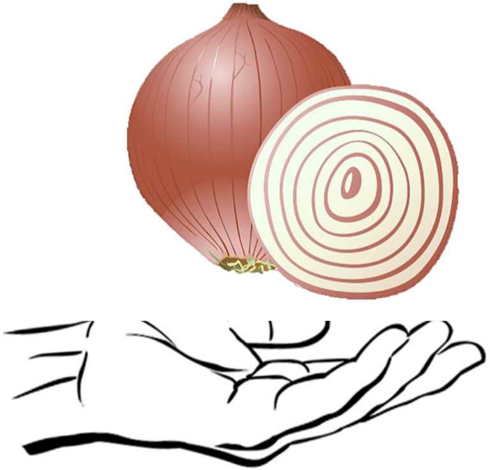
This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

SAND2020-2288C

Hold the onion: using fewer circuits to characterize your qubits.



Erik Nielsen[1]

Robin Blume-Kohout[1], Timothy Proctor[1],

Kenneth Rudinger[1], Kevin Young[1]

[1](Quantum performance laboratory, Sandia National Laboratories)

APS March Meeting 2020

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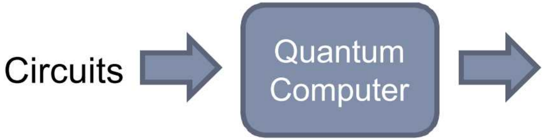
U.S. DEPARTMENT OF ENERGY

Motivation

- Eventually, we want:

Solutions to problems we couldn't solve before.

- Now, we want:



Information telling me how good this quantum computer is and maybe how to make it better.

What circuits do you run? How to you analyze the data?

There **are two broad types** of analysis you can run.

Benchmarking
Answers: How well is this device working, often in an overall sense?
- Randomized benchmarking (RB)
- Direct RB
- Cycle benchmarking
- Mirror RB

 # circuits: typically a qubit-independent "base" times a number of benchmarks performed.

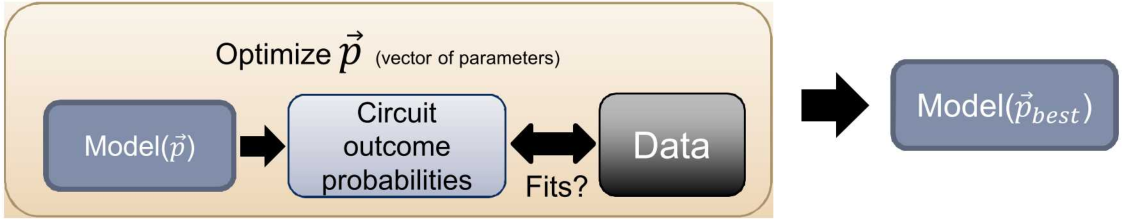
Model-based characterization
Answers: What is a predictive error model that can be used to explain this device's behavior.
- Gate set tomography (GST)
- General modeling (this talk!)

 # circuits: proportional to the number of parameters in your model.

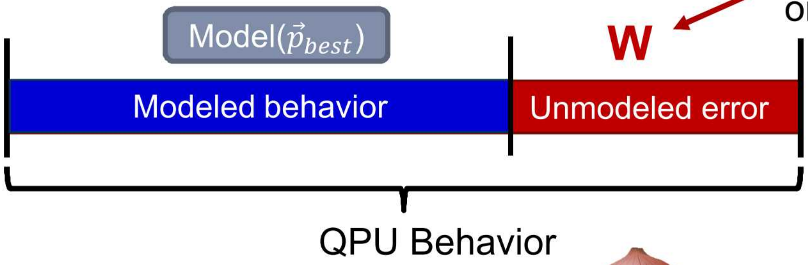
Modeling is not *necessarily* more expensive than benchmarking

Model-based characterization

- How it works:
  - Given a parameterized model that predicts circuit outcome probabilities, find the parameters that result in the best fit between the model and some data.



  - Compute the amount of unmodeled-error-per-gate

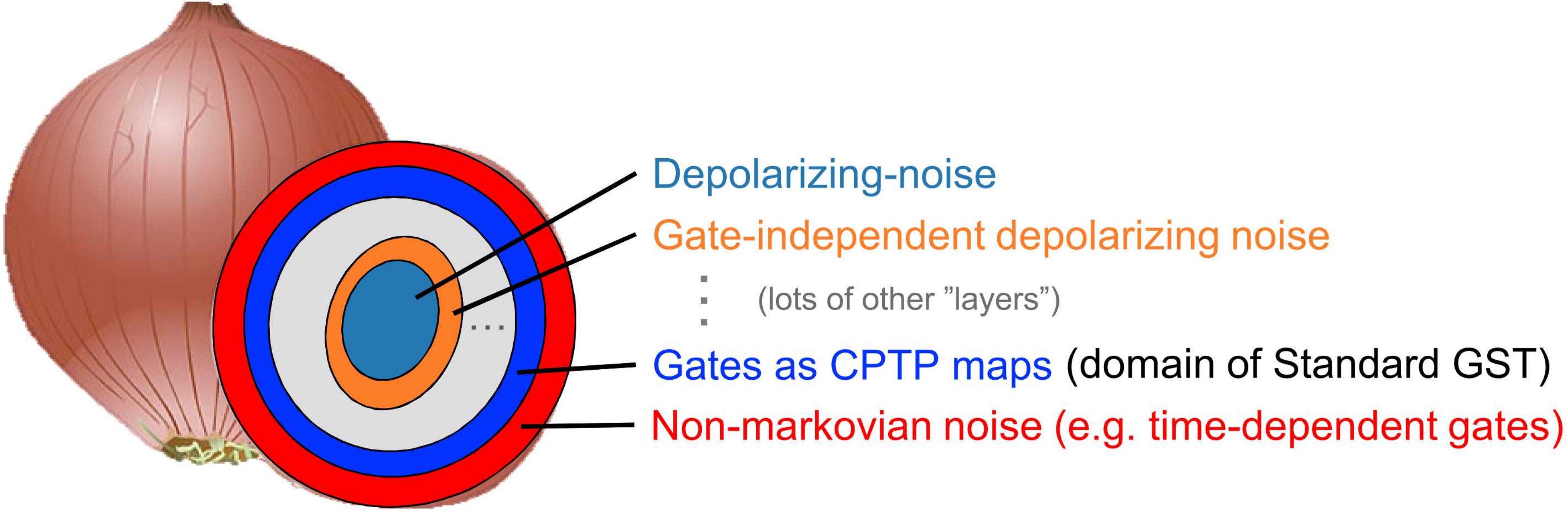


"whatever else is wrong this this thing" on a **per-gate** basis

- Models can be nested, creating an "**onion**"

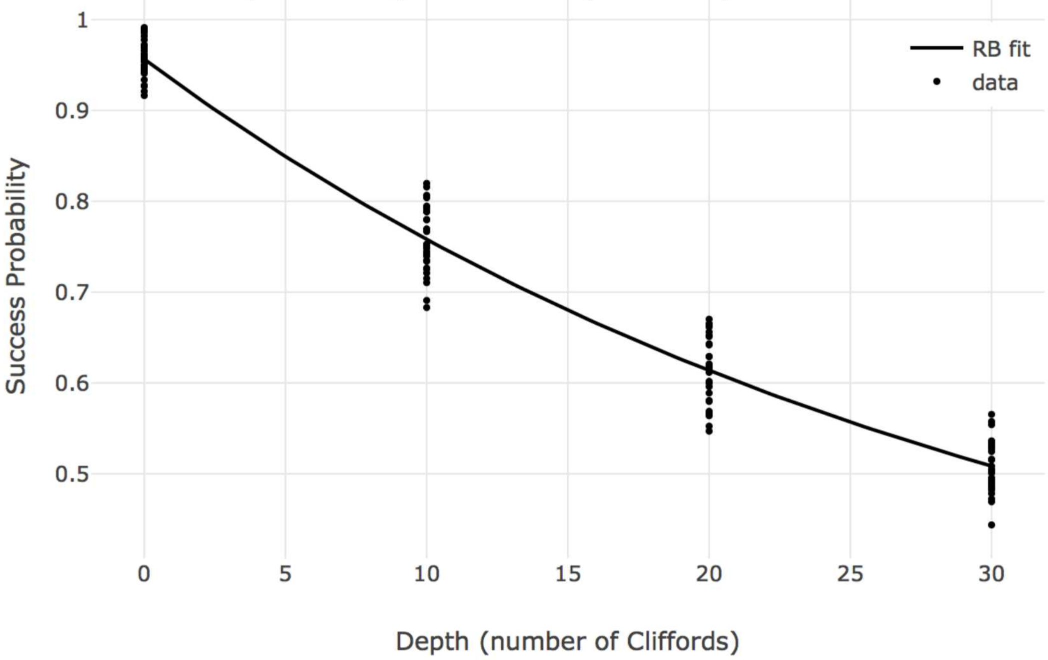
Nested models

For example:



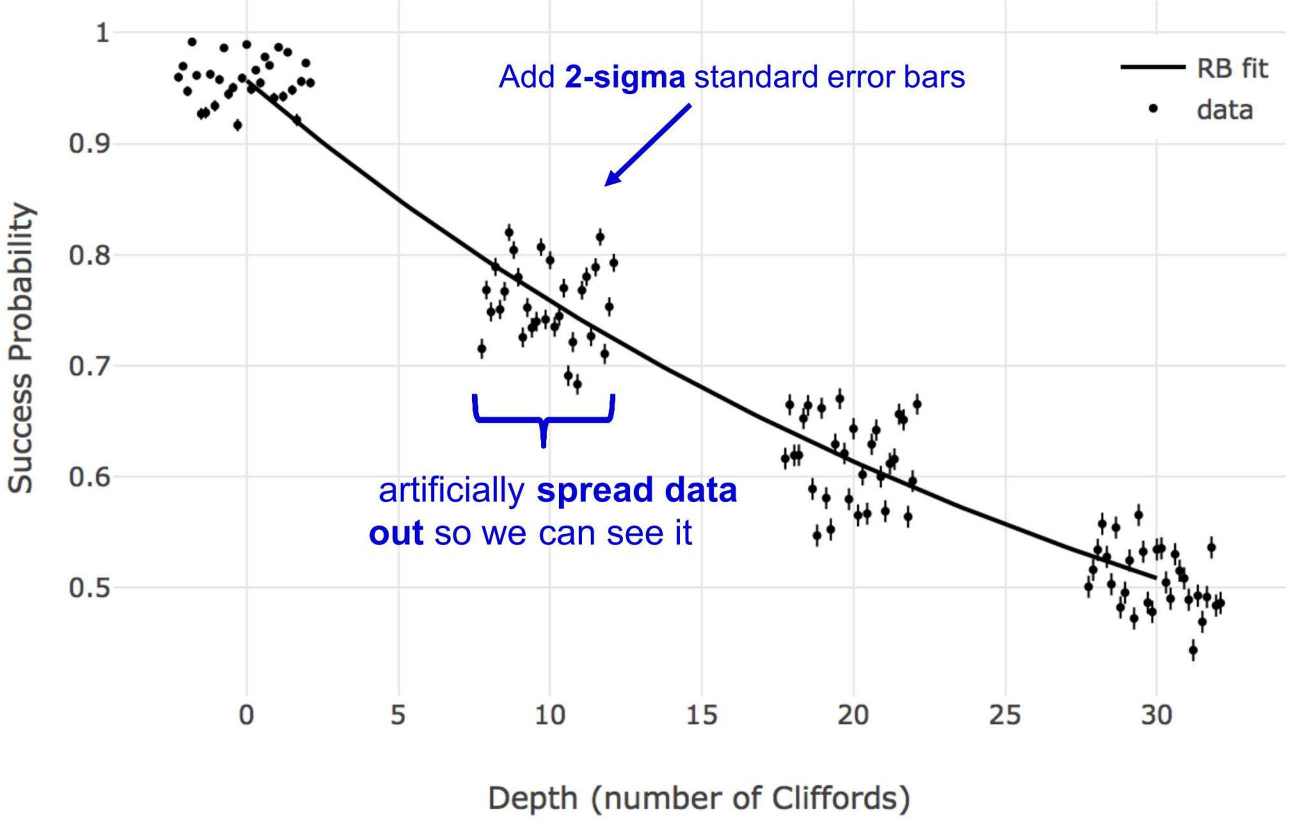
Case study: **2-qubit processor w/physical noise**

- Simple noise model including a mix of stochastic and coherent noise, with noise concentrated on 2-qubit gate coherent errors.
- We'll start by running standard (Clifford) RB: 120 circuits x 10,000 repetitions



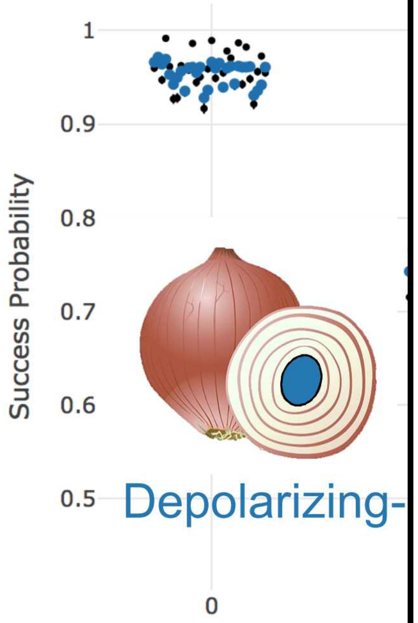
RB number r = 0.029
(average error per Clifford)

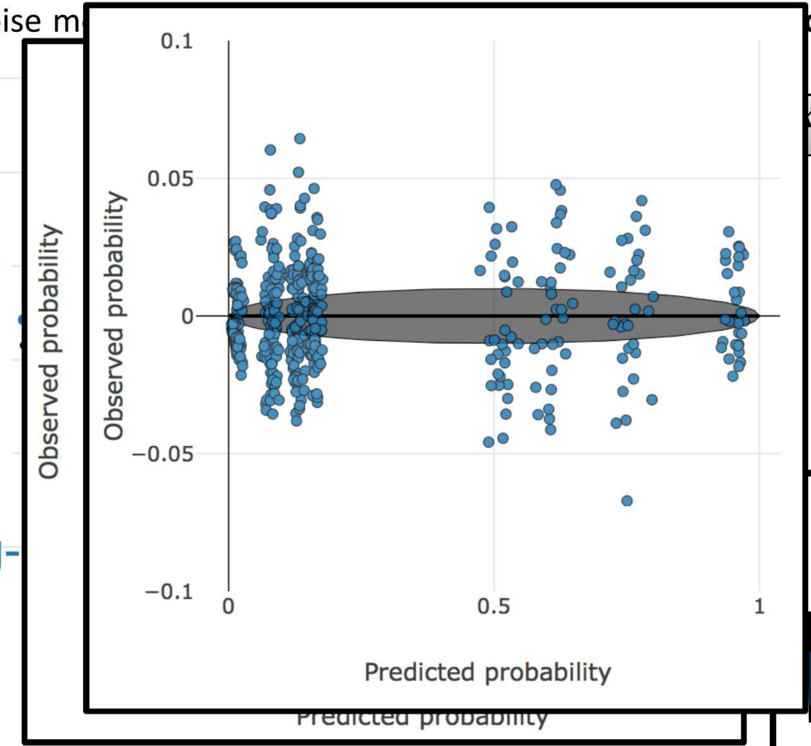
2Q processor w/physical noise: reformat RB data

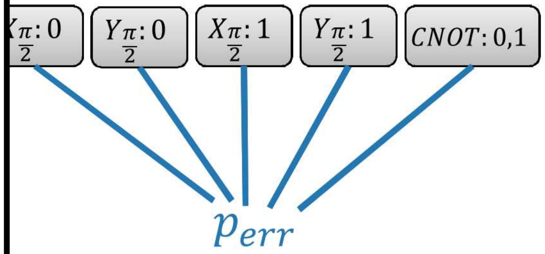


2Q processor: Depolarizing model, RB data

Construct a depolarizing-noise m… …ct the success probabilities?

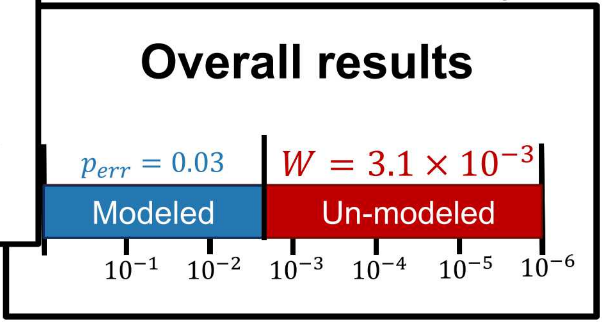






… gate parameter (not counting SPAM)

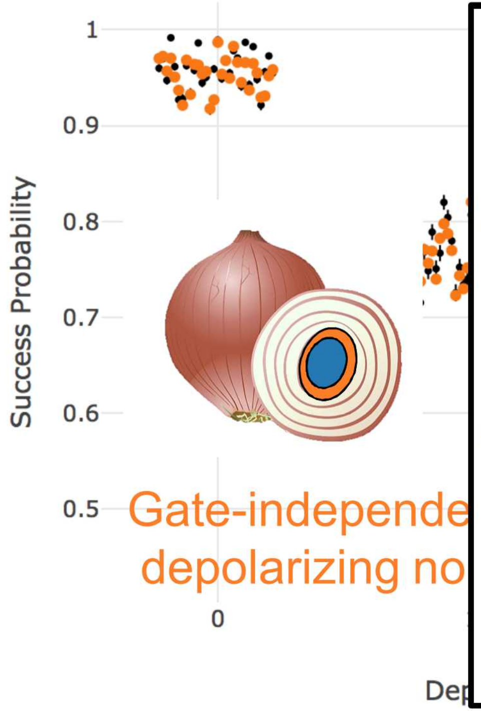
$N_\sigma = 603$

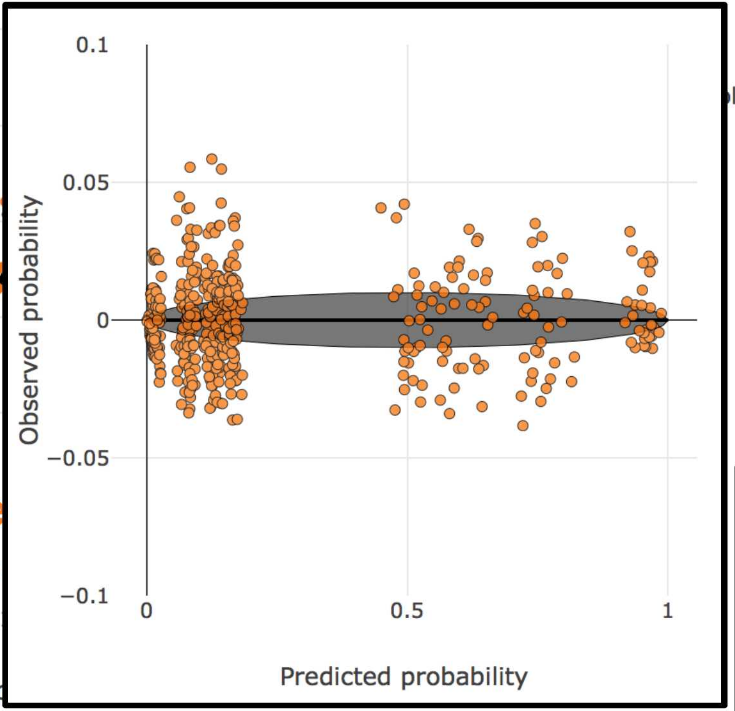


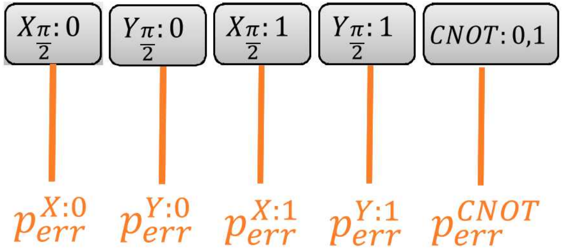
What do we do now?

1. Call it good enough ☺
2. Improve the model ➡ **Independent-gate depolarizing model**

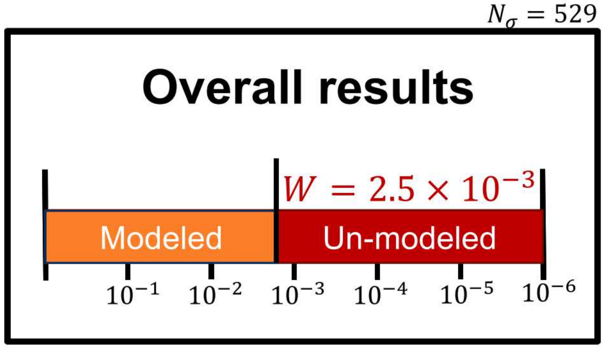
2Q processor: Gate-indep. depol. model, RB data







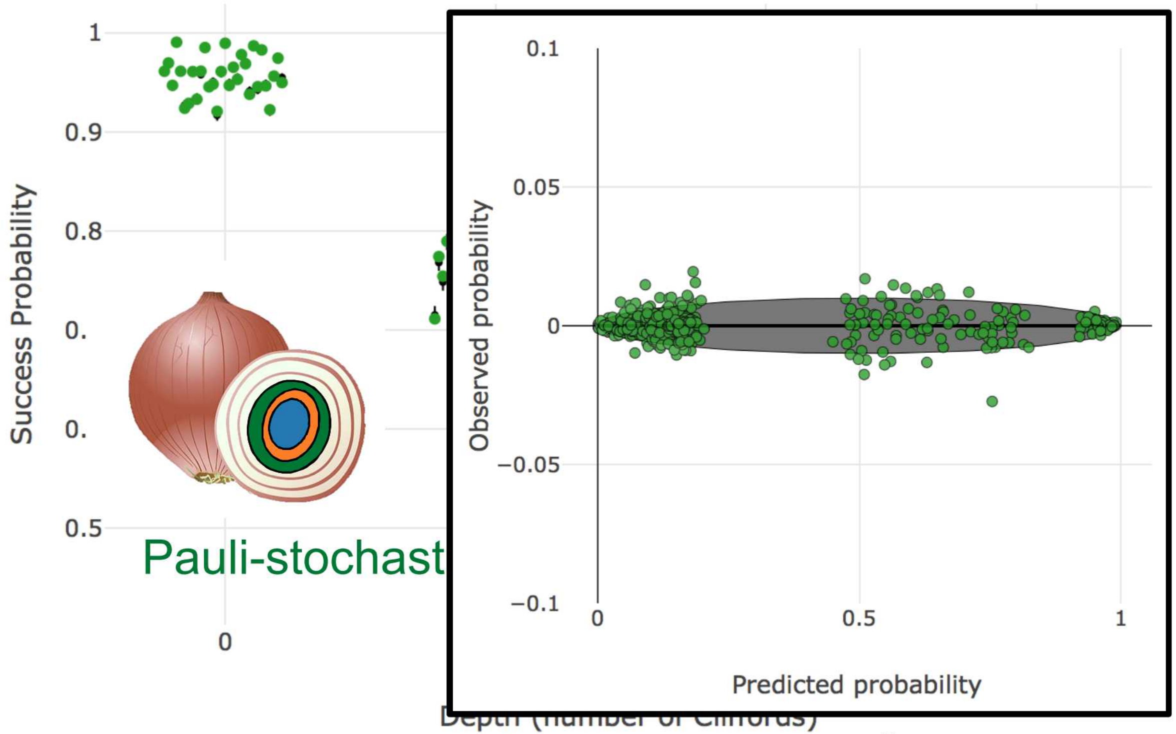
N_p= 5 gate parameters

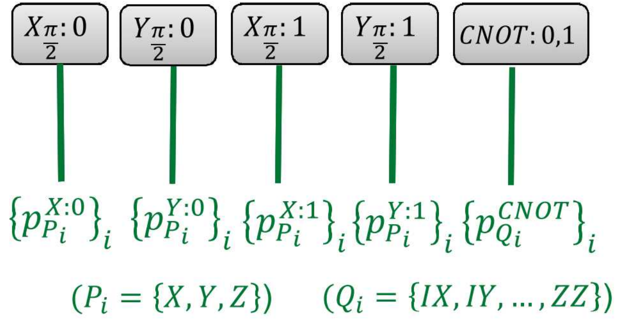


What do we do now?

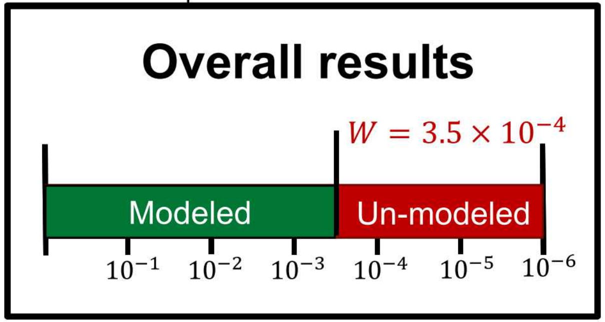
1. Call it good enough ☺
2. Improve the model ➡ **Independent-Pauli-stochastic-error model**

2Q processor: Pauli-stochastic model, RB data





N_p= 27 gate parameters



$N_\sigma = 13$

What do we do now?

1. Call it good enough ☺
2. Improve the model
3. Do a harder test → **Test a set of 400 Rabi-like sequences**

2Q processor: Depolarizing model, Rabi data

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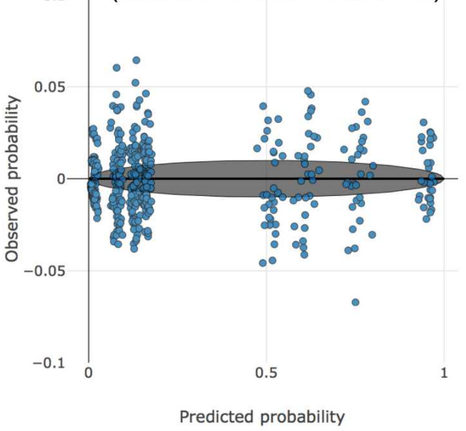
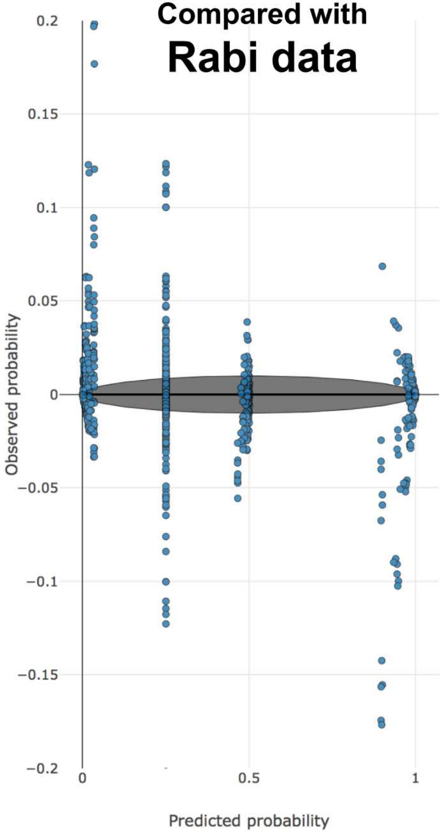
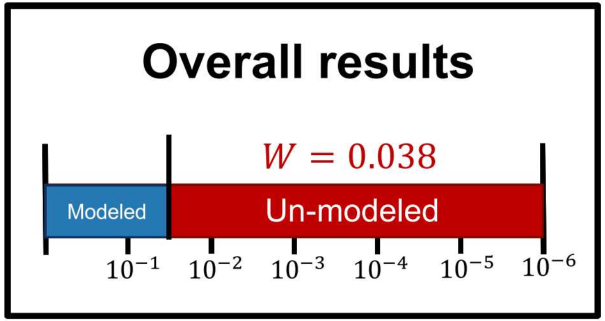
Depolarizing-noise model

Compared with the RB data
(that this model was fit to)



Compared with
Rabi data

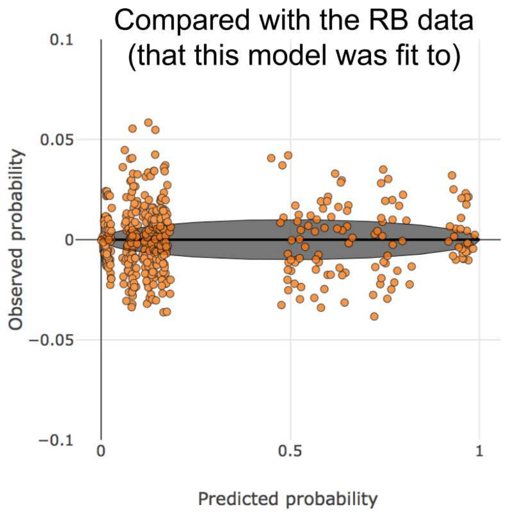


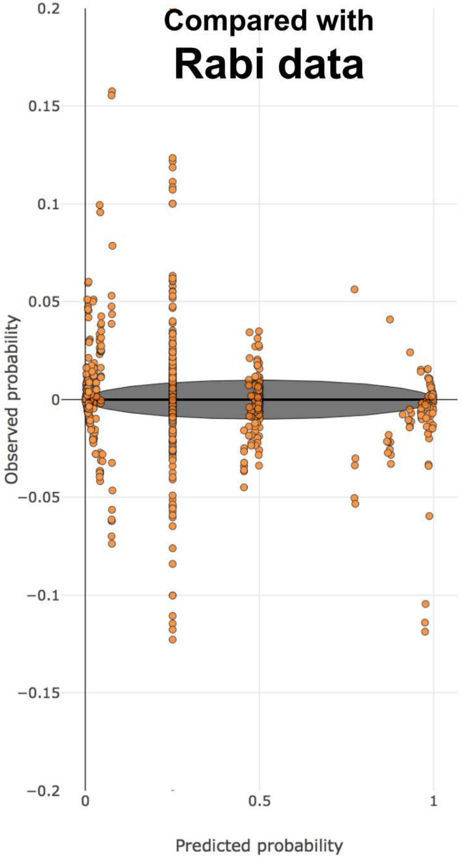


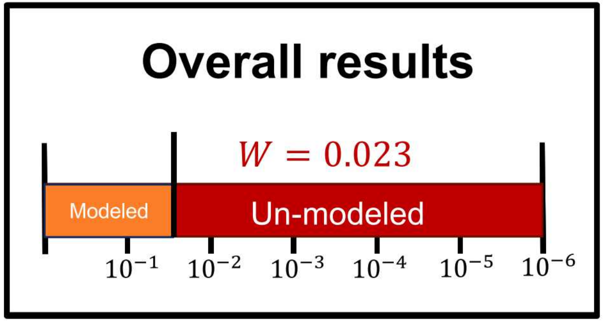
$N_\sigma = 1988$

2Q processor: Gate-indep. depol. model, Rabi data

Gate-independent depolarizing noise





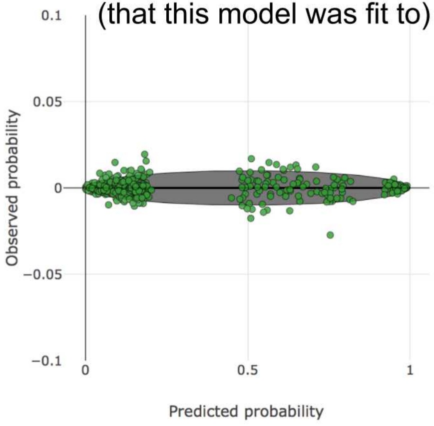


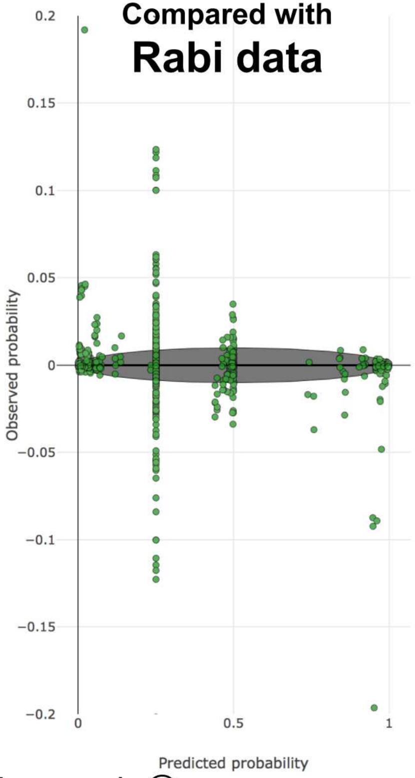
$N_\sigma = 1717$

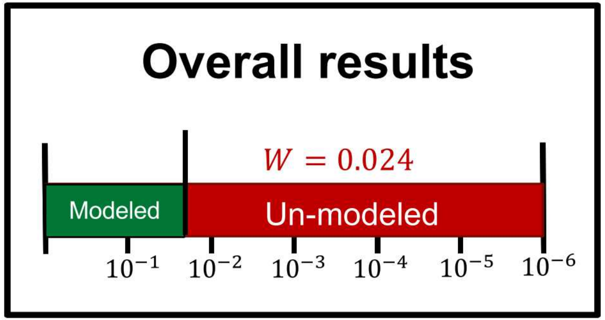
2Q processor: Pauli-stochastic model, Rabi data

Pauli-stochastic noise

Compared with the RB data (that this model was fit to)







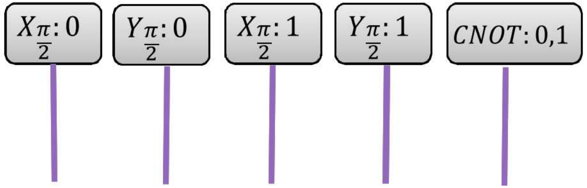
$N_\sigma = 735$

None of the models can explain the Rabi-data

1. Call it good enough ☺
2. Improve the model → **Local coherent & stochastic noise model**

2Q processor w/physical noise (cont.)

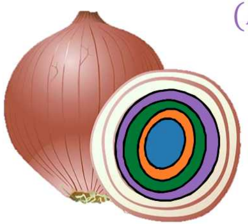
- Coherent and Pauli-stochastic errors



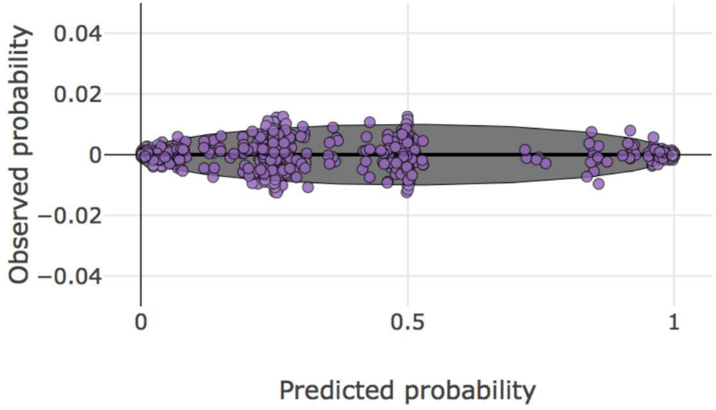
Stochastic $\{p_{P_i}^{X:0}\}_i$ $\{p_{P_i}^{Y:0}\}_i$ $\{p_{P_i}^{X:1}\}_i$ $\{p_{P_i}^{Y:1}\}_i$ $\{p_{Q_i}^{CNOT}\}_i$

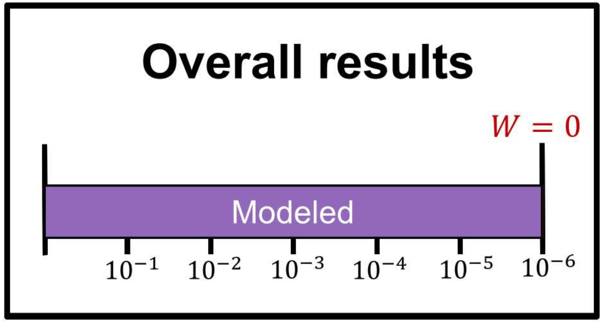
Coherent $\{\theta_{P_i}^{X:0}\}_i$ $\{\theta_{P_i}^{Y:0}\}_i$ $\{\theta_{P_i}^{X:1}\}_i$ $\{\theta_{P_i}^{Y:1}\}_i$ $\{\theta_{Q_i}^{CNOT}\}_i$

$(P_i = \{X, Y, Z\})$ $(Q_i = \{IX, IY, \dots, ZZ\})$



N_p=54 gate parameters





$N_\sigma = 1$

What about RB data, does this model work for random circuits?

2Q processor w/physical noise (cont.)

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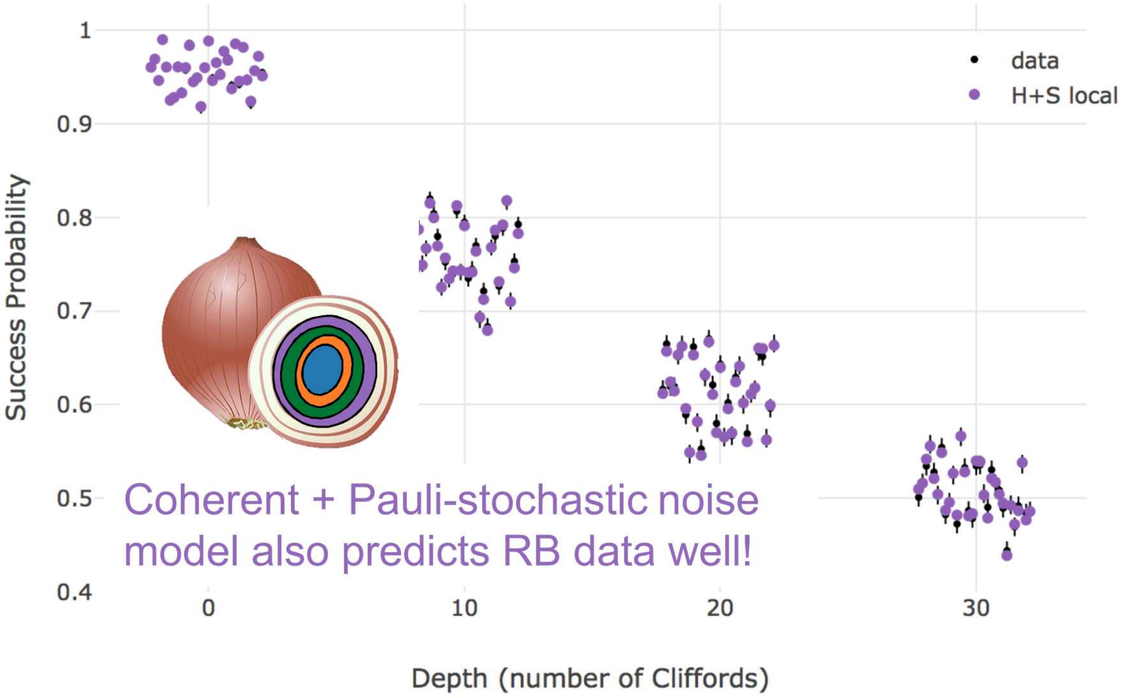
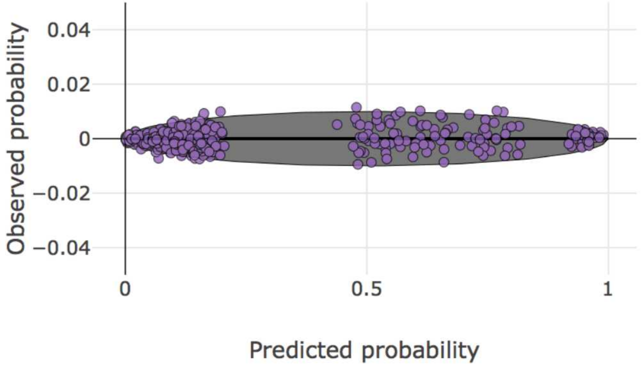
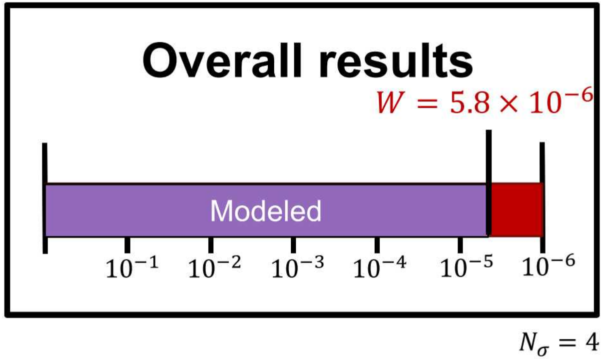


Coherent + Pauli-stochastic noise model also predicts RB data well!

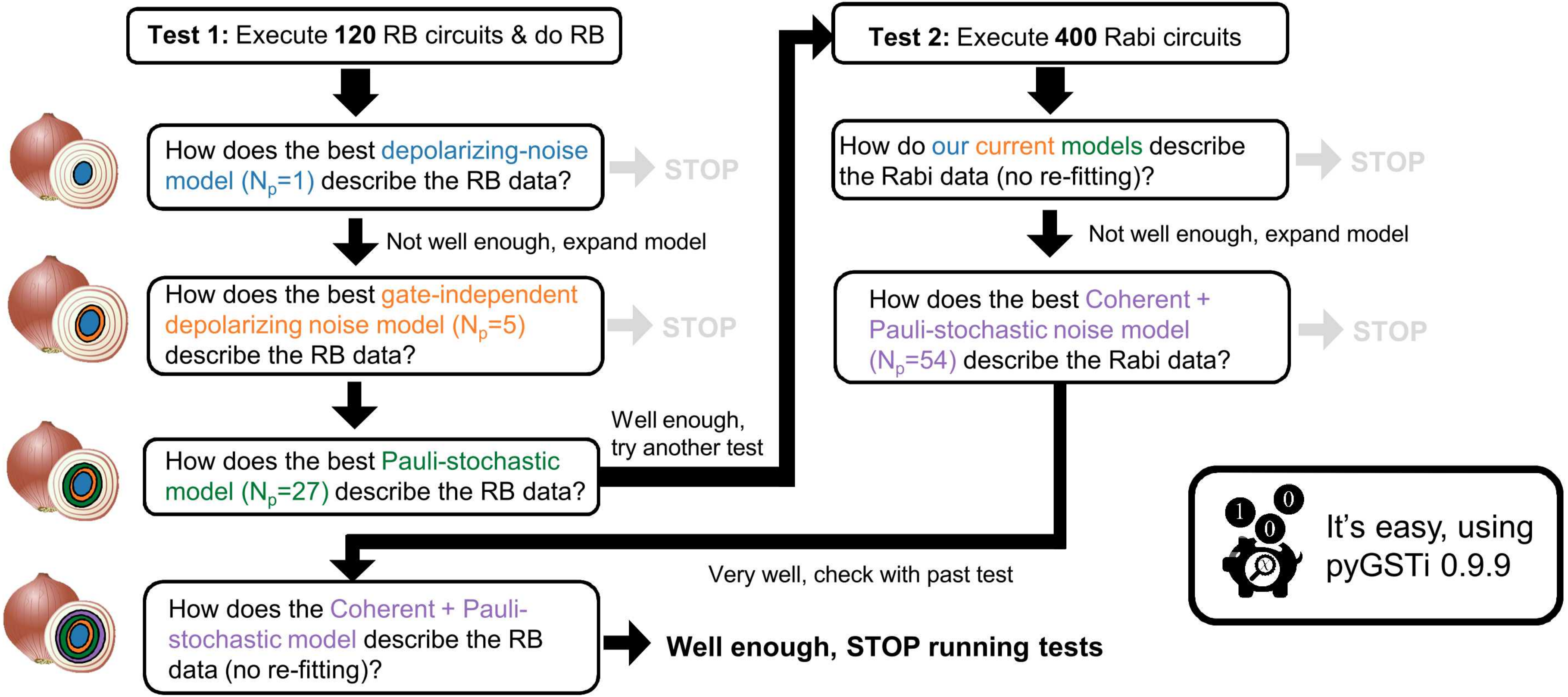




What do we do next?

1. Call it good enough ☺ **STOP**
2. Do a harder test

Recap: what we did and how much it cost



Conclusions

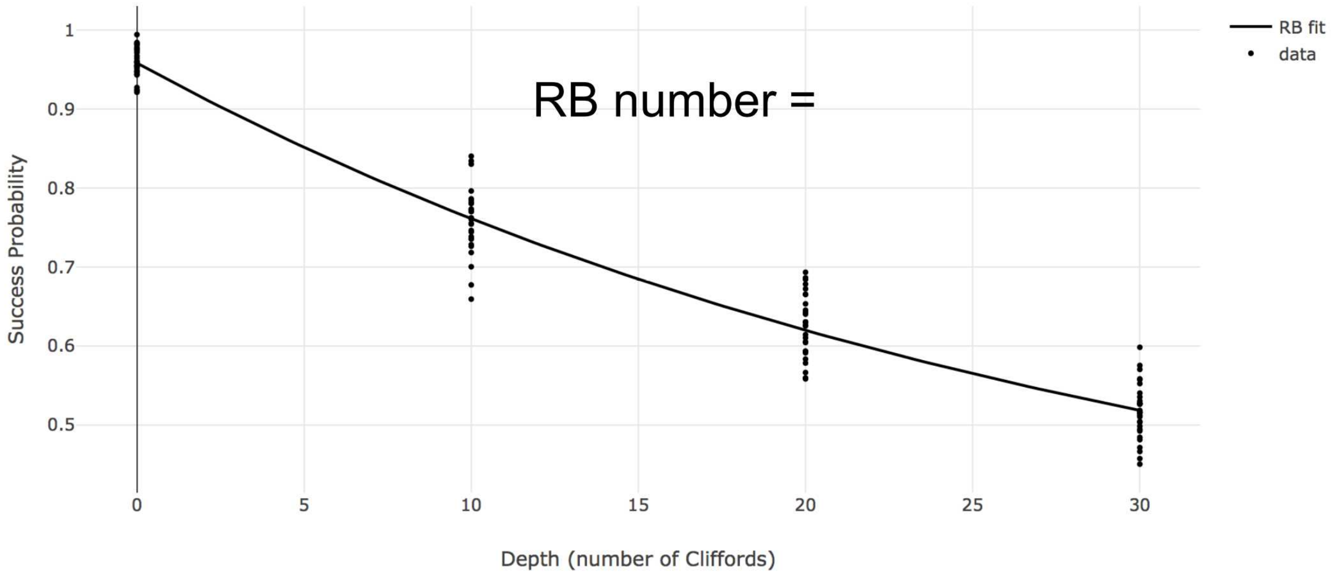
- Model-based characterization can be a powerful tool in understanding a quantum processor.
  - Models *predict* behavior and give insight into noise processes.
  - Un-modelable behavior can be quantified.
  - Not as cost-prohibitive as you might think: # of circuits scales with model parameters, and so can be small, and *any* circuits can be used. **Can be done with more qubits**, limited by model complexity (# parameters) and circuit simulate-ability.
  - Customizable, e.g. physics-informed models.

- Interesting asides illustrated by our example:
  - Depolarizing noise model derived from RB does not predict RB data to statistical precision.
  - Scatter in RB data does not imply coherent noise.
  - RB data is sufficient to construct a stochastic-noise model (at least in some cases).

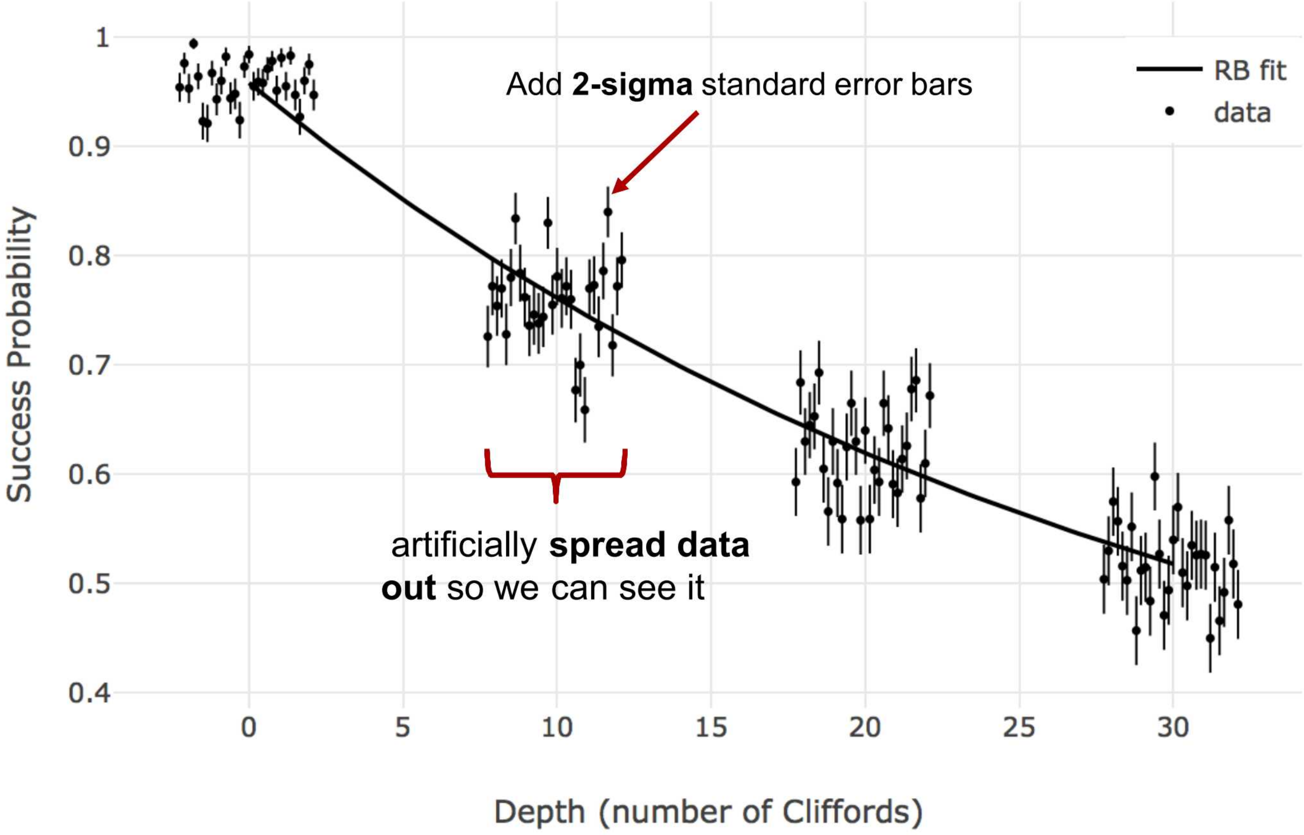
SAME FOR 1K SAMPLES (EXTRA)

Case study: **2-qubit processor w/physical noise**

- Simple noise model including a mix of stochastic and coherent noise, with noise concentrated on 2-qubit gate coherent errors.
- We'll start by running standard (Clifford) RB:

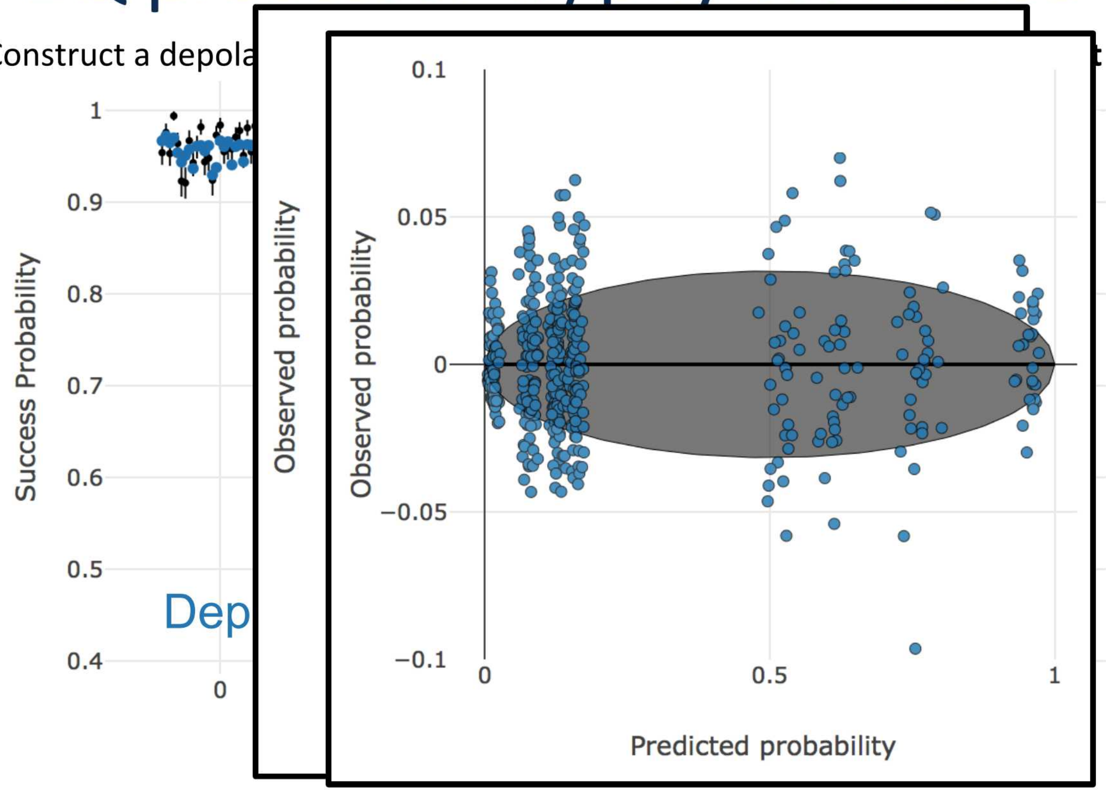


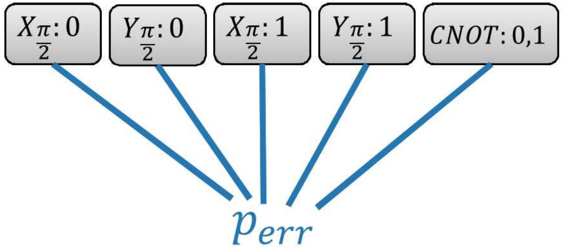
2Q processor w/physical noise (cont.)



2Q processor w/physical noise (cont.)

Construct a depola... **...t predict the success probabilities?**





1 gate parameter (not counting SPAM)

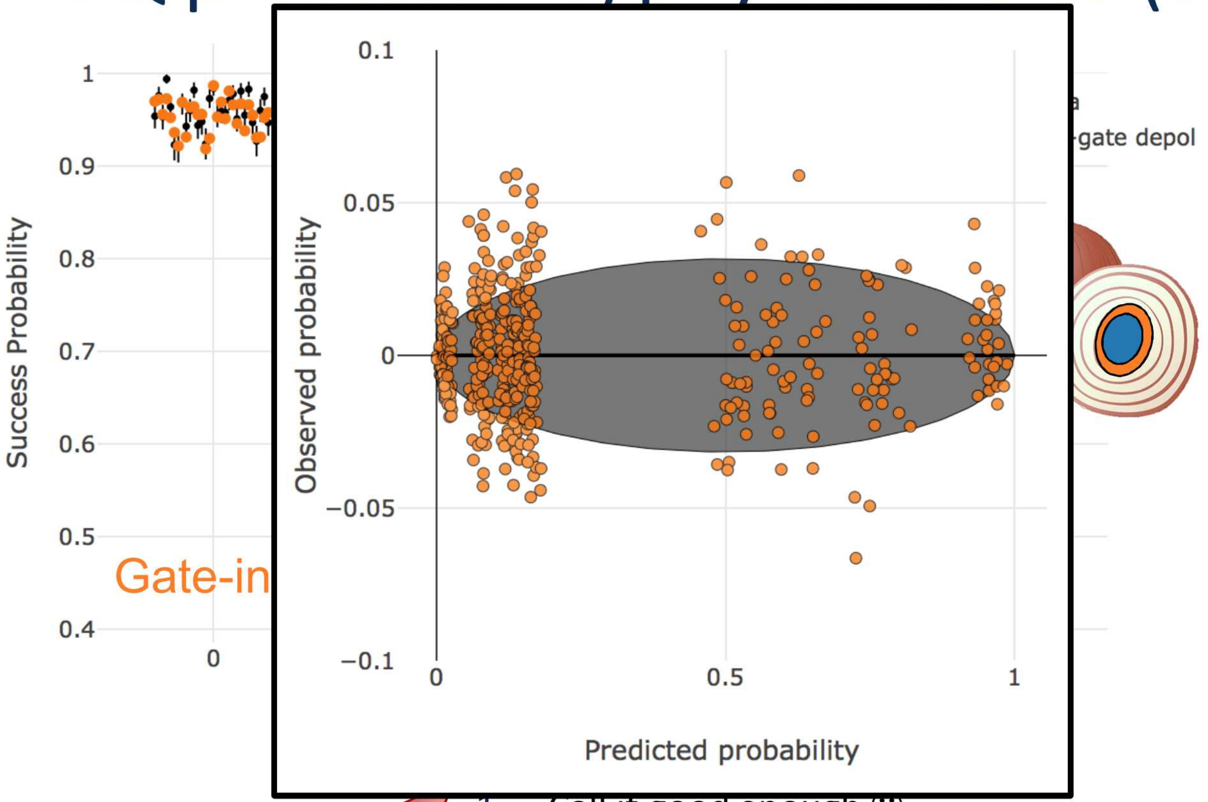
Results

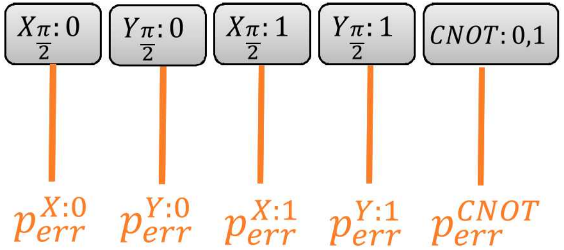
- model doesn't explain data ($N_\sigma = 62$)
- But it's not bad: $W = 0.2\%$

What do we do now?

1. Call it good enough ☺
2. Improve the model → **Independent-gate depolarizing model**

2Q processor w/physical noise (cont.)





5 gate parameters

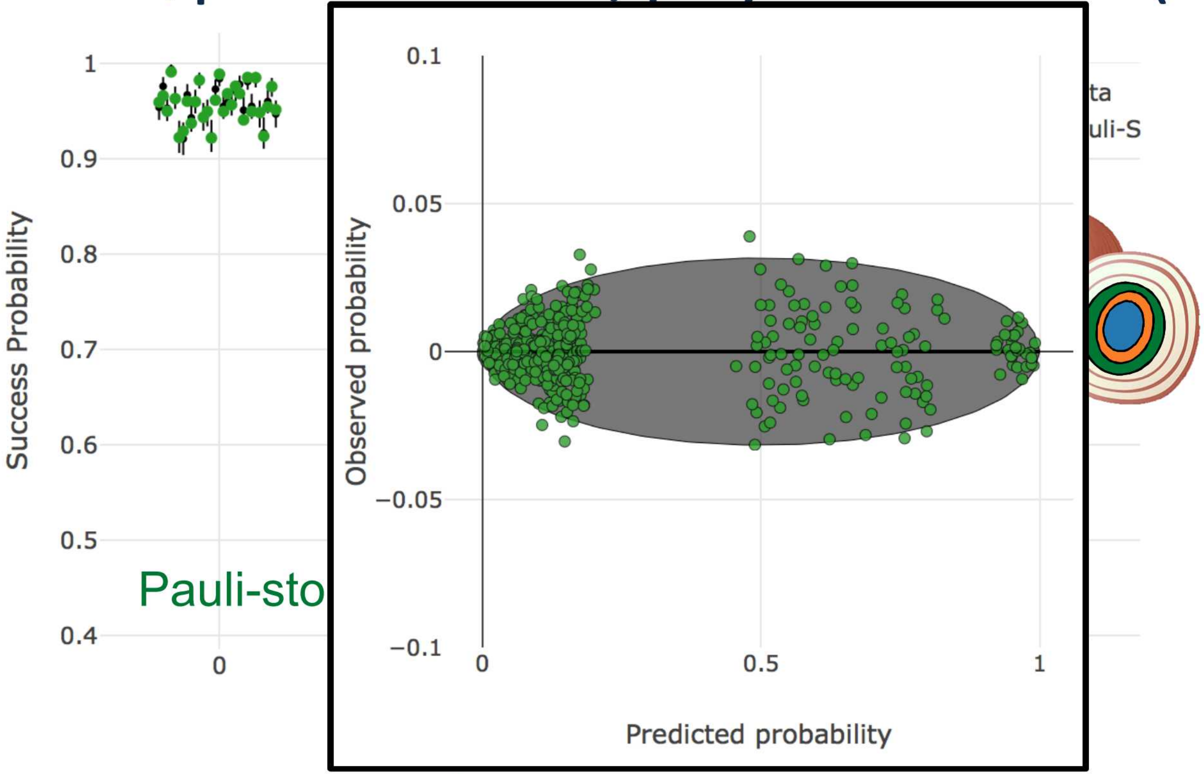
Results

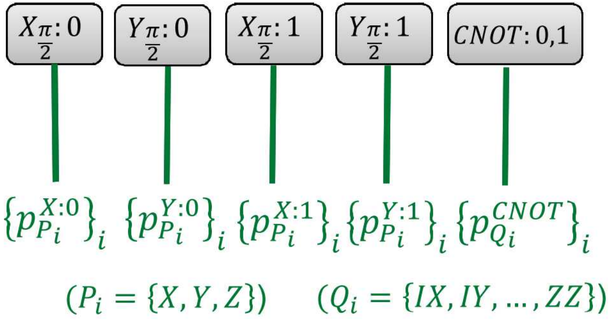
- model doesn't explain data ($N_\sigma = 54$)
- But it's not bad: $W = 0.1\%$ (better than depol. model)

What do we do now?

1. Call it good enough ☺
2. Improve the model → **Independent-Pauli-stochastic-error model**

2Q processor w/physical noise (cont.)





27 gate parameters

Results

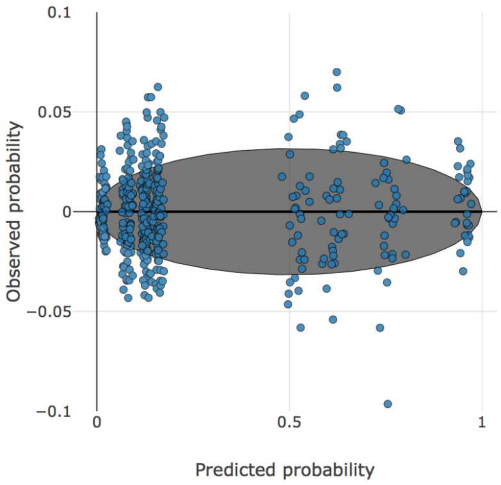
- Does explain data ($N_\sigma = 1$)
- $W = 0$

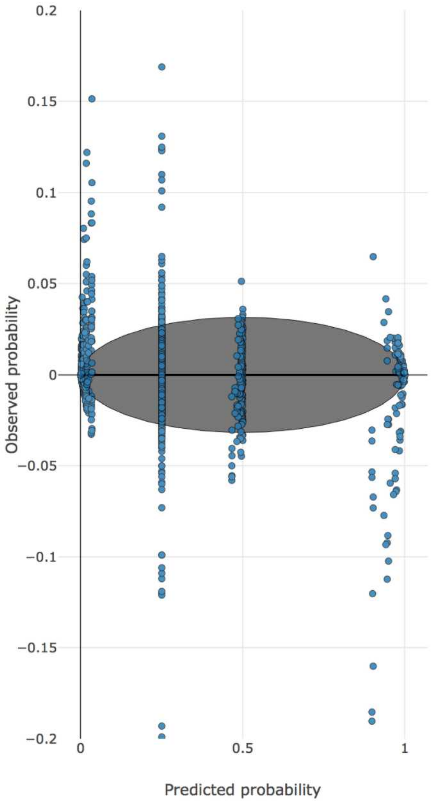
Yay! We have a model that explains 1 set of RB data!

1. Call it good enough ☺
2. Try to predict more data / do a harder test

What about Rabi-like sequences?

2Q processor w/physical noise (cont.)

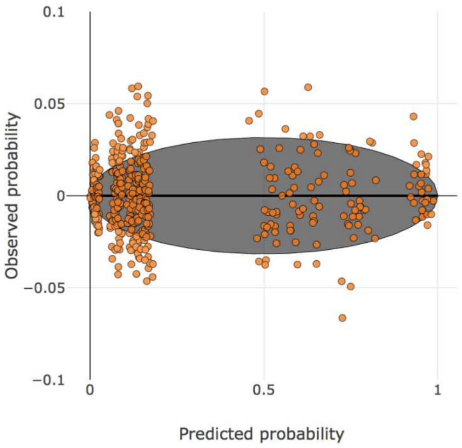


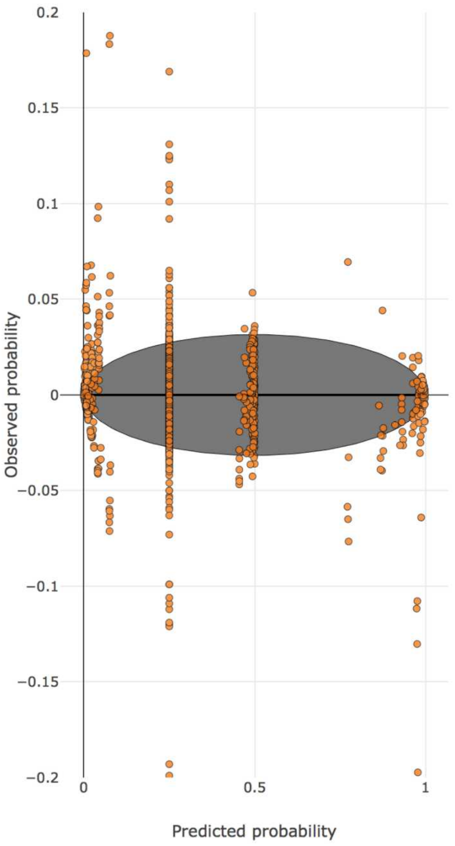


Results

- $N_\sigma = 203$
- $W = 0.027$

2Q processor w/physical noise (cont.)

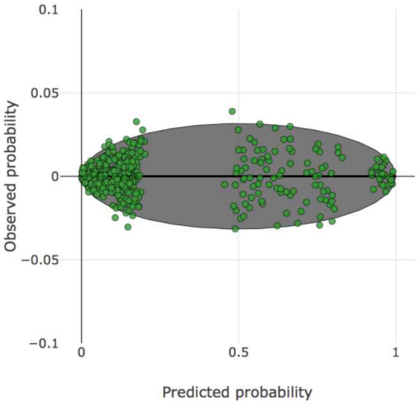


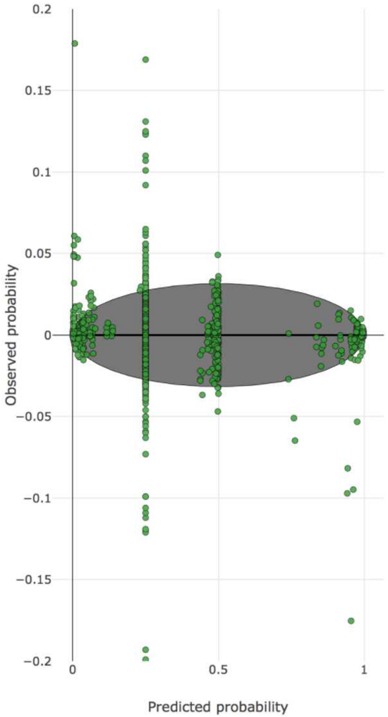


Results

- $N_\sigma = 170$
- $W = 0.019$

2Q processor w/physical noise (cont.)





Results

- $N_{\sigma} = 93$
- $W = 0.023$

None of the models can explain the Rabi-data

1. Call it good enough ☺
2. Expand model

Local coherent & stochastic noise model

2Q processor w/physical noise (cont.)

- Pauli-coherent and stochastic errors

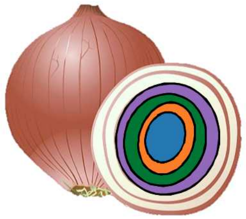
$X\frac{\pi}{2}:0$ | $Y\frac{\pi}{2}:0$ | $X\frac{\pi}{2}:1$ | $Y\frac{\pi}{2}:1$ | $CNOT:0,1$

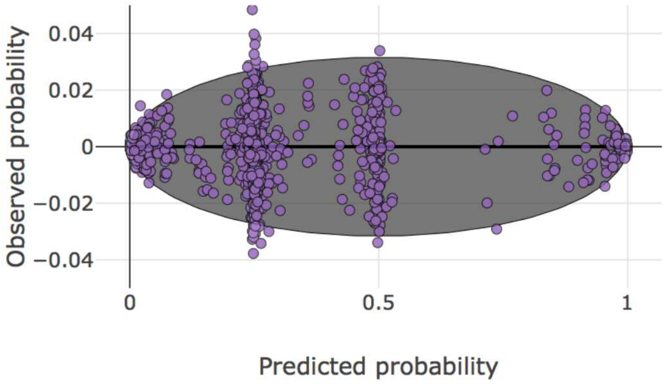
Stochastic $\{p_{P_i}^{X:0}\}_i$ $\{p_{P_i}^{Y:0}\}_i$ $\{p_{P_i}^{X:1}\}_i$ $\{p_{P_i}^{Y:1}\}_i$ $\{p_{Q_i}^{CNOT}\}_i$

Hamiltonian $\{\theta_{P_i}^{X:0}\}_i$ $\{\theta_{P_i}^{Y:0}\}_i$ $\{\theta_{P_i}^{X:1}\}_i$ $\{\theta_{P_i}^{Y:1}\}_i$ $\{\theta_{Q_i}^{CNOT}\}_i$

$(P_i = \{X, Y, Z\})$ $(Q_i = \{IX, IY, \ldots, ZZ\})$

54 gate parameters



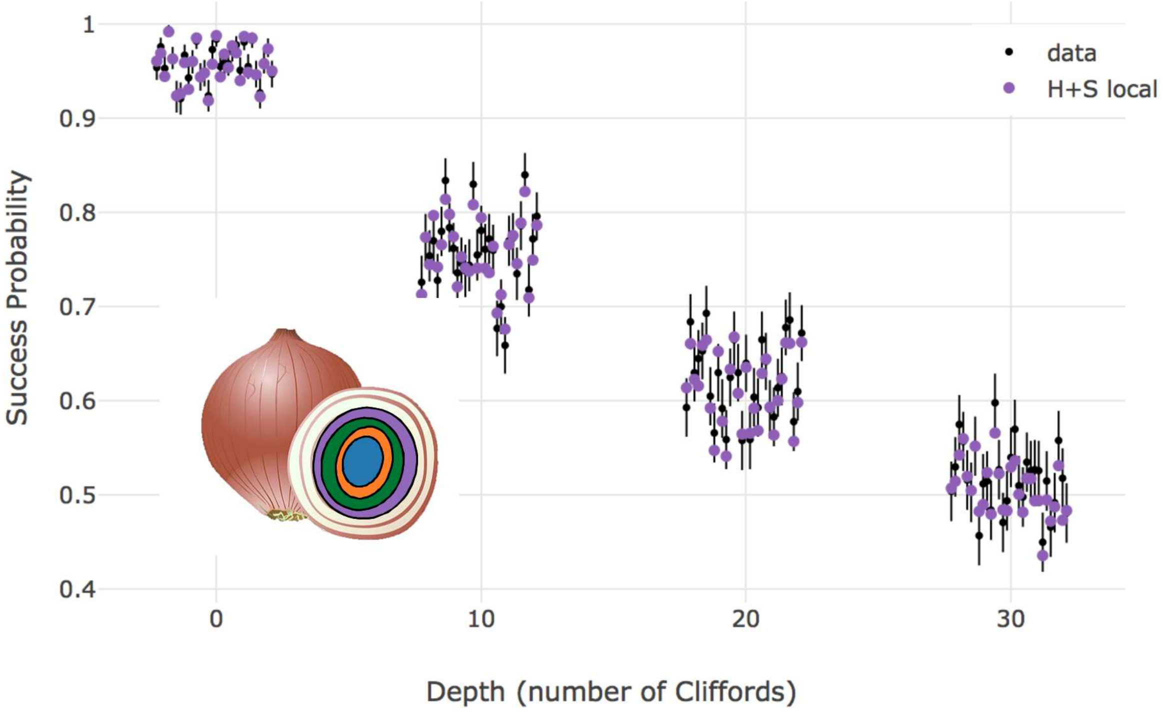


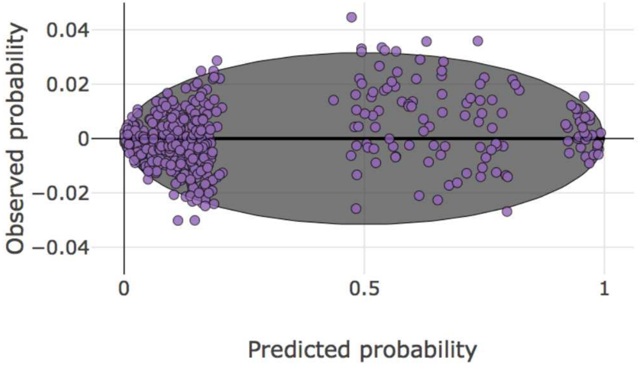
Results

- $N_\sigma = -3$
- $W = 0$

What about RB data, does this model work for random circuits?

2Q processor w/physical noise (cont.)





Results

- $N_\sigma = 5.8$
- $W = 0.0056\%$

Yay! We have a model that explains a set of RB data and Rabi data!

1. Call it good enough ☺ → **STOP**
2. Do a harder test

SCRATCH