Experimental Quantum Channel Discrimination

Using Metastable States of a Trapped Ion

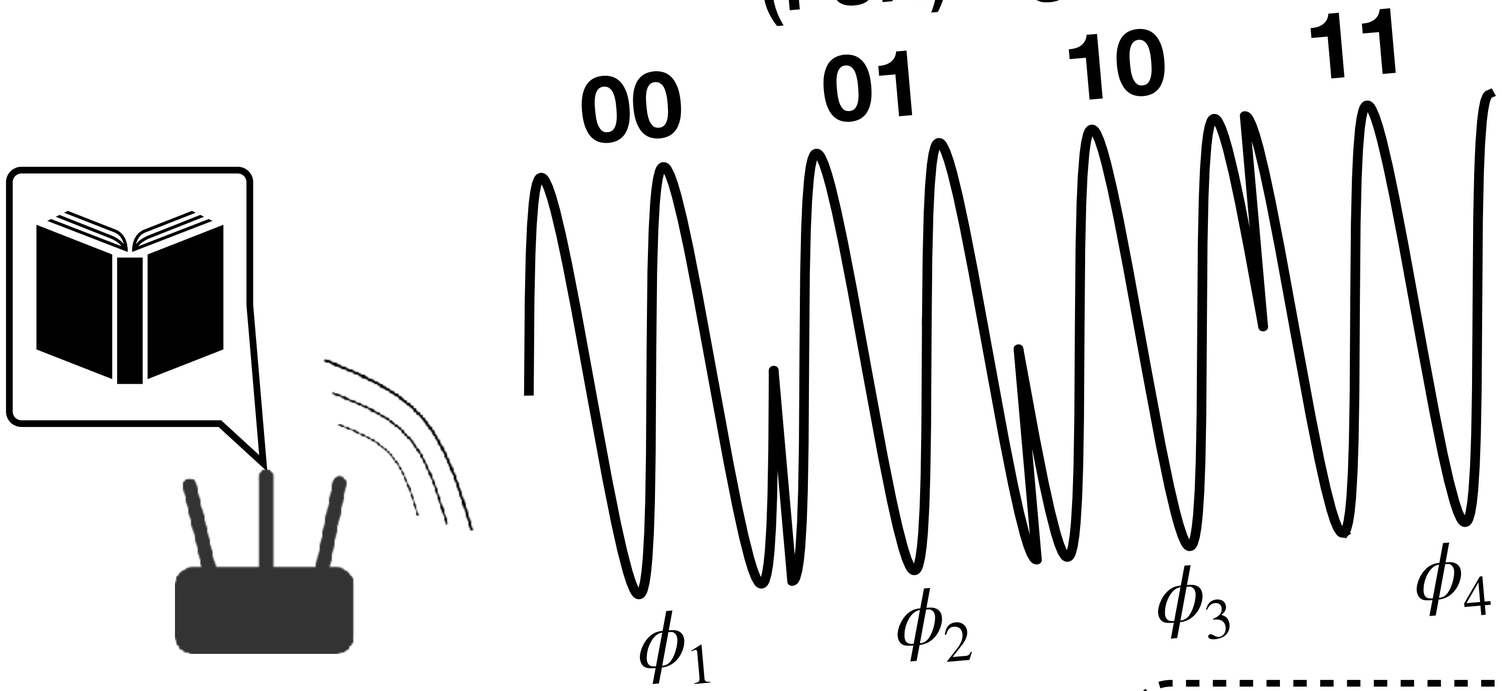
Kyle DeBry[a,b], Jasmine Sinanan-Singh[a], Colin D. Bruzewicz[b], David Reens[b], May E. Kim[b], Matthew P. Roychowdhury[b], Robert McConnell[b], Isaac L. Chuang[a], and John Chiaverini[a,b]

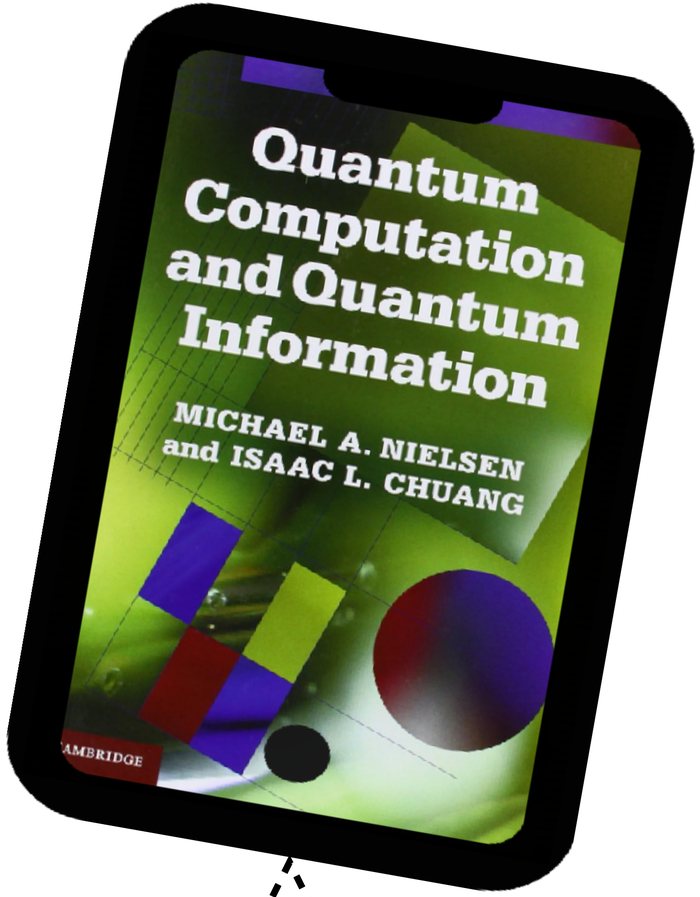
[a]*Massachusetts Institute of Technology* [b]*MIT Lincoln Laboratory*

This research was supported by the U.S. Army Research Office through grant W911NF-20-1-0037.

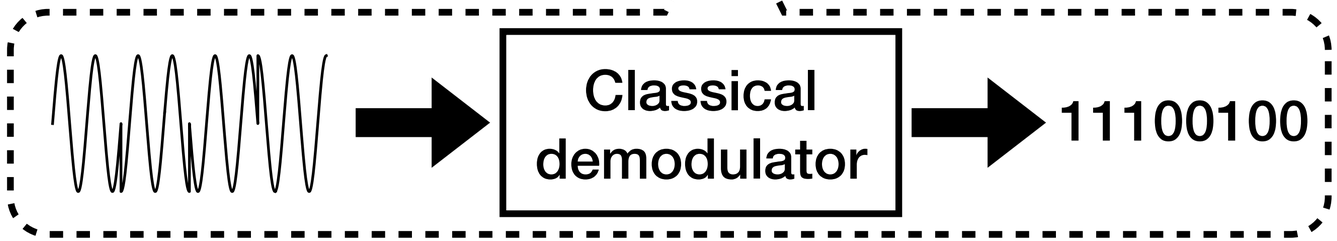
Signal discrimination

Phase shift keying (PSK) signal:



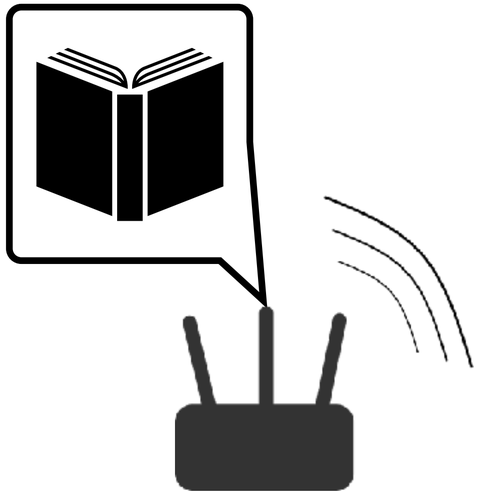


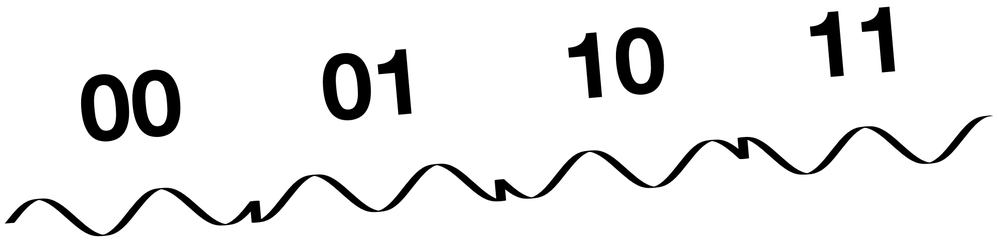
Classical signal processing:



Signal discrimination

Q: What if the signal is ***very*** weak (only a few photons)?

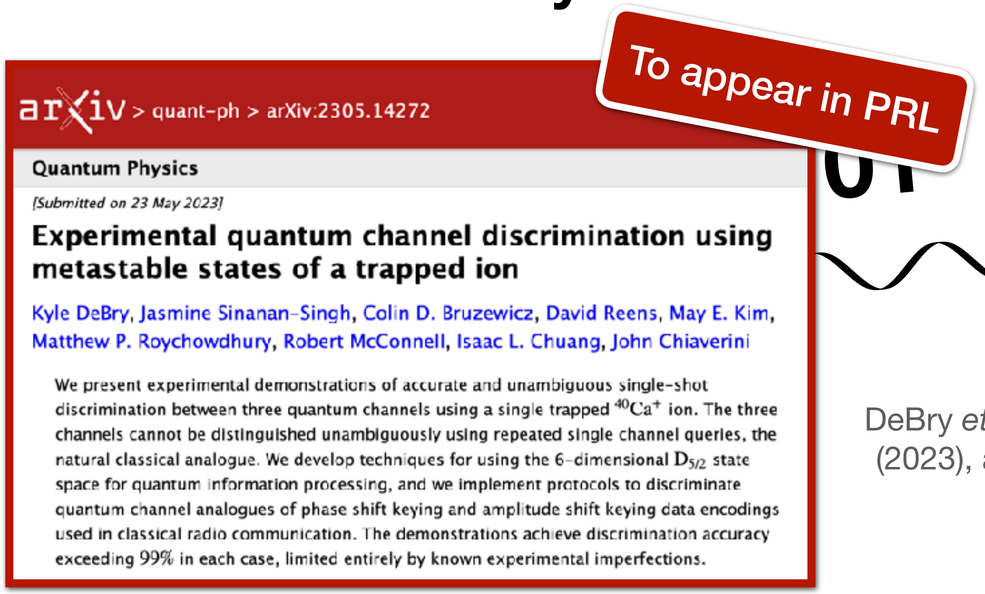




Signal discrimination

Q: What if the signal is ***very*** weak (only a few photons)?

A: Use atomic systems!


arXiv > quant-ph > arXiv:2305.14272

Quantum Physics

[Submitted on 23 May 2023]

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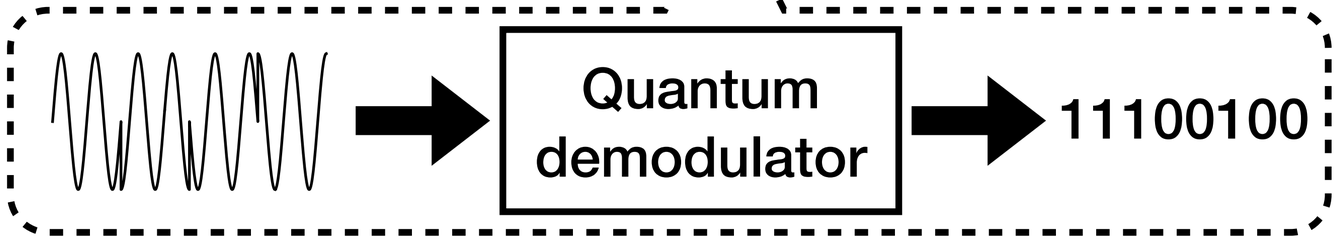
To appear in PRL

DeBry *et al.*, PRL, in press (2023), arxiv:2305.14272

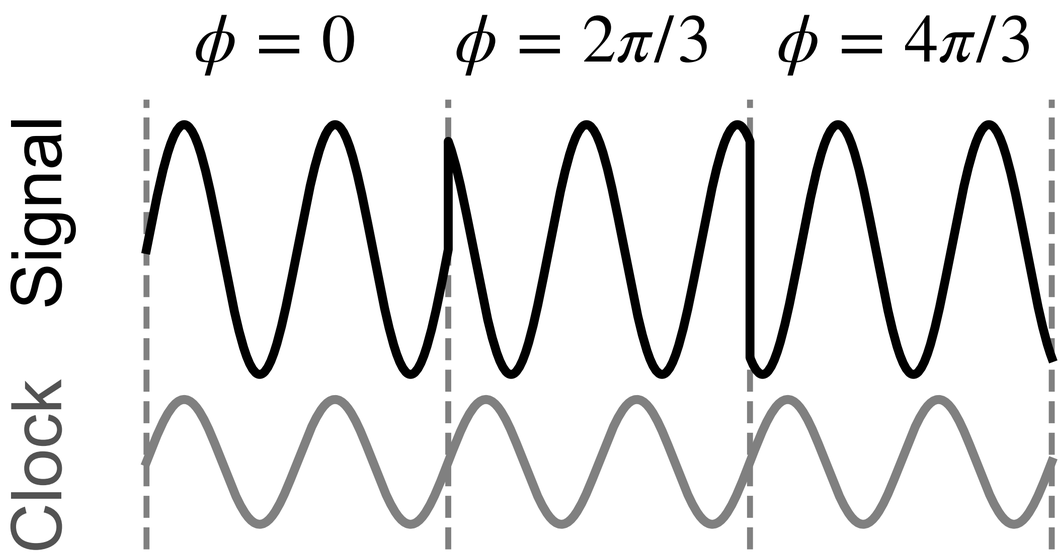
Quantum signal processing (QSP):



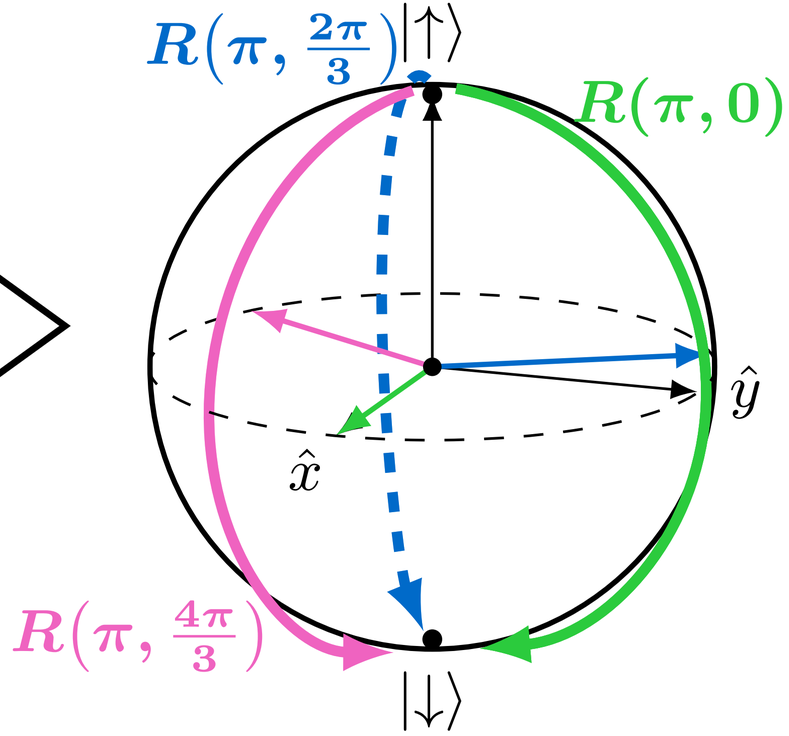
Quantum channel discrimination

Atomic interaction: $U = R(\theta, \phi)$

PSK signal



PSK channel[1]



[1]S. Pirandola *et al.*, npj Quantum Inf. 5, 1 (2019)

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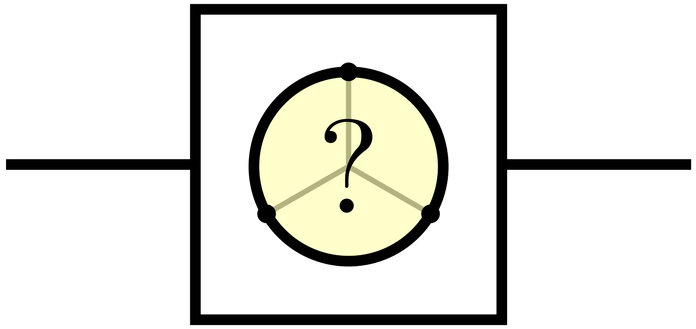

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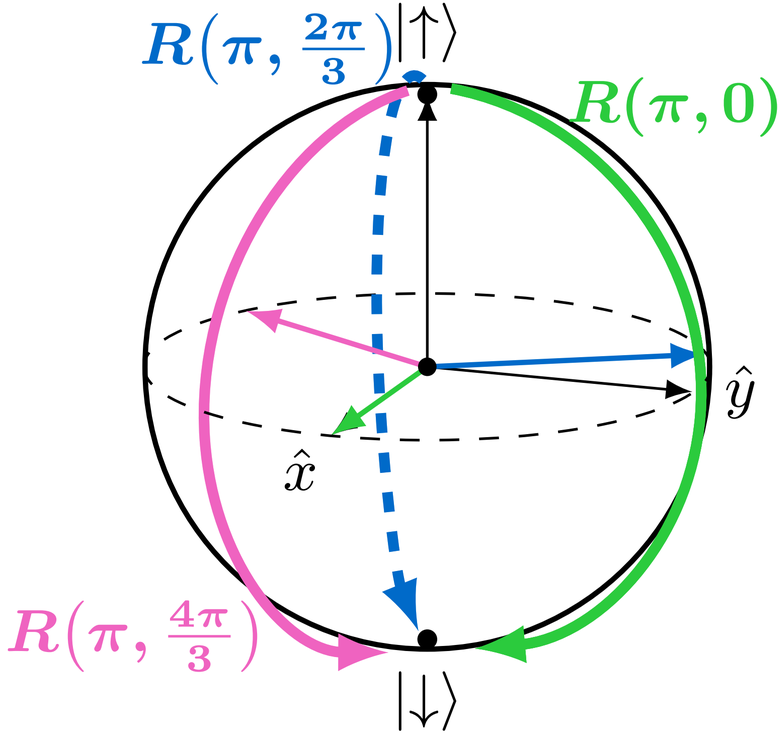
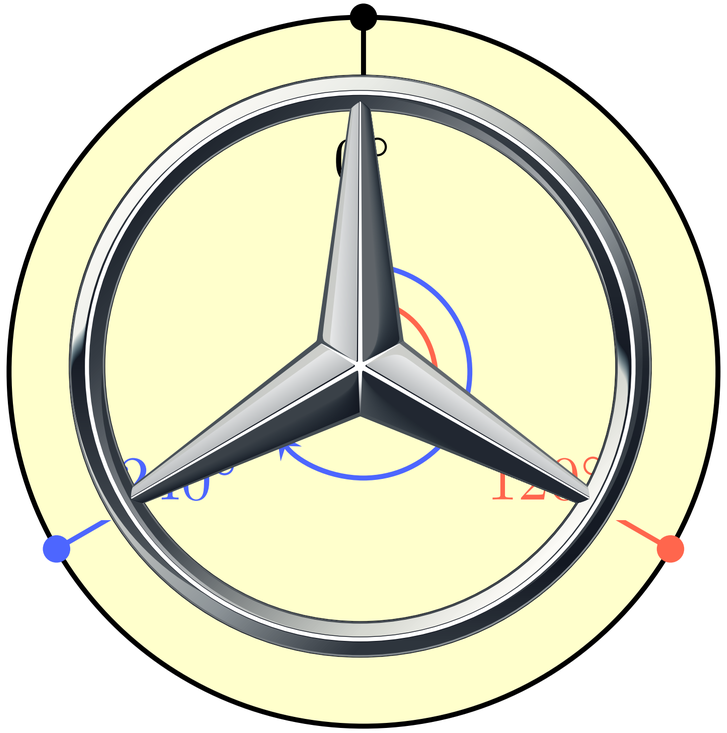


Quantum channel discrimination

Goal: determine which of three potential rotations (the “Mercedez-Benz operator”[2]) was applied to an ion in the **fewest** queries of the operator ()



Mercedes-Benz

[2]J. Kovačević and A. Chebira, Found. Trends Signal Process. 2, 1 (2008).

Quantum channel discrimination

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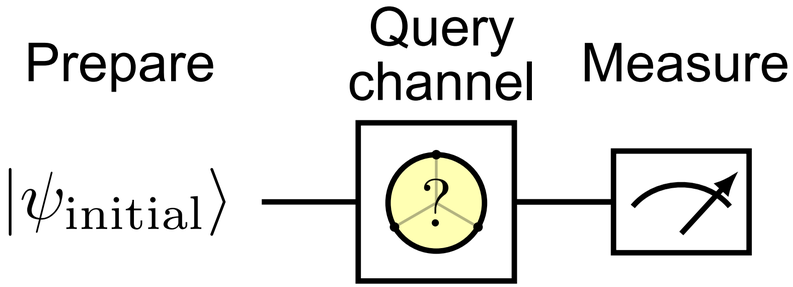
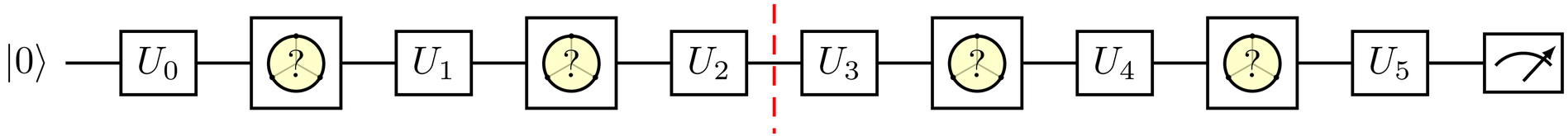
Semi-classical:



Single-measurement success probability[3] $\mathscr{P} \leq$ **2/3**

Exploit quantum coherence to achieve an advantage!

Quantum:



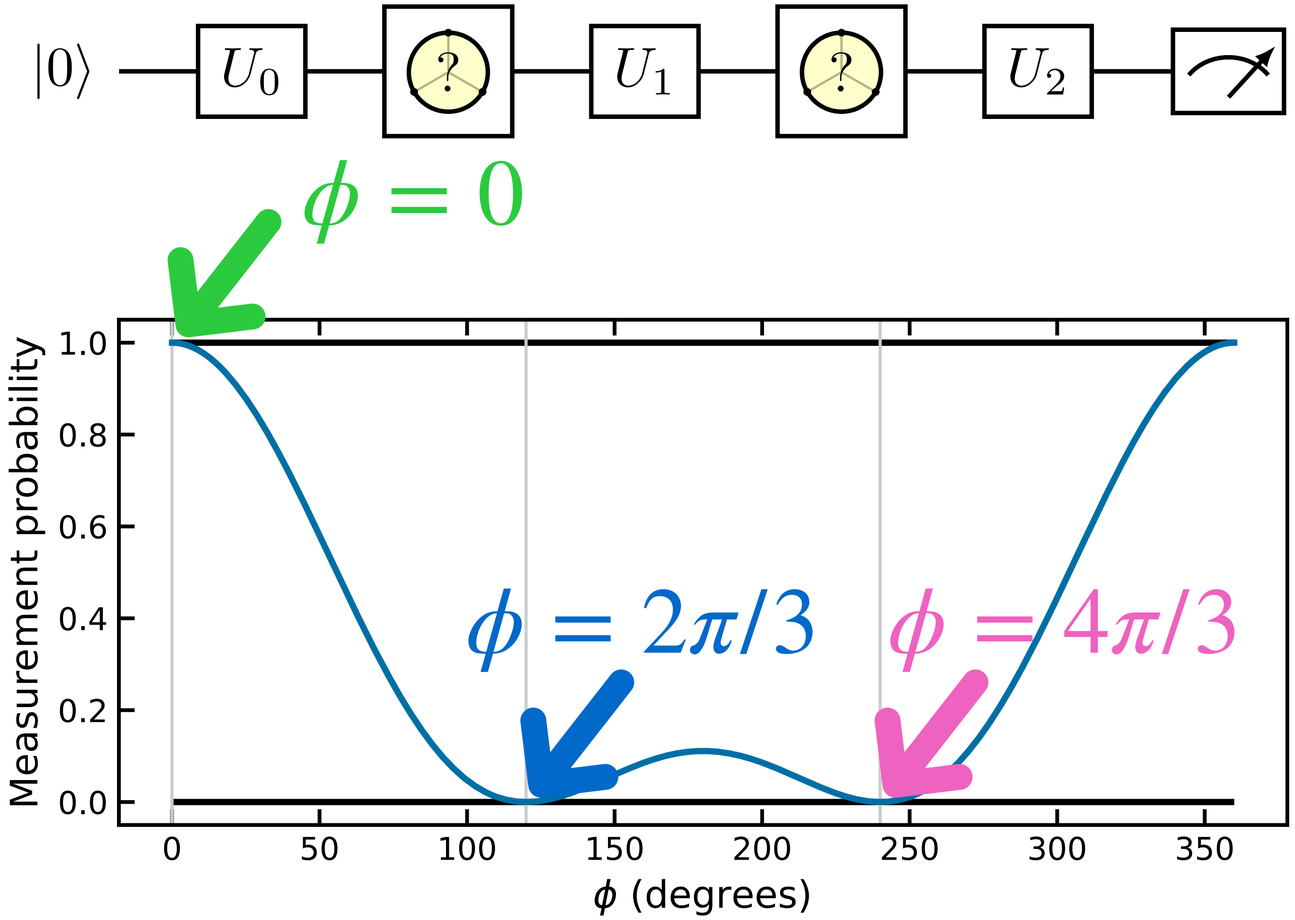
Single-measurement success probability[4] $\mathscr{P} =$ **1**

[3]A. Laing *et al.*, Phys. Rev. Lett. 102, 160502 (2009)

[4]Rossi, Z. M., & Chuang, I. L., Physical Review A, 104(1) (2021)

Quantum signal processing

Key idea: interleave signal operator with processing pulses to filter out specific angles



See also: Martyn, J. M. *et al.*, PRX Quantum, 2(4) (2021), Kikuchi, Y. *et al.*, arXiv:2303.05533v2 (2023)

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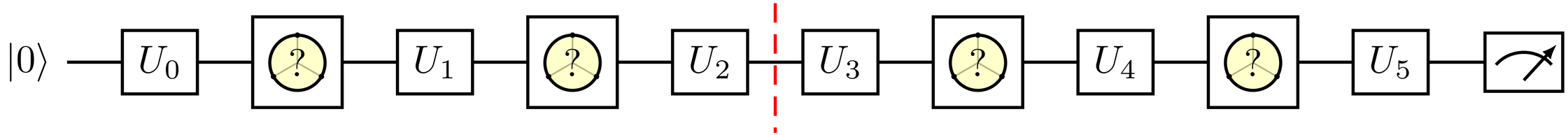
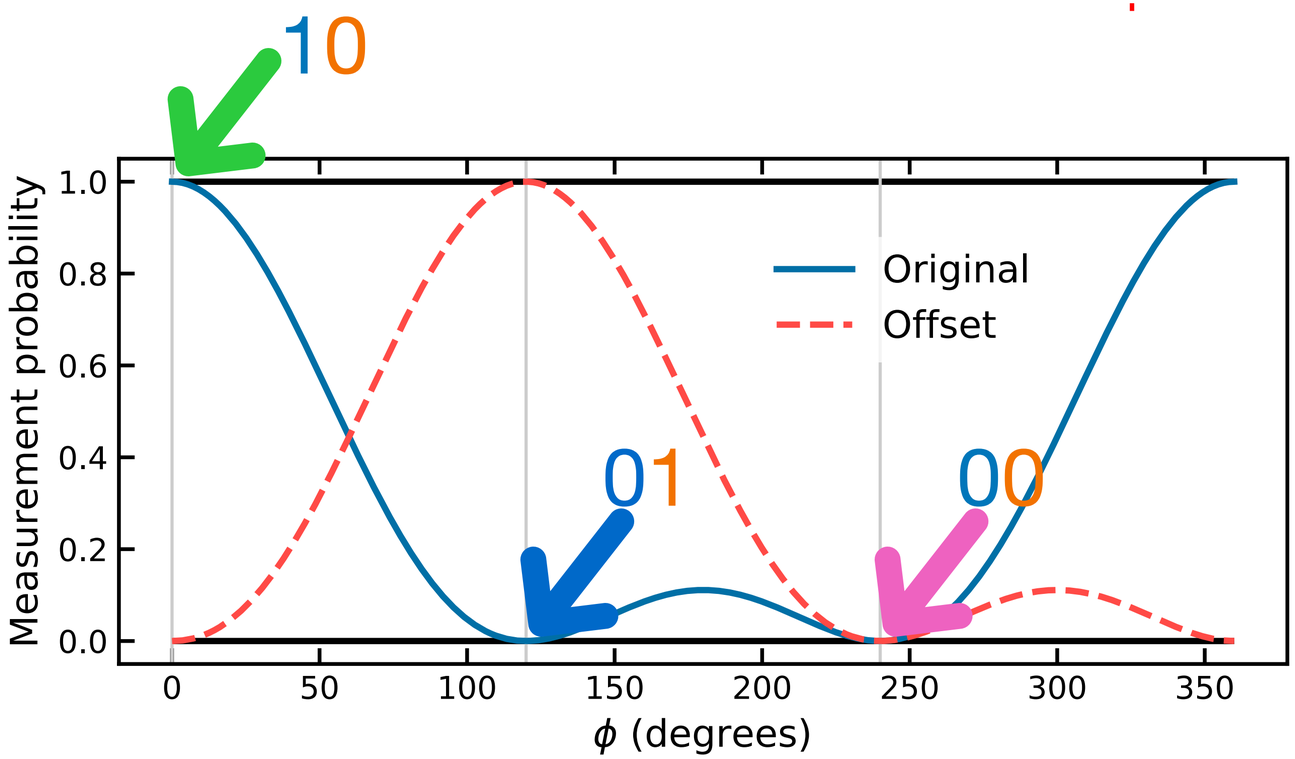




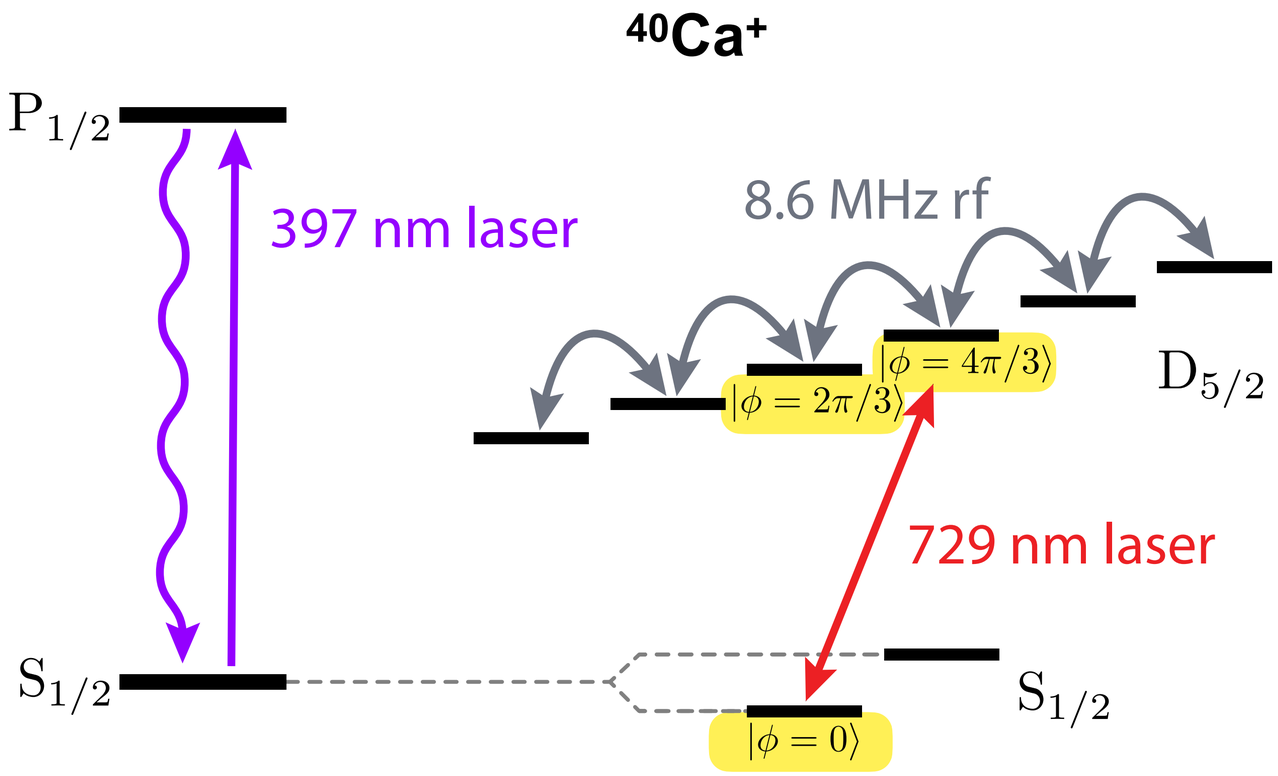
- Ternary readout requires larger Hilbert space!
- Larger Hilbert space requires more advanced experimental control and higher fidelity operations

See also: Martyn, J. M. *et al.*, PRX Quantum, 2(4) (2021), Kikuchi, Y. *et al.*, arXiv:2303.05533v2 (2023)

[4]Rossi, Z. M., & Chuang, I. L., Physical Review A, 104(1) (2021)

Hilbert space of $^{40}Ca^{+}$

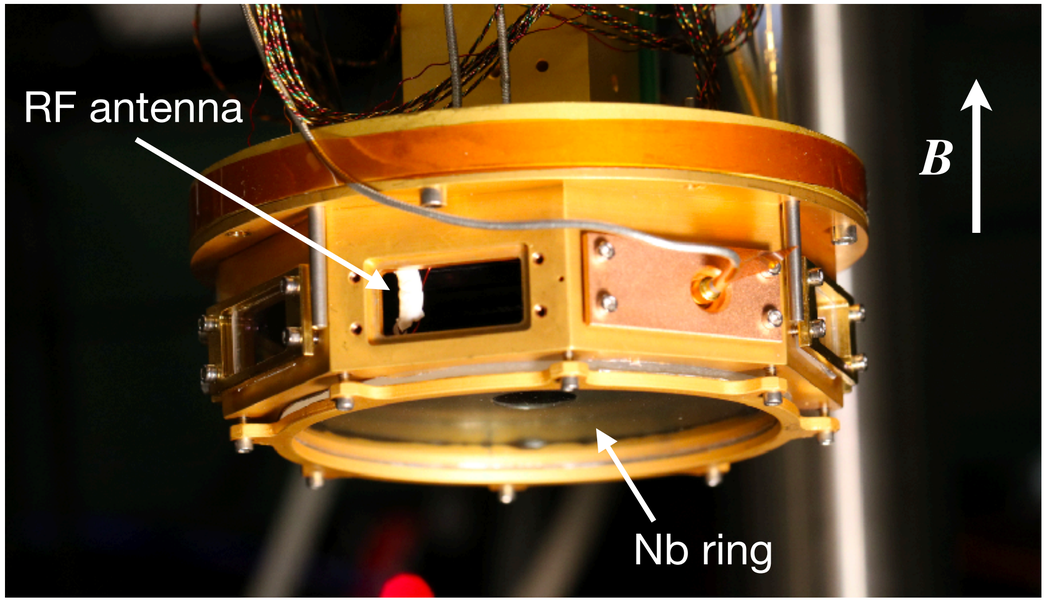
- Use larger Hilbert space of metastable manifold, building on *omg* techniques[5]
- Encode readout states in $D_{5/2}$ and $S_{1/2}$
  - $|\phi = 0\rangle, |\phi = 2\pi/3\rangle, |\phi = 4\pi/3\rangle$
- Qudit-style sequential readout[6,7]



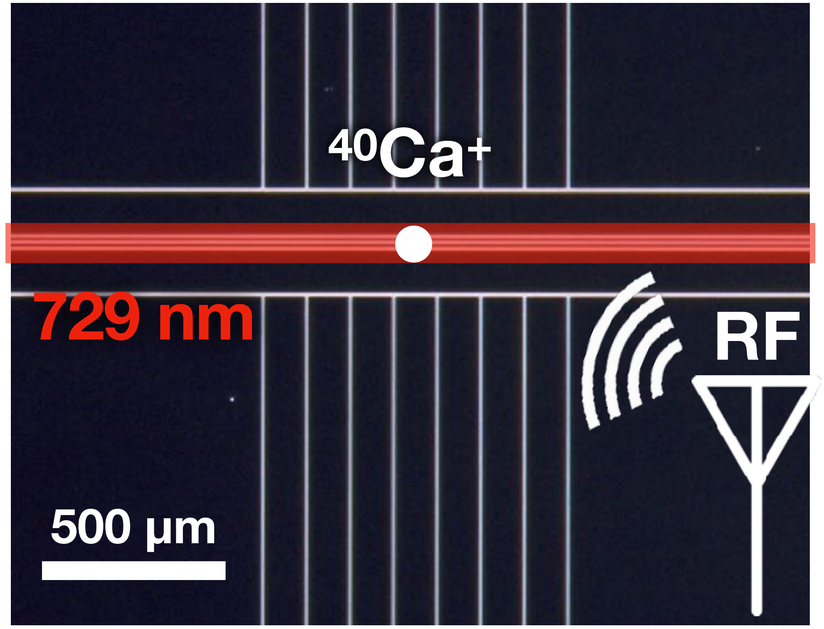
[5]Allcock, D. T. C. Allcock *et al.*, APL 119, 214002 (2021); Yang, H. -X. *et al.,* Nature Phys., 18 (2022)
[6]Ringbauer, M., *et al.*, Nature Phys., 1–5 (2022)
[7]Low, P. J., *et al.*, Phys. Rev. Res., 2(3), 033128 (2020)

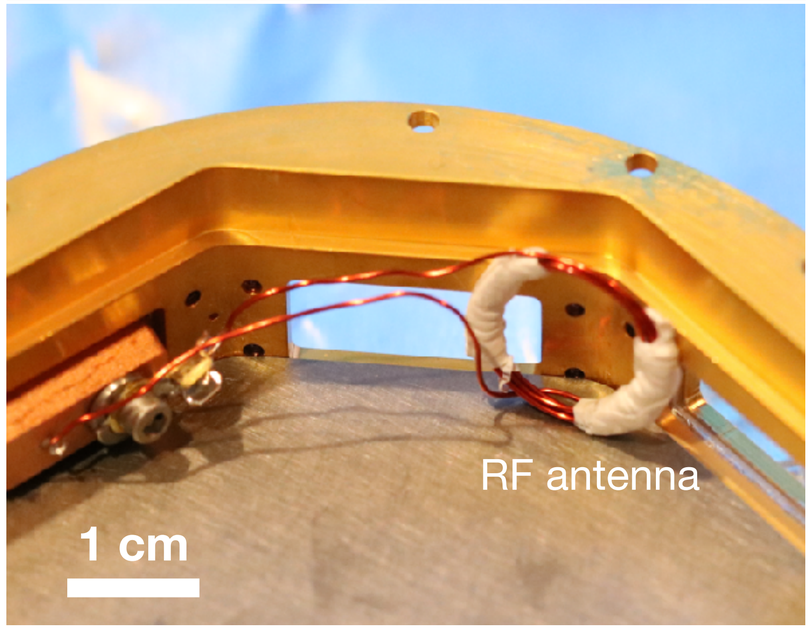
Experimental setup

- Cryogenic surface-electrode trap operated at 5 K
- Superconducting Nb rings stabilize B field[8,9,10]
- Narrow 729 nm laser addresses $S_{1/2}$ to $D_{5/2}$ transitions
- RF coil antenna addressing metastable Zeeman splitting



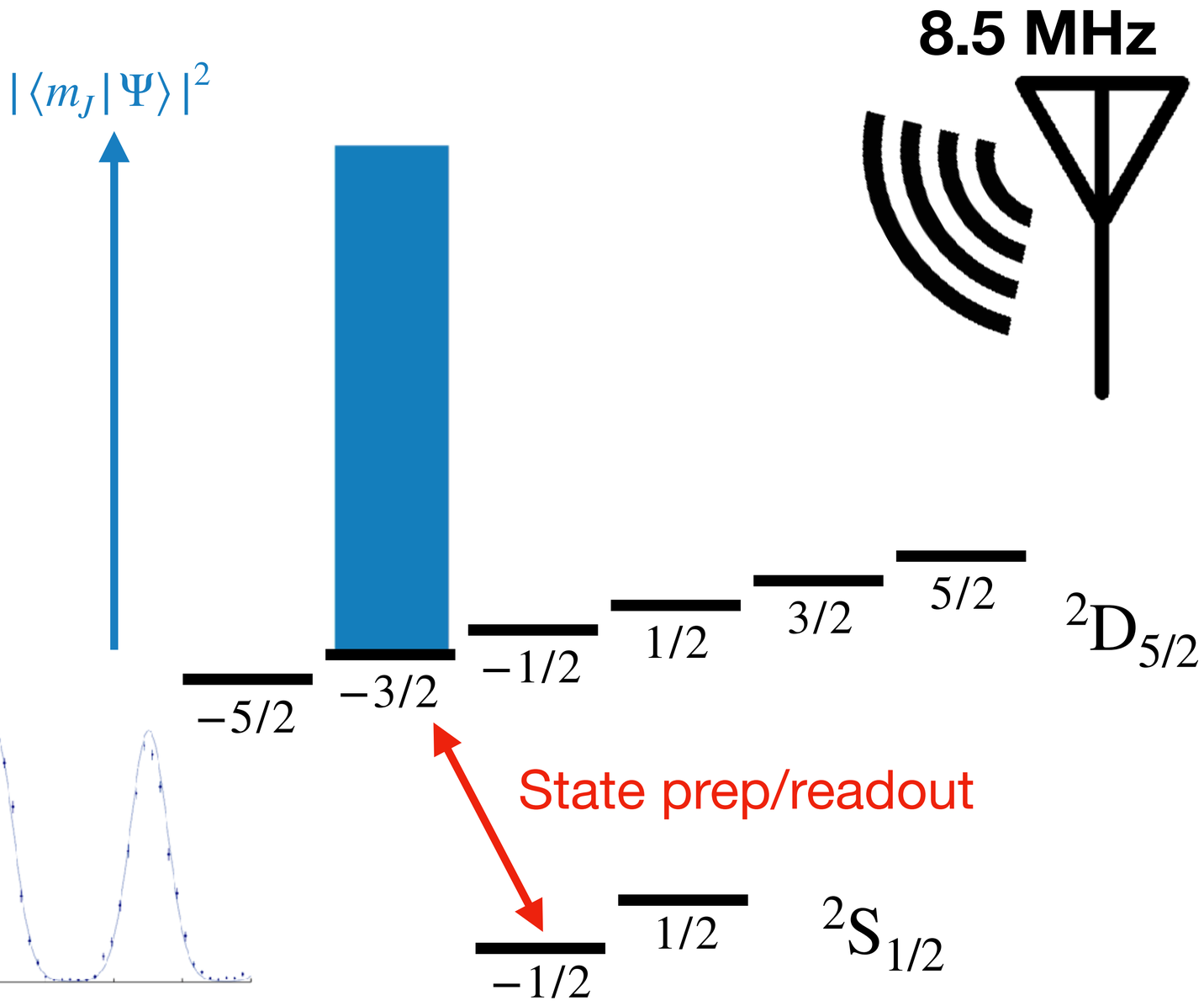
[8]Gabrielse *et al.*, J. Mag. Res. 91, 564 (1991)
[9]Wang *et al.*, PRA 81, 062332 (2010)
[10]Bruzewicz *et al.*, npj QI 5, 102 (2019)

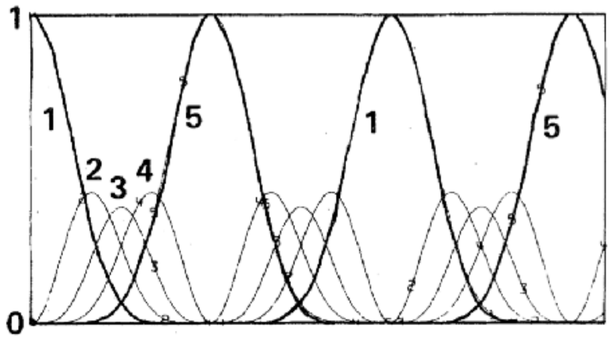


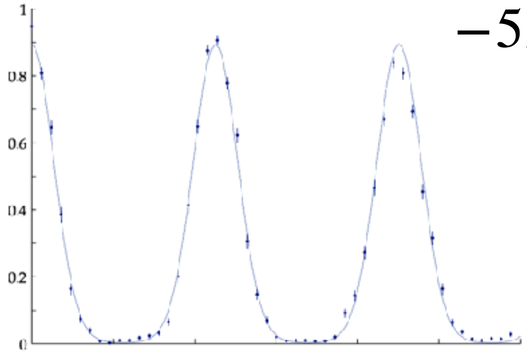


$D_{5/2}$ manifold

- RF drive causes population to evolve through all states
- We can use this for QIP!
  - Rotations work like SU(2)
  - Sequences that add to $n\pi$-rotations behave as expected[10,11]





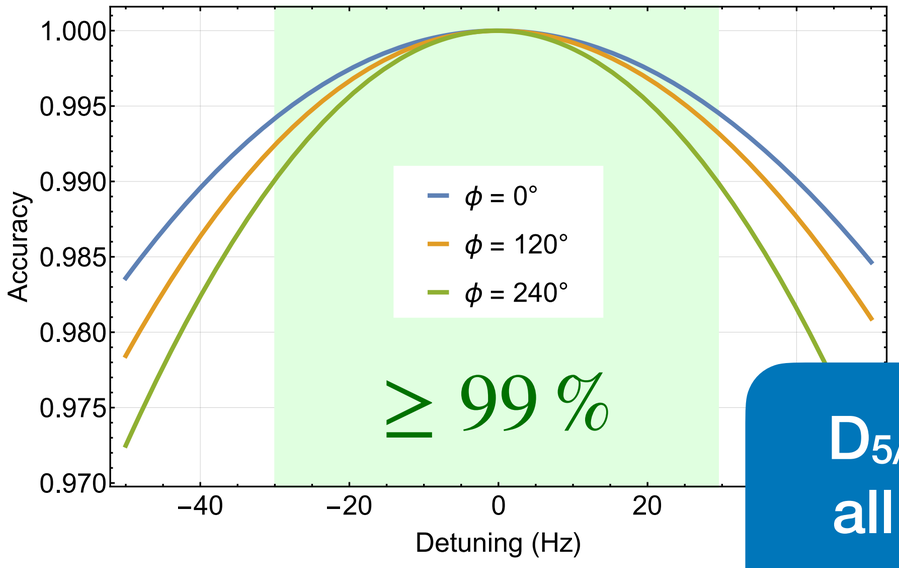


[10]R. J. Cook *et al.*, Phys. Rev. A 20, 539 (1979)

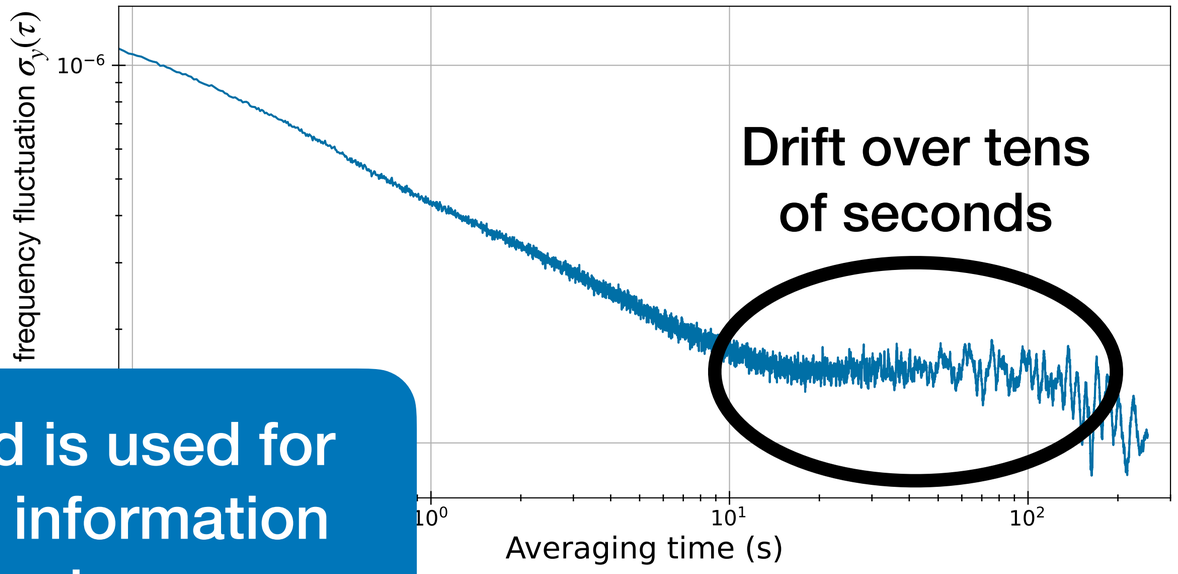
[11]M. J. Curtis, Ph.D. thesis, Oxford University (2010).

$D_{5/2}$ manifold: B field compensation

Simulated detuning-induced error

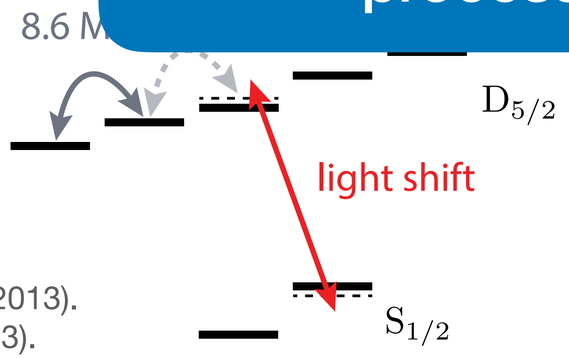


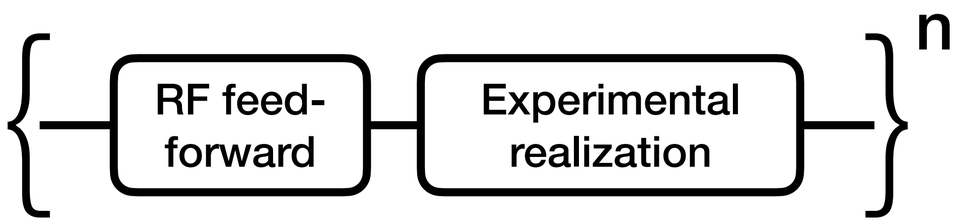
Zeeman frequency Allan deviation



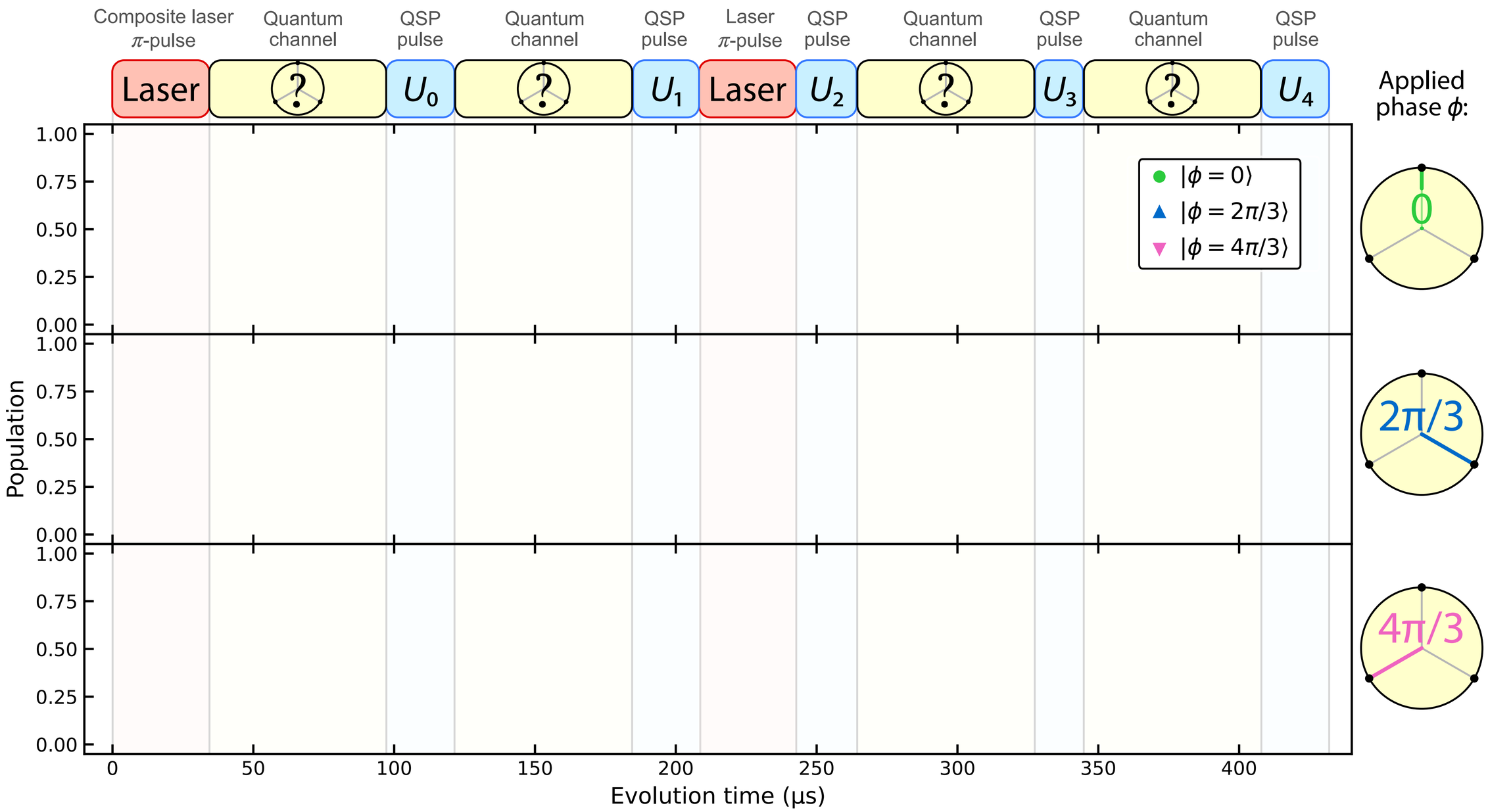
$D_{5/2}$ manifold is used for all quantum information processing

Feed-forward Ramsey measurement using $D_{5/2}$ qubit:[12,13]

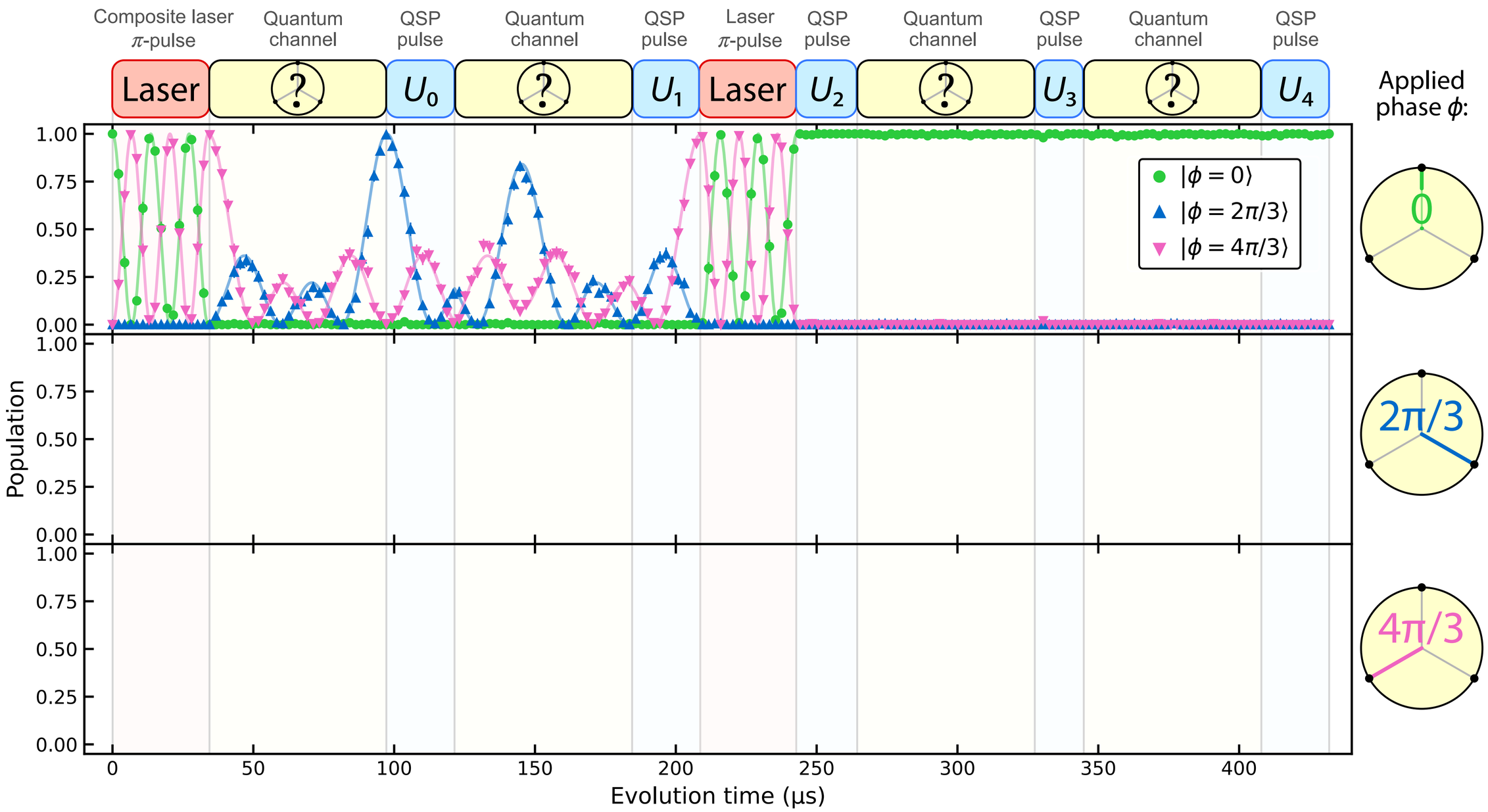




[12]J. Sherman *et al.*, Phys. Rev. Lett. 111, 180501 (2013).
[13]O. Băzăvan *et al.*, Phys. Rev. A 107, 022617 (2023).



DeBry *et al*., PRL, in press (2023)/arxiv:2305.14272



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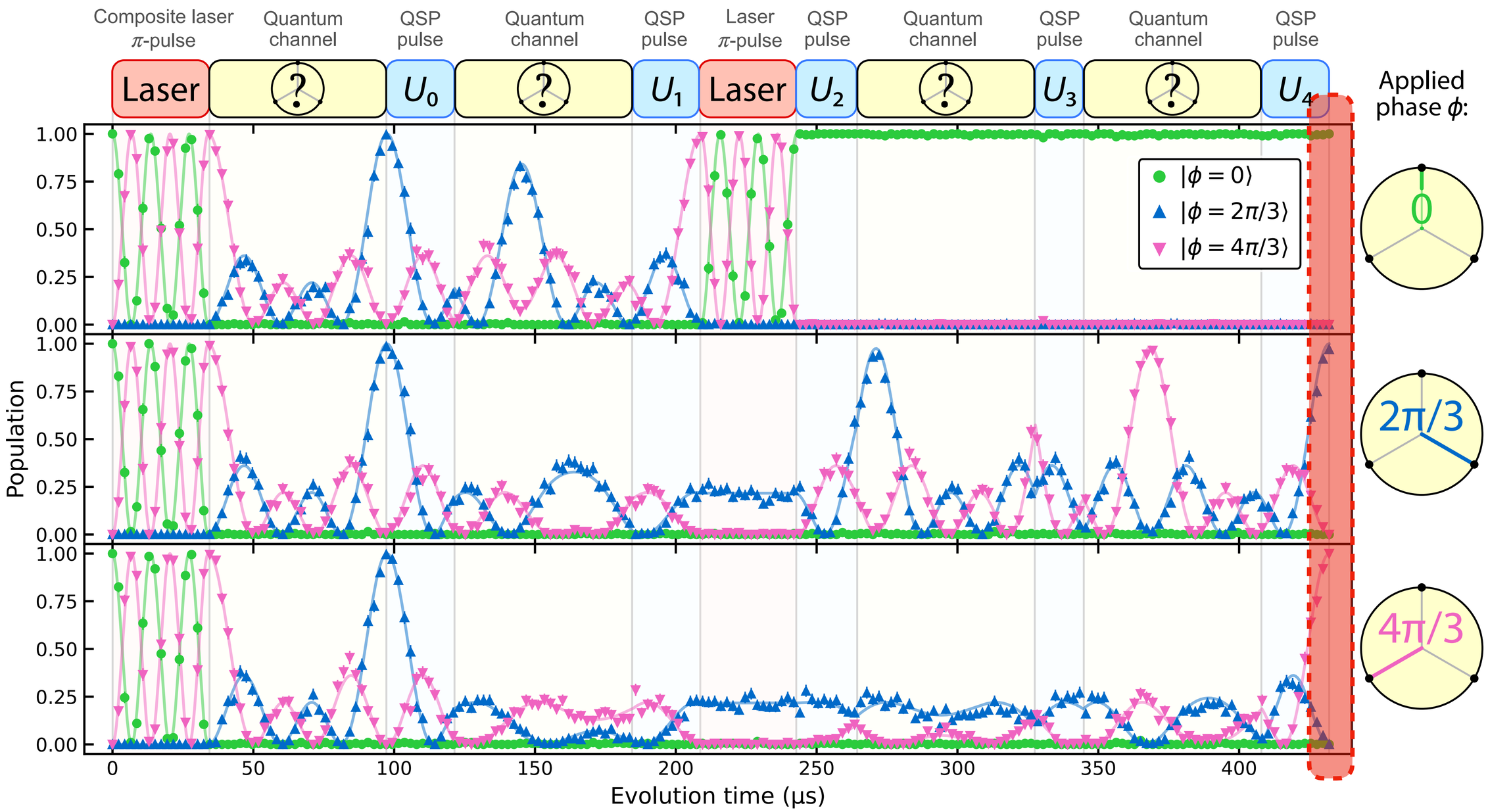

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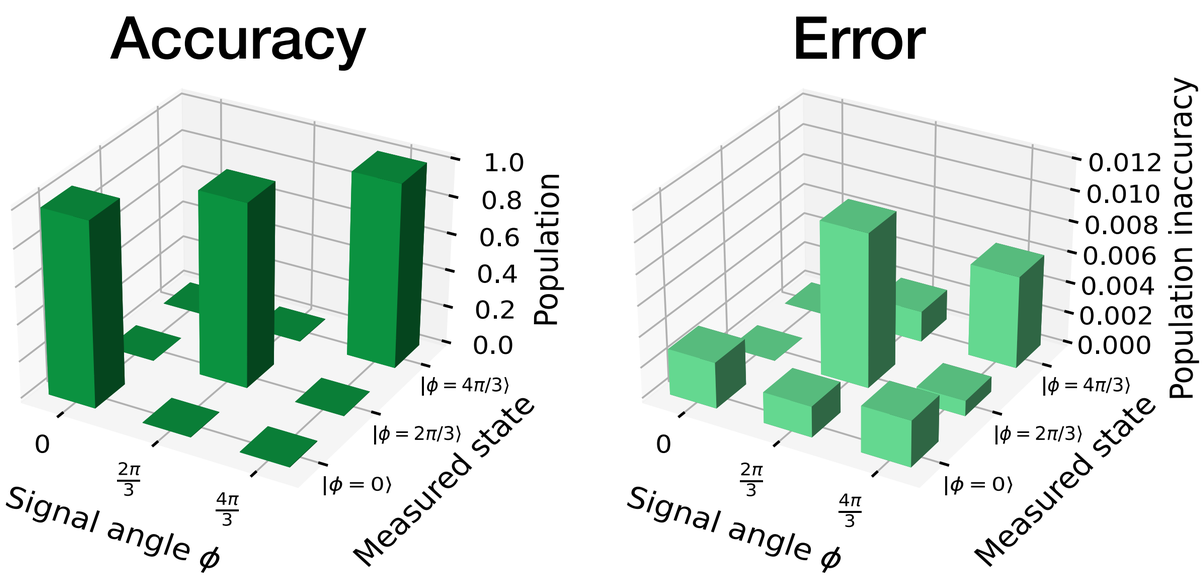
Phase shift keying performance

$99.4^{+0.1}_{-0.2}\,\%$



Error estimates

RF detuning:	0.3%
SPAM:	0.2%
Spontaneous decay:	< 0.1%

- 28 total pulses
- 9 gates in $D_{5/2}$ manifold
- ~99.98% fidelity each

What about other data encodings?

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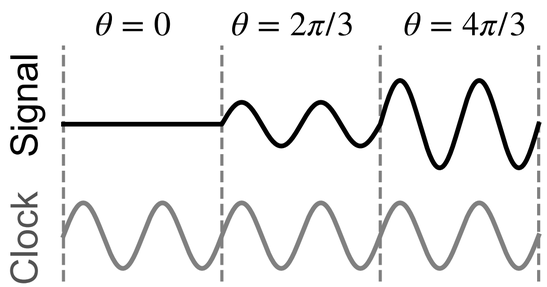
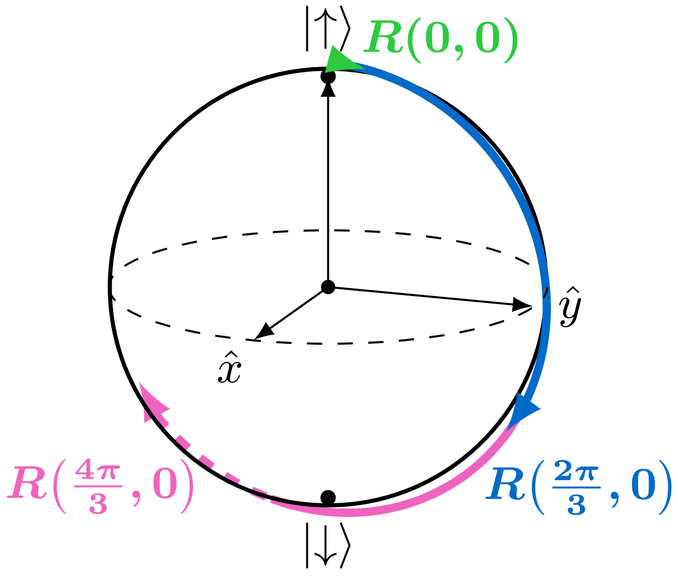
Amplitude shift keying (ASK) implementation

ASK Signal

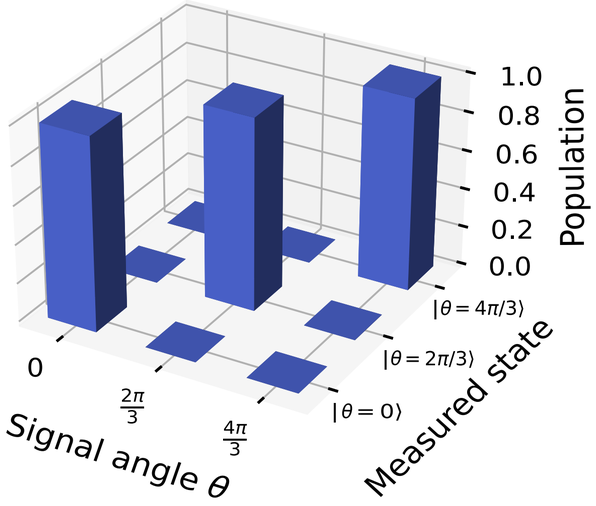


ASK Channel

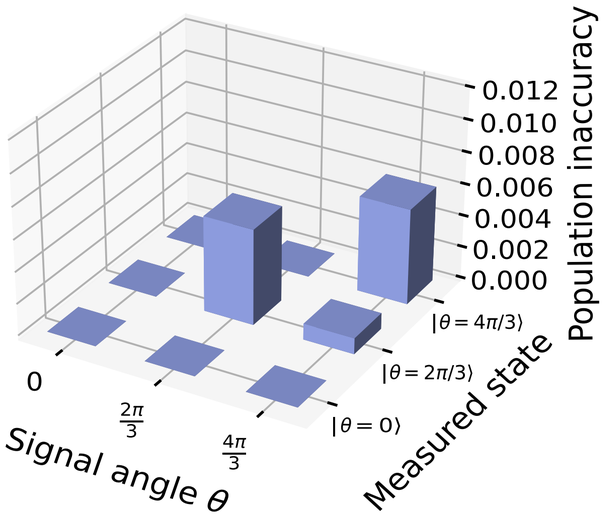


$$99.6^{+0.1}_{-0.1}\,\%$$

Accuracy



Error



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Summary

- Single shot, deterministic differentiation between non-orthogonal rotations
- Novel use of $D_{5/2}$ manifold for QIP
- Quantum advantage over “semi-classical” result

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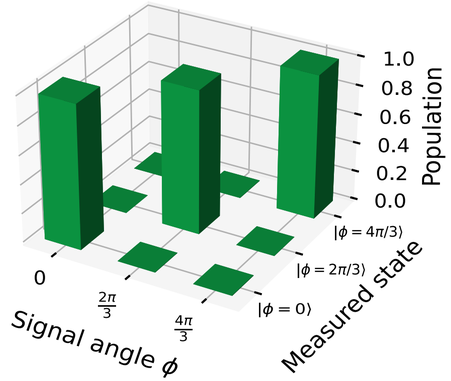

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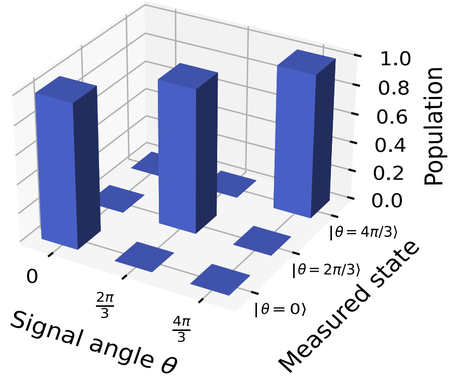

Read more!

arxiv:2305.14272

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Acknowledgements

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- Susanna Todaro
- Ethan Clements
- Felix Knollmann
- Xiaoyang Shi
- Gabriel Mintzer

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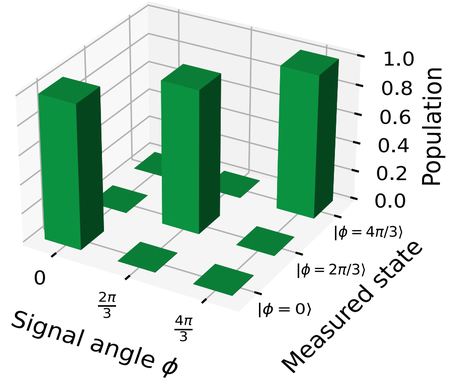

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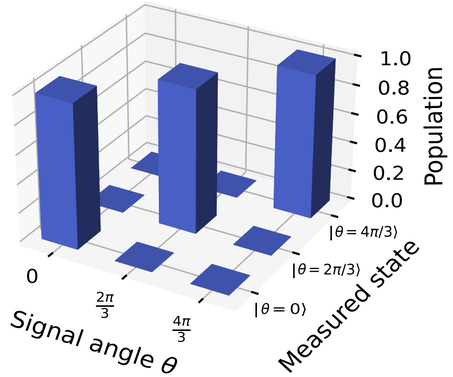

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