# Non-conventional receivers for coherent communication


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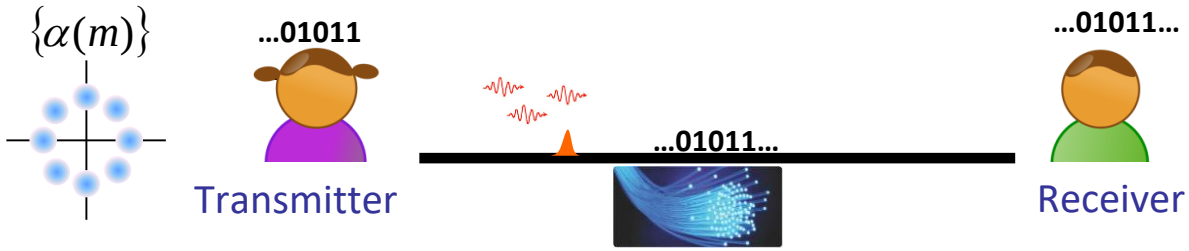
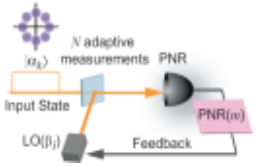
*University of New Mexico, Albuquerque, NM, USA*

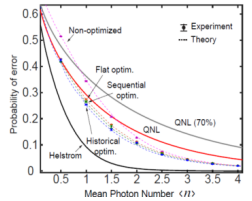

**Munich Workshop on Information Theory of Optical Fiber (MIO 2018)**

December 6, 2018

Munich, Germany





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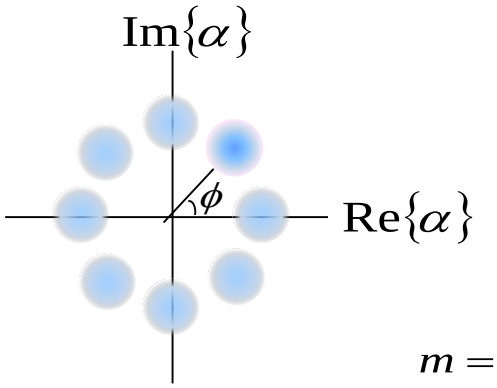
# Measurements in Quantum Mechanics

- Intrinsic noise of the system limits our ability to measure
- How can we perform better measurements? Quantum resources!
- **Increase Sensitivity (Enhanced Quantum Measurements)**
  - Quantum Metrology: (continuous) parameter estimation
  - **Nonorthogonal State Discrimination:** Distinguish states (from a finite known set)
    - Theoretical predictions in the 70's
    - Experimental discrimination below the SQL (~0.2 dB) * Only 2 coherent states

* K. Tsujino et al., PRL **106**, 250503 (2011).

# Multiple Coherent States

**Coherent state** $\left| e^{i\phi}\alpha_s \right\rangle$




$$\phi = \frac{2\pi\ m}{M}$$

$$m = \{0, 1, 2, .., M-1\}$$

## M-ary Phase Shift Keying (PSK)

*M=2: Binary Phase Shift Keying (BPSK)*

$$Signal = \{|\ \alpha\rangle, |-\alpha\rangle\}$$

*M=4: Quadrature Phase Shift Keying (QPSK)*

$$Signal = \{|\ \alpha\rangle, |i\alpha\rangle, |\ -\alpha\rangle, |-i\alpha\rangle\}$$

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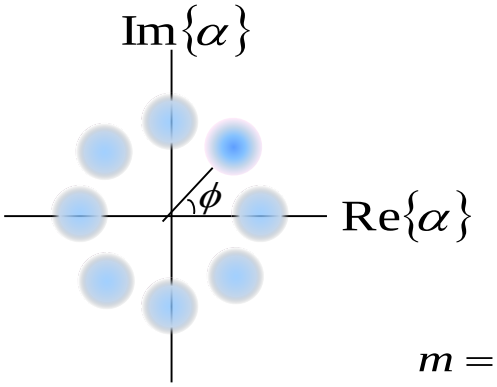


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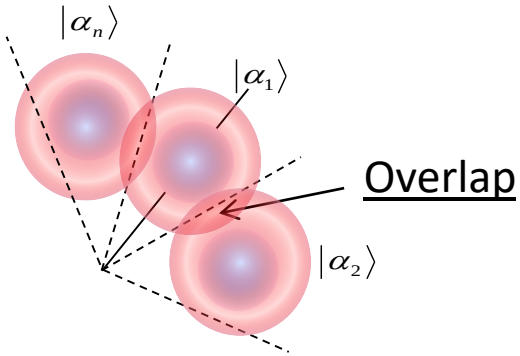
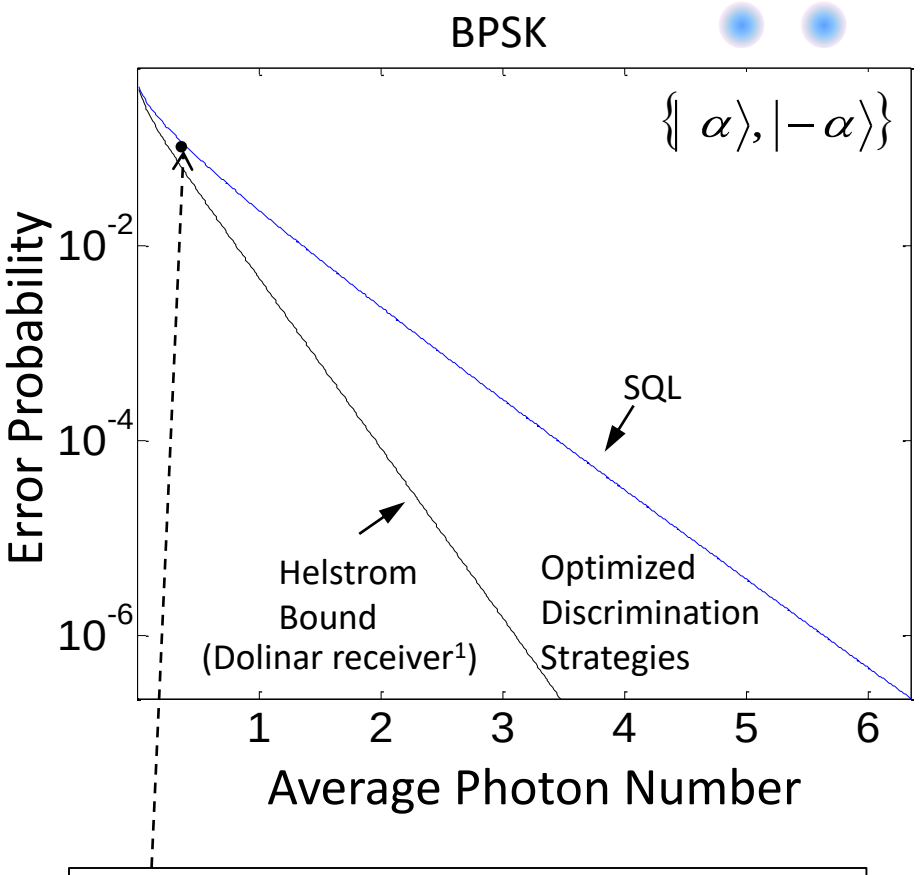
Coherent States are Nonorthogonal

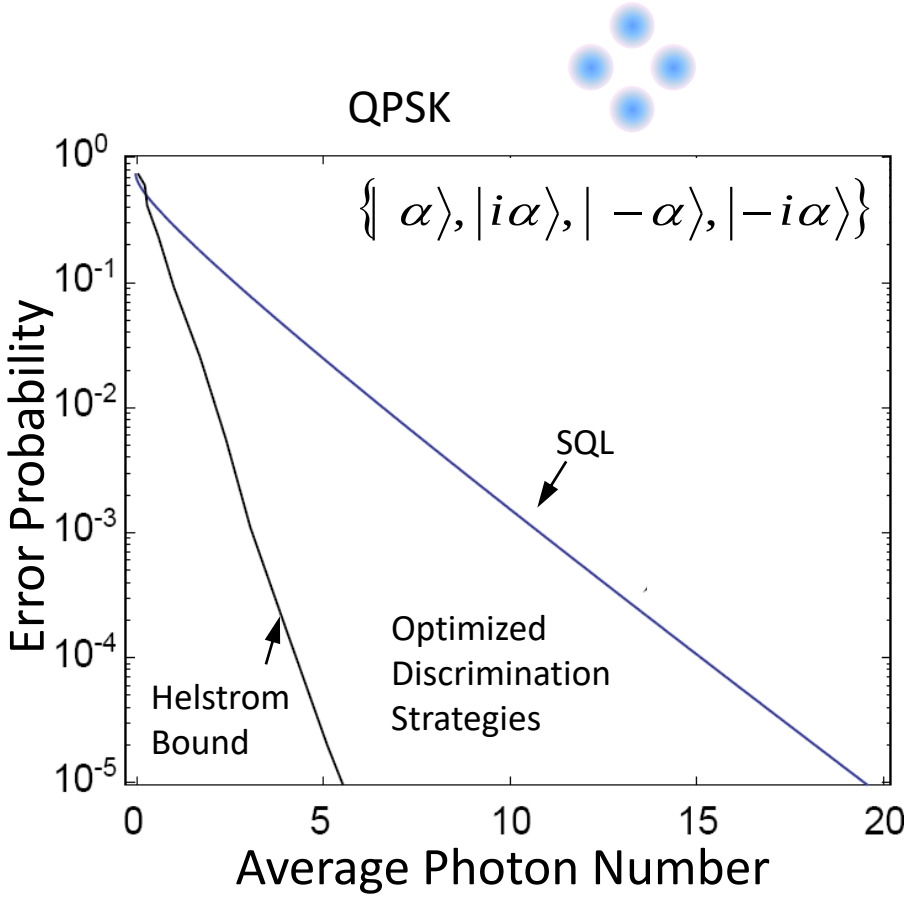



**Discrimination**
Unavoidable Errors

Standard Quantum Limit (SQL)
*(Minimum Error by direct detection)*

# Quantum Limit: Helstrom Bound

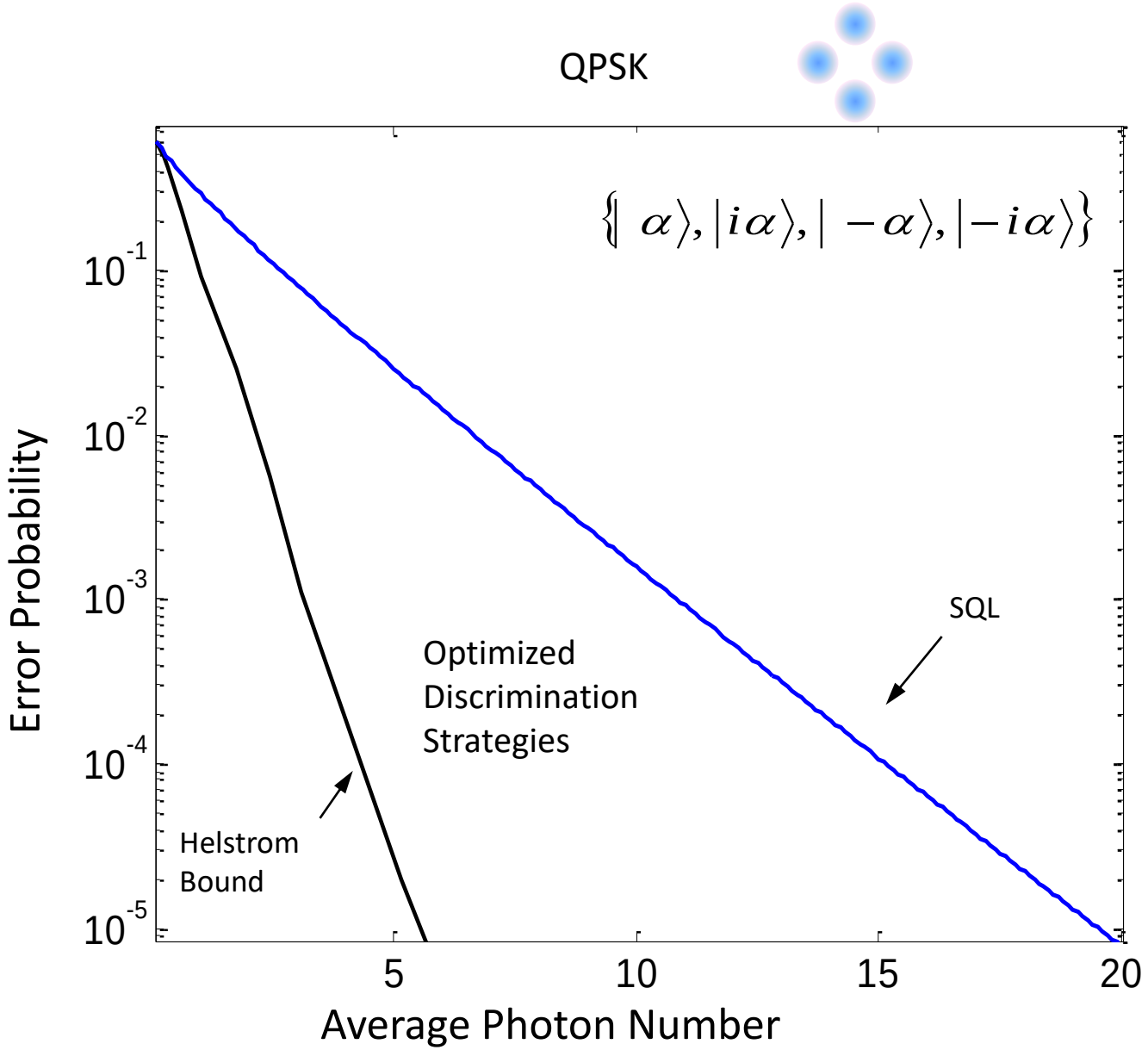



**Demonstration of binary receiver beyond the SQL**
K. Tsujino et al., PRL **106**, 250503 (2011).

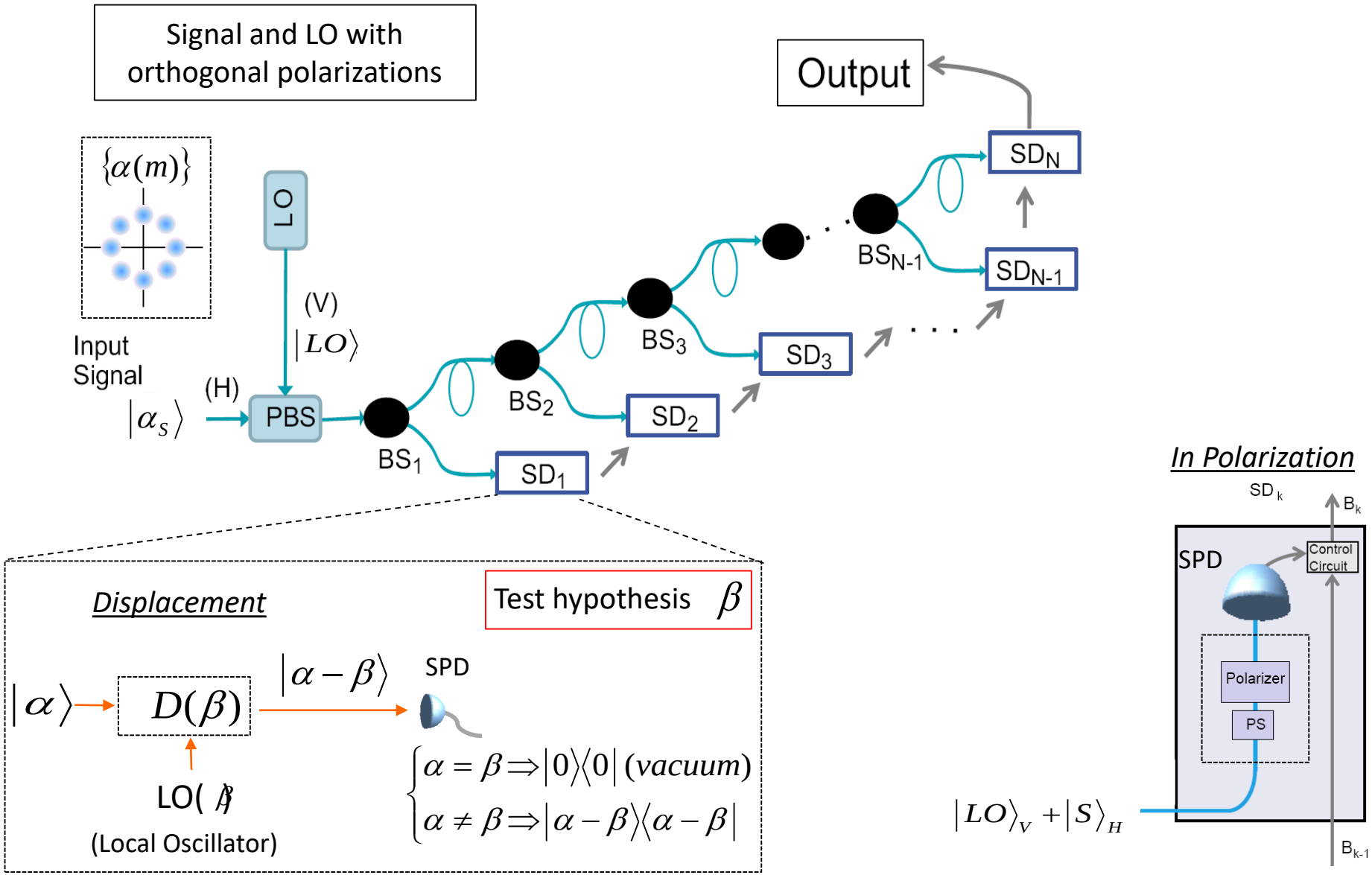
[1] S. J. Dolinar, Research Laboratory of Electronics, MIT, Quarterly Progress Report No. 111 (1973).

# Quantum Limit: Helstrom Boun



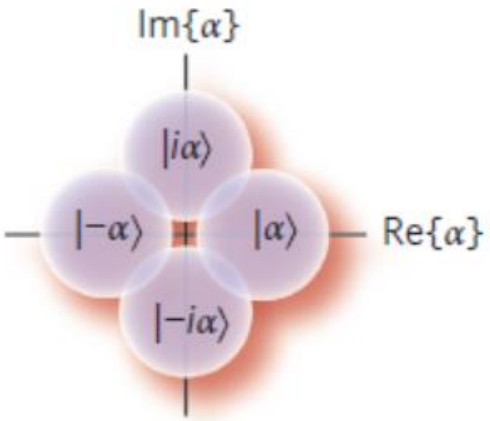
# Feed-Forward Receiver Design

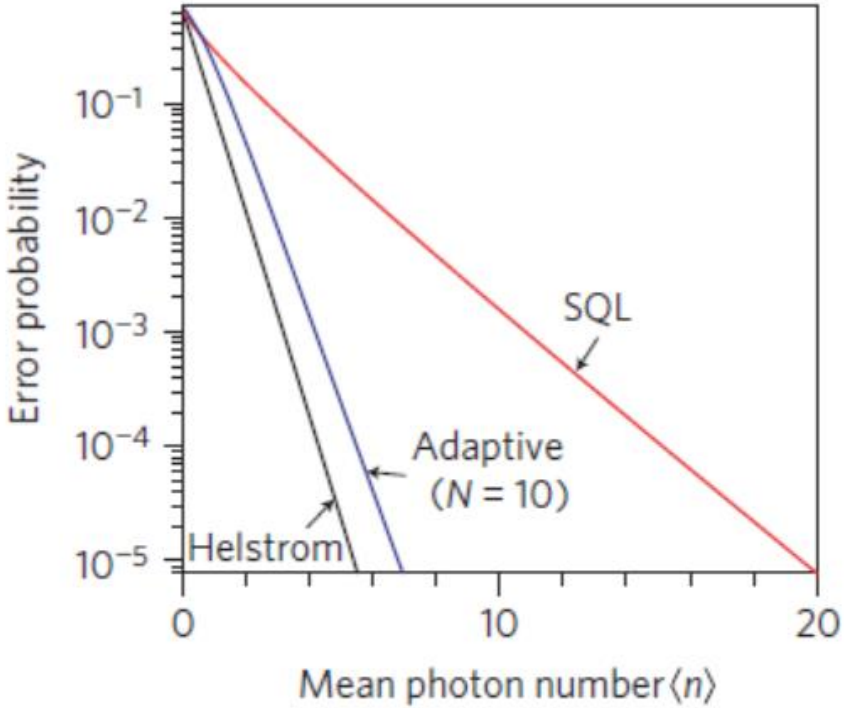
(M-ary Signals)

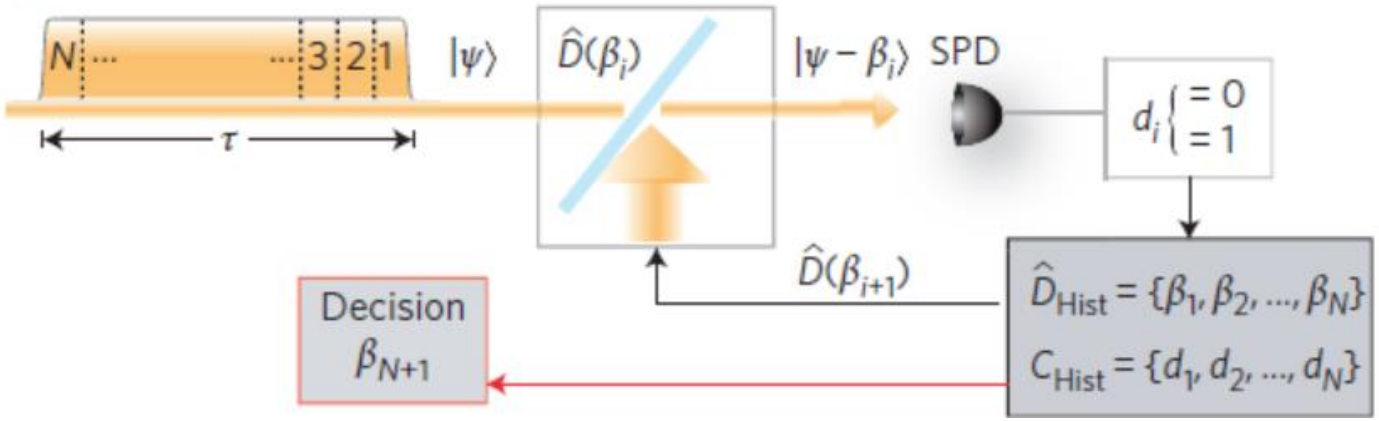


# Experimental concept

(4-ary Signals)

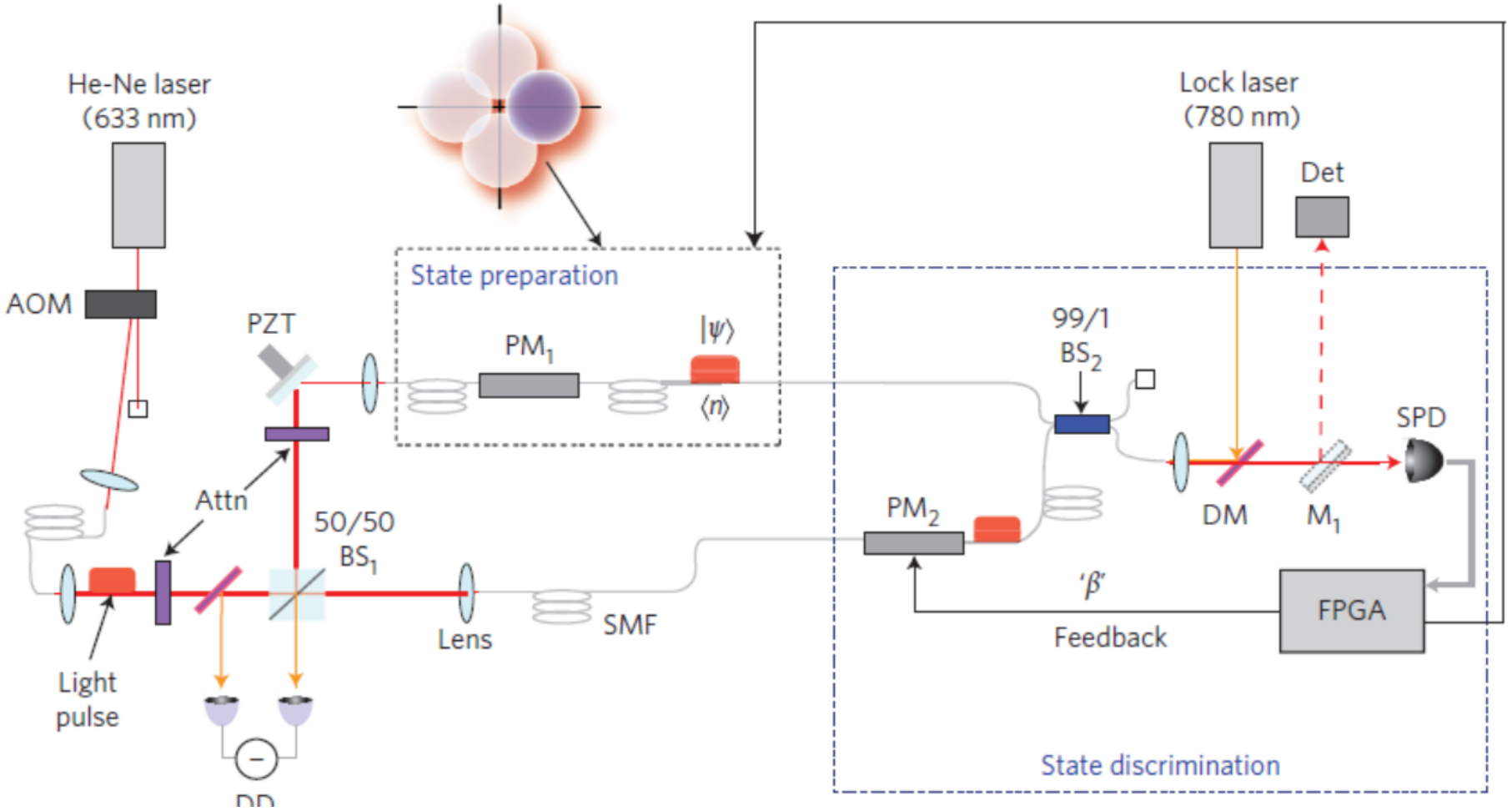


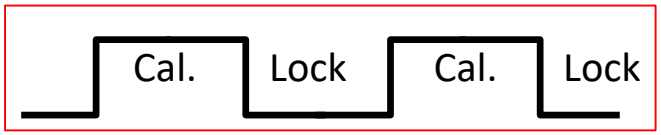



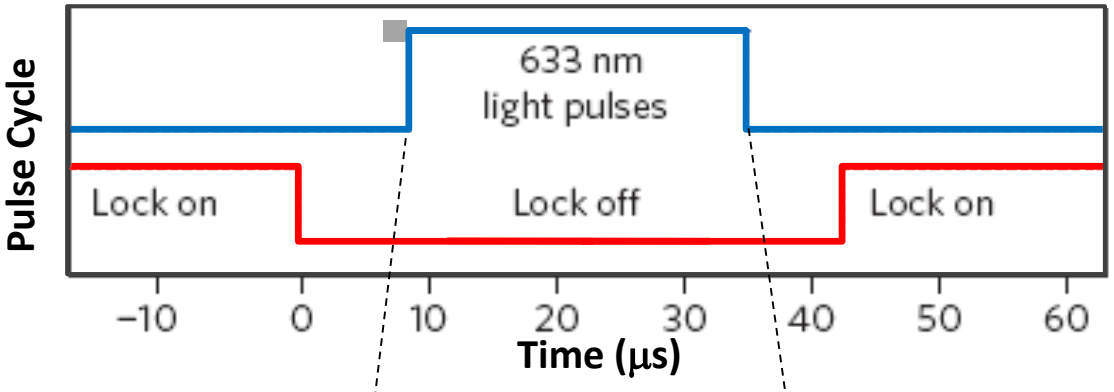
# Experimental Configuration

(4-ary Signals)

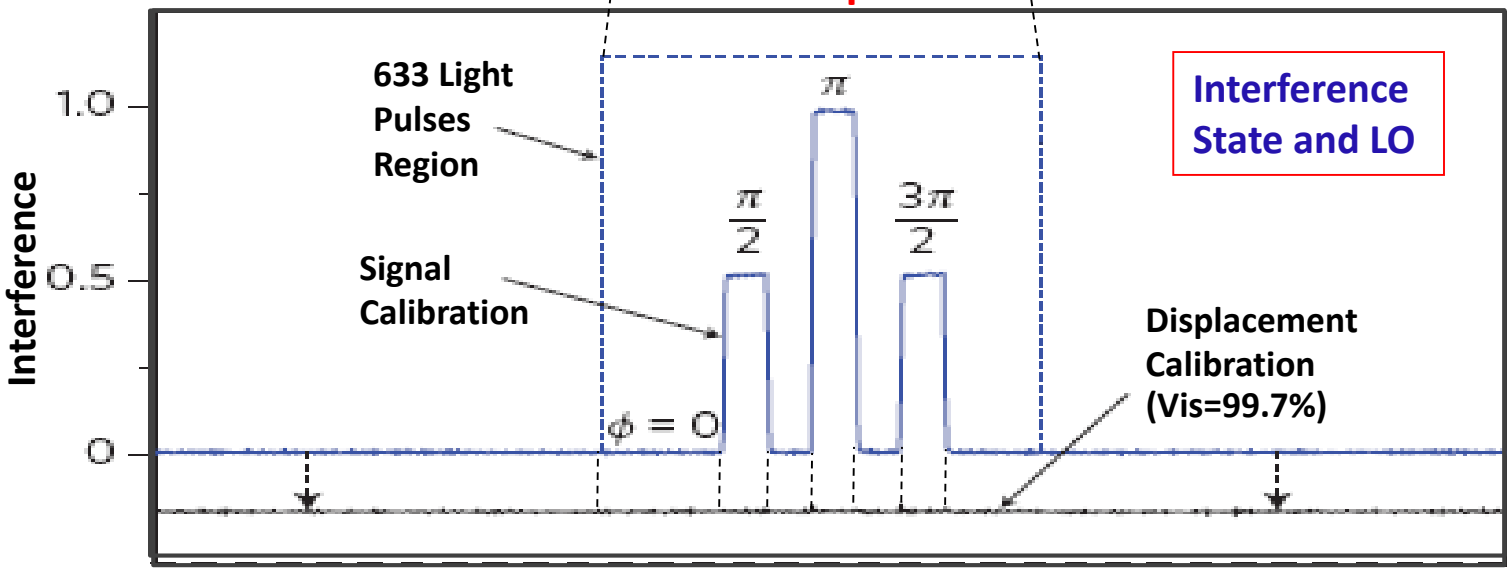


# Phase Preparation (50% duty cycle)




**Phase Preparation**



# Experimental Data Sample

$$\{|\alpha\rangle, |i\alpha\rangle, |-\alpha\rangle, |-i\alpha\rangle\}$$

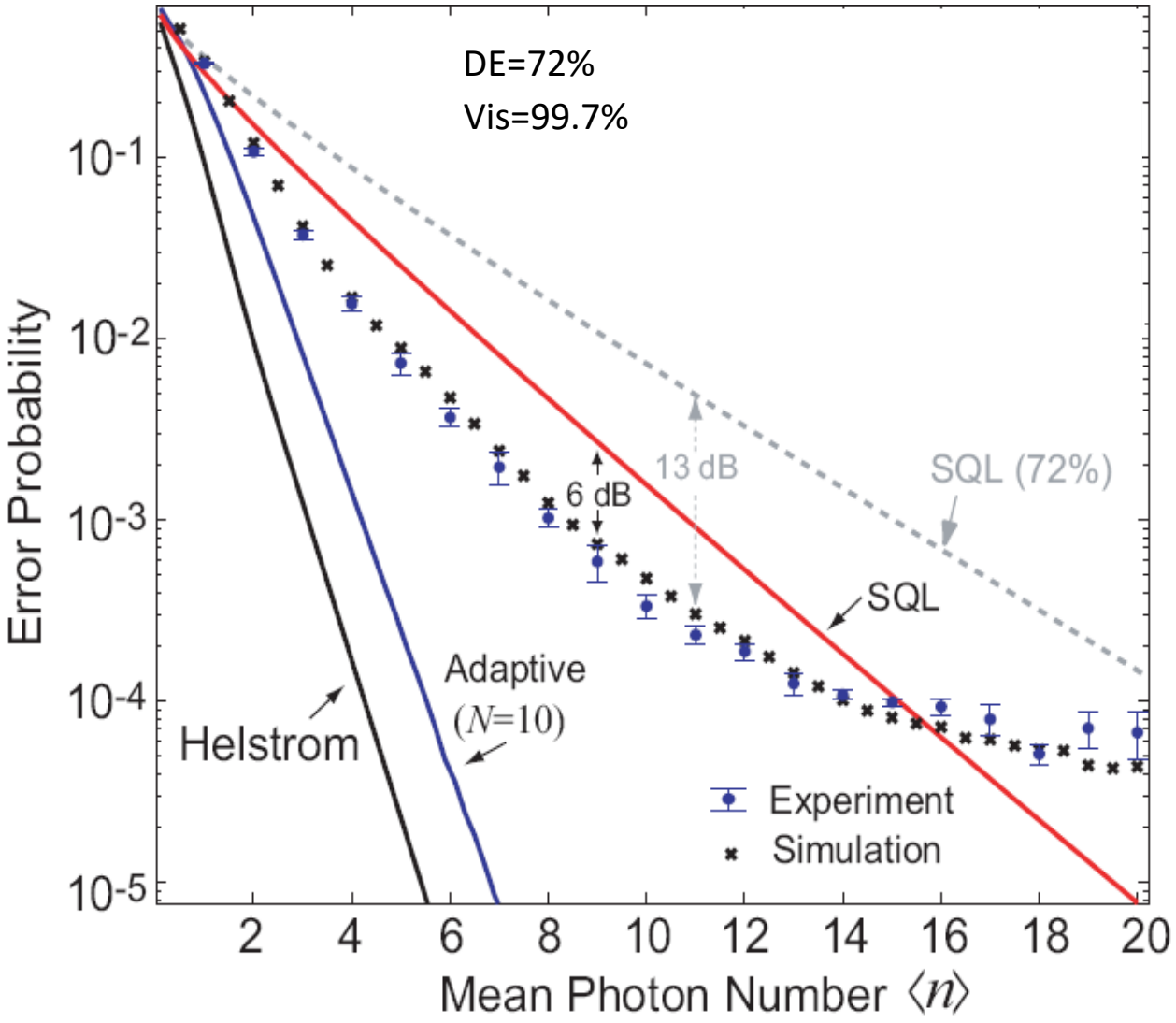
**Prepared state** $|-i\alpha\rangle$

| Hypothesis | Photon Detection | Feedback Period |
|---|---|---|
| 0 | 1 | 1 |
| π | 1 | 2 |
| 3π/2 | 0 | 3 |
| 3π/2 | 0 | 4 |
| 3π/2 | 0 | 5 |
| 3π/2 | 1 | 6 |
| π/2 | 1 | 7 |
| 3π/2 | 0 | 8 |
| 3π/2 | 0 | 9 |
| 3π/2 | 0 | 10 |
| **3π/2** | | |

**Decision** $|-i\alpha\rangle$

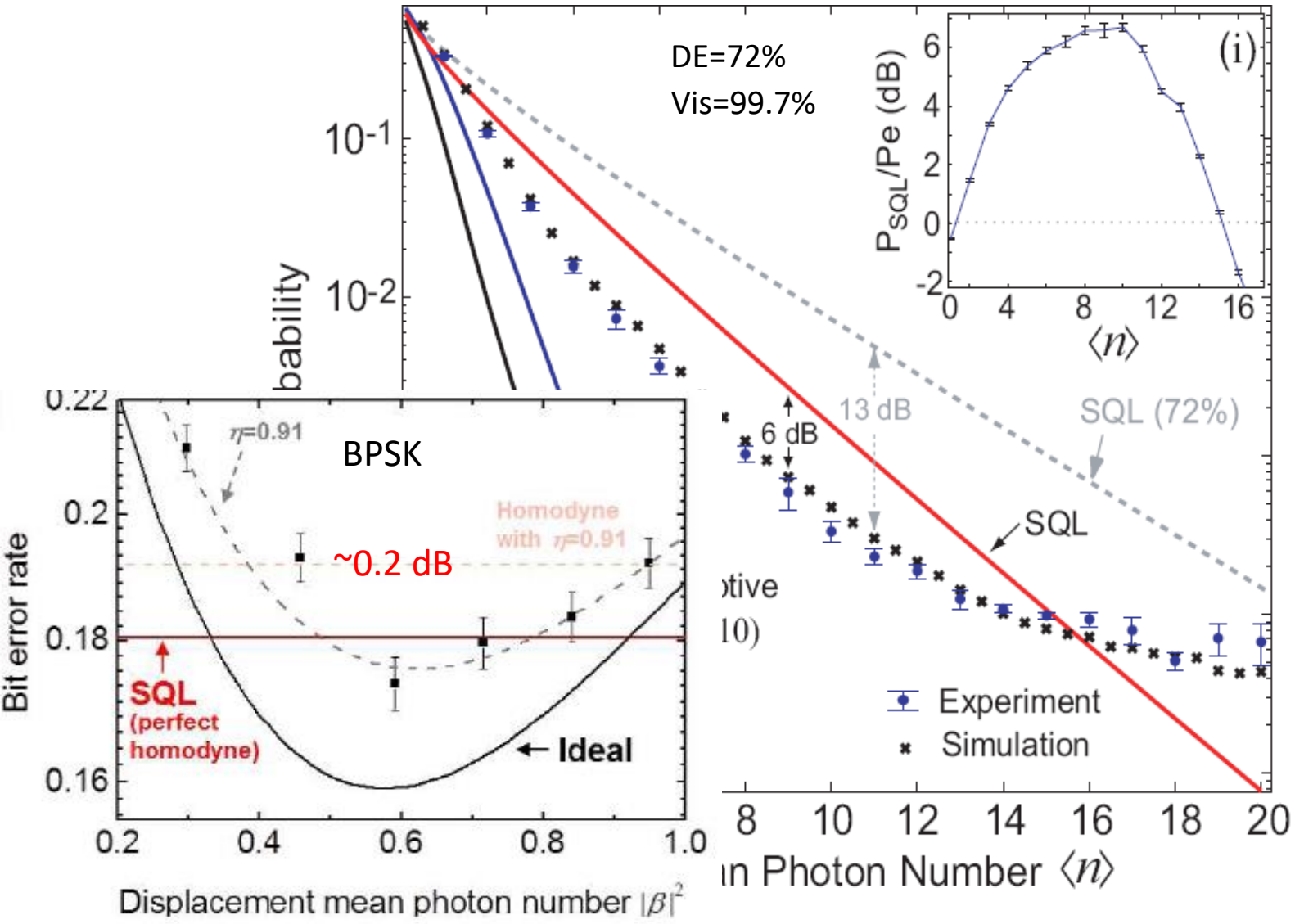
# Experimental Error Probability

$$\{|\alpha\rangle, |i\alpha\rangle, |-\alpha\rangle, |-i\alpha\rangle\}$$



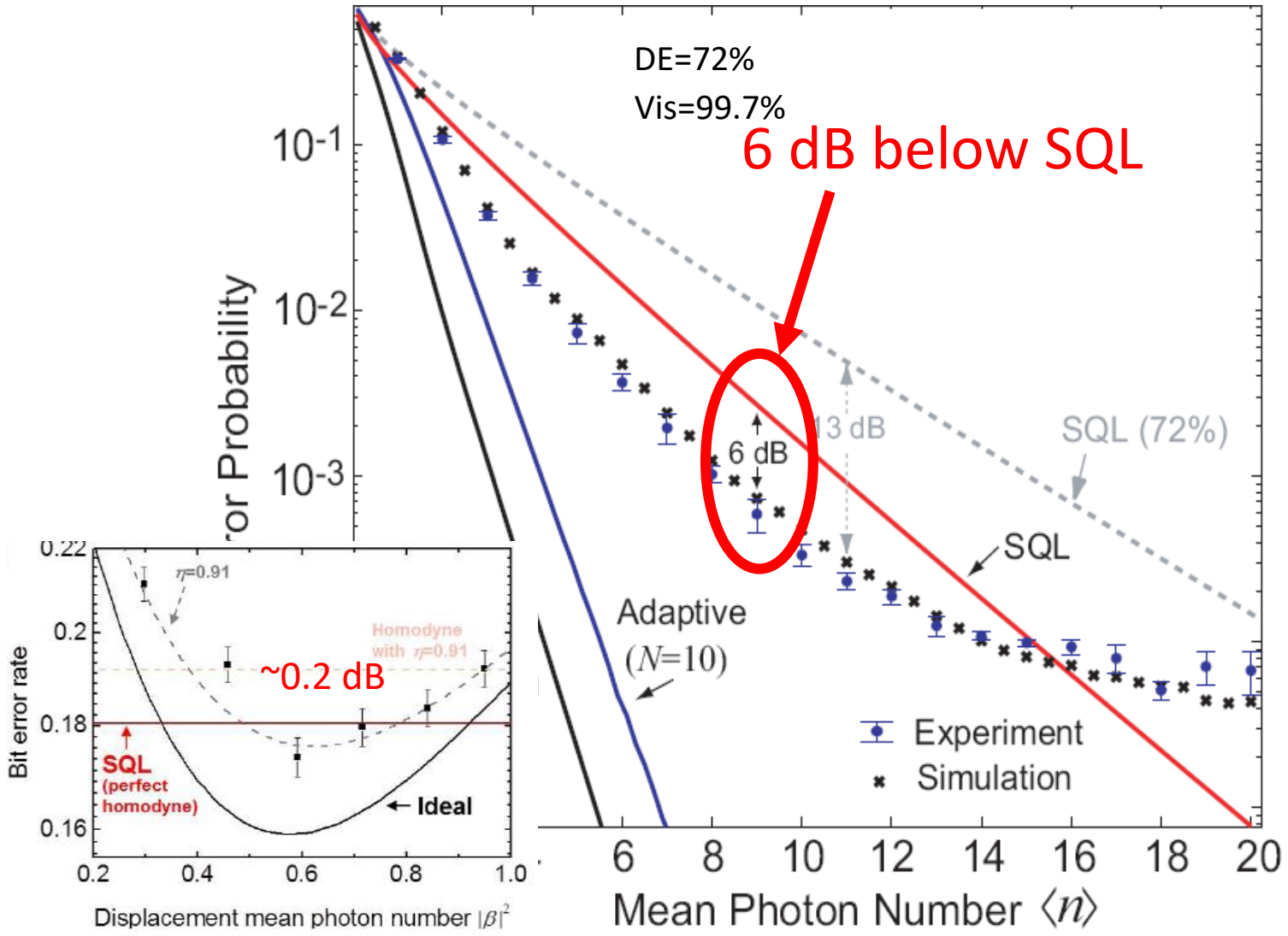
# Experimental Error Probability

$$\{|\alpha\rangle, |i\alpha\rangle, |-\alpha\rangle, |-i\alpha\rangle\}$$



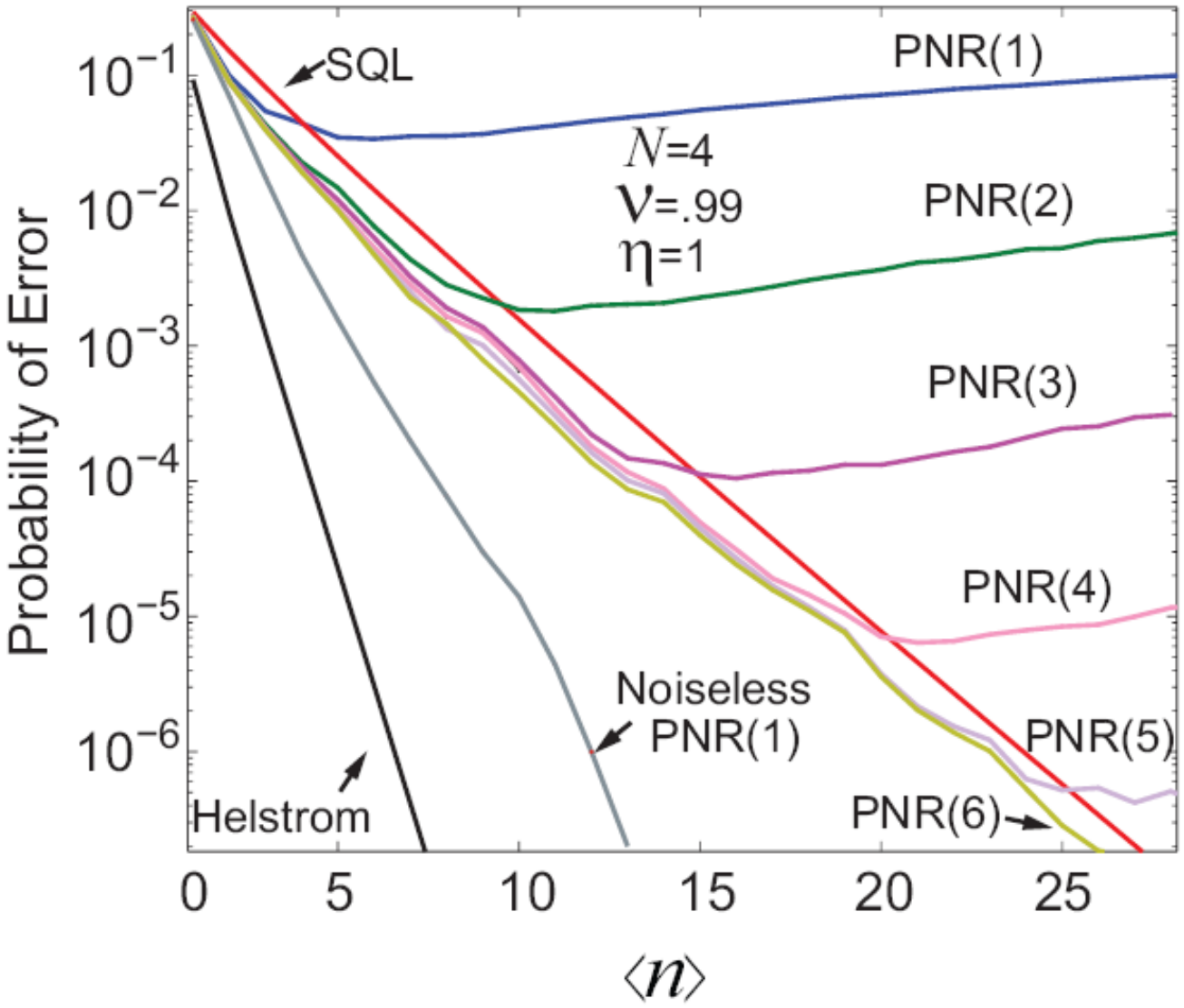
# Experimental Error Probability

$$\{|\alpha\rangle, |i\alpha\rangle, |-\alpha\rangle, |-i\alpha\rangle\}$$



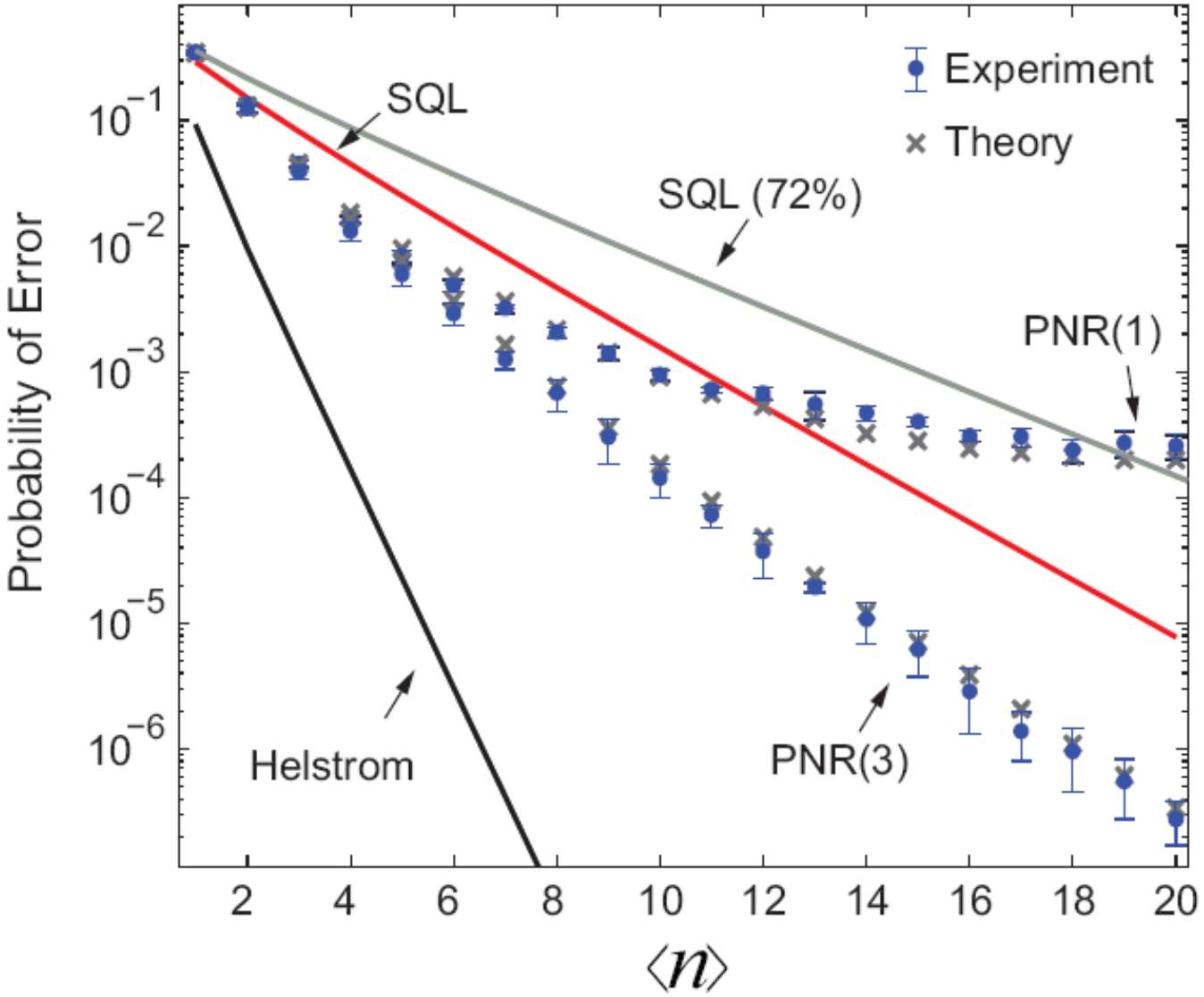
# PNR Quantum Receiver (Theory)

$$\{|\alpha\rangle, |i\alpha\rangle, |-\alpha\rangle, |-i\alpha\rangle\}$$

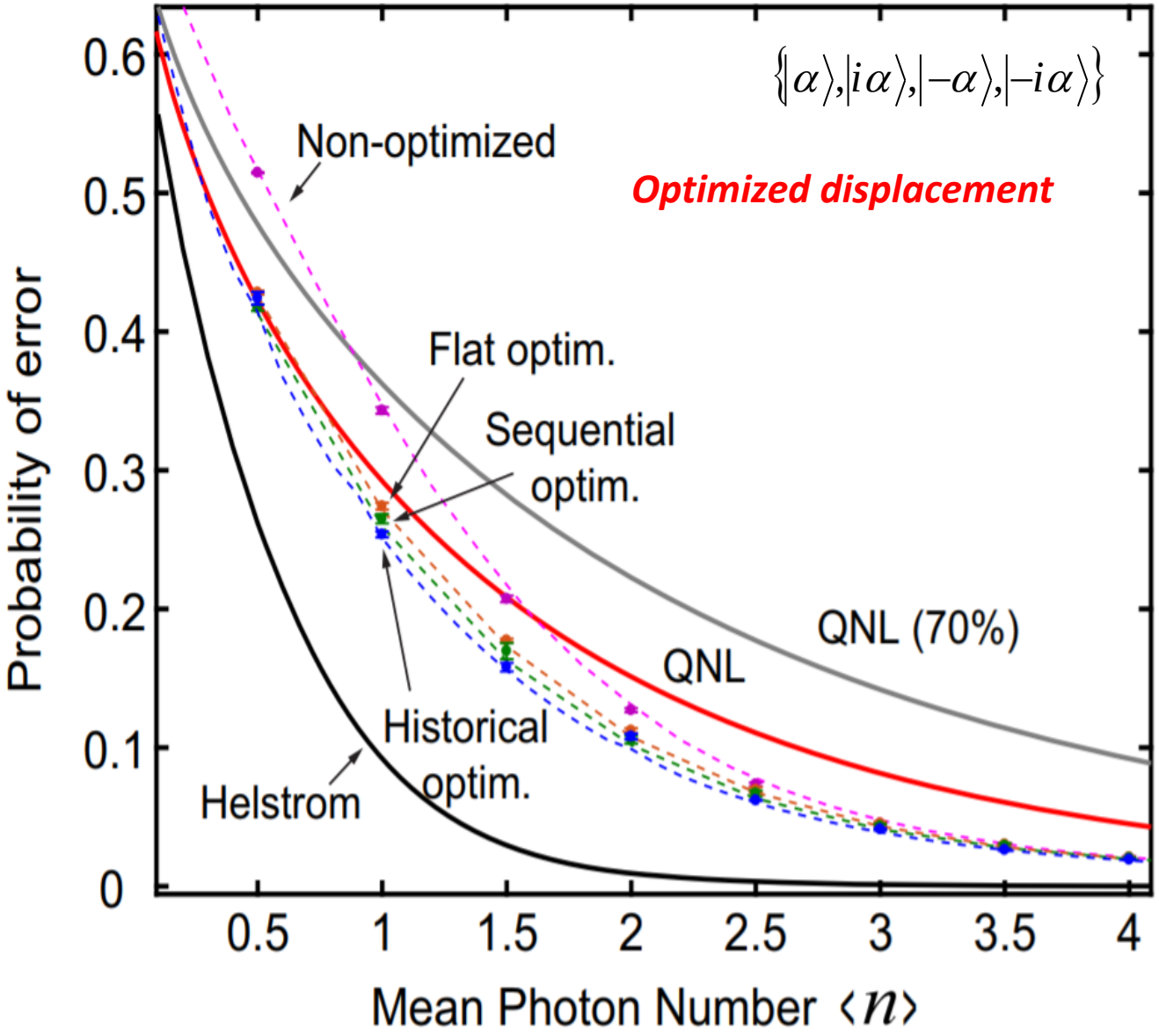


# PNR Quantum Receiver (Experiment)

$$\{|\alpha\rangle, |i\alpha\rangle, |-\alpha\rangle, |-i\alpha\rangle\}$$



# Optimized Displacement Receivers

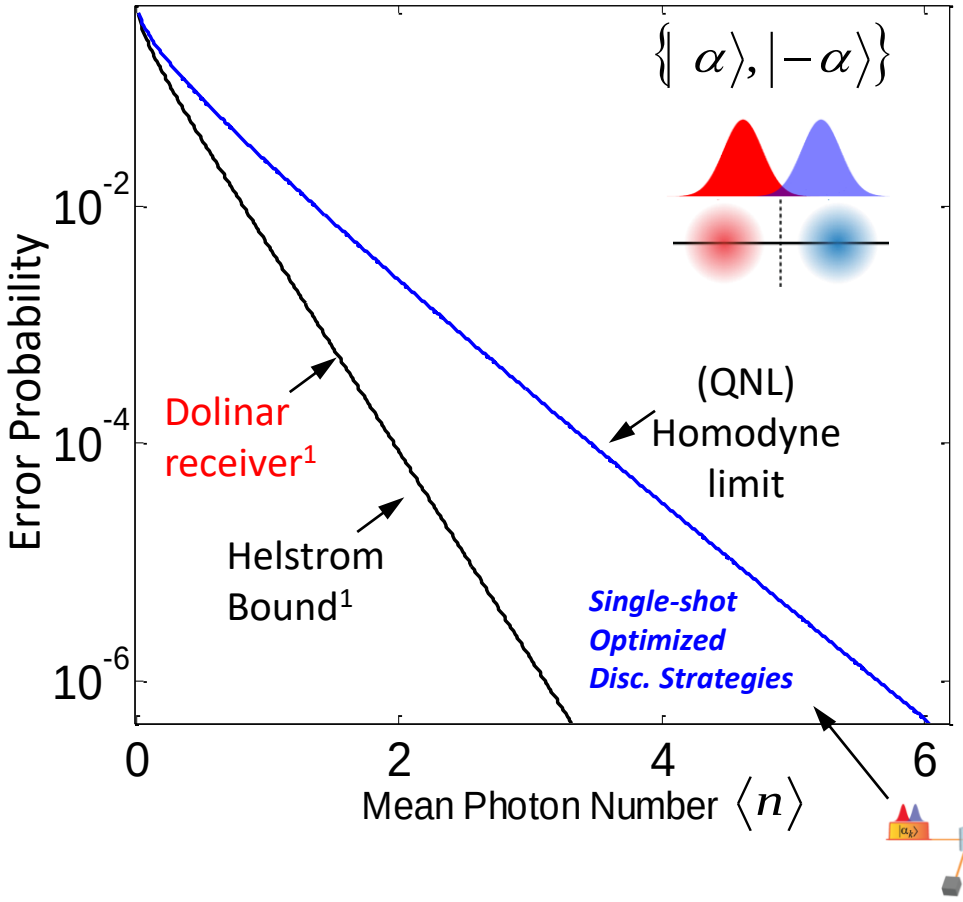



*Muller, C. and Marquardt, C., New J. Phys. 17, 032003 (2015)

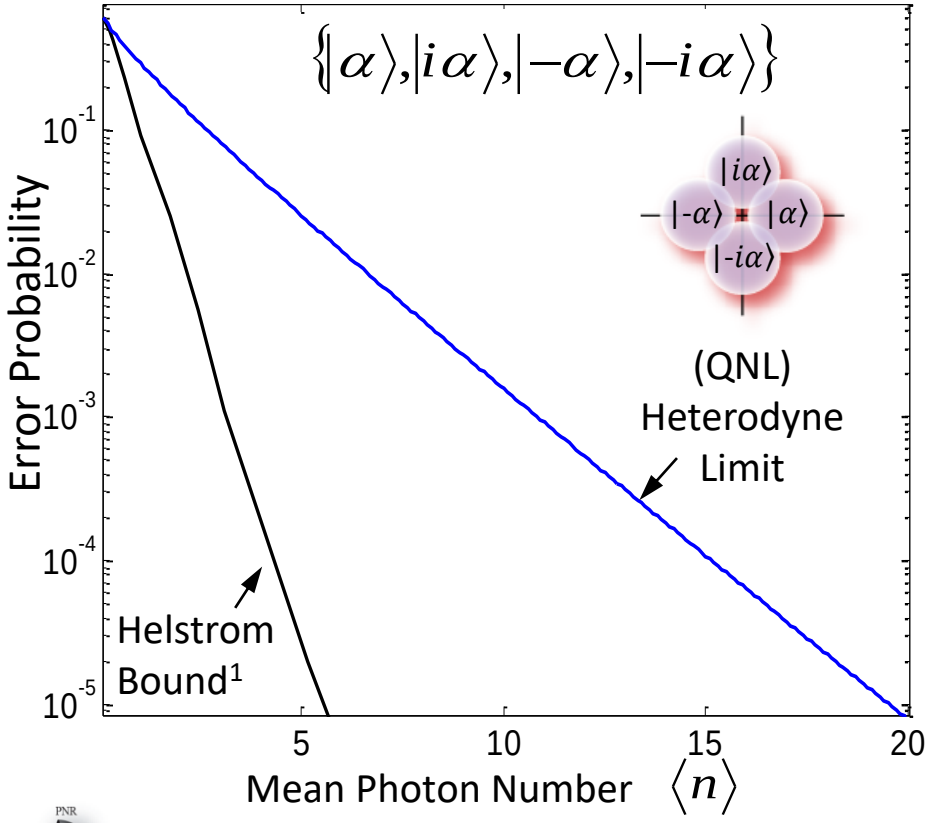
A. R. Ferdinand, M. T. DiMario, F. E. Becerra, *npj Quantum Information* **3**, 43 (2017).

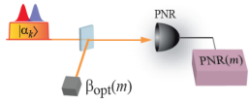
# State Discrimination: Probability of error

## Binary Phase-shift Keying (BPSK)




## 4-state discrimination (QPSK)





R. S. Kennedy, MIT Technical Report No. 110 (1972).

M. Takeoka and M. Sasaki, Phys. Rev. A 78, 022320 (2008).

[1] S. J. Dolinar, Research Lab. of Elec., MIT, Quart. Prog. Rep. No. 111 (1973).

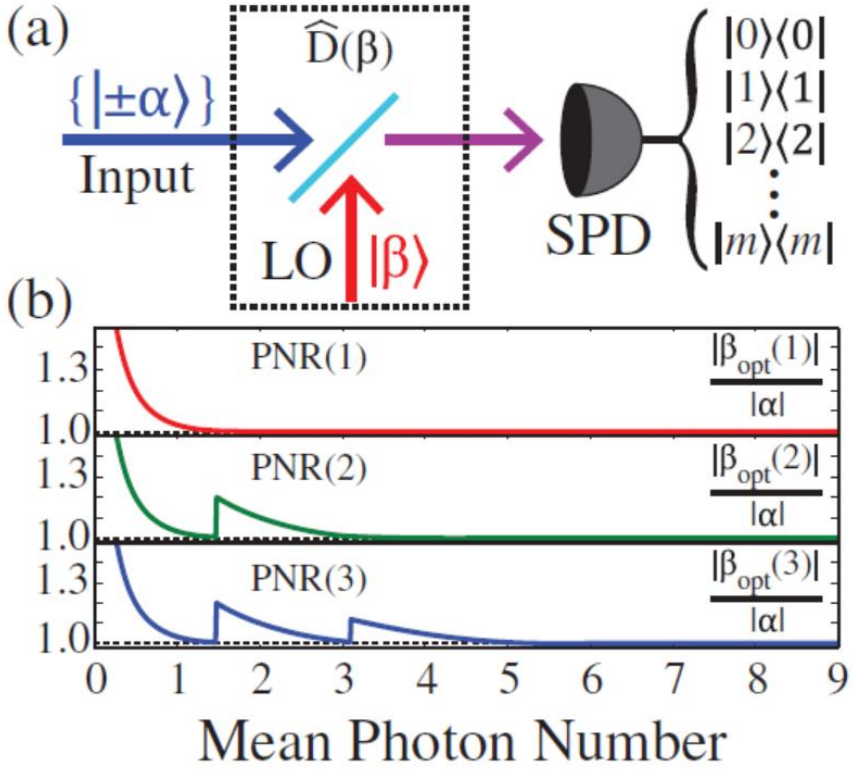
C. Wittmann, et. al, Phys. Rev. Lett. **101**, 210501 (2008).

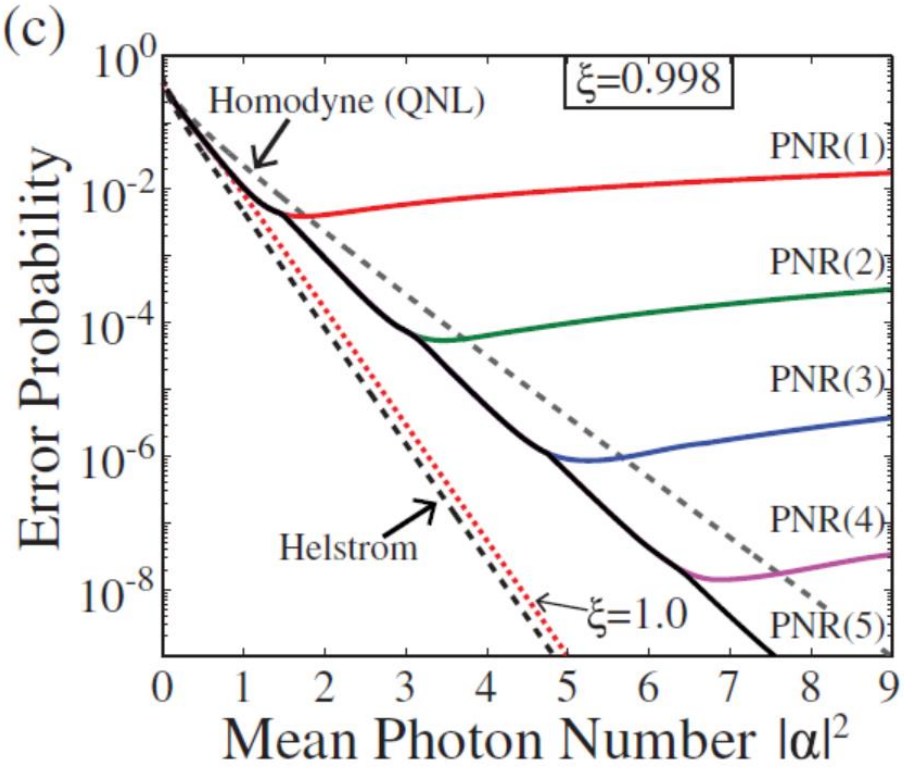
K. Tsujino, et. al, Phys. Rev. Lett. **106**, 250503 (2011).

M. T. DiMario and F. E. Becerra, Phys. Rev. Lett. **121**, 023603 (2018)

# Non-ideal visibility degrades performance

***Visibility (ξ)*** *of Displacement characterizes noise and imperfections*





[1]: C. Wittmann, et. al, Phys. Rev. Lett. **101**, 210501 (2008).

[2]: K. Tsujino, et. al, Phys. Rev. Lett. **106**, 250503 (2011).

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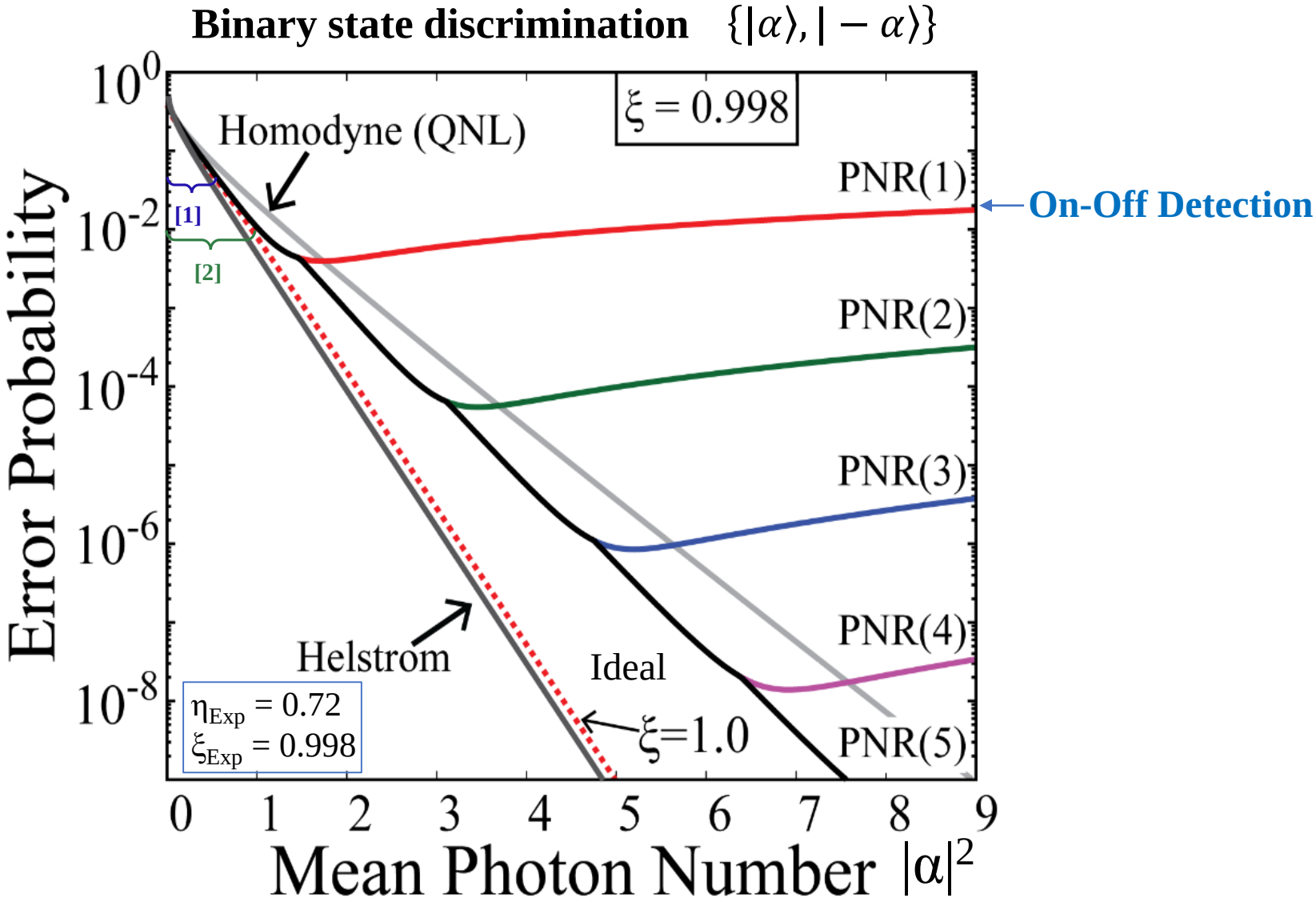


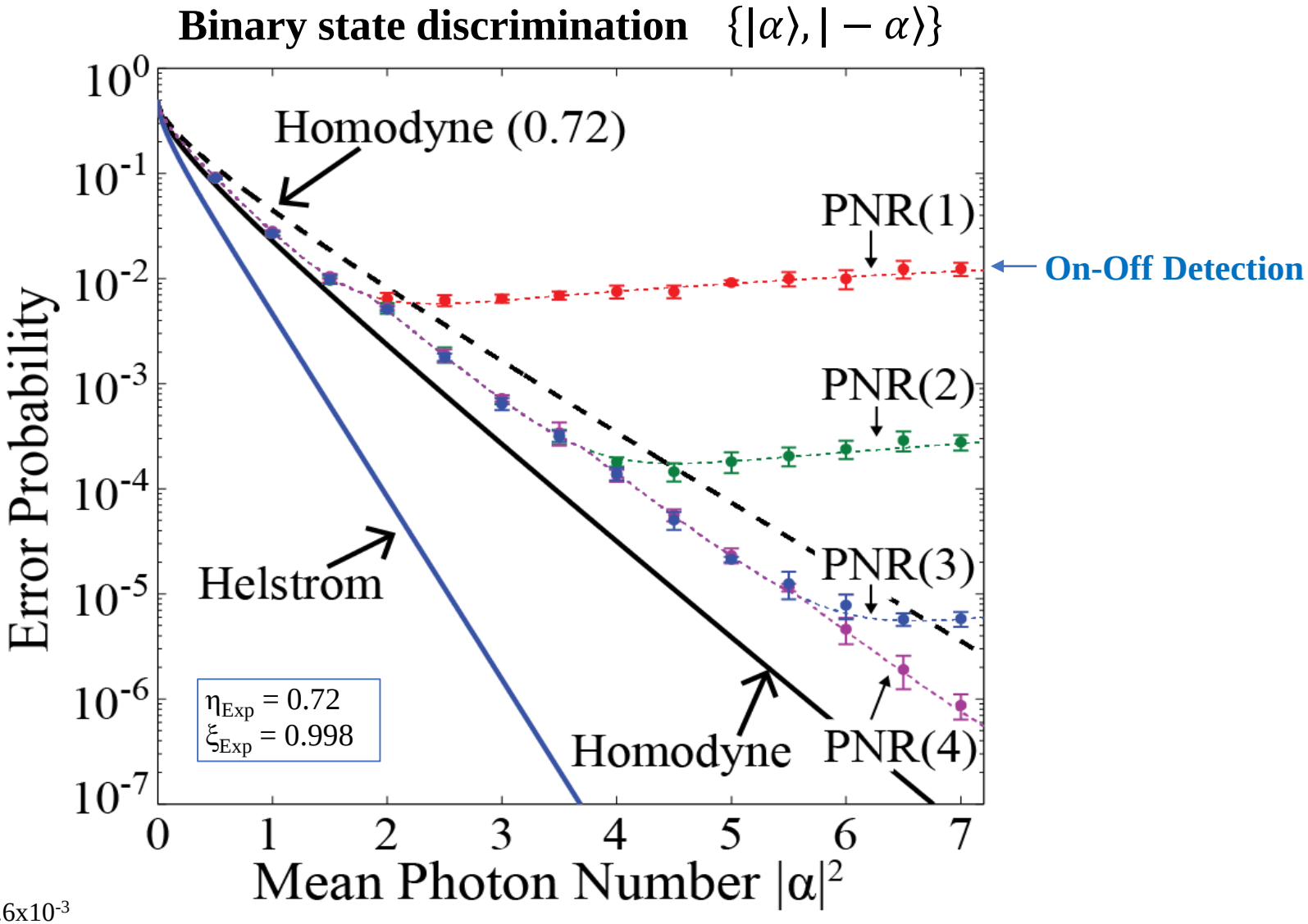


[1]: C. Wittmann, et. al, Phys. Rev. Lett. **101**, 210501 (2008).

[2]: K. Tsujino, et. al, Phys. Rev. Lett. **106**, 250503 (2011).

M. T. DiMario and F. E. Becerra, Phys. Rev. Lett. **121**, 023603 (2018)

# Experimental Error Probability

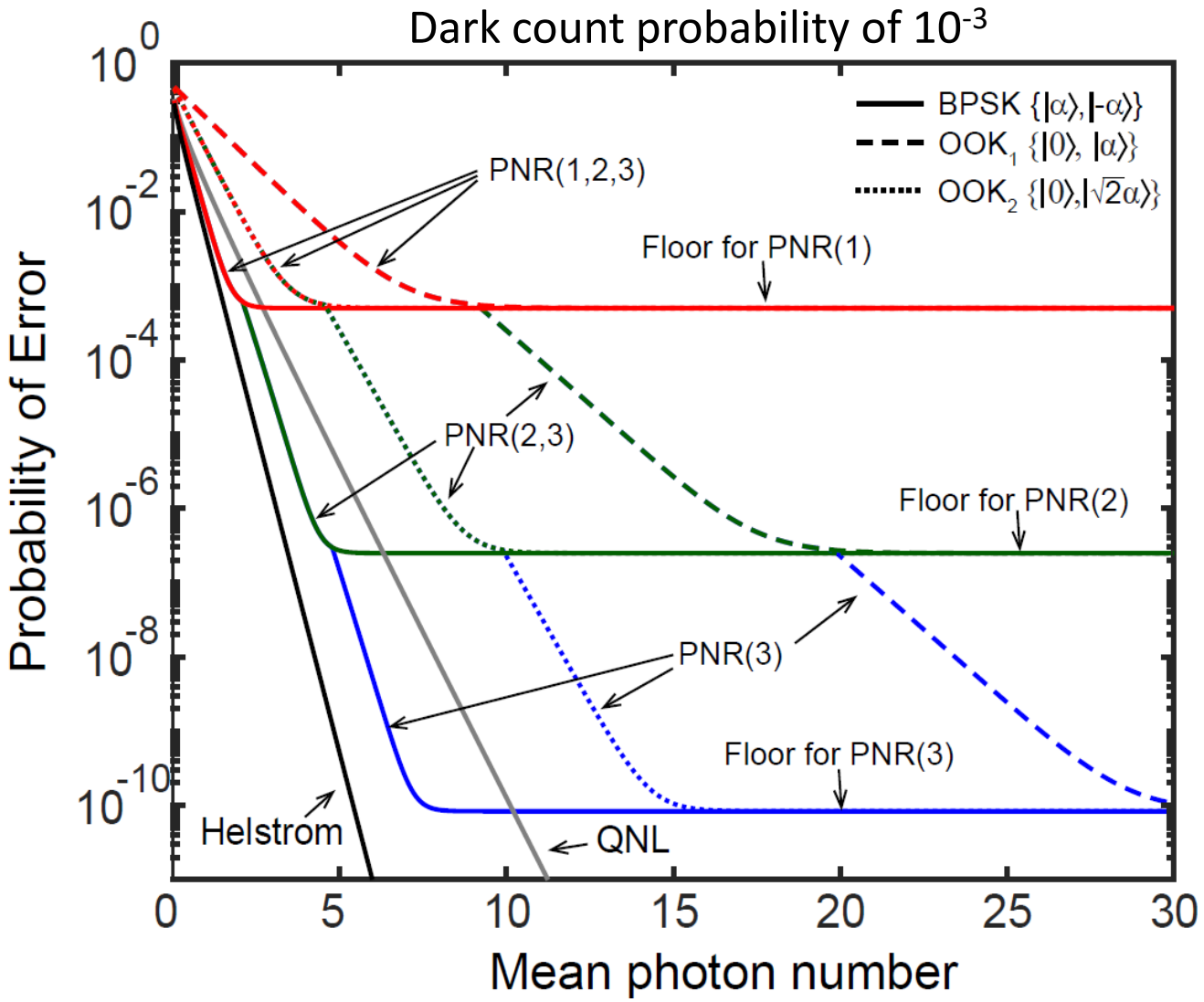



Dark count Prob. = $3.6 \times 10^{-3}$
After pulsing Prob.=$1.1 \times 10^{-2}$

M. T. DiMario and F. E. Becerra, Phys. Rev. Lett. **121**, 023603 (2018)

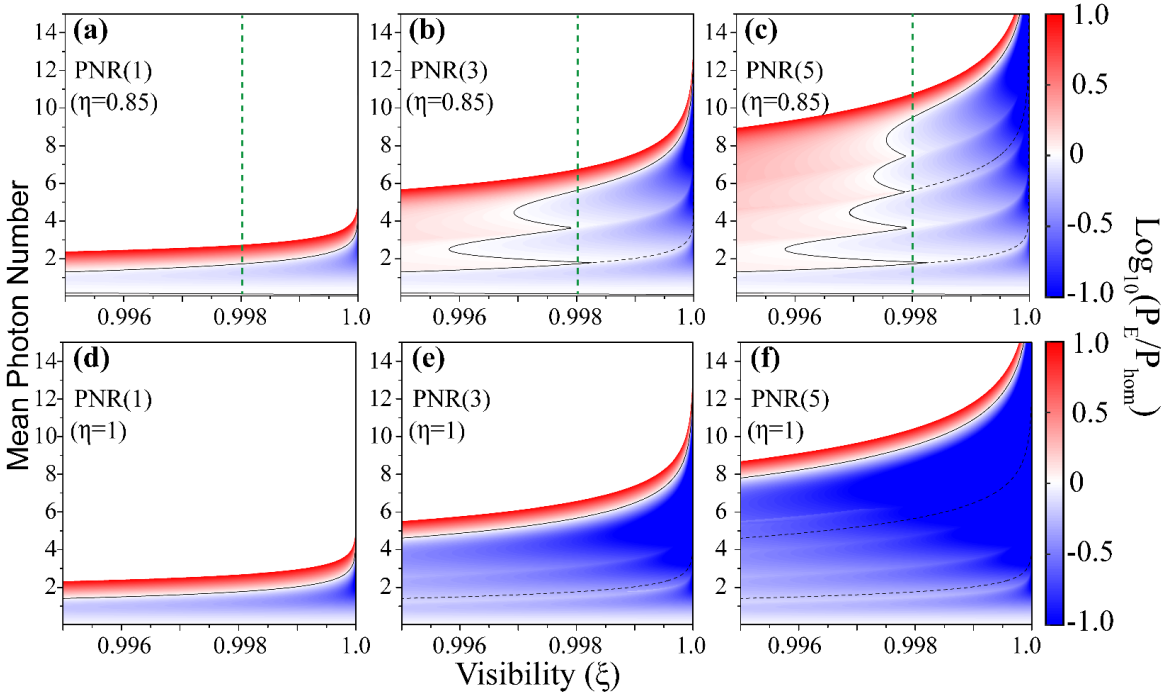
# PNR provides robustness to dark counts

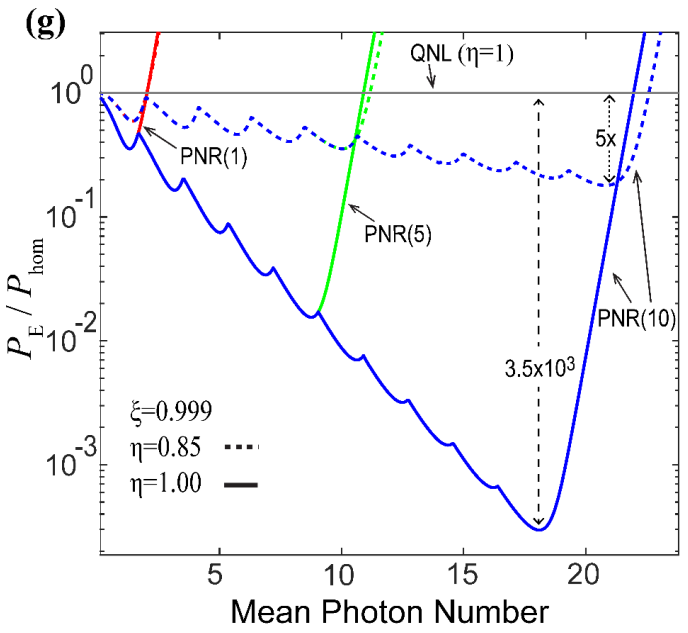
***Phase (PSK) and Intensity OOK encoding***




M. T. DiMario and F. E. Becerra, Phys. Rev. Lett. **121**, 023603 (2018)`

# How To Surpass Homodyne




M. T. DiMario and F. E. Becerra, Phys. Rev. Lett. **121**, 023603 (2018)`

# References State Discrimination

nature photonics

ARTICLES

PUBLISHED ONLINE: 6 JANUARY 2013 | DOI: 10.1038/NPHOTON.2012.316

## Experimental demonstration of a receiver beating the standard quantum limit for multiple nonorthogonal state discrimination

F. E. Becerra[1]*, J. Fan[1], G. Baumgartner[2], J. Goldhar[3], J. T. Kosloski[2] and A. Migdall[1]

npj | Quantum Information

www.nature.com/npjqi

ARTICLE OPEN

## Multi-state discrimination below the quantum noise limit at the single-photon level

A. R. Ferdinand[1], M. T. DiMario[1] and F. E. Becerra[1]

ARTICLES

PUBLISHED ONLINE: 17 NOVEMBER 2014 | DOI: 10.1038/NPHOTON.2014.280

nature photonics

## Photon number resolution enables quantum receiver for realistic coherent optical communications

F. E. Becerra[1]*, J. Fan[2] and A. Migdall[2]

PHYSICAL REVIEW LETTERS 121, 023603 (2018)

## Robust Measurement for the Discrimination of Binary Coherent States

M. T. DiMario and F. E. Becerra*

*Center for Quantum Information and Control, Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico 87131, USA*

nature COMMUNICATIONS

ARTICLE

Received 18 Jan 2013 | Accepted 21 May 2013 | Published 18 Jun 2013

DOI: 10.1038/ncomms3028

## Implementation of generalized quantum measurements for unambiguous discrimination of multiple non-orthogonal coherent states

F. E. Becerra[1], J. Fan[1] & A. Migdall[1]

Research Article | Journal of the Optical Society of America B | 1

## Implementation of a Single-Shot Receiver for Quaternary Phase-Shift Keyed Coherent States

M. T. DiMario[1,*], E. Carrasco[1], R. A. Jackson[1,2], and F. E. Becerra[1,†]

[1] *Center for Quantum Information and Control, University of New Mexico, Albuquerque, New Mexico 87131*
[2] *Nanoscience and Microsystems Engineering, University of New Mexico, Albuquerque, New Mexico 87131*
[*] *Corresponding author: mdimario@unm.edu*
[†] *Corresponding author: fbecerra@unm.edu*

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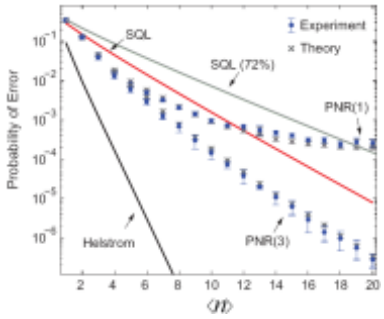
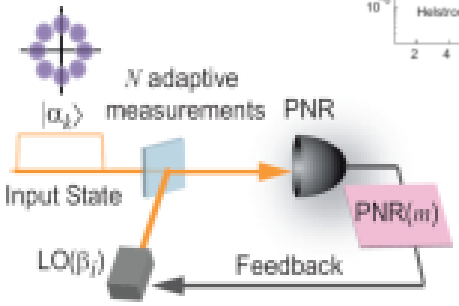
# *Non-Gaussian Receivers for multi-state discrimination*

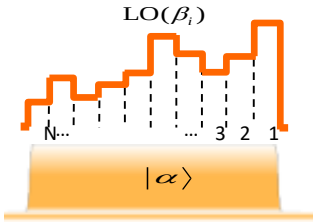
CQuIC

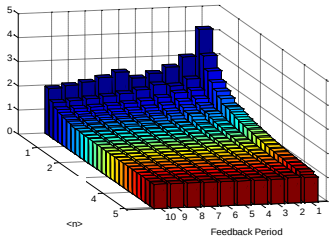
- Multiple state discrimination
  - Strategies surpassing the QNL
  - Photon-number resolution provides robustness




- Optimized strategies
  - Surpassing the QNL at all powers
  - Enhance information at low powers

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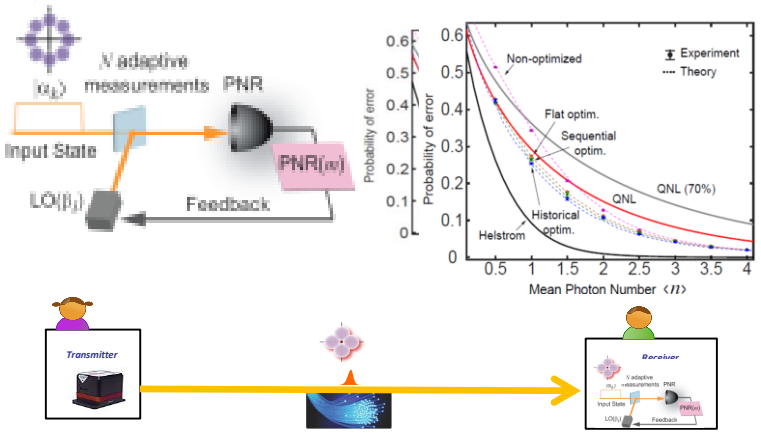
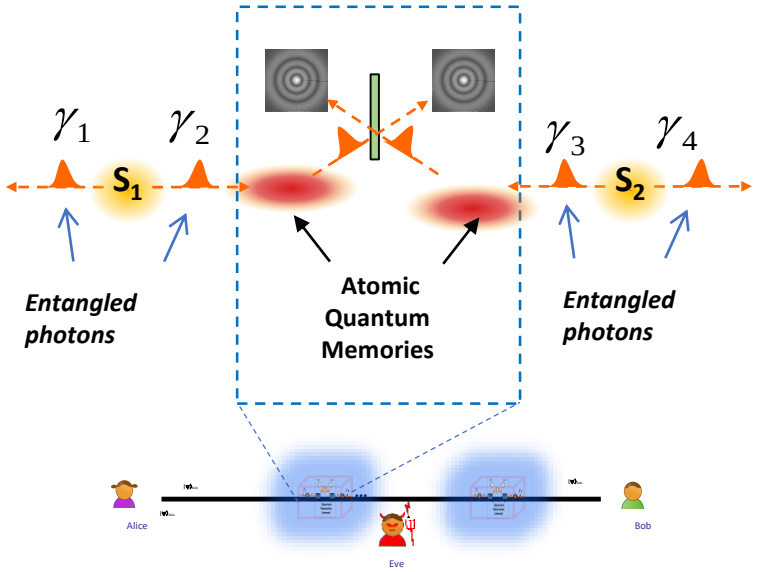
# Quantum Optics Lab

## Quantum Measurements: Nonconventional Detection




## High-Capacity Atom-Photon Interfaces




**NSF (CAREER)**

**AFOSR (YIP)**

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