Towards Violations of Local Friendliness with Quantum Computers

arxiv: 2409.15302

– Will Zeng

Joint work w/ Vincent Russo, Farrokh Labib

Unitary Fund

wignersfriends.com

Outline

→ Local Friendliness inequalities

→ Quantum Mechanics violates Local Friendliness in Extended Wigner's Friend Scenarios

Experimental program for LF violation

→ "Good branches" as observers

→ Results: violations on quantum computers

→ open questions and next steps

Experimental Metaphysics

Using experiments to explore the space of physical theories.

e.g. Bell's inequality violations

e.g. All vs. nothing Mermin games

e.g. Kochen- Specker

Absoluteness of Observed Events + Local Agency

= Local Friendliness

Bong et al arXiv: 1907.05607

Absoluteness of Observed Events + Local Agency

observed events are objective

i.e. not relative to anyone or anything

= Local Friendliness

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Absoluteness of Observed Events

observed events are objective

i.e. not relative to anyone or anything

+

Local Agency

we can construct independent variables

i.e. we can make choices uncorrellated with events outside the past lightcone

[Interventionist causation + Relativistic causal arrow]

= Local Friendliness

Bong et al arXiv: 1907.05607

Assume

Absoluteness of Observed Events + Local Agency

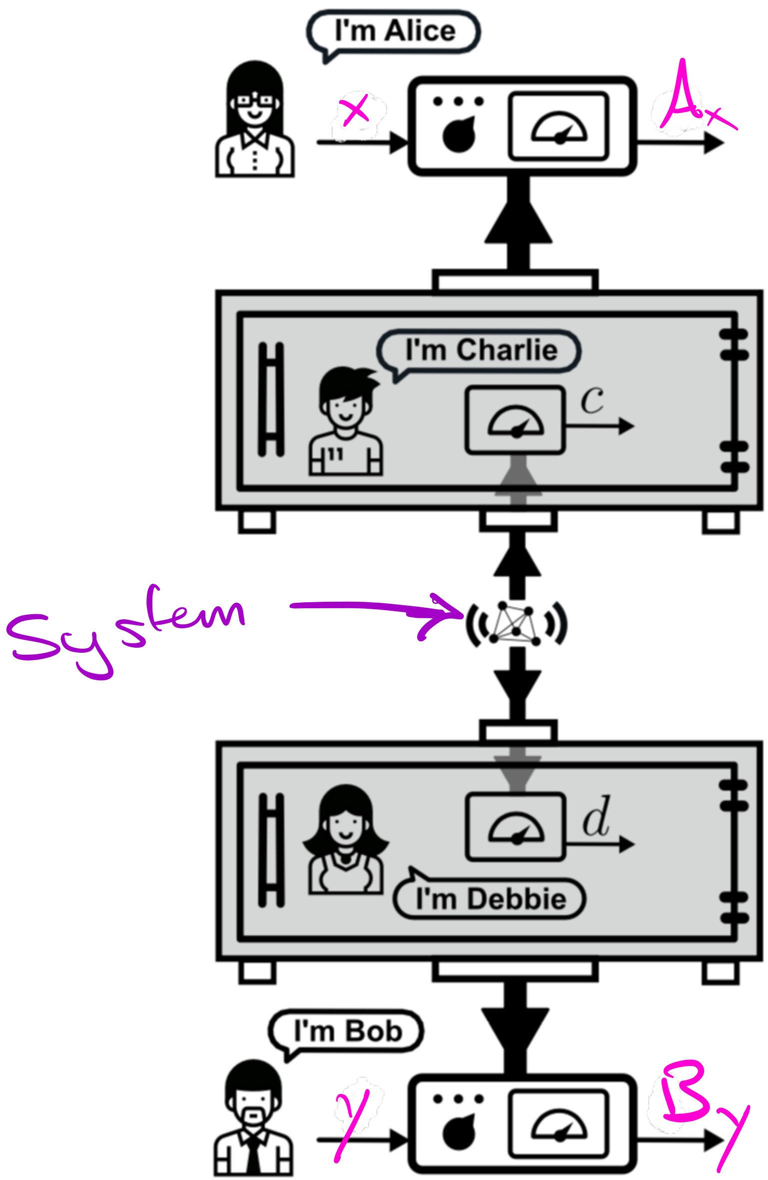
= Local Friendliness

Get Inequality bounds on expectation values from Extended Wigner's Friend Experiments

Textbook quantum mechanics violates these bounds

Bong et al arXiv: 1907.05607

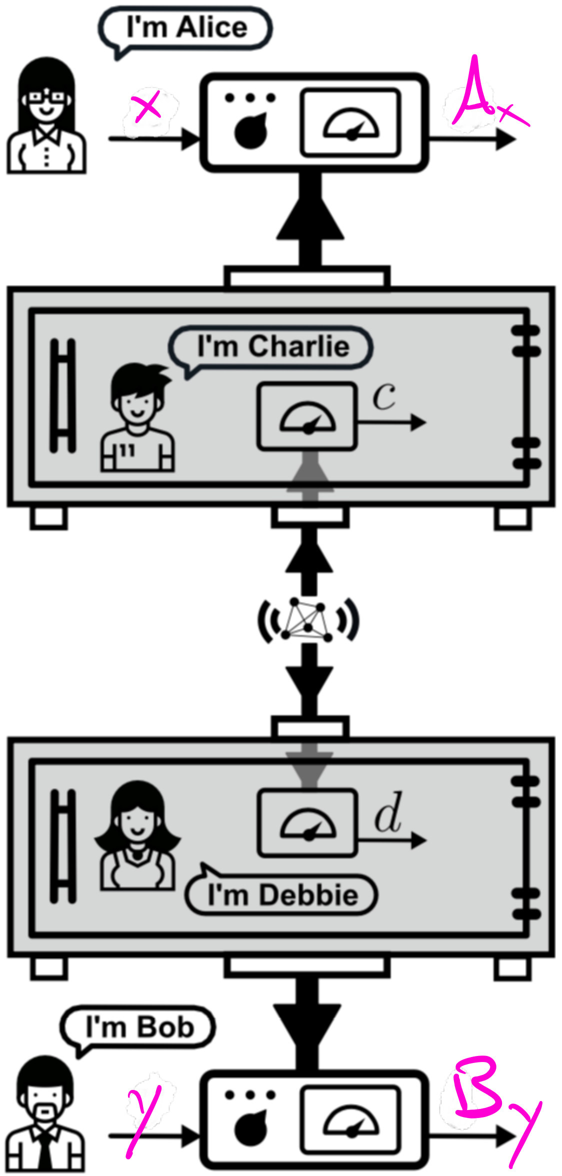
Extended Wigner's Friend Scenario



A_x and B_y are classical bits

Brukner arXiv:1804.00749

EWFS violations of Local Friendliness



1. Genuine LF inequality:

$$-\langle A_1\rangle - \langle A_2\rangle - \langle B_1\rangle - \langle B_2\rangle - \langle A_1B_1\rangle - 2\langle A_1B_2\rangle$$
$$-2\langle A_2B_1\rangle + 2\langle A_2B_2\rangle - \langle A_2B_3\rangle - \langle A_3B_2\rangle - \langle A_3B_3\rangle - 6 \leq 0.$$

2. Bell I_{3322} inequality:

$$-\langle A_1\rangle + \langle A_2\rangle + \langle B_1\rangle - \langle B_2\rangle + \langle A_1B_1\rangle - \langle A_1B_2\rangle - \langle A_1B_3\rangle$$
$$-\langle A_2B_1\rangle + \langle A_2B_2\rangle - \langle A_2B_3\rangle - \langle A_3B_1\rangle - \langle A_3B_2\rangle - 4 \leq 0.$$

3. Brukner inequality:

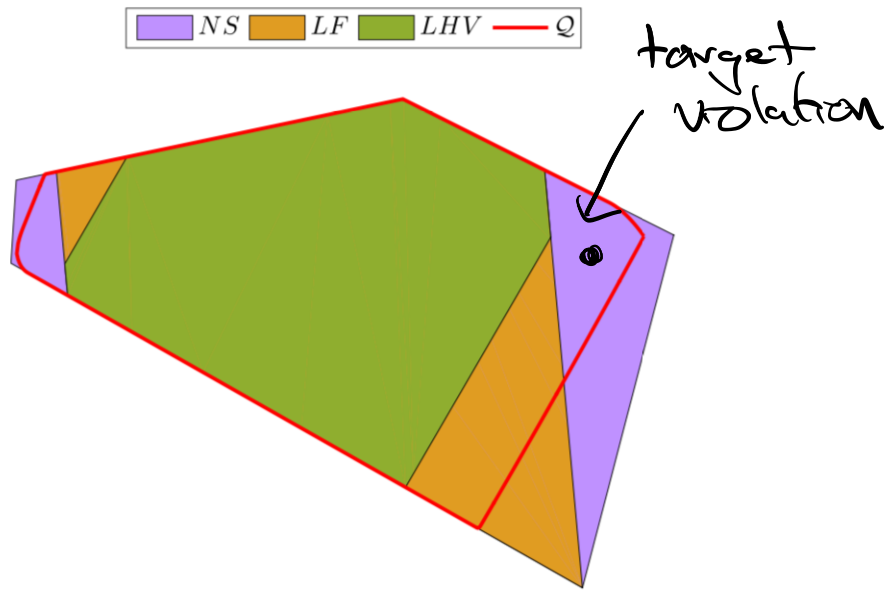
$$\langle A_1B_1\rangle - \langle A_1B_3\rangle - \langle A_2B_1\rangle - \langle A_2B_3\rangle - 2 \leq 0.$$

4. Semi-Brukner inequality:

$$-\langle A_1B_2\rangle + \langle A_1B_3\rangle - \langle A_3B_2\rangle - \langle A_3B_3\rangle - 2 \leq 0.$$

5. Bell non-LF inequality:

$$\langle A_2B_2\rangle - \langle A_2B_3\rangle - \langle A_3B_2\rangle - \langle A_3B_3\rangle - 2 \leq 0.$$

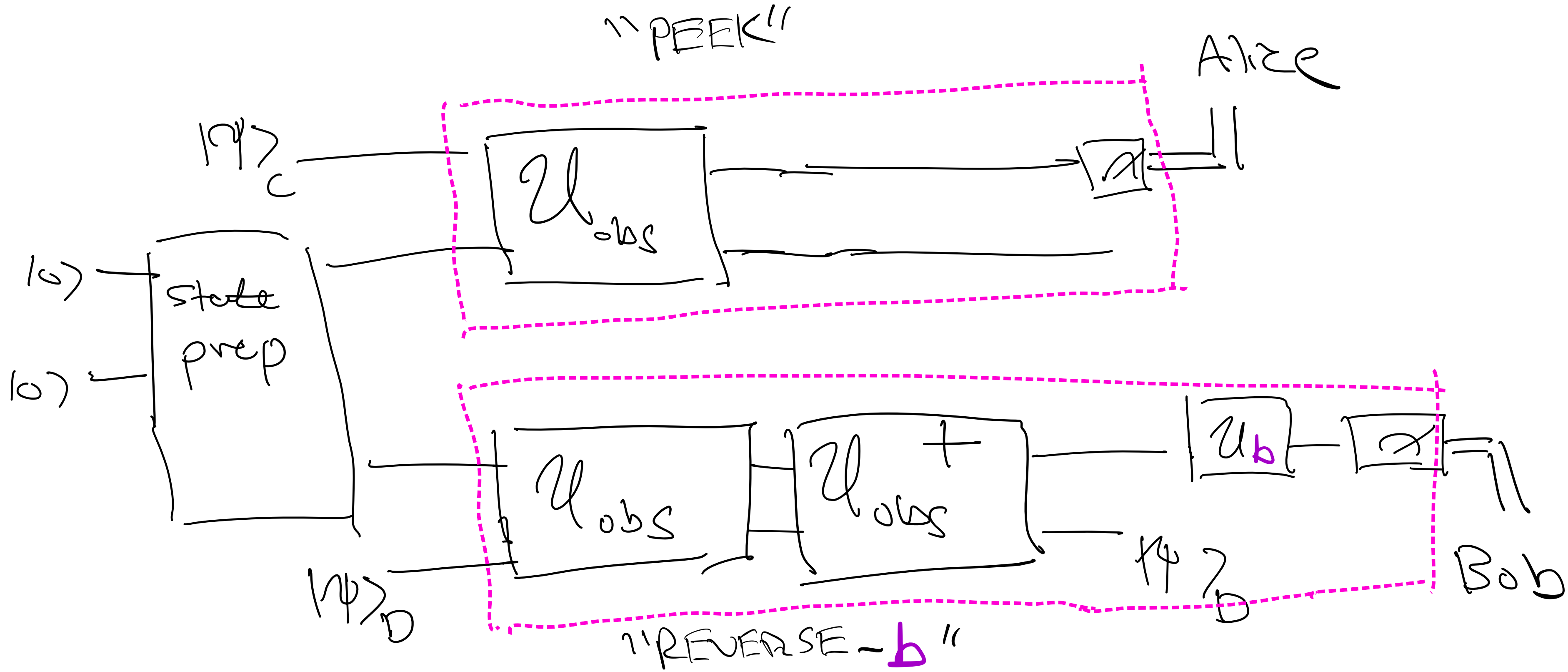


Bong et al arXiv: 1907.05607

Quantum Circuit for Local Friendliness Violations

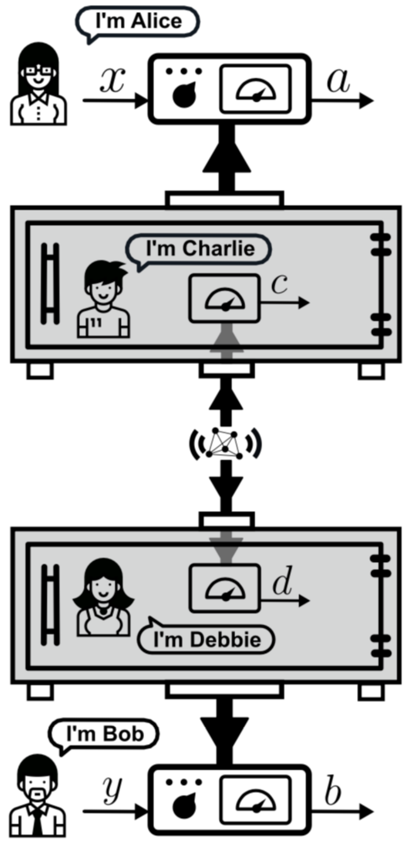
$|\psi_C\rangle$ = Charlie　　　　= Friend box

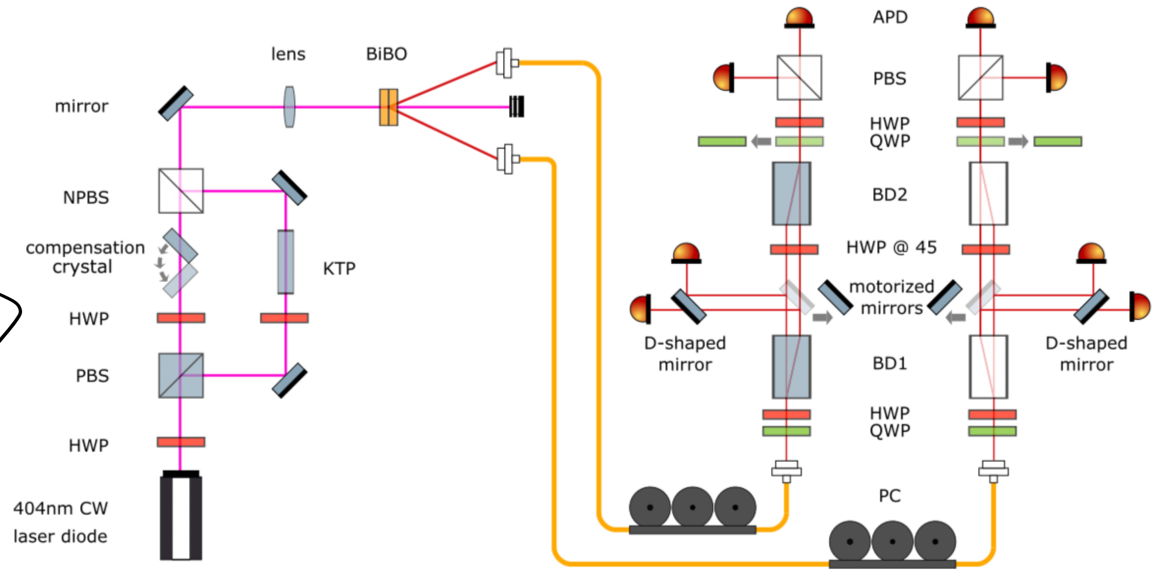
$|\psi_D\rangle$ = Debbie



LF Experimental violation

Charlie, Debbie = 1 photon qubit





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LF Experimental violation

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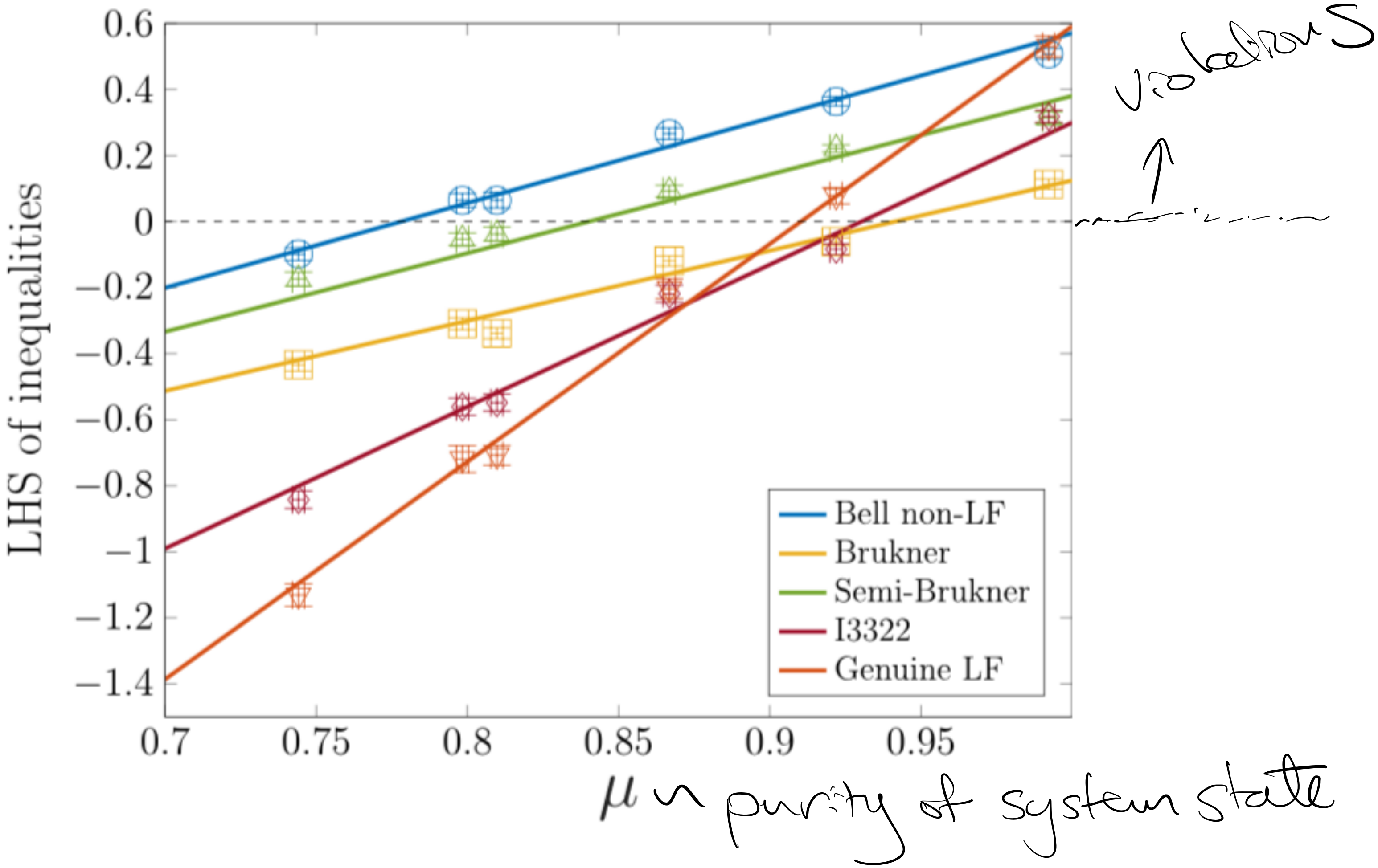

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Interpretations of Bong et al

1. Drop Absoluteness of Observed Events

2. Drop Local Agency

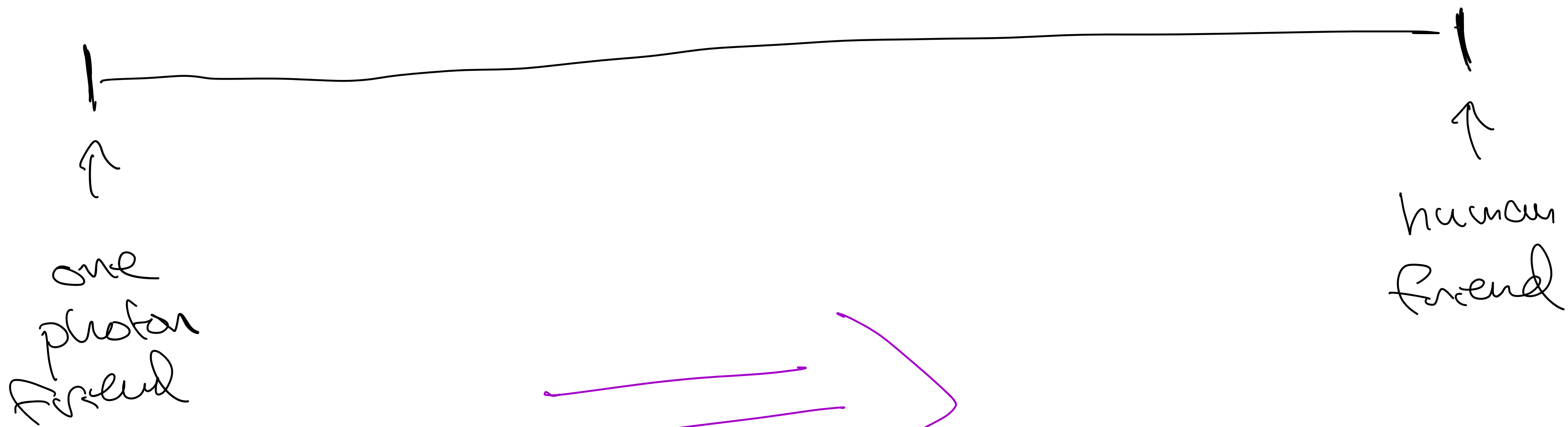
3. Deny a photon is an observer

What is an observer?

Something that has a "reality"?

Proposal for a Local Friendliness Experimental Program

LF violations scale:



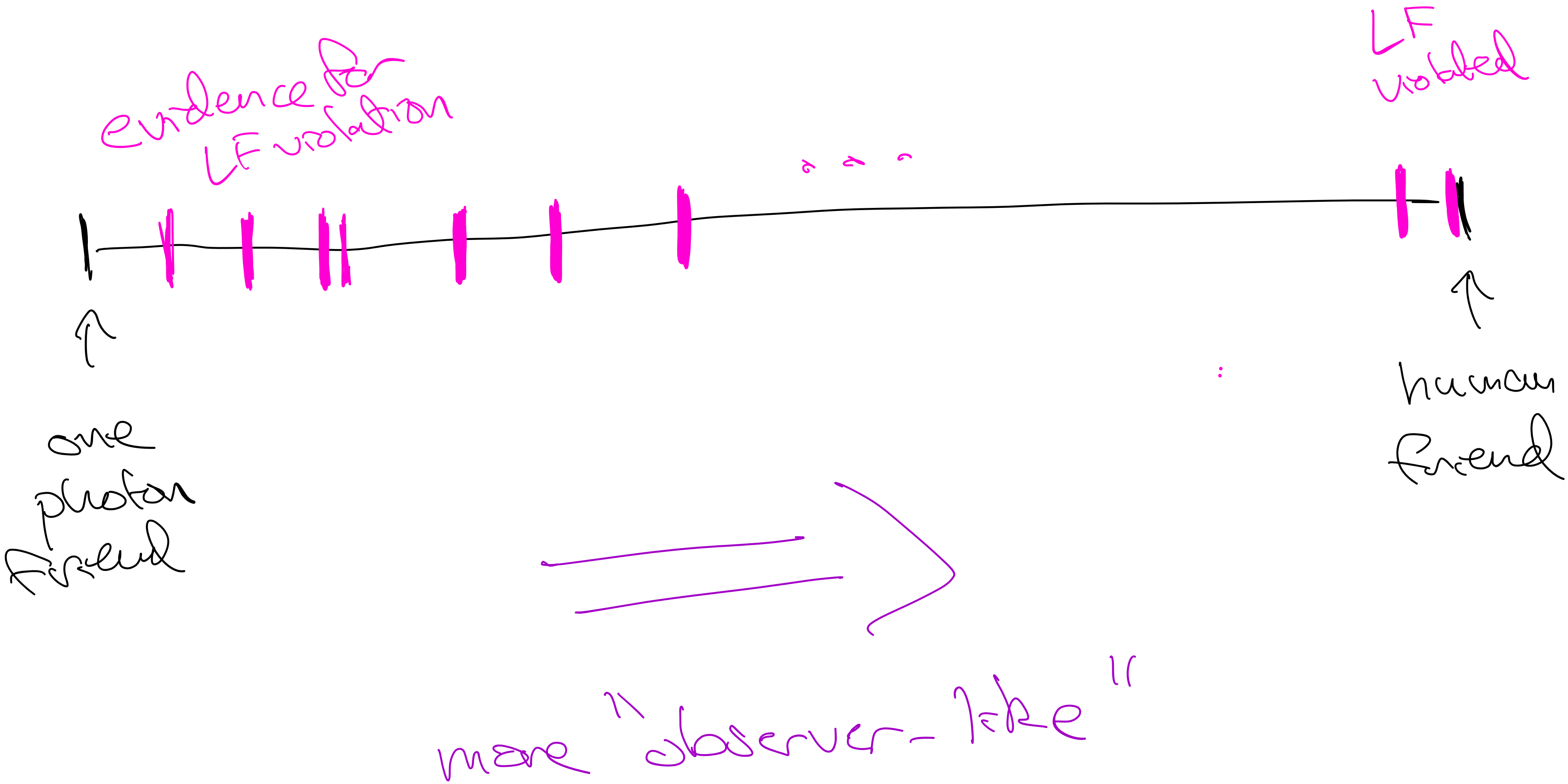
$\Longrightarrow$

more "observer-like"

Proposal for a Local Friendliness Experimental Program

OPTION 1

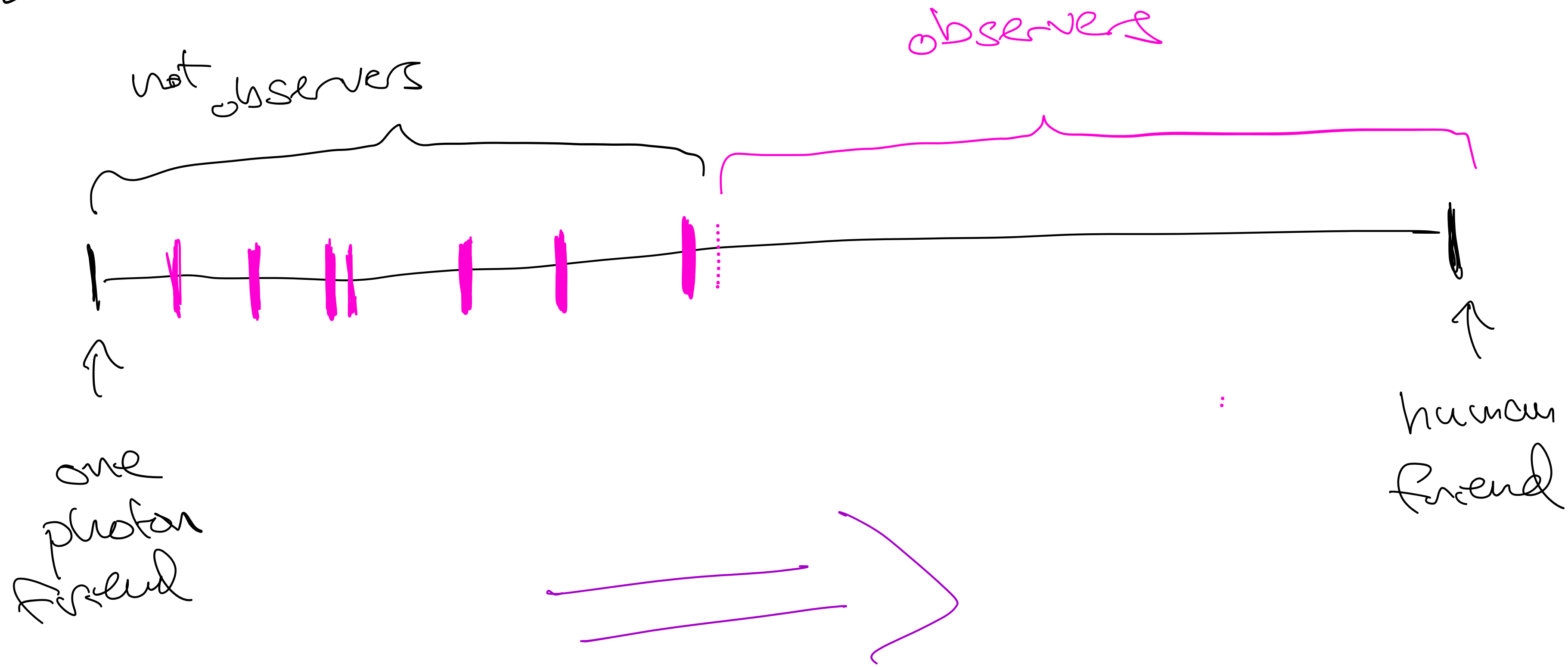
LF violations scale:



Proposal for a Local Friendliness Experimental Program

OPTION 2

LF violations scale:

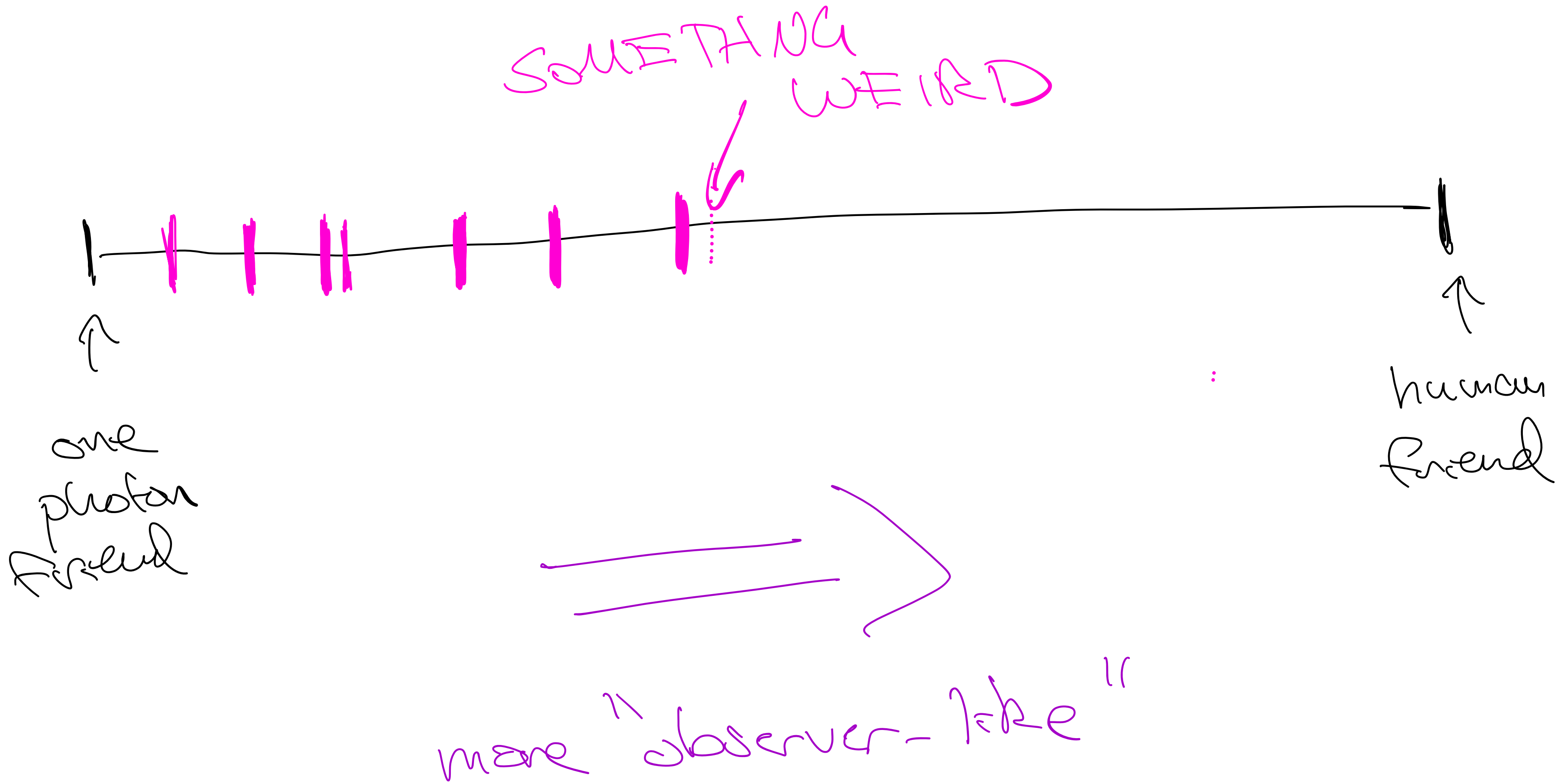


more "observer-like"

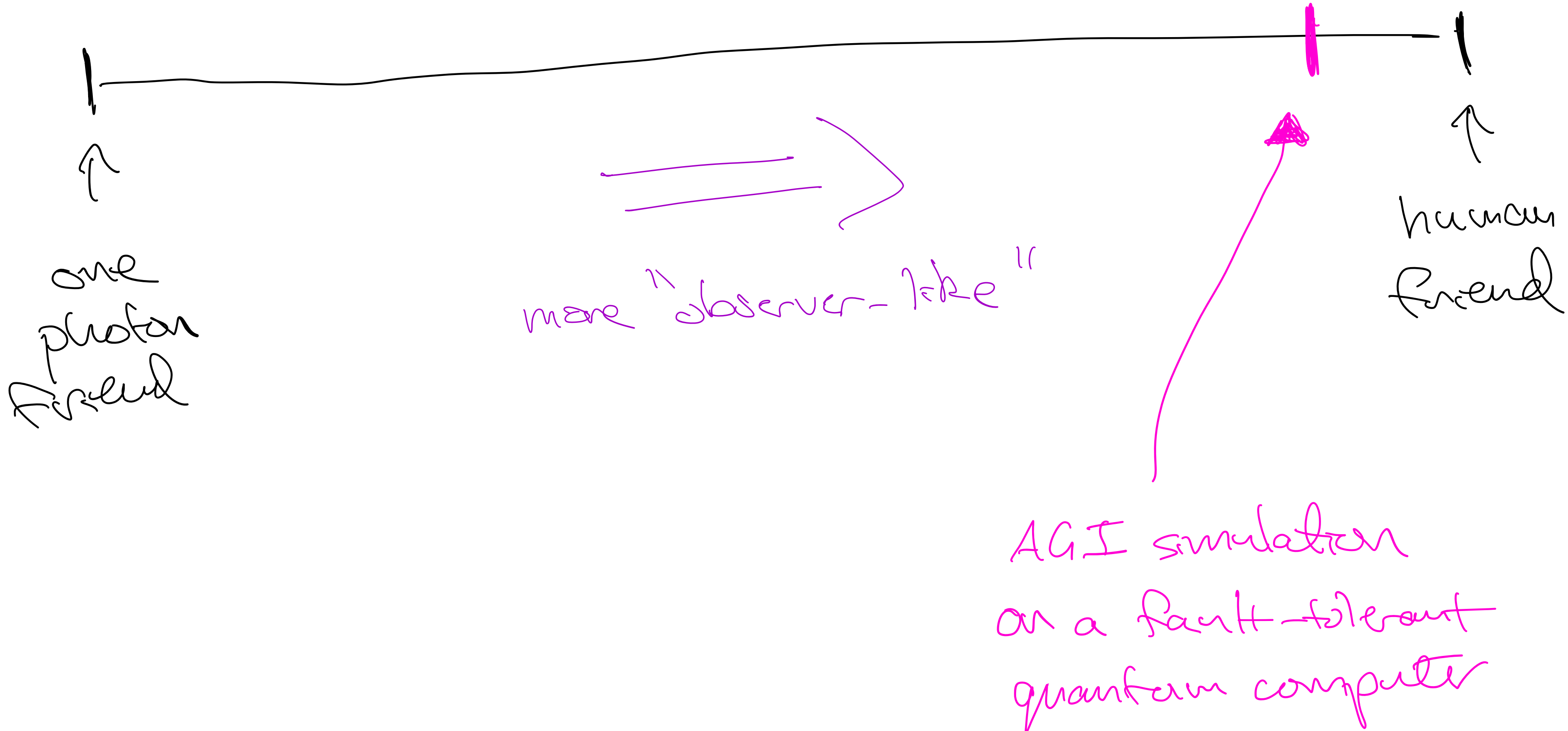
Proposal for a Local Friendliness Experimental Program

OPTION 3

LF violations scale:



AI observers



3×10^{19} logical qubits

10^{14} logical depth

Wiseman et al arXiv: 2209.08491

Obeserver-like Dimensions

- more mass
- more objectivity (e.g. redundancy + consensus)
- more degrees of freedom
- more entropy
- more agency
- more concious (e.g. IIT)
- more irreversible (e.g. Measurement Equilibration Hypothesis)

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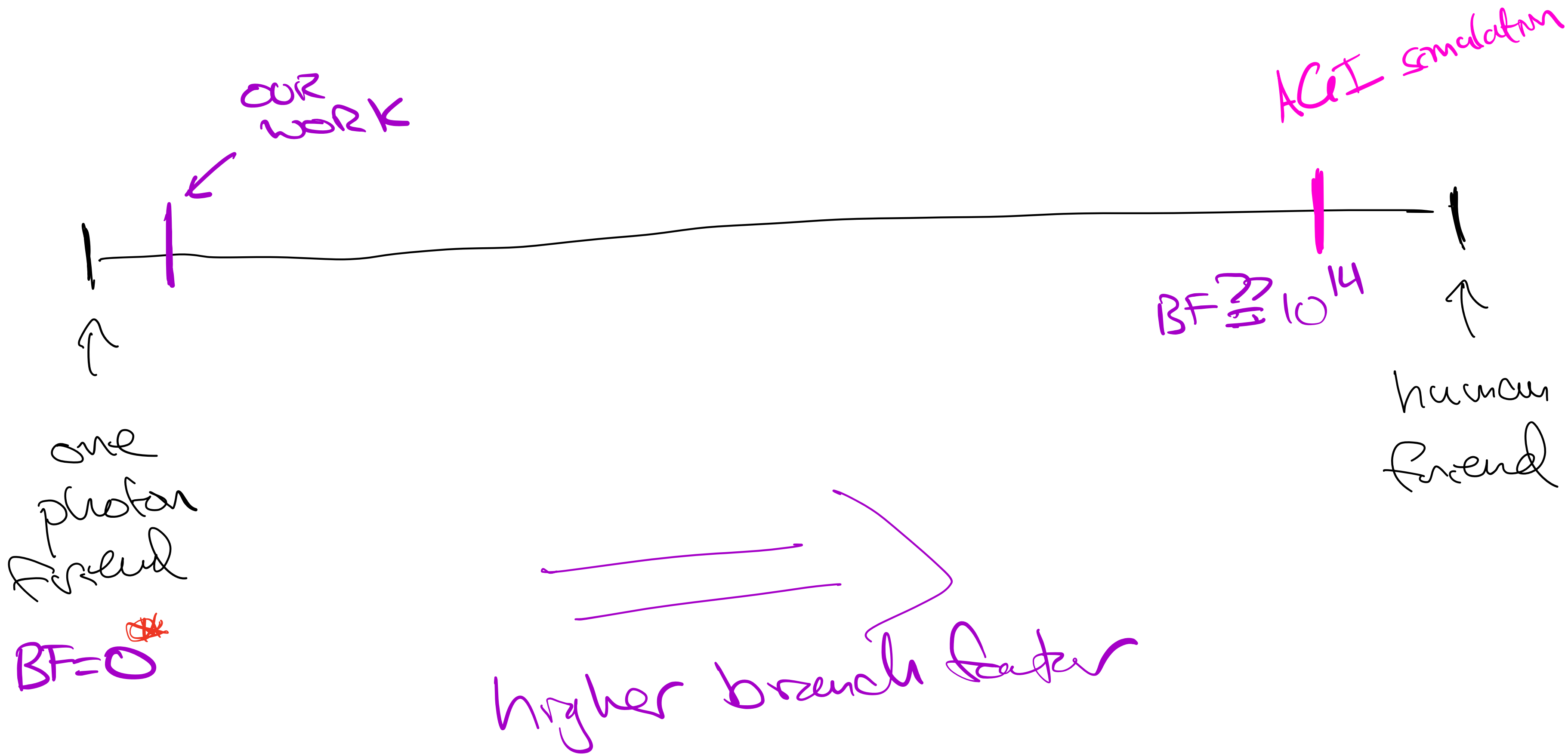
- more irreversible (e.g. Measurement Equilibration Hypothesis)
- higher branch factor } our focus

Taylor & McCullogh arXiv: 2308.04494

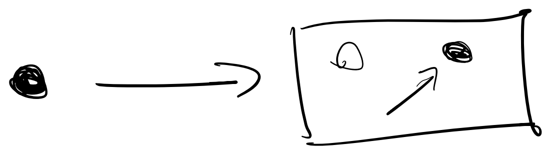


using quantum computers for experiments

* violations are not space separated

Branching

Branches form when superpositions can't be distinguished from classical mixtures.



system states i → measurement device states $|\varphi_i\rangle$

$$|\Psi\rangle = \sum_i c_i |\varphi_i\rangle$$

such that

$\rho := |\Psi\rangle\langle\Psi|$ is undistinguishable from

$$\rho_{\text{classical mixture}} := \sum_i |c_i|^2 |\varphi_i\rangle\langle\varphi_i|$$

Intuition: when

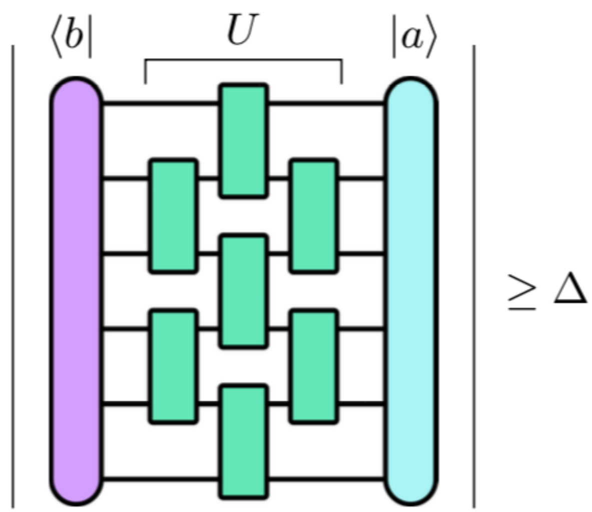
→ it is easy to distinguish the $|\varphi_i\rangle$

→ and hard to interfere them

Taylor & McCulloch arXiv: 2308.04494

State complexity

<u>Defn</u> $C(U)$ for two states $|a\rangle$ and $|b\rangle$ is the minimum number of gates (one and two qubit) needed to satisfy:



e.g. for $\Delta = 1$, U maps $|b\rangle$ to $e^{i\phi}|a\rangle$

Proposed 2nd law for state complexity

Distinguishability Complexity and Interference Complexity

- Smallest unitary that causes a measurable outcome change.

Definition 2 *The distinguishability complexity $\mathcal{C}_{\mathrm{D}}(|a\rangle, |b\rangle, \Delta)$ is the minimum number of gates in any circuit U satisfying $|P(m\,|\,U|a\rangle) - P(m\,|\,U|b\rangle)| \geq \Delta$, where m is any local product-state outcome on some or all of the qubits, and $P(m\,|\,|\psi\rangle)$ is the probability of that outcome given the state $|\psi\rangle$.*

Taylor & McCullogh arXiv: 2308.04494

Aaronson, Atia, Susskind arXiv: 2009.07450

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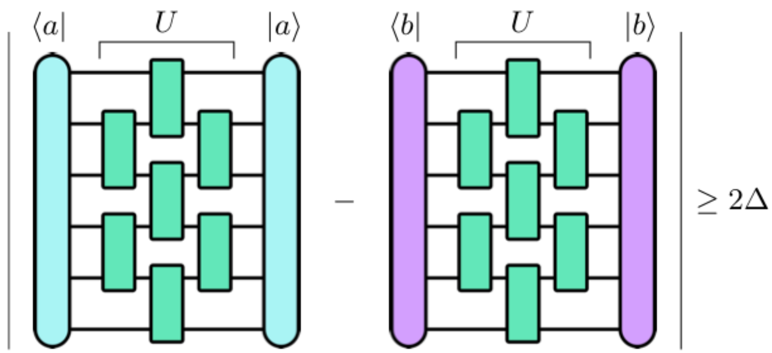
- Up to a constant this is ↓

Definition 3 *The* *distinguishability complexity proxy* $\mathcal{C}_{\tilde{\mathrm{D}}}(|a\rangle\,, |b\rangle\,, \Delta)$ *is the minimum number of gates in any circuit* U *satisfying* $|\langle a|U|a\rangle - \langle b|U|b\rangle| \geq 2\Delta$,



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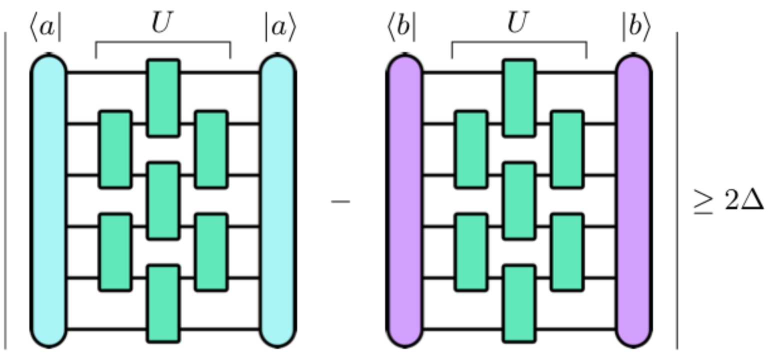

- Ability to measure phase info
  $\Rightarrow$ distinguish $(|a\rangle \pm e^{i\phi}|b\rangle)/\sqrt{2}$

Definition 4 *The* *interference complexity* $\mathcal{C}_{\mathrm{I}}(|a\rangle, |b\rangle, \Delta)$ *is the minimum number of gates in any circuit* U *satisfying* $\left|P(m\,|\,U\frac{|a\rangle+e^{i\theta}|b\rangle}{\sqrt{2}}) - P(m\,|\,U\frac{|a\rangle-e^{i\theta}|b\rangle}{\sqrt{2}})\right| \geq \Delta$, *where* θ *is any phase,* m *is any local product-state outcome on some or all of the qubits, and* $P(m\,|\,|\psi\rangle)$ *is the probability of that outcome given the state* $|\psi\rangle$.

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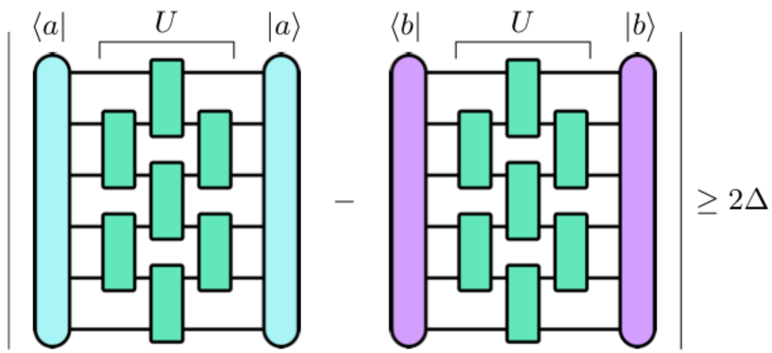

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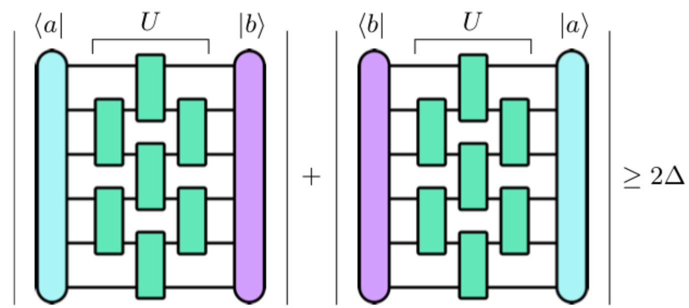
Definition 5 *The interference complexity proxy* $\mathcal{C}_{\tilde{\mathrm{I}}}(|a\rangle, |b\rangle, \Delta)$ *is the minimum number of gates in any circuit* U *satisfying* $|\langle a|U|b\rangle| + |\langle b|U|a\rangle| \geq 2\Delta$*,*



Taylor & McCulloch arXiv:2308.04494

Aaronson, Atia, Susskind arXiv:2009.07450

Observer metric: Branch Factor

- Pointer states: $|\Psi_0\rangle$ and $|\Psi_1\rangle$

<u>Defn</u> Branch Factor. Let $0 \le \delta \le 1$

$$BF(|\Psi_0\rangle, |\Psi_1\rangle, \delta) := C_I(|\Psi_0\rangle, |\Psi_1\rangle, \delta) - C_D(|\Psi_0\rangle, |\Psi_1\rangle, \delta)$$

Hard to interfere and easy to distinguish

Taylor & McCullough arXiv: 2308.04494

Observer memory: Branch factor

Ex GHZ state $|000\ldots\rangle + |111\ldots\rangle$

$C_I = N \qquad C_D = 1$

$$\overline{BF}_{GHZ} = N - 1$$

Haar-random

Ex Product + random $\alpha|000\ldots\rangle + \beta|\eta\rangle$

$C_I \simeq O(\exp(N)) \qquad C_D = O(1)$

Ex Two random states w/ depth D_1, D_2

$C_I = \Theta((D_1 + D_2)N)$

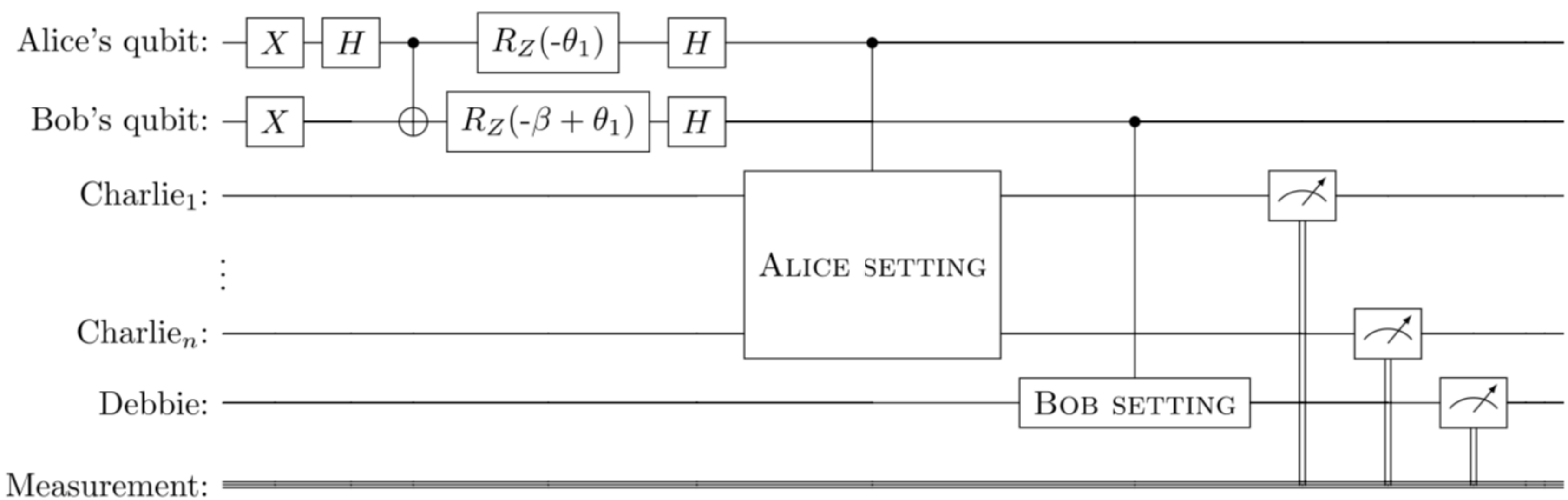
$C_D = \Theta(\min(D_1, D_2)N)$

Taylor & McCulloch arXiv:2308.04494

Quantum Circuit for LF violations

obs metric = branch factor

friend states = $|0\rangle^n$ and $|1\rangle^n$

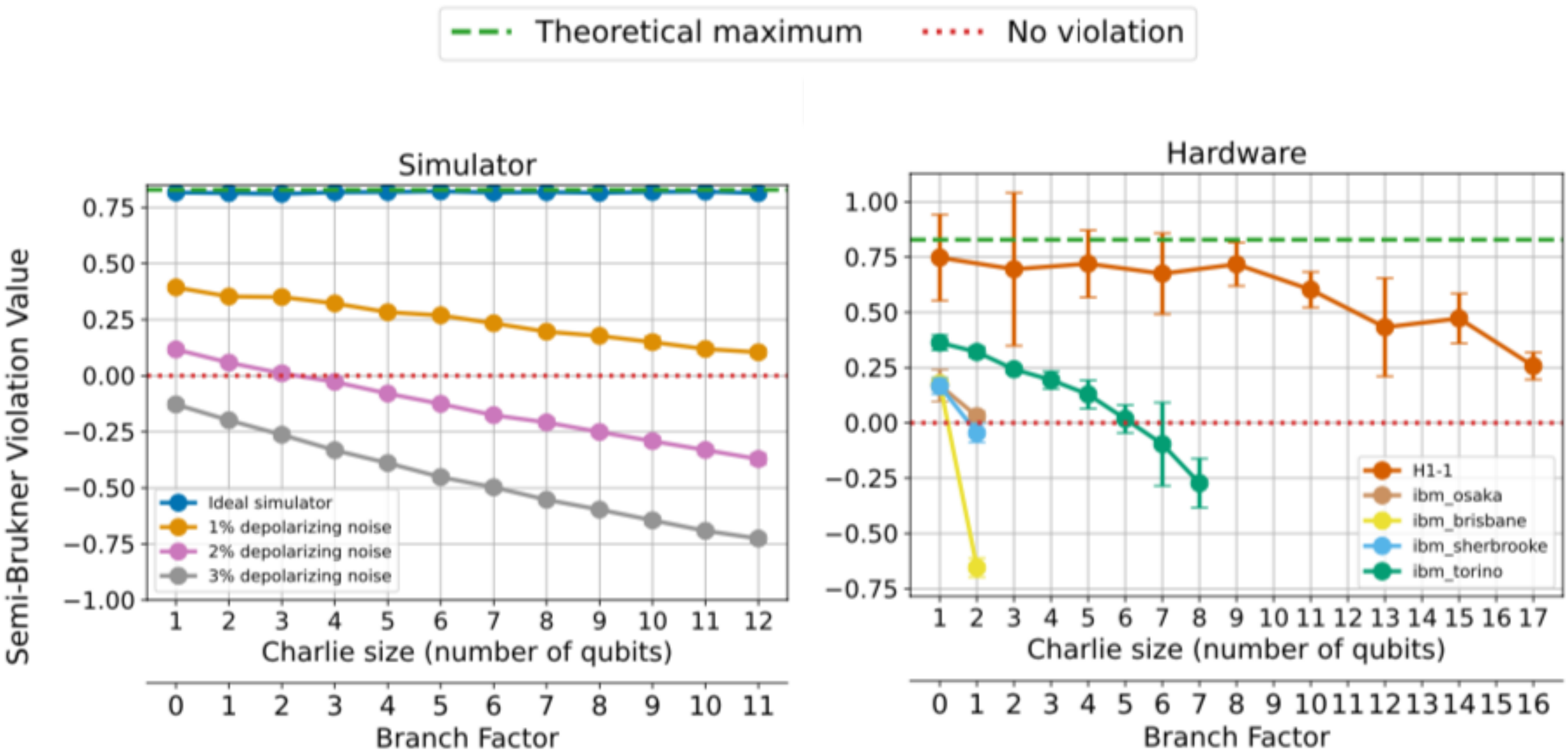


Semi-Brukner inequality

$$\langle A_2B_2\rangle - \langle A_2B_3\rangle - \langle A_3B_2\rangle - \langle A_3B_3\rangle - 2 \leq 0.$$

choosing optimal bases for Alice/Bob settings gives max violation ~ 0.828

Results



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Validating our prepared branch factor

> Friend state target $|\Psi\rangle := (|\Psi_0\rangle + |\Psi_1\rangle)/\sqrt{2}$
but w/ noise we prepare ρ

> Fidelity $\langle\Psi|\rho|\Psi\rangle \leq$ prob q we prepared $|\Psi\rangle$

Semi-Brukner $X := \langle A_2B_2\rangle - \langle A_2B_3\rangle - \langle A_3B_2\rangle - \langle A_3B_3\rangle \geq 2$

$$\langle A_iB_j\rangle = q\langle A_iB_j\rangle^{\text{valid}} + \underbrace{(1-q)\langle A_iB_j\rangle^{\text{invalid}}}_{\text{Assume worst case}}$$

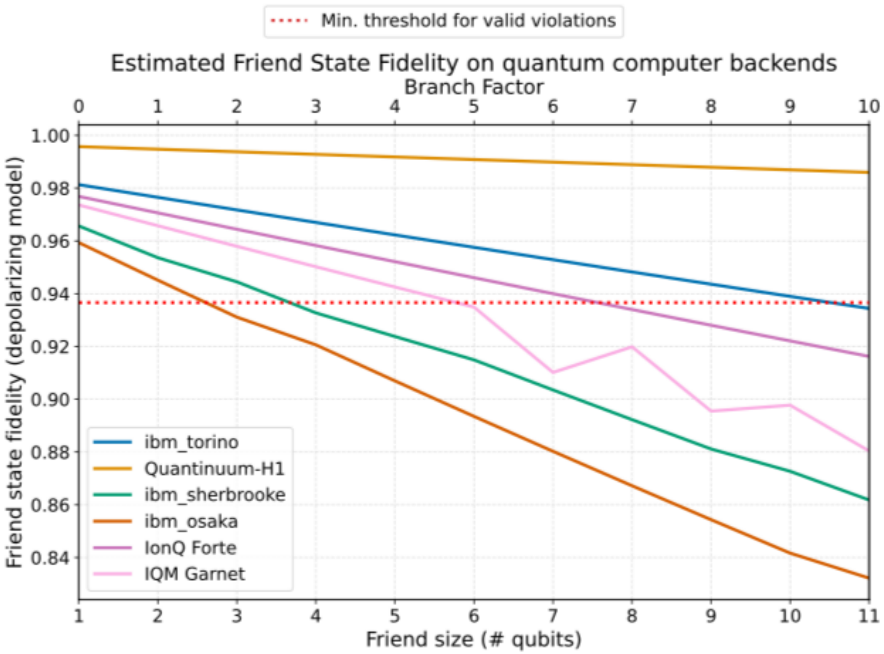
$\Rightarrow$ measured

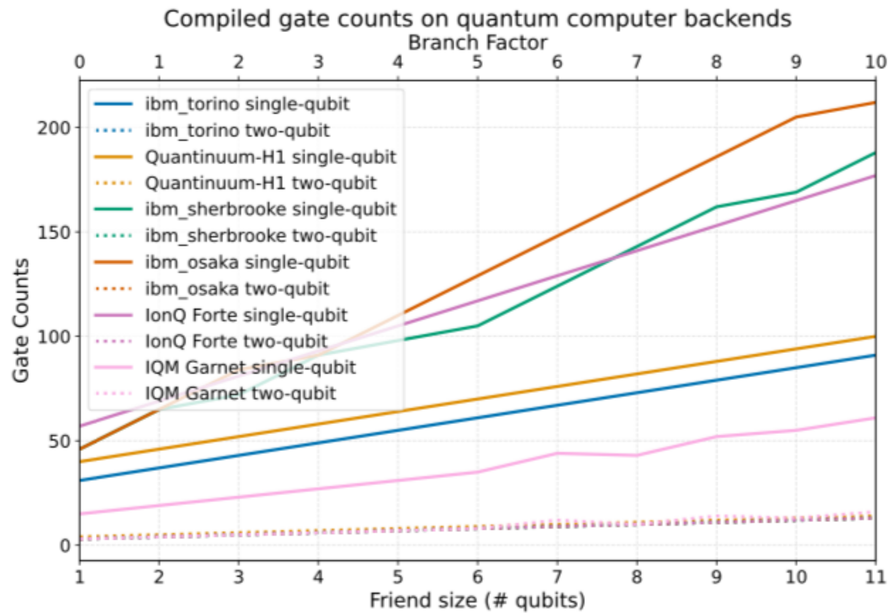
$$\bar{X} \geq 8 - 6q \text{ to ensure violations}$$

max $\bar{X}$ of 0.828 means

friend state fidelity $q \geq \sim 93.6\%$

Validating Branch Factors





Next Steps

- More data on better QPUs
- Can we calculate the branch factors for meaningful physical systems, e.g. photodetectors, brains, etc.
- other observer metrics potentially w/ other experimental setups e.g. macro superposition
- closing loopholes w/ spacelike separation

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