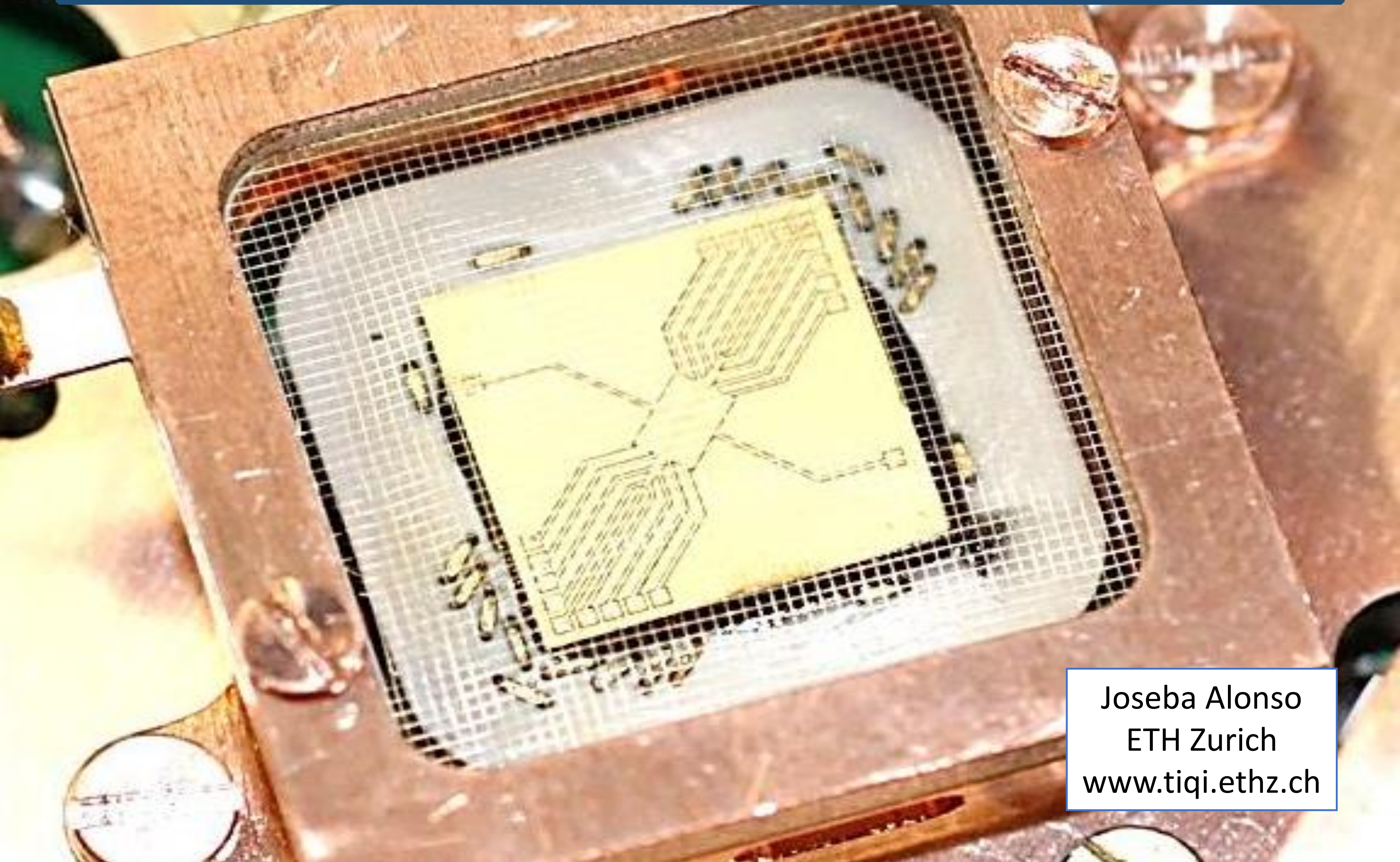
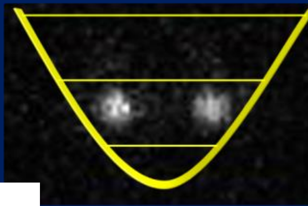
Quantum contextuality tests with a single trapped-ion qutrit



Joseba Alonso
ETH Zurich
www.tiqi.ethz.ch

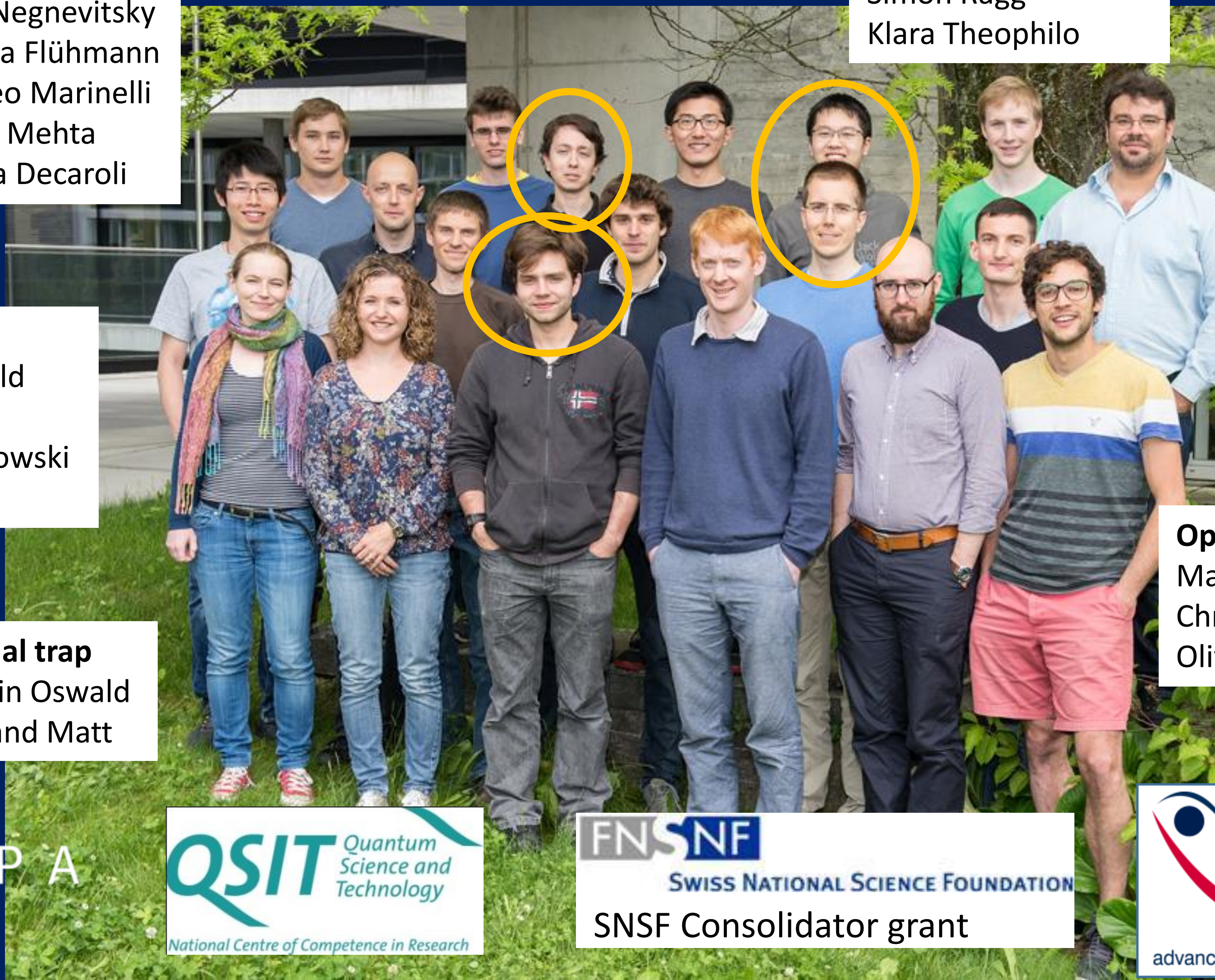
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Trapped Ion Quantum Information Group
ETH Zürich
www.tiqi.ethz.ch



PCF trap
Frieder Lindenfelser
Simon Ragg
Klara Theophilo

3-D wafer trap
Vlad Negnevitsky
Christa Flühmann
Matteo Marinelli
Karan Mehta
Chiara Decaroli



Collaborator
Adán Cabello

Cryo trap
Florian Leupold
Chi Zhang
Maciej Malinowski
Peng Zhou

Optical traps
Matt Grau
Christoph Fischer
Oliver Wipfli

eQual trap
Robin Oswald
Roland Matt

IARPA
BE THE FUTURE

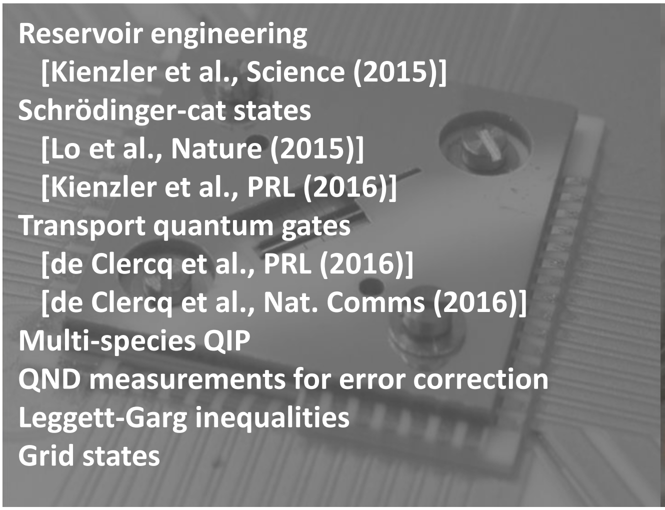
QSIT Quantum Science and Technology
National Centre of Competence in Research

FNSNF
SWISS NATIONAL SCIENCE FOUNDATION
SNSF Consolidator grant

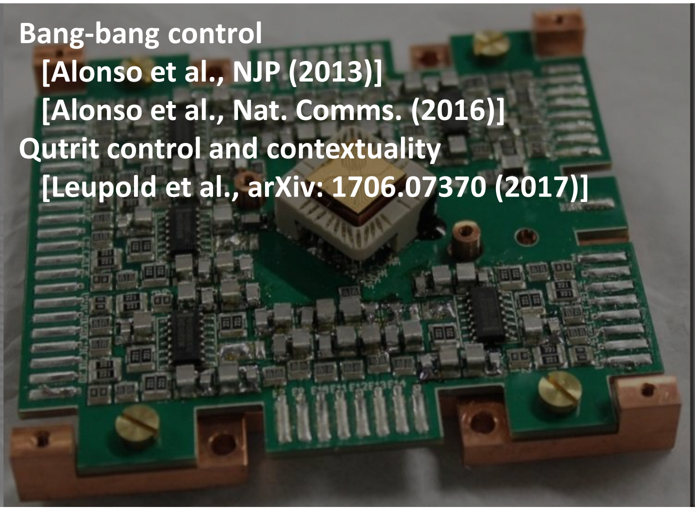
SAOT
erlangen graduate school in advanced optical technologies

Ion trap: electrodes + vacuum

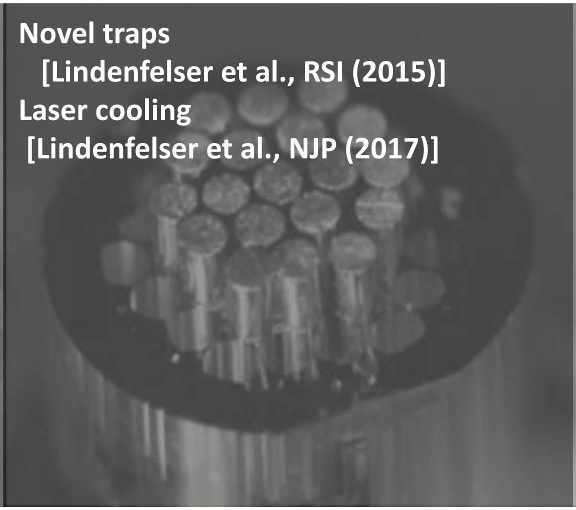
3D wafer trap



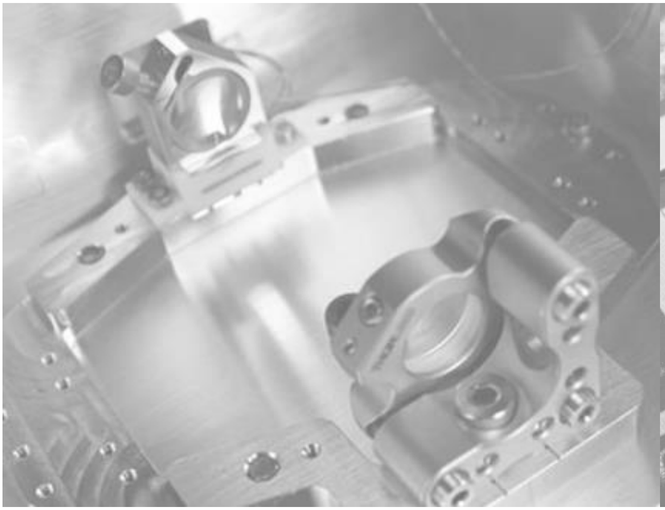
Cryo surface trap



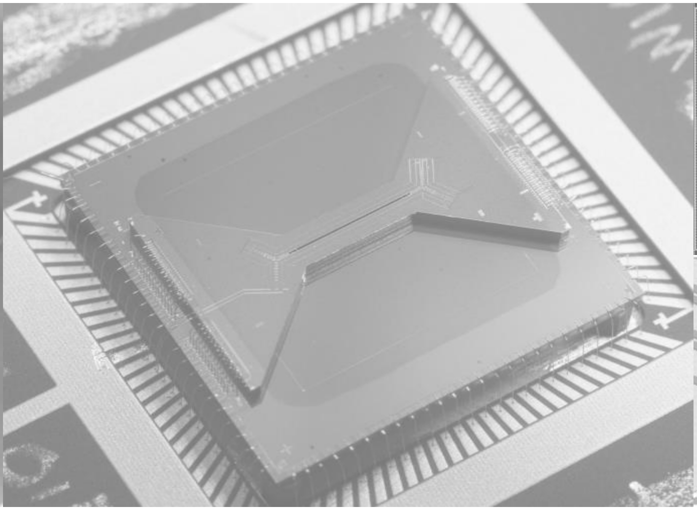
PCF trap



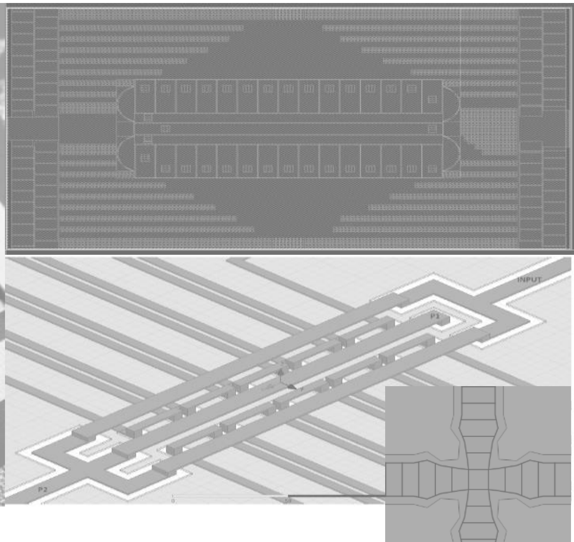
Optical trap



HOA2 trap

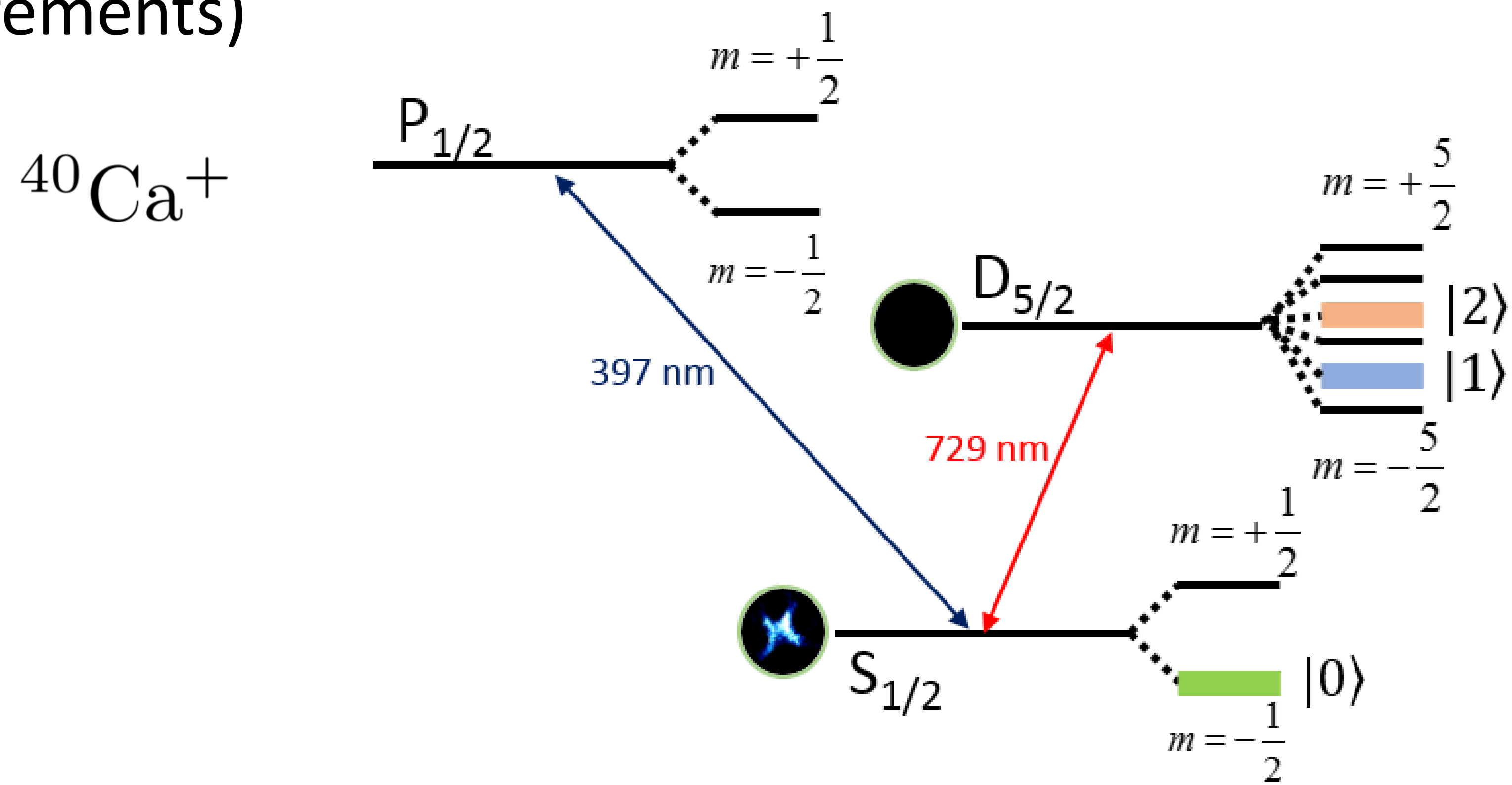


More traps



Trapped ions for contextuality tests

- Long coherence
- High-fidelity operations
- Non-destructive fluorescence detection (projective measurements)

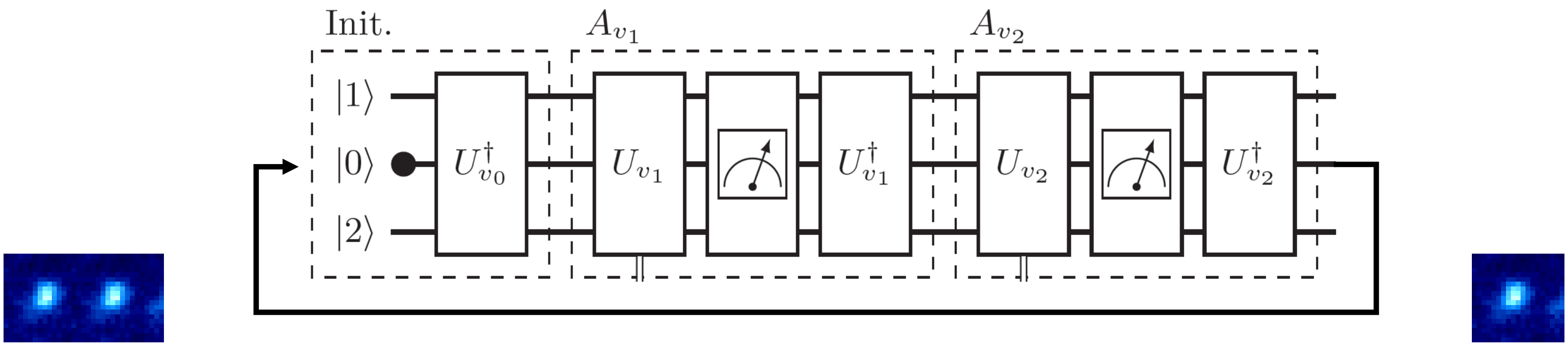


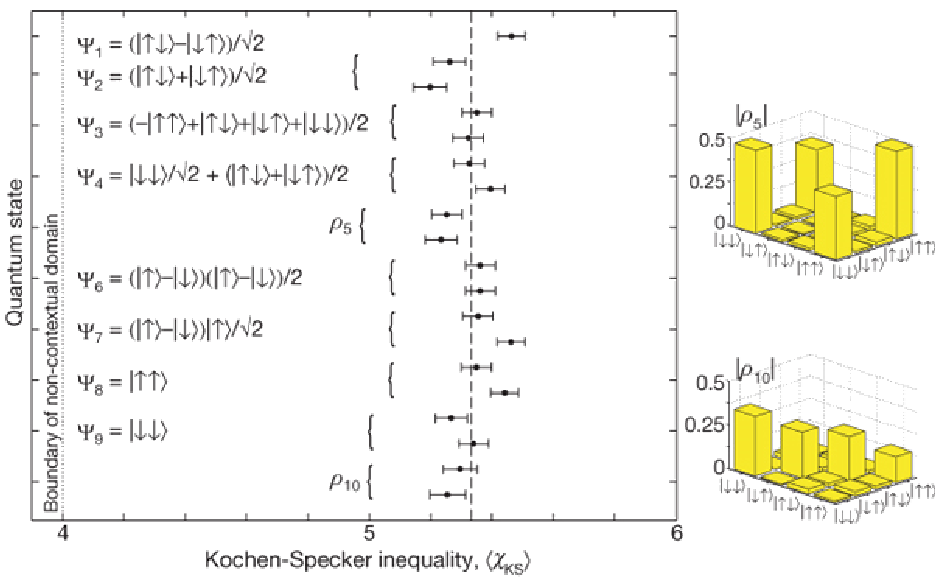
Outline

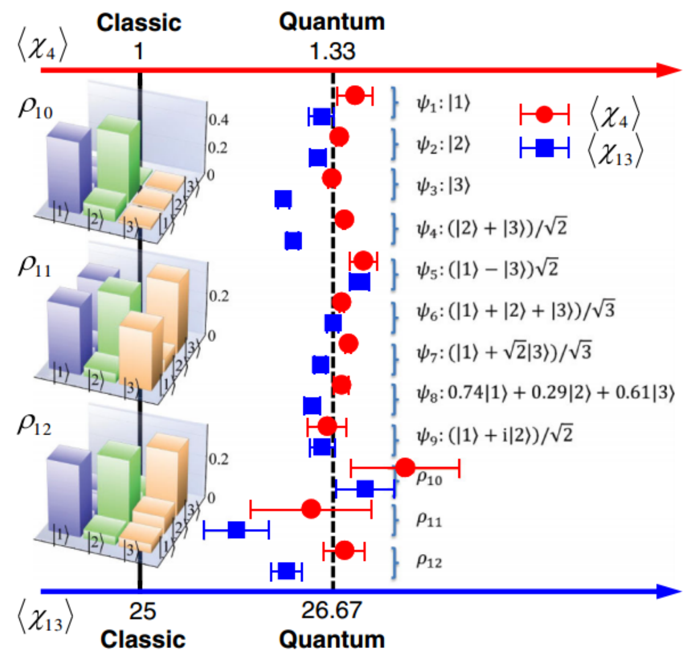
1. SIC à la Wajs

2. Extended KCBS tests

Previous trapped-ions SIC tests





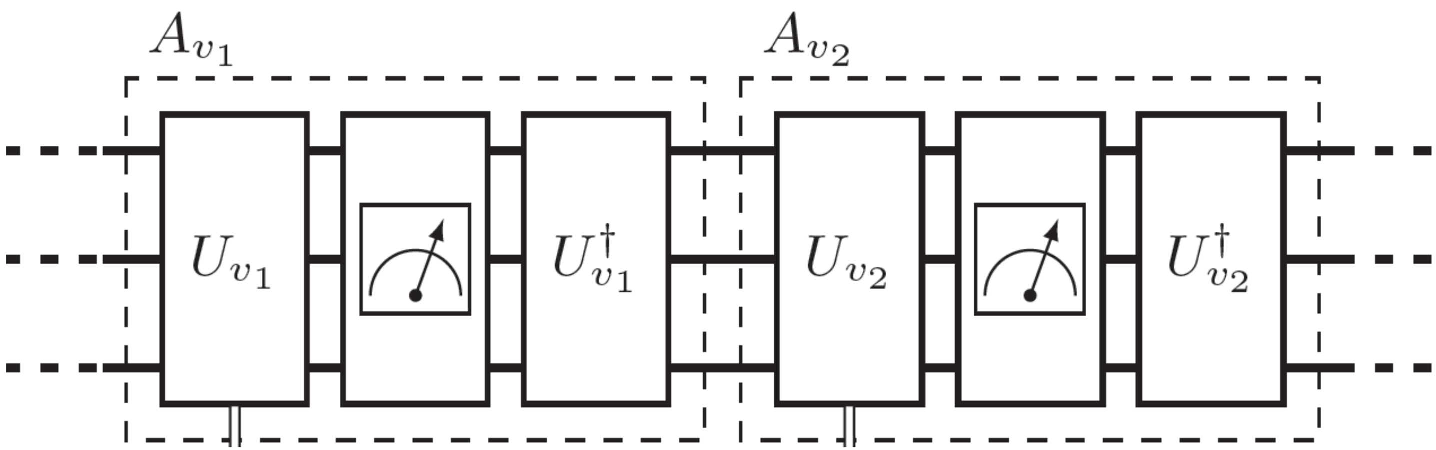


[G. Kirchmair et al., Nature 460 (2009)]
[A. Peres, Phys. Lett. A 151 (1990)]

[X. Zhang et al., Phys. Rev. Lett. 110 (2013)]
[S. Yu and C.H. Oh, Phys. Rev. Lett. 108 (2012)]

SIC à la Wajs

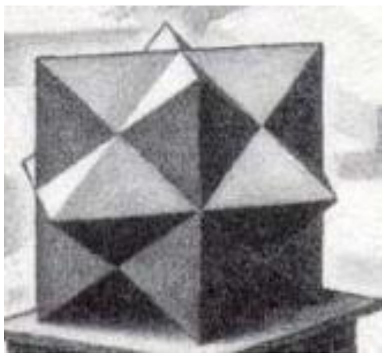
[M. Wajs et al., Phys. Rev. A 93 (2016)]

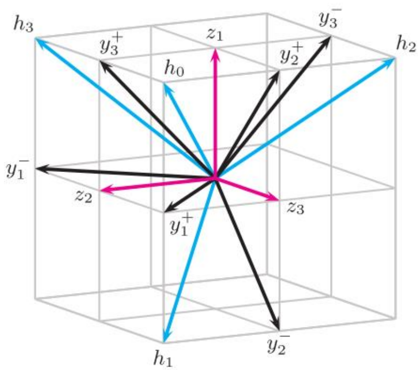


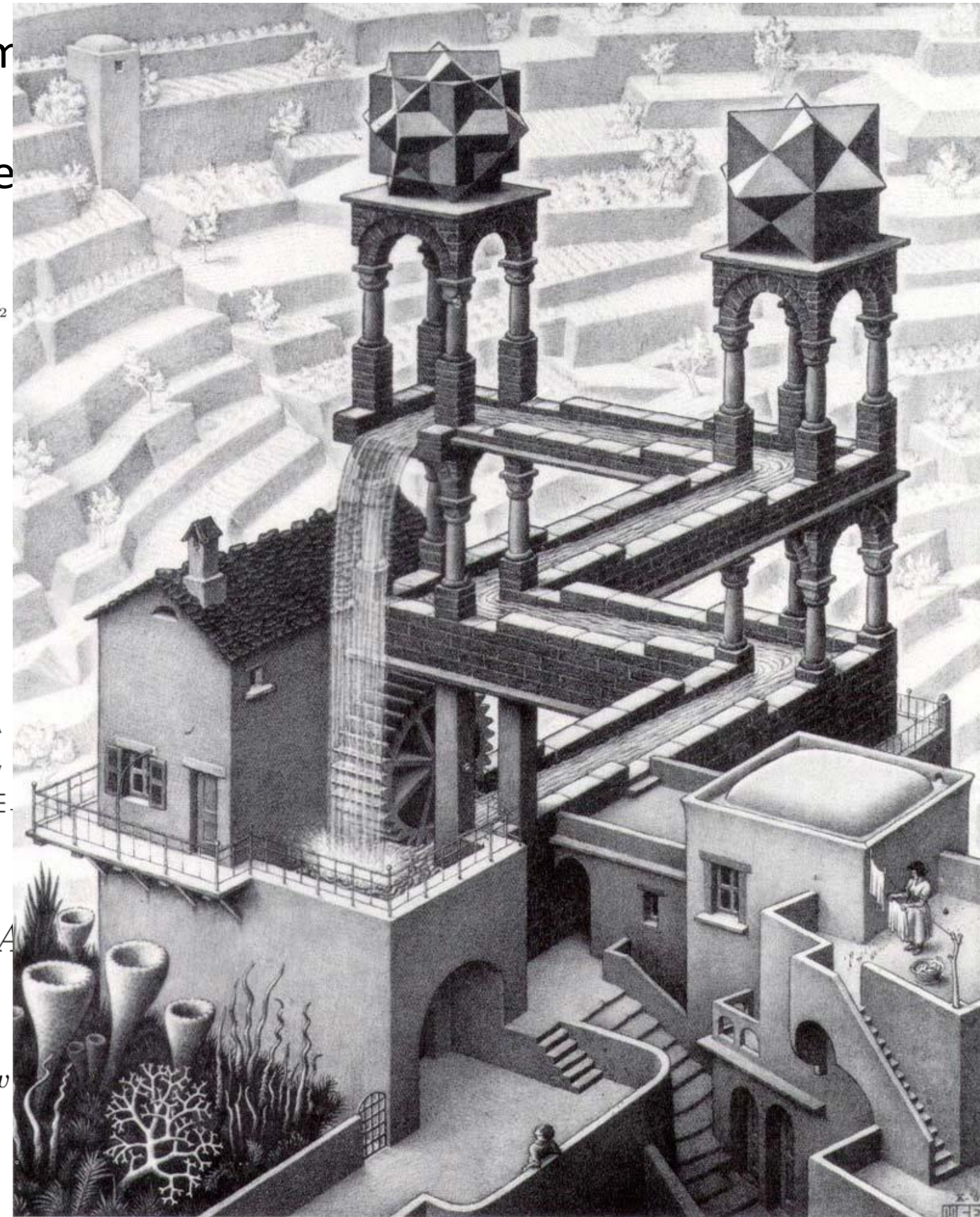
Repeated measurements
Random input states
No state initialization – self correcting
High-order correlators
"Quantumness" is about measurements, not designated states

Yu & Oh SIC set

- Qutrit: smallest contextual system
- Yu & Oh set: smallest SIC set
- opt3 witness: largest deviation be





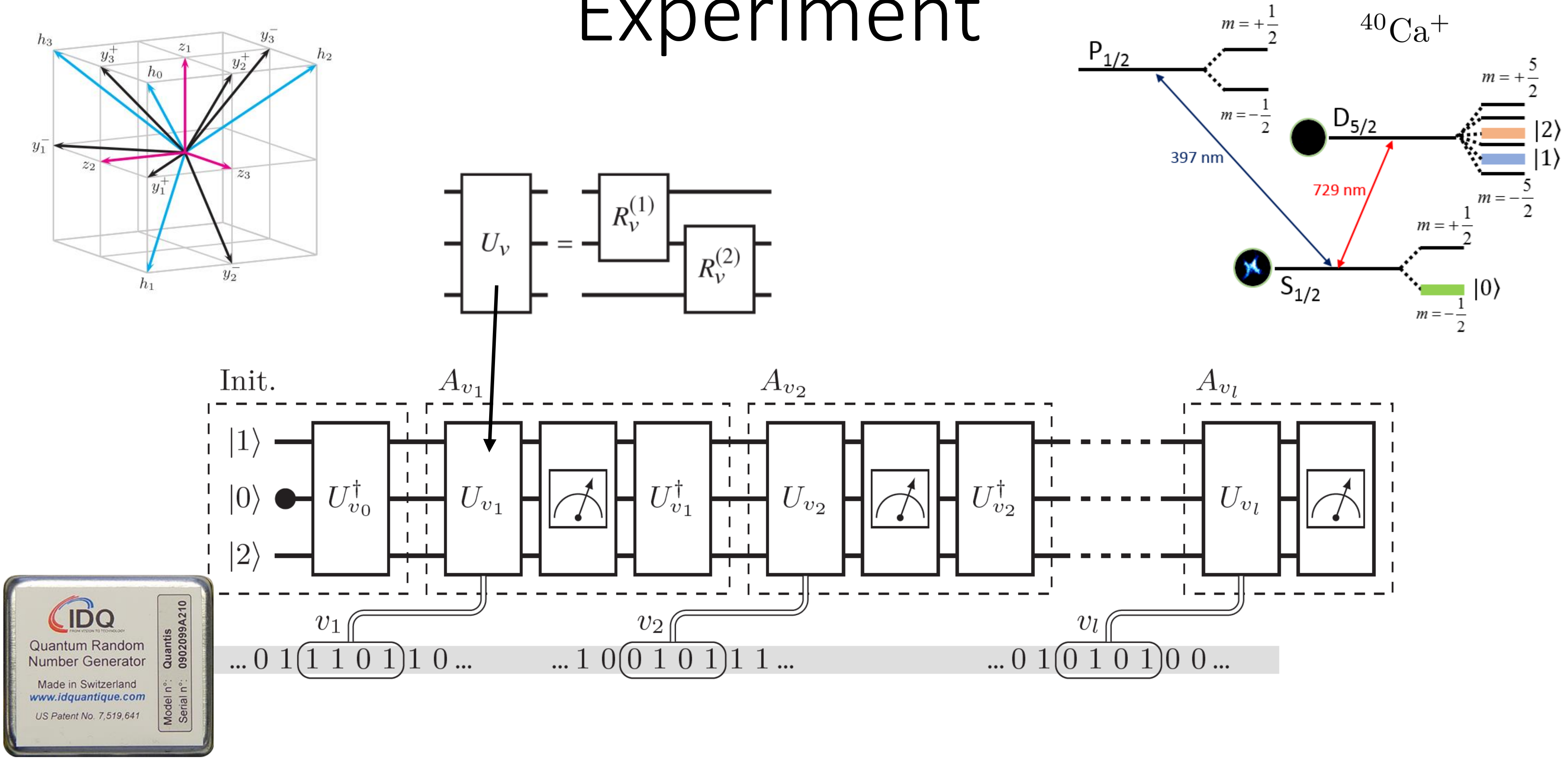


$$\langle \chi_{\mathrm{YO}} \rangle = \sum_{v \in V} \langle A_v \rangle - \sum_{(u,v)\in}$$

$$\langle \chi_{\mathrm{opt3}} \rangle = \sum_{v \in V_h} 2 \langle A_v \rangle + \sum_{v \in V \setminus V_h} \langle A$$

$$- \sum_{(u,v,w) \in C_3} 3 \langle A_u A_v A_w$$

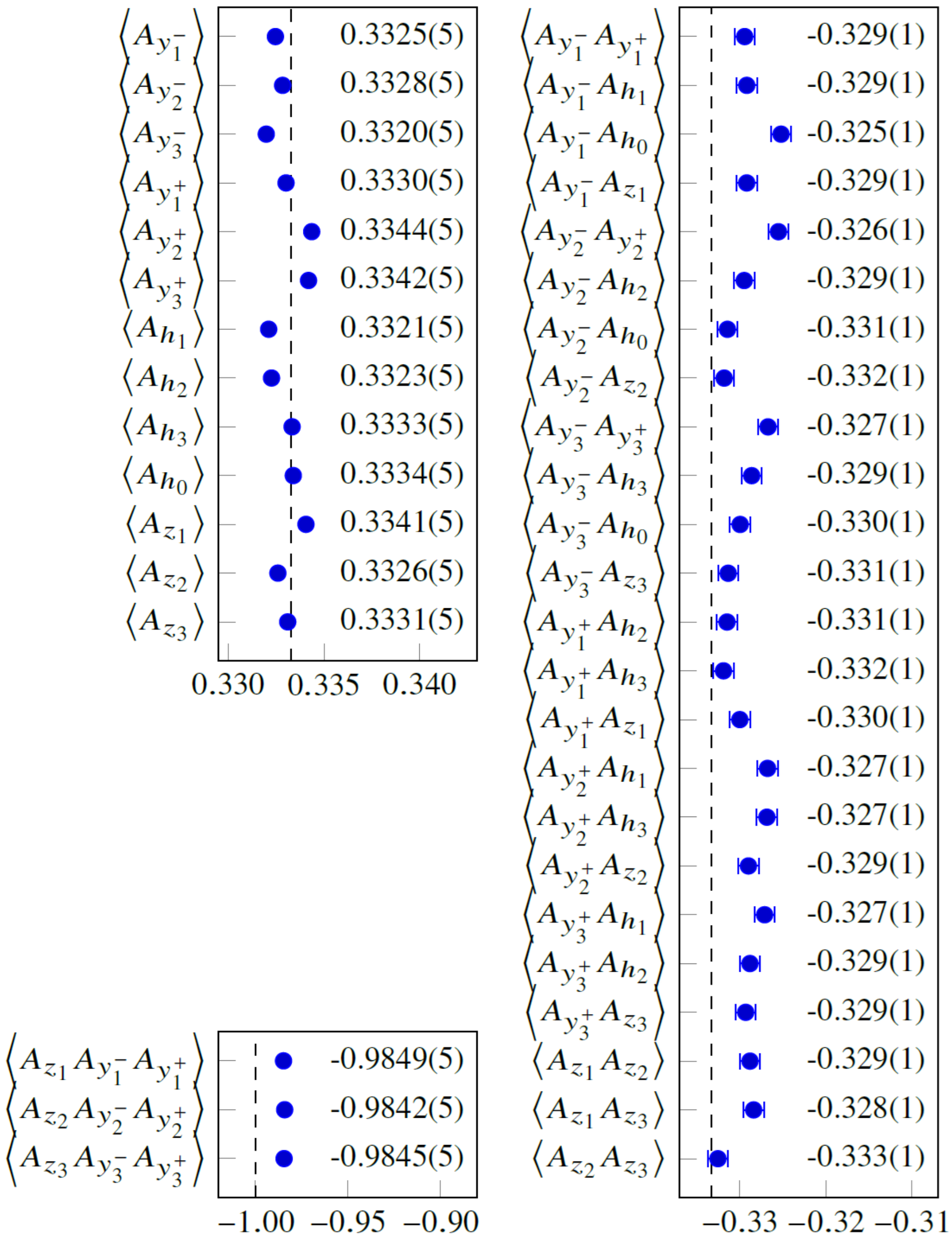
Experiment



- Measurement choice made in real-time during sequence
- 54 million sequential measurements (groups of 1000 + bright restart)

[F.M. Leupold et al., 1706.07370 (2017)]

Yu & Oh results



$$\langle \chi_{\mathrm{YO}} \rangle = \sum_{v \in V} \langle A_v \rangle - \sum_{(u,v)\in E} \frac{1}{2} \langle A_u A_v \rangle \overset{\text{NCHV}}{\leq} 8 \overset{\text{QM}}{\leq} \frac{25}{3} \approx 8.33$$

$$\langle \chi_{\mathrm{YO}} \rangle = 8.279(4)$$

$$\langle \chi_{\mathrm{opt3}} \rangle = \sum_{v \in V_h} 2 \langle A_v \rangle + \sum_{v \in V \setminus V_h} \langle A_v \rangle - \sum_{(u,v)\in E \setminus C_2} 2 \langle A_u A_v \rangle - \sum_{(u,v)\in C_2} \langle A_u A_v \rangle - \sum_{(u,v,w)\in C_3} 3 \langle A_u A_v A_w \rangle \underset{\text{NCHV}}{\leq} 25 \underset{\text{QM}}{\leq} \frac{83}{3} \approx 27.67$$

$$\langle \chi_{\mathrm{opt3}} \rangle = 27.357(11)$$

[F.M. Leupold et al., 1706.07370 (2017)]
http://www.tiqi.ethz.ch/publications-and-awards/public-datasets.html

System characterization

First 20 data points

v	A_v
13	-1
6	-1
7	1
4	-1
4	-1
3	-1
1	-1
12	-1
12	-1
5	-1
4	-1
9	-1
11	1
8	-1
8	-1
12	-1
13	-1
4	-1
11	-1
4	-1
⋮	⋮

54M

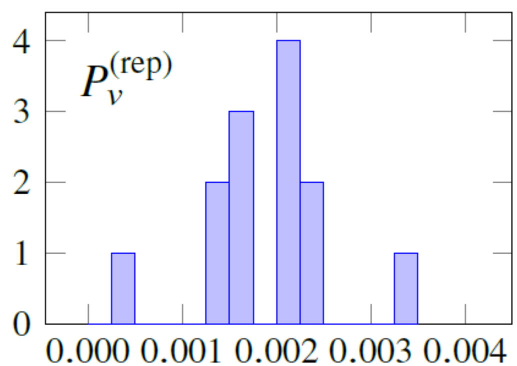
Repeatability

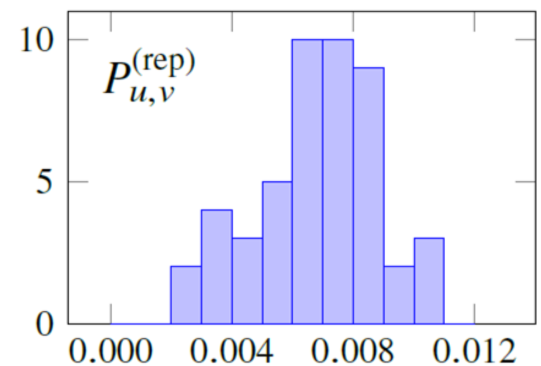
$$P_v^{(\mathrm{rep})} = \frac{\sum_{a_1} N(A_v{=}a_1, A_v{=}{-a_1})}{N(A_v, A_v)}$$

Repeatability with interleaved compatible meas.

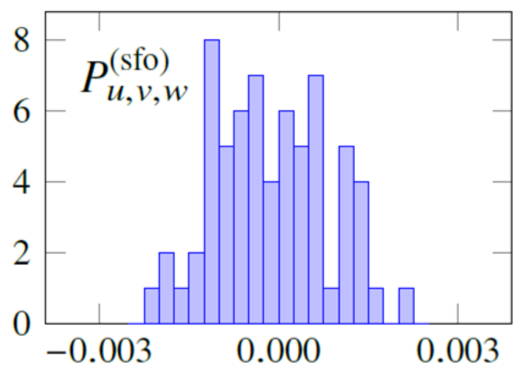
$$P_{u,v}^{(\mathrm{rep})} = \frac{\sum_{a_1} N(A_u{=}a_1, A_v, A_u{=}{-a_1})}{N(A_u, A_v, A_u)}$$

Sharpness

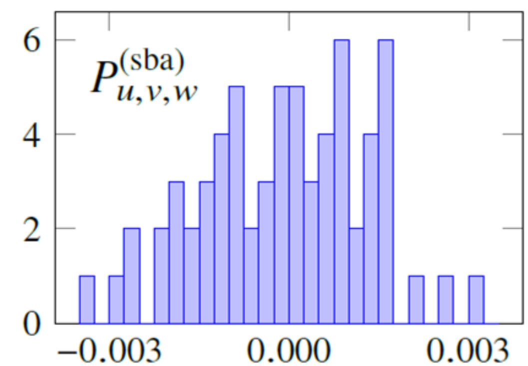




Compatibility



Signaling forwards in time



Signaling backwards in time

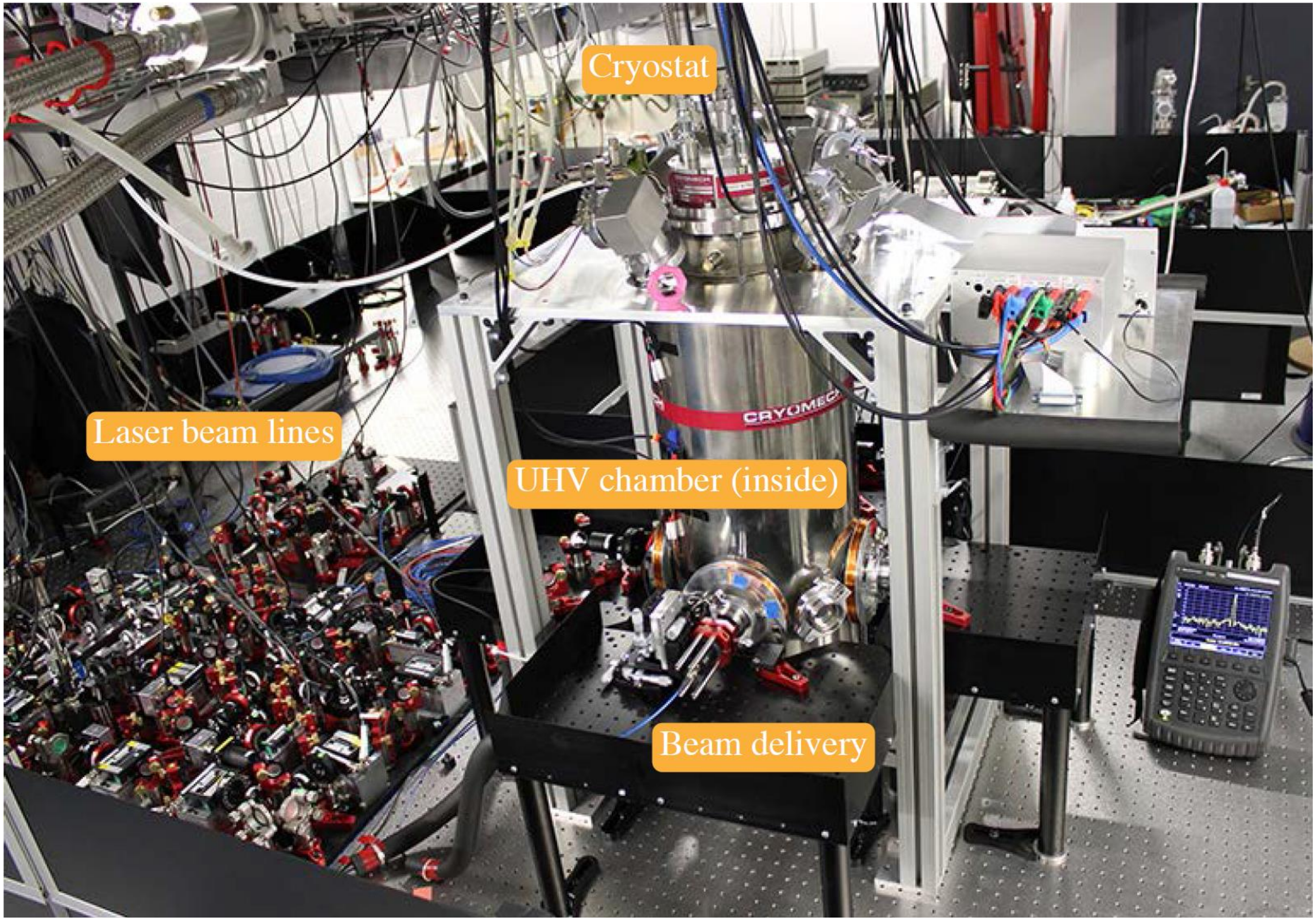
$$P_{u,v,w}^{(\mathrm{sfo})} = \frac{N(A_v, A_u{=}1)}{N(A_v, A_u)} - \frac{N(A_w, A_u{=}1)}{N(A_w, A_u)}$$

$$P_{u,v,w}^{(\mathrm{sba})} = \frac{N(A_u{=}1, A_v)}{N(A_u, A_v)} - \frac{N(A_u{=}1, A_w)}{N(A_u, A_w)}$$

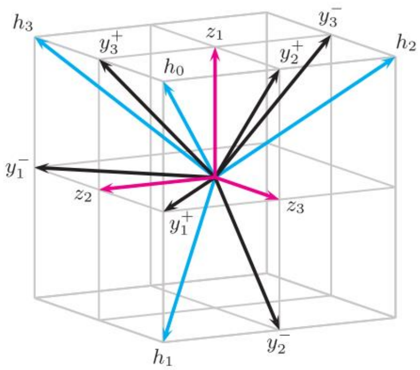
[F.M. Leupold et al., 1706.07370 (2017)]

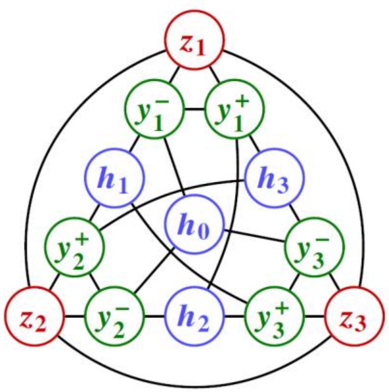
http://www.tiqi.ethz.ch/publications-and-awards/public-datasets.html

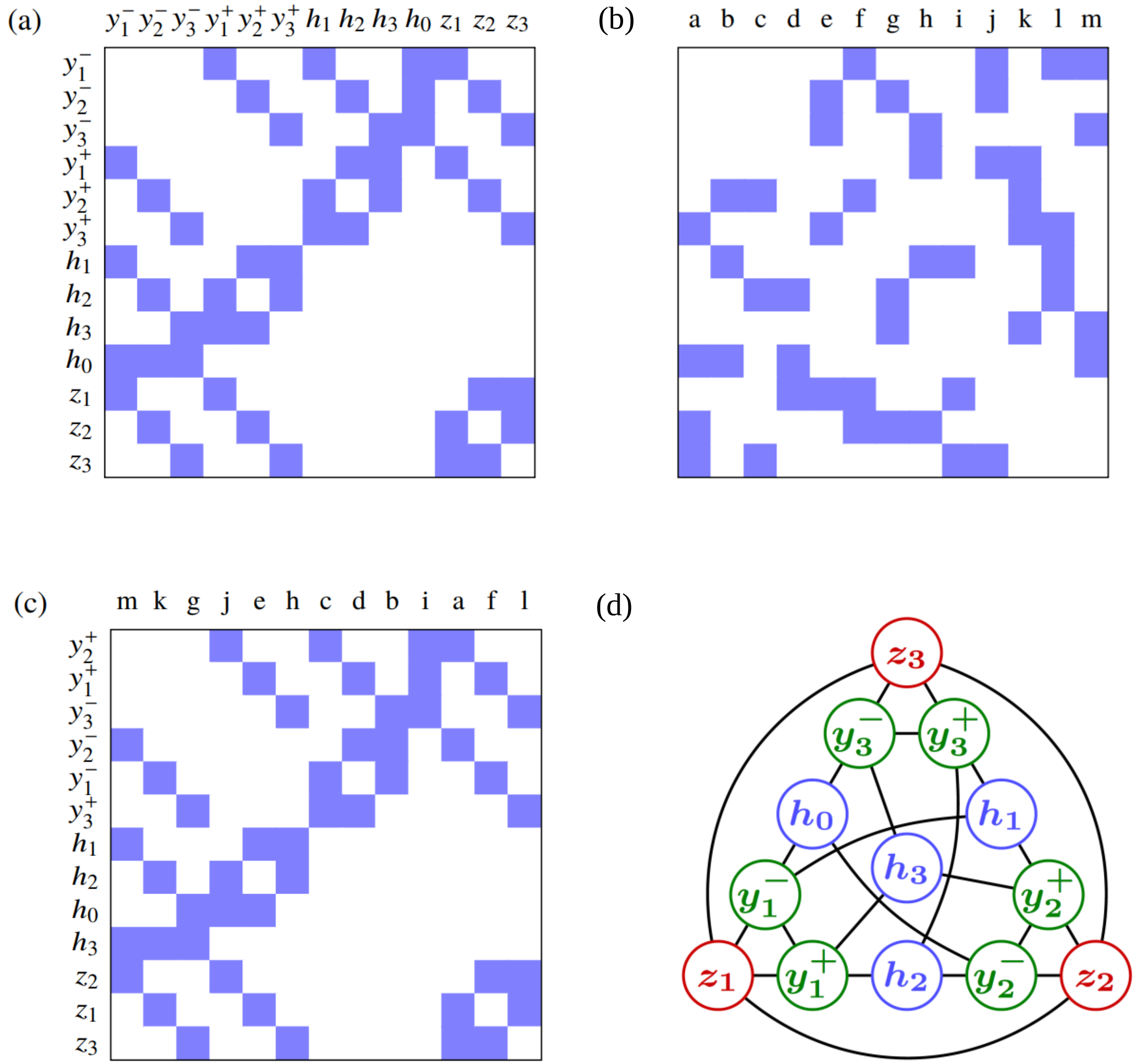
Cryostat vibrations



Blind analysis







Contextuality supplies the magic for quantum computation

Mark Howard[1,2], Joel Wallman[2], Victor Veitch[2,3] & Joseph Emerson[2]

Quantum computers promise dramatic advantages over their classical counterparts, but the source of the power in quantum computing has remained elusive. Here we prove a remarkable equivalence between the onset of contextuality and the possibility of universal quantum computation via 'magic state' distillation, which is the leading model for experimentally realizing a fault-tolerant quantum computer. This is a conceptually satisfying link, because contextuality, which precludes a simple 'hidden variable' model of quantum mechanics, provides one of the fundamental characterizations of uniquely quantum phenomena. Furthermore, this connection suggests a unifying paradigm for the resources of quantum

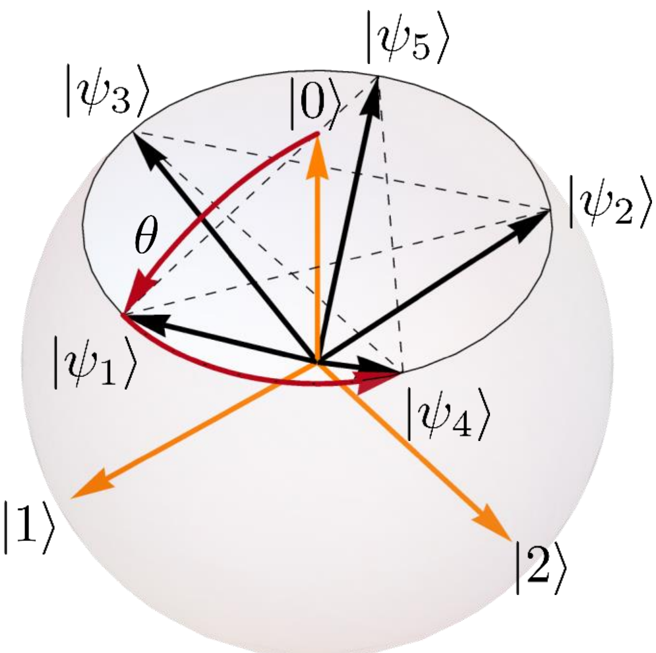
[M. Howard et al., Nature 510 (2014)]

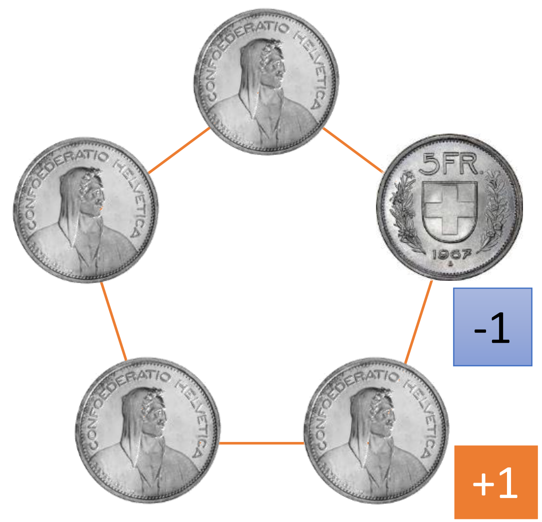
Limits of correlations

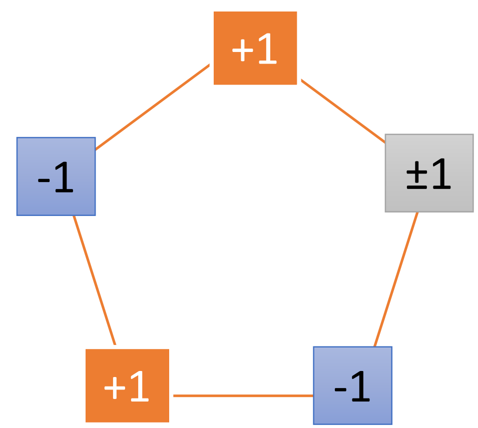
Does QM correctly predict the limits of correlations in Nature?

- Qutrit: smallest contextual system
- KCBS set
  - Most fundamental compatibility structure
  - Largest deviation between NCHV and QM
  - State dependent

[A. Klyachko, M. Can, A. Binicioglu, A. Shumovsky, Phys. Rev. Lett. 101 (2008)]





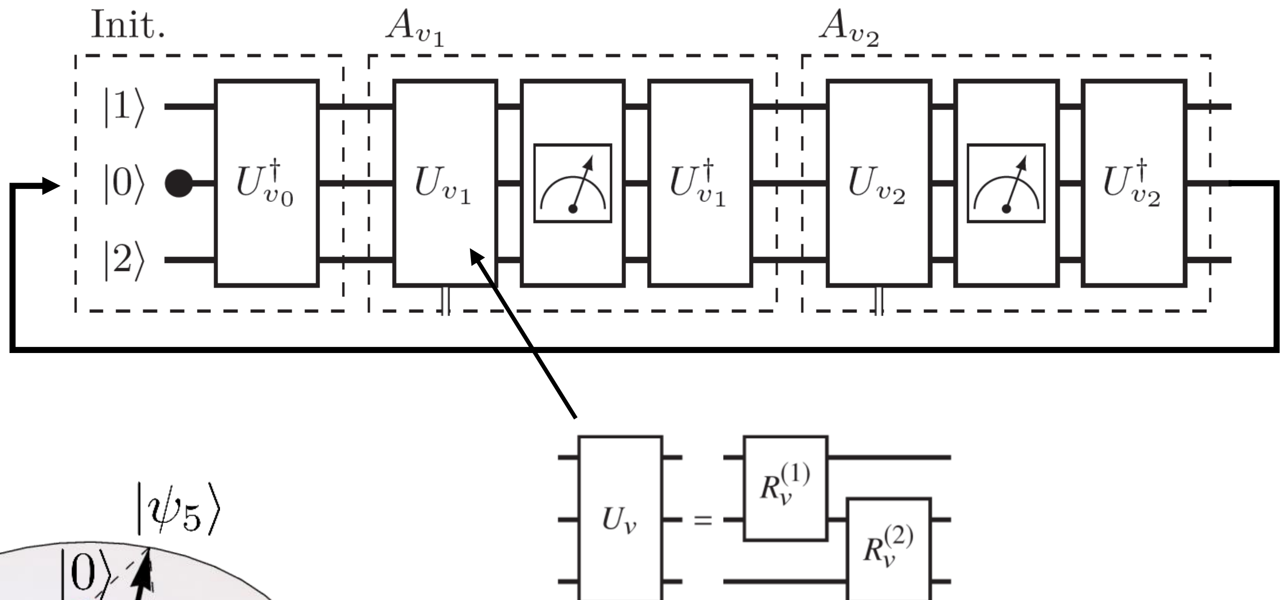


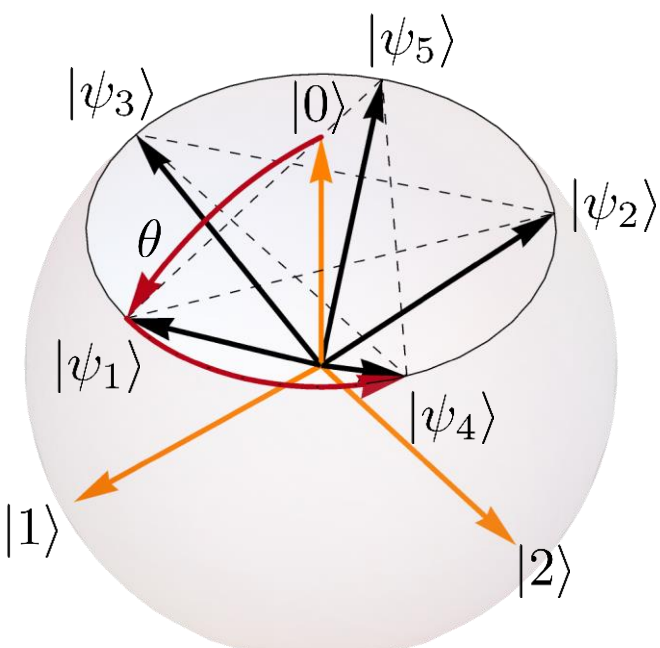
NCHV QM

$$S_5 = \sum_{i=1}^{5} \langle A_i A_{i+1} \rangle \geq -3 \geq 5 - 4\sqrt{5} \approx -3.944$$

[B. Christensen et al., Phys. Rev. X 5 (2015)]

Experiment

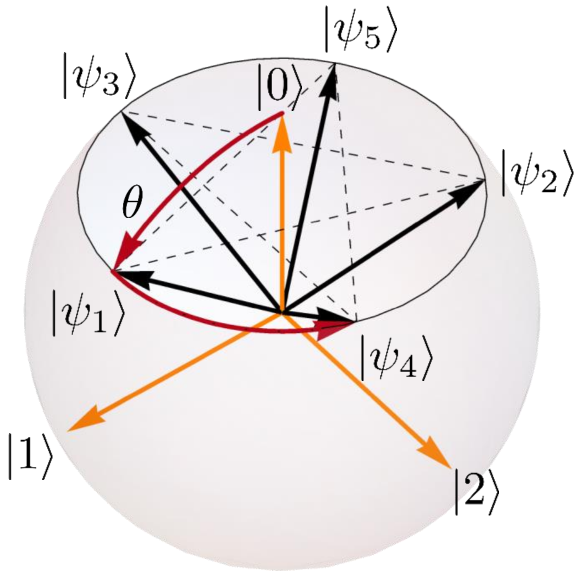




Criticisms to contextuality tests

- Detection loophole ✓
- Joint measurements ✓
- Non-projective measurements ✓
- Compatibility/finite-precision loophole

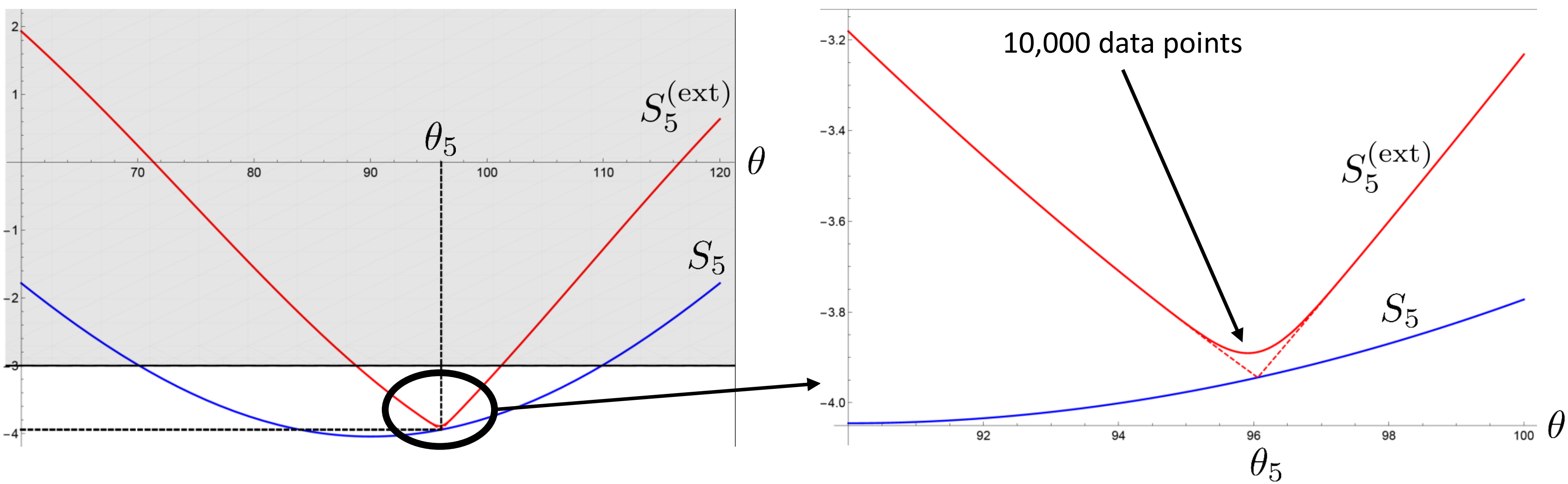
On compatibility and finite precision



Perfect compatibility when $\theta = \theta_5 \approx 48 \text{ deg}$

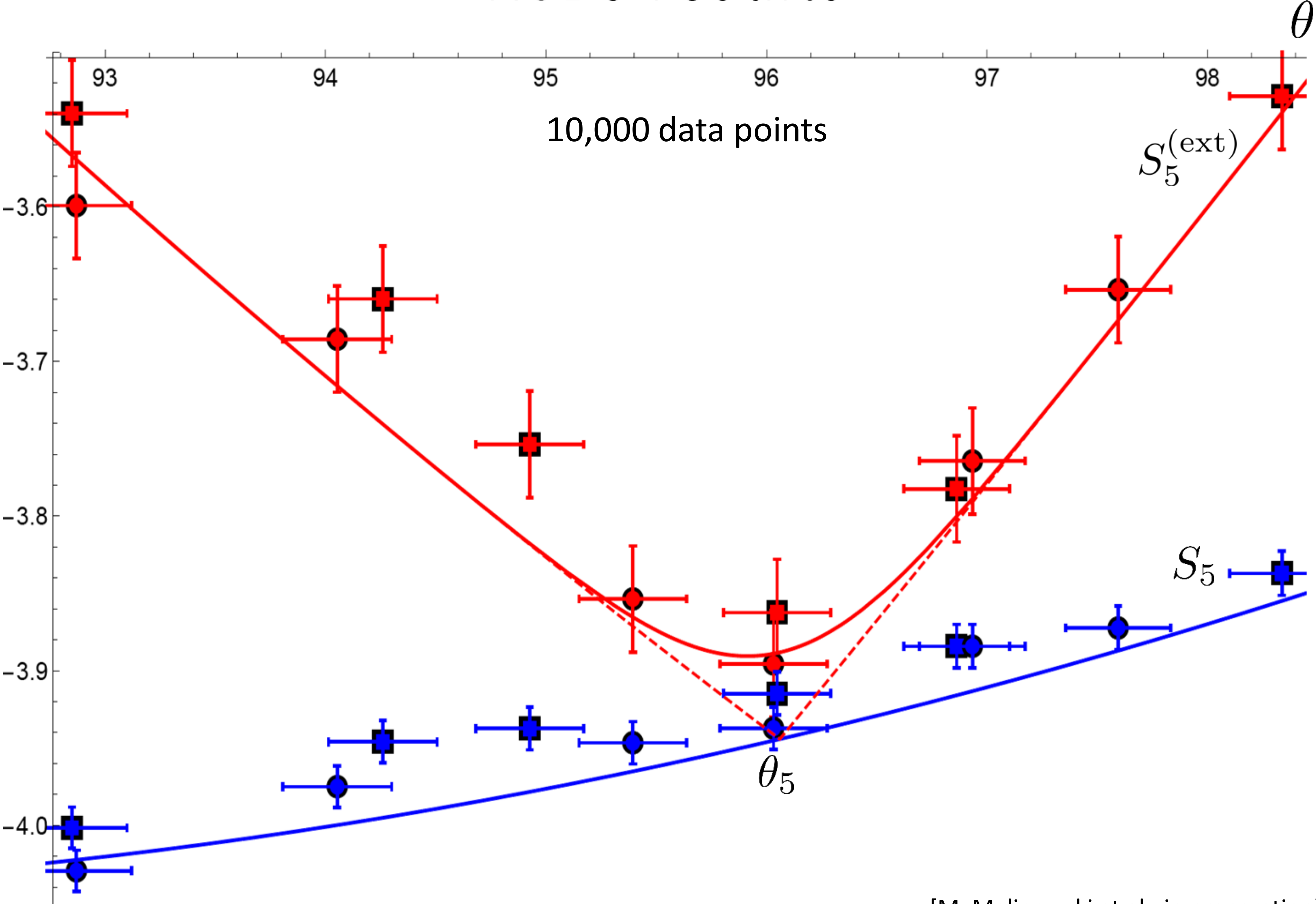
$$S_5^{(\text{ext})} = \sum_{i=1}^{5} \langle A_i A_{i+1} \rangle + \sum_{i=1}^{5} \epsilon_i \geq \bar{S}_5^{\text{NCHV}}$$

$$\epsilon_i = \left| \langle A_i^{(1)} \rangle - \langle A_i^{(2)} \rangle \right|$$



[R. Kujala et al., Phys. Rev. Lett. 115 (2015)]

KCBS results



[M. Malinowski et al., in preparation]

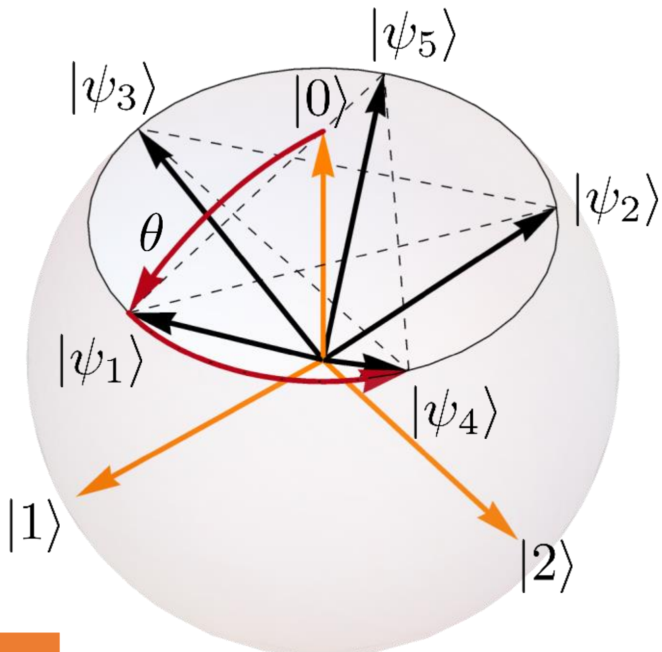
Comparison with previous KCBS tests

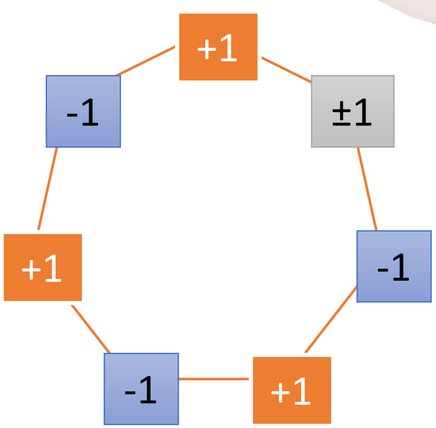
Reference	Platform	$S_5/\bar{S}_N^{\mathrm{QM}}$	$\sum_{i=1}^{5} \epsilon_i/\bar{S}_N^{\mathrm{QM}}$	Open loopholes and criticisms
[R. Lapkiewicz et al, Nature 474 (2011)]	Photons	0.987(2)	0.019	• Detection loophole • Simultaneous measurements • Same observable but different setup in different contexts

[M. Malinowski et al., in preparation]

Limits of correlations: larger *gons*

- Fundamental understanding of inequality violation
- NCHV and QM predictions approach as N increases



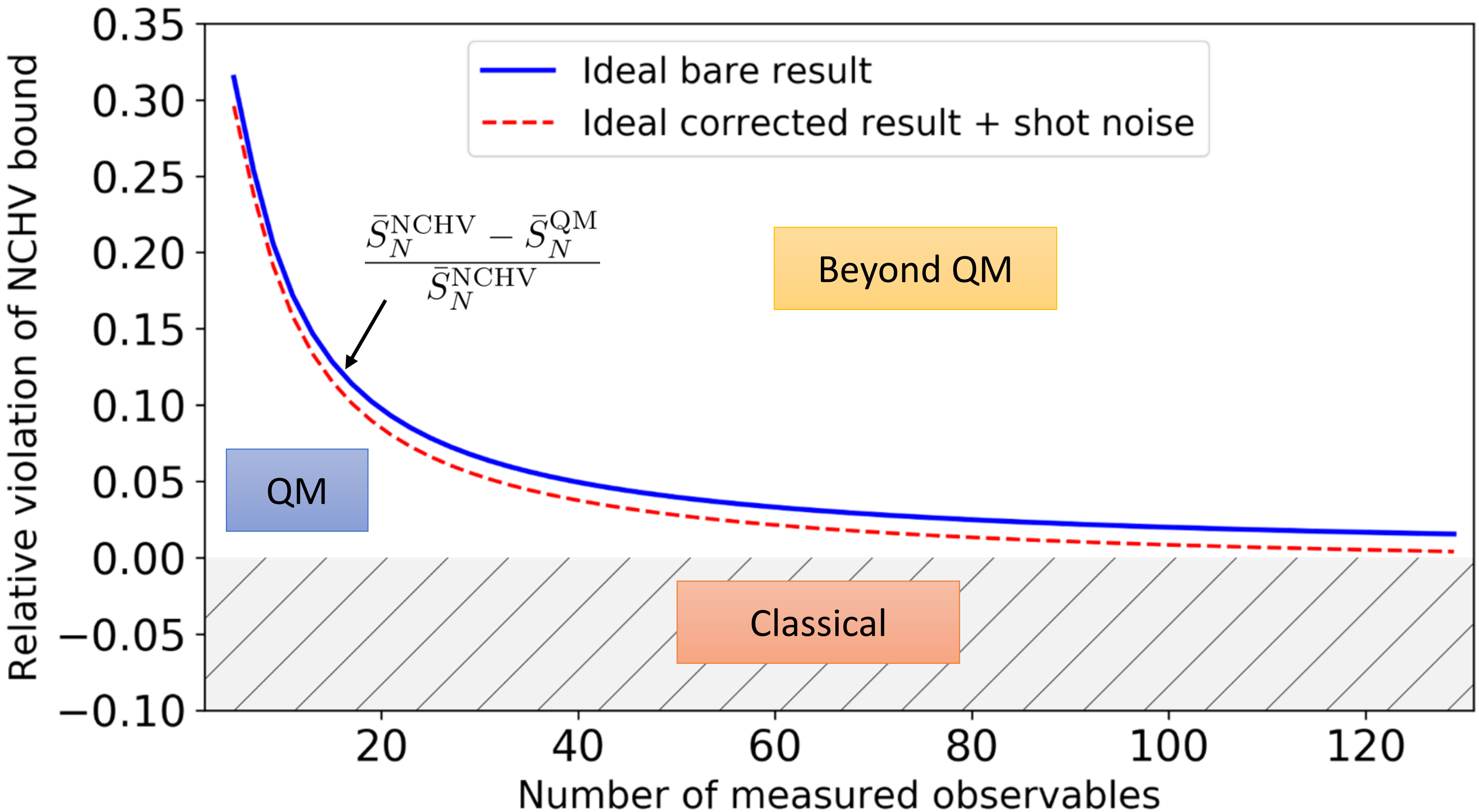


$$\bar{S}_N^{\mathrm{NCHV}} = -\frac{N-1}{2}$$

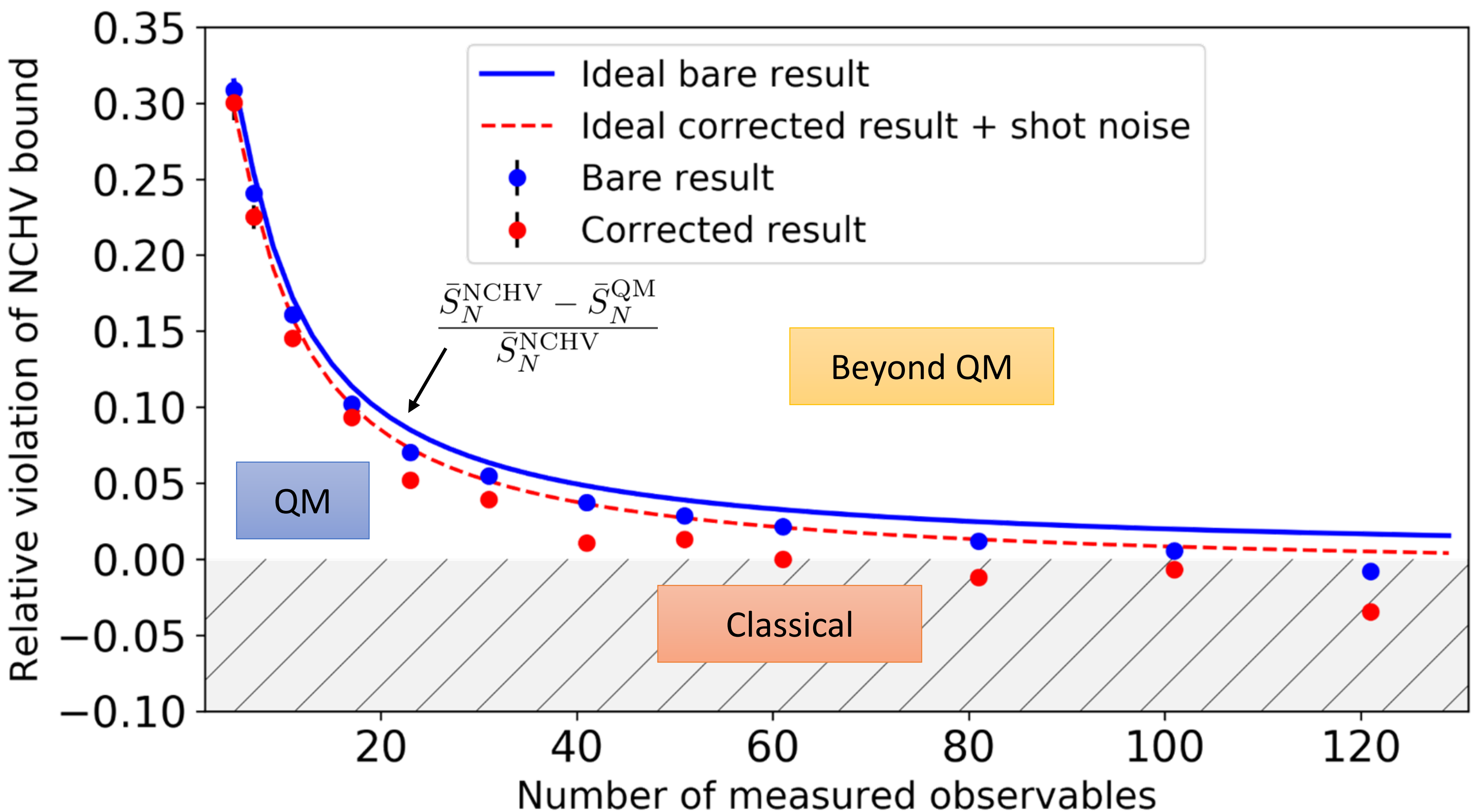
$$\bar{S}_N^{\mathrm{QM}} = -\frac{N\cos(\pi/N)}{1+\cos(\pi/N)}$$

[A. Cabello, Phys. Rev. Lett. 110 (2013)]

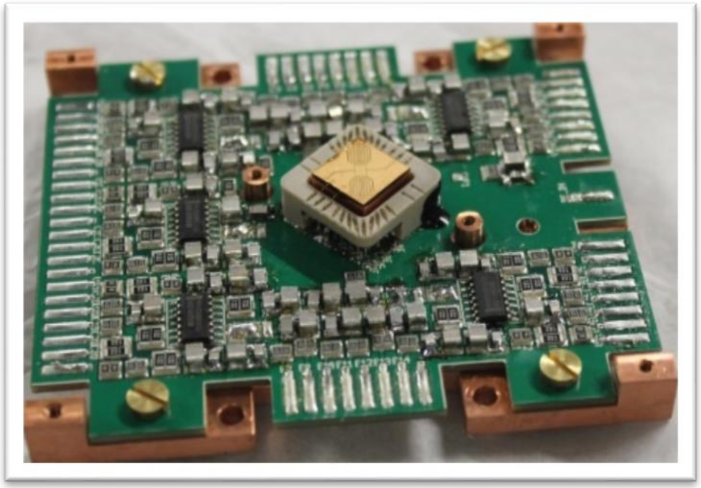
Limits of correlations: larger *gons*

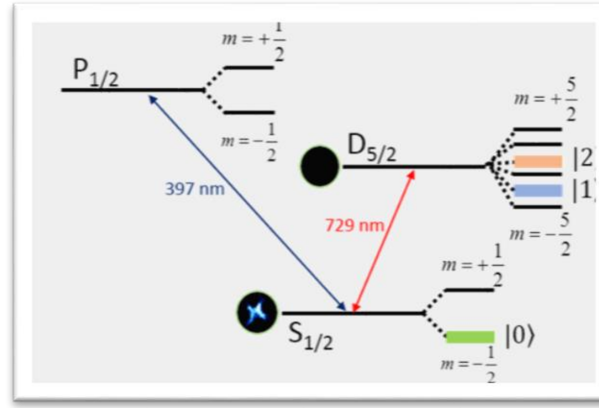


Limits of correlations: larger *gons*

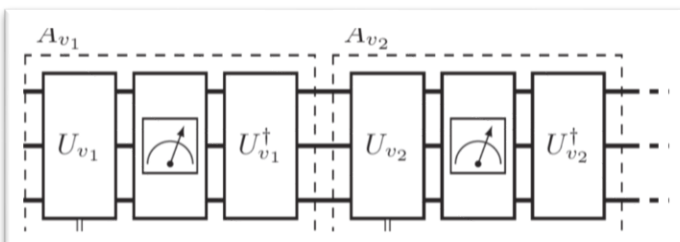


Conclusion

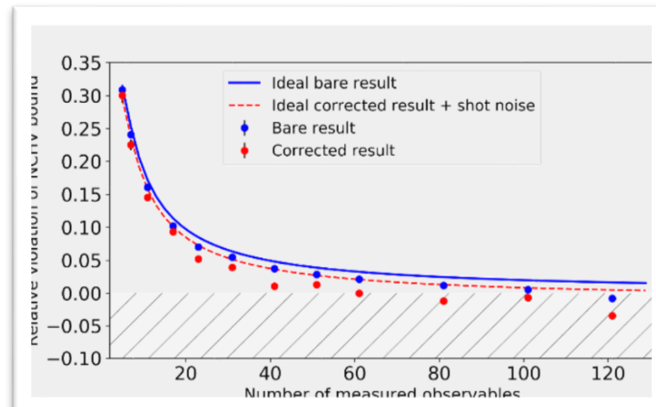




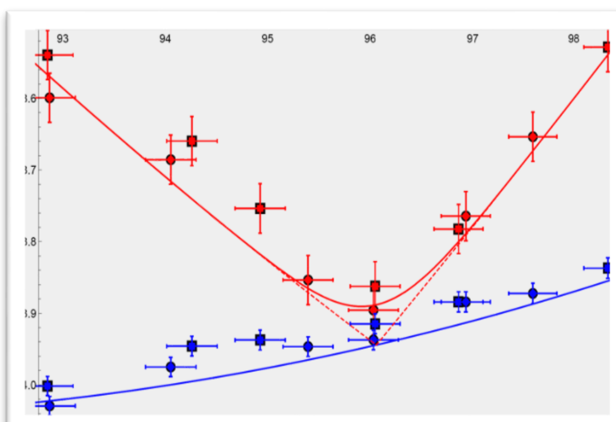
P1/2
m = +1/2
m = −1/2
397 nm
D5/2
m = +5/2
|2
|1
m = −5/2
729 nm
m = +1/2
S1/2
|0⟩
m = −1/2



A_{v_1}
A_{v_2}
U_{v_1}
$U_{v_1}^\dagger$
U_{v_2}
$U_{v_2}^\dagger$



0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
−0.05
−0.10
20
40
60
80
100
120
Ideal bare result
Ideal corrected result + shot noise
Bare result
Corrected result



93
94
95
96
97
98