

Experimental Subdiffraction Source Discrimination Enabled by Spatial Demultiplexing and Single-Photon Detectors

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We experimentally demonstrate a universal, parameter-independent test for asymmetric source discrimination below the diffraction limit. The test exploits spatial-mode demultiplexing (SPADE) and single-photon detection to discriminate the presence of a faint source in the vicinity of a brighter one. We develop a complete theory of the test in the presence of arbitrary modal crosstalk and show that the crosstalk-affected test retains a favorable error exponent over diffraction-limited direct imaging, provided that the crosstalk remains below a threshold $C_{\max} \simeq 1/9$. This establishes a quantitative condition under which the subdiffraction advantage of SPADE survives realistic imperfections. We experimentally test the scheme for a range of source separations and intensity ratios, without requiring prior knowledge of these parameters. The measured false-negative error rates are in good agreement with the theoretical model and systematically outperform direct imaging. These results demonstrate that SPADE provides a robust and experimentally accessible advantage for asymmetric subdiffraction hypothesis testing in the photon-starved regime, even in the presence of realistic modal crosstalk.

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Resolving images with high precision is a fundamental requirement across multiple fields and applications, such as bioimaging [1,2], nanotechnologies [3], and astronomy [4]. The natural limit on the resolution imposed in the optical domain by the diffraction of light passing through finite apertures has pushed the scientific community into a successful quest to find feasible “subdiffraction” imaging techniques [5–11]. As an example, for exoplanet observations, resolving a faint planetary signal in close angular proximity to a bright host star poses a particularly stringent subdiffraction imaging problem [12]. In this context, established approaches such as coronagraphy [13,14] and starshades [15] aim to physically block the starlight to reduce the contrast ratio of the imaged scene. In recent years, spatial-mode demultiplexing (SPADE) [16,17] has garnered significant attention as an alternative subdiffraction parameter estimation technique both theoretically [18–21] and experimentally [22–30] for its applicability to biosensing, surface metrology, and astronomical observations. By projecting the incoming field onto an optimized set of transverse

spatial modes and measuring them via photon counting, SPADE separates the signal and background at the level of the measurement, rather than through optical shading. This approach exploits the efficiency of modern single-photon detection technologies, while being grounded on the theoretical framework of quantum information and sensing.

SPADE has been found to be a quantum-optimal technique for several tasks at the subdiffraction regime, including source discrimination [31–34] and in particular exoplanet detection [35,36], where the goal is to correctly guess the presence of an exoplanet orbiting a star through statistical hypothesis testing (HT) on the observed data. Employing the conventional terminology of standard binary decision HT, the absence or presence of an exoplanet constitutes the two hypotheses, H_0 and H_1 , respectively. Any test has a probability of error, either by guessing H_1 when H_0 is true (type I error or “false positive”), or by guessing H_0 when H_1 is true (type II error or “false negative”). Because of the rarity of exoplanets, a type II error is more costly than a type I. Therefore, the problem of exoplanet detection is best studied within the framework of an asymmetric HT that aims to minimize the type II error probability β while keeping the type I error probability α bounded. Within this framework, SPADE achieves a theoretical rate of false negatives well below what can be achieved by diffraction-limited direct imaging [35,36].

In moving from theory to experiments, the presence of noise and modal crosstalk must be taken into consideration, since these drastically hinder the efficiency of SPADE-based

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measurements [26,31,37]. Specifically, crosstalk is quantified by a nonvanishing probability of observing photons in a spatial mode at the output of the demultiplexer that is different from the input signal, and it is mainly caused by the imperfections in the device fabrication process. Naive tests that work for ideal demultiplexers, generally based on checking whether photons can be detected in higher order modes, do not work in the presence of crosstalk, even if small. In this direction, some authors have proposed tests that tolerate crosstalk. Schlichtholz *et al.* [38] have proposed a crosstalk-tolerant test for sources of equal intensities that requires some prior knowledge on the source separation. Zanforlin *et al.* [39] provided a proof-of-principle HT experiment using a two mode interferometer that is sub-optimal with respect to SPADE and requires prior knowledge of the physical parameters. Linowski *et al.* [40] have theoretically proposed a test that is crosstalk-tolerant and does not depend on the intensity ratio between the two sources. Although SPADE-based HT employing a response thresholds calibrated on the measurement apparatus was recently performed [41], an experimental demonstration of the advantage provided by SPADE in source-independent asymmetric HT in the presence of crosstalk is still lacking.

This Letter fills this gap. The experiment is supported by a complete theory of HT, including a generally noninvertible model of crosstalk. The test we implement is an adaptation to our crosstalk model of the test theoretically proposed in Ref. [40], which is universal as it does not depend on the physical parameters. We show that the test beats the subdiffraction limit, as it achieves a type II error probability β that is lower than the error rate of an ideal direct-imaging-based test. We find a “superresolution threshold” for the performance of SPADE-based detection below which SPADE outperforms direct imaging. We show that the probability of incorrectly observing a photon in higher modes is the major cause of reduction of the error rate, which must be smaller than the threshold value $C_{\max} = 1/9$ for SPADE to outperform direct imaging. As a comparison, we estimated the crosstalk of our demultiplexer $C \simeq 0.01$ to be 1 order of magnitude lower than this threshold, while state-of-the-art mode demultiplexers can achieve 2 orders of magnitude smaller crosstalk factors $C \simeq 3 \times 10^{-3}$ [42].

Theory and methods—Let us first review the theory of asymmetric HT applied to exoplanet detection as known in the literature and then introduce our model of crosstalk and theoretical results. Employing the formalism of quantum detection theory, the two hypotheses of absence H_0 or presence H_1 of the exoplanet are represented by two density matrices ρ_0 and ρ_1 . Let ϵ be the intensity ratio I_B/I_A between the exoplanet and the main source, d_a their distance normalized over the width of the point-spread function (PSF) of the optical system, which for simplicity we assume to be Gaussian, with $\epsilon, d_a \ll 1$. Let α and β be the probabilities of type I and type II errors, respectively, of a given test. In asymmetric HT, a quantum optimal test over

an asymptotically large number $N \gg 1$ of copies attains, by the quantum Stein lemma, a type II error probability $\beta \simeq \exp[-ND_Q(\rho_0||\rho_1)]$ that decays exponentially with N [43,44], where

$$D_Q(\rho_0||\rho_1) \simeq \epsilon d_a^2/4 \quad (1)$$

is the quantum relative entropy between ρ_0 and ρ_1 , representing the error exponent of the test [36]. In the same asymmetric HT scenario, any given test based on a measurement whose outcomes x follow a probability distribution $p_i(x) \equiv p(x|H_i)$, conditioned on hypothesis H_i , attains for large N at best $\beta \simeq \exp[-ND(p_0||p_1)]$, where $D(p_0||p_1) \leq D_Q(\rho_0||\rho_1)$ is the relative entropy between the two distributions.

In the remainder of this Letter, we identify with N the total number of photons that can be detected in a given integration time. A test based on direct imaging with an ideal camera attains a relative entropy [40]

$$D_{DI}(p_0||p_1) \simeq \epsilon^2 d_a^4/4, \quad (2)$$

where DI stands for Direct Imaging, with a suboptimal scaling both in d_a and ϵ [45]. On the other hand, ideal SPADE detection, projecting onto the Hermite-Gauss (HG) basis $\{HG_{ij}\}$ for a Gaussian PSF, is known to saturate the quantum Stein lemma in Eq. (1) [36,40]. In particular, for small intensity ratios ϵ and normalized distances d_a , we can approximate the probabilities $p_j = [P(0|H_j), P(1|H_j)]$ of observing under hypothesis H_j a photon in mode HG_{00} or a photon in either mode HG_{01} or HG_{10} as

$$p_0 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad p_1 = \begin{pmatrix} 1 - \epsilon d_a^2/4 \\ \epsilon d_a^2/4 \end{pmatrix}, \quad (3)$$

as shown in Sec. S2 of Supplemental Material [46]. Therefore, the outcomes follow Bernoulli distributions whose relative entropy is quantum optimal, that is, $D_{SD}(p_0||p_1) = -\ln[P(0|H_1)] \simeq \epsilon d_a^2/4 = D_Q(\rho_0||\rho_1)$, where SD stands for Spatial Demultiplexing [47].

We now introduce our crosstalk model via an effective incoherent mixing of the outcome probabilities p_j via a stochastic matrix [48],

$$p'_j = \begin{pmatrix} P'(0|H_i) \\ P'(1|H_i) \end{pmatrix} = \begin{pmatrix} C_{00} & C_{01} \\ C_{10} & C_{11} \end{pmatrix} \begin{pmatrix} P(0|H_i) \\ P(1|H_i) \end{pmatrix}, \quad (4)$$

with $C_{0k} + C_{1k} = 1$ for $k = 0, 1$. We can assume without loss of generality $C_{10}, C_{01} \leq 1/2$, where the equality corresponds to a purely noisy measurement. Notice that generally, the transformation in Eq. (4) is not invertible, and therefore extends to nonunitary channels, e.g., when the mode projection is coupled with some hidden and unobserved degrees of freedom. We evaluate in Sec. S4 of Supplemental Material the relative entropy between the two

crosstalk-affected Bernoulli distributions with probabilities p'_0 and p'_1 for $C_{10}, C_{01} \gg \epsilon d_a^2$,

$$D_{SD}(p'_0||p'_1) \simeq \frac{1}{32} \epsilon^2 d_a^4 \frac{(1 - C_{01} - C_{10})^2}{C_{10}(1 - C_{10})} \simeq \frac{\epsilon^2 d_a^4}{32 C_{10}}, \quad (5)$$

where in the last step we assume $C_{10}, C_{01} \ll 1$ [46]. The relative entropy $D_{SD}(p'_0||p'_1)$ vanishes when $C_{10} = C_{11}$, i.e., when the probability of observing a photon in either mode HG₁₀ or HG₀₁ becomes independent of the source. By comparing D_{DI} in Eq. (2) and D_{SD} in Eq. (5), we see that SPADE asymptotically outperforms direct imaging in asymmetric HT, provided that the crosstalk satisfies

$$\frac{(1 - C_{01} - C_{10})^2}{32 C_{10}(1 - C_{10})} \geq \frac{1}{4}. \quad (6)$$

In Fig. 1 we plot the relative entropies for SPADE and direct imaging, showcasing the higher performance of SPADE with respect to direct imaging in the low crosstalk regime. The lower panel of Fig. 1 shows the existence of a “superresolution threshold” on the crosstalk below which SPADE outperforms direct imaging. The factor C_{10} plays a major role in determining the efficiency of SPADE, and there is a maximum value of crosstalk allowed, $C_{10} \leq C_{\max} = 1/9$, obtained imposing $C_{01} = 0$ in Eq. (6), for SPADE to outperform direct imaging, while any value of C_{01} is acceptable.

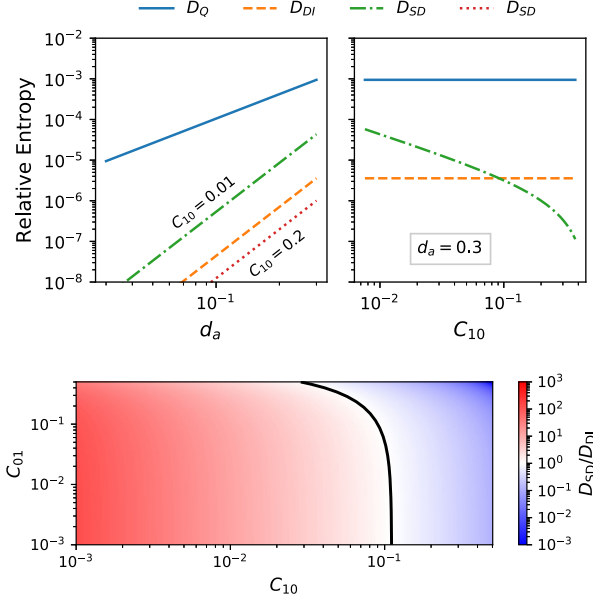


FIG. 1. Top: plots of the quantum relative entropy D_Q in Eq. (1) (solid blue) and of the relative entropies for direct imaging D_{DI} in Eq. (2) (orange dashed) and SPADE detection D_{SD} in Eq. (5) (green dash-dotted and red dotted) while varying the distances d_a (left) and the crosstalk C_{10} (right). $\epsilon = 0.042$, $C_{01} = C_{10}$. Bottom: plot of the ratio D_{SD}/D_{DI} while varying the crosstalk factors C_{10} and C_{01} . The black curve delimits the region where SPADE outperforms direct imaging.

We now describe the parameter-independent test based on SPADE measurement that achieves the optimal exponential scaling. The test consists in comparing the number N_1 of photons observed overall in modes HG₀₁ and HG₁₀ with a threshold value N_1^* fixed by the type I error probability α allowed, and the test rejects hypothesis H_0 if N_1 is larger than N_1^* . We can find such a threshold as the value N_1^* such that $P(N_1 > N_1^* | H_0) = \alpha$, thereby fixing the type I error probability α . Notice that N_1^* can either be measured in a previous calibration stage performed in absence of exoplanet, or exactly retrieved for large N via the ϵ - and d_a -independent expression

$$N_1^* \simeq NC_{10} + K(\alpha) \sqrt{NC_{10}(1 - C_{10})}, \quad (7)$$

where $K(\alpha) = \sqrt{2} \text{Erf}^{-1}(1 - 2\alpha)$, e.g., with $K(\alpha) = 1.65$ for $\alpha = 0.05$. Indeed, one can easily check that the expression of N_1^* in Eq. (7) coincides with the $(1 - \alpha)$ th percentile of the large- N Gaussian approximation of the binomial distribution $B(N, C_{10})$ associated with the photon count N_1 given hypothesis H_0 . We can calculate the type II error $\beta = P(N_1 \leq N_1^* | H_1)$ in the presence of crosstalk for large N if we approximate the binomial distribution $B[N, P'(1|H_1)]$, given hypothesis H_1 to a Gaussian distribution with average $\mu_1 = NP'(1|H_1)$ and variance $\sigma_1^2 = NP'(1|H_1)P'(0|H_1)$. For large N , we evaluate, in Sec. S5 of Supplemental Material,

$$\beta_{SD} \simeq \frac{1}{2} \text{Erfc} \left[\frac{\mu_1 - N_1^*}{\sqrt{2}\sigma_1} \right] \simeq e^{-ND_{SD}(p'_0||p'_1)}, \quad (8)$$

confirming the optimality of the test [46].

Experimental setup—Figure 2 shows the experimental setup. Two fiber-coupled light emitting diodes (LEDs) with a central wavelength at about 1550 nm and a bandwidth of about 80 nm (FWHM, coherence time $\tau_c = (0.44\lambda^2/c \times \text{FWHM}) \sim 4 \times 10^{-14}$ s) simulate two incoherent pointlike sources. Both LEDs are free-space collimated using two fiber collimators (FCs) and a pair of two-lens (L) systems to match the beam waist w_0 of the demultiplexer adopted for the collection ($w_0 \simeq 300 \mu\text{m}$). The waist emulates the PSF of a hypothetical imaging system coupled

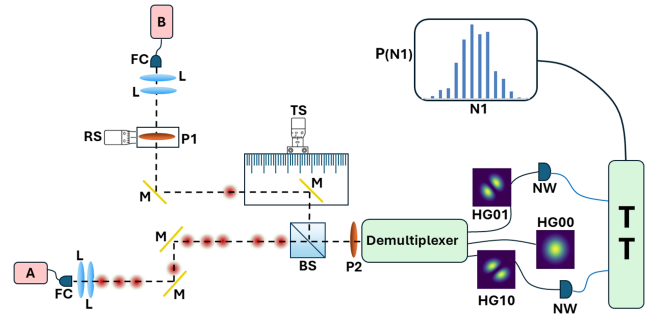


FIG. 2. Schematic representation of the measurement setup. See Letter text for a detailed description.

with demultiplexer. LED A mimics the star and B the exoplanet; both are attenuated, respectively, I_A and I_B intensities through fiber-coupled attenuators not shown in the figure. The A beam, after reflection on two steering mirrors (M), impinges on a cube beam splitter (BS) to be combined with the B beam and, after crossing a fixed polarizer (P2), is coupled with the free-space input port of a HG demultiplexer (PROTEUS-C model from Cailabs with 300 μm input waist). The B beam crosses a polarizer (P1) mounted on a motorized rotation stage (RS) and two steering mirrors, the second of which is mounted on a micrometer translation stage (TS). It is then reflected on the BS, where it is combined with the A beam. Both beams cross a fixed polarizer (P2) to overcome the dependency of detectors efficiency on photon polarization when the RS is rotated. The B beam is coupled with the HG demultiplexer too. The translation stage moves the B beam and in turn changes the separation between the sources. Furthermore, by rotating the RS, the intensity of the B beam changes and in turn the intensity ratio $\epsilon = I_B/I_A$ changes. The intensity and position of A stays fixed during the experiment. Upon entering the demultiplexer, the two beams are first decomposed in the lowest-order HG modes: HG₀₀, HG₀₁, HG₁₀, HG₁₁, HG₀₂, HG₂₀, and finally coupled with single-mode (SM) fibers. The fibers corresponding to HG₀₁ and HG₁₀ are coupled to He-cooled superconducting nanowires (NWs) single-photon detectors by means of SM fibers equipped with polarization paddles to align the photons' polarization with the NW, whose detection efficiency is strongly polarization-dependent. After the photons reach the nanowires, they generate electrical signals that, if exceeding the set threshold, are counted by a time tagger (TT) in the determined temporal window of 10 ms. The detector dark count is 20 Hz, the system efficiency is about 80% and reset time is about 100 ns.

Results and discussion—To measure the type II error probability β of our setup, we repeat the test a number M of times, and we estimate the real value of β as the observed fail rate $\beta_{\text{exp}} = (\text{number of fails})/M$, for different values of ϵ , d_a and N . We choose $M = 100$ in our analysis of β_{exp} while varying d_a , $M = 200$ varying ϵ and $M = 1000$ while varying N to collect more statistics as we expect a smaller fail rate. For each repetition, we count the number N_1 of photons in the HG₀₁ and HG₁₀ modes in a fixed integration window of 10 ms. We calculate the thresholds N_1^* required to perform the test as the 95th percentile of the counts measured in absence of the exoplanet in a prior calibration stage, out of $M = 300$ repetitions for the test with fixed N , and $M = 1000$ for the test varying N , while we estimate its uncertainty via bootstrapping. Notice that fixing the duration of the integration time, instead of the total number of counts, allows us to estimate N_1^* employing only two detectors for the HG₁₀ and HG₀₁ modes, instead of the three normally required to also measure the counts in HG₀₀. Although this experimental compromise introduces some

statistical fluctuations in the total number of photons N and generally reduces the performance of the test, we prove in Sec. S6 of Supplemental Material that its effect is negligible in the small-crosstalk regime [46].

The results are shown in Fig. 3. We compare the measured values of the error rates β_{exp} with the theoretical expression of β_{SD} in Eq. (8), and with an ideal direct imaging test, described in Sec. S4 in Supplemental Material and simulated via Monte Carlo methods, yielding the error rate β_{DI} [46],

$$\beta_{\text{DI}} = \frac{1}{2} \text{Erfc} \left(\frac{\sqrt{N} \epsilon d_a^2 - K(\alpha) \sqrt{2}}{2(1 - \epsilon d_a^2)} \right) \simeq e^{-N D_{\text{DI}}(p_0 \| p_1)}. \quad (9)$$

We observe a good match between theory and experiment, with the experimental SPADE-based test reliably outperforming the ideal direct-imaging-based simulated test. The uncertainties of the experimental points β_{exp} are estimated from the standard deviation of the binomial distribution $B(\beta_{\text{exp}}, M)$. To obtain the theoretical curves for SPADE in panels (a) to (d) from Eq. (8), we had to estimate C_{10} , C_{01} , and N . To measure N , employing only the two available detectors, we coupled one with mode HG₀₀ and the other with mode HG₀₁ for $d_a = 0$. Then we counted the number of photons in the HG₀₀ mode plus twice the number of photons in the HG₁₀ mode in 10 ms as function of ϵ obtaining N between 1010 ± 34 (when $\epsilon = 0$) and 1095 ± 37 (when $\epsilon = 0.096$). This procedure is justified by the fact that the demultiplexer was aligned at a 45° angle with the sources. Known N , and evaluated $N_1^* = 16 \pm 1$ from the data without exoplanet, we could estimate $C_{10} \simeq 0.010 \pm 0.001$ through Eq. (7). Remarkably, this value of crosstalk falls within the region of $C_{10} < 1/9$ for which SPADE detection largely outperforms direct imaging, as shown in Eq. (6) and Fig. 3. Finally, as expected from Eq. (5), the dependency of the theoretical curve on C_{01} is negligible for such small degrees of crosstalk, so we chose $C_{01} = C_{10}/2$ to be consistent with a balanced crosstalk effect, as per vendor specifications, according to our model of effective crosstalk described in Sec. S3 in Supplemental Material [46]. We notice from Fig. 3 that the error rates predicted and measured are relatively high due to the short 10 ms integration window, corresponding to $N \simeq 10^3$ overall photon detected. This is to be expected, since in our experimental conditions the scaling factor of the rate exponent is of the order of $\epsilon^2 d_a^4 \lesssim 10^{-5}$.

For the measurements for different integration times in Fig. 3(e), we considered larger values of ϵ and d_a , with the scaling factor $\epsilon^2 d_a^4 \simeq 4 \times 10^{-3}$, to achieve the asymptotic regime for smaller N . Once again we first estimated the threshold values N_1^* , different for each N , from the counts in absence of exoplanet, obtaining the values $N_1^* = 6, 10, 14, 17, 21$, and uncertainties estimated to be below the unit via bootstrapping. In turn, from the experimental error rates $\beta_{\text{SD}}^{\text{exp}}$ for different values of N , we computed

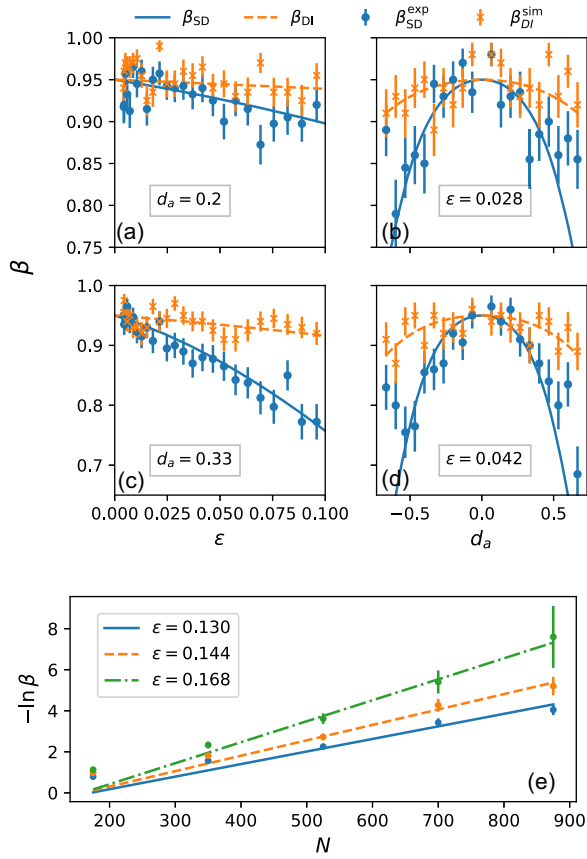


FIG. 3. (a)–(d) Plots of the theoretically predicted error rate β_{SD} for SPADE in Eq. (8) (blue solid line) and β_{DI} for direct imaging in Eq. (9) (orange dashed line), of the error rates achieved with our experimental HT (blue dots), and of the error rates achieved by a Monte Carlo simulation of an ideal direct imaging test (orange crosses) for different values of the normalized distance d_a and relative intensity ϵ . (e) Plots of the experimental error rates for increasing integration times with $d_a = 0.67$.

$C_{10} \simeq 0.017 \pm 0.001$ by first determining C_{10} from each of the linear regressions of the last three points and then averaging the resulting values. We then estimated N via $N = N_1/C_{10}$ in the absence of an exoplanet, obtaining $N = 848 \pm 34$ for the last data point. The curves in Fig. 3(e) correspond to the linear regressions of the last three estimated β_{SD}^{exp} points, with slope D_{SD} determined using the average value $C_{10} \simeq 0.017$. The larger value of crosstalk compared to the plots in Figs. 3(a)–3(d), still comfortably lower than the superresolution threshold $C_{\text{max}} \simeq 1/9$, can be caused by a different alignment of the setup. Nevertheless, the expected exponential behavior of β is experimentally confirmed.

Conclusions—We have theoretically analyzed and experimentally demonstrated a parameter-independent SPADE-based asymmetric HT for the detection of a secondary faint source in the subdiffraction regime. By assessing the measurement in terms of the relative-entropy error exponent, we have shown how modal crosstalk modifies the performance of the test and derived a general crosstalk

model that also accounts for noninvertible, nonunitary transformations. The resulting test retains the exponential scaling of the false-negative error probability associated with the crosstalk-affected SPADE measurement, without requiring prior knowledge of the source separation or intensity ratio. The analysis reveals a threshold of the crosstalk for SPADE to outperform direct imaging, and in particular a maximum value of crosstalk $C_{\text{max}} = 1/9$ allowed to reach a larger error exponent than direct imaging. In our experiment, the measured crosstalk is of order 10^{-2} , well within this favorable regime.

These results establish that the subdiffraction advantage of SPADE for asymmetric HT is not restricted to ideal mode demultiplexers, but can persist under experimentally realistic crosstalk and imperfections. More broadly, our work provides the first experimental proof of concept of HG-SPADE-based asymmetric hypothesis testing, representing a key stepping stone toward applications on real observational data [49]. While atmospheric turbulence remains the principal challenge for ground-based astronomical observations and will require adaptive optics or space-based implementations, the demonstrated parameter-independent framework is directly applicable to a broad class of photon-limited subdiffraction detection problems. Beyond faint-source and exoplanet detection, an increasing number of applications of SPADE in fields outside astronomical observation are being recently proposed, such as microscopy [51] and nanoscale sensing for advanced manufacturing [52], where reliable discrimination of weak or closely spaced optical signals is essential.

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L. S. A. performed the experiment. D. T. developed the theoretical model and performed data analysis. L. S. A. and D. T. cowrote the manuscript. C. L. supervised the project and revised the manuscript.

Data availability—There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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- [45] The hypotheses considered here are chosen so that they share the same center of brightness. This is compatible with a standard exoplanet detection scenario, in which the only prior knowledge on the system is the position of its center [40]. In some other works, a different binary decision problem is formulated, in which the position of the star is known and common in the two hypotheses, while the centers of brightness are slightly offset [36]. This different choice of hypotheses leads to a different scaling in d_a of the direct imaging relative entropy since the two hypotheses can be distinguished more easily via their offset centres. In Sec. S1 of Supplemental Material we discuss more in depth this discrepancy.
- [46] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/xkvt-xvqm> for the discussion on the two different binary tests, derivations of the probability distributions associated with SPADE, our crosstalk model, relative entropies, theoretical error rates, and the effect of measuring fixing the integration window instead of the overall photon count.
- [47] Notice that the two sources, if present, might not be aligned with the orientation of the demultiplexer, yielding non-vanishing and different probabilities of observing photons in modes HG_{01} and HG_{10} , proportional to the projections of the relative position of the exoplanet onto the demultiplexer reference frame. Measuring these probabilities separately is not required to reach quantum optimality. However, if the position of the exoplanet relative to the star is unknown, observing only one between the HG_{01} and HG_{10} would discard useful information and, in the worst case scenario, render the measurement completely blind to the presence of the exoplanet.
- [48] The effective crosstalk matrix generally depends on the physical crosstalk between the modes of the demultiplexer due to manufacturing imperfections and on the properties of the imaged system. We present in Sec. S3 of Supplemental Material a model to retrieve the effective crosstalk from the instrument crosstalk.
- [49] We recently came across a preprint article performing an on-sky experimental realization of parameter-dependent asymmetric hypothesis testing using less precise double clad fiber as a binary mode sorter [50]. Beside demonstrating the timeliness of our results, this work showcases the feasibility of on-sky SPADE measurements, and it is a further evidence that SPADE can achieve 1 or 2 order-of-magnitude increases in performance compared with direct imaging, as we demonstrate in our experiment, if state-of-the-art detection setups and optimal hypothesis testing are employed with real observational data.
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