National Aeronautics and Space Administration

2025 NASA SCIENCE

Science Mission Directorate Quantum Day
July 9, 2025

Astrophysics Division

Mario R. Perez (with assistance from Babak Saif & Mark Clampin)
Chief Technologist

Astrophysics Quantum Applied Technologies

1. **Ultra-sensitive Photon Detection** – Detect faint and distant sources with MKIDs, SNSPDs, TESs, and Microcalorimeters
   a) Super-Resolution (DARPA Program -> TRL3)
   b) Absolute Calibration
   c) Exoplanet Detection (w/o Coronagraph)

2. **Quantum-Enhanced Telescopes**
   a) **Quantum Processing Enhanced Optical Imaging** – By coherently encoding photonic amplitude information into qubit registers and applying quantum algorithms prior to detection (Harvard, GSFC, & Quera) [TRL3]
   b) **Utilize entangled photons for very long baseline interferometry** promises improved imaging of astronomical objects and remote sensing, potentially allowing for higher resolution and deeper insights into cosmic structures (U. Maryland, U. Arizona & GSFC). [TRL1]

3. **Precision Gravity Measurements**
   a) **Quantum gravity gradiometers based on atom interferometry** can detect gravitational fields with extreme accuracy. This can offer insights into the nature of stochastic gravitational waves, Dark Matter and Dark Energy. (Standford U., UC Berkeley, Fermi Lab, GSFC). [TRL3]
   b) **Optical quantum clocks to detect gravitational potential**. (NIST, U. Colorado, GSFC). [TRL3]

SCIENCE MISSION DIRECTORATE

518 Vol. 12, No. 4 / April 2025 / Optica **Research Article**

OPTICA

Experimental demonstration of a quantum-optimal coronagraph using spatial mode sorters

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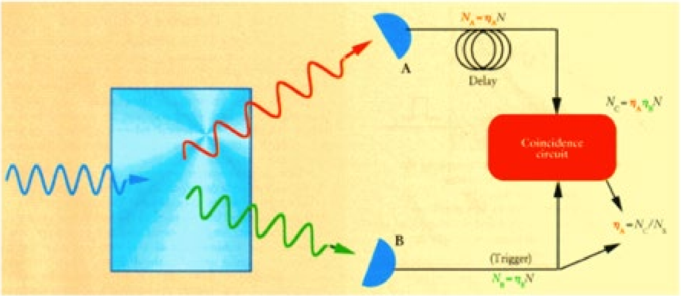
Deep sub-diffraction exoplanet discovery currently lies beyond the reach of state-of-the-art direct imaging coronagraphs, which typically have an inner working angle larger than the diffraction scale. We present an experimental demonstration of a direct imaging coronagraph design capable of achieving the quantum limits of exoplanet detection and localization below the Rayleigh diffraction limit. Our benchtop implementation performs a forward and inverse pass through a free-space programmable spatial mode sorter configured to isolate photons in a point spread function-adapted mode basis. During the forward pass, the fundamental mode is rejected, effectively eliminating light from an on-axis point-like star. On the inverse pass, the remaining modes are coherently recombined to form an image of a faint companion. Our experimental system is shown localizing an artificial exoplanet at sub-diffraction distances from its host star under a 1000:1 star–planet contrast.

https://doi.org/10.1364/OPTICA.545414

Correlated-Photon Metrology for Photo-Detector Absolute Calibrations



Physics Today, January 1999, 41
Twin-photon techniques for photo-detector calibration, G. Brida et al. 2006, Laser Physics Letters, 3, 115
Absolute calibration of a charge-coupled device camera with twin beams, A. Meda, et al. 2014, Appl. Phys. Lett. 105, 10113

PHYSICAL REVIEW LETTERS **129,** 180502 (2022)

Identifying Objects at the Quantum Limit for Superresolution Imaging

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(Received 29 April 2022; revised 4 August 2022; accepted 1 September 2022; published 25 October 2022)

We consider passive imaging tasks involving discrimination between known candidate objects and investigate the best possible accuracy with which the correct object can be identified. We analytically compute quantum-limited error bounds for hypothesis tests on *any* library of incoherent, quasimonochromatic objects when the imaging system is dominated by optical diffraction. We further show that object-independent linear-optical spatial processing of the collected light exactly achieves these ultimate error rates, exhibiting scaling superior to spatially resolved direct imaging as the scene becomes more severely diffraction limited. We apply our results to example imaging scenarios and find conditions under which superresolution object discrimination can be physically realized.

DOI: 10.1103/PhysRevLett.129.180502

Quantum Processing Enhanced Optical Imaging

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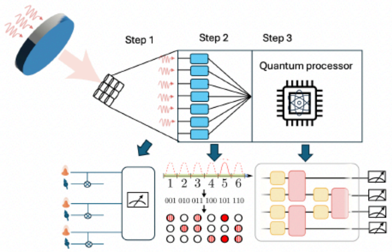
(Dated: July 1, 2025)

Extracting information from weak optical signals is a critical challenge across a broad range of technologies. Classical techniques, constrained to intensity measurements and post-processing, face fundamental limits in signal-to-noise ratio (SNR) from the need of tomographic methods and shot noise accumulation in the post-processing. We show that by coherently encoding photonic amplitude information into qubit registers and applying quantum algorithms prior to detection these limitations can be overcome. As a concrete example, we develop a quantum algorithm for imaging unresolved point sources and apply it to exoplanet detection demonstrating that orders-of-magnitude improvements in performance can be achieved under realistic imaging conditions.

INTRODUCTION

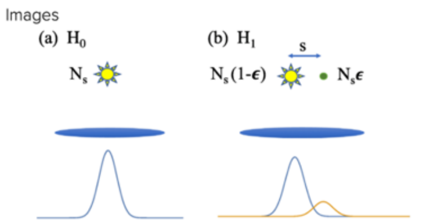
The ability to extract information from faint light sources is vital across a wide range of applications, including molecular imaging [1], satellite surveillance [2], and astrophotography [3–7]. Enhancing key performance metrics, such as resolution and signal-to-noise ratio (SNR), is essential to improve image quality and expand the scope of observable phenomena. Such improvements could deepen our understanding of molecular dynamics, enable the detection of distant astronomical objects, and advance scientific discovery more broadly.

In conventional optical imaging systems, the recorded data are typically limited to intensity measurements



Quantum Hypothesis Testing for Exoplanet Detection

Zixin Huang and Cosmo Lupo
Phys. Rev. Lett. **127**, 130502 – Published 23 September 2021



ϵ depends on:

1. angular separation between the star and the planet,
2. the brightness ratio of the two objects, and
3. the number of photos collected by the telescope.

PHYSICAL REVIEW LETTERS **129,** 180502 (2022)

Identifying Objects at the Quantum Limit for Superresolution Imaging

Michael R. Grace and Saikat Guha
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We consider passive imaging tasks involving discrimination between known candidate objects and investigate the best possible accuracy with which the correct object can be identified. We analytically compute quantum-limited error bounds for hypothesis tests on *any* library of incoherent, quasimonochromatic objects when the imaging system is dominated by optical diffraction. We further show that object-independent linear-optical spatial processing of the collected light exactly achieves these ultimate error rates, exhibiting scaling superior to spatially resolved direct imaging as the scene becomes more severely diffraction limited. We apply our results to example imaging scenarios and find conditions under which superresolution object discrimination can be physically realized.

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Adaptive Super-Resolution Imaging Without Prior Knowledge Using a Programmable Spatial-Mode Sorter

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Compiled May 15, 2024

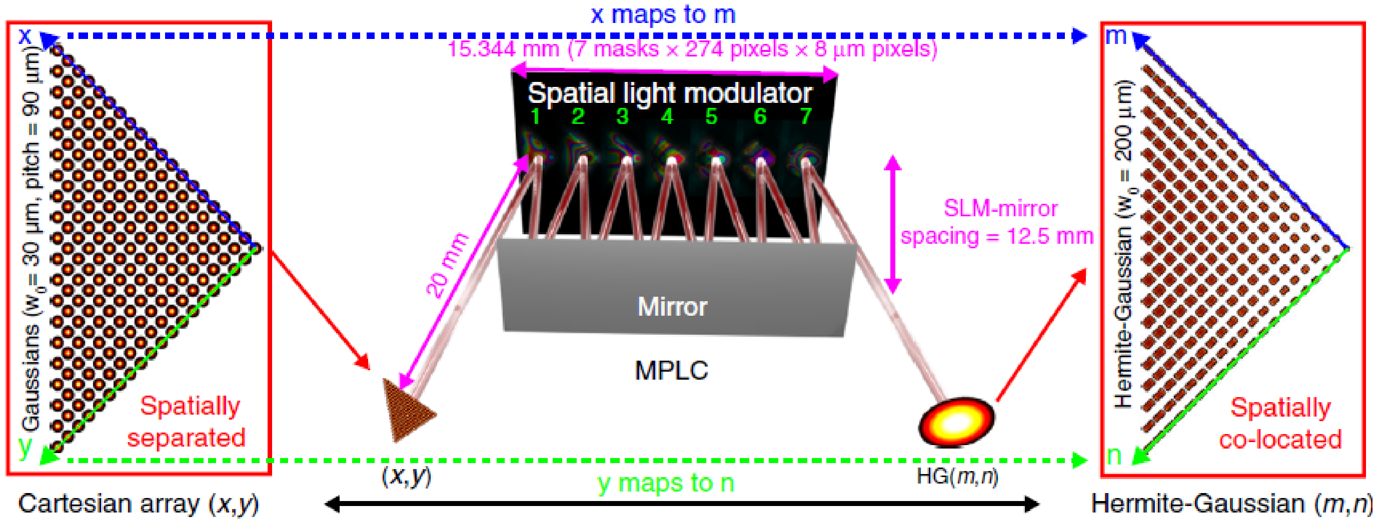
We consider an imaging system tasked with estimating the angular distance between two incoherently-emitting sub-Rayleigh-separated point sources, without any prior knowledge of the centroid of the constellation and with a fixed collected-photon budget. It was shown theoretically that splitting the optical recording time into two stages—focal-plane direct imaging to obtain a pre-estimate of the centroid, and using that estimate to center a spatial-mode sorter followed by photon detection of the sorted modes—can achieve 10 to 100 times lower mean squared error in estimating the separation [1]. In this paper, we demonstrate this in proof-of-concept, using a programmable mode sorter we have built using multi-plane light conversion (MPLC) using a reflective spatial-light modulator (SLM) in an emulated experiment where we use a single coherent source to character-

tion constraint often referred to as the Rayleigh limit (θ_{res}) [2], beyond which the features of the scene become exceedingly hard to resolve. The limitation in resolution stems from diffraction effects arising due to the finite aperture of the imaging system, as illustrated in Fig.1. For a telescope-like system with a circular aperture, this limit is defined as follows:

$$\theta_{res} = 1.22 \times \frac{\lambda \times f}{D}, \quad (1)$$

where λ is the wavelength of the incoming light, f is the focal length of the optical system, and D is the diameter of the entrance pupil of the optical system, which is dictated by the finite circular aperture. An analogous diffraction limit is encountered in microscopy due to the finite numerical aperture of a circular objective lens.

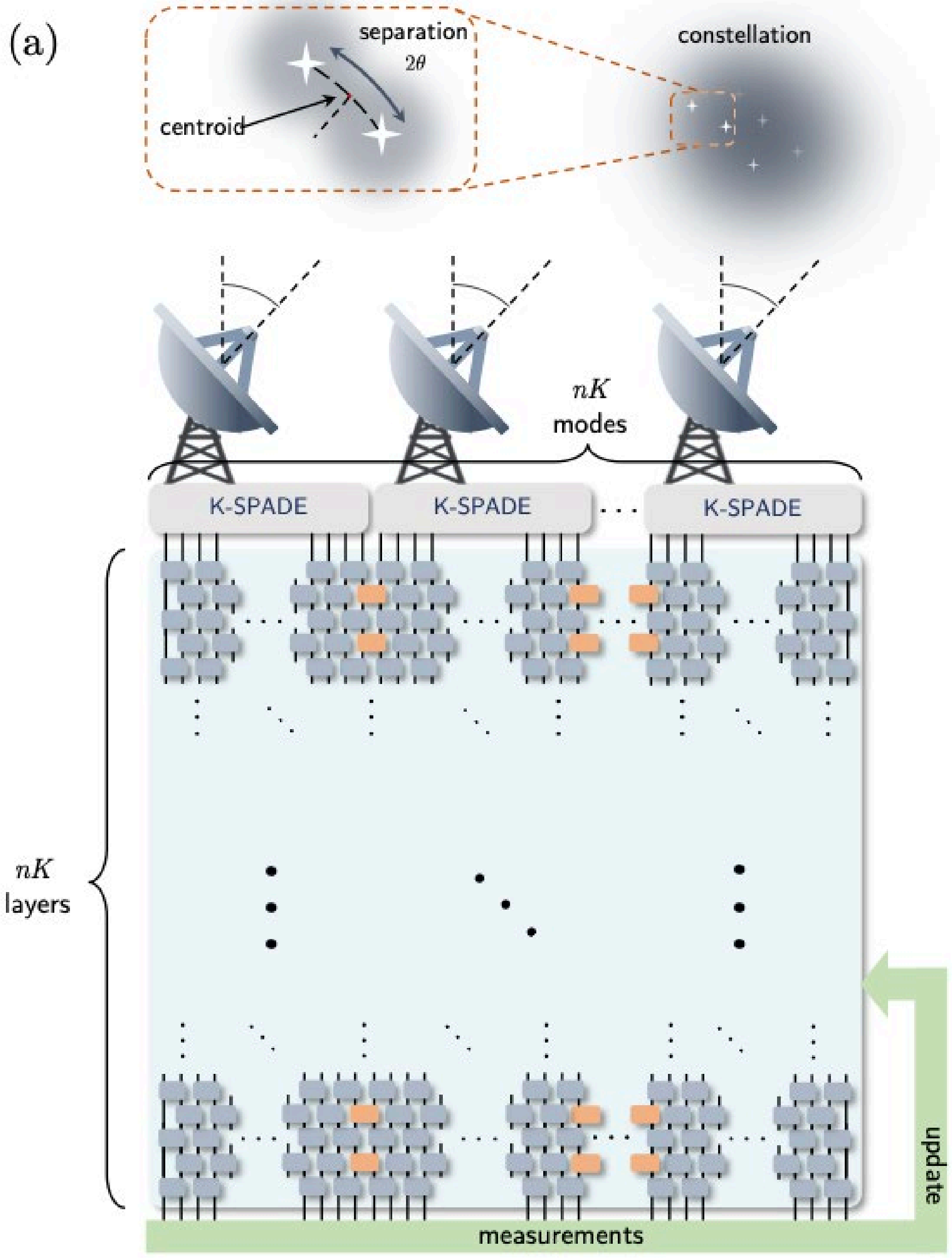
Mode Sorting



Pixelated Array → Mode sorter → PSF Eigenstates

https://www.nature.com/articles/s41467-019-09840-4

https://journals.aps.org/prx/pdf/10.1103/PhysRevX.6.031033



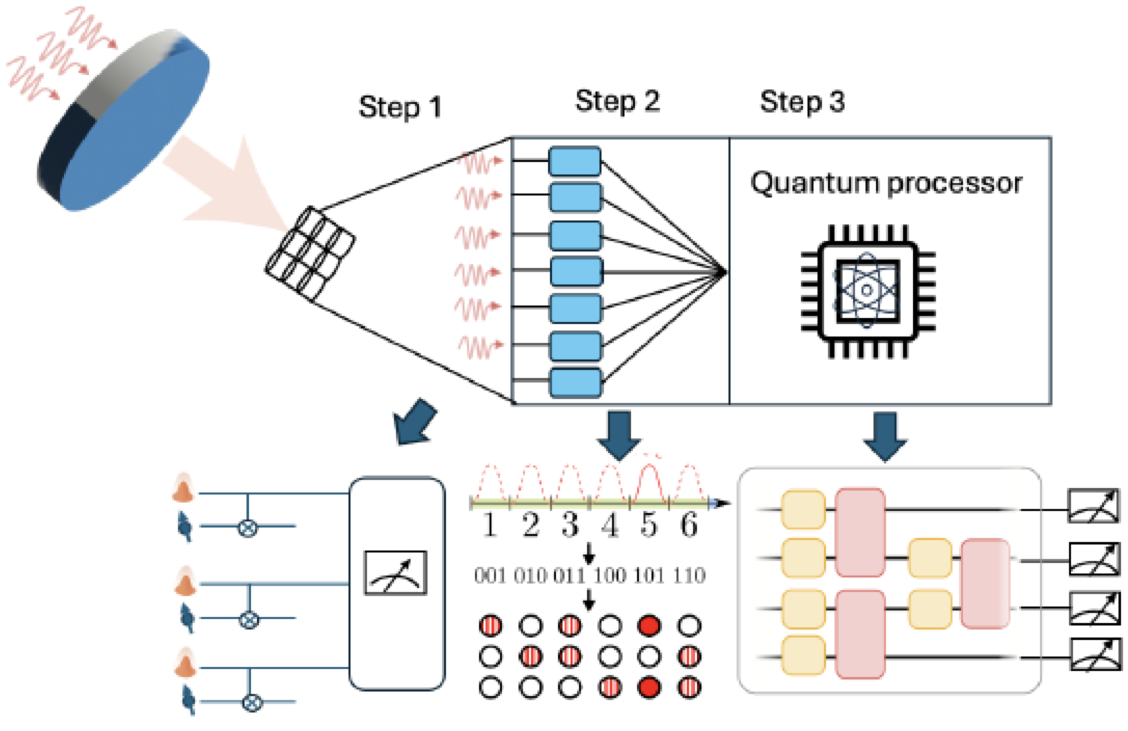
Long-baseline interferometry using mode sorting

Light from a stellar scene is being collected at n telescope sites. Each telescope employs a K-mode mode sorter front-end that decomposes the incoming optical field into K orthogonal spatial modes of a chosen basis. The sorted modes, across all the telescope sites, is fed into a general nK-mode linear-optical processor.

https://arxiv.org/abs/2406.16789

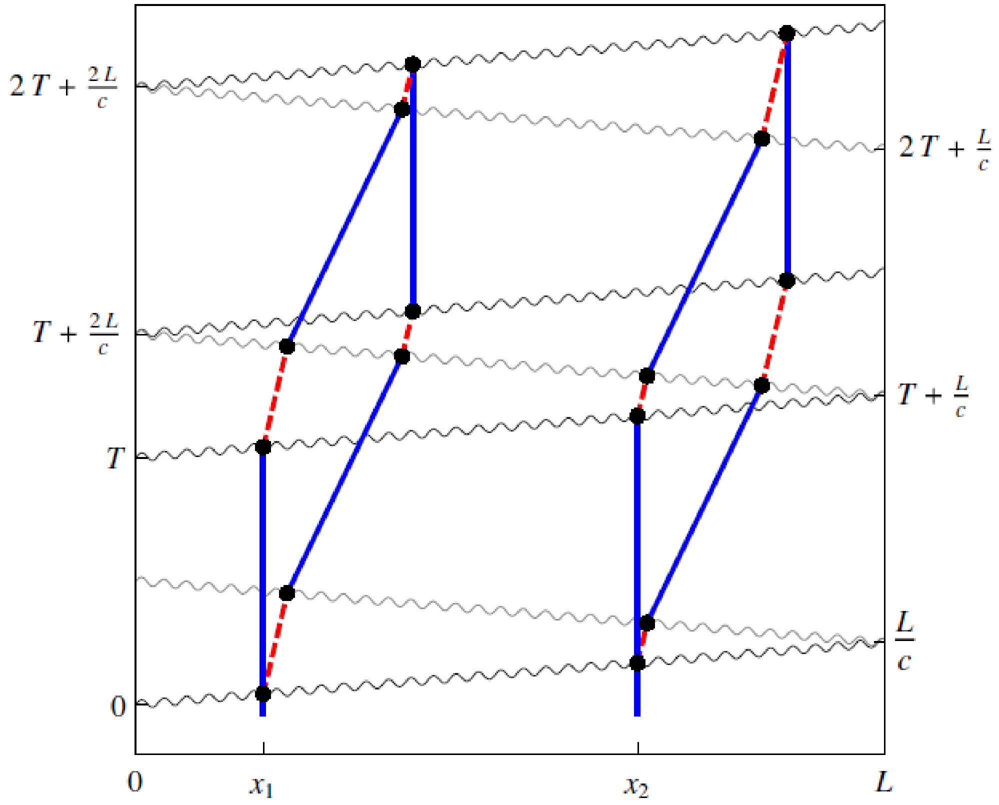
Quantum processor-enhanced imaging

Sketch of a quantum processing enhanced imaging system. Step 1: The quantum state of the light collected through the optics is is mapped to a qubit register in a heralded way by means of qubit-photon controlled gates followed by joint detection of the photonic modes. Step 2: For a weak optical signal where only a single photon is coherently distributed across the detection modes, the information can be compressed into a logarithmic number of processing qubits using a unary-to-binary encoding. Step 3: Quantum processing of the received light to extract the parameters of interest with higher SNR than possible from classical direct detection and post-detection processing.



Mokeev+ in preparation for Physical Review X

Quantum Gravity Gradiometer for Gravity Measurements



A space-time diagram of the proposed configuration of a differential measurement between two atom interferometers beginning at positions x_1 and x_2.

This figure represents two atom interferometers. Combined, they become a quantum gravity gradiometer.

Used for: static, dynamic, mergers, dark energy, dark matter, and stochastic gravitational wave signals

journals.aps.org/prl/pdf/10.1103/PhysRevLett.110.171102