Some notes on Interrogating Random Quantum Circuits

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Outline

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Goals of the presentation:

- Convey our preliminary understanding of the certifiable-QRNG setting
- Discuss distinguishability / paremetrization aspects
- Identify questions for subsequent followup / research directions (?)

Outline 1

The protocol at a high-level

Towards certified/certifiable randomness.

1. The operator is given a freshly chosen random quantum circuit.
2. Soon after, the operator publishes many circuit output strings.
3. Client extracts randomness for use in applications.
4. Long after, a supercomputer outputs the "P-values" of the strings.
5. By analysis of the "P-values", get a retroactive statistical assurance that a sufficiently large set of outputs were sampled from the quantum circuit.

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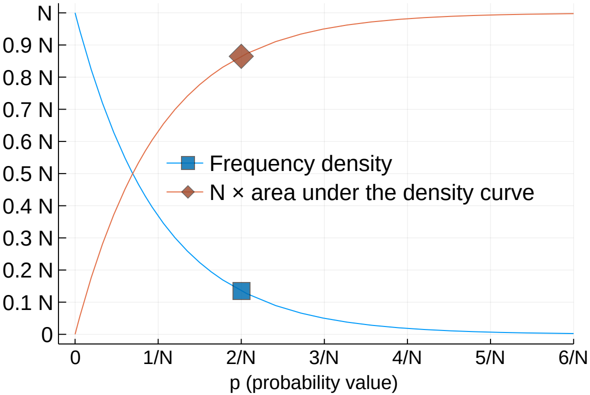
We want to look at suitable parameters for implementation of this protocol

Outline 2

Exponential model: frequency density

$f(p)$: **Counting** the number of strings that, when sampling from a quantum random circuit, occur with each **probability** (p).



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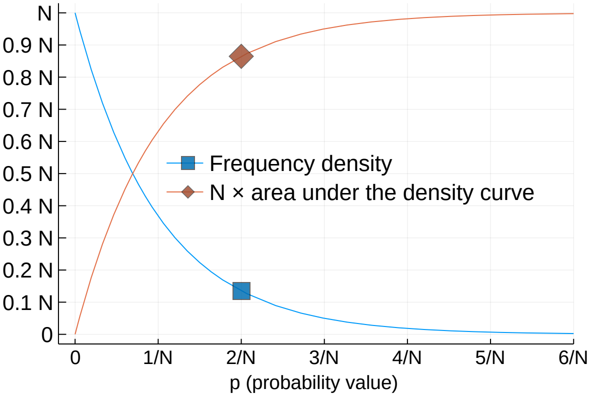

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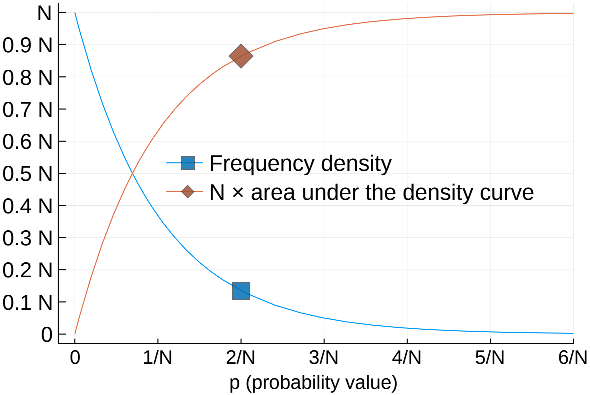

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Note: the "frequency density" is a probability density (a continuous approximation) across the P-values, rather than across the strings.

More on P-values

Once we obtain a freshly random quantum circuit C:

- Evaluating the circuit ($s \leftarrow C$) is easy/fast with a quantum computer and super slow with a classical computer.
- There is a map $P_{\mathsf{val},C} : \{0,1\}^n \to [0,1[$, where $P_{\mathsf{val},C}(s) = p$ means the string s has probability p of being output by an quantum-evaluation of C
- Computing $P_{\mathsf{val}}(s)$ is very expensive for any $s \in \{0,1\}^n$
- A priori, without need to actually compute $P_{\mathsf{val},C}(\cdot)$), the range $\{P_{\mathsf{val},C}(s) : s \in \{0,1\}^n\}$ of P-values is assumed to be match the frequency characterization of function $f = N \cdot e^{-N \cdot p}$.

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This is a model — which this presentation simply assumes.

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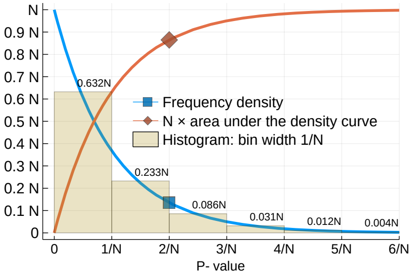
x	$1/N$	$2/N$	$3/N$	$4/N$
Upon uniform sampling	63%	95%	98%	99%



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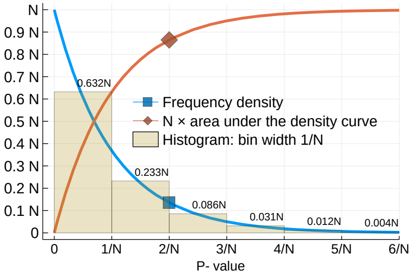
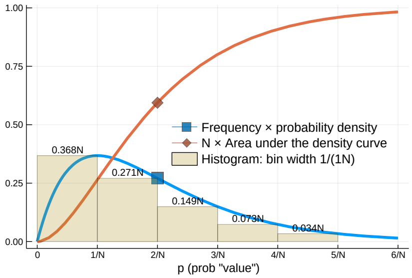
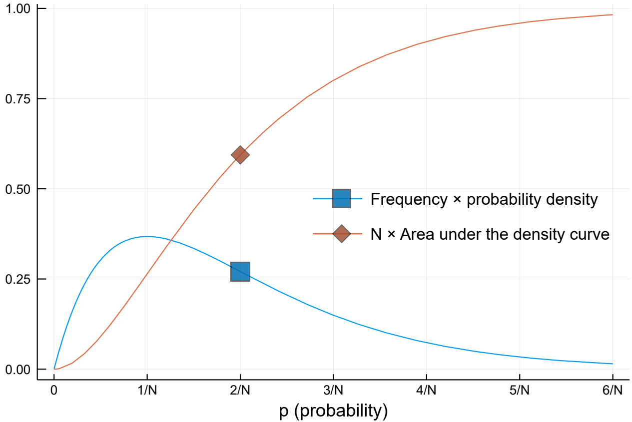
x	$1/N$	$2/N$	$3/N$	$4/N$
Upon uniform sampling	63%	95%	98%	99%
Upon circuit evaluation	26%	59%	80%	91%





Frequency times P-value

$f(p) \cdot p$: Frequency times P-value as a function of P-value



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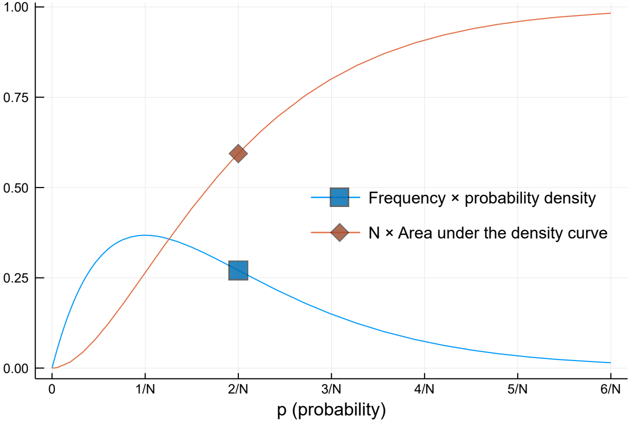

$$E[X_Q] = 2/N$$

$$V[X_Q] = 2/N^2$$

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Fidelity

We are told that making a correct quantum evaluation is hard:

- Correct evaluation happens with probability ϕ
- Otherwise the output is uniform

Statistics for sum of P-value of m sampled strings:

Sampling type	Random variable $X_{*,m[,*]}$	Expected value $E(X)$	Variance $V(X)$
Uniform	$X_{U,m}$	m/N	m/N^2
Pure **Q**uantum	$X_{Q,m}$	$2 \cdot m/N$	$2 \cdot m/N^2$
Q-**F**idelity ϕ	$X_{F,m,\phi}$	$(1+\phi) \cdot m/N$	$(1+\phi \cdot (2-\phi)) \cdot m/N^2$

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We will want to compare obtained P-values vs. several distributions.

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For simplicity we focus here on the "Sum of m obtained P-values". Rationale:

- The E[X] is the *mean* times the *number of samples*
- We already know that $\text{mean}_{\text{Honest}} > mean_{\text{uniform}}$
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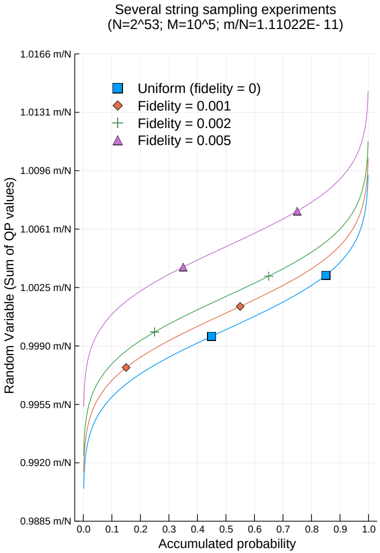
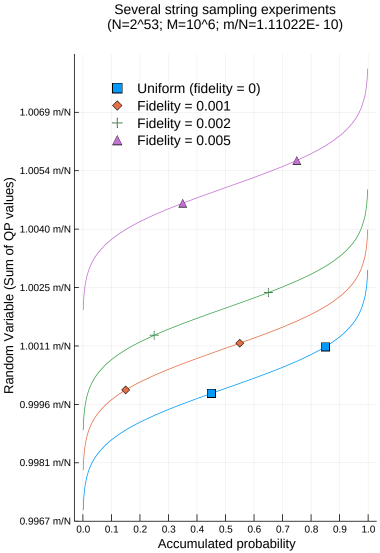
$$X_{F,m,\phi} \approx \mathcal{N}\left(\frac{(1+\phi)\cdot m}{N}, \frac{\sqrt{(1+\phi(2-\phi))\cdot m}}{N}\right)$$

Curves for $M = 10^5$ and $M = 10^6$





Outline 3

1. Introduction
2. Exponential model
3. Distinguishability
4. Min-entropy estimation
5. Concluding remarks

Hypothesis testing

Some intro definitions:

- **False negative (FN):** reject when it is actually good (e.g., fid. 0.002)
- **False positive (FP):** accept when it is actually bad (e.g., uniform)

Example: If we have FN=20%, what do we get for FP?

It depends on the setup. In the last curves we had:

- If $m = 10^5$, then FP = 58.3%
- If $m = 10^6$, then FP = 12.4%

Different FP: We can formulate different definitions for FP, depending what we want to compare. For example, we can compare fidelity 0.002 (assumed honest) vs. 0.001 (the malicious case). This can be useful for entropy estimation. Then we would get

- If $m = 10^5$, then FP = 70.1%
- If $m = 10^6$, then FP = 12.4%

What metrics for FN vs. FP?

Confusion matrix		Classification	
		Positive	Negative
Actual condition	Positive (Honest operator)	TP ratio	FN ratio
	Negative (Malicious operator)	FP ratio	TN ratio

accuracy = (TP + TN)/All; precision = TP / (TP + FP); recall = TP / (TP + FN); ...

Is TN or TP more costly than the other? May depend on the application.

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Is TN or TP more costly than the other? May depend on the application.

- **Are FN's worse?** Can a FN, determined after the fact, impose rolling out / impugn some past legal procedure? E.g., assume the "randomness" was used to select a small sample of voting booths to recount votes in a tied election, leading to a tight win to one candidate. Will the procedure be contested if later the sample is rejected?
- **Are FP's worse?** A cryptographic application that hinges on fresh randomness for security. What if a completely deterministic (PRG) output is accepted, and the randomness provider is in cohots with an adversary?

Setting thresholds for FN and FP

- A la cryptographer: let FN $=$ FP $= 2^{-40}$ (common benchmark for "one-shot" security applications, e.g., cut-and-choose protocols)

- Different criteria for other applications (?)

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Let us look at some tables ...

Table: Fixed FN ratios vs. FP ratios (using ϕ=0.002)

$M \in \{10^5, 10^6\}$, $\phi = .002$.

What is a "FP" depends on the comparison (e.g., consider "Uniform P_U")

M	ϕ	FN ratio p_ϕ	Threshold $T_{H,M,\phi}$	(Uniform) p_U	(Fidelity) $p_{\phi/4}$	(Fidelity) $p_{\phi/2}$	(Fidelity) $p_{3\phi/4}$
10^5	0.002	2^{-40}	1.08765E-11	1.00000	1.00000	1.00000	1.00000
		2^{-30}	1.09130E-11	1.00000	1.00000	1.00000	1.00000
		2^{-20}	1.09569E-11	0.99998	0.99999	1.00000	1.00000
		0.001	1.10157E-11	0.99313	0.99561	0.99726	0.99833
		0.01	1.10426E-11	0.95530	0.96825	0.97793	0.98498
		0.1	1.10794E-11	0.74269	0.79085	0.83321	0.86956
		1/3	1.11093E-11	0.42040	0.48296	0.54587	0.60760
10^6	0.002	2^{-40}	1.10460E-10	1.00000	1.00000	1.00000	1.00000
		2^{-30}	1.10576E-10	0.99997	1.00000	1.00000	1.00000
		2^{-20}	1.10714E-10	0.99722	0.99946	0.99992	0.99999
		0.001	1.10901E-10	0.86355	0.94471	0.98188	0.99524
		0.01	1.10986E-10	0.62967	0.79689	0.90819	0.96624
		0.1	1.11102E-10	0.23703	0.41458	0.61173	0.78317
		1/3	1.11196E-10	0.05839	0.14279	0.28507	0.47277

Table: Fixed FN ratios vs. FP ratios (using ϕ=0.005)

$M \in \{10^5, 10^6\}$, $\phi = .005$

M	ϕ	FN ratio p_H	Threshold $T_{H,M,\phi}$	(Uniform) p_U	(Fidelity) $p_{\phi/4}$	(Fidelity) $p_{\phi/2}$	(Fidelity) $p_{3\phi/4}$
10^5	0.005	2^{-40}	1.09091E-11	1.00000	1.00000	1.00000	1.00000
		2^{-30}	1.09457E-11	1.00000	1.00000	1.00000	1.00000
		2^{-20}	1.09897E-11	0.99933	0.99984	0.99997	0.99999
		0.001	1.10487E-11	0.93630	0.97240	0.98954	0.99654
		0.01	1.10757E-11	0.77541	0.87506	0.93865	0.97353
		0.1	1.11125E-11	0.38468	0.54060	0.69010	0.81308
		1/3	1.11425E-11	0.12543	0.22601	0.36062	0.51494
10^6	0.005	2^{-40}	1.10791E-10	0.98136	0.99956	1.00000	1.00000
		2^{-30}	1.10907E-10	0.85066	0.98888	0.99979	1.00000
		2^{-20}	1.11046E-10	0.41555	0.84976	0.98873	0.99979
		0.001	1.11233E-10	0.02909	0.25992	0.72711	0.96775
		0.01	1.11318E-10	0.00388	0.07922	0.43578	0.86079
		0.1	1.11434E-10	0.00010	0.00697	0.11332	0.51507
		1/3	1.11529E-10	0.00000	0.00046	0.01960	0.20780

Table: Fixed FN ratios vs. FP ratios (higher fidelity)

$M = 10^4$, $\phi \in \{.05, .1\}$

M	ϕ	FN ratio p_H	Threshold $T_{H,M,\phi}$	(Uniform) p_U	(Fidelity) $p_{\phi/4}$	(Fidelity) $p_{\phi/2}$	(Fidelity) $p_{3\phi/4}$
10^4	0.05	2^{-40}	1.08376E-12	0.99142	0.99983	1.00000	1.00000
		2^{-30}	1.09584E-12	0.90243	0.99404	0.99989	1.00000
		2^{-20}	1.11034E-12	0.49593	0.88965	0.99246	0.99985
		0.001	1.12979E-12	0.03898	0.30630	0.76418	0.97245
		0.01	1.13868E-12	0.00519	0.09734	0.47553	0.87404
		0.1	1.15083E-12	0.00013	0.00870	0.12927	0.53560
		1/3	1.16072E-12	0.00000	0.00056	0.02275	0.22038
10^4	0.1	2^{-40}	1.13589E-12	0.01039	0.57286	0.99486	1.00000
		2^{-30}	1.14847E-12	0.00029	0.17824	0.93119	0.99992
		2^{-20}	1.16356E-12	0.00000	0.01225	0.57414	0.99413
		0.001	1.18382E-12	0.00000	0.00003	0.05998	0.79225
		0.01	1.19307E-12	0.00000	0.00000	0.00938	0.51407
		0.1	1.20572E-12	0.00000	0.00000	0.00029	0.15147
		1/3	1.21603E-12	0.00000	0.00000	0.00001	0.02886

Other random variables

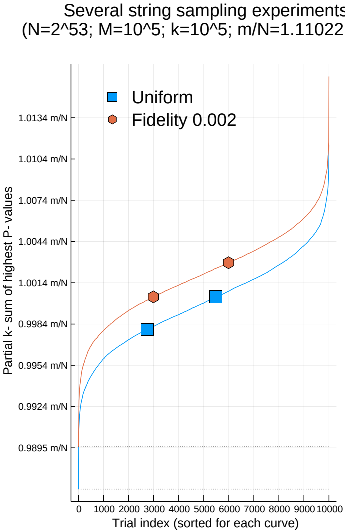
Once all P-values are assessed, what is the best strategy for confirmation?

Example: Client has a “small” budget to verify P-values, e.g., 10% of them. How should they be chosen?

- Uniformly?
- the 10% highest?
- Sampling related to the f distribution?
- Something else?

Example: partial sum of the highest 10% P-values

Using $M = 10^5$, compare the cases $k = 10^5$ vs. $k = 10^4$



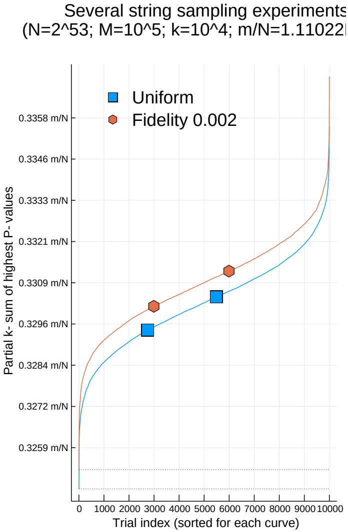


Table: comparing some FP ratios for the same FN

Example:

- Positive case: honest circuit evaluation with fidelity $\phi = 0.002$.
- Negative case: uniform string sampling.

M	k	k/M	(FN = 0.25) FP	(FN = 0.1) FP
10^6	10^3	.001	0.64	0.82
	10^4	.01	0.45	0.68
	10^5	.1	0.21	0.41
10^5	10^3	.01	0.69	0.86
	10^4	.1	0.59	0.79
	10^5	1	0.50	0.74

(Each curve based on simulation of 10^4 trials of partial-sums)

Observation: for fixed k and ϕ, higher M leads to better results.

Outline 4

Entropy needs / assumptions

Assume a correct experiment execution with a honest operator:

- (n qubits, # samples, fidelity ϕ) = $(n, M, \phi) = (53, 10^5, 0.002)$
- Let H_Q be the entropy of a circuit generated string.
- Let $q = M \cdot \phi$, e.g., $(M, \phi) = (10^5, 0.002) \rightarrow q = 200$

Then entropy $\approx (M - q) \cdot 2^n + q \cdot H_Q \approx 5 \times 10^6$ bits

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- **Post-sampling (min-entropy question):** Given a list of P-values, measured for some set of strings,* what is the highest min-entropy that we should estimate, under an adversarial scenario, with assurance p?

Conceivable attacks

Setup:

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Conclusion: entropy $= 0$ ... but attack does not work if FP$_U$ is very small

Conceivable attacks

Attack 2 (higher fidelity):

1. Operator has a fidelity 1 computer, but claims to only have fidelity .05.
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Attack 3 (use lower fidelity):

- Change the FP — another Negative condition (Uniform $\rightarrow$ half fidelity)
- Example: $(\phi, \text{FN}) = (0.05, 0.1) \Rightarrow \text{FP}_U = 0.0013$, but $\text{FP}_{\phi/2} = 0.129 \approx 1/8$
- Attackers try their luck ($\approx 1/8$ chance of winning) using half entropy.

Conceivable attacks

Conceivable attacks

Attack 4 (post-sampling choice — in complement to attacks 2 and 3):

1. Operator PRG-generates $M - q$ strings (0 entropy), e.g., with $q = 100$
2. With fidelity 1, privately evaluate circuit about $2^{25} \cdot q$ times
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Conceivable attacks

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Entropy: $\approx q \cdot (H_Q - 25) \approx 100 \cdot 27 \approx 2700$

(more subtleties are needed, e.g., PR order of strings ...)

To-do:

- Play with concrete parameters, get concrete results.
- Application appropriate parameters
- If you trust PRGS, why would you need thousands of bits?

Outline 5

Some questions worth exploring:

- Suitable (FN,FP) threshold for conceivable applications?
- Verification budget of P-Values for the user? (and oracle budget)
- What are the best statistics to measure? Full-sum, partial-sum, KS, ...?
- Application motivation: when are more than 512 random bits actually needed at once?
- Security proofs
- Research problem: (efficiently-verifiable) probabilistic checkable proofs (PCPs) for this problem

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Overall this field has interesting challenges

Engaging in this has a potential to foster the understanding of applications of quantum randomness.

A major caveat

There is a major caveat in our analysis!

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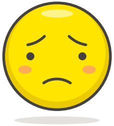
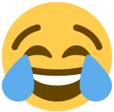


Our simulations used classical randomness!

Would we get better results with quantum randomness?



- NISTIR 8213: https://doi.org/10.6028/NIST.IR.8213-draft
- Beacon project: https://csrc.nist.gov/Projects/Interoperable-Randomness-Beacons

Thank you

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- Beacon project: https://csrc.nist.gov/Projects/Interoperable-Randomness-Beacons

Some notes on Interrogating

Random Quantum Circuits

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Presentation at NIST/Google meeting

December 13, 2019 @ NIST Gaithersburg, USA

Using Kolmogorov-Smirnov

This slide and the next are tentative.

Results obtained this morning ... requires further sanity check.

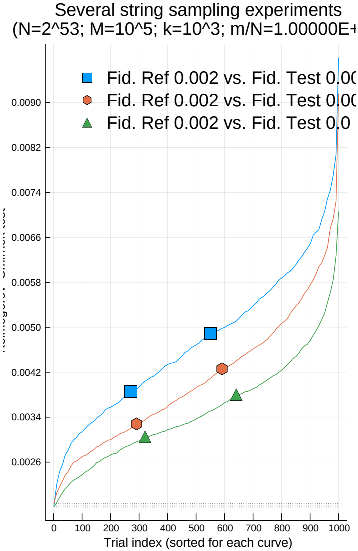

Table: Fixed FN ratios vs. FP ratios (higher fidelity)

$M = 10^4$, $\phi \in \{.05, .1\}$

M	ϕ	FN ratio p_H	Threshold $T_{H,M,\phi}$	(Uniform) p_U	(Fidelity) $p_{\phi/2}$
10^5	0.002	2^{-20}	1.85008E-03	0.99600	1.00000
		0.001	1.92992E-03	0.98800	0.99700
		0.01	2.22990E-03	0.94600	0.97600
		0.1	3.16900E-03	0.62100	0.75400
		2/3	5.28000E-03	0.05000	0.16900

List of slides