Robust Characterization of Quantum Processes

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Why Characterize Quantum Operations?

- Better understanding of the errors in system
  - If know cause of errors, easier to correct
  - Can determine if error rates are low enough to apply error correcting codes / if codes will counteract the errors

Standard Techniques Not Robust

Need perfect knowledge of state preparation, measurement and other operations. Otherwise give inaccurate or even invalid results.

Not "robust"

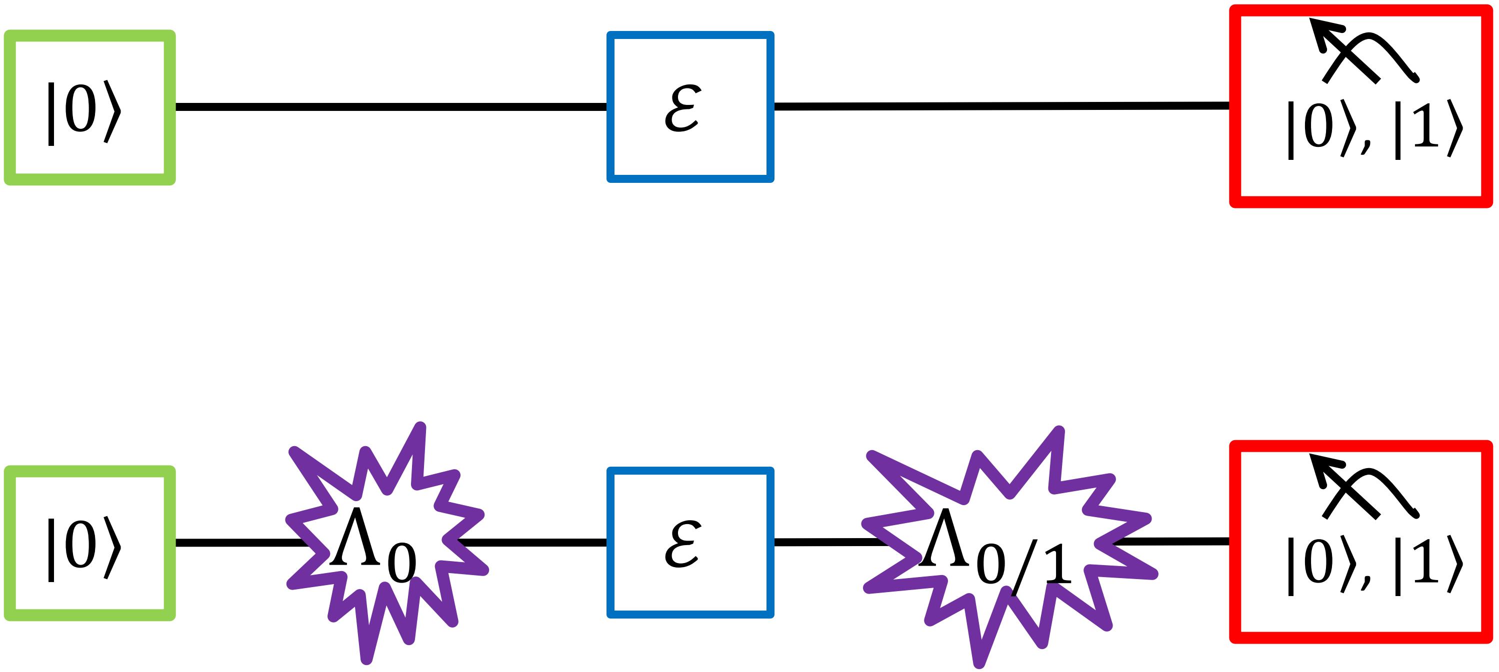
Robust Techniques

- Gate Set Tomography Procedures [Stark '13, Blume-Kohout et al. '13, Merkel et al. '12]
  - Characterizes many processes at once
- Randomized Benchmarking (RB) [Emerson et al. '05, Knill et al. '08, Magesan et al. '11, '12]
  - Can only characterize ~~1~~ parameter of ~~1~~ type of process. almost all any
  - Can efficiently test performance of a universal gate set.

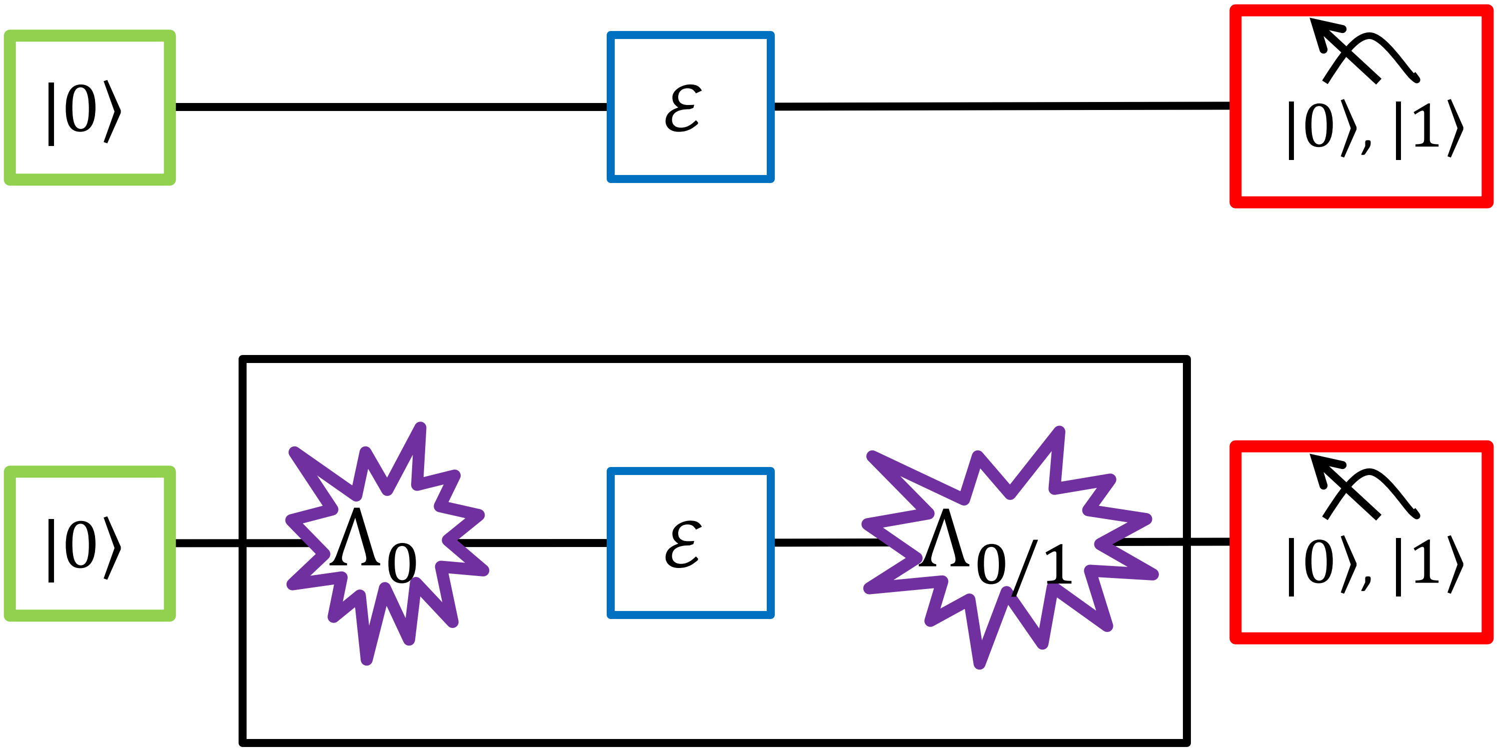
Outline

- **Background**:
  - Standard Process Tomography
  - Randomized benchmarking framework, challenges of current implementation
- **Our Results**:
  - Robust characterization of unital part of any process
  - Experimental results and challenges

Problem with Standard Process Tomography



Problem with Standard Process Tomography



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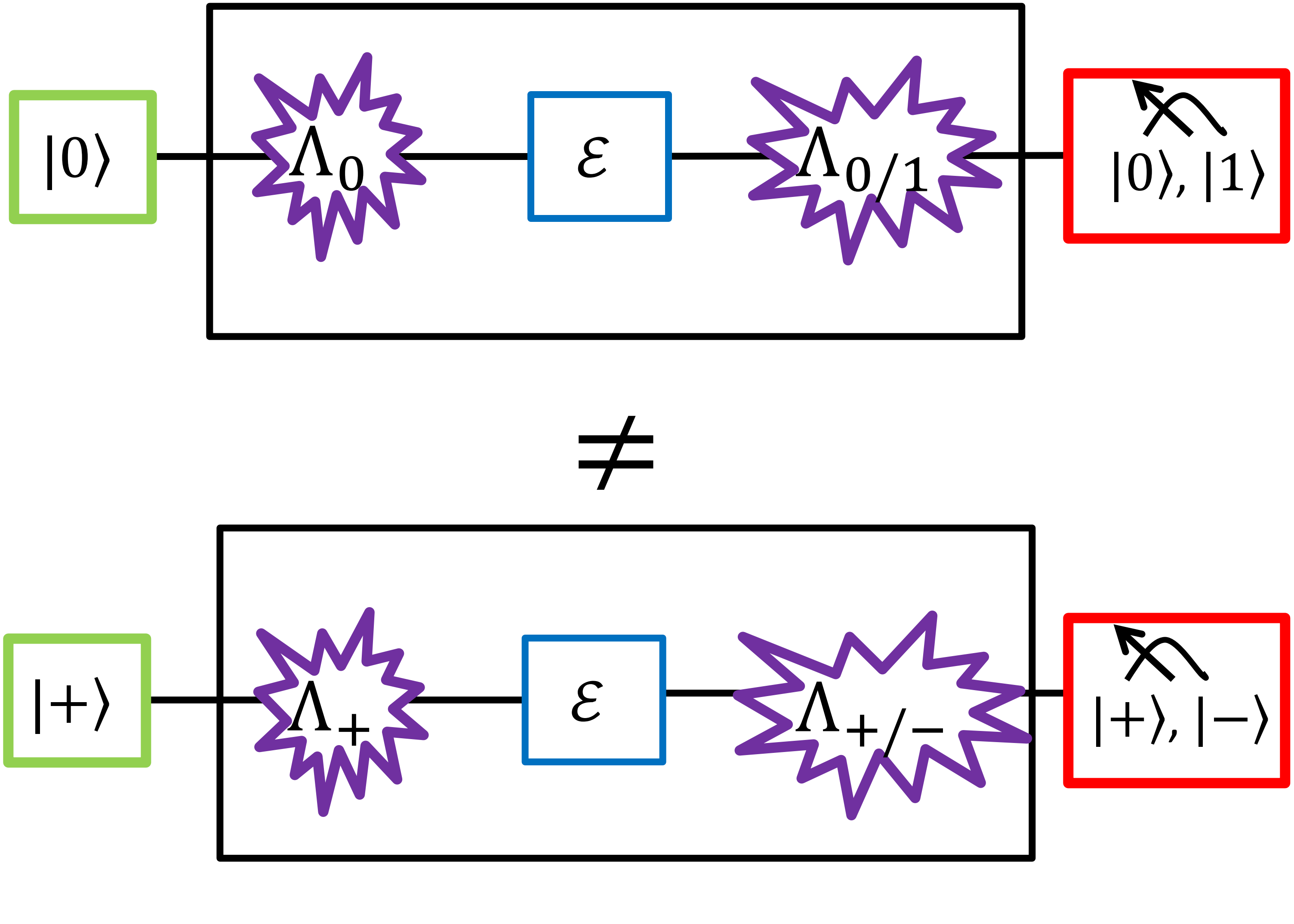
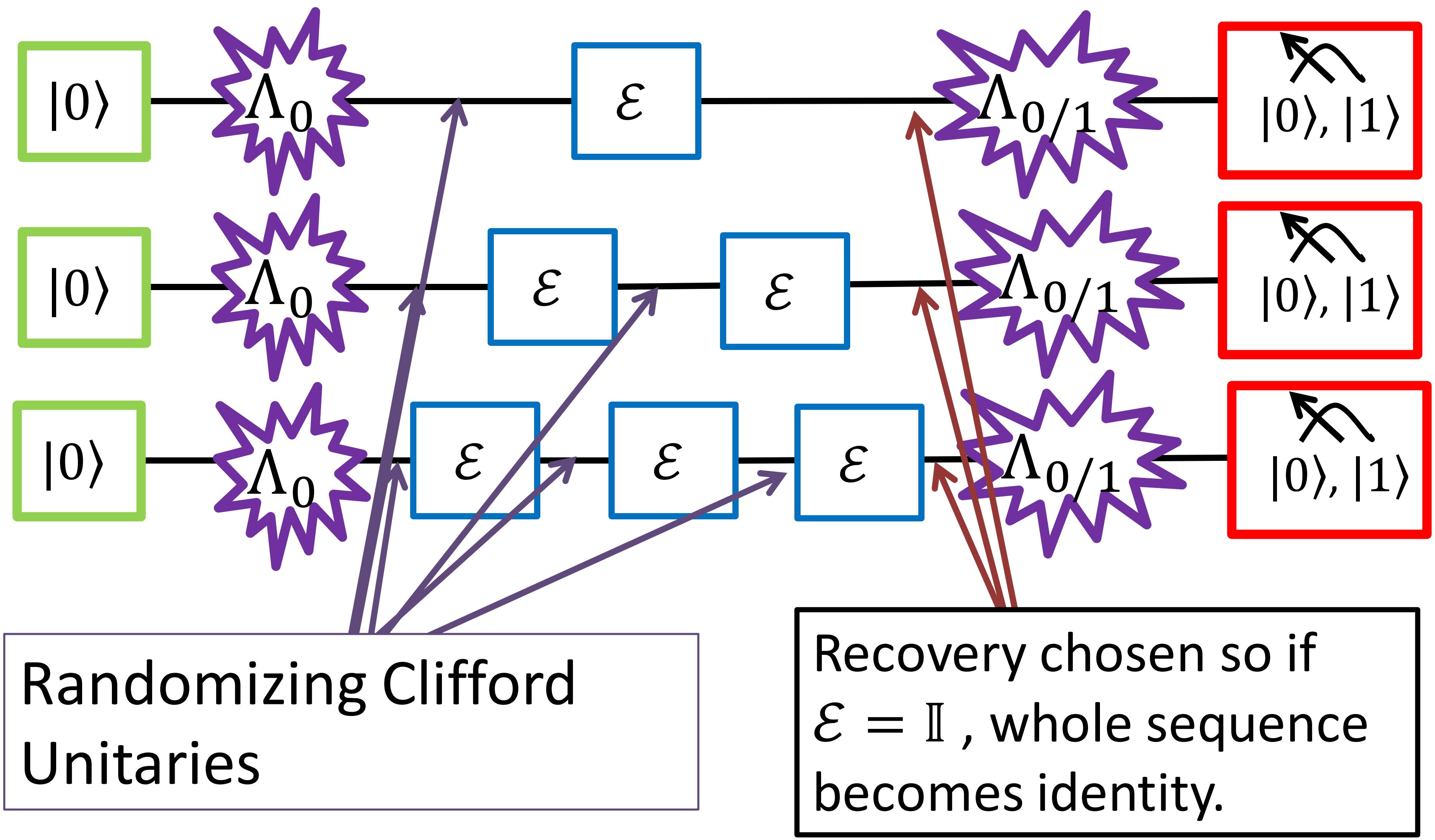
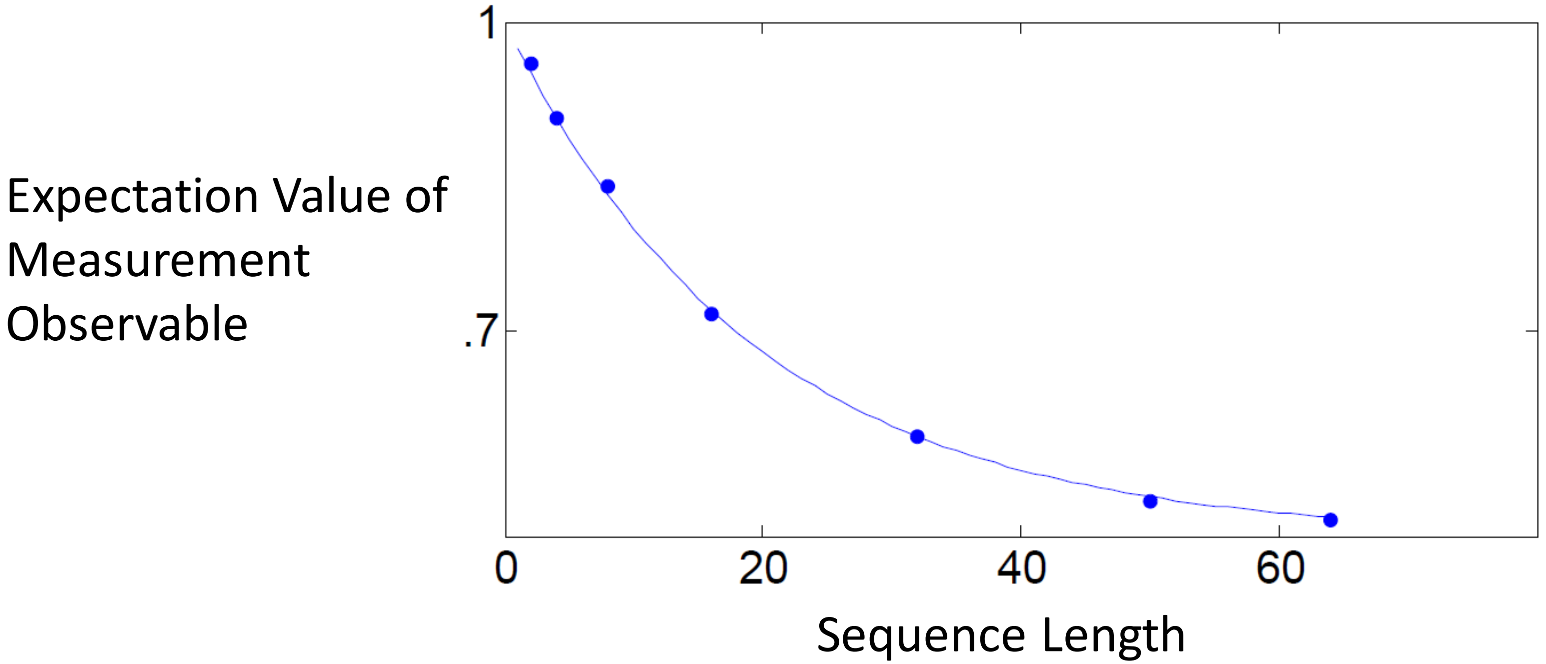


Randomized Benchmarking (RB)

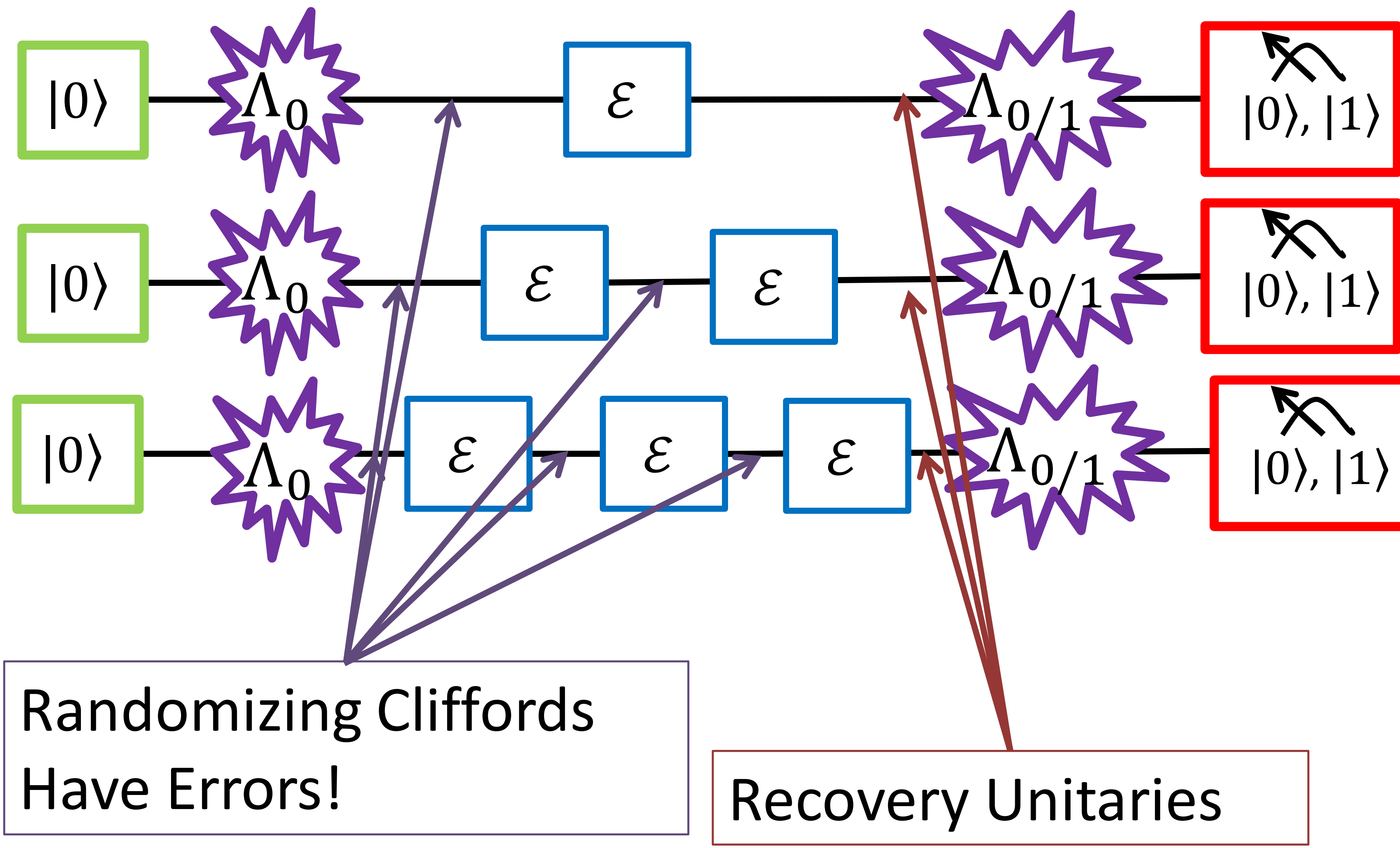


Randomized Benchmarking



- State Prep and Measurement don't affect decay parameter
- If Cliffords are perfect, recovery Clifford chosen so that if $\mathcal{E}$ is identity, whole sequence is identity, then decay constant depends only on average fidelity of $\mathcal{E}$ to identity

Randomized Benchmarking



Randomized Benchmarking

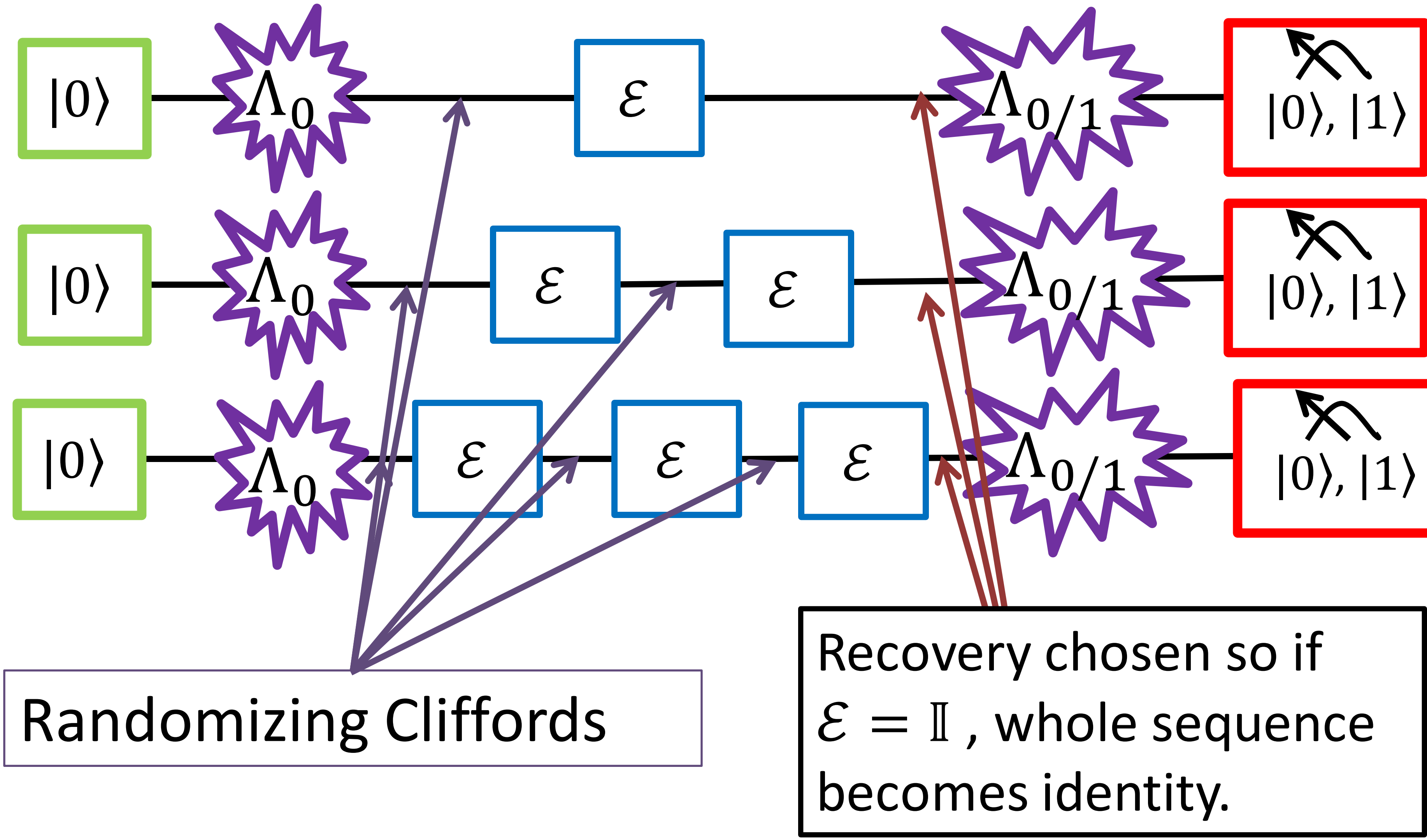
Pros

1. State preparation and measurement completely factored out
2. Easy to fit exponential decays

Issues

1. How can we extract more than just 1 parameter?
2. How can we deal with errors on the randomizing operations?

1. Extracting More Information



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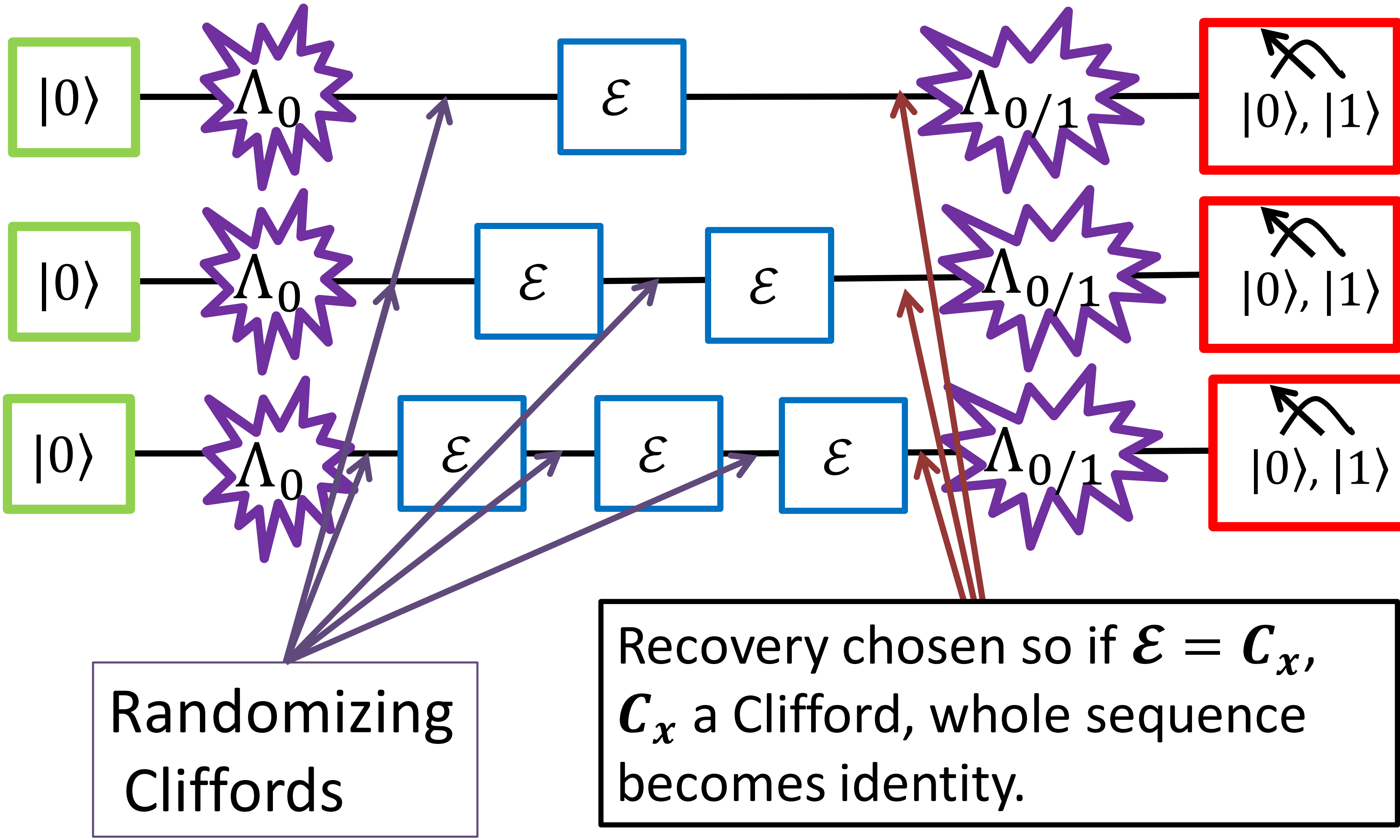

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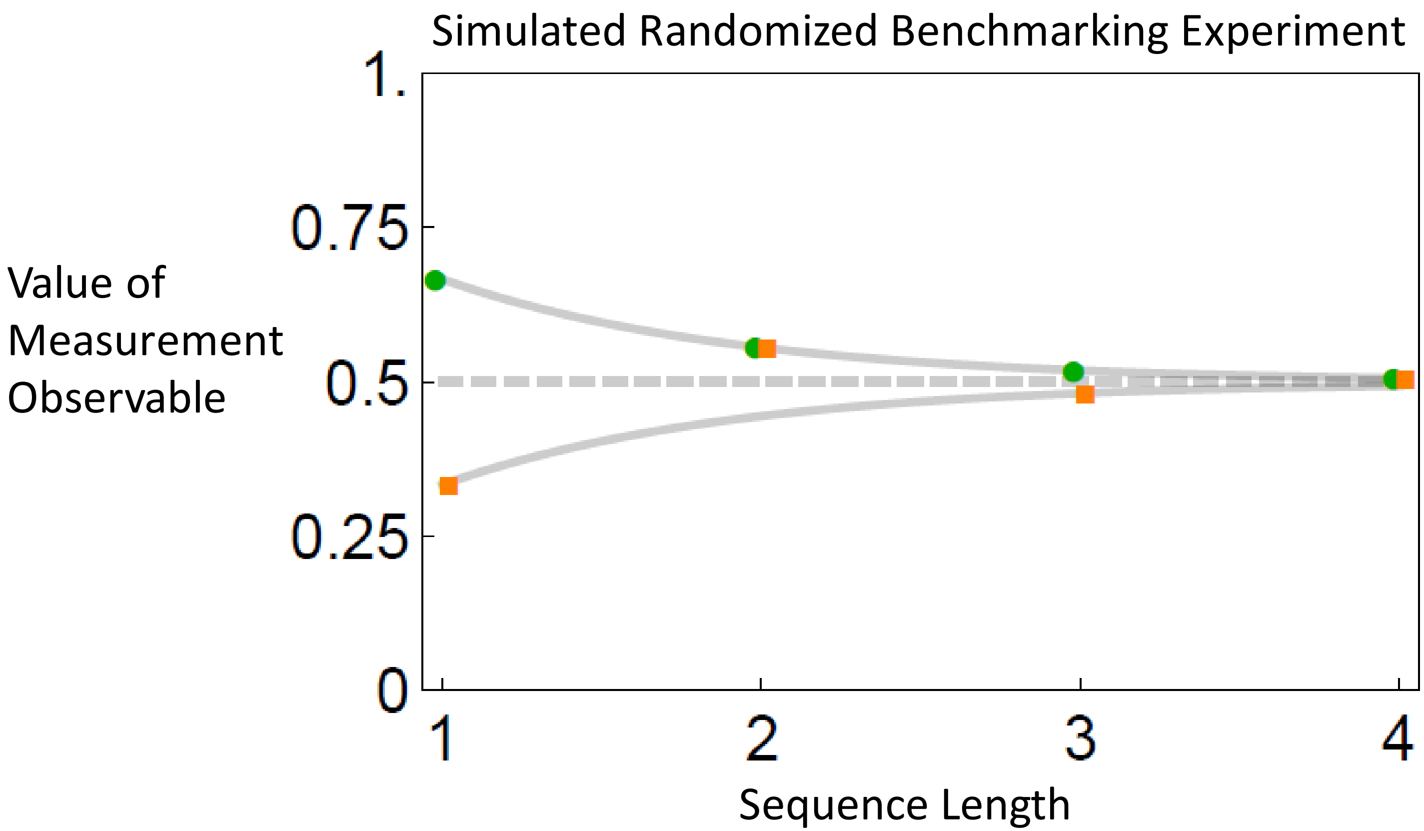


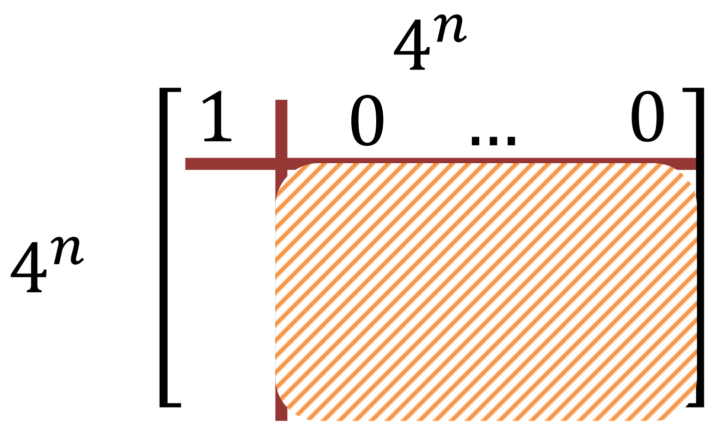
Decay constant depends on 1 parameter of $\mathcal{E}$:

Average Fidelity of $\mathcal{E}$ to C_x (can have fast decays)

1. Extracting More Information

Quantum map: $16^n - 4^n$ parameters for n-qubit map

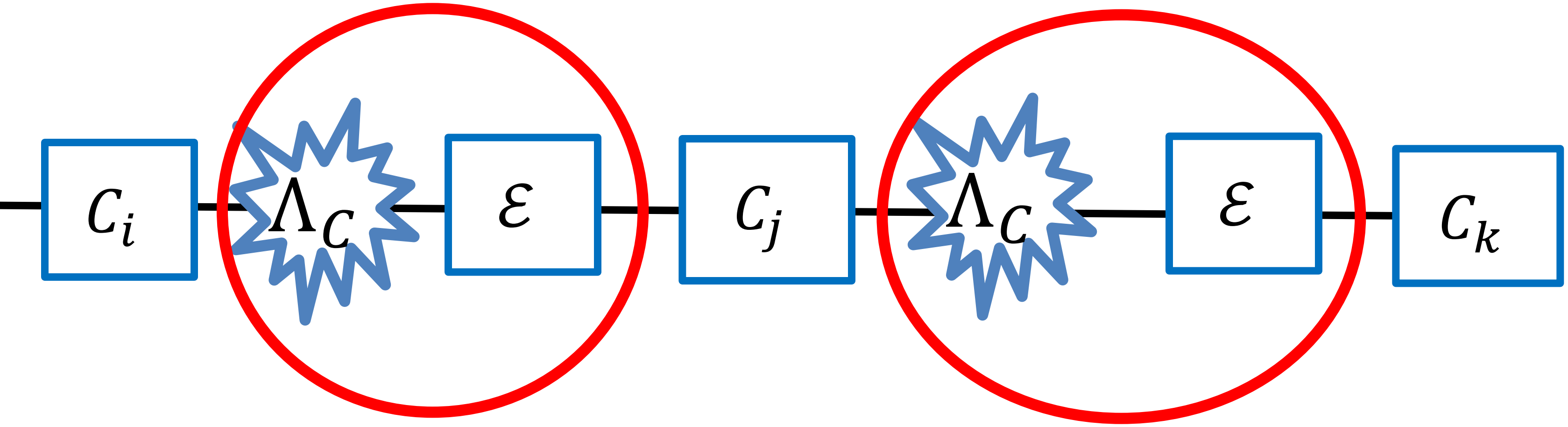
To compose two maps, just multiply matrices!



- Vectors V span a subspace S
- Learn inner product between V and unknown vector u
- Can learn projection of u onto S

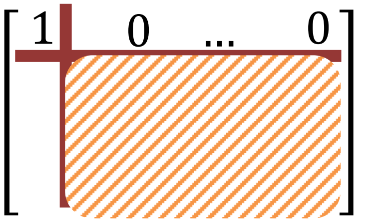
- Cliffords span unital part
- Learn inner product between Cliffords and $\mathcal{E}$
- Learn projection of $\mathcal{E}$ onto unital subspace

2. Dealing with Errors



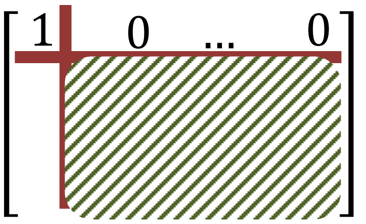
2. Dealing with Errors

almost complete characterization of Λ_C



$+$

almost complete characterization of $\Lambda_C \circ \mathcal{E}$



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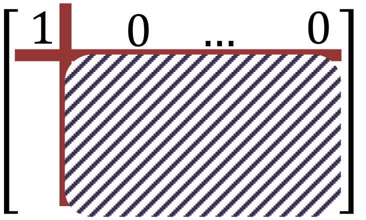
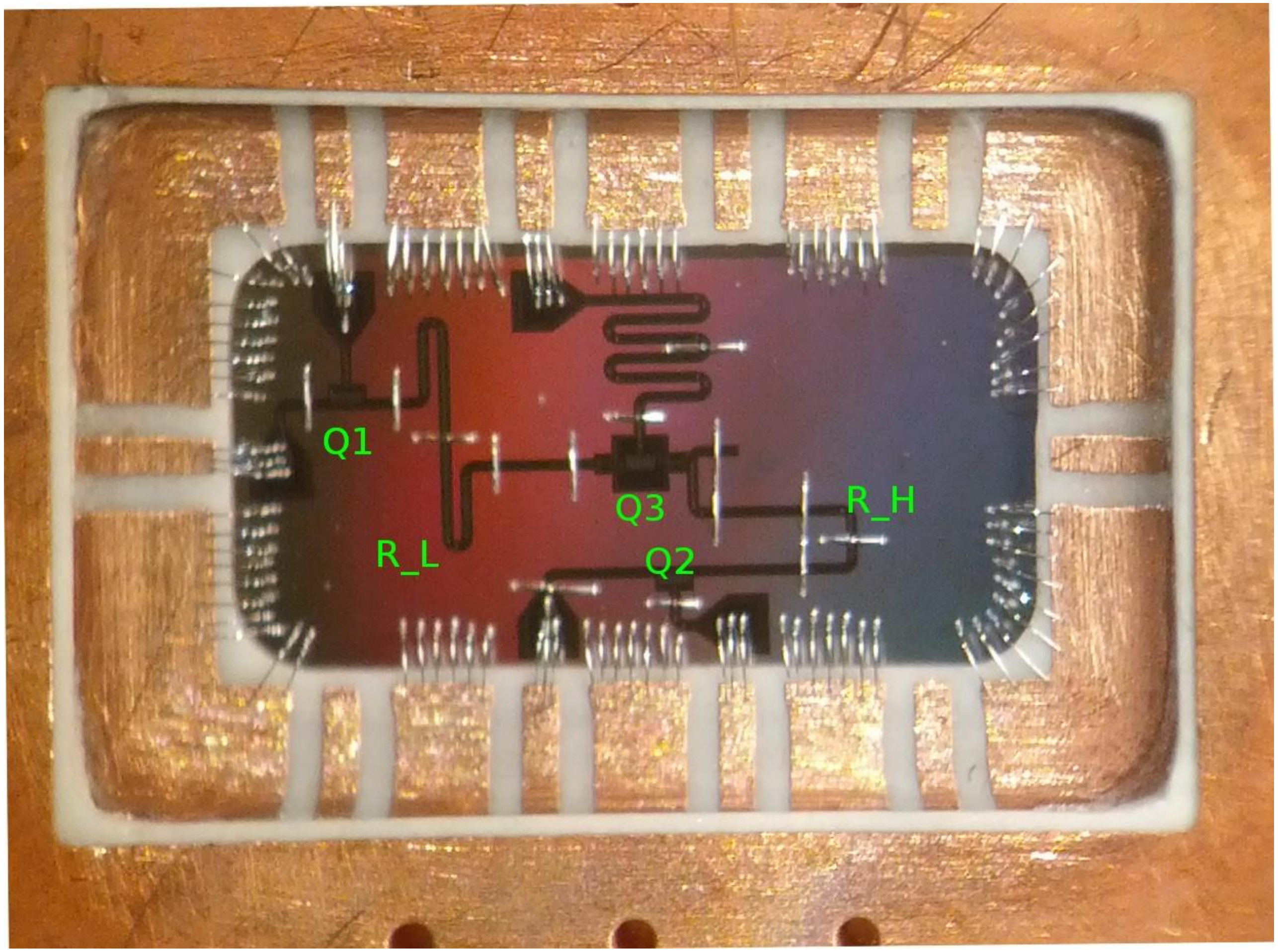
almost complete characterization of $\mathcal{E}$



Without many of the systematic errors of previous procedures!

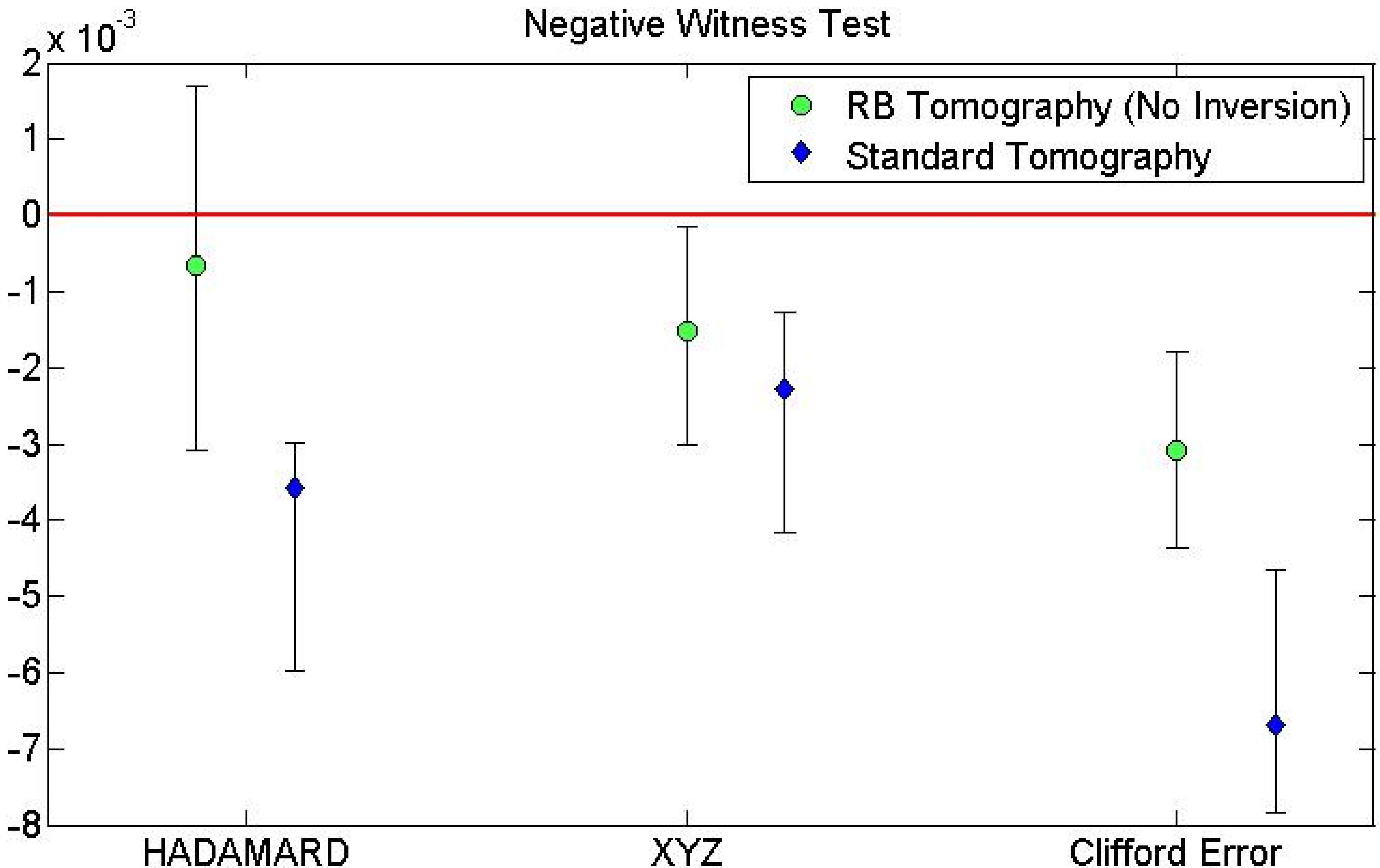
Experimental Implementation



Negative Witness Test [Moroder et al. '13]

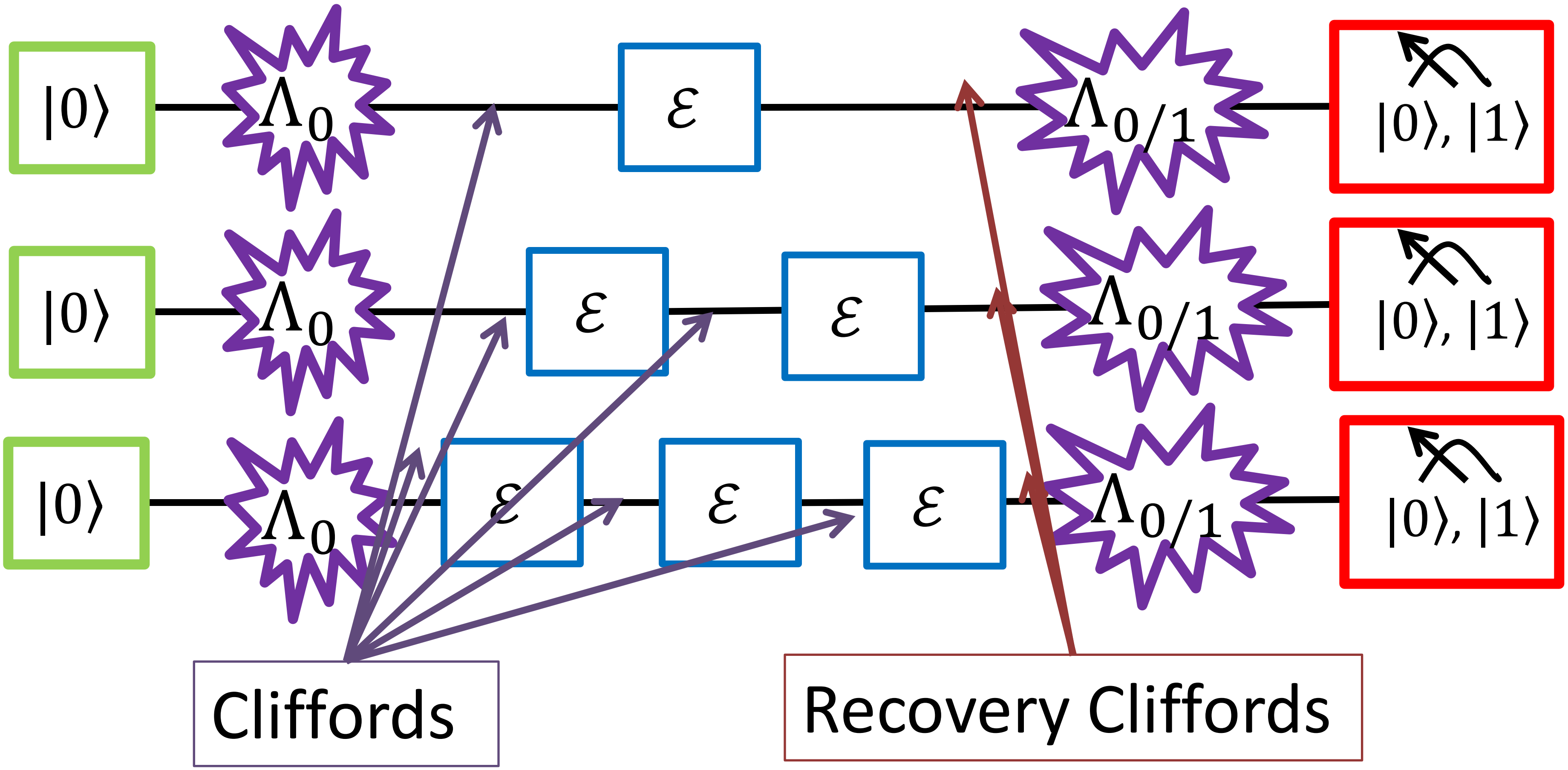
- To be a valid quantum process, must be trace preserving and completely positive
- Complete positivity = in Choi representation, all eigenvalues must be positive

- Negative witness test:
  - Look at value of smallest eigenvalues of reconstructed map in Choi representation.
  - If negative, BAD!



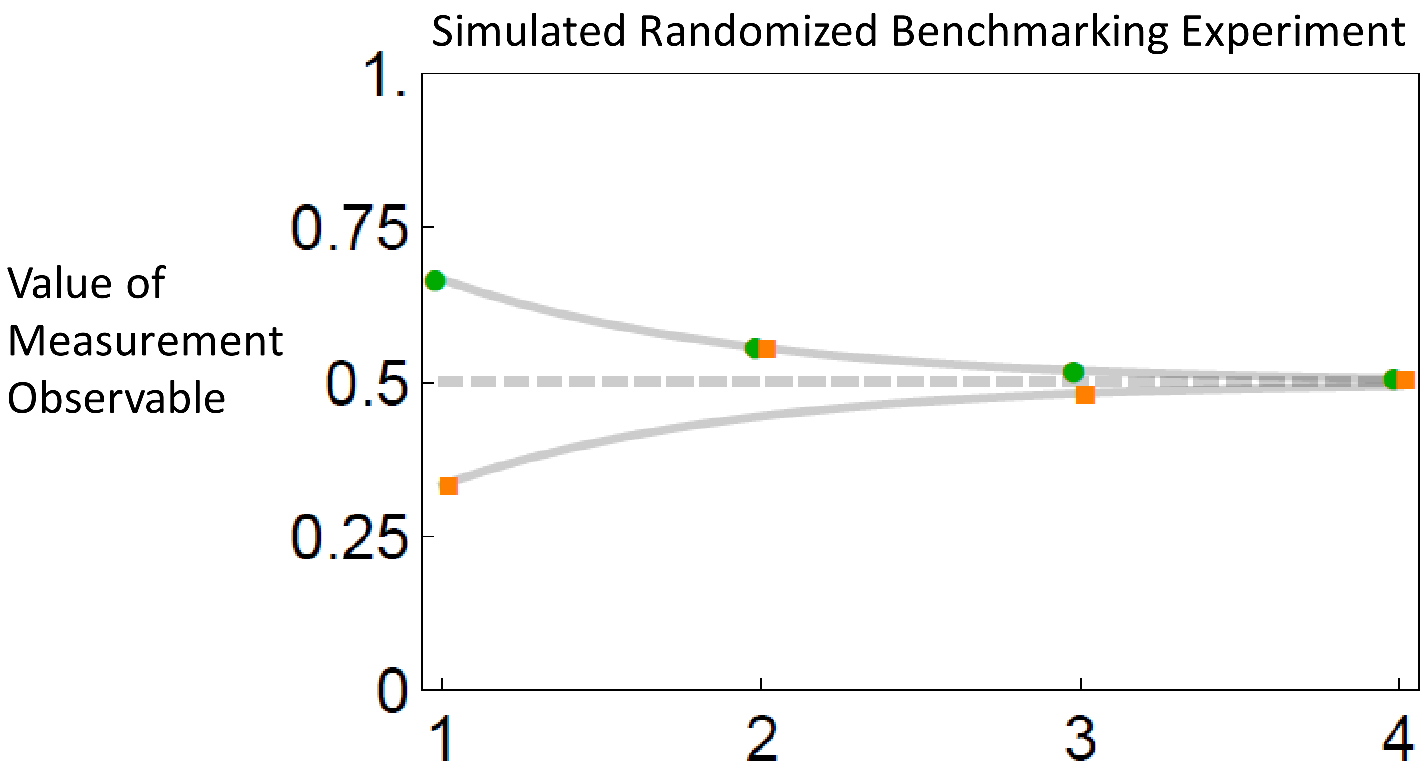
Negative Witness Test
x 10^-3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
RB Tomography (No Inversion)
Standard Tomography
HADAMARD
XYZ
Clifford Error

Why Negative? (Experimental Setup?)



If state preparation, measurement (or even and Cliffords) are unstable, can cause systematic errors.

Why Negative? (Data Analysis?)



We fit all 10 exponential decays together to avoid bad fits.
But we have evidence that this leads to biased results.

Conclusions and Open Questions

- Can robustly measure unital part of any quantum process
- Experimentally implemented with superconducting qubit system at BBN

- Can we reduce systematic errors in our procedure?
- Can we extract other information efficiently and robustly (compressed sensing)? What about non-unital part?
- How does RB compare to Gate Set Tomography methods?

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