ISTITUTO NAZIONALE DI RICERCA METROLOGICA

QUANTUM CHANNEL DISCRIMINATION APPLIED TO EXPERIMENTAL SENSING: FROM QUANTUM READING TO PATTERN RECOGNITION

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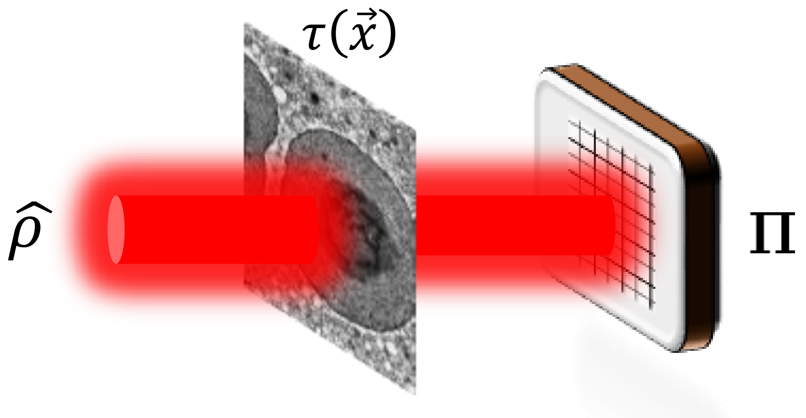
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 862644 (QUARTET)

QUARTET

I- OPTICAL LOSS ESTIMATION/DISCRIMINATION

GENERAL PROBLEM: Extracting information encoded in the optical loss (transmission or reflection) property of a spatial object

IMAGING → Quantum Metrology



- Spatial estimation of a continuous parameter

- Quantum estimation theory

$\hat{\tau}(\vec{x})$ estimate

$\Delta\tau(\hat{\rho}, \Pi)$ Uncertainty

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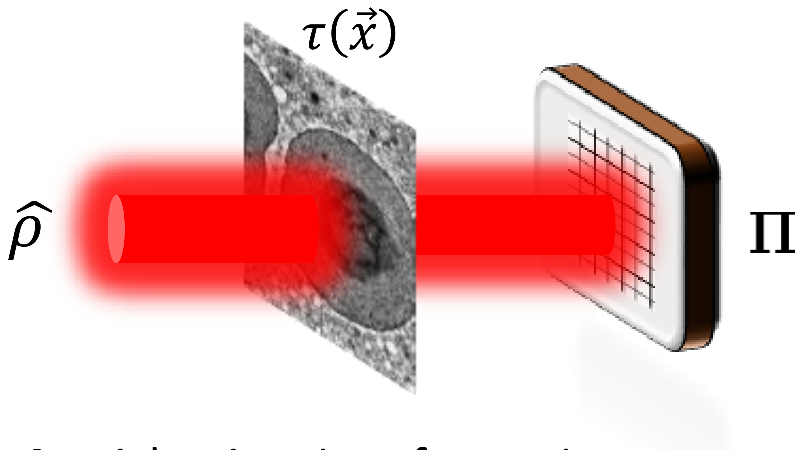

- Spatial estimation of a continuous parameter
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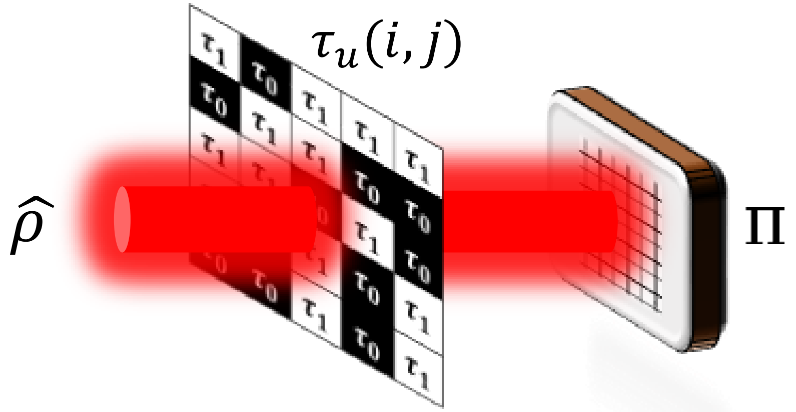
$\hat{\tau}(\vec{x})$ estimate

$\Delta\tau(\hat{\rho}, \Pi)$ Uncertainty

READOUT OF CLASSICAL DATA → Quantum Hypothesis Testing



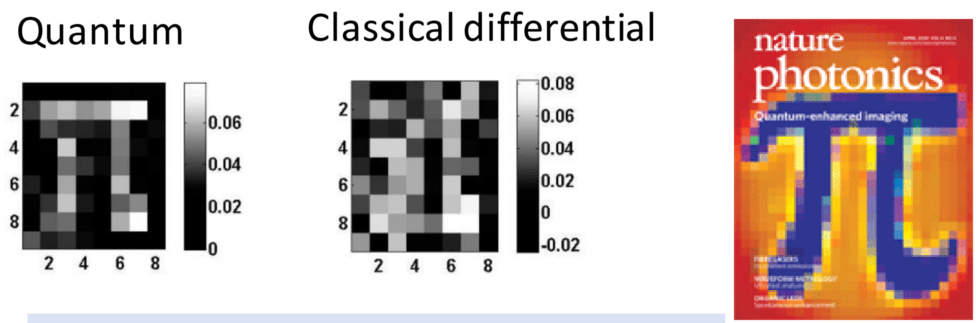
- Array of cells (i,j) encoding bits in two value of optical parameter τ_u $(u = 0,1)$
- Bosonic Loss channel discrimination

$v(i,j)$ Assigned bit value

$p_{err}(\hat{\rho}, \mathbf{\Pi})$ Error probability

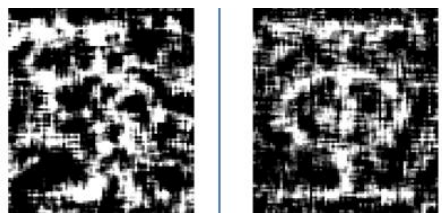
I- IMAGING RESULTS

- **2010:** Sub shot noise imaging: Proof of principle



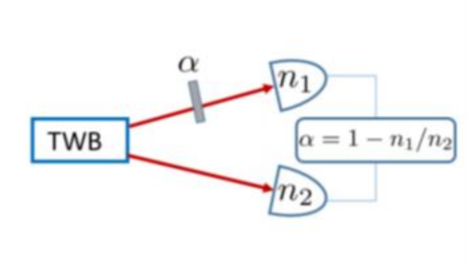
Nat. Phot. **4**, 227 (2010)

- **2017:** Sub shot noise microscopy: beating the best classical strategy (70% shot noise removed)



Light: S&A. 6 e17005 (2017)

- **2018:** TMSV + photon counting strategy approachs the Ultimate Quantum Limit

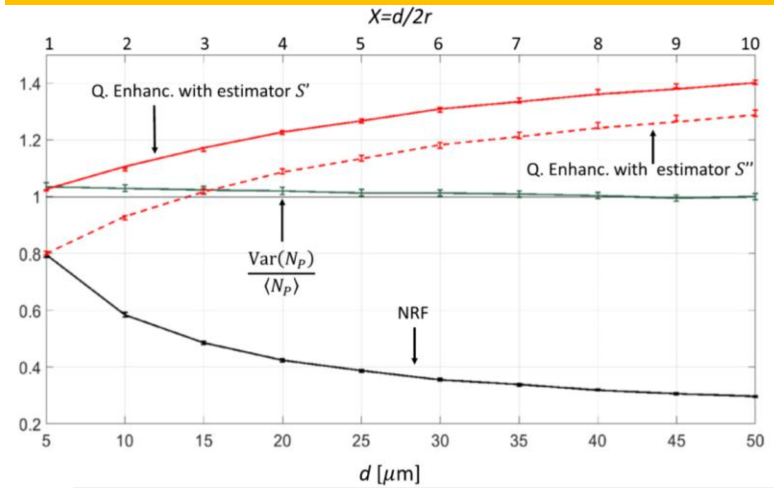


$$|TWB\rangle = \otimes^{M}|TMSV\rangle$$

$$|TMSV\rangle = \sum_{n=0}^{\infty} c_n |n\rangle_S |n\rangle_I$$

Scientific Reports, 8, 7431 (2018)

- **2020:** optimized estimator for quantum enhanced sensitivity obtained at the diffraction limit



Appl. Phys. Lett. 116, 214001 (2020)

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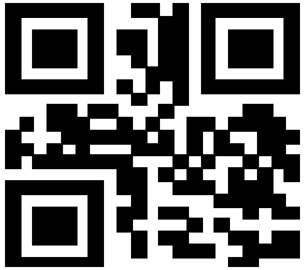
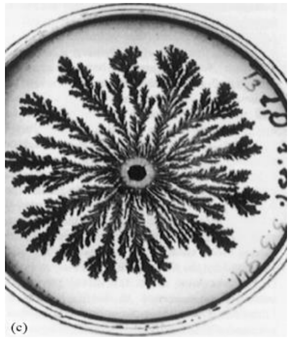
Examples of applications



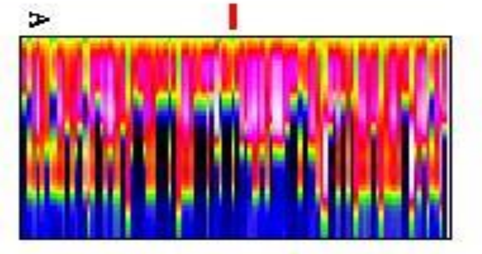
Bar Code/QR

Optical Memory

5

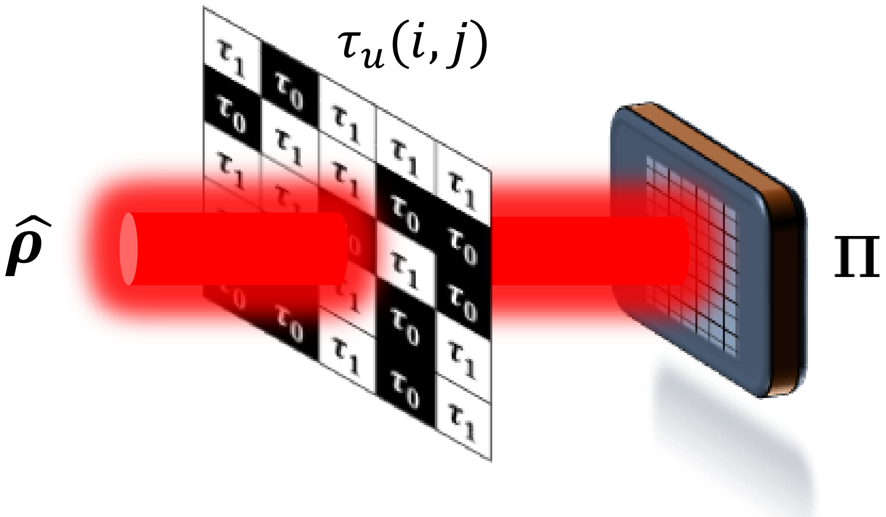


Pattern recognition (Petri Pattern)



Fingerprints of a substance in spectroscopy

READING: read-out of classical data/pattern recognition



- Array of cells (i,j) encoding bits in two value of optical parameter τ_u $(u = 0,1)$
- Loss channel discrimination

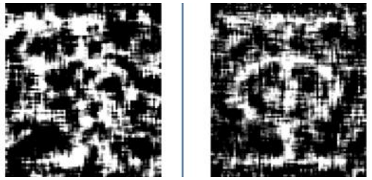
$v(i,j)$ Assigned bit value

$p_{err}(\hat{\rho}, \Pi)$ Error probability

OUTLINE

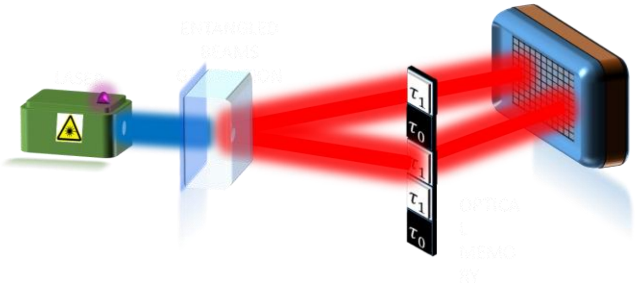
I– INRODUCTION

- Optical loss discrimination
- Previous results in imaging



II – QUANTUM READING

- Classical lower bound vs specific quantum strategy
- Experimental realization

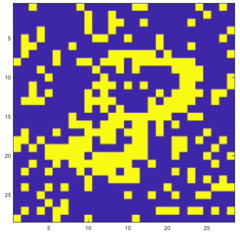


III – QUANTUM CONFORMANCE TEST

- Discrimination among two loss parameter distributions
- Simulation and experimental results

IV – QUANTUM PATTERN RECOGNITION

- From cell readout to patter classification
- Preliminary experimental results



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II- QUANTUM READING

SINGLE CELL READOUT: Assigning the value of a bit codified in two level of transmittance τ_0 and τ_1 of a cell in an optical digital memory

S. Pirandola, Phys. Rev. Lett. 106, 090504 (2011)

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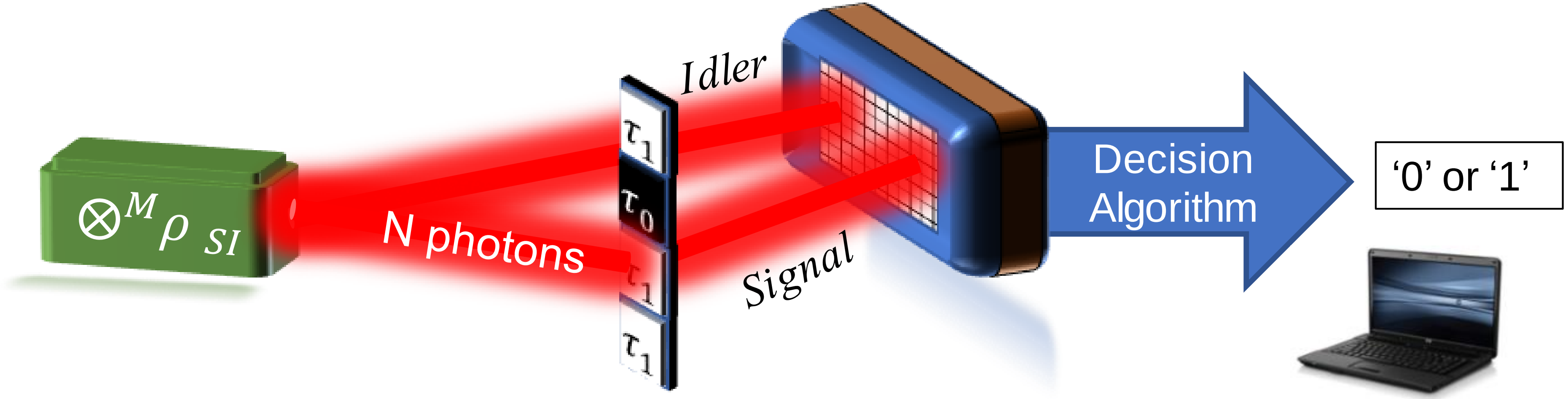
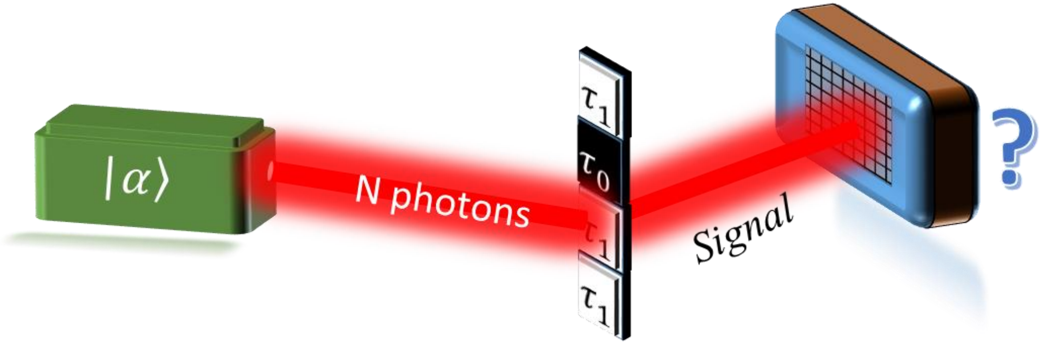


- A probe signal $\otimes^M \rho$, consists of M replicas of a correlated bipartite state ρ
- N photons are addressed to the cell
- The ancillary correlated idlers modes may be used in a joint measurement
- Post processing to guess the value of the bit u=0,1

S. Pirandola, Phys. Rev. Lett. 106, 090504 (2011)

II- QUANTUM READING

CLASICAL LOWER BOUND



$$p_{err}^{cla} \geq \mathcal{C}(N,\tau_0,\tau_1) := \frac{1-\sqrt{1-e^{-N\left(\sqrt{\tau_1}-\sqrt{\tau_0}\right)^2}}}{2}$$

- Single coherent mode is the optimal classical transmitter $\otimes^M \rho_{SI} \rightarrow |\alpha\rangle_s$, $|\alpha|^2 = \text{N}$
- The optimal measurement is undefined

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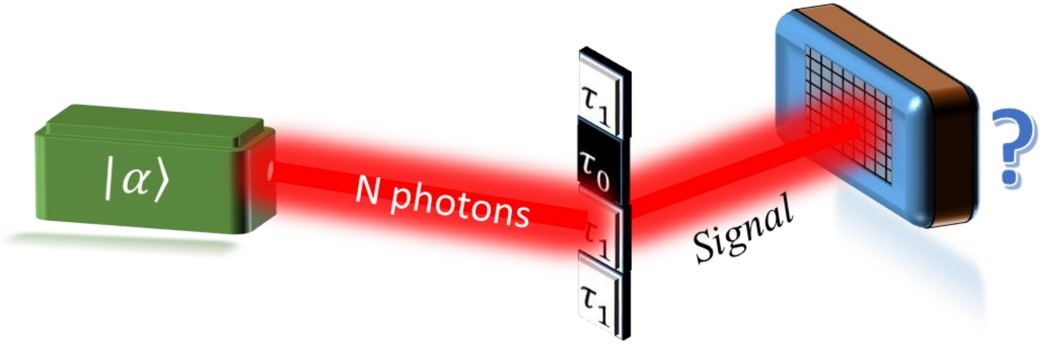
S. Pirandola, Phys. Rev. Lett. 106, 090504 (2011)

II- QUANTUM READING

OPTIMAL CLASSICAL BOUND



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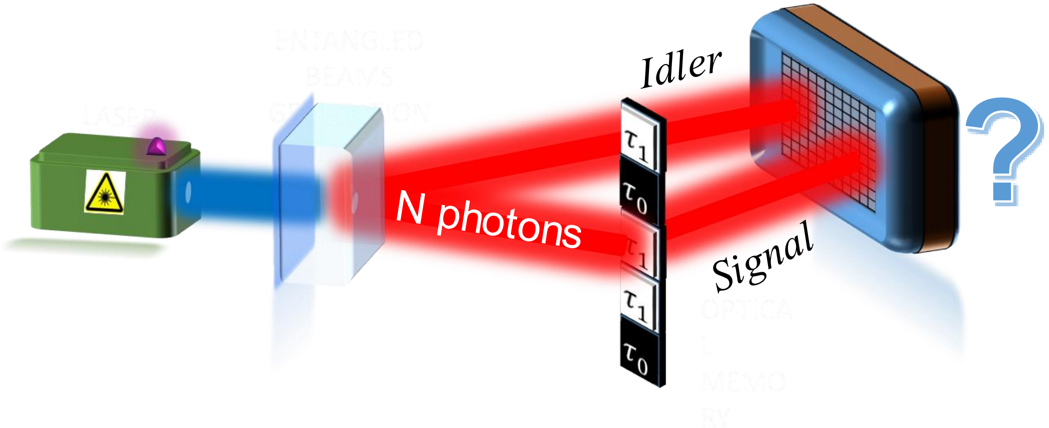
A SPECIFIC QUANTUM TRANSMITTER



M replicas of Two Mode Squeezed Vacuum (TMSV)

$$|\mathrm{TMSV}\rangle_{S,I}^{\otimes M} \qquad |TMSV\rangle = \sum_{n=0}^{\infty} c_n |n\rangle_S |n\rangle_I$$

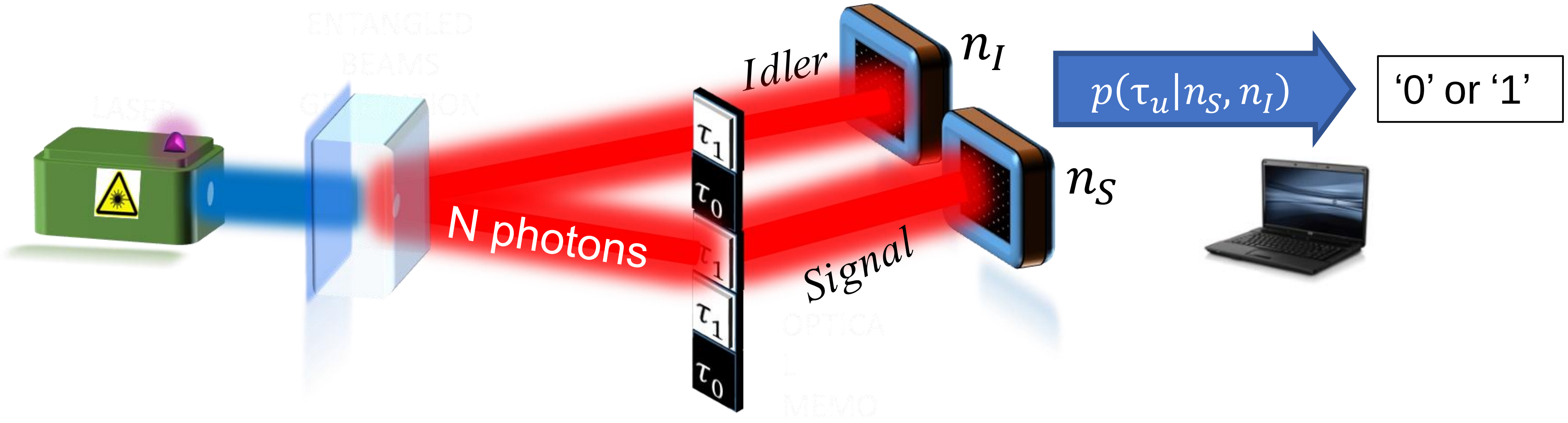
Given $N > N_{th}(\tau_0,\tau_1)$ There is $\overline{M}$

$$p_{err}^{TMSV} < \mathcal{C}(N,\tau_0,\tau_1)$$

S. Pirandola, Phys. Rev. Lett. 106, 090504 (2011)

II- QUANTUM READING

PHOTON COUNTING RECEIVER



Twin Beams + **Local photon counting** + **Maximum Likelihood decision**

$|\mathrm{TMSV}\rangle_{S,I}^{\otimes M}$

n_S, n_I

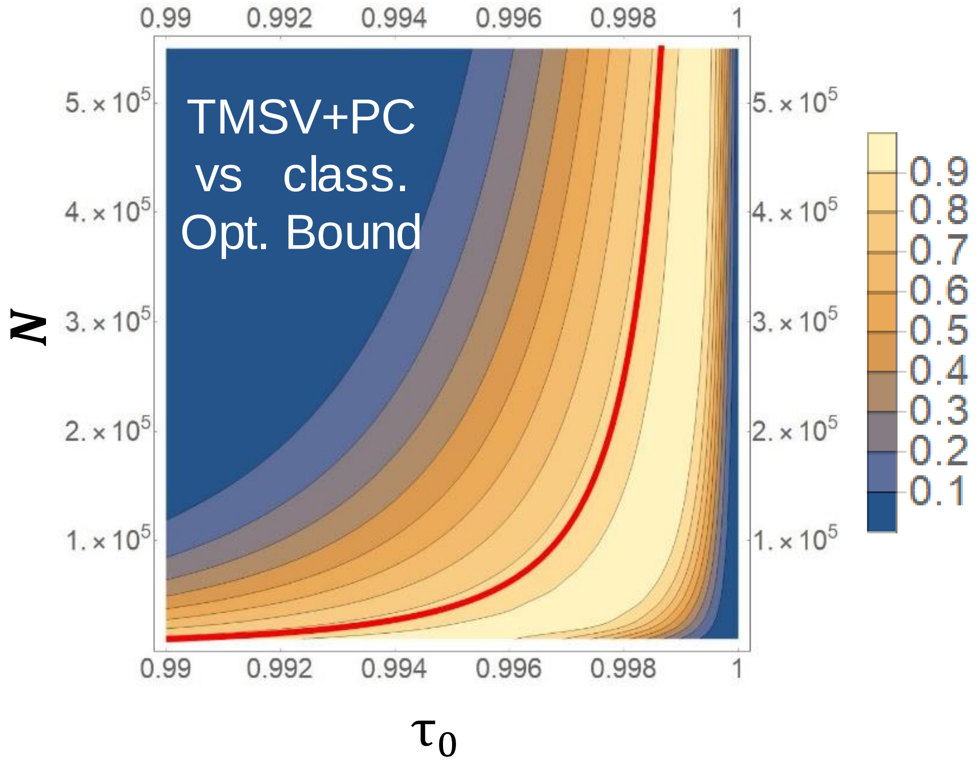
$u = \mathrm{argmax}_u \, p(\tau_u|n_S, n_I)$

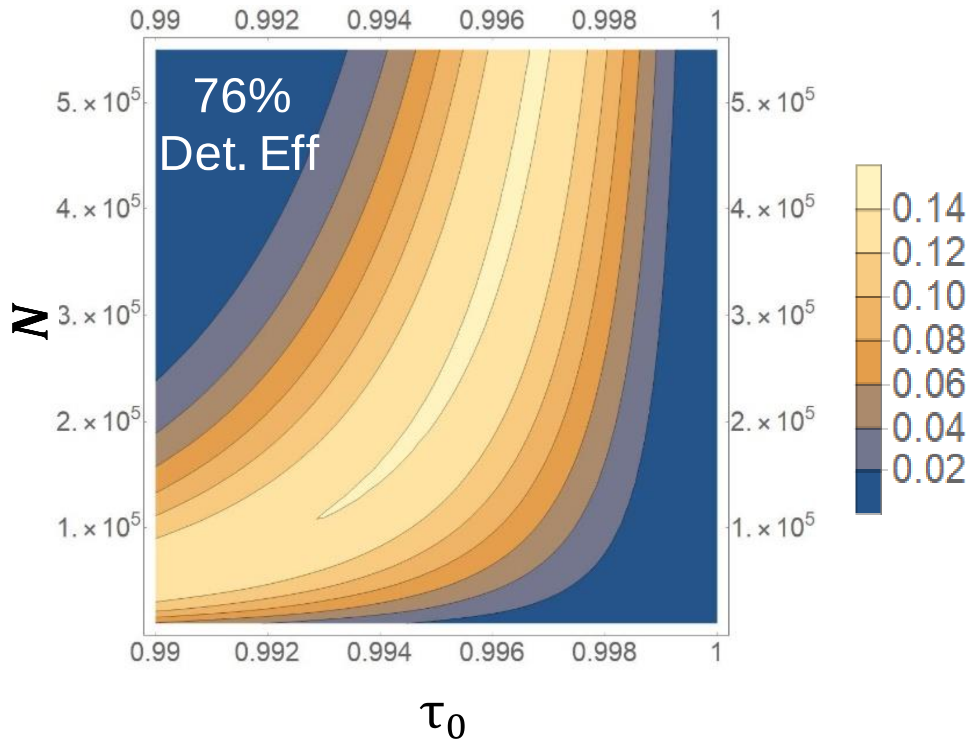
Performance is close to the theoretical bound for the optimal receiver

Sci. Adv.7 (4), eabc7796 (2021)

II- QUANTUM READING

Theoretical Quantum Gain *(bits/cell) in function of transmissivity* $\boldsymbol{\tau_0}$ *mean number of photons* ***N*** *(higher transmissivity is set to* $\tau_1 = 1$*)*





For certain region of the parameter space QR retrieves almost all the information while the best classical strategy completely fails!

Sci. Adv.7 (4), eabc7796 (2021)

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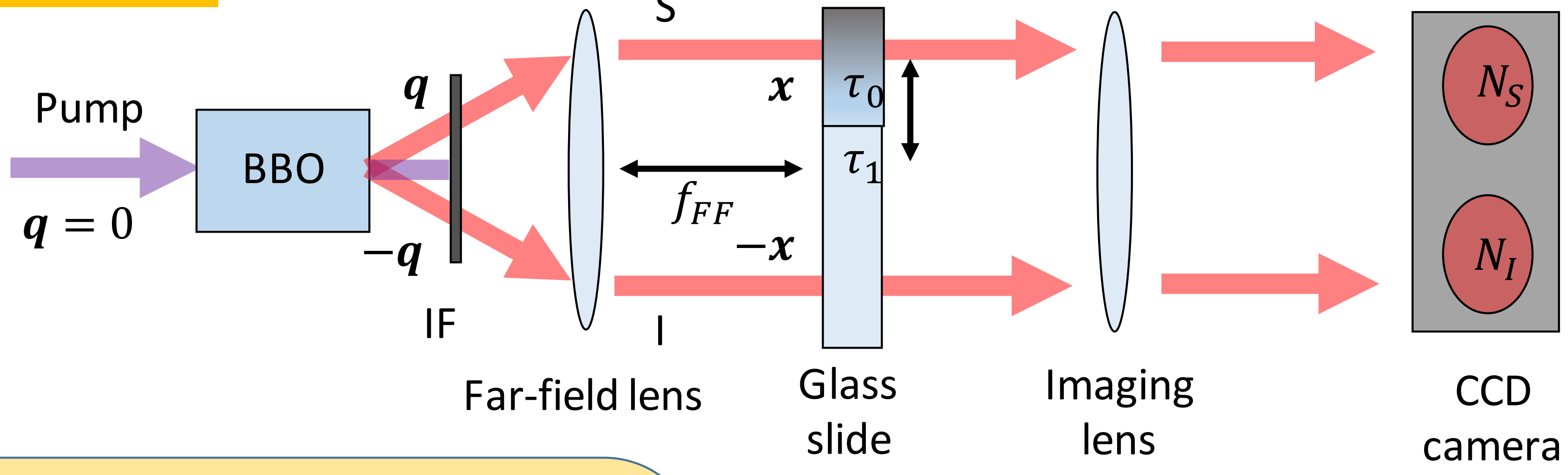
II- QUANTUM READING

Experimental setup



- Single measurement Time: 10 ms
- Spatio-temporal mode: $M \sim 10^{13}$
- Mean number of Photon: $N \sim 10^{5}$
- Transmittance (bit): $\tau_0 \sim 0.995$, $\tau_1 = 1$
- Detection efficiency: $\eta_S, \eta_I = 0.78$

$N/M << 1$
Poissonian marginal distribution (shot noise limited)

Sci. Adv.7 (4), eabc7796 (2021)

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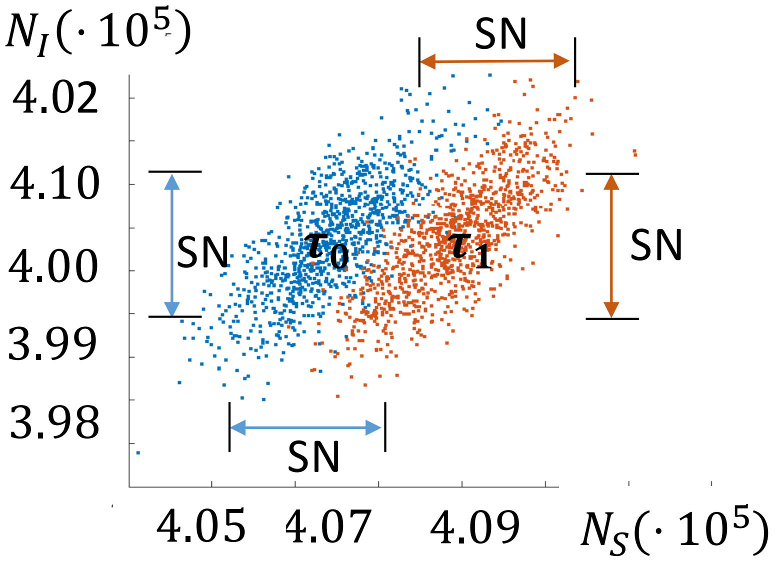
II- QUANTUM READING

QUANTUM JOINT PHOTON NUMBER PROBABILITY DSTRIBUTION OF SIGNAL (S) AND IDLER (I) PHOTONS



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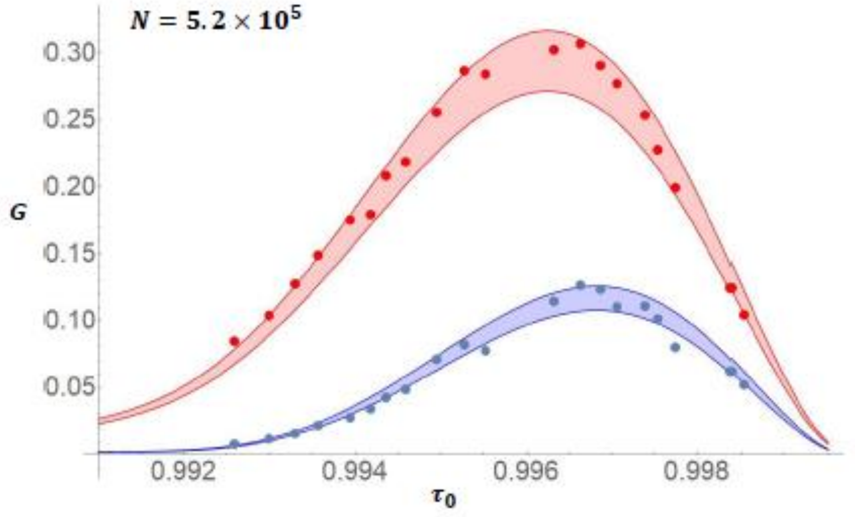
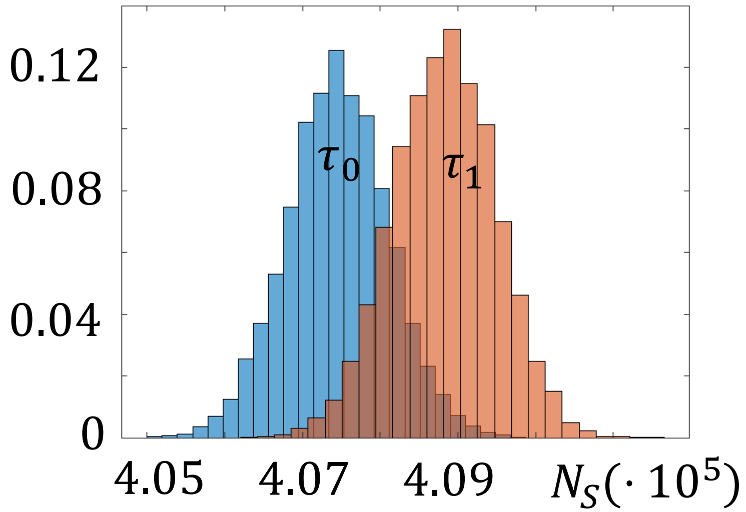
QUANTUM GAIN (BITS)



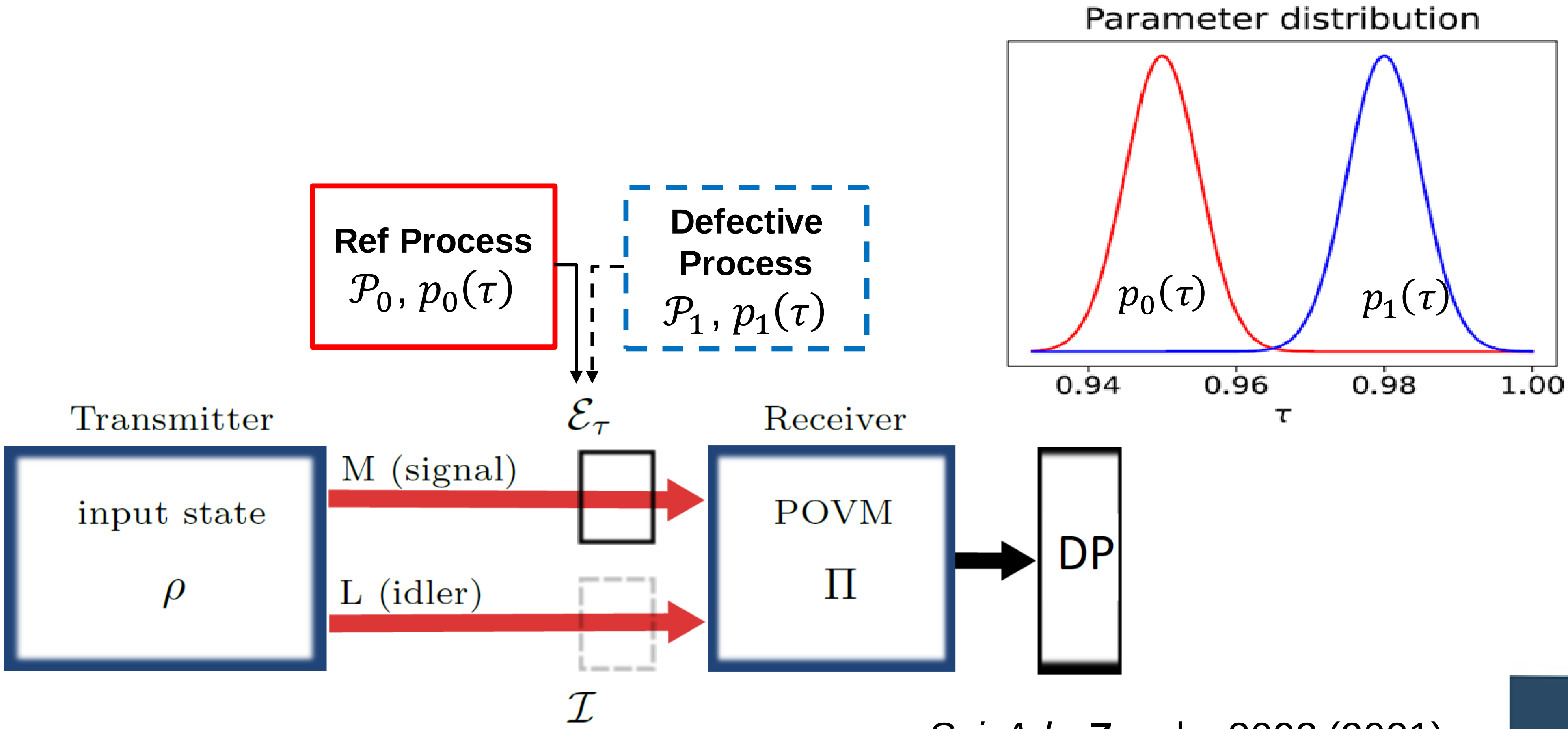
CLASSICAL (SHOT NOISE LIM) PROBABILITIES OF THE SIGNAL (S) PHOTONS ONLY



- **0.15 bit per cell compared to the optimal classical strategy (coherent state +unknown receiver)**
- **0.3 bit per cell compared to a the optimal classical strategy based on photon counting**

III- QUANTUM CONFORMANCE TEST

Given a single quantum channel ε_τ, deciding if it has been produced by a reference (conform) process $\mathcal{P}_0$ with distribution $p_0(\tau)$ or by different (defective) process $\mathcal{P}_1$ with $p_1(\tau)$



Sci. Adv. **7**, eabm3093 (2021)
Sensors , ***22***(6), 2266 ***(2022)***

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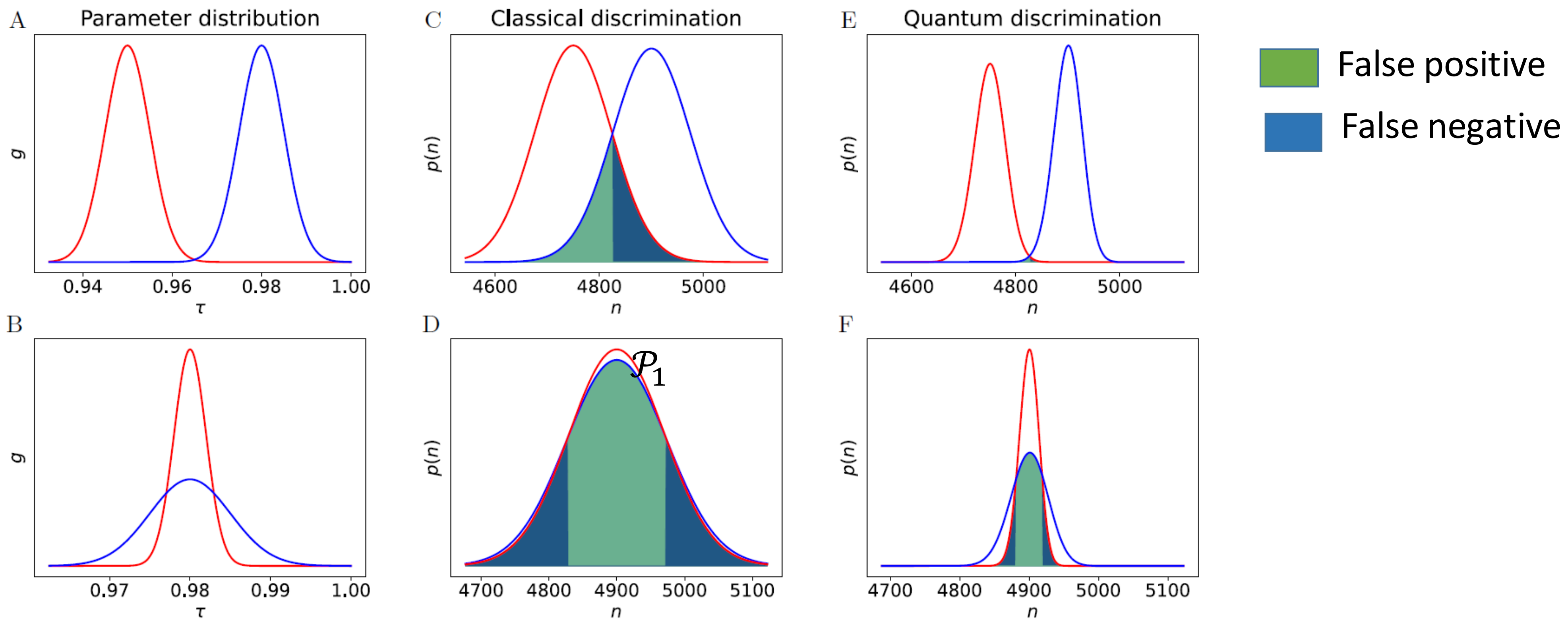
III- QUANTUM CONFORMANCE TEST

An ILLUSTRATION of the ERROR PROBABILITIES for LOSS CHANNELS



- **A** and **B** present archetypal examples of possible distributions for the reference (red) and defective (blue) processes.
- **C** and **D** present the corresponding distributions of photon counting outcomes for classical input states (they are more overlapping because of the quantum shot noise).
- **E** and **F** show the corresponding photon counting distributions with reduced noise due to the entanglement (ideal detection). They are better distinguishable than the classical counterpart

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III- QUANTUM CONFORMANCE TEST

Optimal Classical strategy

general classical transmitter + **unspecified optimal receiver**

$$\rho_{cla} = \int d^{2M}\boldsymbol{\alpha}\, d^{2L}\boldsymbol{\beta}\, P(\boldsymbol{\alpha},\boldsymbol{\beta})|\boldsymbol{\alpha}\rangle\langle\boldsymbol{\alpha}| \otimes |\boldsymbol{\beta}\rangle\langle\boldsymbol{\beta}|$$

$$P(\alpha,\beta) \geq 0$$

$$\mathcal{C} := p_{err}^{cla} \geq \frac{1 - \mathbb{E}_{\mathcal{P}_0}\left[\mathbb{E}_{\mathcal{P}_1}\left[\sqrt{1 - e^{-n_S(\sqrt{\tau_0}-\sqrt{\tau_1})^2}}\right]\right]}{2}$$

Classical lower bound to the error prop.
It is expected to be not tight (because of the derivtion

Proposed quantum strategy

Twin Beams + **Photon counting** + **Maximum Likelihood decision**

$$|\mathrm{TMSV}\rangle_{S,I}^{\otimes M}$$

$$n_S, n_I$$

$$x = \mathrm{argmax}_x\, p(n_S, n_I|\mathcal{P}_x)$$

Sci. Adv. **7**, eabm3093 (2021)

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III- QUANTUM CONFORMANCE TEST

Recognizing a defective process

$\mathcal{P}_0$: $\{\mathrm{p}_0(\tau), \tau\}$

$\mathrm{p}_0(\tau) = \delta(\tau - \tau_0)$

Reference (known)

$\mathcal{P}_1$: $\{\mathrm{p}_1(\tau), \tau\}$

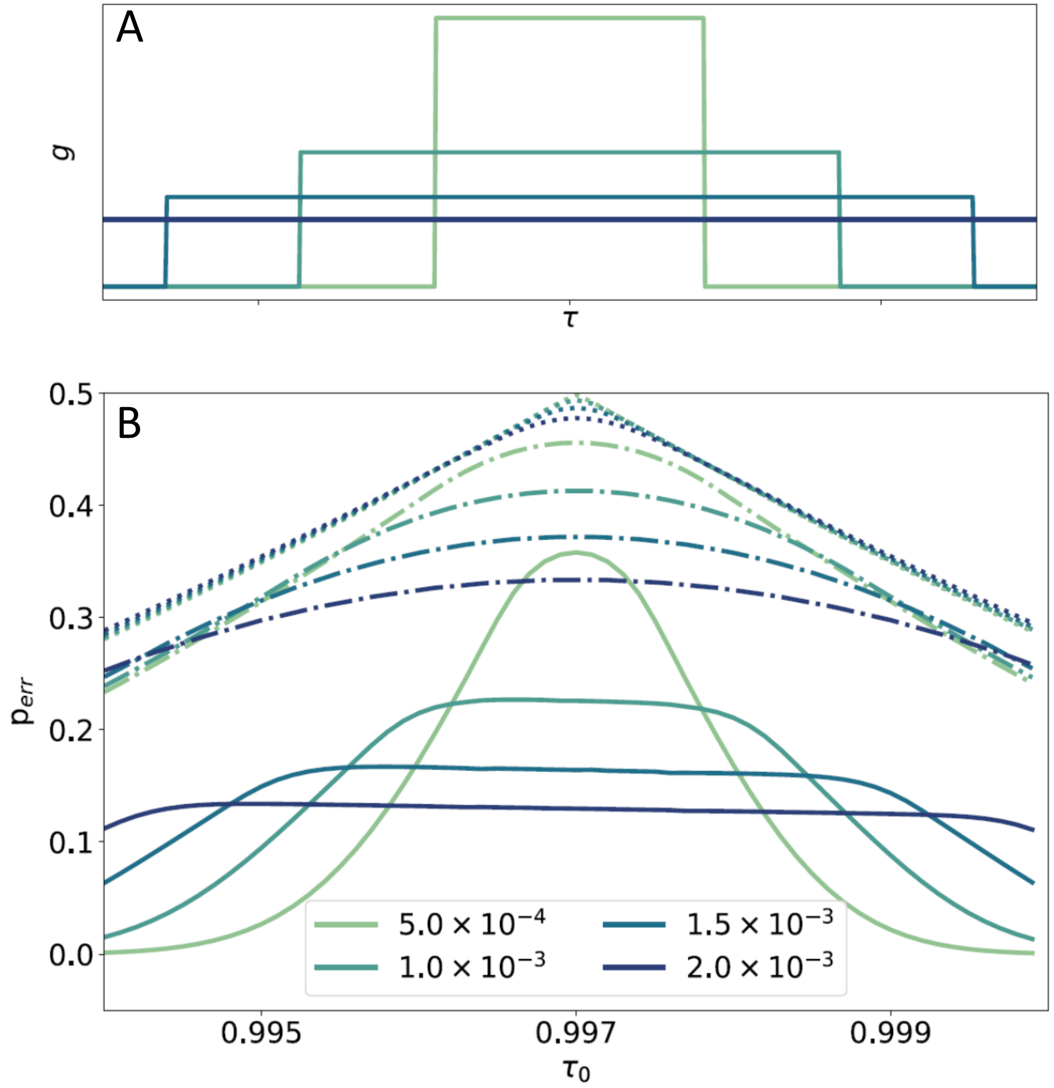
$\mathrm{p}_1(\tau)$ uniform

Defective (unknown)

A: Uniform distribution of the defective process with different variance as reported in the legend

B: Corresponding error probabilities in function of the value of the reference transmittance

———	$\mathcal{Q}$	Quantum (TMSV+PC receiver)
—·—	$\mathcal{C}$	Classical optimal bound
······	$\mathcal{C}^{pc}$	Classical probe + PC receiver



Sci. Adv. **7**, eabm3093 (2021)

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DI RICERCA METROLOGICA

III- QUANTUM CONFORMANCE TEST

Experimental Results

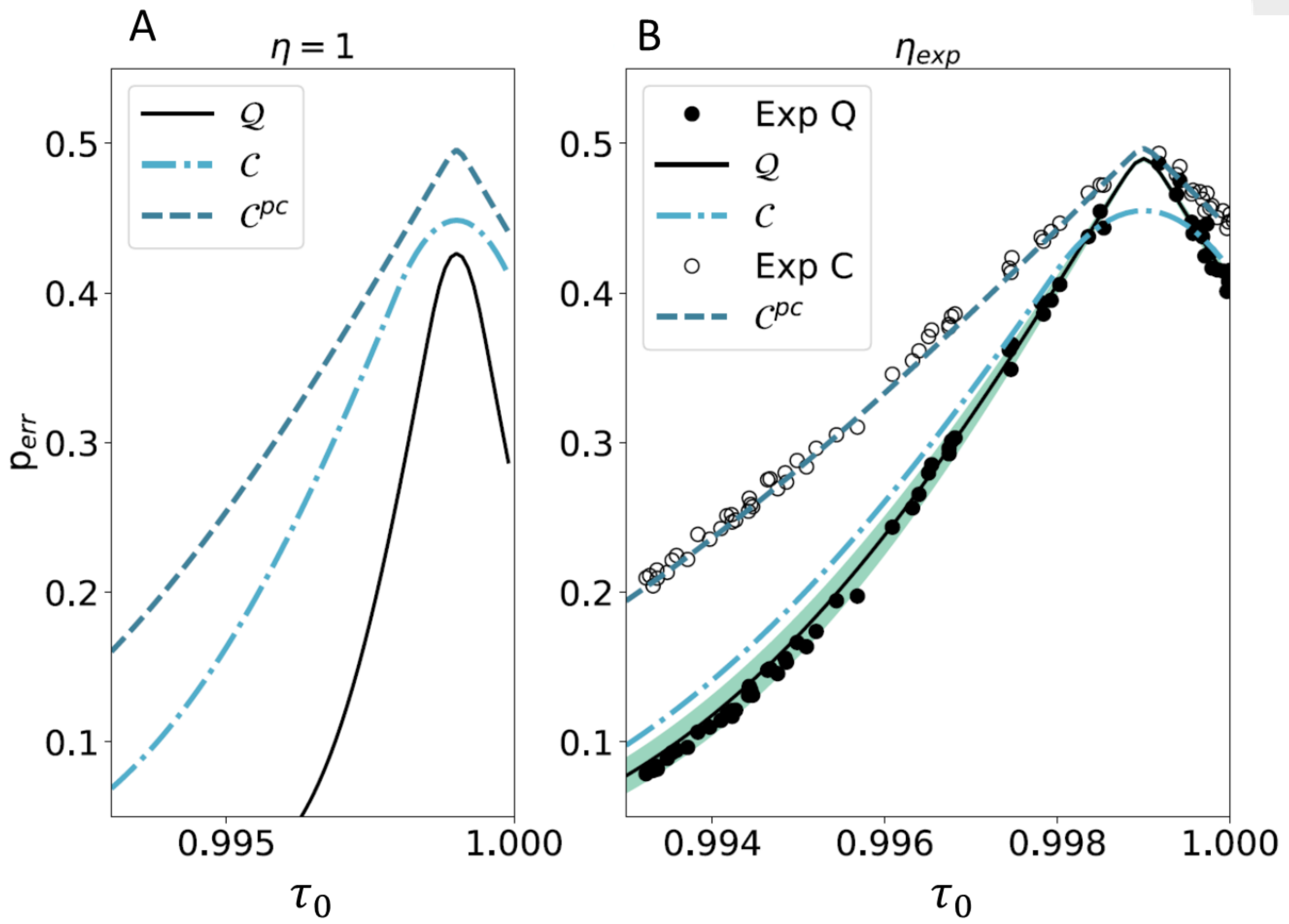
A: Ideal detection

B: Experimental detection efficiency

$$\eta_{exp} = 0.8$$

Number of photons $n_S = 10\text{^}5$

- **Some advantage is preserved with respect to the classical lower bound (coherent state +unknown receiver) in presence of detection losses of 20%**
- **Significant advantage is always achieved if compared to the optimal classical strategy based on photon counting**



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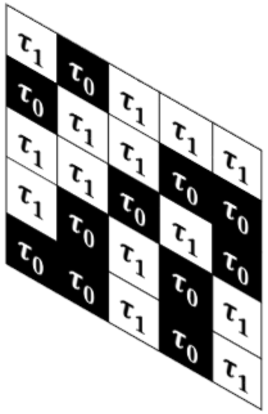
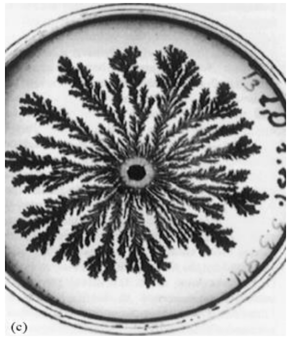
IV- QUANTUM PATTERN RECOGNITION

From quantum reading/single cell task....

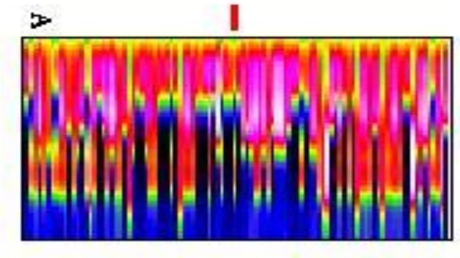


Optical Memory

.... To pattern recognition/multicell



Pattern recognition, e.g. biological structures (Petri Pattern)



Fingerprints of a substance in spectroscopy

How does the error in the single cell readout affect the error in the classification (machine learning) ?

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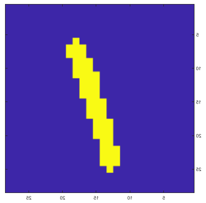
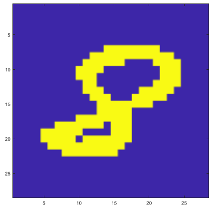
IV- QUANTUM PATTERN RECOGNITION

CLASSIFICATION OF HANDWRITTEN DIGITS

Leonardo Banchi et al. Phys. Rev. Applied **14**, 064026 (2020)





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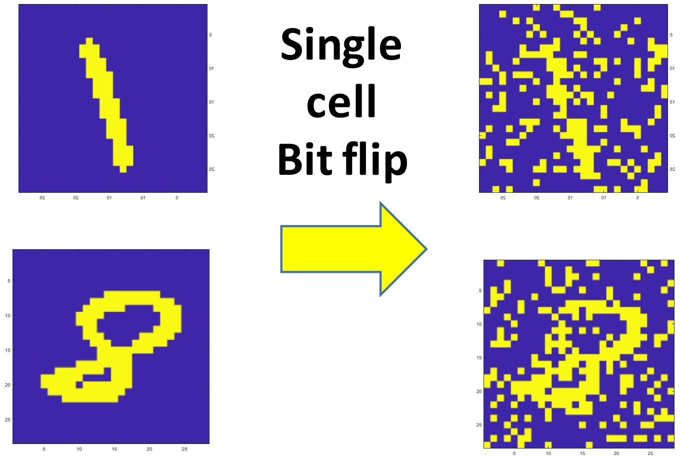

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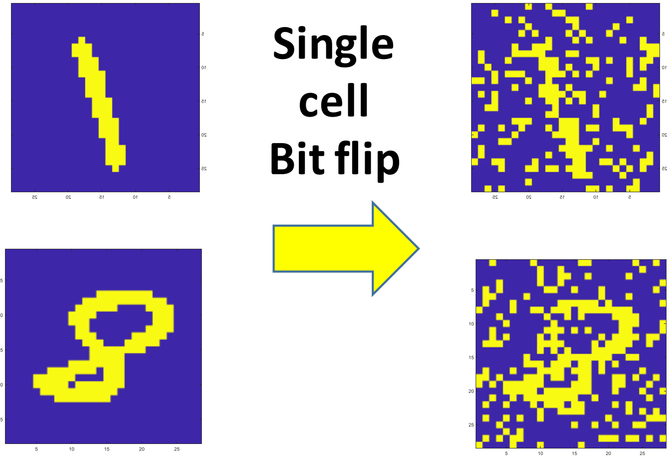
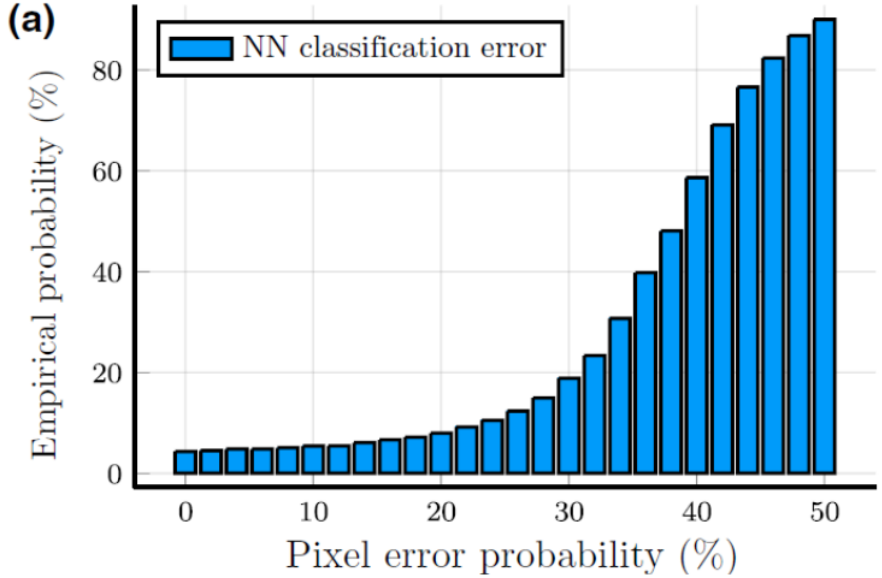


Single cell Bit flip

Nearest-neighbor classifier (Hamming distance)



- Classification performance is non linear with the single cell

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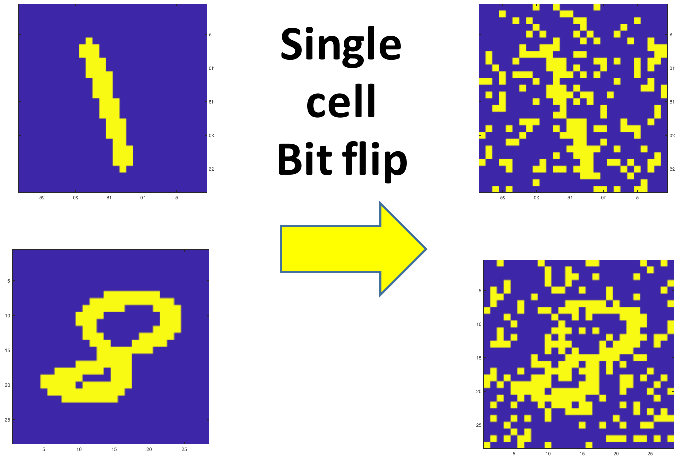

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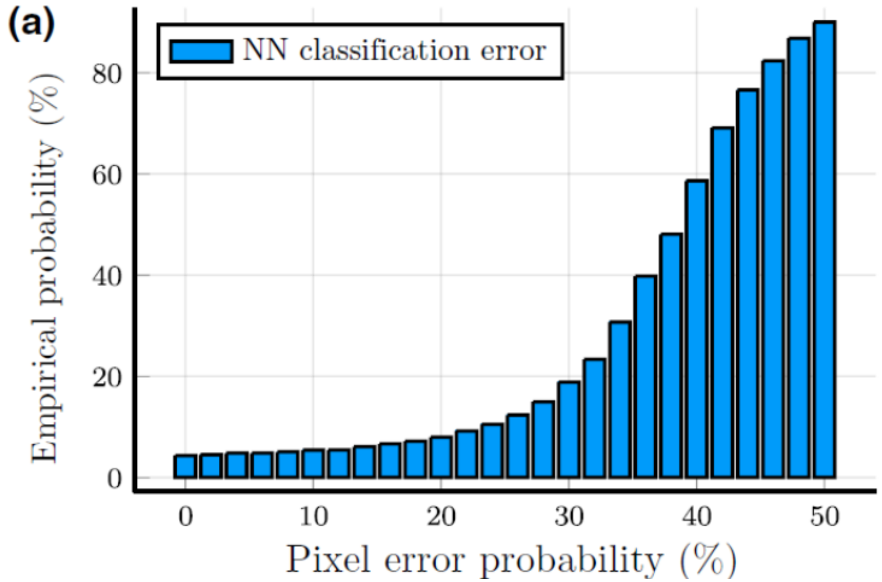
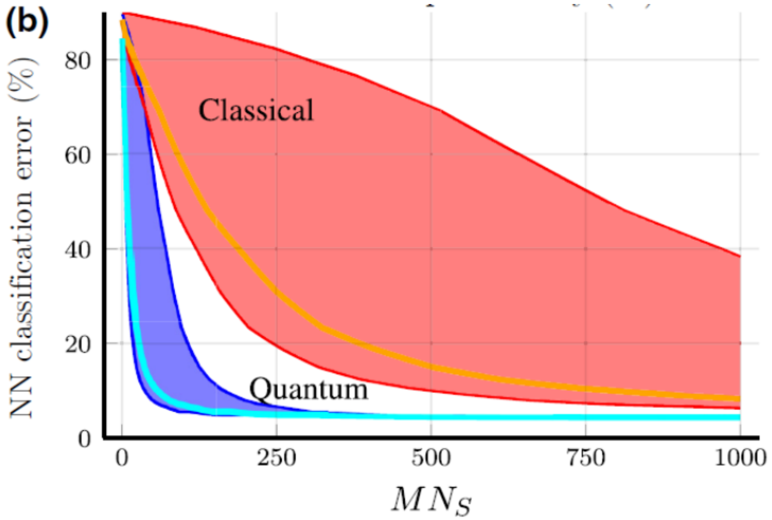


Combining with actual readout prob.



- Classification performance is non linear with the single cell
- Quantum strategy with photon counting (cyan) is close to the lower bound

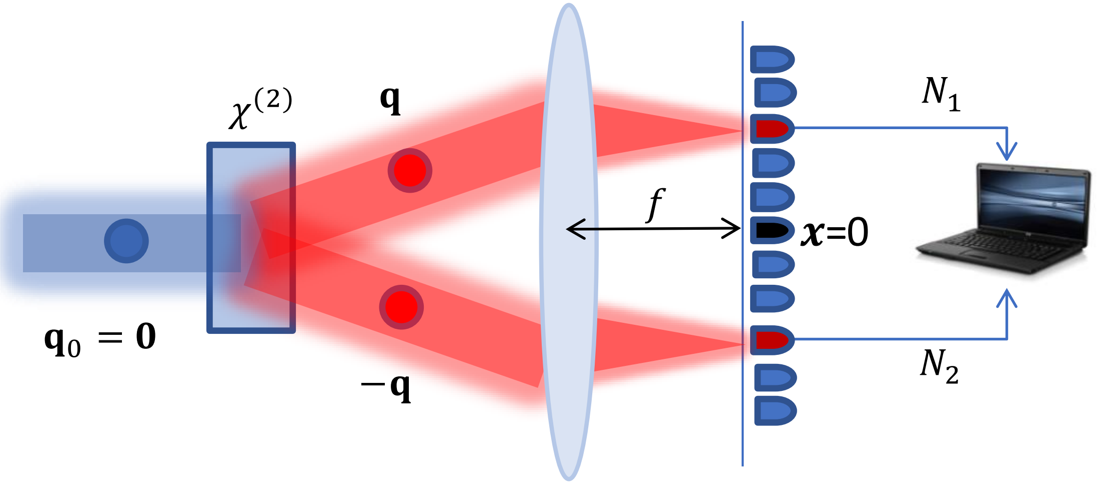
IV- QUANTUM PATTERN RECOGNITION

Spontaneous Parametric Down Conversion (SPDC)

Energy and momentum conservation

$$\omega_s + \omega_i = \omega_p$$

$$\mathbf{q}_s = -\mathbf{q}_i$$



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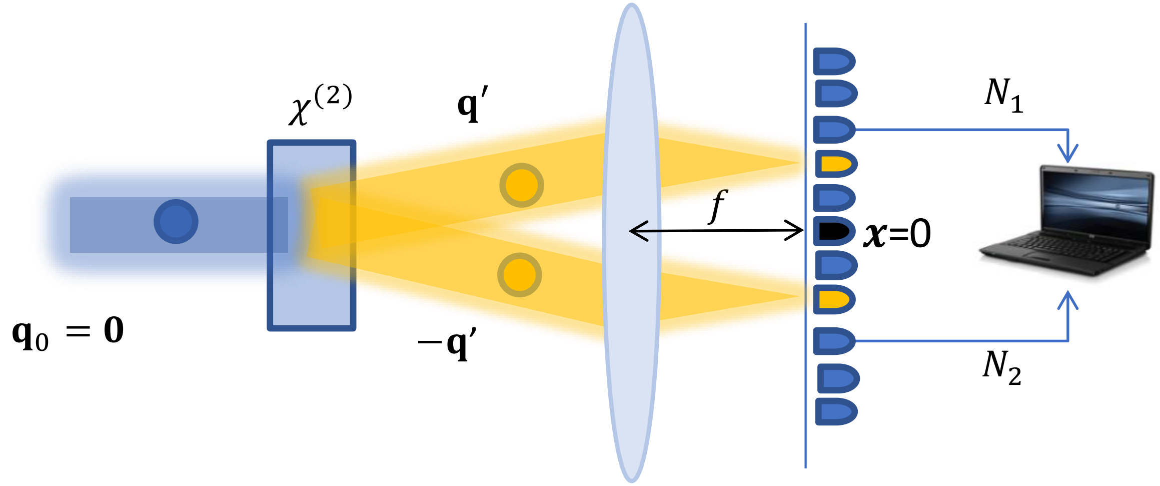
$$\mathbf{q}_s = -\mathbf{q}_i$$



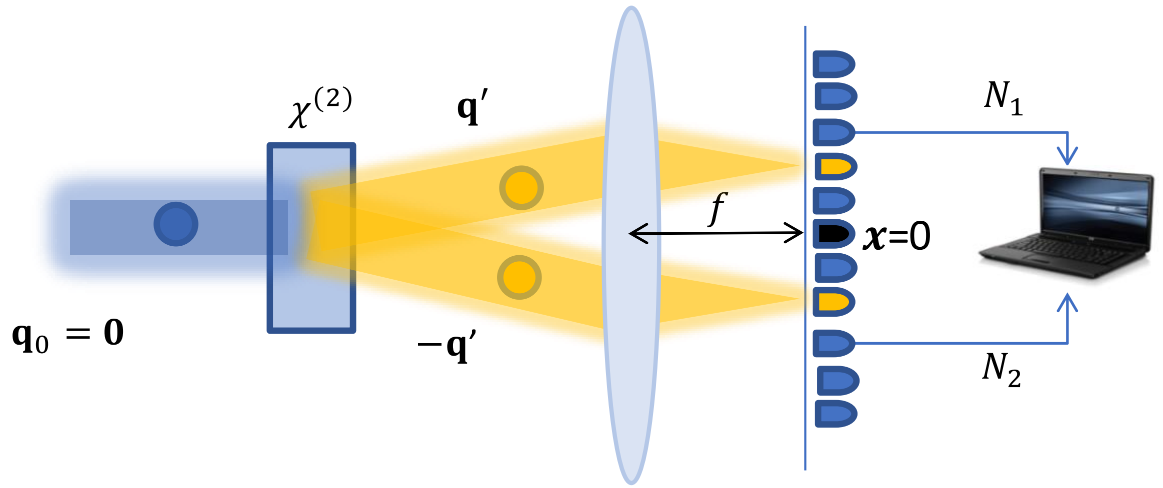
IV- QUANTUM PATTERN RECOGNITION

Spontaneous Parametric Down Conversion (SPDC)

Energy and momentum conservation

$$\omega_s + \omega_i = \omega_p$$

$$\mathbf{q}_s = -\mathbf{q}_i$$



losses

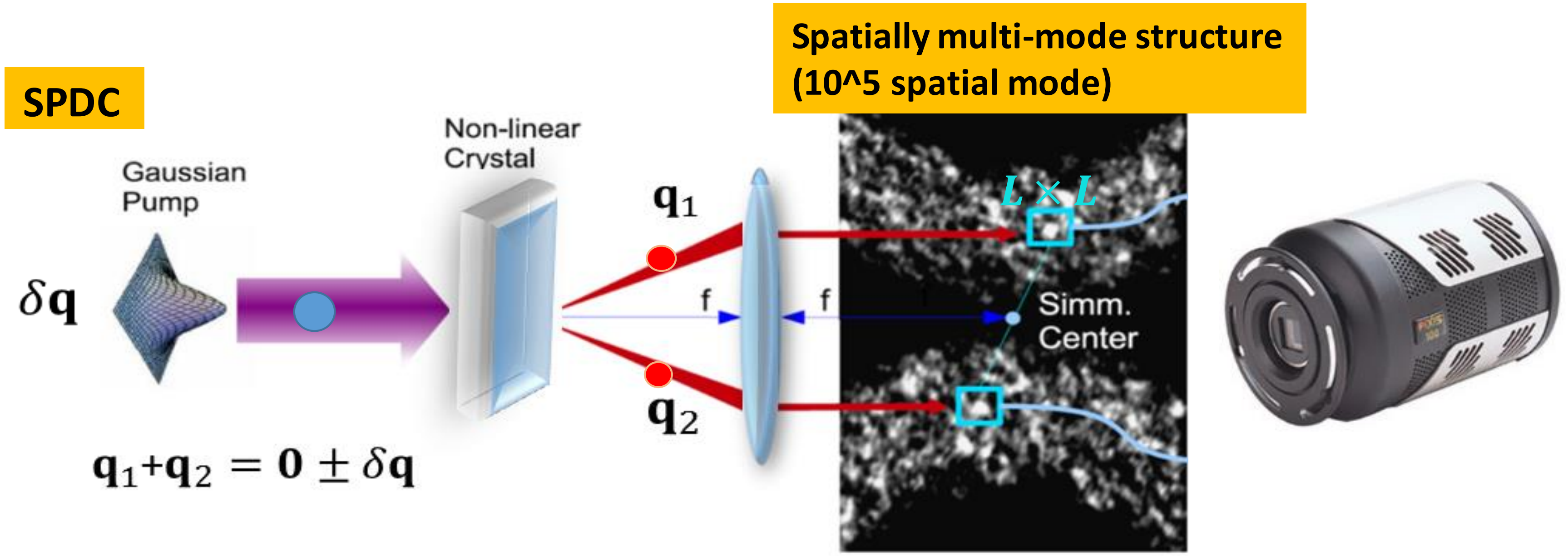
Strong **temporal** and **spatial** **photon number correlation**

$$NRF = \frac{Var(N_1 - N_2)}{\langle N_1 + N_2 \rangle} = (1-\eta) < 1$$

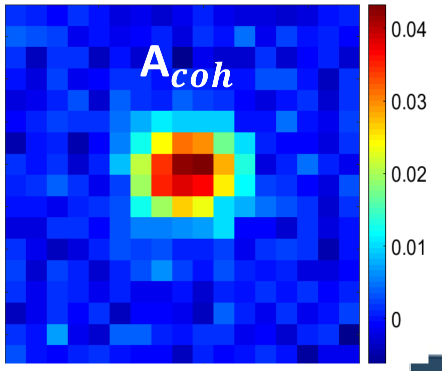
NON-CLASSICAL

High detection efficiency η needed

IV- QUANTUM PATTERN RECOGNITION



- Transverse size of the system (pump size) determines an uncertainty in the propagation direction of correlated photons which spread according to diffraction in an certain 'coherence' area A_{coh}
- Pixels must be larger than this A_{coh} to collect all the correlated photon pairs (larger the pixel better the correlation degree)



There is a tradeoff between the resolution and the sensitivity

IV- QUANTUM PATTERN RECOGNITION

EXPERIMENT

I. 10 spatial patterns (digit 0-9) are physically realized by deposition of a titanium thin layer on a coated slide

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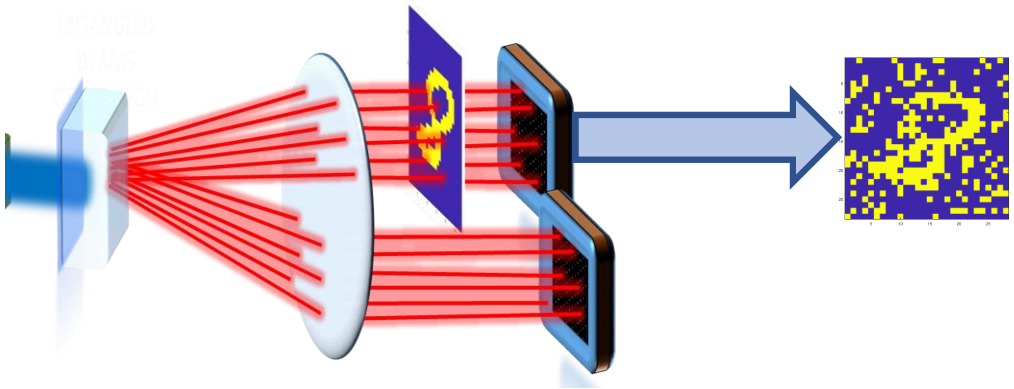
IV- QUANTUM PATTERN RECOGNITION

EXPERIMENT

I. 10 spatial patterns (digit 0-9) are physically realized by deposition of a titanium thin layer on a coated slide

II. The photon count in each pixel is used to assign the value of the bit → the final image is binary (black and white)



CLASSICAL READING

IV- QUANTUM PATTERN RECOGNITION

EXPERIMENT

I. 10 spatial patterns (digit 0-9) are physically realized by deposition of a titanium thin layer on a coated slide

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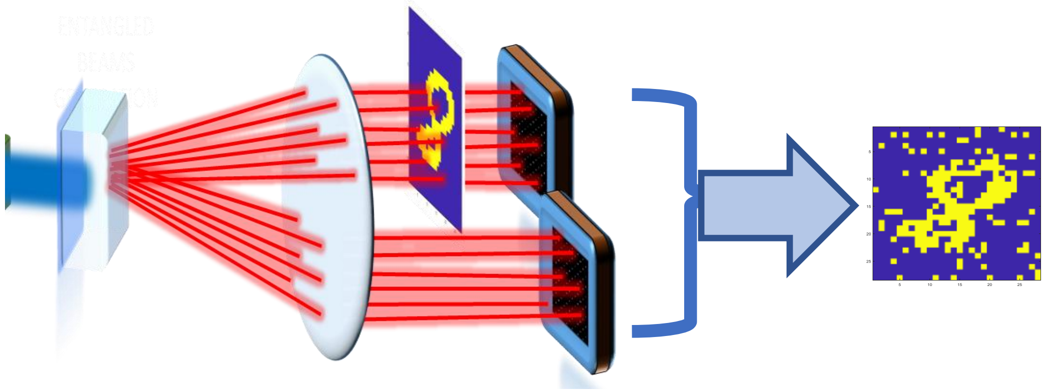


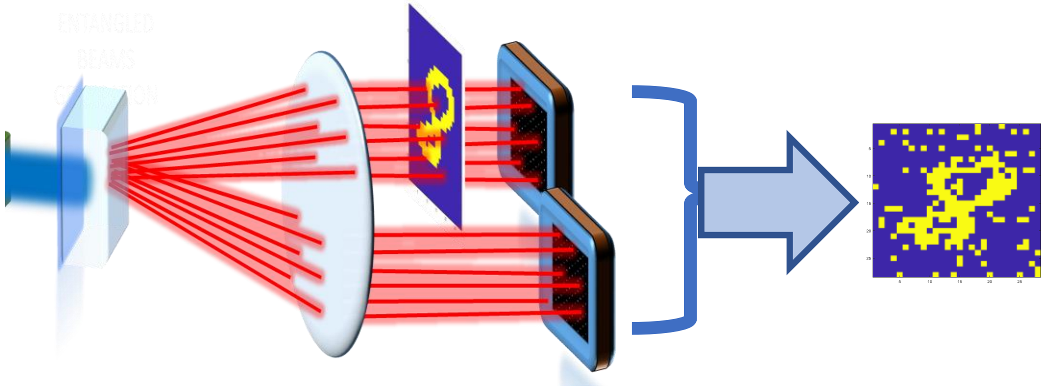
QUANTUM READING

IV- QUANTUM PATTERN RECOGNITION

EXPERIMENT

I. 10 spatial patterns (digit 0-9) are physically realized by deposition of a titanium thin layer on a coated slide

II. The photon count in each pixel is used to assign the value of the bit → the final image is binary (black and white)



QUANTUM READING

III. Binary image are classified by the **supervised NN learning algorithm** trained on the noiseless training set (60000 images)

Classification Error determined

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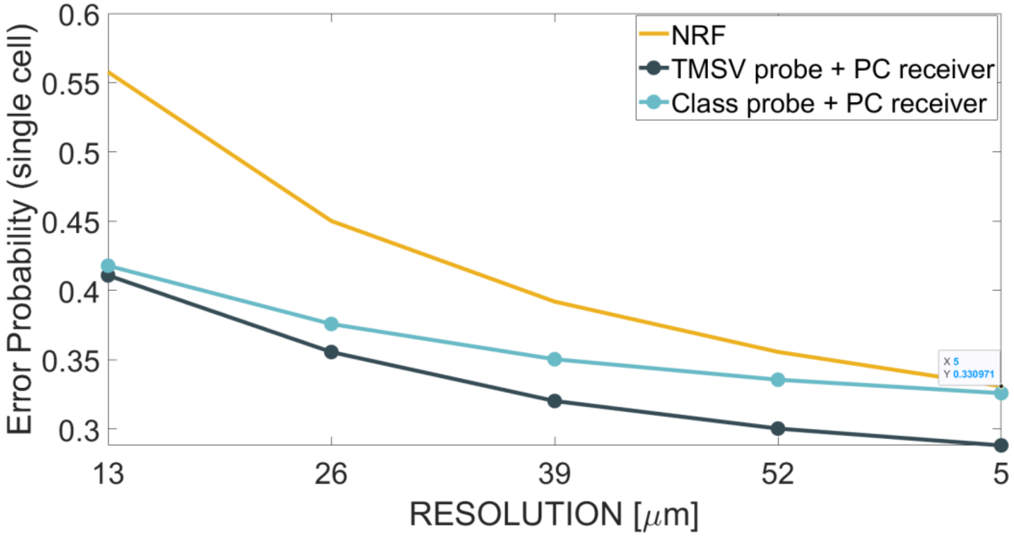
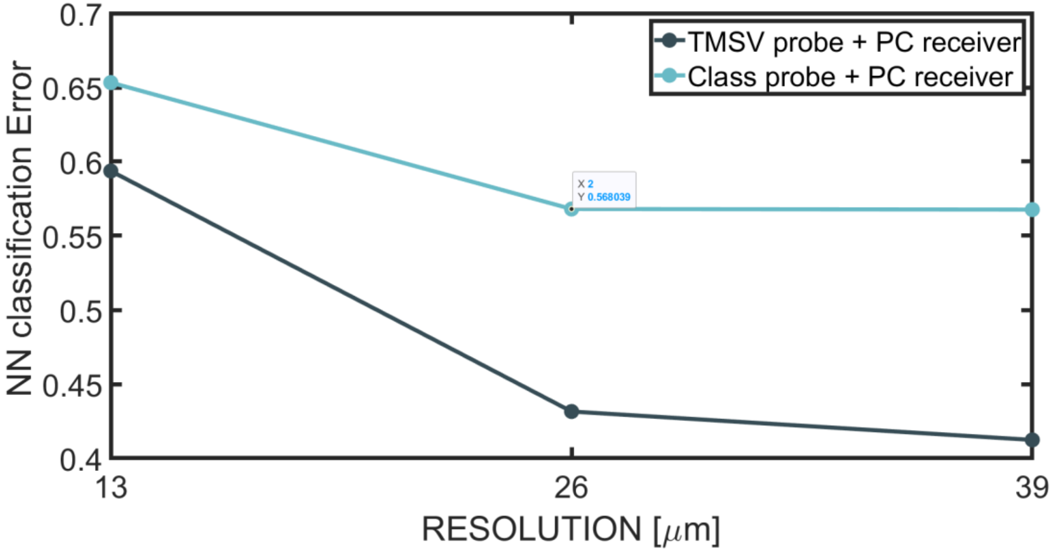
IV- QUANTUM PATTERN RECOGNITION

EXPERIMENTAL RESULTS (**PRELIMINARY**)





- Noise Reduction Factor (NRF) is the residual fraction of the shot noise, depending on the resolution in our scheme
- Quantum advantage in the Error probability of the single cell is obtained
- As expected, the quantum advantage amplifies in the classification is amplified

- Some technical problem does not allow to clearly compare the actual results with the theoretical classical lower bound

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CONCLUSIONS

QUANTUM ENHANCED READOUT of CLASSICAL DATA has been demonstrated experimentally

- QUANTUM READING of optical memories
- QUANTUM CONFORMANCE TEST to monitoring the quality of production process
- QUANTUM PATTERN RECOGNITION, quantum sensing combined with machine learning

PERSPECTIVE

- Different quantum transmitter, more elaborated detection
- Different discrimination problem (quantum position finding)

APPLICATIONS

- Spectroscopy (chemical finger prints)
- Biological pattern recognition (bacteria growth structure in Petri disk…)
- Target detection and ranging

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Thank you!