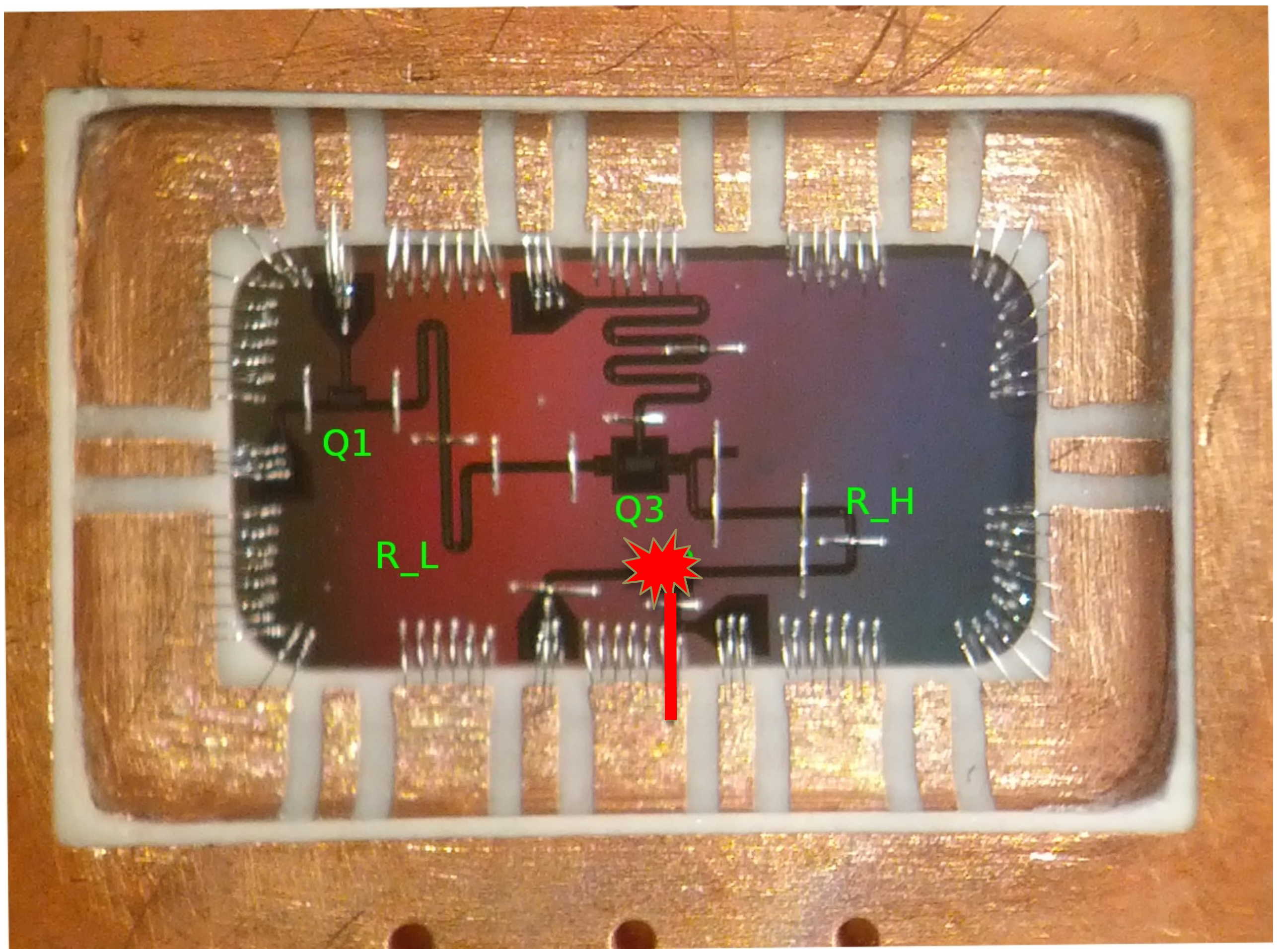
Exploring Quantum Process Characterization

Shelby Kimmel
MIT
Marcus Silva
Raytheon BBN Technologies

Raytheon
BBN Technologies

Quantum Device



Quantum Process Characterization

$$\mathcal{E} = ?$$

Write $\mathcal{E}$ in term of Pauli operators.
(n qubits, 4^n Pauli operations, $P_i = X \otimes Y \otimes \cdots \otimes I \otimes Z$, etc.)

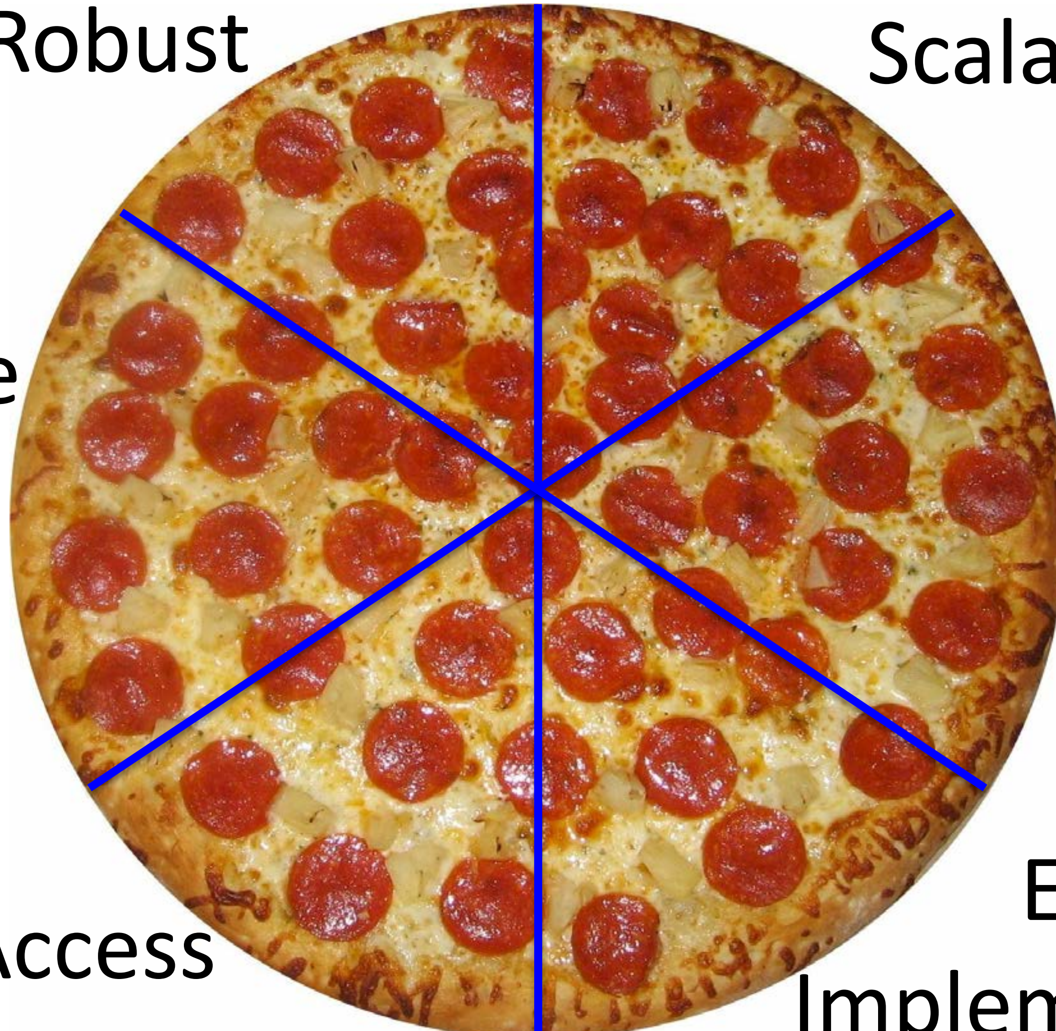
$$\mathcal{E}(\rho) = \sum_{i,j=1}^{4^n} \chi_{i,j} P_i \rho P_j$$

For operation on n qubits, $16^n - 4^n$ free parameters.

Ideal Process Characterization

Robust

Scalable



Flexible Input

$\mathcal{E}$ can be anything

Easy Post-processing

Experiment outcome is a selected $\chi_{i,j}$

Large Access

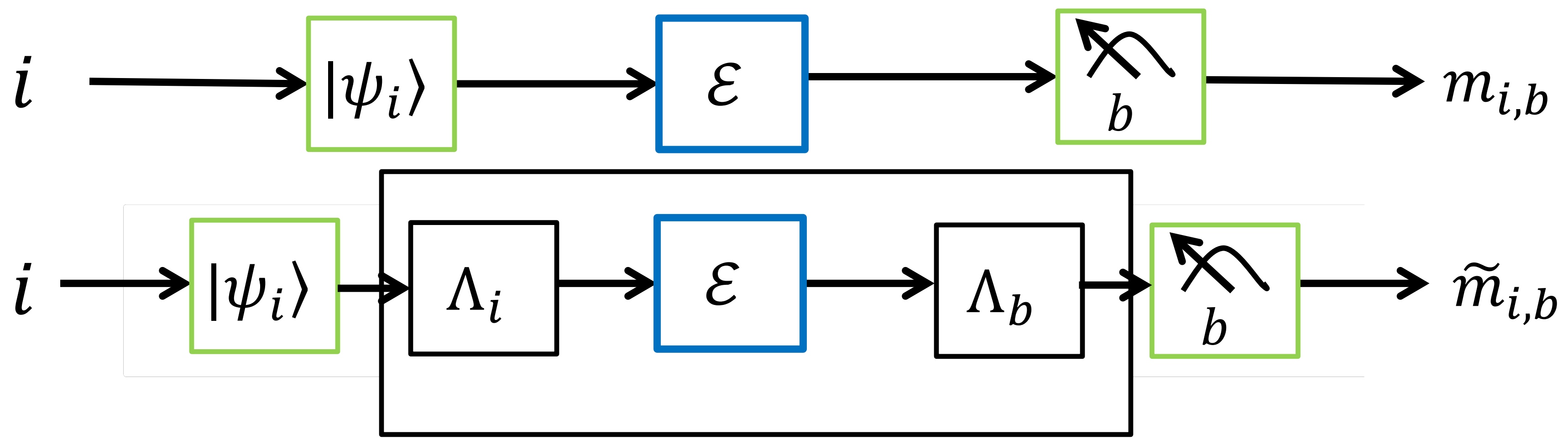
Can get information about many parameters $(\chi_{i,j})$

Easy Implementation

Procedure uses high fidelity gates= local gates

Robust Characterization

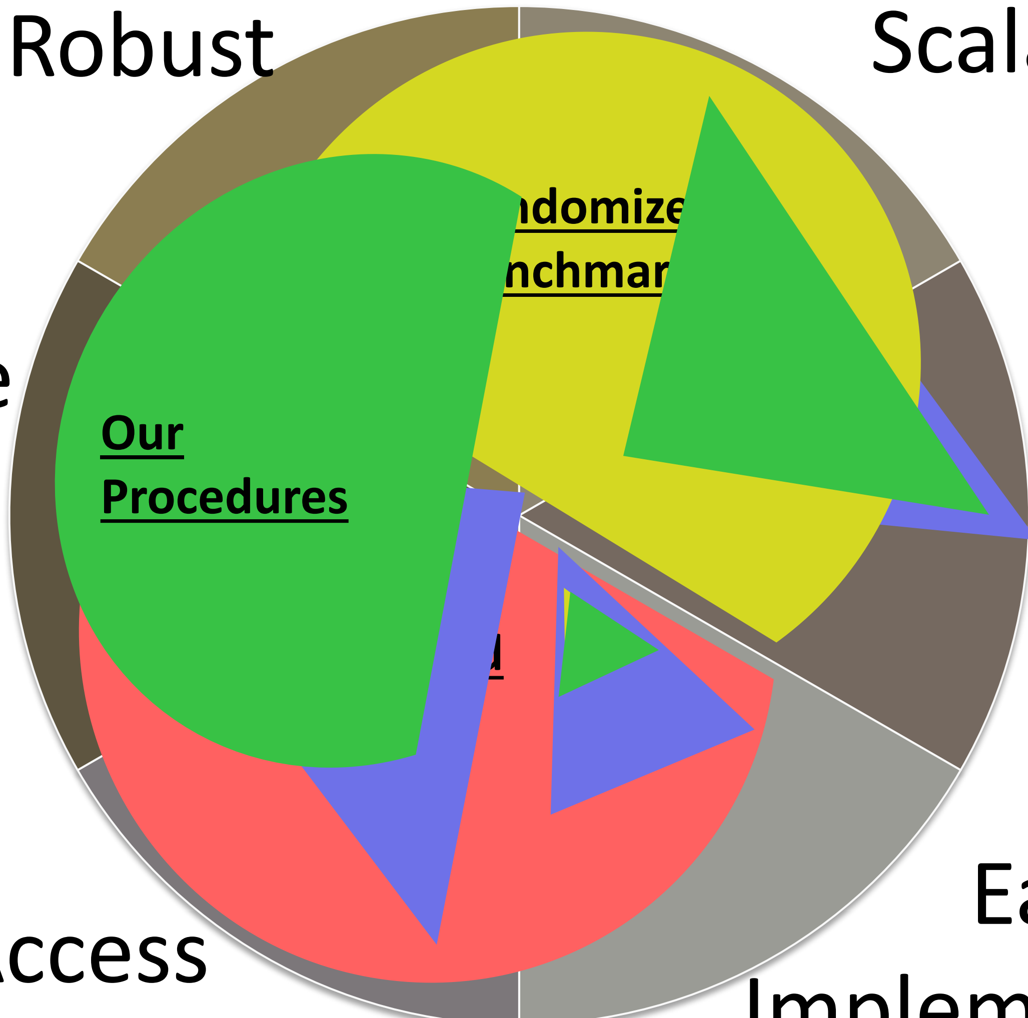
Accessing process involves preparing a state, and a measurement



Ideal Process Characterization

Robust

Scalable



Flexible Input

$\mathcal{E}$ can be anything

Easy Post-processing

Experiment outcome is a selected $\chi_{i,j}$

Large Access

Can get information about many parameters ($\chi_{i,j}$)

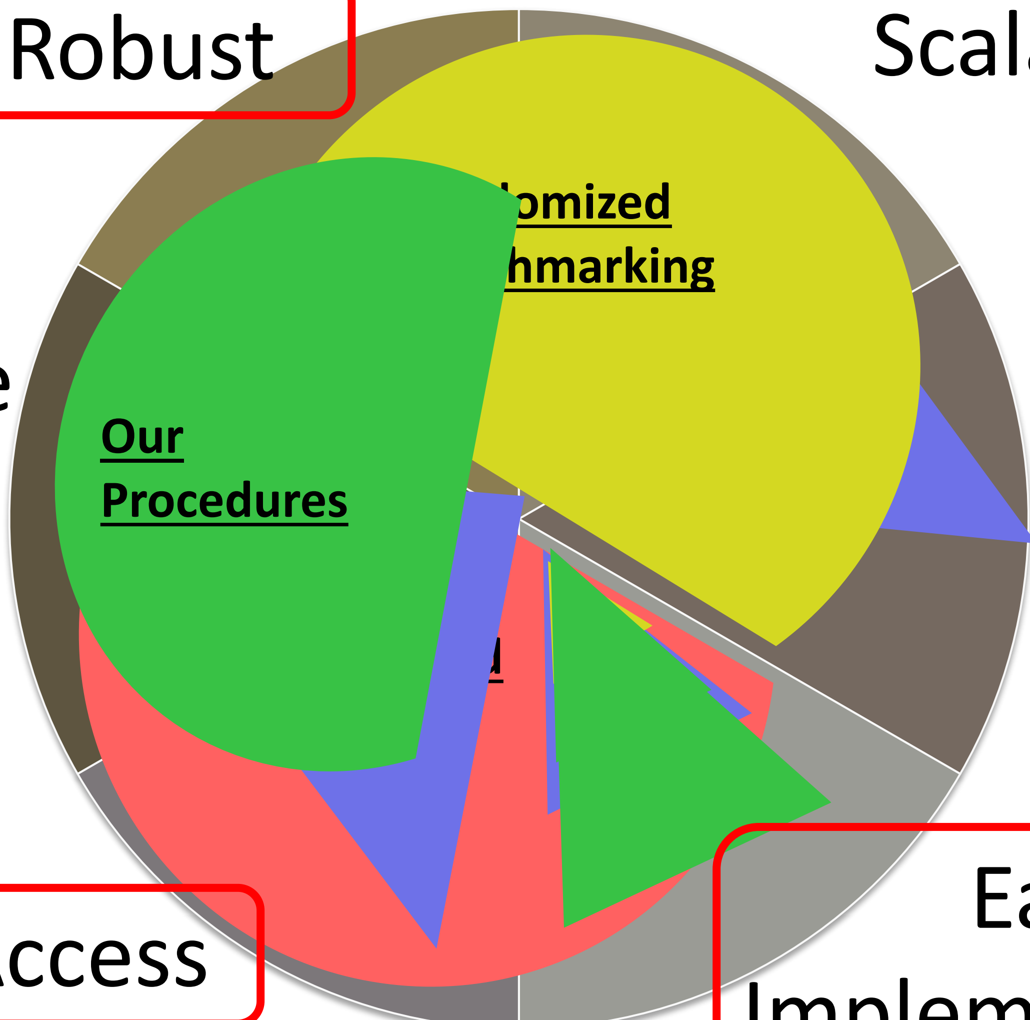
Easy Implementation

Procedure uses high fidelity gates= local gates

Ideal Process Characterization

Robust

Scalable



Flexible Input

$\mathcal{E}$ can be anything

Easy Post-processing

Experiment outcome is a selected $\chi_{i,j}$

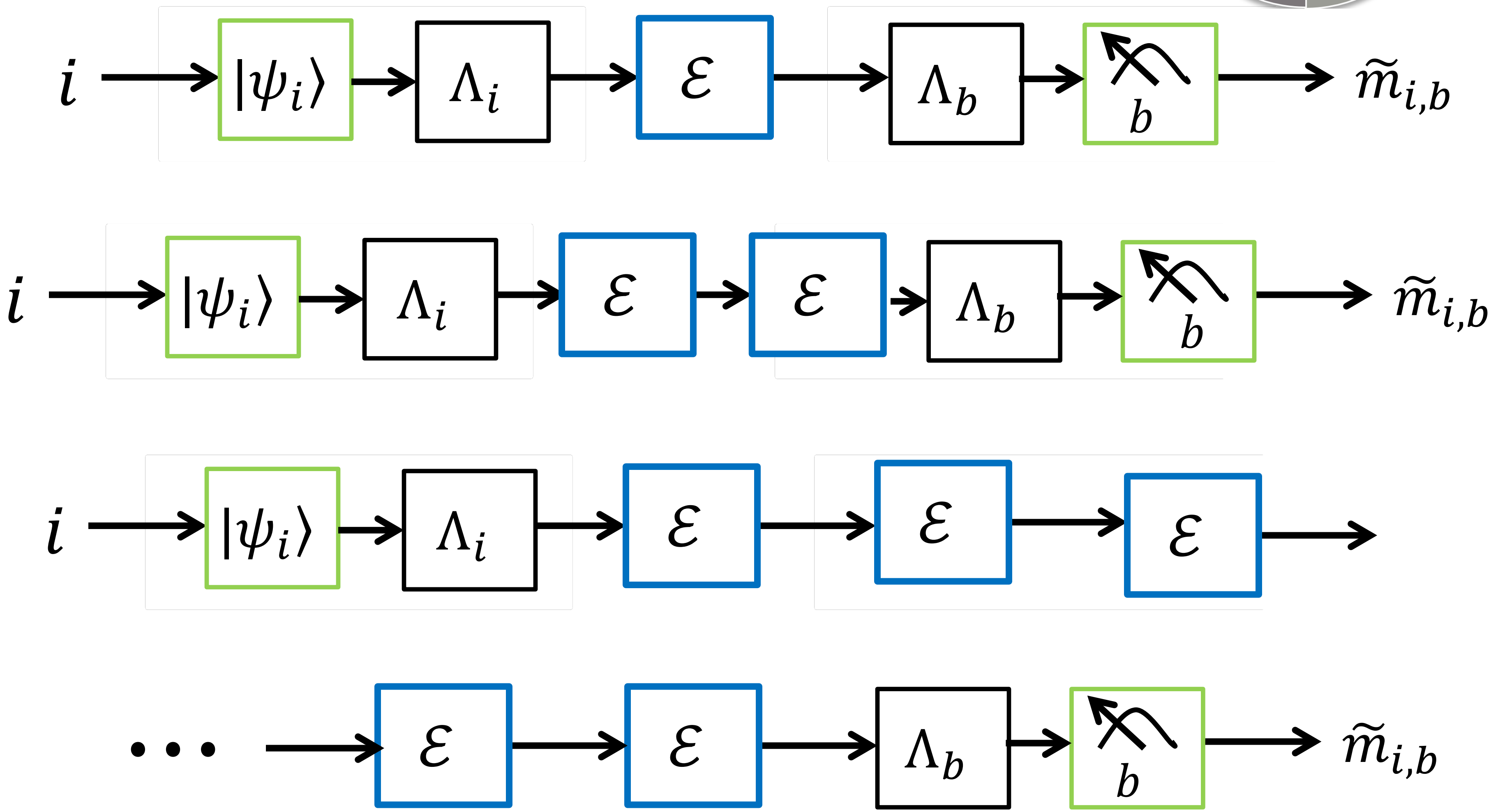
Large Access

Can get information about many parameters ($\chi_{i,j}$)

Easy Implementation

Procedure uses high fidelity gates= local gates

Robust


i
$|\psi_i\rangle$
Λ_i
$\mathcal{E}$
Λ_b
b
$\tilde{m}_{i,b}$
i
$|\psi_i\rangle$
Λ_i
$\mathcal{E}$
$\mathcal{E}$
Λ_b
b
$\tilde{m}_{i,b}$
i
$|\psi_i\rangle$
Λ_i
$\mathcal{E}$
$\mathcal{E}$
$\mathcal{E}$
$\cdots$
$\mathcal{E}$
$\mathcal{E}$
Λ_b
b
$\tilde{m}_{i,b}$

Robust Cont.

Pauli Twirl → tractable

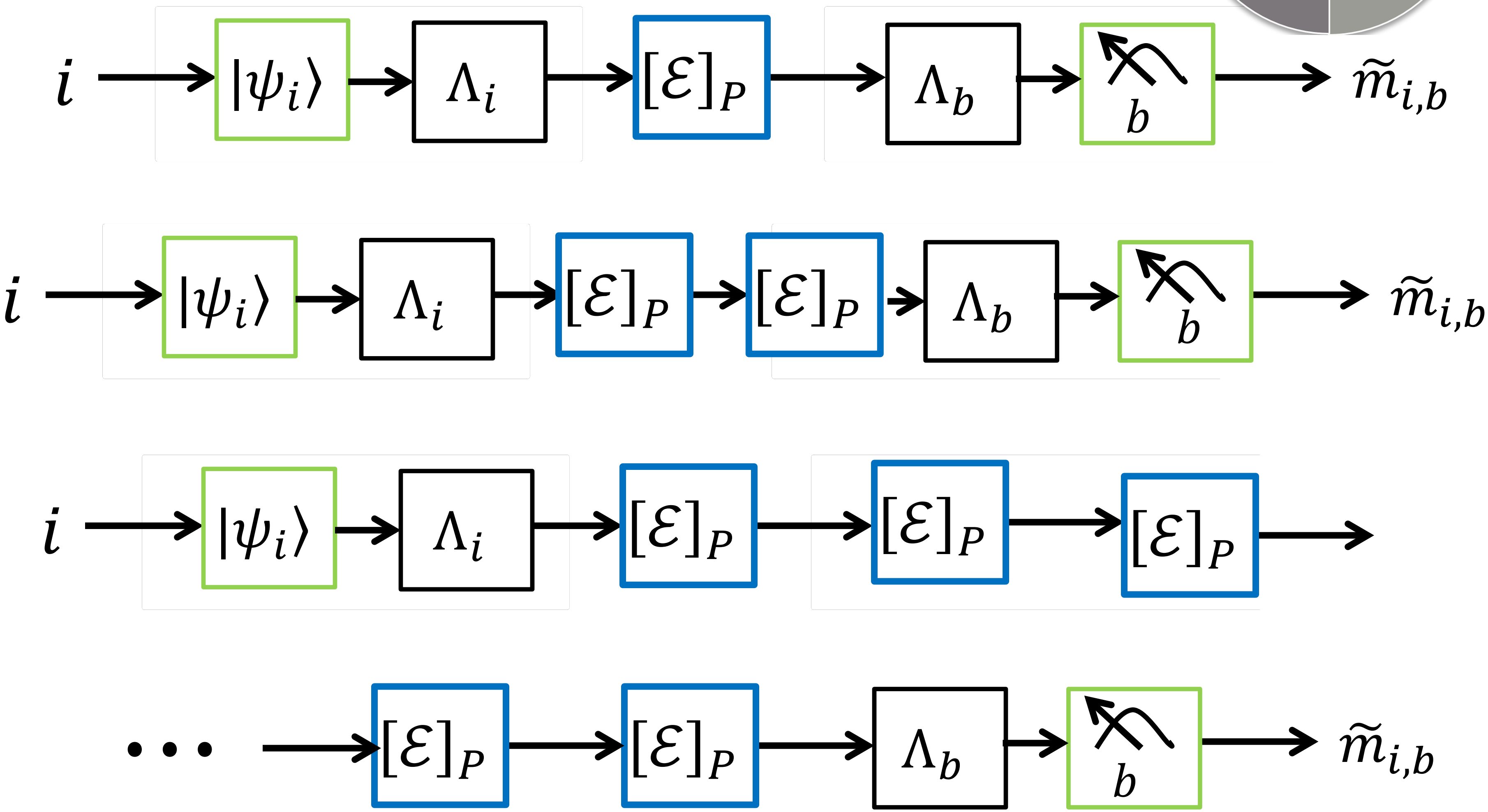
$$[\mathcal{E}(\rho)]_P = \frac{1}{4^n} \sum_{i=1}^{4^n} {P_i}^{\dagger} \circ \mathcal{E} \circ P_i(\rho)$$

Average over conjugation with all Paulis

$$[\mathcal{E}(\rho)]_P = \sum_{i=1}^{4^n} \chi_{i,i} P_i \rho P_i$$

No off diagonal elements!

Robust Cont.



i
$|\psi_i\rangle$
Λ_i
$[\mathcal{E}]_P$
Λ_b
b
$\tilde{m}_{i,b}$
i
$|\psi_i\rangle$
Λ_i
$[\mathcal{E}]_P$
$[\mathcal{E}]_P$
Λ_b
b
$\tilde{m}_{i,b}$
i
$|\psi_i\rangle$
Λ_i
$[\mathcal{E}]_P$
$[\mathcal{E}]_P$
$[\mathcal{E}]_P$
$\cdots$
$[\mathcal{E}]_P$
$[\mathcal{E}]_P$
Λ_b
b
$\tilde{m}_{i,b}$

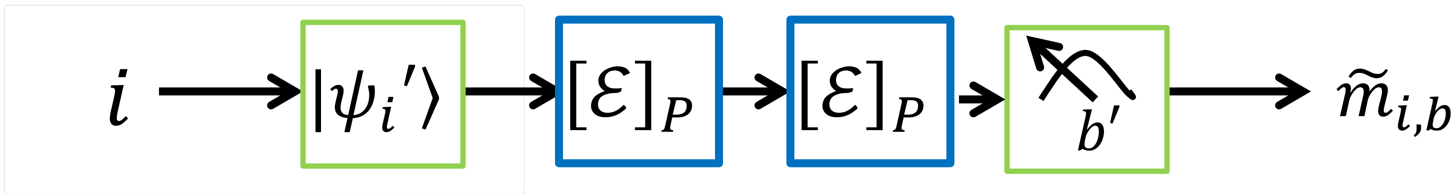
Robust Cont.

Compared to Previous Robust Protocol:

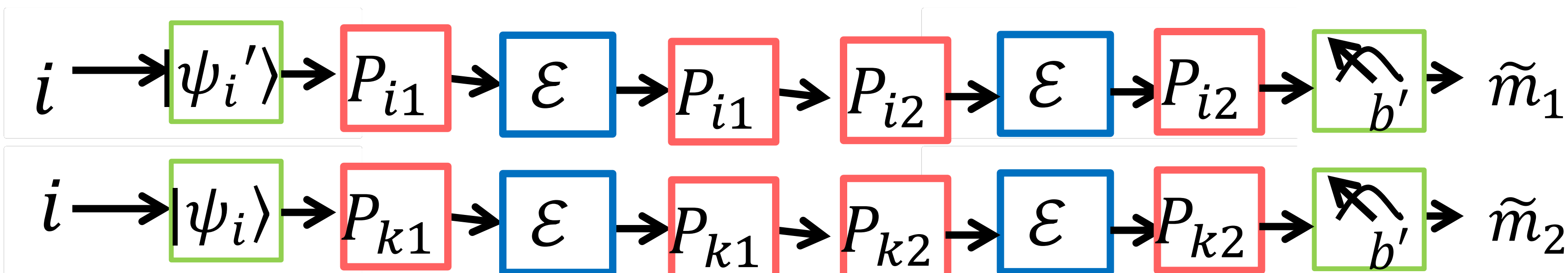
- Previous used a twirl that only preserved $\chi_{I,I}$.
- Even simpler form of $\mathcal{E}$, so analysis easier, but lost more information about χ matrix

Easy Implementation

To approximate the following operation,



Do:

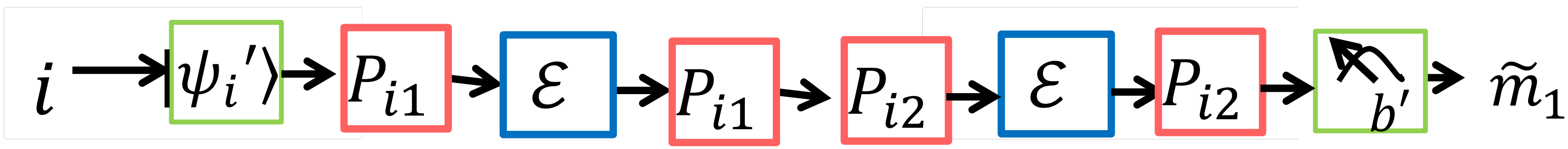


$\vdots$ Constant # of times

P = Choose Pauli Randomly

Finally: Average outcomes

Easy Implementation

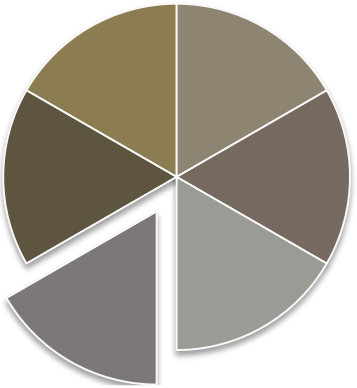


All Pauli operations are local, so can implement the above sequence with high fidelity!

Still can't implement perfectly! How do errors on Paulis effect the result?

- Instead of exact values, get bounds on χ matrix elements.

Large Access



n qubits:
accesible parameters

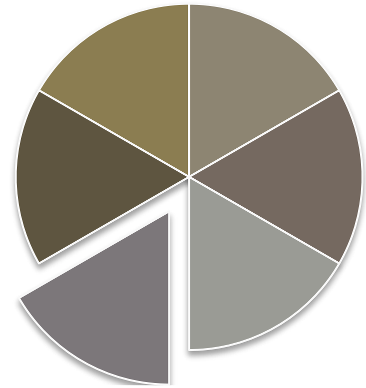
$16^n - 4^n$ — N&C, Selective Tomography

1 — Randomized Benchmarking

0

$$\mathcal{E}(\rho) = \sum_{i,j=1}^{4^n} \chi_{i,j} P_i \rho P_j$$

Large Access



<u>n qubits:</u>

<u># accesible parameters</u>

$16^n - 4^n$ — N&C, Selective Tomography

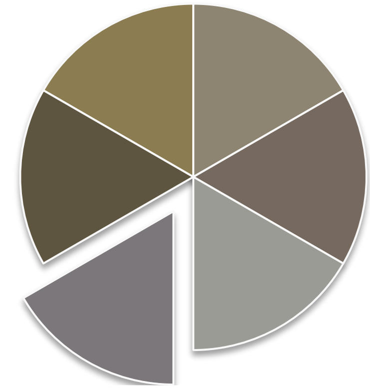
$4^n - 1$ — **Repeated Pauli Twirling**

1 — Randomized Benchmarking

0

$$[\mathcal{E}(\rho)]_P = \sum_{i=1}^{4^n} \underbrace{\chi_{i,i}}_{4^n} P_i \rho P_i$$

Large Access



Pauli operators not unique!

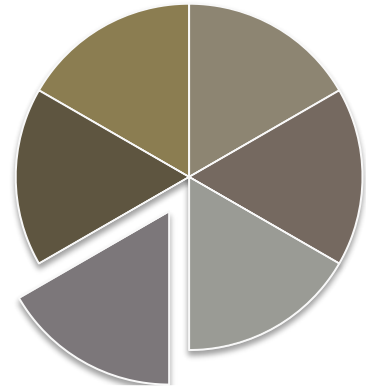
$$U\{P_i\}U^{\dagger} \rightarrow \{\widetilde{P_i}\}$$

Still want local operations:

$$U_1 \otimes U_2 \cdots \otimes U_n \{P_i\} {U_1}^{\dagger} \otimes {U_2}^{\dagger} \cdots \otimes {U_n}^{\dagger} \rightarrow \{\widetilde{P_i}\}$$

$$\{\widetilde{P_i}\} \rightarrow \{\widetilde{\chi}_i\}$$

Large Access



n qubits:

\# accesible parameters

$16^n - 4^n$ — N&C, Selective Tomography

$O(\frac{16^n}{2})$ — **Non-Locally rotated repeated Pauli Twirling**

$7^n - 1$ — **Locally rotated repeated Pauli Twirling**

$4^n - 1$ — Repeated Pauli Twirling

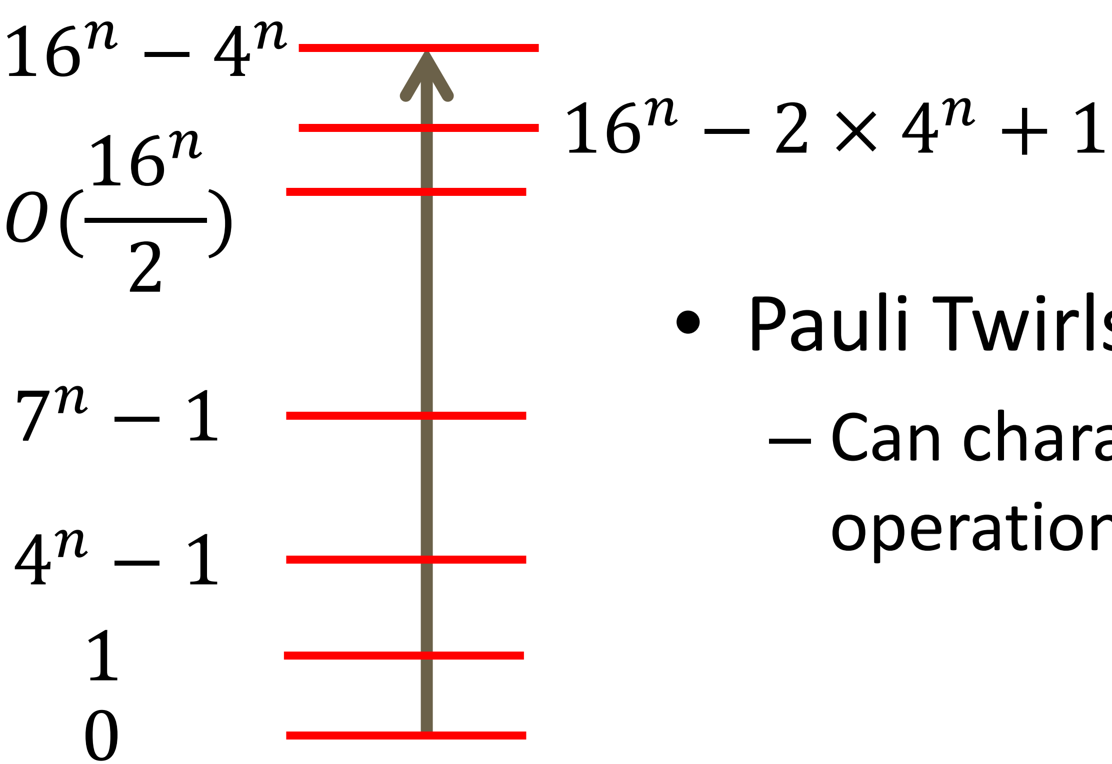
1 — Randomized Benchmarking

0

Large Access

n qubits:

\# accesible parameters



- Pauli Twirls→Clifford Twirls
  - Can characterize all unital operations. ($\mathcal{E}(I) = I$)

Bad News

- Not Scalable/Post-Processing Hard
  - To extract single $\chi_{i,i}$ need to learn 4^n other parameters $\{\lambda_i\}$.
  - To extract a single λ_i, need to fit for a sum of decaying exponentials, a notoriously tricky (although well studied) problem.

To Do/Open Questions

- Implement!
- Get better trade offs between ease of implementation/ease of post-processing/scalability?

Thank you!

- Questions?

χ Matrix Examples

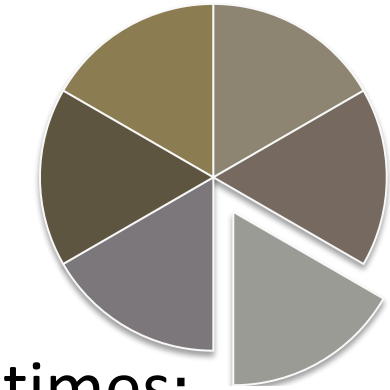
$$\mathcal{E}(\rho) = \sum_{i,j=1}^{4^n} \chi_{i,j} P_i \rho P_j$$

Identity: $\chi_{I,I} = 1$, all other $\chi_{i,j}$=0

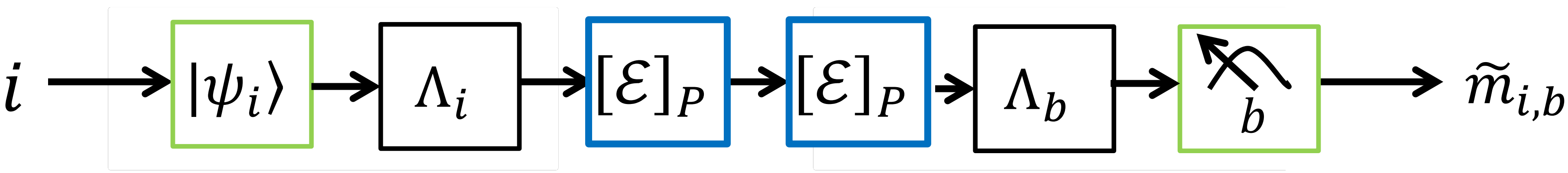
Hadamard: $\frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$

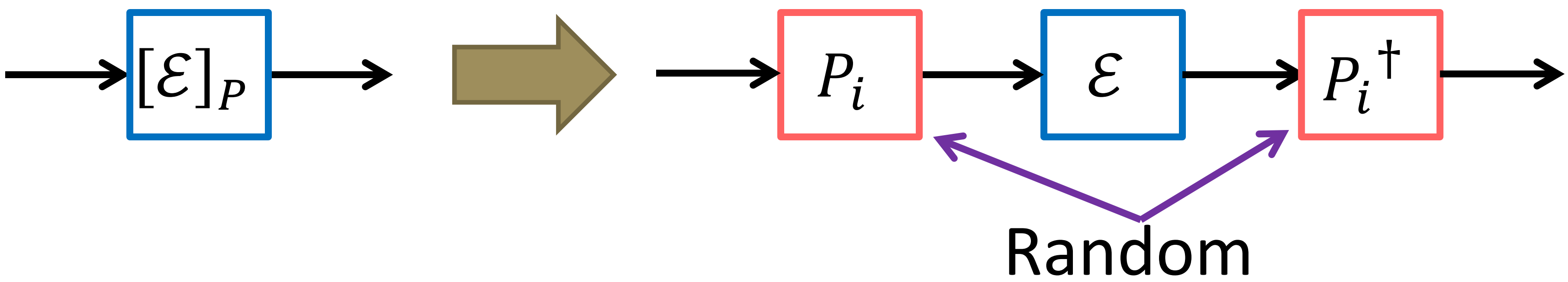
$\chi_{X,X} = \chi_{Z,X} = \chi_{X,Z} = \chi_{Z,Z} = \frac{1}{2}$, all other $\chi_{i,j}$=0

Easy Implementation



Repeat each sequence a constant number of times:





All Pauli Operations are Local!

Not perfect Paulis – but we can bound the effect of these errors