SAND2014-18226PE

Gate-set tomography:

calibration-free full characterization of quantum devices using error-amplifying circuits

Robin Blume-Kohout

Sandia National Labs

U.S. DEPARTMENT OF ENERGY

Sandia National Laboratories

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

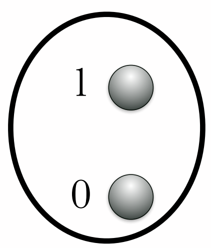
Part 1:
Quantum Information

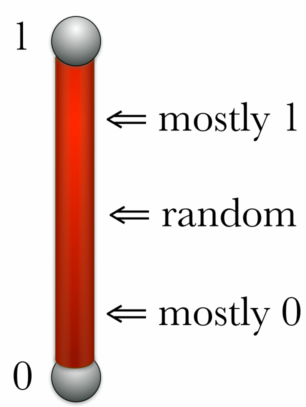
Robin Blume-Kohout

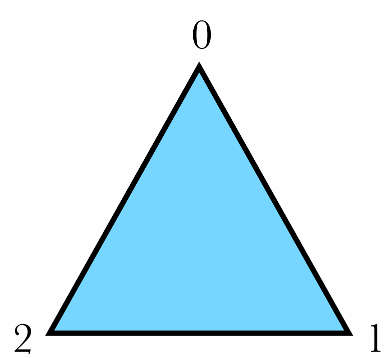
U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

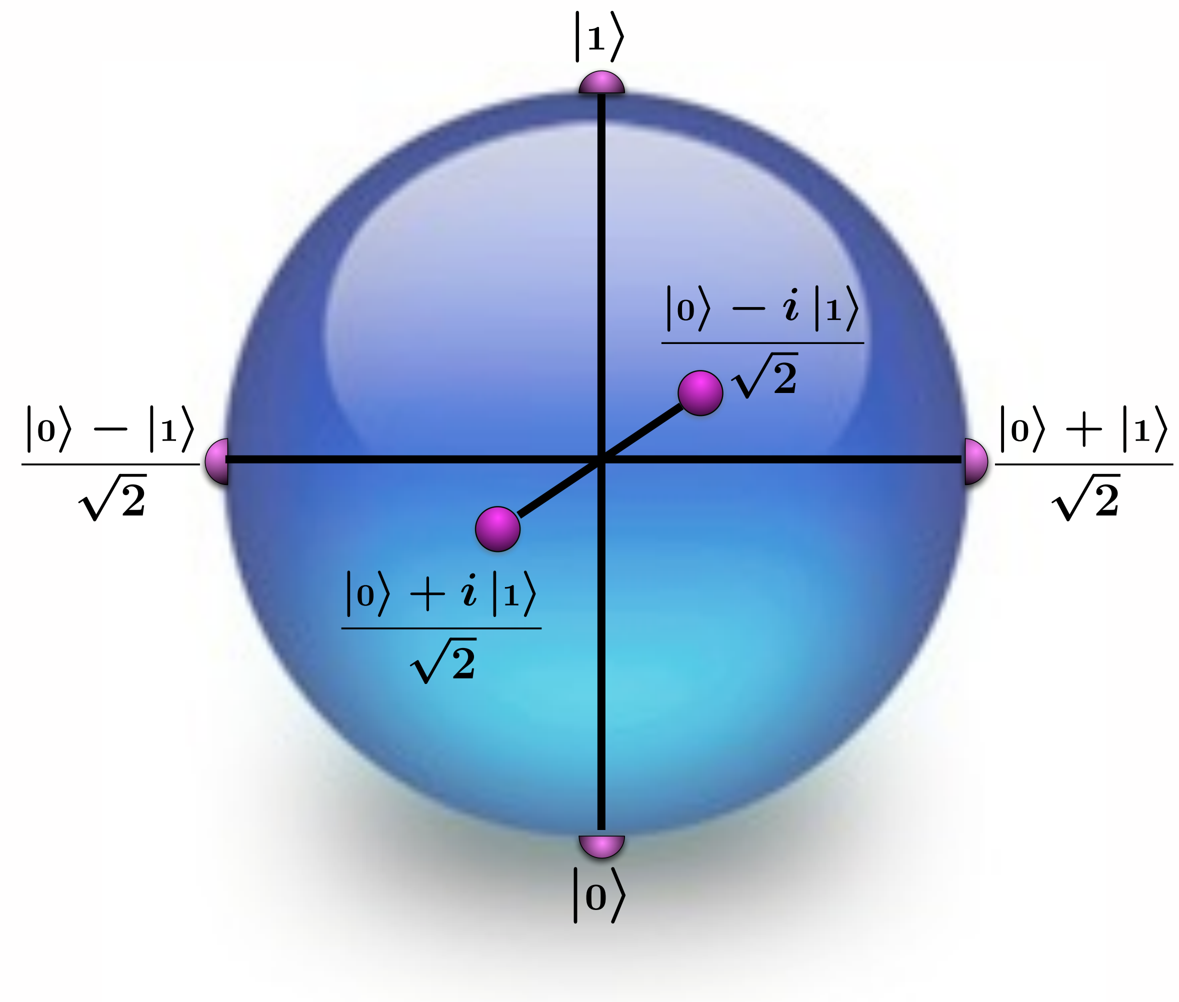
Qubits and Qudits







Quantum Bit & the Bloch Sphere

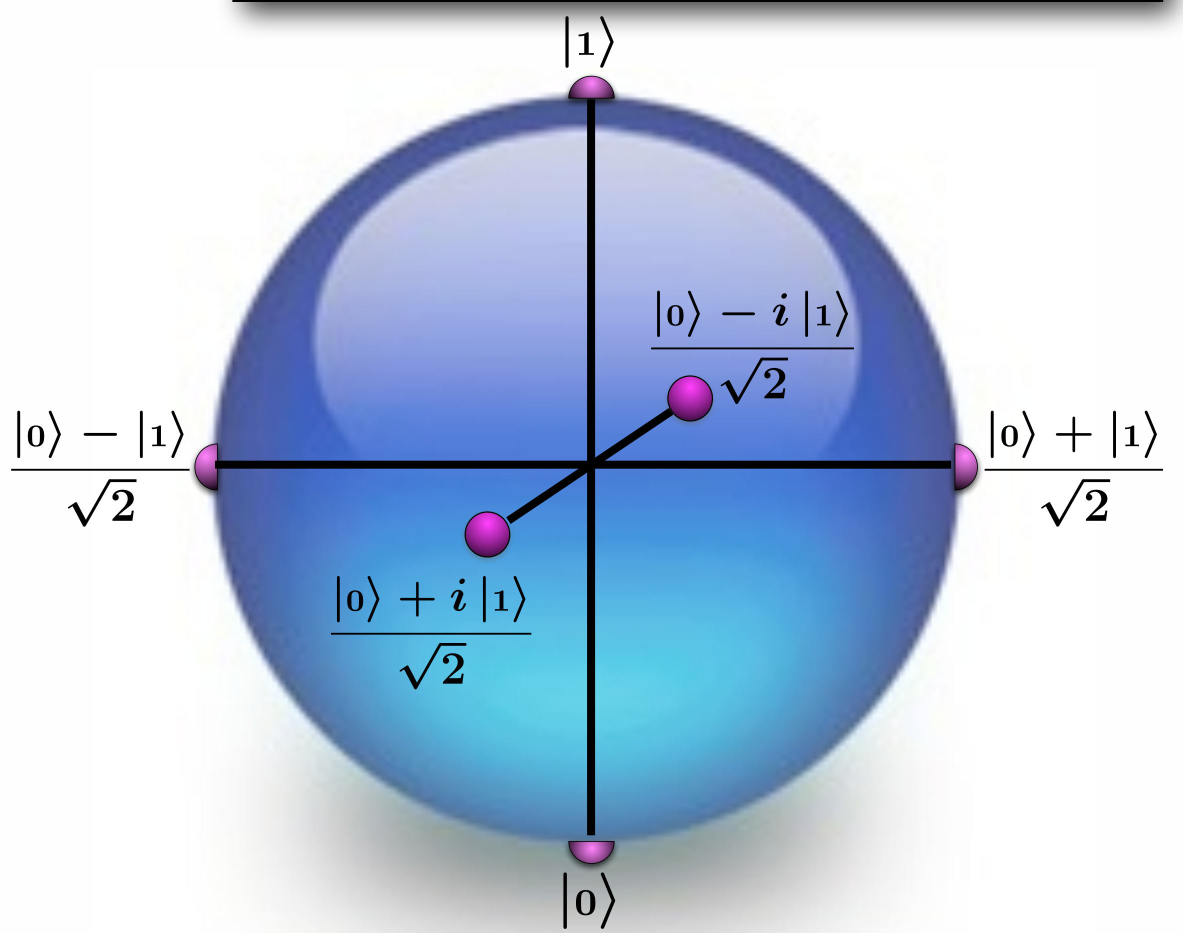


U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

The Bloch Sphere

Pure quantum states (state vectors) are like classical *definite* states -- e.g. "on" or "off" or "0" or "1".

$$|\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle$$
$$= \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$$



Mixed quantum states (density matrices) are like classical probability distributions.

$$\rho = |\psi\rangle\langle\psi| = \vec{\psi}\vec{\psi}^* = \begin{pmatrix} |\alpha|^2 & \alpha\beta^* \\ \alpha^*\beta & |\beta|^2 \end{pmatrix}$$

or

$$\rho = p_1|\psi_1\rangle\langle\psi_1| + p_2|\psi_2\rangle\langle\psi_2| \ldots$$

so

$$\rho = \tfrac{1}{2}\mathbb{1} + x\mathbf{X} + y\mathbf{Y} + z\mathbf{Z}$$

$$|\rho\rangle\rangle = \begin{pmatrix} 1/2 \\ x \\ y \\ z \end{pmatrix}$$

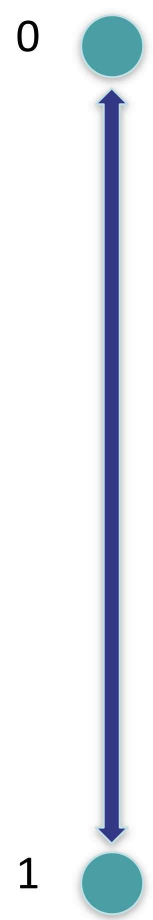
U.S. DEPARTMENT OF ENERGY

Sandia National Laboratories

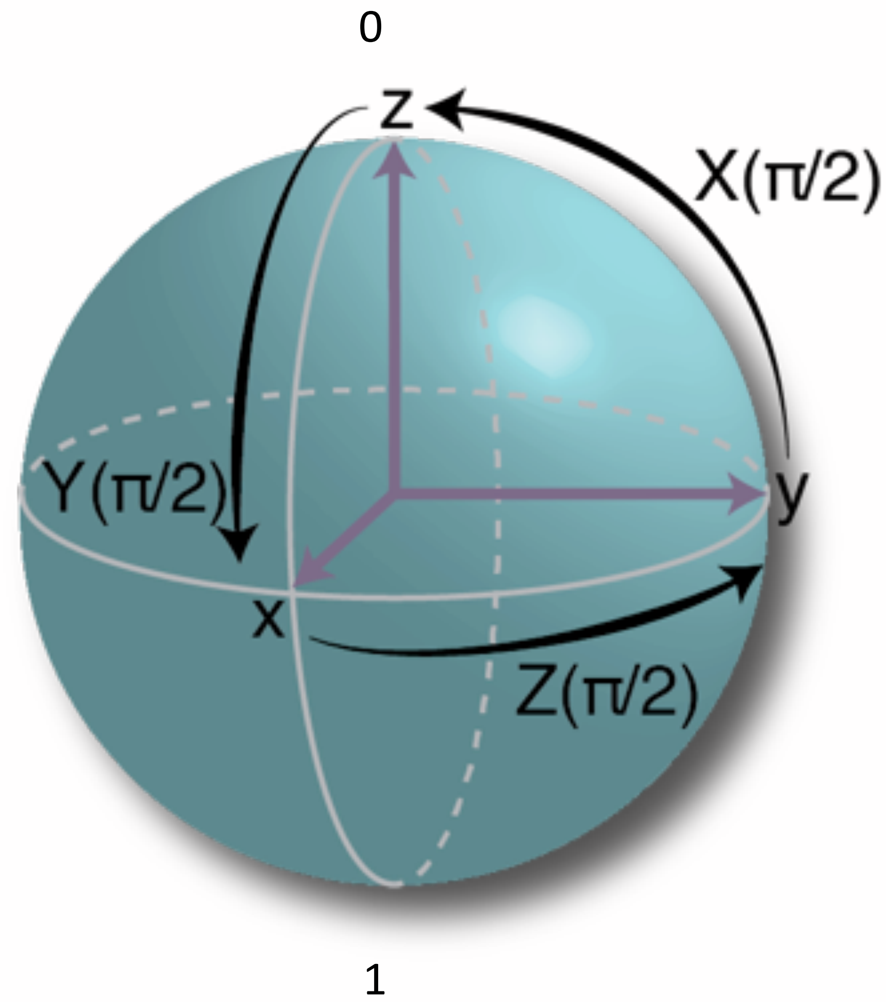
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Quantum Logic Gates

classical
logic gates



quantum
logic gates



Ideal logic gate
=
Unitary matrix

$$\mathbf{U} = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$$

$$|\psi\rangle \rightarrow \mathbf{U}\,|\psi\rangle$$

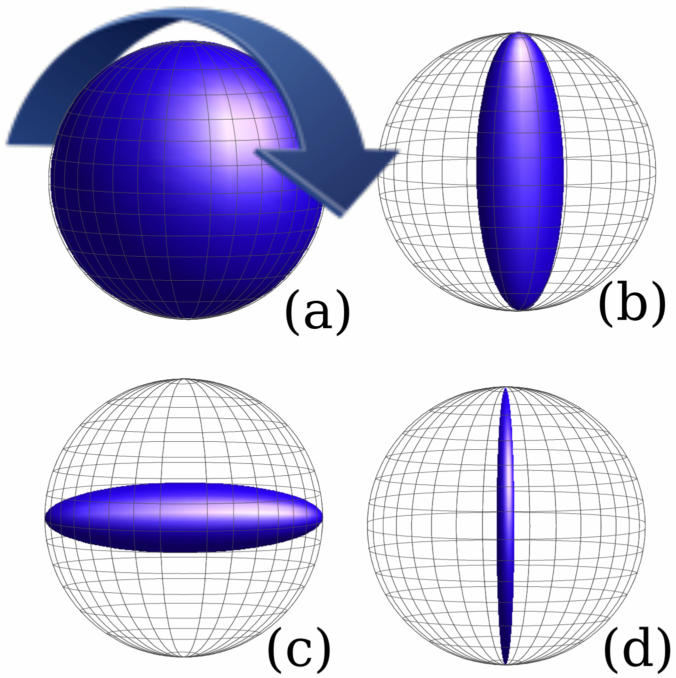
$$\rho \rightarrow \mathbf{U}\rho\mathbf{U}^\dagger$$

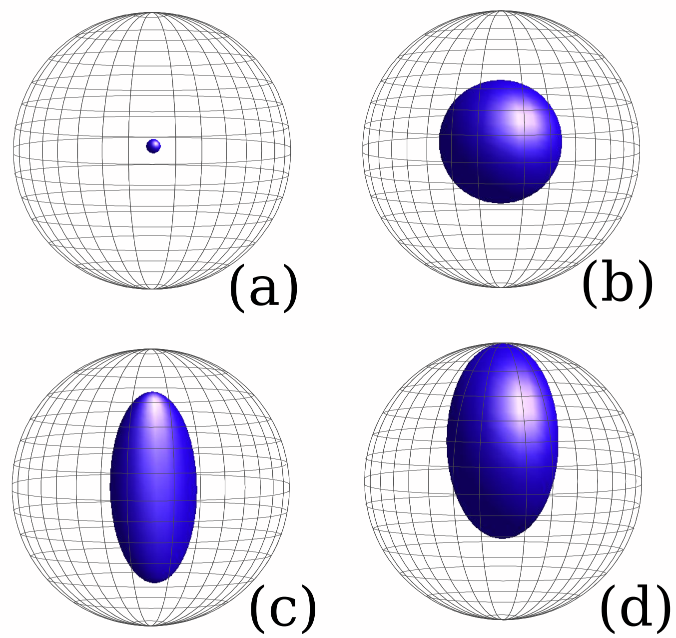
$$|\rho\rangle\rangle \rightarrow \mathcal{U}\,|\rho\rangle\rangle$$

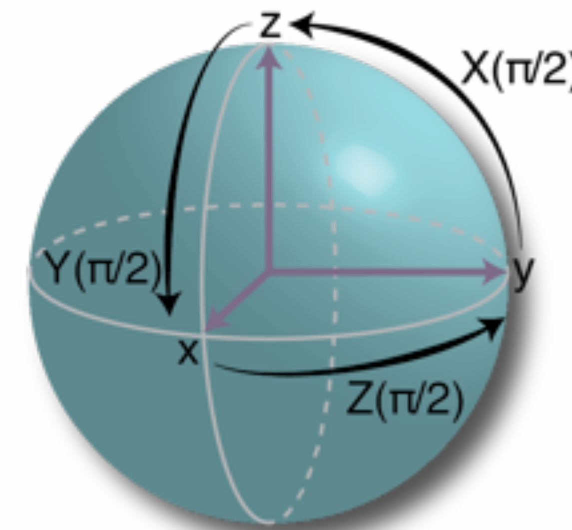
$$= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & x & x & x \\ 0 & x & x & x \\ 0 & x & x & x \end{pmatrix} \begin{pmatrix} 1/2 \\ x \\ y \\ z \end{pmatrix}$$

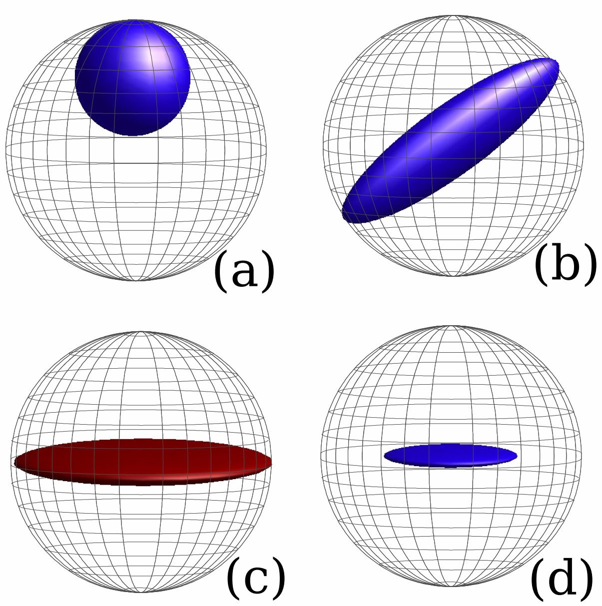
U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Noisy Quantum Operations









$$|\rho\rangle\rangle \rightarrow \mathbf{G}\,|\rho\rangle\rangle$$

$$\mathbf{G} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ x & x & x & x \\ x & x & x & x \\ x & x & x & x \end{pmatrix}$$

Trace-changing block

Non-unital (affine) block

Unital block

U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Measurements & Born's Rule

- States exist solely to predict outcomes of observations.
- Measurements (observations) are sets of possible *events*.

$$\mathcal{M} = \{E_k : k = 1 \ldots K\}$$

Simple ("pure" measurement)

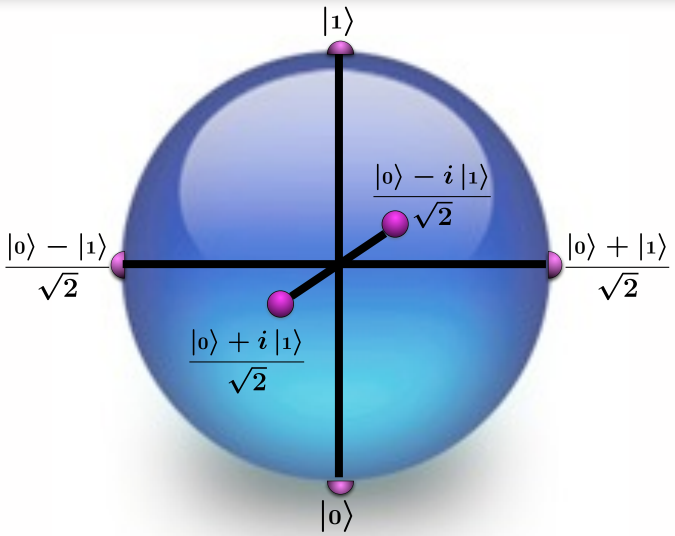
$$\mathcal{M} = \{\langle\phi_1|, \langle\phi_2| \ldots\}$$
$$Pr(k|\psi) = |\langle\phi_k|\psi\rangle|^2$$
$$= \mathrm{Tr}\big(|\phi_k\rangle\langle\phi_k||\psi\rangle\langle\psi|\big)$$

General ("POVM" measurement)

$$\mathcal{M} = \{E_1, E_2 \ldots E_K\}$$
$$Pr(k|\rho) = \mathrm{Tr}\big(E_k\rho\big)$$
$$= \langle\!\langle E_k|\rho\rangle\!\rangle$$

Probability for a *general* experiment:

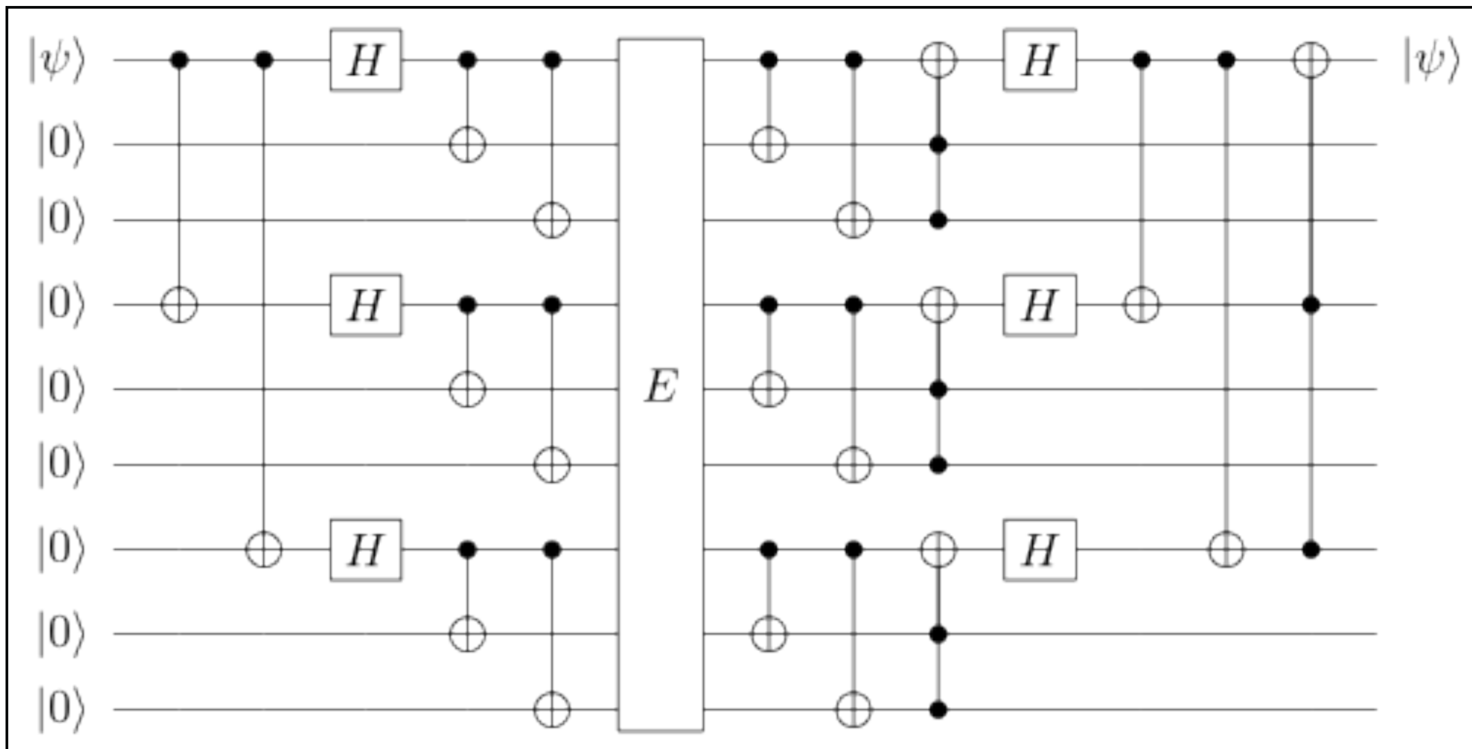
$$Pr(\text{success}) = \langle\!\langle E_{\text{success}}|\, G_{\text{stuff}}\, |\rho\rangle\!\rangle$$



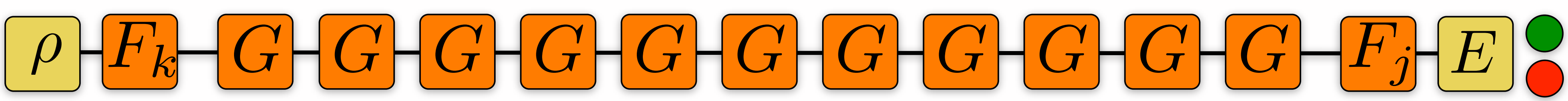
U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Quantum Circuits

- Quantum logic experiment on qubits = *quantum circuit.*



- Circuit on 1 qubit = *gate sequence*



$$Pr(\bullet) = \langle\langle E|\, F_j \; G^{11} \; F_k \,|\rho\rangle\rangle$$

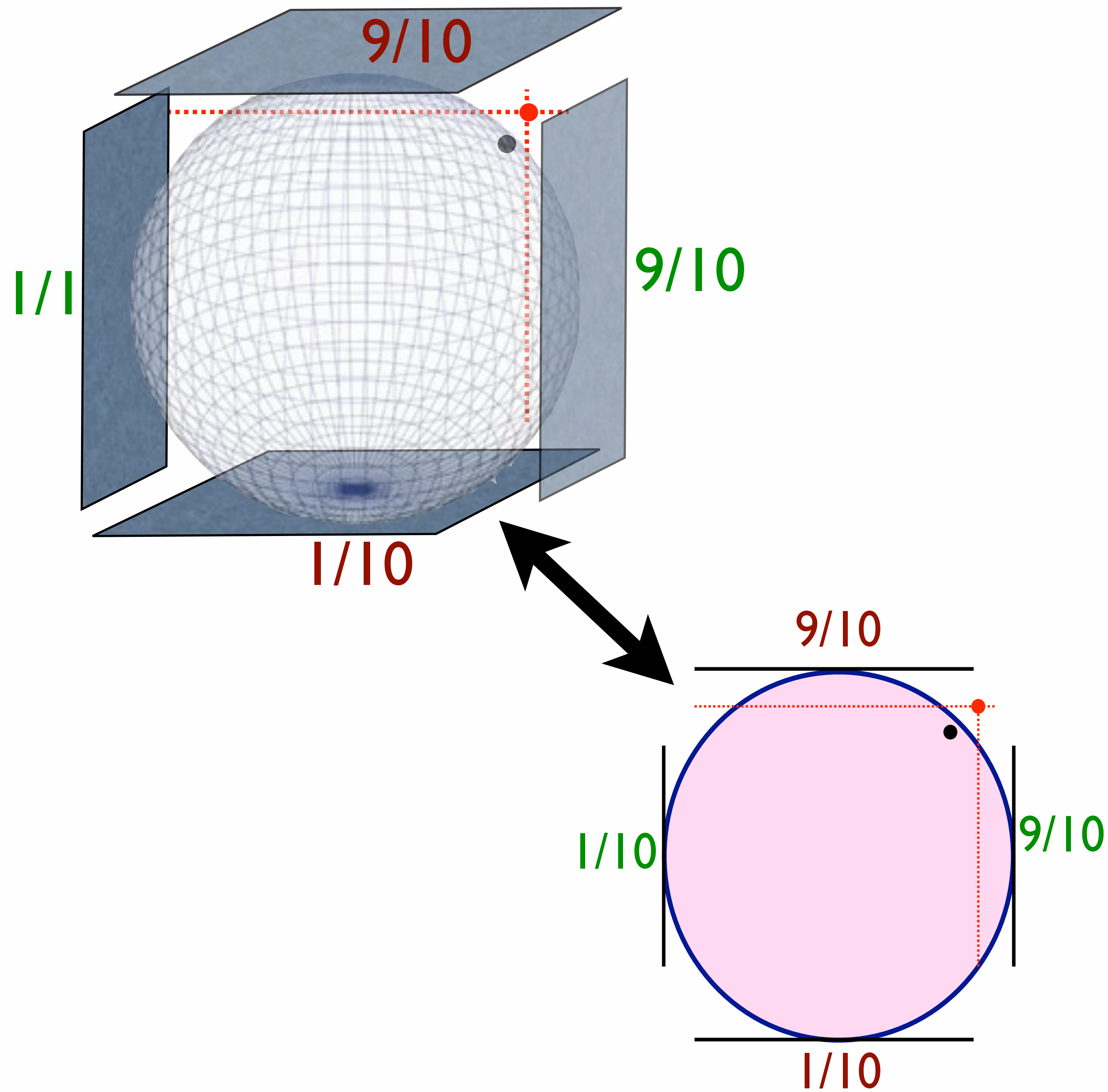
U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Part 2:
Quantum Statistical Inference
(okay, *tomography*)

Robin Blume-Kohout

U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

State Tomography



Goal: determine (estimate) a quantum state that can be parameterized like this:

$$\rho = \tfrac{1}{2}\mathbb{1} + x\mathbf{X} + y\mathbf{Y} + z\mathbf{Z}$$

$$|\rho\rangle\rangle = \tfrac{1}{2}|\mathbb{1}\rangle\rangle + x|\mathbf{X}\rangle\rangle + y|\mathbf{Y}\rangle\rangle + z|\mathbf{Z}\rangle\rangle$$

Sol'n: estimate each of the parameters by estimating observable probabilities:

$$z = \langle\langle \mathbf{Z}|\rho\rangle\rangle$$

$$= \langle\langle |0\rangle\langle 0| |\rho\rangle\rangle - \langle\langle |1\rangle\langle 1| |\rho\rangle\rangle$$

SO

$$z = Pr(0|\rho) - Pr(1|\rho)$$

...etc, etc, for y and z.

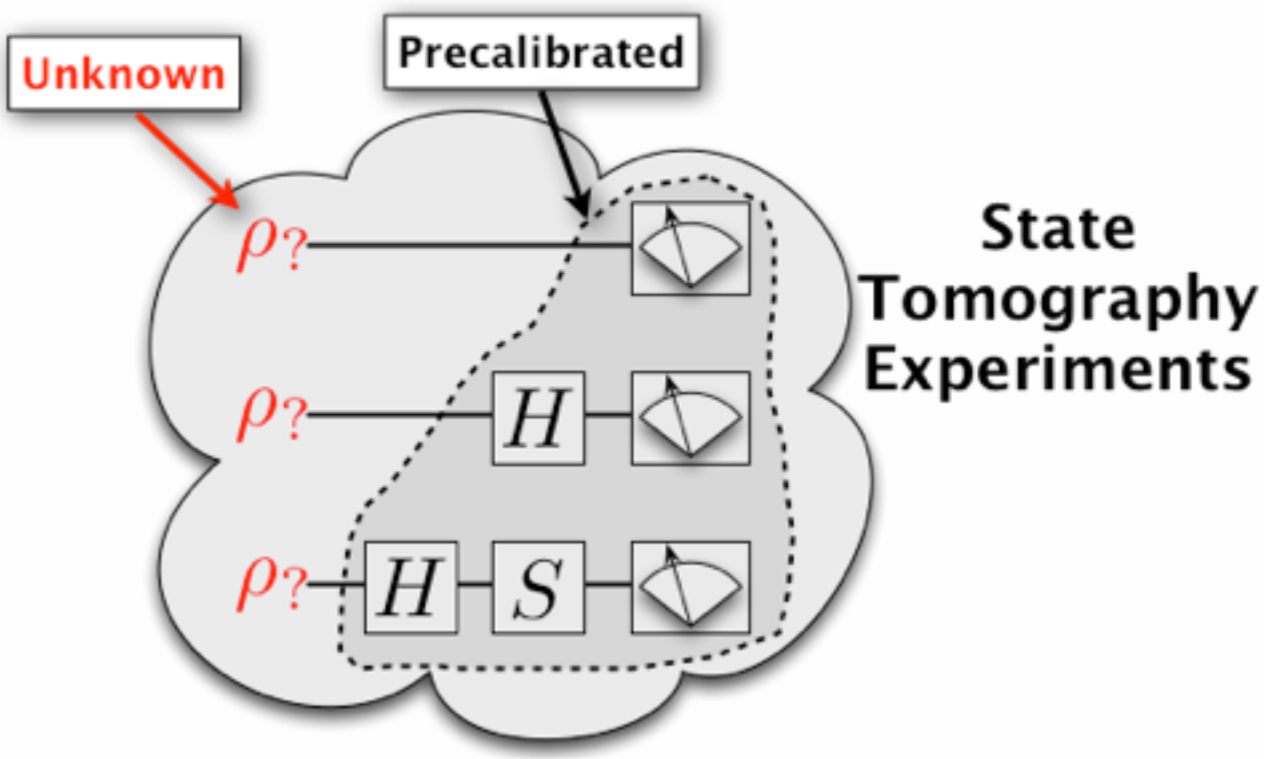
(and many more if the system is bigger than a single qubit...)

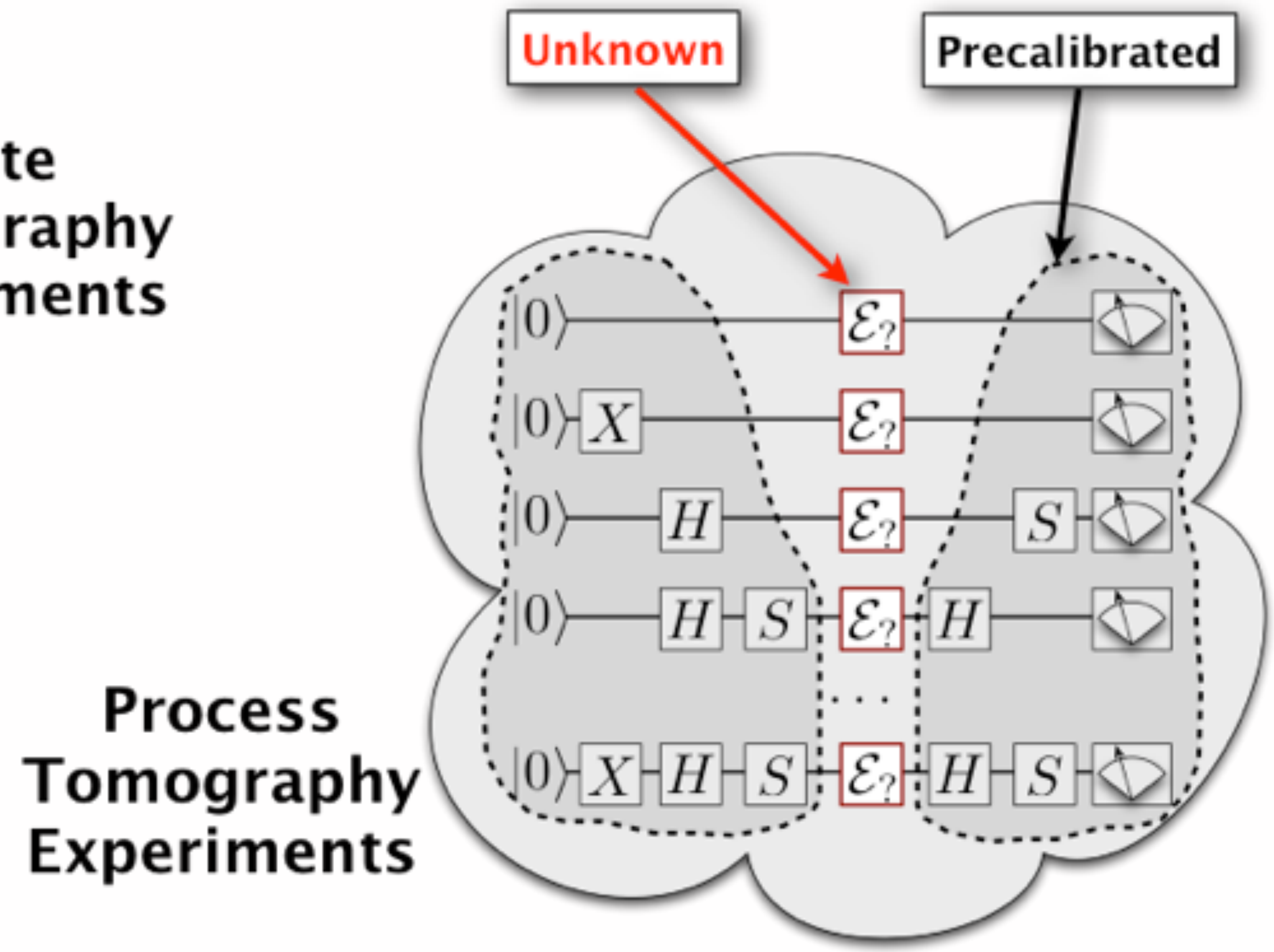
U.S. DEPARTMENT OF ENERGY Sandia National Laboratories

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Process Tomography

- Quantum processes (a.k.a. operations or logic gates) can be characterized in a very similar way to states.

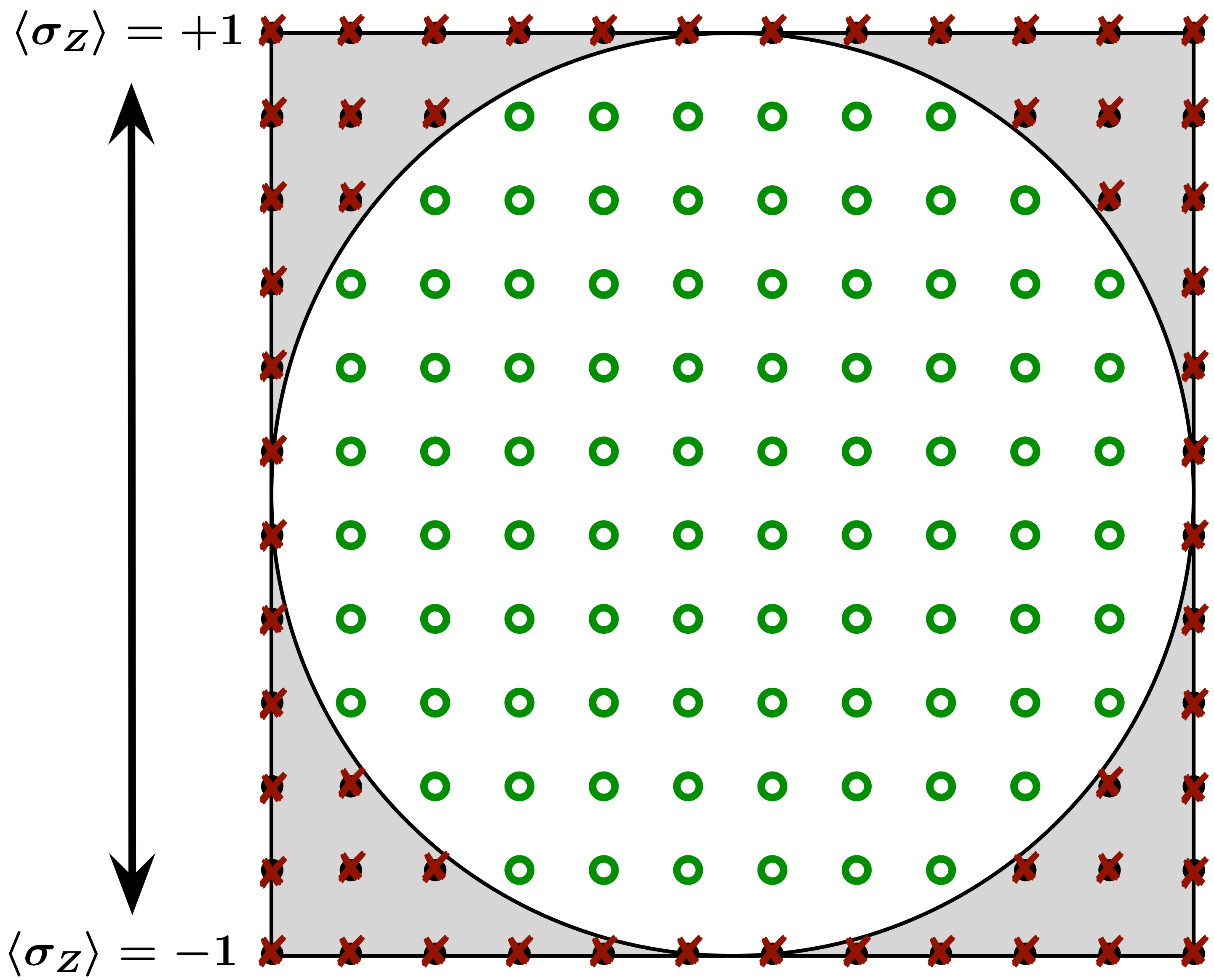


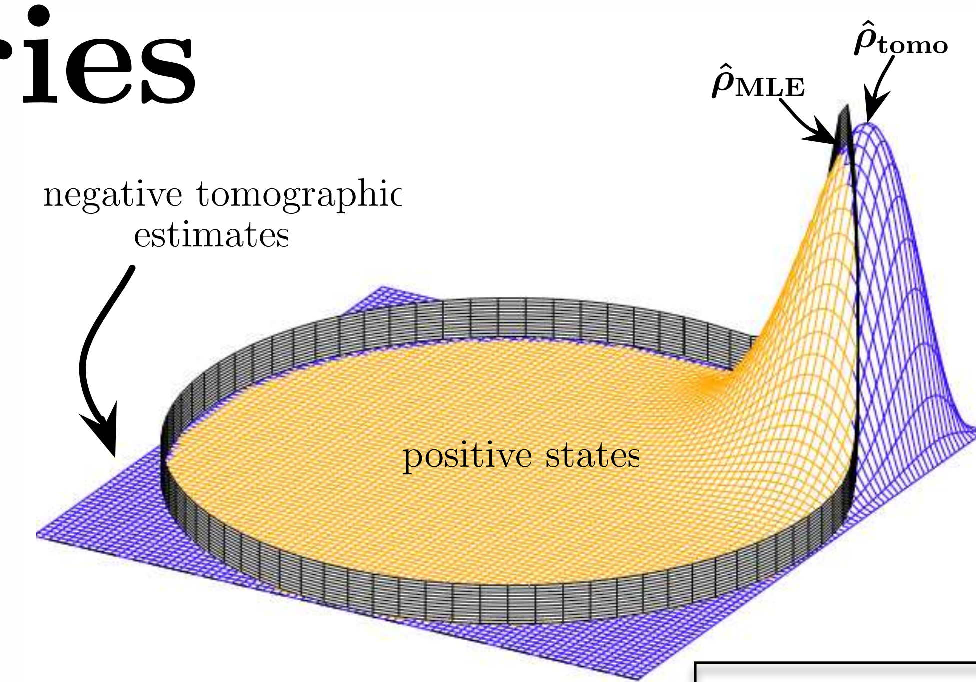


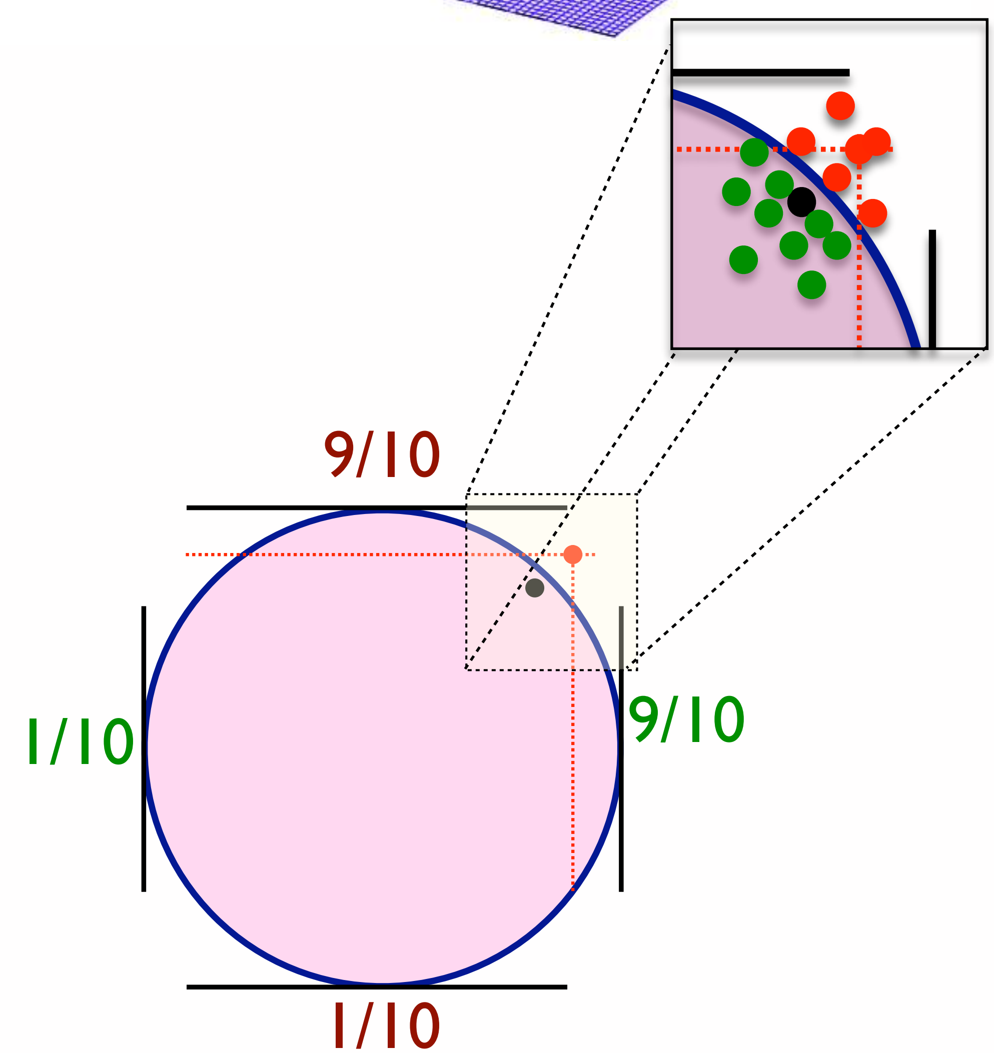
U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Why quantum is different: Boundaries



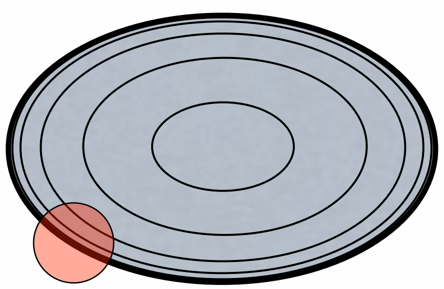


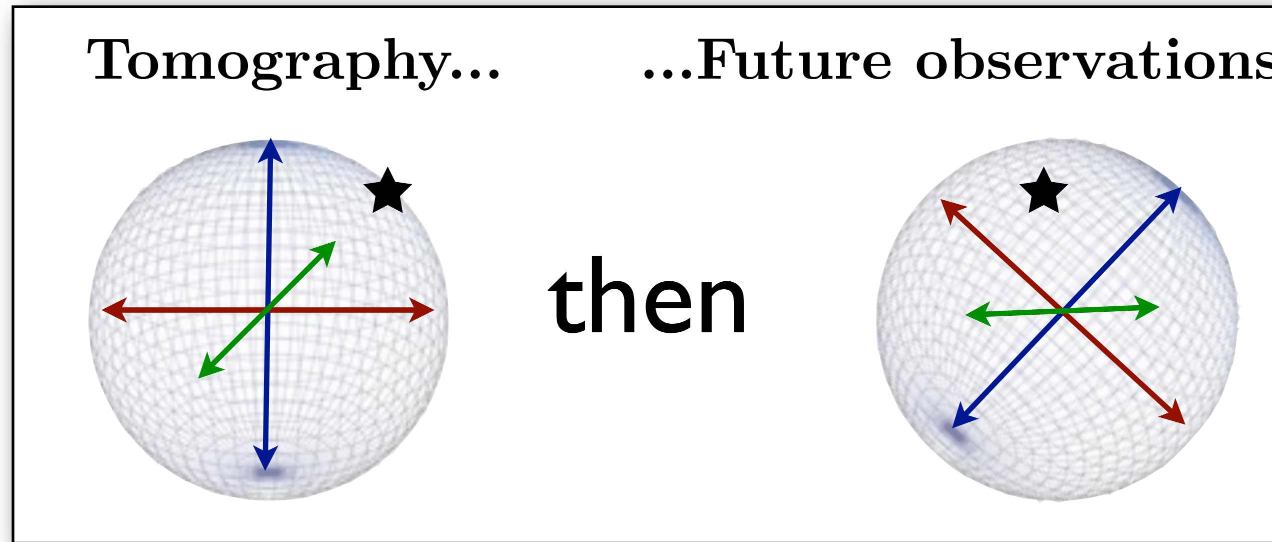


U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

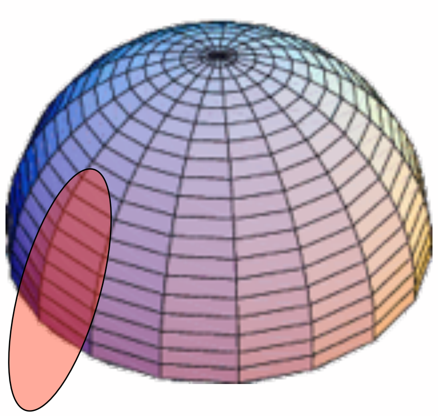
Why quantum is different: Choice of measurements

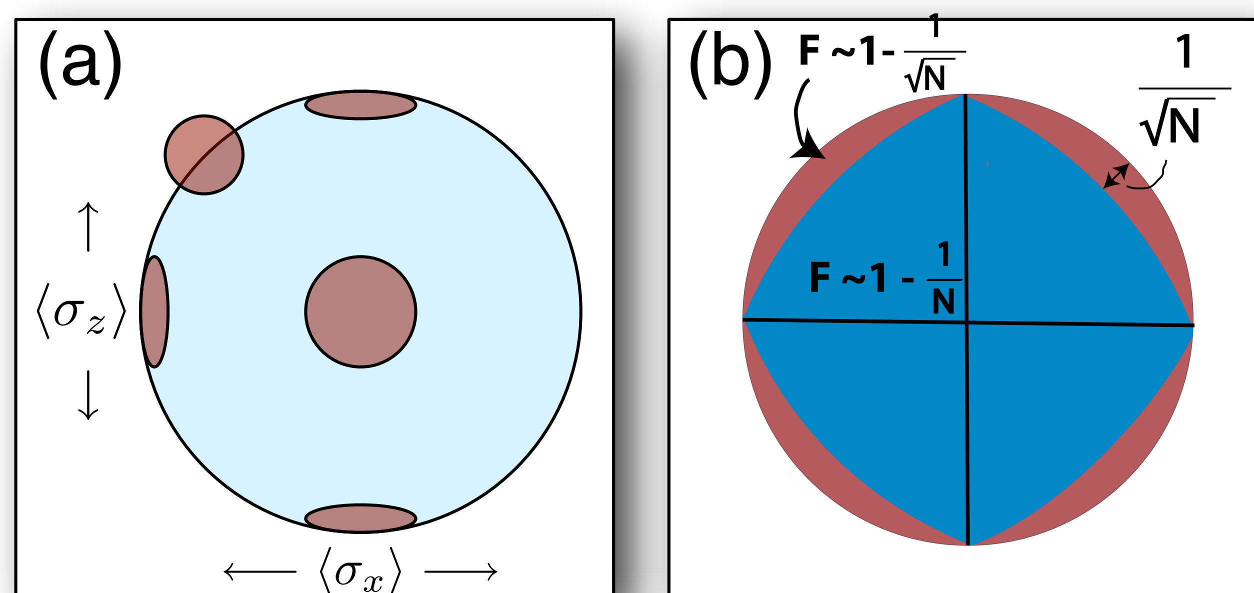
Bloch Sphere Geometry





Fisher Metric Geometry



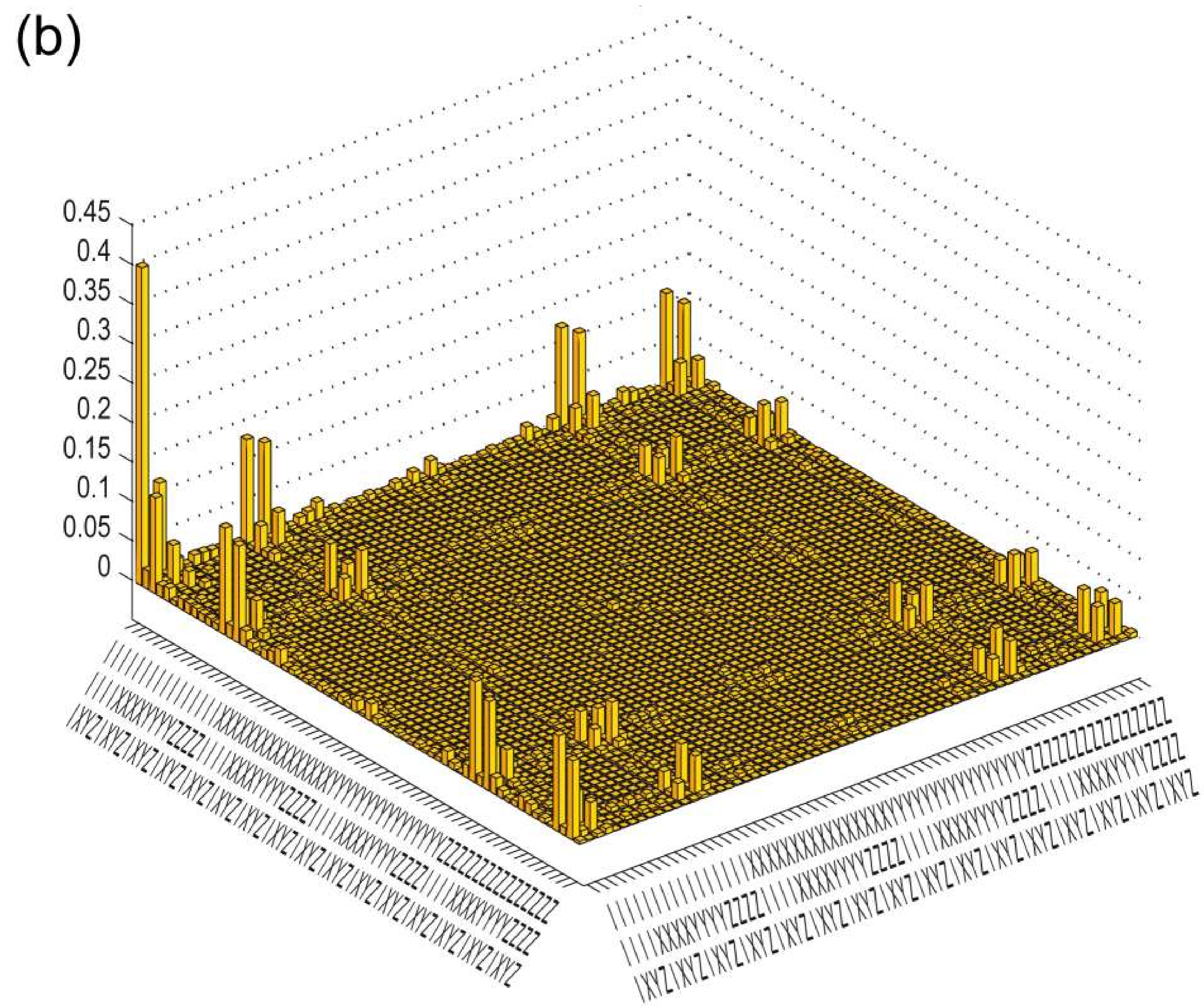


U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Why quantum is different: Parameter overload!

Process tomography is the same for larger systems -- but requires O(d^4) different settings (16^N for N qubits!)

- The plot shows results of a 3-qubit (Toffoli gate) process tomography experiment (Innsbruck).
- 64 x 64 matrices have a lot of numbers in them! -- and each number corresponds to a different experimental configuration.
- Process tomography gets impractical *very* fast as N increases.



U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Why <u>gates</u> are *not* like <u>states</u>

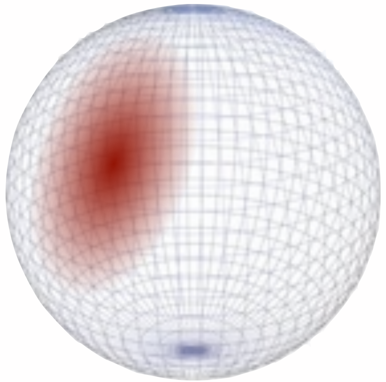
- There is a famous theorem in QI called the *Choi-Jamiolkowski isomorphism*:

$$\rho_J \equiv \left(\mathbf{G}_S \otimes 1\!\!1_A\right)\Big[|\Psi\rangle\langle\Psi|\Big]$$

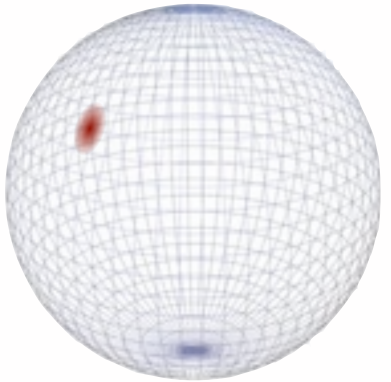
$$\text{where } |\Psi\rangle = d^{-1/2}\textstyle\sum_k |kk\rangle$$

- If you think this means that *gates* are isomorphic to *states*, then you are missing something very important:

  Gates can be repeated <u>sequentially</u>.



- If you realize this, then you can characterize a gate with much higher precision (1/N) than the corresponding Jamiolkowski state $(1/\sqrt{N})$.



U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

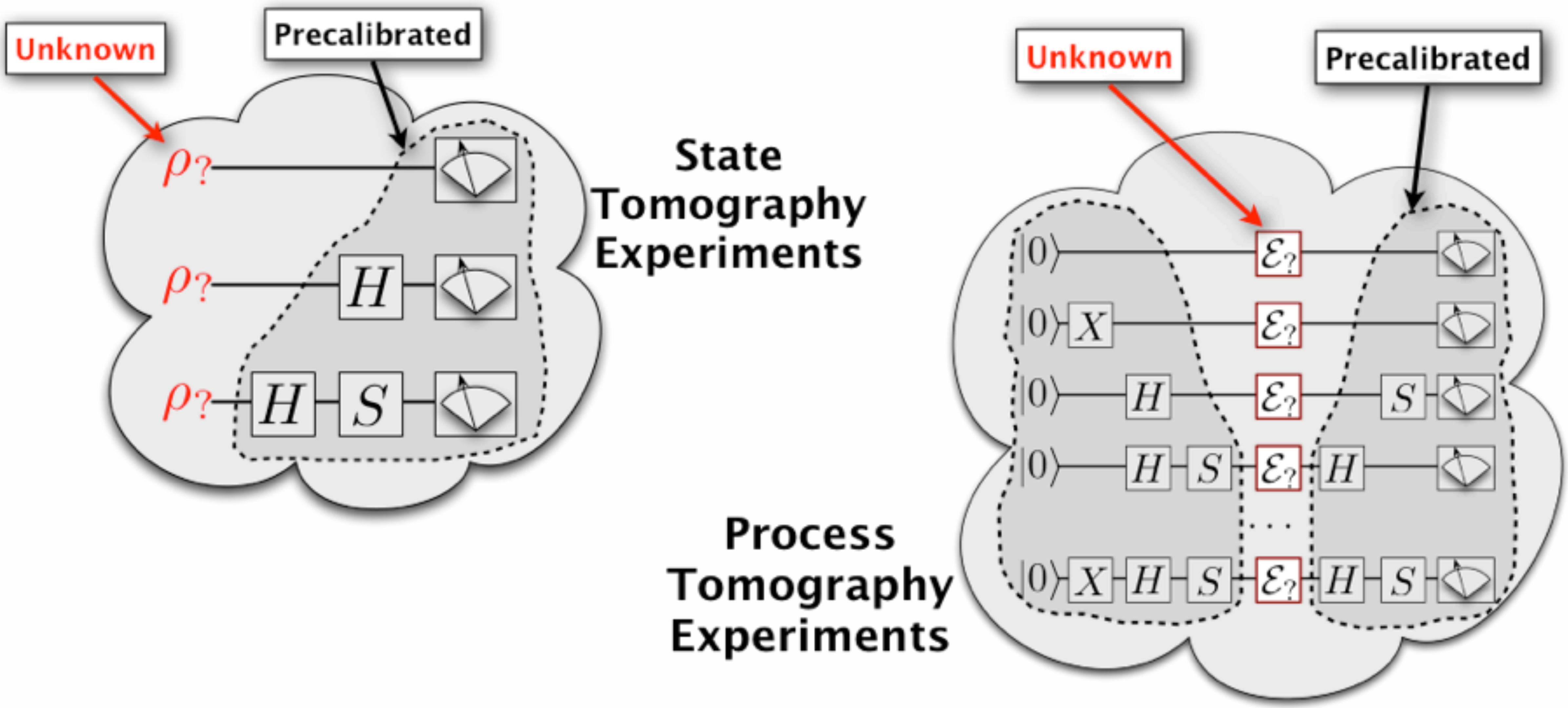
Part 3:
Gate-set Tomography

Robin Blume-Kohout

U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

The problem with tomography



Standard tomography relies on precalibrated gates…

…but we don't have any of those in real hardware!

U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories

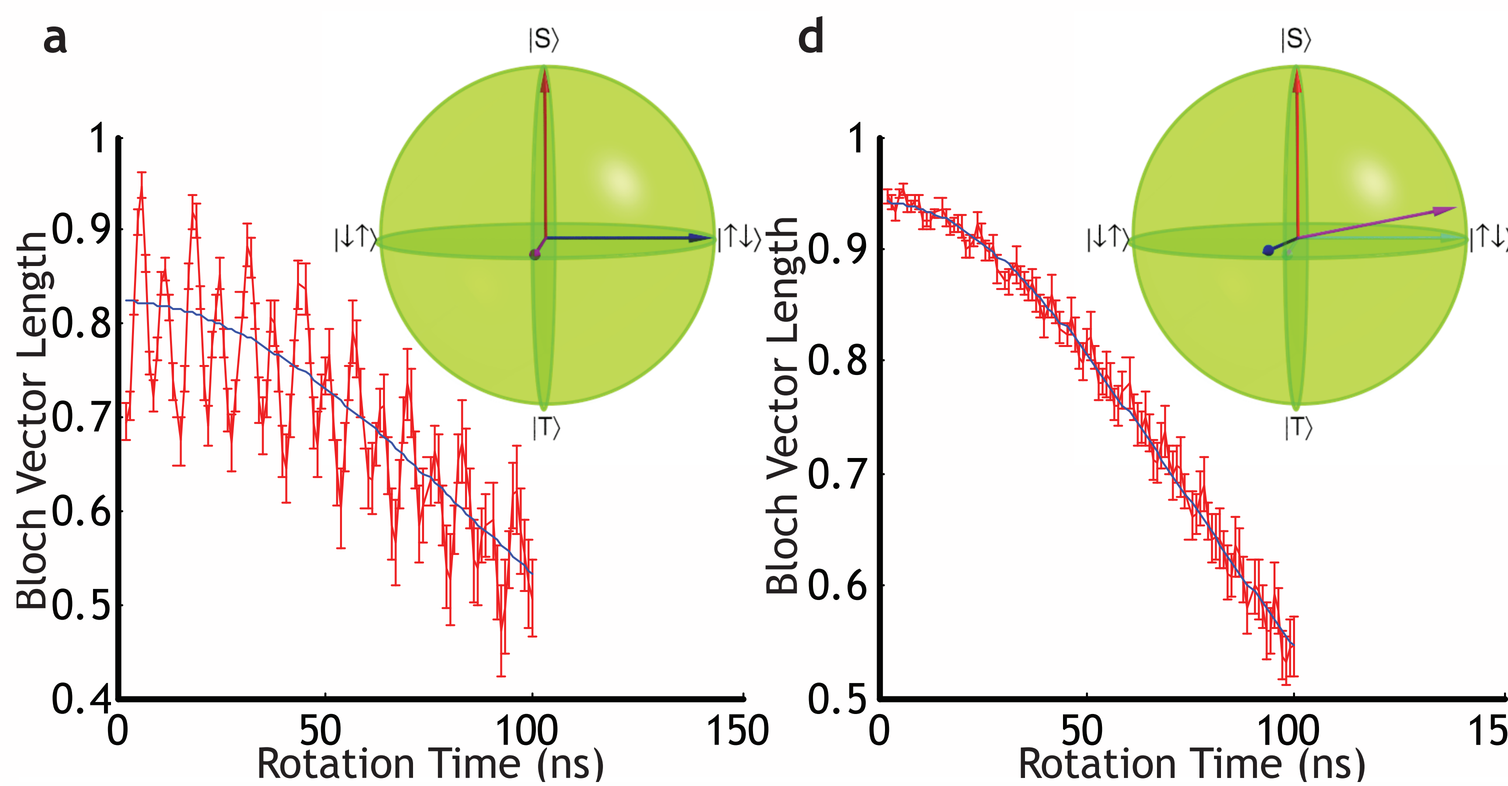
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

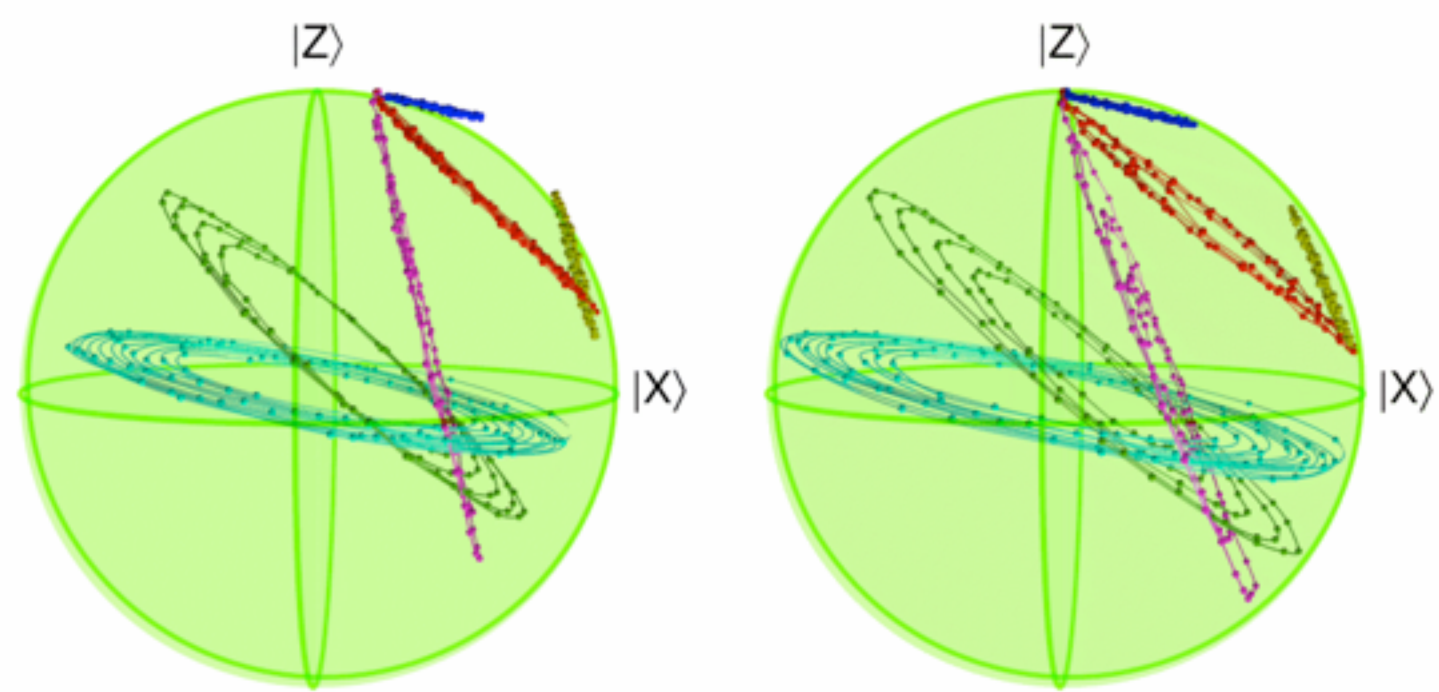
Consequences of bad calibration

1) Estimated purity (length of Bloch vector) oscillates in a very non-Markovian way.

2) The tomographic estimate of the state is consistently outside of the Bloch sphere.

What went wrong? X and Y measurements are not native. They were implemented by *gates* that are not perfectly calibrated!





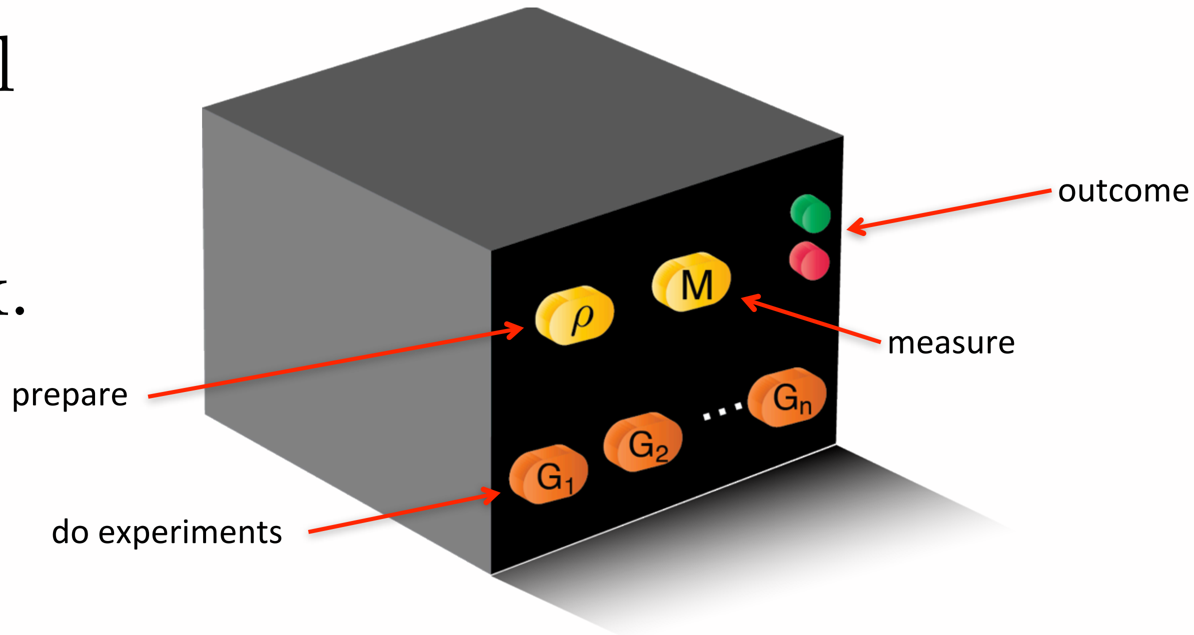
Figures and results courtesy of Oliver Dial:
M.D. Shulman *et al*, **Science** 336, 202-205 (2012)

U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

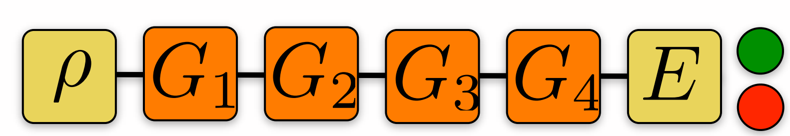
Gate sets

- A *gate set* is a complete statistical <u>model</u> for a quantum device (e.g. qubit) treated as a black box.

$$\left\{ \langle\langle E|,\ |\rho\rangle\rangle,\ G_1 \ldots G_N \right\}$$



- The gate set framework explicitly rules out "external" reference frames -- the only way to interact with the quantum device is by pushing buttons and reading L.E.D.s.



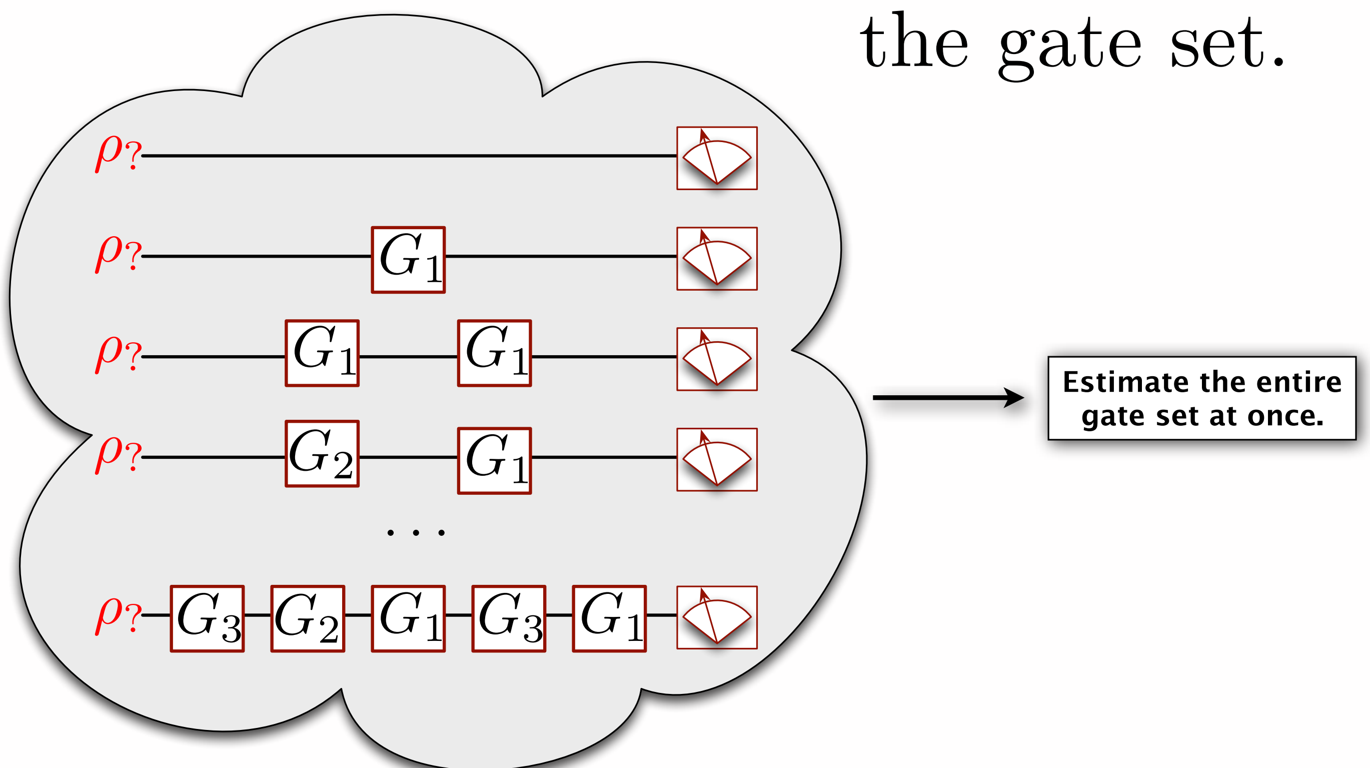
Everything we can "measure" is a probability of this form:

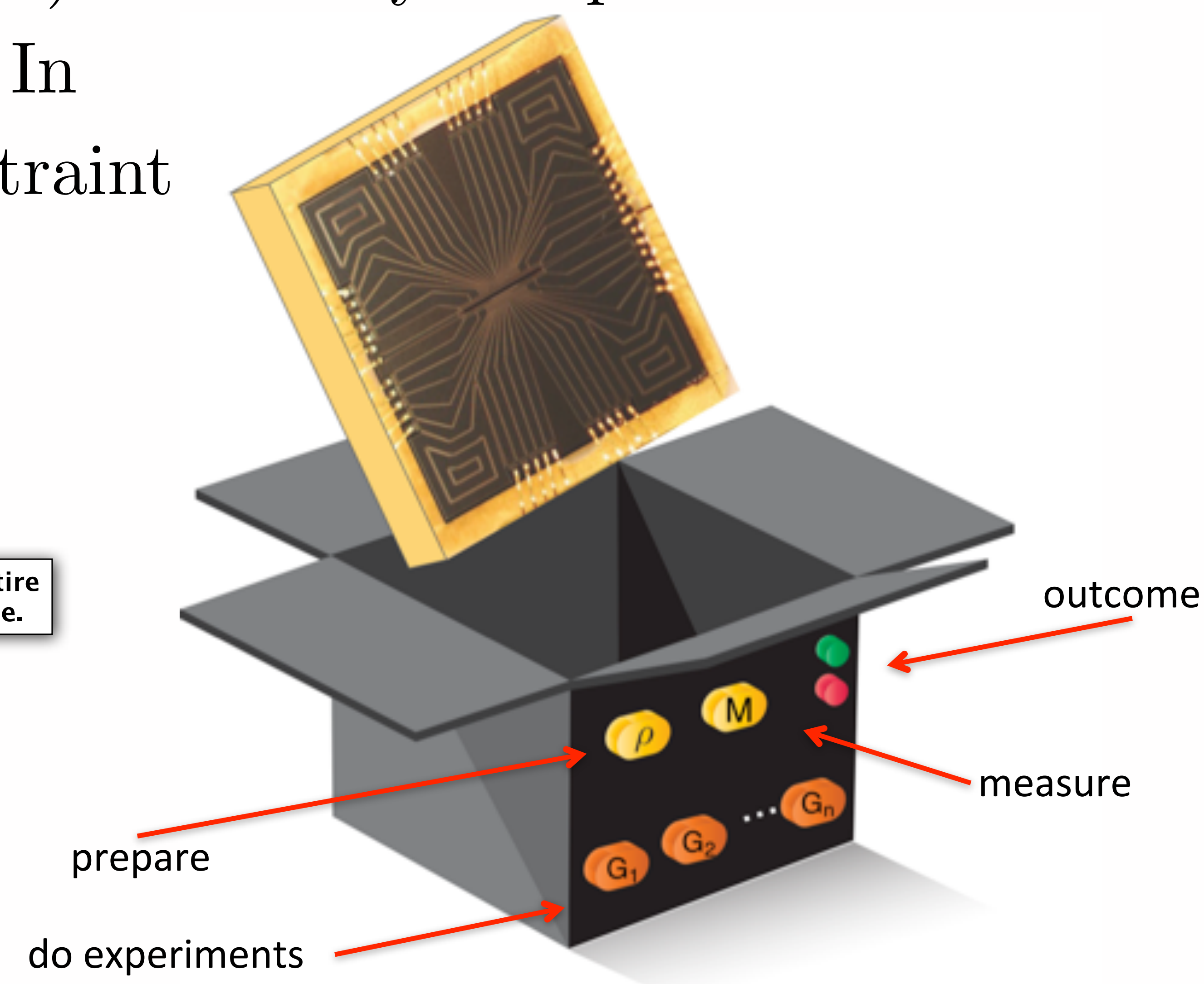
$$p(\bullet) = \langle\langle E|G_{s_1} \ldots G_{s_L}|\rho\rangle\rangle$$

U.S. DEPARTMENT OF ENERGY Sandia National Laboratories
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Principles of GST

- A set of m gates has a few parameters (for 1 qubit, $16m+8$).
- So we just measure (estimate) that many independent experimental probabilities. In *principal*, those should constraint the gate set.





U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

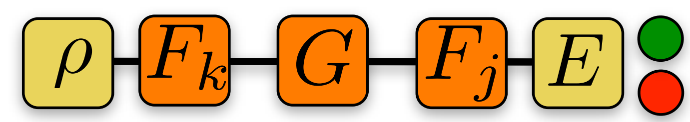
Linear GST

(1) Choose a set of *fiducial sequences:*

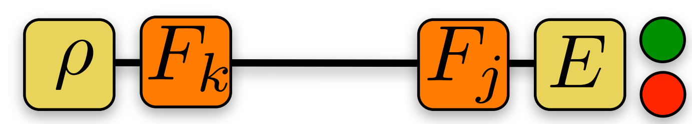
$$\{F_1, F_2, F_3, F_4\} \overset{\text{e.g.}}{=} \{G_1, G_2, G_3, G_2^2\}$$

(2) Do "tomography" by measuring:

$$(\tilde{G}_i)_{j,k} = \langle\langle E|\, F_j\, G_i\, F_k\, |\rho\rangle\rangle$$



and $\tilde{1\!\!1}_{j,k} = \langle\langle E|\, F_j\, F_k\, |\rho\rangle\rangle$



(3) Use linear algebra to get the estimate:

$$\hat{G}_i = \tilde{1\!\!1}^{-1}\tilde{G}_i, \text{ etc.} \iff \hat{G}_i = B^{-1}G_iB,\ \langle\langle\hat{E}| = \langle\langle E|B,\ |\hat{\rho}\rangle\rangle = B^{-1}|\rho\rangle\rangle$$

(4) Transform the estimated gateset by a *gauge transformation* to make it as close as possible to the desired target gateset:

$$\hat{G}_i \to S^{-1}\hat{G}_iS \text{ and } \langle\langle\hat{E}| \to \langle\langle\hat{E}|S \text{ and } |\hat{\rho}\rangle\rangle \to S^{-1}|\hat{\rho}\rangle\rangle$$

U.S. DEPARTMENT OF ENERGY Sandia National Laboratories

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

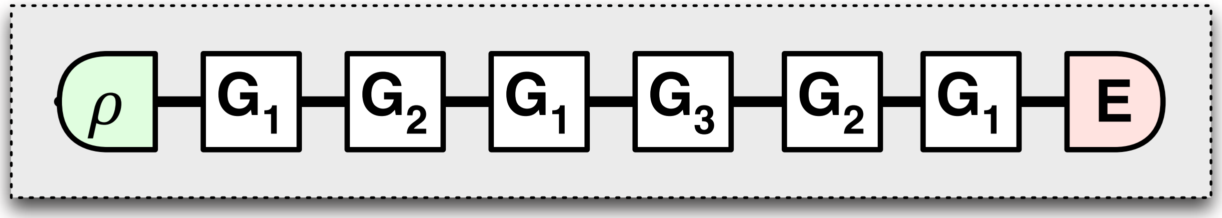
The Gauge

- Let T be invertible.
  Transform the gateset:

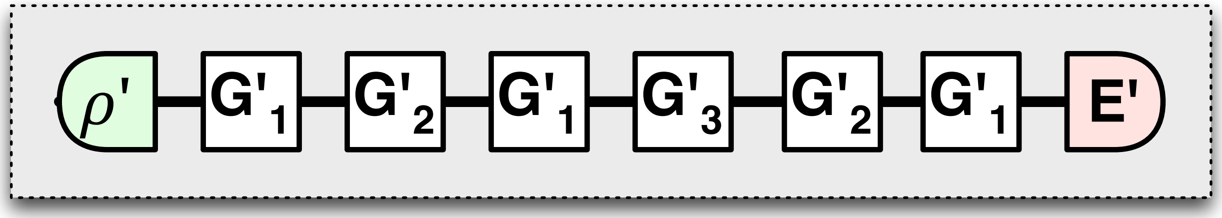
$$\langle\langle E'| = \langle\langle E| T$$

$$|\rho'\rangle\rangle = T^{-1} |\rho\rangle\rangle$$

$$G'_k = T^{-1} G_k T$$



$$P(E) = \langle\langle E| G_1 \ldots G_1 |\rho\rangle\rangle$$



$$\begin{aligned} P(E') &= \langle\langle E'| G'_1 \ldots G'_1 |\rho'\rangle\rangle \\ &= \langle\langle E| T T^{-1} G_1 T T^{-1} \ldots T T^{-1} G_1 T T^{-1} |\rho\rangle\rangle \\ &= P(E) \end{aligned}$$

- *All* observable probabilities are left unchanged!

  => $\{\boldsymbol{G_k}\}$ and $\{\boldsymbol{G'_k}\}$ are different *descriptions* of exactly the *same* physical device.

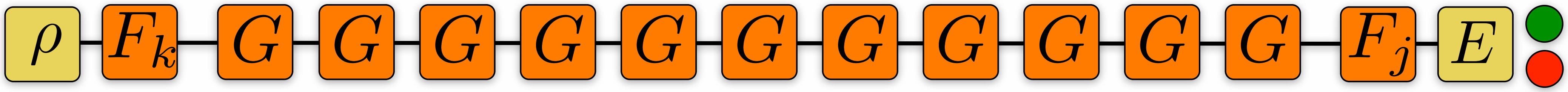
U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Long circuit GST

- "Traditional" tomography is linear -- observable probabilities are *linear* functions of the parameters (e.g., elements of $\boldsymbol{G}_k$).

- This no longer holds for GST. Even in LGST, probabilities involve multiple $\boldsymbol{G}_k$.

- So can we get an advantage from going whole-hog and using *really* nonlinear probabilities (many uses of $\boldsymbol{G}_k$ at once?)



- Yes! Long circuits can amplify small errors.
  - **(1) What long circuit experiments should we perform?**
  - **(2) How do we fit a gateset to the resulting data?**

U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

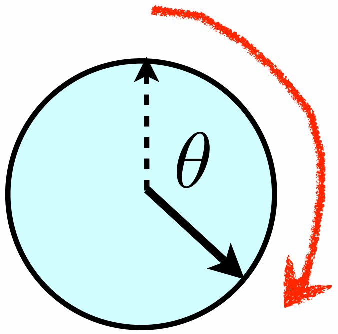
Part 4:
Hyperaccuracy
&
Error-amplifying circuits

Robin Blume-Kohout

U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Basics of Error Amplification

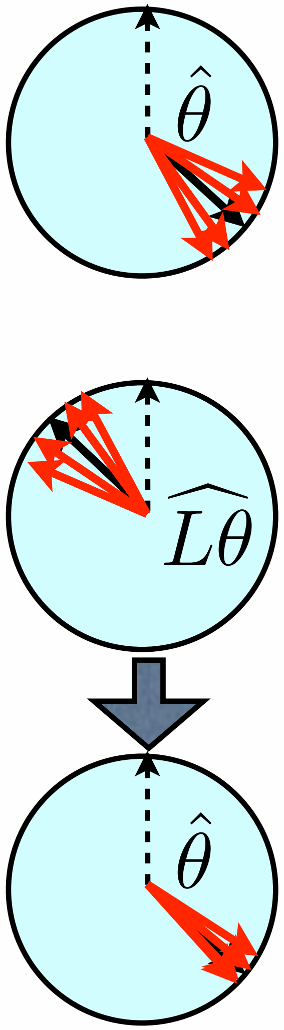
- Simple toy example: $G = e^{i\theta}$
  Goal: estimate $\boldsymbol{\theta}$.



- N observations of $\langle\langle E|\, G\,|\rho\rangle\rangle$ yield $\hat{\theta} = \theta \pm O(1/\sqrt{N})$.

- But N observations of $\langle\langle E|\, G^L\,|\rho\rangle\rangle$ yield

$$\widehat{L\theta} = L\theta \pm O(1/\sqrt{N}) \implies \hat{\theta} = \widehat{L\theta}/L = \theta \pm O(1/L\sqrt{N})$$



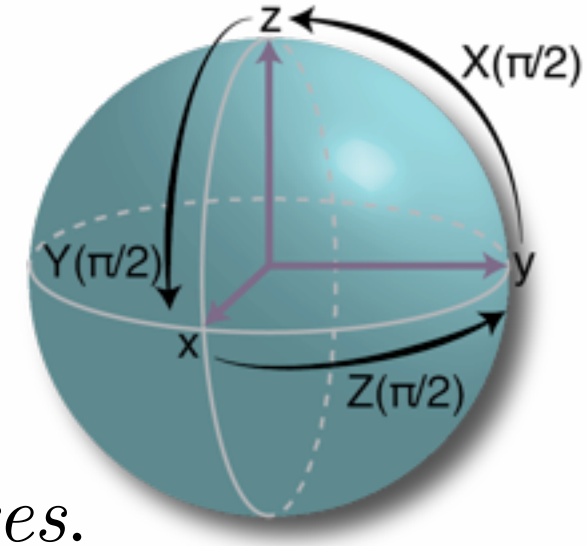
- **Problem**: *branch cuts.* We only observe rotations modulo 2π, so if *8*$\boldsymbol{\theta}$=π/2, is $\boldsymbol{\theta}$ equal to π/16 or 5π/16?

- **Solution**: gather data at many scales: L=1,2,4,8,...

U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Germs and Germ-powers

- If gates were scalars (e.g. $G_k = e^{i\theta_k}$) we could just estimate sequences ${G_k}^L$ for L=1,2,4,8... and infer the G_k from them.
- But the G_k are matrices... which make things more complex!
- Repeating G_k (i.e., ${G_k}^L$) only amplifies *eigenvalues* of G_k.



- In early experiments, we got great precision in rotation *angles*... but inaccurate rotation *axes*.
- **Solution**: we do many repetitions not just of single gates but of short *germs* -- e.g. G_1G_2 -- that generate long sequences like $(G_1G_2)^L$. We call these *germ power sequences*.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

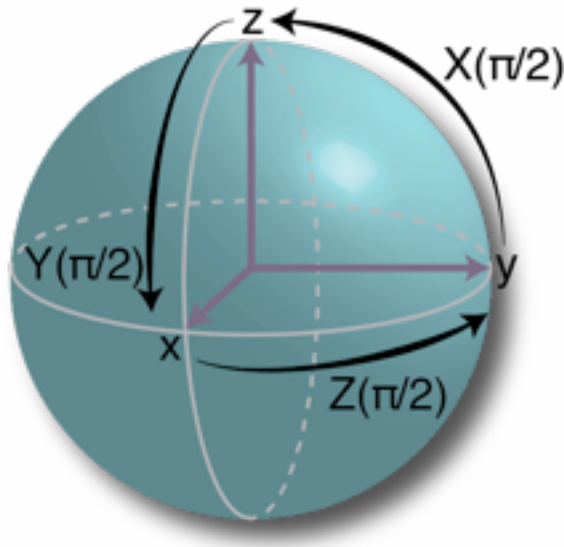
Completeness

- A set of experiments is *informationally complete* (IC) if its observable results constrain every parameter of the model (for gatesets, "every non-gauge parameter").

- We want not just IC -- even LGST is IC. We want every parameter *amplified* proportional to L (sequence length).

- Designing IC germ sets is something of a black art right now (it's a condition on the rank of a Jacobian), but we can do it for any given gate set. Example:

$$\{G_x,\ G_y,\ G_z,\ G_{\mathbb{1}},\ G_xG_y,\ G_xG_z,\ G_yG_z,\ G_xG_xG_y,\ G_xG_xG_z,\ G_xG_yG_z,\ G_yG_yG_z\}$$



U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

eLGST and LSGST

- We need to fit a gateset $\{\rho, \mathrm{E}, G_k\}$ to long-sequence data.

- *Extended LGST:* fast, simple, reasonably accurate

  1. Do LGST using short sequences to get a rough estimate.

  2. Use long sequences of the form $\mathrm{F_i}(\mathbf{germ})^{\mathrm{L}}\mathrm{F_j}$ to get LGST estimates of the quantum operation for $(\mathbf{germ})^{\mathrm{L}}$.

  3. Iteratively tweak the rough estimate to agree with estimated germ-powers of length L=2, 4, 8, ... $\mathrm{L_{max}}$.

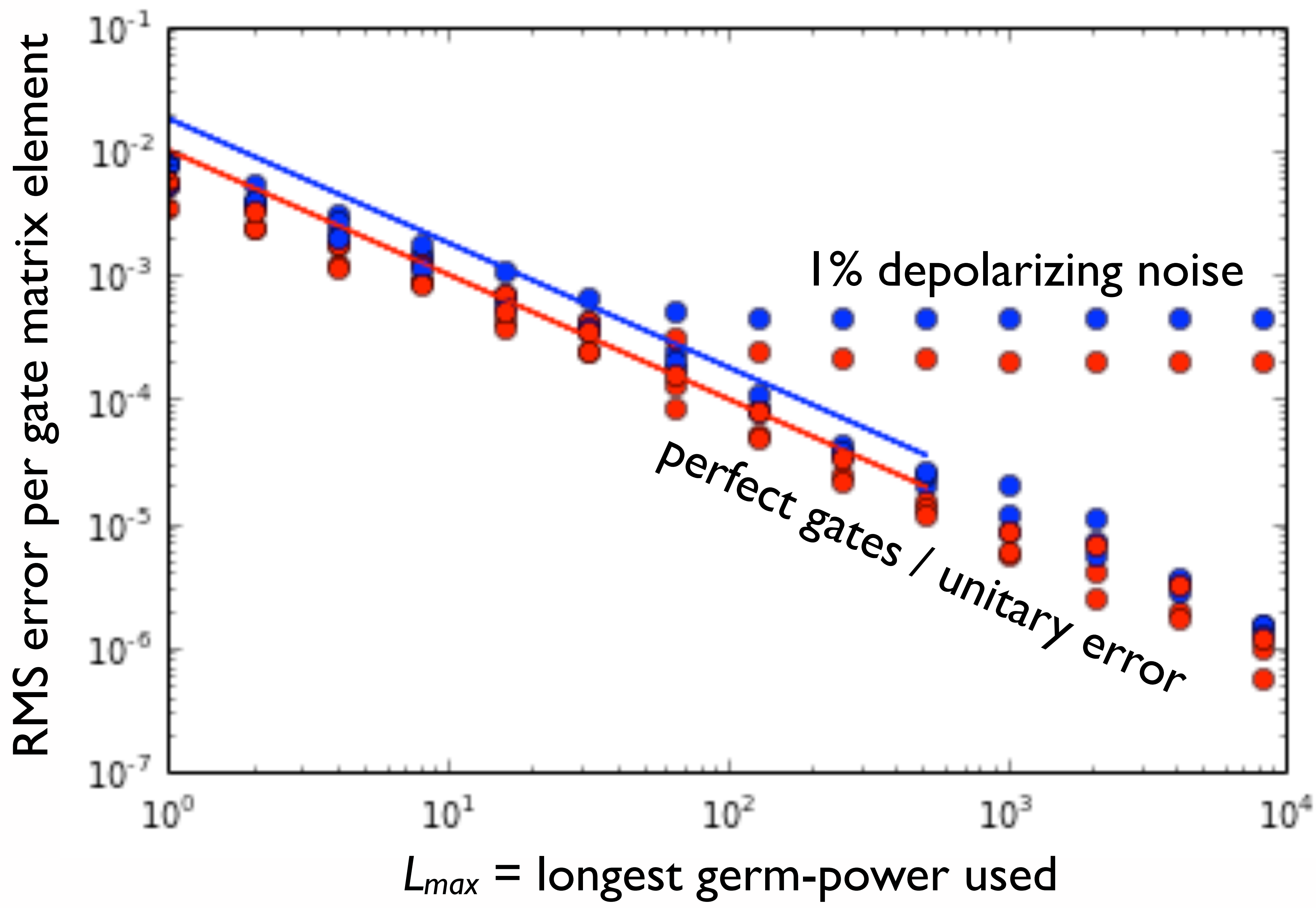
- *Least-squares GST*: most accurate & statistically justified

  1. Do LGST using short sequences to get a rough estimate.

  2. Iteratively improve the rough estimate by doing a weighted least-squares fit (minimize χ^2) to the same sequences used for eLGST.

U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

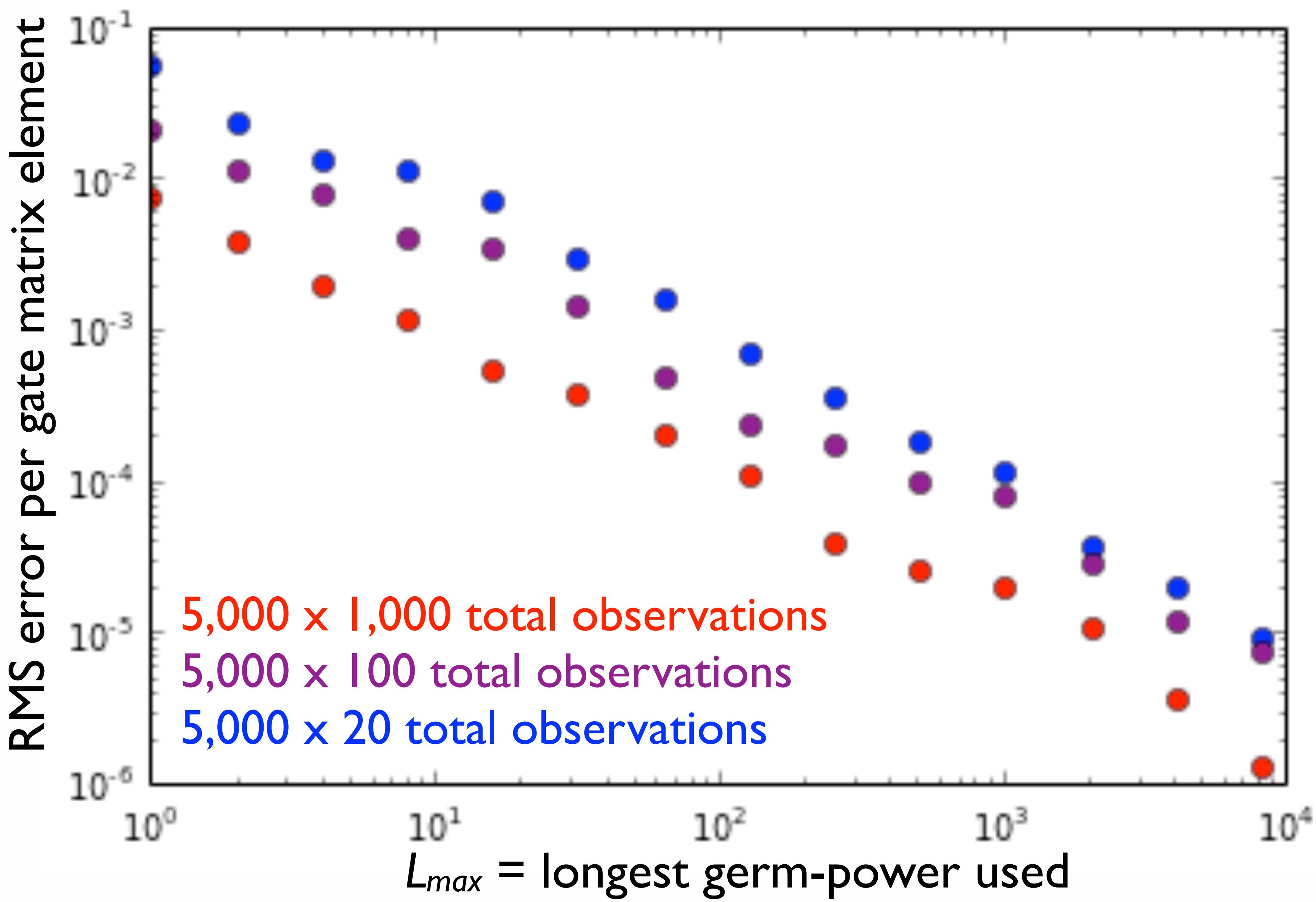
Hyperaccuracy: Simulations



U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Efficiency: counting clicks



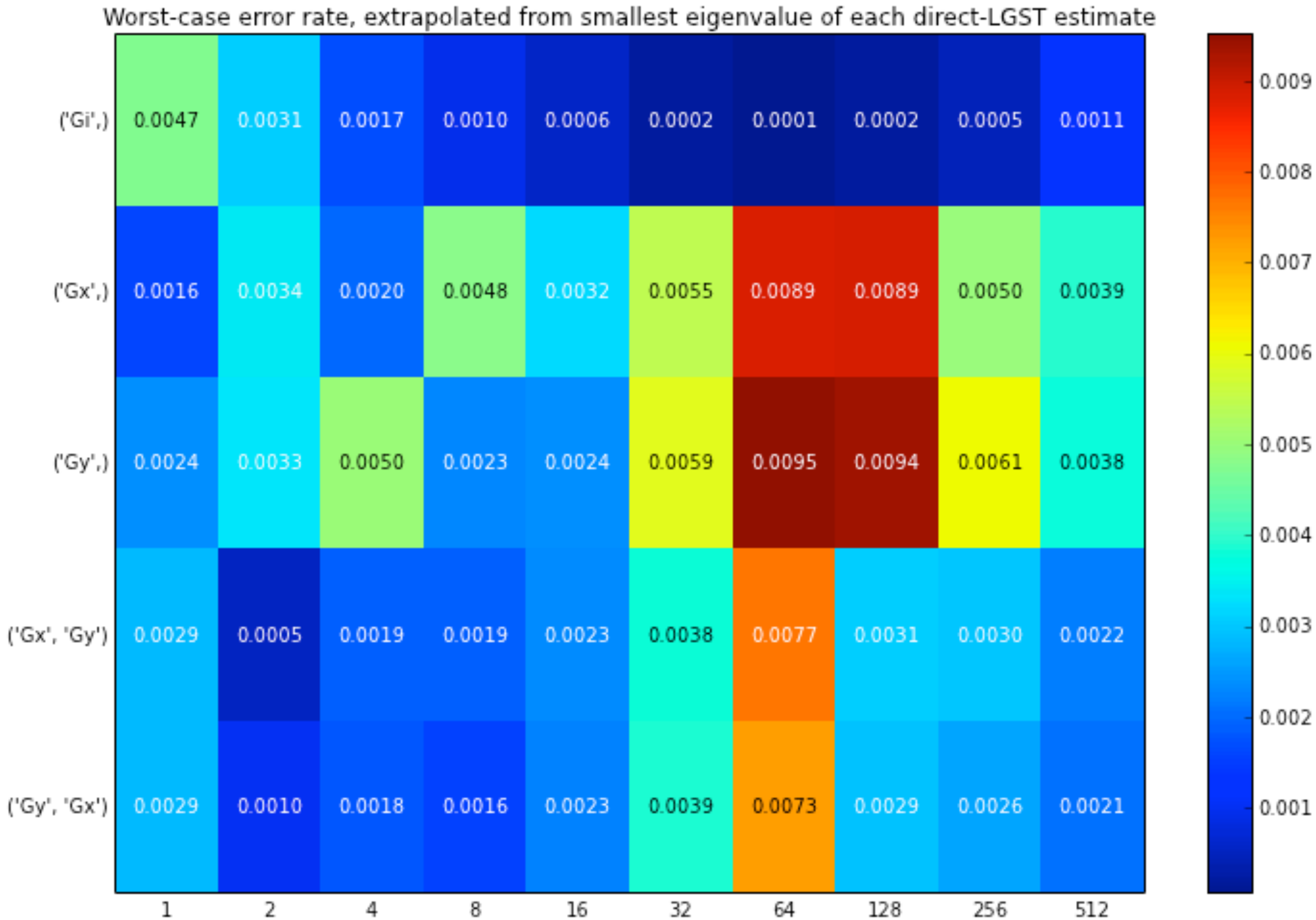
U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Part 4:
Experimental Results

Robin Blume-Kohout

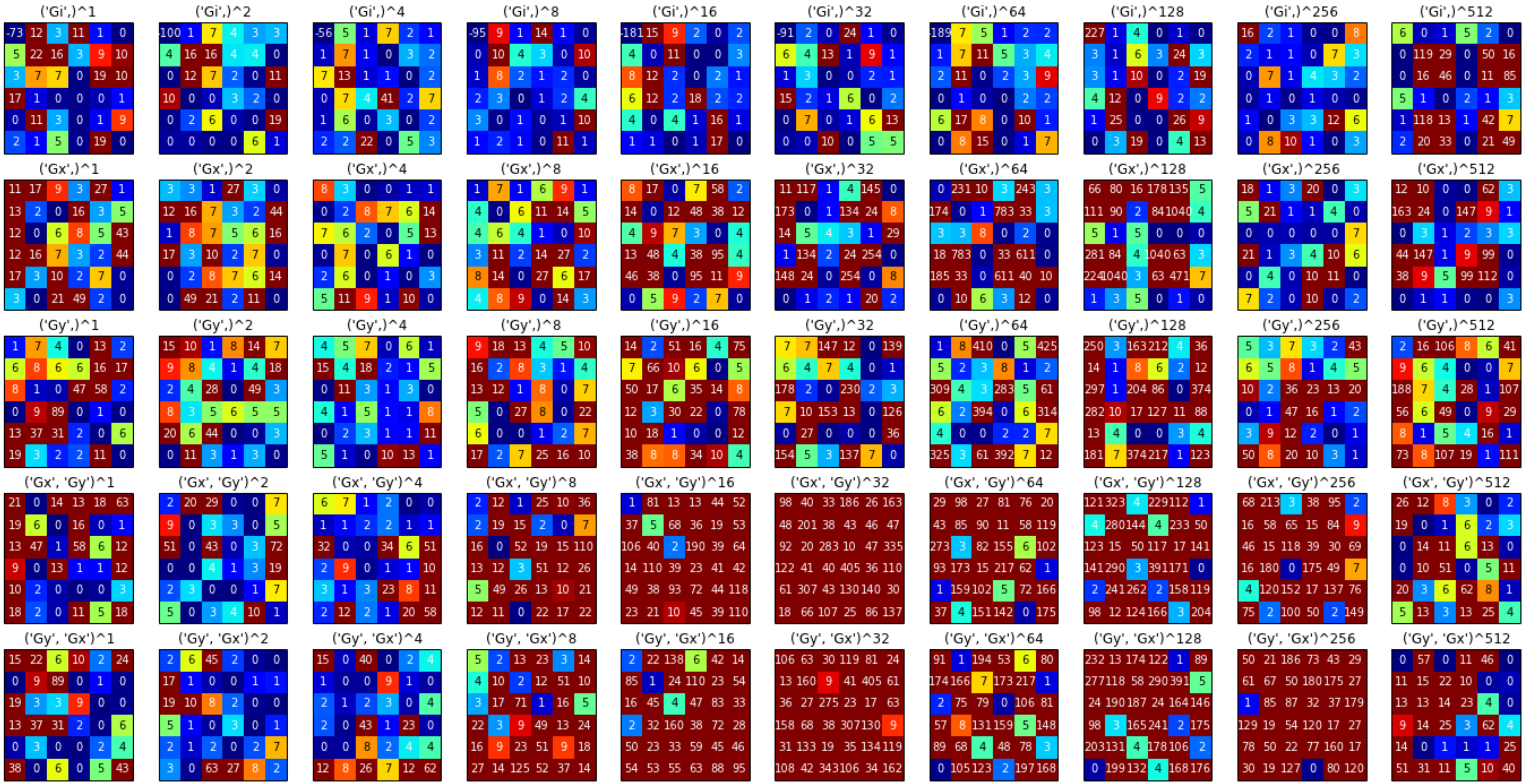
U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Extracting Error Rates



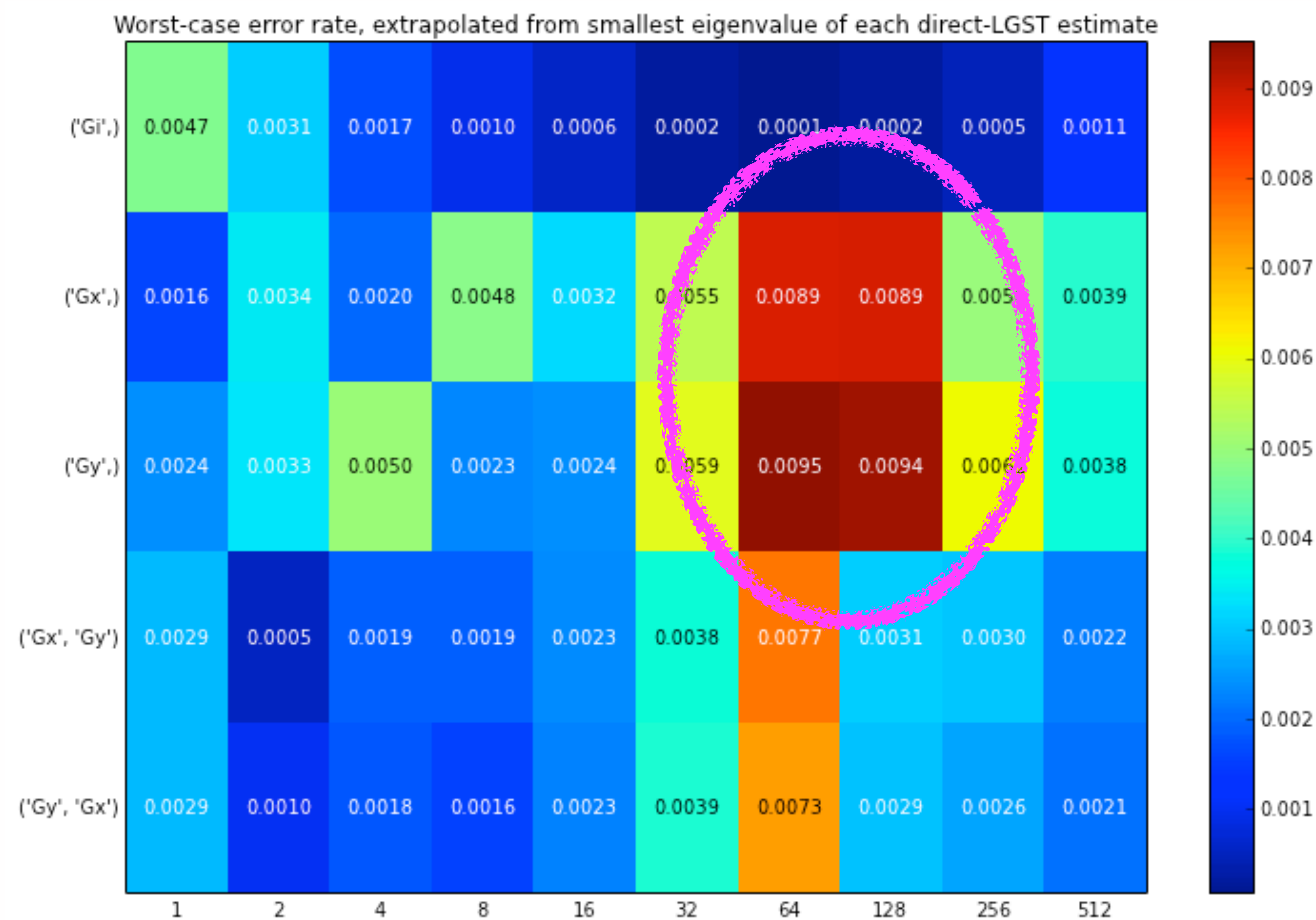
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Self-consistency: χ^2



U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

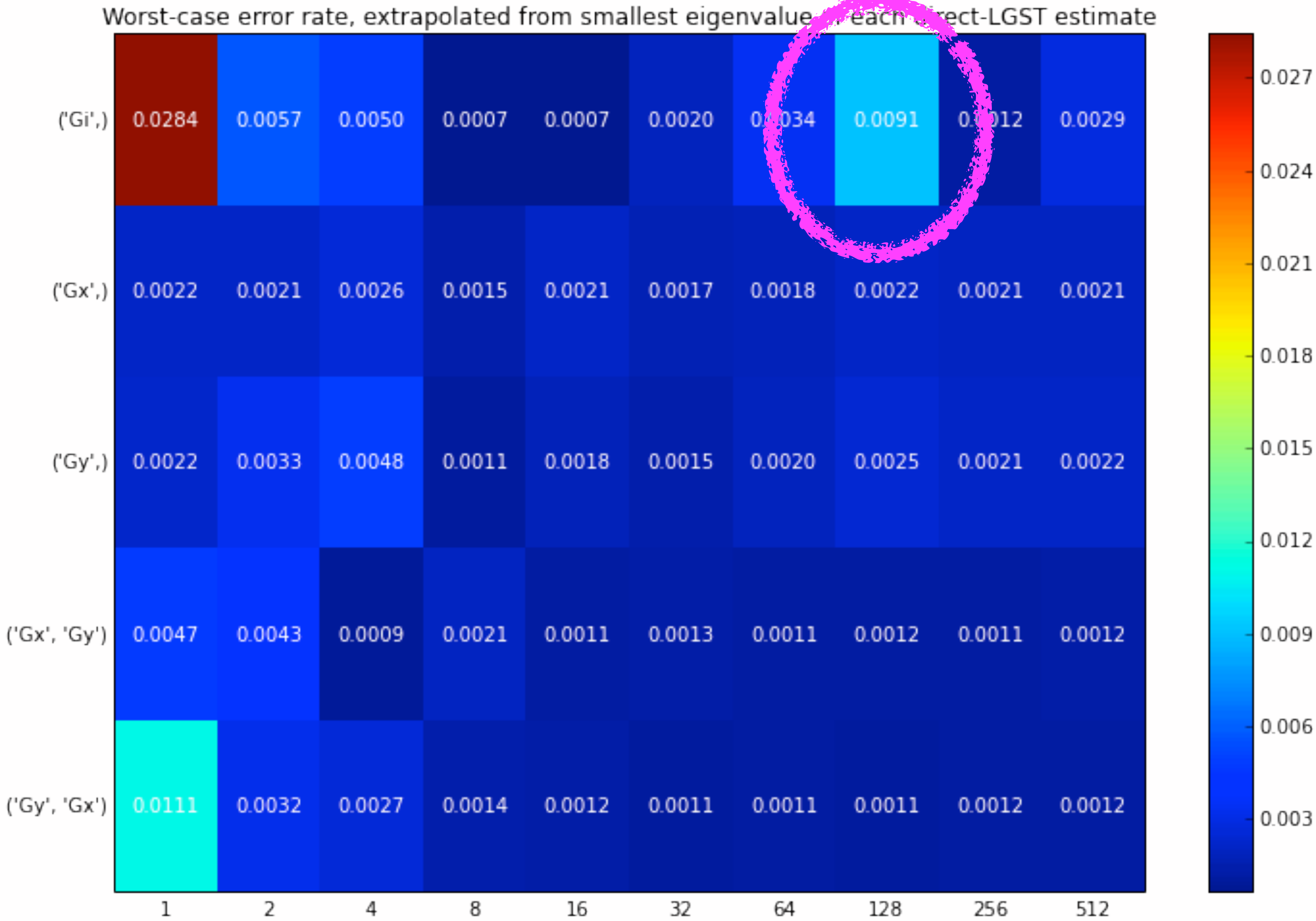
Non-Markovian noise



U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories

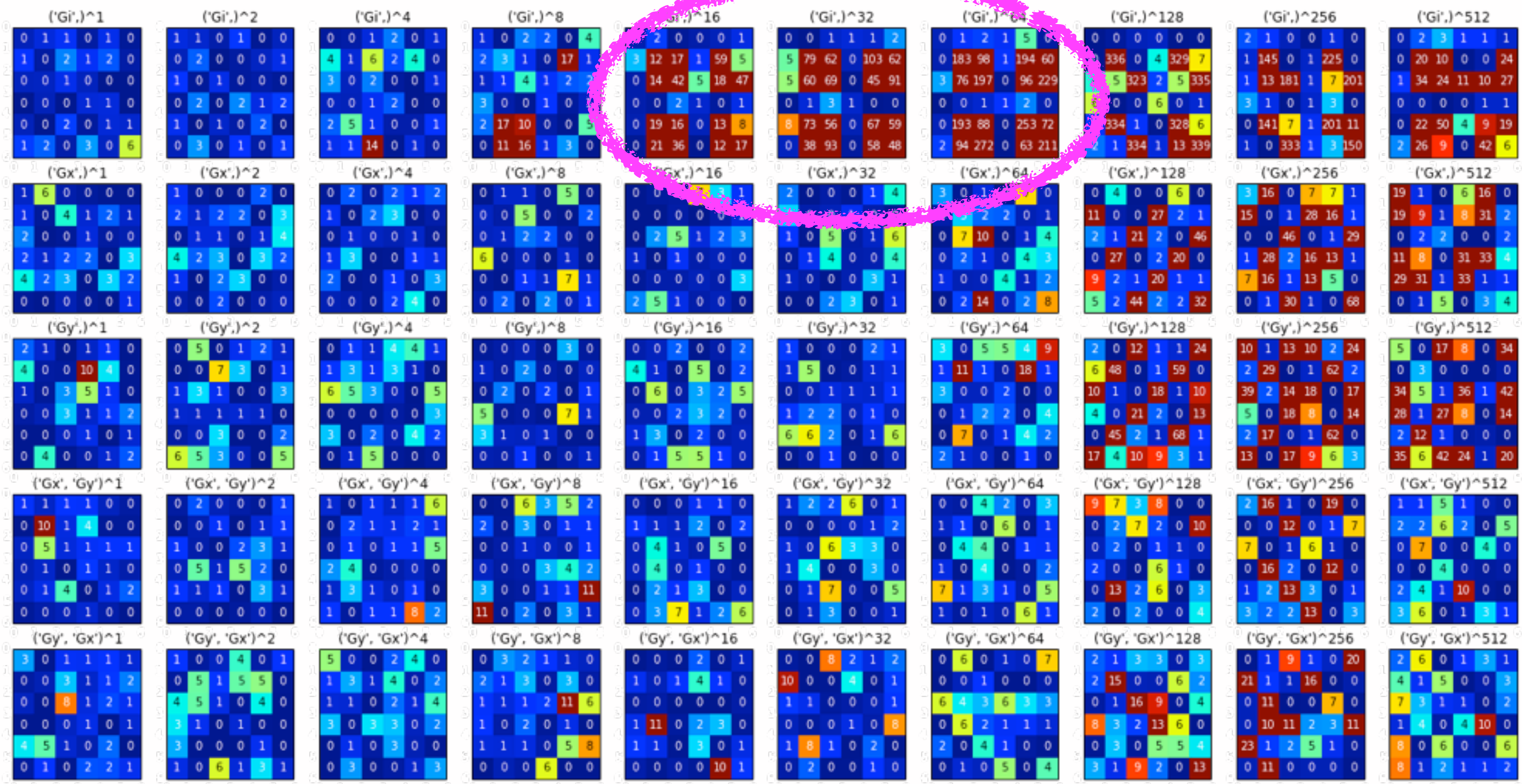
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Debugging: Improved Gates



U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Debugging: Improved χ^2



U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Conclusions & Future

- There's no excuse for doing the "old" tomography any more -- assuming precalibrated gates is unsafe and unnecessary.
- GST can achieve unprecedented accuracy & efficiency by leveraging long circuits that amplify gate errors.
- **Every (?) qubit has significant non-Markovian noise.**
- Serious statistical techniques are becoming more and more important for quantum device characterization. We rely critically on goodness-of-fit, and model selection is rapidly becoming an essential concept.
- **Quantum statistical inference is (after all) just another application of statistics... but with some near-unique caveats and challenges!**

U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.