SCIENCE ADVANCES | RESEARCH ARTICLE

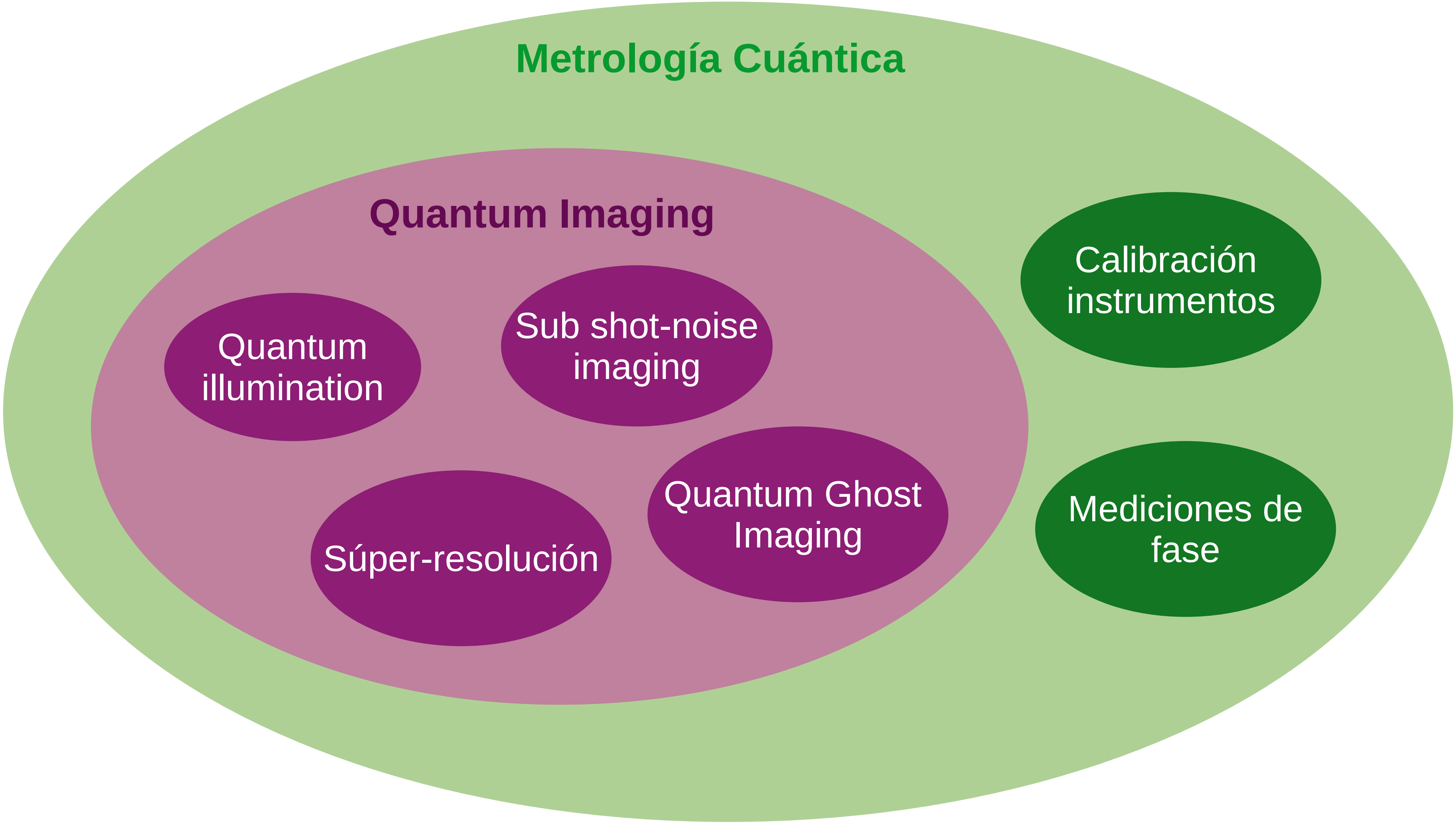
OPTICS

Imaging through noise with quantum illumination

T. Gregory, P.-A. Moreau, E. Toninelli, M. J. Padgett*

The contrast of an image can be degraded by the presence of background light and sensor noise. To overcome this degradation, quantum illumination protocols have been theorized that exploit the spatial correlations between photon pairs. Here, we demonstrate the first full-field imaging system using quantum illumination by an enhanced detection protocol. With our current technology, we achieve a rejection of background and stray light of up to 5.8 and also report an image contrast improvement up to a factor of 11, which is resilient to both environmental noise and transmission losses. The quantum illumination protocol differs from usual quantum schemes in that the advantage is maintained even in the presence of noise and loss. Our approach may enable laboratory-based quantum imaging to be applied to real-world applications where the suppression of background light and noise is important, such as imaging under low photon flux and quantum LIDAR.

School of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, UK.
*Corresponding author. Email: miles.padgett@glasgow.ac.uk

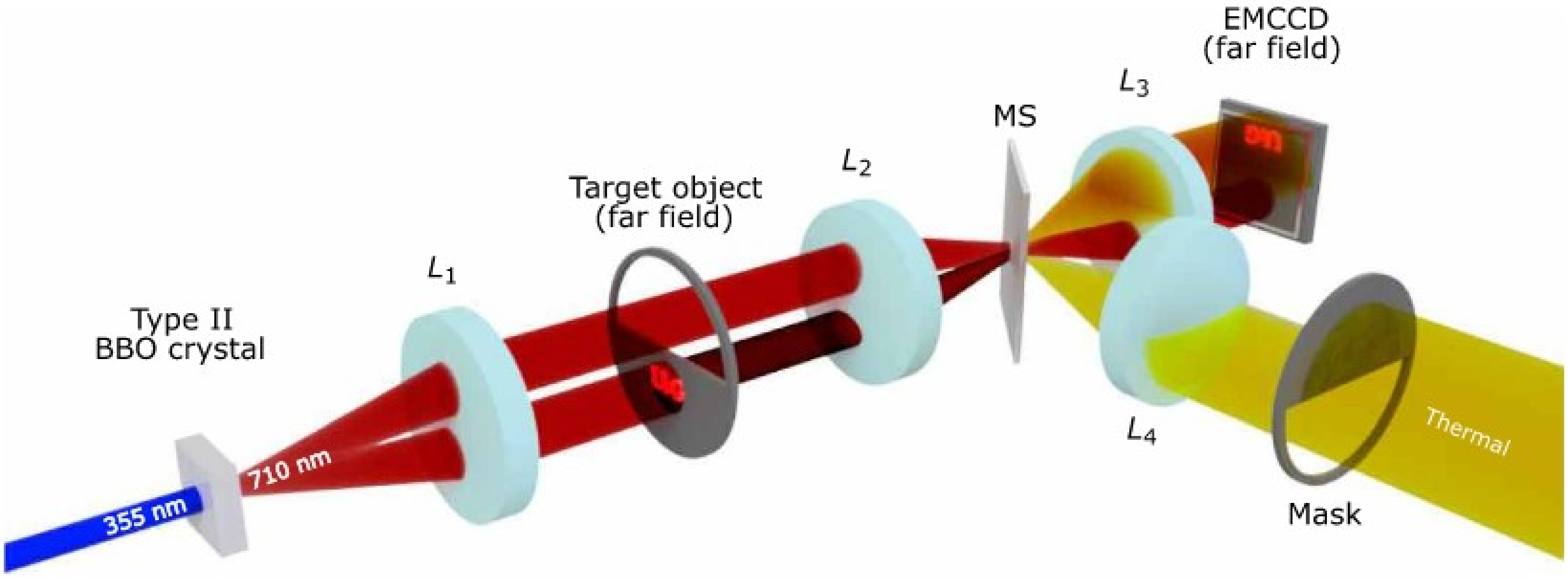

Metrología Cuántica
Quantum Imaging
Quantum illumination
Sub shot-noise imaging
Súper-resolución
Quantum Ghost Imaging
Calibración instrumentos
Mediciones de fase

Objetivo del trabajo

Obtener una imagen de un objeto lejano o inmerso en ruido, utilizando fuentes de luz cuánticas para obtener un mejor contraste con respecto a una fuente de luz clásica.

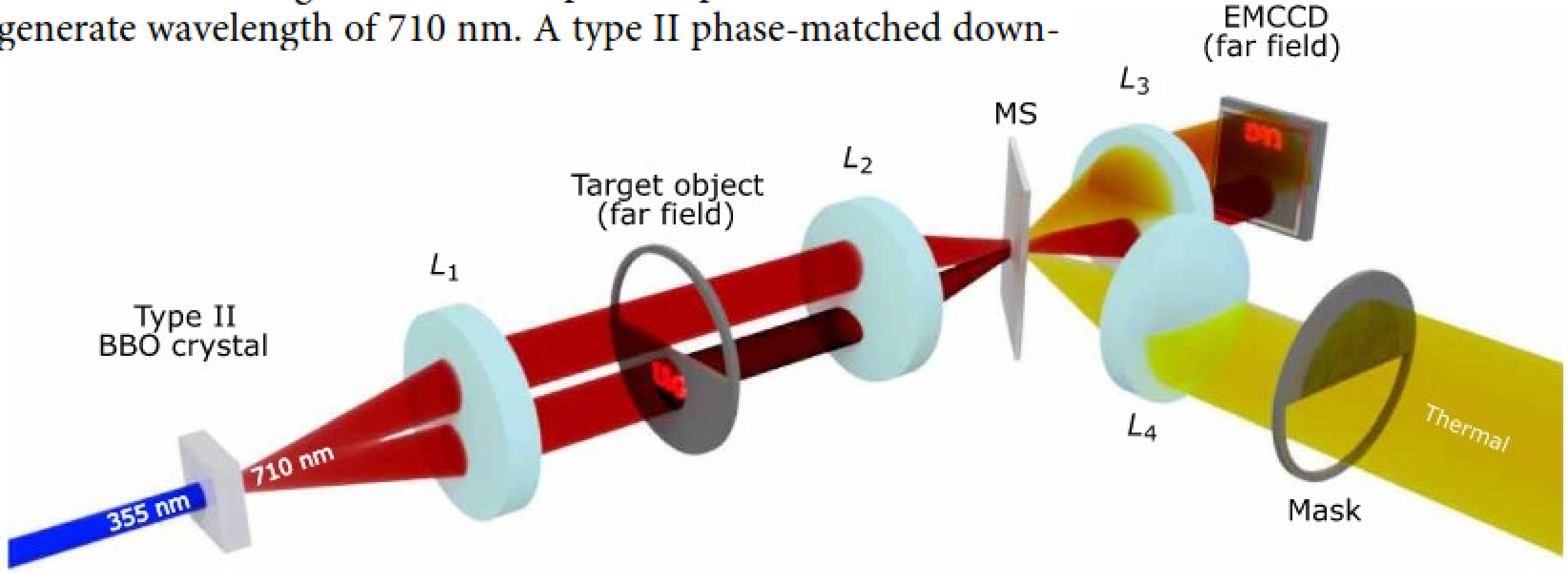
subtraction. Through resilience to environmental noise and losses, such a quantum illumination protocol should find applications in real-world implementations including quantum microscopy for low–light level imaging, quantum LIDAR imaging applications, and quantum radar. Improvements in detector technologies such as SPAD

Arreglo experimental



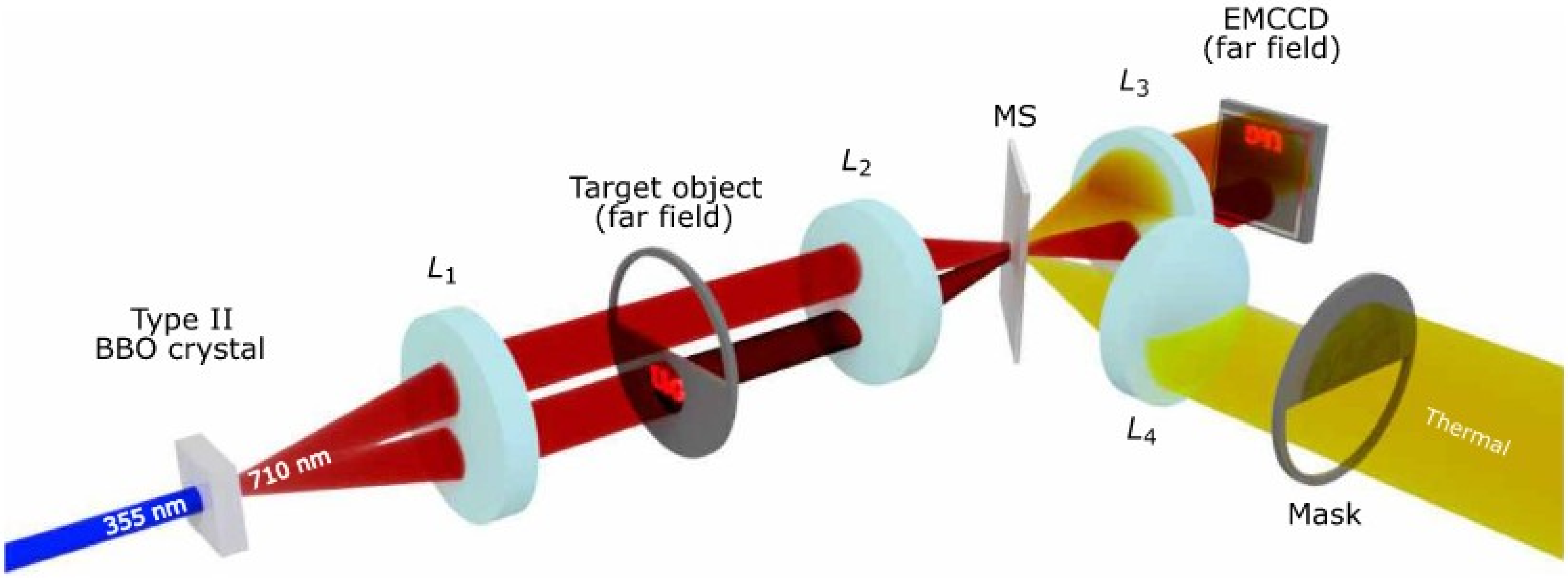
Arreglo experimental

" The experimental configuration is shown in Fig. 1. A 3-mm-thick β-barium borate (BBO) nonlinear crystal cut for type II degenerate downconversion is pumped by a collimated ~8-mm-diameter laser beam at 355 nm to generate SPDC photon pairs centered on the degenerate wavelength of 710 nm. A type II phase-matched down- "



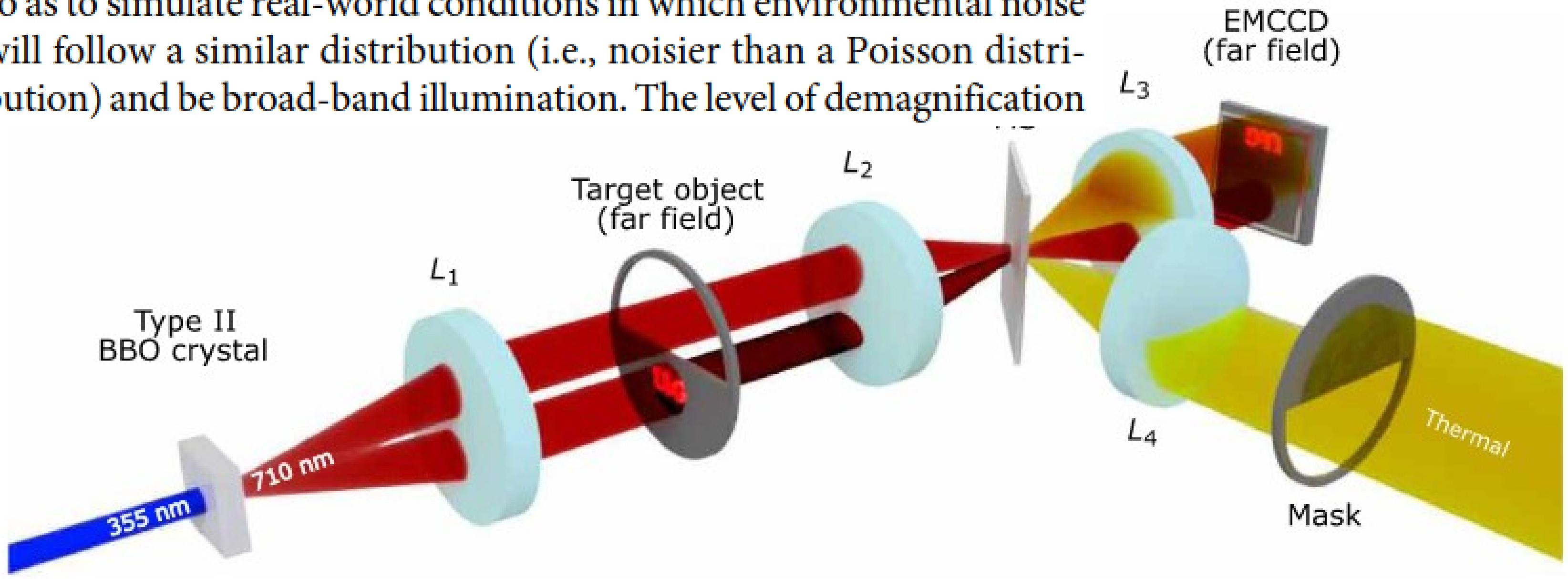
Arreglo experimental

" The probe beam illuminates the object and may be subject to environmental losses and noise, while the reference beam neither interacts with the object nor is it subject to environmental losses and noise. "



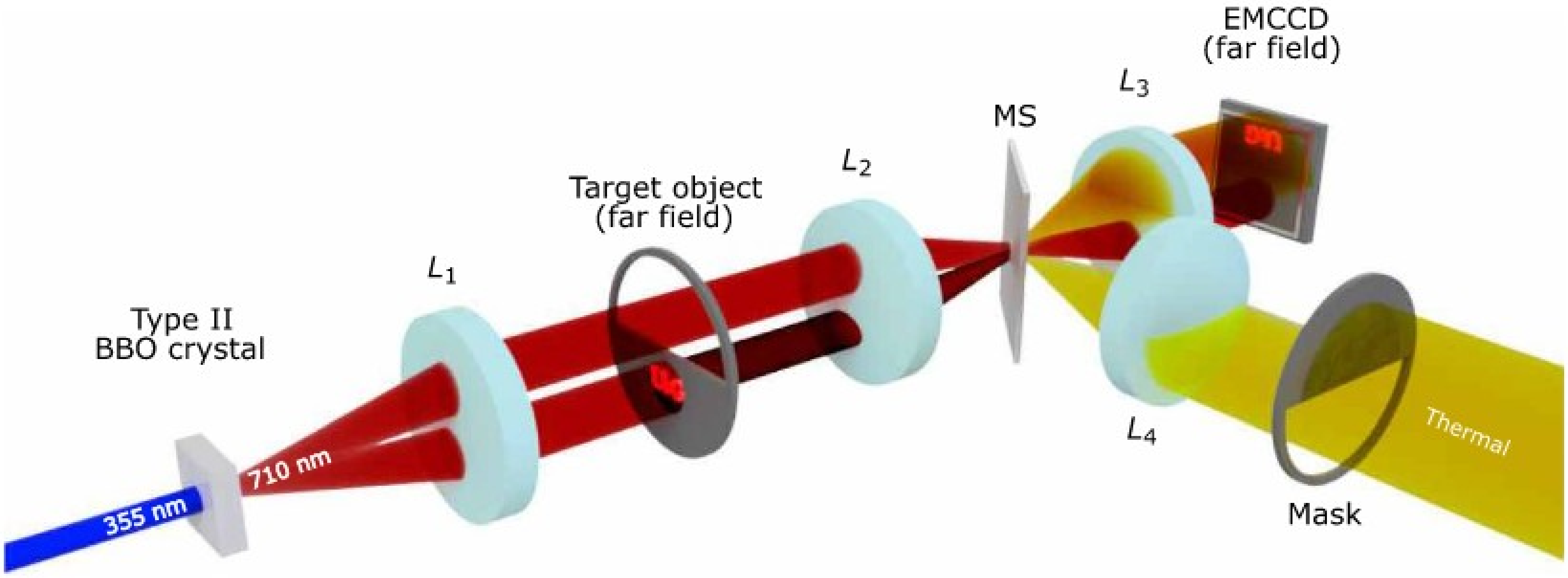
Arreglo experimental

“ chip. A background light field is deliberately introduced using a thermal light source to illuminate a mask, which overlays the probe beam through a reflection from a microscope slide slip cover (MS) placed in the image plane of the crystal. A thermal light source is used so as to simulate real-world conditions in which environmental noise will follow a similar distribution (i.e., noisier than a Poisson distribution) and be broad-band illumination. The level of demagnification ”

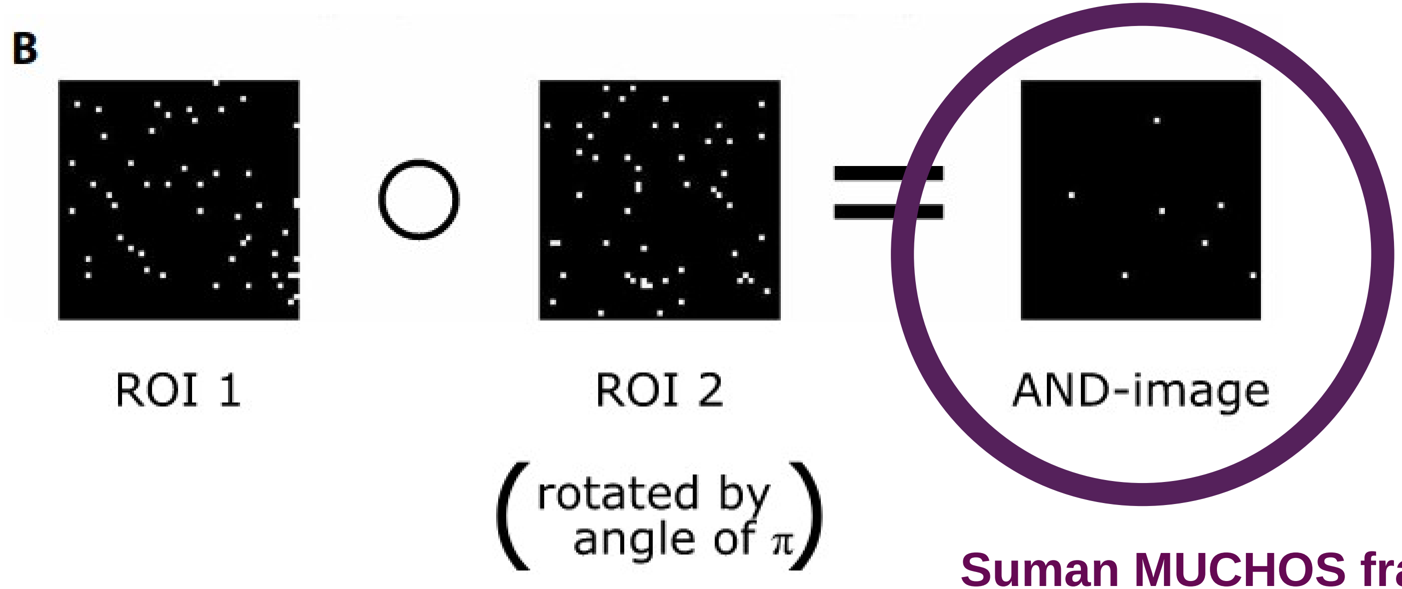


Arreglo experimental

“ ~0.0016 events per pixel per frame ”



Análisis de las imágenes



Suman MUCHOS frames de estos

Rechazo de fondo estructurado

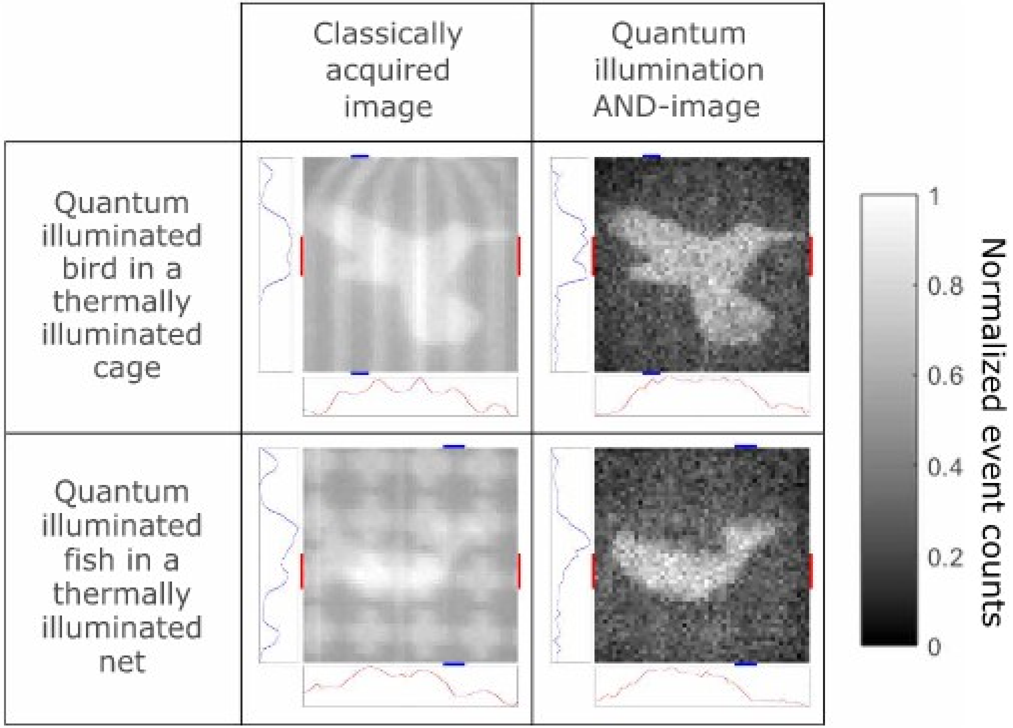
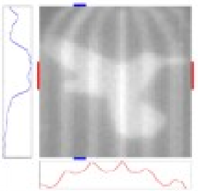
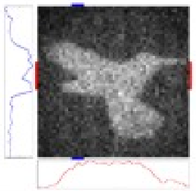
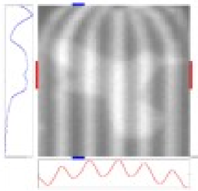
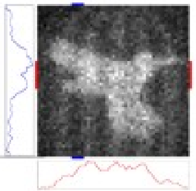
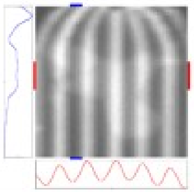
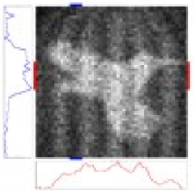
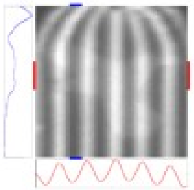
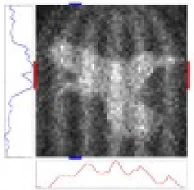
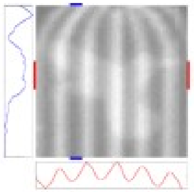
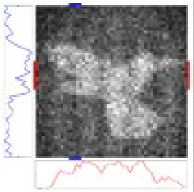


Fig. 3. Images of quantum illuminated target object preferentially selected over thermally illuminated mask. Images of an object under quantum illumination overlaid with a thermally illuminated mask (second column). By applying the AND-operation on the data, the quantum illuminated object may be separated from the thermally illuminated mask (third column). In doing so, the bird may be released from its cage, and the fish may be released from its net. Red lines indicate the rows of the image used to generate the cut graph as shown below the images, while blue lines indicate the columns used to generate the cut graph to the left of the images. Rows and columns used to generate the cut graphs as denoted by the red lines and blue lines, respectively, are rows 19 to 27 and columns 12 to 15 for the bird in a cage and rows 25 to 32 and columns 33 to 37 for the fish in a net. The scale of the cut graphs is normalized intensity (arbitrary units). Images are constructed over 2.5 million frames and are 49 × 49 pixels.

Thermal to SPDC illumination ratio	Classically acquired image	Quantum illumination AND-image	Distinguish-ability ratio D_Q/D_C
0.5			1.35
1.5			2.39
2.5			3.50
3.5			3.87
1.5 with additional 50% loss introduced			2.51

Distinguishability:

$$D_{Q/C} = \frac{\langle O \rangle}{\langle S \rangle + \sigma_O}$$

levels of thermal illumination. In all cases, the prominence of the bars is reduced in the quantum illumination AND-image compared with the classically acquired image; however, some structure remains visible as a result of false correlations. The rejection of background

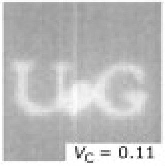
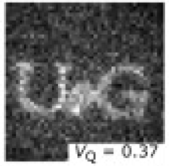
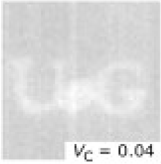
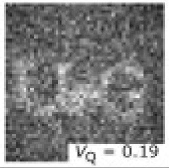
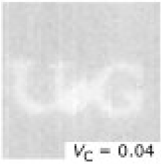
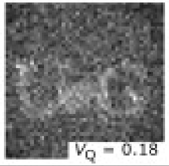
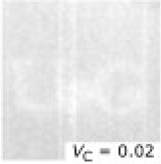
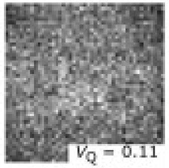
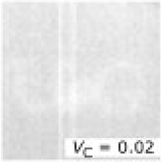
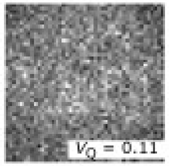
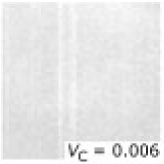
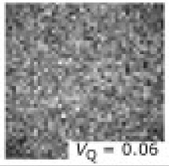
Rechazo de fondo no estructurado

Contraste:

$$V_{Q/C} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

Ventaja:

$$A = \frac{V_Q}{V_C}$$

Transmission at 710 nm (%)	Classically acquired image	Quantum illumination AND-image	Quantum illumination advantage ratio $A = V_Q/V_C$
100	 $V_C = 0.11$	 $V_Q = 0.37$	3.36 ± 0.07
68.4	 $V_C = 0.04$	 $V_Q = 0.19$	4.74 ± 0.17
54.8	 $V_C = 0.04$	 $V_Q = 0.18$	4.57 ± 0.16
41.4	 $V_C = 0.02$	 $V_Q = 0.11$	6.06 ± 0.41
34.2	 $V_C = 0.02$	 $V_Q = 0.11$	6.64 ± 0.43
17.2	 $V_C = 0.006$	 $V_Q = 0.06$	10.95 ± 1.30

Trabajos previos en Quantum Illumination

- Propuesto originalmente por Lloyd en el 2008.
  S.Lloyd, Enhanced sensitivity of photodetection via quantum illumination. Science 321, 1463–1465 (2008).

- Primera demostración experimental por el grupo del INRIM de Marco Genovese en el 2013.
  E.D.Lopaeva, I.R.Berchera, I.P.Degiovanni, S.Olivares, G.Brida, M.Genovese, Experimental realization of quantum illumination. Phys. Rev. Lett. 110, 153603 (2013).
  Solo miden la presencia de un objeto pero no sacan una foto. Fondo térmico.

- Propuesta con microondas (2015).
  S.Barzanjeh, S.Guha, C.Weedbrook, D.Vitali, J.H.Shapiro, S.Pirandola, Microwave quantum illumination. Phys. Rev. Lett.114, 080503 (2015).
  Solo miden la presencia de un objeto pero no sacan una foto. Fondo térmico.

Recientemente

- Microwave quantum illumination using a digital receiver (2020)
  Barzanjeh et al., Sci. Adv. 2020; 6 : eabb0451
  Presencia del objeto. Objeto a 1 m de distancia. Mediciones de fase.

- Quantum enhanced noise radar (2019)
  Appl. Phys. Lett. 114, 112601 (2019);
  Propuesta de protocolo con two-mode squeezed states, en variable continua. Microondas. Presencia de objeto.

- Quantum-enhanced standoff detection using correlated photon pairs (2019).
  D. G. England, B. Balaji, B. J. Sussman, Quantum-enhanced standoff detection using correlated photon pairs. Phys. Rev. A 99, 023828 (2019).
  Longitudes de onda del infrarrojo. Four-wave mixing. Resolución temporal pero con método raster-scanning.

Resúmenes de la semana

Spontaneous Parametric Down-Conversion from Resonant Metasurfaces

Tomás Santiago-Cruz,[*,†,‡,¶,#] Anna Fedotova,[§,#] Vitaliy Sultanov,[†,‡] Maximilian A. Weissflog,[§,¶] Dennis Arslan,[§] Mohammadreza Younesi,[§] Thomas Pertsch,[§,¶,∥] Isabelle Staude,[§,⊥] Frank Setzpfandt,[§] and Maria V. Chekhova[†,‡,¶]

†*Max Planck Institute for the Science of Light, Staudtstraße 2, 91058 Erlangen, Germany.*

‡*University of Erlangen-Nürnberg, Staudtstraße 7/B2, 91058 Erlangen, Germany.*

¶*Max Planck School of Photonics, Albert-Einstein-Str. 6, 07745 Jena, Germany.*

§*Institute of Applied Physics, Abbe Center of Photonics, Friedrich Schiller University Jena, 07745 Jena, Germany.*

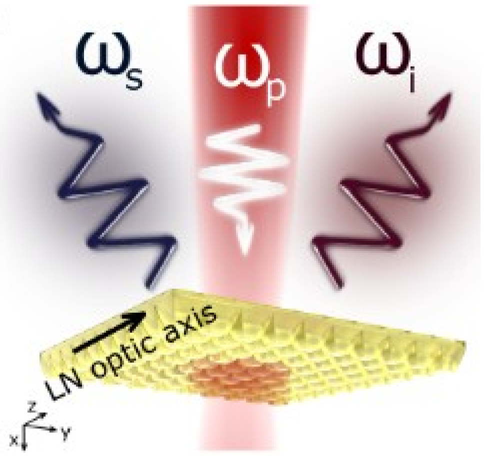
∥*Fraunhofer Institute for Applied Optics and Precision Engineering, 07745 Jena, Germany.*

⊥*Institute of Solid State Physics, Friedrich Schiller University Jena, 07743 Jena, Germany.*

#*These authors contributed equally.*

Here we observe, for the first time, SPDC from resonant QOMs, schematically shown in Fig. 1(a). Due to the resonances, the photon pairs are emitted only into a narrow wavelength range, which opens a possibility to engineer their spectrum. Furthermore, within the emission bandwidth we observe two orders of magnitude enhancement of the pair generation rate compared to an unstructured film of the same thickness as the metasurface, despite the fact that nanostructuring reduces the volume of the nonlinear material and our optics do not collect all photon pairs generated from the QOM. The experiment is run in the reflection geometry, common for nonlinear optics and fluorescence experiments, but quite 'unorthodox' for SPDC.

a)



Experimental Side-Channel-Free Quantum Key Distribution

Chi Zhang,[1,2,3] Xiao-Long Hu,[4] Jiu-Peng Chen,[1,2,3] Yang Liu,[1,2,3] Weijun Zhang,[5] Zong-Wen Yu,[4,6] Hao Li,[5] Lixing You,[5] Zhen Wang,[5] Xiang-Bin Wang,[2,3,4] Qiang Zhang,[1,2] and Jian-Wei Pan[1,2]

Abstract

Quantum key distribution can provide unconditionally secure key exchange for remote users in theory. In practice, however, in most quantum key distribution systems, quantum hackers might steal the secure keys by listening to the side channels in the source, such as the photon frequency spectrum, emission time, propagation direction, spatial angular momentum, and so on. It is hard to prevent such kinds of attacks because side channels may exist in any of the encoding space whether the designers take care of or not. Here we report an experimental realization of a side-channel-free quantum key distribution protocol which is not only measurement-device-independent, but also immune to all side-channel attacks in the source. We achieve a secure key rate of 4.80×10^{-7} per pulse through 50 km fiber spools.

Experimental Side-Channel-Free Quantum Key Distribution

Chi Zhang,[1,2,3] Xiao-Long Hu,[4] Jiu-Peng Chen,[1,2,3] Yang Liu,[1,2,3] Weijun Zhang,[5] Zong-Wen Yu,[4,6] Hao Li,[5] Lixing You,[5] Zhen Wang,[5] Xiang-Bin Wang,[2,3,4] Qiang Zhang,[1,2] and Jian-Wei Pan[1,2]

Here, for the first time, we realize the side-channel-free QKD. Secure key rate of 4.80×10^{-7} per pulse is achieved over 50 km. Precise wavelength control and fast phase compensation have been utilized to accurately control and estimate the phase difference in the single-photon interference of two independent laser sources. High efficiency detection has also been applied to meet the demand of estimating phase drift between two users' fibers and improve the detection rates of signal pulses simultaneously.

Informational steady-states and conditional entropy production in continuously monitored systems

Gabriel T. Landi,[1,*] Mauro Paternostro,[2] and Alessio Belenchia[3,2]

[1]Instituto de Física da Universidade de São Paulo, 05314-970 São Paulo, Brazil.
[2]Centre for Theoretical Atomic, Molecular, and Optical Physics,
School of Mathematics and Physics, Queens University, Belfast BT7 1NN, United Kingdom
[3]Institut für Theoretische Physik, Eberhard-Karls-Universität Tübingen, 72076 Tübingen, Germany

(Dated: March 11, 2021)

Design, fabrication and characterisation of a micro-fabricated double-junction segmented ion trap

Chiara Decaroli, Roland Matt, Robin Oswald, Maryse Ernzer, Jeremy Flannery, Simon Ragg, and Jonathan P. Home

Trapped Ion Quantum Information Group,
Institute for Quantum Electronics,
ETH Zurich, 8093 Zurich,
Switzerland

(Dated: March 11, 2021)

We describe the implementation of a three-dimensional Paul ion trap fabricated from a stack of precision-machined silica glass wafers, which incorporates a pair of junctions for 2-dimensional ion transport. The trap has 142 dedicated electrodes which can be used to define multiple potential wells in which strings of ions can be held. By supplying time-varying potentials, this also allows for transport and re-configuration of ion strings. We describe the design, simulation, fabrication and packaging of the trap, including explorations of different parameter regimes and possible optimizations and design choices. We give results of initial testing of the trap, including measurements of heating rates and junction transport.

Tensor networks and efficient descriptions of classical data

Sirui Lu,[1,2] Márton Kanász-Nagy,[1,2] Ivan Kukuljan,[1,2] and J. Ignacio Cirac[1,2]

[1] *Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching, Germany*
[2] *Munich Center for Quantum Science and Technology (MCQST), Schellingstr. 4, D-80799 München, Germany*
(Dated: March 12, 2021)

We investigate the potential of tensor network based machine learning methods to scale to large image and text data sets. For that, we study how the mutual information between a subregion and its complement scales with the subsystem size L, similarly to how it is done in quantum many-body physics. We find that for text, the mutual information scales as a power law L^ν with a close to volume law exponent, indicating that text cannot be efficiently described by 1D tensor networks. For images, the scaling is close to an area law, hinting at 2D tensor networks such as PEPS could have an adequate expressibility. For the numerical analysis, we introduce a mutual information estimator based on autoregressive networks, and we also use convolutional neural networks in a neural estimator method.