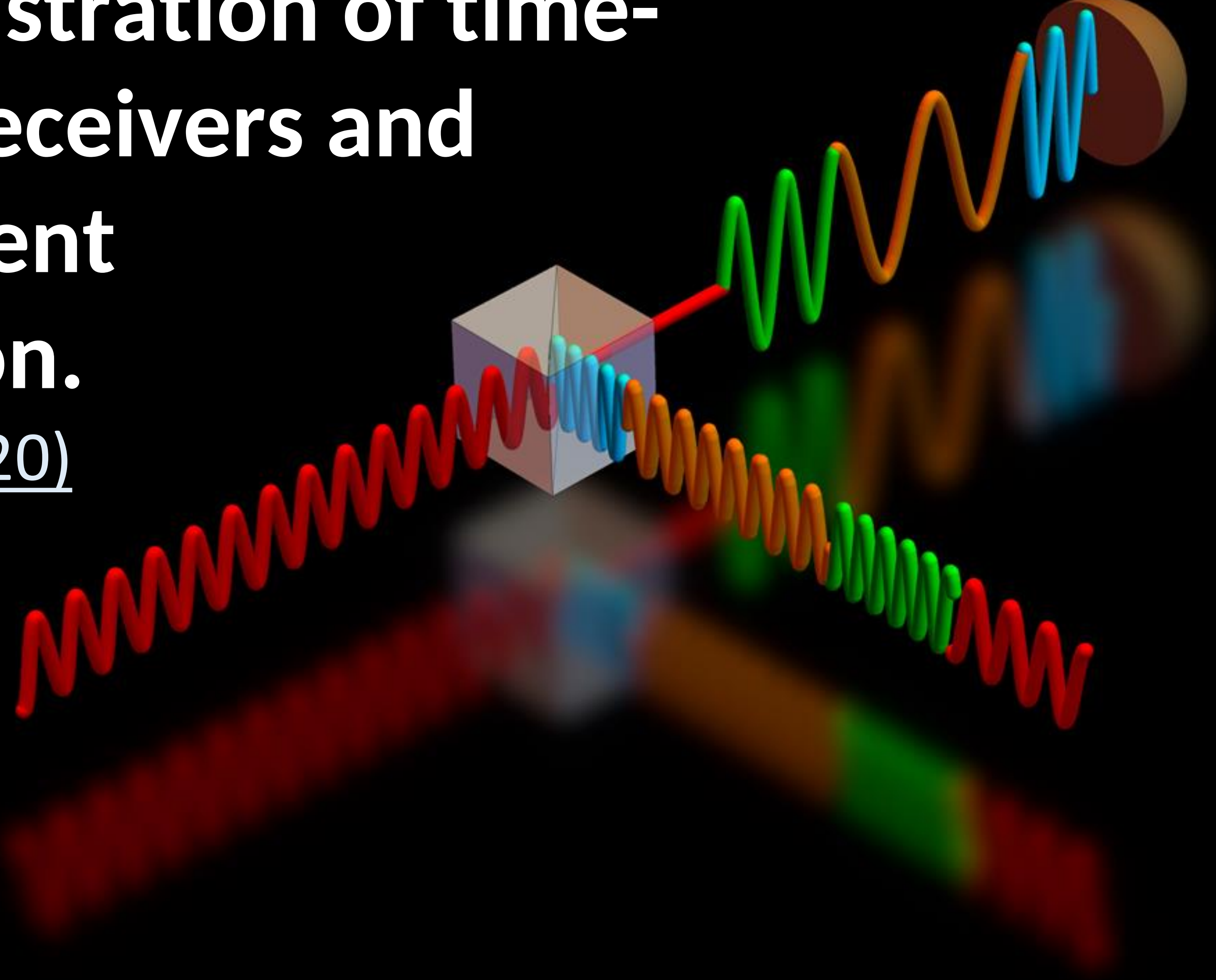
Experimental demonstration of time-resolving quantum receivers and quantum measurement confidence estimation.

PRX Quantum **1**, 010308 (2020)



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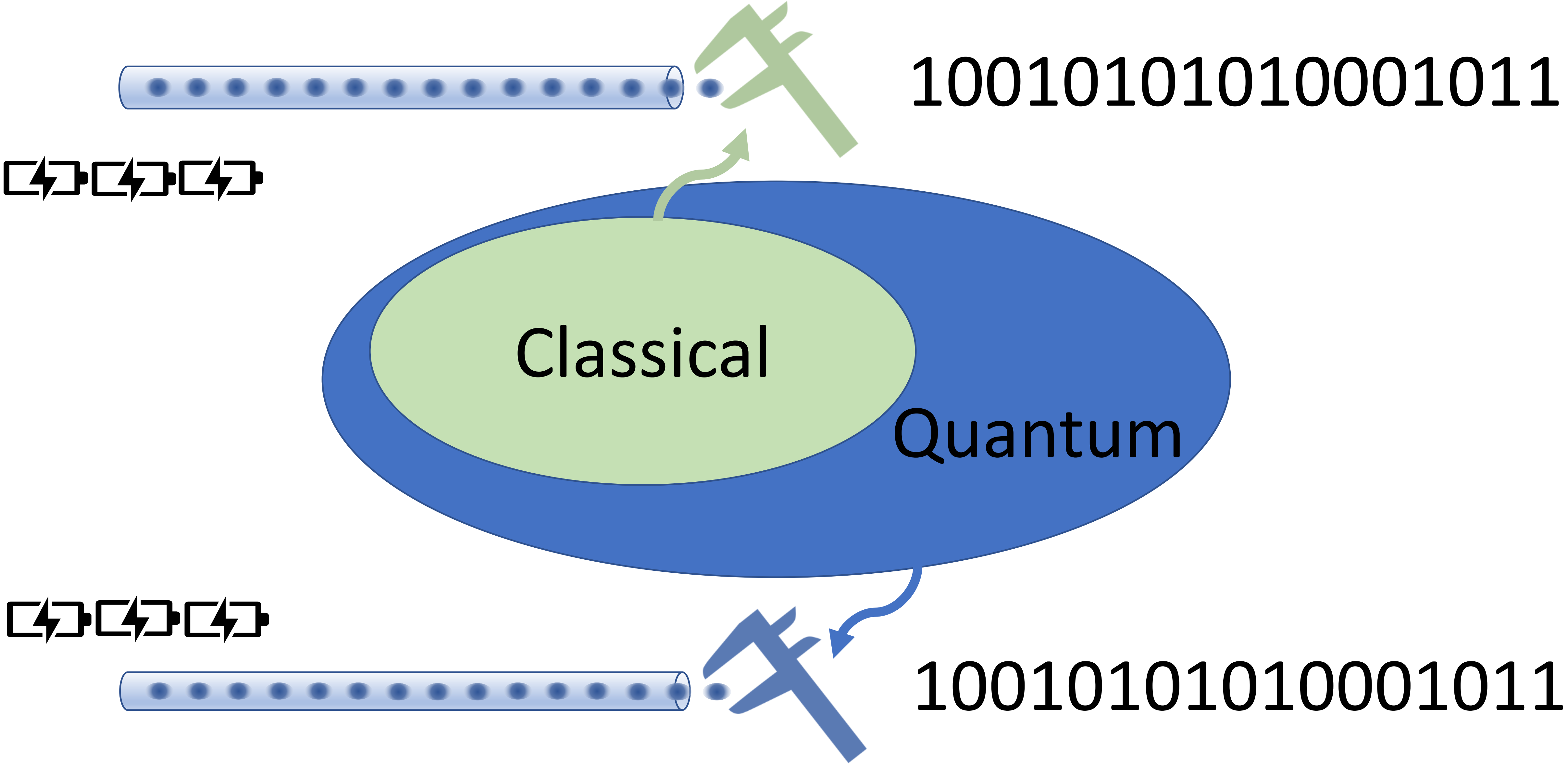
Measurement



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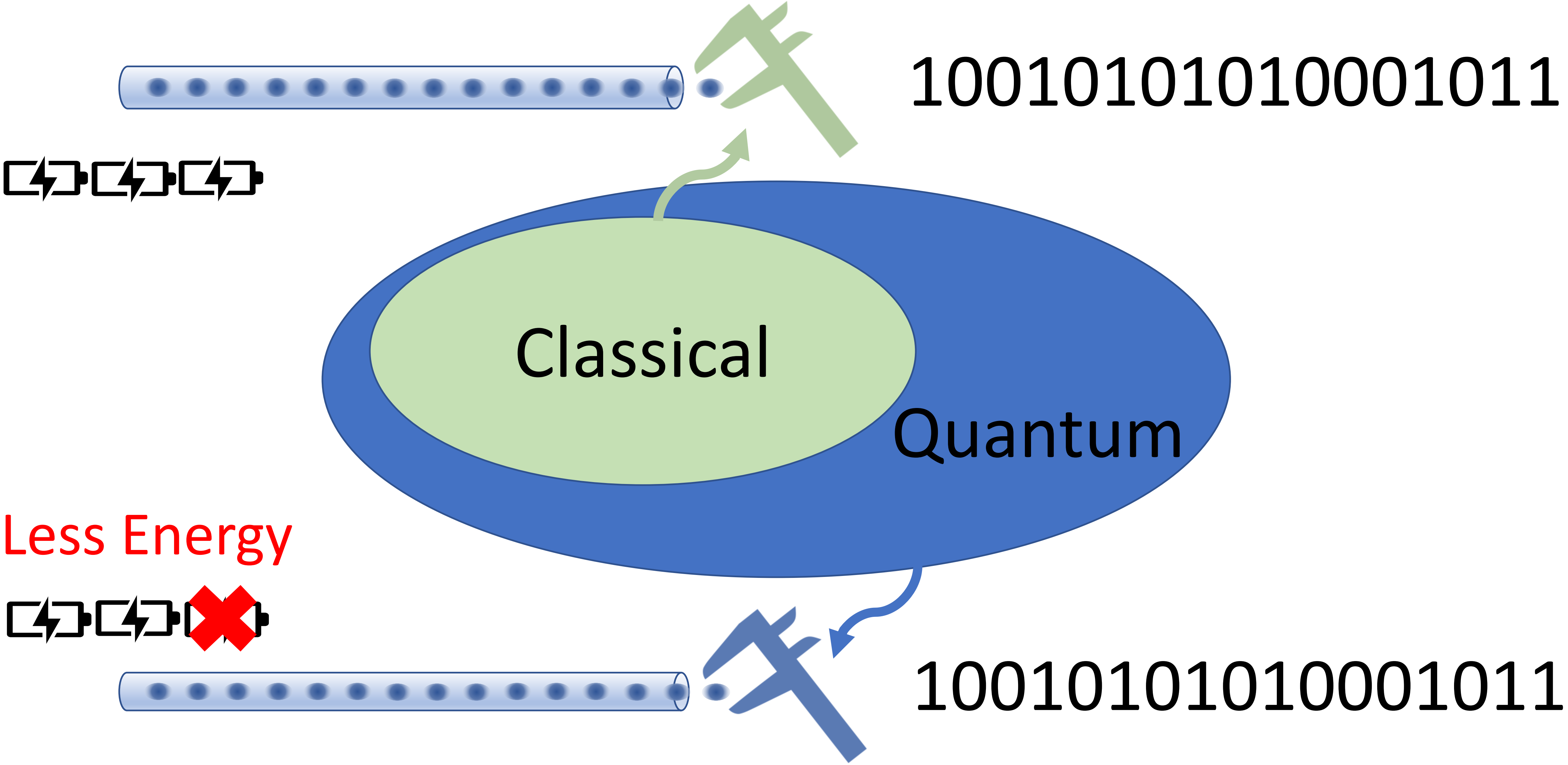
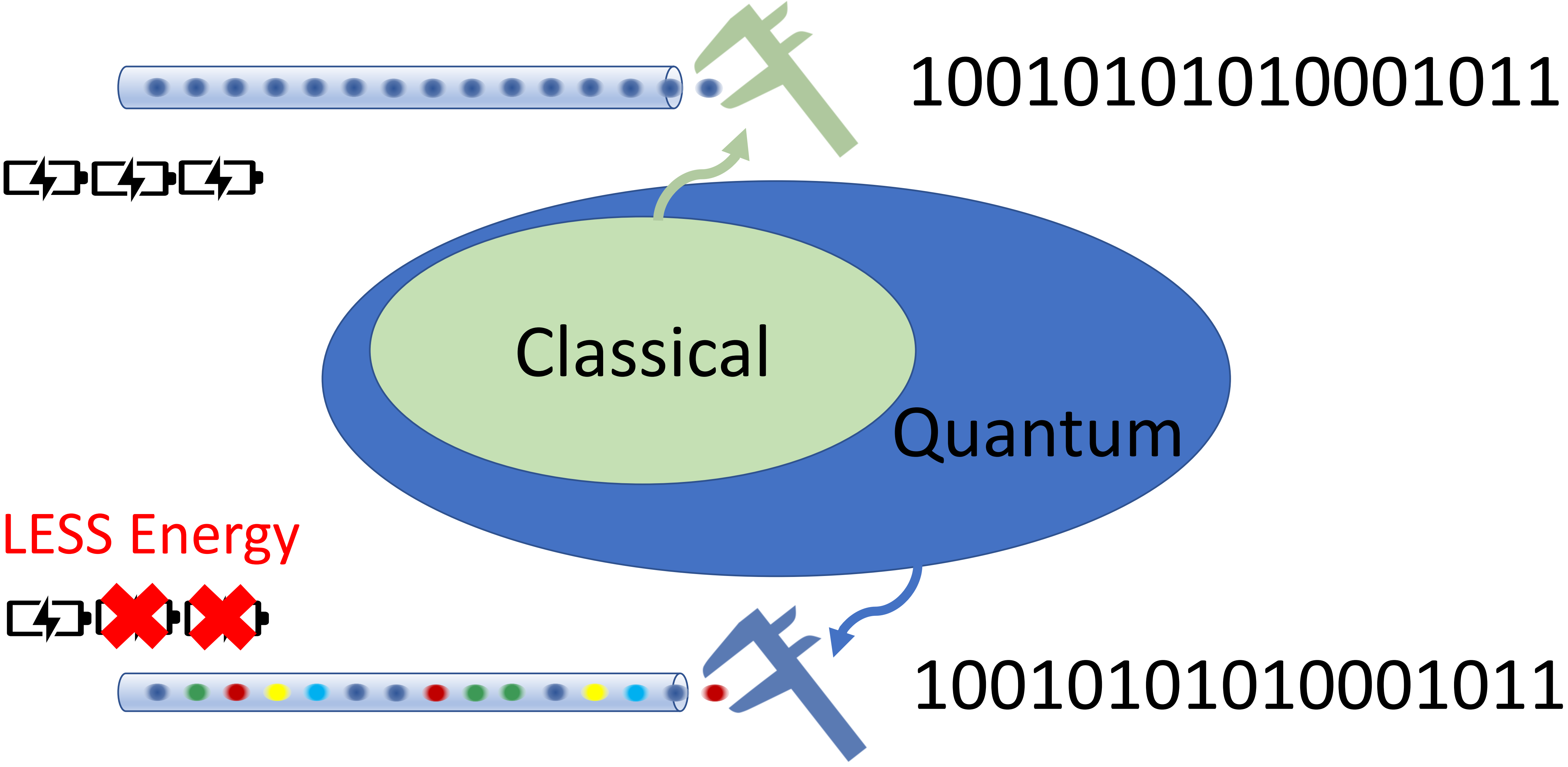
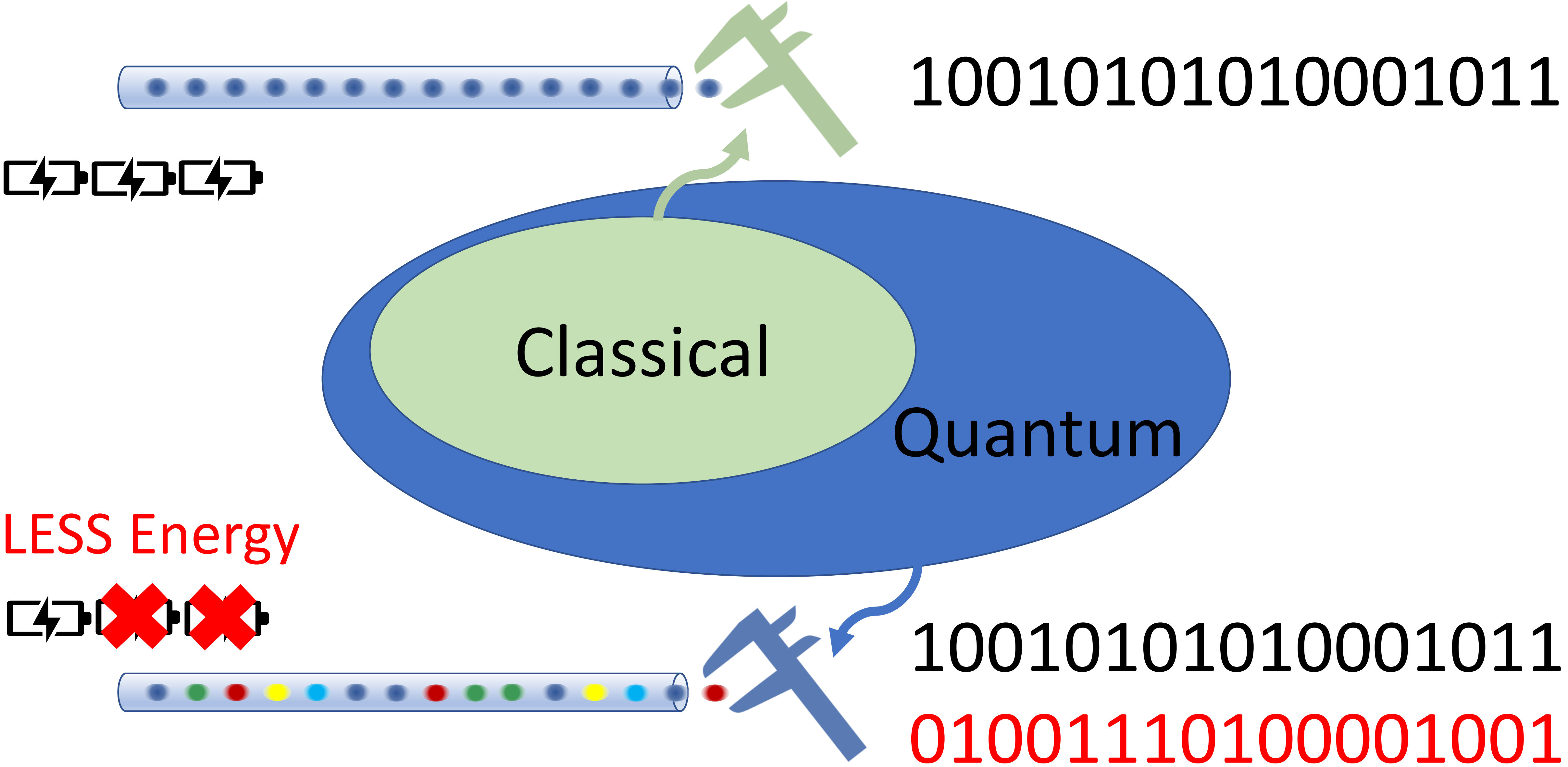
Measurement



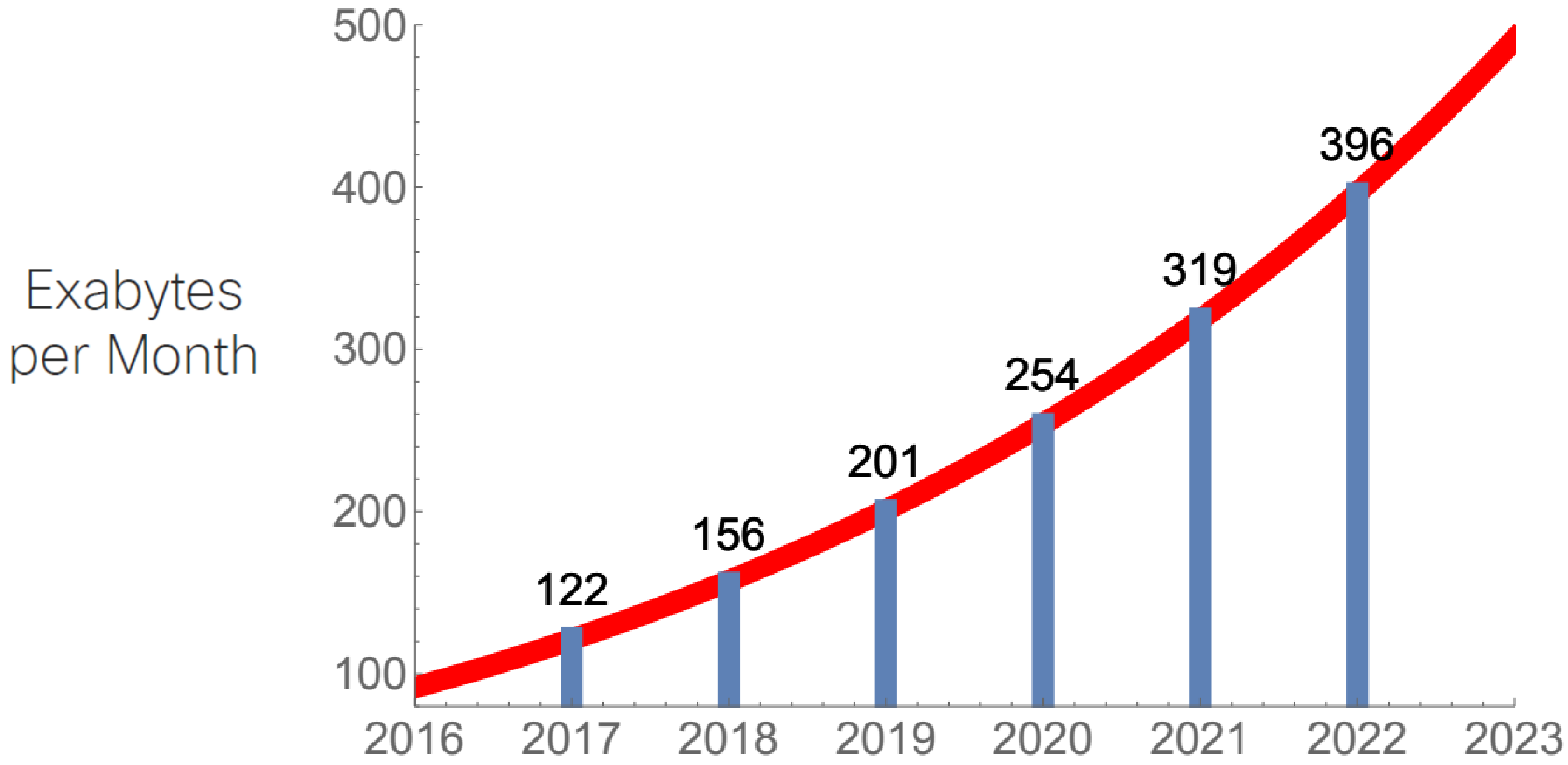
Measurement



Measurement



The Internet: Exponential increase in data transfer

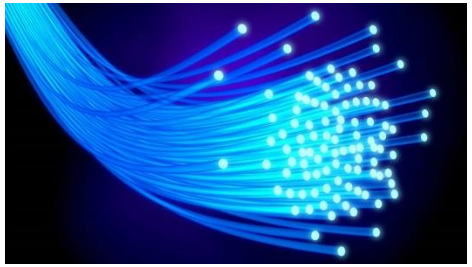


Source: Cisco VNI Global IP Traffic Forecast, 2017–2022

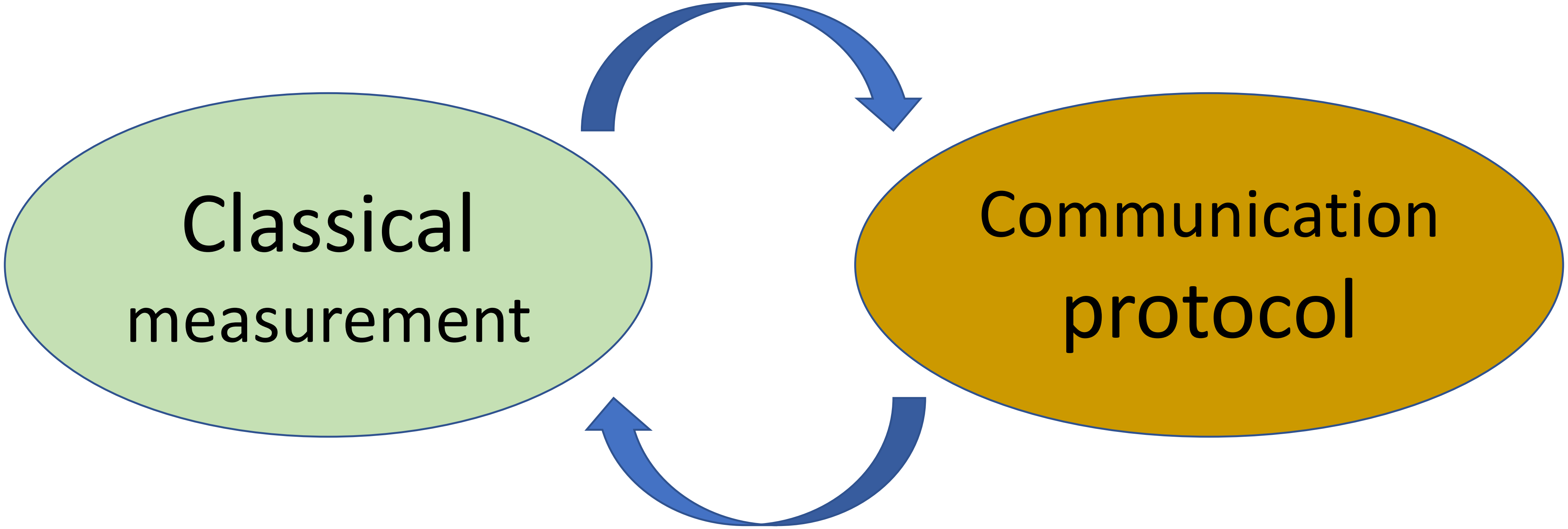
- Energy $E = \langle n \rangle \hbar\omega$

Resources of communication

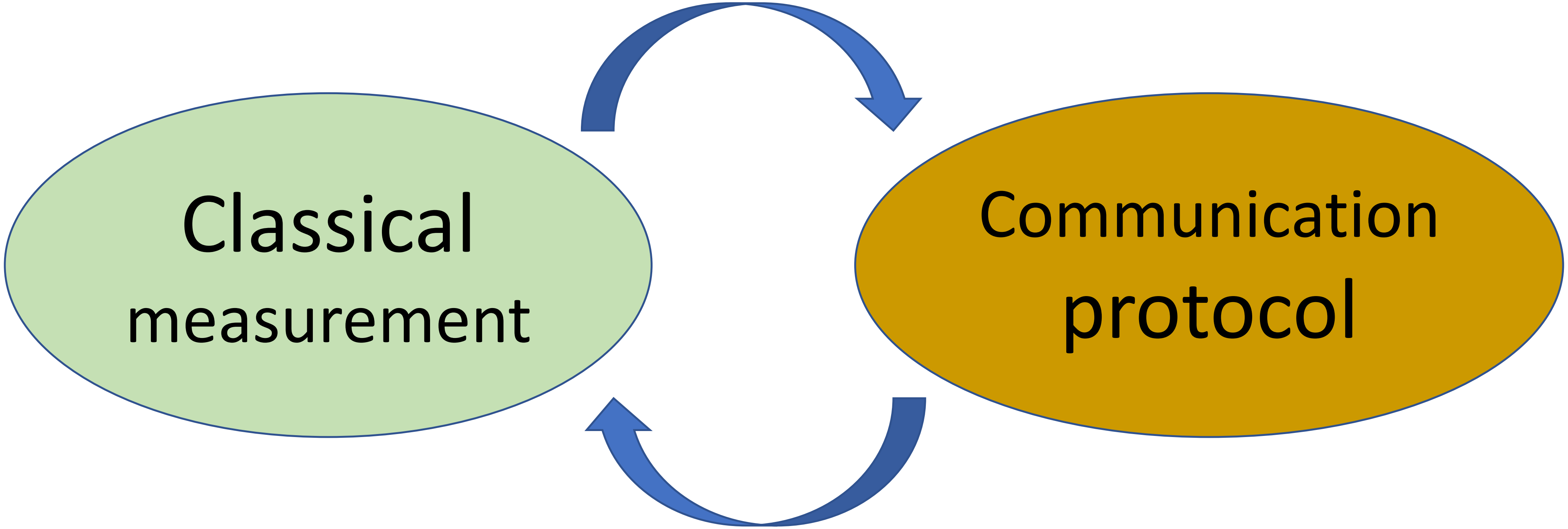
- Energy $E = \langle n \rangle \hbar\omega$

- Bandwidth 

Application of measurements

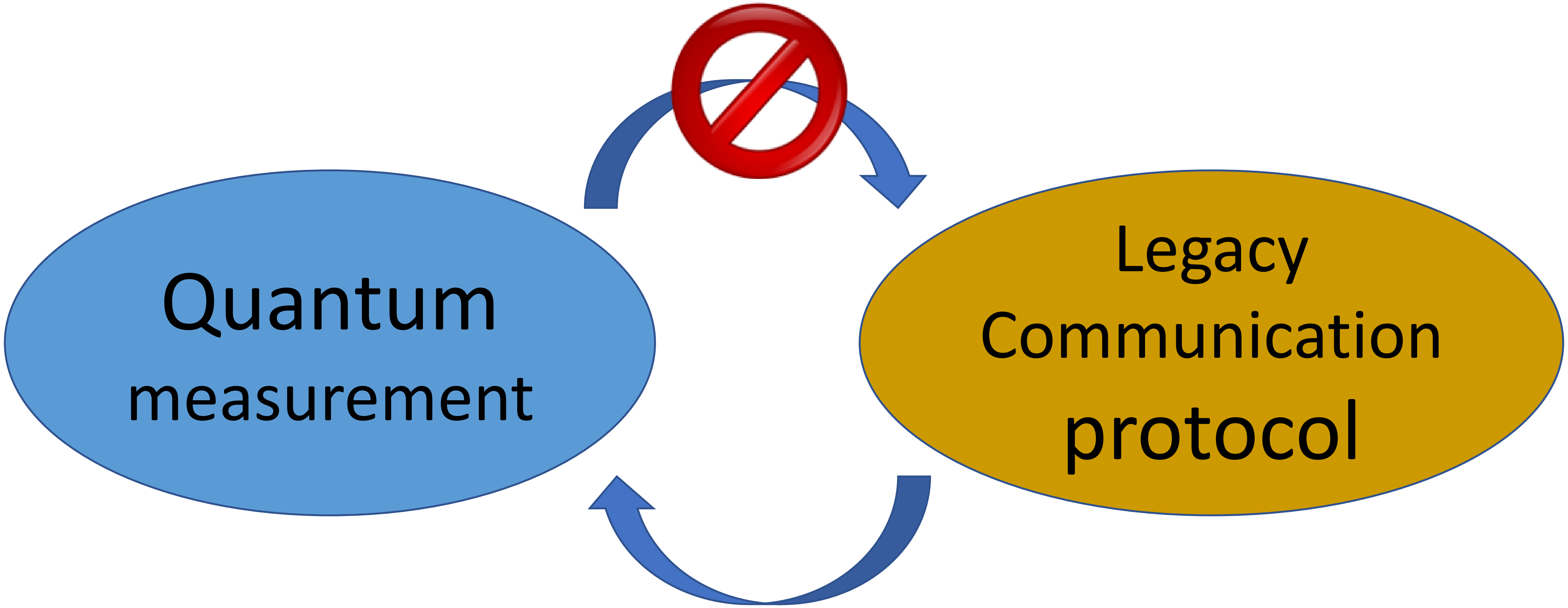


Application of measurements



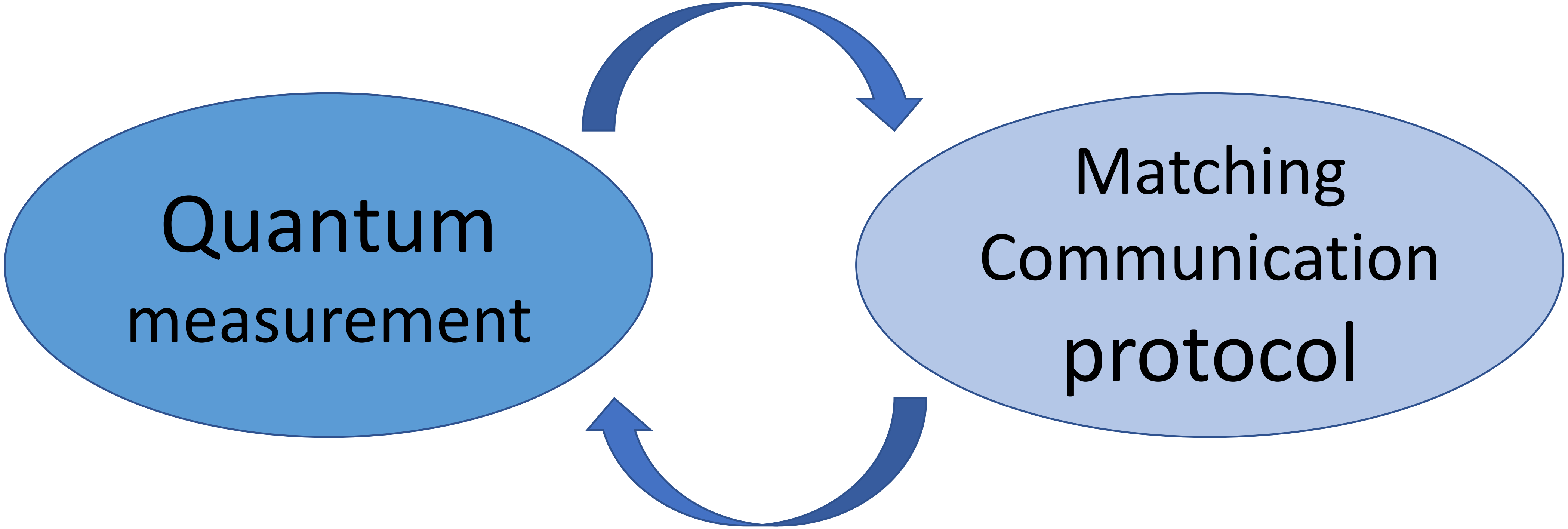
Communication requires Measurement

Application of measurements



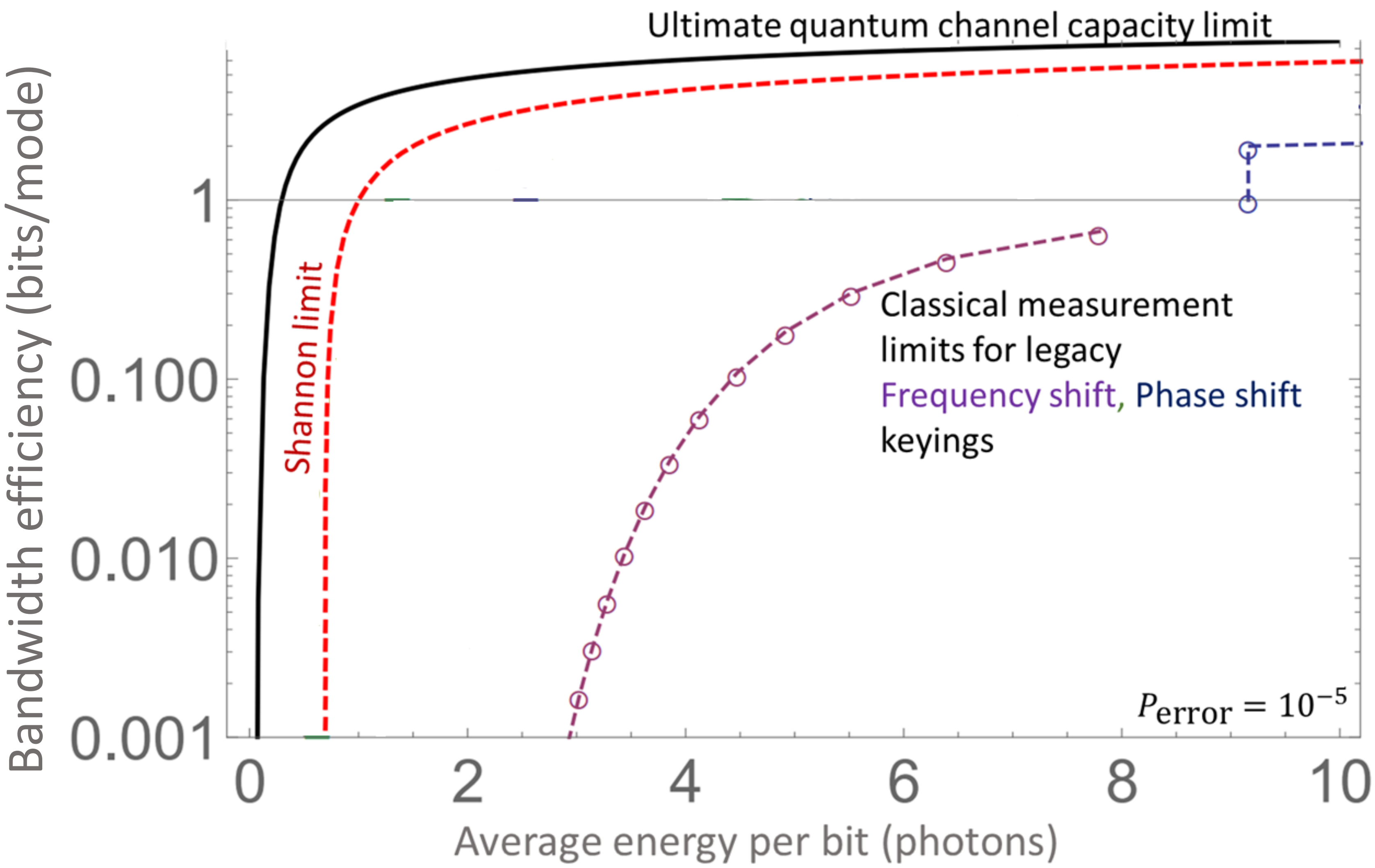
- Better sensitivity (below shot noise limit measurement)

Matching measurements and protocol



- Extra benefits?

Classical Vs Quantum Measurement Limits



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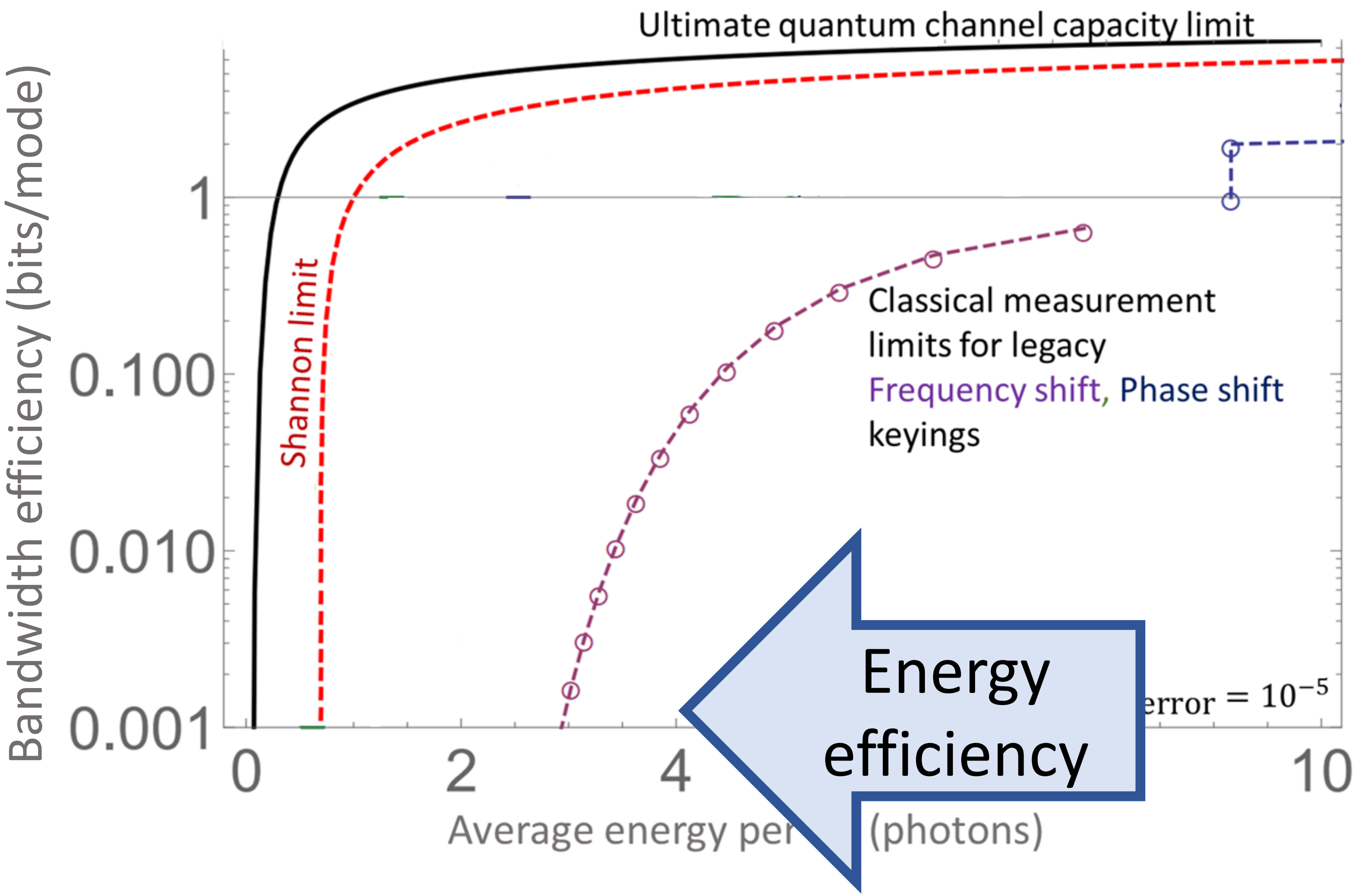
Classical Vs Quantum Measurement Limits



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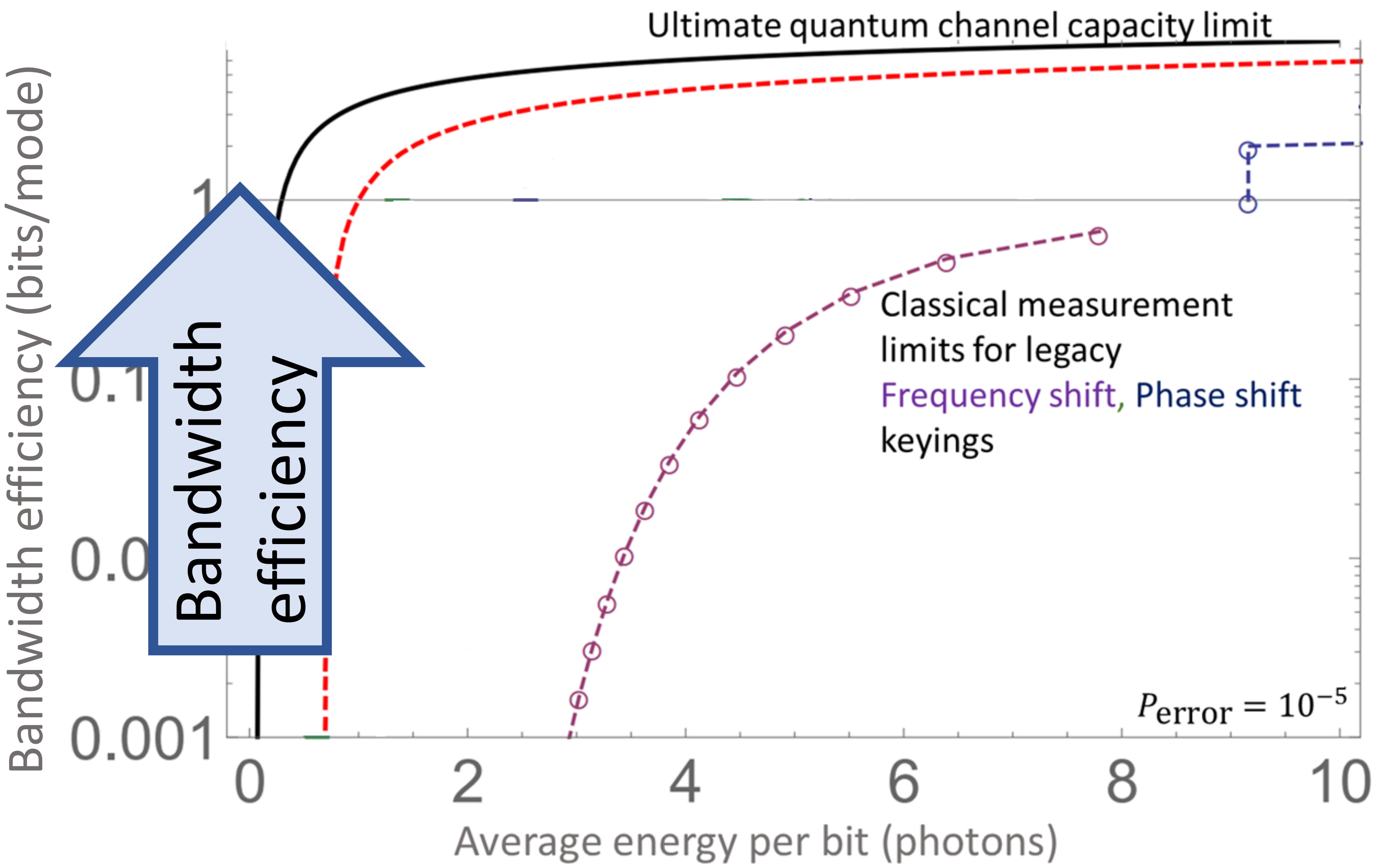
Classical Vs Quantum Measurement Limits



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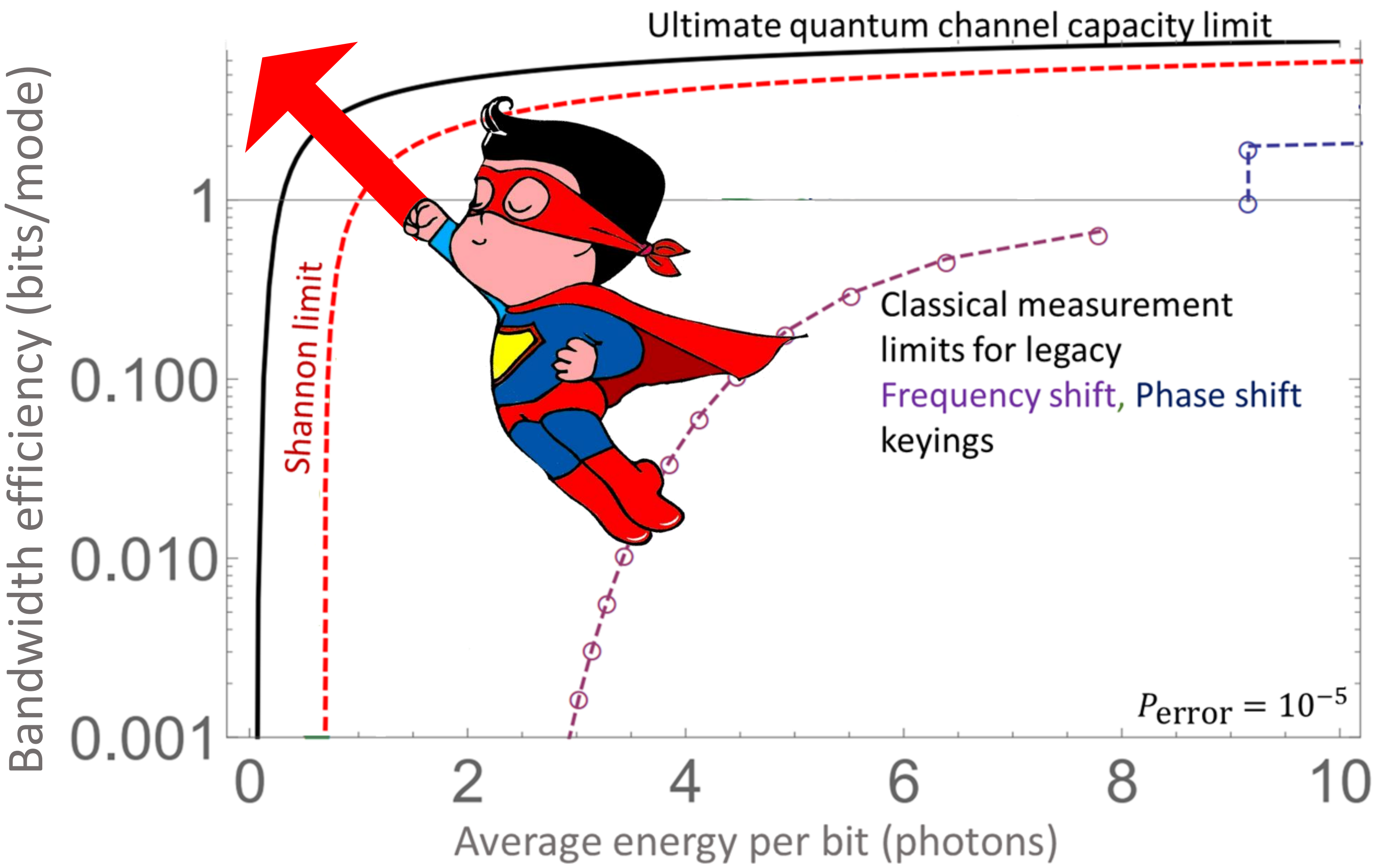
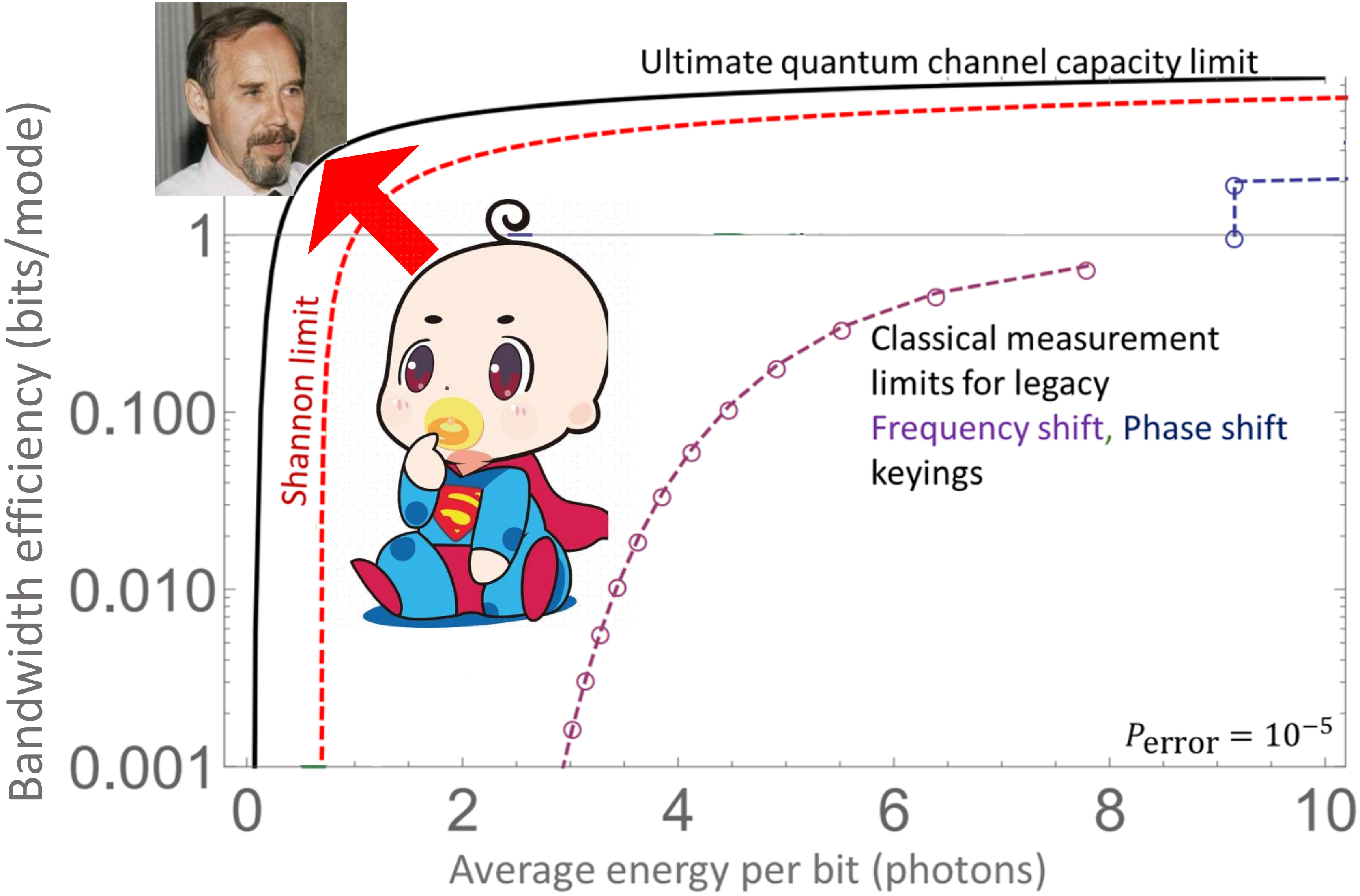
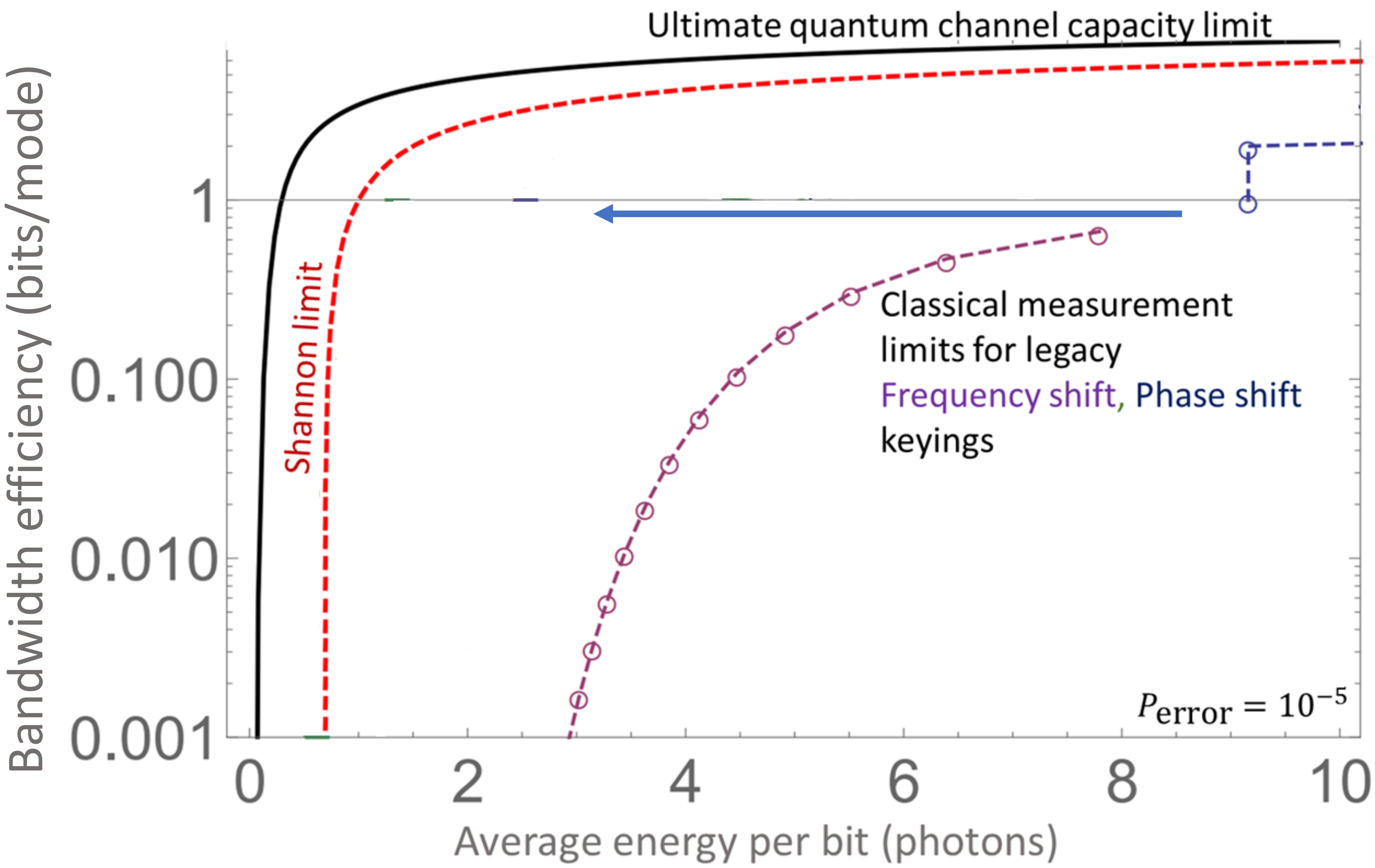
Classical Vs Quantum Measurement Limits



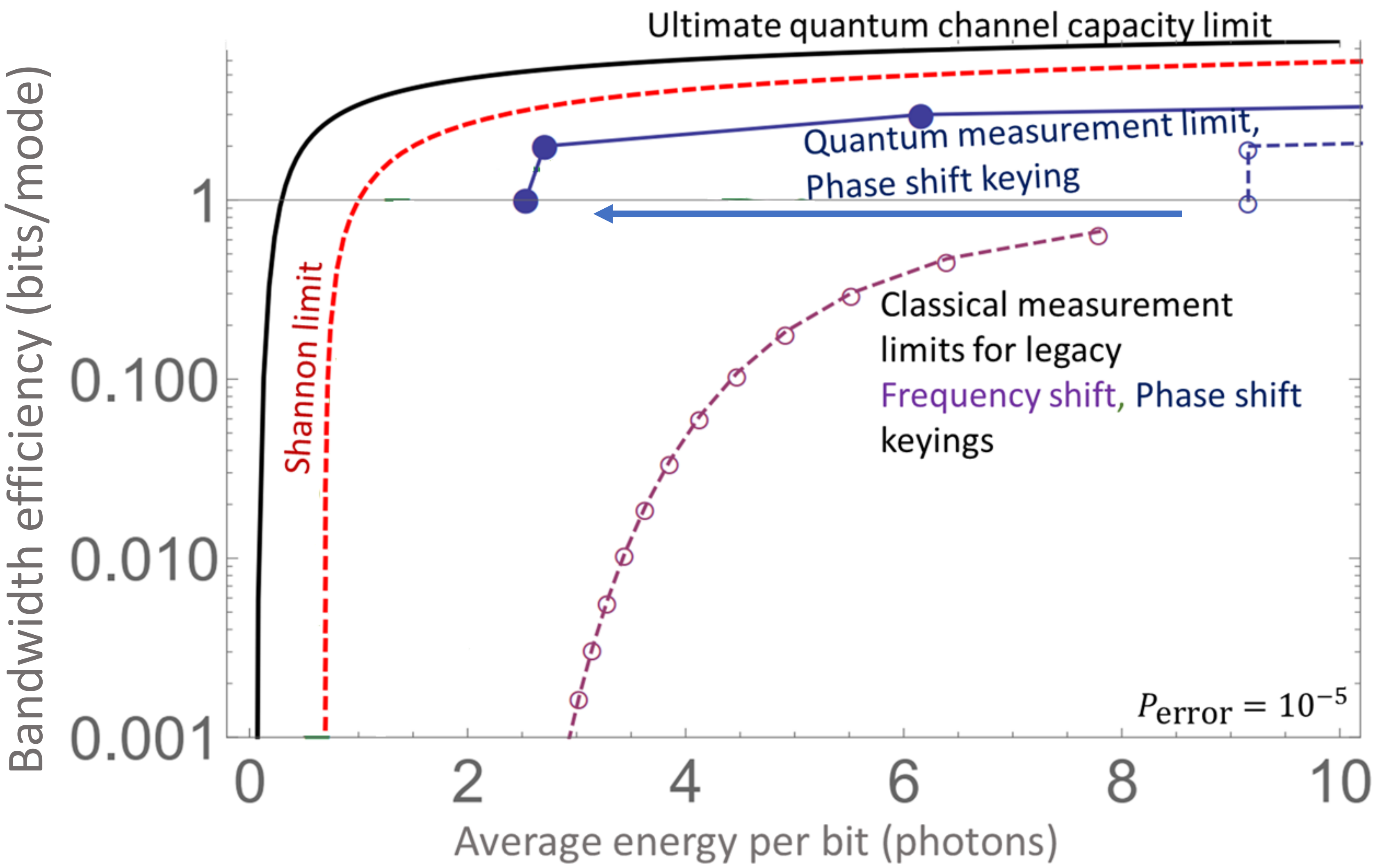
Classical Vs Quantum Measurement Limits



Classical Vs Quantum Measurement Limits



Classical Vs Quantum Measurement Limits



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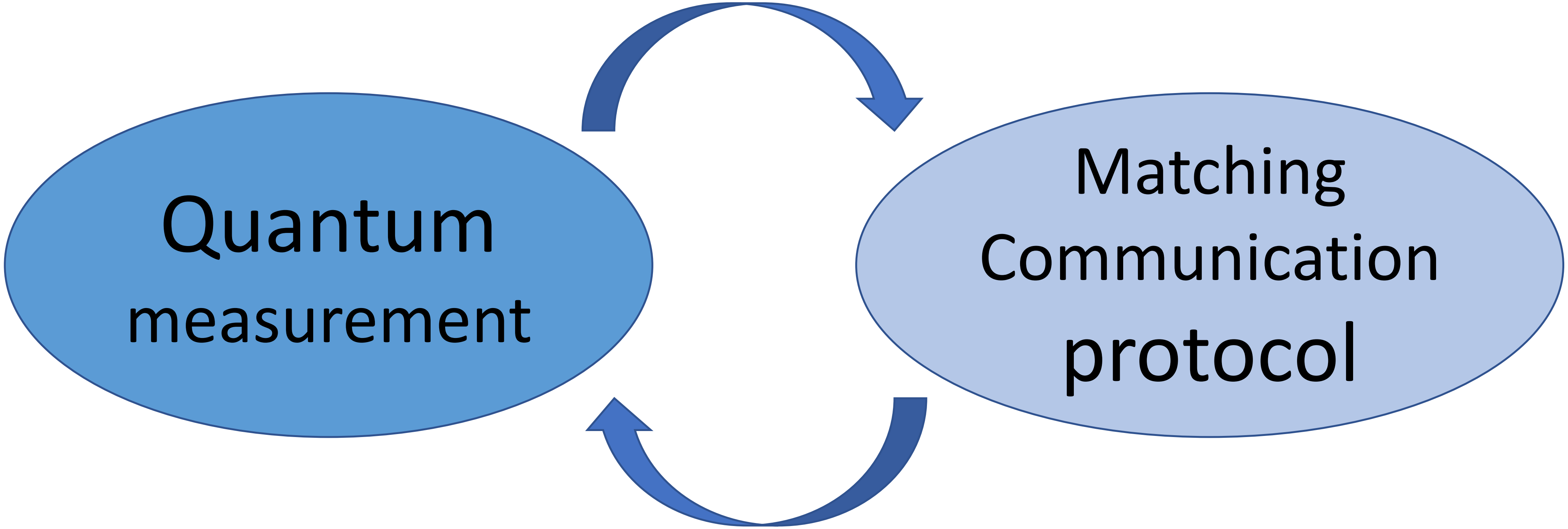
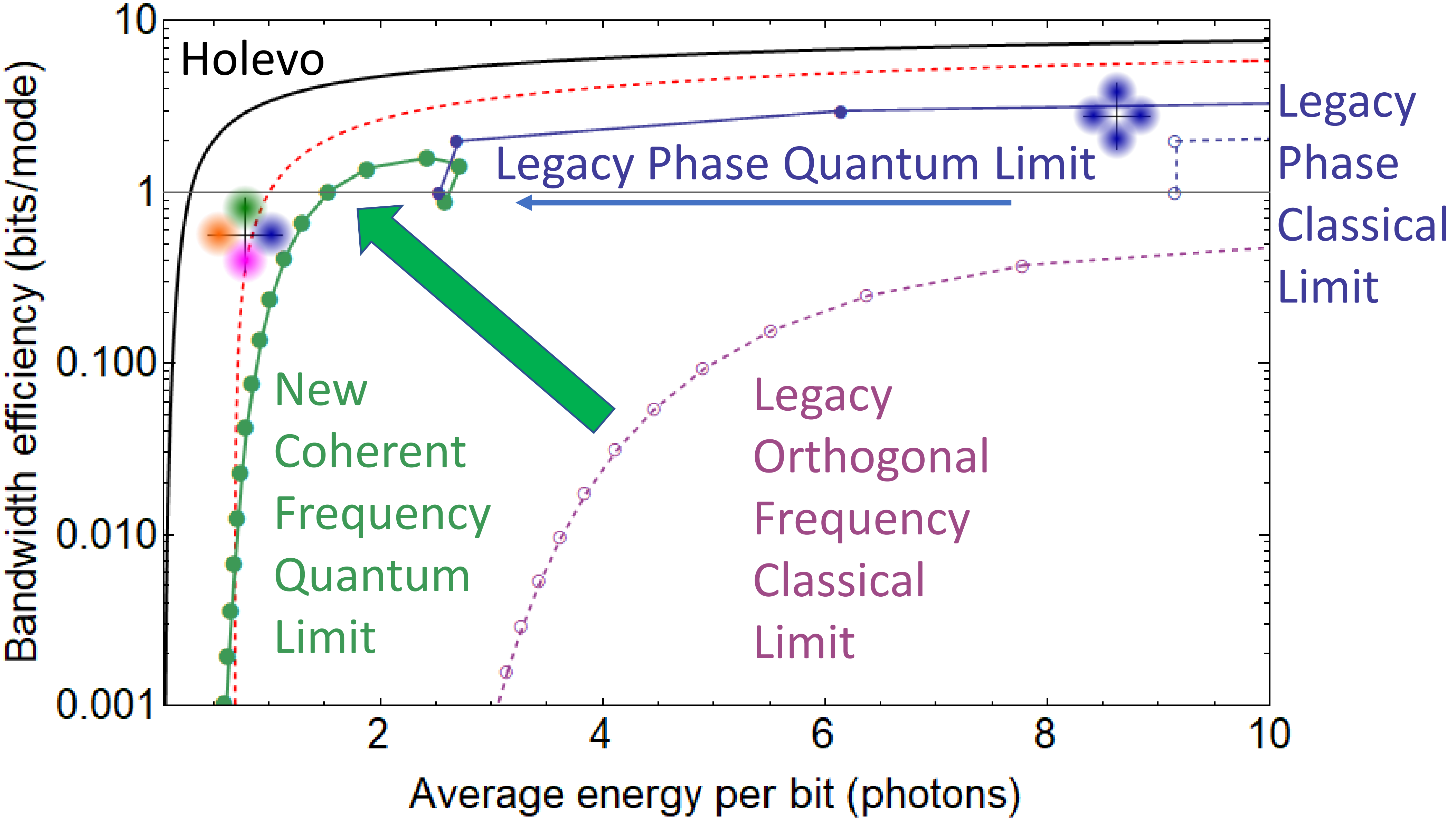
Matching measurements and protocol



Do we get any extra benefits with our holistic approach?

Classical V Quantum Measurement Limits



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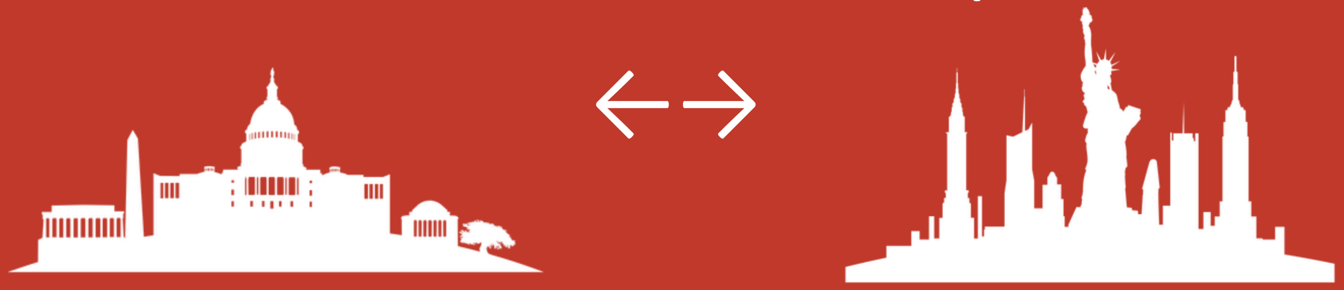
Compatibility

- Fiber or free-space
- Existing global network
- *Quantum channels*

Advantages

- Longer amplification-free range
- Lower signal power
- Better resource efficiency

NY-DC fiber link without amplification?



Advantages

- Longer amplification-free range
- Lower signal power
- Better resource efficiency

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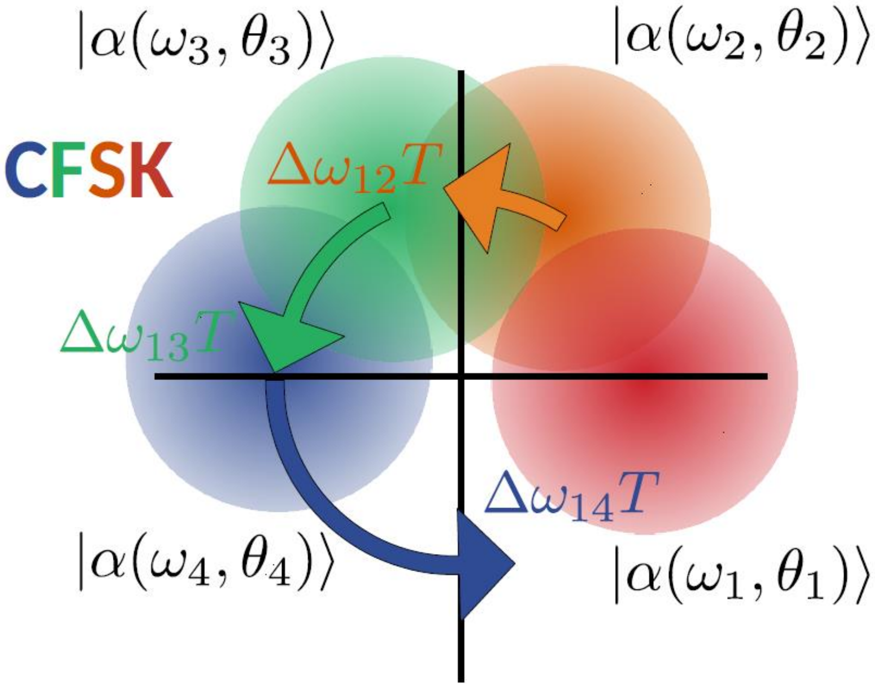
Alphabet of M states:



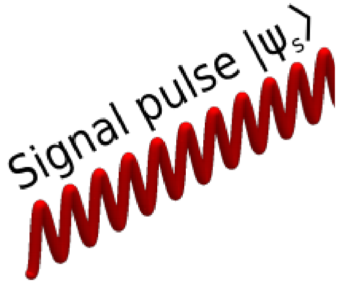
Two parameters:

- $\Delta\omega_{ij}T = (j-i)\boldsymbol{\Delta\omega}\mathbf{T}$
- $\theta_i = (i-1)\boldsymbol{\Delta\theta}$

Time-resolving quantum receiver

Alphabet

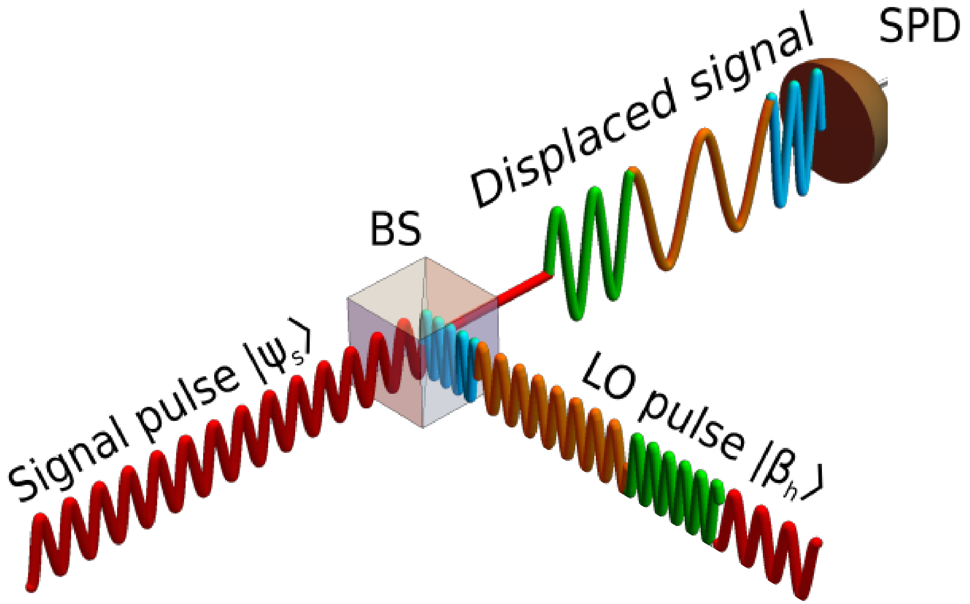
- 00
- 01
- 10
- 11



Time-resolving quantum receiver

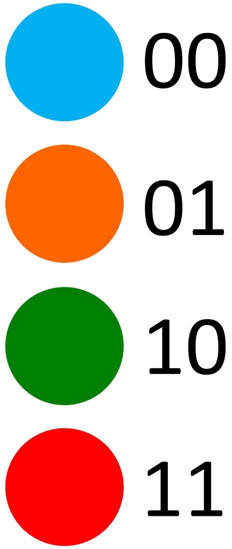
Alphabet

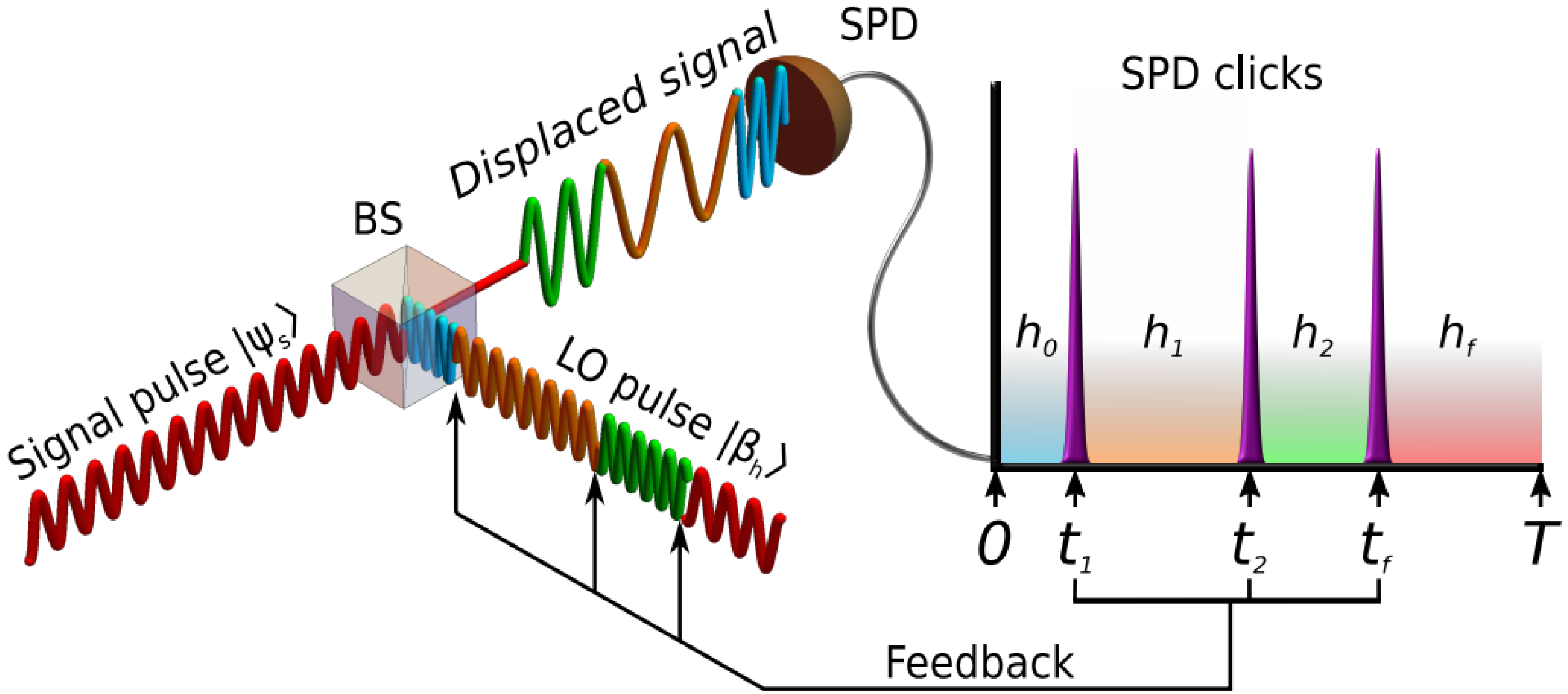
- 00
- 01
- 10
- 11



Time-resolving quantum receiver

Alphabet

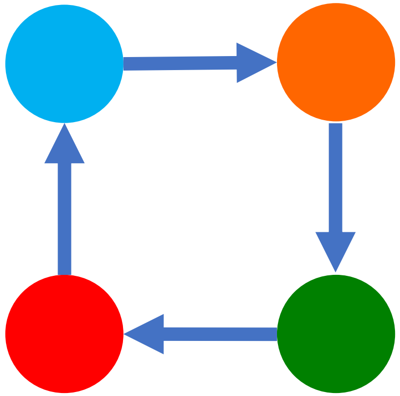


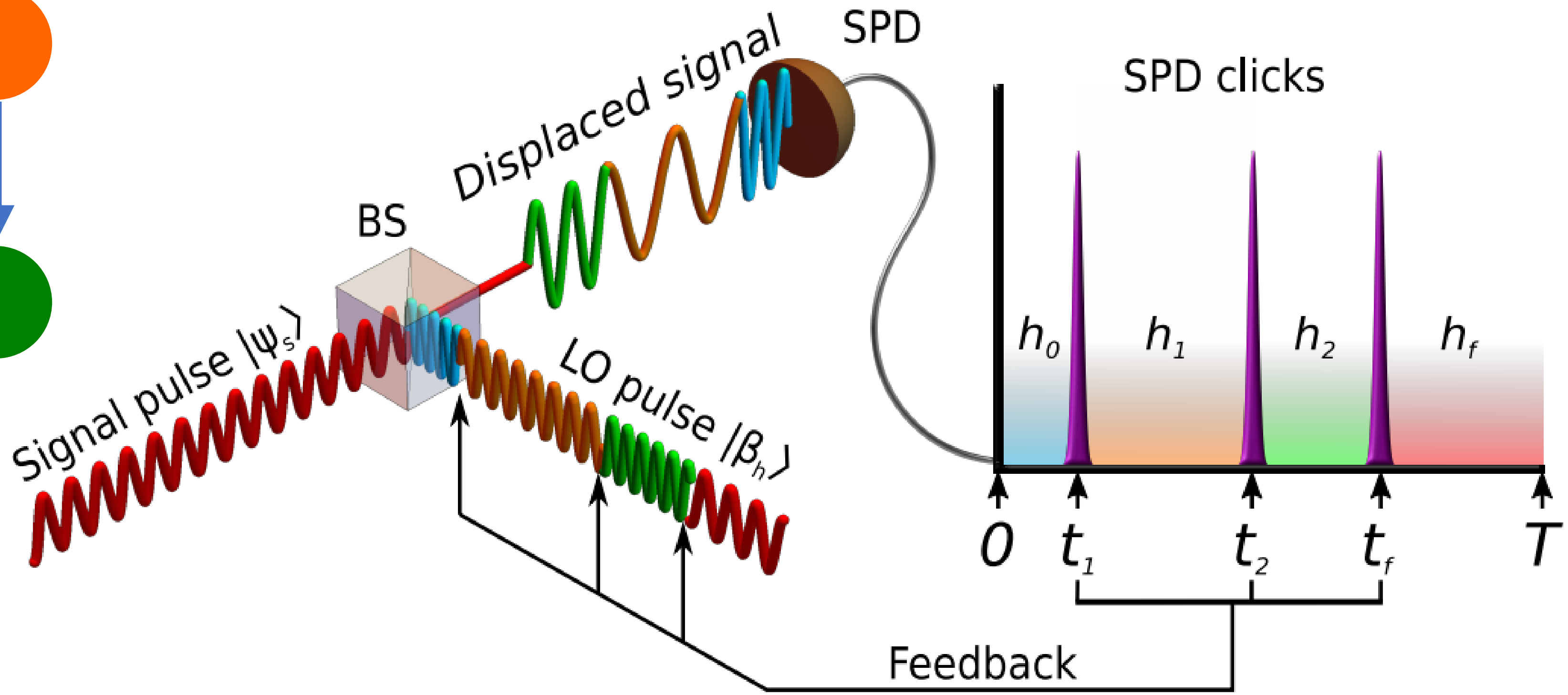


More theory here: Optica, **5**, p. 227 (2018), US Patent 10,382,141 (2019)

Time-resolving quantum receiver

Alphabet





Bondurant receiver

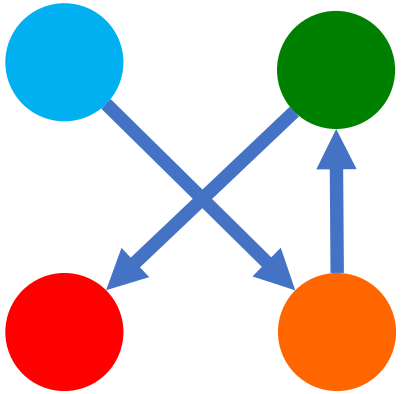
Theory: *Opt. Lett.* **18(**22), 1896 (1993)

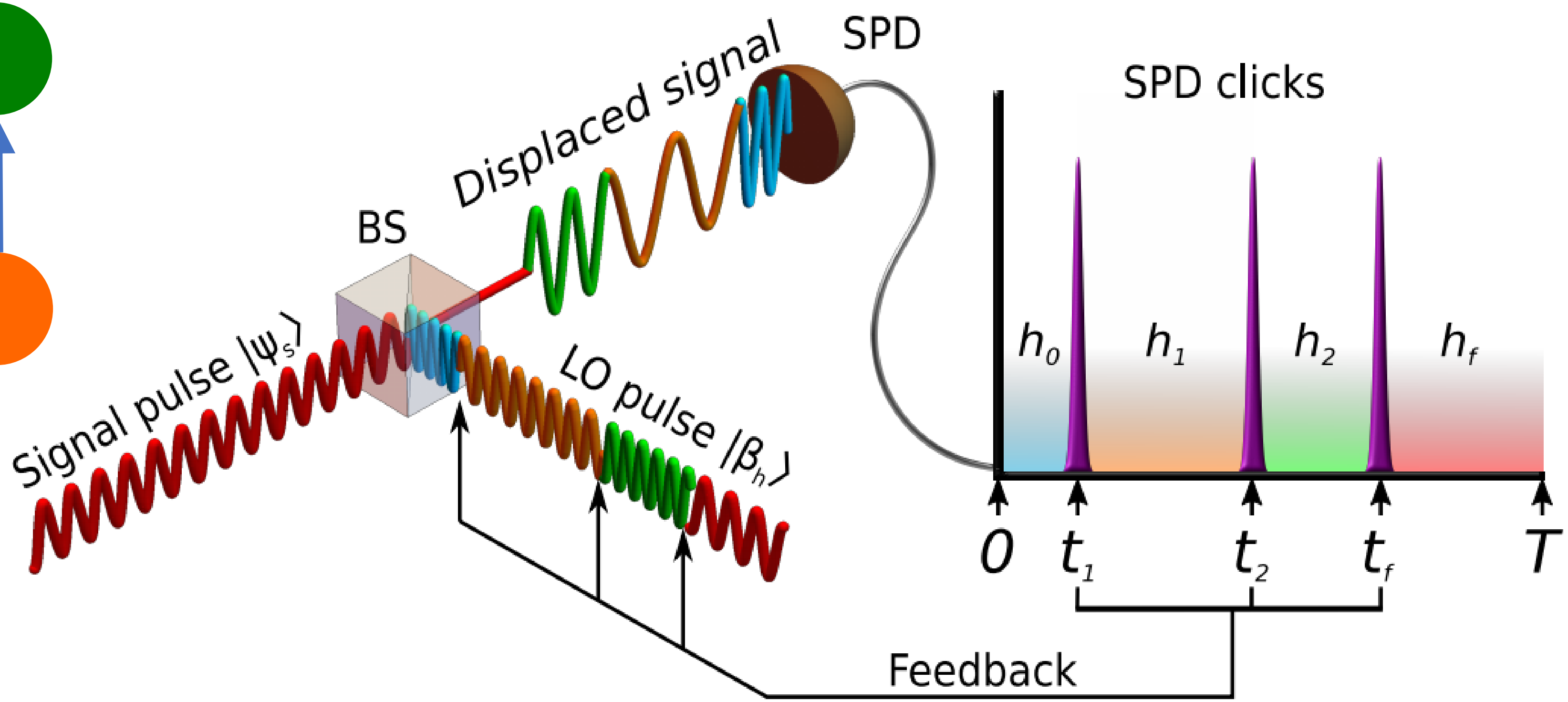
Experiment: *OSA Continuum* **3**(12), 3324 (2020)

More theory here: Optica, **5**, p. 227 (2018), US Patent 10,382,141 (2019)

Time-resolving quantum receiver

Alphabet





Time-resolving receiver with Bayesian inference

Theory: Optica, **5**, p. 227 (2018)

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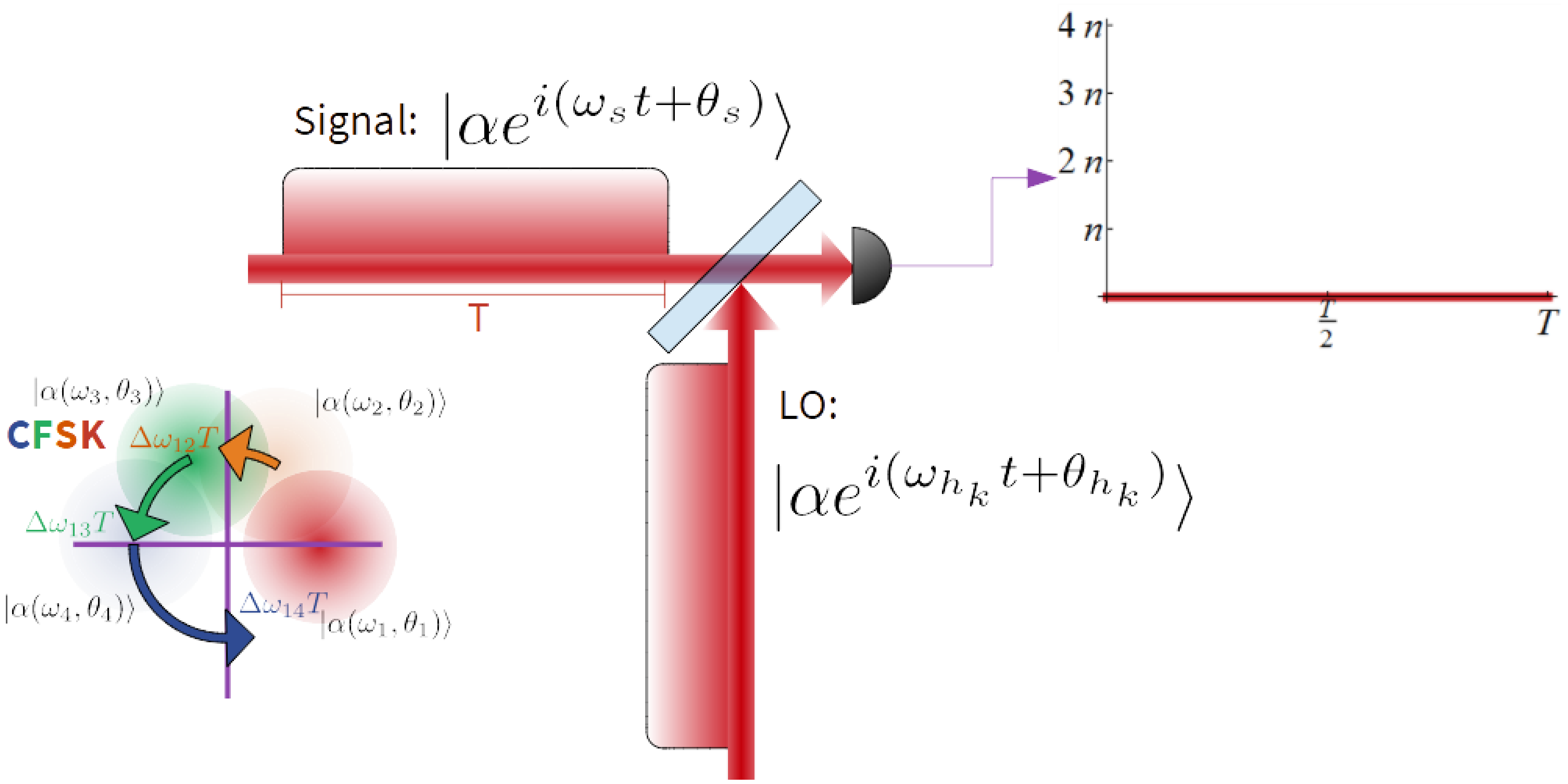
More theory here: Optica, **5**, p. 227 (2018), US Patent 10,382,141 (2019)

Time-resolving quantum receiver



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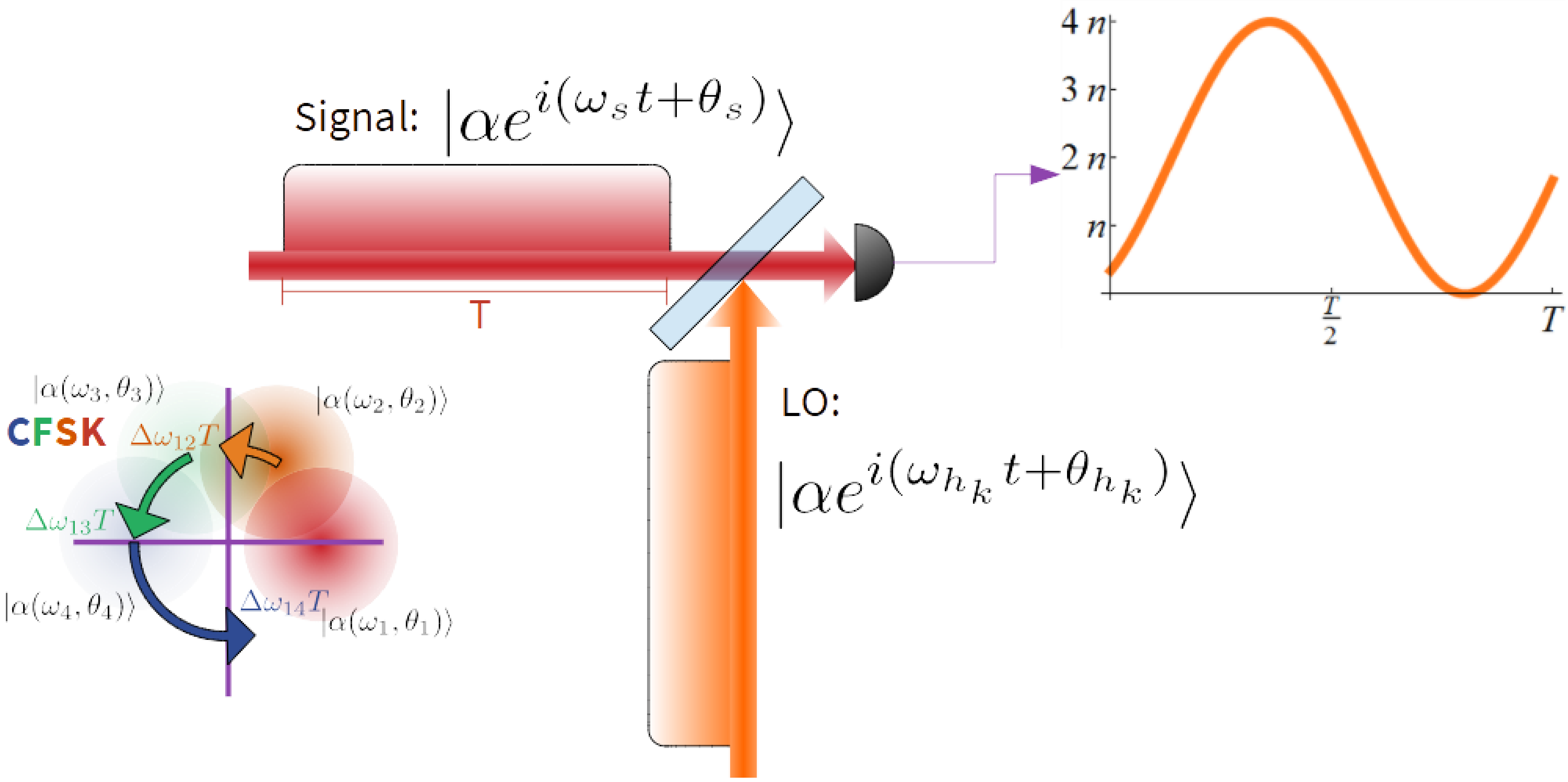
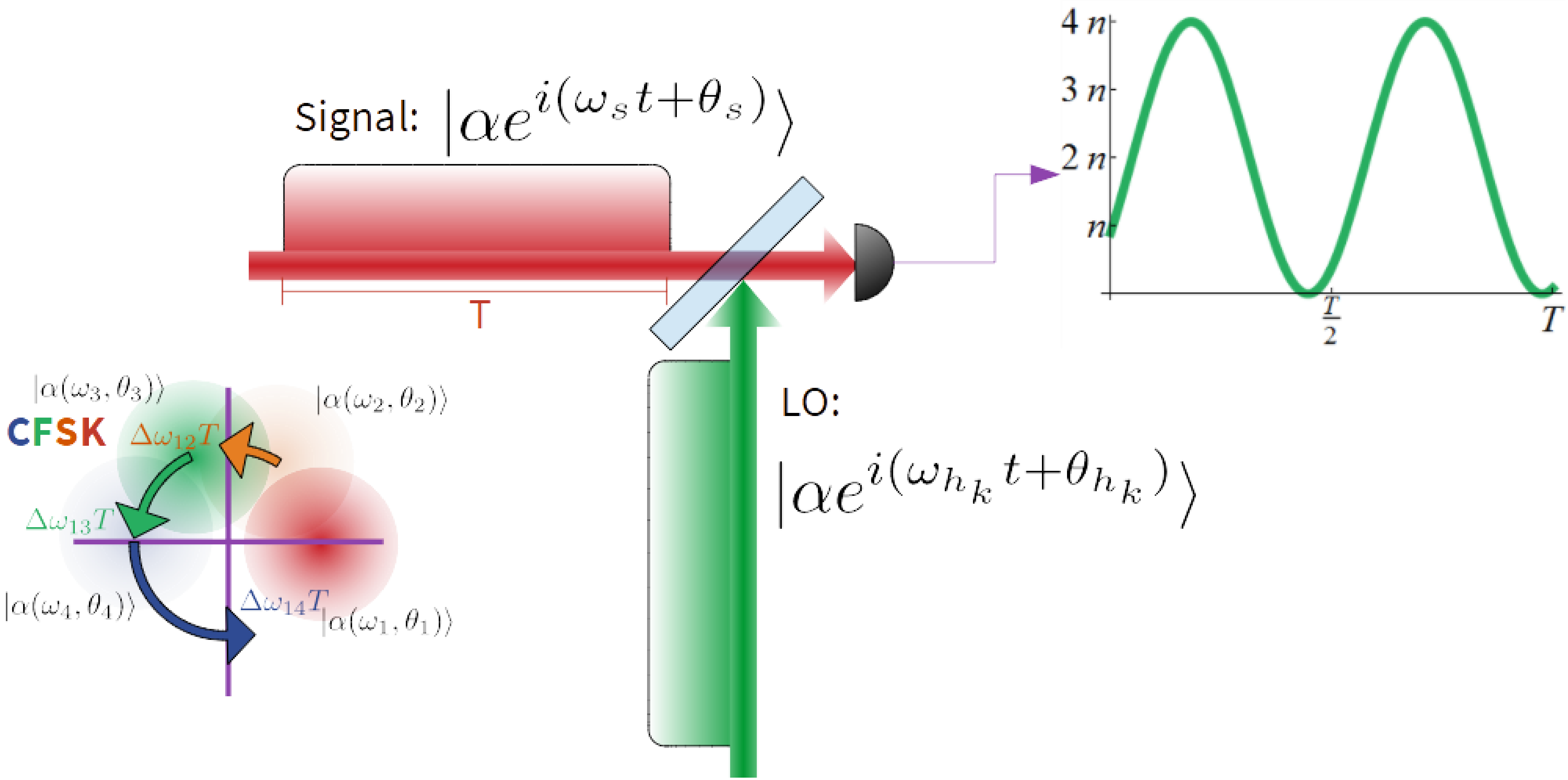
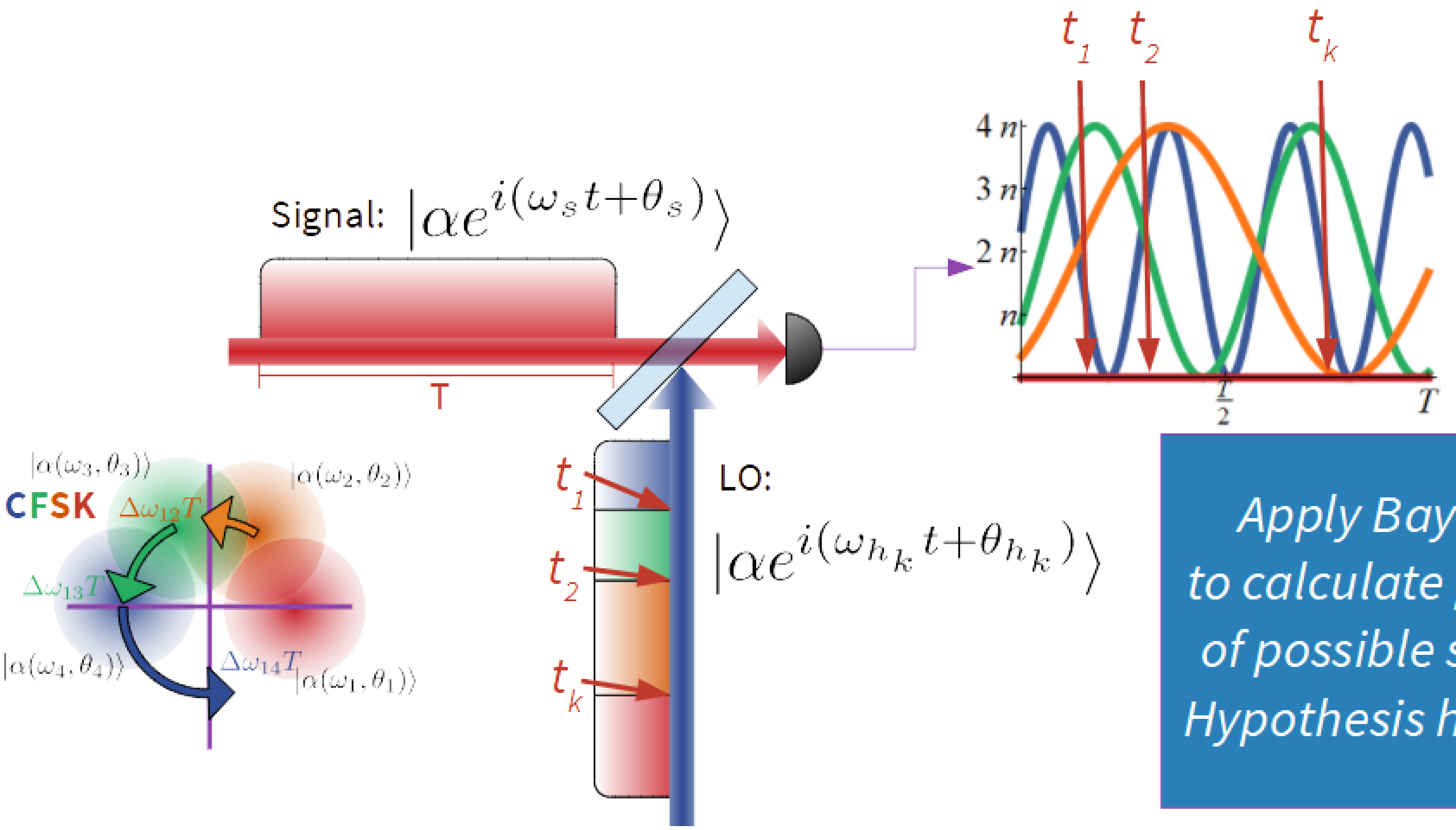
Time-resolving quantum receiver



Time-resolving quantum receiver

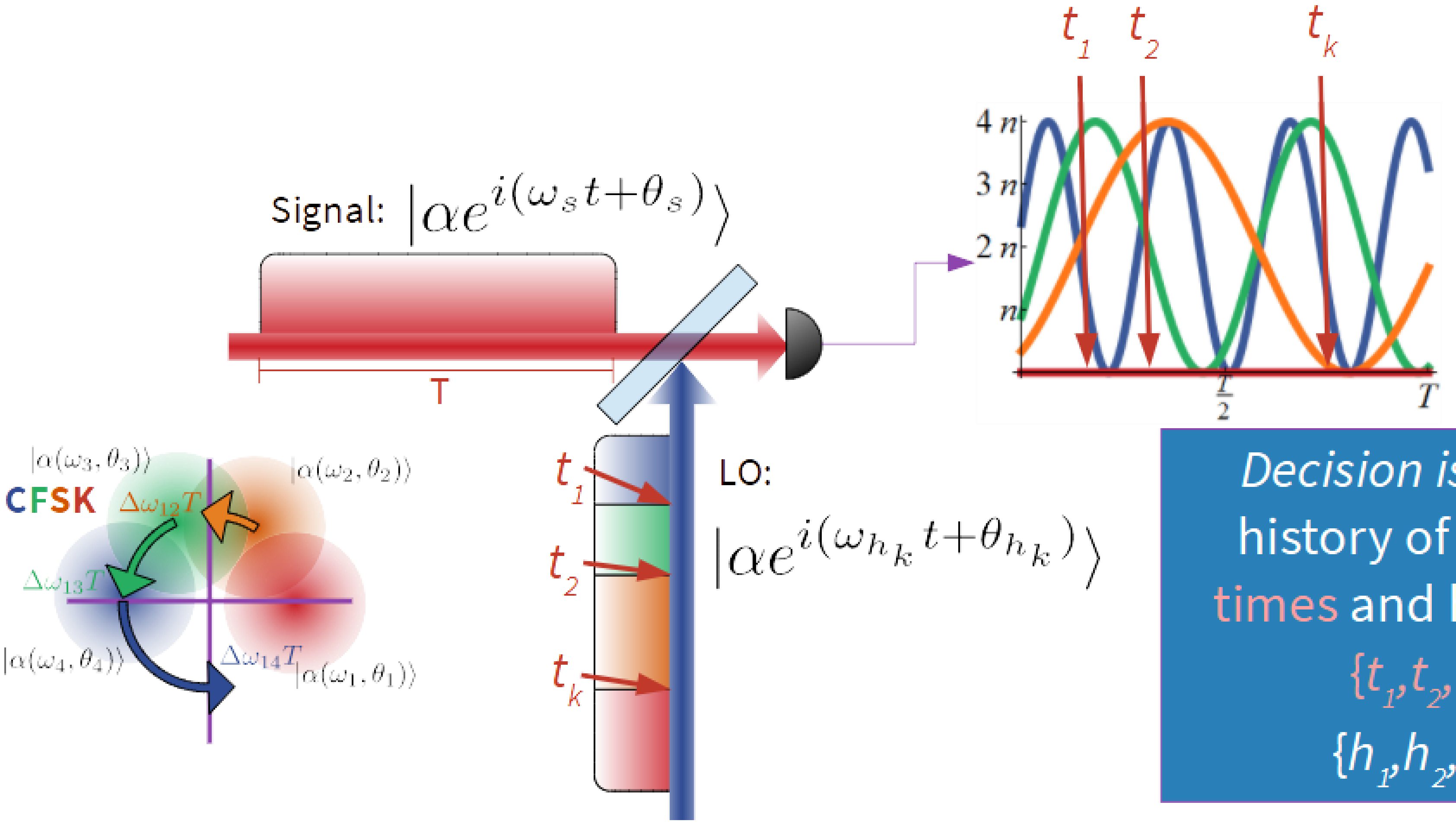


Time-resolving quantum receiver



Apply Bayesian rule to calculate probabilities of possible symbol m for Hypothesis h_k and time t_k

Time-resolving quantum receiver

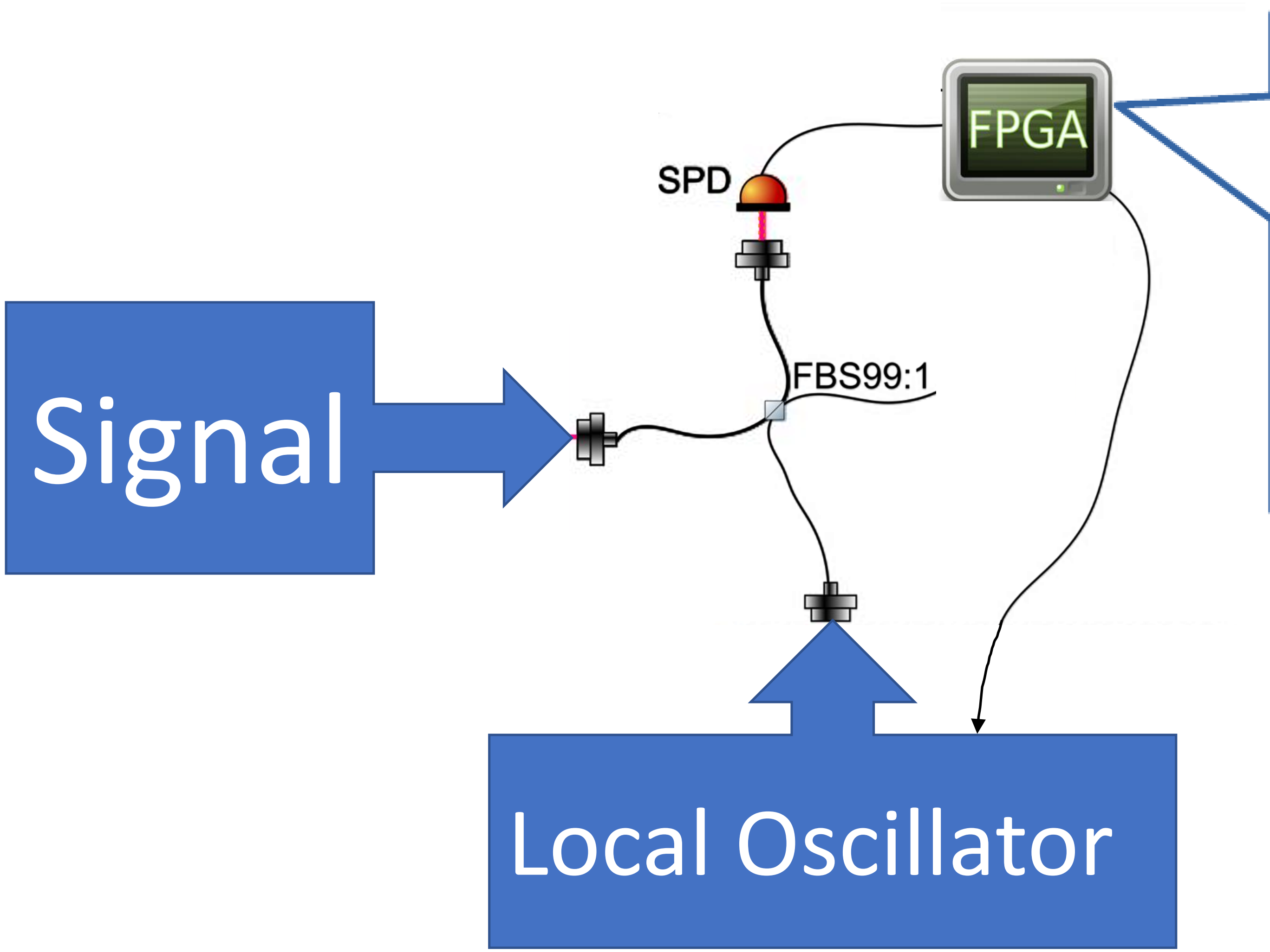


Decision is based on history of detection times and hypothesis:

$\{t_1, t_2, \ldots, t_N\}$

$\{h_1, h_2, \ldots, h_N\}$

Experimental receiver



- Direct RF synthesis
- Time-resolved photon detection
- Real-time feedback and discrimination

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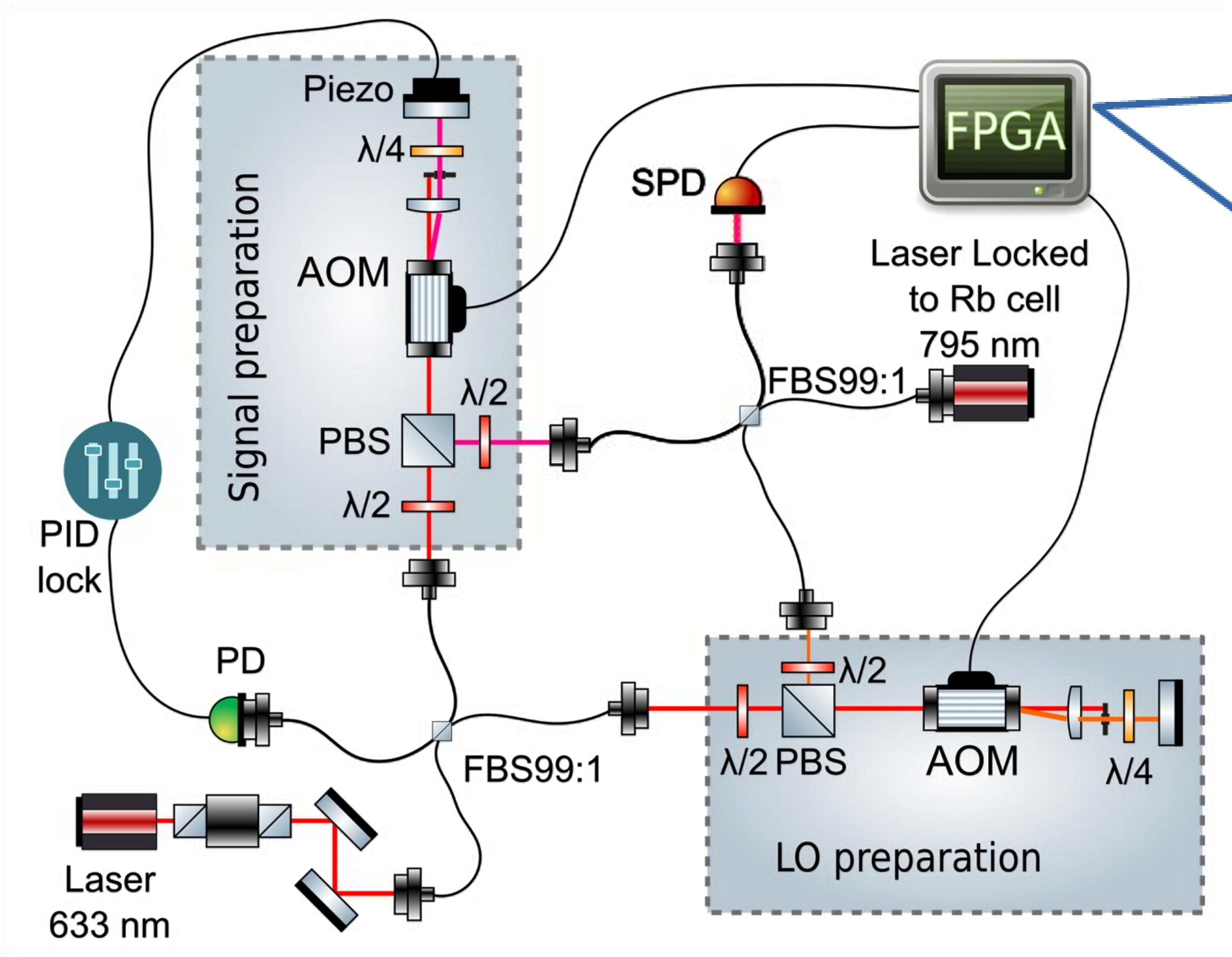
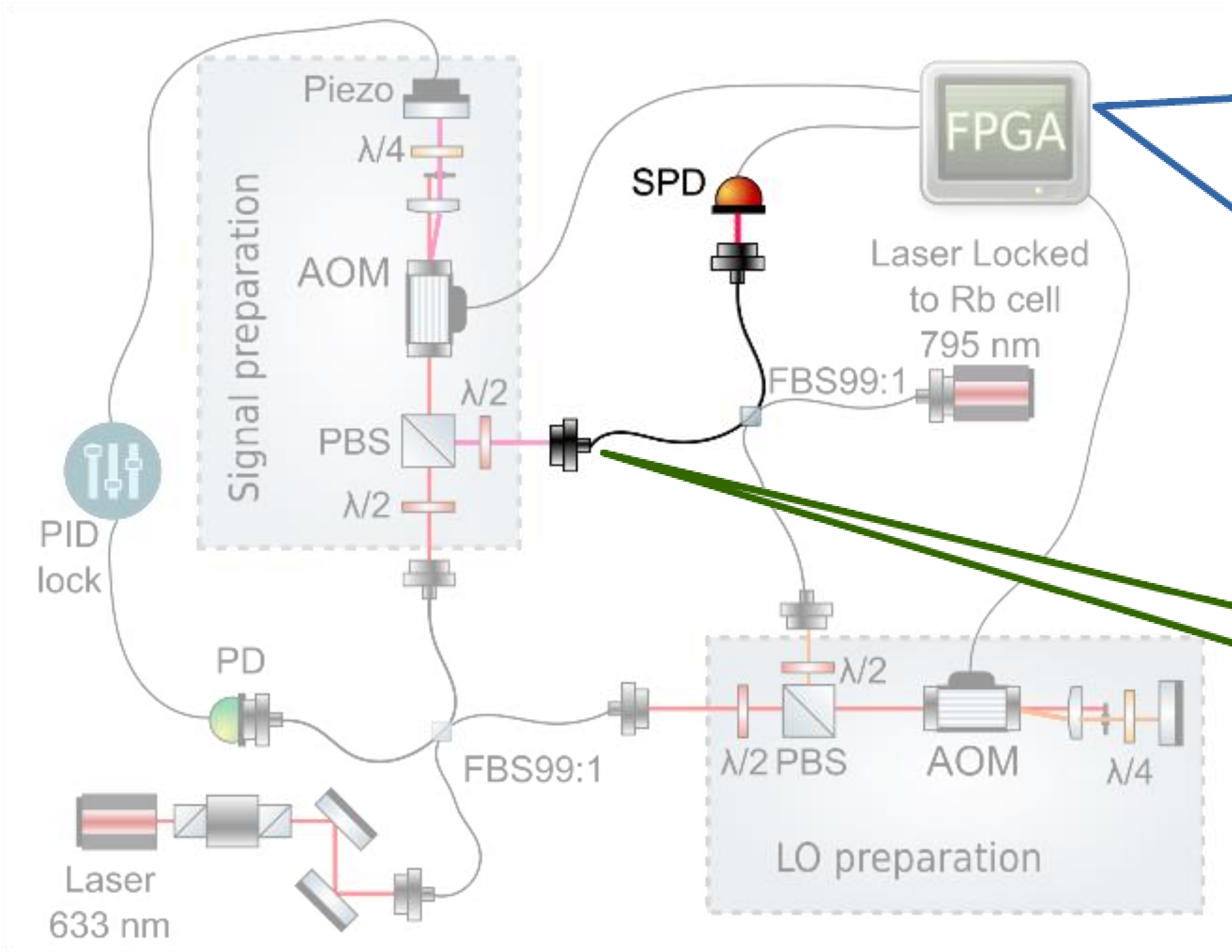
Experimental testbed



- Direct RF synthesis
- Time-resolved photon detection
- Real-time feedback and discrimination

PRX Quantum **1**, 010308 (2020)

Experimental efficiency



- Direct RF synthesis
- Time-resolved photon detection
- Real-time feedback and discrimination

System efficiency ~74%

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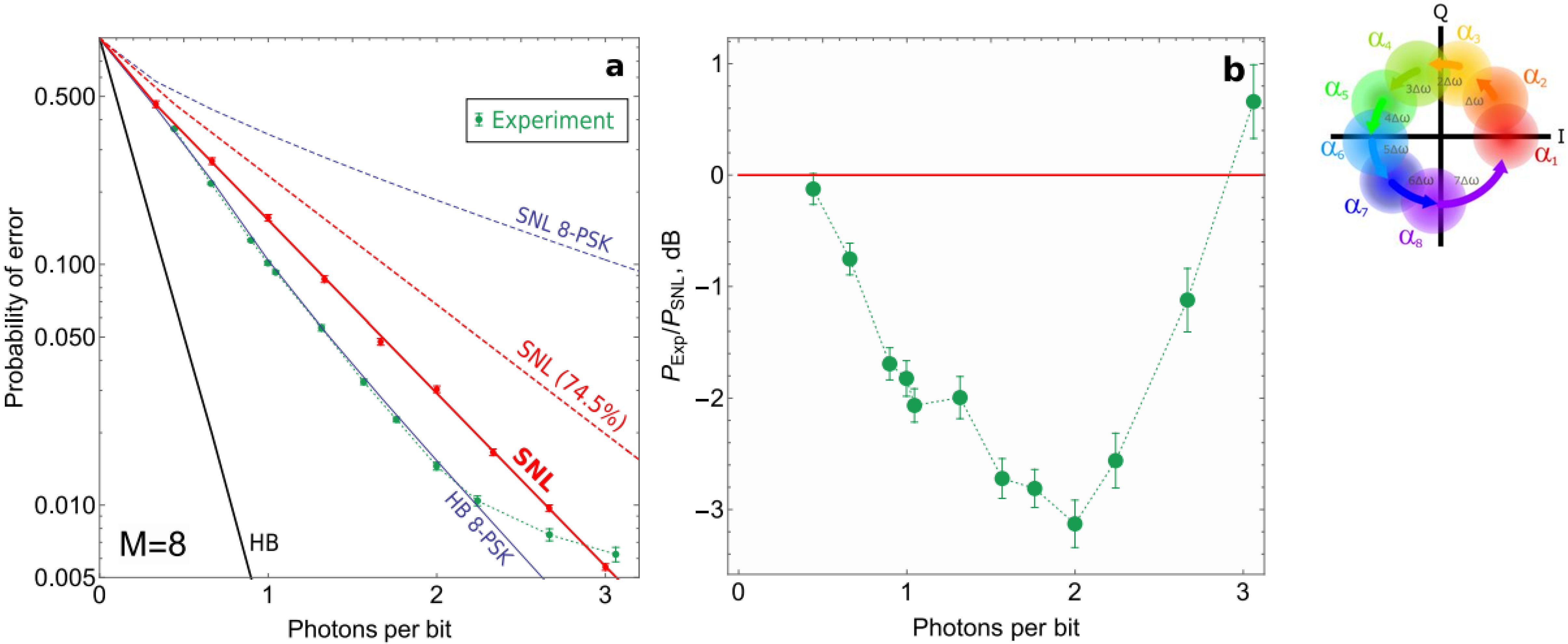
Experimental results



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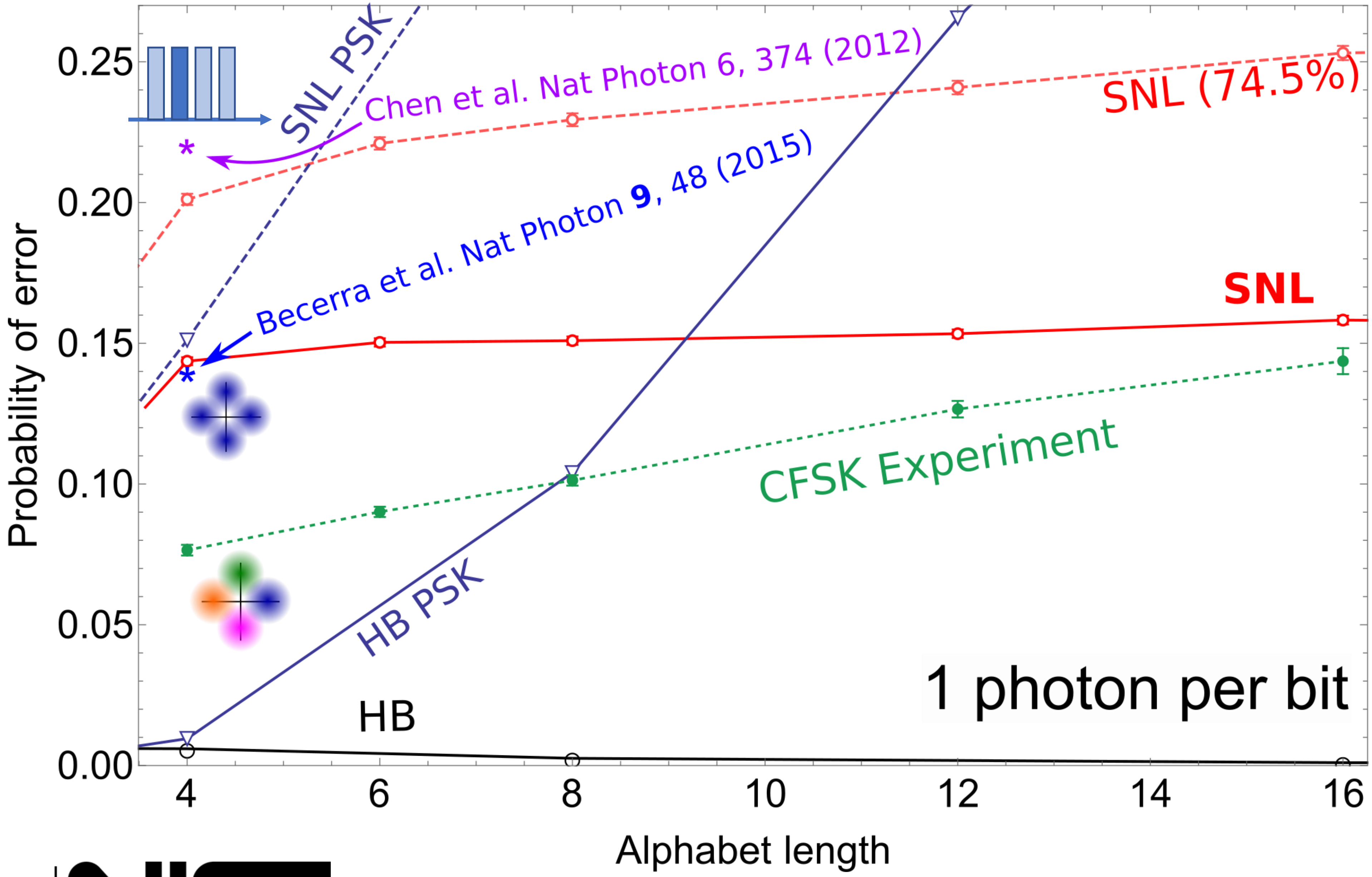
Scalability with the alphabet length



Contributions

- ‘Holistically’-designed communication protocol optimizing resource efficiency

- Experimental quantum-enabled communication testbed

- Highest energy sensitivity to date P_{err}≈7.5% @ 1 photon/bit

- First demonstration of below the SNL error rates for M>4

- Bondurant receiver: *OSA Continuum* **3**(12), 3324 (2020)
- Future work: Hybrid protocols/telecom

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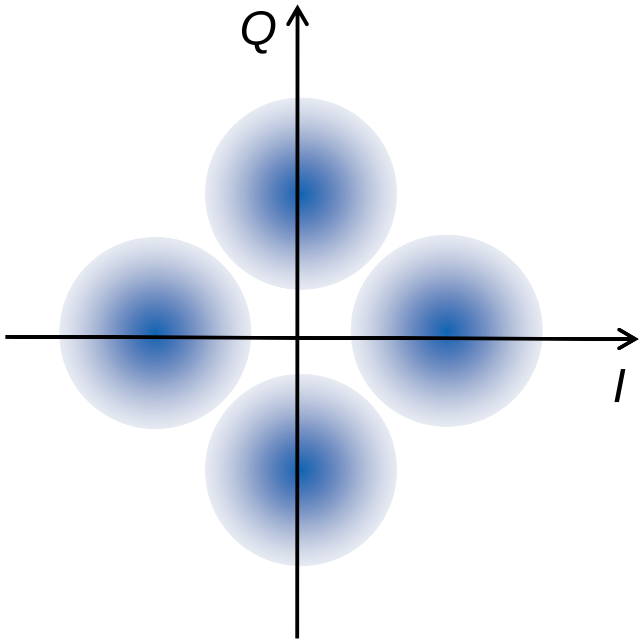
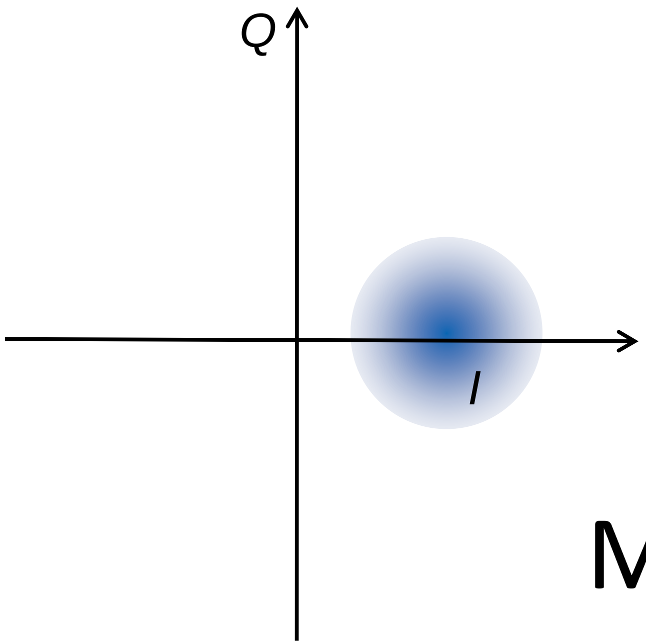
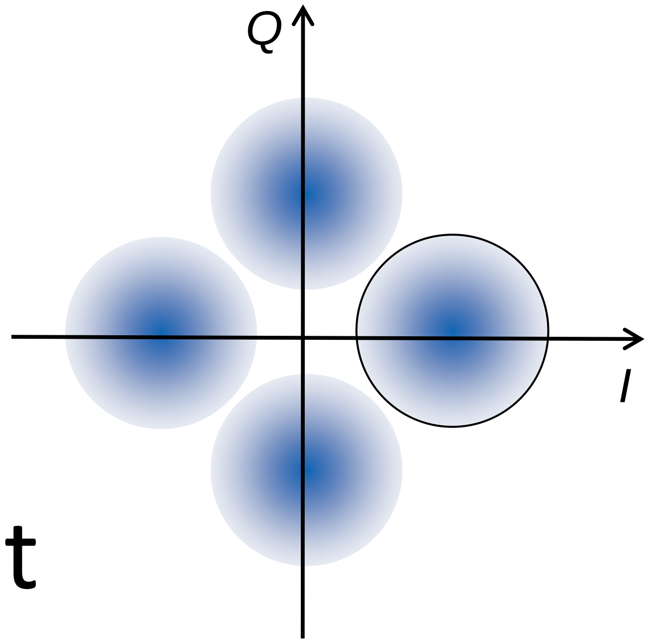
State identification



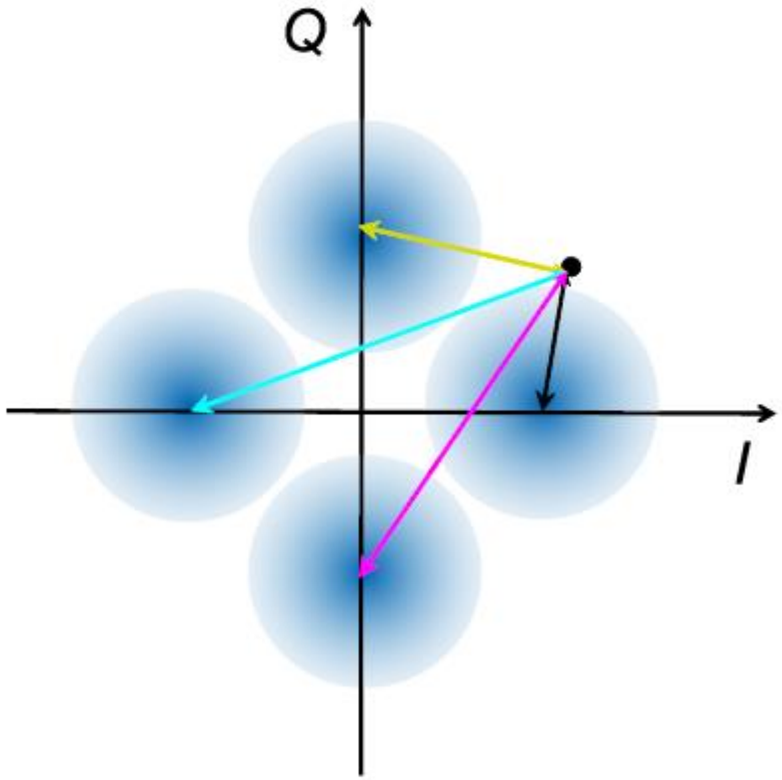


Measurement



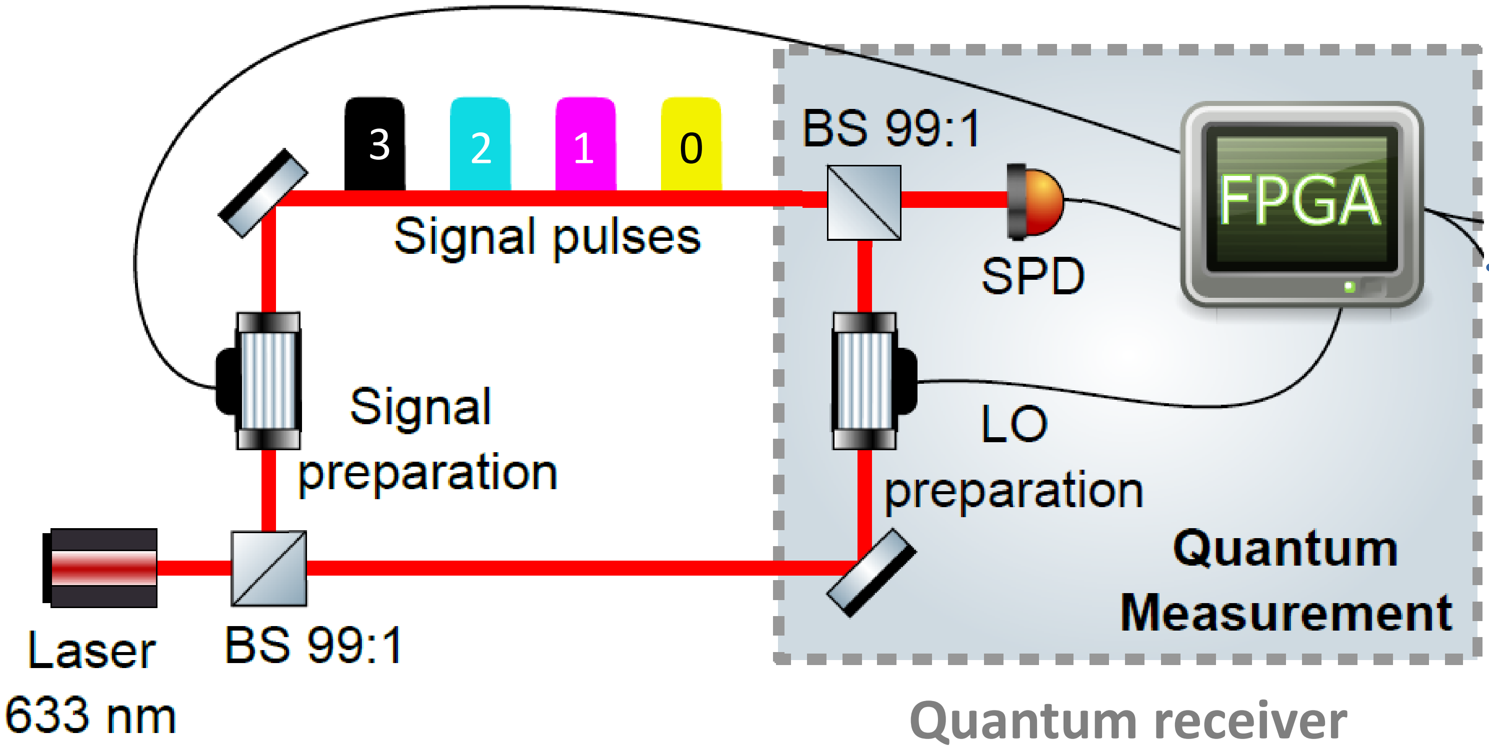
How confident are you?

Confidence: classical measurement



$$p_C(\phi_s|I,Q) = \frac{p(I,Q|\phi_s)\tilde{p}_s}{\sum_{j=1}^{M} p(I,Q|\phi_j)\tilde{p}_j}$$

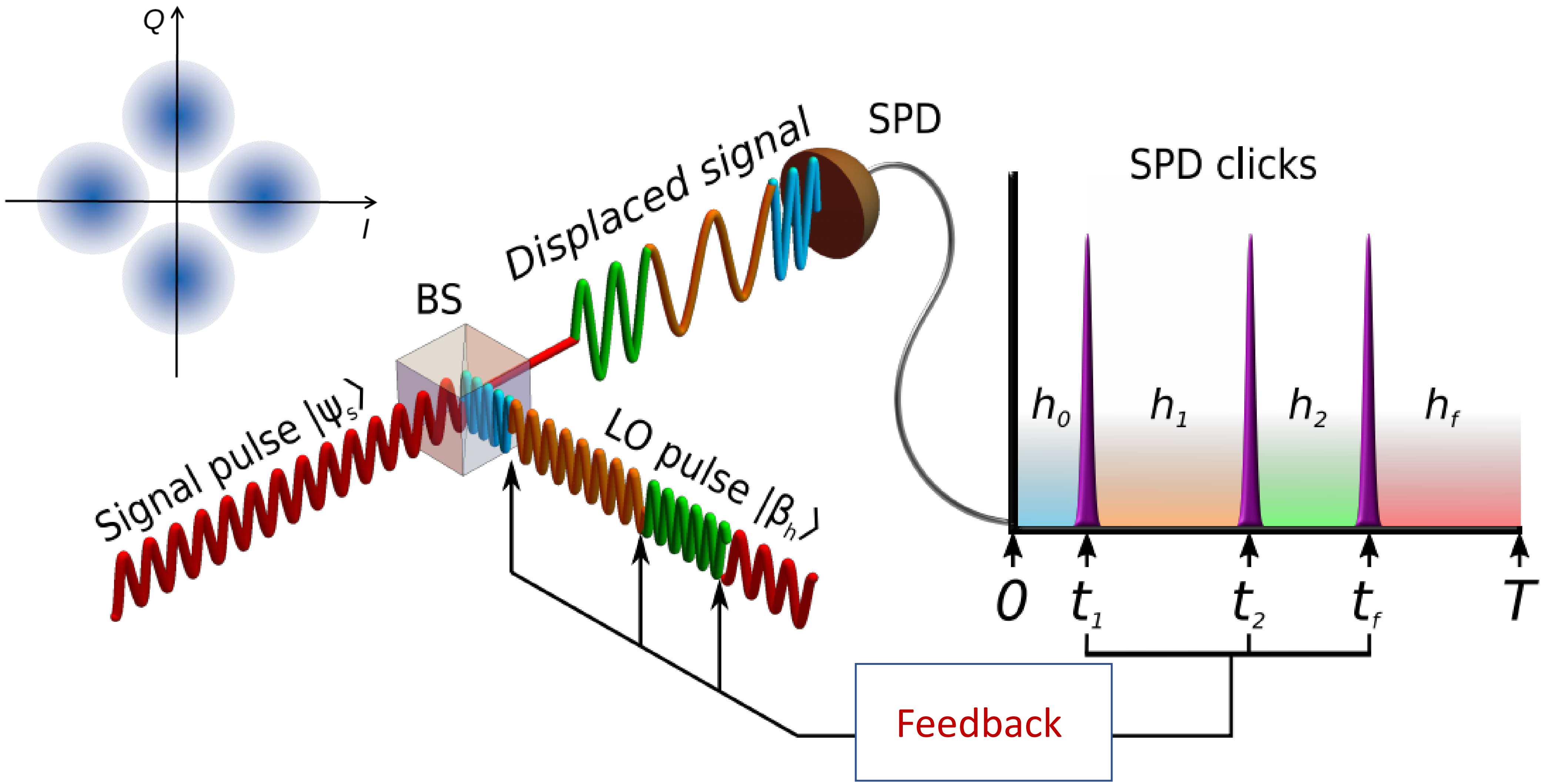
Continuous quantum measurement



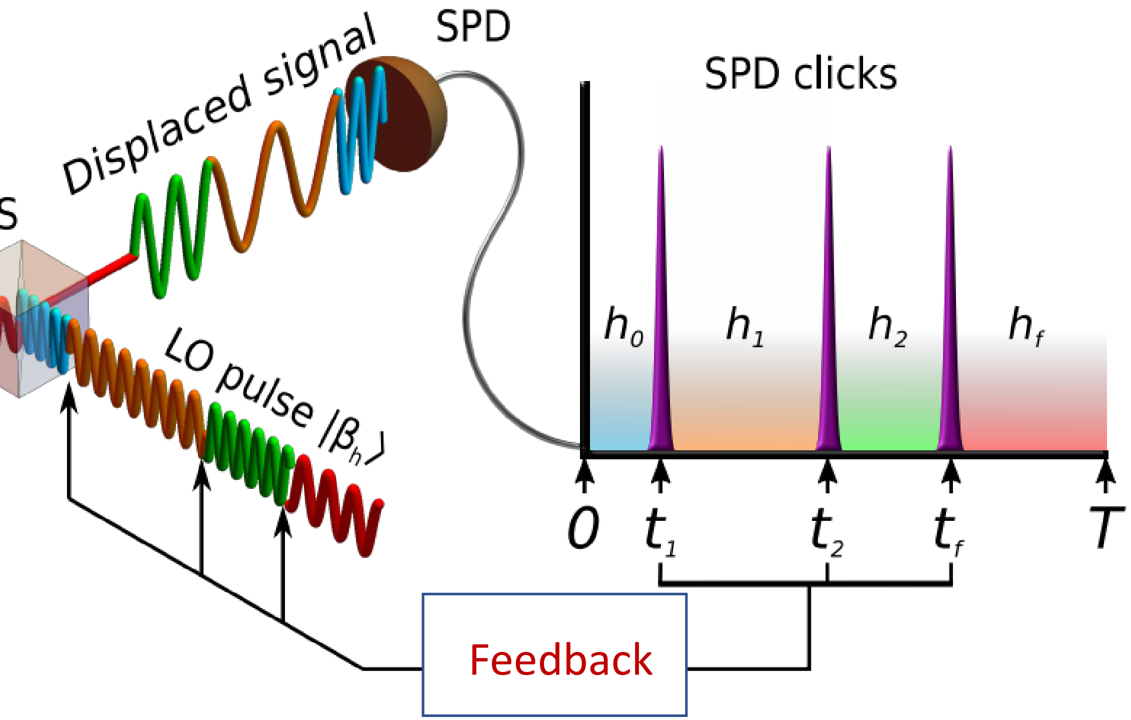
Quantum receiver

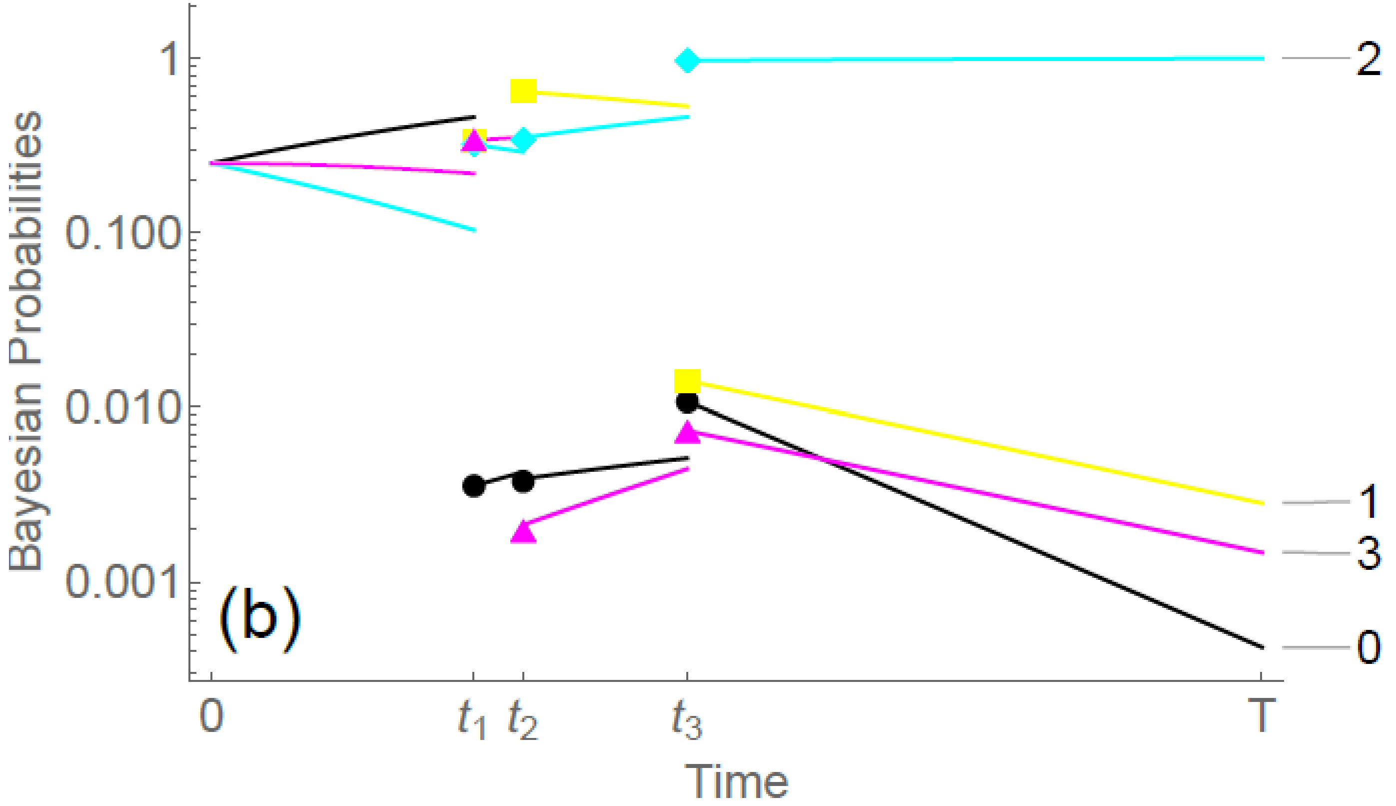
- Performs a continuous quantum measurement
- Enables user data tx/rx

Continuous quantum measurement



Confidence: quantum measurement



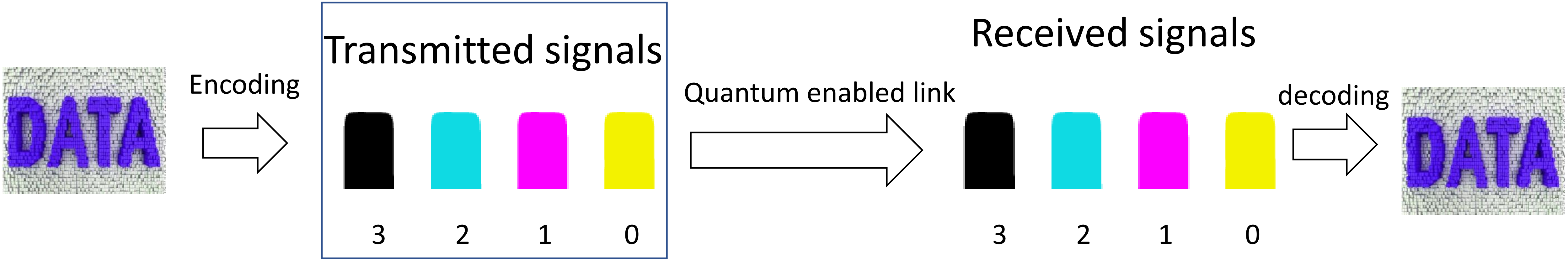


$$\mathbb{Z}[0,t] = \left(\lambda_t, \ldots, \lambda_{2dt}, \lambda_{dt}; \hat{U}_t, \ldots, \hat{U}_{2dt}, \hat{U}_{dt}\right)$$

clicks feedbacks

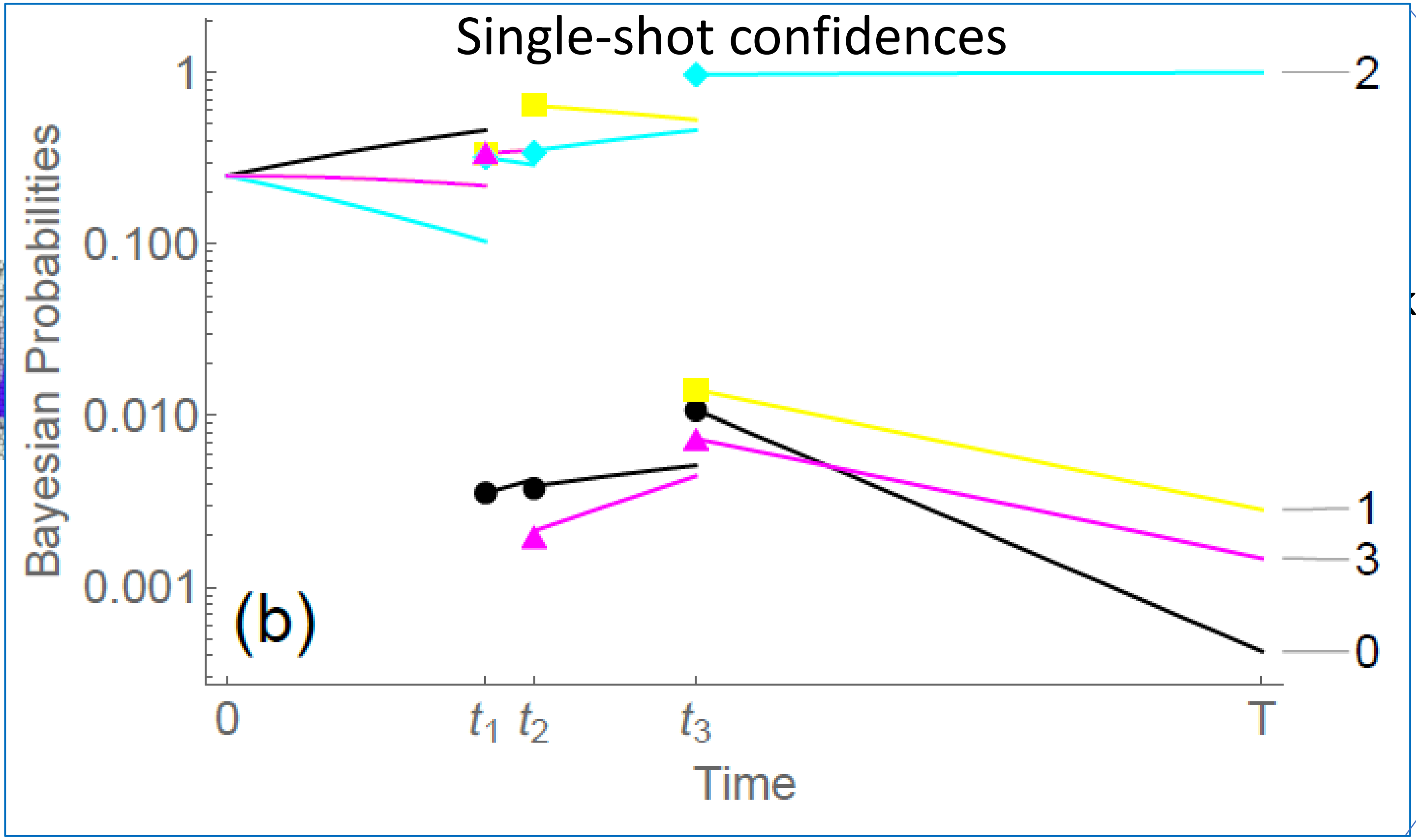
$$p(\phi_s|\mathbb{Z}[0,t]) = \frac{p(\mathbb{Z}[0,t]|\phi_s)\tilde{p}_s}{p(\mathbb{Z}[0,t])}$$

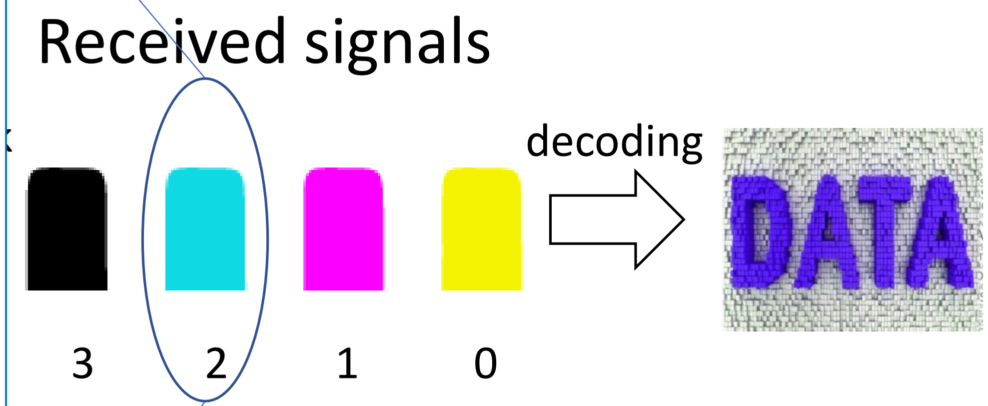
Receiver for arbitrary user data



First ever quantum single-shot accuracy estimation

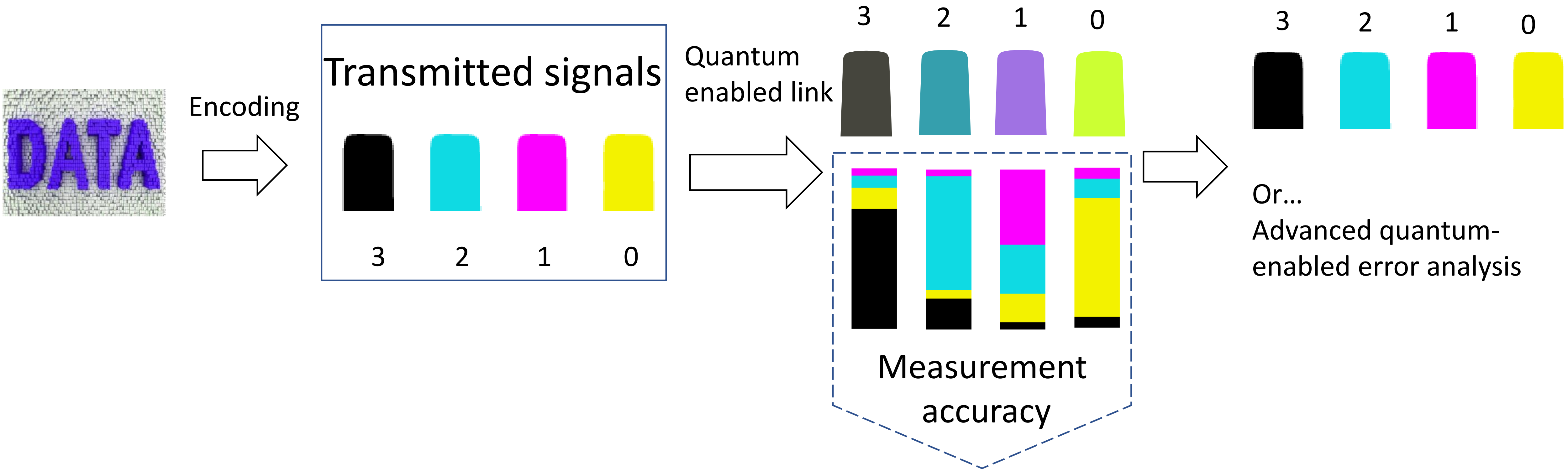
Single-shot "accuracy" estimates





First ever quantum single-shot accuracy estimation

Single-shot "accuracy" estimates



First ever quantum single-shot accuracy estimation

User data transmission

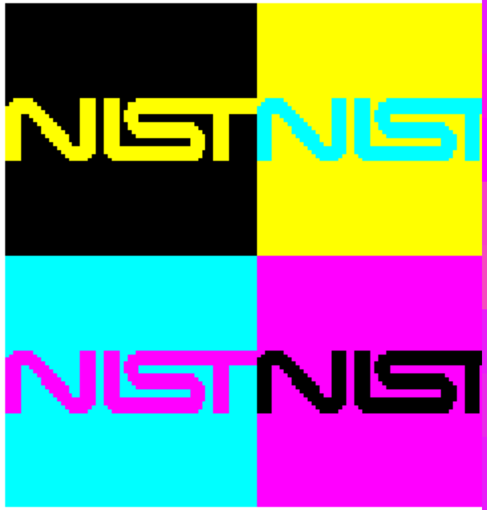
Transmitted

128x128

Only 2.68 photons/pixel => 1.34 photon/bit is used

User data transmission

Transmitted



128*128 pixel

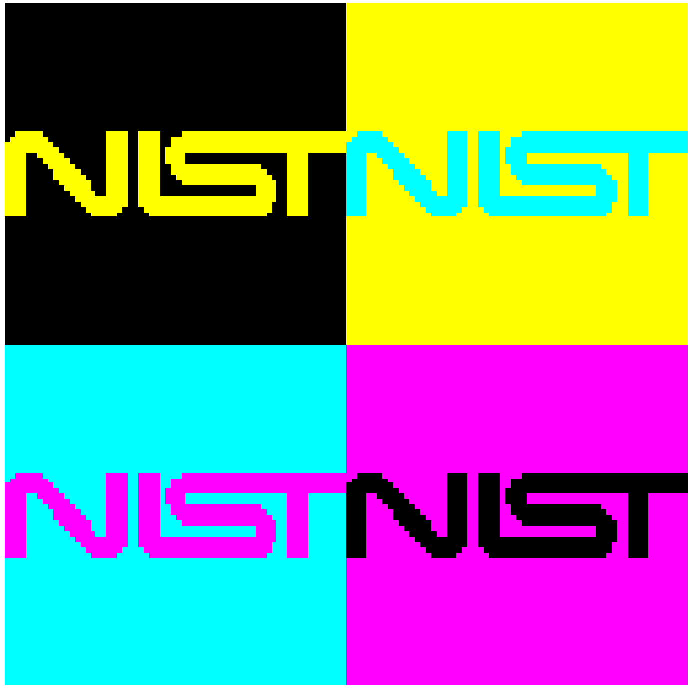
Received

Only 2.68 photons/pixel => 1.34 photon/bit is used

User data transmission

NIST

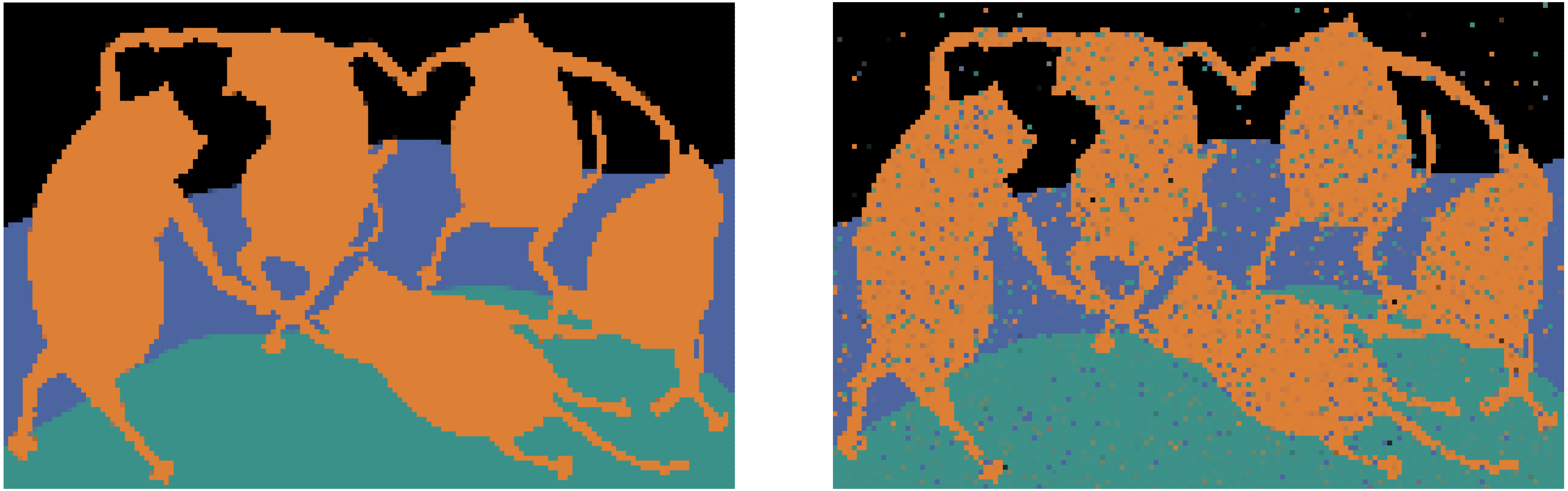
Transmitted



128x128

Only 2.68 photons/pixel => 1.34 photon/bit is used

User data transmission



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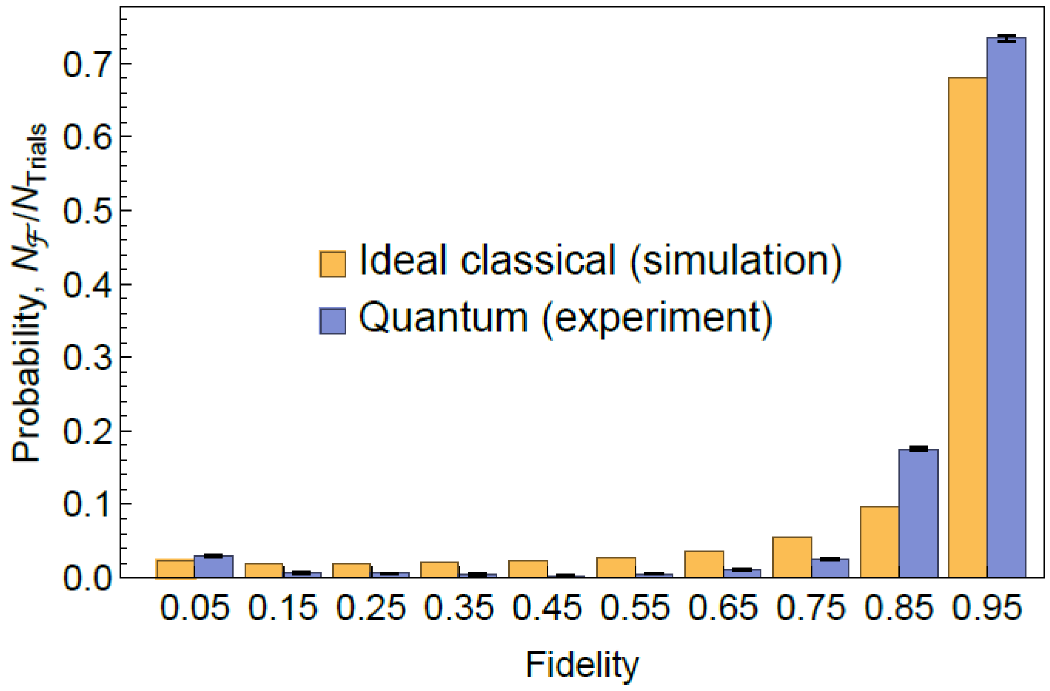
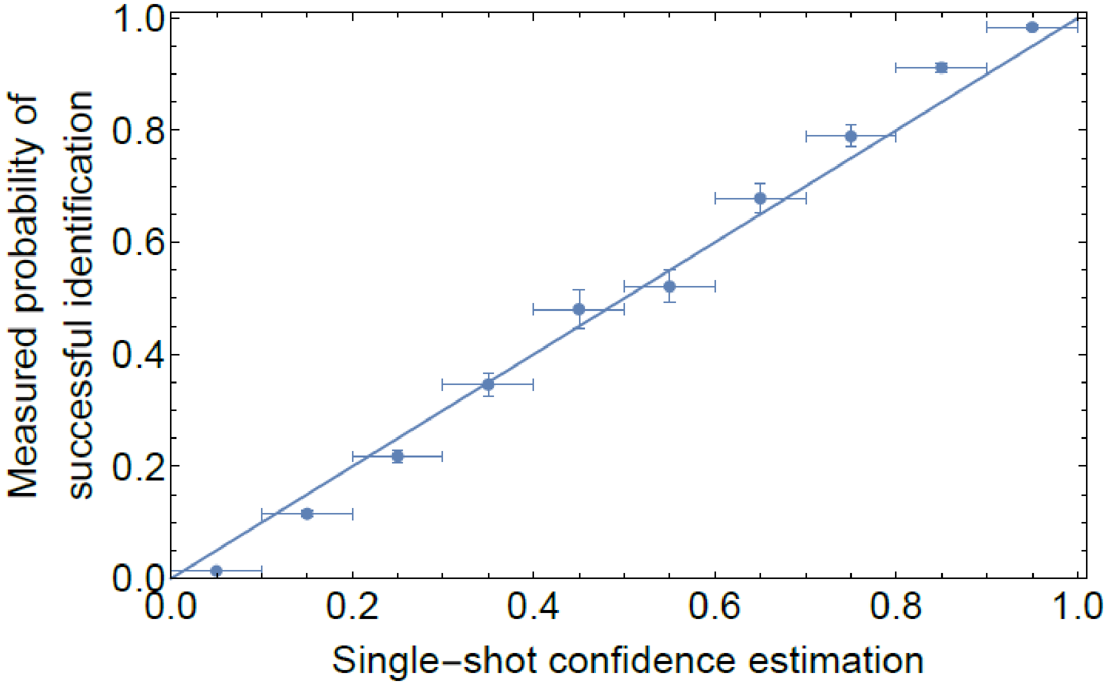
Only 2.68 photons/pixel => 1.34 photon/bit is used

First single-shot measurements!





Contributions

- Experimentally obtained single-shot "accuracy" (confidence) estimations in a quantum state identification measurement for the first time
- Proved experimentally that the single-shot fidelity of the quantum measurement is greater than that of the idealized (classical) homodyne
- Proved that single-shot "accuracy" estimations correctly predict the ensemble-averaged error rate.

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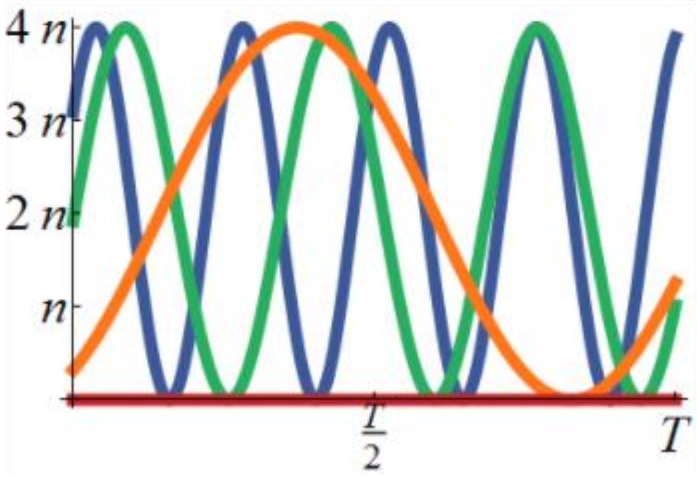
Displacement comparison

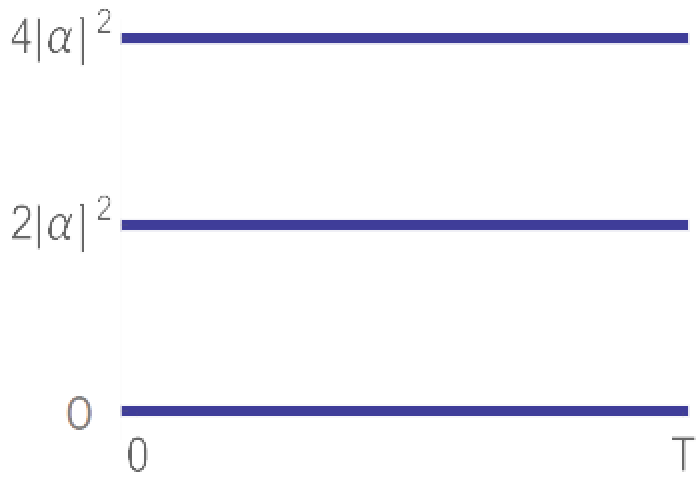
CFSK

$$\langle n(t)\rangle = 2n\left\{1-\cos\left[\Delta\omega_{sh}t+\Delta\theta_{sh}\right]\right\}$$

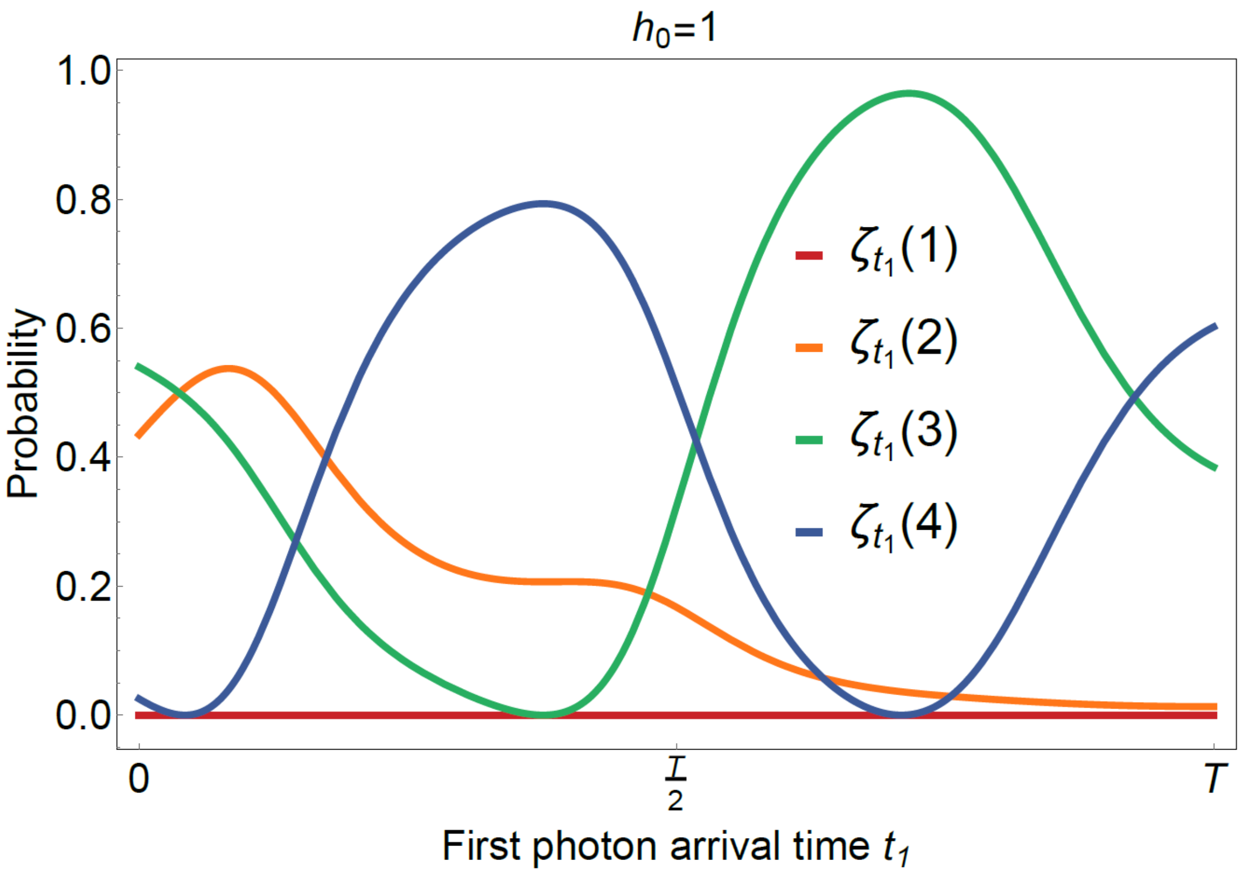


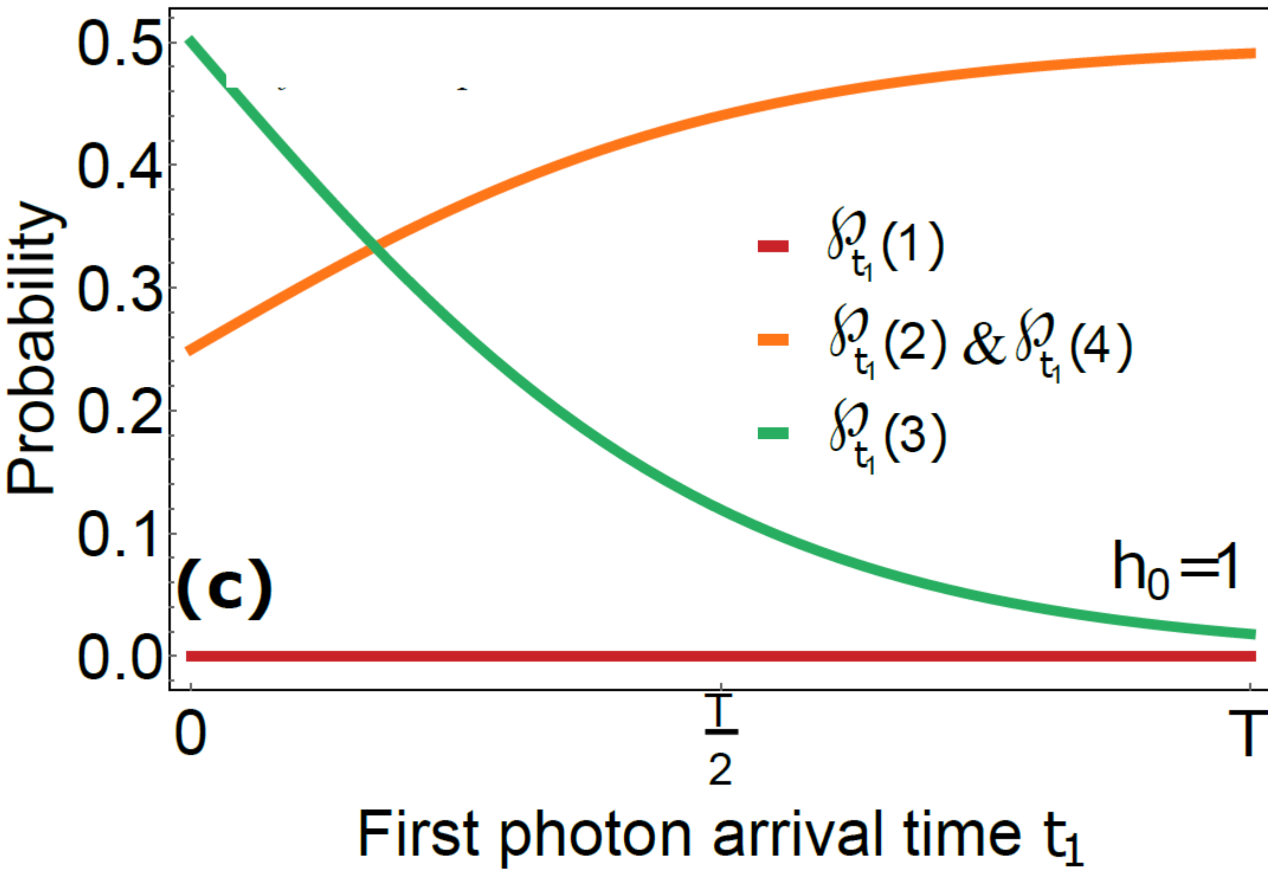
QPSK

$$\langle n\rangle = 2|\alpha|^2\left\{1-\cos\left[(s-h)(2\pi/M)\right]\right\}$$



Bayesian probabilities





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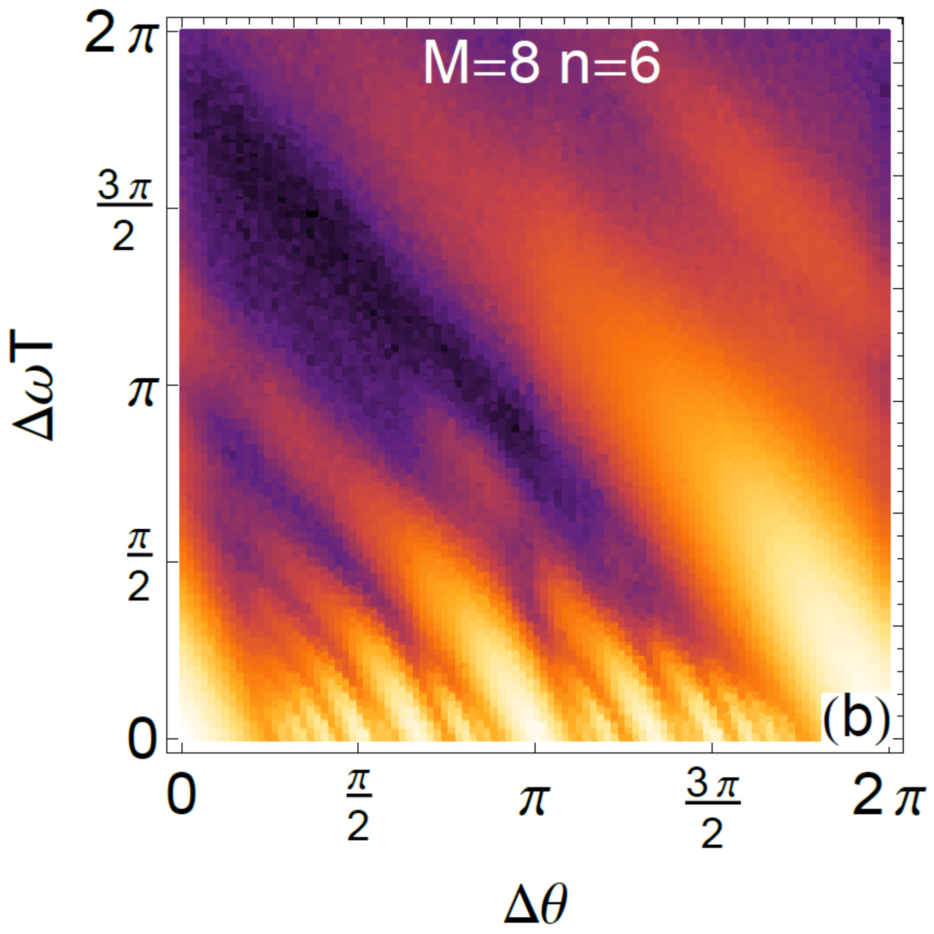
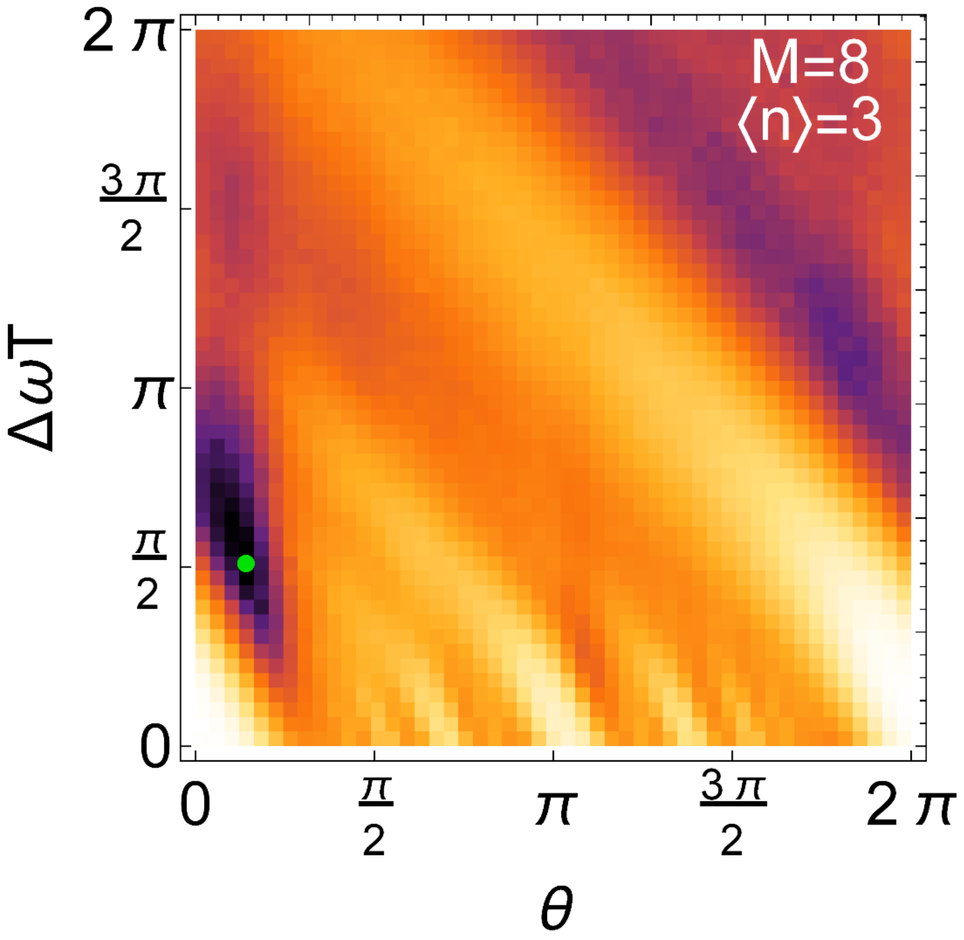
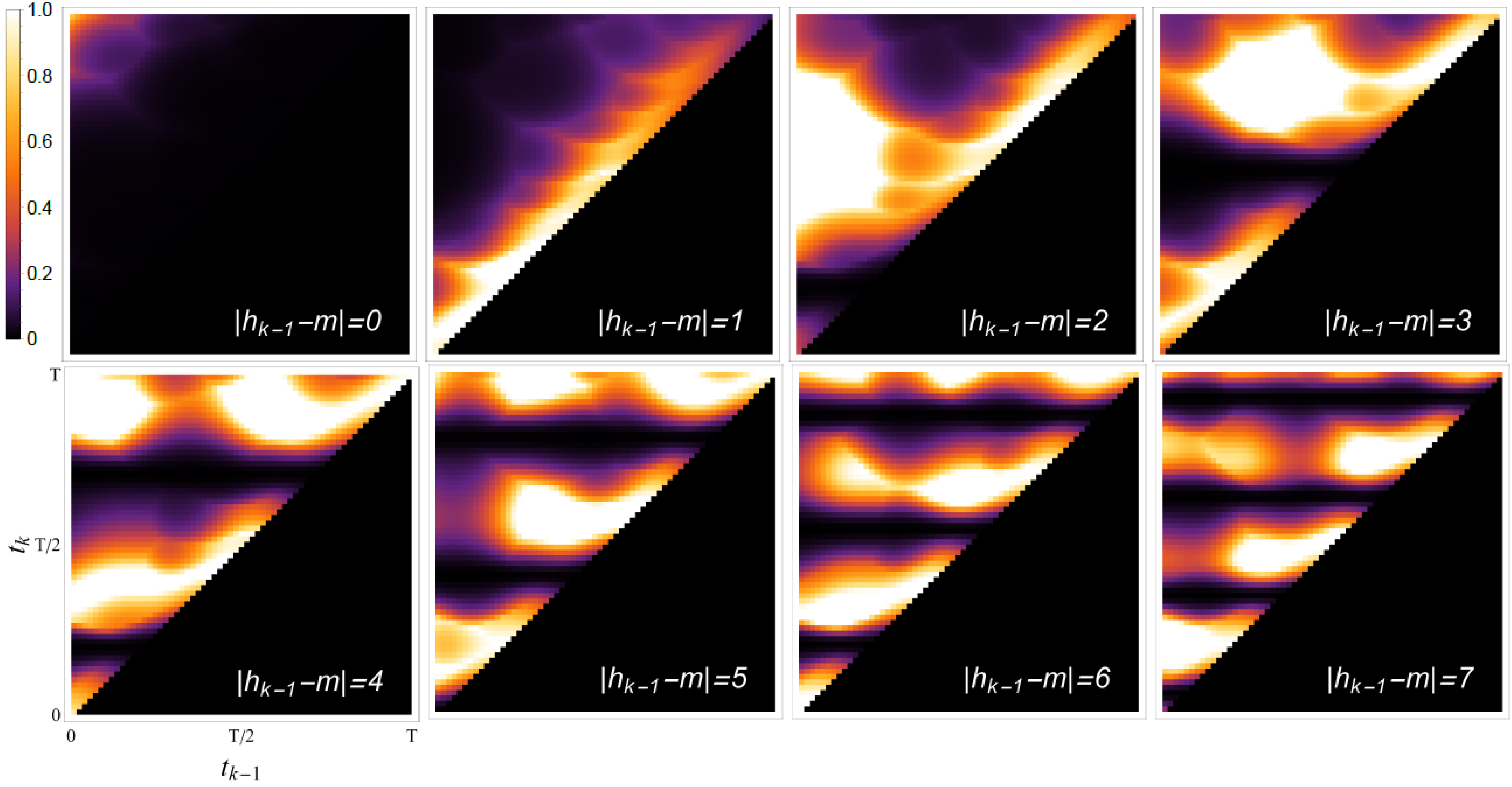
CFSK optimization





LUT


1.0
0.8
0.6
0.4
0.2
0
$|h_{k-1}-m|=0$
$|h_{k-1}-m|=1$
$|h_{k-1}-m|=2$
$|h_{k-1}-m|=3$
T
t_k T/2
0
$|h_{k-1}-m|=4$
$|h_{k-1}-m|=5$
$|h_{k-1}-m|=6$
$|h_{k-1}-m|=7$
0
T/2
T
t_{k-1}

Complex computations

$$\aleph(t_k, t_{k-1}, m, h_{k-1}) =$$

$$(\langle n(m, h_{k-1}, t_k)\rangle / T) e^{-\int_{t_{k-1}}^{t_k} \langle n(m, h_{k-1}, \tau)\rangle d\tau / T}$$

$$\langle n(m, h, t)\rangle = 2\mathcal{T} n_0 \left(1 - \cos\left[(h - m)(\Delta\omega t + \Delta\theta)\right]\right)$$

$$\zeta_{t_k}(m) = \frac{\aleph(t_k, t_{k-1}, m, h_{k-1})\zeta_{t_{k-1}}(m)}{\sum_{j=1}^{M} \aleph(t_k, t_{k-1}, j, h_{k-1})\zeta_{t_{k-1}}(j)}$$