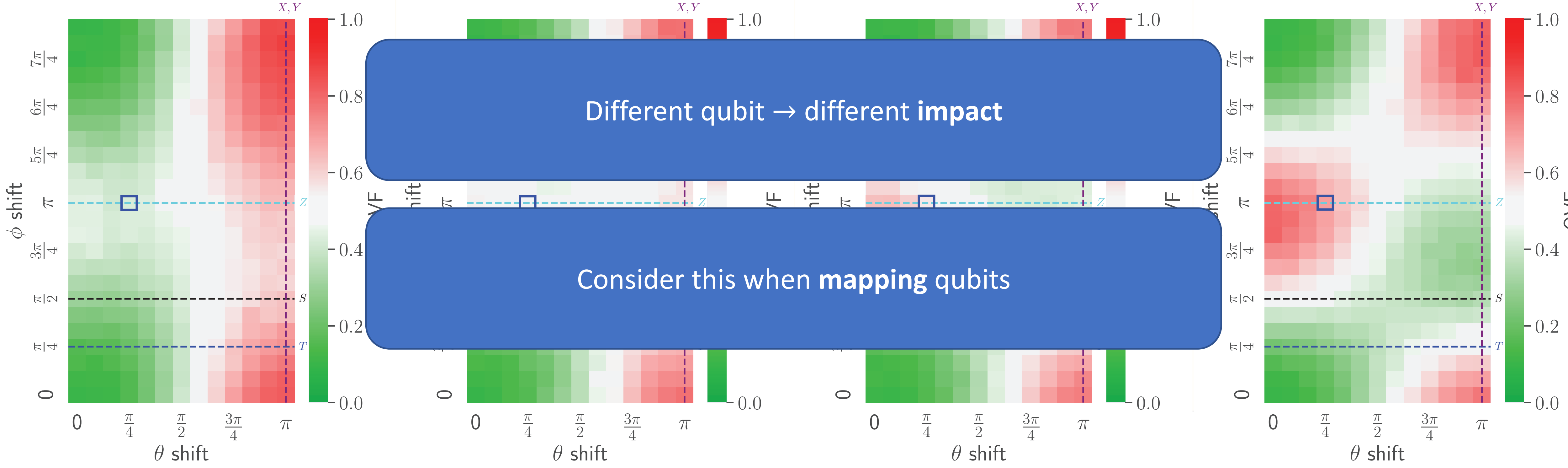
Qubit by qubit close-up, QFT



Qubit #1

Qubit #2

Qubit #3

Qubit #4

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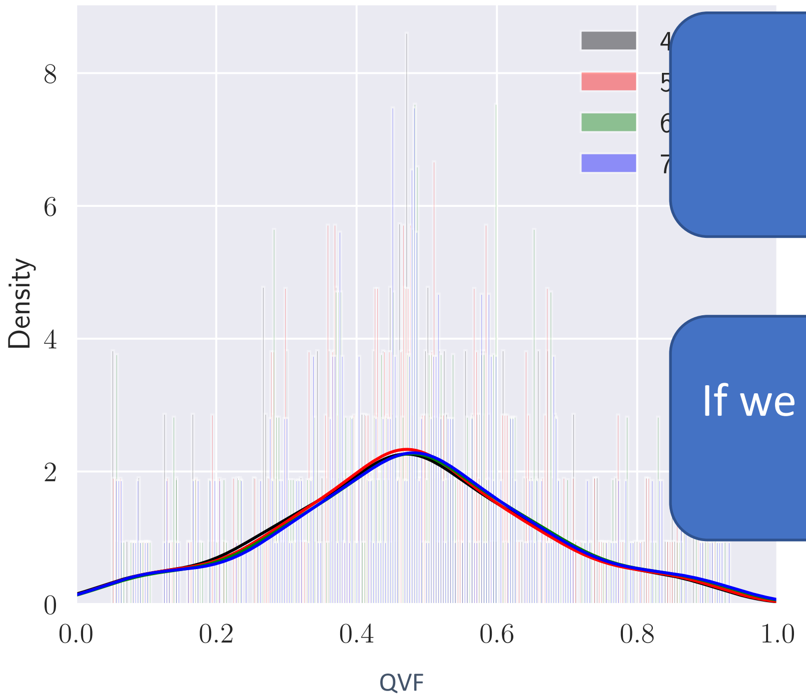
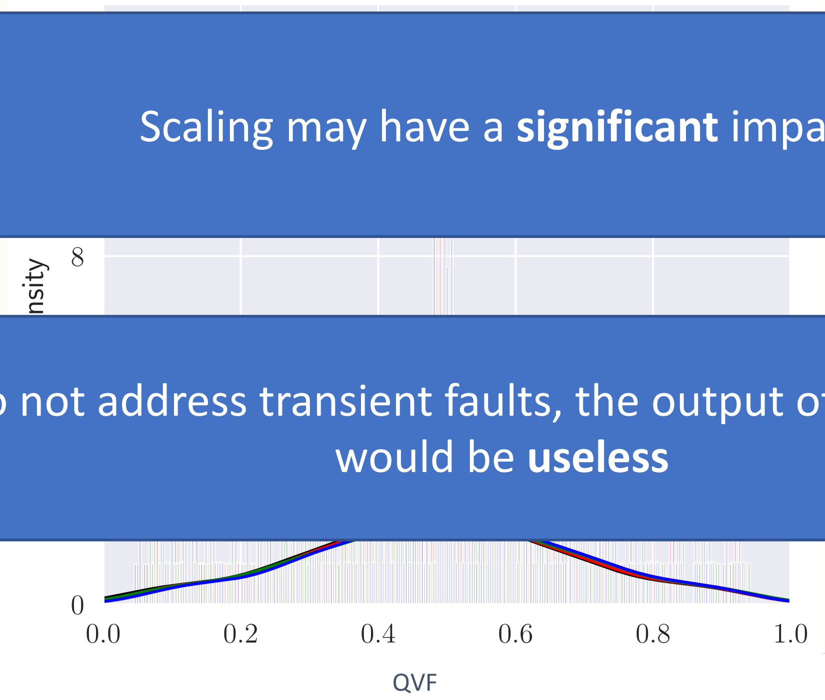
Scaling - QVF distribution

Scaling may have a **significant** impact

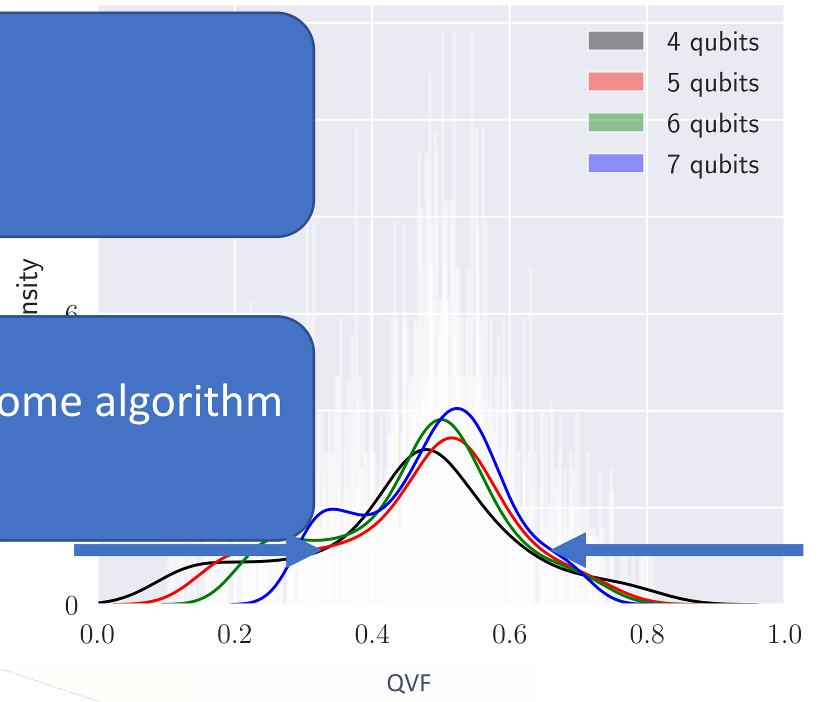
If we do not address transient faults, the output of some algorithm would be **useless**



Bernstein-Vazirani



Deutsch-Josza



Quantum Fourier Transform

Publications:

- Daniel Chen, Betis Baheri, Vipin Chaudhary, Qiang Guan, Ning Xie, Shuai Xu, Approximate Quantum Circuit Reconstruction, IEEE Quantum Week (QCE), 2022.
- Qiang Guan, Betis Baheri, Zixhuan Xu, Ying Mao, Vipin Chaudhary, Shuai Xu, Bo Fang, Pinpointing the System Reliability Degradation in NISQ Machines, IEEE Quantum Week (QCE), 2022.
- Shaolun Ruan, Yong Wang, Weiwen Jiang, Ying Mao, Qiang Guan, VACSEN: A Visualization Approach for Noise Awareness in Quantum Computing, IEEE VIS, 2022.
- Samuel A Stein, Betis Baheri, Daniel Chen, Ying Mao, Qiang Guan, Ang Li, Shuai Xu, Caiwen Ding, Quclassi: A hybrid deep neural network architecture based on quantum state fidelity, MLSys 2022
- Daniel Oliveira, Edoardo Giusto, Emanuele Dri, Nadir Casciola, Betis Baheri, Qiang Guan, Bartolomeo Montrucchio, Paolo Rech, QuFI: a Quantum Fault Injector to Measure the Reliability of Qubits and Quantum Circuits, DSN 2022.
- Betis Baheri, Vipin Chaudhary, Ang LI, Qiang Guan, Quantum Noise in the Flow of Time: A Temporal Study of the Noise in Quantum Computers, IEEE Symposium on On-line Testing and Robust System Design, (IOLTS), 2022.
- Samuel A Stein, Ray Marie Tischio, Betis Baheri, Yiwen Chen, Ying Mao, Qiang Guan, Ang Li, Bo Fang, “A Hybrid System for Learning Classical Data in Quantum States”, IPCCC 2021.
- Samuel A. Stein, Betis Baheri, Daniel Chen, Ying Mao, Qiang Guan, Ang Li, Bo Fang and Shuai Xu, “QuGAN: A Quantum State Fidelity based Generative Adversarial Network”, IEEE Quantum Week (QCE) 2021.

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Collaborations

Los Alamos NATIONAL LABORATORY EST. 1943

Pacific Northwest NATIONAL LABORATORY

OAK RIDGE National Laboratory

CASE WESTERN RESERVE UNIVERSITY EST. 1826

FORDHAM THE JESUIT UNIVERSITY OF NEW YORK

GEORGE MASON UNIVERSITY

Politecnico di Torino 1859

WESTLAKE UNIVERSITY

SMU SINGAPORE MANAGEMENT UNIVERSITY

UNIVERSITY OF TRENTO

Cleveland Clinic

IBM Q HUB

RESEARCH

COMMUNITY

TRAINING

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Thank You.

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