Guaranteeing non-classicality in experimental quantum networks without assuming quantum mechanics

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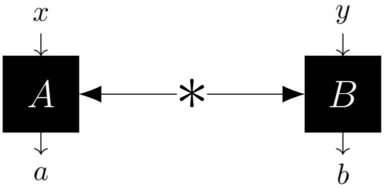
What you are about to see

Nonlocality



$$p(a,b|x,y) = \int \mathsf{d}\lambda\, q(\lambda)p(a|x,\lambda)p(b|y,\lambda)$$

$$\text{CHSH} := \sum_{a,b,x,y} (-1)^{a+b+xy} p(a,b|x,y) \leq 2$$

Tavakoli, APK, Luo, Renou, *Rep. Prog. Phys.* **85**, 056001 (2022), arXiv:2104.10700

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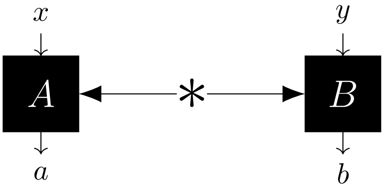

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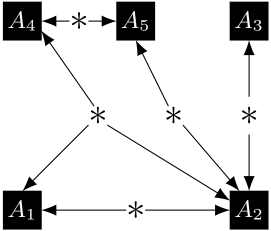

$$p(\bar{a}|\bar{x}) = \int \left[\prod_{j=1}^{m} \mathsf{d}\lambda_j q(\lambda_j) \right] \prod_{i=1}^{n} p(a_i|x_i, \bar{\lambda}_i)$$

Tavakoli, APK, Luo, Renou, *Rep. Prog. Phys.* **85**, 056001 (2022), arXiv:2104.10700

What does a violation of a network Bell inequality mean?

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Option 1: The network is not the one you think

NOT this talk. Check poster 51 (Andrés Ulibarrena, today's session)

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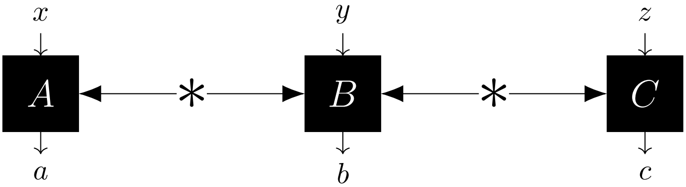
Option 2: Something non-classical is going on

In Bell scenarios, nonlocality ⇒ the source is non-classical

But the opposite of *all sources are classical* is *at least one source is non-classical*

$$\sqrt{|I|} + \sqrt{|J|} \overset{\text{C-C}}{\leq} 1$$



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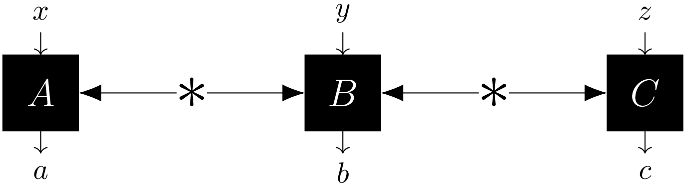
$$\sqrt{|I|}+\sqrt{|J|} \overset{\text{C-C}}{\leq} 1 \overset{\text{C-Q}}{\leq} 2^{1/4}$$



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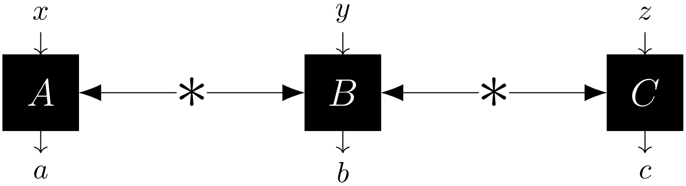

What if we don't assume QM?

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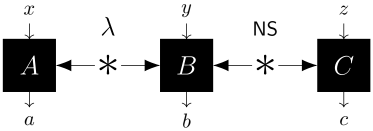


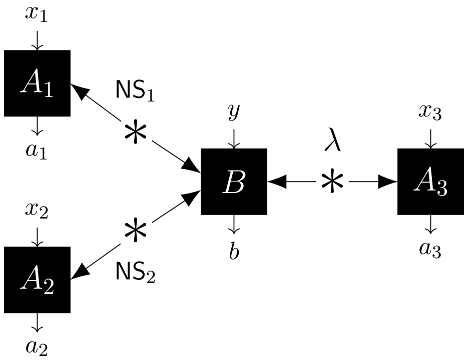
A and B share $\Lambda \in \{0,1\}$ with $p(\lambda)=\frac{1}{2}$.

B and C share $p(b,c|\lambda,z)=\frac{1}{4}[1+(-1)^{b+c+\lambda z}]$

If we do not assume quantum mechanics, can we guarantee non-classicality?

APK, Gisin, Tavakoli, *Phys. Rev. Lett.* **128**, 010403 (2022), arXiv:2105.09325

Full network nonlocality



In a given network and input/output scenario, $p(\bar{a}|\bar{x})$ is fully NN iff it *cannot* be modelled by allowing at least one source in the network to be of a local-variable nature.

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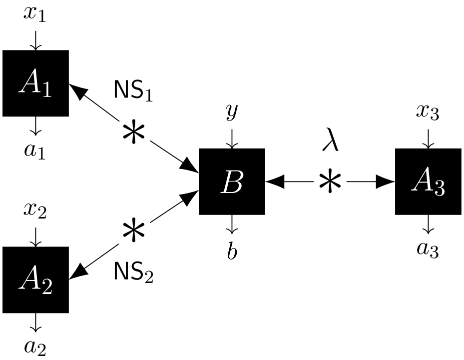

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Guarantee of non-classicality

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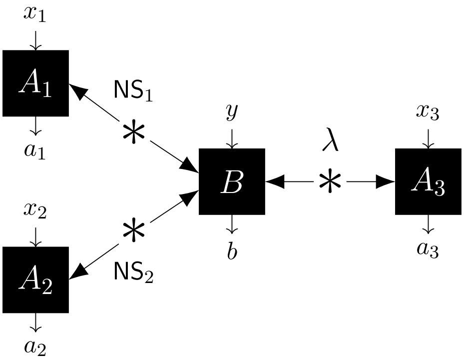

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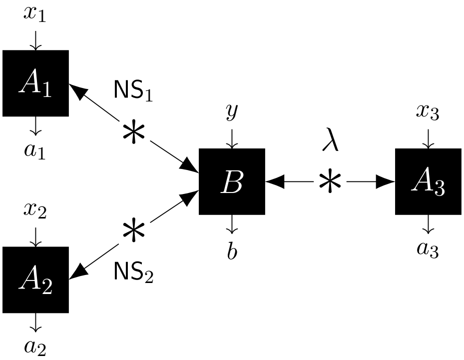

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Guarantee of non-classicality

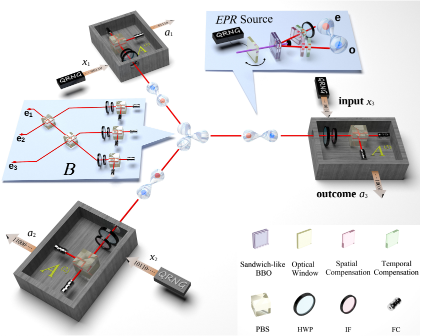
No mention to quantum mechanics

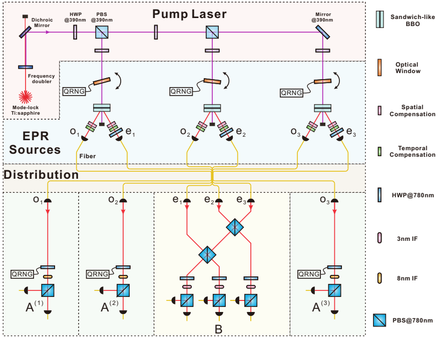
Easy to characterize via inflation

Wolfe, Spekkens, Fritz, *J. Causal Inference* **7**, 2017-0020 (2019), arXiv:1609.00672

APK, Gisin, Tavakoli, *Phys. Rev. Lett.* **128**, 010403 (2022), arXiv:2105.09325

First ever demonstration on star network





Branch parties perform 2 binary-outcome measurements

Central party performs 1 binary-outcome measurement

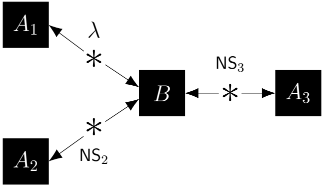
$$p(a_1, a_2, a_3, b|x_1, x_2, x_3)$$

Wang, APK *et al.*, *Nat. Commun.* **14**, 2153 (2023), arXiv:2212.09765

First ever demonstration on star network

Found using inflation [J. Causal Inference 7, 2017-0020 (2019)]

$$\begin{aligned}\mathcal{I}_1 = &-\langle A_0^{(1)} A_0^{(2)} A_0^{(3)} B\rangle - \langle A_1^{(1)} A_0^{(2)} A_0^{(3)} B\rangle - \langle A_0^{(1)} A_0^{(2)} A_1^{(3)} B\rangle + \langle A_1^{(1)} A_0^{(2)} A_1^{(3)} B\rangle \\ &- \langle A_0^{(1)} A_0^{(2)} A_0^{(3)}\rangle - \langle A_1^{(1)} A_0^{(2)} A_0^{(3)}\rangle - \langle A_0^{(1)} A_0^{(2)} A_1^{(3)}\rangle + \langle A_1^{(1)} A_0^{(2)} A_1^{(3)}\rangle - \langle A_0^{(1)} A_0^{(3)} B\rangle \\ &- \langle A_1^{(1)} A_0^{(3)} B\rangle - \langle A_0^{(1)} A_1^{(3)} B\rangle + \langle A_1^{(1)} A_1^{(3)} B\rangle - \langle A_0^{(1)} A_0^{(3)}\rangle - \langle A_1^{(1)} A_0^{(3)}\rangle - \langle A_0^{(1)} A_1^{(3)}\rangle \\ &+ \langle A_1^{(1)} A_1^{(3)}\rangle - 2\langle A_0^{(2)} B\rangle - 2\langle A_0^{(2)}\rangle - 2\langle B\rangle - 2\end{aligned}$$



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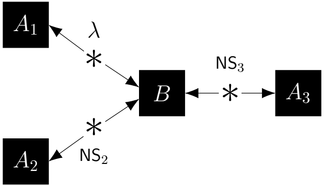

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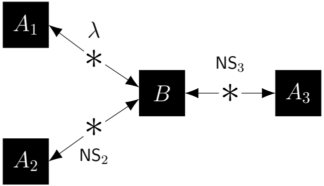
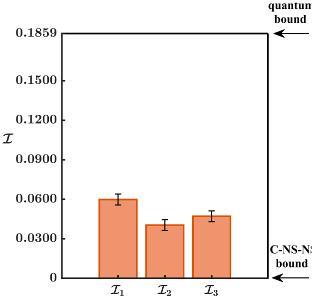
We need

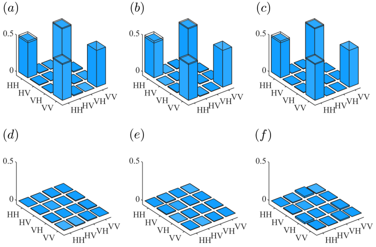
1. S_1 and S_3 non-classical
2. B performs an entangling measurement



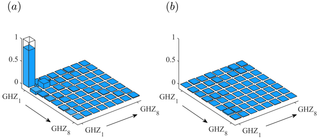
Wang, APK *et al.*, *Nat. Commun.* **14**, 2153 (2023), arXiv:2212.09765

First ever demonstration on star network: results





Fidelities $> 97.8\%$



Fidelity $\approx 82\%$

We need

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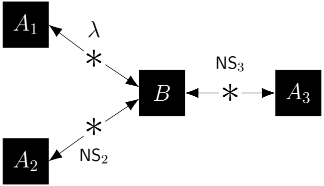

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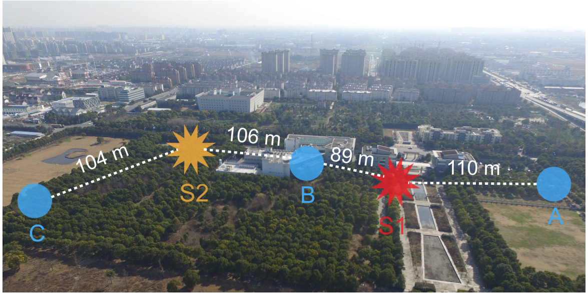
Loopholes: Locality, measurement independence, detection efficiency, *source independence*, ...

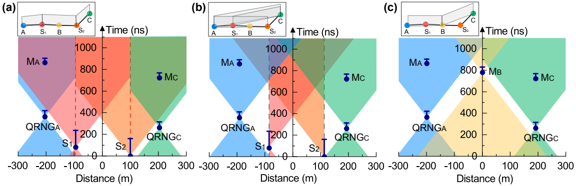
A paranoid demonstration



- Two separate lasers

  (spectral + time + space indistinguishability)
- Real-time QRNGs
- Precise timing

  Ultrafast optics & electronics



Closed loopholes

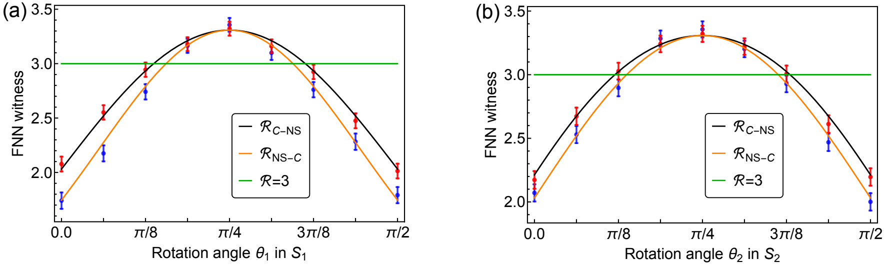
Locality

Measurement independence

Source independence

Gu, Huang, APK *et al.*, *Phys. Rev. Lett.* **130**, 190201 (2023), arXiv:2302.02472

A paranoid demonstration: results



Model: Sources have white noise

HOM projects into $\Pi^{\pm} = v_h \Phi^{\pm} + \frac{1-v_h}{2}(\Phi^+ + \Phi^-)$ or $\mathbb{1} - \Pi^+ - \Pi^-$

MES visibilities: $v_{\mathsf{S}_1} = 0.9710 \pm 0.0035$ and $v_{\mathsf{S}_2} = 0.9860 \pm 0.0007$

HOM visibility: $v_h = 0.943 \pm 0.027$

At maximum: $\mathcal{R}_{\text{C-NS}} = 3.3212 \pm 0.0638$, $\mathcal{R}_{\text{NS-C}} = 3.3563 \pm 0.0632$ ($\mathcal{R}_{\text{Q-Q}} \approx 3.356$)

Gu, Huang, APK *et al.*, *Phys. Rev. Lett.* **130**, 190201 (2023), arXiv:2302.02472

The end

Conclusions

- FNN: correlations impossible to attain unless all sources are nonclassical
- Guarantees without assuming QM
- Strong observations in hard conditions

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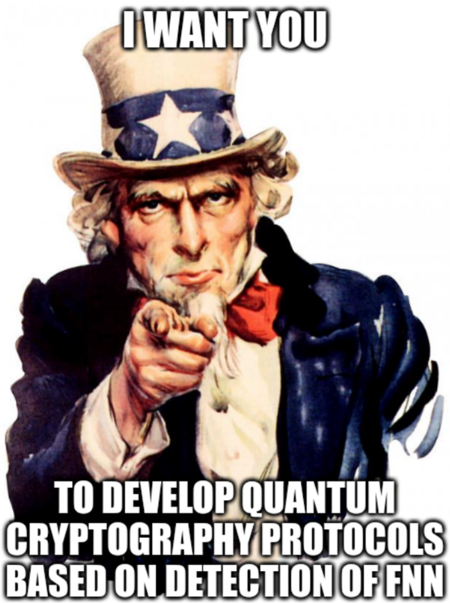
Next steps

- More networks (triangle)
- Certification of network structure

  See poster 51 today (Andrés Ulibarrena)
- Close remaining loopholes

More importantly...

- Strong observations in demanding conditions
- Networks are a natural theoretical model
  Milder requirements in visibilities, etc.
- Can bring back the assumption of QM to get even milder conditions



Xue-Mei Gu (USTC-MPL)

Chao Zhang (USTC)

Andrés Ulibarrena (Heriot-Watt)

Thank you for your attention

Questions? Comments?

2104.10700	NN Review	(Rep. Prog. Phys. 85, 056001)
2105.09325	Full NN	(Phys. Rev. Lett. 128, 010403)
2212.09765	3-branch star	(Nat. Commun. 14, 2153)
2302.02472	Bilocality	(Phys. Rev. Lett. 130, 190201)

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